THE UNIVERSITY OF MELBOURNE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Improving Dark Matter Capture in Neutron Stars

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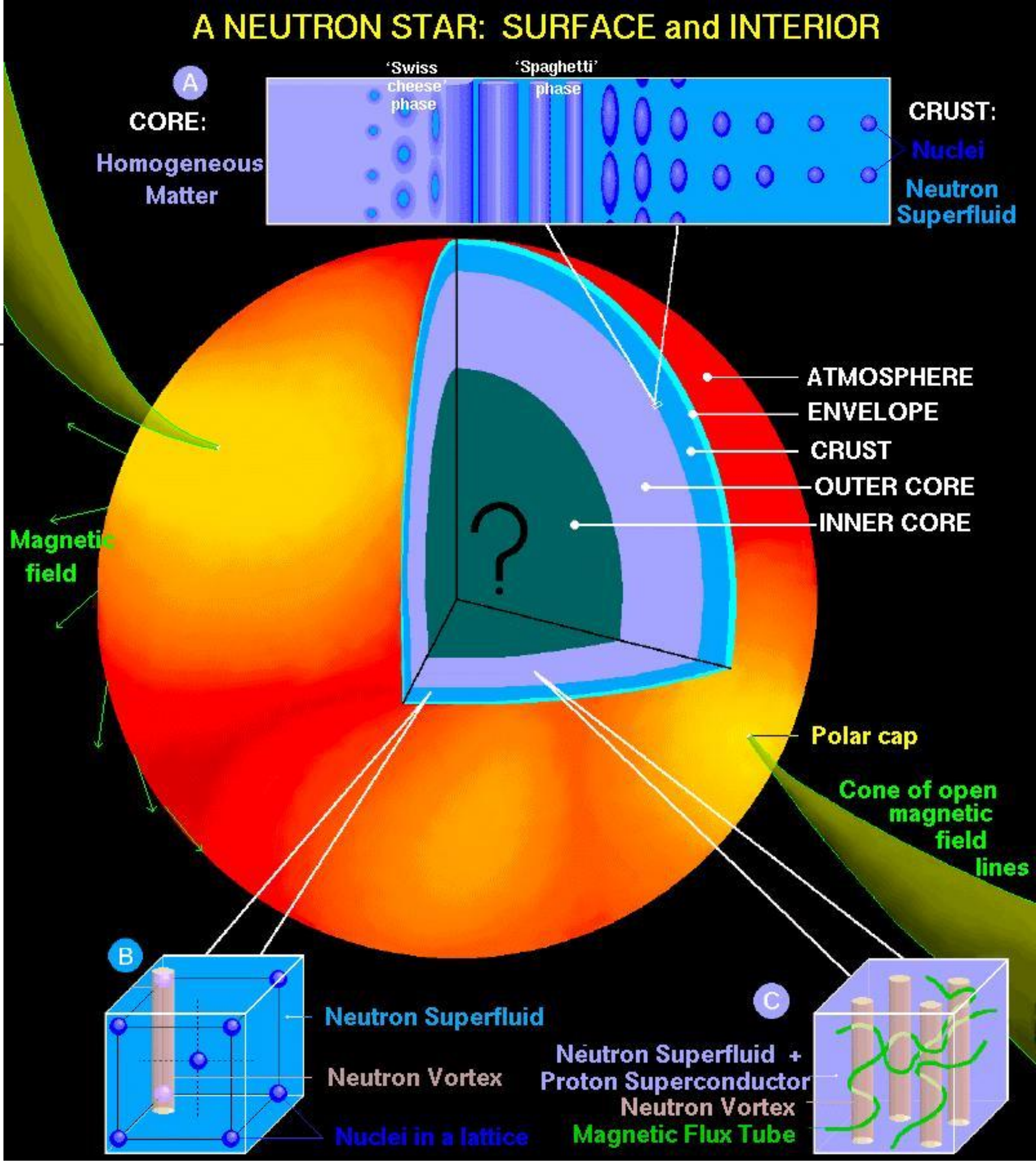
Neutron Stars as Probes for Dark Matter

- Neutron Stars are highly efficient at capturing Dark Matter due to
  - Extreme densities ~ 0.3 fm^{-3}
  - Velocities boosted to $v_\chi \sim 0.3c - 0.7c$
- Treat spin-dependent/independent interactions agnostically
- Effectively wipes out velocity/momentum suppression in interactions
- Observations of old, cold Neutron Star can be used to set potential bounds

(Baryakhtar et.al. 1704.01577, Raj et.al. 1707.09442)

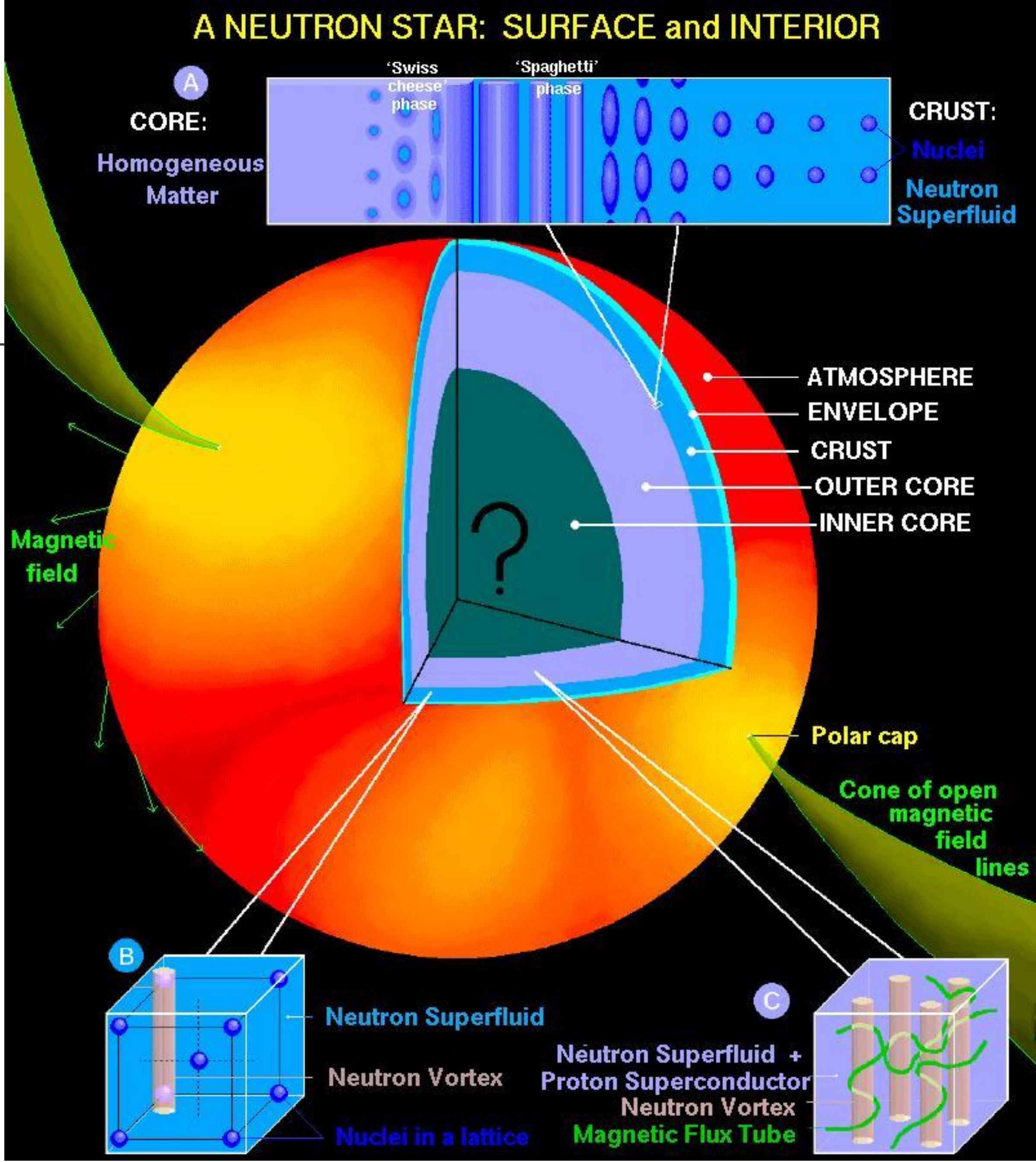
Neutron Stars

- Created in Type-II Supernova of massive stars, $> 8\ M_\odot$
- Masses $\sim 1\ - 2.4 M_\odot$
- Radii a few km
- Mass-Radius relation has large uncertainties



Neutron Stars

- Composition:
  - Crust:
    - Heavy nuclei in lattice and “pasta” phases
- Outer Core:
  - Primarily superfluid neutrons
  - Protons, electrons and muons appear
- Inner Core
  - Exact composition of inner core unknown (possibly exotic phases of matter)



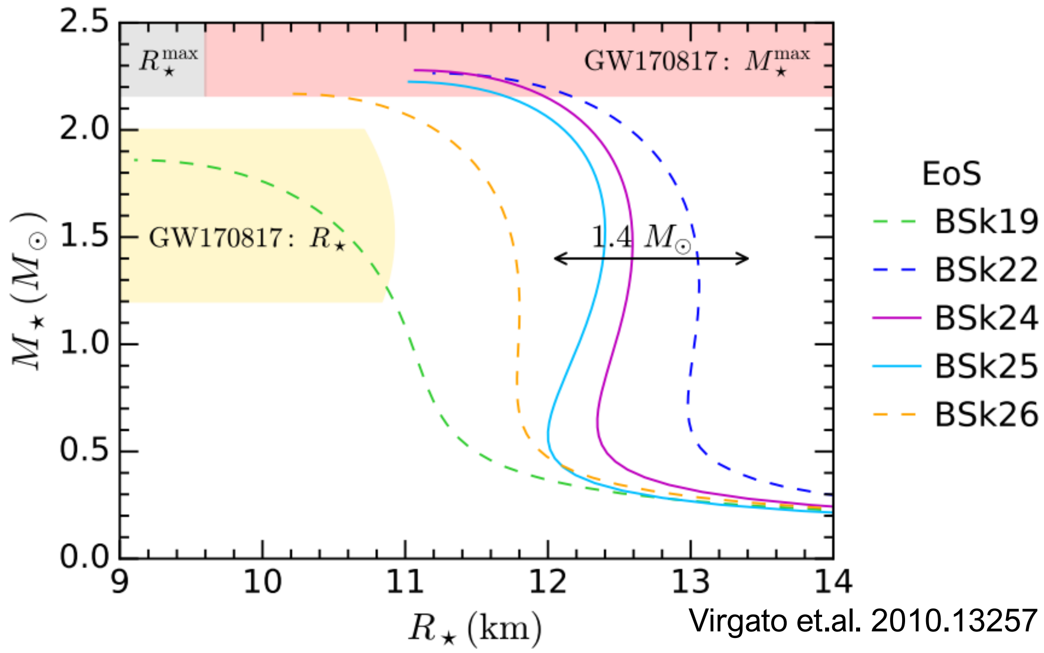
Neutron Star Model: $Npe\mu$ matter

- Unified Equation of State for cold, non-accreting matter using Brussels-Montreal functionals (Pearson el.al. 1903.04981)
  - Gives consistent description from surface to core
  - Authors provide helpful analytic fits

EoS config:	**BSk24-1**	**BSk24-2**	**BSk24-3**	**BSk24-4**
$\rho_c\ (g\ cm^{-3})$	5.95×10^{14}	7.76×10^{14}	1.04×10^{15}	1.42×10^{15}
$n_b^c\ (fm^{-3})$	0.330	0.430	0.594	0.670
$M_\star\ (M_\odot)$	1.000	1.500	1.900	2.160
$R_\star\ (km)$	12.215	12.593	12.419	11.965
$B(R_\star)$	0.763	0.648	0.548	0.467

$$d\tau^2 = B(r)dt^2 - \cdots$$

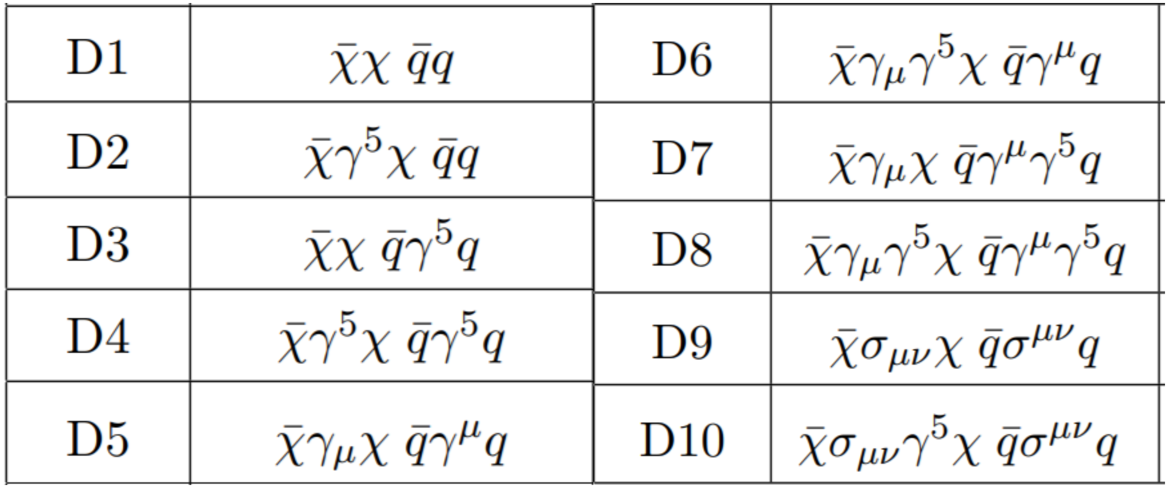
Benchmark Config.



Virgato et.al. 2010.13257

Effective Field Theory for Dark Matter

- Focus on Dimention-6 EFT operators for Dirac fermion DM



D1	$\bar{\chi}\chi\ \bar{q}q$	D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu q$
D2	$\bar{\chi}\gamma^5\chi\ \bar{q}q$	D7	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu\gamma^5 q$
D3	$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	D8	$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$
D4	$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	D9	$\bar{\chi}\sigma_{\mu\nu}\chi\ \bar{q}\sigma^{\mu\nu}q$
D5	$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$	D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{q}\sigma^{\mu\nu}q$

Dark Matter Capture Process

- DM capture in celestial bodies well established

(Press and Spergel ’85, Griest and Seckel ’86, Gould ’87, Goldman et.al. ’89, Gould ‘89)

  - Including Multiple Scattering
    (Bramante et.al. 1703.04043 , Dasgupta et.al. 1906.04204)

- NSs require:
  - Relativistic kinematics (targets and DM)
  - Correct treatment of degenerate targets

    (Garani et.al 1812.08773)

- Consider NS in Local neighbourhood:
  - Maxwell-Boltzmann velocity dispersion: $v_d \sim 270\ km/s$
  - NS relative velocity to DM halo: $v_\star \sim 230\ km/s$

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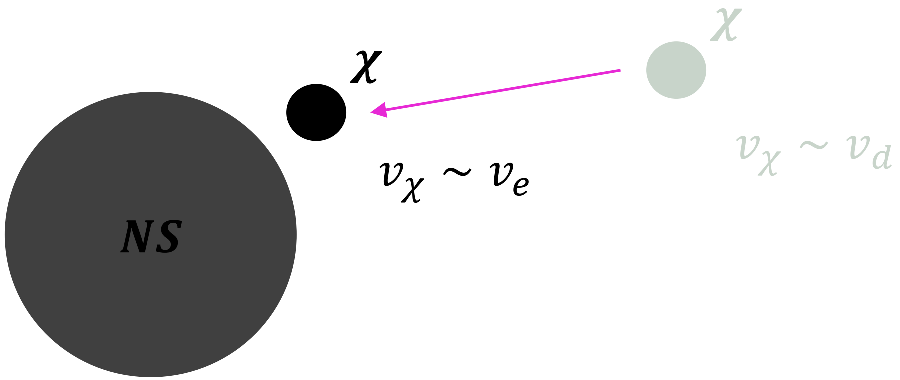

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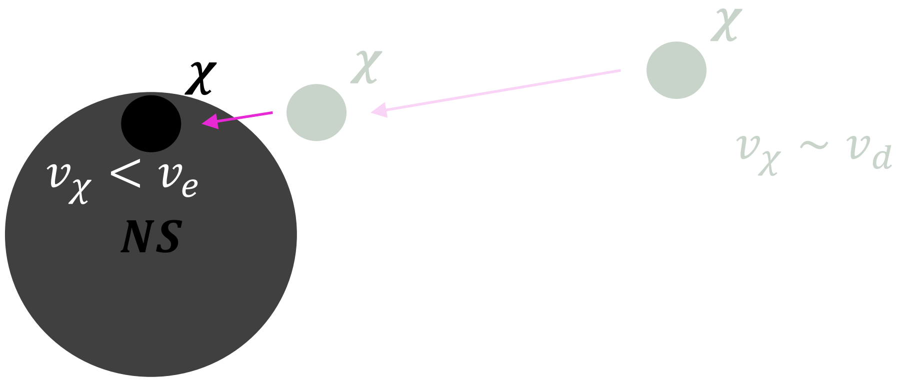


Capture Rate

- Total capture rate is then

DM flux

$$C = \frac{4\pi}{v_\star}\frac{\rho_\chi}{m_\chi} Erf\left(\sqrt{\frac{3}{2}}\frac{v_\star}{v_d}\right)\int_0^{R_\star} dr\, r^2 \frac{\sqrt{1-B(r)}}{B(r)}\Omega^-(r)$$

Gravitational Focusing

Simplifying functions:

$$\beta(s) = s - \left(m_\chi^2 + m_n^2\right)$$

$$\gamma(s) = \sqrt{\beta^2(s) - 4m_n^2 m_\chi^2}$$

Interaction Rate:

$$\Omega^-(r) = \int dt\, dE_n\, ds\, \zeta(r) \frac{d\sigma}{dcos\theta_{cm}} \frac{E_n}{2\pi^2 m_\chi} \sqrt{\frac{B(r)}{1-B(r)}}\frac{s}{\beta(s)\gamma(s)} f_{FD}(E_n)(1 - f_{FD}(E_n'))$$

Number density correction: $\frac{n_n(r)}{n_{free}}$

(Garani et al. 1812.08773)

Differential cross section

Relativistic kinematics

Pauli Blocking

Virgato et al. 2004.14888

Geometric Limit

- Maximum rate of capture given by geometric limit

$$C_{geom} \sim 3.84 \times 10^{25} s^{-1} \left(\frac{1GeV}{m_\chi}\right)$$

- Corresponds to cross sections above a threshold value

$$\sigma_{th} \sim \begin{cases} \sigma_{ref} \dfrac{GeV}{m_\chi}, & m_\chi < 1GeV \\ \sigma_{ref}, & 1\ GeV < m_\chi < 10^6\ GeV \\ \sigma_{ref} \dfrac{m_\chi}{10^6 GeV}, & 10^6\ GeV < m_\chi \end{cases}$$

Pauli Blocking

Intermediate

Multi-scatter

$$\sigma_{ref} \sim 10^{-45} cm^2$$

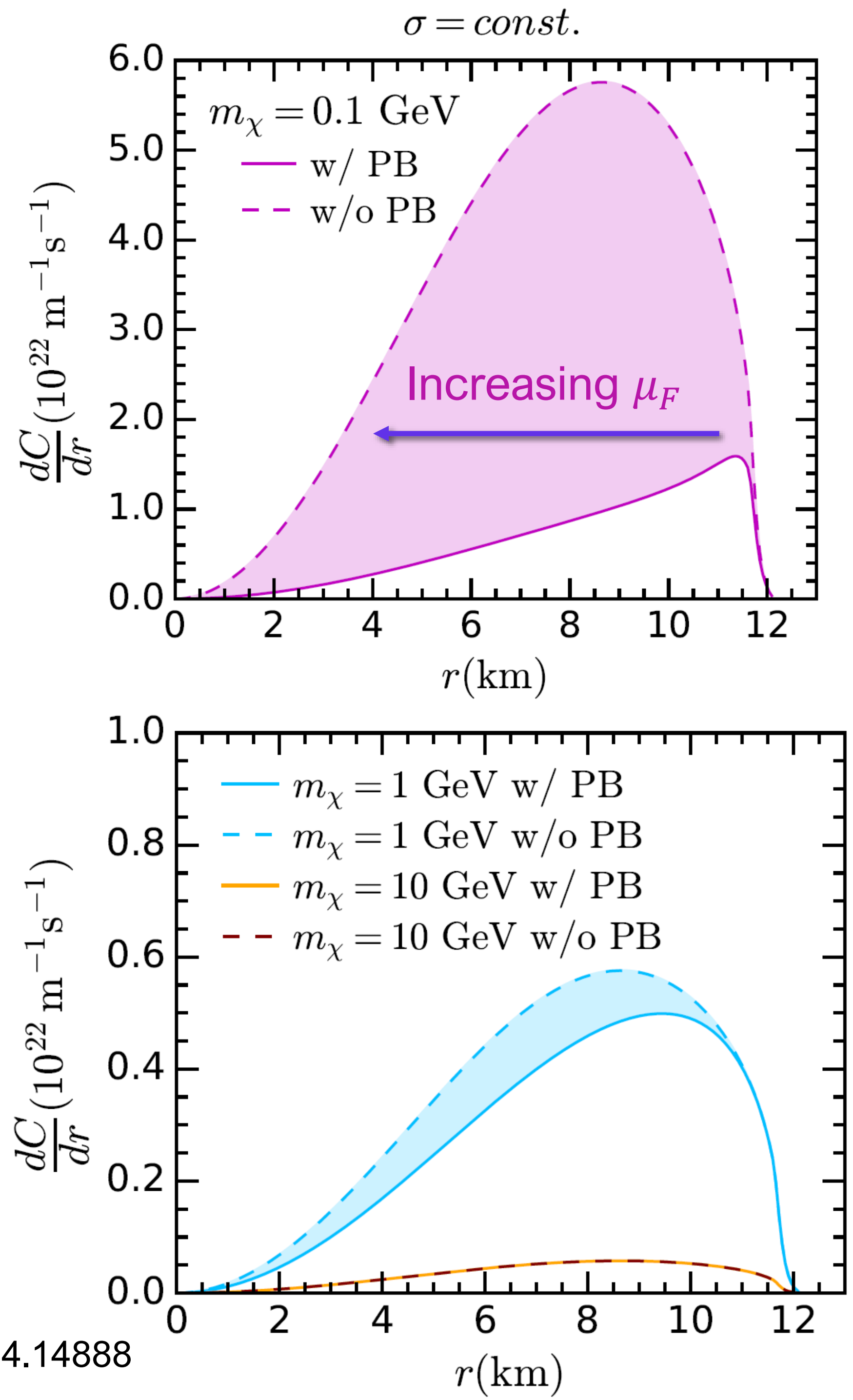
(Raj et.al. 1707.09442)

Pauli Blocking ($m_\chi < 1\ GeV$)

- Require momentum transfers

  $p_{final} = p_{initial} + q > p_F$

- Only targets close to Fermi-Surface interact
- Effect seen in radial profile of differential capture rate

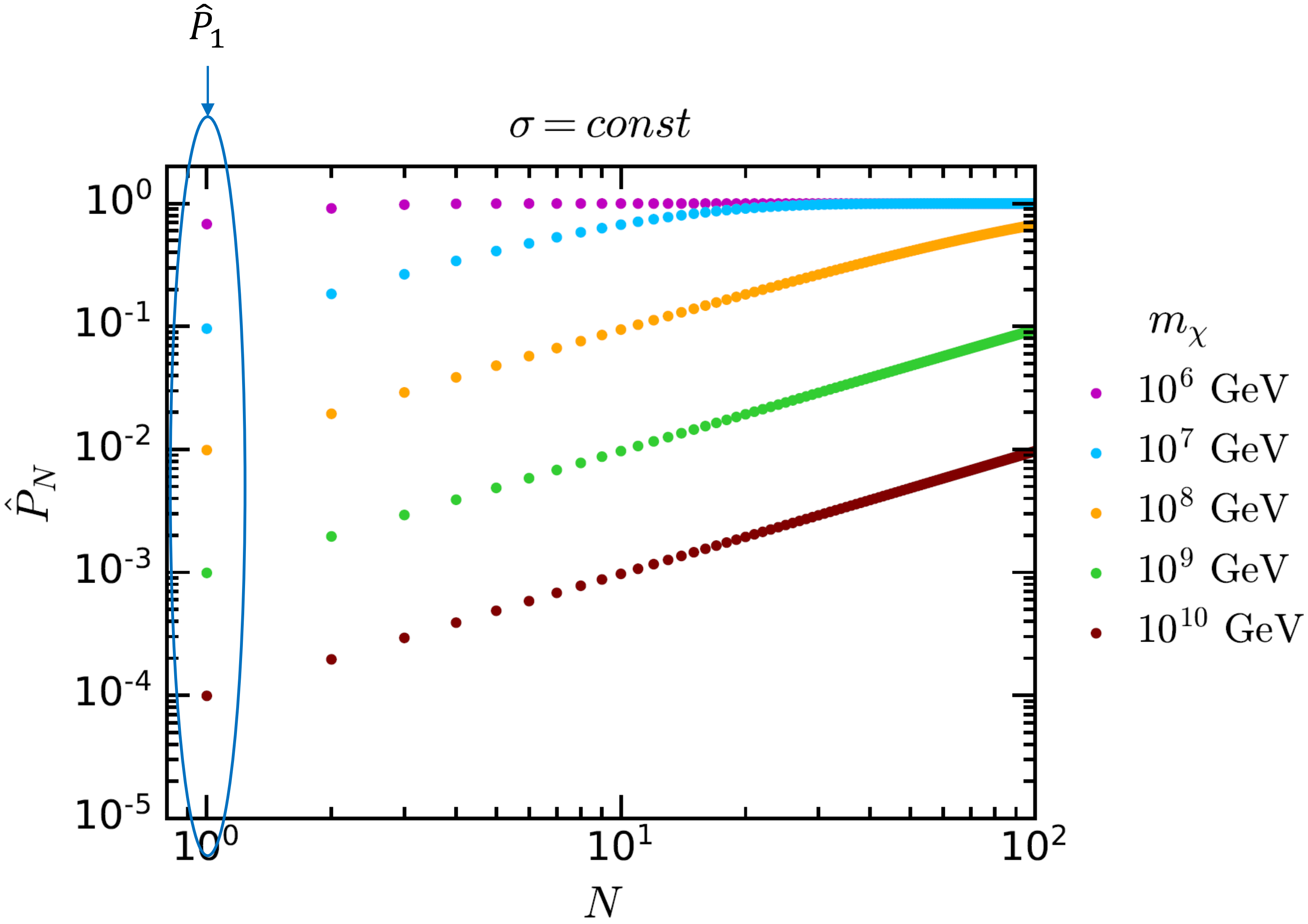


Virgato et al. 2004.14888

Multiple Scattering ($m_\chi > 10^6\ GeV$)

- Min. energy loss required not achieved in single scatter
- Include factor $\hat{P}_1$ in master equation
- Obtained using energy loss PDF from interaction rates

$$\xi(q_0) = \frac{1}{\Omega^-}\frac{d\Omega^-}{dq_0}$$



Cumulative probability of capture after *N* interactions

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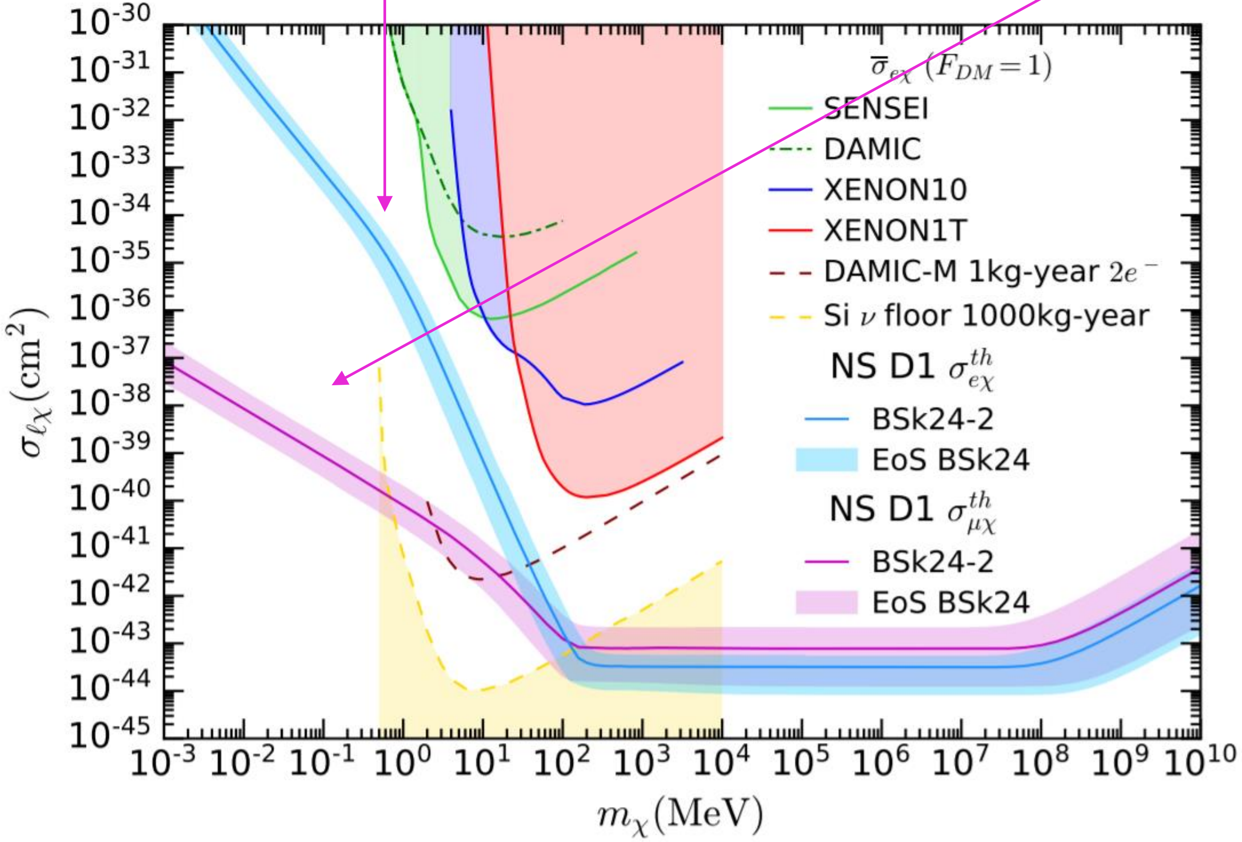
Lepton Threshold Cross Sections

Leading order term in matrix element changes due to small electron mass

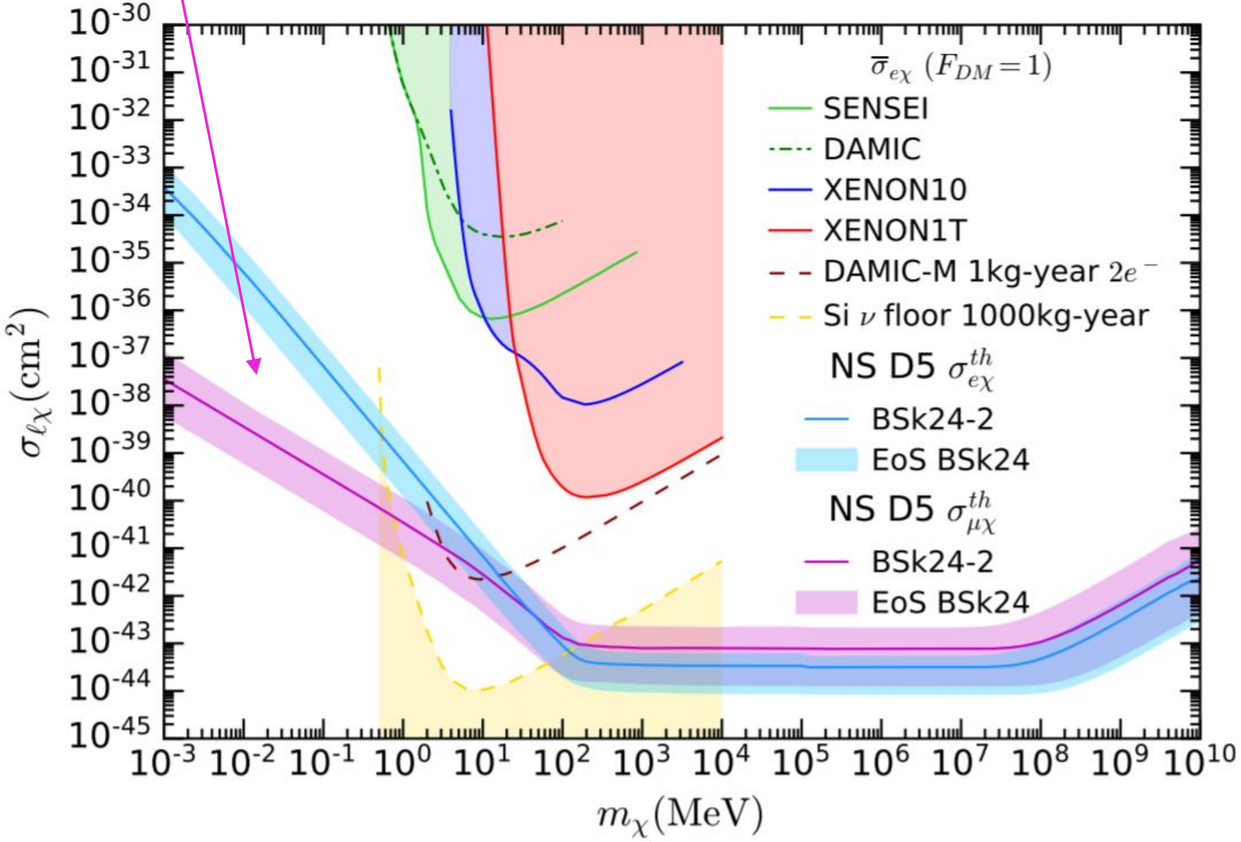
Muons beat electrons despite lower abundance:

Less Pauli blocked

$D1: \propto m_\ell^2 \,\overline{\chi}\chi\overline{N}N$



$D5: \propto \overline{\chi}\gamma_\mu\chi\overline{N}\gamma^\mu N$



Nucleon Form Factors and Strong Interactions

- Nucleon form factors are momentum dependent:

$$c_N^i \to \frac{c_N^i}{\left(1-\frac{t}{Q_0^2}\right)^2}$$

$$Q_0 \sim 0.9\ GeV$$

- Nucleons are strongly interacting:

$$m_N \to m_N^{eff}$$

$$\zeta(r) \to 1$$

- Note: QMC EoS used here, not BSk-24
(Motta et.al. 1904.03794)

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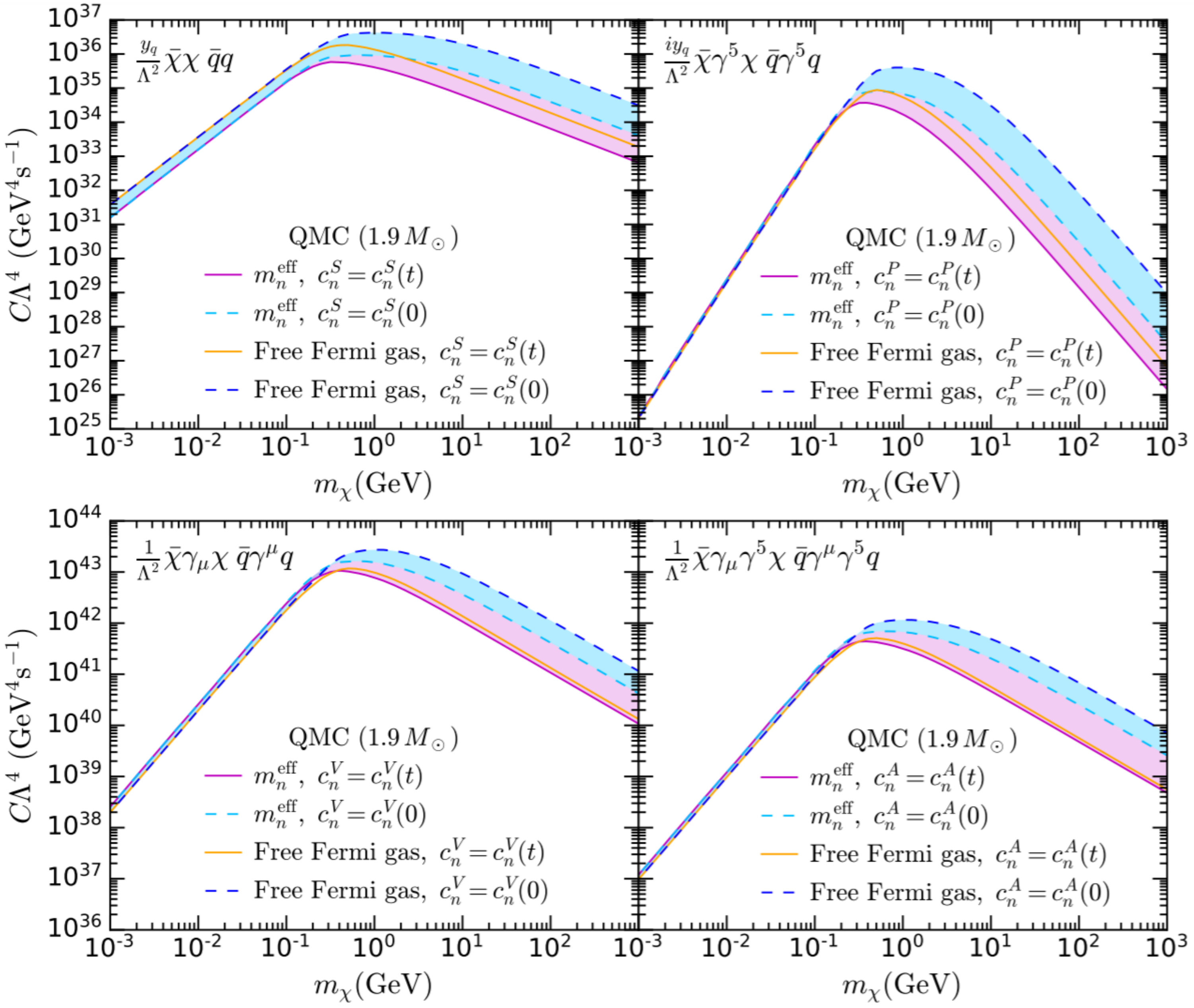

Virgato et al. 2012.08918

Summary

- Neutron Stars offer unique laboratory to study Dark Matter
- The capture rate is a key ingredient
- We consistently incorporate important pieces of physics including:
  - Relativistic Kinematics
  - Neutron Star structure
  - Pauli Blocking
  - Multiple Scattering
  - Strong Interactions

Thank you

Questions?

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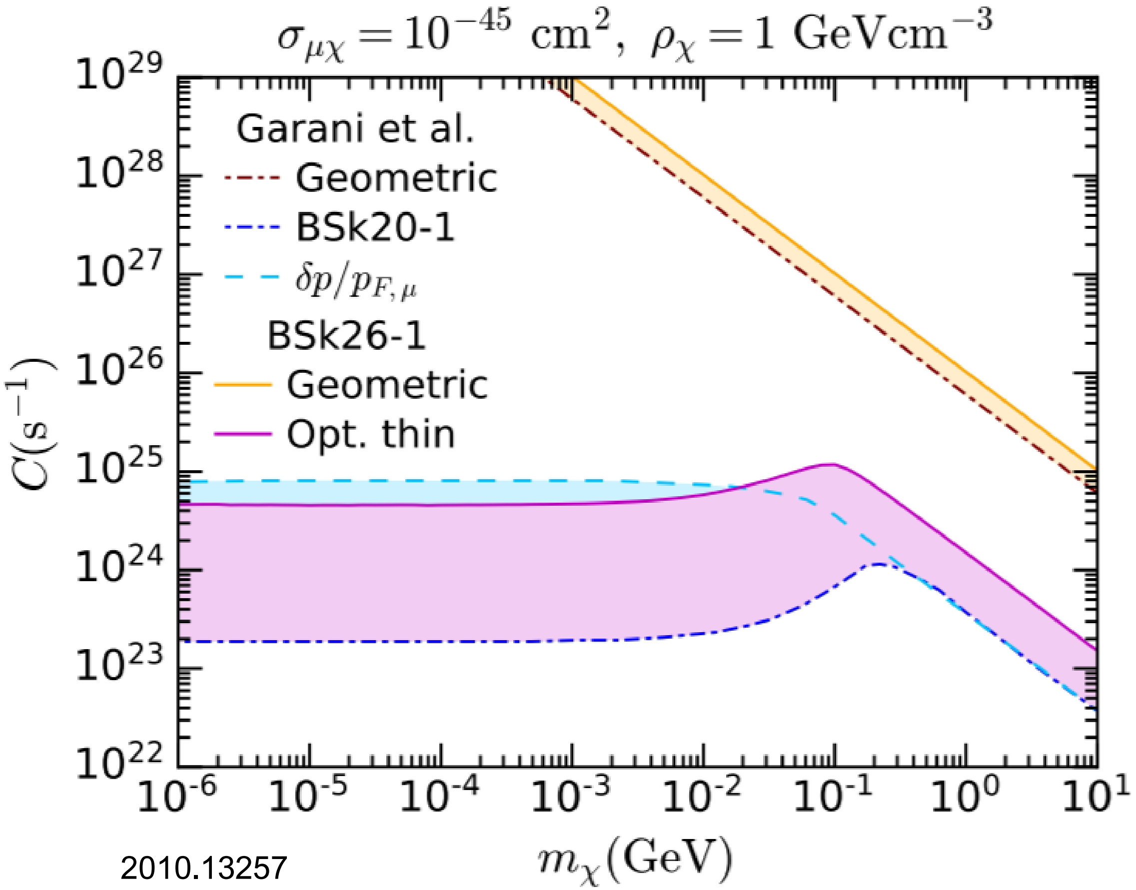
Backup



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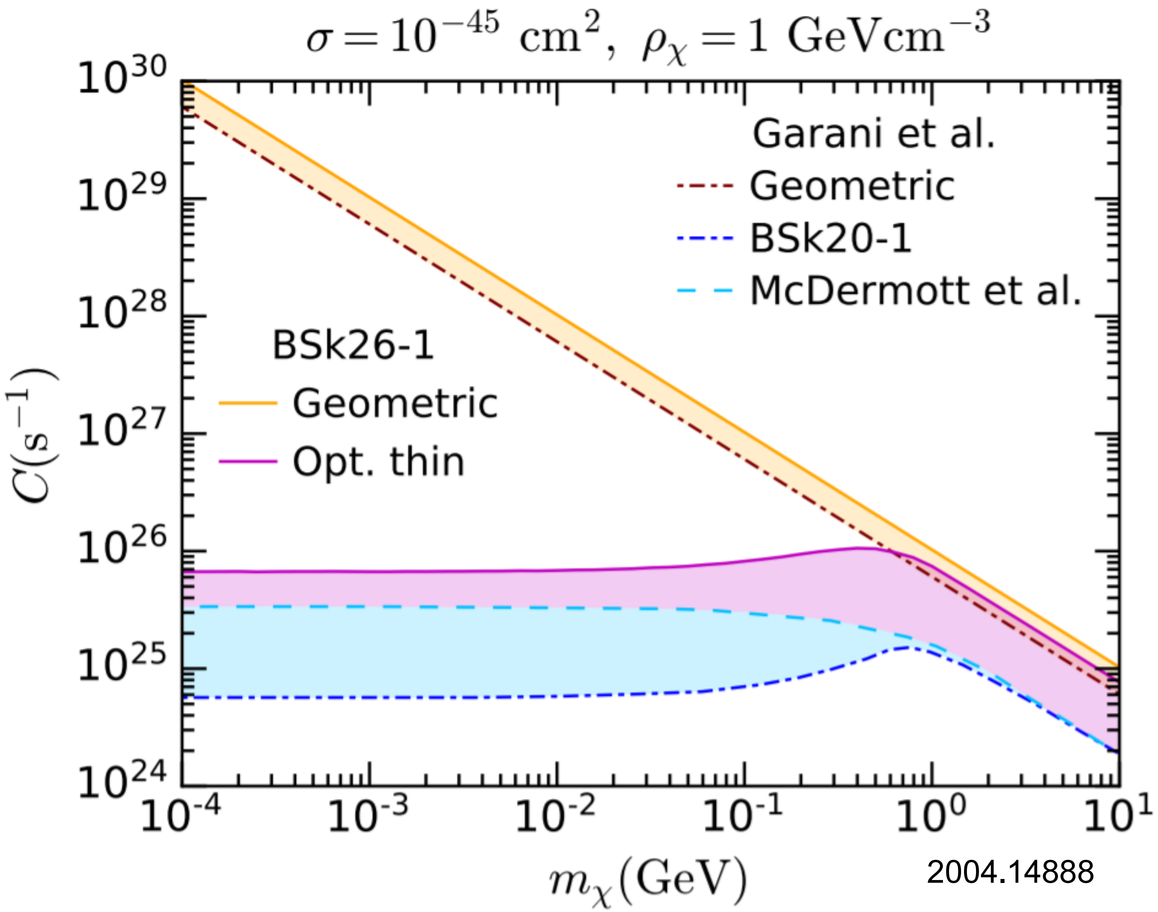


2004.14888

Comparisons with previous works

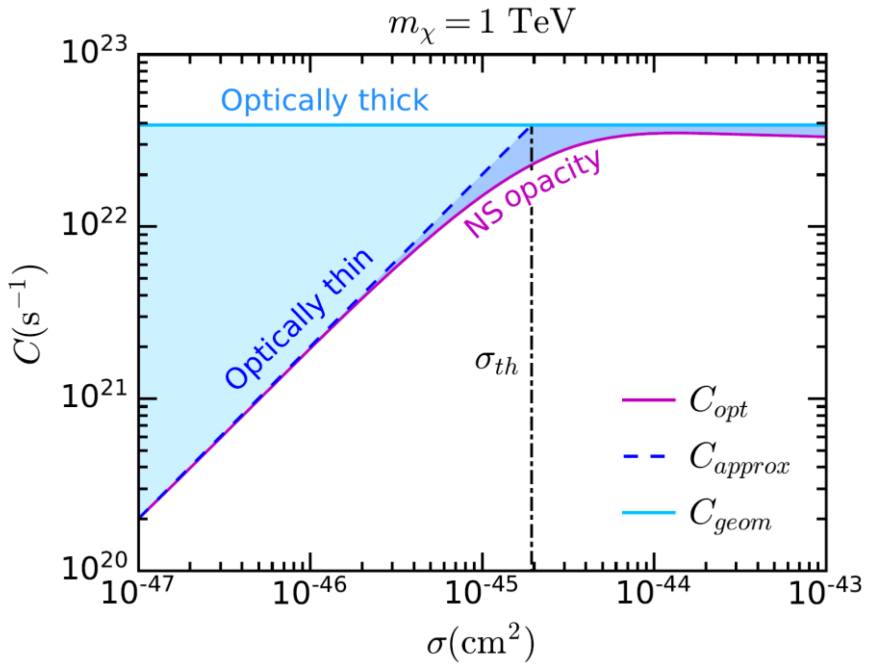
Star Opacity: Large Cross Sections

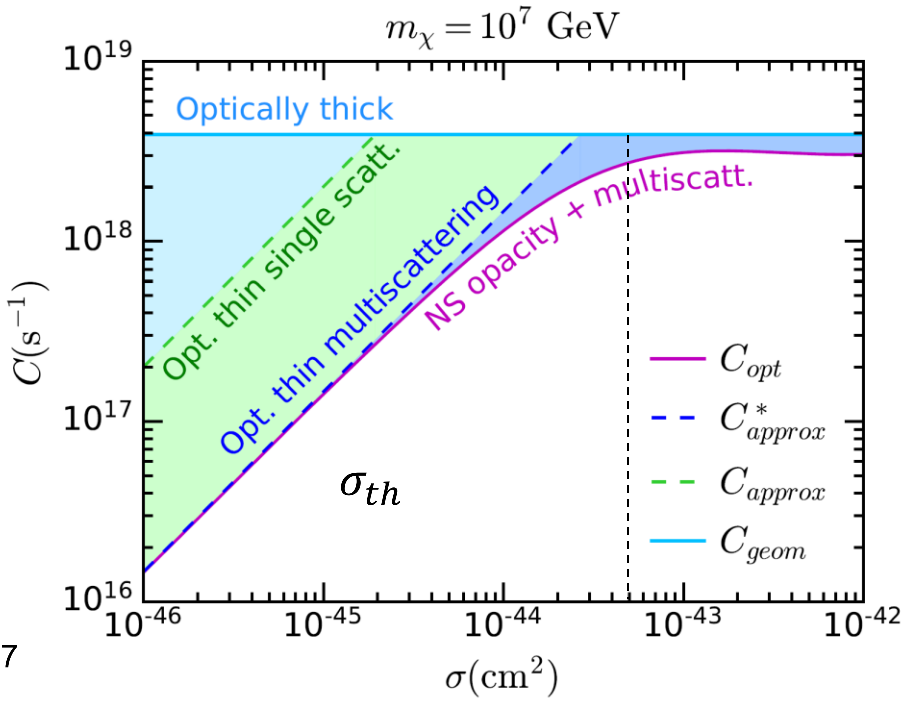
- $\sigma \sim \sigma_{th}$
- Need extinction factor

$$\eta(r) = e^{-\tau_\chi} \leftarrow \text{Optical Depth}$$

- In multi-scatter regime:

$$\eta(r) \approx \frac{1}{n_*} e^{-\tau_\chi / n_*}$$





Virgato et.al. 2010.13257