Signatures of Mirror Stars

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Motivation

Dark Complexity:
- Non-minimal hidden / dark sectors are interesting.
- Where to start? Dark sectors related to SM by symmetry.

Hierarchy problem:
- Neutral naturalness suggests a family of non-minimal hidden sector models.
- Mirror Twin Higgs – mirror sector with $Z_2$ symmetry.
New states protect Higgs mass up to $\sim 10$ TeV cutoff, assuming $Z_2$ symmetric Yukawas and gauge couplings.

Can solve cosmological issues in $Z_2$ symmetric case with asymmetric reheating.
Mirror Twin Higgs

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Mirror Twin Higgs

Mirror sector mass scale $\sim v_B$
- Collider searches $\rightarrow v_B/v_A > 3$
- $\Delta N_{\text{eff}}$, asymmetric reheating $\rightarrow v_B/v_A > 5$.

Mirror nuclear physics can be similar to SM nuclear physics.

Mirror sector is at most 10% of total dark matter density (self interaction and large scale structure bounds.)

Predictive framework for cosmology, e.g. Helium mass fraction $\rightarrow 75\%$ (25% in SM).

[Chacko, Curtin, Geller, Tsai, arXiv:1803.03263]
If physics of the mirror sector is similar enough to SM physics, it’s reasonable to suppose mirror stars might form.

Mirror stars of an exact mirror sector have been discussed before.


But no estimate of expected signal.

We’re interested in a broad class of models with mirror nuclear physics – MTH model is a good benchmark.
Mirror Photons

As usual in models with a second $U(1)$ gauge boson we expect a kinetic mixing term:

$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu}$$

Current bounds on $\epsilon$ are

$$\epsilon \lesssim 10^{-9}.$$ 

In MTH, $\epsilon$ is not generated at up to 3-loop, so small value arises naturally.

We consider values in the range $\epsilon = 10^{-10} - 10^{-13}$.

[Vogel, Redondo, arXiv:1311.2600]
How can we see a mirror star?

$\epsilon^2 L_{\text{star}}$ surface brightness:

Captured SM matter is heated via $\epsilon^2$-suppressed processes: collisions with mirror nuclei, and photon conversion.
PHOTON CONVERSION, X-RAY SIGNATURE

SM matter catalyzes mirror photon conversion:

\[ p, e^- \rightarrow \gamma' \rightarrow p, e^- \]

Converted photons can heat up the captured material. There is an X-ray photosphere from which converted X-ray escape → potential signature.
CALCULATION PROGRAM

MODEL STARS

CAPTURE

PROPERTIES OF NUGGET (temperature, optical depth)

SIGNAL
## Optical Depth of Nugget

<table>
<thead>
<tr>
<th></th>
<th>Optically thin</th>
<th>Optically thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal photons</td>
<td>Nugget cools via collisional processes e.g. bremsstrahlung</td>
<td>Nugget cools as blackbody with effective surface temperature</td>
</tr>
<tr>
<td>Converted X-rays</td>
<td>All X-rays escape</td>
<td>Most X-rays deposit energy as heating, while conversions in photosphere can escape.</td>
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</tbody>
</table>
X-rays that convert within the nugget will scatter until absorbed via photoionization.

\[ \epsilon = 10^{-11} \]

\[ M = 5 \, M_{\text{sun}} \]
RESULTS: SPECTRUM

Shape of spectrum depends on optical depth: black body / bremsstrahlung emission. For higher $\epsilon$ there is attenuation due to absorption by mirror star matter.
Two distinct thermal spectra – can plot separately on a Hertzsprung-Russell diagram:

\[
\begin{align*}
L / L_{\odot} & = 10^{-14} \\
T / K & = 10^8 \\
\epsilon & = 10^{-10} \\
\epsilon & = 10^{-11} \\
\epsilon & = 10^{-12} \\
\end{align*}
\]
CONCLUSIONS

- Mirror sectors theoretically well-motivated.

- Mirror stars can efficiently capture interstellar matter, which leads to a signal in SM photons.

- Two thermal signatures: the temperature of the nugget and the temperature of the mirror star core.

- Weird signal – faint, nearby, hot object with an X-ray signal. Close $\rightarrow$ parallax.
Back-up slides
PROFILE OF CAPTURED MATTER

Assume that the captured material is in isothermal hydrostatic equilibrium, in an external gravitational well.
Simplifying assumption, isothermal profile.

\[ kT_{nugget} \frac{dn}{dr} = - \frac{GM_{mirror}(r) m_{SM} n(r)}{r^2} \]

(Ignores captured matter gravitational self-interactions)

Solution given by

\[ n(r) = Ce^{-\int A(r)dr}, \quad A(r) = \frac{GM_{mirror}(r) m_{SM}}{kT_{nugget}r^2} \]  

(1)

Virial theorem, characteristic radius:

\[ r_{capture} = \sqrt{\frac{9kT_{mirror}}{4\pi G\rho_{mirror} m_{SM}}} \]  

(2)
SM-like mirror stars

- Mirror stars are SM-like, i.e. same opacity, same reaction rates and energy output.
- Generate stellar profiles using MESA for different masses.
\[
\frac{dP_{x-ray}}{d\nu_{obs}} = \int_0^{R_{nugget}} dr 4\pi r^2 \int_0^\infty d\nu_i \frac{\nu_f}{\nu_i} \frac{dP_{conv}}{dV d\nu_i} \times \\
\Theta(\lambda_{abs}(\nu_f) - N_{scat}(r)\lambda_{scatter})\delta(\nu_{obs} - \nu_f(\nu_i, r))
\] 

Heaviside function accounts for absorption, delta function forces observed frequency to be equal to the final frequency \(\nu_f(\nu_i, r)\) after the X-ray has scattered to the surface of the nugget.

\[
\frac{d^2P_{conv}}{dVd\nu} = \epsilon^2 n_{SM}\sigma_{thoms} 4\pi B_\nu(\nu, T)
\]