

Massive Neutrino Self-Interactions and Inflation

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

- **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,

$$\sum m_\nu \equiv m_1 + m_2 + m_3, \quad (1)$$

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,

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

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

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: $\Lambda\text{CDM} + \log_{10} [\mathbf{G_{\text{eff}}\text{MeV}^2}] + N_{\text{eff}} + \sum m_\nu$.
- Kreisch et. al., Phys. Rev. D 101, 123505 (2020) found the 68% bounds:
 $\log_{10} [\mathbf{G_{\text{eff}}\text{MeV}^2}] = -1.41_{-0.066}^{+0.20}$ (strong self-interactions),
 $\mathbf{H_0} = 71.1 \pm 2.2 \text{ km/s/Mpc}$,
 $\mathbf{N_{\text{eff}}} = 3.80 \pm 0.45$,
 $\sum m_\nu = 0.39_{-0.20}^{+0.16} \text{ eV}$
with **Planck 2015 low- l and high- l TT+lensing** combined with **BAO**, with similar goodness of fit to the data as ΛCDM .
- In this model, N_{eff} and H_0 are **positively correlated** \rightarrow Solution to the Hubble tension came from high $N_{\text{eff}} \simeq 4$ 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 $\log_{10} [\mathbf{G}_{\text{eff}} \text{MeV}^2]$, i.e. $-5.5 \rightarrow -0.1$.
- We also run the non-interacting case ($\mathbf{NI}\nu: \mathbf{G}_{\text{eff}}=0$), the moderately interacting case $\mathbf{MI}\nu$ ($\log_{10} [\mathbf{G}_{\text{eff}} \text{MeV}^2] \lesssim -2$), and the strongly interacting case ($\mathbf{SI}\nu$) ($\log_{10} [\mathbf{G}_{\text{eff}} \text{MeV}^2] \gtrsim -2$) separately.

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

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

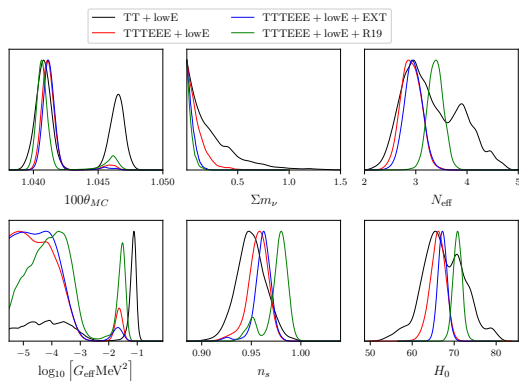


Figure: Here TTTEEE+lowE denotes the full Planck 2018 temperature and polarisation data. EXT denotes Planck 2018 lensing + BAO + RSD + SNeIa. R19 is the Gaussian prior of $H_0 = 74.03 \pm 1.42$ km/s/Mpc.

Mode separation: $M\nu$ and $S\nu$ plots shown separately

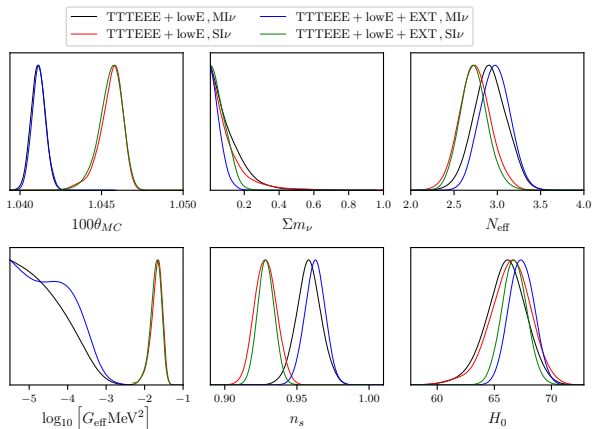


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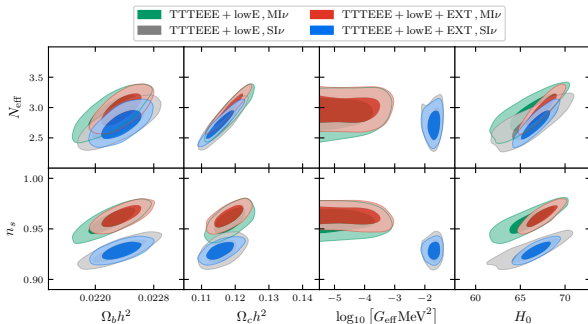


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Roy Choudhury et al, arXiv 2012.07519 (JCAP 03 (2021) 084)

Discussion

- $\log_{10} [\mathbf{G_{eff} MeV^2}]$ 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 **SI ν**
$$H_0 = 66.7_{-2.1}^{+2.2} \text{ km/s/Mpc}$$
$$N_{\text{eff}} = 2.73_{-0.31}^{+0.34}$$
$$\sum m_\nu < 0.15 \text{ eV.}$$
- Even if one were to re-analyze the data with a fixed $N_{\text{eff}} = 3.044$ 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 (**NI ν : $\Lambda\text{CDM} + N_{\text{eff}} + \sum m_\nu$**), we find $H_0 = 67.3 \pm 2.2 \text{ km/s/Mpc}$ (95%) \rightarrow The strongly interacting model doesn't work better than this simple extension to ΛCDM .

Discussion

- Furthermore, **Neutrino self-interactions are also strongly constrained from particle physics experiments**, with the exception of flavour specific interaction among the τ -neutrinos.
- We find, $-2 [\log (\mathcal{L}_{\text{SI}\nu} / \mathcal{L}_{\text{NI}\nu})] = 3.4$ (approx. $\Delta\chi^2$), and $Z_{\text{SI}\nu} / Z_{\text{NI}\nu} = 0.06$ (evidence ratio), with **TTTEEE+lowE+EXT**.
- **Bayesian evidences and log likelihood values both disfavour very strong self-interactions** compared to $\Lambda\text{CDM} + N_{\text{eff}} + \sum m_\nu$, i.e. the non-interacting scenario **NI**.
- **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: 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:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi), \quad (3)$$

- Slow roll parameters: $\epsilon(\phi) \equiv \frac{m_{\text{pl}}^2}{16\pi} \left(\frac{V'}{V}\right)^2$; $\eta(\phi) \equiv \frac{m_{\text{pl}}^2}{8\pi} \left(\frac{V''}{V}\right)$.
- 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: $N_* \simeq -\frac{8\pi}{m_{\text{pl}}^2} \int_{\phi_s}^{\phi_e} \frac{V}{V'} d\phi$.
- $N_* \simeq 40 - 60$ 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).
- $V_{\text{NI}}(\phi) = \lambda^4 \left(1 + \cos \left(\frac{\phi}{g} \right) \right)$
- $V_{\text{CWI}}(\phi) = A\phi^4 \left[\ln \left(\frac{\phi}{f} \right) - \frac{1}{4} \right] + \frac{Af^4}{4}$.
- Both models are ruled out by current cosmological data at more than 2σ in the minimal $\Lambda\text{CDM} + \mathbf{r}$ model.
- Now the cosmological model of interest is:
 $\Lambda\text{CDM} + \log_{10} [\mathbf{G}_{\text{eff}} \text{MeV}^2] + \mathbf{N}_{\text{eff}} + \sum m_\nu + r_{0.05}$,
- $k_* = 0.05h \text{ Mpc}^{-1}$ 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

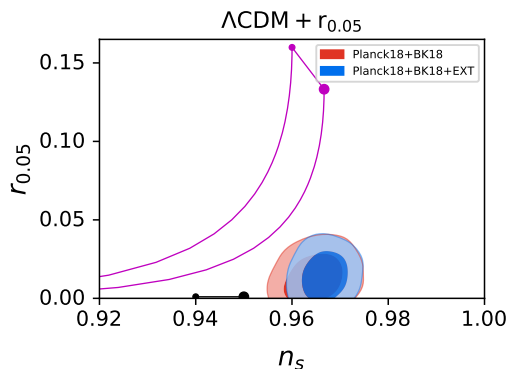


Figure: Natural Inflation (Magenta). CW Inflation (Black). $50 < N_* < 60$.
Planck18=TT,TE,EE+lowE. BK18=BICEP/Keck CMB B-mode data. EXT denotes Planck 2018 lensing + BAO + RSD + SNeIa.

Roy Choudhury et al, arXiv:2207.07142 (JCAP 10 (2022) 018).

Disfavoured by Cosmological Data

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

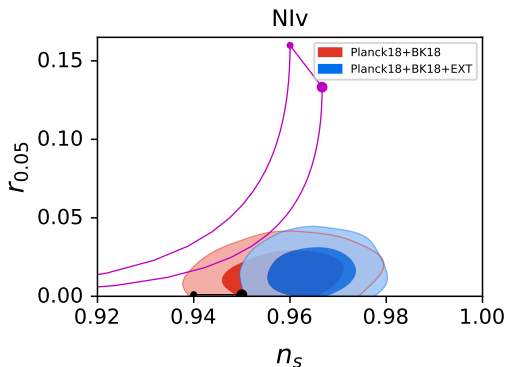


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Effect of Neutrino self-interactions: allowed at 2σ

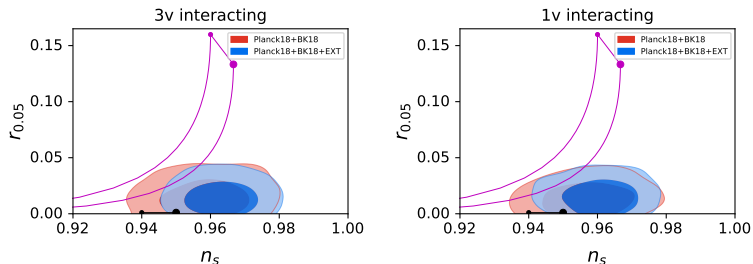


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Roy Choudhury et al, arXiv:2207.07142 (JCAP 10 (2022) 018).

Discussion

- Strong neutrino self-interactions induce changes in the CMB spectra that lead to lower 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 $\log_{10} [G_{\text{eff}}\text{MeV}^2]$, both NI and CWI are allowed at 2σ , though not at 1σ .

THE END

THANK YOU