Taming Instabilities in Mass-Varying Neutrino Cosmology

Galileo Galilei Institute workshop: Exploring New Frontiers in Cosmology

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The neutrino tension

Main observational tensions

Assuming $\Lambda\mathrm{CDM}$:

- H_0 tension
- S_8 tension
- Neutrino tension

Neutrino masses

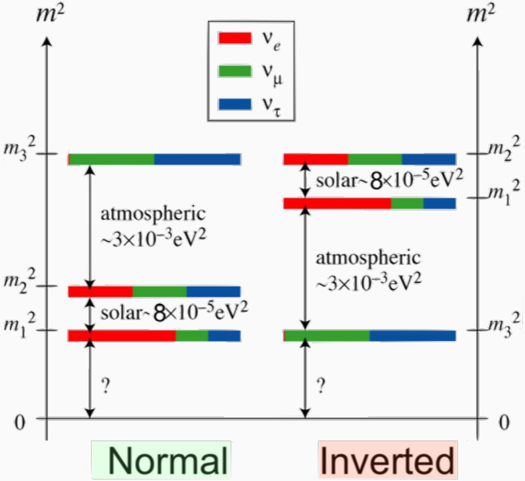
- Weakly interacting, uncharged elementary particles
- Three flavors: electron (ν_e), muon (ν_μ), and tau (ν_τ)
- Massless in the original SM (only left-handed neutrino ν_L fields)
- Solar neutrino problem
- Neutrino oscillation experiments

$$|\nu_\alpha\rangle = \sum_i^3 U^*_{\alpha i} |\nu_i\rangle$$

- $\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\,\mathrm{eV}^2$ and $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$

Lower bounds from flavor oscillations (95% CL)

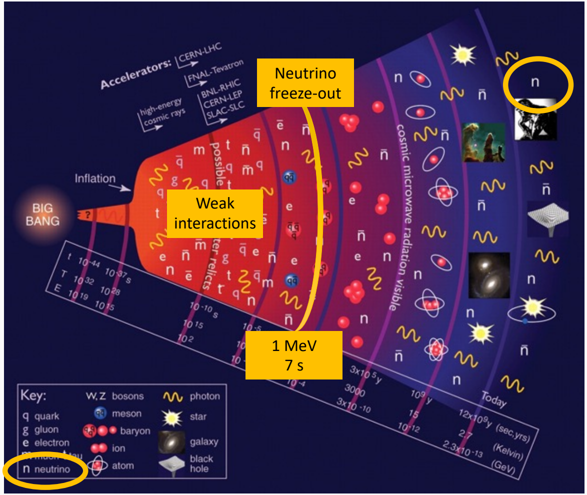
From Sabin Stoica



$$\sum m_\nu > 0.058\,\mathrm{eV} \qquad \sum m_\nu > 0.098\,\mathrm{eV}$$

Cosmic neutrino background

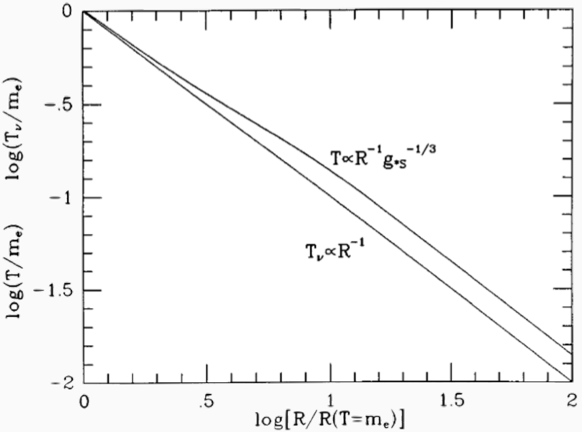
From Particle Data Group



Relic neutrinos predicted by the standard hot big bang model

Neutrino thermal history

From Kolb&Turner



$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

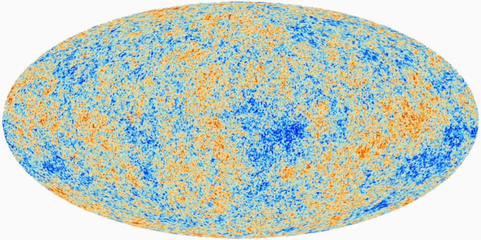
$$T_{\gamma,0} = 2.725\,\mathrm{K}$$

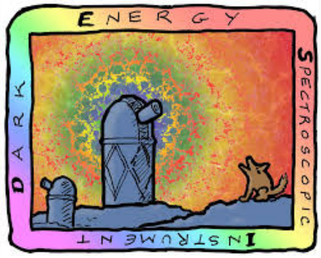
$$n_{\gamma,0} \simeq 400\,\mathrm{cm}^{-3}$$

$$T_{\nu,0} \simeq 1.9\,\mathrm{K}\,, \quad n_{\nu,0} = \frac{3}{2}\frac{\zeta(3)}{\pi^2}T_{\nu,0}^3 \simeq 113\,\mathrm{cm}^{-3}\,(\times 3)\,, \quad \Omega_\nu h^2 = \frac{\sum m_\nu}{93.12\,\mathrm{eV}}$$

Upper limits from cosmological observations

- In the 60's: $\Omega_\nu < 1 \Rightarrow \sum m_\nu < 100\,\mathrm{eV}$
- Katrin: $m_\beta < 0.45\,\mathrm{eV}$ (90% CL) $\Rightarrow \sum m_\nu \lesssim 1.35\,\mathrm{eV}$ (90% CL)





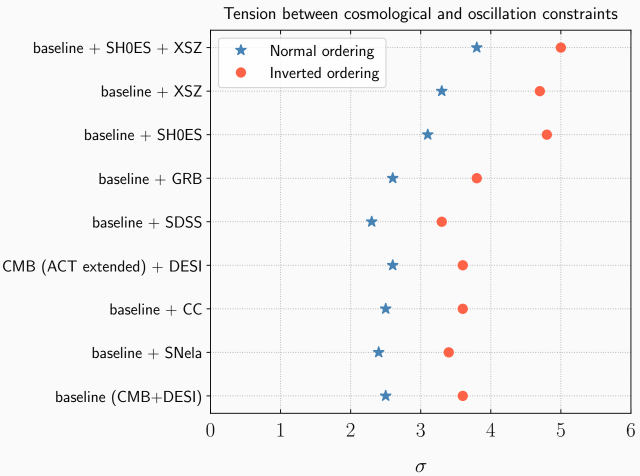
$\sum m_\nu < 0.13\,\mathrm{eV}$ (95% CL) $\longrightarrow$ $\sum m_\nu < 0.072\,\mathrm{eV}$ (95% CL)

standard seven-parameter model

Tension between cosmological and oscillation constraints

from Jun-Qian Jiang et al. (2025)

- Oscillation experiments: $\sum m_\nu > 0.058\,\mathrm{eV}$ (NO) and $\sum m_\nu > 0.098\,\mathrm{eV}$ (IO)
- Planck+ACT+SPT+DESI: $\sum m_\nu < 0.055\,\mathrm{eV}$ (3σ tension)



How to reconcile laboratory and cosmological constraints

- Oscillation experiments: $\sum m_\nu > 0.058\,\mathrm{eV}$ (NO) and $\sum m_\nu > 0.097\,\mathrm{eV}$ (IO)
- Planck+ACT+SPT+DESI: $\sum m_\nu < 0.055\,\mathrm{eV}$ (3σ tension)

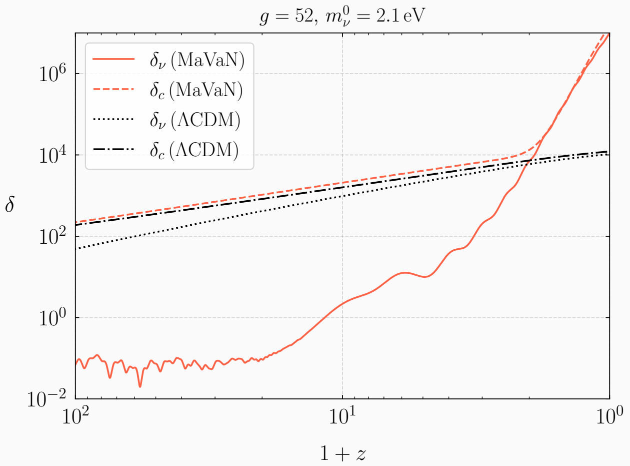
- Cosmological constraints are model dependent

- Role of dark energy:

- $w_0 w_a\mathrm{CDM} \longrightarrow \sum m_\nu < 0.16\,\mathrm{eV}$ arXiv:2503.14744

- Mass-Varying Neutrino (MaVaN) models $\longrightarrow \sum m_\nu < 0.72\,\mathrm{eV}$ arXiv:2311.01803

MaVaN instabilities



Additional attractive force, enhancing neutrino clustering and draging dark matter perturbations

Taming the instabilities

Inverse symmetron for a MaVan model

- Field-dependent effective neutrino mass

$$m_\nu(\phi) = m_\nu^0\, A(\phi)$$

- Extension of the Standard Model

$$\mathcal{L}_\nu = i\bar{\nu}\gamma^\mu \nabla_\mu \nu - m_\nu(\phi)\,\bar{\nu}\nu$$

- Equivalently, conformal coupling to an effective metric

$$\tilde{g}^{(\nu)}_{\mu\nu} = A^2(\phi)\, g_{\mu\nu}$$

- Conformal factor

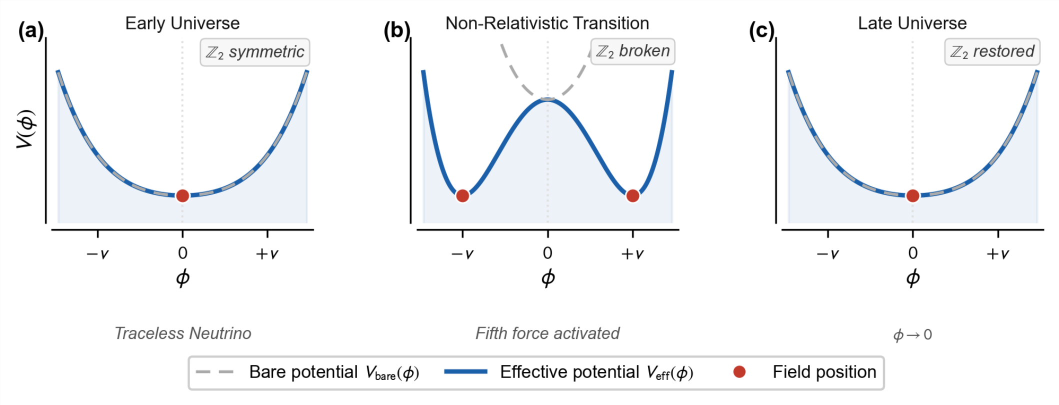
$$A(\phi) = \exp\left(-\frac{\phi^2}{2M^2}\right)$$

- Scalar potential

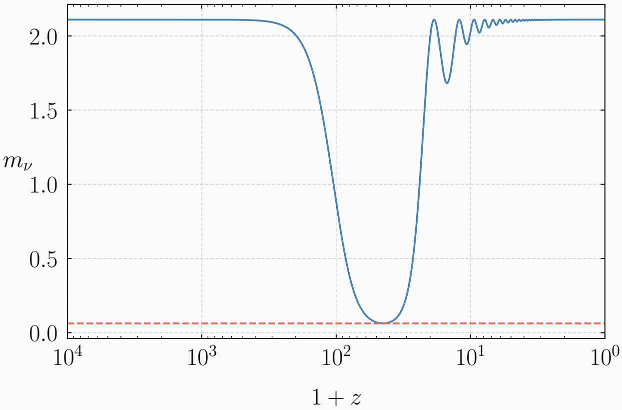
$$V(\phi) = +\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Inverse phase transition model

- Effective potential V_{eff} with $V'_{\text{eff}}(\phi) = \left(\mu^2 + \frac{T_\nu}{M^2}\right)\phi + \lambda\phi^3$
- Scalar effective mass $m^2_{\text{eff}} \equiv V''_{\text{eff}} = \mu^2 + \frac{T_\nu}{M^2}$
  has the opposite sign structure compared to the standard symmetron case

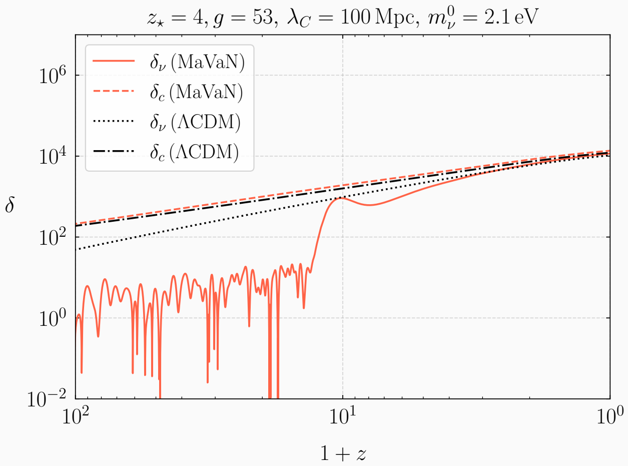


Time evolution of the neutrino mass



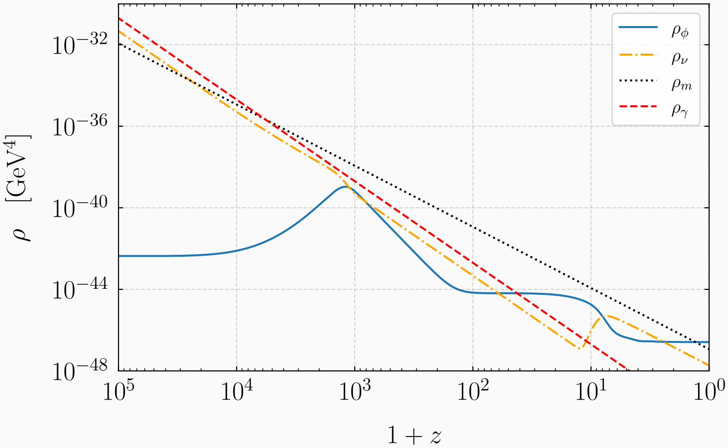
Evolution of the neutrino mass in the inverse phase transition model

Decoupling at late time



Growth of neutrino perturbations are driven by gravity alone, avoiding the instability due to the large scalar-mediated enhancement of neutrino clustering

Phantom like and Hubble tension



$$w_\phi^{\text{eff}} = w_\phi - \frac{\phi\dot{\phi}}{3\mathcal{H}M^2}\frac{\rho_\nu - 3p_\nu}{\rho_\phi}$$

Takeaways

- MaVan models can address the neutrino tension
- But usually suffer from instabilities in the linear regime
- Tamed by MaVaN from an inverse symmetron field
- Potential to address the Hubble tension like with other neutrino-assisted early dark energy scenarios
- Worth studying the inverse phase transition model in the non-linear regime