Capture of Dark Matter in Compact Stars

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

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Outline

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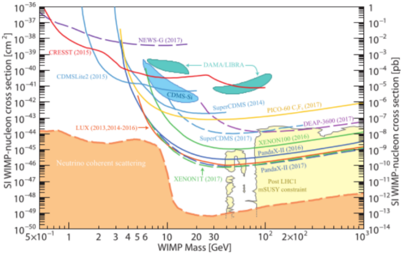
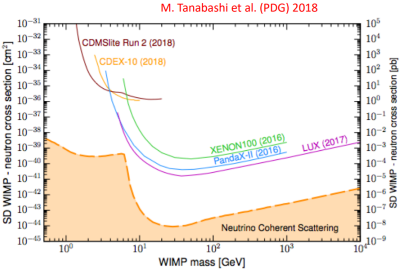
Direct Detection





SI interaction give much stronger bounds that SD ones

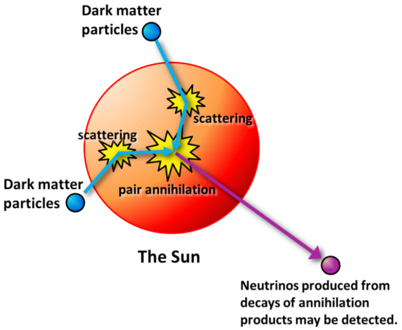
Searching for DM collisions
Direct Detection

- 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

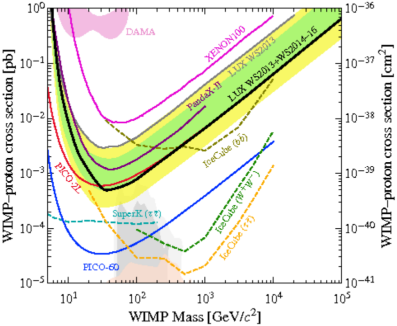
DM Capture in Stars

- 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

arXiv:1705.03380



Some other ways to infer indirectly DM presence in the Sun: modified energy transport (see 1411.6626 , 1703.07784)

Outline

- 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 a maximum equilibrium temperature of $T_{eq,th} \sim 1700K$ if whole DM flux is captured
- Kin+Ann heating: maximum equilibrium temperature is raised to $T_{eq,th} \sim 2400K$

Equilibrium Temperature

$$C_{geom} = \frac{\pi R^2 (1 - B(R))}{v_s B(R)} \frac{\rho_\chi}{m_\chi} Erf\left(\sqrt{\frac{3}{2}} \frac{v_s}{v_d}\right) \tag{1}$$

$$C \langle \delta E_R \rangle = \sigma_{SB} T_{eq}^4 \pi R^2 \tag{2}$$

T_{eq} independent of star radius for geometric limit, $T_{eq}^4 \propto \rho_\chi$. Can define threshold cross section:

$$C = C_{geom} \frac{\sigma}{\sigma_{th}}, \quad T_{eq} \propto \left(\frac{\sigma}{\sigma_{th}}\right)^{1/4} \tag{3}$$

Outline

Searching for DM collisions

Advantages of NS

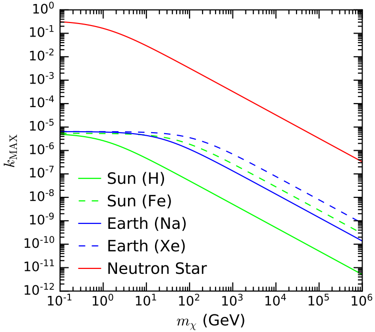
- High capture probability
- DM particles accelerated to $\mathcal{O}(0.5)c$ means no momentum/velocity suppression
- Cross section of $\sigma_{th} = 10^{-45} cm^2$ enough to reach maximum capture
- No threshold recoil energy
- Similar sensitivity for SI and SD interaction
- Similar sensitivity for momentum/velocity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

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

Searching for DM collisions
Advantages of NS

Example: Inelastic DM

- The high incoming energy allows to probe larger mass splittings
- For large mass, $\delta < 330MeV$
- For small mass, $\delta < 330MeV \dfrac{m_\chi}{GeV}$
- This is 3-4 orders of magnitude more than for Sun or Earth
- Absence of energy threshold give further advantage comparing to DD

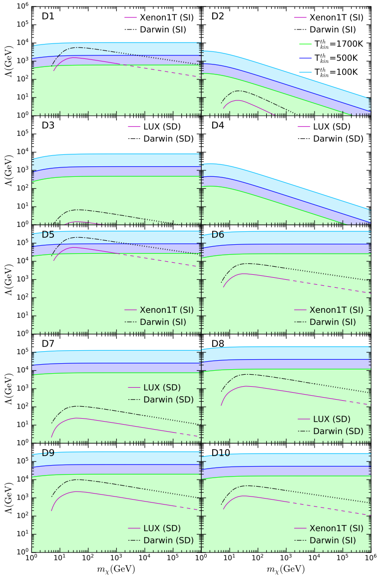


Searching for DM collisions

Advantages of NS

Example: Momentum-suppressed Operators

- The high incoming energy makes all types of operators giving similar results at large energies
- This is opposed to DD, where there is a hierarchy due to non-relativistic suppression

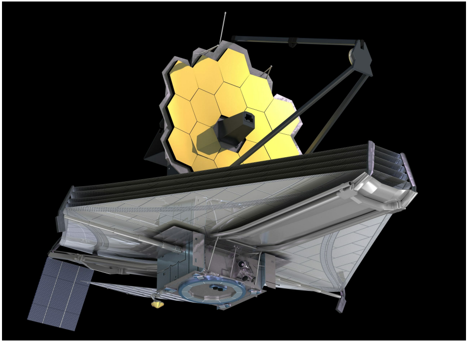


Outline

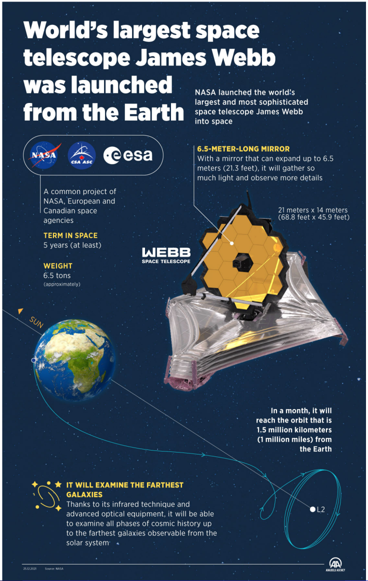
1. Why Compact Stars?
   - Searching for DM collisions: Direct Detection
   - Searching for DM collisions: DM Capture in the Sun
   - Searching for DM collisions: DM Capture in Neutron Stars
   - Advantages of NS
   - Detection prospects
2. From capture in the Sun to NS and WD
   - Key differences
3.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

James Webb Telescope

- Lauched 25 December 2021
- Situated at L2
- Primary mirror: $6.5m$
- Operating wavelengths: $0.6 - 28.5\mu m$

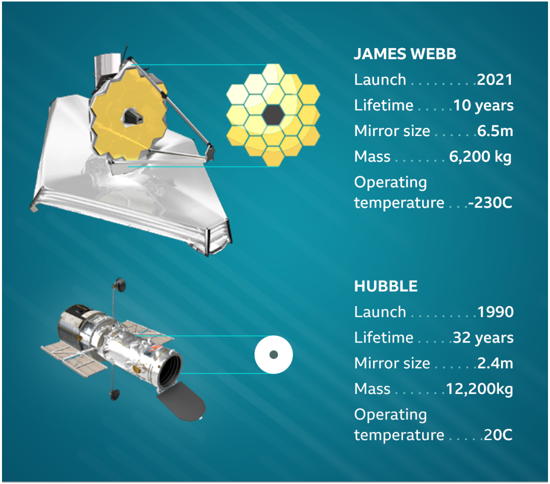


Searching for DM collisions
Detection prospects



Searching for DM collisions
Detection prospects

James Webb and Hubble compared

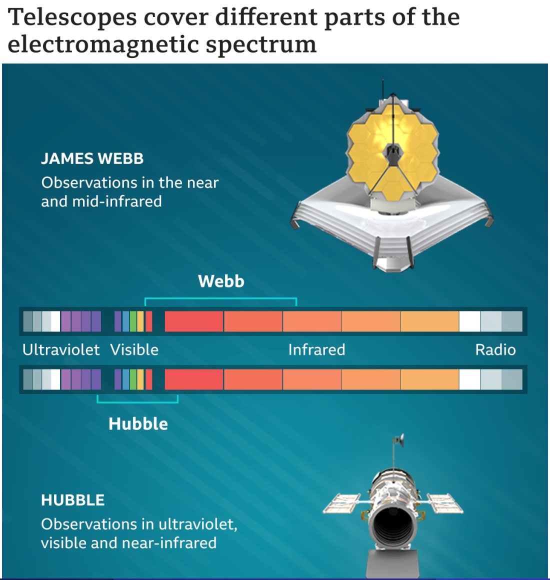


Source: Nasa

BBC

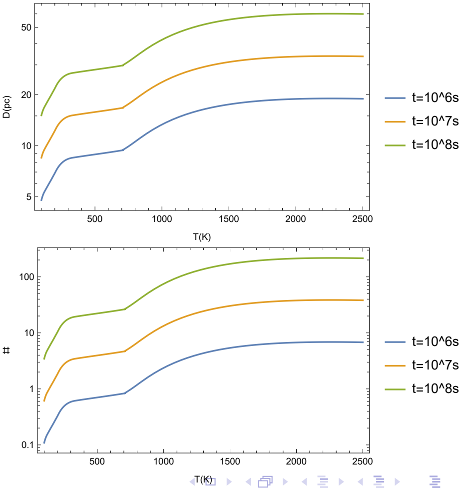
Searching for DM collisions

Detection prospects



Detection prospects

- Warning: rough estimates
- Cold NS very faint: need large observation time
- Need $t_{obs} \gtrsim 10^5 s \sim 1d$
- $t_{obs} \sim \mathcal{O}(10^6 s), \mathcal{O}(10^7 s)$ should allow detection of some NS of $T \gtrsim 1000K$
- Coldest NS: PSR J2144–3933, $T < 42000K$



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

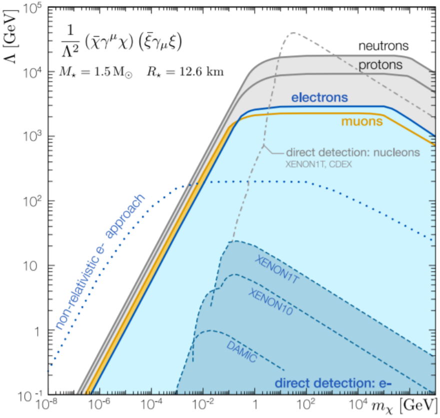
Sun/Gould+Extensions	NS/Our
Newtonian gravity	GR
Sun structure from Standard Solar Model	NS structure from EOS
Non-relativistic kinematics	Relativistic kinematics
Atomic Nuclei Targets	Baryon and Lepton targets
Non-relativistic matrix element	Relativistic matrix element
MB distribution for targets	FD 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

Outline

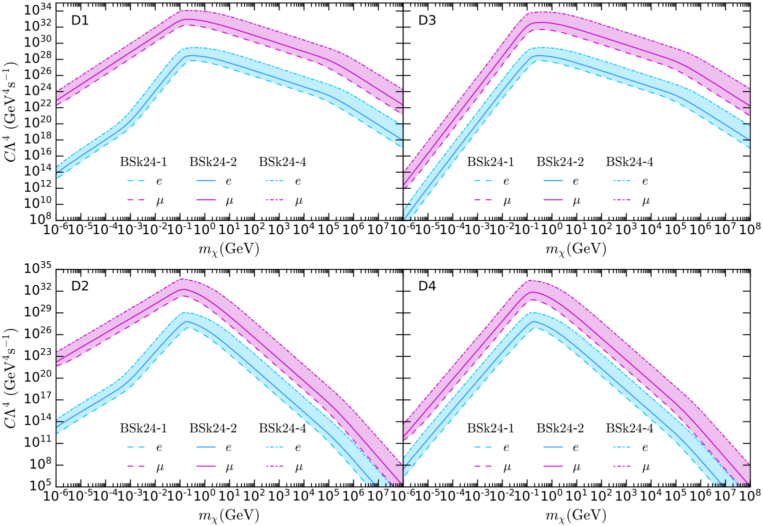
- Very degenerate and relativistic target due to their low mass
- Relativistic treatment is very important for these targets

1911.13293



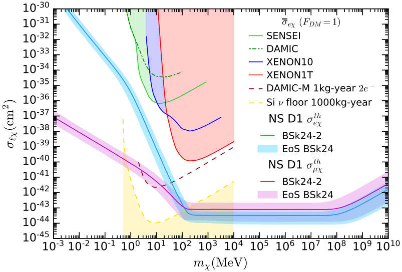
From capture in the Sun to NS and WD

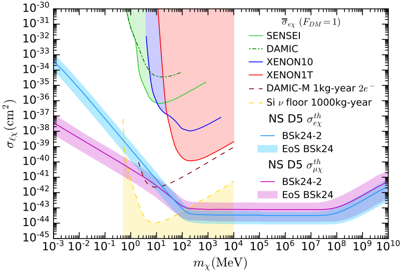
Leptons: highlights and results

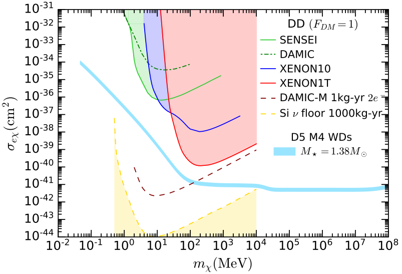


From capture in the Sun to NS and WD

Leptons: highlights and results





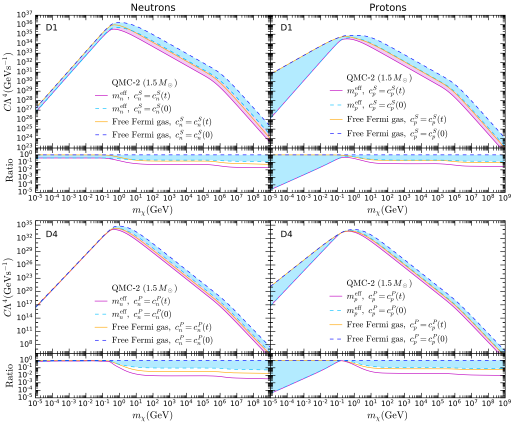


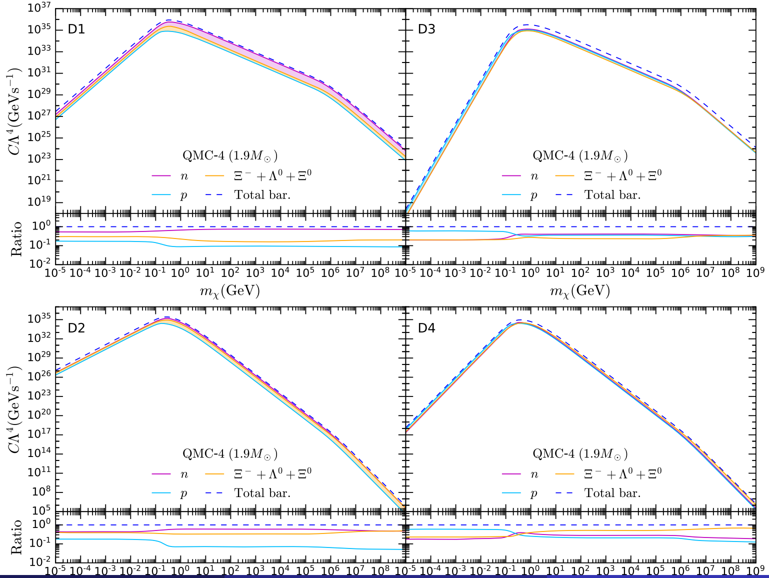
Outline

From capture in the Sun to NS and WD

Baryons: highlights and results

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

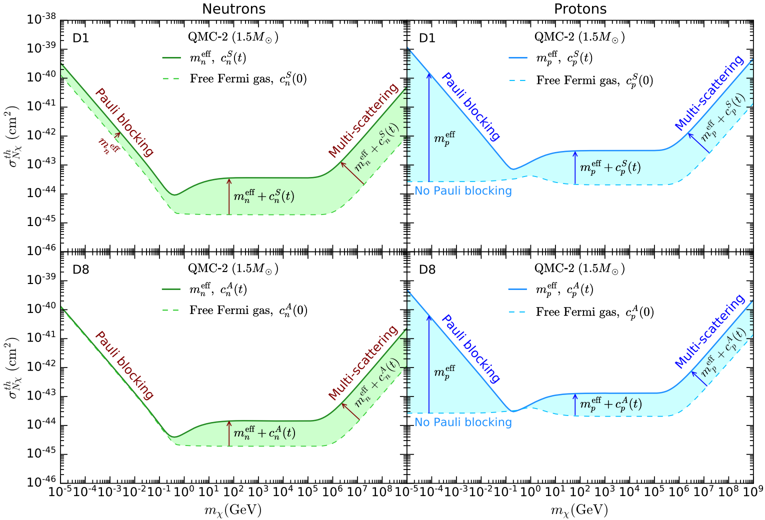




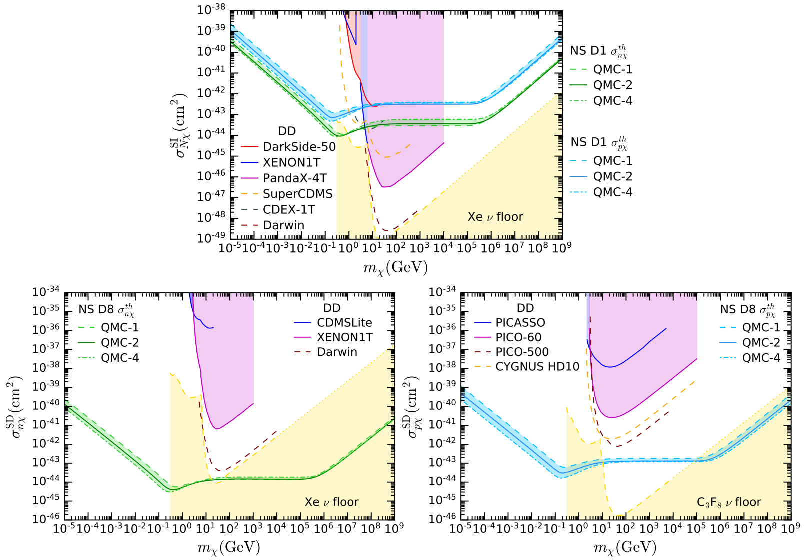
D1
D3
D2
D4
QMC-4 ($1.9M_\odot$)
n
p
$\Xi^- + \Lambda^0 + \Xi^0$
Total bar.
$C\Lambda^4(\mathrm{GeV s^{-1}})$
Ratio
$m_\chi(\mathrm{GeV})$

From capture in the Sun to NS and WD

Baryons: highlights and results



Baryons: highlights and results



Outline

- 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