Minimal Model of Majoronic Dark Radiation and Dark Matter and its Phenomenology

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(PLB730,347, PRD90,065034, arXiv:1604.02017, with J.Wu and J. Ng)

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Outline

- Introduction
- The Model
- Numerical study
- Phenomenology

Need New Physics-1

- New phys. beyond the SM are called for: (1) $m_\nu \neq 0$ and (2) $\Omega_{DM} h^2 \sim 0.12$
- (Too) Many models. The key is the Weinberg operator $(LH)^2$ at the low energy which breaks $U(1)_L$.
- Accidental global $U(1)_L$ is free in SM and it connects to neutrino masses.
- Majorona mass is controlled by the scale of $U(1)_L$ SSB in the type-I (and inverse see-saw) (PLB730, 347.)

$$y\overline{N}^c N S_L \to m_N = y\langle S_L\rangle$$

- We need something electrically charge neutral and (meta)stable.
- DM is stabilized by the Krauss-Wilczek, $U(1)_L \to Z_2$.
- Goldstone is built in global SSB $U(1)_l$ DM-m_ν model, and it contributes to radiation energy density.

Need New Physics-2:effective neutrino number

- Neutrinos decouple at $T \sim 1\text{MeV}$ ($\Gamma_{weak} \lesssim H$). Later, the photons were heated up by e^+e^- annihilation,

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 2K$$

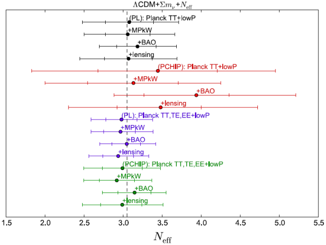
- The present relativistic energy density of the universe

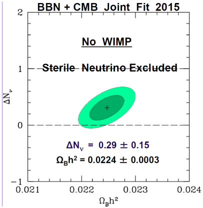
$$\rho_{rad} = g_\gamma \frac{\pi^2}{30} T_\gamma^4 + g_\nu \frac{\pi^2}{30} \frac{7}{8} T_\nu^4 = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right] \rho_\gamma$$

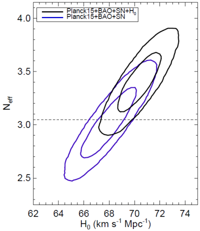
- Taking into account the incomplete decoupling, $N_{eff}^{SM} = 3.046$ (Mangano et al. 2005). Nonzero $\triangle N_{eff} = N_{eff} - 3.046$ call for new relativistic DOF beyond the SM.
- This new DOF is coined as dark radiation.

N_{eff} After Planck 2015

- Planck 2015, 1502.01589, $N_{eff} = 3.15(46)$ at 95%CL.
  Although the SM seems OK, the statistical significance to rule out DR is still very poor.



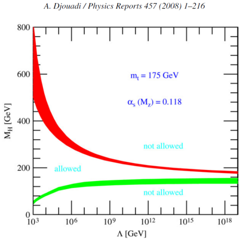




- $2.5 < N_{eff} < 3.5$ at 95%CL, Valentino et el, PRD93,083523.
- $\triangle N_{eff} = 0.29(15)$, G. Steigman, June 2015, INT talk.
- $\triangle N_{eff} = 0.4 - 1.0$, Riess et el(WFC3 on HST), 1604.01424

One more thing to be taken into account

- $\mu_{VS}^{SM} \simeq 10^{10-12}$ GeV



- Operational see-saw needs stable vacuum at the $\not{L}$ scale μ_{LV}, or $\mu_{LV} < \mu_{VS}^{SM}$.

$$(\overline{\nu^c}, \overline{\nu_R}) \begin{pmatrix} 0 & y_D v_{SM} \\ y_D v_{SM} & M_N (= y_s v_l) \end{pmatrix} \begin{pmatrix} \nu \\ \nu_R^c \end{pmatrix}$$

- For ϕ_A, ϕ_B in $V = \lambda_A \phi_A^4 + \lambda_B \phi_B^4 + \lambda_{AB} \phi_A^2 \phi_B^2 + ...$, $\lambda_A > 0$, $\lambda_B > 0$, $\lambda_{AB} > -2\sqrt{\lambda_A \lambda_B}$ at any given energy scale. RGE study is necessary.

Outline

- Motivation and experimental facts
- **The Model**
- Numerical study
- Phenomenology

Model

Particle content:

	L, Z_2	$SU(2)$	$U(1)_Y$
S	$2_{SSB,+}$	**1**	**0**
Φ	1_- (DM candidate)	**1**	**0**
H	$0_{SSB,+}$	**2**	$\frac{1}{2}$
N_{iR}	1_-	**1**	**0**
L_i	1_-	**2**	$-\frac{1}{2}$

Renormalizable Lagrangian: (8 new parameters)

$$\mathcal{L}_{scalar} = (D_\mu H)^\dagger (D^\mu H) + (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) + (\partial_\mu S)^\dagger (\partial^\mu S) - V(H, S, \Phi)$$

$$\begin{aligned} V(H, S, \Phi) = & -\mu^2 H^\dagger H - \mu_s^2 S^\dagger S + m_\Phi^2 \Phi^\dagger \Phi + \lambda_H (H^\dagger H)^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 \\ & + \lambda_s (S^\dagger S)^2 + \lambda_{SH} (S^\dagger S)(H^\dagger H) + \lambda_{\Phi H} (\Phi^\dagger \Phi)(H^\dagger H) \\ & + \lambda_{\Phi S} (S^\dagger S)(\Phi^\dagger \Phi) + \frac{\kappa}{\sqrt{2}} \left[(\Phi^\dagger)^2 S + S^\dagger \Phi^2 \right] \end{aligned}$$

and we take κ to be real, $m_\Phi^2 > 0$, and define $\bar{\kappa} \equiv \lambda_{\Phi S} v_s + \kappa$.

Model

- After SSB, $\langle S \rangle \neq 0$ and $\langle H \rangle \neq 0$, the fields are expanded as $\Phi = \frac{1}{\sqrt{2}}(\rho + i\chi)$, $S = \frac{1}{\sqrt{2}}(v_s + s + i\omega)$ and for the Higgs $H = (0, \frac{v+h}{\sqrt{2}})^T$. ω is the massless Goldstone or Majoron.
- $\langle S \rangle$ is inv. under a $U(1)_l$ $\pi-$rotation, a Z_2 parity remains:

$$s, \omega, h \longrightarrow s, \omega, h$$

$$\rho, \chi \longrightarrow -\rho, -\chi$$

- Due to mixing, the physical mass eigenstates are

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

  with mixing angle $\tan 2\theta = \frac{\lambda_{HS} v_H v_S}{\lambda_S v_S^2 - \lambda v_H^2}$.
- Identify $h_1 \equiv h_{SM}$ with a mass of 125 GeV, h_2 is a new neutral scalar(just call them H and S).

Model

- In terms of the physical masses and mixing, we have

$$\lambda_H = \frac{\cos^2\theta M_H^2 + \sin\theta^2 M_S^2}{2v_H^2}, v_S = -\frac{\sin\theta\cos\theta(M_H^2 - m_S^2)}{v_H\lambda_{SH}},$$
$$\lambda_S = \frac{\sin^2\theta M_H^2 + \cos\theta^2 M_S^2}{2v_S^2}, y_S = \frac{\sqrt{2}M_N}{v_S}.$$

- $v_H = 246\text{GeV}$, $m_H = 125$ GeV
- for a given set of $\{M_S, \theta, \lambda_{SH}\}$, v_S and λ_S are determined.
- No solution found for $M_N < 0.5\text{TeV}$, not sensitive otherwise. We take $M_N = 1\text{TeV}$ as a benchmark value.
- leptons interact with the Majoron via

$$\frac{1}{2v_s}(\partial_\mu\omega\,\bar{\psi}_l\gamma^\mu\psi_l)$$

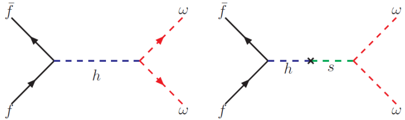
- couplings of the Majoron to charged fermions generated at the one-loop level. Very small, no constraints from stellar cooling

Majoron decoupling

- However a dim-5 int.

$$\mathcal{L}_{f\omega} = -\frac{\lambda_{HS} m_f}{M_h^2 M_s^2} \bar{f} f \partial^\mu \omega \partial_\mu \omega$$

can be generated through scalar mixing:



- Order of magnitude estimation gives

$$\Gamma(f\bar{f} \leftrightarrow \omega\omega) \sim \frac{\lambda_{HS}^2 m_f^2}{M_H^4 M_S^4} \times T_{\rm dec}^7 \times N_c^f$$

- Since $H \sim T_{dec}^2 / M_{pl}$,

$$\frac{N_c \lambda_{HS}^2 m_{eff}^2 T_{\rm dec}^5 M_{Pl}}{M_H^4 M_s^4} \approx 1.$$

$\triangle N_{eff}$ and T_{dec}

- Conservation of Entropy in the co-moving volume give:

$$\triangle N_{eff} = \frac{4}{7}\left(\frac{g_*(T_\nu^+)}{g_*(T_\omega^-)}\right)^{\frac{4}{3}}$$

  where g_* is the effective number of relativistic DOF.
  $\Delta N_{\rm eff} = \{0.39, 0.055, 0.0451, 0.0423\}$ for
  $T_{dec} = \{m_\mu, 1GeV, m_c, m_\tau\}$ respectively.
- Due to scalar mixing, H can always decays into a pair of invisible ω's,

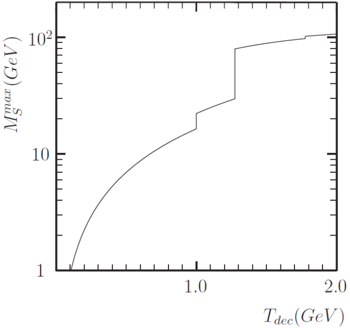
$$\Gamma_{\omega\omega} = \frac{1}{32\pi}\frac{\sin^2\theta M_H^3}{v_S^2}$$

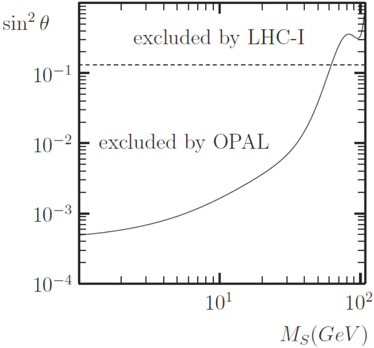
- $\Gamma_{\omega\omega} \leq \Gamma_H^{inv} < 0.8$ MeV gives M_S^{max} via

$$\frac{M_S^4}{(M_H^2 - M_S^2)^2} \leq \cos^2\theta \frac{32\pi m_{eff}^2 T_{\rm dec}^5 M_{pl}}{v_H^2 M_H^7}\Gamma_H^{inv}$$

M_S, T_{dec}, and $\sin\theta^2$

- LHC-I, $\mu = 1.1 \pm 0.11$ gives indirect bound $\sin\theta^2 < 0.13$ at 2 σ. Direct search from OPAL $e^+e^- \to hZ$.

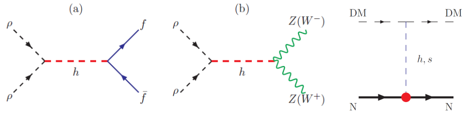


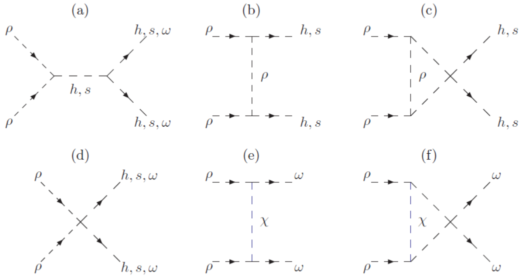


- From rare B decay, $|\theta| < 0.002$ for $M_S < 2$GeV.
- With this, the decoupling condition yields

$$\lambda_{SH} \sim \frac{M_H^2 M_S^2}{T_{dec}^3 \sqrt{T_{dec} M_{pl}}} \ll 1$$

Relic density and direct detection





- Relic density/ SI scattering can be calculated.
- Thermal $\Omega_{DM} h^2 \sim \frac{0.1\text{pb}}{\langle \sigma v \rangle}$, $\langle \sigma v \rangle = 2.5(1) \times 10^{-9} (GeV)^{-2}$.
- limit from LUX ($M_\rho \sim \mathcal{O}(TeV)$)

1-loop beta function

$$
\begin{aligned}
16\pi^2\frac{d\lambda_H}{dt} &= 12\lambda_H^2 + 6\lambda_H y_t^2 - 3y_t^4 - \frac{3}{2}\lambda_H(3g_2^2+g_1^2) + \frac{3}{16}\left[(g_1^2+g_2^2)^2 + 2g_2^4\right] \\
&\quad + \frac{1}{2}(\lambda_{HS}^2 + \lambda_{\Phi H}^2) \\
16\pi^2\frac{d\lambda_\Phi}{dt} &= 10\lambda_\Phi^2 + \lambda_{\Phi H}^2 + \frac{1}{2}\lambda_{\Phi S}^2 \\
16\pi^2\frac{d\lambda_S}{dt} &= 10\lambda_S^2 + \lambda_{HS}^2 + \frac{1}{2}\lambda_{\Phi S}^2 - 8Y_S^4 + 4Y_S^2\lambda_S \\
16\pi^2\frac{d\lambda_{HS}}{dt} &= 2\lambda_{HS}^2 + \lambda_{HS}(6\lambda_H + 4\lambda_S) + 2\lambda_{HS}Y_S^2 - \frac{3}{4}\lambda_{HS}(3g_2^2+g_1^2) \\
&\quad + 3\lambda_{HS}y_t^2 + \lambda_{\Phi S}\lambda_{\Phi H} \\
16\pi^2\frac{d\lambda_{\Phi H}}{dt} &= 2\lambda_{\Phi H}^2 + \lambda_{\Phi H}(6\lambda_H + 4\lambda_\Phi) - \frac{3}{4}\lambda_{\Phi H}(3g_2^2+g_1^2) \\
&\quad + 3\lambda_{\Phi H}y_t^2 + \lambda_{\Phi S}\lambda_{HS} \\
16\pi^2\frac{d\lambda_{\Phi S}}{dt} &= 2\lambda_{\Phi S}^2 + 4\lambda_{\Phi S}(\lambda_\Phi + \lambda_S) + 2\lambda_{\Phi S}Y_S^2 + 2\lambda_{\Phi H}\lambda_{HS} \\
16\pi^2\frac{dY_S}{dt} &= 3Y_S^3\,, \quad 16\pi^2\frac{d\kappa}{dt} = \kappa\left(2\lambda_{\Phi S} + 2\lambda_\Phi + Y_S^2\right)
\end{aligned}
$$

- Fermionic y^4 contributions responsible for vacuum instability.
- In general, new scalar DOF's help VS.
- Possible new Landau pole in λ_Φ

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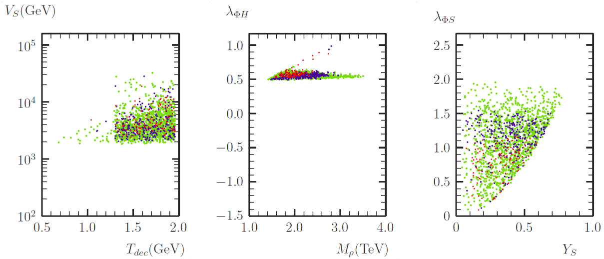
Numerical Scan

- Comprehensive scan of the whole parameter space. Randomly scan T_{dec}, M_S, θ, M_ρ, $\lambda_{\Phi S}(\in [-4\sqrt{\pi\lambda_S}, 4\pi])$, $\bar{\kappa}$, $\lambda_{\Phi H}$, λ_Φ.
- Requirements and experimental constraints in our search:
  - Improve the SM vacuum stability, $\mu_{VS} > \mu_{VS}^{SM}$ ($\mu_{VS1-loop}^{SM} = 2 \times 10^5$GeV)
  - No Landau pole below μ_{VS}^{SM}
  - $\Gamma_{inv}^H < 0.8$MeV.
  - $T_{dec} \in [m_\mu, 2GeV]$.
  - θ complies with all experimental bounds.
  - relic density $\langle \sigma v \rangle = 2.5(1) \times 10^{-9} (GeV)^{-2}$.
  - Spin-independent direct DM search bound (LUX)
- The largest $R_{VS} \equiv \log_{10} \mu_{VS}/\mu_{VS}^{SM}$ we got ~ 11. New scalar DOF help to go up to GUT scale, but not M_{pl}.
- $T_{dec} > 1.3$GeV, 1.5TeV $< M_\rho <$ 4TeV, $M_S \in [20, 100]$GeV, $v_S, -\kappa \in [2 - 20]$TeV

Some qualitative understanding

- $T_{dec} < 2\text{GeV}$, small λ_{SH}.
- λ_S V.S. needs large v_S to suppress $y_S = \sqrt{2}M_N/v_s$.
- large $v_S \Rightarrow$ large mixing $\Rightarrow$ large M_S and higher T_{dec}.
- To counter act y_S in λ_S V.S. $\Rightarrow$ sizable $\lambda_{\Phi S}$.
- to improve λ_H V.S. $\Rightarrow \lambda_{\Phi H} \sim \mathcal{O}(1)$.
- $\lambda_{\Phi H} \sim \mathcal{O}(1) \Rightarrow M_\rho > 1.5\text{TeV}$.
- to avoid λ_Φ Landau pole $\Rightarrow$ small $\lambda_\Phi, \lambda_{\Phi S}$ are preferred.
- small $\lambda_{\Phi S} \Rightarrow M_\rho < 4\text{TeV}$, or too much DM.

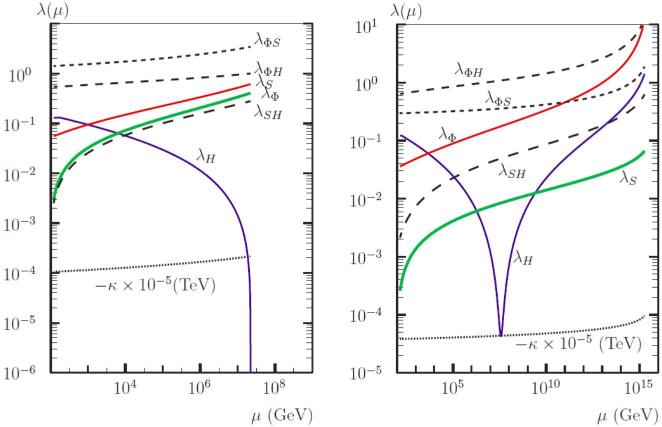


R_{VS} G:2 − 4, B:4 − 6, R:> 6.

Numerical Scan: 2 examples

Config.	T_{dec}	M_S	θ	M_ρ	v_S	R_{VS}	$Br(\omega\omega)$	$Br(b\bar{b})$
A	1.94	27.3	-0.03	2.2	6.7	2.1	0.87	0.11
B	1.87	67.6	-0.32	1.8	12.1	10.0	0.07	0.78

T_{dec} and M_S (M_ρ and v_S) are in GeV (TeV).



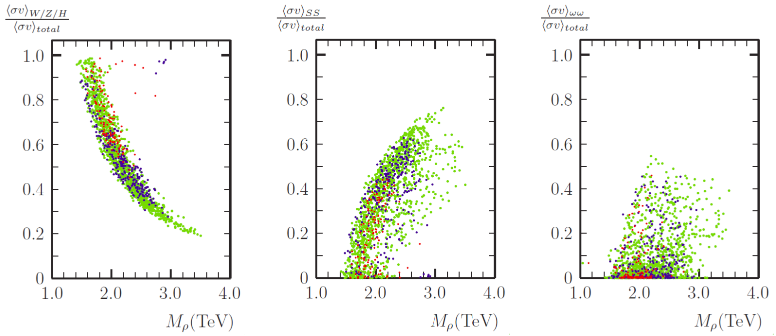
Numerical Scan:DM annihilation

For $\lambda_S, \lambda_{SH} \ll 1$ and $M_\rho \gg M_W, M_Z, M_H$, the total annihilation cross section of $\rho\rho \to W^+W^-, ZZ, HH$ can be estimated to be

$$\langle \sigma v \rangle_{W/Z/H} \equiv \langle \sigma v \rangle_{W^+W^-} + \langle \sigma v \rangle_{ZZ} + \langle \sigma v \rangle_{HH} \sim \frac{1}{64\pi} \frac{\lambda_{\Phi H}^2}{M_\rho^2} \times [2+1+1]$$

$$\sim 5 \times 10^{-9} (GeV)^{-2} \left(\frac{\lambda_{\Phi H}}{0.5} \right)^2 \left(\frac{1\text{TeV}}{M_\rho} \right)^2 .$$

The channels $\rho\rho \to SS, \omega\omega$ open only when $M_\rho > 2$TeV.



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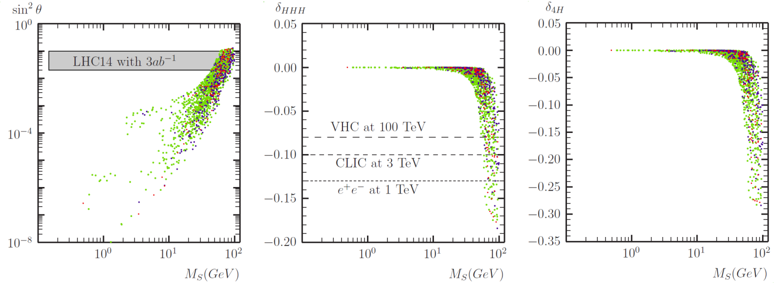
Indirect search at LHC

- A universal value $\cos^2\theta$ for all signal strengthes due to $H - S$ mixing. $M_S > 40\text{GeV}$ deteactable at LHC14 with $3ab^{-1}$.
- the SM Higgs triple coupling $\lambda_{HHH}^{SM} = 3M_H^2/v_H$ is modified to $\lambda_{HHH} = 6\lambda_H v_H c_\theta^3 - 6\lambda_S v_S s_\theta^3 + 3\lambda_{SH} s_\theta c_\theta (v_H s_\theta - v_S c_\theta)$. And $\delta_{HHH} \equiv (\lambda_{HHH} - \lambda_{HHH}^{SM})/\lambda_{HHH}^{SM}$
- similarly, $\lambda_{4H}^{SM} = 6\lambda_H = 3(M_H/v_H)^2$ is replaced by $\lambda_{4H} = 6(\lambda_H c_\theta^4 + \lambda_S s_\theta^4)$ in this model. $\delta_{4H} \equiv (\lambda_{4H} - \lambda_{4H}^{SM})/\lambda_{4H}^{SM}$, XS for triple Higgs production is too small.



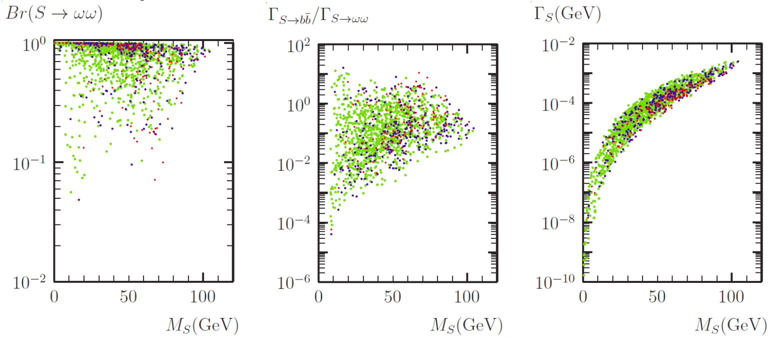
S decay

The relevant modes are s into quarks, leptons, and ω's.

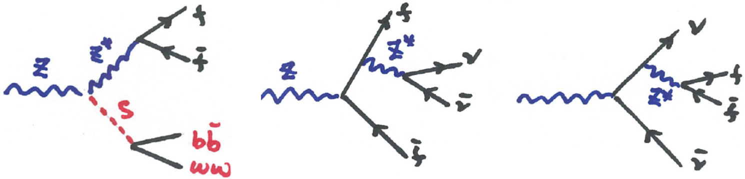
$$\Gamma(s \to \omega\omega) = \frac{1}{32\pi}\frac{c_\theta^2 M_s^3}{v_s^2}$$

$$\Gamma(s \to f\bar{f}) = \frac{M_s}{8\pi} N_c^f \beta_f^3 \left(\frac{m_f s_\theta}{v}\right)^2$$

where $\beta_f = \sqrt{1 - \frac{4m_f^2}{M_s^2}}$ for the fermion.



At Z factory

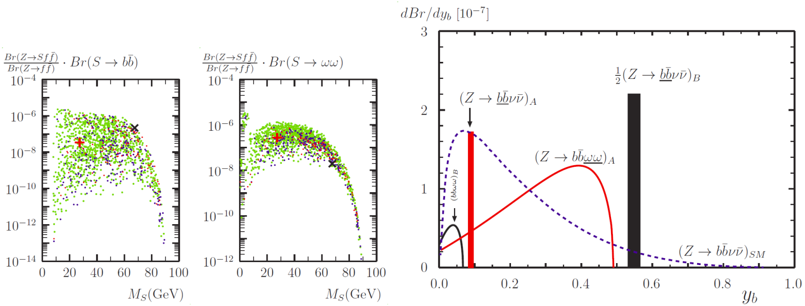


- Future Circular Collider expects to have 10^{12-13} Z bosons at $\sqrt{s} = M_Z$ with multi-ab^{-1} luminosity.(JHEP1401,164)
- Defining $y_f = \frac{M^2_{f\bar{f}}}{M_Z^2}$ we obtain

$$\frac{dBr(Z \to Sf\bar{f})}{dy} = \frac{g^2 \sin^2\theta}{192\pi^2\cos^2\theta_W}\sqrt{y_f^2 - 2y_f(1+r_Z^2) + (1-r_Z^2)^2} \times \frac{\left[y_f^2 + 2y_f(5-r_Z^2) + (1-r_Z^2)^2\right]}{(1-y_f)^2} \times Br(Z \to f\bar{f})$$

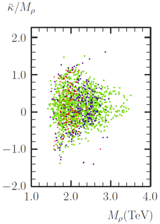
where $r_Z = \frac{M_S}{M_Z}$ and $0 \le y_f \le (1-r_Z)^2$. The kinematic lower bound can be safely taken to be zero even for y_b.

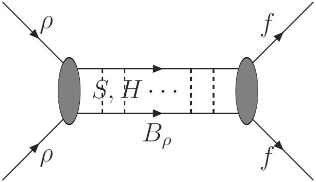
At Z factory-1



- Note the lower bound for each decay mode.
- $Br(Z\to b\bar{b}\,\not{E})_{SM} = 5.25\times 10^{-8}$
- $Z\to S\bar{f}f$ signal stands out from the SM background.

DM bound state?





- DM $\rho - \rho$ interact by exchanging $t-$channel S and H and this force is attractive. The relevant terms are:

$$\mathcal{L} \supset \frac{1}{2}[\lambda_{\Phi H} v_H h + \bar{\kappa} s]\rho^2$$

- $\bar{\kappa} \gg \lambda_{\Phi H} v_H$, s mediation dominates.
- $\bar{\kappa}/M_\rho \in [-1.0, 1.0] \Rightarrow$ DM may form bound state, B_ρ.
- Write the effective coupling between B_ρ and 2 ρ as

$$\mathcal{L} \sim \alpha_B B_\rho \rho^2 \,.$$

By dimensional analysis, $\alpha_B \sim (\bar{\kappa}^2/M_\rho)$.

DM bound state decay Width

- Decay width of B_ρ, $\Gamma_B \propto |\psi(0)|^2 \times |\mathcal{M}_{B_\rho}|^2$.
- $|\psi(0)|^2 \sim \bar{\kappa}^6/M_\rho^3$ by dimension analysis.
- Rescale the decay amplitude square and make it dimensionless, broken into

$$|\mathcal{M}_{B_\rho}|^2 = \gamma_{ss} + \gamma_{HH} + \gamma_{sH} + \gamma_{\omega\omega} + \gamma_{W,Z} + \gamma_{f\bar{f}}$$

  subscripts label the decay final state.
- drop terms of $\mathcal{O}(v_H/M_\rho)$.

$$\gamma_{ss} \simeq \left[\lambda_{\Phi S} - \frac{\bar{\kappa}^2}{M_\rho^2}\right]^2 , \ \gamma_{HH} \simeq \lambda_{\Phi H}^2 ,$$

$$\gamma_{\omega\omega} \simeq \left[\lambda_{\Phi S} - \frac{\kappa^2}{M_\rho^2 - \kappa v_S}\right]^2 , \ \gamma_{W,Z} \simeq 3\lambda_{\Phi H}^2$$

- Finally, the decay width:

$$\Gamma_B \sim M_\rho \left(\frac{\bar{\kappa}}{M_\rho}\right)^6 [\gamma_{ss} + \gamma_{\omega\omega} + 4\lambda_{\Phi H}^2]$$

$\langle \sigma v \rangle$ and DM bound state

- Put Γ_B into the propagator squared, annihilation XS due to B_ρ resonant

$$\sigma v \sim \frac{\alpha_B^2(\Gamma_B/M_B)}{(s-M_B^2)^2+\Gamma_B^2 M_B^2}$$

  Γ_B/M_B takes care the nearly on-shell B_ρ decay.

- When $v \ll 1$, $s \sim M_B^2$, no temperature dependence,

$$\langle \sigma v \rangle \sim \frac{\alpha_B^2}{M_B^3 \Gamma_B} \sim \frac{R_B}{M_\rho^2}[\gamma_{ss}+\gamma_{\omega\omega}+4\lambda_{\Phi H}^2]$$

  and

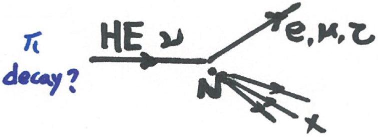
$$R_B \equiv \left(\frac{M_\rho}{\bar{\kappa}}\right)^2 [\gamma_{ss}+\gamma_{\omega\omega}+4\lambda_{\Phi H}^2]^{-2}$$

  is the boost factor for indirect DM detection.

- For $|\mathcal{M}_{B_\rho}|^2 \sim \mathcal{O}(10^0)$ and $\bar{\kappa} \sim 0.1 M_\rho$, the boost factor around 100.

At IceCube

- DM annihilate into Majoron pair is a few to 40%. With boost factor 100, $\langle \sigma v \rangle (DM + DM \to \omega\omega) \sim 10^{-26} - 10^{-24} (cm^3/s)$.
- ω could be a component of the 'apparent' neutrino flux at $E_\nu = M_\rho$ in IceCube and other neutrino observatories.
- Shower events, mostly from the Galactic center.



Summary

- Minimal Majoron model with SM singlet scalars carrying lepton numbers takes care of DR+DM+m_ν+V.S.
- $\triangle N_{eff} \sim 0.05$, or $T_{dec} > m_c$ is preferred.
- Scalar DM, ρ, of mass $1.5 - 4$ TeV is required by V.S. and an operational type-I see-saw.
- $M_S \in [10, 100]$ GeV, mixing as large as 0.1.
- S mainly decays into $b\bar{b}$ and/or $\omega\omega$.
- Sensitive search will be $Z \to S + f\bar{f}$, followed by S into a pair of Majoron and/or b-quarks.
- Possible DM bound state due to sizable $S\rho\rho$-coupling.
- shower-like events with apparent neutrino energy at M_ρ could contribute to the neutrino flux in underground neutrino detectors.