# 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

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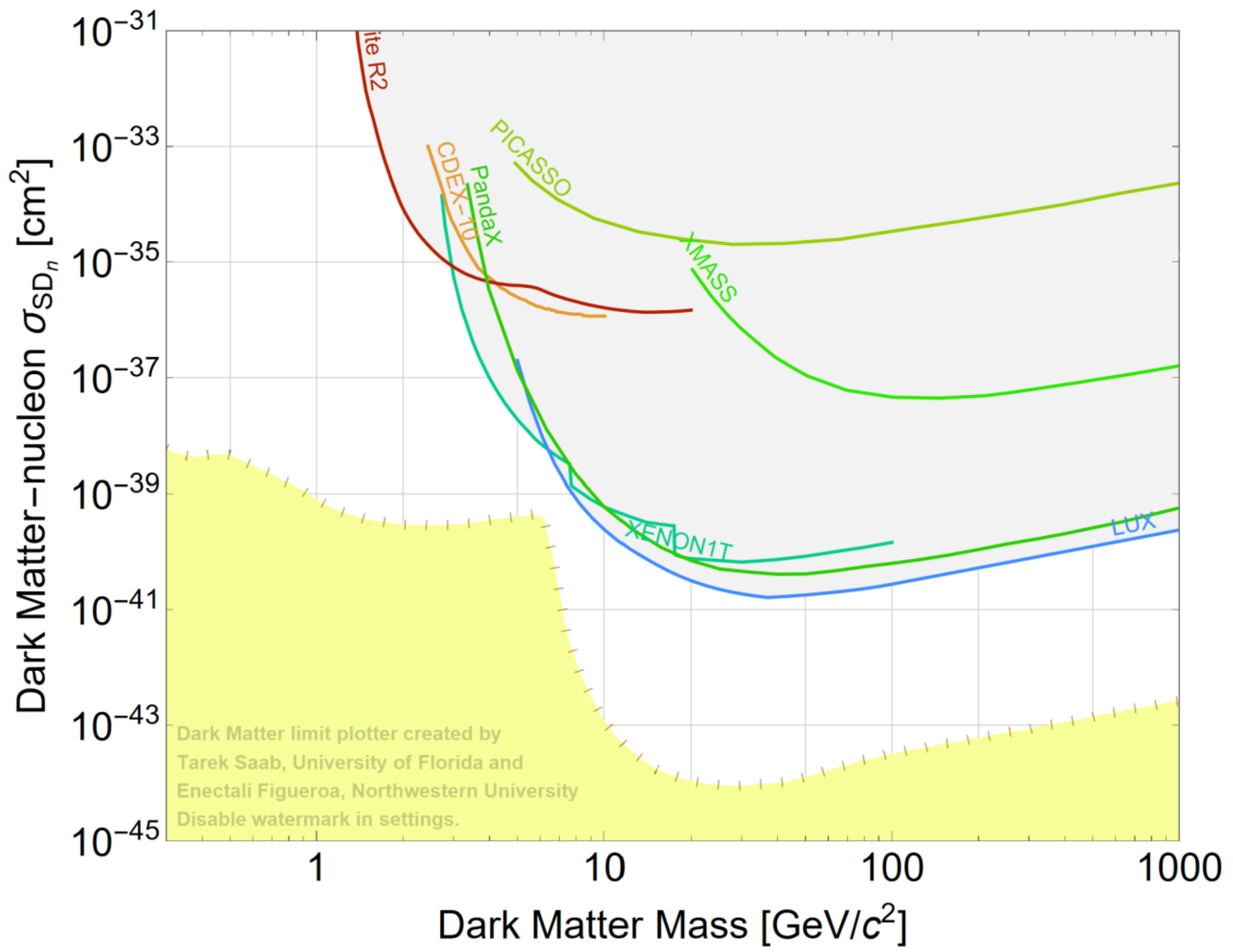
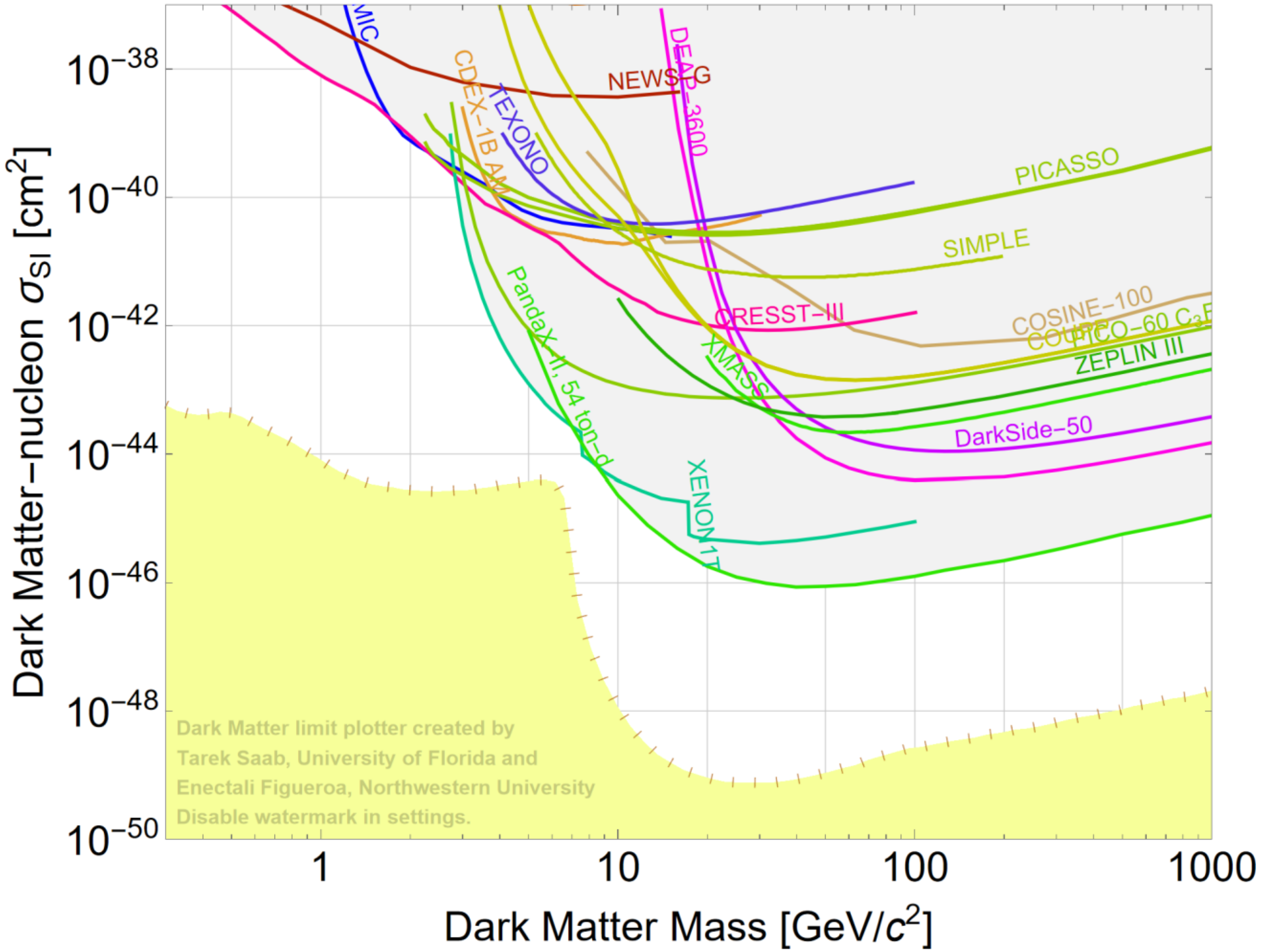
INT PROGRAM INT-22-2B

# Outline

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



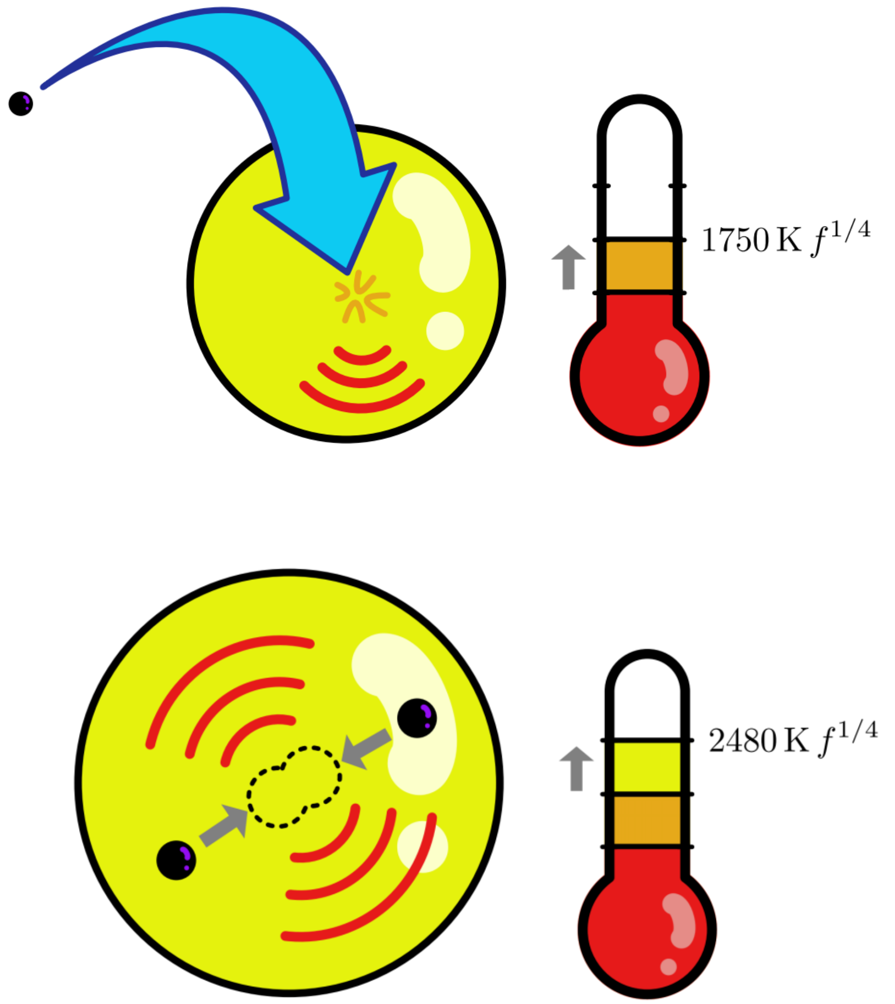




# Direct Detection Bounds

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

# Compact Objects as Dark Matter Probes

- Compact objects are highly efficient at capturing Dark Matter
- Capture + Annihilation can heat star to detectable temperatures
  (Baryakhtar et.al. 1704.01577)
- Observations of old + cold objects can set potential constraints
- Capture Rates Require:
  - Relativistic kinematics (targets and DM)
  - Correct treatment of degenerate targets (Garani et.al 1812.08773)
- Nucleons also require:
  - Baryon strong interactions
  - Momentum dependent Form Factors




(Raj et.al. 1707.09442)

# Effective Field Theory for Dark Matter

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

| Operator | | Coupling | Direct Detection | Momentum Suppressed? |
|---|---|---|---|---|
| D1 | $(\bar{\chi}\chi)(\bar{q}q)$ | $y_q/\Lambda^2$ | SI | ✗ |
| D2 | $(\bar{\chi}\gamma_5\chi)(\bar{q}q)$ | $iy_q/\Lambda^2$ | SI | ✓ |
| D3 | $(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$ | $iy_q/\Lambda^2$ | SD | ✓ |
| D4 | $(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$ | $y_q/\Lambda^2$ | 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 | $(\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi)(\bar{q}\sigma^{\mu\nu} q)$ | $i/\Lambda^2$ | SI | ✓ |

OR $\mathrm{d}\sigma \propto 1, t, t^2$, where $t = q_0^2 - q^2$

# Neutron Stars

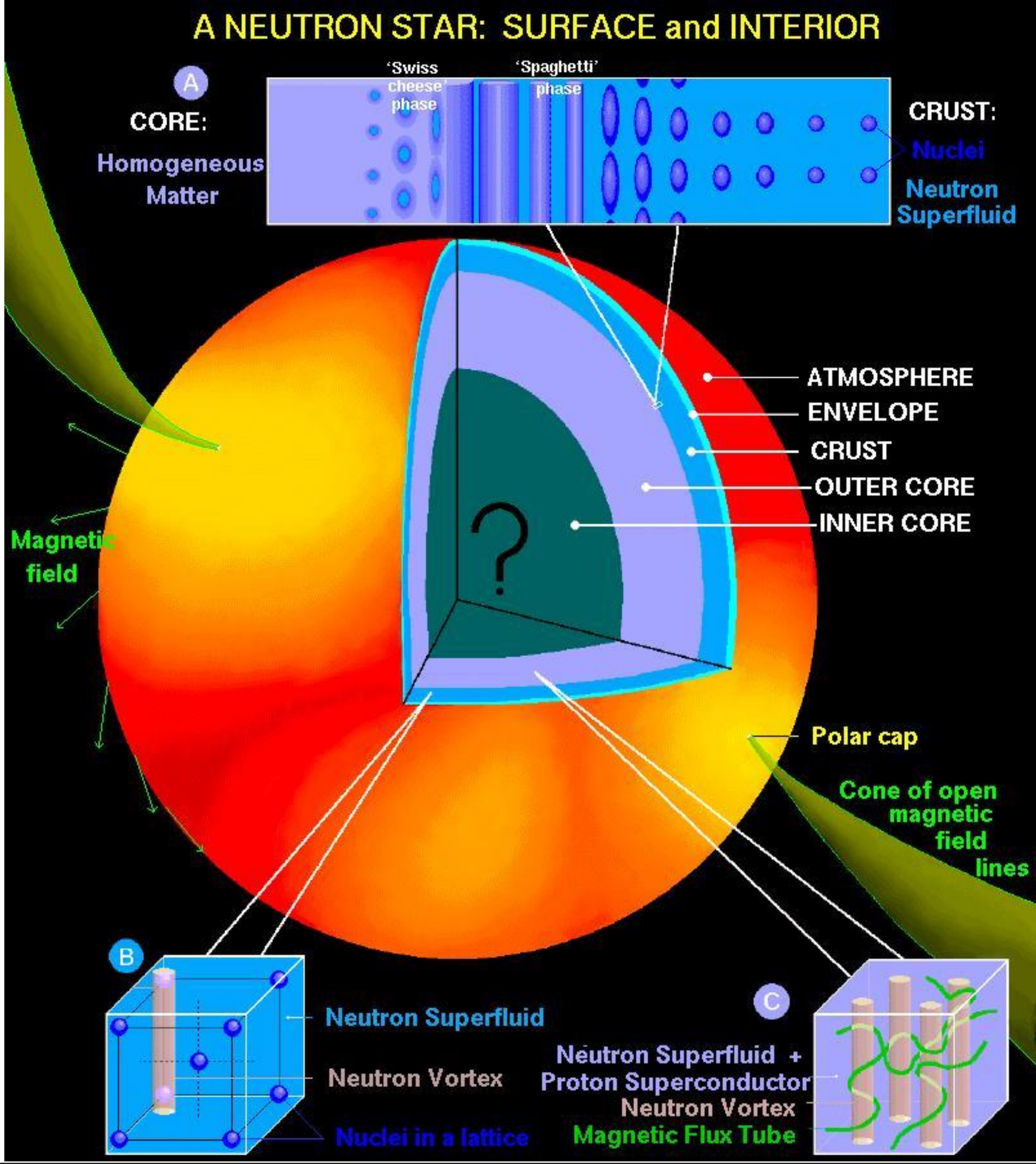
## FORMALISM AND POTENTIAL SENSITIVITIES

# Neutron Stars

- Produced from core collapse supernova of massive stars

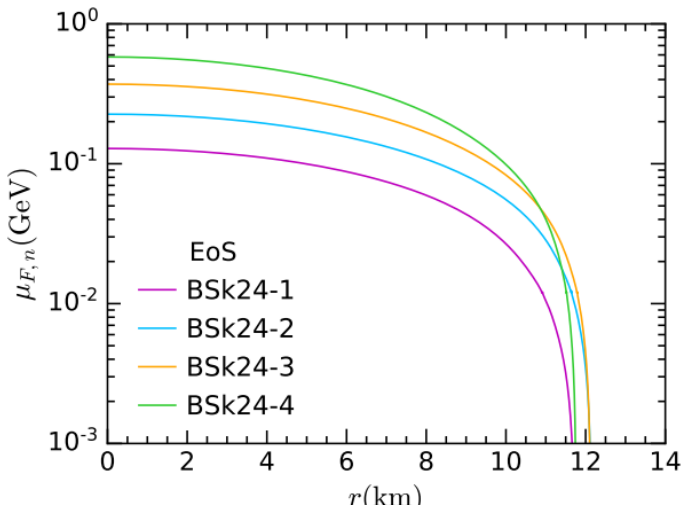
Composition:

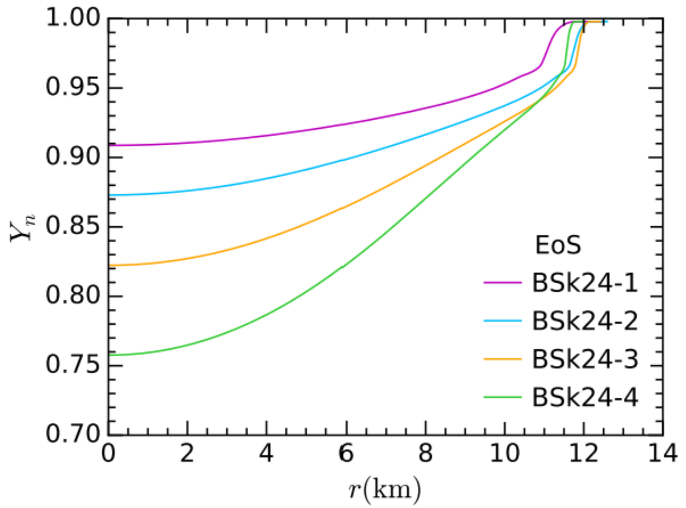
- Crust:
  - Heavy nuclei in lattice and “pasta” phases
- Outer Core:
  - Primarily superfluid neutrons
  - Protons, electrons and muons appear
- Inner Core
  - Exact composition of inner core unknown (possibly exotic phases of matter; hyperons, QGP, kaon condensates, …)

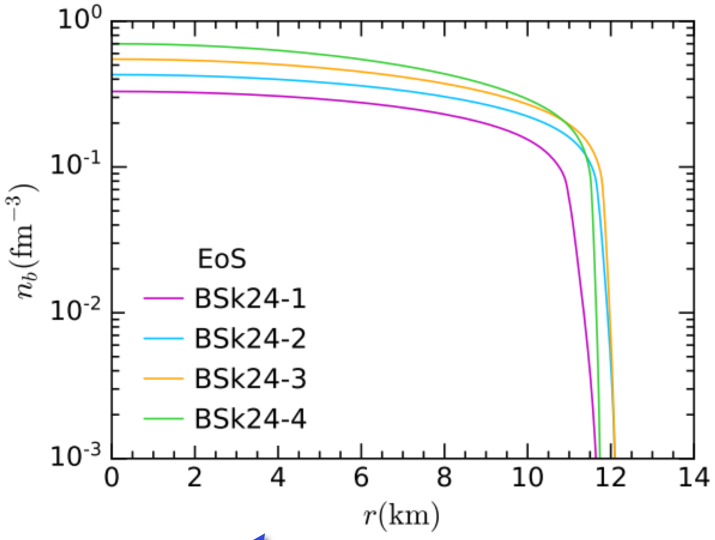


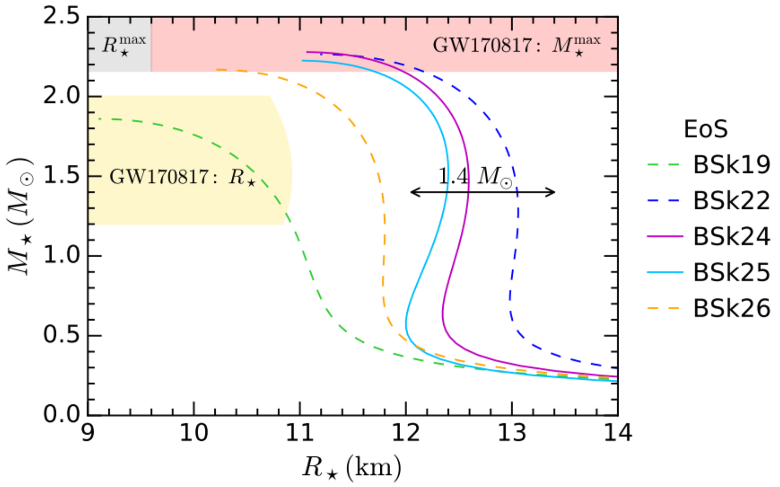
# Neutron Star Equation of State: BSk

- 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



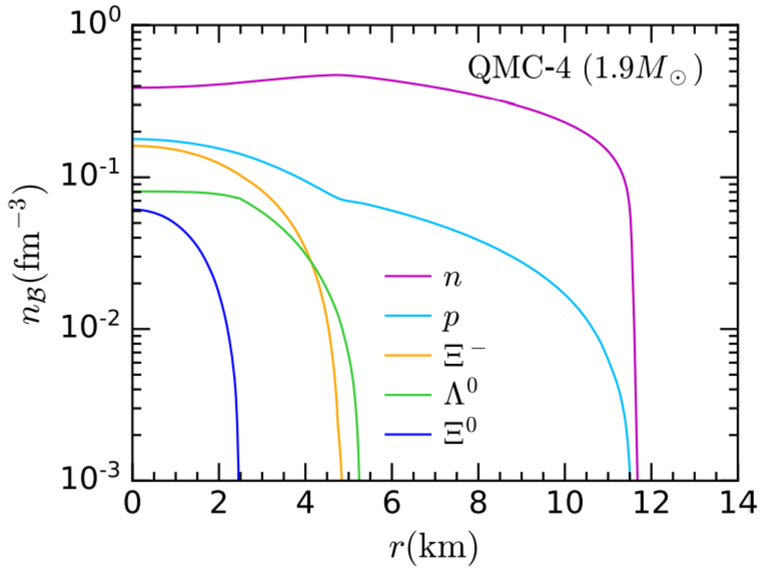



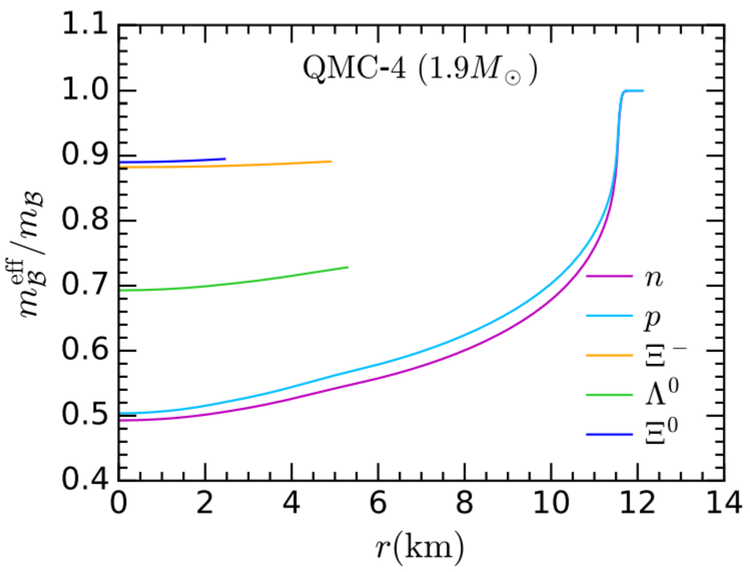



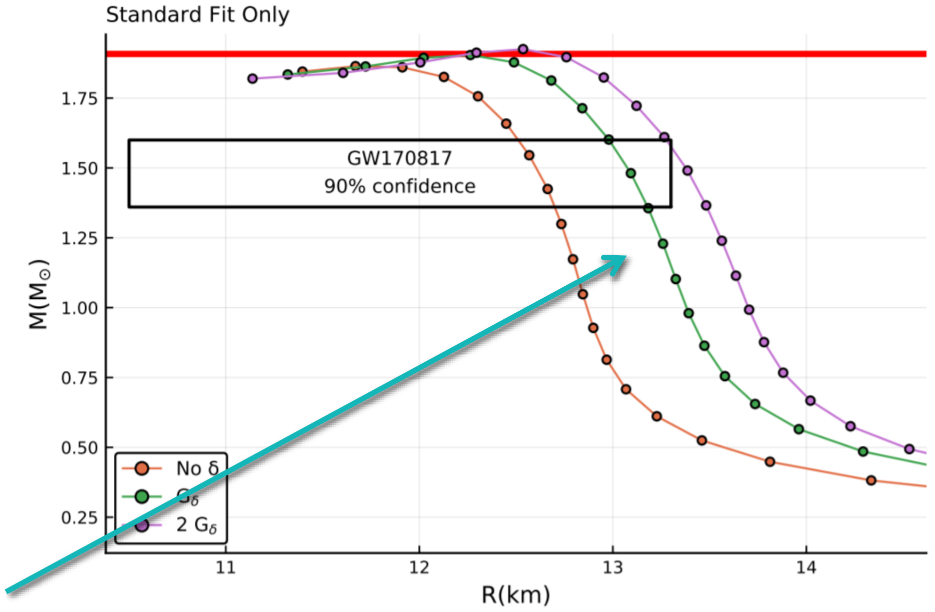

EoS + TOV = Radial Profiles

# Neutron Star Equation of State: QMC

- Quark-Meson-Coupling Model
- Relativistic, accounts for exotic matter, self-consistent nucleon interactions (Guichon et .al. 1802.08368)




Green line is EoS used

Motta et. al. 1904.03794

# 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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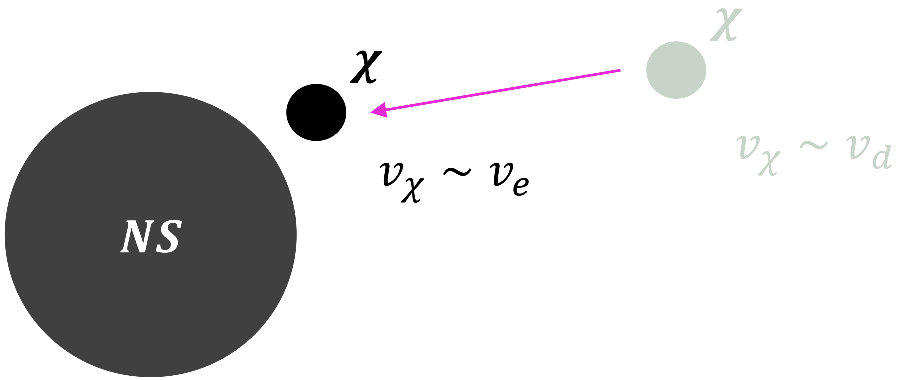

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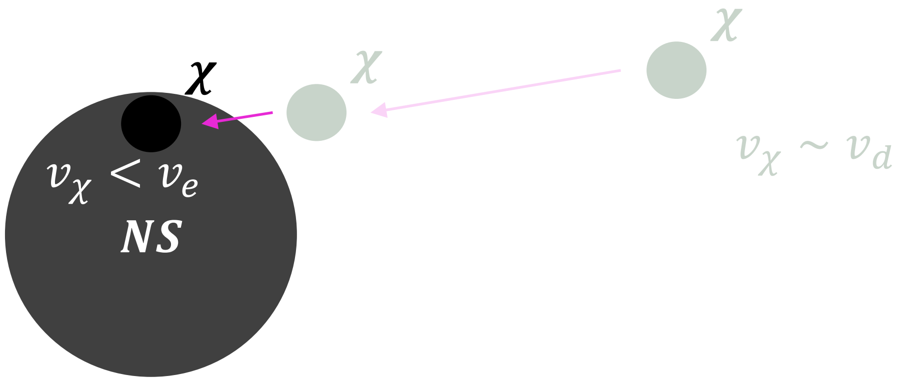
  - NS relative velocity to DM halo: $v_\star \sim 230\ km/s$
  - DM boosted to $\sqrt{v_e^2 + v_d^2} \sim v_e > 0.5c$



# 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

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)

( $\rightarrow 1$ for interacting baryons)

Differential cross section

Relativistic kinematics

Pauli Blocking

Bell, Busoni, Robles and MV 2004.14888

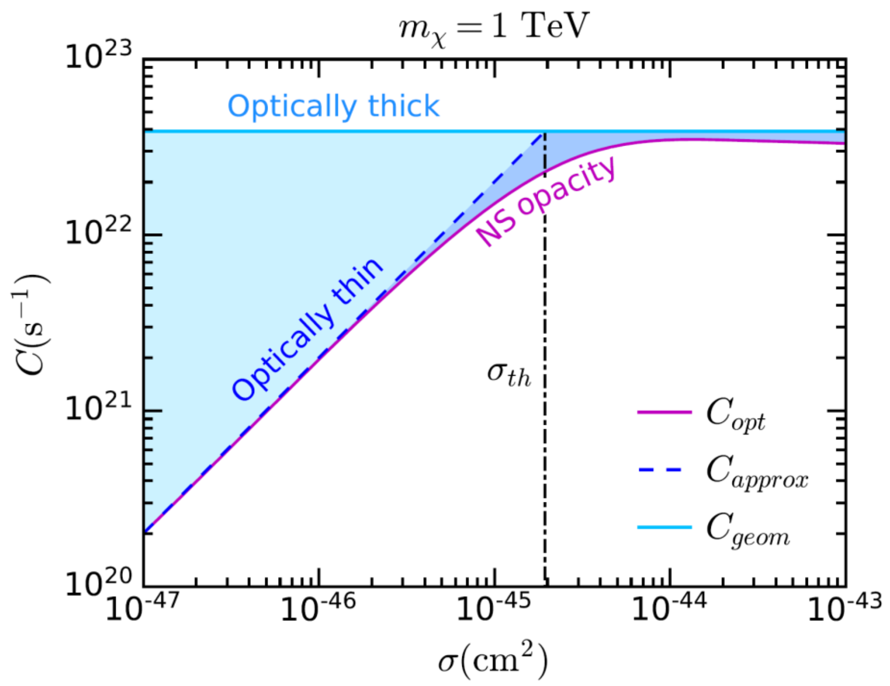
# Threshold Cross Section

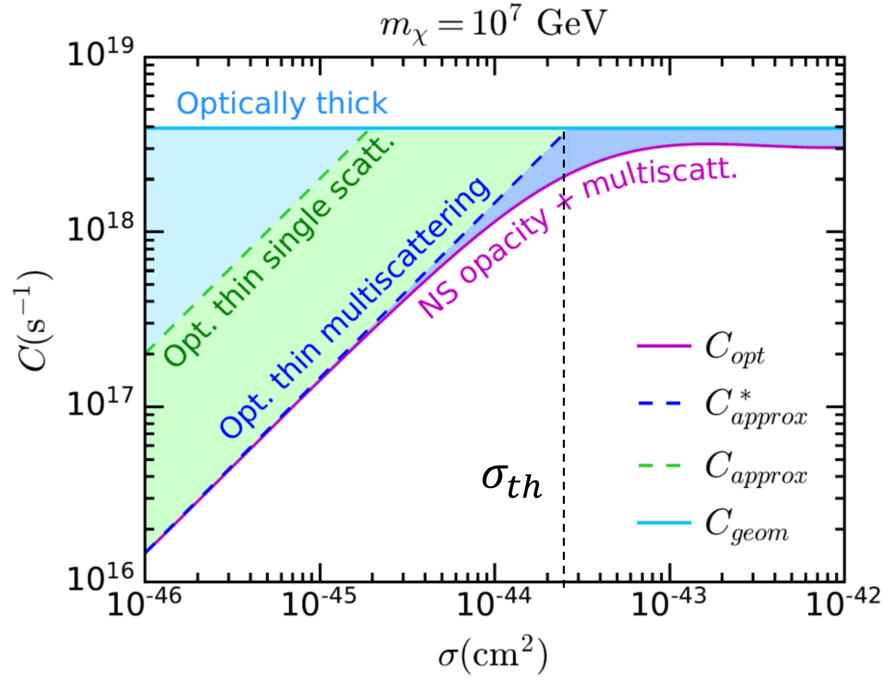
Capture rate saturates to geometric limit for cross sections above

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

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

(Not quite for baryons…)



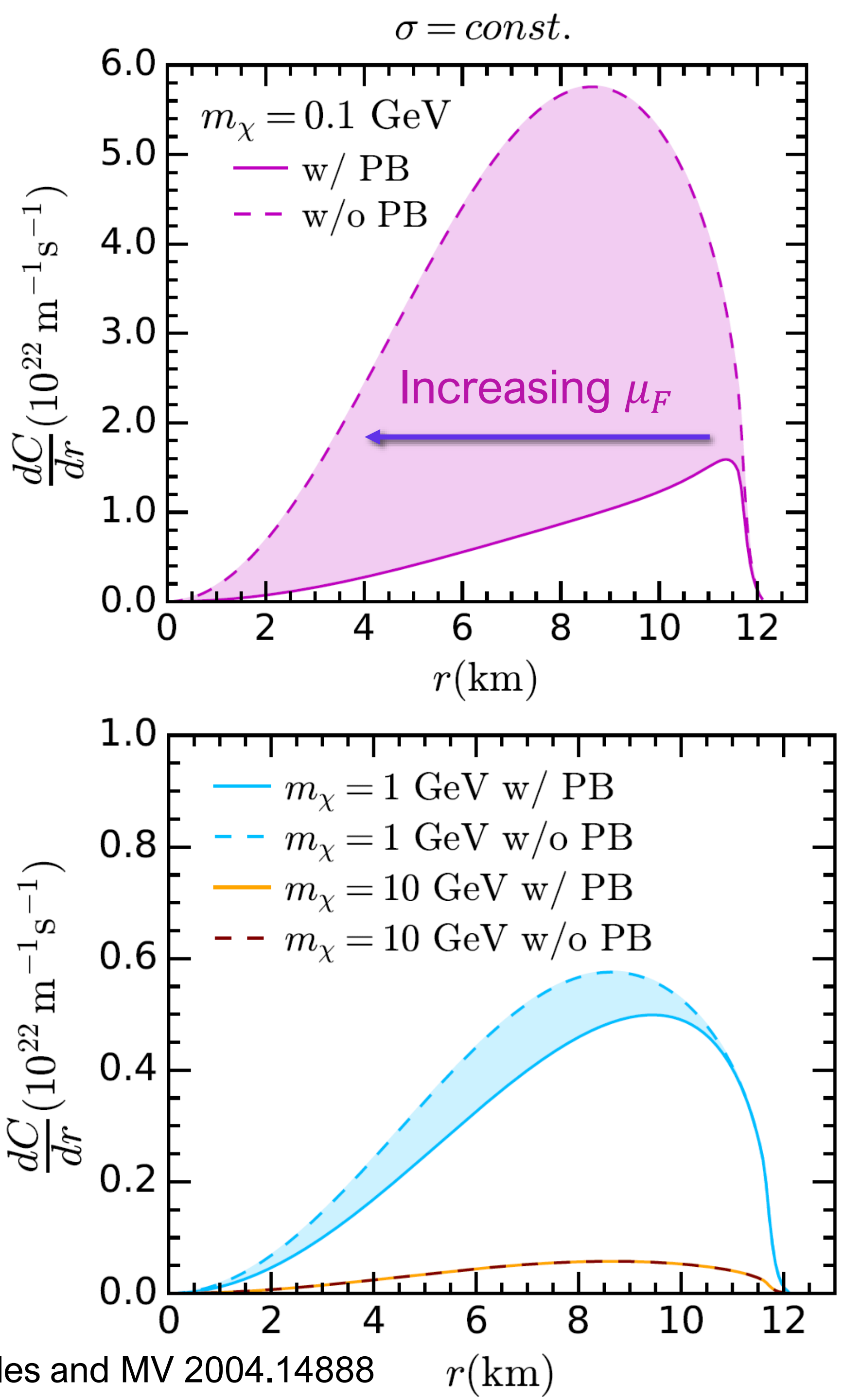

NFB, GB, SR and MV 2010.13257

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

- 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



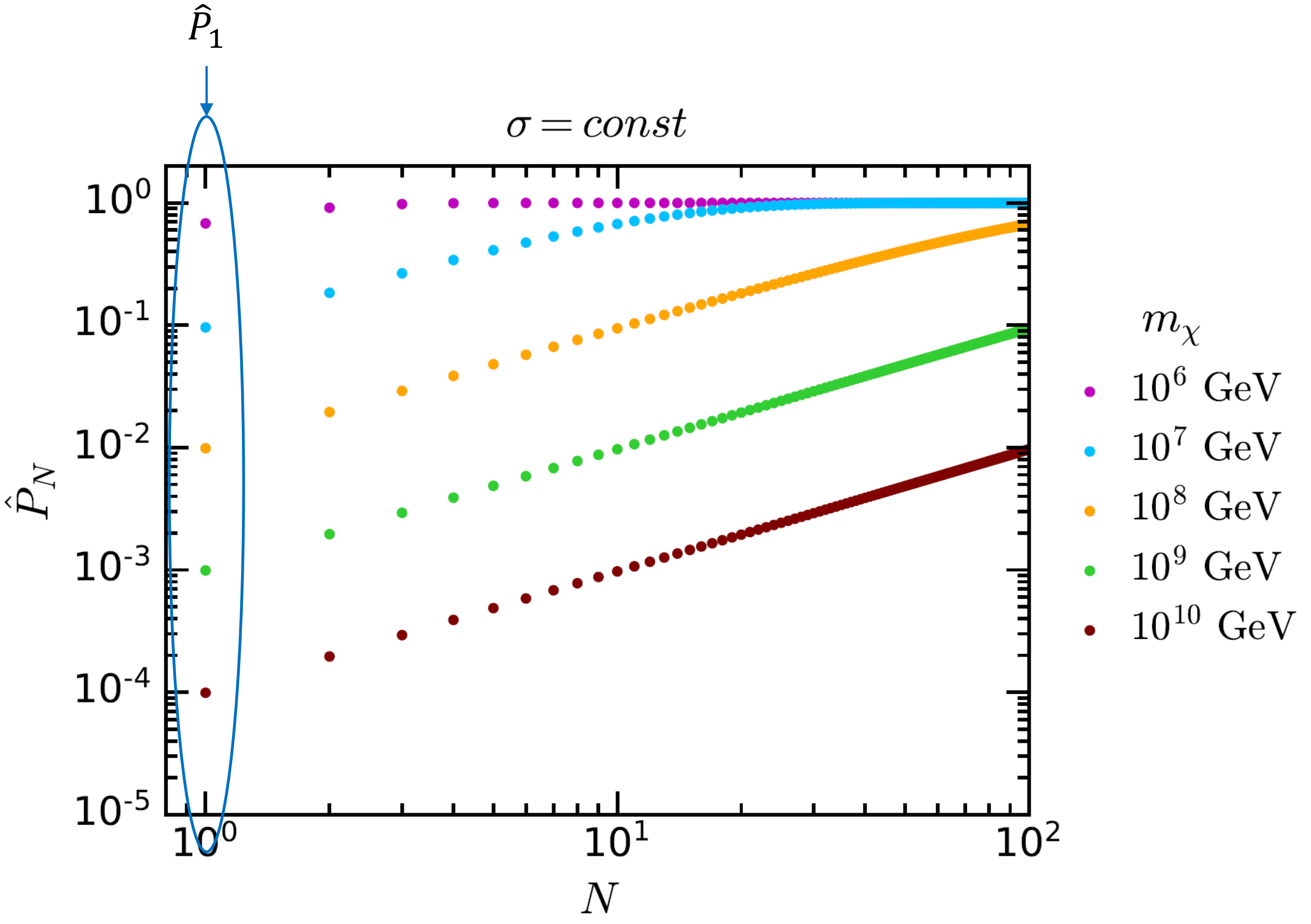

Bell, Busoni, Robles and MV 2004.14888

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

- Require min. energy loss

$$q_{0,min} = \frac{1}{2} u_\chi^2 \frac{m_\chi}{\sqrt{B}}$$

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




Cumulative probability of capture after *N* interactions

Bell, Busoni, Robles and MV 2004.14888

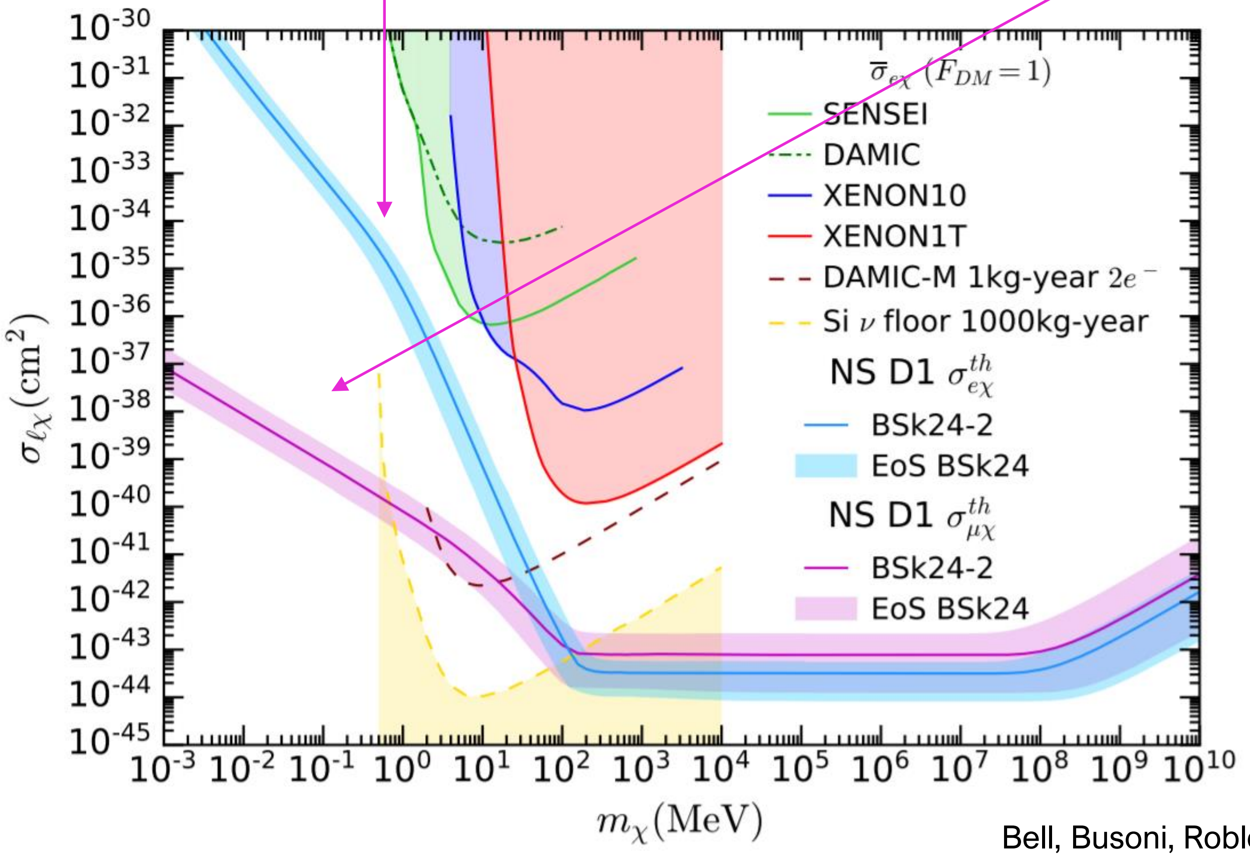
# Lepton Threshold Cross Sections

Leading order term in cross section changes

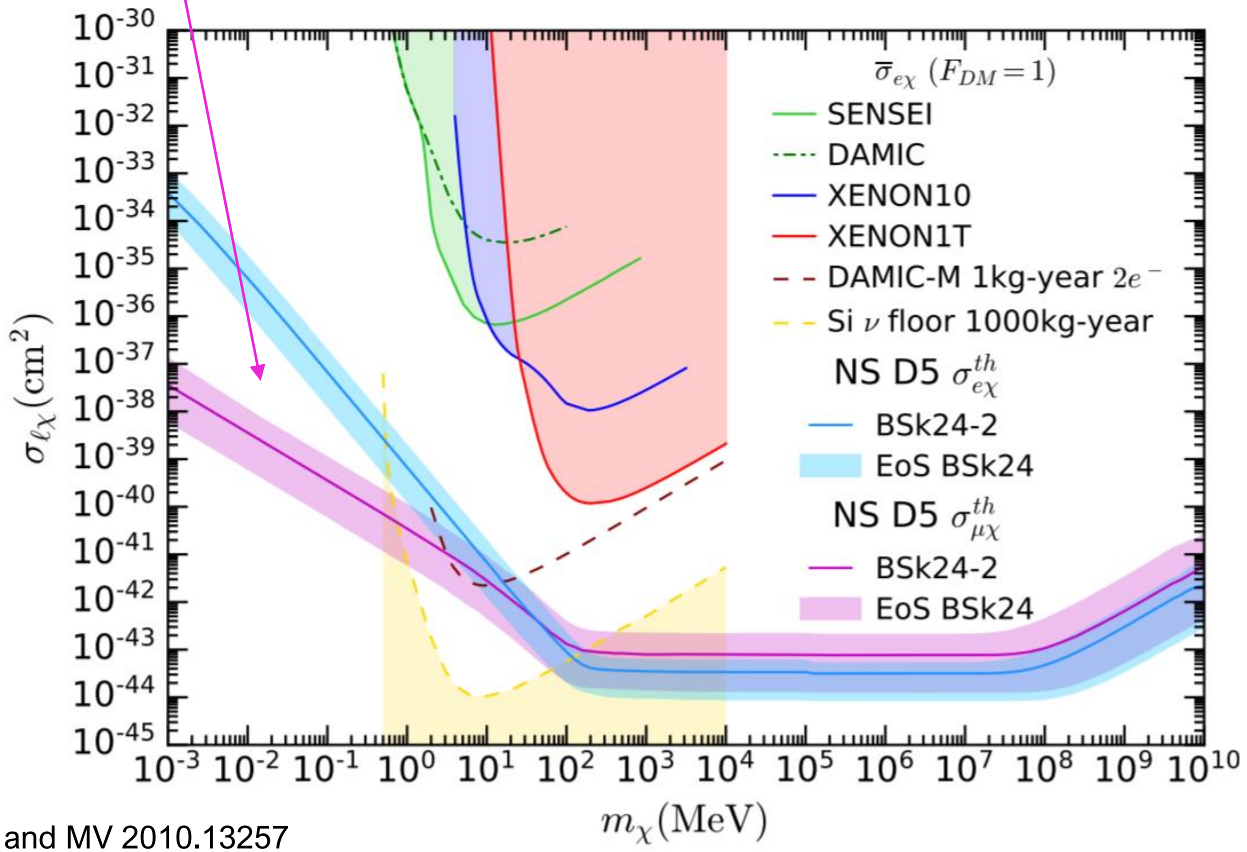
Muons beat electrons despite lower abundance:

Less Pauli blocked

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




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




Bell, Busoni, Robles and MV 2010.13257

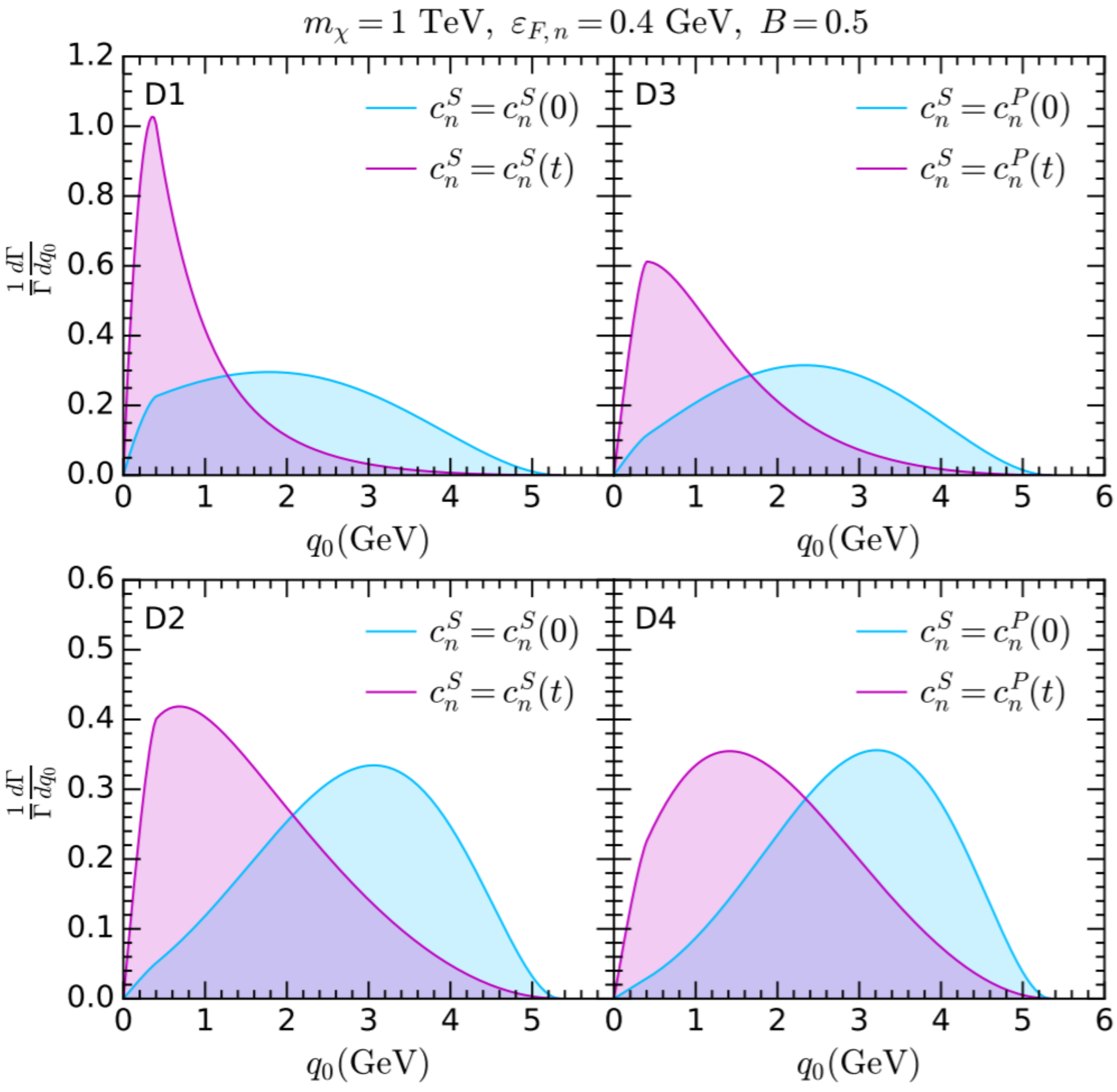
# Nucleon Form Factors

- Momentum transfers can reach $\sim 10\ GeV$
- Nucleon form factors are momentum dependent:

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

$Q_0 \sim 0.9\ GeV$

- Supresses interaction rate at large momentum transfers
- Affects DM with $m_\chi \gtrsim 0.2\ GeV$



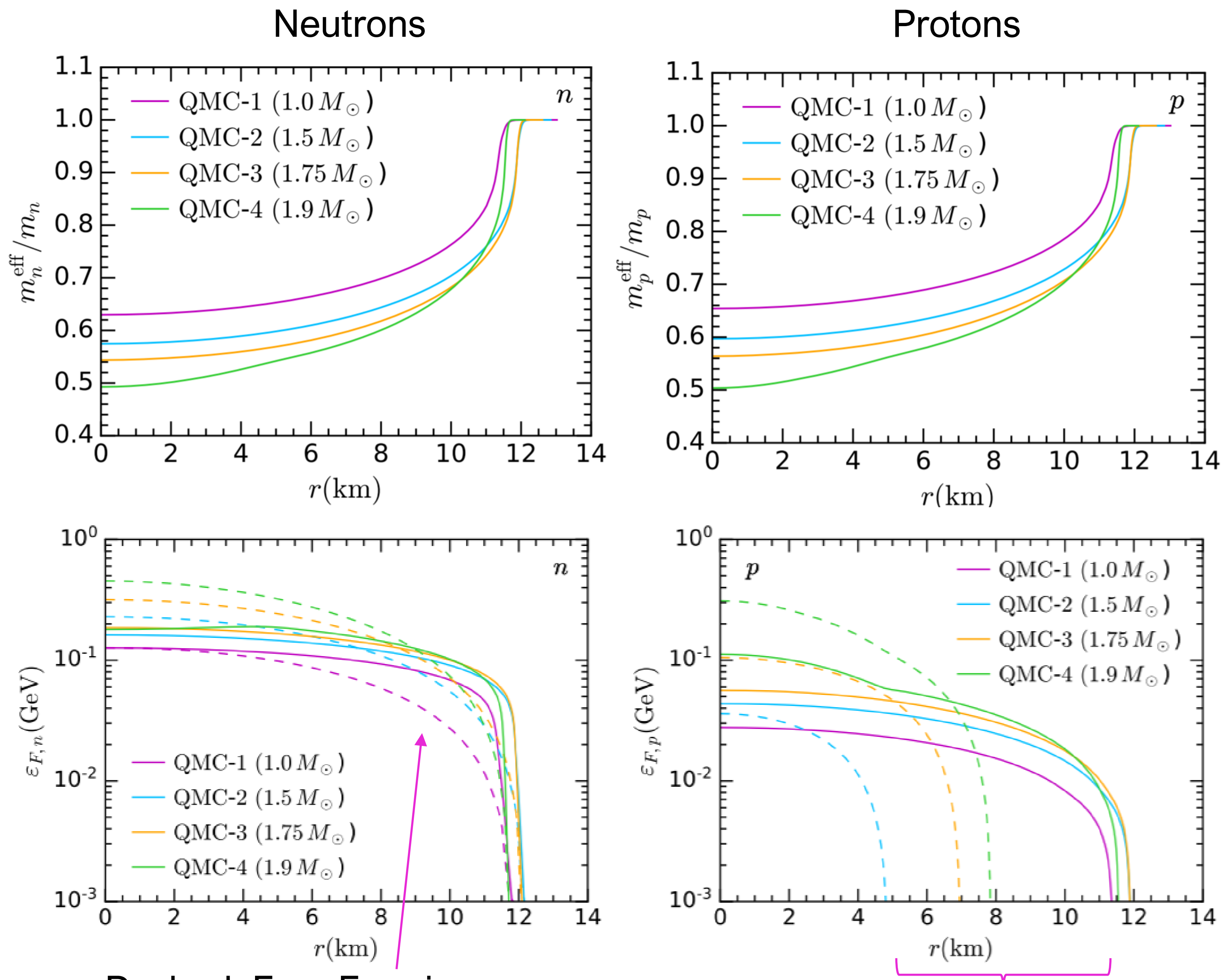

Anzuini, Bell, Busoni, Motta, Robles, Thomas and MV 2108.02525

# Strongly Interacting Baryons

- Nucleons develop an effective mass

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

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




Dashed: Free Fermi gas

Proton $\varepsilon_F = 0$ in Free gas



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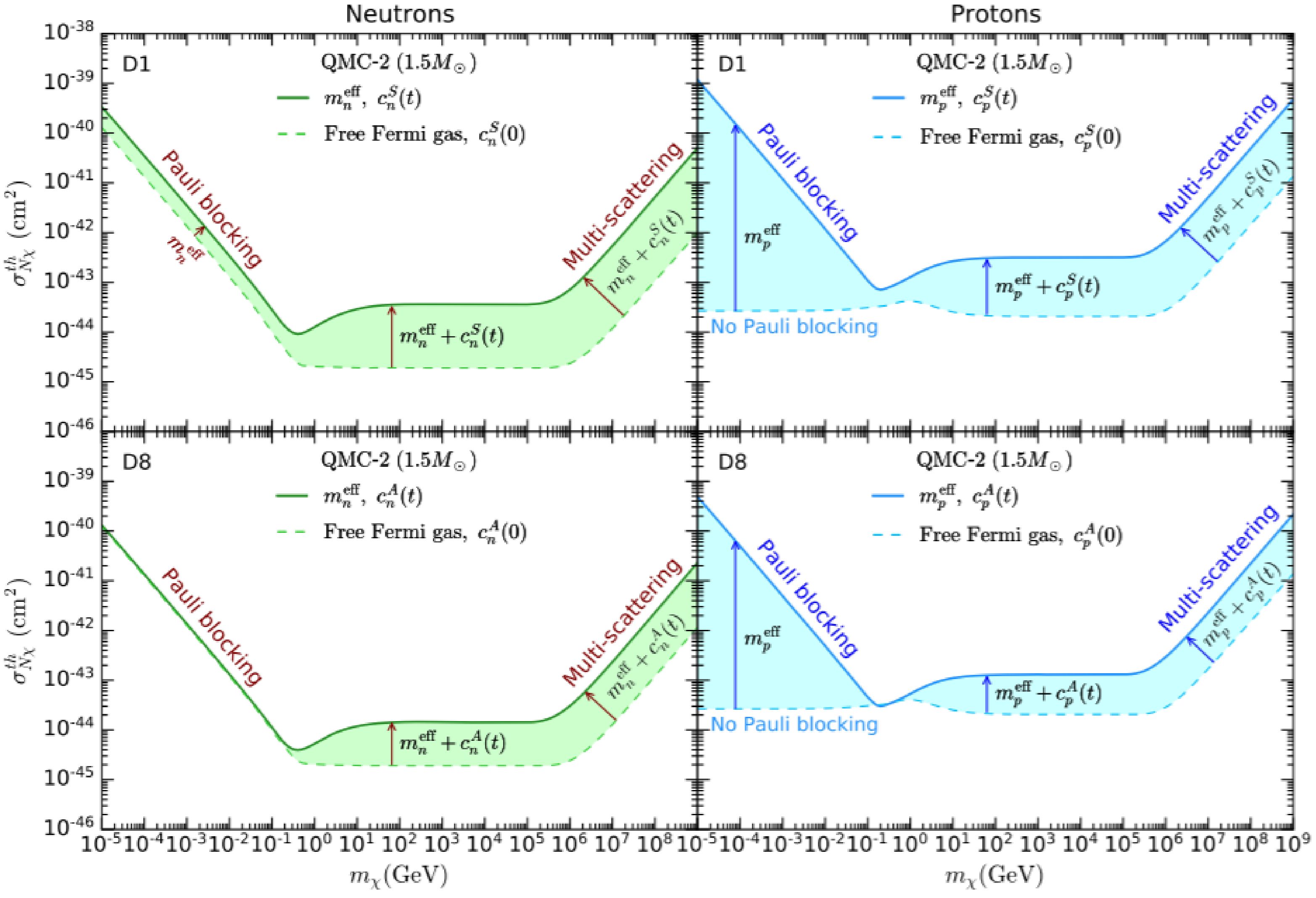
# Nucleon Threshold Cross Sections

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

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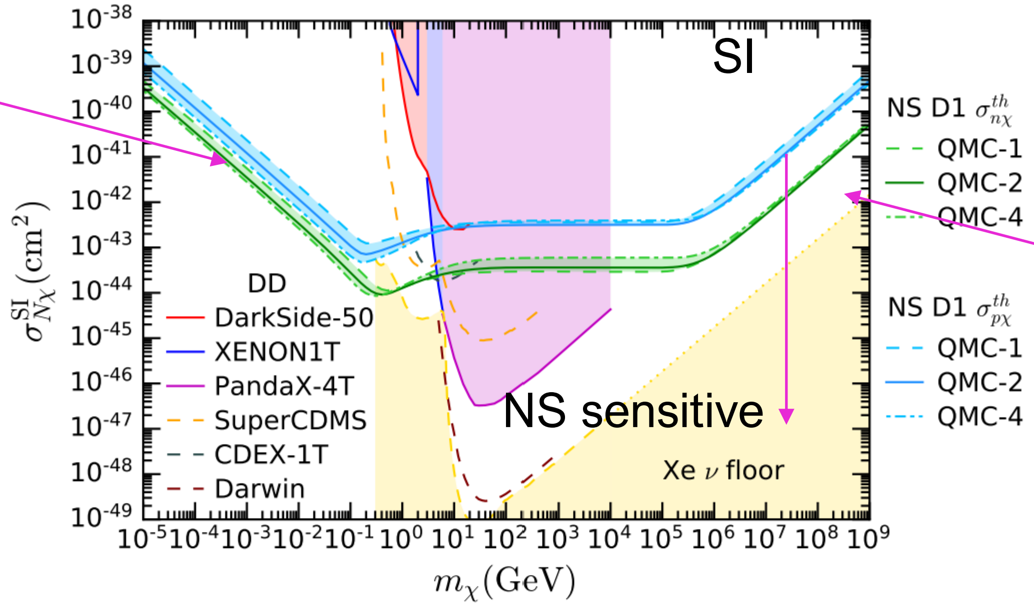
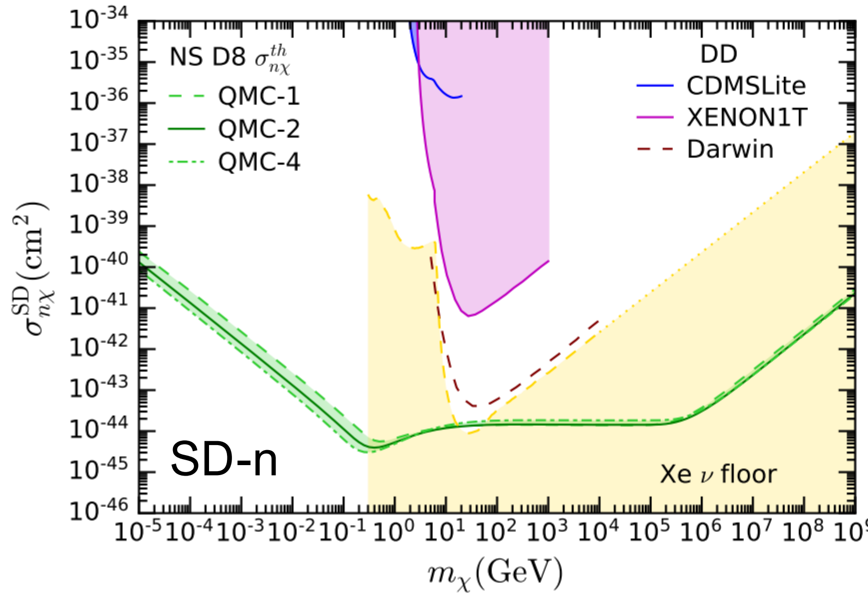
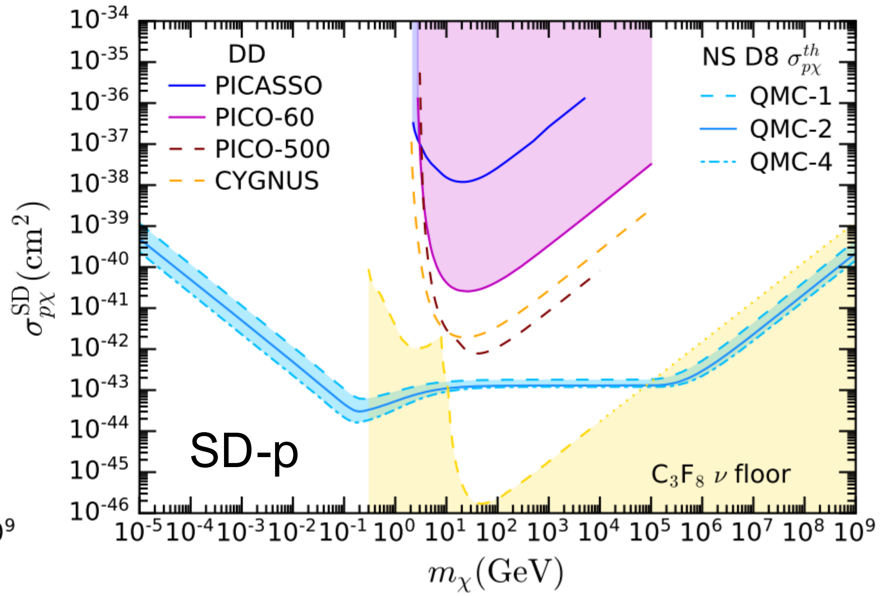
# Nucleon Threshold Cross Sections

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




Multiple Scattering:
$\sigma_{th} \propto m_\chi$

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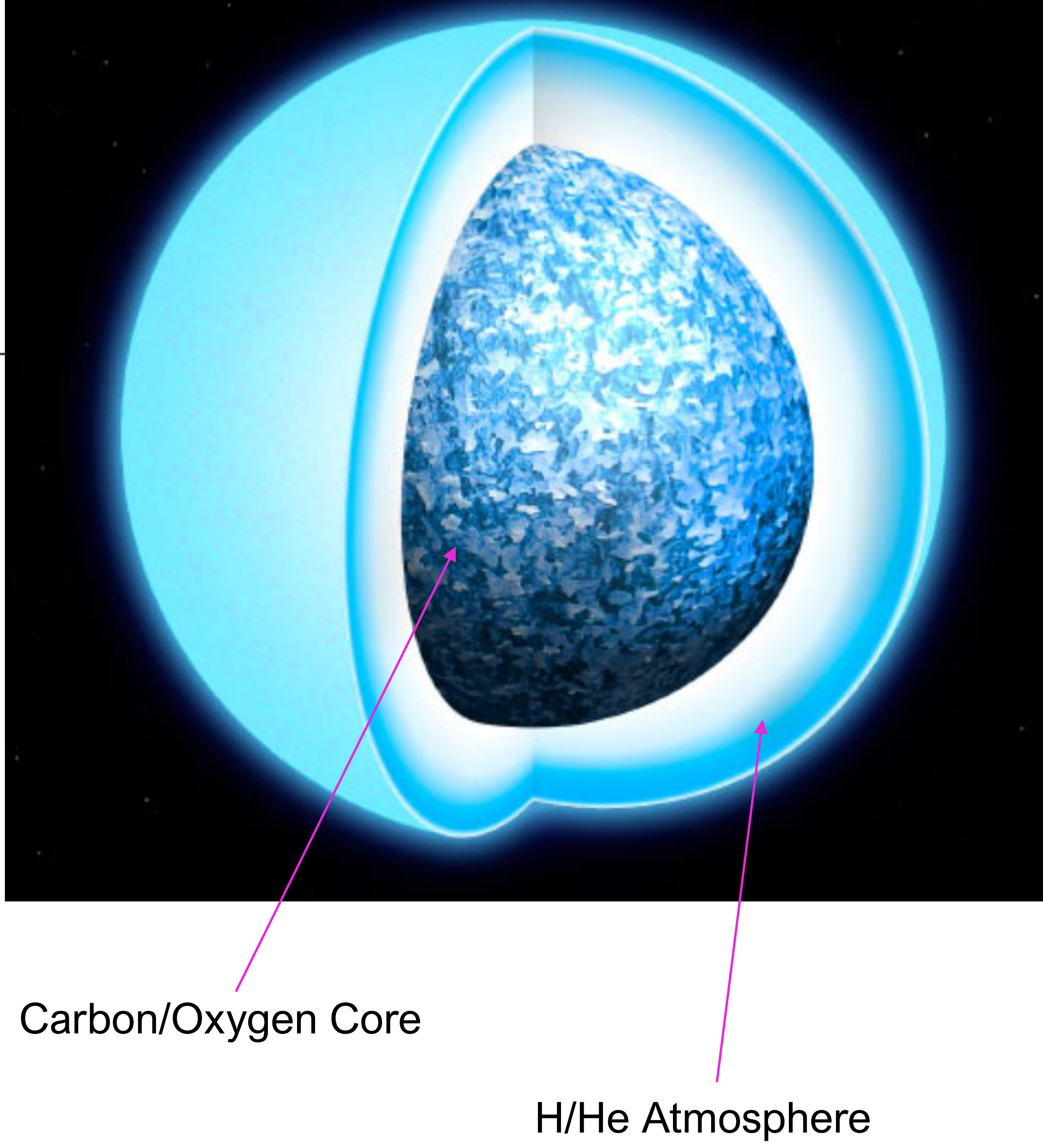
# White Dwarfs

## DM CAPTURE AND HEATING IN GLOBULAR CLUSTER M4

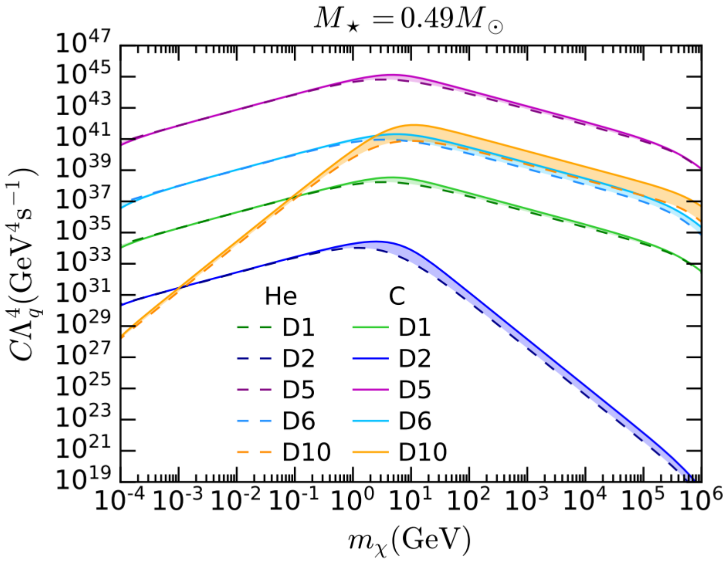
# White Dwarfs

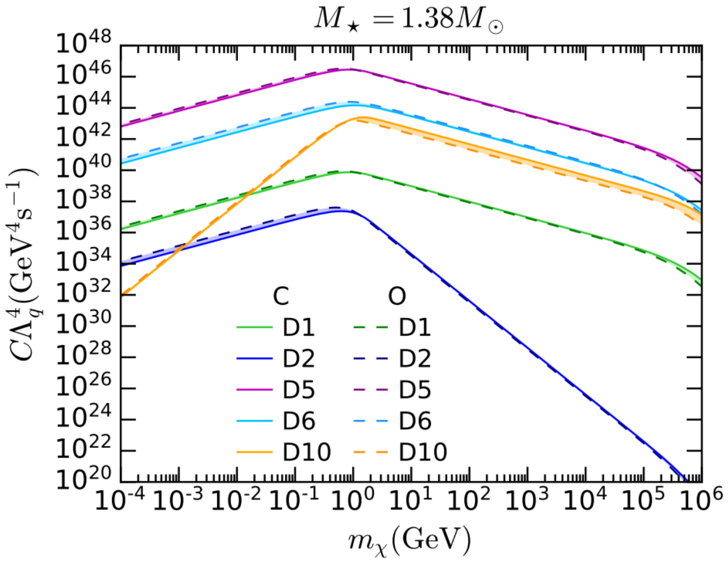
- Ions in Coulomb lattice (if crystalised)
- Electrons highly degenerate + relativistic
  - Perfect for new formalism!
- Much weaker gravitational fields
  - Need denser DM environment to sufficiently heat up
- Look to Globular Cluster Messier 4 (M4)
  - Closest GC ($1.9\ kpc$)
  - Age $11.6\ Gyrs$
  - $\rho_\chi = 798\ (532)\ GeV/cm^3$ for (un)contracted halo
  - May/may not contain DM

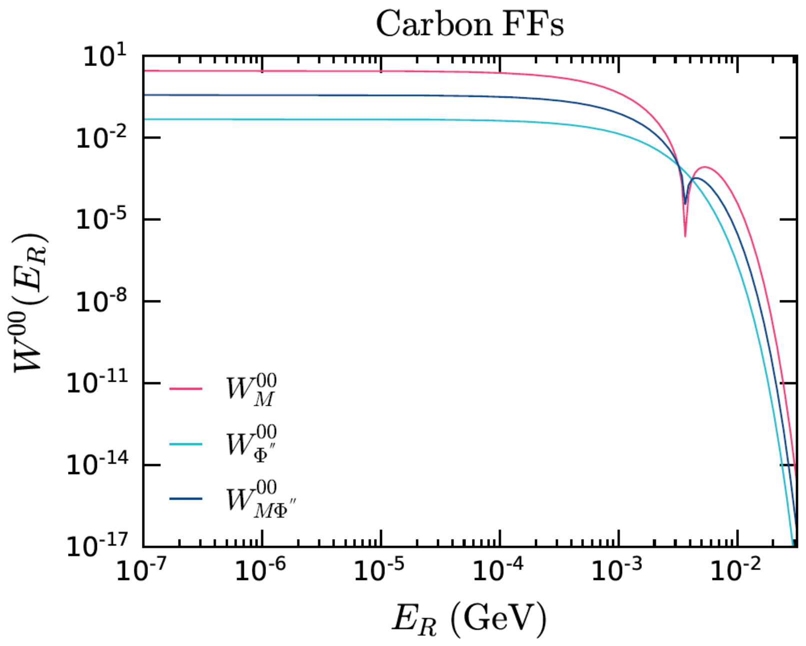


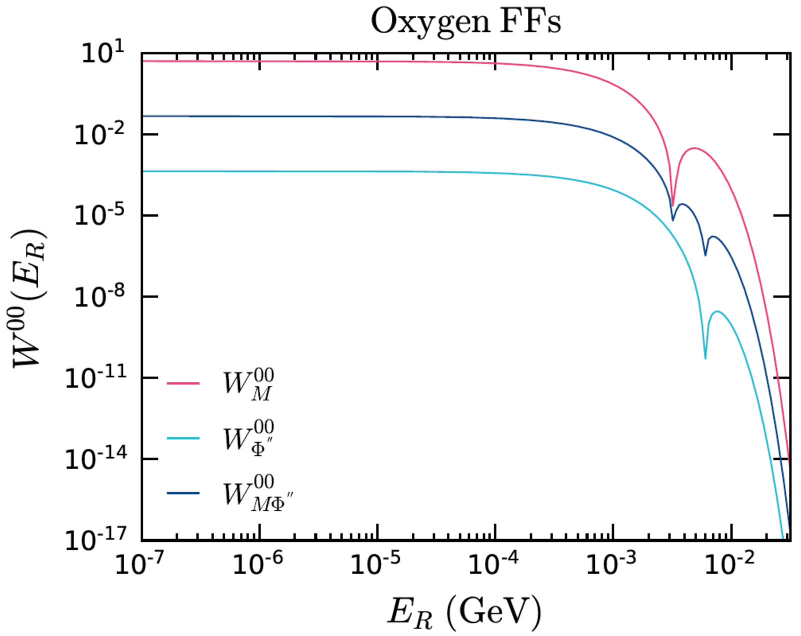
# Capture on Ions

- 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



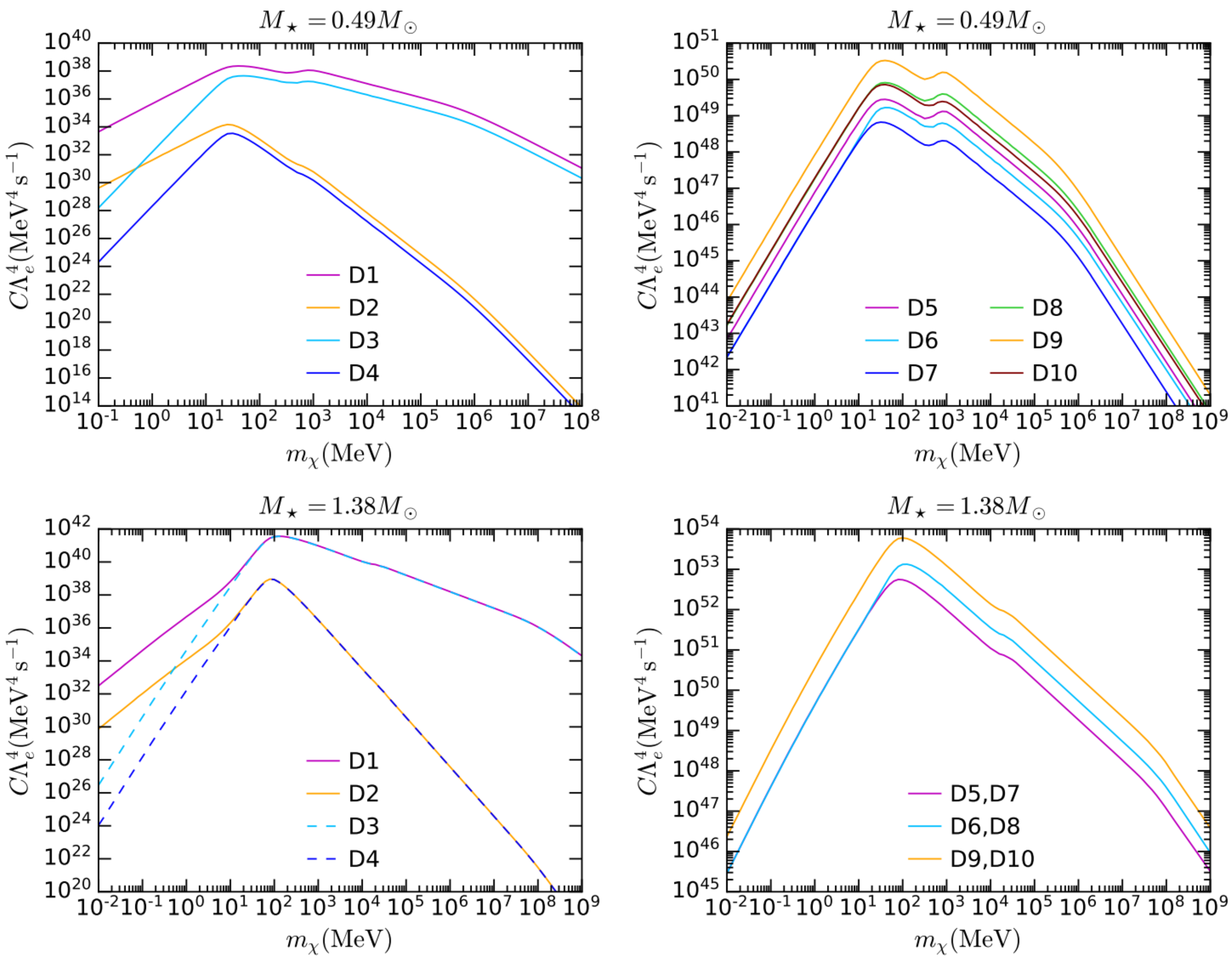



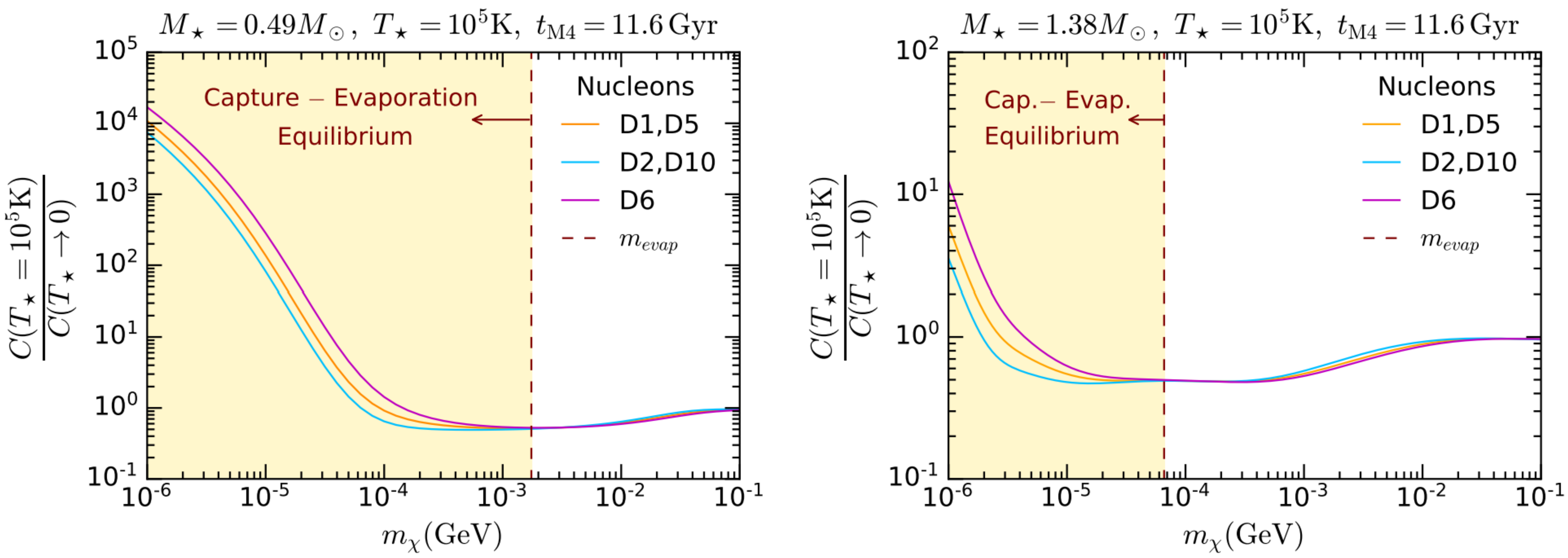
# Capture on Electrons

- 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

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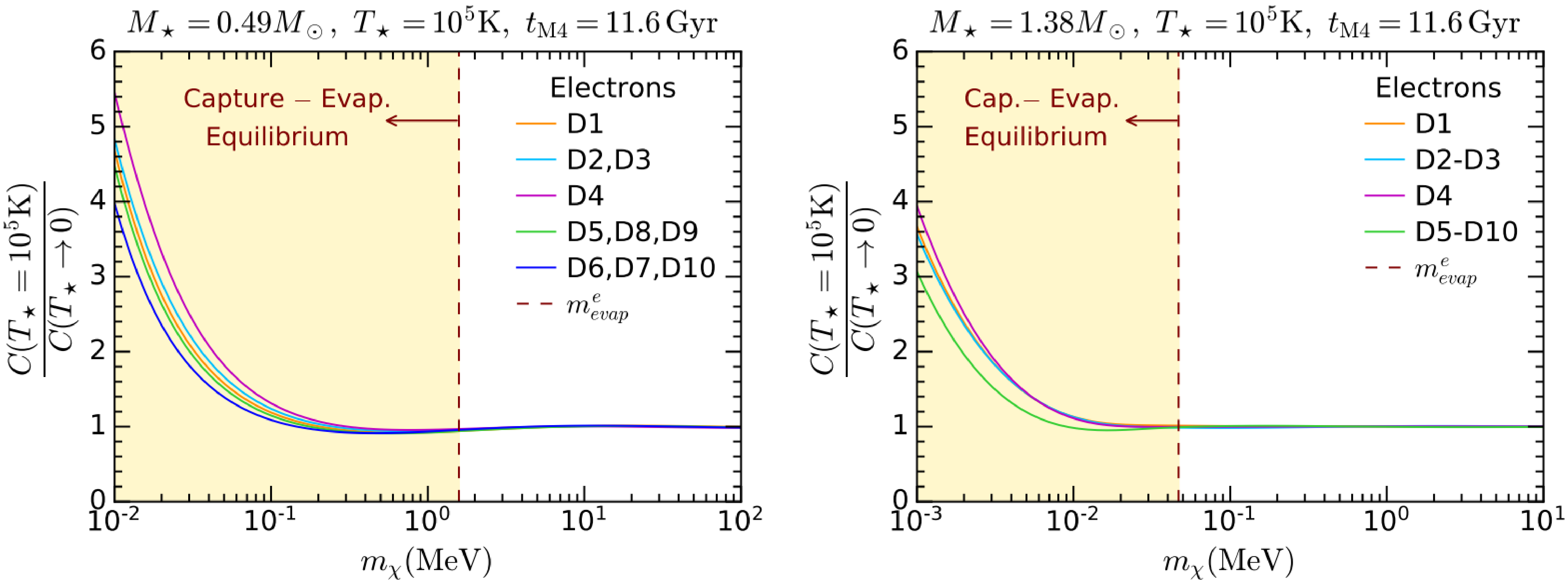
# Finite Temperature Effects: Ions

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

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# Finite Temperature Effects: Electrons

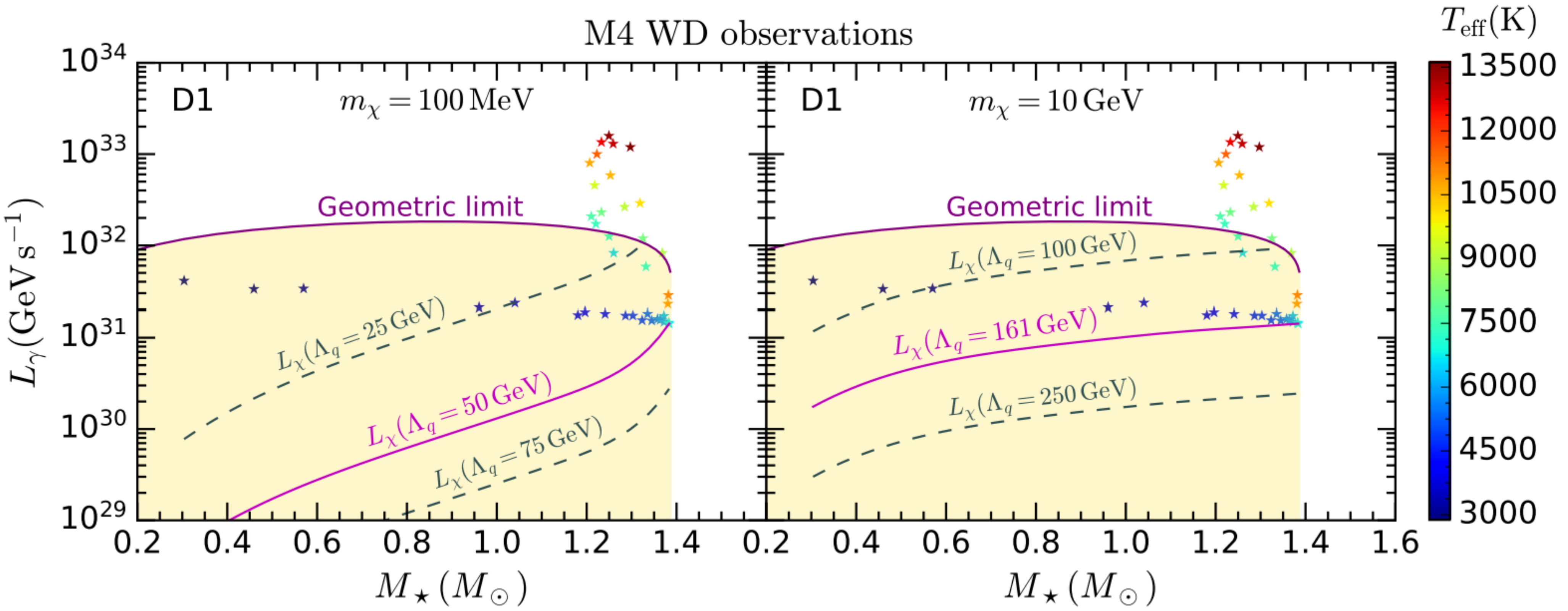
- Fermi-Dirac distributions spread out reducing Pauli Blocking
- DM can up-scatter and evaporate

# 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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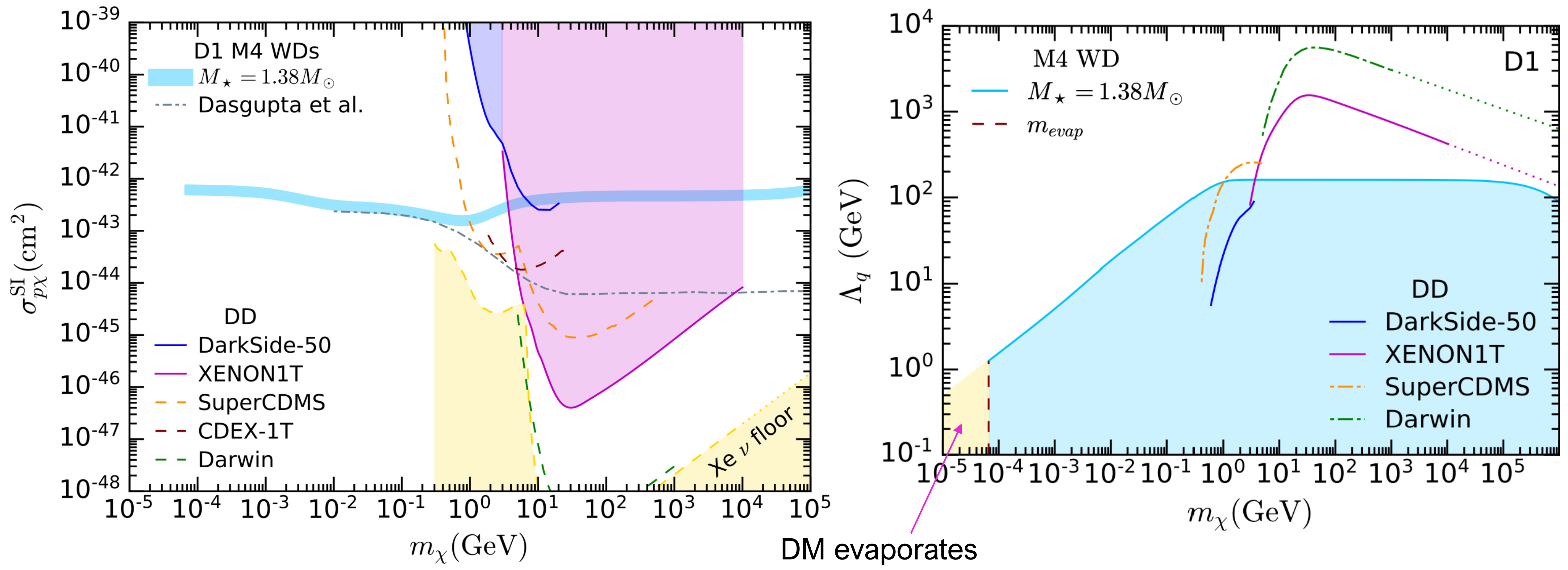


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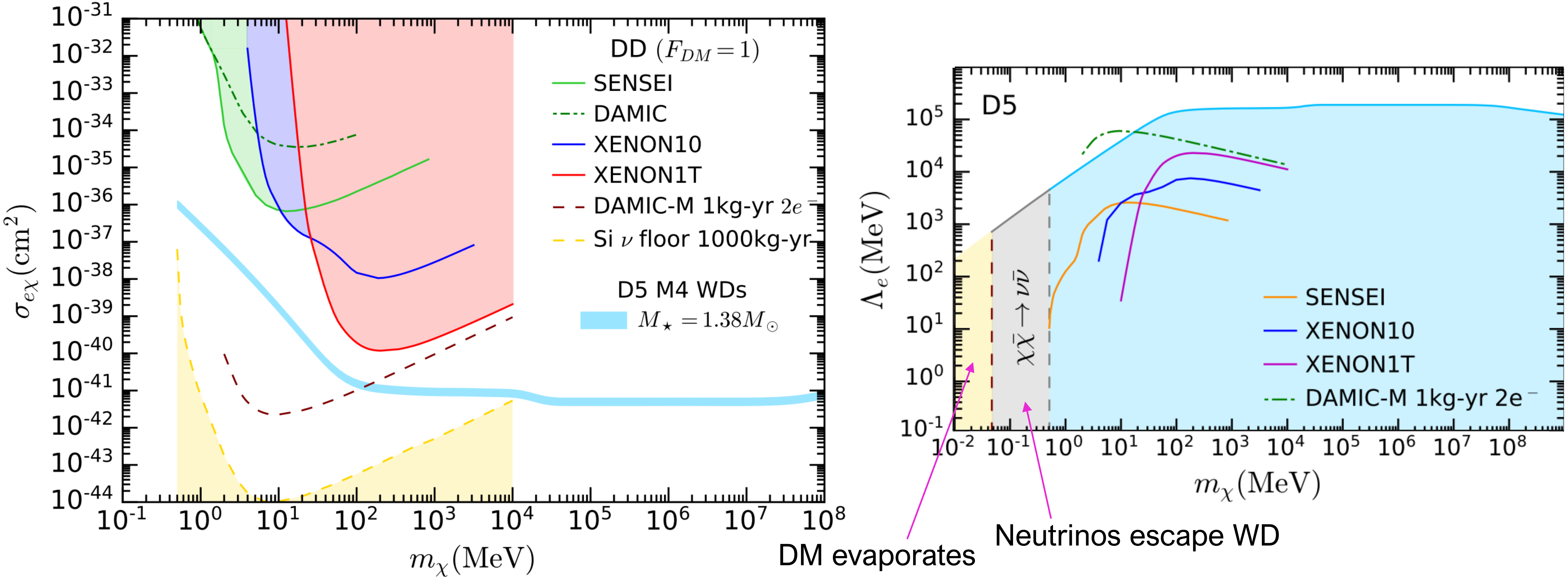
# Prospective Heating Constraints: Ions

Relies on DM existing in M4

Can potentially reach beyond direct detection

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# Prospective Heating Constraints: Electrons

Relies on DM existing in M4

Can potentially reach beyond direct detection

# Summary

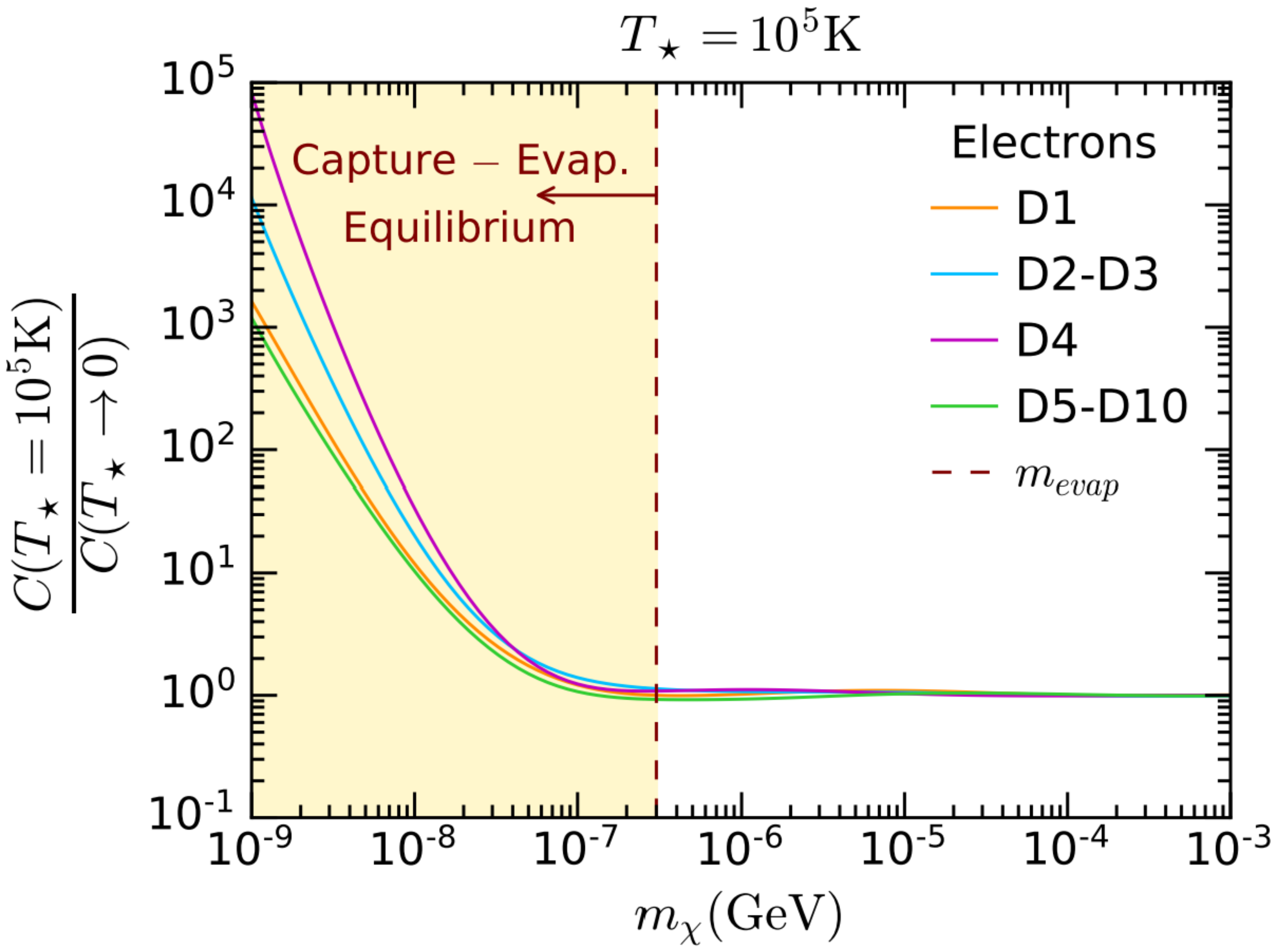
- Compact Objects offer unique laboratory to study Dark Matter
- We consistently incorporate important pieces of physics including:
  - Pauli Blocking
  - Multiple Scattering
  - Momentum dependent Form Factors
  - Nucleon Strong Interactions
- More work to be done:
  - Collective effects of in medium scattering (DeRocco et. al. 2201.05167)
  - Cooling of NSs still not well understood
- Credit to Sandra for being a key collaborator

# Thank you

Questions?

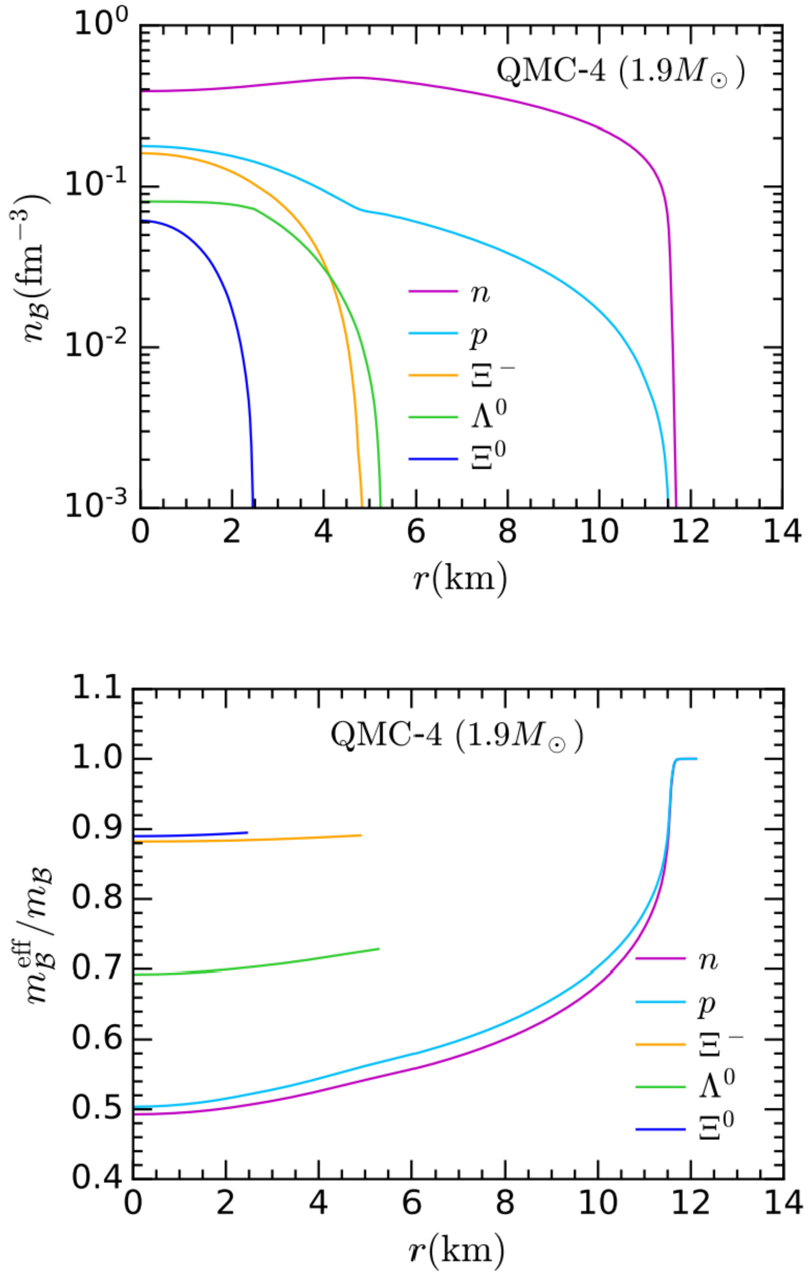
# Backup Slides

# 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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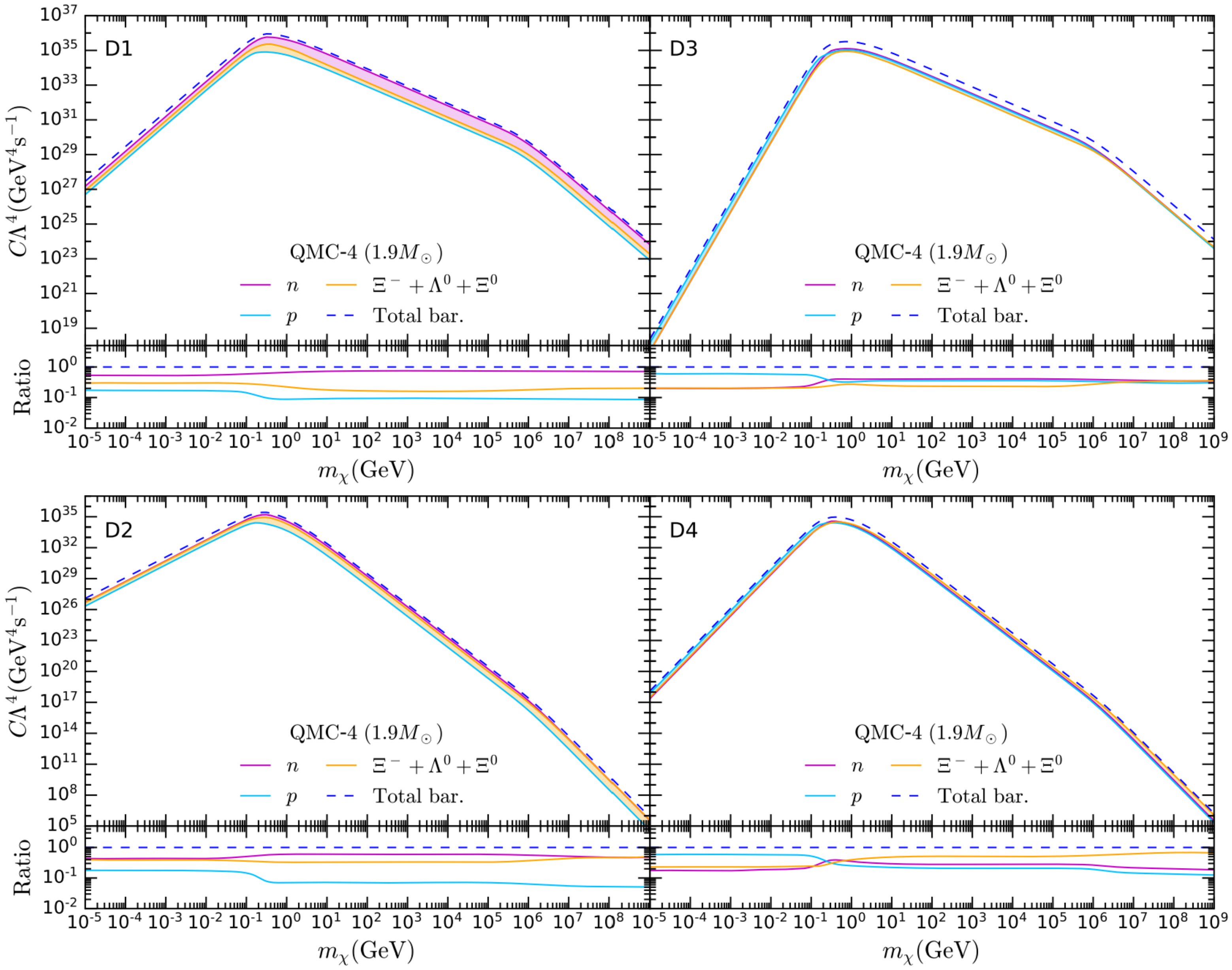

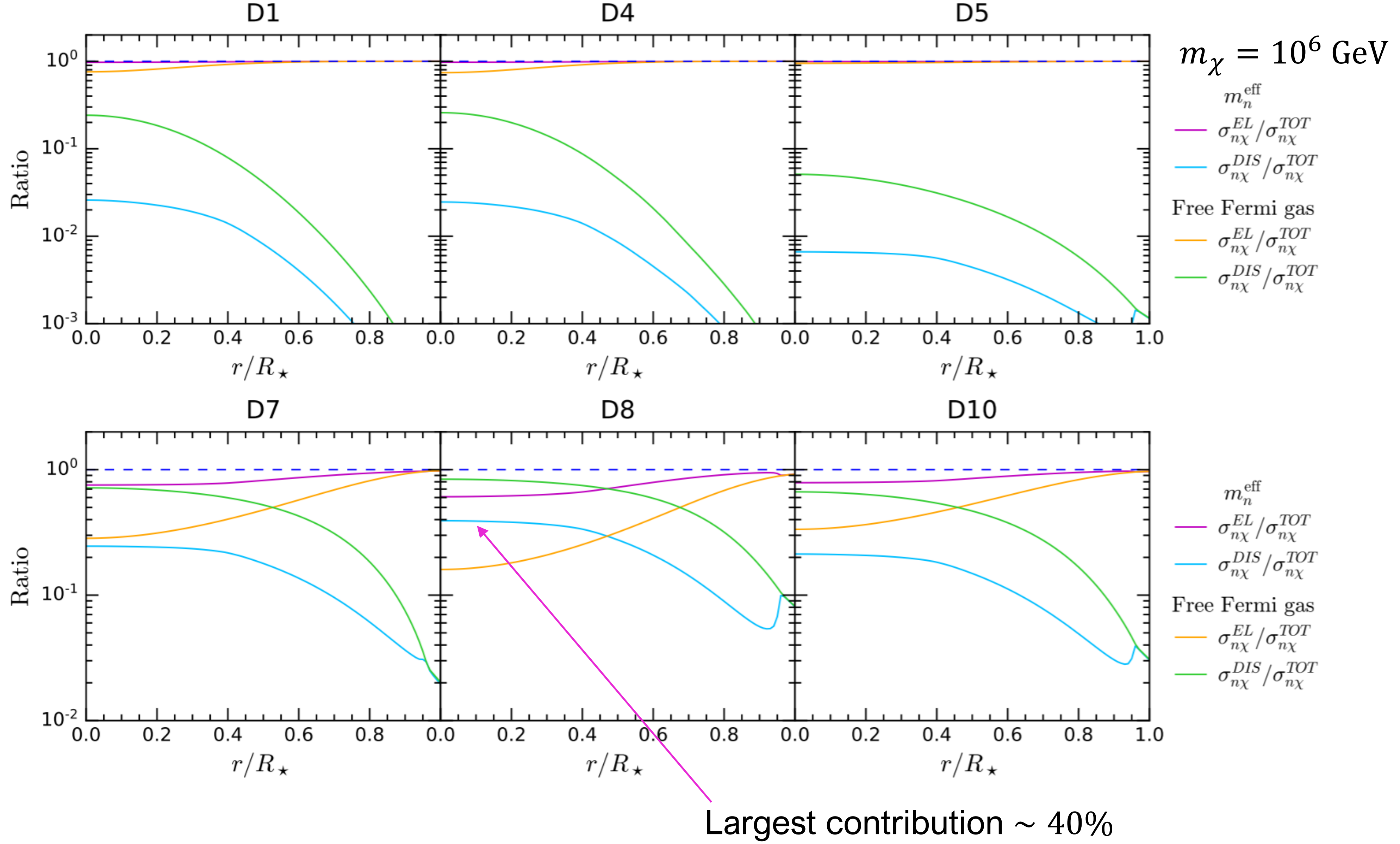


# Deep Inelastic Scattering

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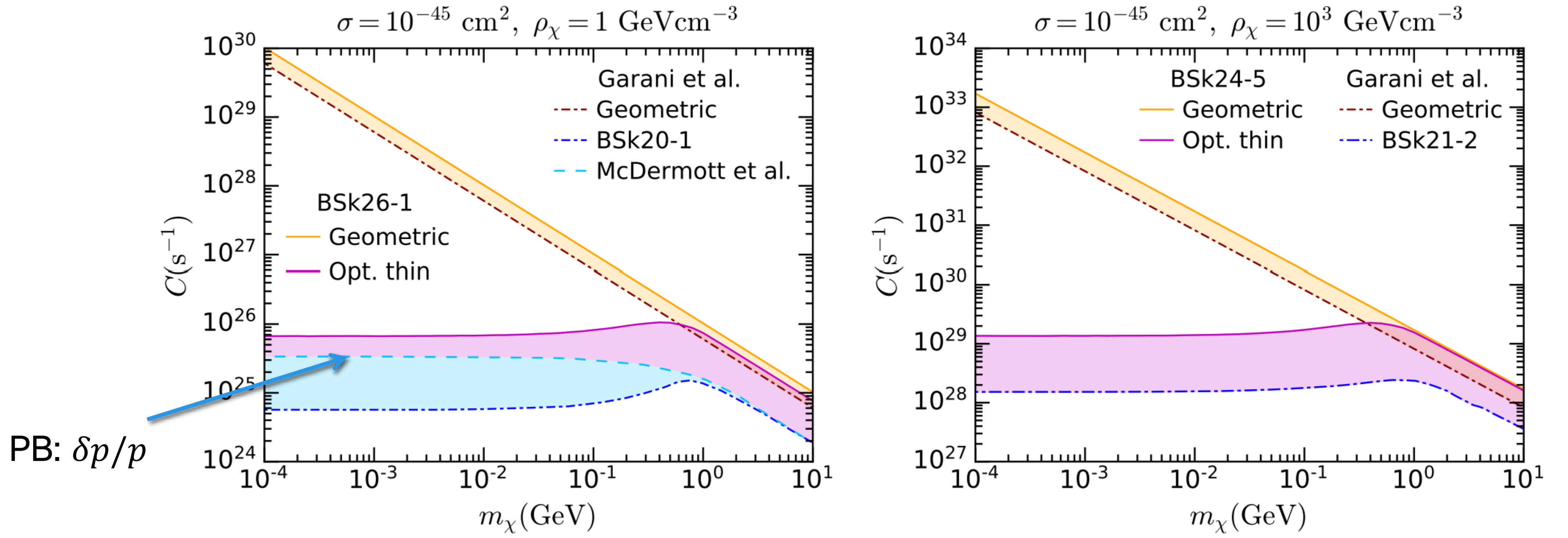
# Comparison to Previous Works

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

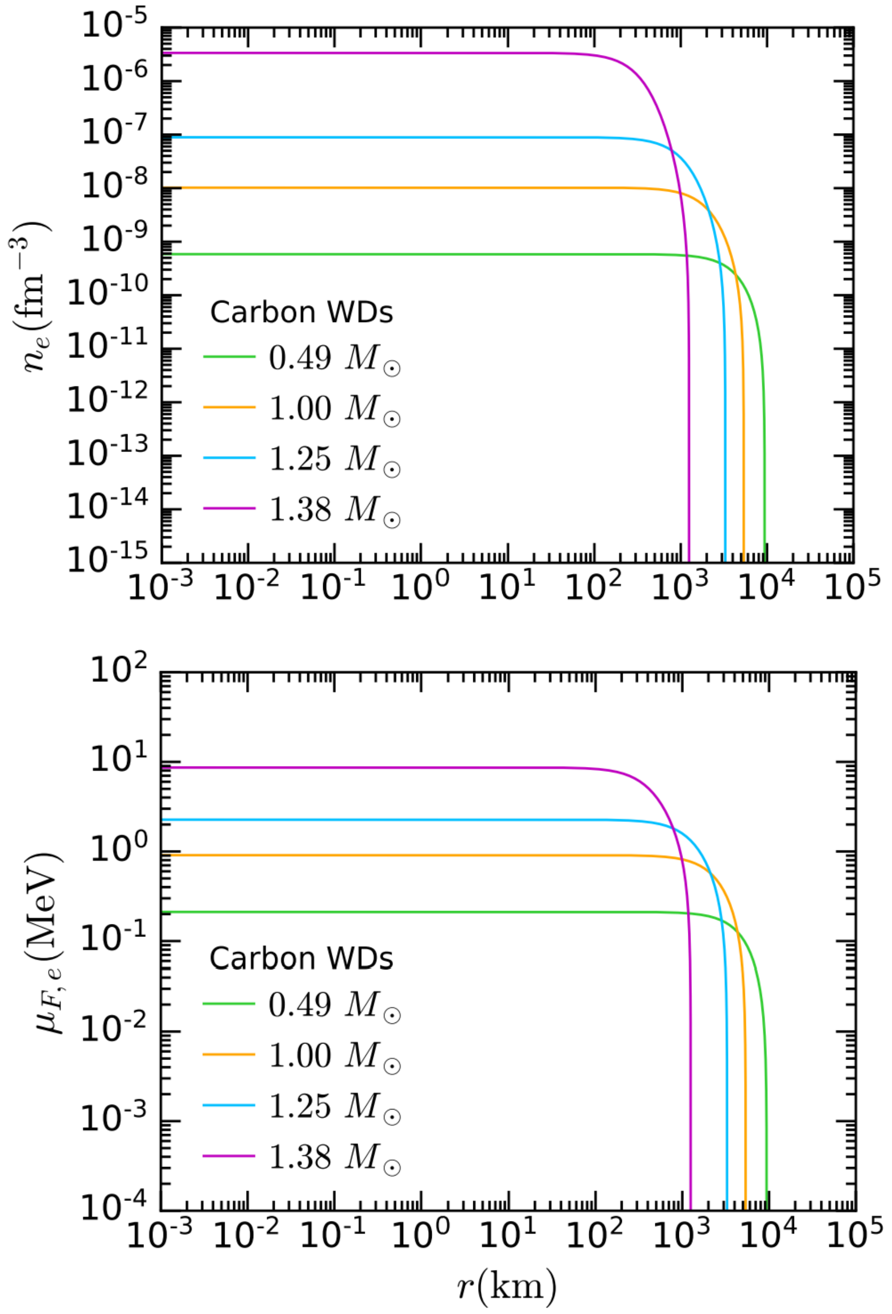


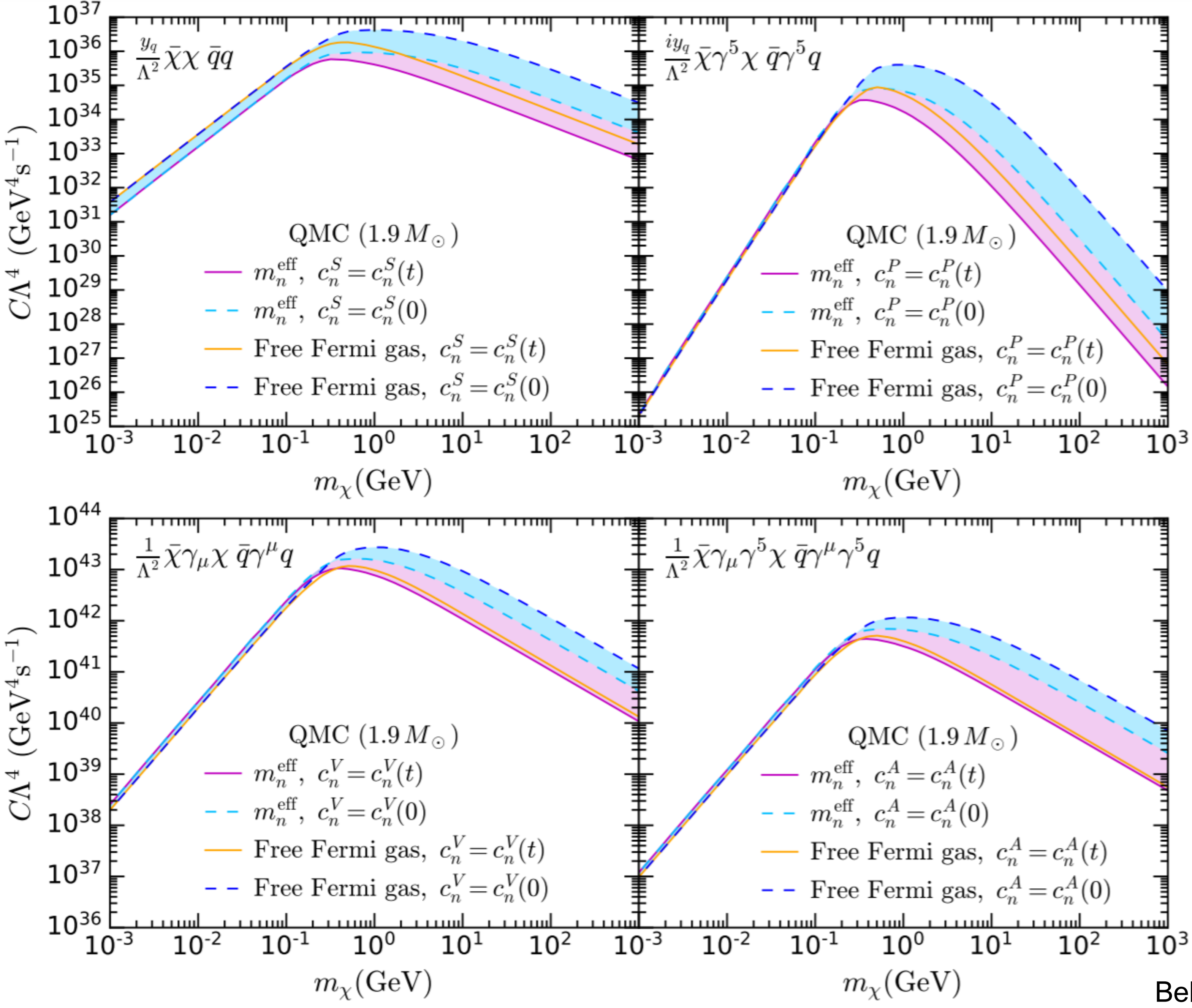

Bell, Busoni, Robles and MV 2004.14888

# 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