Heating up Neutron Stars with Dark Matter

[1807.02840] + in preparation

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9 Apr 2019
1. Introduction
   - DM Capture by NS
   - Interactions suppressed at low energy
   - Advantages of NS

2. Neutron Star heating
   - Scattering off Nucleons
   - Scattering off Leptons

3. Conclusions
   - Summary
1 Introduction
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Direct Detection: sun rotation in the galaxy originates wimp wind non-gravitational interactions \(\rightarrow\) may scatter off ordinary matter

DD: huge detectors on earth at low \(T\) \(\rightarrow\) DM scattering deposits energy in the detector

Same mechanism used for Indirect detection in Earth and Sun \(\rightarrow\) energy loss may make the DM particle gravitationally bound to the star/planet
Neutron Stars: very efficient for DM capture
Mass similar to the Sun, but very small radius $O(10)\text{Km}$
Very small Cross Sections $\sim 10^{-45}\text{cm}^2$ are enough for the NS to capture all the incident DM flux
DM kinetic energy of the same order of the mass, thanks to gravitational acceleration
After capture, trapped inside the NS, DM undergoes subsequent scatterings, losing all its energy
This heating mechanism defines a minimum temperature ($1700K$) for the NS, assuming equilibrium by radiation loss
For Cross sections smaller than $10^{-45}\text{cm}^2$, NS does not capture the whole flux, and equilibrium temperature is also lower
Observation of very cold NS with $T < 1700K \rightarrow$ upper bound on $\sigma n\chi$
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DD usually considers only SI and SD. Other operators are suppressed by powers of $q_{\text{tr}}$ or $v_{\text{rel}}$.

$$\frac{d\sigma}{d\cos\theta} \propto v_{\text{rel}}^{2n} q_{\text{tr}}^{2n}, \ n > 0$$

$q_{\text{tr}} \sim v_{\text{rel}} \mu \rightarrow v_{\text{rel}} \ll 1, \ q_{\text{tr}} \ll \mu$

Effective suppression of $v_{\text{rel}}^{2n} \ll 1$ comparing to standard SI and SD.

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>$\bar{\chi}\chi \bar{q}q$</td>
<td>SI</td>
</tr>
<tr>
<td>D2</td>
<td>$\bar{\chi}\gamma^5 \chi \bar{q}q$</td>
<td>SI, $q^2$</td>
</tr>
<tr>
<td>D3</td>
<td>$\bar{\chi}\chi \bar{q}\gamma^5 q$</td>
<td>SD, $q^2$</td>
</tr>
<tr>
<td>D4</td>
<td>$\bar{\chi}\gamma^5 \chi \bar{q}\gamma^5 q$</td>
<td>SD, $q^4$</td>
</tr>
<tr>
<td>D5</td>
<td>$\bar{\chi}\gamma_\mu \chi \bar{q}\gamma^\mu q$</td>
<td>SI</td>
</tr>
<tr>
<td>D6</td>
<td>$\bar{\chi}\gamma_\mu \gamma^5 \chi \bar{q}\gamma^\mu q$</td>
<td>SI, $q^2 + v^2$</td>
</tr>
<tr>
<td>D7</td>
<td>$\bar{\chi}\gamma_\mu \chi \bar{q}\gamma^\mu \gamma^5 q$</td>
<td>SD, $q^2 + v^2$</td>
</tr>
<tr>
<td>D8</td>
<td>$\bar{\chi}\gamma_\mu \gamma^5 \chi \bar{q}\gamma^\mu \gamma^5 q$</td>
<td>SD</td>
</tr>
<tr>
<td>D9</td>
<td>$\bar{\chi}\sigma_{\mu\nu} \chi \bar{q}\sigma^{\mu\nu} q$</td>
<td>SD</td>
</tr>
<tr>
<td>D10</td>
<td>$\bar{\chi}\sigma_{\mu\nu} \gamma^5 \chi \bar{q}\sigma^{\mu\nu} q$</td>
<td>SI, $q^2 + v^2$</td>
</tr>
</tbody>
</table>
Inelastic Dark matter: 2 states separated by a small mass splitting

- The lighter state $\chi_1$ accounts for the observed relic density. Heavier state unstable on cosmological scales

Elastic scattering $\chi_1 N \rightarrow \chi_1 N$ not allowed

Upscattering $\chi_2$: $\chi_1 N \rightarrow \chi_2 N$ is possible if allowed kinematically

$\delta m < \frac{1}{2} \mu v_{rel}^2$

$v_{rel}$ is capped by the galactic escape speed, so there is a maximum $\delta m/m_\chi$ that can be tested on earth

When allowed, inelastic cross section is $\sigma_{inel} \sim \sigma_{el} \sqrt{1 - \frac{\delta m}{\frac{1}{2} \mu v_{rel}^2}}$
Outline

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Advantages of NS
Higher energy

- $v_{rel} \sim 10^{-3}$ on Earth
- $v_{rel} \sim \text{few} \times 10^{-3}$ in the Sun
- $v_{rel} \sim 1$ on Neutron Stars!

In [1704.01577] is suggested how to use convert lower limits on observed NS to upper limits on DM-matter interactions.

In [1707.09442] follows up in the idea for $q^2$ and $q^4$ operators.

In [1807.02840] we study elastic and inelastic EFT operators limits arising from neutron star temperatures.
Advantages of NS
Larger Mass splittings

- DM loses energy during capture
- Remaining energy lost during thermalization
- \( \approx \) the whole kinetic energy is transferred to the NS
- Inelastic DM: maximum mass splitting depends on target
- NS allows much larger \( \delta m \) than on earth
- At high DM mass, \( \delta m < 330 \text{MeV} \)
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Neutron Star heating
Scattering off Nucleons

10^0 10^1 10^2 10^3 10^4 10^5 10^6
Λ(GeV)
D1 Xenon1T (SI)
Darwin (SI)
D2 Xenon1T (SI)
Darwin (SI)
D3 LUX (SD)
Darwin (SD)
D4 LUX (SD)
Darwin (SD)
D5 Xenon1T (SI)
Darwin (SI)
D6 Xenon1T (SI)
Darwin (SI)
D7 LUX (SD)
Darwin (SD)
D8 LUX (SD)
Darwin (SD)
D9 LUX (SD)
Darwin (SD)
D10 LUX (SD)
Darwin (SD)

100 10^1 10^2 10^3 10^4 10^5 10^6
mχ(GeV)
D10
Xenon1T (SI)
Darwin (SI)

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\[ \Lambda (\text{MeV}) \]

L1 XENON1T (SI)

Darwin (SI)

L2 NS (BSk24-1)

\[
\sigma_{e\chi} (F_{DM} = 1)
\]

Xenon10

DarkSide-50

DAMIC-M 1kg-year

\[ m_{\chi} (\text{MeV}) \]

L5 XENON1T (SI)

Darwin (SI)

L6 NS (BSk24-1)

\[ e^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

\[ \mu^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

\[ n^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

\[ p^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

\[ \sigma_{e\chi} (F_{DM} = 1) \]

CDMS

Xenon10

DarkSide-50

DAMIC-M 1kg-year

\[ m_{\chi} (\text{MeV}) \]

L7 XENON1T (SI)

Darwin (SD)

L8 NS (BSk24-1)

\[ e^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

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\[ n^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

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DAMIC-M 1kg-year

\[ m_{\chi} (\text{MeV}) \]

L9 LUX (SD)

Darwin (SD)

L10 NS (BSk24-1)

\[ e^{-T_{\infty}, \text{th}} = 1700 \text{ K} \]

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Summary

- Neutron Stars: an interesting possibility to place upper bounds on DM cross sections
- High energy scattering washes away low energy suppression
- Higher reach on inelastic scattering
- Prospected limits competitive with current bound for unsuppressed operators (D1,D5)
- Prospected limits orders of magnitude stronger for suppressed operators
- Current coolest NS of $\mathcal{O}(10^4)K$
- Prospects for observation in the coming decade