Dark Matter Capture in Neutron Stars

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Dark Matter Capture in Stars

→ an alternative approach to DM-nucleon scattering experiments

Considerable quantities of dark matter can accumulate in the Earth, Sun or other stars.

Due to their extreme density, *neutron stars* capture dark matter very efficiently.

NS Capture probability is of order unity when $\sigma_{n\chi} > \sigma_{th} \sim 10^{-45}\text{cm}^2$
Neutron Stars → Black holes?

• Due to their density, neutron stars capture dark matter very efficiently

• Can neutron stars accumulate so much dark matter that they would collapse to black holes? Yes, but typically only if:
  • No annihilation (e.g. asymmetric DM)
  • DM is bosonic and condenses to a small self gravitating BEC, or
  • DM is fermionic with attractive self-interactions, and
  • No repulsive-self interactions that prevent collapse (even very very tiny self-interaction is enough) NFB, Petraki & Melatos, PRD 2013

→ Black hole formation quite unlikely for typical WIMP-like dark matter
Neutron Star Kinetic Heating

Collisions transfer the dark matter kinetic energy to the neutron star → heating

M. Baryakhtar et al.
PRL 119, 131801 (2017)
arXiv:1704.01577

$T_{NS} \sim 1700$ K
1 - 2 $\mu$m
near IR
Dark matter heating

→ from scattering plus annihilation

Baryakhtar, Bramante, Li, Linden and Raj

• Capture (plus subsequent energy loss)
  → DM *kinetic energy* heats neutron star ~ 1700K

• Annihilation of thermalised dark matter
  → DM *rest mass energy* heats neutron star ~ additional 700K

Thermalisation is essentially guaranteed for unsuppressed DM-nucleon scattering. If there is some kinematic suppression of the scattering process, it can take much longer (velocity or momentum suppressions; inelastic, etc)
Cooling and Heating

In the standard NS cooling scenario, nucleons and charged leptons in beta equilibrium

\[ C \frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty + L_{DM}^\infty + L_{\text{other heating}}^\infty \]

= cooling by \( \nu \) and \( \gamma \) emission + heating due to dark matter

• Early cooling is dominated by neutrino emission
• Photon emission dominates at late times

Coolest known neutron star (PSR J2144-3933) has a temperature of \( 4.2 \times 10^4 \) K. 

Old isolated neutron stars should cool to:  
1000 K after \( \sim \) 10 Myr  
100 K after \( \sim \) 1 Gyr
Detecting the Heating

Nearby $\lesssim 50$ pc isolated old NSs

M. Baryakhtar et al.
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$T_{NS} \sim 1700$ K
1 - 2 $\mu$m
near IR

FAST (radio)

JWST (NIRCam)
Neutron Star Heating: Advantages

✓ High probability of gravitational capture.
✓ DM particles accelerated to $\mathcal{O}(0.5c)$ → no momentum suppression

✓ Cross section for efficient trapping $\mathcal{O}(10^{-45} \text{ cm})$ for large DM mass range
✓ Unlike direct detection, not restricted by recoil detection threshold.
✓ Similar sensitivity to SI and SD cross scattering
✓ Elastic and inelastic scattering cross sections of same order of magnitude.
Kinetic Heating Sensitivity

Pauli blocking from degenerate neutrons restricts scattering when $m_{DM} < 1$ GeV.
Need: momentum transfer $> \text{neutron Fermi momentum}$

Momentum transfer in single collision not sufficient for capture when $m_{DM} > 10^6$ GeV

NFB, Busoni, Robles, arXiv:1807.02840
Direct Detection vs Neutron Stars

<table>
<thead>
<tr>
<th>Operator</th>
<th>Coupling</th>
<th>Direct Detection</th>
<th>Momentum suppressed</th>
<th>DD vs NS</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1 SS</td>
<td>$(\bar{\chi} \chi)(\bar{q} q)$</td>
<td>$y_q/\Lambda^2$</td>
<td>SI</td>
<td>×</td>
</tr>
<tr>
<td>D2 PS</td>
<td>$(\bar{\chi} \gamma_5 \chi)(\bar{q} q)$</td>
<td>$y_q/\Lambda^2$</td>
<td>SI</td>
<td>✓</td>
</tr>
<tr>
<td>D3 SP</td>
<td>$(\bar{\chi} \chi)(\bar{q} \gamma_5 q)$</td>
<td>$y_q/\Lambda^2$</td>
<td>SD</td>
<td>✓</td>
</tr>
<tr>
<td>D4 PP</td>
<td>$(\bar{\chi} \gamma_5 \chi)(\bar{q} \gamma_5 q)$</td>
<td>$y_q/\Lambda^2$</td>
<td>SD</td>
<td>✓</td>
</tr>
<tr>
<td>D5 VV</td>
<td>$(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma_\mu q)$</td>
<td>$1/\Lambda^2$</td>
<td>SI</td>
<td>×</td>
</tr>
<tr>
<td>D6 VA</td>
<td>$(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma_\mu \gamma_5 q)$</td>
<td>$1/\Lambda^2$</td>
<td>SI,SD</td>
<td>✓</td>
</tr>
<tr>
<td>D7 AV</td>
<td>$(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma_\mu q)$</td>
<td>$1/\Lambda^2$</td>
<td>SD</td>
<td>✓</td>
</tr>
<tr>
<td>D8 AA</td>
<td>$(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma_\mu \gamma_5 q)$</td>
<td>$1/\Lambda^2$</td>
<td>SD</td>
<td>×</td>
</tr>
</tbody>
</table>

Projected neutron star heating sensitivity:
• comparable to direct detection experiments for scalar and vector interactions
• more sensitive than DD for all other interaction types (typically by orders of magnitude.
Neutron star sensitivity - SI scattering

**SI scattering**

\[ \chi \gamma \mu \chi \bar{q} \gamma^\mu q \]

\[ \chi \chi \bar{q} \gamma^5 q \]

\[ \chi \gamma^5 \chi \bar{q} \gamma^5 q \]

**\( q^2 \) suppressed SD scattering**

**\( q^4 \) suppressed SD scattering**

NS sensitivity comparable to direct detection

NS sensitivity greatly surpasses direct detection experiments

NFB, Busoni, Robles, arXiv:1807.02840
Leptons in Neutron Stars

Beta-decay equilibrium in the core determines the composition:

- Degenerate neutrons
- Smaller and approximately equal electron and proton abundances
- Small muon component
Leptons in Neutron Stars

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- Degenerate neutrons
- Smaller and approximately equal electron and proton abundances
- Small muon component
**Leptons in Neutron Stars**

Lepton density of few % in NS core, lower in crust.
Fermi-momentum ~ constant in core.

![Graphs showing lepton density and Fermi-momentum as functions of radius](image)

**Crust-core boundary**
Neutron Star Equation of State


<table>
<thead>
<tr>
<th>EoS</th>
<th>BSk24-1</th>
<th>BSk24-2</th>
<th>BSk25-1</th>
<th>BSk25-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_c$ [g cm$^{-3}$]</td>
<td>$7.76 \times 10^{14}$</td>
<td>$2.00 \times 10^{15}$</td>
<td>$7.46 \times 10^{14}$</td>
<td>$2.10 \times 10^{15}$</td>
</tr>
<tr>
<td>$M$ [$M_\odot$]</td>
<td>1.500</td>
<td>2.271</td>
<td>1.400</td>
<td>2.222</td>
</tr>
<tr>
<td>$R$ [km]</td>
<td>12.593</td>
<td>11.310</td>
<td>12.387</td>
<td>11.166</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NS core</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{core}}$ [$M_\odot$]</td>
<td>1.483</td>
<td>2.266</td>
<td>1.383</td>
<td>2.217</td>
</tr>
<tr>
<td>$R_{\text{core}}$ [km]</td>
<td>11.643</td>
<td>10.977</td>
<td>11.389</td>
<td>10.834</td>
</tr>
<tr>
<td>$\langle Y_n(r) \rangle$</td>
<td>92.68 %</td>
<td>86.43 %</td>
<td>93.69 %</td>
<td>86.41 %</td>
</tr>
<tr>
<td>$\langle Y_p(r) \rangle$</td>
<td>7.32 %</td>
<td>13.57 %</td>
<td>6.31 %</td>
<td>13.59 %</td>
</tr>
<tr>
<td>$\langle Y_e(r) \rangle$</td>
<td>5.46 %</td>
<td>8.41 %</td>
<td>4.86 %</td>
<td>8.37 %</td>
</tr>
<tr>
<td>$\langle Y_\mu(r) \rangle$</td>
<td>1.85 %</td>
<td>5.16 %</td>
<td>1.44 %</td>
<td>5.22 %</td>
</tr>
<tr>
<td>$\langle p_{F,n}(r) \rangle$ [MeV]</td>
<td>372.56</td>
<td>426.11</td>
<td>374.80</td>
<td>428.72</td>
</tr>
<tr>
<td>$\langle p_{F,p}(r) \rangle$ [MeV]</td>
<td>160.23</td>
<td>230.36</td>
<td>152.79</td>
<td>230.57</td>
</tr>
<tr>
<td>$\langle p_{F,e}(r) \rangle$ [MeV]</td>
<td>145.64</td>
<td>197.67</td>
<td>140.31</td>
<td>197.98</td>
</tr>
<tr>
<td>$\langle p_{F,\mu}(r) \rangle$ [MeV]</td>
<td>50.38</td>
<td>89.58</td>
<td>45.66</td>
<td>90.01</td>
</tr>
</tbody>
</table>

Composition varies according to the neutron star EoS
Insensitive to details of NS Equation of State

NFB, Busoni & Robles arXiv:1904.09803
Neutron star limits on leptophilic DM

NFB, Busoni & Robles
arXiv:1904.09803

Electron scattering

Muon scattering
Leptophilic DM

NS sensitivity has the potential to greatly surpass electron-recoil direct detection experiments.
Improved capture calculations

Early treatments of the capture process used various simplifying assumptions.

Important physical effects include:

- Consistent treatment of NS structure
  - Radial profiles of EoS dependent parameters, and GR corrections by solving the Tolman-Oppenheimer-Volkov eqns.

- Gravitational focusing
  - DM trajectories bent toward the NS star

- Fully relativistic (Lorentz invariant) scattering calculation
  - Including the fermi momentum of the target particle

- Pauli blocking
  - Suppresses the scattering of low mass dark matter

- Neutron star opacity
  - Optical depth

- Multi-scattering effects
  - For large DM mass, probability that a collision results in capture is less than 1

Neutron star opacity

Improved capture calculations

Including Pauli blocking, multiscattering and opacity effects.
Summary & Conclusions

Dark matter capture in stars → cosmic laboratory to probe DM scattering interactions

- Completely different kinematic regime to direct detection experiments
  - Scattering of quasi-relativistic dark matter → no velocity or momentum suppressions
- Excellent sensitivity to DM-lepton scattering cross sections, with electron and especially muon scattering.
- Neutron Star kinetic heating sensitivity is better than current and forthcoming direct detection experiments, for both nuclear-recoil and electron-recoil scattering.
- Capture calculations have recently been refined and improved.