Capture of Dark Matter in Compact Stars

[2004.14888] + [2010.13257] + [2012.08918] + [2104.14367] + [2108.02525]

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1. Why Compact Stars?
   - Searching for DM collisions: Direct Detection
   - Searching for DM collisions: DM Capture in the Sun
   - Searching for DM collisions: DM Capture in Neutron Stars
   - Advantages of NS

2. From capture in the Sun to NS and WD
   - Key differences
   - Leptons: highlights and results
   - Baryons: highlights and results

3. Conclusions
   - Summary
Outline

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Searching for DM collisions

Direct Detection

Direct Detection

SI interaction give much stronger bounds than SD ones

M. Tanabashi et al. (PDG) 2018
Searching for DM collisions

Direct Detection

- Constraints depend strongly on interaction type
- Strong target dependence
- Some operators are suppressed by kinematics (momentum/velocity suppressed)
- Recoil energy is small, nonrelativistic kinematics
- Experimental detectors have recoil energy thresholds
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DM Capture in Stars

- DM can be captured and accumulate in Stars
- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates in centre of Sun
- Can potentially annihilate at the center
- At equilibrium, Capture=Annihilation
- Probes same observables as DD
Searching for DM collisions
DM Capture in the Sun

- SI: DD wins
- SD: DM in Sun wins
- DM in Sun requires some few more assumptions, like that it annihilates, and the annihilation channel

Some other ways to infer indirectly DM presence in the Sun: modified energy transport (see 1411.6626, 1703.07784)
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Very large density means very efficient capture

Whole DM flux can be captured already for \( \sigma \sim 10^{-45} \text{cm}^2 \)
Searching for DM collisions
DM Capture in NS

Possible observable signals

- NS to BH collapse (more likely for bosonic DM)
- Gravitational waves: DM increases tidal deformability (1803.03266)
- Kinetic + Annihilation heating (Bramante, Delgado and Martin 1704.01577)
NS temperature evolution

- NS have no known large heating sources
- Lose energy by neutrino and photon emission
- Neutrino dominates early stages of NS life, photon the late stages
- In absence of other heating sources, one expects $T \sim 1000K$ after 10 Myr and $T \sim 100K$ after 1 Gyr
- Kinetic heating: sets an equilibrium temperature of $T \sim 1700K$ if whole DM flux is captured
- Kin+Ann heating: equilibrium temperature is raised to $T \sim 2400K$
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Searching for DM collisions

Advantages of NS

- High capture probability
- DM particles accelerated to $O(0.5)c$ means no momentum/velocity suppression
- Cross section of $\sigma_{th} = 10^{-45} cm^2$ enough to reach maximum capture
- No threshold recoil energy
- Similar sensitivity for SI and SD interaction
- Similar sensitivity for momentum/velocity suppressed interactions comparing to unsuppressed ones
- Observation of old cold NS of temperature $T < T_{eq}$:

$$\sigma \leq \sigma_{th} \left( \frac{T}{T_{eq}} \right)^4$$ (1)
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DM Capture in the Sun formalism developed by Gould in the ’80
We adapted this formalism to NS

<table>
<thead>
<tr>
<th>Sun/Gould+Extensions</th>
<th>NS/Our</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian gravity</td>
<td>GR</td>
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<td>Sun structure from Standard Solar Model</td>
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<tr>
<td>Non-relativistic kinematics</td>
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<td>Atomic Nuclei Targets</td>
<td>Baryon and Lepton targets</td>
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<tr>
<td>Non-relativistic matrix element</td>
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<td>MB distribution for targets</td>
<td>FD distribution for targets</td>
</tr>
<tr>
<td>Capture probability ≠ 1</td>
<td>Capture probability = 1*</td>
</tr>
<tr>
<td>Star opacity</td>
<td>Star Opacity</td>
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<tr>
<td>MS requires MC approach</td>
<td>MS can be treated analytically</td>
</tr>
<tr>
<td>Targets have FF</td>
<td>Targets have FF</td>
</tr>
<tr>
<td>Fixed Target mass</td>
<td>Density-dependent Target mass</td>
</tr>
</tbody>
</table>

* for some masses
From capture in the Sun to NS and WD

Key differences

Our Papers

- 2004.14888 Basics of NS formalism, including GR, EOS, relativistic kinematics/matrix elements/interaction rates, Pauli Blocking effects, Star opacity, Multiple Scattering, for Neutron targets
- 2010.13257 Extension to lepton targets, interaction rates generalised for all Dim 6 EFT operators
- 2012.08918 Baryon Targets have structure and cannot be approximated by free gas
- 2108.02525 Full treatment of baryonic targets, including the above effects
- 2104.14367 Application of formalism to WD (electrons are fully degenerate)
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Very degenerate and relativistic target due to their low mass

Relativistic treatment is very important for these targets

Muon targets: also check next talk about them
From capture in the Sun to NS and WD
Leptons: highlights and results

G. Busoni (MPI for Nuclear Physics)
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Leptons: highlights and results
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- Baryons are composite particles
- Strong force mean field effects require treatment beyond free Fermi gas
From capture in the Sun to NS and WD
Baryons: highlights and results

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Summary

- Neutron Stars: cosmic laboratory to probe DM scattering interactions
- Completely different kinematic regime to direct detection experiments
- High energy scattering washes away momentum suppression
- Higher reach on inelastic scattering [1807.02840]
- Can probe a very large mass range
- Very sensitive for all interactions, including momentum-suppressed and leptons
- Current coolest NS of $O(10^4)K$
- Prospects for observation in the coming decade