Bounds on Light Sterile Neutrinos from Cosmology and Laboratory

arXiv 2003.02289

Steffen Hagstotz

with Pablo de Salas, Stefano Gariazzo, Martina Gerbino, Massimiliano Lattanzi, Sunny Vagnozzi, Sergio Pastor & Katie Freese

Neutrinos

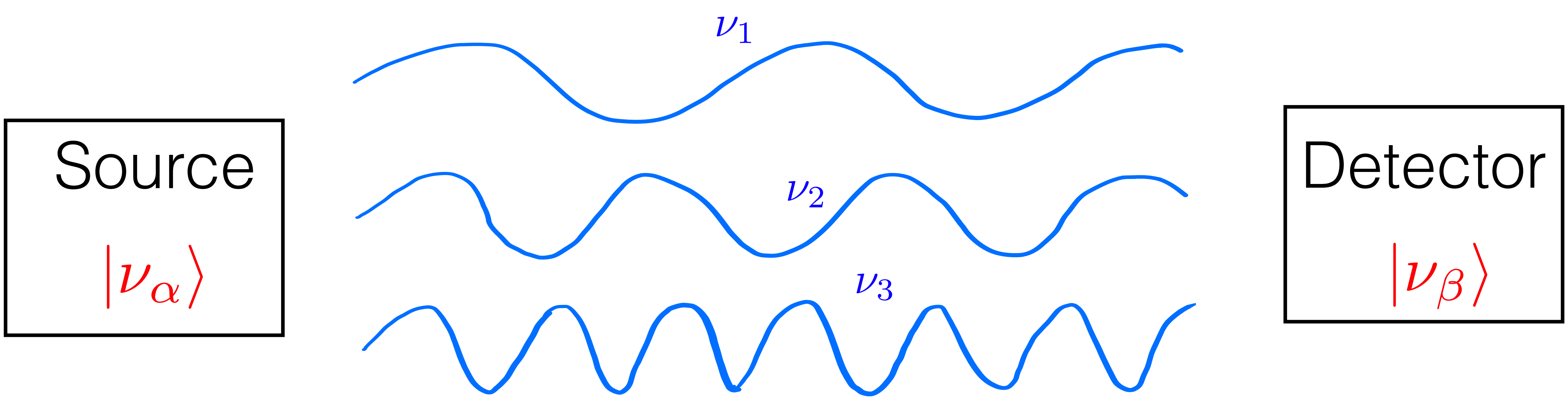
Neutrinos are good for surprises!

- Small mass requires new physics
- Oscillations between flavour states
- Weak interactions make constraints difficult

Neutrino oscillations

flavour states $\boxed{|\nu_\alpha\rangle = U_{\alpha k}|\nu_k\rangle}$ mass states

$\alpha \in [e, \mu, \tau]$ $k \in [1, 2, 3]$

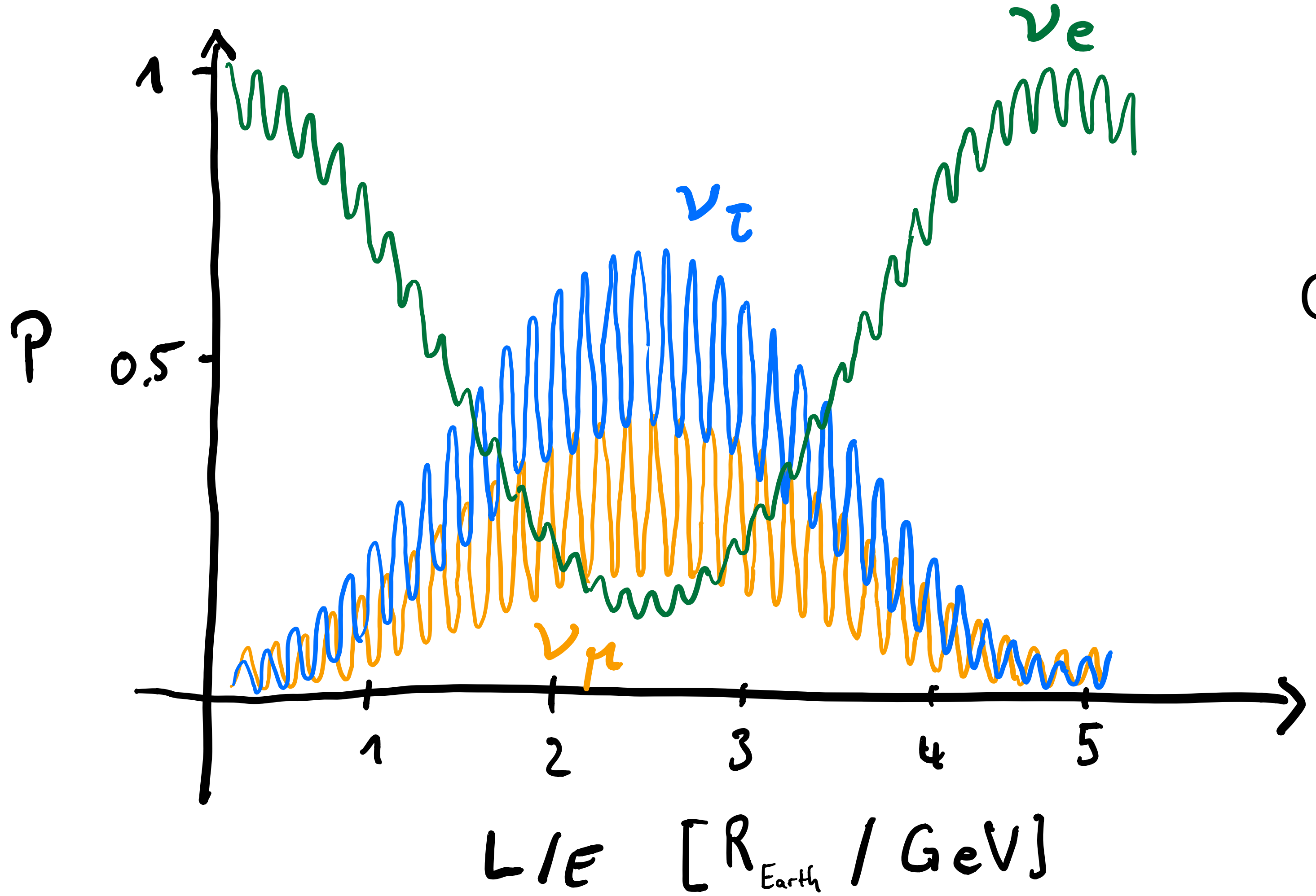


$$|\nu(t)\rangle = \sum_k U_{\alpha k} \mathrm{e}^{-iE_k t}|\nu_k\rangle \quad \text{with} \quad E_k = p^2 + m_k^2$$

Neutrino oscillations

Oscillation probabilities governed by

$$P_{\nu_\alpha \to \nu_\beta} = \langle \nu_\alpha | \nu(L) \rangle = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$



oscillation scale set by

$$\frac{L}{E} \sim \Delta m^2_{kj}$$

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Extended oscillations

Extension straightforward: $\alpha \in [e, \mu, \tau, \dots]$ $k \in [1, 2, 3, \dots]$

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

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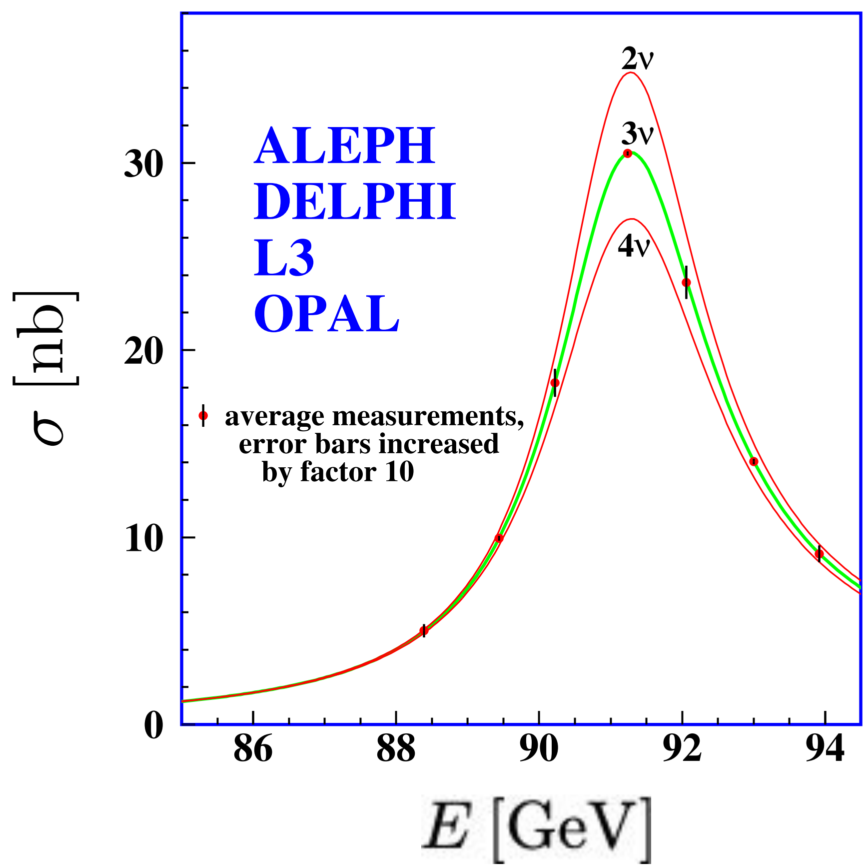

arXiv hep-ex/0509008

But: Z-decay limits number of weakly interacting light neutrinos

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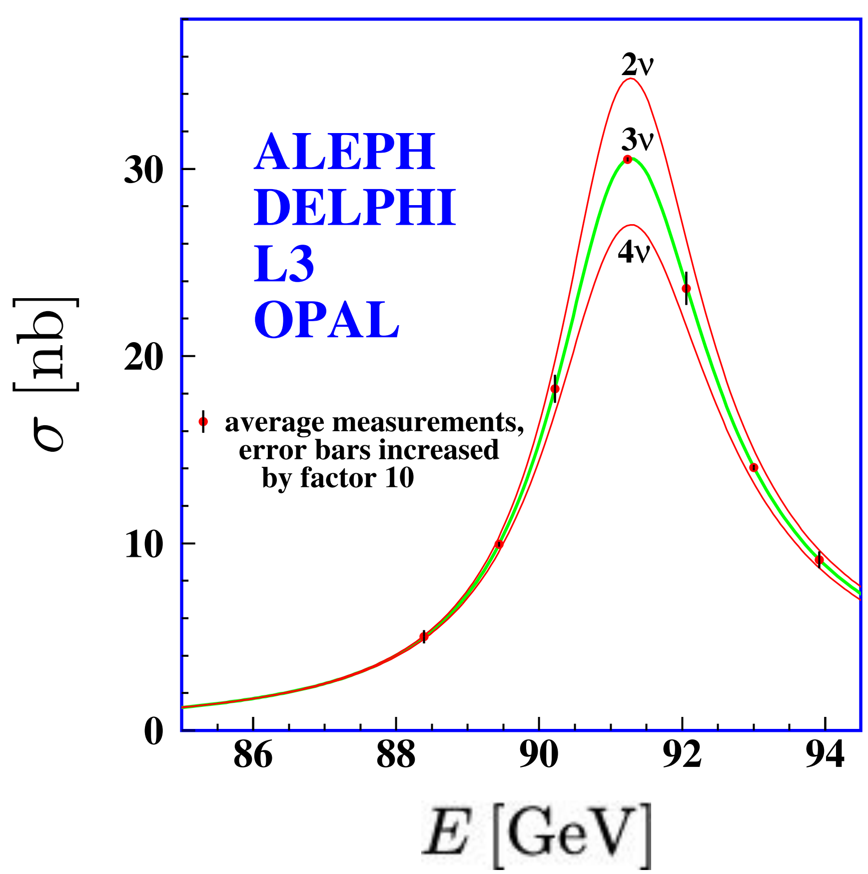

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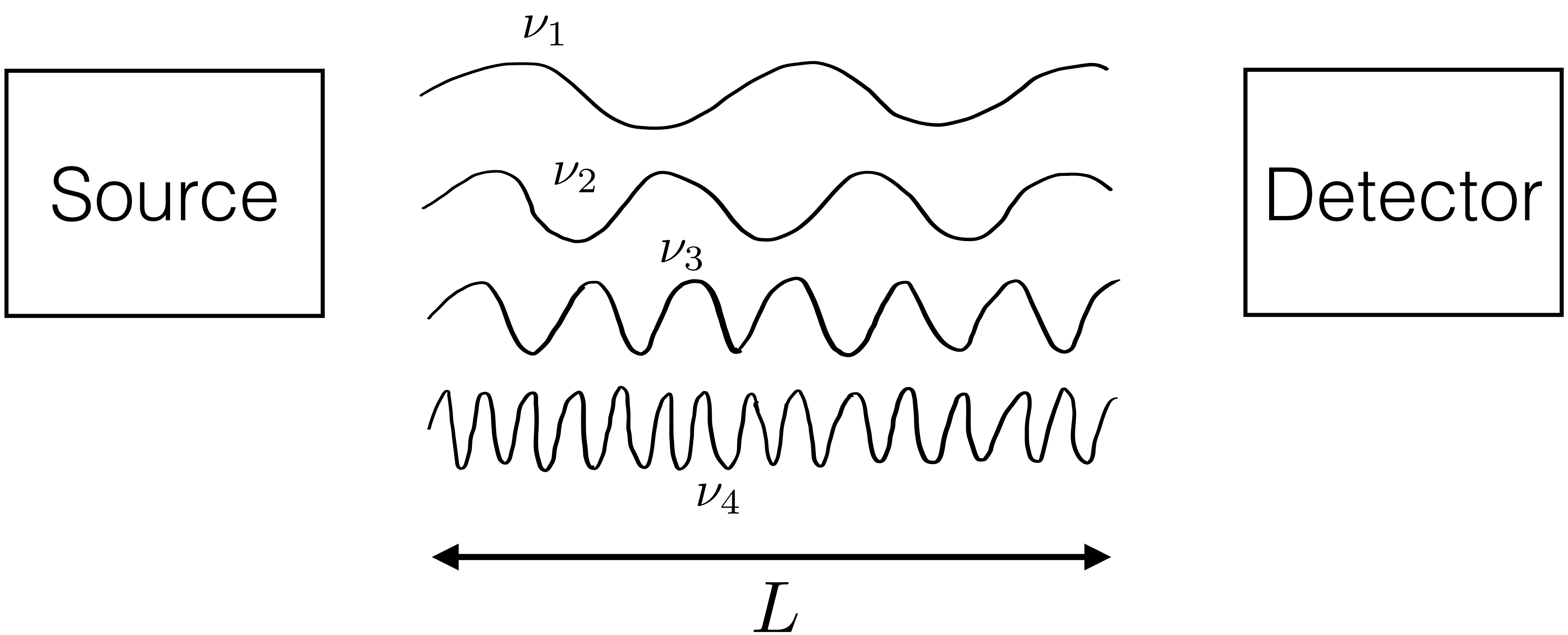
But: Z-decay limits number of weakly interacting light neutrinos

Any additional light neutrino must be **sterile**

Short Baseline (SBL) searches

- Short: $L/E \sim \mathcal{O}(\mathrm{eV}^2)$



- Other oscillations with Δm^2_{21}, $\Delta|m_{31}|^2$ don't have time to develop

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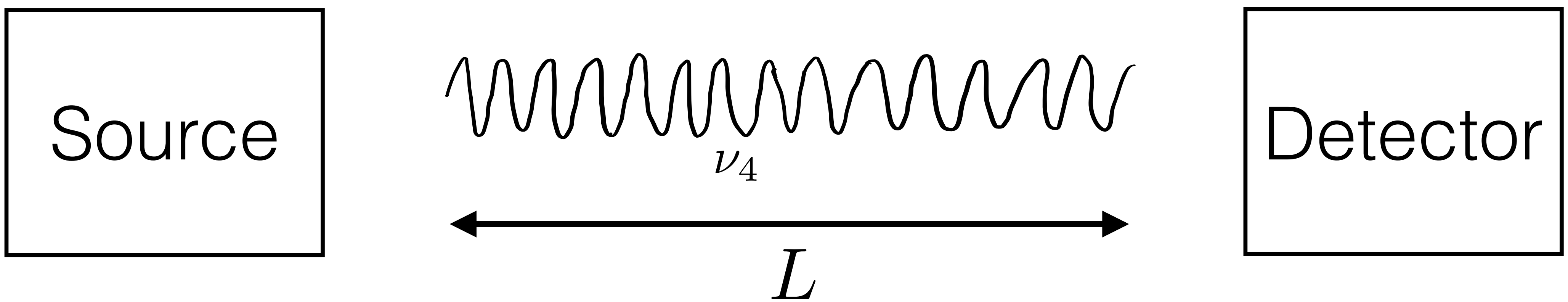

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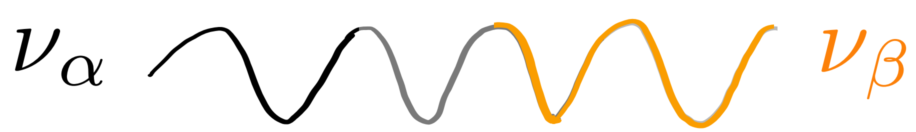
Short Baseline (SBL) searches

$$\boxed{L/E \sim \mathcal{O}(\mathrm{eV}^2)}$$

Appearance



Detect different flavour

$$P^{\mathrm{SBL}}_{\nu_\alpha \to \nu_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Effective mixing angles:

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

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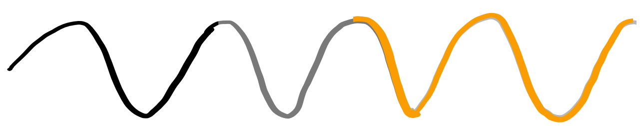
Appearance

ν_α  ν_β

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Disappearance

ν_α  ν_α

Detect same flavour

$$P^{\text{SBL}}_{\nu_\alpha \to \nu_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Effective mixing angles:

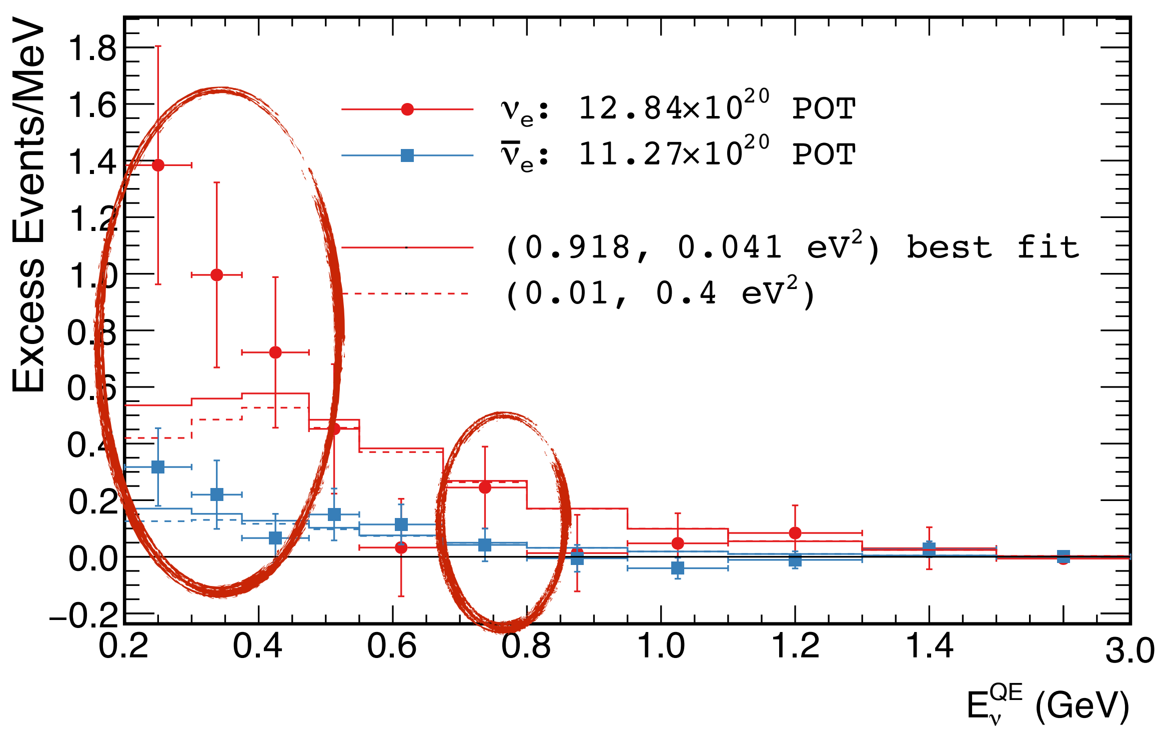
$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

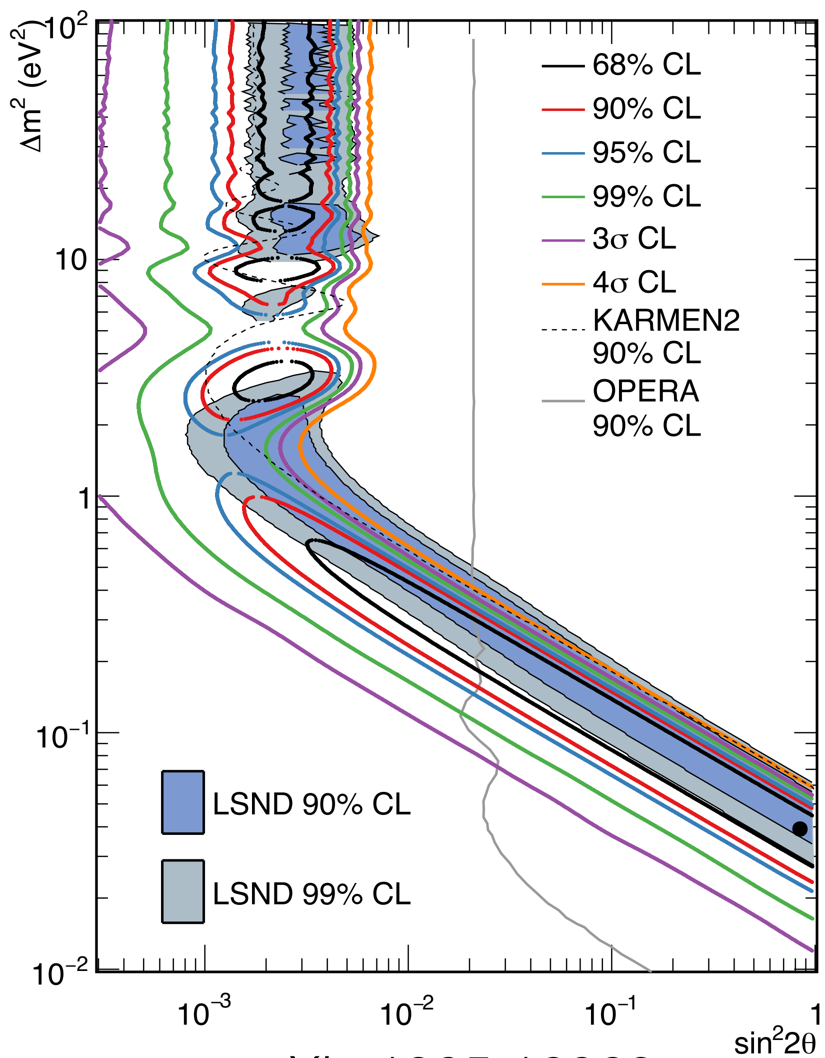
LSND/MiniBooNE

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\downarrow$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \qquad \bar{\nu}_e + p \to n + e^+$$

Detect **appearance** of $\bar{\nu}_e$



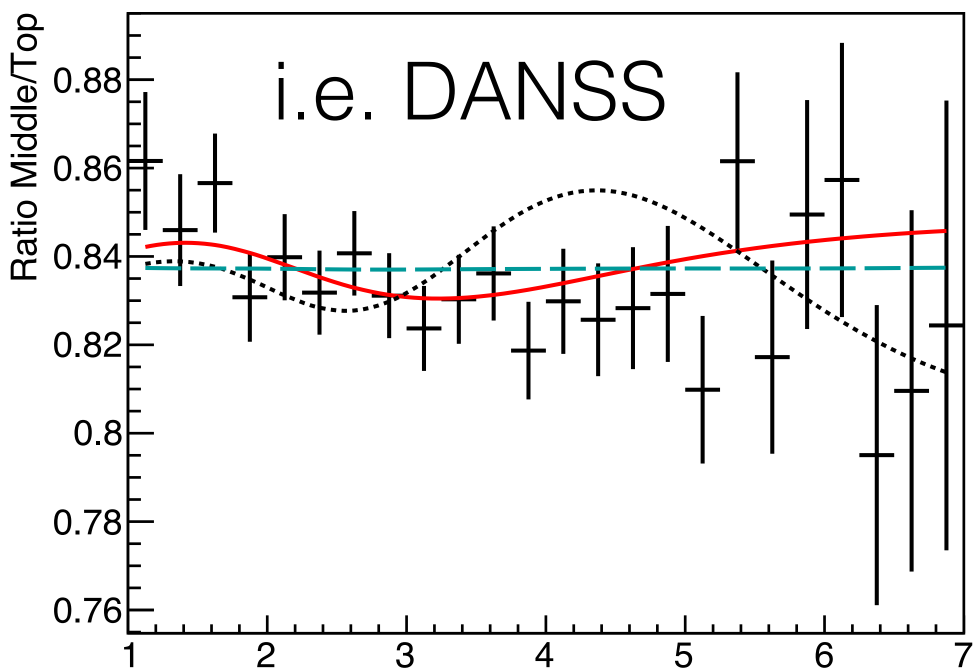
3.8σ Combined excess



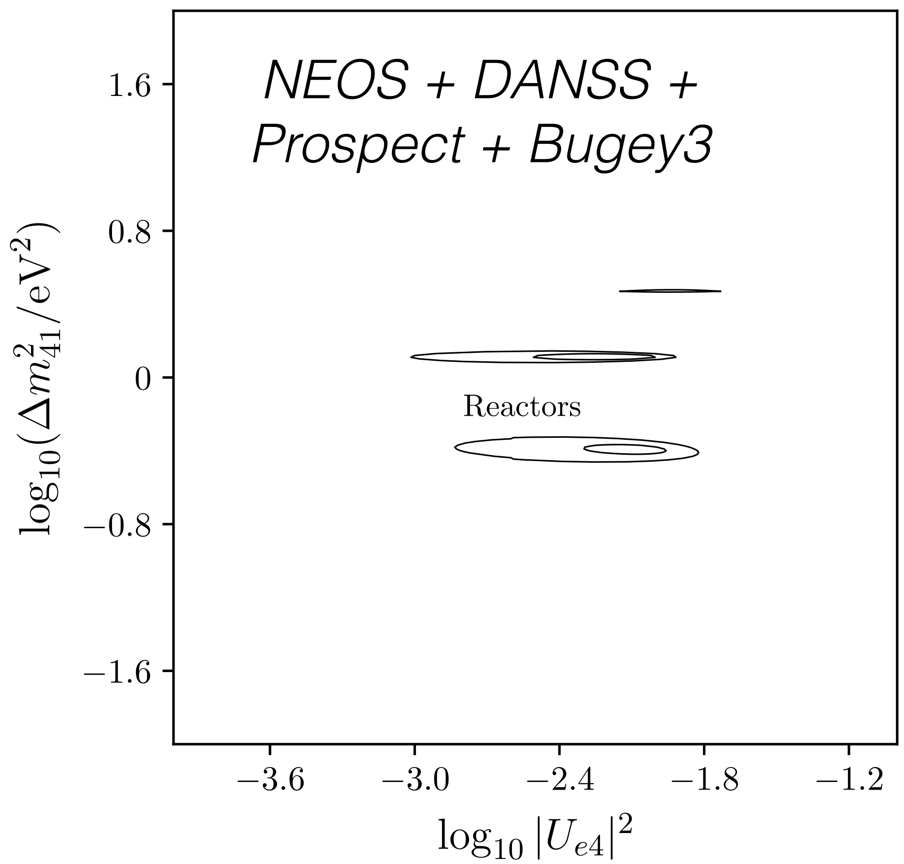
arXiv 1805.12028

Nuclear Reactors

$\bar{\nu}_e$ **disappearance** measurements at various reactors



arXiv 1804.04046



Find **modulation** of the flux at various reactors with L/E

$\sim 3\sigma$ preference for

$$\Delta m^2_{41} \approx 1.3\,\mathrm{eV}^2$$

$$|U_{e4}|^2 \approx 2 \times 10^{-2}$$

Gariazzo et al 1801.06467

Oscillation anomalies

LSND/MiniBooNE (ν_e appearance) $\quad \sin^2 2\vartheta_{e\mu} > 0$

Reactors/Gallium (ν_e disappearance) $\quad \sin^2 2\vartheta_{ee} > 0$

$$\left.\begin{array}{l} \sin^2 2\vartheta_{e\mu} > 0 \\ \\ \sin^2 2\vartheta_{ee} > 0 \end{array}\right\} \sin^2 2\vartheta_{\mu\mu} > 0$$

But: not seen in ν_μ disappearance (MINOS+, IceCube)

also see global fits:

Gariazzo et al 1703.00860

Esteban et al 1811.05487

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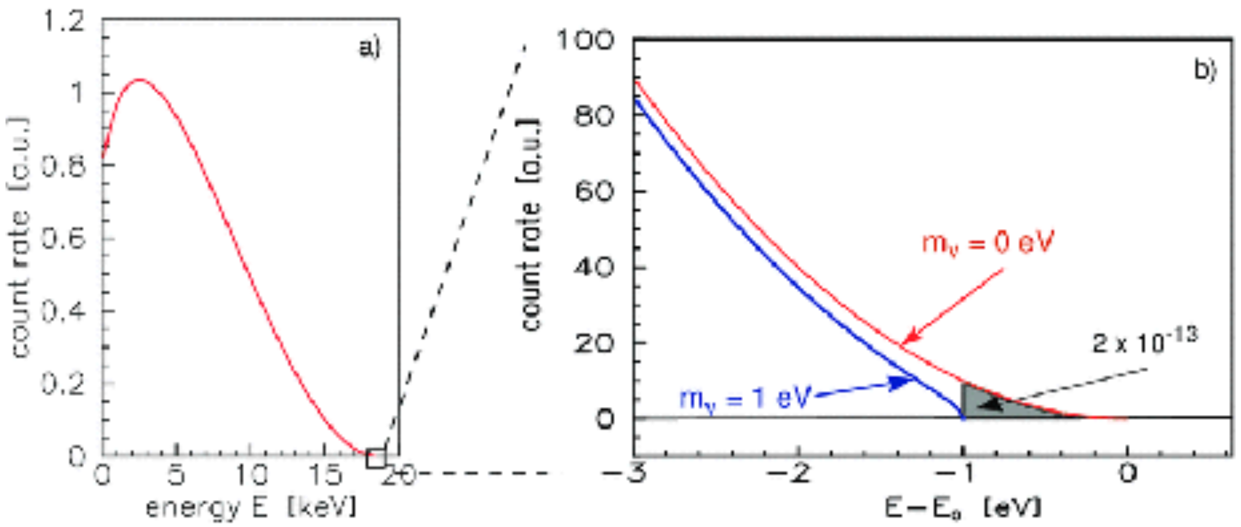
Beta (Tritium) decay



Diaz et al 2011

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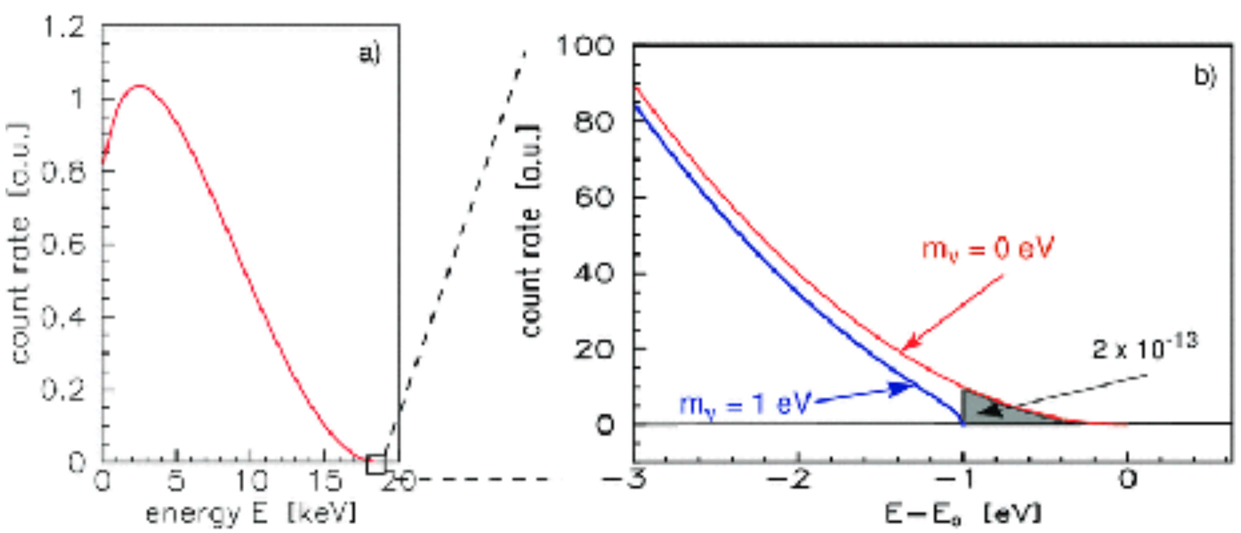

Diaz et al 2011

Effective end-point mass

$$m_\beta^2 = \sum_{k=1}^{4} |U_{ej}|^2 m_j^2$$

KATRIN limit $m_\beta < 1.1\,\mathrm{eV}$

KATRIN collaboration arXiv 1909.06048

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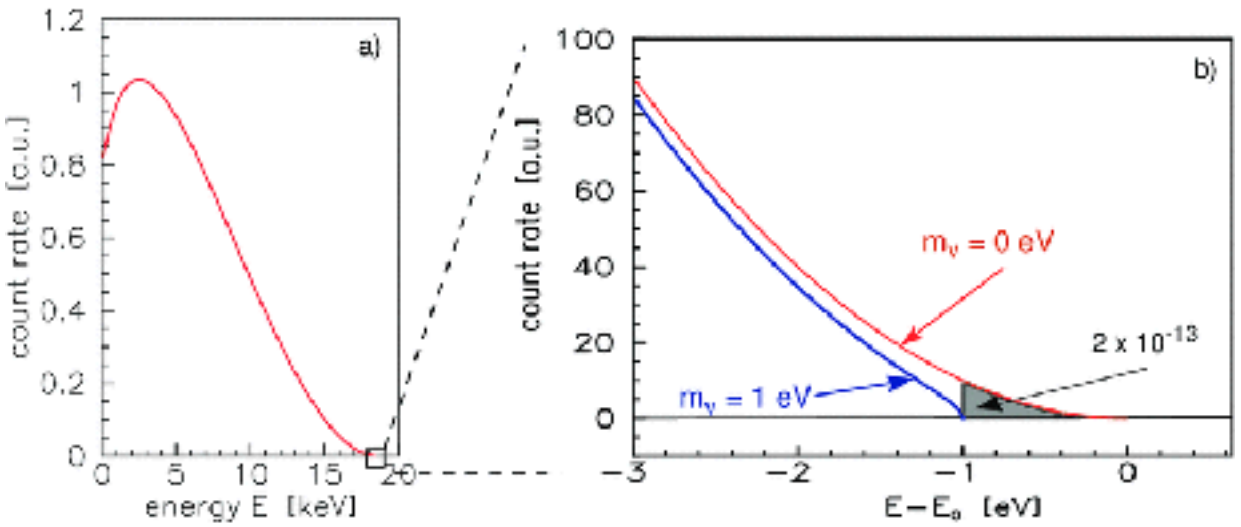

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Double-beta decay ($0\nu\beta\beta$)

If neutrinos are **Majorana**:

$$n + n \to 2p + 2e^-$$

Measure half-life

$$T_{1/2} = \frac{m_e^2}{G_{0\nu}|M_{0\nu}|^2 m_{\beta\beta}^2}$$

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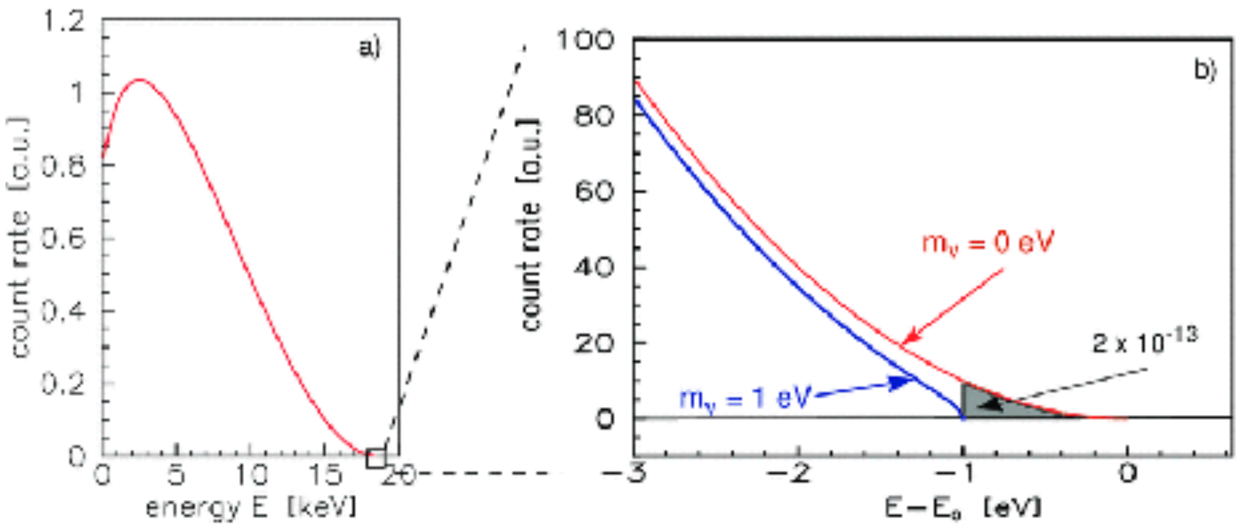

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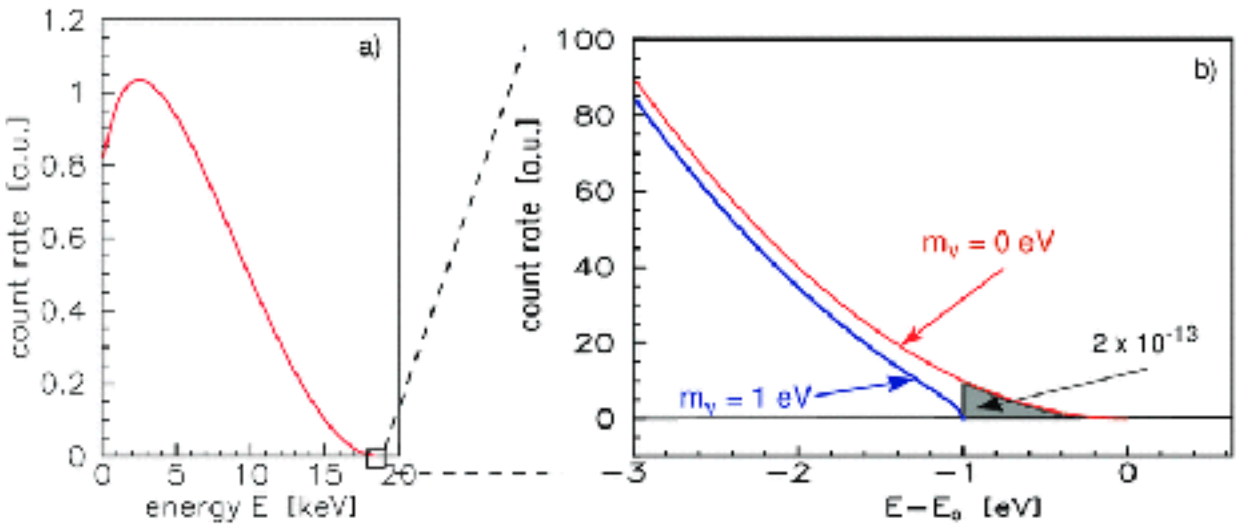

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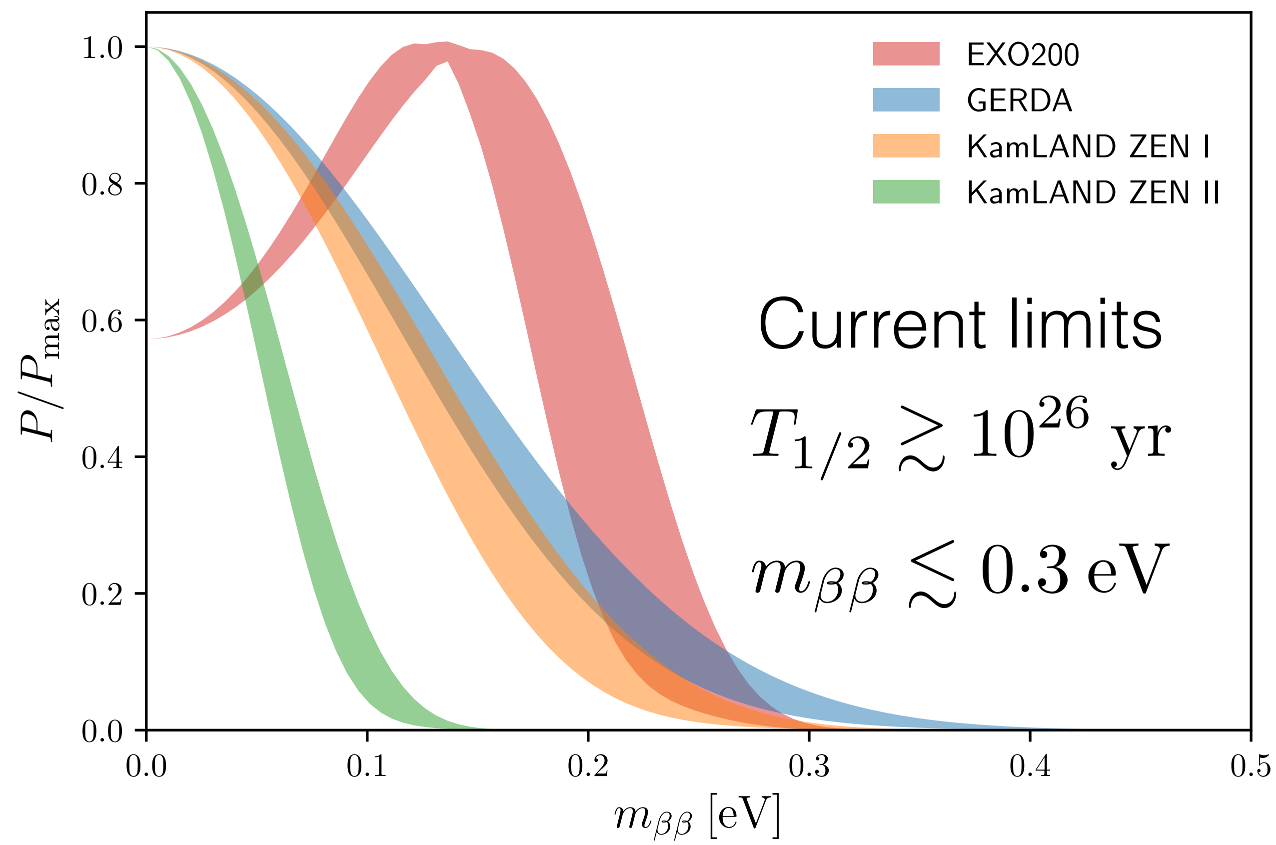

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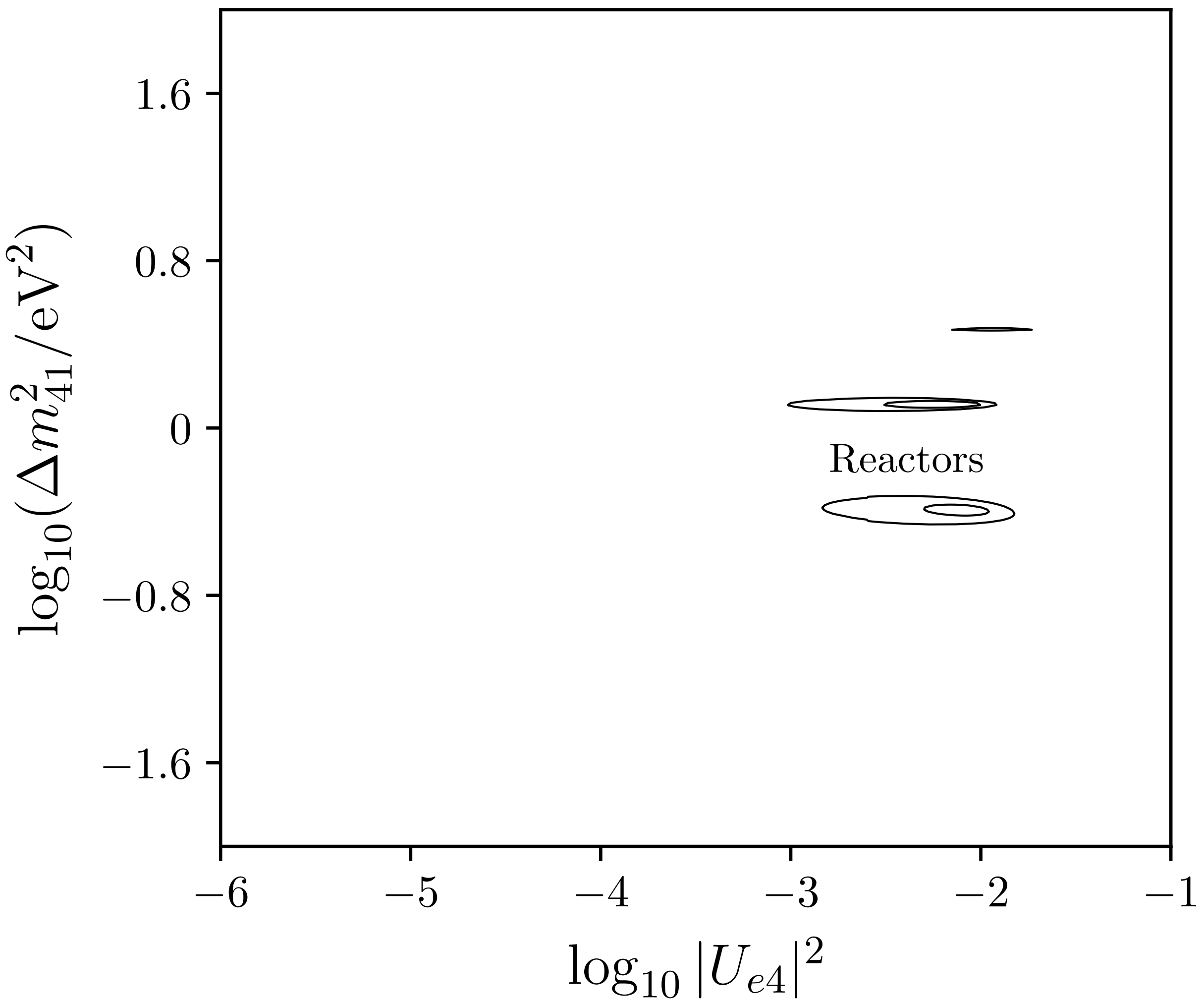
Joint direct limits



Combine resulting constraints

- Reactors: preferred region

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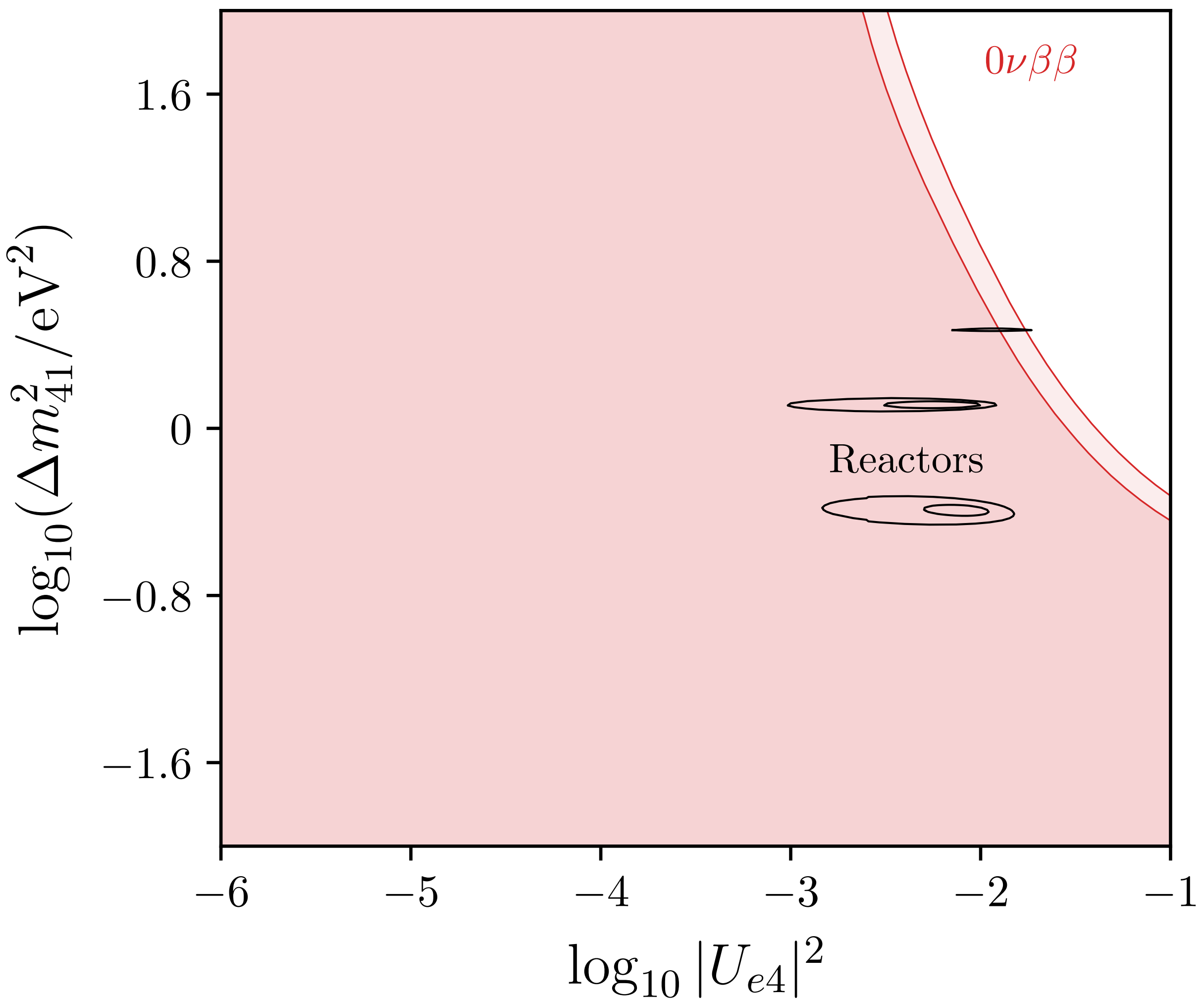

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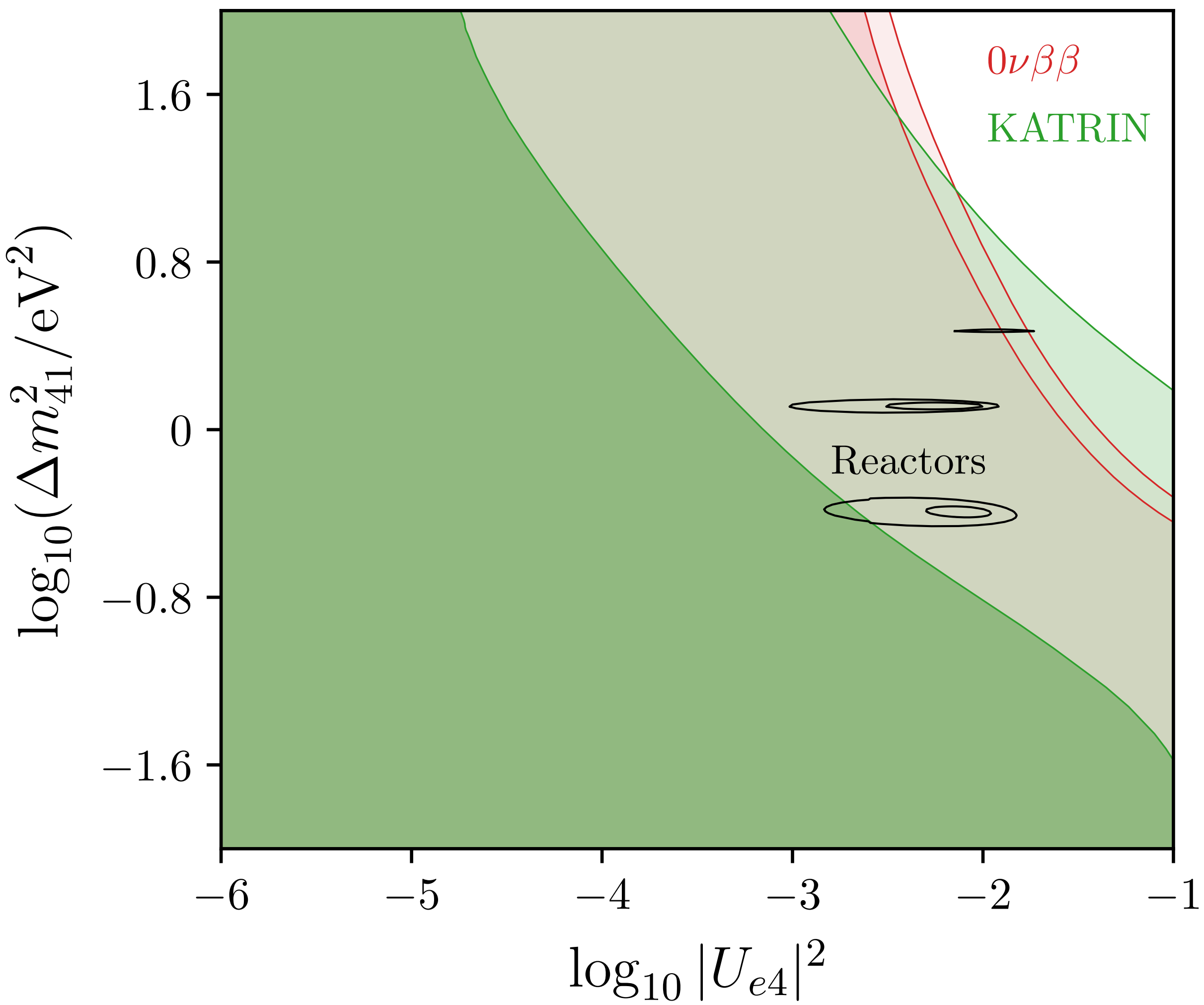

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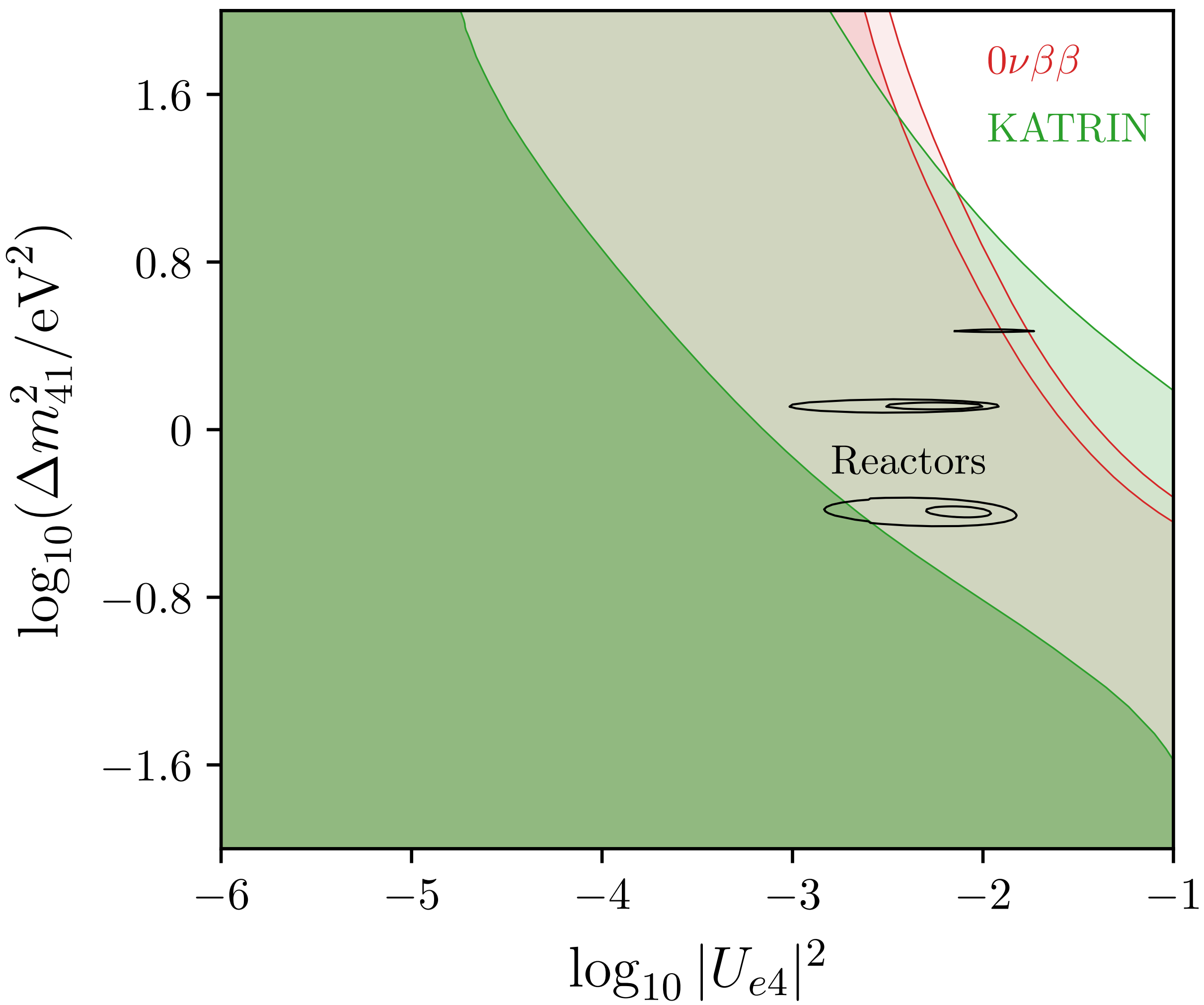

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Can we see this in cosmology?

Neutrino cosmology

sterile parameters $\boxed{\Delta m_{41}^2,\ |U_{\alpha j}|^2} \longrightarrow \boxed{C_\ell^{AB},\ P(k)}$ cosmological observables

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Production in the early universe described by Liouville equation

$$i\left(\partial_t - Hp\partial_p\right)\rho_\nu(t) = \left[\left(\frac{1}{2p}U\mathcal{M}(\rho_\nu)U^\dagger - \frac{G_F}{m_W^2}p\mathcal{E}(\rho_e) - \frac{G_F}{m_Z^2}p\mathcal{E}(\rho_\nu)\right), \rho_\nu\right] + \mathcal{C}[\rho_\nu, \rho_e]$$

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vacuum oscillations

lepton background

neutrino background

interactions

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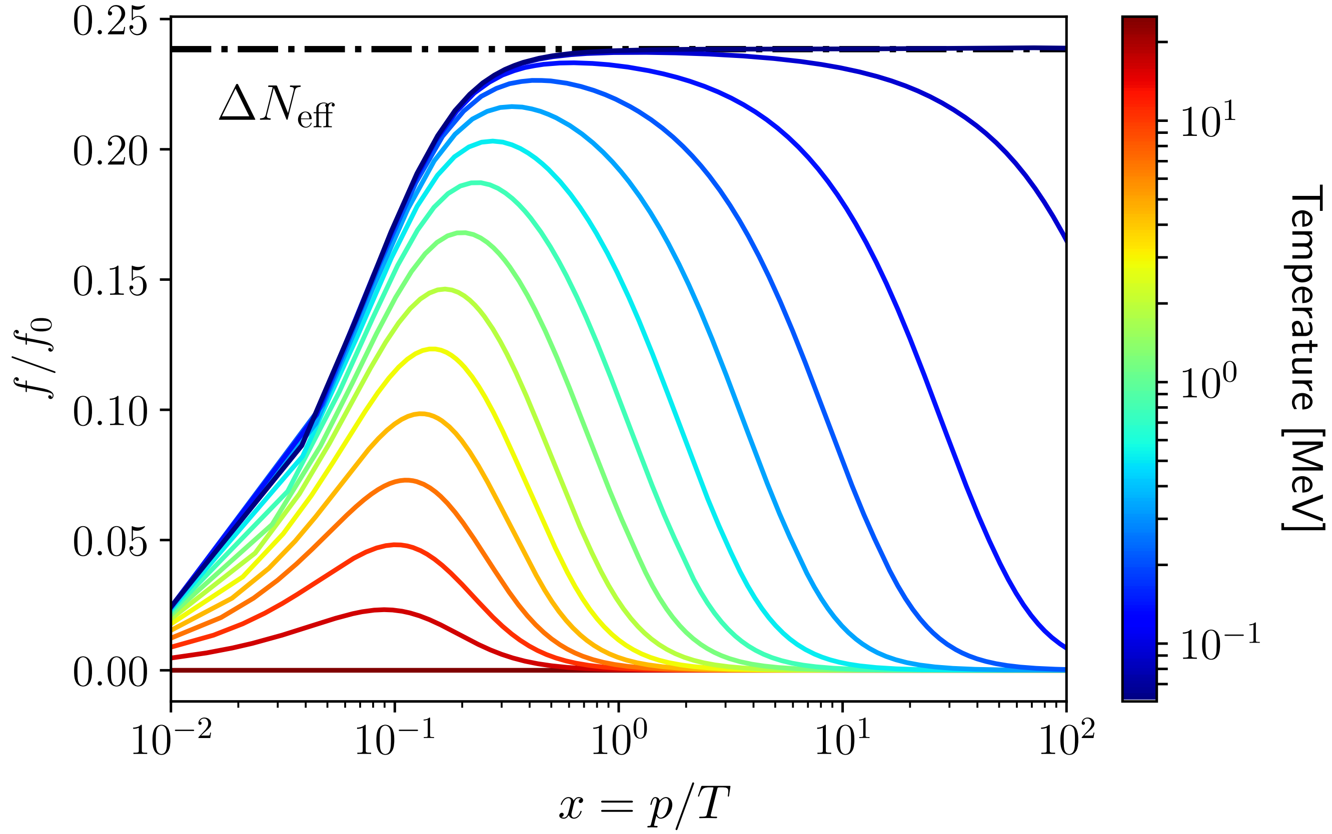
expansion | vacuum oscillations | lepton background | neutrino background | interactions

- Usually assume 1+1 neutrinos to simplify
- Here: go to **full 3+1** case (`FortEPiaNO`, Gariazzo et al 1905.11290)

Distribution functions



FortEPiaNO explicitly calculates all distribution functions

At late times

$$f_s(p) \approx \frac{\Delta N_{\rm eff}}{\exp(p/T_\nu)+1}$$

Dodelson & Widrow 94

For cosmology: just another neutrino described by

$$\boxed{\Delta N_{\rm eff},\ \Omega_s}$$

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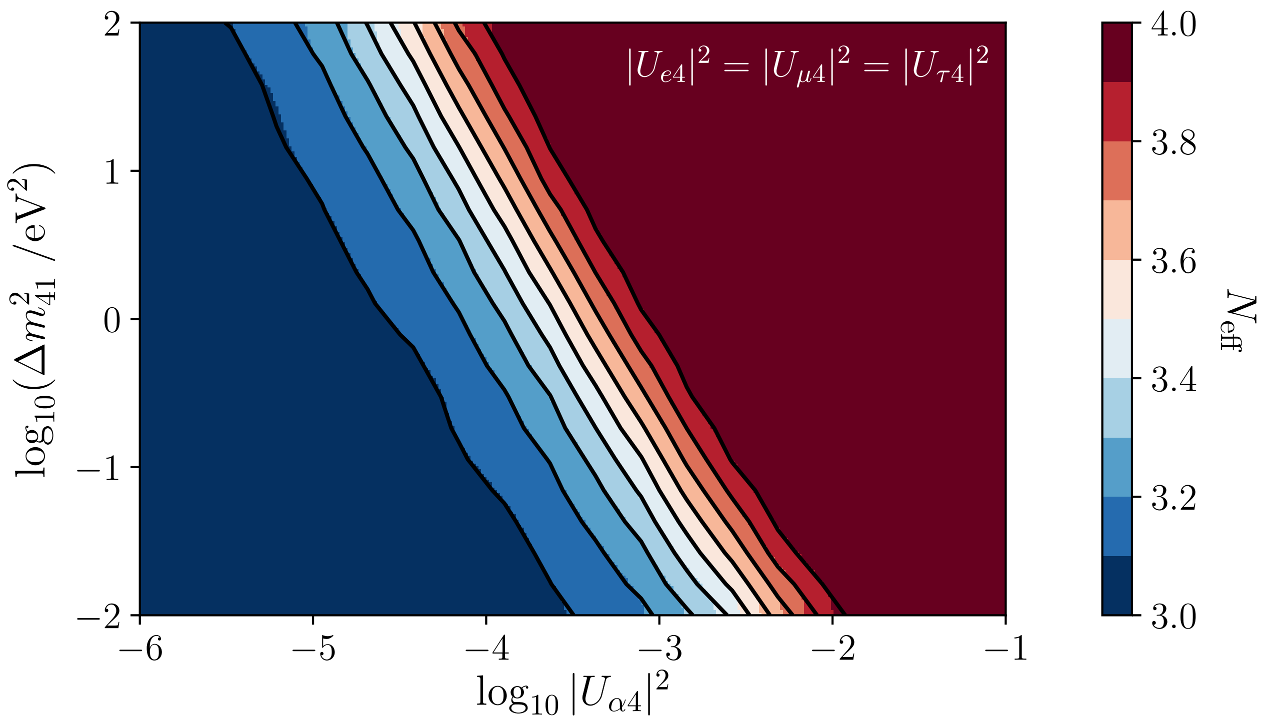
Production of steriles



Sterile relativistic for large mixing or small mass

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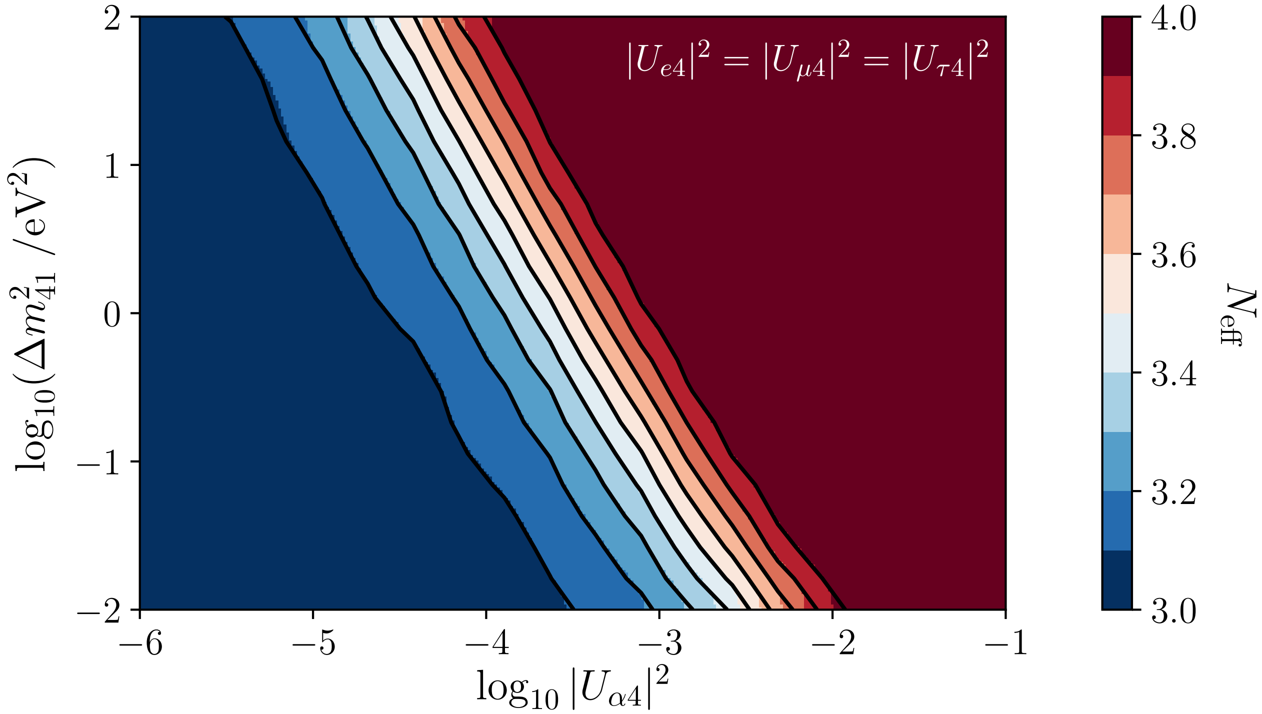

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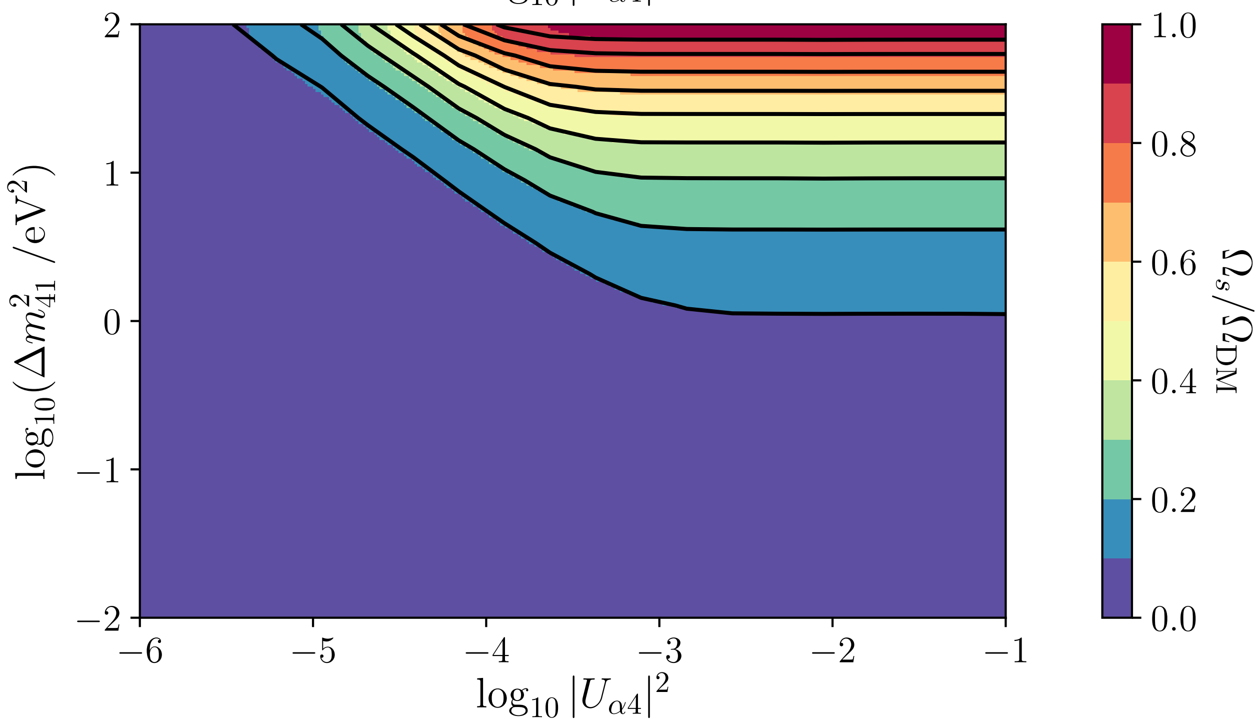


Cosmic density

$$\Omega_s \propto \Delta N_{\mathrm{eff}}\, m_s$$

Method

From neutrino parameters to cosmological observables:

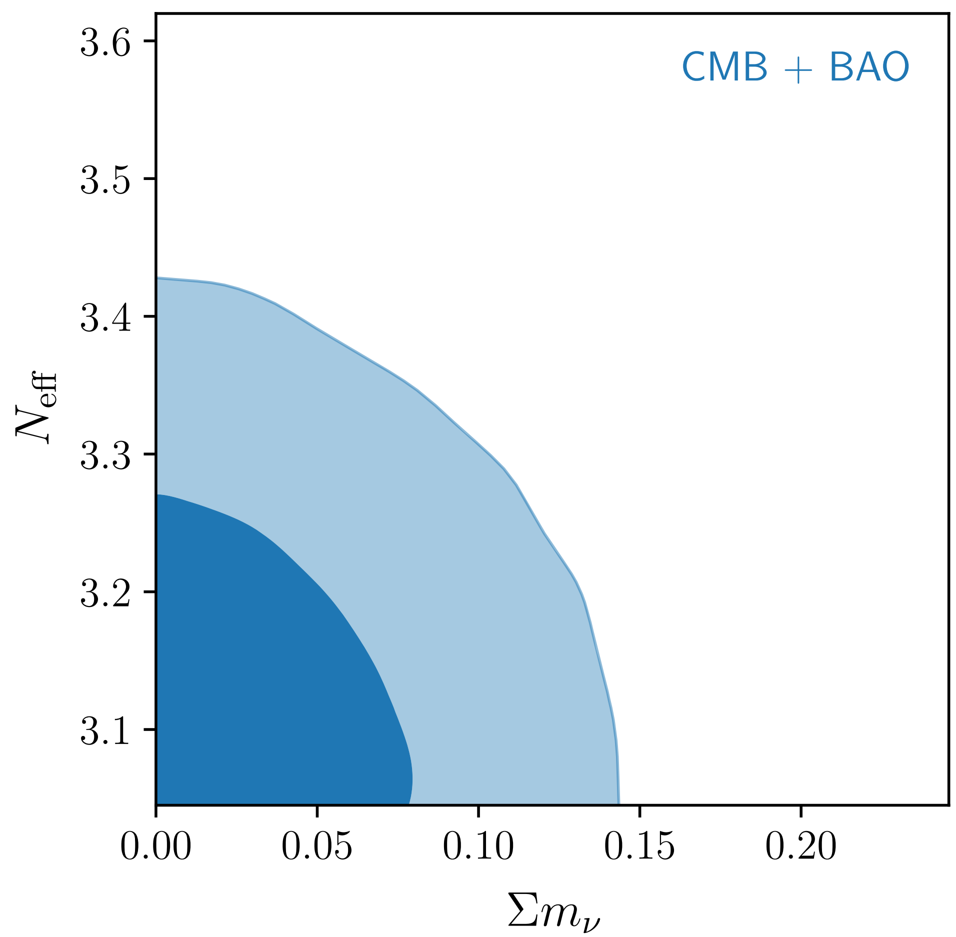
$$\Delta m^2_{41},\ |U_{\alpha j}|^2 \xrightarrow{\texttt{FortEPiaNO}} f_s(p)$$

$$f_s(p) \xrightarrow{\text{shortcut}} \Delta N_{\text{eff}},\ \Omega_s$$

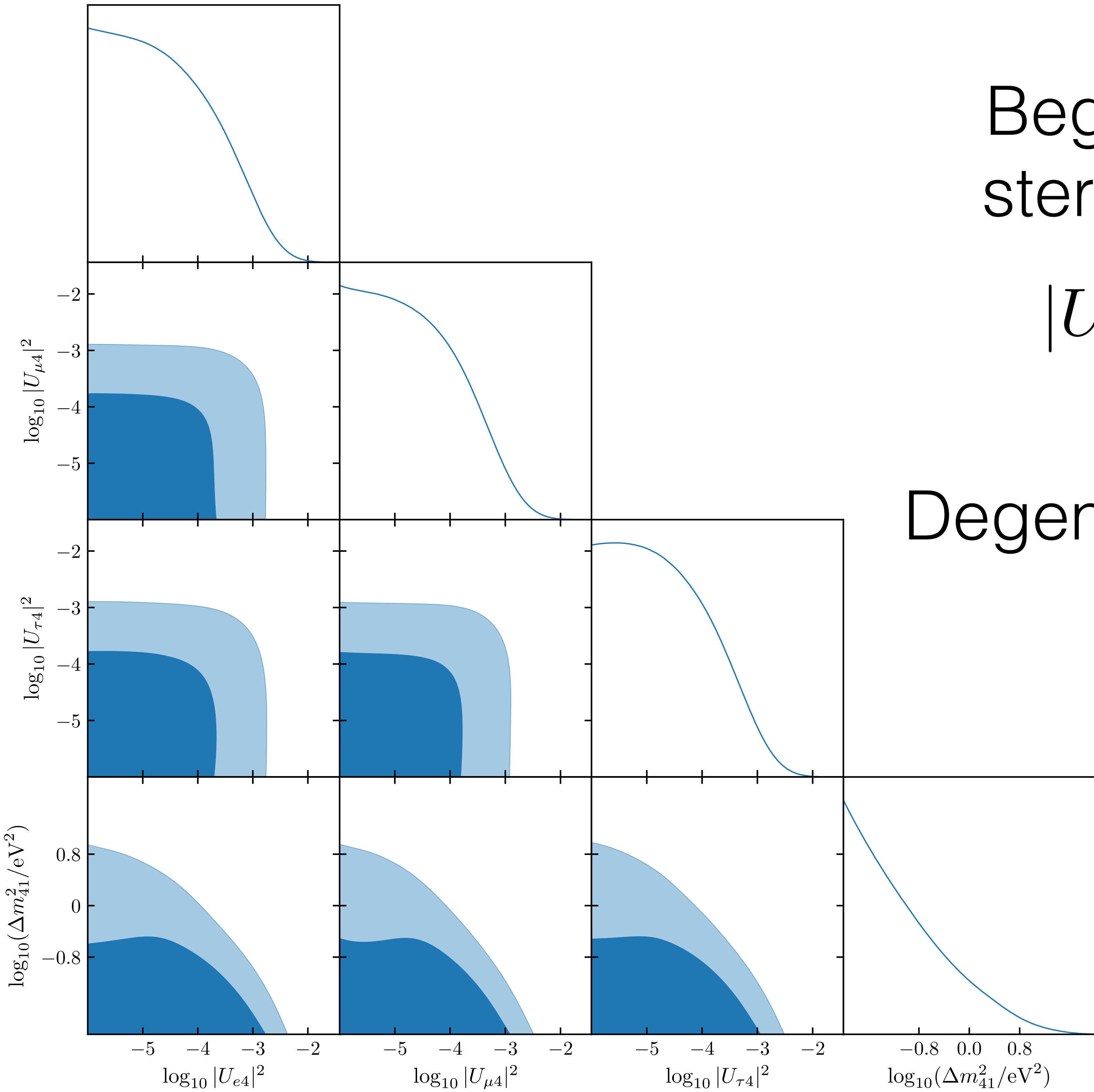
$$f_s(p) \xrightarrow{\texttt{CLASS}} C_\ell^{AB},\ P(k)$$

$$\Delta N_{\text{eff}},\ \Omega_s \xrightarrow{\texttt{CLASS}} C_\ell^{AB},\ P(k)$$

$$C_\ell^{AB},\ P(k) \longrightarrow \mathcal{L}_{\text{CMB}},\ \mathcal{L}_{\text{BAO}}$$



Cosmological limits

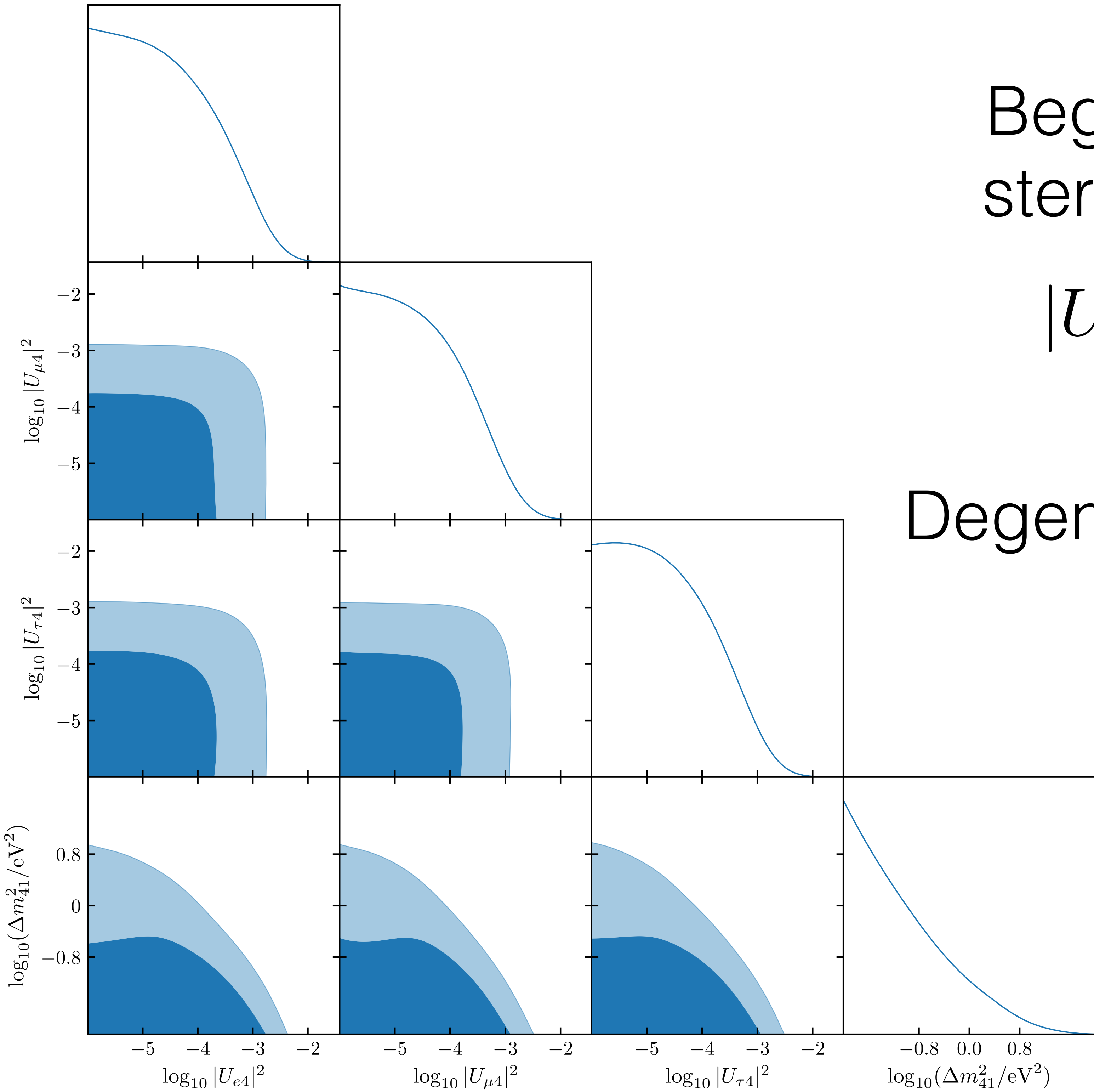


Begin populating sterile as soon as

$$|U_{\alpha j}|^2 \sim 10^{-3}$$

Degeneracy with Δm^2_{41}

Cosmological limits



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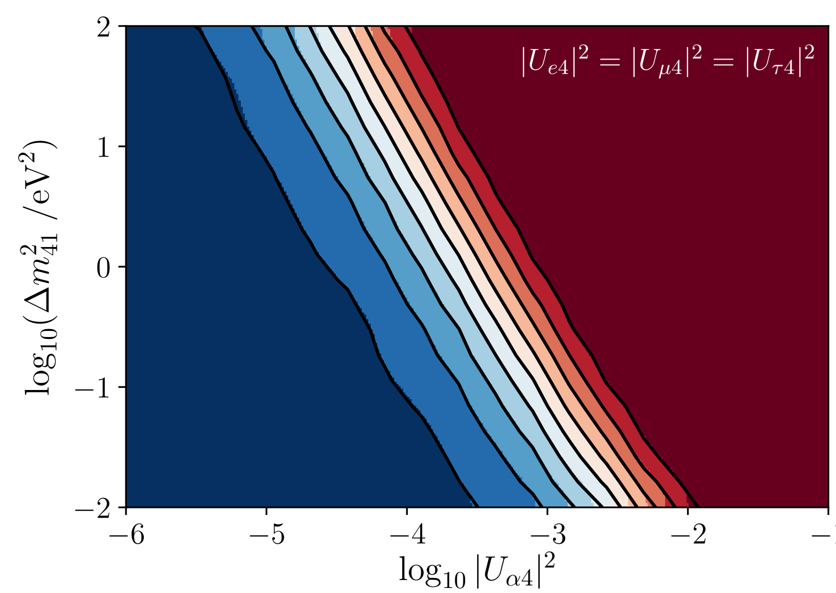

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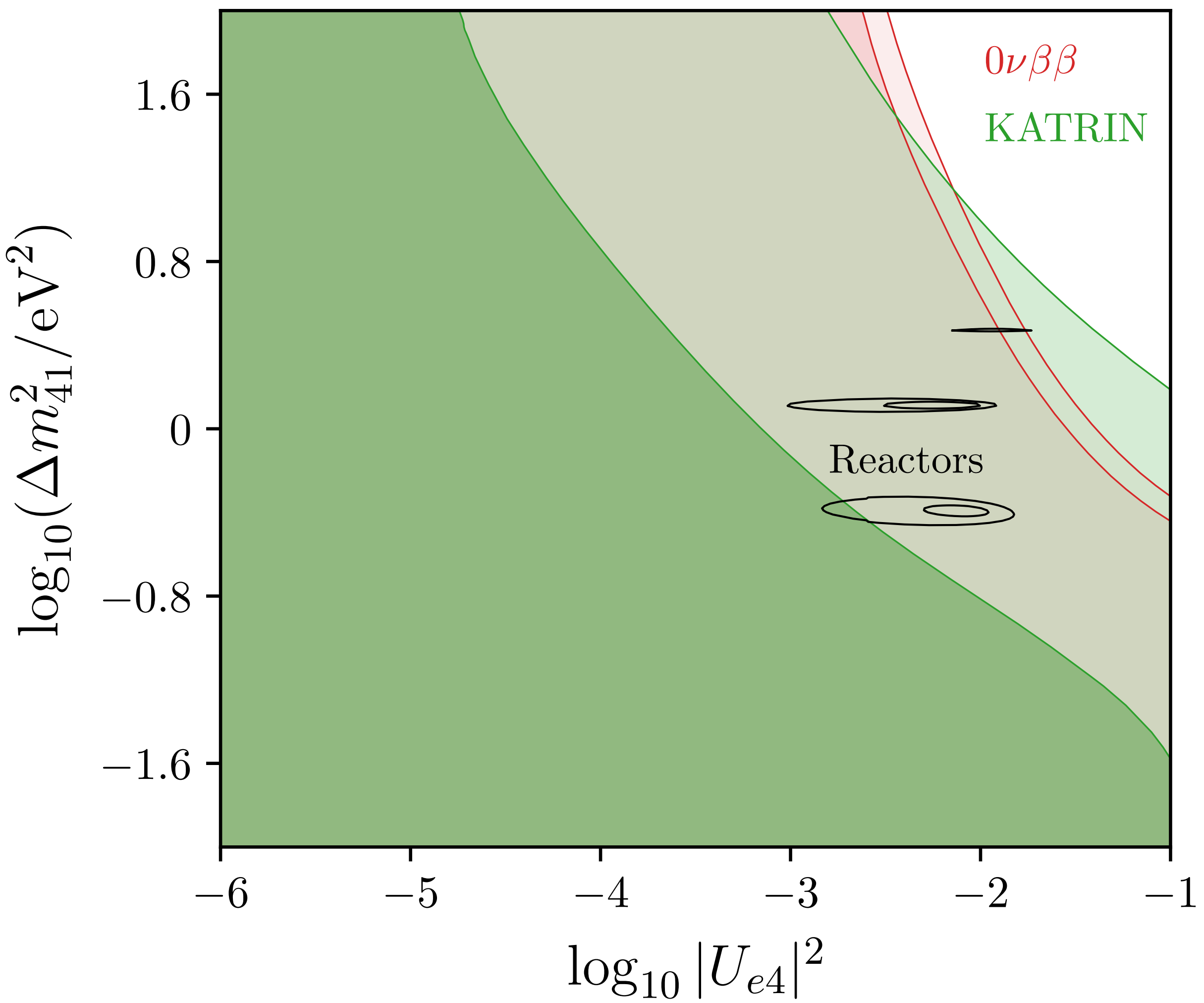
Reactors revisited

Combine resulting constraints



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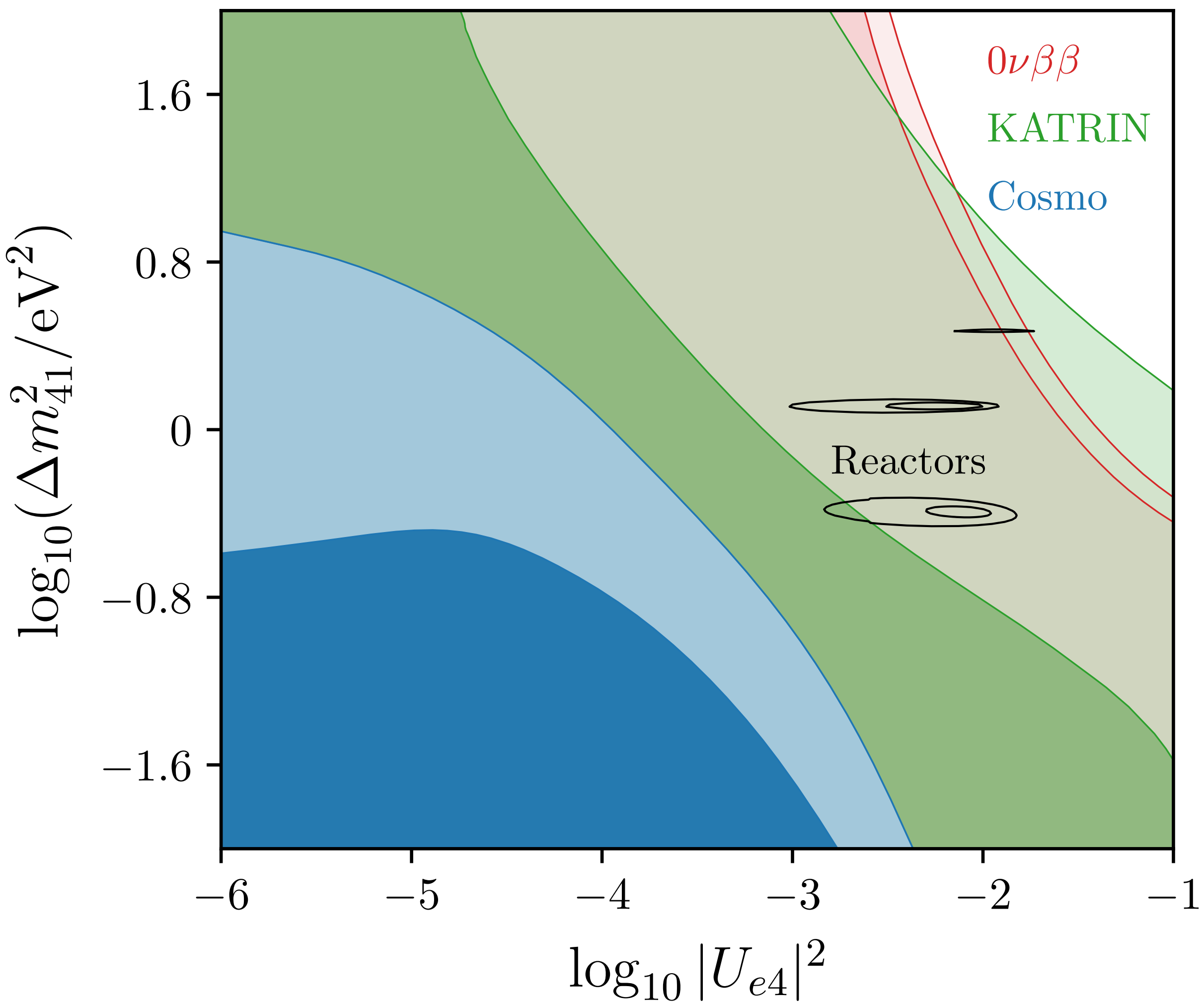

Combine resulting constraints

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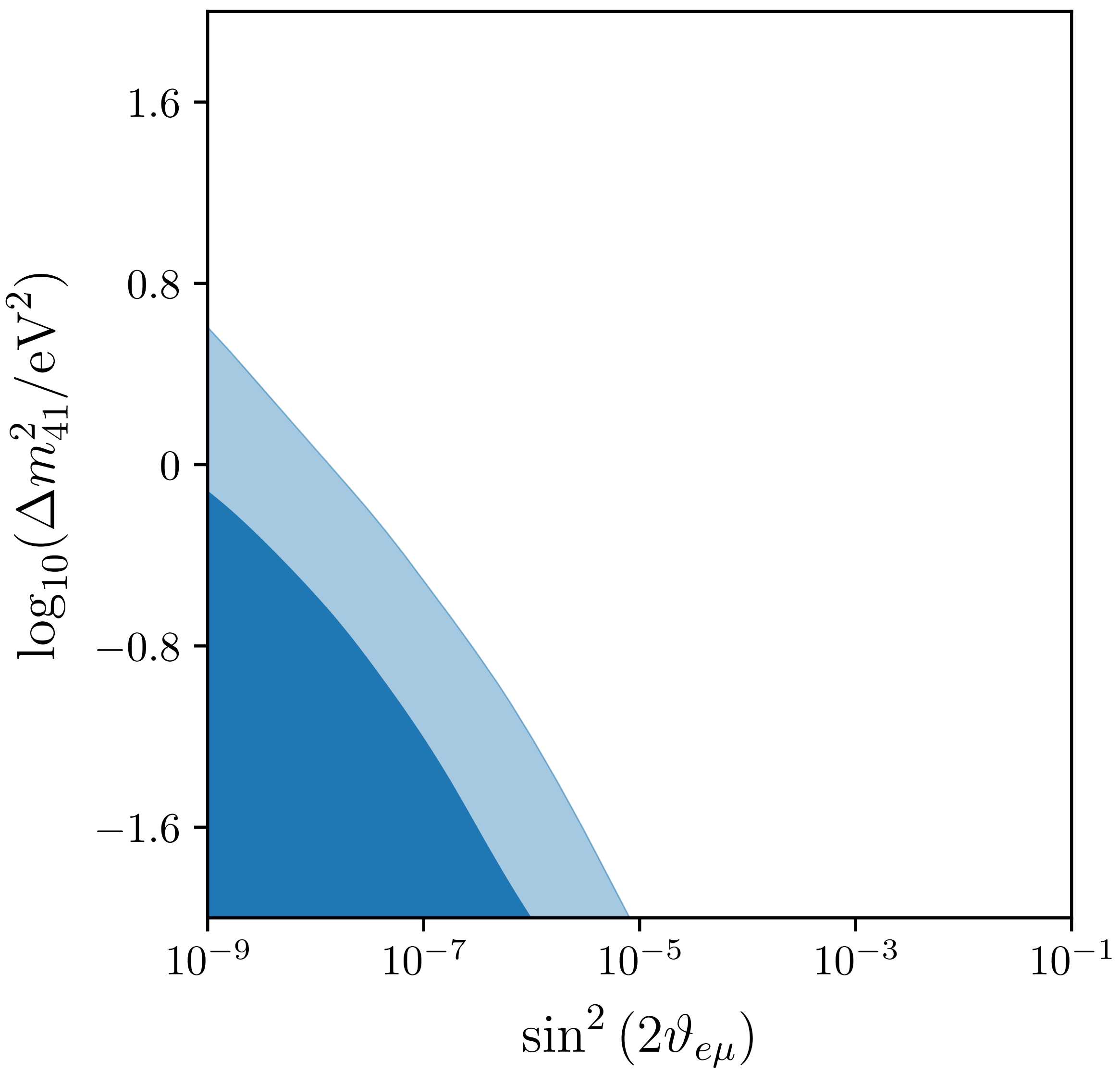
- **Ruled out** by cosmology

MiniBooNE revisited



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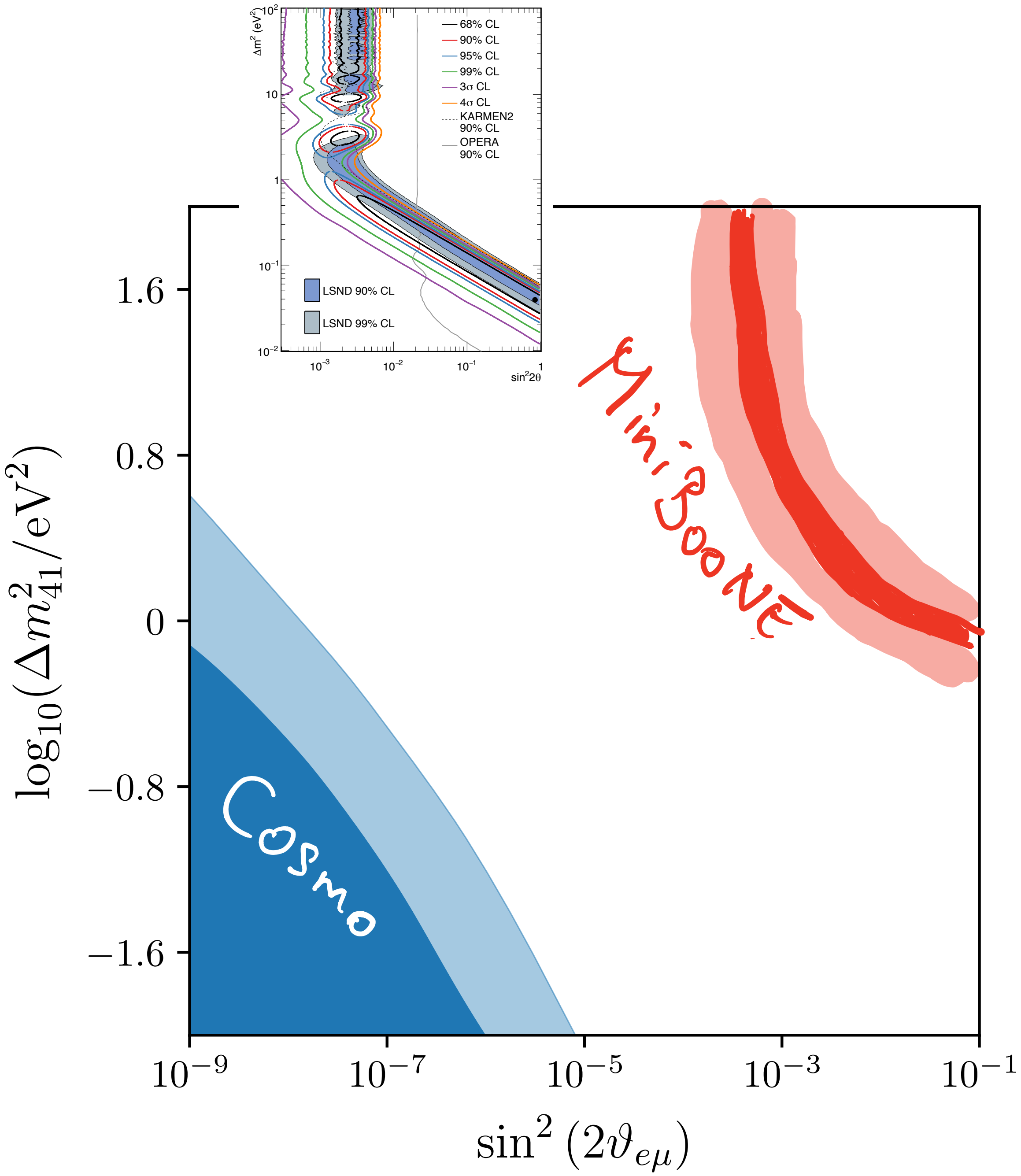

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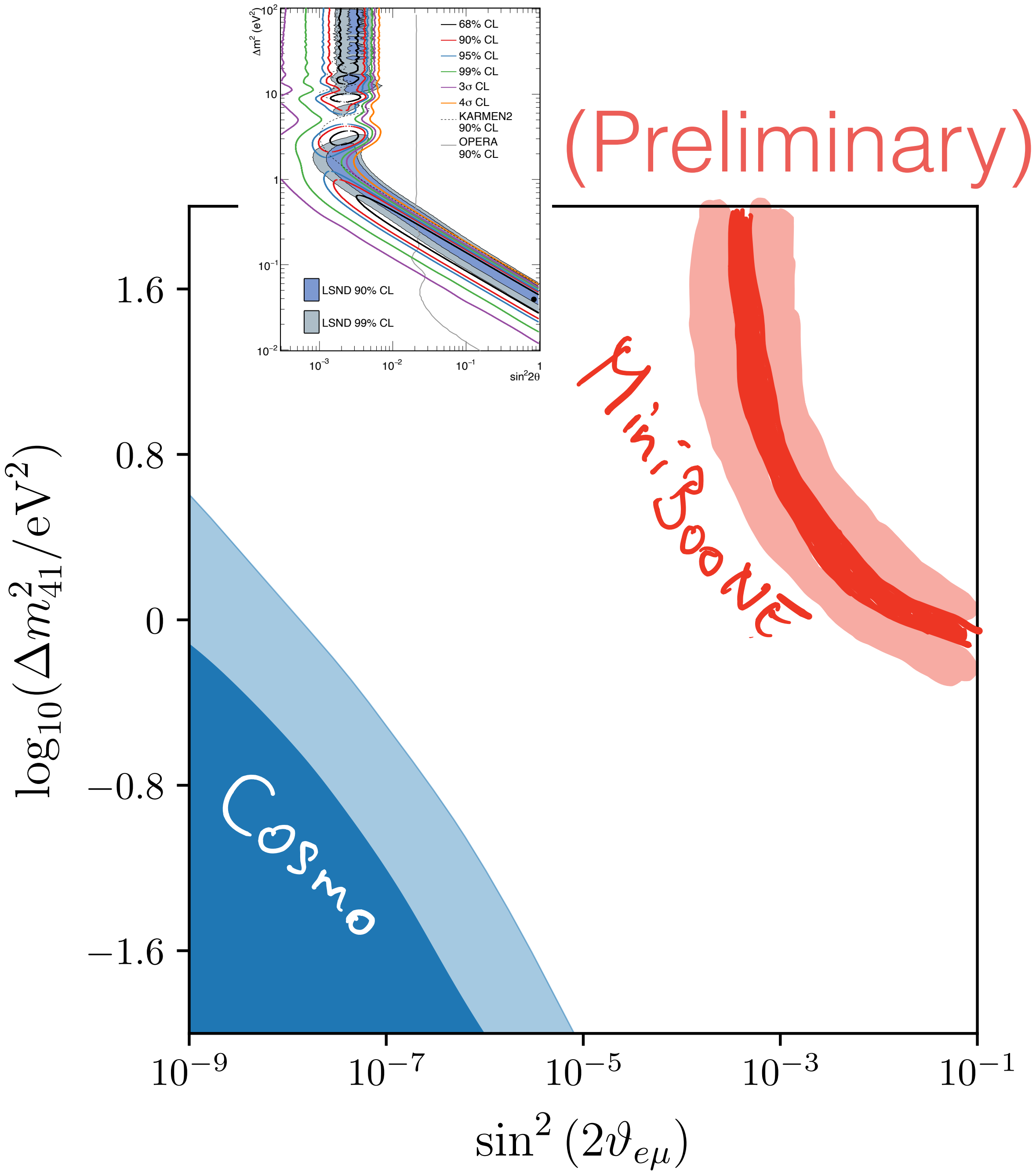
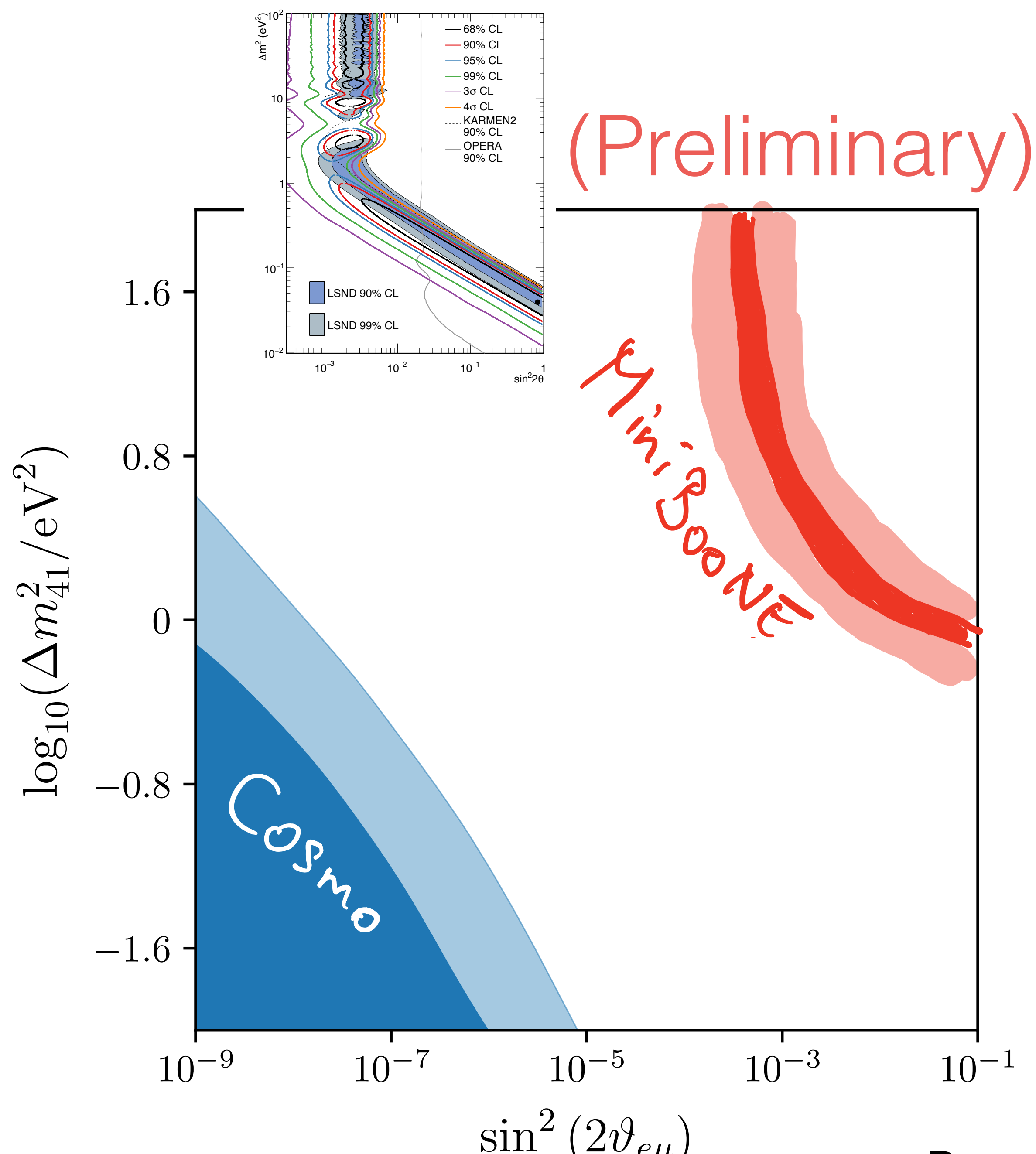
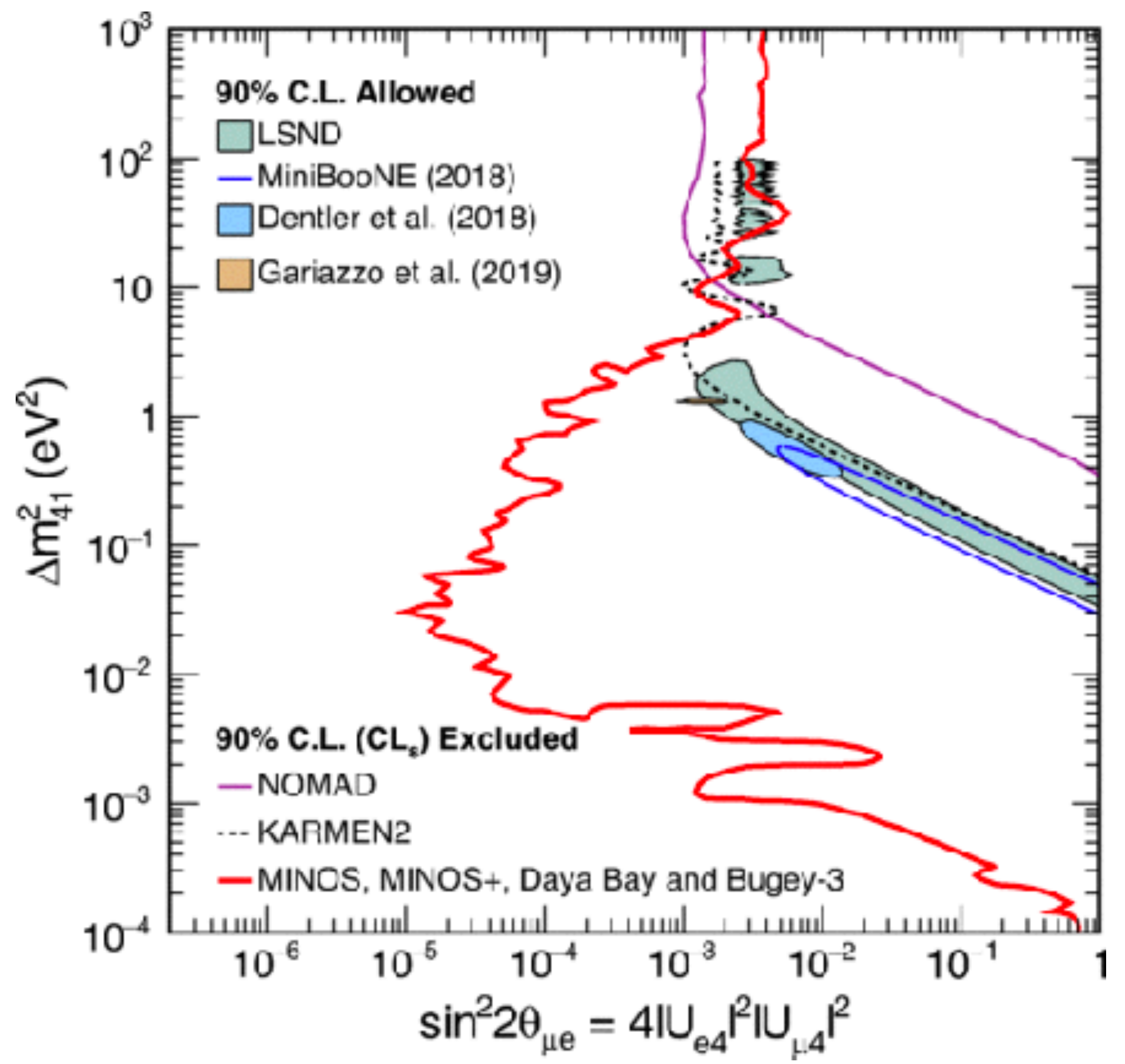


Sterile neutrino interpretation of MiniBooNE **ruled out** by cosmology

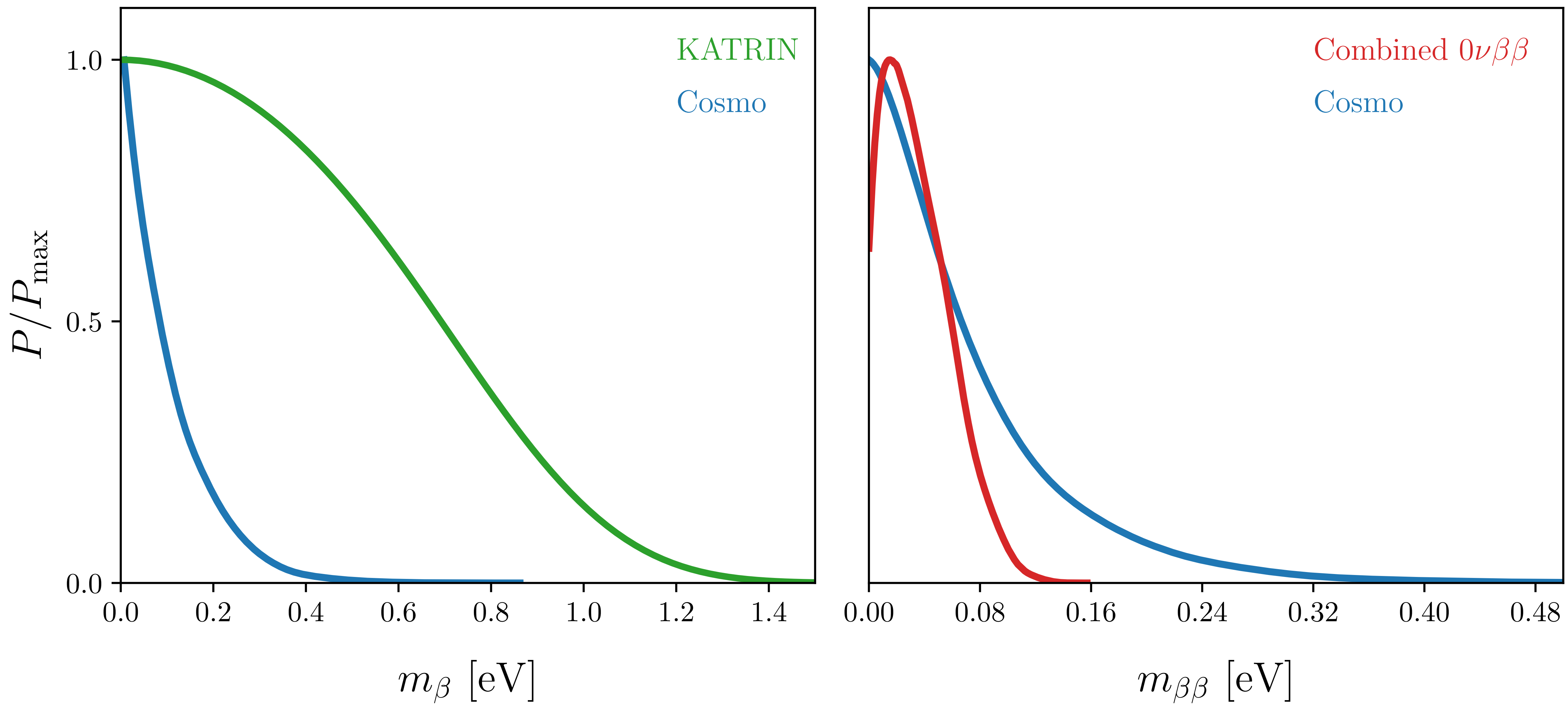
MiniBooNE revisited





Daya Bay & MINOS+ collaborations, Adamson et al. 2020

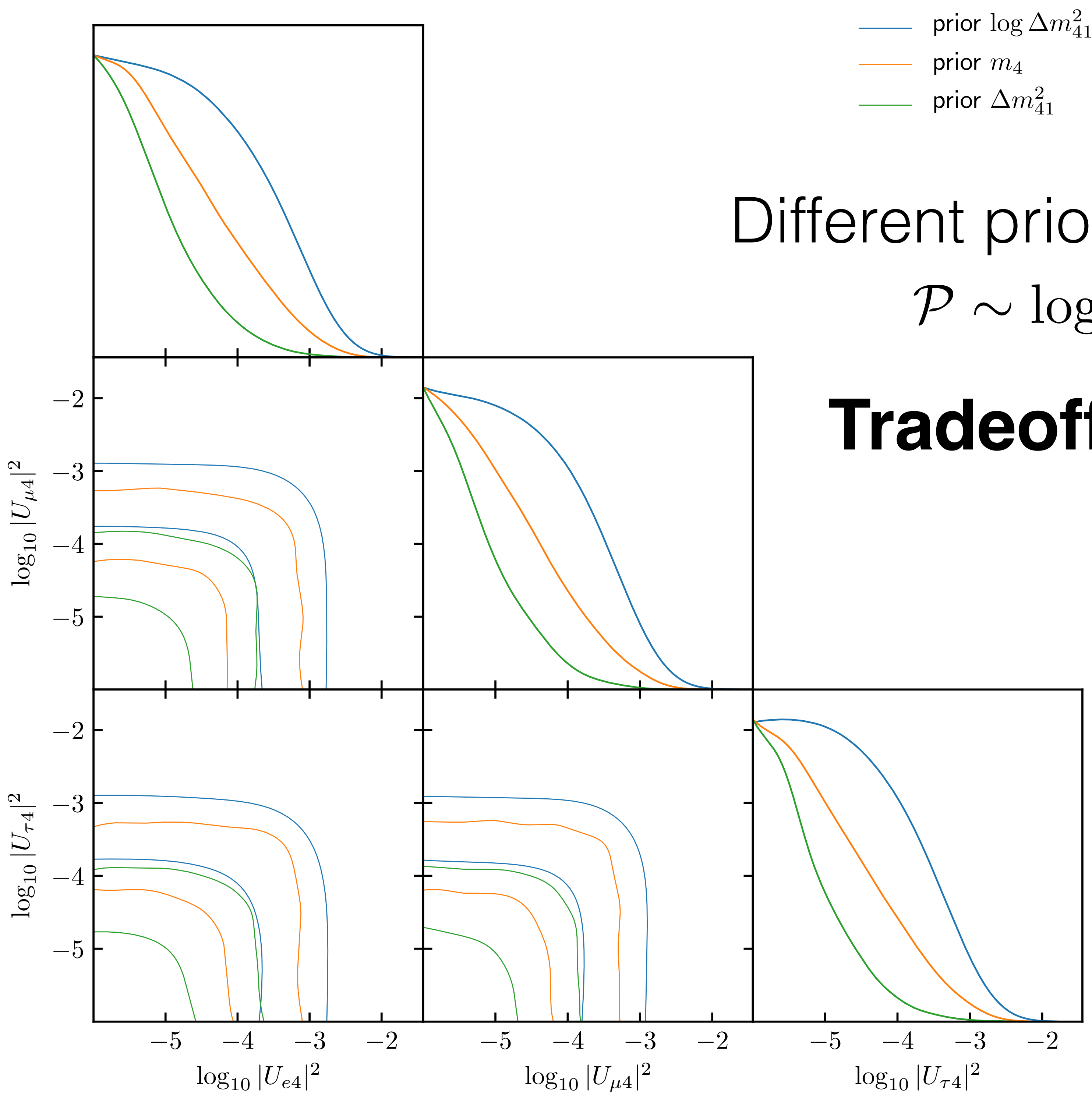
Beta decay limits



Tightest available constraints on m_β and $m_{\beta\beta}$
- but **model dependent**

Steffen Hagstotz

Prior effects

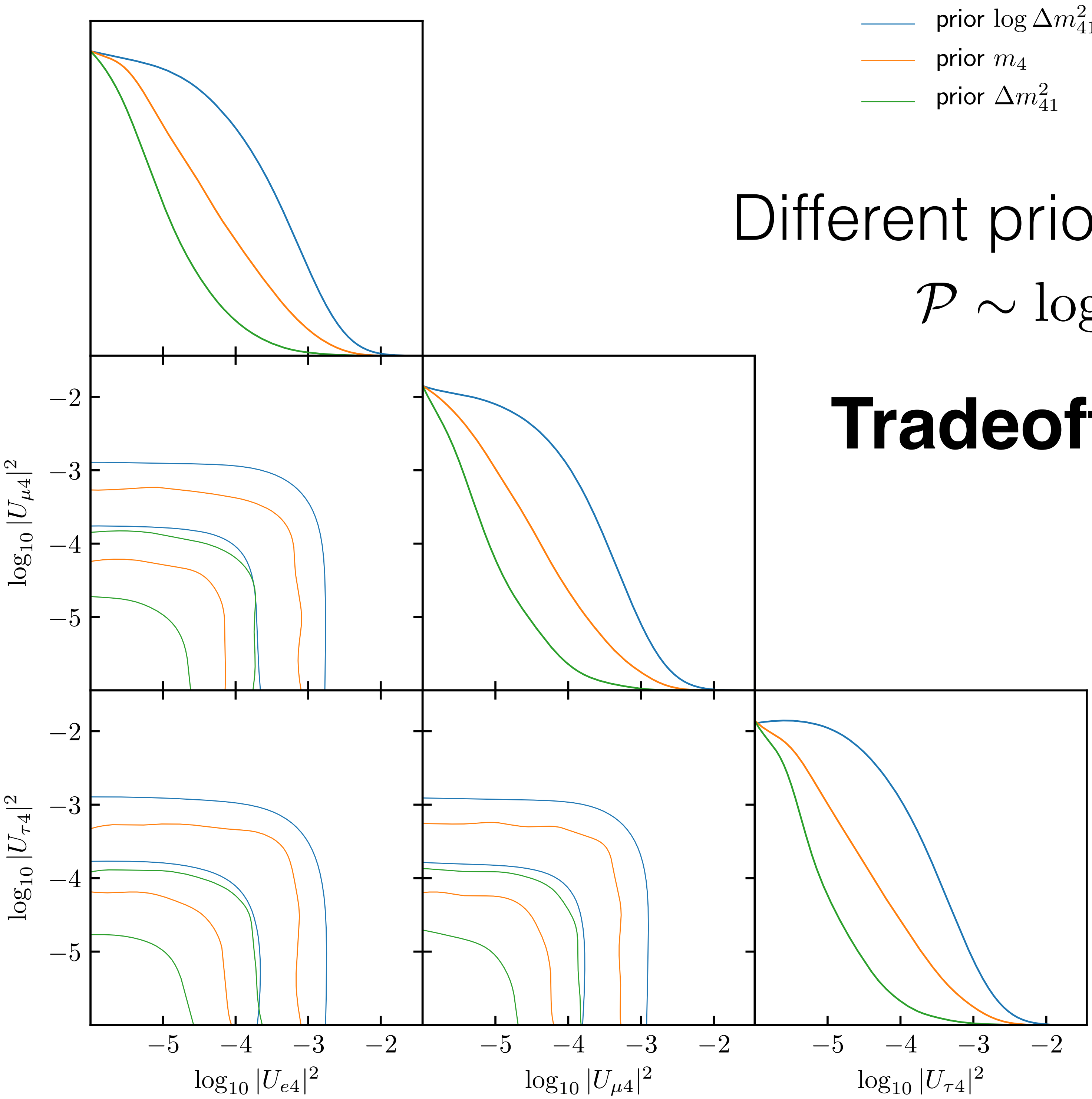


Different priors on mass scale possible:

$$\mathcal{P} \sim \log \Delta m_{41}^2 \;/\; \Delta m_{41}^2 \;/\; m_4 \;\ldots$$

Tradeoff between $\Delta m_{41}^2, \; |U_{\alpha j}|^2$

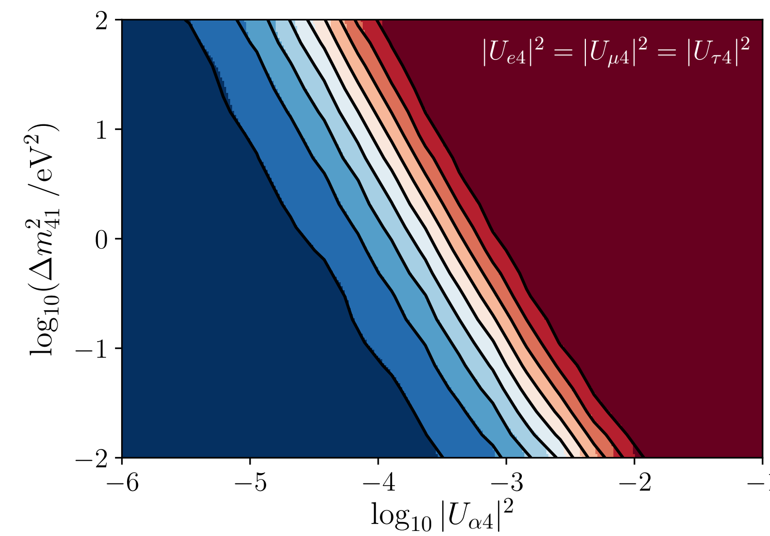
Prior effects



Different priors on mass scale possible:

$$\mathcal{P} \sim \log \Delta m^2_{41} \;/\; \Delta m^2_{41} \;/\; m_4 \;\ldots$$

Tradeoff between $\Delta m^2_{41},\ |U_{\alpha j}|^2$

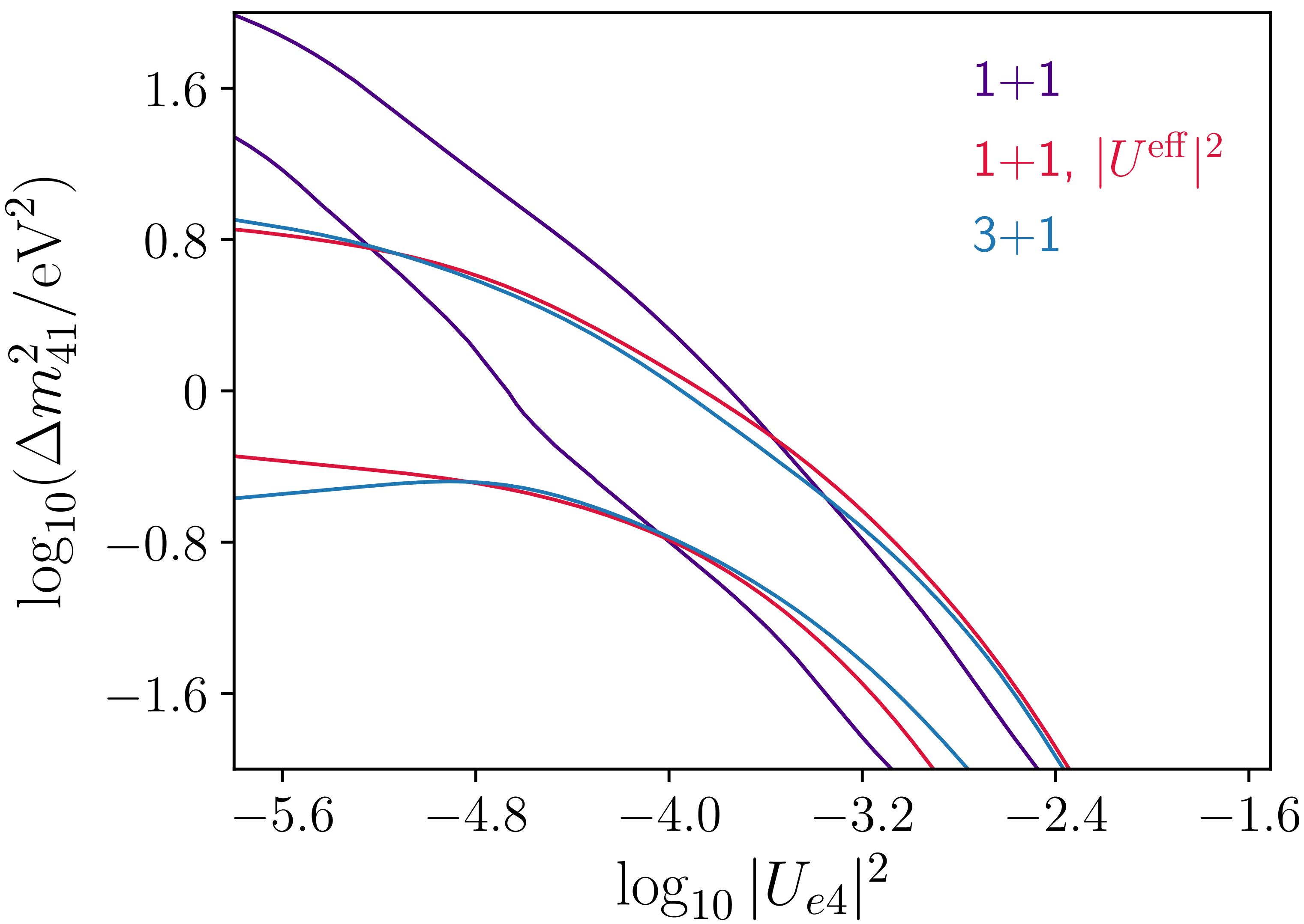


But:

big picture **unaffected**

3+1 vs 1+1

What is the **difference** to previous 1+1 scenarios?



Mostly parameter space **volume** effect:

$$|U^{\mathrm{eff}}|^2 = \sum_{e,\mu,\tau} |U_{\alpha 4}|^2$$

and same prior volume gives almost identical results

Conclusion

- Situation in SBL oscillation experiments **unclear**
- Different probes provide valuable cross-checks
- Any simple sterile neutrino explanation **ruled out** by cosmology
- Cosmology provides **strongest** available limits on sterile neutrino & beta decay parameters

arXiv 2003.02289