Improved Treatment of Dark Matter Capture in Compact Stars

Sandra Robles

King's College London

with

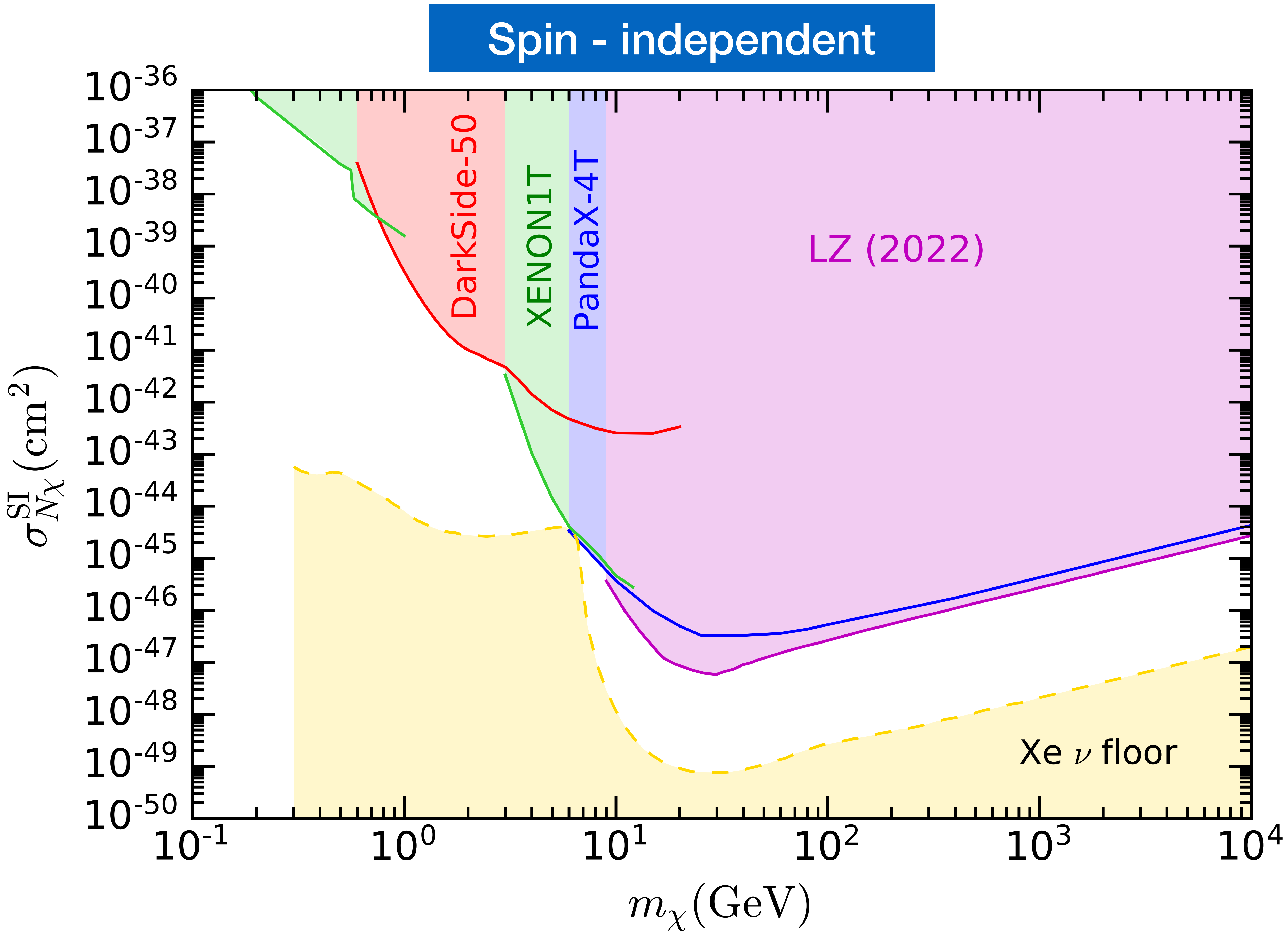
Nicole F. Bell, Giorgio Busoni, Michael Virgato, Anthony W. Thomas, Theo F. Motta & Maura E. Ramirez-Quezada

arXiv: 2004.14888 (JCAP), arXiv: 2010.13257 (JCAP), arXiv: 2012.08918 (PRL), arXiv: 2104.14367 (JCAP), arXiv: 2108.02525 (JCAP)

Introduction

Direct Detection

- Stringent constraints on spin-independent (SI) interactions.
- Restricted by
  - ➡ Nuclear mass of the target
  - ➡ Recoil threshold
- Less sensitivity to interactions with momentum or velocity suppressed cross sections.

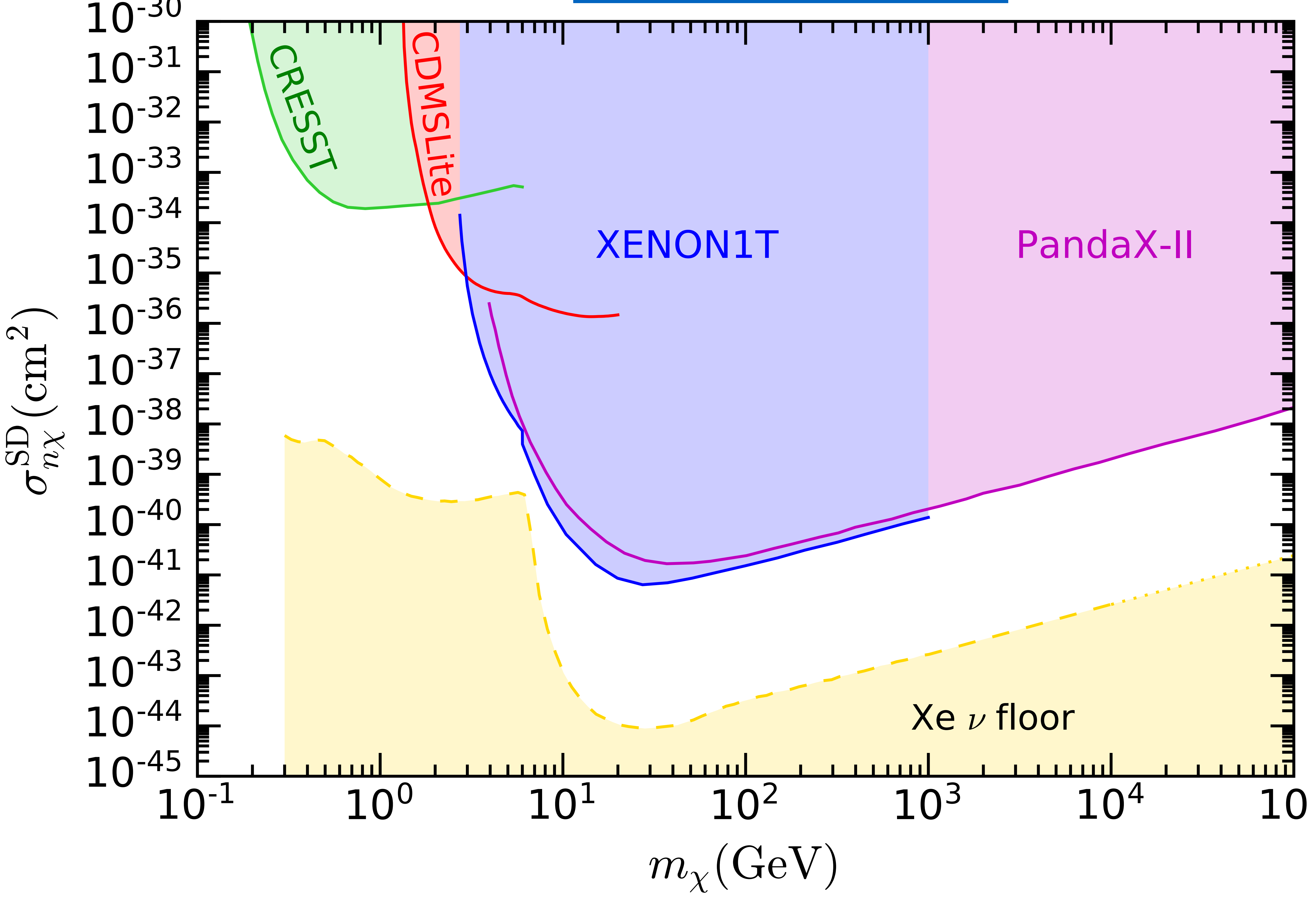


Introduction

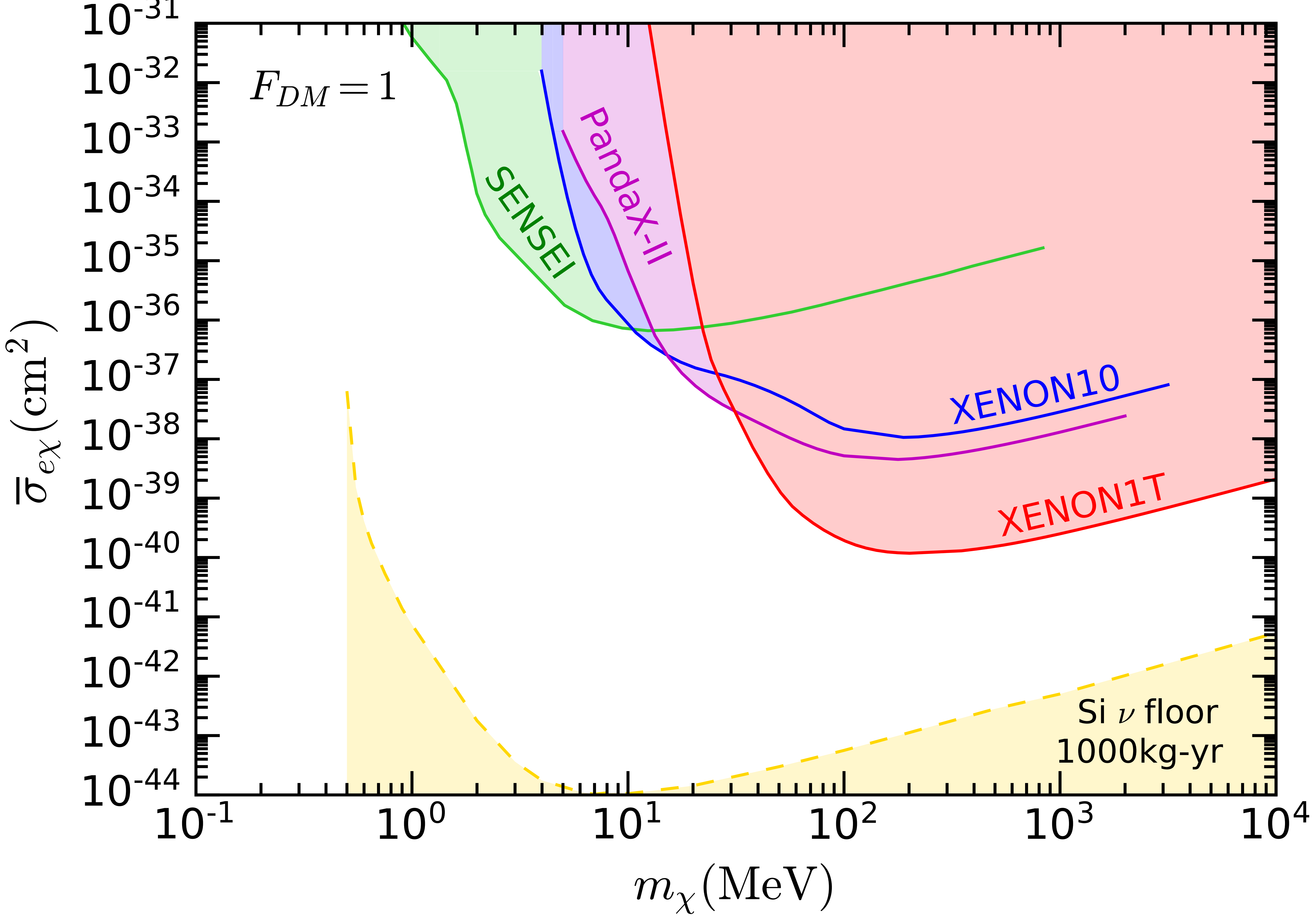
Direct Detection

- Much weaker sensitivity to spin-dependent and DM-electron interactions.

Spin - dependent

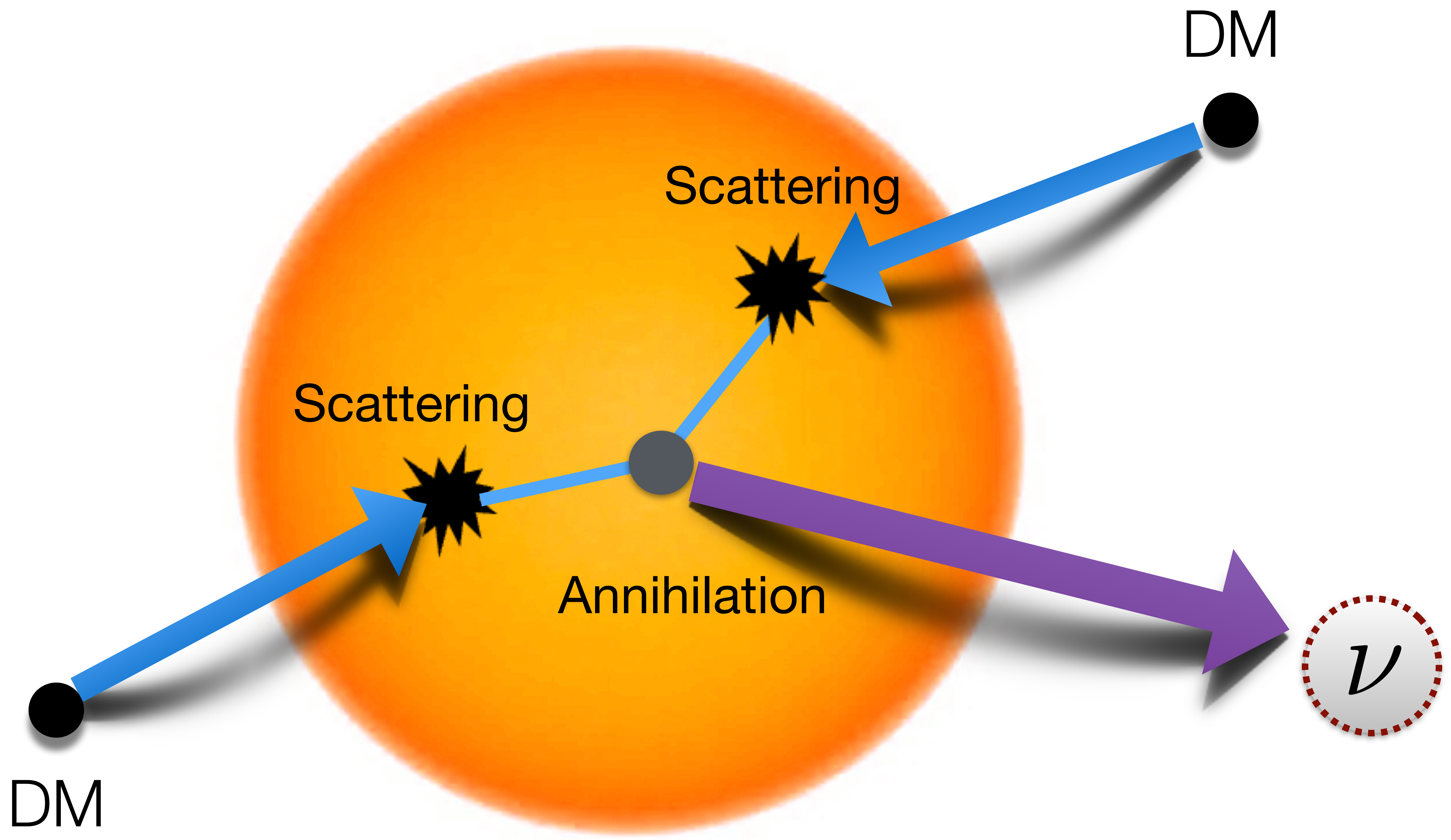


Electon recoil



DM Capture in the Sun

- DM scatters, loses energy, becomes gravitationally bound to the Sun.
- Accumulates and annihilates in the centre of the Sun.
- Annihilation rate proportional to the DM-nucleon scattering cross section.
- Neutrinos from DM annihilation can be detected in the Earth (Super-Kamiokande, Antares, IceCube).



SuperK

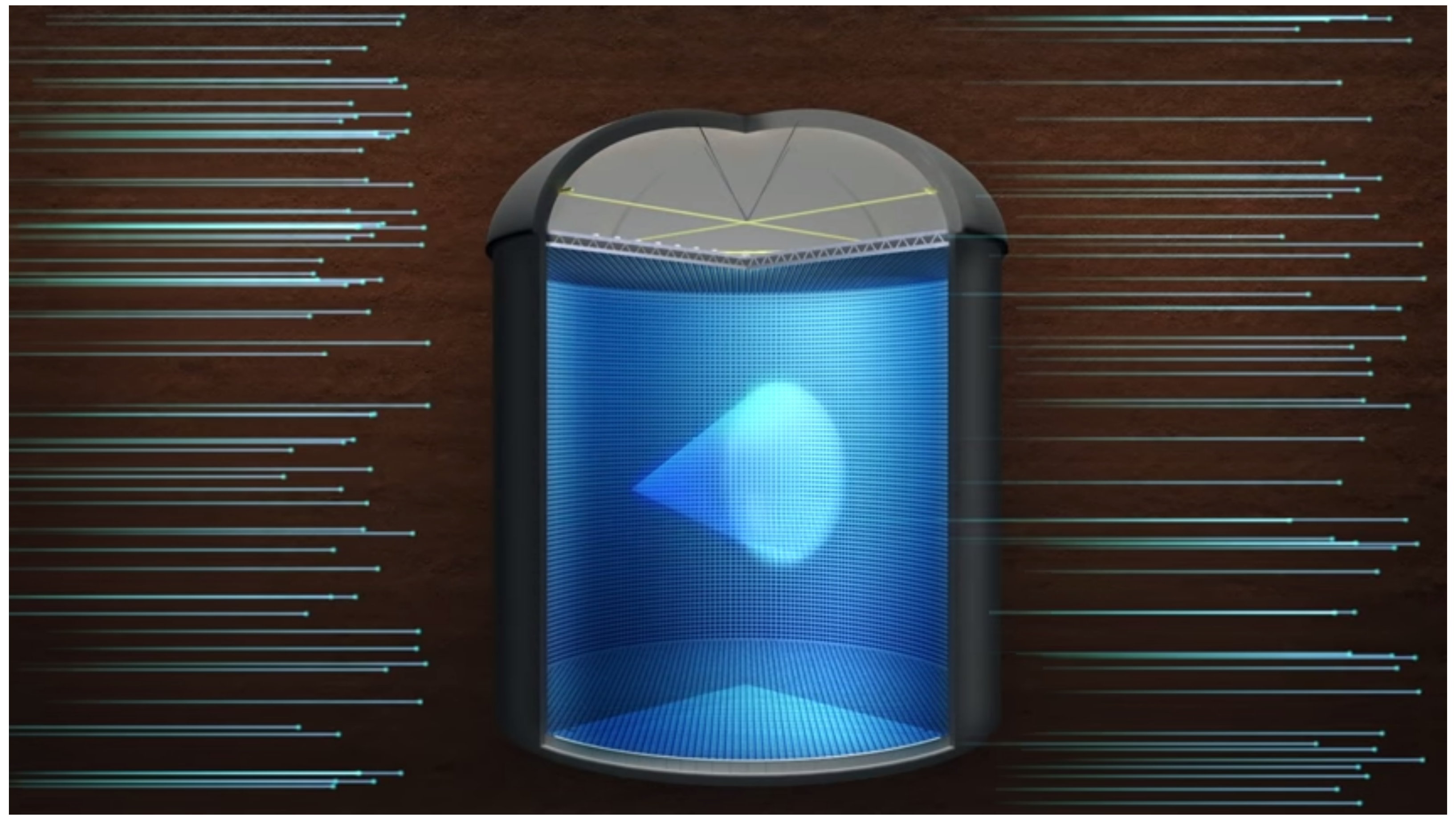


Image credit: Institute for Cosmic Ray Research,The University of Tokyo

DM Capture in the Sun

- Indirect signatures from DM annihilation, probes elastic scattering cross section.
- Limits on the SI cross section from DM annihilation to neutrinos much weaker than DD.

Compact Stars

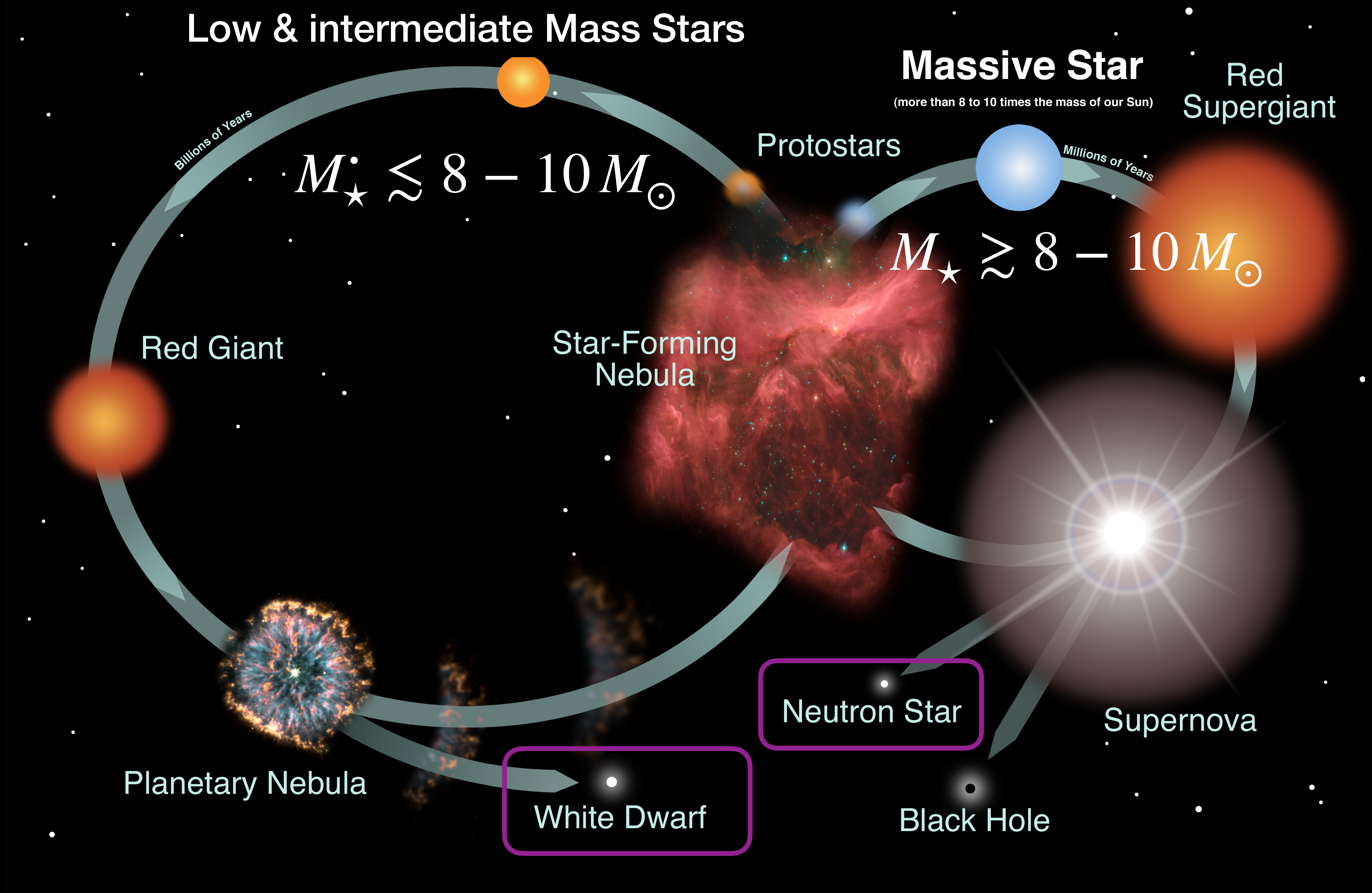
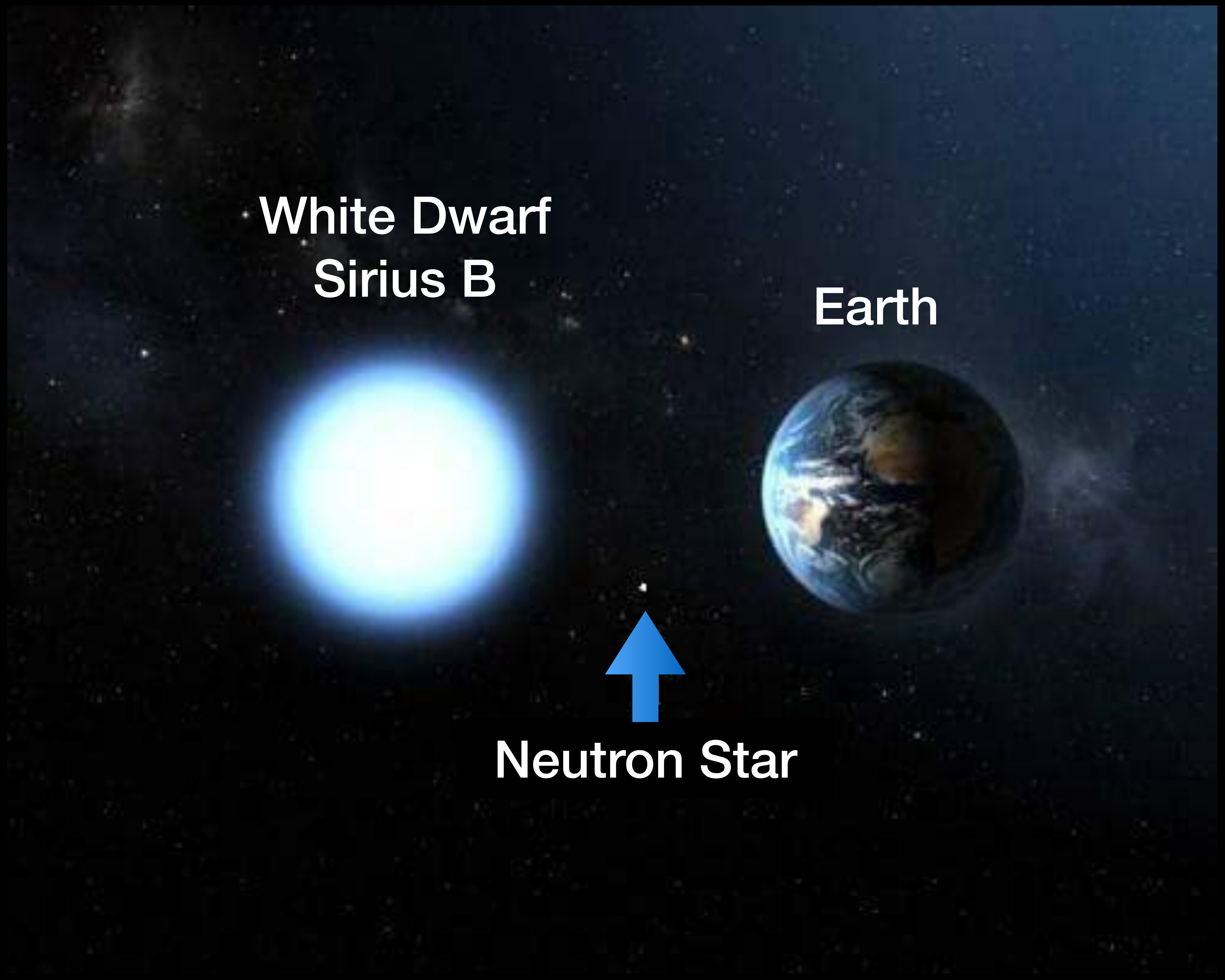


Image Credit: NASA

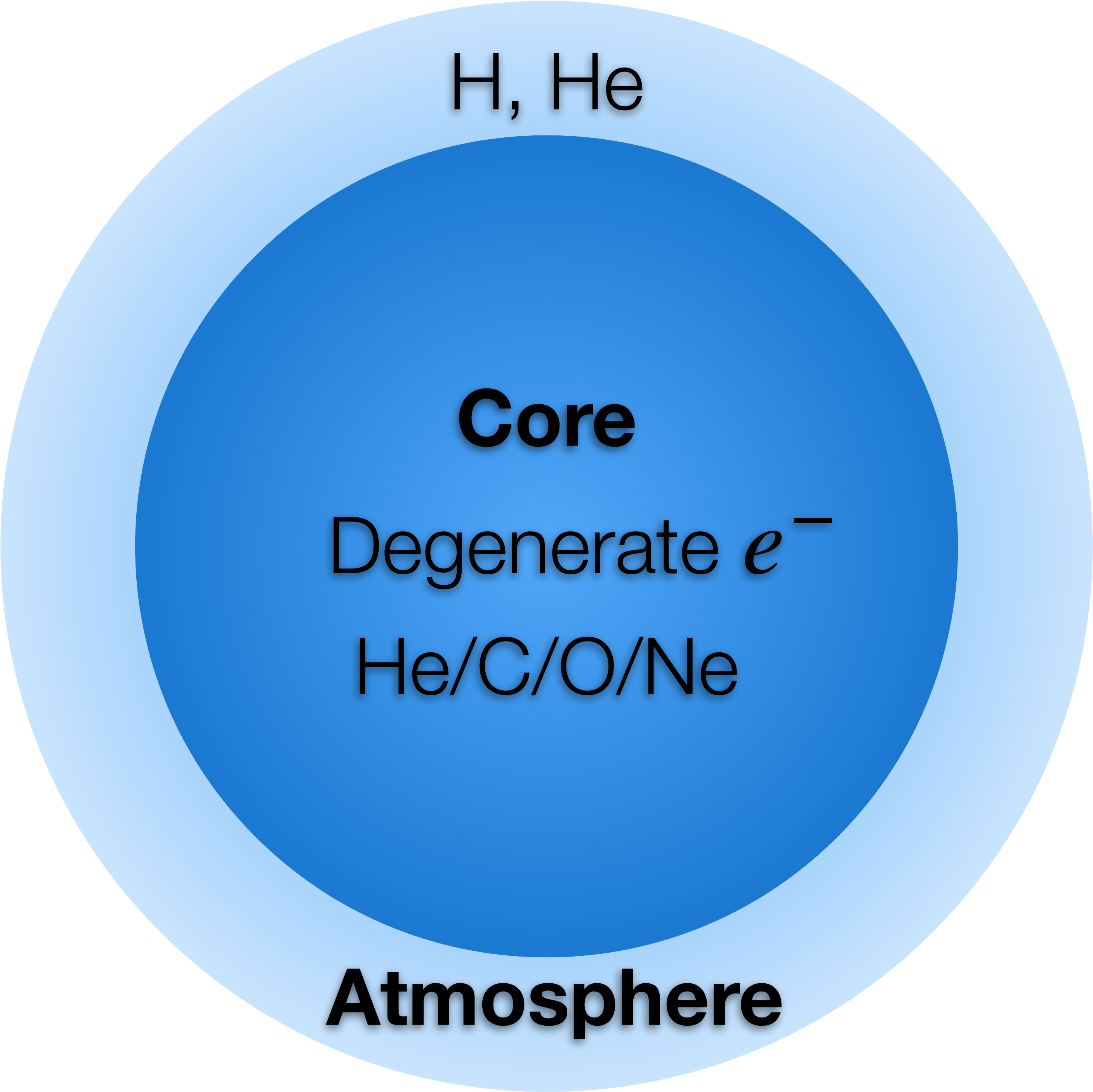


White Dwarfs versus Neutrons Stars

White Dwarfs

✓ ~90% of the stars in the Galaxy are WDs.

✓ Supported against collapse by electron degeneracy pressure.



H, He

Core

Degenerate e^-

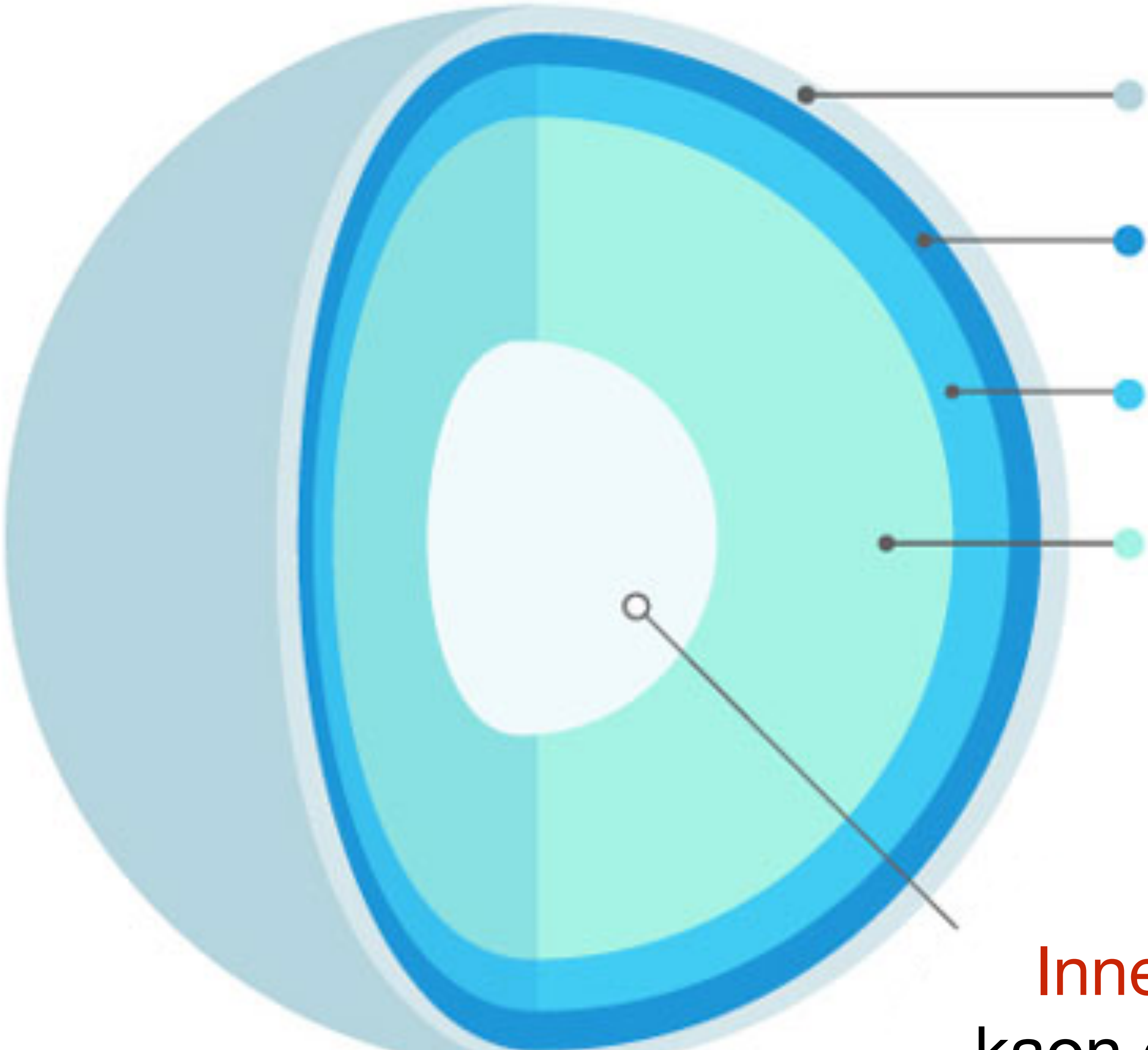
He/C/O/Ne

Atmosphere

Neutron Stars

✓ The densest stars known.

✓ Supported against collapse by neutron degeneracy pressure.



Atmosphere: H, He

Outer crust: Heavy ions, e^-

Inner crust: Free n, p, e^-

Outer core: $npe^-\mu^-$

Inner core?: hyperons, kaon condensates, quarks

Image Credit: Feryal Ozel

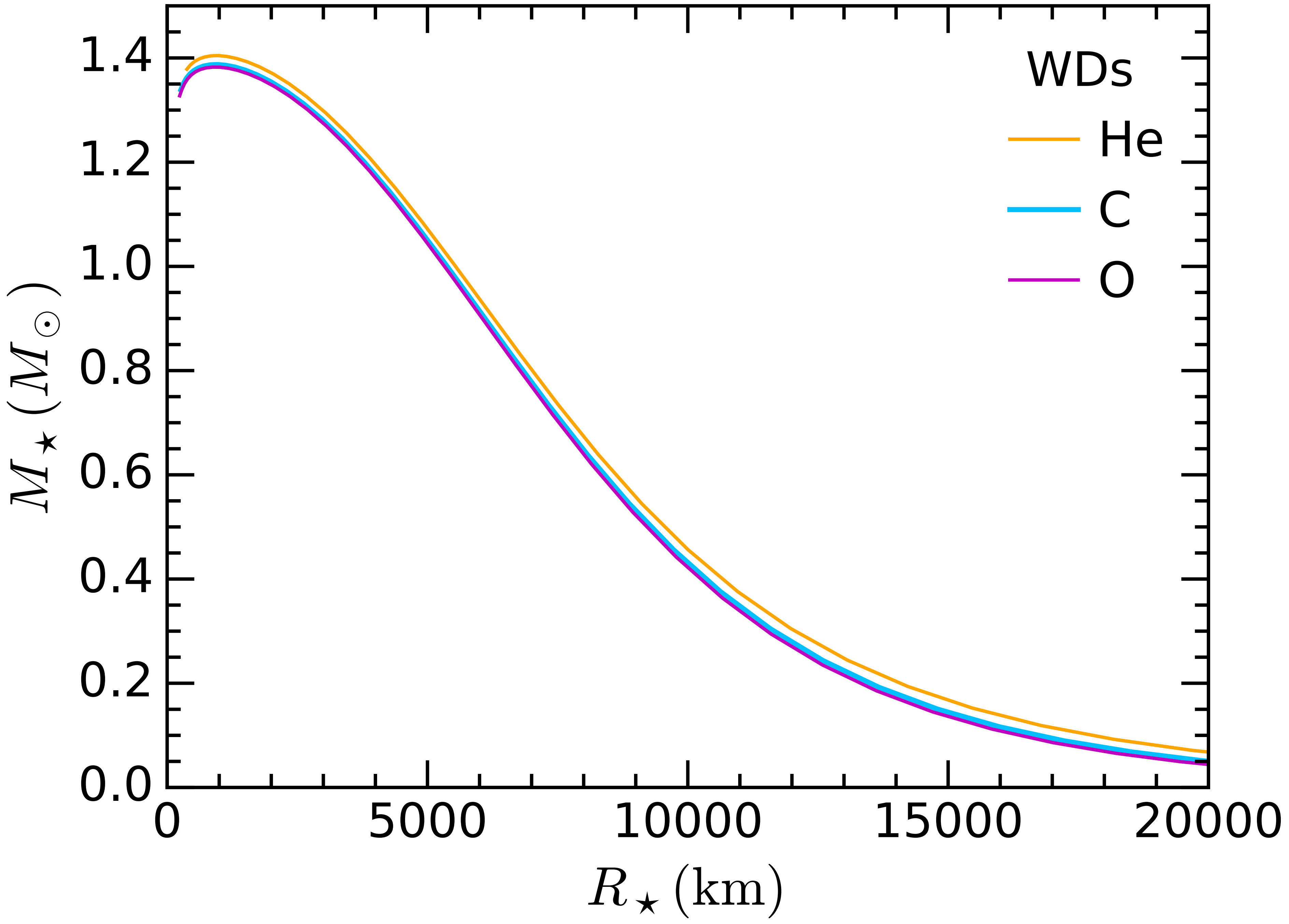
White Dwarfs versus Neutrons Stars

WD's main advantages

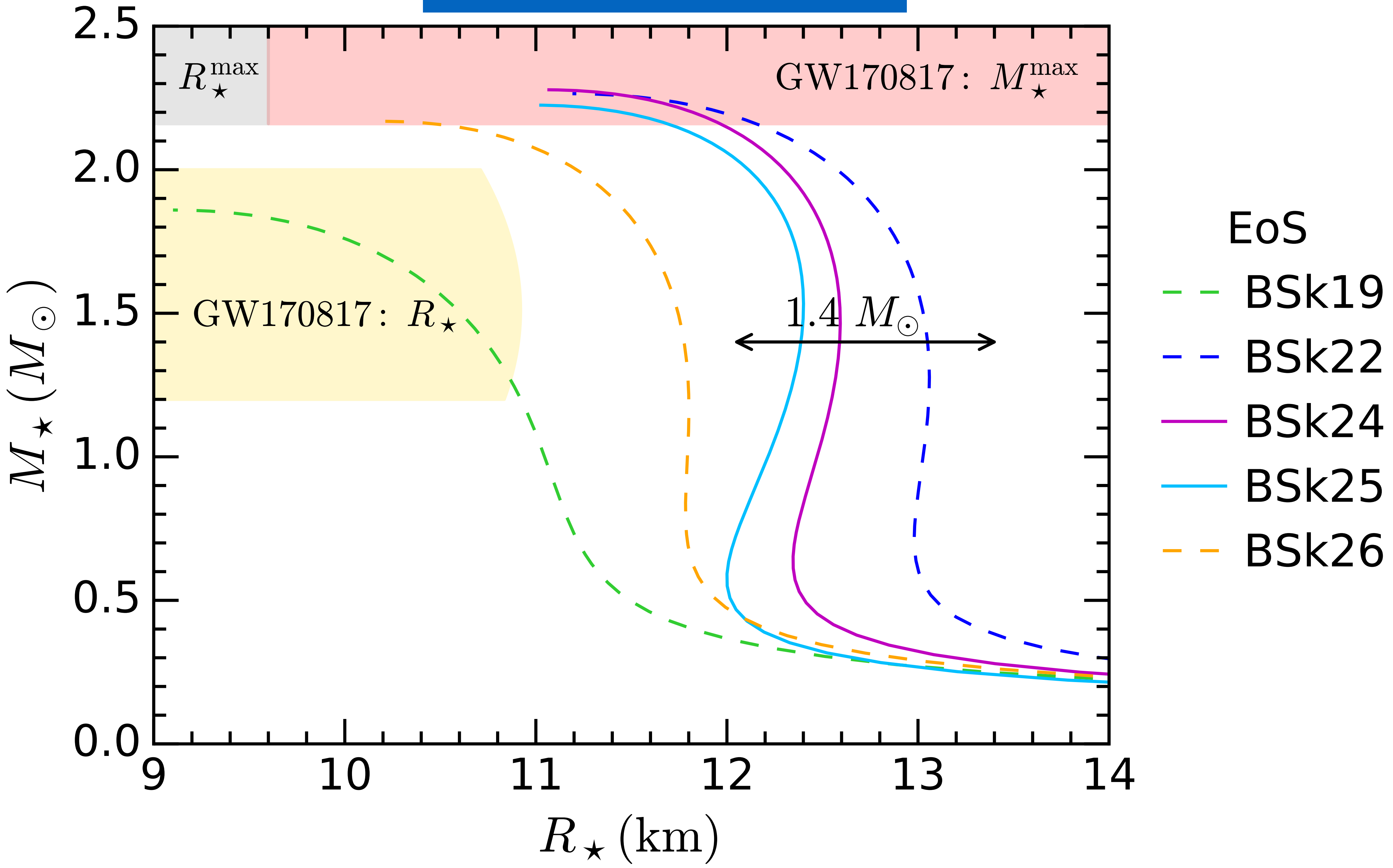
- Well defined mass-radius relation

➡ Less uncertainty in the equation of state

White Dwarfs



Neutron Stars

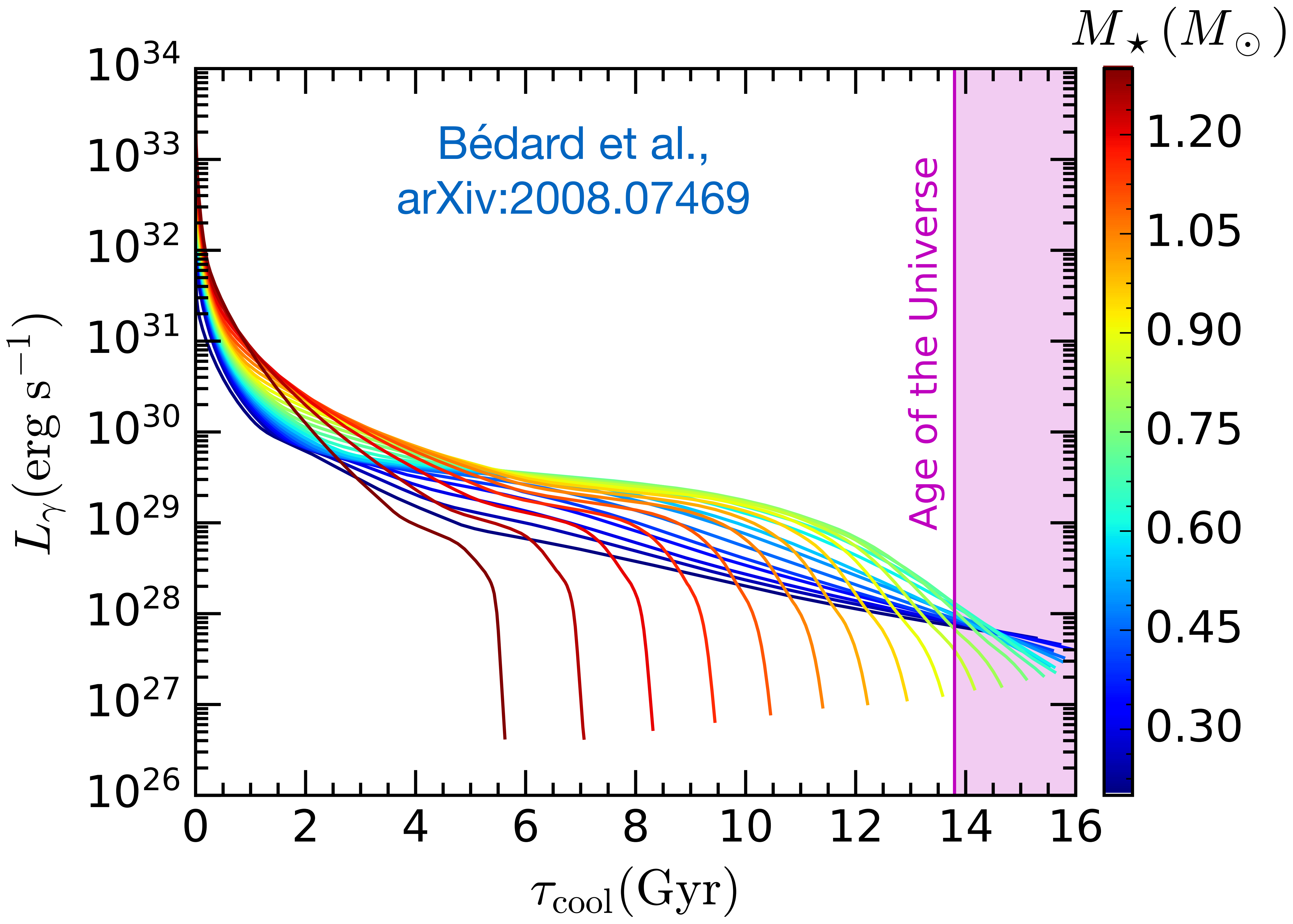


BSk: Brussels-Montreal Equation of State

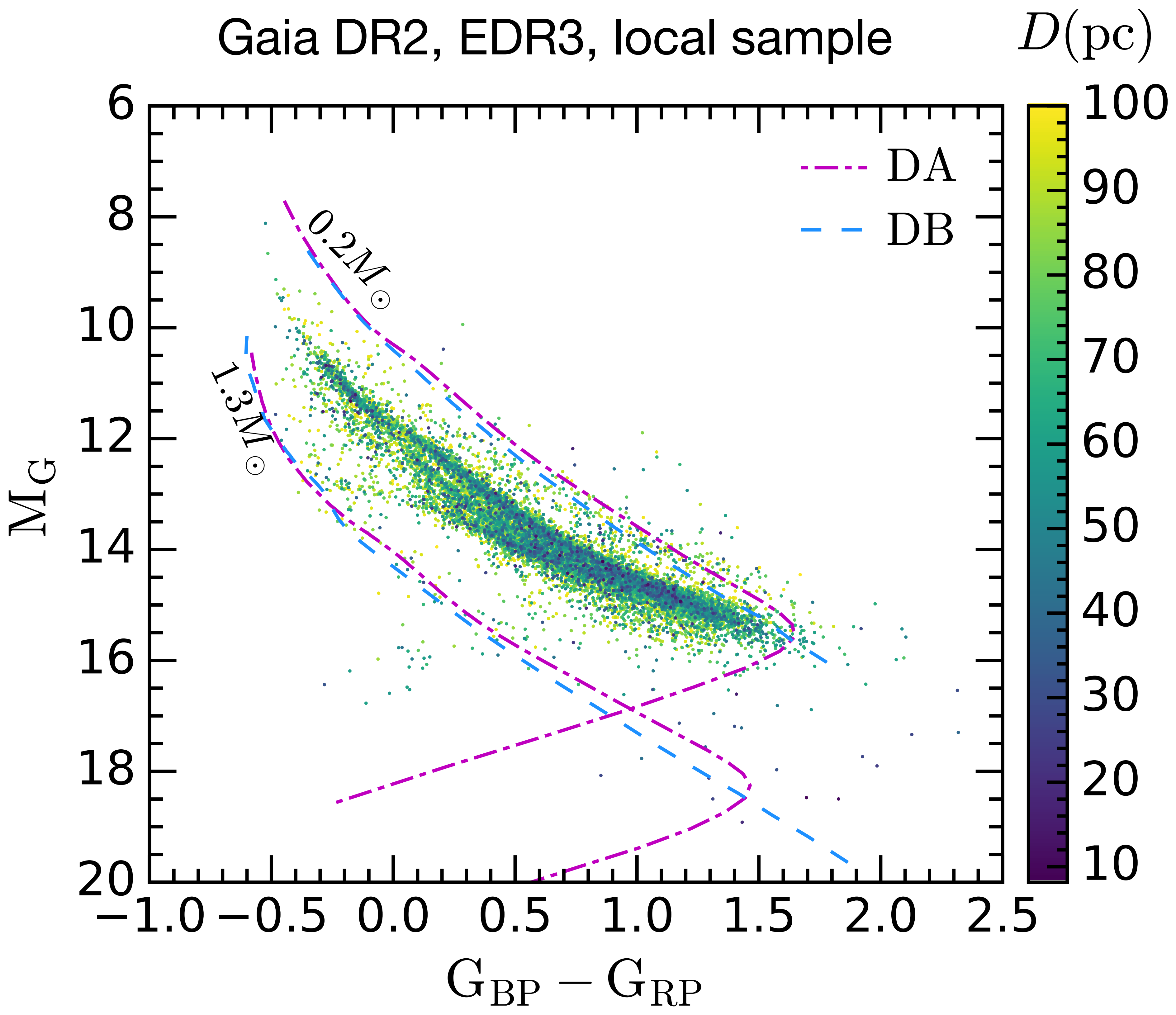
White Dwarfs versus Neutrons Stars

WD's main advantages

- Better understood luminosity-age relation



- Easier to observe



DM-induced heating in WDs

- DM passing through the WD scatters off nuclei/electrons and loses energy.

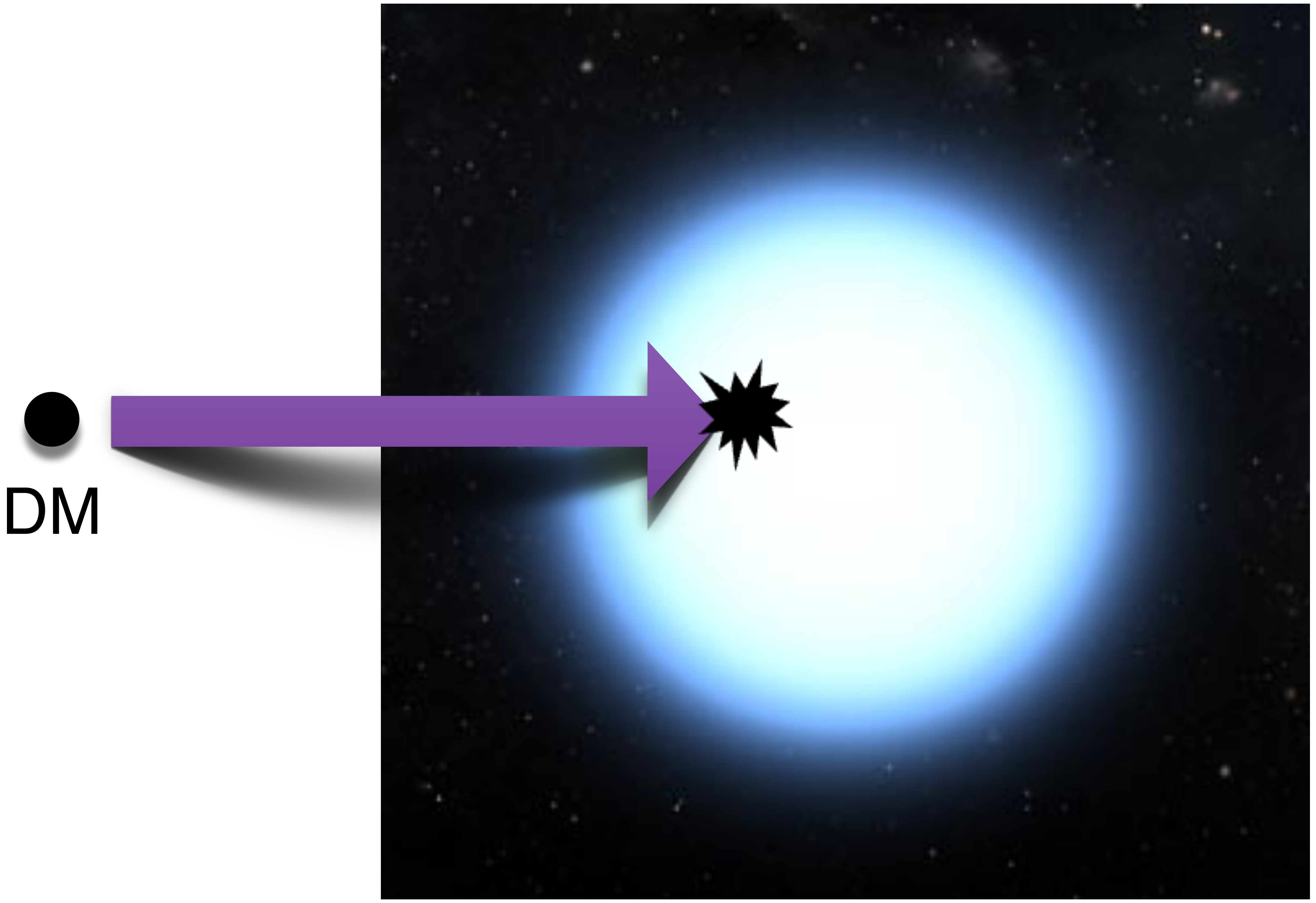


Image credit: NASA/ESA

- Captured DM annihilates in the WD's core

➡ WDs in DM rich environments

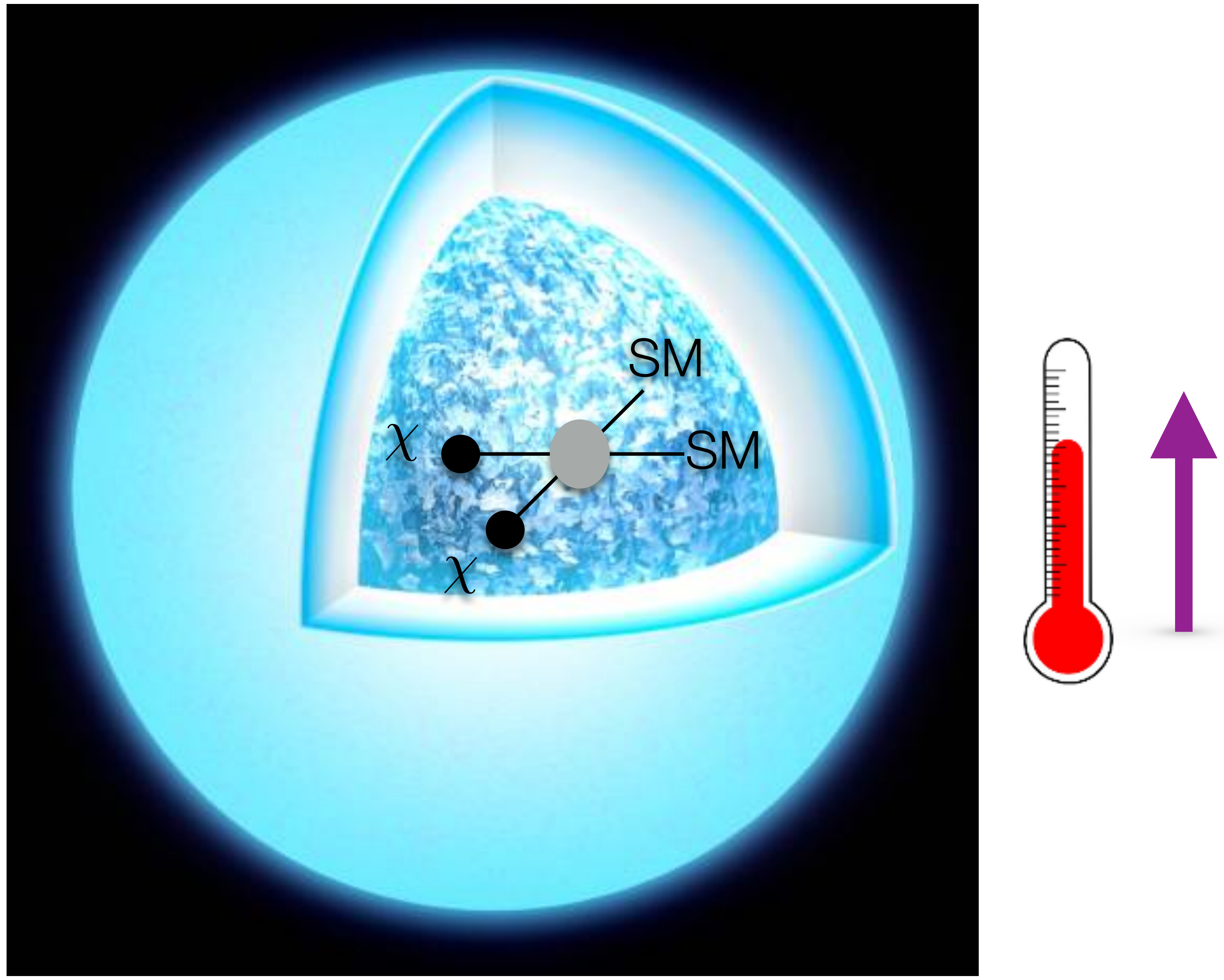
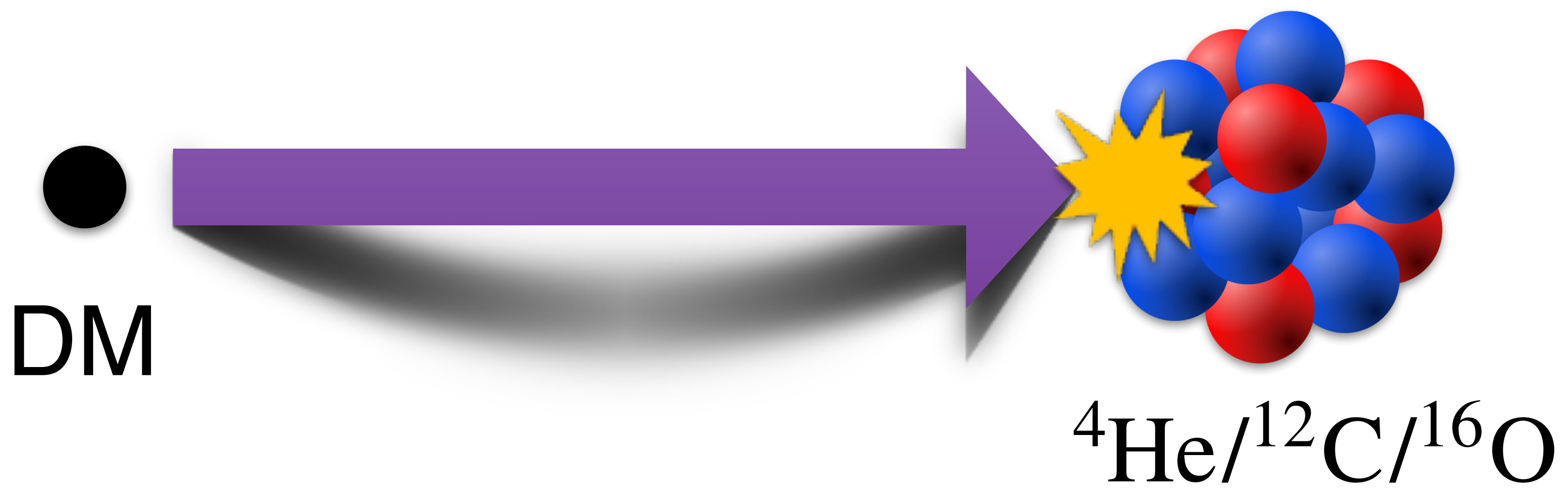


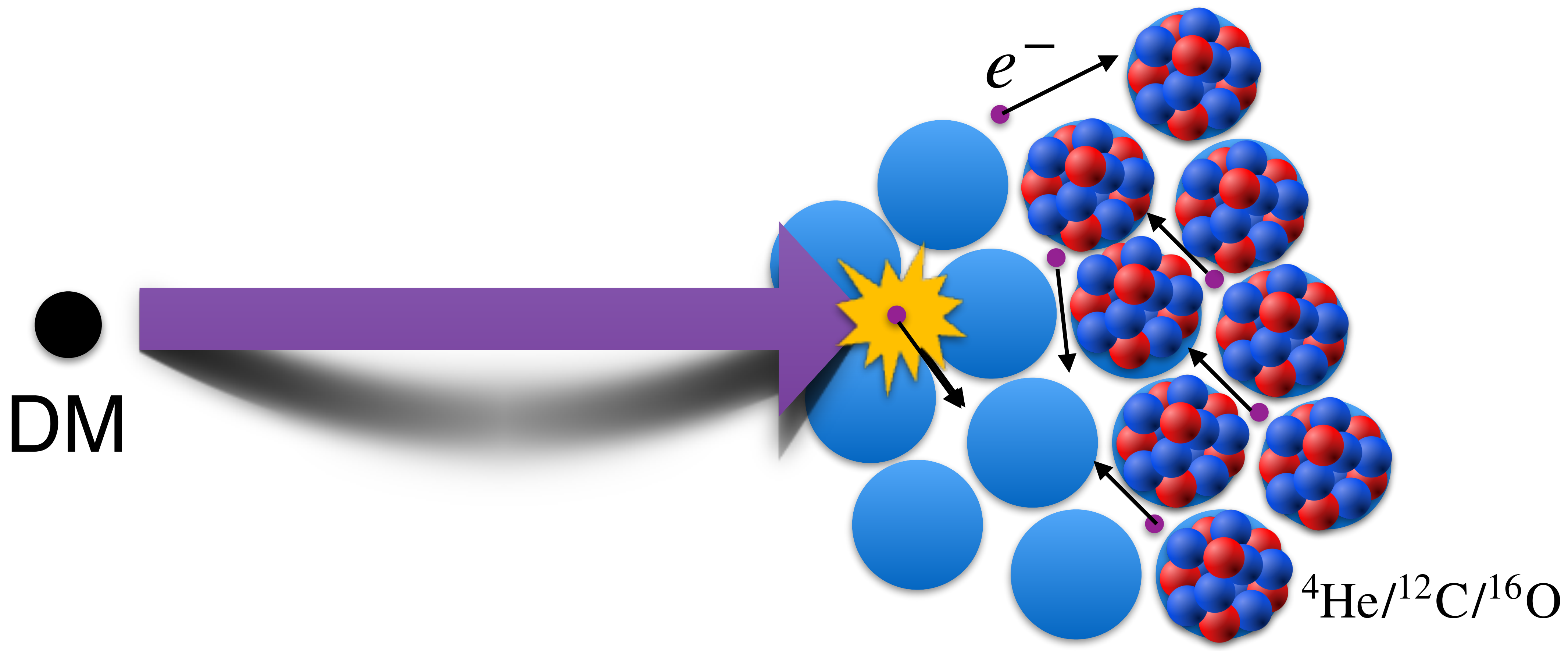
Image credit: Mark Garlick (University of Warwick)

DM capture in White Dwarfs

Ions



Electrons



Targets

- Ions
  - ➡ Non-relativistic
  - ➡ Nuclear form factors

- Degenerate electrons
  - ➡ Relativistic
  - ➡ Pauli blocking

DM capture in White Dwarfs

Scattering off Ions

- Capture rate $T_\star \to 0$

$$C(\sigma) = \frac{\rho_\chi}{m_\chi} \int_0^{R_\star} 4\pi r^2 \eta(r) \int_0^\infty du_\chi \frac{w(r)}{u_\chi} f_{\rm MB}(u_\chi) \Omega^-(w,\sigma)$$

Interaction rate

$$\Omega^-(\sigma, w) = \frac{4\mu_+^2}{\mu w} n_T(r) \int_{w(r)\frac{|\mu_-|}{\mu_+}}^{v_{esc}(r)} dv v \frac{d\sigma_{T\chi}}{d\cos\theta}$$

- ✓ Requires: WD internal structure
- ✓ Gravitational focusing
- ✓ Star opacity $\eta(r)$
- ✓ Nuclear response function for He/C/O in $\frac{d\sigma_{T\chi}}{d\cos\theta}$

Catena & Schwabe
arXiv:1501.03729

Bell, Busoni, Ramirez-Quezada, SR & Virgato, arXiv: 2104.14367

Compact stars: Internal Structure

- Structure equations:

Equation of State (EoS)

$$P = P(\rho)$$

WDs

- Salpeter
- Relativistic FMT

NSs

- APR
- BSk
- QMC
- SLy, …

+

Hydrostatic Equilibrium

$$\frac{dP}{dr} = -\rho(r)c^2\left[1+\frac{P(r)}{\rho(r)c^2}\right]\frac{d\Phi}{dr}$$

$$\frac{d\Phi}{dr} = \frac{GM(r)}{c^2r^2}\left[1+\frac{4\pi P(r)r^3}{M(r)c^2}\right]\left[1-\frac{2GM(r)}{c^2r}\right]^{-1}$$

$$\frac{dM}{dr} = 4\pi r^2\rho(r)$$

- Tolman-Oppenheimer-Volkoff (TOV) equations

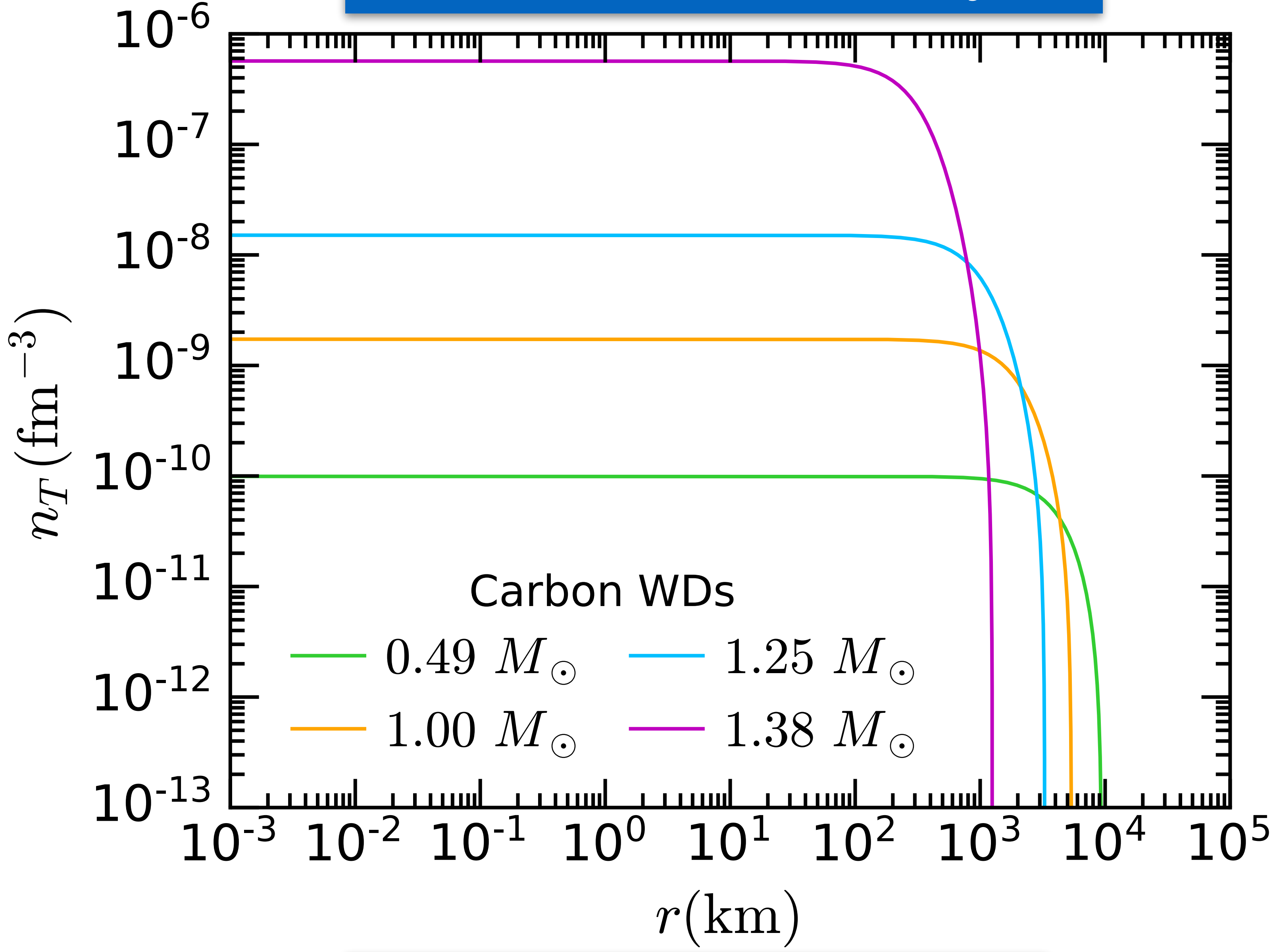
White Dwarfs: Internal Structure

➡ EoS: Relativistic Feynman-Metropolis-Teller (FMT)

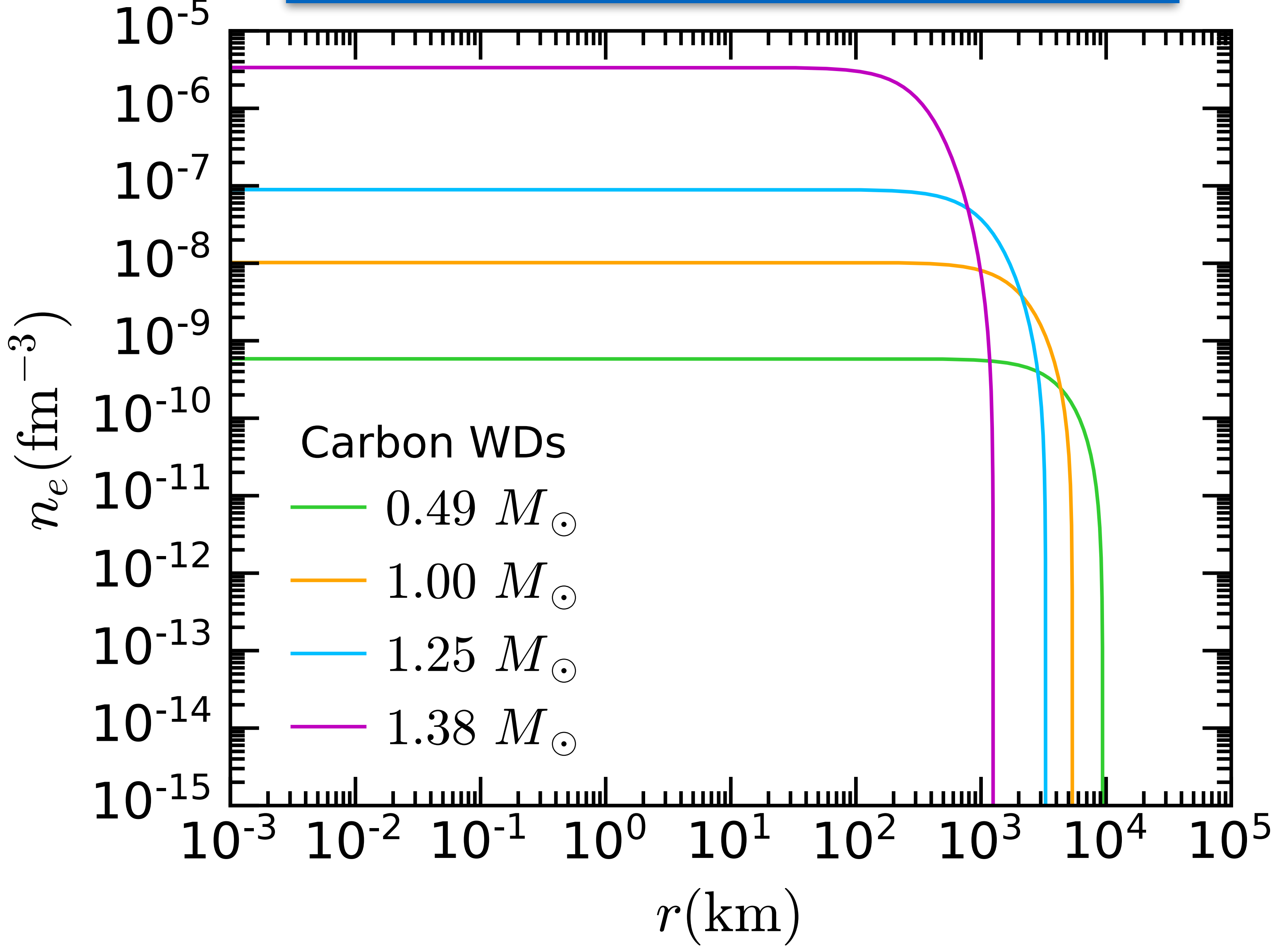
Rotondo et al., arXiv:0911.4622, arXiv:1012.0154

Bell, Busoni, Ramirez-Quezada, SR & Virgato, arXiv: 2104.14367

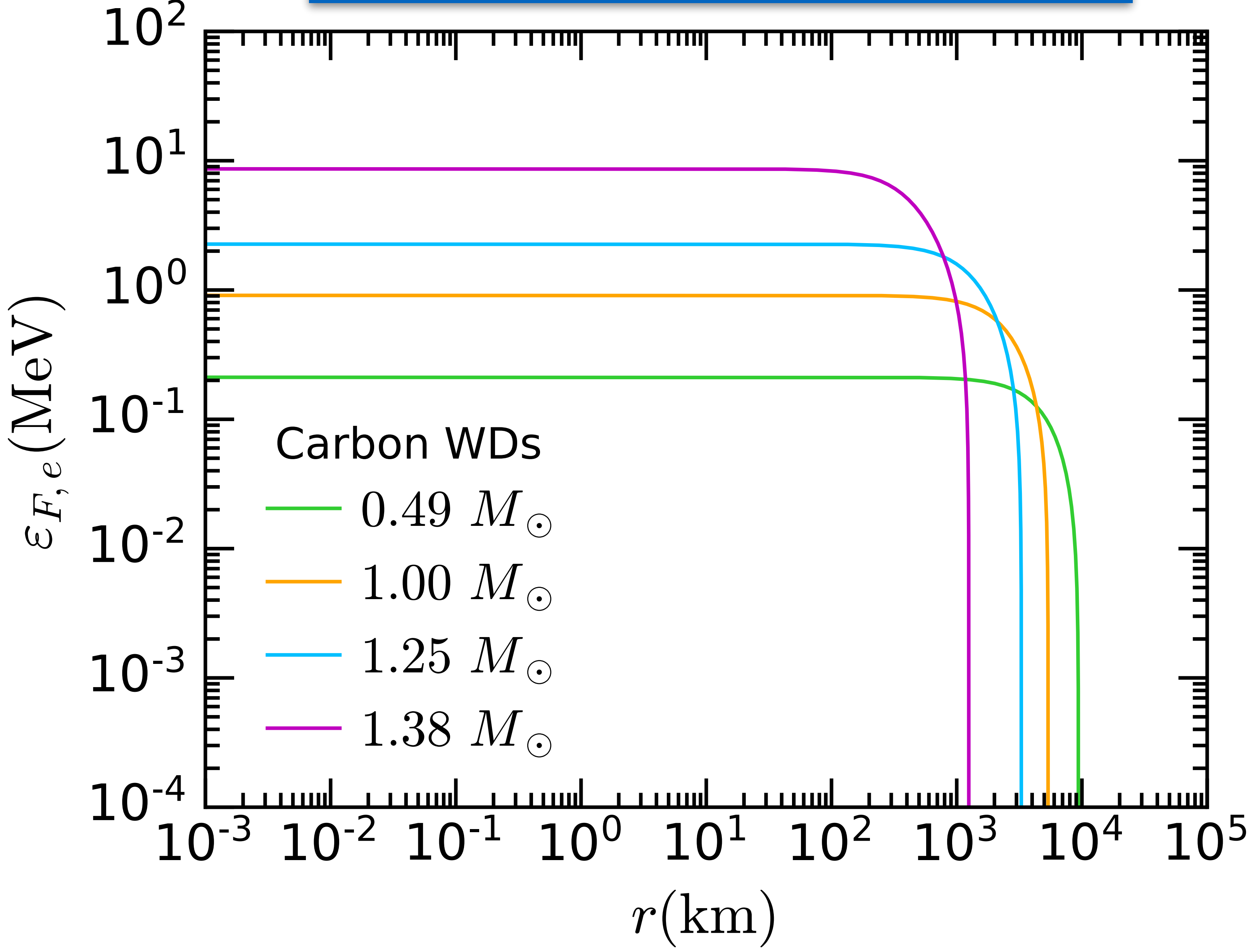
Ion number density



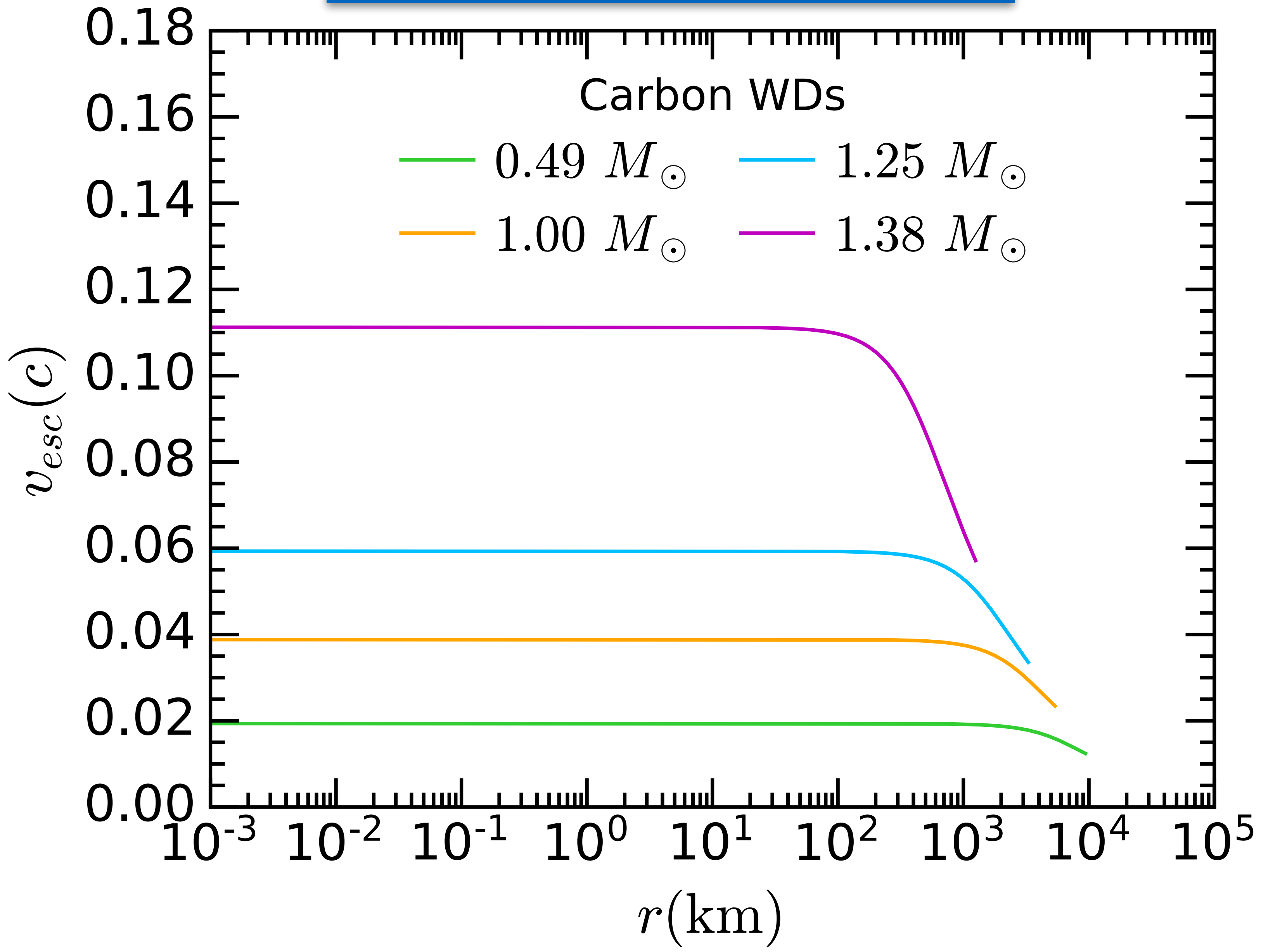
Electron number density



Electron Fermi energy

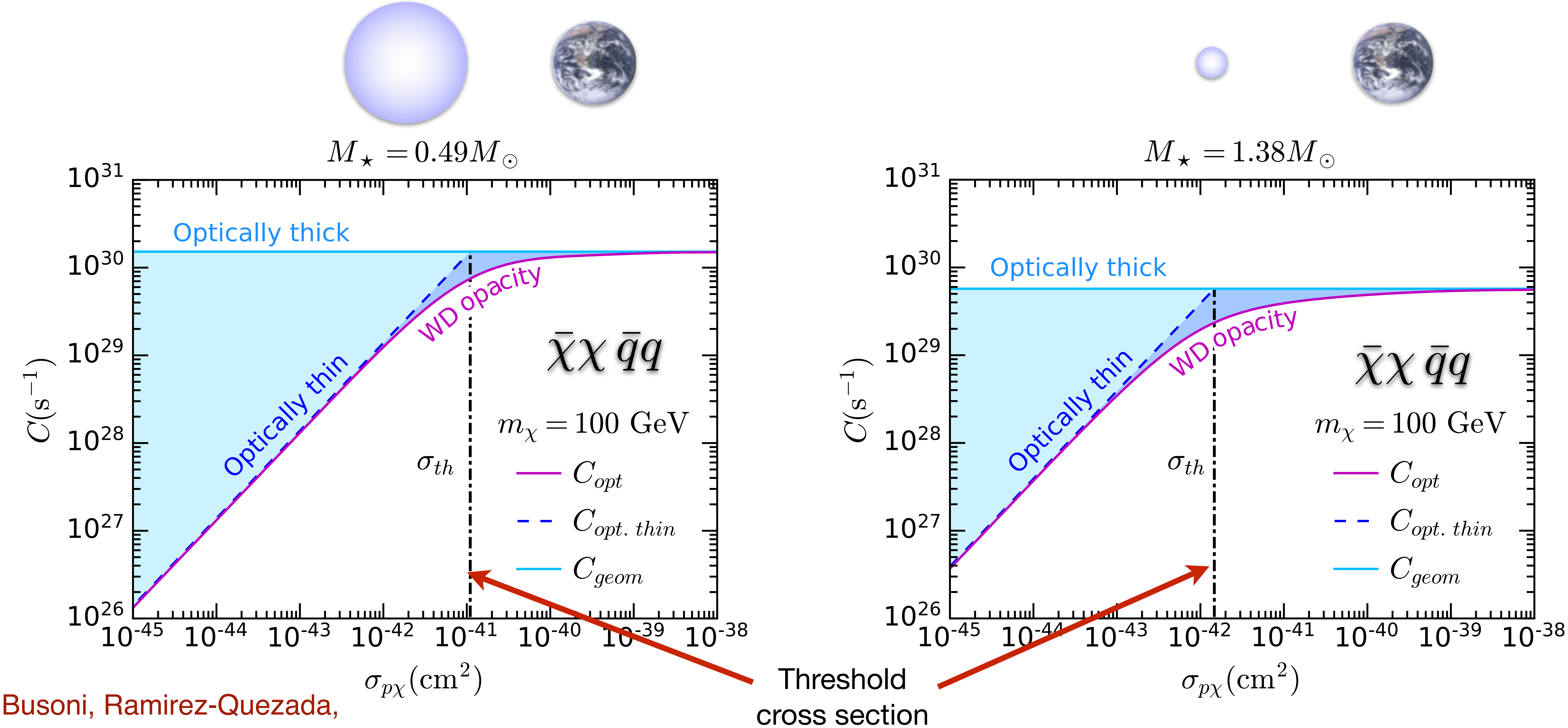


Escape velocity



DM capture in White Dwarfs

Scattering off Ions



Threshold
cross section

Bell, Busoni, Ramirez-Quezada,
SR & Virgato, arXiv: 2104.14367

White Dwarfs in Messier 4

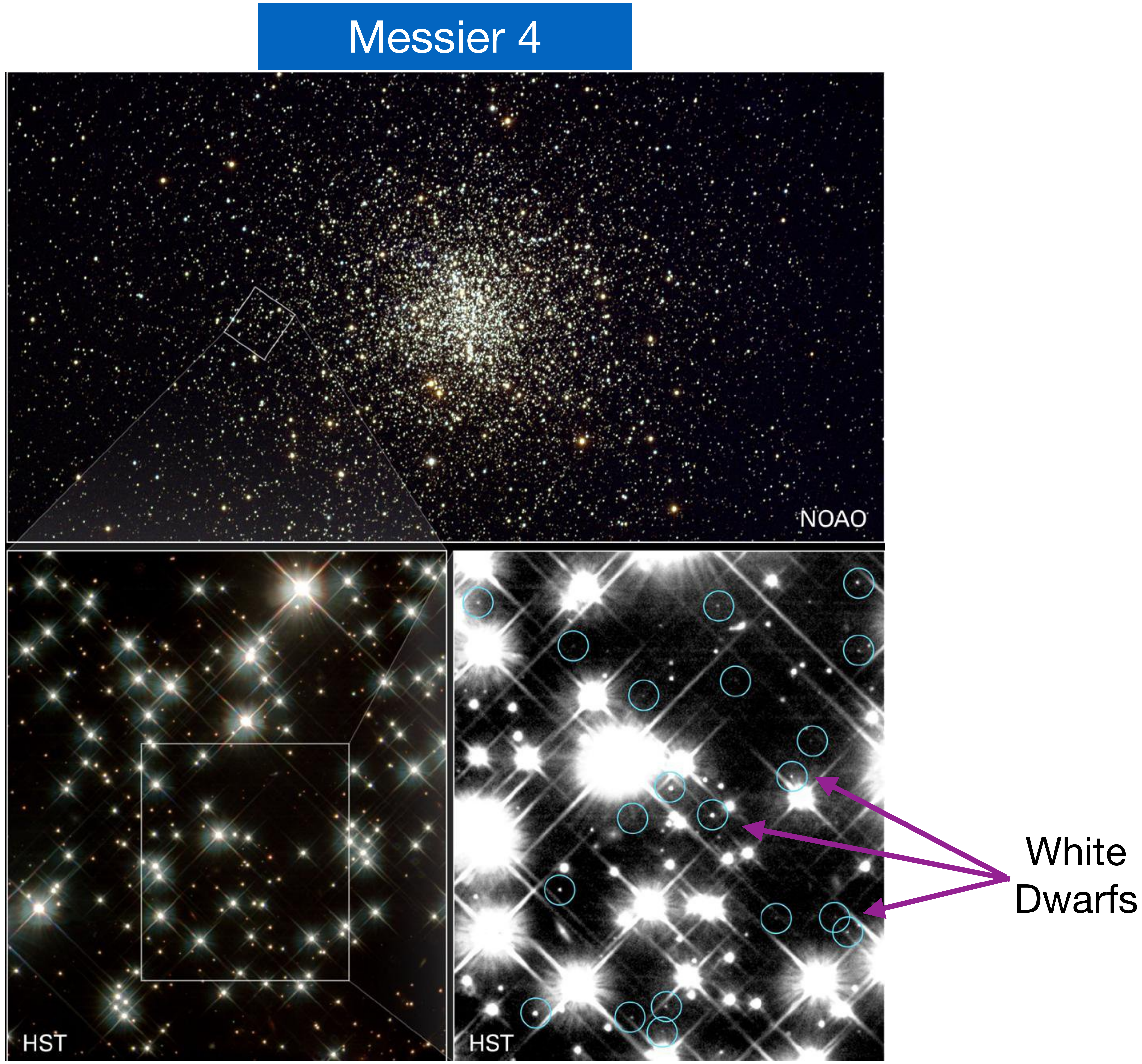


Image credit: NASA/JPL/NOAO/HST

- Messier 4 (M4), NGC 6121 globular cluster
  - Distance ~ 1.9 kpc
  - Age ~ 11.6 Gyr
- If formed in a DM subhalo
  - $\rho_\chi \simeq 798\,\mathrm{GeV\,cm^{-3}}$ contracted NFW

McCullough & Fairbairn
arXiv:1001.2737

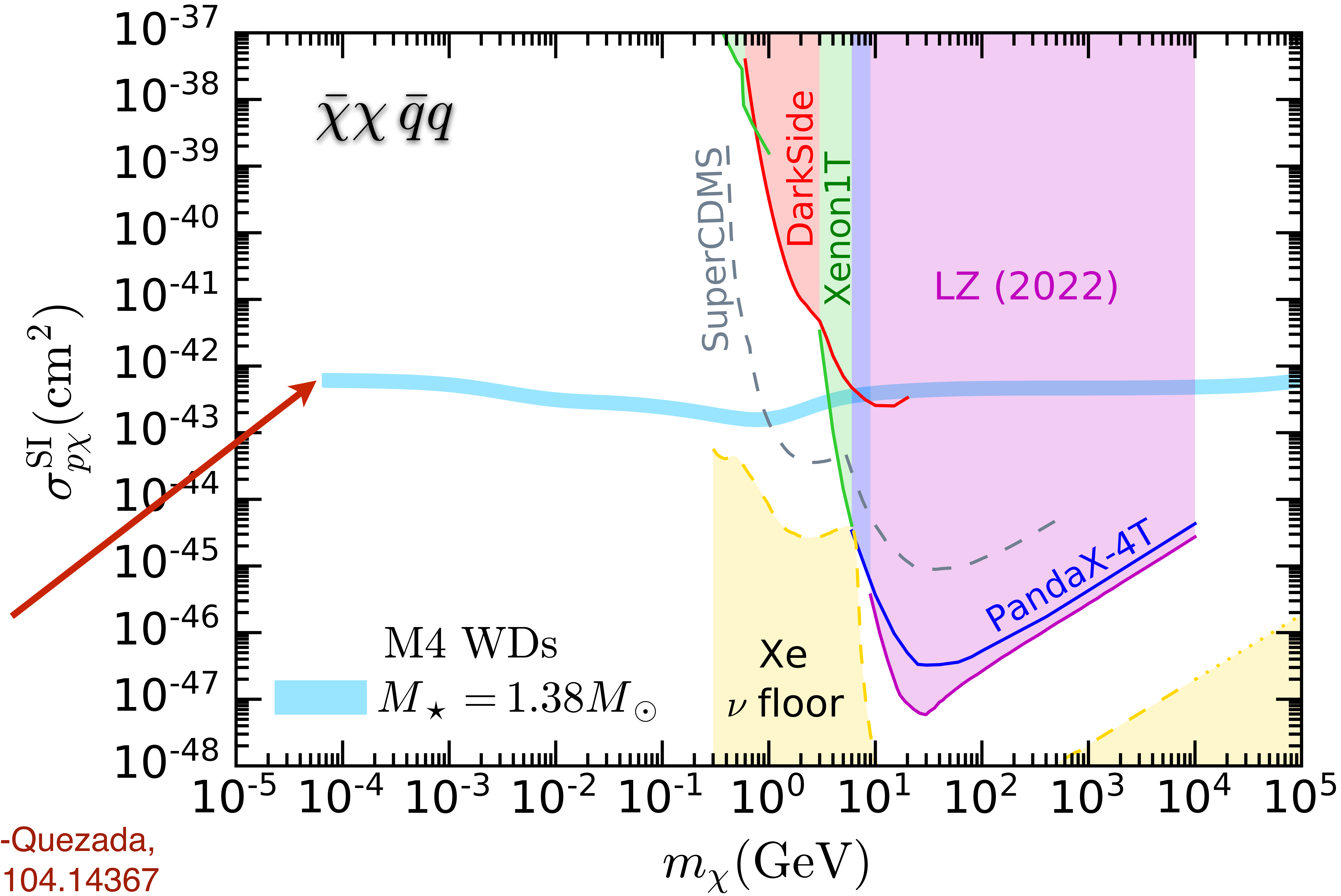
- Observations of old white dwarfs
  - Hubble Space Telescope

Bedin et al.
arXiv:0903.2839

Scattering Operators for Fermionic DM

Operator	Coupling	Interaction	Momentum supressed
$\bar{\chi}\chi\ \bar{q}q$	y_q/Λ^2	SI	✘
$\bar{\chi}\gamma^5\chi\ \bar{q}q$	iy_q/Λ^2	SI	✔
$\bar{\chi}\chi\ \bar{q}\gamma^5 q$	iy_q/Λ^2	SD	✔
$\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$	y_q/Λ^2	SD	✔
$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$	$1/\Lambda^2$	SI	✘
$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu q$	$1/\Lambda^2$	SI, SD	✔
$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$	SD	✔
$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$	SD	✘
$\bar{\chi}\sigma_{\mu\nu}\chi\ \bar{q}\sigma^{\mu\nu} q$	$1/\Lambda^2$	SD	✘
$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\ \bar{q}\sigma^{\mu\nu} q$	i/Λ^2	SI	✔

DM-nucleon scattering cross section



Evaporation

Bell, Busoni, Ramirez-Quezada,
SR & Virgato, arXiv: 2104.14367

DM capture in Compact Stars

Scattering off a free Fermi gas of leptons

- Capture rate derived using the TOV equations and Schwarzchild metric
  - ✓ Requires WD/NS internal structure

Capture rate

$$C = \frac{\rho_\chi}{m_\chi}\int_0^\infty \overbrace{\frac{f_{\rm MB}(u_\chi)du_\chi}{u_\chi}}^{\text{DM velocity distribution}} \times \int_0^{R_\star} 4\pi r^2 \frac{\sqrt{1-\overbrace{B(r)}^{\text{GR: } B(r)\sim 1-v_{esc}^2(r)}}}{B(r)}\Omega^-(r)$$

$$\Omega^-(r) = \frac{\zeta(r)}{2\pi^2}\int \underbrace{dtdE_\ell ds\frac{E_\ell}{m_\chi}\sqrt{\frac{B(r)}{1-B(r)}}\frac{s}{\beta(s)\gamma(s)}\frac{d\sigma_{\ell\chi}}{d\cos\theta_{cm}}}_{\text{Reltivistic kinematics}}\underbrace{f_{\rm FD}(E_\ell,r)}_{\text{PB target initial states}}\underbrace{(1-f_{\rm FD}(E_\ell',r))}_{\text{Pauli Blocking target final states}}$$

Interaction rate

Bell, Busoni, SR & Virgato, arXiv: 2004.14888, arXiv: 2010.13257 (Neutron stars), arXiv: 2104.14367 (White dwarfs)

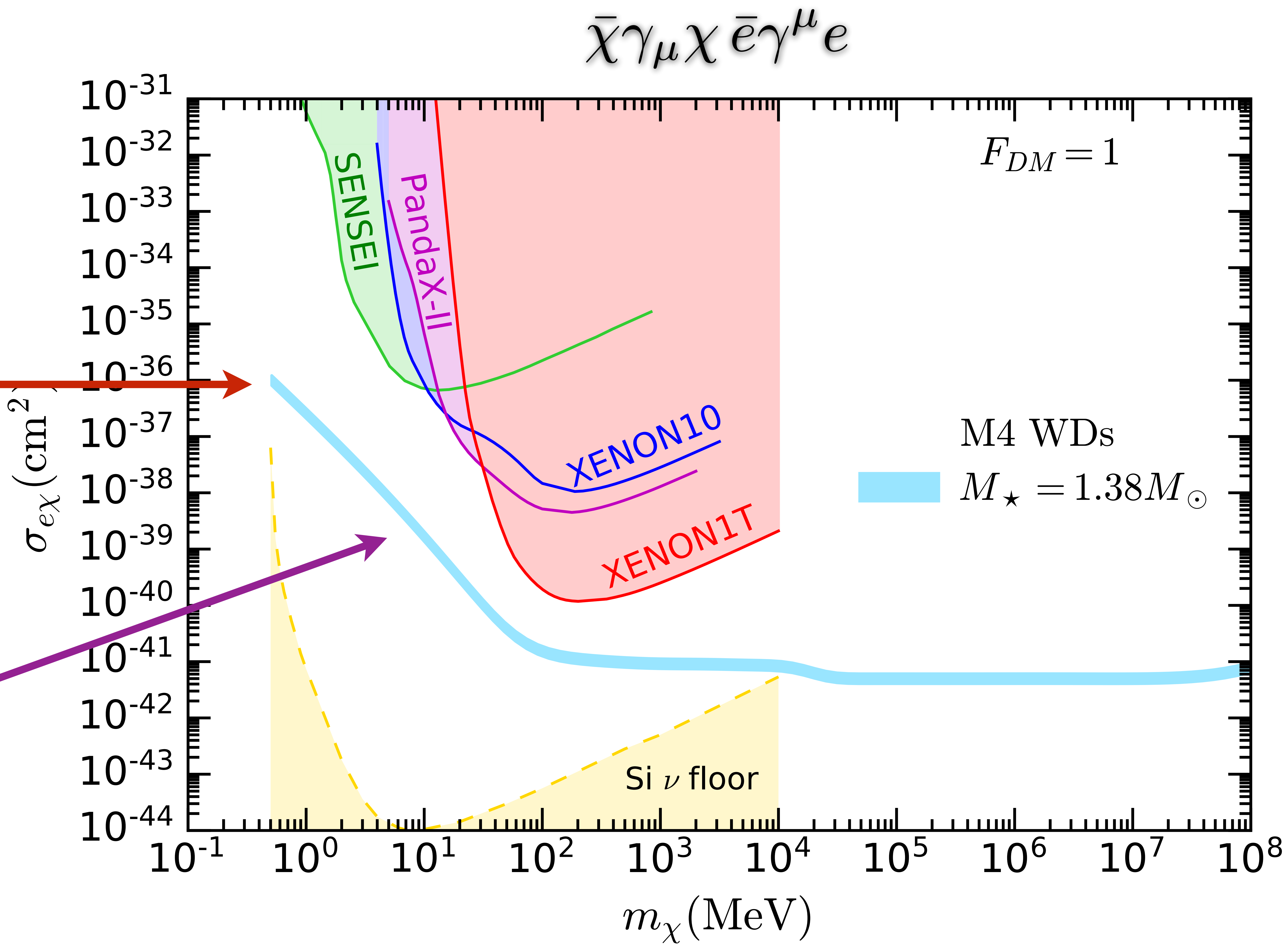
DM-electron scattering cross section

Limited by

$\chi\chi \to \nu\bar{\nu}$

Pauli blocking

Momentum transfer > electron p_F



Bell, Busoni, Ramirez-Quezada, SR & Virgato, arXiv: 2104.14367

DM-induced heating in NSs

- DM scatters off nucleons/leptons, loses energy and becomes gravitationally bound to the star

DM capture

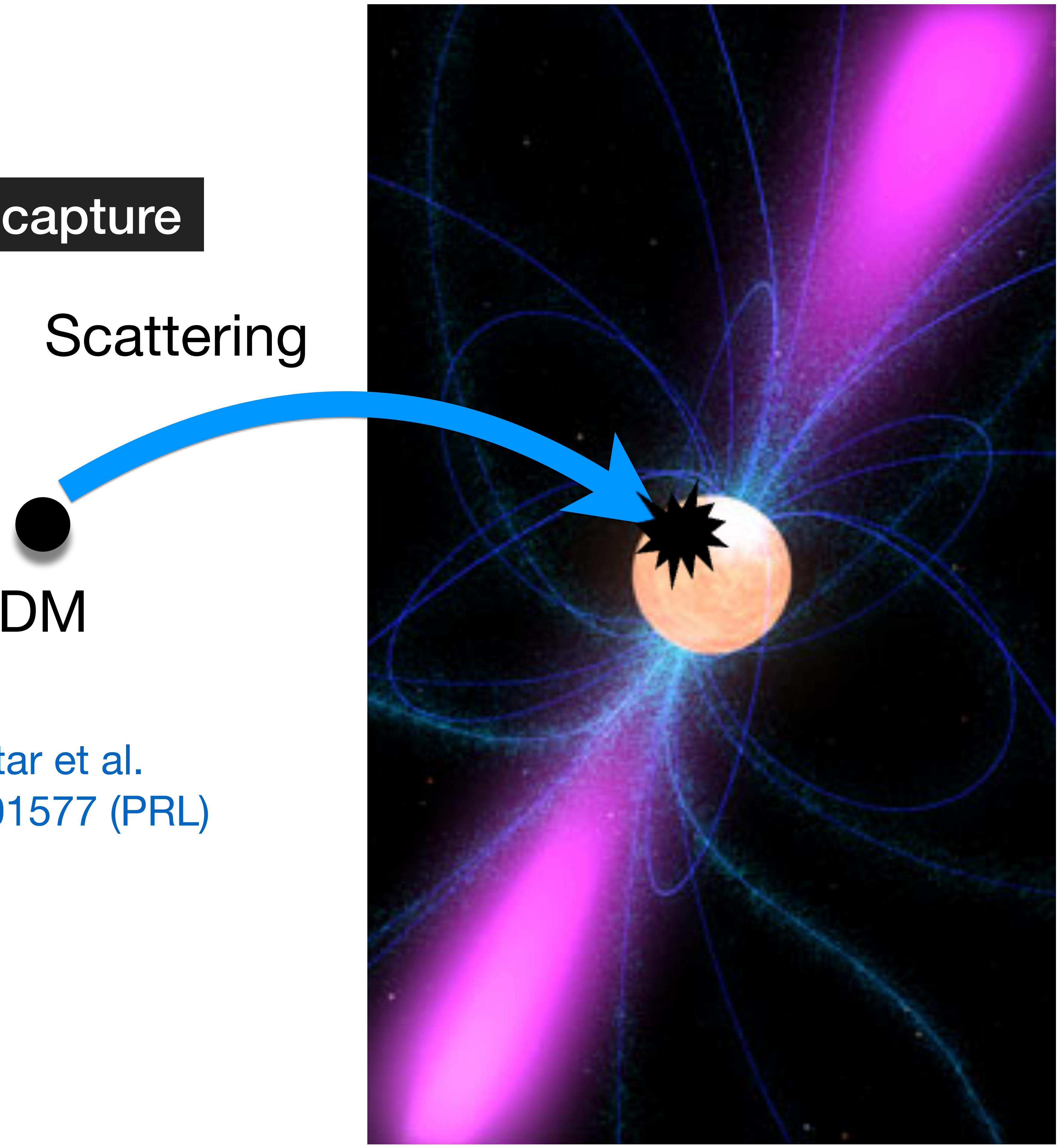
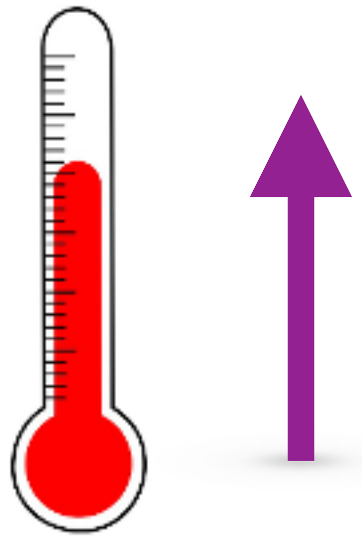


Image credit: NASA/ESA

Baryakhtar et al.
arXiv:1704.01577 (PRL)

Nearby, isolated NS



Only detectable in old (cold) neutron stars

Kinetic Heating		Annihilation
$T_\infty \sim 1700$ K	+	~700 K
1 - 2 μm		
near IR		

For maximal capture

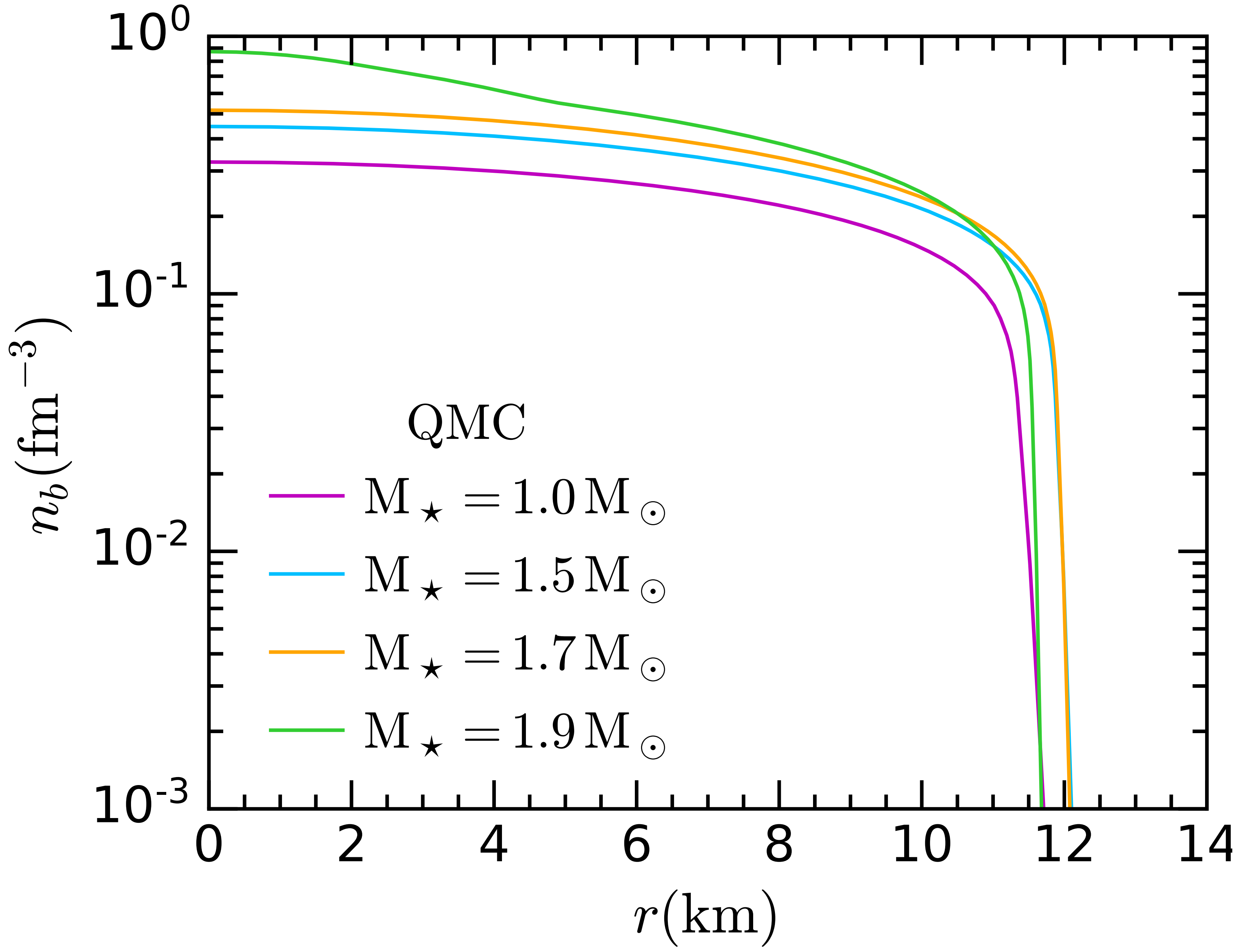
Neutron Stars: Internal Structure

➡ Relativistic EoS: Quark-Meson Coupling (QMC) model

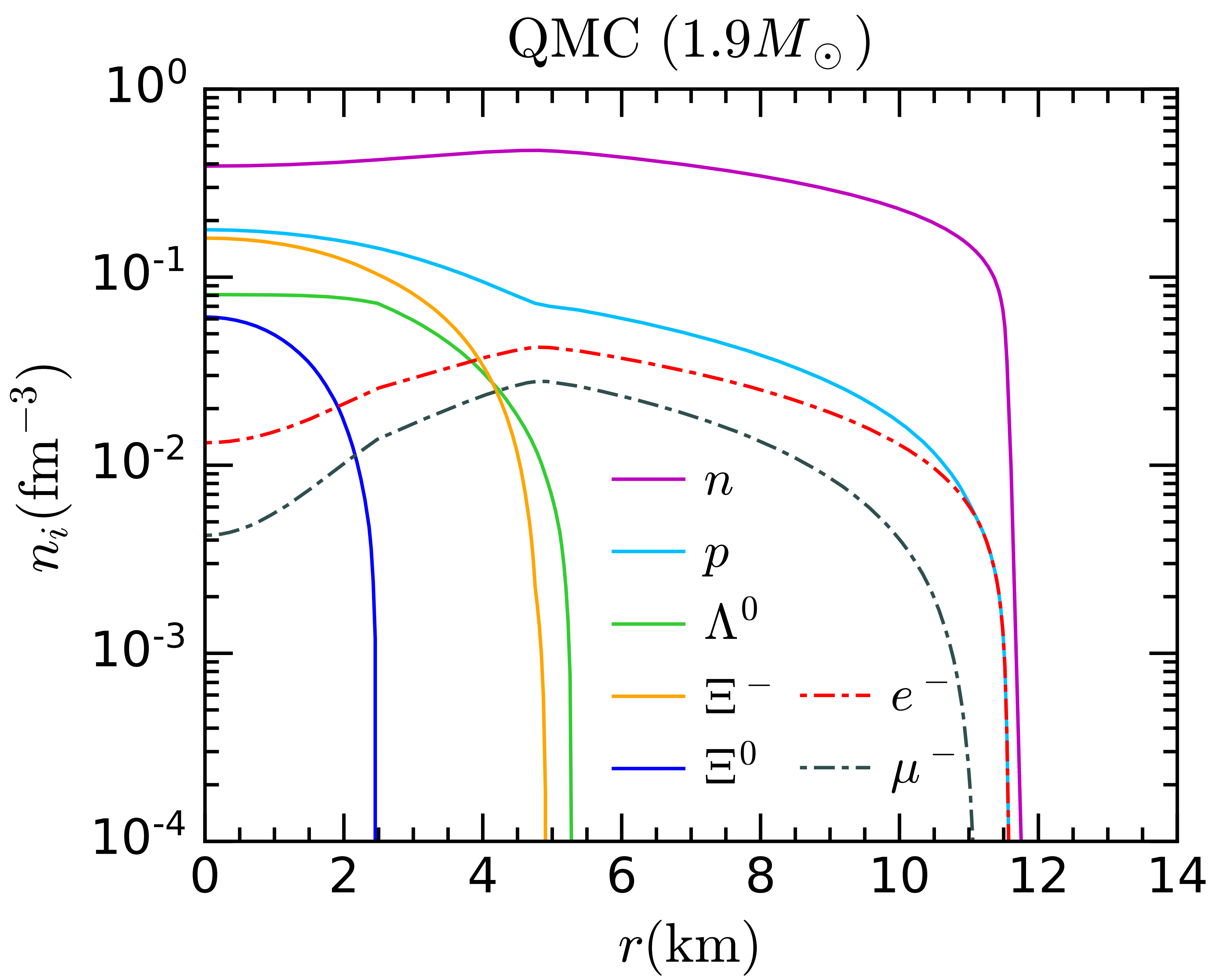
Guichon, Stone & Thomas, arXiv:1802.08368, Motta et al., arXiv:1904.03794

Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918, arXiv: 2108.02525

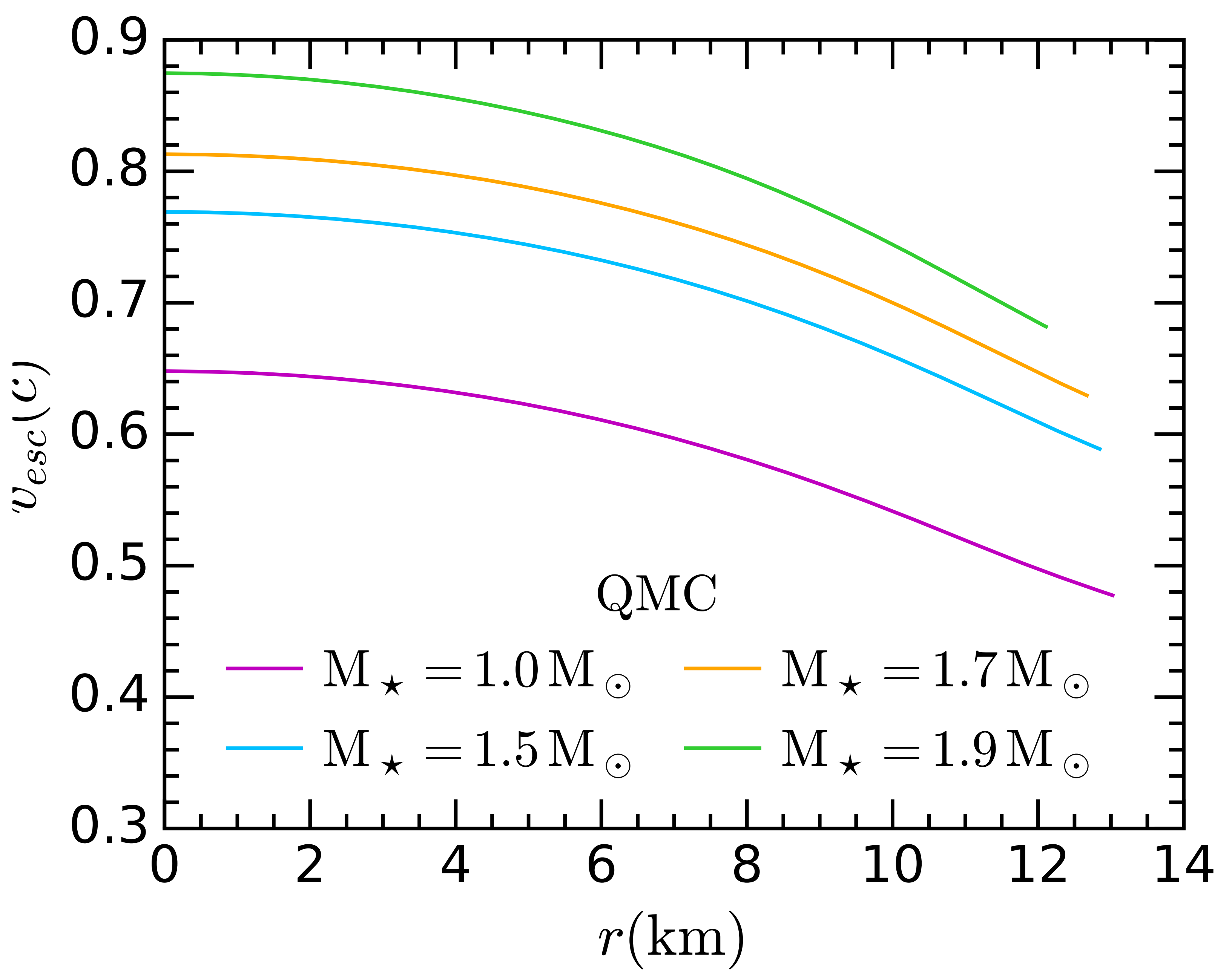
Baryon number density



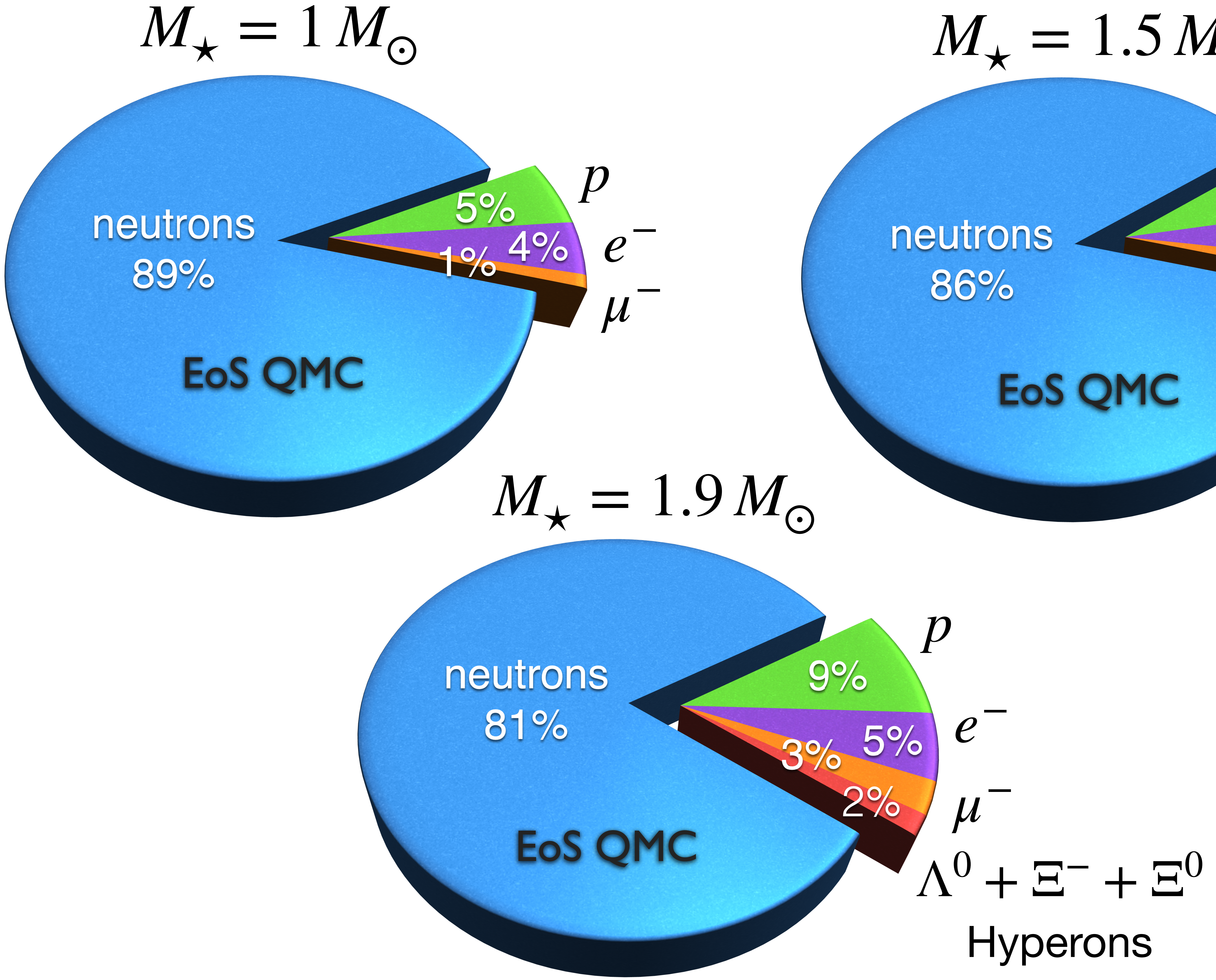
Baryonic & leptonic species



Escape velocity



DM capture in Neutron Stars



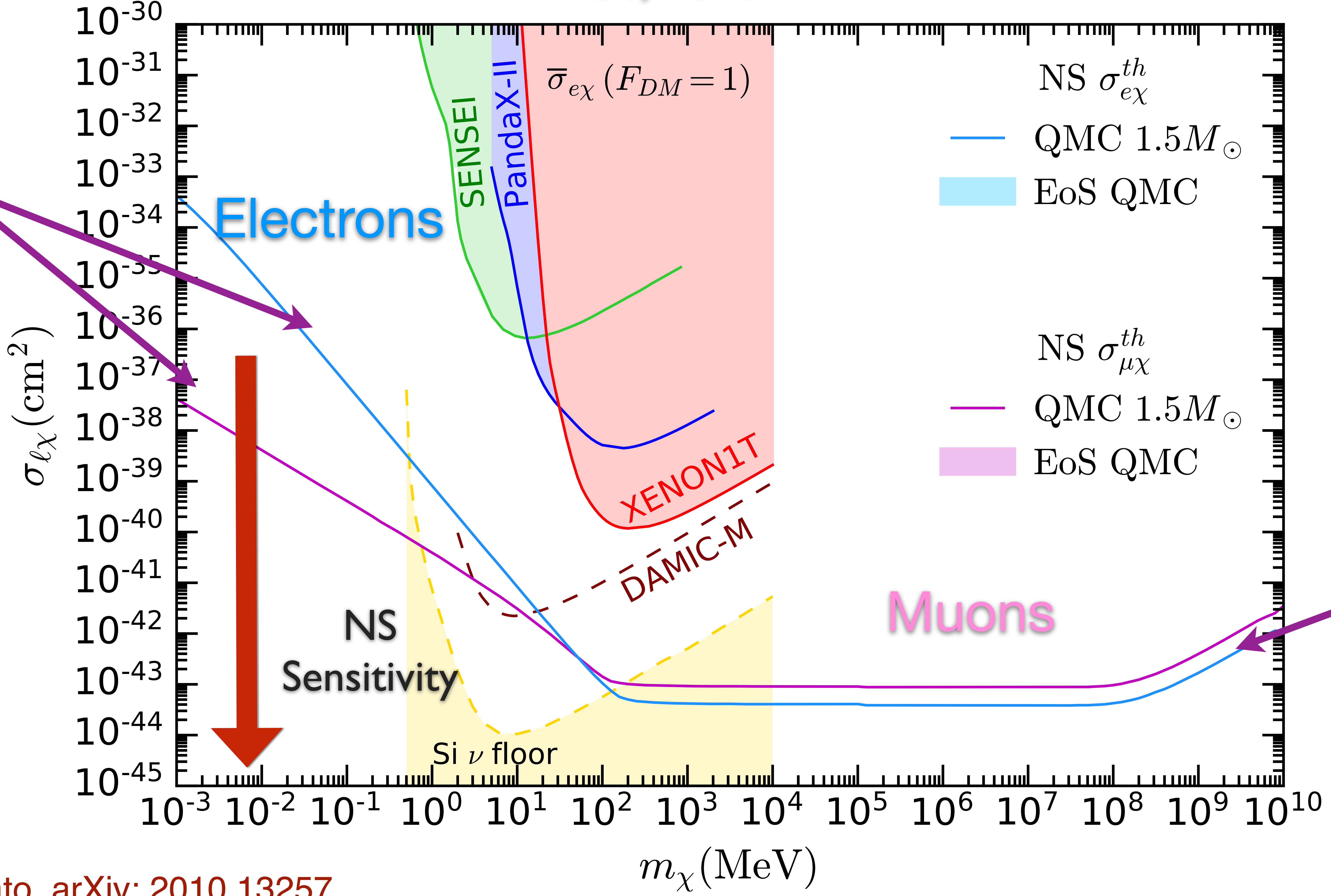
Targets

- Baryons
  - ➡ Strongly interacting
  - ➡ Hadronic form factors
  - ➡ Pauli blocking (interacting Fermi gas)
- Leptons
  - ➡ Relativistic
  - ➡ Pauli blocking (free Fermi gas)

NS sensitivity to DM-lepton scattering cross section

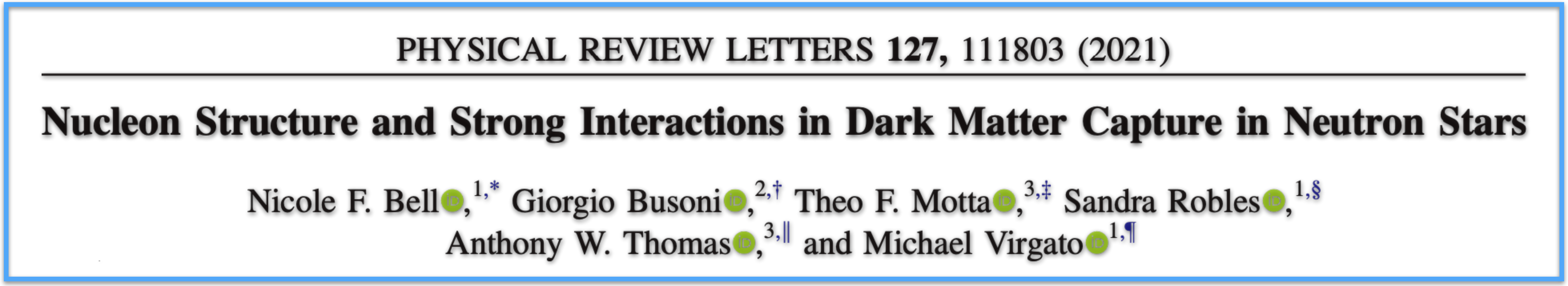
$$\bar{\chi}\gamma_\mu\chi\ell\gamma^\mu\bar{\ell}$$

Pauli blocking
Momentum
transfer >
lepton p_F



Multiple Scattering
momentum transfer
in single collision
not sufficient for
capture

Bell, Busoni, SR & Virgato, arXiv: 2010.13257



PHYSICAL REVIEW LETTERS **127,** 111803 (2021)

Nucleon Structure and Strong Interactions in Dark Matter Capture in Neutron Stars

Nicole F. Bell,[1,*] Giorgio Busoni,[2,†] Theo F. Motta,[3,‡] Sandra Robles,[1,§]
Anthony W. Thomas,[3,∥] and Michael Virgato[1,¶]

- Two important effects missing in all previous calculations:

➡ Momentum dependence of the hadronic matrix elements

Nucleon couplings

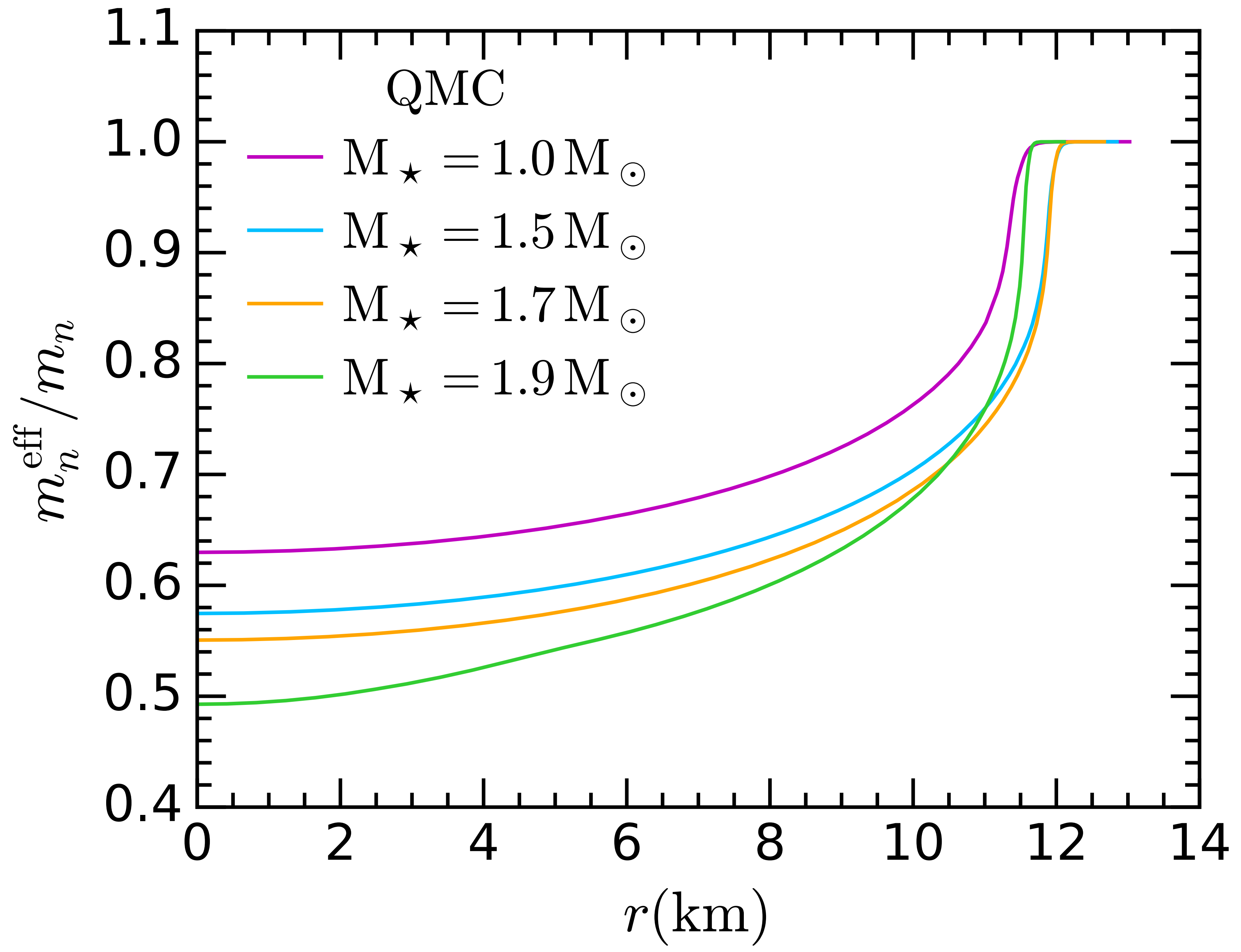
$$c_n(q) = \frac{c_n(0)}{1 - q^2/Q_0^2}$$

$$Q_0 \sim 1\,\mathrm{GeV}$$

➡ Nucleons undergo strong interactions, free Fermi gas is not a good approximation.

Nucleon effective mass

$$m_n \rightarrow m_n^{\mathrm{eff}}(r)$$



Nucleon structure and strong interactions

Scattering off a Fermi gas of interacting baryons

Neutron couplings

$$c_n(q) = \frac{c_n(0)}{1 - q^2/Q_0^2}$$

Neutron effective mass

$$m_n \rightarrow m_n^{\rm eff}(r)$$

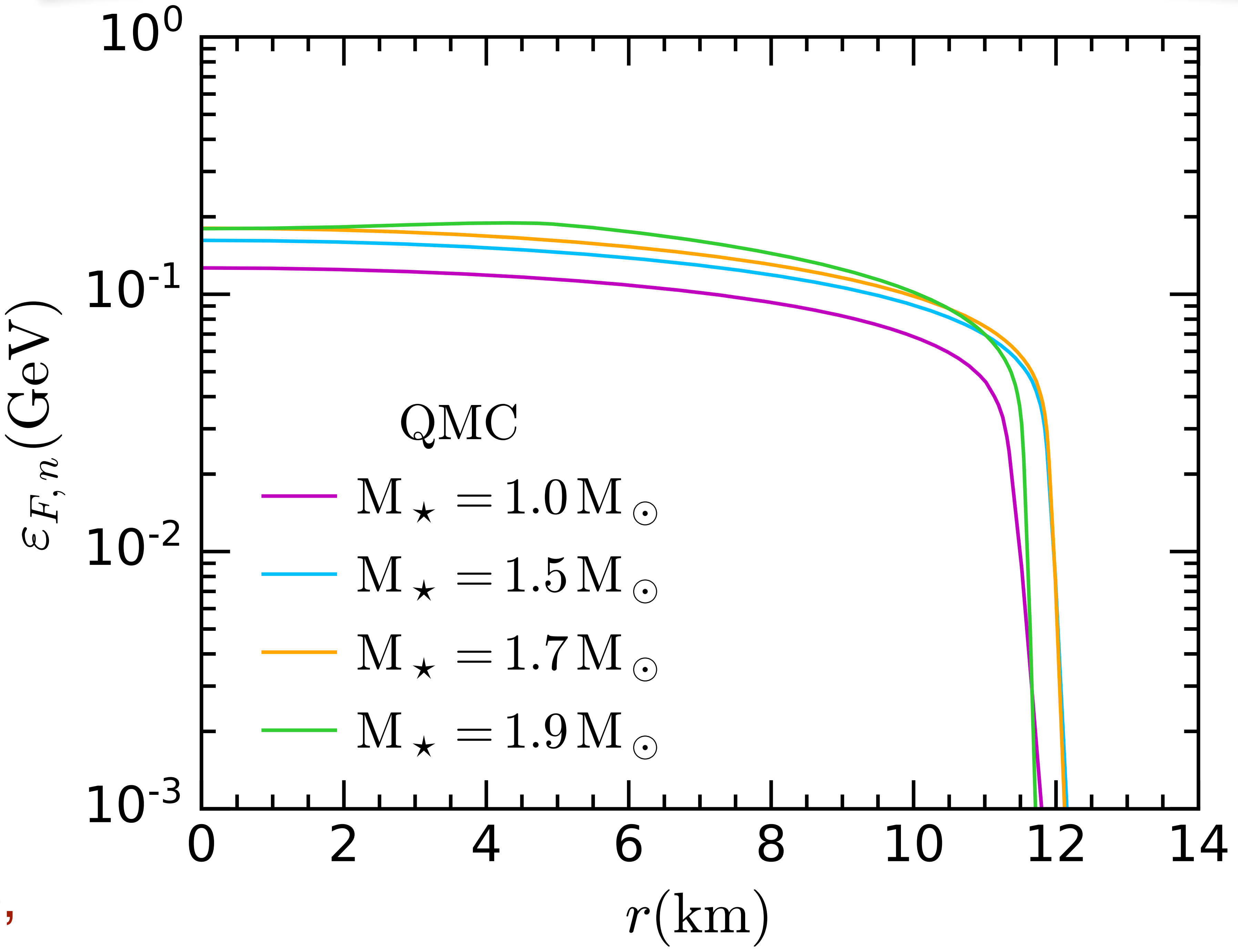
Neutron Fermi energy

$$\varepsilon_{F,n}(r) = \sqrt{k_{F,n}^2(r) + (m_n^{\rm eff})^2} - m_n^{\rm eff}$$

$$\frac{d\sigma_{n\chi}}{d\cos\theta_{cm}}(m_n^{\rm eff}(r), c_n(q), s, t)$$

Interaction rate

$$\Omega(m_n^{\rm eff}(r), \varepsilon_{F,n}(r))$$

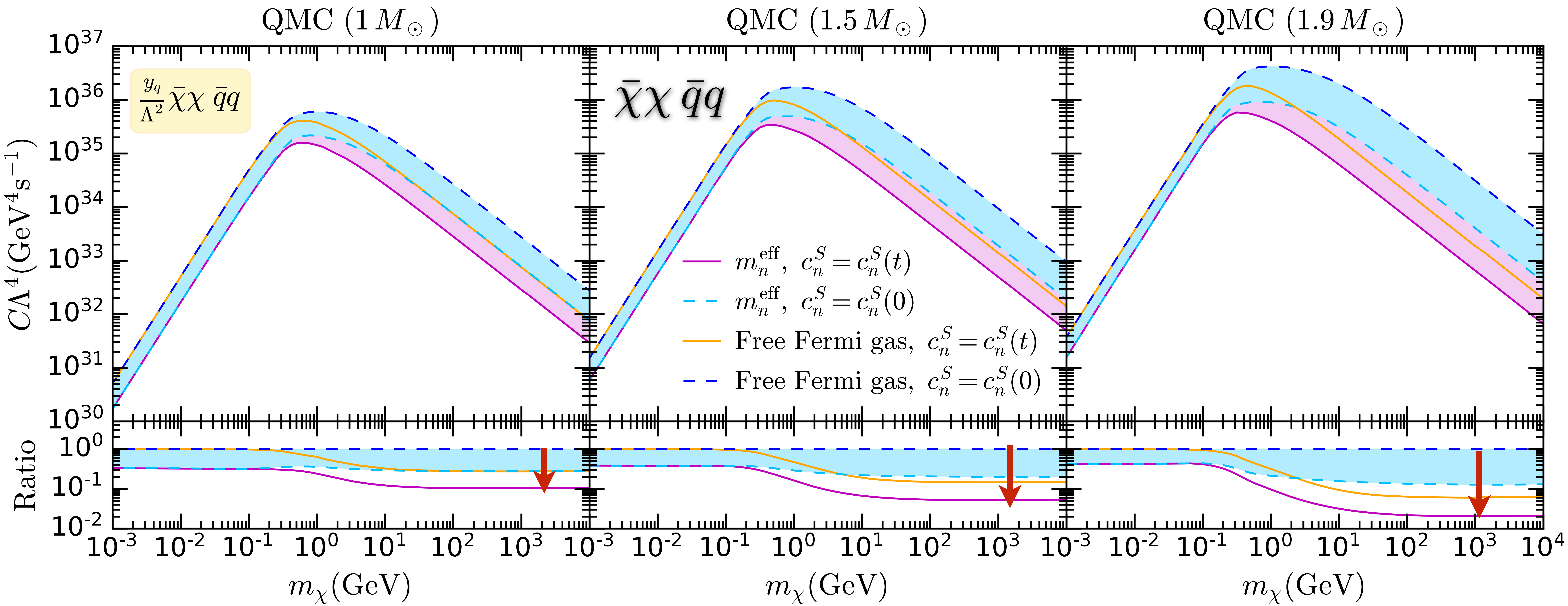


Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918, arXiv: 2108.02525

DM-neutron capture rate in NSs

- Accounting for nucleon structure and strong interactions suppresses the capture rate

Suppression of the capture rate

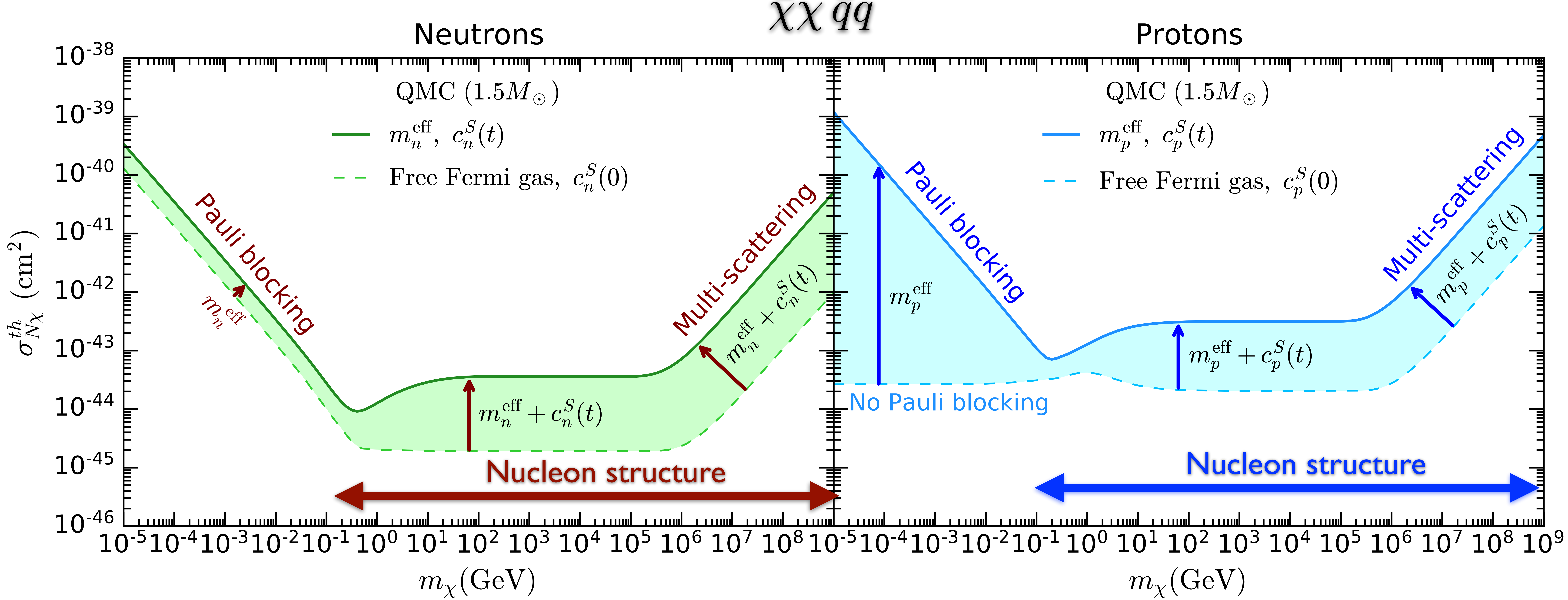


Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918, arXiv: 2108.02525

NS sensitivity to DM-nucleon scattering cross section

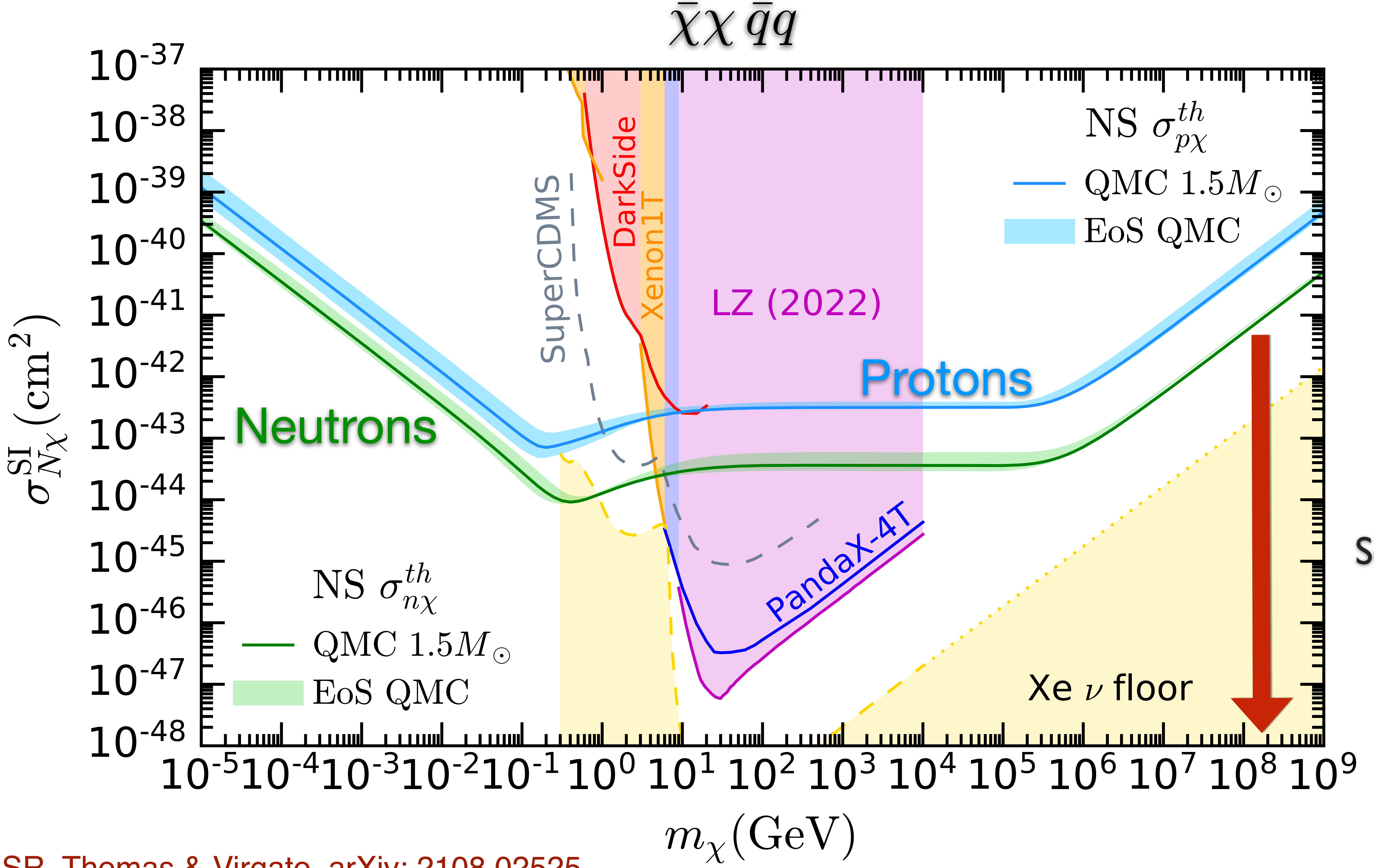
- Geometric (threshold) cross section

$\bar{\chi}\chi\,\bar{q}q$



Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525

NS sensitivity to SI DM-nucleon scattering cross section

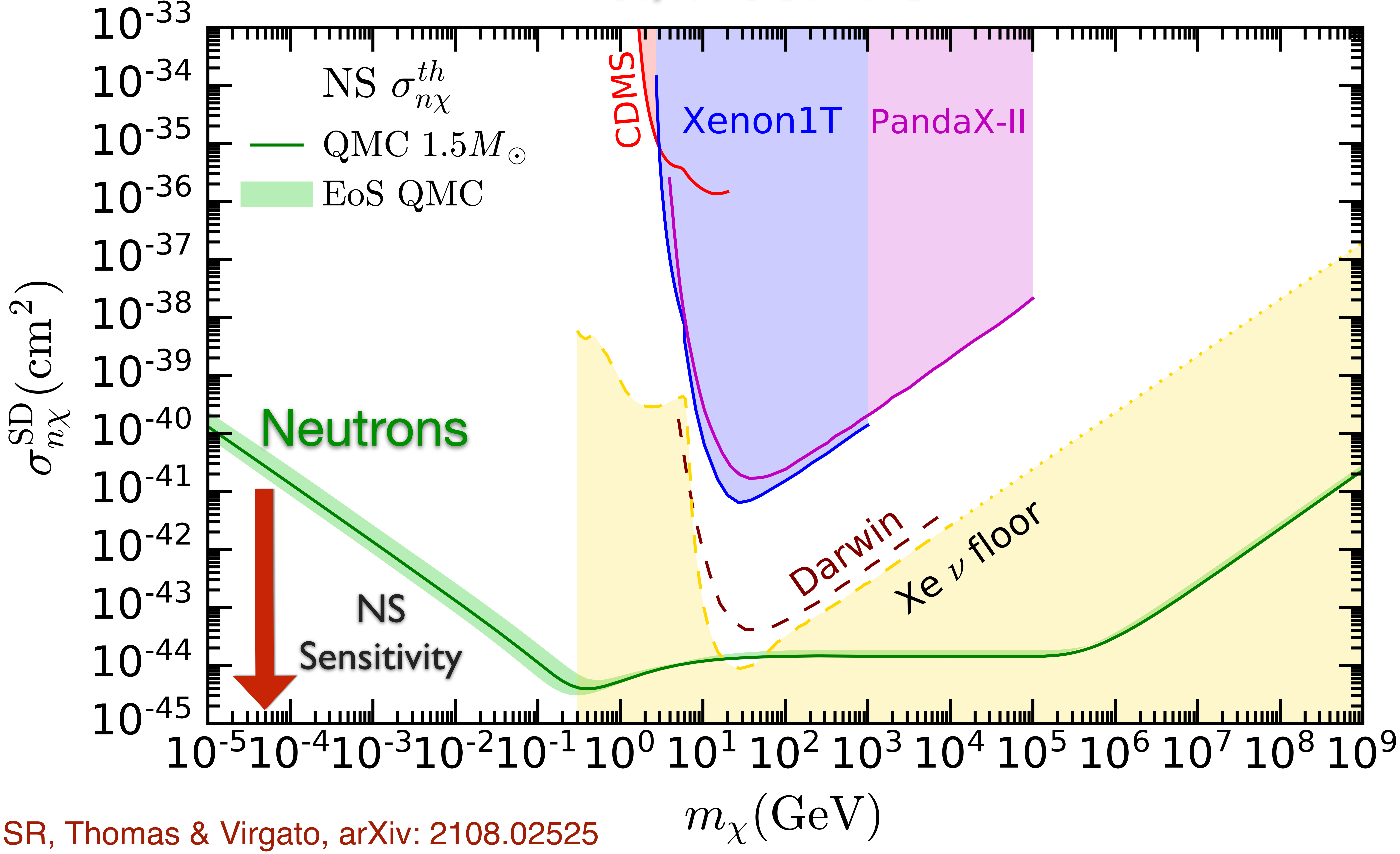


NS
Sensitivity

Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525

NS sensitivity to SD DM-neutron scattering cross section

$$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q$$

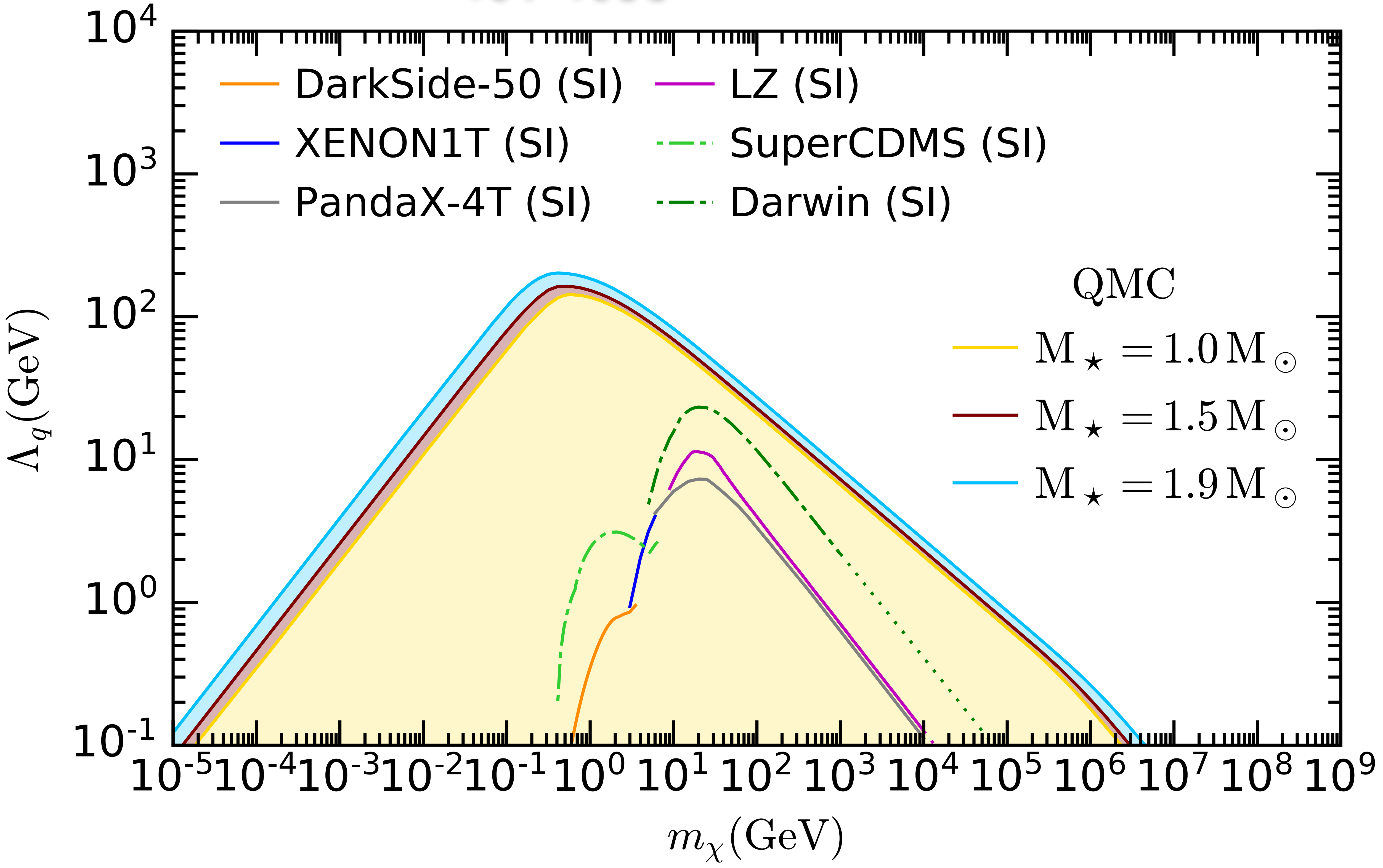


Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525

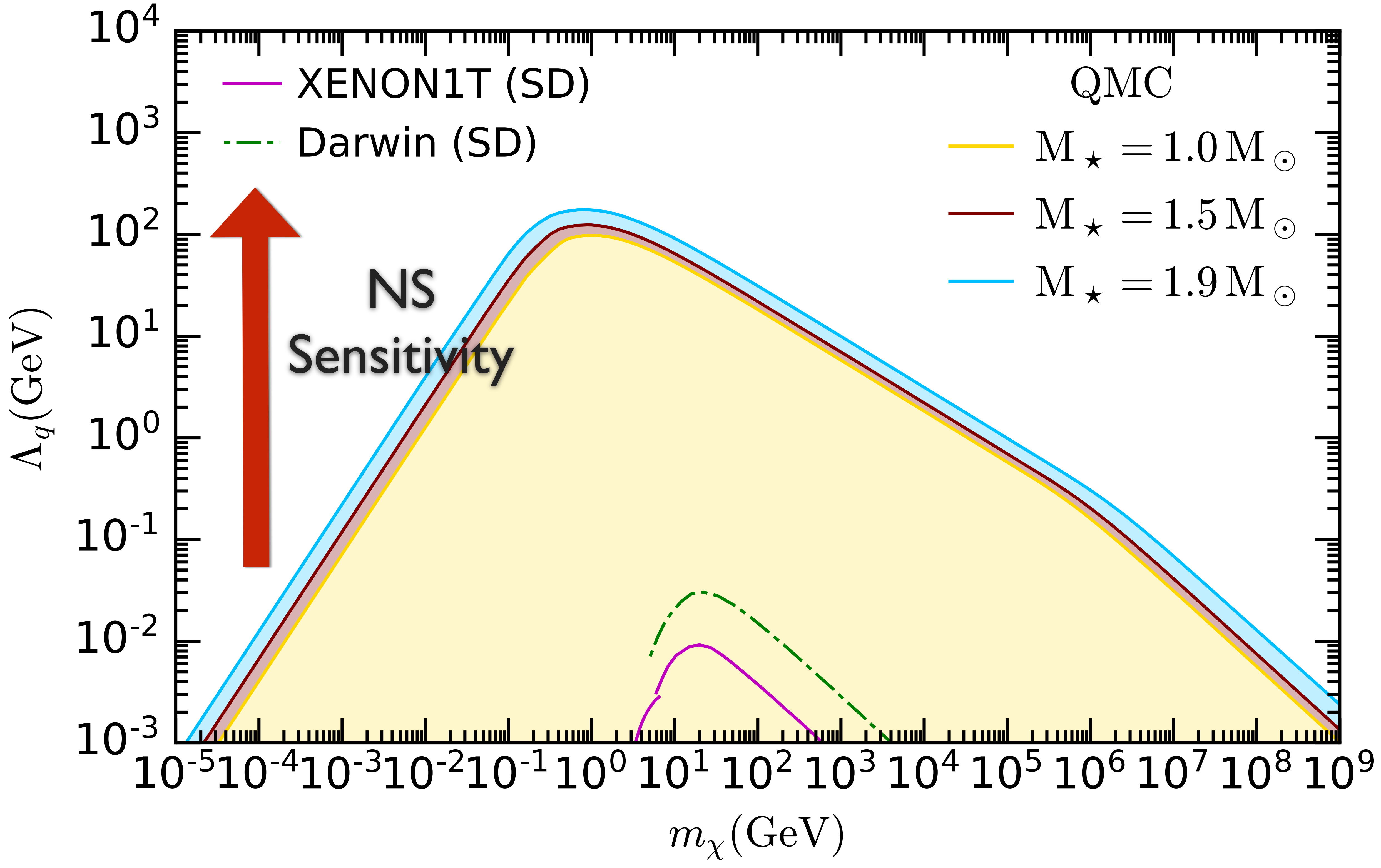
NS sensitivity to DM-nucleon scattering cross section

Momentum suppressed EFT operators

$\bar{\chi}\gamma^5\chi q\bar{q}$ q^2 suppressed



$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$ q^4 suppressed



Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525

Summary

- Improved calculation of the DM capture in compact stars for (non-)relativistic, degenerate targets.
  - ➡ Strong interactions in NSs require treatment beyond the free Fermi gas approximation.
- Observations of cold white dwarfs in DM rich environments can constraint DM interactions with ordinary matter.
- Assuming that M4 was formed in a DM sub-halo, we derived limits on DM-nucleon (SI) and DM-electron interactions.
- Neutron stars can accelerate DM to quasi-relativistic speeds
  - ➡ Potential to constrain different types of interactions, including those that are velocity and momentum suppressed.
  - ➡ Sensitivity to DM-lepton interactions.
- Constraining DM interactions using DM-induced anomalous heating of compact stars require
  - ➡ Observation of old (cold) compact stellar objects.
  - ➡ Better understanding of the cooling process especially in neutron stars.

Thank you for your attention!