Neutrino Physics and Dark Matter

LPHYS2223

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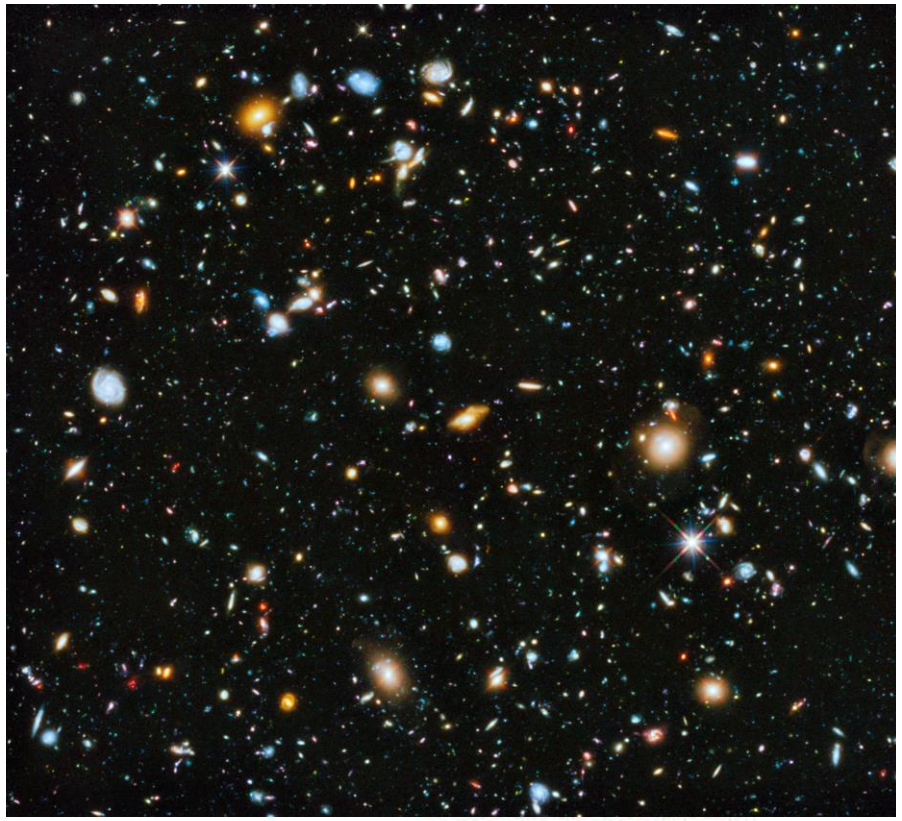
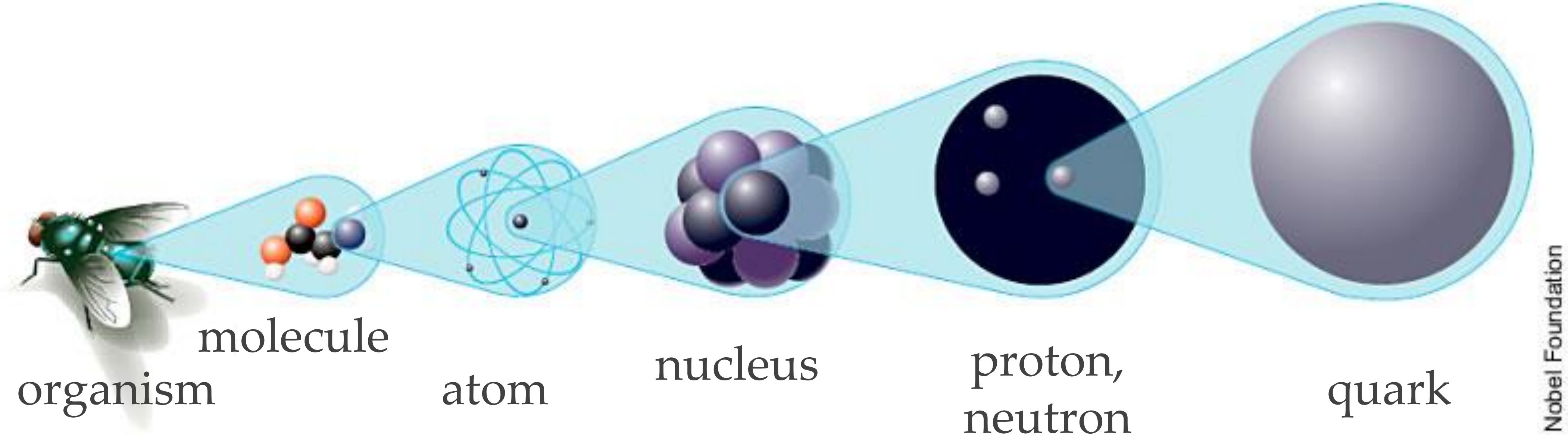
The Standard Model of Particle Physics

The elementary constituents of matter…

What are the fundamental laws of Nature, and how do they shape the universe that we live in?



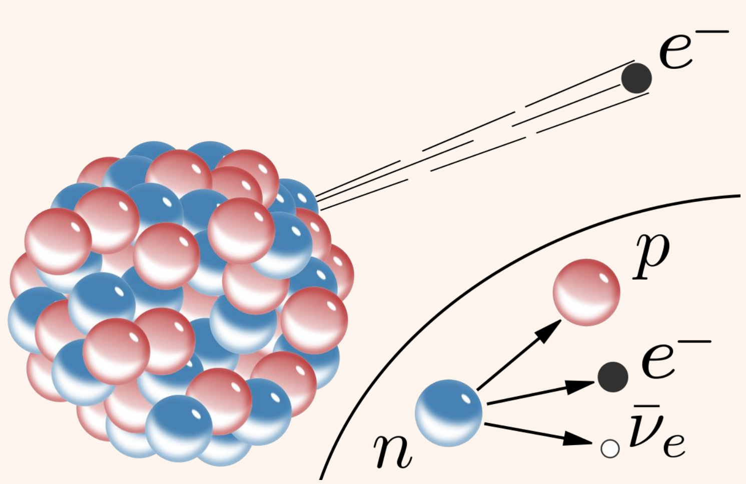


…and the forces between them

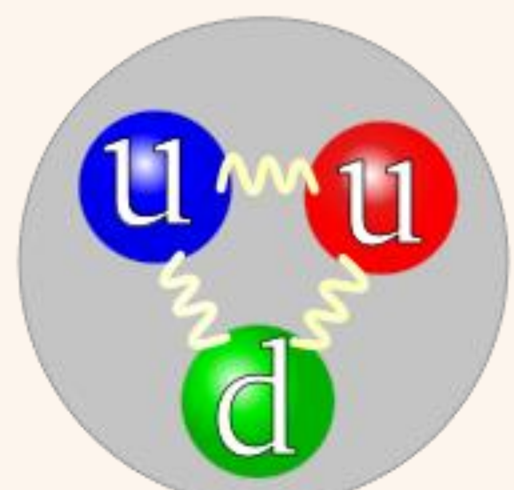
Gravity

Electromagnetism

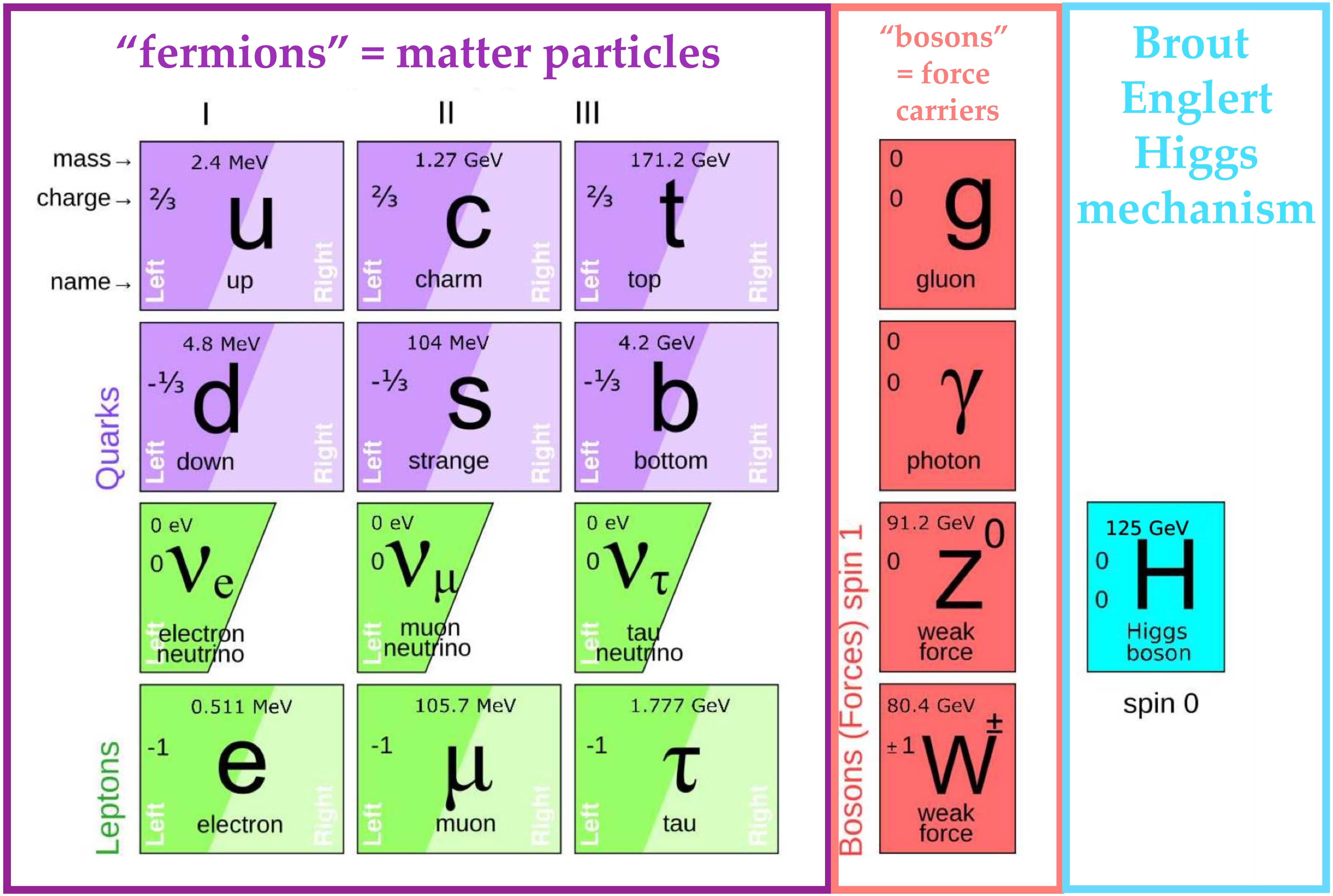
Weak Nuclear Force



Strong Nuclear Force



The Standard Model of Particle Physics



The "periodic table" of elementary particles

What the SM cannot explain

What the SM cannot explain

What is the Dark Matter made of?

- About 80% of the mass in the observable universe are made of an unknown non-luminous ("dark") substance (which is actually transparent, not dark…)

Neutrino Flavour oscillations / Neutrino masses

- Where do neutrino masses come from, and why are they so small? Why is the neutrino mixing matrix so different from the quark mixing matrix?

Baryon asymmetry of the universe

- Why was more matter than antimatter created in the "big bang"?

Big bang initial conditions

- Why is the universe so homogeneous and isotropic and spatially flat?

Theoretical consistency

- What about quantum gravity?

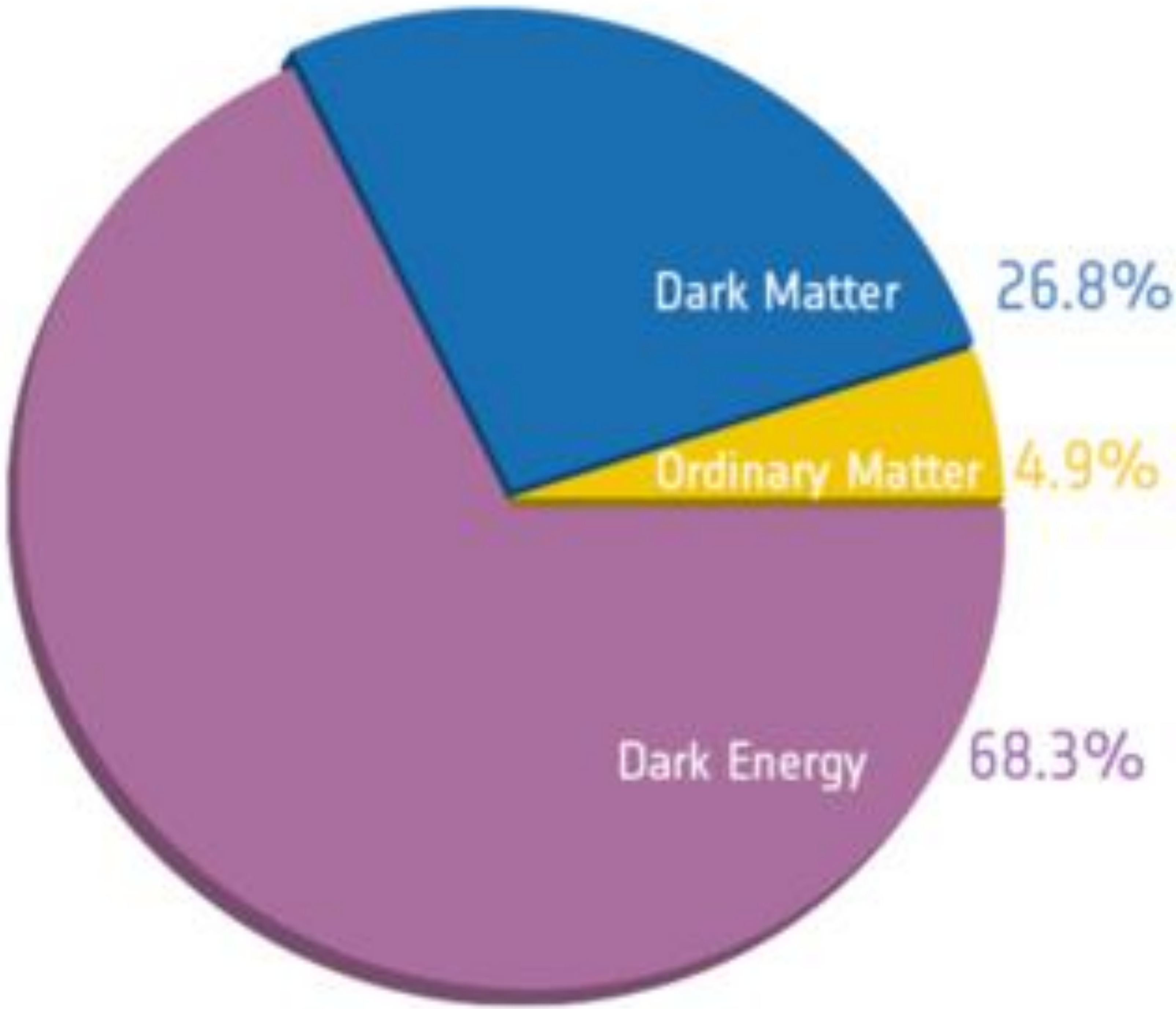
Various anomalies

- Hubble tension, muon magnitic moment…

Tuning problems and "naturalness"

- Why are parametrs so vastly different (e.g. Planck mass vs Higgs mass, value of cosmological constant…)

The Dark Matter Puzzle



Neutrinos

Why are neutrinos interesting?

Why are neutrinos interesting?

Neutrino oscillations and neutrino masses

- Neutrino masses are the only firmly established piece of evidence for physics beyond the SM seen in the laboratory.
- They may provide a key how to embed the SM in a more fundamental theory of nature

Neutrino masses and global symmetries in nature: Majorana or Dirac?

- Neutrino masses violate lepton flavour, a global U(1) x U(1) x U(1) in the SM
- Neutrinos could be their own antiparticles and thereby violate the total lepton number conservation in the SM!

Neutrino masses and discrete symmetries in nature: Origin of matter?

- Neutrino oscillations appear to violate CP – related to matter-antimatter asymmetry? ("leptogenesis")
- Neutrinos are the only elementary fermions that are known only with LH parity – key to understanding parity violation in nature?

Neutrino masses and Dark Matter

- "Sterile neutrinos" could be the Dark Matter
- Neutrinos could be a "portal" to an extended "Dark Sector"

References

Solar neutrino problem (and neutrino physics in general)

- Raffelt - Stars as a Laboratory for Fundamental Physics
  http://wwwth.mpp.mpg.de/members/raffelt/mypapers/199613.pdf
- Giunti - Neutrino Physics and Astrophysics
  http://theor.jinr.ru/~vnaumov/Eng/JINR_Lectures/books/Giunti2007.pdf

Massive neutrinos in cosmology

- Lesgourgues/Pastor - Massive Neutrinos and Cosmology, astro-ph/0603494

Sterile neutrino Dark Matter

- Boyarsky et al - Sterile Neutrino Dark Matter, arXiv:1807.07938 [hep-ph]

Leptogenesis , right handed neutrinos

- Buchmuller/Peccei/Yanagida, Leptogenesis as the Origin of Matter, hep-ph/0502169
- Canetti et al, Matter and antimatter in the universe, arXiv:1204.4186 [hep-ph]
- Drewes, The phenomenology of right handed neutrinos, arXiv:1303.6912 [hep-ph]

Neutrino Detection

Neutrino Experiments

One can distinguish them by neutrino source:

reactor, particle accelerator, sun, cosmic rays

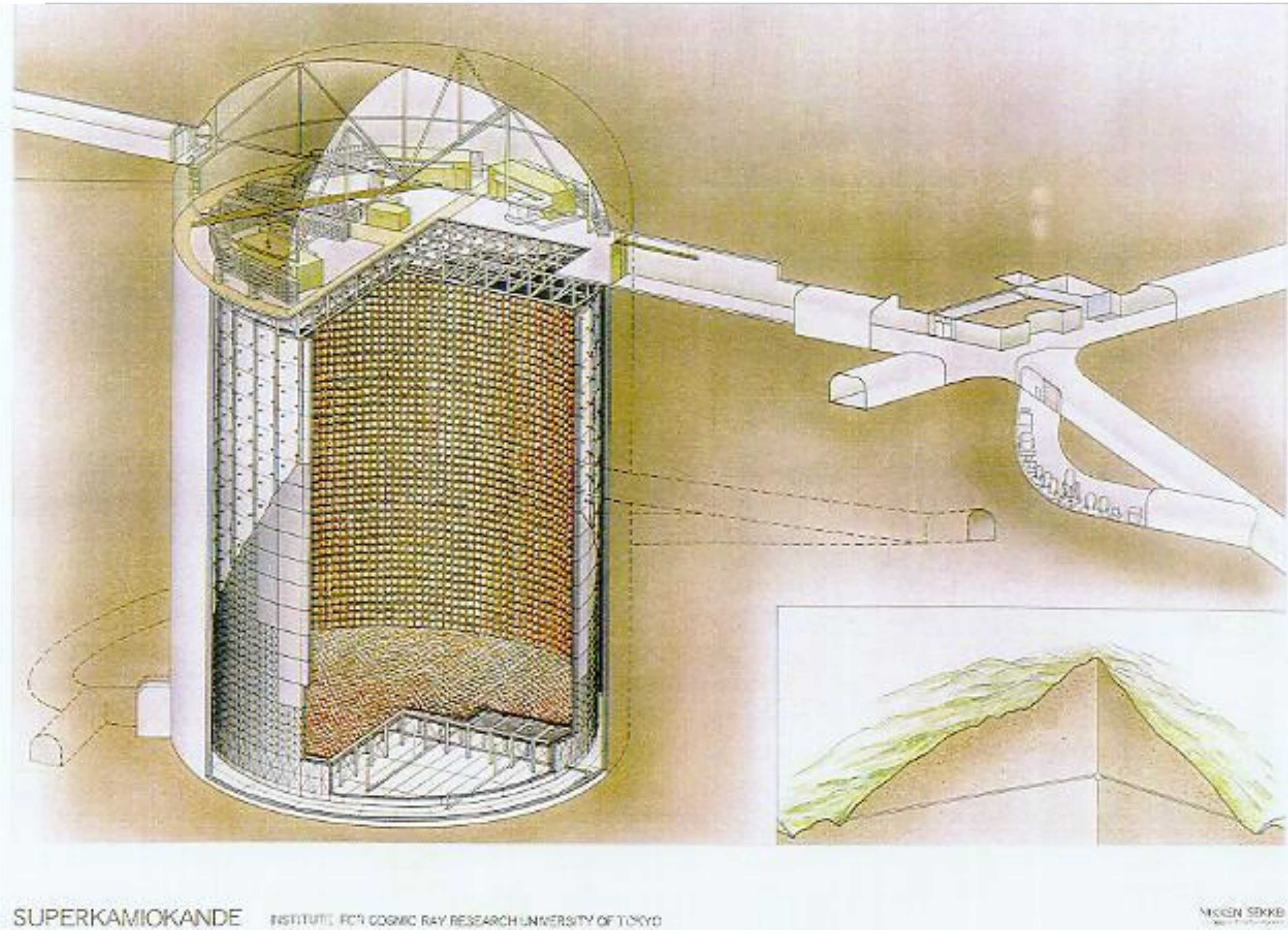
One can distinguish them by detection method:

Cherenkov light, nuclear reaction

One can distinguish them by what they observe:

appearance or disappearance

Super Kamiokande

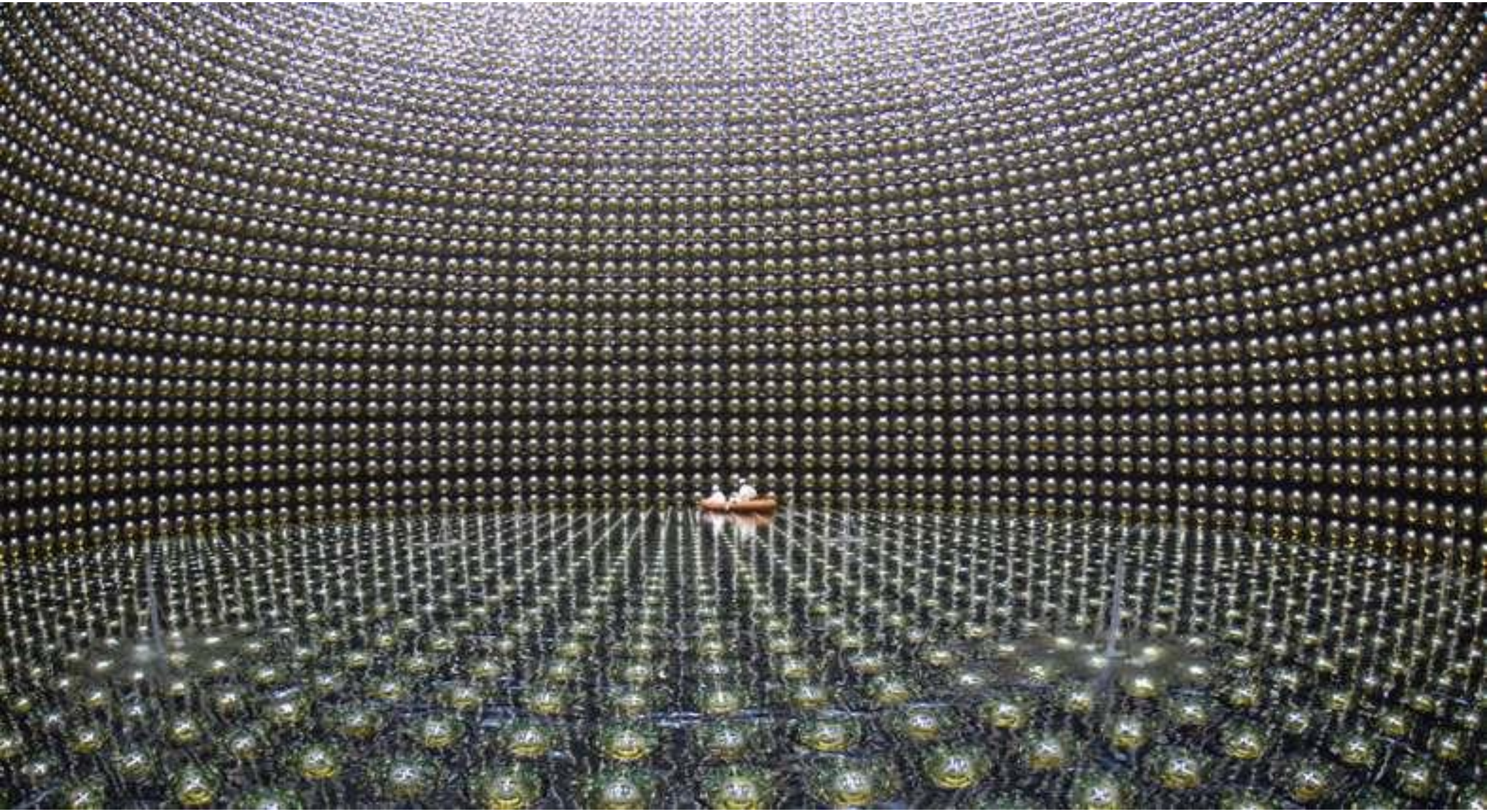


Water Cherenkov detector

Sees:

- solar neutrinos
- atmospheric neutrinos
- neutrinos from T2K beam
- reactor neutrinos

Super Kamiokande



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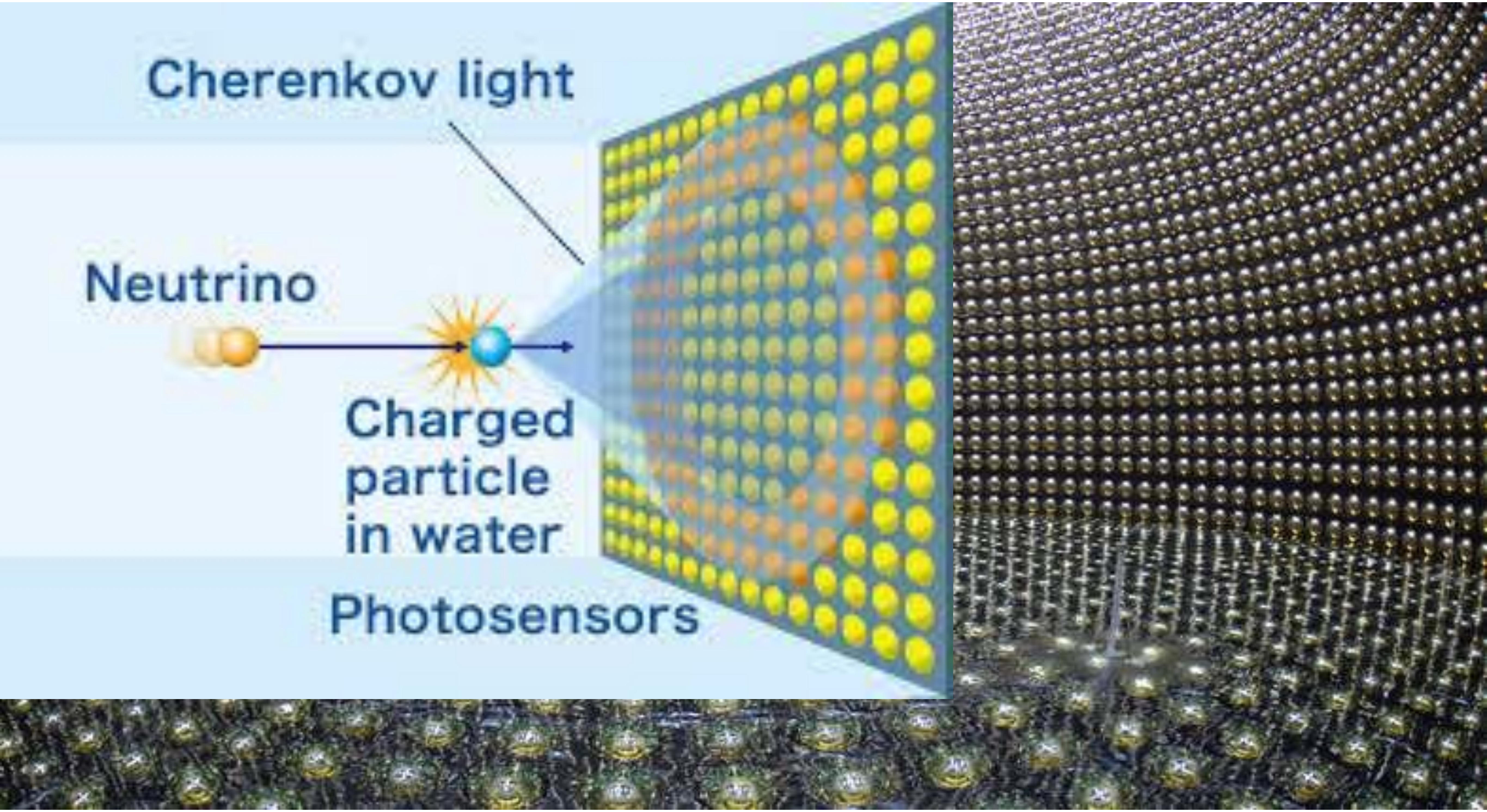

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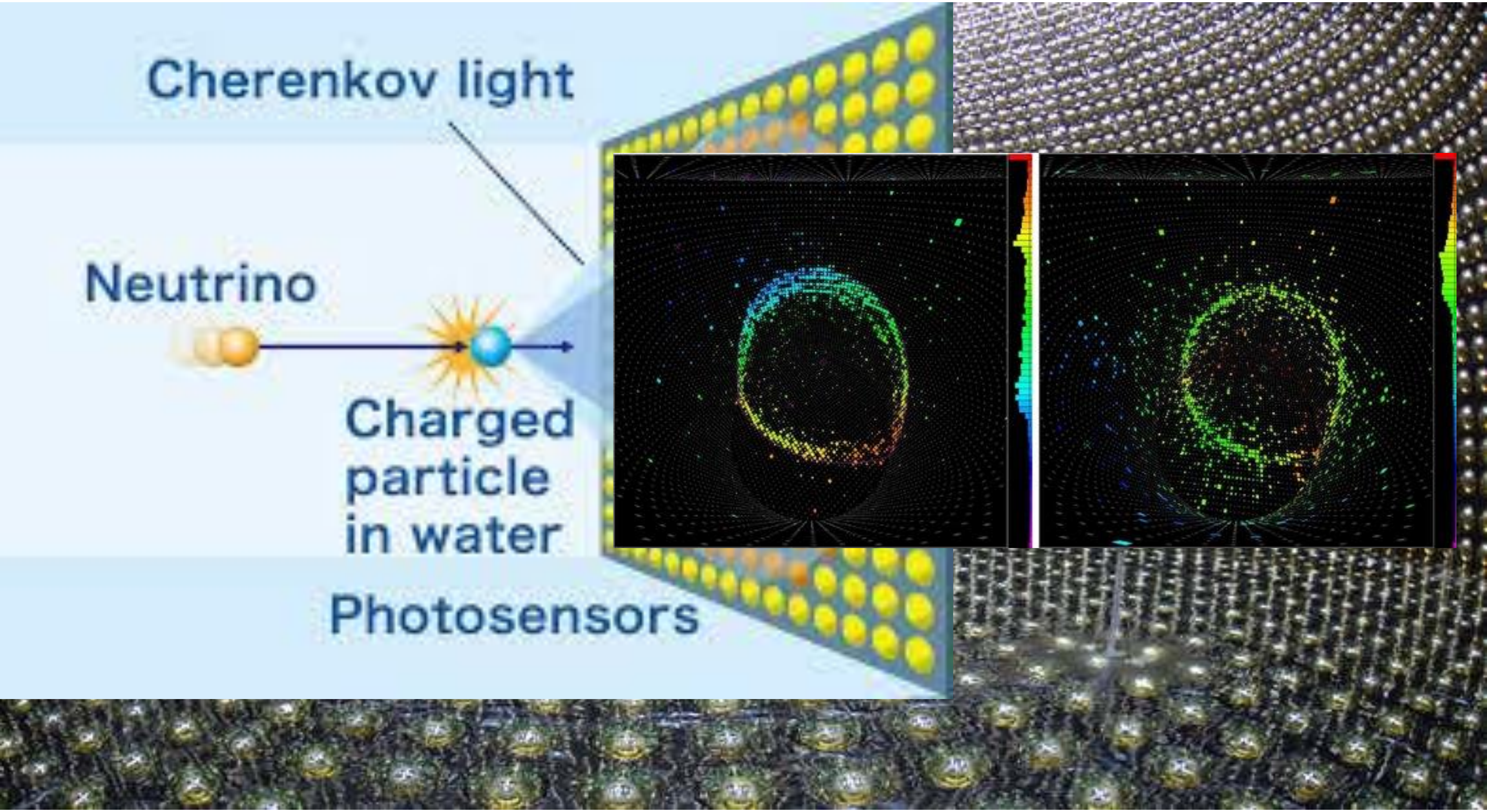
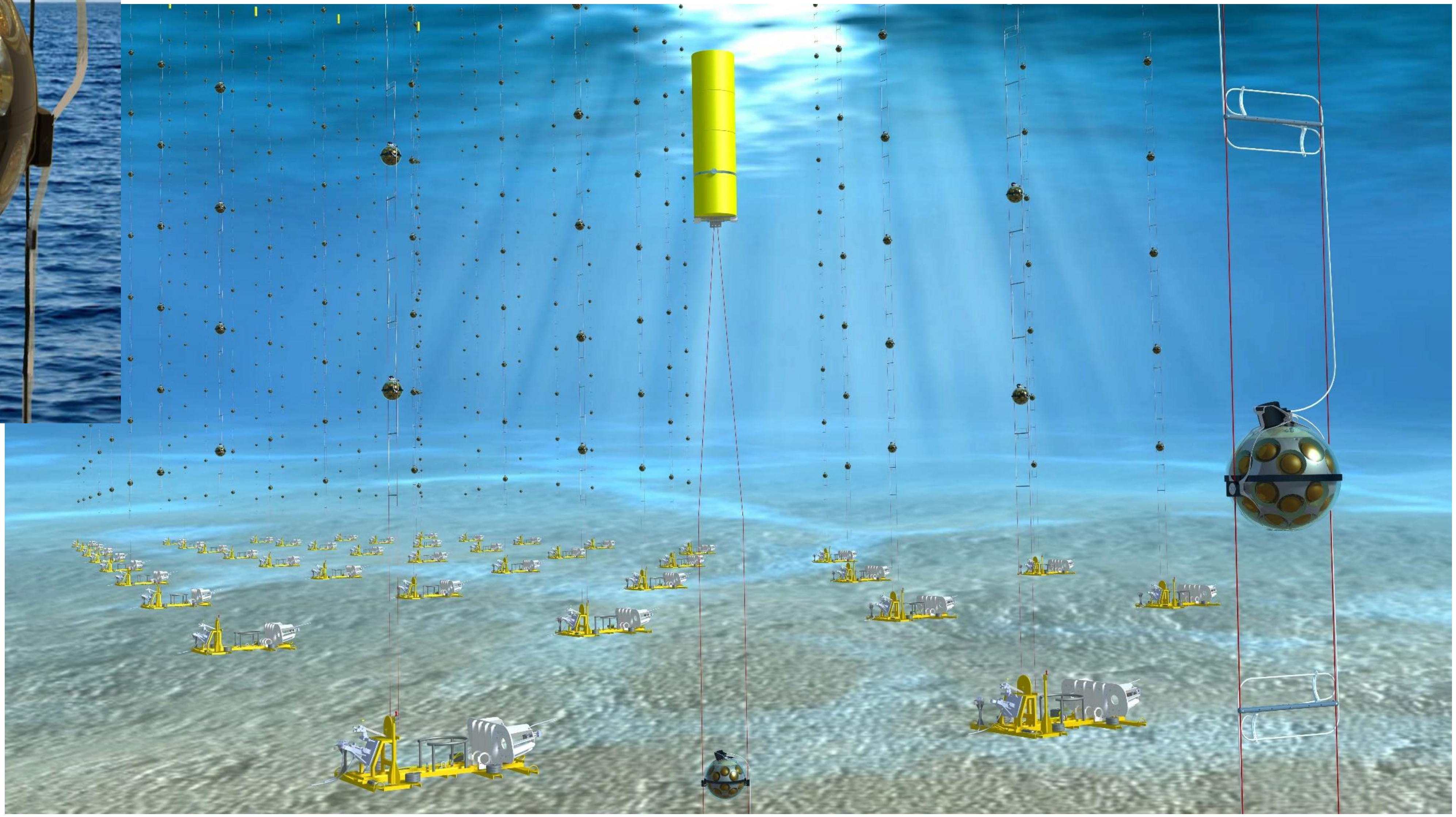
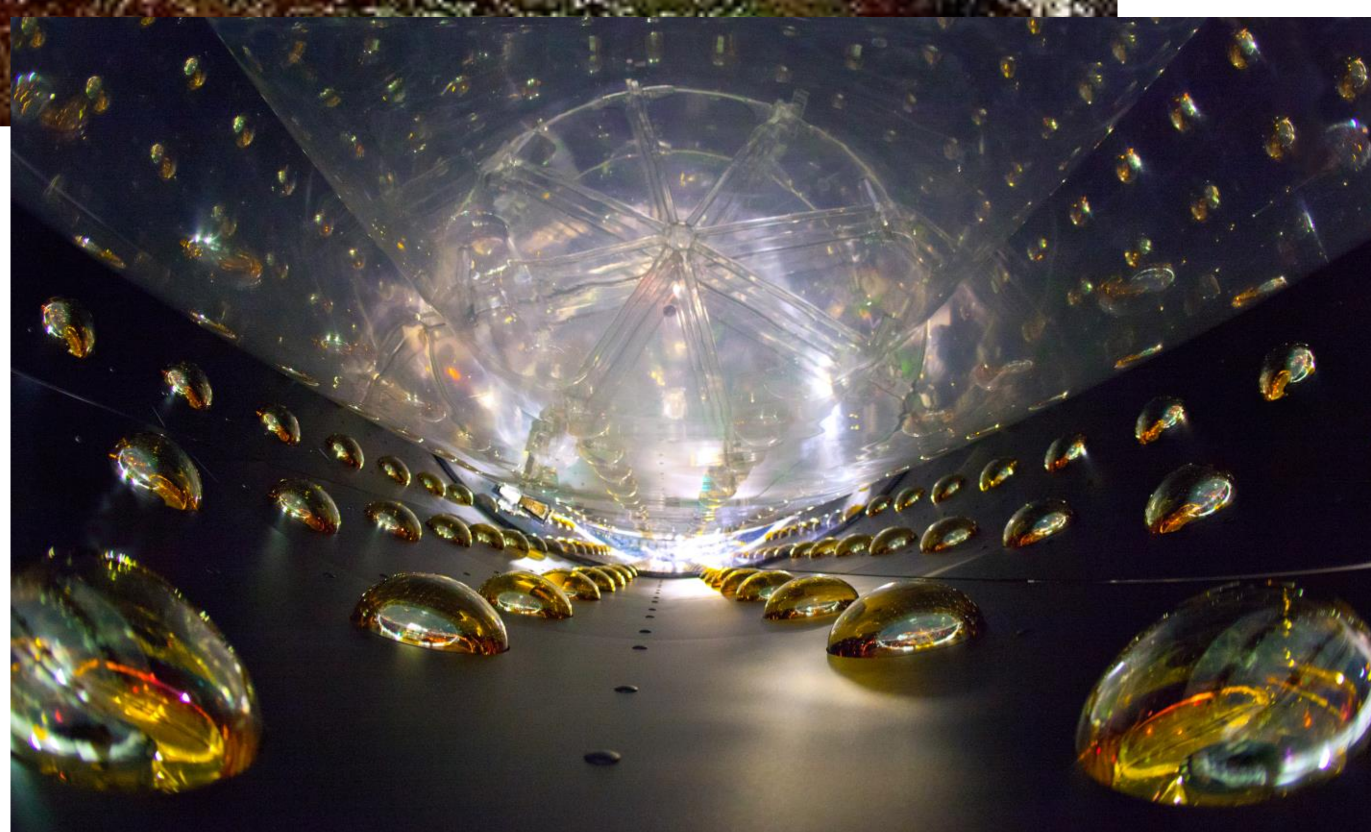


KM3NeT

- Water Cherenkov detector in the Mediterranean Sea
- Three locations: M3NeT-Fr (off Toulon, France), KM3NeT-It (off Portopalo di Capo Passero, Sicily, Italy) and KM3NeT-Gr (off Pylos, Peloponnese, Greece)
- Sub-detectors ARCA (TeV-PeV energies) and ORCA (GeV energies)



Daya Bay

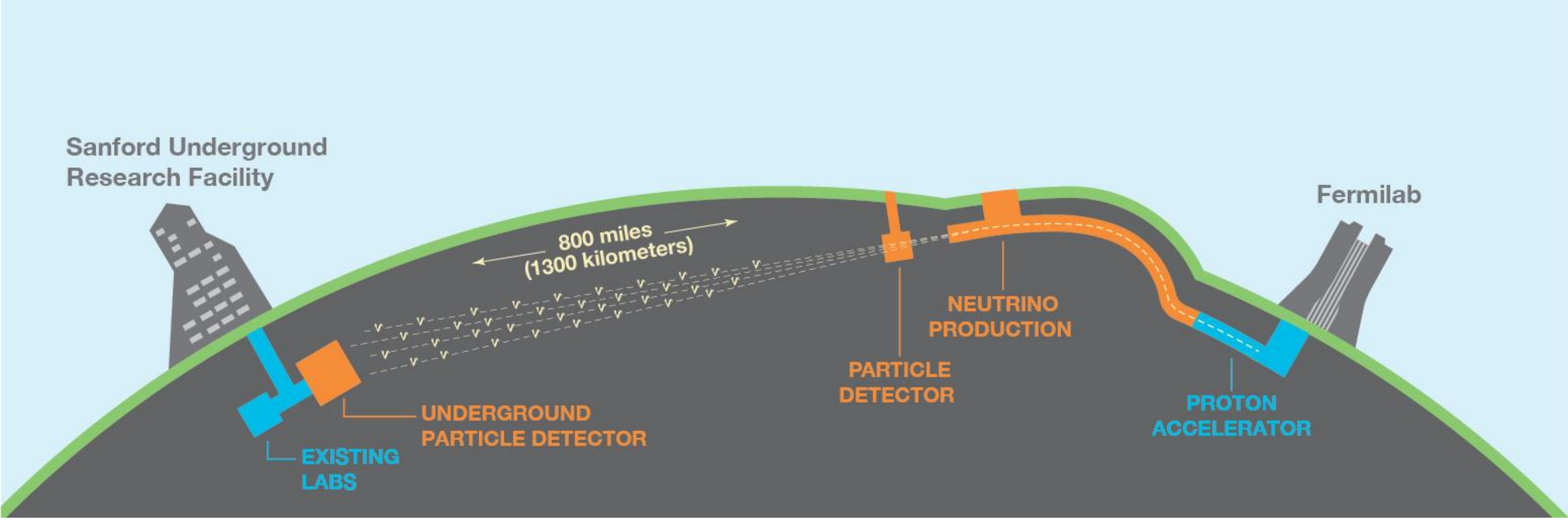


liquid scintillator

built next to reactor

discovered θ_{13}

DUNE

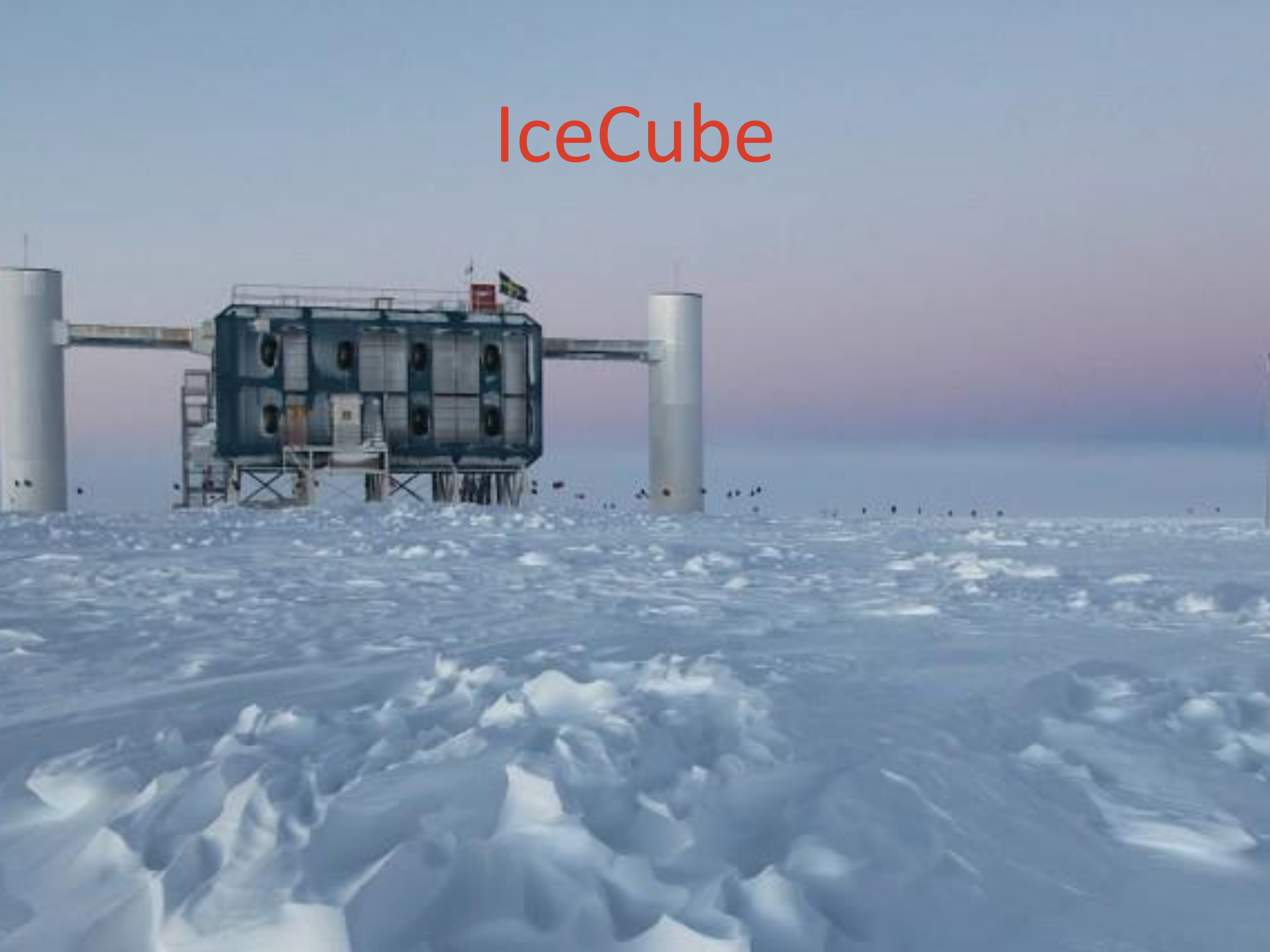


Liquid Argon Time-Projection Chamber
https://www.youtube.com/watch?v=R5G1_hW0ZUA#action=share

catches beam for Fermilab
https://www.youtube.com/watch?v=U_xWDWKq1CM

is expected to discover CP violation in electron neutrino appearance

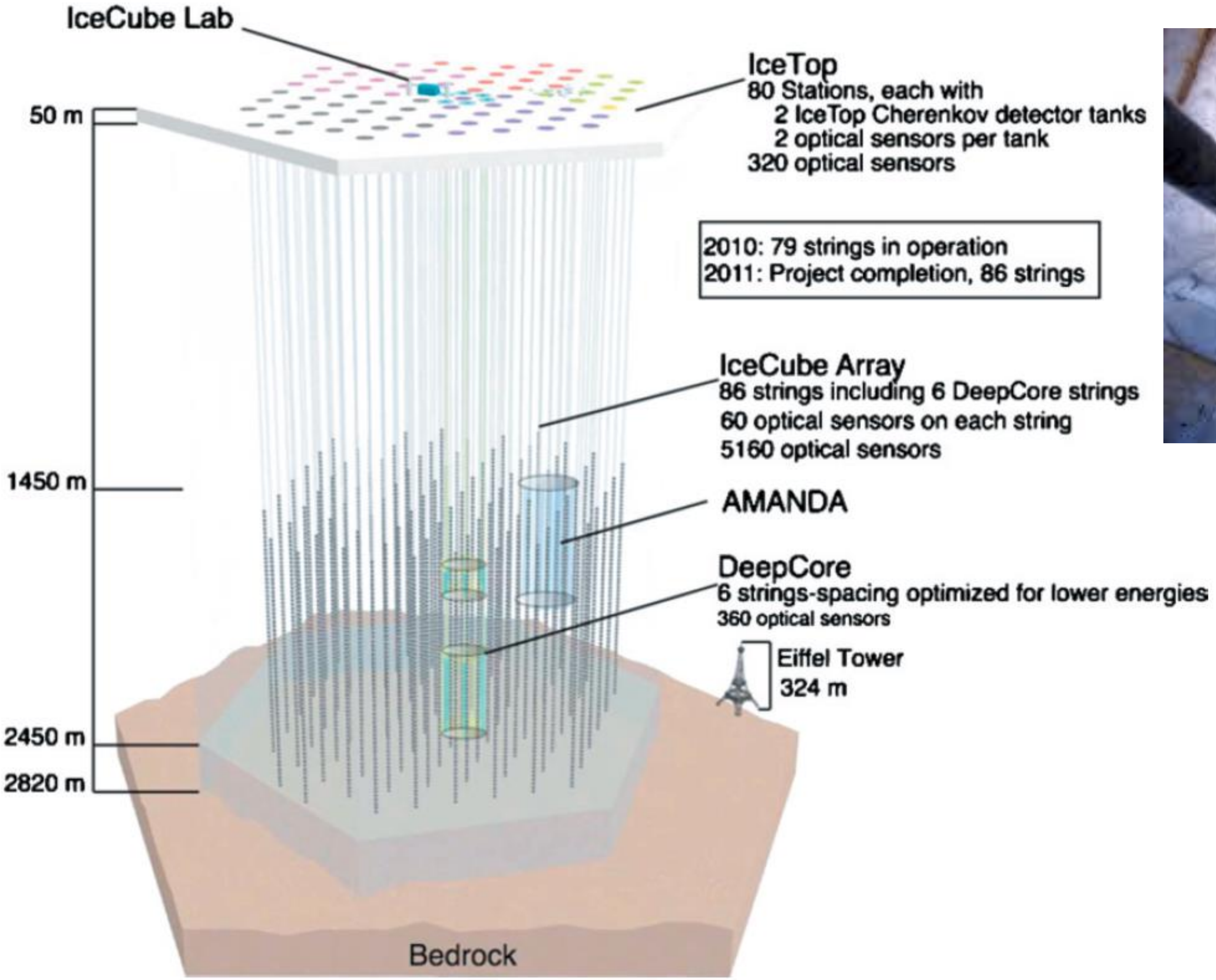
IceCube



IceCube

Represented at UCLouvain by
Gwenhael de Wasseige

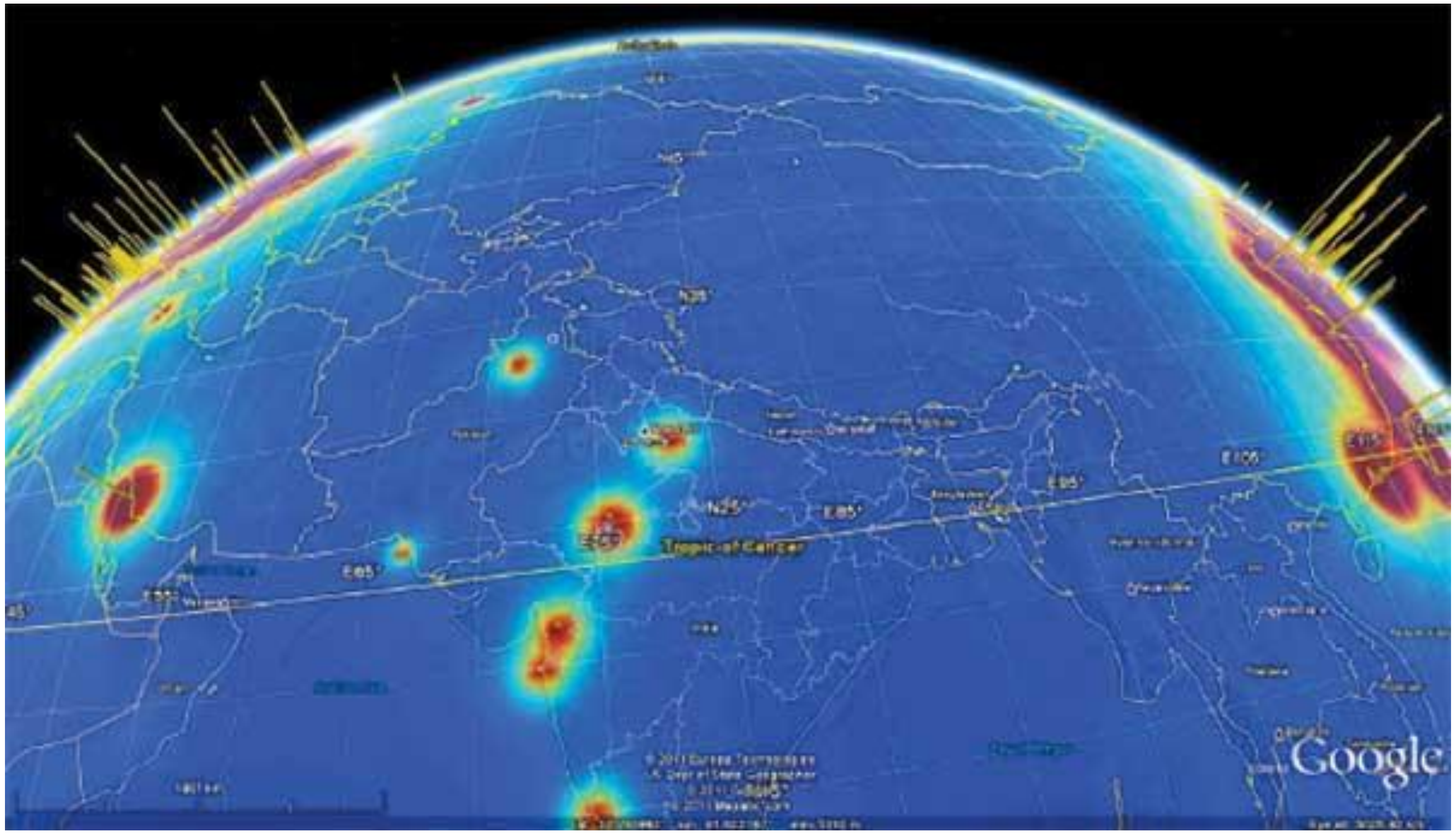
IceCube


IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 optical sensors on each string
5160 optical sensors
AMANDA
DeepCore
6 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

Neutrinos as Messengers

- **monitor sources on earth**
- **probe the inner structure of earth**
- **monitor nuclear fusion in stars**
- **provide insight into supernova explosions**
- **provide information about the early universe**

Sources on Earth

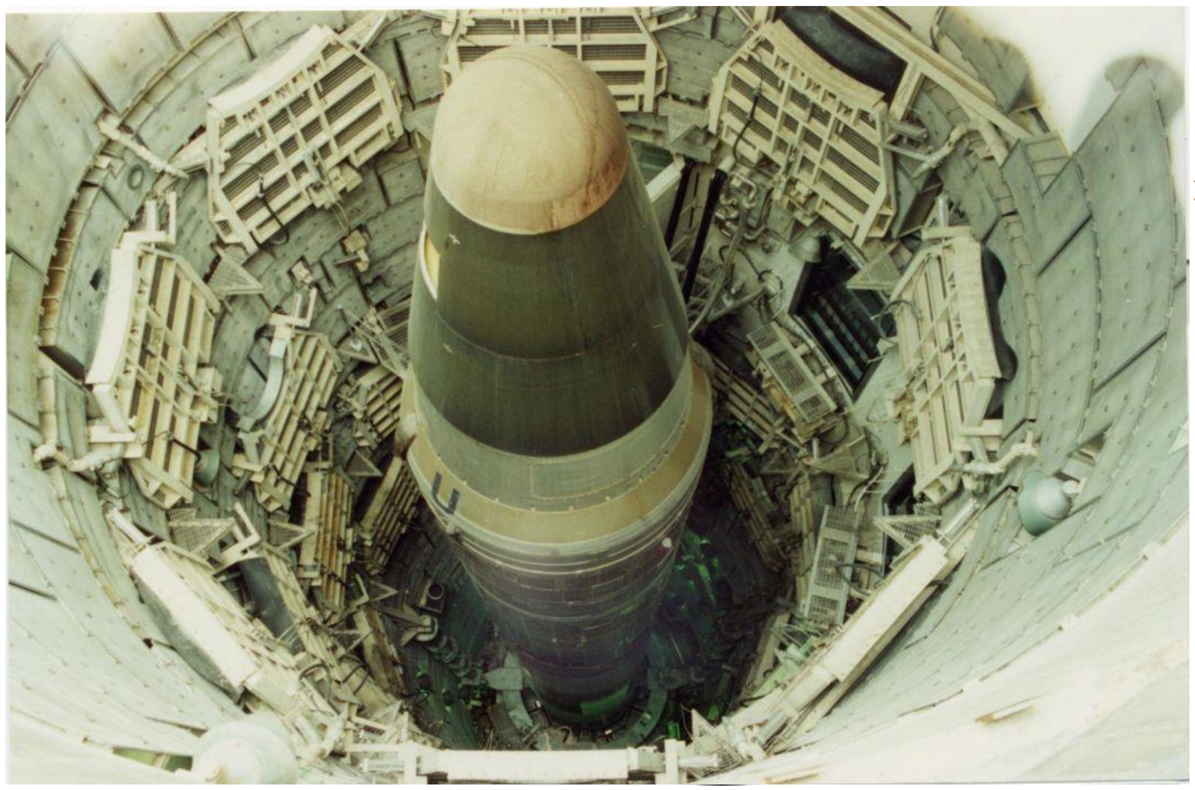


WATer CHerenkov Monitor of AntiNeutrinos (WATCHMAN):

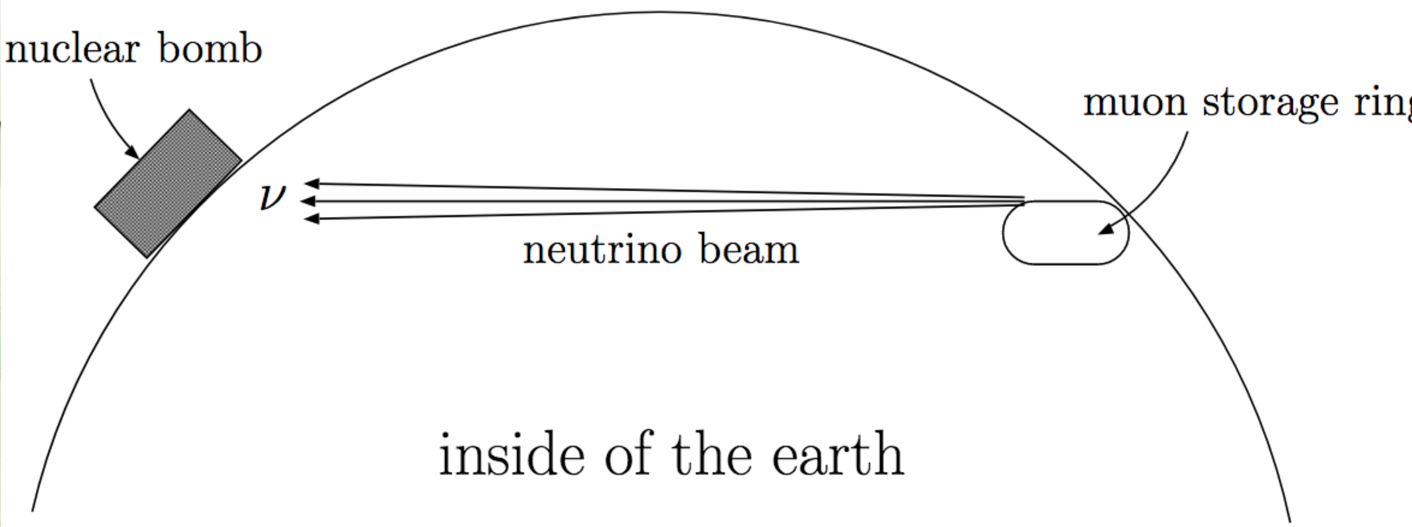
aims to monitor enrichment of nuclear fuel from a distance

part of nuclear non proliferation control

Can one destroy nuclear weapons with Neutrinos?



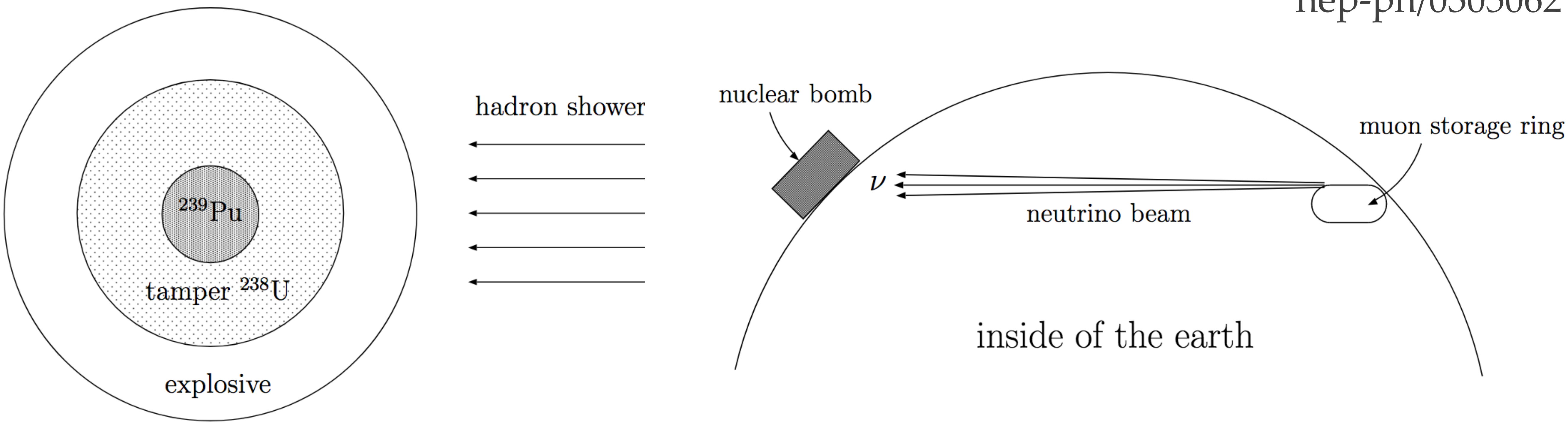
hep-ph/0305062



Can one detonate the enemy's weapons inside their own silo?

Can one destroy nuclear weapons with Neutrinos?

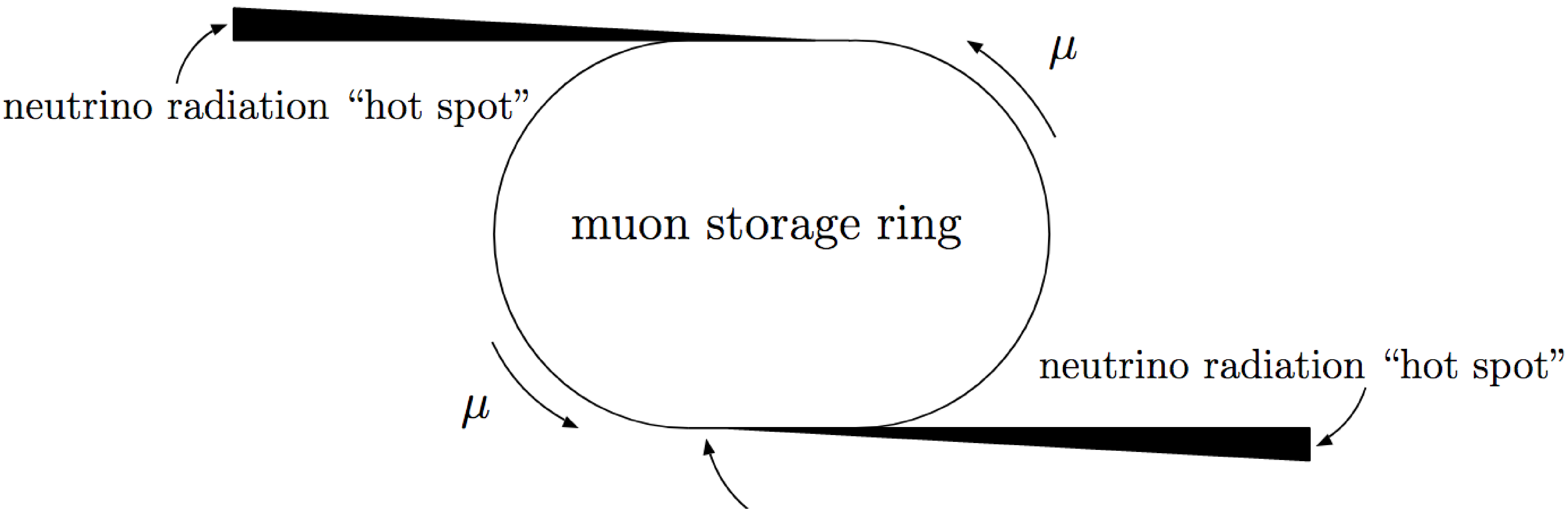
hep-ph/0305062



Can one detonate the enemy's weapons inside their own silo?

Would need 1000 TeV neutrinos… if it works at all…

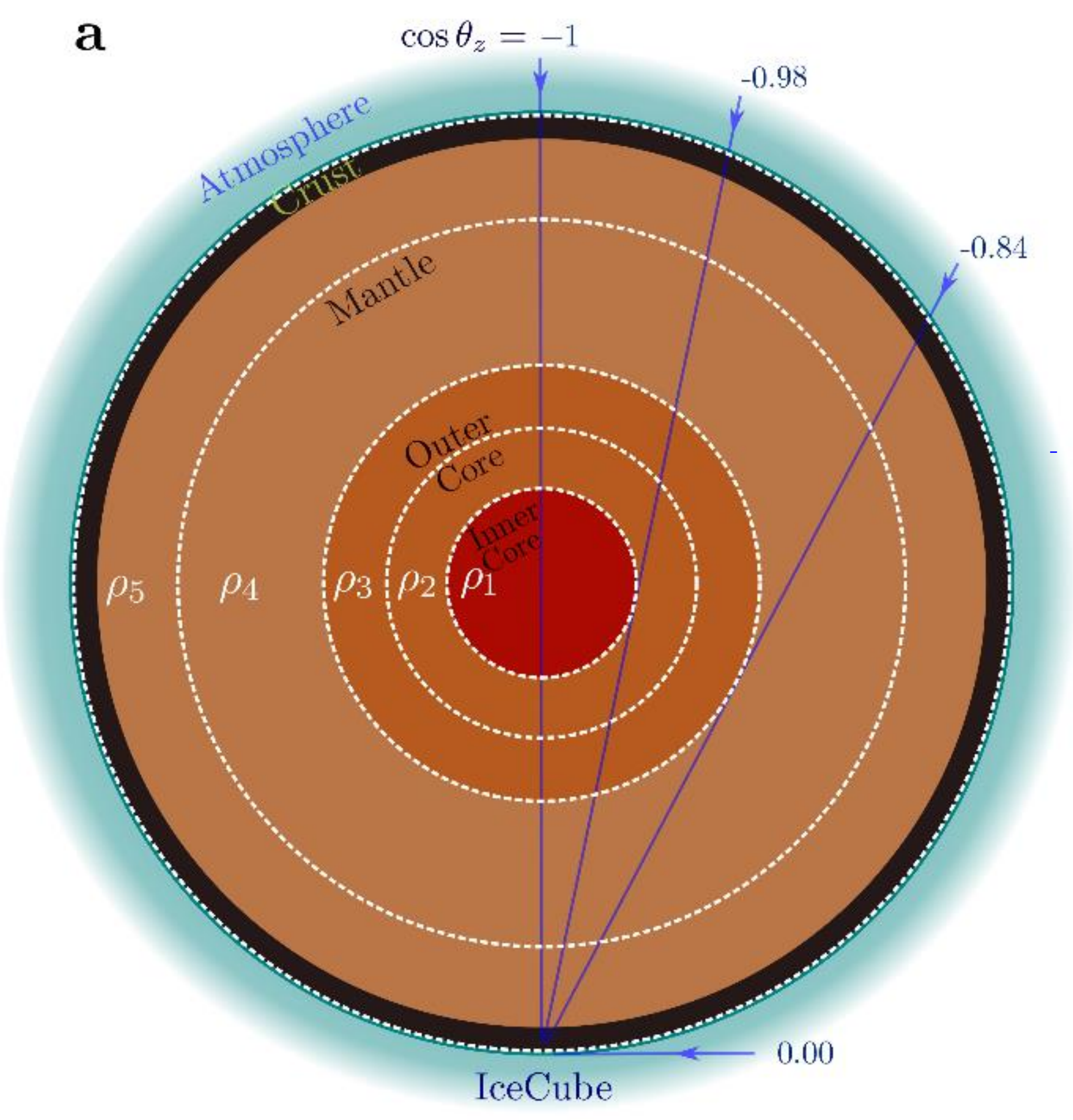
Can one destroy nuclear weapons with Neutrinos?

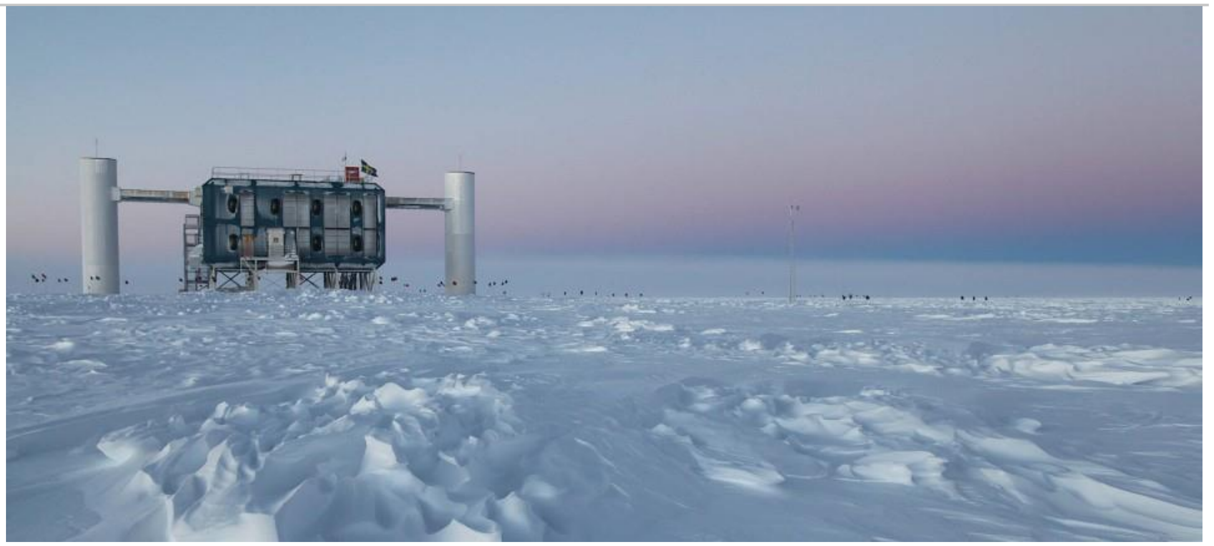


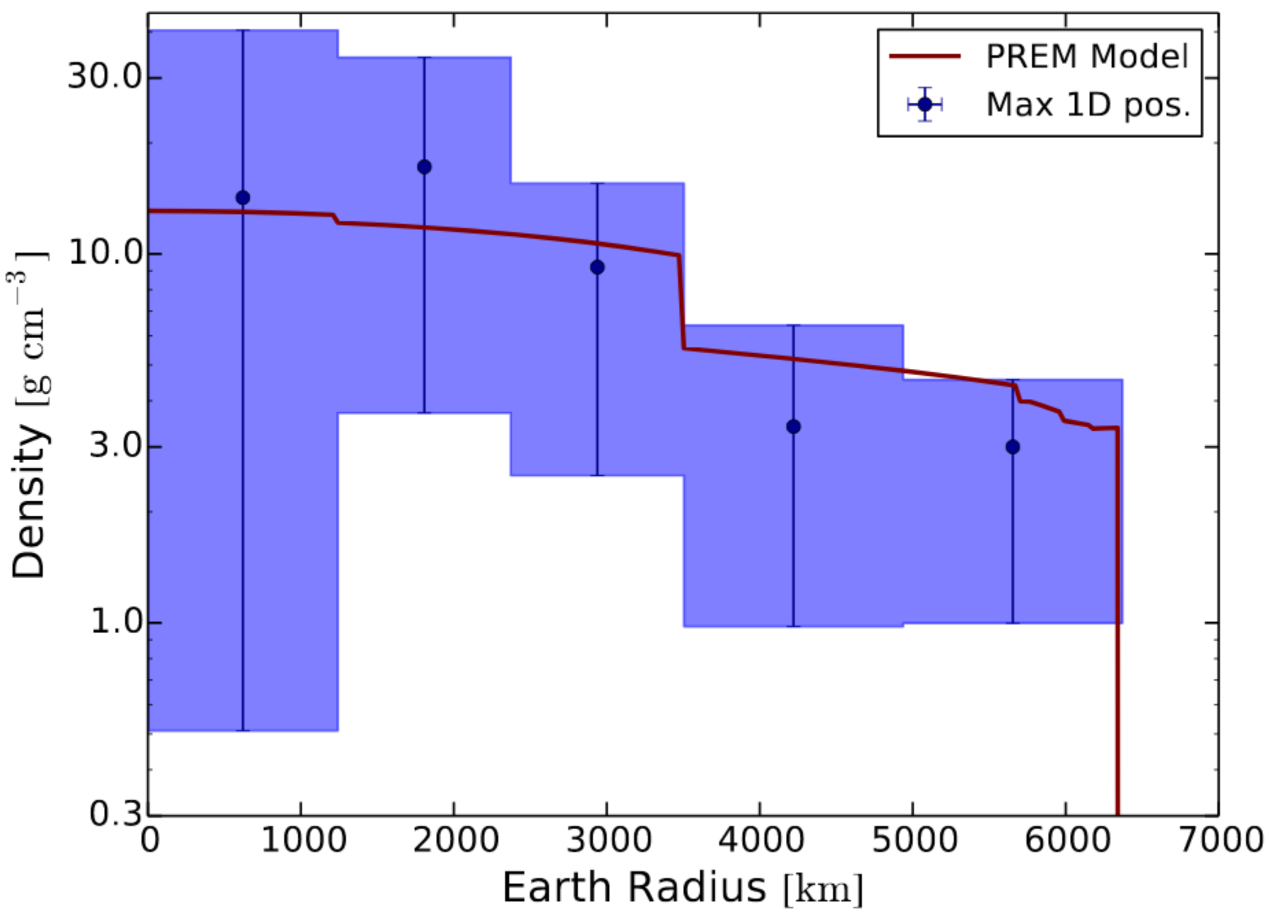
Can one detonate the enemy's weapons inside their own silo?

Would need 1000 TeV neutrinos… if it works at all…

Looking inside the Earth…

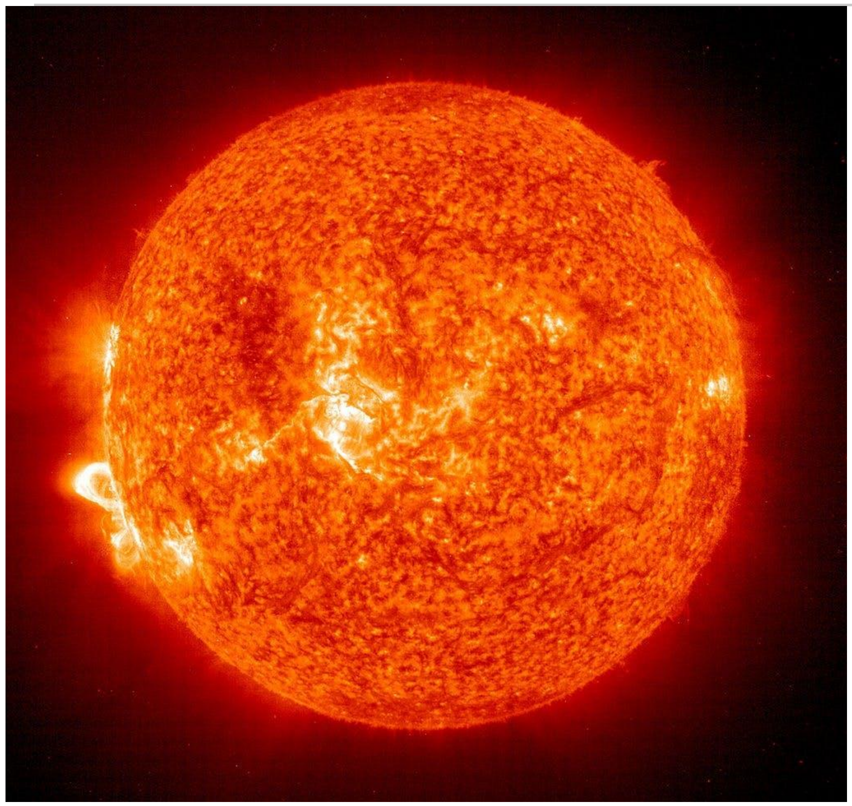






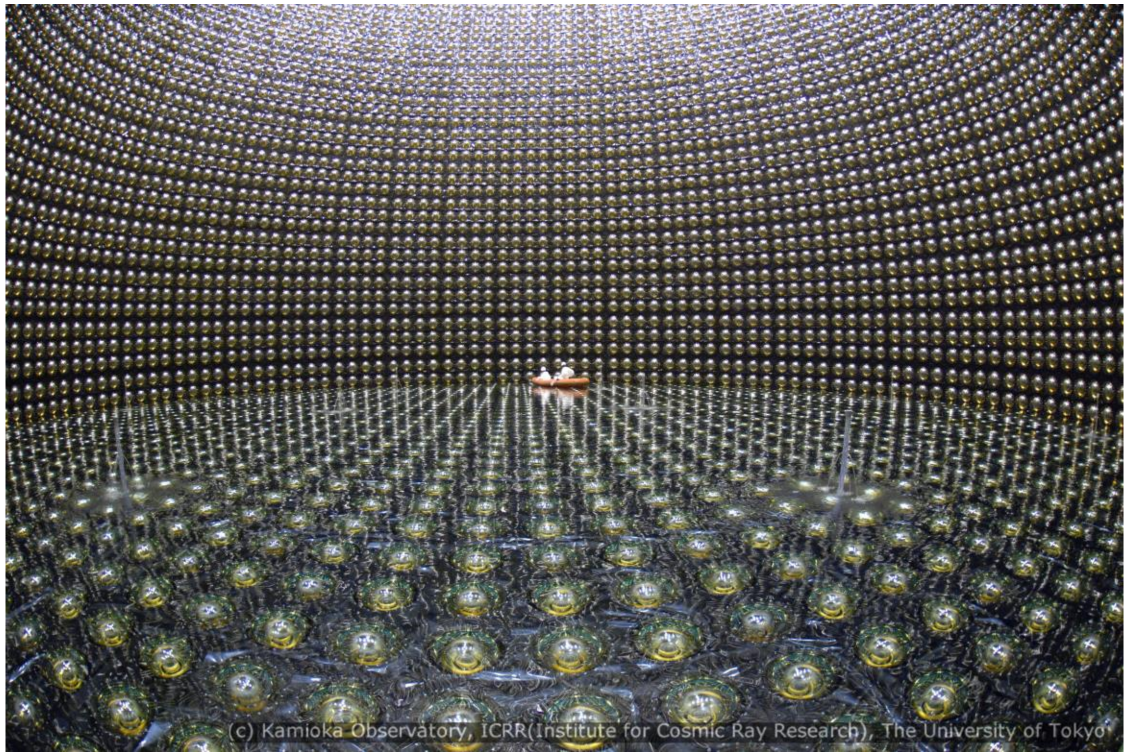
arXiv:1803.05901

Fussion in Stars



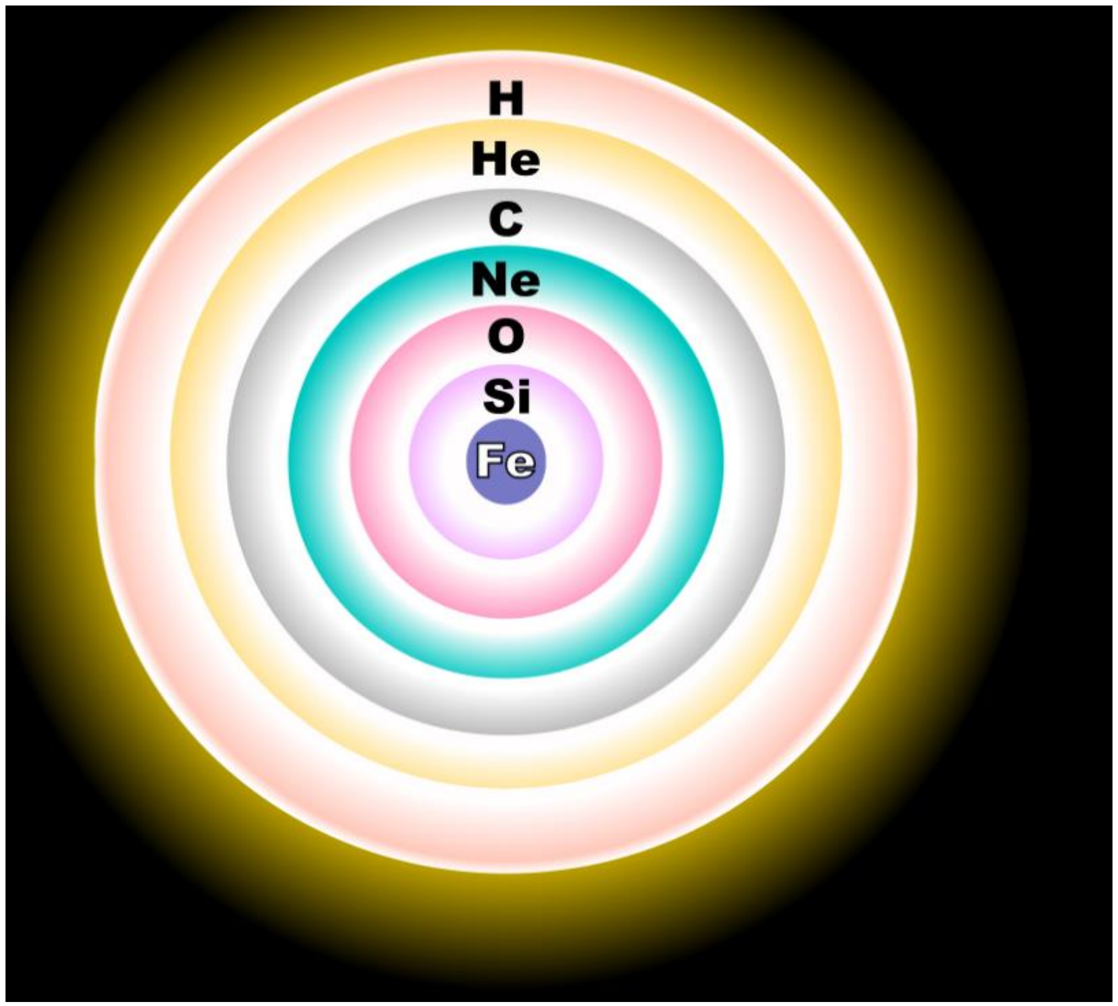
Nuclear fusion creates electron neutrinos

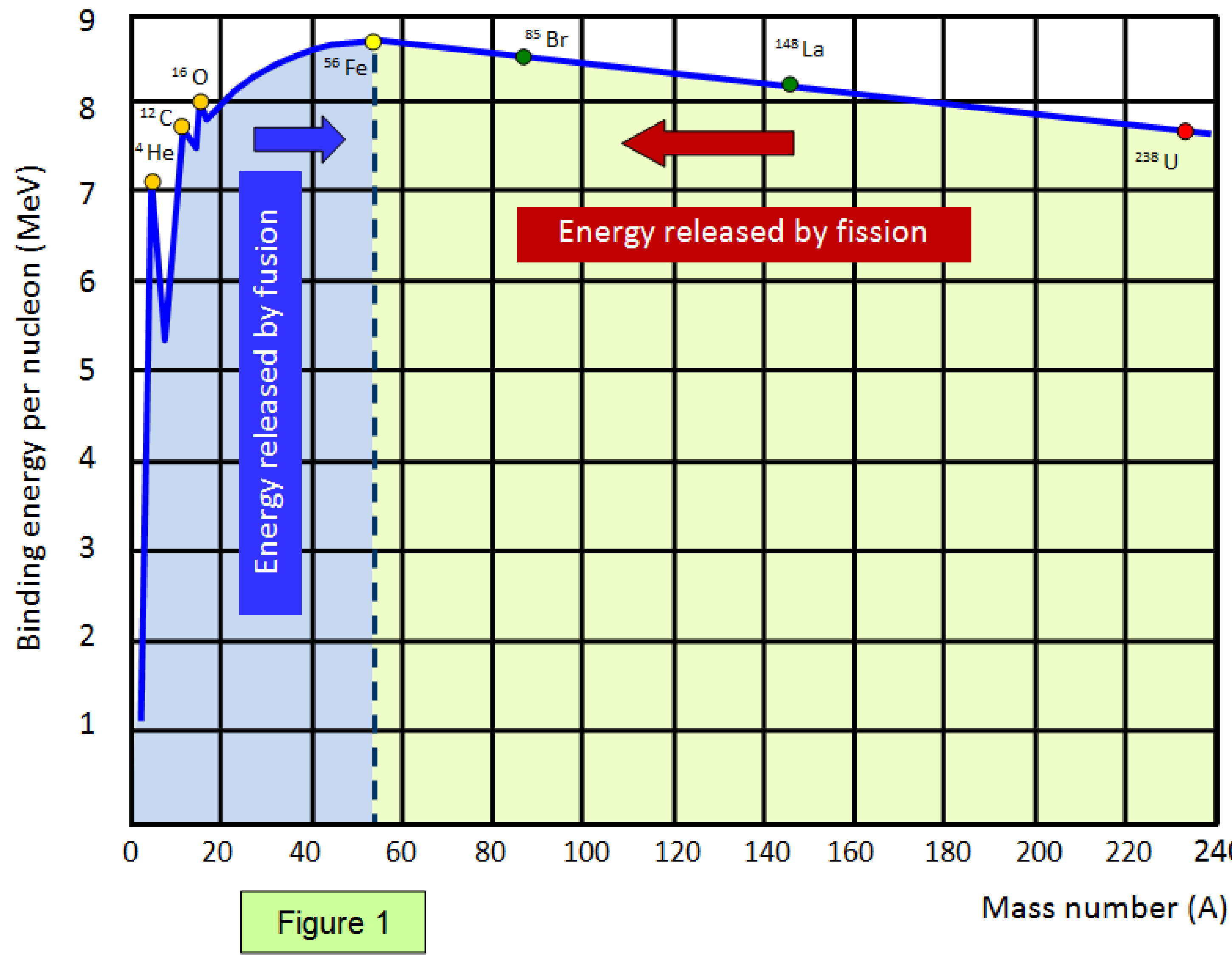
$$
\begin{aligned}
p + p &\rightarrow d + e^+ + \nu_e \\
e^- + {}^7\mathrm{Be} &\rightarrow {}^7\mathrm{Li} + \nu_e \\
{}^8\mathrm{B} &\rightarrow {}^8\mathrm{Be} + e^+ + \nu_e
\end{aligned}
$$



Solar neutrinos provide an important consistency check for the solar model

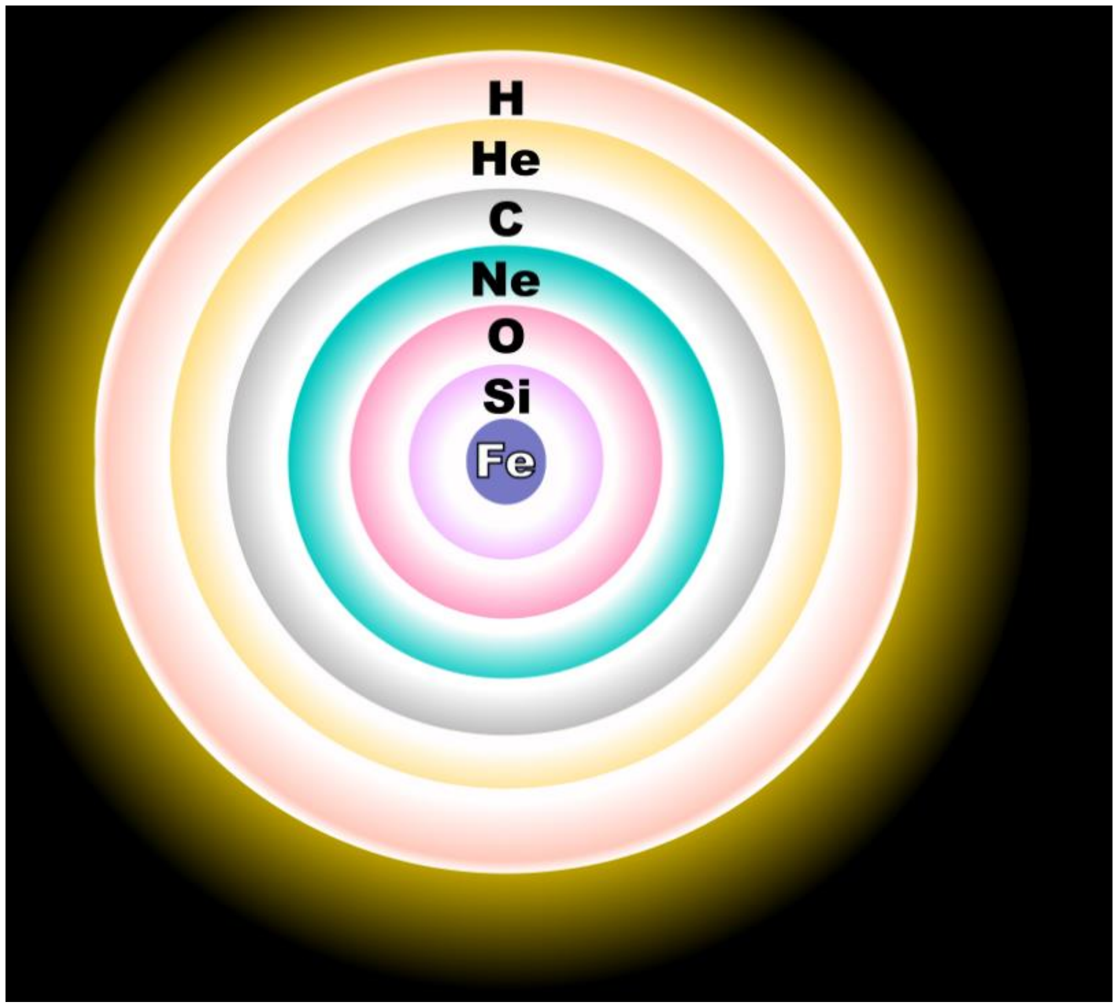
Core Collapse Supernova





Stars produce heavier and heavier elements though nuclear fusing in their core… up to iron (highest binding energy per nucleon)

Core Collapse Supernova



Star is stabilised by equilibrium between thermal and gravitational pressure. When fuel runs out, it is stabilised by the Fermi pressure:

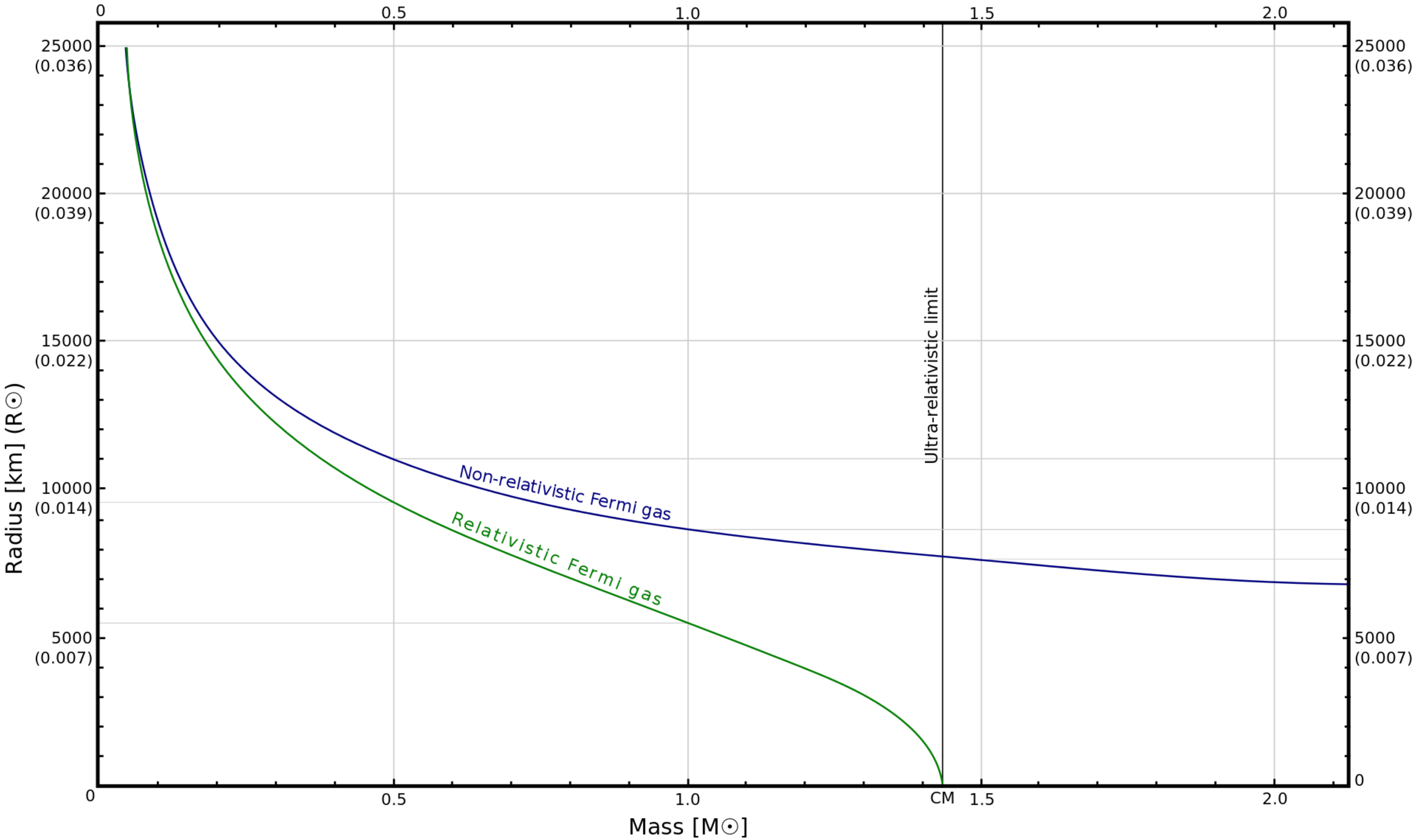
$$P = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\,\frac{\mathbf{p}^2}{3\omega_p}f(\mathbf{p}) \simeq \frac{g}{24\pi^2}\mu^4$$

$$n = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\,f(\mathbf{p}) \simeq \frac{g}{6\pi^2}\mu^3$$

$$\Rightarrow P \propto n^{4/3}$$

This is to balance the gravitational pressure. Solving for the radius yields the Chandrasekhar limit of 1.44 solar masses

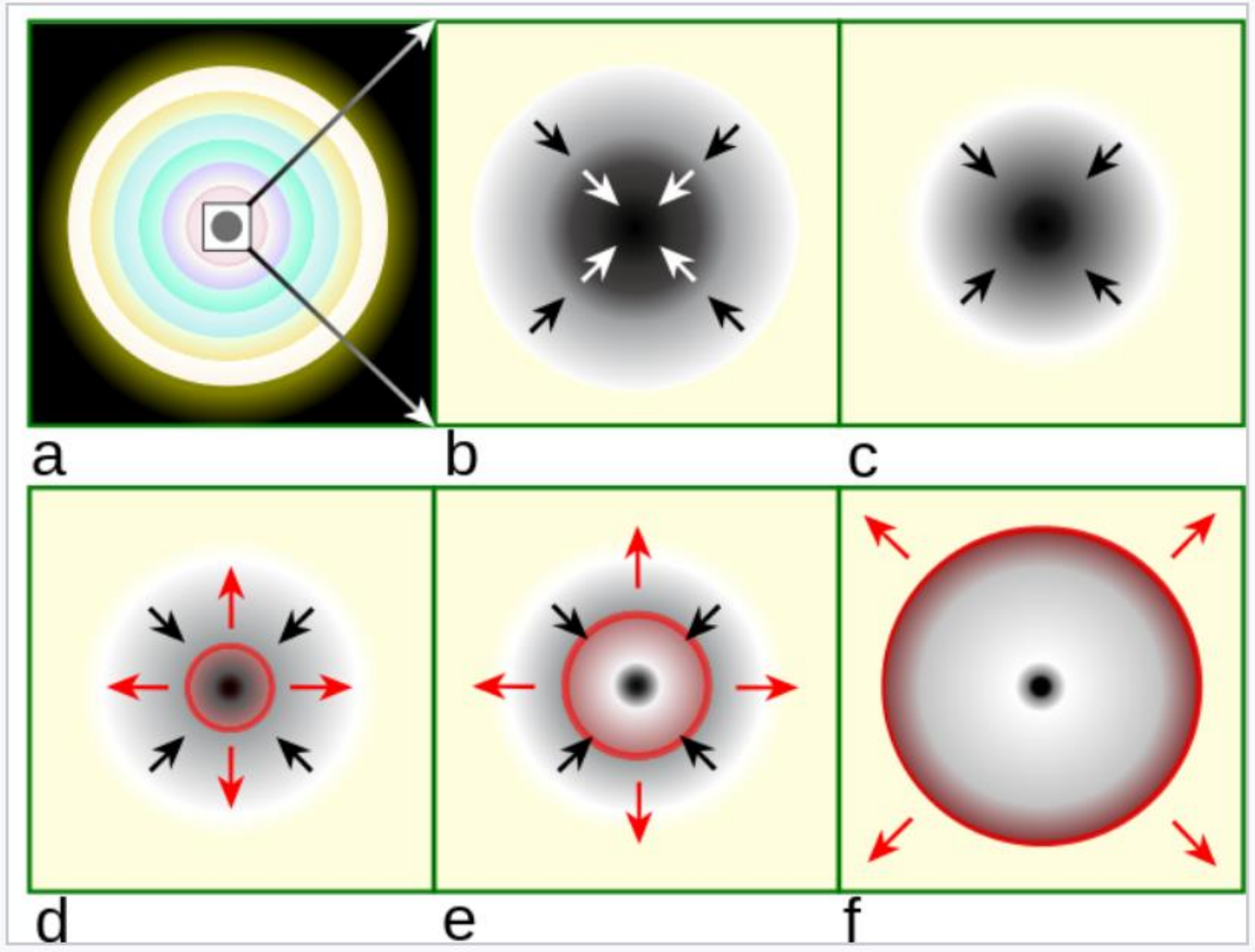
Core Collapse Supernova



Core Collapse Supernova

b) electrons an protons in core combine into neutrons

a) fusion in shells forms iron core, collapses when Chandrasekhar-mass is reached



c) inflating matter bounced back from hard core

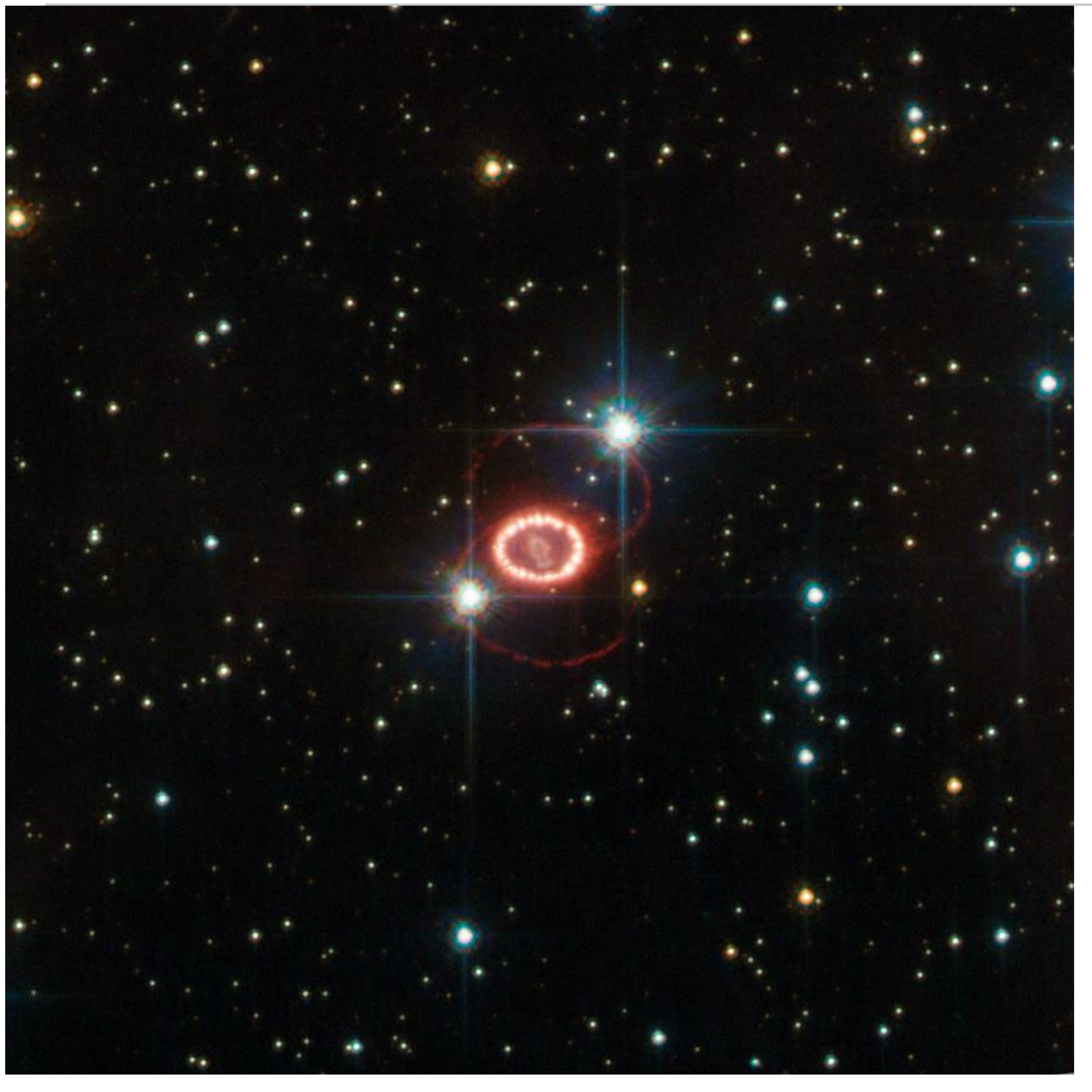
d) bouncing matter forms shock wave

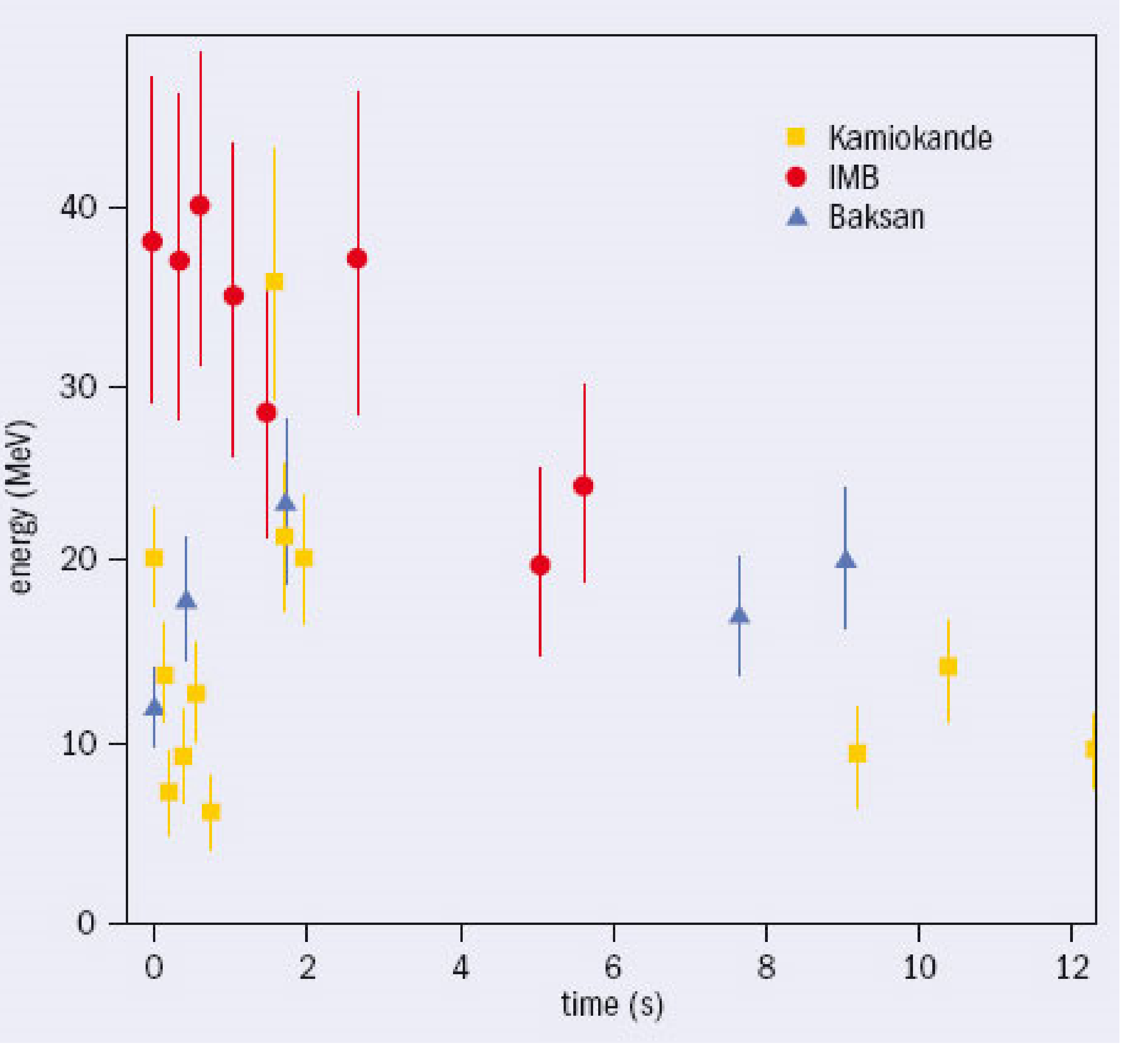
f) shell is based off

e) complicated dynamics involving neutrino interactions/heating,

many neutrinos emitted because they can escape the dense medium easier

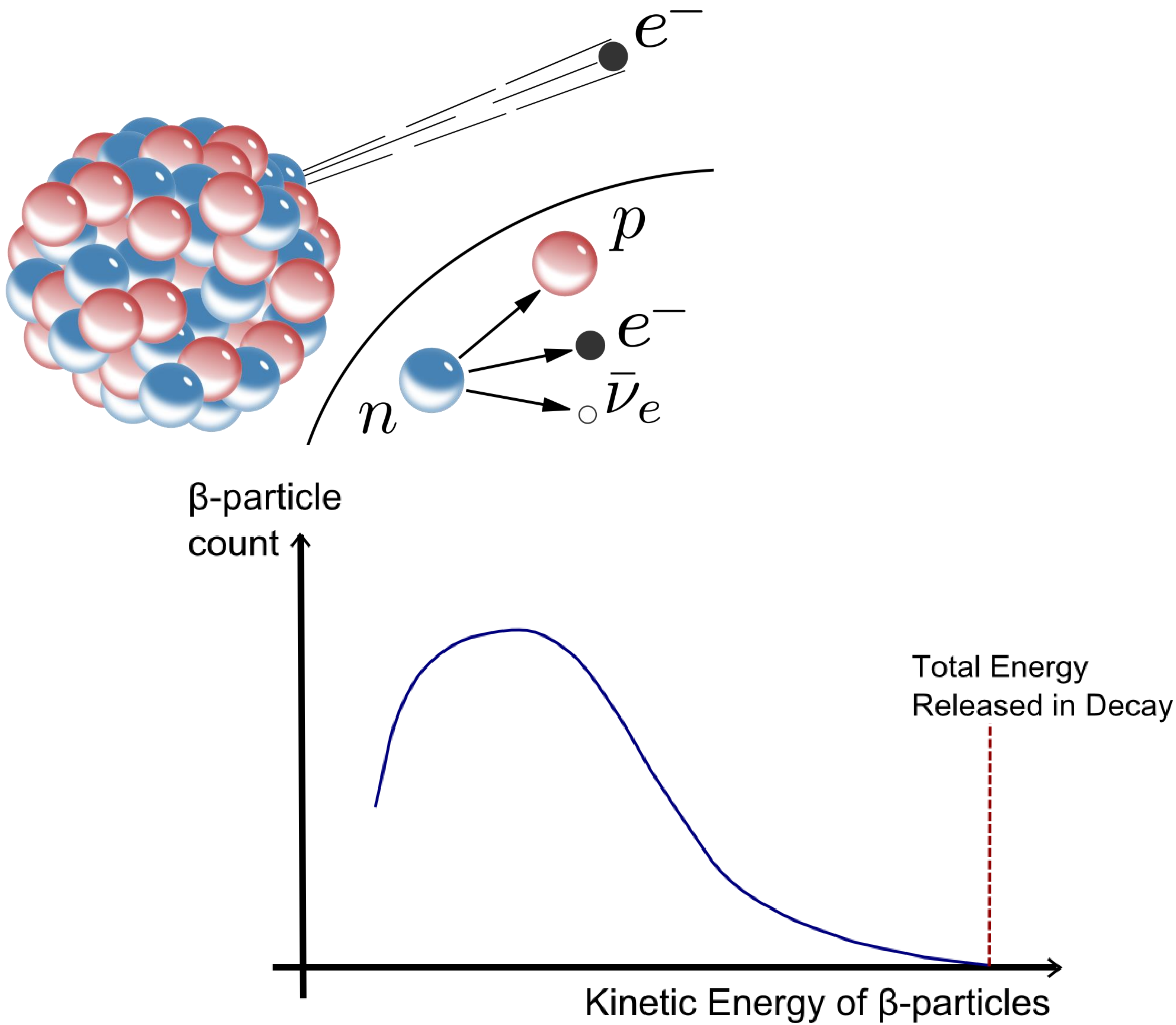
SN1987a





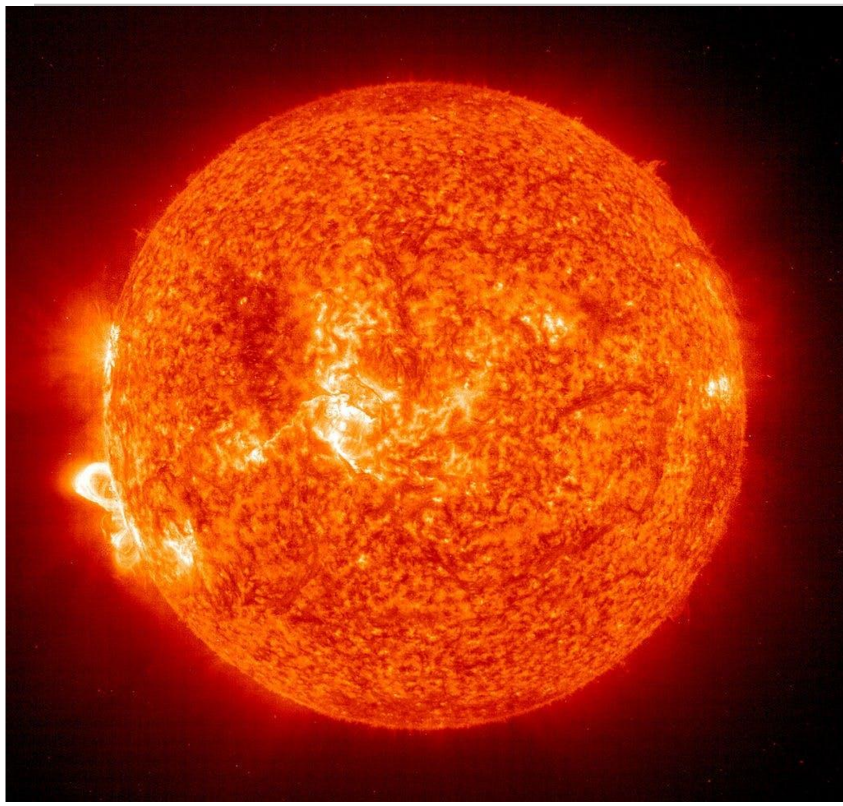
Observation of neutrinos confirms theory that 99% of the energy is emitted in the form of neutrinos!

Neutrio Oscillations



e^-
p
e^-
$\bar{\nu}_e$
n
β-particle count
Total Energy Released in Decay
Kinetic Energy of β-particles

The Solar Neutrino Problem



Nuclear fusion creates electron neutrinos

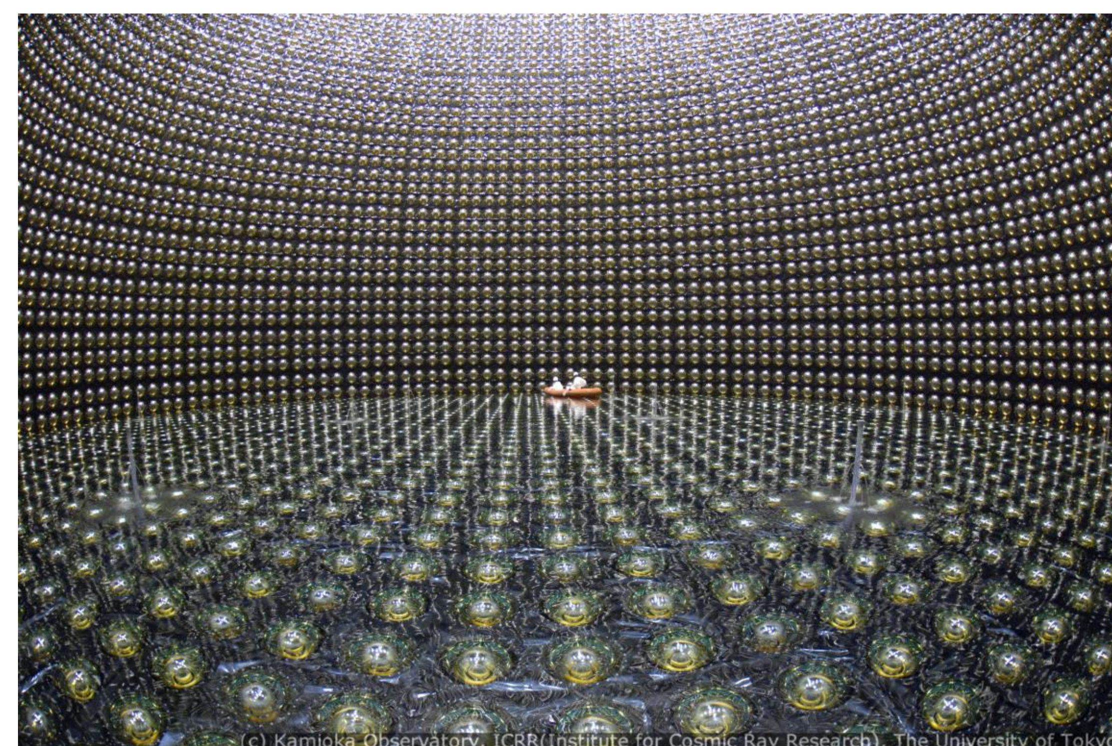
$$p + p \rightarrow d + e^+ + \nu_e$$
$$e^- + {}^7\mathrm{Be} \rightarrow {}^7\mathrm{Li} + \nu_e$$
$${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$$

We know how bright the sun is.

We know the nuclear reactions.

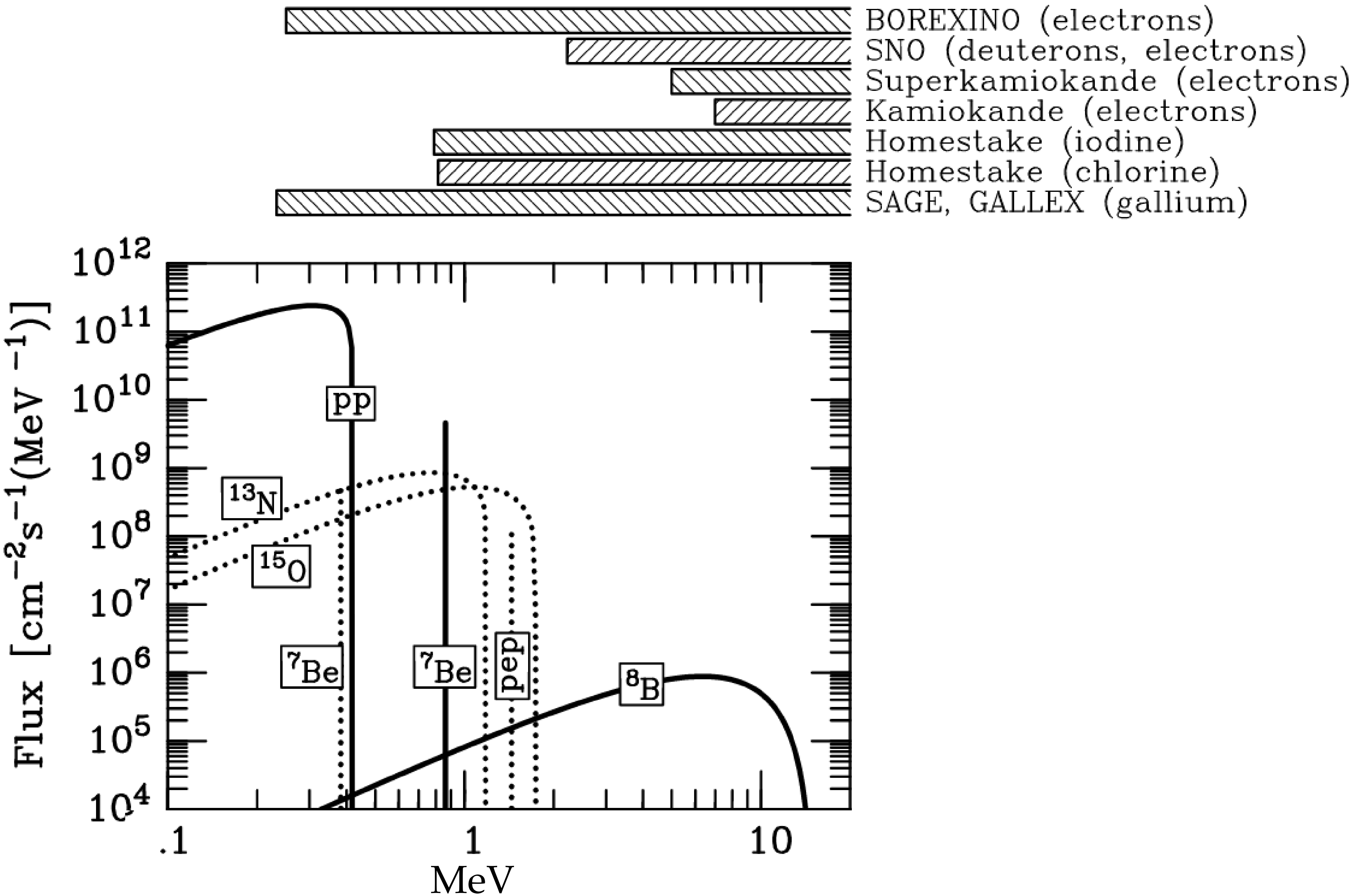
So we can predict the neutrino flux.

Experiments see only 1/3 - 1/2 of that!



Solar Model

Total flux: 66 billion ν / (s cm²)



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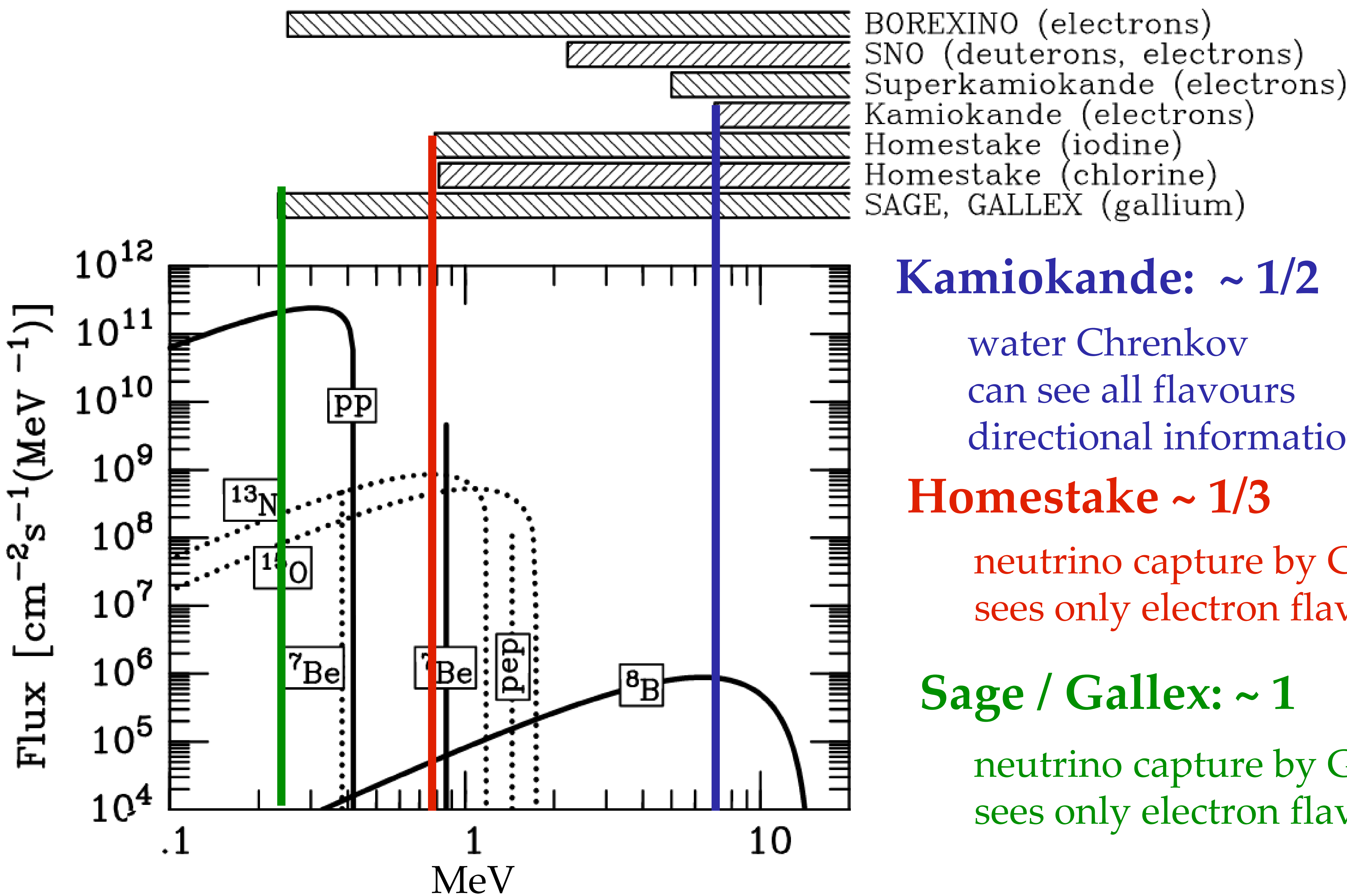


Kamiokande: ~ 1/2

water Chrenkov
can see all flavours
directional information

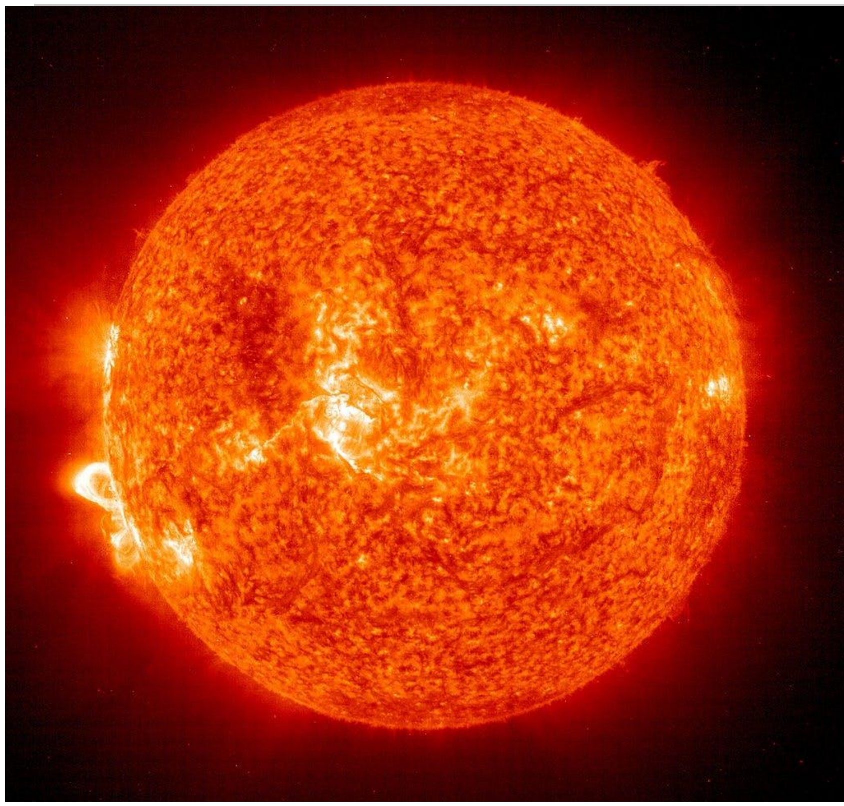
Homestake ~ 1/3

neutrino capture by Cl
sees only electron flavour

Sage / Gallex: ~ 1

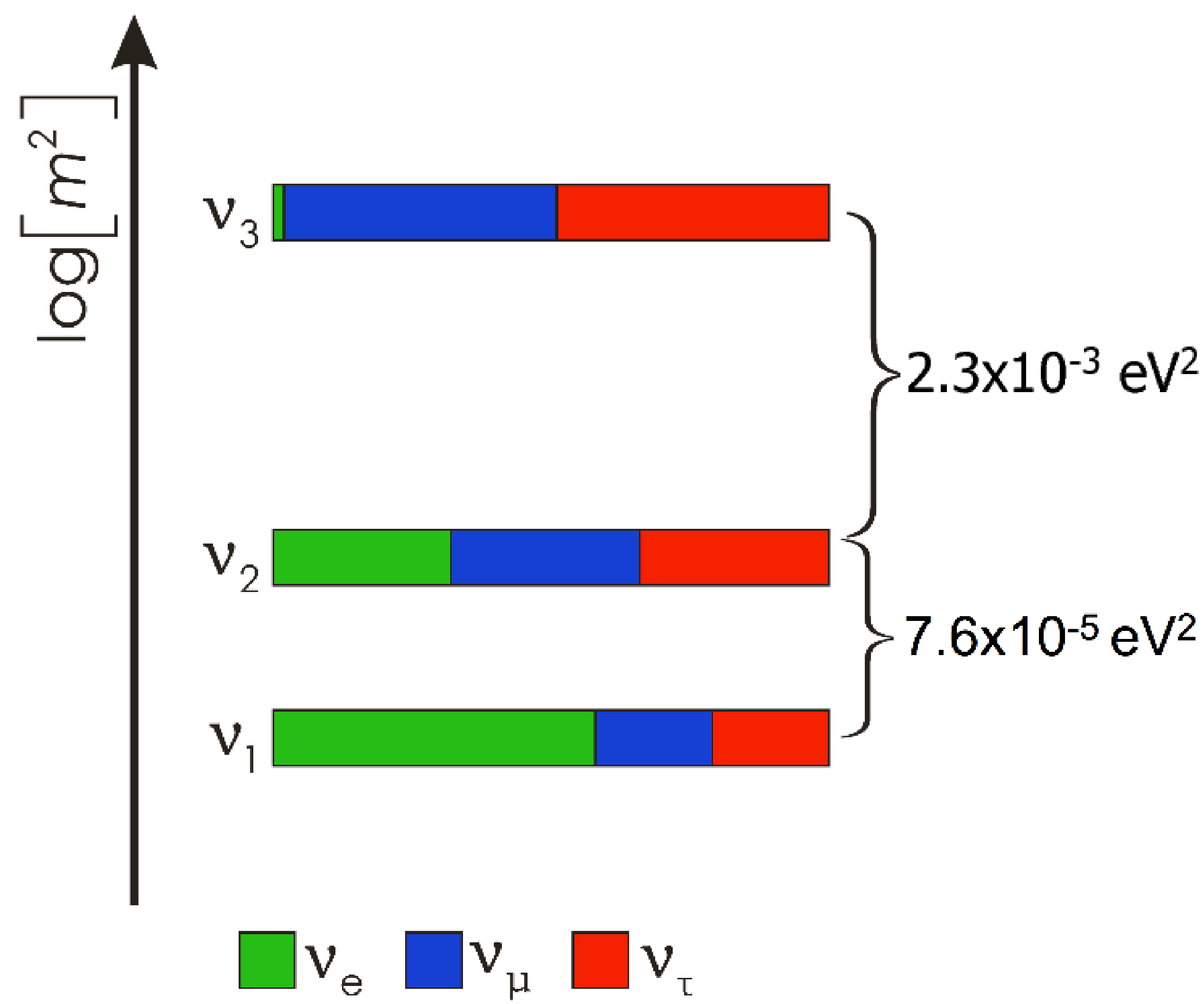
neutrino capture by Ga
sees only electron flavour

The Solar Neutrino Problem



Neutrinos are quantum mechanical objects…

$$\begin{pmatrix} \psi_e \\ \psi_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

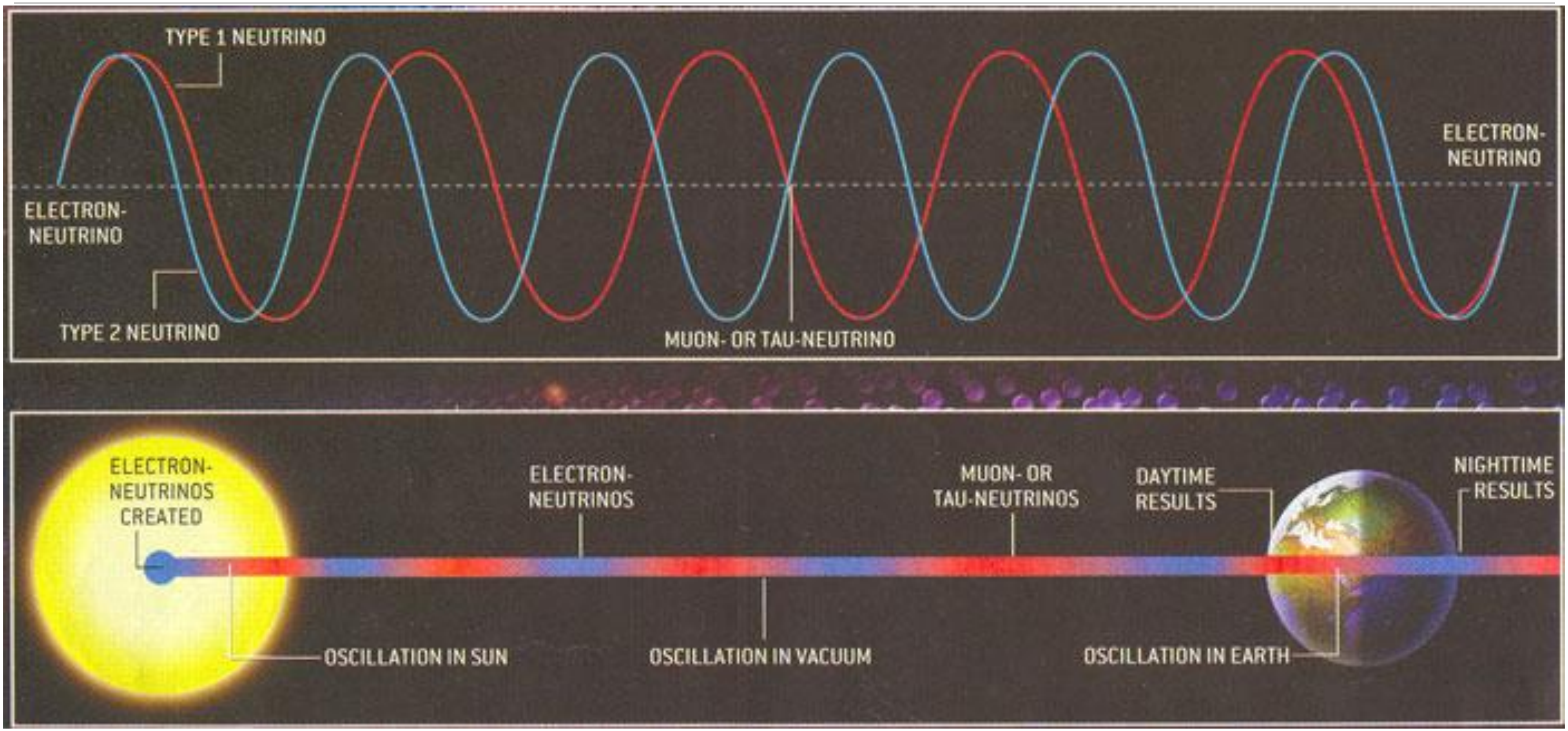


The "electron neutrino" quantum state has no well-defined mass.

It is a superposition of quantum states with well-defined mass!

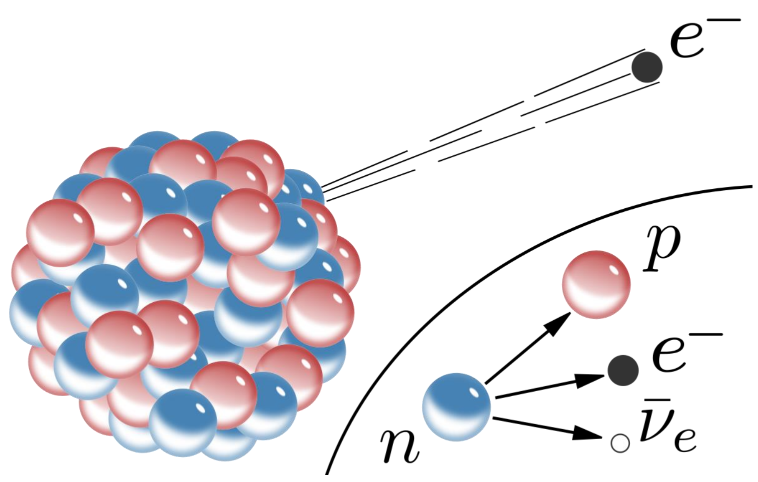
Their wave functions oscillate at different frequencies.

The Solar Neutrino Problem



Constructive and destructive interference along the path changes the decomposition of the quantum state.
Electron Neutrinos turn into muon neutrinos!

What defines the Neutrino Flavour?



An electron neutrino is the thing that gets produced together with an electron.

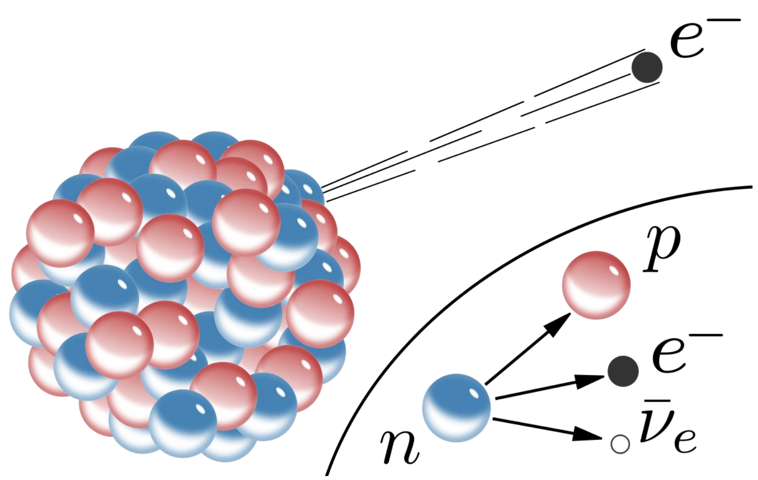
At the level of Lagrangians, the "interaction basis" is the flavour basis where the weak currents are diagonal:

$$-\frac{g}{\sqrt{2}}\overline{\nu_L}\gamma^\mu e_L W_\mu^+ - \frac{g}{\sqrt{2}}\overline{e_L}\gamma^\mu \nu_L W_\mu^- - \frac{g}{2\cos\theta_W}\overline{\nu_L}\gamma^\mu \nu_L Z_\mu,$$

If it related to the "mass basis" by a flavour rotation:

$$\nu_{L\alpha} = (V_\nu)_{\alpha i}\nu_i. \qquad V_\nu = (1+\eta)\,U_\nu.$$

What defines the Neutrino Flavour?



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If it related to the "mass basis" by a flavour rotation:

deviation from unitarity

$$\nu_{L\alpha} = (V_\nu)_{\alpha i}\nu_i.$$

$$V_\nu = (1+\eta)U_\nu.$$

unitary part

Relativistic Wave Equation

$$(\partial_t^2 - \nabla^2 + M^2)\,\Psi = 0$$

relativistic wave equation
(for each spinor component)

$$\Psi(t,\mathbf{x}) = \Psi_{\mathbf{k}}(t)\,e^{i\mathbf{k}\cdot\mathbf{x}}$$

decomposition into plane waves

$$(\partial_t^2 + \mathbf{k}^2 + M^2)\,\Psi_{\mathbf{k}}(t) = 0$$

$$\partial_t^2 + \mathbf{k}^2 = (i\partial_t + k)(-i\partial_t + k)$$

relativistic approximation

$$k = |\mathbf{k}| \gg m_i \qquad \partial_t^2 + \mathbf{k}^2 \approx 2k(-i\partial_t + k)$$

$$i\partial_t \Psi_{\mathbf{k}} = \Omega_{\mathbf{k}} \Psi_{\mathbf{k}} \quad \text{where} \quad \Omega_{\mathbf{k}} \equiv \left(k + \frac{M^2}{2k}\right)$$

effective Schrodinger equation in time

Neutrino Flux in Space

But in reality we are more interested in the flux as a function of position

$$(\partial_t^2 - \nabla^2 + M^2)\,\Psi = 0, \qquad \Psi_\omega(\mathbf{x})e^{-i\omega t};$$

$$(-\omega^2 - \nabla^2 + M^2)\,\Psi_\omega(\mathbf{x}) = 0.$$

$$i\partial_z \Psi_\omega = -K_\omega \Psi_\omega \quad \text{where} \quad K_\omega \equiv \left(\omega - \frac{M^2}{2\omega}\right).$$

effective Schrodinger equation in space

solution: $\Psi_\omega(z) = e^{iKz}\Psi_\omega(0)$

with $W(z) \equiv (e^{iKz})_{\text{weak}} = U\,(e^{iKz})_{\text{mass}}\,U^\dagger$

Two Flavour Oscillation

$$W(z) \equiv (e^{iKz})_{\text{weak}} = U(e^{iKz})_{\text{mass}}\, U^{\dagger}$$

For two flavour case: $$U = \cos\theta\, I + i\sin\theta\, \sigma_2$$

Parameterise mass as: $$M^2/2\omega = b_0 - \tfrac{1}{2}\,\mathbf{B}\cdot\boldsymbol{\sigma},$$

with $$\mathbf{B} = \frac{2\pi}{\ell_{\text{osc}}}\begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix}, \qquad b_0 = (m_1^2 + m_2^2)/4\omega. \qquad \ell_{\text{osc}} \equiv \frac{4\pi\,\omega}{m_2^2 - m_1^2}$$

Two Flavour Oscillation

$$W(z) \equiv (e^{iKz})_{\text{weak}} = U(e^{iKz})_{\text{mass}}\, U^{\dagger}$$

For two flavour case: $U = \cos\theta\, I + i \sin\theta\, \sigma_2$

Parameterise mass as: $M^2/2\omega = b_0 - \frac{1}{2}\, \mathbf{B} \cdot \boldsymbol{\sigma},$

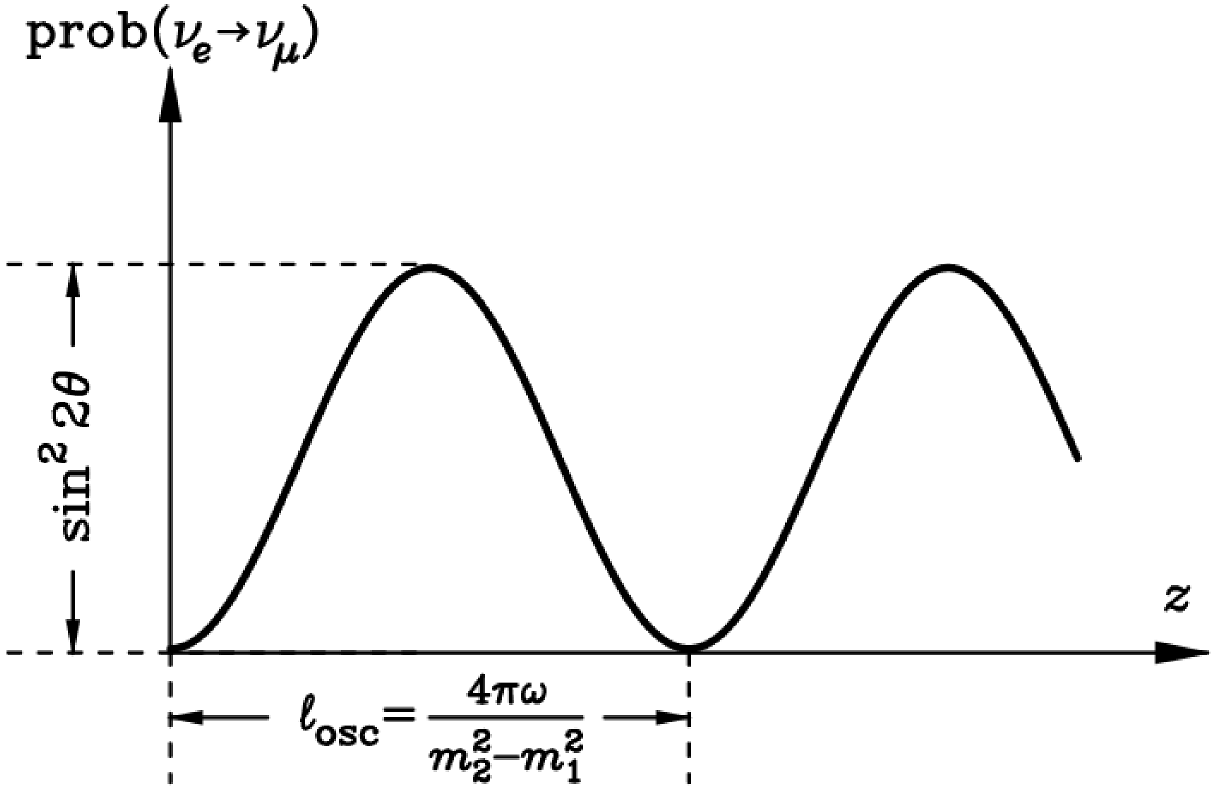
with $\mathbf{B} = \frac{2\pi}{\ell_{\text{osc}}} \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix},$ $b_0 = (m_1^2 + m_2^2)/4\omega.$

$$\ell_{\text{osc}} \equiv \frac{4\pi\, \omega}{m_2^2 - m_1^2}$$

Appearance and Disappearance

$$W = e^{i(\omega - b_0)z} \left[\cos\left(\frac{\pi z}{\ell_{\rm osc}}\right) - i \sin\left(\frac{\pi z}{\ell_{\rm osc}}\right) \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \right].$$

$$K = \omega - b_0 + \tfrac{1}{2} \bar{\mathbf{B}} \cdot \boldsymbol{\sigma}$$



$$\text{prob}\,(\nu_e \to \nu_\mu) = |W_{e\mu}|^2 = \sin^2(2\theta)\ \sin^2(\pi z/\ell_{\rm osc}),$$

$$\text{prob}\,(\nu_e \to \nu_e) = |W_{ee}|^2 = 1 - \text{prob}\,(\nu_e \to \nu_\mu).$$

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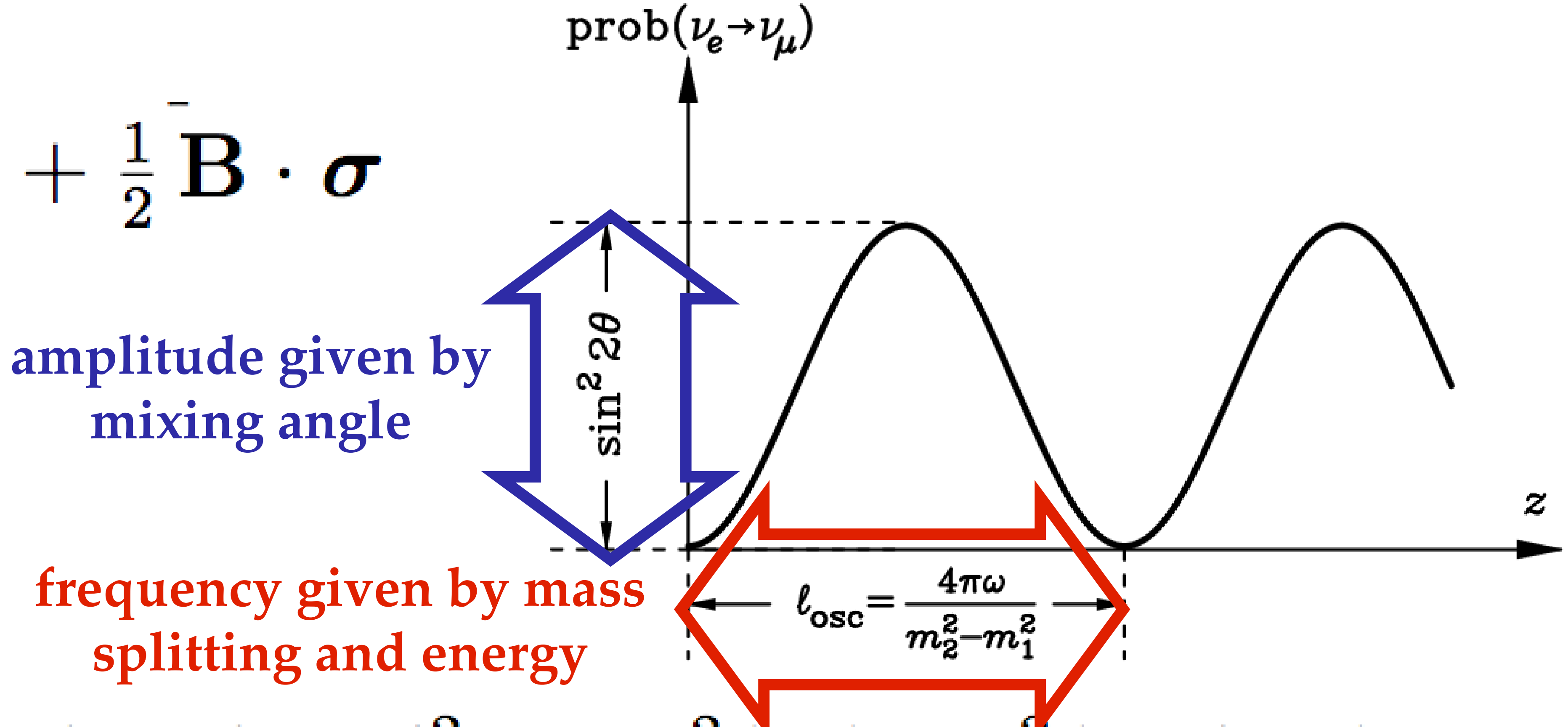

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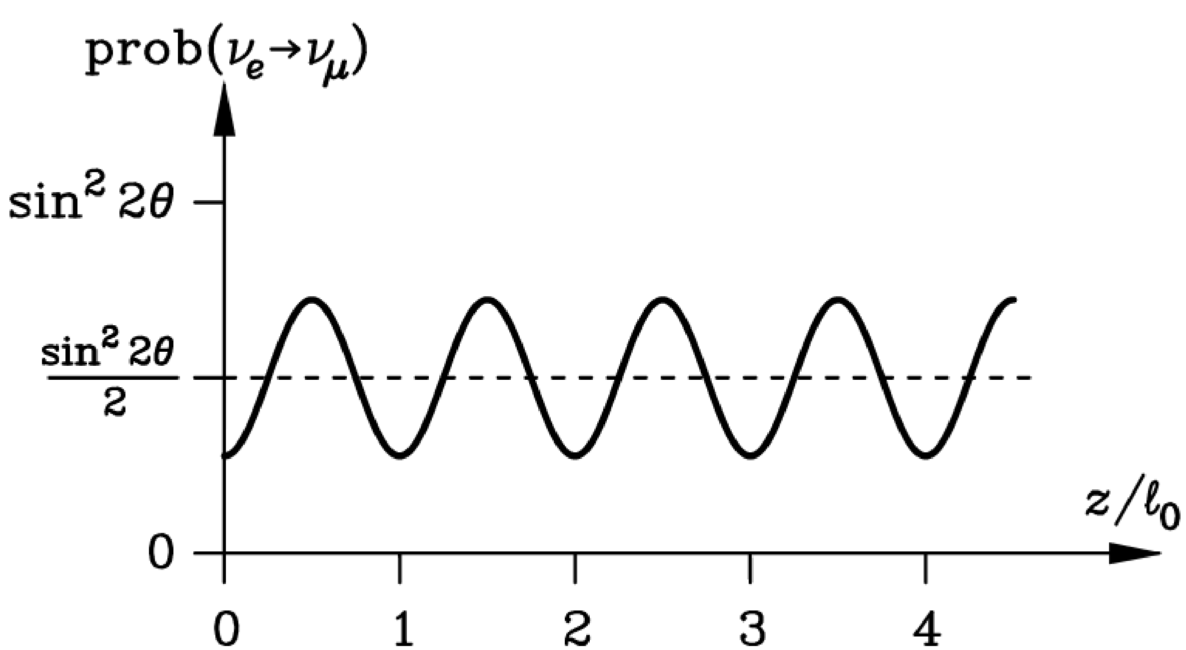
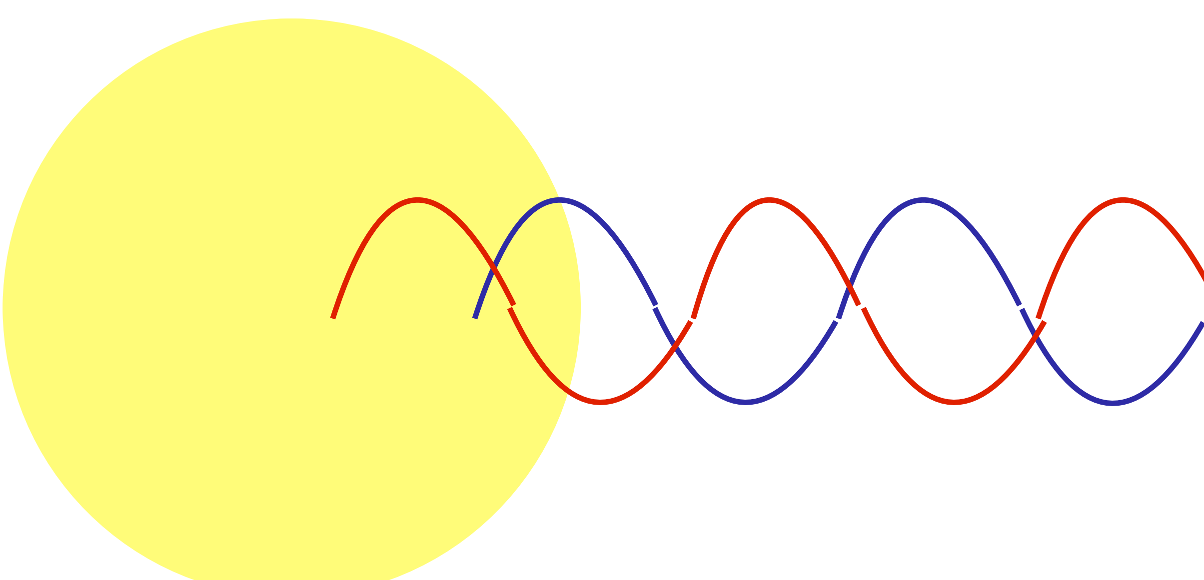
Spatially Extended Source

$$\text{prob}\,(\nu_e \to \nu_\mu) = \sin^2 2\theta \int dz_0\, f(z_0)\, \sin^2 \frac{\pi\,(z - z_0)}{\ell_{\text{osc}}}$$

For Gaussian shape: $f(z_0) = e^{-z_0^2/2s^2}/s\sqrt{2\pi}$

$$\text{prob}\,(\nu_e \to \nu_\mu) = \tfrac{1}{2}\,\sin^2 2\theta \left[1 - e^{-2\pi^2 (s/\ell_{\text{osc}})^2}\,\cos(2\pi z/\ell_{\text{osc}})\right]$$





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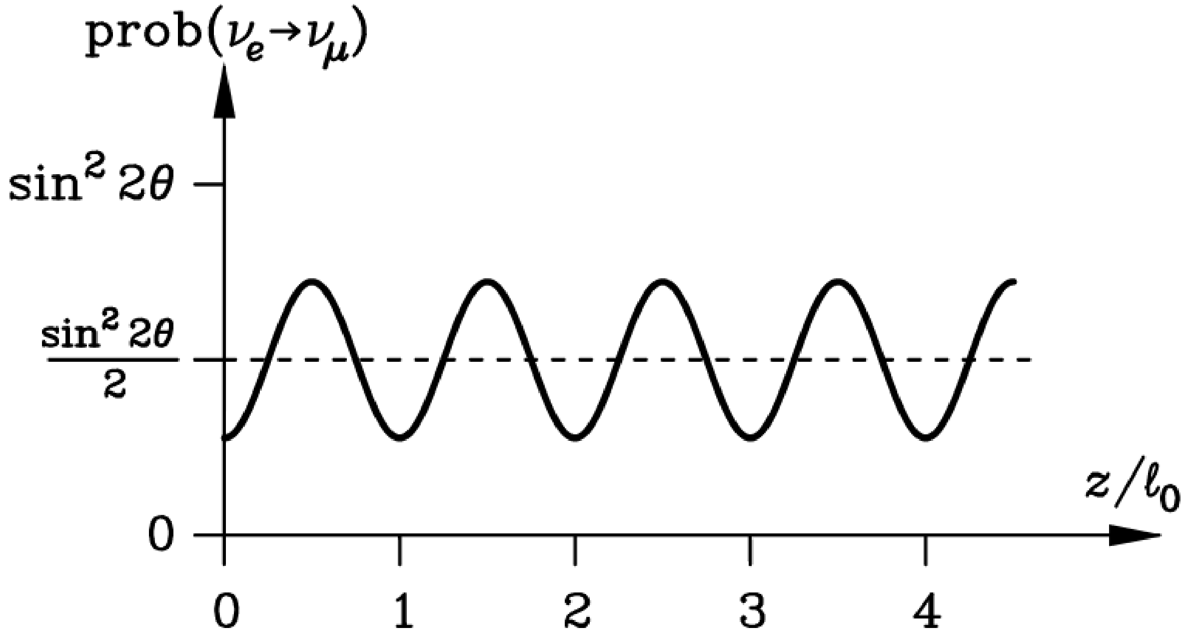


large source limit

$$s \gg \ell_{\text{osc}}$$

$$\tfrac{1}{2}\,\sin^2 2\theta$$

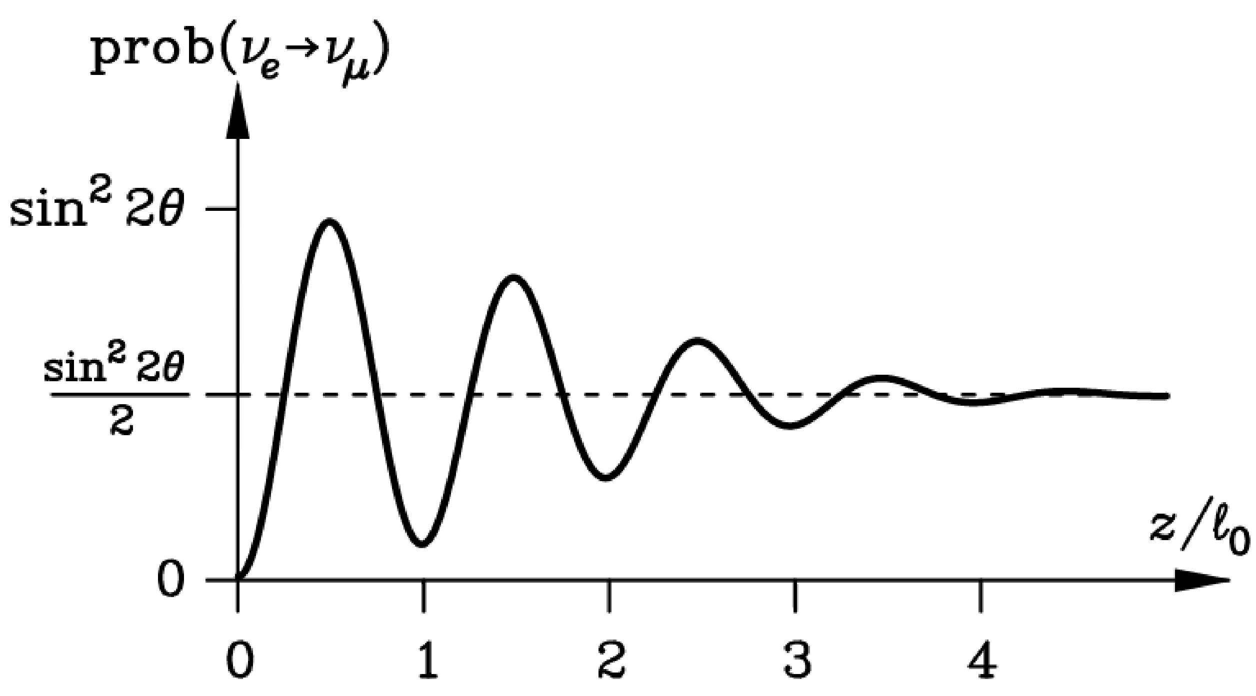
Non-Monochromatic Source

$$\text{prob}\,(\nu_e \to \nu_\mu) = \sin^2 2\theta \int d\omega\, g(\omega)\, \sin^2 \frac{(m_2^2 - m_1^2)\, z}{4\omega}$$

For Gaussian shape: $e^{-(\Delta-\Delta_0)^2/2\delta^2}/\delta\sqrt{2\pi}$

$$\Delta = 2\pi/\ell_{\text{osc}}$$

$$\text{prob}\,(\nu_e \to \nu_\mu) = \frac{1}{2}\sin^2 2\theta \left[1 - e^{-\delta^2 z^2/2} \cos(2\pi z/\ell_0)\right]$$



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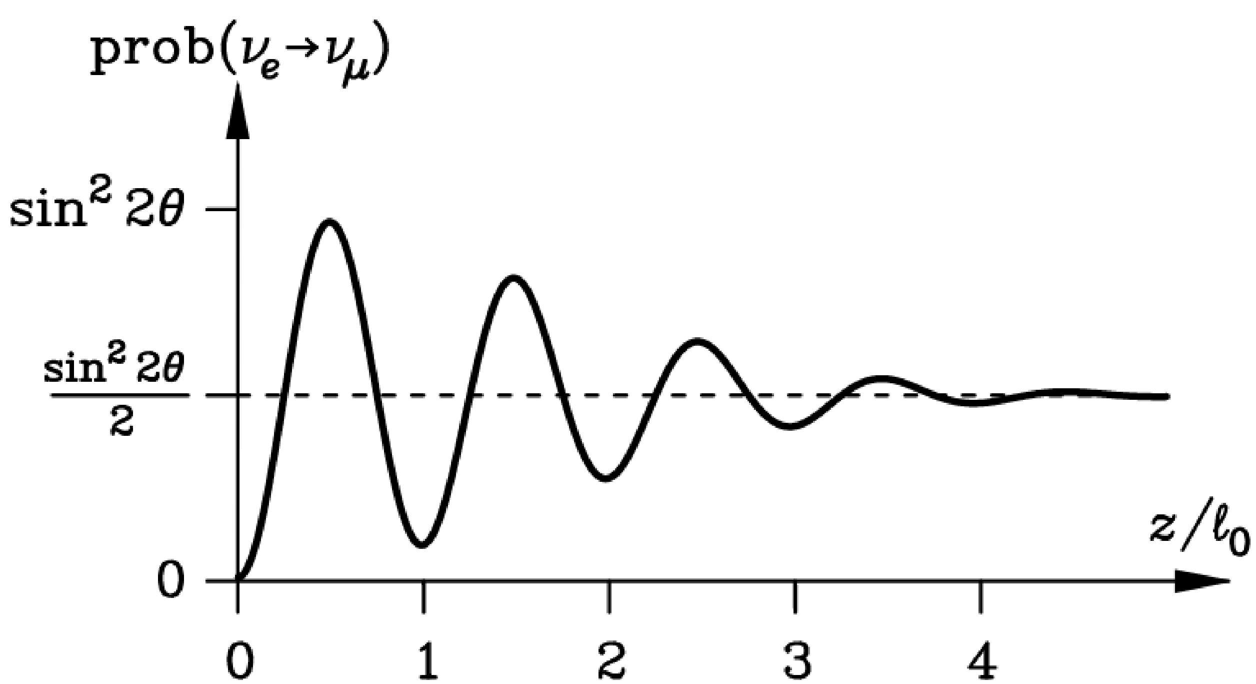


continuum spectrum

$$z \gg \delta^{-1}$$

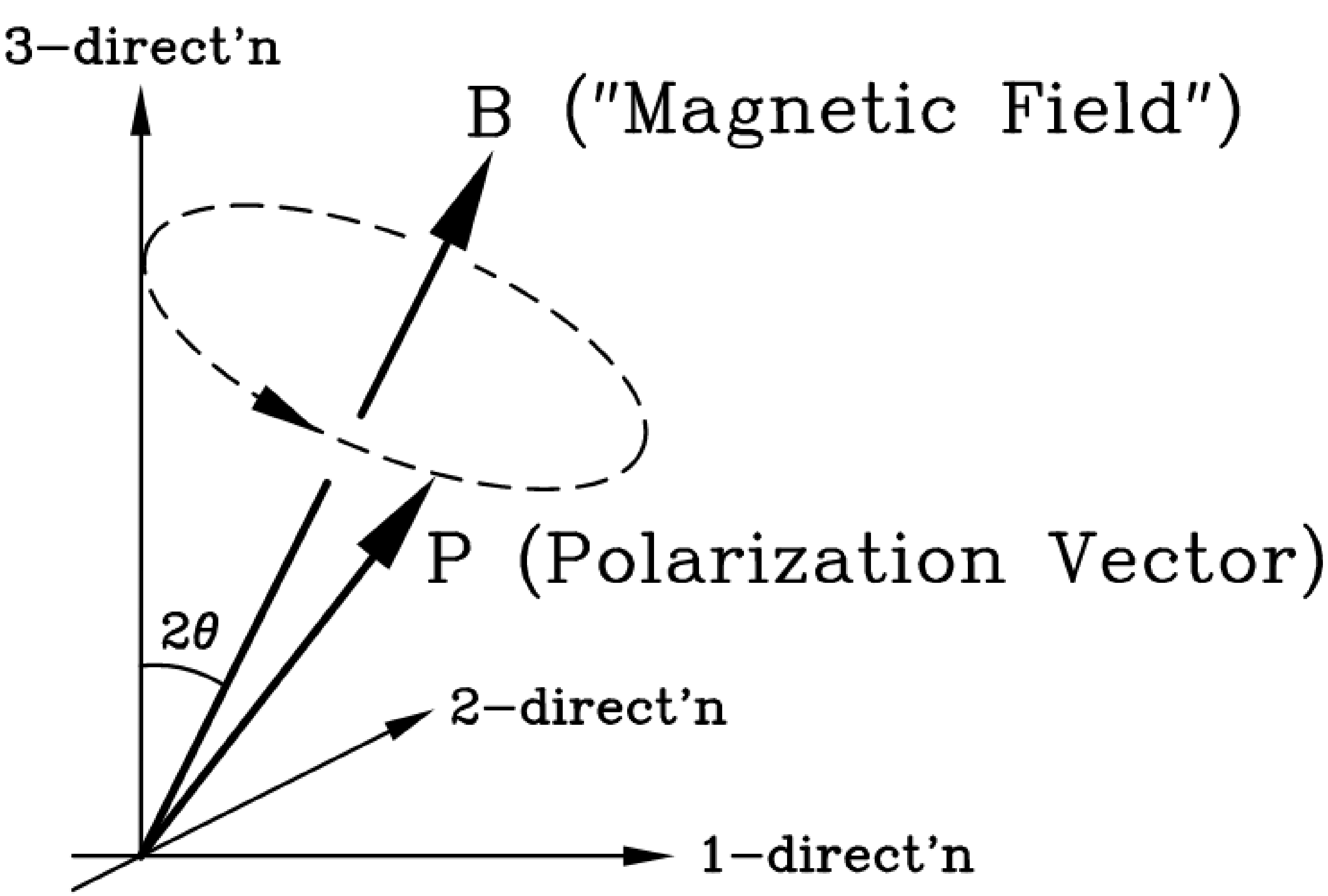
$$\frac{1}{2}\sin^2 2\theta$$

Flavour Pendulum

$\rho_{ab} = \Psi_b^* \Psi_a$ "density matrix"

$$\rho = \frac{1}{2}\left(1 + \mathbf{P} \cdot \boldsymbol{\sigma}\right)$$

$$\mathbf{B} = \frac{2\pi}{\ell_{\rm osc}} \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix},$$



$$|\Psi_e|^2 = \frac{1}{2}\left(1 + \mathbf{P}_3\right)$$

$$|\Psi_\mu|^2 = \frac{1}{2}\left(1 - \mathbf{P}_3\right)$$

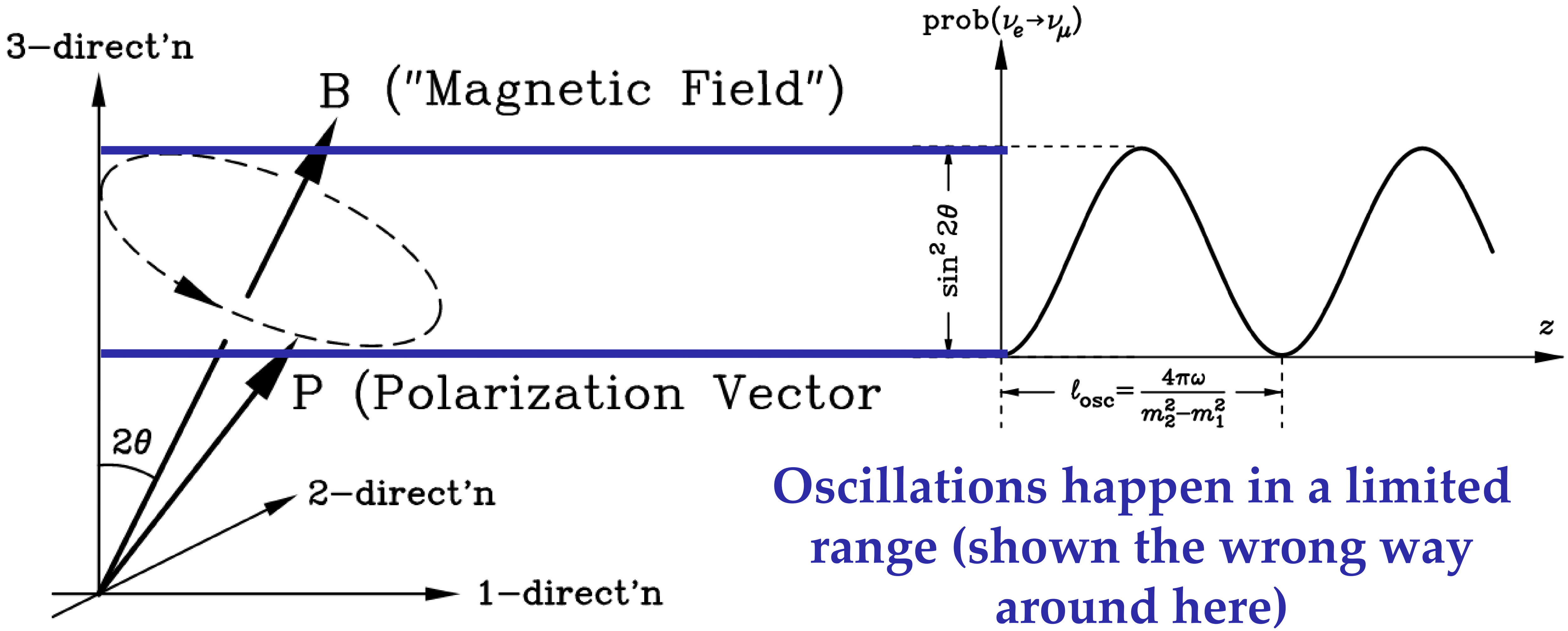
flavour evolution mimics spin precession in magnetic field

$$\partial_z \mathbf{P} = \mathbf{B} \times \mathbf{P}$$

Flavour Pendulum

$$|\Psi_e|^2 = \tfrac{1}{2}(1 + \mathbf{P}_3)$$
$$|\Psi_\mu|^2 = \tfrac{1}{2}(1 - \mathbf{P}_3)$$

$$\mathbf{B} = \frac{2\pi}{\ell_{\rm osc}} \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix},$$

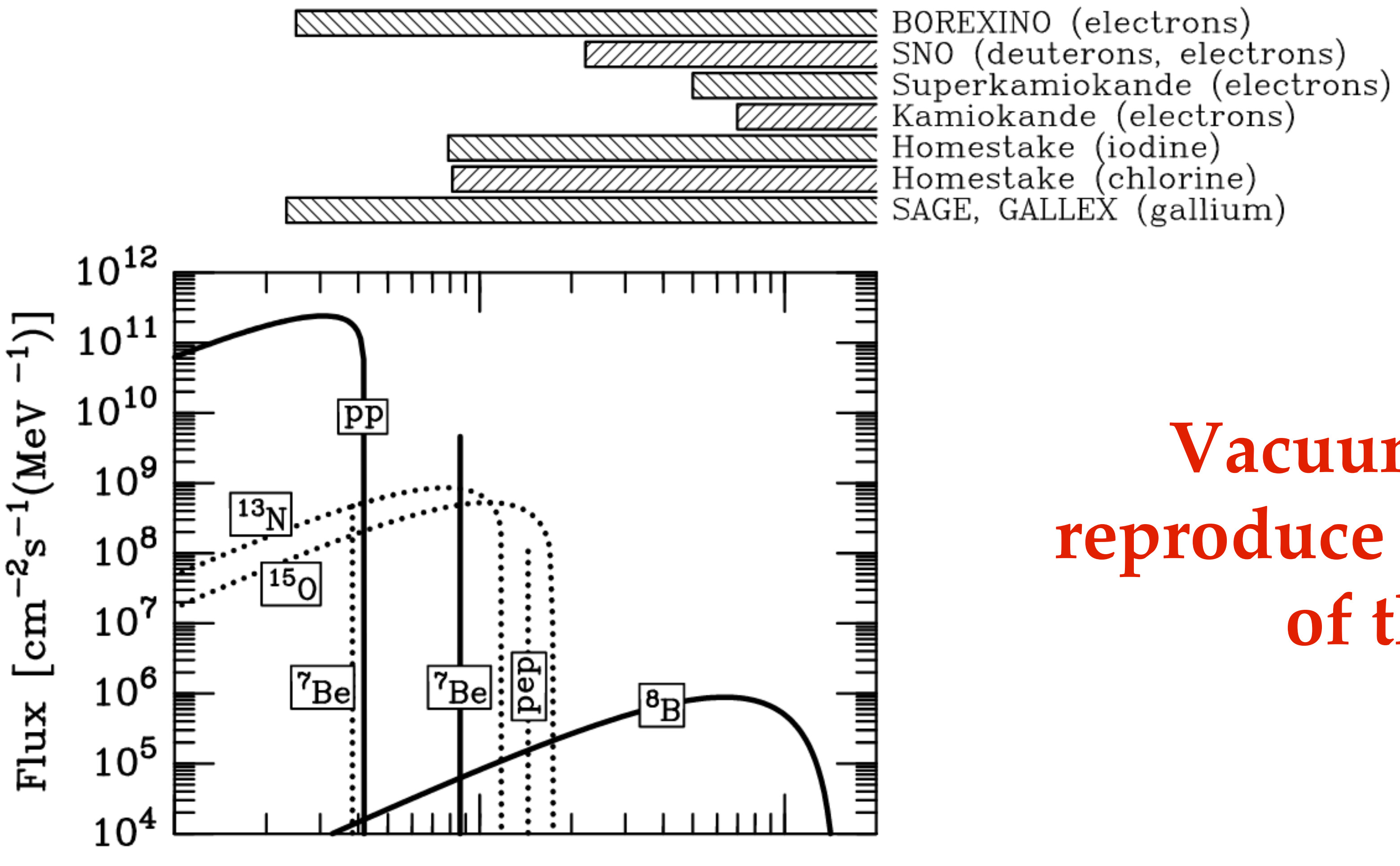


Oscillations happen in a limited range (shown the wrong way around here)

Can this explain the Solar Neutrino Problem?

The sun is large and not monochromatic….

$$\text{prob}\,(\nu_e \rightarrow \nu_\mu) = \frac{1}{2}\sin^2 2\theta$$



Vacuum oscillations fail to reproduce the energy dependence of the observations!

Matter Potentials

In matter the neutrinos have effective masses due to the interaction with the medium, just like electrons in condensed matter systems

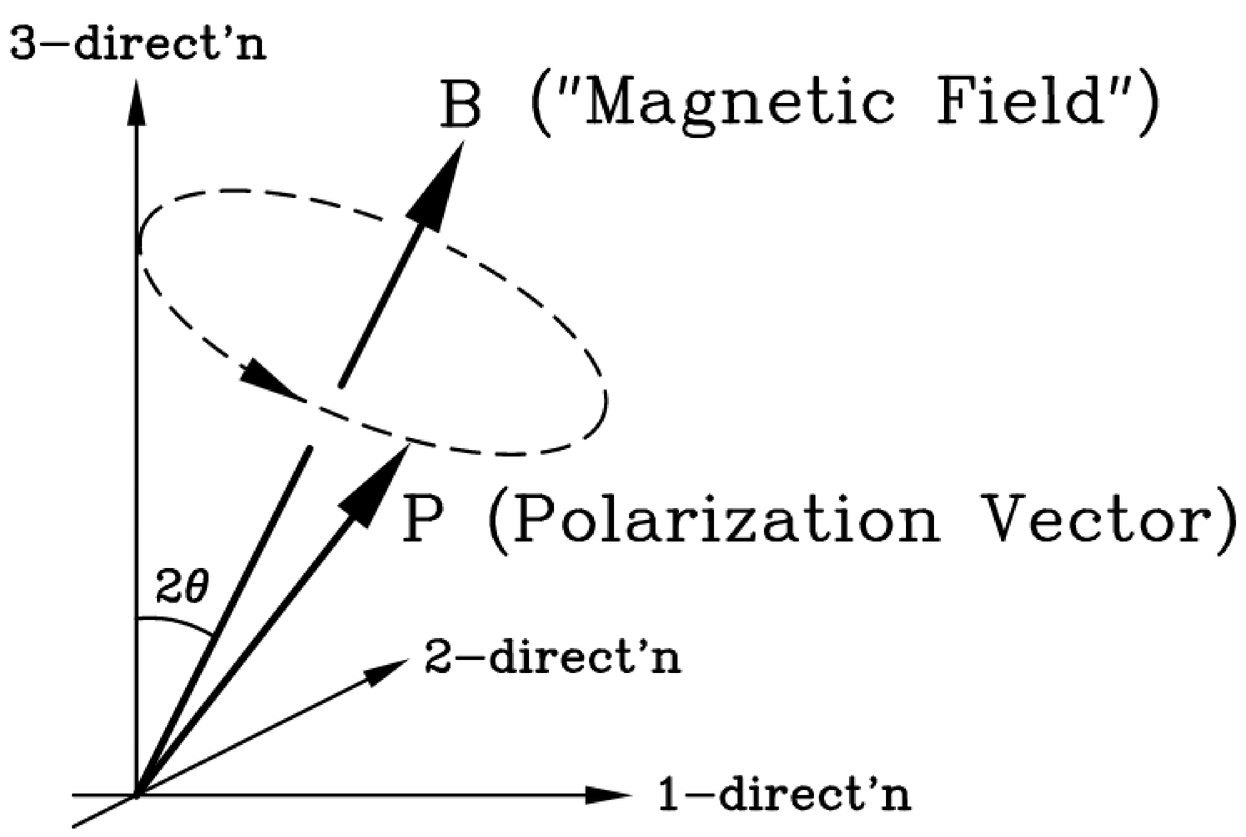
$$\left\{\left[\omega - \frac{G_\mathrm{F} n_B}{\sqrt{2}} \begin{pmatrix} 3Y_e - 1 & 0 & 0 \\ 0 & Y_e - 1 & 0 \\ 0 & 0 & Y_e - 1 \end{pmatrix}\right]^2 - k^2 - U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger \right\} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = 0$$

The "matter potentials" depend on flavour because the sun contains electrons, but no muons and tauons

Two Flavour Oscillations in Matter

$$b_0 = (m_1^2 + m_2^2)/4k + \sqrt{2}\, G_{\rm F} n_B \left(Y_e - \tfrac{1}{2}\right)$$

$$\mathbf{B} = \frac{m_2^2 - m_1^2}{2\omega}\begin{pmatrix}\sin 2\theta_0 \\ 0 \\ \cos 2\theta_0\end{pmatrix} - \sqrt{2}\, G_{\rm F} n_e \begin{pmatrix} 0 \\ 0 \\ 1\end{pmatrix}$$



effective "B field" depends on electron density, and therefore on space and time!

flavour state can completely be changed by changing *B*.

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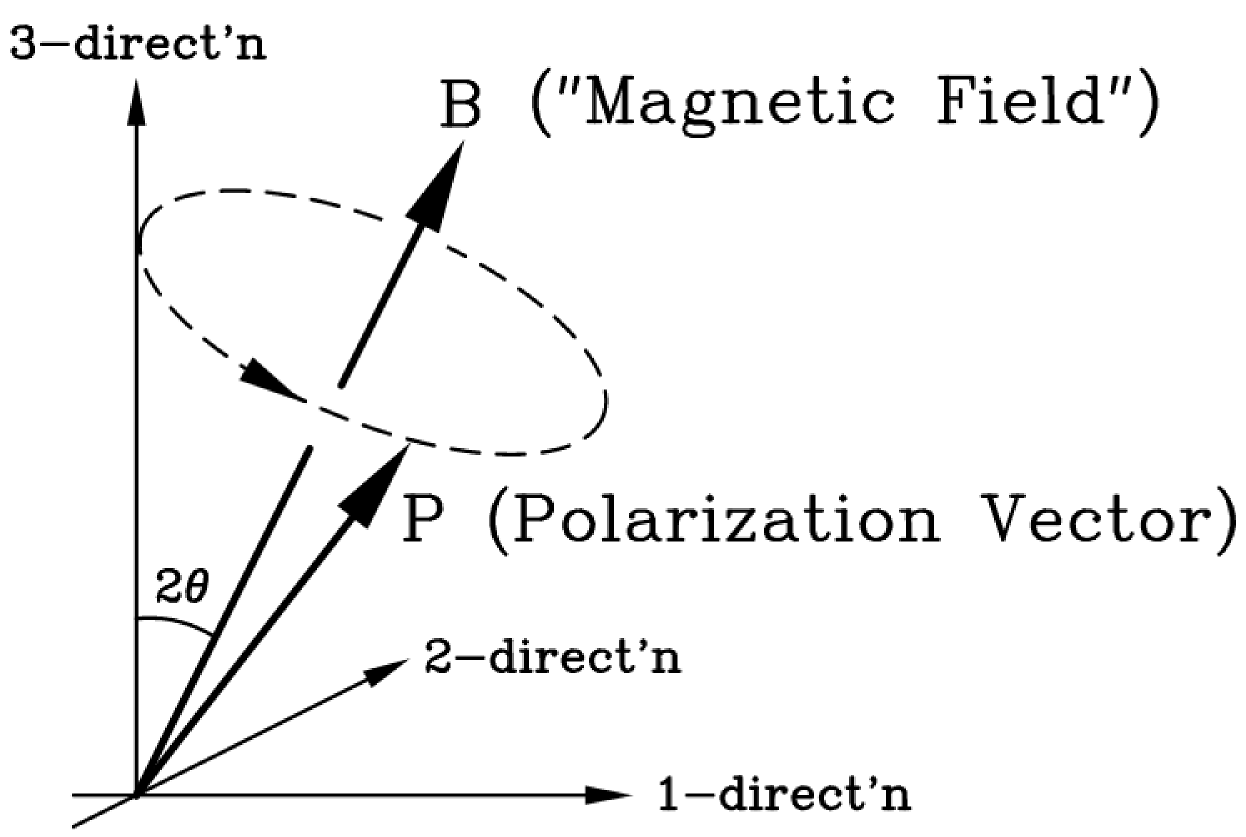
$$\mathbf{B} = \frac{2\pi}{\ell_{\rm osc}} \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix} = \frac{m_2^2 - m_1^2}{2\omega} \begin{pmatrix} \sin 2\theta_0 \\ 0 \\ \cos 2\theta_0 \end{pmatrix} - \sqrt{2}\,G_F n_e \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$



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flavour state can completely be changed by changing *B*.

Effective Mass and Mixing

Effective mixing angle in matter:

$$\sin 2\theta = \frac{\sin 2\theta_0}{[\sin^2 2\theta_0 + (\cos 2\theta_0 - \xi)^2]^{1/2}}$$

Effective oscillation length in matter:

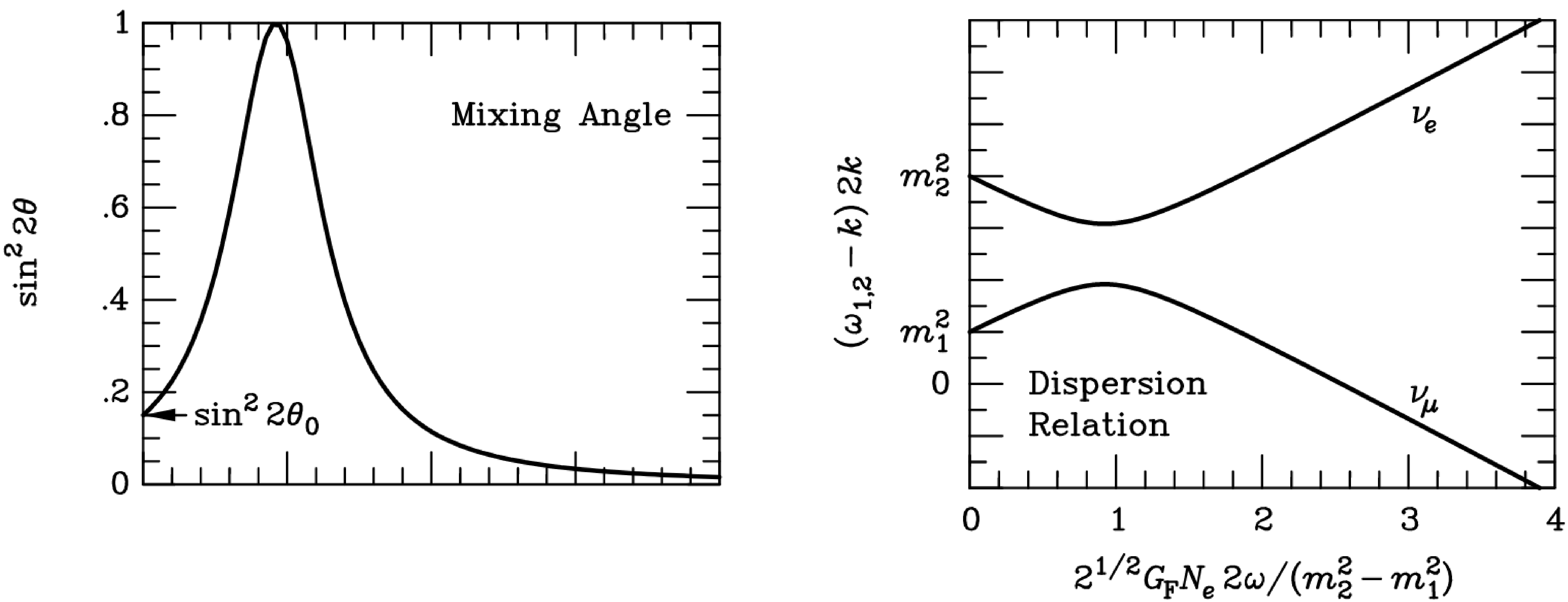
$$\ell_{\rm osc} = \frac{4\pi\,\omega}{m_2^2 - m_1^2}\,\frac{\sin 2\theta}{\sin 2\theta_0}\,.$$

The decisive parameter depends on density, masses and energy:

$$\xi \equiv \frac{\sqrt{2}\,G_{\rm F} n_e\, 2\omega}{m_2^2 - m_1^2} = 1.53\times 10^{-7}\,\frac{Y_e\,\rho}{\rm g\,cm^{-3}}\,\frac{\omega}{\rm MeV}\,\frac{\rm eV^2}{m_2^2 - m_1^2}\,,$$

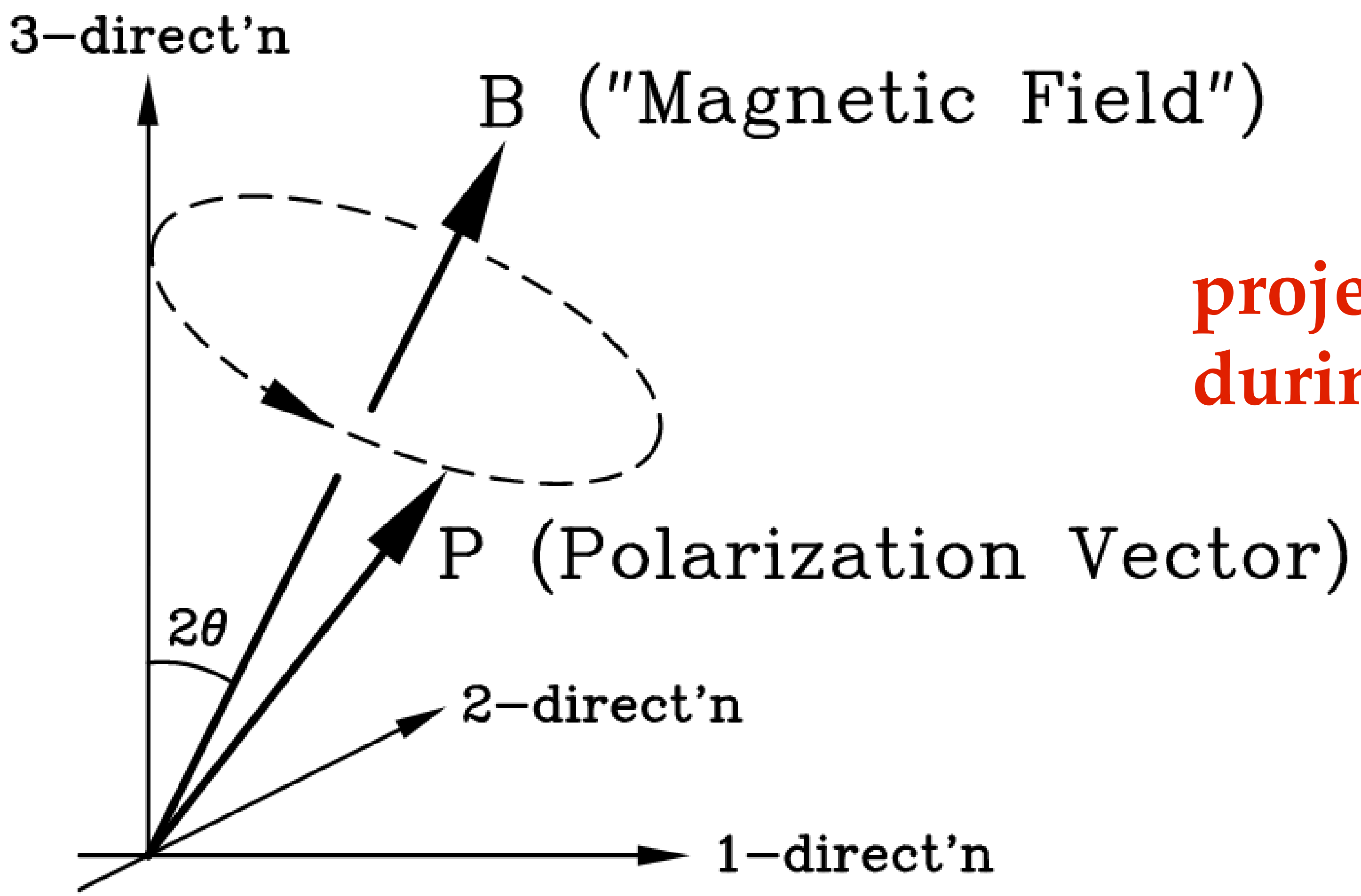
MSW Resonance

$$\sin 2\theta = \frac{\sin 2\theta_0}{[\sin^2 2\theta_0 + (\cos 2\theta_0 - \xi)^2]^{1/2}}$$



Adiabatic Limit

$$\mathrm{prob}(\nu_e \rightarrow \nu_e) = \frac{1}{2}\left(1 + \cos 2\theta_0 \cos 2\theta\right)$$



projection of P on B is preserved during adiabatic evolution

Non-Adiabatic Limit

$$|\nabla\theta| \ll \pi/\ell_{\rm osc}.$$ adiabaticity condition

$$\xi \sin^3 2\theta\, |\nabla \ln n_e| \ll \sin^2 2\theta_0\, |m_2^2 - m_1^2|/2\omega.$$

probability p to jump from one dispersion relation to the other:

$$\text{prob}(\nu_e \to \nu_e) = \tfrac{1}{2} + \left(\tfrac{1}{2} - p\right) \cos 2\theta_0 \cos 2\theta$$

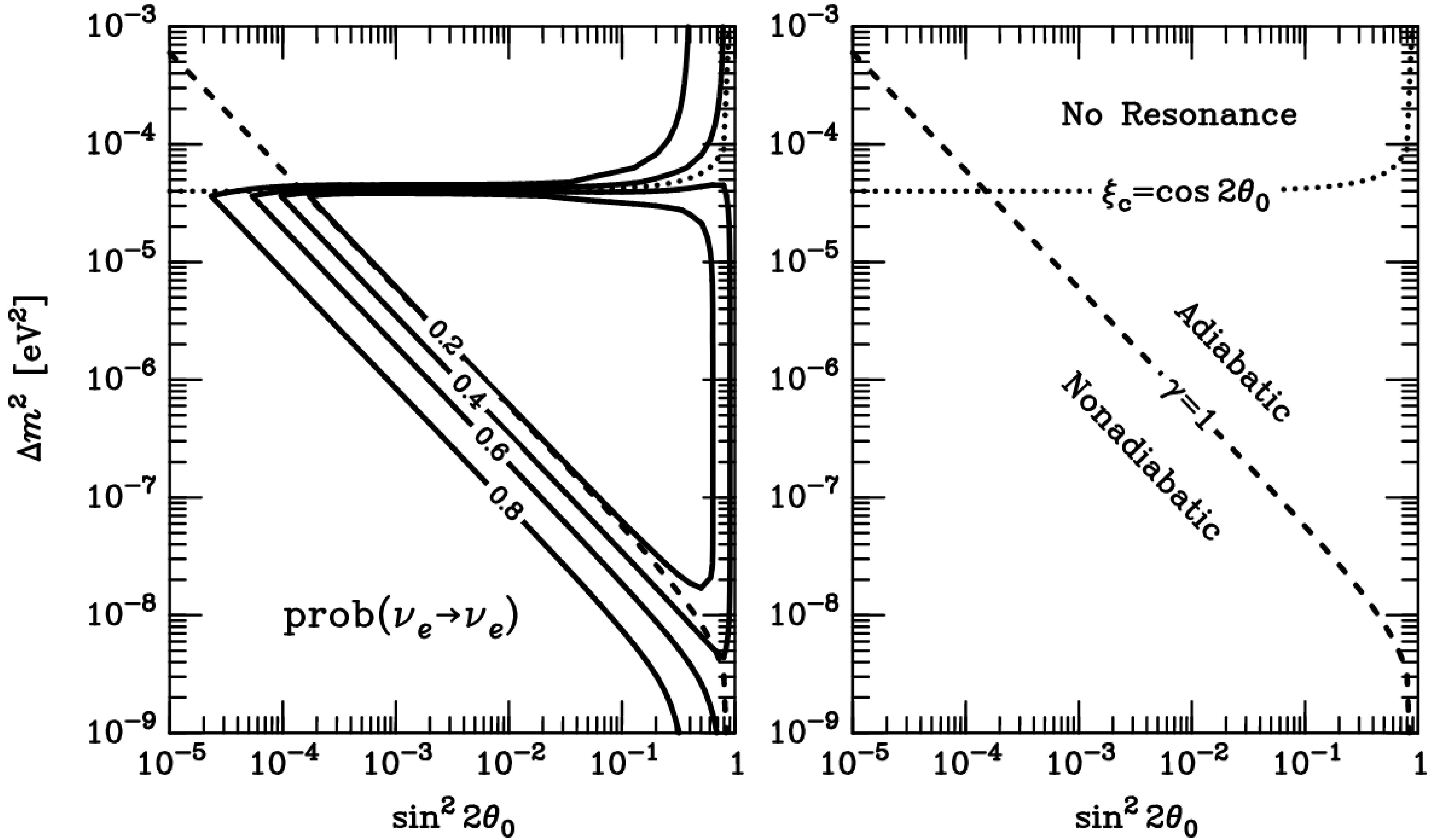
$$p = \frac{e^{-(\pi\gamma/2)\,F} - e^{-(\pi\gamma/2)\,F'}}{1 - e^{-(\pi\gamma/2)\,F'}}$$

$$F = 1 - \tan^2\theta_0$$

$$\gamma \equiv \frac{m_2^2 - m_1^2}{2\omega}\, \frac{\sin 2\theta_0\, \tan 2\theta_0}{|\nabla \ln n_e|_{\rm res}}$$

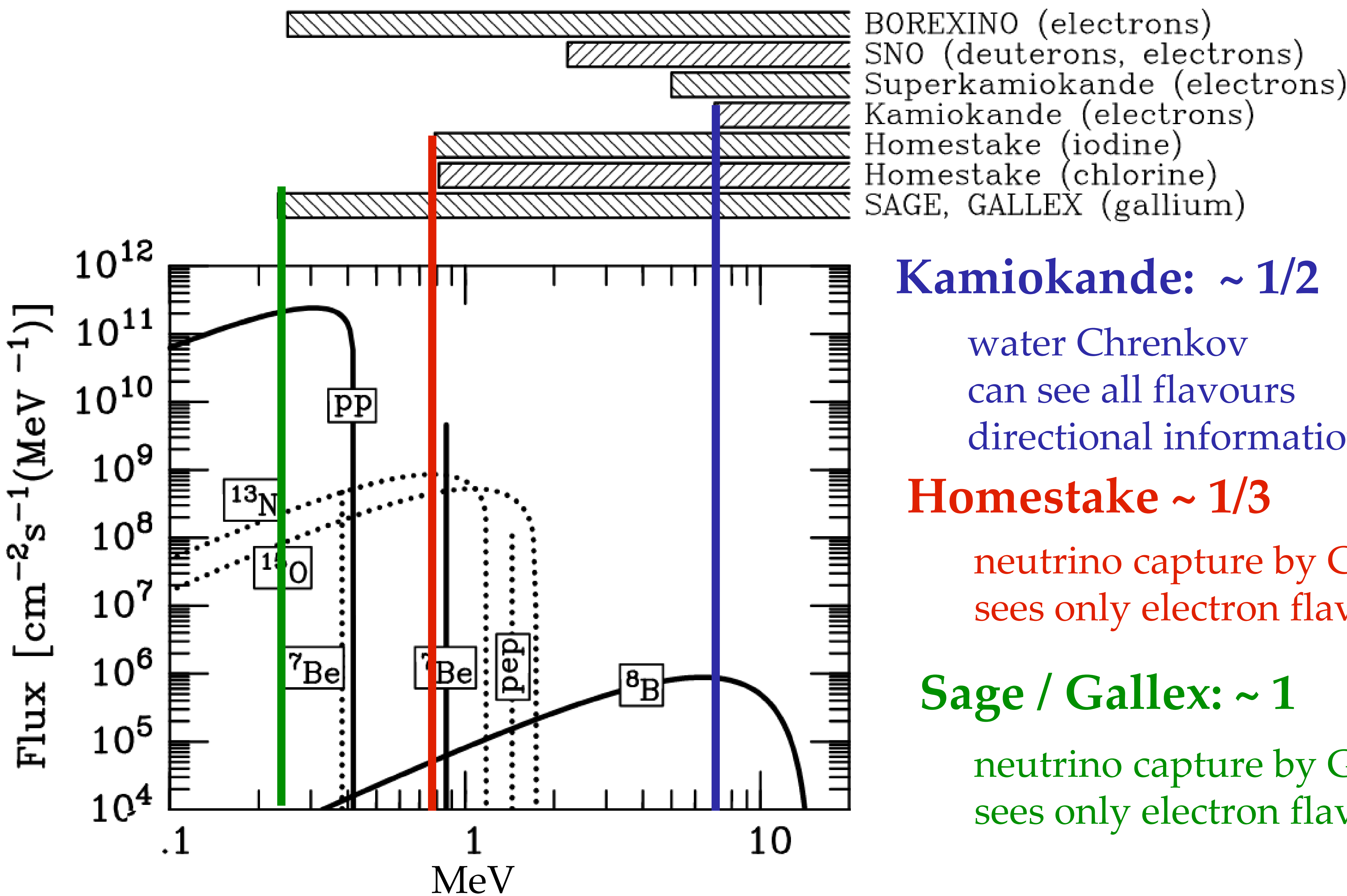
for an exponential profile

MSW Resonance in the Sun



Solar Model

Total flux: 66 billion ν / (s cm²)



Kamiokande: ~ 1/2

water Chrenkov
can see all flavours
directional information

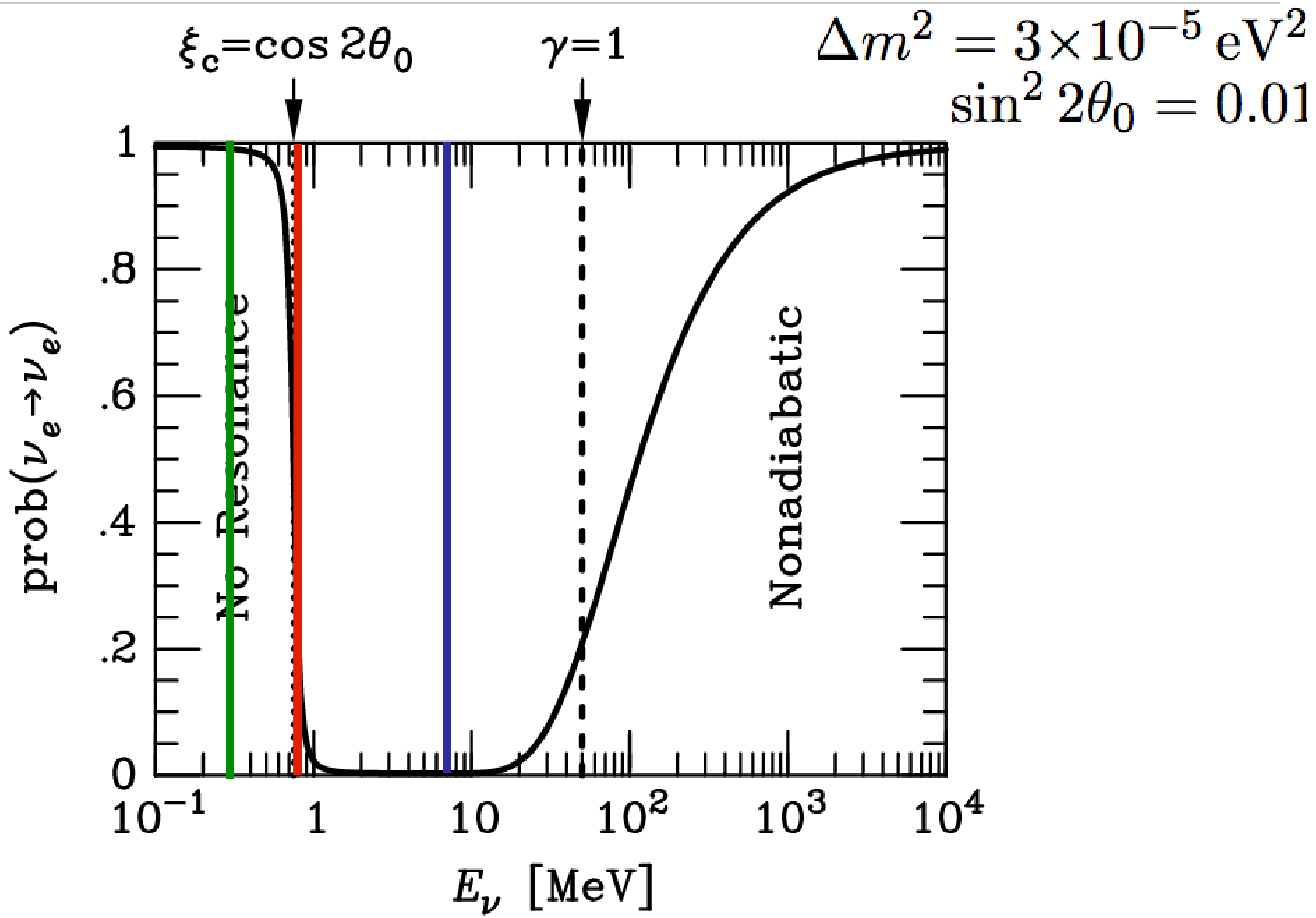
Homestake ~ 1/3

neutrino capture by Cl
sees only electron flavour

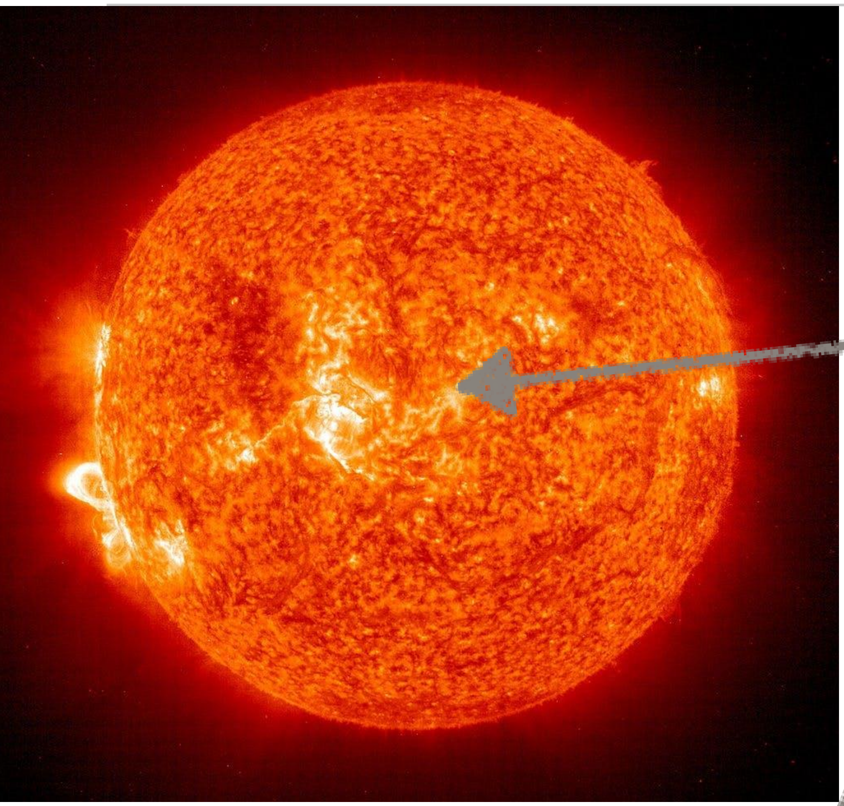
Sage / Gallex: ~ 1

neutrino capture by Ga
sees only electron flavour

The "Bathtub Plot"



Neutrino Oscillations



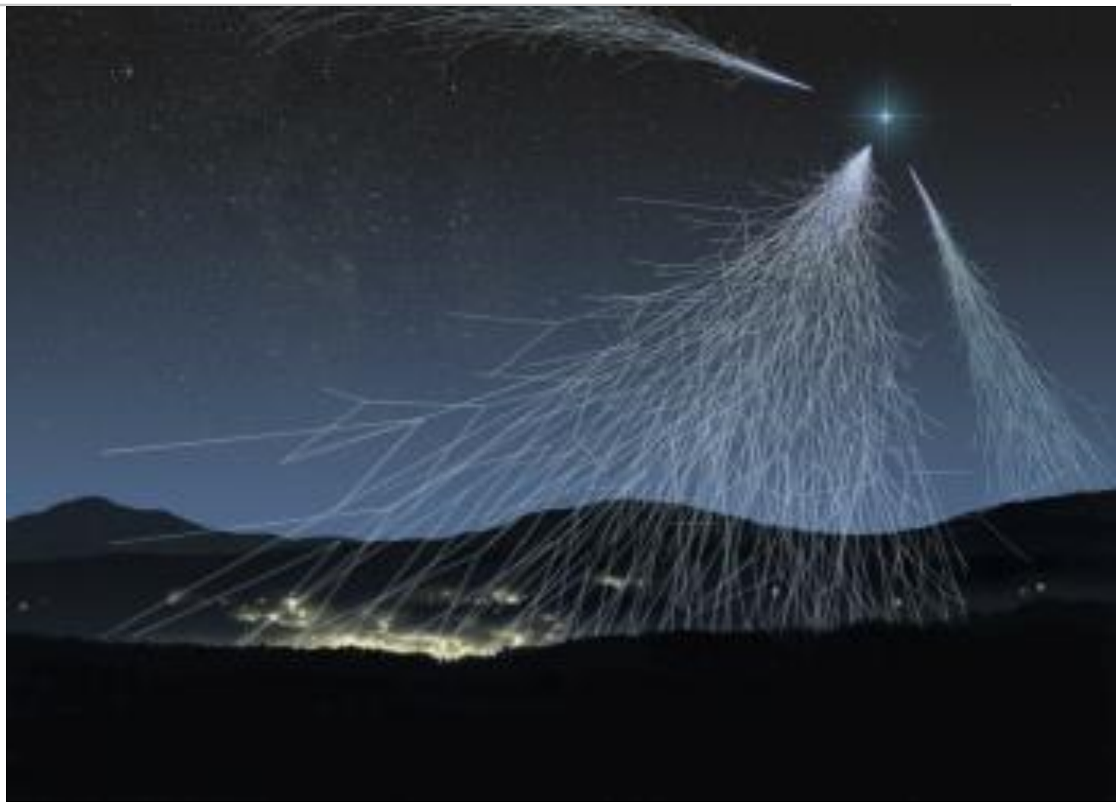
Evidence comes from many sources:

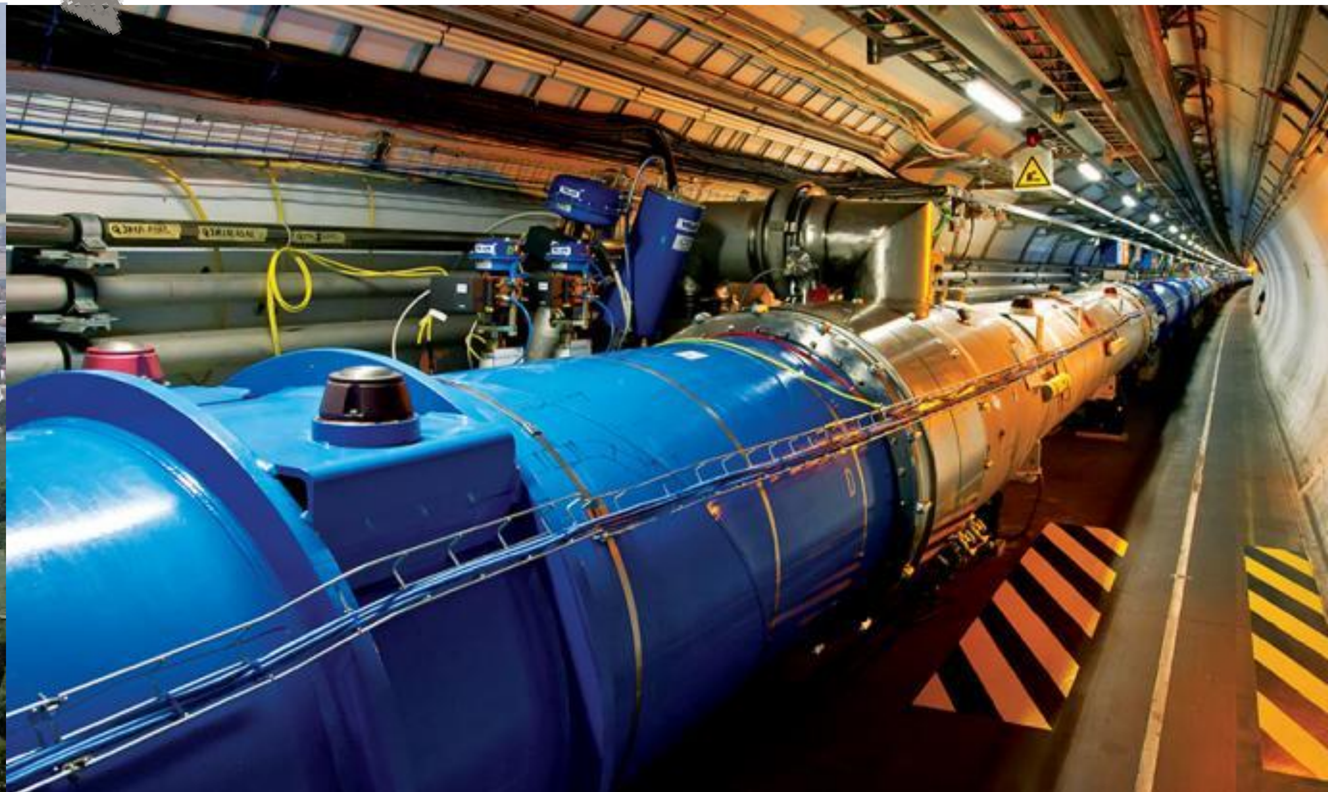
sun

cosmic rays

nuclear reactors

particle colliders





Neutrino Properties

What we know

- neutrinos undergo flavour oscillations
- those can be explained by a Dirac or Majorana mass term

$$\overline{\nu_L} m_D \nu_R + h.c. \qquad \overline{\nu_L} m_M \nu_L^c + h.c.$$

- …which can be diagonalised as

$$\mathrm{diag}(m_1, m_2, m_3) = U_\nu^\dagger m_D \tilde{U}_\nu \qquad \mathrm{diag}(m_1, m_2, m_3) = U_\nu^\dagger m_M U_\nu^*$$

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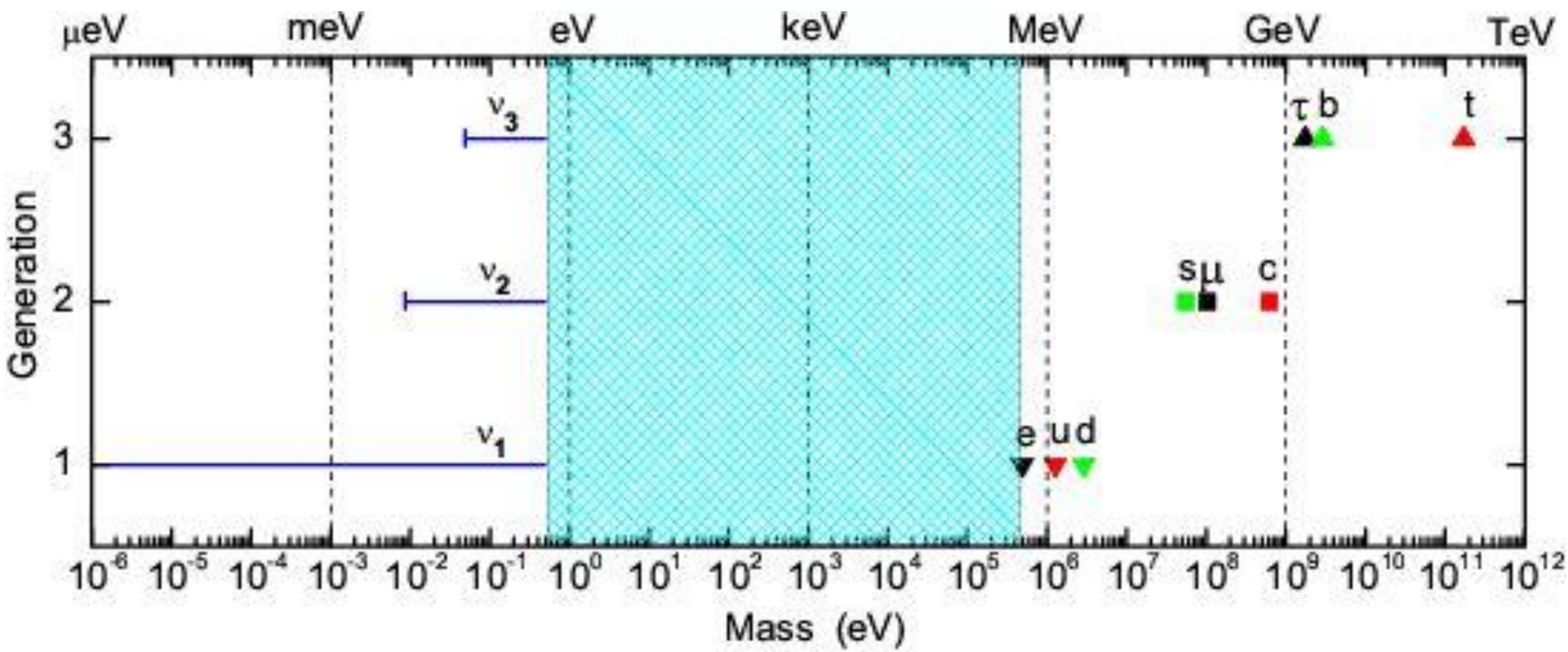
leptons are just like quarks without colour… but:

- Why are the m_i so tiny?
- Why is the mixing matrix so different from the CKM matrix?
- What forbids the Majorana mass for the RH neutrino?



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Neutrino Mixing Matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

"PMNS matrix"
Pontecorvo-Maki-Nakagawa-Sakata

Common parameterisation of the matrix *U*:

$$U_\nu = V^{(23)} U_\delta V^{(13)} U_{-\delta} V^{(12)} \mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$$

$$U_{\pm\delta} = \mathrm{diag}(e^{\mp i\delta/2}, 1, e^{\pm i\delta/2})$$

$$V^{(12)} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V^{(23)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad V^{(13)} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

NuFIT 5.1 (2021)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

J_ν^*

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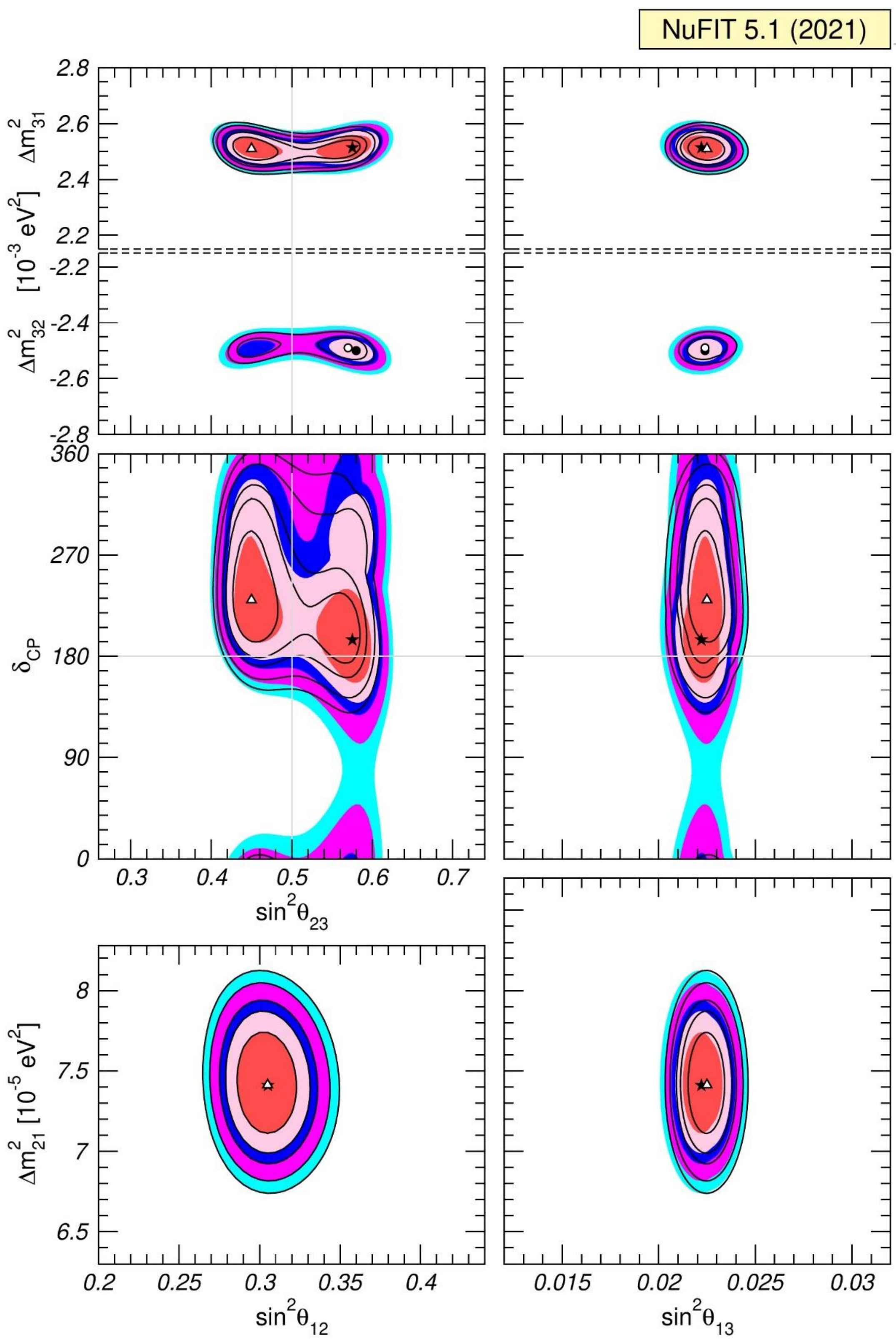
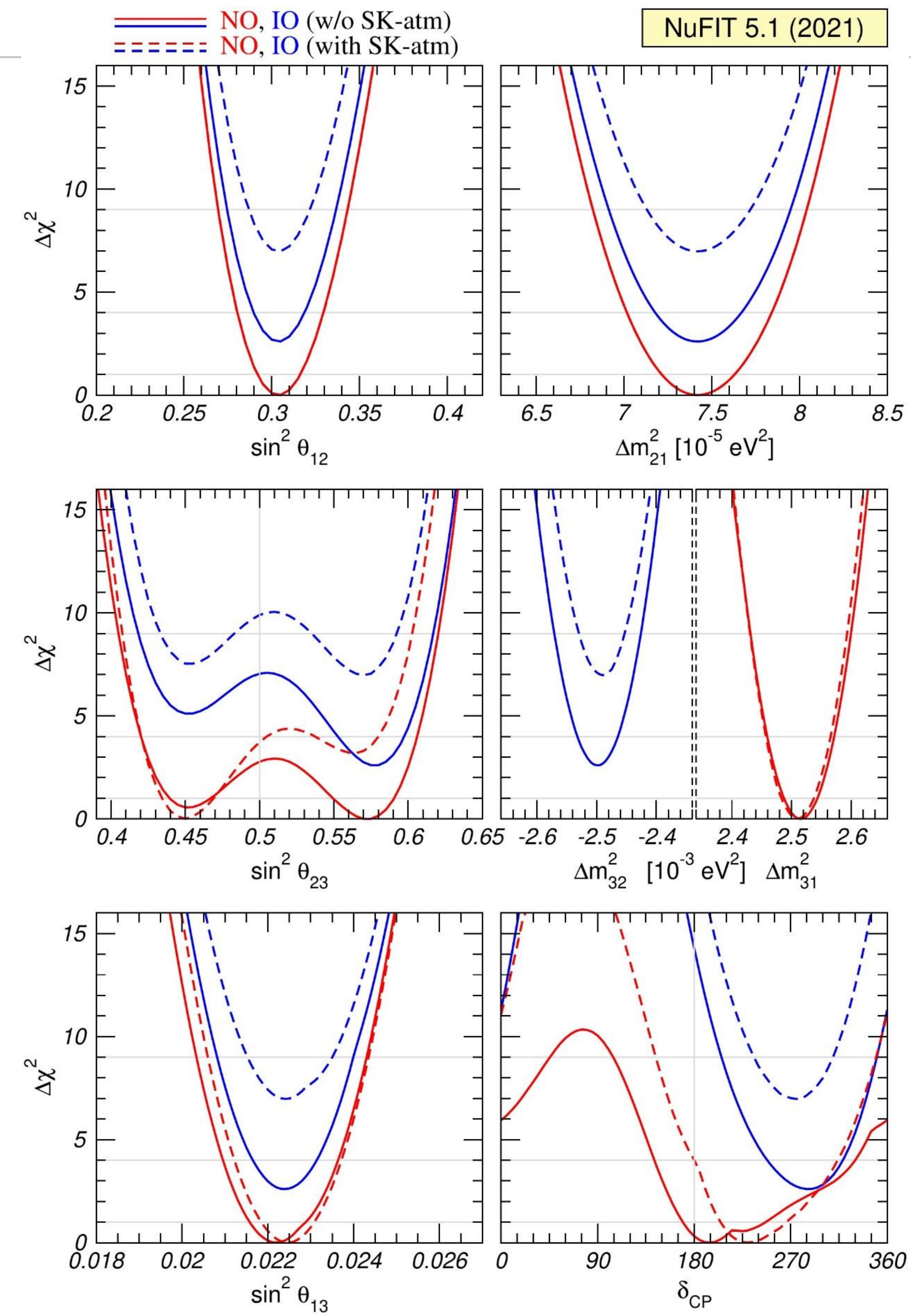
Current Best Fit (NuFit 2021)





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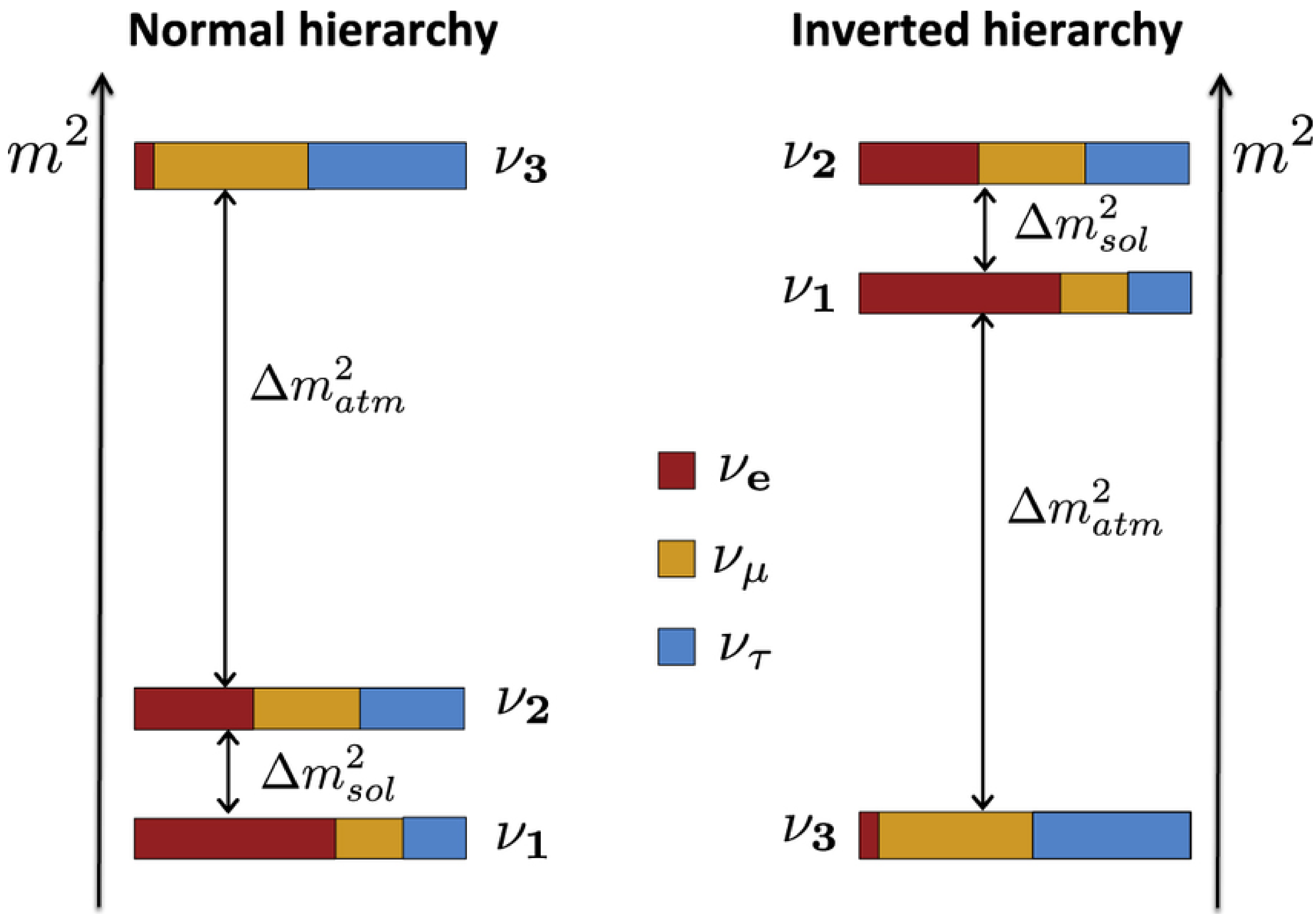
- Majorana fermion
  NEW PHYSICS!
- can be generated in gauge invariant way by higher dim operators
  NEW PHYSICS!
  should be generated by integrating out some heavier states with masses ~Λ >> E_v

What we want to know

- **the mass hierarchy**
  "normal" or "inverted"?
- **the absolute mass scale**
  is there a massless elementary fermion?
- **CP-violation**
  … and connection to baryogenesis?
- **Dirac or Majorana?**
  Is B-L conserved in nature? Connection to baryogenesis?
- **Are there extra (sterile) neutrinos?**
- **mechanism of mass generation**
  Hint towards more fundamental theory (e.g. GUT)?
  Scale Λ in the context of the hierarchy problem?
  Connection to Baryogenesis or Dark Matter?

The Neutrino Mass Hierarchy

“Normal” and “Inverted” Ordering



Effect of Ordering on Oscillations

Electron neutrino appearance probability

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

To leading order only depends on

- two mixing angles
- the square of the larger mass splitting

$$\Delta = \frac{\Delta m^2_{31} L}{4E} \qquad A = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

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$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

$$+ \ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

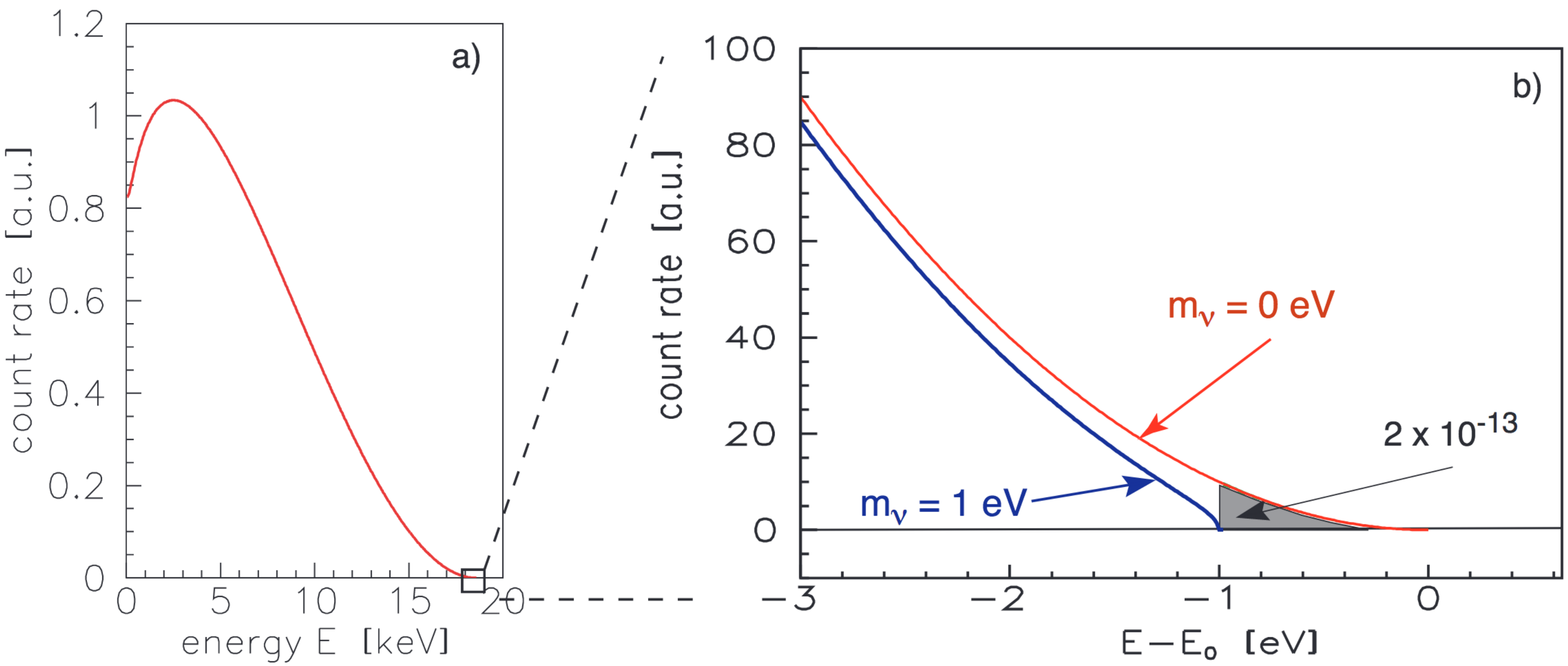
$$- \ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

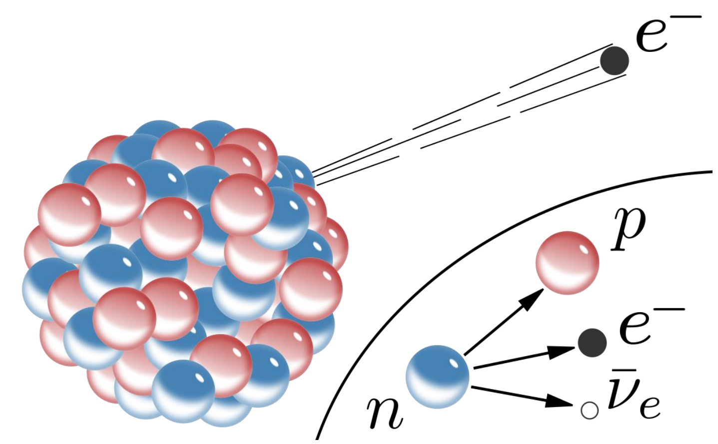
But subheading corrections depend on sign of splittings!

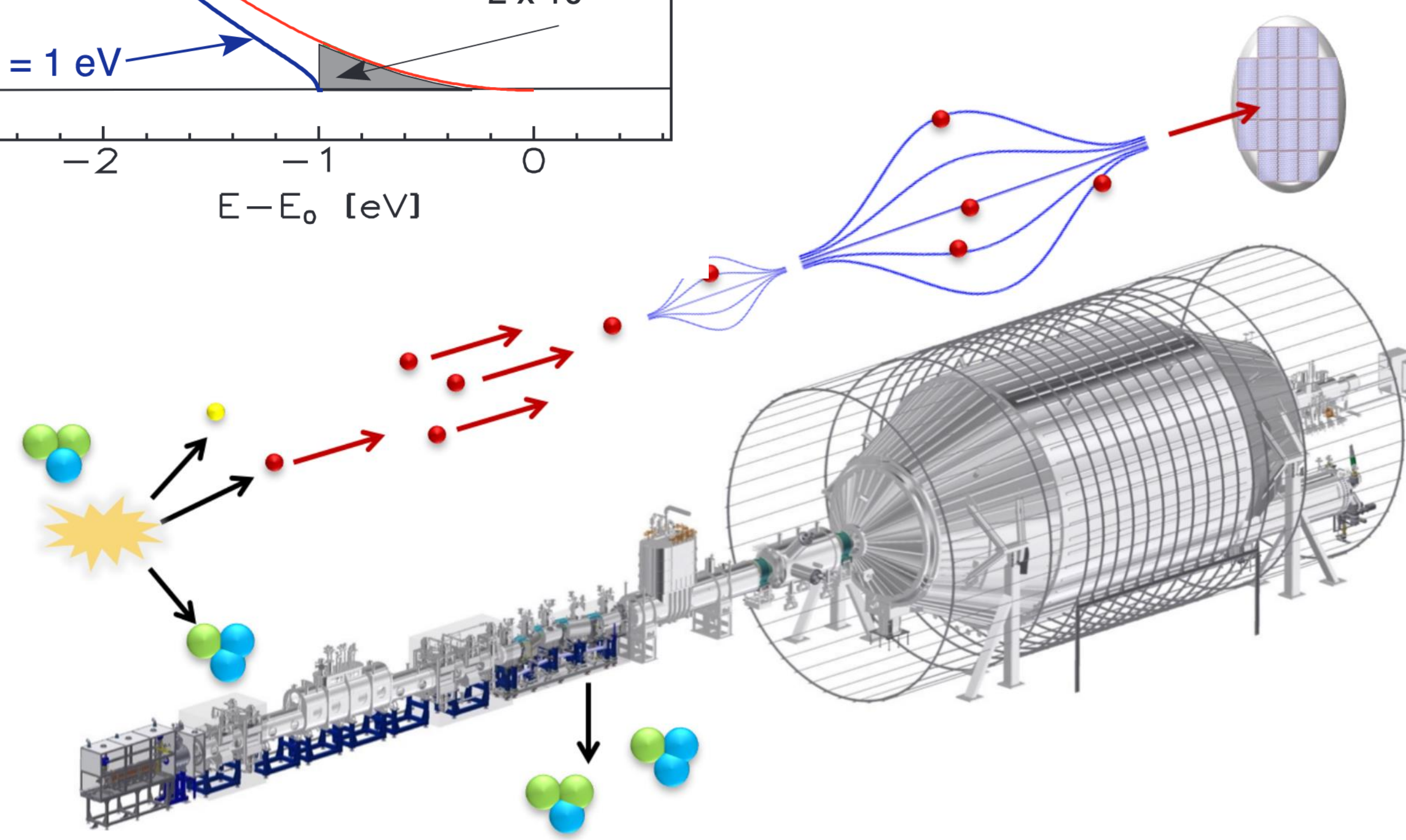
$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \qquad \Delta = \frac{\Delta \mathrm{m}_{31}^2 L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

lightest neutrino mass

Direct Measurement of the Neutrino Mass

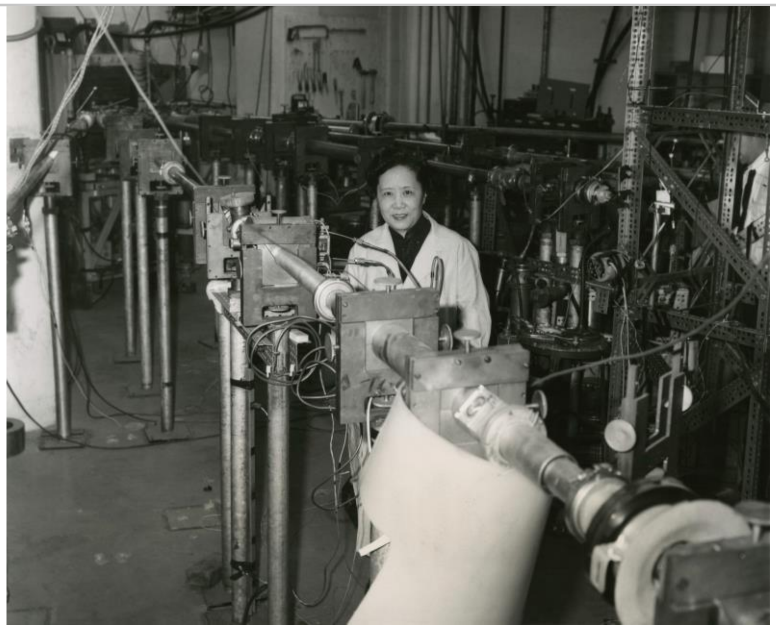


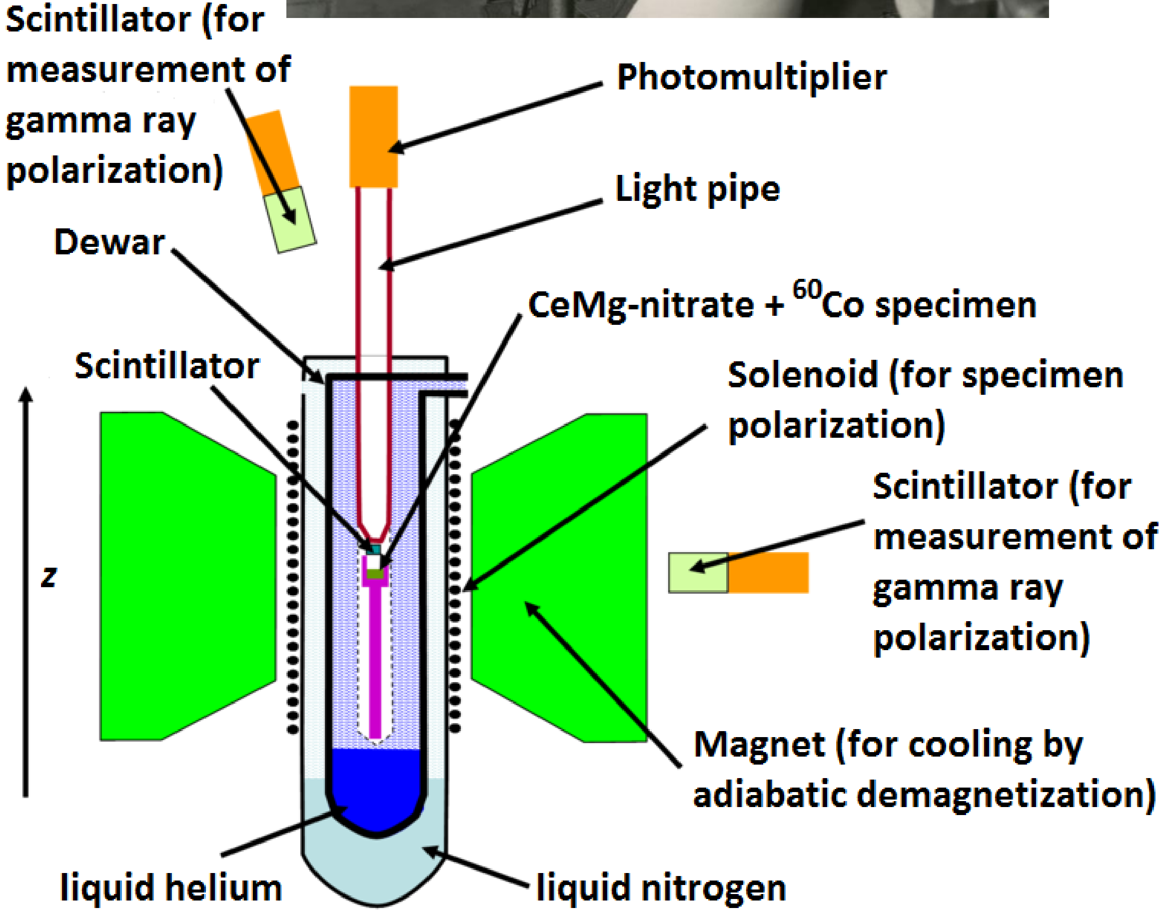


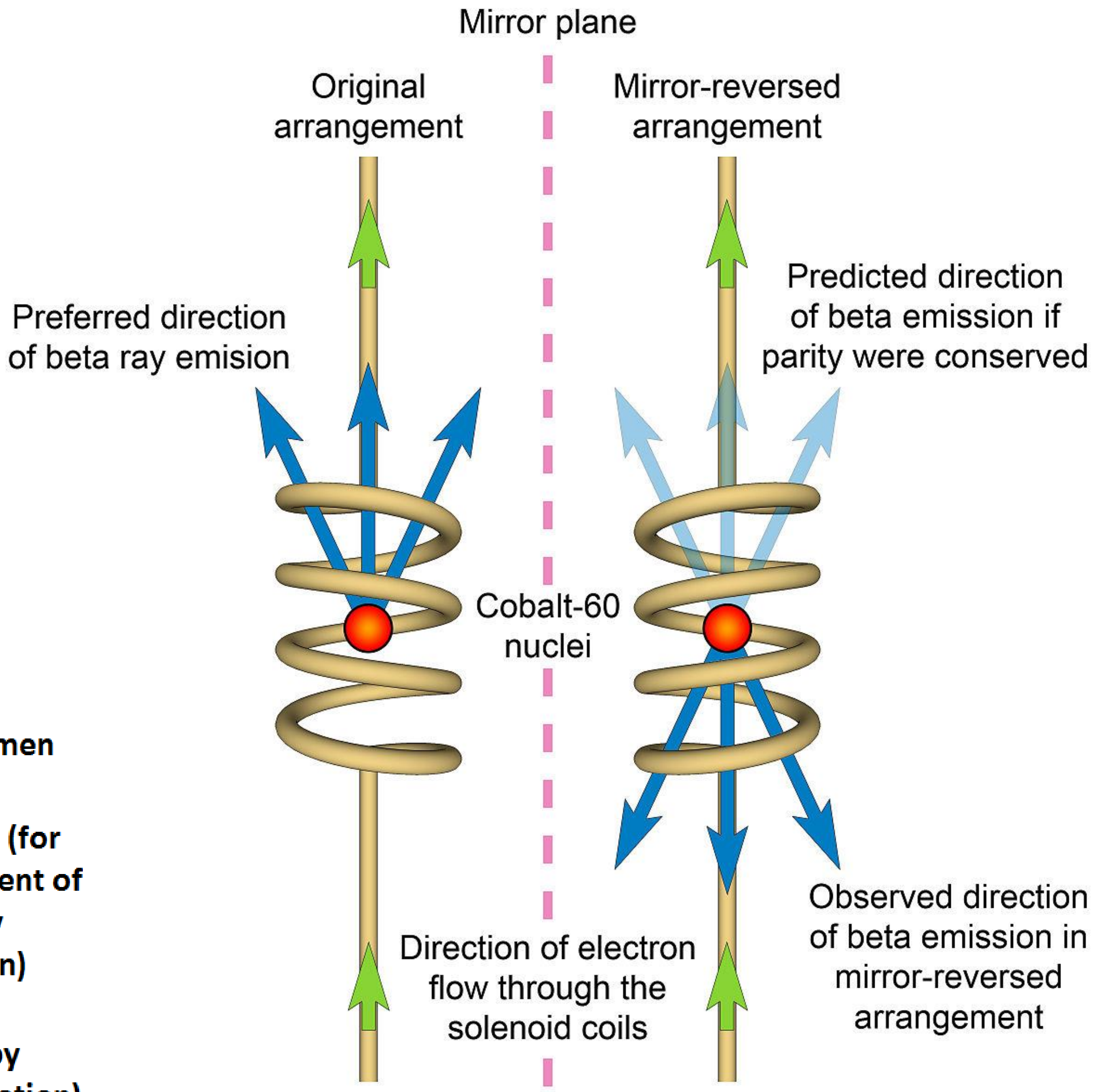


Parity Violation

The Wu Experiment







The hunt for CP violation

Effect of CP-Violation on Oscillations

Electron neutrino appearance probability

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

Is sensitive to Dirac phase!

$$+ \boxed{2\alpha} \boxed{\sin\theta_{13}} \boxed{\cos\delta_{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

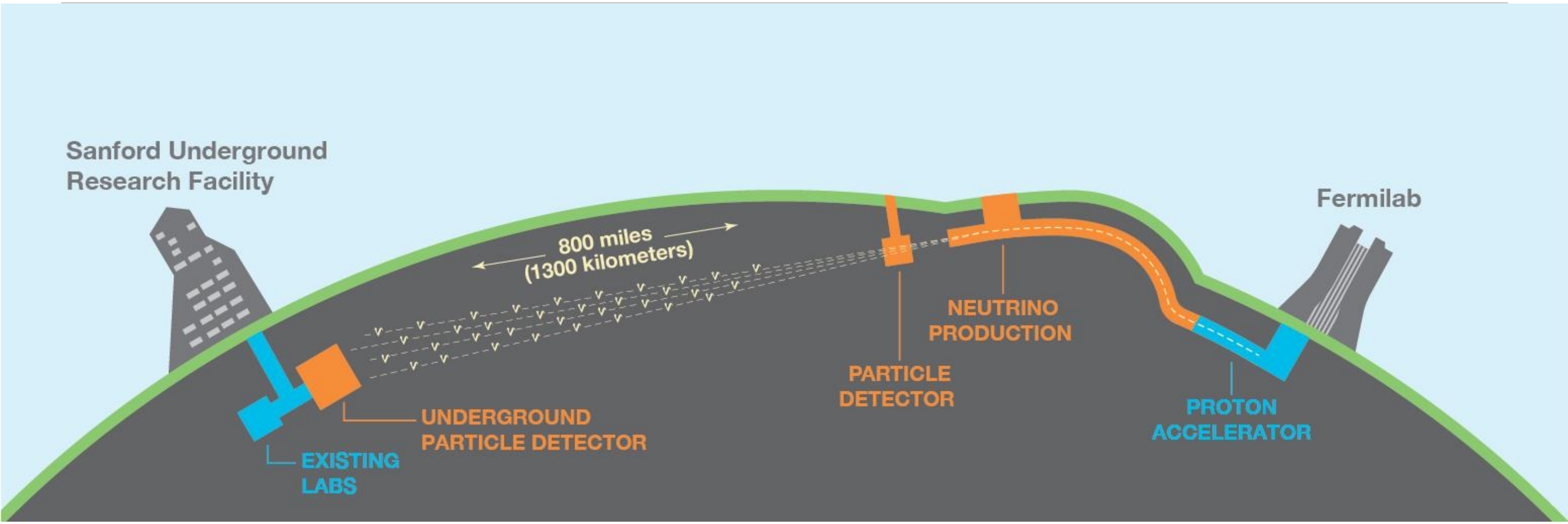
$$- \boxed{2\alpha} \boxed{\sin\theta_{13}} \boxed{\sin\delta_{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

dependence on CPV suppressed by ratio of mass splittings…

…luckily θ_{13} is not too small!

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

DUNE

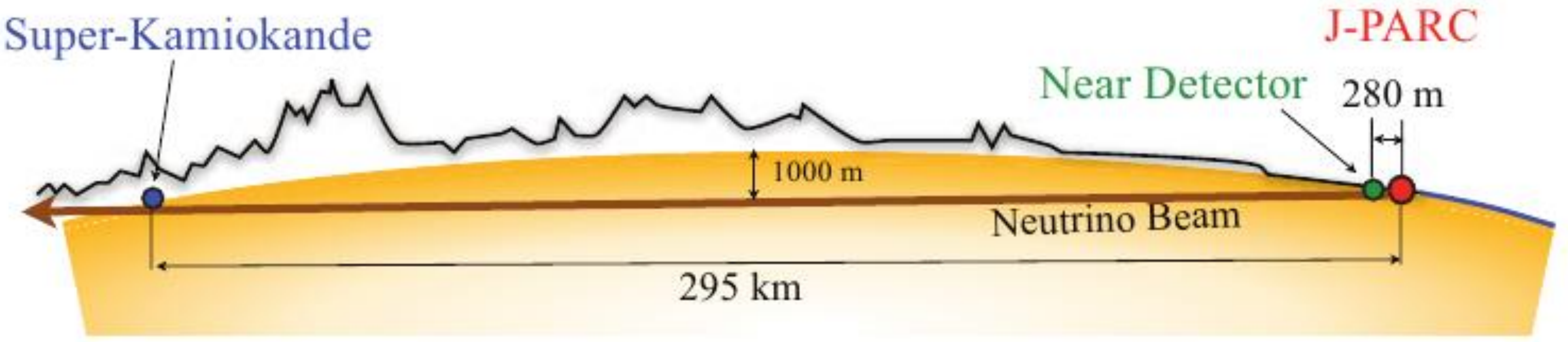


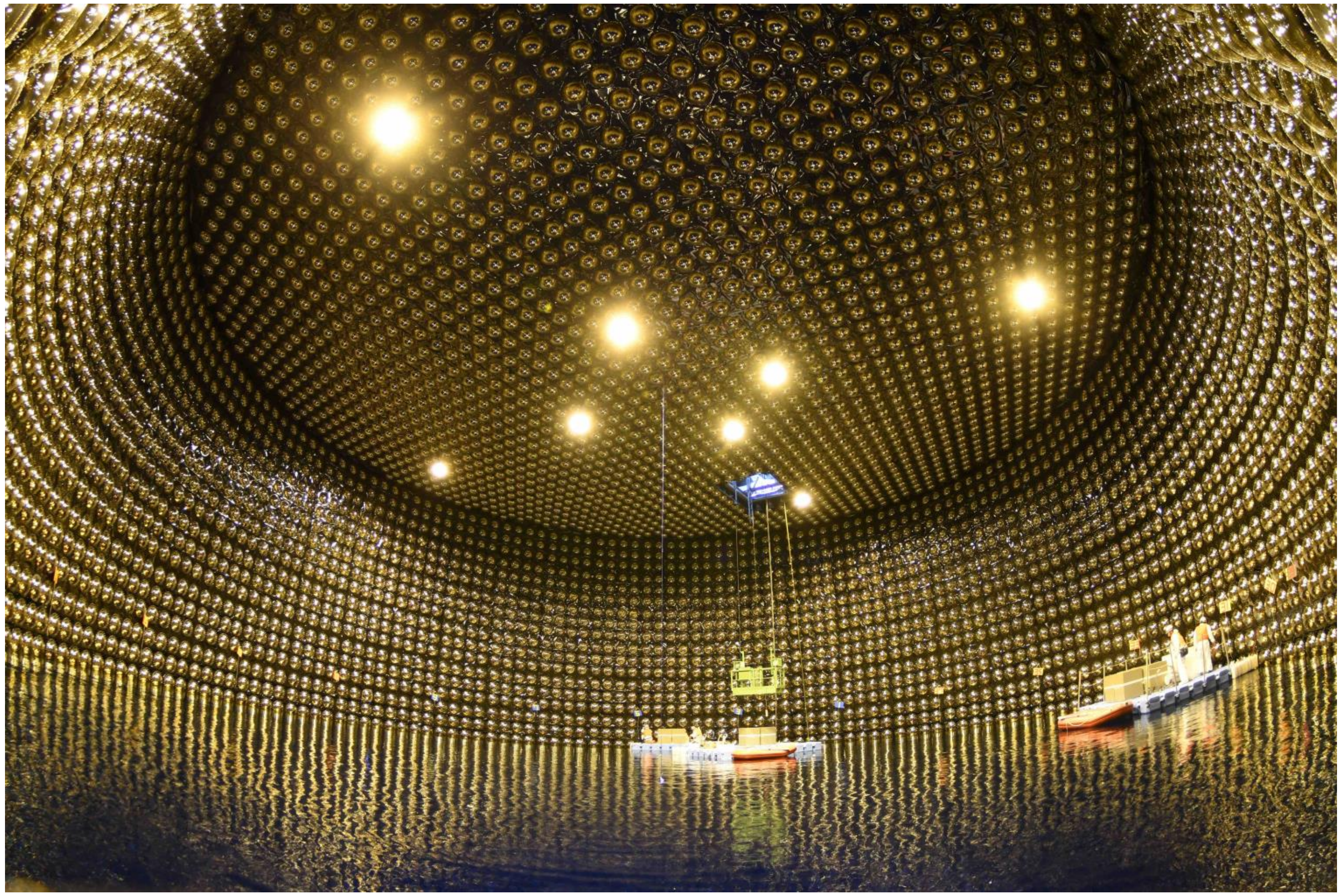
Liquid Argon Time-Projection Chamber
https://www.youtube.com/watch?v=R5G1_hW0ZUA#action=share

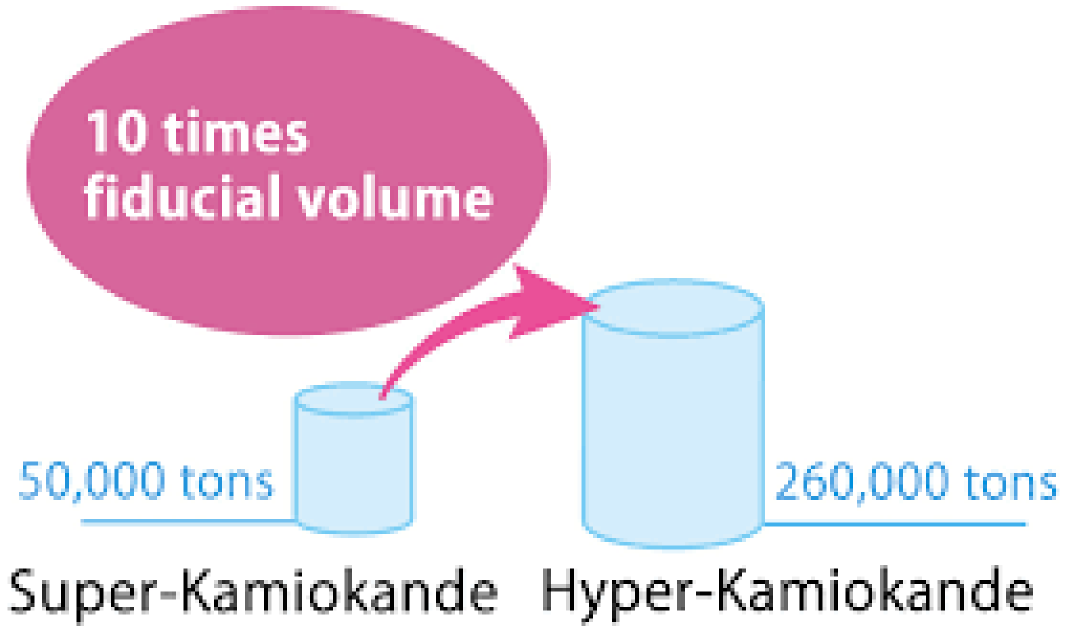
catches beam for Fermilab
https://www.youtube.com/watch?v=U_xWDWKq1CM

is expected to discover CP violation in electron neutrino appearance

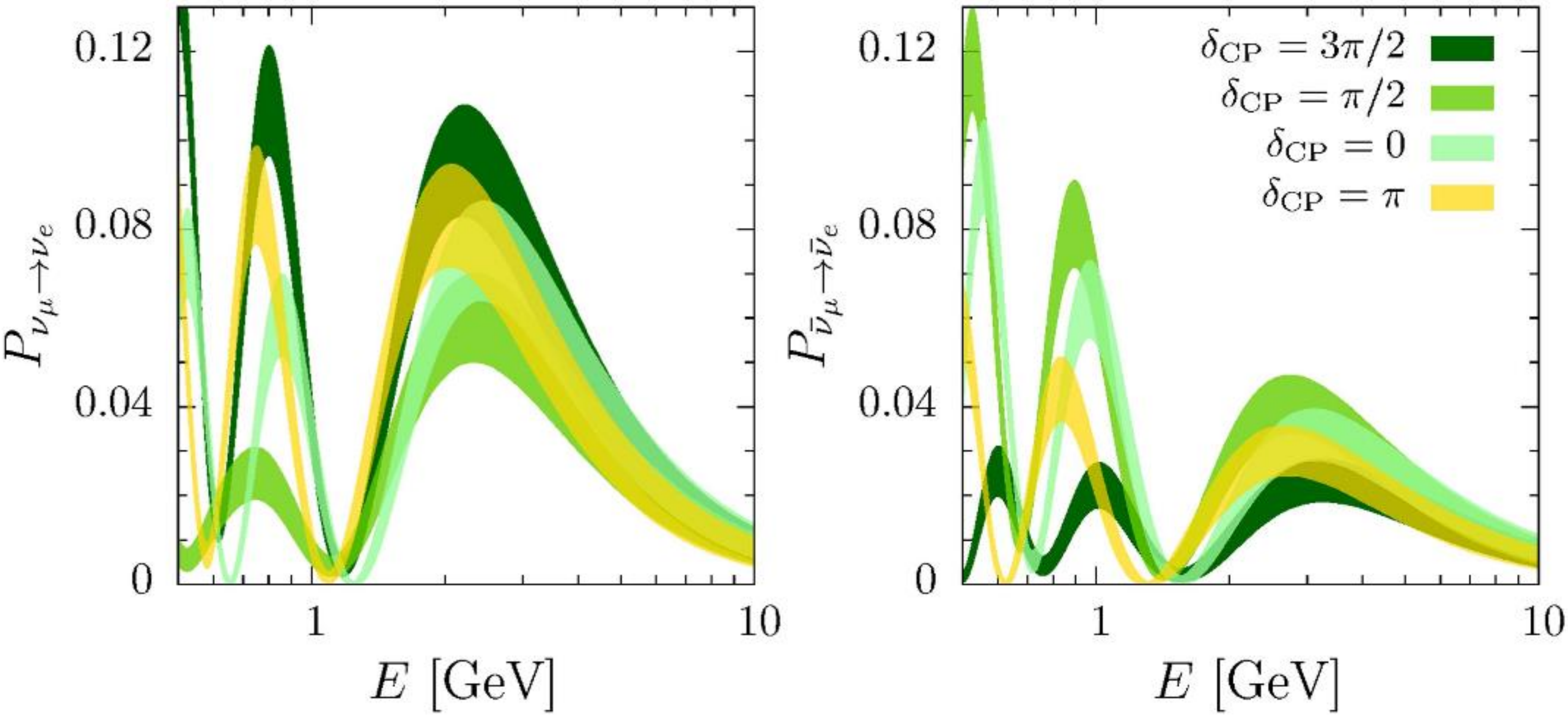
T2HyperK


Super-Kamiokande
J-PARC
Near Detector
280 m
1000 m
Neutrino Beam
295 km

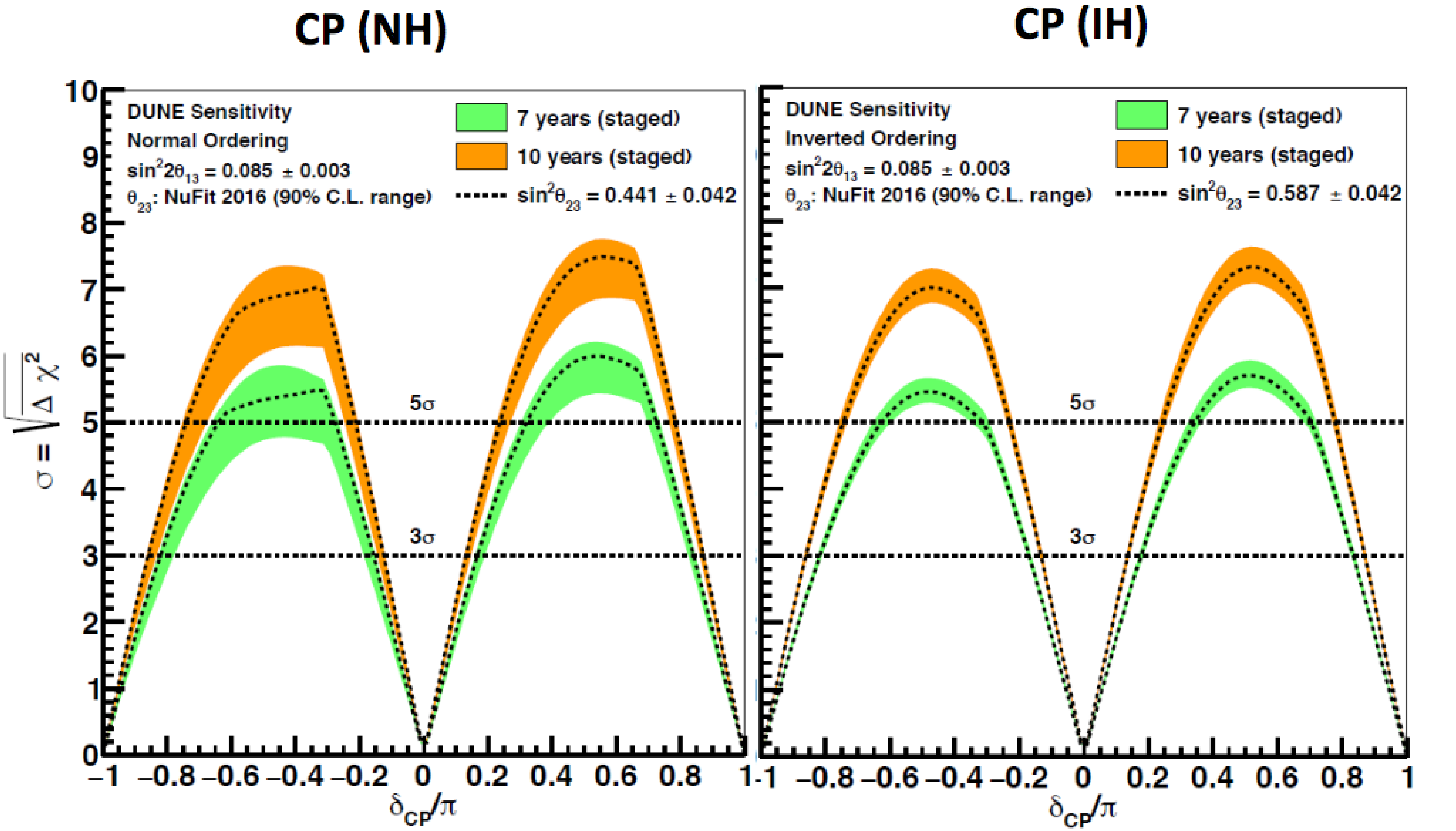



10 times
fiducial volume
50,000 tons
260,000 tons
Super-Kamiokande
Hyper-Kamiokande

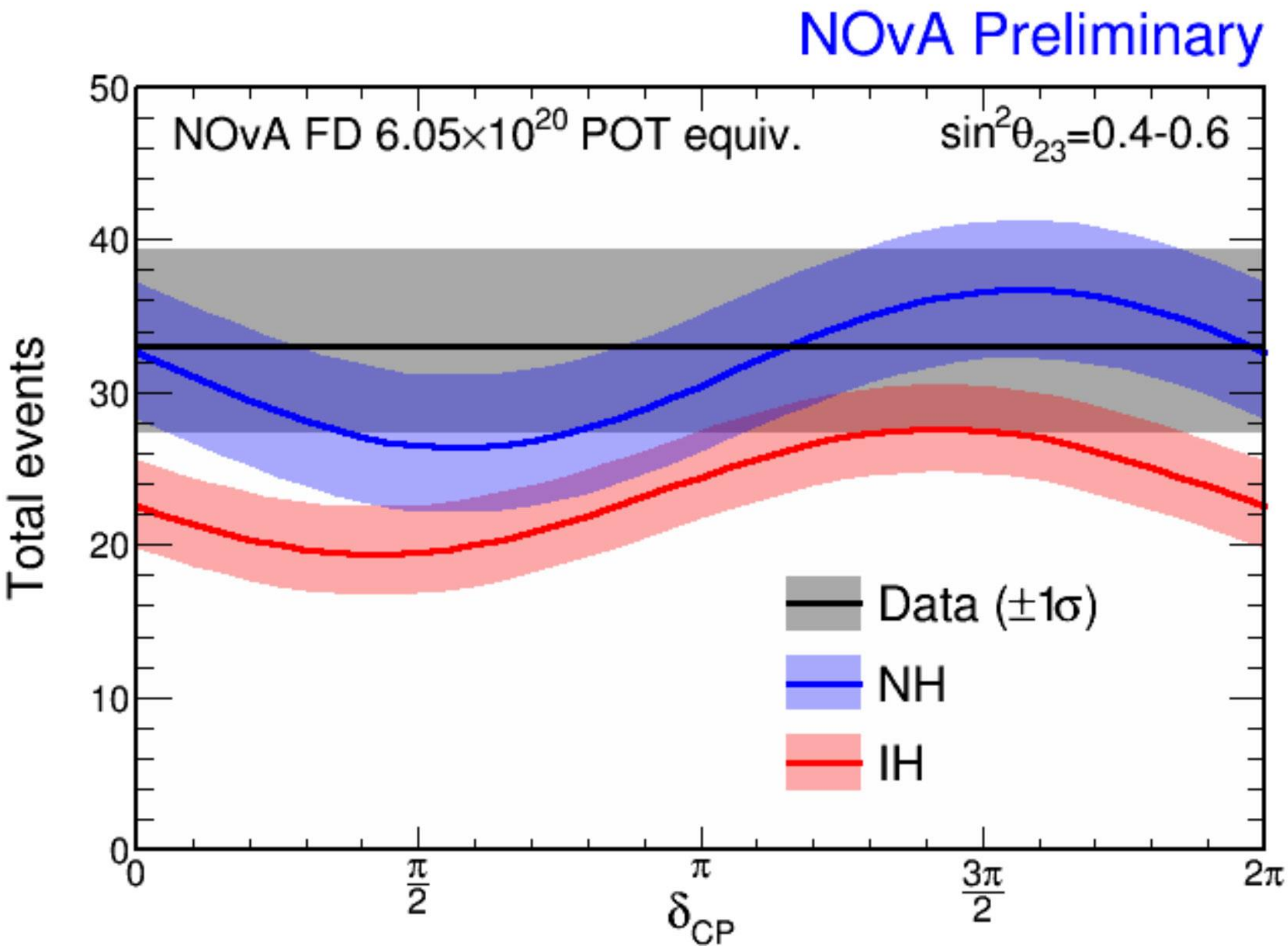
Electron Neutrino Appearance



Expected Sensitivity: Example DUNE

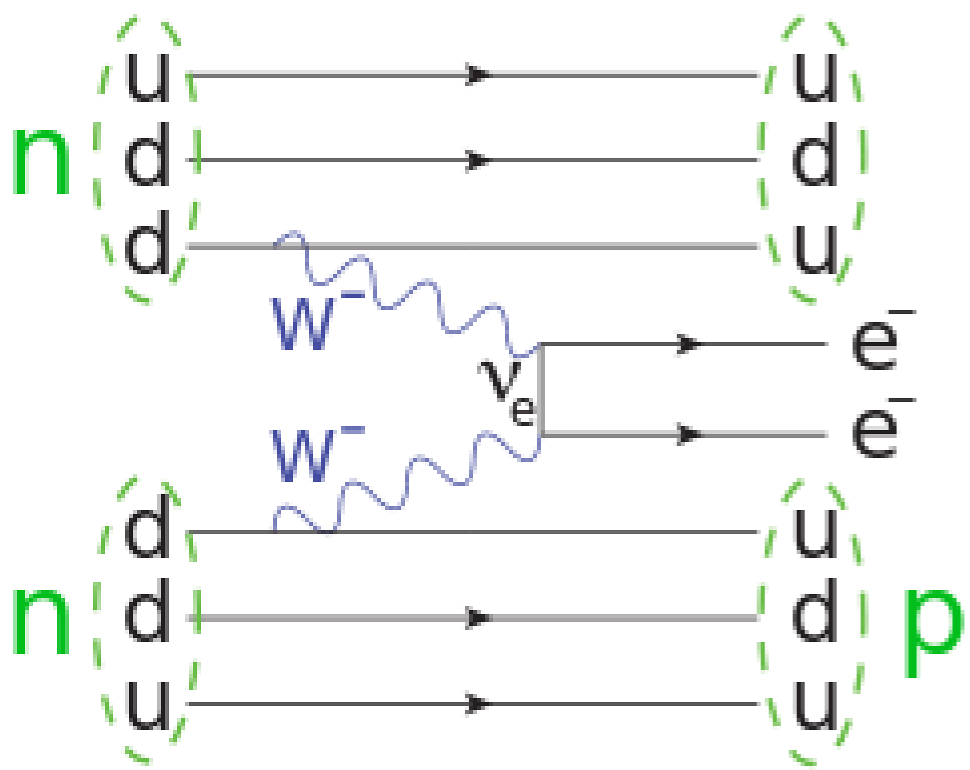


Example: NovA



Dirac or Majorana?

Neutrinoless Double β Decay



Rate depends on nuclear matrix element

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \left| \sum_N (U^2_{eN} m_N)\, m_p\, M'^{\,0\nu}(m_N, g_A^{\rm eff}) \right|^2$$

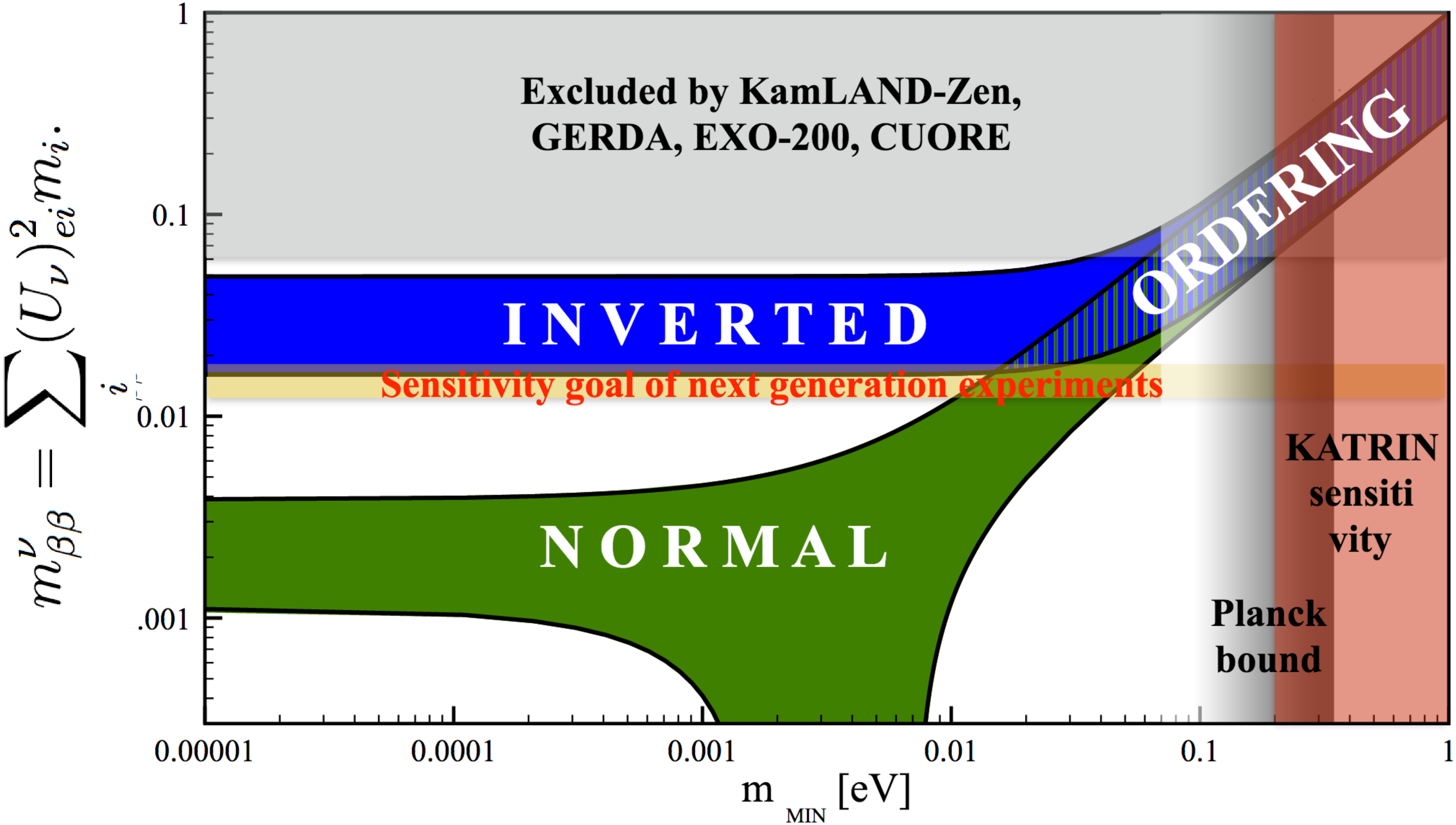
Often assumed: factorisation!

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A} \cdot \left| m_p \sum_N U^2_{eN} \frac{m_N}{\langle p^2 \rangle + m_N^2} \right|$$

All neutrino physics inside one number

$$m^{\nu}_{\beta\beta} = \sum_i (U_\nu)^2_{ei} m_i$$

Neutrinoless Double β Decay



Sterile neutrinos

Sterile neutrino - mixing

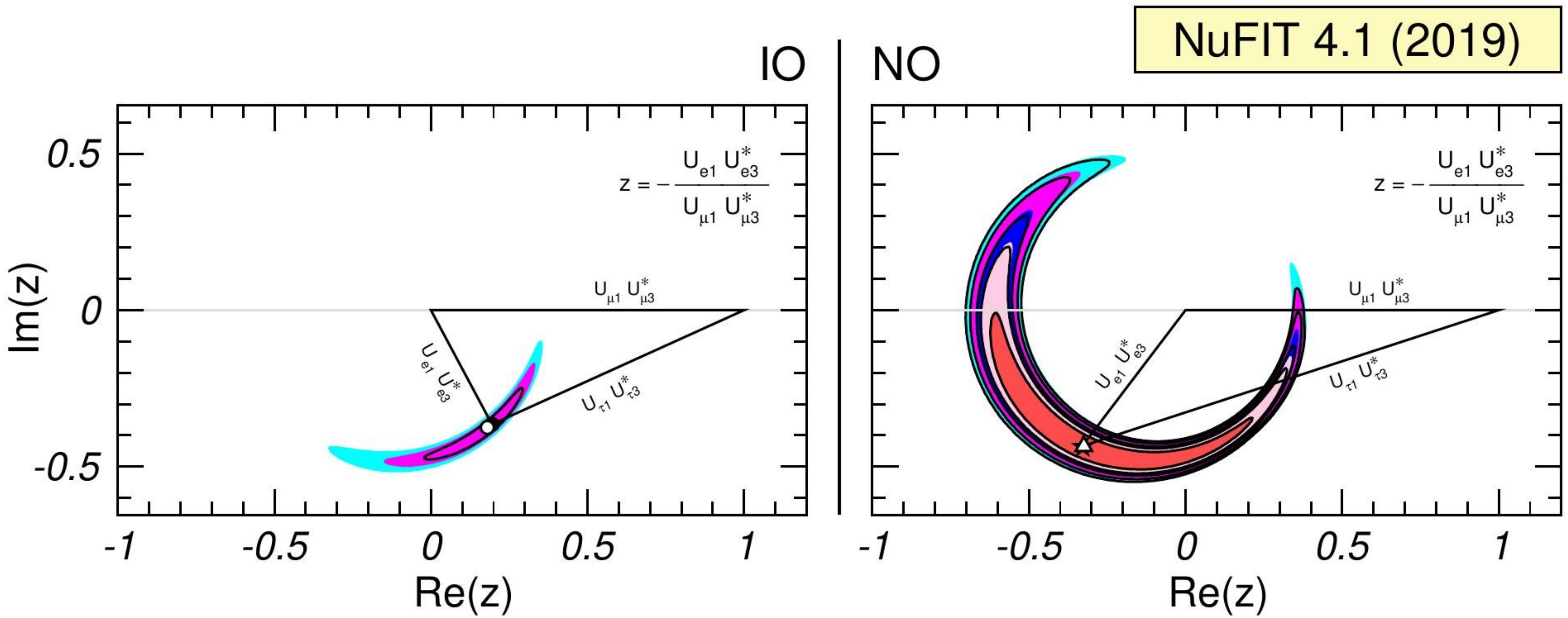
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Sterile neutrino is gauge singlet, feels no electromagnetic or nuclear forces!

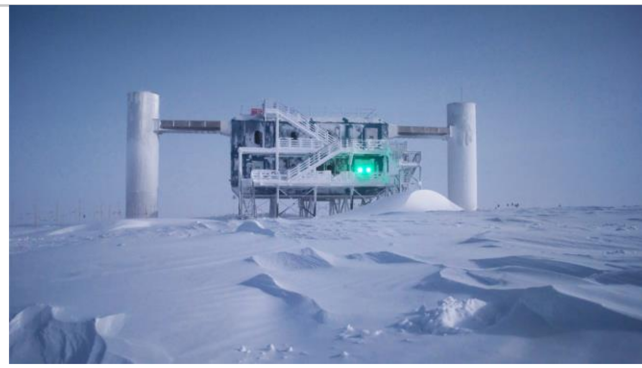
But mixing with ordinary neutrinos affects neutrino oscillation data:
- if the new states are light enough, neutrinos can oscillate into them
- if they are too heavy, they induce a non-unitarity in the observable 3x3 sub matrix of the full neutrino mixing matrix

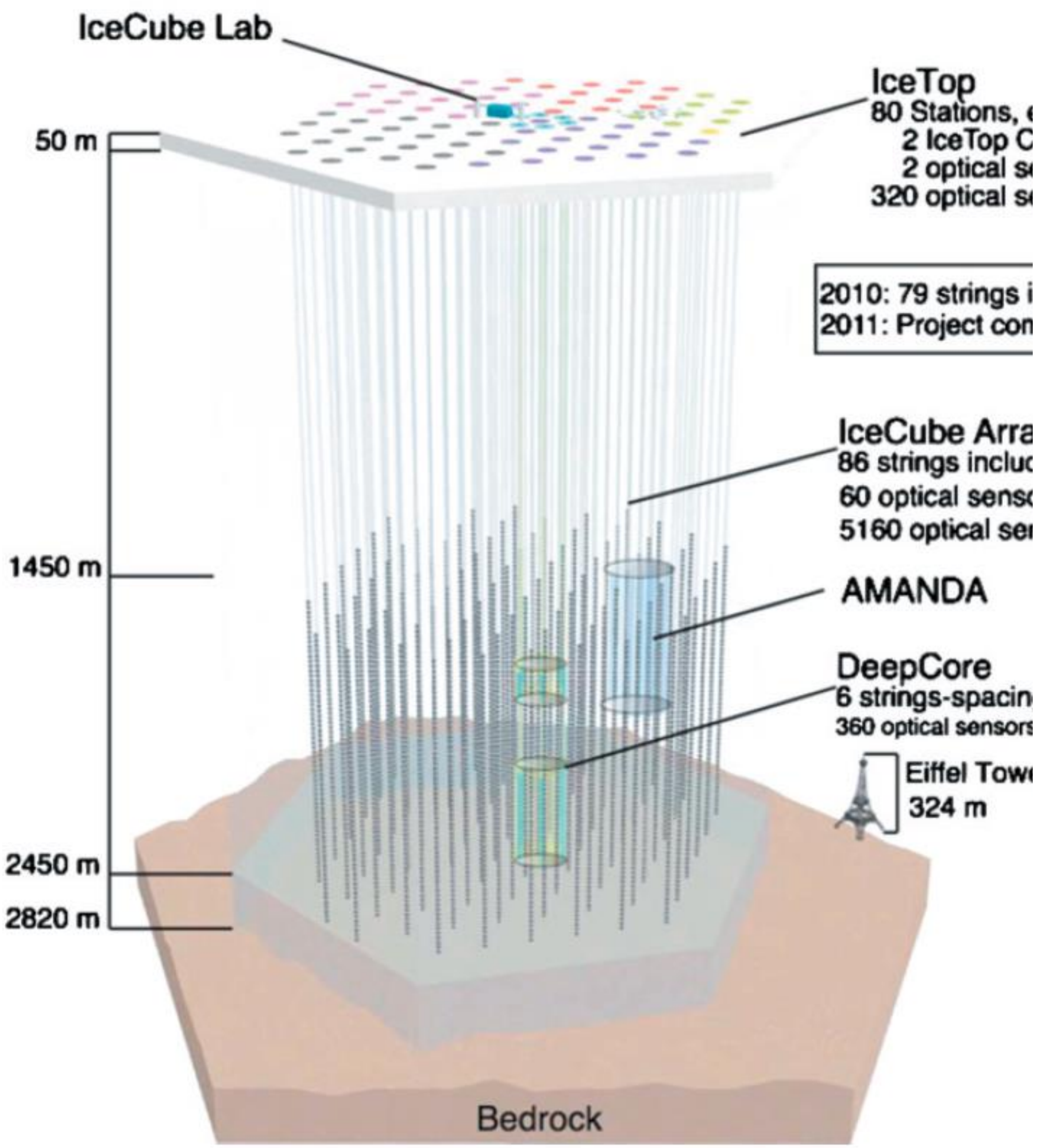
$$\nu_{L\alpha} = (V_\nu)_{\alpha i} \nu_i . \qquad V_\nu = (1+\eta)\, U_\nu .$$

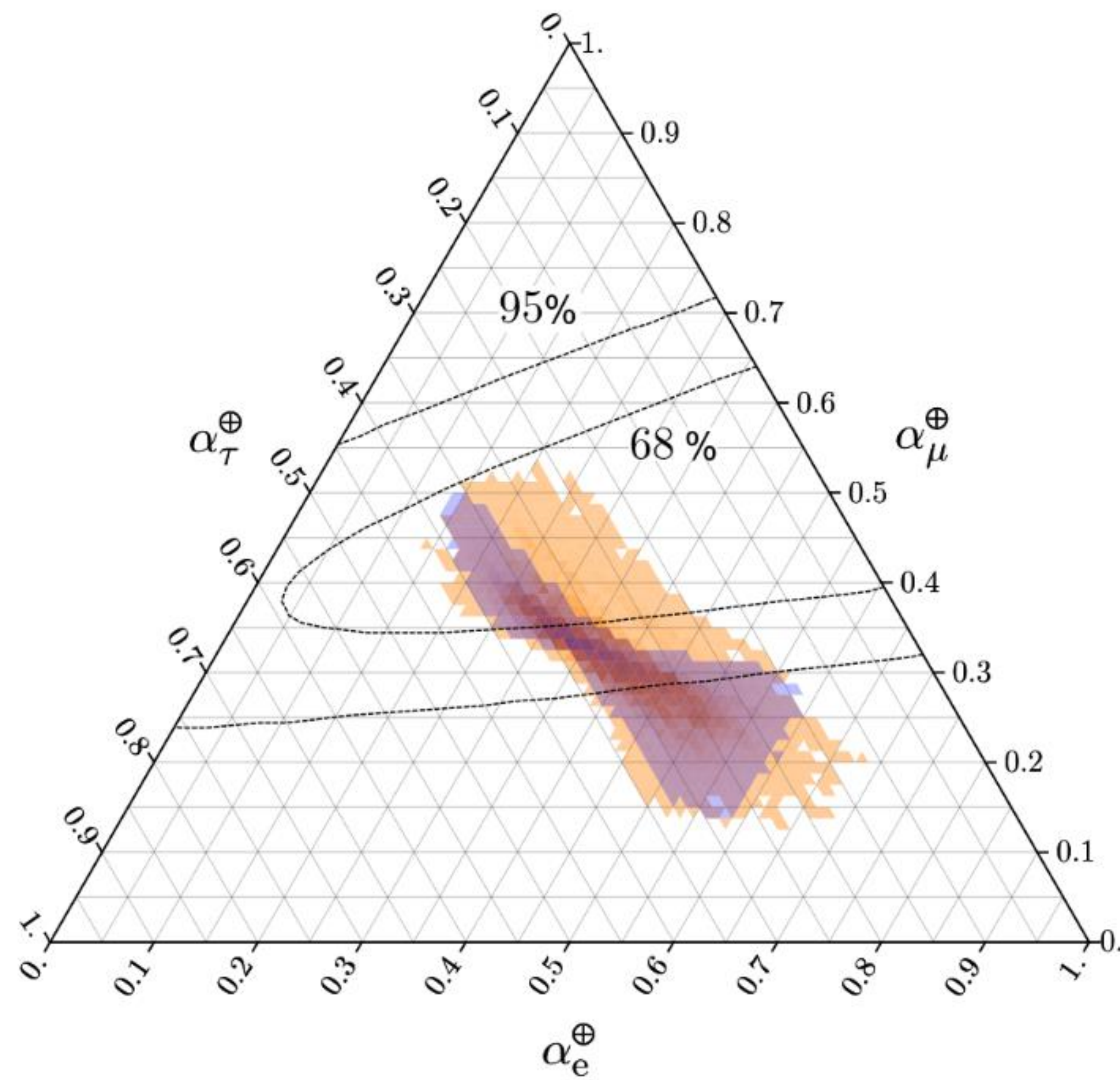
Unitarity Triangle



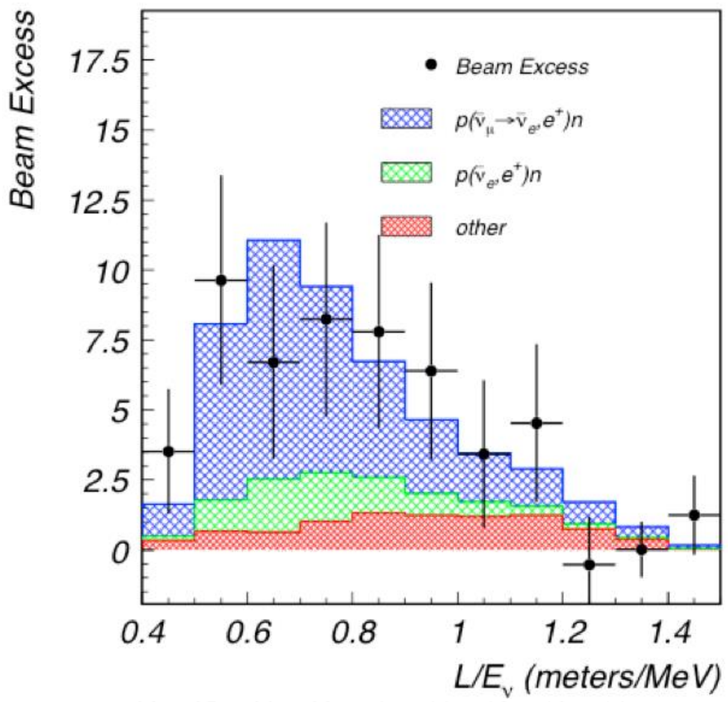
Unitarity test with IceCube







Have we seen it?



LSND:

excess of

electron

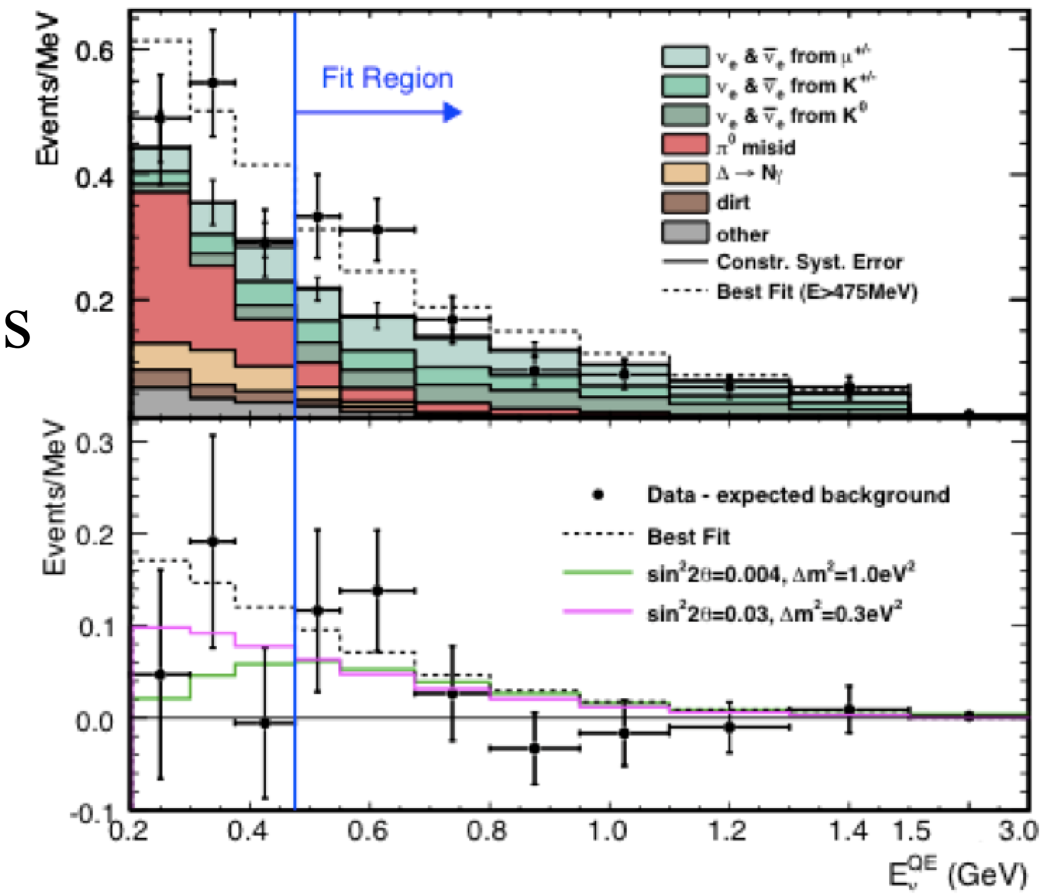
antineutrinos

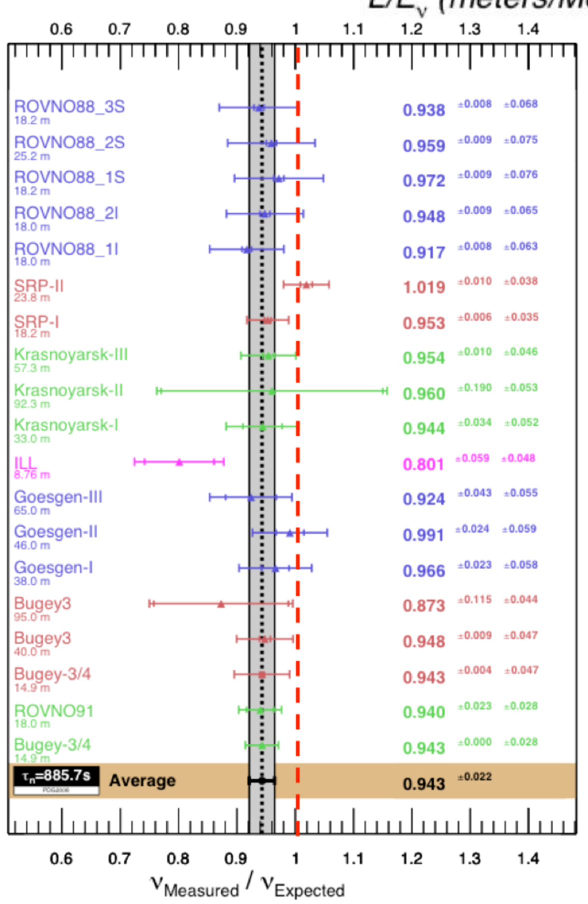
MiniBoone:

extra electron

(anti)neutrinos

at low energy





Reactor anomaly:

too few

neutrinos from

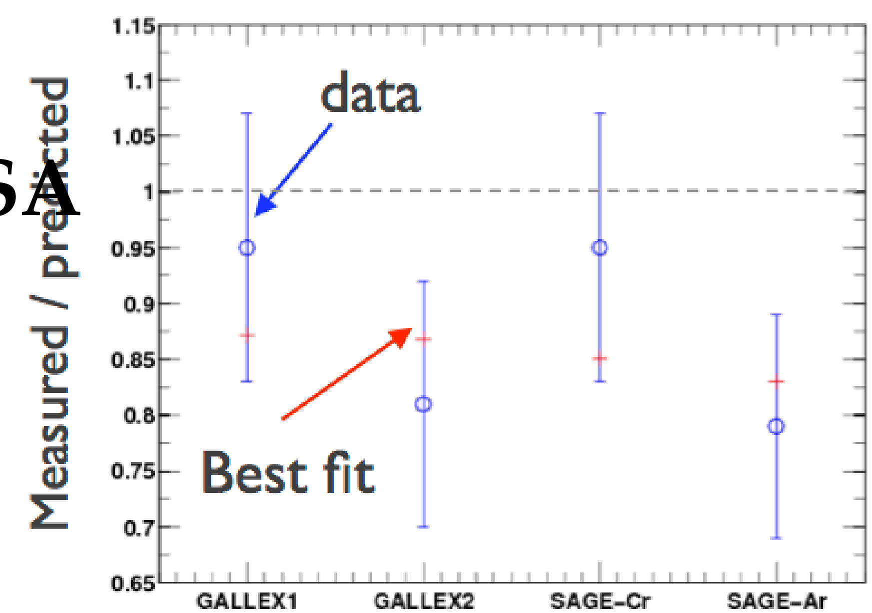
reactors?

GALLEX/SAGE:

missing

electron

neutrinos



A Multi-Frontier Problem

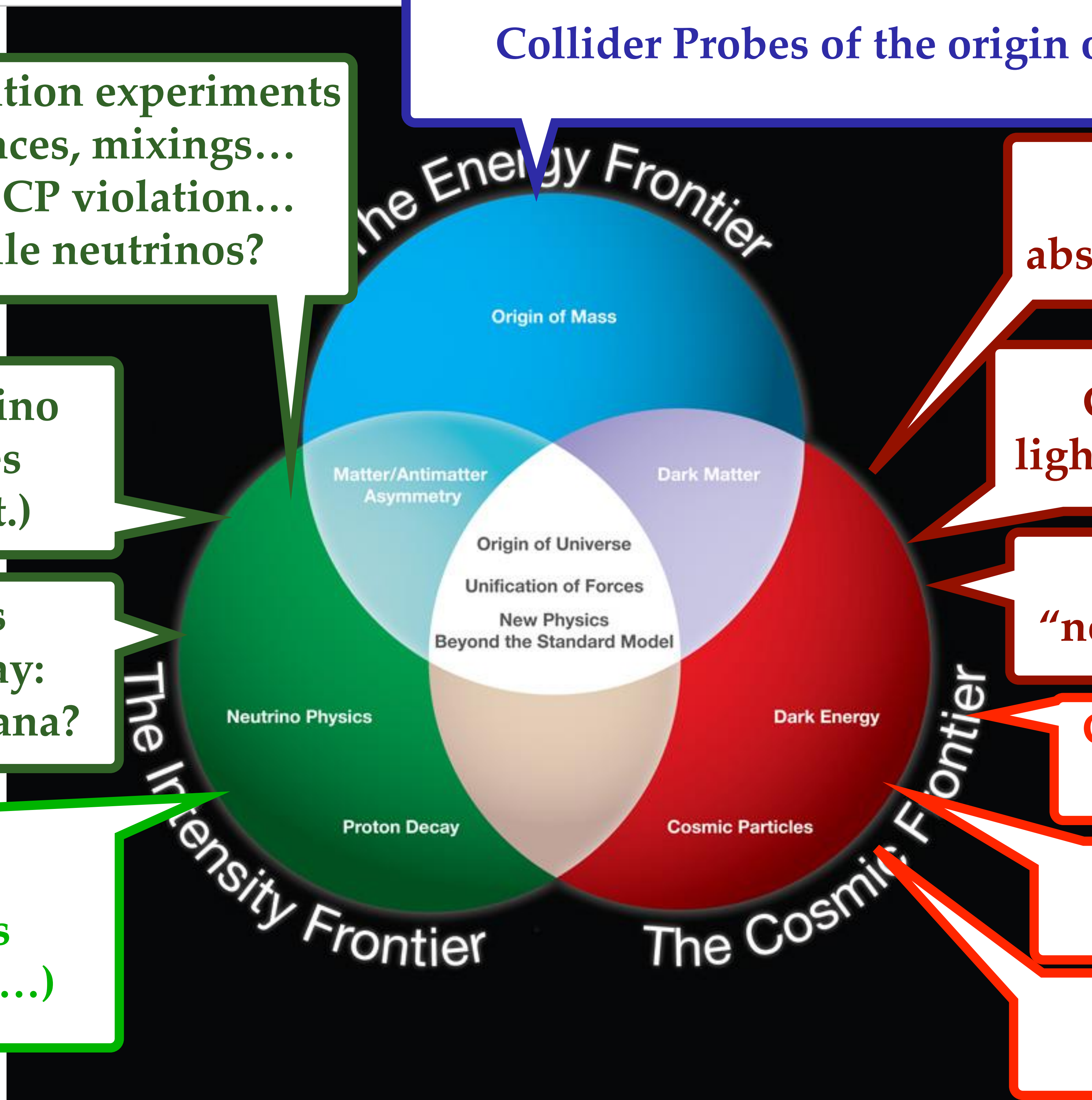
Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)



CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

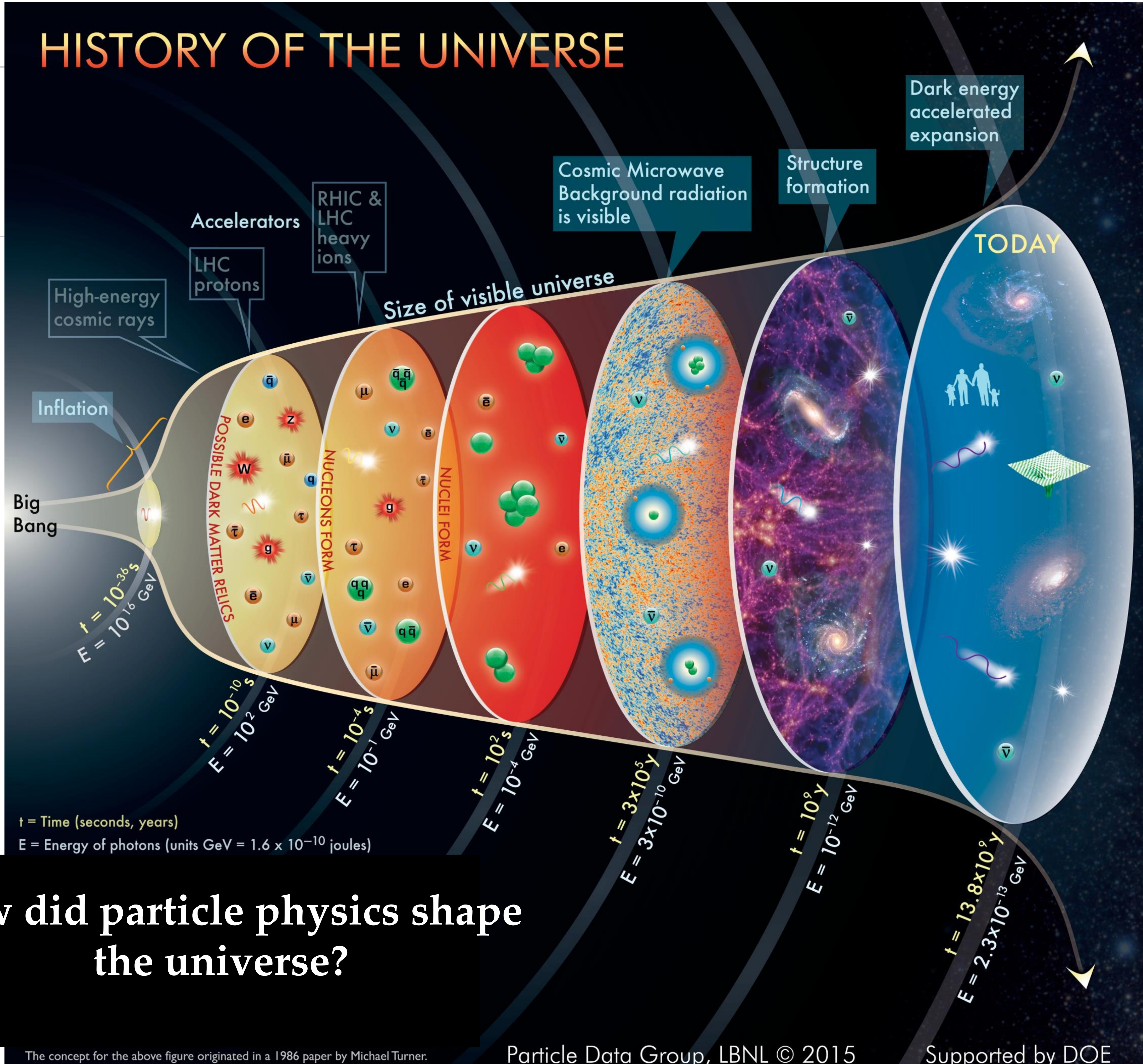
IceCube
“neutrino astronomy”

Cosmic Neutrino
Background

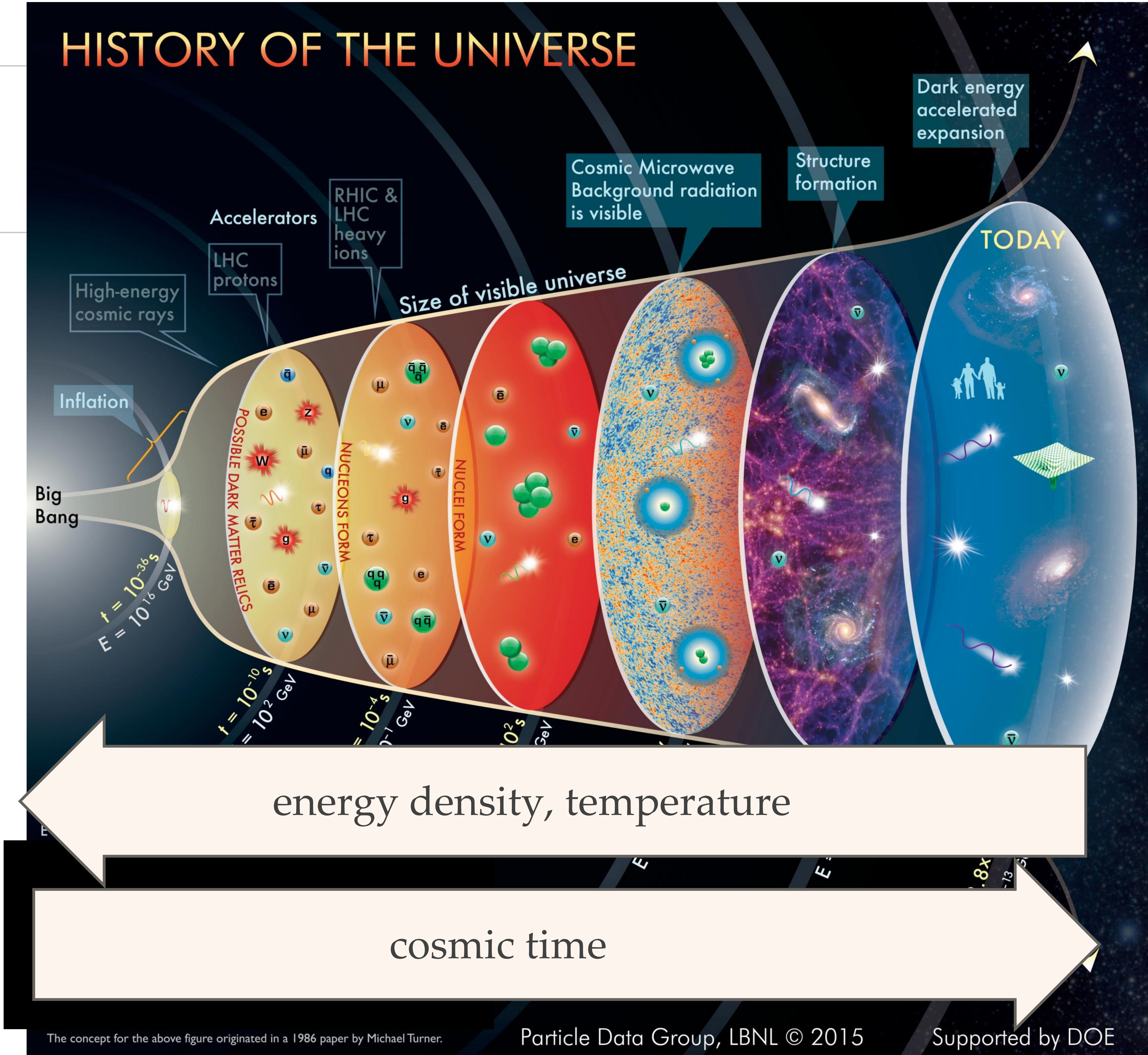
Leptogenesis?

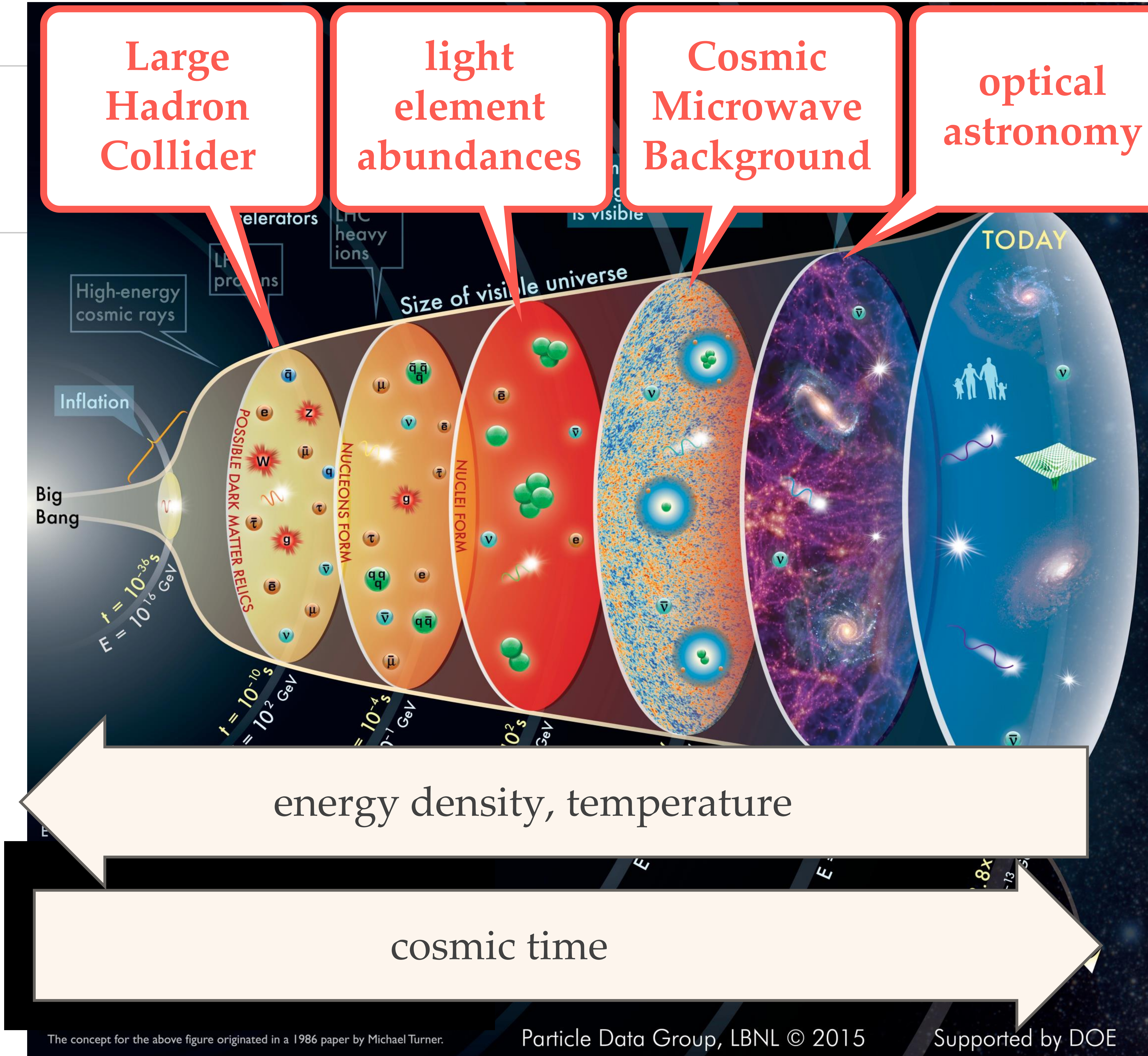
Sterile Neutrino
Dark Matter?

Neutrinos in cosmology



w did particle physics shape the universe?


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
energy density, temperature
cosmic time
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


Large Hadron Collider
light element abundances
Cosmic Microwave Background
optical astronomy
Size of visible universe
TODAY
High-energy cosmic rays
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
heavy ions
energy density, temperature
cosmic time
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Crucial Events in Cosmic History

T ~ 1.4 MeV: neutrino decoupling

fixes neutrino number density

T ~ 0.5 MeV: electron-positron annihilation

"heats" CMB relative to CνB, slightly distorts neutrino spectra

T ~ 0.1 MeV: big bang nucleosynthesis

sensitive to N_{eff} and baryon density

T ~ 0.8 eV: matter-radiation equality

structures start to grow

T ~ 0.25 eV: photon decoupling

CMB spectrum fixed

T ~ 0.05 eV: neutrinos become non-relativistic

free streaming ends, neutrinos behave like Dark Matter

Background and Perturbation Effects

Effect on background evolution

Neutrinos affect the background evolution through Friedmanns equation

$$H^2 = \frac{8\pi}{3} G\rho,$$

$$\rho_\gamma + \rho_{\text{neutrinos}} + [\text{new physics effects}] \equiv \rho_\gamma + N_{\text{eff}}\,\rho_\nu = \frac{\pi^2}{15} T_\gamma^4 \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3}\right]$$

This indirectly affects the cosmological perturbations that we observe

Effect on perturbations

Perturbations are also affected directly because neutrinos stream and cluster differently from other components

Background Effects

Neutrinos affect the evolution of the universe in different ways:

1) When they are relativistic they contribute to the radiation pressure

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{\rm eff} \left(\frac{4}{11}\right)^{4/3}$$

2) When they are non-relativistic they contribute to the matter density

$$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\rm crit}^0} = \frac{\sum m_\nu}{93.14 h^2 \, {\rm eV}}$$

Effects of N_{eff} and Ω_ν

Physical quantities affected by the presence of neutrinos

- **moment of matter-radiation equality**
- **baryonic to Dark Matter density ratio**
- **free streaming**

This affects observables in different ways:

- **BBN (expansion rate of the universe, neutrinos in nuclear reactions)**
- **CMB (expansion rate of the universe, Silk damping, anisotropic stress, gravitation between neutrino and photon perturbations, weak lensing of the CMB…)**
- **Matter spectrum (matter-radiation equality, expansion rate, enhancement of "collapsing" component increases growth of structure that are larger than neutrino free streaming length…)**

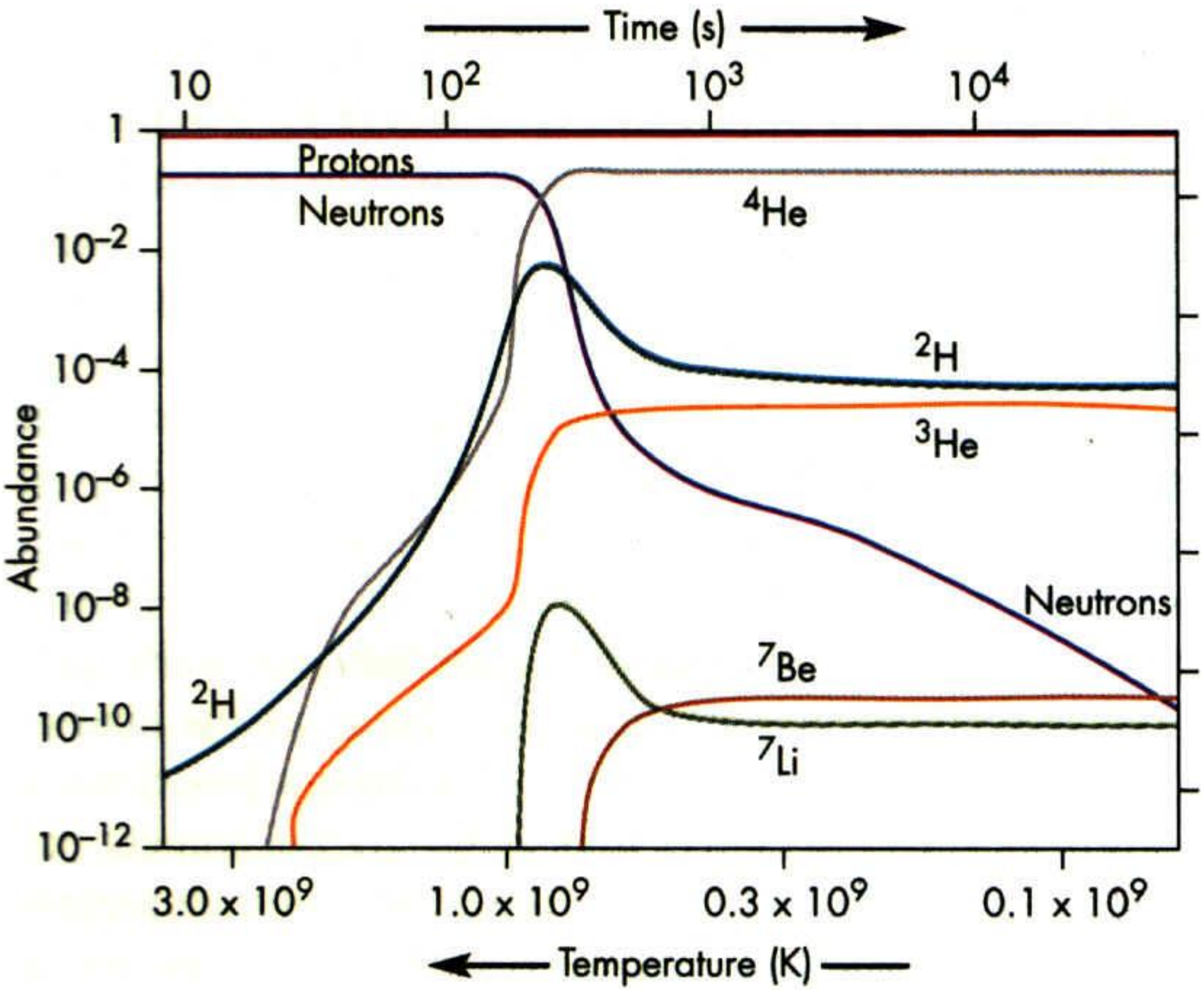
Effects of Neutrino Masses

- **CMB**
  1) Matter density at late times affects expansion rate and ISW effect.
  2) Change in equation of state when becoming non-relativistic
  3) Decrease in matter power spectrum reduce weak lensing
  4) Low momentum neutrinos that become relativistic earlier, affects photons through gravity

- **Matter spectrum**
  1) neutrinos only contribute to growth of structures larger than their free streaming
  2) they contribute to average matter density, but not to fluctuations on small scales

Cosmology currently provides best upper bound on the sum of neutrino masses < 0.12 eV

Big Bang Nucleosynthesis

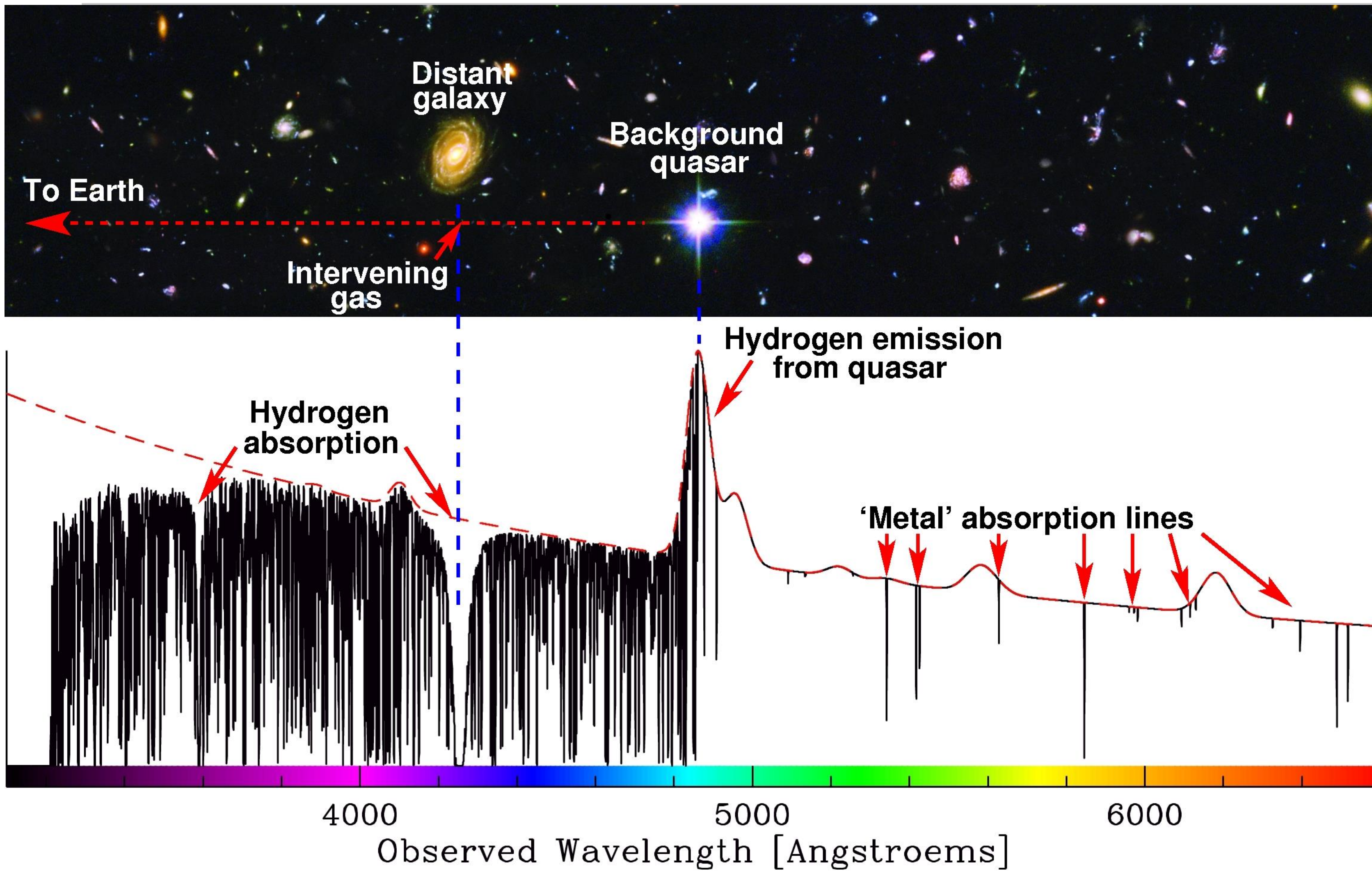


light elements are produced in a chain of nuclear reactions.

sensitive to *Neff* through expansion rate and neutrino density through Boltzmann equation

only unknown parameter is the baryon-to-photon ratio.

Big Bang Nucleosynthesis



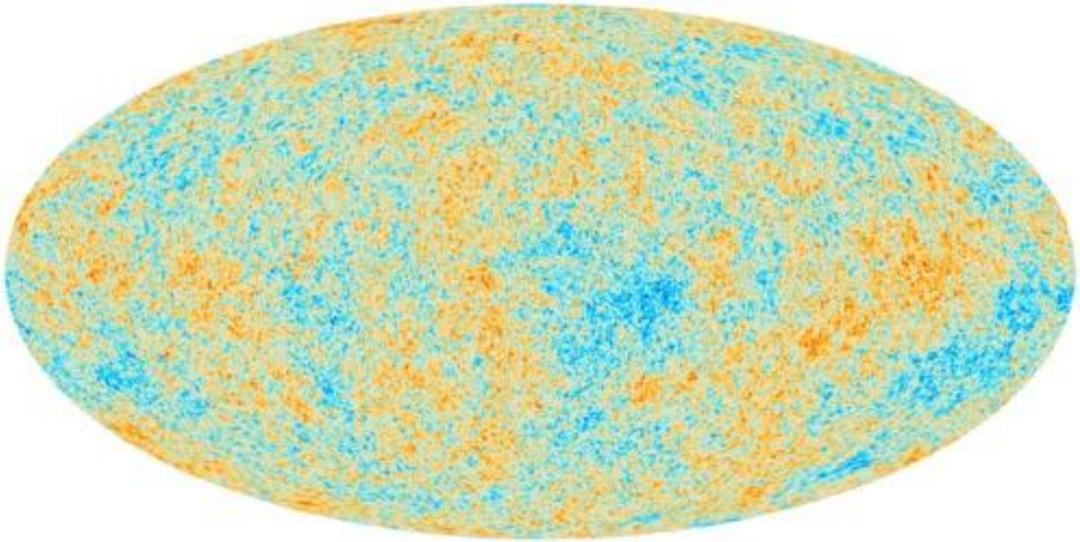
- light element abundances in intergalactic medium can be measured in quasar spectra
- Deuterium is sensitive to baryon asymmetry and not produced in stars
- Helium then fixes N_{eff}

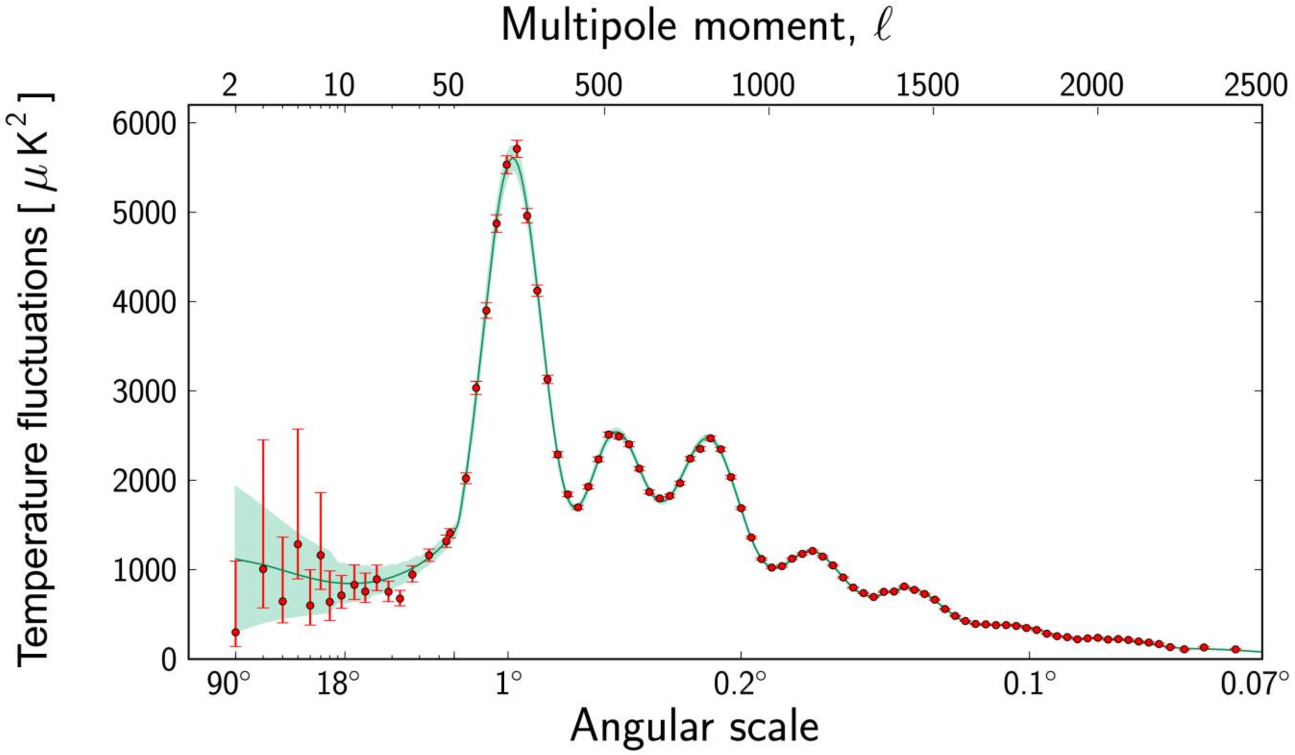
$$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$$

PDG 2016

$$2.3 < N_{eff} < 3.4$$

CMB





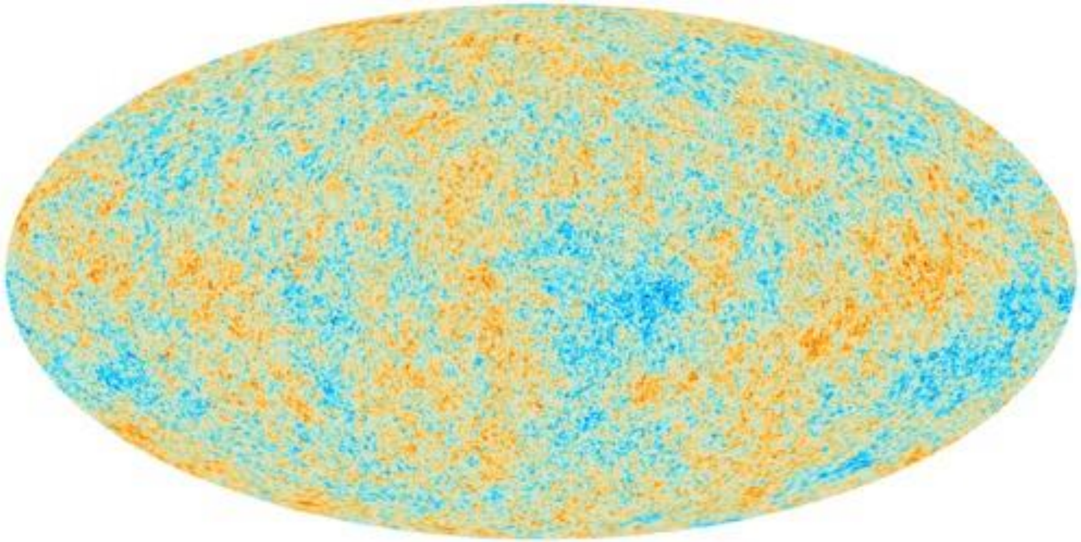
Before photon decoupling

- equation of state
- matter to radiation equality
- free streaming / Silk damping
- …

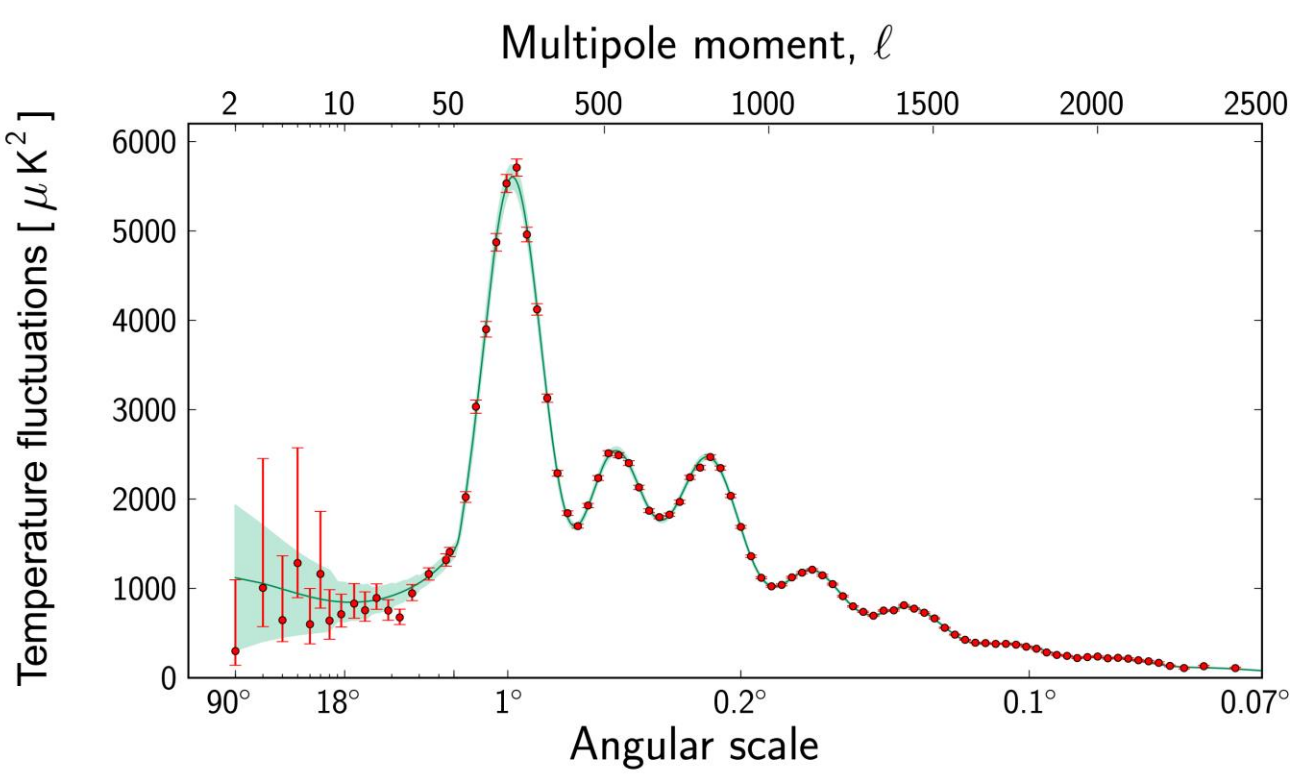
After photon decoupling

- expansion history (angular size of perturbations)
- weak lensing (via matter power spectrum)
- gravitational potential that photons feel (also via effect on matter power spectrum)

Baryon Acoustic Oscillations

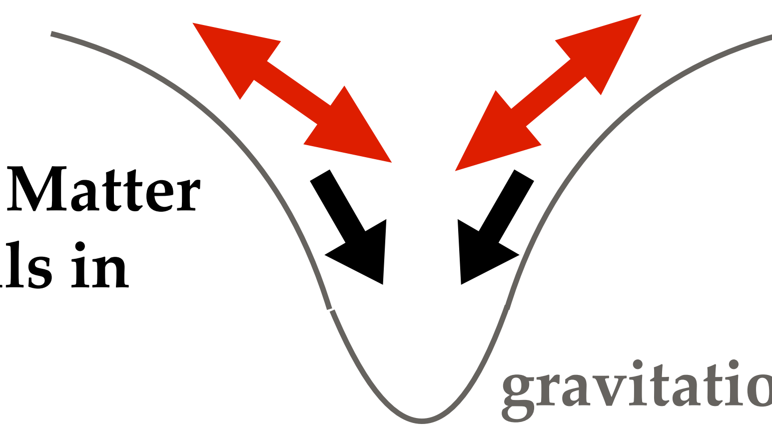


Radiation, baryons and Dark Matter affect the acoustic oscillations in the primordial plasma in different ways…



ordinary matter/radiation oscillates due to radiation pressure

Dark Matter falls in



gravitational potential well

neutrinos stream freely until they become non-relativistic

What to fix?

How neutrinos affect the CMB strongly depends on what quantities one keeps fixed while varying the neutrino parameters.

Example: changing N_{eff}

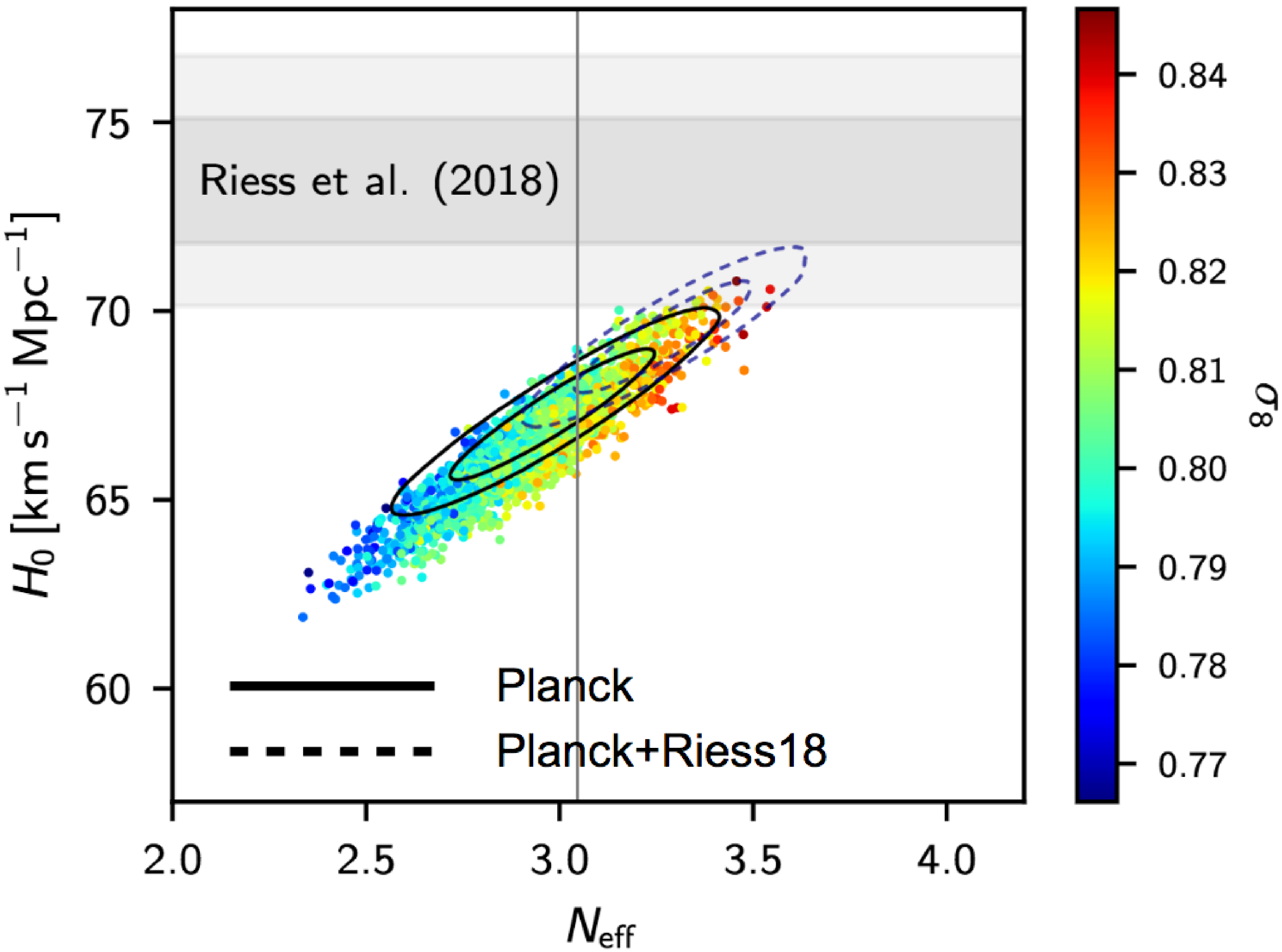
- *keep all other densities fixed*: Changing N_{eff} changes matter radiation equality, this affects the position and amplitude of CMB peaks
- *keep ratios between matter, radiation and Dark Energy fixed*: Changing N_{eff} changes the scale of "Silk damping"

Example: changing the neutrino masses

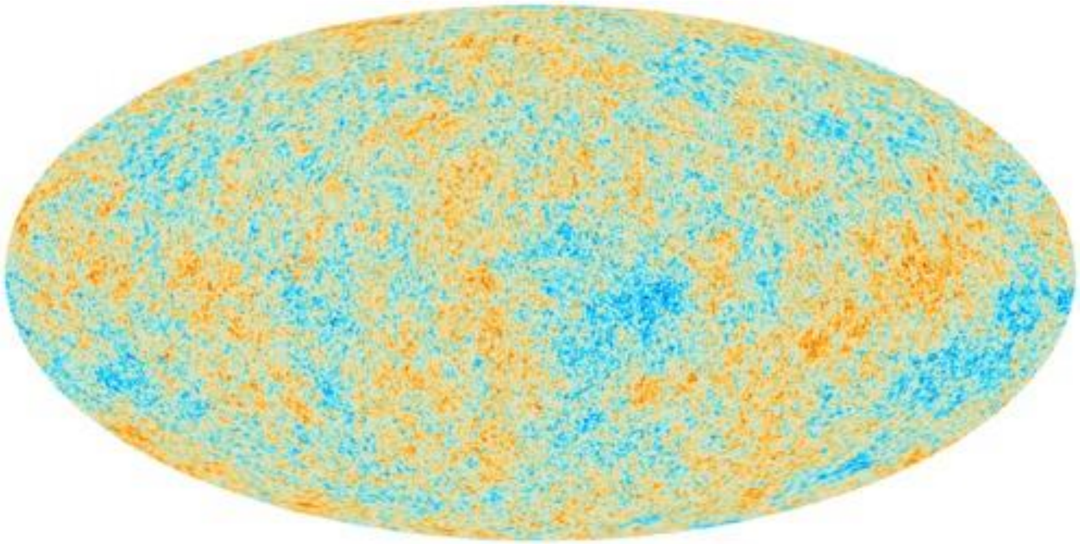
- *keep matter density today fixed*: Changing m_ν changes matter radiation equality
- *keep matter-radiation equality fixed*: Changing m_ν modifies today's total matter density

The H_0 Tension

- Local measurement of the Hubble rate disagrees with cosmological measurement
- This is degenerate with *Neff*

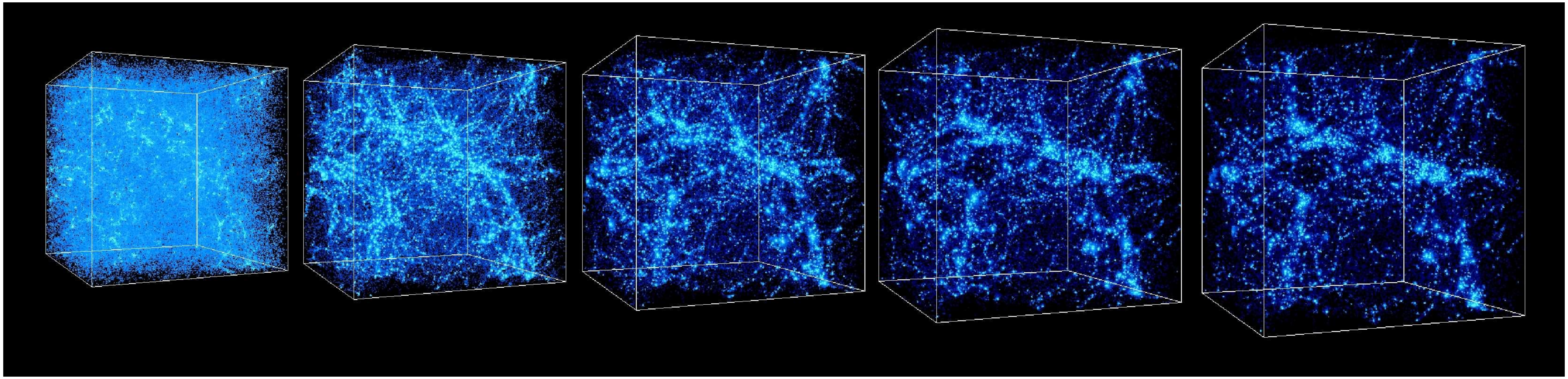


Structure Formation

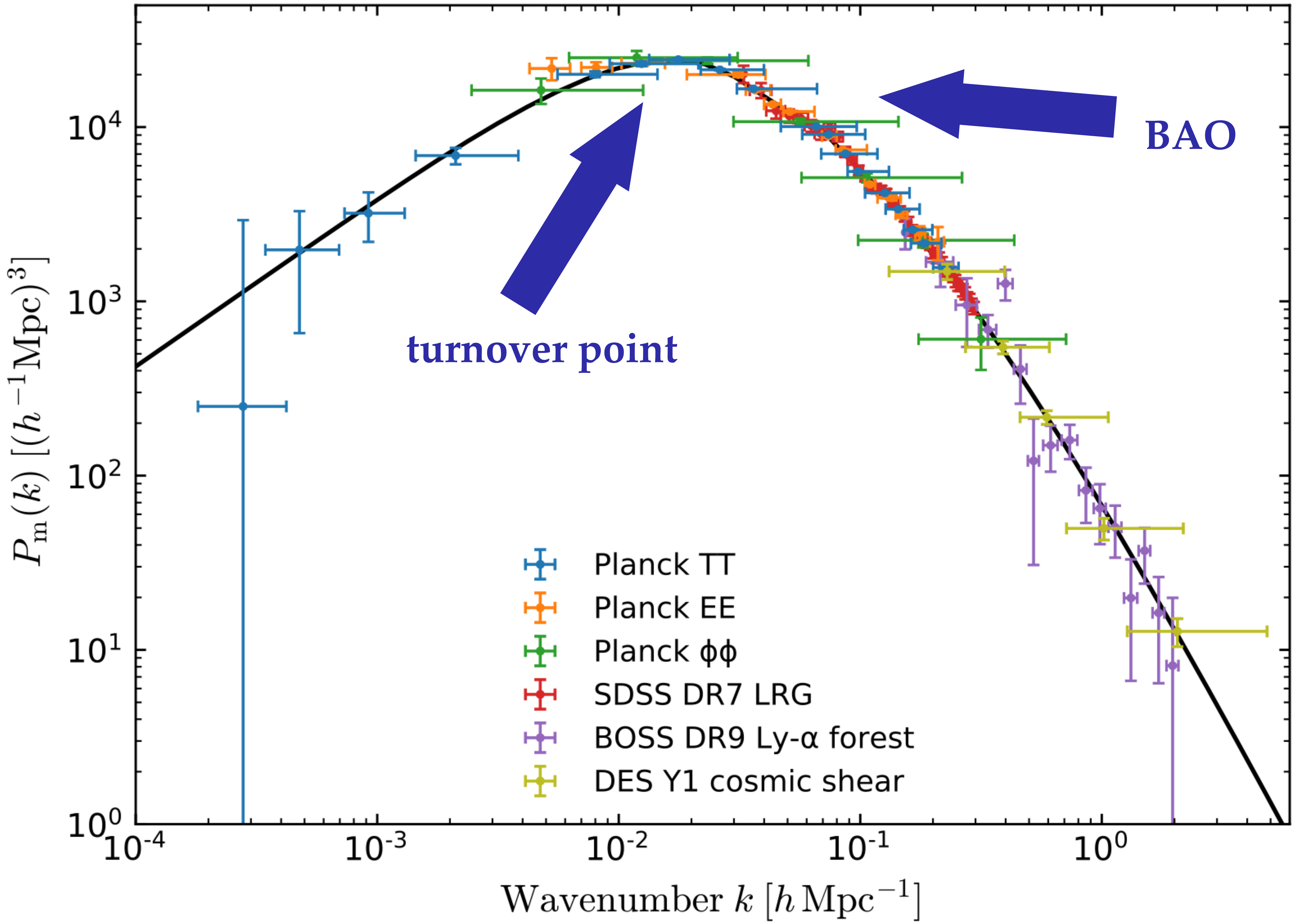


The early universe was very homogeneous and isotropic…

… structure formed by gravitational collapse of small inhomogeneities ~1/100.000



Matter Power Spectrum



Effect of N_{eff} on the Turnover Point

The growth of perturbations

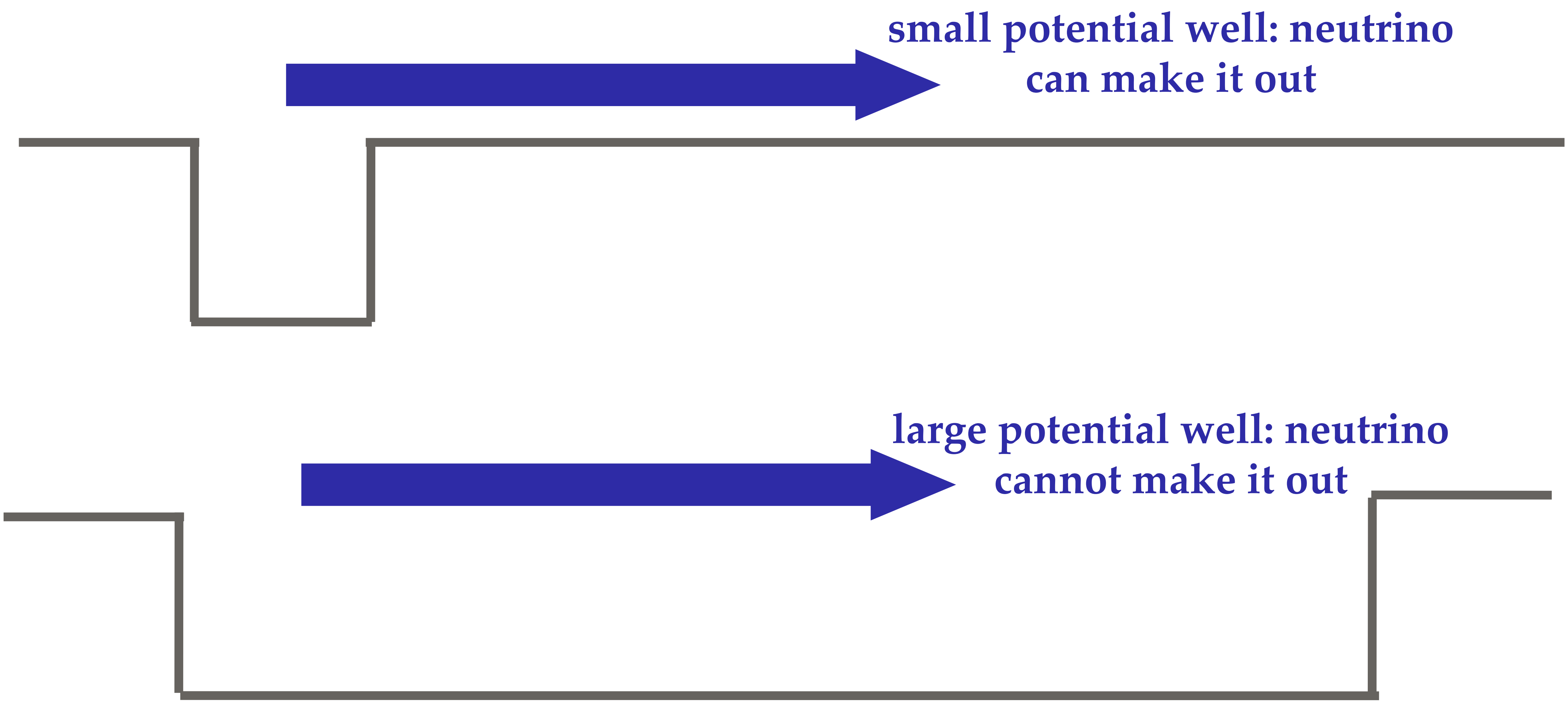
- cosmic perturbations are "frozen" when they are larger than the horizon
- in the radiation dominated era, sub-horizon modes grow slower than in the matter dominated era

How N_{eff} comes into play

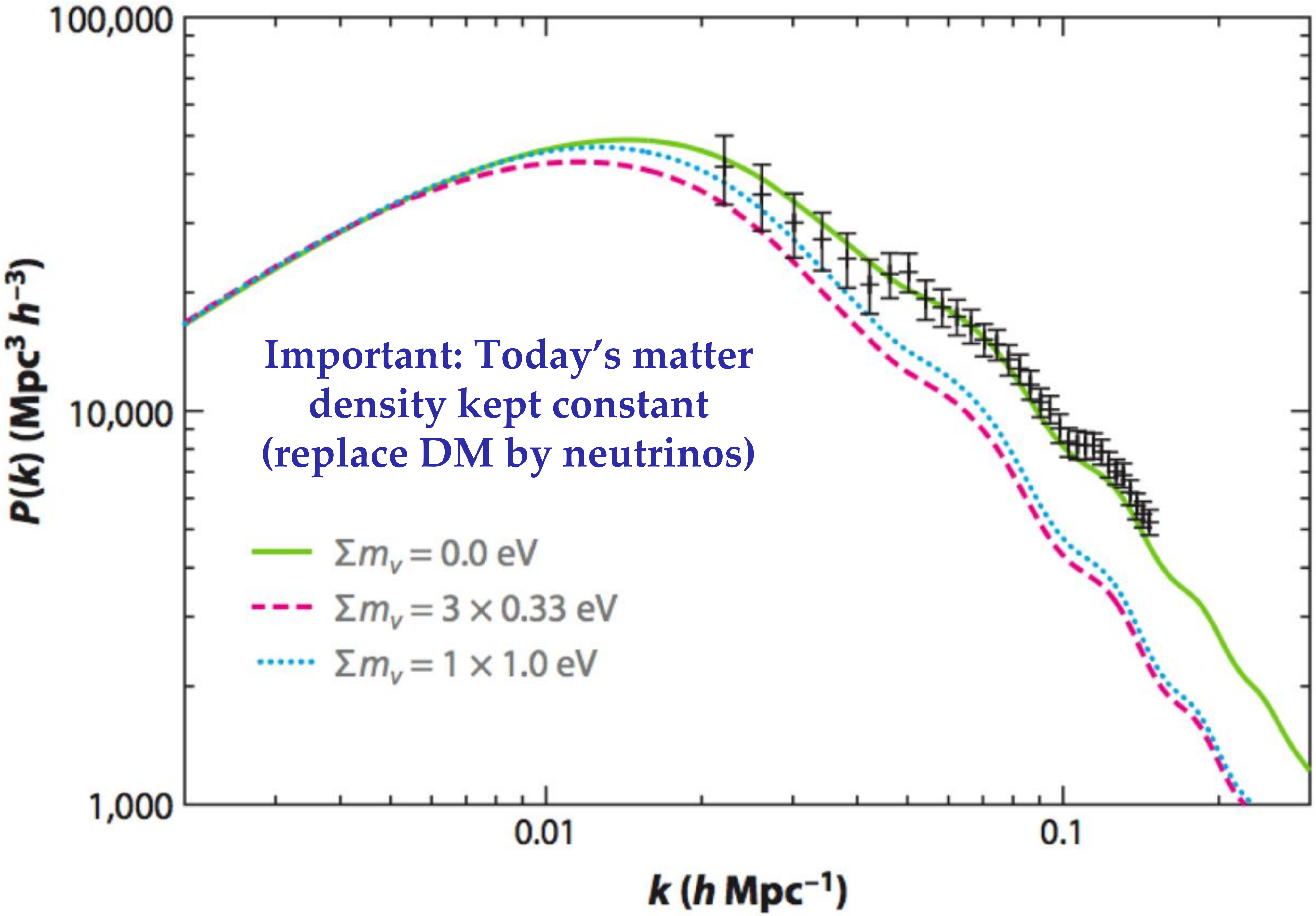
- initial power spectrum is almost scale invariant
- modes that entered the horizon during radiation domination grew only slowly
- modes that entered after matter radiation equality grew quicker
- N_{eff} modifies the moment of matter-radiation equality and shifts the turnover point

Effects of Massive Neutrinos on Clustering

Neutrinos only contribute to the growth of structures that are larger than their free streaming length



Effects of Massive Neutrinos on Clustering



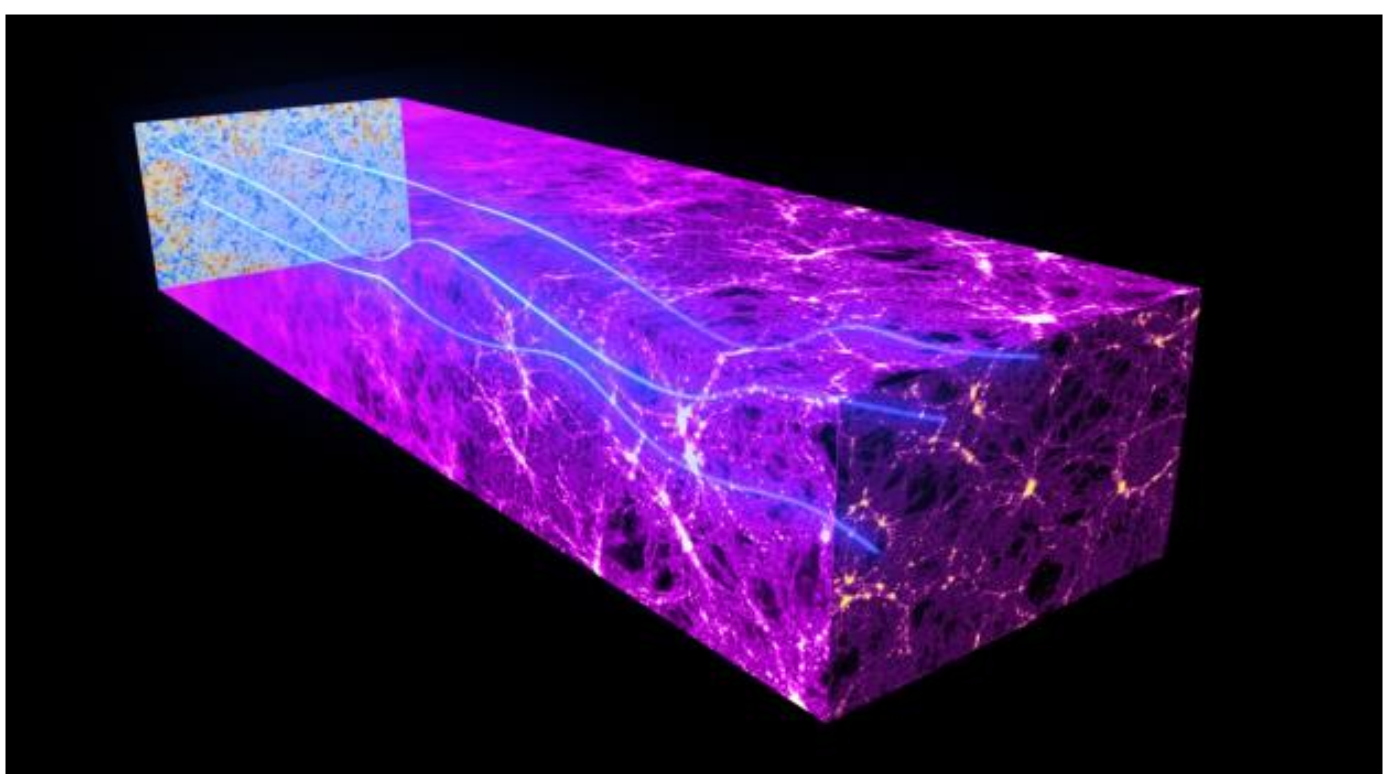
Indirect Effects on the CMB

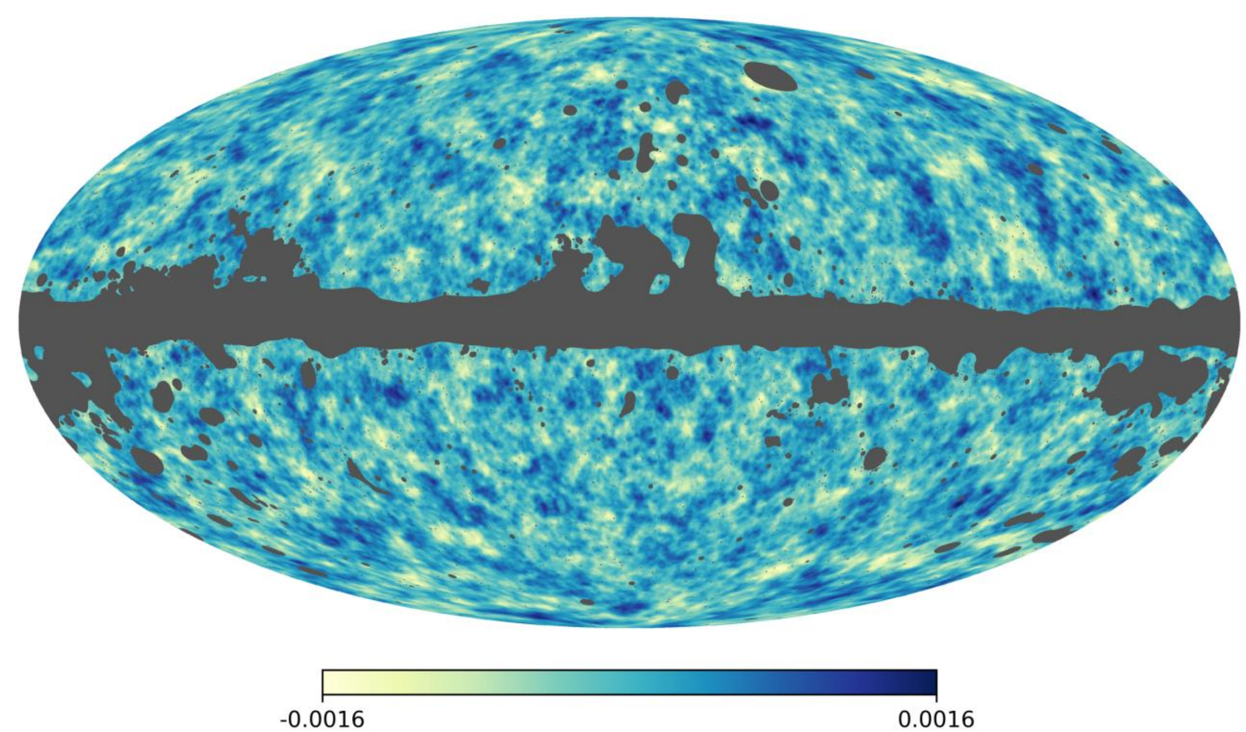
Integrated Sachs-Wolfe Effect (ISW)

CMB photons fall in and climb out of gravitational wells on their way to us… but the wells change why they do so

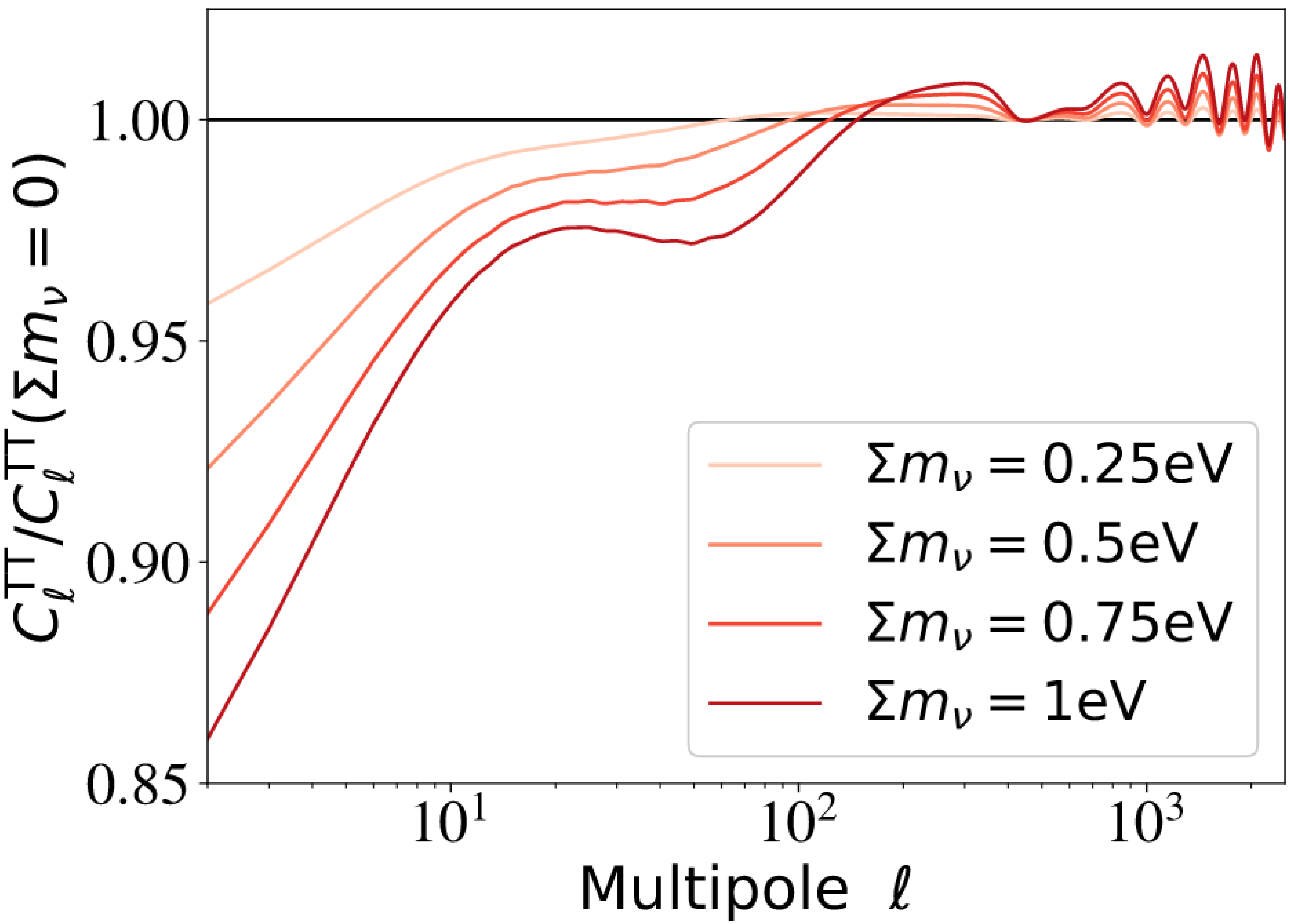
Weak Lensing

CMB photons get lensed on their way so us

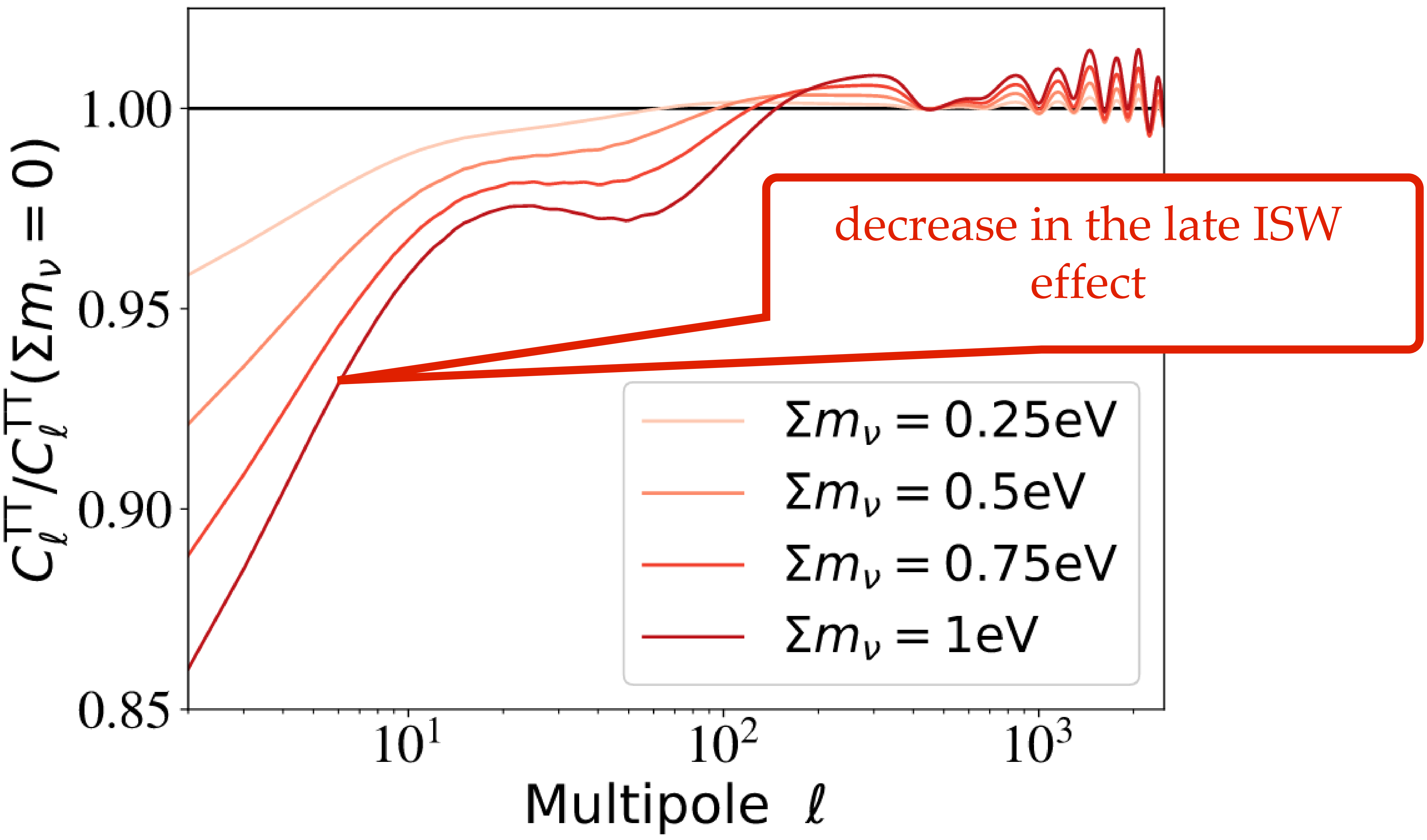




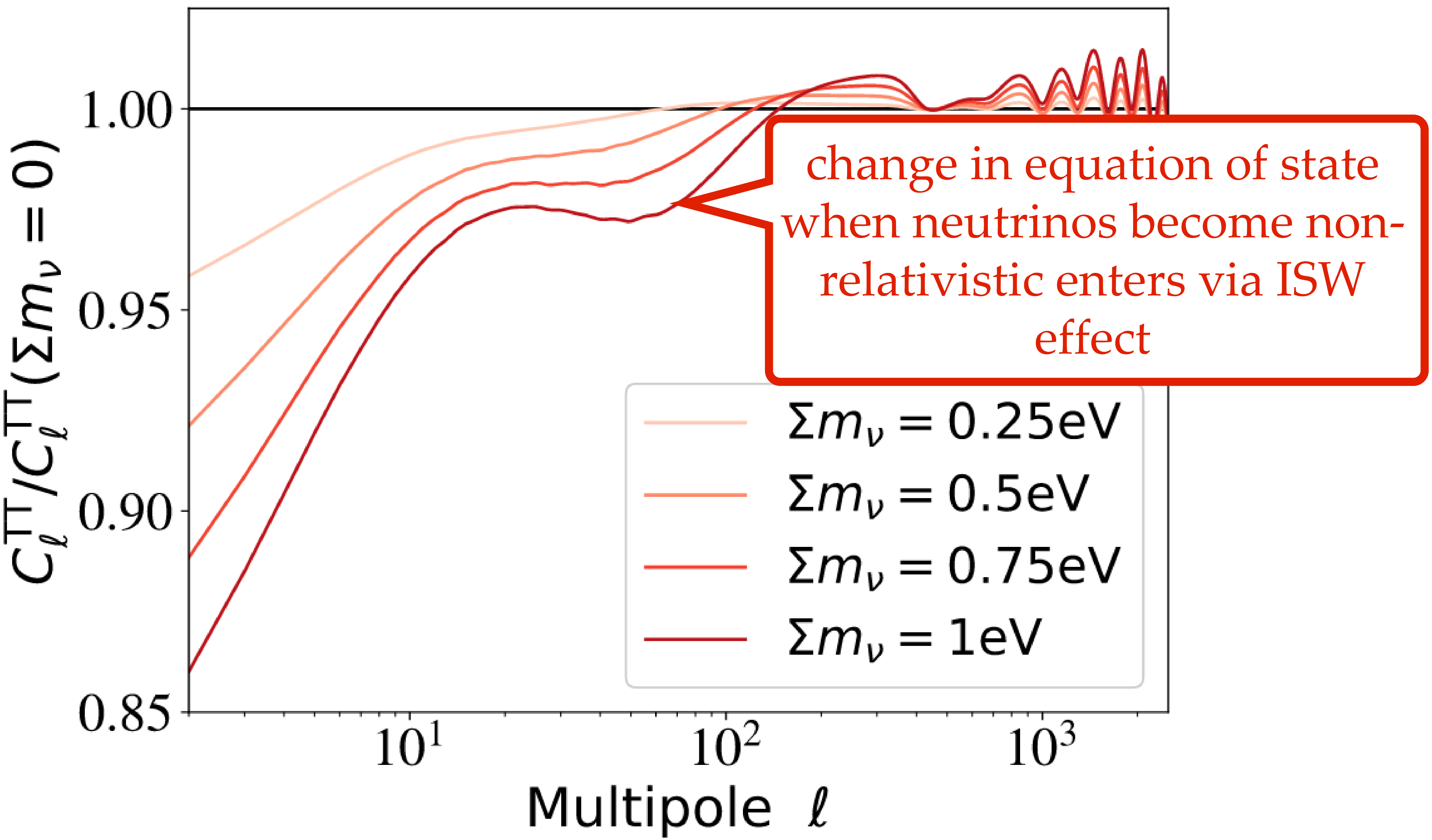
Changing m_ν with fixed d_A



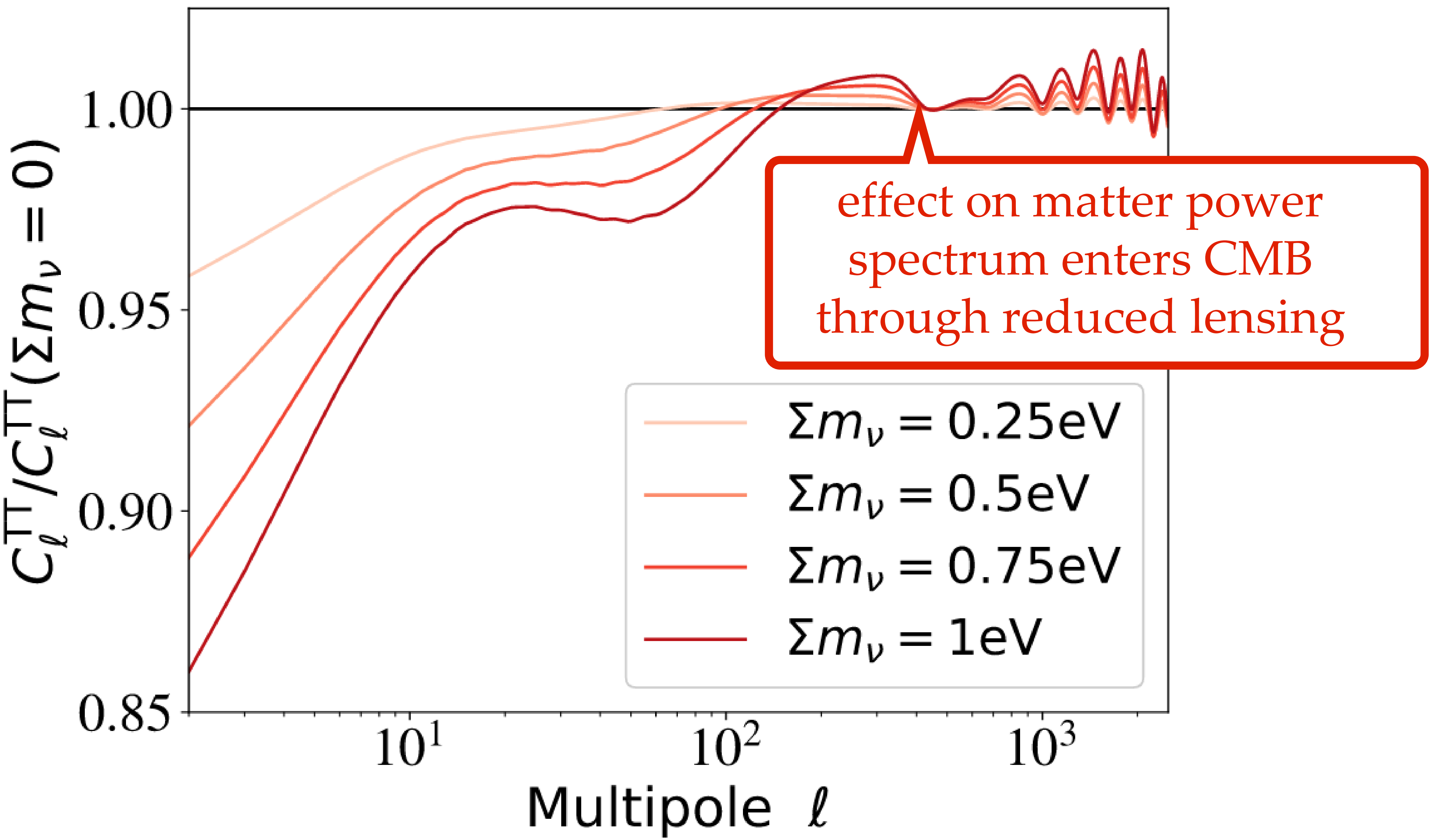
Changing m_ν with fixed d_A



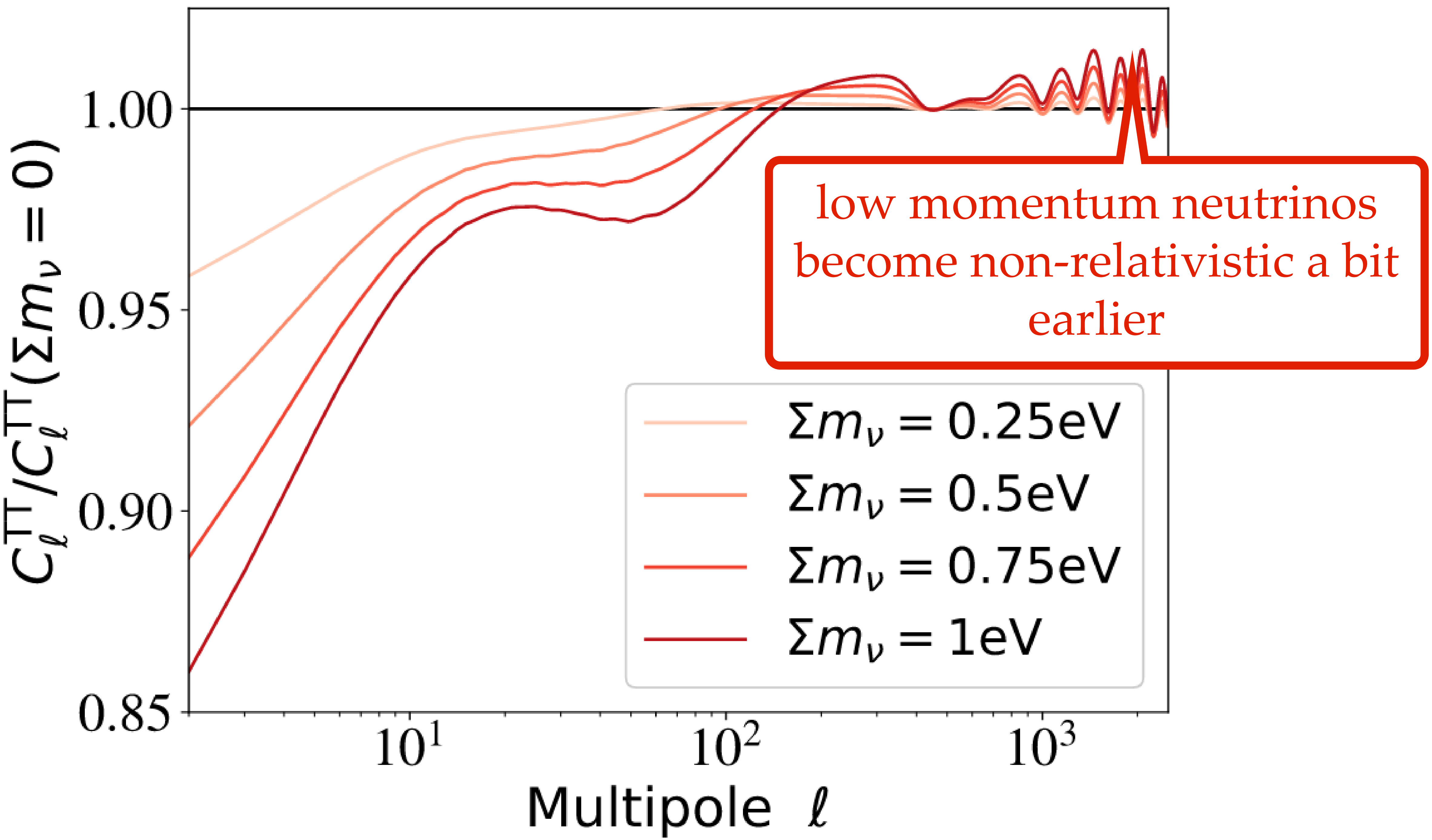
Changing m_ν with fixed d_A



Changing m_ν with fixed d_A



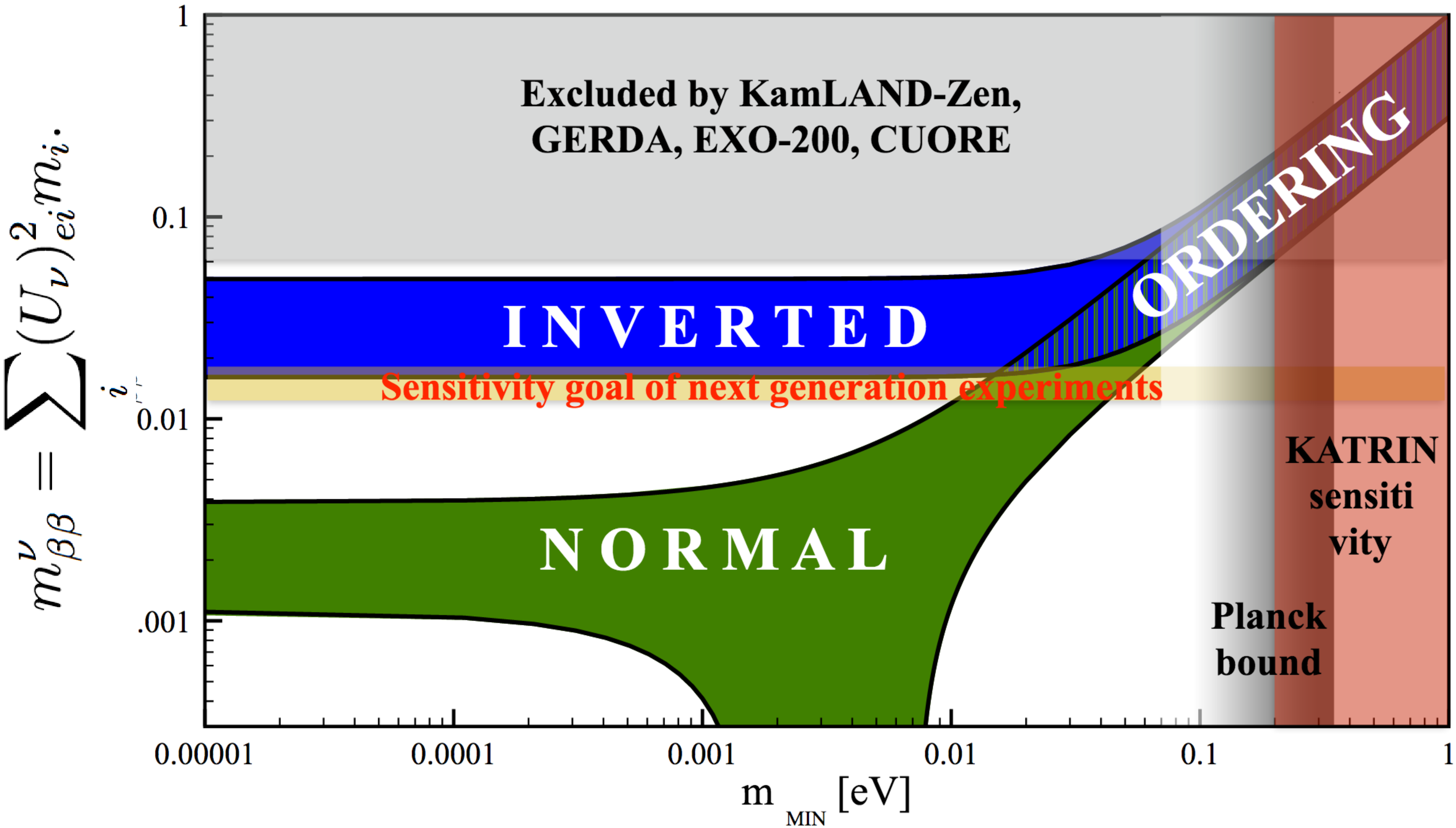
Changing m_ν with fixed d_A



	Model	68%CL
CMB alone		
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$	3.13 ± 0.32
Pl15[TT+lowP]	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.08 ± 0.31
CMB + probes of background evolution		
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$	3.15 ± 0.23
Pl15[TT+lowP] + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	$3.18^{+0.24}_{-0.27}$
CMB + probes of background evolution + LSS		
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$3.08^{+0.22}_{-0.24}$
" + BAO + JLA + HST	ΛCDM+$N_{\rm eff}$	3.41 ± 0.22
" + BAO	ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	3.2 ± 0.5
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$N_{\rm eff}$+5-params.	$2.93^{+0.51}_{-0.48}$

	Model	95% CL (eV)
CMB alone		
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$	< 0.72
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.73
Pl16[TT+SimLow]	ΛCDM+$\sum m_\nu$	< 0.59
CMB + probes of background evolution		
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$	< 0.21
Pl15[TT+lowP] + JLA	ΛCDM+$\sum m_\nu$	< 0.33
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.27
CMB + probes of background evolution + LSS		
Pl15[TT+lowP+lensing]	ΛCDM+$\sum m_\nu$	< 0.68
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.25
Pl15[TT+lowP] + $\mathrm{P(k)}_{\mathrm{DR12}}$	ΛCDM+$\sum m_\nu$	< 0.30
Pl15[TT,TE,EE+lowP] + BAO+ $\mathrm{P(k)}_{\mathrm{WZ}}$	ΛCDM+$\sum m_\nu$	< 0.14
Pl15[TT,TE,EE+lowP] + BAO+ $\mathrm{P(k)}_{\mathrm{DR7}}$	ΛCDM+$\sum m_\nu$	< 0.13
Pl15[TT+lowP+lensing] + Lyα	ΛCDM+$\sum m_\nu$	< 0.12
Pl16[TT+SimLow+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.17
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+Ω_k	< 0.37
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+w	< 0.37
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.32
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$\sum m_\nu$+5-params.	< 0.66

Neutrinoless Double β Decay



A Multi-Frontier Problem

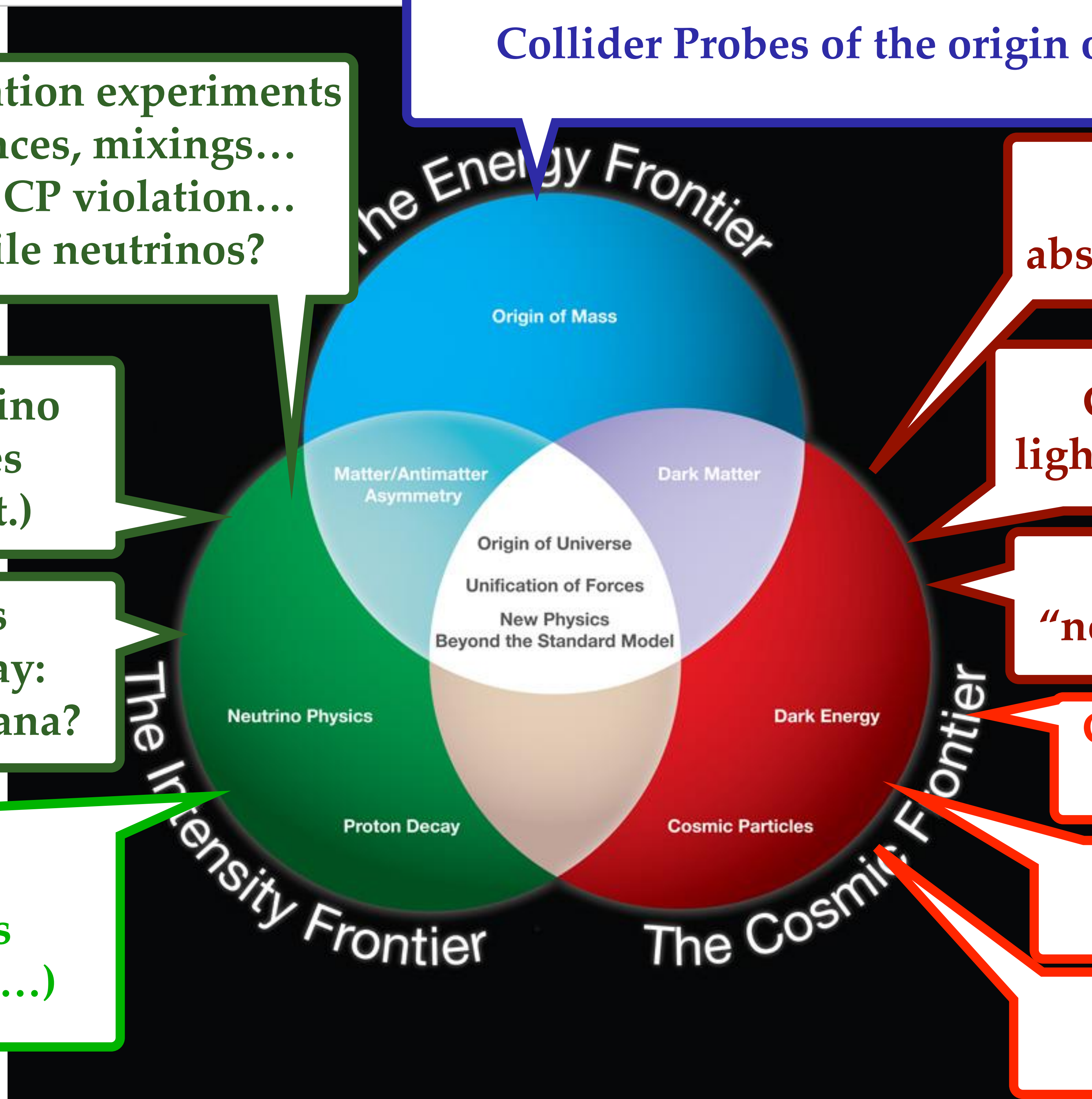
Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)



CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

IceCube
"neutrino astronomy"

Cosmic Neutrino
Background

Leptogenesis?

Sterile Neutrino
Dark Matter?

Neutrinos and New Physics

Origin of Neutrino Mass

- neutrinos undergo flavour oscillations
- those can be explained by a Dirac or Majorana mass term

$$\overline{\nu_L} m_D \nu_R + h.c. \qquad \overline{\nu_L} m_M \nu_L^c + h.c.$$

- …which can be diagonalised as

$$\mathrm{diag}(m_1, m_2, m_3) = U_\nu^\dagger m_D \tilde{U}_\nu \qquad \mathrm{diag}(m_1, m_2, m_3) = U_\nu^\dagger m_M U_\nu^*$$

leptons are just like quarks without colour… but:

- Why are the m_i so tiny?
- Why is the mixing matrix so different from the CKM matrix?
- What forbids the Majorana mass for the RH neutrino?

Origin of Neutrino Mass

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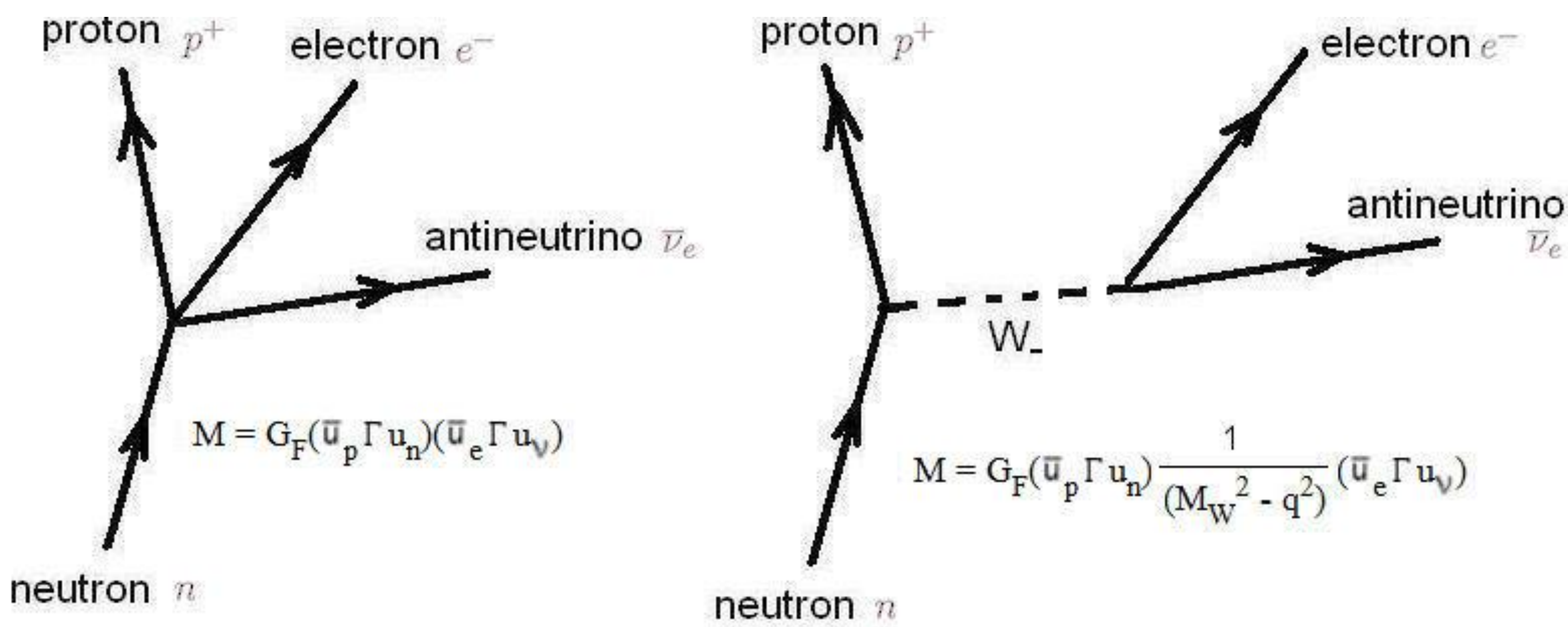
- Majorana fermion
  NEW PHYSICS!
- can be generated in gauge invariant way by higher dim operators
  NEW PHYSICS!
  should be generated by integrating out some heavier states with masses ~$\Lambda \gg E_\upsilon$

“Integrating out” Heavy Particles



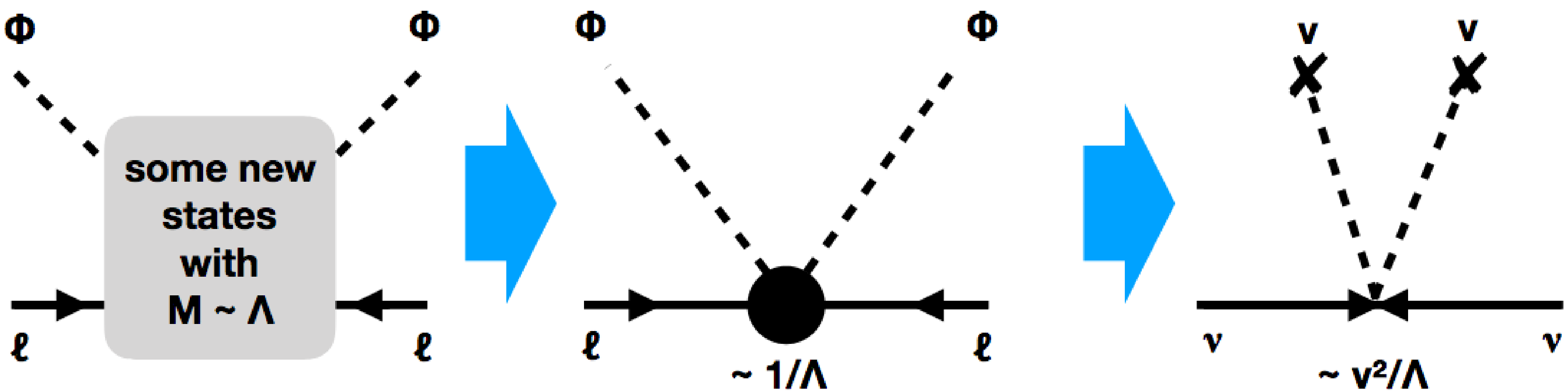
a. Fermi's 4-point Interaction, 1934 b. Weak Interaction mediated by boson, 1938

The weak gauge bosons are too heavy to be produced in the decay…

…but appear as “virtual particles”, giving rise to an effective vertex

Neutrino Mass as a Portal to New Physics

$\Phi = (0, v)$ + fluctuations h



$\Phi\, l\, l\, \Phi / \Lambda =$

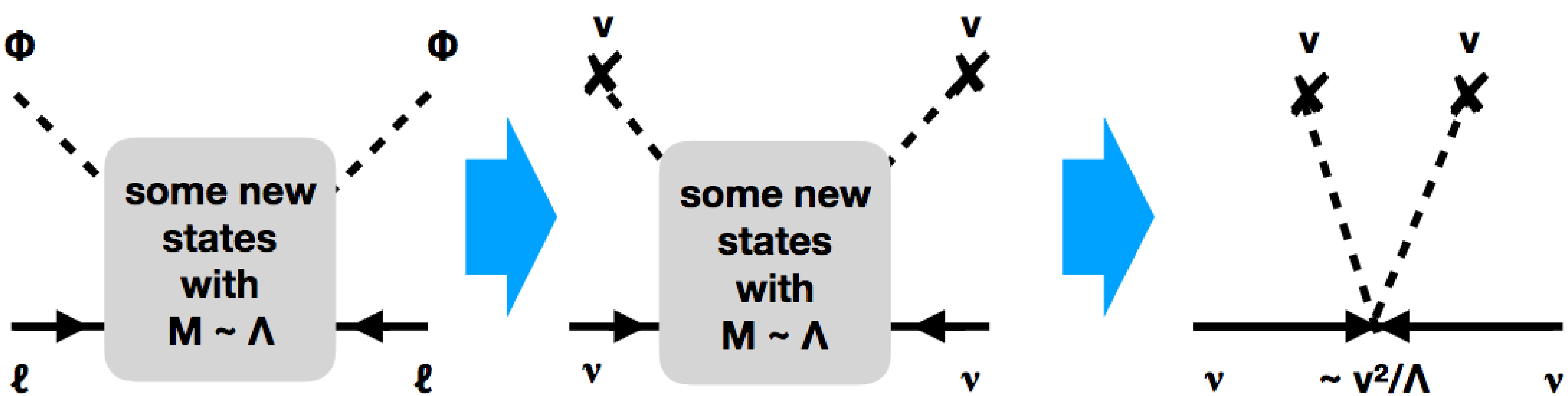
$v\ \nu_L\ \nu_L\ v / \Lambda$

$+\ h\ \nu_L\ \nu_L\ h / \Lambda$

$+$ mixed / Λ

High Scale Seesaw: Λ ≫ v

$$\overline{\nu_L} m_M \nu_L^c + h.c.$$



Low Scale Seesaw: Λ ≲ v

"integrating out" heavier states with masses ~$\Lambda \gg E_\upsilon$

Tree Level Seesaw Mechanisms

$$\overline{\nu_L} m_M \nu_L^c + h.c.$$

- **Type I: fermonic singlet *N* ("right handed neutrino")**

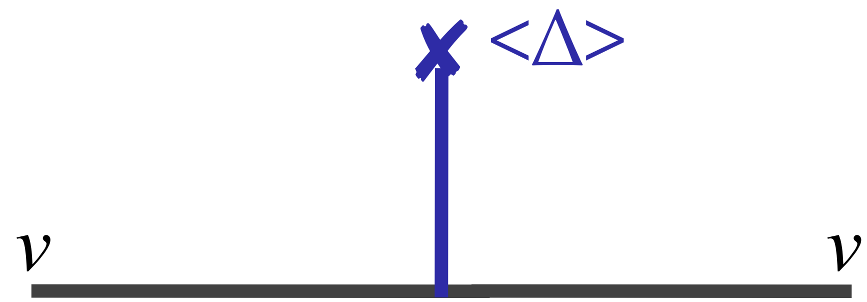
Minkowski 79, Gell-Mann/Ramond/Slansky 79,
Mohapatra/Senjanovic 79, Yanagida 80

$$-\overline{\ell_L} Y_{\rm I} N \tilde{\Phi} - \frac{1}{2} \overline{N} M N$$

- **Type II: scalar triplet Δ**

Schechter/Valle 80, Cheng/Li 1980,
Lazarides/Shafi/Wetterich 80, Mohapatra/Senjanovic 81

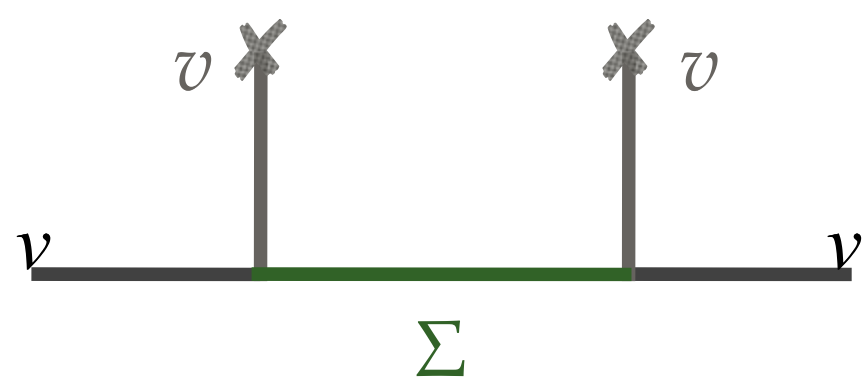
$$-\overline{\ell_L^c} Y_{\rm II} i\sigma_2 \Delta_L \ell$$



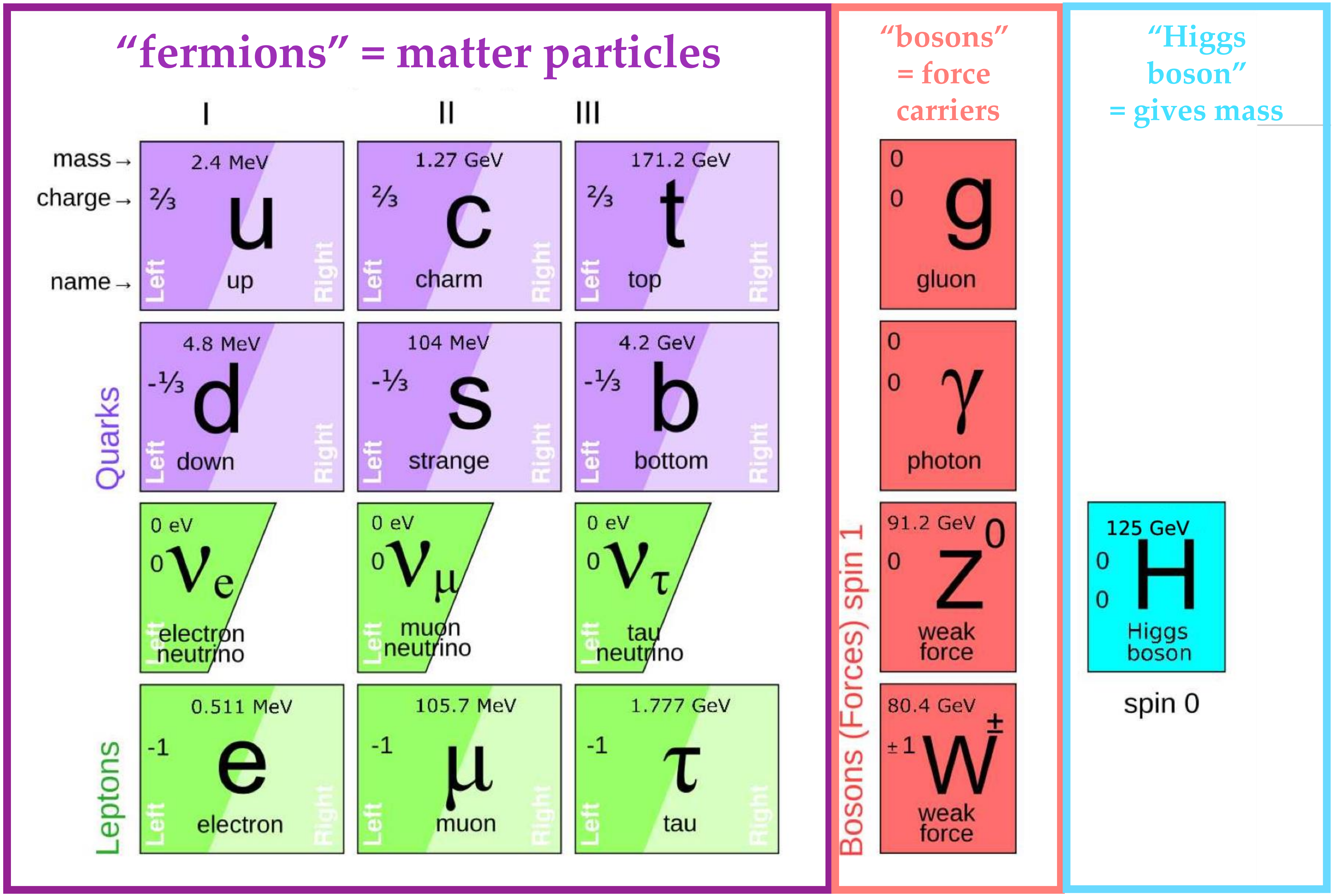
- **Type III: fermonic triplet Σ**

Foot/Lew/He/Joschi 89

$$-\overline{\ell_L} Y_{\rm III} \Sigma_R^c \tilde{\Phi}$$

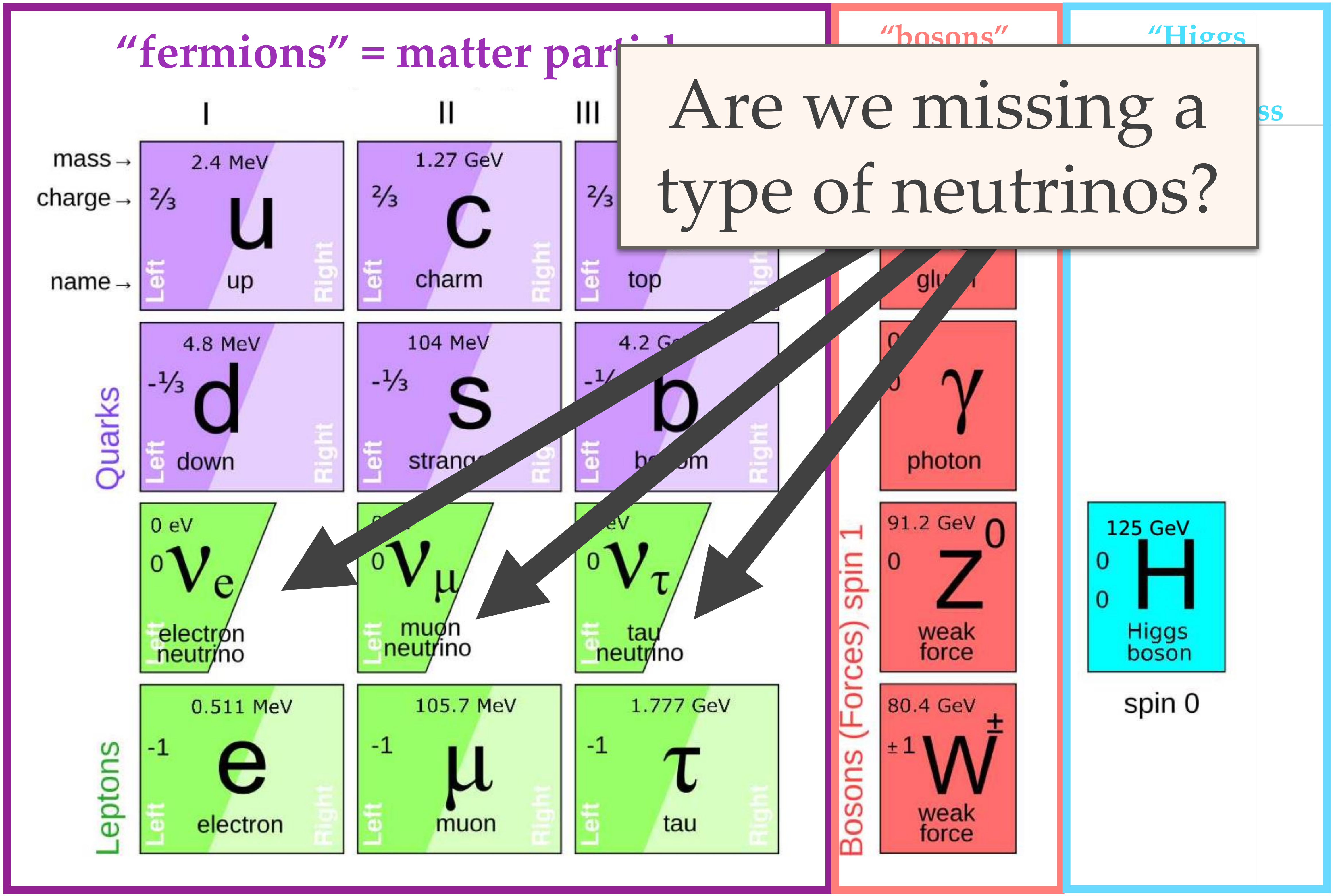


The Standard Model of Particle Physics



The "periodic table" of elementary particles - who is missing?

The Standard Model of Particle Physics



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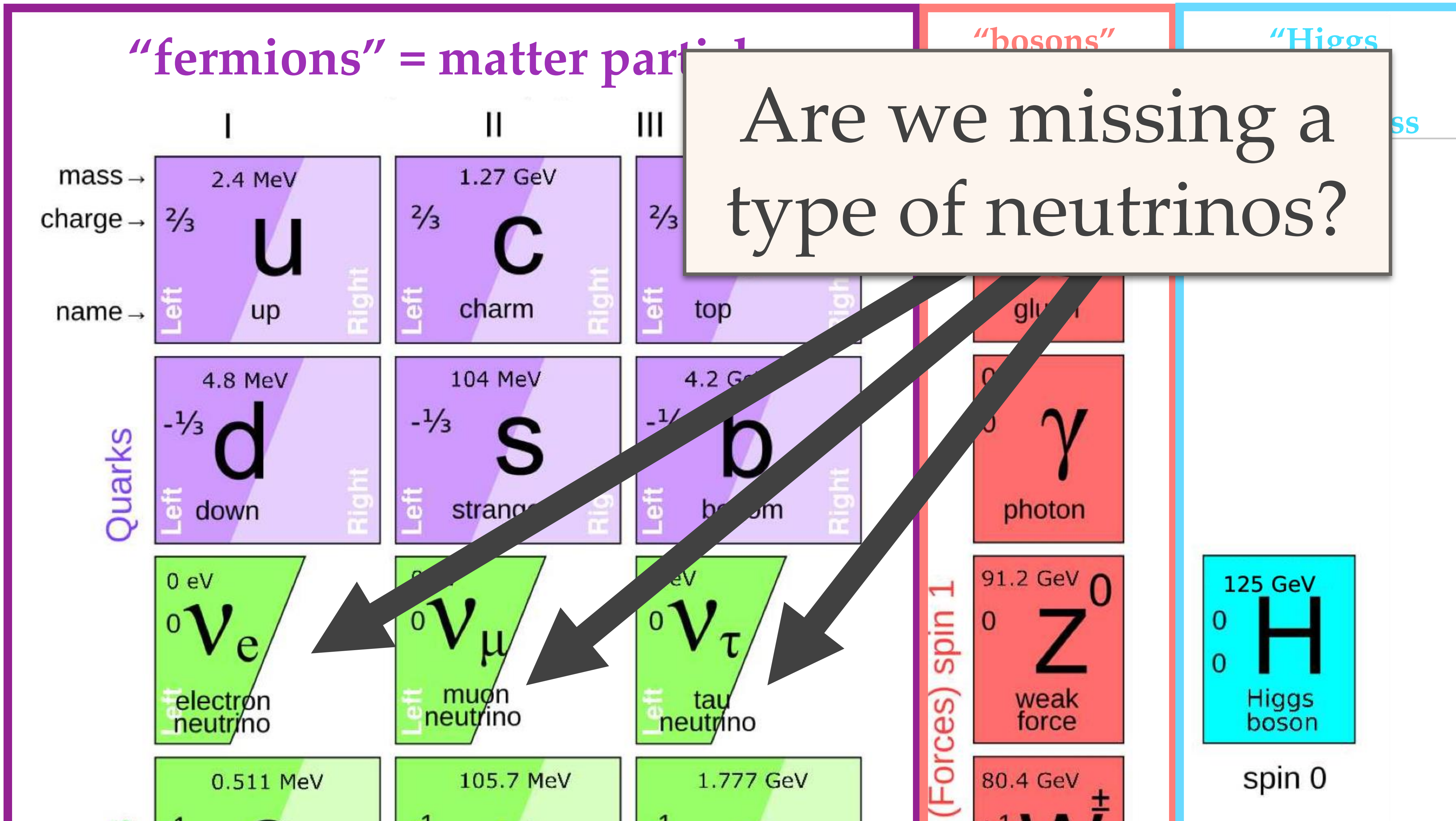
The Standard Model of Particle Physics



Are we missing a type of neutrinos?

Ordinary “left handed” neutrinos

- Are massless in the Standard Model
- Can feel the weak nuclear force

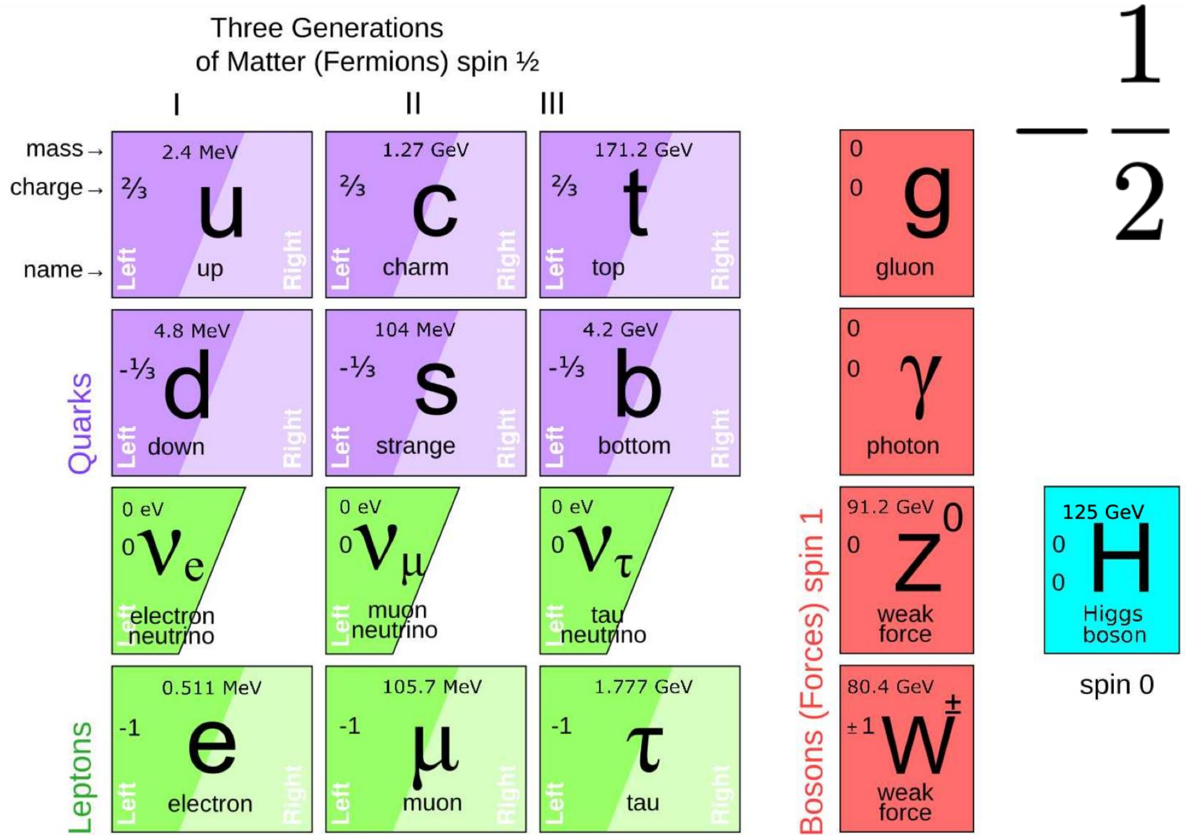
Sterile “right handed” neutrinos

- Can have a (Majorana) mass.
- Do not feel any of the forces of nature (except gravity)

The Seesaw Mechanism

$H = (v, 0)$

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$



$$-\frac{1}{2}\left(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c\right)$$

electroweak symmetry breaking generates a Dirac mass term

$$m_D \equiv F v$$

$$\overline{\nu_L} m_D \nu_R + h.c.$$

The complete mass term can then be written as

$$\frac{1}{2}\left(\overline{\nu_L}\ \overline{\nu_R^c}\right)\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.,$$

The Seesaw Mechanism

$$\frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c})\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.,$$

Full mass term is diagonalised as

$$\mathcal{U}^\dagger \mathcal{M} \mathcal{U}^* = \begin{pmatrix} m_\nu^{\rm diag} & \\ & M_N^{\rm diag} \end{pmatrix} \qquad \text{with} \qquad \begin{aligned} M_N^{\rm diag} &= U_N^T M_N U_N \\ m_\nu^{\rm diag} &= U_\nu^\dagger m_\nu U_\nu^* \end{aligned}$$

The rotation matrix is given by

$$\mathcal{U} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta^\dagger) & \cos(\theta^\dagger) \end{pmatrix}\begin{pmatrix} U_\nu & \\ & U_N^* \end{pmatrix} \qquad \text{with} \qquad \begin{aligned} \sin(\theta) &= \sum_{n=0}^{\infty} \frac{(-\theta\theta^\dagger)^n \theta}{(2n+1)!}. \\ \cos(\theta) &= \sum_{n=0}^{\infty} \frac{(-\theta\theta^\dagger)^n}{(2n)!} \end{aligned}$$

The Seesaw Mechanism

At linear order in $\theta \equiv m_D M_M^{-1}$

we find two sets of mass eigenstates

light "active" neutrinos

$$\nu \simeq U_\nu^\dagger \left(\nu_L - \theta \nu_R^c\right) + \text{c.c.}$$

with mass matrix

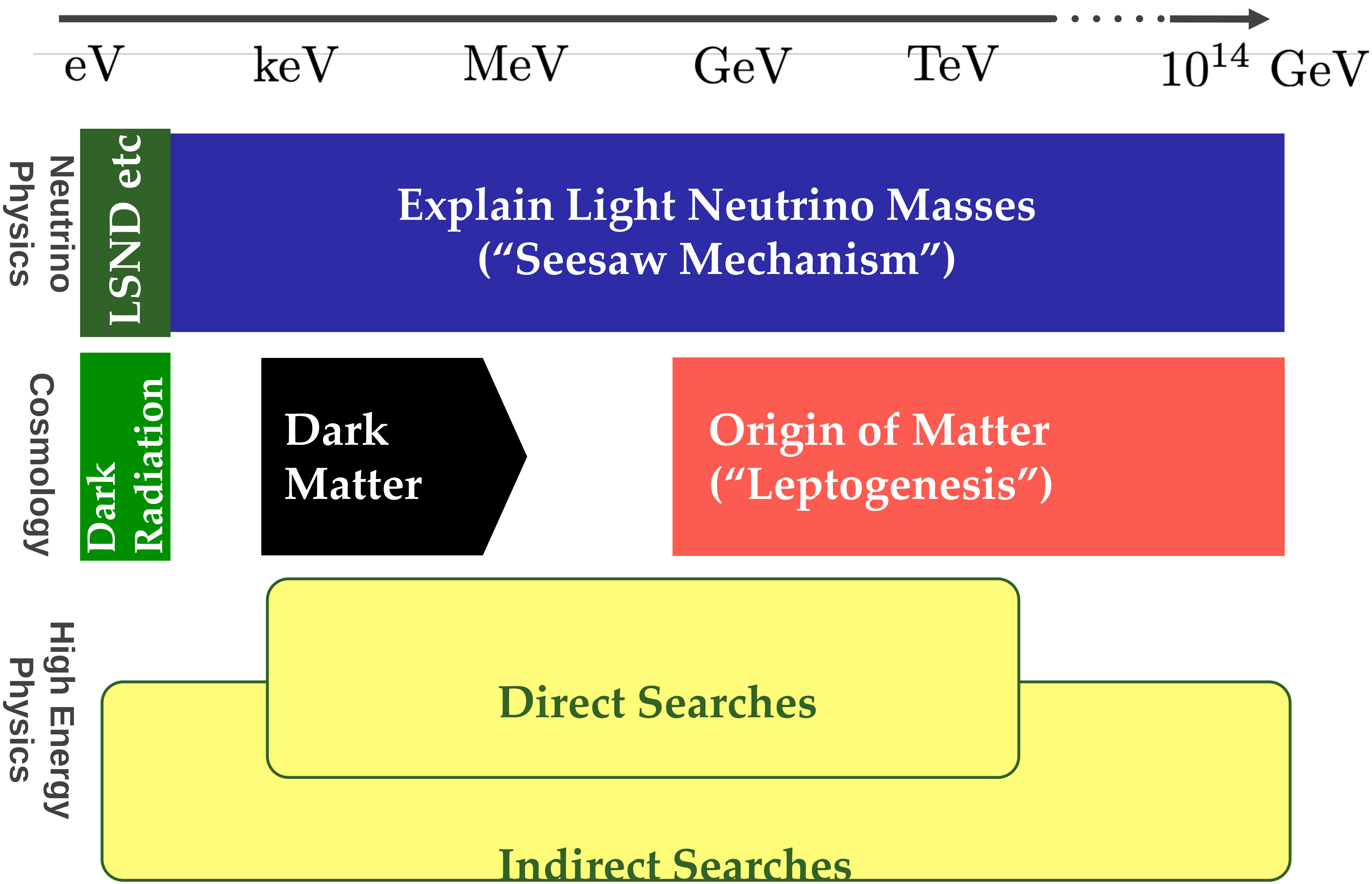
$$m_\nu = -v^2 F M_M^{-1} F^T = -m_D M_M^{-1} m_D^T = -\theta M_M \theta^T$$

heavy sterile neutrinos

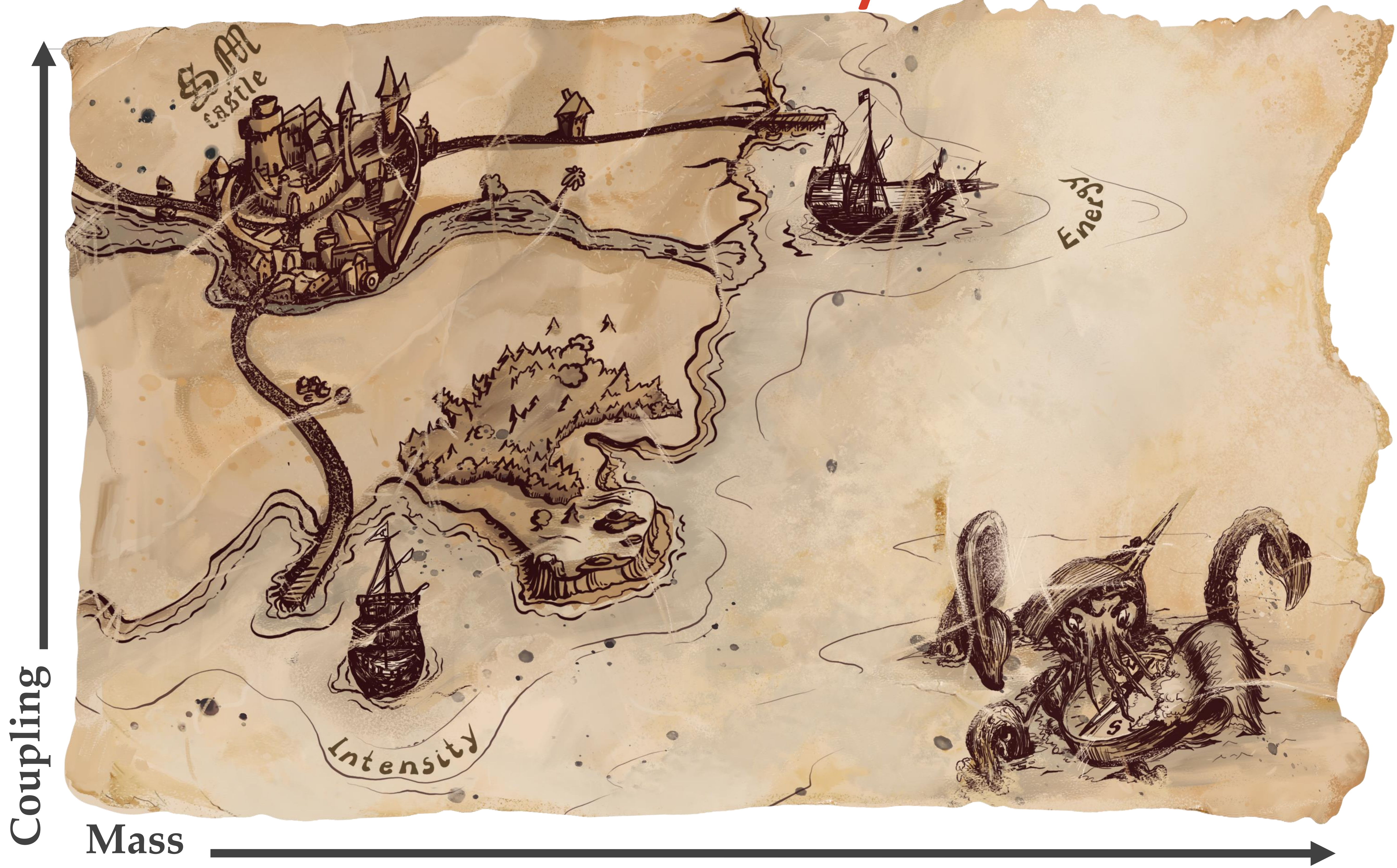
$$N \simeq U_N^\dagger \left(\nu_R + \theta^T \nu_L^c\right) + \text{c.c.}.$$

with mass matrix $$M_N = M_M + \frac{1}{2}\left(\theta^\dagger \theta M_M + M_M^T \theta^T \theta^*\right)$$

Right Handed Neutrino Mass Scale



Where are the Heavy Neutrinos?



Right Handed Neutrino Mass Scale

nuclear decay spectra

TRISTAN, ECHO

fixed target experiments

SHiP

Search for Hidden Particles

NA62

b factories

LHCb

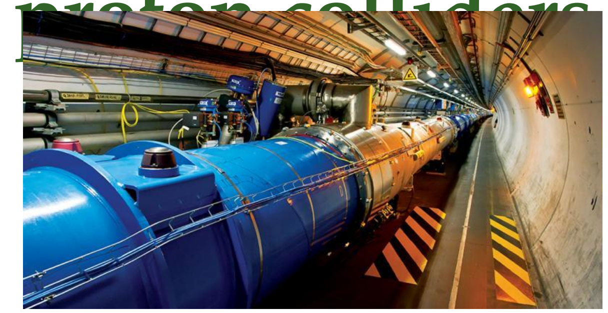
Belle II

far detector

FASER

MATHUSLA

proton colliders



lepton colliders

ilc

international linear collider

FCC

hh ee he

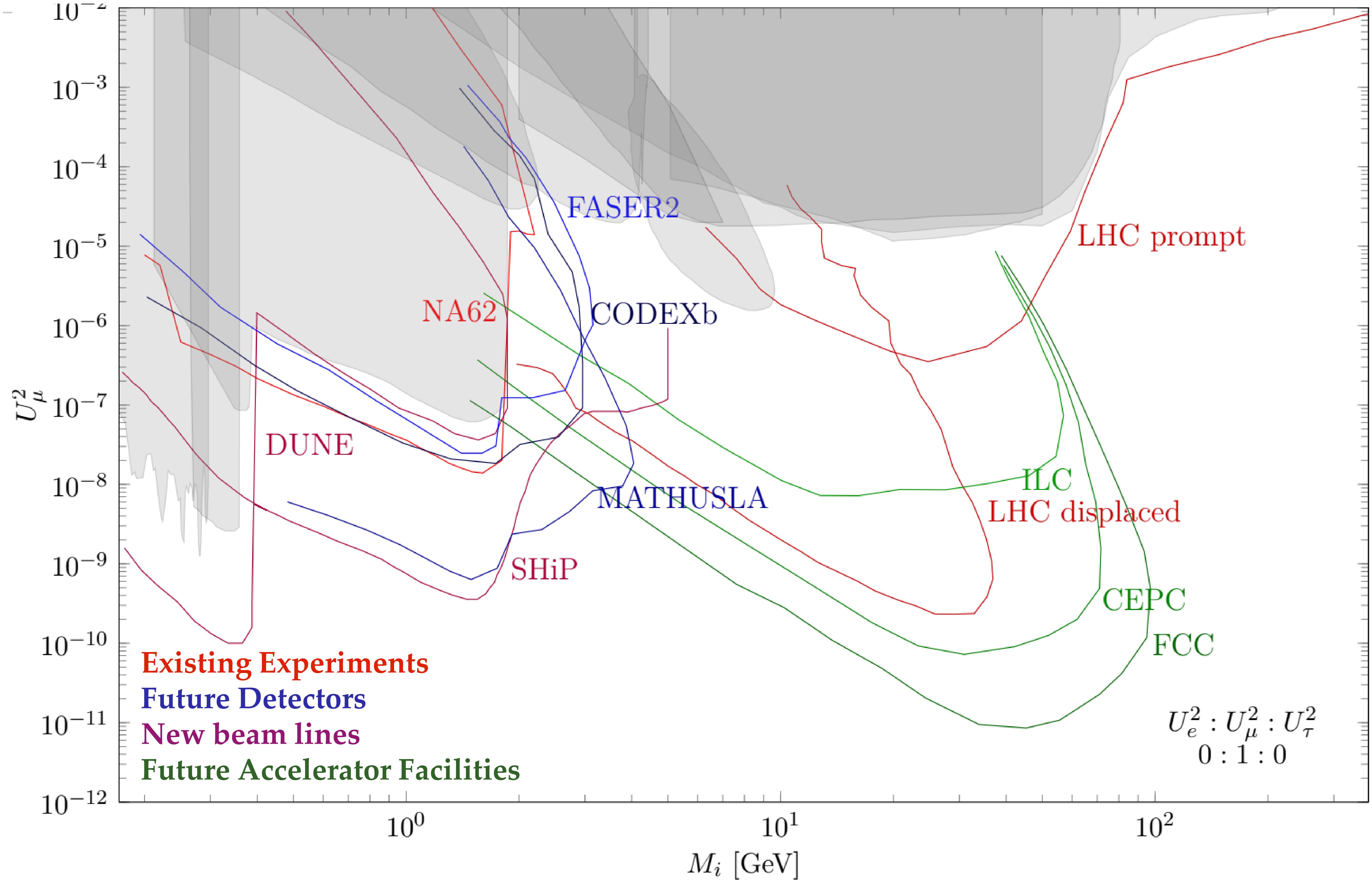
CEPC

Direct Searches

Indirect Searches

High Energy Physics

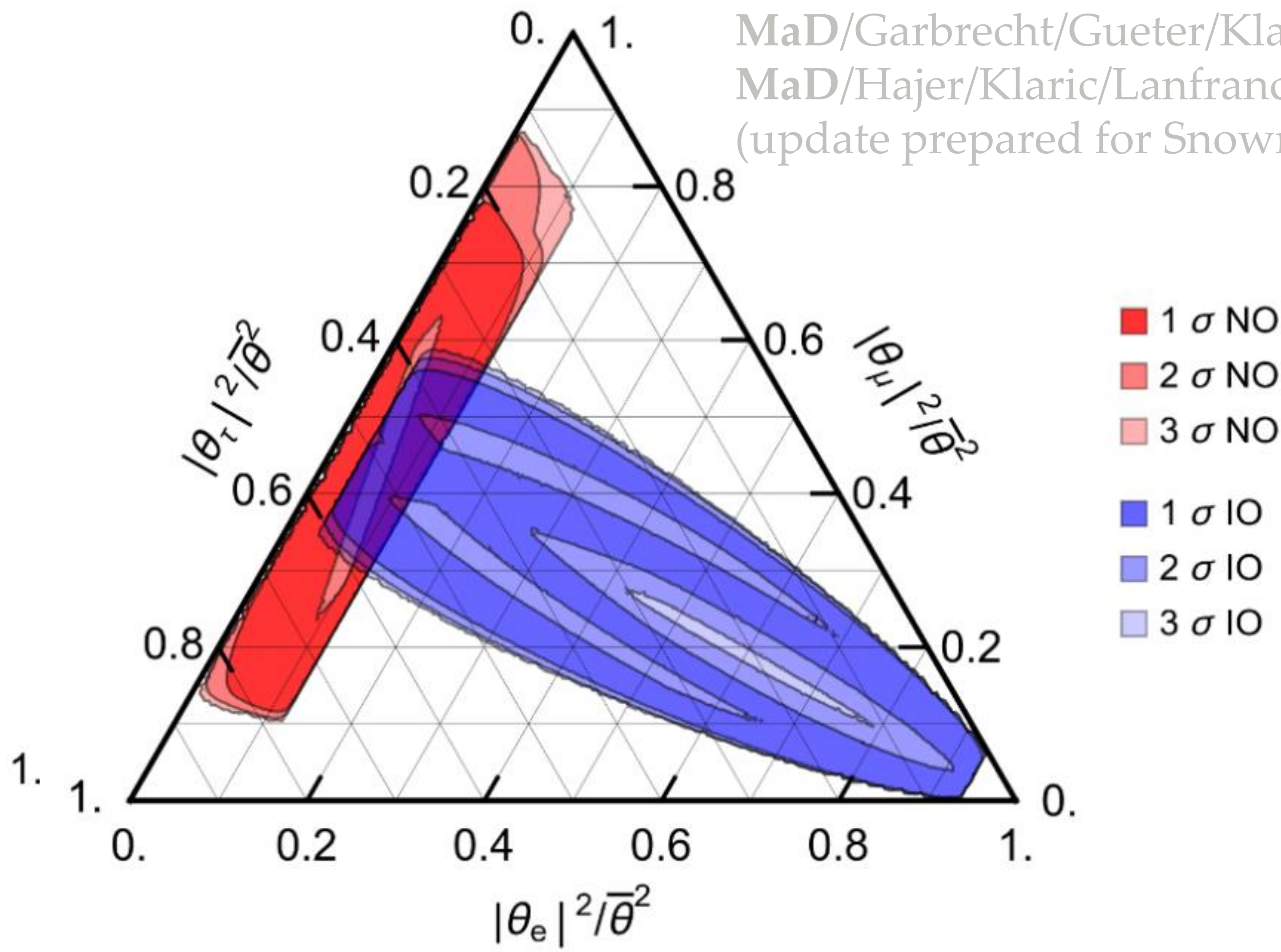
Heavy Neutrino Searches



Branching ratios from ν-Oscillation Data

- If RH neutrinos generate light neutrino masses, requirement to reproduce neutrino oscillation data constrains their properties
- In particular: branching ratio in their decays into SM flavours

MaD/Garbrecht/Gueter/Klaric 1609.09069
MaD/Hajer/Klaric/Lanfranchi 1801.04207
(update prepared for Snowmass)



Forecast with DUNE

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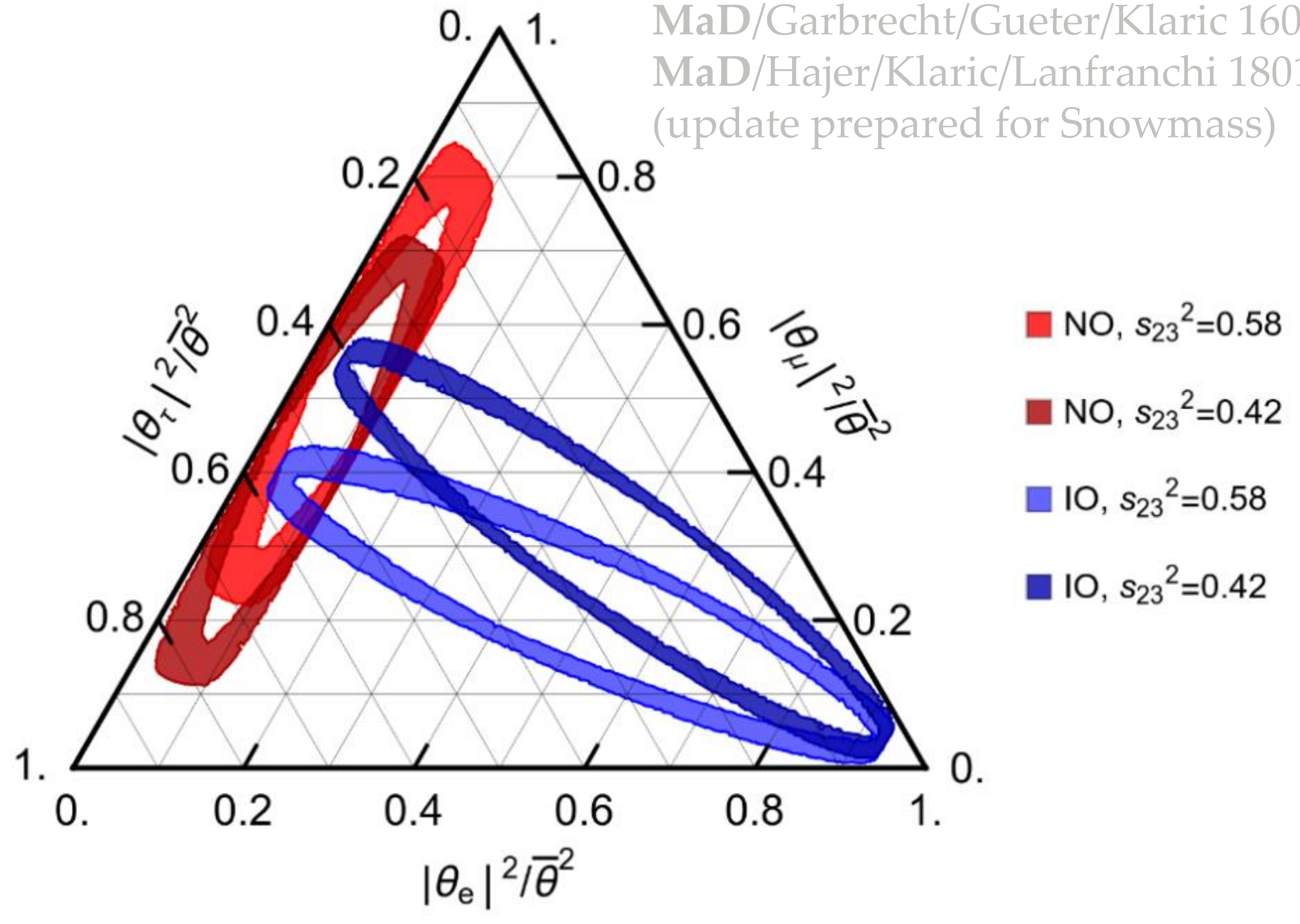
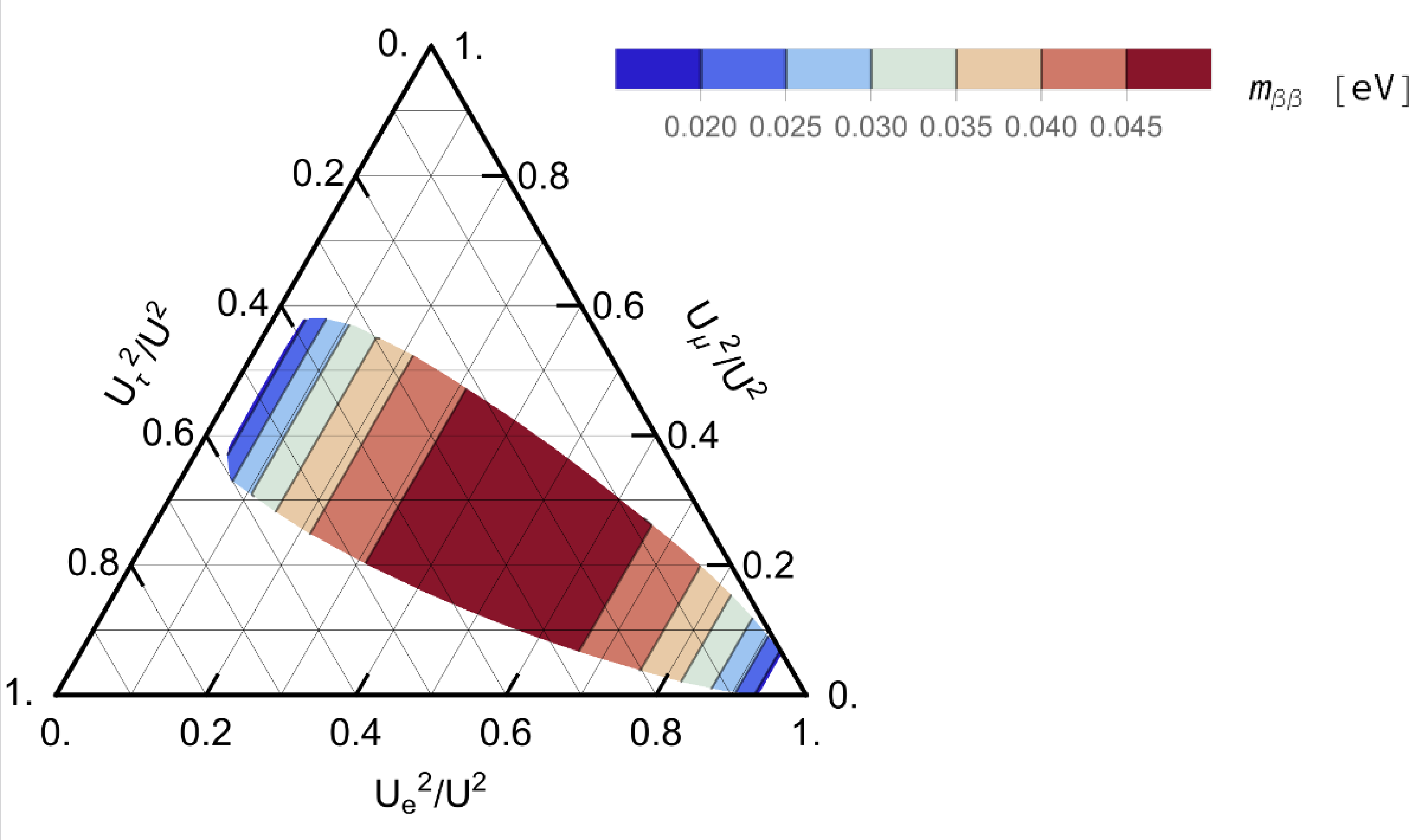


Connection to Neutrinoless Double β Decay

- If RH neutrinos generate light neutrino masses, requirement to reproduce neutrino oscillation data constrains their properties
- In particular: branching ratio in their decays into SM flavours



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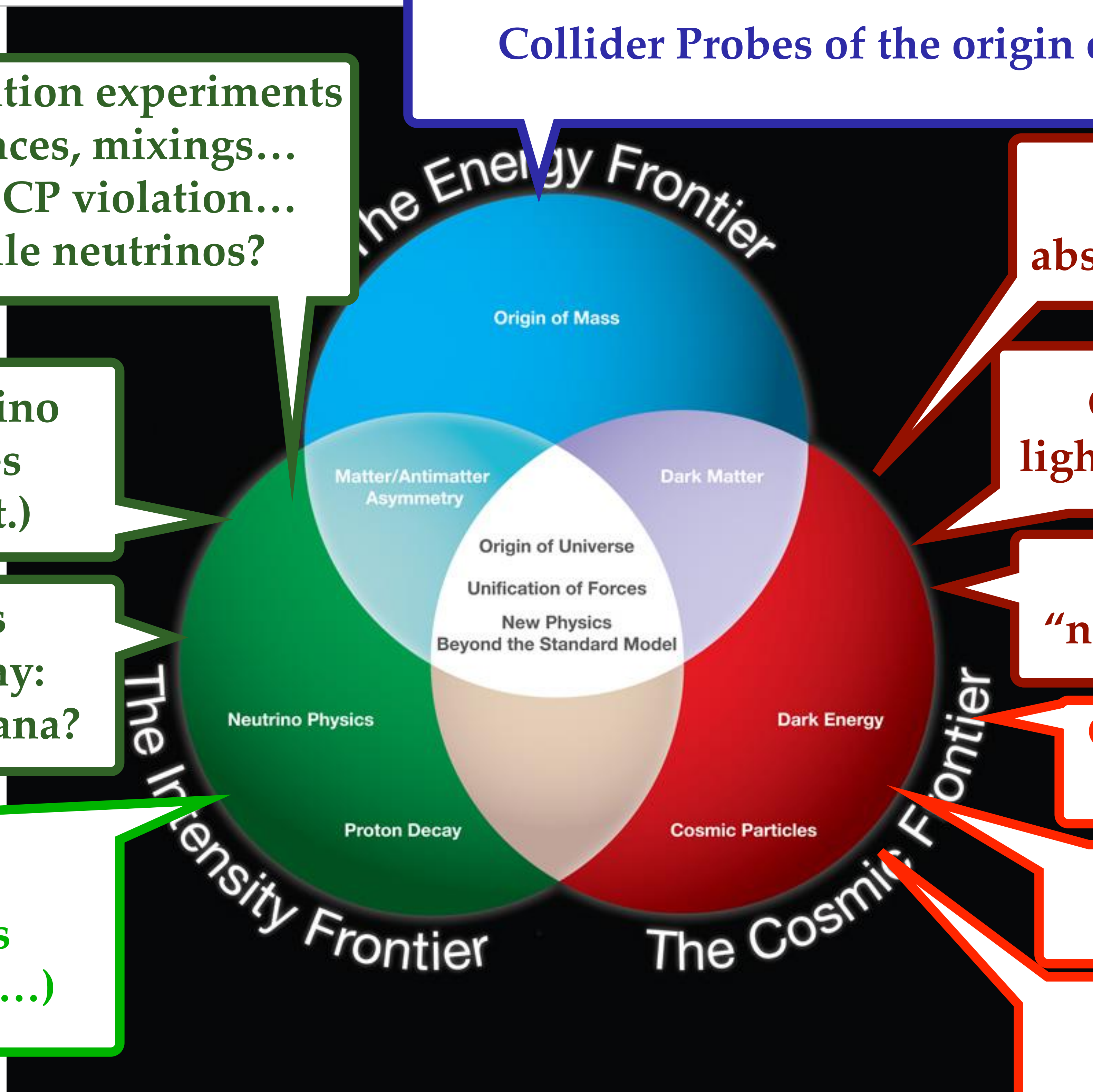

CMB and LSS :
absolute neutrino mass

CMB and BBN :
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IceCube
“neutrino astronomy”

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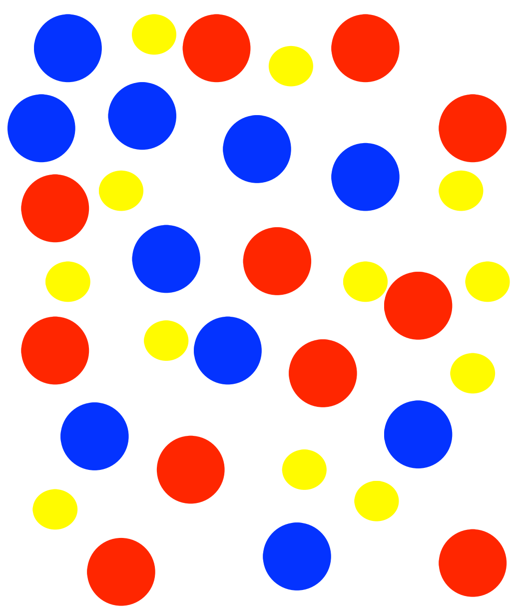
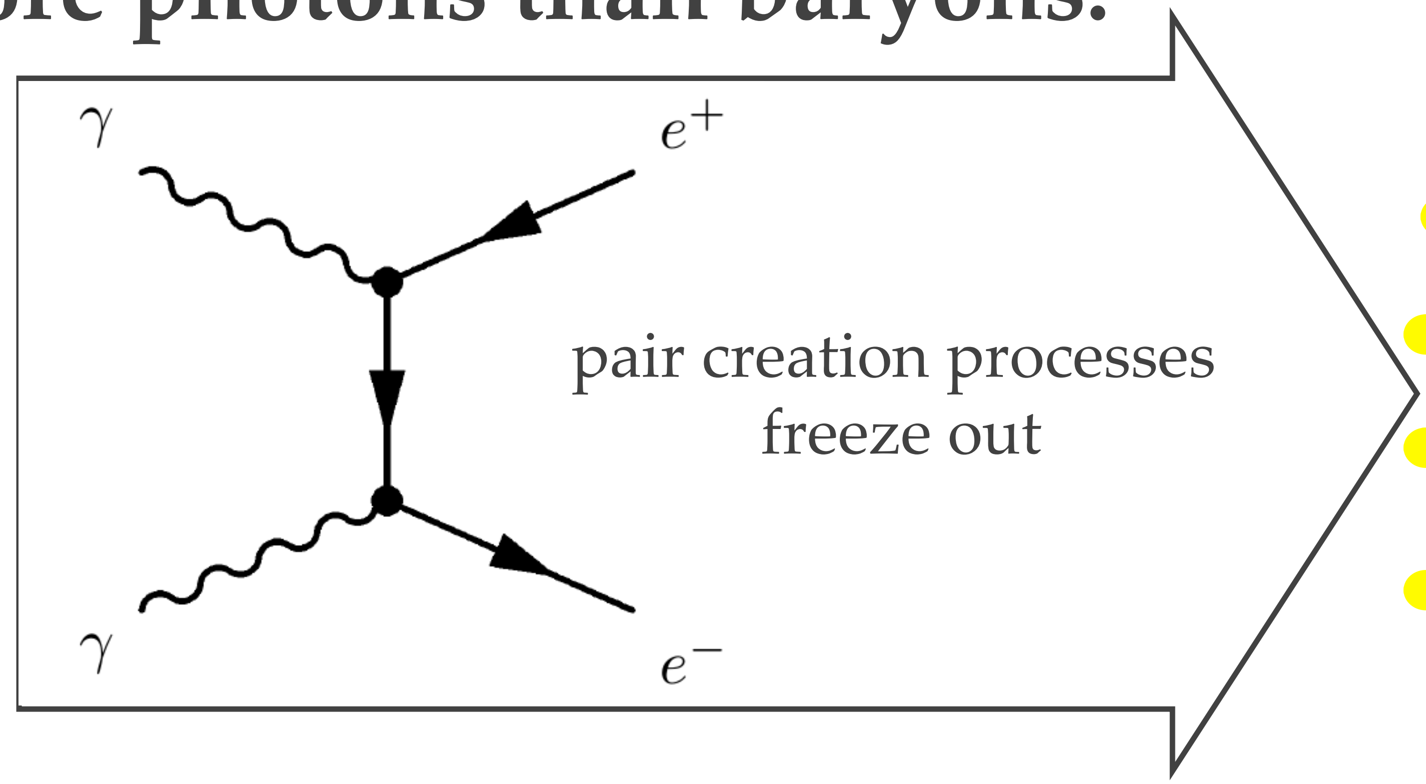
Dark Matter?

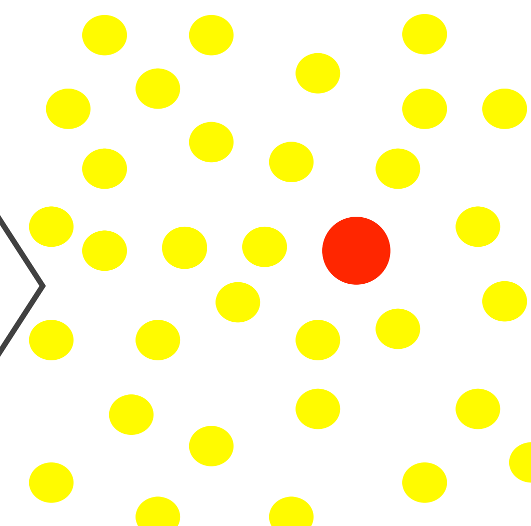
Leptogenesis

Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons.







$T > 2\ mc^2$

$T < 2\ mc^2$

CMB constraint on baryon-to-photon ratio η:

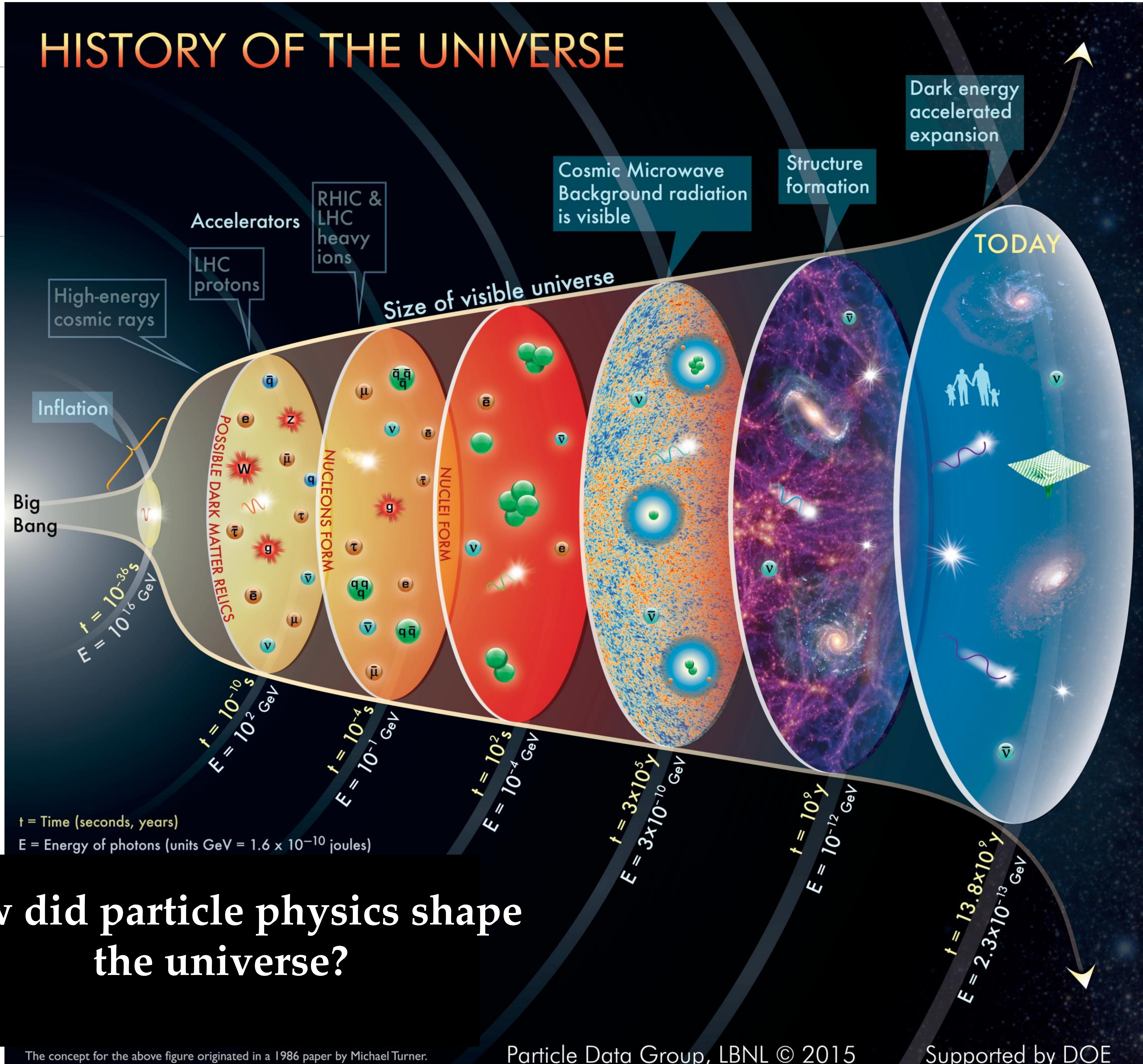
$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$

(Planck Collaboration)

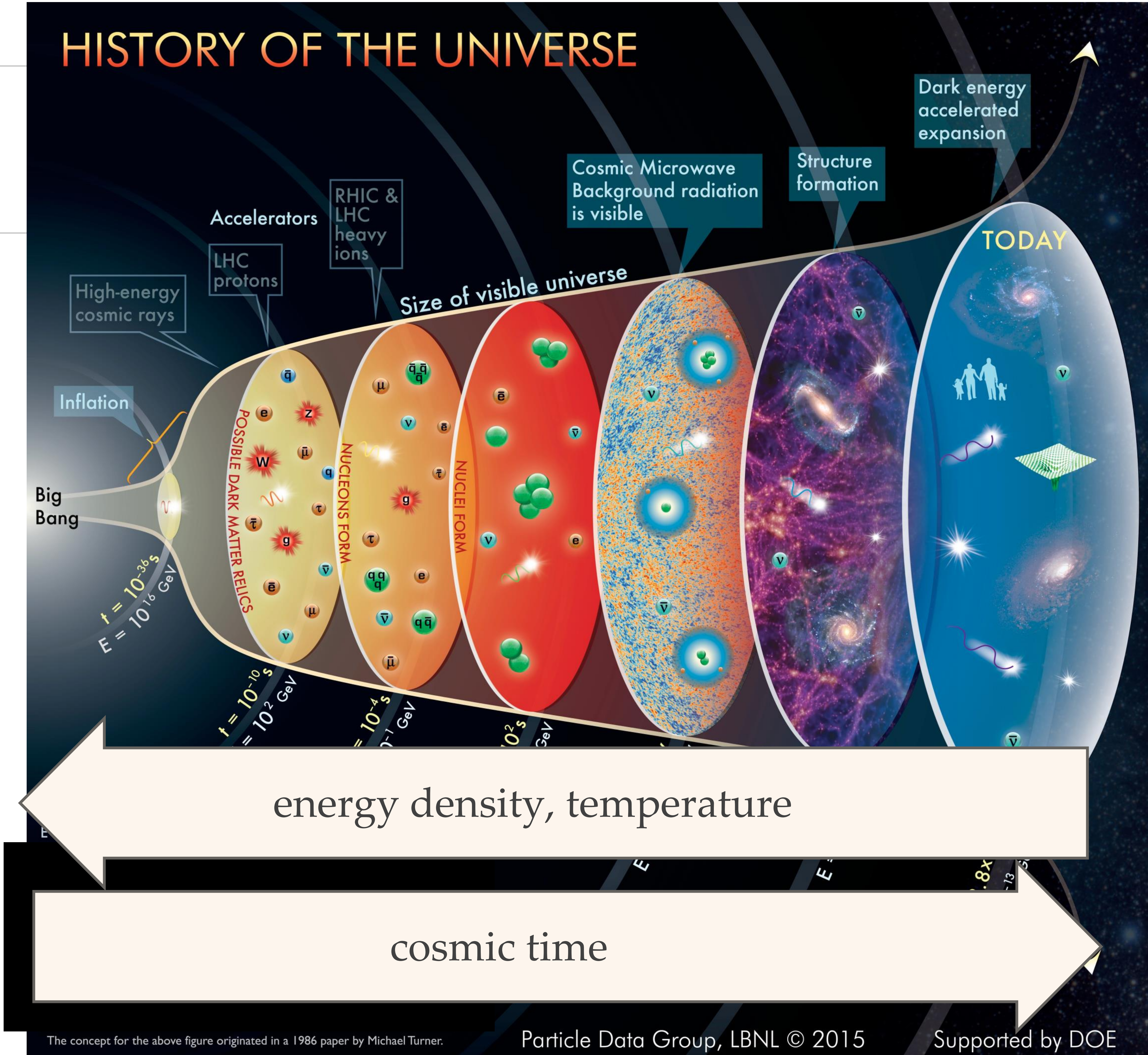
BBN constraint on baryon-to-photon ratio η:

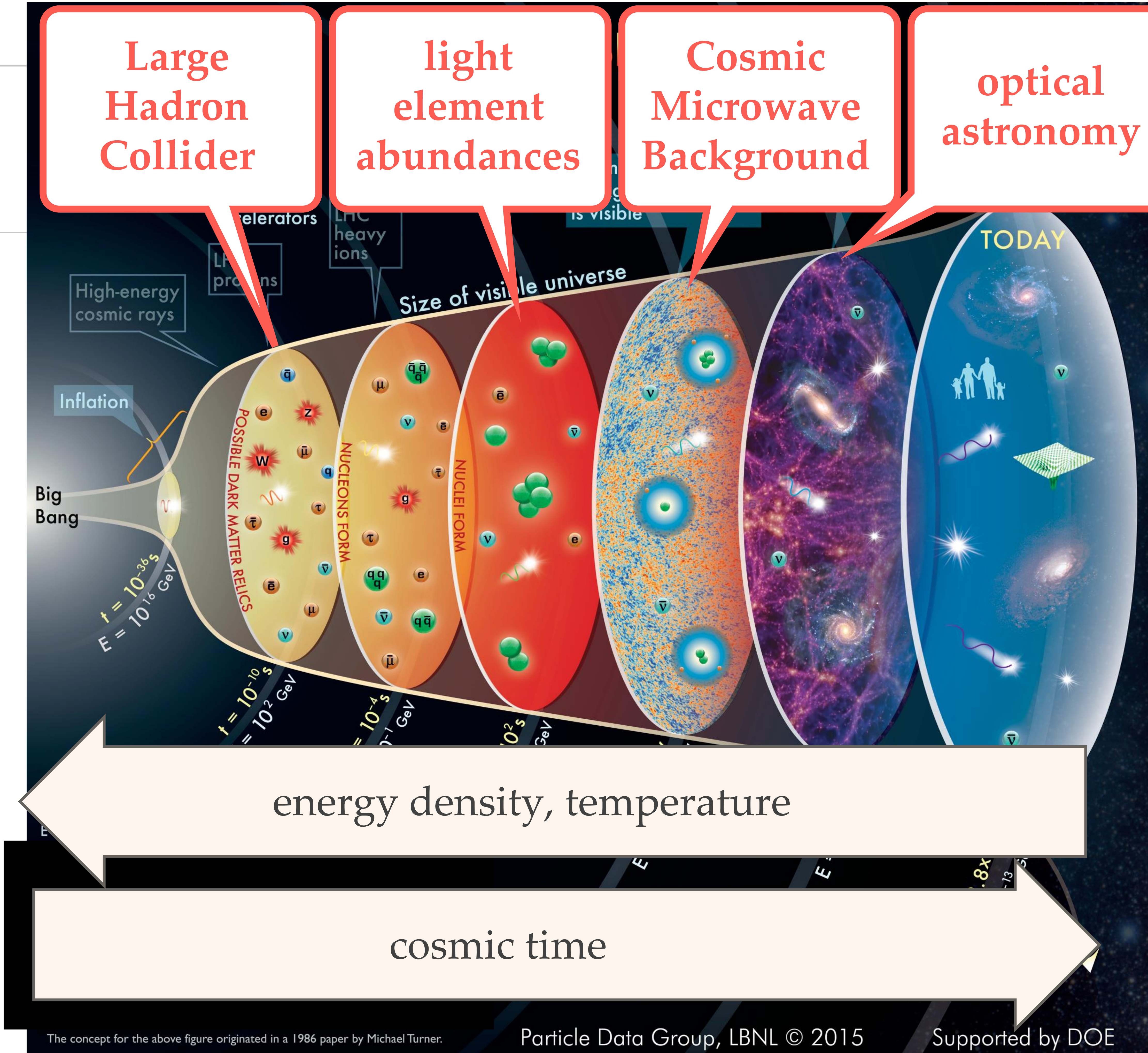
$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)



w did particle physics shape the universe?


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
energy density, temperature
cosmic time
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE


Large Hadron Collider
light element abundances
Cosmic Microwave Background
optical astronomy
High-energy cosmic rays
heavy ions
Inflation
Big Bang
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
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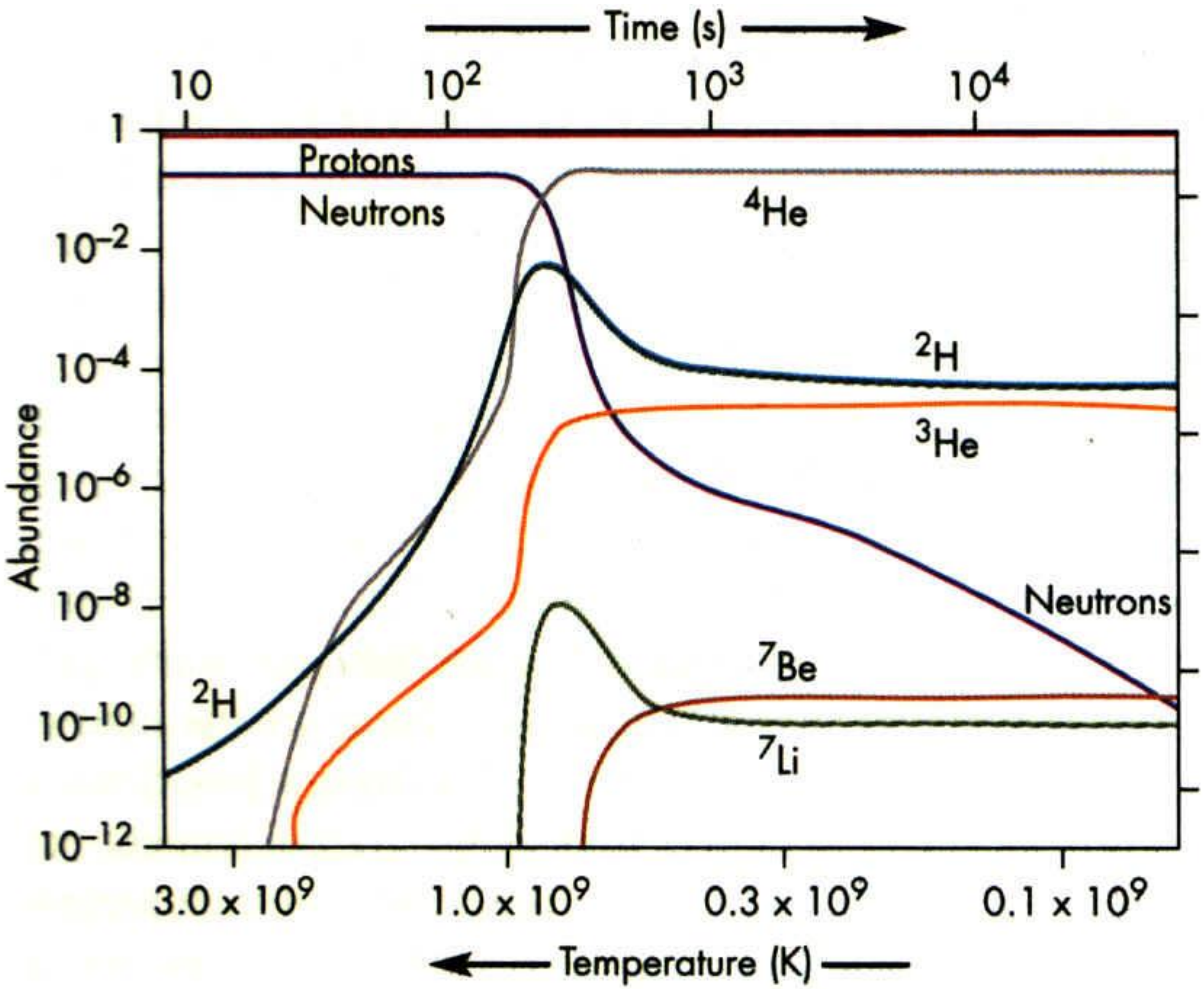
Big Bang Nucleosynthesis

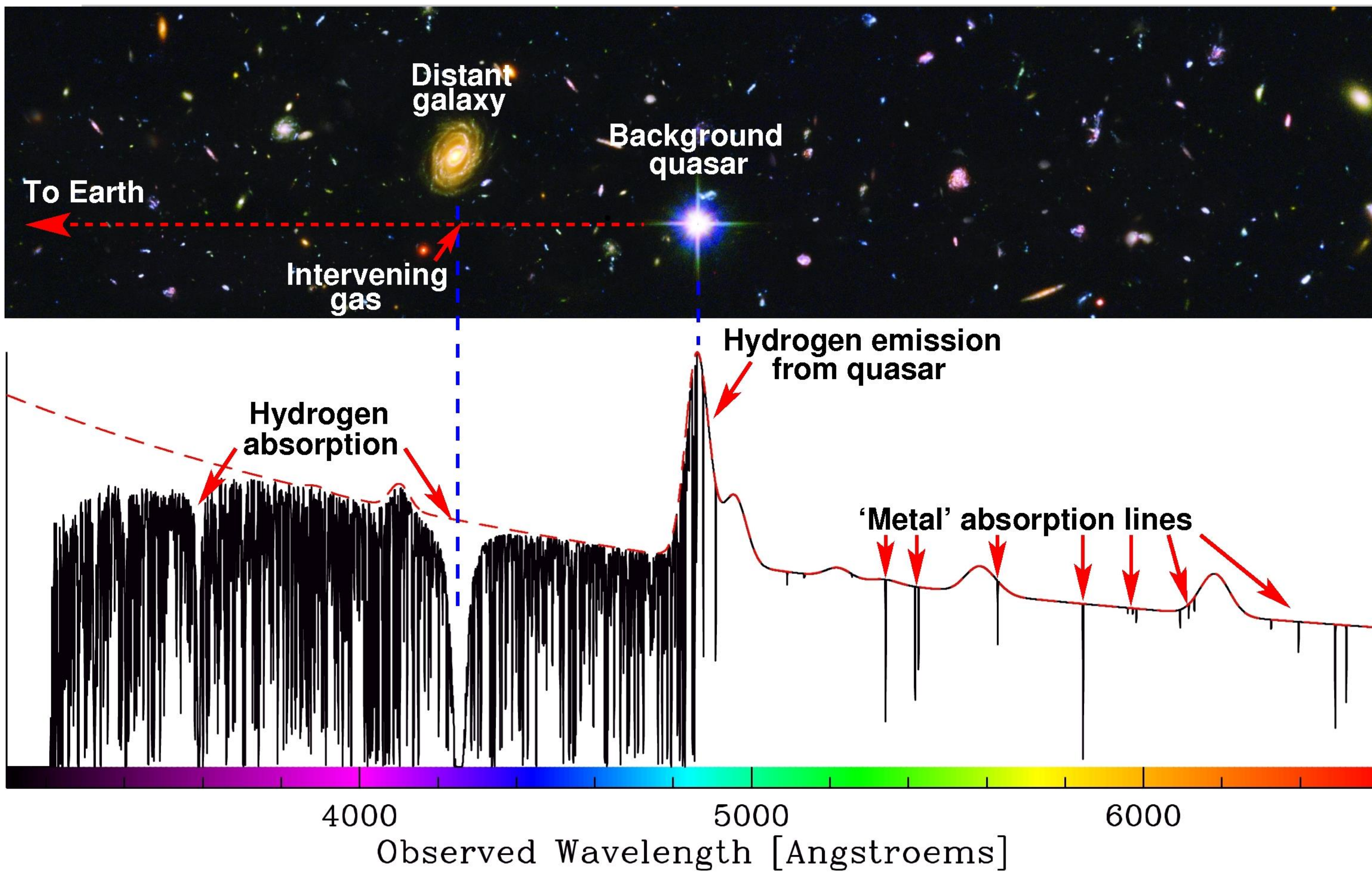


Light elements are produced in a chain of nuclear reactions.

The only unknown parameter is the baryon-to-photon ratio

Primordial light element abundances measure the baryon asymmetry!

Big Bang Nucleosynthesis

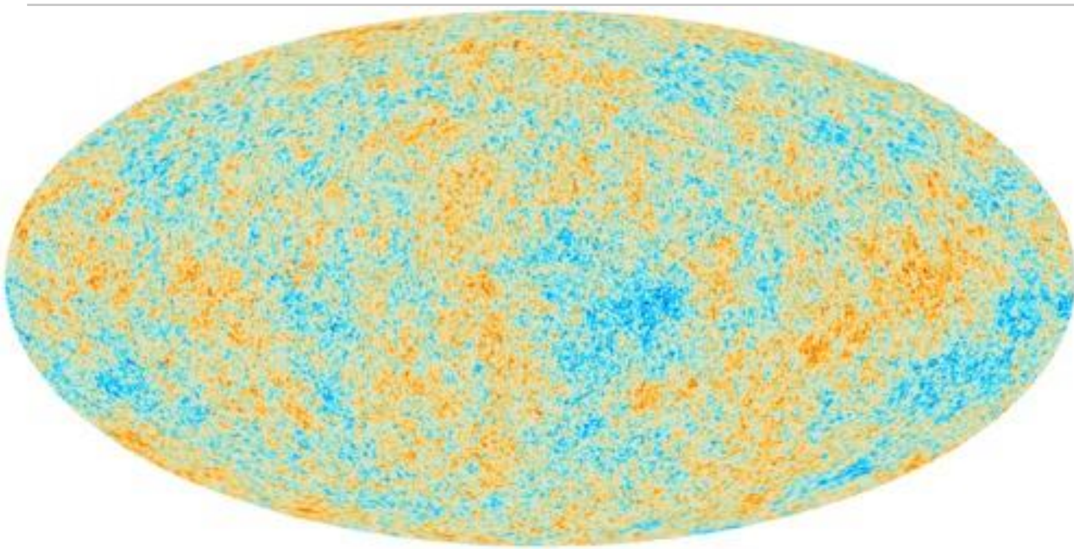


- light element abundances in intergalactic medium can be measured in quasar spectra
- Deuterium is sensitive to baryon asymmetry and not produced in stars

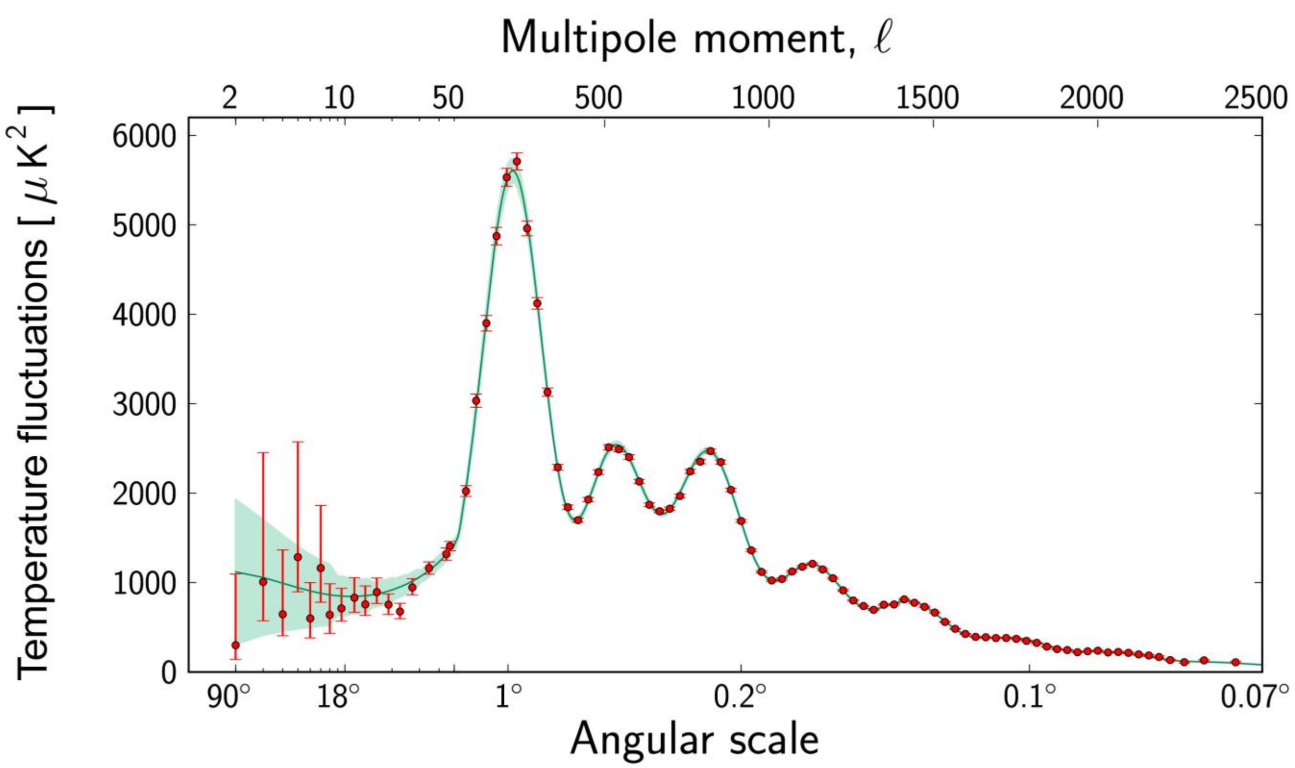
Constraint on baryon-to-photon ratio η:

$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$ PDG 2016

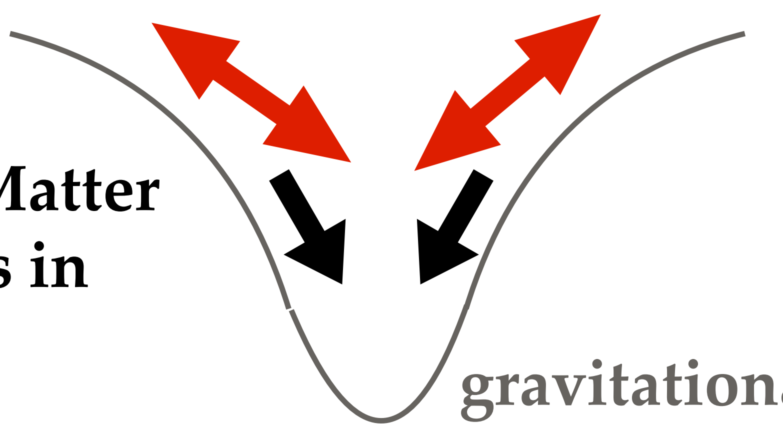
Baryon Acoustic Oscillations



Radiation, baryons and Dark Matter affect the acoustic oscillations in the primordial plasma in different ways…

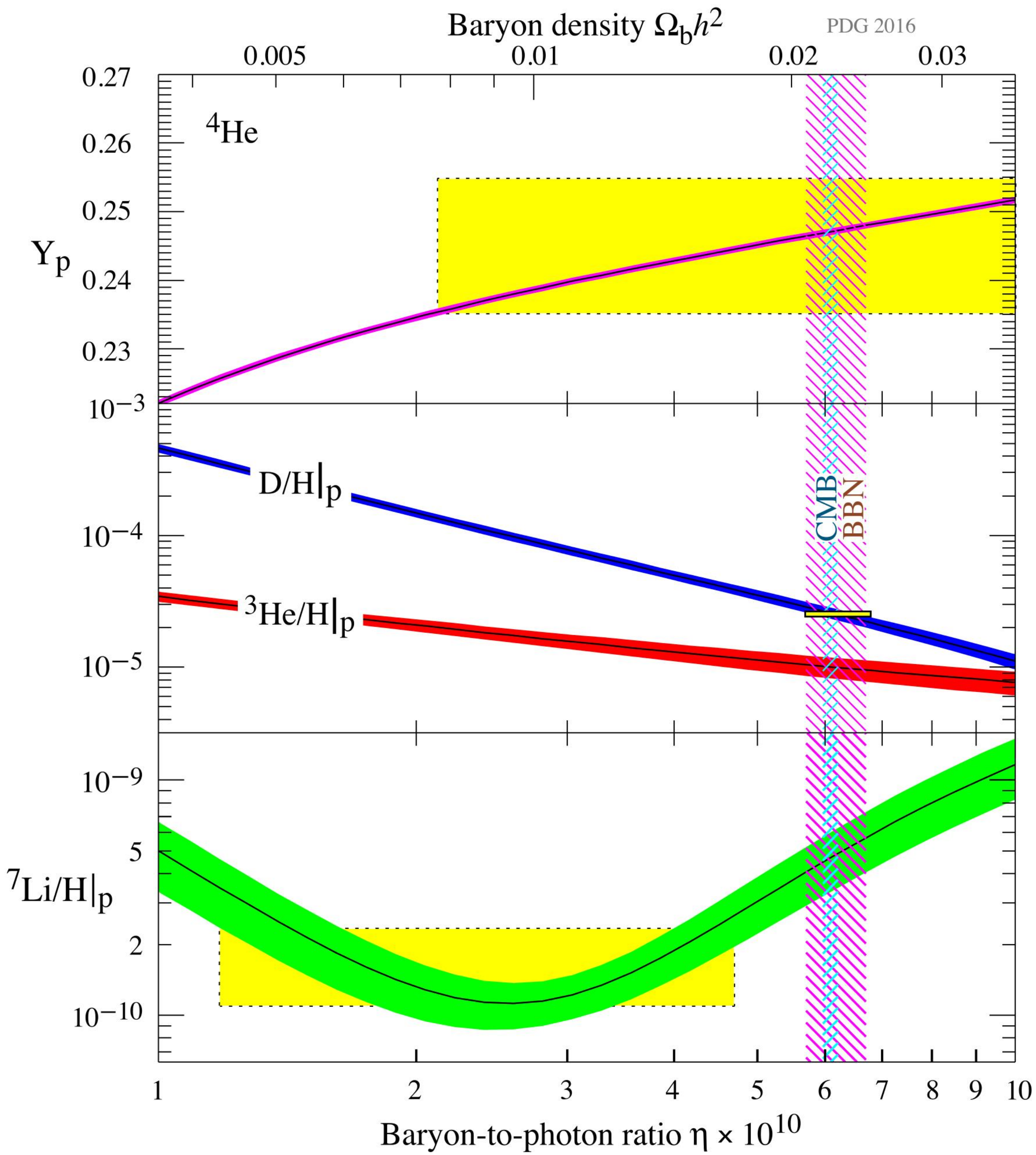


ordinary matter/radiation oscillates due to radiation pressure



neutrinos stream freely until they become non-relativistic

Cosmic Microwave Background



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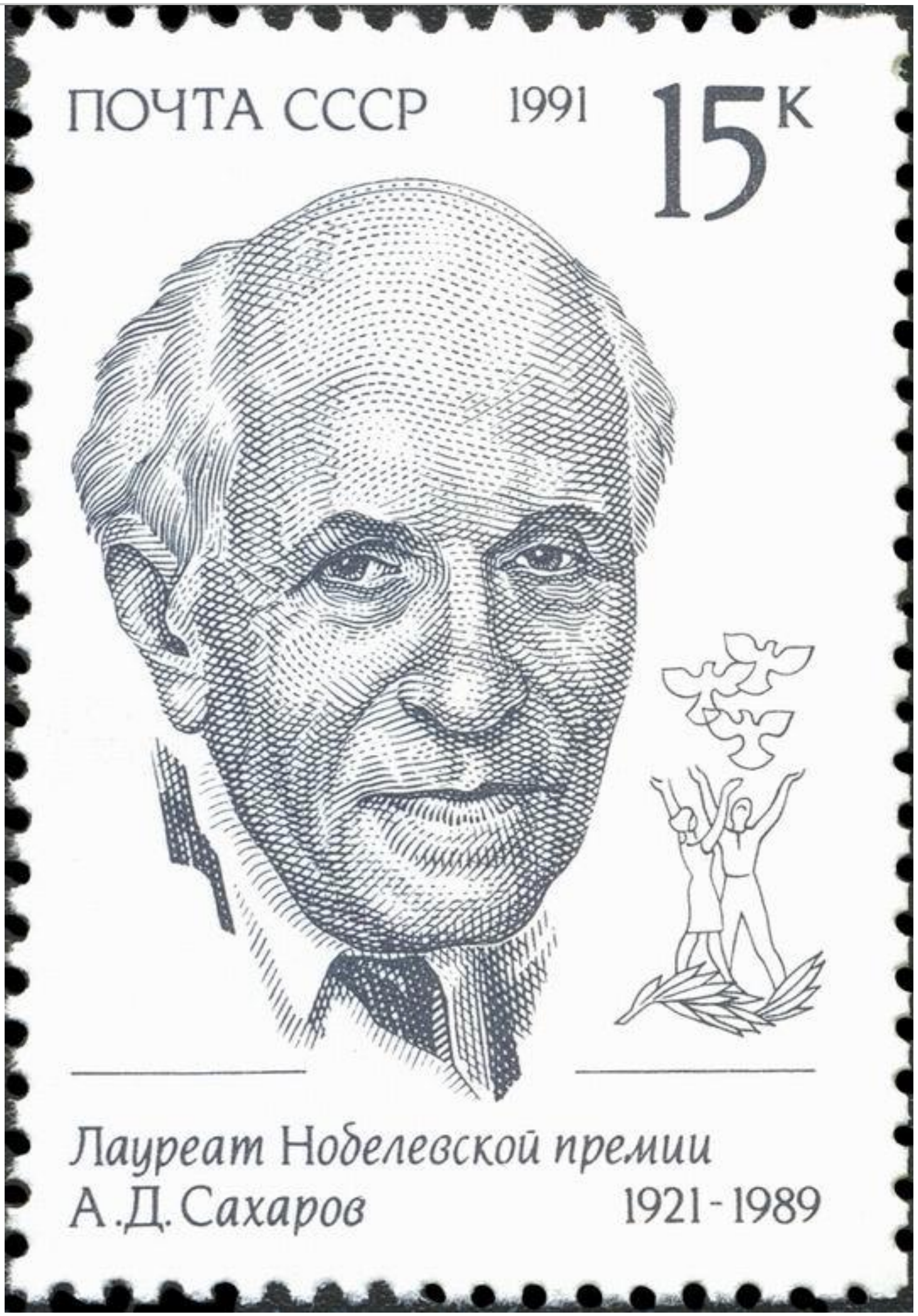
BBN constraint on baryon-to-photon ratio η:

$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

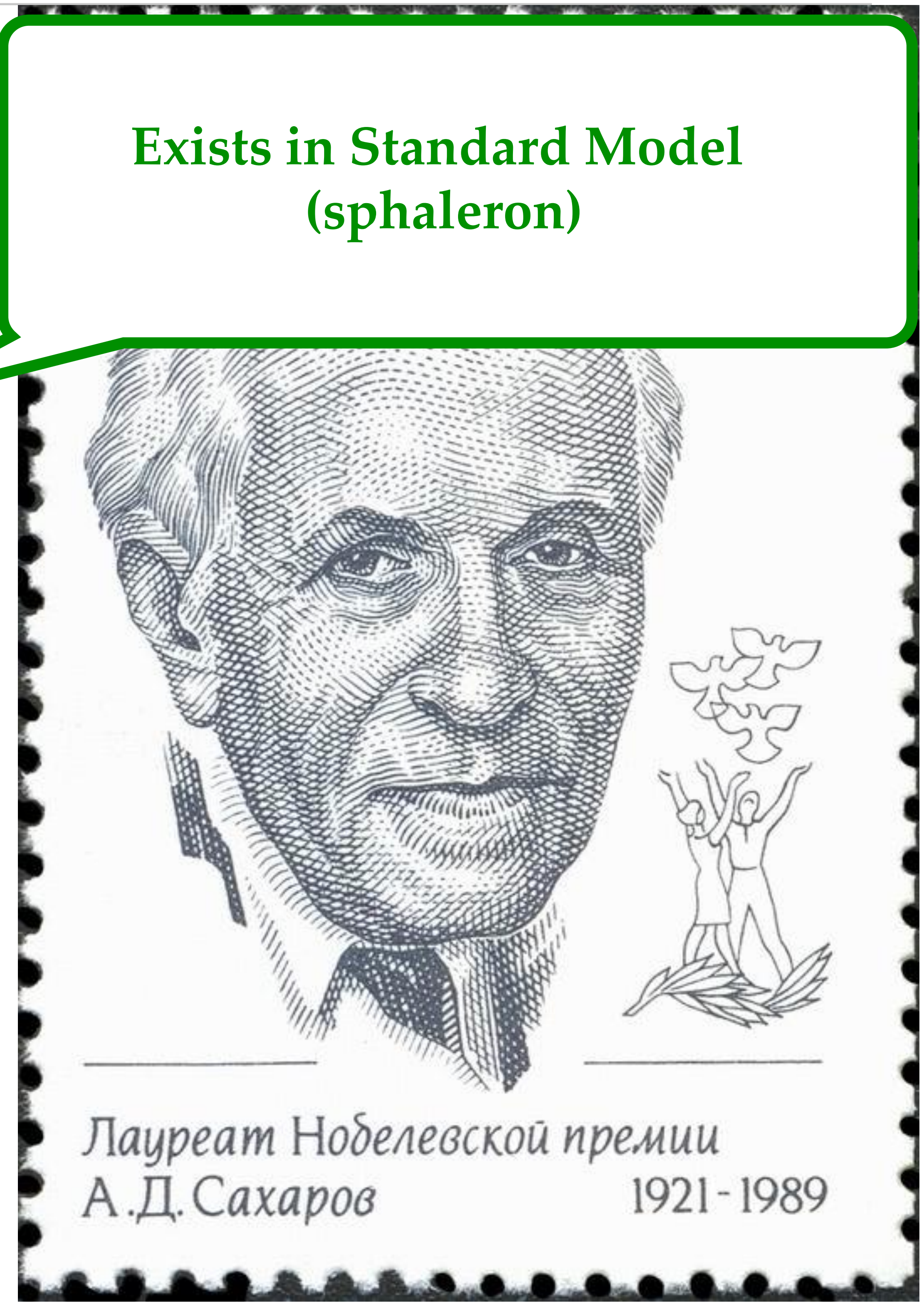


Where does the asymmetry come from?

Sakharov Conditions (1967)

Exists in Standard Model (sphaleron)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium



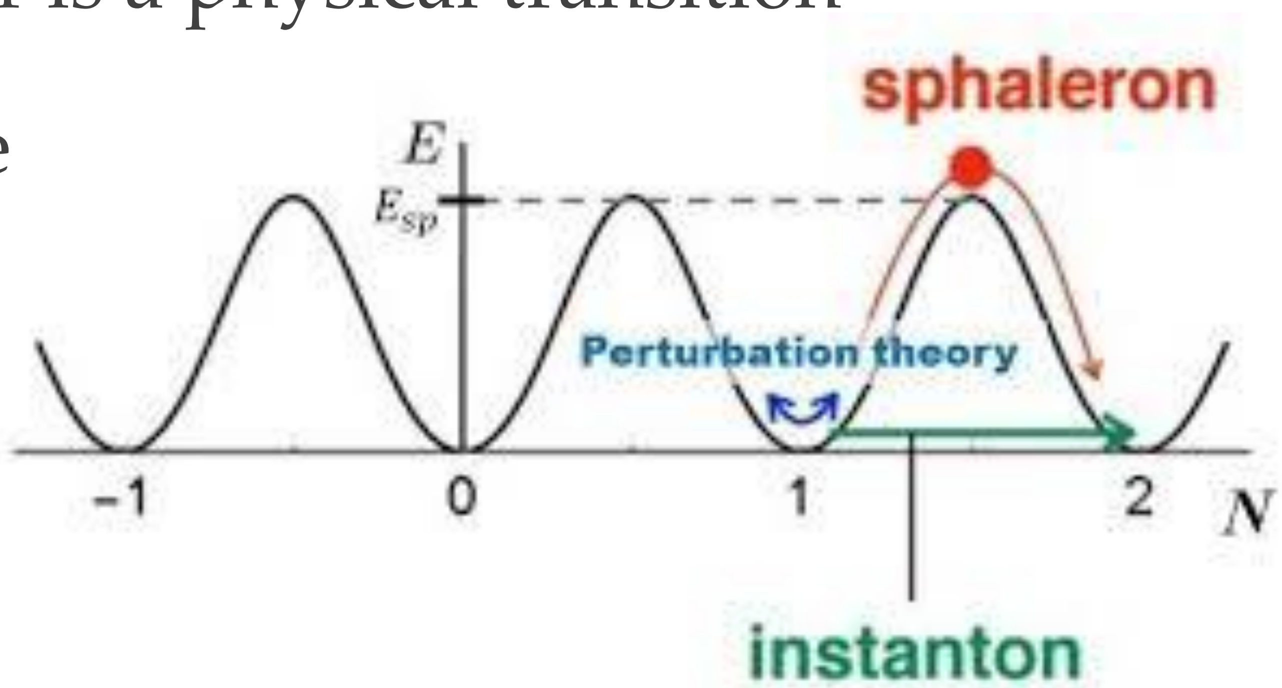
B-L Violation in the SM

- B and L are conserved in the SM at the perturbative level
- But B-L is violated by the quantum anomaly

$$\partial^\mu j^B_\mu = \frac{n_f}{32\pi^2}\left(- g^2 \mathrm{tr}(\mathrm{F}_{\mu\nu}\tilde{\mathrm{F}}^{\mu\nu}) + g'^2 \mathrm{F}'_{\mu\nu}\tilde{\mathrm{F}}'^{\mu\nu}\right)$$

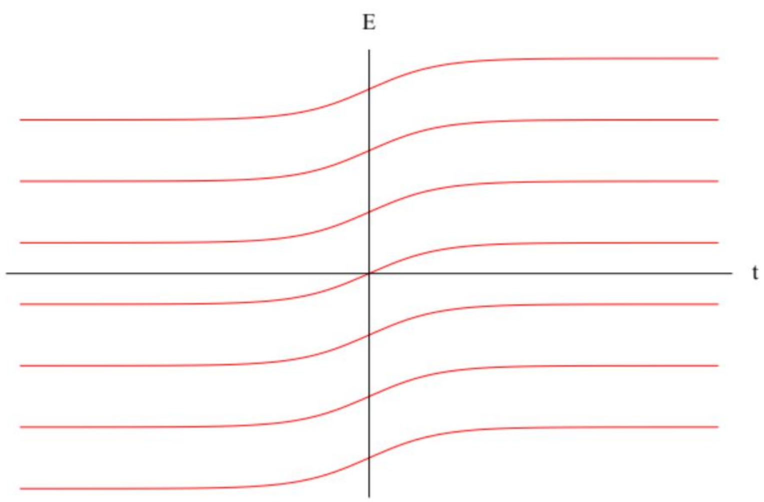
- EW theory has infinitely many degenerate vacua that are related by gauge transitions
- It is impossible to distinguish in what vacuum one is, but going from one to another is a physical transition

- At vanishing temperature the transition can only happen via tunnelling
- At T > 0 thermal fluctuations can induce a transition

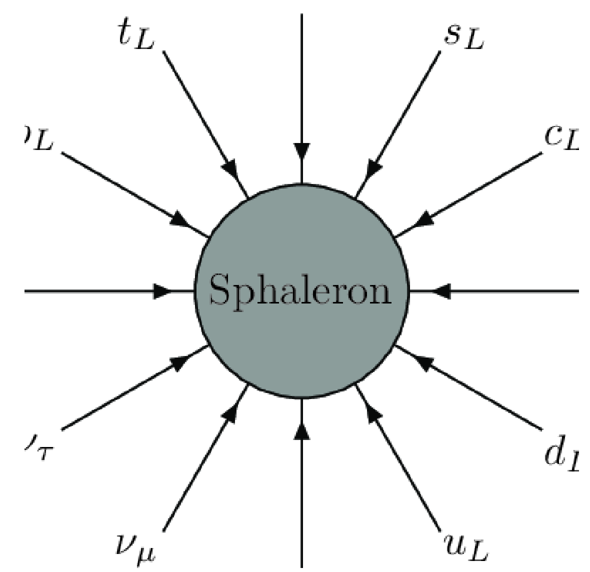


Sphaleron

- Doing the transition corresponds to a change in the background gauge field configuration that is felt by the fermions



- Intuitively this lifts up the levels in the Dirac sea, leading to a production of particles…



- The rate is given by:

$$\Gamma_{\rm sph} = (25.4 \pm 2.0)\alpha_W^5 T^4 \quad (\text{ symmetric phase })$$

$$\Gamma_{\rm sph} = A\,(\alpha_W T)^4 \left(\frac{M_{\rm sph}}{T}\right)^7 \exp\left(-\frac{M_{\rm sph}}{T}\right) \quad (\text{ Higgs phase})$$

- This equals the Hubble rate at roughly $T = 131\ GeV$

Where does the asymmetry come from?

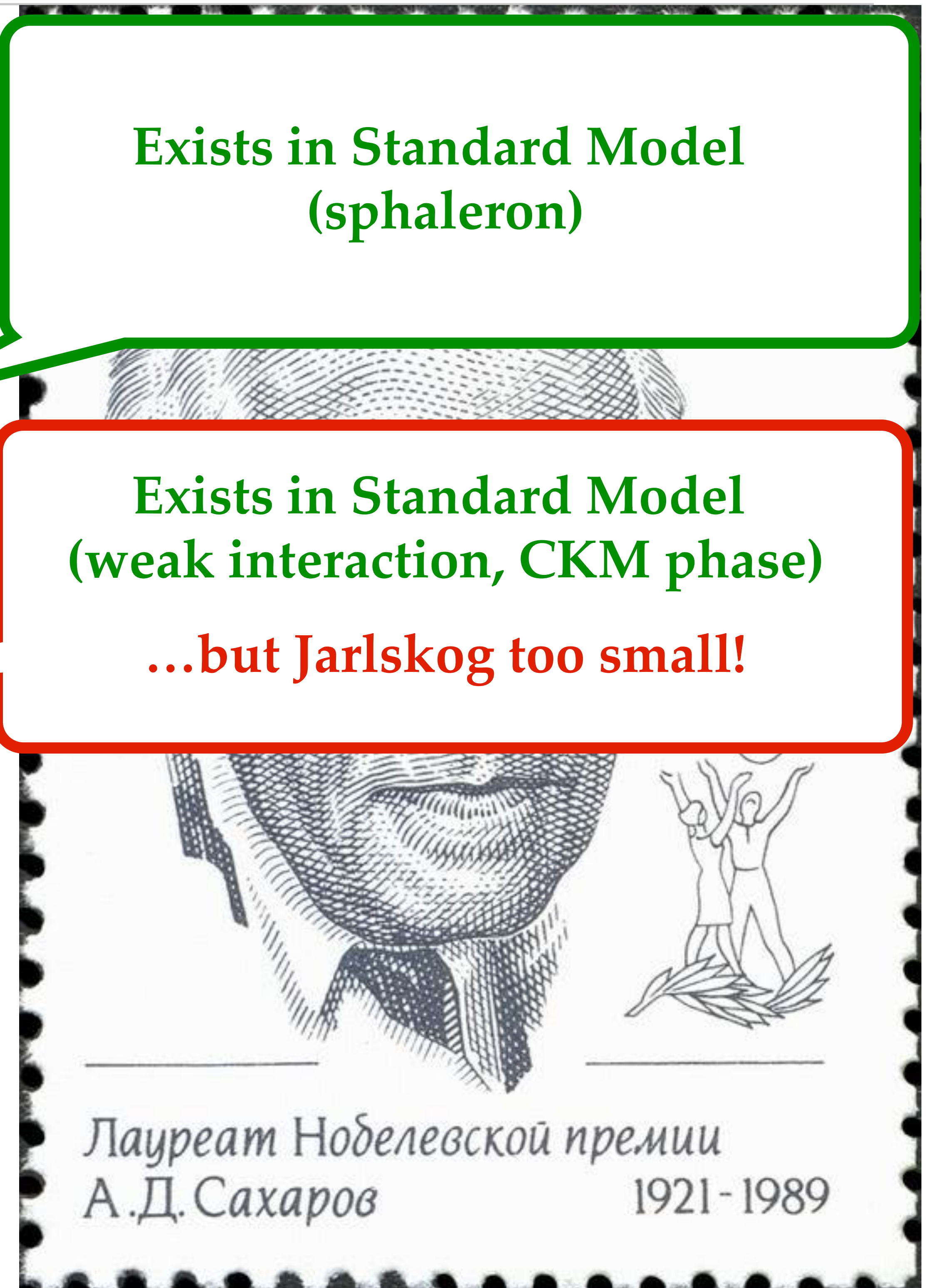
Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

Exists in Standard Model (sphaleron)

Exists in Standard Model (weak interaction, CKM phase)

…but Jarlskog too small!



CKM Matrix

- *CKM m*atrix mixes quark mass- and interaction eigenstates

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

$$U_\nu = V^{(23)} U_\delta V^{(13)} U_{-\delta} V^{(12)} \qquad U_{\pm\delta} = \mathrm{diag}(e^{\mp i\delta/2}, 1, e^{\pm i\delta/2})$$

$$V^{(23)} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad V^{(13)} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \quad V^{(12)} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- But relevant CP violation an the early universe is given by Jarlkogg determinant in units of the temperature *T*

$$\begin{aligned} D &= \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\delta_{KM} \\ &\quad (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2). \end{aligned}$$

- Since *T ~ 131 GeV* greatly exceeds the quark masses, this is small!

Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

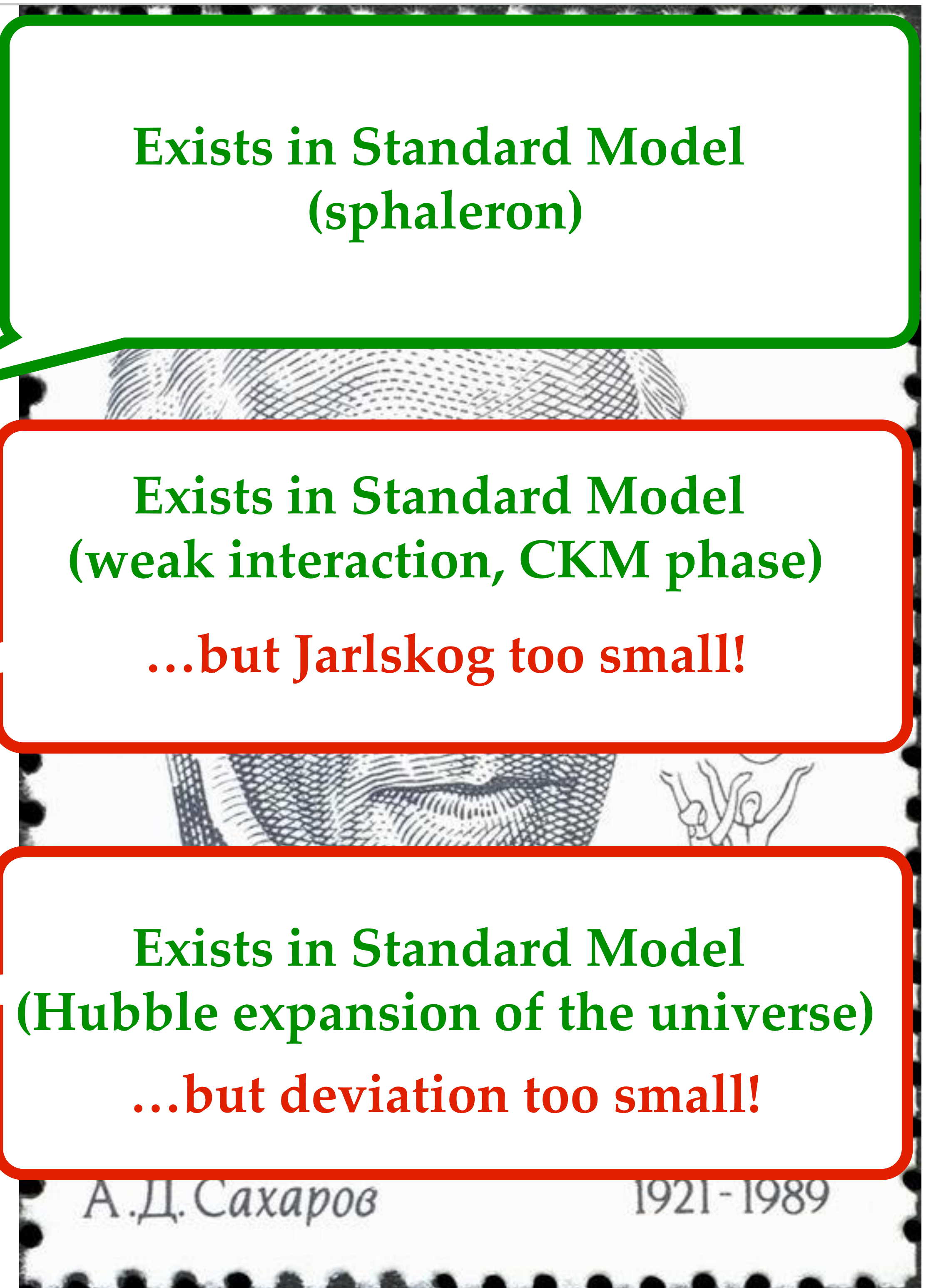
Exists in Standard Model (sphaleron)

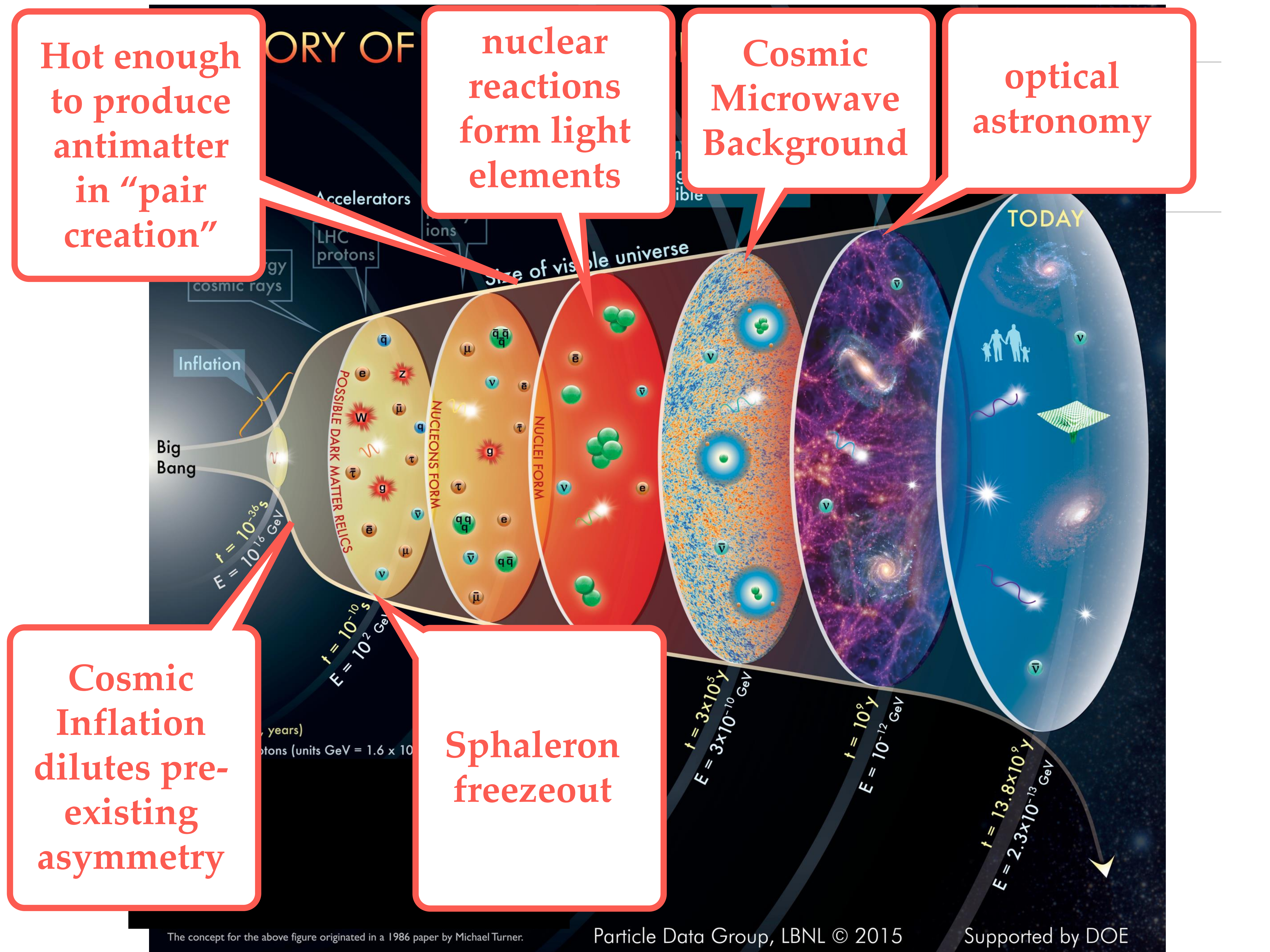
Exists in Standard Model (weak interaction, CKM phase)

...but Jarlskog too small!

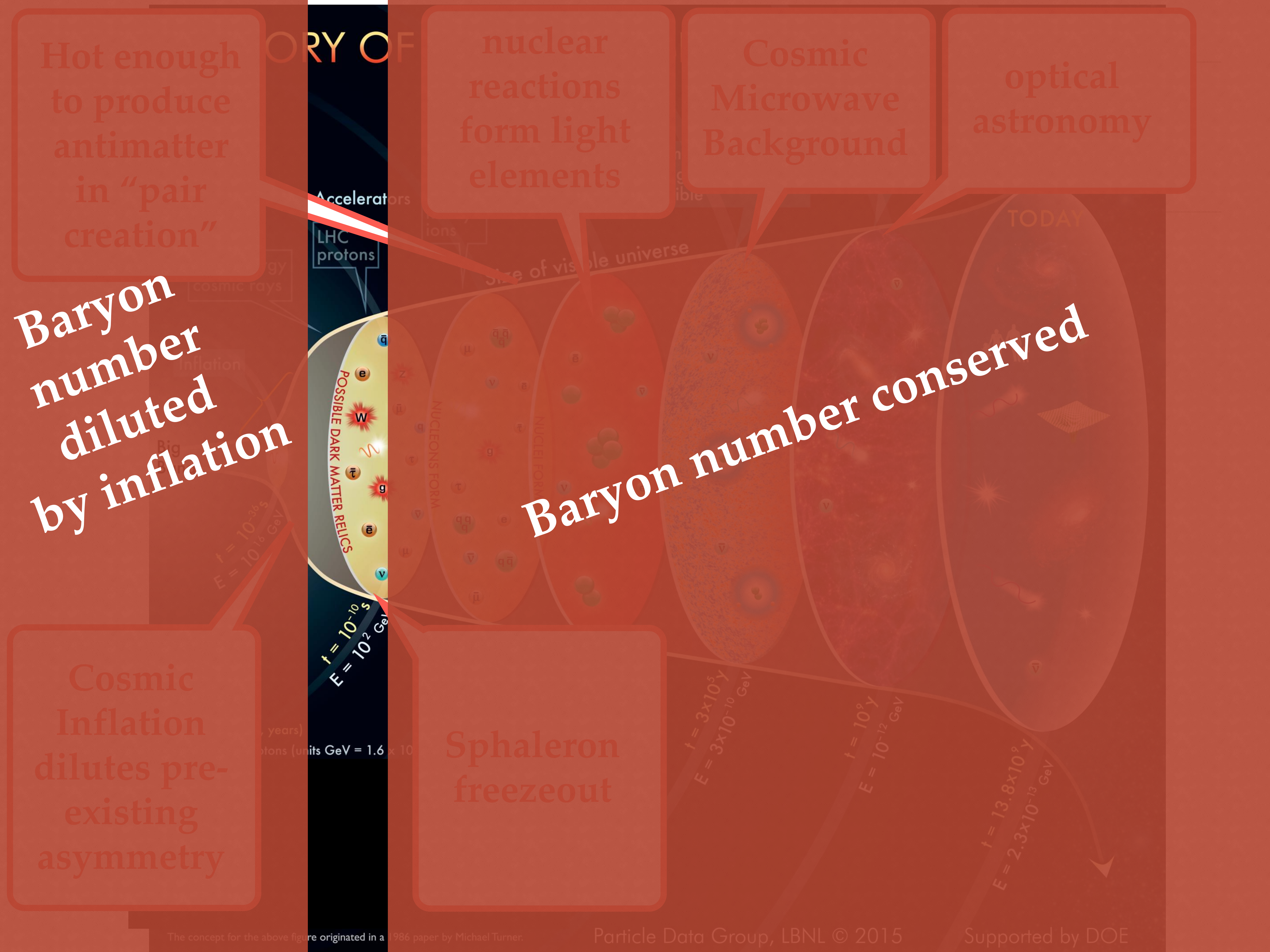
Exists in Standard Model (Hubble expansion of the universe)

...but deviation too small!





Hot enough to produce antimatter in "pair creation"
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Cosmic Inflation dilutes pre-existing asymmetry
Sphaleron freezeout
ORY OF
Accelerators
LHC protons
ions
cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
years)
otons (units GeV = 1.6 x 10
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



Hot enough to produce antimatter in "pair creation"
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Baryon number diluted by inflation
Baryon number conserved
Cosmic Inflation dilutes pre-existing asymmetry
Sphaleron freezeout
Accelerators
LHC protons
POSSIBLE DARK MATTER RELICS
Size of visible universe
TODAY
t = 10^-10 s
E = 10^2 GeV
Particle Data Group, LBNL © 2015
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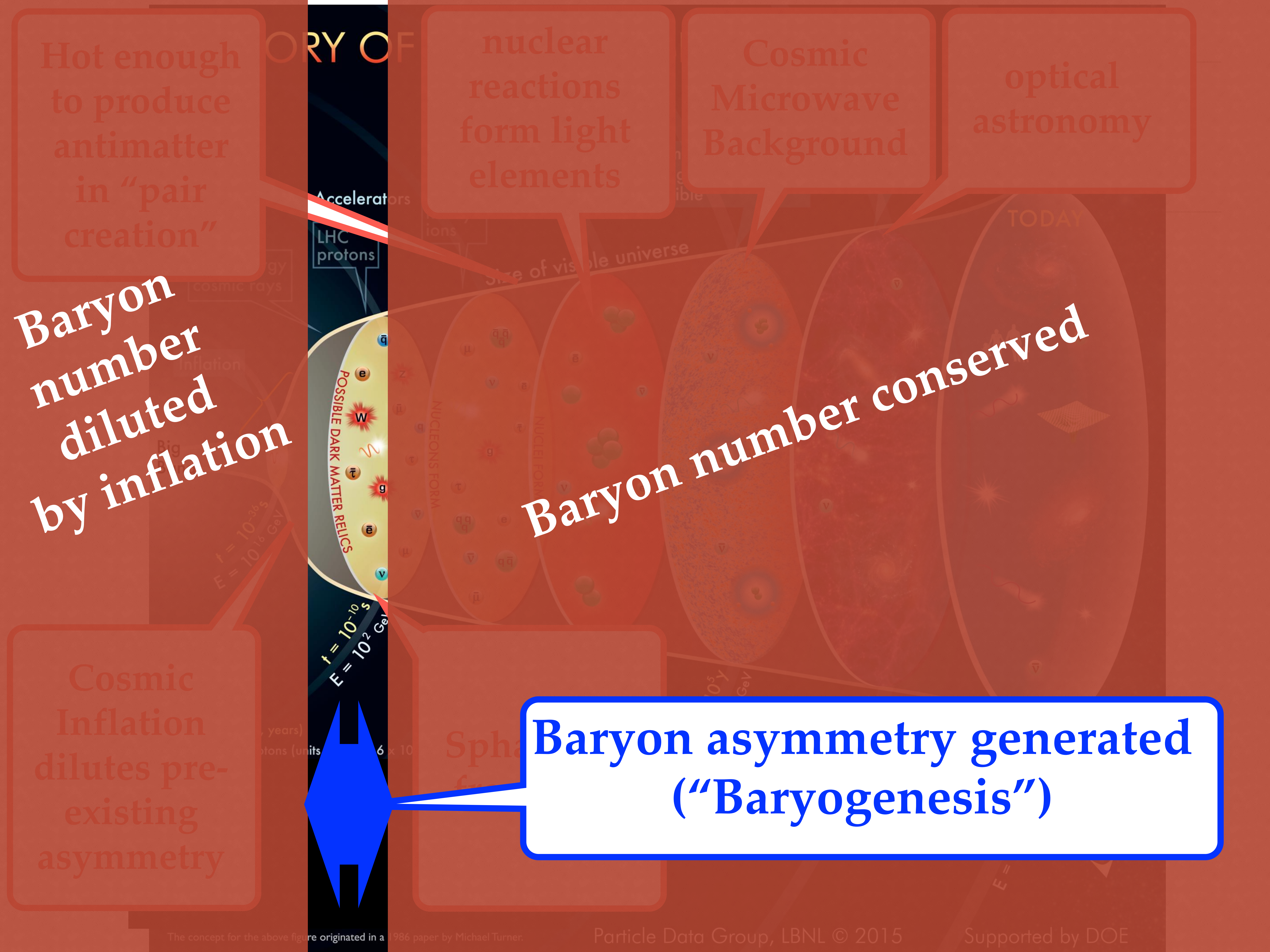
The concept for the above figure originated in a 1986 paper by Michael Turner.


Hot enough to produce antimatter in "pair creation"
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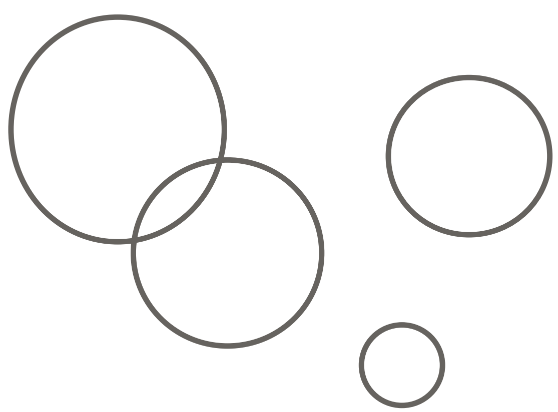
LHC protons
TODAY
Size of visible universe
Baryon number diluted by inflation
Baryon number conserved
POSSIBLE DARK MATTER RELICS
Cosmic Inflation dilutes pre-existing asymmetry
Baryon asymmetry generated ("Baryogenesis")
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Where does the asymmetry come from?

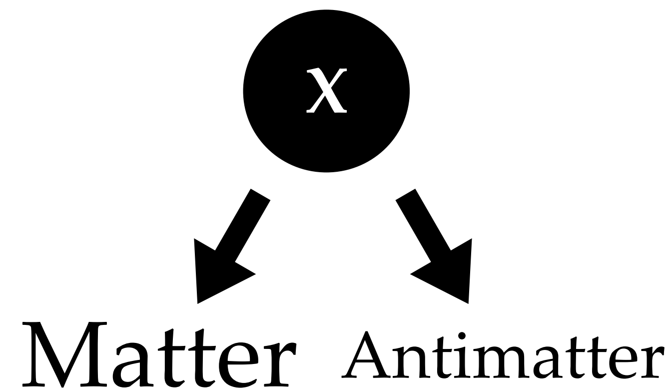
Baryogenesis requires New Physics!

Cosmic phase transition?



Electroweak baryogengesis,
…

Decay of a heavy particle?



GUT baryogengesis,
leptogenesis,
…

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

- C and CP violation

- Deviation from thermal equilibrium

Leptogenesis

General idea:
The matter-antimatter asymmetry was created amongst leptons and then transferred to baryons in the early universe.

Original framework: Fukugita/Yanagida 86
Right handed neutrinos (type I seesaw)

Keep in mind:
Many other neutrino mass models exist. And many of them can accommodate leptogenesis!

Thermal Leptogenesis

Basic idea

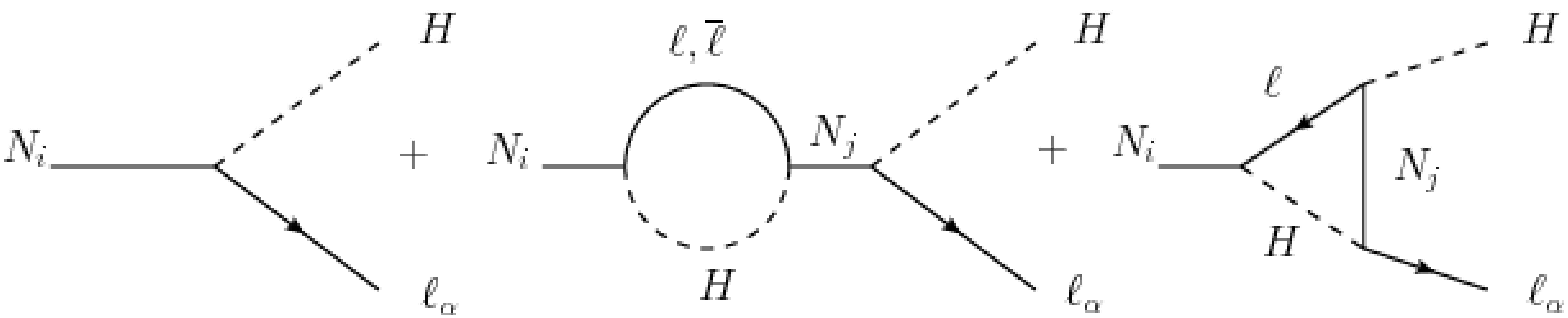
- *N* are around in the early universe
- Yukawas *F* are CP violating
- *N* may preferably decay into matter

CP violating parameter ϵ

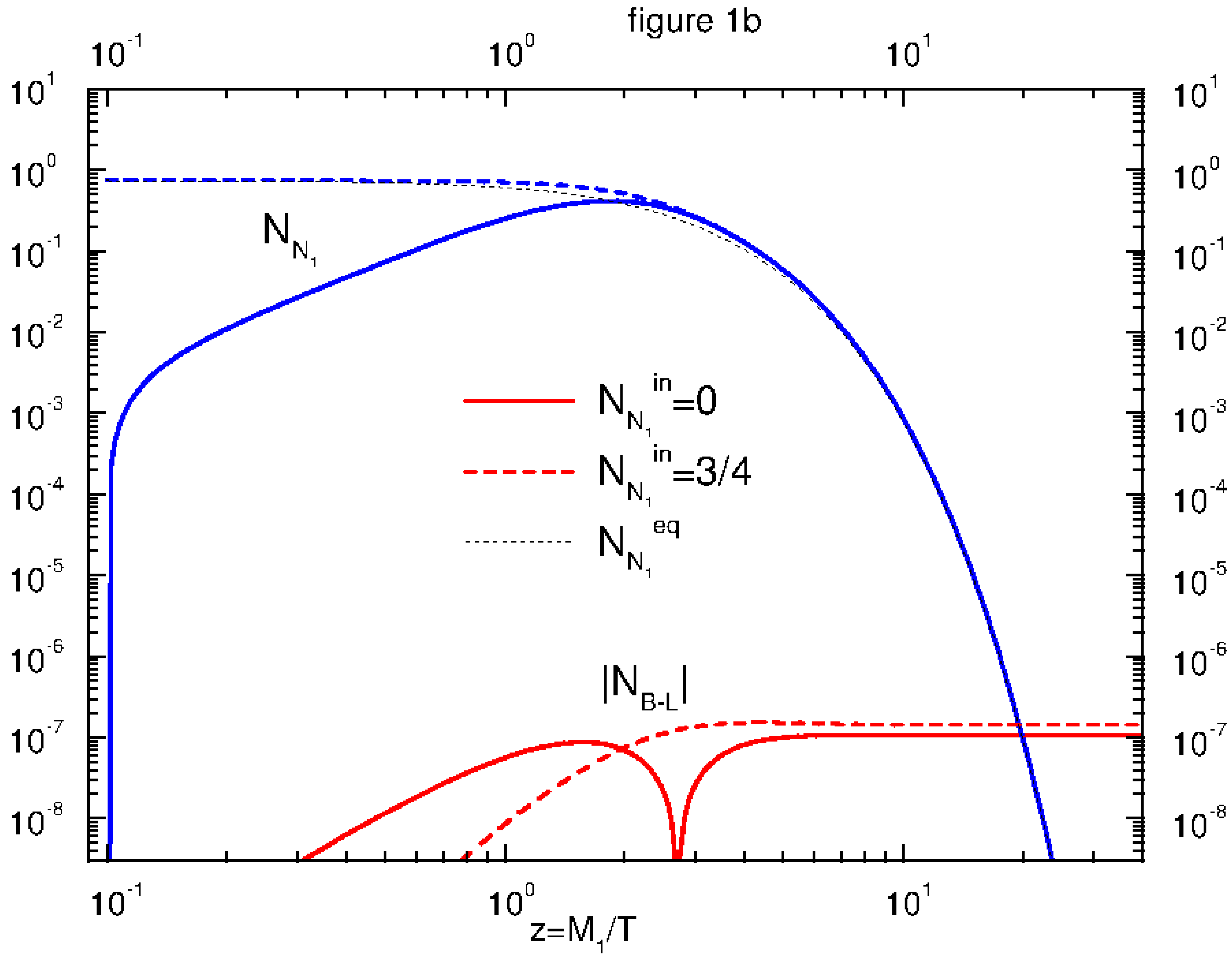
$$\epsilon = \frac{\Gamma_{N\to\ell H} - \Gamma_{N\to\bar{\ell}H^*}}{\Gamma_{N\to\ell H} + \Gamma_{N\to\bar{\ell}H^*}}$$

final asymmetry

$$Y_{B-L} \;\propto\; \epsilon/g_*$$



Boltzmann Equation



$$\epsilon = \frac{\Gamma_{N\to\ell H} - \Gamma_{N\to\bar{\ell}H^*}}{\Gamma_{N\to\ell H} + \Gamma_{N\to\bar{\ell}H^*}}$$

Evolution of heavy neutrinos and asymmetries is described by Boltzmann equations

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"

"Vanilla Leptogenesis"

Temperature $T > 10^{12}$ GeV

- gauge interactions in equilibrium
- charged lepton Yukawa interactions slower than cosmic expansion

SM flavours indistinguishable!

CP violating parameter ϵ

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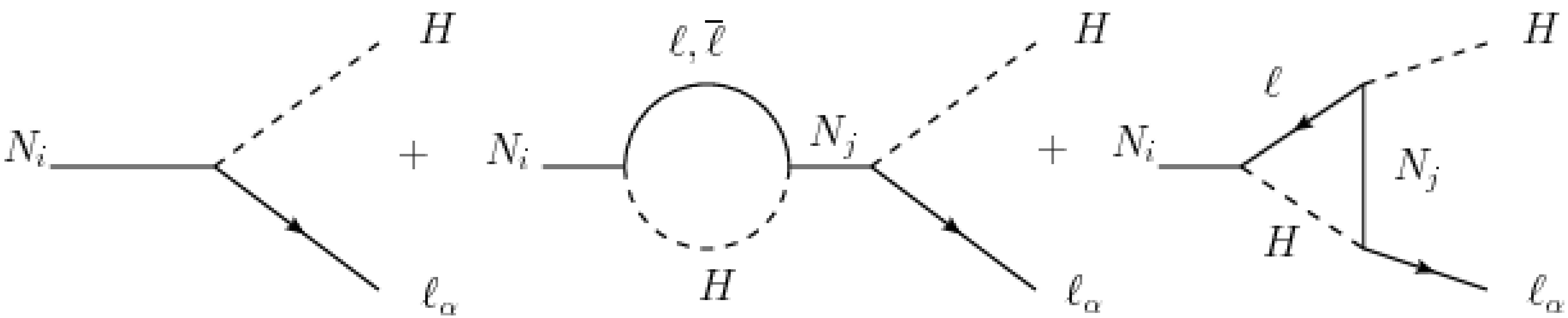

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final asymmetry

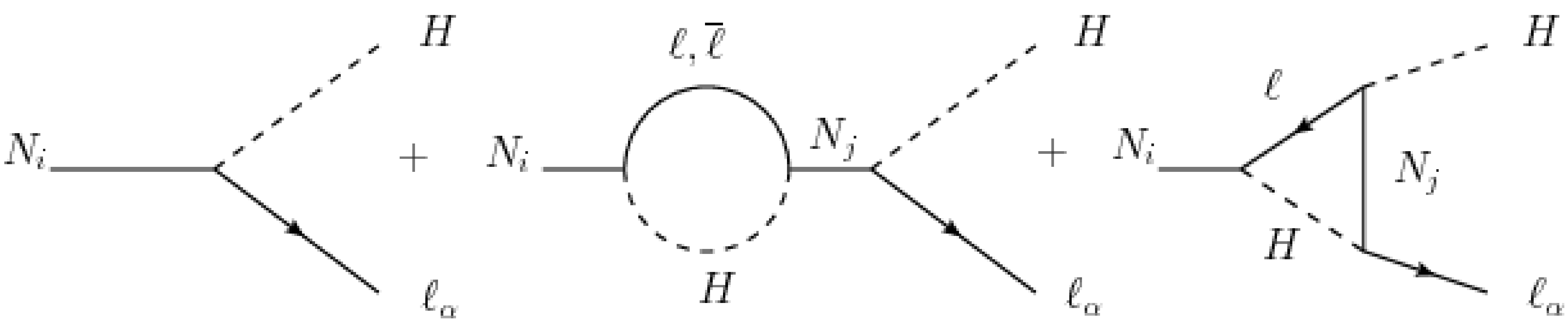
$$Y_{B-L} \propto \epsilon/g_*$$

Casas-Ibarra parameters for Yukawa coupling

$$F = \frac{1}{v}U_\nu\sqrt{m_\nu^{\rm diag}}\mathcal{R}\sqrt{M^{\rm diag}}$$

heavy neutrino parameters

light neutrino parameters



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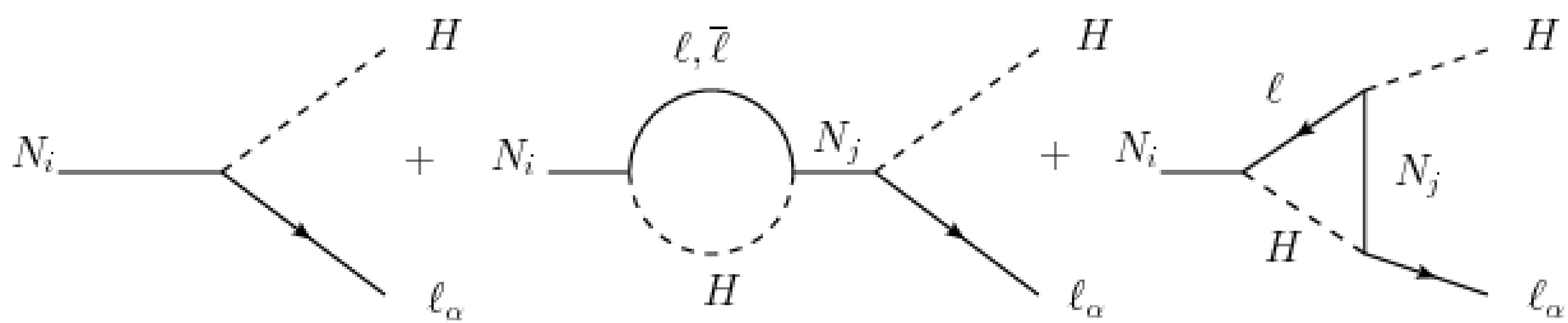
final asymmetry

$$Y_{B-L} \propto \epsilon/g_*$$

Asymmetry only depends on the combination $F^\dagger F$

$$\epsilon \simeq -\frac{3}{16\pi}\frac{1}{(F^\dagger F)_{11}}\sum_I \mathrm{Im}\left[(F^\dagger F)_{I1}\right]^2 \frac{M_1}{M_I}$$



"Vanilla Leptogenesis"

Temperature $T > 10^{12}$ GeV

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SM flavours indistinguishable!

CP violating parameter ϵ

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Asymmetry only depends on the combination $F^\dagger F$

$$\epsilon \simeq -\frac{3}{16\pi}\frac{1}{(F^\dagger F)_{11}}\sum_I \mathrm{Im}\left[(F^\dagger F)_{I1}\right]^2 \frac{M_1}{M_I}$$

But $$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

gives $$F^\dagger F = \sqrt{M^{\mathrm{diag}}} \mathcal{R}^\dagger \frac{m_\nu^{\mathrm{diag}}}{v^2} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

ϵ is independent of the PMNS matrix!
So is the asymmetry…

"Flavoured Leptogenesis"

10^{12} GeV > T > 1 TeV

- **gauge interactions in equilibrium**
- **charged lepton Yukawa interactions faster than cosmic expansion**

SM flavours distinguishable!

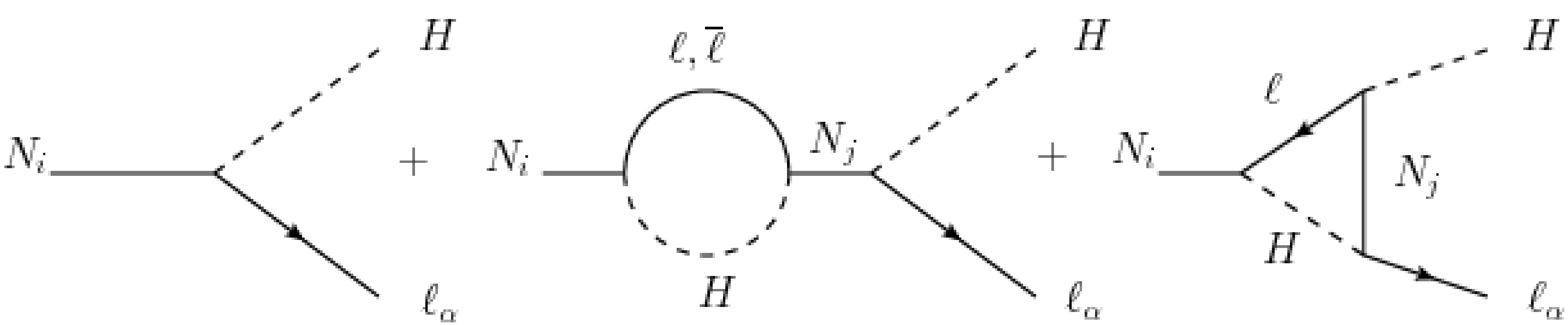
CP violating parameters $\epsilon_{\alpha\beta}$

Lepton number matrix $(Y_{B-L})_{\alpha\beta}$

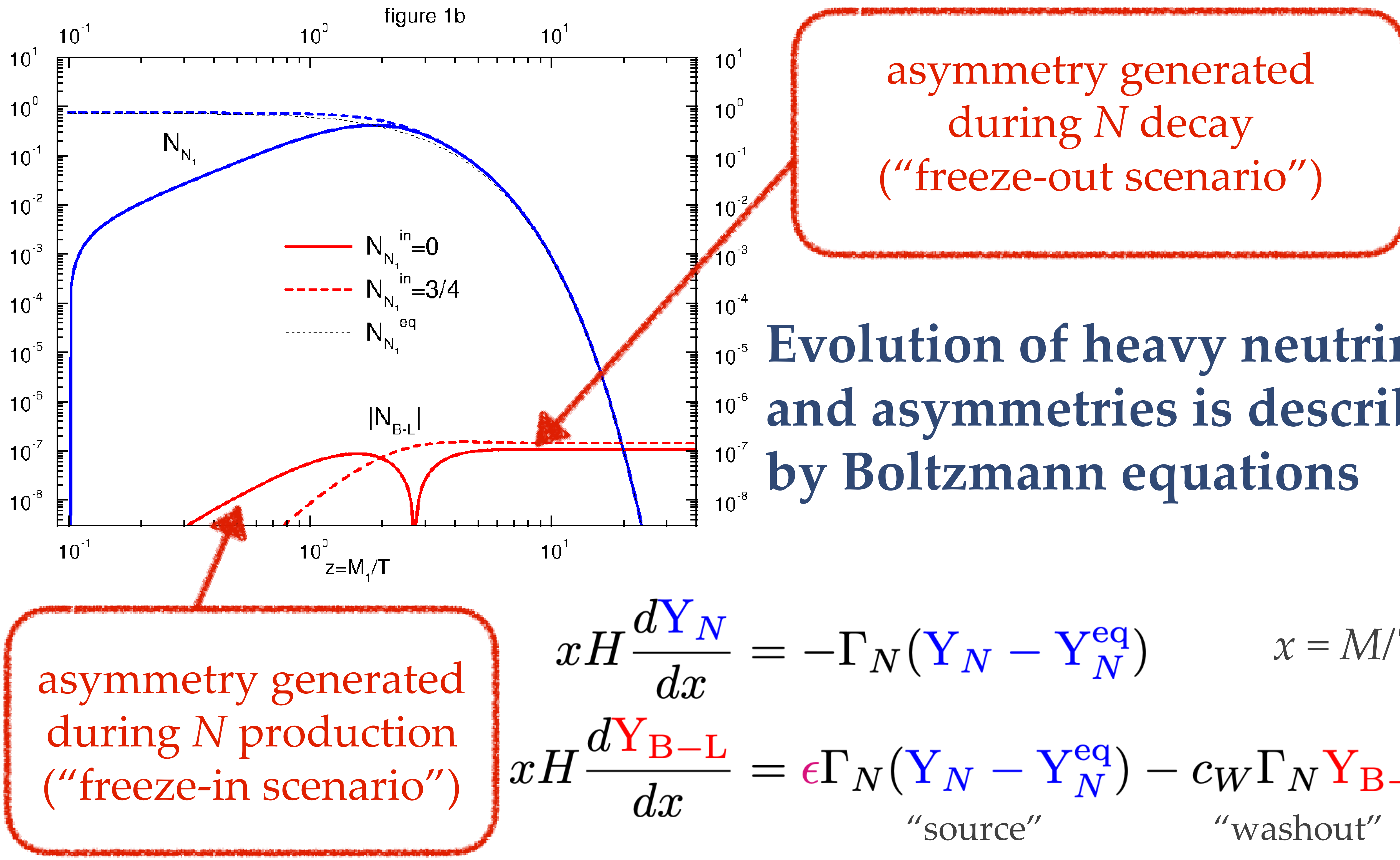
$(Y_{B-L})_{\alpha\alpha}$ is charge in flavour α

Flavoured asymmetries depend on individual $F_{\alpha I}$ $\Rightarrow$ **Baryon asymmetry depends on δ!**

…δ alone is even sufficient



Leptogenesis with small M ?



Evolution of heavy neutrinos and asymmetries is described by Boltzmann equations

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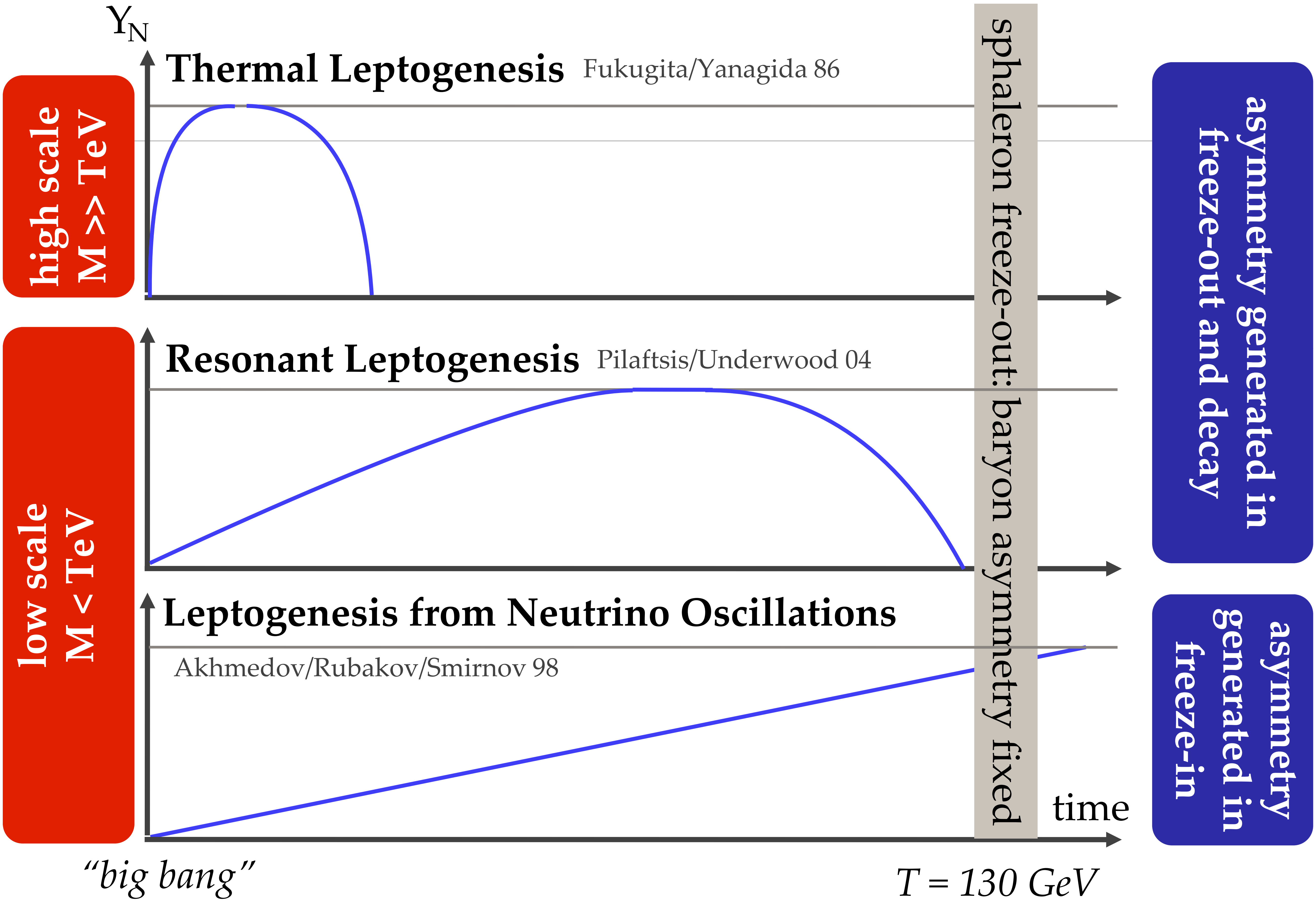
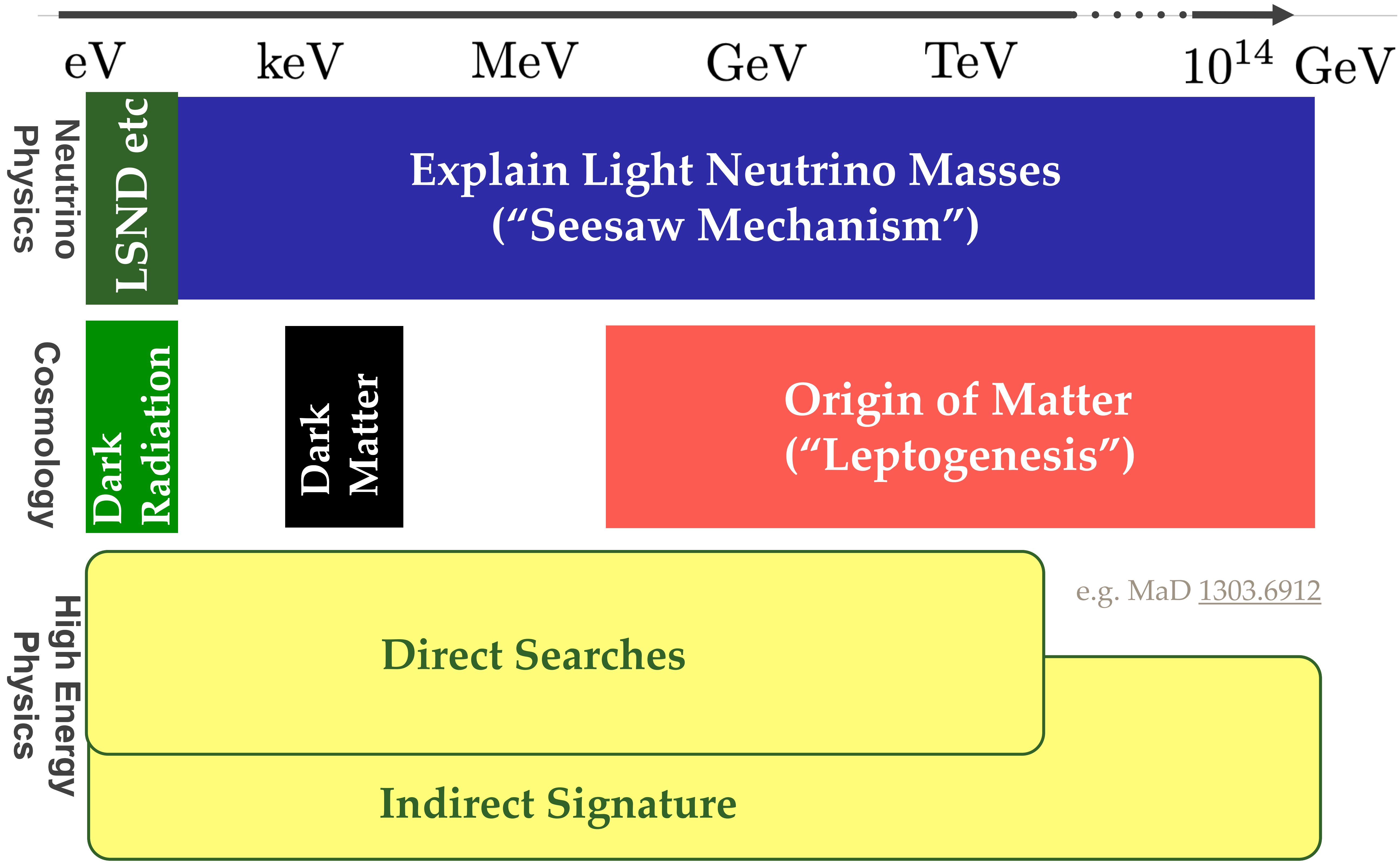
$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"

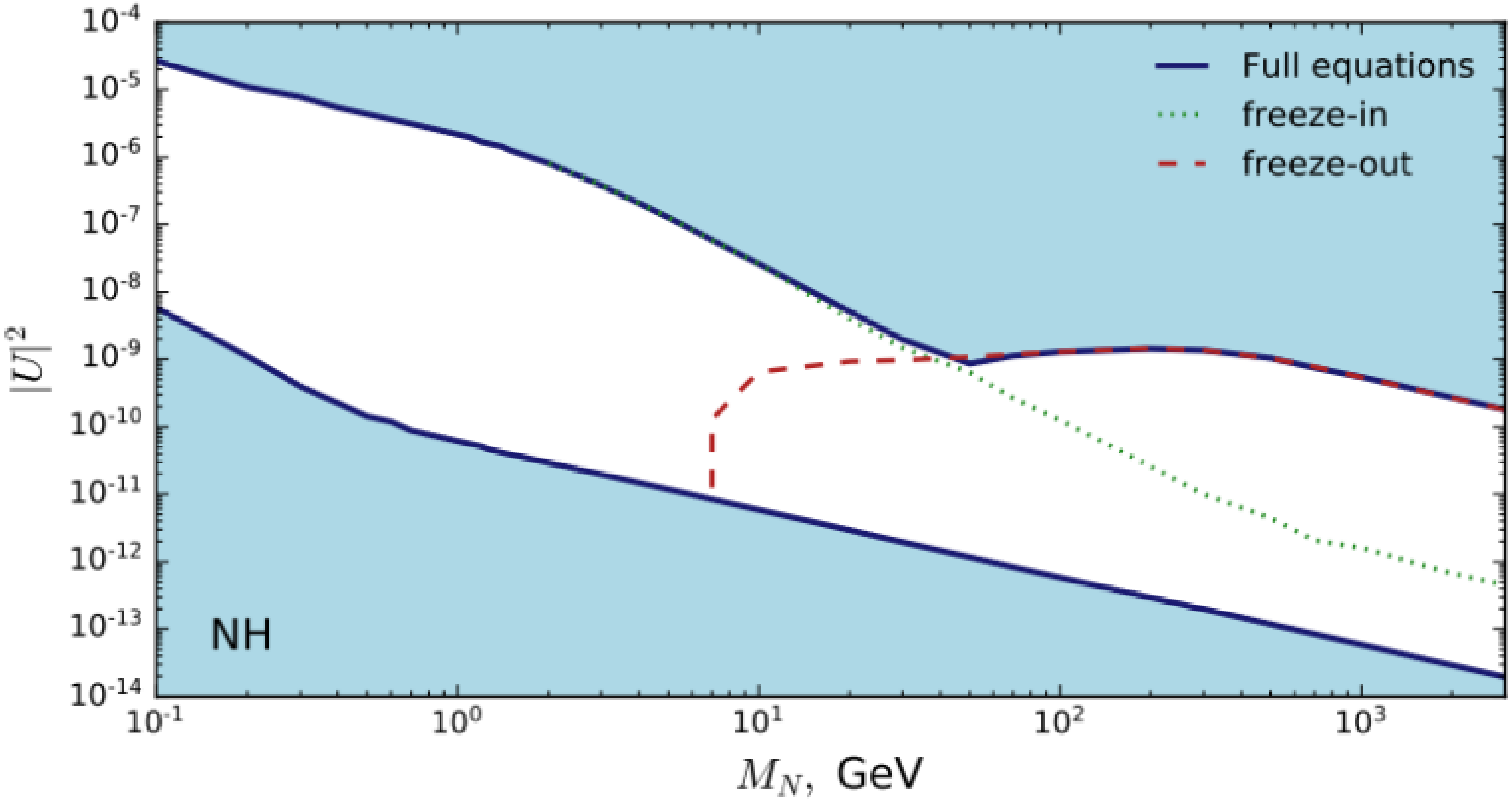


Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
high scale
M >> TeV
Resonant Leptogenesis
Pilaftsis/Underwood 04
low scale
M < TeV
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated in freeze-in
time
"big bang"
T = 130 GeV

Heavy Neutrino Mass Scale



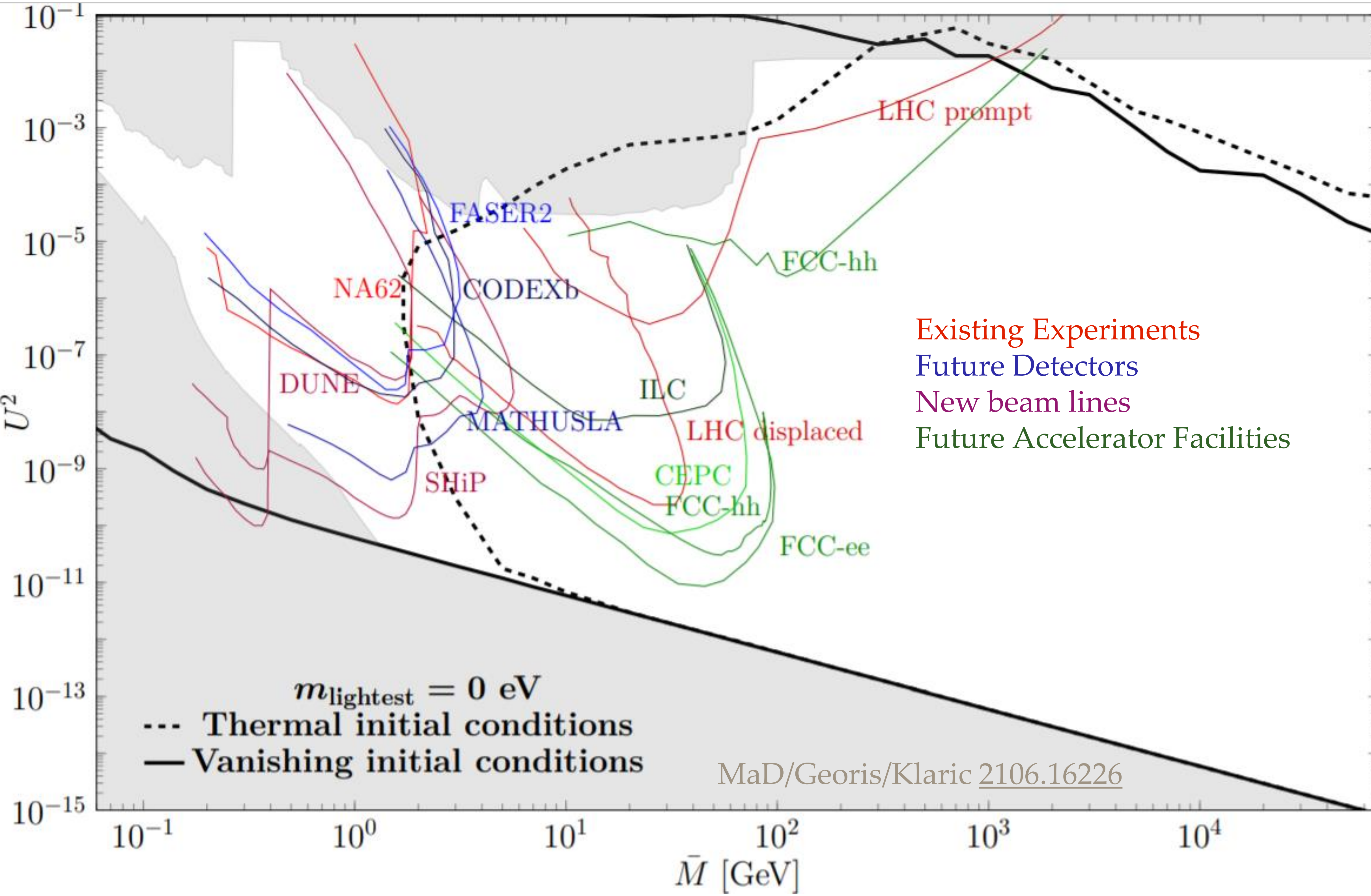
Leptogenesis with 2 RH Neutrinos



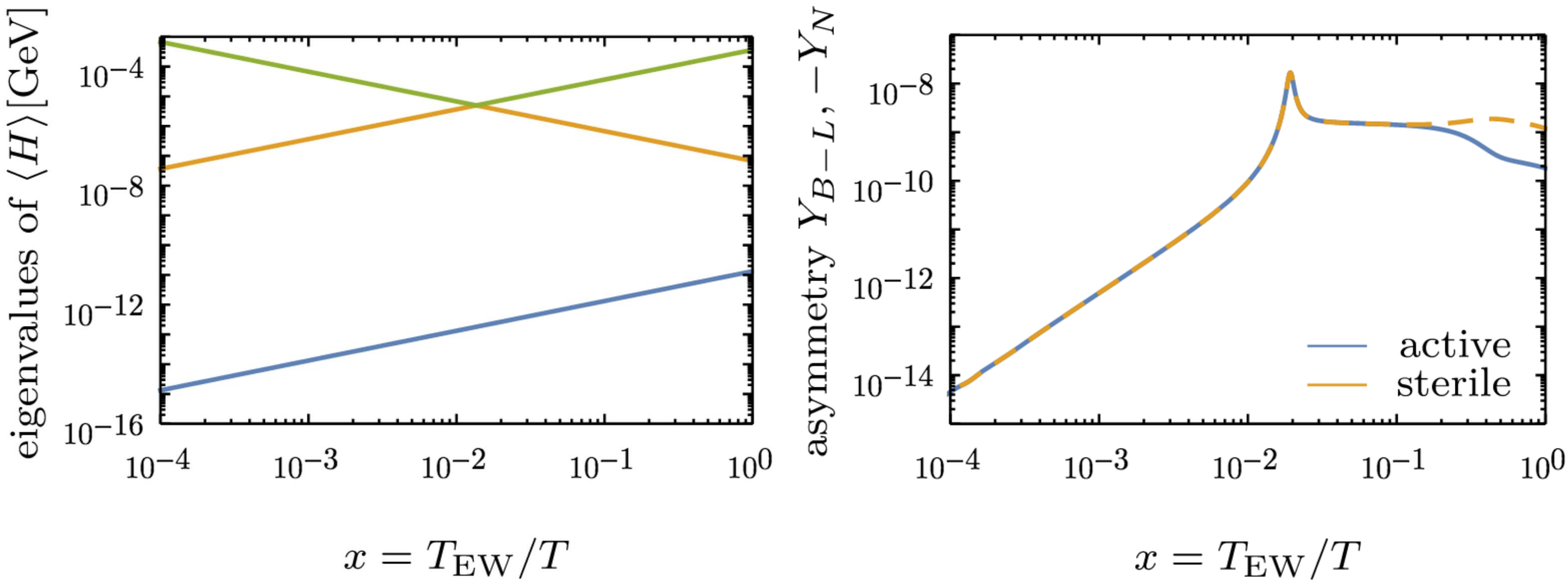
The region in which the freeze-out scenario ("resonant leptogenesis") and freeze-in scenario ("ARS leptogenesis") work overlap!

Klaric/Shaposhnikov/Timirsyasov [2008.13771]

Leptogenesis with 3 RH Neutrinos



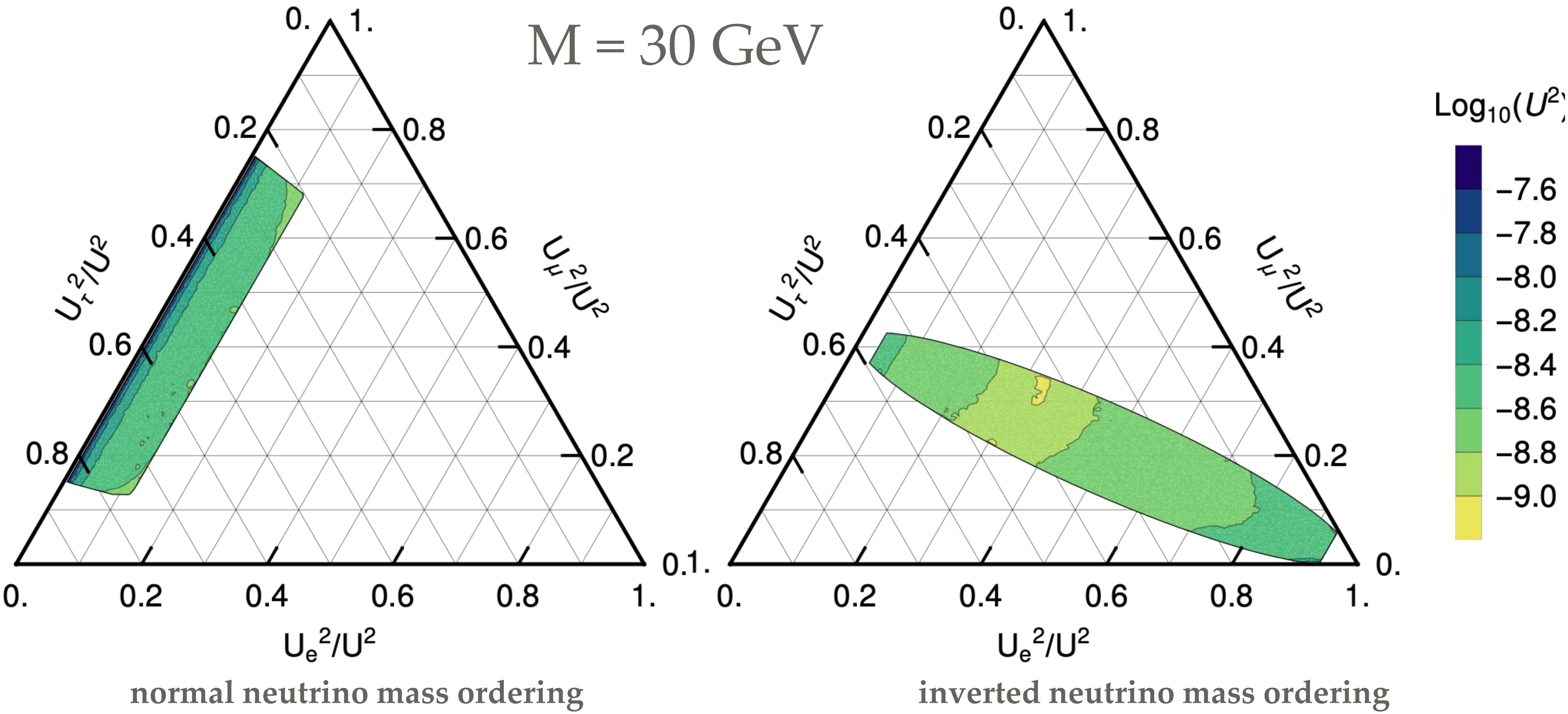
Dynamical Generation of Resonance



Abada et al 1810.12463

- quantum kinetic equations describe screening, quantum statistics and (de)coherence etc.
- level crossing between the quasiparticle dispersion relations in the plasma ("thermal masses") can dynamically generate a resonance

Current Status:
Constraints from Leptogenesis



The dark regions are preferred for testable leptogenesis

Neutrino masses vs collider searches

neutrino masses m_i are small (sub eV)

→ **active-sterile mixing angle θ must be small**

Problem!

Solution →

approximate B-L conservation

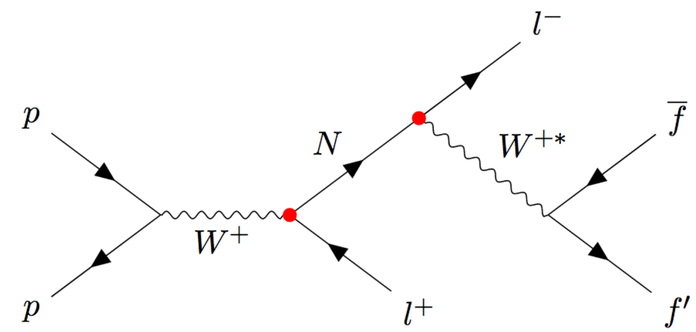
Shaposhnikov 0605047
Kersten/Smirnov 0705.3221

colliders rely on branching ratio

→ **active-sterile mixing angle θ must be large**

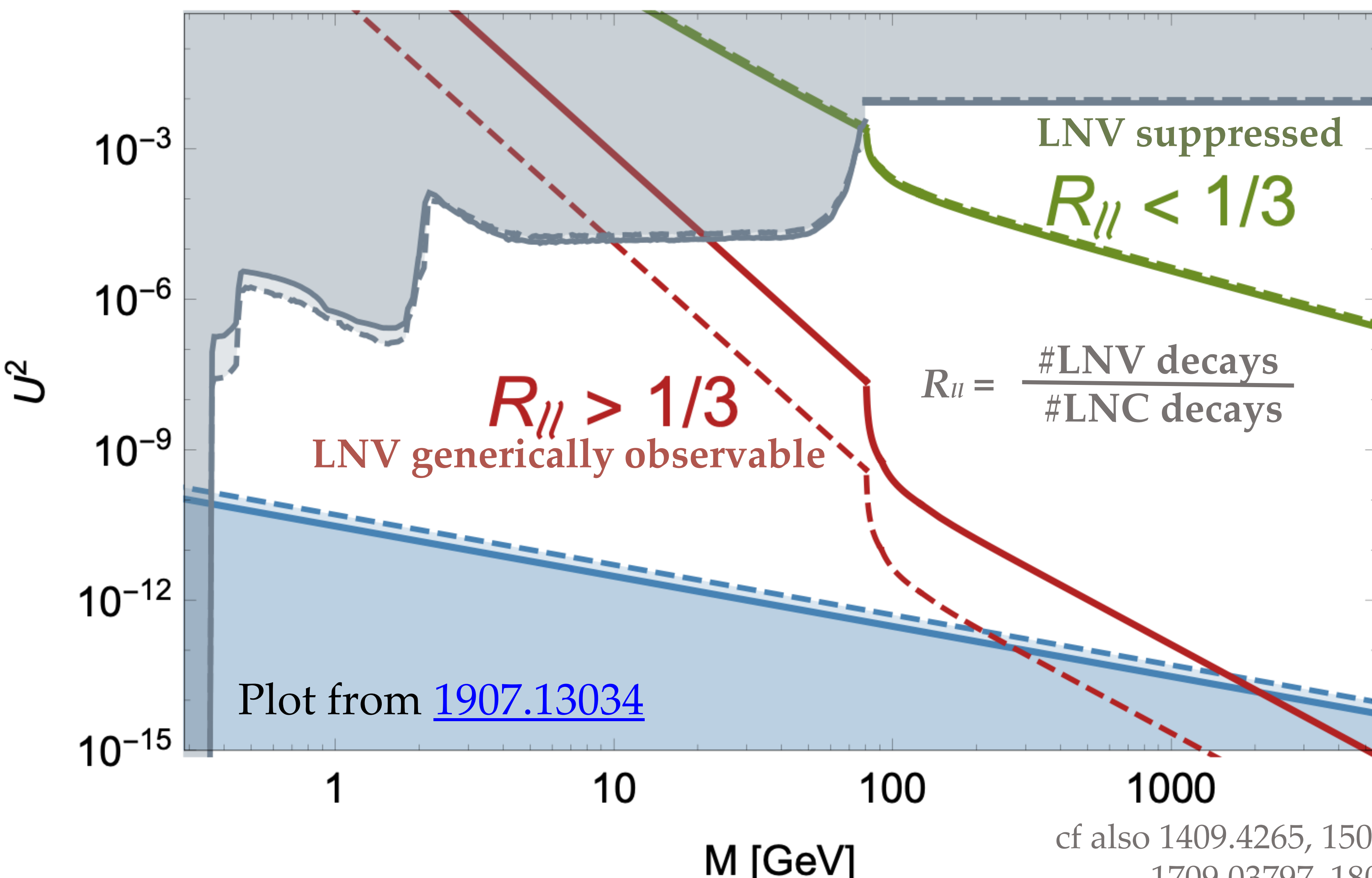
Can LNV be observed?

B-L symmetry: destructive interference amongst contributions from different HNL flavour



(a) Charged current decay

But: B-L is broken to generate neutrino mass.
Is this enough???



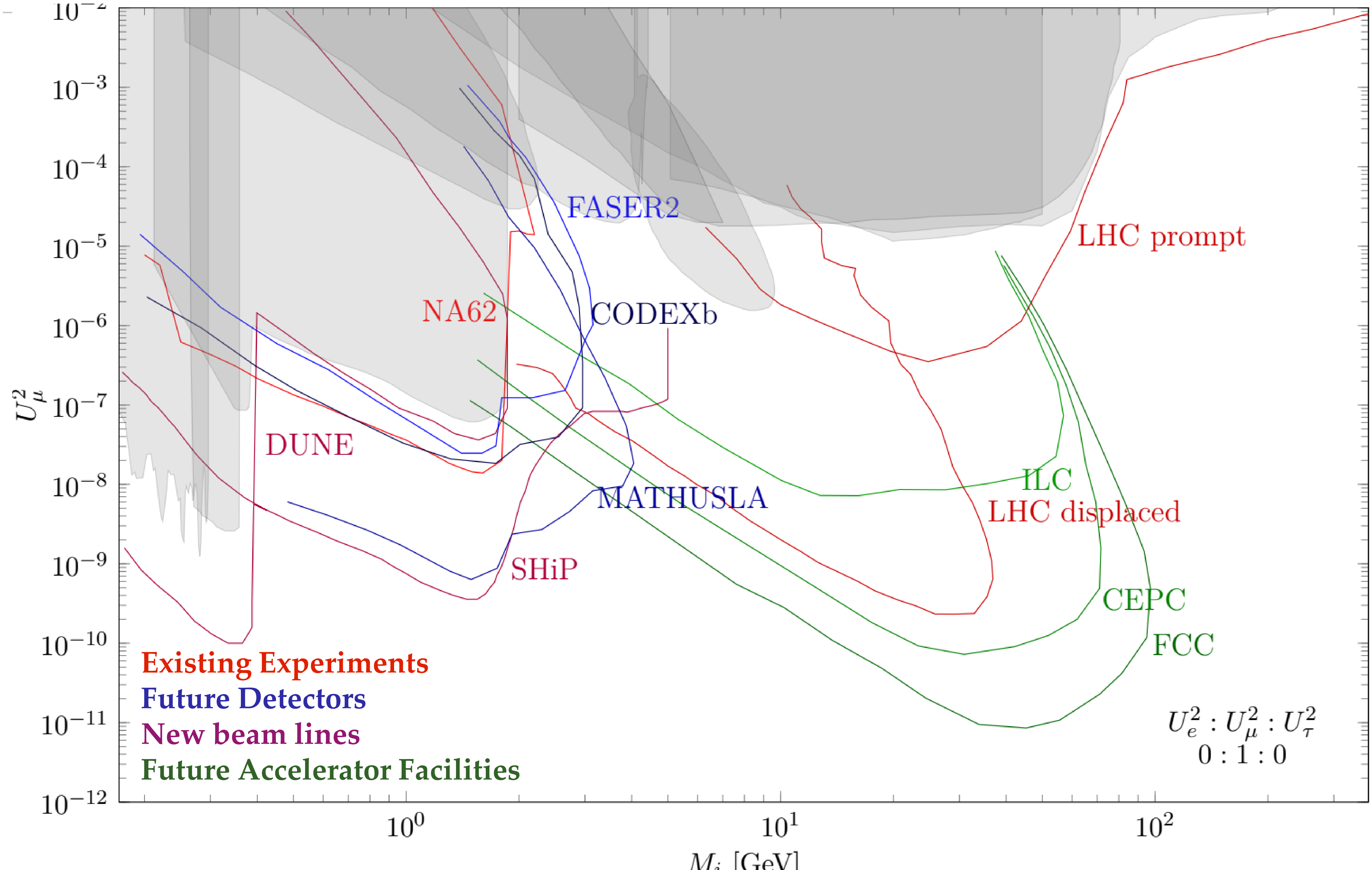
HNL oscillations destroy coherence and make LNV observable!
Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}$$

Does neutrino osc. data allow for this without fine tuning? It depends
MaD/Klaric/Klose 1907.13034

cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367

Heavy Neutrino Searches

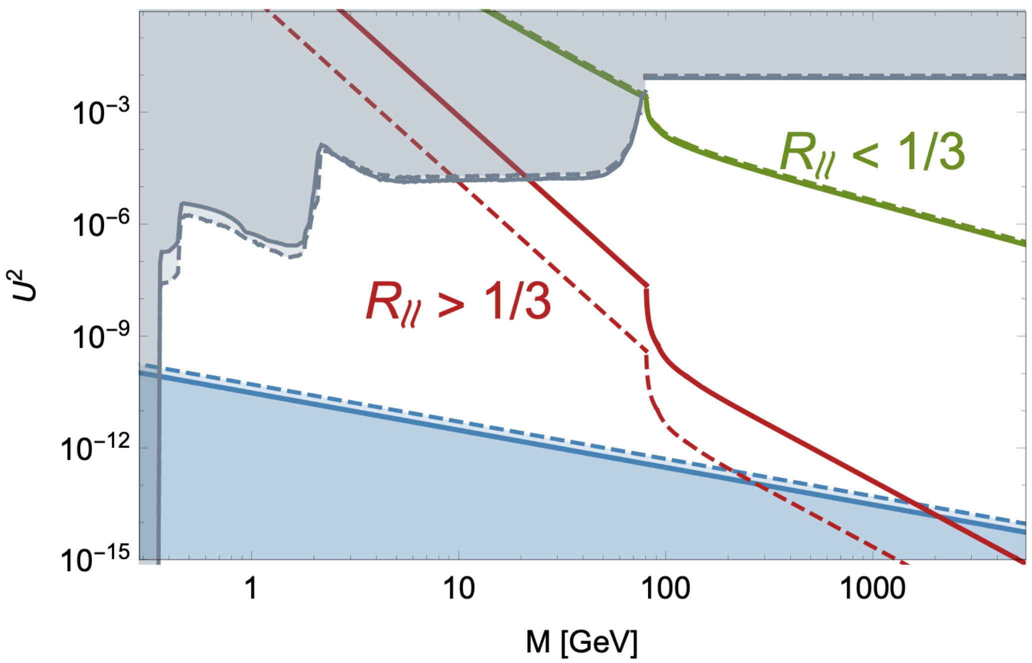


How to measure ΔM?

ratio of LNV to LNC decays
is sensitive to ΔM

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}$$

Anamiati et al 1607.05641



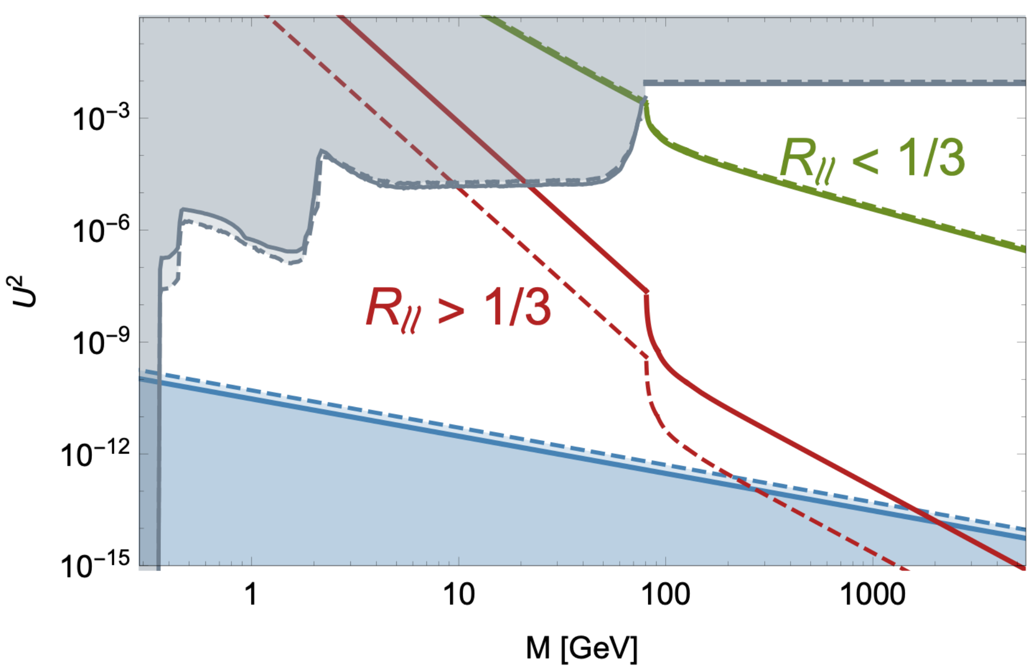
MaD/Klaric/Klose 1907.13034

How to measure ΔM?

ratio of LNV to LNC decays is sensitive to ΔM

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

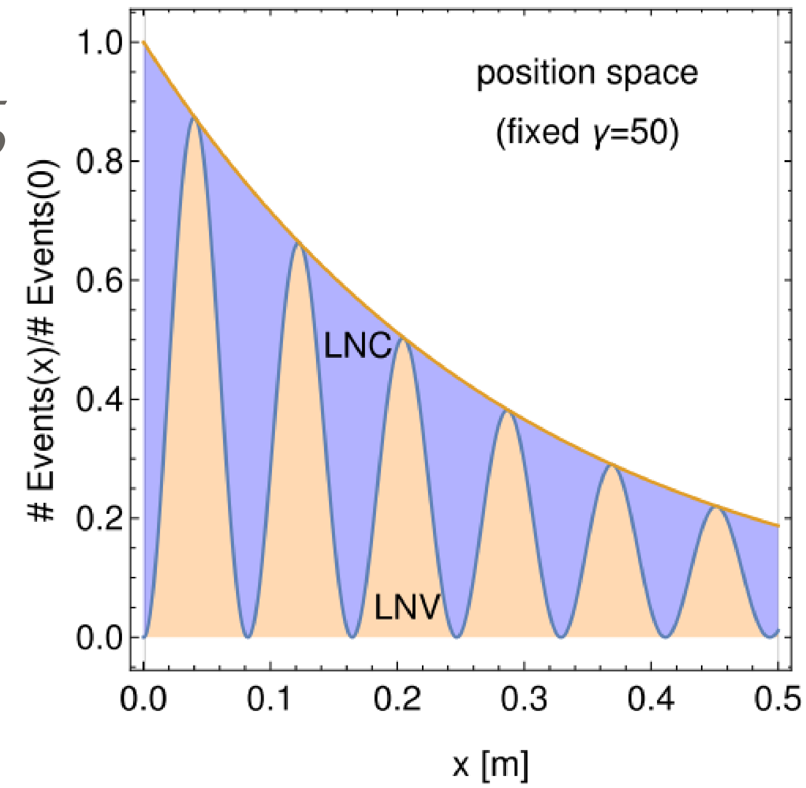
Anamiati et al [1607.05641]

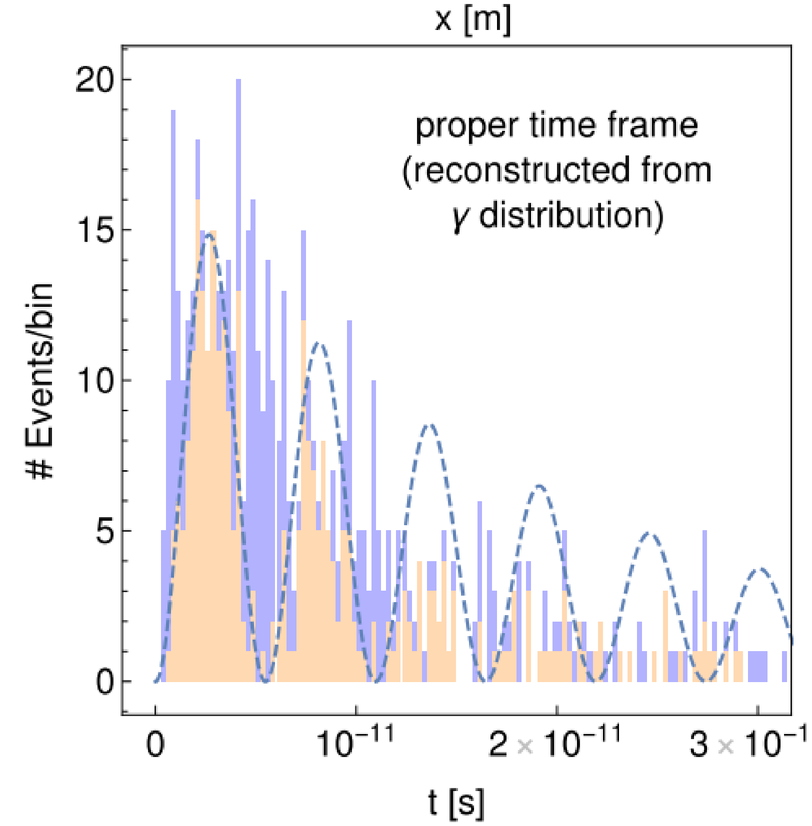


MaD/Klaric/Klose [1907.13034]

spatially resolving this ratio gives more information!

Antusch et al [1709.03797]





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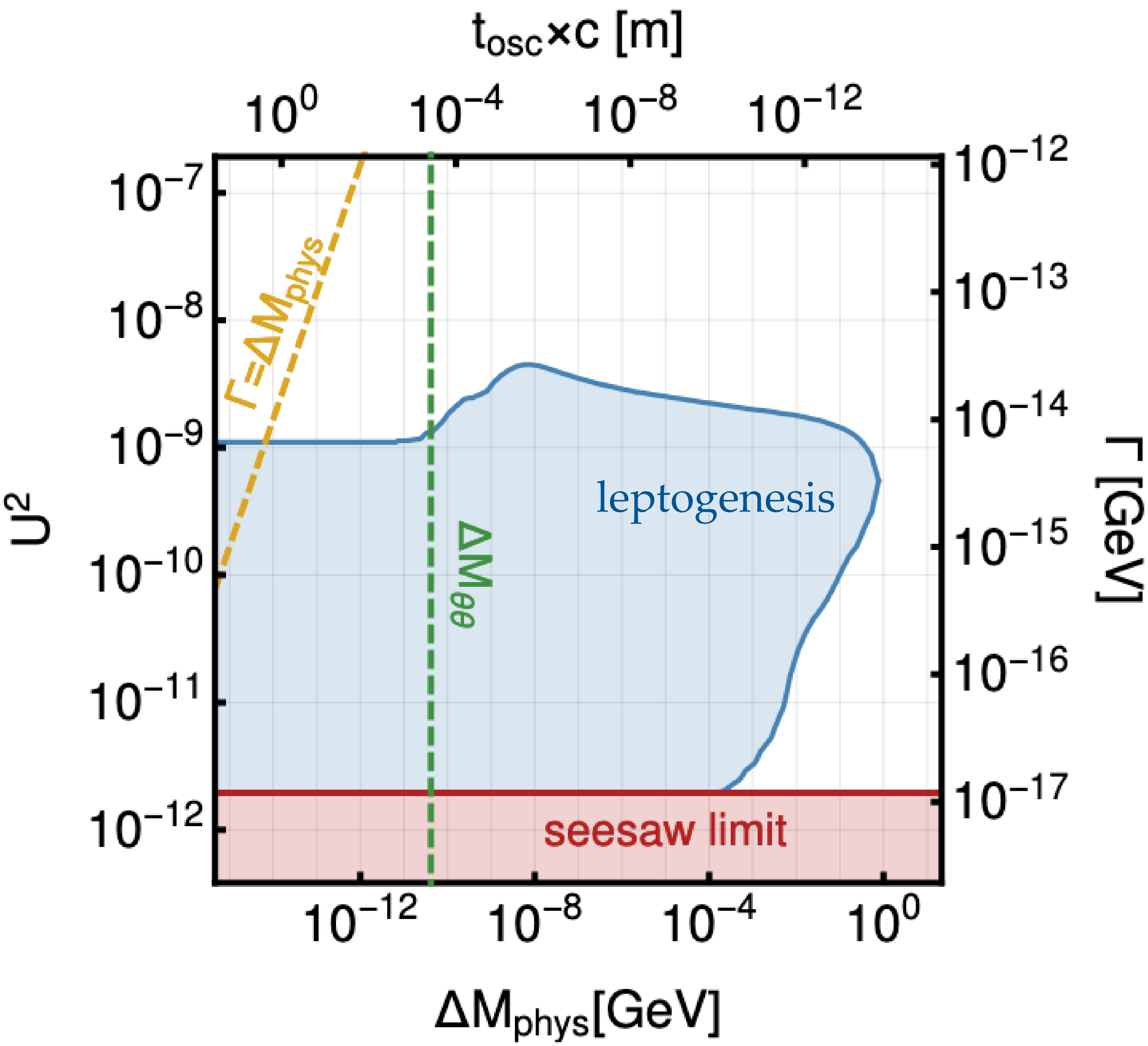
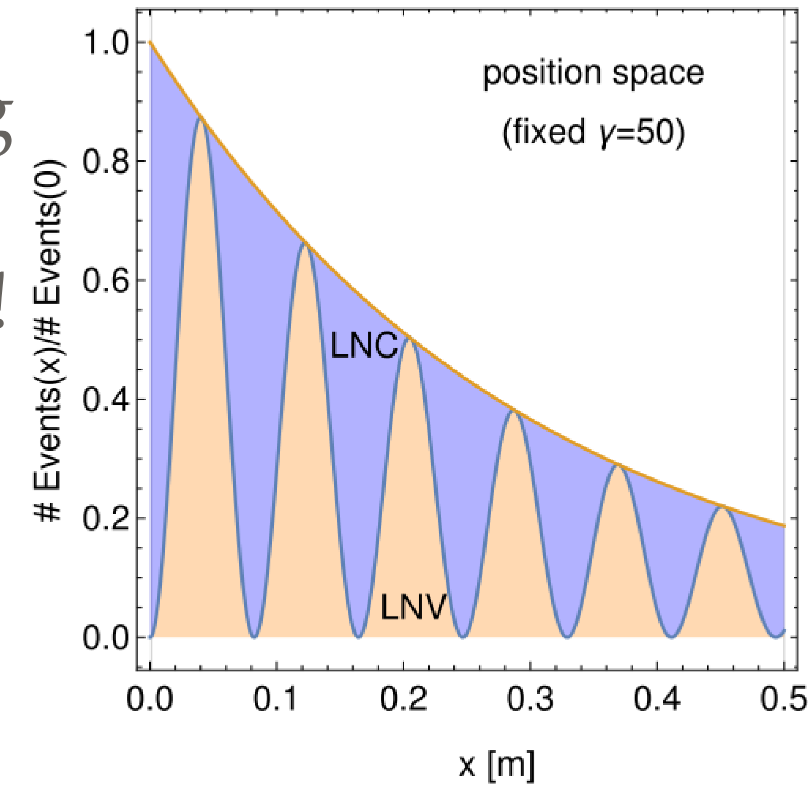
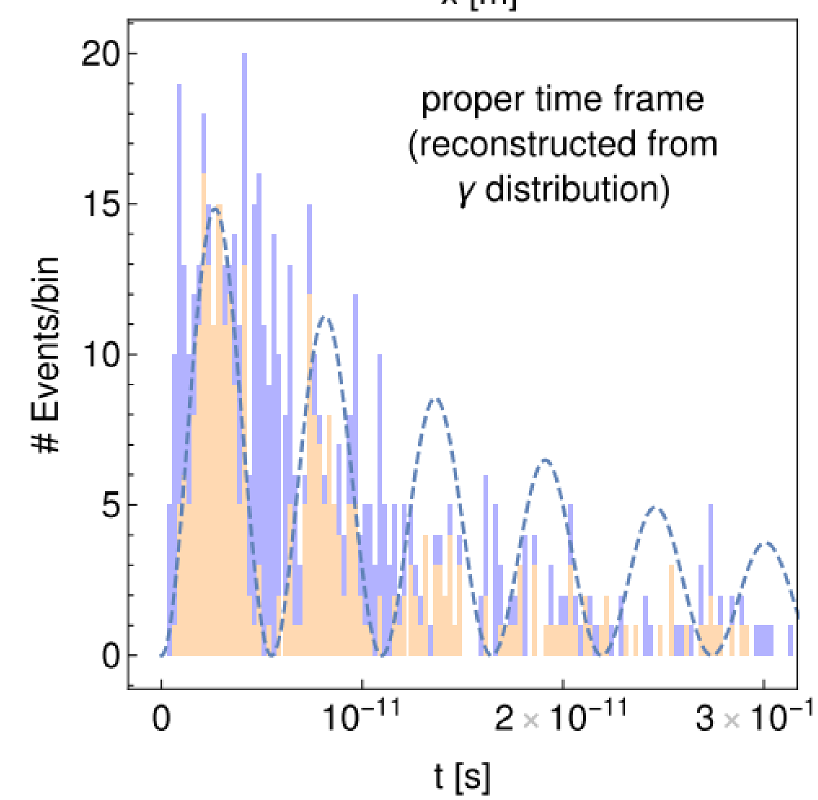


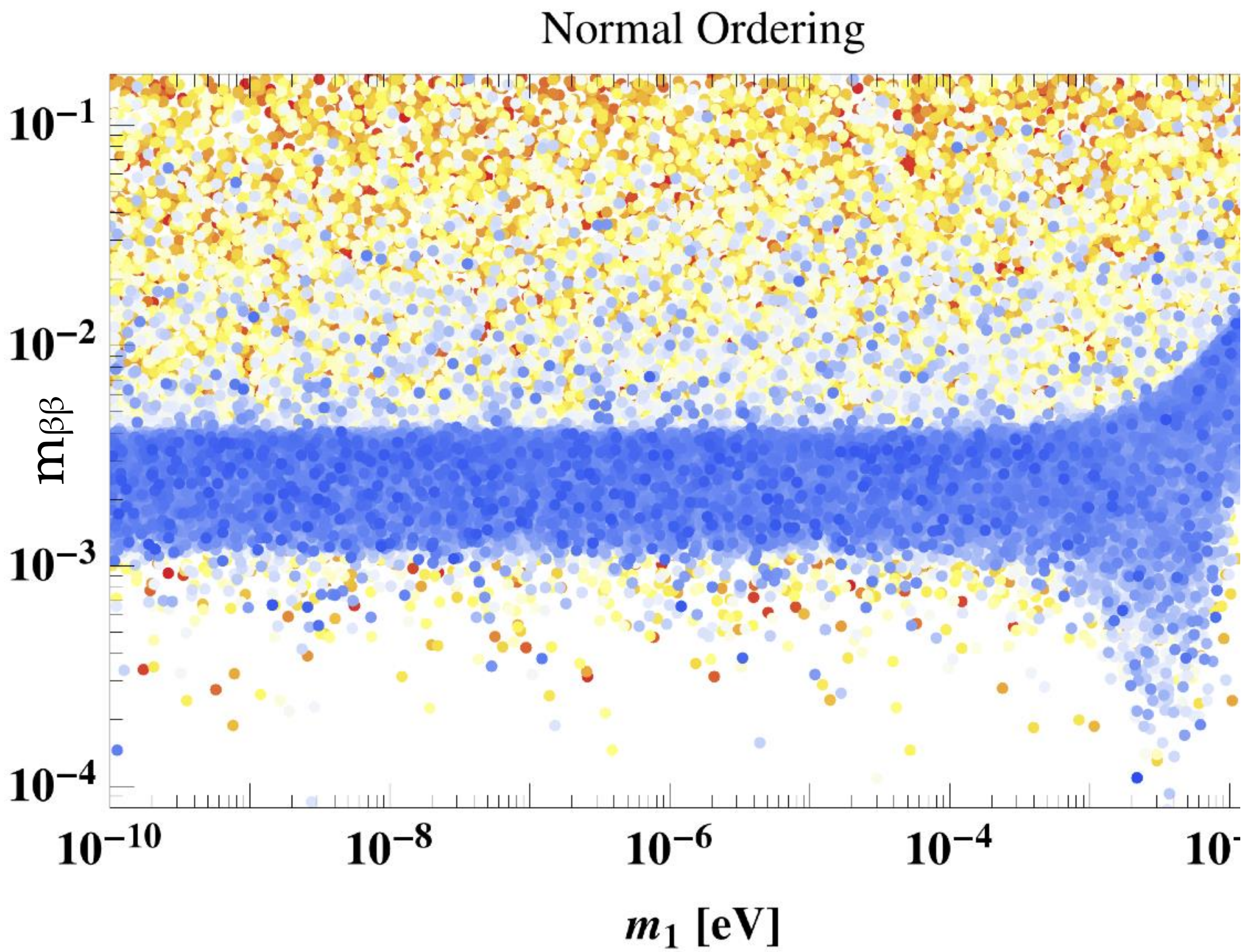




The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…
…even in the leptogenesis region
⇒ additional probe of Reω !

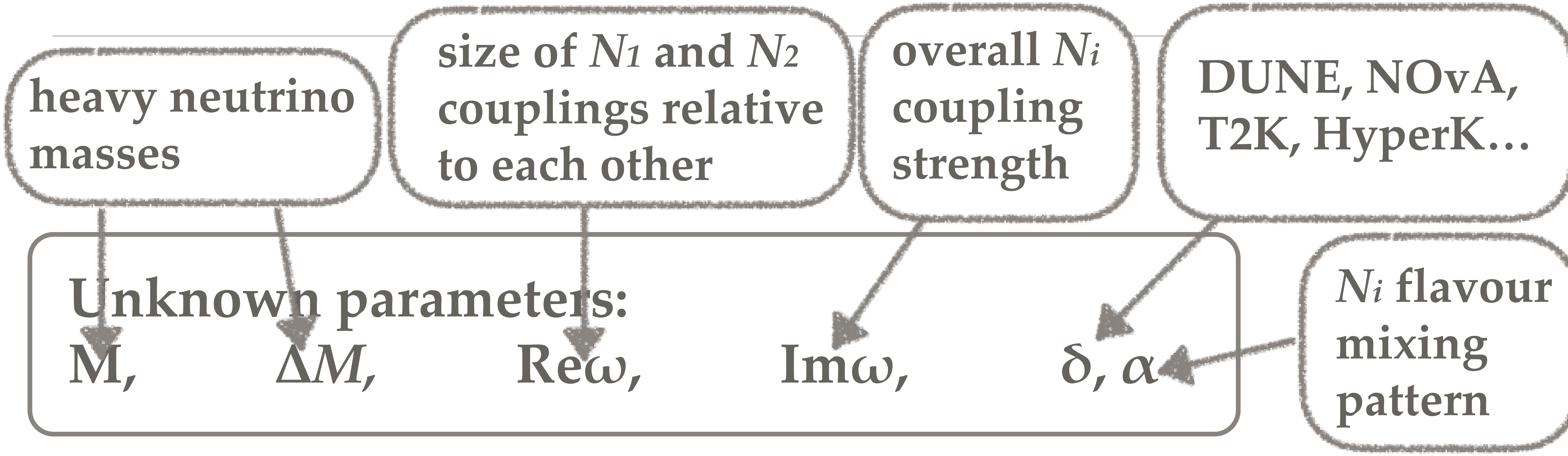
Bezrukov 0505247
Blennow et al 1005.3240
Lopez Pavon et al 1209.5342
MaD/Eijima 1606.06221
Hernandez et al 1606.06719
Asaka et al 1606.06686
Abada et al 1810.12463



Abada et al 1810.12463

- **colourful points: can explain baryon asymmetry and neutrino mass**
- **colour code measures the degree of fine tuning**
- **points outside the standard 0νββ band are possible…**
- **…..observing a non-standard value provides a probe of RH neutrino properties!**

Full Testability



- In principle all parameters can be measured
  ⇒ fully testable model of neutrino masses and baryogenesis
- This requires a combination of collider/fixed target experiment data and ν-osc. data (and possibly 0νββ)
  ⇒ poster child example for synergy between collider and long baseline programs!

A Multi-Frontier Problem

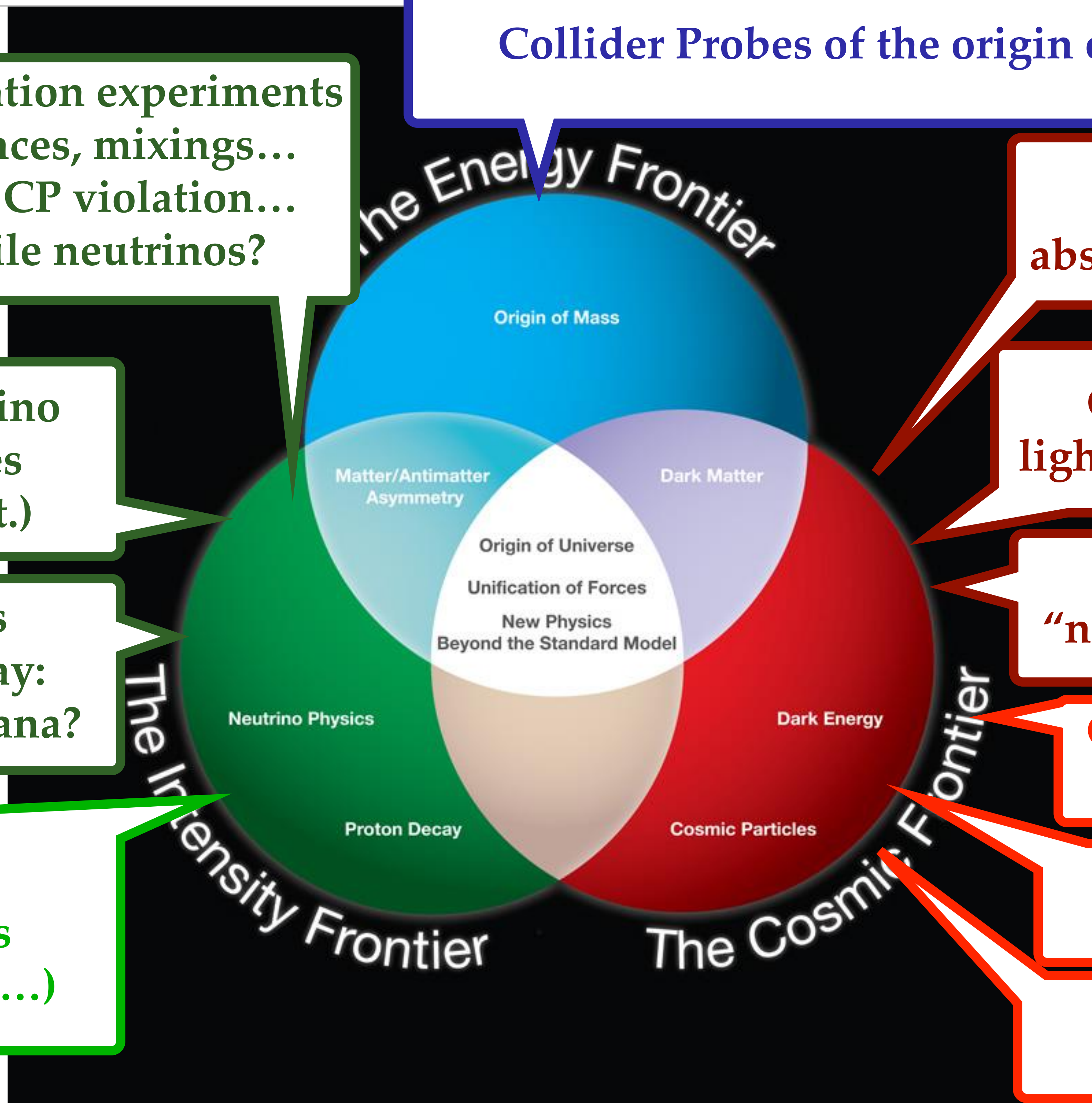
Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)



CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

IceCube
“neutrino astronomy”

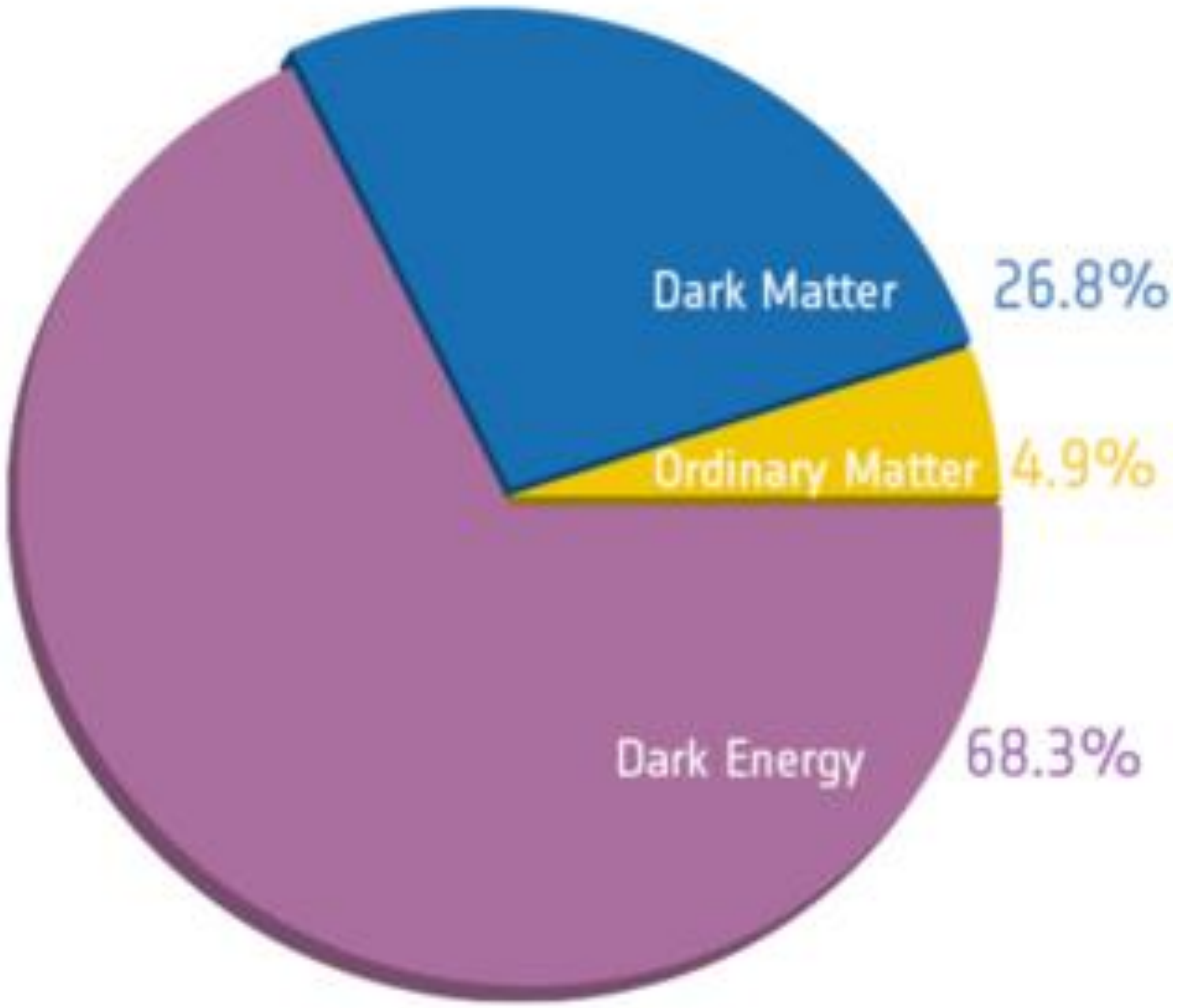
Cosmic Neutrino
Background

Leptogenesis?

Sterile Neutrino
Dark Matter?

Dark Matter

Energy Content of the Universe



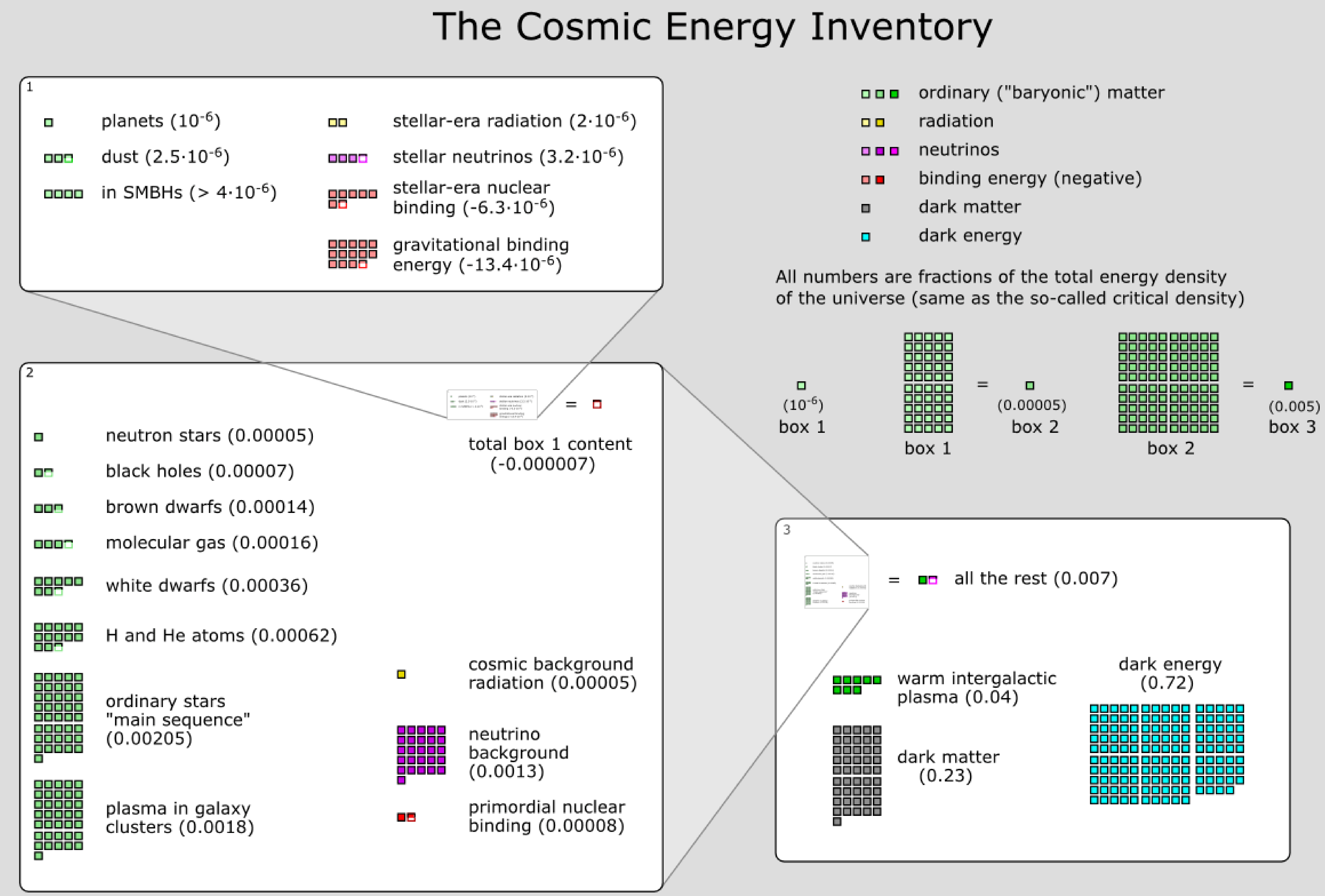
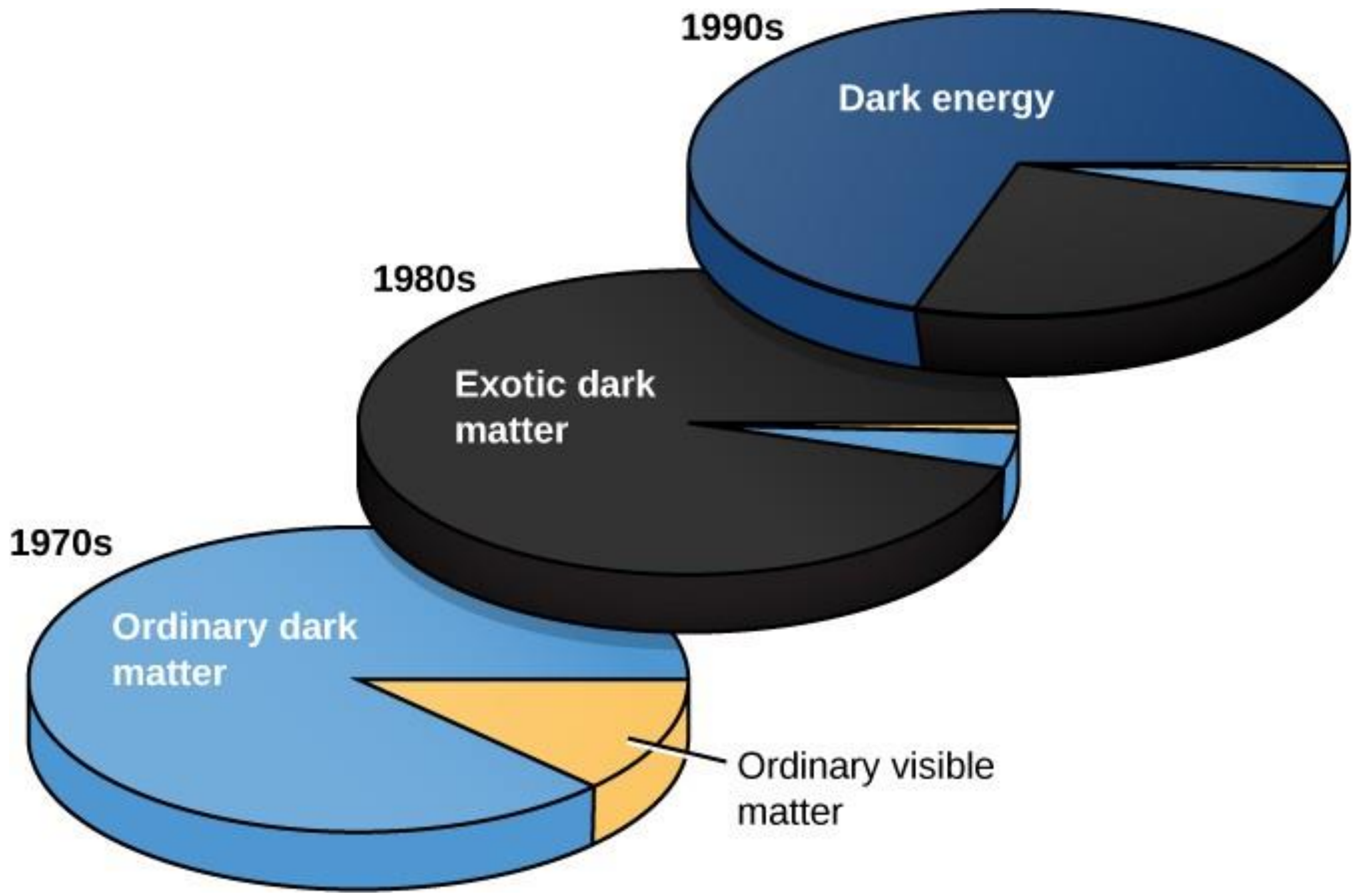


Chart by Markus Pössel [www.haus-der-astronomie.de] -
Data from M. Fukugita & P.J.E. Peebles, "The Cosmic Energy Inventory" (2004) [adsabs.harvard.edu/abs/2004ApJ...616..643F]
Chart style following Randall Munroe's xkcd.com/radiation

Energy Content of the Universe



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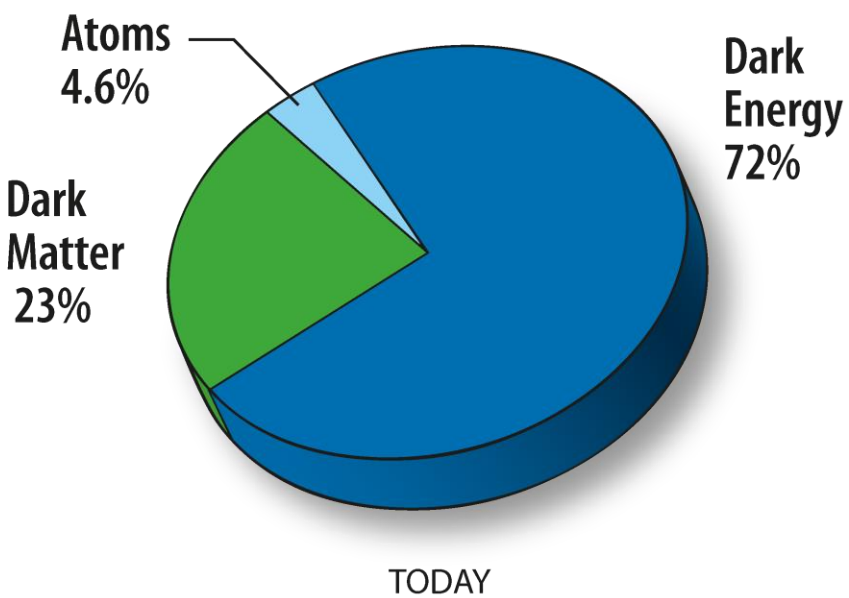
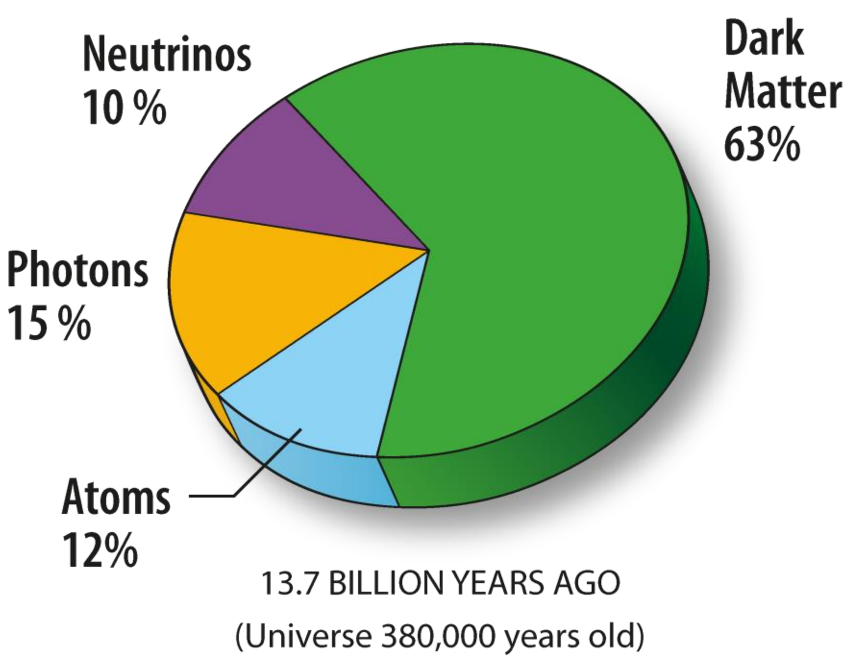




These fractions change as a function of time because different components get diluted by the expansion of the universe in a different way:

$$\rho_{\text{matter}} \propto a^{-3}$$ **dilution of number density**

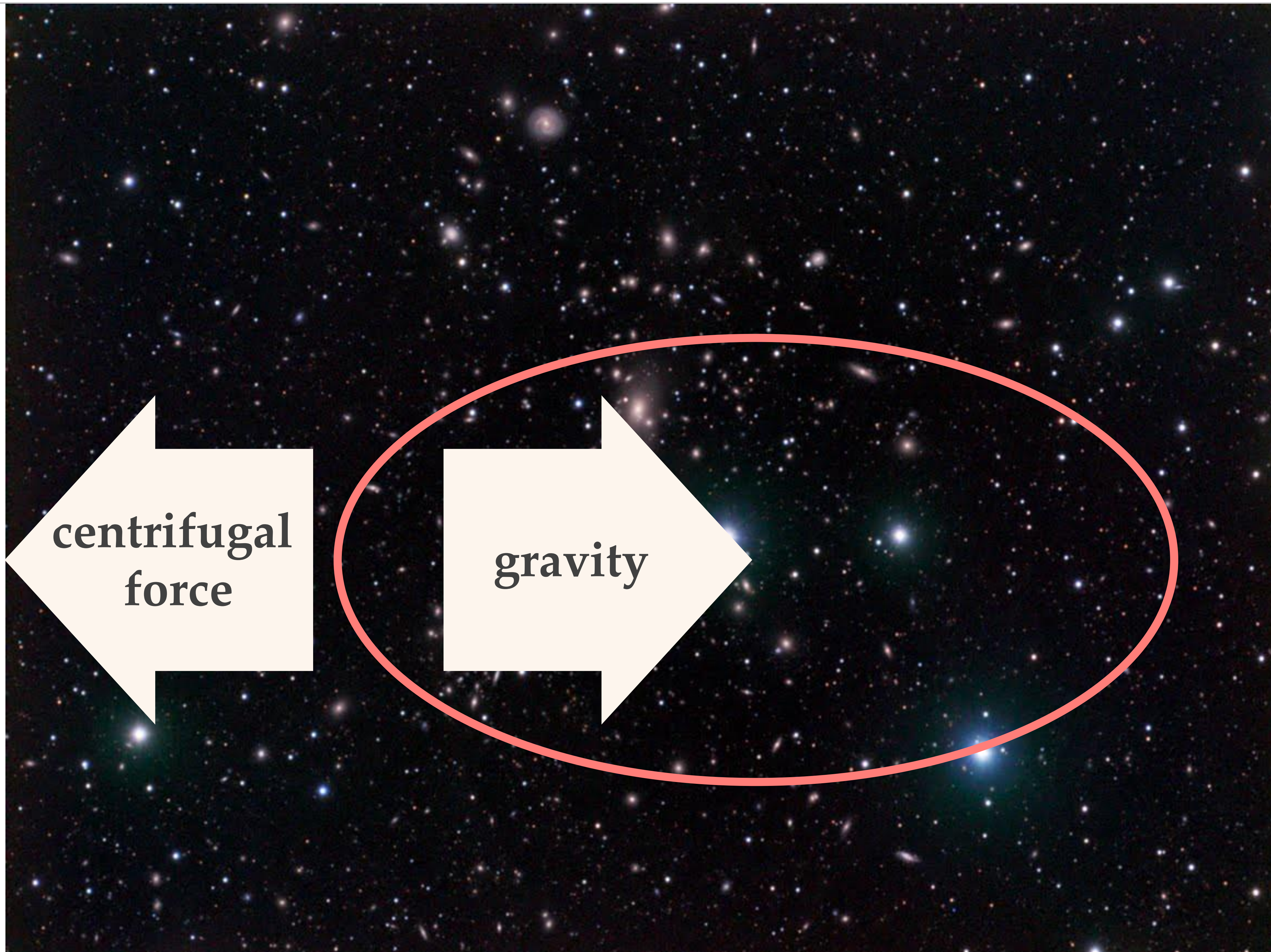
$$\rho_{\text{radiation}} \propto a^{-4}$$ **dilution of number density, redshifting of frequencies**

$$\rho_{\text{vacuum}} = \text{constant}$$ **no dilution**

Energy Content of the Universe

Evidence for Dark Matter

1) Galaxy Clusters



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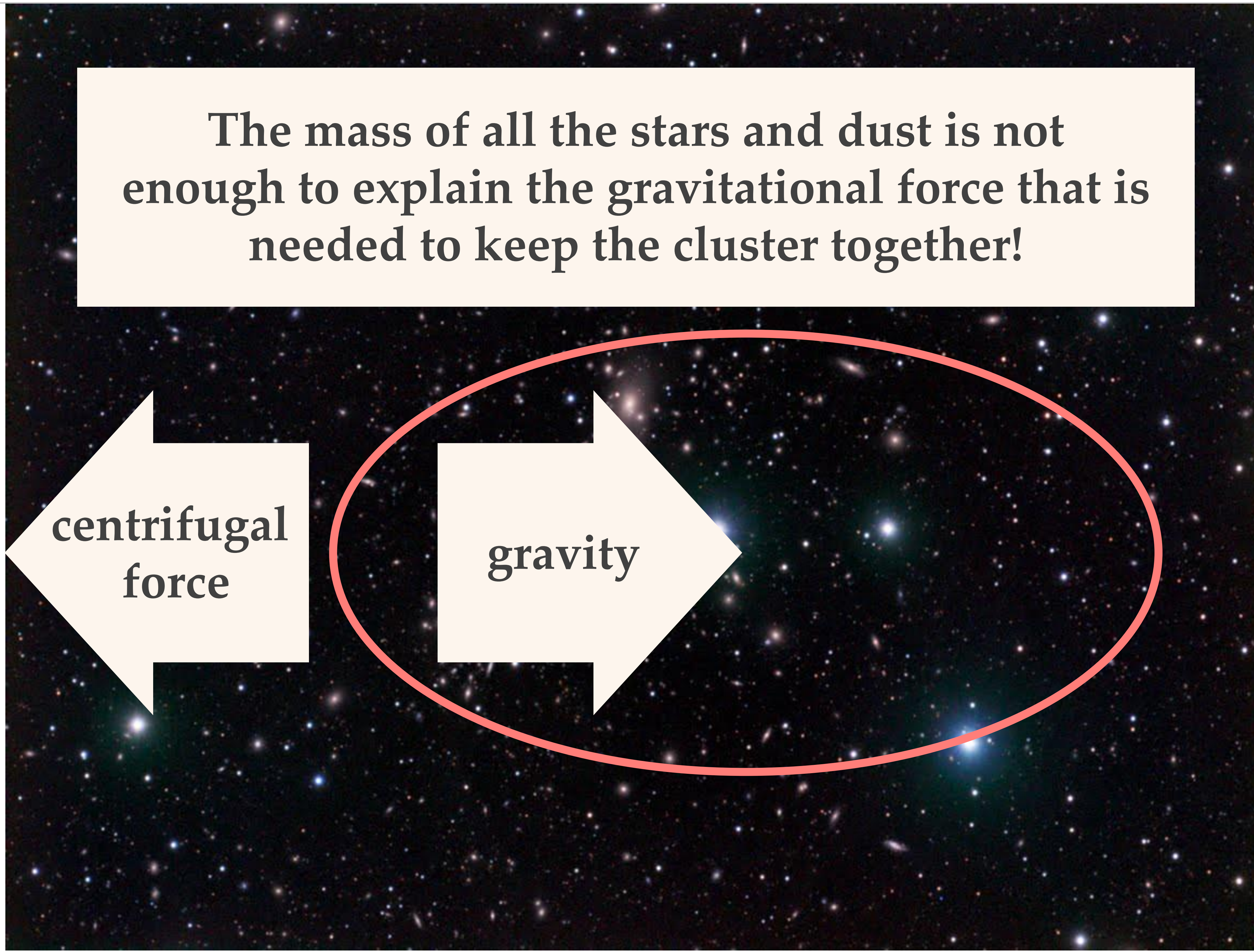

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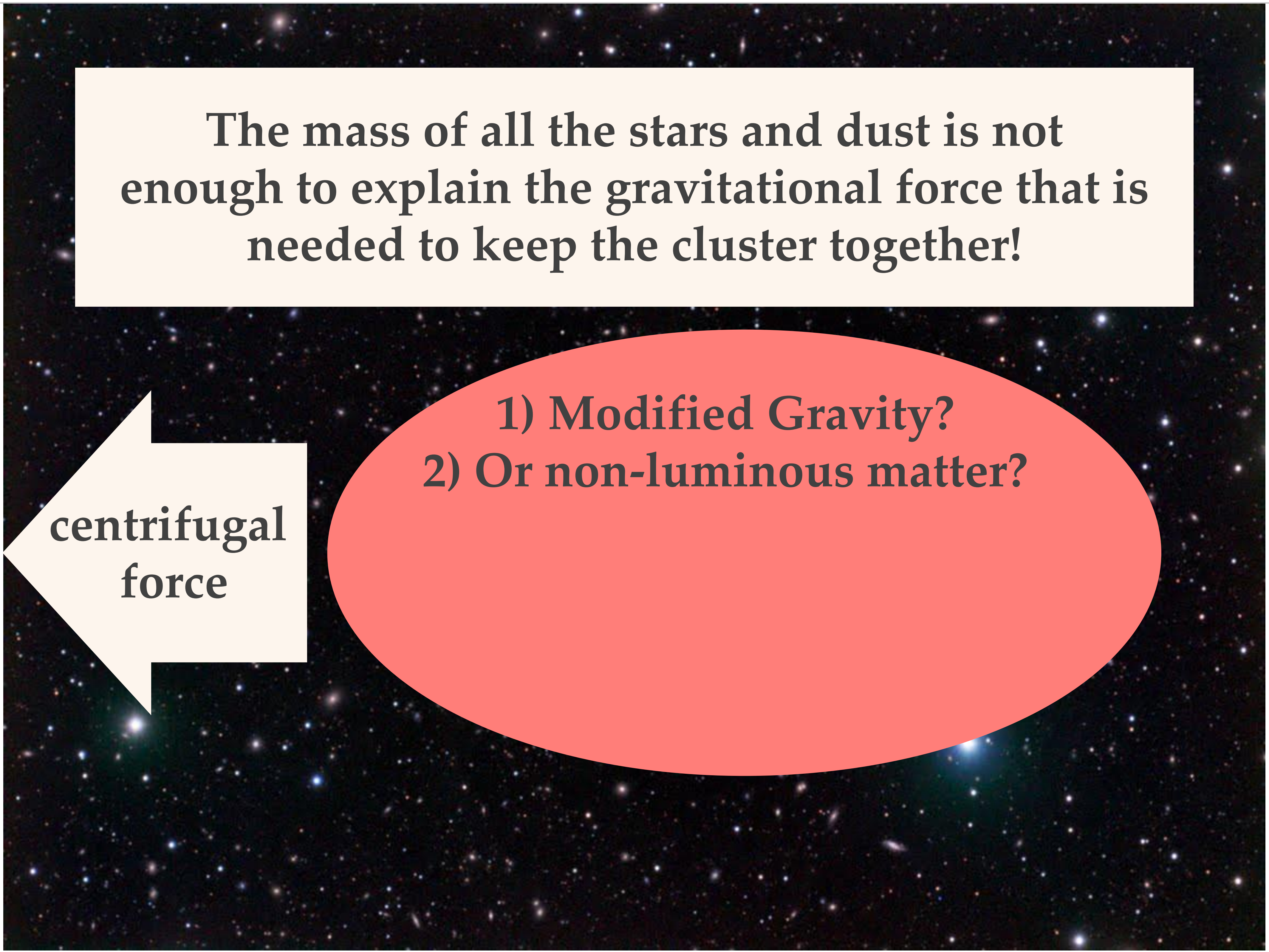

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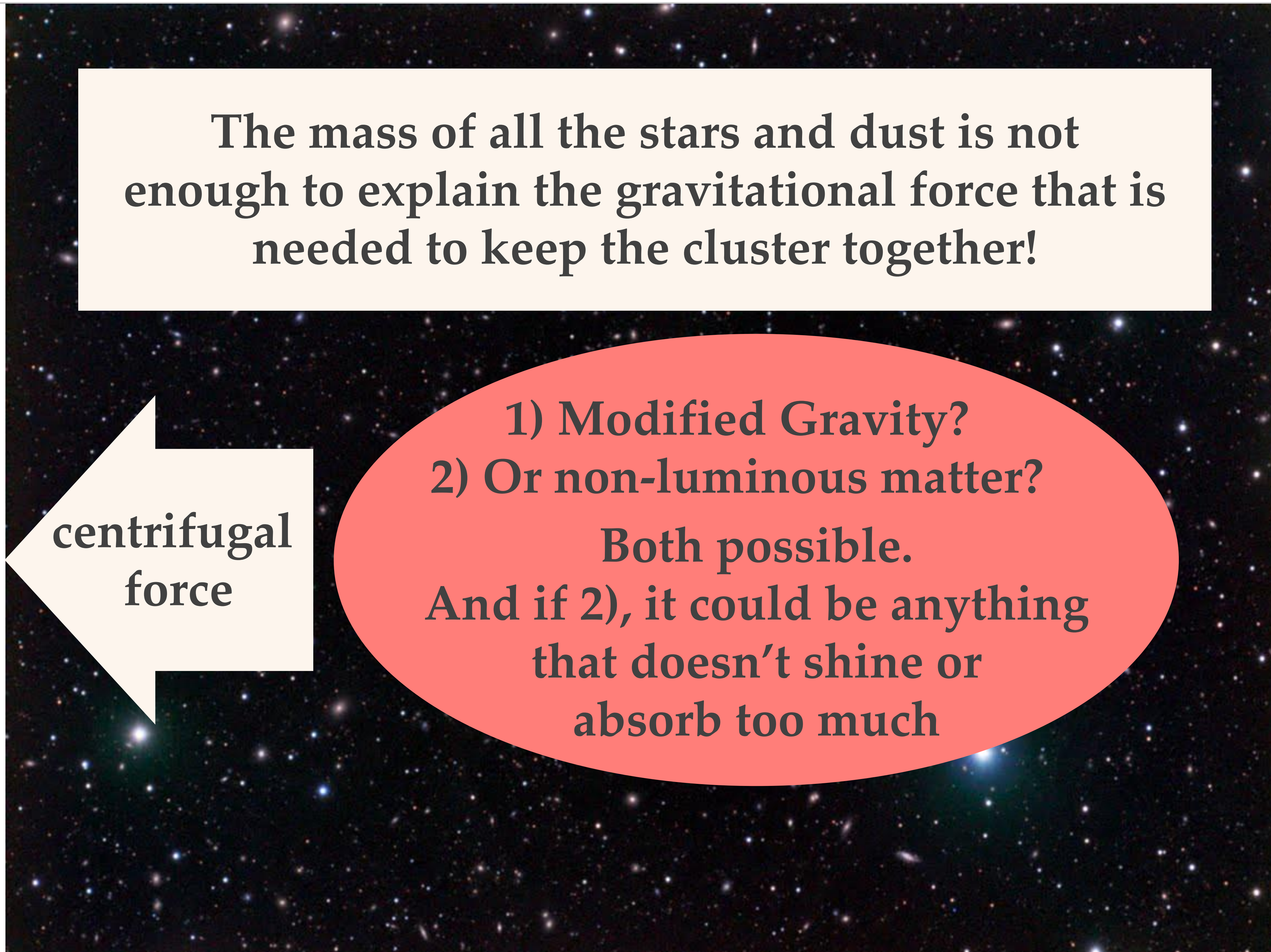
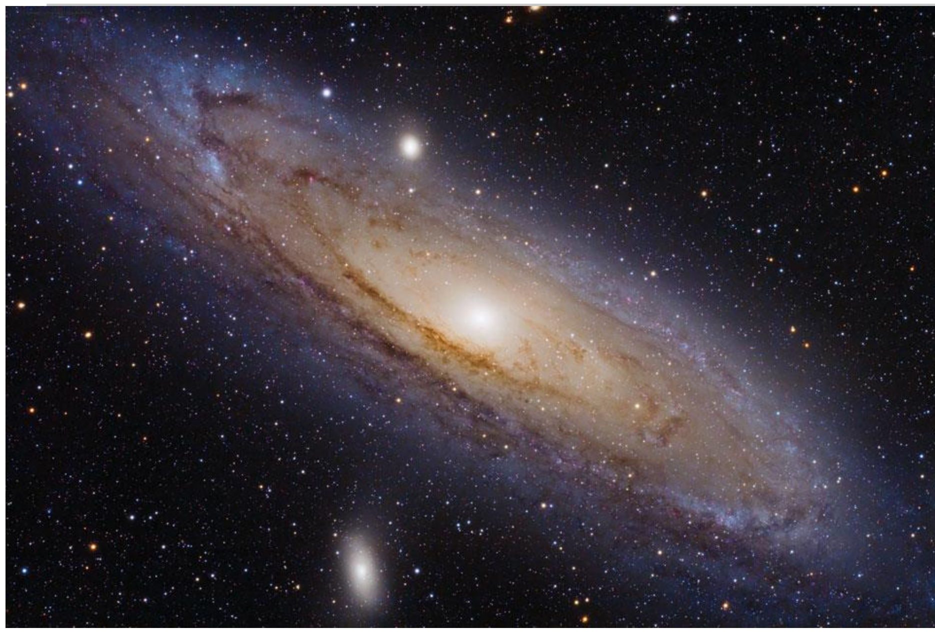
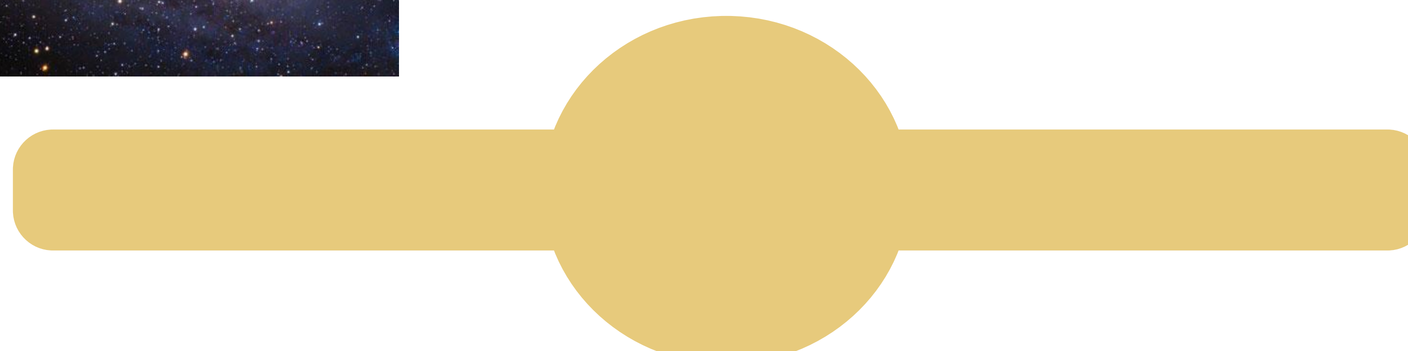


2) Galaxy Rotation Curves





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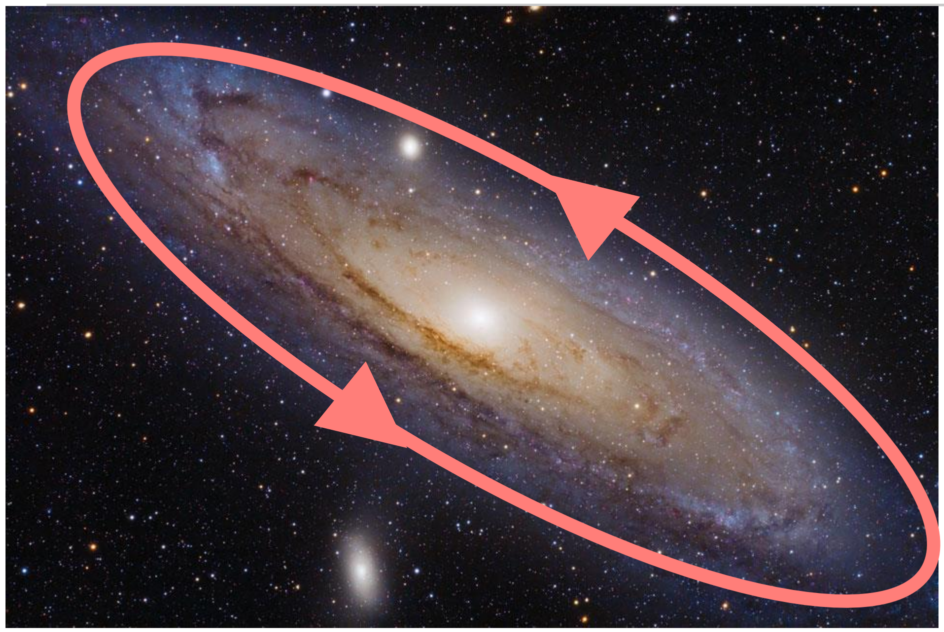

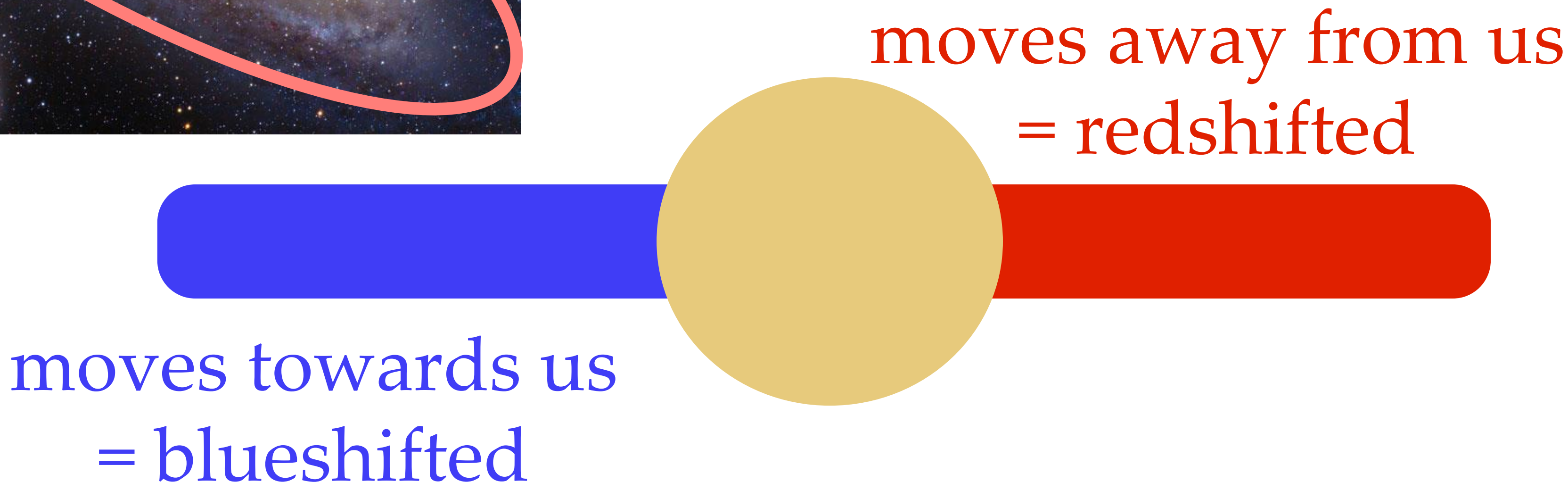

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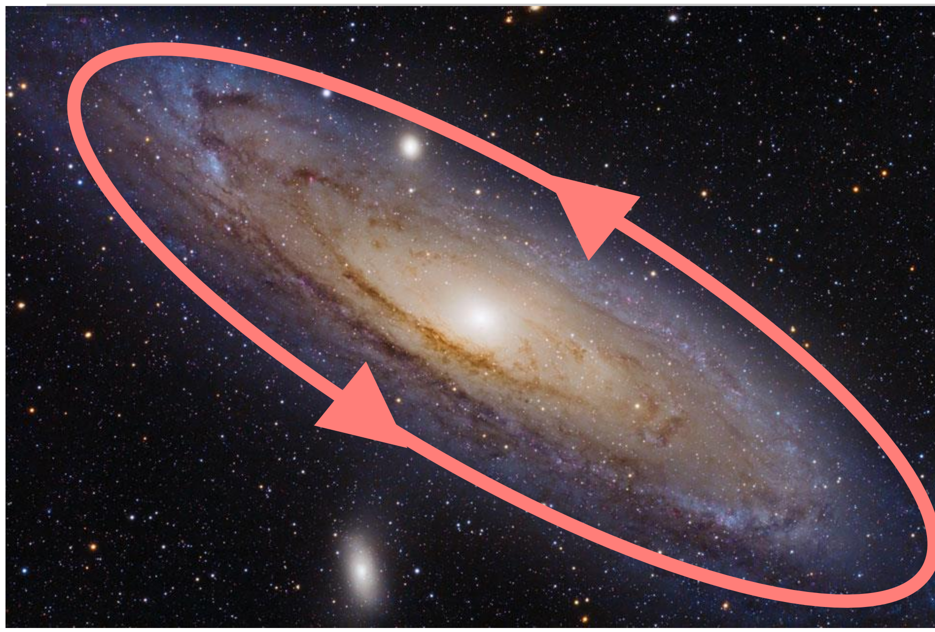
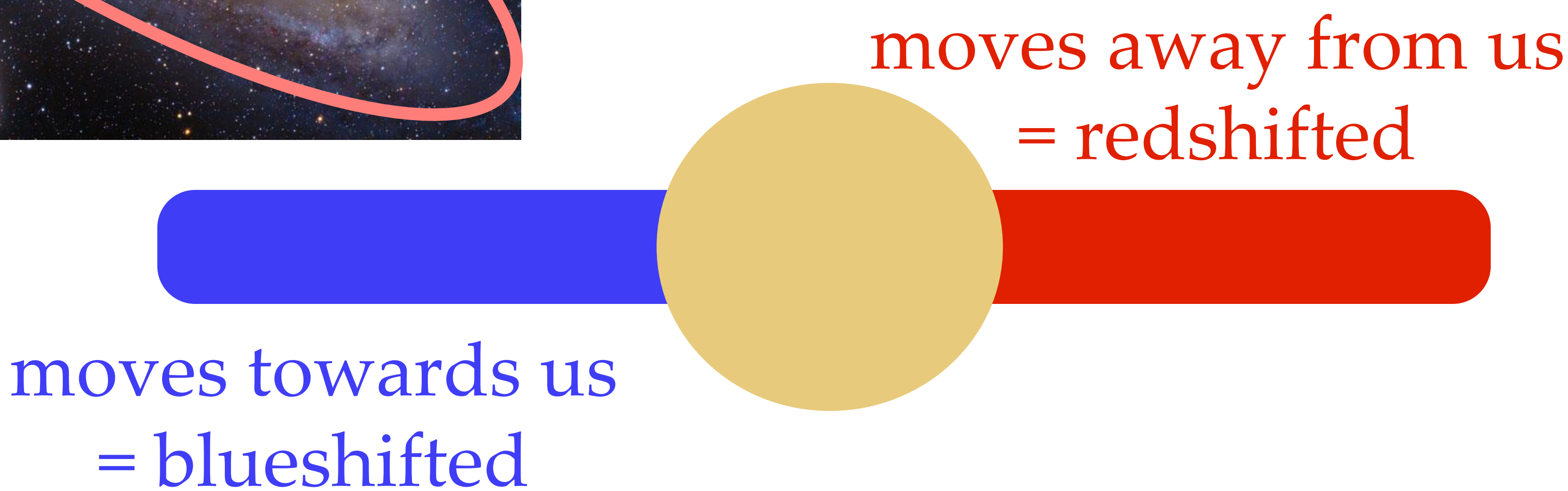


$$\frac{m\ M(r)}{r^2}G = \frac{m\ \ v^2(r)}{r}$$

$$\Rightarrow v^2(r) = \frac{M(r)}{r}G$$



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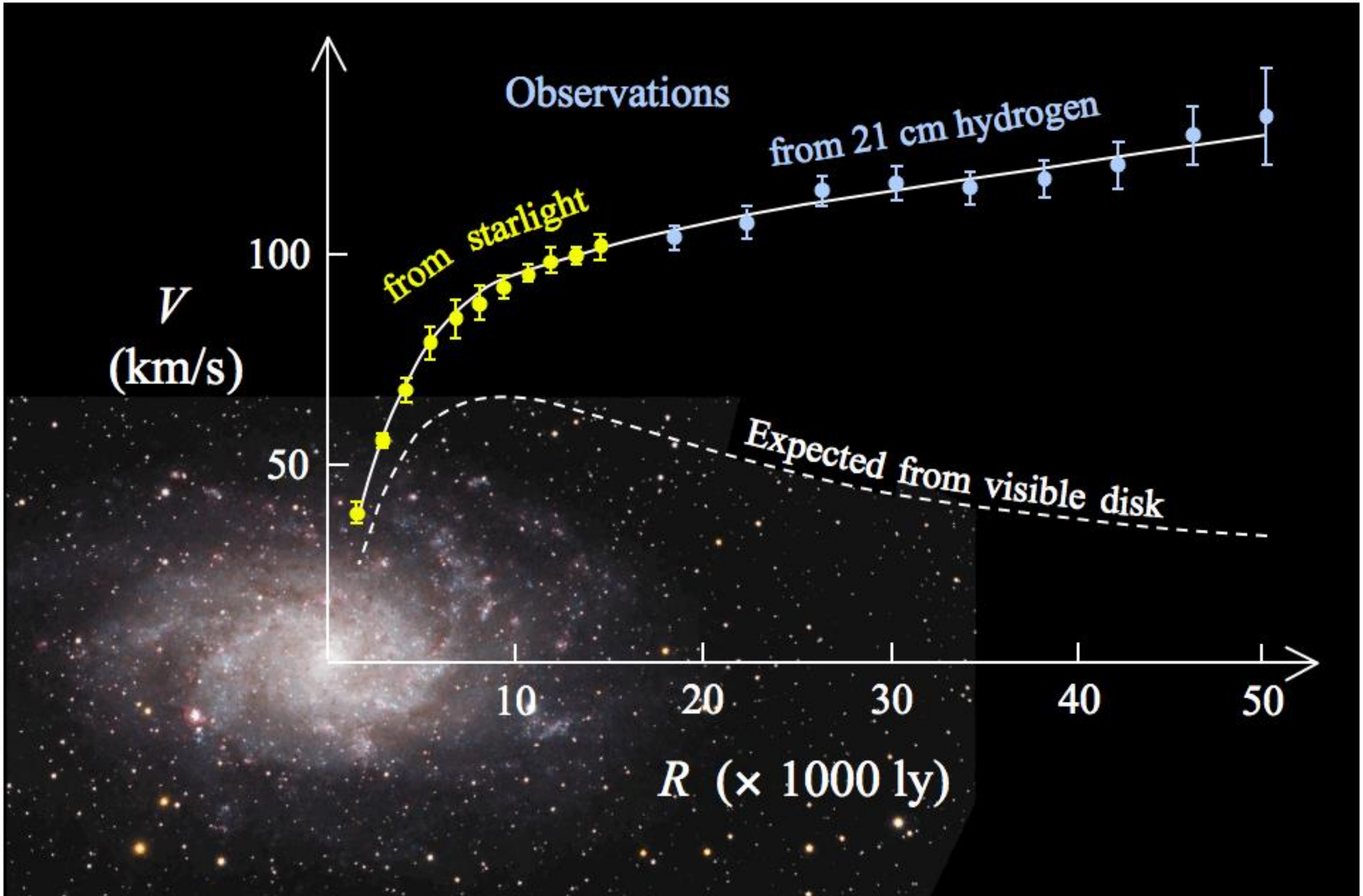

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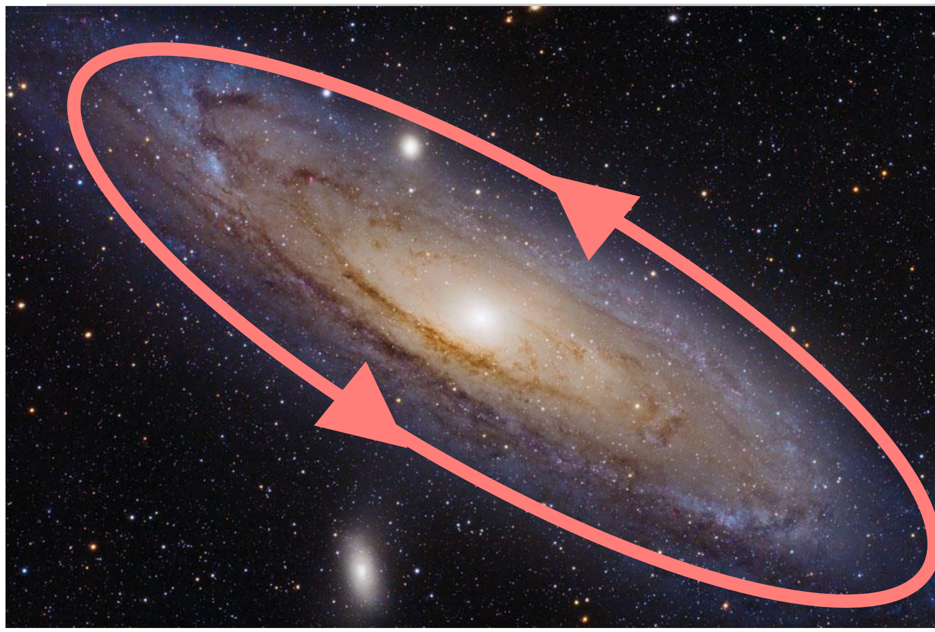

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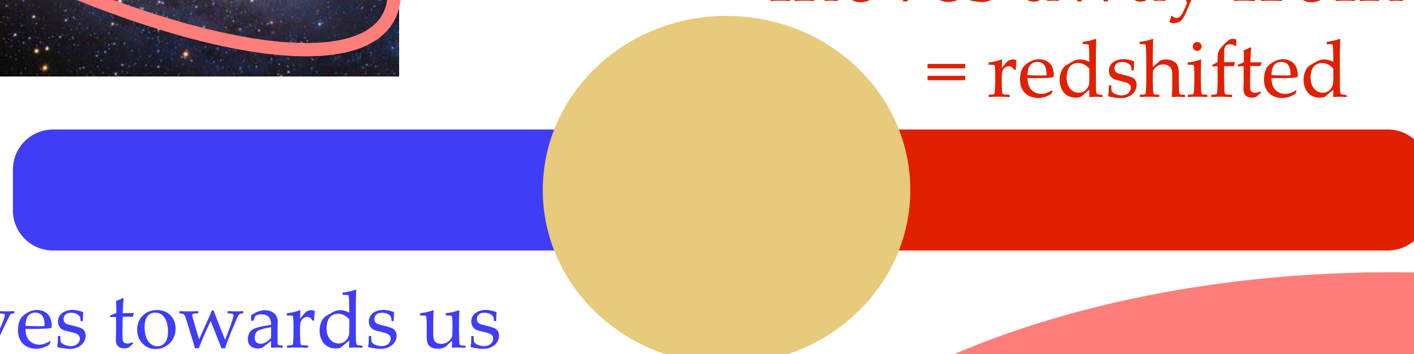
moves away from us
= redshifted

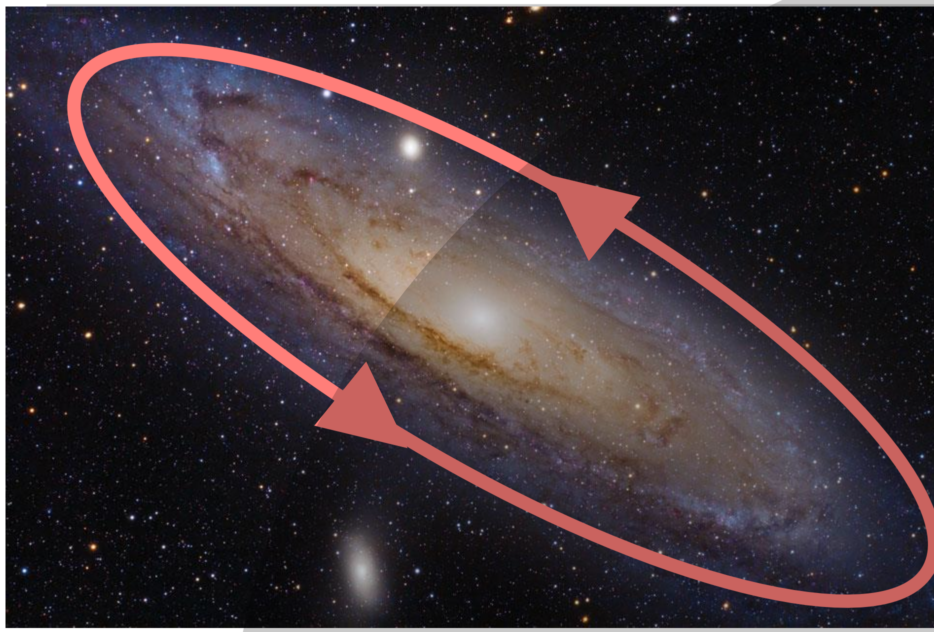


moves towards us
= blueshifted

1) Modified Gravity?
2) Or non-luminous matter?

e.g. MACHOS (Massive Astrophysical Compact Halo Objects)

2) Galaxy Rotation Curves



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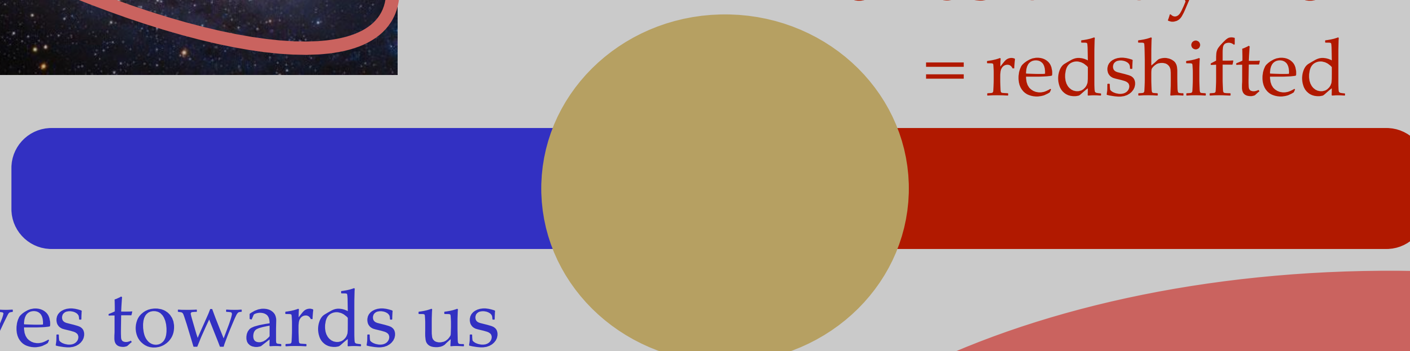
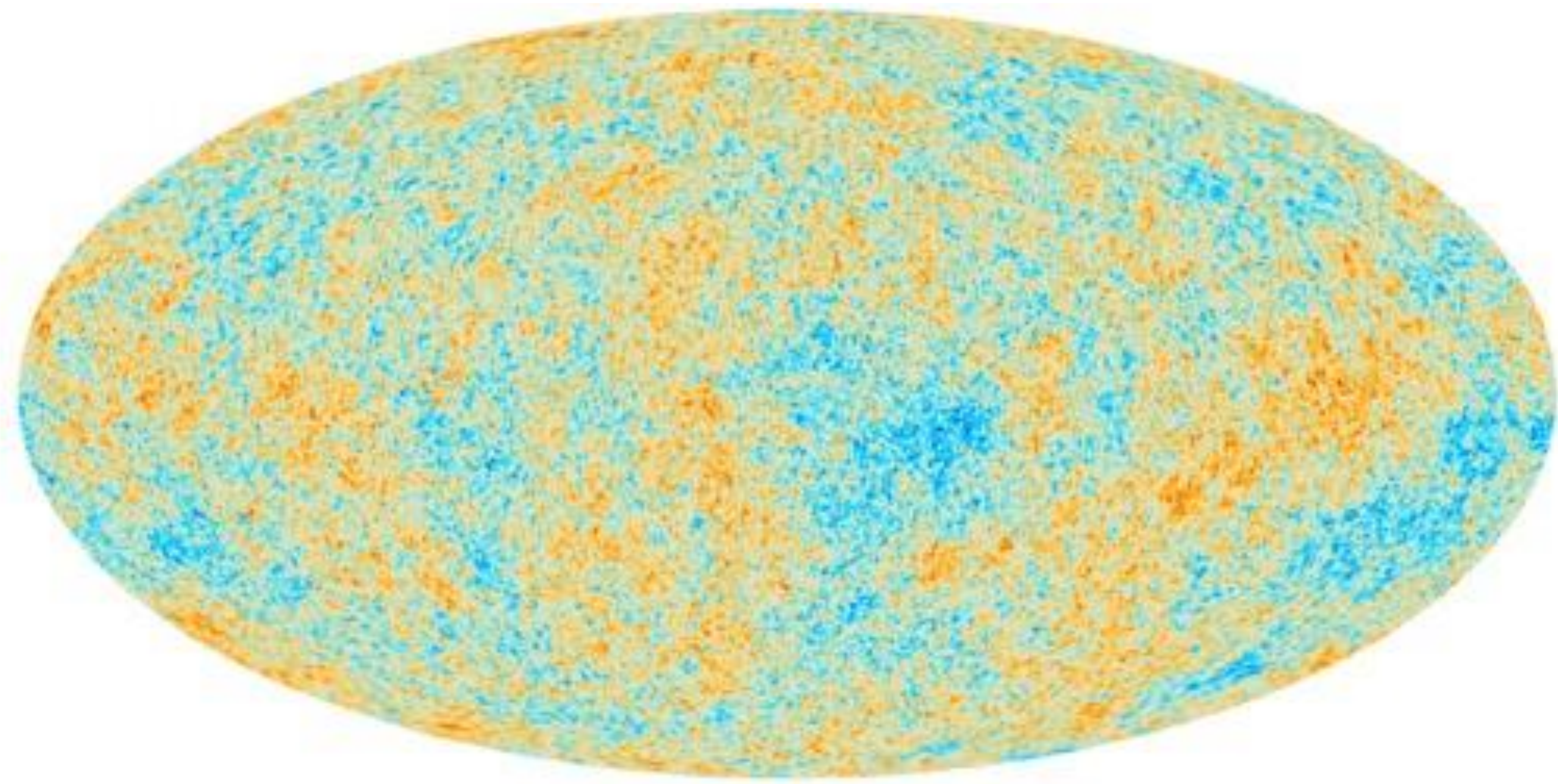
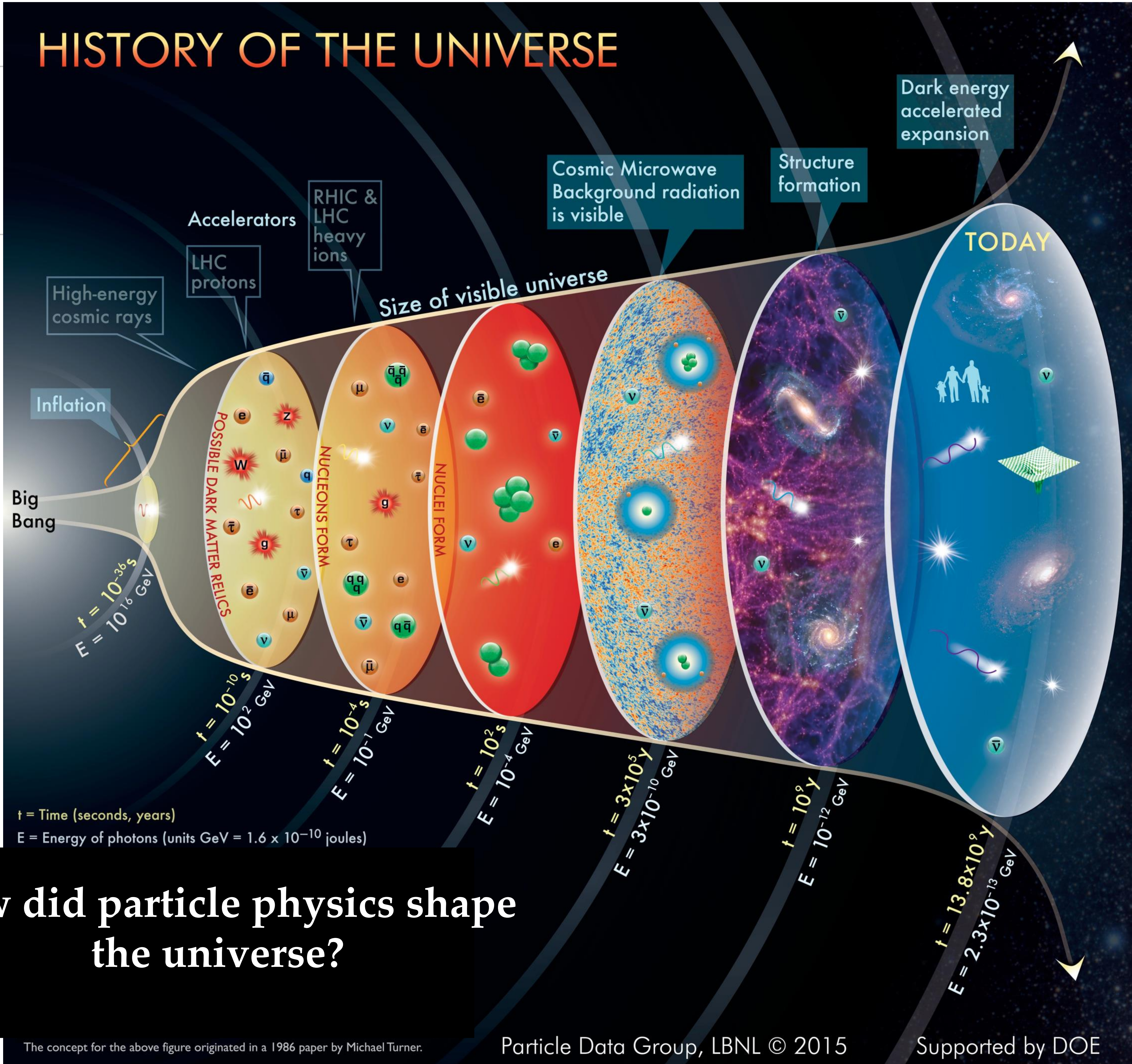


moves towards us
= blueshifted

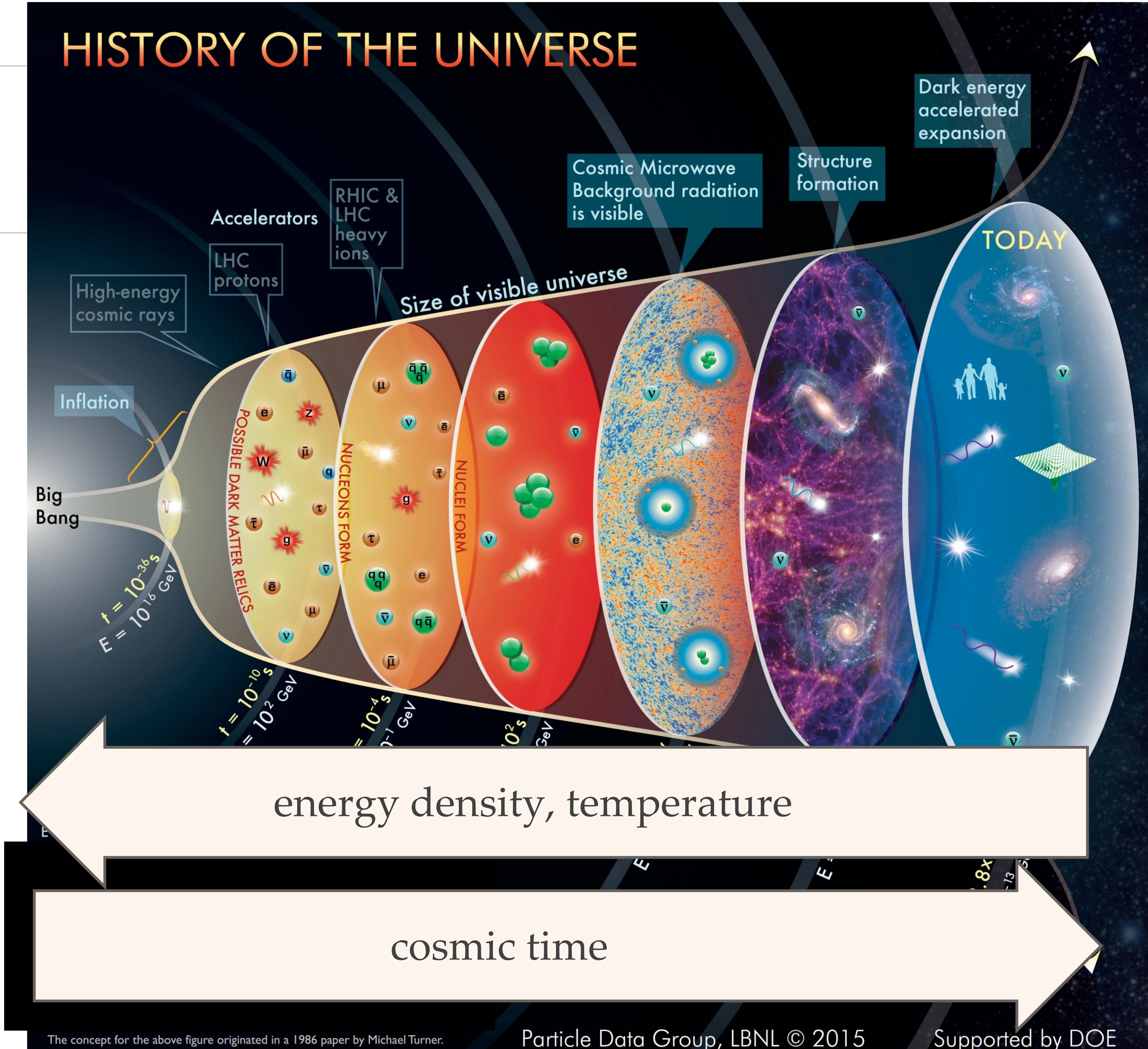
1) Modified Gravity?
2) Or non-luminous matter?
Both possible.
And if 2), it could be anything that doesn't shine or absorb too much

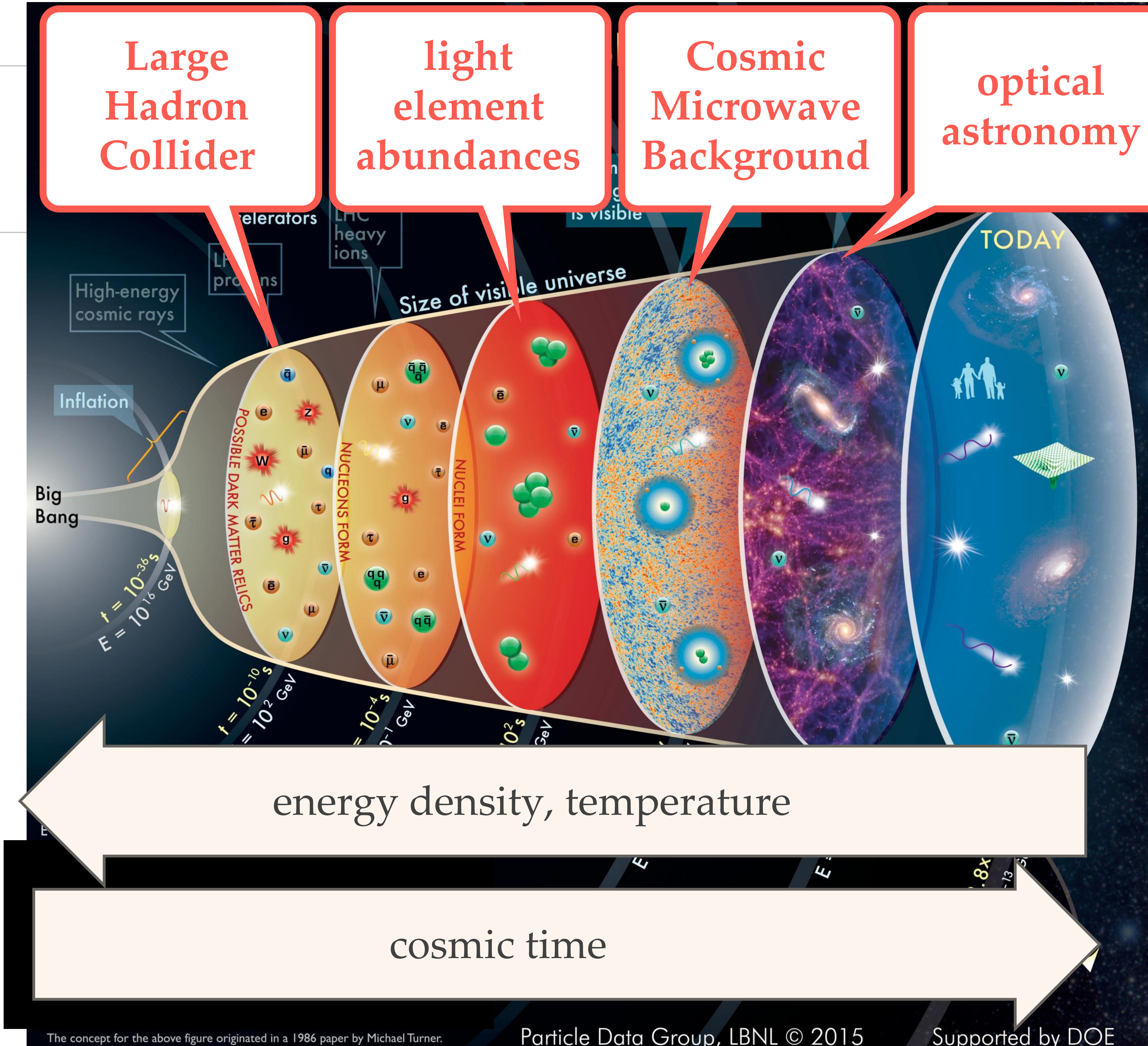
3) Cosmic Microwave Background





w did particle physics shape the universe?


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-10}$ s
energy density, temperature
cosmic time
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



Large Hadron Collider
light element abundances
Cosmic Microwave Background
optical astronomy
High-energy cosmic rays
Inflation
Big Bang
heavy ions
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
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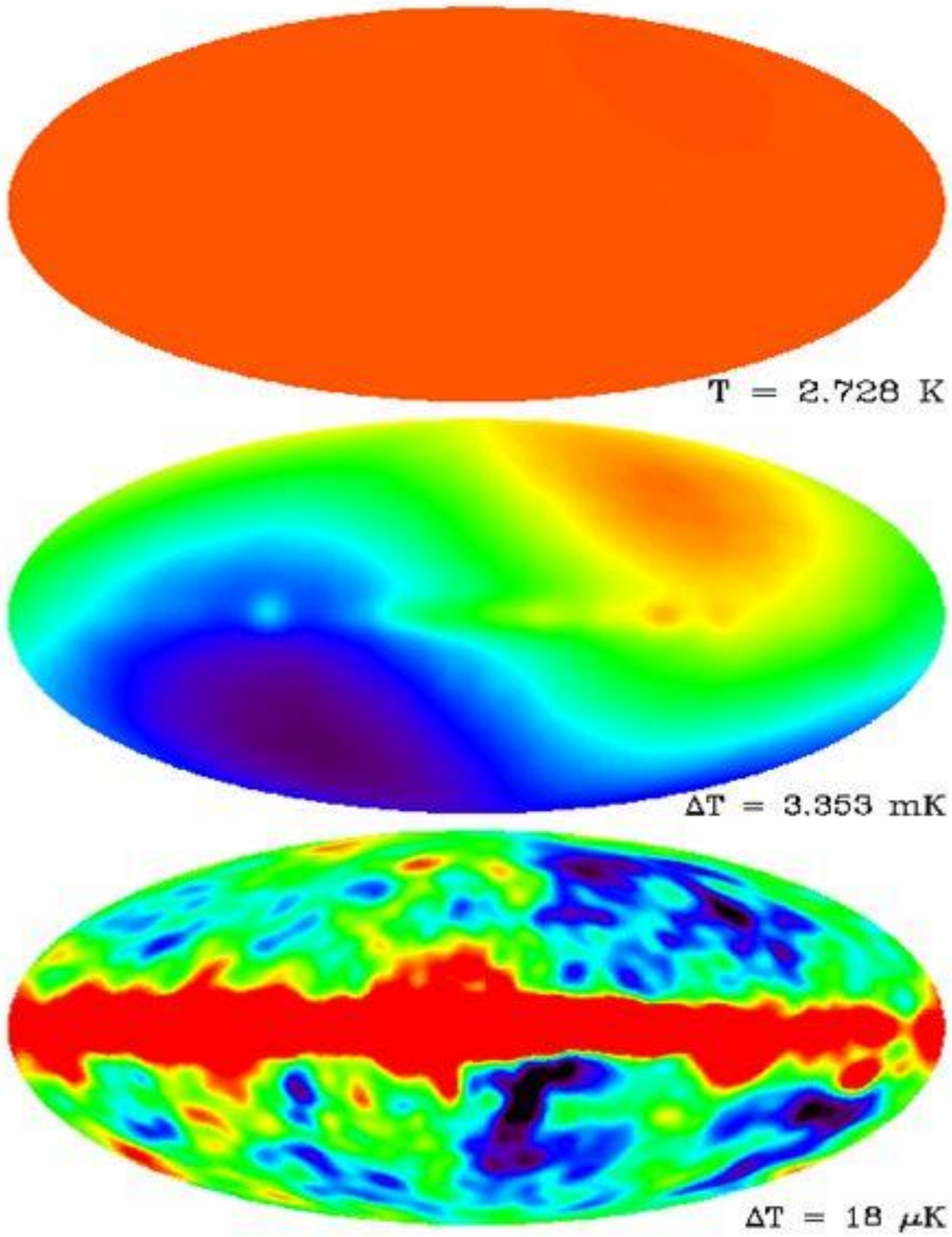
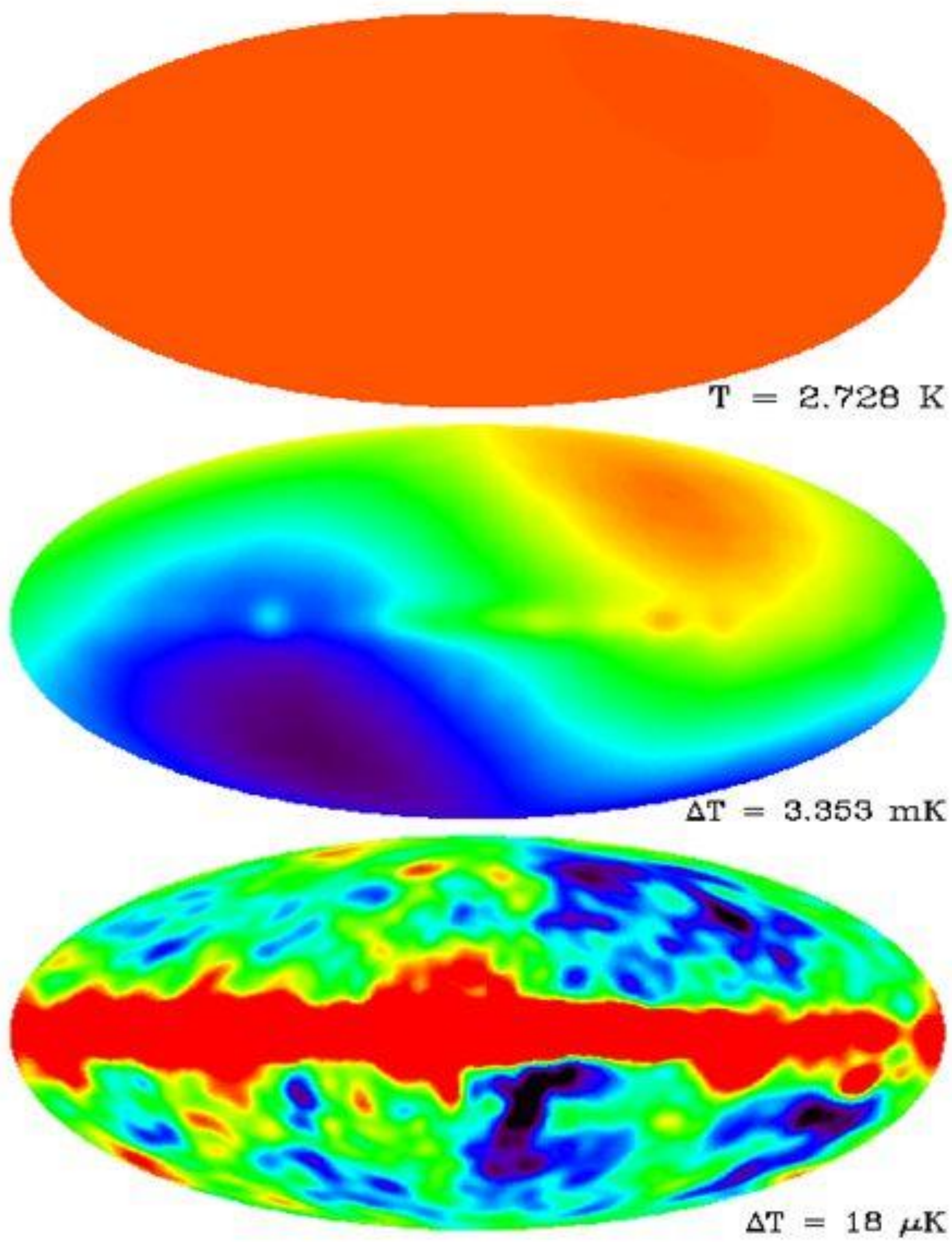


Isotropic 3K background.
The most perfect blackbody
we know

Dipole (3.4 mK).
Our motion relative to CMB

Primordial fluctuations
20 μK

3) Cosmic Microwave Background



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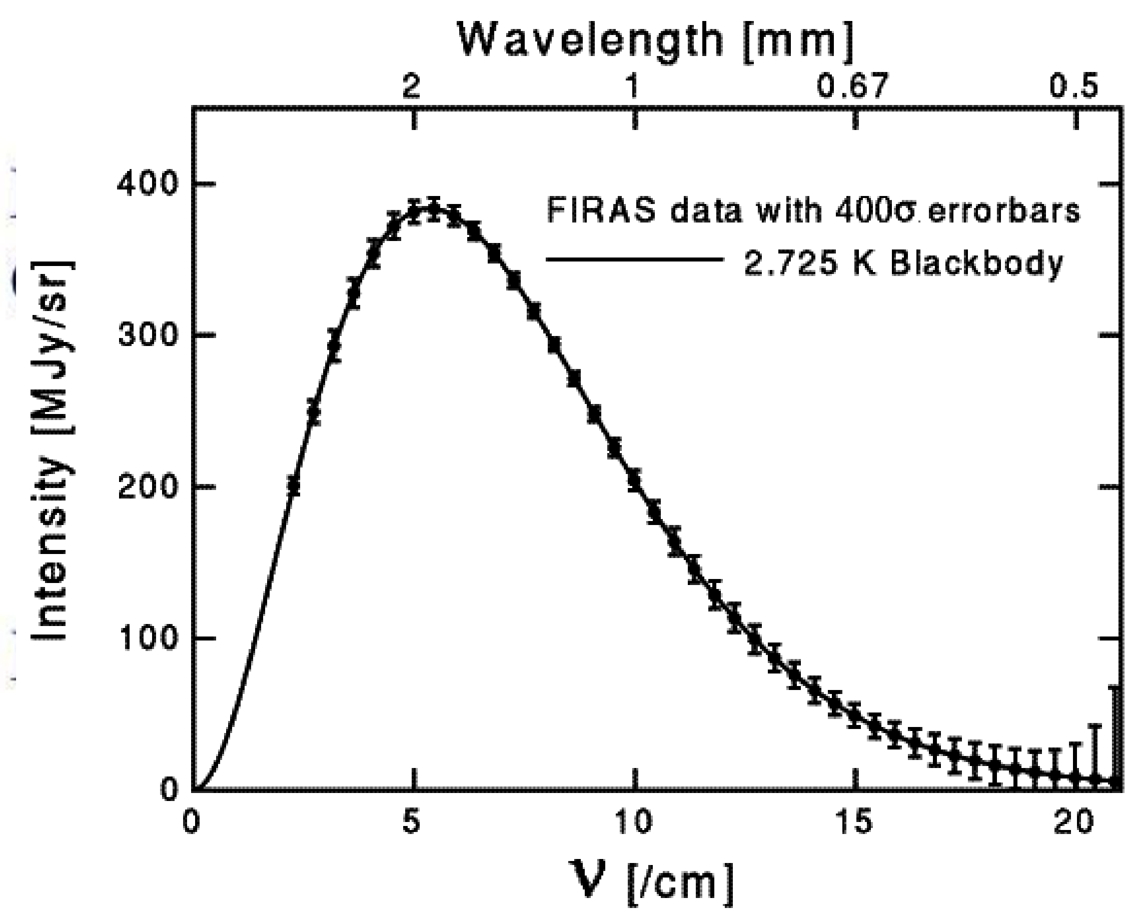

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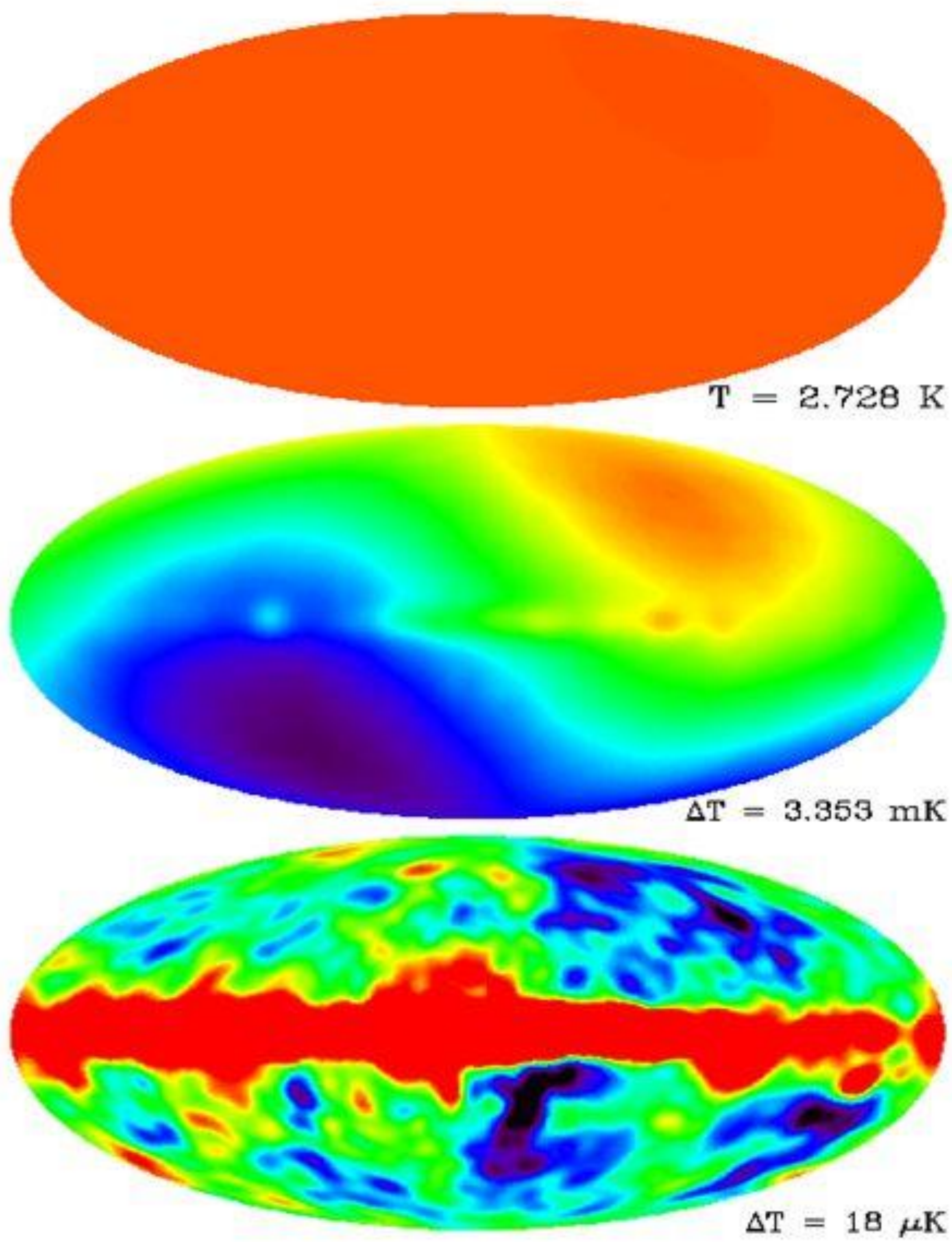

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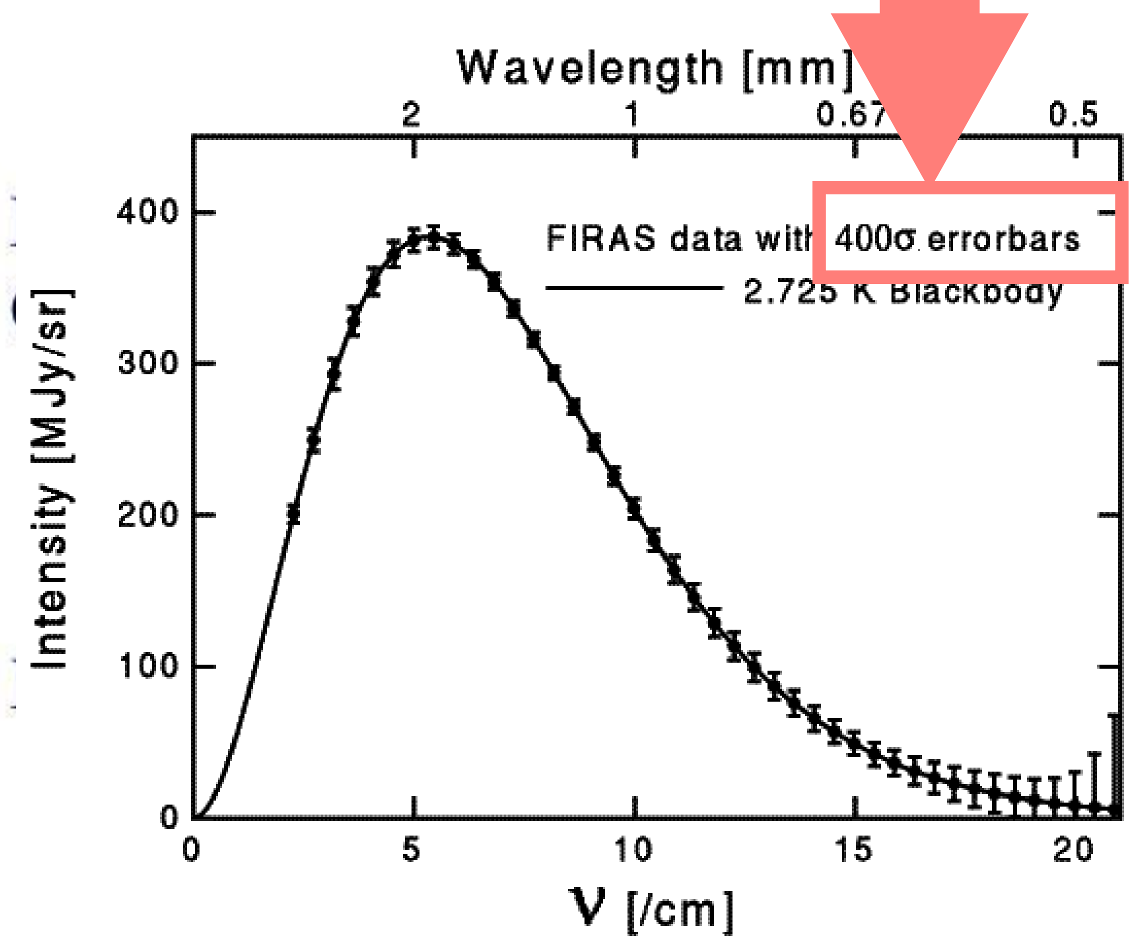

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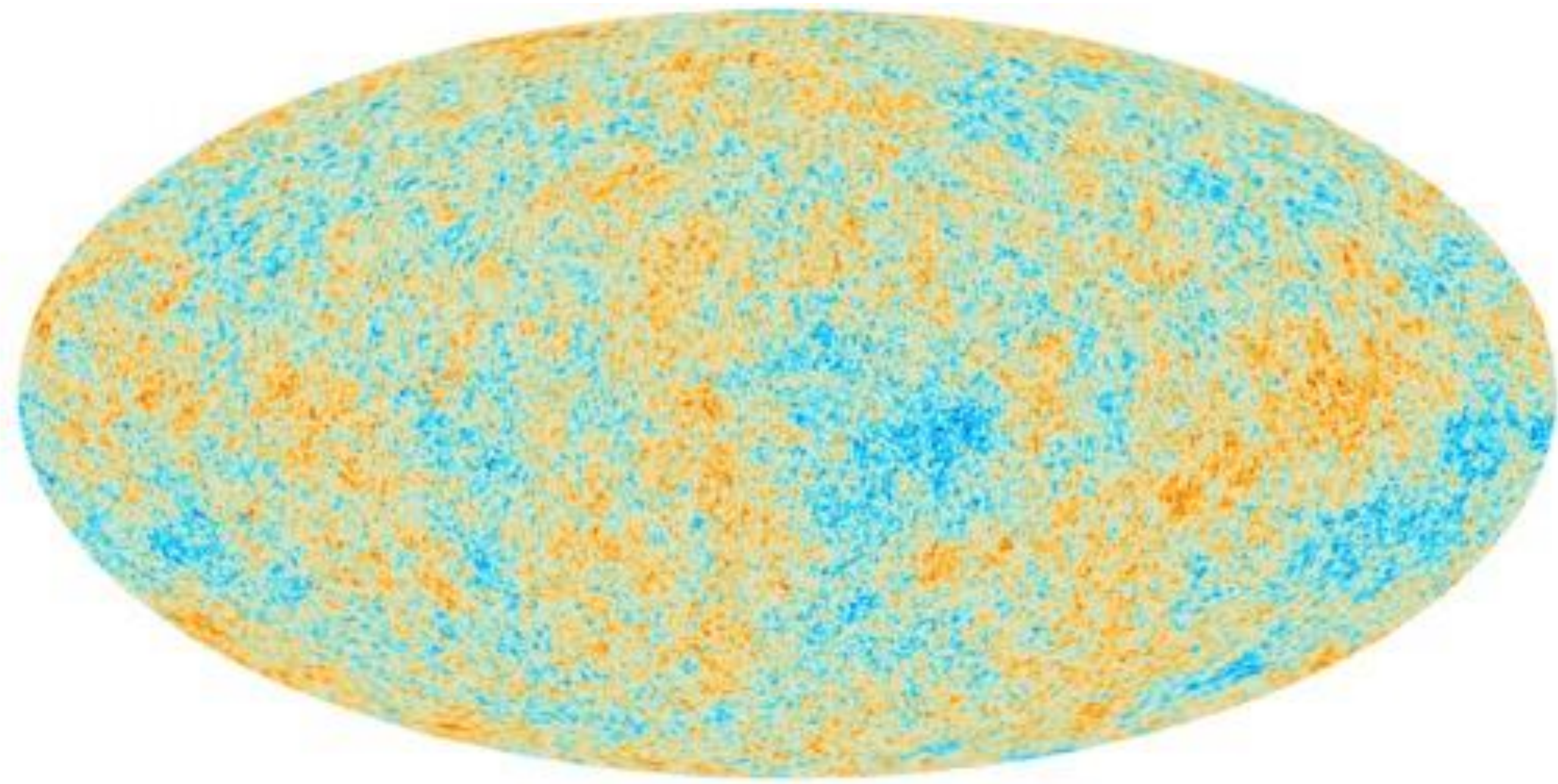

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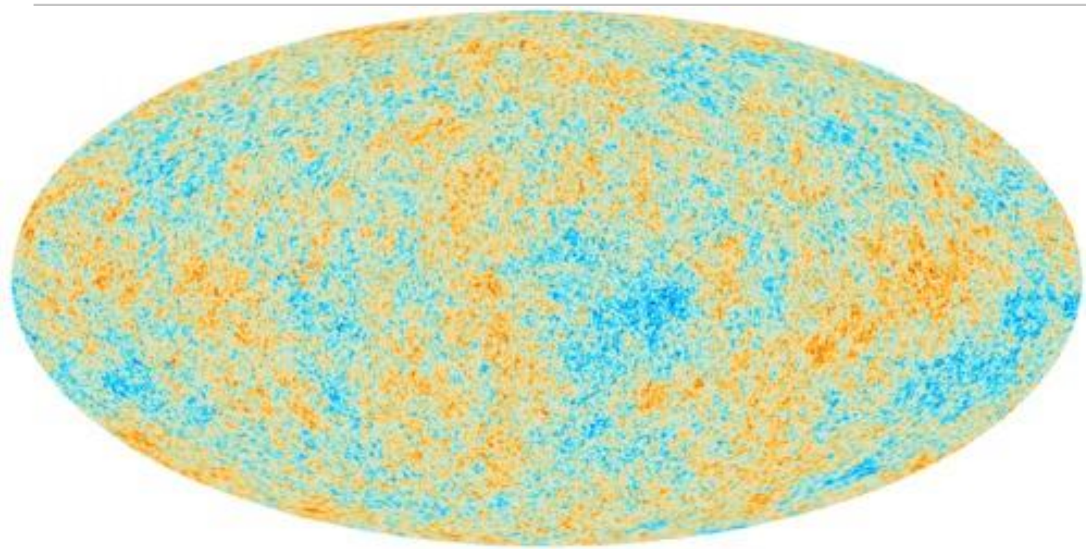
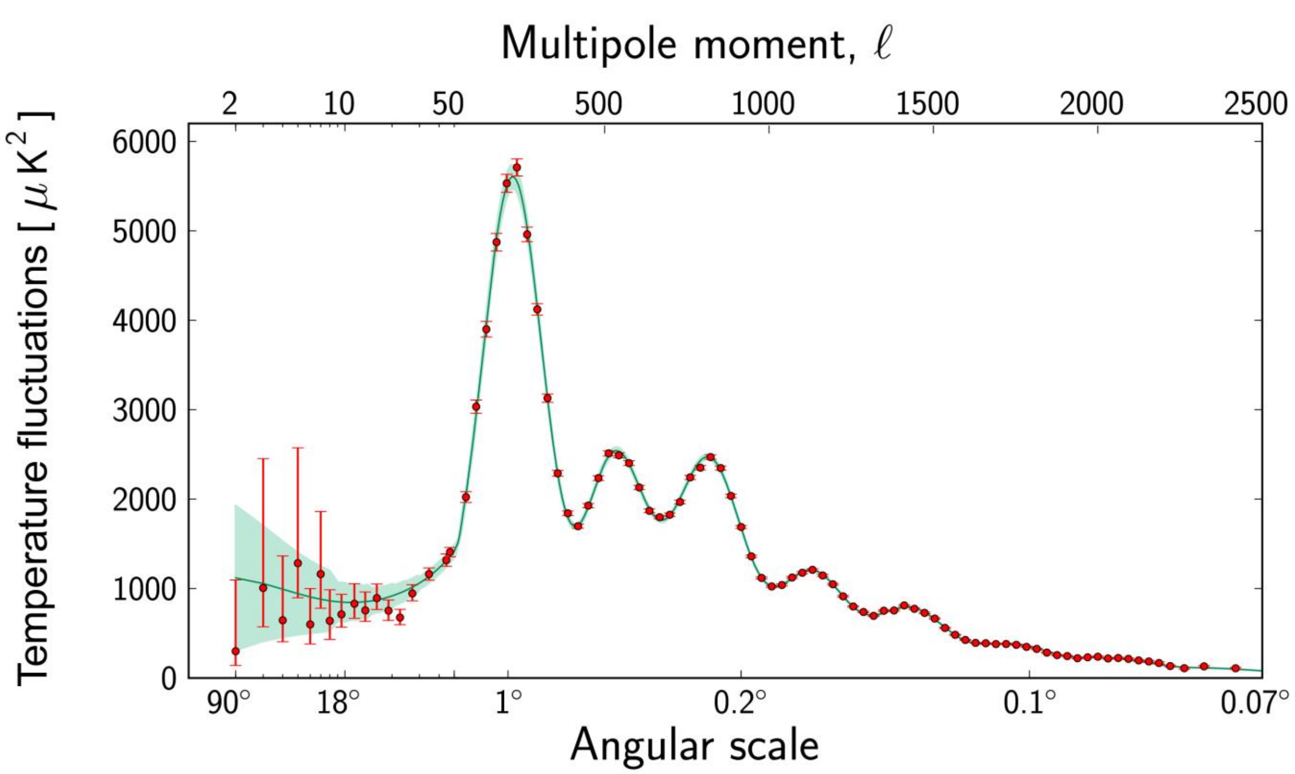
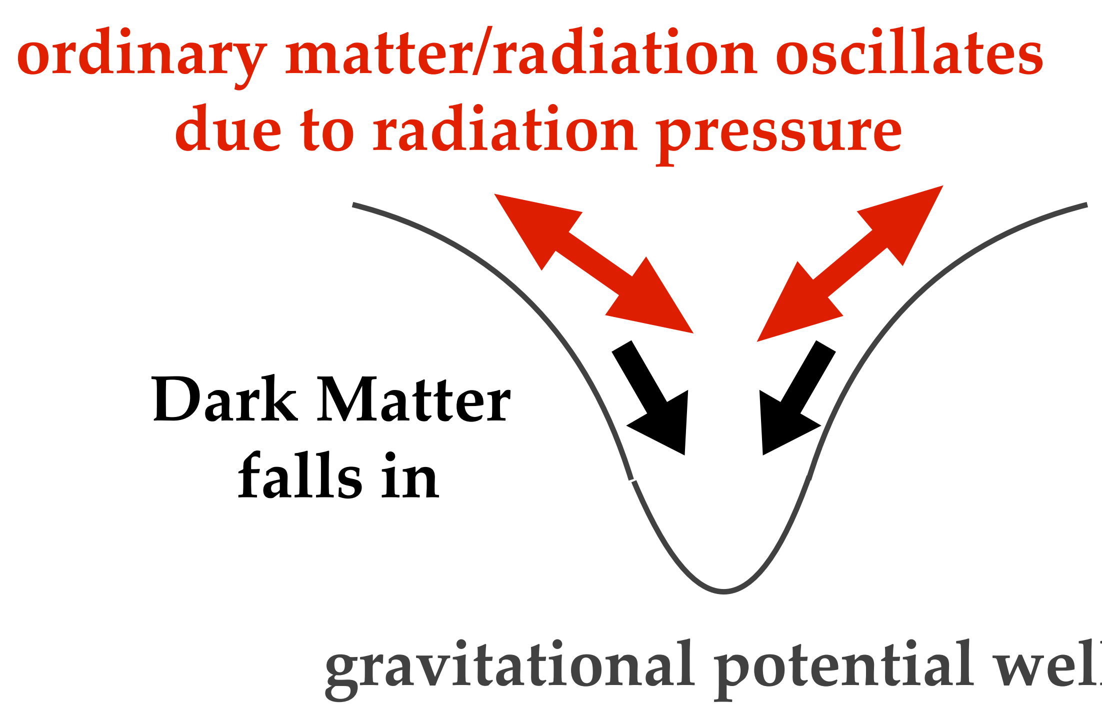


Radiation, baryons and Dark Matter affect the acoustic oscillations in the primordial plasma in different ways…





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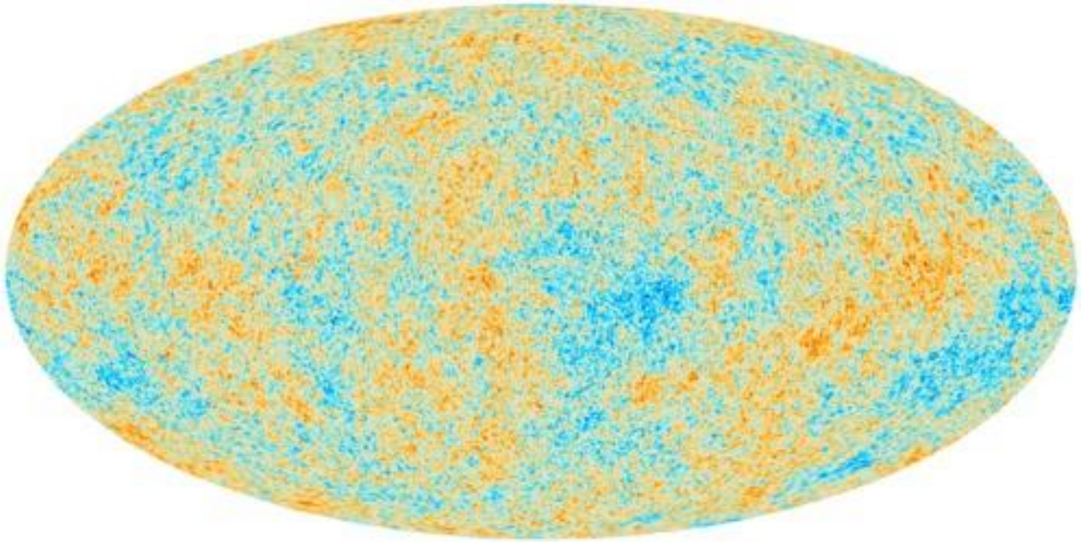
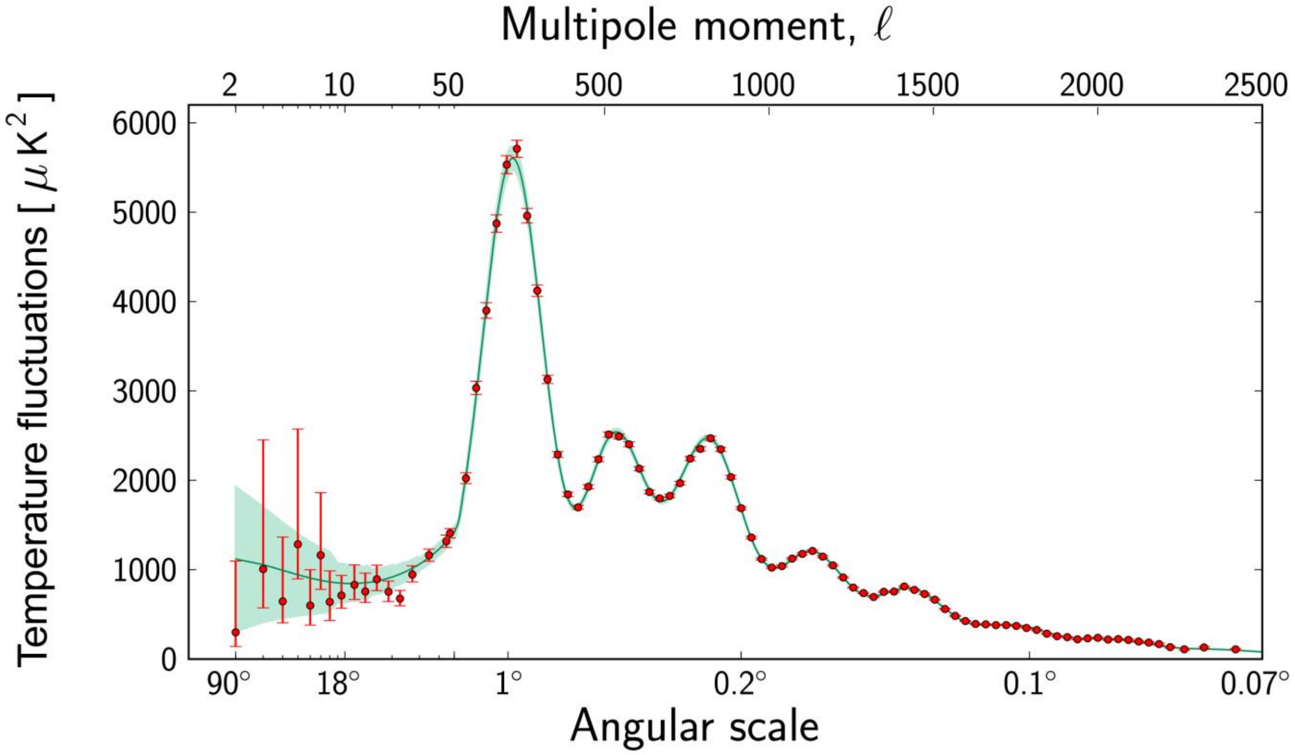
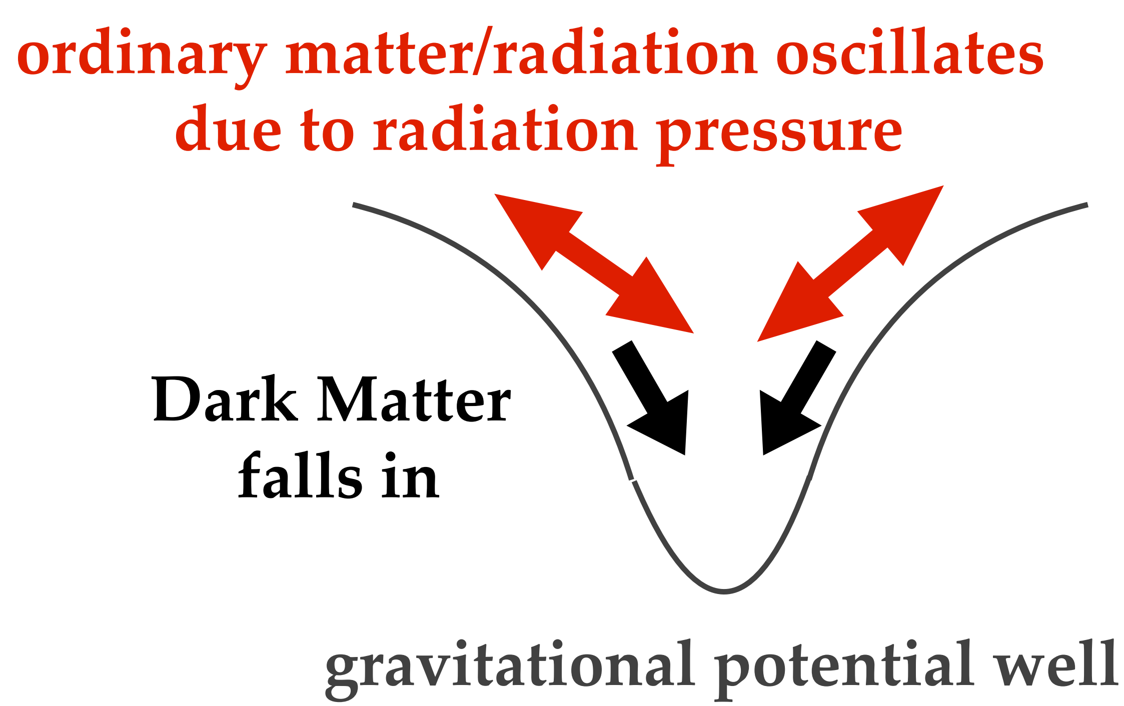


1) Modified Gravity?
2) Or non-luminous matter?





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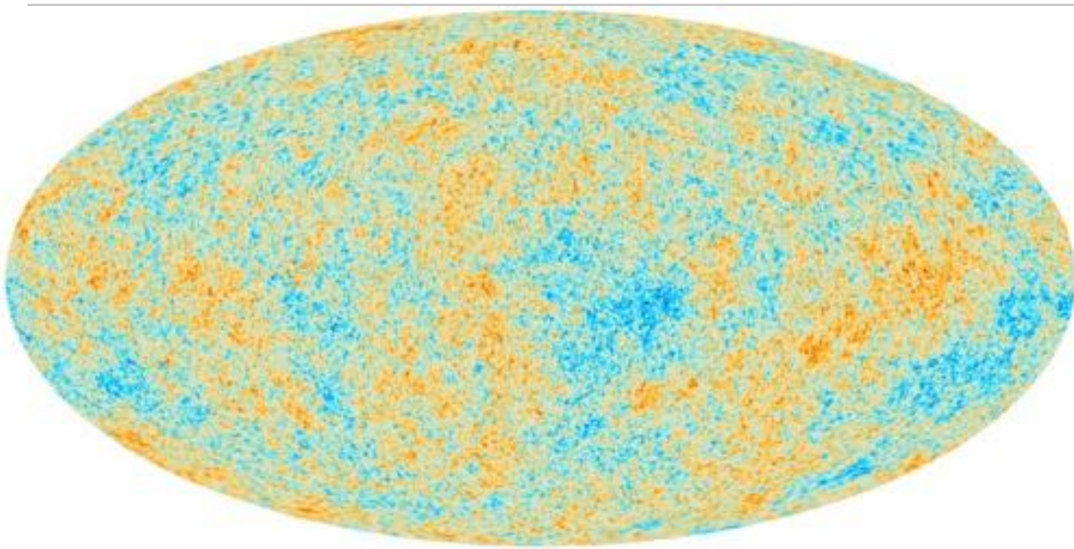

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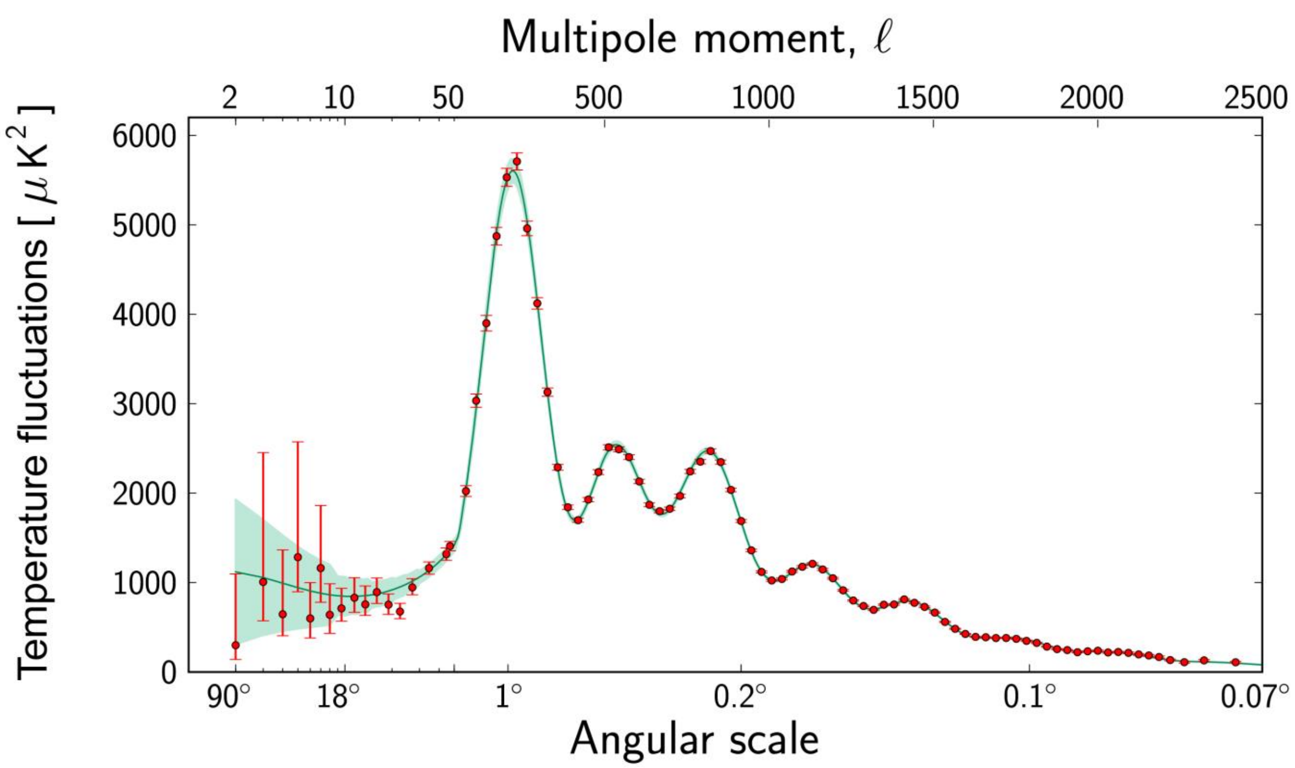
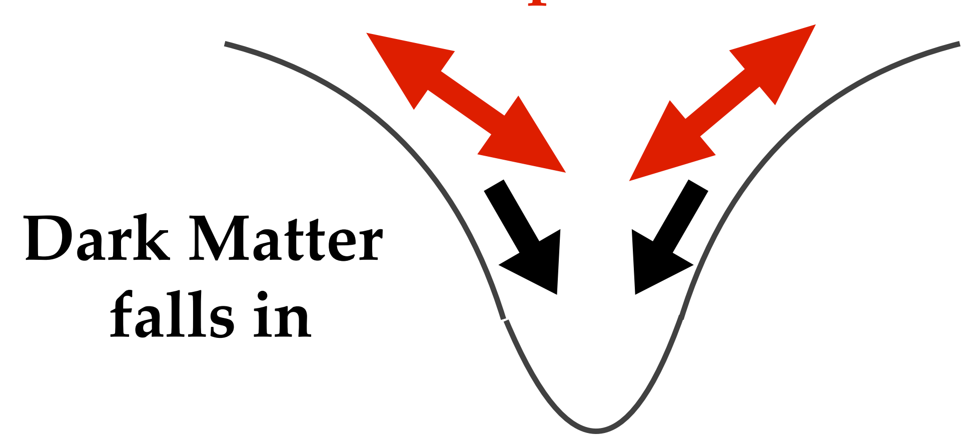
Shows that DM is not made of lumps of baryons.

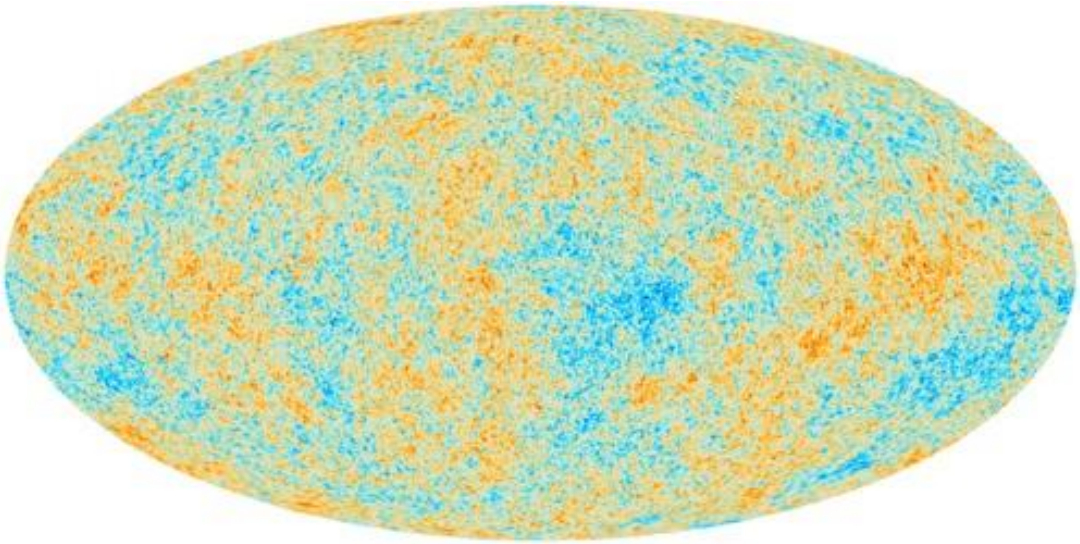


ordinary matter/radiation oscillates due to radiation pressure



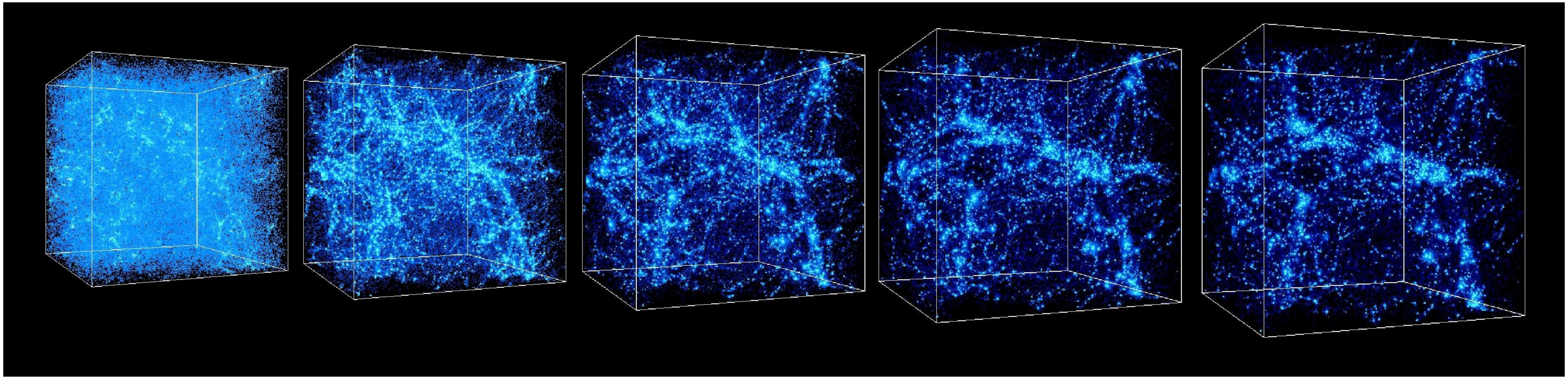
gravitational potential well

4) Structure Formation

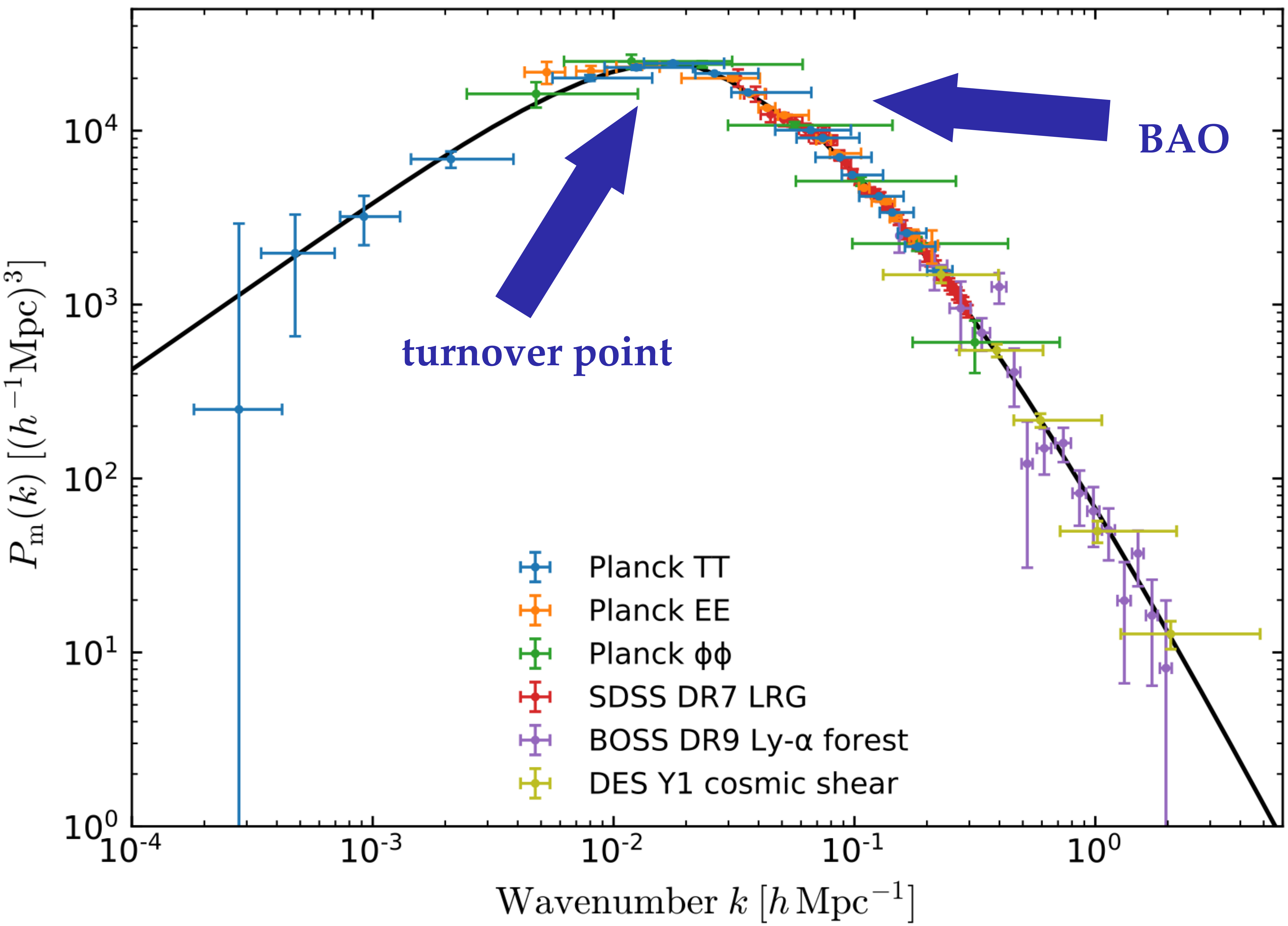


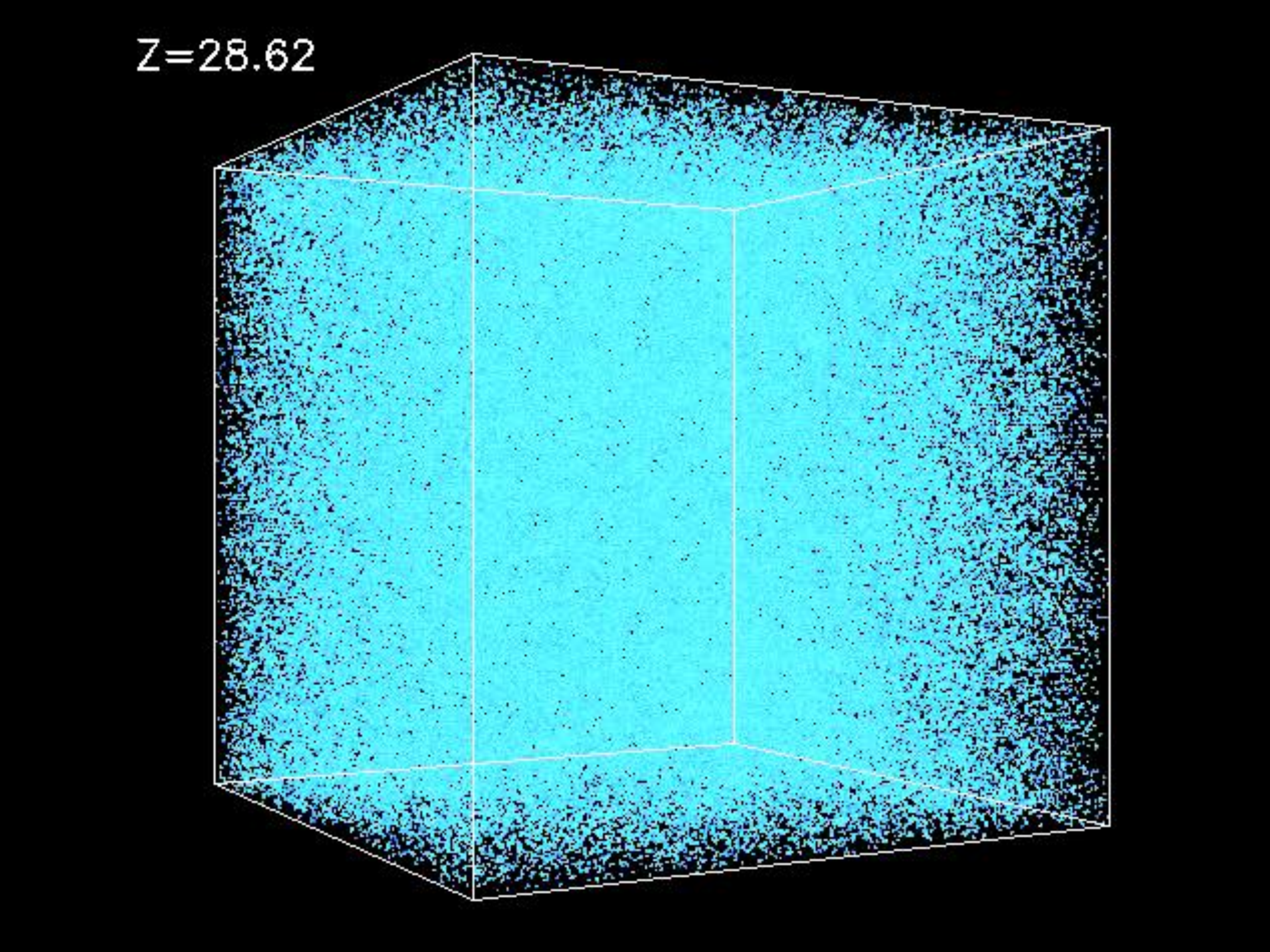
The early universe was very homogeneous and isotropic…

… structure formed by gravitational collapse of small inhomogeneities ~1/100.000



Matter Power Spectrum




Z=28.62

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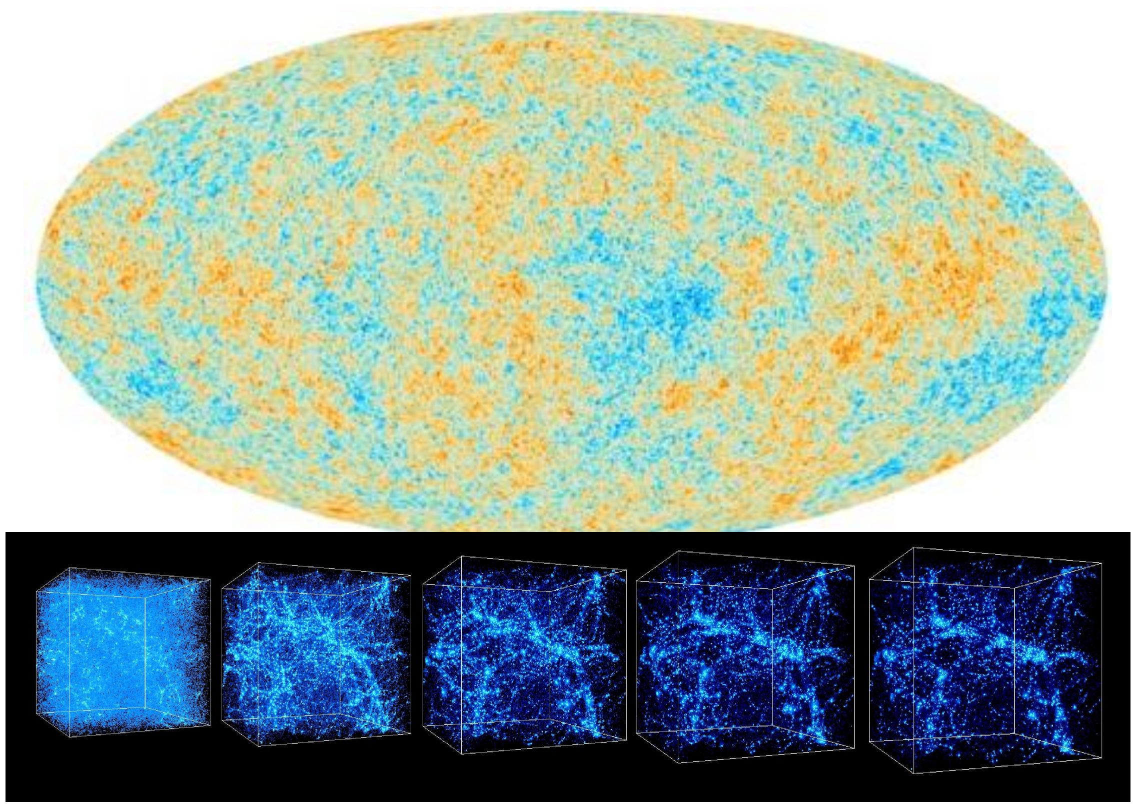

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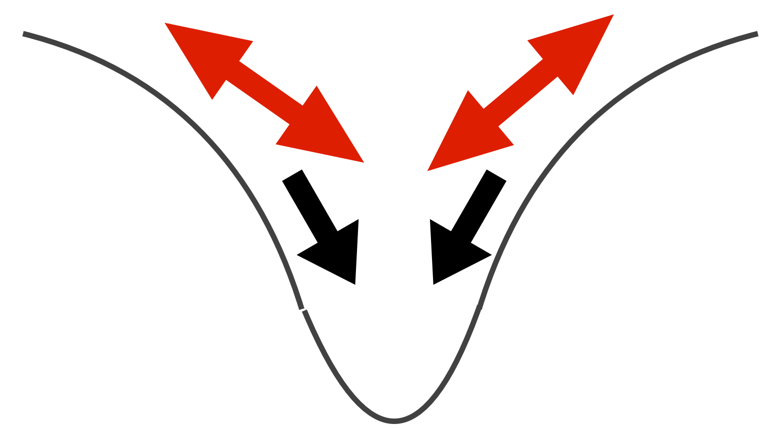

gravitational potential well

Simulations only agree with observation if this process starts before the CMB decoupled

Must be driven by particles that do not feel the radiation pressure!

4) Structure Formation

1) Modified Gravity?
2) Or non-luminous matter?

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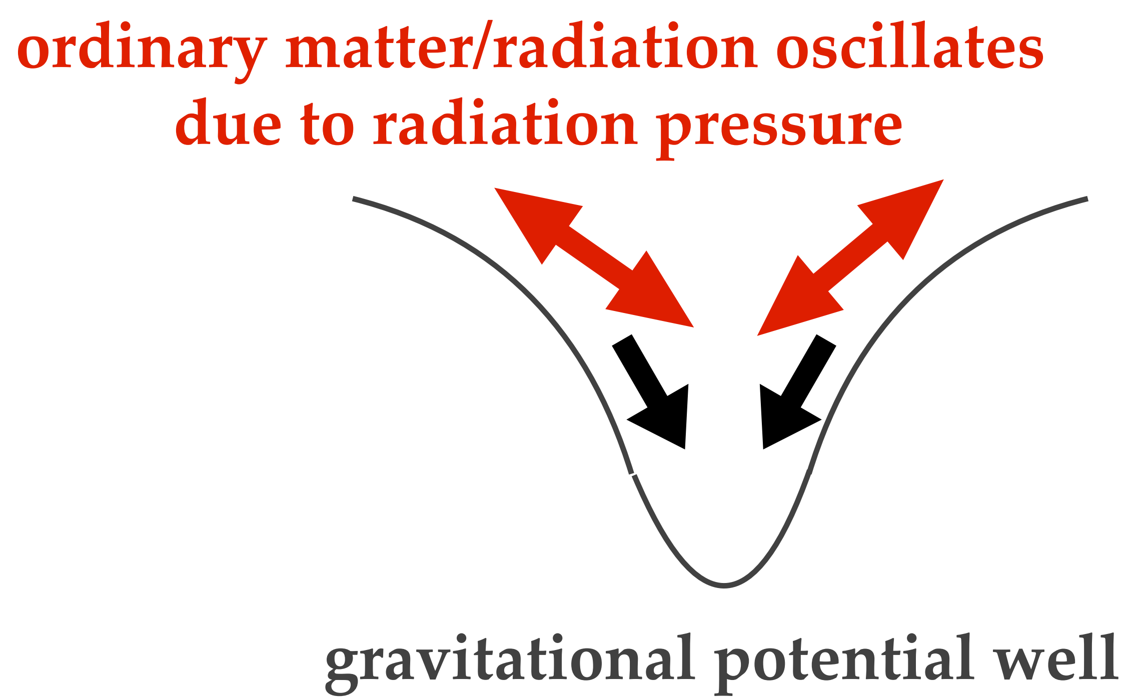

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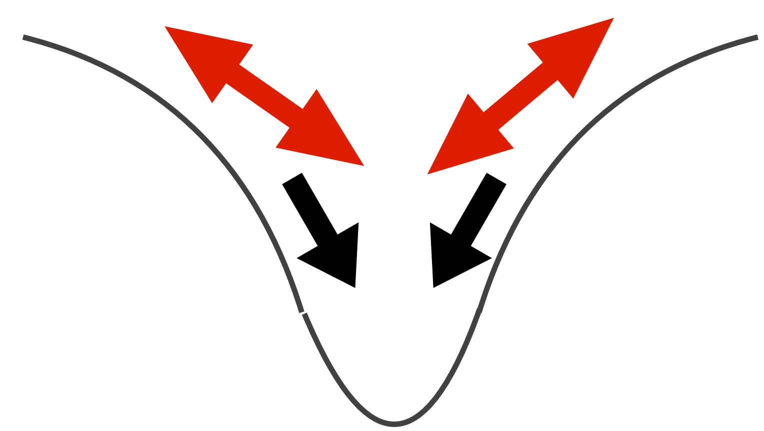

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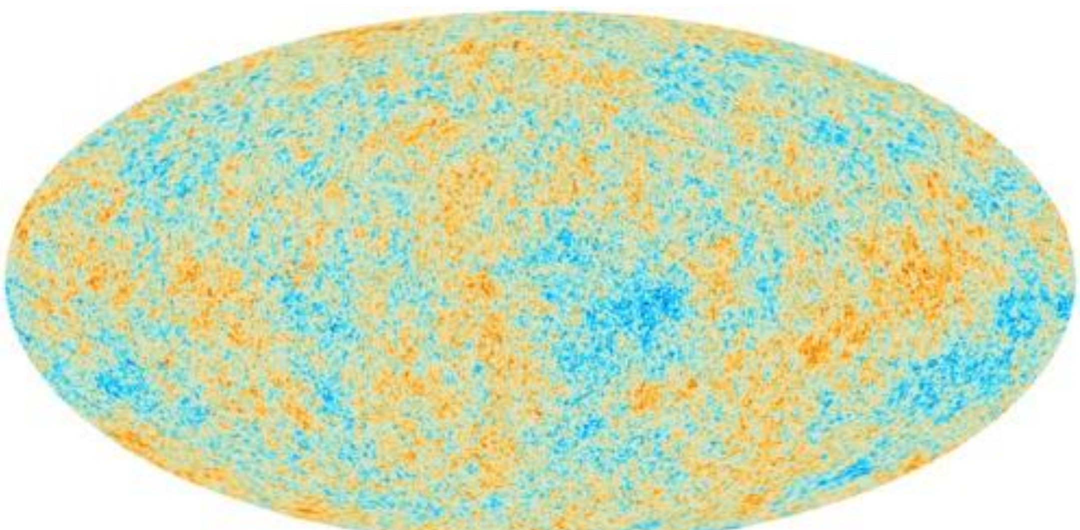
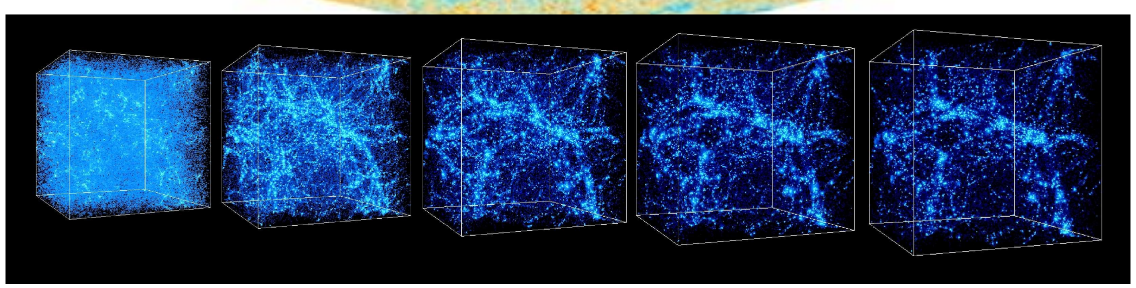
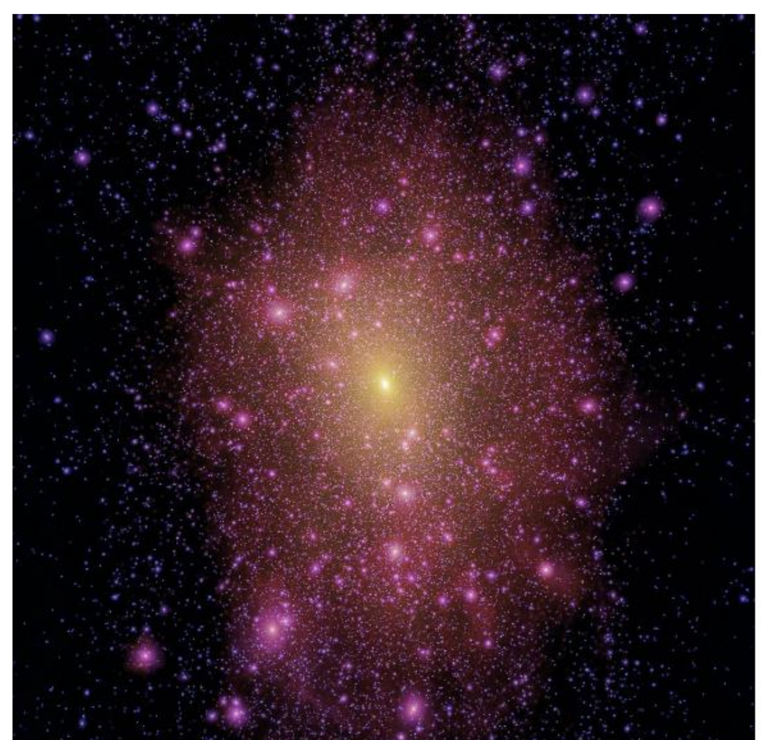




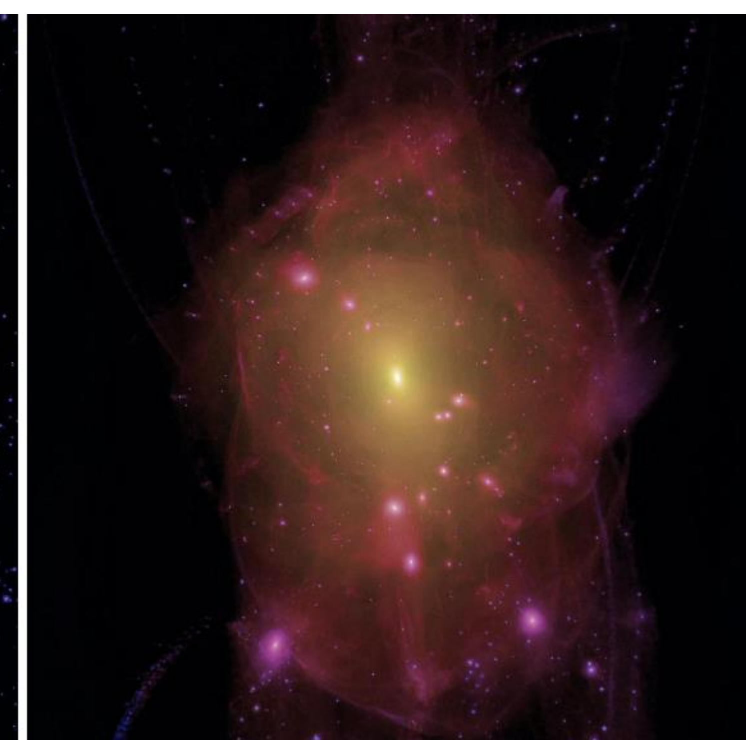
Movement of Dark Matter particles during structure formation “smears out” the inhomogeneities…

… which leads to a suppression of small scale structures in the universe!

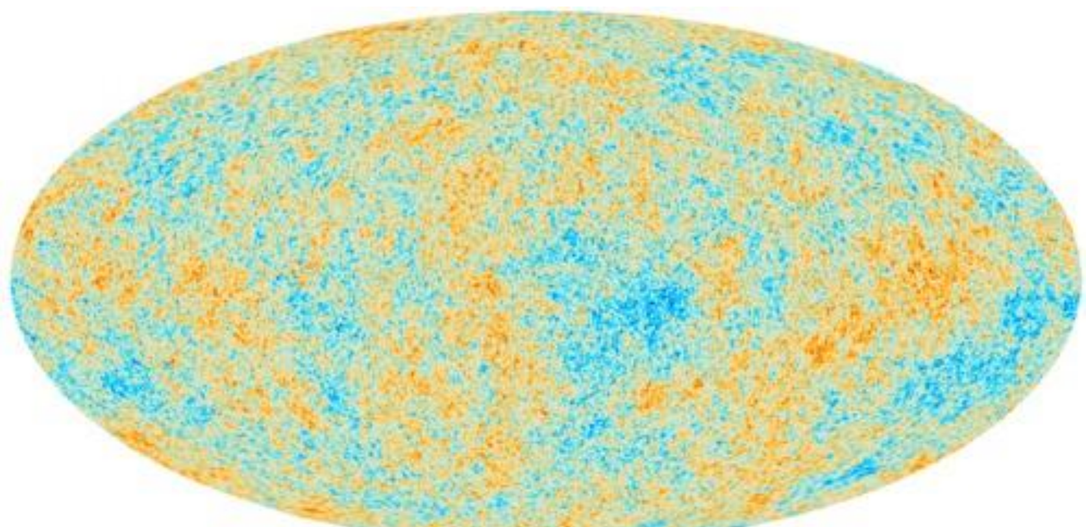
“cold” DM

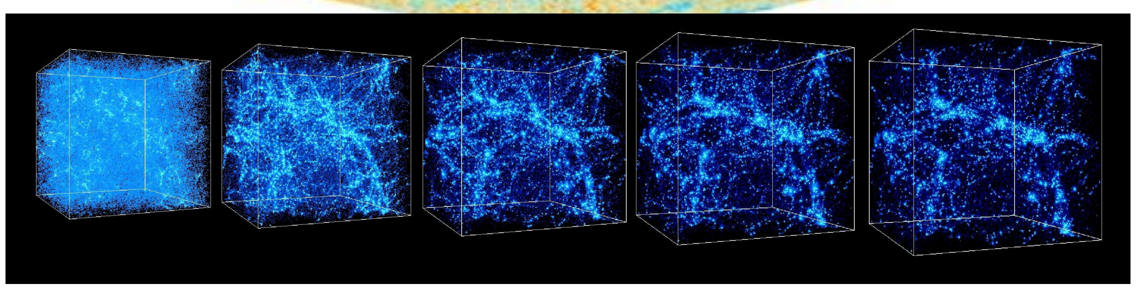


“warm” DM



4) Structure Formation





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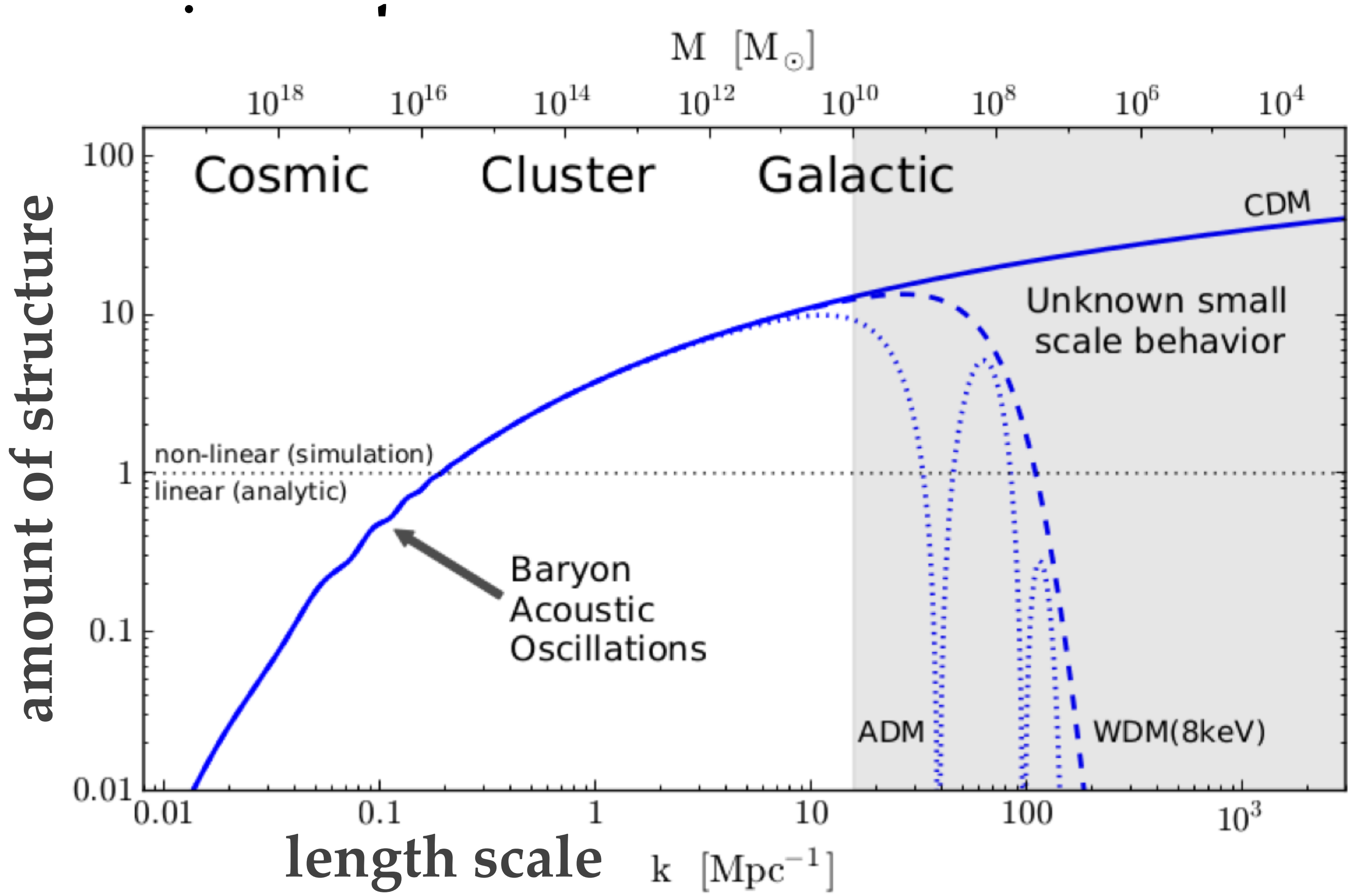


This can be quantified in terms of the **matter power spectrum**

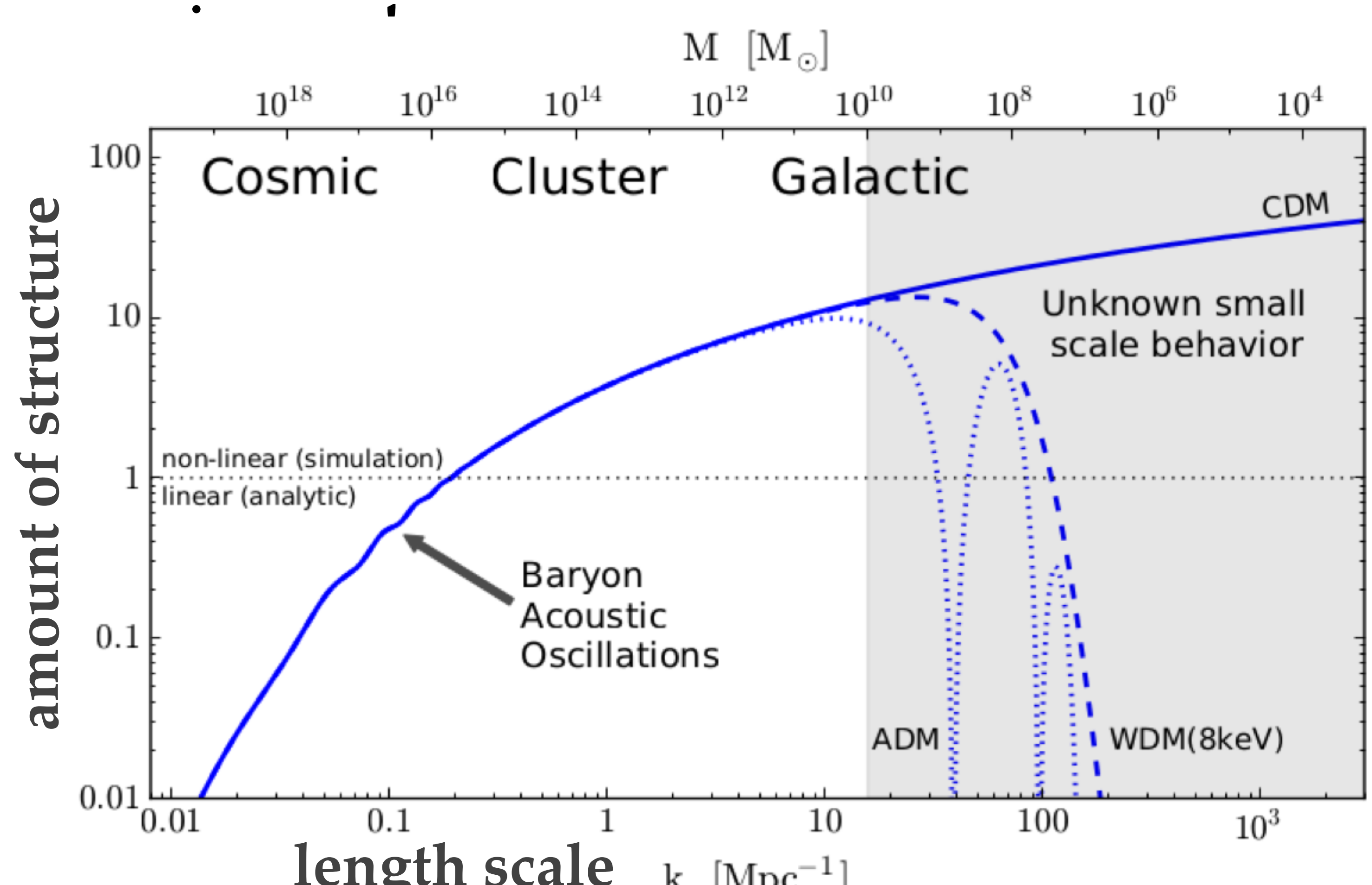
4) Structure Formation

Dark Matter must be (relatively) "cold", i.e., non-relativistic at the time of structure formation

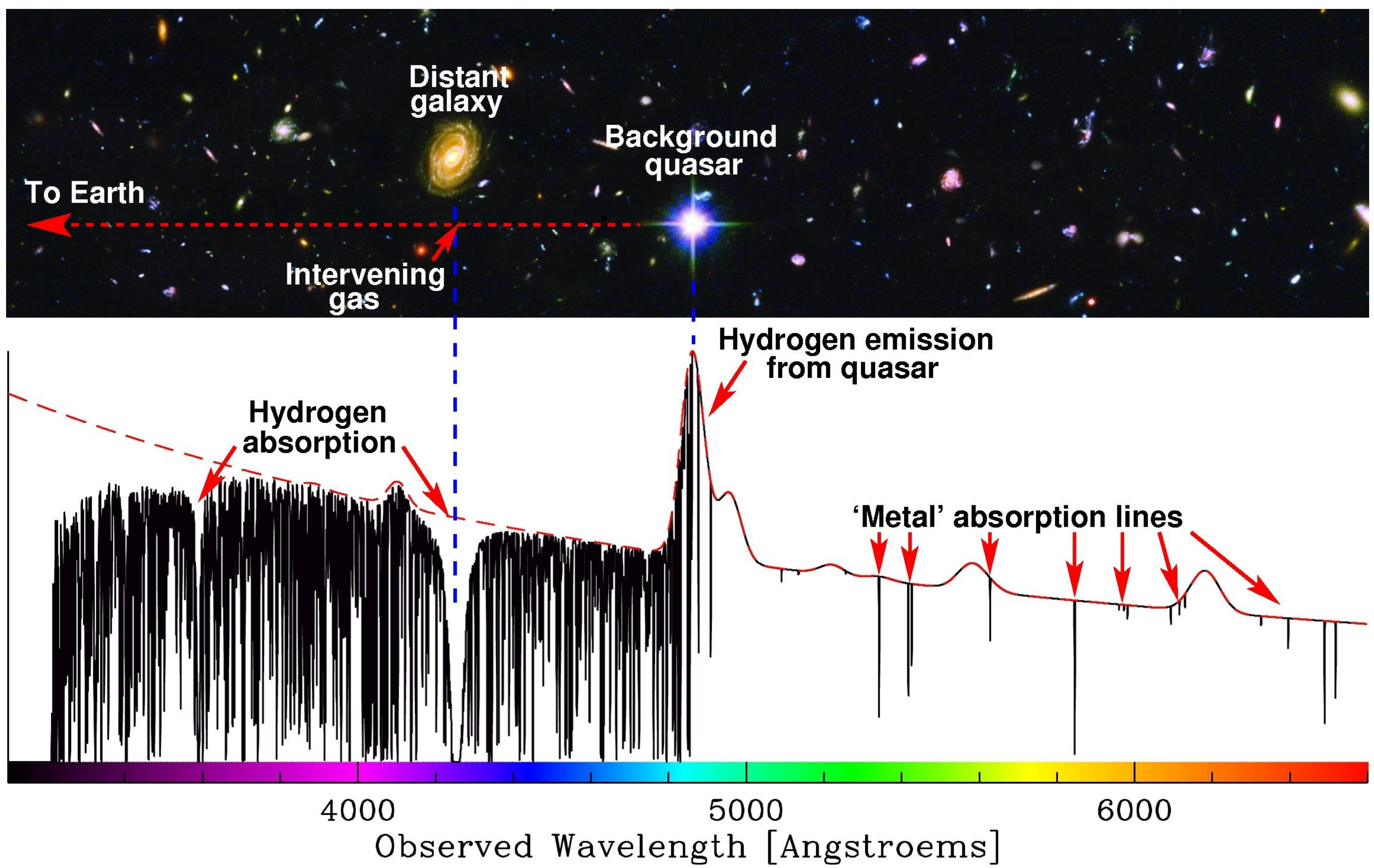
Movement of Dark Matter particles during structure formation "smears out" the inhomogeneities…

… which leads to a suppression of small scale structures in the

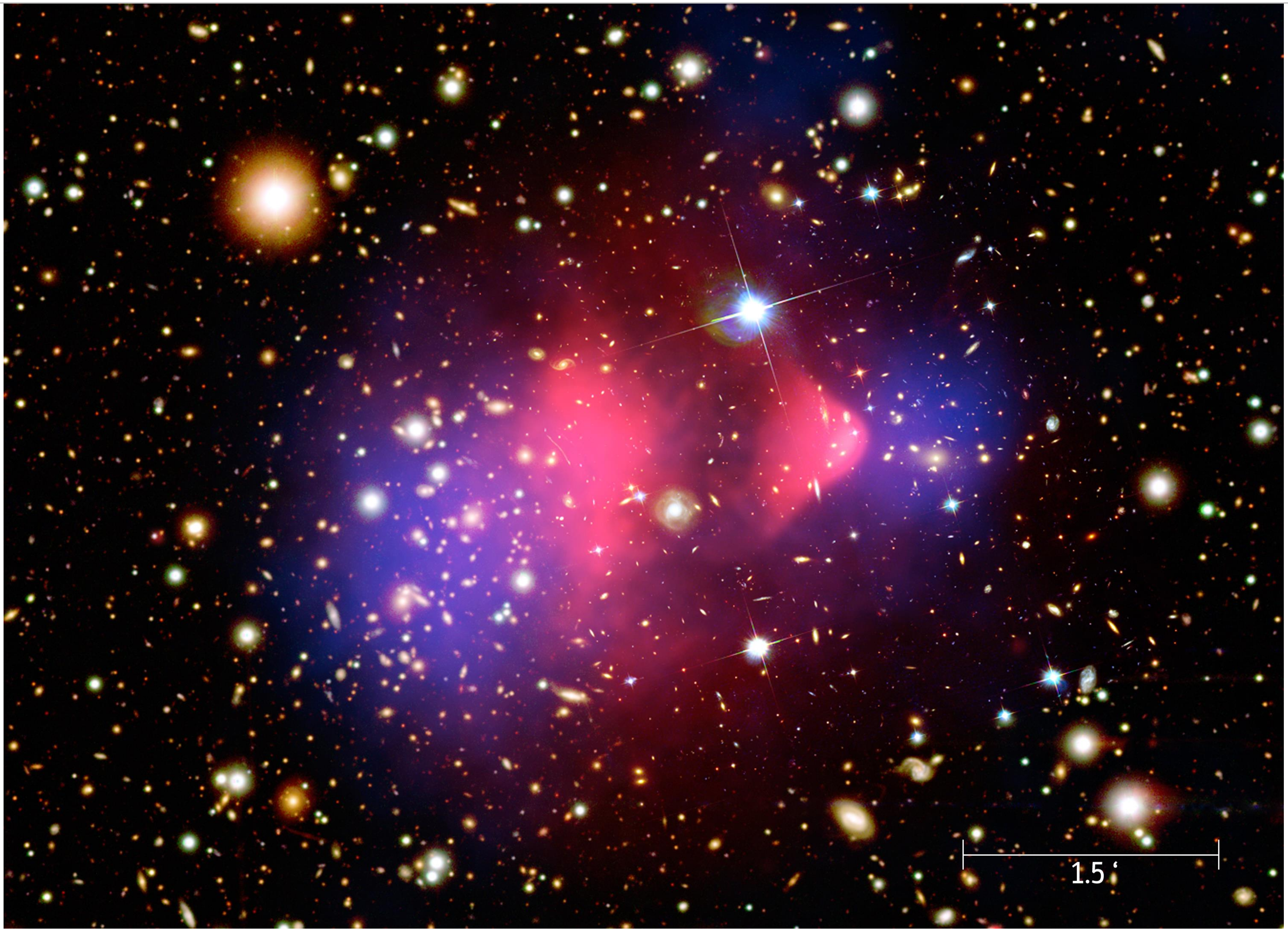
This can be quantified in terms of the **matter power spectrum**



Lyman Alpha Forest



5) Bullet Cluster (and friends)



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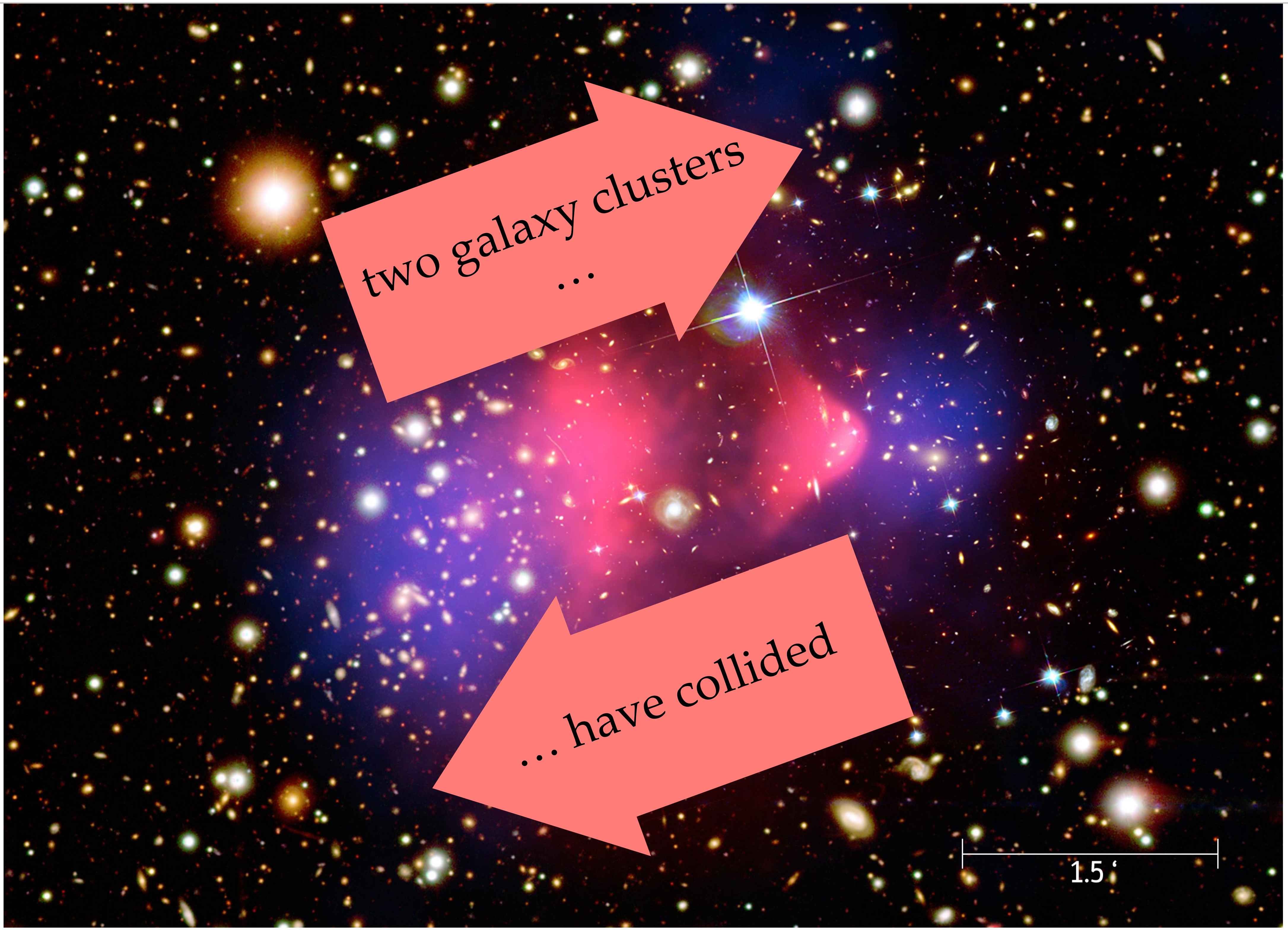

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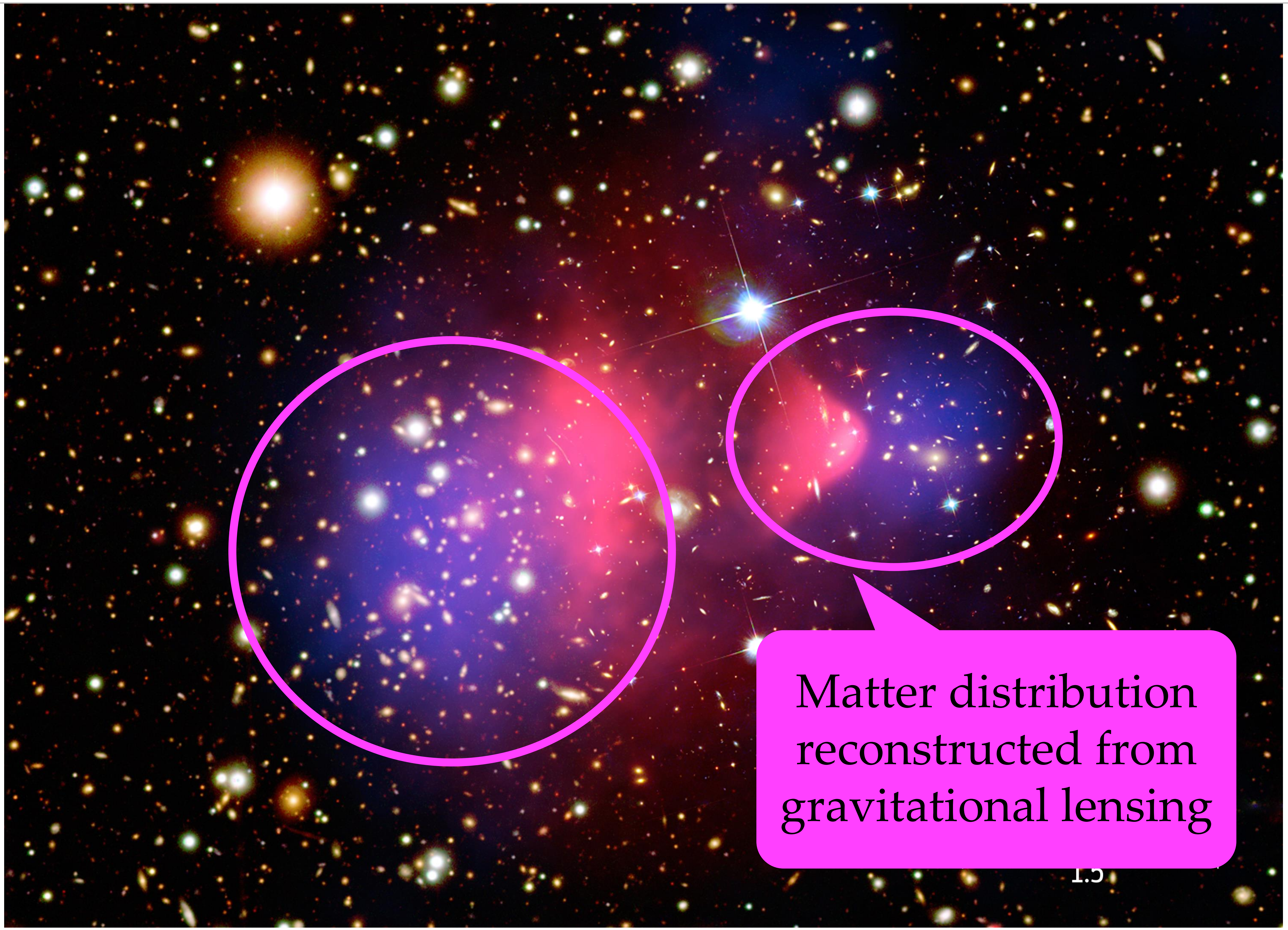

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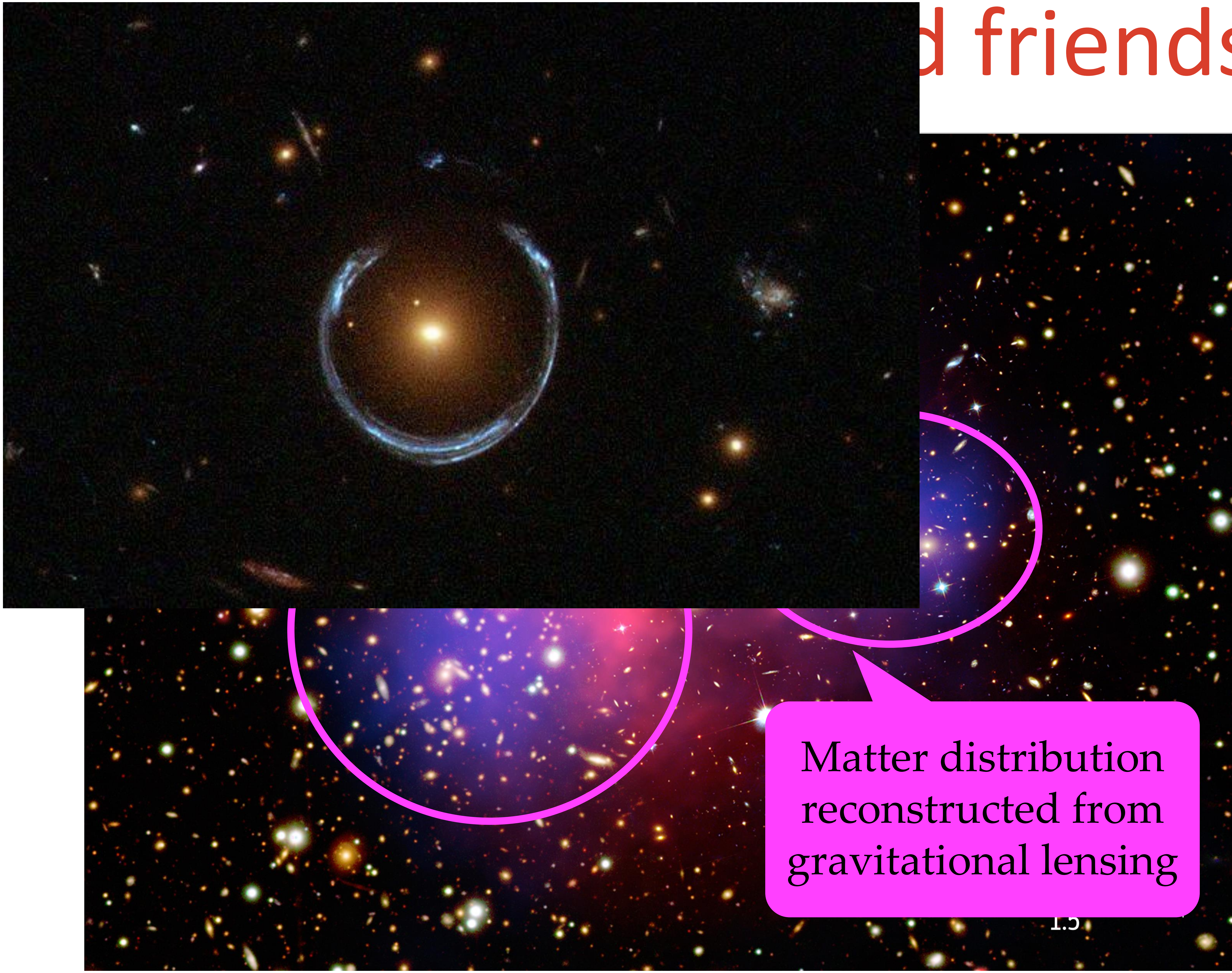
Matter distribution
reconstructed from
gravitational lensing

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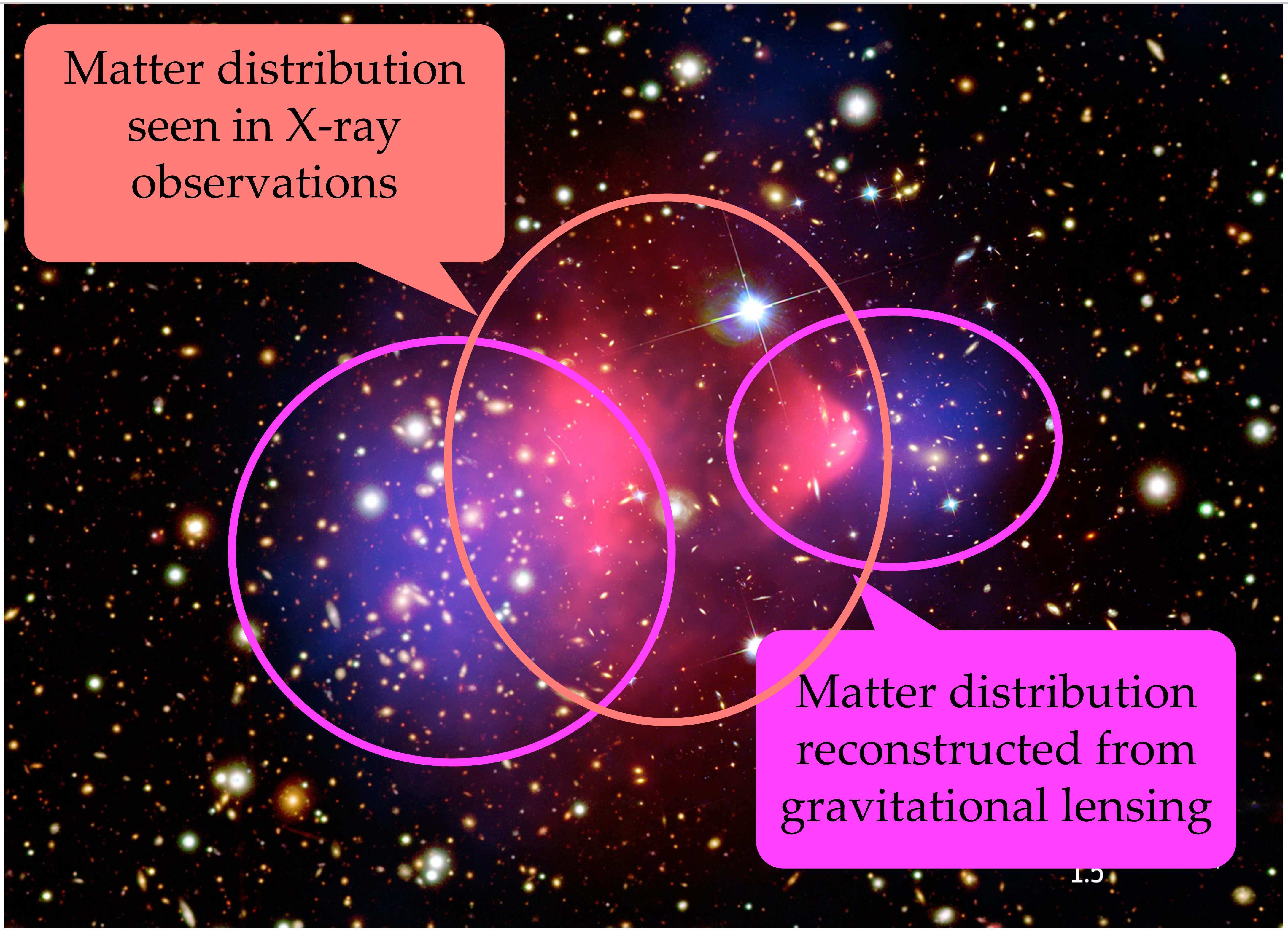

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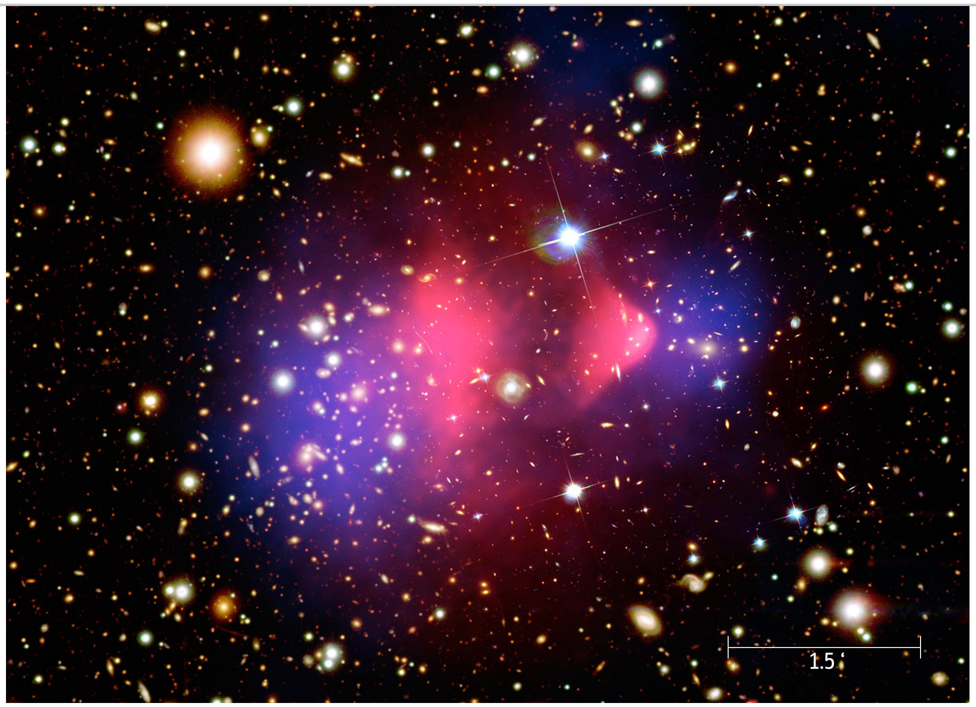

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The visible matter scatters and undergoes a merger.

The Dark Matter is collision free and passes.

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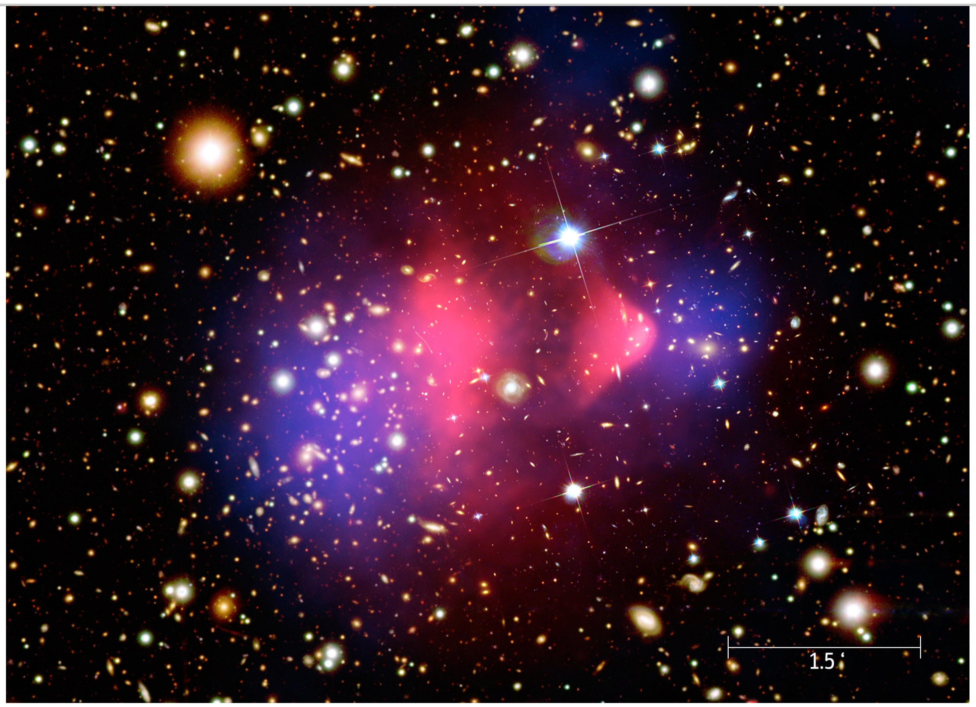

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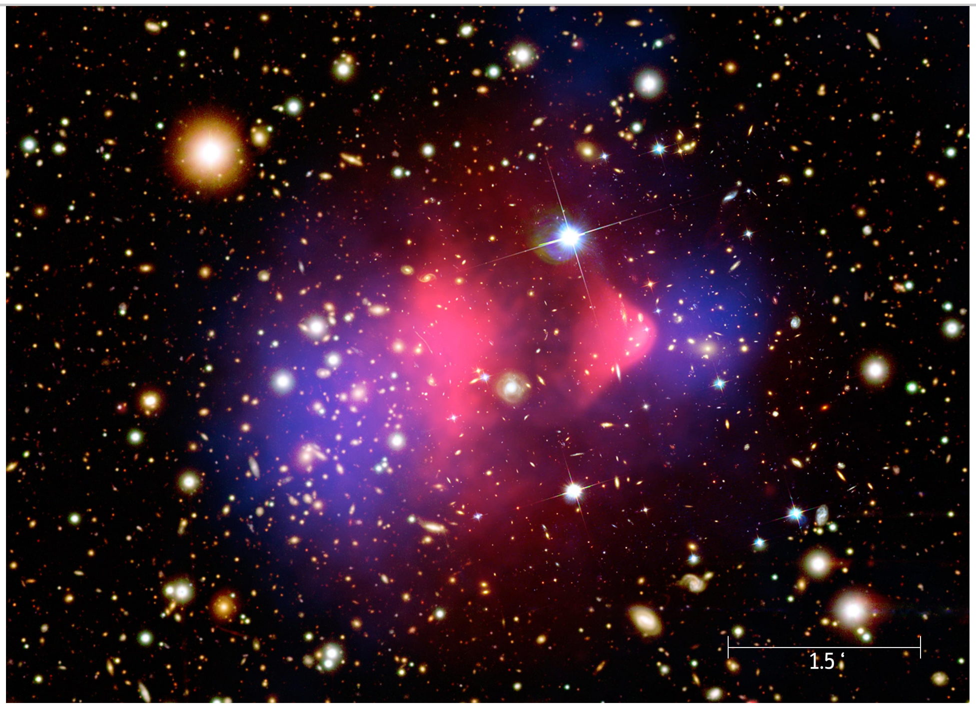

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The Dark Matter is collision free and passes.

1) Modified Gravity?
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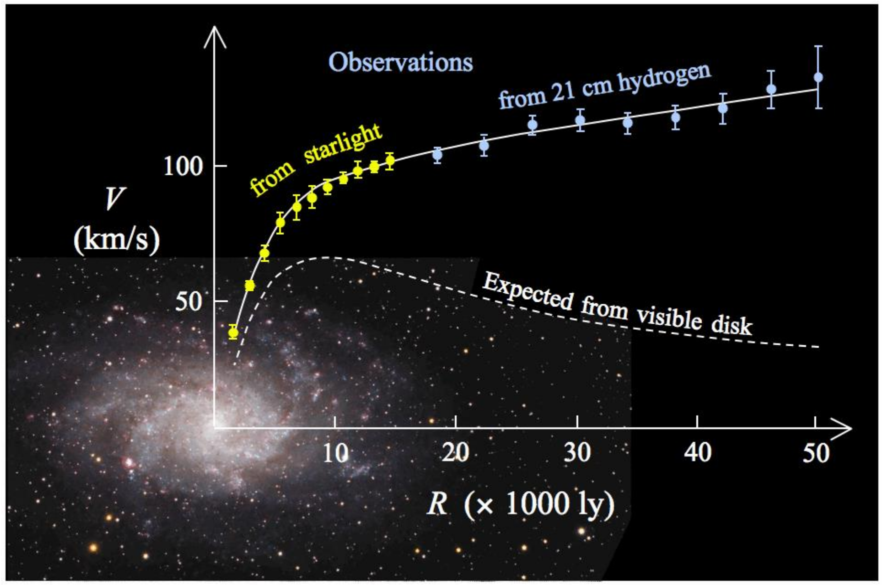
Very difficult to explain with modified gravity.
Shows that DM is collisionless.

Summary

There is compelling evidence that ~80% of the mass in the universe is made of particles that are



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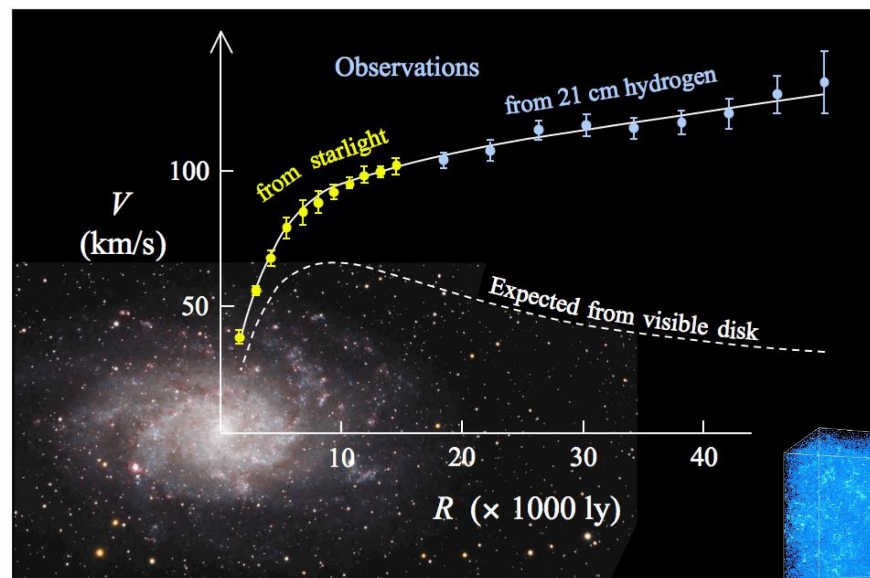

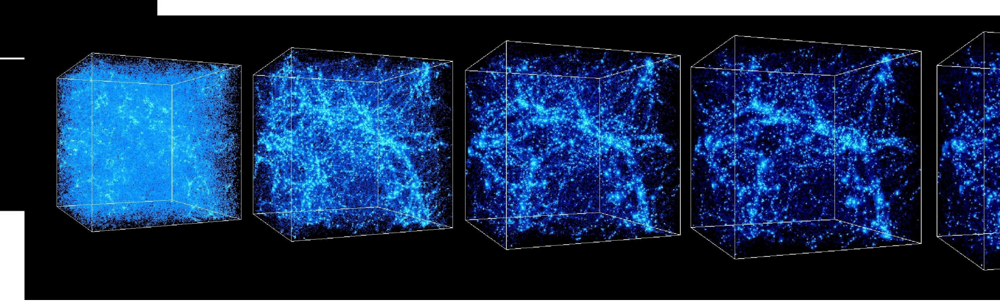

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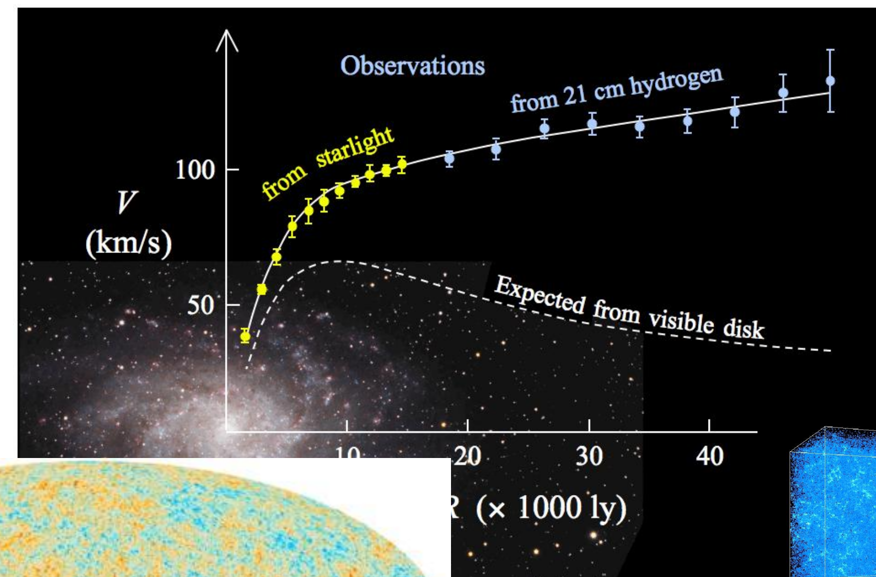

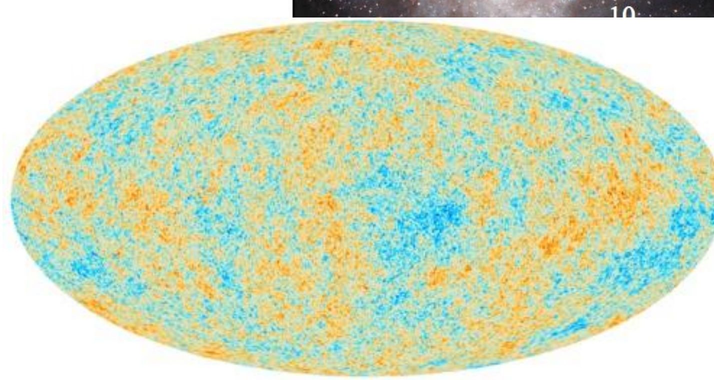

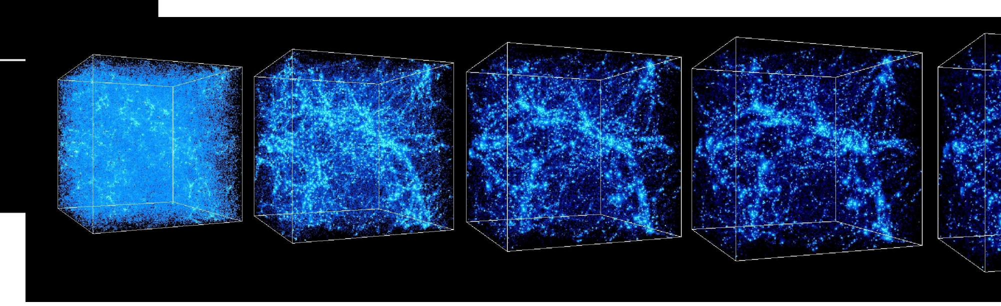

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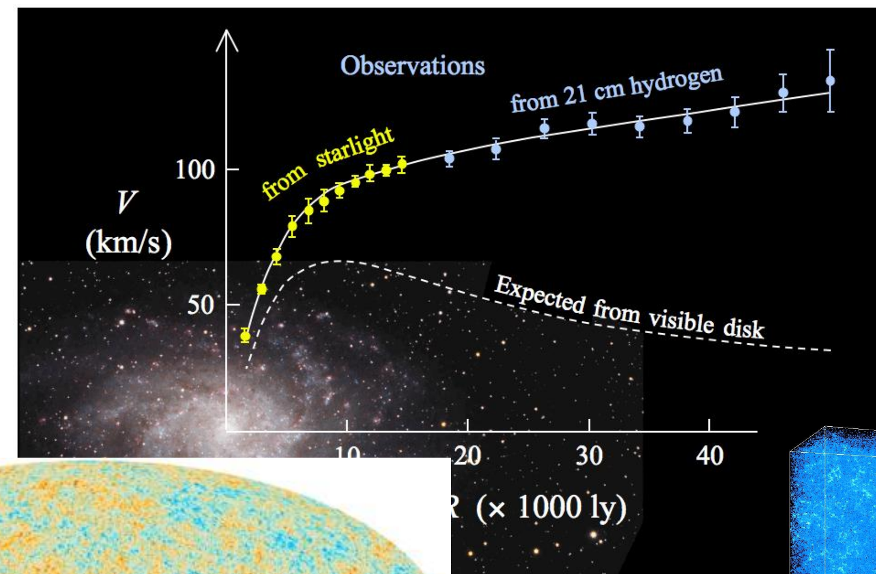

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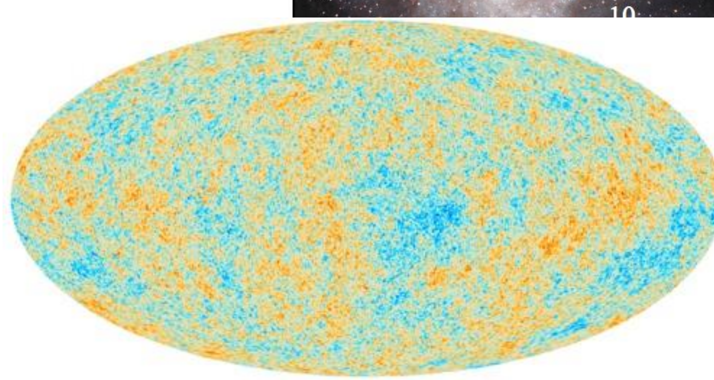

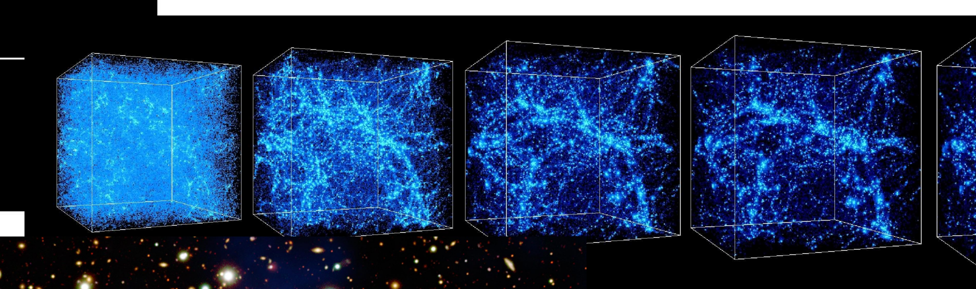

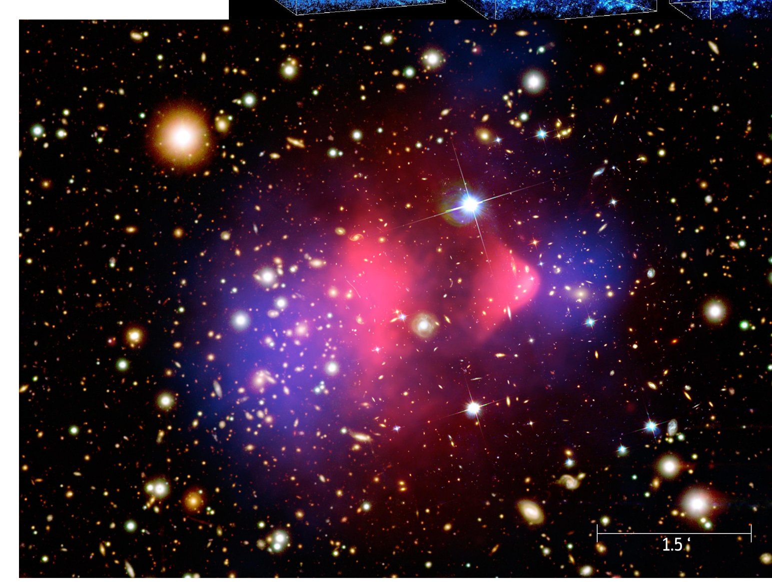

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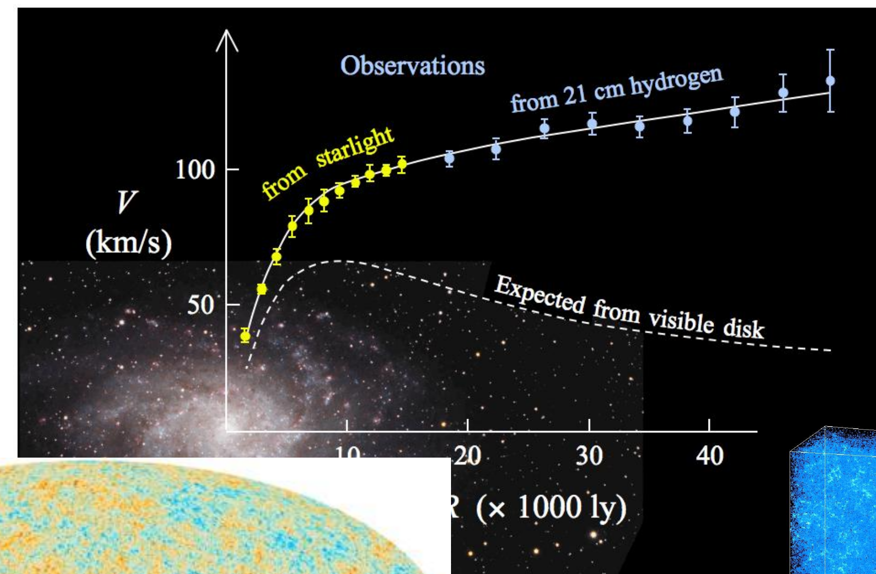

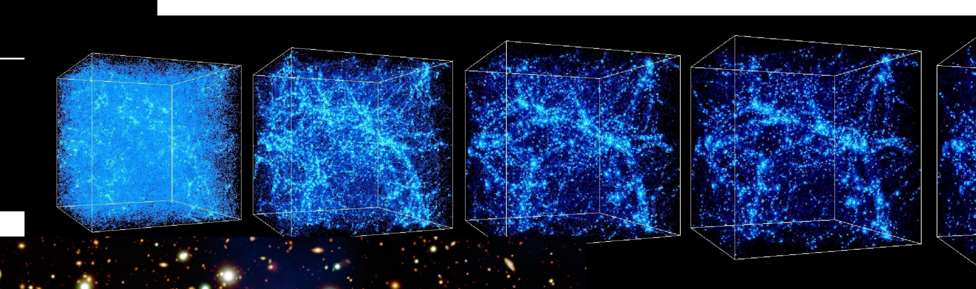

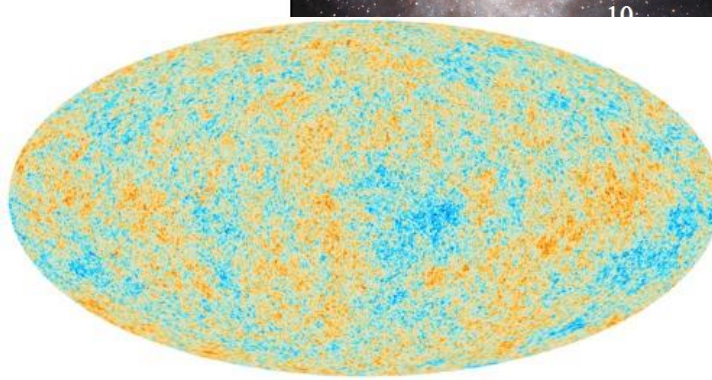

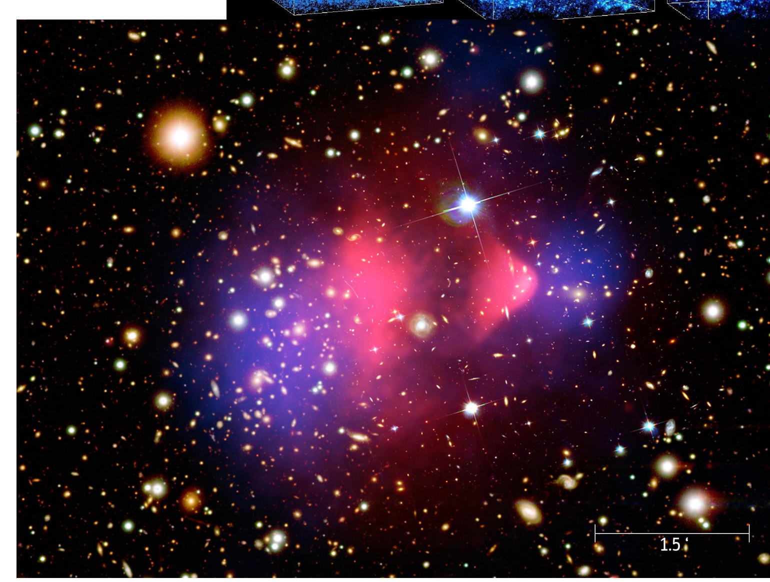

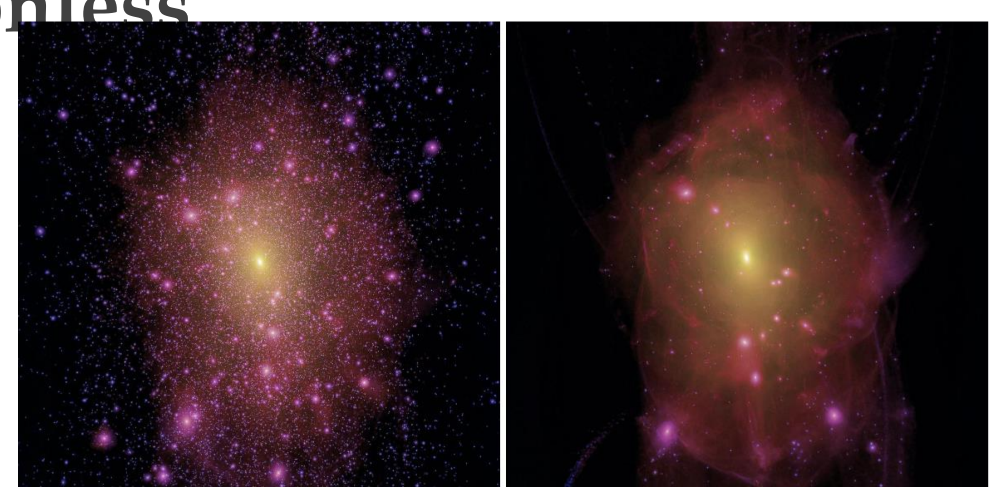

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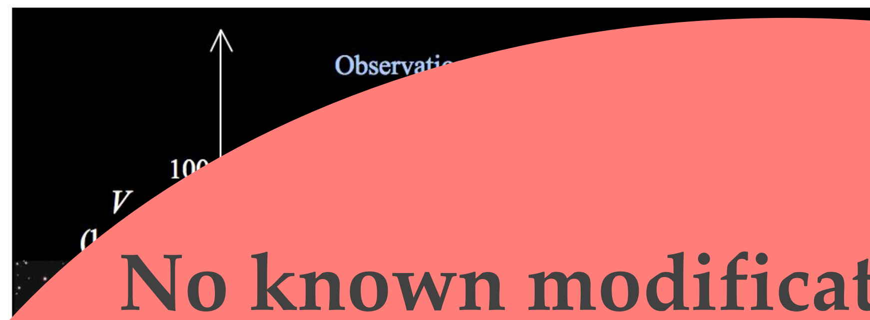

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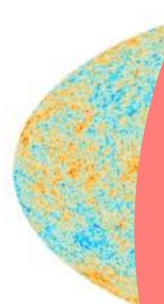

No known modification of gravity can explain all of this.

The Standard Model cannot, either.

A simple extension by one (or several) new “Dark Matter” particles could do the job.

…but no such “Dark Matter” particle has been seen yet

DM Candidates

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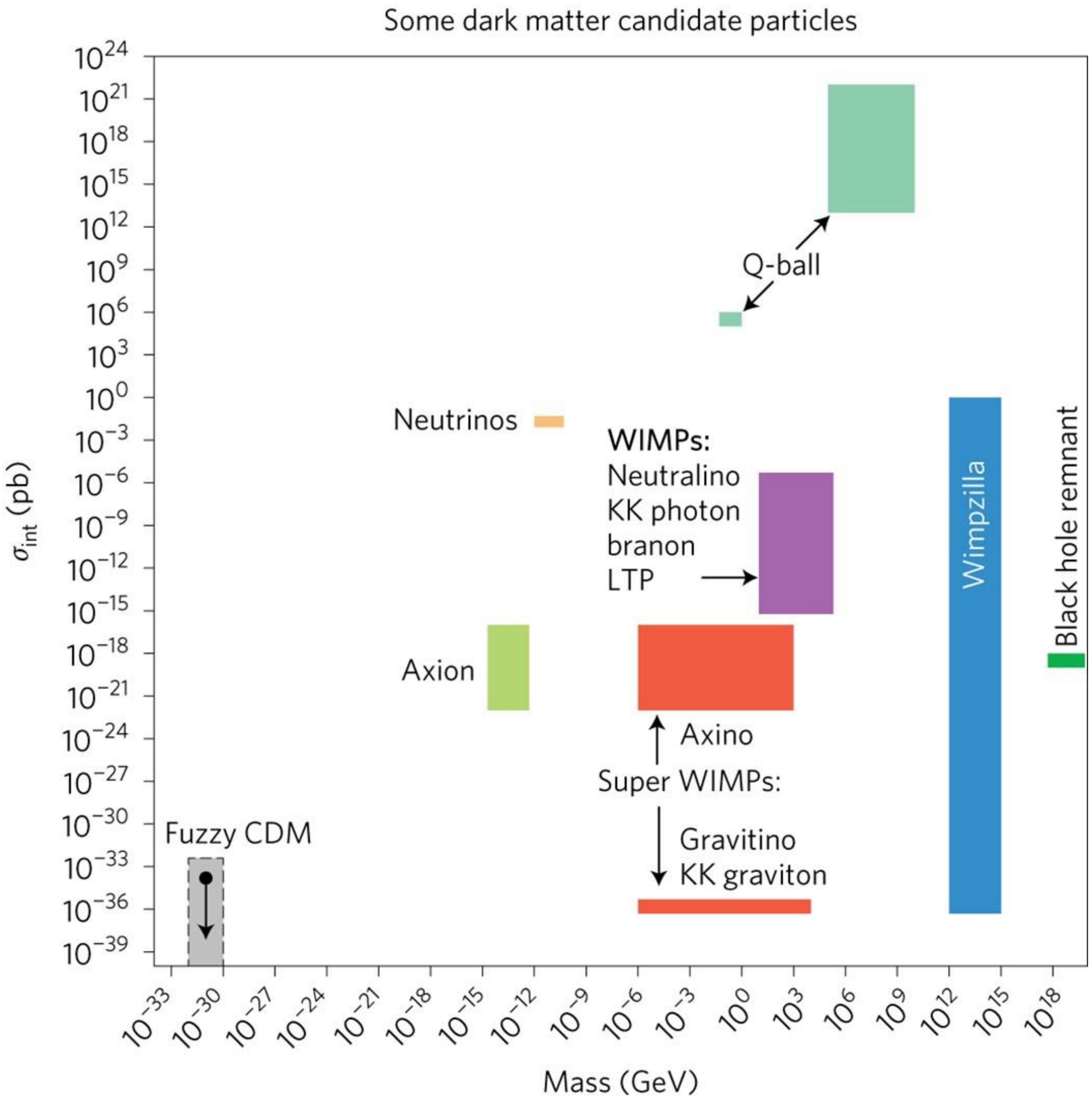

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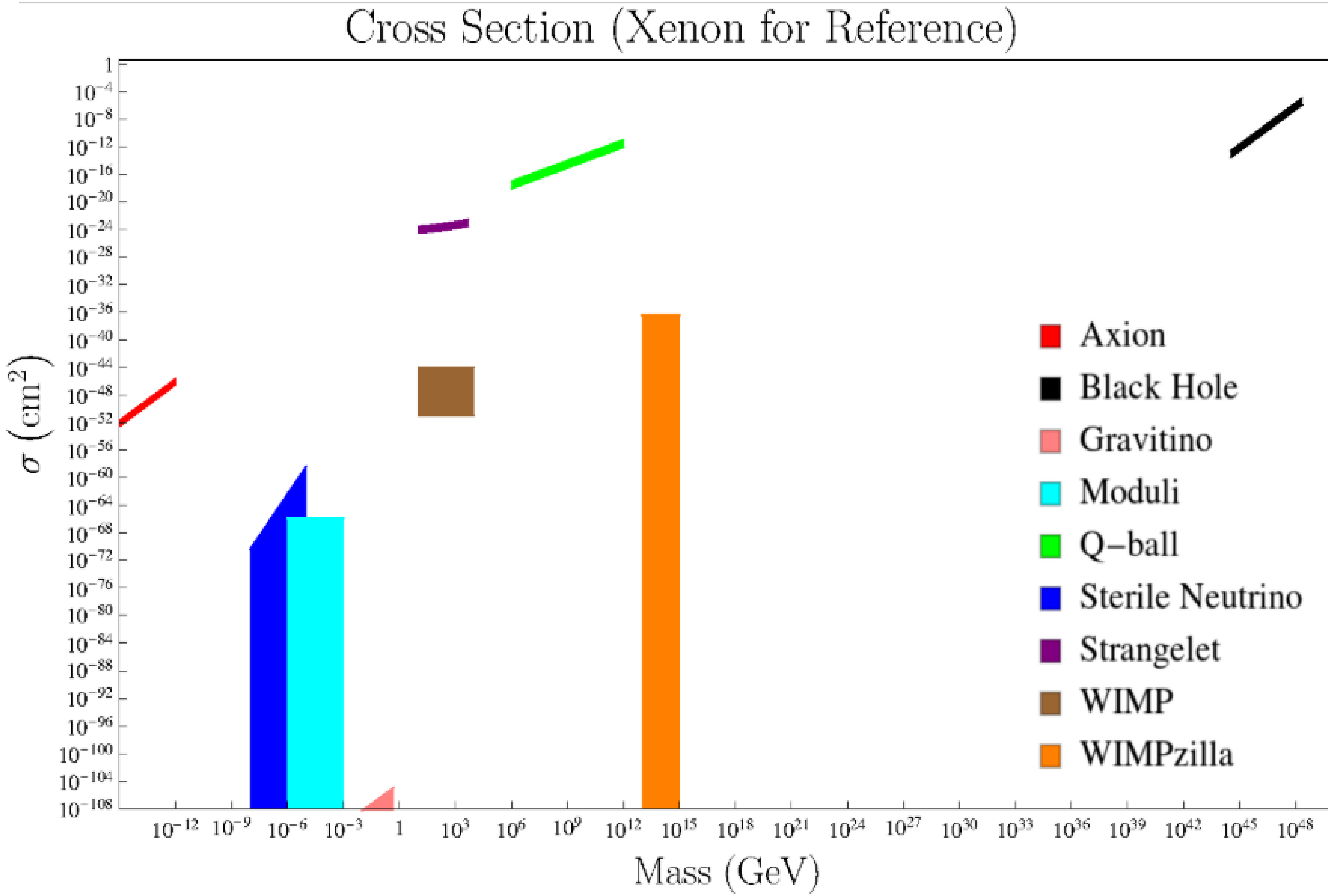

The WIMP Miracle

Particle Dark Matter

Let's assume that Dark Matter is made of new particles…

I) How did it come into existence?

II) How can we uncover what it is?

Particle Dark Matter

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I) How did it come into existence?

II) How can we uncover what it is?

It depends on the kind of particle that we postulate.

Today: The WIMP.

Weakly Interacting Massive Particles

There are two reasons to believe in WIMPs:

i) They "naturally" appear in many theories beyond the SM (e.g. supersymmetry)

ii) They "naturally" give the correct amount of Dark Matter.

The WIMP Miracle

[following Kolb/Turner chapter 5]

Useful relations in equilibrium

number density $$n = \frac{g}{(2\pi)^3}\int f(\vec{p})d^3p$$

energy density $$\rho = \frac{g}{(2\pi)^3}\int E(\vec{p})f(\vec{p})d^3p$$

pressure density $$p = \frac{g}{(2\pi)^3}\int \frac{|\vec{p}|^2}{3E}f(\vec{p})d^3p$$

ultra-relativistic limit (“radiation”)

$$\rho = \begin{cases} (\pi^2/30)gT^4 & \text{(BOSE)} \\ (7/8)(\pi^2/30)gT^4 & \text{(FERMI)} \end{cases}$$

$$n = \begin{cases} (\zeta(3)/\pi^2)gT^3 & \text{(BOSE)} \\ (3/4)(\zeta(3)/\pi^2)gT^3 & \text{(FERMI),} \end{cases}$$

$$p = \rho/3$$

non-relatvistic limit (“matter”)

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2}\exp[-(m-\mu)/T]$$

$$\rho = mn$$

$$p = nT \ll \rho.$$

the exponential suppression implies that the number densities are dominated by “radiation”

Effective number of relativistic degrees of freedom

number density $\rho = \begin{cases} (\pi^2/30)gT^4 & \text{(BOSE)} \\ (7/8)(\pi^2/30)gT^4 & \text{(FERMI)} \end{cases}$

energy density $n = \begin{cases} (\zeta(3)/\pi^2)gT^3 & \text{(BOSE)} \\ (3/4)(\zeta(3)/\pi^2)gT^3 & \text{(FERMI),} \end{cases}$

pressure density $p = \rho/3$

uktra-relativistic limit ("radiation")

the total radiation and pressure densities can be written as

$$\rho_R = \frac{\pi^2}{30} g_* T^4,$$

$$p_R = \rho_R/3 = \frac{\pi^2}{90} g_* T^4$$

with the effective number of relativistic degrees of freedom

$$g_* = \sum_{i=bosons} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=fermions} g_i \left(\frac{T_i}{T}\right)^4.$$

analogously we find for the entropy density

$$s = \frac{2\pi^2}{45} g_{*S} T^3 \quad \text{with} \quad g_{*S} = \sum_{i=bosons} g_i \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{i=fermions} g_i \left(\frac{T_i}{T}\right)^3$$

$H = \frac{\dot{a}}{a}$ = HUBBLE PARAMETER

Γ_i = RATE AT WHICH PARTICLES OF TYPE i INTERACT

$\Gamma_i \gtrsim H \Rightarrow$ PARTICLES ARE "COUPLED"

$\Gamma_i \lesssim H \Rightarrow$ "DECOUPLED"

BOLTZMANN EQ. ABSTRACT: $f_i(\vec{x}, \vec{p})$ = PHASE SPACE DISTRIB. ON-SHELL

$$\hat{L}[\{f_i\}] = C[\{f_i\}]$$

$\hat{L}$: ACTS ON f_i ONE BY ONE "FREE STREAMING"

C: COUPLES f_i

CLASSICAL NEWTONIAN MECH:

$$\hat{L} = \frac{d}{dt} + \frac{d\vec{x}}{dt} \cdot \vec{\nabla}_x + \frac{d\vec{p}}{dt} \cdot \vec{\nabla}_p$$

$$\hat{L} = p^{\mu}\frac{\partial}{\partial x^{\mu}} - \Gamma^{\mu}_{\alpha\beta}\, p^{\alpha} p^{\beta}\frac{\partial}{\partial p^{\mu}}$$

$\Gamma^{\mu}_{\nu\rho}$ = CHRISTOFFEL SYMBOLS

$$\Gamma^{\mu}_{\alpha\beta} = \frac{1}{2} g^{\mu\sigma}\left(\partial_{\beta} g_{\sigma\alpha} + \partial_{\alpha} g_{\sigma\beta} - \partial_{\sigma} g_{\alpha\beta}\right)$$

$g_{\alpha\beta}$ = METRIC

LEMAITRE-FRIEDMANN-ROBERTSON-WALKER:

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2\right]$$

$$\Rightarrow L[f_i] = \omega_p \frac{\partial f_i}{\partial t} - \underbrace{\frac{\dot{a}}{a}}_{H} |\vec{p}|^2 \frac{\partial f}{\partial \omega_p}$$

- DM MOM. DISTR. $f(x, p)$ IS IMPORTANT FOR STRUCTURE FORMATION

↳ RELEVANT FOR SOME DM CANDIDATE

- BUT FOR WIMP $\vec{p}$ IS NEGLIGIBLE WHEN MATTER DOMINATION STARTS ($T \sim 0.8$ eV)

$\Rightarrow$ ONLY $n(t) = g \int \frac{d^3\vec{p}}{(2\pi)^3} f$ MATTERS.

$\Rightarrow$ DIVIDE BY ω

$$\dot{f}_i - H\frac{\vec{p}^2}{\omega}\frac{\partial f_i}{\partial \omega} = \frac{1}{\omega}C[\{f_i\}]$$

$$\int u v' = uv - \int u' v$$

INTEGRATE

$$\dot{n}_i - gH\int\frac{d^3p}{(2\pi)^3}\underbrace{\frac{\vec{p}^2}{\omega}\frac{\partial f_i}{\partial \omega}} = g\int\frac{d^3p}{(2\pi)^3}\frac{1}{\omega}C[\{f\}]$$

$$\frac{\vec{p}^2}{\omega}\frac{\partial f}{\partial p}\frac{\partial p}{\partial \omega} = \frac{\vec{p}^2}{\omega}\frac{\omega}{p}\frac{\partial f}{\partial p} = p\frac{\partial f}{\partial p}$$

NOW $g\int\frac{d^3p}{(2\pi)^3}\, p\frac{\partial f}{\partial p} = g\int d\varphi\, d[\cos\theta]\, dp\, p^3\frac{\partial f}{\partial p} = -g3\int d\varphi\, d[\cos\theta]\, dp\, p^2 f = 3n$

$$\dot{n} + 3Hn = \frac{g}{(2\pi)^3}\int \frac{d^3p}{\omega} C[f_i]$$

NOW WE NEED AN EXPRESSION FOR C.

ASSUME:

- PARTICLES PROPAGATE FREELY BETWEEN ISOLATED SCATTERINGS
- SCATTERINGS DESCRIBED BY S-MATRIX ELEMENTS FROM VACUUM QFT

NOT CAPTURED

- QUANTUM EFFECTS IN PROPAGATION (E.G. COHERENT OSC.)

- SCREENING BY PLASMA

- THERMAL CORRECTIONS TO SCATTERING RATES

PROCESS $a\,b\,c \ldots \longrightarrow i\,j\,k$

$$\frac{g}{(2\pi)^3}\int C[f]\frac{d^3p}{\omega} = -\int \Pi_a \Pi_b \ldots \Pi_i \Pi_j \ldots \times (2\pi)^4 \delta(p_a + p_b \ldots - p_i - p_j \ldots)$$

$$\times \Big[|M_{ab\ldots \to ij\ldots}|^2 f_a f_b \ldots (1 \pm f_i)(1 \pm f_j) \ldots$$

$$- |M_{ij\ldots \to ab\ldots}|^2 f_i f_j \ldots (1 \pm f_a)(1 \pm f_b) \Big]$$

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PROCESS $a\,b\,c\ldots \longrightarrow i\,j\,k$

$$\frac{g}{(2\pi)^3}\int C[f]\,\frac{d^3p}{\omega} = -\int \Pi_a \Pi_b \ldots \Pi_i \Pi_j \ldots (2\pi)^4\,\delta(p_a + p_b \ldots - p_i - p_j \ldots)$$

$$\times \Big[\,|M_{ab\to ij}|^2 f_a f_b \ldots (1 \pm f_i)(1 \pm f_j) \ldots$$

$$- |M_{ij\ldots\to ab\ldots}|^2 f_i f_j \ldots (1 \pm f_a)(1 \pm f_b)\,\Big]$$

WITH

$$d\Pi_i = g_i \frac{1}{(2\pi)^3} \frac{d^3 p_i}{2\omega_{p_i}}$$

ASSUME:

1) $|\mathcal{M}|^2_{ab\to ij} = |\mathcal{M}_{ij\to ab}|^2 \equiv |\mathcal{M}|^2$

2) BOLTZMANN: $1 \pm f \simeq 1$, $f \simeq \exp(-(\omega_i - \mu_i)/T)$

$$\dot{n}_a + \underbrace{3Hn_a}_{\text{DILUTION}} = -\int d\Pi_i \ldots d\Pi_a (2\pi)^4 |\mathcal{M}|^2 \delta^{(4)}(p_a + p_b \ldots - p_i - p_j \ldots) \times [f_a f_b \ldots - f_i f_j \ldots]$$

INTRODUCE

$Y = \frac{n}{s}$ $\qquad$ s = ENTROPY DENSITY $= \frac{2\pi^2}{45} g_{*s} T^3$

ADIABATIC EXPANSION: $sa^3 = \text{CONST}$

$$\Rightarrow \frac{\partial}{\partial t}(sa^3) = 0 = 3a^2\dot{a}s + a^3\dot{s}$$

$$\Rightarrow \dot{s} = -3\frac{a^2\dot{a}}{a^3}s = -3Hs$$

NOW

$$\dot{n} + 3Hn = \frac{\partial}{\partial t}(Ys) + 3HYs$$

$$= \dot{Y}s + \dot{s}Y + 3HYs = \dot{Y}s - 3HsY + 3HsY$$

$$= \dot{Y}s$$

$$t = \frac{1}{2}\sqrt{\frac{45}{4\pi^3 g_*}}\ \frac{m_{PL}}{T^2} = \frac{1}{2}\sqrt{\frac{45}{4\pi^3 g_*}}\ \frac{m_{PL}}{m^2}X^2 = \frac{1}{2H}$$

$$\left(\text{WITH } H = \frac{T^2}{m_{PL}}\sqrt{\frac{4\pi^3 g_*}{45}}\right)$$

$$\frac{\partial}{\partial t} = \frac{\partial X}{\partial t}\frac{\partial}{\partial X} = \left[\frac{\partial t}{\partial X}\right]^{-1}\frac{\partial}{\partial X} = \left[\frac{\partial}{\partial X}\frac{1}{2H}\right]^{-1}\frac{\partial}{\partial X}$$

WE CAN DEFINE

$$\mathcal{H} = \frac{1}{X}\left(\frac{\partial}{\partial X}\frac{1}{2H}\right)^{-1} = \frac{1}{X}\left(\frac{\partial}{\partial X}\frac{1}{2}\sqrt{\frac{45}{4\pi g_*}}\ \frac{m_{PL}}{m^2}X^2\right)$$

$$\frac{\partial}{\partial t} = \mathcal{H}X\frac{\partial}{\partial X}$$

$$\Longrightarrow\ \mathcal{H}X\frac{\partial}{\partial X}Y = \frac{-1}{S}\int d\Pi_i \ldots d\Pi_a \ldots |\mathcal{M}|^2\delta^4(p_a \ldots p_i)\cdot\left[f_a \ldots - f_i \ldots\right]$$

TAKE STABLE WIMP ψ WITH

$$\psi\bar{\psi} \longleftrightarrow X\bar{X}$$

X IN EQUILIBRIUM, NO CHEM. POT $\rightarrow f_X = f_{\bar{X}} = \exp(-\omega_X/T)$

δ-FUNCTION:

$$f_X f_{\bar{X}} = \exp\left(-(\omega_X + \omega_{\bar{X}})/T\right) = \exp\left(-(\omega_\psi + \omega_{\bar{\psi}})/T\right) = f_\psi^{EQ} f_{\bar{\psi}}^{EQ}$$

$$\rightarrow \left[f_\psi f_{\bar{\psi}} - f_X f_{\bar{X}}\right] = \left[f_\psi f_{\bar{\psi}} - f_\psi^{EQ} f_{\bar{\psi}}^{EQ}\right]$$

f_ψ IN GENERAL IS NOT IN EQUILIBRIUM
HOWEVER, WE CAN ASSUME
"KINETIC EQUILIBRIUM"

$$f_\psi \propto f_\psi^{EQ} \Rightarrow f_\psi = c_\psi f_\psi^{EQ}$$

$$\Rightarrow n_\psi = c_\psi n_\psi^{EQ}$$

THEN (ASSUMING $g_X = g_\Psi = 1$)

$$\frac{-1}{S}\int \frac{d^3p_X}{(2\pi)^3}\frac{d^3p_{\bar{X}}}{(2\pi)^3}\frac{d^3p_\Psi}{(2\pi)^3}\frac{d^3p_{\bar{\Psi}}}{(2\pi)^3}|M|^2\delta\left(p_\Psi + p_{\bar{\Psi}} - p_X - p_{\bar{X}}\right)$$

$$\times \underbrace{\left[f_\Psi f_{\bar{\Psi}} - f_\Psi^{EQ} f_{\bar{\Psi}}^{EQ}\right]}_{f_\Psi^{EQ} f_{\bar{\Psi}}^{EQ}\left[c_\Psi c_{\bar{\Psi}} - 1\right]}$$

$$= \underbrace{-\frac{\left[c_\Psi c_{\bar{\Psi}} - 1\right]}{S}}_{-\frac{1}{S}\left[n_\Psi n_{\bar{\Psi}} - n_\Psi^{EQ} n_{\bar{\Psi}}^{EQ}\right]\frac{1}{n_\Psi^{EQ} n_{\bar{\Psi}}^{EQ}}}\int \frac{d^3p_X\, d^3p_{\bar{X}}\, d^3p_\Psi\, d^3\bar{\Psi}}{(2\pi)^{12}}|M|^2\delta(p_\Psi + p_{\bar{\Psi}} - p_X - p_{\bar{X}})\, f_\Psi^{EQ} f_{\bar{\Psi}}^{EQ}$$

$$\Rightarrow \quad Hx \frac{dY}{dX} = -S\left(Y_\psi Y_{\bar\psi} - Y_\psi^{EQ} Y_{\bar\psi}^{EQ}\right)\langle \sigma |v| \rangle$$

$$\langle \sigma |v| \rangle = \frac{1}{n_\psi^{EQ} n_{\bar\psi}^{EQ}} \int \frac{d^3p_\chi\, d^3p_{\bar\chi}\, d^3p_\psi\, d^3p_{\bar\psi}}{(2\pi)^{12}} |M|^2 \delta(p_\psi + p_{\bar\psi} - p_\chi - p_{\bar\chi}) f_\psi^{EQ} f_{\bar\psi}^{EQ}$$

ASSUMING $Y_\psi = Y_{\bar\psi}$ (SYMM. DM

$$Hx \frac{dY}{dX} = -S\left(Y_\psi^2 - Y_\psi^{EQ^2}\right)\langle \sigma |v| \rangle$$

OR

$$\frac{dy}{dx} = -\frac{\langle \sigma v \rangle S}{Hx}\left(Y_\psi^2 - Y_\psi^{EQ^2}\right)$$

The Boltzmann equation

$$\frac{x}{Y_{\mathrm{EQ}}}\frac{dY}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y}{Y_{\mathrm{EQ}}}\right)^2 - 1\right]$$

in terms of abundances $Y \equiv \frac{n_\psi}{s}$

and the annihilation rate $\Gamma_A \equiv n_{\mathrm{EQ}}\langle\sigma_A|v|\rangle$

which is given by the thermally averaged cross section

$$\langle\sigma_{\psi\bar{\psi}\to X\bar{X}}|v|\rangle \equiv \left(n_\psi^{\mathrm{EQ}}\right)^{-2}\int d\Pi_\psi d\Pi_{\bar{\psi}} d\Pi_X d\Pi_{\bar{X}} (2\pi)^4$$
$$\times\delta^4(p_\psi + p_{\bar{\psi}} - p_X - p_{\bar{X}})|\mathcal{M}|^2 \exp(-E_\psi/T)\exp(-E_{\bar{\psi}}/T)$$

with the convenient integration measure $d\Pi \equiv g\frac{1}{(2\pi)^3}\frac{d^3p}{2E}$

and the dimensionless time variable $x \equiv m/T$

The Boltzmann equation
$$\frac{x}{Y_{\rm EQ}}\frac{dY}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y}{Y_{\rm EQ}}\right)^2 - 1\right]$$

particle "freezes out" when the interaction rate Γ is much smaller than the Hubble rate

in terms of abundances $Y \equiv \frac{n_\psi}{s}$

and the annihilation rate $\Gamma_A \equiv n_{\rm EQ}\langle\sigma_A|v|\rangle$

which is given by the thermally averaged cross section

$$\langle\sigma_{\psi\bar\psi\to X\bar X}|v|\rangle \equiv \left(n_\psi^{\rm EQ}\right)^{-2}\int d\Pi_\psi d\Pi_{\bar\psi} d\Pi_X d\Pi_{\bar X}(2\pi)^4$$
$$\times\delta^4(p_\psi + p_{\bar\psi} - p_X - p_{\bar X})|\mathcal{M}|^2 \exp(-E_\psi/T)\exp(-E_{\bar\psi}/T)$$

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The Boltzmann equation

$$\frac{x}{Y_{EQ}}\frac{dY}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y}{Y_{EQ}}\right)^2 - 1\right]$$

particle "freezes out" when the interaction rate *Γ* is much smaller than the Hubble rate

in terms of abundances $Y \equiv \frac{n_\psi}{s}$

and the annihilation rate $\Gamma_A \equiv n_{EQ}\langle\sigma_A|v|\rangle$

Γ decreases with temperature and is exponentially surpassed for T < M, i.e., x > 1

which is given by the thermally averaged cross section

$$\langle\sigma_{\psi\bar\psi\to X\bar X}|v|\rangle \equiv \left(n_\psi^{EQ}\right)^{-2}\int d\Pi_\psi d\Pi_{\bar\psi} d\Pi_X d\Pi_{\bar X}(2\pi)^4$$

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with the convenient integration measure $d\Pi \equiv g\frac{1}{(2\pi)^3}\frac{d^3p}{2E}$

and the dimensionless time variable $x \equiv m/T$

Hot Relics

If a particle freezes our while being relativistic *($x_f < 3$)*, **then it simply has an equilibrium distribution**

$$Y_\infty = Y_{\rm EQ}(x_f) = 0.278 g_{\rm eff}/g_{*S}(x_f) \quad (x_f \lesssim 3)$$

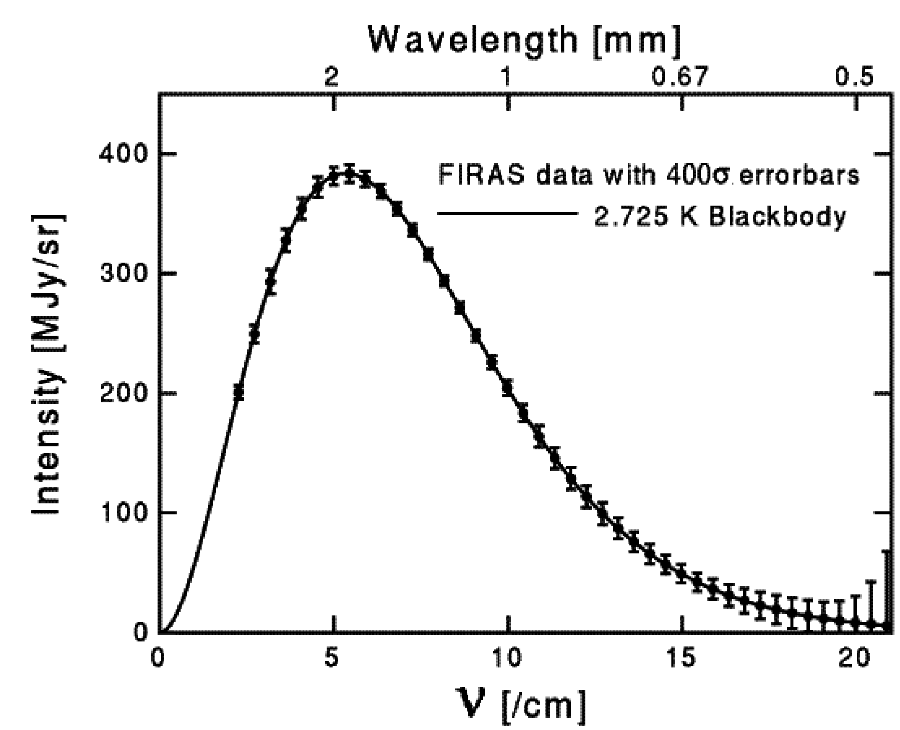
$$n_{\psi 0} = s_0 Y_\infty = 2970 Y_\infty \ {\rm cm}^{-3}$$

$$= 825[g_{\rm eff}/g_*(x_f)] \ {\rm cm}^{-3}.$$

Example I: photons.

- The CMB photons have a perfect black body spectrum even though they are not "in equilibrium" because they do not interact.
- The shape of the spectrum is invariant because $g_{*S}\ a^3\ T^3$ is constant for adiabatic evolution, i.e., for a massless particle the energy and temperature in the distribution function redshift in the same way

$$T \propto g_{*S}^{-1/3}\ a^{-1} \qquad E = p \propto a^{-1}$$



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$$= 825[g_{\rm eff}/g_*(x_f)] \ {\rm cm}^{-3}.$$

Example II: neutrinos.

- Neutrinos are relativistic when they freeze out, but become non-relativistic afterwards. Their energy density is now

$$\rho_{\psi 0} = s_0 Y_\infty m = 2.97 \times 10^3 Y_\infty (m/{\rm eV}) \ {\rm eV\ cm}^{-3}$$

$$\Omega_\psi h^2 = 7.83 \times 10^{-2} [g_{\rm eff}/g_{*S}(x_f)](m/{\rm eV}).$$

- note that g has changed after neutrino decoupling due to electron-positron annihilation,

$$\Omega_\nu = \frac{\rho_\nu^0}{\rho_{\rm crit}^0} = \frac{\sum m_\nu}{93.14 h^2 \, {\rm eV}}$$

Cold Relic

We can parameterise the averaged cross section as

$$\langle \sigma_A |v| \rangle \equiv \sigma_0 (T/m)^n = \sigma_0 x^{-n} \quad (for\ x \gtrsim 3)$$

and hence write the Boltzmann equation as

$$dY/dx = -\lambda x^{-n-2}(Y^2 - Y_{\mathrm{EQ}}^2)$$

where we have further introduced

$$\lambda = \left[\frac{x\langle \sigma_A |v|\rangle s}{H(m)}\right]_{x=1} = 0.264(g_{*s}/g_*^{1/2}) m_{Pl}\, m\, \sigma_0,$$

$$Y_{\mathrm{EQ}} = 0.145(g/g_{*s}) x^{3/2} e^{-x}.$$

It is more convenient to track the deviation from equilibrium $\Delta \equiv Y - Y_{\mathrm{EQ}}$

$$\Delta' = -Y'_{\mathrm{EQ}} - \lambda x^{-n-2} \Delta (2Y_{\mathrm{EQ}} + \Delta)$$

Cold Relic

$$\Delta' = -Y'_{EQ} - \lambda x^{-n-2}\Delta(2Y_{EQ} + \Delta)$$

At early times we can neglect Δ' and solve the equation algebraically:

$$\begin{aligned} \Delta &\simeq -\lambda^{-1} x^{n+2} Y'_{EQ}/(2Y_{EQ} + \Delta) \\ &\simeq x^{n+2}/2\lambda. \end{aligned}$$

At late times the equilibrium abundance is negligible and we can approximate

$$\Delta' = -\lambda x^{-n-2}\Delta^2.$$ and hence $$Y_\infty = \Delta_\infty = \frac{n+1}{\lambda} x_f^{n+1}.$$

Matching the two solutions requires determination of the freeze-out point x_f

We define x_f as the point when $\Delta(x_f) = cY_{EQ}(x_f)$

and use the early time solution $\Delta(x_f) \simeq x_f^{n+2}/\lambda(2+c)$ to find

$$x_f \cong \ln[(2+c)\lambda ac] - \left(n + \frac{1}{2}\right)\ln\{\ln[(2+c)\lambda ac]\}$$

with $a = 0.145(g/g_{*S})$.

Cold Relic

The analytic estimate is relatively insensitive to the choice of *c*, best agreement with numerical results is obtained for $c(c+2) = n+1$, which yields

$$x_f = \ln[0.038(n+1)(g/g_*^{1/2})m_{Pl}\, m\, \sigma_0] - \left(n+\frac{1}{2}\right)\ln\left\{\ln\left[0.038(n+1)(g/g_*^{1/2})m_{Pl}\, m\, \sigma_0\right]\right\}$$

and $Y_\infty = \dfrac{3.79(n+1)x_f^{n+1}}{(g_{*S}/g_*^{1/2})m_{Pl}\, m\, \sigma_0}$ or $\Omega_\psi h^2 = 1.07\times 10^9 \dfrac{(n+1)x_f^{n+1}\ \mathrm{GeV}^{-1}}{(g_{*S}/g_*^{1/2})m_{Pl}\sigma_0}.$

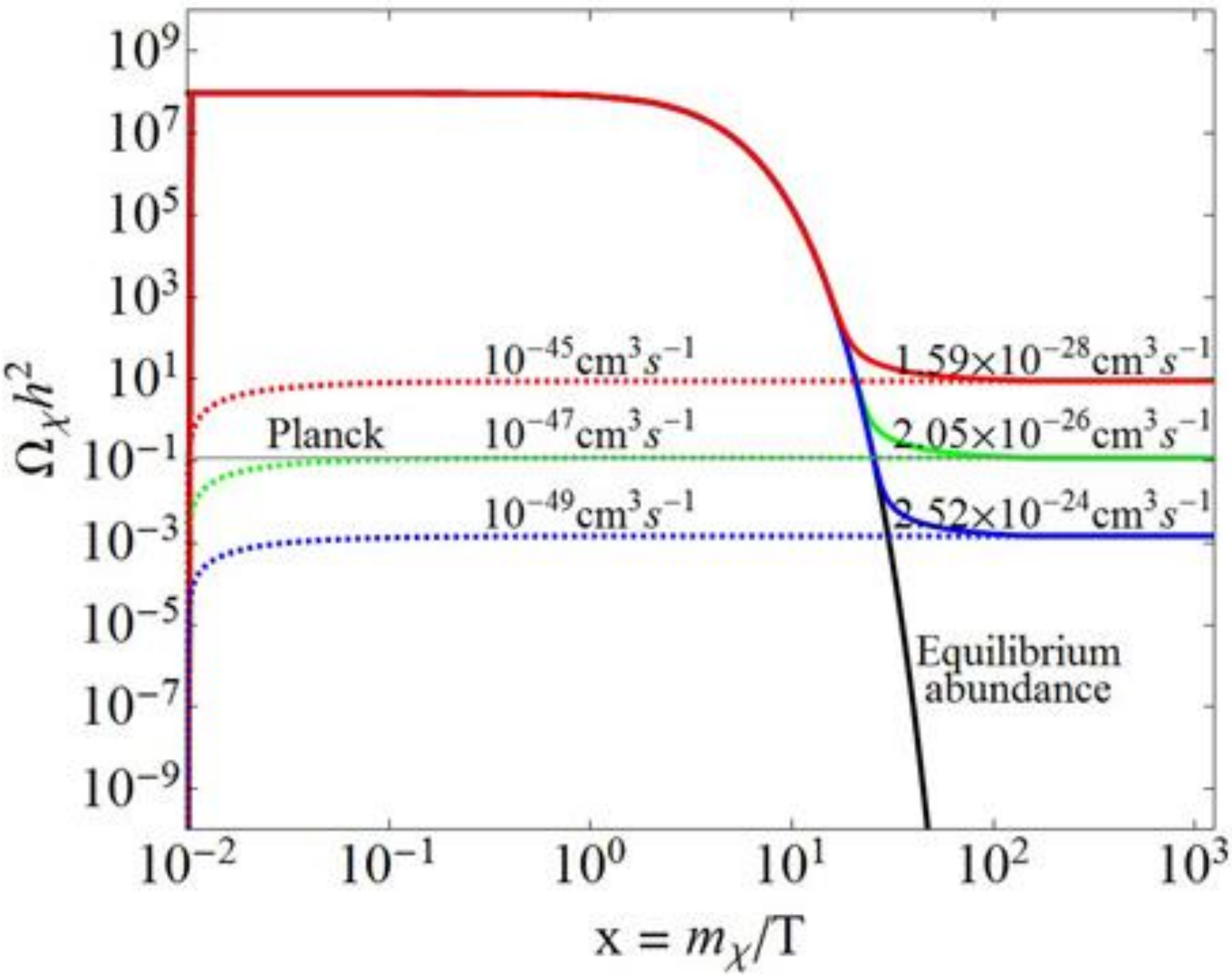
A similar result could have been obtained if one determined x_f by solving $H = \Gamma$ for x.

It is worthwhile noting that the final abundance is inversely proportional to the averaged cross section and the DM mass:

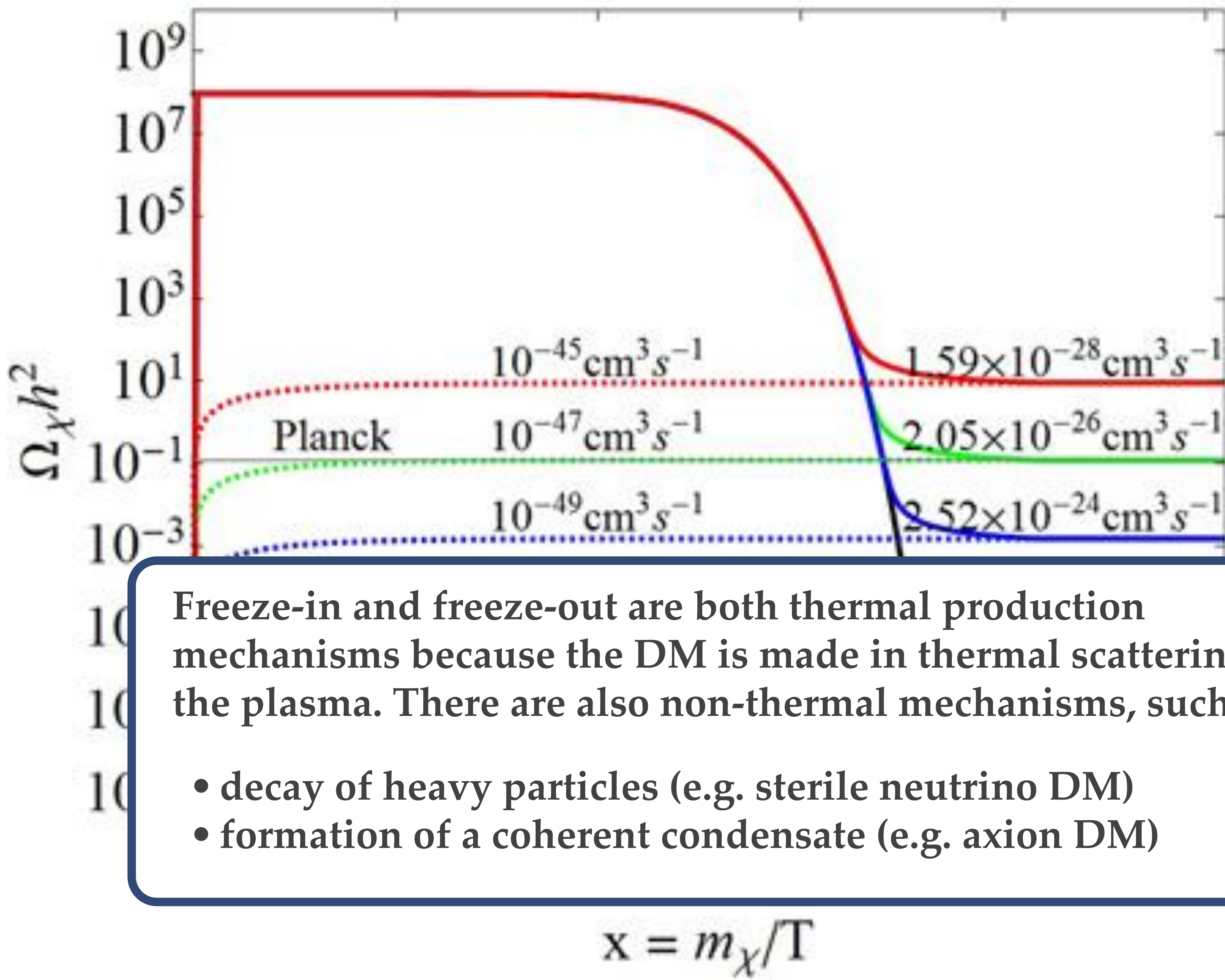
$$Y_\infty = \frac{3.79(n+1)(g_*^{1/2}/g_{*S})x_f}{m\, m_{Pl}\langle\sigma_A|v|\rangle}$$

WIMP Miracle: If one inserts a mass and cross section of the EW order, one roughly gets the observed DM density! (not really, but good enough to call it a miracle and dominate the field for decades…)

Freeze-out and freeze-in



Freeze-out and freeze-in

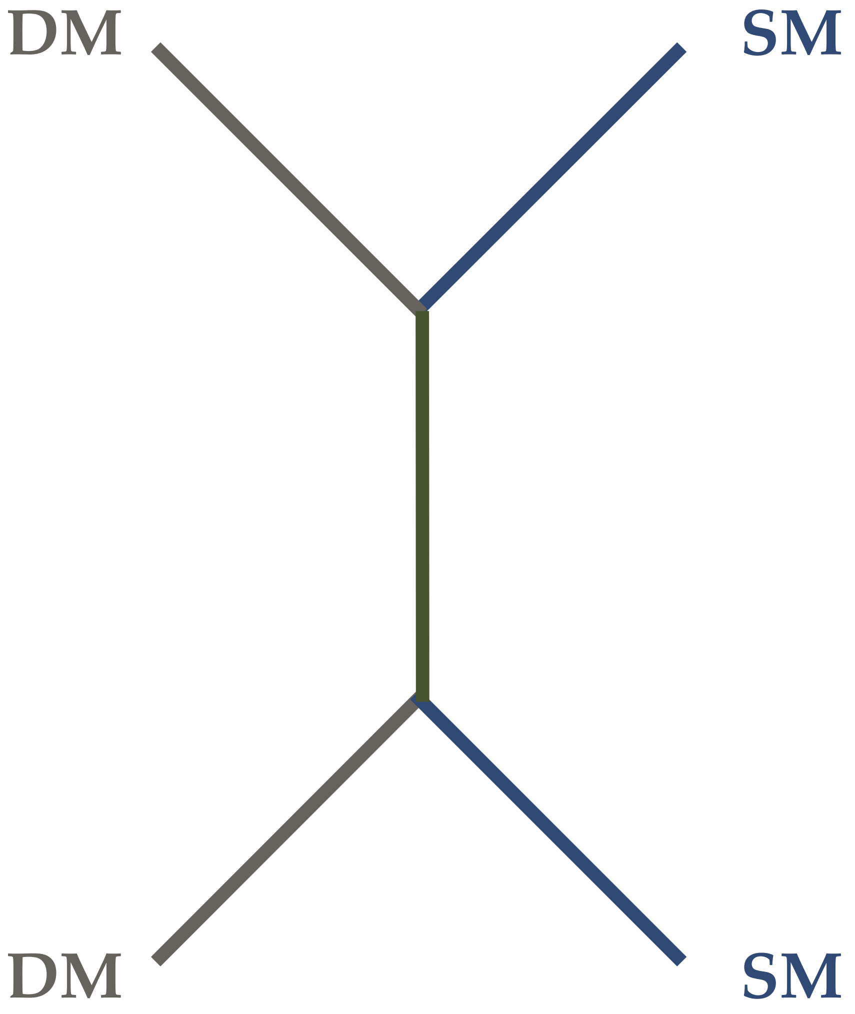


Freeze-in and freeze-out are both thermal production mechanisms because the DM is made in thermal scatterings in the plasma. There are also non-thermal mechanisms, such as

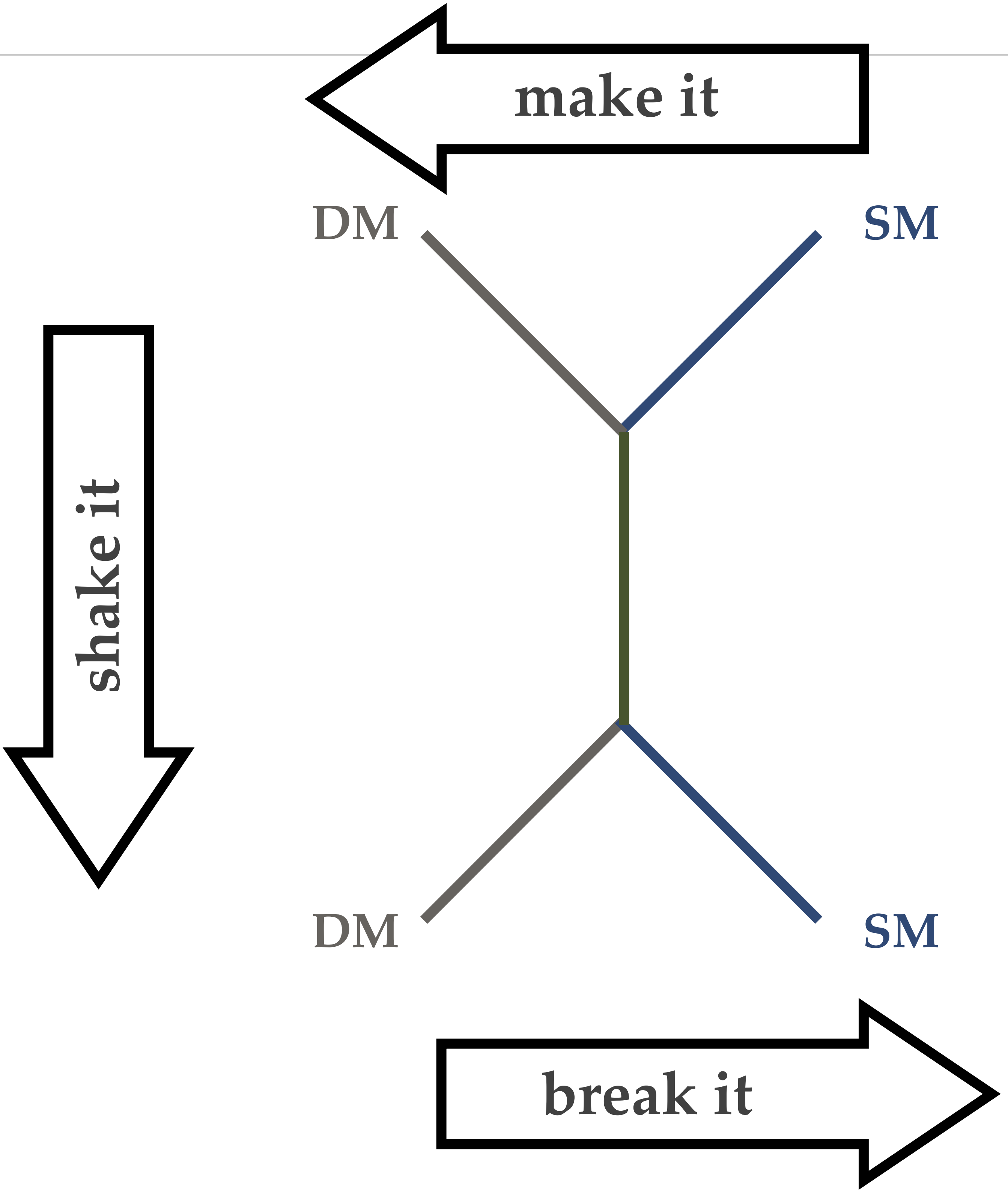
- decay of heavy particles (e.g. sterile neutrino DM)
- formation of a coherent condensate (e.g. axion DM)

WIMP DM Searches

How to detect Dark Matter?



How to detect Dark Matter?



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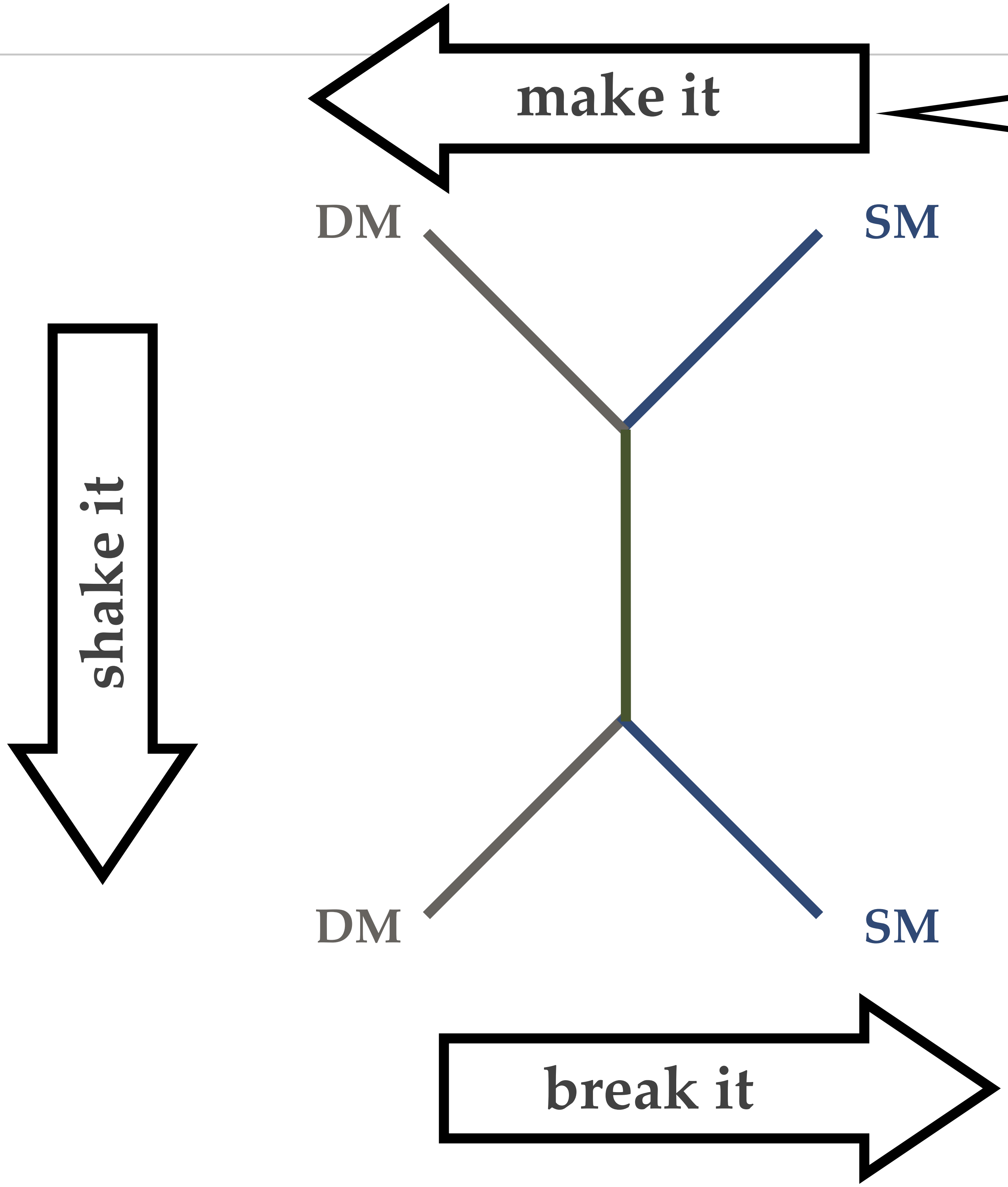
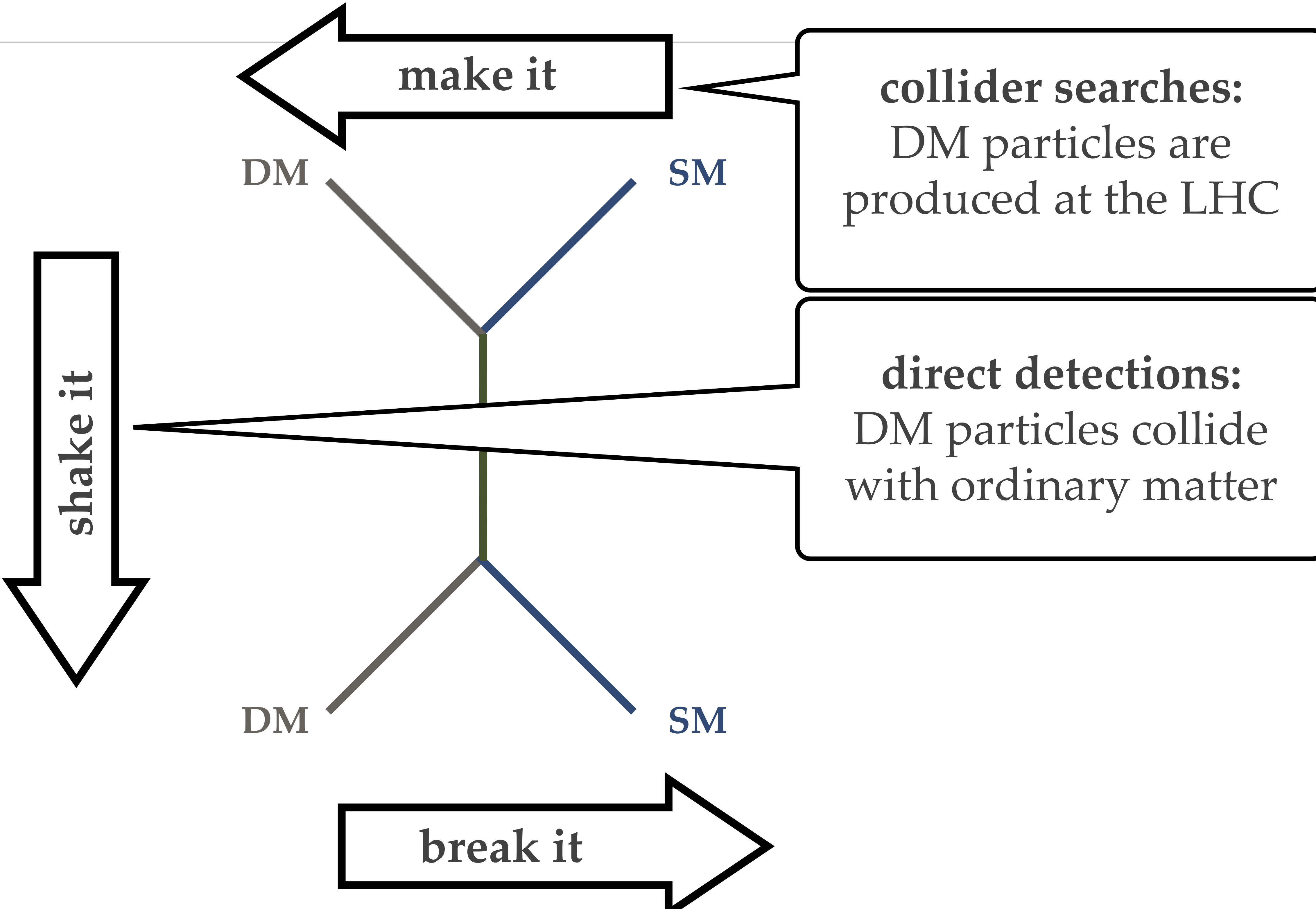
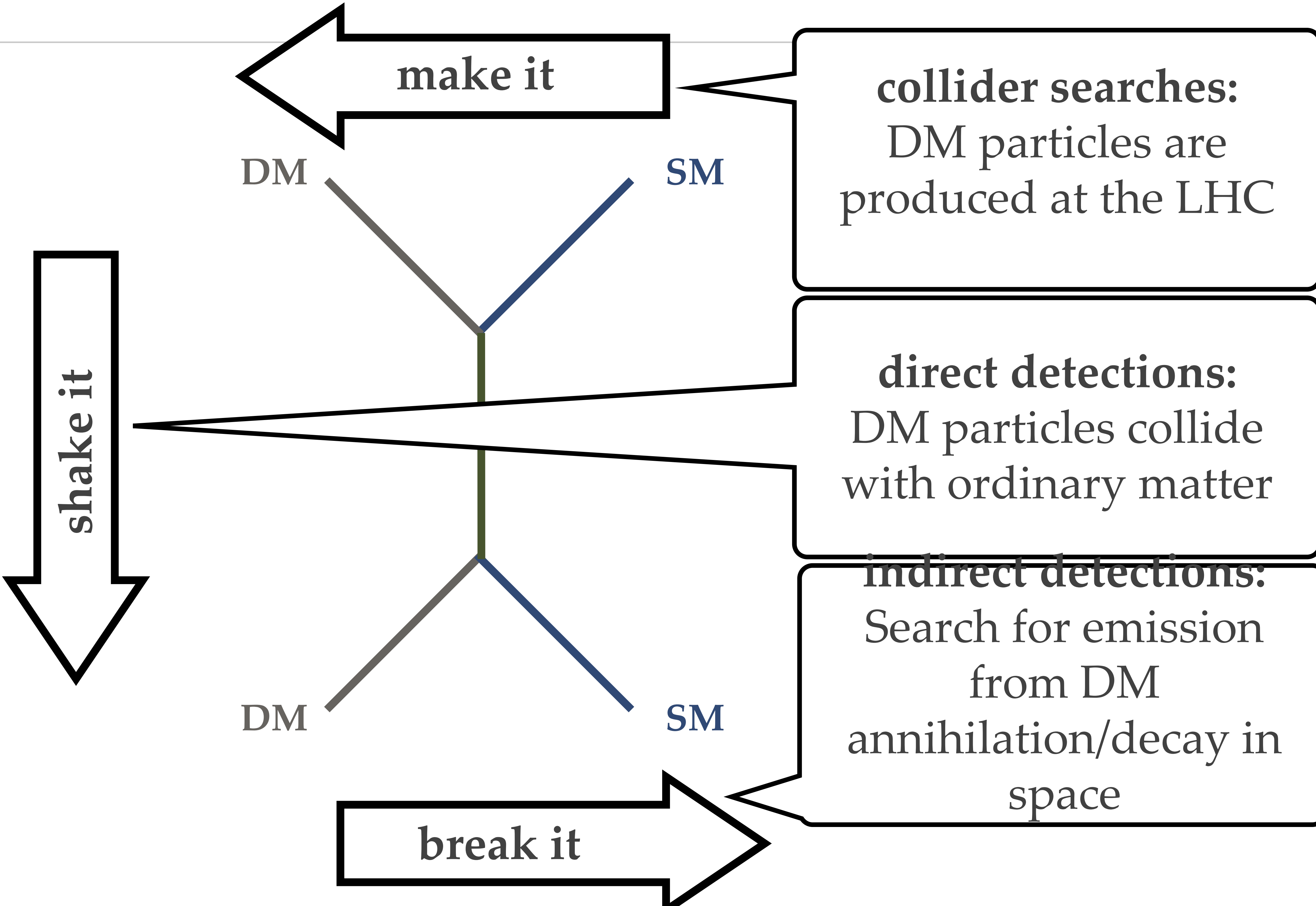


collider searches:
DM particles are produced at the LHC

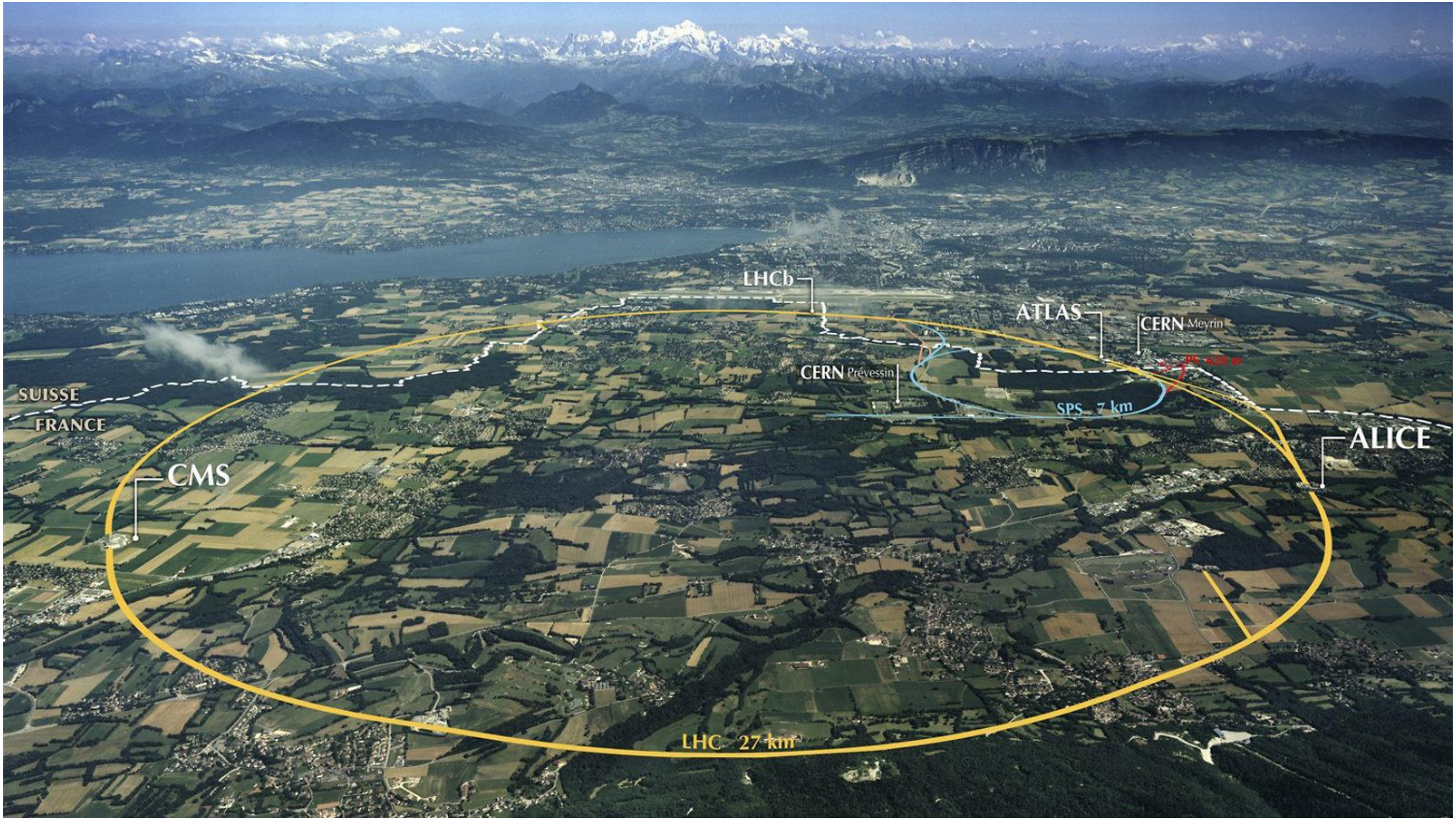
How to detect Dark Matter?



How to detect Dark Matter?



Make It: Collider Searches



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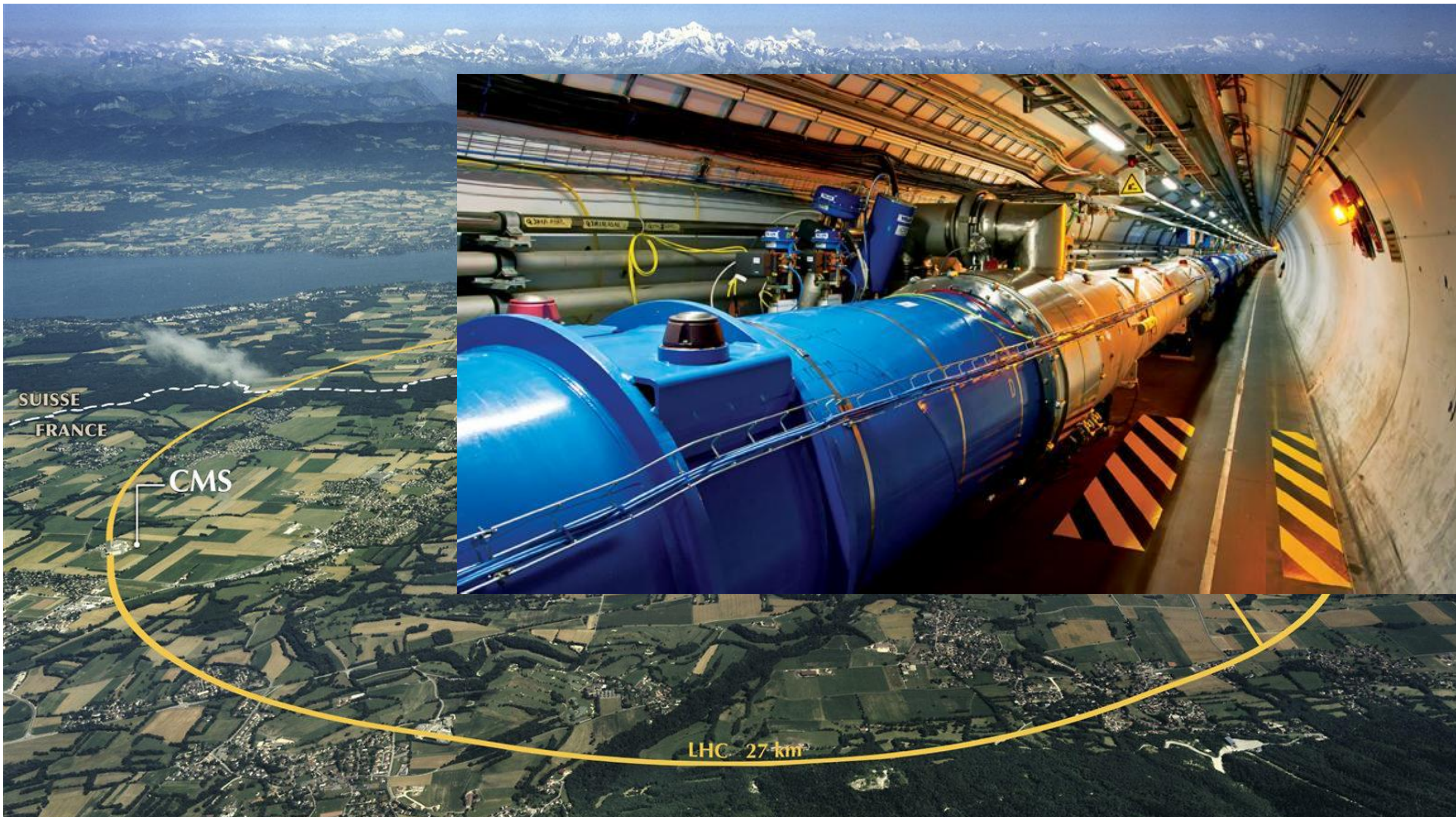
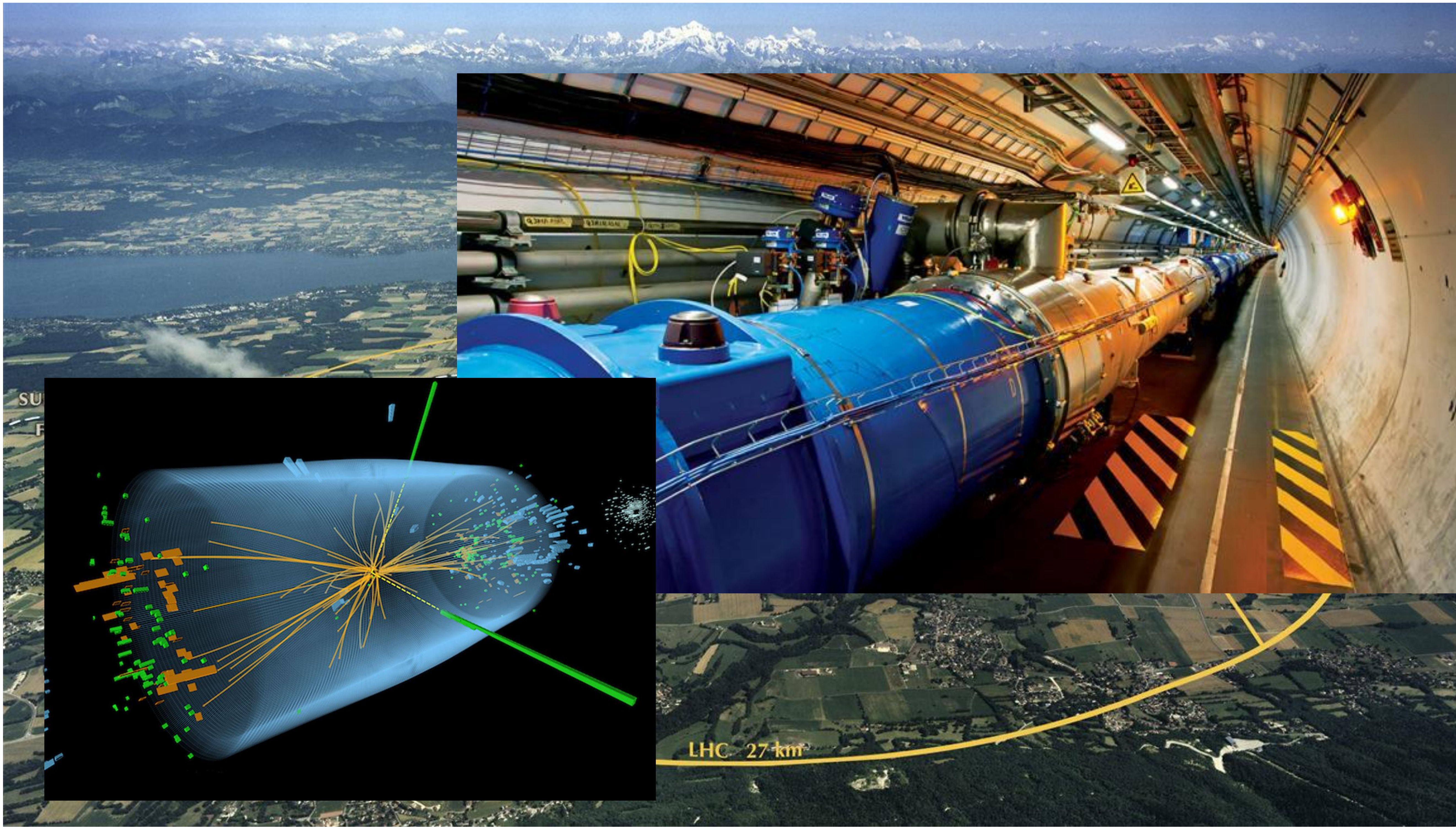


Make It: Collider Searches



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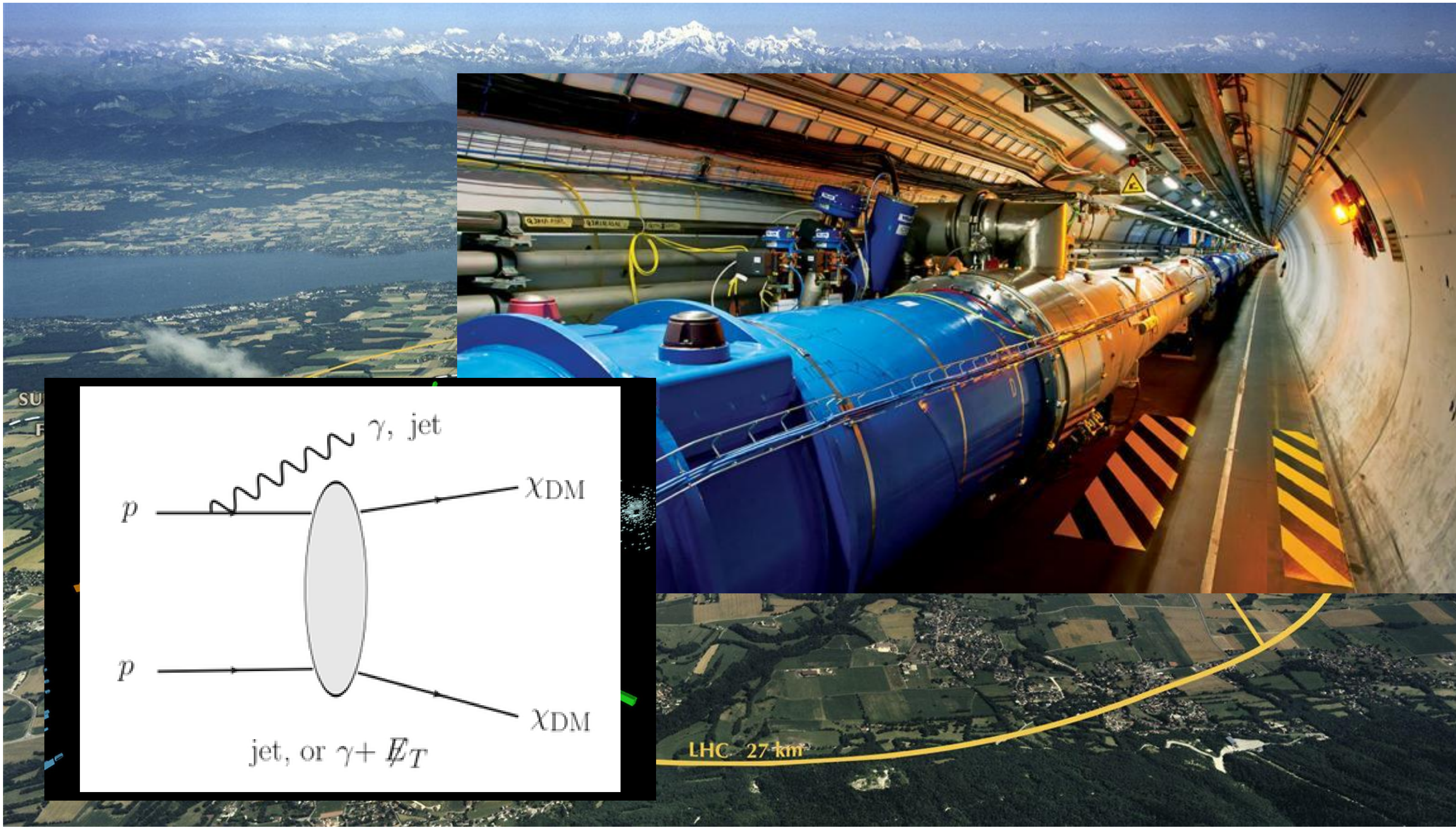
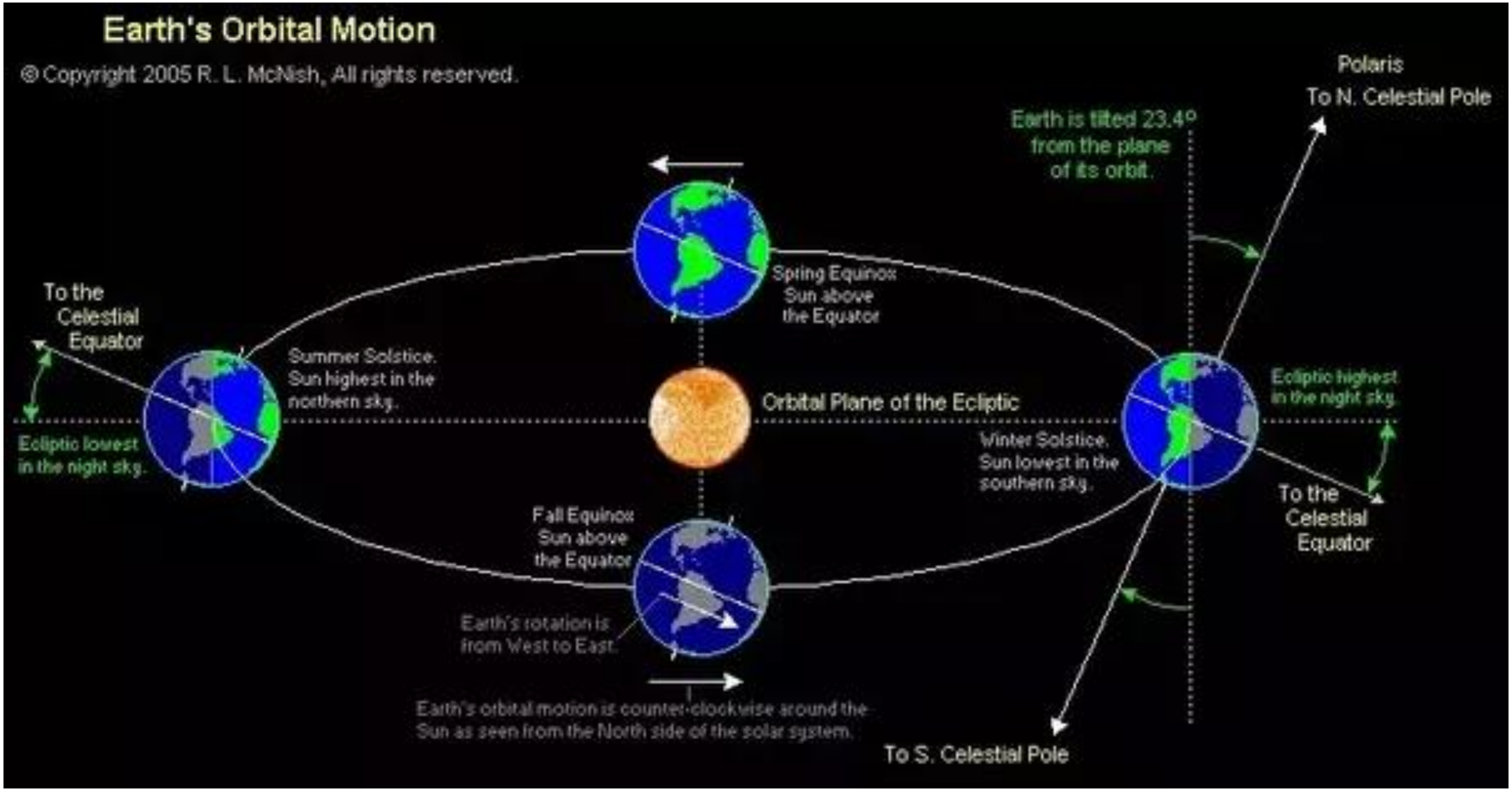


Shake It: Direct Detection

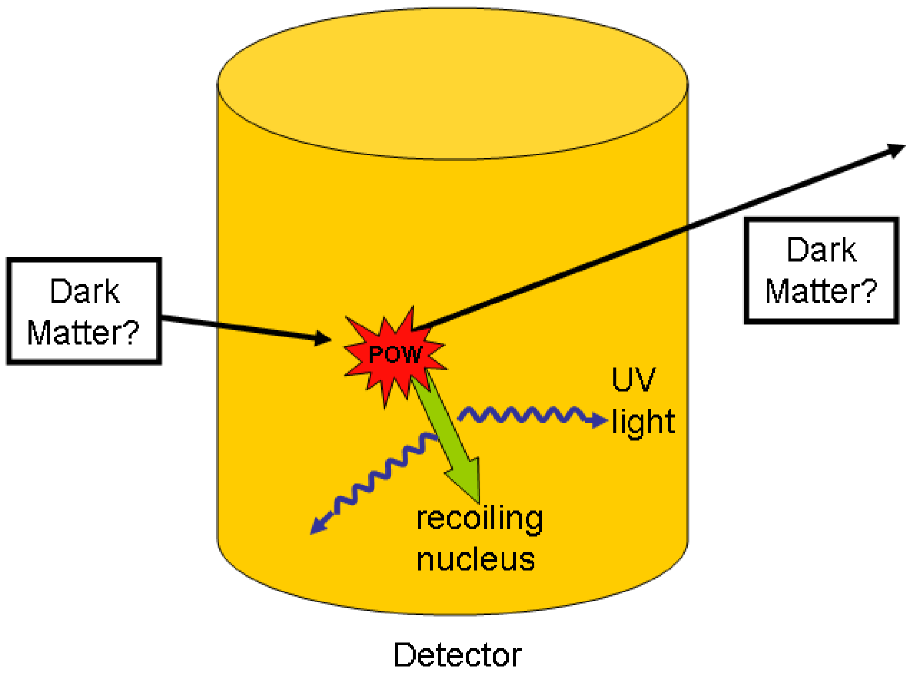
Eppur si muove…

Earth moves through the DM halo, so cold DM particles should hit us from different directions in summer and winter.



Shake It: Direct Detection

Cryogenic crystal detectors (e.g. CDMS, CRESST, CoGeNT, EDELWEISS): Search for heat deposition in very cold crystals (T~ 50 mK)



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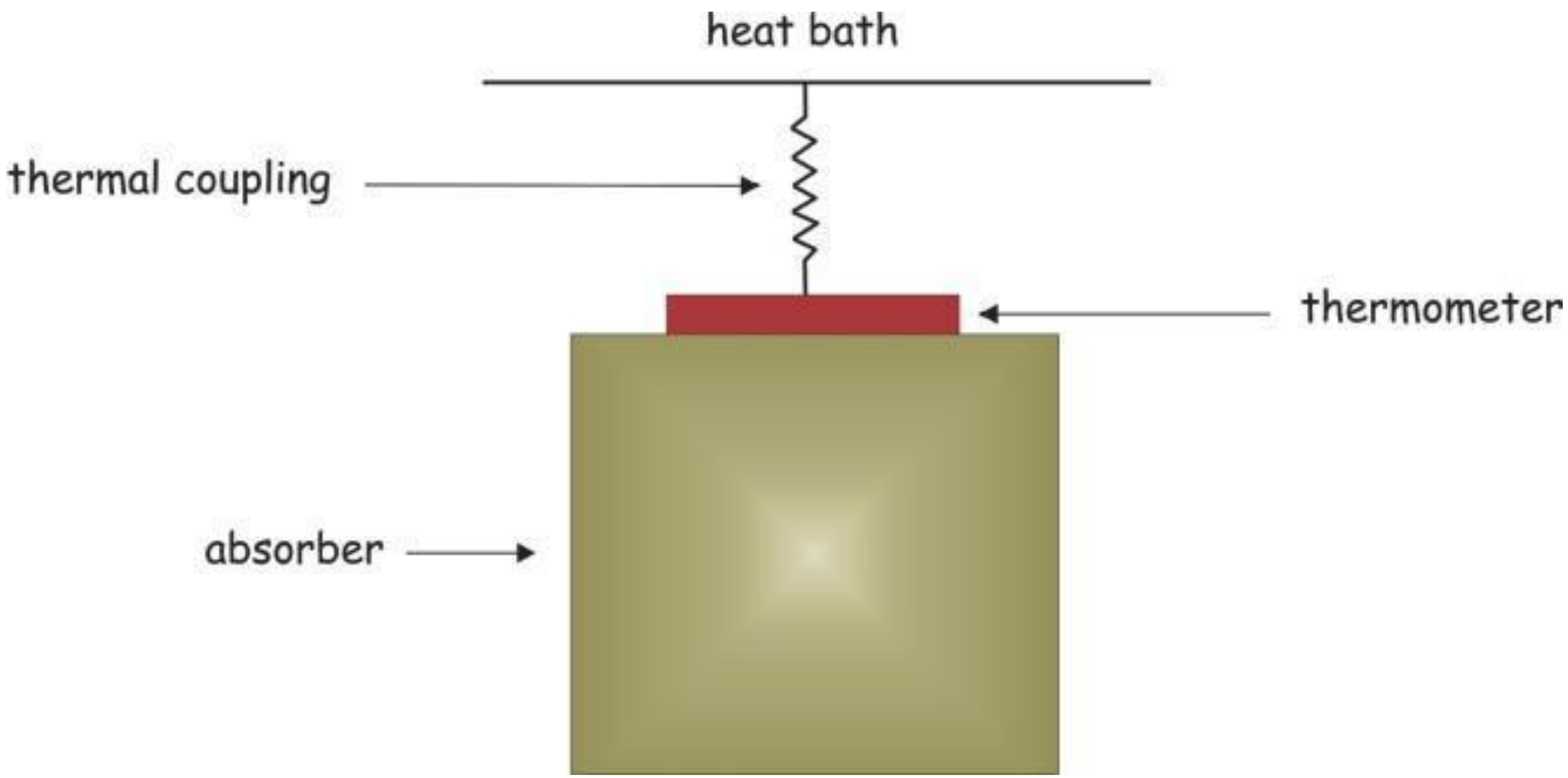
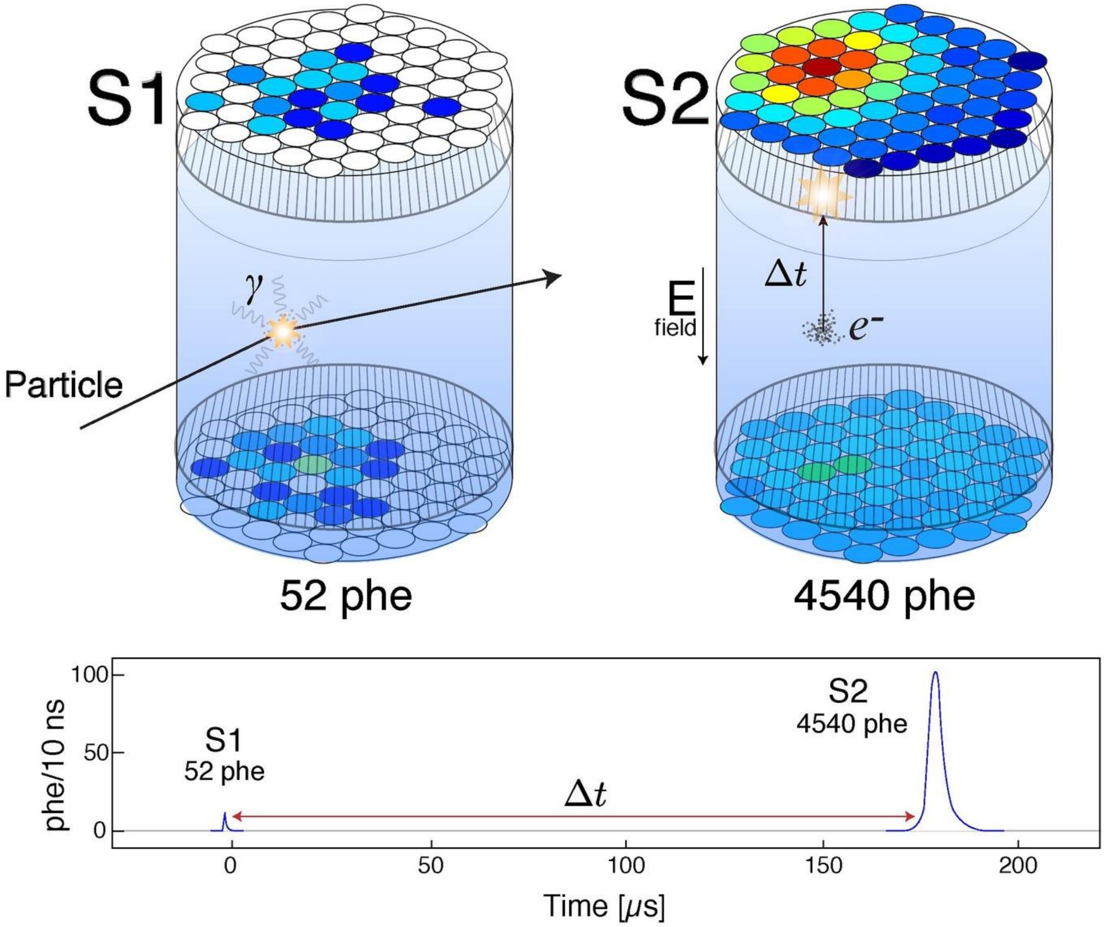


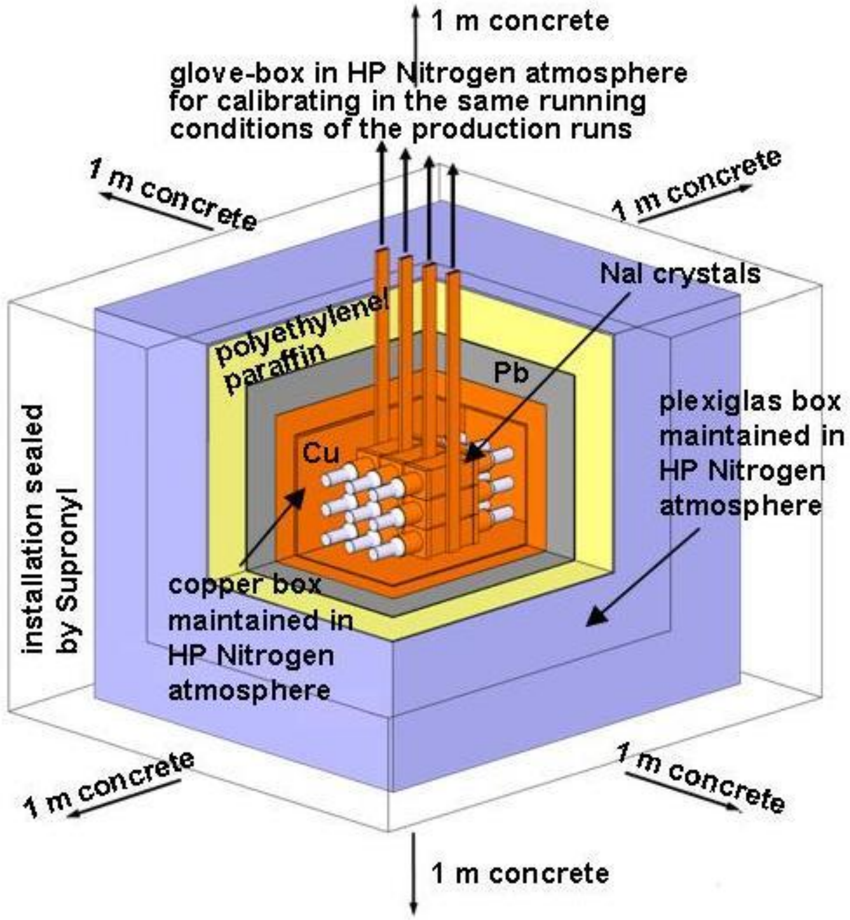
Shake It: Direct Detection

Scintillator detectors:
Convert kinetic energy from DM "knock" into radiation

Noble gas scintilator:
XENON, LUX, PandaX

Crystal scintilator:
DAMA, ANAIS





Simplified schema of ~ 100 kg NaI(Tl) set-up

Shake It: Direct Detection

Scintillator detectors:
Convert kinetic energy from DM "knock" into radiation

Noble gas scintilator:
XENON, LUX, PandaX

Crystal scintilator:
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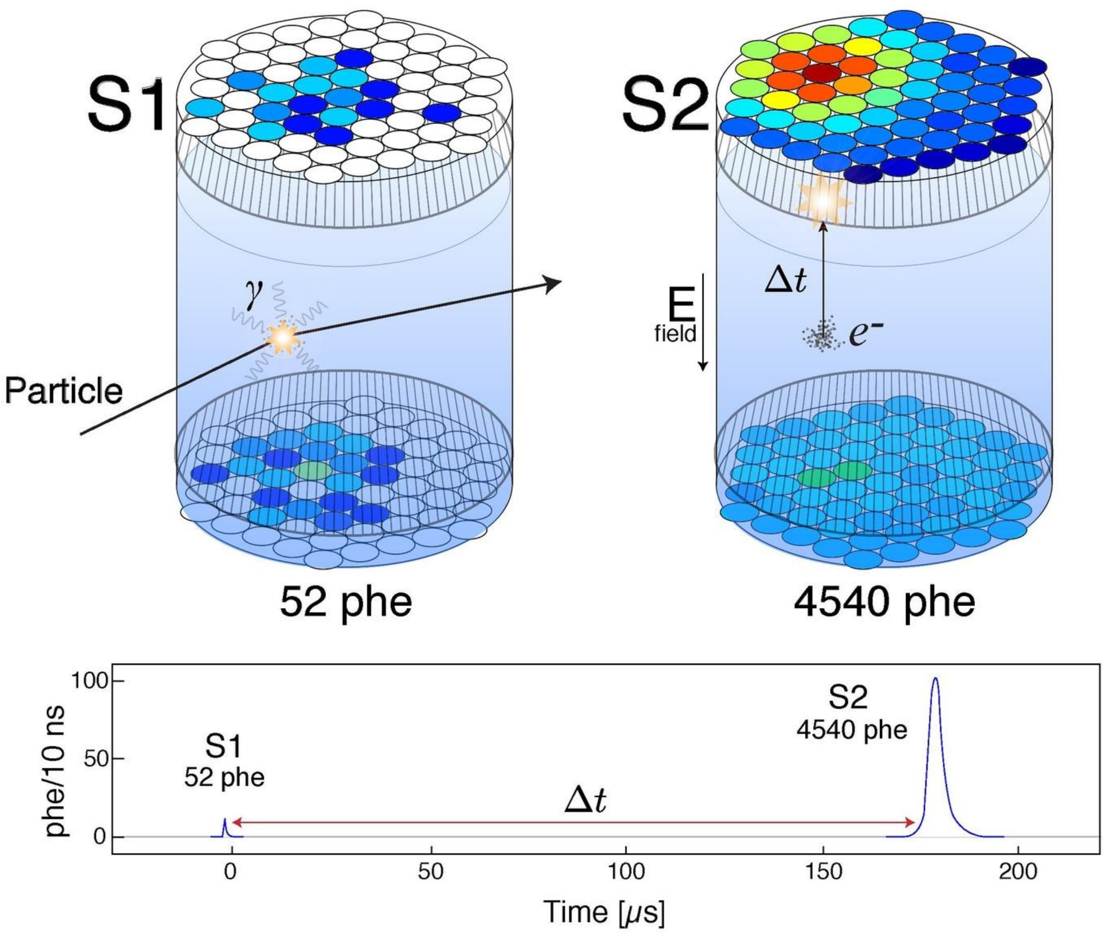
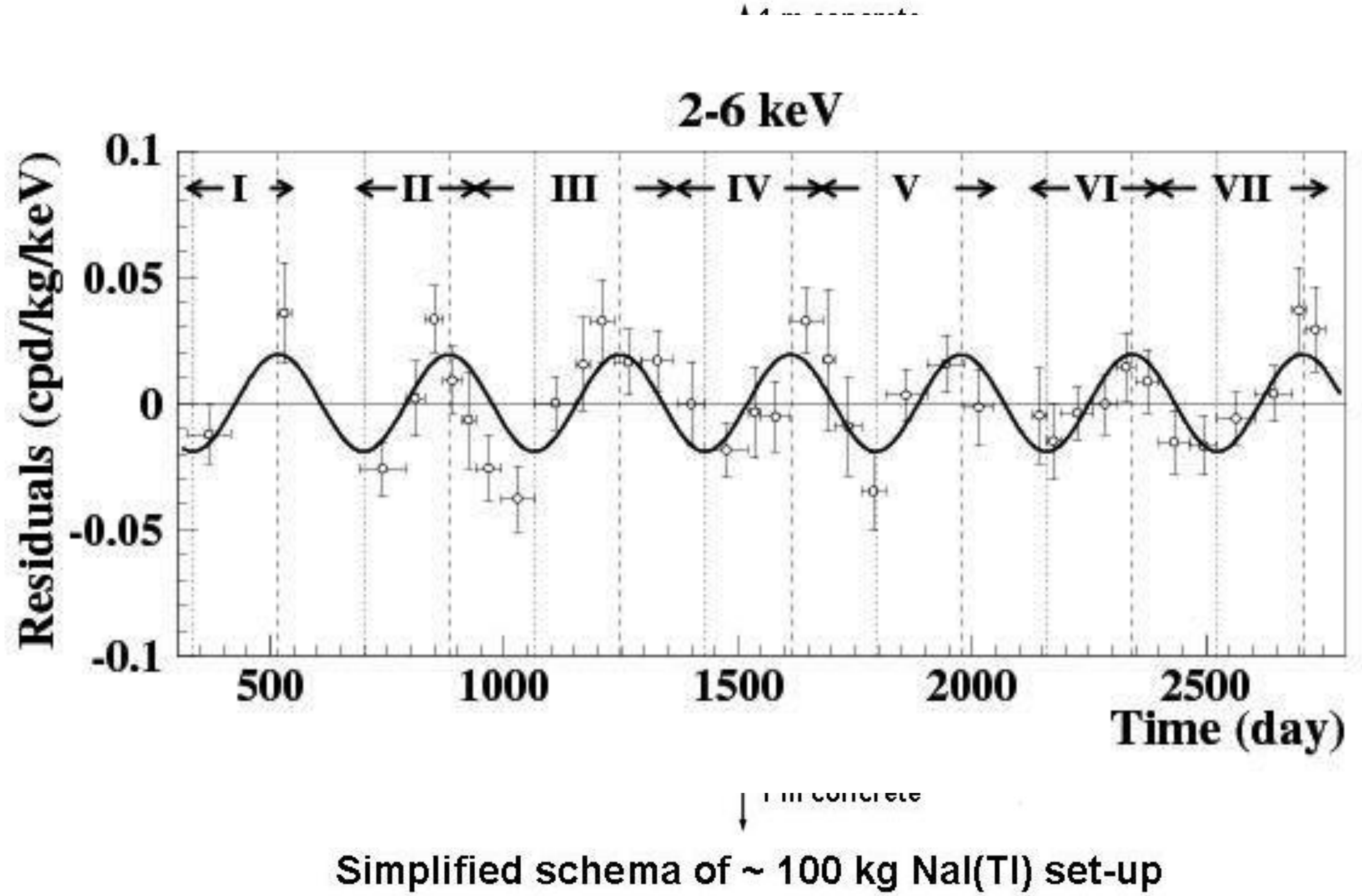
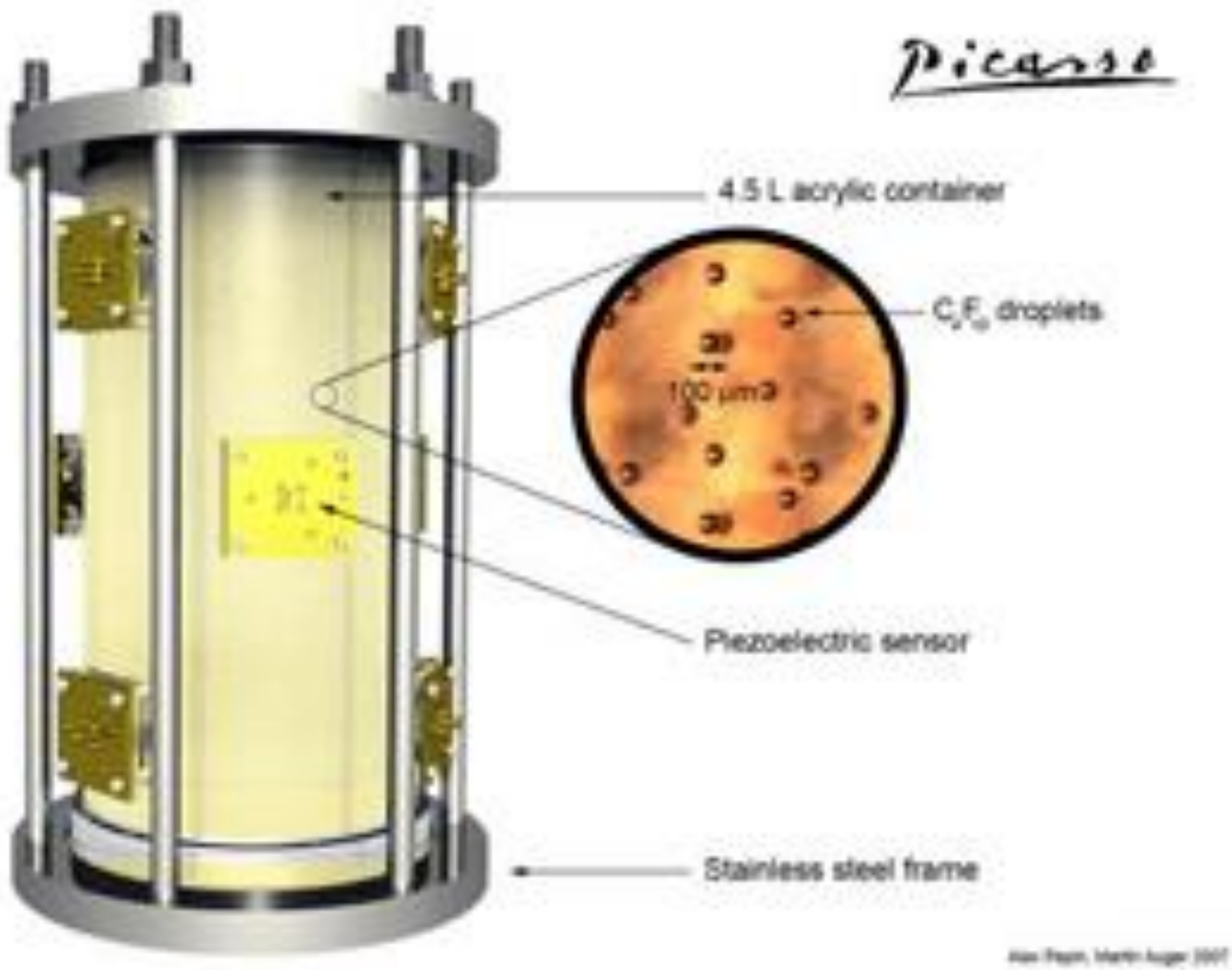




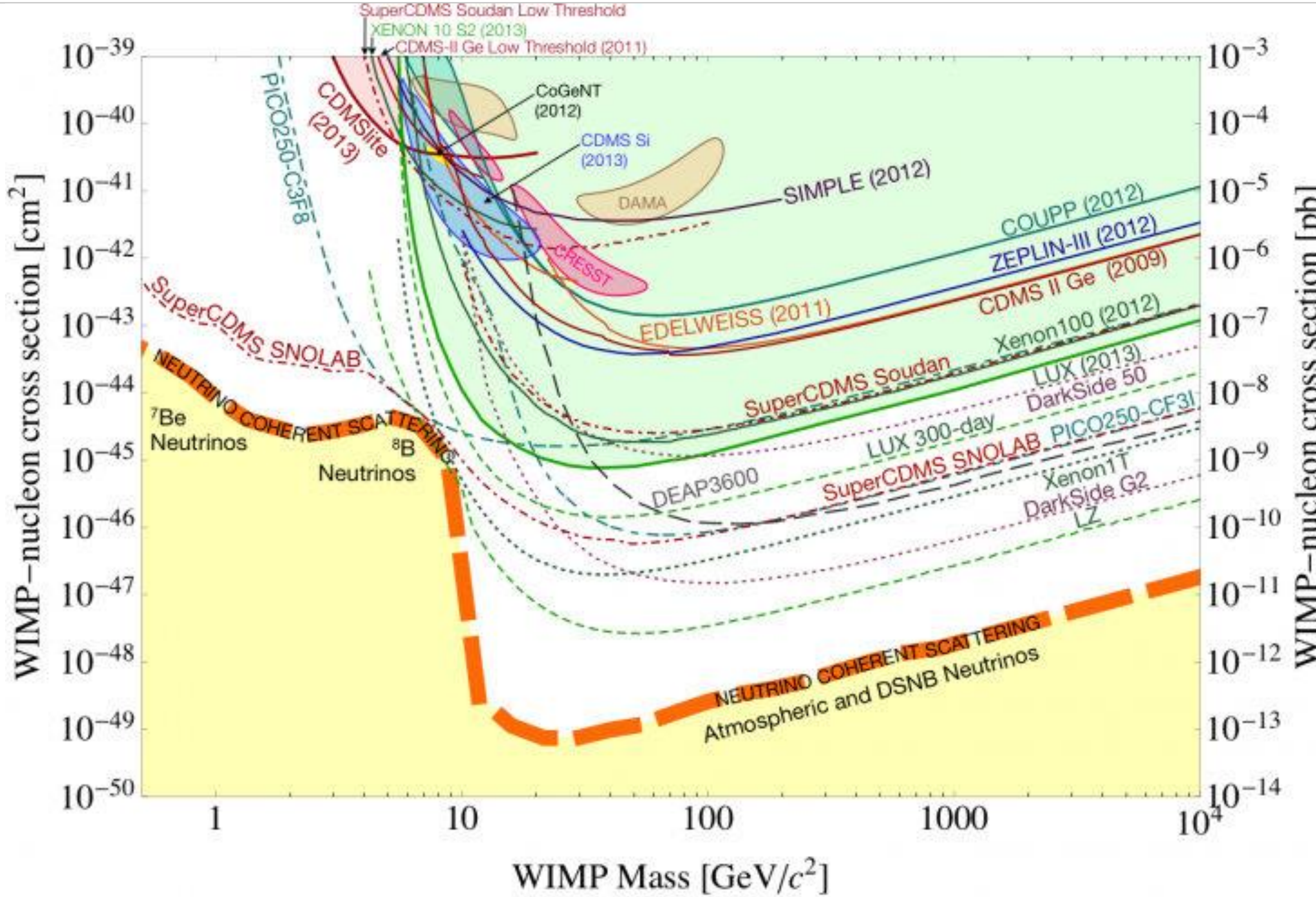
Shake It: Direct Detection

Bubble chamber

sees tracks of "knocked" particles (PICASSO)



Currnent Constraints



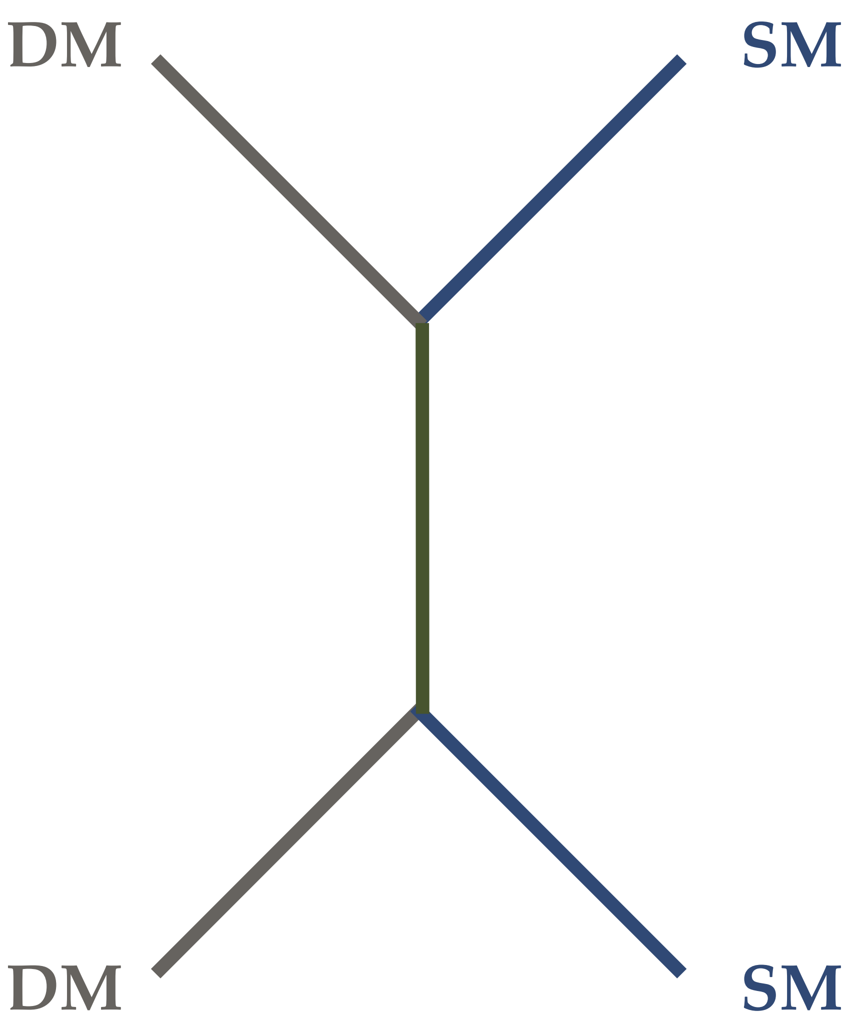
Break It: Indirect DM Detection

DM has existed since before the CMB decoupled. That leaves two possibilities:

1. **DM is made of stable particles.**
   Examples: standard WIMP, axion, macroscopic black holes…
   Expect emission from DM dense region due to DM annihilations

2. **DM is made of very long lived particles.**
   Examples: sterile neutrinos, small black holes…
   Expect emission from DM dense regions due to DM decay

Annihilating Dark Matter

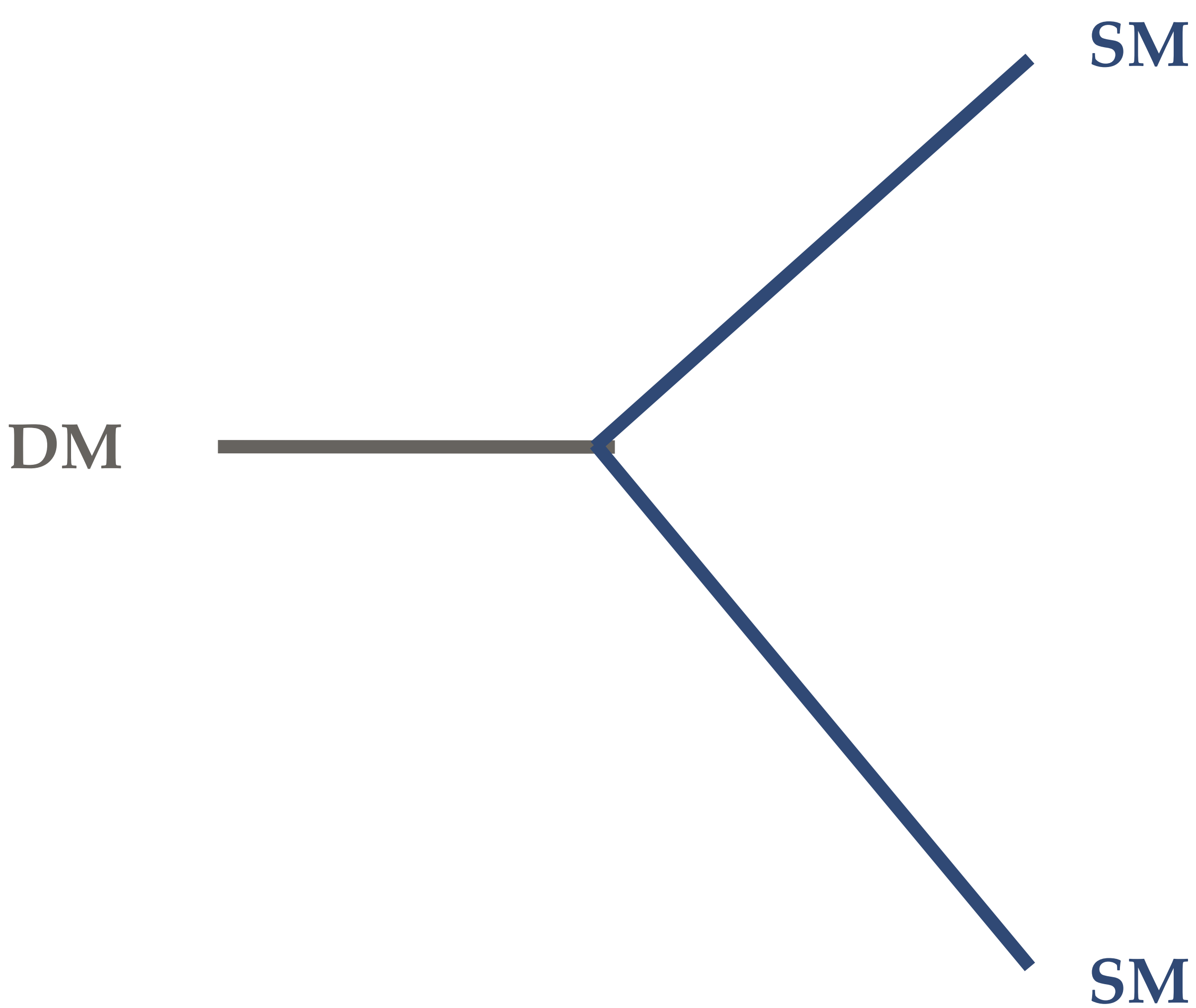


- **Unstable SM particles** further decay in a cascade into stable particles. ***Examples***: *mesons, neutrons excited baryons, muons, tauons …*

- **Stable SM particles** can travel astronomical distances ***Examples***: *electrons, protons, neutrinos, photons*

Signal is proportional to the DM density squared ϱ^2

Decaying Dark Matter



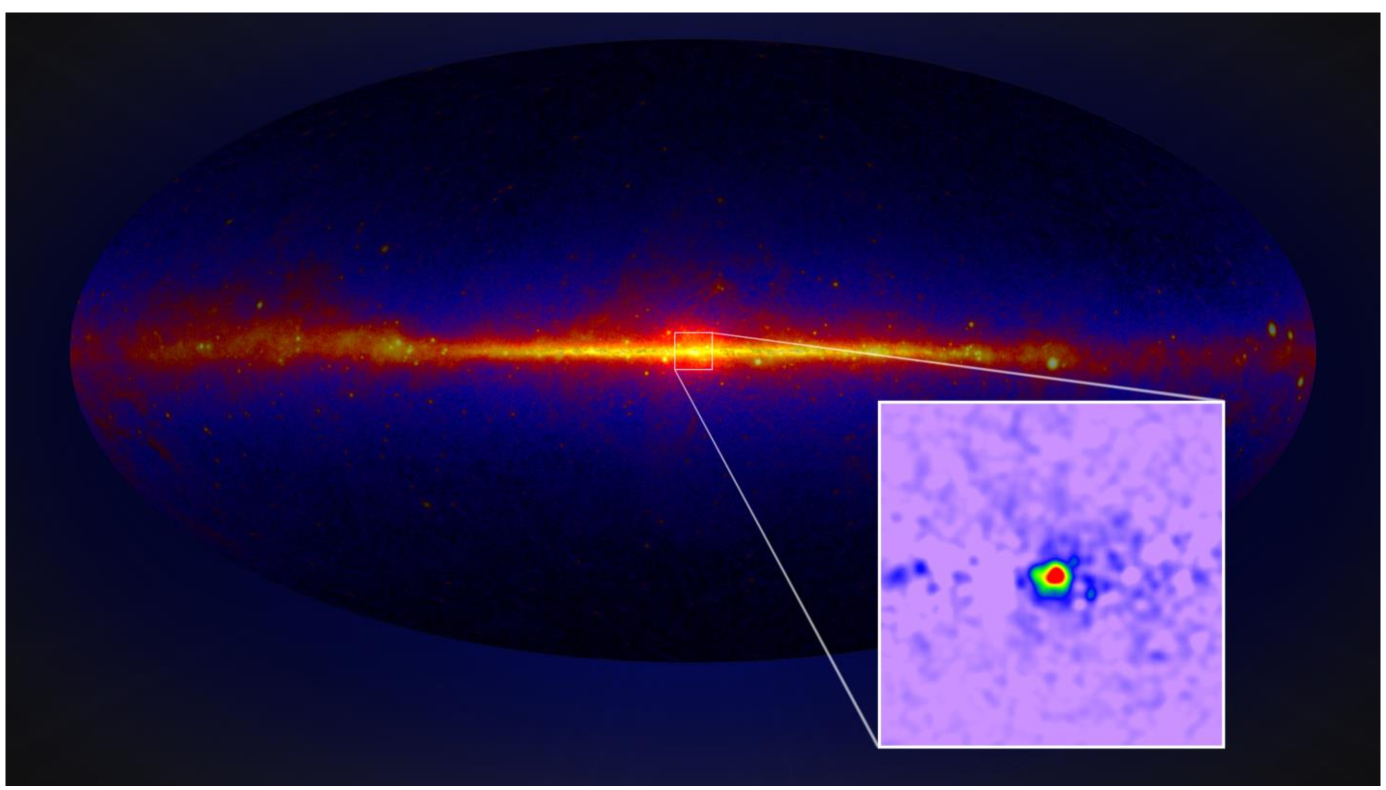
- **Unstable SM particles** further decay in a cascade into stable particles. ***Examples***: *mesons, neutrons excited baryons, muons, tauons …*

- **Stable SM particles** can travel astronomical distances ***Examples***: *electrons, protons, neutrinos, photons*

Signal is simply proportional to the DM density ϱ

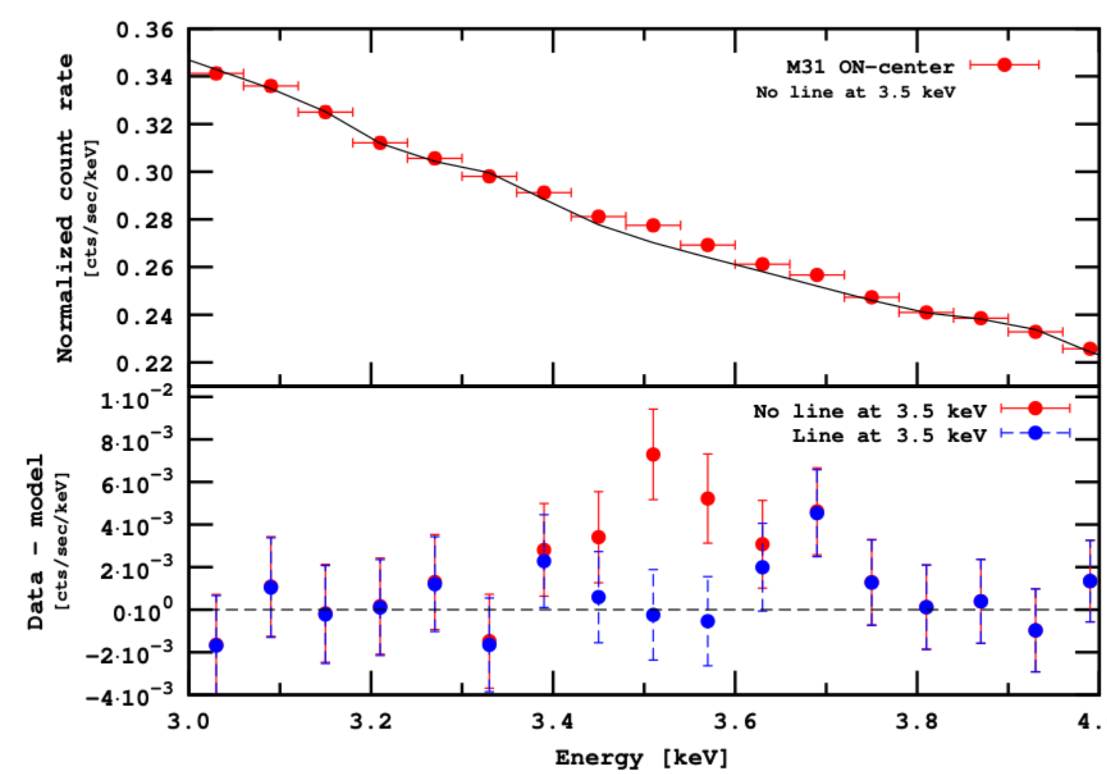
Photons

- Photons are the most direct messengers, they travel from the source to us on a straight line. This allows to identify the **location of the source** and the **energy released in the decay**.
- For two body decays, the photons form a **monochromatic emission line** and energy directly tells the **DM mass**.



GeV mass Dark Matter?

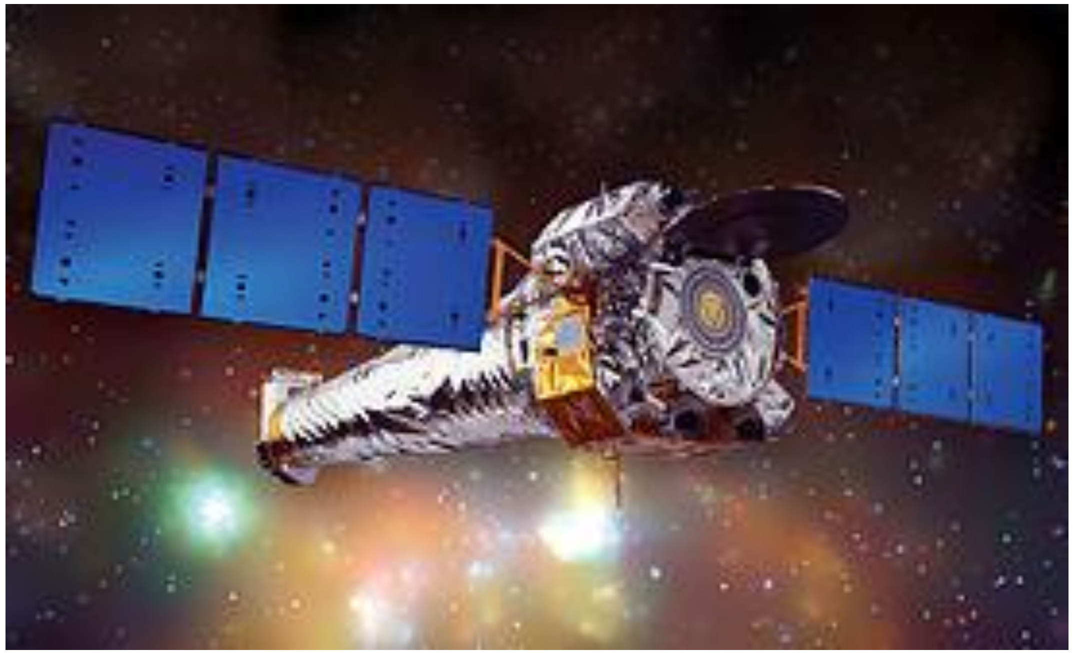
e.g. Goodenough/Hooper 2009



keV mass Dark Matter?

Boyarsky et al 2014, Bulbul et al 2014

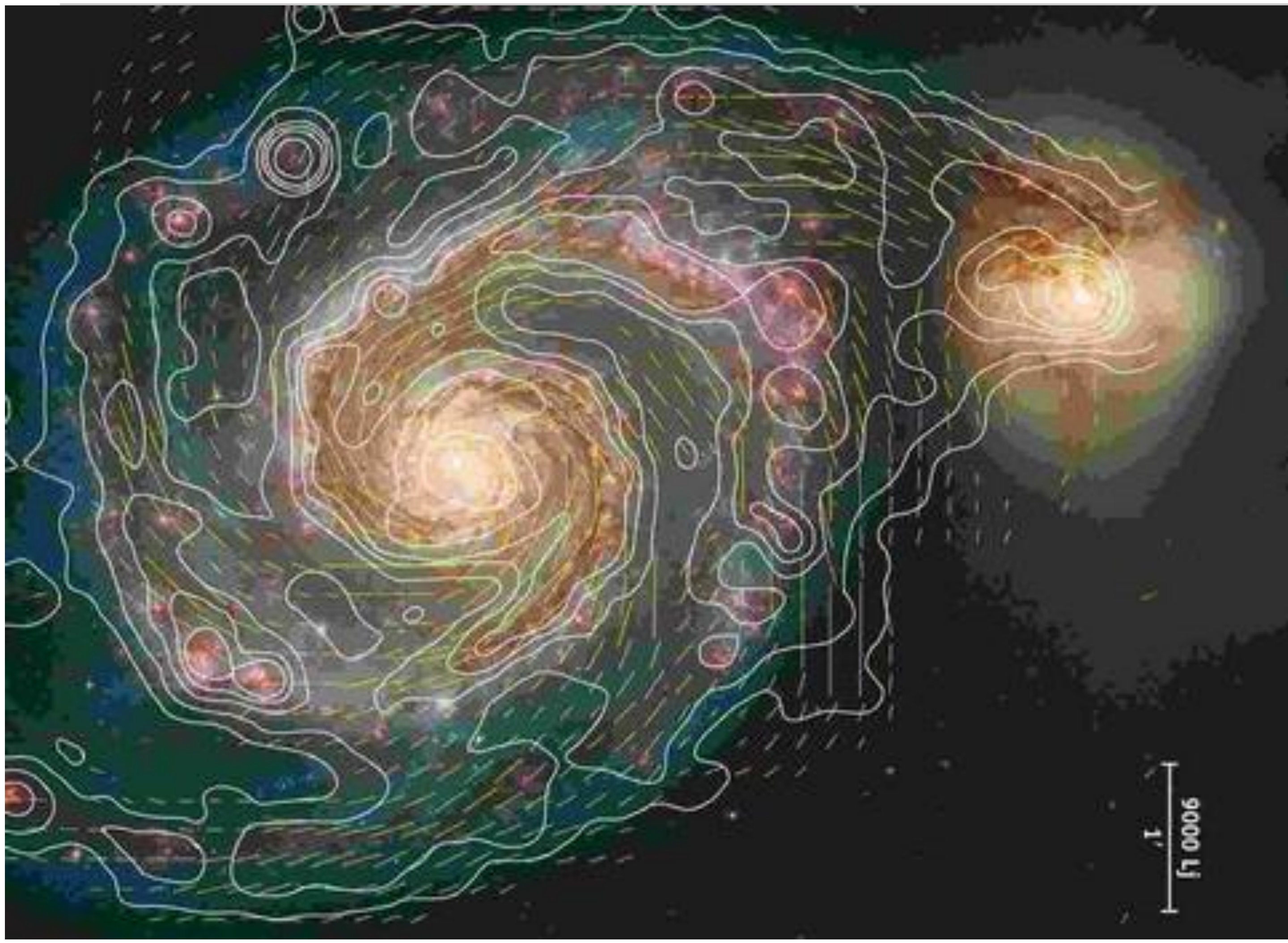
Detecting Photons



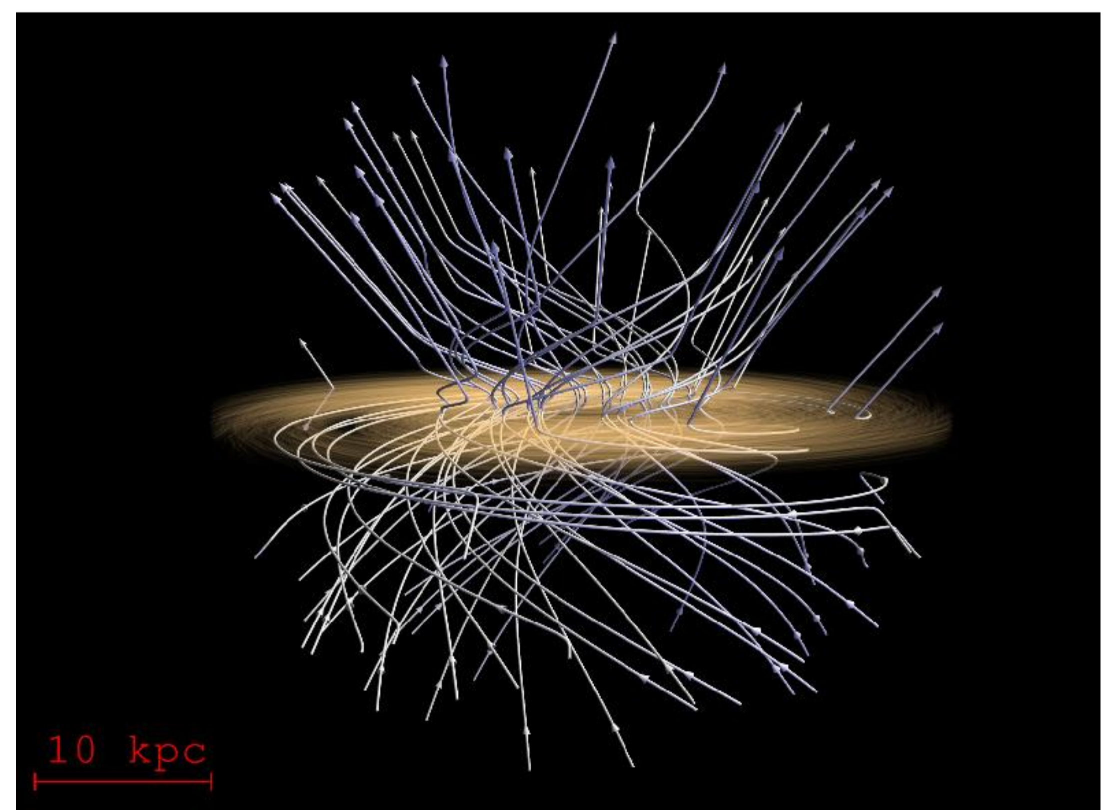
Chandra X -ray Telescope

Fermi Gamma-ray Space Telescope

Charged Cosmic Rays

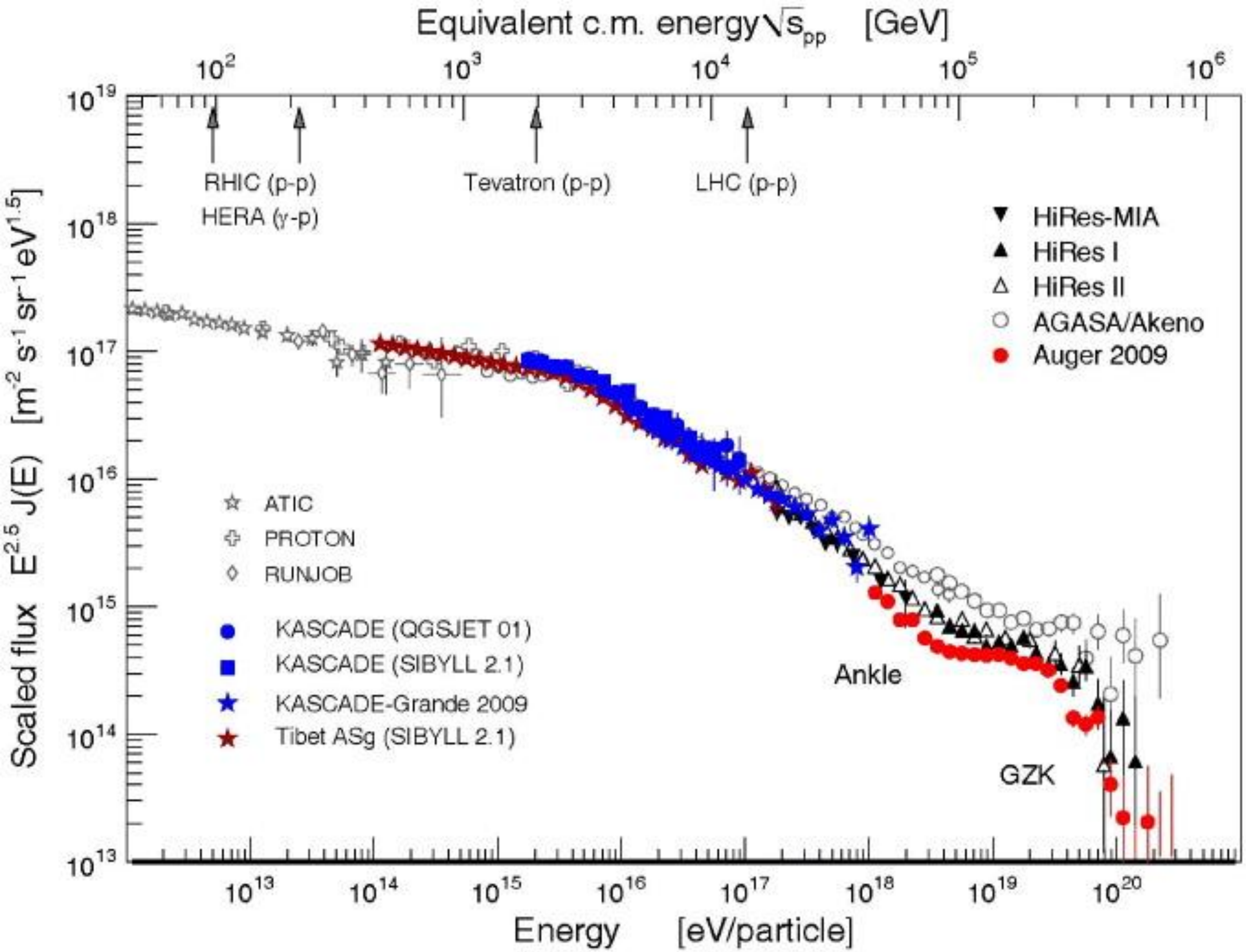


Galaxies (including our own) have magnetic fields. Those fields affect hared cosmic ray propagation.

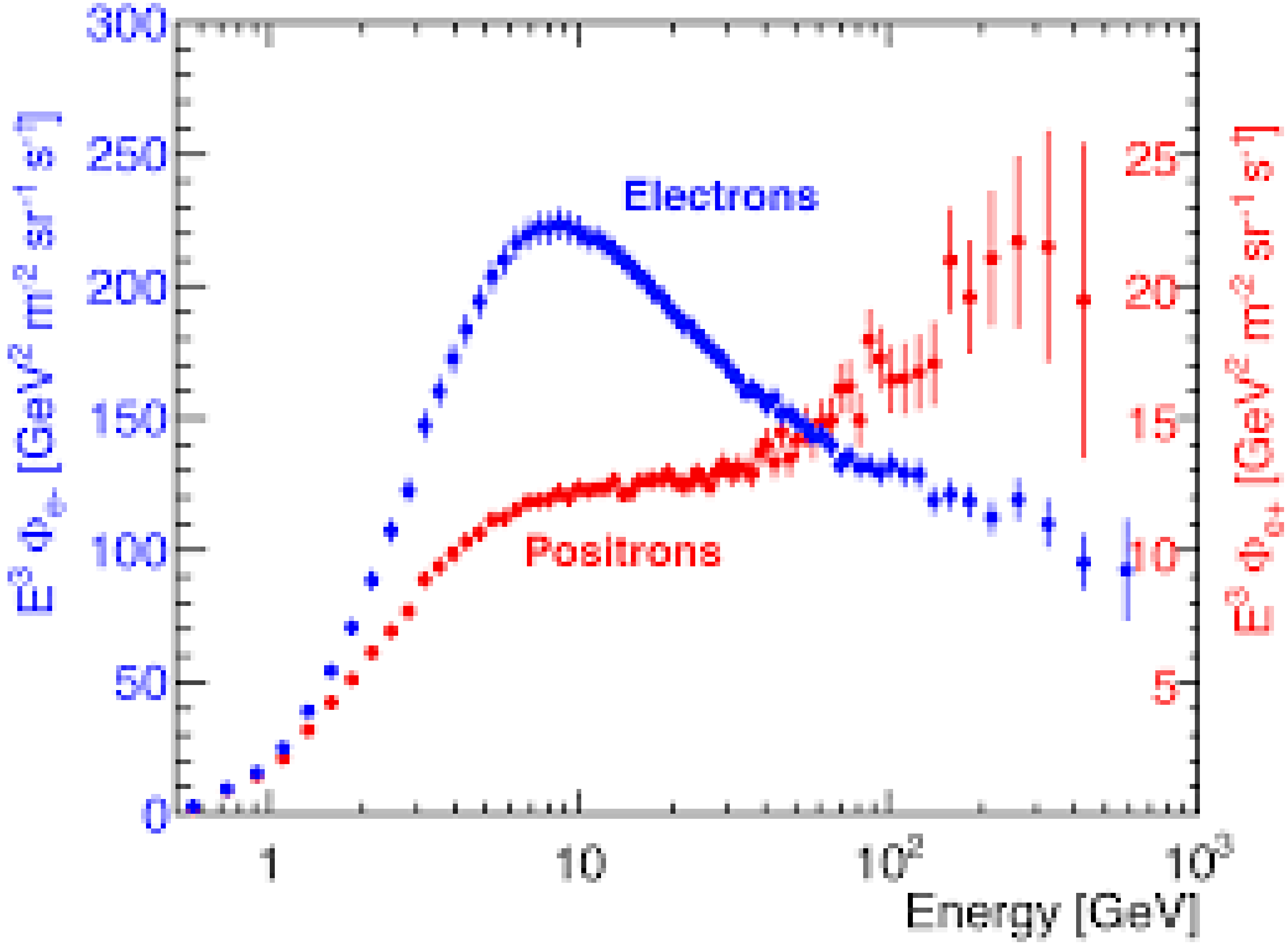


As a result, only limited information about the position of the source can be extracted, the main observable is the spectrum.

Cosmic Ray Spectrum

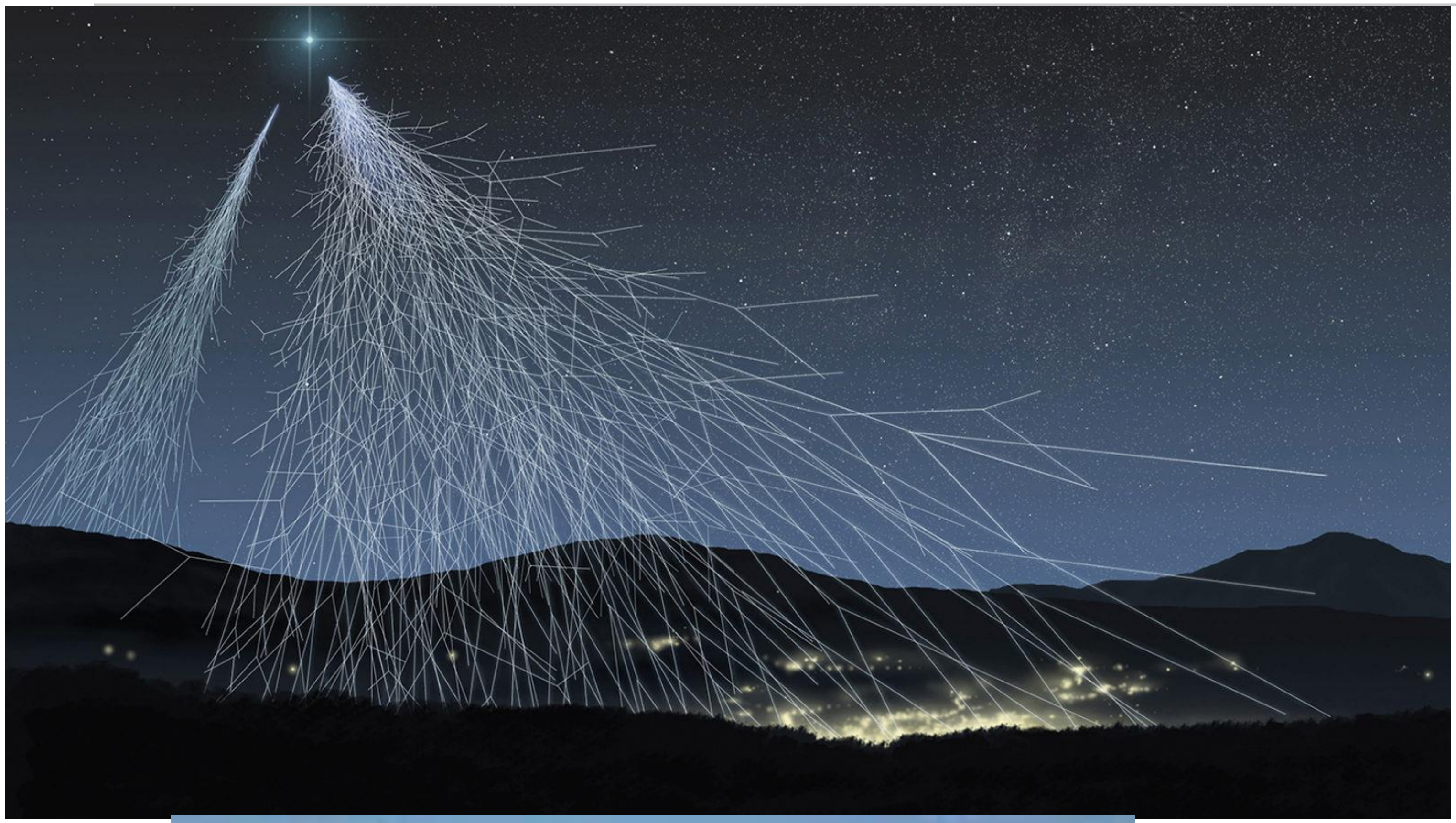


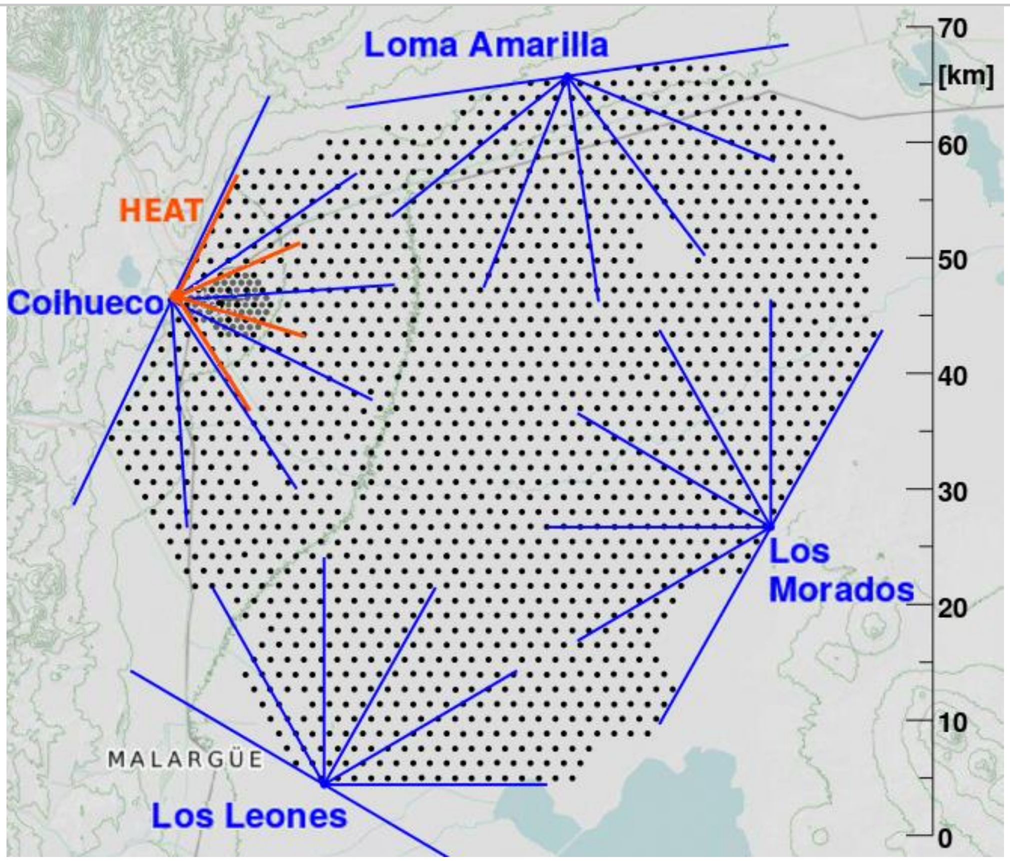
Positron Excess



Positron spectrum shows funny rise at high energies - from DM?

Ground Based Cosmic Ray Detection

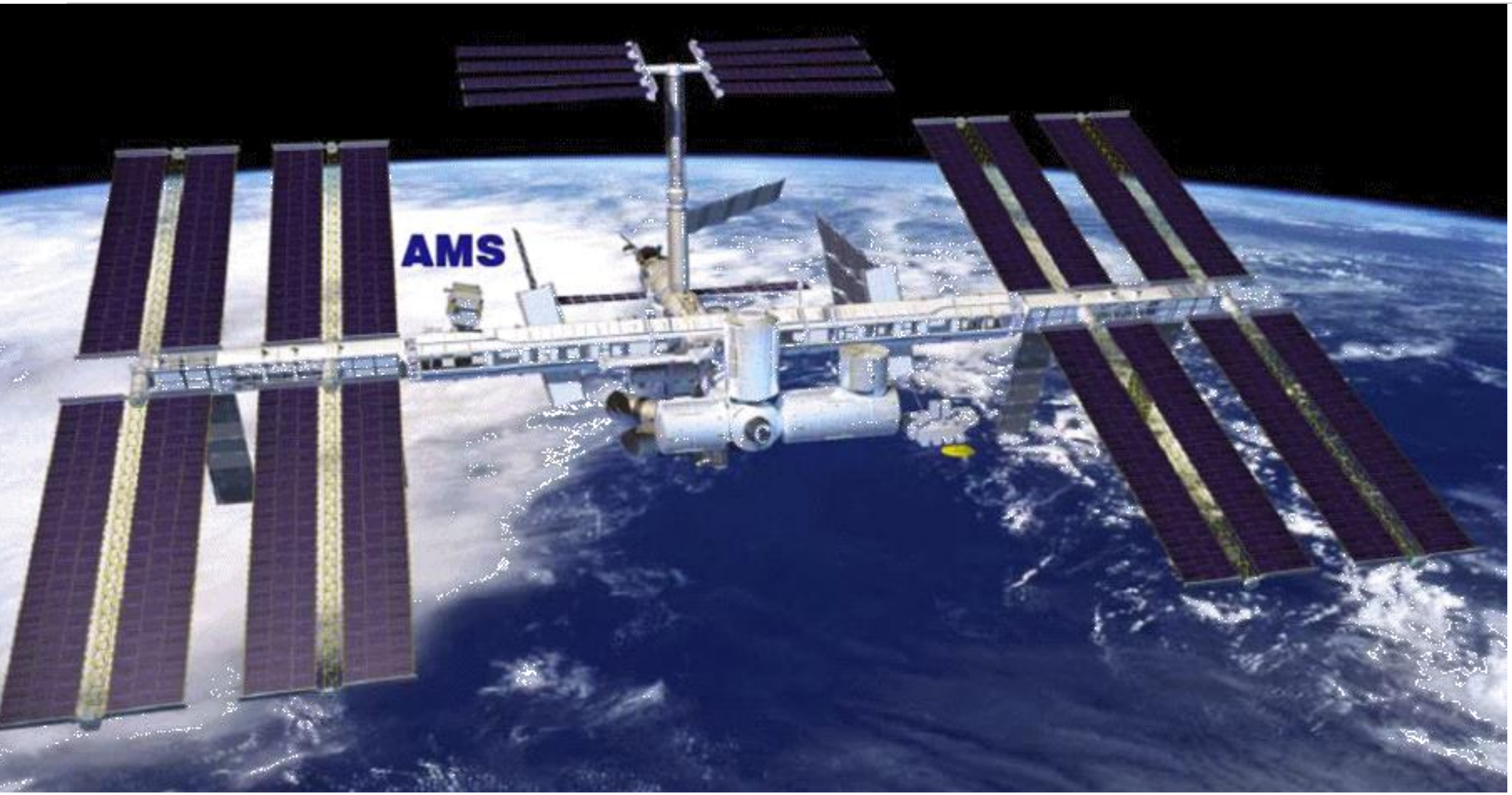




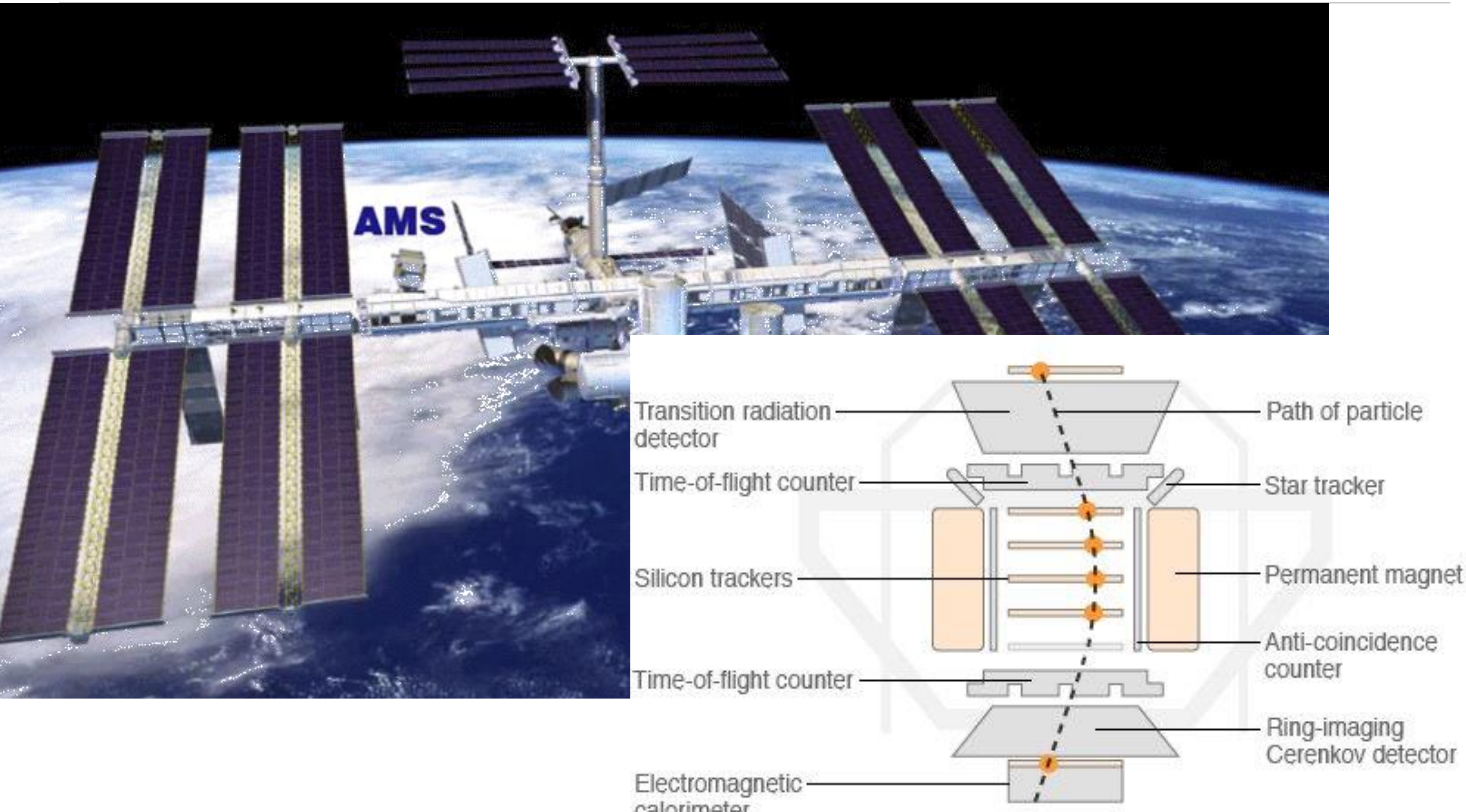
Pierre Auger Observatory

- Cherenkov detectors (water tanks)
- fluorescence (optical telescopes)
- muon detectors (underground scintillators)
- radio detectors (antenna)

Space-born Detectors

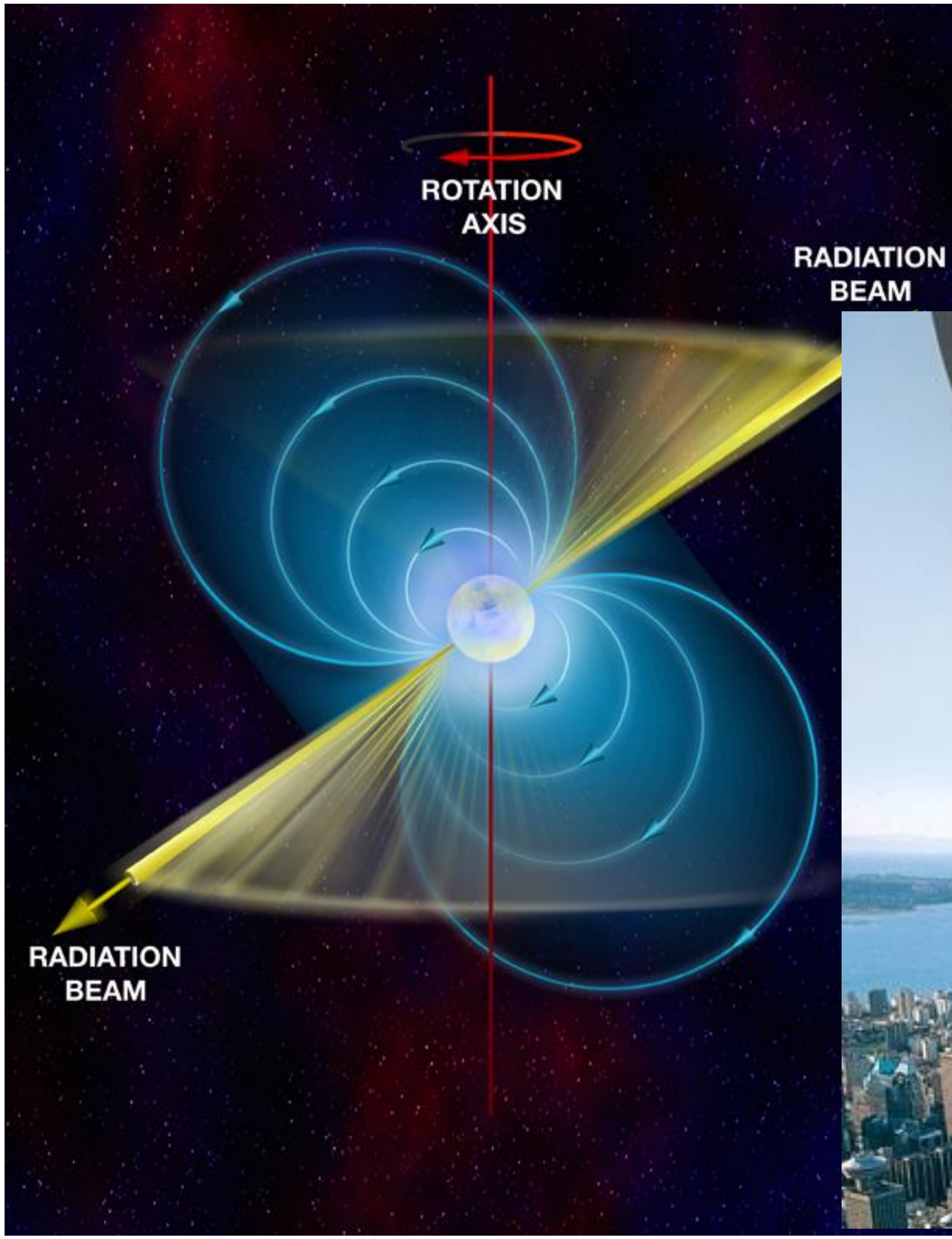


Space-born Detectors



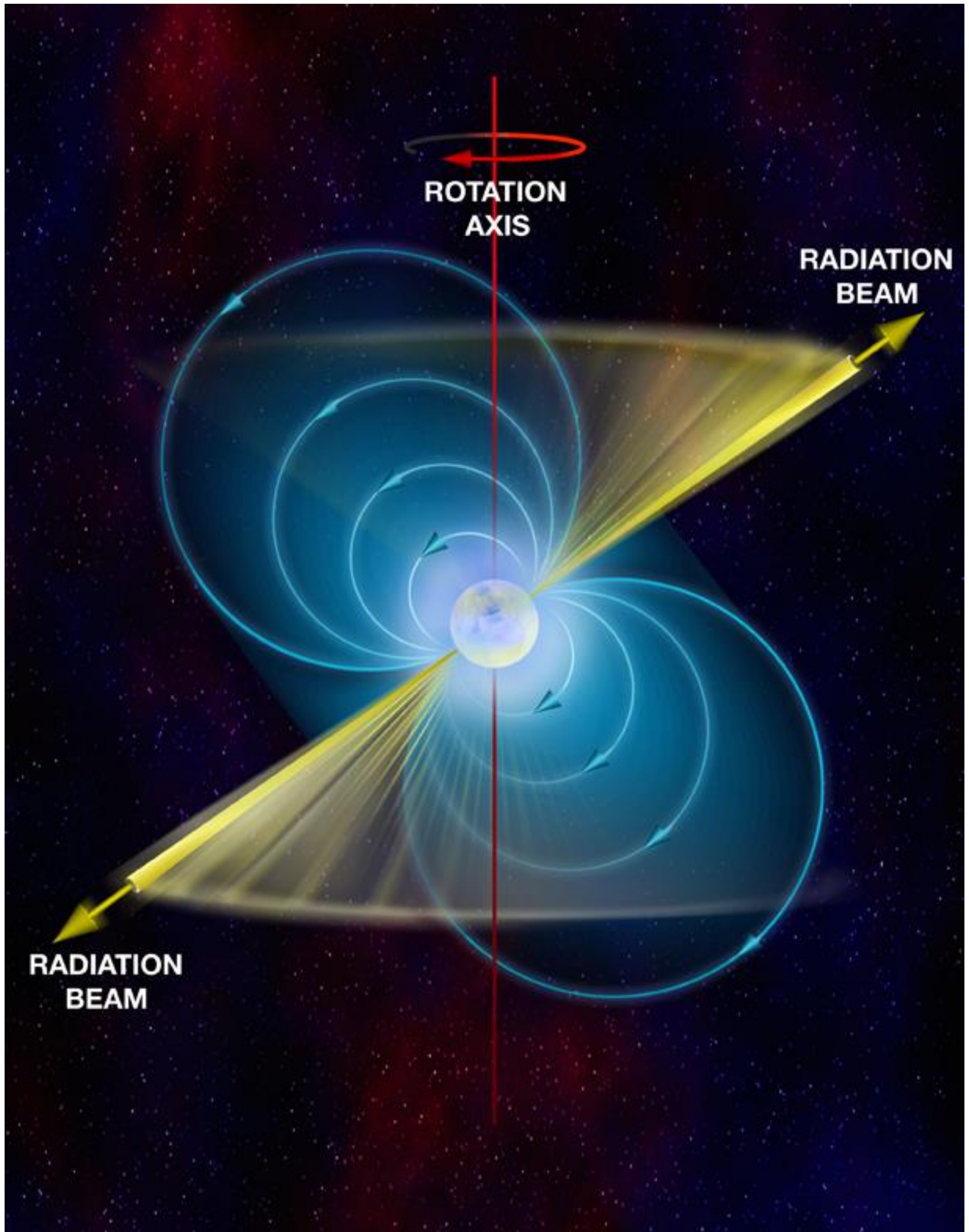
Source: CERN

DM Hunter's Nemesis: The Pulsar



- **Pulsars** are neutron stars, i.e., very compact objects that form at the end of a massive star's live.

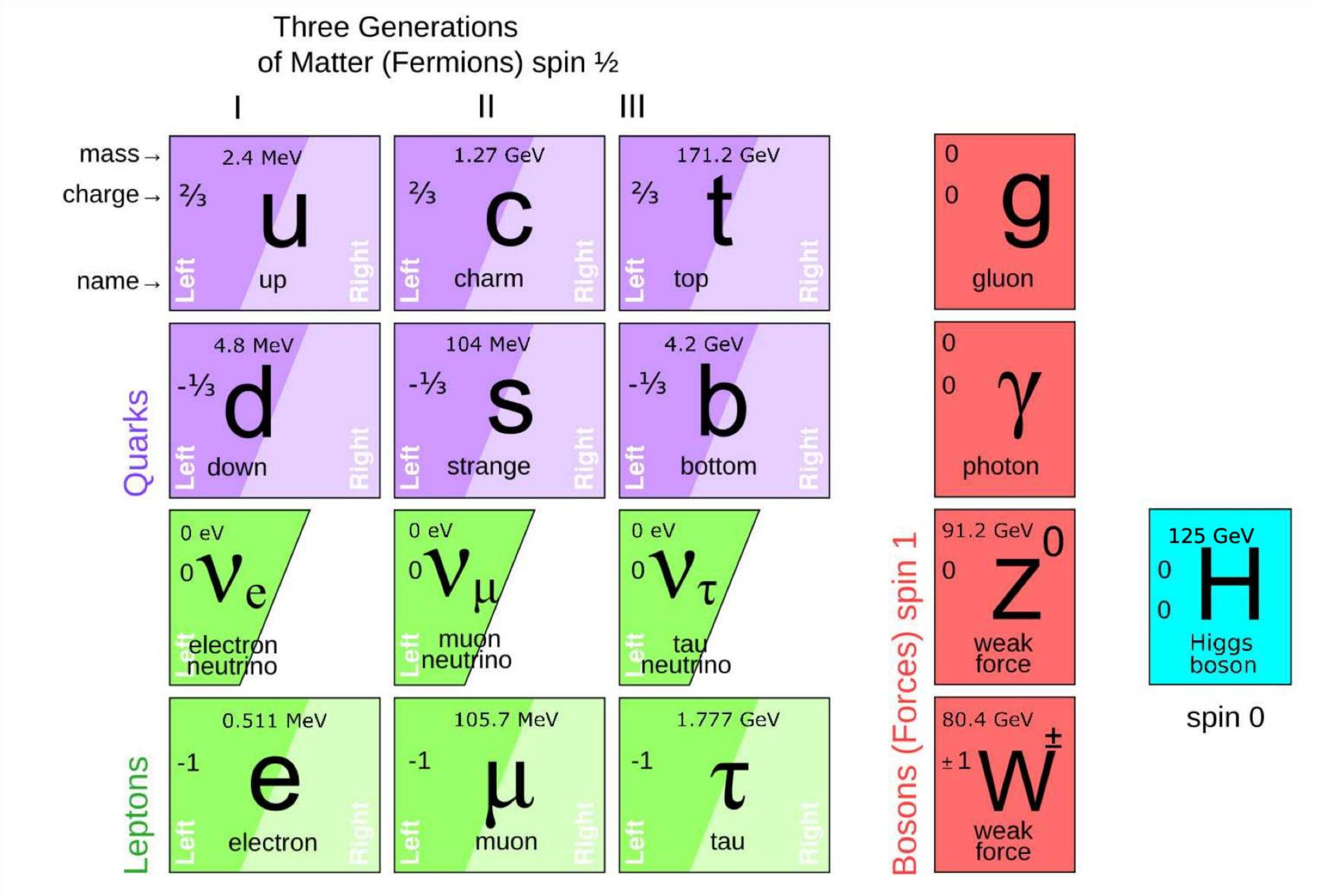
DM Hunter's Nemesis: The Pulsar



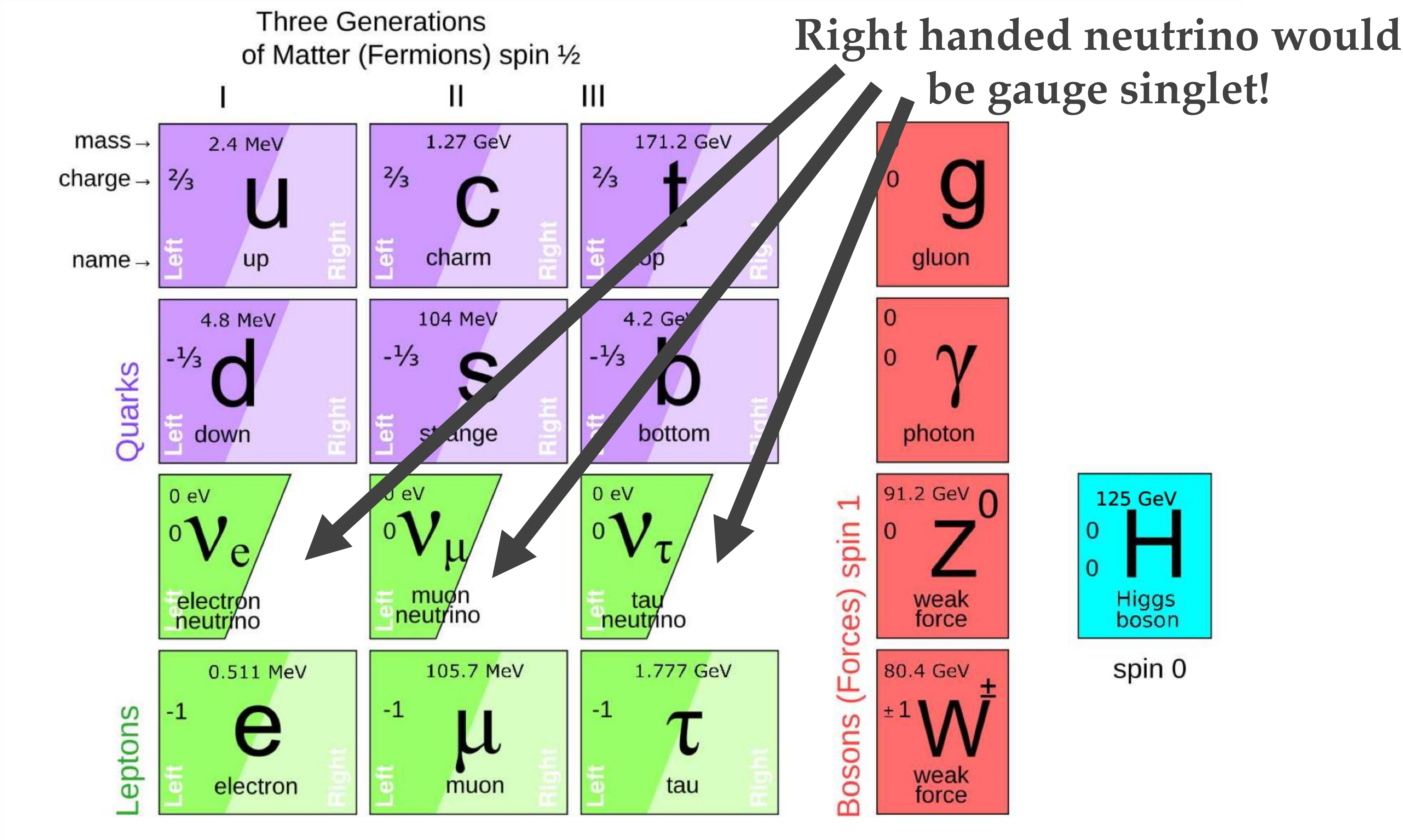
- **Pulsars** are neutron stars, i.e., very compact objects that form at the end of a massive star's live.
- They do not shine like normal stars, but have enormous magnetic fields that cause polar lights which are visible on earth. Because they spin rapidly, they blink like a lighthouse.
- **The enormous electromagnetic fields can also act as a particle accelerator and generate high energy cosmic rays**.

Sterile neutrino Dark Matter

Sterile Neutrinos



Sterile Neutrinos



Sterile neutrino - mixing

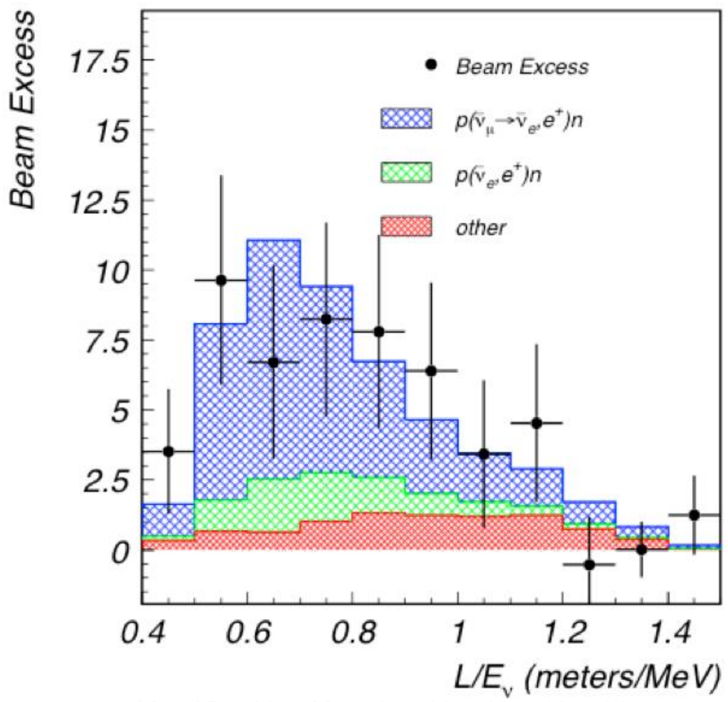
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Sterile neutrino is gauge singlet, feels no electromagnetic or nuclear forces!

But can mix with ordinary neutrinos…

…this would affect neutrino oscillation data

Have we seen it?

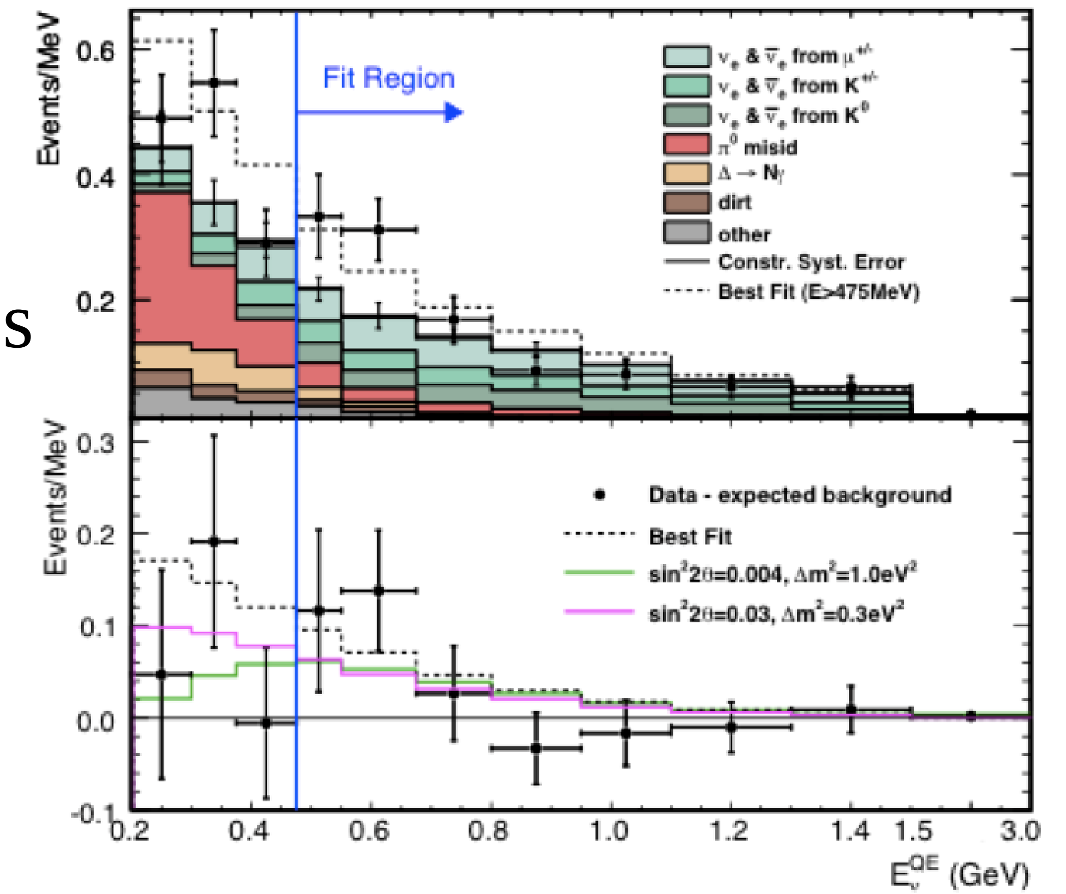


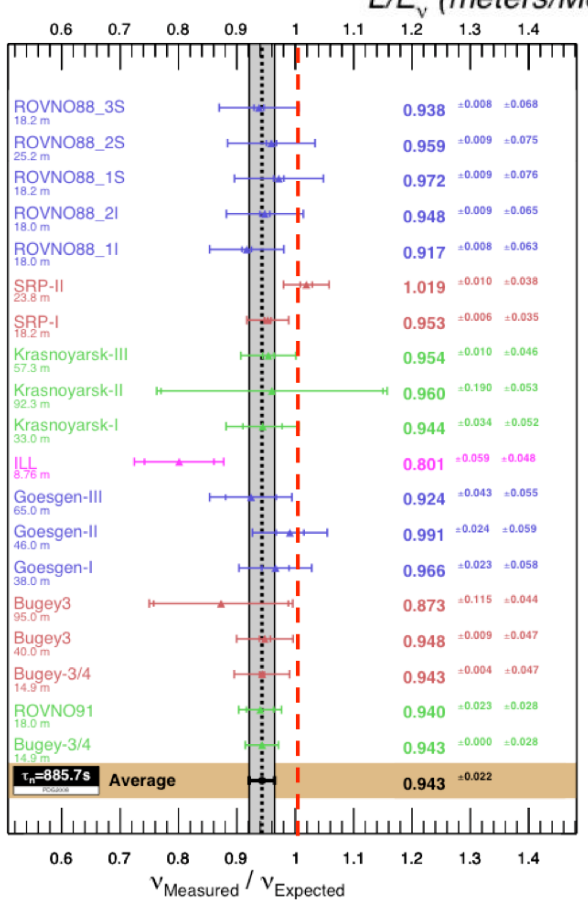
LSND:

excess of electron antineutrinos

MiniBoone:

extra electron (anti)neutrinos at low energy



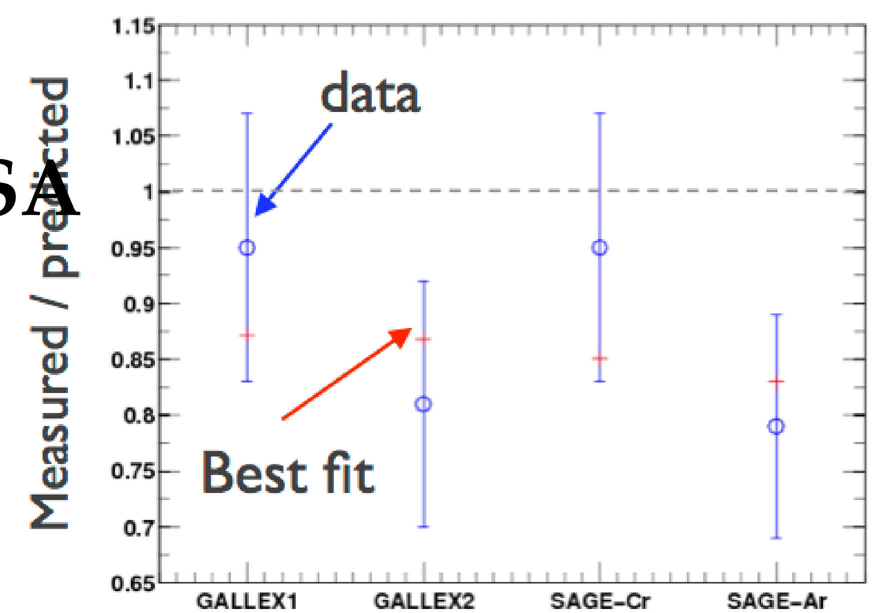


Reactor anomaly:

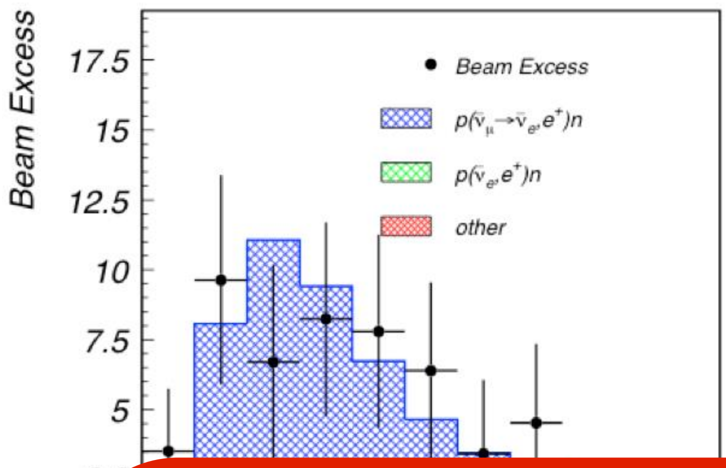
too few neutrinos from reactors?

GALLEX/SAGE:

missing electron neutrinos



Have we seen it?



LSND:

excess of

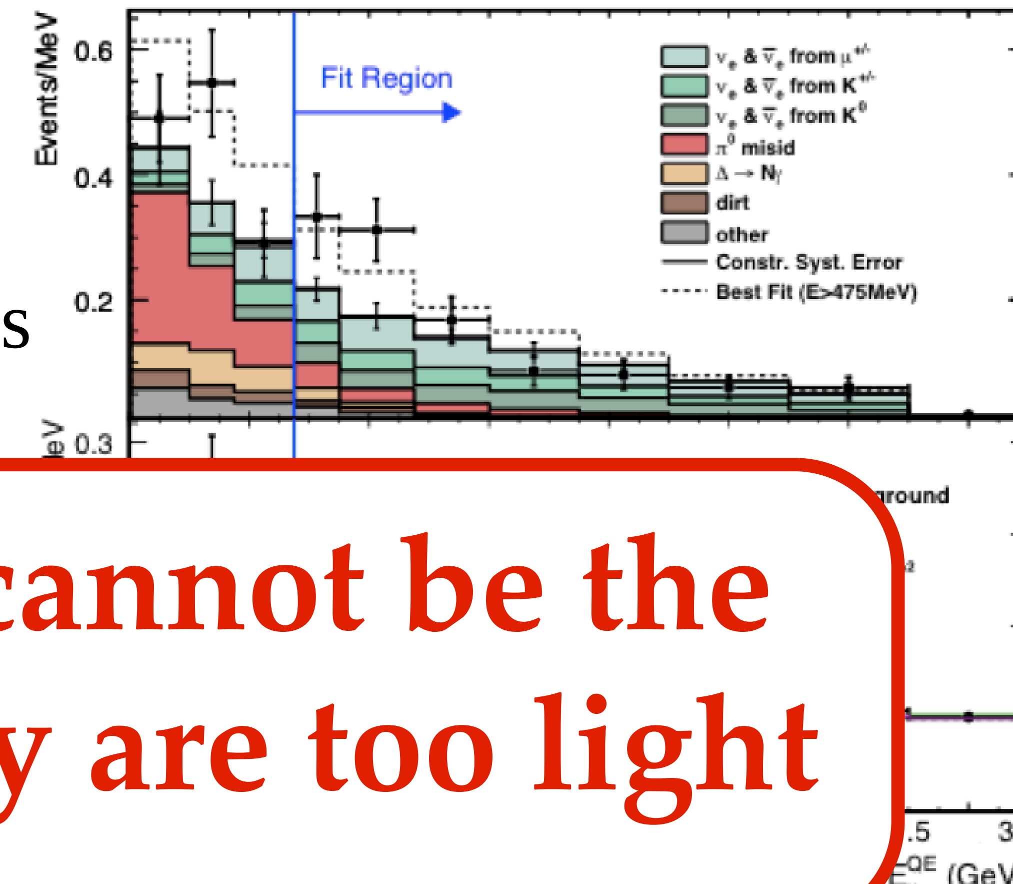
electron

MiniBoone:

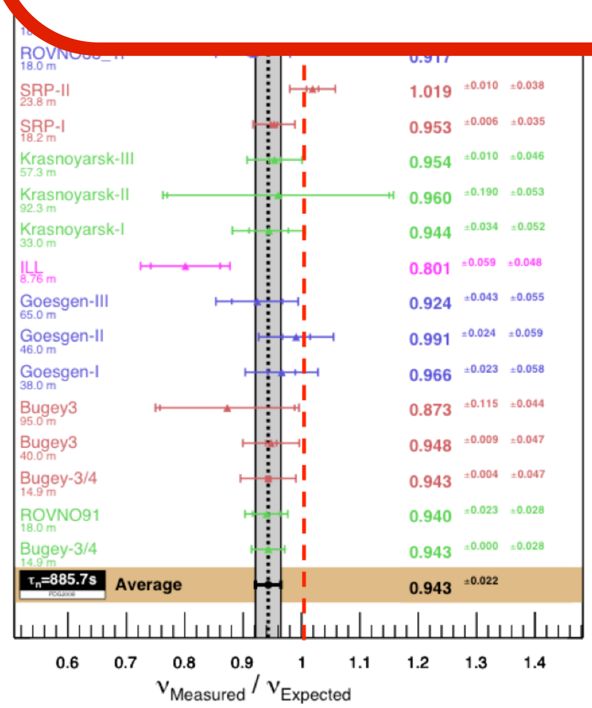
extra electron

(anti)neutrinos

at low energy



These sterile neutrinos cannot be the Dark Matter because they are too light



anomaly:

too few

neutrinos from

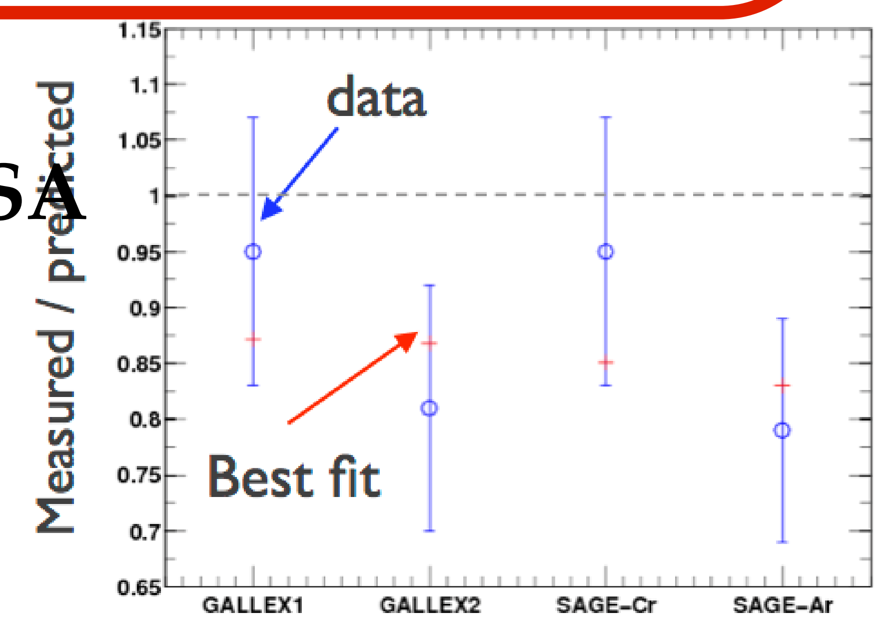
reactors?

GALLEX/SAGE:

missing

electron

neutrinos



Heavy “Sterile” Neutrino Dark Matter

Dark Matter Particles are

- heavy
- long lived
- neutral
- feebly interacting

❖ **What is the Dark Matter made of?**

It makes up most of the mass in the universe.

Heavy “Sterile” Neutrino Dark Matter

Dark Matter Particles are

- heavy
- long lived
- neutral
- feebly interacting

Neutrinos are the only known particles that fulfil three conditions…

…but they are too light

- **What is the Dark Matter made of?**

It makes up most of the mass in the universe.

Heavy “Sterile” Neutrino Dark Matter

Dark Matter Particles are

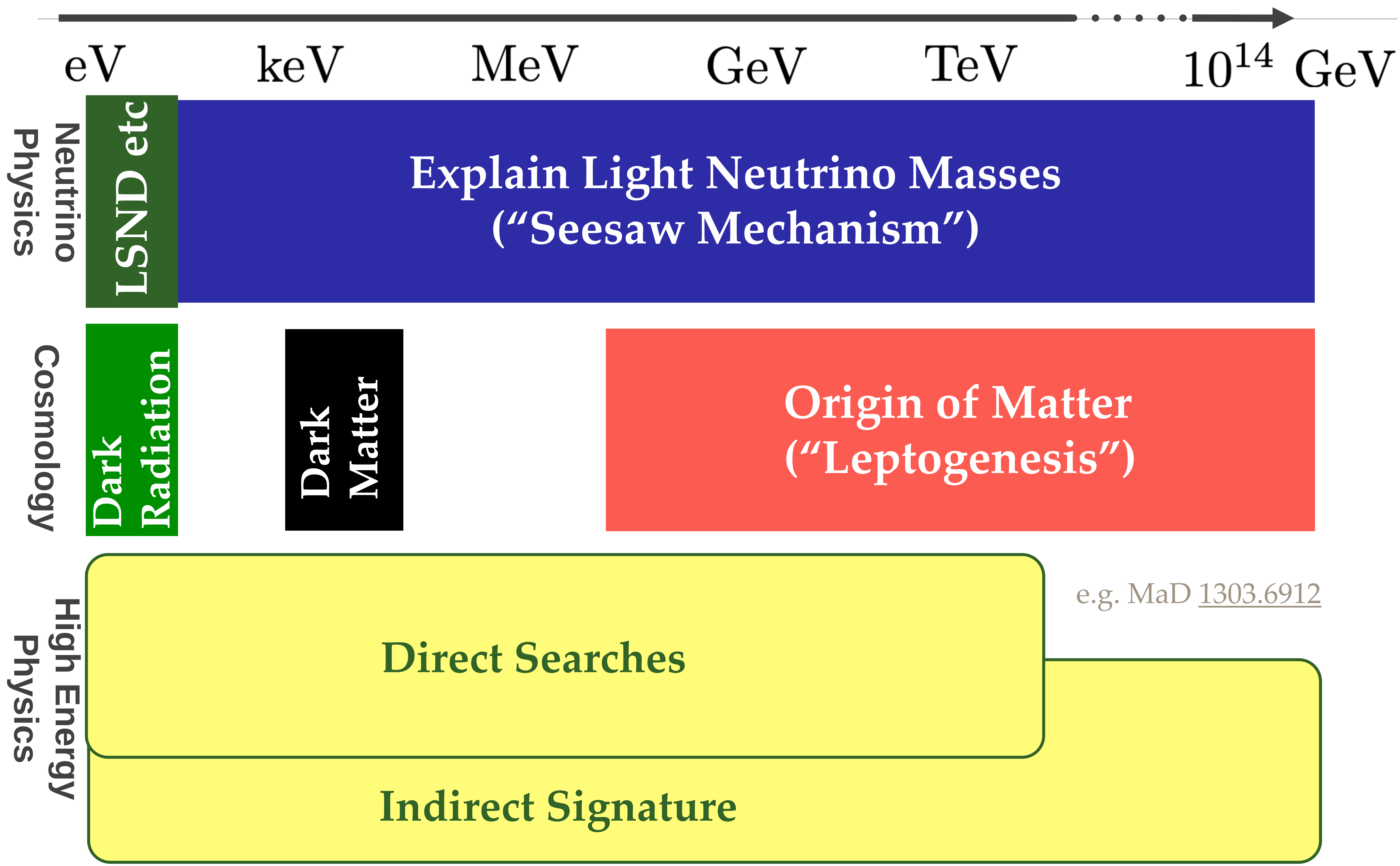
- heavy
- long lived
- neutral
- feebly interacting

} heavy sterile neutrinos can fulfil all conditions!

❖ **What is the Dark Matter made of?**

It makes up most of the mass in the universe.

Heavy Neutrino Mass Scale



How heavy do they have to be?

velocity distribution for DM particles:

$$F_X(\mathbf{v}) = \frac{1}{\left(\sqrt{2\pi}\, M_X\, \sigma_X\right)^3} \exp\left(-\frac{\mathbf{v}^2}{2\,\sigma_X^2}\right),$$

the maximum number density must be consistent with Pauli principle

$$f_X^{\max}(\mathbf{v}, \mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} F_X(0)$$

$$f_F^{\rm crit} \equiv \frac{g_X}{(2\,\pi)^3},$$

$$\frac{(2\,\pi)^{3/8}}{g_X^{1/4}} \left(\frac{\rho_X}{\sigma_X^3}\right)^{1/4} \leq M_X$$

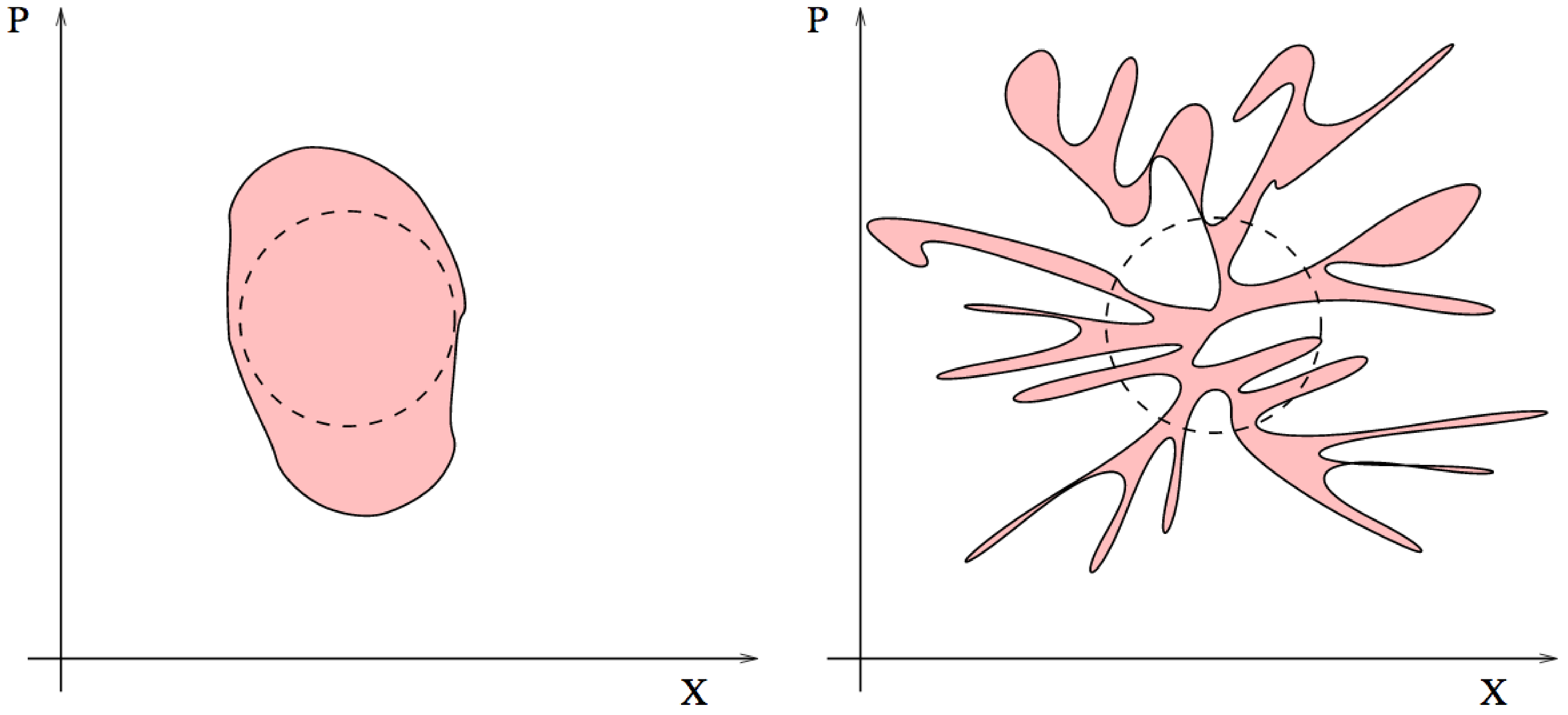
Pauli limit on fermionic Dark Matter mass

for milky way:

$$M_X \gtrsim 25\,\mathrm{eV}$$

DM Phase Space Density

Liouville's theorem: phase space volume constant



But coarse grained phase space density decreases in dense regions

$$\tilde{f}(\mathbf{k}, \mathbf{x}, t) \leq \max_k f_i(\mathbf{k})\;.$$

Tremaine Gunn Bound

Astronomical data constraints the quantity

$$Q \equiv \frac{\rho_0}{\langle \mathbf{v}_{\parallel}^2 \rangle^{3/2}}$$

For spheroidal dwarf galaxies:

$$\langle \mathbf{v}_{\parallel}^2 \rangle = \langle \mathbf{v}^2 \rangle / 3, \qquad \rho_0 = M_X \, n_X \qquad \langle \mathbf{p}^2 \rangle = M_X^2 \langle \mathbf{v}^2 \rangle$$

Combining the equations

$$Q = 3^{3/2} \, M_X^4 \, \frac{n}{\langle \mathbf{p}^2 \rangle^{3/2}} \simeq 3^{3/2} \, M_X^4 \, \tilde{f}(\mathbf{p}, \mathbf{X}, t_0)$$

using coarse grained phase space distribution

Tremaine Gunn bound

$$M_X \gtrsim \left(\frac{Q}{3^{3/2} \max \tilde{f}_i} \right)^{1/4}$$

Dark Matter Decay

primary decay channel $N \to 3\nu$

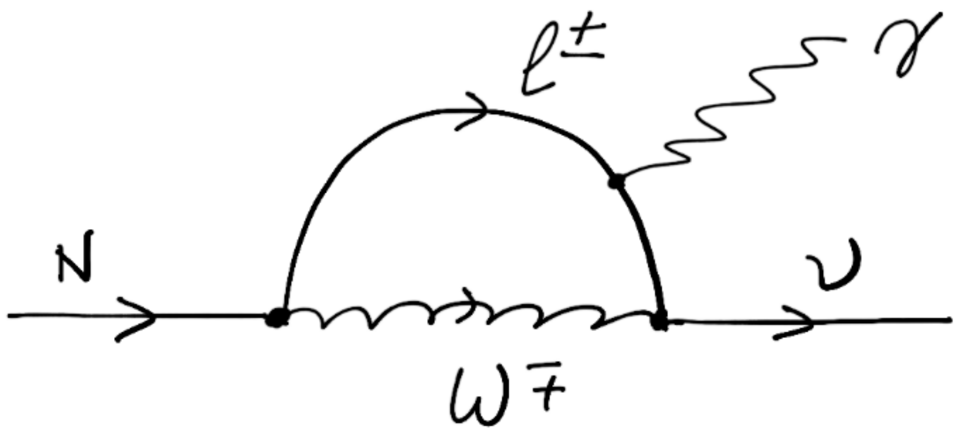
$$\Gamma_{N\to 3\nu} = \frac{G_F^2 M^5}{96\pi^3} \sum_\alpha |\theta_\alpha|^2 \approx \frac{1}{1.5 \times 10^{14}\,\mathrm{sec}} \left(\frac{M}{10\,\mathrm{keV}}\right)^5 \sum_\alpha |\theta_\alpha|^2$$

lifetime must be longer than the age of the universe

$$\theta^2 < 3.3 \times 10^{-4} \left(\frac{10\,\mathrm{keV}}{M}\right)^5$$

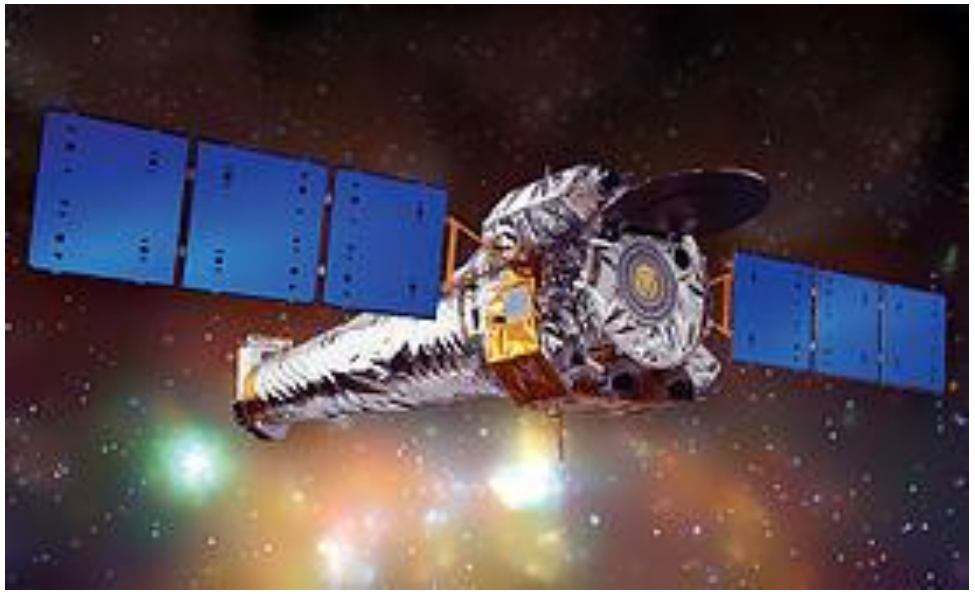
Indirect DM Searches

loop level decay into photons

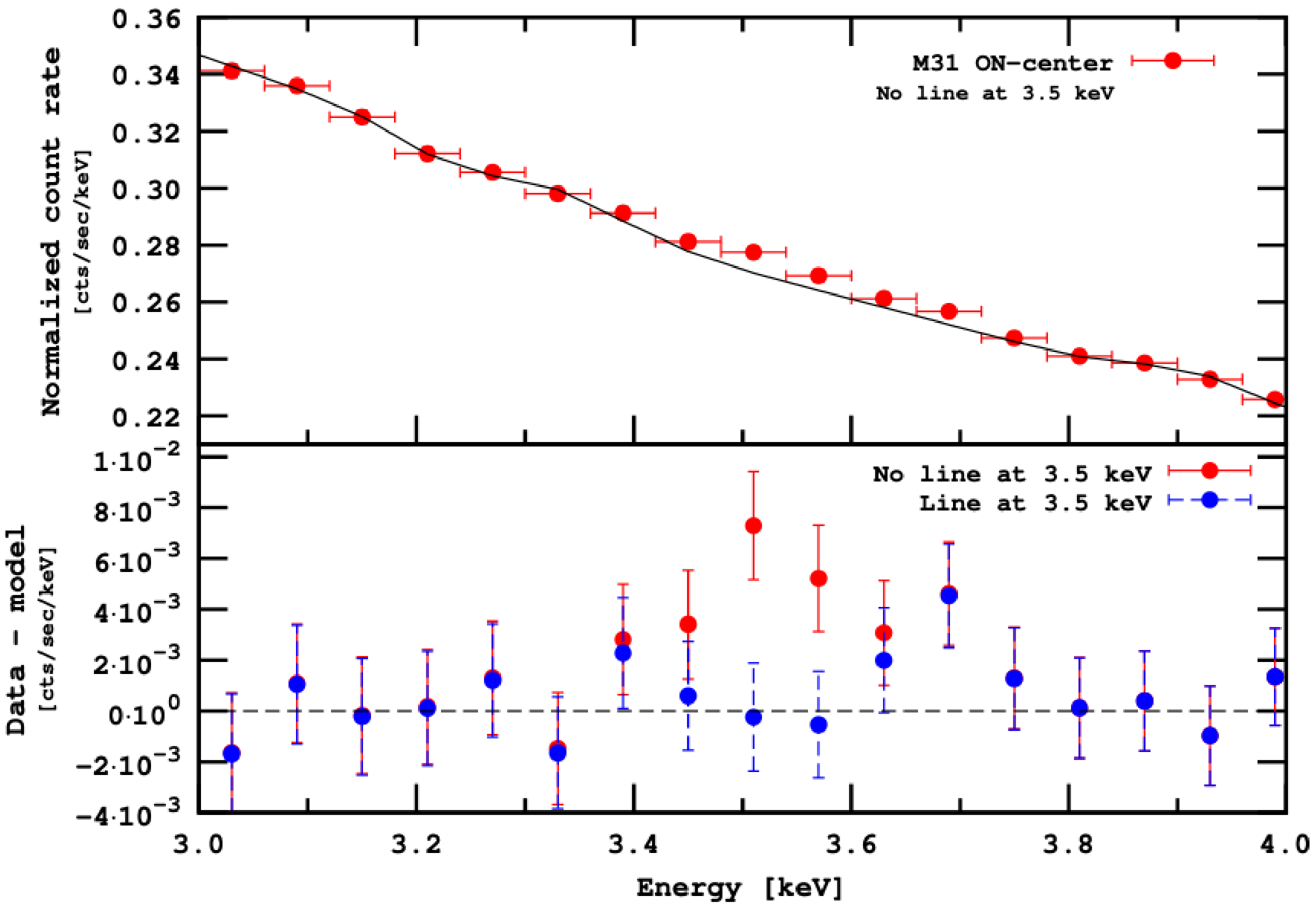


$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5 = 5.5\times 10^{-22}\theta^2\left[\frac{M}{1\,\mathrm{keV}}\right]^5\ \mathrm{sec}^{-1}\,.$$

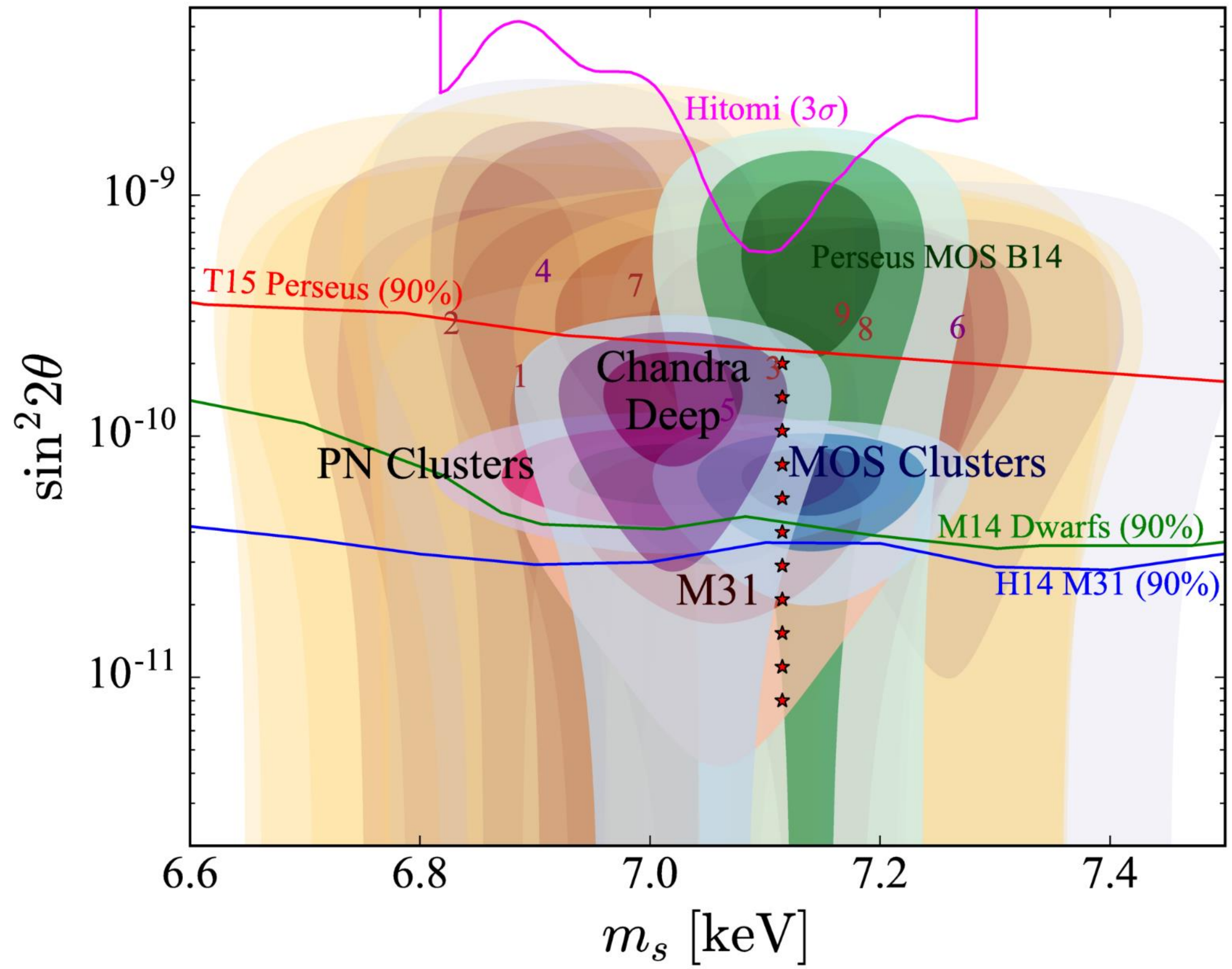
One can search for an emission line!



Has the line been seen?



Boyarsky/Ruchayskiy/Iakubovskyi/Franse 2014
see also
Bulbul/Markevitch/Foster/Smith/Loewenstein/Randall 2014



Situation unclear…

need better spectral resolution (XARM and ATHENA will help)

How to make Sterile Neutrino DM?

1. **thermal production through mixing**

2. **thermal production through new interactions at high energy**

3. **non-thermal production in decay of heavy particles**

Production through Mixing

Consider system with one active and one sterile neutrino

$$
\begin{aligned}
|\nu_a\rangle &= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle, \\
|\nu_s\rangle &= -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle.
\end{aligned}
$$

In the primordial plasma there is an effective mixing angle

$$
\begin{aligned}
|\nu_a\rangle &= \cos\theta_m(t)\;|\nu_1(t)\rangle + \sin\theta_m(t)\;|\nu_2(t)\rangle, \\
|\nu_s\rangle &= -\sin\theta_m(t)\;|\nu_1(t)\rangle + \cos\theta_m(t)\;|\nu_2(t)\rangle
\end{aligned}
$$

Thermal production rate $\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$

Effective Mixing Angle

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

And the "matter potentials" are

$$V_T \simeq -\frac{8}{3}\sqrt{2}G_F\left[\frac{\rho_\nu}{m_Z^2} + \frac{\rho_\ell}{m_W^2}\right]E_\nu,$$

$$V_D \simeq 2\sqrt{2}G_F n_\gamma l_\nu = 2\sqrt{2}G_F\frac{2\zeta(3)}{\pi^2}T^3 l_\nu,$$

Non-resonant Production

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

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$$\Delta(p) = \Delta m^2/(2p)$$

And the "matter potentials" are

$$V_T \simeq G_{\rm eff}^2 T^4 p \qquad G_{\rm eff}^2 \sim 10^2 G_F^2$$

$$V_D \simeq 0$$

Thermal production rate peaks at T ~ 0.1 - 1 GeV

$$\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$$

Non-resonant Production

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

vacuum mixing angle smaller than 10-6
(X -ray searches)

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The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

at high T the matter potential suppresses the effective mixing angle

And the "matter potentials" are

$$V_T \simeq G_{\rm eff}^2 T^4 p \qquad G_{\rm eff}^2 \sim 10^2 G_F^2$$

$$V_D \simeq 0$$

Thermal production rate peaks at T ~ 0.1 - 1 GeV

$$\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$$

Non-resonant Production

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

at low T the light neutrino flux is too low

And the "matter potentials" are

$$V_T \simeq G_{\rm eff}^2 T^4 p \qquad G_{\rm eff}^2 \sim 10^2 G_F^2$$

$$V_D \simeq 0$$

Thermal production rate peaks at T ~ 0.1 - 1 GeV

$$\Gamma_N \sim G_F^2 T^5 \sin^2(2\theta_m)$$

Resonant Production

$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2}.$$

The active-sterile mass splitting enters via

$$\Delta(p) = \Delta m^2/(2p)$$

resonance condition

$$\Delta(p)\cos(2\theta) - V_D - V_T = 0$$

resonance condition strongly depends on lepton asymmetries

$$M^2 - 2\frac{4\sqrt{2}\zeta(3)}{\pi^2}G_F l_\nu p T^3 + 2G_{\text{eff}}^2 p^2 T^4 = 0, \quad l_\nu \equiv (n_\nu - n_{\bar{\nu}})/n_\gamma.$$

Resonance Condition

resonance for mode with $x \equiv p/T$ occurs at

$$x_{res} = \frac{G_F}{G_{\rm eff}^2 T^2}\frac{4\zeta(3)}{\sqrt{2}\pi^2} l_\nu \left[1 \pm \sqrt{1 - \frac{1}{2}\frac{M^2}{T^2}\frac{G_{\rm eff}^2}{G_F^2}\frac{\pi^4}{8\zeta(3)^2}\frac{1}{l_\nu^2}}\right]$$

resonance requires a lepton asymmetry

$$|l_\nu| > \frac{1}{2}\frac{M}{T}\frac{G_{\rm eff}}{G_F}\frac{\pi^2}{2\zeta(3)},$$

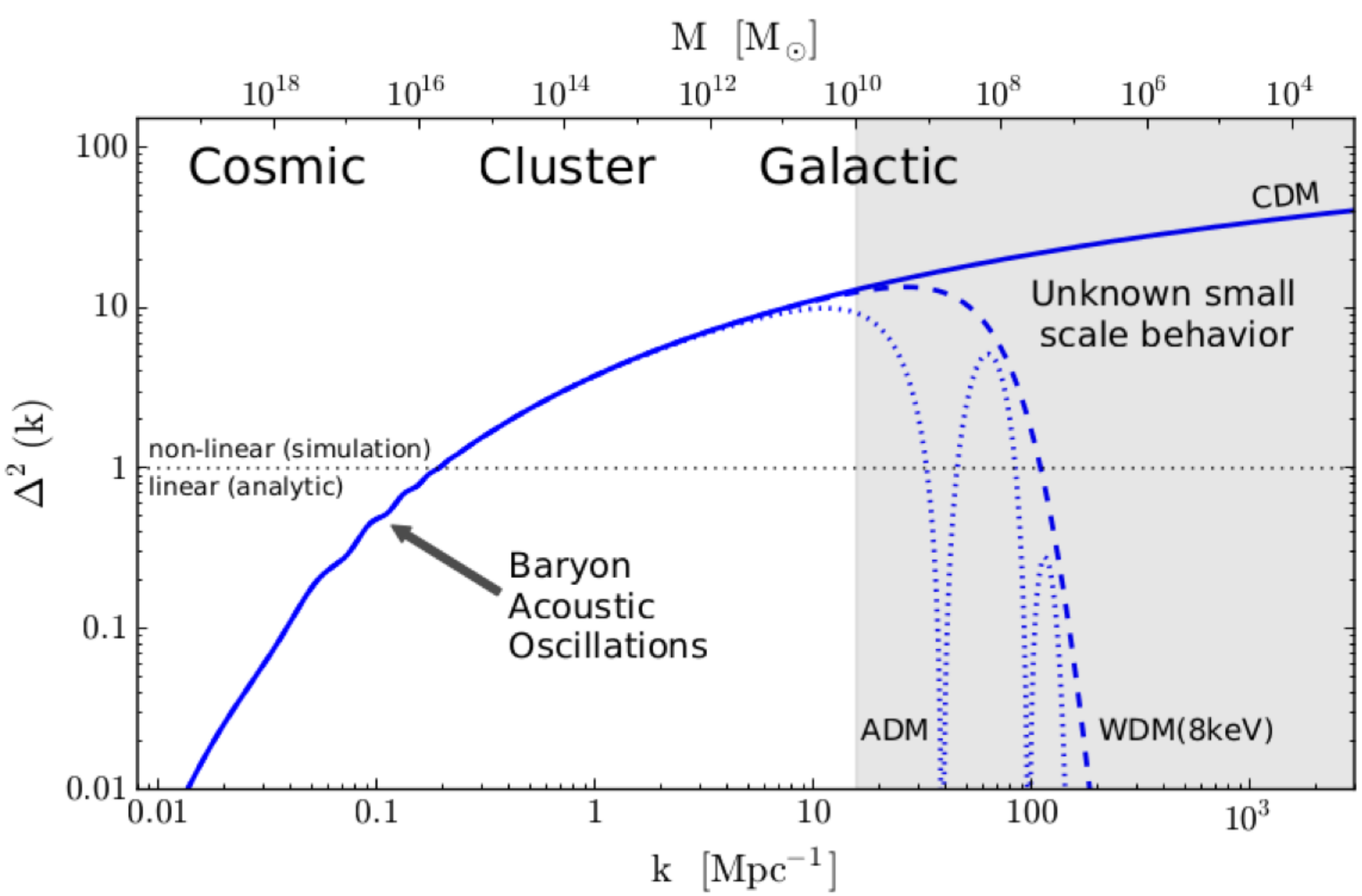
this is several orders of magnitude larger than the baryon asymmetry!
(but well below the observational bound)

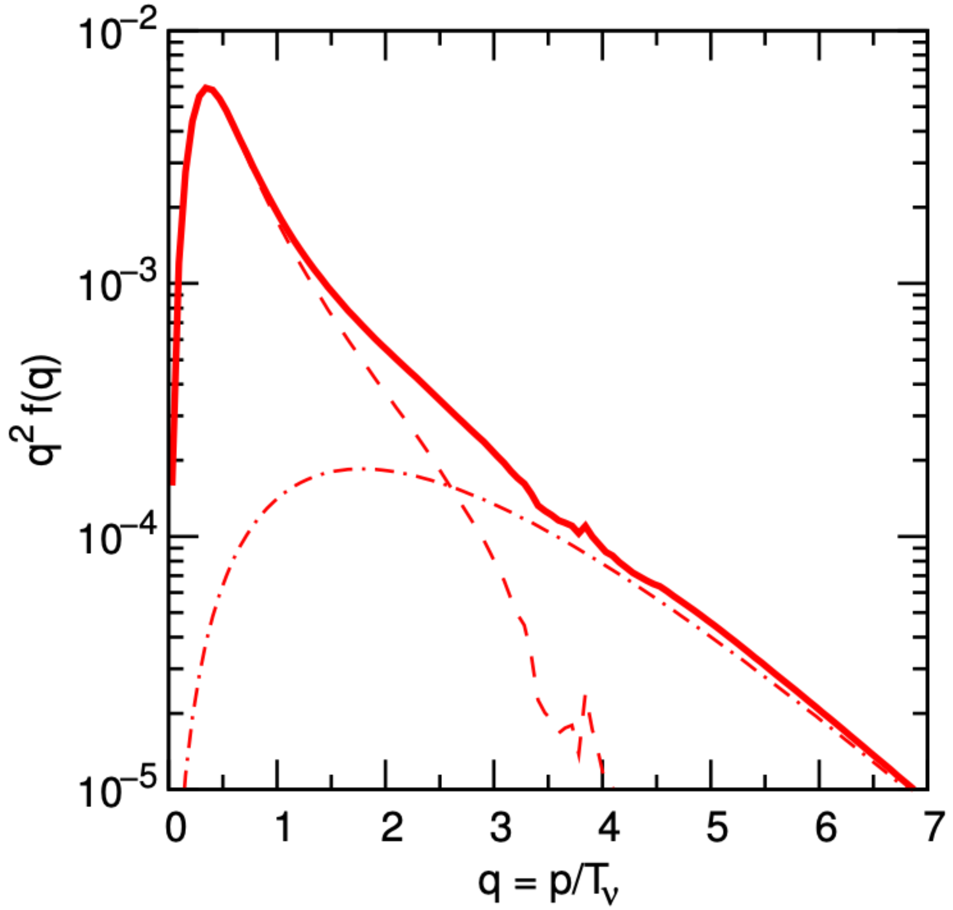
Structure Formation

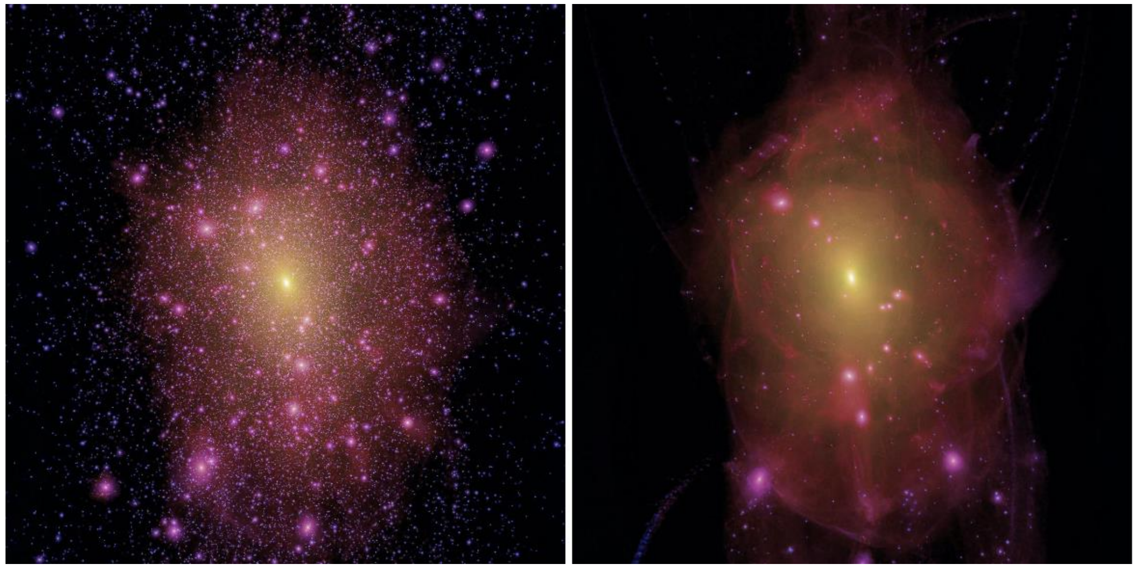
DM free streaming length

$$\lambda_{\rm fs}(t) \equiv a(t) \int_{t_i}^{t} dt' \, \frac{v(t')}{a(t')} \approx 1\,{\rm Mpc} \frac{\rm keV}{M} \frac{\langle p_{\rm DM} \rangle}{\langle p_\nu \rangle}$$

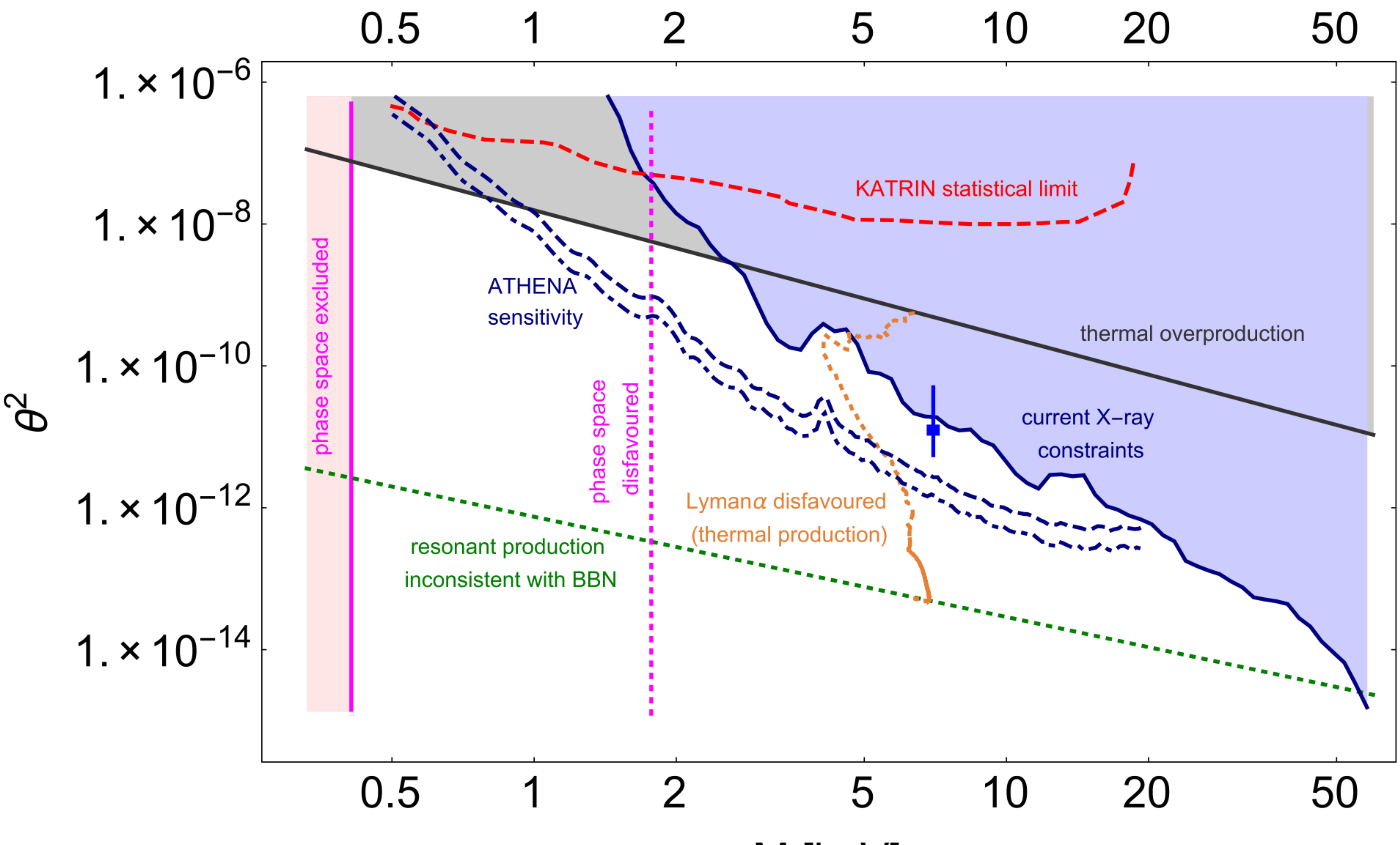
affects matter power spectrum





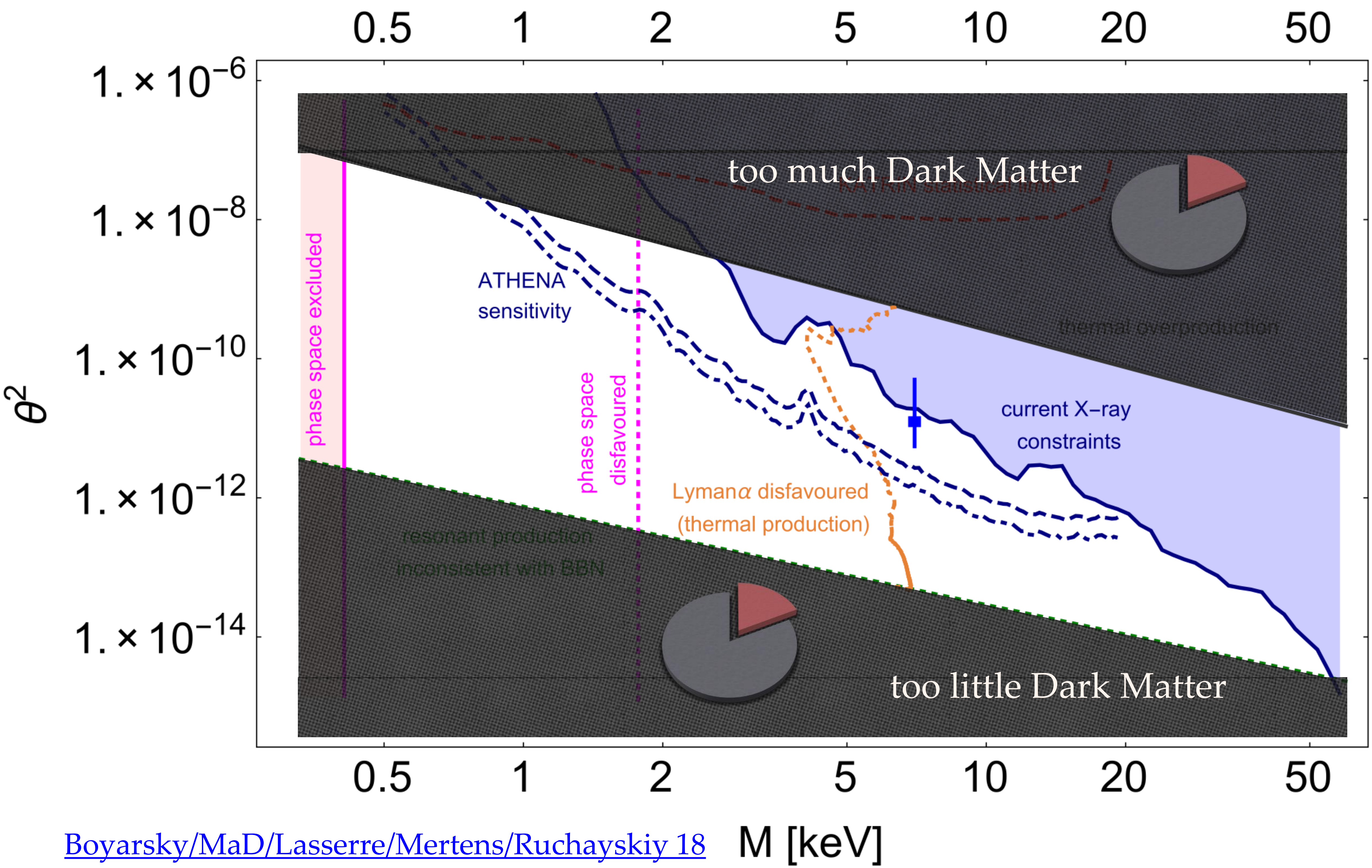


Sterile Neutrino Dark Matter



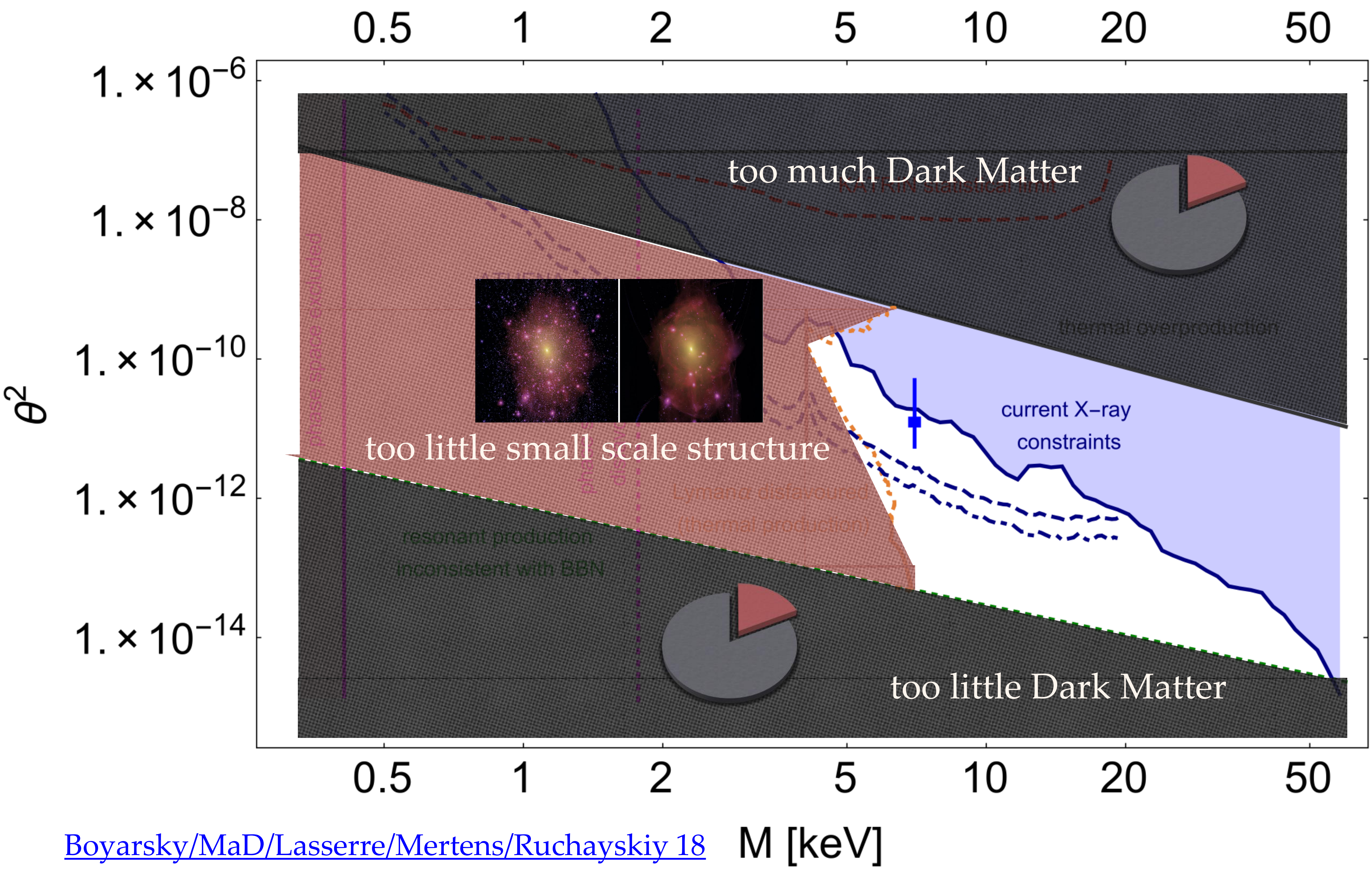
Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



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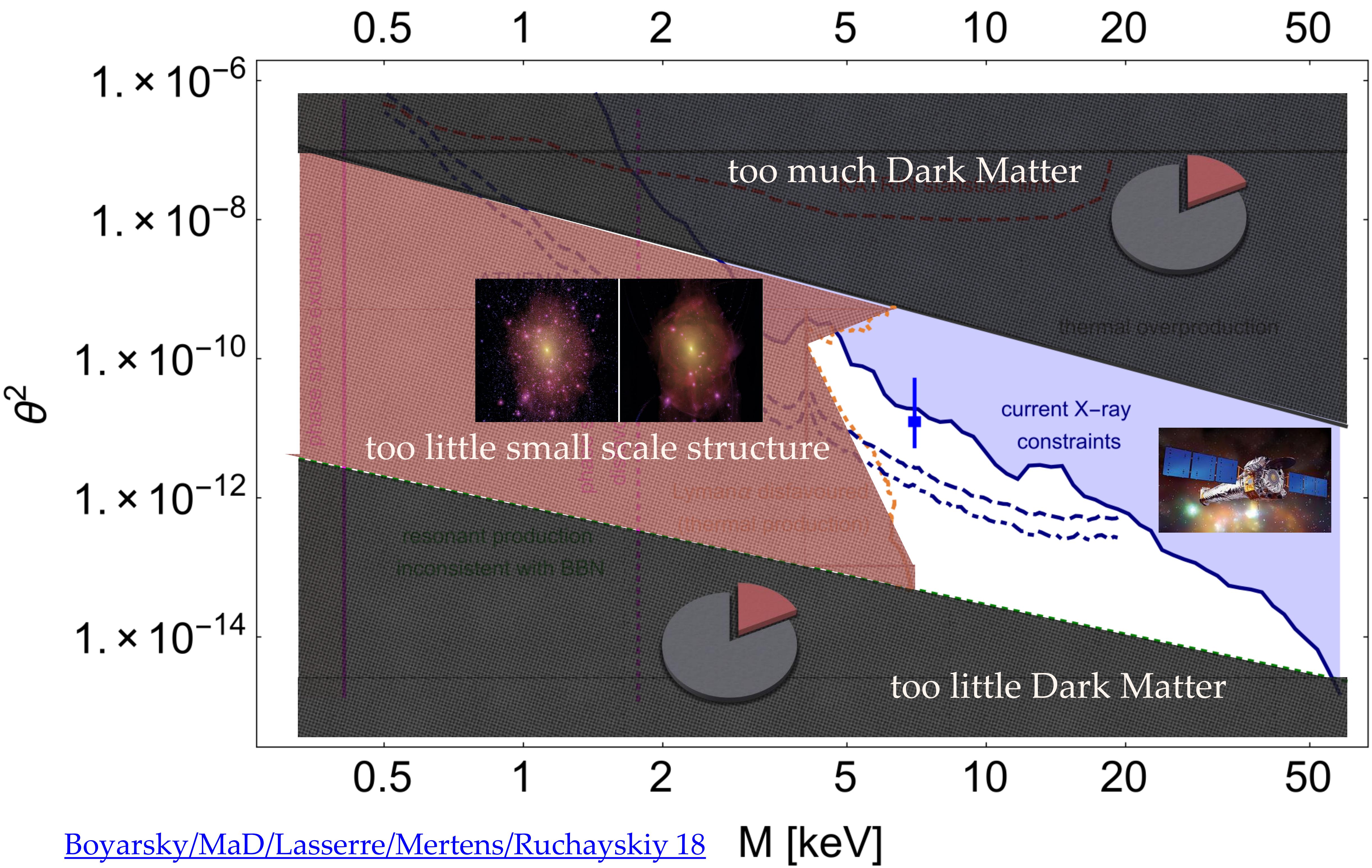

[Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18]()