Karlsruhe Institute of Technology

KIT Center for Particle and Astroparticle Physics

Collaborative Research Center
Particle Physics Phenomenology after the Higgs Discovery (P3H)

Light scalars from triplet Higgs fields: neutrinos, cosmology, and colliders

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G. Barenboim and UN, *Modified majoron model for cosmological anomalies, Phys.Rev.D* 104 (2021) 2, 023013 [arXiv:2005.13280 [hep-ph]]

1. Cosmological anomalies and neutrino interactions

During inflation two types of perturbations are produced:

- scalar (or matter) perturbations
  and
- tensor (or metric) perturbations (gravity waves)

The prediction of their ratio r from inflationary models based on the Standard Model (SM) and the ΛCDM model is in tension with the value found from the anisotropies of the cosmic microwave background (CMB).

Hubble tension:

The value of the Hubble constant inferred from local measurements differs from the value found from CMB data.

Both tension can be alleviated by postulating a new interaction between neutrinos mediated by a light (pseudo-)scalar.

- Tensor-to-scalar ratio:

I. M. Oldengott, T. Tram, C. Rampf and Y. Y. Wong, JCAP 11 (2017), 027.
L. Lancaster, F. Y. Cyr-Racine, L. Knox and Z. Pan, JCAP 07 (2017), 033.
C. D. Kreisch, F. Y. Cyr-Racine and O. Doré, *Phys.Rev.D* 101 (2020) 12, 123505.
G. Barenboim, P. B. Denton and I. M. Oldengott, Phys. Rev. D 99 (2019) no.8, 083515.

- Hubble tension:

N. Blinov, K. J. Kelly, G. Z. Krnjaic and S. D. McDermott, Phys.Rev.Lett. 123 (2019) no.19, 191102.
M. Escudero and S. J. Witte, Eur. Phys. J. C 80 (2020) no.4, 294.

Effective description for neutrino interaction with a scalar ϕ:

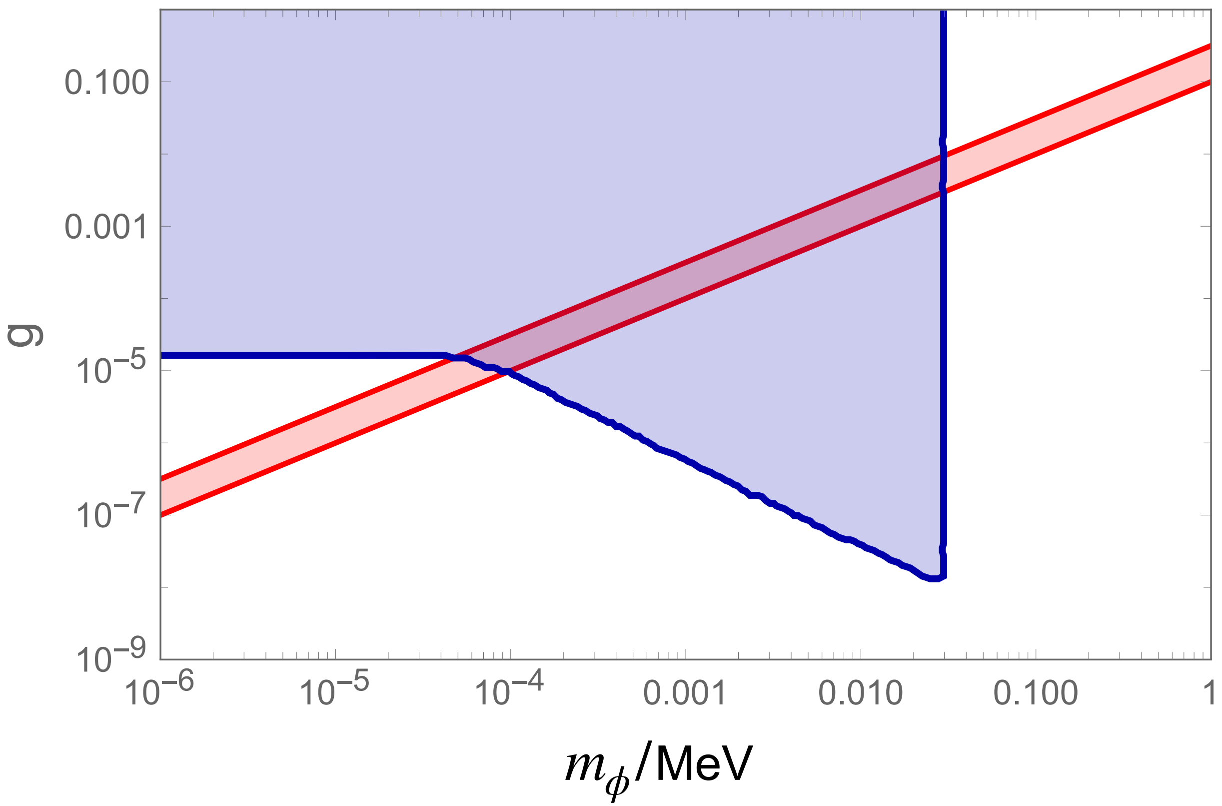
$$L_{\text{eff}} = g_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi$$

with generation indices $\alpha, \beta = 1,2,3$.

From now one specify to $\alpha = \beta = 3$, i.e. interactions of ν_τ, for which laboratory bound are weakest.

Red: Preferred region for coupling and mass:

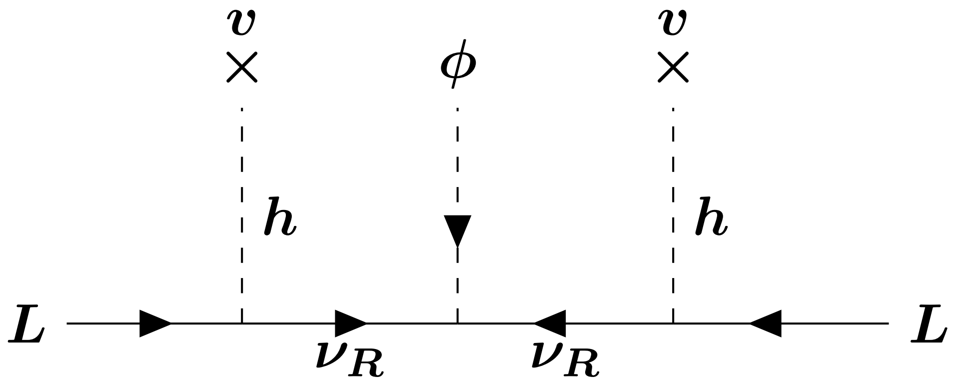
Blue: Excluded by primordial helium and deuterium abundances

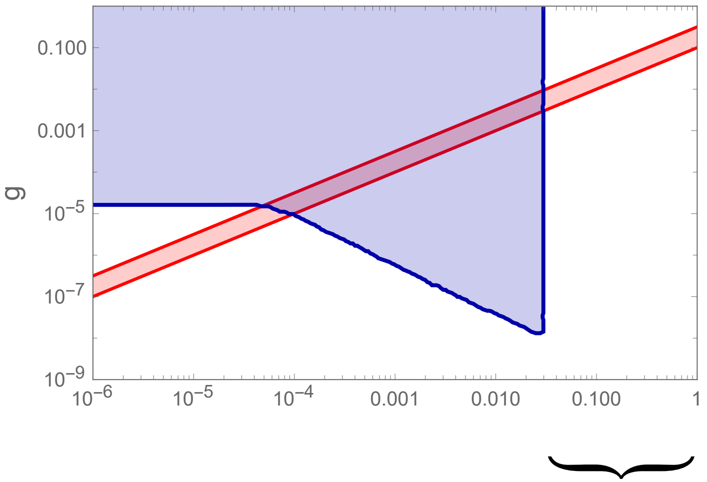


$L_{\text{eff}} = g\,\bar{\nu}_\tau \nu_\tau\, \phi$ is not gauge invariant, need lagrangian in terms of the lepton doublet

$$L = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Standard solution: ϕ is SU(2) singlet. Then L_{eff} is a higher-dimensional interaction from e.g.





$\Rightarrow g$ is tiny.

most interesting region inaccessible

An SU(3) triplet field Δ permits a renormalisable coupling:

$$\Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ v_s + \frac{h_s + i a_s}{\sqrt{2}} & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}$$

$v_s \ll v$, with electroweak vev $v = 174\,\mathrm{GeV}$

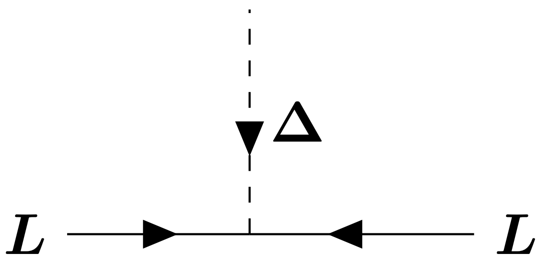
$$L_y^{\Delta} = \frac{y_\tau^{\Delta}}{2} \overline{L^c} \Delta L + h.c.$$

coupling y_τ^{Δ} can be large

$$\supset \; - \frac{m^{\Delta}_{\nu_\tau}}{2} (\bar{\nu}_\tau \nu_\tau^c + \overline{\nu_\tau^c} \nu_\tau)$$

Majorana mass term

$$- \frac{y_\tau^{\Delta}}{2\sqrt{2}} \left[(h_s + i a_s) \overline{\nu_\tau^c} \nu_\tau \; + \; (h_s - i a_s) \bar{\nu}_\tau \nu_\tau^c \right]$$



2. Majoron models and modifications

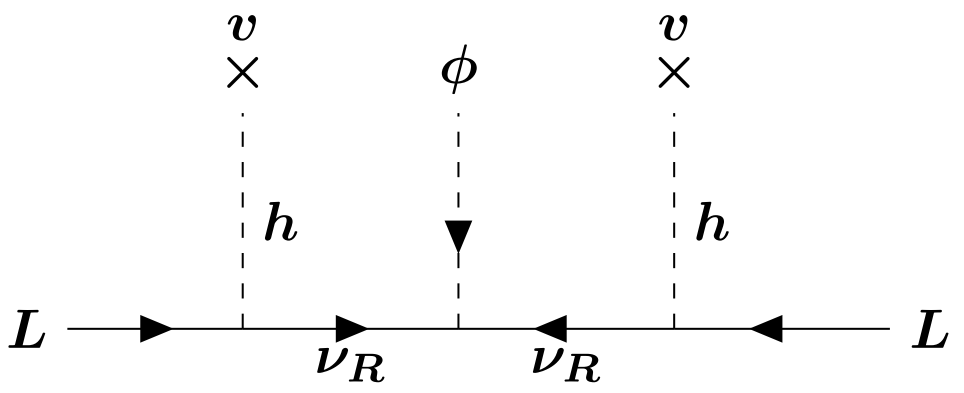
If lepton number L is broken spontaneously, there is a massless Goldstone boson, the majoron.

Original idea: SU(2) singlet majoron, complex ϕ with $L=-2$

Y. Chikashige, R. N. Mohapatra and R. Peccei, 1980

$\Rightarrow$ tiny coupling to active neutrinos

$\langle\phi\rangle$ breaks L



Higgs potential

$$\Phi = \begin{pmatrix} \phi^+ \\ v + \frac{h+ia}{\sqrt{2}} \end{pmatrix} \qquad \Phi^c = \begin{pmatrix} v + \frac{h-ia}{\sqrt{2}} \\ -\phi^- \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ v_s + \frac{h_s+ia_s}{\sqrt{2}} & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}$$

$$\begin{aligned} V = & -\mu^2\Phi^\dagger\Phi - \mu_\Delta^2 \,\mathrm{Tr}\,(\Delta^\dagger\Delta) + \lambda(\Phi^\dagger\Phi)^2 \\ & + \lambda_\Delta \left[\mathrm{Tr}\,(\Delta^\dagger\Delta)\right]^2 + \alpha_1\,\Phi^\dagger\Delta^\dagger\Delta\Phi + \alpha_2\,\Phi^\dagger\Delta\Delta^\dagger\Phi \\ & + \alpha_3\,\Phi^\dagger\Phi\,\mathrm{Tr}\,(\Delta^\dagger\Delta) - \beta\left(\Phi^{c\,\dagger}\Delta^\dagger\Phi + \Phi^\dagger\Delta\Phi^c\right) \end{aligned}$$

SU(2) triplet majoron Δ with $L = -2$ Gelmini and M. Roncadelli, 1981

For $\beta = 0$ potential conserves L, which is broken spontaneously by $v_s \neq 0$.

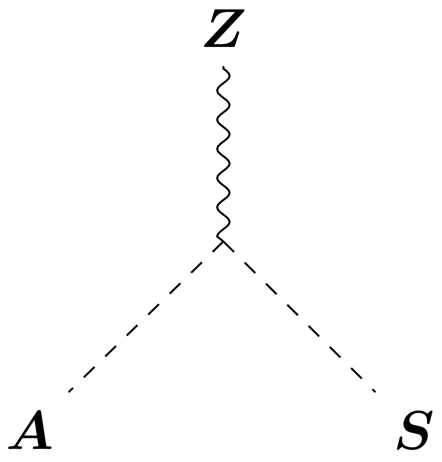
Show stopper

$v_s \ll v$ implies two extra neutral Higgs mass eigenstates states: $S \simeq h_s$ and $A \simeq a_s$.
For $\beta = 0$, however, one finds $m_S = \mathcal{O}(v_s)$.

LEP 1 data on $Z \to$ invisible killed the SU(2) triplet majoron.

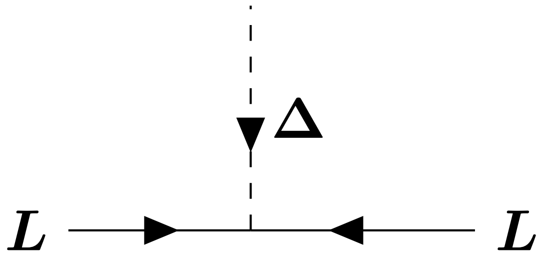
Breaking L explicitly through $\beta \neq 0$ adds a term $\propto \dfrac{\beta v^2}{v_s}$ to both m_S^2 and m_A^2.

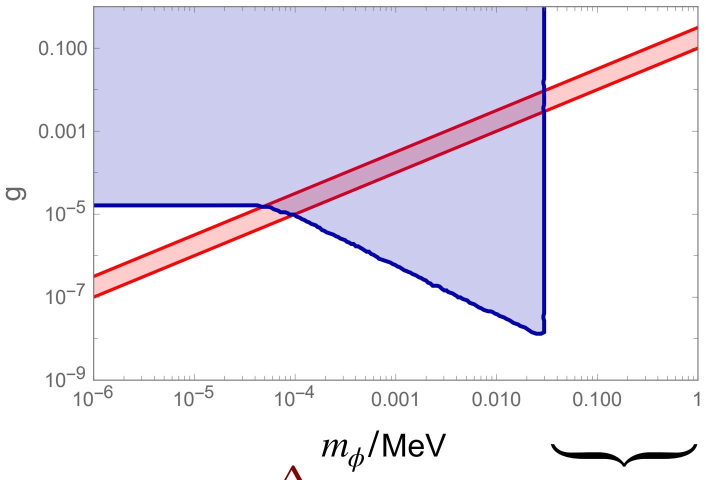
$\Rightarrow$ Either both S and A are light or both are heavy.



Can one build a triplet model with S/A light and A/S heavy?

$$L_y^{\Delta} = \frac{y_\tau^{\Delta}}{2} \overline{L_3^c} \Delta L_3 + h.c.$$





easily accessible with $g = -\frac{y_\tau^{\Delta}}{2\sqrt{2}}$

Dimension-6 operators:

$$Q_1 = \delta_1 \left(\Phi^{c\,\dagger} \Delta^\dagger \Phi + \Phi^\dagger \Delta \Phi^c \right)^2$$

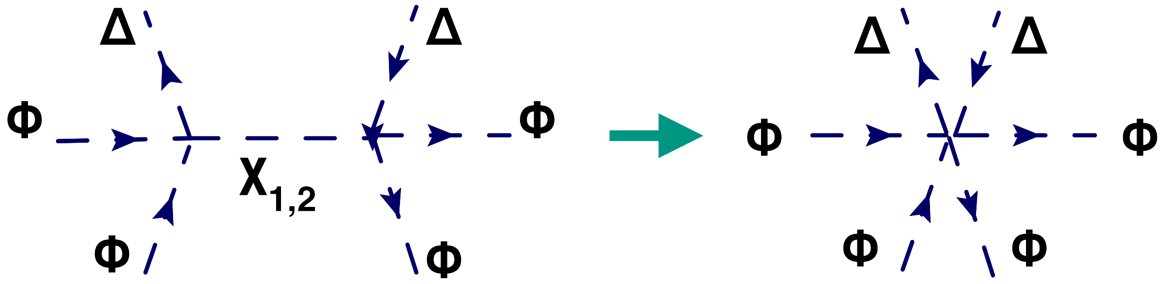
$$Q_2 = -\delta_2 \left(\Phi^{c\,\dagger} \Delta^\dagger \Phi - \Phi^\dagger \Delta \Phi^c \right)^2$$

Adding Q_1 to V lifts m_S^2, while adding Q_2 lifts m_A^2!

Higgs potential with dim-6 terms:

$$
\begin{aligned}
V = & -\mu^2\Phi^\dagger\Phi - \mu_\Delta^2 \,\mathrm{Tr}\,(\Delta^\dagger\Delta) + \lambda(\Phi^\dagger\Phi)^2 \\
& + \lambda_\Delta \left[\mathrm{Tr}\,(\Delta^\dagger\Delta)\right]^2 + \alpha_1\,\Phi^\dagger\Delta^\dagger\Delta\Phi + \alpha_2\,\Phi^\dagger\Delta\Delta^\dagger\Phi \\
& + \alpha_3\,\Phi^\dagger\Phi\,\mathrm{Tr}\,(\Delta^\dagger\Delta) - \beta\left(\Phi^{c\,\dagger}\Delta^\dagger\Phi + \Phi^\dagger\Delta\Phi^c\right) \\
& + \delta_1\left(\Phi^{c\,\dagger}\Delta^\dagger\Phi + \Phi^\dagger\Delta\Phi^c\right)^2 \\
& - \delta_2\left(\Phi^{c\,\dagger}\Delta^\dagger\Phi - \Phi^\dagger\Delta\Phi^c\right)^2
\end{aligned}
\Bigg\}\ \text{inspired by}
$$

$$\delta_{1,2} \propto \frac{1}{M^2_{X_{1,2}}}$$



Masses

Abbreviation: $m^2 \equiv -\mu_\Delta^2 + \alpha_2 v^2 + \alpha_3 v^2$

Neutral Higgses:

$$m_A^2 = 4\delta_2 v^4 + m^2 + 2\lambda_\Delta v_s^2$$
$$m_S^2 = 4\delta_1 v^4 + m^2 + 6\lambda_\Delta v_s^2$$

We can choose $m_A^2 \gg m_S^2$ or $m_A^2 \ll m_S^2$ to forbid $Z \to AS$.

$$m_H^2 = 4\lambda v^2 = (125\text{GeV})^2,$$

(Doubly) charged Higgs: $m_{H^{++}}^2 = 2m_{H^+}^2 = \alpha_1 v^2$

m_A^2 in terms of $\delta_1, \delta_2, \beta$: $m_A^2 = 4(\delta_2 - \delta_1)v^4 + \frac{\beta v^2}{v_s}$

L violating parameters

$\Rightarrow$ With appropriate parameters we realise a triplet model with one very light spin-0 boson and all other Higgs masses $\mathcal{O}(100-400\,\text{GeV}^2)$.

3. Phenomenology

Recall: $\delta_{1,2} \propto \frac{1}{\Lambda^2}$ with UV scale Λ

Perturbativity limit $|\alpha_1| \leq 5 \quad \Rightarrow$

$$m_{H^{++}} \leq 400\,\mathrm{GeV}$$
$$m_{H^{+}} \leq 280\,\mathrm{GeV}$$

Choosing $\delta_1 \ll \delta_2$ we can have m_S in the desired range $m_S < 1\,\mathrm{MeV}$,

while $m_A^2 \simeq 4\,\delta_2 v^4 \leq \mathcal{O}\,(120\,\mathrm{GeV})^2$ for $\Lambda \geq 500\,\mathrm{GeV}$.

Phenomenology

Since Δ does not couple to quarks, S, A, H^+, H^{++} production at the LHC will involve gauge couplings; e.g. may proceed through vector-boson fusion.

Decays like $H^{++} \to \tau^+\tau^+, H^+ \to \tau^+\bar{\nu}_\tau$ are interesting, but maybe suppressed if the Yukawa coupling y_τ^Δ is small.

Safer: Look for gauge-coupling driven decays like $H^+ \to W^+ S, W^+ A.$

Summary

- Cosmological anomalies have triggered interest in a light scalar interacting with active neutrinos.
  SU(2) singlet scalars permit only tiny neutrino couplings.
- An SU(2) Higgs triplet permits renormalisable, $\mathcal{O}(1)$ couplings to neutrinos of two neutral (pseudo-)scalars A and S.
  But with a renormalisable Higgs potential either none or both are light and the latter possibility is in conflict with $Z \to AS$.
- With dimension-6 terms one can fix this and make either A or S heavy while keeping the other boson light.
- This mechanism opens up the parameter range with testable features at colliders. Upper bounds on triplet Higgs masses make the model falsifiable.

Backup

Minimisation conditions

Minimum of the Higgs potential: $\partial V/\partial v = 0 = \partial V/\partial v_s$

$$\mu^2 = 2\lambda v^2 + \mathcal{O}\left(\frac{v_s^4}{v^2}\right)$$

$$\beta = v_s \left(\frac{m^2}{v^2} + 4\delta_1 v^2 + 2\lambda_\Delta \frac{v_s^2}{v^2}\right)$$

with $$m^2 \equiv -\mu_\Delta^2 + \alpha_2 v^2 + \alpha_3 v^2$$

choose small to get desired light (pseudo-)scalar

At tree-level there is no fine-tuning between large parameters.