Neutrino Self-Interactions. Hubble Tension, and Inflation

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- **Collaborators: Steen Hannestad and Thomas Tram, Aarhus University, Denmark**

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)**.
- **Shouvik Roy Choudhury**, Steen Hannestad, Thomas Tram, "*Massive neutrino self-interactions and Inflation*," **arXiv:2207.07142 (JCAP 10 (2022) 018)**.

Part 1

- **Part 1: Related to Hubble Tension.**

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} the parameter used by CosmoMC to parametrize the **angular size of the sound horizon**, i.e. ratio between the sound horizon and the angular diameter distance 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 $P(k) = A_s(k/k_*)^{n_s-1}$.

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.

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) found the 68% bounds:
  $\mathbf{\log_{10}\left[G_{eff} MeV^2\right] = -1.41^{+0.20}_{-0.066}}$ (strong self-interactions),
  $\boldsymbol{H_0 = 71.1 \pm 2.2}$ **km/s/Mpc**,
  $\boldsymbol{N_{eff} = 3.80 \pm 0.45}$,
  $\boldsymbol{\sum m_\nu = 0.39^{+0.16}_{-0.20}}$ **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, $\boldsymbol{N_{eff}}$ and $\boldsymbol{H_0}$ are **positively correlated** $\rightarrow$ Solution to the Hubble tension came from high $\boldsymbol{N_{eff} \simeq 4}$ values.
- Planck polarization data was not used for main conclusions.

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 $\mathbf{\log_{10}}\left[\mathbf{G_{eff}}\mathrm{MeV}^{\mathbf{2}}\right]$, i.e. $\mathbf{-5.5 \rightarrow -0.1}$.
- We also run the non-interacting case ($\mathbf{NI\nu}$:$\boldsymbol{G}_{\mathbf{eff=0}}$), the moderately interacting case $\mathbf{MI\nu}$ ($\mathbf{\log_{10}}\left[\mathbf{G_{eff}MeV^2}\right] \lesssim \mathbf{-2}$), and the strongly interacting case ($\mathbf{SI\nu}$) ($\mathbf{\log_{10}}\left[\mathbf{G_{eff}MeV^2}\right] \gtrsim \mathbf{-2}$) separately.

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

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

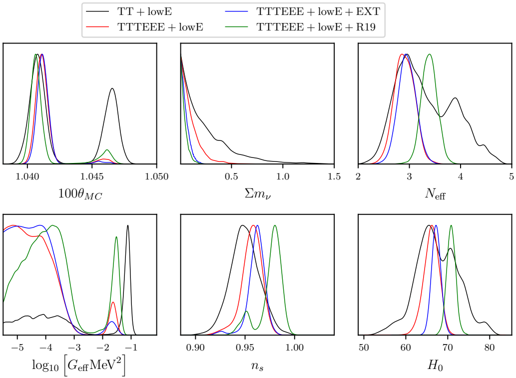
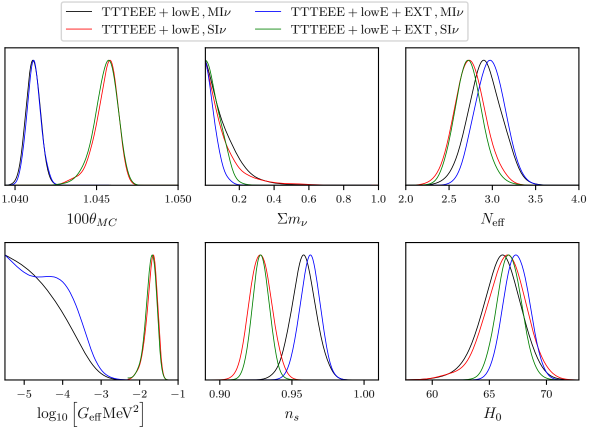


Figure: Here TTTEEE+lowE denotes the full Planck 2018 temperature and polarisation data. EXT denotes Planck 2018 lensing + BAO + RSD + SNeIa. R19 is the Gaussian prior of $H_0 = 74.03 \pm 1.42$ km/s/Mpc.

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

Mode separation: MIν and SIν plots shown separately



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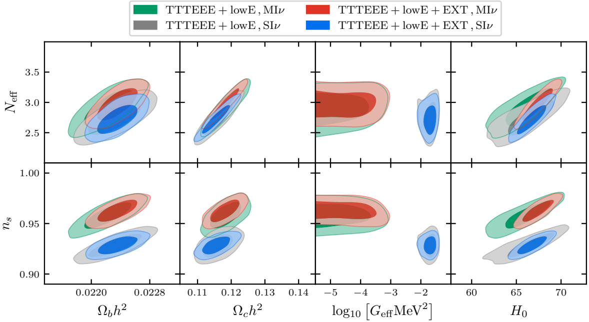

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Discussion

- $\log_{10}\left[G_{\rm eff} \text{MeV}^2\right]$ 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 $\mathbf{NI\nu}$.
- **To conclude, with current data, the strong neutrino self-interaction model does not look like a promising solution to the current H_0 discrepancy.**

Part 2

- **Part 2: Related to Inflationary models.**

Inflationary Models

- The primordial scalar and tensor power spectra are usually parameterized as: $\mathcal{P}_s = A_s(k/k_*)^{n_s-1}$ and $\mathcal{P}_t = A_t(k/k_*)^{n_t}$, respectively, with the tensor-to-scalar ratio $r \equiv A_t/A_s$. Pivot scale : k_*.
- A general slow roll single field inflationary model Lagrangian:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi), \tag{4}$$

- Slow roll parameters: $\epsilon(\phi) \equiv \frac{m_{\rm pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2; \quad \eta(\phi) \equiv \frac{m_{\rm pl}^2}{8\pi}\left(\frac{V''}{V}\right).$
- Cosmological observables: $n_s = 1 - 6\epsilon(\phi_s) + 2\eta(\phi_s); \;\; r = 16\epsilon(\phi_s).$
- Inflation ends when $\epsilon(\phi_e) = 1$.
- Number of e-folds: $N_* \simeq -\frac{8\pi}{m_{\rm pl}^2} \int_{\phi_s}^{\phi_e} \frac{V}{V'} d\phi.$
- $N_* \simeq 40 - 60$ for observable fluctuations in CMB.
- So given a potential $V(\phi)$, and a choice of N_*, one can predict the scalar spectral index n_s, and tensor to scalar ratio r.

Models of Concern: Inflationary and Cosmological

- We are interested in Natural inflation (NI) and Coleman-Weinberg Inflation (CWI).
- $V_{\mathrm{NI}}(\phi) = \lambda^4 \left(1 + \cos\left(\frac{\phi}{g}\right)\right)$
- $V_{\mathrm{CWI}}(\phi) = A\phi^4 \left[\ln\left(\frac{\phi}{f}\right) - \frac{1}{4}\right] + \frac{Af^4}{4}$.
- Both models are ruled out by current cosmological data at more than 2σ in the minimal $\Lambda\mathrm{CDM} + \mathrm{r}$ model.
- Now the cosmological model of interest is: $\Lambda\mathrm{CDM} + \log_{10}\left[\mathrm{G_{eff}MeV^2}\right] + \mathrm{N_{eff}} + \sum m_\nu + r_{0.05}$,
- $k_* =$0.05h Mpc^{-1} is the pivot scale.
- We modify the Boltzmann equations both for scalar and tensor perturbations.
- Two scenarios: 3ν interacting and 1ν interacting.

Disfavoured by Cosmological Data

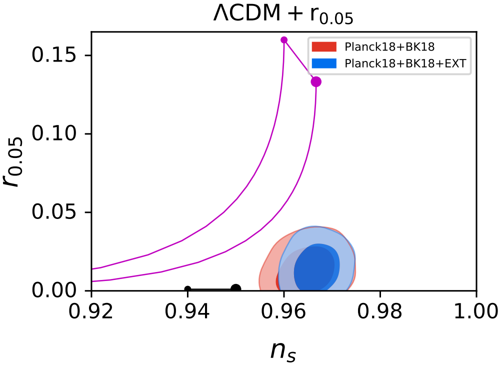

Figure: Natural Inflation (Magenta). CW Inflation (Black). $\mathbf{50 < N_* < 60}$. Planck18=TT,TE,EE+lowE. BK18=BICEP/Keck CMB B-mode data. EXT denotes Planck 2018 lensing + BAO + RSD + SNeIa.

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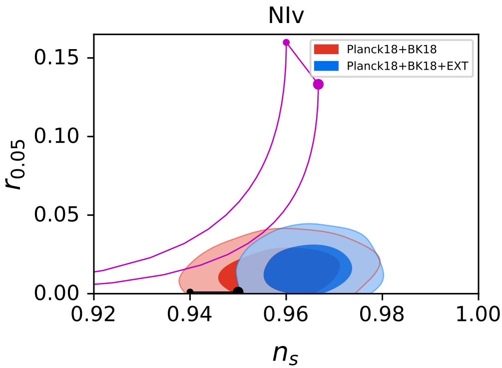
Disfavoured by Cosmological Data

- They are disfavoured at 2σ even in the $\mathrm{NIv} \equiv \mathbf{\Lambda CDM + r_{0.05} + N_{eff} + \sum m_{\nu}}$ model, with the most constraining dataset combination.



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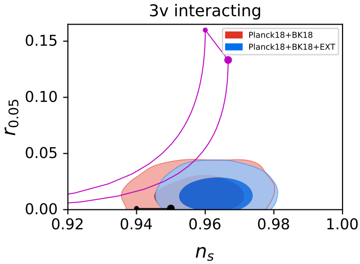
Effect of Neutrino self-interactions: allowed at 2σ



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Discussion

- Strong neutrino self-interactions induce changes in the CMB spectra that lead to lower $\boldsymbol{n_s}$ values.
- In this analysis, we include the neutrino interaction in both scalar and tensor perturbation equations.
- We consider two scenarios: 1. all 3 neutrinos interacting, 2. only one neutrino interacting.
- We find that for the full range runs of $\mathbf{log_{10}}\left[\boldsymbol{G}_{\rm eff}\mathrm{MeV}^{\mathbf{2}}\right]$, both NI and CWI are allowed at $2\boldsymbol{\sigma}$, though not at $1\boldsymbol{\sigma}$.

THE END

THANK YOU