Model for Neutrino Masses and Dark Matter with the Discrete Gauge Symmetry

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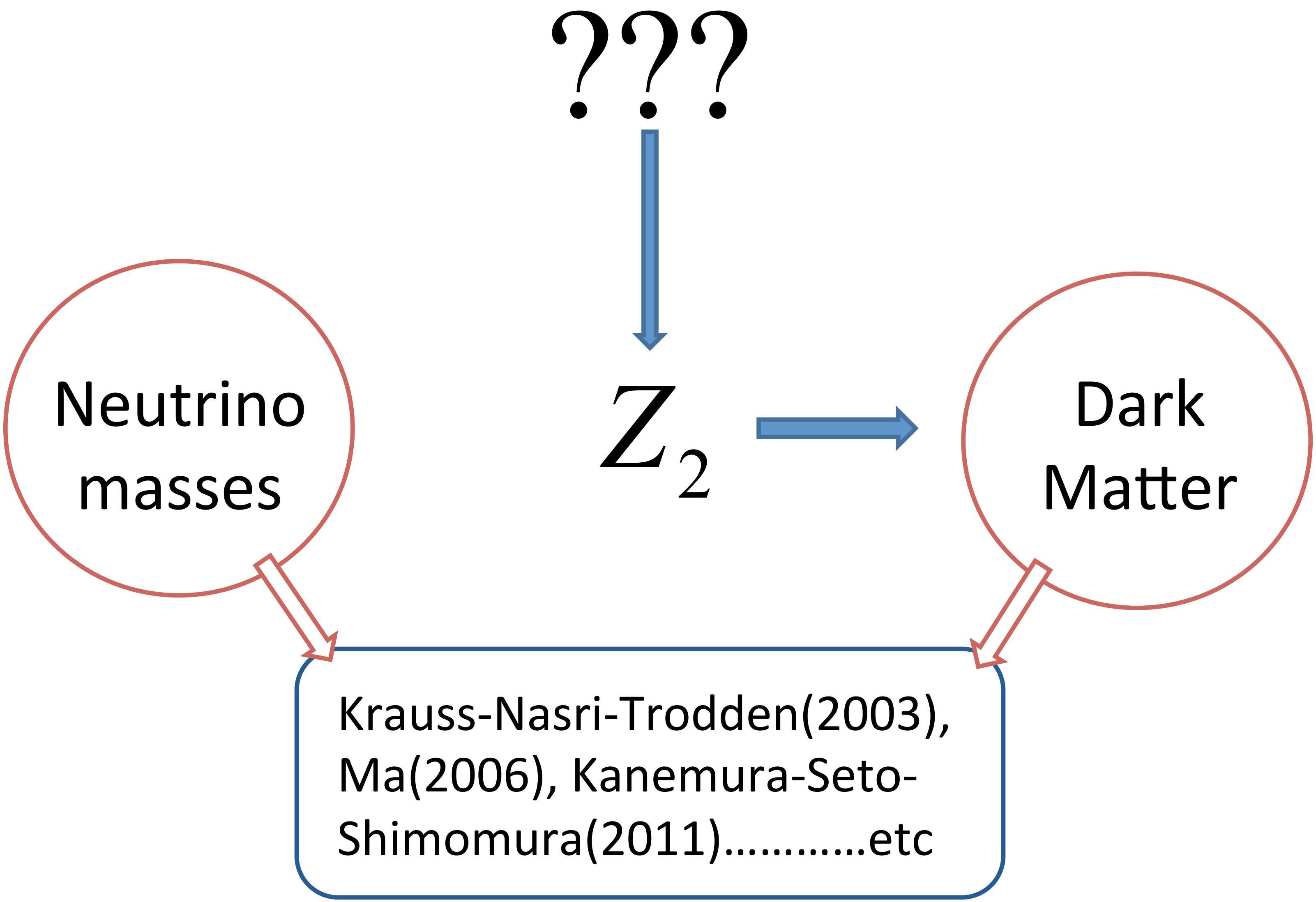
Motivation

- Simplest Seesaw mechanism is untestable.
- For making the scale of neutrino masses generation lower, loop quantum correction is a natural choice.
- The usual loop correction model need some discrete symmetry to forbidden tree mass. It can be used to stablize Dark Matter candidate. eg. Ma model….etc.

Background



???

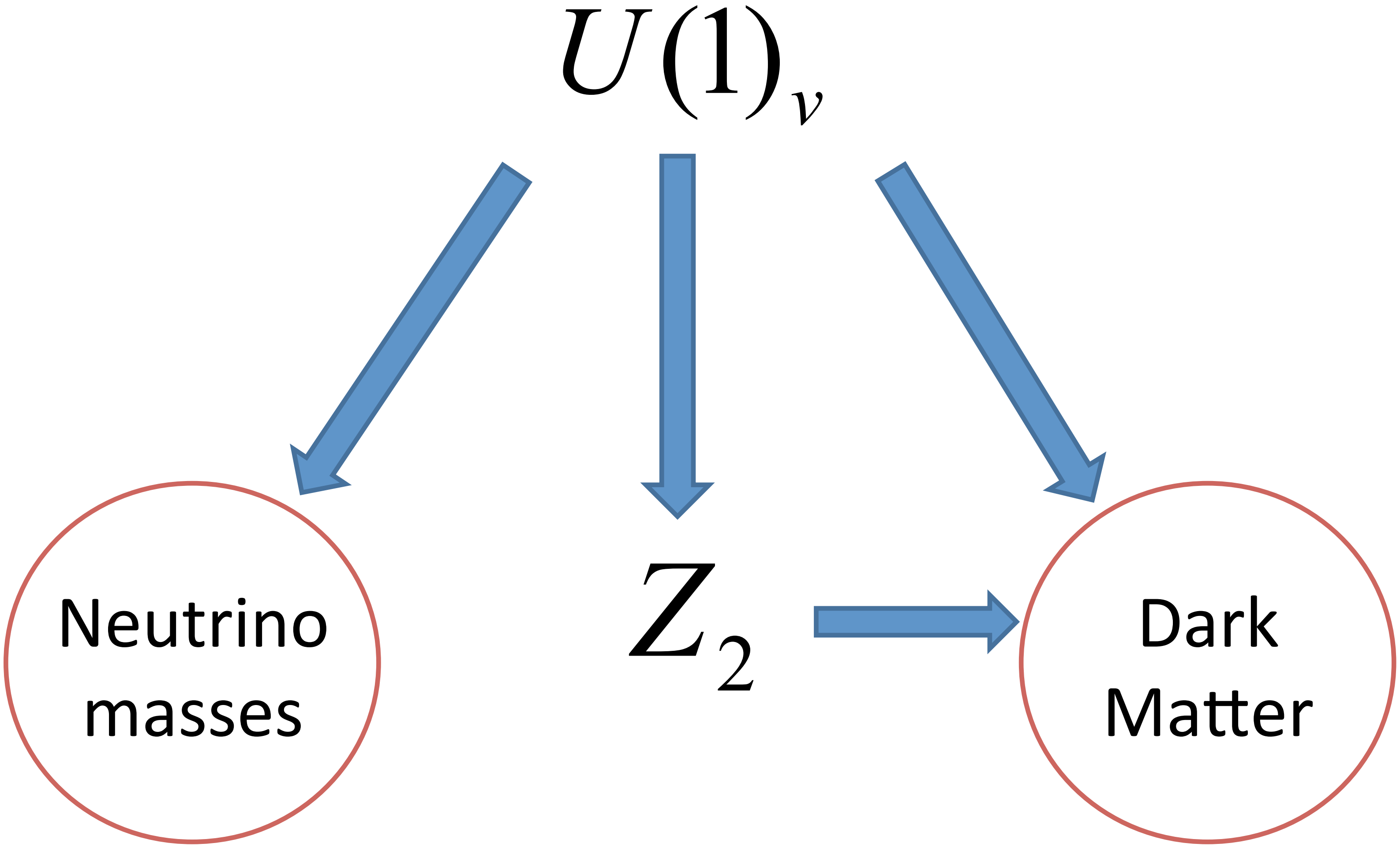
Z_2

Neutrino masses

Dark Matter

Krauss-Nasri-Trodden(2003), Ma(2006), Kanemura-Seto-Shimomura(2011)…………etc

Our model



$U(1)_\nu$

Z_2

Neutrino masses

Dark Matter

Outline

- Origin of Z_2
- The model

- Neutrino masses

- Lepton flavor violation
- Z’ in collider
- Z_2 odd fermions
- Scalar sector

- Summary

Z2 parity from U(1) gauge symmetry

A toy model (Krauss-Wilczek, 1989):

U(1) gauge symmetry:

$$\begin{aligned} \phi &\longrightarrow exp(i\theta)\phi \\ S &\longrightarrow exp(2i\theta)S \end{aligned} \quad \Longrightarrow \quad \phi \to -\phi$$

$$\theta \text{ arbitrary} \quad \Longrightarrow \quad \theta = n\pi$$

$$U(1)_{\nu} \quad \Longrightarrow \quad Z_{2\nu}$$

After SSB of U(1), ϕ become a Z2 odd particle.

Gauge Symmetry and Particle content

$$G = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_\nu$$

We assume SSB of U(1)$_\nu$ symmetry happen around TeV scale:

$$SU(2)_L \otimes U(1)_Y \otimes U(1)_\nu \xrightarrow{SSB} SU(2)_L \otimes U(1)_Y \otimes Z_{2\nu}$$

	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
$Z_{2\nu}$	$+$	$+$	$+$	$+$	$+$	$-$	$-$	$+$	$-$	$-$	$\times$

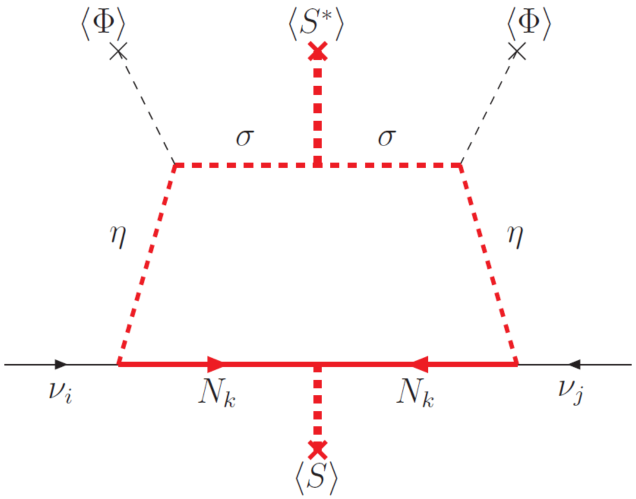
New

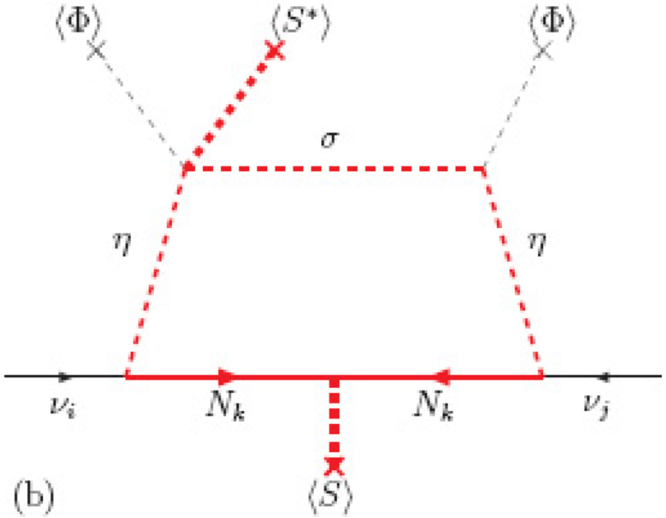
New

Neutrino masses

$$\mathcal{L}_{new} \supset \frac{y_a^n}{2}\overline{n_{aL}^c}n_{aL}S + \frac{y_a^N}{2}\overline{N_{aR}^c}N_{aR}S + m_{ab}^D\overline{n_{aL}}N_{bR} + g_{ia}\overline{L_i}\widetilde{\eta}N_{aR} + h.c.$$

Dim-7 operator: $(L\phi)^2 S^+ S$





$$\mathcal{M}_{ij}^{\nu} \sim \frac{1}{16\pi^2}\frac{\mu_1\mu_2^2 v_\Phi^2 v_S^2}{\Lambda^6}\sum_a y_a^N g_{ia}^* g_{ja}^*$$

$$\mathcal{M}_{ij}^{\nu} \sim \frac{1}{16\pi^2}\frac{\kappa\mu_2 v_\Phi^2 v_S^2}{\Lambda^4}\sum_a y_a^N g_{ia}^* g_{ja}^*$$

Neutrino masses

- For $\mu_i, \Lambda \sim TeV, m_\nu \sim 0.01eV$, we demend:

$$g \sim 10^{-4} \sim 10m_e / v_\Phi$$

For only one generation of n_L , N_R :

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

It give eigenmasses: $0, 0, g_1^2 + g_2^2 + g_3^2$

- We need at least 2 generation of n_L and N_R .

Lepton Flavor violation

- When neutrinos get Majorana mass $\mu \to eee$, $\mu \to e\gamma$ could happen.
- Experimentally,

$$Br(\mu \to e\gamma) < 10^{-12}$$

In this model, $\mu \to e\gamma$ can rise via dim-6 operator:

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

Give:

$$\frac{Br(\mu \to e\gamma)}{Br(\mu \to e\bar{\nu}_e\nu_\mu)} \sim \left(\frac{e|g_{\mu k}g_{ke}|}{(16\pi^2)G_F\Lambda^2}\right)^2 \sim \overbrace{10^{-8}\times|g_{\mu k}g_{ke}|^2}^{10^{-24}}\times\left(\frac{\overset{\overset{O(1)}{\downarrow}}{1\text{TeV}}}{\Lambda}\right)^4$$

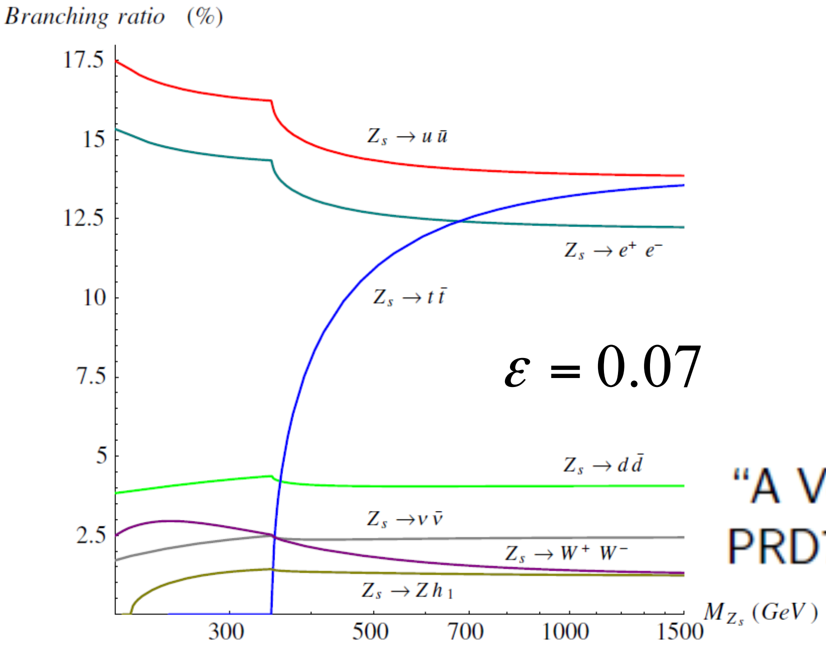
$$g \sim 10^{-4}$$

Z’ in collider

The Kinetic mixing between field strengths of U(1)$_Y$ and U(1)$_\nu$ is possible: $\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} X_{\mu\nu}$

So the Drell-Yan production of Z’ in LHC is possible.

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



“A Very Narrow Shadow Extra Z-boson at Colliders” PRD74:095005,2006.

Z_2-odd fermions

After SSB:

$$\mathcal{L}_{new} \supset \underbrace{\frac{y_a^n v_S}{2}\overline{n_{aL}^c} n_{aL} + \frac{y_a^N v_S}{2}\overline{N_{aR}^c} N_{aR}}_{\text{Majorana mass terms}} + \overbrace{m_{ab}^D \overline{n_{aL}} N_{bR}}^{\text{Dirac term}} + h.c.$$

m^D is arbitrary, in principle. But NAUTRALLY it shall be around TeV.

Thus we get 4 new Majorana fermions with TeV masses.

$$\Rightarrow \{\chi_1, \quad \chi_2, \quad \chi_3, \quad \chi_4\}$$

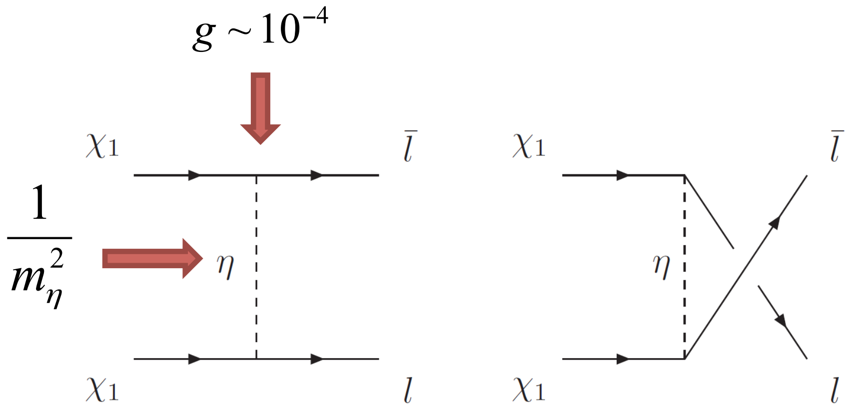
Z_2-odd fermions as DM

Let us call the lightest mass eigenstates of n_L and N_R be χ_1, if χ_1 is the lightest Z_2-odd particle, it should be stable and become the Dark Matter.

$$\Omega_{DM} h^2 \sim 0.12 \propto \frac{1}{\langle \sigma v \rangle}$$

$$\sigma_{ann} v_{rel} = \frac{v_{rel}^2}{24\pi M_\chi^2} \sum_{ij} |g_{i1} g_{j1}^*|^2 x^2 (1 - 2x + 2x^2)$$

$$x = M_\chi^2 / (M_\eta^2 + M_\chi^2)$$



Z2-odd fermions as DM

- The Z2-odd new fermions in our model cannot be DM because $M_{\chi_{1-4}} >> M_{\eta}$ for fitting $\Omega_{DM}h^2 \sim 0.12$
- χ_i decays into SM particles and Z2-odd bosons.

Scalar spectrum

The complete scalar potential is :

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

The parameter space is plenty enough to have:

Vacuum: $\langle\Phi\rangle = 246 GeV, \quad \langle\eta\rangle = \langle\sigma\rangle = 0, \quad \langle S\rangle \sim TeV$

Scalar spectrum

Unitary gauge: $S = (v_S + s_R)e^{i\theta_S}$

s_R → Integrate out

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

We can parameterize them as: $\eta = \begin{pmatrix} \eta^\pm \\ Re\eta^0 + i\,Im\eta^0 \end{pmatrix}$

$$\sigma = Re\sigma^0 + i\,Im\sigma^0$$

Scalar spectrum

Mass of $\eta^{\pm}$: $M_{\pm}^2 = \mu_\eta^2 + \lambda_5 v_\Phi^2$

Mass matrix of $\{Re\eta^0, Re\sigma^0\}$:

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

Mass matrix of $\{Im\eta^0, Im\sigma^0\}$:

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

$\{Re\eta^0, Re\sigma^0\} \Longrightarrow \{H_1, H_2\}$

$\{Im\eta^0, Im\sigma^0\} \Longrightarrow \{A_1, A_2\}$

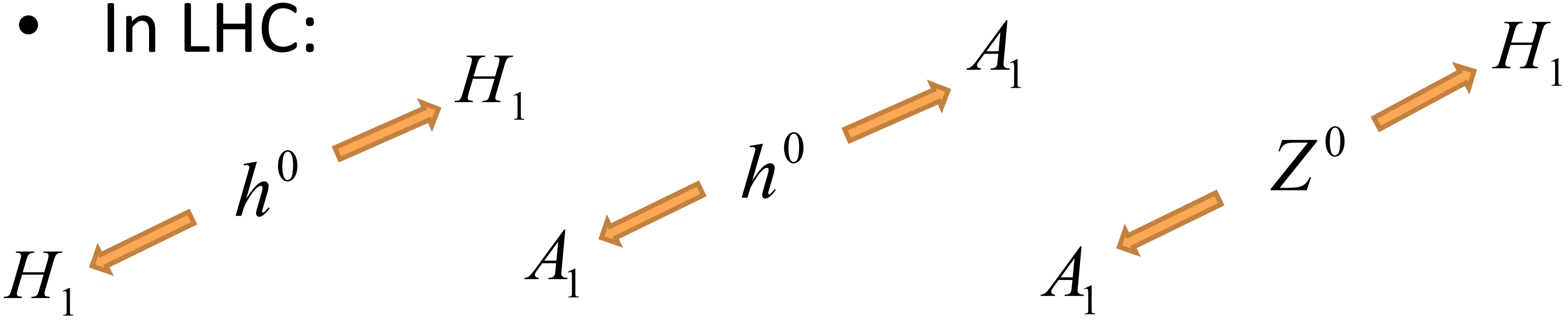
$H_{1,2}, A_{1,2}$ masses should be around v_Φ to v_S .

Scalar spectrum

This model have 4 classes of scalar bosons:

$$\left\{ \begin{array}{cc} h & \text{standard model Higgs boson} \to 1 \\ \eta^{\pm} & \text{Charged } Z_2 \text{ odd scalar} \to 2 \\ H_{1,2} & \text{Neutral } Z_2 \text{ odd scalar} \to 2 \\ A_{1,2} & \text{Neutral } Z_2 \text{ odd pseudoscalar} \to 2 \end{array} \right.$$

- SM Higgs doesn’t mix with Z_2-odd scalar bosons.
- In LHC:

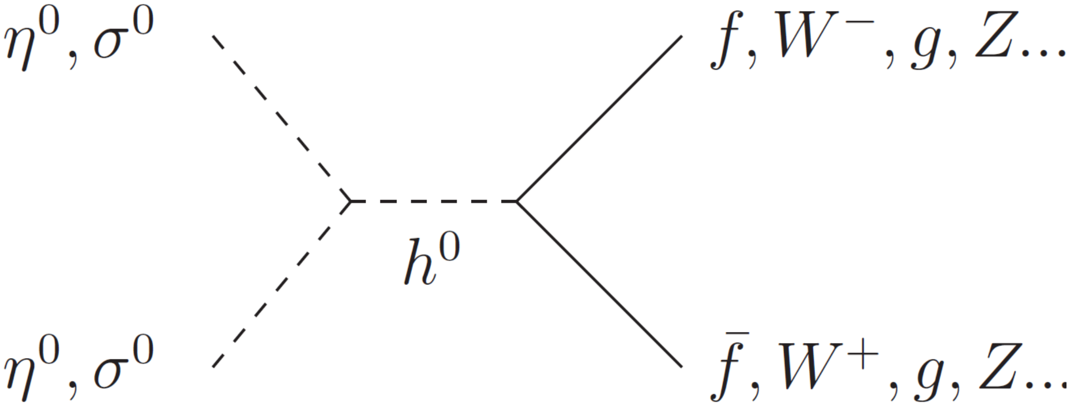


Z_2-odd scalar as DM

Either H_1 or A_1 is the lightest Z_2-odd scalar boson, it would be stable and play a role as DM.

$$\mathcal{L}_{scalar} \supset \lambda_{H_1} h H_1^2 + \lambda_{A_1} h A_1^2$$

- This model contains the usual singlet scalar DM model.



Z2-odd scalar as DM

Annihilation:

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

$$\lambda = \cos^2\alpha(\lambda_5 + \lambda_6) + \sin^2\alpha\lambda_7 + \sin 2\alpha(\mu_2 + \kappa v_S)/v_\Phi$$

$$\lambda = \cos^2\delta(\lambda_5 + \lambda_6) + \sin^2\delta\lambda_7 + \sin 2\delta(\mu_2 - \kappa v_S)/v_\Phi$$

Γ is decay width of Higgs
M_S is mass of H_1 or A_1.

- For $M_S >> m_{h^0}$, hh, ZZ, WW decay channel open.

Z_2-odd scalar as DM

C.P. Burgess et al. / Nuclear Physics B 619 (2001) 709–728

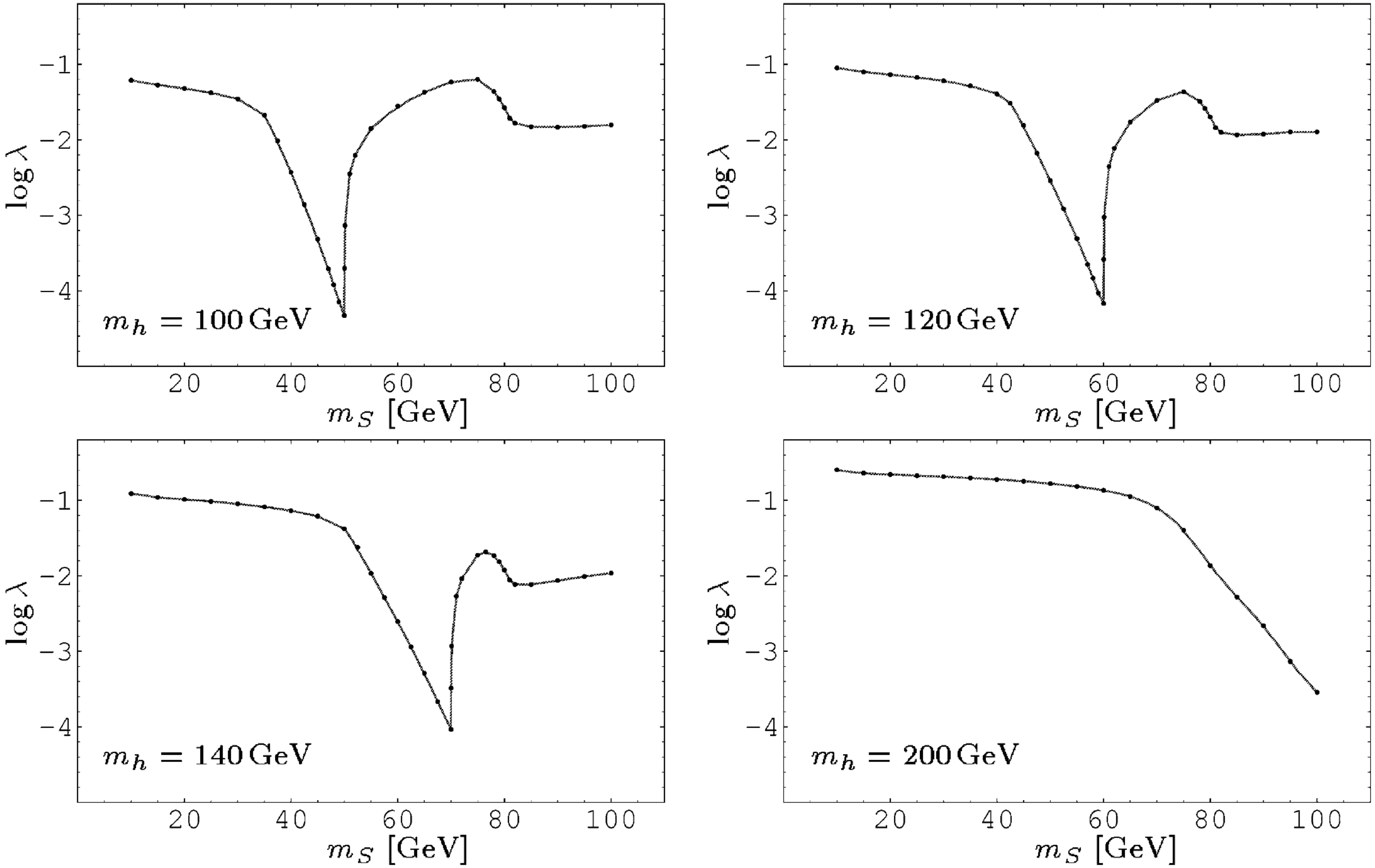
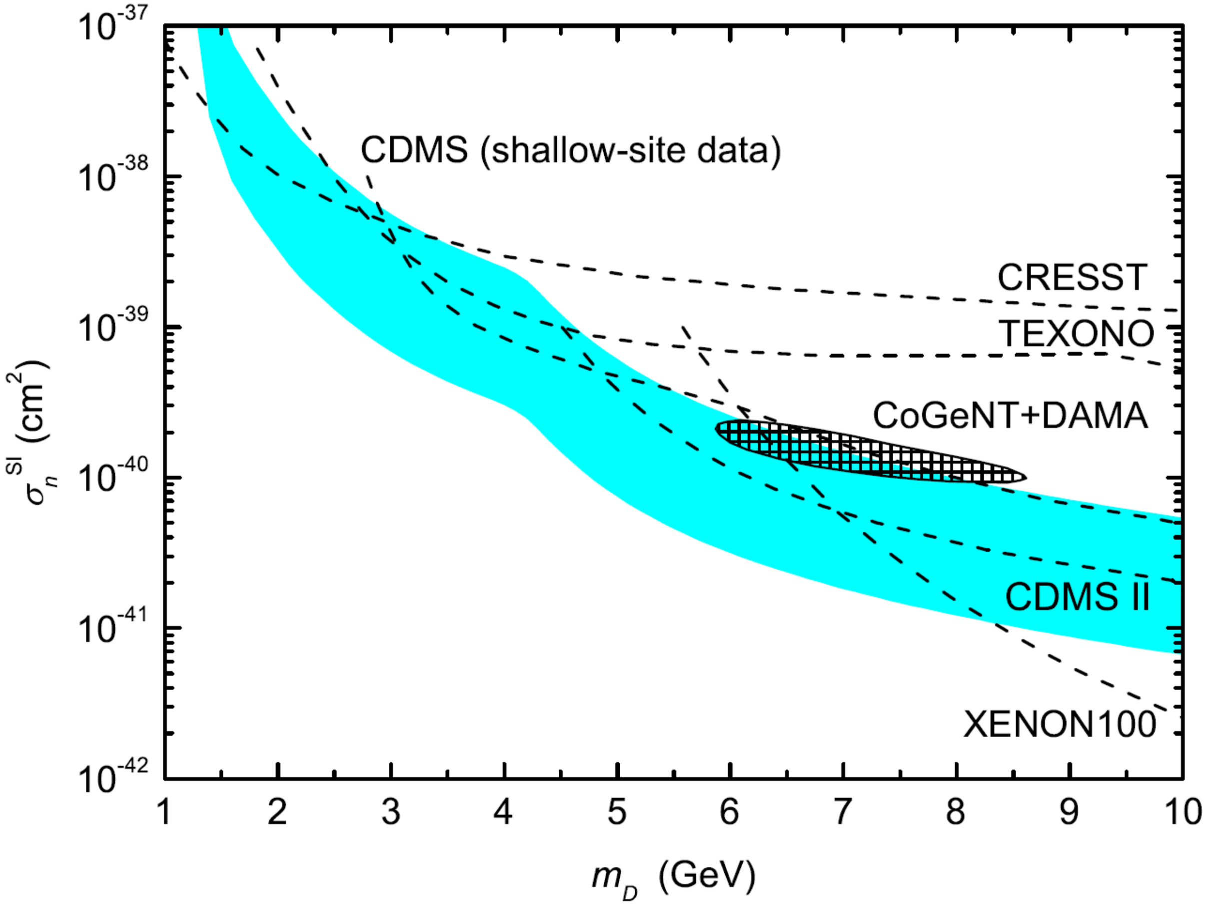


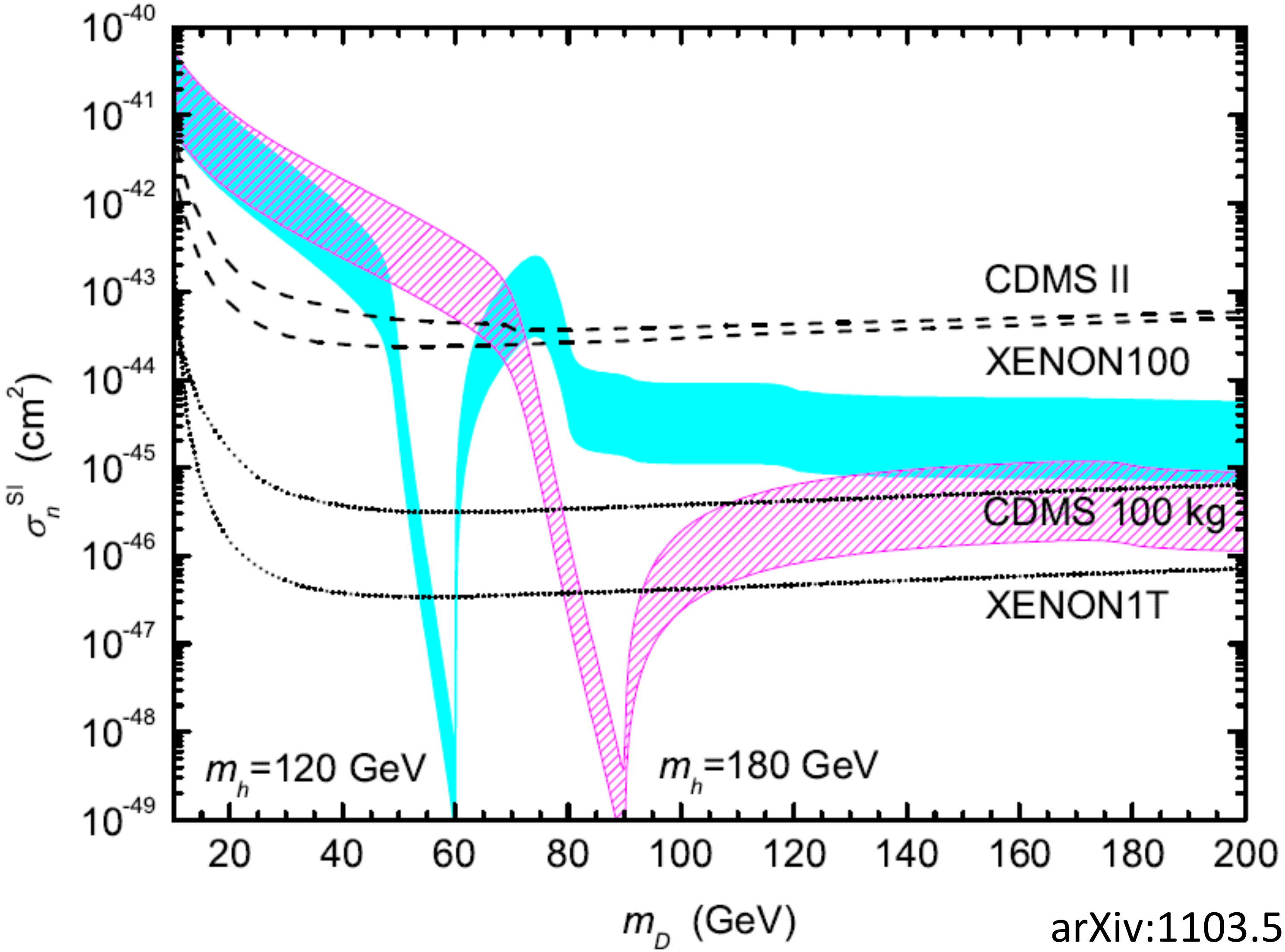
Fig. 2. Four samples of the $\log\lambda$–m_S relationship between λ and m_S, which gives the correct cosmic abundance of S scalars. For these plots the Higgs mass is chosen to be 100, 120, 140, and 200 GeV. The abundance is chosen to be $\Omega_s h^2 = 0.3$.

Z_2-odd scalar as DM

Spin-Independent direct detection: arXiv:1103.5606



Z_2-odd scalar as DM

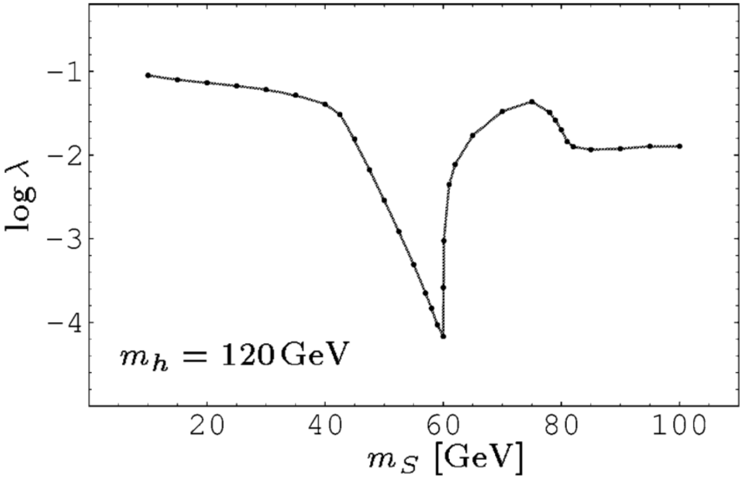


arXiv:1103.5606

Z2-odd scalar as DM

Our model $\supset$ Singlet Scalar DM model

- One thing new is that if masses of H_1 and A_1 are close, $H_1 A_1 \rightarrow Z^0 \rightarrow SM$ is important for their depletion.
- A tight relation between coupling λ and M_S can't come out by usual scalar DM model and our model.



Summary

- With introduce a U(1) gauge symmetry and several degree of freedoms, this model can give:
  1. neutrino masses via a 1-loop correction.
  2. provide a singlet scalar DM candidate to explain DM abundance.
  3. stabilize DM by a Z_2 parity a la Krauss-Wilczek.
  4. all the new d.o.f. can be explored in TeV scale. ie. LHC.

Thank You !!