Neutral Naturalness: From Colliders to Cosmology and Astrophysics

New Physics with LLPs Workshop
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Based on
1803.03263, 1905.xxxxx Chacko, DC, Geller, Tsai
1906.xxxxx DC, Jack Setford
ongoing work with Shayne Gryba
Cảm ơn bạn to the organizers and the ICISE center
Exploring Hidden Sectors
There has to be new physics…

The usual fundamental mysteries (Hierarchy Problem, DM, Baryogenesis, Neutrinos, …) aren’t going anywhere.

*Higgs discoveries and DM astro measurements sharpen these questions!*  

Canonical solutions (SUSY, WIMP DM, …) generally involve IR-minimal models, where the new degree of freedom which solves the mystery has sizable direct coupling to the SM.

This leads to irreducible signatures that haven’t shown up so far.

… where is it?
Hidden Sectors

Particles & forces hidden from us due to small coupling, not high mass.

Generically arise due to the grammar of QFT.

Confirmed examples: ν’s, DM

Give non-minimal IR spectra from minimal theory input (e.g. QCD cousins like Hidden Valleys)

Can couple to SM via small portal couplings, e.g.

**Heavy Mediators**  **Higgs Portal**  **Photon Portal**
1. Exotic Higgs Decays as probes

LHC can probe tiny exotic branching ratios if decays spectacular. Sizable Higgs Portal couplings to new physics are generic.

2. Long Lived Particles (LLPs) are generic

Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes. The LLP lifetime is (almost…) a free parameter!

3. Complementarity between Cosmology and Colliders

Models which avoid signatures in one will often show up in the other

(e.g. dark radiation, DM with structure, etc.)
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3. Complementarity between Cosmology and Colliders

Models which avoid signatures in one will often show up in the other

(e.g. dark radiation, DM with structure, etc.)
Hidden sectors can give rise to “arbitrarily” rich cosmology and astrophysics.

Can we make this predictive?

Yes: make the hidden sector solve some of these fundamental mysteries.

→ “signature generator” of complex hidden sector phenomena
Big Picture II

Cosmology

LLP Signatures

Hidden Sectors

Most of this talk

See
Jonathan Feng’s talk

Lots of talks at several LLP workshops :)

Jonathan Feng's talk
Neutral Naturalness
Neutral Naturalness

Solves the (little) Hierarchy Problem without colored top partners to explain LHC null results.

Example of a particularly motivated hidden sector.

Solution to the hierarchy problem that is discoverable via non-standard searches and demonstrates collider-cosmo complementarity: either get LLP signals or very rich cosmology and astrophysics
Minimal Twin Higgs (MTH)

$\text{SM}_A \times \text{SM}_B$ (mirror sector) particle content with $Z_2$ symmetry

Higgs sector: SU(4), broken by Gauge + Yukawa interactions to $\text{SU}(2)_A \times \text{SU}(2)_B \times Z_2$, which generate mass for goldstone boson.

\[ \Delta V = \frac{3}{8\pi^2} \Lambda^2 \left( \lambda_A^2 H_A^\dagger H_A + \lambda_B^2 H_B^\dagger H_B \right) \quad \lambda_A = \lambda_B \equiv \lambda \quad \Delta V = \frac{3\lambda^2}{8\pi^2} \Lambda^2 \left( H_A^\dagger H_A + H_B^\dagger H_B \right) = \frac{3\lambda^2}{8\pi^2} \Lambda^2 H^\dagger H \]

$Z_2$ symmetry of quadratically divergent contributions mimics full SU(4) symmetry, protects pNGB Higgs mass @ 1-loop.

This is an IR model up to few TeV.
Have to UV complete.
O(dozen) examples in literature
$Z_2$ symmetry → hidden sector copy of SM [a complicated hidden valley!]

Strassler, Zurek 2006

Soft $Z_2$ breaking to make hidden higgs vev higher than SM to avoid Higgs bounds: $v_B/v_A > \sim 3$

This requires tuning $\sim (v_B/v_A)^2 \sim \text{Br}(h \rightarrow \text{mirror})$

Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos) $\Rightarrow \Delta N_{\text{eff}} \sim 5$

Minimal model incompatible with cosmology.
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Minimal model incompatible with cosmology.
Fix 1: *Hard* $Z_2$ breakings
e.g. Fraternal Twin Higgs

→ mirror QCD
gives rise to **light LLPs**
produced via Higgs portal

$Z_2$ symmetry → hidden sector copy of SM [a complicated hidden valley!]

Soft $Z_2$ breaking to make hidden higgs vev higher than SM to avoid Higgs bounds: $v_B/v_A > ~ 3$

This requires tuning $\sim (v_B/v_A)^2 \sim Br(h \rightarrow \text{mirror})$

Uncolored top partners.

Massless degrees of freedom:
(twin photon, neutrinos)
⇒ $\Delta N_{\text{eff}} \sim 5$

**Minimal model incompatible with cosmology.**
LLPs @ LHC!

\[
\sqrt{s} = 14 \text{ TeV}, \ 3000 \text{fb}^{-1}, \ N > 4
\]
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Minimal model incompatible with cosmology.
Fix 2: dilute mirror sector cosmological abundance: Asymmetric Reheating!

\[ \text{Z}_2 \text{ symmetry} \rightarrow \text{hidden sector copy of SM} \] [a complicated hidden valley!]

Strassler, Zurek 2006

\textbf{Soft Z}_2 \text{ breaking to make hidden higgs vev higher than SM to avoid Higgs bounds: } \frac{v_B}{v_A} > \sim 3

This requires tuning \sim (\frac{v_B}{v_A})^2 \sim \text{Br}(h \rightarrow \text{mirror})

\textbf{Uncolored top partners.}

\textbf{Massless degrees of freedom:} (twin photon, neutrinos)

\[ \Rightarrow \Delta N_{\text{eff}} \sim 5 \]

\textbf{Minimal model incompatible with cosmology.}
Asymmetrically Reheated Mirror Twin Higgs
Example: νMTH

Let’s also solve the Neutrino Mass problem: add RH neutrinos to MTH and implement type-I See-saw

Toy model with 1 RH neutrino without $Z_2$ breaking (can extend to 3 & various realistic flavor models):

$$\mathcal{L} \supset -y(L_A H_A N_A + L_B H_B N_B) - \frac{1}{2} M_N (N_A^2 + N_B^2) - M_{AB} N_A N_B + \text{h.c.}$$

RH-neutrino mass eigenstates live in both sectors:

$$N_+ = \frac{1}{\sqrt{2}} (N_A + N_B)$$

$$N_- = \frac{1}{\sqrt{2}} (N_A - N_B)$$
Example: νMTH

Only source of $Z_2$ breaking is larger mirror Higgs vev, but this causes lightest RH neutrino to decay preferentially to SM (heavier mirror $W$ boson):

$$\Gamma_{N \rightarrow i} \propto \frac{m_{\nu_i}^2}{m_{W_i}^4}$$

$$\epsilon = \frac{\Gamma_{N \rightarrow B}}{\Gamma_N} \approx \frac{v^2}{f^2}$$

If the Neutrinos have mass at GeV scale, decay out of equilibrium AFTER the higgs portal freezes out (mirror & visible sector decoupled). $\rightarrow$ Dilute mirror sector!

$$M_N < 1 \text{ GeV} \left( \frac{0.01 \text{ eV}}{m_\nu} \right)^{1/2}$$

$$\Delta N_{\text{eff}} \sim 5 \epsilon = 5 (v/f)^2$$
Phenomenology

In the νMTH, the dilution is dictated by \((v_A/v_B)^2\), which is the tuning of the model and also measurable at colliders via \(Br(h\rightarrow\text{invis})\).

Long-lived RH neutrino might also be detectable.

But let’s focus on cosmology and astrophysics.

Choose a general parameterization of the Asymmetric Reheating mechanism within the MTH framework:

\[
\Delta N_{\text{eff}}, \quad \frac{v_B}{v_A}, \quad r_{\text{all}} = \frac{\Omega_{\text{all mirror baryons}}}{\Omega_{\text{DM}}}.
\]

- model like νMTH connects these two
- any mirror-baryogenesis mechanism will give some asymmetric mirror relic abundance

1803.03263 Chacko, DC, Geller, Tsai
Three parameters determine a family of rich hidden sector dictated by the hierarchy problem.

\[ \Delta N_{\text{eff}}, \quad \frac{v_B}{v_A}, \quad r_{\text{all}} = \frac{\Omega_{\text{all mirror baryons}}}{\Omega_{\text{DM}}}. \]

What does the cosmology and astrophysics look like?

We have to recalculate all of cosmological history…

*For now, no assumptions on what the majority of DM is made of… [work in progress with Shayne Gryba]*
Asymmetric MTH Cosmology

- BBN: predicts ~ 75% mirror Helium mass fraction in mirror sector (compare to 25% SM).

- Mirror-baryo-acoustic oscillations modify matter power spectrum, shows up in CMB & LSS:
  Current Ly-α constrains r_{all} < ~ 10%
  CMB Stage IV will probe r_{all} ~ 1%

- ΔNeff ~ 0.few
  same free-streaming vs scattering fraction as SM

- Mirror baryons part of our galaxy, but cool slower than SM baryons. **Feedback is complicated.**
  Distribution may be disk-like or halo-like.
Mirror Baryons Direct Detection

SuperCDMS (nuclear recoil) taking data, SENSEI (electron recoil) is approved.

If there is *any* ambient mirror ionization, fast mirror electrons provide excellent discovery channel!
(Detection possible in other cases too)
But complex mirror sectors can give rise to MUCH weirder astrophysical phenomena...
Mirror Stars
Hierarchy Problem → Mirror Stars?

Mirror DM (perfect SM copy) is an old idea.

Foot, Ignatiev, Volkas astro-ph/0011156 and more

Mirror star signatures never really studied.

Neutral Naturalness motivates *family* of mirror sectors that are *fundamentally* motivated and allow for mirror stars.

Similar to SM but different enough to change detailed stellar astrophysics.

Want to consider mirror stars as a *general* class of hidden sector signatures!
Factorize the Question

Mirror Stars

1. What do they look like in the sky?

2. Hidden Sector Model → Mirror Star Characteristics?
Factorize the Question

**Mirror Stars**

1. What do they look like in the sky?

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*Figure this out first for general mirror star*

1907.xxxxx DC, Jack Setford
Factorize the Question

Mirror Stars

1. What do they look like in the sky?
2. Hidden Sector Model $\rightarrow$ Mirror Star Characteristics?

Figure this out first for general mirror star

Neutral Naturalness is a great signature generator!

1907.xxxxx DC, Jack Setford

next paper
How to discover Mirror Stars?

Use SM stars as benchmark “mirror stars” to study signature in detail.

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<th>Mass / $M_{\text{sun}}$</th>
<th>He mass fraction</th>
<th>Radius / $R_{\text{sun}}$</th>
<th>$T_{\text{core}}$ / $10^7$ K</th>
<th>Luminosity / $L_{\text{sun}}$</th>
<th>Lifetime / years</th>
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<td>5.15</td>
<td>4.13</td>
<td>$1.05 \times 10^5$</td>
<td>?</td>
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Table 1: MESA benchmark stars used in the calculations.

Source of signal: mirror photon mixing!

$$\epsilon F_{\mu\nu} F'_{\mu\nu}$$
Mirror Star Signals
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Mirror Star Signals

1) Photons from surface $\sim \varepsilon^2$
Mirror Star Signals

1) Photons from surface \( \sim \epsilon^2 \)

Also straight from core? NO!
Mirror Star Signals

1) Photons from surface $\sim \epsilon^2$

Also straight from core? NO!

$\propto \epsilon^2$
SM Baryon Capture in Mirror Star

\[ \frac{d\sigma}{dE_R} = \frac{2\pi \epsilon^2 \alpha^2 Z_1^2 Z_2^2}{m_T v^2 E_R^2}, \]

There is capture due to mirror-SM collisions...

\[
\left( \frac{dN_i}{dt} \right)_{\text{mirror}} = n_i^{\text{ISM}} \sum_j \frac{4\pi N_j \epsilon^2 \alpha^2 Z_i^2 Z_j^2}{m_i m_j u^3}
\]

and SM-SM collisions

\[
\left( \frac{dN_i}{dt} \right)_{\text{geometric}} = n_i^{\text{ISM}} \sqrt{\frac{3}{2}} \frac{v_{\text{esc}}^2}{u} \pi R^2.
\]

Total amount captured \( \propto \) age of star!
Mirror Star Signals

1) Photons from surface $\sim \epsilon^2$

Also straight from core? NO!

SM baryons (interstellar medium)
Mirror Star Signals

1) Photons from surface $\sim \epsilon^2$

Also straight from core? NO!

SM baryons (interstellar medium)

Captured SM Baryon “nugget”

$\propto \epsilon^2$
Captured SM “Nugget”

Captured matter arranges itself in profile with $R \sim$ virial radius given by equilibrium temperature.

Equilibrium temperature given by SM ionization energy where \textit{bremsstrahlung cooling} becomes efficient.

$$T_{eq} \sim 10^4 \text{ K}$$

$r_{SM} \sim 10^{-3} R_{\text{star}}$. Nugget is $\sim$ planet size!

Nugget is \textit{optically thin} for optical photons (bremsstrahlung cooling), but \textit{optically thick} for ionization and X-ray photons.
Mirror Star Signals

1) Photons from surface $\sim \epsilon^2$

Also straight from core? NO!

Captured SM Baryon “nugget”

SM baryons (interstellar medium)

$p \leftrightarrow p'$

$p \times \epsilon 

p' \leftrightarrow p'$

$\propto \epsilon^2$
Mirror Star Signals

1) Photons from surface \( \sim \epsilon^2 \)

Also straight from core? NO!

2) Thermal emission from SM nugget: Optical!
SM “Nugget” Emission Spectrum
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Bremsstrahlung Cooling gives optical signal!

Given its low luminosity, MUCH too hot to be standard astrophysical object
SM “Nugget” Emission Spectrum

Bremsstrahlung Cooling gives optical signal!

What’s this… X-ray Black Body Signal!?

Given its low luminosity, MUCH too hot to be standard astrophysical object
Mirror Star Signals

1) Photons from surface $\sim \varepsilon^2$

*Also straight from core? NO!*

2) Thermal emission from SM nugget: \textbf{Optical!}
Mirror Star Signals

1) Photons from surface $\sim \epsilon^2$

Also straight from core? NO!

2) Thermal emission from SM nugget: **Optical**!

3) Mirror Thomson Conversion: **X-rays**
X-Ray Signal

Visible to our X-ray telescopes!

- Mirror Fusion
  As in regular star, does not reach surface directly

- Mirror Thomson Conversion

- X-ray photosphere of SM nugget
These mirror stars have a very bizarre double-signal: optical bremsstrahlung photons from the captured SM matter and converted X-ray photons straight from the mirror star core
Mirror Stars in HR Diagram
Mirror Stars in HR Diagram

Some of these mirror stars could show up in GAIA data.

Requires closer analysis.

Could then diagnose mirror star with X-ray observations.
Mirror Stars in HR Diagram

Some of these mirror stars could show up in GAIA data. Requires closer analysis. Could then diagnose mirror star with X-ray observations.
Upshot

Mirror stars have a *robust* and *highly distinctive* signal.

**Hot! (~10,000K)**

**X-rays** = Mirror Star Core Temperature!

Only visible if close $\rightarrow$ parallax $\rightarrow$ get absolute lumi $\rightarrow$ **Faint!**

Upon detailed examination, this will look nothing like anything from SM astrophysics!
Conclusions
Conclusions

Hidden sectors are motivated from bottom-up and top-down.

Collider (LLP) vs Cosmology (stable)

Top-down formulations give rich, predictive hidden sectors with rich cosmology and astrophysics that you can interrogate in detail.

Asymmetrically reheated MTH:
- solves the little hierarchy problem
- if no LLP signatures, can still measure \( \text{Br}(h \rightarrow \text{invis}) \sim v_B^2/v_A^2 \)
- this parameter is correlated with many many cosmo + astro observables: \( \Delta N_{\text{eff}} \), LSS deviations, direct detection, mirror stars

MIRROR STARS can a rise in many hidden sectors.
We found they produce a highly robust and distinctive signal!