Asymmetric Mirror Dark Matter and Energy Dependent Direct Detection

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Content

Motivations

The existence and relic abundance of Dark Matter is well-established by cosmological and astrophysical observations.

WMAP tells us

- Baryonic Matter: $\Omega_b h^2 = 0.0223 \pm 0.0007$.
- Dark Matter: $\Omega_{dm} h^2 = 0.106 \pm 0.008$.

Properties of Dark Matter

Neutral, Non-baryonic, Massive (cold/warm), Stable or Long-lived, Weakly interacting, (Leptophilic).

The identity and interactions of dark matter still remains mystery. Experiments are designed or being designed to search for dark matter.

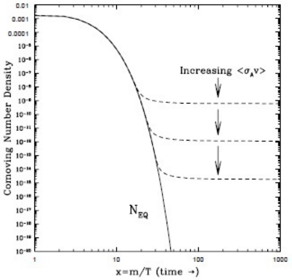
Relic density of WIMPs

Symmetric DM: stability protected by some symmetry, e.g. Z_2.

Thermal freezeout

$\chi\chi \rightarrow \psi_{\rm SM}\psi_{\rm SM}$: $\Omega_{\rm dm} \sim 0.1{\rm pb}/\sigma_{\rm anni}$.

The WIMP Miracle: $\sigma \sim g^4/M^2_{\rm weak}$ is naturally 1 pb.



Other possibilities:

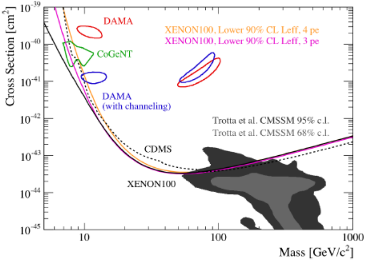
- Non-thermal production of dark matter from late decays, e.g. wino.
- “Freeze-in” production, e.g. gravitino.

Popular candidates:

- LSP (Neutralino, Gravitino, Sneutrino, etc), LKP, LTP, etc.

ASYMMETRIC DARK MATTER: ADM

- The baryon # of the universe is asymmetric, and $\Omega_{\rm b} \sim \Omega_{\rm dm}/5$. Baryon # can be explained by baryogenesis.
- Light ($5 - 10$ GeV) dark matter is preferred by recent direct detection experiments.
- If $m_{\rm DM} \approx 5 m_{\rm proton}$, then $n_{\rm b} \approx n_{\rm dm}$, naturally point to common origin.



- Assign the DM some global quantum number similar to $B - L$ and generate the asymmetry through our-of-equilibrium interactions.

EXAMPLE: DM CARRYING LEPTON NUMBER

Assume $B - L$ asymmetry is generated at high temperature. Introduce effective interactions between DM and leptons $\mathcal{W}_{\rm eff} = \bar{\chi}^2 (LH)/\Lambda$ later freezes out and DM asymmetry freezes in. (Kaplan, Luty, Zurek, 0901.4117)

ADM FROM MIRROR MODELS

Mirror sector provide a ideal accomodation for ADM: an exact copy of the SM.

- Mirror baryons as DM. Mirror baryon # survive till today (similar to baryon #). Mirror QCD – scaled-up QCD – we know the SM well (light baryon spectrum).
- $m_{\rm dm}/m_{\rm b} \sim 5 \Rightarrow \Lambda'_{QCD}/\Lambda_{QCD} \sim \mathcal{O}(10)$, can predict the mirror electroweak scale $v' \sim 10^3 v$ (Mirror symmetry: $\alpha_3 = \alpha'_3$ in the UV).
- Common origin? Generate $B - L$ and mirror $B' - L'$ asymmetry simultaneously via out-of-equilibrium interactions $\frac{(L'H')(LH)}{\Lambda}$. (Berezhiani, hep-ph/0111116)
- Need operators $\frac{(LH)(LH)}{\Lambda'}$, $\frac{(L'H')(L'H')}{\Lambda''}$ for ν, ν' masses.

More questions to be addressed

- If the mirror photon is massless, relativistic during BBN. Make $T' < T$. (Feng, 0808.2318) – Alternative: Massive mirror photon (10–100 MeV) decays before BBN?
- The mirror electron, proton – atomic dark matter, severe cosmological constraints. (Kaplan et al, 0909.0753). Self-interactions.. – Make mirror neutron dark matter?
- How to discover or falsify such models from experiments?– Bridge to mirror sector?

THE MIRROR SYMMETRY AND PORTALS

Mirror symmetry:

- Guarantees the same couplings in the two sectors.
- Broken softly in the Higgs potential, yield different symmetry breaking scales and pattens.

Portal between two sectors:

- $\nu - \nu'$ mixing can be induced by common RH neutrino, relate L' to L.
- $H - H'$ mixing, $(H^\dagger H)(H'^\dagger H')$ is a relevant operator, could get renormalized before symmetry breaking.
- $U(1) - U(1)'$ gauge kinetic mixing $\varepsilon F_{\mu\nu} F'^{\mu\nu}$ is generically allowed.

What do these portals do? – For $T \lesssim 1$ GeV, only the $\nu - \nu'$ and $\gamma - \gamma'$ mixing are relevant, if $m_{\gamma'}$ is sufficiently light.

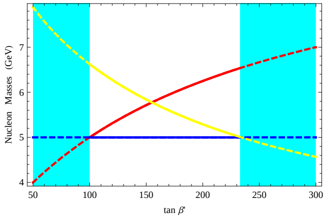
- Help everything from mirror sector decay before BBN except for the dark matter.
- Provide a force to detect the dark matter in underground detectors.

Mirror baryon as dark matter

The mirror nucleon masses (heavy mirror quarks)

$$m_{p'} \approx 2m_{u'} + m_{d'}, \quad m_{n'} \approx 2m_{d'} + m_{u'}$$

- Λ'_{QCD} determines by v', which determines m_q, $\Lambda'_{QCD} \sim m_{u',d'} \sim \mathrm{GeV}$.
- To make n' lighter than p', need $m_{d'} < m_{u'}$ or $\tan\beta' > \tan\beta$. (Possible with 2HDM)
- If $\tan\beta'$ further increases, $m_{d'} \ll m_{u'}$, the $\Delta'^{-}(d'd'd')$ could be the lightest mirror baryon.



- The $n - \Delta^{-}$ mass difference: In SM, $m_\Delta \approx 1.2\,\mathrm{GeV}$, hyperfine interaction among constituent quarks, $m_\Delta - m_n \propto |\psi_B(0)|^2/m_q^2 \approx \Lambda_{QCD}^3/m_q^2$.

So $m_{\Delta'^{-}} = m_{n'} - m_{u'} + m_{d'} +$ mass difference due to hyperfine interaction.

Choose the mirror neutron as DM

There are upper bound on the DM self-interaction cross section from

- Observation of the bullet cluster $\sigma_{\chi\chi} < 10^{-23}$ cm^2 for $M_{\rm dm} = 5\,{\rm GeV}$. (S.Randall, 0704.0261)
- Halo shape formation of galaxies can push the bound by one or more orders. (J.Feng et al, 0911.0422)

Self-interactions of Mirror nucleon as DM in the model

- Strong interaction: Infer from $\sigma_{np} \approx \sigma_{nn} \approx 10^{-24}\,{\rm cm}^2$ and $\Lambda'_{QCD} \approx 10\Lambda_{QCD}$, so $\sigma^{strong}_{N'N'} \approx 10^{-26}\,{\rm cm}^2$. – marginally allowed (H.Yu, private communication)
- Electromagnetic interaction: Mirror neutron n' as dark matter, $\sigma^{em}_{n'n'} \approx 10^{-35}\,{\rm cm}^2$; Mirror proton p' as dark matter, $\sigma^{em}_{p'p'} \approx 10^{-23}\,{\rm cm}^2$, similar for Δ'^{-} —- light charged mirror nucleon as DM is less preferred.

Detections of dark matter

Direct detection

- Nuclear recoil when dark matter scatters low-background detectors.
- Annual modulation, DAMA.
- Null results: XENON, CDMS, etc.
- CoGeNT.

Indirect detection

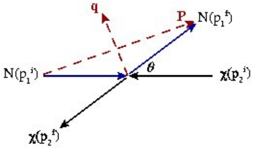
- Cosmic rays (e^+, $\bar{p}$, neutrinos) and gamma rays via halo/cosmological DM annihilate/decay.
- PAMELA, Fermi-LAT, etc.
- Infer the existence and interaction of DM (Mass TeV, $\sigma_{\rm anni} \approx 1\text{nb}$ or $\Gamma \approx 10^{26}$ s).

Combined

Capture of dark matter in astrophysical bodies (sun), then annihilate/decay to neutrinos, Super-Kamiokande, IceCube.

Direct detection of dark matter

- Direct detection of halo DM in terrestrial detectors (CDMS, DAMA, Xenon, CoGeNT).
- Elastic scattering producing a nucleus recoil [phonons (heat), ionization, scintillation].



- Recoil energy: $E_{\rm rec} = \frac{|\mathbf{q}|^2}{2m_A} = \frac{\mu^2 v^2}{2m_A}(1-\cos\theta)$.
- Detection rate ($R \sim n\sigma v$): $\frac{dR}{dE_r} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\rm min}}^{v_{\rm max}} \frac{d\sigma}{dE_r} v f(v) d^3\mathbf{v}$.
- Differential cross sections: $\frac{d\sigma}{dE_r} = \frac{m_A}{2\mu^2 v^2}\left[\sigma^0_{\rm SI} F^2(|\mathbf{q}|) + \sigma^0_{\rm SD} S(|\mathbf{q}|)/S(0)\right]$.

- Spin-independent: $\mathcal{M}_{\rm SI} \sim (\bar{N}N)(\bar{\chi}\chi)/\Lambda^2$, coherent Z^2 enhancement.
- Spin-dependent: $\mathcal{M}_{\rm SD} \sim (\bar{N}\gamma^\mu\gamma^5 N)(\bar{\chi}\gamma_\mu\gamma^5\chi)/\Lambda^2$.
- Most analysis takes $\sigma^0_{\rm SI}$, $\sigma^0_{\rm SD}$ to be recoil energy/momentum independent, no v or θ dependence.

Energy/momentum dependent cross sections

Energy/momentum dependent cross section. Possible operators

- Parity is broken in SM, also possible for DM interactions, $(\bar{q}q)(\bar{\chi}\gamma_5\chi)$, $(\bar{q}\gamma_5 q)(\bar{\chi}\chi)$, $(\bar{q}\gamma_5 q)(\bar{\chi}\gamma_5\chi)$. (Chang et al, 0908.3192)
- The mirror neutron is neutral under mirror electromagnetism. Interacts with the proton via mirror magnetic dipole moment or charge radius. Mirror QCD or QED conserves Parity.
- Momentum transfer $|\mathbf{q}| \sim$ MeV. The cross section is large enough to be visible only when the force carrier is $10 - 100$ MeV for $m_{\rm dm} = 5GeV$.

Mirror photon portal: mirror neutron as DM

$$\mathcal{L} = \epsilon_\gamma e\bar{p}\gamma^\mu p A'_\mu + \epsilon_\gamma \frac{\mu_N}{2}\bar{N}\sigma^{\mu\nu}NF'_{\mu\nu} ,$$

$$\mathcal{L}' = c_1\frac{e}{2m_\chi}\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu} + c_2\frac{e}{2m_\chi^2}\bar{\chi}\gamma^\mu\chi D_\nu F'_{\mu\nu} + c_3\frac{e}{m_\chi^2}\bar{\chi}\gamma^\mu D_\nu\chi F'_{\mu\nu} + \text{h.c.} .$$

Detection of mirror neutron as dark matter

Integrate out mirror photon, NR reduction ⇒ SI and SD matrix elements

$$
\begin{aligned}
\mathcal{M}_{\rm nr} \;=\;& \epsilon_\gamma \frac{(c_1+c_2)e^2}{2m_\chi^2 m_{\gamma'}^2}|\mathbf{q}|^2(p_h^\dagger p_h)(\chi_h^\dagger\chi_h) + \epsilon_\gamma \frac{c_1 e^2}{2\mu m_\chi m_{\gamma'}^2}(\mathbf{q}\times\mathbf{P})^i(p_h^\dagger p_h)(\chi_h^\dagger\sigma^i\chi_h) \\
+\;& \epsilon_\gamma \frac{(\frac{e}{2m_p}+\mu_p)c_1 e}{m_\chi m_{\gamma'}^2}(|\mathbf{q}|^2\delta_{ij}-q^iq^j)(p_h^\dagger\sigma^i p_h)(\chi^\dagger\sigma^j\chi_h) \\
+\;& \epsilon_\gamma \frac{\mu_n c_1 e}{m_\chi m_{\gamma'}^2}(|\mathbf{q}|^2\delta_{ij}-q^iq^j)(n_h^\dagger\sigma^i n_h)(\chi^\dagger\sigma^j\chi_h)\,.
\end{aligned}
$$

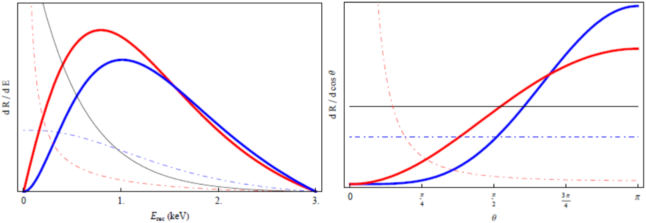
- We have written down all the P-even effective operators up to dimension six.
- The amplitudes depends on the recoil energy transfer, via $|\mathbf{q}|^2$ or $(\mathbf{q}\times\mathbf{P})\cdot\sigma$.
- The nucleon part can only take form of $N^\dagger N$ or $N^\dagger\sigma_i N$, so only SI/SD form factors.
- c_1 amd c_2 are related to EM form factors, correspond to magnetic dipole moment and charge radius, respectively. c_3 term does not contribute.

$$F_1'(0)=\frac{c_2}{2m_\chi^2},\quad F_2(0)=2c_1$$

Energy/Momentum dependent scattering

Unlike the usual dark matter SI and SD interaction, the cross sections have strong momentum dependence. The rate has distinct spectral.

$$\frac{d\sigma_{\rm SI}}{dE_r} = \varepsilon_\gamma^2 \frac{8Z^2 e^2 m_A \mu^2 v^2 \mu_\chi^2}{\pi m_{\gamma'}^4} \left[\left(1 + \frac{c_2}{c_1}\right)^2 (1 - \cos\theta)^2 + \frac{\mu^2}{m_\chi^2} \sin^2\theta \right] F^2(|\mathbf{q}|)$$



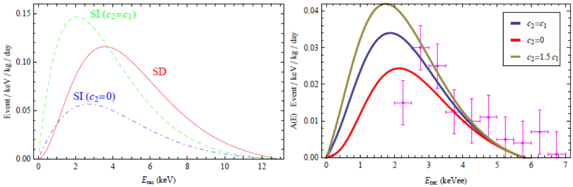
Red/Blue: SI/SD; Black: conventional case; Dashed: (without mirror) dark matter carrying tiny, visible mangetic dipoles and charge radus.

To measure direction dependence from experiment: Sciolla, 0811.2764

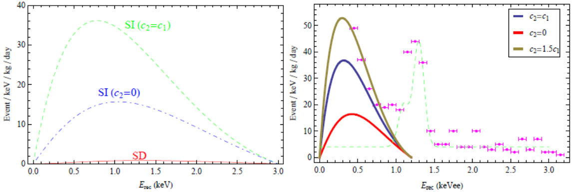
Fitting DAMA and CoGeNT

Calculate c_1 using the quark model picture, take c_2 as a free parameter.

DAMA: $m_{\gamma'} = 10\,\mathrm{MeV}$, $\varepsilon^2_{\gamma'} = 0.5 \times 10^{-7}$.



CoGeNT: $m_{\gamma'} = 10\,\mathrm{MeV}$, $\varepsilon^2_{\gamma'} = 2 \times 10^{-7}$.



QED precision measurement muon $g-2$: $\varepsilon^2_{\gamma} < 2 \times 10^{-5} (m_{\gamma'}/100\mathrm{MeV})^2$.

More visible effects about asymmetric dark matter

- Anti-neutrinos from asymmetric dark matter (Feldstein and Fitzpatrick, 1003.5662).
- Experiment designed at Jefferson Lab to search for the light γ' (mass tens to hundreds of MeV) (Essig, 2010, *Proposal: Search for a New Vector Boson A' Decaying to e^+e^-*).

The complete and viable the model

- Production of dark matter with baryon number.
- Other phenomenological constraints.

Leptogenesis as common origin for matter and dark matter

SM itself is incapable to generate enough baryon number: Lack of first order phase transition, too small CP violation.

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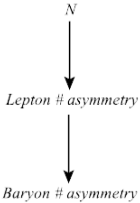
Baryogenesis via Leptogenesis is one elegant way, introduce righthanded neutrino N.



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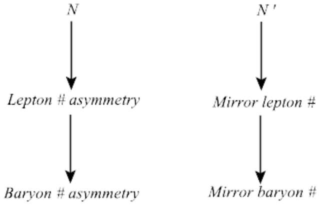

LEPTOGENESIS AS COMMON ORIGIN FOR MATTER AND DARK MATTER

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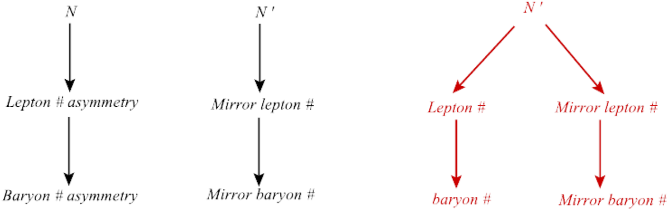


Economical way: Introduce common RH neutrinos for both sectors.

$$\mathcal{L} = y\bar{L}HN + y'\bar{L}'H'N + M_R NN + \text{h.c.} \quad (\text{mirror symmetry} : y = y')$$

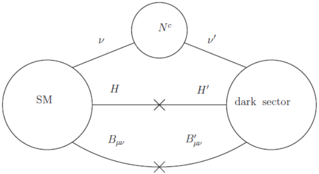
$$\Rightarrow \; n_{\rm b} = n_{\rm dm}, \;\; m_{\rm dm} = \Omega_{\rm dm}/\Omega_{\rm b} m_p \approx 5\text{GeV} \; .$$

More features about the model

Phenomenological considerations:

- Introduce two Higgs doublets for each sector: $\tan\beta \neq \tan\beta'$, so $m_{d'}$ can be lighter than $m_{u'}$, dark matter candidate include n', p' and Δ^- (Δ^{++}).
- Introduce a Higgs triplet for each sector, with non-zero VEV, for neutrino mass. Inverse seesaw:

$$\mathcal{M} = \begin{pmatrix} \mu & M_D & 0 \\ M_D^T & M_R & M_D'^T \\ 0 & M_D' & \mu' \end{pmatrix}$$



For $M_R\mu' < M_D'^2$ (if μ is negligible), we have $m_{\nu'} = M_D' M_R^{-1} M_D'$, and $m_\nu = \mu'(v/v')^2$.

- Break the mirror QED force, possible in 2HDM, (Baumgart, Cheung, Ruderman, Wang, Yavin, 0901.0283), $v'_+ = 10 - 100\,\mathrm{MeV}$. For ε large enough, $\varepsilon F_{\mu\nu}F'^{\mu\nu}$ will keep the two sectors in thermal equilibrium until γ' decays.

The consequences

Take a typical set of parameter values:

$$M_R = 10^8\text{GeV},\ y_\nu \sim 0.015,\ v'/v = 10^3,\ \mu' = 100\text{KeV}$$

- Neutrino mass $m_\nu \approx 0.1\,\text{eV}$, $m_{\nu'} \approx 140\,\text{MeV}$ and $U_{\nu\nu'} \approx 10^{-3}$. So $\tau(\nu' \to e^+e^-\nu) < 0.5\,\text{sec}$, decays before BBN.
- Leptogenesis: wash out factor $\kappa \approx 10^{-6}$, need resonant leptogenesis $\epsilon \sim 0.05$. Increase M_R will reduce the ν' mass, late decay threatens BBN if too light.
- Extra d.o.f. will change the expansion rate during BBN. Massive mirror photon $\gamma' \to e^+e^-$. $\tau_{\gamma'} \approx (50\text{MeV}/m_{\gamma'})\left(7\times 10^{-11}/\varepsilon_\gamma\right)^2\,\text{sec}$.
- Broken mirror QED, $e' \to \nu'\gamma'$, $\tau(e') < 0.05\,\text{sec}$. For $m_{p'} - m_{n'} \gtrsim 100$ MeV, $p' \to n'\gamma'$, $\tau_{p'} < 10^{-15}\,\text{sec}$ and vice versa.
- Most mirror particle will decay to SM except for the lightest mirror nucleon (dark matter candidate).
- $0\nu\beta\beta$ decay: $m_{\text{eff}} = \sum_i U_{ei}^2 m_{\nu_i} + \sum_i (v/v')^2 U_{ei}'^2 \bar{q}_F^2/m_{\nu_i'}$, calls for some fine-tuning, potentially large enough to be probed.

Conclusion

- Asymmetric dark matter can naturally arise from mirror models. The mass of dark matter is predicted about 5 GeV.
- The origins for matter and dark matter can be unified.
- The U(1)-U(1)' kinetic mixing along with a massive mirror photon provide a way to maintain the consistency of the model with BBN. The mirror photon, therefore, provides a portal linking the two sectors and makes the direct detection of the dark matter possible.
- The direct detection of the dark baryon is investigated. Contrary to usual dark matter, the interaction cross section depends on the energy/momentum transfer. The differential rate has very special energy and direction dependence.

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Thanks

Happy brithday to Goran!