Capture of Dark Matter in Compact Stars

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

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Lomonosov 2021, 25 Aug 2021

Outline

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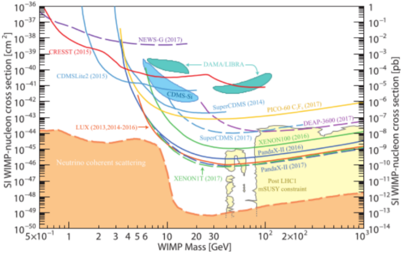
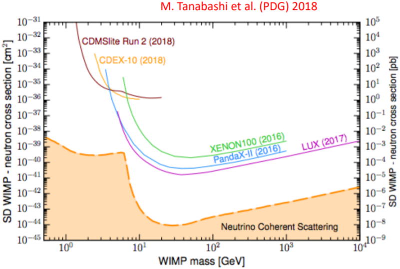
Searching for DM collisions
Direct Detection

Direct Detection





SI interaction give much stronger bounds that SD ones

Searching for DM collisions

Direct Detection

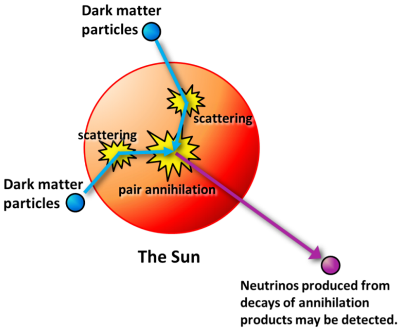
- Constraints depend strongly on interaction type
- Strong target dependence
- Some operators are suppressed by kinematics (momentum/velocity suppressed)
- Recoil energy is small, nonrelativistic kinematics
- Experimental detectors have recoil energy thresholds

Outline

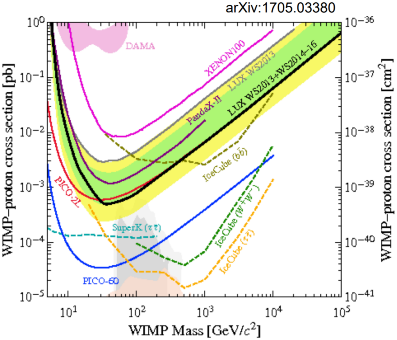
1. Why Compact Stars?
   - Searching for DM collisions: Direct Detection
   - Searching for DM collisions: DM Capture in the Sun
   - Searching for DM collisions: DM Capture in Neutron Stars
   - Advantages of NS
2. From capture in the Sun to NS and WD
   - Key differences
   - Leptons: highlights and results
   - Baryons: highlights and results
3. Conclusions
   - Summary

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



- 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 $\sigma \sim 10^{-45} cm^2$

Possible observable signals

- NS to BH collapse (more likely for bosonic DM)
- Gravitational waves: DM increases tidal deformability (1803.03266)
- Kinetic Heating (M. Baryakhtar et al. PRL 119, 131801 (2017) arXiv:1704.01577)
- Kinetic + Annihilation heating (Bramante, Delgardo and Martin 1704.01577)

NS temperature evolution

- NS have no know 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 $10Myr$ and $T \sim 100K$ after $1Gyr$
- 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 $\mathcal{O}(0.5)c$ 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 $T < T_{eq}$:

$$\sigma \leq \sigma_{th} \left(\frac{T}{T_{eq}} \right)^4 \tag{1}$$

Outline

From capture in the Sun to NS and WD

Key differences

- DM Capture in the Sun formalism developed by Gould in the '80
- We adapted this formalism to NS

Sun/Gould+Extensions	NS/Our
Newtonian gravity	GR
Sun structure from Standard Solar Model	NS structure from EOS
Non-relativistic kinematics	Relativistic kinematics
Atomic Nuclei Targets	Baryon and Lepton targets
Non-relativistic matrix element	Relativistic matrix element
MB distribution for targets	FD distribution for targets
Capture probability $\neq 1$	Capture probability $= 1^*$
Star opacity	Star Opacity
MS requires MC approach	MS can be treated analytically
Targets have FF	Targets have FF
Fixed Target mass	Density-dependent Target mass

* for some masses

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)

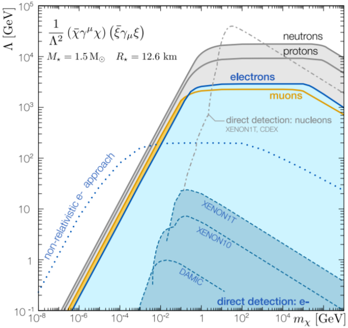
Outline

From capture in the Sun to NS and WD

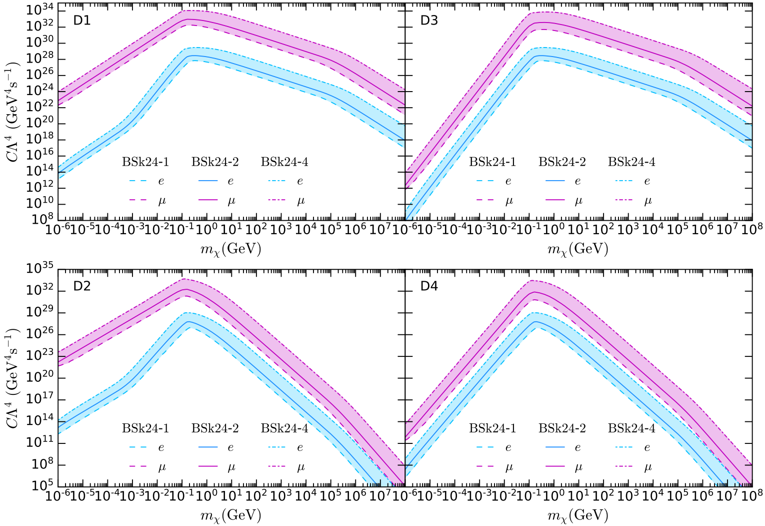
Leptons: highlights and results

- 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

1911.13293

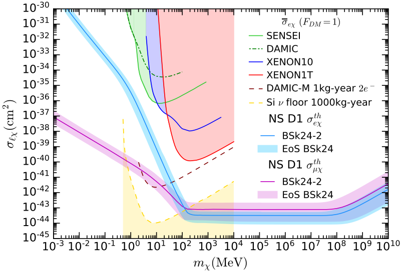


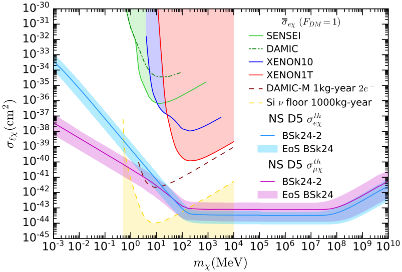
From capture in the Sun to NS and WD
Leptons: highlights and results

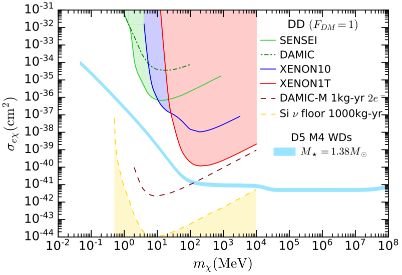


From capture in the Sun to NS and WD

Leptons: highlights and results

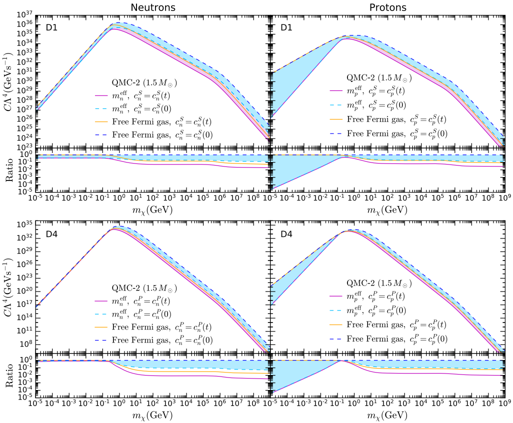






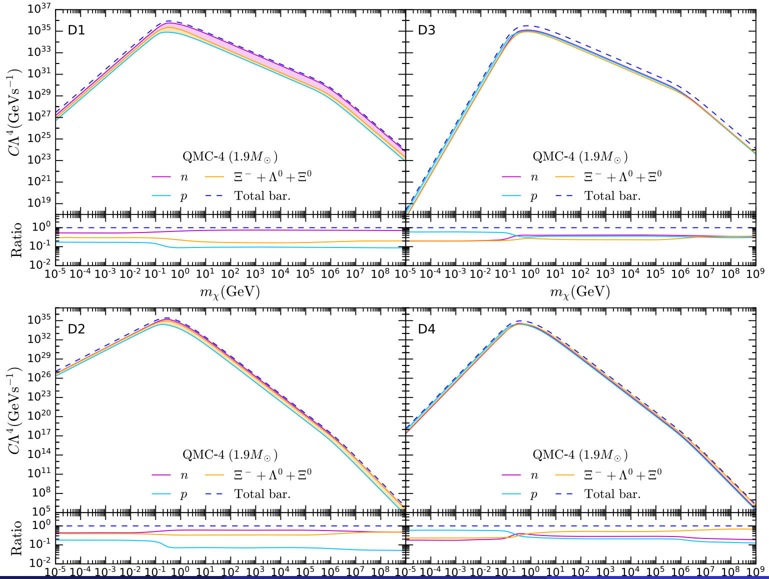
Outline

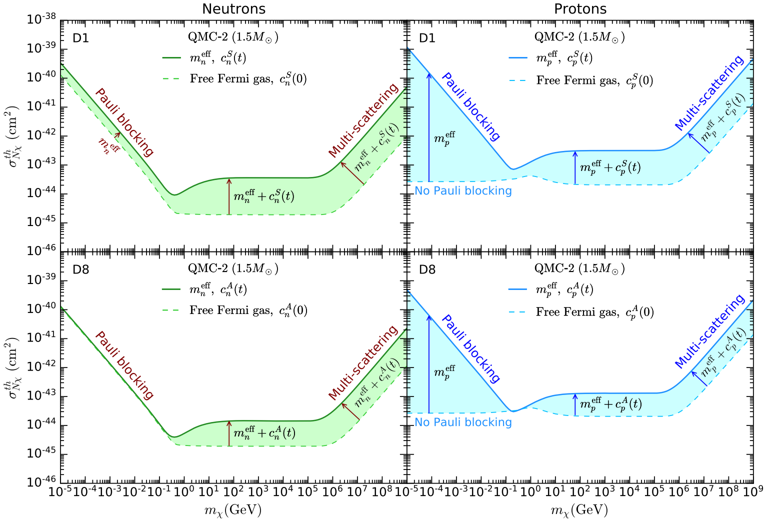
- Baryons are composite particles
- Strong force mean field effects require treatment beyond free Fermi gas



From capture in the Sun to NS and WD

Baryons: highlights and results

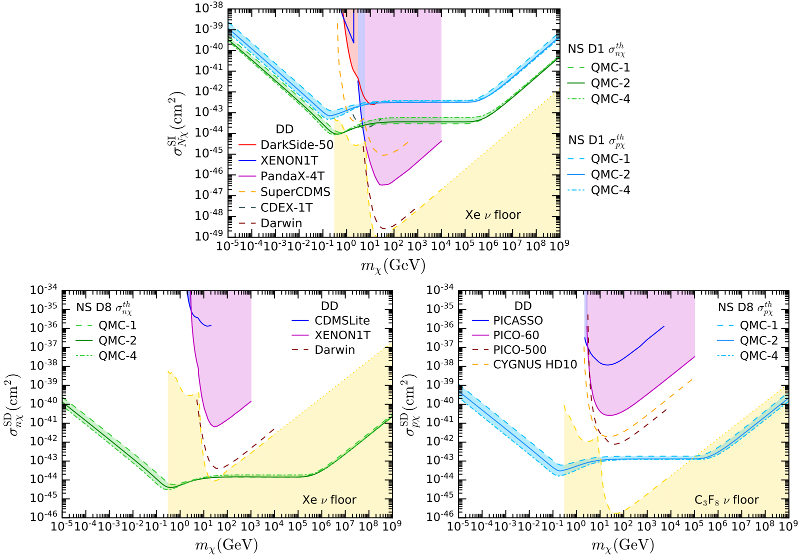




Neutrons
Protons
D1
QMC-2 ($1.5M_\odot$)
$m_n^{\rm eff}$, $c_n^S(t)$
Free Fermi gas, $c_n^S(0)$
Pauli blocking
$m_n^{\rm eff}$
$m_n^{\rm eff} + c_n^S(t)$
Multi-scattering
$m_p^{\rm eff}$, $c_p^S(t)$
Free Fermi gas, $c_p^S(0)$
$m_p^{\rm eff}$
$m_p^{\rm eff} + c_p^S(t)$
No Pauli blocking
D8
$m_n^{\rm eff}$, $c_n^A(t)$
Free Fermi gas, $c_n^A(0)$
$m_n^{\rm eff} + c_n^A(t)$
$m_p^{\rm eff}$, $c_p^A(t)$
Free Fermi gas, $c_p^A(0)$
$m_p^{\rm eff} + c_p^A(t)$
$\sigma_{N\chi}^{th}$ (cm^2)
m_χ(GeV)

From capture in the Sun to NS and WD

Baryons: highlights and results



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Conclusions

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 $\mathcal{O}(10^4)K$
- Prospects for observation in the coming decade