

Dark neutron star formation in a heavy mirror dark sector

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JL, João Rosa [arXiv:2507.XXXX]

Overview

1. Heavy mirror dark sector

Dark sector has heavier particles & inverted quark hierarchy.
Generically predicts $\Omega_{DM} \sim \Omega_b \times \mathcal{O}(1)$.

2. Early universe

Inefficient dark recombination, but sufficient dark dissipative cooling.

3. Dark neutron star properties

Typically smaller and lighter than visible NS.

4. Prospective observational signatures

Gravitational microlensing + visible luminosity via kinetic mixing.

Why is $\Omega_{DM} \approx 5\Omega_b$?

Λ CDM quite successful at describing our universe on large scales. A variety of physical models can play the role of CDM

- ▶ single BSM particle e.g. thermal WIMPs, axions
- ▶ multiple dark particle species, perhaps with some gauge structure e.g. atomic DM, twin Higgs

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- In mirror models with asymmetric dark/visible particle production, the coincidence in relic abundance is exchanged for a coincidence in particle mass.

In a “mirror” dark sector (without a discrete symmetry with the visible sector), we can resolve this coincidence, as well as make some interesting predictions.

Heavy “mirror” dark sector

Everything assumed to be unified above GUT scale

Strings ($E_8 \times E_8$)

$$\downarrow M_{\text{GUT}} \sim 10^{16} \text{ GeV}$$

Two sequestered MSSM (G, G')

$$M_{\text{SUSY}} \sim \text{TeV} \downarrow$$

$$SU(3) \times SU(2) \times U(1)$$

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Affleck-Dine baryogenesis in both sectors: MSSM replete with scalar superpartners, some of which carry B or L as the conserved charge of a global $U(1)$: $\varphi \rightarrow e^{i\alpha}\varphi \implies \partial_\mu j^\mu = 0$ with $j^\mu = i(\varphi^* \partial^\mu \varphi - \varphi \partial^\mu \varphi^*)$

$$\varphi = |\varphi| e^{i\theta}, \quad j^0 = 2i|\varphi|^2 \dot{\theta} = n_B$$

$V(\varphi)$ breaks this $U(1)$, generating $\dot{\theta}$ and hence increases baryon number.

$\rightarrow \varphi$ decays into SM *particles* more than *antiparticles*.

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Different in the two sectors: $n_B \propto M_{\text{SUSY}}^{-1+\delta_n} (\delta_6 = 1/2)$

Explains the similar visible/dark sector energy densities

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Different $M_{\text{SUSY}} \rightarrow$ different Λ_{QCD} , etc. in the two sectors

$$m_n \approx m_p \sim \Lambda_{\text{QCD}} \approx \text{GeV} \left(\frac{M_{\text{SUSY}}}{\text{TeV}} \right)^{0.6}$$

for $m_t \sim 0.1 M_{\text{SUSY}}$.

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But, these effects cancel to give generically similar energy densities:

$$\frac{\rho'}{\rho} = \frac{m'\eta'}{m\eta} = \frac{\Lambda'_{\text{QCD}} n'_B}{\Lambda_{\text{QCD}} n_B} = \left(\frac{M'_{\text{SUSY}}}{M_{\text{SUSY}}} \right)^{\xi_n} \times \mathcal{O}(1) \quad (\xi_6 \approx 0.1)$$

$\rightarrow \rho' \sim \rho$ for $M'_{\text{SUSY}} = 10^4 - 10^{12}$ GeV.

Stable dark neutron

Standard model quark masses			
Q	u/d	c/s	t/b
+2/3	2.2 MeV	1.27 GeV	173 GeV
-1/3	4.7 MeV	94 MeV	4.2 GeV

Why is the hierarchy different in the first generation?

Natural in the dark sector to instead have

$$m'_u > m'_d \rightarrow m'_p > m'_n$$

so the neutron is the stable dark nucleon instead of the proton.

The dark neutron can conveniently play the role of CDM:

- ▶ stable,
- ▶ no long range interactions.

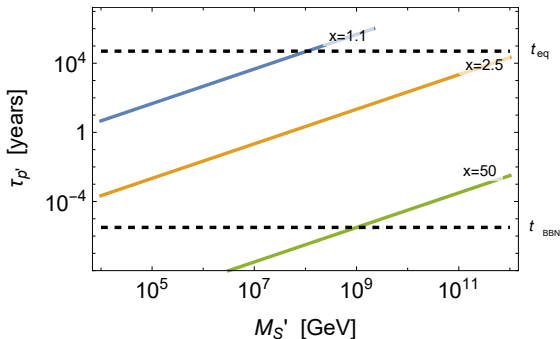
But baryogenesis produces both neutrons and protons, with $m_{p,n} \sim \Lambda_{\text{QCD}}$.

Dark proton decay

- ▶ We can have the proton decay quickly and definitely not affect halo formation.
- ▶ Or, let the proton live long enough to provide a dissipative mechanism in the dark sector.

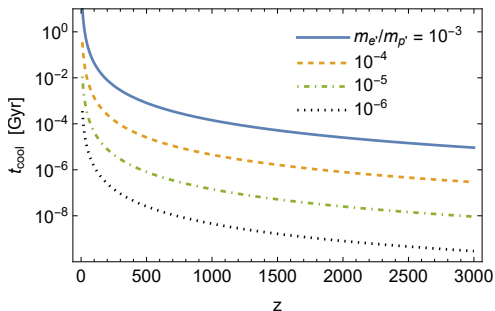
$$\tau_{p'} \approx \mathcal{F}(x) \left(\frac{m_{p'}}{m_{e'}} \right)^5 \left(\frac{M'_{\text{SUSY}}}{\text{GeV}} \right) \times 10^{-17} \text{ seconds}$$

$$x \equiv \frac{m_{p'} - m_{n'}}{m_{e'}} \quad (\text{visible sector has } x \approx 2.5)$$



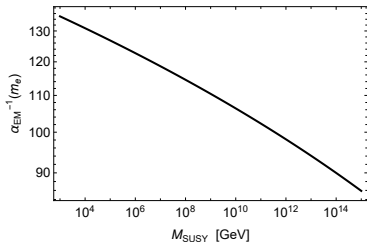
Dissipative cooling

$$t_{cool} = \frac{K_{vir}}{P_{brem} V_{halo}} \quad P_{brem} \propto n_{e'} n_{p'} \frac{\alpha'^3}{m_{e'}^{3/2}} \sqrt{T'}$$
$$= \left(\frac{m_{e'}}{\text{GeV}}\right)^{3/2} \left(\frac{m_{p'}}{\text{TeV}}\right)^{3/2} \left(\frac{M}{10^{-6} M_{\odot}}\right)^{1/3} \frac{4.6 \times 10^3 \text{ Gyr}}{(1+z)^{5/2}}$$



Realistically $z \lesssim 60$ to have in mind the usual matter overdensities.

Dissipative cooling

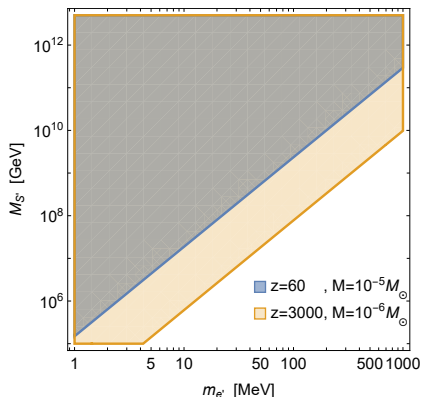


Range of M'_{SUSY} and $m_{e'}$ such that $t_{\text{cool}} < \tau_{p'}$:

Keep in mind $m_{e'} \sim 10$ MeV and $M'_{\text{SUSY}} \sim 10^8$ GeV ($\implies m_{p'} \sim \text{TeV}$).

$$P_{\text{brem}} \propto n_{e'} n_{p'} \frac{\alpha_{\text{EM}}'^3}{m_{e'}^{3/2}} \sqrt{T}$$

Interaction strength slightly enhanced for larger M'_{SUSY} , but P suppressed anyway.



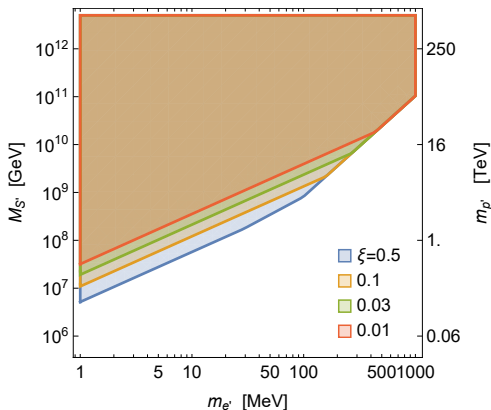
Dark recombination

Residual dark ionization
fraction not very suppressed:

$$\chi_{e'} = 10^{-2} \xi \left(\frac{m_{p'}}{\text{TeV}} \right) \left(\frac{m_{e'}}{\text{MeV}} \right)$$

Bounds on relativistic d.o.f.
at BBN require

$$\xi \equiv T'/T \lesssim 0.4$$



Collapse ($t_{cool} < \tau_{p'}$) of the earliest-forming ($z = 60$) proto-halos ($M_{halo} \sim 10^{-6} M_{\odot}$) after dark recombination can occur for T' within BBN bound.

Formation recap

1. Sufficiently long-lived dark proton allows dissipative processes.
2. Virialized dark matter cools enough to form stars (or black holes).
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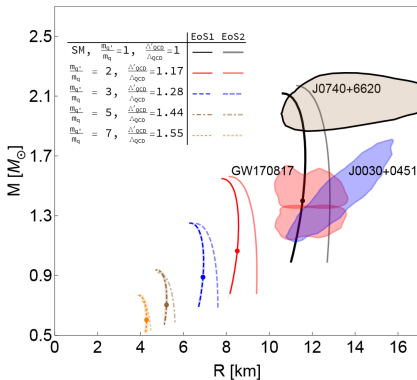
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Dark NS properties

Detailed numerical calculations exist for multiple EoS, comparisons to data from observed pulsars and mergers...

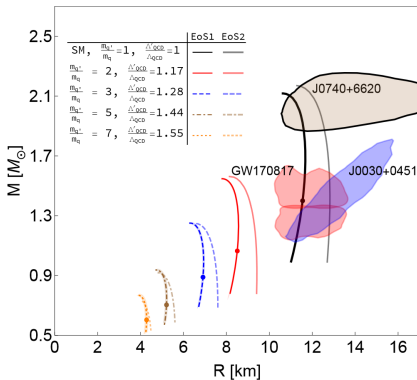
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Unfortunately, we cannot use any of these nice results.

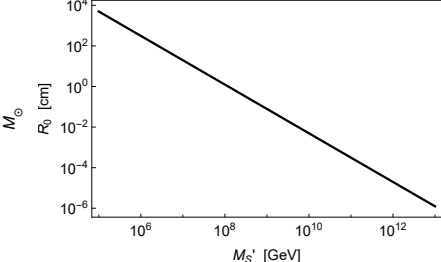
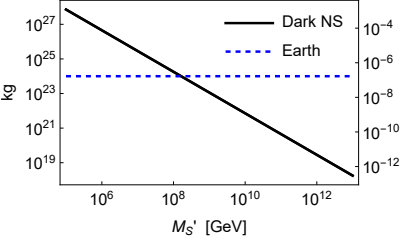
- ▶ $M'_{\text{SUSY}} \gg M_{\text{SUSY}}$ (very heavy dark sector),
- ▶ inverted quark mass hierarchy (stable dark neutron),

so our dark QCD sector is not perfectly analogous to that of the SM.

Dark NS properties

Fermi gas approximation gives R and M scalings in terms of M'_{SUSY} :

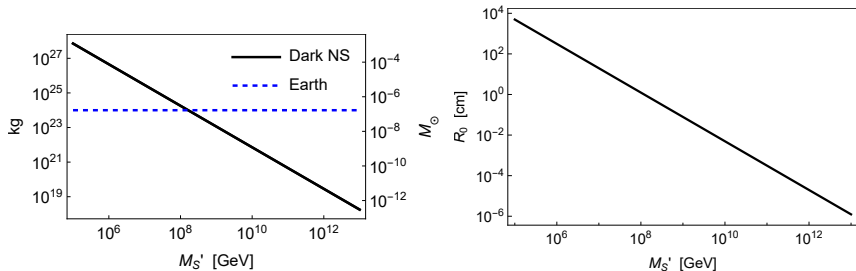
$$R_0 \approx \frac{M_{\text{Pl}}}{m_{n'}^2}, \quad M_0 \approx \frac{M_{\text{Pl}}^3}{m_{n'}^2}, \quad m_{n'} \sim \Lambda'_{\text{QCD}} = 1 \text{ GeV} \times \left(\frac{M'_{\text{SUSY}}}{\text{TeV}} \right)^{0.6}$$



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Cosmological formation suggests $M'_{\text{SUSY}} \gtrsim 10^8 \text{ GeV}$ ($\implies m_{n'} \gtrsim 1 \text{ TeV}$)

- ▶ Dark neutron stars with $M_{\text{NS}'} \lesssim 10^{-6} M_\odot$, $R_{\text{NS}'} \lesssim \text{cm}$.

Dark NS properties

Naively, the stable dark neutron allows for pure dark neutron stars.

With $m_{p'} > m_{n'}$, dark “beta decay” $n' \rightarrow p' + e'^- + \bar{\nu}'_e$ needs

$$k_{F,n'}^2 = (3\pi^2 \hbar^3 n_{n'})^{2/3} > m_{p'}^2 - m_{n'}^2 + m_{e'}^2$$

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With M_0 and R_0 scalings, beta equilibrium gives $n_{p'}/n_{n'} \approx 0.087$.

- Only dependent on model parameters through a very small factor $\sim (m_{e'}/m_{n'})^2$.

Observational signatures

OGLE has seen a handful of short microlensing events, indicating wide-orbit or free-floating objects with mass \sim Earth – Jupiter.

Sumi *et al.* Nature (2011), Mroz *et al.* Nature (2017)

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Gravitational waves would give a unique signal:

- ▶ no visible EM radiation like visible NS mergers,
- ▶ tidal effects give different waveform compared to BH mergers.

However, we don't anticipate a strong GW signal.

Kinetic mixing

In principle, the theory includes a kinetic mixing term

$$\Delta\mathcal{L} = \epsilon F^{\mu\nu} F'_{\mu\nu}$$

with $\epsilon \lesssim 10^{-8}$ to not thermalize the dark sector in the early universe.

With dark proton fraction similar to visible NS, can try to estimate maximum dark magnetic field, rotation frequency, and

- ▶ dark photon luminosity \rightarrow visible luminosity from kinetic mixing as another potentially observable signal.

(Preliminary: GHz signal with faint luminosity, nearby dark NS could be visible.)

Summary

Conceptually simple model: copy of the visible sector but with larger dark SUSY-breaking scale, and explains the similar DM and visible sector densities.

The dark sector can form neutron stars (and small black holes). Would be interesting to know more about star formation processes with these dark neutron stars.

Observable with gravitational microlensing, but hard to uniquely identify only from lensing. In principle, can have visible luminosity from kinetic mixing.