A Model for Neutrino Mass and Dark Matter with discrete gauge symmetry

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(**1104.3934** with Chi-Fong Wong)

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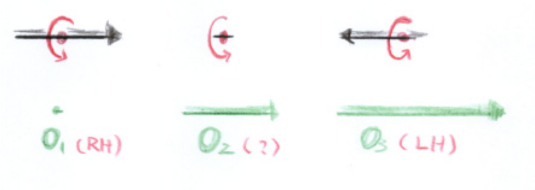
Outlines

- Evidence for massive neutrino and the existence of dark matter.
- Model for neutrino mass and dark matter
- Our proposal and how it works
- Consequences
- Conclusion

SM neutrino

- Mass requires Both the RH and LH components



- Neutrinos are massless in SM
- If being massive, they could mix with each other.

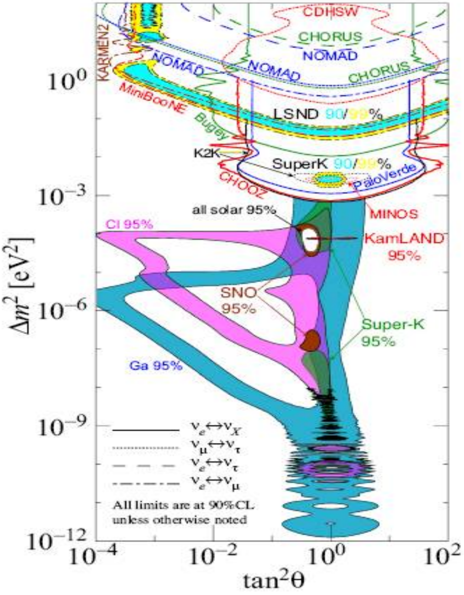
$$|\nu_a, t\rangle = \cos\theta|\nu_1\rangle \exp\frac{-im_1^2 t}{2p} + \sin\theta|\nu_2\rangle \exp\frac{-im_2^2 t}{2p}$$

- flavor oscillation

$$P(a \to a) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\triangle m^2 L}{E}\right)$$

in the units of $(eV)^2, km, GeV$

Neutrino Oscillation

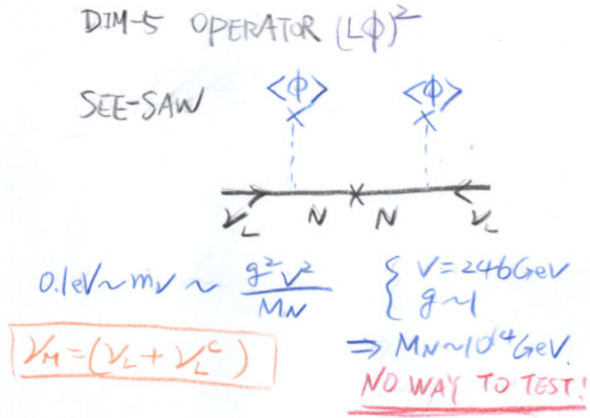


Pressing Questions

To generate nonzero neutrino masses, we need to go beyond SM.

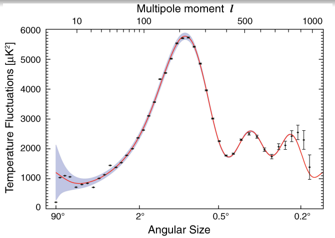
- How many extra degrees of freedom BSM?
- Are they fermionic or bosonic?
- Can the mechanism be tested?

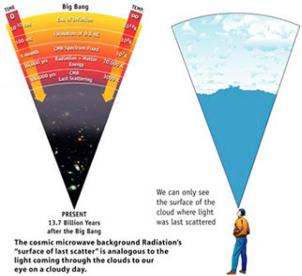
Traditional See-Saw

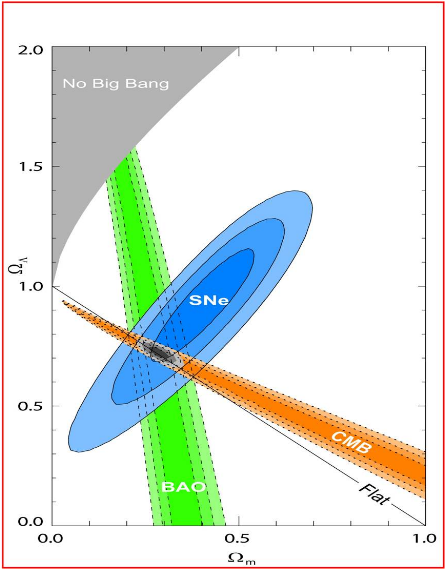


- More than 2 fermionic DOFs.
- Impossible to be tested directly.

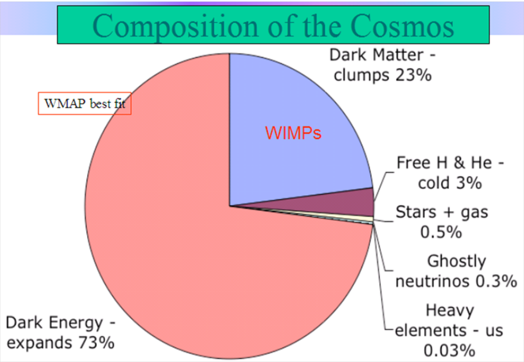
Flat Universe







Dark universe



- What are the DM and DE?
- DM must be electrically neutral and long lived.

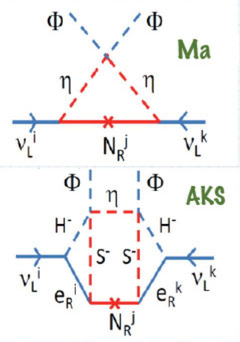
One week before the Japan earthquake

From the talk given by Takashi Shimomura at KEKPH2011.

Radiative Seesaw Models

tiny neutrino masses from quantum effects

- 1 loop : Ma (2006), Kanemura-Ota (2010)
- 2 loop: Zee, Babu (1988),
- 3 loop: Krauss-Nasri-Trodden (2003), Aoki-Kanemura-Seto (2009)



neutrino mass (n loop, dim. 5+2m)

$$m_\nu = c\left(\frac{1}{16\pi^2}\right)^n\left(\frac{v}{M}\right)^{2m}\frac{v^2}{M}$$

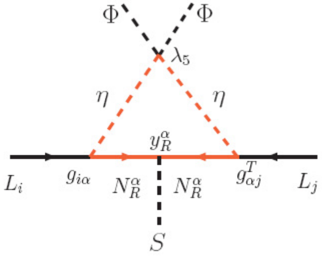
loop factor   higher dim.

→ $M \sim \mathcal{O}(1)$ TeV

common feature

- extra Higgs
- Z_2 parity → the lightest particle can be the dark matter

arXiv:1101.5731, Kanemura, Seto, Shimomura



	Q^i	d_R^i	u_R^i	L^i	e_R^i	Φ	η	S	N_R^α
$SU(3)_C$	3	3	3	1	1	1	1	1	1
$SU(2)_W$	2	1	1	2	1	2	2	1	1
$U(1)_Y$	1/6	−1/3	+2/3	1/2	−1	1/2	1/2	0	0
$U(1)_{B-L}$	1/3	1/3	1/3	−1	−1	0	0	+2	−1
Z_2	+	+	+	+	+	+	−	+	−

Common origin of the TeV Majorana mass and Z_2?

- Where comes the Z_2?
- It is not respected by the gravity anyway!
- Then I asked the question: " Can we cook up a model which has a unified origin for the TeV Majorana mass and the Z_2 to stabilize the Dark Matter"?
- The answer is confirmative. By using the Krauss-Wilczek Mechanism, PRL62,1221 (1989).

Krauss-Wilczek Mechanism

U(1) gauge transformation $\psi \to \exp(-i g \alpha(x,t))\,\psi$

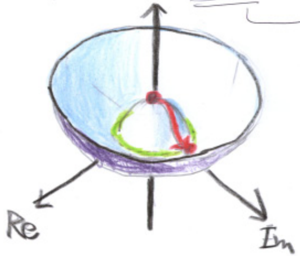
U(1) charge

$\sim S_1$

$$\begin{cases} D_\mu \psi = (\partial_\mu - i g A_\mu)\,\psi \\ A_\mu(x) \to A_\mu(x) + \partial_\mu \alpha \end{cases}$$

Spontaneous Symmetry Breaking (by a scalar, say $g_{vev} = 2$)

→ redundant degree of freedom

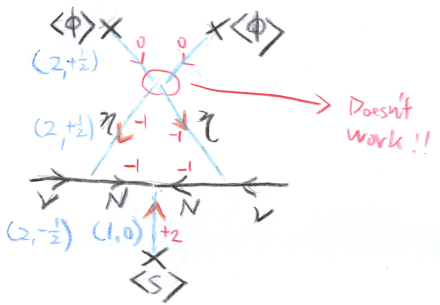


fields with diff charge rotate at diff "ω"

First Try

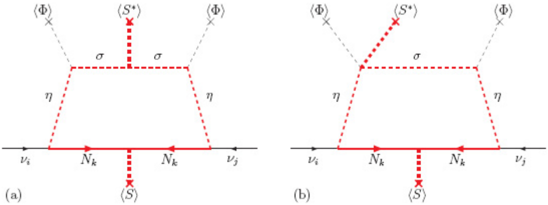
Requirements:

- Anomaly free charge assignment, residue Z_N
- N_R is Z_2-odd, its mass should be around TeV
- SM Φ is Z_2-even
- All vertices go!



Active neutrino mass

- Active neutrino masses arise from the 1-loop diagrams



- dim-7 operator $(\Phi L)^2 S^\dagger S$ (dominated by diag-(b))

$$\mathcal{M}^\nu_{ij} \sim \frac{1}{16\pi^2}\frac{\kappa\mu_2 v_\Phi^2 v_S^2}{\Lambda^4}\sum_a y^N_a g^*_{ia} g^*_{ja} \sim 0.001 \times \frac{|g|^2}{16\pi^2}\mu_2$$

- For $\Lambda \sim v_S \sim$TeV, $\kappa y \sim 0.1$, and $\mu_2 \sim 0.1$TeV, $g \sim 10^{-4} \sim 10 m_e/v$

Charge assignment

	Q_L	u_R	d_R	L	e_R	N_{Ra}	n_{Lb}	Φ	η	σ	S
$SU(2)_L$	2	1	1	2	1	1	1	2	2	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_\nu$	0	0	0	0	0	-1	-1	0	-1	-1	2
$Z_{2\nu}$	$+$	$+$	$+$	$+$	$+$	$-$	$-$	$+$	$-$	$-$	$\times$

- Charge assignment and the remaining discrete $Z_{2\nu}$ parity for the fields, where Q_L, u_R, d_R, L, e_R are the standard notation for SM quark and lepton.
- As always, there is price to pay to simplify things.

Masses of new fermionic DOF

- The $U(1)_\nu$ allowed Yukawa and the Dirac mass

$$\frac{y_a^N}{2}\overline{N_a^C}SN_a + \frac{y_a^n}{2}\overline{n_a^C}Sn_a + g_{ia}\overline{L_i}\tilde{\eta}N_a + m_{ab}^D\bar{n}_a N_b + h.c.$$

- What value should m^D take? (Traditional see-saw does not have this term.)

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- If the first two terms were absent (or $y^N = y^n = 0$), the $U(1)_A$ symmetry

$$N_R \to e^{i\theta}N_R\,,\ e_L \to e^{-i\theta}n_L$$

forbids the Dirac mass!

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Singlet fermion masses

- Let's consider only one pair of vector fermion N_R and n_L.
- After SSB, the fermionic DOF take the following mass matrix:

$$\mathcal{L} \supset \frac{1}{2}\left(\overline{n_L^{\mathbf{c}}}, \overline{N_R}\right) \begin{pmatrix} g^n v_S & m^D \\ m^D & g^N v_S \end{pmatrix} \begin{pmatrix} n_L \\ N_R^{\mathbf{c}} \end{pmatrix} + h.c.$$

Two eigenvalues:
$\frac{1}{4}\left[v_S(g^N + g^n) \pm \sqrt{v_S^2(g^N - g^n)^2 + (m^D)^2}\right]$

- Two mass eigenstate Majorana fermions:

$$\chi_1 = \cos\theta(n_L + n_L^{\mathbf{c}}) - \sin\theta(N_R + N_R^{\mathbf{c}}) = \chi_1^{\mathbf{c}}$$
$$\chi_2 = \sin\theta(n_L + n_L^{\mathbf{c}}) + \cos\theta(N_R + N_R^{\mathbf{c}}) = \chi_2^{\mathbf{c}}$$
$$\tan 2\theta = \frac{m^D}{v_S(g^n - g^N)}$$

Is one pair of vector fermion enough?

- If there is only one pair of $N - n$, the resulting active neutrino mass matrix is proportional to

$$\mathcal{M}^{\nu}_{ij} \propto \begin{pmatrix} g_1^2 & g_1 g_2 & g_1 g_3 \\ g_2 g_1 & g_2^2 & g_2 g_3 \\ g_3 g_1 & g_3 g_2 & g_3^2 \end{pmatrix}$$

- The eigenvalues are $\{0, 0, g_1^2 + g_2^2 + g_3^2\}$
- Need at least two pairs of $N - n$.
- 4 massive Majorana fermions, χ_{1-4}, large mixing between the N_R and n_L sectors.

potential

- We can write down the most general renormalizable $U(1)_\nu$ inv. potential

$$
\begin{aligned}
V &= \bar{\mu}_\Phi^2|\Phi|^2 + \bar{\mu}_\eta^2|\eta|^2 + \bar{\mu}_\sigma^2|\sigma|^2 + \bar{\mu}_S^2|S|^2 \\
&+ \lambda_1|\Phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\sigma|^4 + \lambda_4|S|^4 \\
&+ \lambda_5|\Phi|^2|\eta|^2 + \lambda_6|\Phi^\dagger\eta|^2 + \lambda_7|\Phi|^2|\sigma|^2 + \lambda_8|\Phi|^2|S|^2 \\
&+ \lambda_9|\eta|^2|\sigma|^2 + \lambda_{10}|\eta|^2|S|^2 + \lambda_{11}|\sigma|^2|S|^2 \\
&+ \kappa(\Phi^\dagger\eta\sigma S) + \mu_1(\sigma\sigma S) + \mu_2(\eta^\dagger\Phi\sigma) + h.c.
\end{aligned}
$$

Effective potential

- After the S get a VEV, we integrate out the heavy degree of freedom.
- The potential becomes

$$
\begin{aligned}
V_{eff} &= \mu_\Phi^2|\Phi|^2 + \mu_\eta^2|\eta|^2 + \mu_\sigma^2|\sigma|^2 + \lambda_1|\Phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\sigma|^4 \\
&+ \lambda_5|\Phi|^2|\eta|^2 + \lambda_6|\Phi^\dagger\eta|^2 + \lambda_7|\Phi|^2|\sigma|^2 + \lambda_9|\eta|^2|\sigma|^2 \\
&+ \kappa v_S(\Phi^\dagger\eta\sigma) + \mu_1 v_S(\sigma\sigma) + \mu_2(\eta^\dagger\Phi\sigma) + h.c.
\end{aligned}
$$

where

$$\mu_\Phi^2 = (\bar{\mu}_\Phi^2 + \lambda_8 v_S^2)\,,\ \mu_\eta^2 = (\bar{\mu}_\eta^2 + \lambda_{10} v_S^2)\,,\ \mu_\sigma^2 = (\bar{\mu}_\sigma^2 + \lambda_{11} v_S^2)$$

- It's easy to have the solution that $\langle\Phi\rangle = 246\text{GeV}$, $\langle\eta\rangle = \langle\sigma\rangle = 0$.

Physical Higgs

- Due to the Z_2, SM Higgs does NOT mix with the η and σ
- 3 out of 4 D.O.F. are the would be Goldstone bosons.
- One SM Higgs. 2 Charged, 2 Scalars, 2 Pseudoscalars.
- $M_{\pm}^2 = \mu_\eta^2 + \lambda_5 v_\Phi^2$

$$
\begin{aligned}
M_{odd}^s &= \begin{pmatrix} M_{\pm}^2 + \lambda_6 v_\Phi^2 & \mu_2 v_\Phi + \kappa v_S v_\Phi \\ \mu_2 v_\Phi + \kappa v_S v_\Phi & \mu_\sigma^2 + \lambda_7 v_\Phi^2 + 2\mu_1 v_S \end{pmatrix}, \\
M_{odd}^p &= \begin{pmatrix} M_{\pm}^2 + \lambda_6 v_\Phi^2 & \mu_2 v_\Phi - \kappa v_S v_\Phi \\ \mu_2 v_\Phi - \kappa v_S v_\Phi & \mu_\sigma^2 + \lambda_7 v_\Phi^2 - 2\mu_1 v_S \end{pmatrix}.
\end{aligned}
$$

in the basis of $\{\mathrm{Re}\,\eta^0, \mathrm{Re}\,\sigma^0\}$ and $\{\mathrm{Im}\,\eta^0, \mathrm{Im}\,\sigma^0\}$ respectively.

- Denote $H_1 = \cos\alpha\,\mathrm{Re}\,\eta^0 + \sin\alpha\,\mathrm{Re}\,\sigma^0$ and $A_1 = \cos\delta\,\mathrm{Im}\,\eta^0 + \sin\delta\,\mathrm{Im}\,\sigma^0$. Masses around v_Φ to v_S.

Lepton Flavor violation

- When neutrino are massive, lepton flavor is no longer conserved.
- For example, $\mu \to e\gamma$, $\mu \to 3e$ could happen.
- However, $Br(\mu \to e\gamma) < 10^{-12}$
- $\mu \to e\gamma$ arises from the dim-6 operator, active neutrinos play no role(GIM).

$$\bar{L}\Phi\sigma^{\mu\nu}e_R F_{\mu\nu}$$

- The branching ratio can be estimated

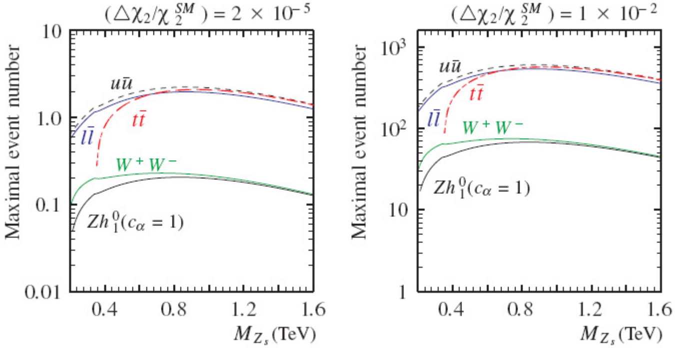
$$\frac{Br(\mu \to e\gamma)}{Br(\mu \to e\bar{\nu}_e\nu_\mu)} \sim \left(\frac{e|g_{\mu k}g_{ke}|}{(16\pi^2)G_F\Lambda^2}\right)^2 \sim 10^{-8} \times |g_{\mu k}g_{ke}|^2 \times \left(\frac{1\text{TeV}}{\Lambda}\right)^4$$

No problem with $g \sim 10^{-4}$.

- A new term can be added

$$-\frac{\epsilon}{2}B^{\mu\nu}X_{\mu\nu}$$

- "A Very Narrow Shadow Extra Z-boson at Colliders", PRD74:095005,2006.
- Drell-Yan Production at LHC, $q(p) + \bar{q}(p) \to Z'^{*} \to X$



- Definite relative decay BRs into SM fermions (determined completely by the hypercharge of fermion and the mixing parameter ϵ):

$$B(Z'_\nu \to u\bar{u}) : B(Z'_\nu \to d\bar{d}) : B(Z'_\nu \to e\bar{e}) : B(Z'_\nu \to \nu\bar{\nu}) = 5.63 : 1.66 : 4.99 : 1$$

  $(\epsilon = 0.07)$

- When χ_1 and H_1, A_1 are much lighter than Z'_ν, $Z'_\nu \to \chi_1\chi_1, H_1H_1, A_1A_1$ will become the dominate decay channels.

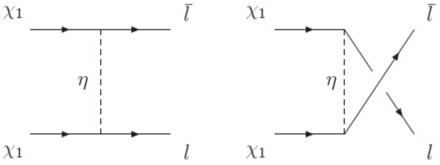
Majorana Dark Matter

- Which DOF is the DM?
- Equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\frac{dn}{dt} + 3Hn = -\langle\sigma_{ann}v_{rel}\rangle(n - n_{eq})$$

- Roughly speaking, the relic density $\Omega_{DM}h^2 \propto 1/\langle\sigma_{ann}v_{rel}\rangle$.
- annihilation for Majorana fermion



Majorana Dark Matter relic density

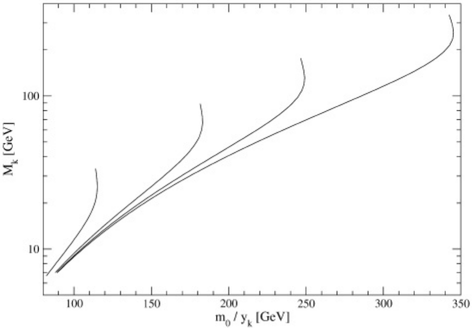


Fig. 3. M_k versus m_0/y_k for $y_k = 0.3, 0.5, 0.7, 1.0$ (left to right) for $\Omega_d h^2 = 0.12$, where y_k is defined in Eq. (9).

The thermally averaged cross section for the annihilation of two N_k's into two leptons is computed by expanding the corresponding relativistic cross section σ in powers of their relative velocity and keeping only the first two terms. Using the result of Ref. [11], and recognizing that lepton masses are very small, we have

$$\langle \sigma v \rangle = a + b_k v^2 + \cdots, \quad a = 0, \; b_k = \frac{y_k^4 r_k^2 (1 - 2r_k + 2r_k^2)}{24\pi M_k^2}, \tag{8}$$

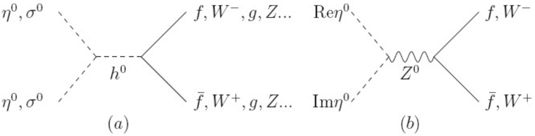
where

$$r_k = M_k^2 / (m_0^2 + M_k^2), \qquad y_k^4 = \sum_{\alpha\beta} |h_{\alpha k} h_{\beta k}^*|^2. \tag{9}$$

Not χ_1

- Given that $g \sim 10^{-4}$, $M_\eta \ll M_\chi$ is required to yield $\Omega_{\chi_1} h^2 \sim 0.11$
- $M_{\chi_{1-4}} > M_\eta$
- All the four Majorana decay into η and SM leptons (through Yukawa and the n_L and N_R mixing).
- Either H_1 or A_1 is the viable dark matter candidate.
- All the heavier $Z_{2\nu}$-odd scalars decay into SM $W^\pm/Z^0$ plus H_1 or A_1.

- diagrams for (co)-annihilation cross section



$$\sigma_{ann} v_{rel} = \frac{8\lambda^2 v_\Phi^2 \sum_i \Gamma(h^0 \to X_i)}{(4M_S^2 - m_{h^0}^2)^2 + \Gamma_{h^0}^2 m_{h^0}^2} \frac{1}{2M_S},$$

$$\lambda = \cos^2\alpha(\lambda_5 + \lambda_6) + \sin^2\alpha\lambda_7 + \sin 2\alpha(\mu_2 + \kappa v_S)/v_\Phi \text{ for } H_1,$$
$$\lambda = \cos^2\delta(\lambda_5 + \lambda_6) + \sin^2\delta\lambda_7 + \sin 2\delta(\mu_2 - \kappa v_S)/v_\Phi \text{ for } A_1.$$

- $\Gamma(h^0 \to X_i)$ is the rate for the virtual Higgs decays into X_i.
- $M_S \gg m_h$, the hh, WW, ZZ channels open up.
- Almost everything about the scalar DM has been studied in the past 25 years.

Scalar Dark Matter relic density-1

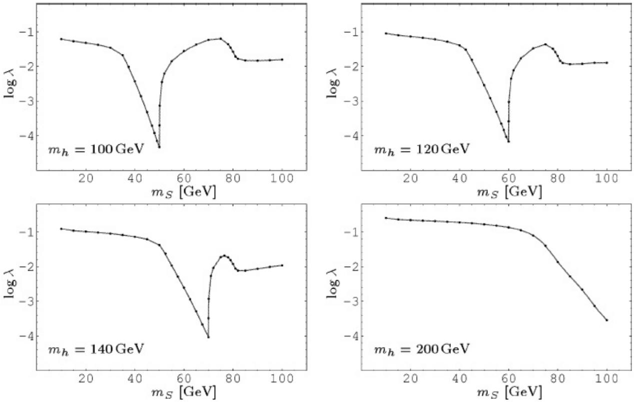


Fig. 2. Four samples of the $\log\lambda$–m_S relationship between λ and m_S, which gives the correct cosmic abundance of S scalars. For these plots the Higgs mass is chosen to be 100, 120, 140, and 200 GeV. The abundance is chosen to be $\Omega_s h^2 = 0.3$.

Scalar Dark Matter relic density-2

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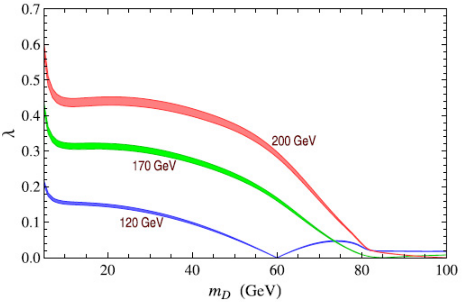

Fig. 1. Darkon–Higgs coupling λ as a function of the darkon mass m_D for Higgs mass values $m_h = 120, 170, 200$ GeV. The band widths in all figures result from the relic-density range which we have taken, $0.1065 \leqslant \Omega_D h^2 \leqslant 0.1181$.

Scalar Dark Matter direct detection

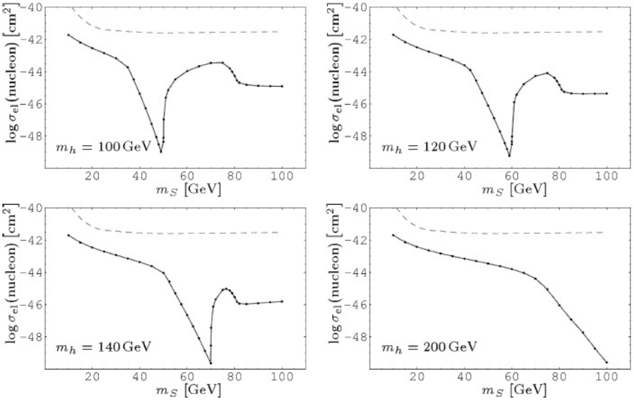

Fig. 4. The predictions for the elastic cross section, σ_{el}, as a function of m_S, which follows from the $\lambda(m_S)$ dependence dictated by the cosmic abundance. Also shown by a dashed line is the exclusion limit from the CDMS experiment [6].

Scalar Dark Matter direct detection-2

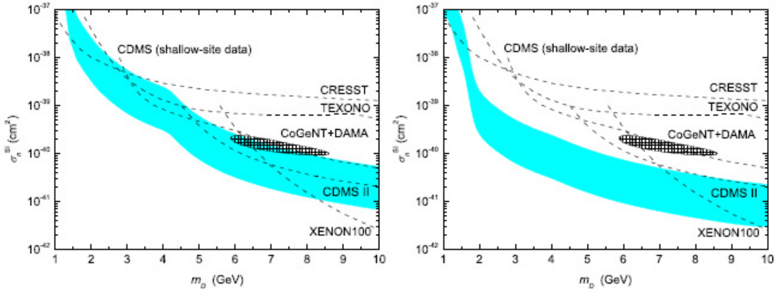

FIG. 1: The predicted DM-nucleon elastic scattering cross section σ_n^{SI} in the SSDM-SM (left panel) and SSDM-2HBDM (right panel) for 1 GeV $\leq m_D \leq$ 10 GeV. The black region corresponds to a combination of the DAMA and CoGeNT [24]. The dashed lines indicate the current experimental upper bounds from the CDMS II [25], CDMS [26], CRESST [27], TEXONO [28] and XENON100 [29].

Scalar Dark Matter direct detection-3

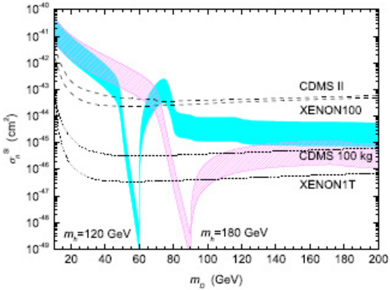

FIG. 2: The predicted DM-nucleon elastic scattering cross section $\sigma_n^{\rm SI}$ for 10 GeV $\leq m_D \leq$ 200 GeV in the SSDM-SM. The dashed lines indicate the current experimental upper bounds from the CDMS II [25] and XENON100 [29]. The short dotted lines denote the future experimental upper bounds from the CDMS 100 kg [30] and XENON1T [31].

Scalar Dark Matter direct detection-4

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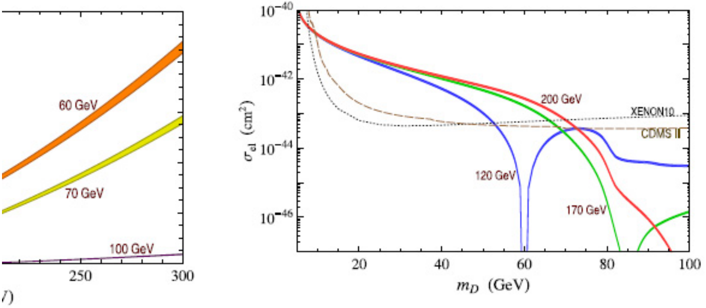

the Higgs mass m_h for darkon mass

Fig. 3. Darkon–nucleon elastic cross-section σ_{el} as a function of the darkon mass m_D for Higgs mass values $m_h = 120, 170, 200$ GeV, compared to 90%-C.L. upper limits from CDMS II (dashed curve) and XENON10 (dotted curve).

Scalar Dark Matter

- In short, all the studies agree that there are plenty of parameter space to make the scalar dark matter viable and could be directly detected at the underground laboratories in the near future.
- However, to have the right dark matter relic density, the mass M_S and the coupling λ are strongly correlated and such tight relation does not naturally come out in the general scalar dark matter models. (Neither in ours)
- We actually have not much to add to the known properties of the scalar dark matter. We just want to point out that there is a new contribution to the depletion of H_1 or A_1 from the $H_1 A_1$ coannihilation if their masses are not too different from each other.

Side Remarks

- The usual leptogenesis mechanism does not work. The Yukawa coupling too large to be out of equilibrium,

$$\sum |g|^2 \leq 8\pi\sqrt{4\pi^3 g_*/45}(M_\chi/M_{Planck}) \sim 10^{-14}$$

- To utilize the TeV scale singlet fermions for leptogenesis requires extra arrangement such as the resonance leptogenesis (Pilaftsis, 03) or via the 3 body decay mechanism (Hambye, 01). But fine tuning is then unavoidable.
- The $Z_{2\nu}$-odd scalar sector still helps to get a stronger first order EW phase transition which is crucial for EWBAU.

Conclusions

- Singlet fermions acquire Majorana masses via $U(1)_\nu$ breaking at TeV scale.
- Active neutrino masses arise from 1-loop diagrams, equivalent to a dim-7 operator, without much fine tuning.
- Z_2 discrete gauge symmetry a la Krauss-Wilczek stabilize the dark matter candidate
- Thermal relic density of the lightest Z_2-odd scalar can explain the observed dark matter abundance.
- New degrees of freedom can be probed at TeV scale.