Majoron,Dark Matter and Dark Radiation

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- It is a Goldstone boson
- Arise from the spontaneous breaking of a global symmetry $\rightarrow$ the Goldstone theorem.
- The global symmetry is lepton number $U(1)_{\mathrm{L}}$
- This is one of two accidental symmetry of the Standard Model. The other being baryon number.
- If the symmetry is gauged two possibilities
  1. Spontaneously broken then it will be swallowed by the corresponding gauge boson resulting in a lepton specific Z-boson.
  2. Not broken $\rightarrow$ lepton specific long range force. Not seen.
- This is **NOT** what we are studying here.

Some remarks

- We have not found any genuine Goldstone bosons in particle physics
- Condensed matter they are gapless excitations
- A standard lore due to Bank and Suskind states that there are NO fundamental global symmetry when gravity is taken into account.
- Lepton number/baryon is a fundamental issue in particle physics and how and if is broken connects in a profound way neutrinos /matter stability quantum gravity.
- It also impacts dark matter and dark radiation

- Known radiation content of the universe
  1. Photons manifest in Cosmic Microwave Background (CMB)
  2. Neutrinos we know of 3 species.
- How you count the number of ν in cosmology?
- Base on the relative energy of neutrinos compare to that of photons in CMB
  1. entropy conservation
  2. Bose-Einstein statistic for photons vs fermi-Dirac for neutrinos
- It is given in terms of N_{eff} For the SM

$$N_{eff} = 3.04$$

- Measured value combining Planck and Hubble

$$N_{eff} = 3.83 \pm 0.54$$

Adding WMAP9 and ACT

$$N_{eff} = 3.62^{+0.50}_{-0.48}$$

It is a 2.4σ effect.

- Evidently

$$\Delta N_{eff} = N_{eff} - 3.046 \neq 0$$

This can be taken as a hint for dark radiation.

- If correct it must be due to new physics. There are many possibilities
  1. Sterile neutrinos
  2. New spin-1 bosons
  3. Spin-0 Goldstone bosons
  4. Decaying WIMP's
- Goldstone boson is particularly interesting due to its simplicity.

First suggested by Weinberg [PRL 110 241301 (2013)]. Originates from the breaking of a dark sector global $U(1)_X$ symmetry. For a relativistic spin-0 particle it counts as $N_{eff} = 4/7$.

- If decouples earlier than muon annihilation it counts less than
- If decoupling temperature $T_d \sim 2m_\mu$ then

$$N_{eff} = 0.39$$

Take take the global symmetry as the lepton number. Its spontaneous breaking will lead to the Goldstone being the Majoron. Advantages are

- Connects the dark sector to seesaw neutrino mass generation
- It naturally has a Tev scale seesaw. Can be probed at colliders
- Can accommodate a dark matter candidate
- Very simple

The symmetry group is $SU(2) \times U(1)_Y \times U(1)_L \times Z_2$ and $U(1)_L$ is not gauged.Z_2 is accidental. The new particles are righthanded neutrinos (at lease 2)(N_{iR}) and two SM singlet spin-0 fields S and Φ.

	L	$SU(2)$	$U(1)_Y$
S	2	**1**	**0**
Φ	1	**1**	**0**
H	0	**2**	$\frac{1}{2}$
N_{iR}	1	**1**	**0**
L_i	1	**2**	$-\frac{1}{2}$

- S is the singlet for seesaw mechanism. It is Higgsed i.e. picks up a v.e.v.
- Φ. To obtain a DM in the model. It is (**NOT**) Higgsed.

- The scalar part

$$\mathcal{L}_{scalar} = (D_\mu H)^\dagger (D^\mu H) + (\partial_\mu S)^\dagger (\partial^\mu S) + (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) - V(H, S, \Phi)\,,$$
$$V(H,S,\Phi) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 - \mu_s^2 S^\dagger S + \lambda_s (S^\dagger S)^2 + \lambda_{SH} (S^\dagger S)(H^\dagger H)$$
$$+ m_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_{\Phi H} (\Phi^\dagger \Phi)(H^\dagger H)$$
$$+ \lambda_{\Phi S} (S^\dagger S)(\Phi^\dagger \Phi) + \frac{\kappa}{\sqrt{2}} \left[(\Phi^\dagger)^2 S + S^\dagger \Phi^2 \right]\,,$$

κ is real and $m_\Phi^2 > 0$

- The scalar fields are expanded as

$$\Phi = \frac{1}{\sqrt{2}} (\rho + i\chi)\,,$$
$$S = \frac{1}{\sqrt{2}} (v_s + s + i\omega)\,,$$

- U-gauge is used for the Higgs field

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

The physical fields are $\hat{S} = (h, s, \rho, \chi)$ and ω is the Goldstone boson which is the Majoron and is massless.(h, s) and (ρ, χ) will mix. The scalar potential becomes

$$\begin{aligned} V =& \frac{1}{2}\tilde{\hat{S}}M^2\hat{S} + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \lambda_s v_s s^3 + \lambda_s v_s \omega^2 s + \frac{1}{4}\lambda_s(s^4 + \omega^4) \\ &+ \frac{1}{2}\lambda_s\omega^2 s^2 + \frac{1}{2}\lambda_{SH} v_s s h^2 + \frac{1}{2}\lambda_{SH} v(s^2 + \omega^2)h + \frac{1}{4}\lambda_{SH}(s^2 + \omega^2)h^2 \\ &+ \frac{1}{4}\lambda_\Phi(\rho^4 + \chi^4 + 2\rho^2\chi^2) + \frac{1}{2}\lambda_{\Phi H} v(\rho^2 + \chi^2)h + \frac{1}{4}\lambda_{\Phi H}(\rho^2 + \chi^2)h^2 \\ &+ \frac{1}{2}\bar{\kappa} s\,\rho^2 + + \frac{1}{4}\lambda_{\Phi S}\left(s^2\rho^2 + s^2\chi^2 + \omega^2\rho^2 + \omega^2\chi^2\right) \\ &+ \frac{1}{2}(\bar{\kappa} - 2\kappa)s\,\chi^2 + \kappa\rho\chi\omega\,, \end{aligned}$$

where $\bar{\kappa} = \lambda_{\Phi S} v_s + \kappa$.

After SSB there remains a parity i.e. the breaking is

$$U(1)_L \times Z_2 \to Z_2$$

Seen by the field transformation

$$\begin{aligned} s, \omega, h &\longrightarrow s, \omega, h \\ \rho &\longrightarrow -\rho \\ \chi &\longrightarrow -\chi \,. \end{aligned} \tag{1}$$

This allows us to identify eitherρ or χ as the DM. Stability is protected by the Z_2. N_R are even under this parity

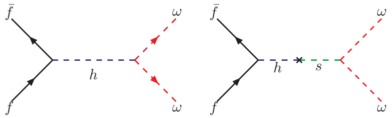
This is the same as the usual type I seesaw

$$-\mathcal{L}_\ell = y\overline{L}_L\tilde{H}N_R + Y\overline{N_R^c}N_R S + h.c.\,,$$

where $L = (n_L, e_L)^T$ is the SM lepton doublet and $\tilde{H} = i\sigma_2 H^*$. After symmetry breaking we get

$$-\mathcal{L}_\ell = \frac{yv}{\sqrt{2}}\overline{n_L}N_R + \frac{Yv_s}{\sqrt{2}}\overline{N_R^c}N_R + \frac{y}{\sqrt{2}}\overline{n_L}N_R h + \frac{Y}{\sqrt{2}}(s+i\omega)\overline{N_R^c}N_R + h.c.$$

- There is no tree level $\omega - f - f$ coupling
- $f\bar{f} \to \omega\omega$ proceeds thru



- This yields the effective Lagrangian

$$\mathcal{L}_{f\omega} \sim \frac{4\lambda_{HS} m_f^3}{M_h^2 M_s^2} \bar{f} f \omega\omega$$

M_h is mass of the SM Higgs and M_s mass of second scalar.

- This annihilation rate to be Hubble expansion rate at decoupling temperature T_{dec} gives

$$\frac{\lambda_{HS}^2 m_\mu^2 T_{dec}^5 m_{Pl}}{m_{h_{SM}}^4 m_{h_2}^4} \approx 1 \Longrightarrow m_{h_2} \approx 9.3\,\mathrm{GeV} \times (T_{dec}/m_\mu)^{5/4} \sqrt{|\lambda_{HS}|}\,,$$

- Decoupling at muon annihilation leads to a light scalar < 10 Gev that mixes with the SM Higgs.
- Massless Goldstone gives a long range force
- The coupling to charged fermions is at one loop and is proportional to m_ν is very weak
- This force also spin dependent
- No constrain from fifth force tests

Due mixing with Higgs s has a coupling to the muon given by

$$c_\mu = 2^{\frac{3}{4}} G_F^{\frac{1}{2}} m_\mu s_\theta$$

- Adds to muon $g-2$

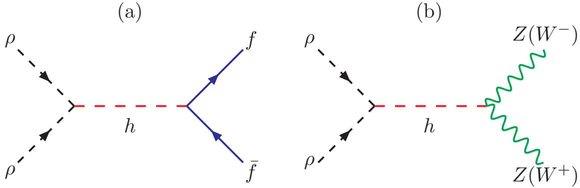
$$\delta a_\mu = \frac{c_\mu^2}{8\pi^2} H(r)$$

  where $H(r) = \frac{3}{2} - r + \frac{r(r-3)}{2} \ln r - (r-1)\sqrt{r(r-4)} \ln \frac{\sqrt{r}+\sqrt{r-4}}{2}$ and $r = \frac{m_s^2}{m_\mu^2}$.
- It is lower than the central value of $\delta a_\mu = (249 \pm 87) \times 10^{-11}$ but within 1σ
- It also contributes to the Lamb shift of muonic hydrogen. Energy difference of $2P - 2S$ is

$$\Delta E = -\frac{c_\mu c_p}{4\pi} \frac{m_s^2 (m_r \alpha)^3}{2(m_s^2 + m_r \alpha)^4}$$

  c_p is the coupling to proton and m_r is the reduced mass.
- can account for $210\mu eV$ not the full $310\mu eV$

ρ is the DM depending on its mass can annihilate in to SM particles or h, s, ω.
$\rho\rho \to f\bar{f}$ and ZZ, WW the digrams are



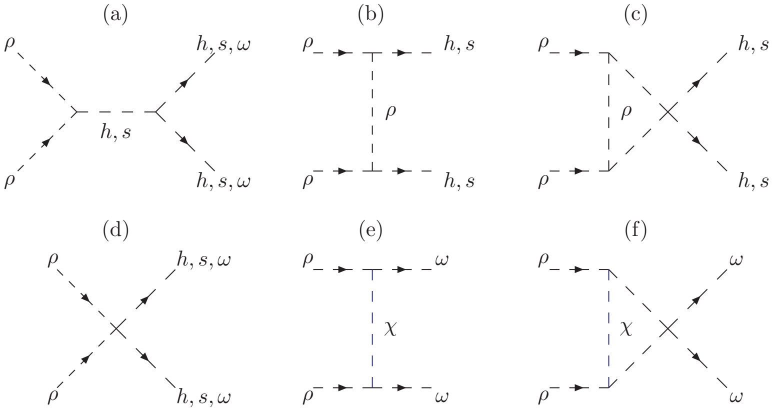


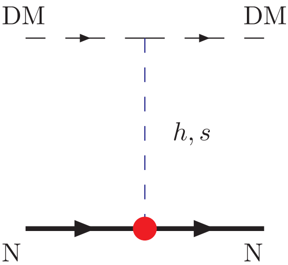
Figure : $\rho\rho$ to a pair of SM Higgs, light scalars and Majorons

We can calculate the thermal average cross section $\langle \sigma v \rangle$. The freeze out temperature is given by

$$x_f \equiv \frac{M_\rho}{T_f} = \ln \left(0.038 g_X \langle \sigma v \rangle M_\rho M_{\text{Pl}} \sqrt{\frac{x_f}{g_*}} \right) ,$$

where M_{Pl} is the Planck Mass and g_* is the effective number of relativistic degree of freedom at temperature T. To get the correct relic density we must have the total $\langle \sigma v \rangle$ should be approximately $3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$. This is one constrain on the parameters of the model

Scattering of ρ with a nucleus. Only spin independent scattering here



The cross section is

$$\sigma_{\rho n} = \frac{G_F M_n^2 \eta^2 m_r^2(n,\rho)}{4\sqrt{2}\pi M_\rho^2 M_H^2 \lambda} \left[\lambda_{\Phi H} \left(c_\theta^2 + s_\theta^2 \left(\frac{M_h}{M_s} \right)^2 \right) - s_\theta c_\theta \frac{\bar{\kappa}}{v} \left(1 - \left(\frac{M_h}{M_s} \right)^2 \right) \right]^2 ,$$

where the reduced mass is $m_r(n,\rho) = \frac{M_\rho M_n}{M_\rho + M_n}$ and M_n is the nucleon mass.
$\eta = 0.3$

There are eight new parameters introduced in the scalar potential. We would like to substitute them by measurable quantities as masses and decay widths as much as possible. We take the range of m_ρ in the range of $[6, 2000]$ Gev,i.e the range for WIMP.

1. $0 < M_s < 1.05$ From ω as DR and invisible Higgs width.
2. The mixing between the Higgs and s is varied in the range $|\sin\theta| < 0.01$ indicated by rare B-meson decays.
3. By requiring the Majoron decouples around $T_{dec} \sim m_\mu$ i.e. $\Delta N_{eff} = 0.39$ we have $|\lambda_{SH}| = \left(\frac{M_s}{22.11\mathrm{GeV}}\right)^2$.
4. Mass diagonalization gives
$$\lambda = \frac{(M_H^2 c_\theta^2 + M_s^2 s_\theta^2)}{2v^2}\,,\ \lambda_S = \frac{(M_s^2 c_\theta^2 + M_H^2 s_\theta^2)}{2v_S^2}\,,\ v_S = \frac{s_\theta c_\theta}{\lambda_{SH} v}(M_s^2 - M_H^2).$$
with $M_H = 125$ GeV
5. $-v < \bar{\kappa} < v$ is chosen for no fine tuning bias.
6. Positivity and staying within perturbation regime gives $-4\sqrt{\pi\lambda_s} < \lambda_{\Phi S} < 4\pi$.
7. Similarly $-4\sqrt{\pi\lambda} < \lambda_{\Phi h} < 4\pi$
8. λ_ϕ does not enter into our calculations; thus remains unconstrained.

The program will register the points when they pass the following criteria

1. $(M_\rho^2 + M_\chi^2 - \lambda_{\Phi H}^2 v^2 - \lambda_{\Phi S}^2 v_S^2) > 0$ so that $M_\Phi^2 > 0$.
2. The SM Higgs invisible decay width $\Gamma_{inv}^h < 0.8$ MeV.
3. The thermal average annihilation cross section is within the range $(2.5 \pm 0.1) \times 10^{-9} (\mathrm{GeV})^{-2}$.
4. The spin-independent elastic ρ-nucleon scattering cross section, is smaller than the LUX 90% confidence limit.

This gives us a feeling of the most probable parameter space to probe in future experiments.

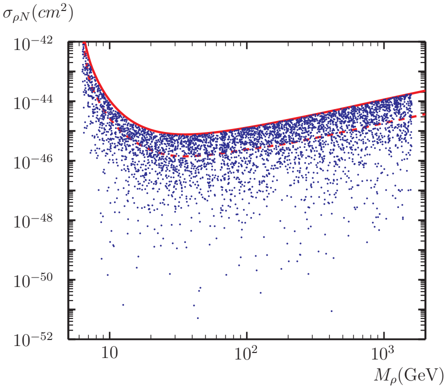


Figure : Spin-independent elastic ρ-nucleon scattering cross section v.s. M_ρ. Where the solid line is the current LUX limit and the dashed line is the LUX 300-day projected sensitivity.

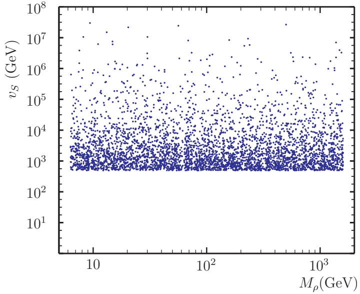


Figure : The lepton number violating scale v_S vs M_ρ

The model prefers a relatively low scale seesaw

This is a Higgs portal model. SM communicates with the dark sector via Higgs interactions only. Implies Higgs invisible decays and displaced vertices New modes are

1. $h \to \omega\omega$ invisible
2. $h \to ss$ depends on M_s
    1. $h \to 4\mu$ or
    2. $h \to 4\pi$
3. $h \to \rho\rho$ if $M_\rho \lesssim M_H/2$. Also invisible.

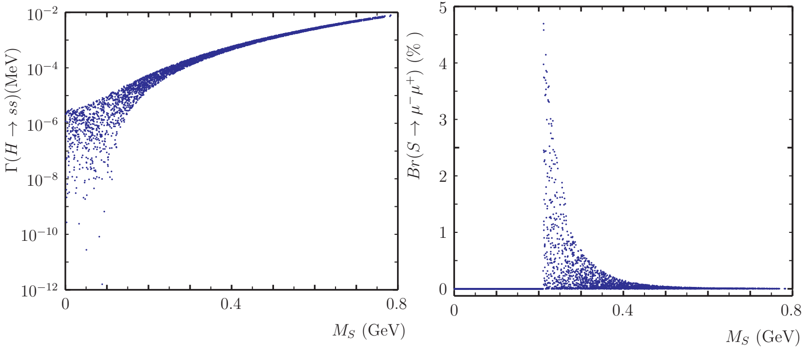


Figure : Decay width $\Gamma(h \to ss)$ in MeV (left panel) and $\mathrm{Br}(s \to \mu\mu)$(right panel).

We can have spectacular signatures Higgs into 2 muons (2 pions)on one side with missing energy recoiling against it. We need high luminosity LHC/Higgs factory

Conclusions

- There exists a light scalar that mixes with the SM Higgs whether the $U(1)$ is associated with lepton number or dark global symmetry
- Contributes to a_μ and muonic hydrogen anomaly
- The model prefers the seesaw scale to be below 10 Tev. Gives a motivation to searches in colliders. very challenging.
- It has a DM candidate which is protected by dark parity.
- Has many interesting rare Higgs decays that can be searched for at the Higgs factory or HLLHC
- It can accommodate anomalous gamma rays from the galactic center.
- Particle physics and cosmology are more closely related than ever
- Very exciting and challenging times ahead.

THANK YOU