Massive Neutrino Self-Interactions and the Hubble Tension

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This Talk is based on ...

- **Shouvik Roy Choudhury**, Steen Hannestad, Thomas Tram, "*Updated constraints on massive neutrino self-interactions from cosmology in light of the H_0 tension,*"
  arXiv: 2012.07519 (JCAP 03 (2021) 084).

Introducing Neutrinos

- Active neutrinos have three mass eigenstates (ν_1, ν_2, and ν_3) which are quantum superpositions of the 3 flavour eigenstates (ν_e, ν_μ, and ν_τ). The sum of the mass of the neutrino mass eigenstates, is the quantity,

$$\sum m_\nu \equiv m_1 + m_2 + m_3, \tag{1}$$

  where m_i is the mass of the i^{th} neutrino mass eigenstate.
- Tightest bounds on $\sum m_\nu$ come from cosmology.
- We use the approximation, $m_i = \sum m_\nu / 3$ for all i.
- The radiation density in the early universe can be written as,

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right]\rho_\gamma \tag{2}$$

  N_{eff} is the effective number of relativistic degrees of freedom.

The ΛCDM parametrization

- The **ΛCDM** model parametrization is given by:

$$\theta = \{\Omega_c h^2, \Omega_b h^2, 100\theta_{MC}, \tau, \ln(10^{10}A_s), n_s\}. \quad (3)$$

- $\omega_c \equiv \Omega_c h^2$ and $\omega_b \equiv \Omega_b h^2$ are the present-day physical CDM and baryon densities respectively.
- θ_{MC} is the parameter for **angular size of the sound horizon**, i.e. ratio between the sound horizon r_s^* and the angular diameter distance D_A^* at photon decoupling.
- τ is the optical depth to reionization. $\tau = \int_0^{z_{re}} n_e \sigma_T dl$ where n_e is free electron number density, σ_T is the Thomson scattering cross-section.
- n_s and A_s are the power-law spectral index and amplitude of the primordial scalar perturbations, respectively, at the pivot scale of $k_* = 0.05$ h Mpc^{-1}, i.e. the primordial power spectrum $P(k) = A_s(k/k_*)^{n_s-1}$.

The sound horizon at last scattering

- The comoving sound horizon at the CMB last scattering is

$$r_s^* = \int_{z_*}^{\infty} \frac{c_s(z)dz}{H(z)} \tag{4}$$

- r_s^{drag} is the comoving sound horizon at the end of drag epoch, which is slightly higher (around 2%) than r_s^*
- The angular diameter distance to the last scattering surface is

$$D_A^* = \int_0^{z_*} \frac{dz}{H(z)} \tag{5}$$

- $\theta_{MC} = r_s^* / D_A^* \simeq \pi / \Delta l$, where Δl is the peak spacing in CMB temperature power spectrum.
- Remember, in ΛCDM (+massive neutrinos):

$$H(z)^2 = \left[\omega_\gamma (1+z)^4 + (\omega_c + \omega_b)(1+z)^3 + \omega_\Lambda + \frac{\rho_\nu(z)}{\rho_{\rm cr,0}}\right]. \tag{6}$$

The Hubble Tension

Value from Planck 2018 in ΛCDM : $H_0 = 67.36 \pm 0.54$ km/s/Mpc
Value from calibrated type Ia Supernovae in the local universe: H_0=73.04 ± 1.04 km/s/Mpc (SH0ES 2022)

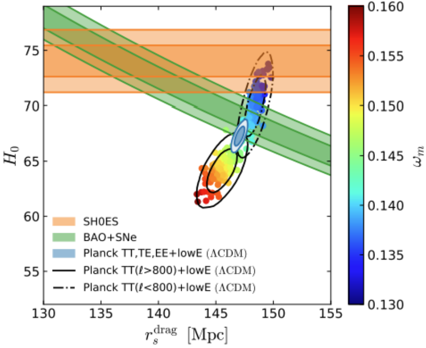


Figure: Depiction of the H0 tension

Lloyd Knox, Marius Millea, arXiv: 1908.03663 (Phys. Rev. D 101, 043533 (2020))

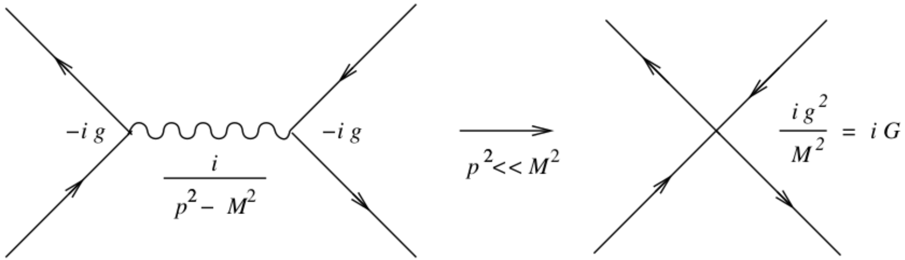
Extra light relics in the early universe

- $100\theta_{MC} = 1.04109 \pm 0.00030$ (68%, Planck 18 TT,TE,EE+lowE). This is a measurement with 0.03%. θ_{MC} is the most well-constrained parameter in all of cosmology.
- Theoretical value of $N_{\rm eff}^{SM} = 3.0440 \pm 0.00024$ assuming standard model of particle physics.
- Extra $\Delta N_{\rm eff} \simeq 1$ can increase $H(z)$ in the early universe, which will decrease r_s^* enough to solve the Hubble tension.
- But in ΛCDM+$N_{\rm eff}$ model: $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (95%, Planck 2018 TT,TE,EE+lowE+lensing+BAO)
- **Simple light relics are not enough to solve the 5σ Hubble tension.**

Neutrino Self-interactions mediated by a heavy scalar

- In this paper we have updated the constraints from cosmology on flavour universal neutrino self-interactions mediated by a heavy scalar ($m_\phi \geq 1$ keV), in the effective 4-fermion interaction limit (CMB temperature is far lower than the keV range).
- Simplified universal interaction: $\mathcal{L}_{\text{int}} \sim g_{ij}\bar{\nu_i}\nu_j\Phi$, with $g_{ij} = g\delta_{ij}$.
- The effective self-coupling, $G_{\text{eff}} = g^2/m_\Phi^2$, with $G_{\text{eff}} > G_F$ (Fermi constant), so that they remain interacting with each other even after decoupling from the photons at $T \sim 1$ MeV.
- The self-interaction rate per particle $\Gamma = n\langle\sigma v\rangle \sim G_{\text{eff}}^2 T_\nu^5$, where $n \propto T_\nu^3$ is the number density of neutrinos. Neutrinos don't free-stream until $\Gamma < H$.
- Introducing this kind of interaction had shown potential in solving the Hubble tension in previous works in the very strong interaction range ($G_{\text{eff}} \sim 10^9 G_F$) using older data.

Feynman Diagram



$\mathrm{M} \equiv m_\Phi$

The Cosmological Model of interest

- Cosmological model: $\mathbf{\Lambda CDM + log_{10}\left[G_{eff}MeV^2\right] + N_{eff}} + \sum \boldsymbol{m_\nu}$.
- Kreisch et. al., Phys. Rev. D 101, 123505 (2020) (arXiv: 1902.00534) found the 68% bounds:
  $\mathbf{log_{10}\left[G_{eff}MeV^2\right] = -1.41^{+0.20}_{-0.066}}$ (strong self-interactions),
  $\boldsymbol{H_0} = \mathbf{71.1 \pm 2.2\ km/s/Mpc}$,
  $\boldsymbol{N_{\mathrm{eff}}} = \mathbf{3.80 \pm 0.45}$,
  $\sum \boldsymbol{m_\nu} = \mathbf{0.39^{+0.16}_{-0.20}\ eV}$
  with **Planck 2015 low-*l* and high-*l* TT+lensing** combined with **BAO**, with similar goodness of fit to the data as $\mathbf{\Lambda CDM}$.
- In this model, $\boldsymbol{N_{\mathrm{eff}}}$ and $\boldsymbol{H_0}$ are **positively correlated** $\rightarrow$ Solution to the Hubble tension came from high $\boldsymbol{N_{\mathrm{eff}}} \simeq \mathbf{4}$ values.
- Planck polarization data was not used for main conclusions.

The Cosmological Model of Interest

Image Credit: Kreisch et. al., Phys. Rev. D 101, 123505 (2020), arXiv: 1902.00534

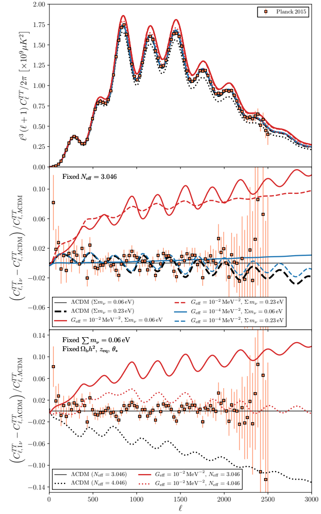


Figure: Degeneracy of of G_{eff} with N_{eff} and $\sum m_\nu$ in the CMB TT spectrum.

The Cosmological Model of interest

- **With the public release of the Planck 2018 likelihoods, we thought it is timely to test the model again.**
- We made runs which incorporated the full prior range of $\mathbf{\log_{10}\left[G_{eff}\mathrm{MeV}^2\right]}$, i.e. $\mathbf{-5.5 \rightarrow -0.1}$.
- We also run the non-interacting case ($\mathbf{NI\nu}$: $\boldsymbol{G_{\rm eff} = 0}$), the moderately interacting case $\mathbf{MI\nu}$ ($\mathbf{\log_{10}\left[G_{eff}MeV^2\right] \lesssim -2}$), and the strongly interacting case ($\mathbf{SI\nu}$) ($\mathbf{\log_{10}\left[G_{eff}MeV^2\right] \gtrsim -2}$) separately.
- We sample the parameter space using the nested sampling technique. We use the publicly available **PolyChord** extension of **CosmoMC**, called **CosmoChord**.
- Use of the nested-sampling package PolyChord enables us to calculate evidences accurately, and properly sample this parameter space of **bimodal posterior distributions**.
- We modify the **CAMB** code to incorporate the neutrino self-interactions in the perturbation equations.

Plots from runs with full prior range of $\log_{10}[G_{\rm eff}\,{\rm MeV}^2]$

Main conclusions follow from the TTTEEE+lowE+EXT dataset (blue curve).

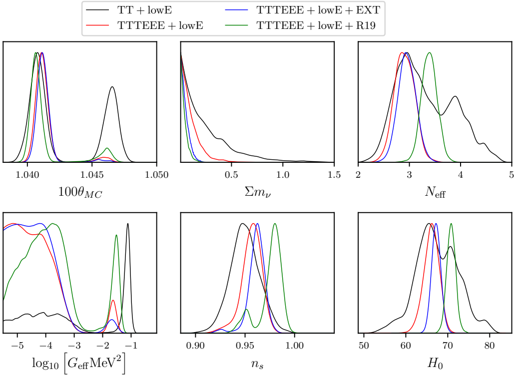
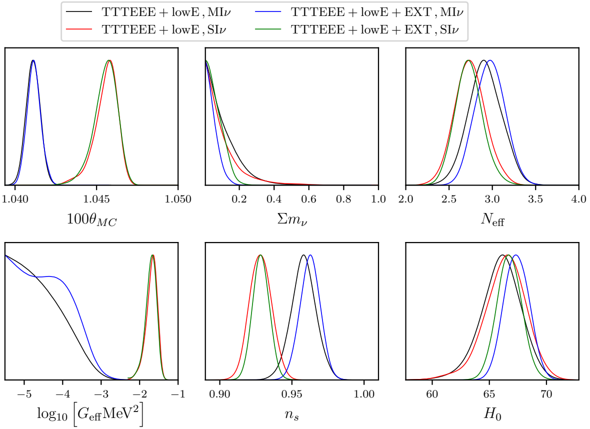


Figure: Here TTTEEE+lowE denotes the full Planck 2018 temperature and polarisation data. EXT denotes Planck 2018 lensing + BAO + RSD + SNeIa. R19 is the Gaussian prior of $H_0 = 74.03 \pm 1.42$ km/s/Mpc.

Roy Choudhury et al, arXiv 2012.07519 (JCAP 03 (2021) 084)

Mode separation: MIν and SIν plots shown separately



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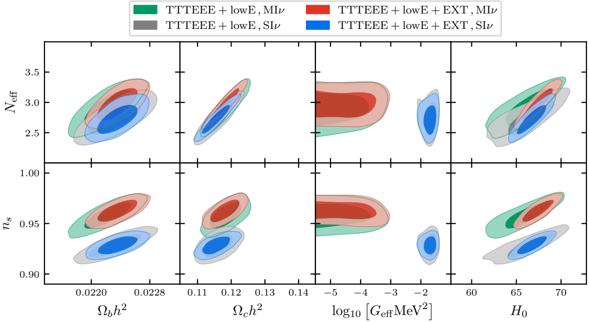

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Discussion

- $\log_{10}\left[\mathbf{G_{eff}MeV^2}\right]$ is degenerate with θ_{MC} and n_s. This allows for a bimodal posterior distribution, even with the latest full Planck data.
- With **TTTEEE+lowE+EXT** we found the following **95% bounds**, for the **SIν**
  $H_0 = 66.7^{+2.2}_{-2.1}$ **km/s/Mpc**
  $N_{\rm eff} = 2.73^{+0.34}_{-0.31}$
  $\sum m_\nu < 0.15$ **eV**.
- Even if one were to re-analyze the data with a fixed $N_{\rm eff} = 3.044$ with massive neutrinos and strong interactions, one would very likely get H_0 values in the ballpark of **69 − 70 km/s/Mpc** (as can be seen from the plots above), which does not work as a solution to the Hubble tension, albeit reducing the tension slightly compared to vanilla **ΛCDM**.
- For the Non-interacting case ($\mathbf{NI\nu : \Lambda CDM + N_{eff} + \sum m_\nu}$), we find $H_0 = 67.3 \pm 2.2$ **km/s/Mpc (95%)** → The strongly interacting model doesn't work better than this simple extension to **ΛCDM**.

EXT ≡ Planck 2018 lensing + BAO + RSD + SNeIa

Discussion

- Furthermore, **Neutrino self-interactions are also strongly constrained from particle physics experiments**, with the exception of flavour specific interaction among the $\boldsymbol{\tau}$-neutrinos.
- We find, $\mathbf{-2\,[\log\left(\mathcal{L}_{SI\nu}/\mathcal{L}_{NI\nu}\right)] = 3.4}$ (approx. $\boldsymbol{\Delta\chi^2}$), and $\boldsymbol{Z_{SI\nu}/Z_{NI\nu} = 0.06}$ (evidence ratio), with **TTTEEE+lowE+EXT**.
- **Bayesian evidences and log likelihood values both disfavour very strong self-interactions** compared to $\mathbf{\Lambda CDM + N_{eff} + \sum m_\nu}$, i.e. the non-interacting scenario $\mathbf{NI\boldsymbol{\nu}}$.
- **To conclude, with current data, the strong neutrino self-interaction model does not look like a promising solution to the current $\boldsymbol{H_0}$ discrepancy.**

Particle Physics Constraints

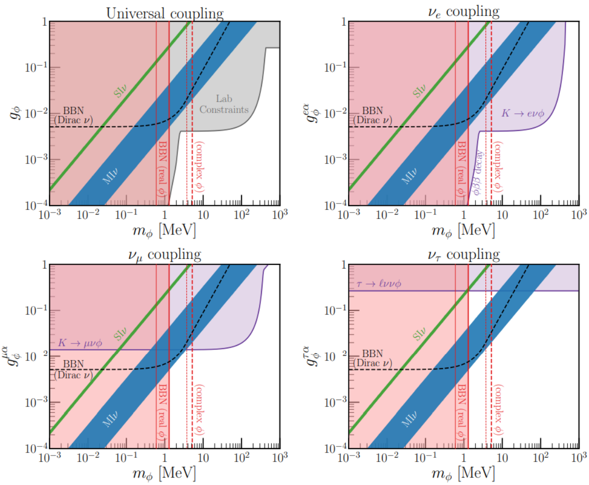

Figure: Constraints from particle physics

Nikita Blinov et al, arXiv 1905.02727 (Phys.Rev.Lett. 123 (2019) 19, 191102)

THE END

Thanks for listeninng! Questions are welcome!