15 minutes review of sterile neutrino

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Anomalies in neutrino data

Appearance

- LSND. $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$ $\langle E_\nu \rangle \approx 30\mathrm{Ge}V$
  - Excess of $\overline{\nu}_e$
- MiniBooNE. $\nu_\mu(\overline{\nu}_\mu)$ fluxes peak at 600 (400) MeV with the same L/E as in LSND.
  - Excess of ν_e and $\overline{\nu}_e$ (4.8σ)

- 13% deficit of $\overline{\nu}_e$ from reactors (RAA)
- 6% deficit of ν_e and $\overline{\nu}_e$ from calibration sources SAGE and GALLEX

Disappearance

Oscillation hypothesis yields

$$\Delta m^2 \approx (1-2)\ \mathrm{e}V^2\ and\ \ \sin^2 2\theta \leq (0.1-0.2)$$

- Needed Δm^2 can not fit into 3-neutrino picture with two well measured

$$\Delta m^2_{12} \simeq 7.5 \cdot 10^{-5}\ \mathrm{e}V^2$$

$$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \simeq 2.4 \cdot 10^{-3}\ \mathrm{e}V^2$$

- Just adding one more neutrino with $m^2_4 \approx (1-2)\ \mathrm{e}V^2$ is impossible because of measured widths of W,Z

$$\Gamma(W \to \ell\nu) \simeq 226\ \mathrm{M}eV,\ \Gamma(W \to all) = 2085 \pm 2.1\ \mathrm{M}eV$$

$$\Gamma(Z \to \bar{\nu}\nu) \simeq 166\ \mathrm{M}eV,\ \Gamma(Z \to all) = 2495 \pm 2.3\ \mathrm{M}eV$$

What is sterile neutrino?

- This is a quantum state = superposition of mass eigenstates $\nu_1, \nu_2, \nu_3, \nu_4, \dots$ with

$$\mathscr{A}(\nu_s + W \to \ell) = \mathscr{A}(\nu_s + Z \to \nu_s) = 0$$

- Meanwhile, each of $\nu_1, \nu_2, \nu_3, \nu_4, \dots$ does interact
- Sterile state as well as flavor eigenstates are not true particles since their fields do not obey the Dirac equation

$$\begin{bmatrix} \nu_L^f \\ \nu_L^s \end{bmatrix} = \begin{bmatrix} V_{3\times3} & K_{3\times1} \\ U_{1\times3} & M_{1\times1} \end{bmatrix} \begin{bmatrix} \nu_L^m \\ \nu_L^4 \end{bmatrix}$$

What is sterile neutrino?

- In QFT neutrino masses require ν_R
- Three generations of neutrinos —> three ν_R
- Sterile state emerge if there are four (or more) ν_R and still three charged leptons. This is the main trick!

Confusions in terminology

- ν_R is sterile because it has zero EW charges.
- ν_L^s is a sterile combination of four mass eigenstates $\nu_1, \nu_2, \nu_3, \nu_4, \ldots$
- ν_4 is called sterile in cosmology silently assuming vanishing $|V_{\alpha 4}|^2 \ll 1$

How sterile state can be observed

ν_L^s

- In neutrino oscillation as a
  - Deficit of the rate
  - E/L oscillation pattern
    - Loss of coherence could be important for eV scale neutrino

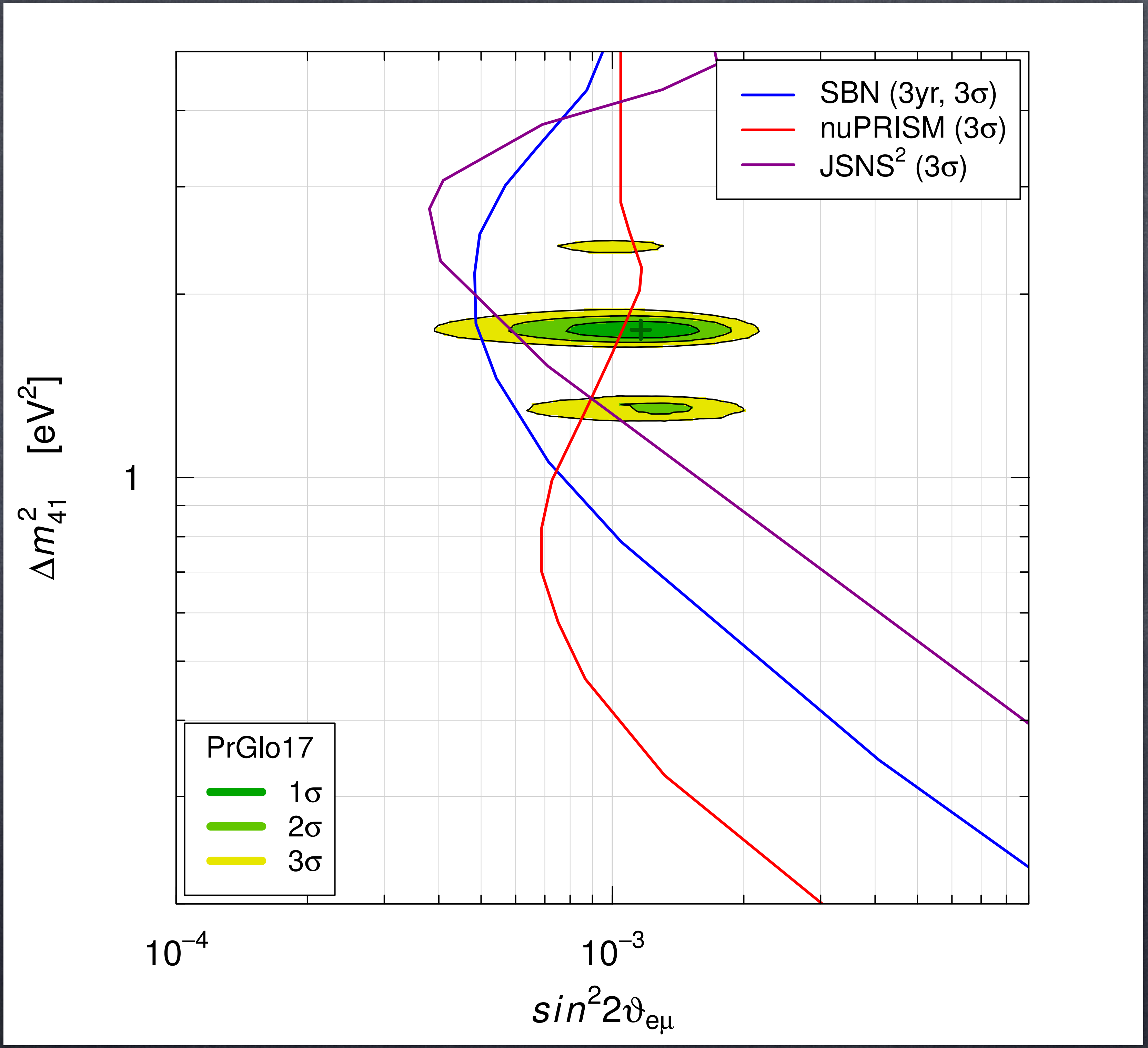
} Both in charged and neutral currents

ν_4

- Non unitarity of $V_{3\times 3}$
- In cosmology
  - ν_4 is an additional relativistic degree-of-freedom
  - Impact Big-Bang-Nucleosynthesis
  - Many observables including

$$\sum_i m_i^\nu = m_1^\nu + m_2^\nu + m_3^\nu + m_4^\nu$$

Status of 3+1 neutrino oscillations at SBL



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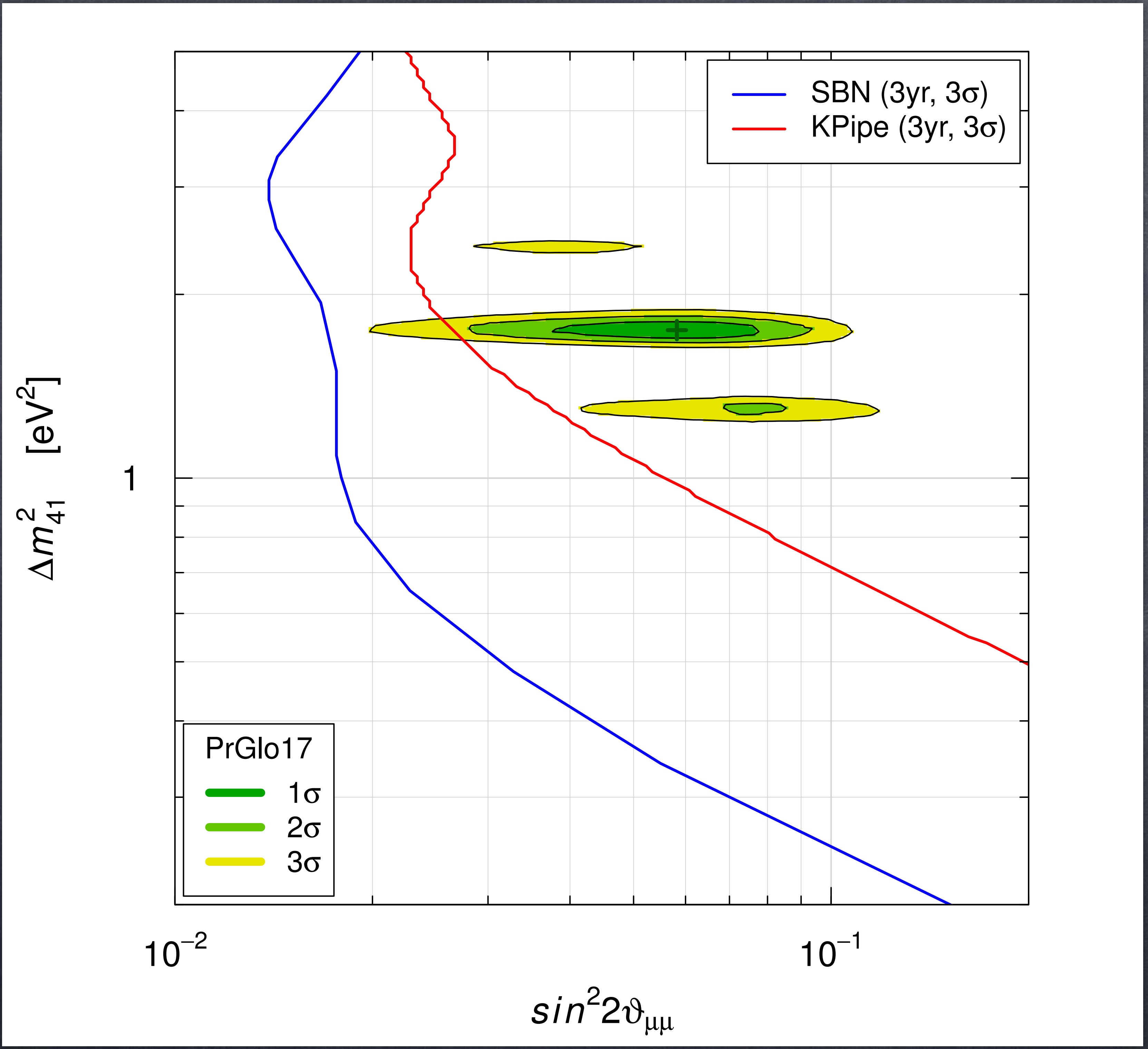

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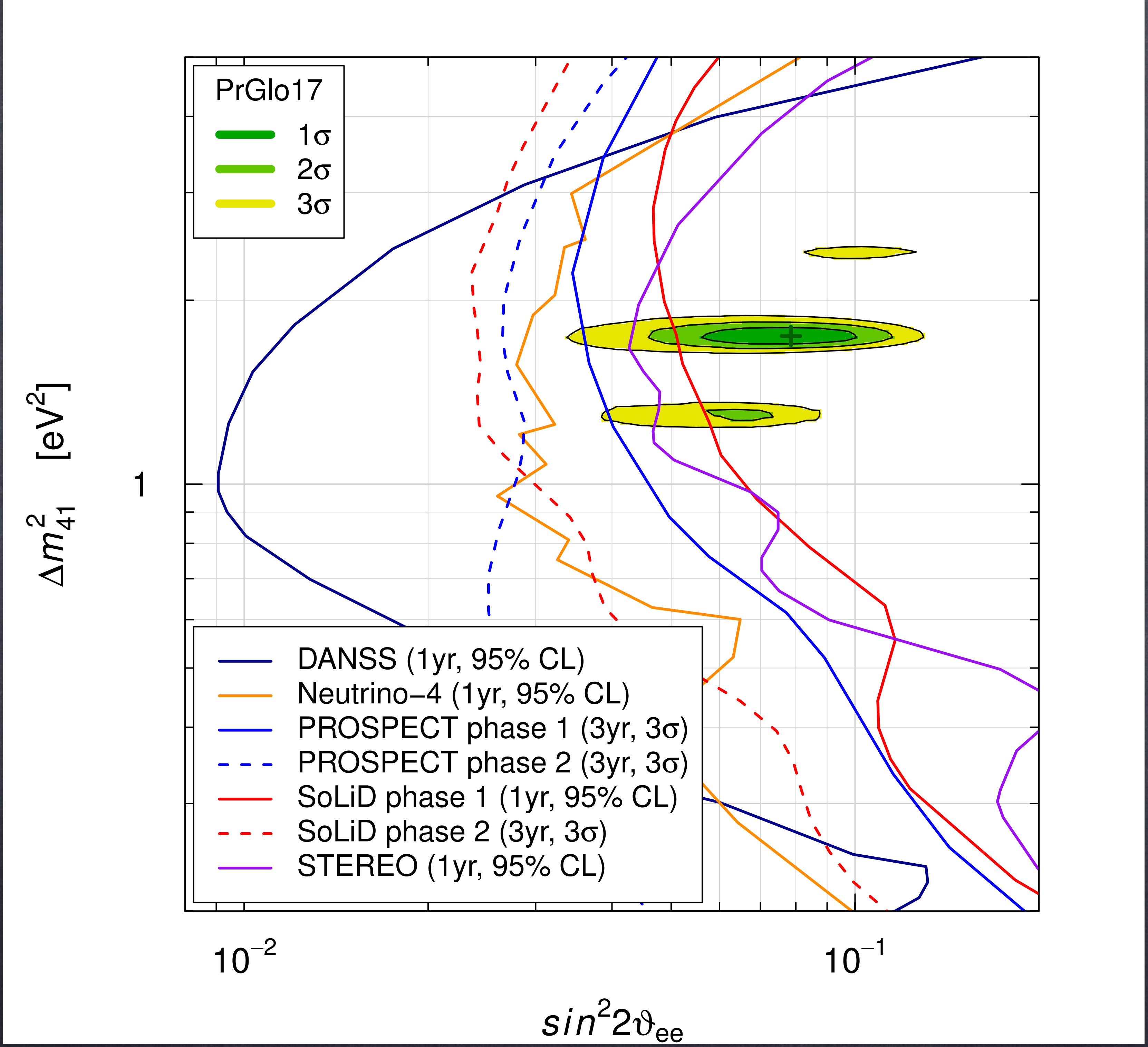

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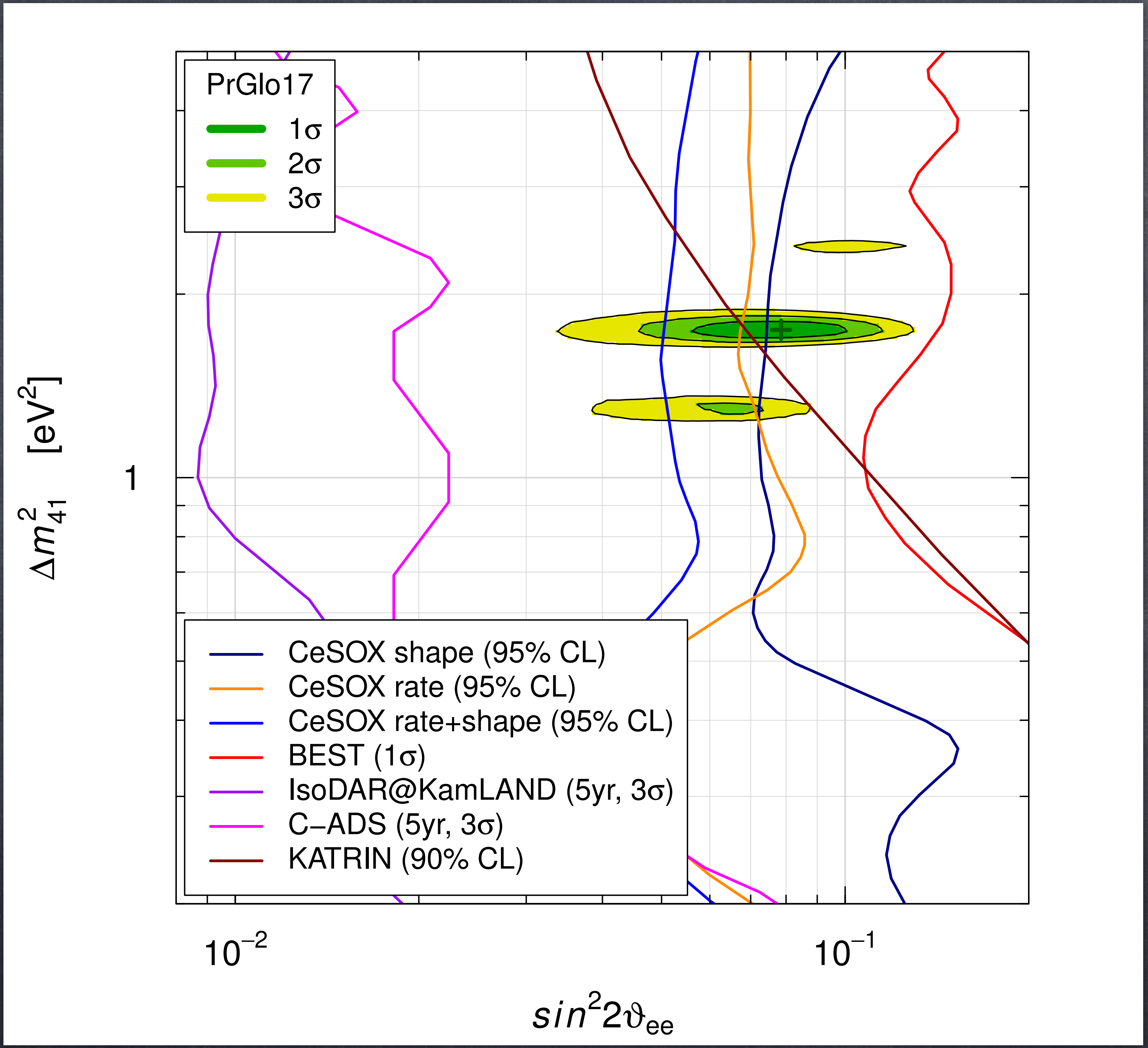

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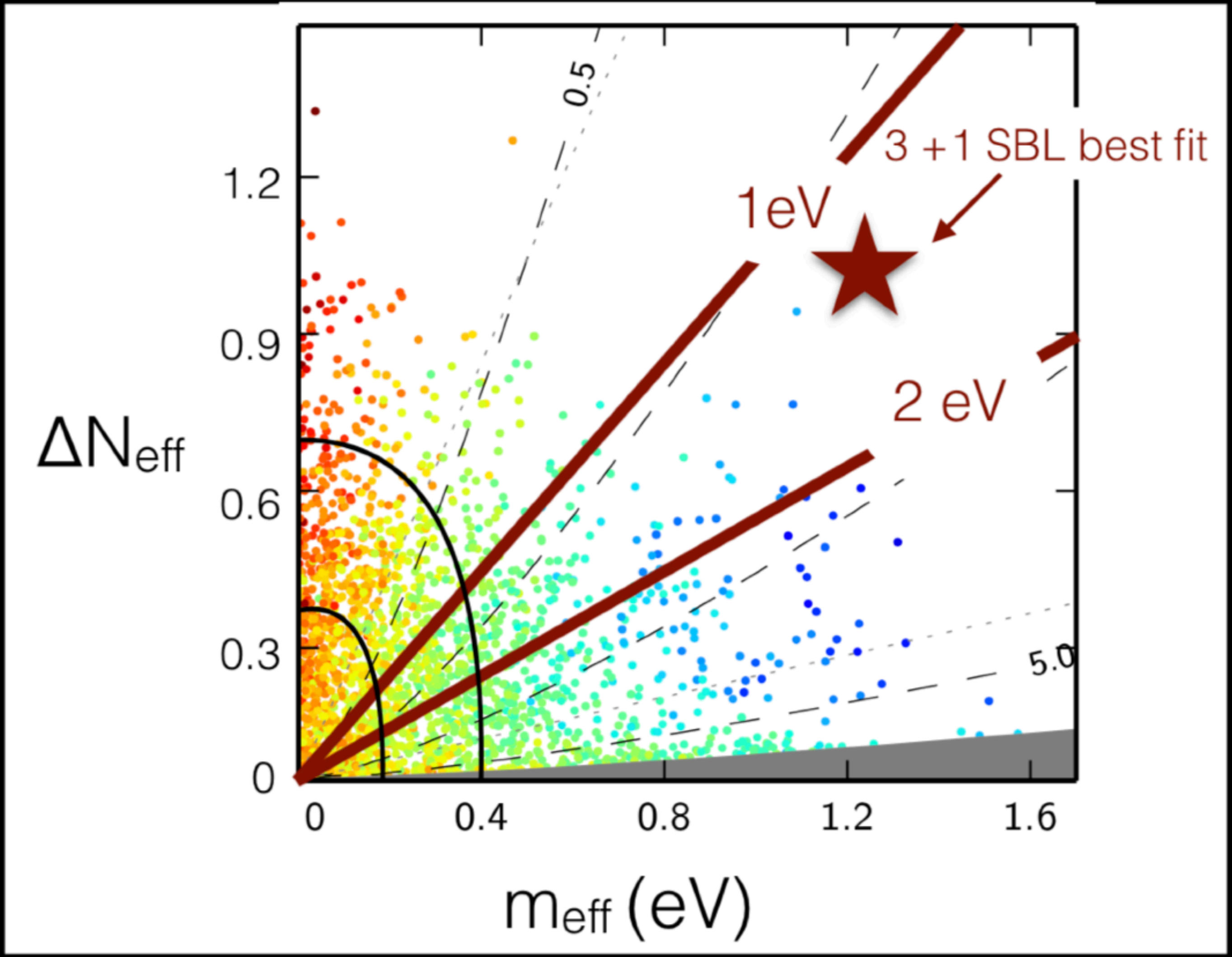
Cosmology rules out SBL best-fit

Effective density parameters	Planck 2015 (TT+lowP+lensing) + BAO
ΔN_{eff} (extra contribution to density *before* NR transition)	<0.7 (95%CL)
m_{eff} (extra contribution to density *after* NR transition)	< 400 meV (95%CL)



For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

Slide credit to J.Lesgourgues (NeuTel-2017)

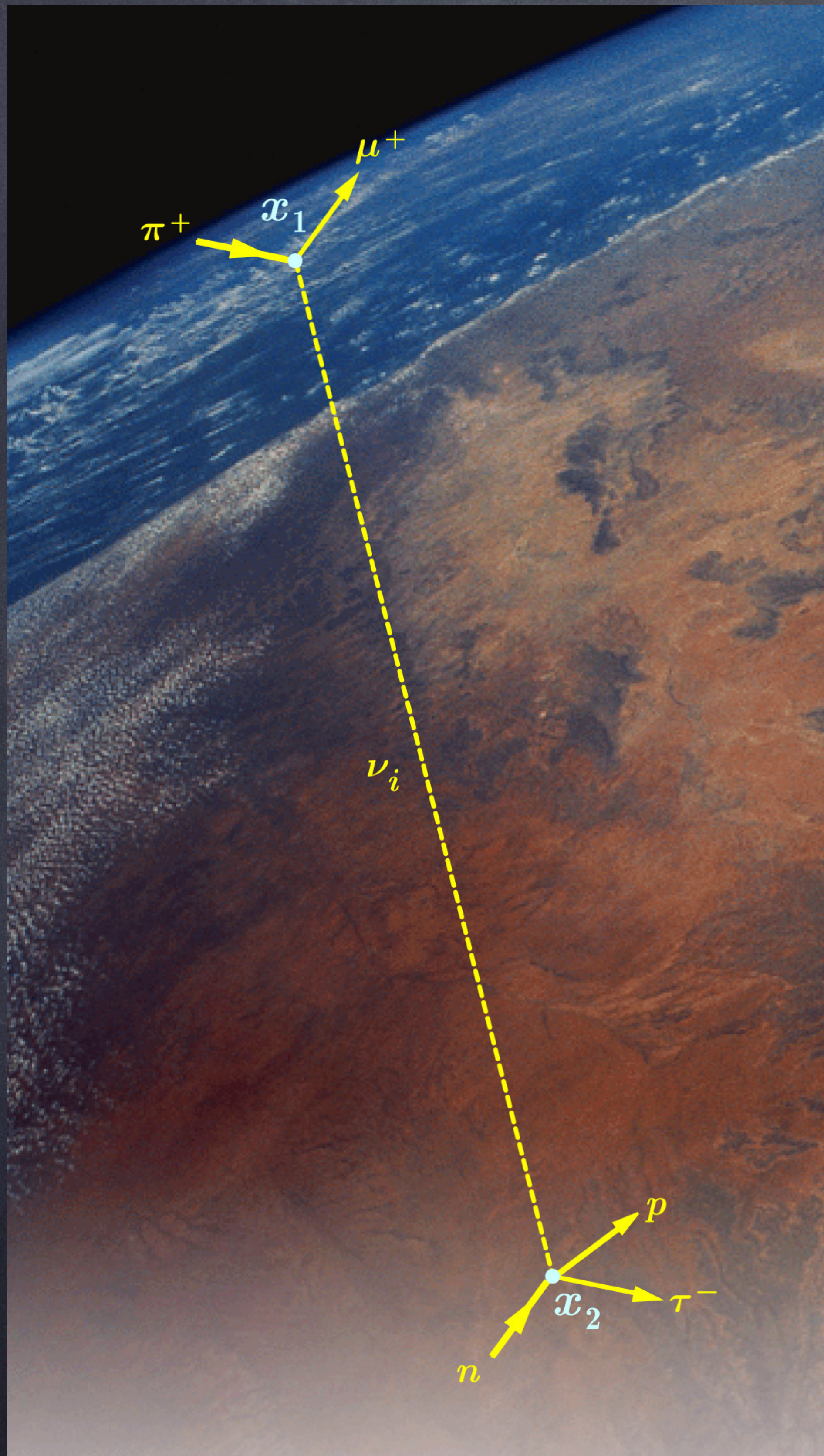
Summary

- There are allowed regions with $\Delta m^2_{41} \approx (1-2)\mathrm{eV}^2$
- The allowed parameters space is in the sensitivity regions of running experiments
- Cosmology already rules out SBL best-fit
- There are however various claims worth to follow in more details. Please, refer to the next couple of talks

More details

Backup slides

- Naive picture:
  - Sterile neutrino does not interact with W,Z
  - Active neutrinos ν_e, ν_μ, ν_τ could oscillate into sterile ν_s (and vice-versa)
- Why naive?
  - Flavor neutrinos ν_e, ν_μ, ν_τ are not real particles. Their fields do not satisfy Dirac equation.
  - True particles are massive neutrinos ν_1, ν_2, ν_3
  - Textbook's mantra: «Mass eigenstates propagate, flavor states interact» is out-dated.



- Neutrino oscillation is due to interference of diagrams with virtual ν_1, ν_2, ν_3
- Each of them interacts with W,Z
- ν_4 also must interact with W,Z. It can not appear out of nothing
- External particles are wave-packets

A Diagrammatic treatment of neutrino oscillations
D.V. Naumov, V.A. Naumov (Dubna, JINR).
J.Phys. G37 (2010) 105014

How to make sterile neutrino in QFT?

Masses of fermions in the Standard Model

- EW sector is $SU_L(2) \times U(1)$ gauge invariant

One generation $\begin{bmatrix} \nu_L \\ \ell_L \end{bmatrix}$ $\quad \ell_R \quad \nu_R$ ← Fully sterile

- Gauge invariance requires fermions to be massless

$$m(\overline{\ell}_L \ell_R + \mathrm{h.c.})$$ ← Not allowed

- Masses are generated via Yukawa interactions and symmetry breaking by the Higgs mechanism

$$\lambda\left(\begin{bmatrix} \overline{\nu}_L & \overline{\ell}_L \end{bmatrix} \begin{bmatrix} 0 \\ \phi \end{bmatrix} \ell_R + \mathrm{h.c.}\right) \rightarrow m(\overline{\ell}_L \ell_R + \mathrm{h.c.}) + \ldots$$

Three generations

Three generations of left fields

$$\begin{bmatrix}\nu_L^e\\ e_L\end{bmatrix}\begin{bmatrix}\nu_L^\mu\\ \mu_L\end{bmatrix}\begin{bmatrix}\nu_L^\tau\\ \tau_L\end{bmatrix}$$

Three generations of right fields

$$e_R, \nu_R^e \quad \mu_R, \nu_R^\mu \quad \tau_R, \nu_R^\tau$$

Massless fields

Yukawa interactions

$$\lambda^\nu_{\alpha\beta}\left(\begin{bmatrix}\overline{\nu}_L^\alpha & \overline{\ell}_L^\alpha\end{bmatrix}\begin{bmatrix}-\phi^c\\ 0\end{bmatrix}\nu_R^\beta + \mathrm{h.c.}\right) \to m^\nu_{\alpha\beta}(\overline{\nu}_L^\alpha \nu_R^\beta + \mathrm{h.c.}) + \ldots$$

$$\lambda^\ell_{\alpha\beta}\left(\begin{bmatrix}\overline{\nu}_L^\alpha & \overline{\ell}_L^\alpha\end{bmatrix}\begin{bmatrix}0\\ \phi\end{bmatrix}\ell_R^\beta + \mathrm{h.c.}\right) \to m^\ell_{\alpha\beta}(\overline{\ell}_L^\alpha \ell_R^\beta + \mathrm{h.c.}) + \ldots$$

Diagonalization

m^ℓ, m^ν — are non-diagonal matrices

- Introduce four matrices $U_L^\nu, U_L^\ell, U_R^\nu, U_R^\ell$ to rotate fields $\nu_L^\ell \;\; \ell_L \;\; \ell_R \;\; \nu_R^\ell$

- To make $U_L^\dagger m^\ell U_R^\ell$ and $U_L^\dagger m^\nu U_R^\nu$ diagonal matrices
- New massive fields mix generations in their interactions with W boson.
- The mixing matrix $V^{\mathrm{PMNS}} \equiv U_L^{\ell\dagger} U_L^\nu$

Sterile neutrino

Three generations of left fields

$$\begin{bmatrix} \nu_L^e \\ e_L \end{bmatrix} \begin{bmatrix} \nu_L^\mu \\ \mu_L \end{bmatrix} \begin{bmatrix} \nu_L^\tau \\ \tau_L \end{bmatrix}$$

Three generations of right fields+one more neutrino

$$e_R, \nu_R^e \quad \mu_R, \nu_R^\mu \quad \tau_R, \nu_R^\tau \quad \nu_R^s$$

Massless fields

- Assume again Yukawa interactions and non-diagonal mass matrices
- Diagonalize them and derive the mixing unitary matrix

$$\begin{bmatrix} V_{3\times3} & K_{3\times1} \\ U_{1\times3} & M_{1\times1} \end{bmatrix}$$

Sterile neutrino

- «Flavor» ν^f and mass ν^m eigenstates read

$$\begin{bmatrix} \nu_L^f \\ (\nu_R^s)^c \end{bmatrix} = \begin{bmatrix} V_{3\times3} & K_{3\times1} \\ U_{1\times3} & M_{1\times1} \end{bmatrix} \begin{bmatrix} \nu_L^m \\ \nu_L^4 \end{bmatrix}$$

- Unitarity of 4x4 mixing matrix yields

$$V^\dagger V + U^\dagger U = 1_{3\times3} \quad U^\dagger U + M^\dagger M = 1_{1\times1}$$
$$K^\dagger K + M^\dagger M = 1_{1\times1} \quad V^\dagger K + U^\dagger M = 0_{3\times1}$$
$$UV^\dagger + MK^\dagger = 0_{1\times3}$$

- The interaction amplitude of sterile state vanishes

$$\mathscr{A}(\nu_s + W^- \to \ell_\alpha^-) = (UV^\dagger + MK^\dagger)_{1\times\alpha}\mathscr{A}_0 = 0$$