# Probing Sterile Neutrino Cosmology with Oscillation Experiments

Jeff Berryman
Virginia Tech – CNP Research Day
Based on arXiv:1905.03254

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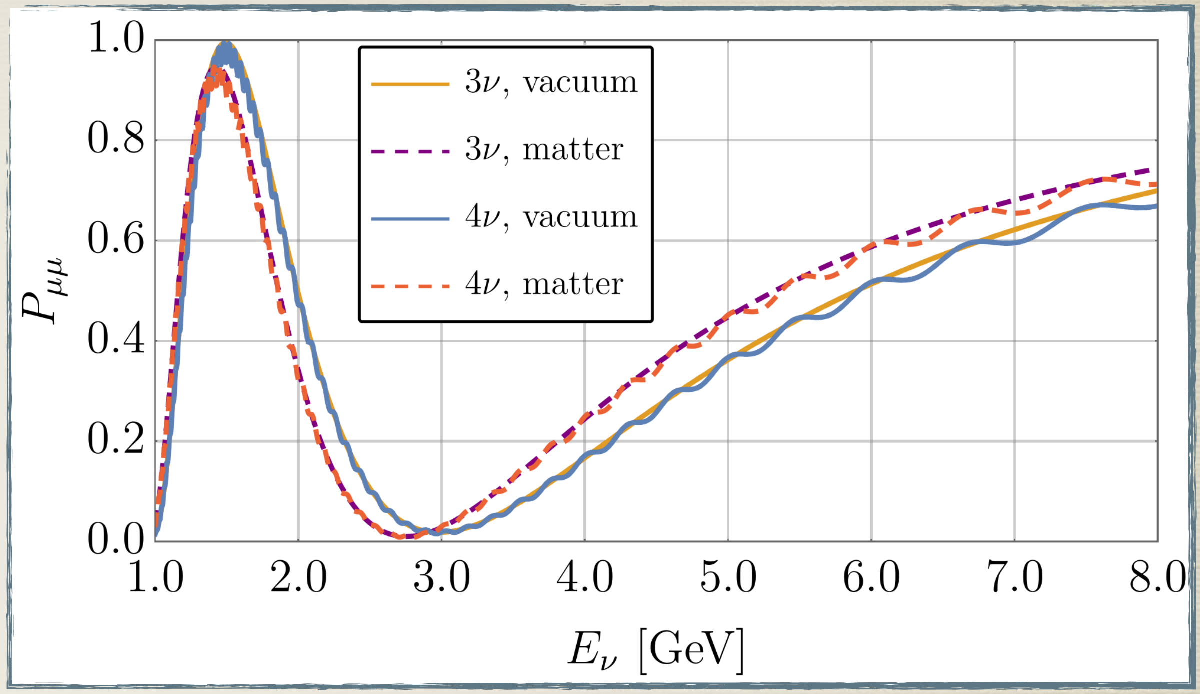
# Sterile Neutrinos: Oscillations vs. Cosmology

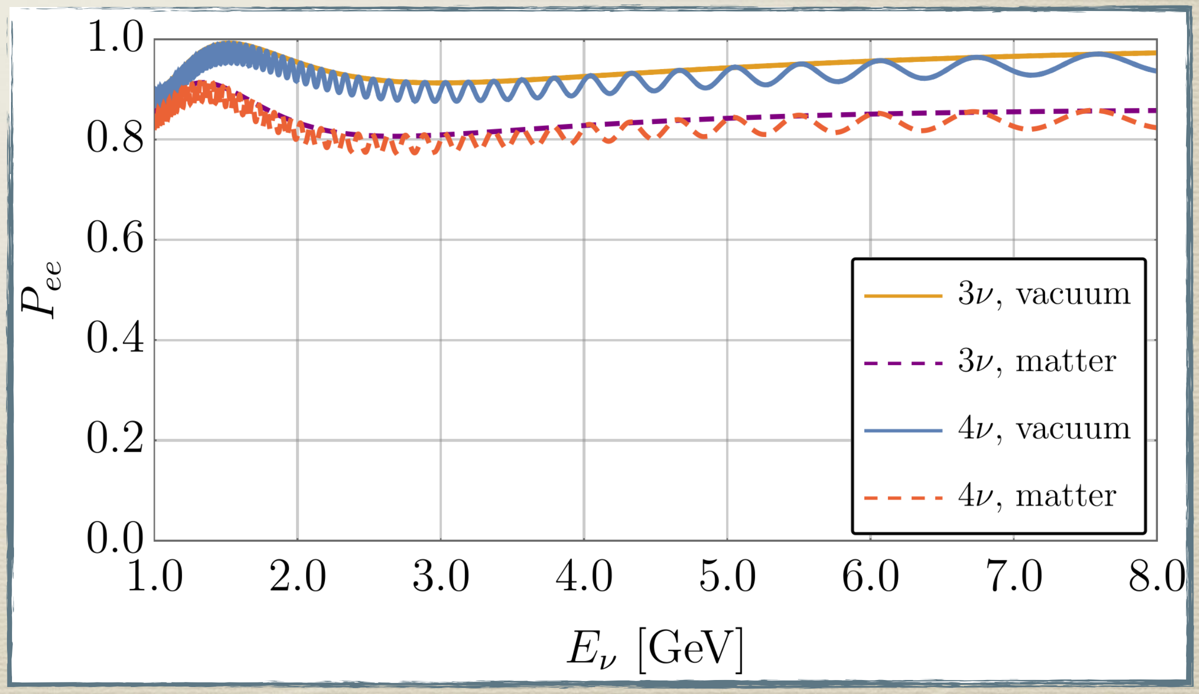
* *Oscillations*: Extra wiggles on top of $3\nu$ oscillation pattern
* *Cosmology*: Shifts in, *e.g.*, CMB relative to $\Lambda$CDM predictions
* Described by different – but related – physical parameters:

$$\{\Delta m^2_{41},\, \sin^2 2\theta_{\alpha\beta}\}$$

vs.

$$\{\Delta N_{\text{eff}},\, m^{\text{eff}}_{\text{sterile}}\}$$



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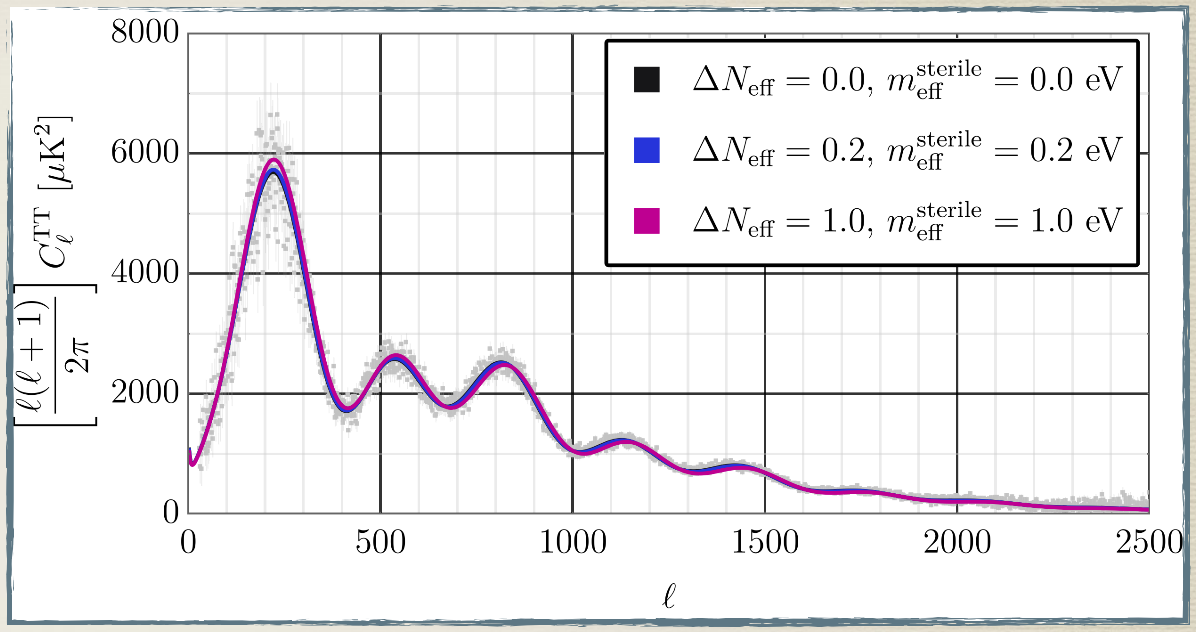
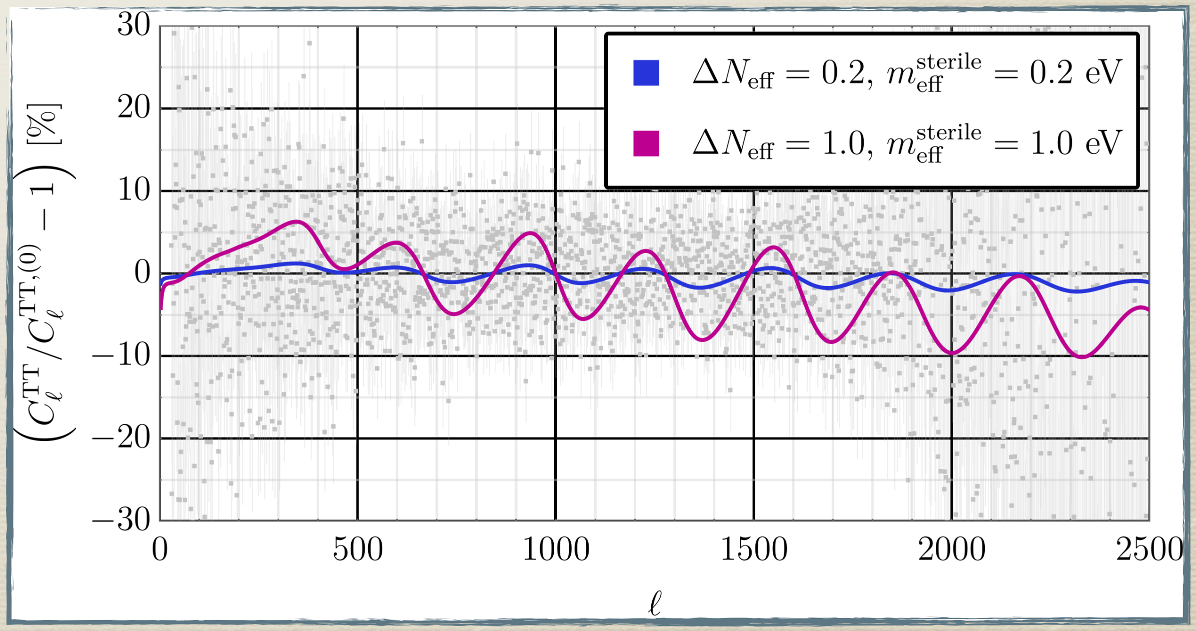


# Neutrinos in the Early Universe

- Simplifying assumption: *two-neutrino fluid*

"Bloch vector"

$$\begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \longrightarrow \rho = \frac{1}{2} f_0 \left( P_0 + \vec{\sigma} \cdot \vec{P} \right)$$

$$\frac{dP_0}{dt} = R^{(a)}$$

$$\frac{d\vec{P}}{dt} = \left( \vec{B} + \vec{V}^{(a)} \right) \times \vec{P} - D^{(a)} \left( P_x \, \hat{x} + P_y \, \hat{y} \right) + R^{(a)} \, \hat{z}$$

$$\vec{B} = \left( \frac{\Delta m^2}{2p} \right) (\sin 2\theta, \, 0, \, -\cos 2\theta)$$

$$\vec{V}^{(a)} = \left( V_1^{(a)} + V_L^{(a)} \right) \hat{z}$$

$$V_1^{(a)} = -\frac{7\pi^2 G_F}{45\sqrt{2} M_Z^2} p \, T^4 \left( n_{\nu_a} + n_{\overline{\nu}_a} \right) g_a$$

$$V_L^{(a)} = \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 L^{(a)}$$

$$\begin{aligned} L^{(e)} &= \left( \frac{1}{2} + 2\sin^2\theta_W \right) L_e \\ &\quad + \left( \frac{1}{2} - 2\sin^2\theta_W \right) L_p - \frac{1}{2} L_n \\ &\quad + 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \\ L^{(\mu,\tau)} &= L^{(e)} - L_e - L_{\nu_e} + L_{\nu_\mu,\nu_\tau} \end{aligned}$$

S. Hannestad, *et al.*, JCAP 1207, 025 (2012)

# Neutrinos in the Early Universe

* Define quantities convenient for numerical evaluation; new corresponding equations of motion:

$$P_i^{\pm} = P_i \pm \overline{P}_i$$
$$P_a^{\pm} = P_0^{\pm} + P_z^{\pm}$$
$$P_s^{\pm} = P_0^{\pm} - P_z^{\pm}$$

$$\begin{aligned}
\frac{dP_a^{\pm}}{dt} &= B_x P_y^{\pm} + \Gamma_a \left(2f_{\rm eq}^{\pm}/f_0 - P_a^{\pm}\right) \\
\frac{dP_s^{\pm}}{dt} &= -B_x P_y^{\pm} \\
\frac{dP_x^{\pm}}{dt} &= -(B_z + V_1^{(a)})P_y^{\pm} - V_L^{(a)} P_y^{\mp} - D^{(a)} P_x^{\pm} \\
\frac{dP_y^{\pm}}{dt} &= (B_z + V_1^{(a)})P_x^{\pm} + V_L^{(a)} P_x^{\mp} - \frac{1}{2} B_x \left(P_a^{\pm} - P_s^{\pm}\right) - D^{(a)} P_y^{\pm}
\end{aligned}$$

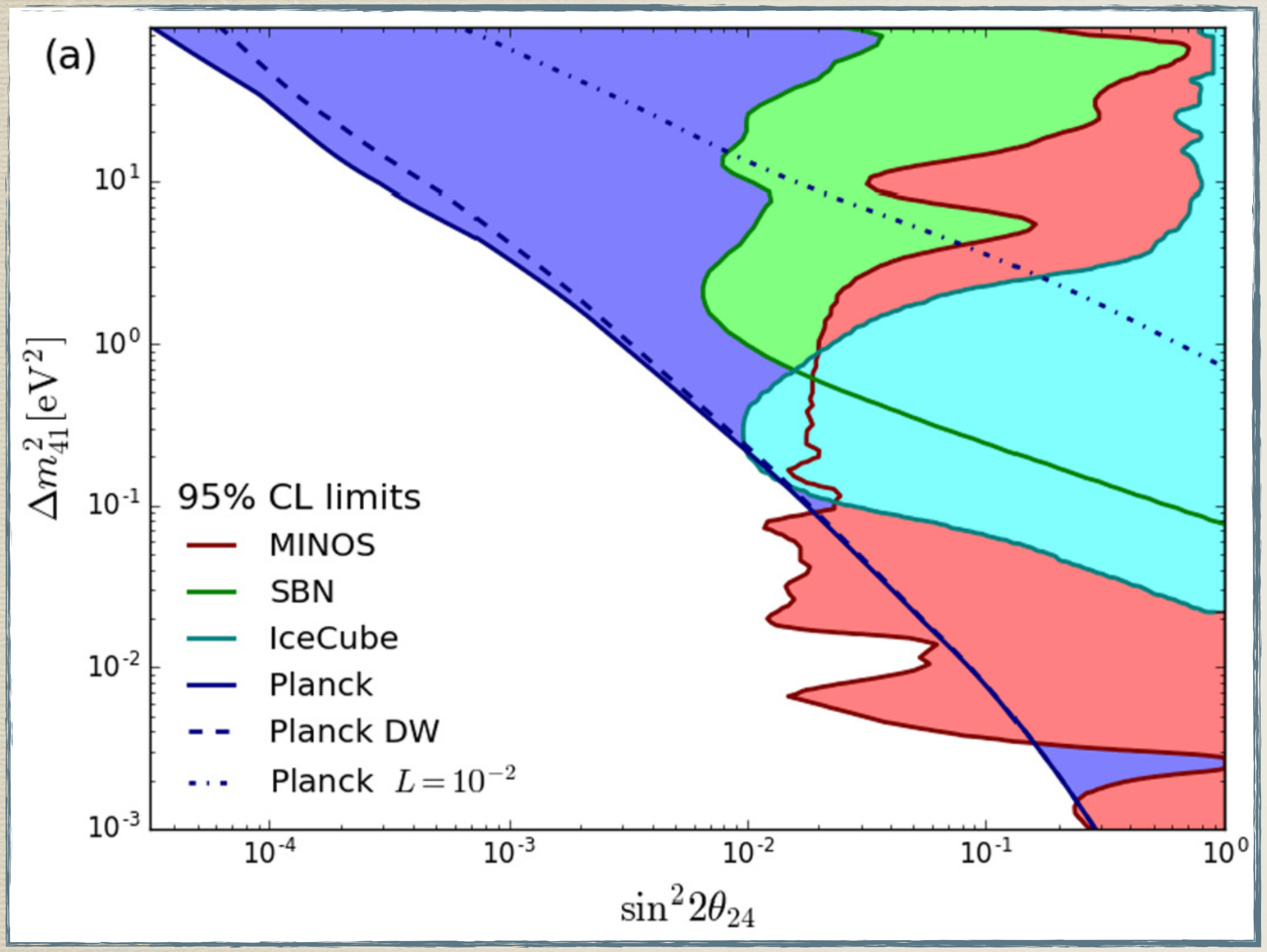
* Calculate observables via:

$$\Delta N_{\rm eff} = \frac{\int dx\, x^3 f_{\rm eq}(x,\mu{=}0)\, P_s^{+}(x)}{4 \int dx\, x^3 f_{\rm eq}(x,\mu{=}0)}$$

$$m_{\rm sterile}^{\rm eff} = (\Delta N_{\rm eff})^{3/4} \sqrt{\Delta m_{41}^2}$$

S. Hannestad, *et al.*, JCAP 1207, 025 (2012)

# Previous Work




S. Bridle, *et al.*, Phys. Lett. B764, 322 (2017);
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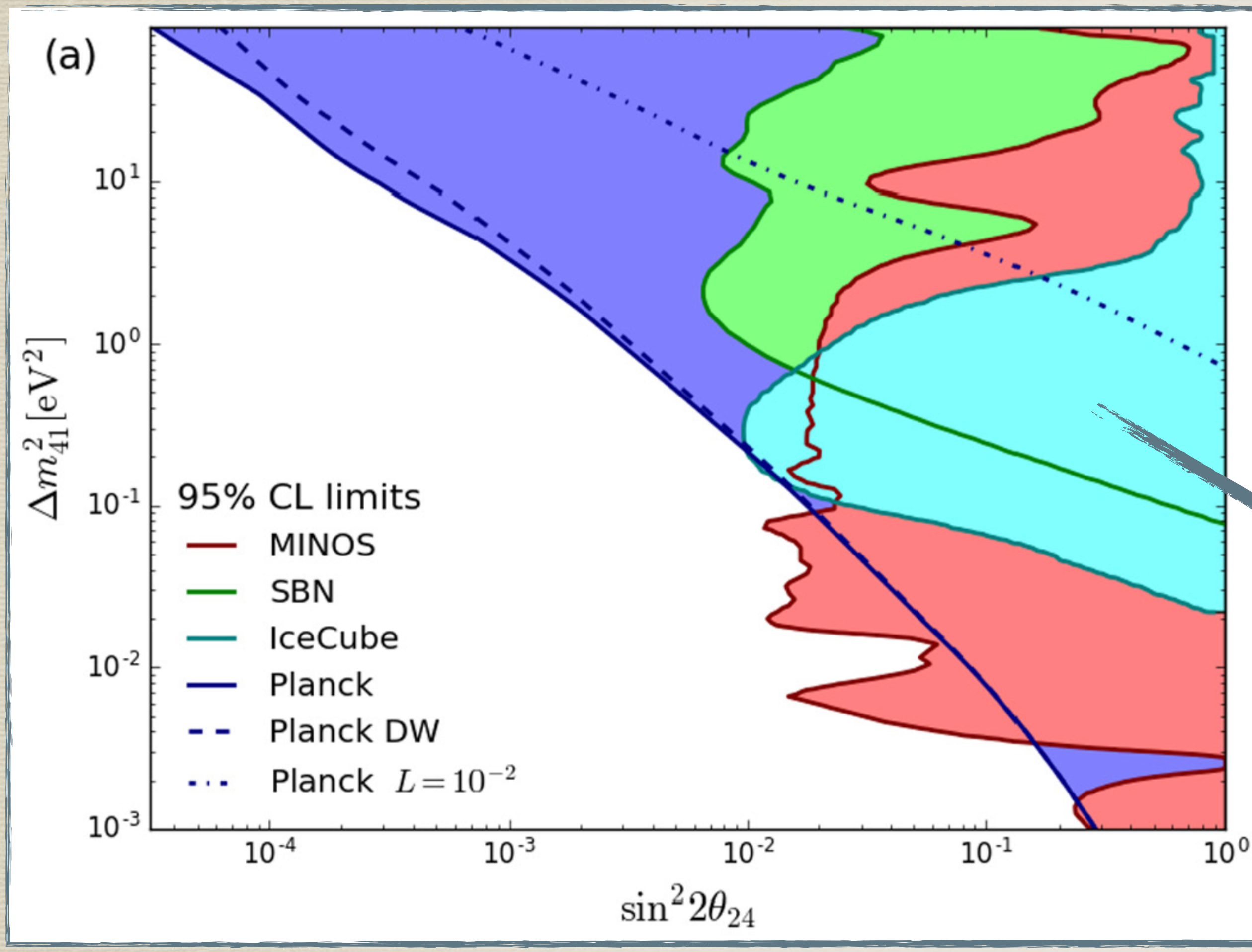
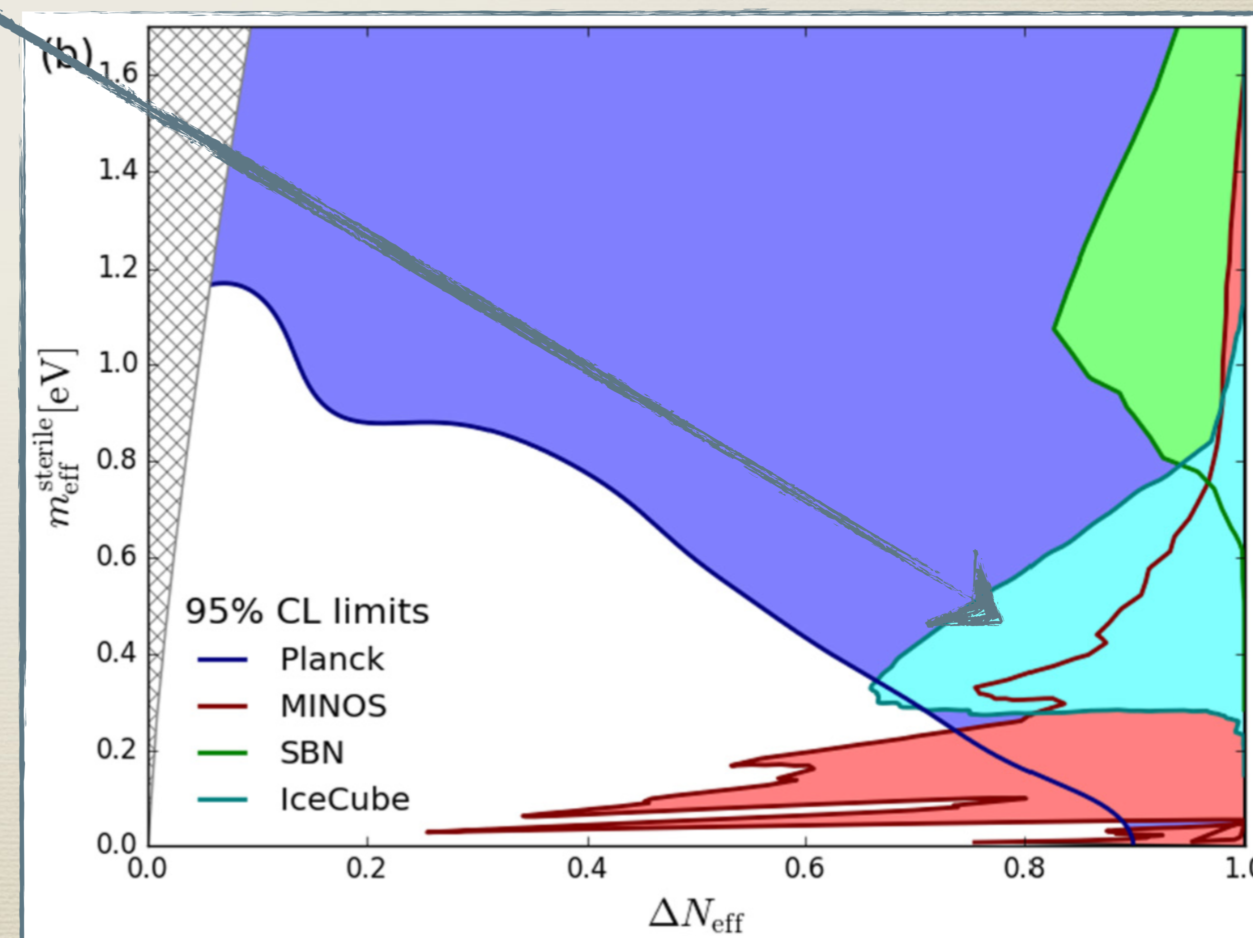



Use LASAGNA module to translate points in *oscillation* parameter space into *cosmology* parameter space

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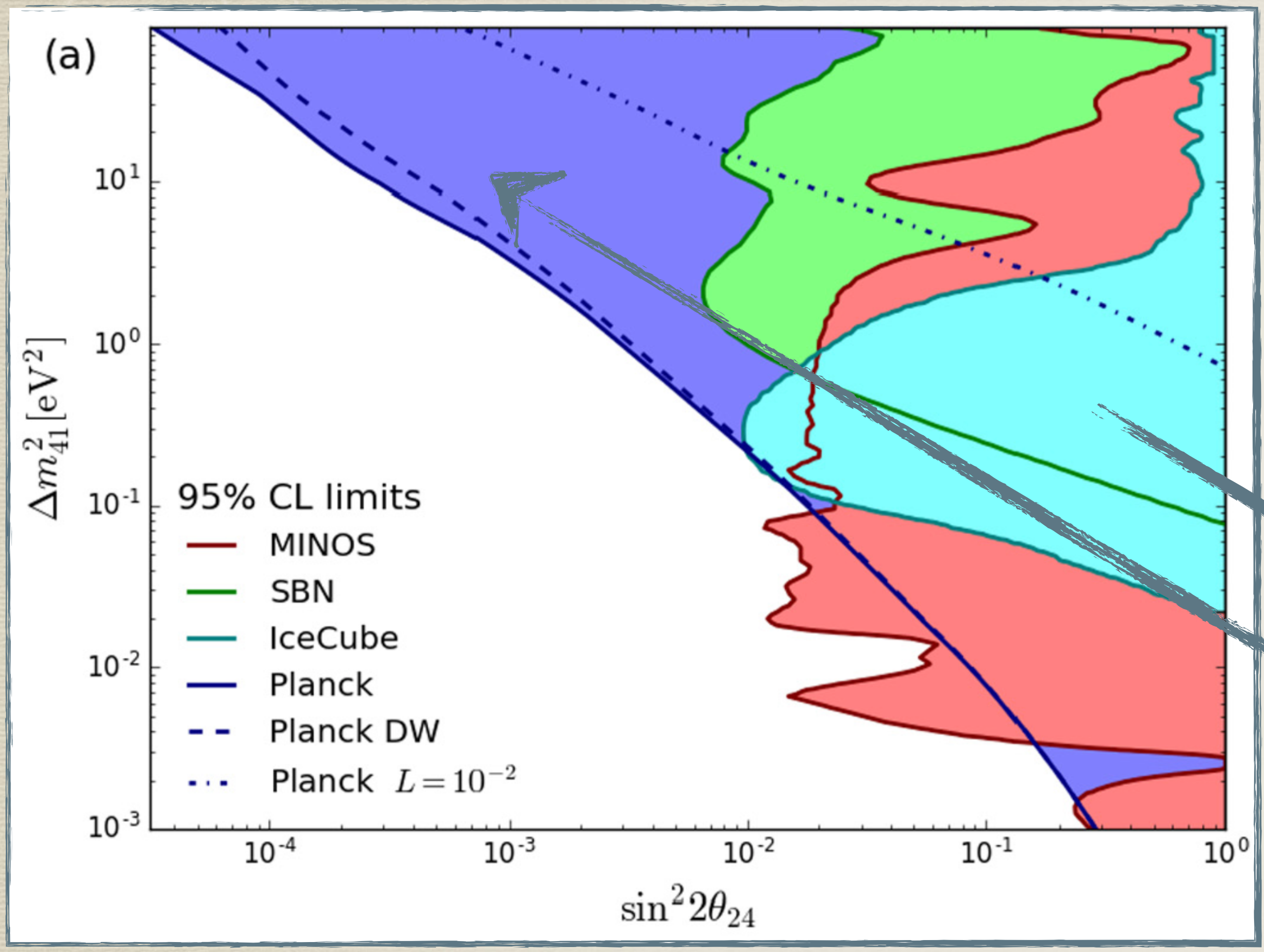


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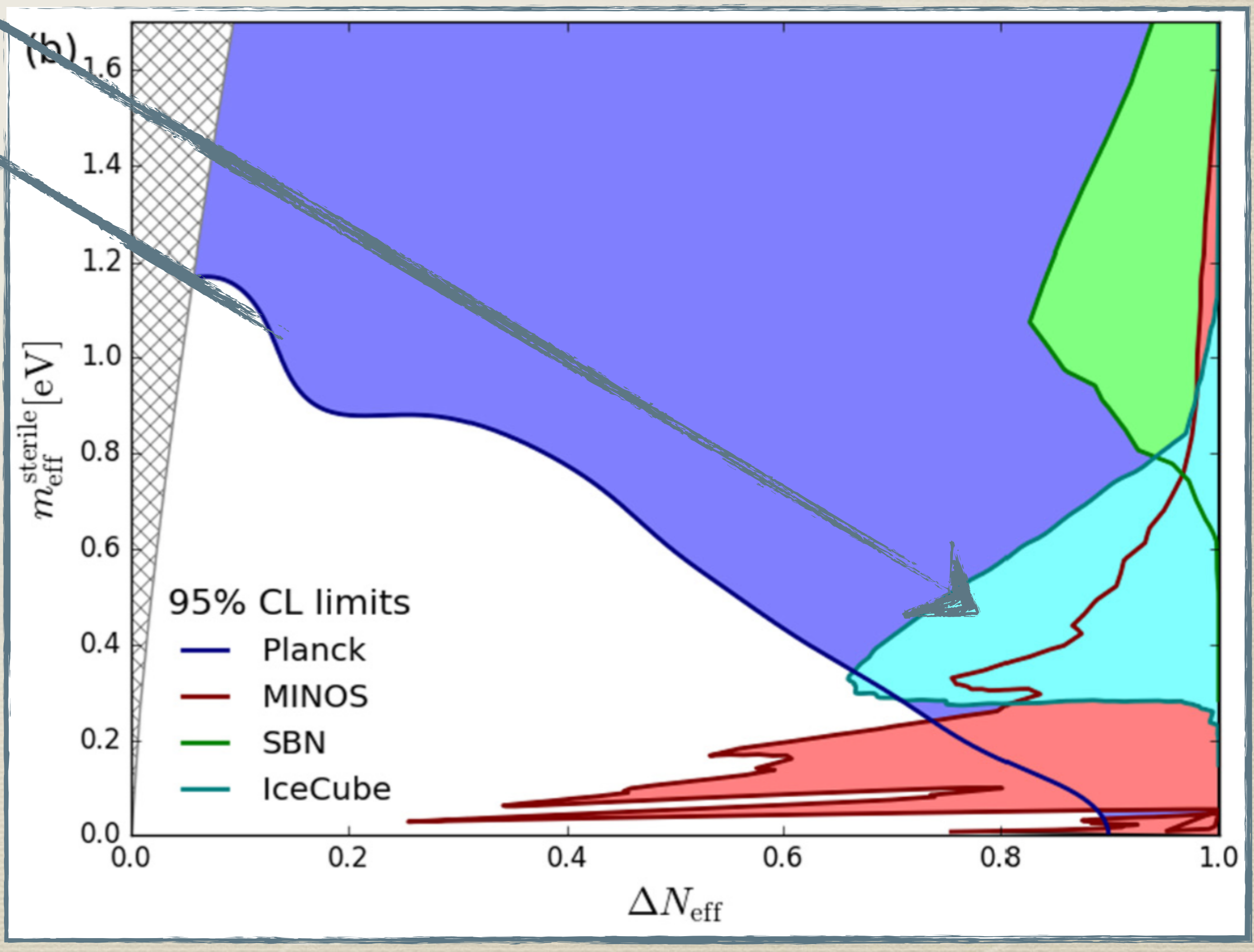


This relation depends on the *initial lepton number asymmetry*!

S. Bridle, *et al.*, Phys. Lett. B764, 322 (2017);
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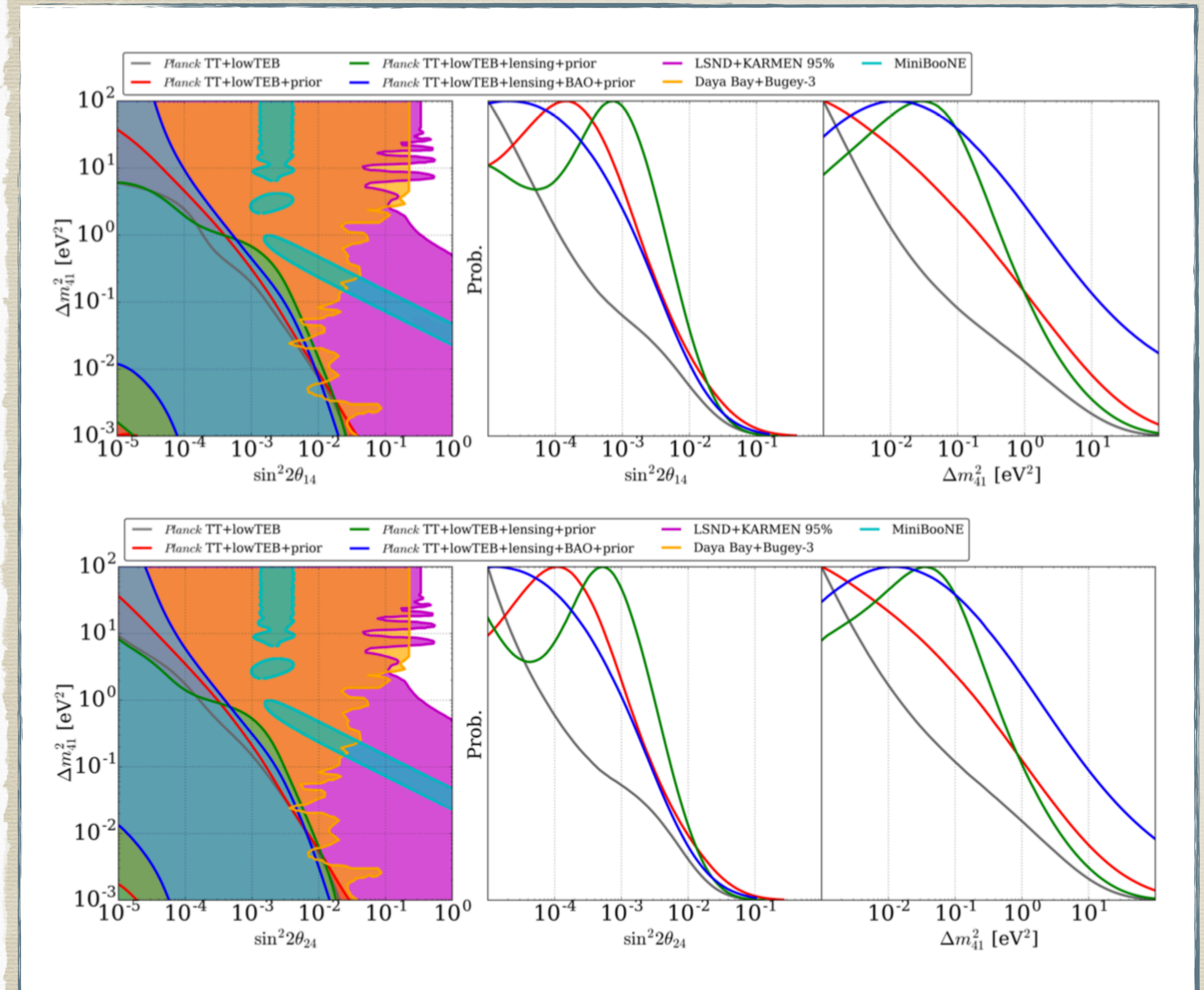


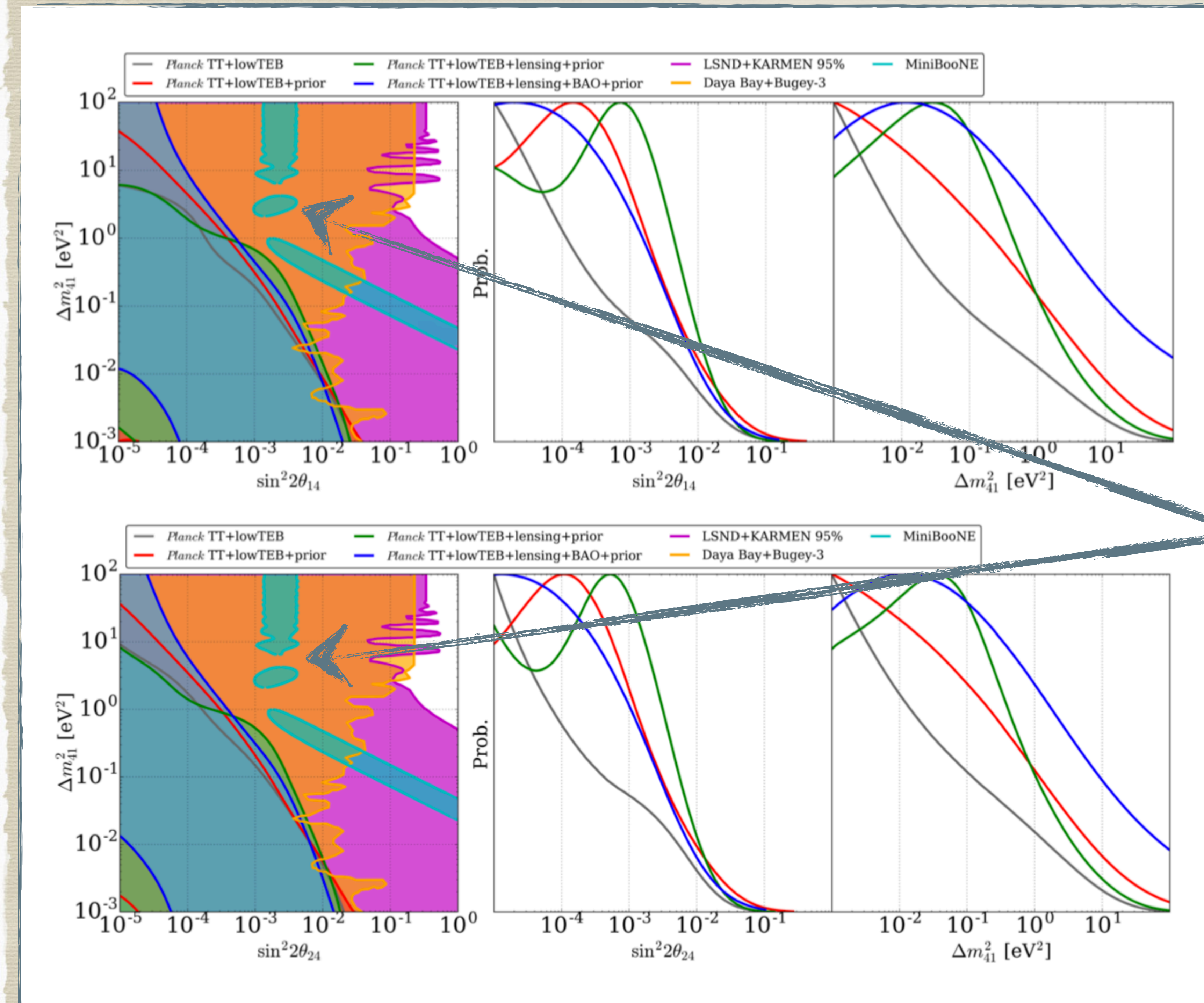

Essentially what we want to do, but in reverse!

<u>Two critiques:</u>

1. MiniBooNE probes neither of these spaces
2. These bounds only constrain $\theta_{14}$

A. Knee, *et al.*, arXiv:1812.02102 [astro-ph.CO];

# Previous Work

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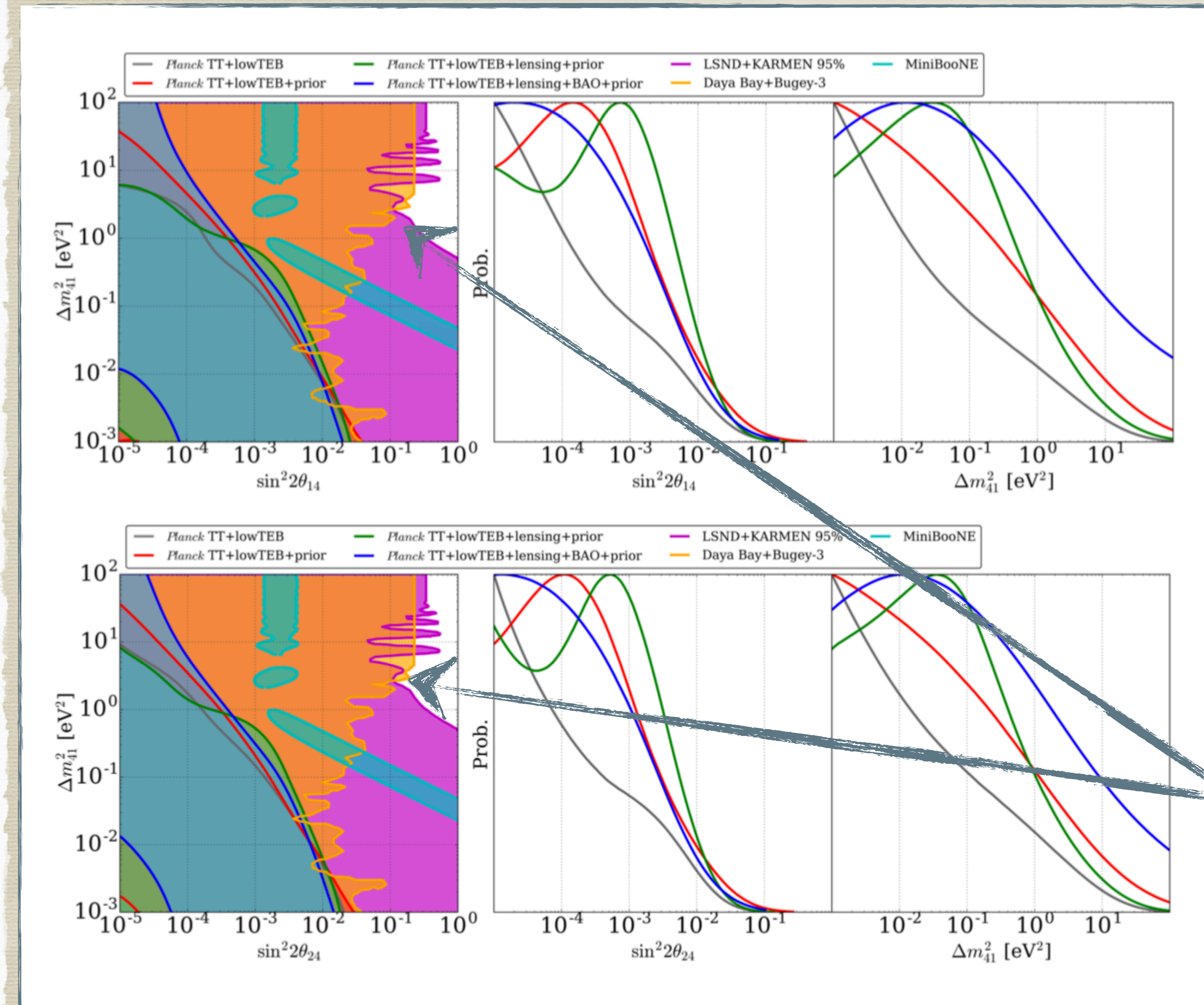


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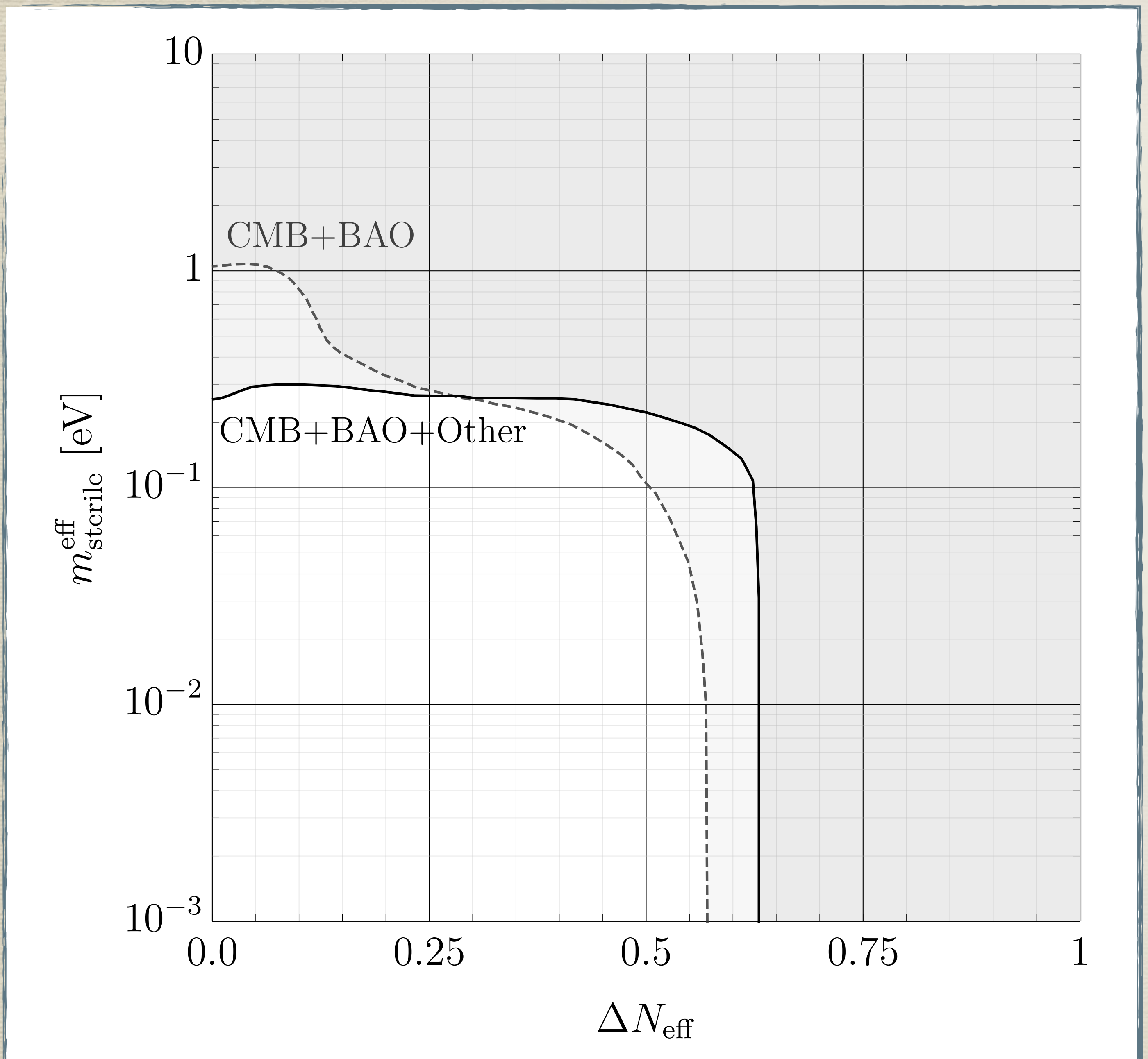
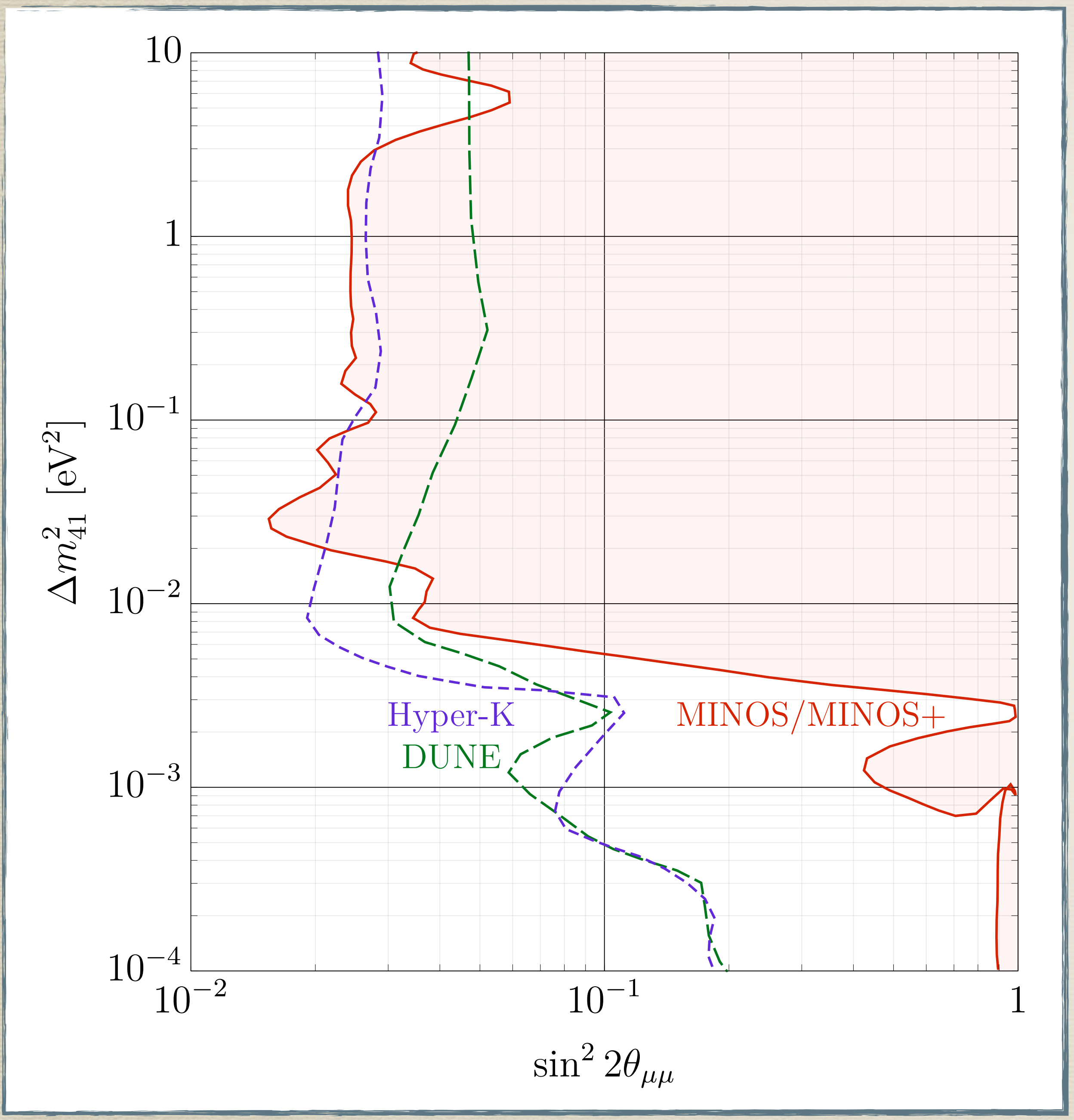
# Sterile Neutrino Cosmology




L. Feng, *et al.*, Eur. Phys. J. C77, 418 (2017)

- *"CMB+BAO"*:
  - Planck 2015 TT,TE,EE+lowP
  - BAO data (BOSS; 6dFGS; SDSS MGS)
- *"CMB+BAO+Other"*:
  - Hubble constant
  - Planck cluster & lensing data
  - CFHTLenS weak lensing

# Accelerator Neutrinos

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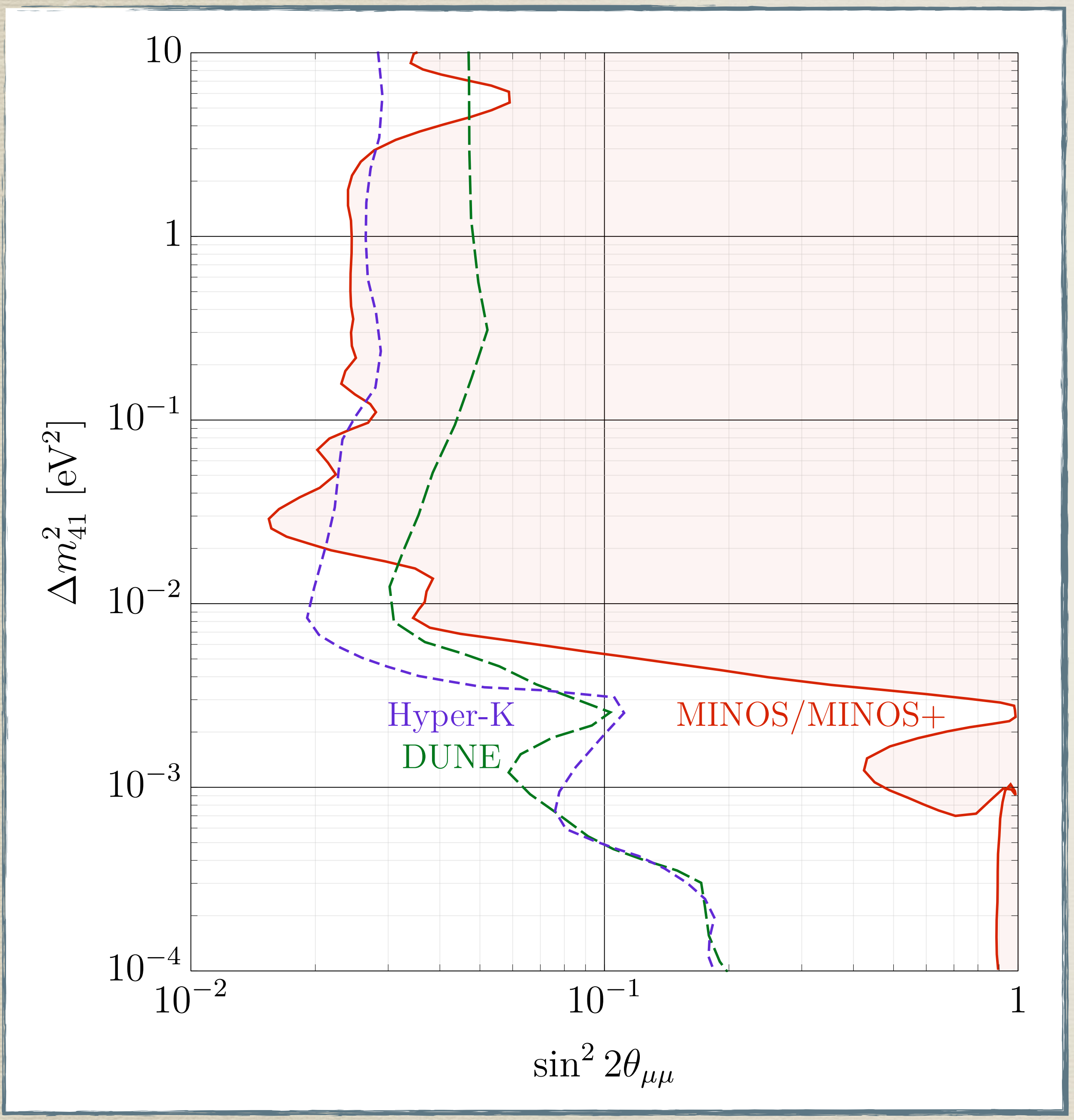


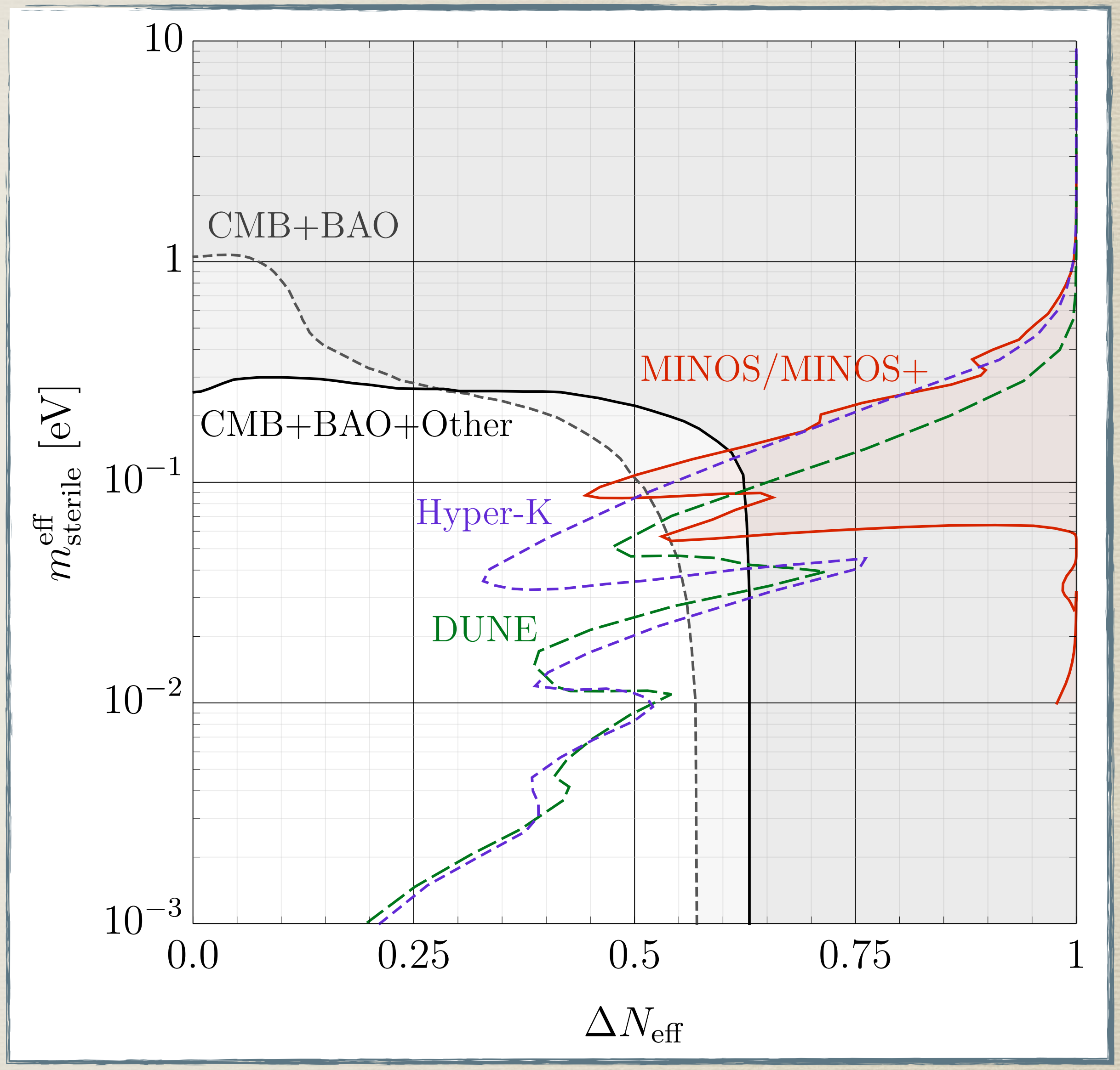


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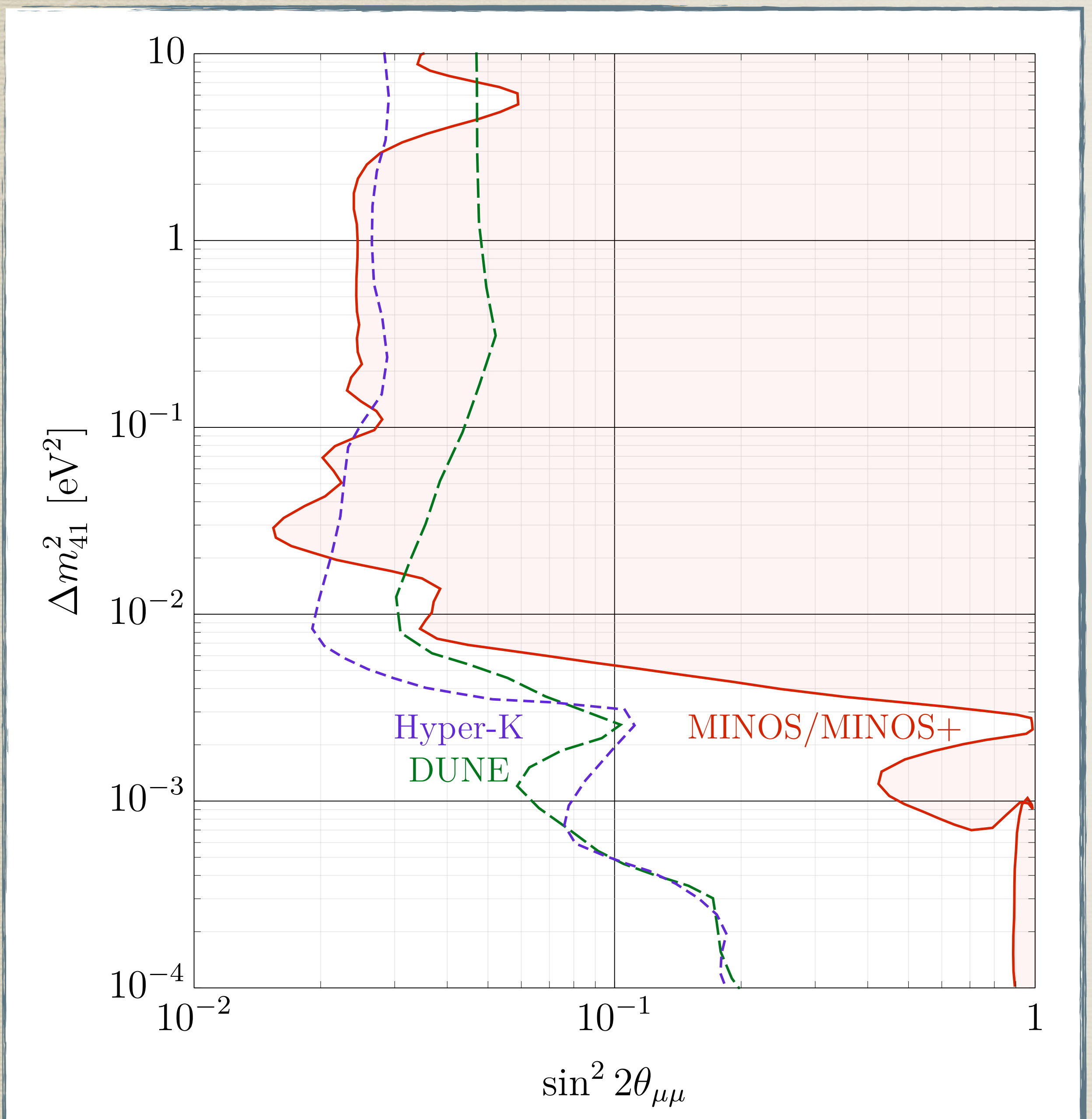


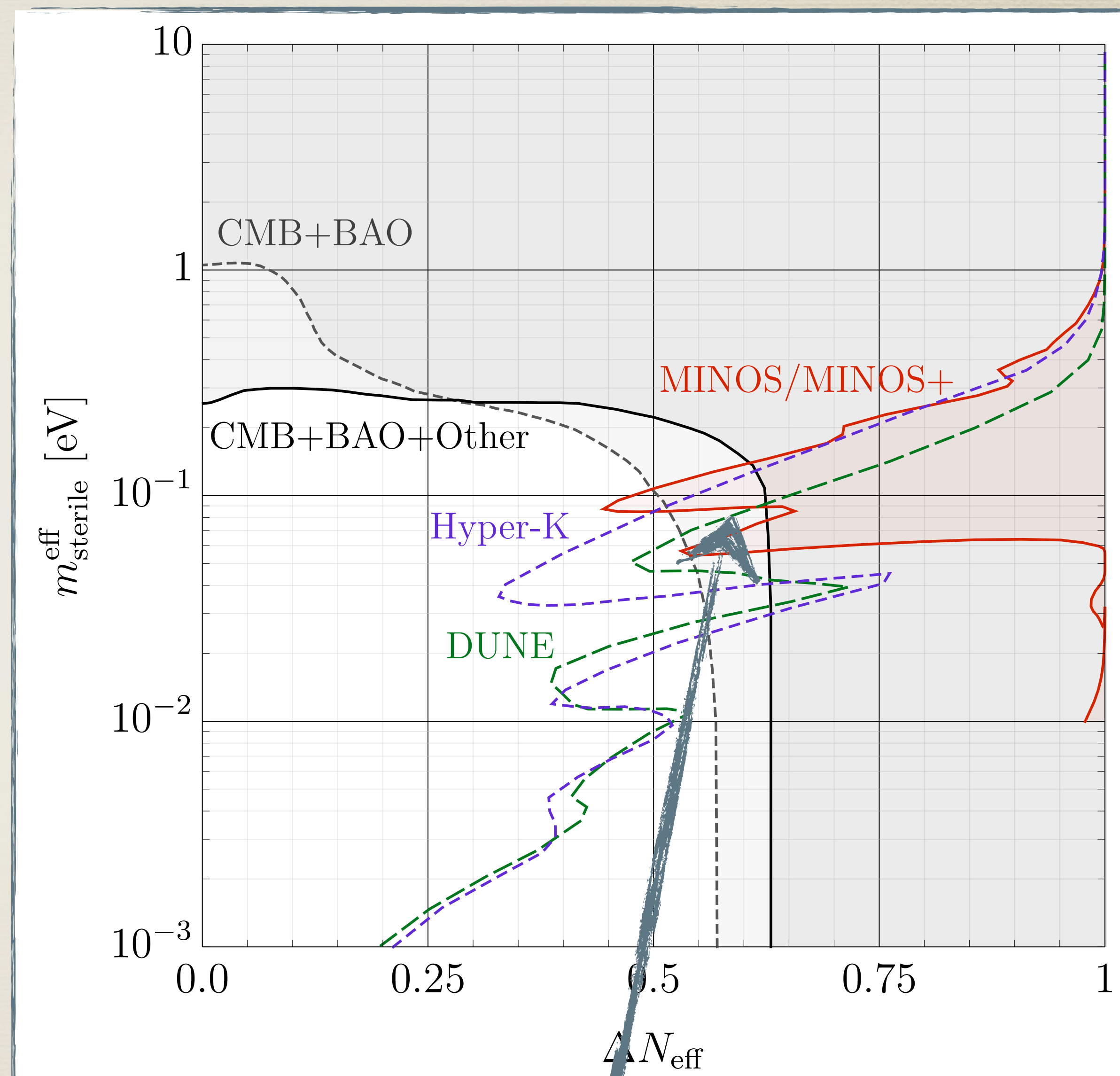


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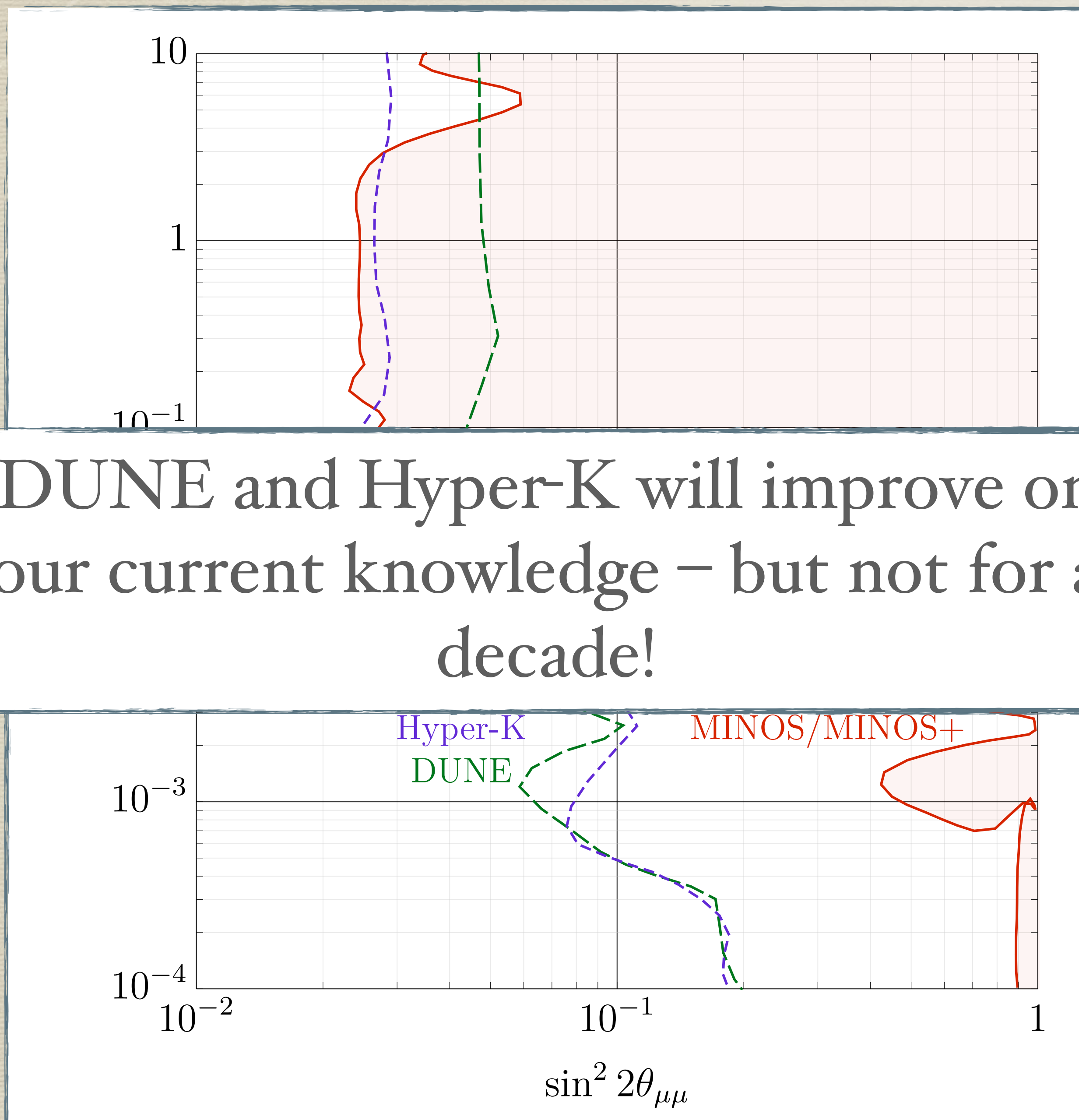
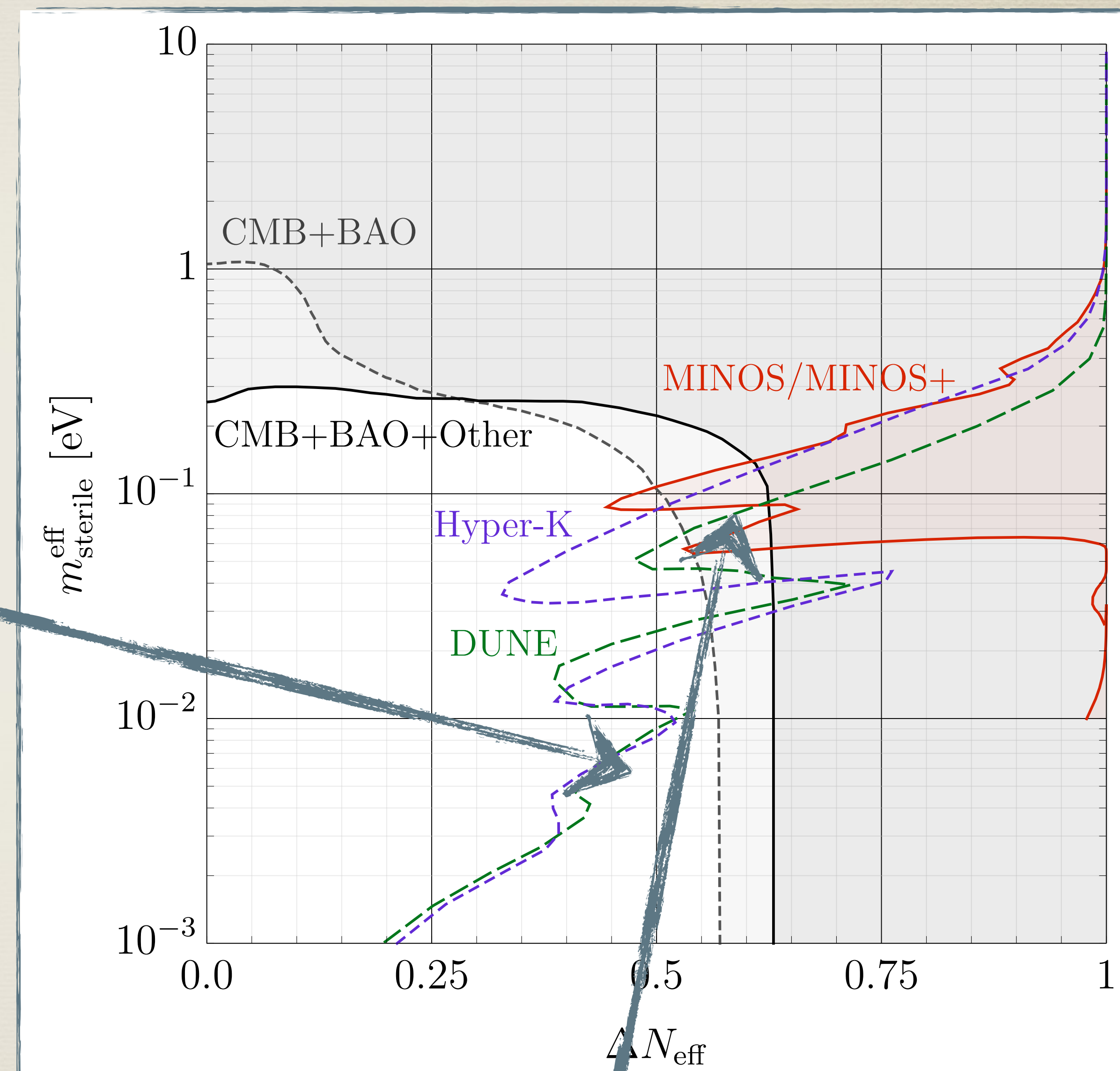



DUNE and Hyper-K will improve on our current knowledge – but not for a decade!

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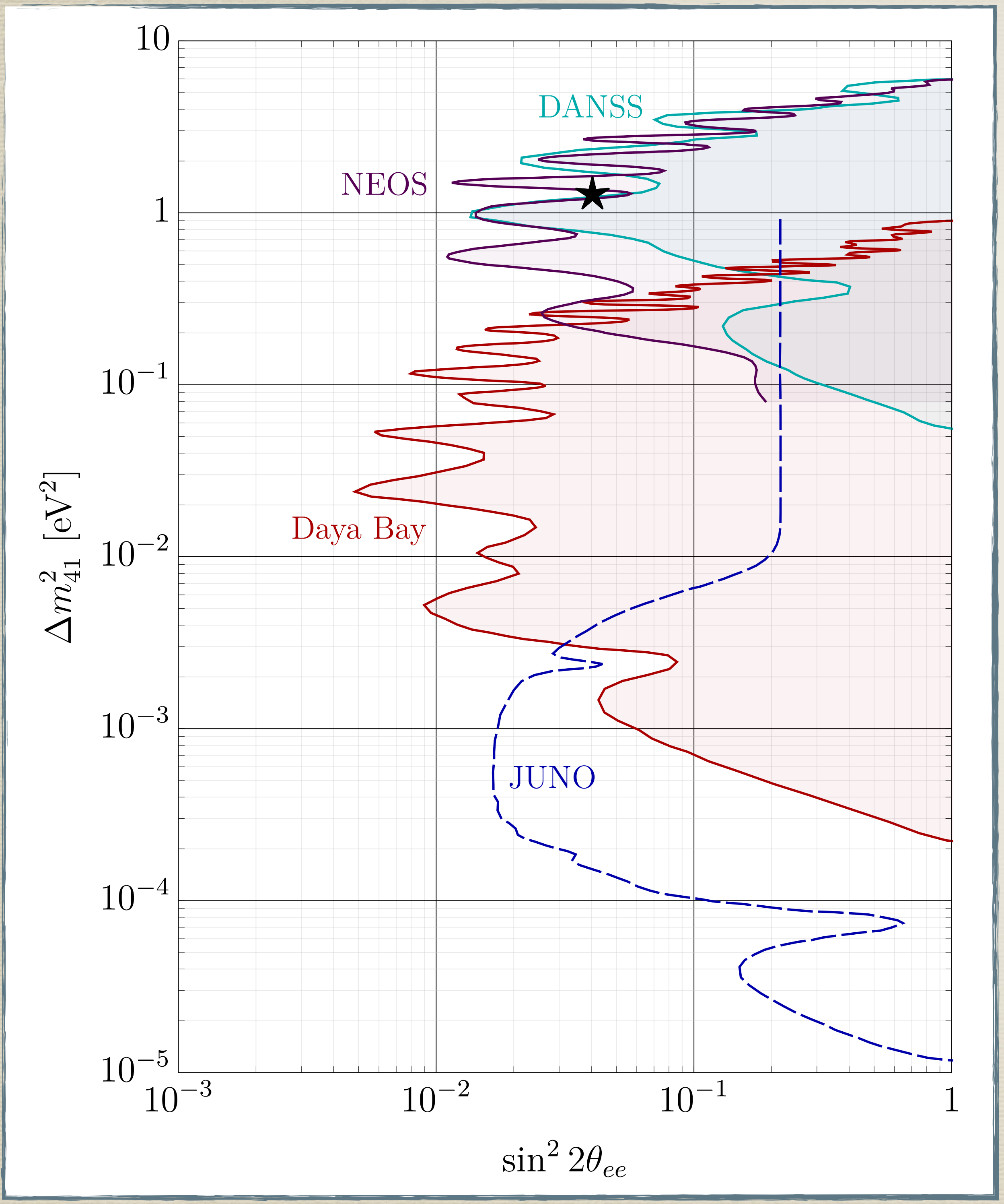
# Reactor Antineutrinos




M. Dentler, *et al.*, JHEP 08, 010 (2018)

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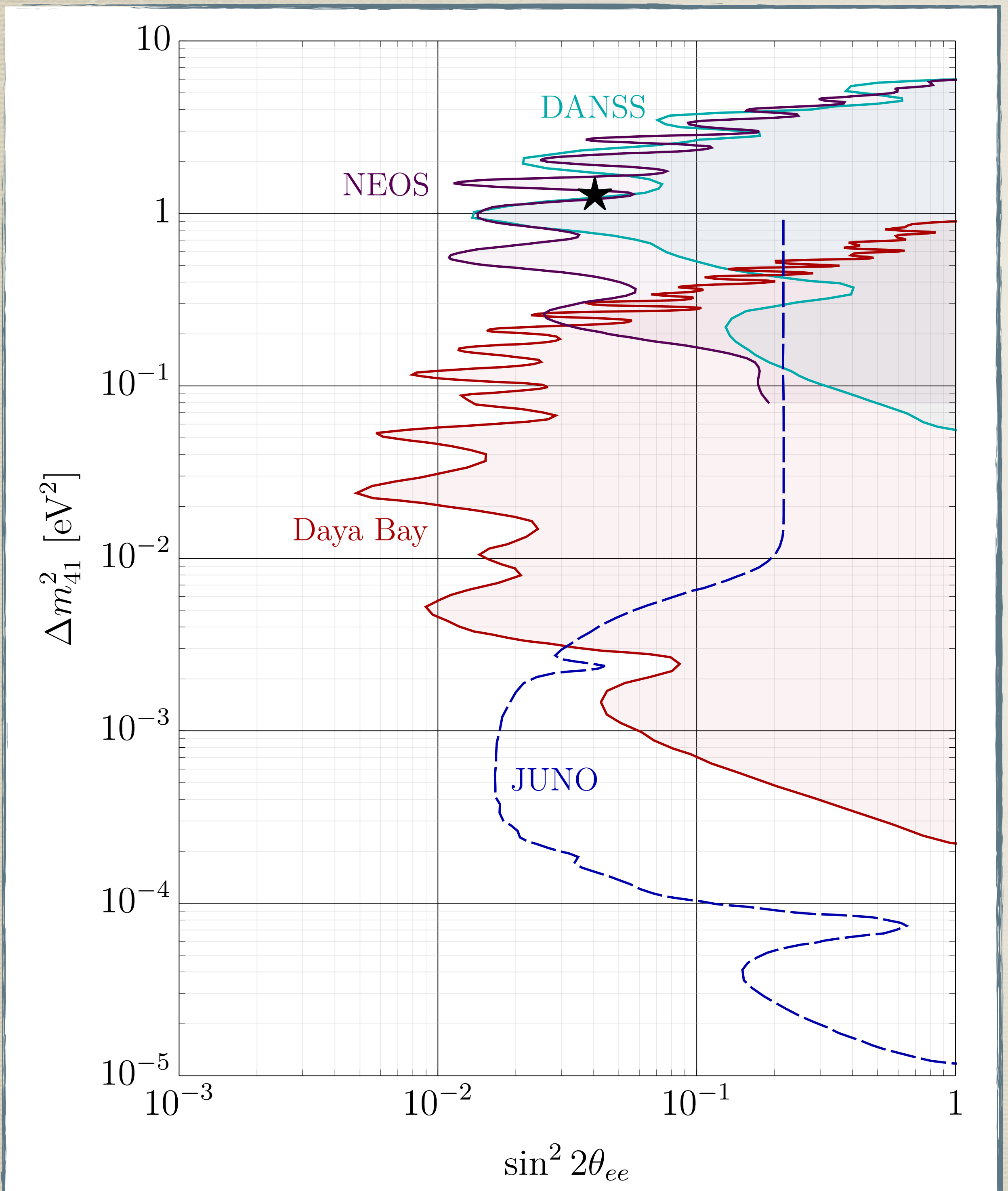


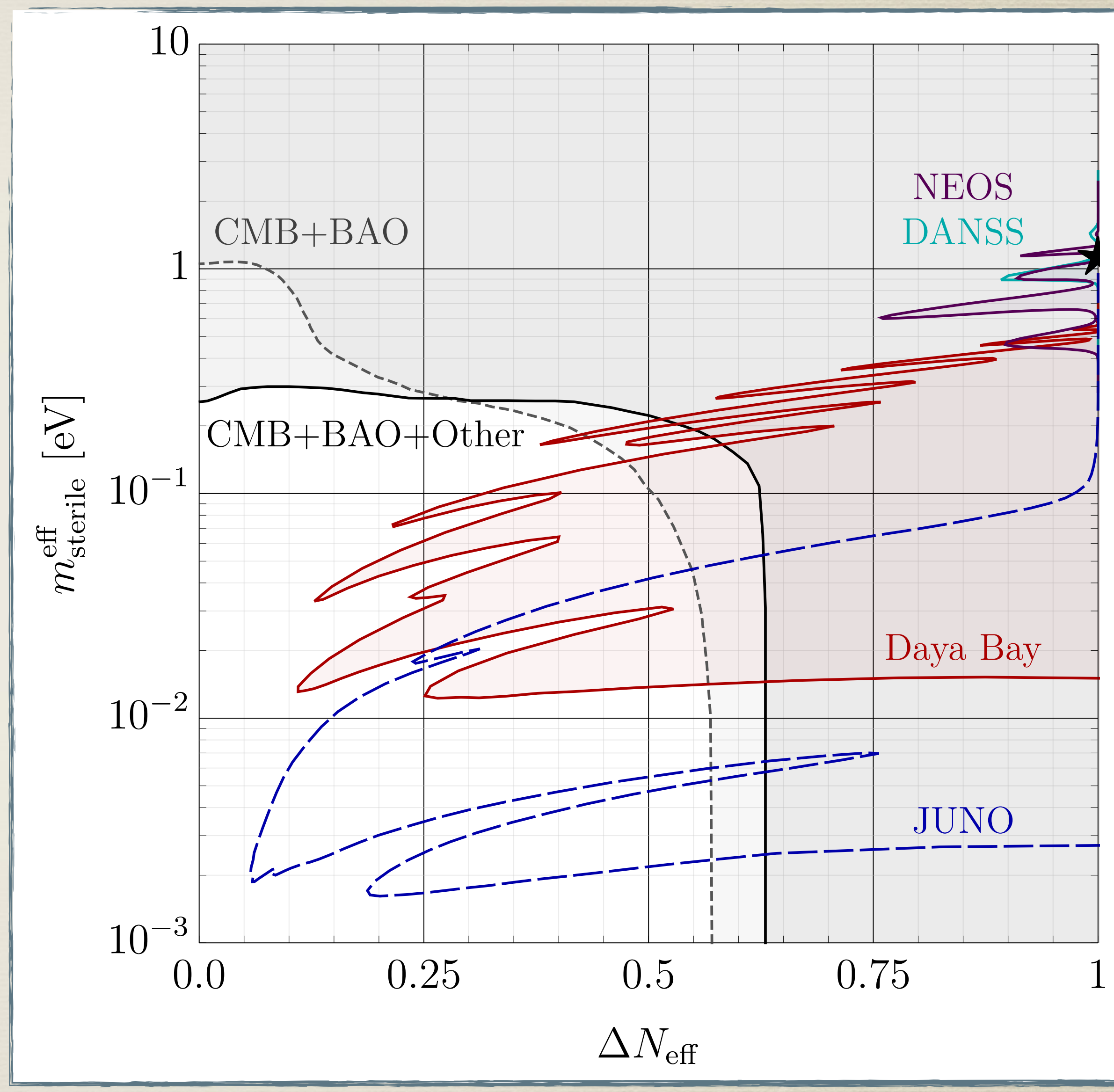


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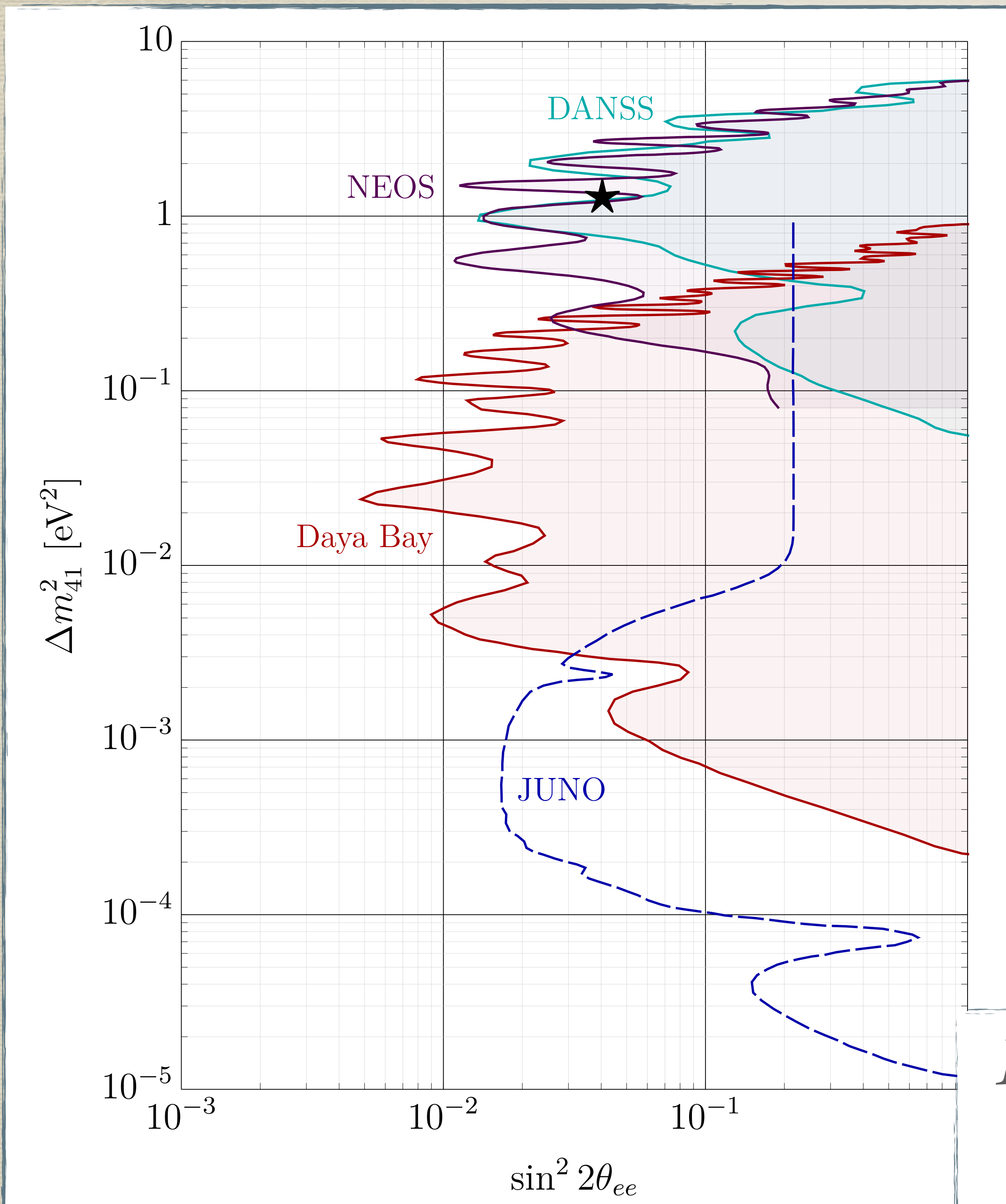
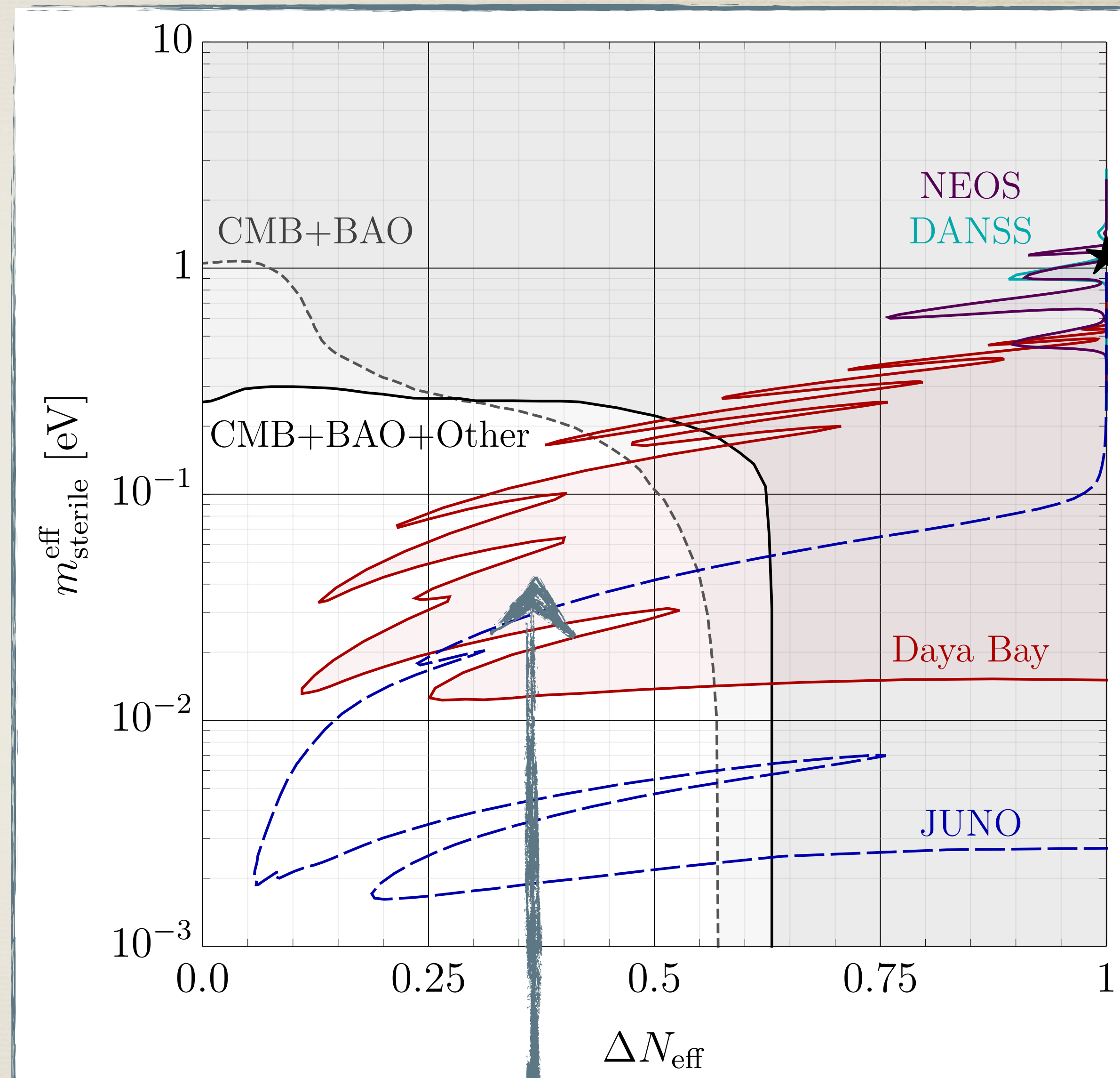
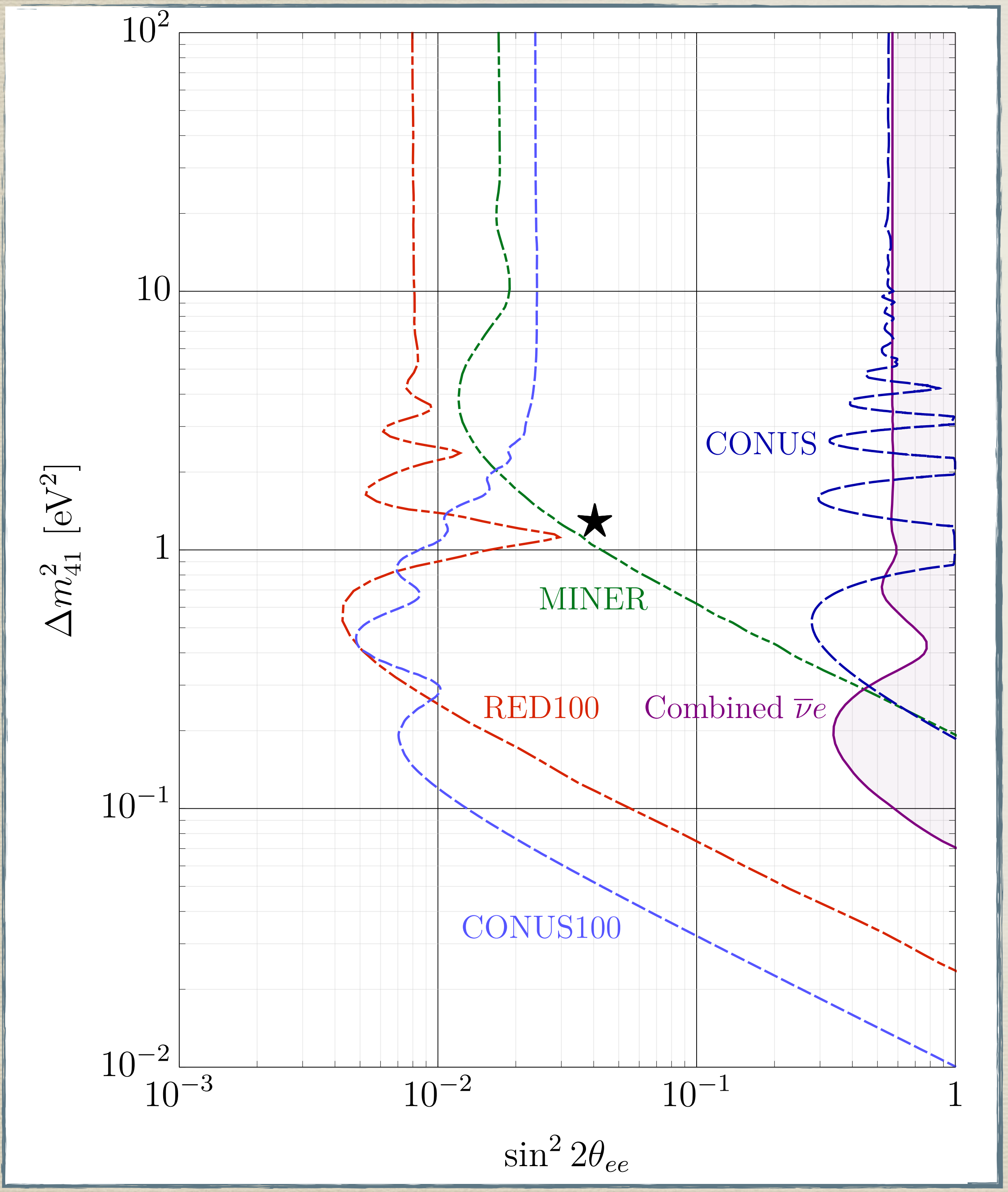



*Daya Bay can already probe parameter space to which astrophysical/cosmological experiments are insensitive!*

M. Dentler, *et al.*, JHEP 08, 010 (2018)

# Low-Threshold Experiments




B.C. Cañas, *et al.*, Phys. Lett. B776, 451 (2018)

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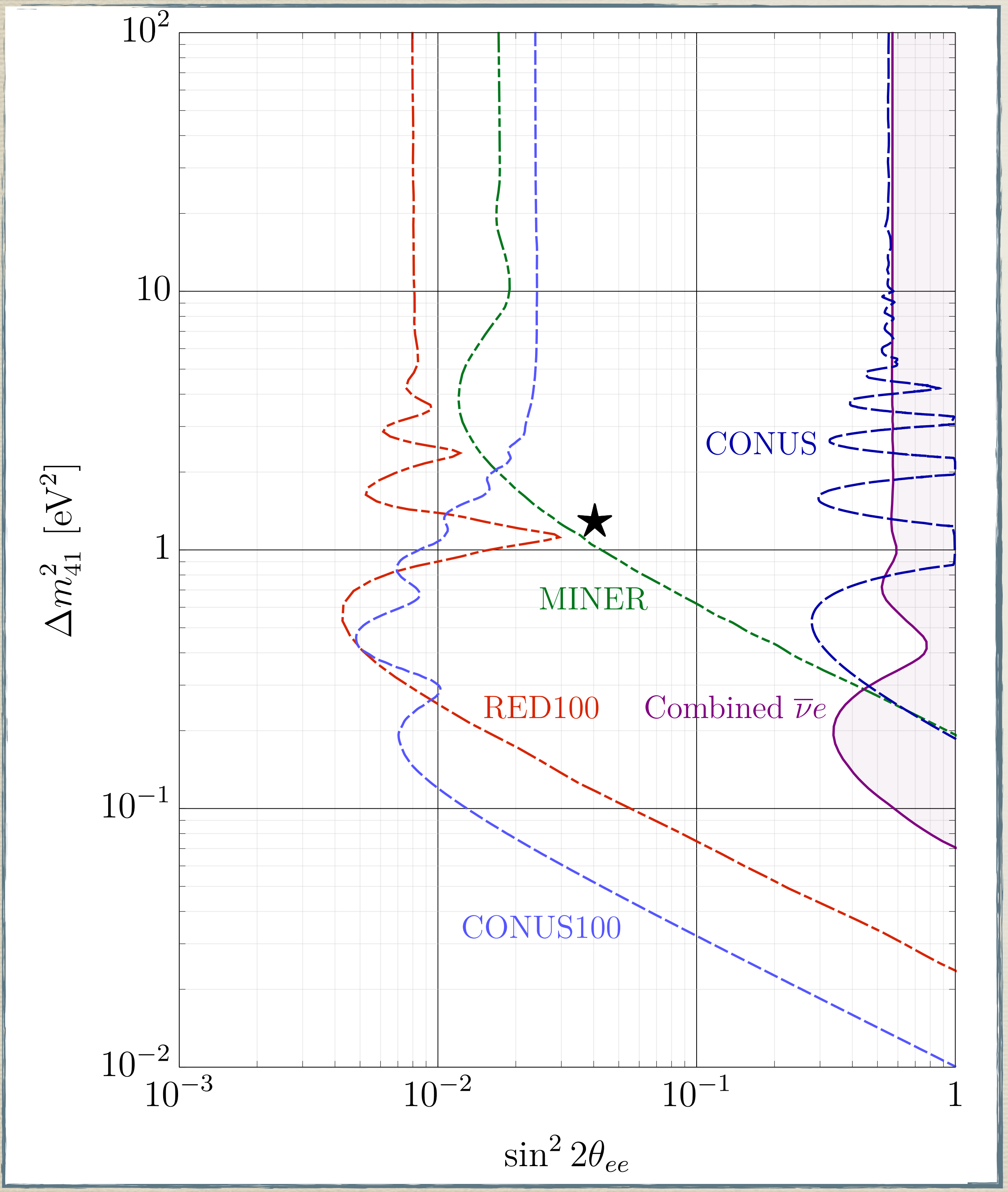


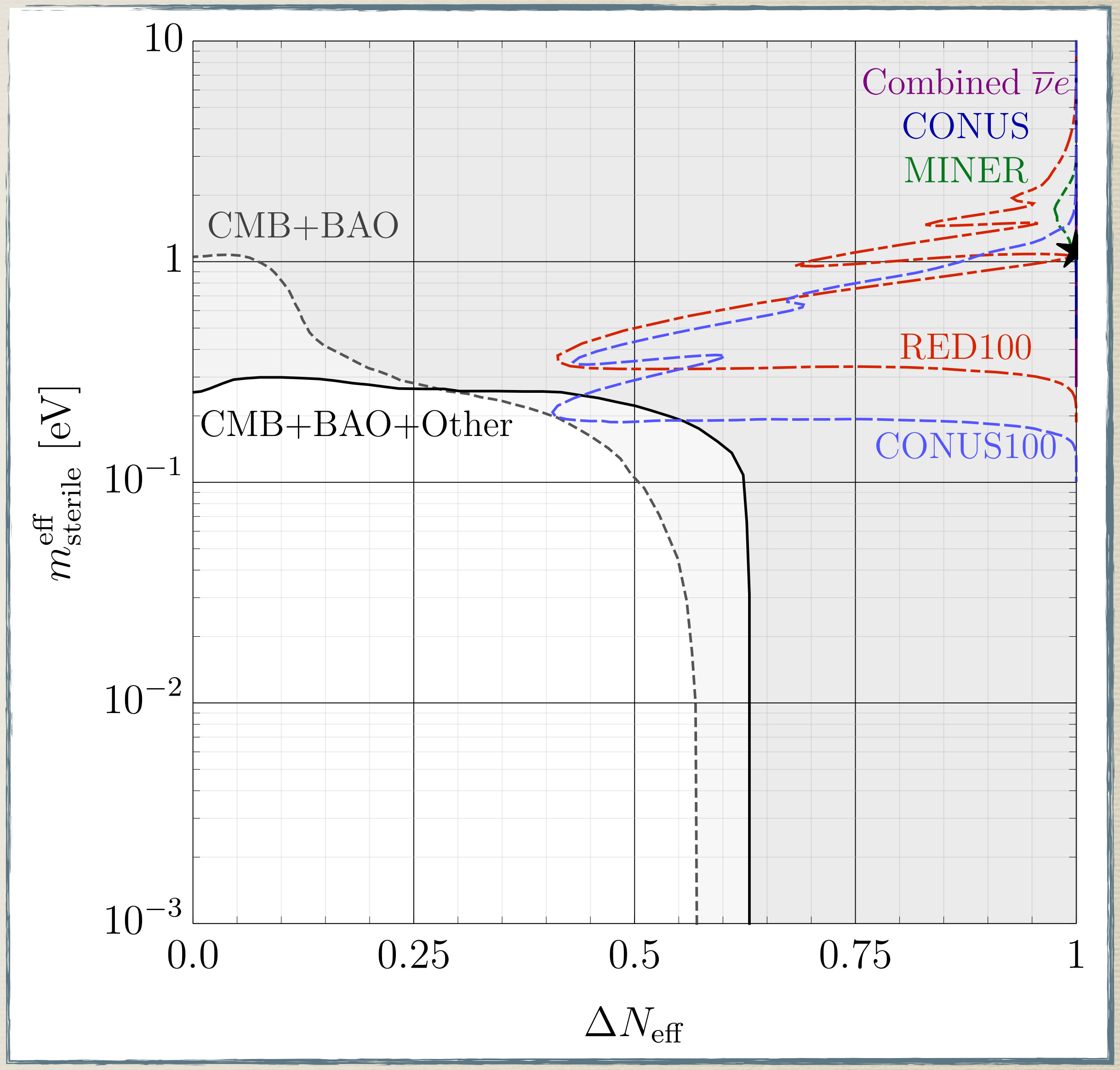


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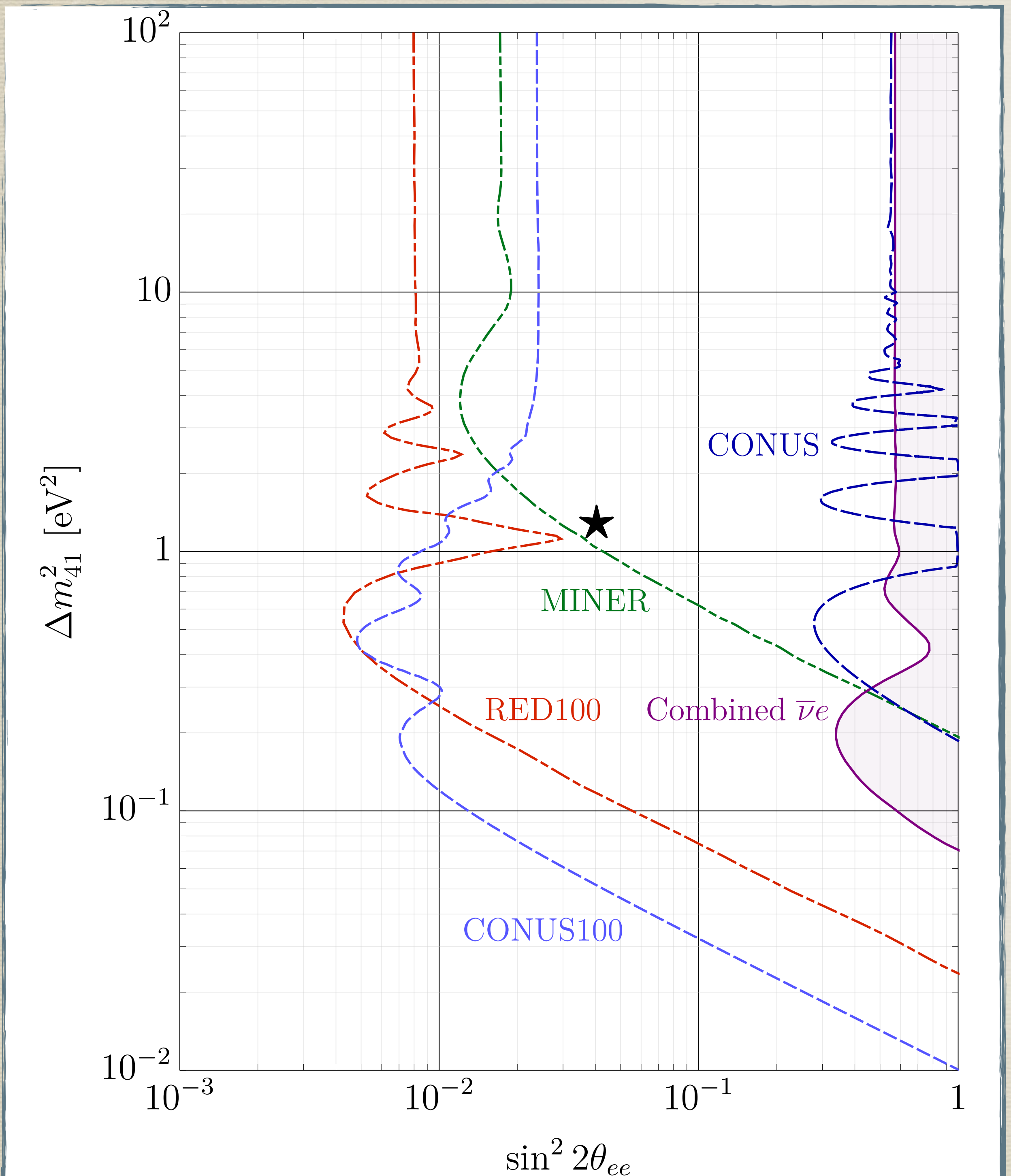


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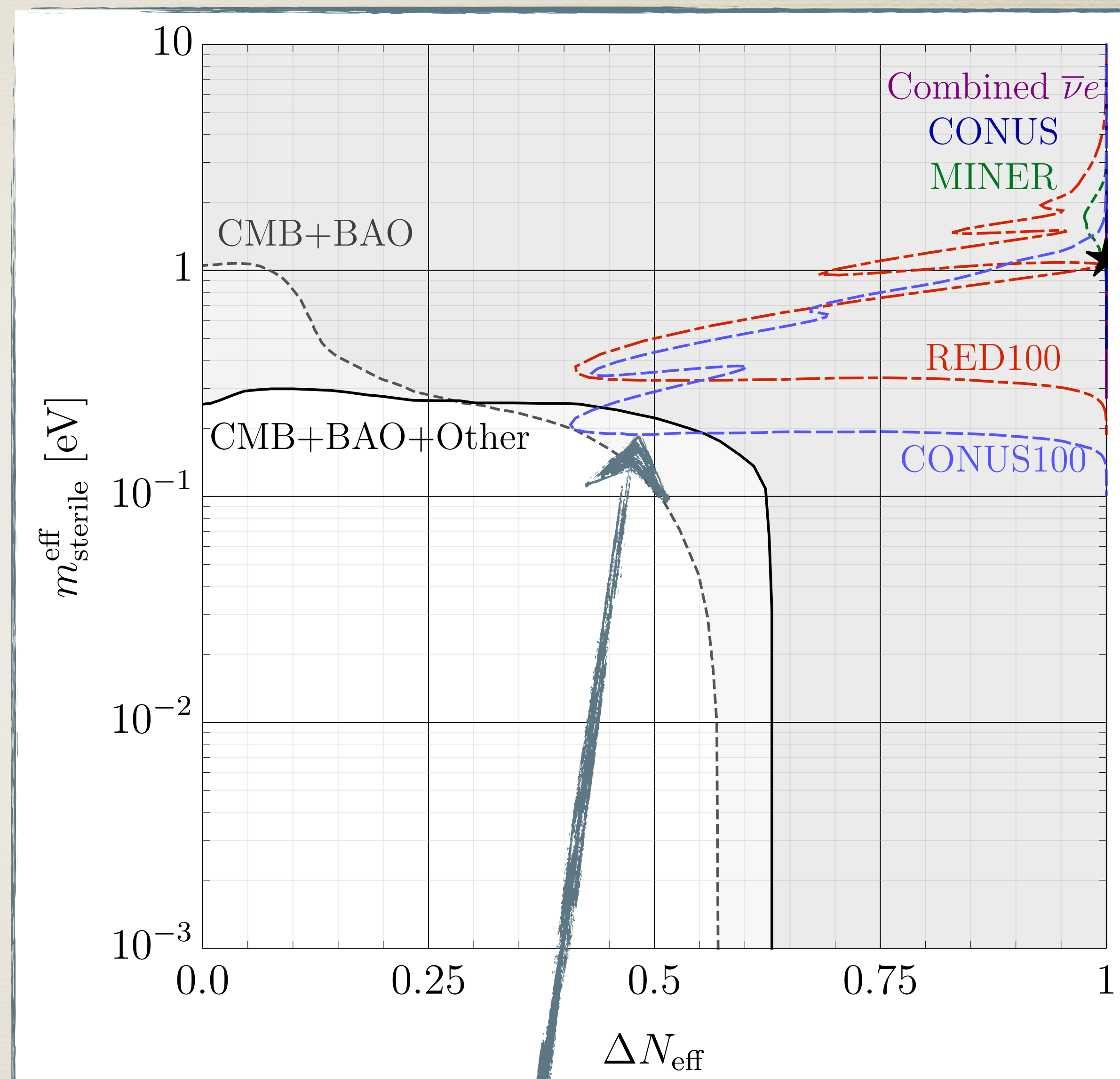



Even with aggressive assumptions, these experiments don't contribute to our knowledge of cosmology!

# Reconciling Reactor Anomaly with Cosmology

*Cosmological measurements very strongly disfavor the sterile-neutrino interpretation of the reactor anomaly. How to reconcile?*

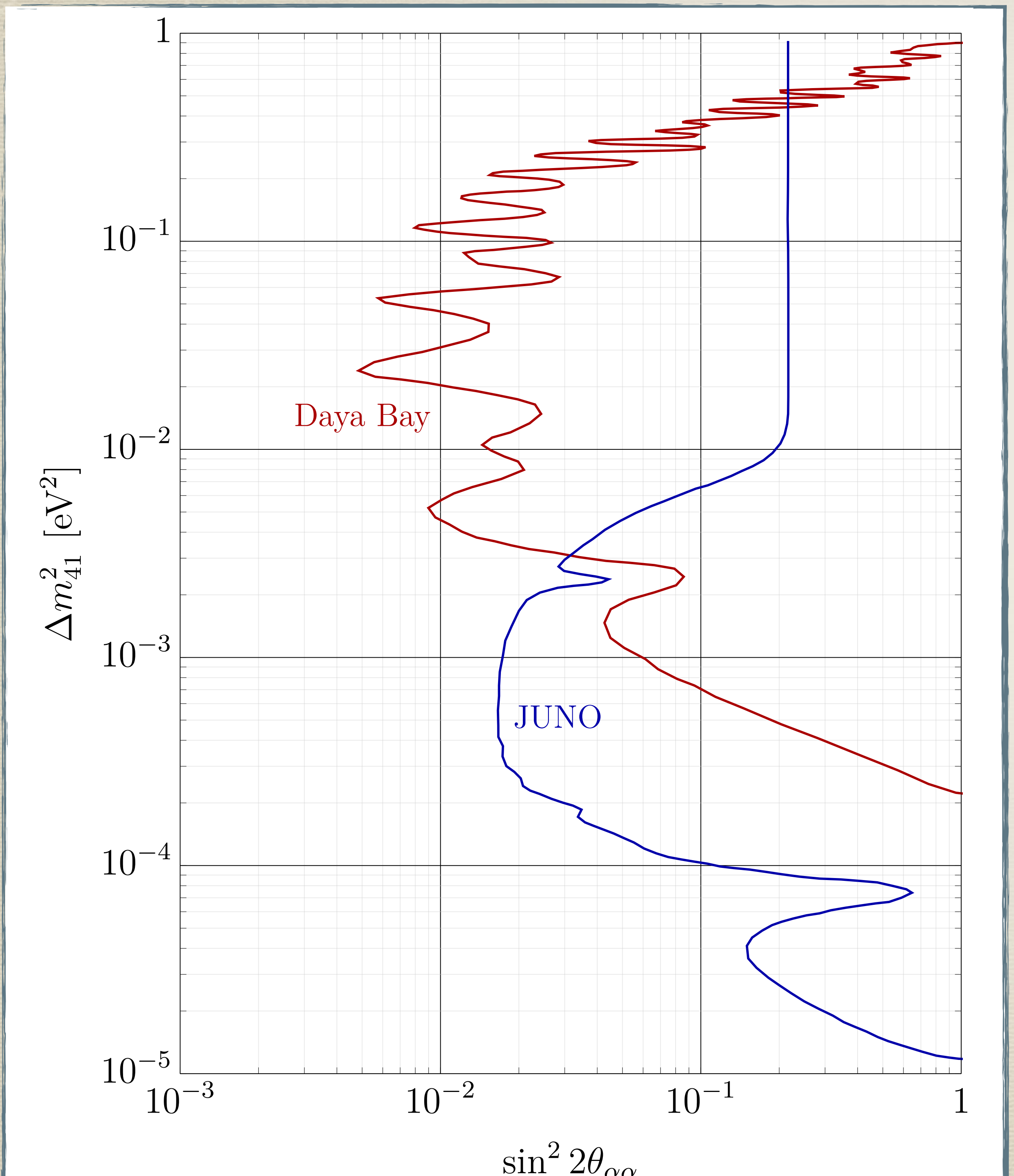
1. The reactor anomaly is an aberration
2. The two-neutrino framework misses essential physics
3. The initial lepton asymmetry of the Universe is large ( ~$10^{-3}$–$10^{-2}$)
4. Neutrinos have additional interactions → new matter potential (See N. Blinov, *et al.*, arXiv:1905.02727)
5. We've misunderstood something about cosmology

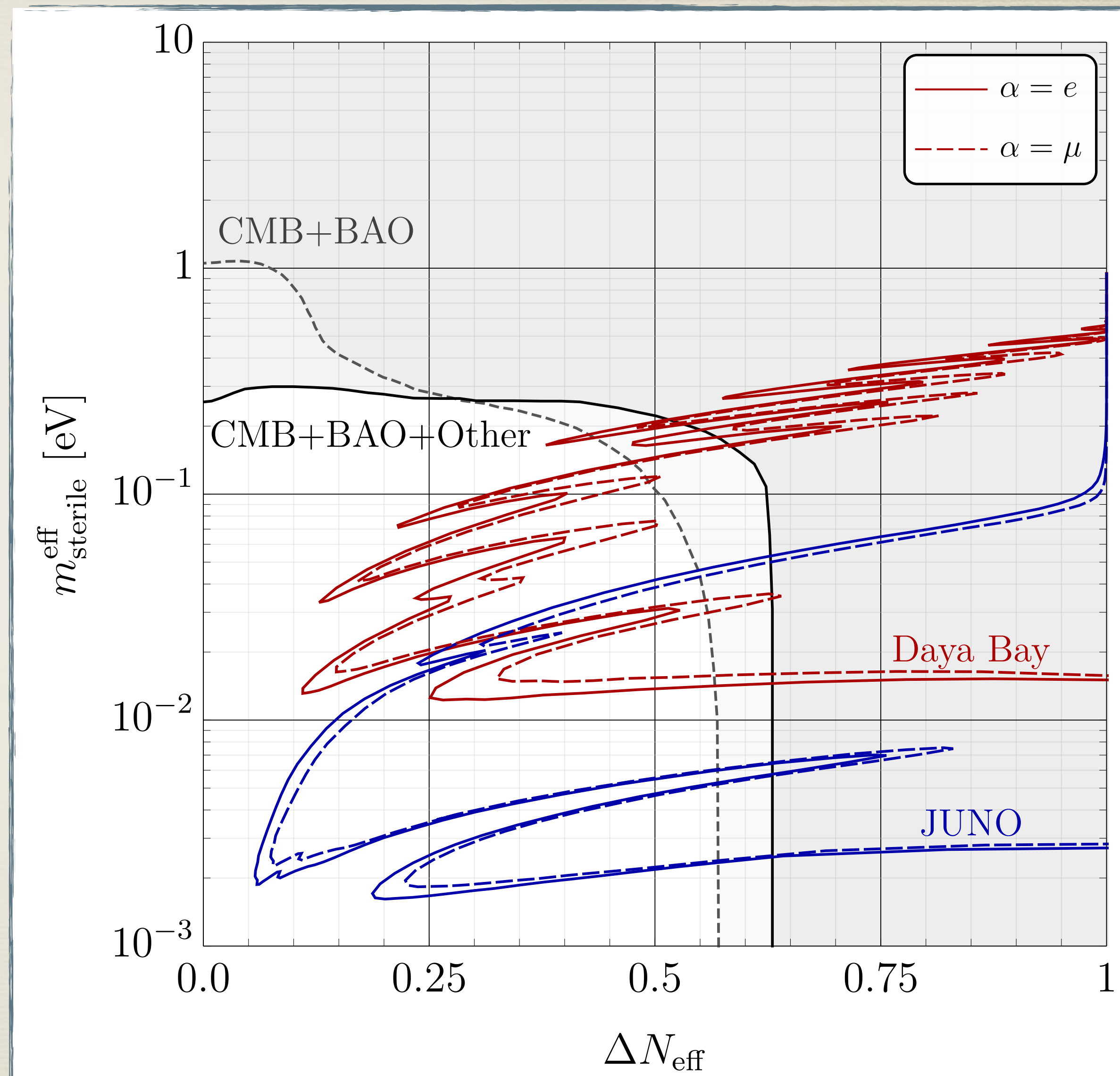
# Conclusions

* Exploiting the complementarity between terrestrial and cosmological experiments can facilitate the hunt for sterile neutrinos
* DUNE, Hyper-K and JUNO *may* improve on our understanding (depending on what happens with, *e.g.*, CMB-S4), *but Daya Bay can already probe new parameter space!*
* *There can be no satisfactory sterile neutrino solution to the reactor antineutrino anomaly that does not address the tension with astrophysical and cosmological measurements.*

# Back-Up

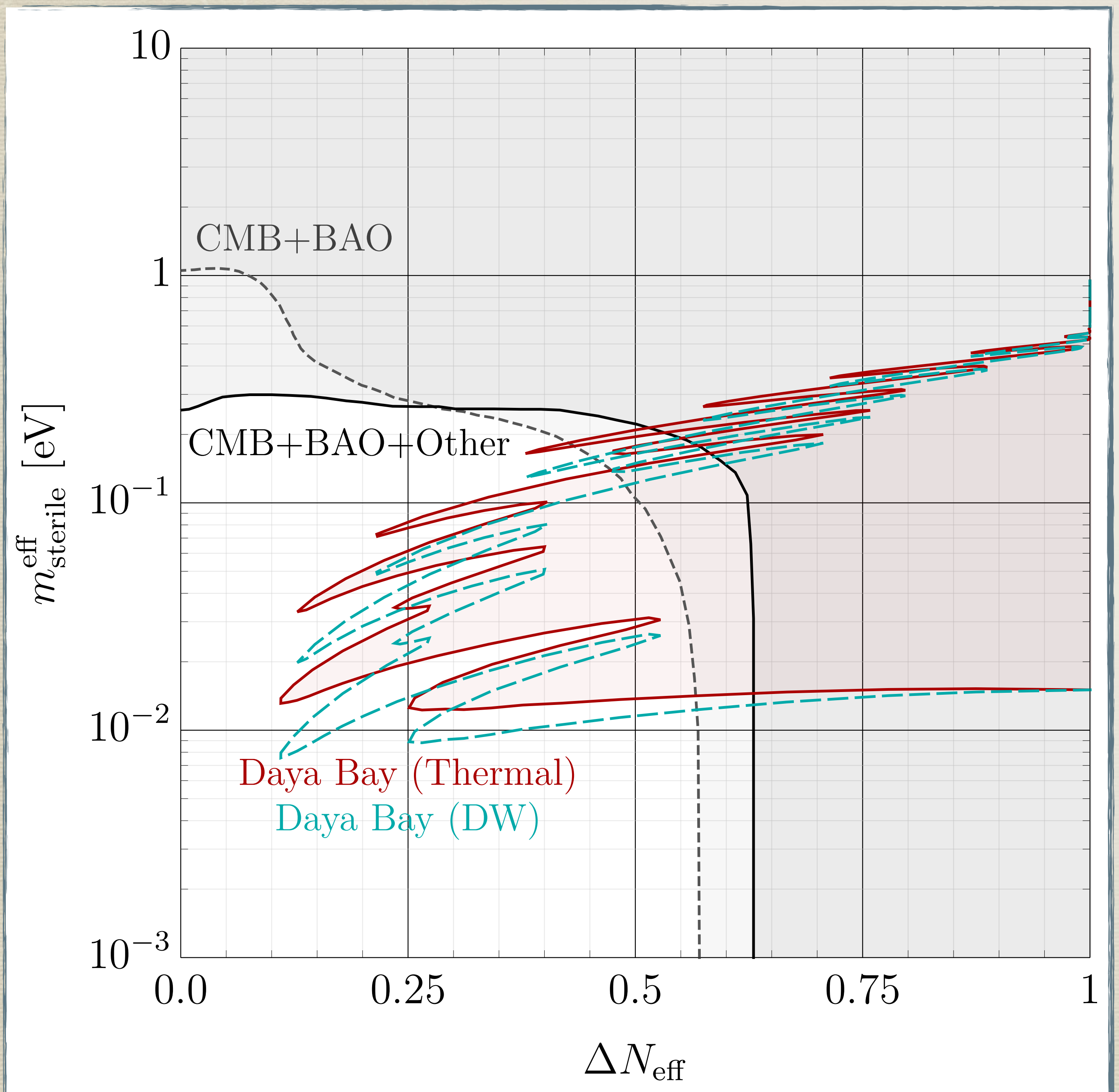
# Electron- vs. Muon-Type Oscillations




The difference between electron- and muon-type oscillations is conceptually important – but numerically small

# Thermal Distribution vs. Dodelson-Widrow




Thermally distributed sterile:

$$m_{\mathrm{sterile}}^{\mathrm{eff}} = (\Delta N_{\mathrm{eff}})^{3/4} \sqrt{\Delta m_{41}^2}$$

Dodelson-Widrow (DW) sterile:

$$m_{\mathrm{sterile}}^{\mathrm{eff}} = \Delta N_{\mathrm{eff}} \sqrt{\Delta m_{41}^2}$$

The difference between thermally-distributed and Dodelson-Widrow is not qualitatively important

S. Dodelson & L.M. Widrow, PRL 72, 17 (1994)

# Slightly More Details on Evolution of Neutrino Fluid

$$i\frac{d\rho_{\vec{p}}}{dt} = \left[\Omega^0_{\vec{p}}, \rho_{\vec{p}}\right] + \left[\Omega^{\rm int}_{\vec{p}}, \rho_{\vec{p}}\right] + \mathbf{C}\left[\rho_{\vec{p}}, \overline{\rho_{\vec{p}}}\right]$$

$$\frac{dP_0}{dt} = R^{(a)}$$

$$\frac{d\vec{P}}{dt} = \left(\vec{B} + \vec{V}^{(a)}\right) \times \vec{P} - D^{(a)}\left(P_x\,\hat{x} + P_y\,\hat{y}\right) + R^{(a)}\,\hat{z}$$

$$\vec{B} = \left(\frac{\Delta m^2}{2p}\right)\left(\sin 2\theta,\ 0,\ -\cos 2\theta\right)$$

$$\vec{V}^{(a)} = \left(V_1^{(a)} + V_L^{(a)}\right)\hat{z}$$

$$V_1^{(a)} = -\frac{7\pi^2 G_F}{45\sqrt{2}M_Z^2}\, p\, T^4\left(n_{\nu_a} + n_{\overline{\nu}_a}\right) g_a$$

$$V_L^{(a)} = \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 L^{(a)}$$

$$g_{\mu,\tau} = 1 \qquad g_e = 1 + 4\sec^2\theta_W / \left(n_{\nu_e} + n_{\overline{\nu}_e}\right)$$

$$\begin{aligned} L^{(e)} &= \left(\frac{1}{2} + 2\sin^2\theta_W\right) L_e \\ &\quad + \left(\frac{1}{2} - 2\sin^2\theta_W\right) L_p - \frac{1}{2} L_n \\ &\quad + 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau} \\ L^{(\mu,\tau)} &= L^{(e)} - L_e - L_{\nu_e} + L_{\nu_\mu,\nu_\tau} \end{aligned}$$

$$D^{(a)} \approx \tfrac{1}{2}\Gamma^{(a)} \qquad \Gamma^{(a)} = C^{(a)} G_F^2 p T^4$$

$$C^{(e)} \approx 1.27 \qquad C^{(\mu,\tau)} \approx 0.92$$

$$R^{(a)} \approx \Gamma^{(a)}\left[\frac{f_{\rm eq}(p,\mu_{\nu_a})}{f_0} - \frac{1}{2}\left(P_0 + P_z\right)\right]$$

# CONUS & CONUS100

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} P_{ee} Q_{\rm eff}^2 F_{\rm Helm}^2(q^2)\left(1 - \frac{MT}{2E_\nu^2}\right)$$

$$N_i = \Delta t \sum_f n_f \int_{T_i}^{T_i+\Delta T} dT \int_0^\infty dE_\nu \Phi(E_\nu)\, \frac{d\sigma_f}{dT}\, \Theta(2E_\nu^2 - MT)$$

$$\chi^2 = \sum_i \frac{\left(N_i^0 - (1+\alpha) N_i(\sin^2 2\theta_{ee}, \Delta m_{41}^2)\right)^2}{N_i + N_{\rm bkg} + \sigma_f^2\left(N_i + N_{\rm bkg}\right)^2} + \frac{\alpha^2}{\sigma_\alpha^2}$$

- CONUS: 4.0 kg natural Ge; $T \in [1.2, 1.75]\,\mathrm{keV}$;
  $\sigma_\alpha = 0.02$; $\sigma_f = 0.01$; one year of running
- CONUS100: 100.0 kg enriched Ge; $T \in [0.1, 1.75]\,\mathrm{keV}$;
  $\sigma_\alpha = 0.005$; $\sigma_f = 0.001$; five years of running
- Background rate: 1 count/(day*keV*kg)

Y. Farzan, *et al.*, JHEP 05, 066 (2018)
V.I. Kopeikin, Phys. Atom. Nucl. 75, 143 (2012)