Common Origin of Matter and Mirror Dark Matter at GeV Scale and LHC Signatures

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Outline

Already too many DM models on the market, we still don't know which one is right !?

Why should I re-talk about anyone of them here ??

But there is one truly special for DM: — the Simplest One, (perhaps, Most Elegant One as well), is strongly motivated by Known Exp Facts (the Parity Violation):

Mirror Model

Are we co-living in a Mirror Universe ??

SKLTP

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- **Let me recall original 1956-paper by Lee and Yang:**

If parity violation is indeed found, the question could still be raised whether there could not exist **corresponding particles exhibiting opposite asymmetry** such that **in broader sense** there will still be **Overall Left-Right Symmetry**.

$\cdots$ there must exist two kinds of protons p_L and p_R. $\cdots$ the free oscillation period between them must be longer than the age of the universe. They could be regarded as **Stable Particles**.

$\cdots$ the Left-Right Asymmetry is therefore ascribed not to a basic non-invariance under inversion, but **to a cosmologically local preponderance** of, say p_L over p_R, a situation not unlike that of preponderance of positive proton p over negative $\bar{p}$.

- This idea was further developed by Kobzarev, Okun, Foot, Lew, Volkas, Mohapatra, $\cdots\cdots$, in the following decades.

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Two Fundamental Ways of Parity Restoration

► **No.1**: Enlarge Matter Content of SM with Mirror Partners, so under P transformation, (⇒ Predicts **Mirror Nucleon as DM** !!)

$$f_L \leftrightarrow f'_R\,, \qquad f_R \leftrightarrow f'_L\,.$$

leading to a Unique "Mirror" of SM Gauge Group: $G_{SM} \otimes G'_{SM}$,

$$G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$G'_{SM} = SU(3)'_c \otimes SU(2)'_R \otimes U(1)'_Y$$

► **No.2**: Enlarge Weak Gauge Group Only and Keep the Same Matter Content — Left-Right Symmetric Gauge Model, which must be spontaneously broken: (⇒ **No New DM Candidate)**

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Matter Content & Mirror Parity

$$Q_L^i \sim (3,\ 2,\ \tfrac{1}{6})(1,\ 1,\ 0)', \qquad (Q_R')^i \sim (1,\ 1,\ 0)(3,\ 2,\ \tfrac{1}{6})',$$

$$u_R^i \sim (3,\ 1,\ \tfrac{2}{3})(1,\ 1,\ 0)', \qquad (u_L')^i \sim (1,\ 1,\ 0)(3,\ 1,\ \tfrac{2}{3})',$$

$$d_R^i \sim (3,\ 1,\ -\tfrac{1}{3})(1,\ 1,\ 0)', \qquad (d_L')^i \sim (1,\ 1,\ 0)(3,\ 1,\ -\tfrac{1}{3})',$$

$$L_L^i \sim (1,\ 2,\ -\tfrac{1}{2})(1,\ 1,\ 0)', \qquad (L_R')^i \sim (1,\ 1,\ 0)(1,\ 2,\ -\tfrac{1}{2})',$$

$$e_R^i \sim (1,\ 1,\ -1)(1,\ 1,\ 0)', \qquad (e_L')^i \sim (1,\ 1,\ 0)(1,\ 1,\ -1)',$$

$$\nu_R^i \sim (1,\ 1,\ 0)(1,\ 1,\ 0)', \qquad (\nu_L')^i \sim (1,\ 1,\ 0)(1,\ 1,\ 0)',$$

$$\phi \sim (1,\ 2,\ \tfrac{1}{2})(1,\ 1,\ 0)', \qquad \phi' \sim (1,\ 1,\ 0)(1,\ 2,\ \tfrac{1}{2})',$$

which is P symmetric under parity transformation:

$$Q_L^i \leftrightarrow (Q_R')^i,\quad u_R^i \leftrightarrow (u_L')^i,\quad d_R^i \leftrightarrow (d_L')^i,\quad L_L^i \leftrightarrow (L_R')^i,\quad e_R^i \leftrightarrow (e_L')^i,\quad \nu_R^i \leftrightarrow (\nu_L')^i,$$

$$G_\mu^\alpha \leftrightarrow (G_\mu^\alpha)',\quad W_\mu^a \leftrightarrow (W_\mu^a)',\quad B_\mu \leftrightarrow B_\mu',\quad \phi \leftrightarrow \phi'$$

Communication between Visible and Mirror Worlds

- Interaction between Visible & Mirror Higgs Doublets:

$$\mathcal{L}_{\phi\phi'} \;=\; \widetilde{\lambda}\,(\phi^\dagger\phi)(\phi'^\dagger\phi')$$

- Mixing between Visible & Mirror Singlet Neutrinos:

$$\mathcal{L}_{\nu\nu'} \;=\; \delta m\,\bar{\nu}_R\nu'_L + \text{h.c.}$$

- Kinetic Mixing between Visible & Mirror Photons:

$$\mathcal{L}_{BB'} \;=\; -\frac{\epsilon_0}{2}B^{\mu\nu}B'_{\mu\nu} \;\Rightarrow\; -\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

where invisible decay of orthopositronium puts Upper Bound:

$$\epsilon < 1.55\times 10^{-7} \qquad \text{(for exact mirror parity)}$$

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The Conjecture

- We conjecture that Mirror Parity is respected by the fundamental Interaction Lagrangian, so its violation arises only from Spontaneous breaking of Higgs Vacuum.

- We further conjecture that all possible soft *P* breakings only arise from the Gauge-Singlet Sector which contains either Singlet Scalar χ or Singlet Heavy Majorana Neutrino mass-term.

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SSB of Mirror Parity: Minimal Higgs Potential

- We introduce a P-odd singlet scalar χ, and have

$$\phi \leftrightarrow \phi', \qquad \chi \leftrightarrow -\chi$$

- Minimal Higgs Potential:

$$V = -\mu_\phi^2 \left(|\phi|^2 + |\phi'|^2\right) + \lambda_\phi^+ \left(|\phi|^2 + |\phi'|^2\right)^2 + \lambda_\phi^- \left(|\phi|^2 - |\phi'|^2\right)^2$$
$$-\tfrac{1}{2}\mu_\chi^2 \chi^2 + \tfrac{1}{4}\lambda_\chi \chi^4 + \beta_{\chi\phi}\,\chi \left(|\phi|^2 - |\phi'|^2\right) + \tfrac{1}{2}\lambda_{\chi\phi}\,\chi^2 \left(|\phi|^2 + |\phi'|^2\right),$$

where $\langle\phi\rangle = v_\phi$, $\langle\phi'\rangle = v_{\phi'}$, $\langle\chi\rangle = v_\chi$.

- Unique Soft P Breaking from Singlet Sector:

$$\Delta V_{\text{soft}} = \beta_\chi \chi$$

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SSB of Mirror Parity: Minimal Higgs Potential

- Quartic mixing coupling in $\widetilde{\lambda}|\phi|^2|\phi'|^2$ is related to:

$$\widetilde{\lambda} = 2(\lambda_\phi^+ - \lambda_\phi^-) .$$

SSB of Parity & EWSB: Vacuum Conditions

- Minimal conditions of Vacuum Potential:

$$\frac{\partial\langle V\rangle}{\partial v_\phi} = 0\,, \qquad \frac{\partial\langle V\rangle}{\partial v_{\phi'}} = 0\,, \qquad \frac{\partial\langle V\rangle}{\partial v_\chi} = 0\,,$$

- Vacuum solutions:

$$v_\phi^2 = \frac{1}{4}\left(\frac{\mu_\phi^2 - \frac{1}{2}\lambda_{\chi\phi}v_\chi^2}{\lambda_\phi^+} - \frac{\beta_{\chi\phi}}{\lambda_\phi^-}v_\chi\right),$$

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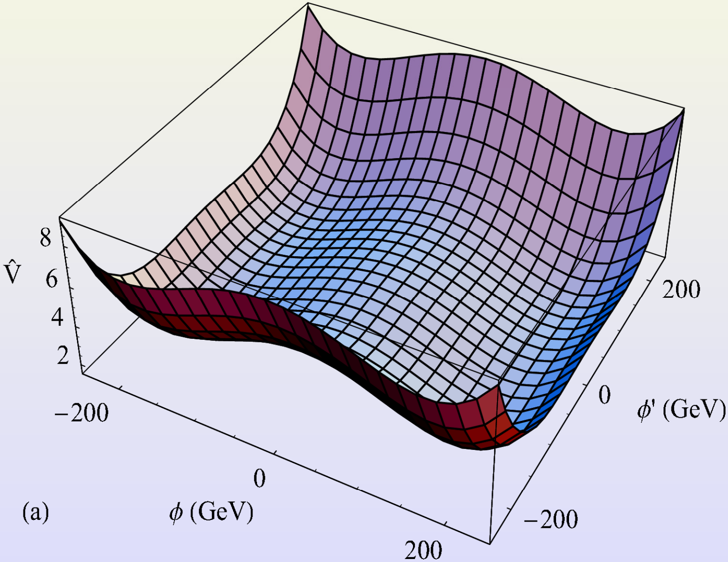
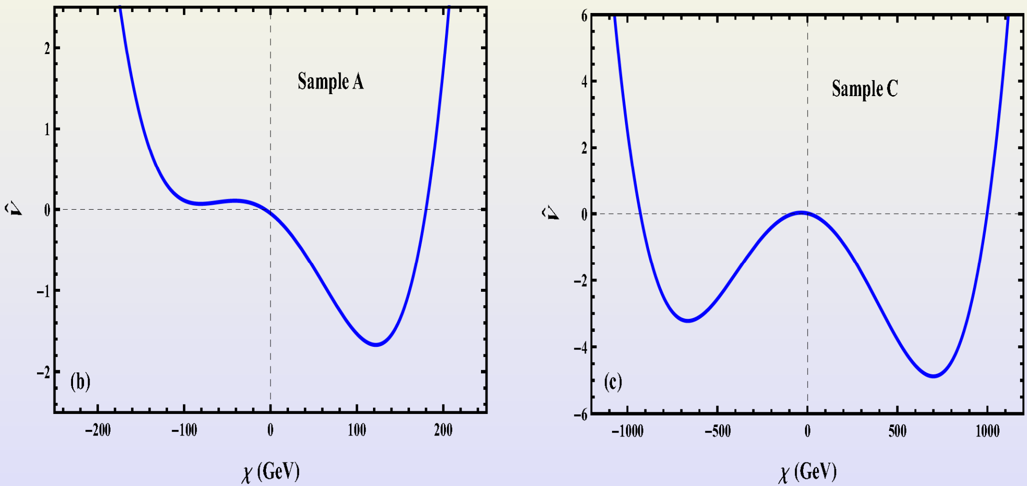
Higgs Vacuum Structure: V vs ϕ and ϕ'

- Sample-A:

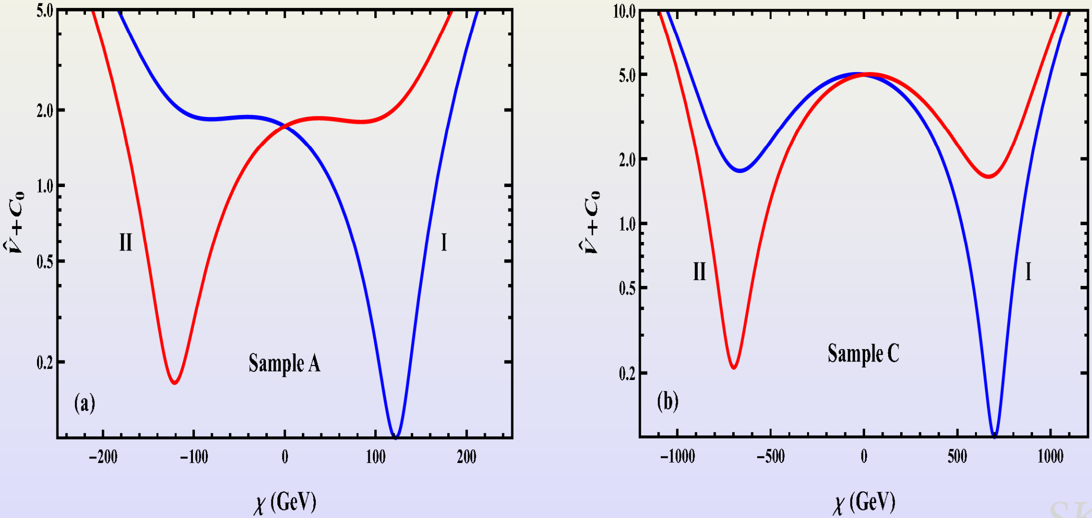


(a)

Higgs Vacuum Structure: V vs χ



Solving the Domain Wall Problem



Common Origin of Visible & Dark Matter

- **Visible Matter** comes from CP-violation in Neutrino Seesaw via Ordinary Leptogenesis.

- **Mirror Matter** comes from CP-violation in Mirror Neutrino Seesaw via Mirror Leptogenesis.

- Visible/Mirror Leptogeneses share the **Same CP-Phase** and **Same Right-handed Neutrino Masses** due to **Mirror Parity**.

- Hence, **Visible/Mirror Matter arise from Common Origin** !

- But, **how to explain** the observation:

$$\Omega_{\rm DM} : \Omega_{\rm B} = 5.00 \pm 0.37$$

with 2σ limit: $4.26 < \Omega_{\rm DM}/\Omega_{\rm B} < 5.74$

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- Ratio of Matter/Dark Matter Densities:

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm M}} \simeq \frac{\Omega_{\rm B'}}{\Omega_{\rm B}} = \frac{\mathcal{N}_{\rm B'}}{\mathcal{N}_{\rm B}}\frac{m_{N'}}{m_N},$$

where $\mathcal{N}_{\rm B}$ and $\mathcal{N}_{\rm B'}$ are visible/mirror baryon densities.

- Nucleon masses are controlled by $\Lambda_{\rm QCD}^{(3)}$. From RG analysis, we derive,

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- In visible sector, baryon number density $\mathcal{N}_B$ and $B-L$ Asymmetry $\mathcal{N}_{B-L}$, as defined in a portion of comoving volume containing one photon at the onset of leptogenesis, are given by

$$\mathcal{N}_B = \xi \mathcal{N}_{B-L} = \frac{3}{4} \xi \kappa_f \epsilon_1$$

where $\xi = 28/79$ for SM, κ_f is efficiency factor, and ϵ_1 is measures CP asymmetry of N_1 decays.

- In parallel, for Mirror Sector, we have,

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$$\frac{\mathcal{N}_B'}{\mathcal{N}_B} = \frac{\xi' \kappa_f' \epsilon_1'}{\xi \kappa_f' \epsilon_1'} = \frac{\kappa_f'}{\kappa_f} = \left(\frac{M_1'}{M_1}\right)^{1.1\pm 0.1} .$$

where κ_f (κ_f') is visible (mirror) efficiency factor.

- Unique Soft Breaking from Singlet Sector via heavy Majorana neutrinos:

$$M_1 \neq M_1'$$

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- So, we derive final formula for Ratio of Dark-Matter vs Matter densities:

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm M}} = \frac{\Omega_{B'}}{\Omega_B} = \frac{\mathcal{N}'_B}{\mathcal{N}_B}\frac{m'_N}{m_N} = \left(\frac{M'_1}{M_1}\right)^{(1.1\pm0.1)}\left(\frac{v_{\phi'}}{v_\phi}\right)^{2/9} .$$

- Thus, we can derive,

$$\frac{M'_1}{M_1} = \left(\frac{\Omega_{\rm DM}}{\Omega_{\rm M}}\right)^{\frac{1}{\varrho}}\left(\frac{v_\phi}{v_{\phi'}}\right)^{\frac{2}{9\varrho}}$$

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- BBN and Naturalness of Higgs potential put upper and lower bounds:

$$0.1 \; < \; \frac{v_{\phi'}}{v_{\phi}} \; < \; 0.7$$

- Imposing data $3.52 < \Omega_{\rm DM}/\Omega_{\rm M} < 6.48$ (2σ), we thus deduce the bound for our sample $v_{\phi'}/v_{\phi} = 0.5$,

$$0.16 \; < \; \frac{M_1}{M_1'} \; < \; 0.28 \, ,$$

at 2σ level, with central value: $M_1/M_1' \simeq 0.2$.

Common Origin of Visible & Dark Matter

► BBN and Naturalness of Higgs potential put upper and lower bounds:

$$0.1 < \frac{v_{\phi'}}{v_\phi} < 0.7$$

► Imposing data $3.52 < \Omega_{\rm DM}/\Omega_{\rm M} < 6.48$ (2σ), we thus deduce the bound for our sample $v_{\phi'}/v_\phi = 0.5$,

$$0.16 < \frac{M_1}{M_1'} < 0.28\,,$$

at 2σ level, with central value: $M_1/M_1' \simeq 0.2$.

Numerical Analysis: 3 Samples

- **Inputs:** (Here μ_ϕ, μ_χ, $\beta_{\chi\phi}$, $\beta_\chi^{\frac{1}{3}}$ are in GeV.)

Sample	μ_ϕ	μ_χ	$\beta_{\chi\phi}$	λ_ϕ^-	λ_ϕ^+	$\lambda_{\chi\phi}$	λ_χ	$\beta_\chi^{\frac{1}{3}}$
A	70	113	-35	.094	.092	$-.28$	2.03	-30
B	63	269	-23	.078	.077	$-.154$	3.44	-30
C	62	56.6	-5	.077	.075	$-.0074$	.0075	-20

- **Outputs:** (All VEVs and masses are in GeV.)

Sample	v_ϕ	$v_{\phi'}$	v_χ	m_h	$m_{h'}$	m_χ	$U_{\phi h}$	$U_{\phi h'}$	$U_{\phi\chi}$
A	174	87	122	122	75.1	203	0.84	.006	-0.54
B	174	87	154	133	68.4	290	0.99	.007	-0.12
C	174	87	699	136	67.8	59.4	0.99	.006	$+0.12$

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Numerical Analysis: Higgs Couplings

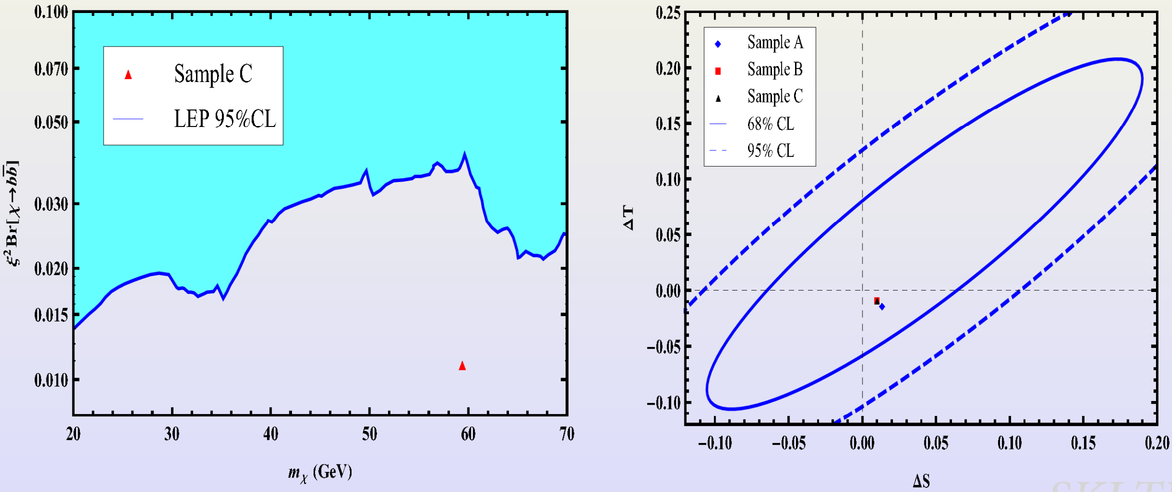
- Higgs Gauge and Yukawa Couplings:

Sample	$\hat{h}VV$	$\hat{\chi}VV$	$\hat{h}f\bar{f}$	$\hat{\chi}f\bar{f}$	$\hat{h}'V'V'$	$\hat{h}'f'\bar{f}'$
A	0.841	-0.541	0.841	-0.541	0.5	1
B	0.992	-0.123	0.992	-0.123	0.5	1
C	0.993	0.119	0.993	0.119	0.5	1

- Higgs Self-Couplings:

	$\hat{\chi}\hat{\chi}\hat{\chi}$	$\hat{\chi}\hat{\chi}\hat{h}$	$\hat{\chi}\hat{h}\hat{h}$	$\hat{h}\hat{h}\hat{h}$	$\hat{\chi}\hat{\chi}\hat{\chi}\hat{\chi}$	$\hat{\chi}\hat{\chi}\hat{\chi}\hat{h}$	$\hat{\chi}\hat{\chi}\hat{h}\hat{h}$	$\hat{\chi}\hat{h}\hat{h}\hat{h}$	$\hat{h}\hat{h}\hat{h}\hat{h}$
A	0.59	1.36	0.43	0.18	0.24	0.65	0.70	0.18	0.05
B	2.11	0.74	-0.07	0.14	0.83	0.42	0.05	-0.02	0.04
C	0.02	-0.01	0.04	0.15	.002	$-.001$	.002	0.02	0.04

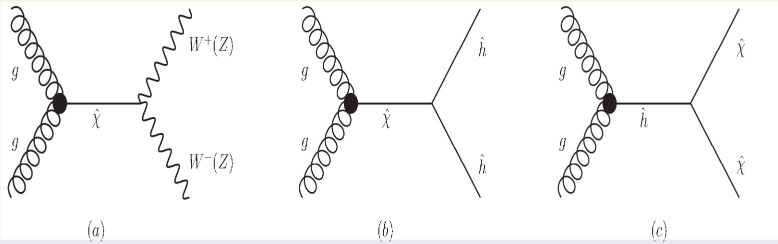
LEP Bound and EW Precision Constraints



Higgs Decay Widths & Branching Fractions

Sample	A		B		C	
Higgs	$\hat{h}$	$\hat{\chi}$	$\hat{h}$	$\hat{\chi}$	$\hat{h}$	$\hat{\chi}$
Γ (MeV)	2.75	452	5.73	127	7.60	0.025
WW	0.137^*	0.728	0.321^*	0.609	0.337^*	0
ZZ	0.014^*	0.268	0.041^*	0.269	0.045^*	0
$\hat{h}\hat{h}$	0	0	0	0.120	0	0
$\hat{\chi}\hat{\chi}$	0	0	0	0	0.100	0
$b\bar{b}$	0.652	0.002	0.469	4.7×10^{-4}	0.361	0.792
$\tau\bar{\tau}$	0.065	2.7×10^{-4}	0.048	7.2×10^{-5}	0.037	0.068
$c\bar{c}$	0.028	4.8×10^{-5}	0.020	9.1×10^{-6}	0.015	0.077
gg	0.083	0.001	0.074	8.0×10^{-4}	0.061	0.020
$\gamma\gamma$	0.002	5.0×10^{-5}	0.002	1.3×10^{-5}	0.002	4.0×10^{-4}
$Z\gamma$	0.001	1.6×10^{-4}	0.002	5.1×10^{-5}	0.002	0

New LHC Higgs Signatures via *gg* Fusion



New Higgs Signatures at LHC: $\sigma \times$ Br

$gg \to \hat{h}$ or $\hat{\chi}$		$\hat{h} \to \gamma\gamma$	$\hat{\chi} \to WW$		$\hat{\chi} \to ZZ$			$\to \hat{h}\hat{h}$ or $\hat{\chi}\hat{\chi}$
Final State		$\gamma\gamma$ (SM)	$\ell\nu\ell\nu$	$\ell\nu jj$	$\ell\ell jj$	$\ell\ell\nu\nu$	$\ell\ell\ell\ell$	$b\bar{b}b\bar{b}$
A	7 TeV	25.0 (36.1)	50.2	319	38.3	11.0	1.84	/
	14 TeV	81.3 (117)	195	1230	148	42.4	7.14	/
B	7 TeV	28.8 (29.5)	1.08	6.85	0.99	0.28	0.05	0.13
	14 TeV	95.9 (98.3)	4.89	31.0	4.47	1.28	0.22	0.60
C	7 TeV	23.2 (27.1)	/	/	/	/	/	106
	14 TeV	77.9 (90.9)	/	/	/	/	/	356

$$U_{\phi h}^2 \frac{\mathrm{Br}[\hat{h} \to \gamma\gamma]}{\mathrm{Br}[\hat{h} \to \gamma\gamma]_{\mathrm{SM}}} \simeq (0.70, 0.98, 0.86), \quad \text{for } (A, B, C).$$

$$U_{\phi\chi}^2 \frac{\mathrm{Br}[\hat{\chi} \to WW\,(ZZ)]}{\mathrm{Br}[h \to WW\,(ZZ)]_{\mathrm{SM}}} \simeq (0.29, 0.013), (0.30, 0.013), \quad \text{for } (A, B).$$

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Direct Detection of Mirror DM

- Around freeze-out temperature T'_f of mirror sector,

$$\frac{n_{n'}}{n_{p'}} \simeq \exp\left(-\frac{\Delta m'}{T'_f}\right),$$

where $\Delta m' = m_{n'} - m_{p'}$.

- Since $T' < T$ after EW phase transition, mirror BBN occurs earlier, so visible photons/neutrinos contribute to Hubble const significantly and makes $T'_f > T_f$. — Hence, **Mirror BBN is Neutron-rich**, $\Rightarrow$ mirror world dominated by **Mirror ^{4}He$'$**, $\Rightarrow$ major Mirror DM Particles!

- We have, $m_{N'}/m_N = (v_{\phi'}/v_\phi)^{2/9} \simeq 0.60 - 0.92$, leading to

$$M_{\mathrm{He}^{4\prime}} \simeq (0.60 - 0.92) M_{\mathrm{He}^4} \simeq 2.3 - 3.5\,\mathrm{GeV}$$

Direct Detection & New Bound by TEXONO

- Kinetic Mixing between Visible & Mirror Photons:

$$\mathcal{L}_{BB'} = -\frac{\epsilon_0}{2} B^{\mu\nu} B'_{\mu\nu} \Rightarrow -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

where invisible decay of orthopositronium puts Upper Bound:

$$\epsilon < 3.4 \times 10^{-5} \quad \text{(our model).}$$

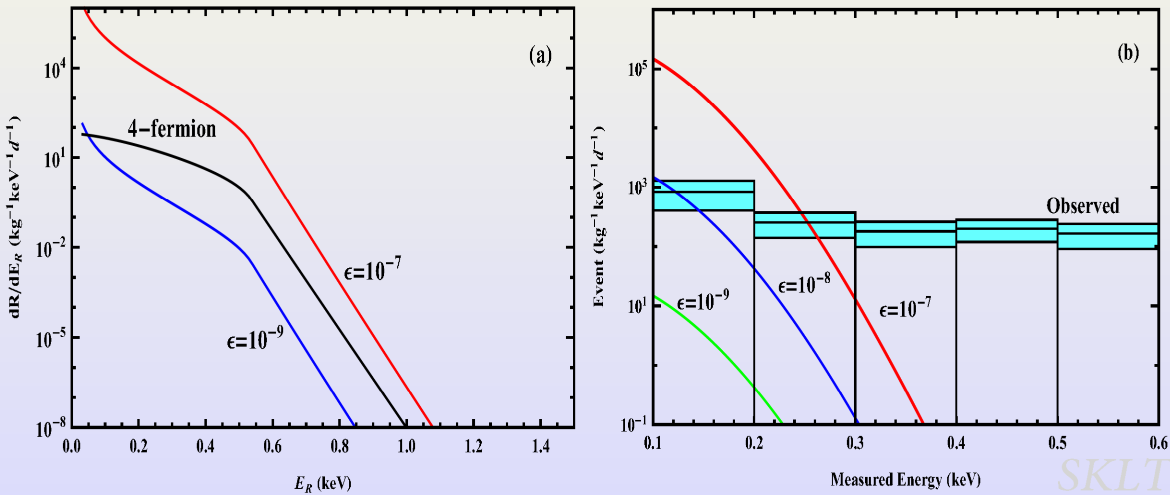
- Cross section of mirror nucleus (A', Z') scattering on ordinary nucleus (A, Z),

$$d\sigma = \frac{4\pi\epsilon^2\alpha^2 Z'^2 Z^2}{Q^4\, v_0^2} F_{A'}^2(Q) F_A^2(Q)\, dQ^2$$

Due to $1/Q^4$ factor, it receives a large enhancement in Low Recoil-Energy Region relative to usual 4-Fermion interactions.

Direct Detection & New Bound by TEXONO

- TEXONO is Ultralow-energy Germanium detector (20 g), with low energy-threshold (1.1keV). $\Rightarrow$ Sensitive to $1-10$GeV DM.



Summary

- **Hidden Mirror World** $\Rightarrow$ **Fundamental Way to Restore Parity.**

  Provides Lightest Mirror Nucleon as GeV-Scale Dark Matter.

- **Mirror Parity: Mirror World has No New Free Parameter !**

  Visible + Mirror Seesaws share the Same CP Violation.
  $\Rightarrow$ **Common Origin of Matter + Dark Matter Genesis.**

- **Unique soft breaking of singlet heavy Majorana masses $M_1 \neq M_1'$ and Spontaneous MPV $v \neq v'$.**

  $\Rightarrow$ **Right amounts of Matter/Dark Matter: $\Omega_{DM} : \Omega_M \simeq 5 : 1$.**

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- **Distinctive Higgs Mass Spectrum and Couplings:**

  $m_h : m_{h'} \approx 2 : 1$ and $m_\chi : m_h \gtrsim 2$

- **LHC Signatures:**

  $gg \to \hat{h} \to \gamma\gamma$ (smaller than SM rates by $31\% - 3\%$)

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  $^4He'$ with mass $2.3 - 3.5$ GeV

  Sensitive by TEXONO and CDEX with Low-Recoil-Energy in Germanium Detectors

  TEXONO data already put constraint: $\epsilon \lesssim 10^{-8}$

  $\Longrightarrow$ CDEX will explore further at Jinping Lab !

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