Gauged neutrino self-interactions and the Hubble tension

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based on **arXiv:2004.13039**
with Max Berbig (Bonn) and Sudip Jana (MPIK)

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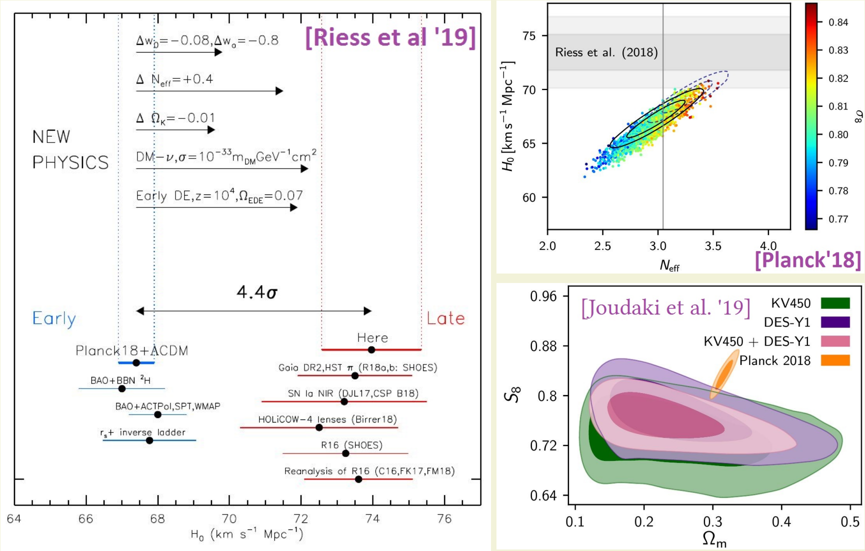
Outline

- The Hubble tension
- Self-interacting neutrino solution
- Explicit model
- Constraints & Comments

The Hubble tension



$$N_{\rm eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} (\rho_{\rm rad.}^{\rm inv.}/\rho_\gamma)\ , \qquad S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3}$$

Self-interacting neutrino solution

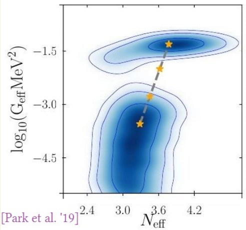
[Cyr-Racine, Sigurdson'13; Archidiacono, Hannestad'14]
[Lancaster, Cyr-Racine, Knox, Pan '17; Oldengott, Tram, Rampf, Wong '17]
[Kreisch, Cyr-Racine, Doré '19; Park, Kreisch, Dunkley, Hadzhiyska, Cyr-Racine'19]

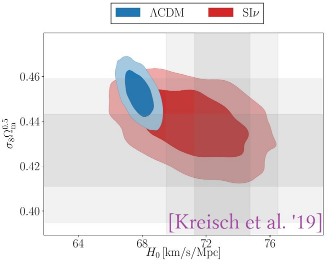
Cosmology (CMB) fit including effective 4ν interaction $G_{\text{eff}}(\overline{\nu}\nu)(\overline{\nu}\nu)$:

$$G_{\text{eff}} \equiv \frac{g_{\text{eff}}^2}{m_{Z'}^2} \approx \begin{cases} (5\ \text{MeV})^{-2} & \text{“SI}\nu\text{”} \\ \lesssim (100\ \text{MeV})^{-2} & \text{“WI}\nu\text{”}\ . \end{cases}$$

[Kreisch et al. 19]

Parameter	Strongly Interacting Neutrino Mode
$\Omega_{\text{b}}h^2$	$0.02245^{+0.00029}_{-0.00033}$
$\Omega_{\text{c}}h^2$	$0.1348^{+0.0056}_{-0.0049}$
$100\theta_{\text{MC}}$	1.04637 ± 0.00056
τ	0.080 ± 0.031
$\sum m_\nu$ [eV]	$0.42^{+0.17}_{-0.20}$
N_{eff}	4.02 ± 0.29
$\log_{10}(\text{G}_{\text{eff}}\text{MeV}^2)$	$-1.35^{+0.12}_{-0.066}$
$\ln(10^{10}A_s)$	3.035 ± 0.060
n_{s}	0.9499 ± 0.0098
H_0 [km/s/Mpc]	72.3 ± 1.4
Ω_{m}	0.3094 ± 0.0083
σ_8	0.786 ± 0.020
$10^9 A_{\text{s}}$	$2.08^{+0.11}_{-0.13}$
$10^9 A_{\text{s}}e^{-2\tau}$	1.771 ± 0.016
r_* [Mpc]	136.3 ± 2.4
$100\theta_*$	1.04604 ± 0.00056
D_{A} [Gpc]	13.03 ± 0.23
r_{drag} [Mpc]	138.8 ± 2.5

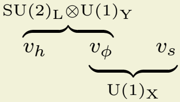


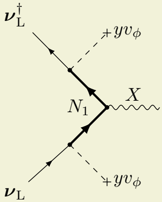


The model

Field	Φ	N_1	N_2	S	X_μ
$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$	$(\mathbf{2}, -\frac{1}{2})$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
$\mathrm{U}(1)_\mathrm{X}$	$+1$	$+1$	-1	$+1$	0
$\mathrm{U}(1)_\mathrm{L}$	0	$+1$	-1	0	0

$$\mathcal{L}_\mathrm{new} = -y\,\overline{\boldsymbol{L}}\,\tilde{\Phi}\,N_1 - M\,N_1\,N_2 + \mathrm{h.c.},$$





$$\Longrightarrow \quad G_\mathrm{eff}^{4\nu} = \frac{g_X^2\,\varepsilon_m^4}{m_{Z'}^2}\,,$$

with $\tan\varepsilon_m := (y v_\phi)/(\sqrt{2}M)$.

(neutrino mass mixing)

The model

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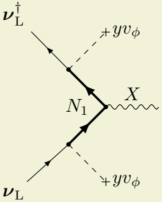
$\mathrm{U(1)_X}$	$+1$	$+1$	-1	$+1$	0
$\mathrm{U(1)_L}$	0	$+1$	-1	0	0

$\mathrm{SU(2)_L \otimes U(1)_Y}$: v_h, v_ϕ

$\mathrm{U(1)_X}$: v_ϕ, v_s



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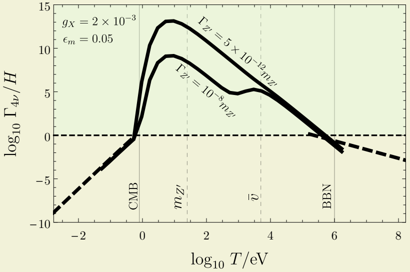
Re- and *de*-coupling behavior:

$$\Longrightarrow 2\times 10^{-7} \lesssim g_X\,\varepsilon_m^2 \lesssim 5\times 10^{-6}\,,$$
$$1\,\mathrm{eV} \lesssim m_{Z'} \lesssim 25\,\mathrm{eV}.$$

$$\Longrightarrow \quad \xi := \frac{\sqrt{v_\phi^2 + v_s^2}}{v_h} \approx \varepsilon_m^2 \times 2\times 10^{-5}$$

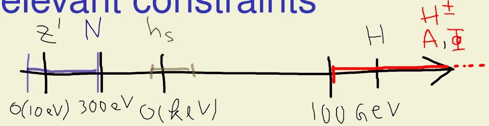
One more useful ratio: $\tan\gamma := \dfrac{v_\phi}{v_s}$;



Parameters to have in mind: $2\times 10^{-5} \lesssim y \lesssim 6\times 10^{-3},\; 5\times 10^{-4} \lesssim \varepsilon_m \lesssim 0.05,\; s_\gamma \lesssim 0.2$

Most relevant constraints

- Particle mass spectrum:



- Z', h_S, N VERY suppressed couplings to SM fermions (other than neutrinos).
- PMNS unitarity / μ/nuclear-decays / LFU
  [Fernandez-Martinez et al.'16],[Farzan, Heeck '20]

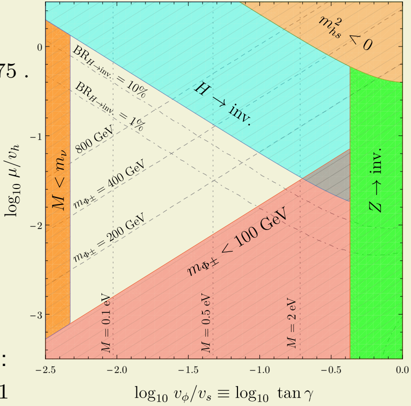
  $\varepsilon_m^{(e)} \leq 0.050\,, \quad \varepsilon_m^{(\mu)} \leq 0.021\,, \quad \varepsilon_m^{(\tau)} \leq 0.075\,.$
- Direct charged scalar searches (LEP/LHC).
- Invisible Z / Higgs decays: $\mathcal{L} \supset -\sqrt{2}\mu\, H^\dagger \Phi S^*$

  $H \to h_S h_S, Z'Z';\ Z \to Z' h_S$
- BBN: $\Delta N_{\rm eff}^{BBN} \approx 0$. No thermal abundance of new states allowed.

  $\Rightarrow \quad y \lesssim 6 \times 10^{-3} (m_{H^\pm(\Phi)}/100\ \mathrm{GeV})$

  $\curvearrowright\ M \lesssim 300\,\mathrm{eV}$
- CMB $\Delta N_{\rm eff} \overset{!}{\approx} 1$. Intriguing: automatically from re-and-decoupling of ν's with Z', h_S, N:

  $\Delta N_{\rm eff}^{CMB} \approx 1.03, 0.93, 0.74$ for $n_\nu = 3, 2, 1$



Two comments

1. “Model independent” constraints? [Blinov, Kelly, Krnjaic, McDermott ’19] [Lyu, Stamou, Wang ’20]

   Exclusion of $G_{\rm eff}^{4\nu}$ from $2\nu\beta\beta$ decay? [Deppisch, Graf, Rodejohann, Xu ’20]

   These basically rule out mediators $m \gtrsim \mathrm{keV}$ generating $G_{\rm eff}^{4\nu}$.

   They do not exclude this model.

2. Z' Coupling to “non-conserved currents” and $1/m_{Z'}^2$ enhanced rates? [Bakhti& Farzan ’17],[Dror, Lasenby, Pospelov ’17]

   Goldstone boson equivalence: rates must be proportional to ys_γ (the $1/m_{Z'}^2$ “enhancement” cancels in gauge invariant models.)

   Upshot: model seems to be currently not constrained by these.

Conclusions

- Despite strong constraints, this model shows that it is, in principle, possible to have consistent self-interacting neutrino models (not only) for Hubble tension.
- Preferred parameter region:
  - Charged Higgses at a few $100\,\mathrm{GeV}$,
  - Sizable $\mathrm{BR}(\mathrm{Higgs} \to \mathrm{inv.})$,
  - Hidden neutrino(s) with mass(es) $M_N \sim 1 \div 300\,\mathrm{eV}$ and active-hidden mixing with angle $\varepsilon_m > 5 \times 10^{-4}$,
  - NSI with $G_{\mathrm{eff}}^{(2\nu)(2f\neq\nu)} \sim \mathcal{O}(10^{-4}) G_{\mathrm{F}}$.

  Note: By chance, this is also the correct range to potentially resolve SBL ν anomalies. Either with eV-scale hidden neutrinos, **or** with $\mathcal{O}(100\,\mathrm{eV})$ "decaying hidden neutrino solution".
  [Dentler,Esteban,Kopp,Machado'19],[De Gouvea,Peres,Prakash'19]

Thank You

Backup slides

Neutrino masses

Masses of neutral gauge bosons up to $\mathcal{O}(\xi^2)$:

$$m_Z \approx \frac{g_2\, v_h}{2c_W} \quad \text{and} \quad m_{Z'} \approx g_X\, \overline{v} := g_X \sqrt{v_\phi^2 + v_s^2}\;.$$

Neutrino mass matrix in gauge basis $(\nu, \overline{N}_1, \overline{N}_2)$:

$$M_\nu = \begin{pmatrix} \mathbf{0} & -y v_\phi/\sqrt{2} & 0 \\ -y v_\phi/\sqrt{2} & 0 & M \\ 0 & M & \mathbf{0} \end{pmatrix}.$$

Diagonalized by 13-rotation by ε_m. Dirac neutrino N with $M_N := \sqrt{M^2 + y^2 v_\phi^2/2}$.

$$M = (y/\sqrt{2})\, \varepsilon_m\, s_\gamma\, (G_{\text{eff}}^{4\nu})^{-1/2} \;\ll\; 5\ \text{MeV}\;.$$

Mass generation for active neutrinos $m_\nu \ll y v_\phi$ is only a small perturbation to this setting. All of the commonly considered neutrino mass generation mechanisms (Weinberg op., Dirac, inv. see-saw) are compatible with this model.

Scalar mass spectrum

Scalar sector $\hat{=}$ 2HDM+scalar singlet + $\mathrm{U}(1)$p.
Scalar masses to leading order in $\xi \equiv \overline{v}/v_h$:

$$m_H^2 = 2\,\lambda_H\,v_h^2\;, \quad m_\Phi^2 = m_A^2 = \frac{2\,v_h\,\mu}{s_{2\gamma}}\;,$$

$$m_{H^\pm}^2 = \frac{v_h\,\mu}{t_\gamma} - \frac{\lambda_4}{2}v_h^2\;,$$

$$m_{h_S}^2 \approx \xi^2 v_h^2 \left(2\lambda_S - \frac{\lambda_{HS}^2}{2\lambda_H}\right) + \mathcal{O}(\gamma\mu/v_h)\;.$$

We diagonalize the neutral scalar mass matrix by three orthogonal rotations $O = R(\theta_{13})R(\theta_{12})R(\theta_{23})$, such that

$$O^{\mathrm{T}}\,M_{\mathrm{n.s.}}^2\,O = \mathrm{diag}\left(m_{h_S}^2, m_H^2, m_\Phi^2\right)\;.$$

Mixing angles, also to leading order in ξ, are

$$s_{12} \equiv s_{S\Phi} = s_\gamma\;, \quad s_{13} \equiv s_{HS} = \xi\,\frac{p\,t_\gamma + q}{2\,v_h\,\lambda_H}\;,$$

$$s_{23} \equiv s_{\Phi H} = \xi\,s_\gamma\,\frac{\mu\,(p\,t_\gamma + q) - 2\lambda_H\,v_h\,p}{2\,\lambda_H\,v_h\,(\lambda_H\,v_h\,s_{2\gamma} - \mu)}\;,$$

where $\lambda_{34} := \lambda_3 + \lambda_4$ and

$$p := \lambda_{34}\,v_H\,s_\gamma - \mu\,c_\gamma\;, \quad q := \lambda_{HS}\,v_H\,c_\gamma - \mu\,s_\gamma.$$

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