Cosmological Constraints on Pseudo-Dirac ν

Chee Sheng Fong
Federal University of ABC (UFABC), Brazil

July 7, 2026
CETUP*, *Deadwood/Lead, South Dakota*

[CSF, Yago Porto, 2512.19782] [CSF, Stefano Gariazzo, Jaume Moncho & Yago Porto, 2607.XXXXX]

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Pseudo-Dirac (24) → Quasi-Dirac (25) → Pseudo-Dirac (26)

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ν physics that keep us awake

- How do they get their tiny masses?
- Do they interact beyond weak interactions?
- Are 3 flavors mixing all that is?
- Is total lepton number conserved?

ν physics that keep us awake

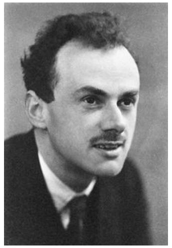
- How do they get their tiny masses? (see Saad's, Raymond's talks)
- Do they interact beyond weak interactions? (see Bhupal's, Julia's, Ankur's, Anna's, Zahra's talks)
- Are 3 flavors mixing all that is? (see Dibya's talk)
- Is total lepton number conserved? (see Saad's, Raymond's talks)

ν's are special

After the electroweak symmetry breaking, we can write

$m_M \bar{\nu}_L \nu_L^c$ $m_D \bar{\nu}_L \nu_R$

Total lepton number violation? **Right-handed neutrinos?**



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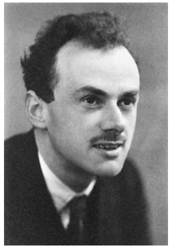

Neither has been observed.

Maybe a bit of both

If ν_R's exist, we can write $\overline{\Psi^c}\mathcal{M}\Psi$

$$\mathcal{M} \;=\; \begin{pmatrix} m_M & m_D \\ m_D^T & m_M' \end{pmatrix}, \quad \Psi \equiv (\nu_e, \nu_\mu, \nu_\tau, \underbrace{\nu_e', \nu_\mu', \nu_\tau'}_{\text{Sterile states, flavor indices arbitrary}})^T$$

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- Are 3 flavors mixing all that is?
- Is total lepton number conserved?

No for both.

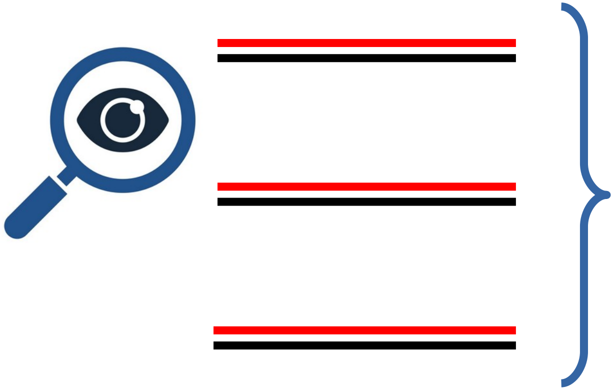
Maybe a bit of both

Pseudo-Dirac condition $|m_M|\,,|m'_M| \ll |m_D|$

[L. Wolfenstein, NPB186 (1981) 147] [Kobayashi & Lim, hep-ph/0012266]

PD mass splitting $$m_{\mp} \simeq m_D \mp \frac{1}{2}|m_M^* + m'_M|$$

Almost maximal mixing $$\theta \simeq \frac{\pi}{4} - \frac{|m'_M|^2 - |m_M|^2}{4|m_M^* + m'_M|m_D} \equiv \frac{\pi}{4} - \delta\theta$$



$0\nu\beta\beta$ challenging

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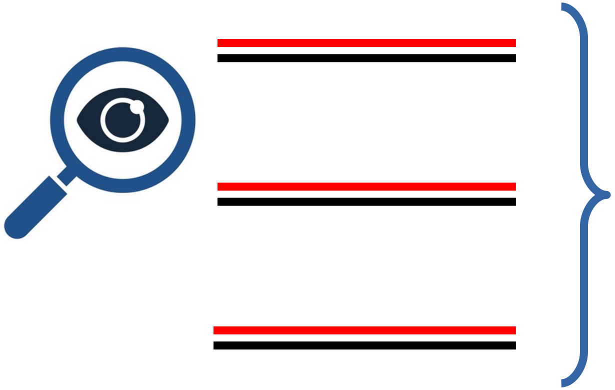
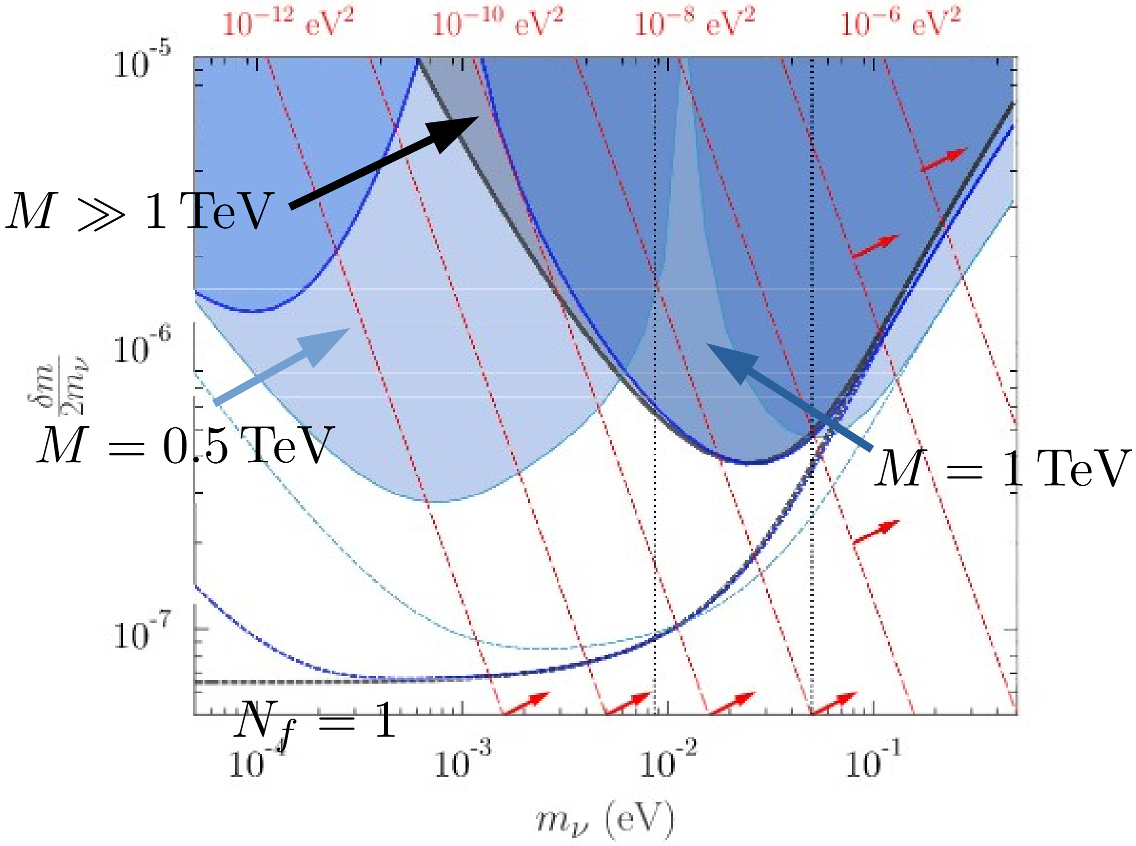


$0\nu\beta\beta$ challenging

Oscillations to ν_R

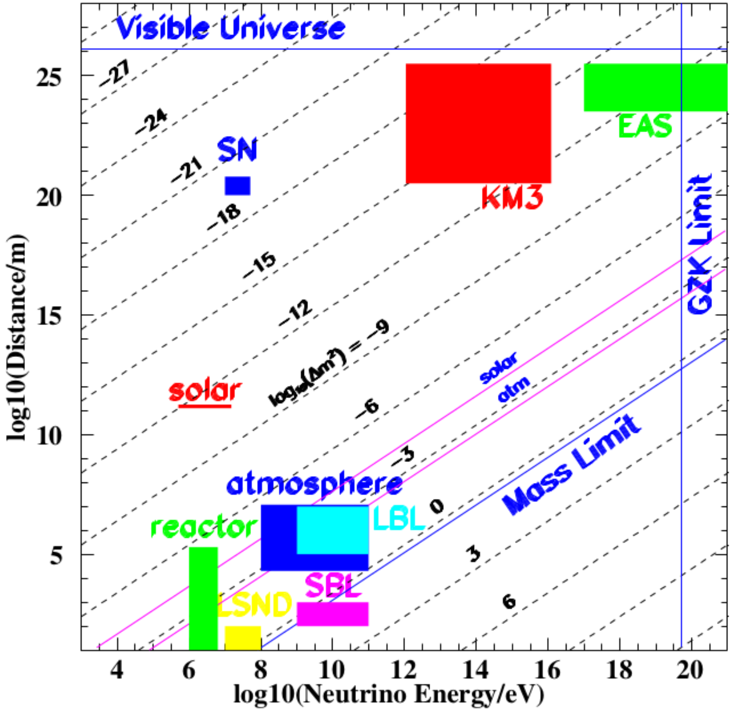
Viable pseudo-Dirac leptogenesis



[CSF, Gregoire, Tonero, 2007.09158]

Need long baseline to probe

$$\Phi_j = 10 \left(\frac{\delta m_j^2}{1.7 \times 10^{-12}\,\mathrm{eV}^2} \right) \left(\frac{L_{\mathrm{eff}}}{15\,\mathrm{kpc}} \right) \left(\frac{100\,\mathrm{TeV}}{E} \right) \gg 1$$



[Beacom et al., hep-ph/0307151]

Solar & atmospheric ν

$$\delta m_{1,2}^2 \lesssim 10^{-11}\,\mathrm{eV}^2$$

$$\delta m_3^2 \lesssim 10^{-5}\,\mathrm{eV}^2$$

[de Gouvêa, Huang & Jenkins, 0906.1611]
[Anamiati, Fonseca & Hirsch, 1710.06249]
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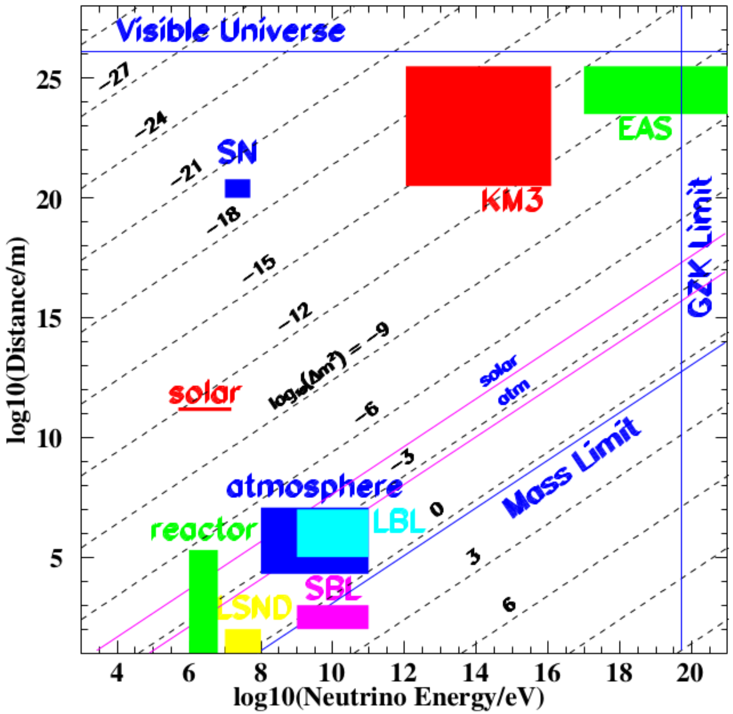

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Solar & atmospheric ν

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Very weak bound!

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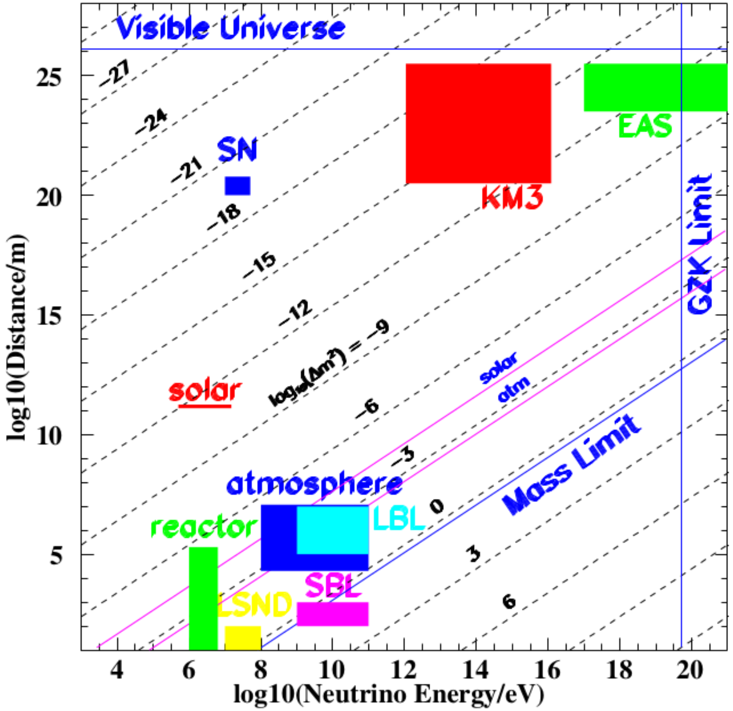

[Beacom et al., hep-ph/0307151]

Astrophysical neutrinos ν

Decoherence, flux reduced by half.
Further sources, can probe smaller δm_j^2

[Cirelli, Marandella, Strumia & Vissani, hep-ph/043158]

[Carloni, Martínez-Solar, Argüelles, Babu & Dev, 2212.00737]

[Dev, Machado & Martinez-Soler, 2406.18507]

[Fong & Porto, 2406.15566]

[Carloni, Porto, Argüelles, Dev & Jana, 2503.19960]

and many more ...

Need long baseline to probe

$$\Phi_j = 10 \left(\frac{\delta m_j^2}{1.7 \times 10^{-12}\,\mathrm{eV}^2} \right) \left(\frac{L_{\mathrm{eff}}}{15\,\mathrm{kpc}} \right) \left(\frac{100\,\mathrm{TeV}}{E} \right) \gg 1$$

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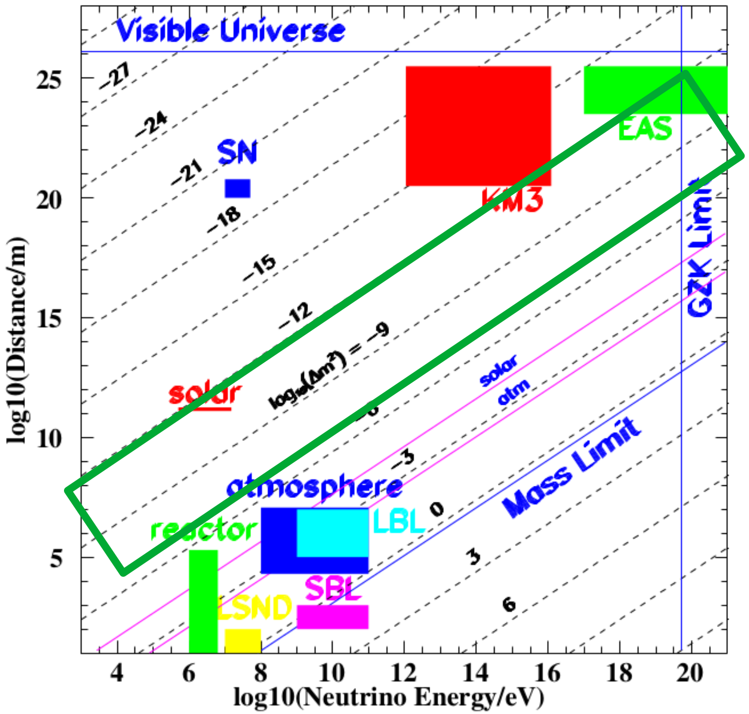

[Beacom et al., hep-ph/0307151]

Cosmological constraints from CMB and BBN

Can constrain all δm_j^2

[Cirelli, Marandella, Strumia & Vissani, hep-ph/043158]
[Barbieri & Dolgov, PLB237, 440 (1990)]
[Enqvist, Kainulainen & Maalampi, PLB249, 531 (1990)]
[Kirilova & Chizhov, hep-ph/9707282]
[Dolgov & Villante, hep-ph/0308083]
[Kirilova & Panayotova, astro-ph/0608103]

Revisit cosmological constraints

Why?

- Measurements in ν parameters have improved
- Measurements in cosmology have improved
- State-of-the-art 3+N calculation with ν phase space matrix density public code is available FortEPiaNO
- BBN code which takes ν_e phase space distribution as input PArthENoPE

[Gariazzo, de Salas & Pastor, 1905.11290]

[Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Wong, 2012.02726]

[Consiglio, de Salas, Mangano, Miele, Pastor & Pisanti, 1712.04378]

Outline

- Pseudo-Dirac ν in the early Universe
- N_{eff} constraints from CMB
- BBN constraints
- Conclusions

Pseudo-Dirac ν in the early Universe

Is maximal mixing assumption OK?

$$\delta\theta \simeq \frac{\left|m'_M\right|^2 - \left|m_M\right|^2}{8\left|m^*_M + m'_M\right|^2}\frac{\delta m^2}{m_D^2} \implies |\delta\theta| \lesssim \frac{\left|\delta m^2\right|}{8 m_D^2}$$

Barring a fine-tuned cancellation in the denominator

$$m_D \sim 0.1\,\mathrm{eV}, \quad |\delta m^2| \lesssim 10^{-5}\,\mathrm{eV}^2 \implies |\delta\theta| \lesssim 10^{-4}$$

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First hint should be in “frequencies” rather “amplitudes”

Pseudo-Dirac ν in the early Universe

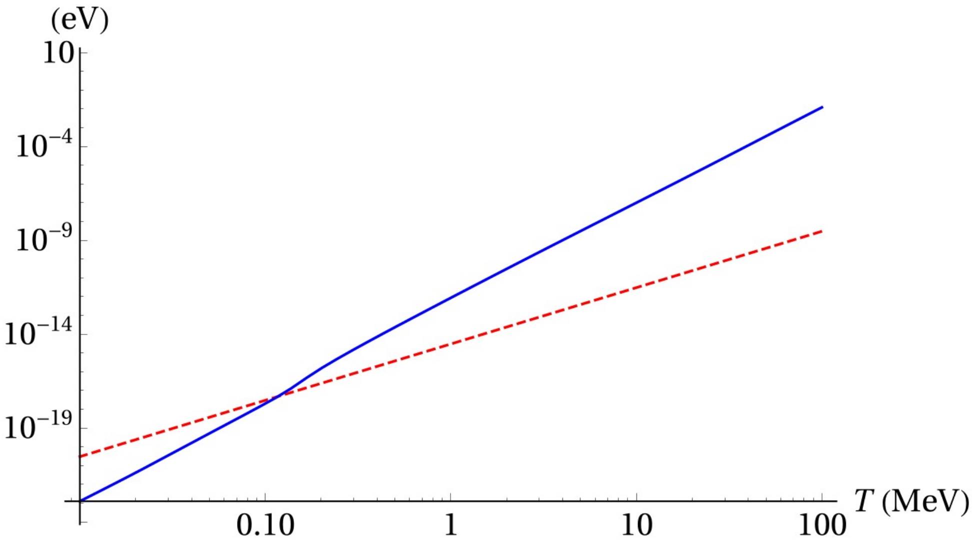
Assuming 1 active + 1 sterile ν

$$\mathcal{H} = \frac{\omega}{2}\begin{pmatrix} -2\cos 2\theta & e^{-i\phi}\sin 2\theta \\ e^{i\phi}\sin 2\theta & 0 \end{pmatrix} + \begin{pmatrix} a & 0 \\ 0 & 0 \end{pmatrix} \qquad \omega \equiv \frac{\delta m^2}{2E}$$

$$a = \underbrace{\mp c_1 Y G_F T^3}_{} - \frac{1}{\alpha} c_2 G_F^2 T^4 E$$

Opposite signs for ν & anti-ν

$$Y = \left(-1.45 + \sin^2\theta_W\right) Y_B$$



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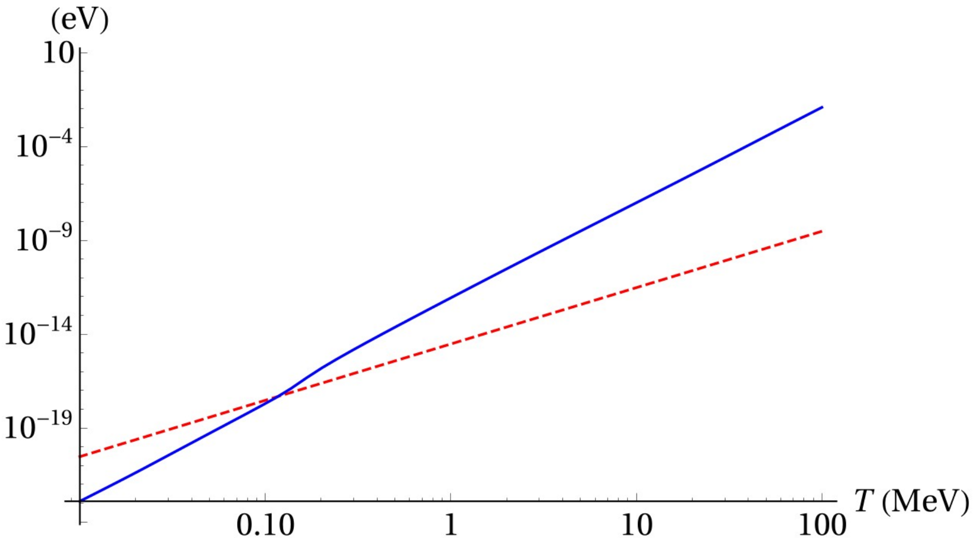
Subdominant unless "unnaturally" large lepton asymmetries



Pseudo-Dirac ν in the early Universe

Matter resonance happens for $\omega\cos 2\theta \simeq V_M \equiv -\frac{1}{\alpha}c_2 G_F^2 T^4 E$

Only happens for negative δm^2

$$|\delta m^2| \gtrsim \sqrt{\frac{8}{\alpha}c_2 G_F T^2 E m_D} = 4.8\times 10^{-5}\,\mathrm{eV}^2 \left(\frac{m_D}{0.05\,\mathrm{eV}}\right)\left(\frac{T}{1\,\mathrm{MeV}}\right)^3$$

However $V_M \simeq \omega\cos 2\theta \ll \omega\sin 2\theta$

$$\sin^2 2\theta_m = \frac{\omega^2\sin^2 2\theta}{(\omega\cos 2\theta - V_\mathrm{M})^2 + \omega^2\sin^2 2\theta} \simeq \frac{\omega^2}{V_\mathrm{M}^2+\omega^2}.$$

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Resonance dominated by vacuum effect, sign of δm^2 irrelevant

Pseudo-Dirac ν in the early Universe

Realistic model: 3 active + 3 sterile ν

$$\mathcal{M}^2_{j,j+3} = m_j^2 \mp \frac{1}{2}\delta m_j^2$$

Not quite feasible numerically

Maximal mixing + one $\delta m_j^2 \neq 0$ at a time

Effective 3+1 PD model $\mathcal{H}^{\rm eff}_{0,j} \equiv \frac{1}{2E}\begin{pmatrix} U\hat{m}^2U^\dagger & \epsilon_j \\ \epsilon_j^\dagger & m_j^2 \end{pmatrix}$

$$\hat{m}^2 \equiv \mathrm{diag}\left(m_1^2, m_2^2, m_3^2\right) \qquad \epsilon_j \equiv -\frac{1}{2}\delta m_j^2 \left(U_{1j}, U_{2j}, U_{3j}\right)^T$$

[Fong & Porto, 2512.19782]

N_{eff} constraints from CMB

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`FortEPiaNO`

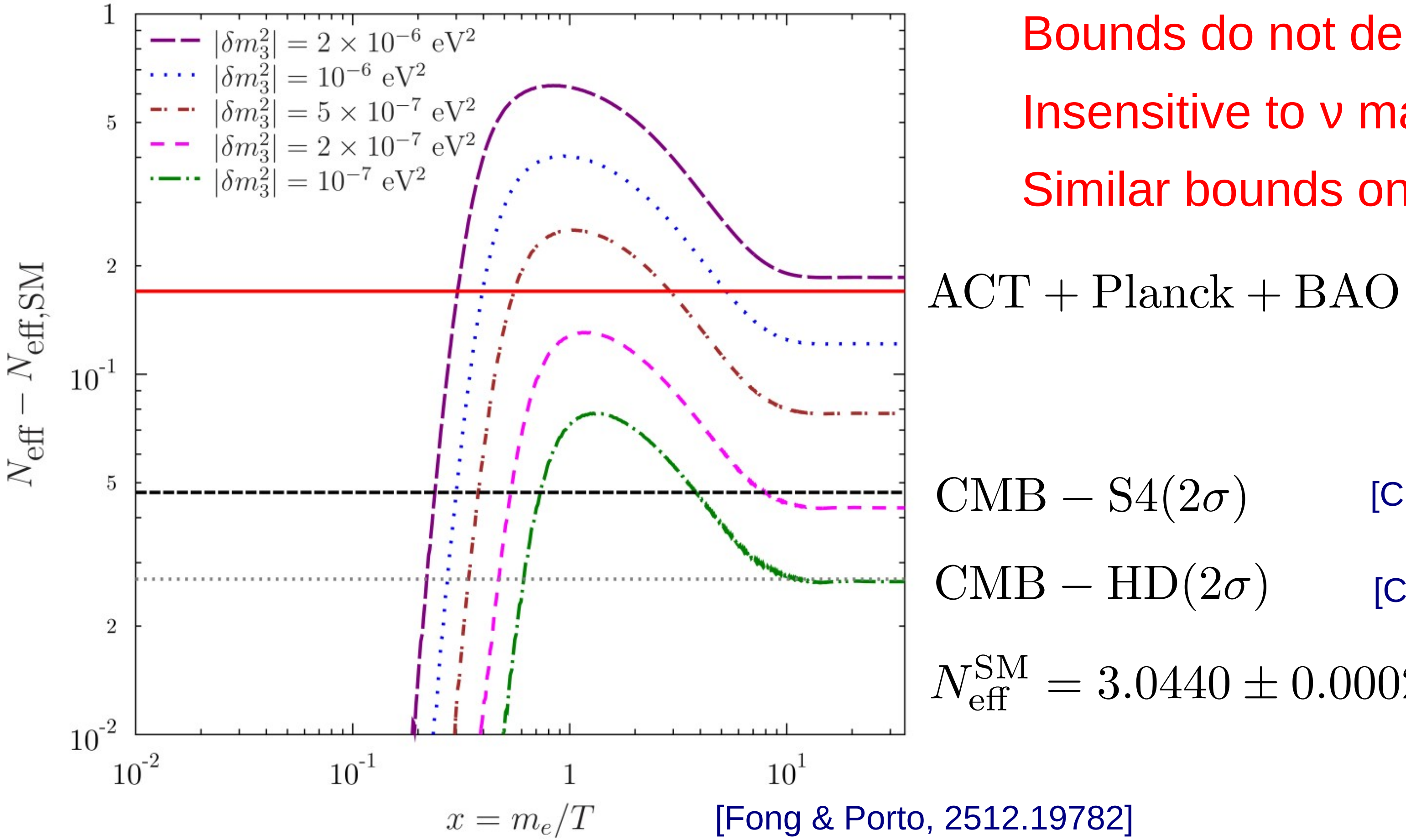
$$(\partial_t - Hp\,\partial_p)\,\varrho(t,p) = -i\left[\mathcal{H}^{\text{eff}}_{0,j}(p) + V_{\text{M}}(t,p), \varrho\right] + \mathcal{C}[\varrho, \bar{\varrho}]$$

Population of sterile ν $\quad e^{\pm} \to \nu_a \to \nu_s$

$$\rho_\nu = \frac{1}{2\pi^2}\int dp\,p^3\,\text{Tr}(\varrho + \bar{\varrho}) \qquad N_{\text{eff}} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left.\frac{\rho_\nu}{\rho_\gamma}\right|_{T/m_e\to 0}$$

Contribute to total radiation radiation density, increase expansion rate H & damps the small scale CMB power spectra

N_{eff} constraints from CMB



Bounds do not depend on sign

Insensitive to ν mass ordering

Similar bounds on $\delta m^2_{1,2}$

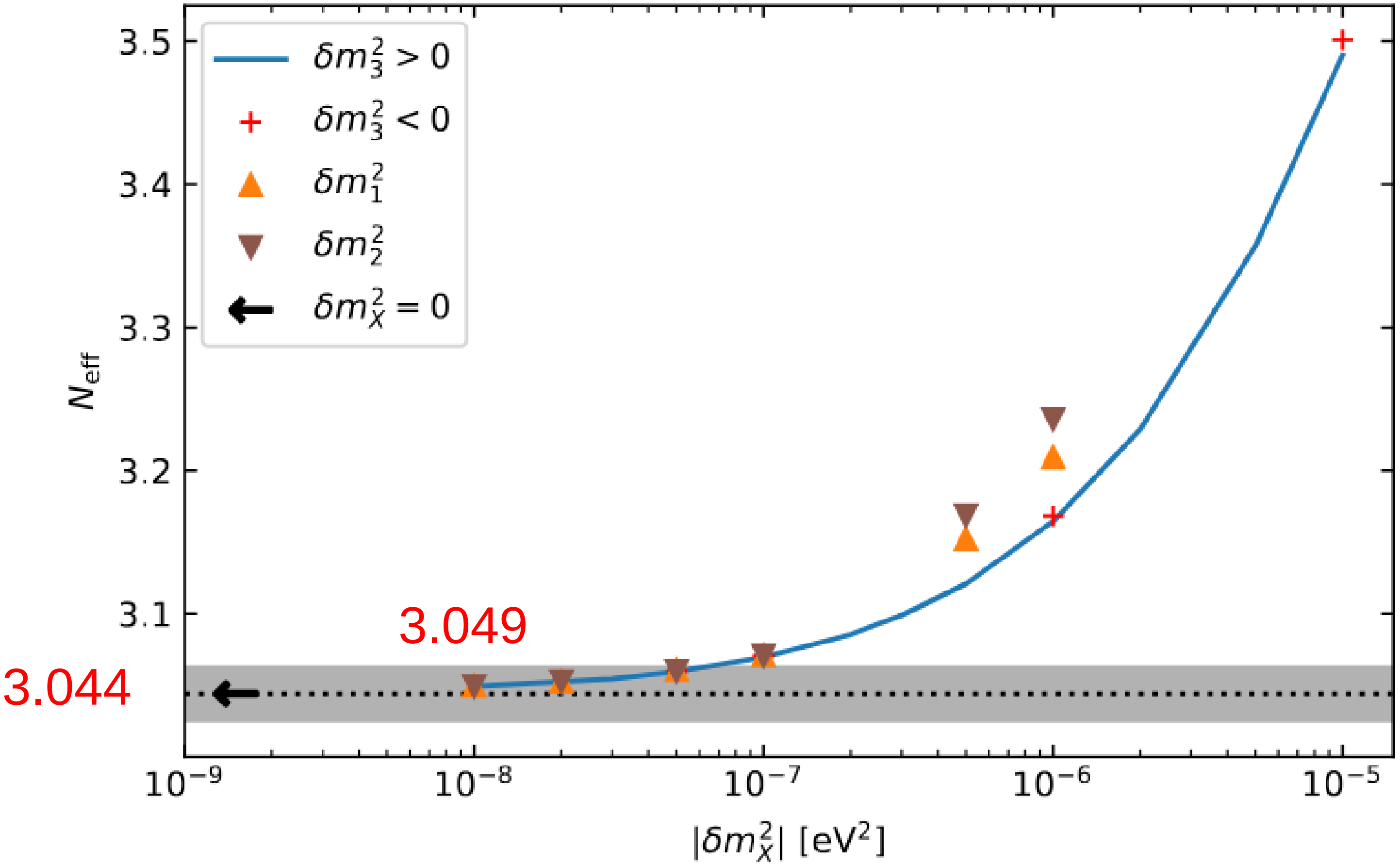
[CMB-S4, 1610.02743]

[CMB-HD, 1906.10134]

$$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.0440 \pm 0.0002$$ [Bennett et al., 2012.02726]

[Fong & Porto, 2512.19782]

N_{eff} constraints from CMB



BBN Constraints

BBN Constraints

The impact on BBN depends on conversion to sterile states relative to neutrino decoupling

$$T_{\rm dec} \sim \left(\frac{1.66\, g_*^{1/2}}{G_F^2 M_{\rm Pl}} \right)^{1/3} \sim {\rm MeV}$$

- Large expansion rate H: more neutrons, decrease of deuterium burning time
- “Depletion” of electron (anti)ν phase space distribution to sterile ν

$$a)\; n + \nu_e \to p + e^- \quad b)\; n + e^+ \to p + \bar{\nu}_e \quad c)\; n \to p + e^- + \bar{\nu}_e$$

$$d)\; p + e^- \to n + \nu_e \quad e)\; p + \bar{\nu}_e \to n + e^+ \quad f)\; p + e^- + \bar{\nu}_e \to n$$

BBN Constraints

Calculate all, in particular electron (anti)ν phase space distribution & pass to BBN calculations

FortEPiaNO

$$\varrho_{ee}(x \equiv m_e/T, y \equiv p/T, \delta m_j^2)$$

Evolution of total plasma density

↓

PArthENoPE

Full BBN calculations

BBN Constraints

Calculate all, in particular electron (anti)ν phase space distribution & pass to BBN calculations

FortEPiaNO

$$\boxed{\begin{array}{l}\varrho_{ee}(x \equiv m_e/T, y \equiv p/T, \delta m_j^2) \\ \text{Evolution of total plasma density}\end{array}}$$

$\downarrow$

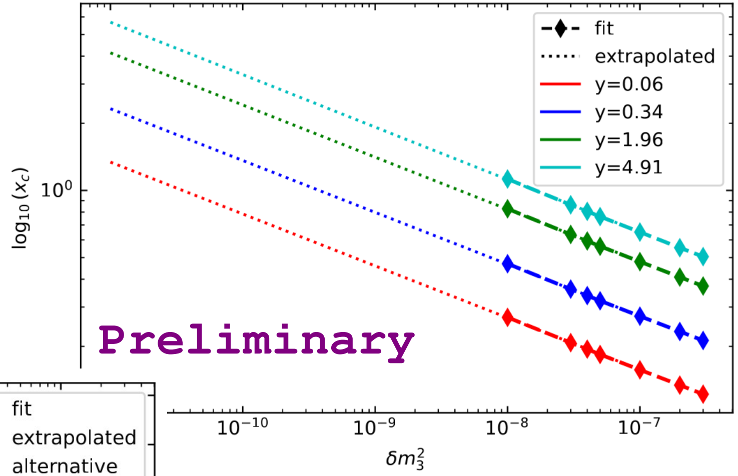
PArthENoPE

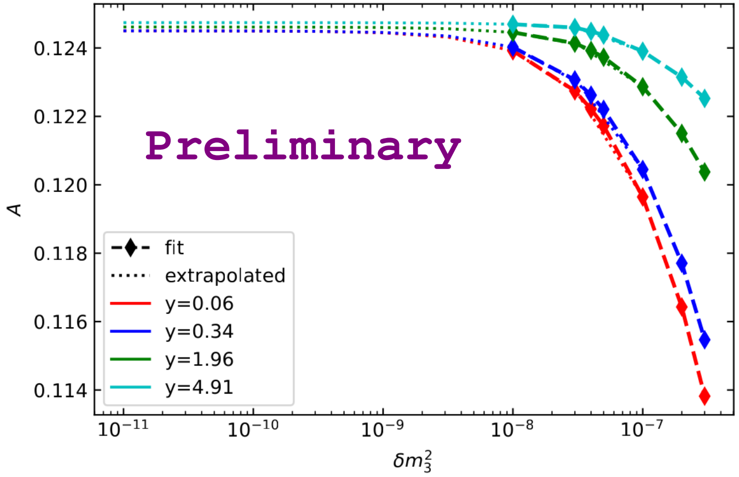
Full BBN calculations

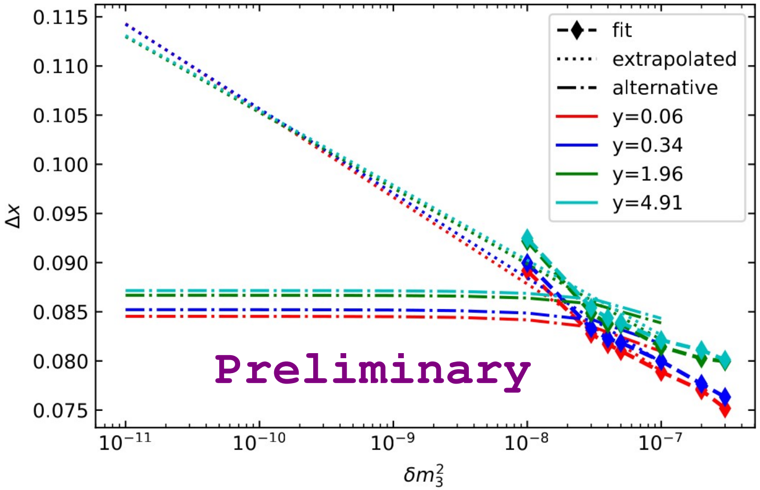
FortEPiaNO fails for $|\delta m_j^2| \lesssim 10^{-8}\,\mathrm{eV}^2$

BBN Constraints

Fixing $N_{\rm eff} = 3.044$ and fitting the distributions $\quad N_{\rm eff} < 3.049, |\delta m_j^2|^2 < 10^{-8}\,{\rm eV}^2$

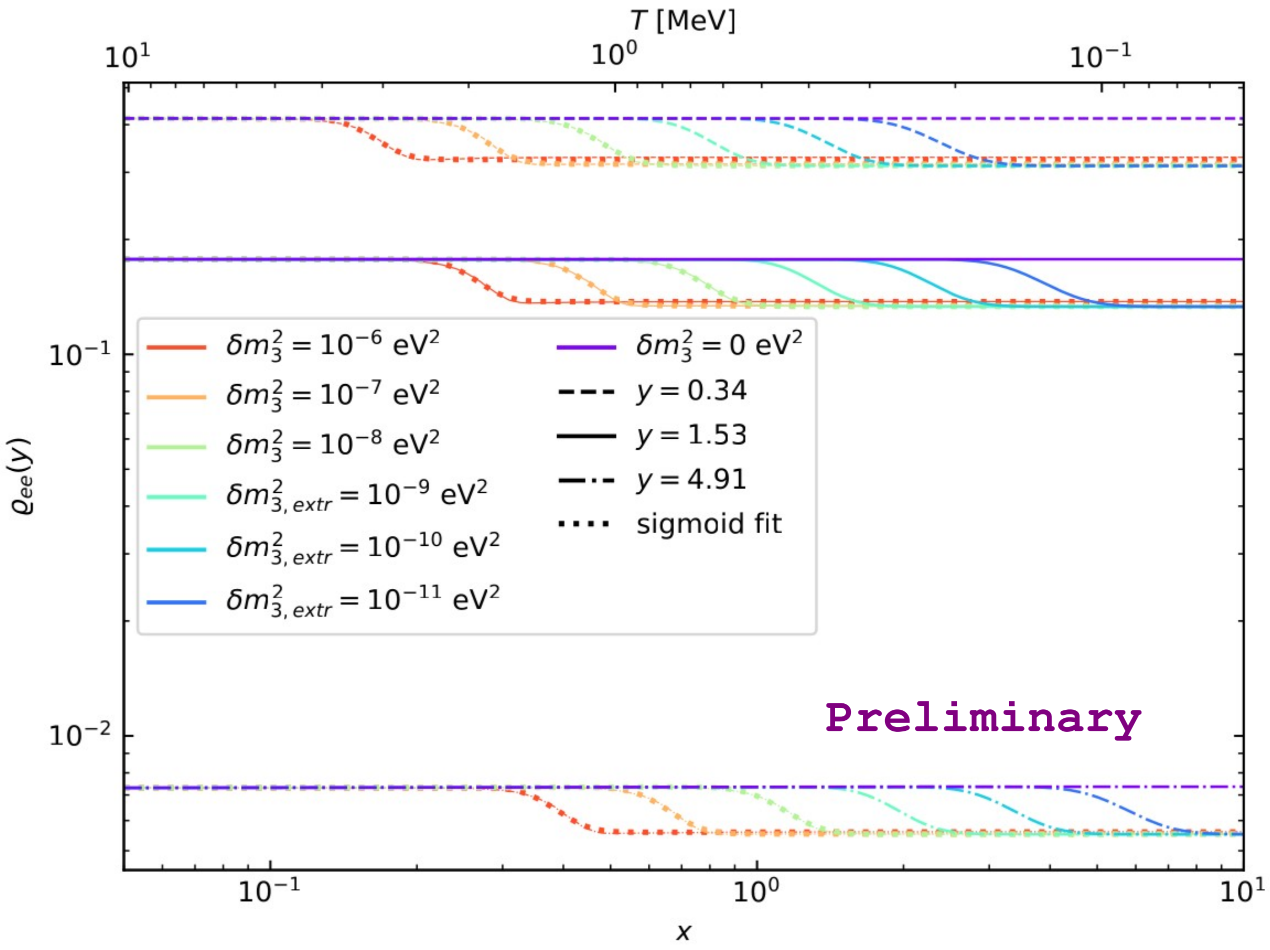






$$\varrho_{ee}(x, y,) = \varrho_{ee}^{\rm std}(x, y)\left[1 - A\left(1 + {\rm erf}((\log_{10} x - \log_{10} x_c)/\Delta x)\right)\right]$$

BBN Constraints



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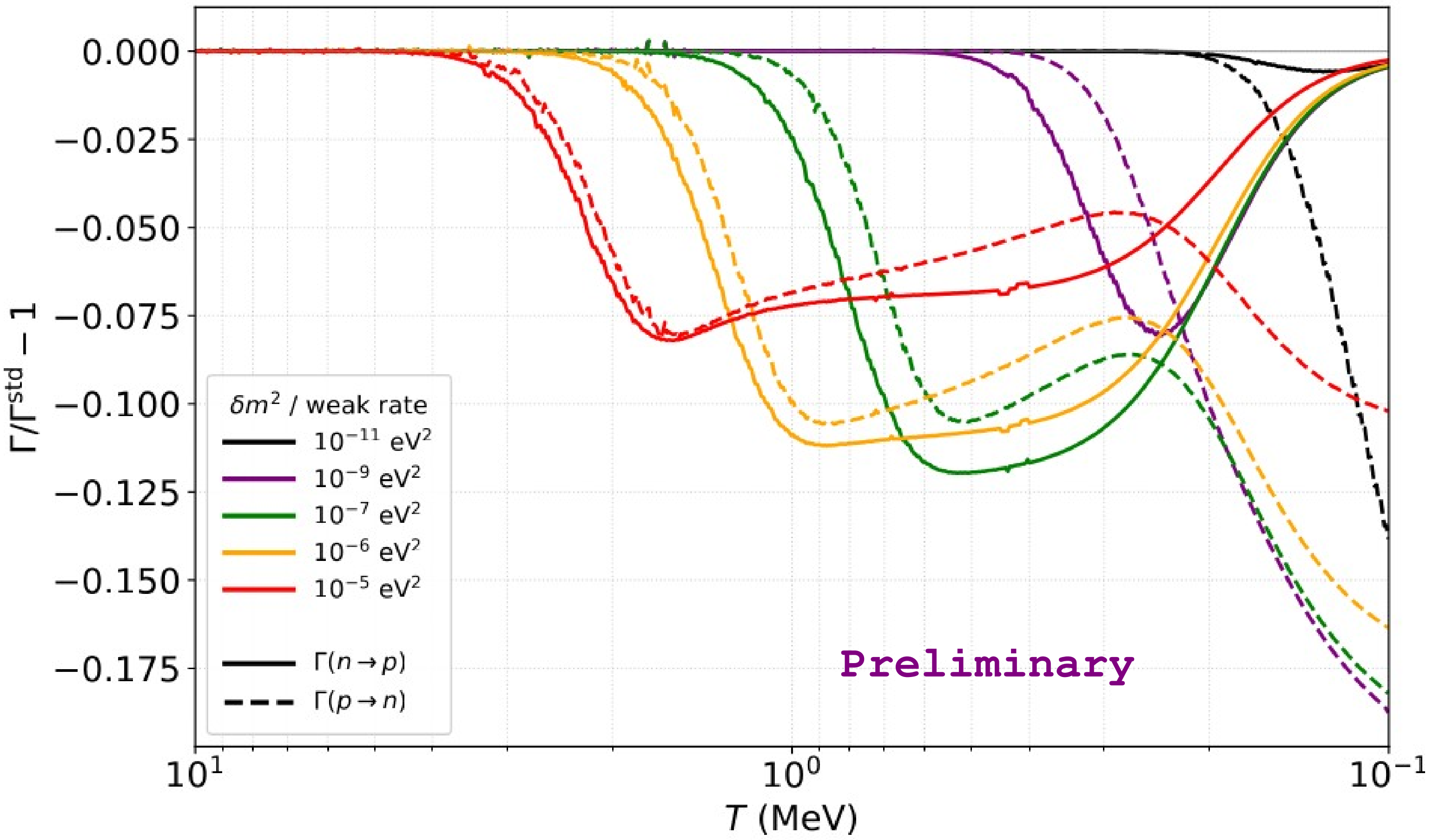

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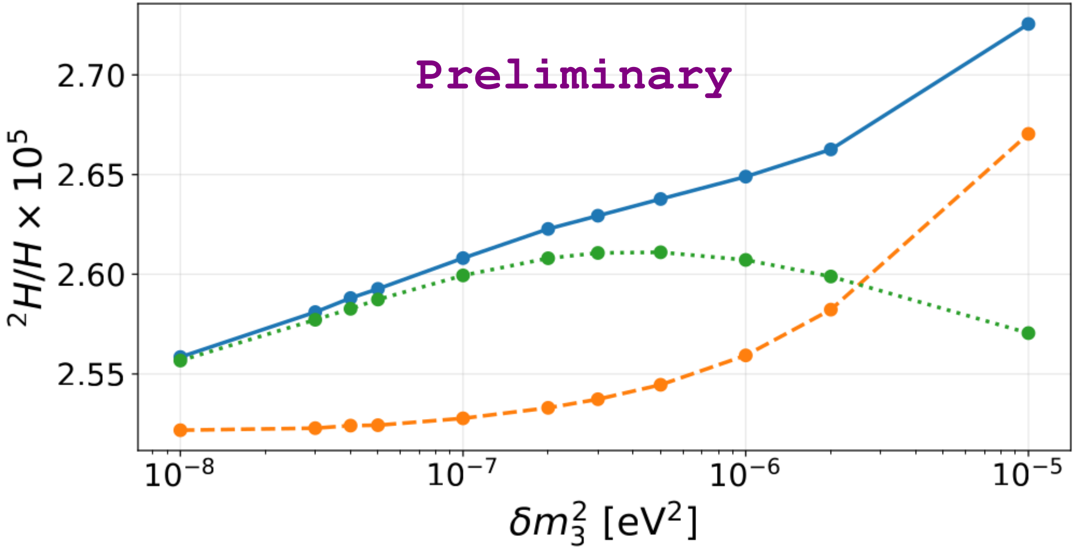

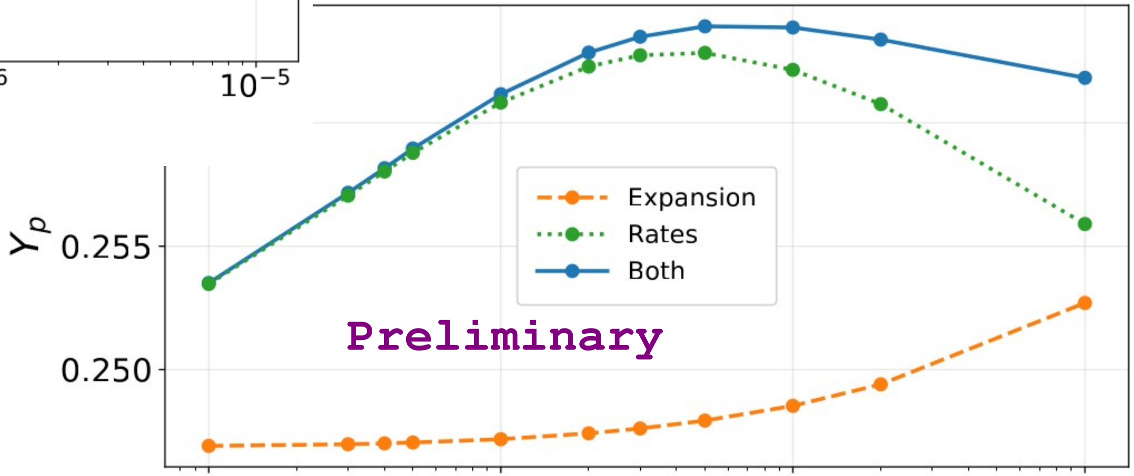

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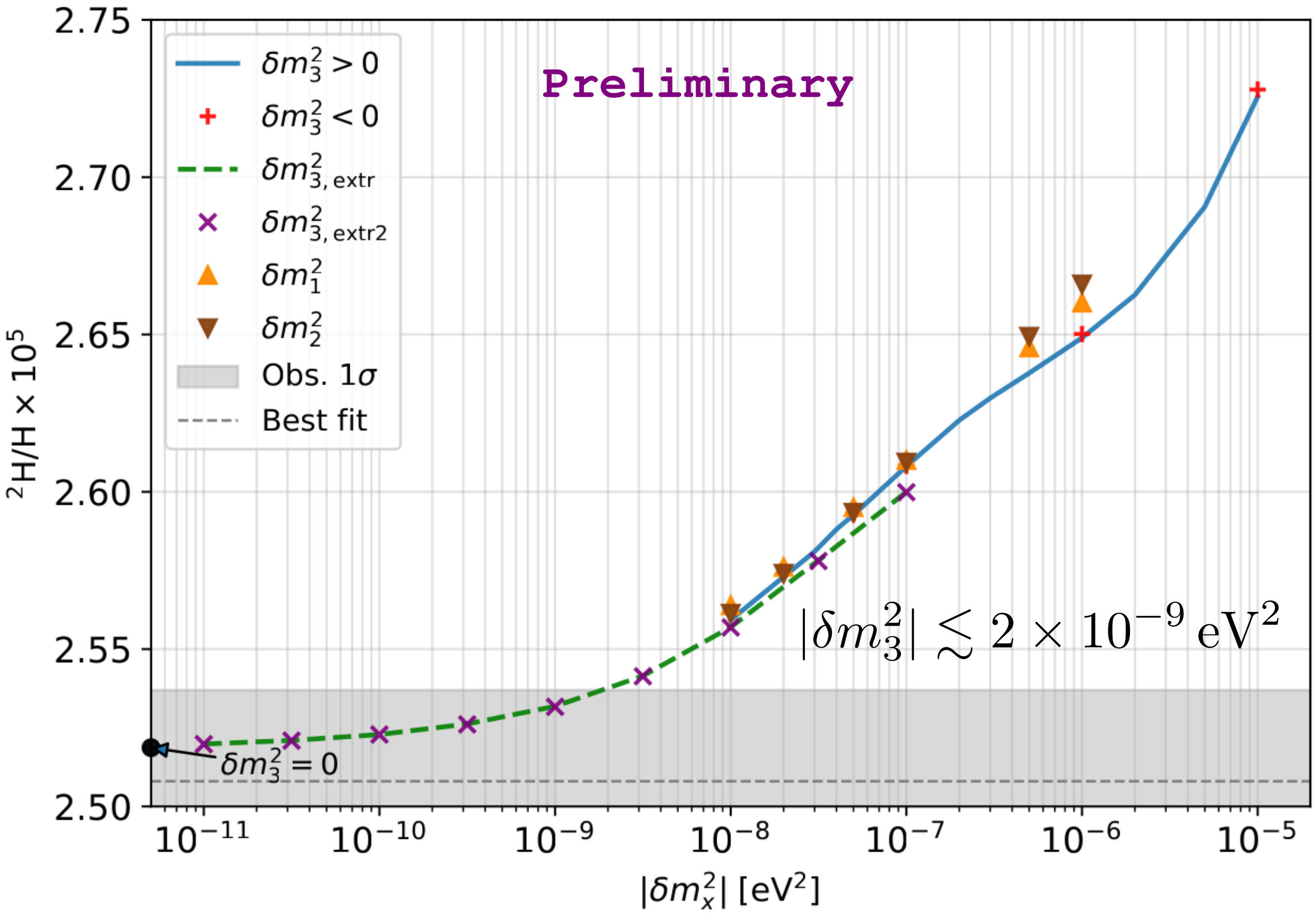

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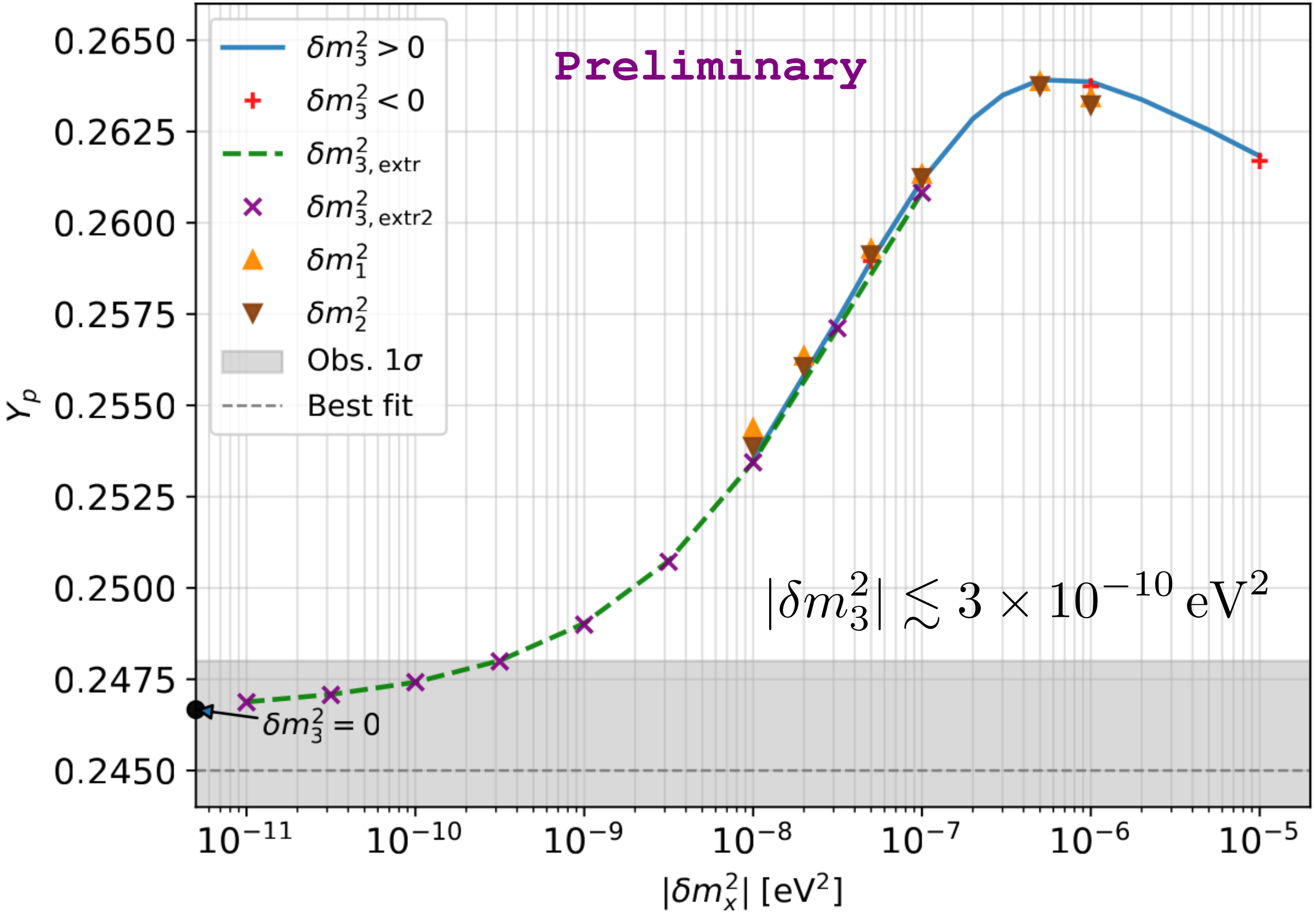

Conclusions

- Assuming maximal active-sterile mixing and one nonzero PD mass splitting at a time, we have effective 3+1 PD model.
- N_{eff} alone constraints $|\delta m_3^2| \lesssim 2 \times 10^{-6}\,\mathrm{eV}^2$
- BBN sensitive to N_{eff} as well as electron (anti)ν distribution.
- Using extrapolation, we obtain

^{2}H $|\delta m_3^2| \lesssim 2 \times 10^{-9}\,\mathrm{eV}^2$ ^{4}He $|\delta m_3^2| \lesssim 3 \times 10^{-10}\,\mathrm{eV}^2$

The sensitivity of BBN to first and second PD mass splittings would be similar; existing solar ν bounds are already very restrictive $\delta m_{1,2}^2 \lesssim 10^{-11}\,\mathrm{eV}^2$