THE UNIVERSITY OF MELBOURNE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Dark Matter Capture in Compact Objects

Based on works: N.F. Bell, G. Busoni, S. Robles and MV: 2004.14888, 2010.13257
+ T.F. Motta and A Thomas: 2012.08918
+ F. Anzuini: 2108.02525
+ M.E. Ramirez-Quezada 2104.14367

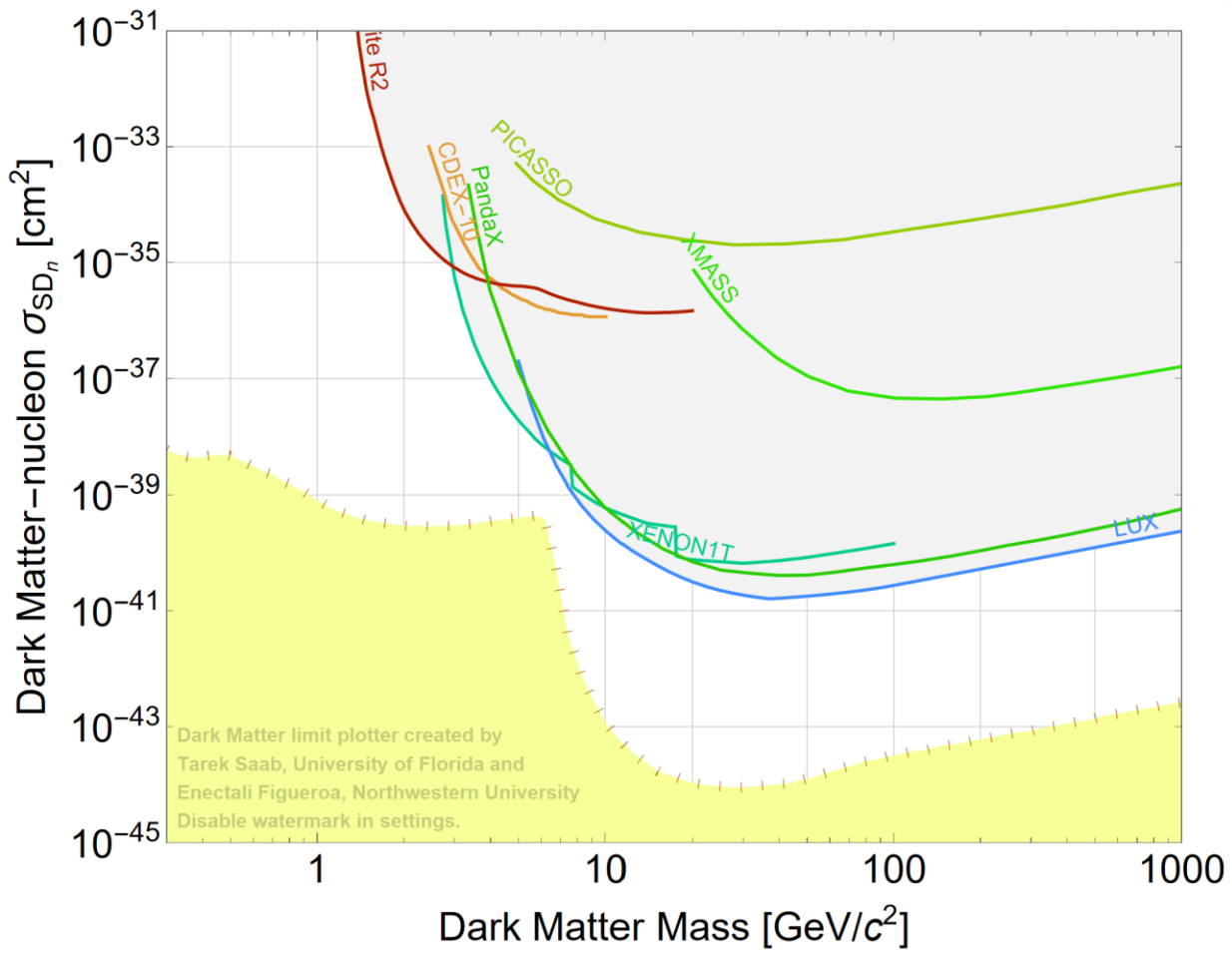
MICHAEL VIRGATO

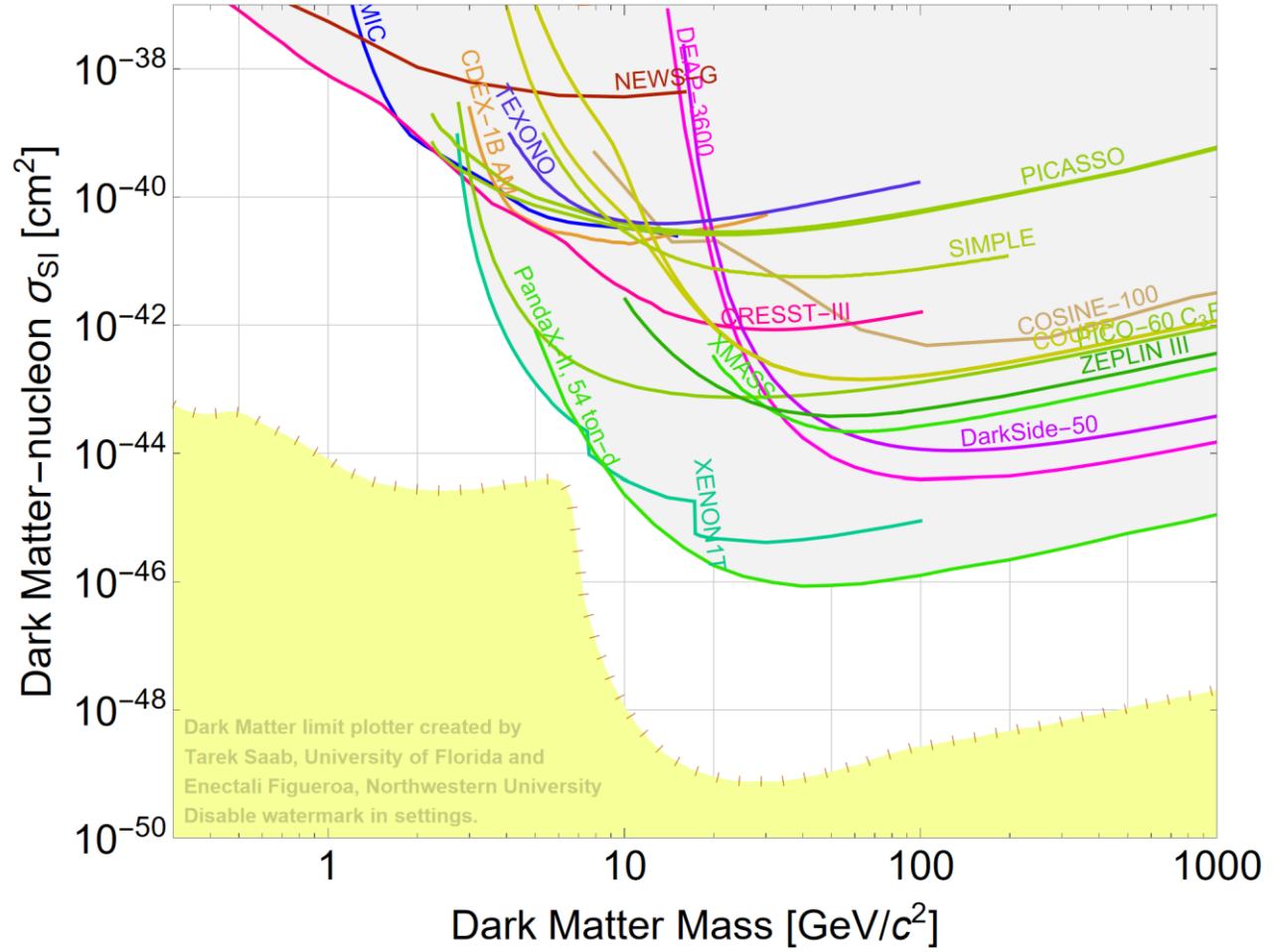
DSU SYDNEY 2022

Outline

- Motivation
- Capture in Neutron Stars: Iteratively improving the formalism
- Dark Matter Capture and Heating of White Dwarfs
  - Electron Targets

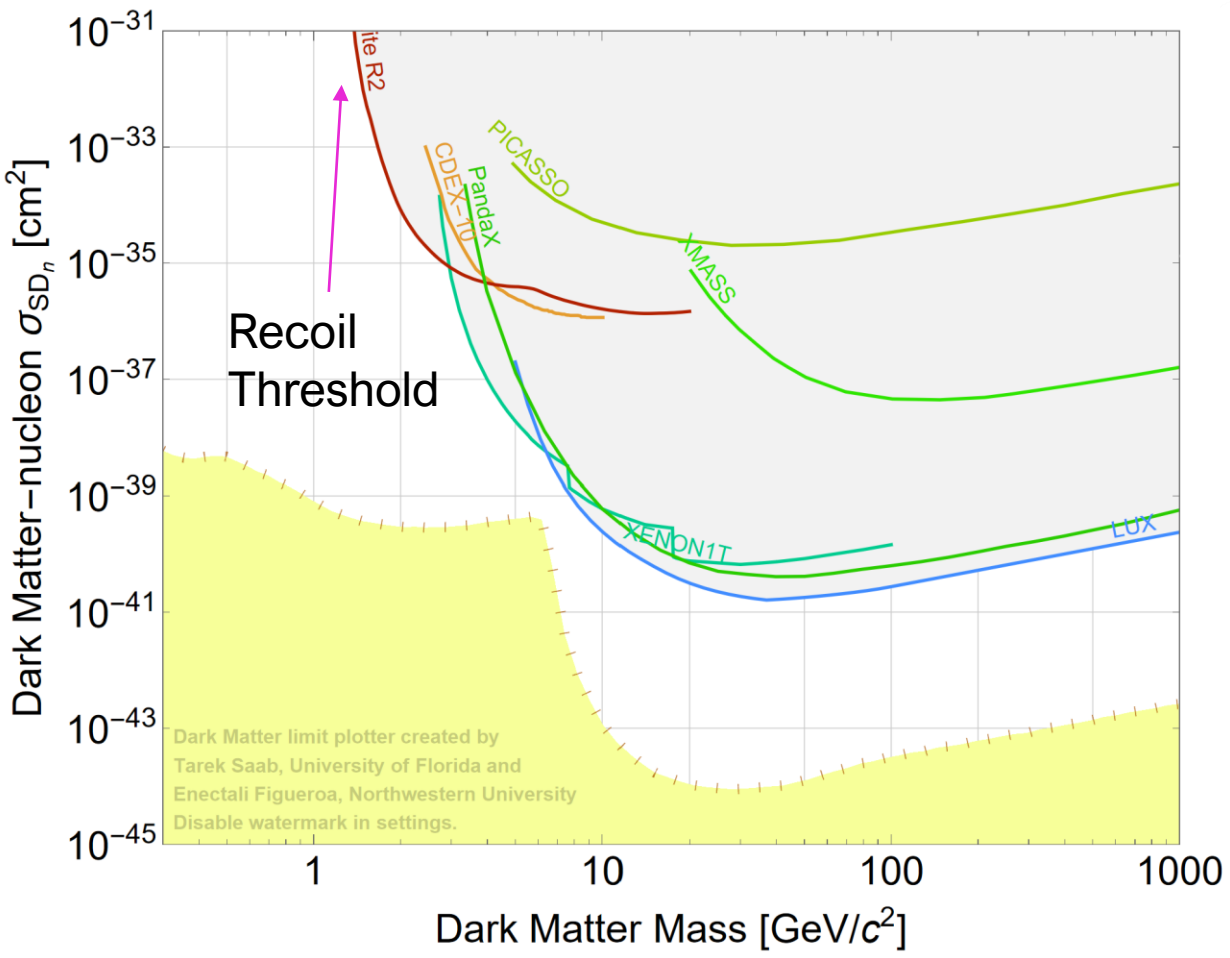
(see following talk by Maura for Ion targets & more)

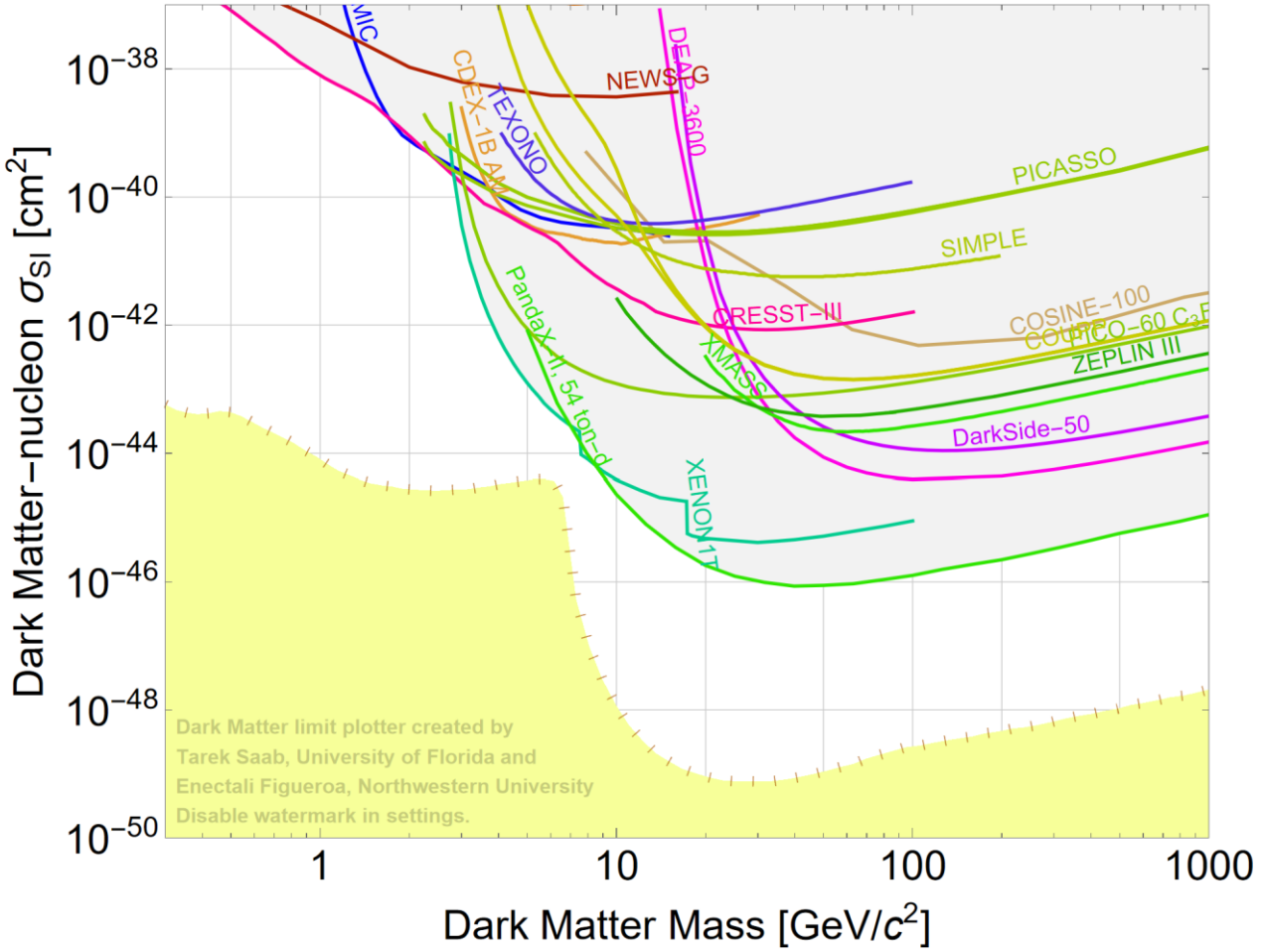




Direct Detection Bounds

Current upper bounds for spin-dependent (**left**) and spin-independent (**right**) DM-nucleon cross sections





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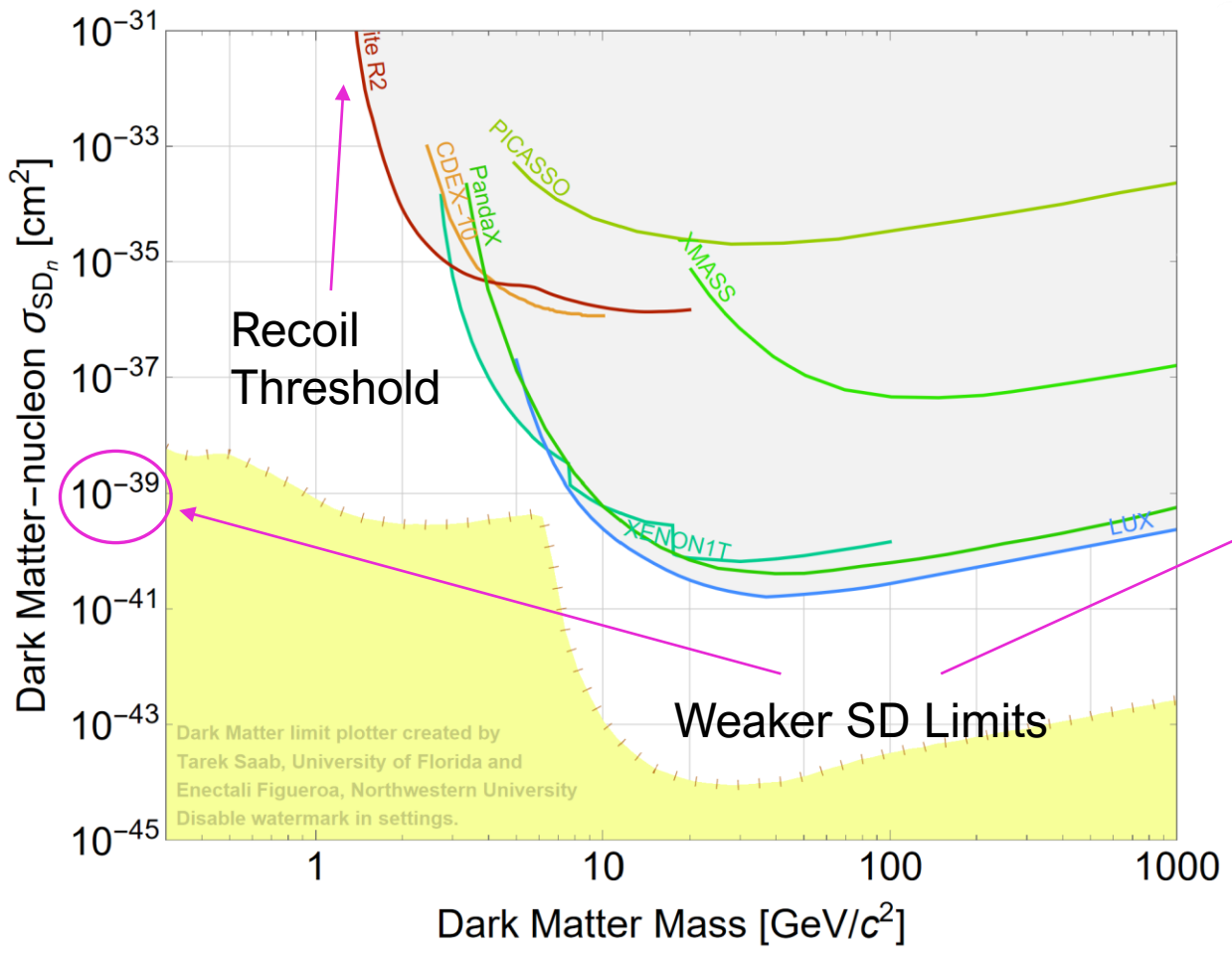

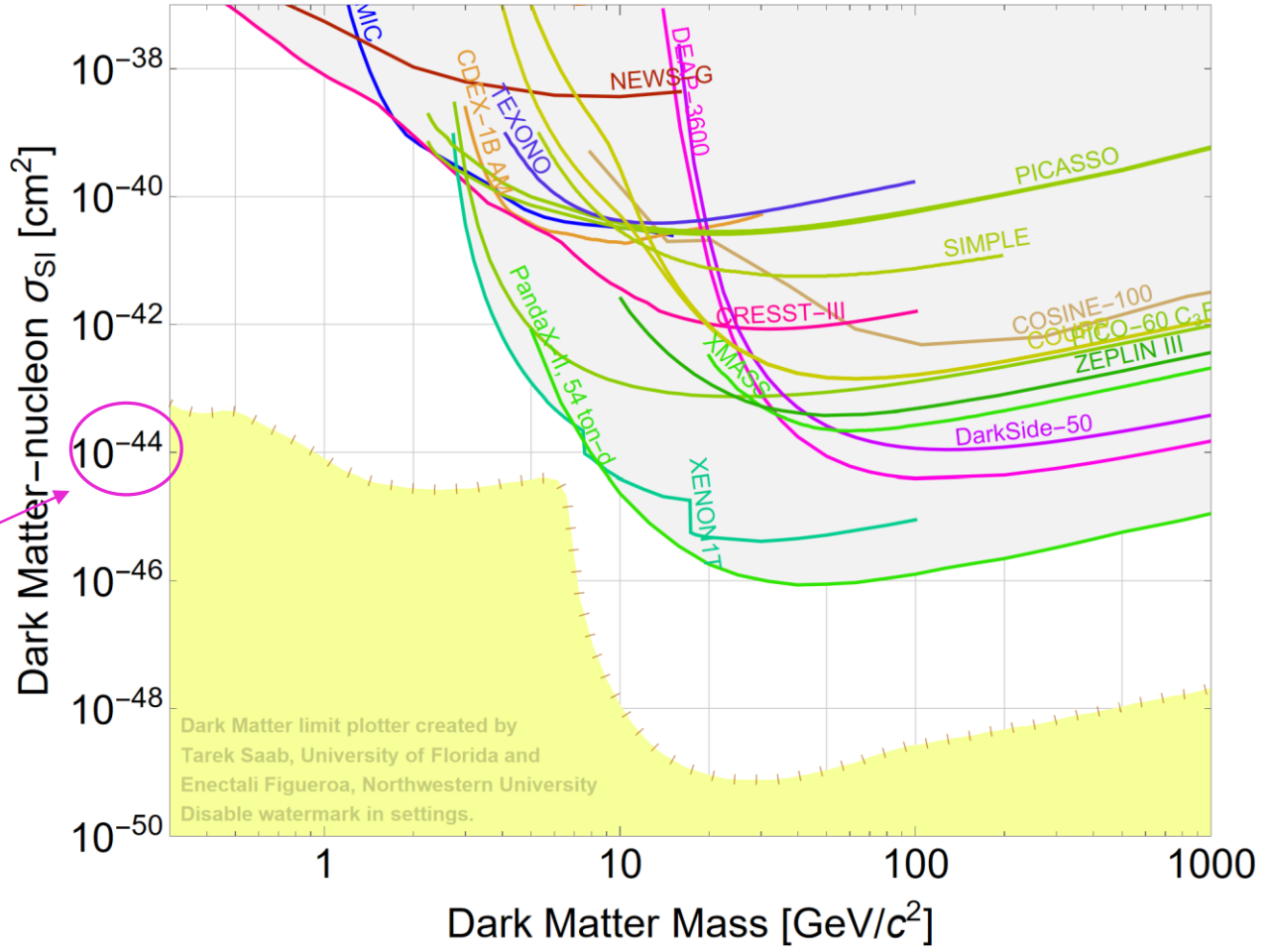

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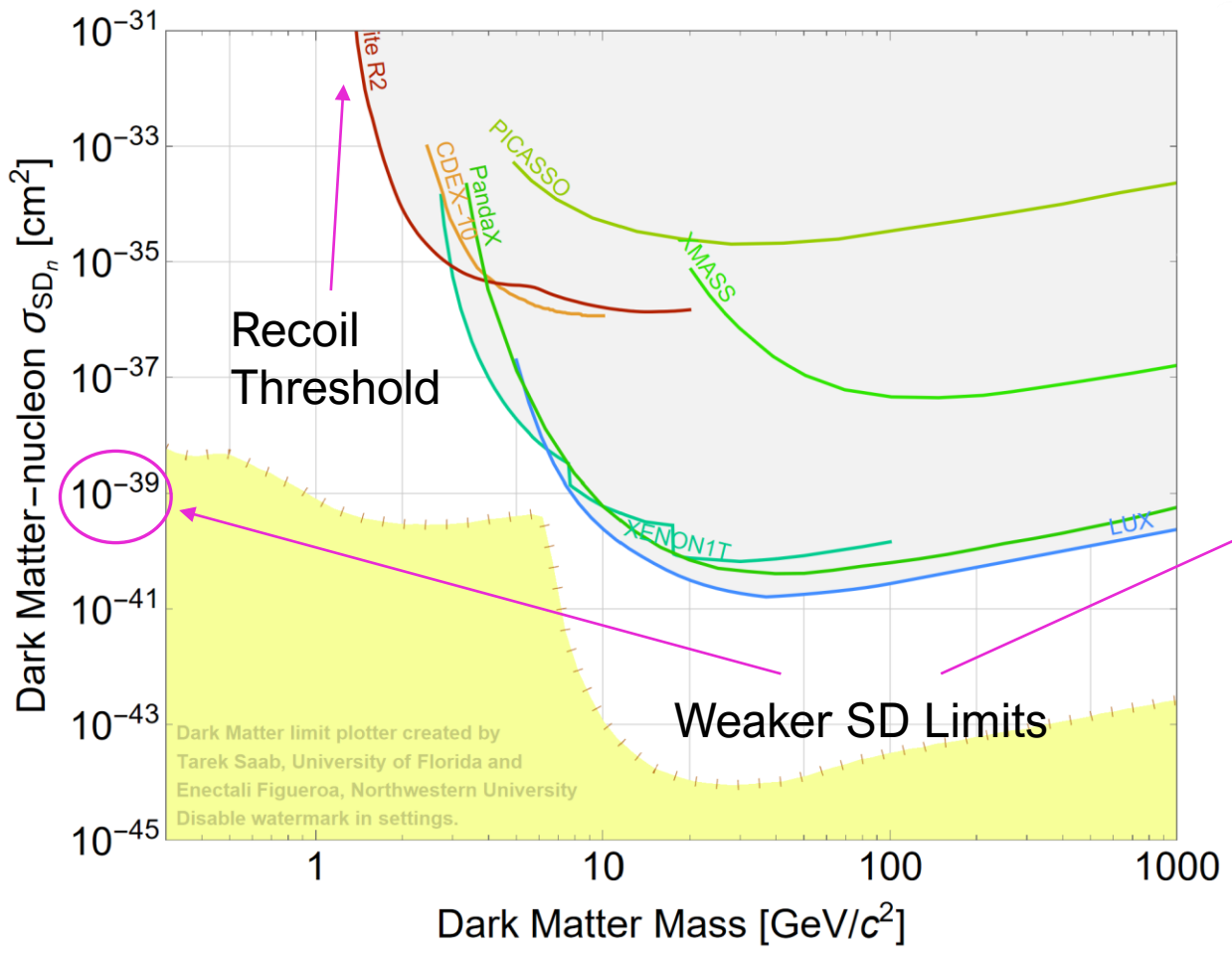

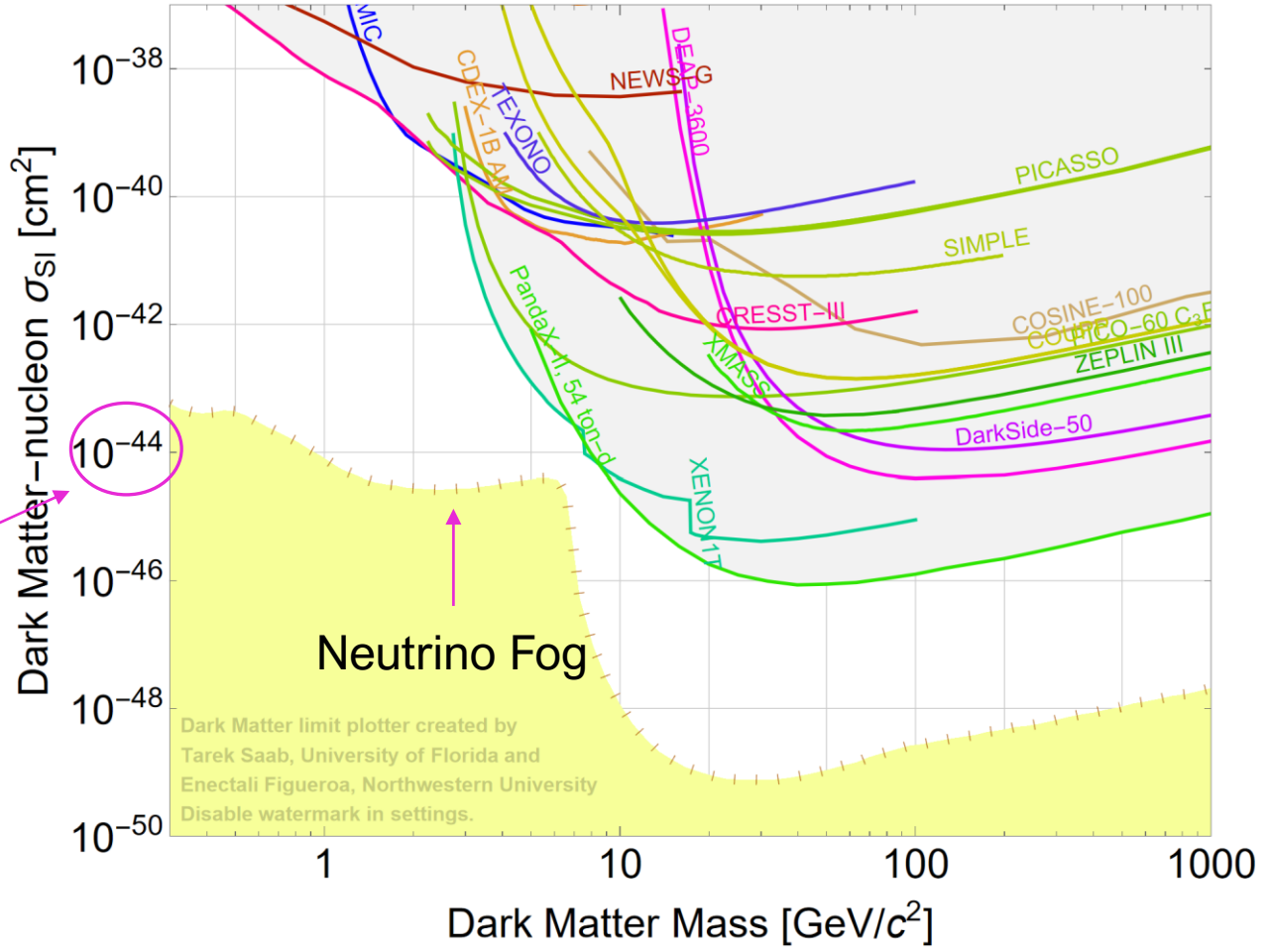

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Compact Objects as Dark Matter Probes

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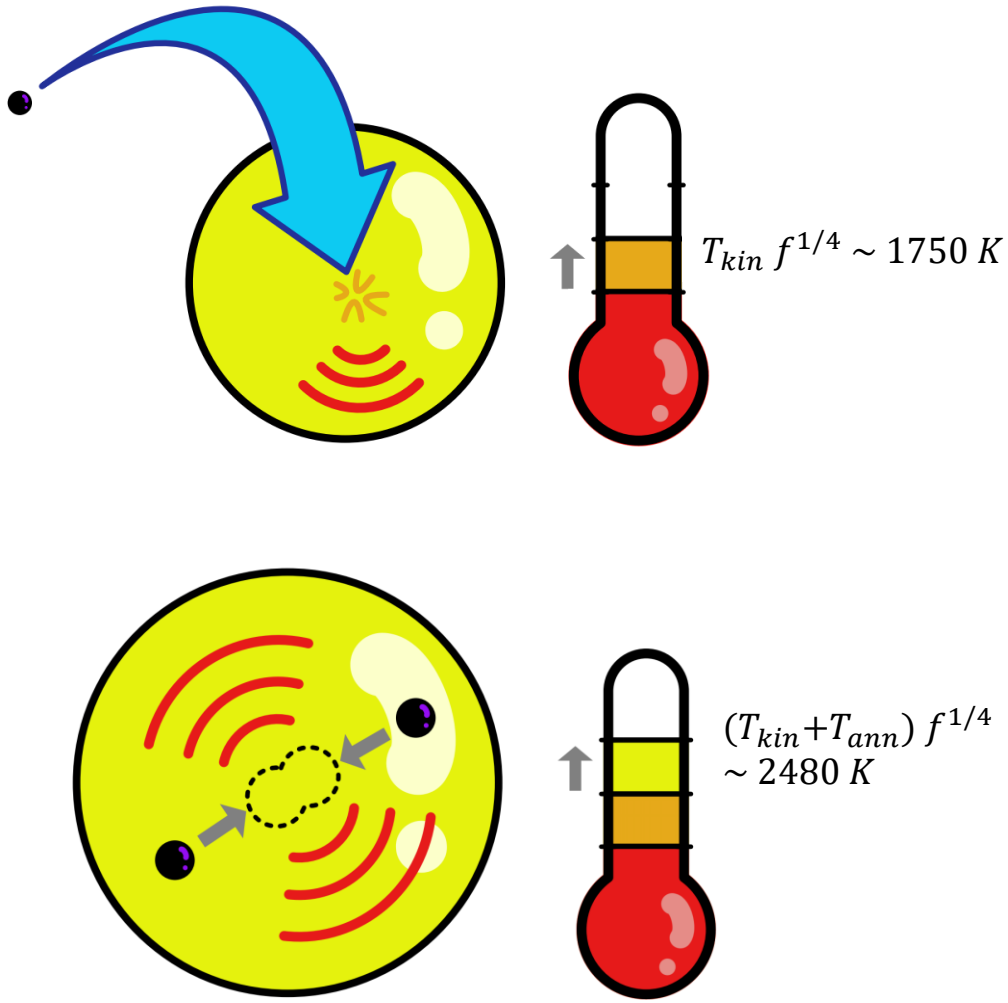

(Raj et.al. 1707.09442)

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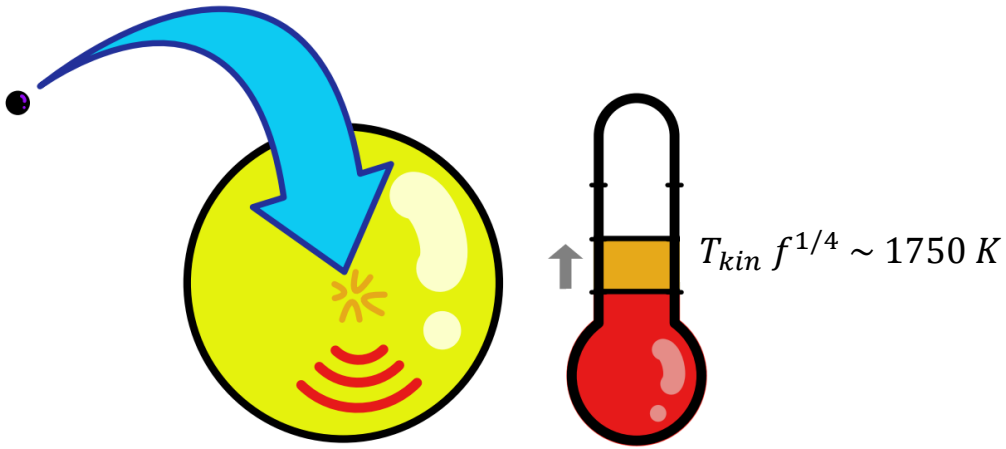

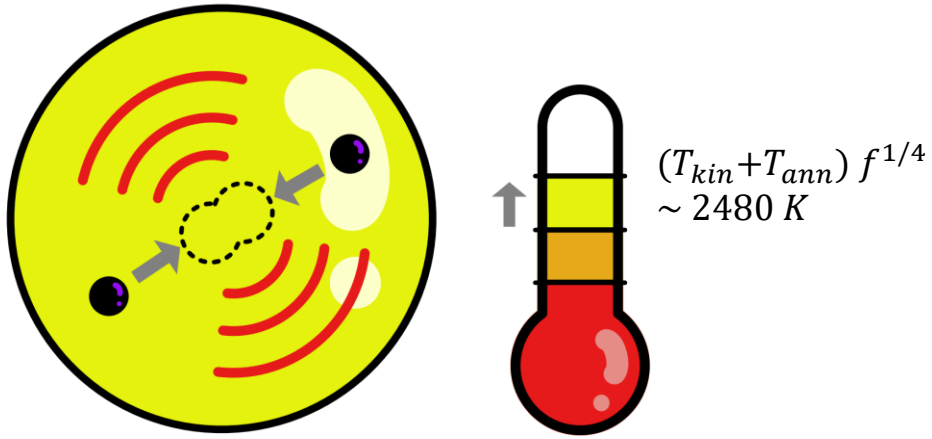

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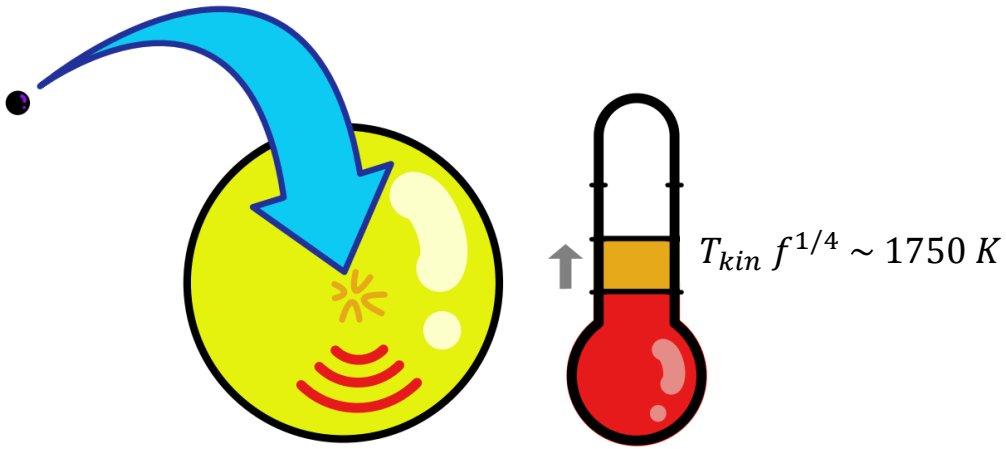

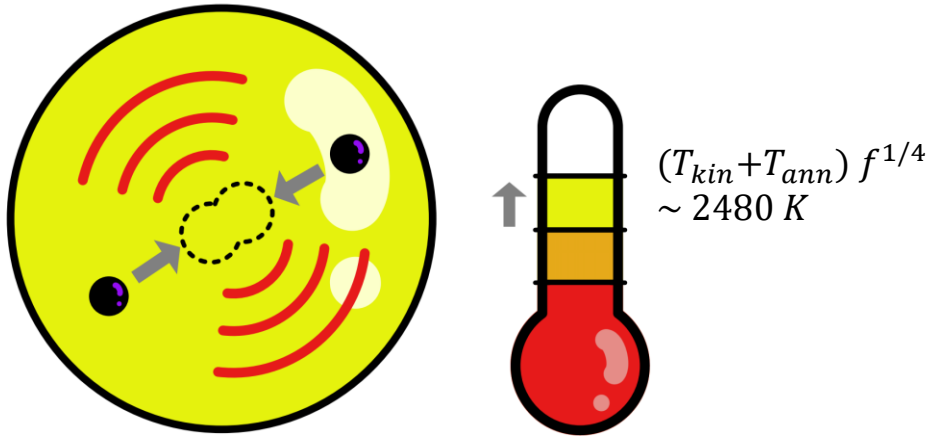

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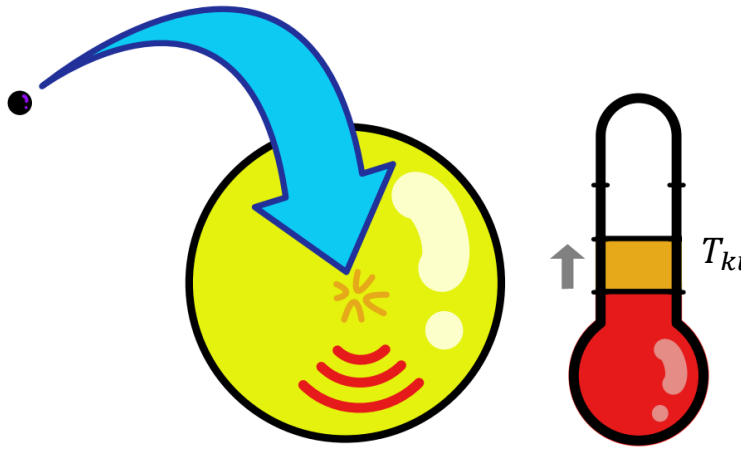
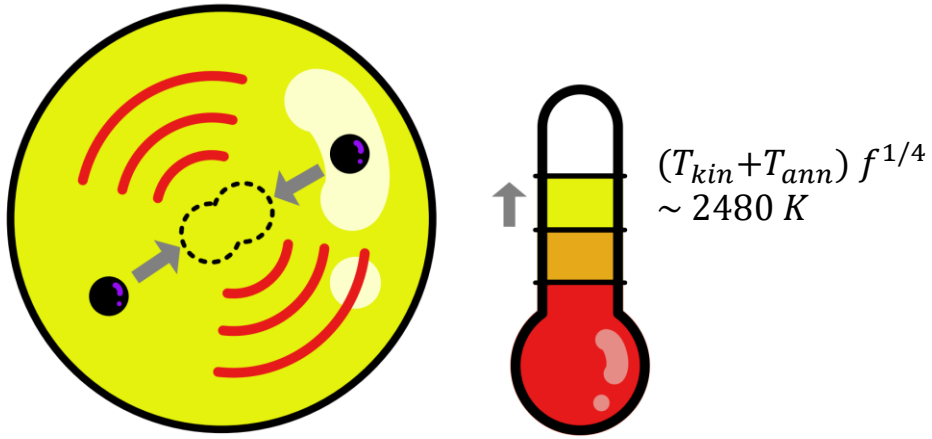
- Nucleons in NSs also require:
  - Baryon strong interactions
  - Momentum dependent Form Factors





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Effective Field Theory for Dark Matter

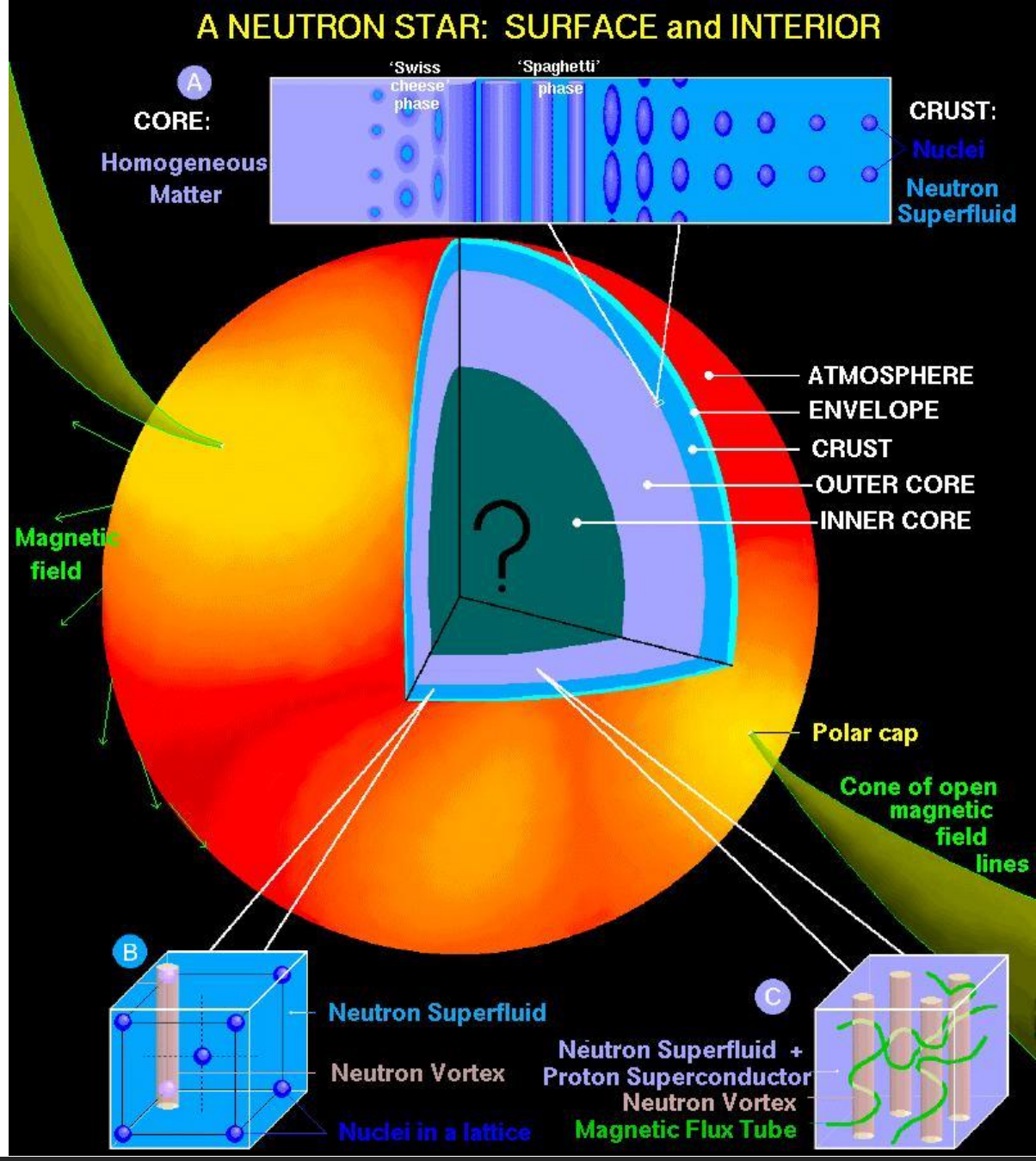
- Dimention-6 EFT operators for Dirac fermion DM

Operator		Coupling	Direct Detection	Momentum Suppressed?
D1	$(\bar{\chi}\chi)(\bar{q}q)$	y_q/Λ^2	SI	✗
D2	$(\bar{\chi}\gamma_5\chi)(\bar{q}q)$	iy_q/Λ^2	SI	✓
D3	$(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$	iy_q/Λ^2	SD	✓
D4	$(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2	SD	✓
D5	$(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$	$1/\Lambda^2$	SI	✗
D6	$(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu\gamma_5 q)$	$1/\Lambda^2$	SI, SD	✓
D7	$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q)$	$1/\Lambda^2$	SD	✓
D8	$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$	$1/\Lambda^2$	SD	✗
D9	$(\bar{\chi}\sigma_{\mu\nu}\chi)(\bar{q}\sigma^{\mu\nu}q)$	$1/\Lambda^2$	SD	✗
D10	$(\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi)(\bar{q}\sigma^{\mu\nu}q)$	i/Λ^2	SI	✓

Neutron Stars

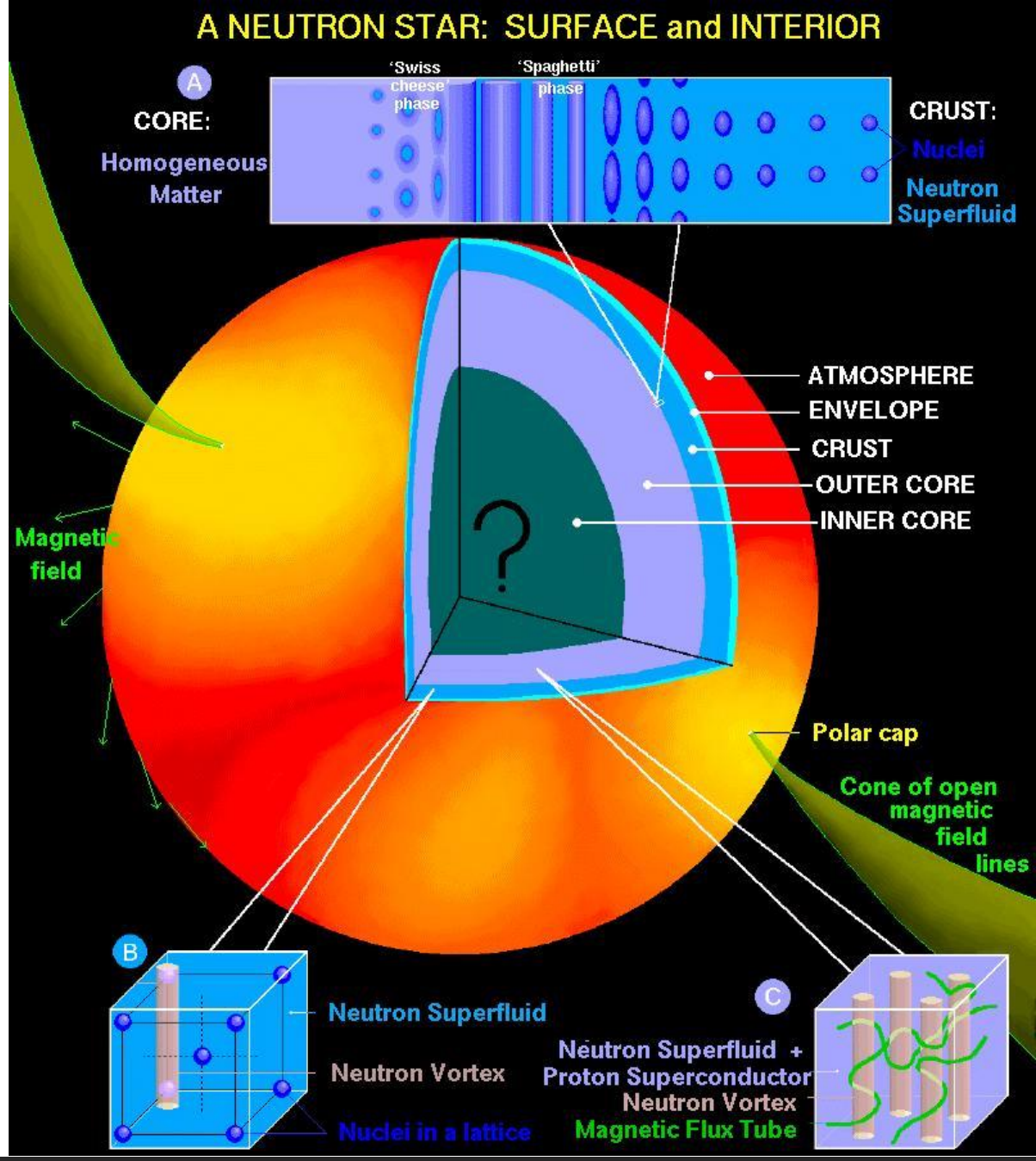
FORMALISM AND POTENTIAL SENSITIVITIES

Neutron Stars



Neutron Stars

- Produced from core collapse supernova of massive stars $\gtrsim 8\, M_\odot$



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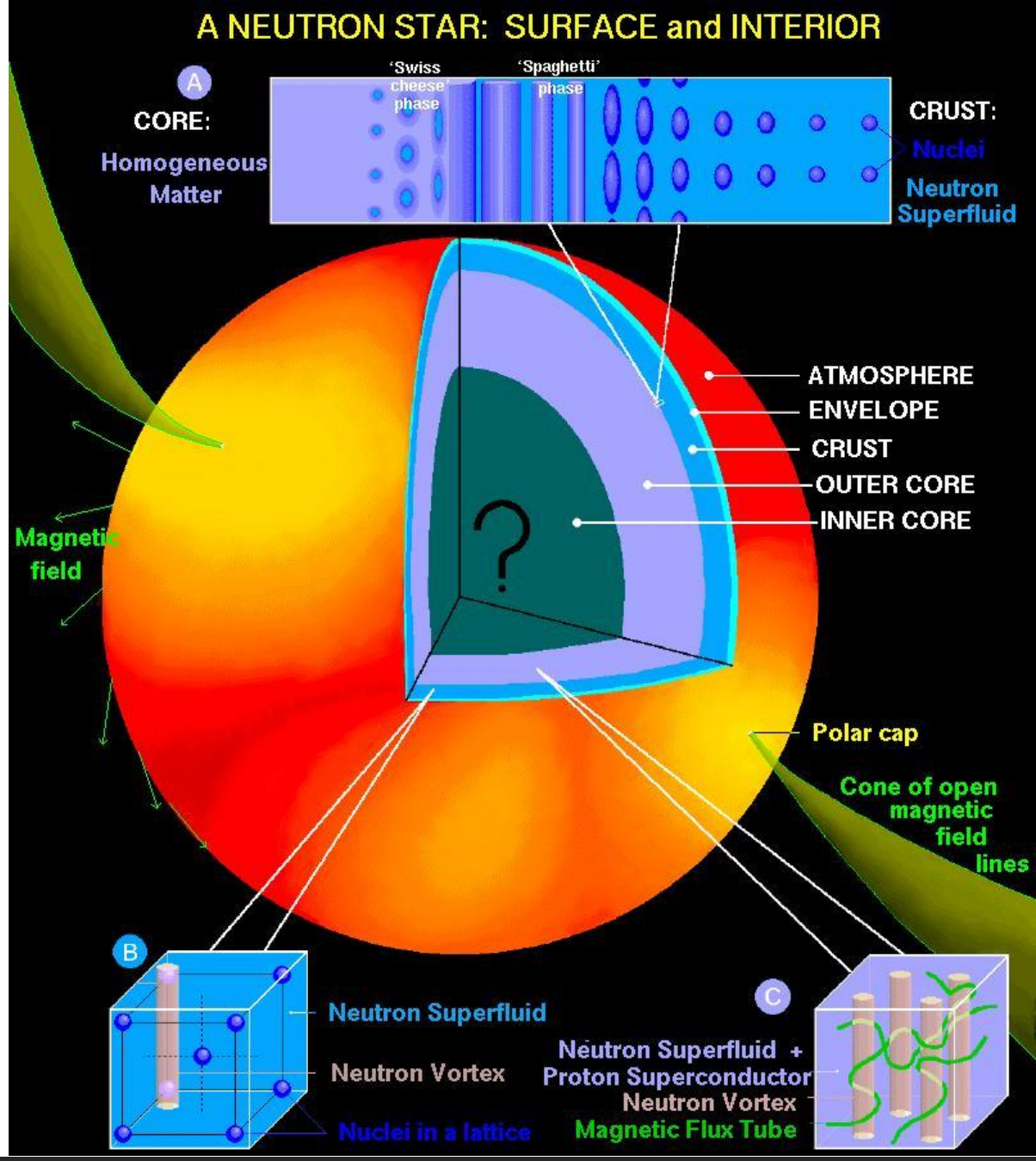

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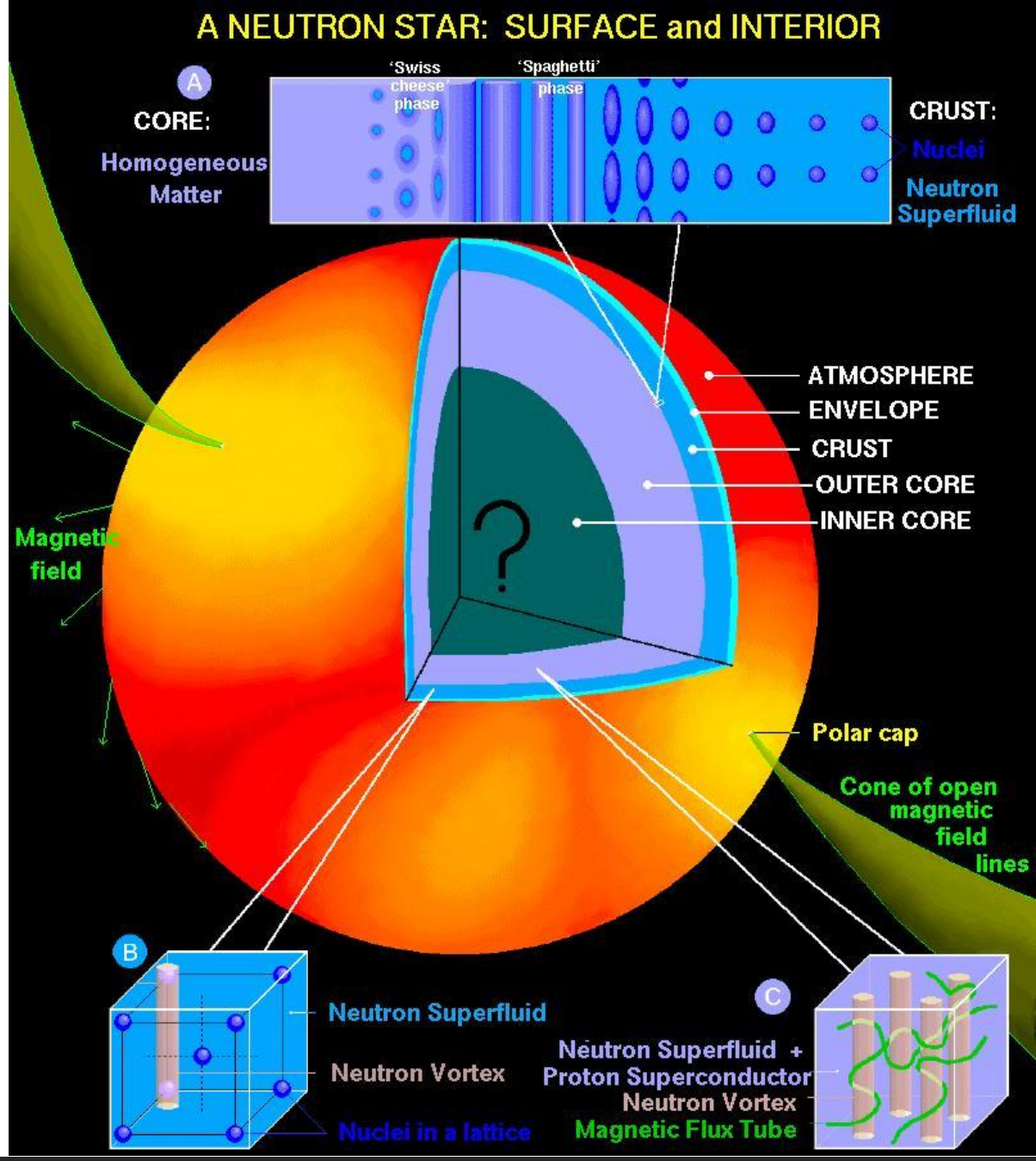

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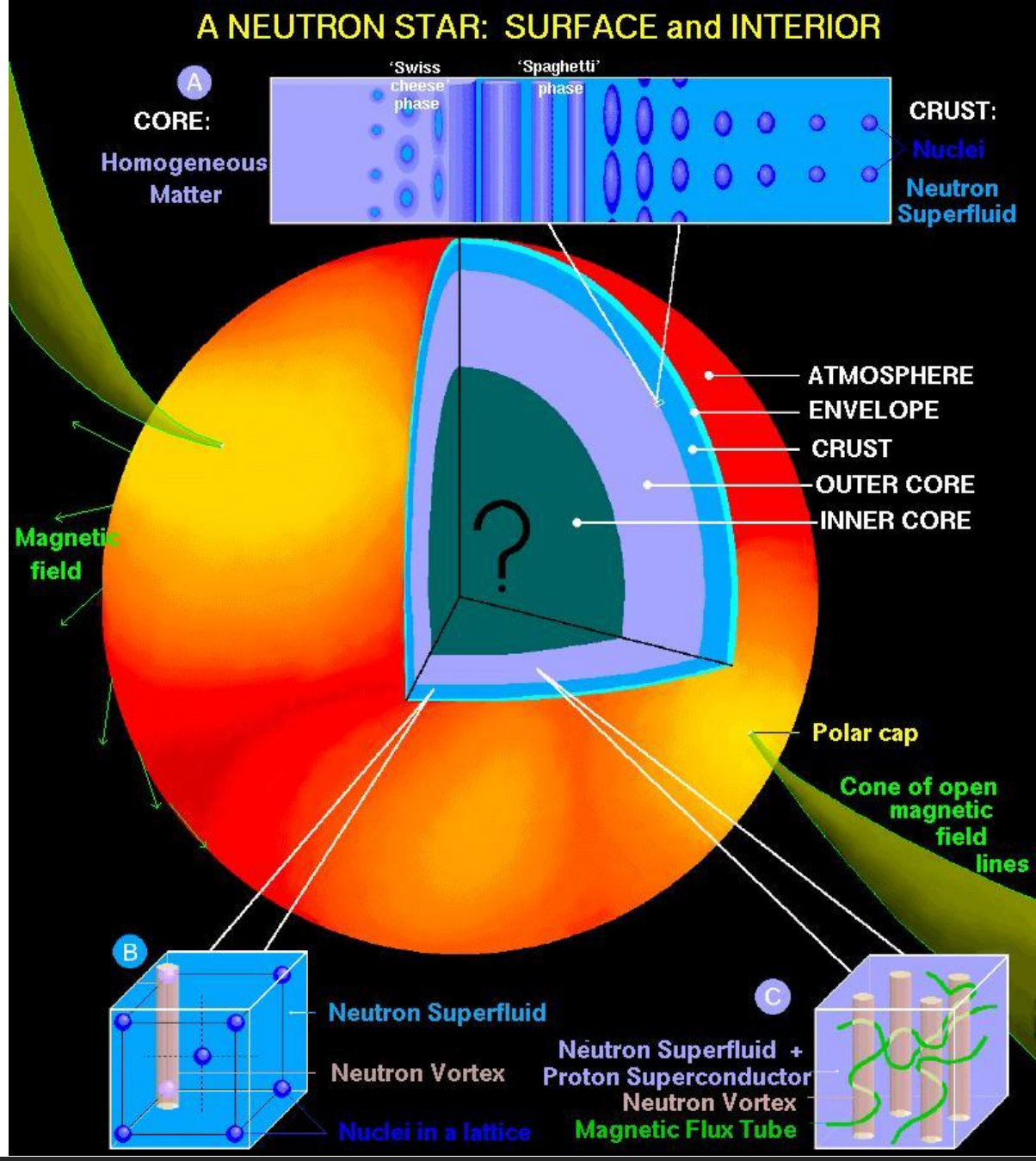
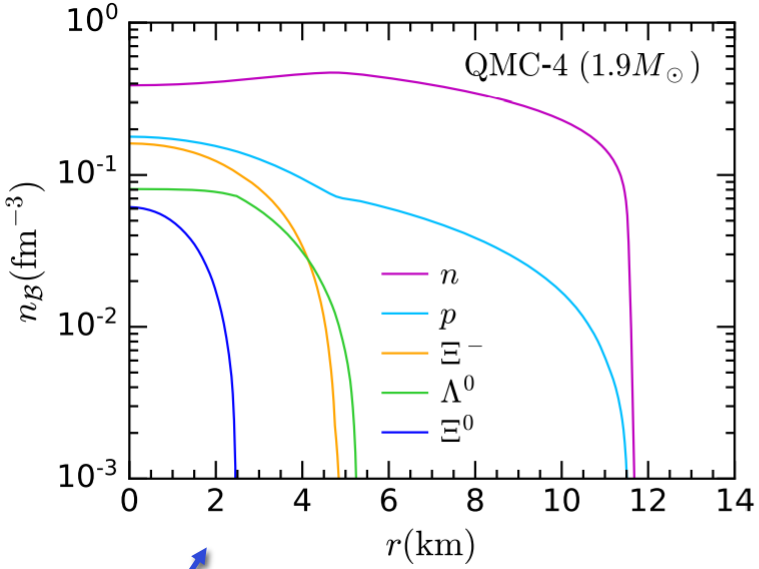
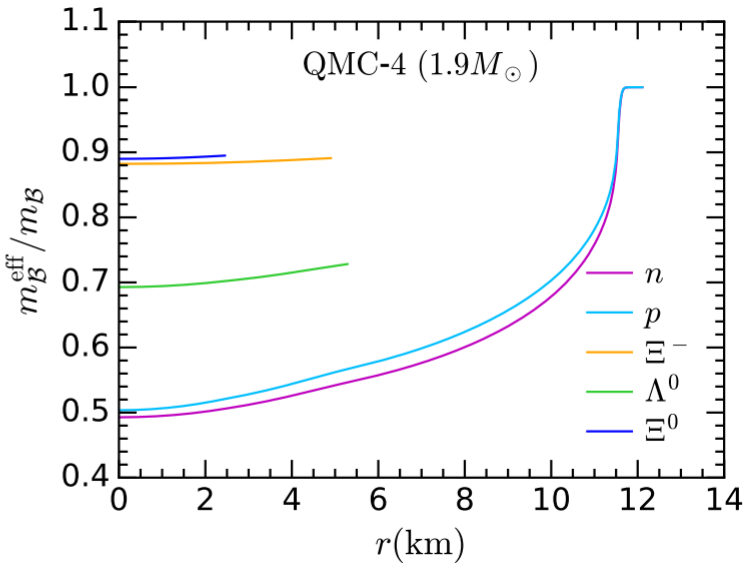
- Inner Core
  - Exact composition of inner core unknown (possibly exotic phases of matter; hyperons, QGP, kaon condensates, …)



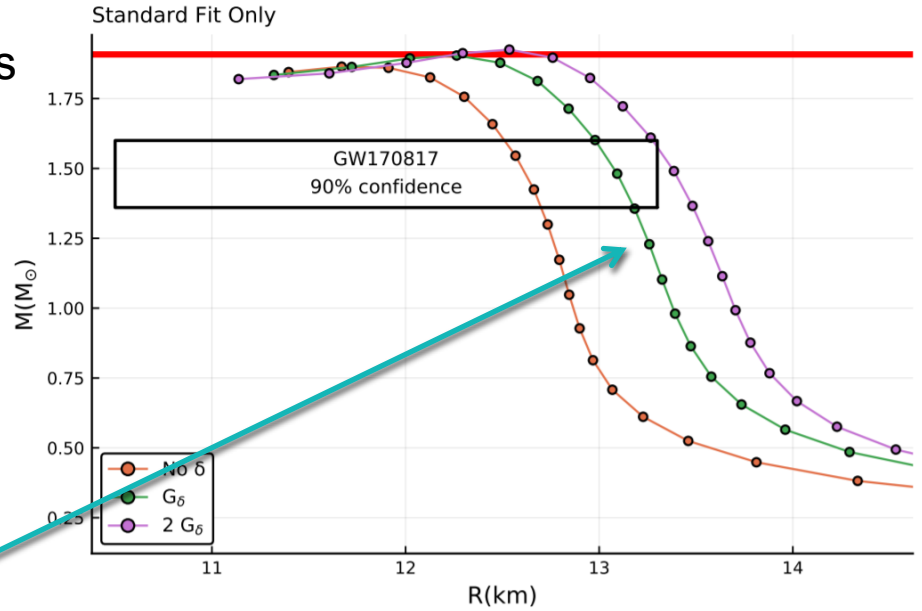
Neutron Star Equation of State: QMC

- Quark-Meson-Coupling Model (Guichon et .al. 1802.08368)
  - Relativistic
  - Contains Hyperons
  - Self-consistent nucleon interactions
  - Can obtain $M_\star \sim 2\ M_\odot$





EoS + TOV = Radial Profiles



Green line is EoS used

(Motta et. al. 1904.03794)

Capture Rate

- Total capture rate is then

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

Interaction Rate:

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

Bell, Busoni, Robles and MV 2004.14888

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Differential cross section

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Relativistic kinematics

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Differential cross section

Relativistic kinematics

Pauli Blocking

Bell, Busoni, Robles and MV 2004.14888

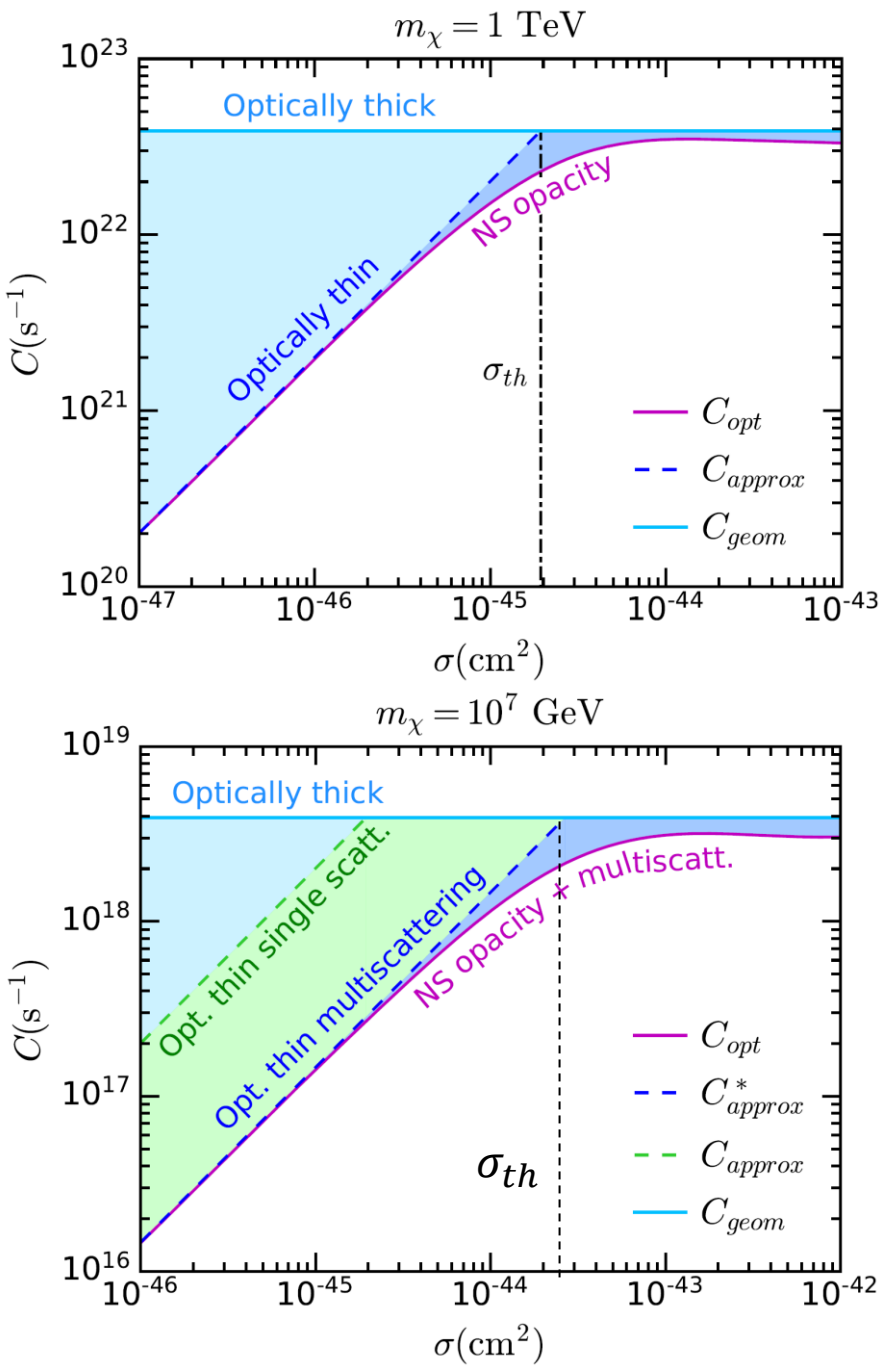
Threshold Cross Section

Capture rate saturates to geometric limit for cross sections above

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

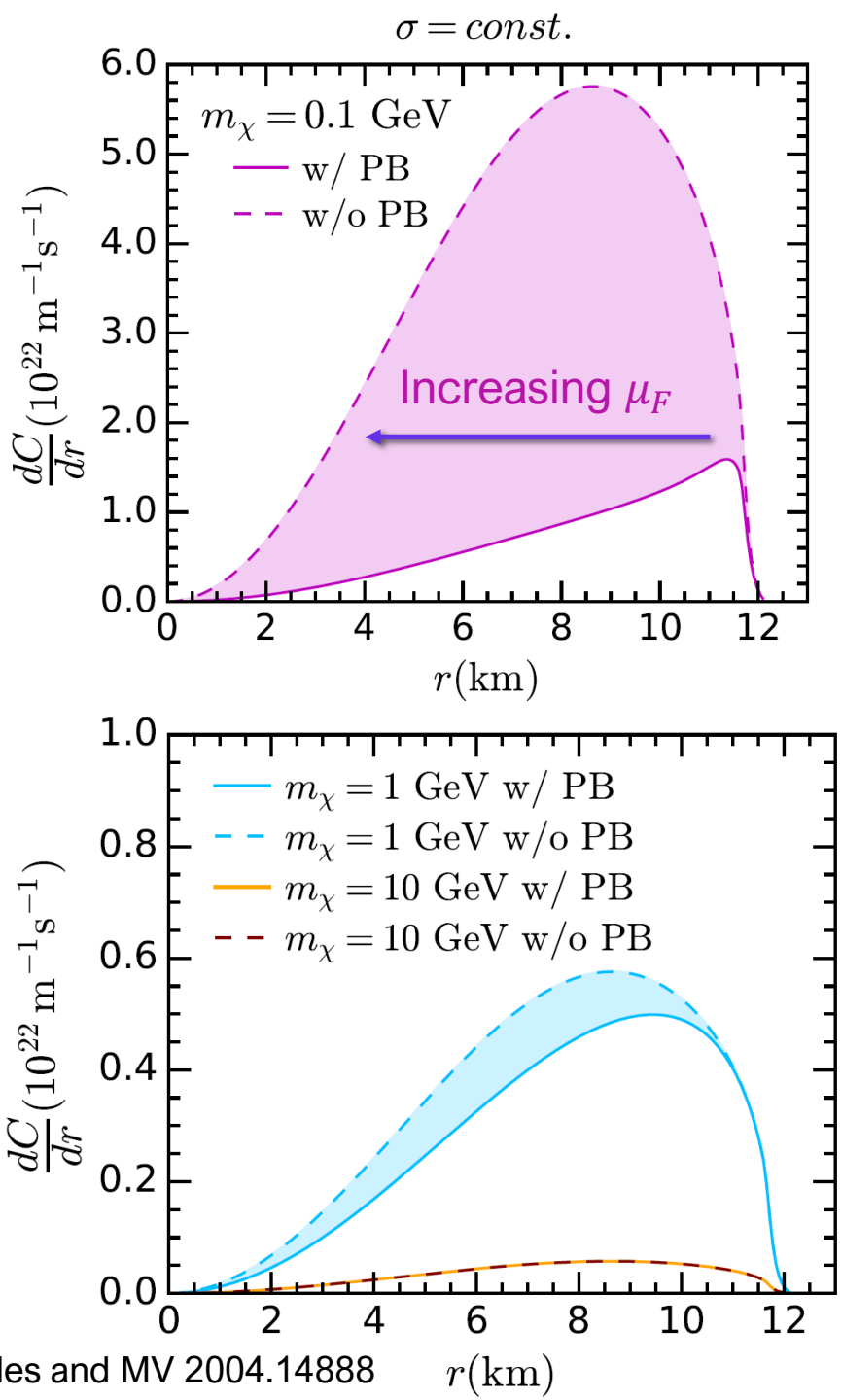
$$\sigma_{ref} \sim 10^{-45}\ cm^2$$

(Not quite for baryons…)



NFB, GB, SR and MV 2010.13257

Pauli Blocking ($m_\chi \lesssim 1\,GeV$)



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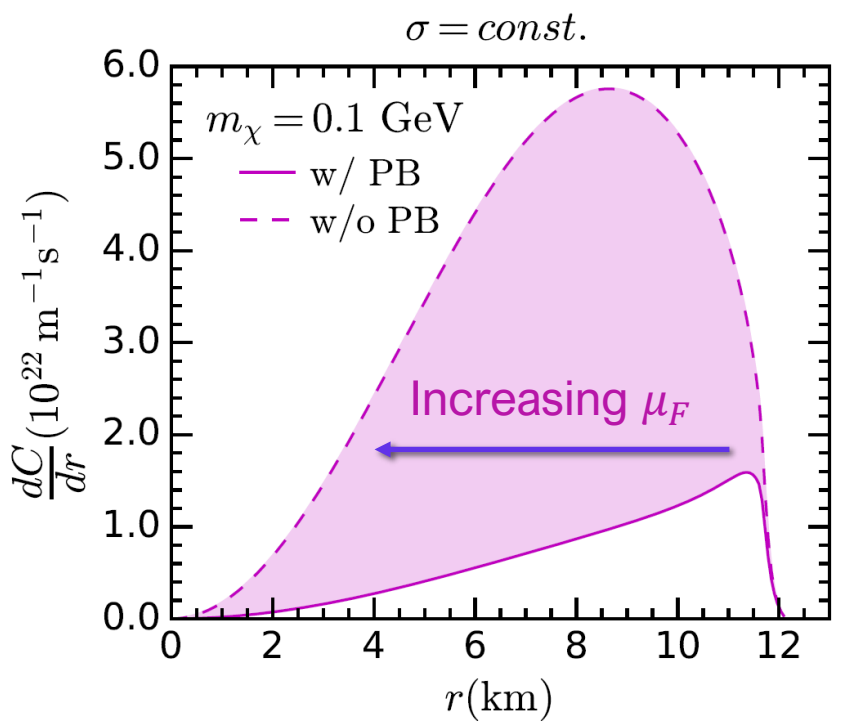
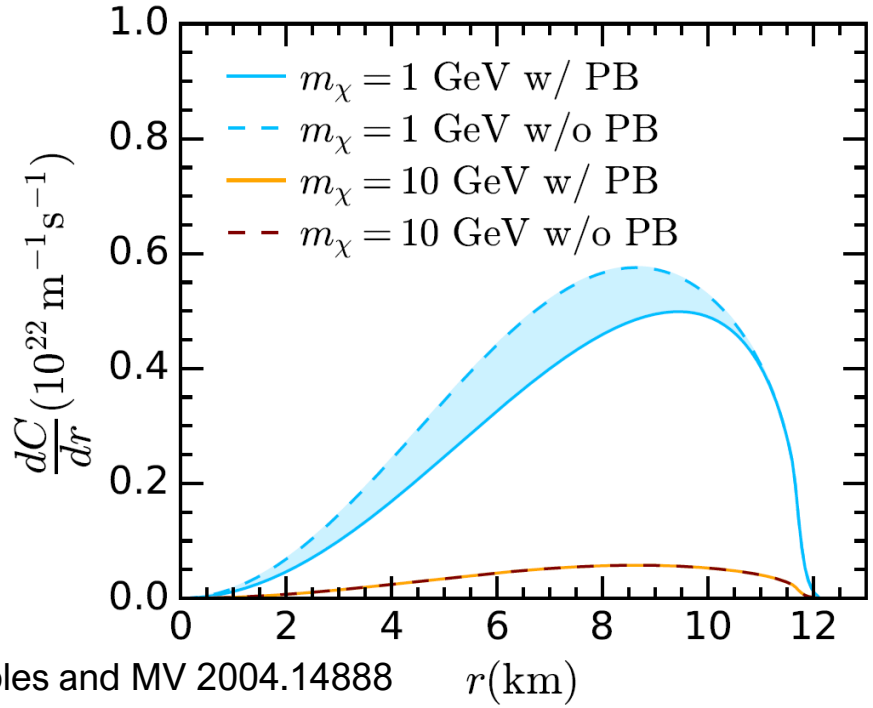
$$p_{final} = p_{initial} + q > p_F$$





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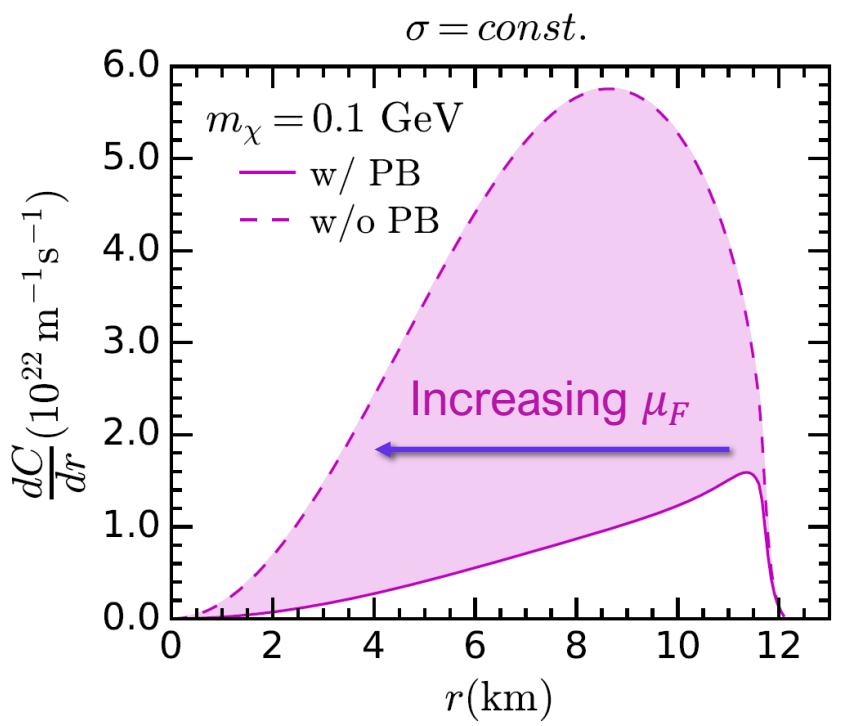

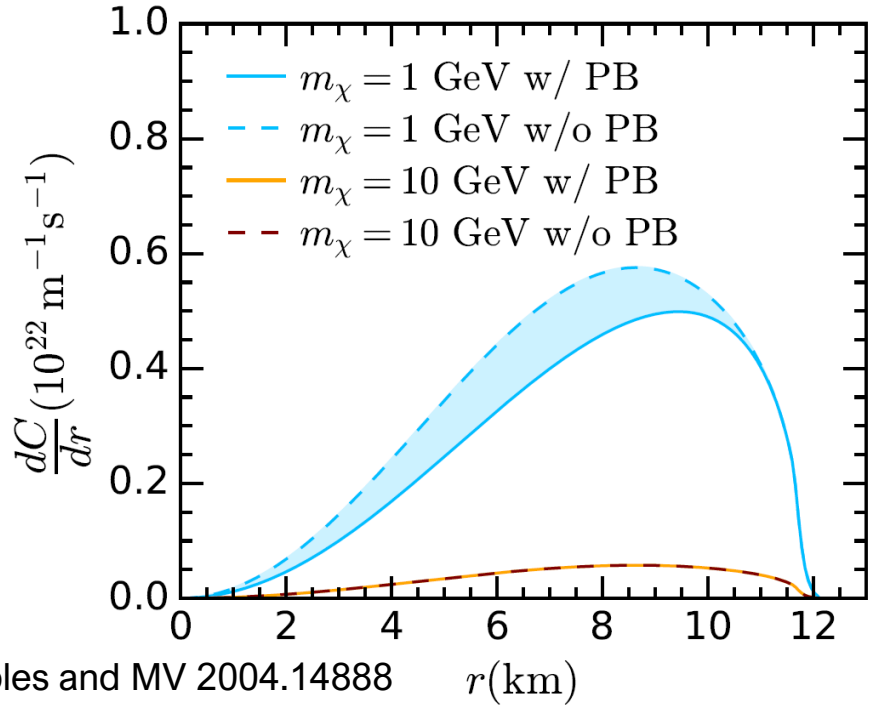

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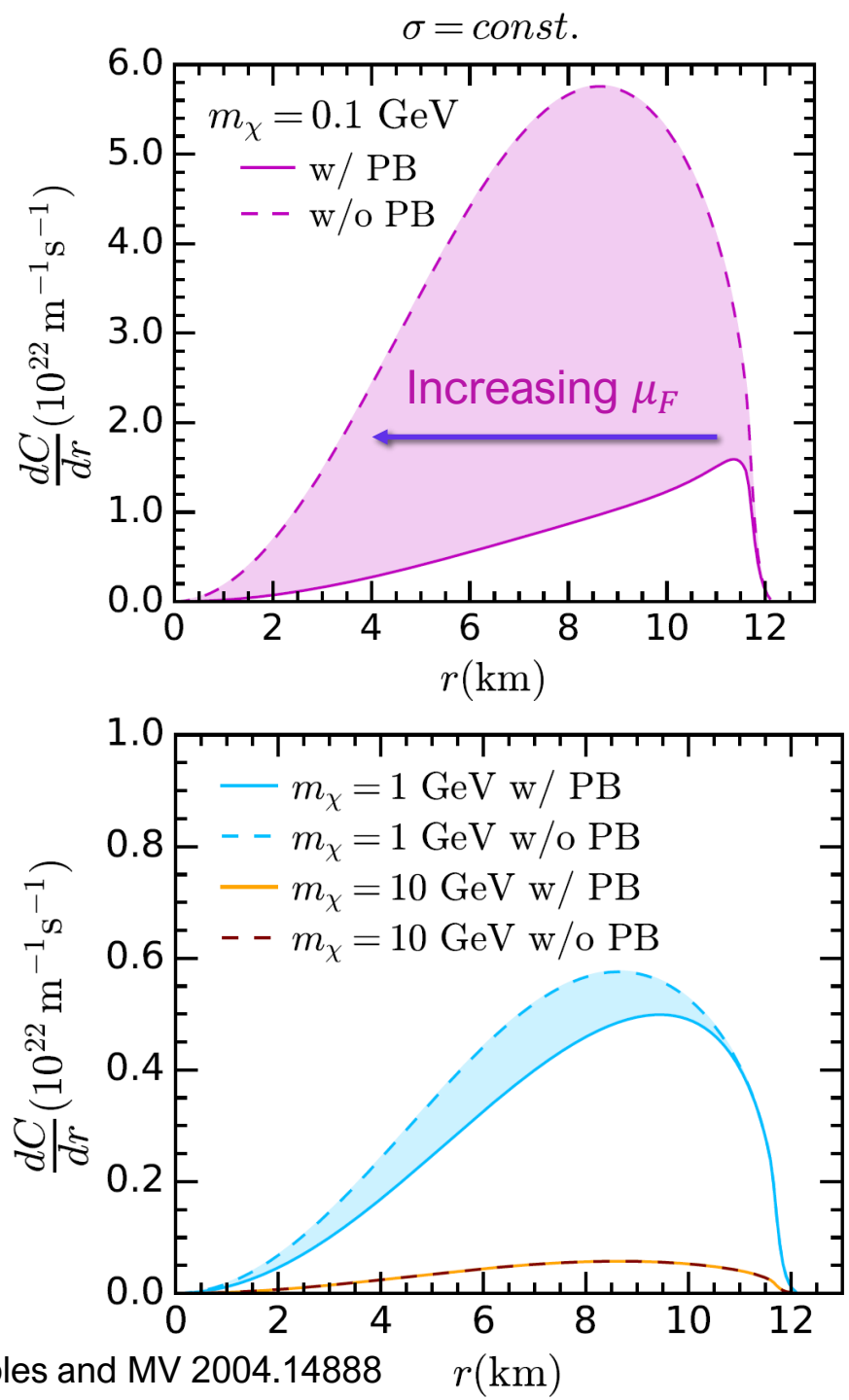
- Effect seen in radial profile of differential capture rate



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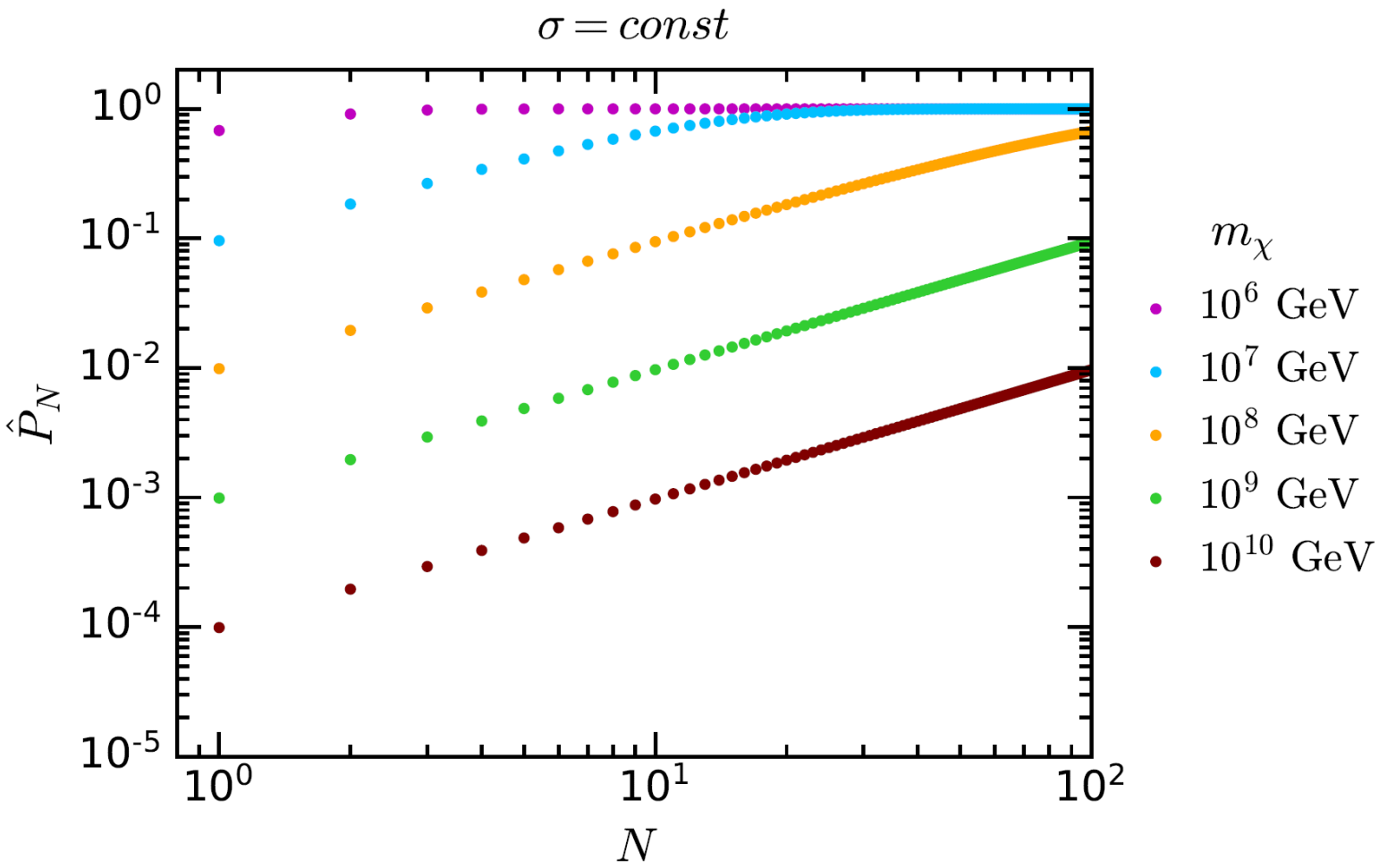
Multiple Scattering ($m_\chi \gtrsim 10^6 \ \ GeV$)



Cumulative probability of capture after *N* interactions

Bell, Busoni, Robles and MV 2004.14888

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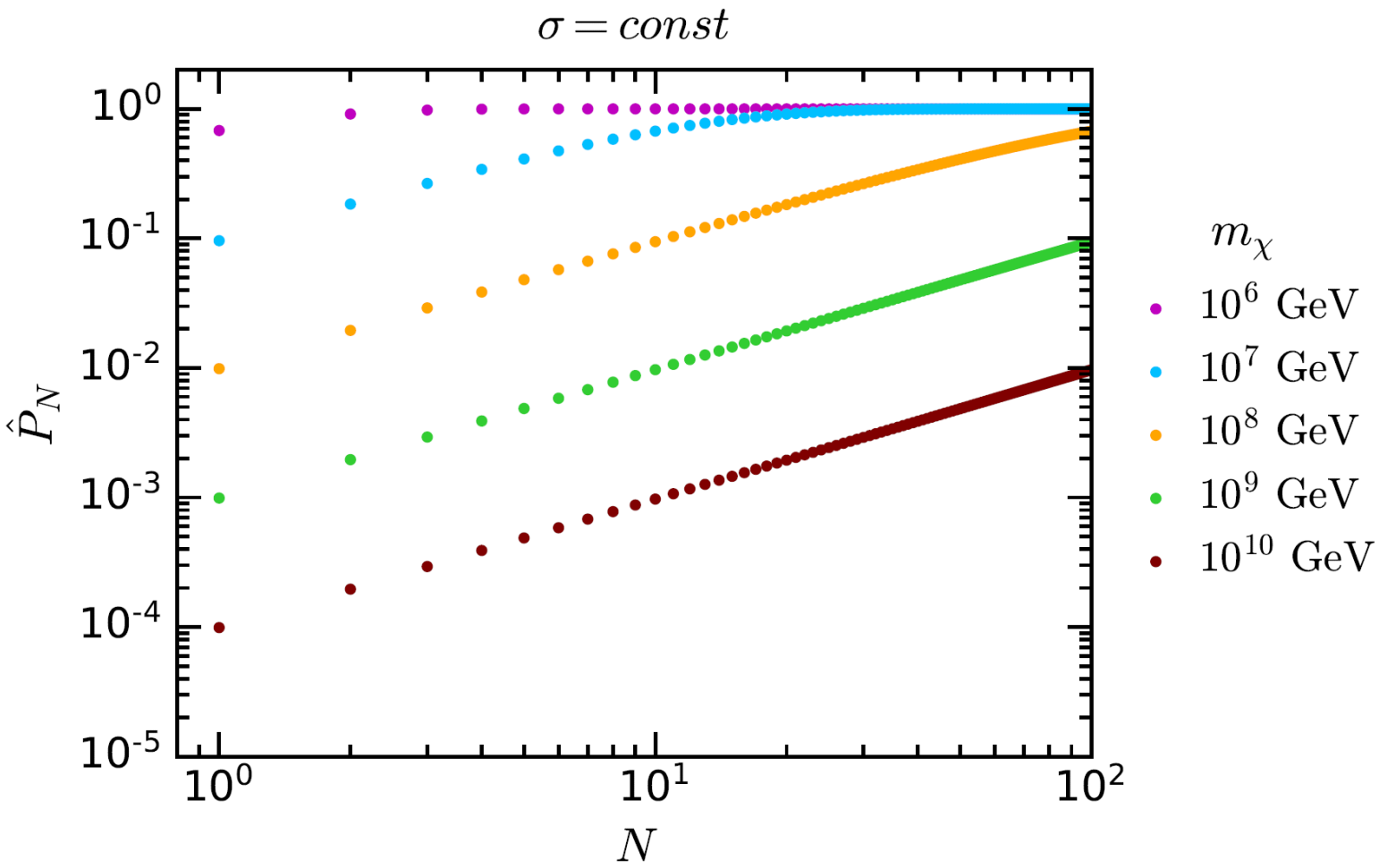
- Require min. energy loss

$$q_{0,min} = \frac{1}{\sqrt{B}} E_{kin}^{\infty}$$



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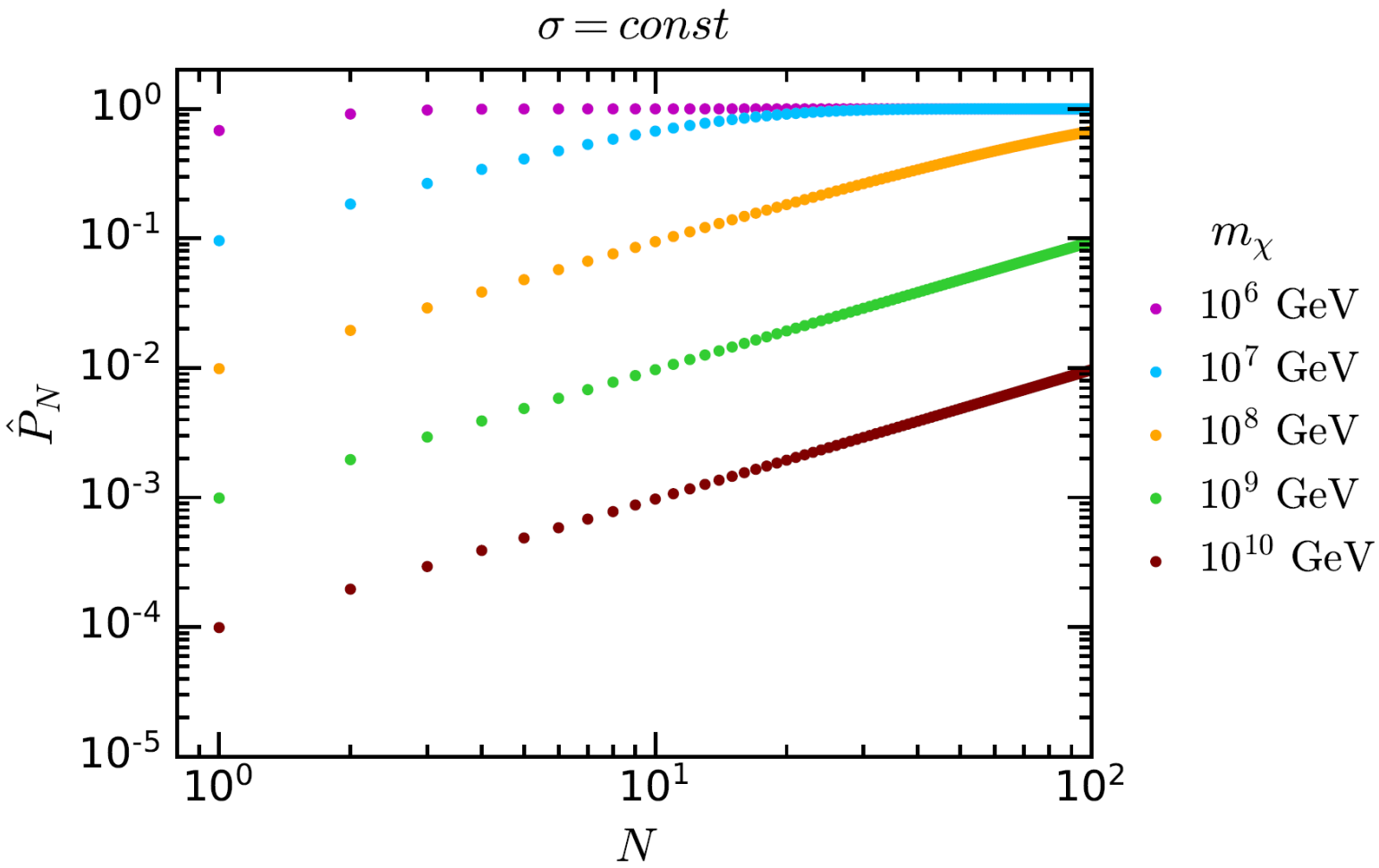

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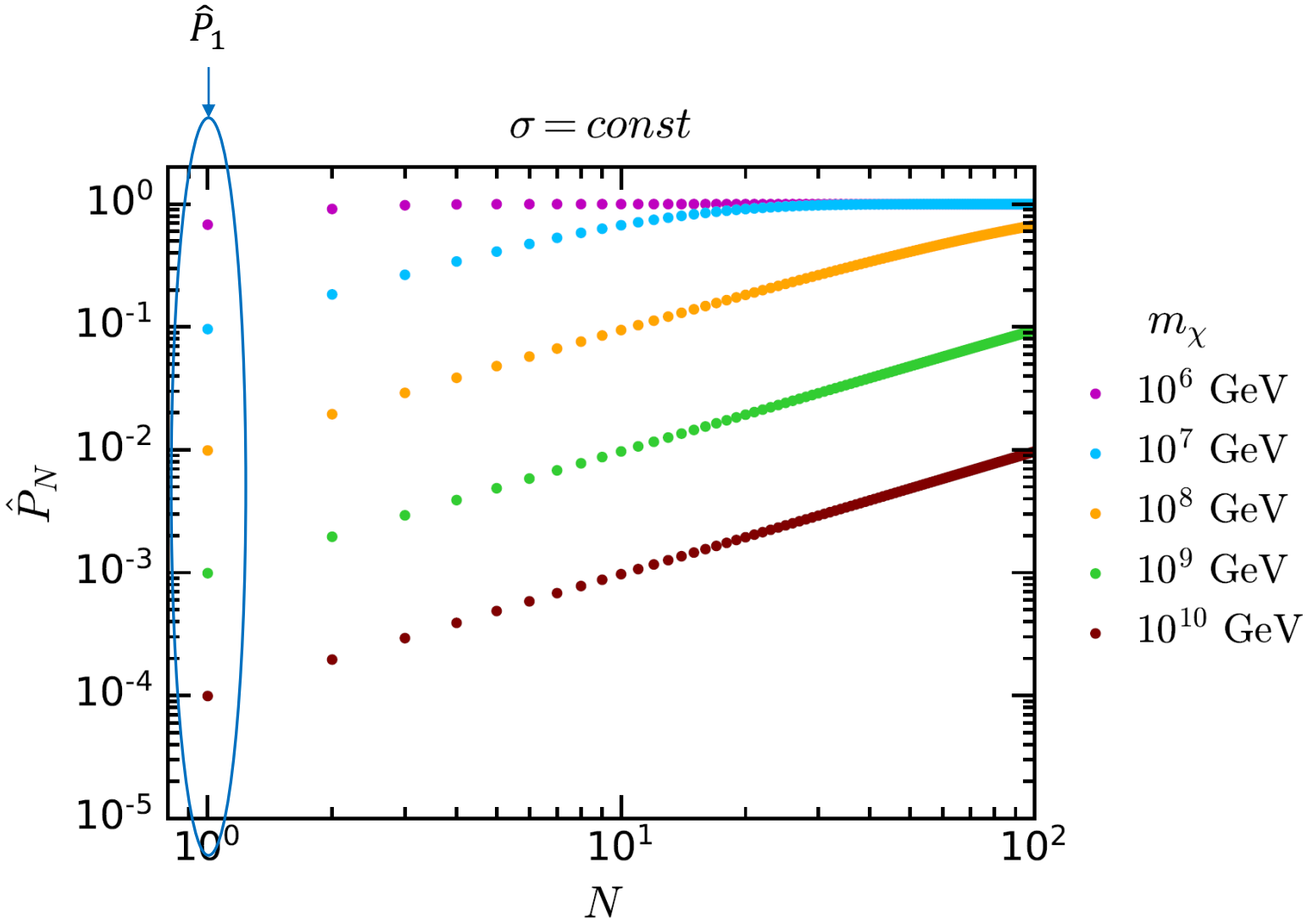
- Assume optically thin regime
- Include factor $\hat{P}_1$ in master equation



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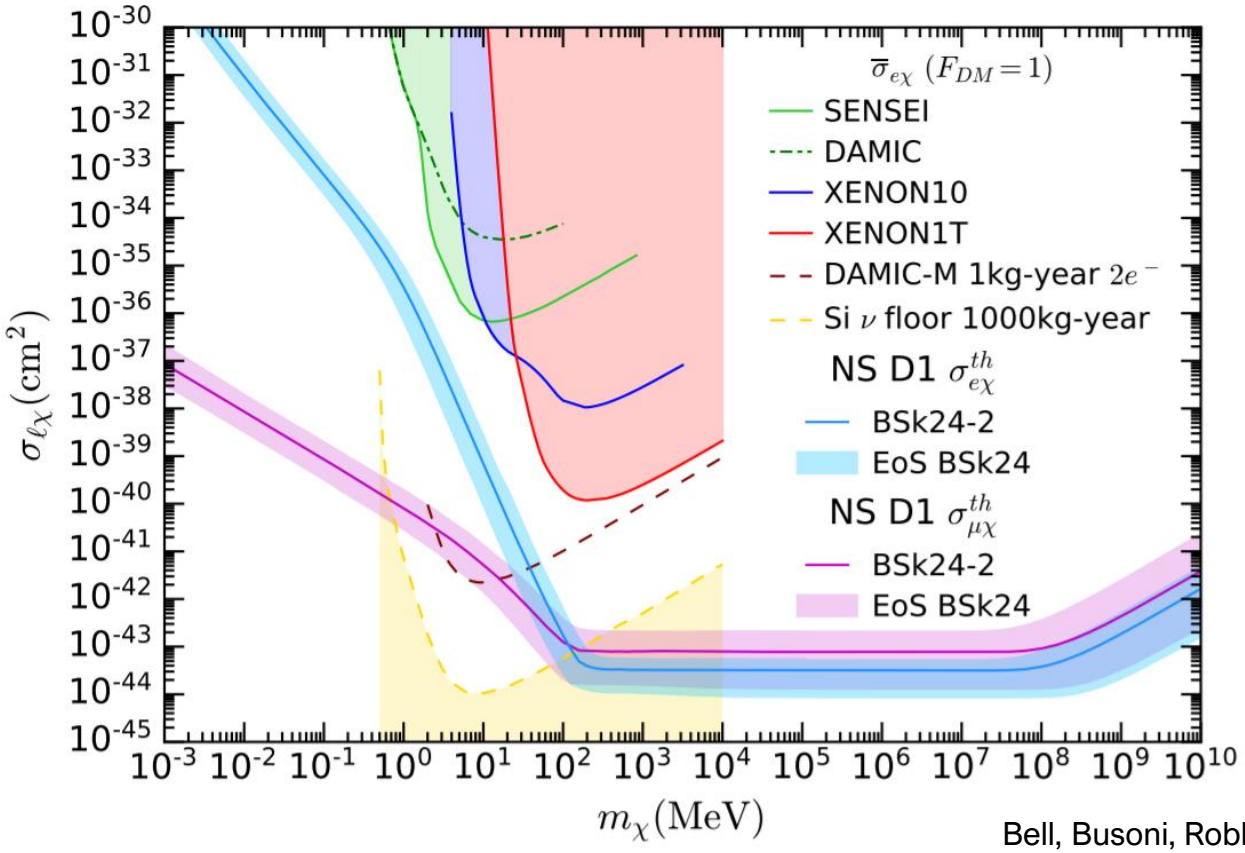
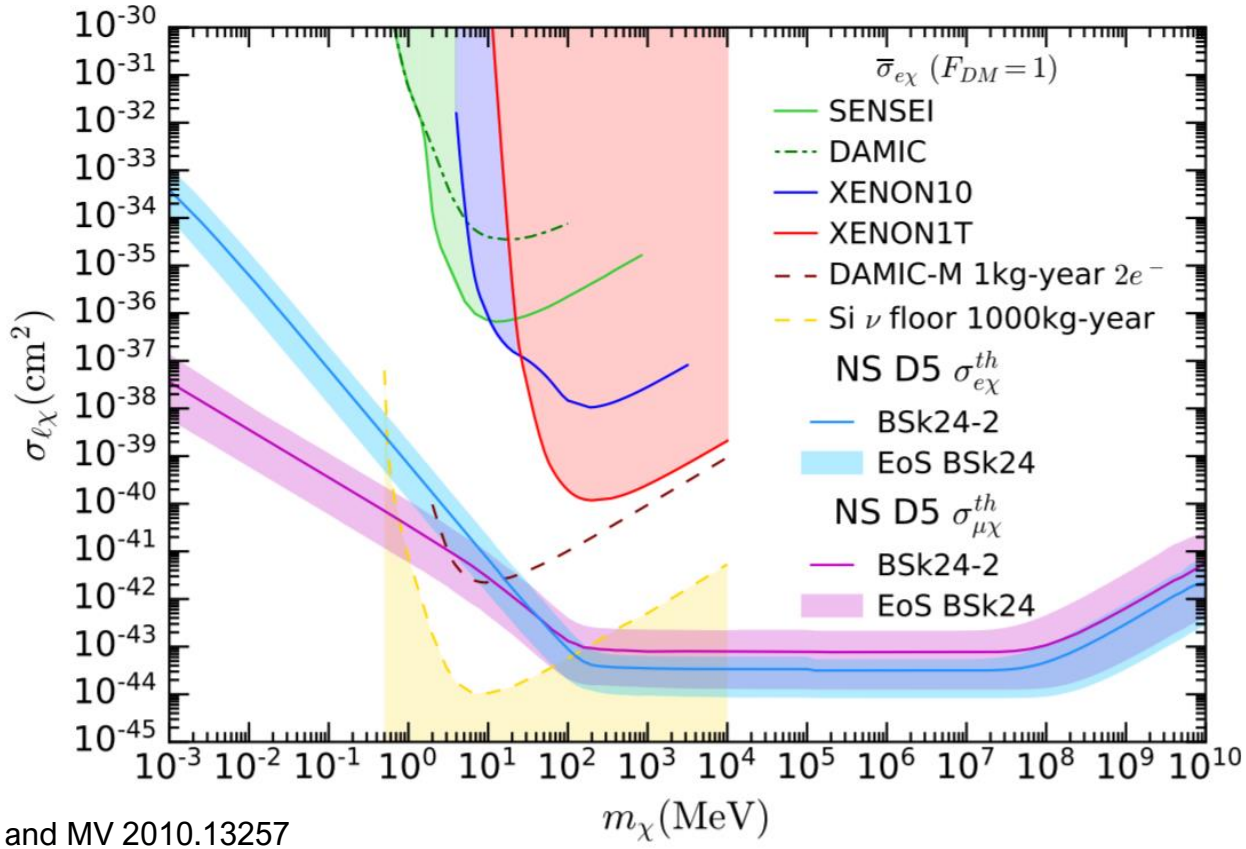
Bell, Busoni, Robles and MV 2004.14888

Lepton Threshold Cross Sections

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



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



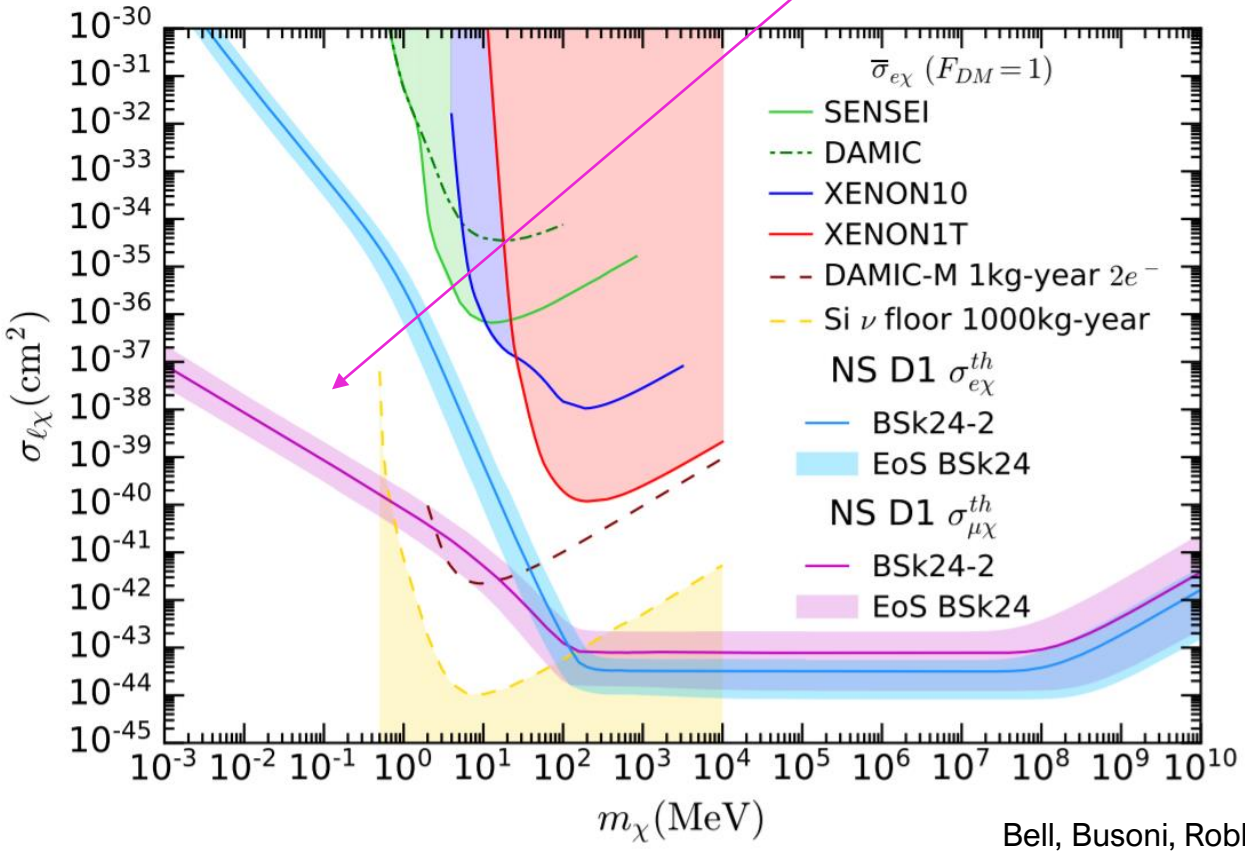
Bell, Busoni, Robles and MV 2010.13257

Lepton Threshold Cross Sections

Muons beat electrons despite lower abundance:

Less Pauli blocked

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



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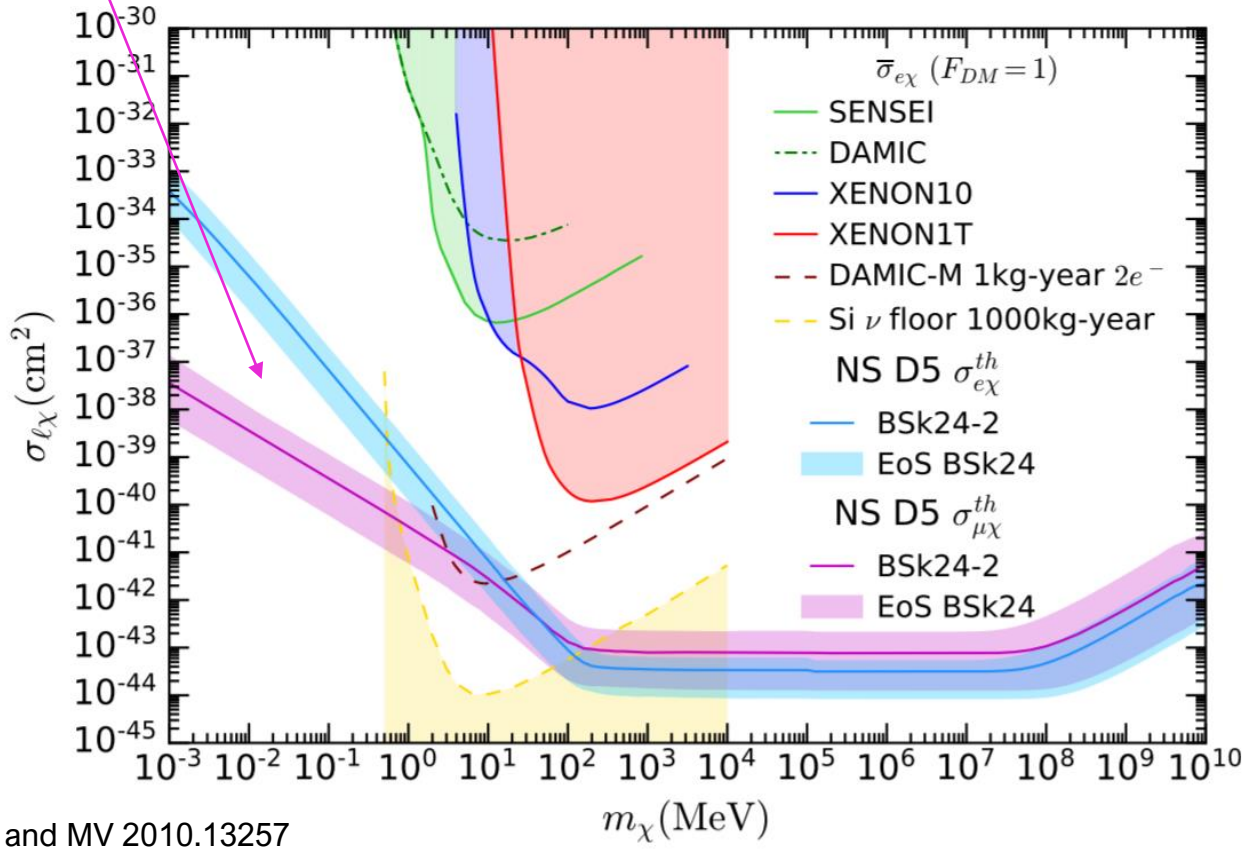
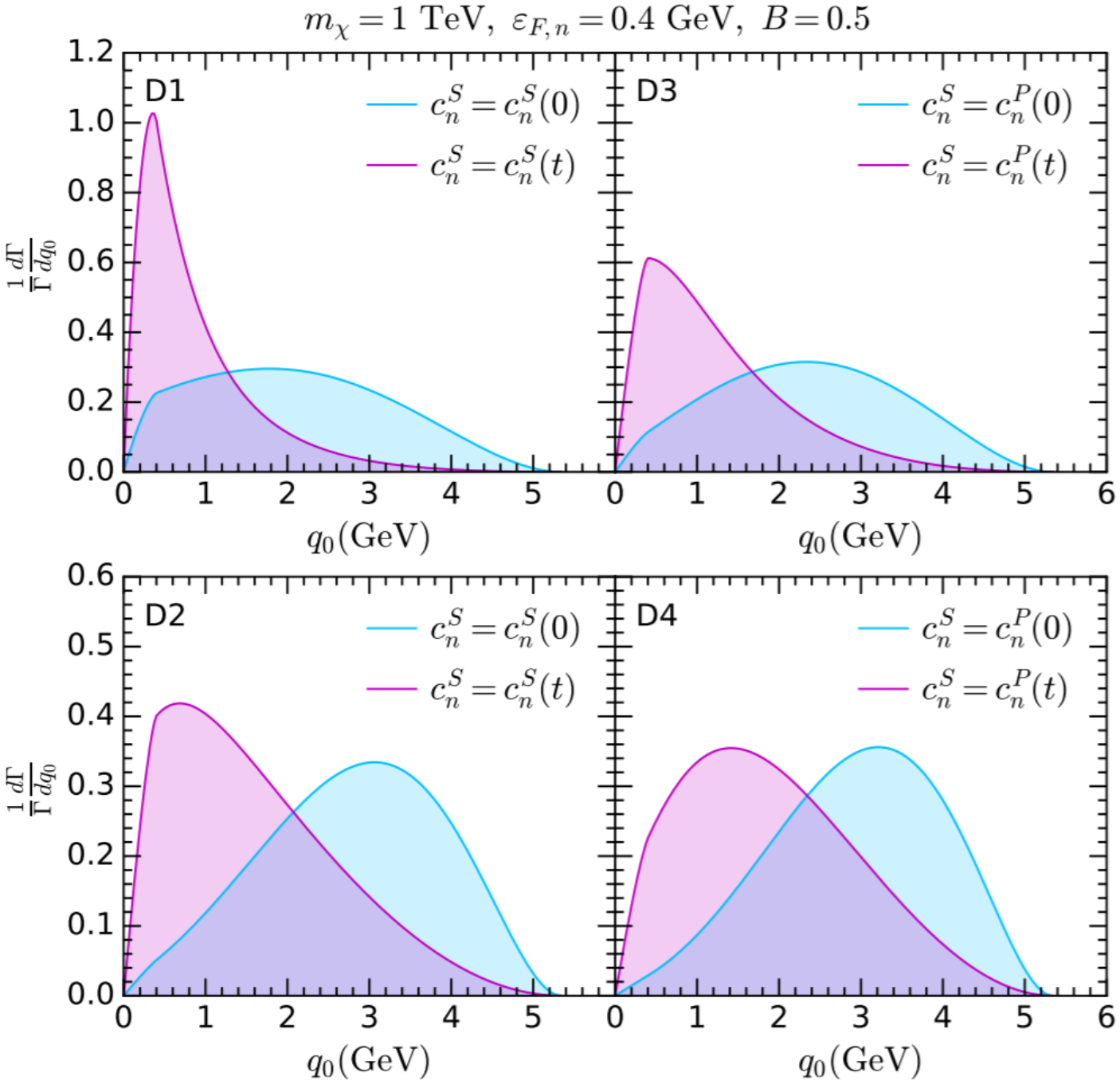


Bell, Busoni, Robles and MV 2010.13257

Nucleon Form Factors



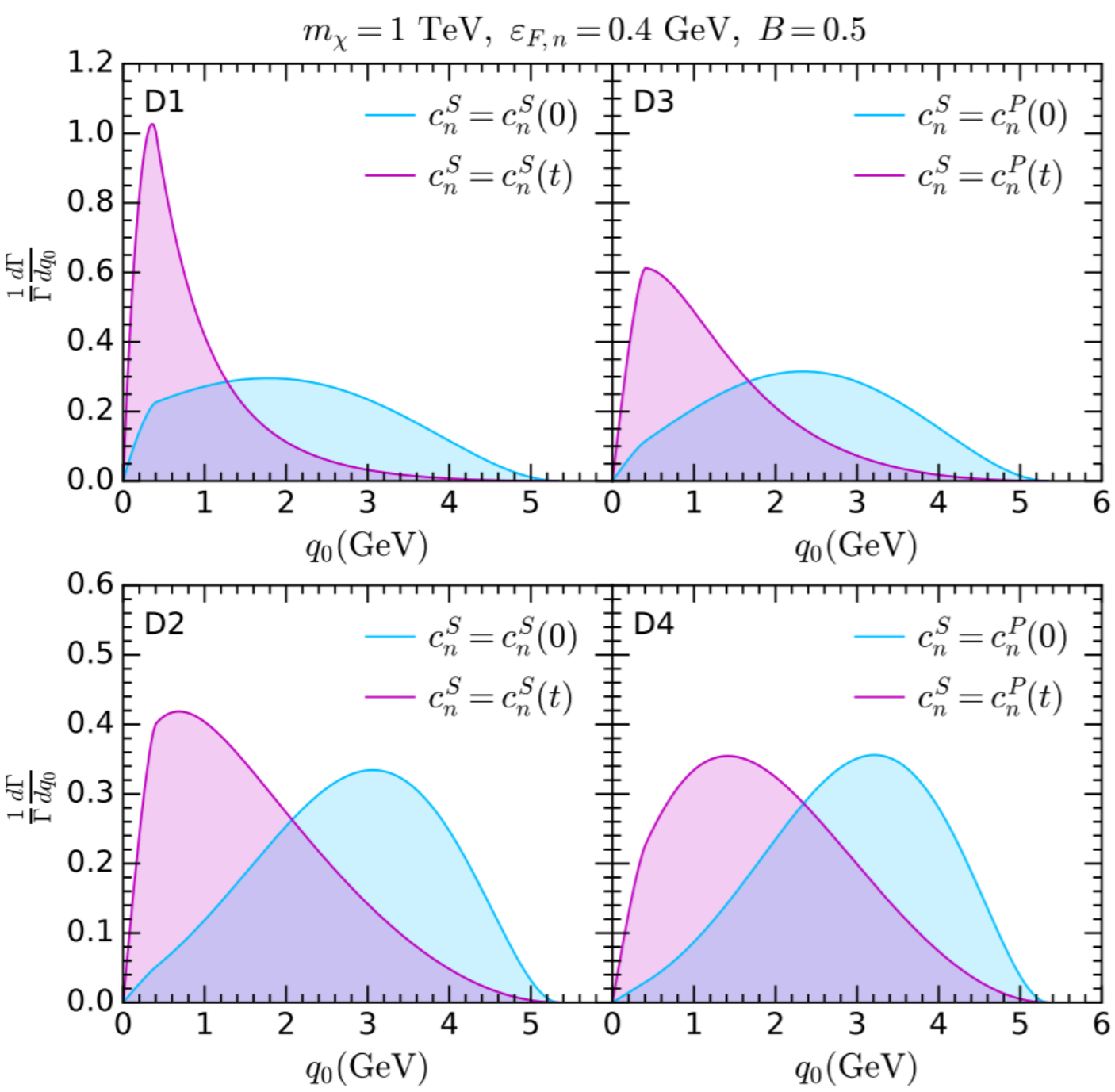
Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

Nucleon Form Factors

- Nucleon form factors are momentum dependent:

$$c_N^i \to \frac{c_N^i}{\left(1 - \frac{t}{Q_0^2}\right)^4}$$

$Q_0 \sim 0.9\ GeV$



Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

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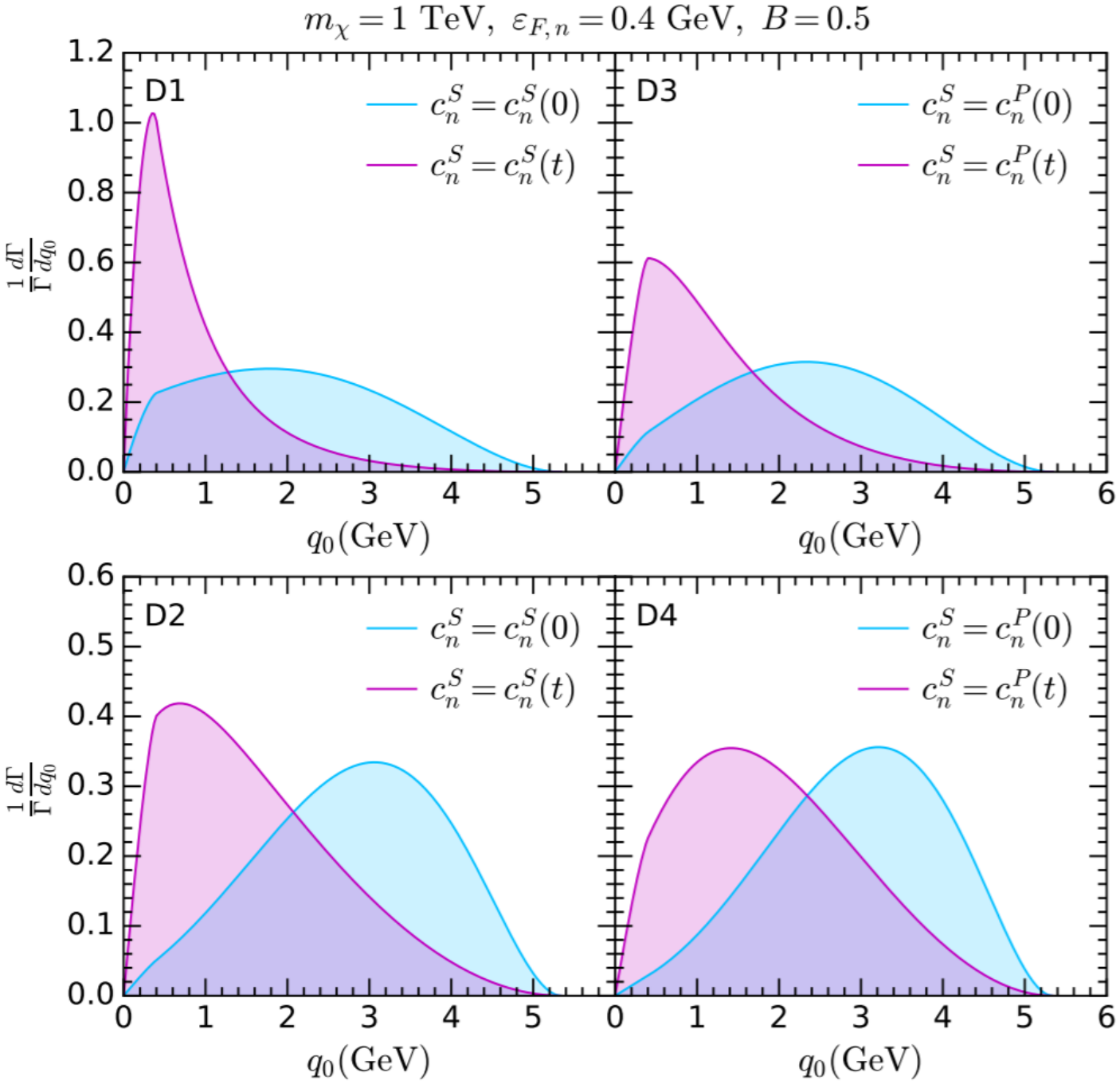

Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

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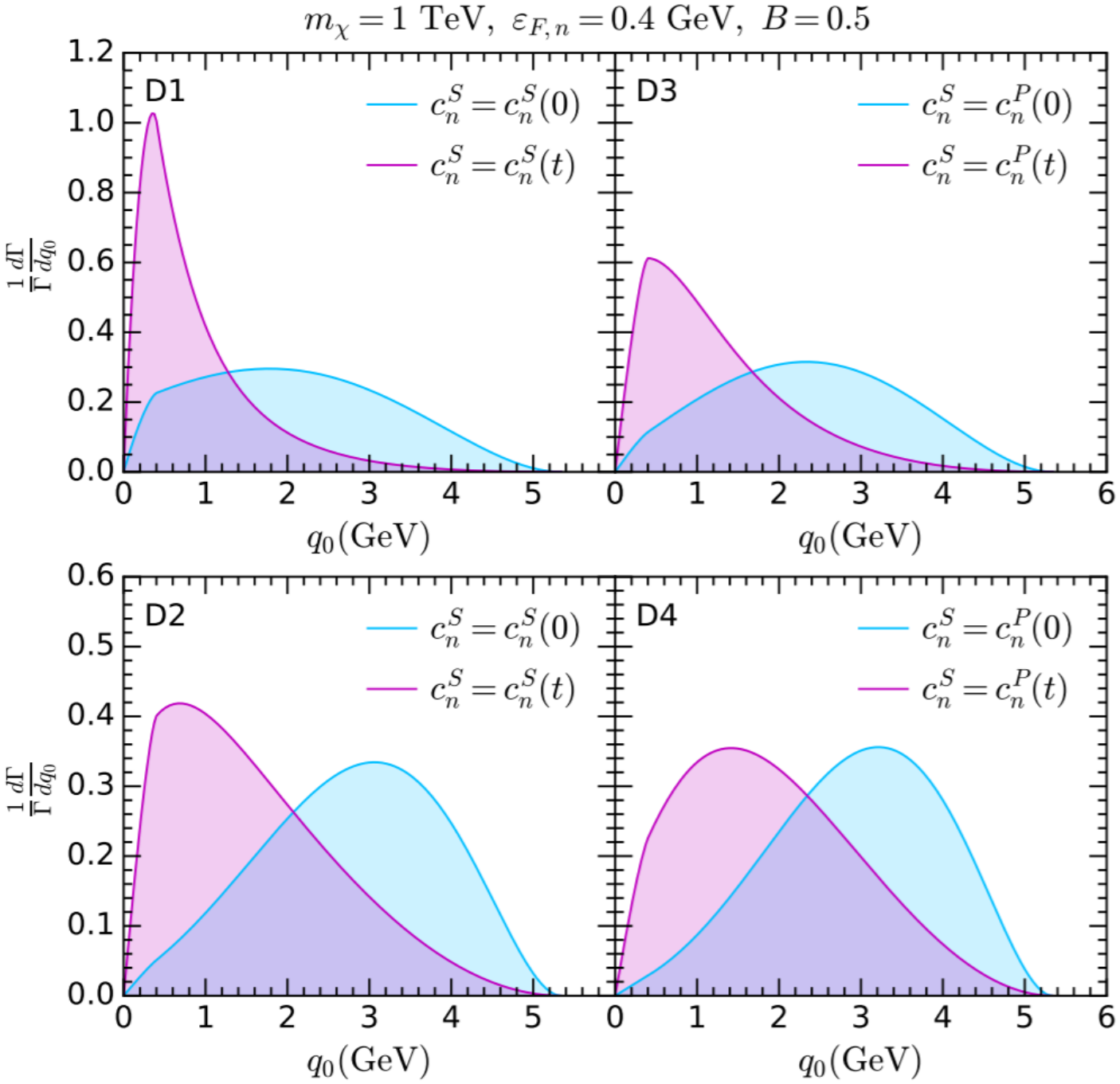
- Supresses interaction rate at large momentum transfers



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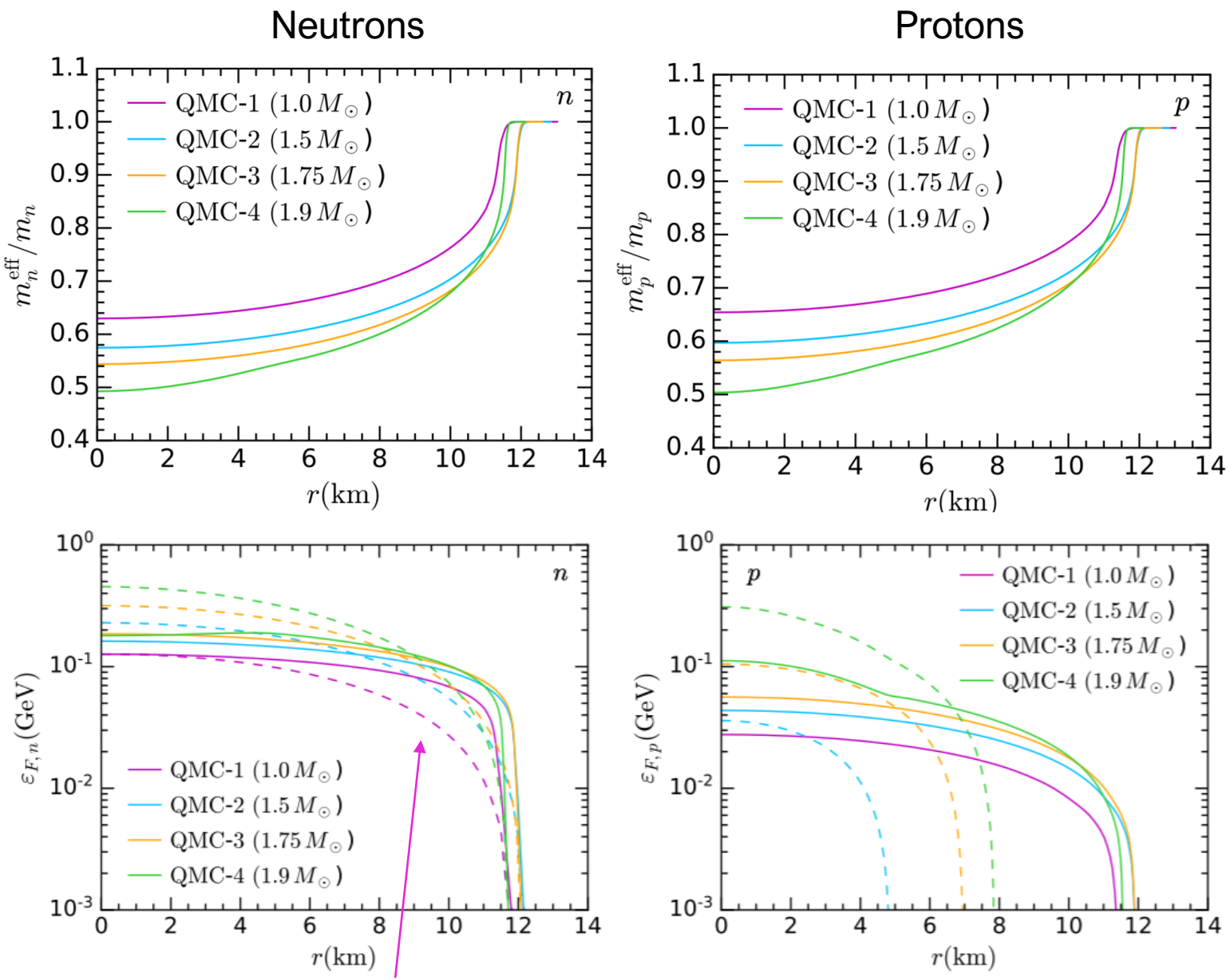
Strongly Interacting Baryons



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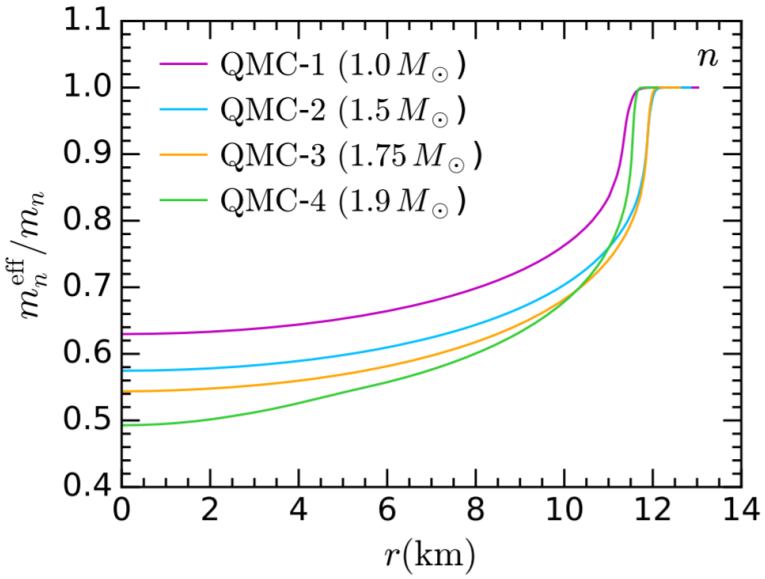
Strongly Interacting Baryons

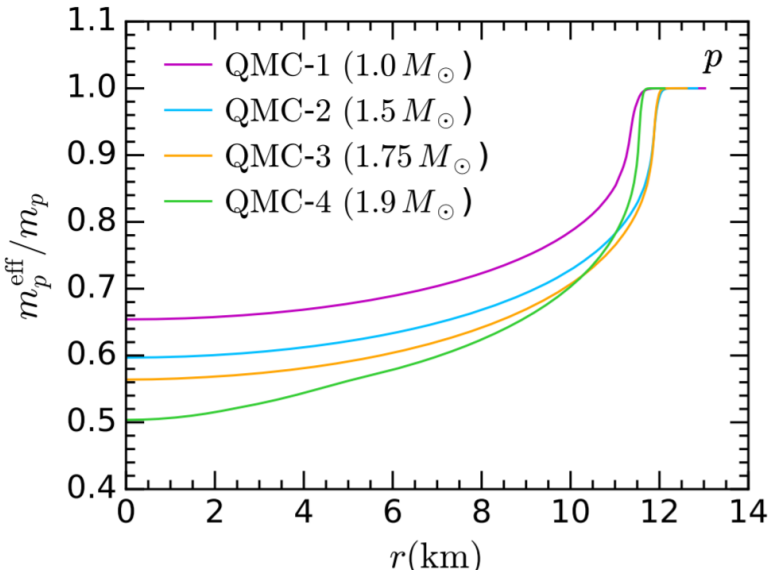
- Nucleons develop an effective mass

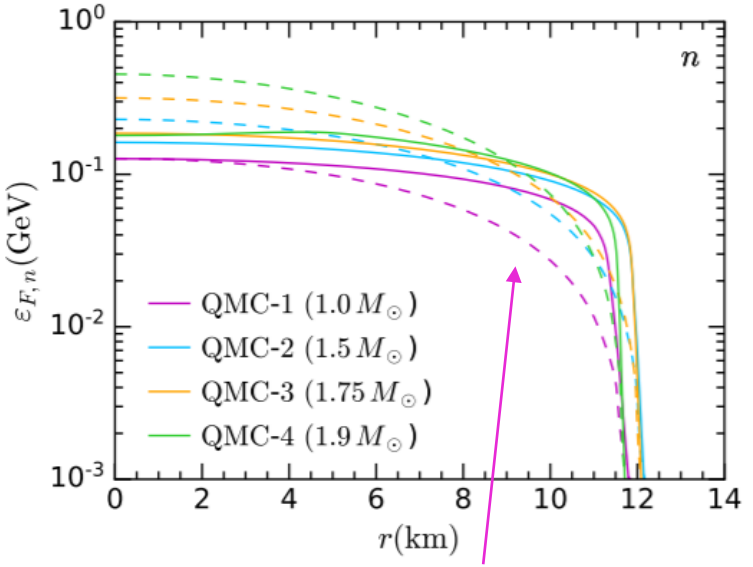
$$m_N^{eff} \leq m_N$$

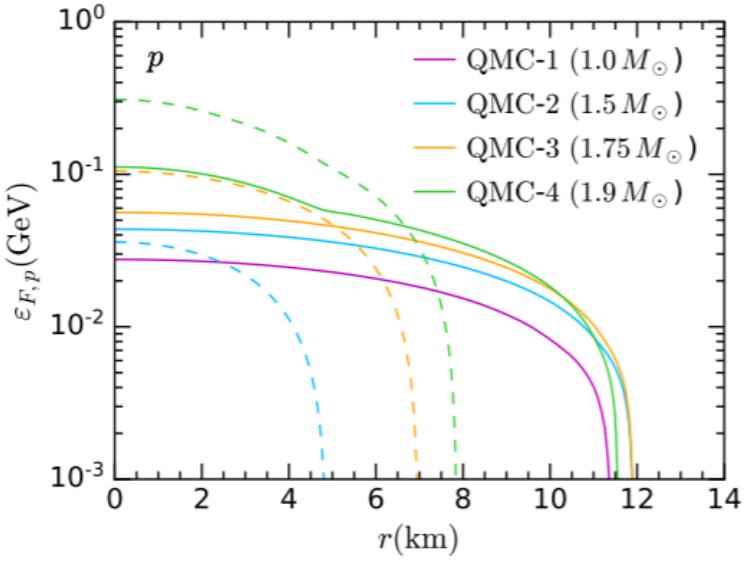
Neutrons



Protons







Dashed: Free Fermi gas

Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

Strongly Interacting Baryons

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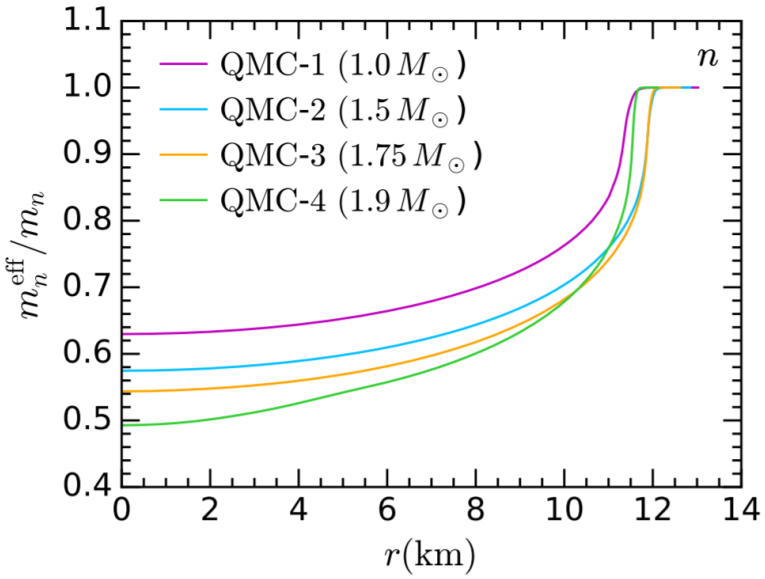
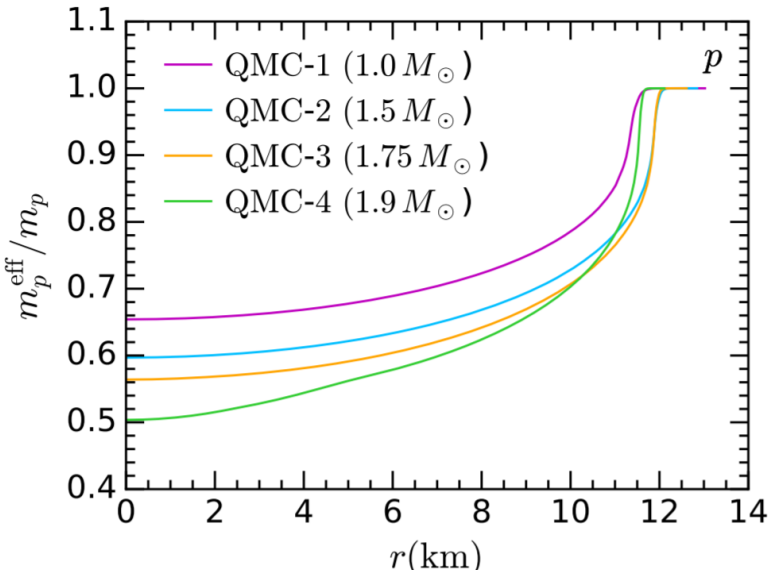
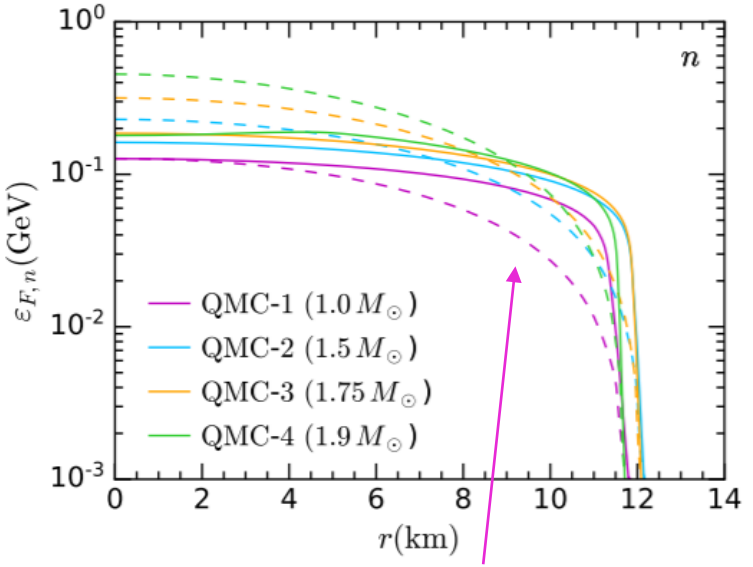
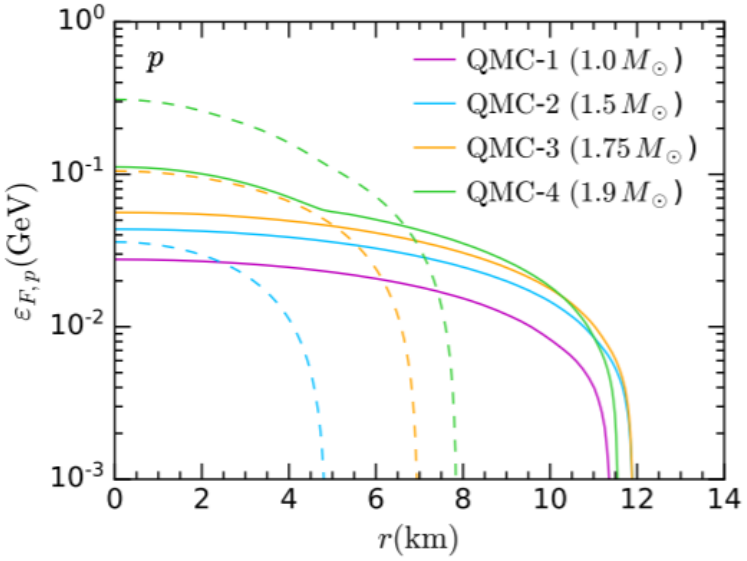
Neutrons



Protons







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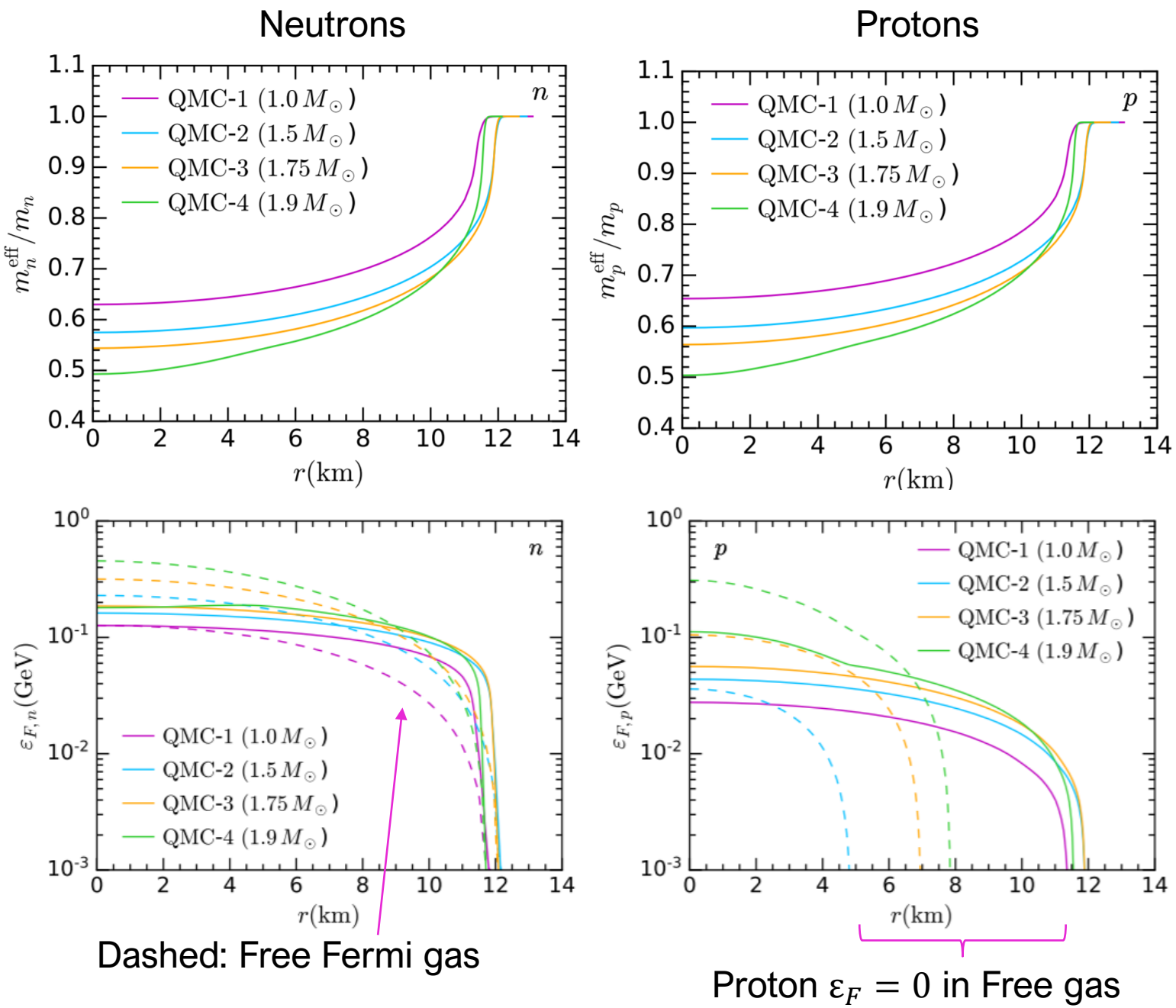
Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

Strongly Interacting Baryons

- Nucleons develop an effective mass

$$m_N^{eff} \leq m_N$$

- Fermi energy, ε_F, significantly different for protons
- Protons non-degenerate in outer regions of NS in Free gas model



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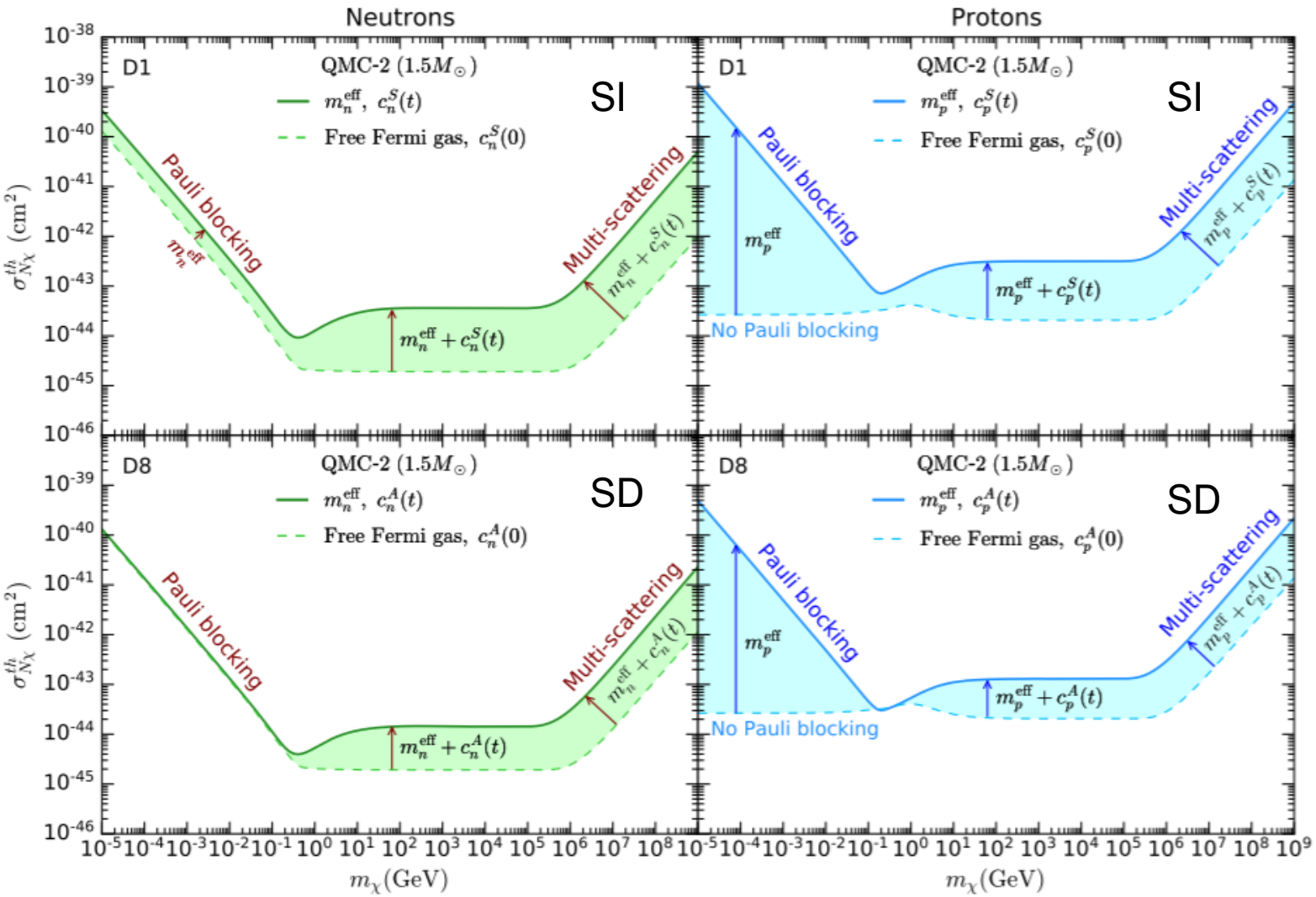
Nucleon Threshold Cross Sections

- Dashed lines:
  - Free-Fermi Gas
  - No momentum dep. FF
- Solid:
  - Interacting Baryons
  - Momentum dep. FF



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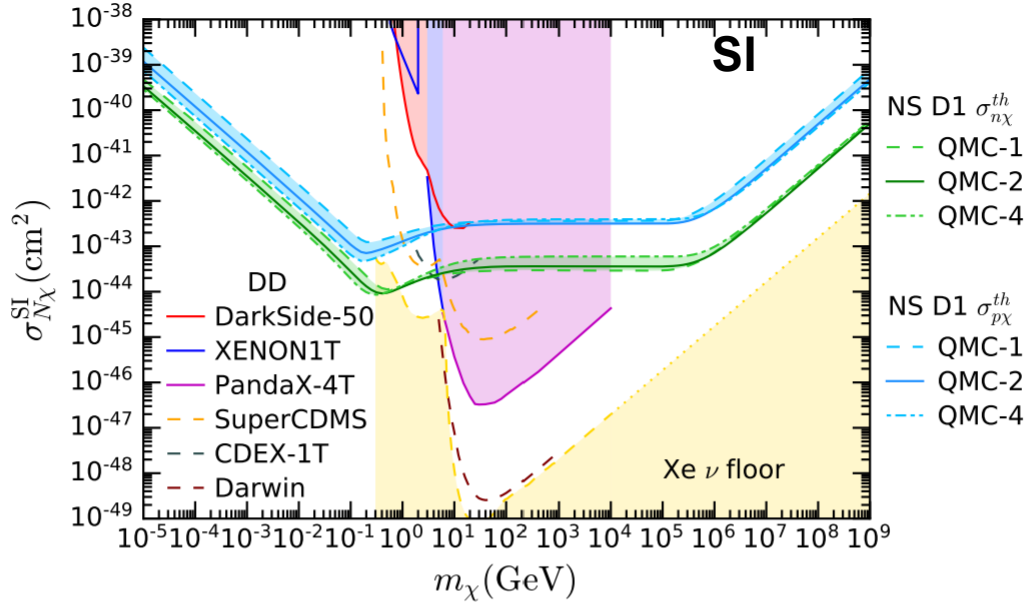
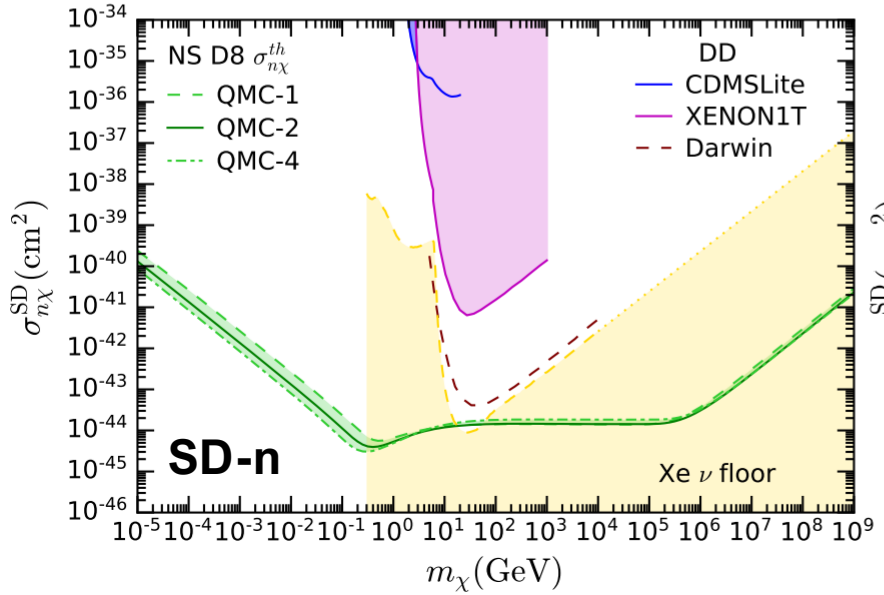
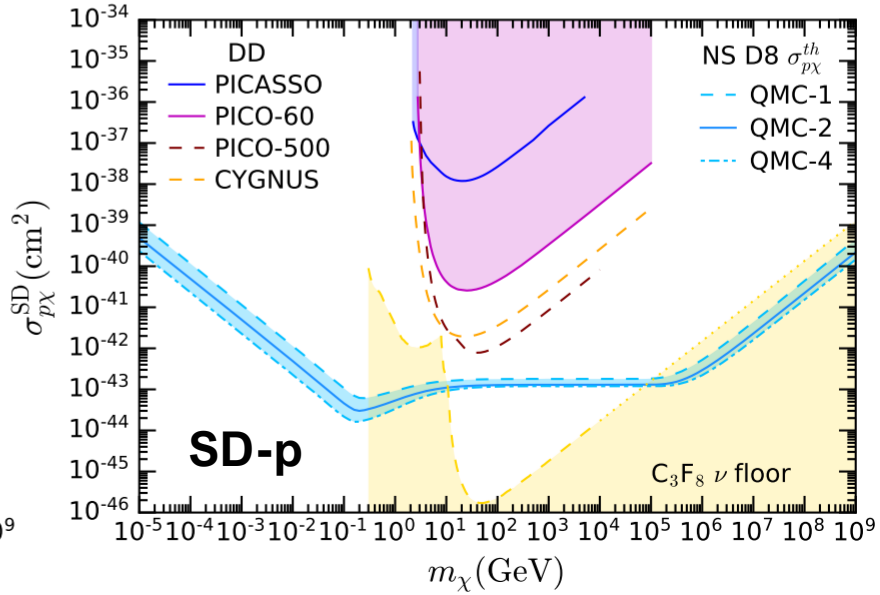
Nucleon Threshold Cross Sections







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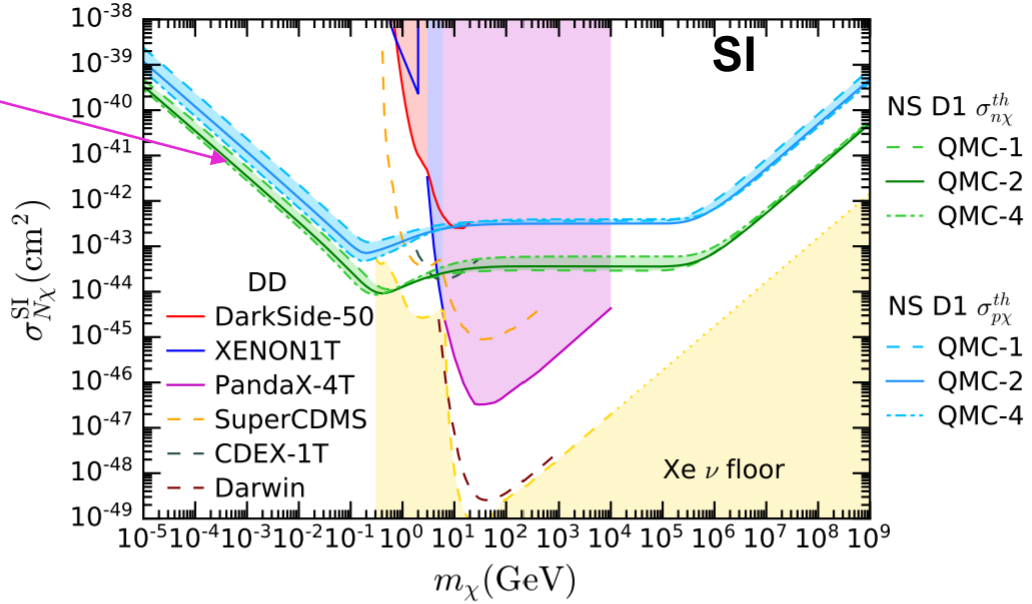
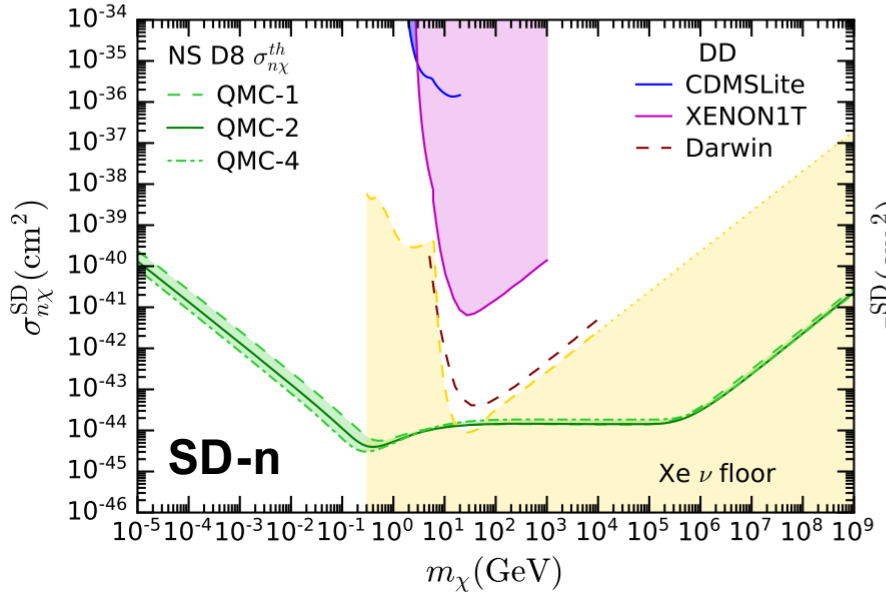
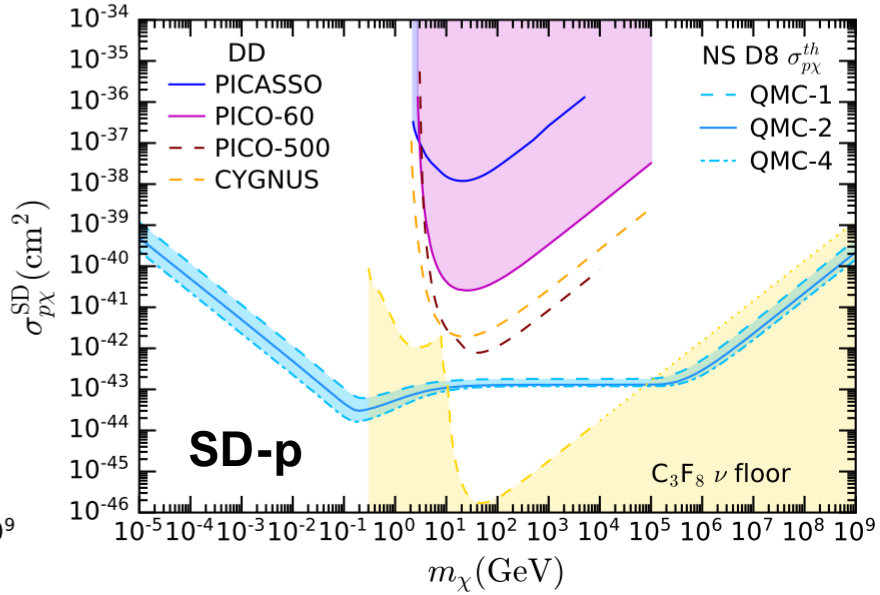
Nucleon Threshold Cross Sections

Pauli Blocking:
$\sigma_{th} \propto 1/m_\chi$







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Multiple Scattering:
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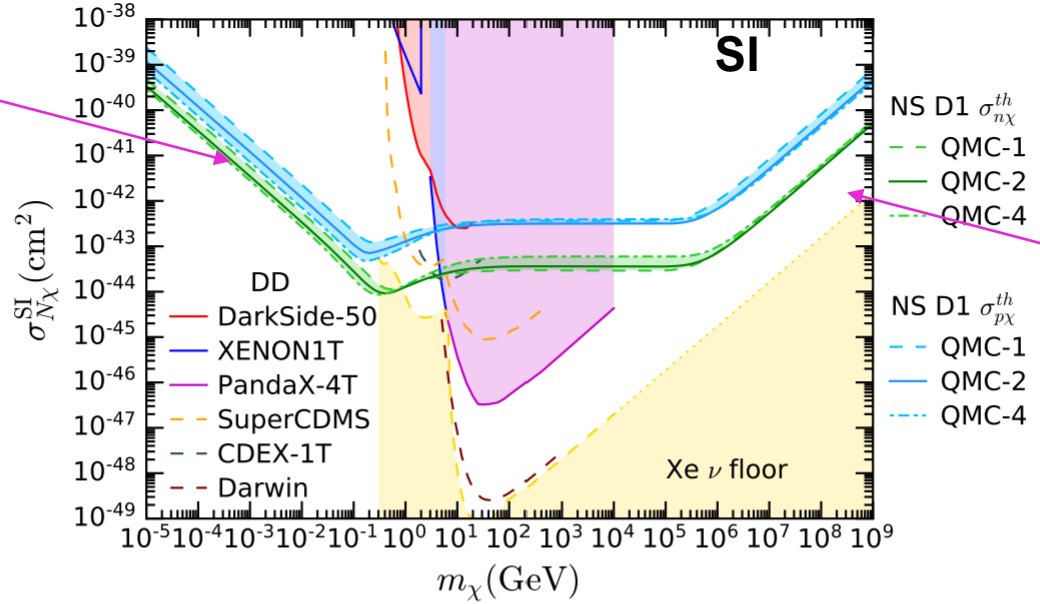

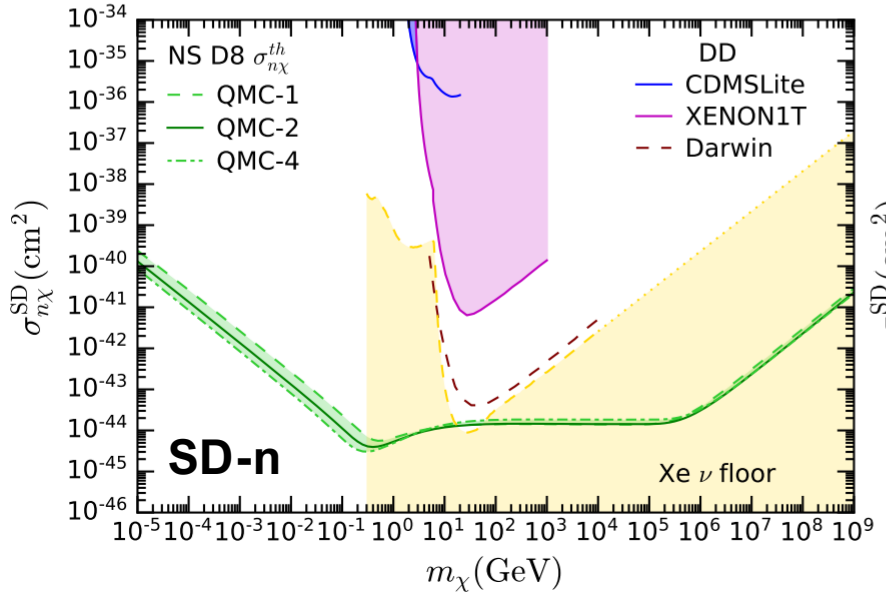

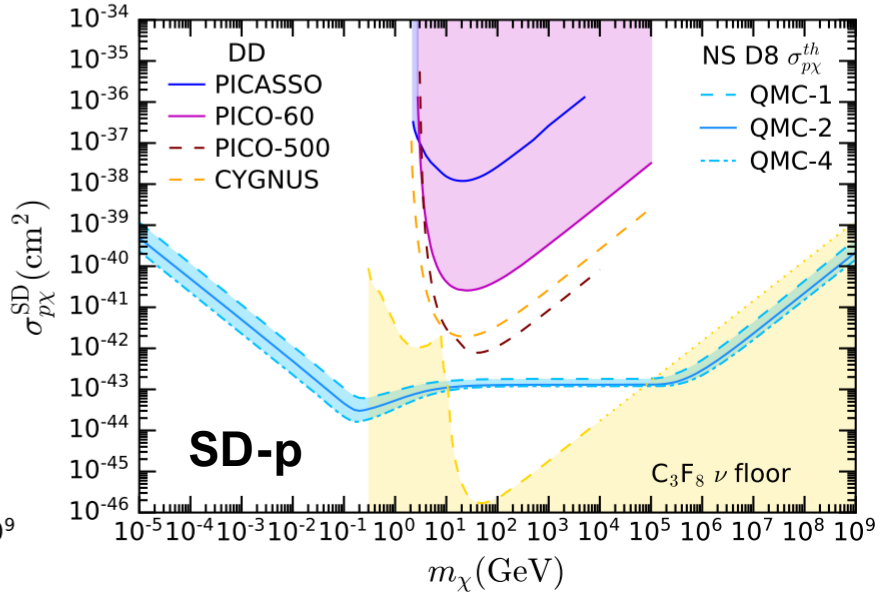

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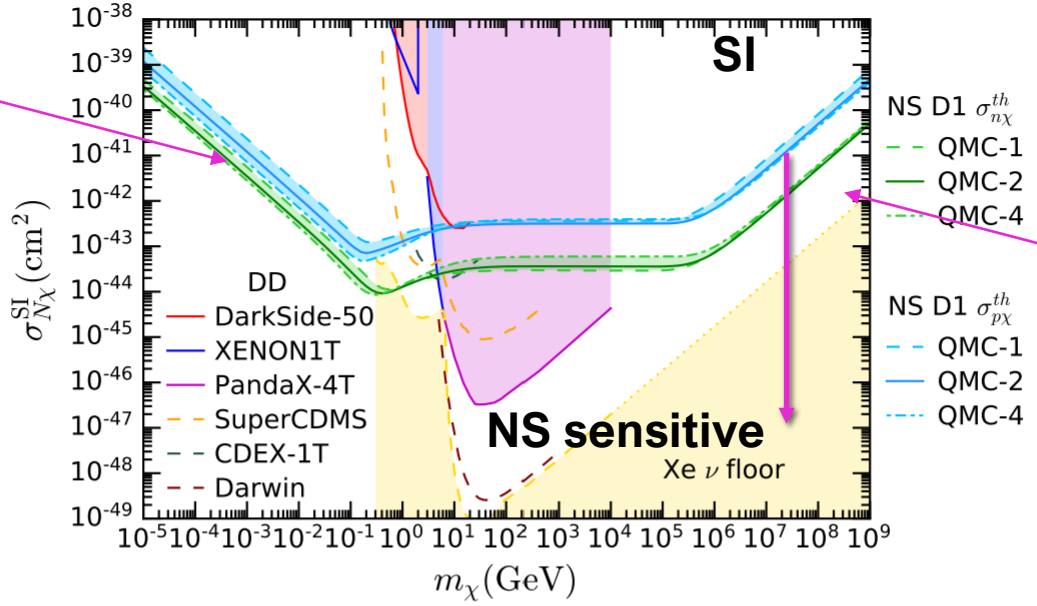

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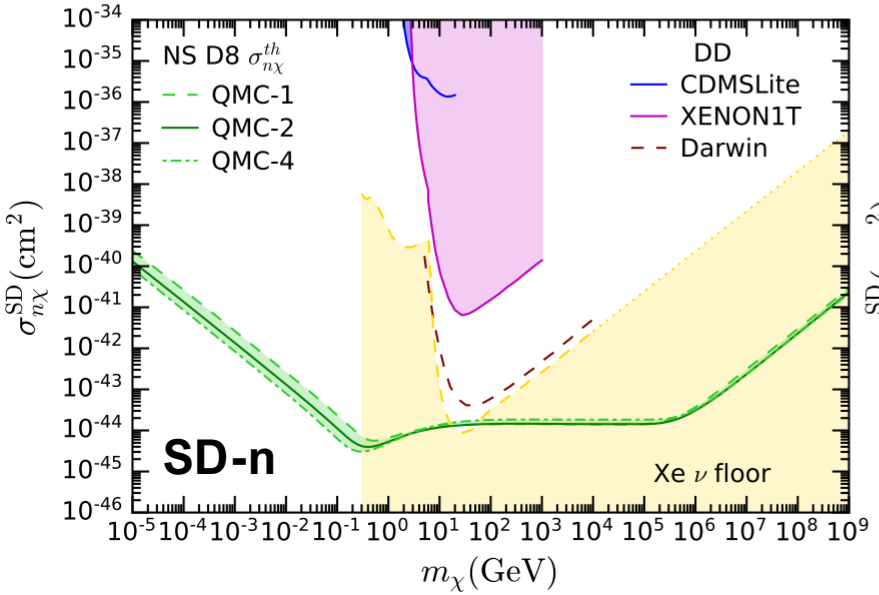
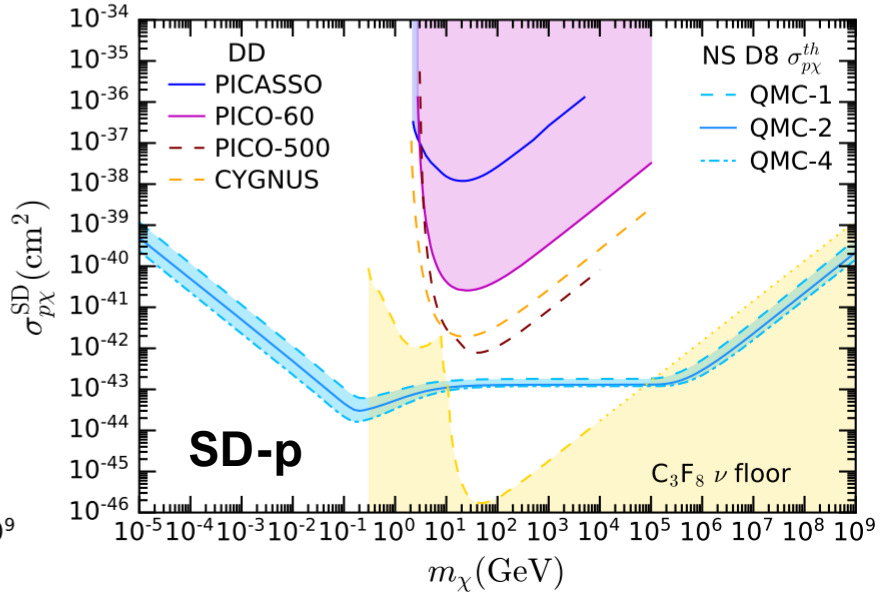


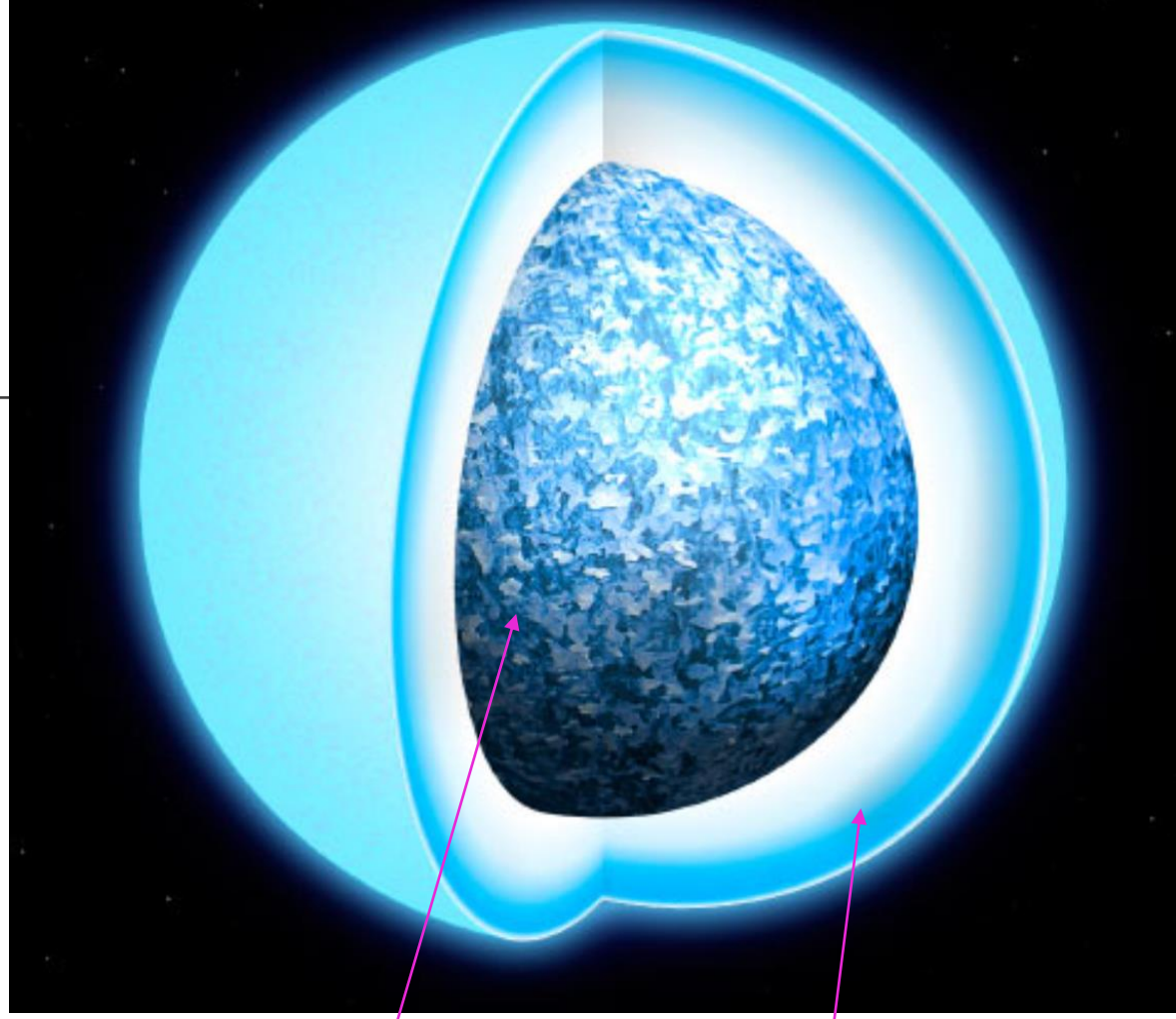


Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

White Dwarfs

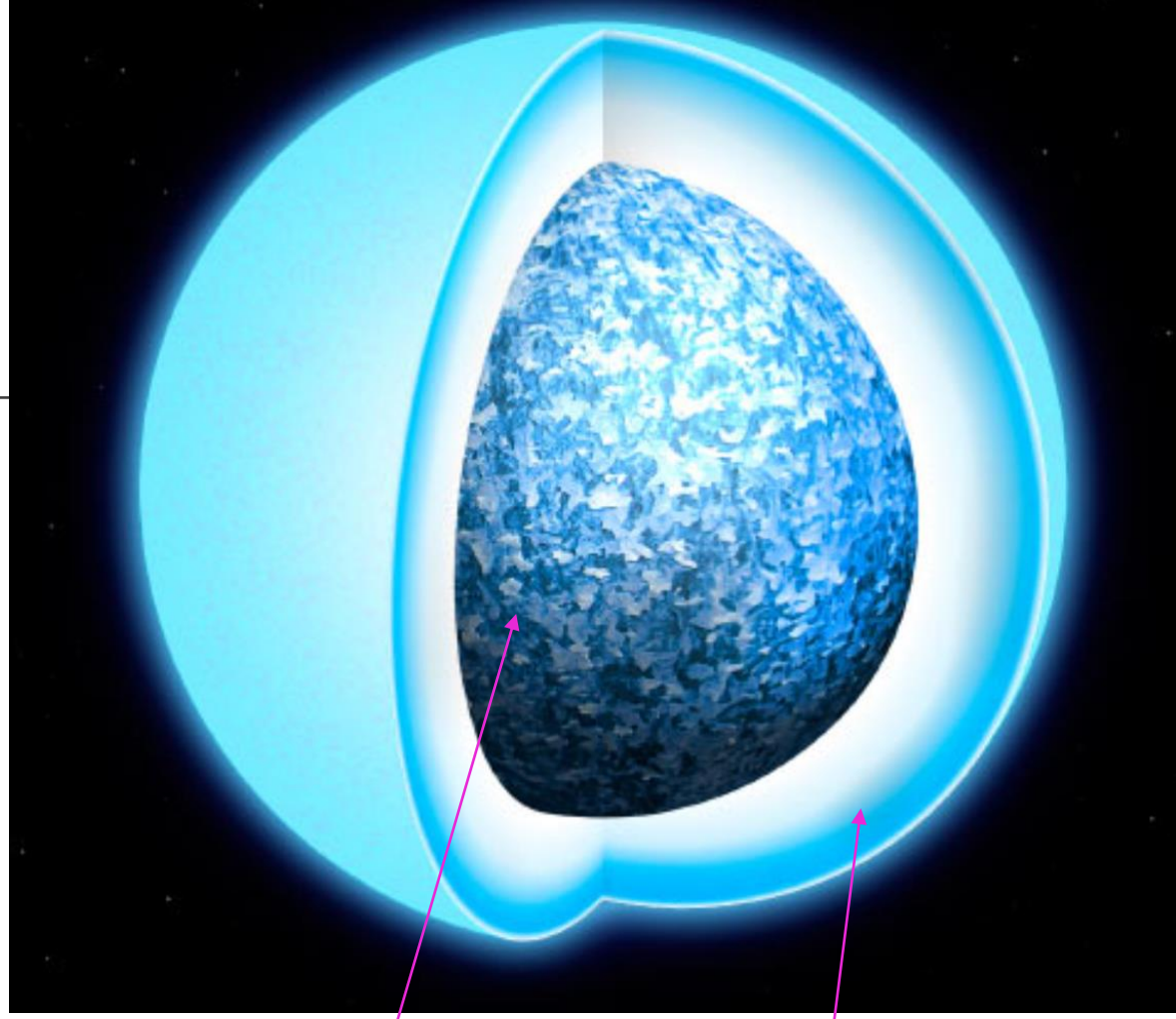
DM CAPTURE AND HEATING IN GLOBULAR CLUSTER M4

White Dwarfs



White Dwarfs

- Ions in Coulomb lattice (if crystalised)



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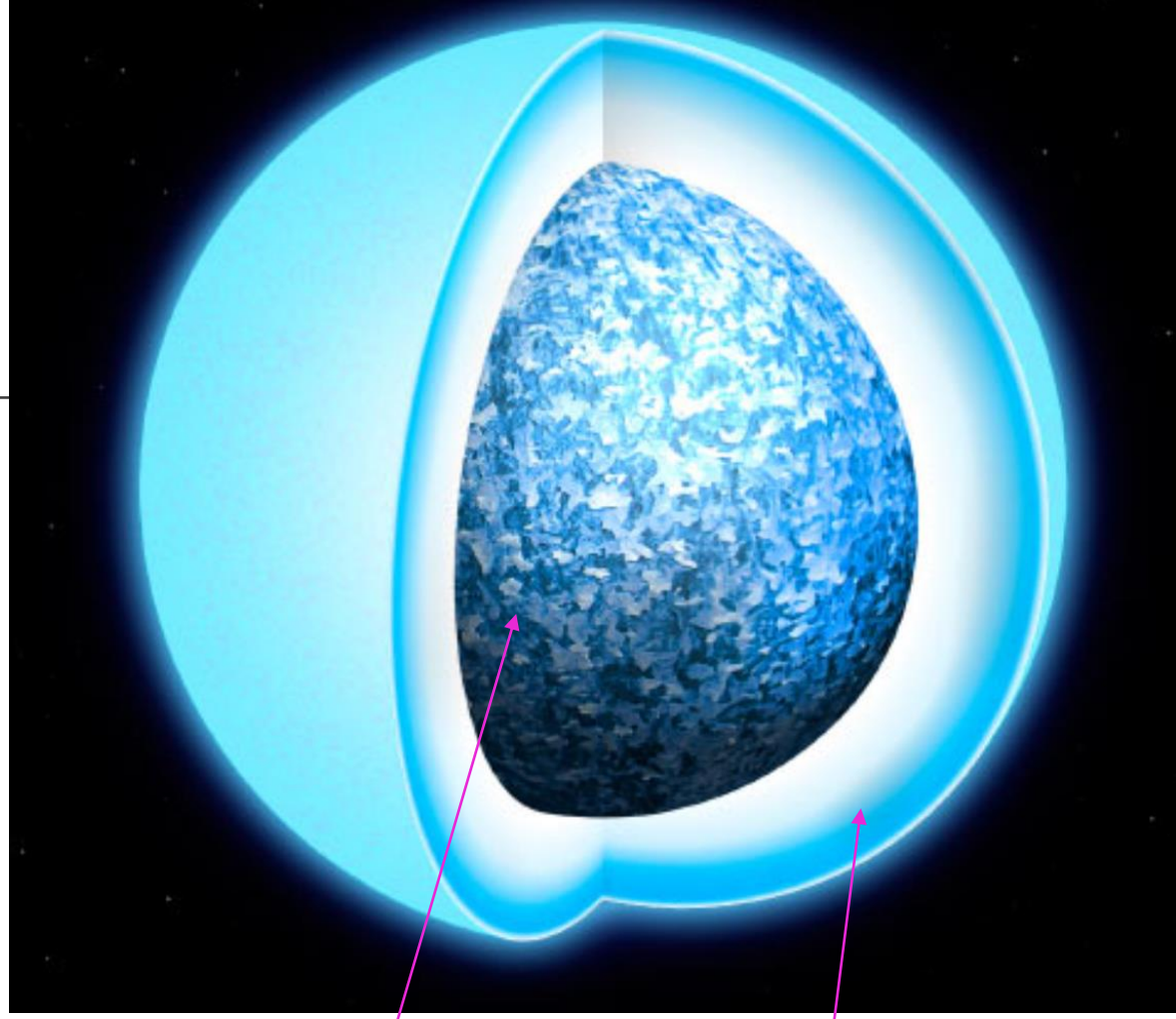
  - Perfect for new formalism!



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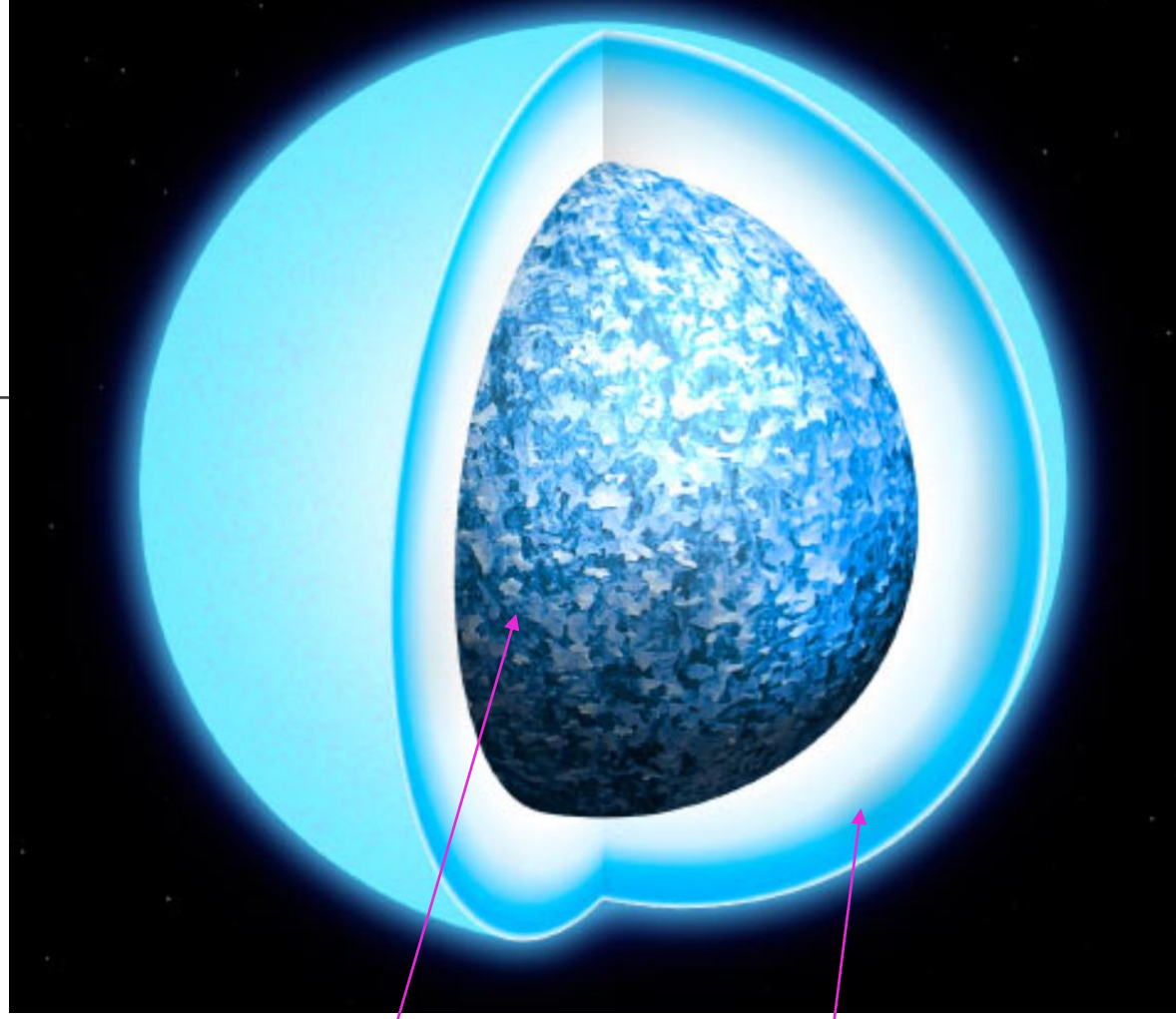

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  - Closest GC ($1.9\ kpc$)
  - Age $11.6\ Gyrs$
  - $\rho_\chi = \mathbf{798}\ (\mathbf{532})\ GeV/cm^3$ for (un)contracted halo (McCullough, Fairbairn 1001.2737)
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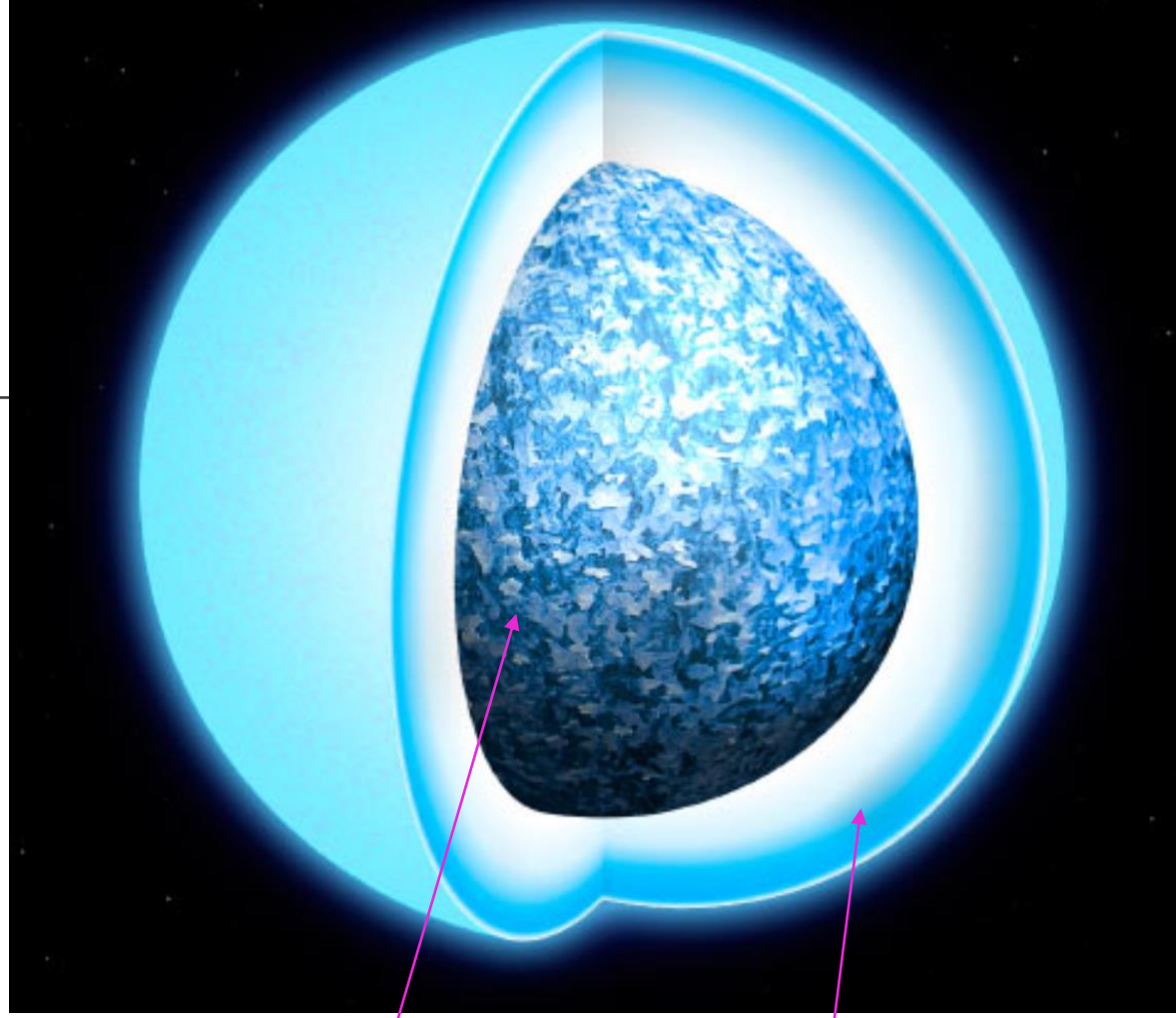

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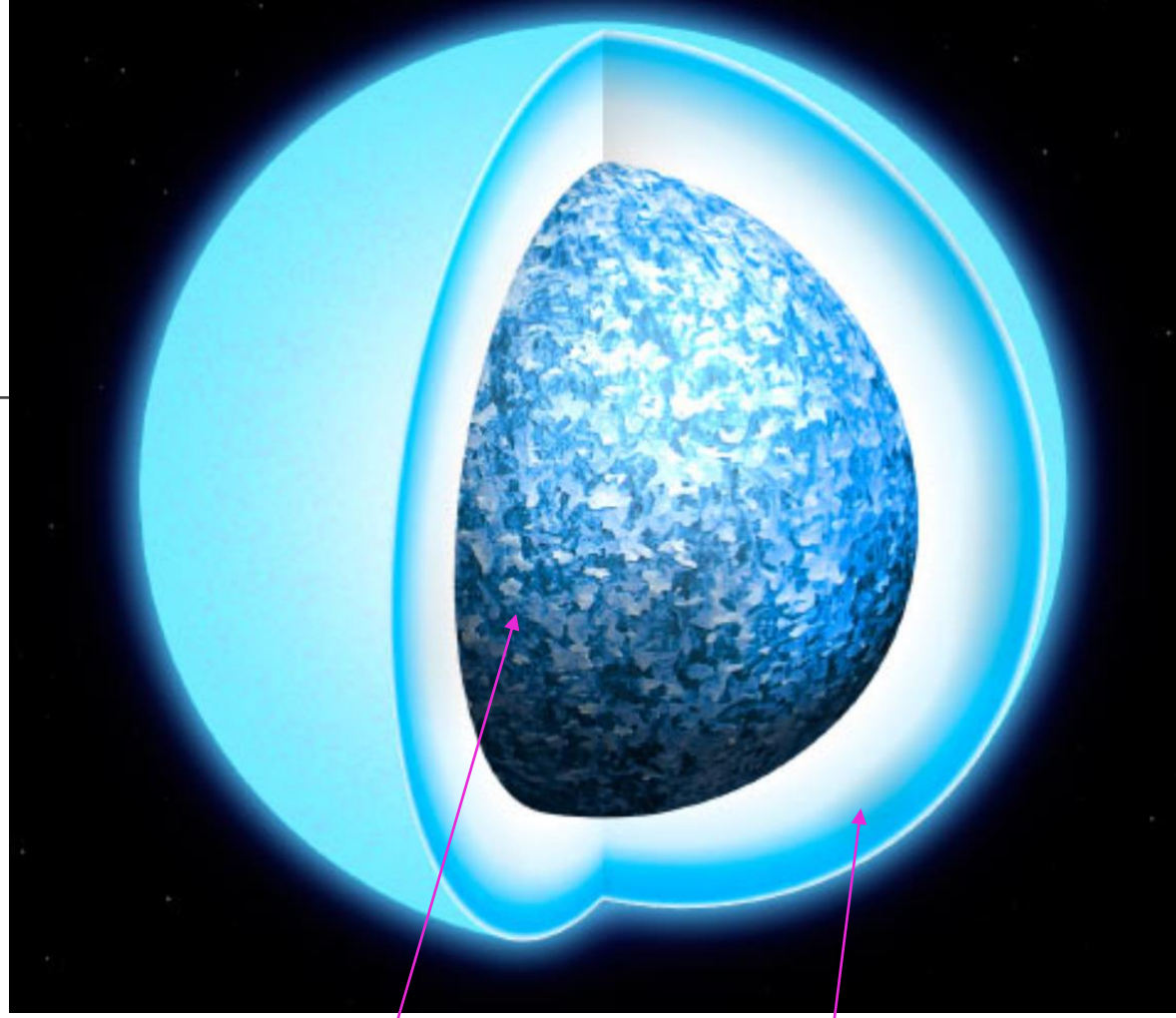
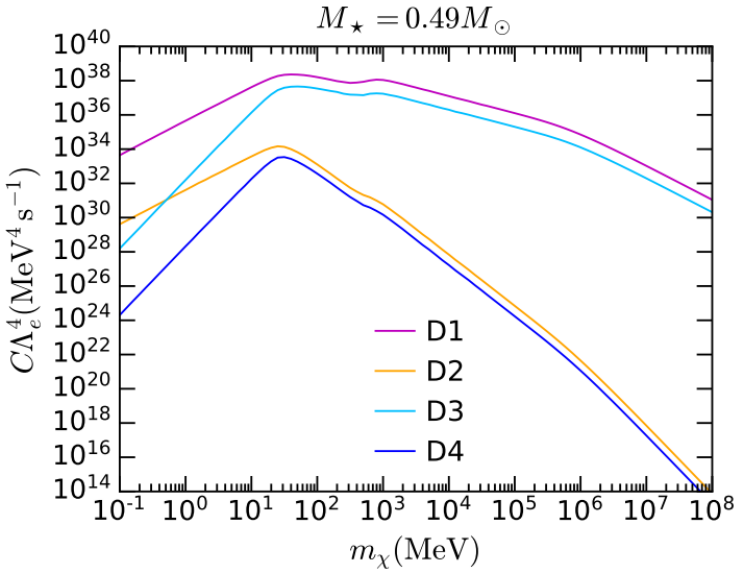
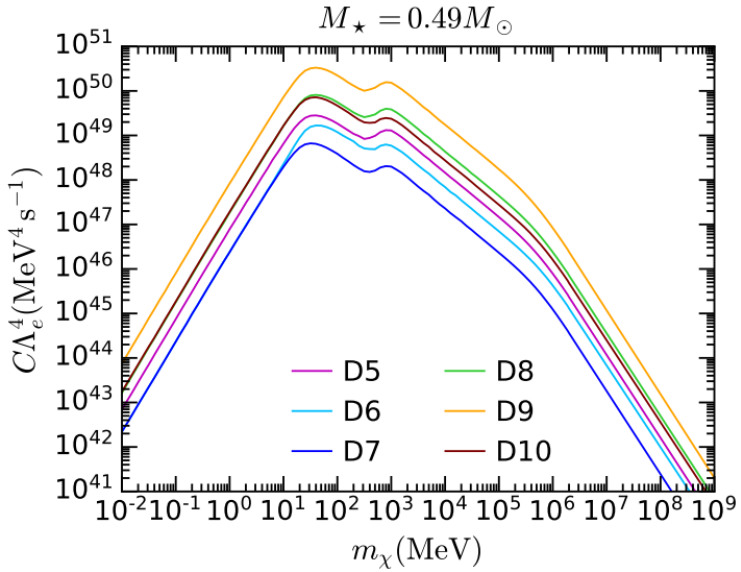
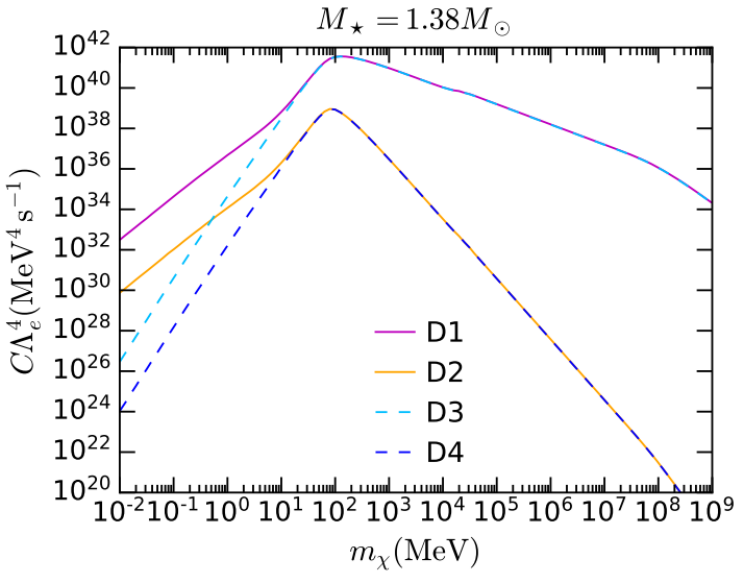
  - May/may not contain DM…

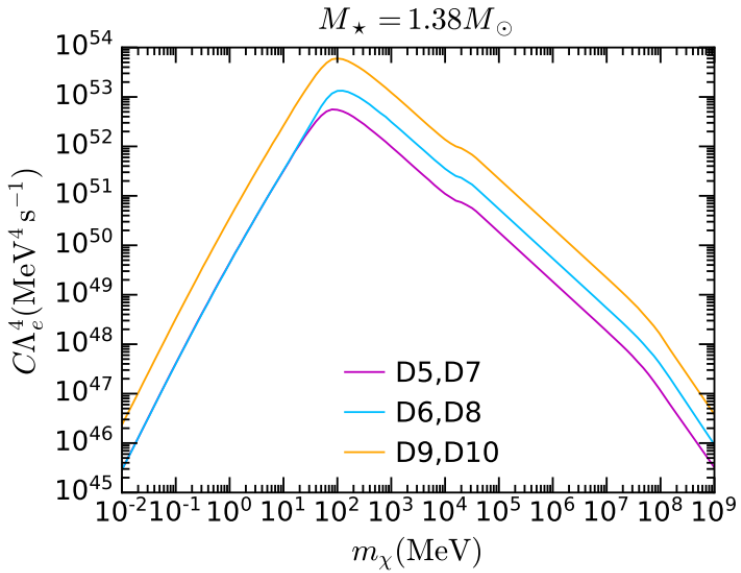


Capture on Electrons





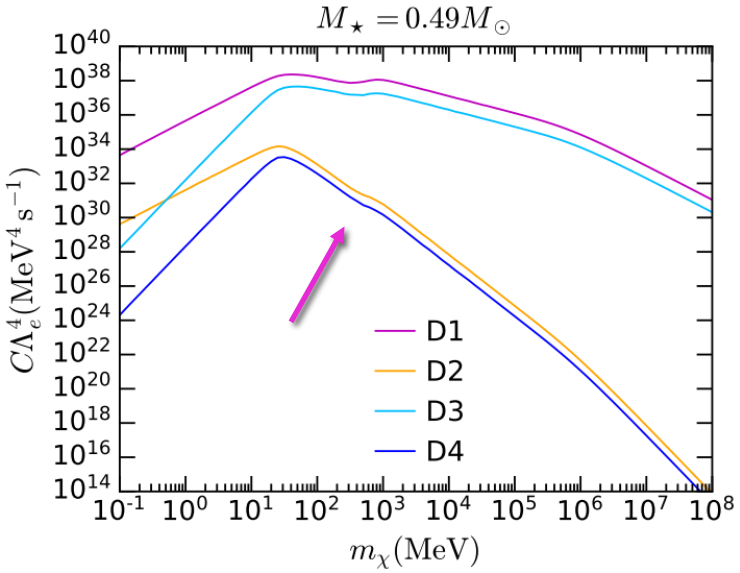


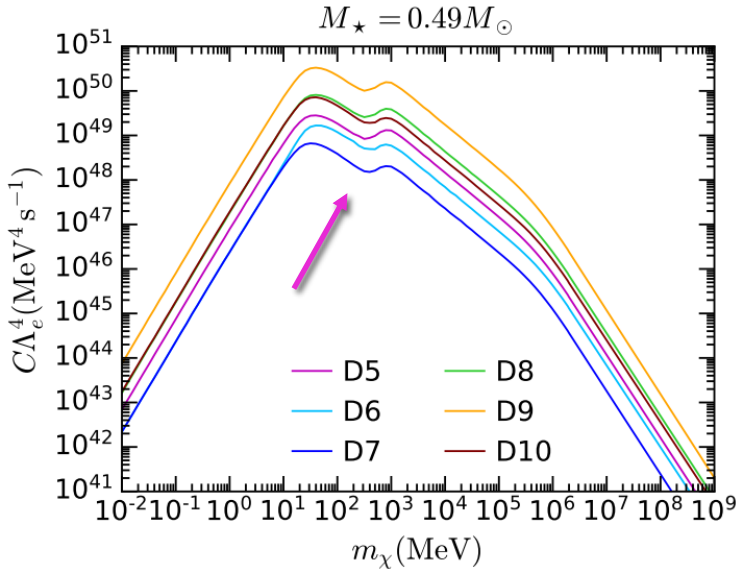


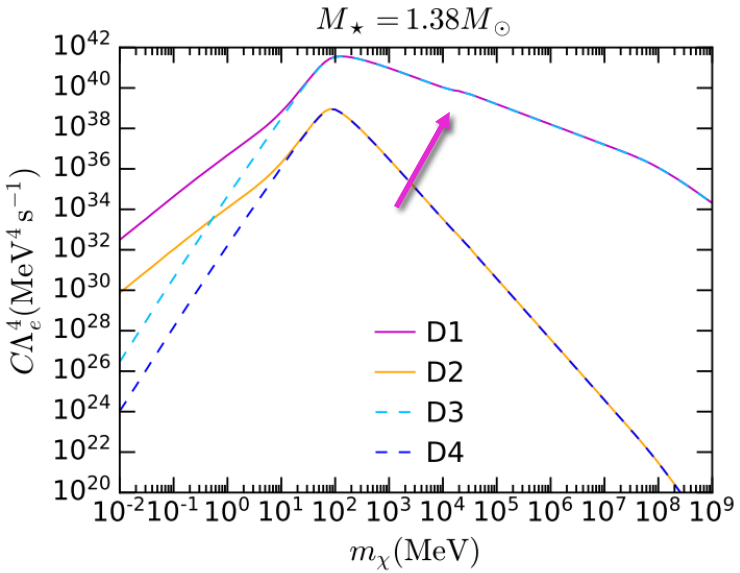
Bell, Busoni, Robles, Ramirez, MV 2104.14367

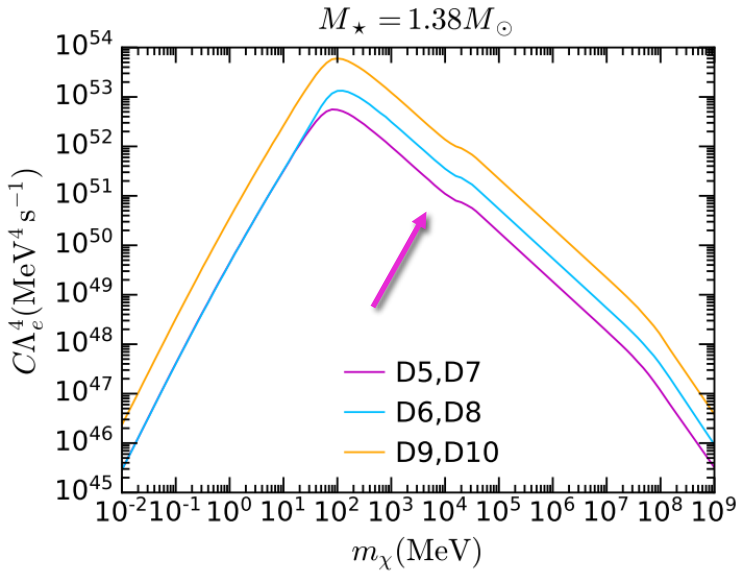
Capture on Electrons

- Cusps: Transition from PB to no-PB regime





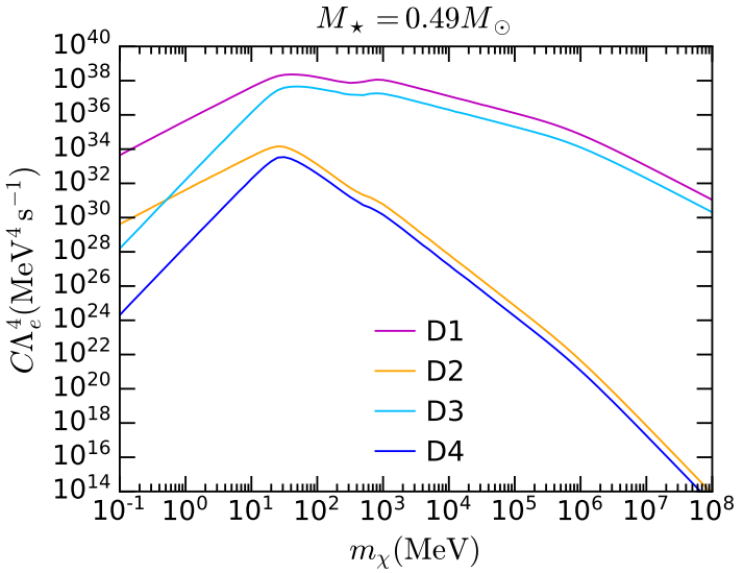


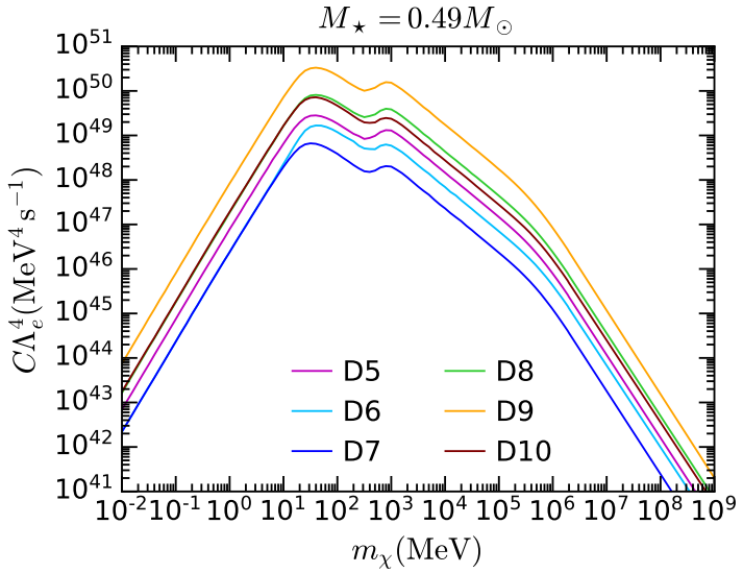


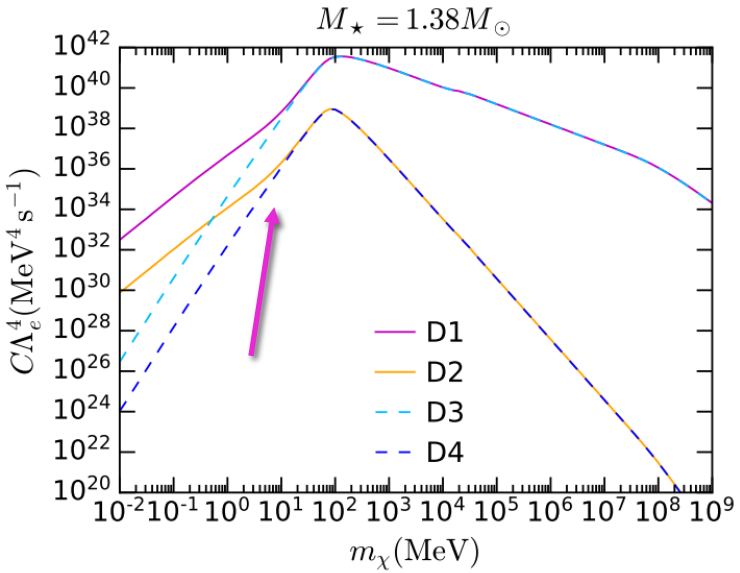
Bell, Busoni, Robles, Ramirez, MV 2104.14367

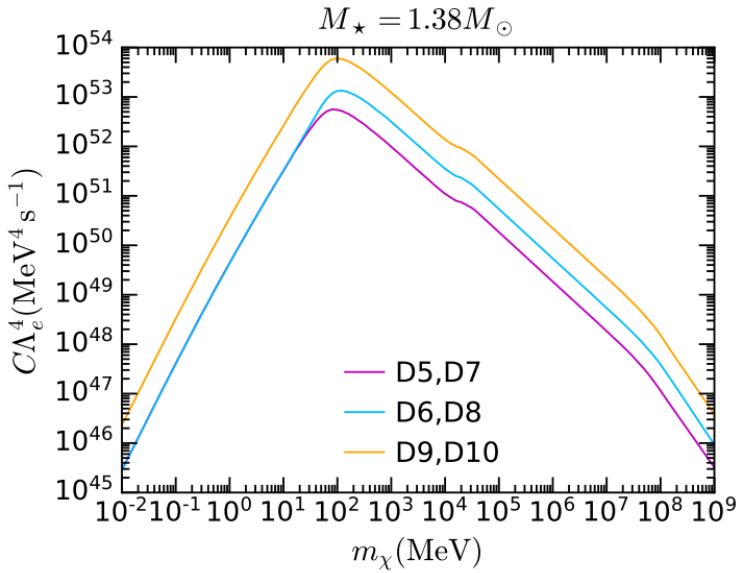
Capture on Electrons

- Cusps: Transition from PB to no-PB regime
- Heavy WD, light DM: Change in kinematics:
  - $\frac{m_e}{m_\chi}$ terms dominate cross section

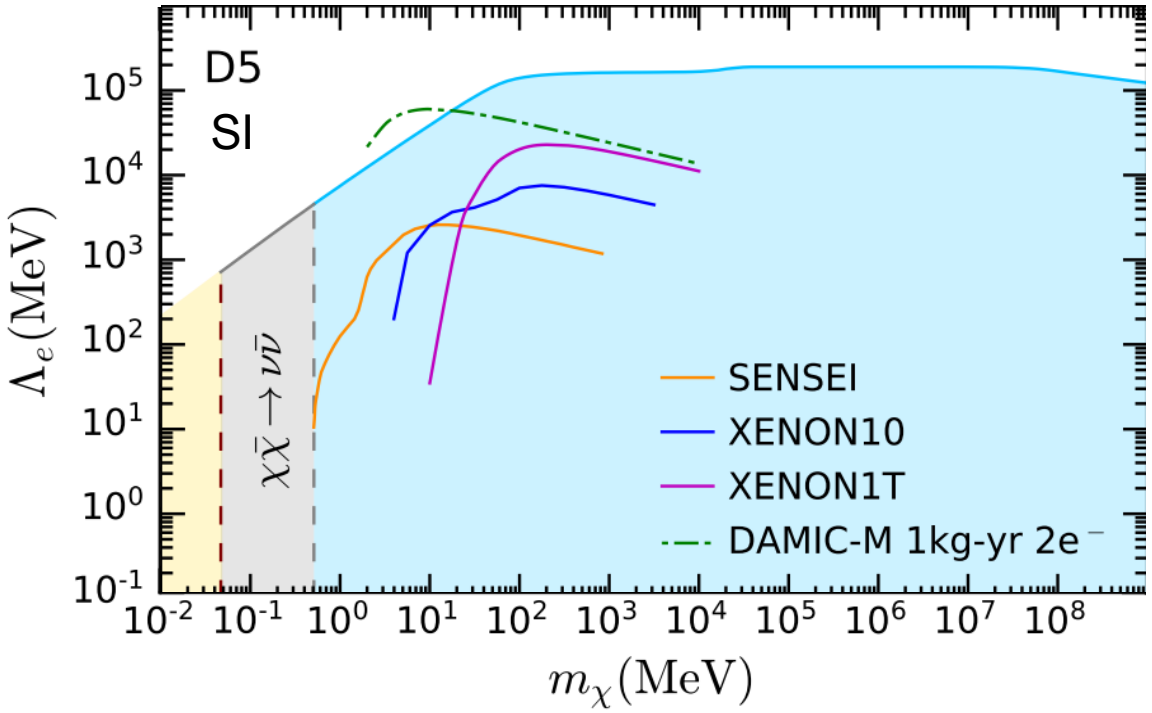








Bell, Busoni, Robles, Ramirez, MV 2104.14367

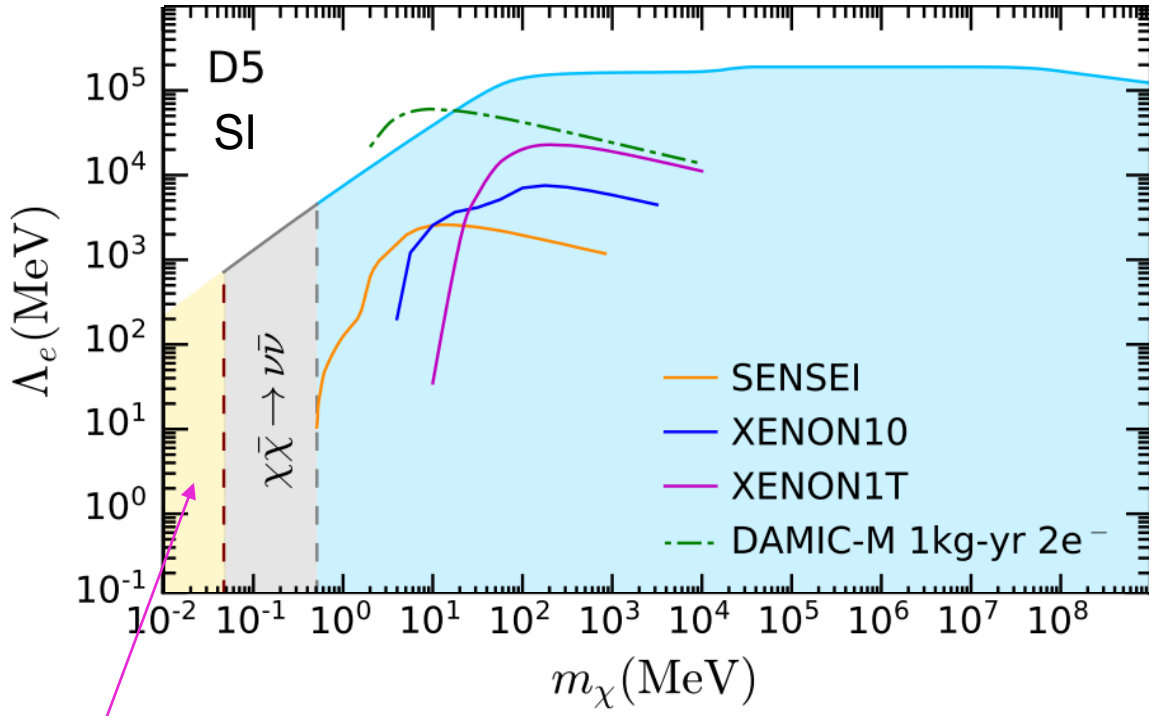


Bell, Busoni, Robles, Ramirez, MV 2104.14367

Prospective Heating Constraints: Electrons

Relies on DM existing in M4

Can potentially reach beyond direct detection



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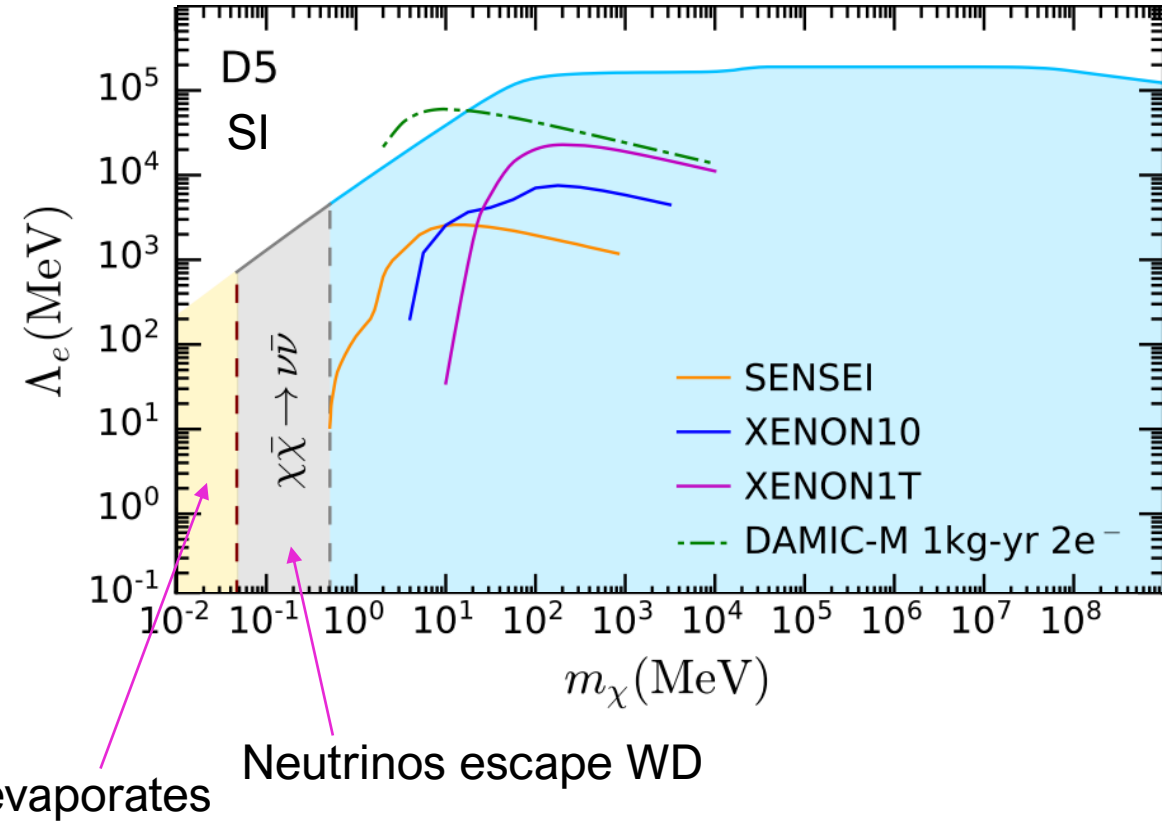

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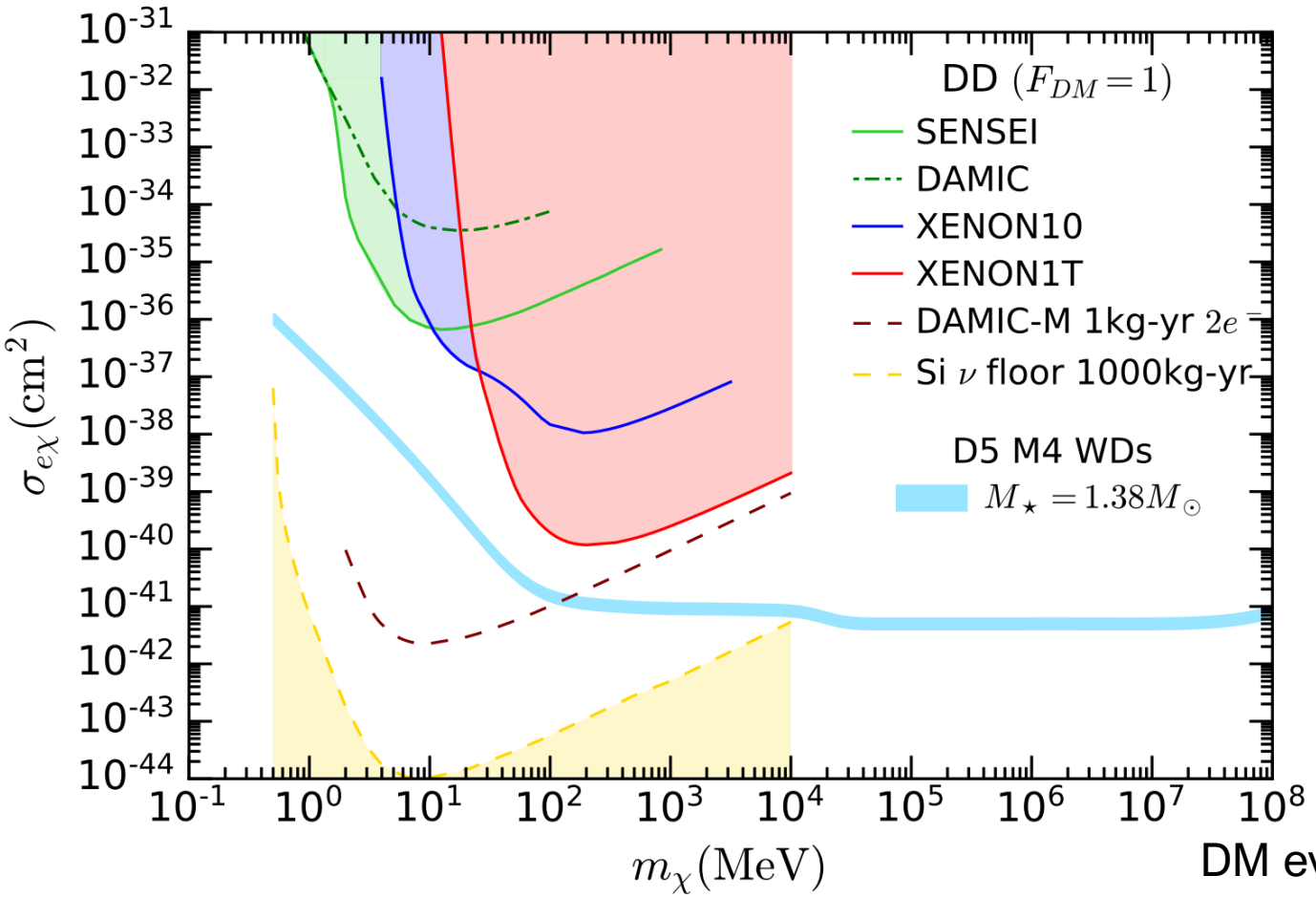

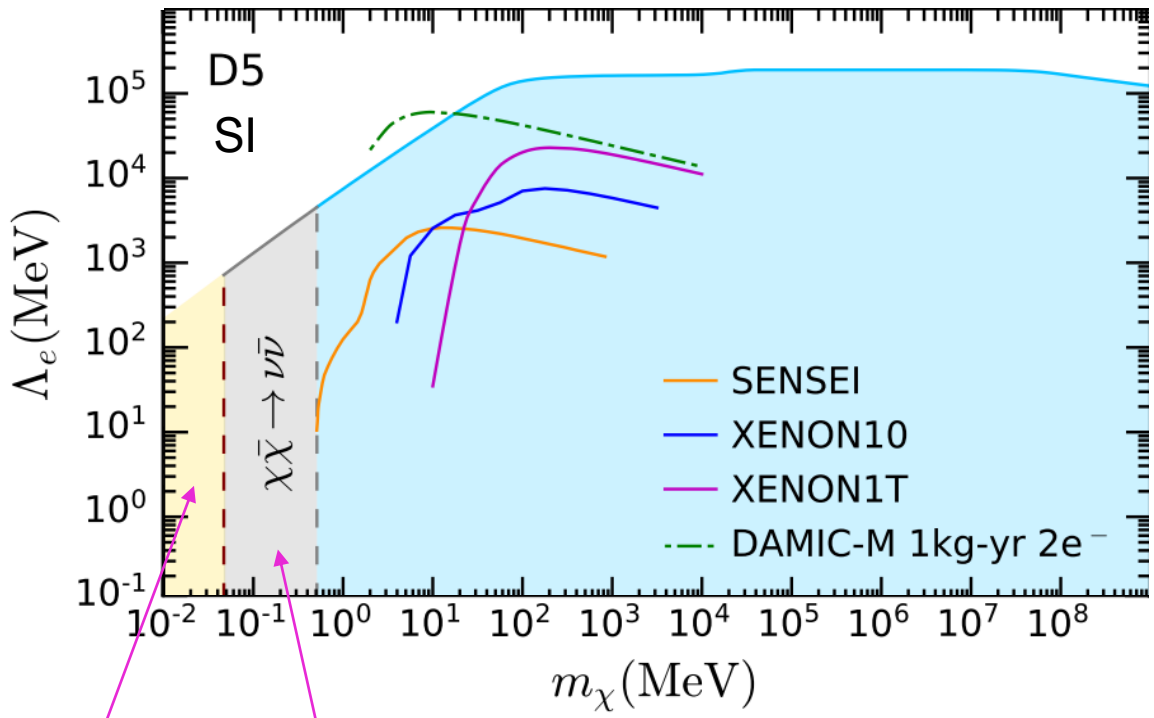

DM evaporates

Neutrinos escape WD

Bell, Busoni, Robles, Ramirez, MV 2104.14367

Prospective Heating Constraints: Electrons

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Summary

- Compact Objects offer unique laboratory to study Dark Matter
- We consistently incorporate important pieces of physics including:
  - Pauli Blocking
  - Multiple Scattering
  - Momentum dependent Form Factors
  - Nucleon Strong Interactions
- Old WDs in GCs can (potentially) set competitive constraints

Thank you

Questions?

Backup Slides

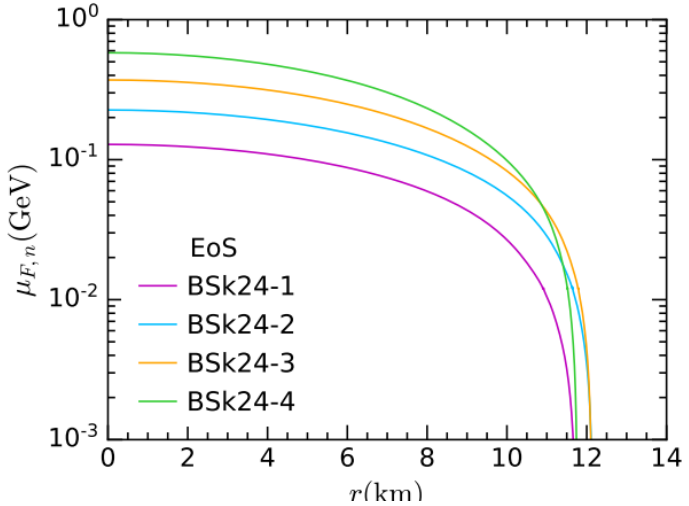
Neutron Star Equation of State: BSk

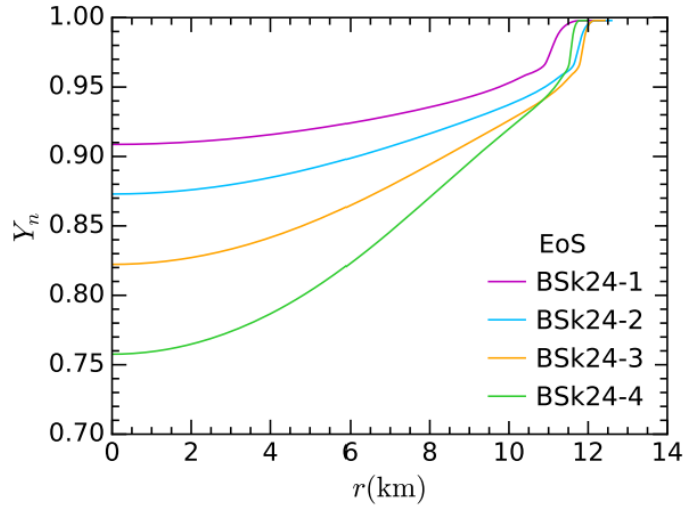
- Brussels-Montreal functionals: Unified EoS for cold, non-accreting matter

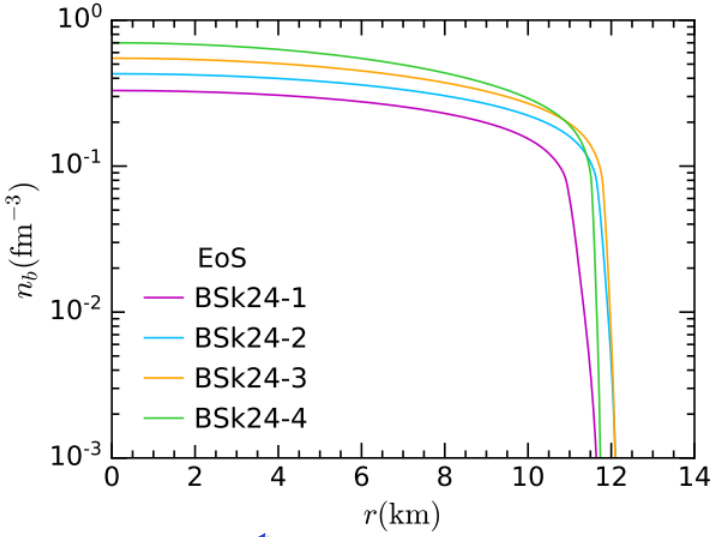
(Pearson et. al. arXiv:1903.04981)

  - Gives consistent description from surface to core
  - $npe\mu$ matter only
  - Authors provide helpful analytic fits

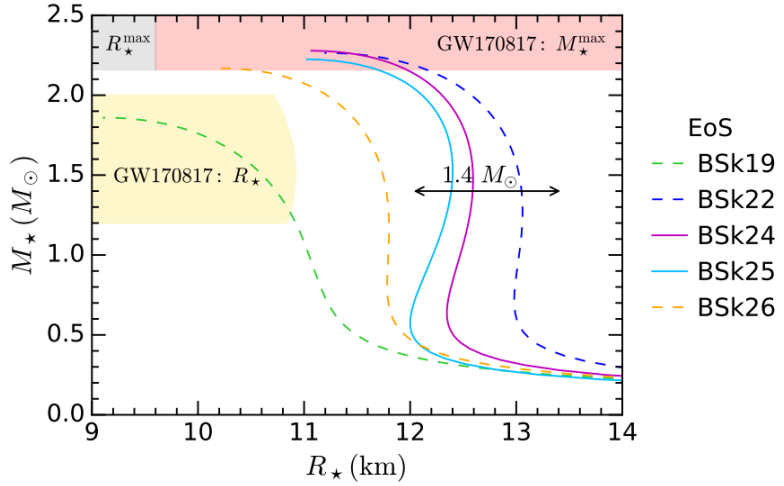
- Non-relativistic, Skyrme type EoS
  - Nucleon interactions added as effective interactions







EoS + TOV = Radial Profiles

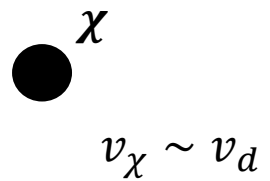


Dark Matter Capture Process

- 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)
    (Joglekar et. al. 1911.13293)
  - Correct treatment of degenerate targets
    (Garani et.al 1812.08773)
  - Baryon strong interactions

- Consider NS in Local neighbourhood:
  - Maxwell-Boltzmann velocity dispersion: $v_d \sim 270\ km/s$
  - NS relative velocity to DM halo: $v_\star \sim 230\ km/s$
  - DM boosted to $\sqrt{v_e^2 + v_d^2} \sim v_e \sim 0.3c - 0.7c$



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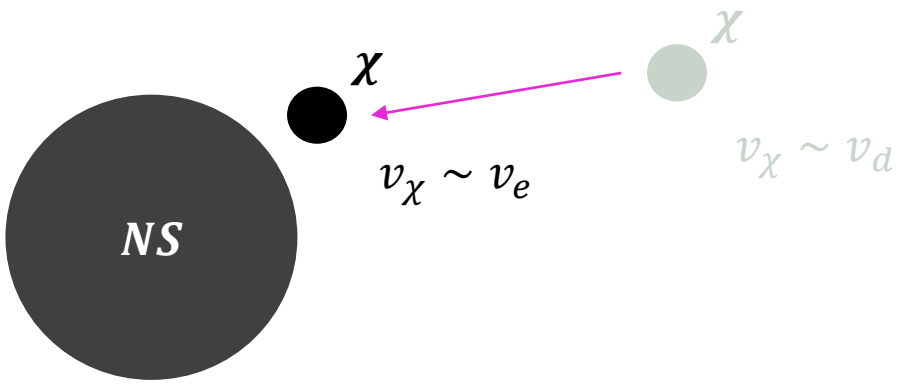

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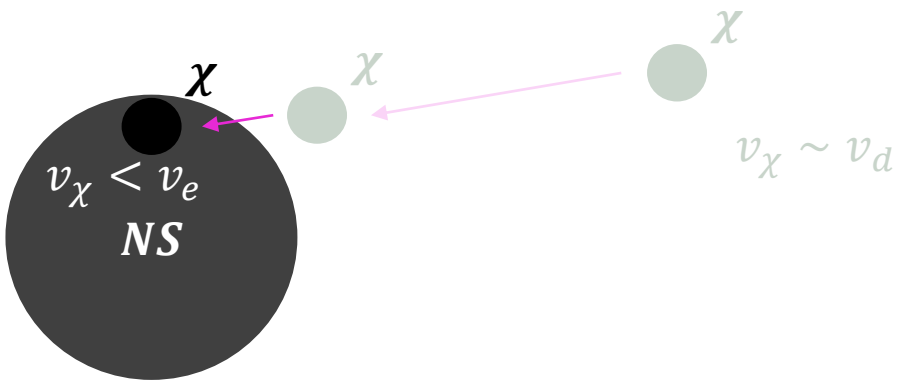
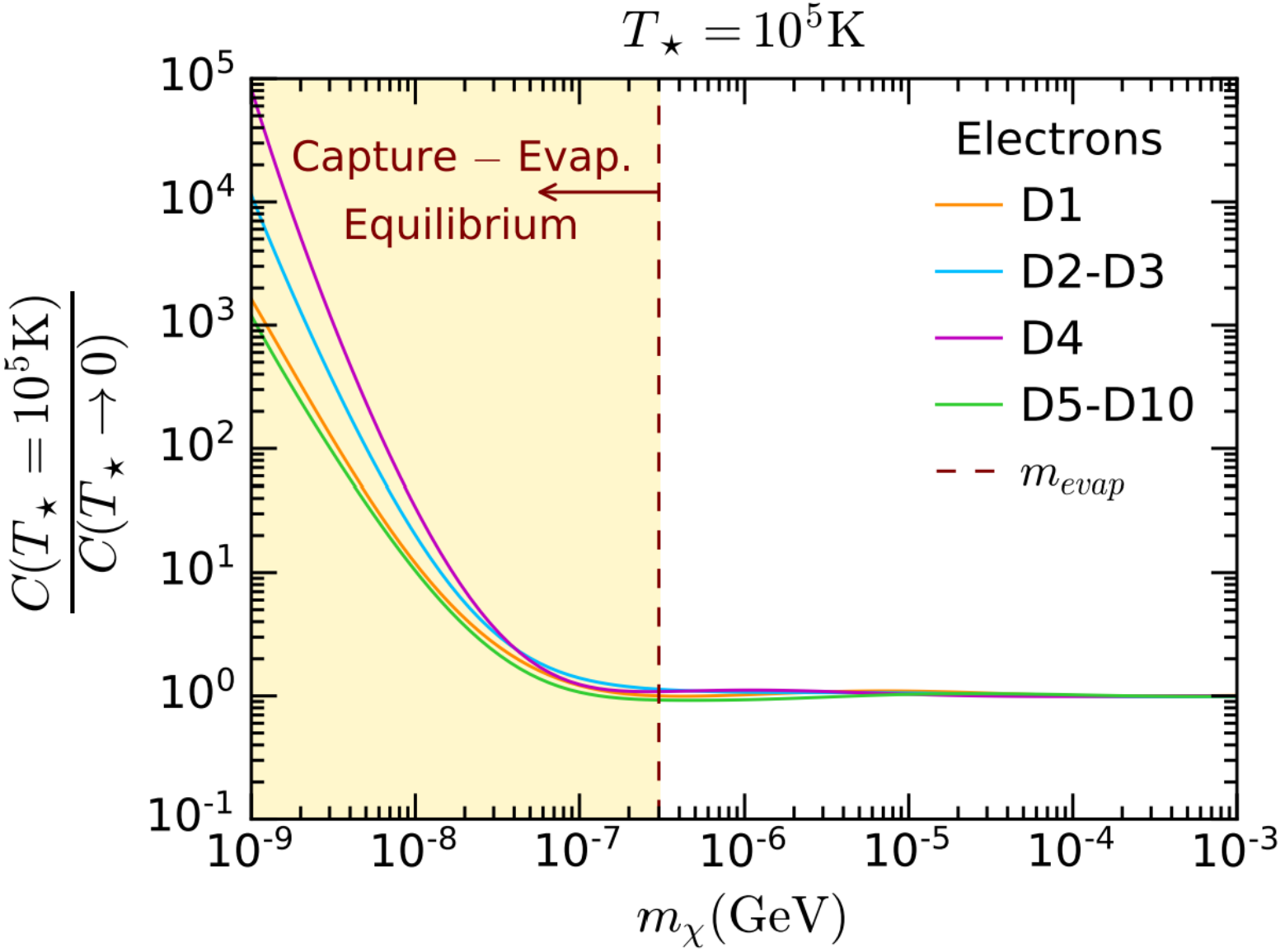
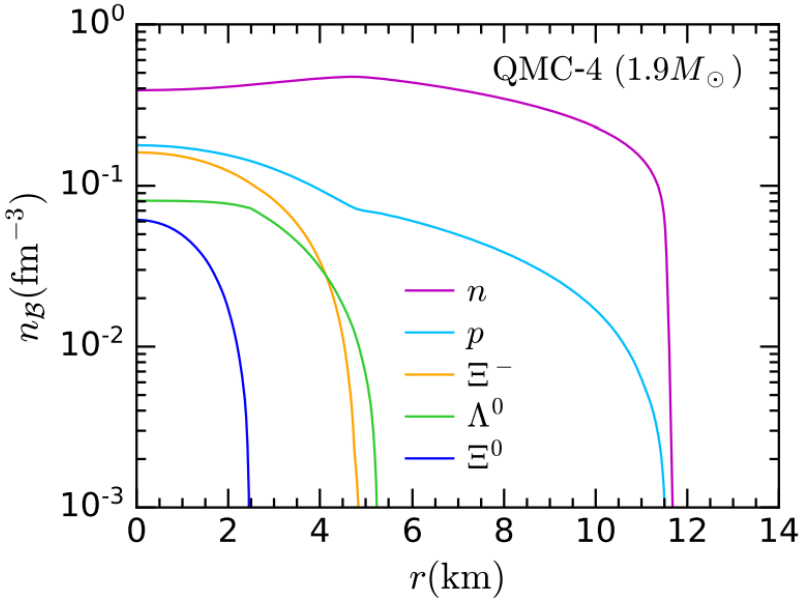


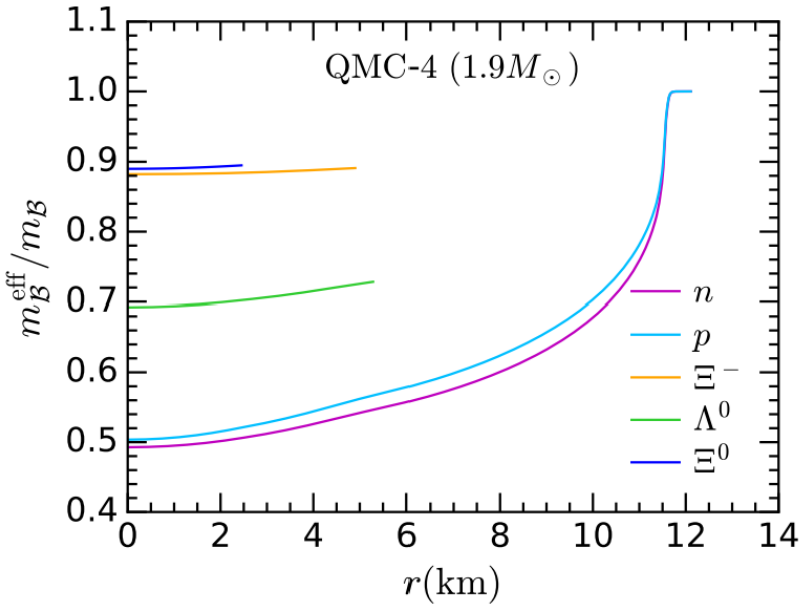
Finite Temperatures in NSs: Electrons



Hyperons in NS Core

- Appear once $\mu_H = \mu_n + Q_H \mu_e$
- Contribute sizable fraction of total capture rate for couplings $\propto m_N$





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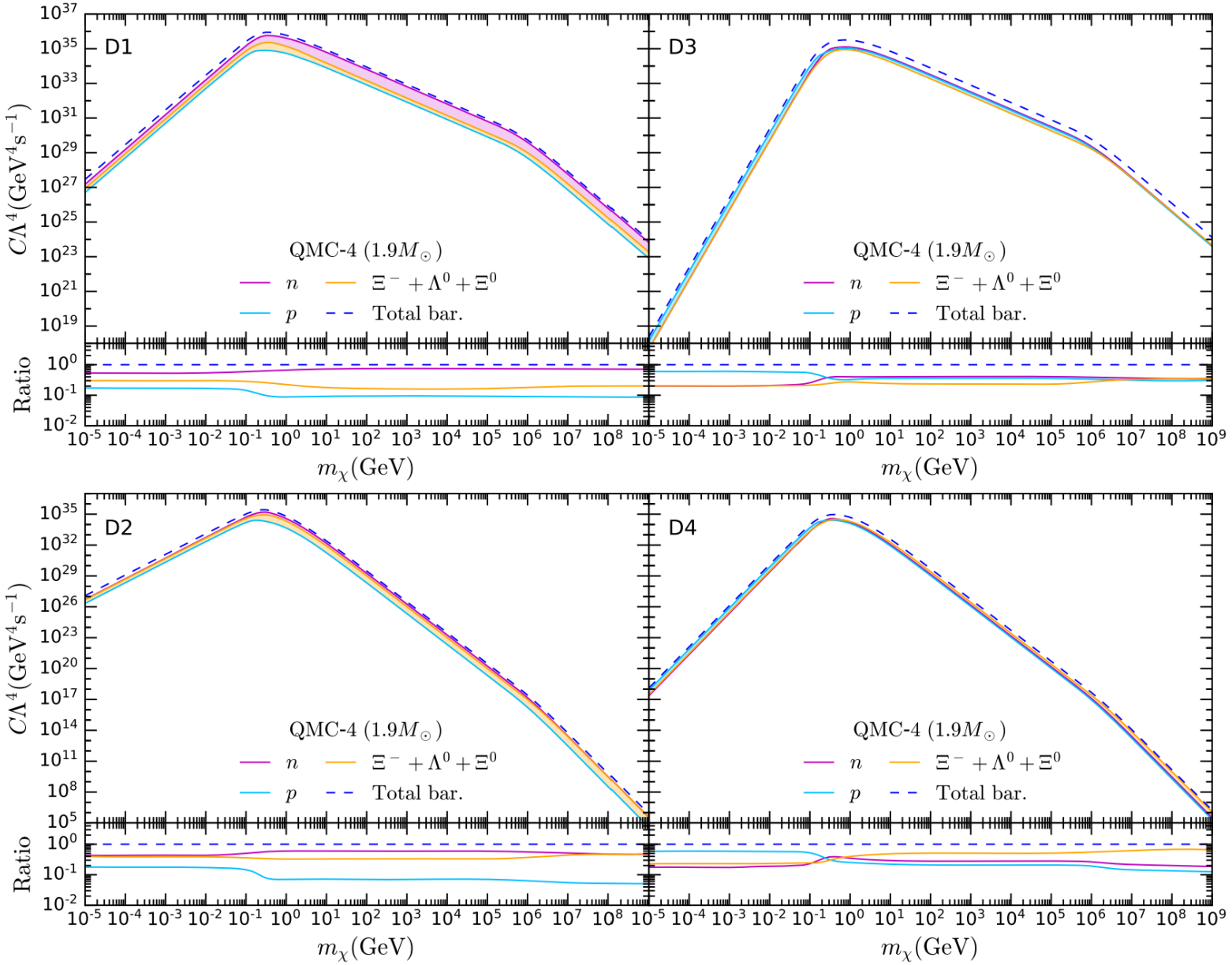
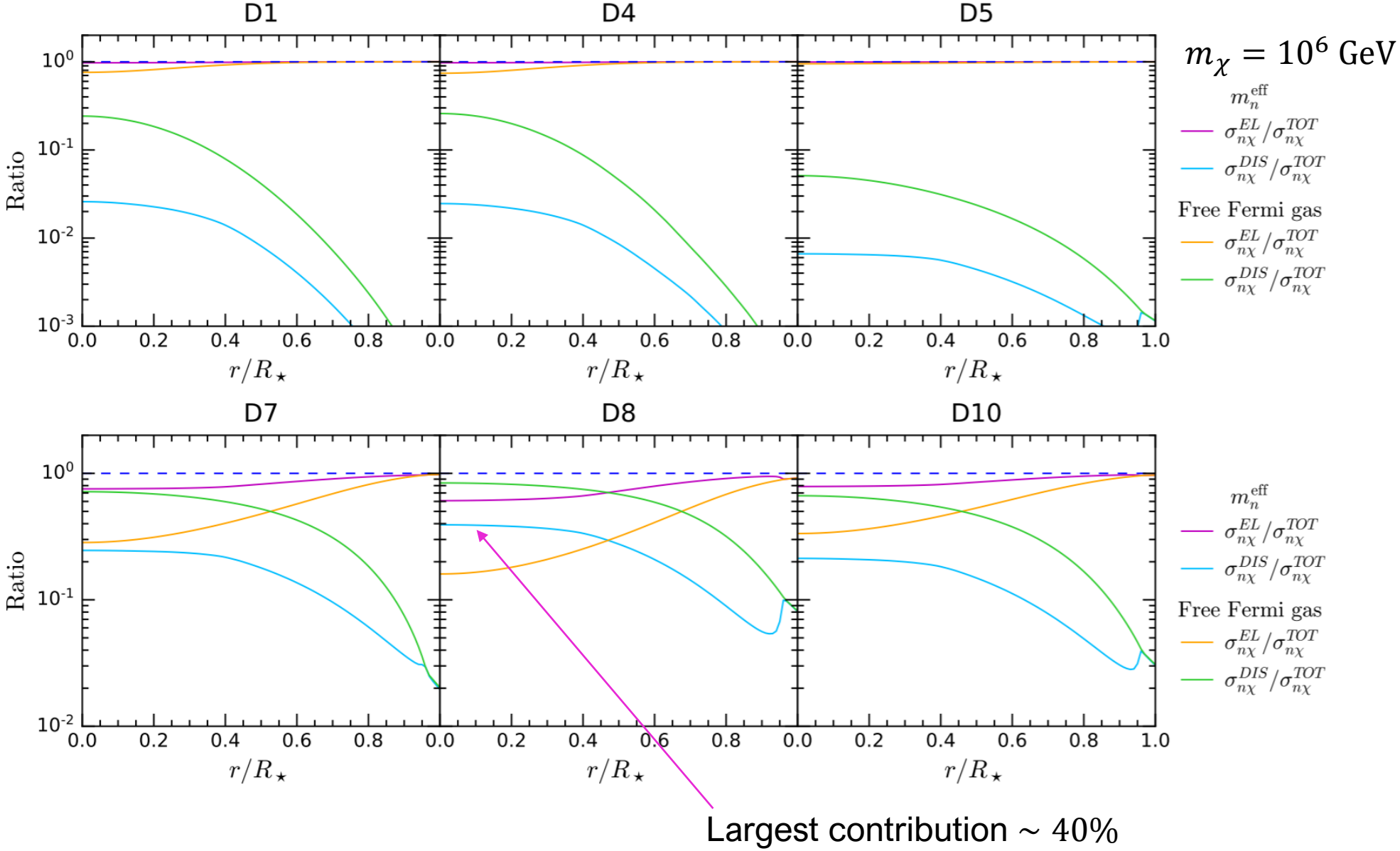


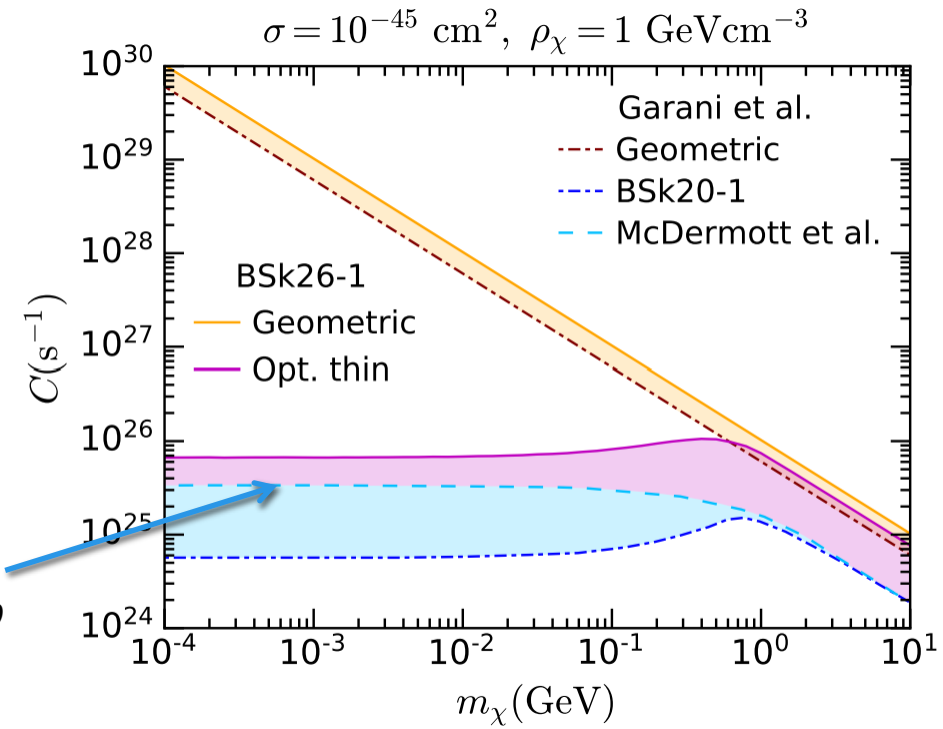


Deep Inelastic Scattering

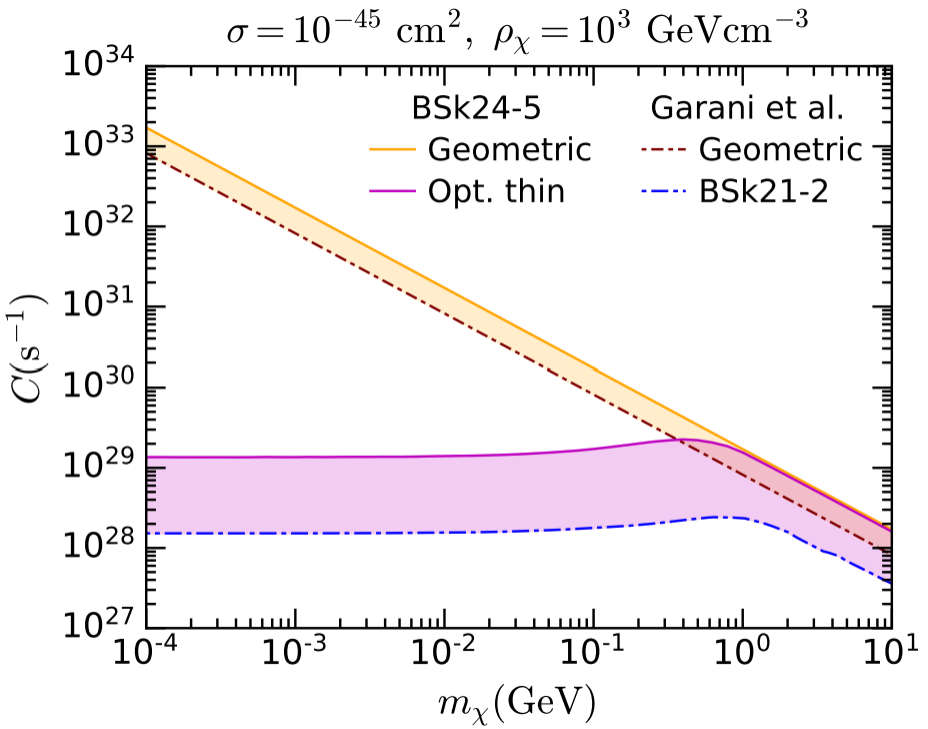
Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

Comparison to Previous Works

(McDemott et. al. 1103.5472, Garani et. al. 1812.08773)



PB: $\delta p/p$

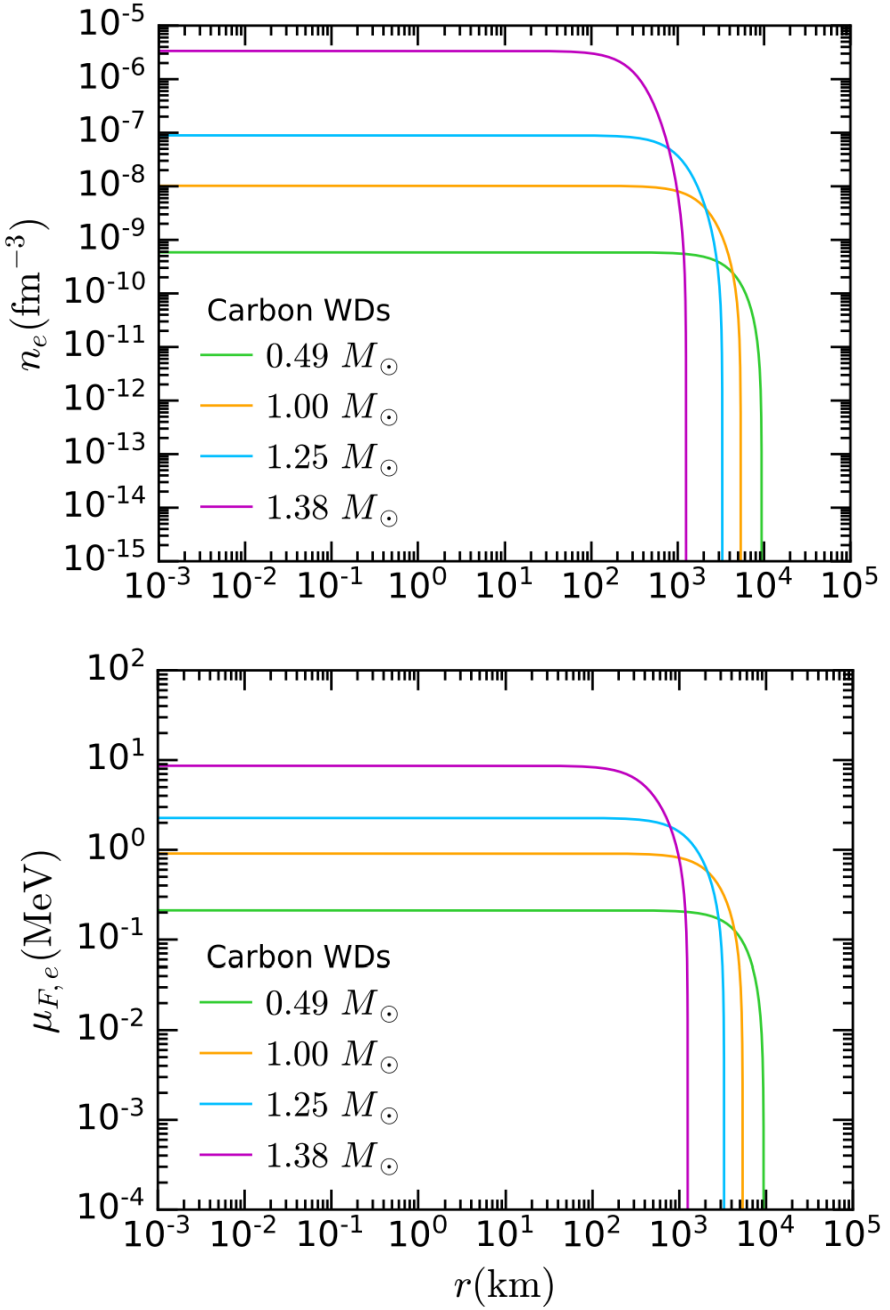


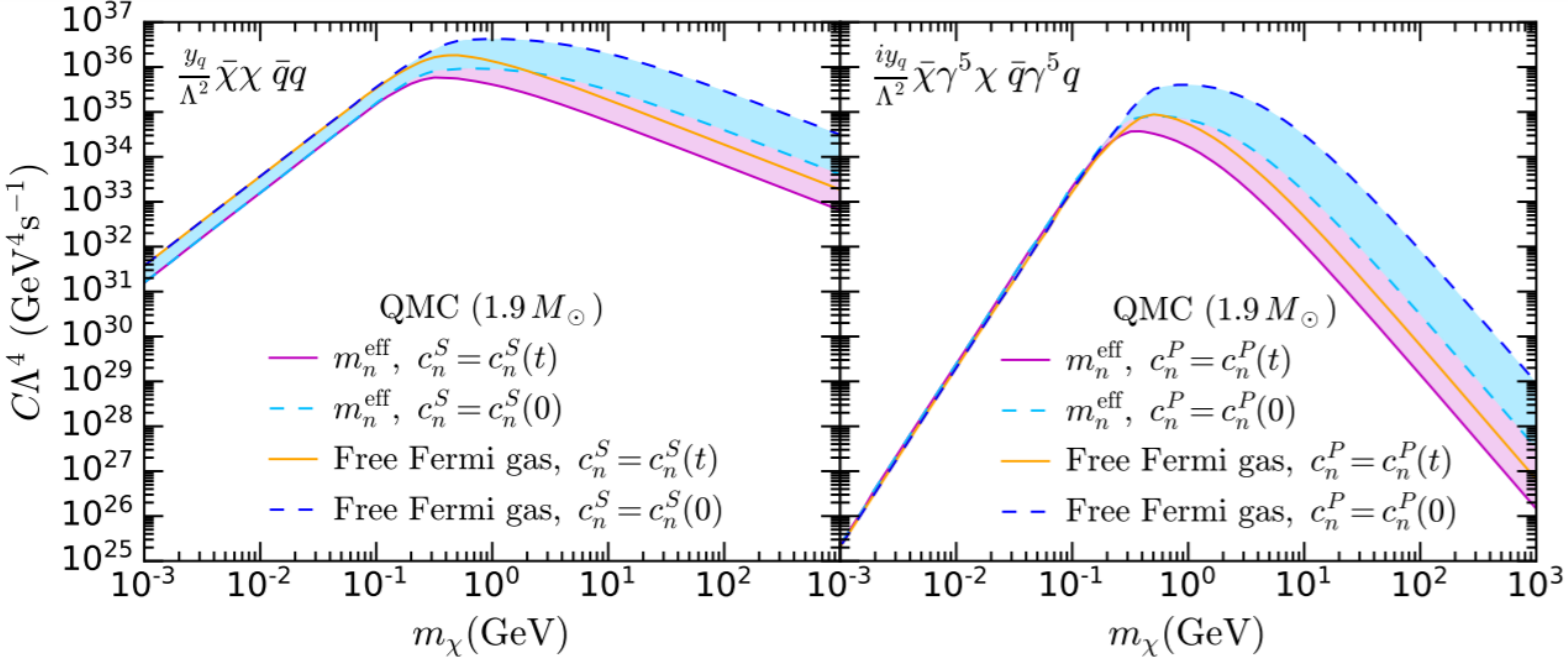
Bell, Busoni, Robles and MV 2004.14888

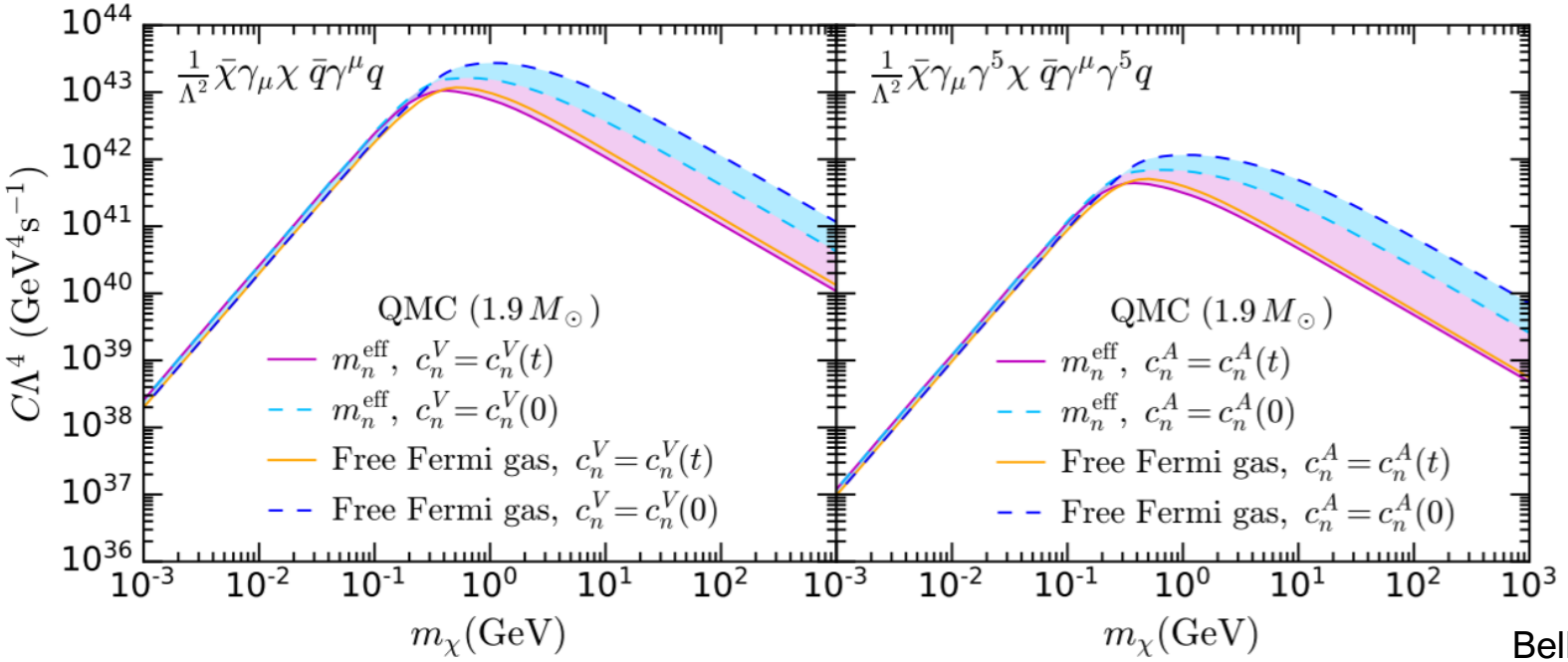
Feynman-Metropolis-Teller Equation of State

- Incorporates self consistently:
  - $e-e$, $e-N$, $N-N$ Coulomb interactions
  - **Beta Equilibrium**
  - **Finite size of nucleus**
  - **Relativistic effects**

- Only allows for single element composition (He/C/O)







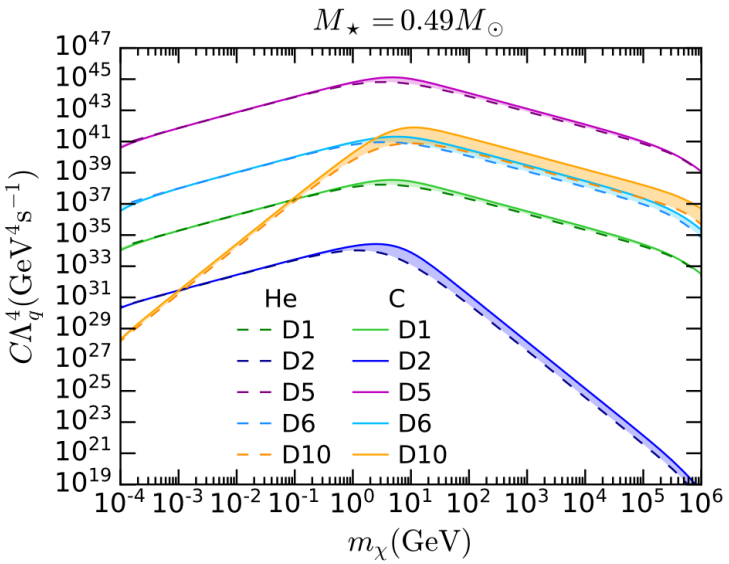
Nucleon Form Factors + Strong Interactions

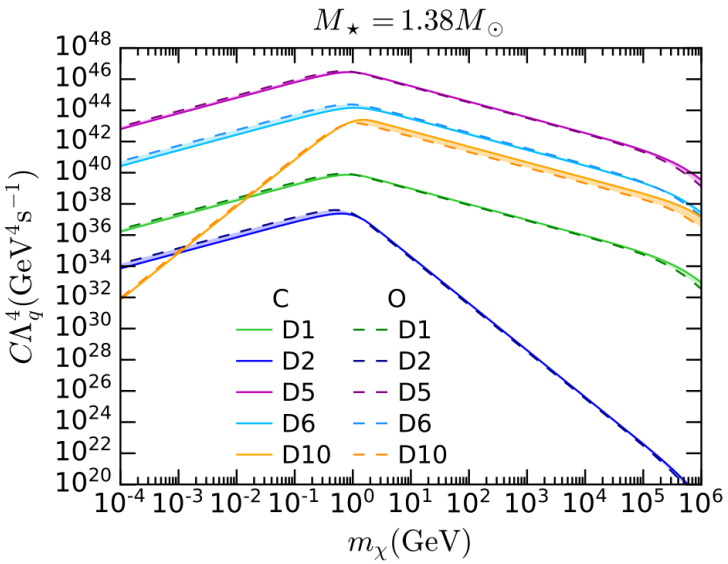
Up to 3 orders of magnitude suppression
In heaviest NS

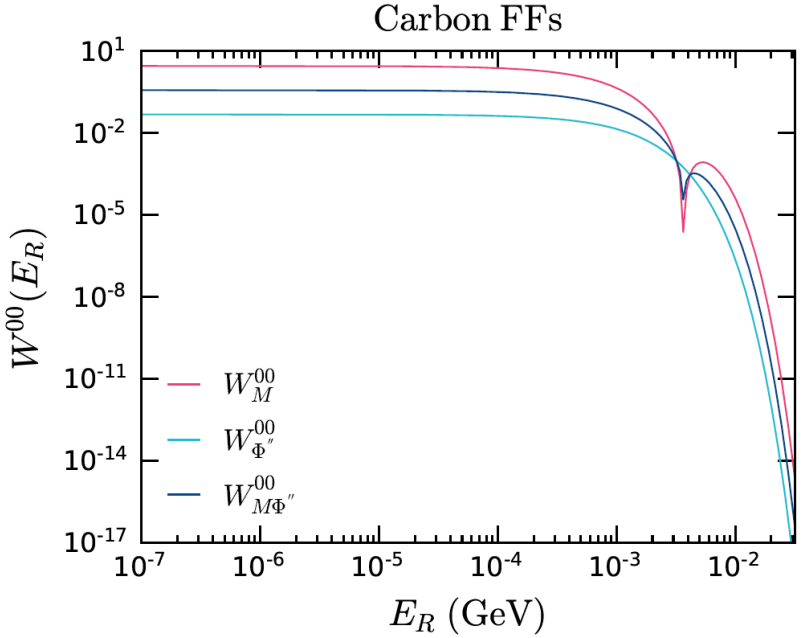
Bell, Busoni, Motta, Robles, Thomas and MV 2012.08918

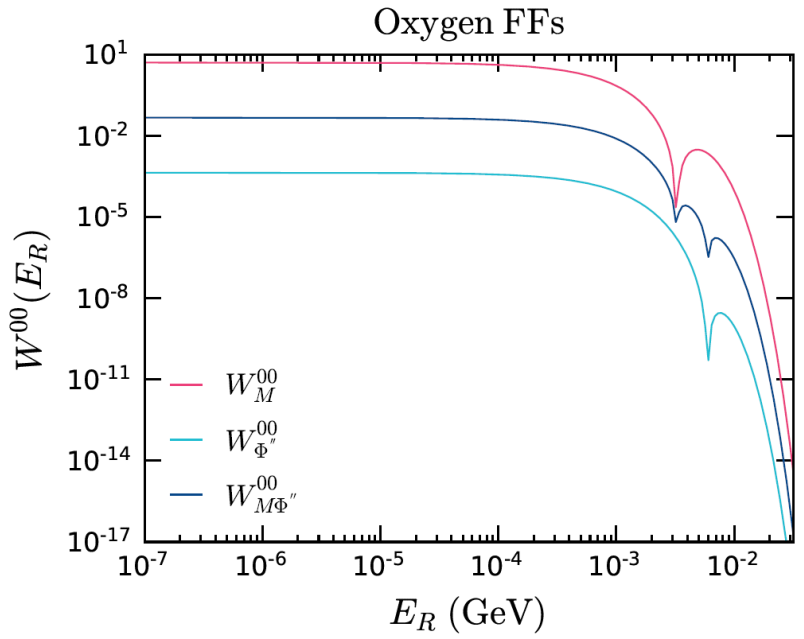
Capture on Ions

- Gould formalism applicable
- Nuclear Form Factors: Catena over Helm (Catena and Schwabe 1501.03729)
  - Suppress interaction rate at high momentum transfer
- He/C/O target → Spin-Independent interactions only
  - D1, D2, D5, D6, D10

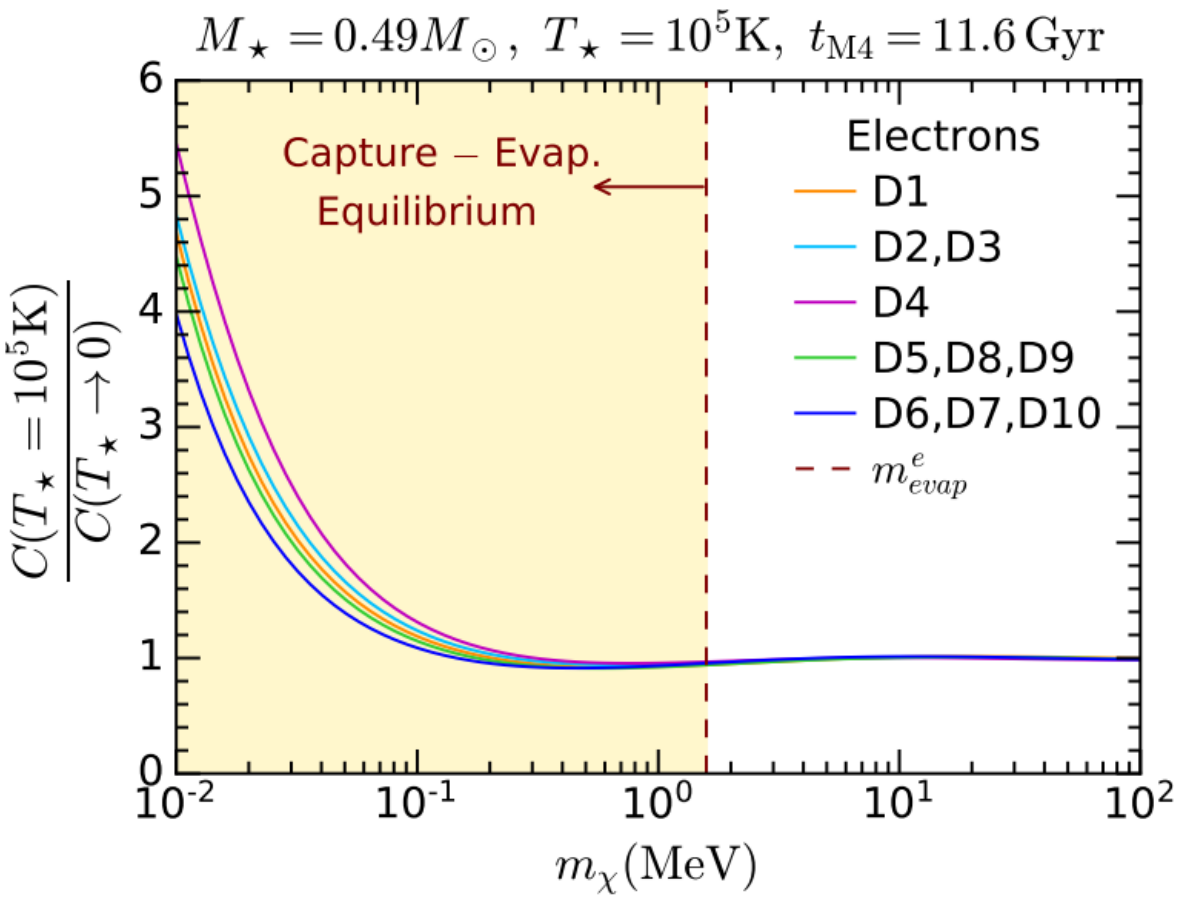


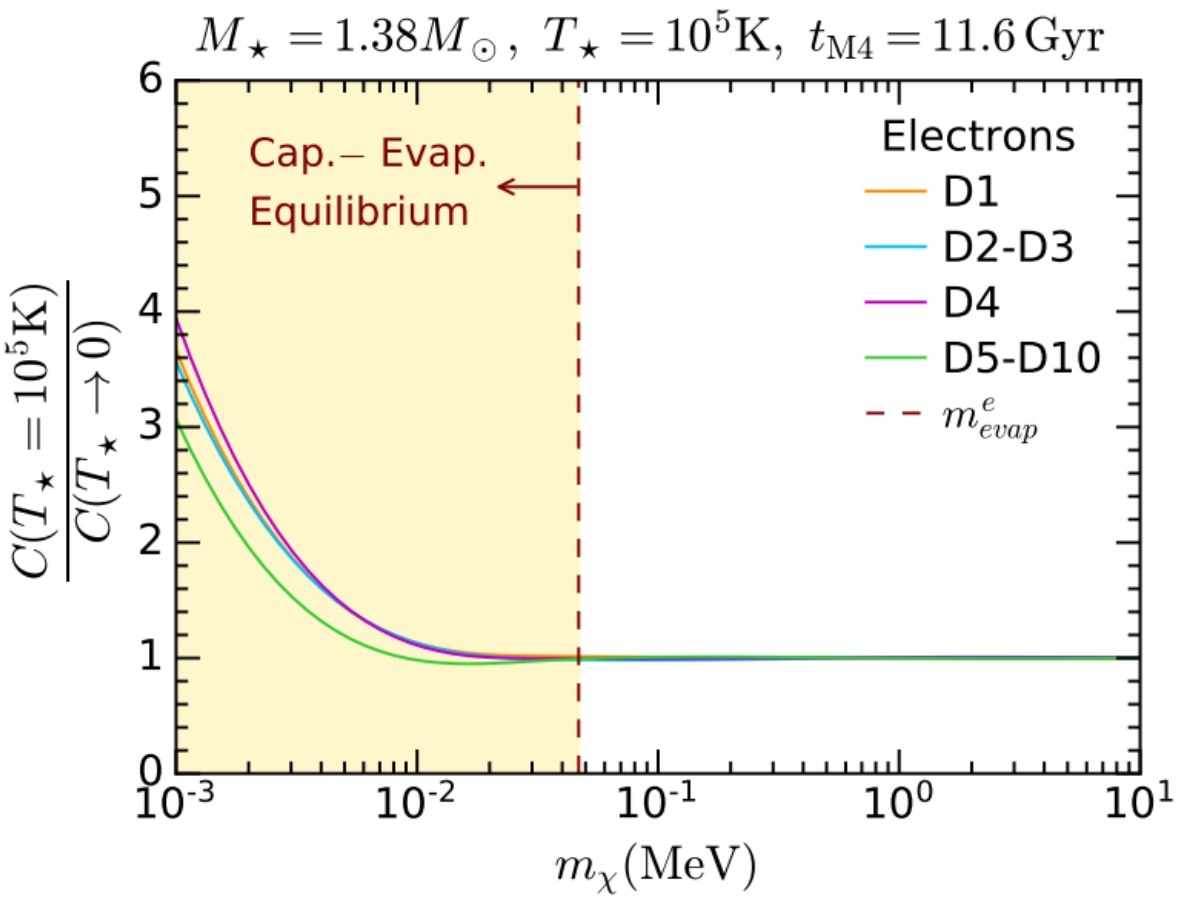






Bell, Busoni, Robles, Ramirez, MV 2104.14367





Bell, Busoni, Robles, Ramirez, MV 2104.14367

Finite Temperature Effects: Electrons

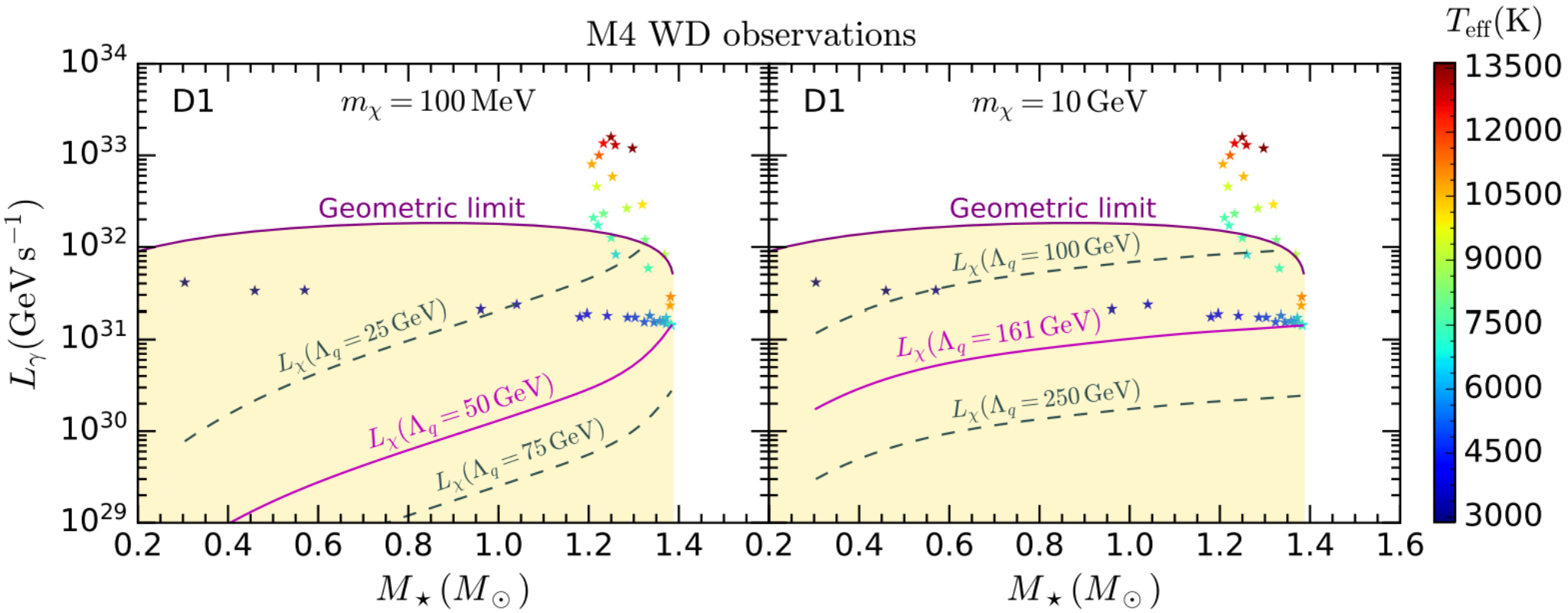
- Fermi-Dirac distributions spread out reducing Pauli Blocking
- DM can up-scatter and evaporate

Constraints from White Dwarf Heating

- DM in capture-annihilation equilibrium:

$$L_\chi^\infty = m_\chi C(m_\chi, \Lambda)$$

$$\tau_\star \sim 11.6\, Gyr > \tau_{eq} + \tau_{therm}$$



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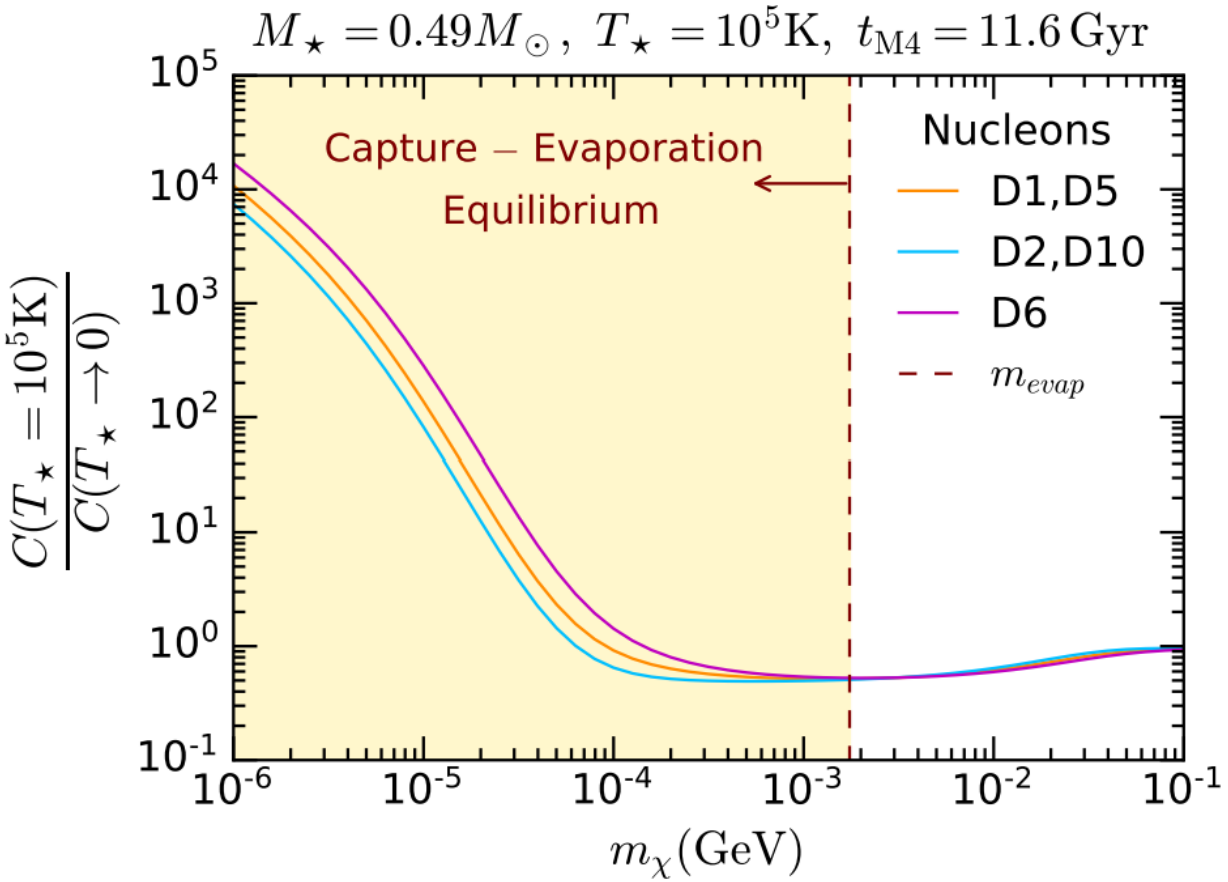
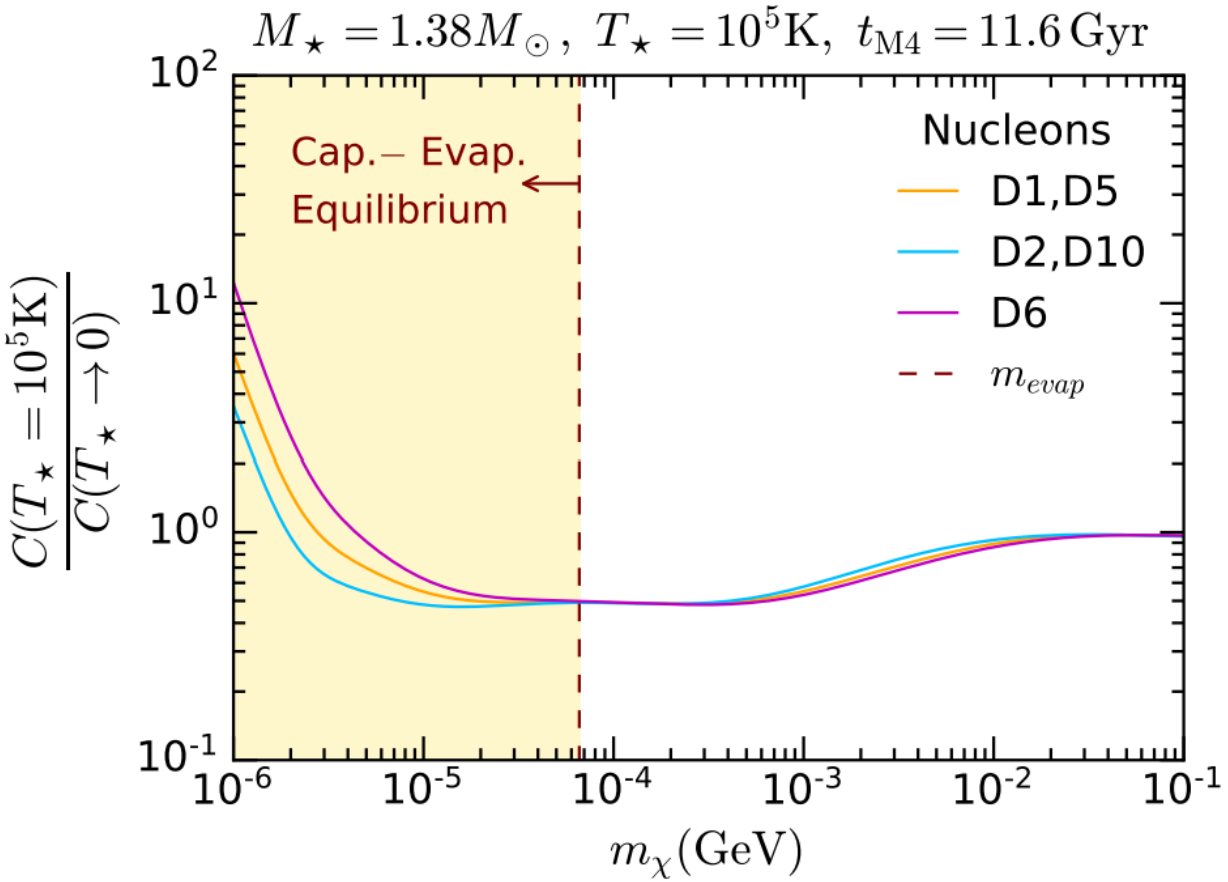
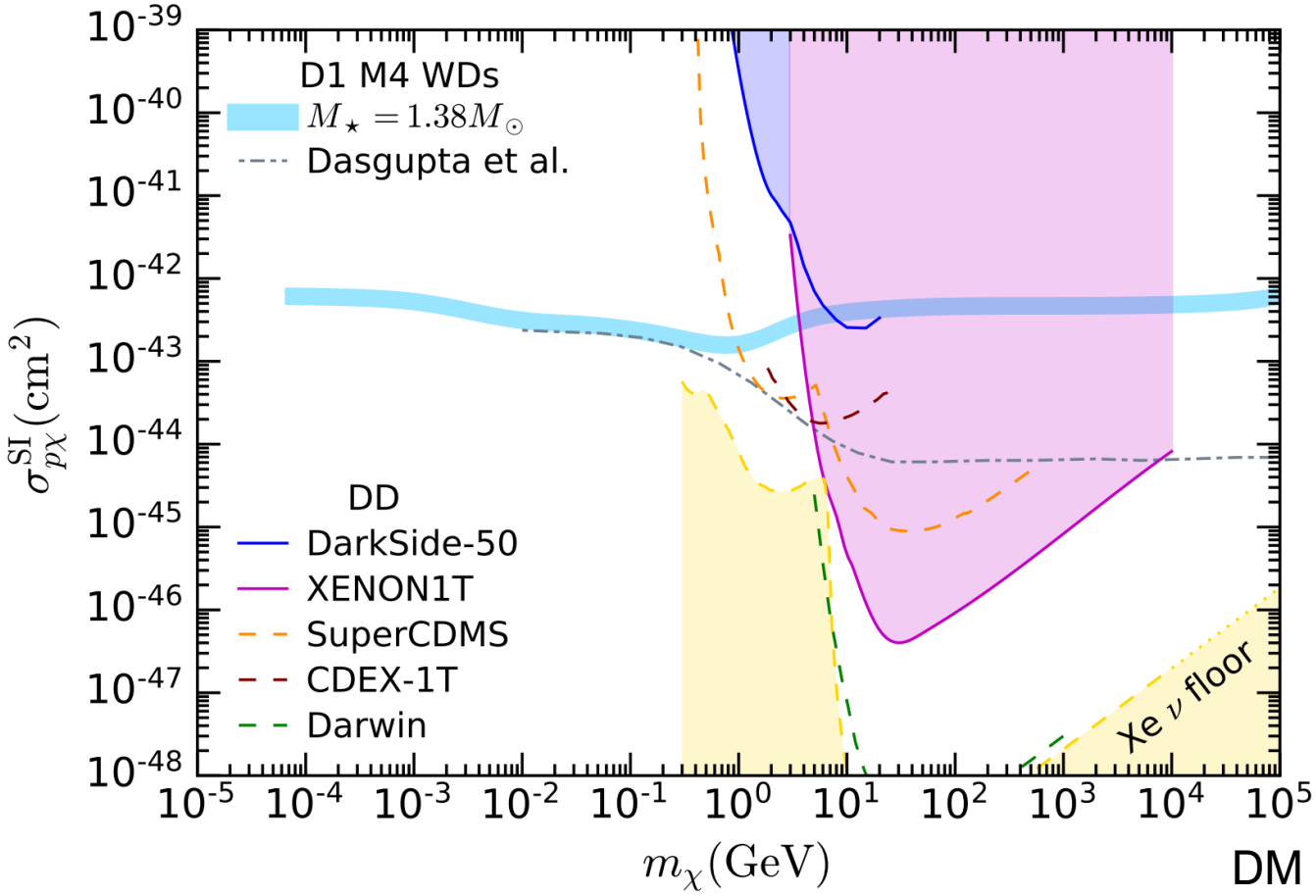


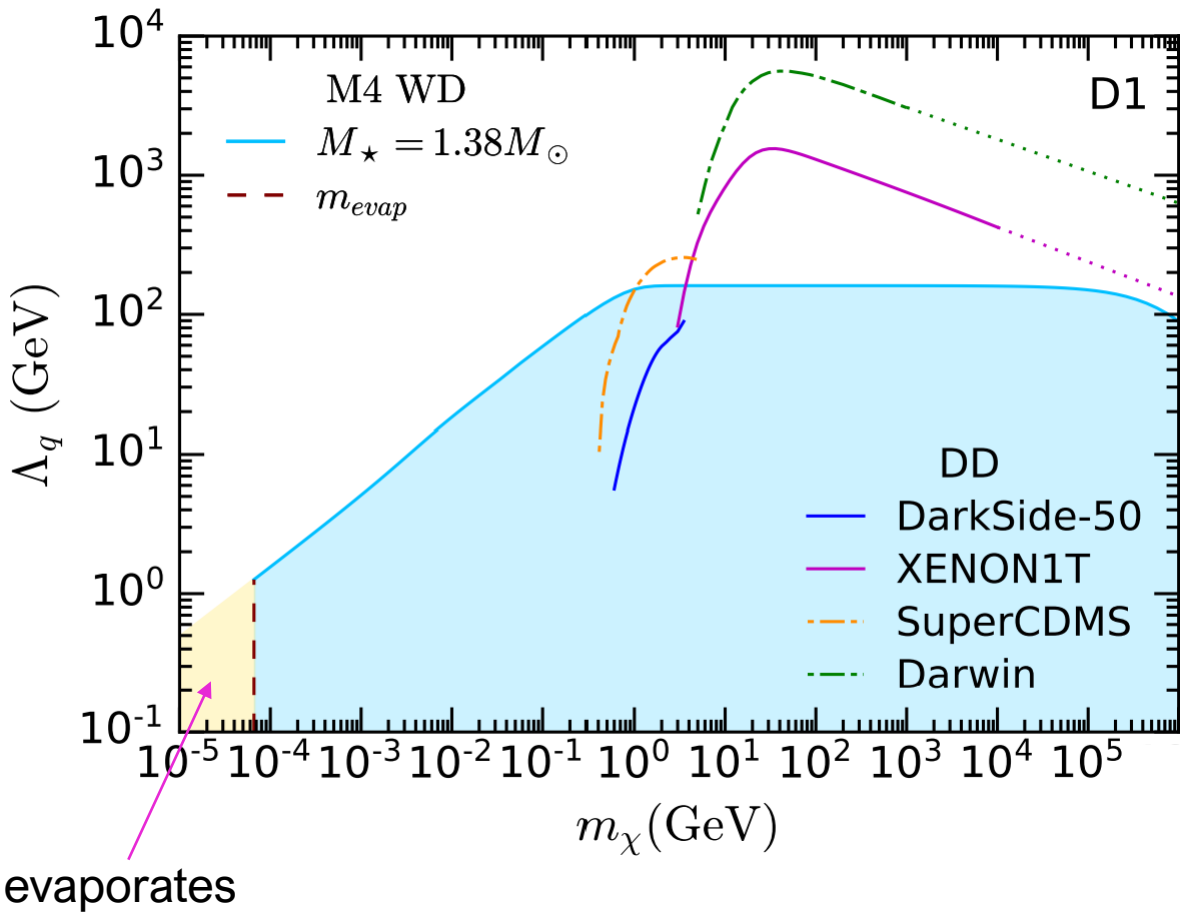


Bell, Busoni, Robles, Ramirez, MV 2104.14367

Finite Temperature Effects: Ions

- $T_\star = 10^5 K$ consistent with GC age and estimated evolutionary sequences
- DM can up-scatter and evaporate





DM evaporates

Bell, Busoni, Robles, Ramirez, MV 2104.14367

Prospective Heating Constraints: Ions

Relies on DM existing in M4

Can potentially reach beyond direct detection