Dark Matter in Celestial Bodies

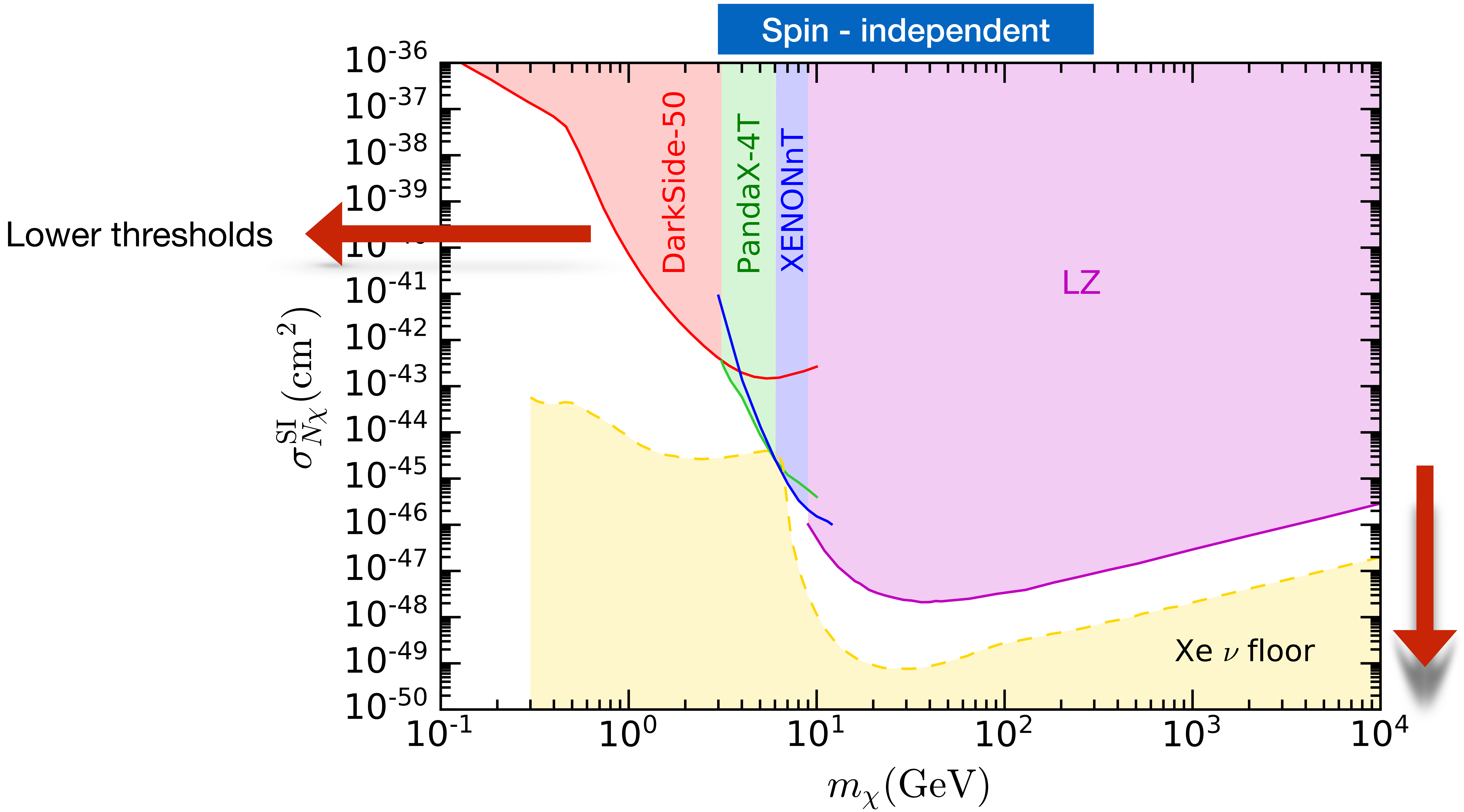
Sandra Robles

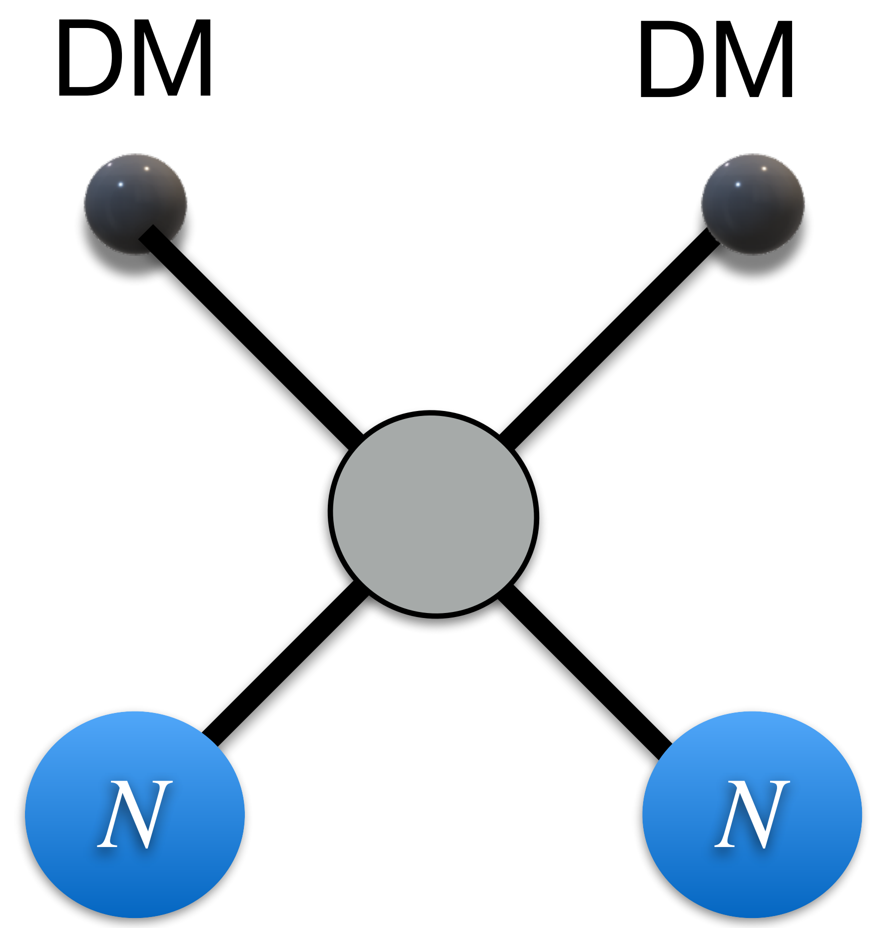
Fermi National Accelerator Laboratory

Light Dark World 2025

Introduction

Direct Detection





DM Capture in the Sun and in the Earth

1980s

THE ASTROPHYSICAL JOURNAL, **296**:679–684, 1985 September 15

The Sun, 1985

CAPTURE BY THE SUN OF A GALACTIC POPULATION OF WEAKLY INTERACTING, MASSIVE PARTICLES

WILLIAM H. PRESS AND DAVID N. SPERGEL
Harvard-Smithsonian Center for Astrophysics
Received 1985 February 4; accepted 1985 March 6

ABSTRACT

A previous calculation showed that hypothetical, massive particles, if present in
tering cross section and in a concentration as low as 10^{-12} by number, could like
discrepancy. We here suppose that the same hypothetical particles make up the m
Galaxy, providing a mass density between 0.01 and 0.1 $M_\odot$ pc^{-3} and with a velo
or 300 (halo) km s^{-1}. We compute the number of particles which would be ca
present age by the capture mechanism of scattering off individual nucleons in the
For scattering cross sections not too far from the value of 4×10^{-36} cm^2, whic
solar neutrinos, we find that just the right number can be captured. The solution
the Sun and the missing mass problem in the Galaxy may thus be one and the sa
Subject headings: elementary particles — galaxies: Milky Way — neutrinos — Su

THE ASTROPHYSICAL JOURNAL, **321**:571–585, 1987 October 1

The Earth, 1987

RESONANT ENHANCEMENTS IN WEAKLY INTERACTING MASSIVE PARTICLE CAPTURE BY THE EARTH

ANDREW GOULD
Stanford Linear Accelerator Center, Stanford University
Received 1987 March 2; accepted 1987 March 17

ABSTRACT

The exact formulae for the capture of weakly interacting massive particles (WIMPs) by a massive body are derived. Capture by the Earth is found to be significantly enhanced whenever the WIMP mass is roughly equal to the nuclear mass of an element present in the Earth in large quantities. For Dirac neutrino WIMPs of mass 10–90 GeV, the capture rate is 10–300 times that previously believed. Capture rates for the Sun are also recalculated and found to be from 1.5 times higher to 3 times lower than previously believed, depending on the mass and type of WIMP. The Earth alone or the Earth in combination with the Sun is found to give a much stronger annihilation signal from Dirac neutrino WIMPs than the Sun alone over a very large mass range. This is particularly important in the neighborhood of the mass of iron where previous analyses could not set any significant limits.
Subject headings: elementary particles — neutrinos

DM capture in Compact Stars

Neutron Stars, 1989

PHYSICAL REVIEW D VOLUME 40, NUMBER 10 15 NOVEMBER 1989

Weakly interacting massive particles and neutron stars

Itzhak Goldman and Shmuel Nussinov
School of Physics and Astronomy, Raymond and Beverley Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel
(Received 21 April 1989)

Neutron stars are used to set constraints on the characteristics of weakly interacting massive particles (WIMP's) suggested as dark-matter candidates. Some special classes of
because they would be trapped
self-gravitating. This results in
transforming it into a black hole,
ous astrophysical systems.

White Dwarfs, 2008

PHYSICAL REVIEW D **77,** 043515 (2008)

Compact stars as dark matter probes

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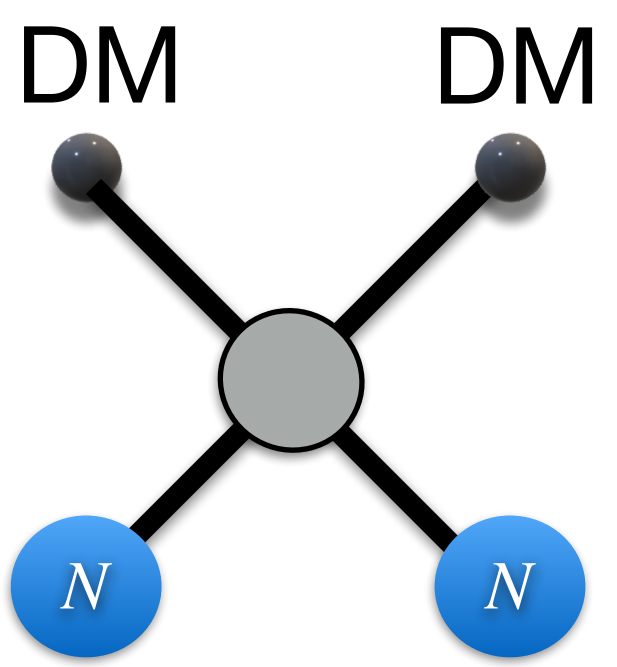
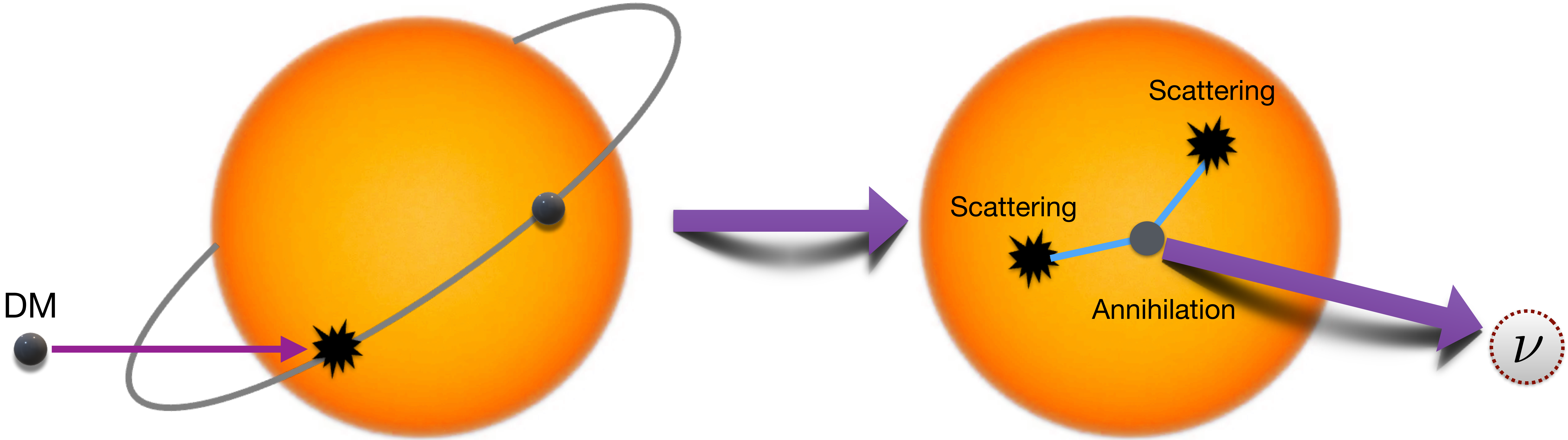
Malcolm Fairbairn†
TH Division, Physics Department, CERN, Geneva, Switzerland
(Received 15 November 2007; published 15 February 2008)

We discuss the consequences of the accretion of dark matter (DM) particles on compact stars such as white dwarfs and neutron stars. We show that in large regions of the DM parameter space, these objects are sensitive probes of the presence of DM and can be used to set constraints both on the DM density and on the physical properties of DM particles.

DM Capture in the Sun

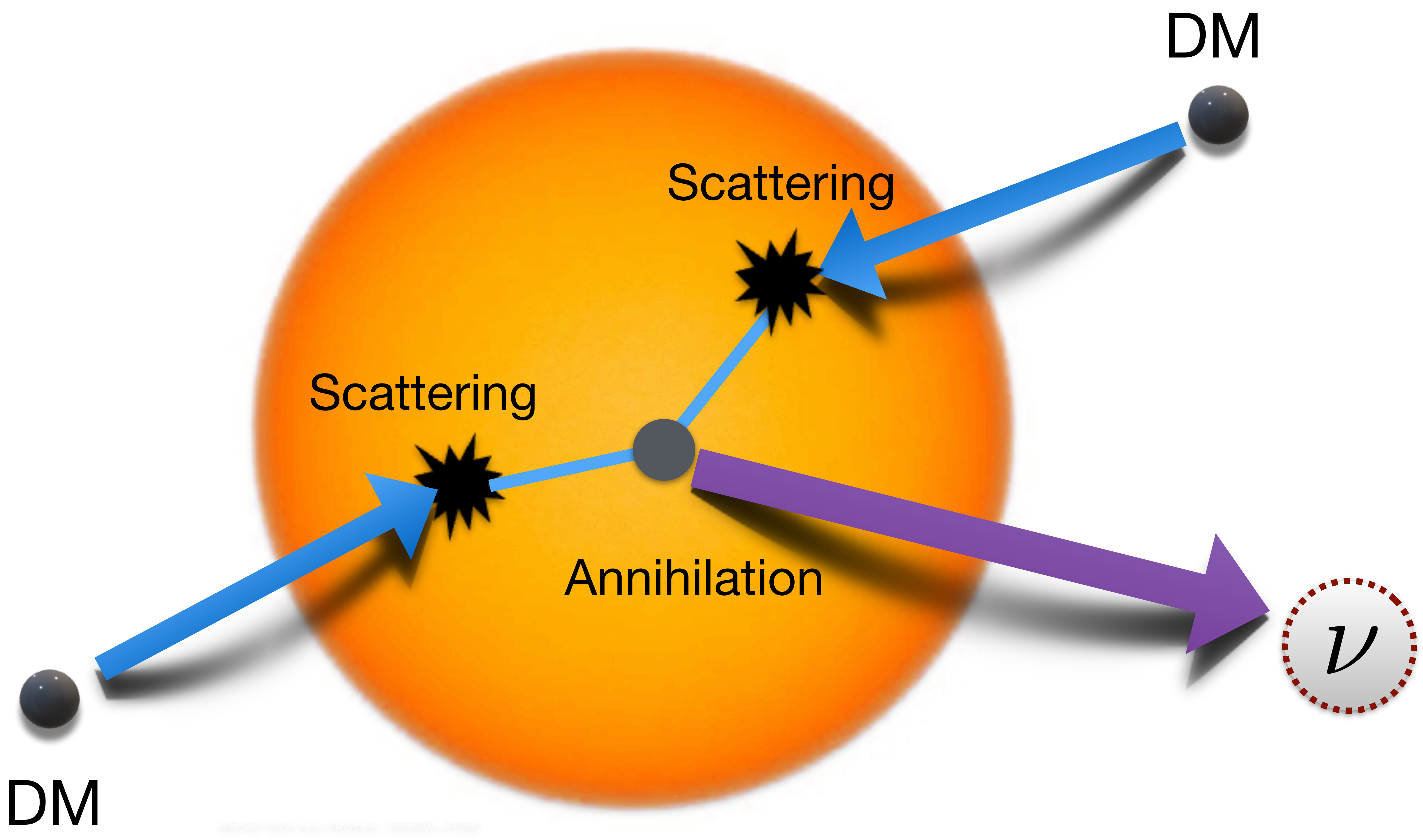


- DM scatters, loses energy, becomes gravitationally bound to the Sun.
- Accumulates and annihilates in the centre of the Sun.



DM Capture in the Sun

- In equilibrium, annihilation rate proportional to the DM-nucleon scattering cross section.
- Neutrinos from DM annihilation can be detected in the Earth (Super-Kamiokande, Antares, IceCube).



$$\frac{d\Phi_\nu}{dE_\nu} = \frac{C(\sigma)}{8\pi D_\odot^2}\frac{dN_\nu}{dE_\nu}$$

SuperK

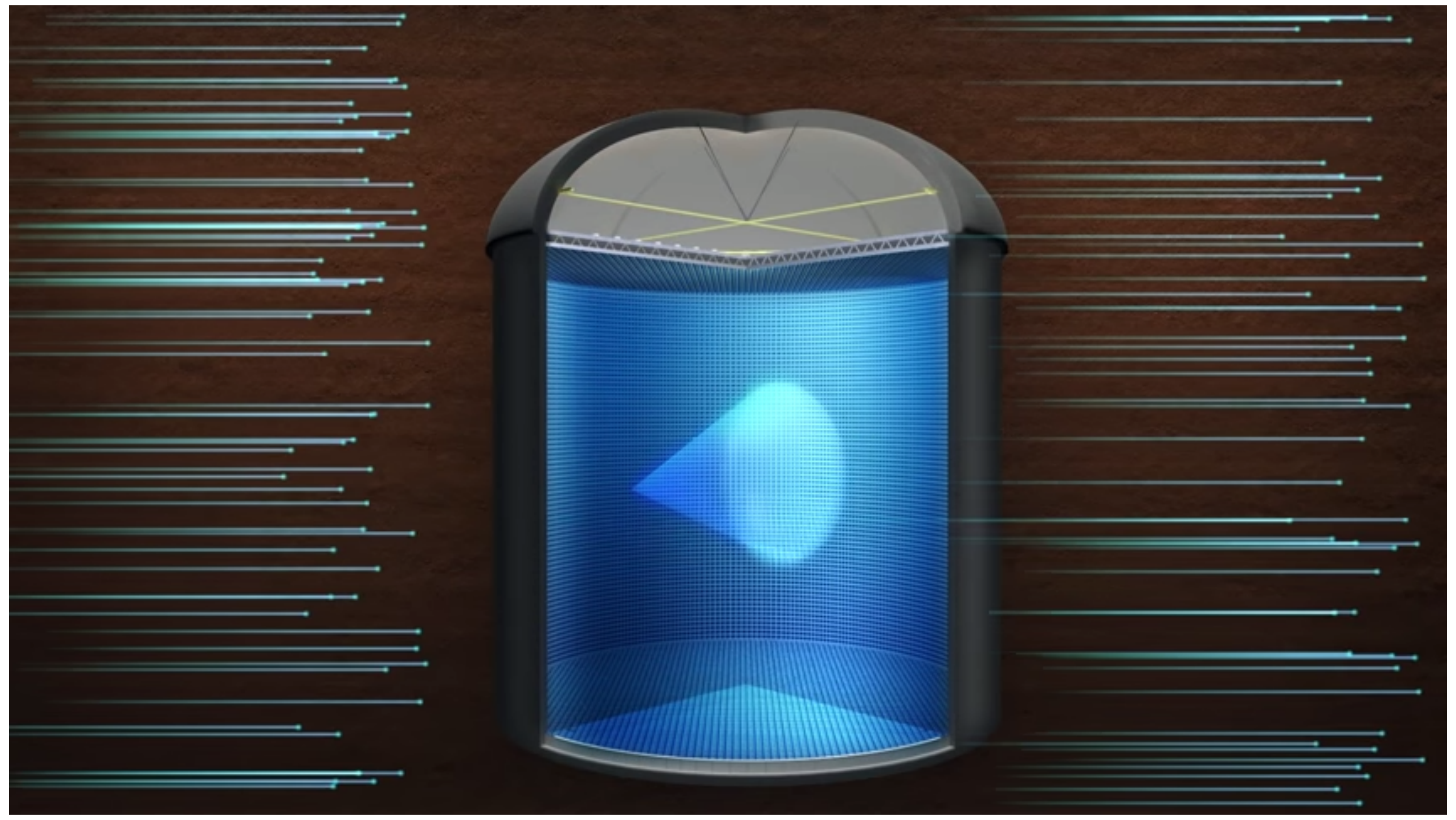
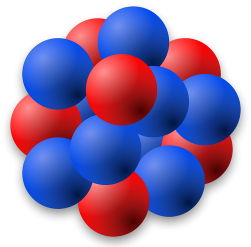


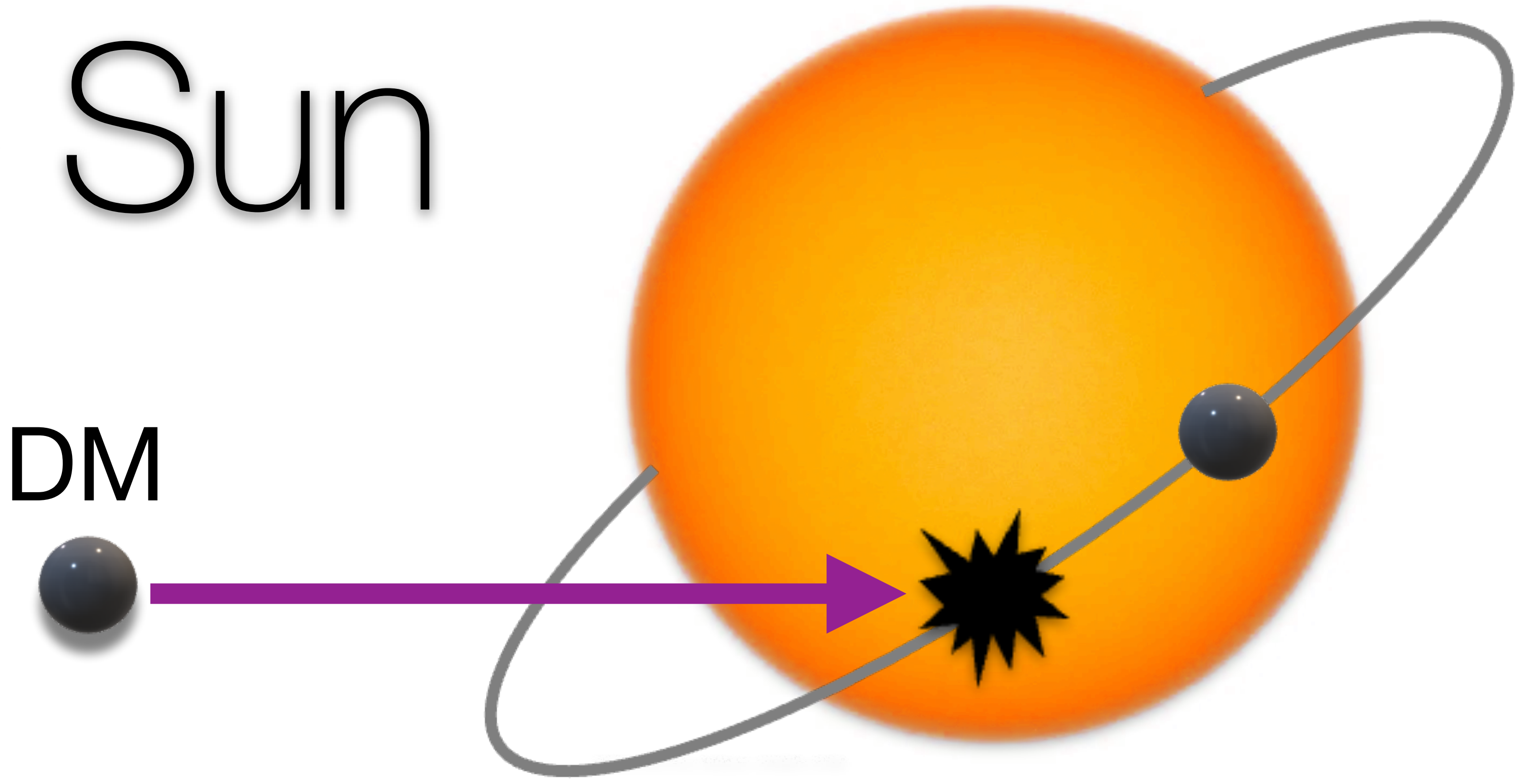
Image credit: Institute for Cosmic Ray Research,The University of Tokyo

DM capture rate in the Sun

The simple picture

- DM with velocity w before the collision scatters off a 

$$w(r) = \sqrt{u_\chi^2 + v_{\rm esc}^2(r)}$$



Capture rate

DM flux

Scattering rate

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

Scattering rate

$$\Omega^-(w,\sigma) = \sigma\, n(r) w(r)\, P(w \to v \leq v_{\rm esc})$$

Total scant. rate

Prob. to scatter to $v \leq v_{\rm esc}$

Gould 1987
Garani & Palomares-Ruiz, 2017
Busoni et al., 2017

DM Capture in the Sun

- Evaporation

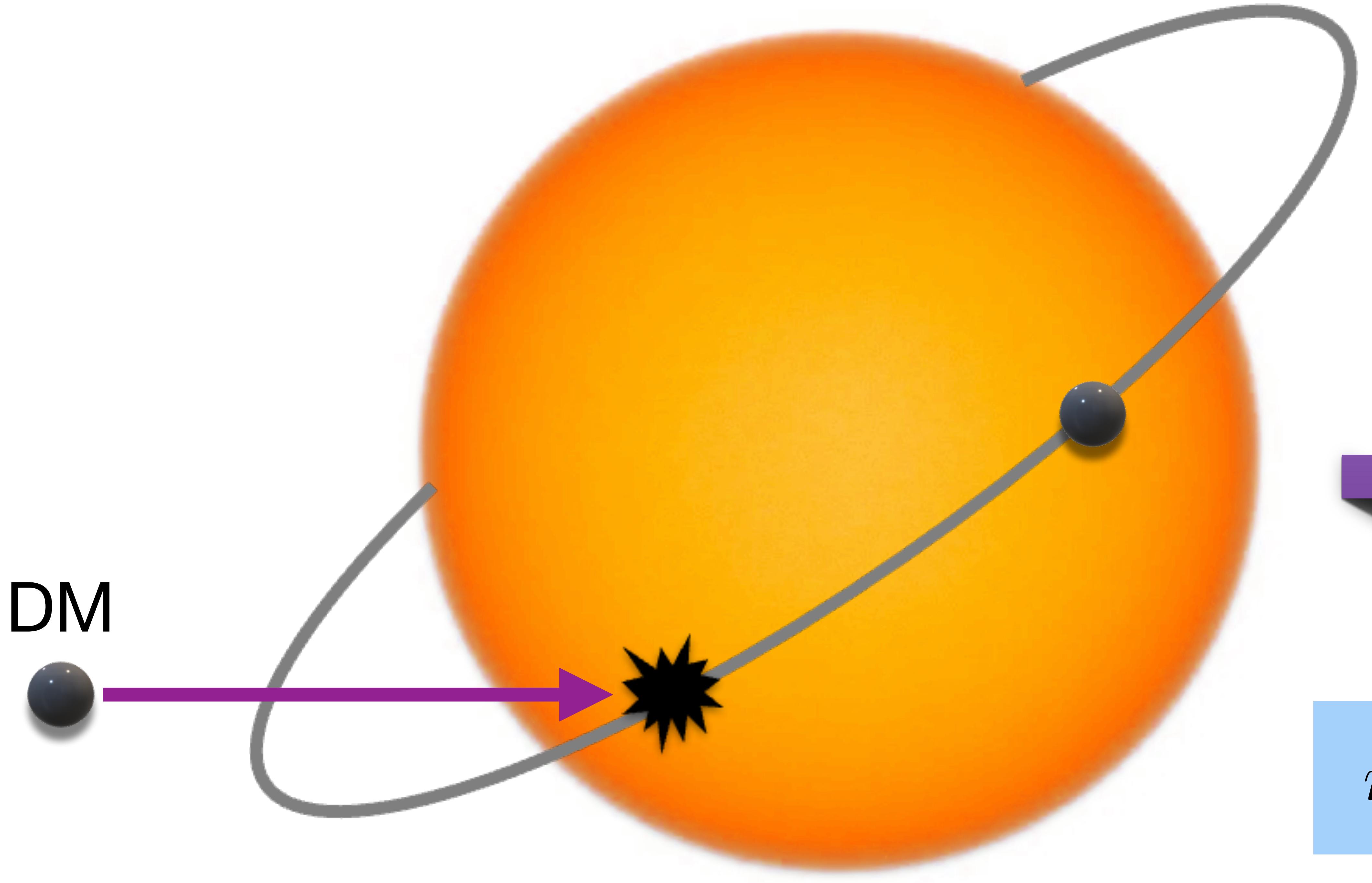
Caveat for light DM

➡ Captured DM can be up-scattered to speeds greater than the escape velocity

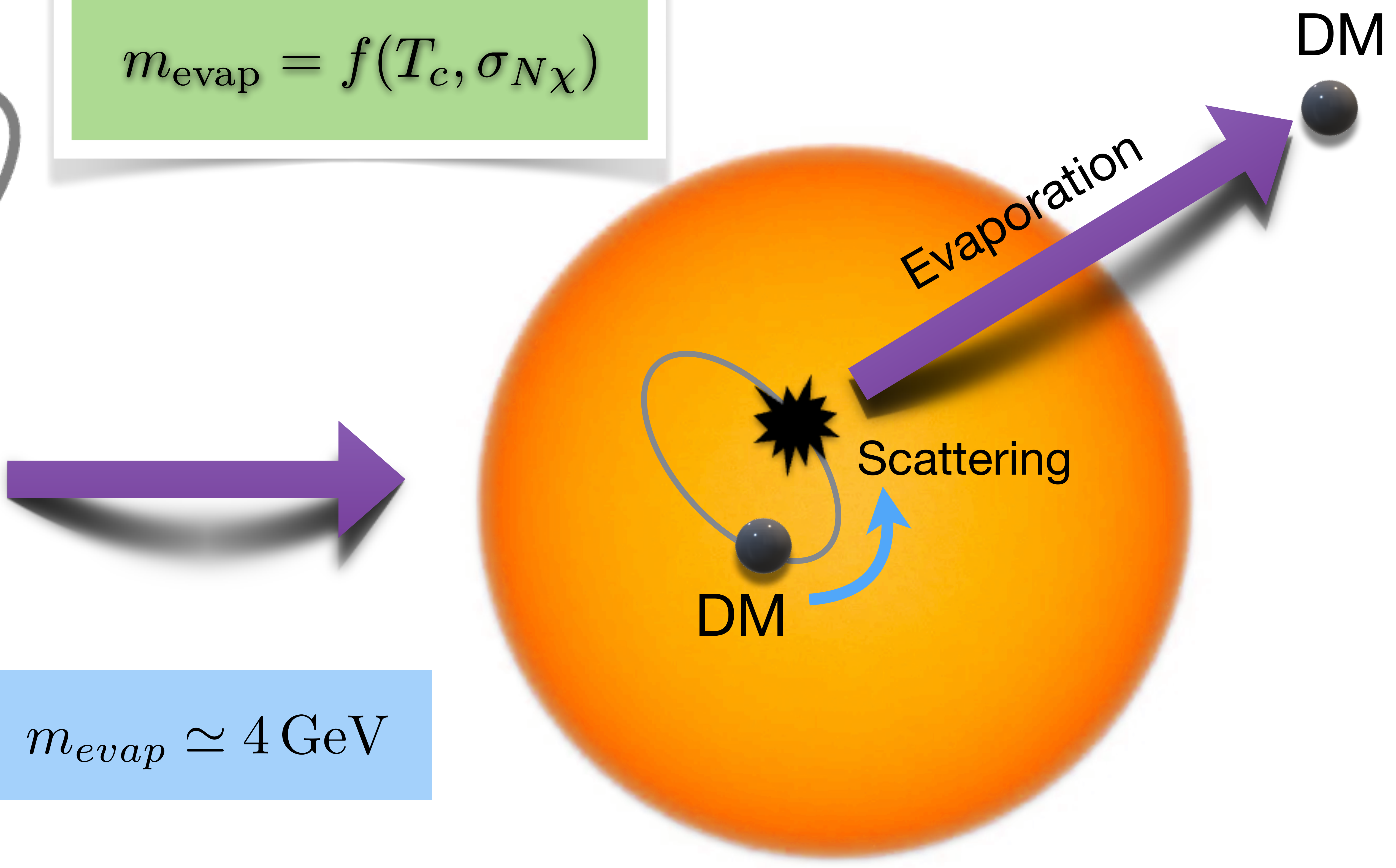
➡ Highly dependent on the stars's central core temperature for the Sun ~ $1.6 \times 10^7\,\mathrm{K}$

➡ Negligible for $m_\chi \gtrsim m_{evap}$

$$m_{\mathrm{evap}} = f(T_c, \sigma_{N\chi})$$



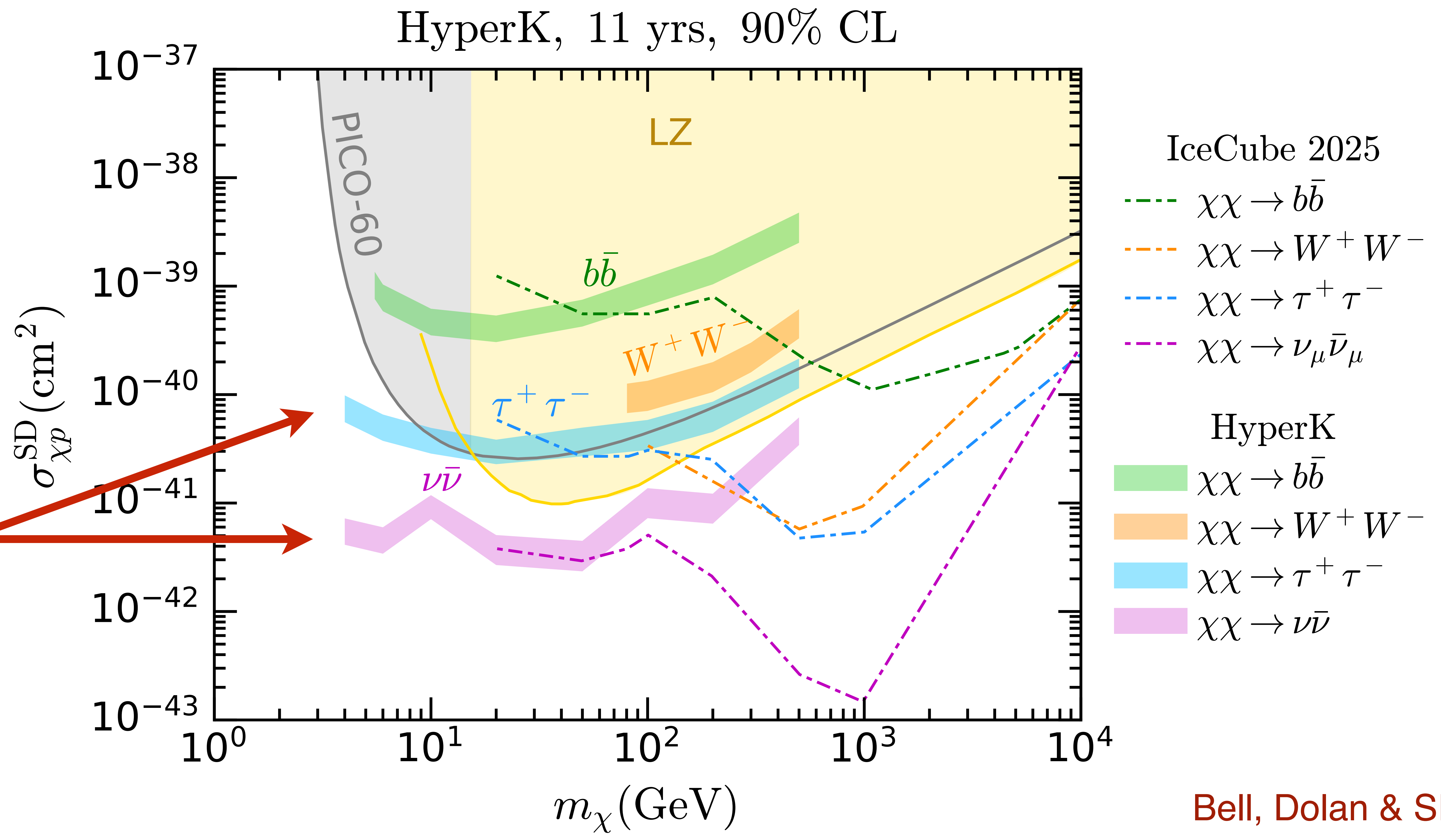
$$m_{evap} \simeq 4\,\mathrm{GeV}$$



Captured DM annihilating in the Sun

- Limits on the SI cross section from DM annihilation to neutrinos much weaker than DD.

Spin - dependent proton



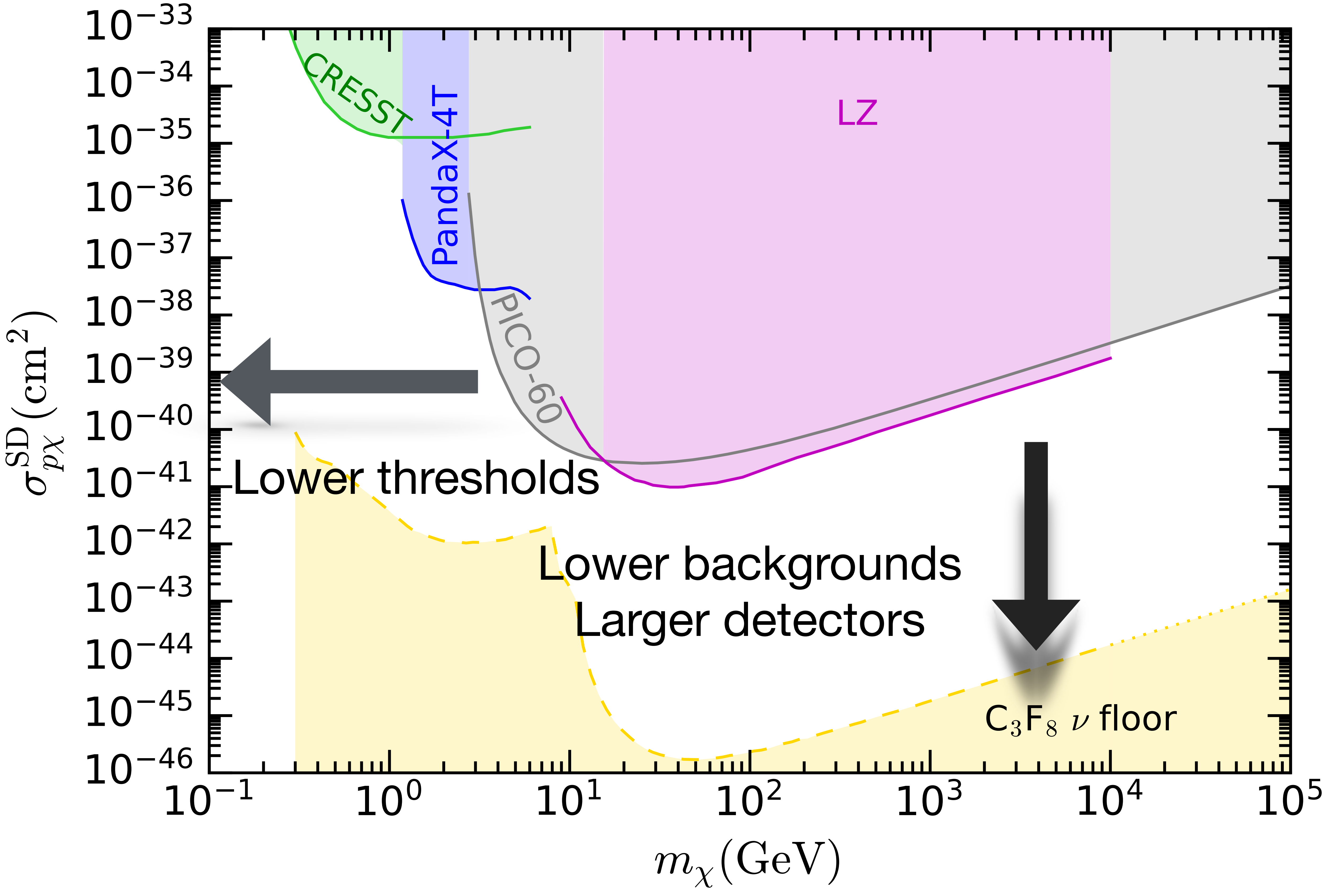
Limited by evaporation

$m_{evap} \simeq 4\,\mathrm{GeV}$

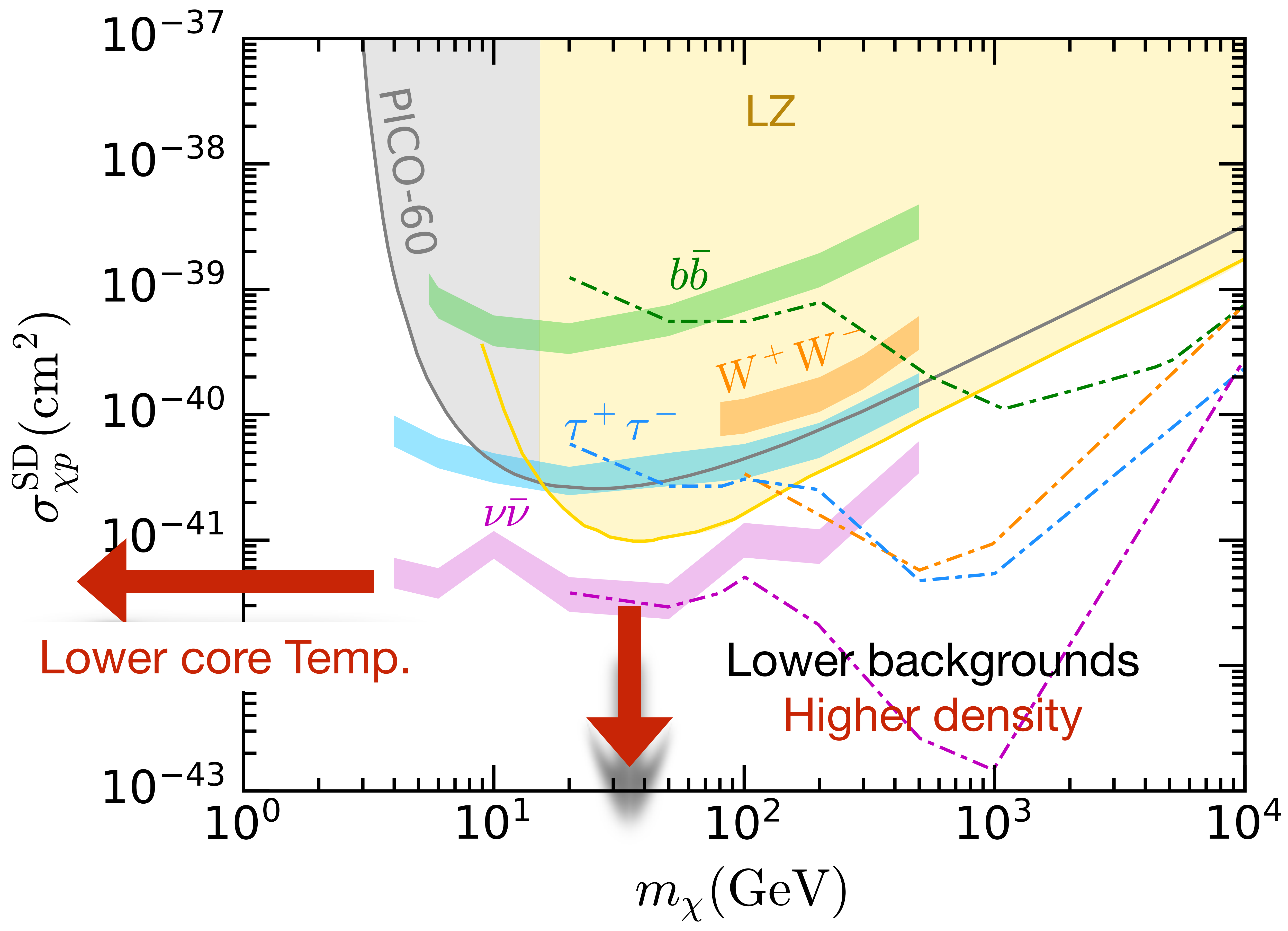
Bell, Dolan & SR, arXiv: 2107.04216 (JCAP)

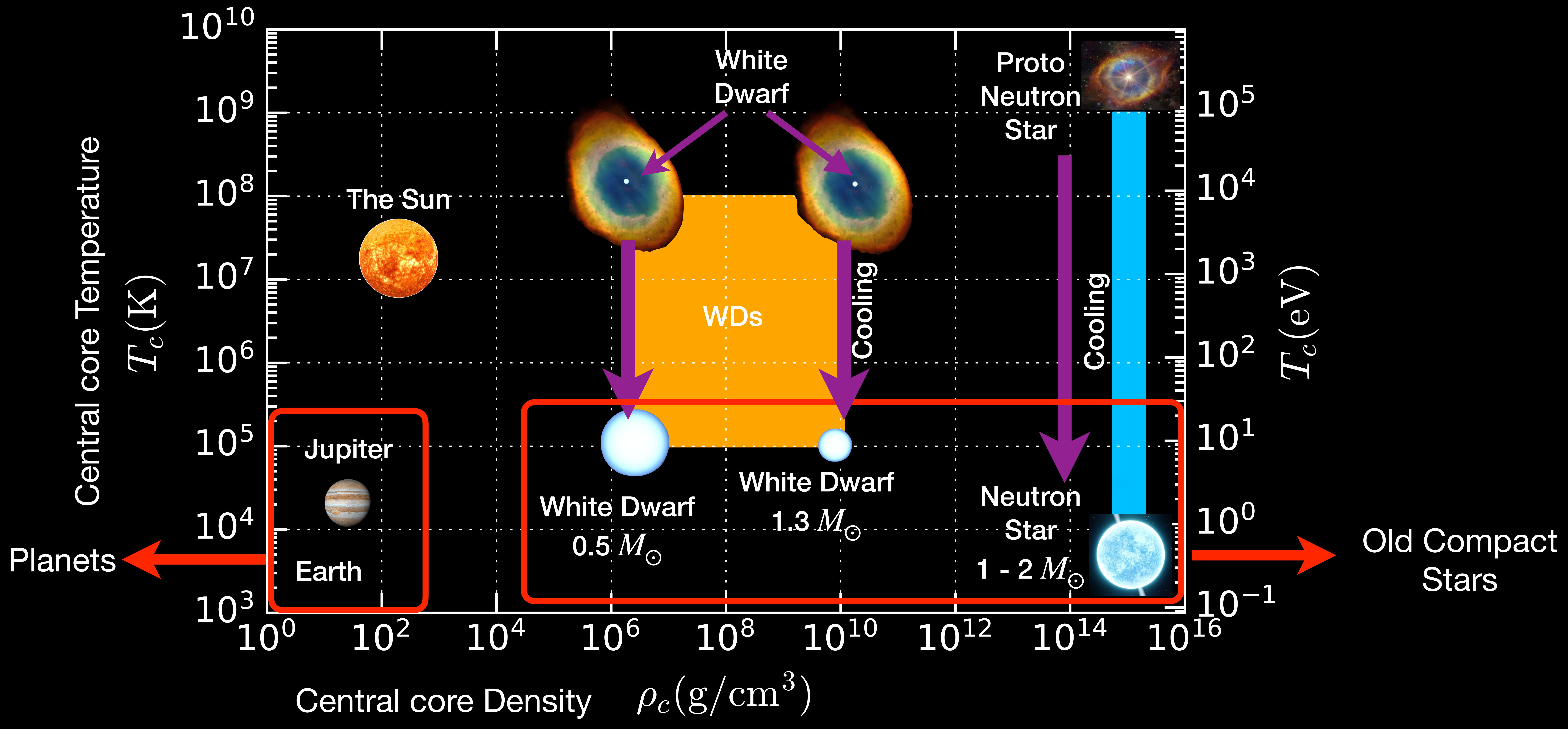
Complementarity to Direct Detection

Direct Detection



DM Capture in the Sun



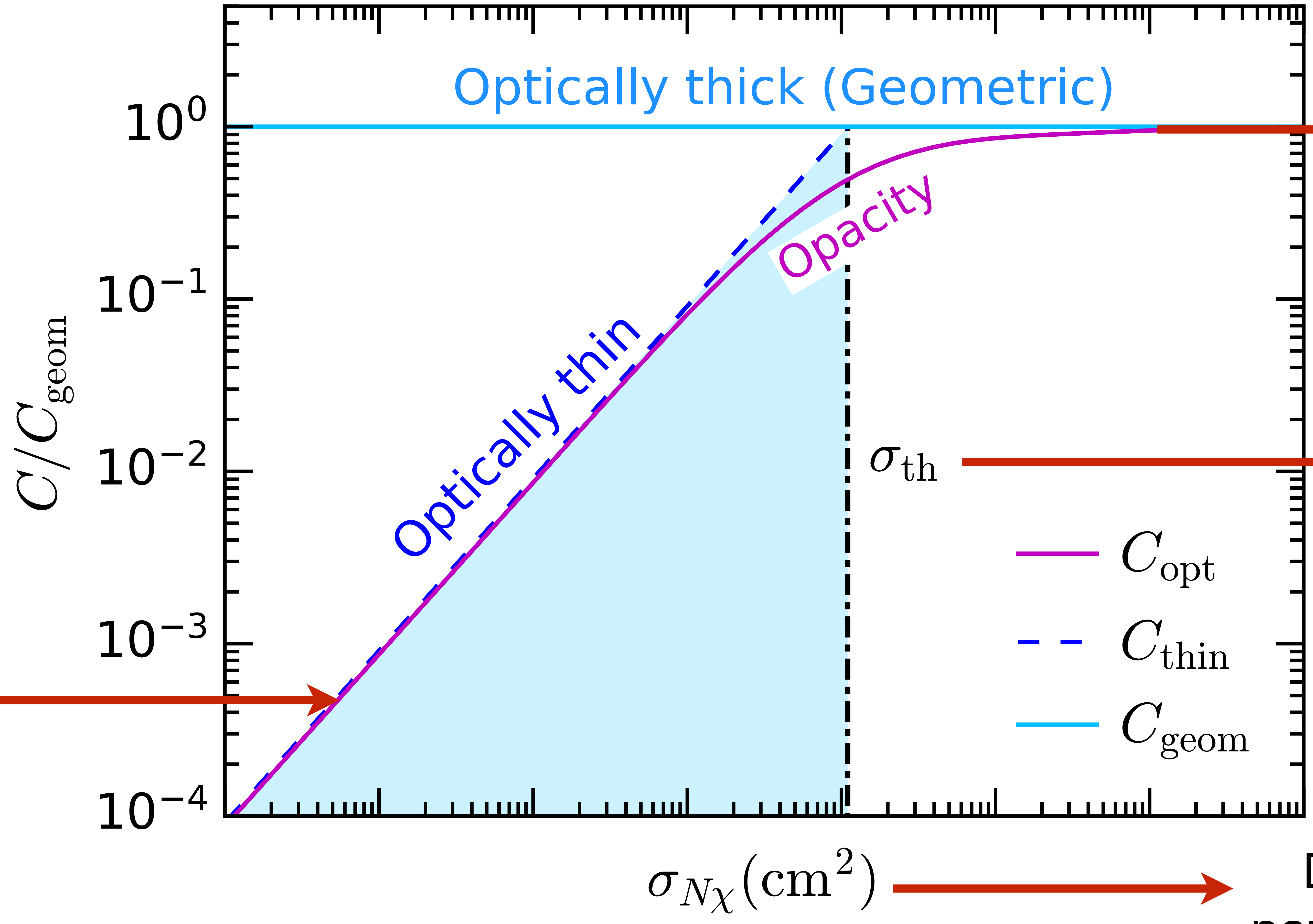


Central core Temperature $T_c(\mathrm{K})$
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
Central core Density $\rho_c(\mathrm{g/cm^3})$
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
$T_c(\mathrm{eV})$
The Sun
White Dwarf
Proto Neutron Star
WDs
Cooling
Cooling
Jupiter
Earth
Planets
White Dwarf $0.5\,M_\odot$
White Dwarf $1.3\,M_\odot$
Neutron Star 1 - $2\,M_\odot$
Old Compact Stars

DM Capture in Celestial Bodies

Figure of merit

- For a given DM mass



Capture probability ~ 1

Threshold (geometric) cross section

No sensitivity to $\sigma_{N\chi} \gtrsim \sigma_{\rm th}$

- For $\sigma_{N\chi} \lesssim \sigma_{\rm th}$

$C \propto \sigma_{N\chi}$

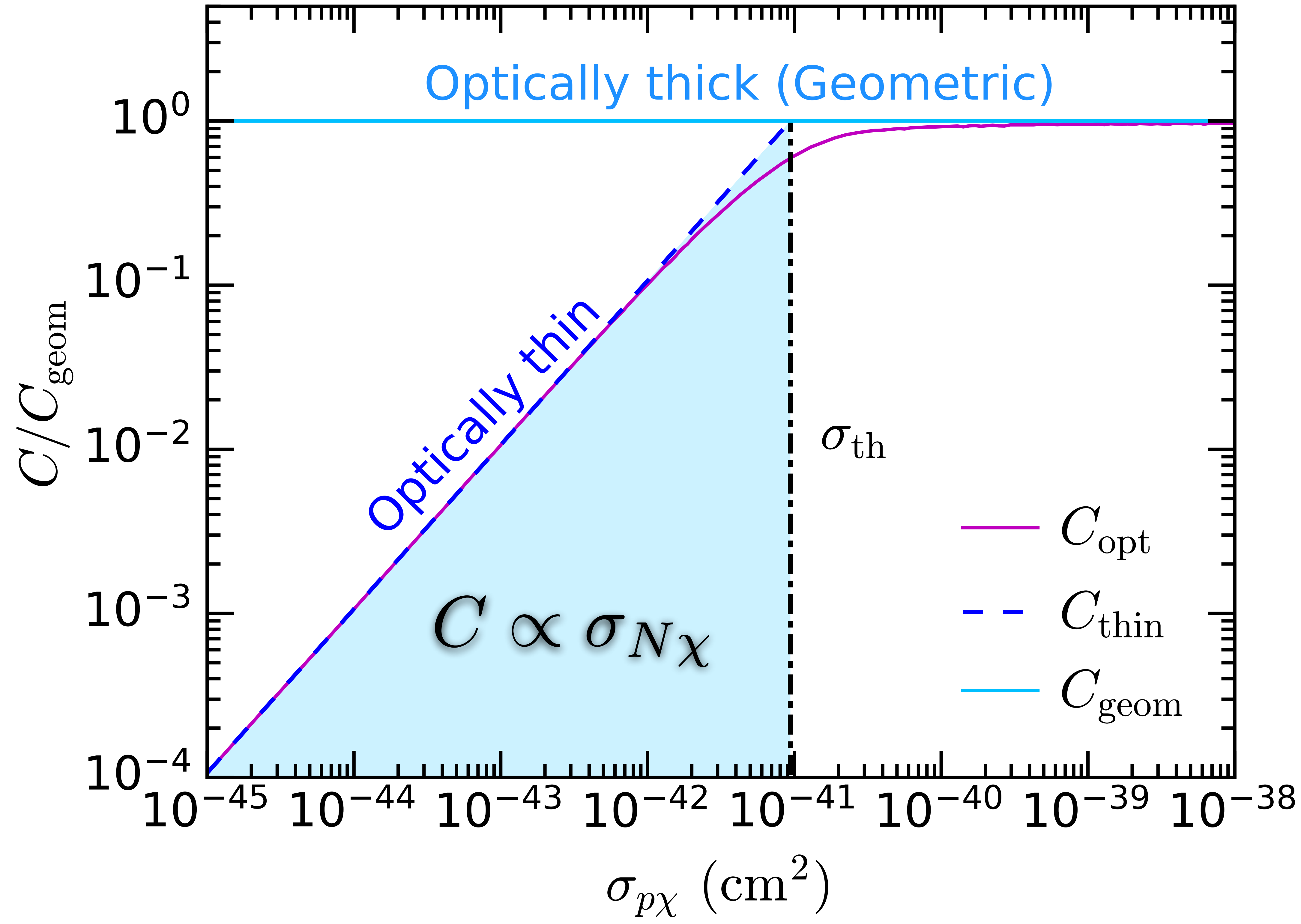
The region we are usually interested in

Depends on the particular star/planet

Examples

- White Dwarf

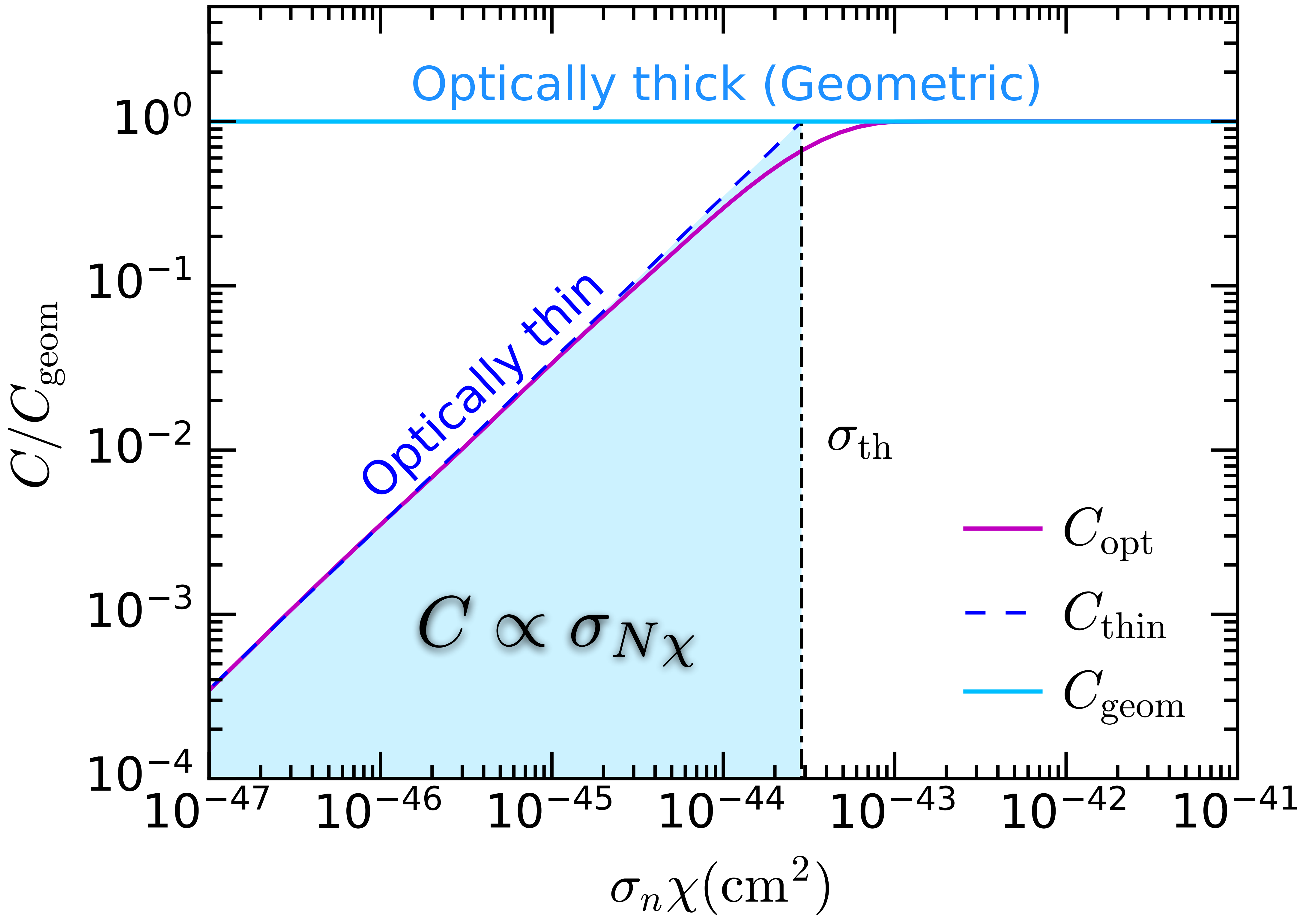
$R_\star = 5377\,\mathrm{km}$



Bell, Busoni, SR & Virgato, arXiv: 2404.16272 (JCAP)

- Neutron Star

$R_\star = 13\,\mathrm{km}$

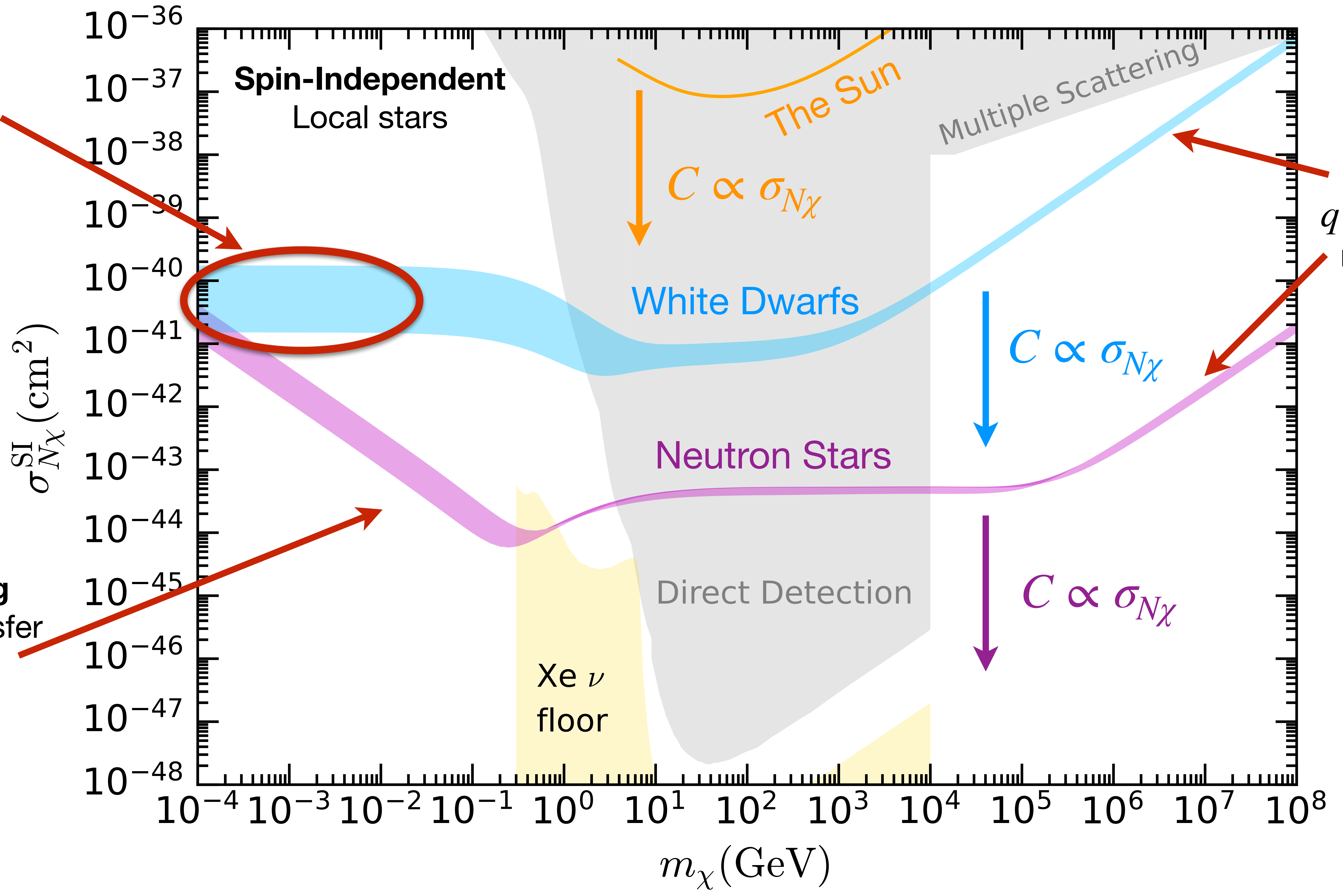


SR, Vatsyayan and Busoni, arXiv: 2507.22881

Geometric DM-nucleon cross section

WDs
Evaporation
Finite Temp
Corrections

Pauli blocking
Momentum transfer
> neutron k_F



Multiple Scattering
q transfer in single collision
not sufficient for capture

DM Capture in Celestial Bodies

Geometric Limit

- Stars and white dwarfs

$$C_{\rm geom} = \frac{\pi R_\star^2 \rho_\chi}{m_\chi} \int_0^{u_\chi^{\rm max}} \frac{u_\chi^2 + v_{\rm esc}^2(R_\star)}{u_\chi} f(u_\chi, v_\star) du_\chi$$

DM escape velocity from the Galaxy

DM relative velocity distribution

- Usual choice
  - Maxwell-Boltzmann
  - Works well only in the local bubble
- Inner regions

Lopes et al., arXiv:2007.15927

- Neutron Stars

$$C_{\rm geom} = \frac{\pi R_\star^2 \rho_\chi}{m_\chi (1 - 2GM_\star/R_\star)} \int_0^{u_\chi^{\rm max}} \frac{u_\chi^2 + v_{\rm esc}^2(R_\star)}{u_\chi} f(u_\chi, v_\star) du_\chi$$

GR correction

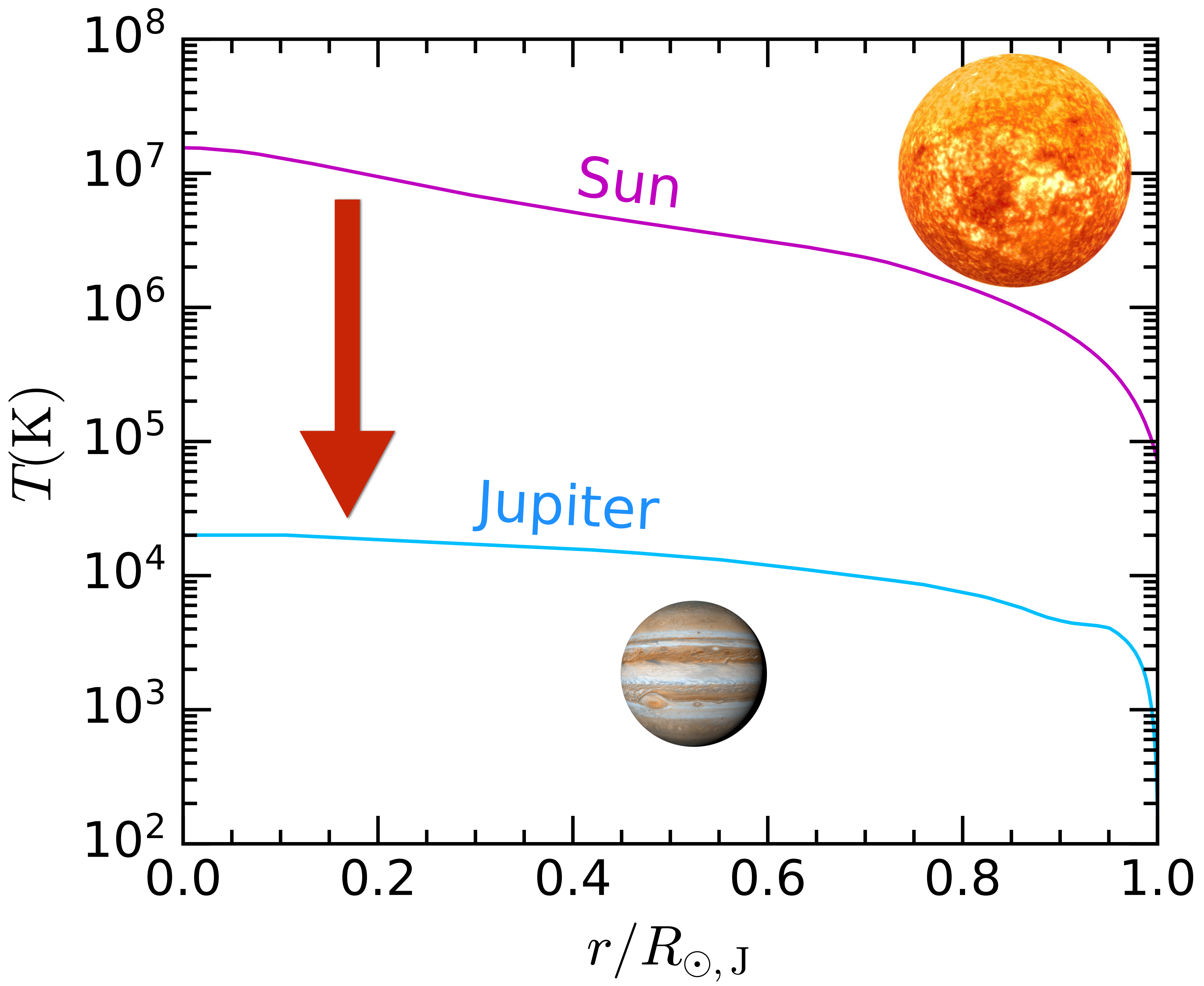
DM Capture in Celestial Bodies

Observable signatures

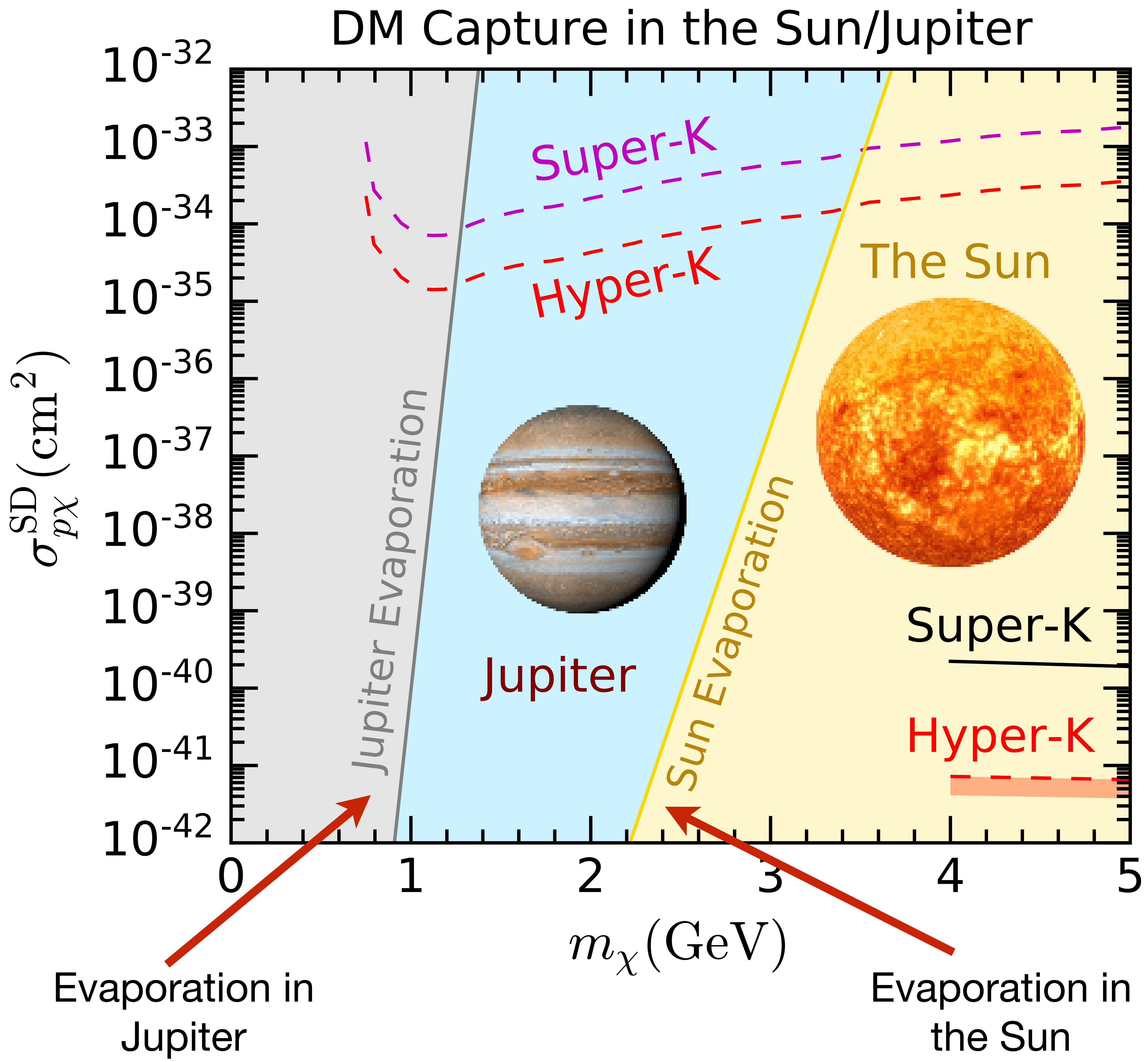
- Annihilating DM
  - ➡ Byproducts of annihilation that escape the star
  - ➡ $\chi\chi \rightarrow \nu\bar{\nu}$ Neutrino experiments & telescopes
  - ➡ $\chi\chi \rightarrow \phi\phi \rightarrow \gamma\gamma\gamma\gamma$ Gamma ray signals
  - ➡ Increase in luminosity (heating)
- Non-annihilating DM
  - ➡ Compact star destruction via supernova or BH formation

Jupiter

- Jupiter vs the Sun
  - ➡ Much lower core temperature



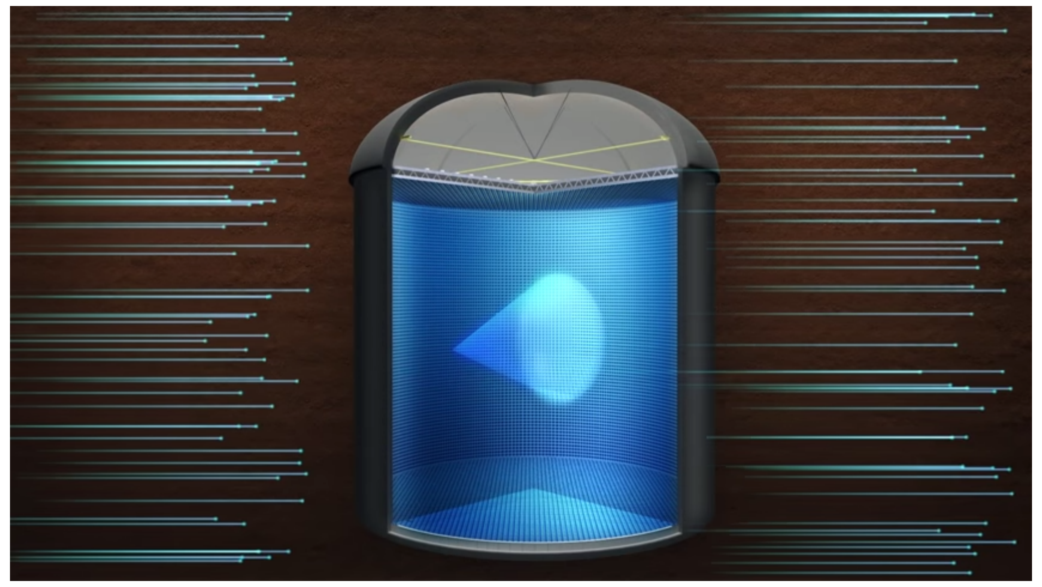
SR & Meighen-Berger, arXiv: 2411.04435 (PRD Letter)

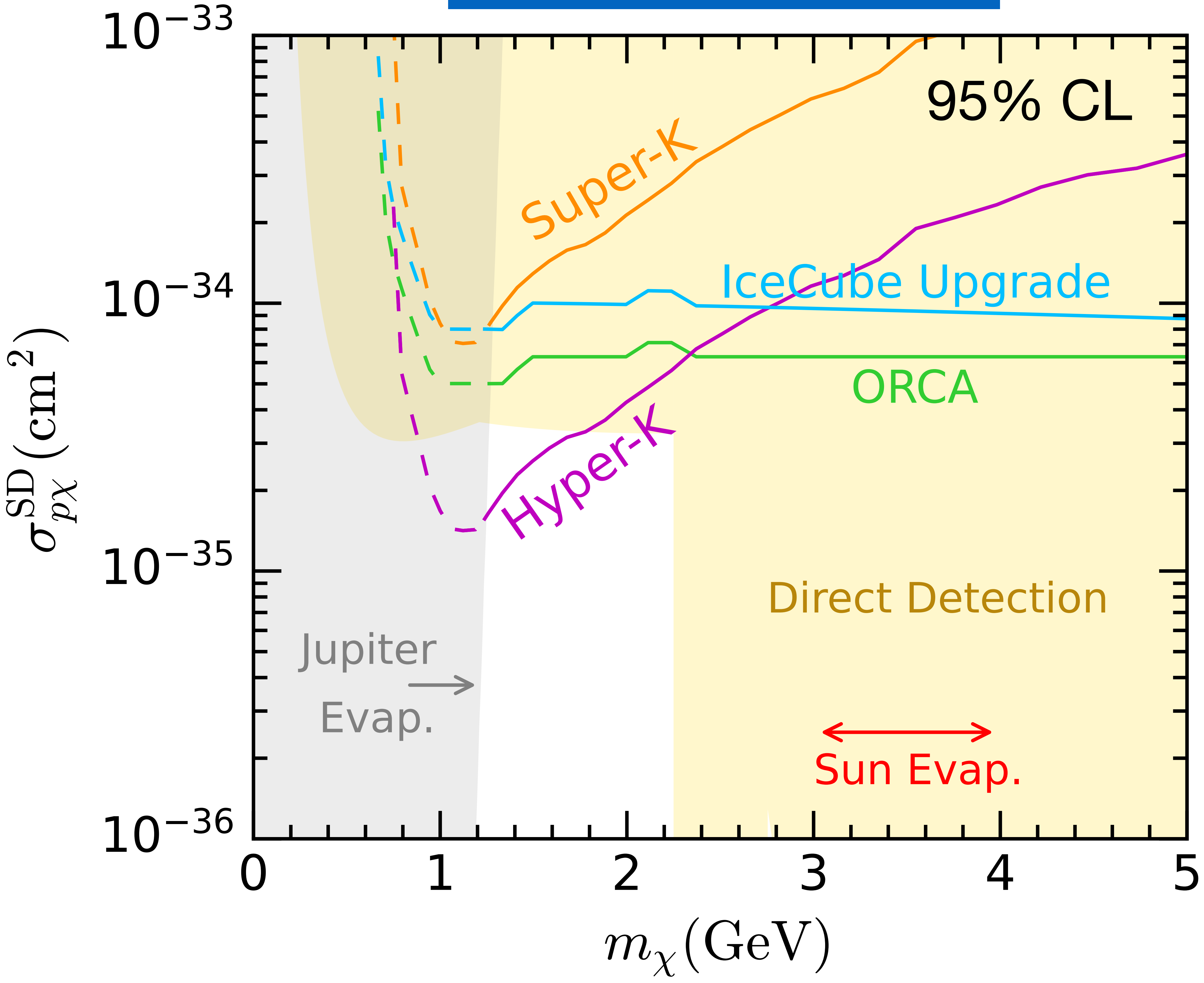


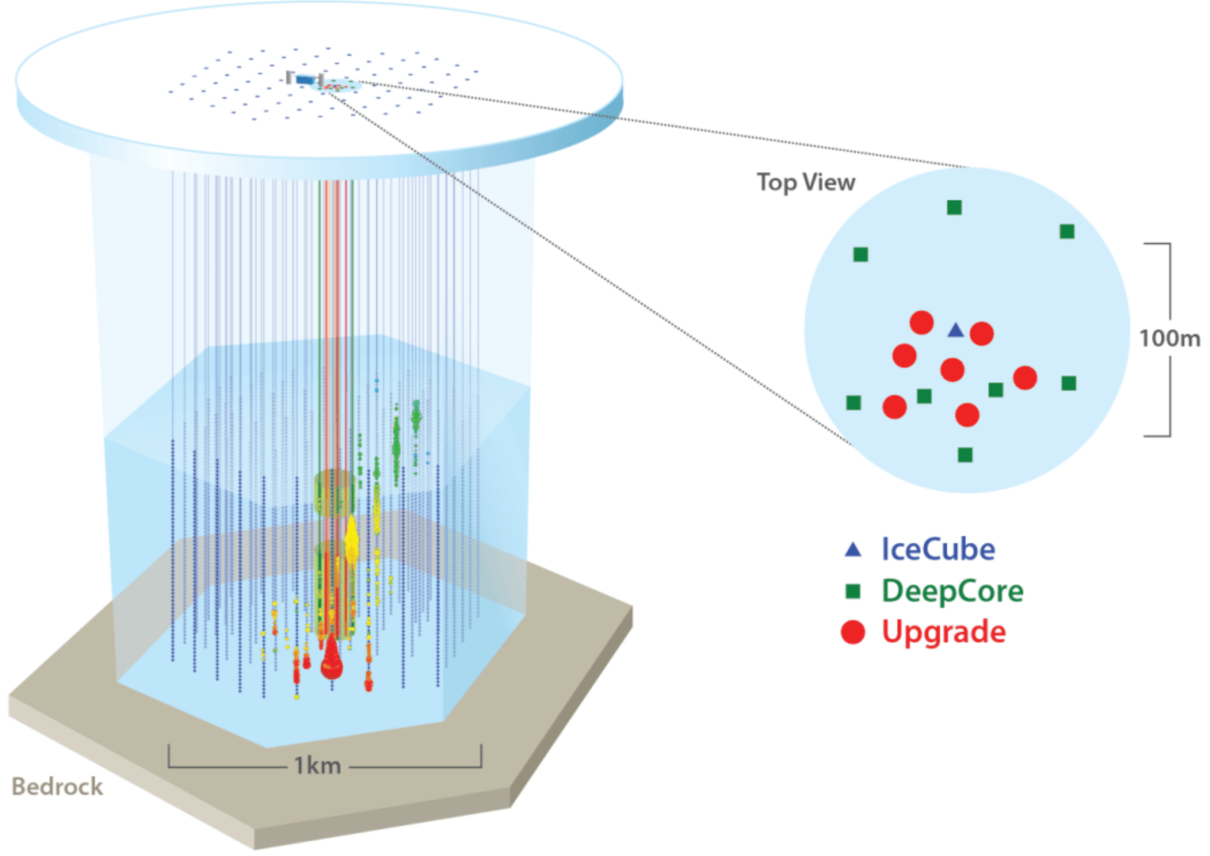
Jupiter

Neutrino Experiment Sensitivities

Super-K/Hyper-K







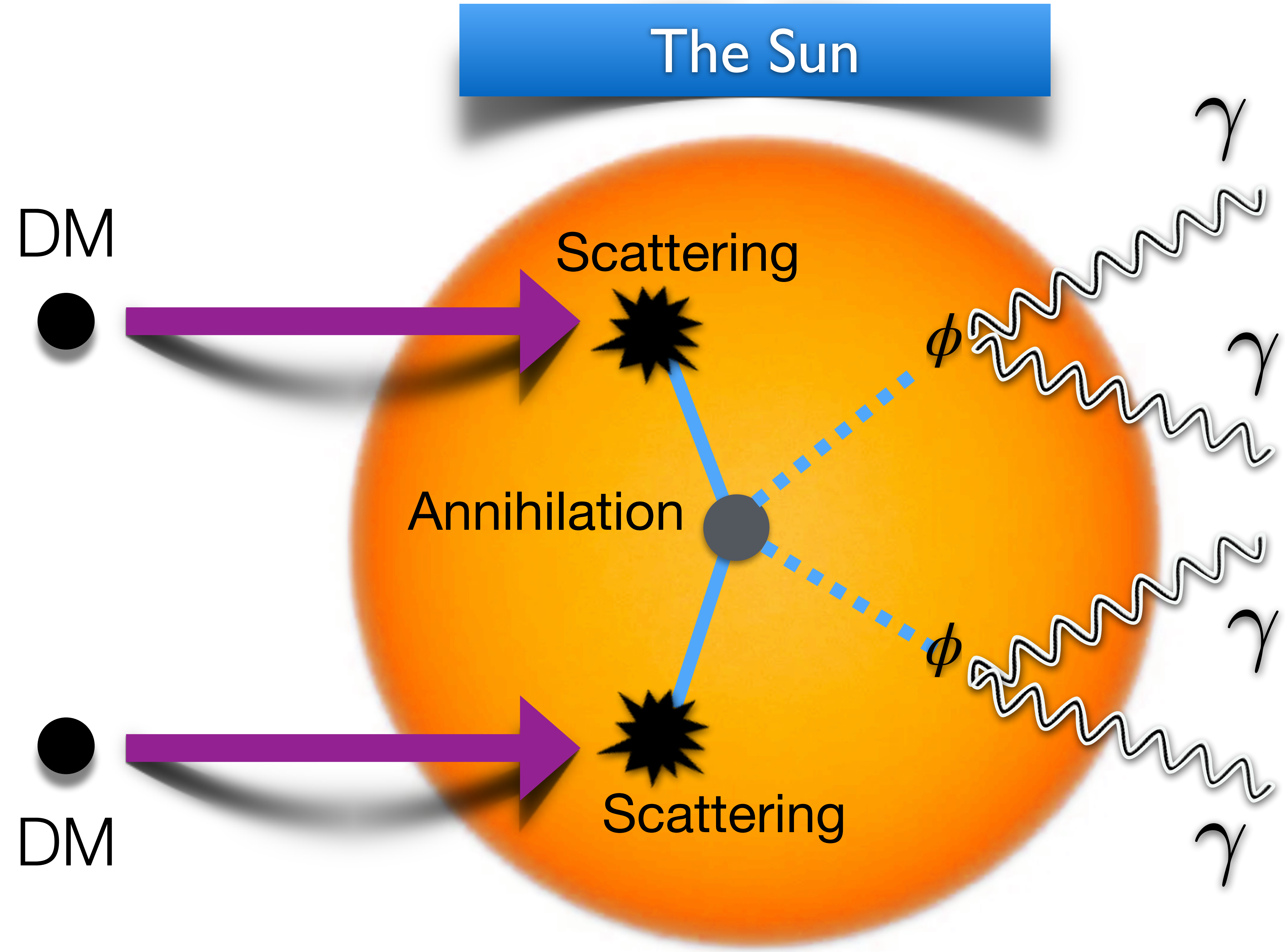
IceCube Upgrade

SR & Meighen-Berger,
arXiv: 2411.04435 (PRD Letter)

Gamma Ray Signal

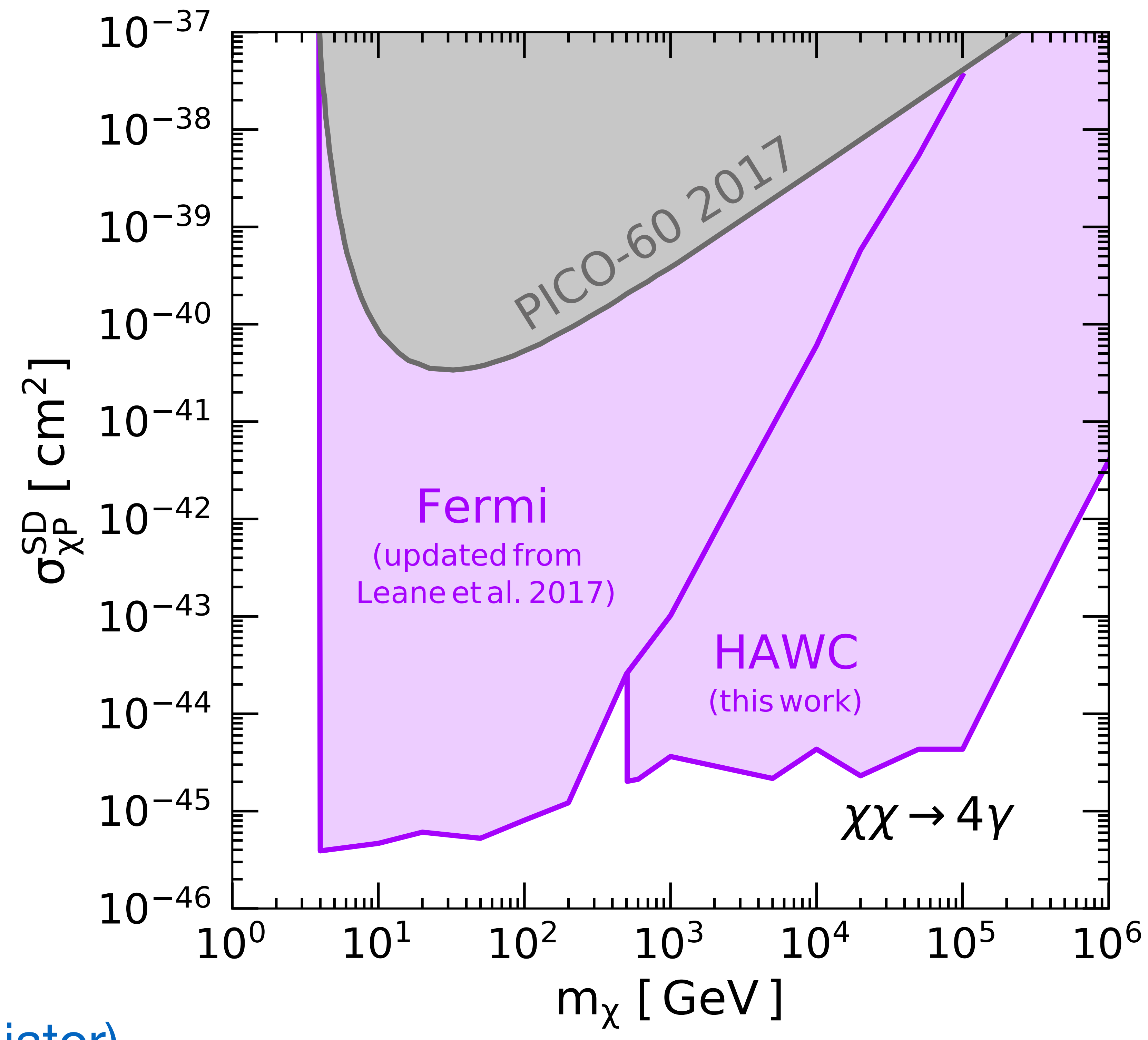
DM annihilating into long-live mediators

- Long-live mediators decay into photons outside the Sun $\chi\chi \rightarrow \phi\phi \rightarrow \gamma\gamma\gamma\gamma$



Batell et al., arXiv:0910.1567
Rothstein et al., arXiv:0903.3116

$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{\Gamma_{\rm ann}}{4\,\pi\,D_\odot^2}\left(\frac{dN_\gamma}{dE_\gamma}\right) P_{\rm surv}$$

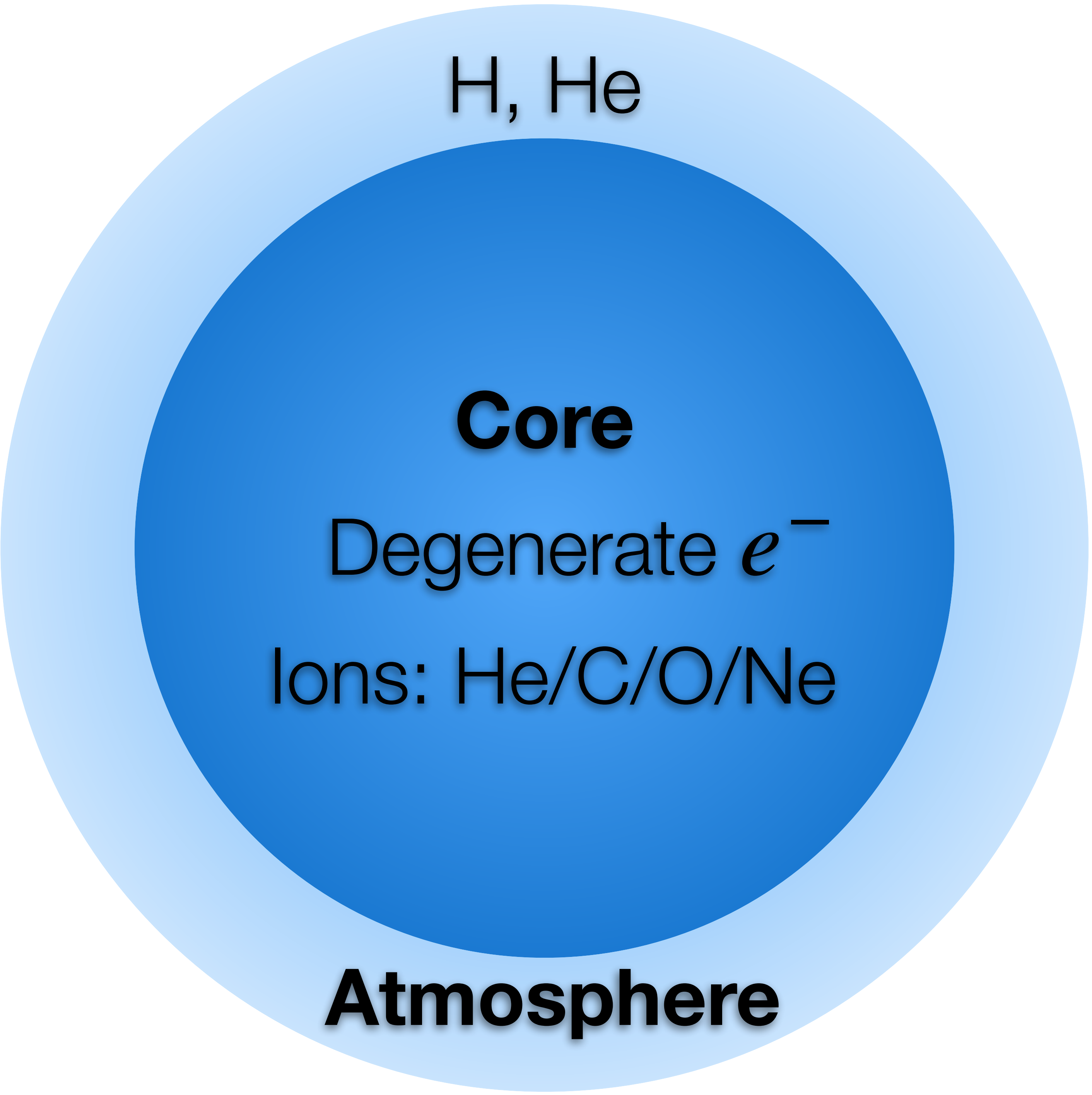


Leane et al., arXiv:1703.04629
HAWC Collab., arXiv:1808.05624
Bell et al., arXiv:2103.16794 (dark photon mediator)

Compact Stars

White Dwarfs

- $\gtrsim$ 90% of the stars in the Galaxy are WDs.
- Supported against collapse by electron degeneracy pressure.



Neutron Stars

- The densest stars known.
- Supported against collapse by neutron degeneracy pressure.

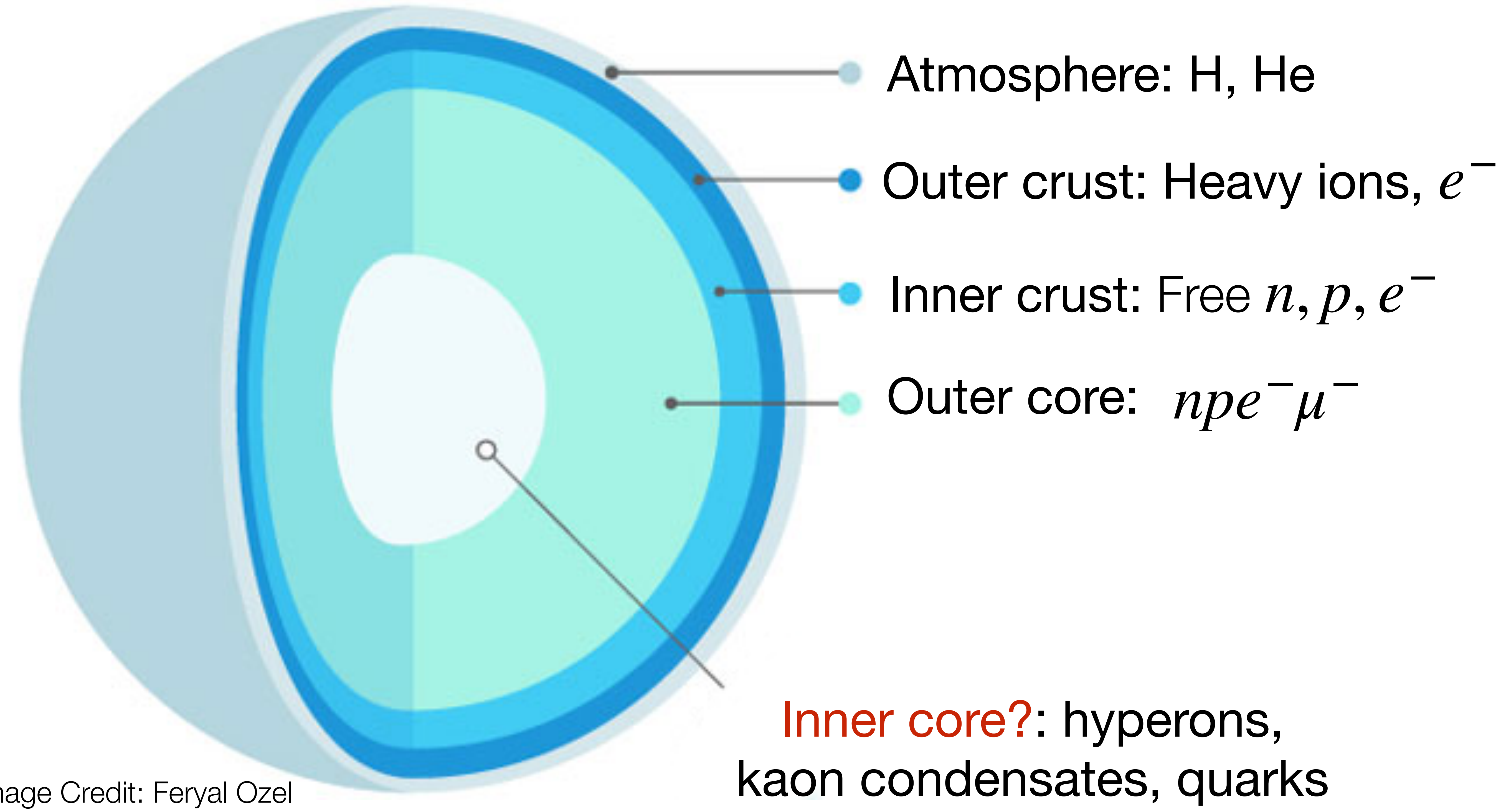
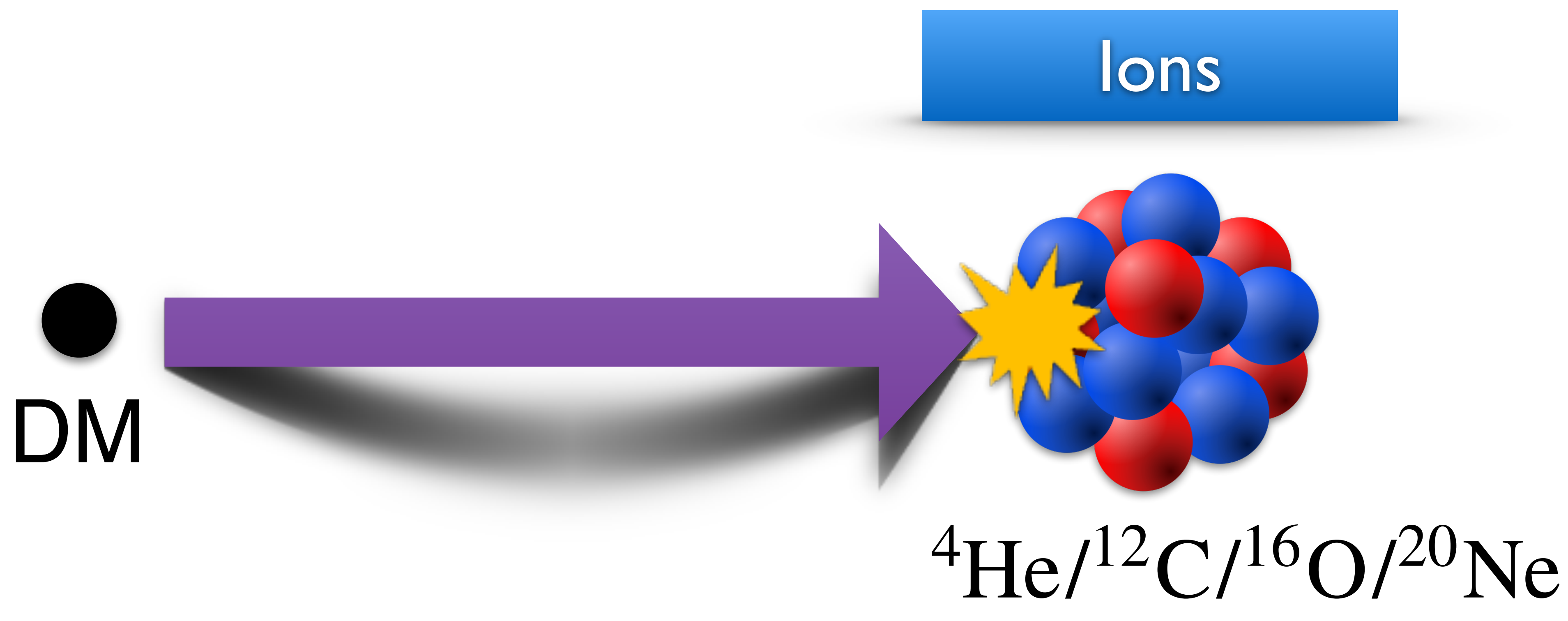
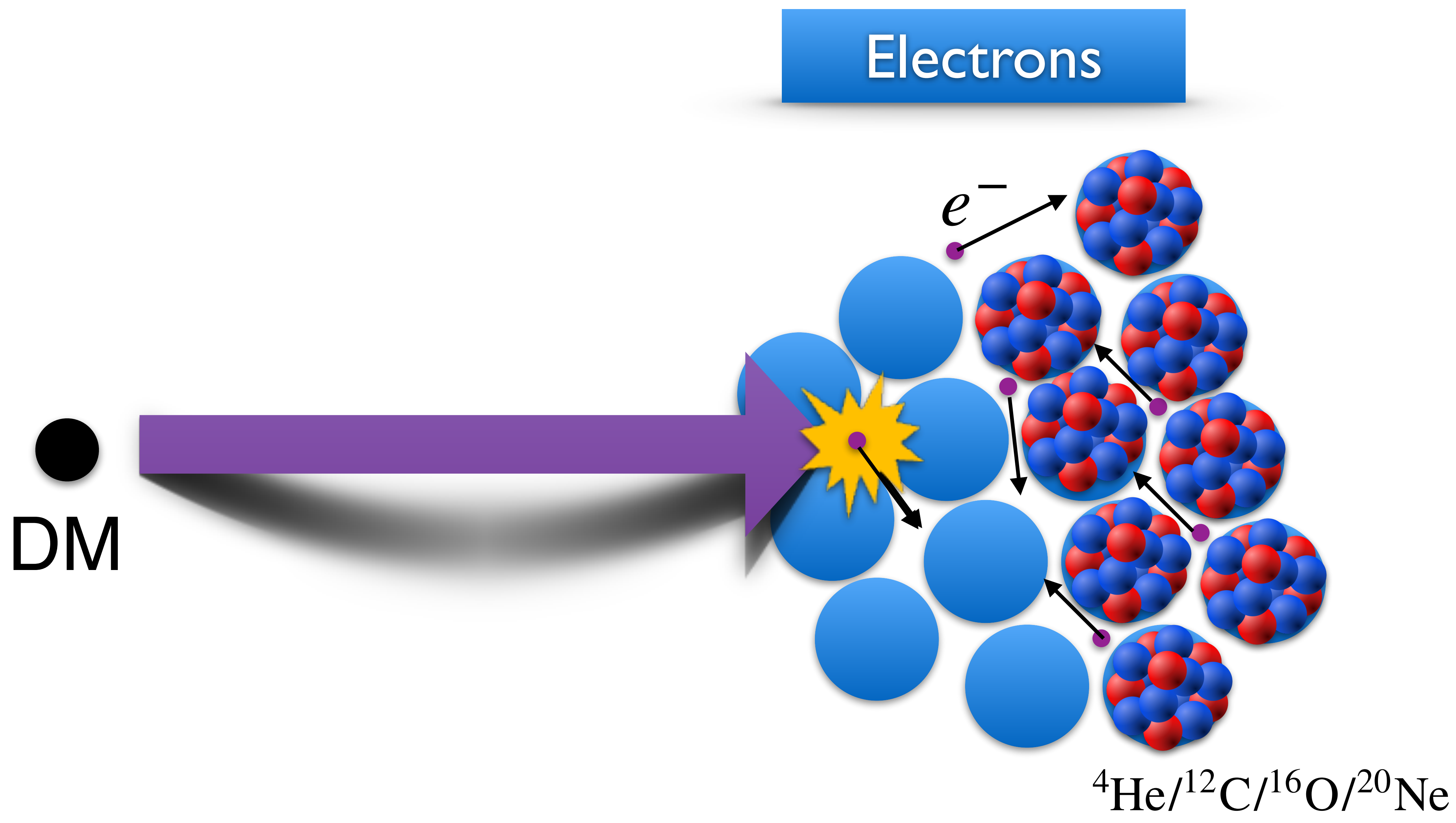


Image Credit: Feryal Ozel

DM capture in White Dwarfs





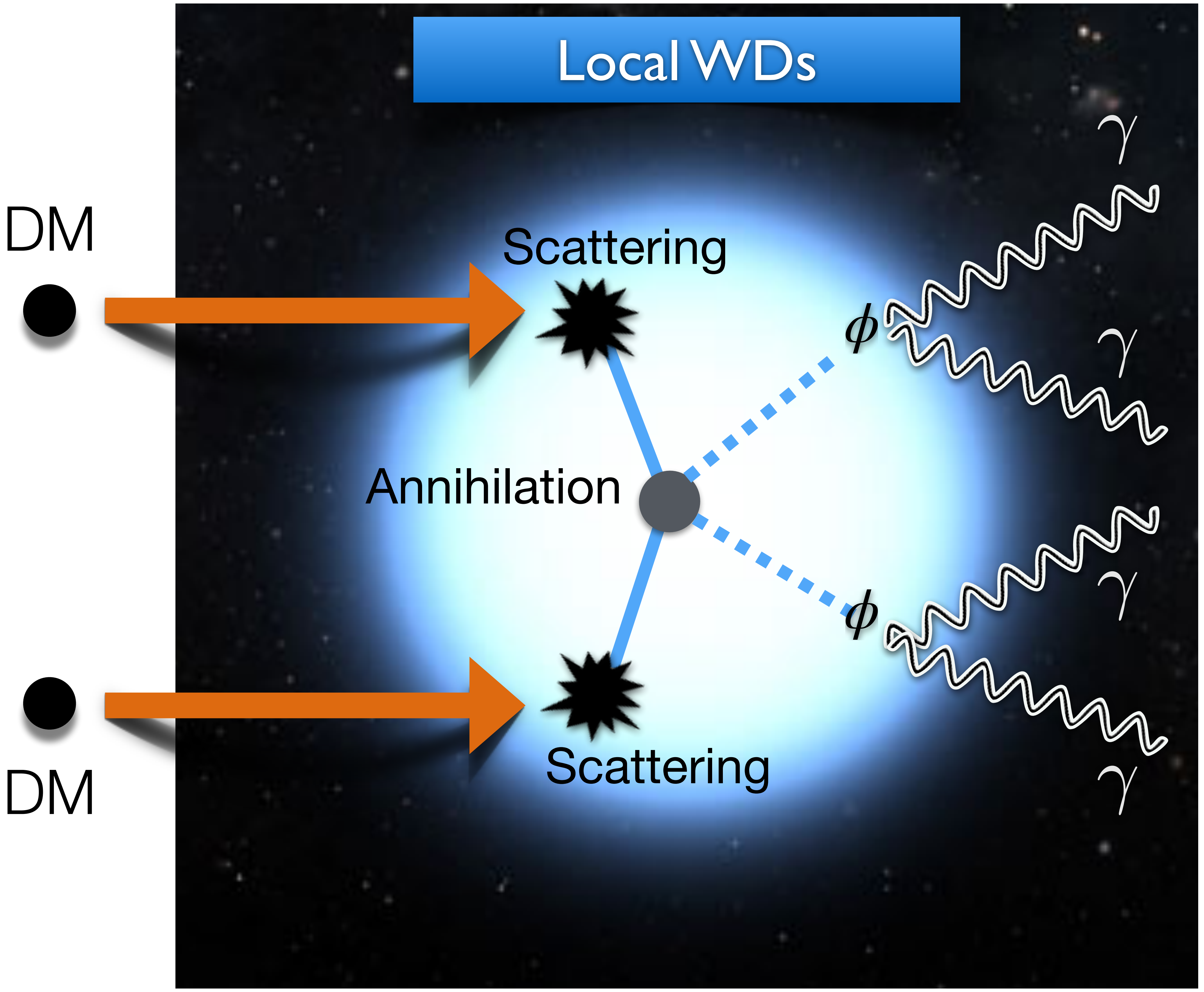
Targets

- Ions
  - ➡ Non-relativistic
  - ➡ Nuclear form factors
  - ➡ SI interactions
  - ➡ C calculated as in the Sun
- Degenerate electrons
  - ➡ Relativistic
  - ➡ Pauli blocking
  - ➡ C calculated as in neutron stars

Gamma Ray Signal

DM annihilating into long-live mediators

- Long-live mediators decay into photons outside the WD $\chi\chi \to \phi\phi \to \gamma\gamma\gamma\gamma$



- WDs within 13 pc from the Sun

  Limbach et al., arXiv:2209.12914

- CTA, LHAASO, SWGO

$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{\Gamma_{\rm ann}}{4\,\pi\, d_{\rm WD}^2}\left(\frac{dN_\gamma}{dE_\gamma}\right)$$

Batell et al., arXiv:0910.1567
Rothstein et al., arXiv: 0903.3116

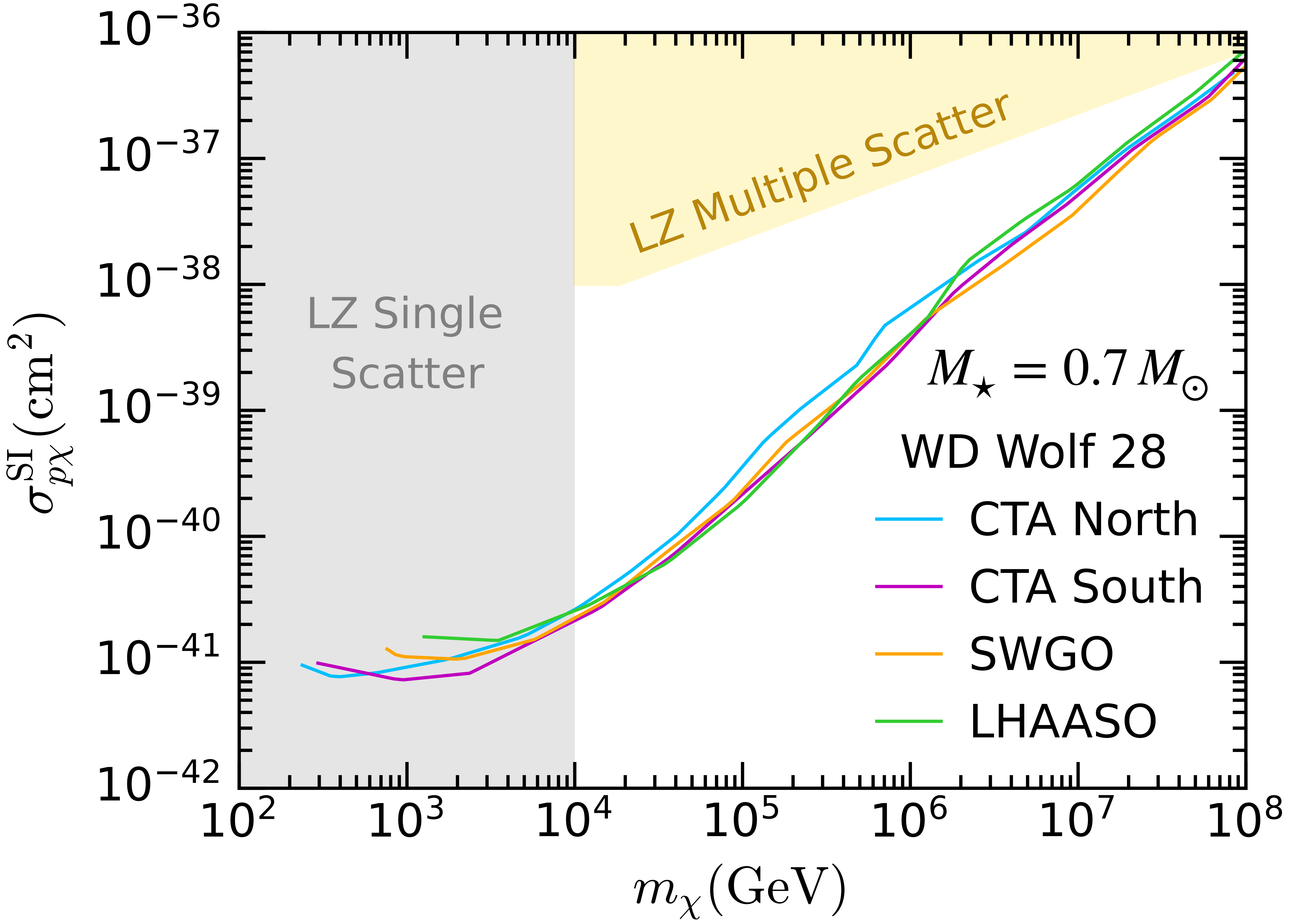
$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = \frac{4\Theta(E - E_-)\Theta(E_+ - E)}{\Delta E}$$

Bhattacharjee, SR, Meighen-Berger & Calore, arXiv: 2505.13629

Gamma Ray Signal

DM annihilating into long-live mediators

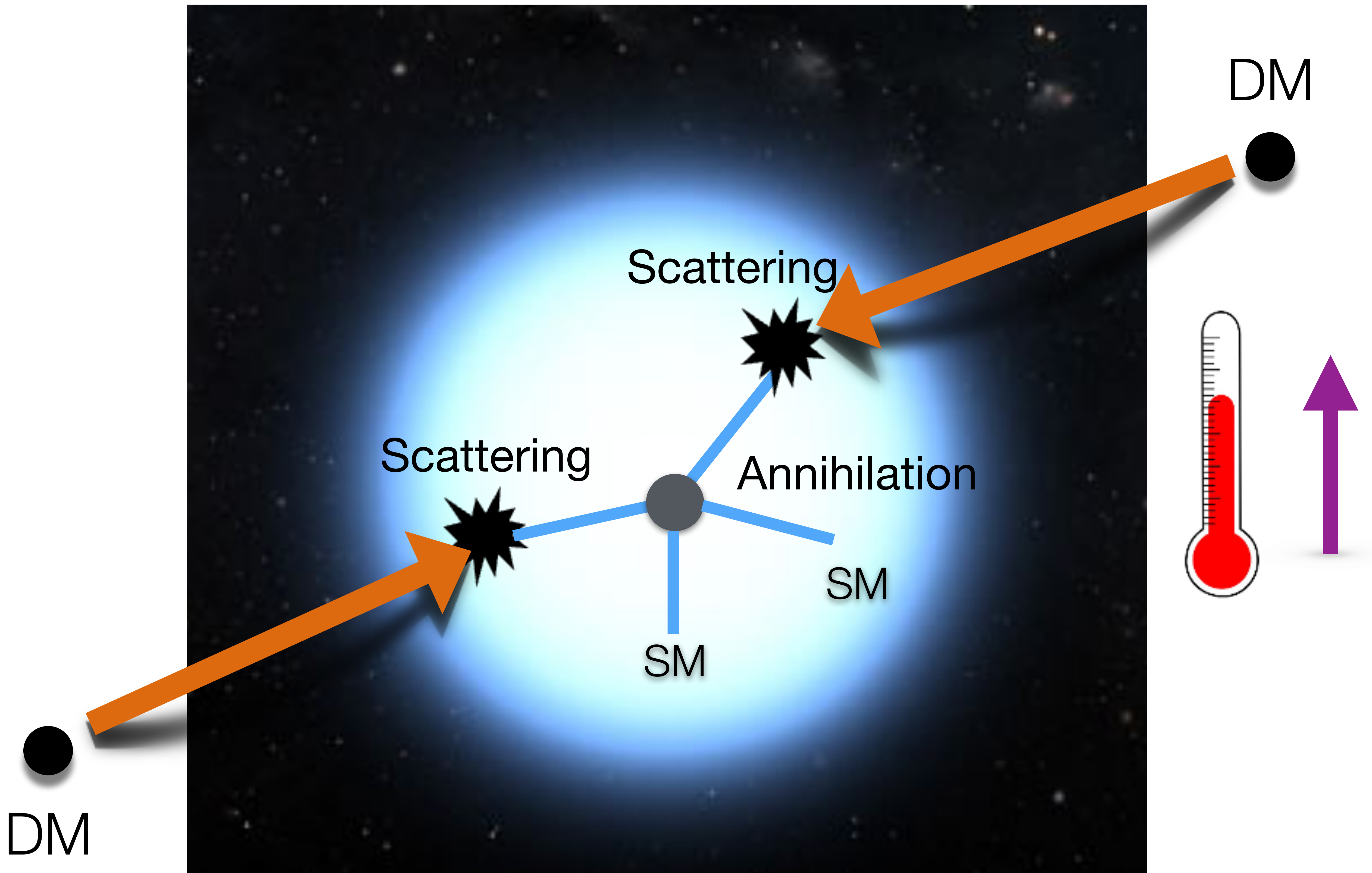
- Future gamma ray telescopes and observatories



Bhattacharjee, SR, Meighen-Berger & Calore, arXiv: 2505.13629

DM-induced heating of old Compact Stars

- Captured DM annihilates in the star's core



WDs in DM rich environments

$$\rho_\chi = \mathcal{O}(100\,\mathrm{GeV\,cm^{-3}})$$

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

NSs in the local bubble

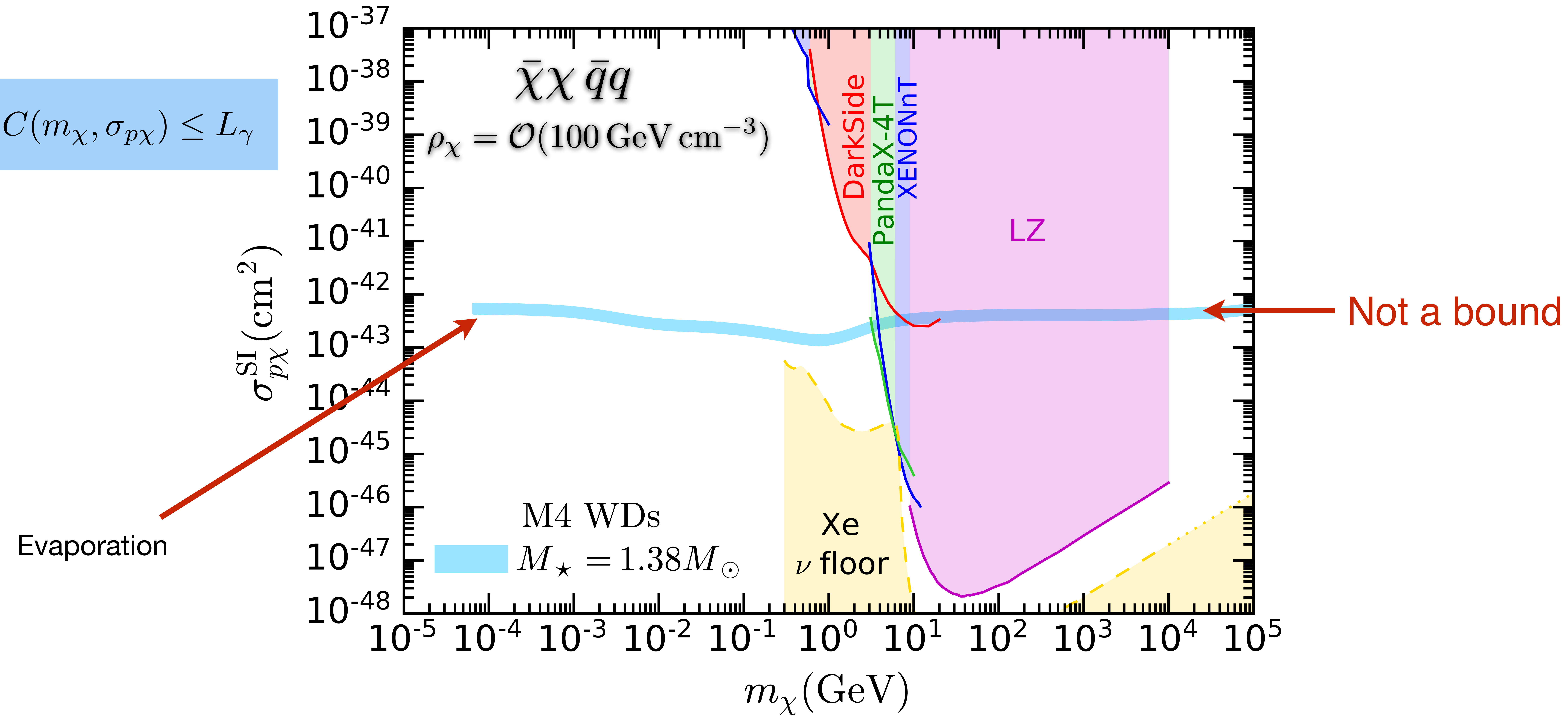
$$T_\chi^\infty \sim 2400\,\mathrm{K}$$

near IR
1 - 2 μm

Baryakhtar et al. arXiv:1704.01577 (PRL)
Chatterjee et al. arXiv: 2205.05048 (PRD Letter)

White Dwarfs in DM-rich environments

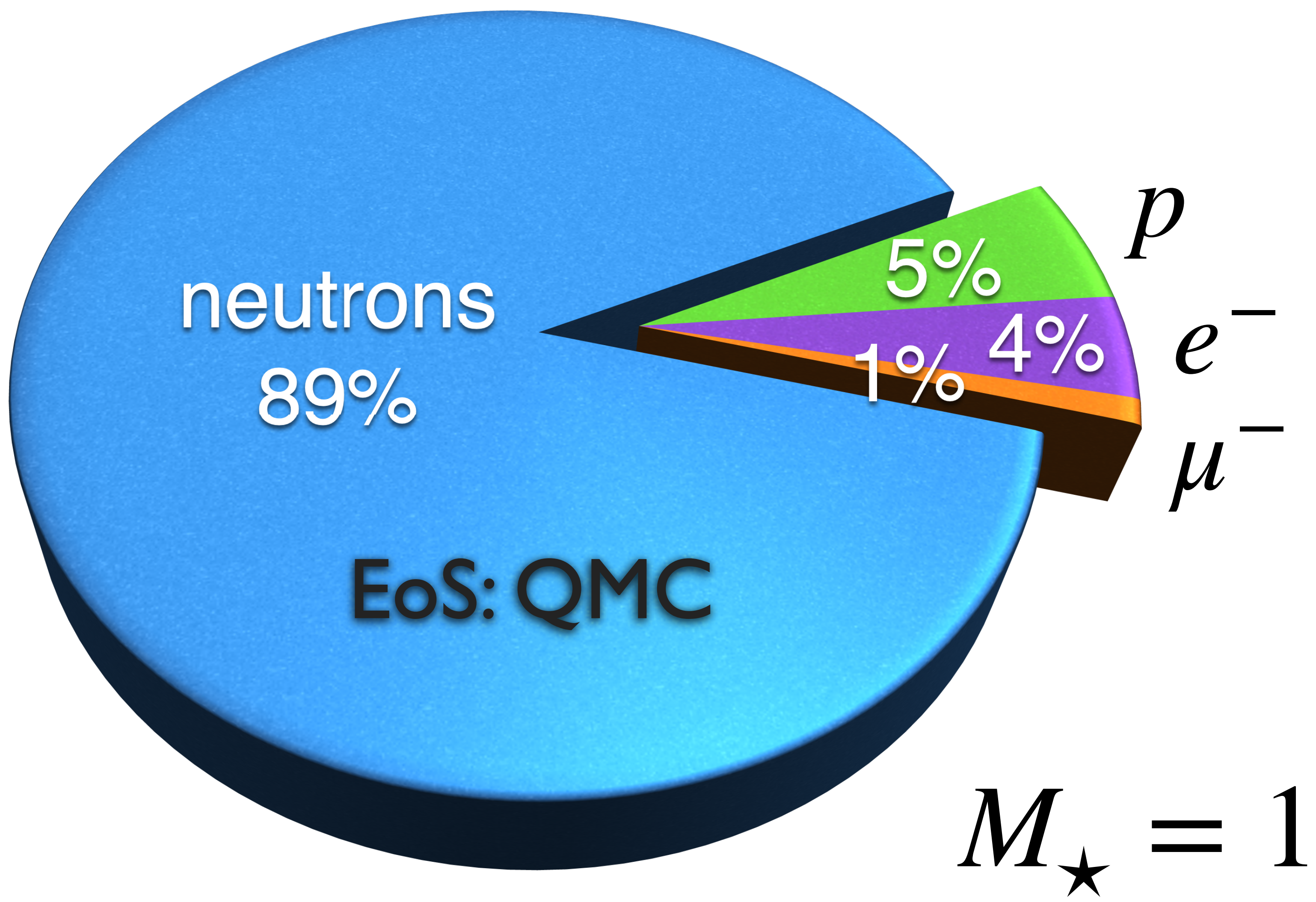
$$L_\chi = m_\chi C(m_\chi, \sigma_{p\chi}) \leq L_\gamma$$



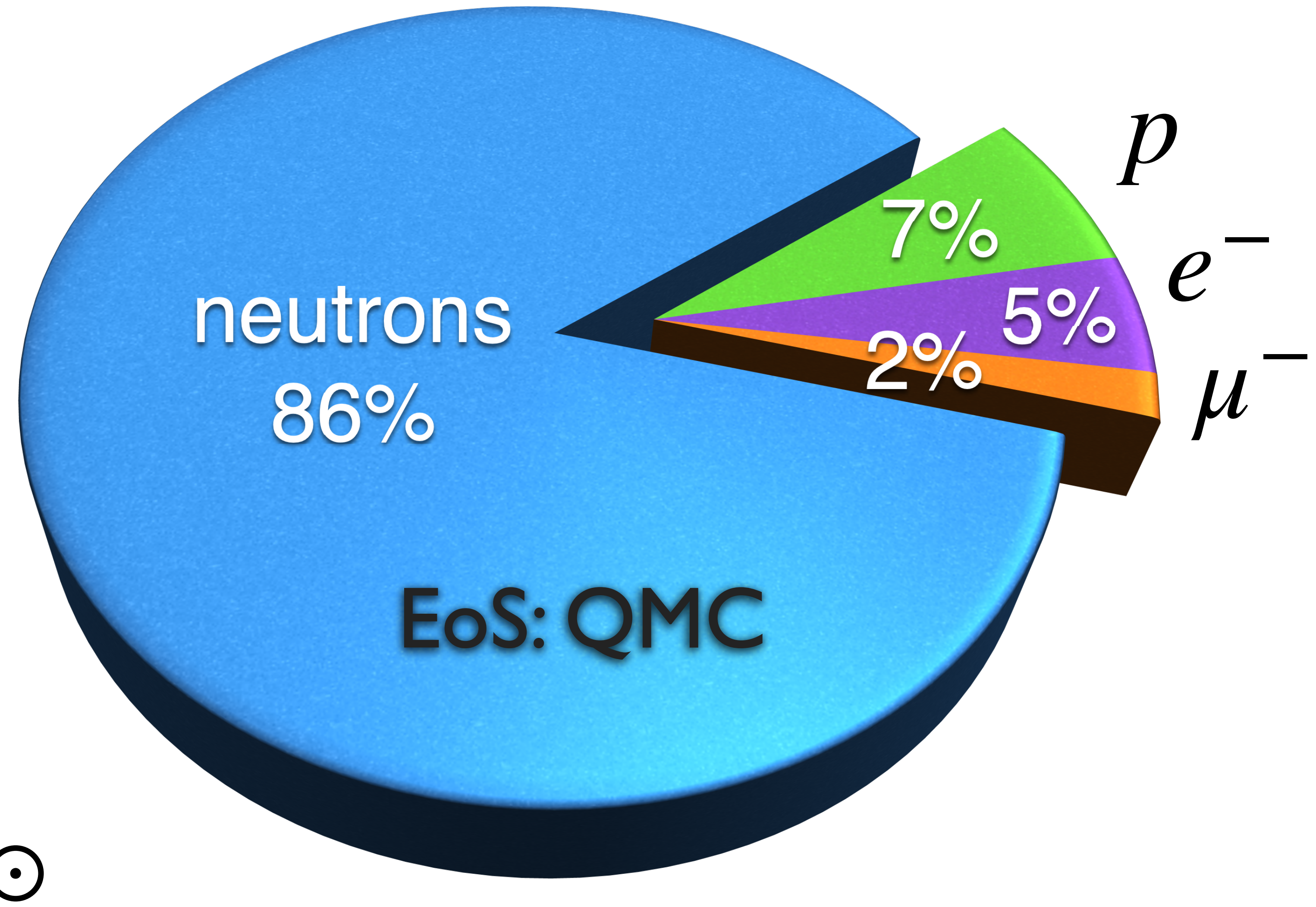
Bell, Busoni, Ramirez-Quezada, SR & Virgato, arXiv: 2104.14367 (JCAP)

DM capture in Neutron Stars

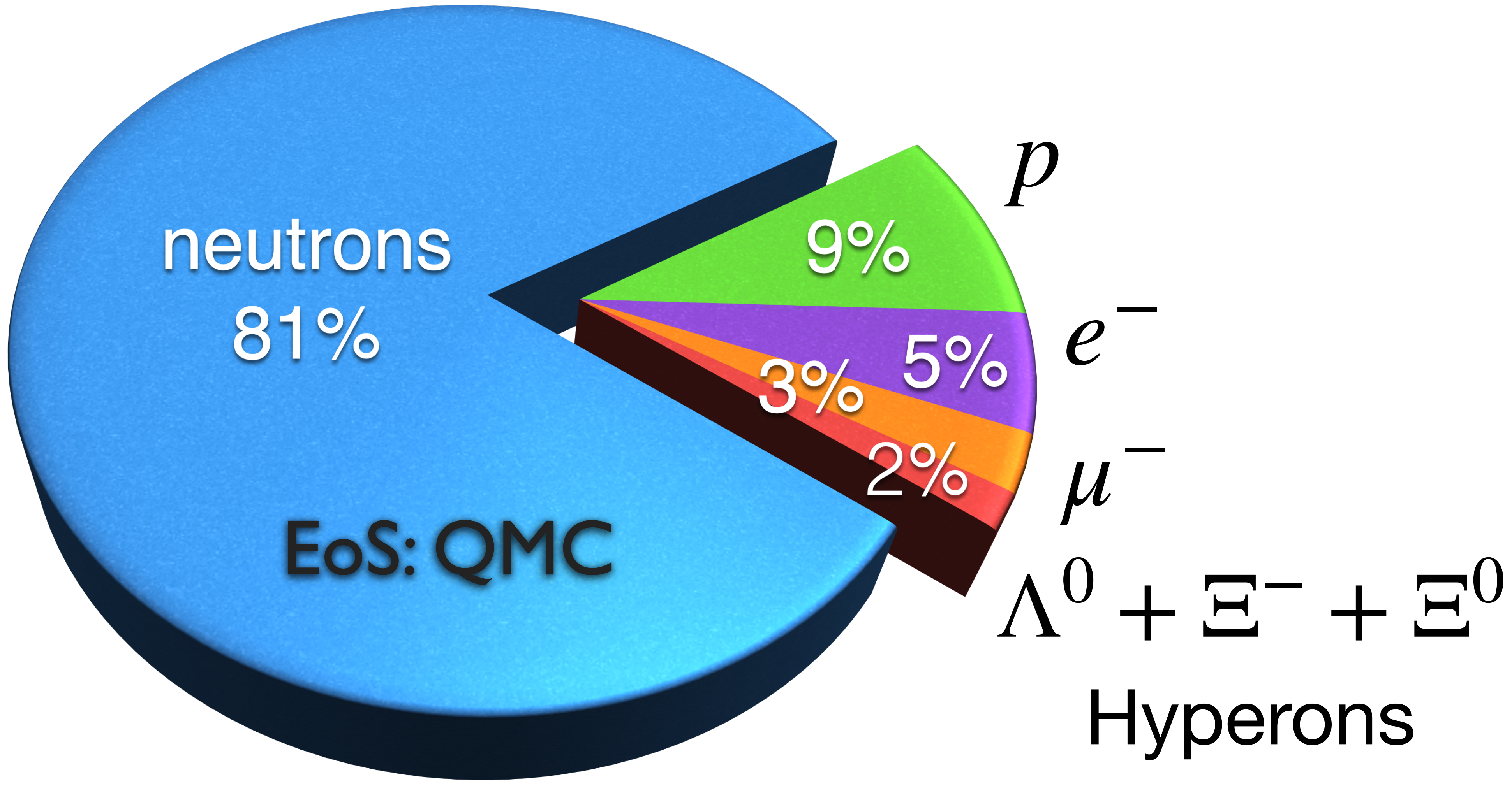
$M_\star = 1\, M_\odot$



$M_\star = 1.5\, M_\odot$



$M_\star = 1.9\, M_\odot$



Targets

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

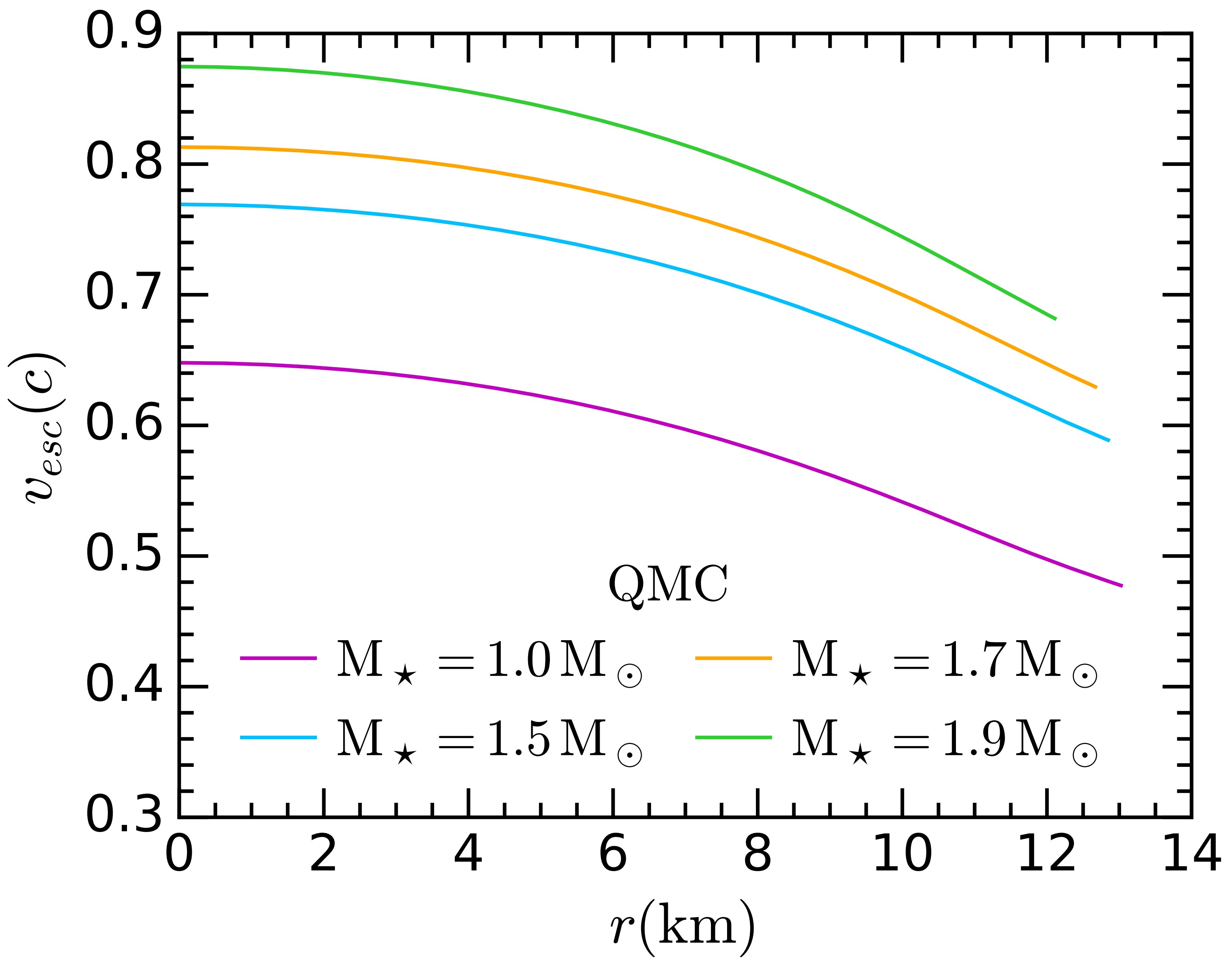
DM capture in Neutron Stars

- Different kinematic regime:
  - ➡ DM accelerated to quasi-relativistic speeds
  - ➡ Relativistic kinematics
  - ➡ GR corrections

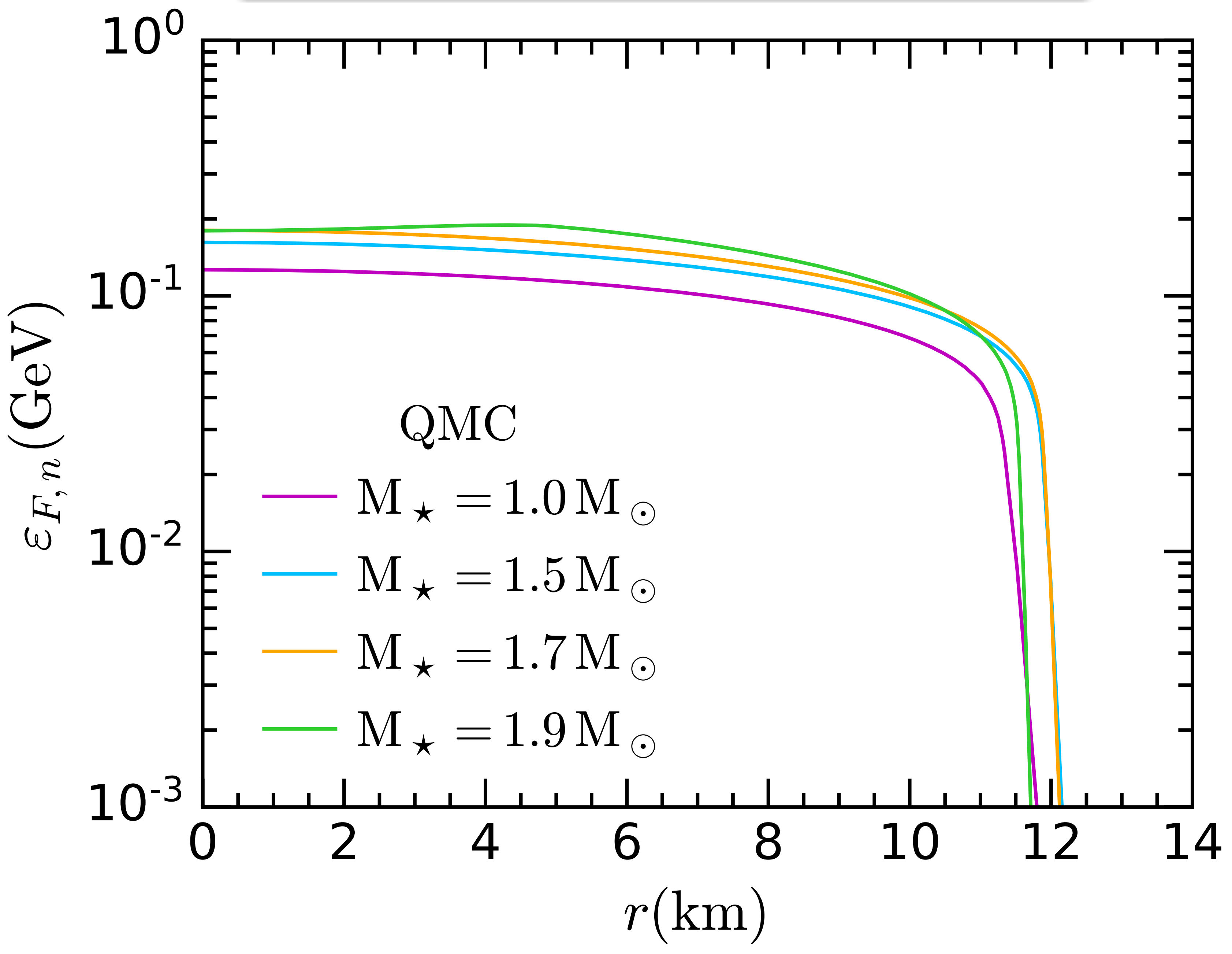
- Scattering off a sea of degenerate targets
  - ➡ Pauli blocking $m_\chi \lesssim m_n$

Bell, Busoni, SR & Virgato, arXiv: 2004.14888 (JCAP)

Escape velocity



Neutron Fermi energy



DM capture in Neutron Stars

Scattering off a Fermi gas of interacting baryons

- Two important effects missing in all previous calculations:

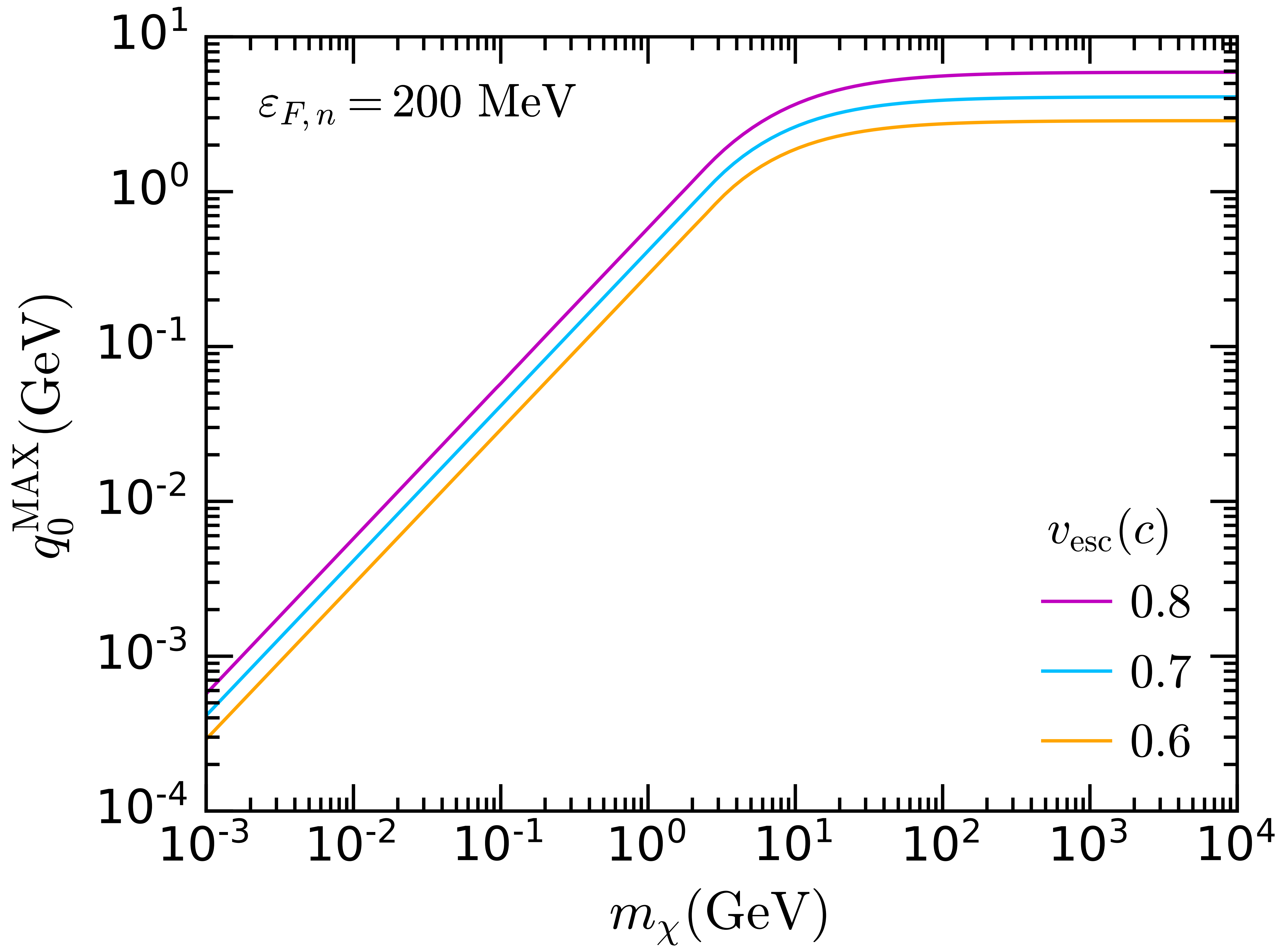
➡ Momentum transfer $\mathcal{O}(10\,\mathrm{GeV})$

➡ Momentum dependence of the hadronic matrix elements

1. Nucleon couplings

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

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



Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918 (PRL), + Anzuini arXiv: 2108.02525 (JCAP)

DM capture in Neutron Stars

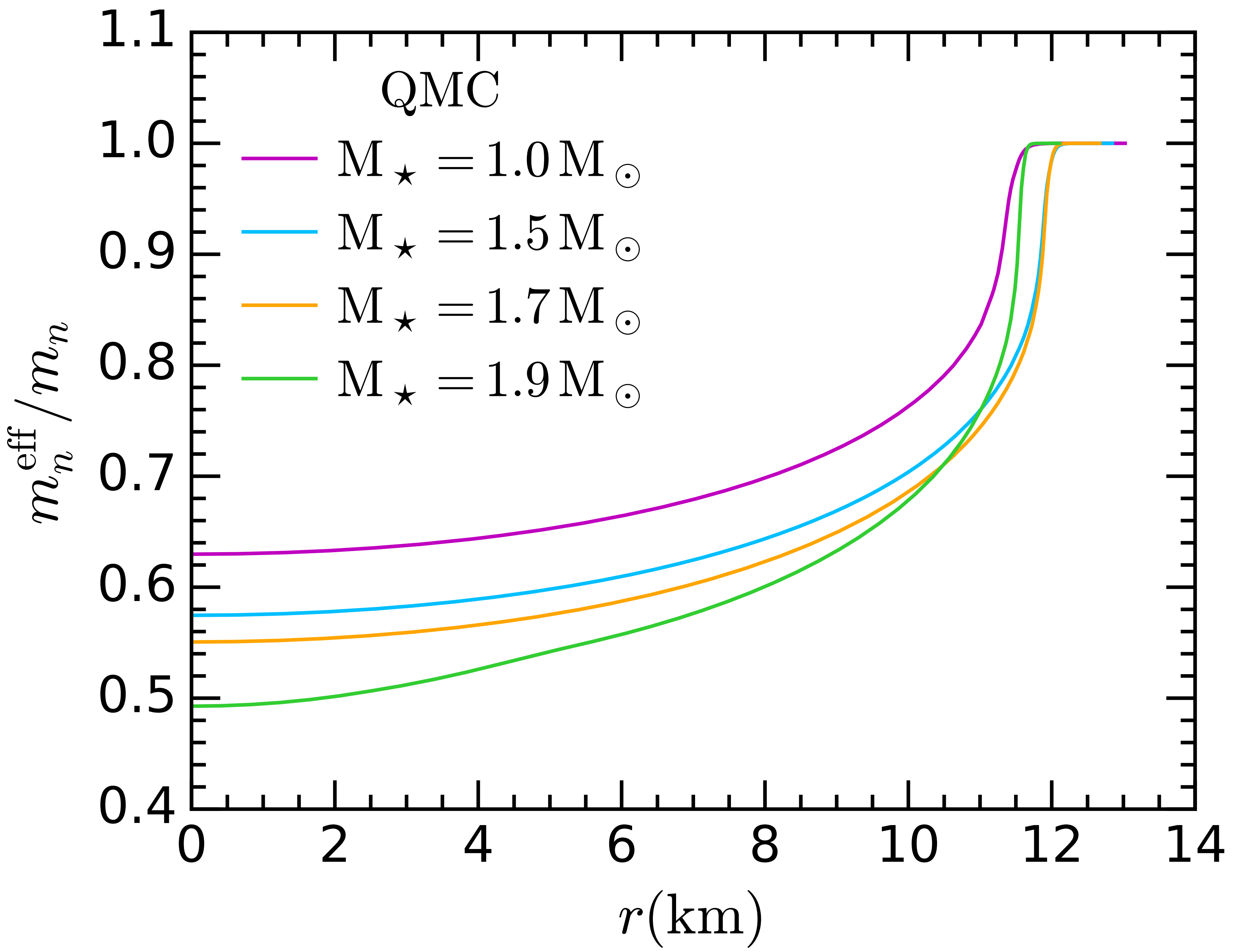
Scattering off a Fermi gas of interacting baryons

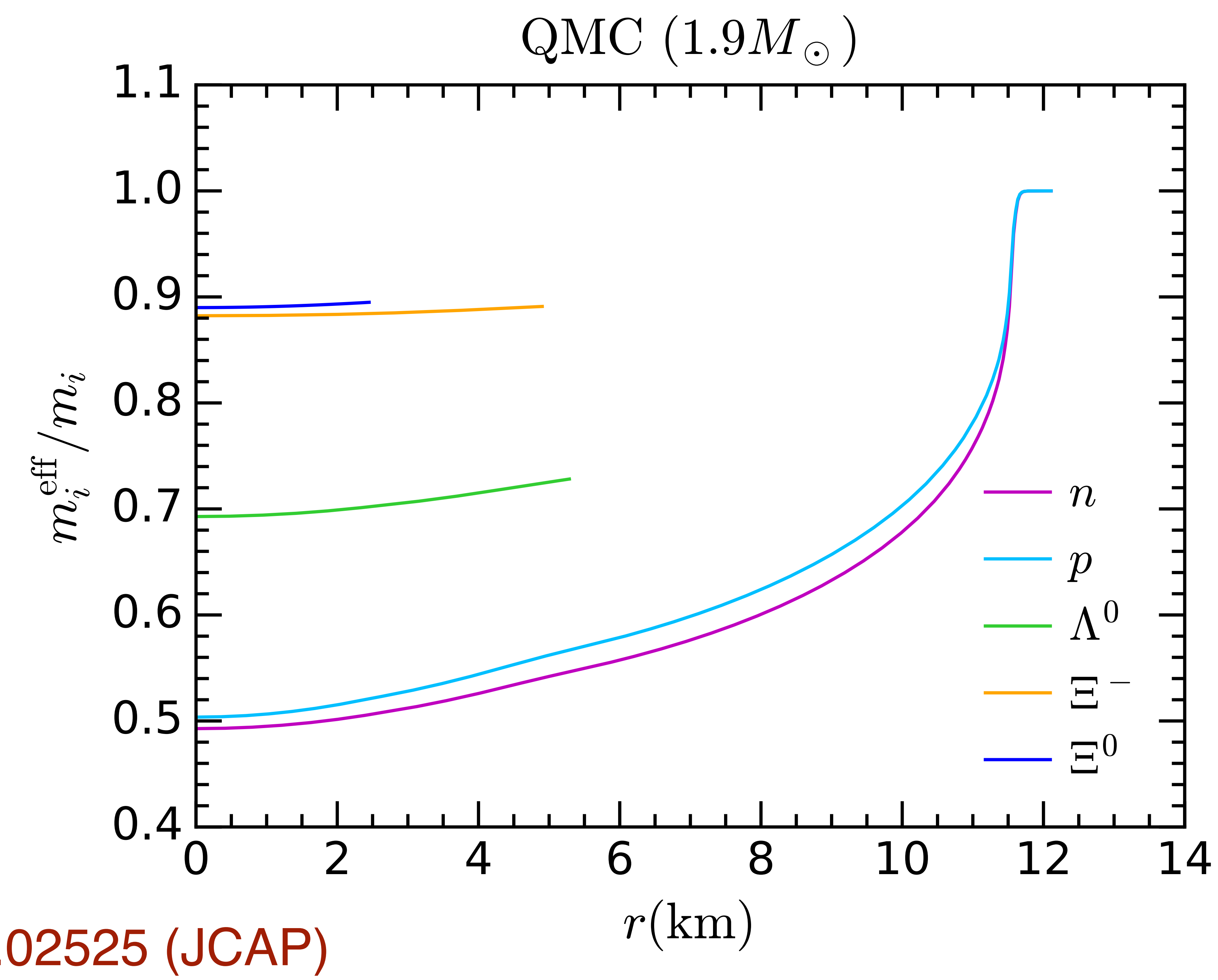
- Two important effects missing in all previous calculations:

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

2. Nucleon effective mass

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

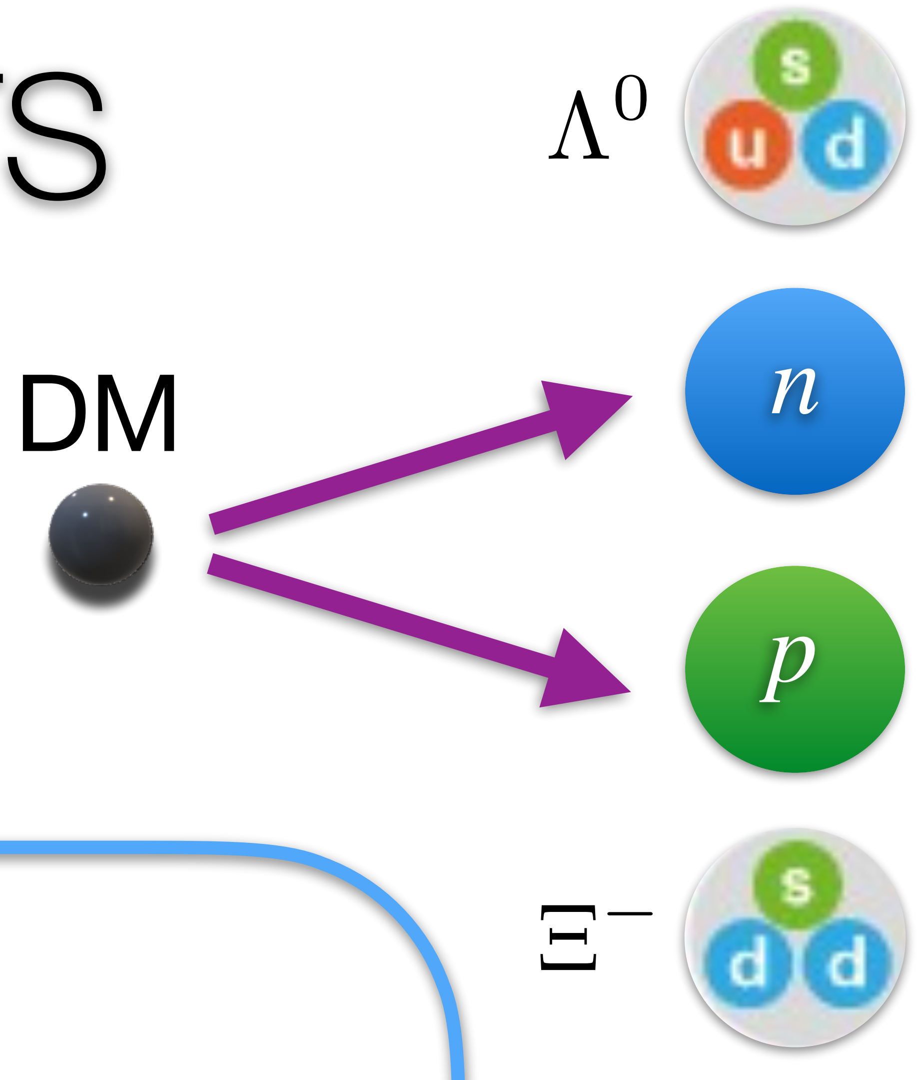




Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918 (PRL), + Anzuini arXiv: 2108.02525 (JCAP)

DM capture rate in Neutron Stars

Scattering off a Fermi gas of interacting baryons



- Capture rate derived using TOV equations and Schwarzchild metric

$$ds^2 = -d\tau^2 = -B(r)c^2dt^2 + A(r)dr^2 + r^2d\Omega^2$$

Capture rate

$B(r) \sim 1 - v_{esc}^2(r)$

$$C = \int_0^{R_\star} dr\, 4\pi r^2 \int_0^\infty du_\chi \frac{\rho_\chi}{m_\chi} \frac{f_{\rm MB}(u_\chi)}{u_\chi} \frac{\sqrt{1-B(r)}}{B(r)} \Omega^-(r)$$

Scattering rate

$$\Omega^-(r) = \frac{1}{2\pi^2} \int dt dE_i ds \frac{E_i}{m_\chi} \sqrt{\frac{B(r)}{1-B(r)}} \frac{s}{\beta(s, m_i^{\rm eff})\gamma(s, m_i^{\rm eff})} \frac{d\sigma_{i\chi}}{d\cos\theta_{cm}} f_{\rm FD}(E_i, r)(1 - f_{\rm FD}(E_i', r))$$

Relativistic kinematics

PB target initial states

Pauli Blocking target final states

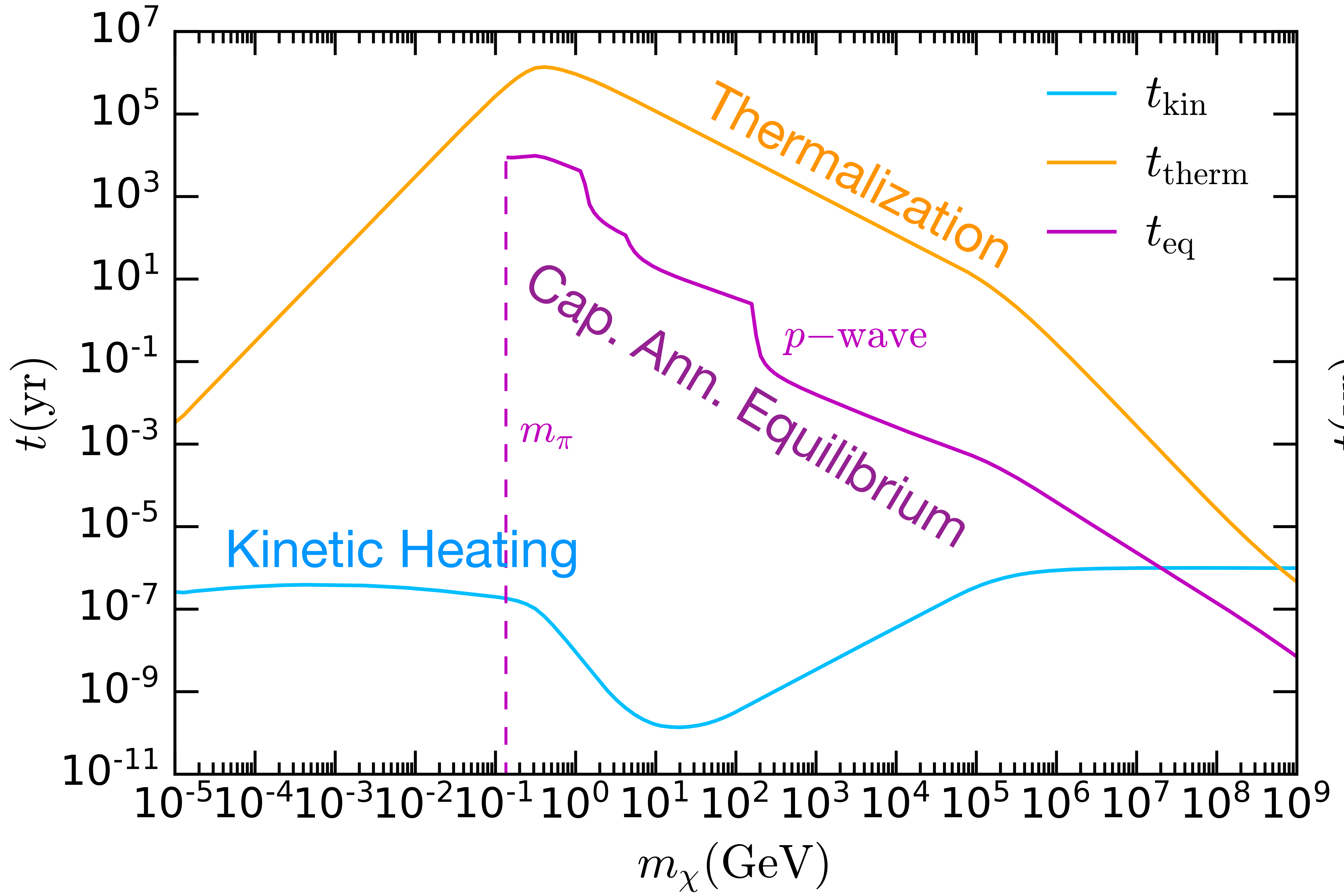
Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918 (PRL), + Anzuini arXiv: 2108.02525 (JCAP)

Timescales for DM heating of old NSs

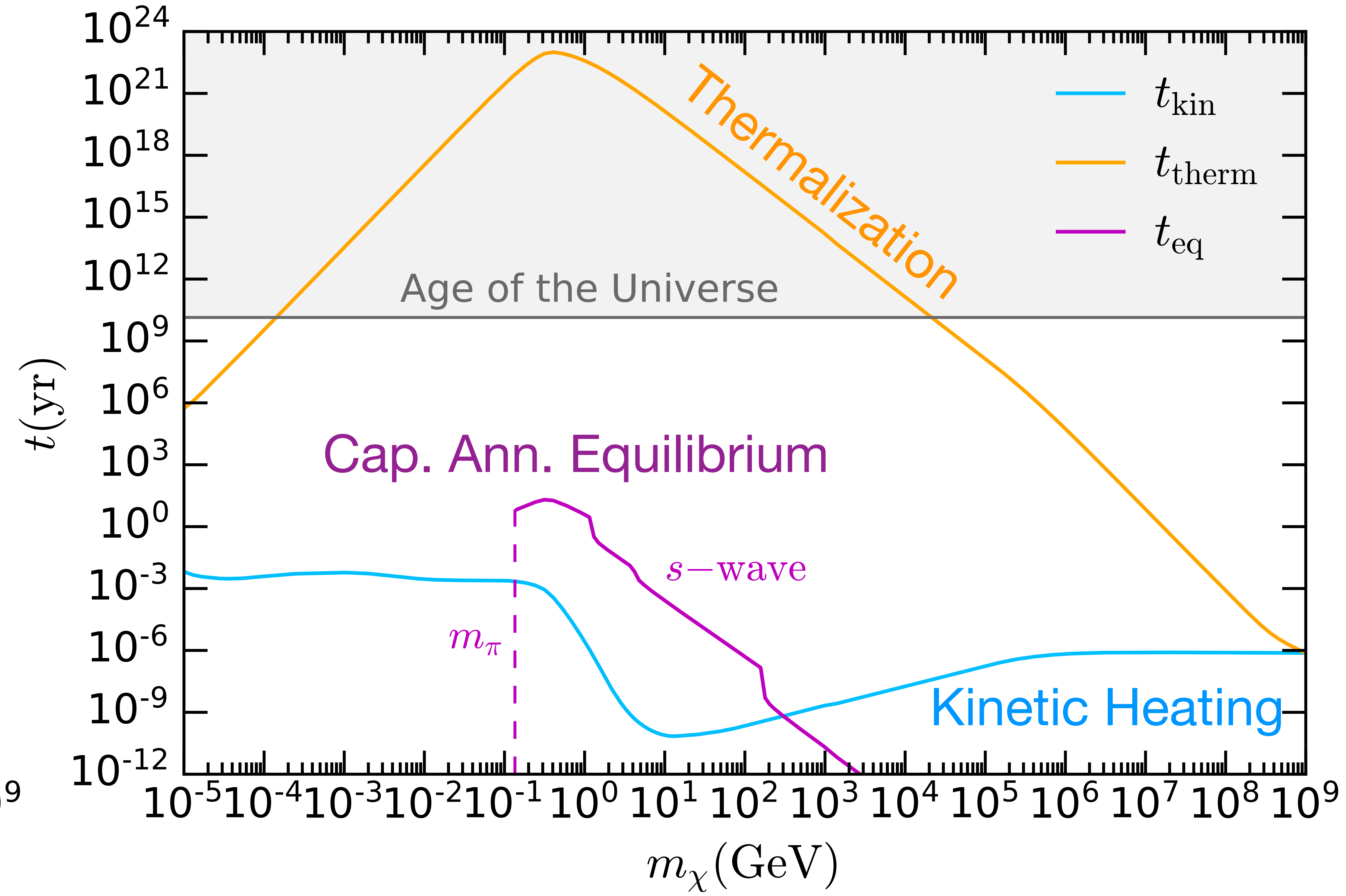
Maximal capture

- Capture-annihilation equilibrium reached in ~1 yr (s-wave) up to 100 kyr (p-wave).

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



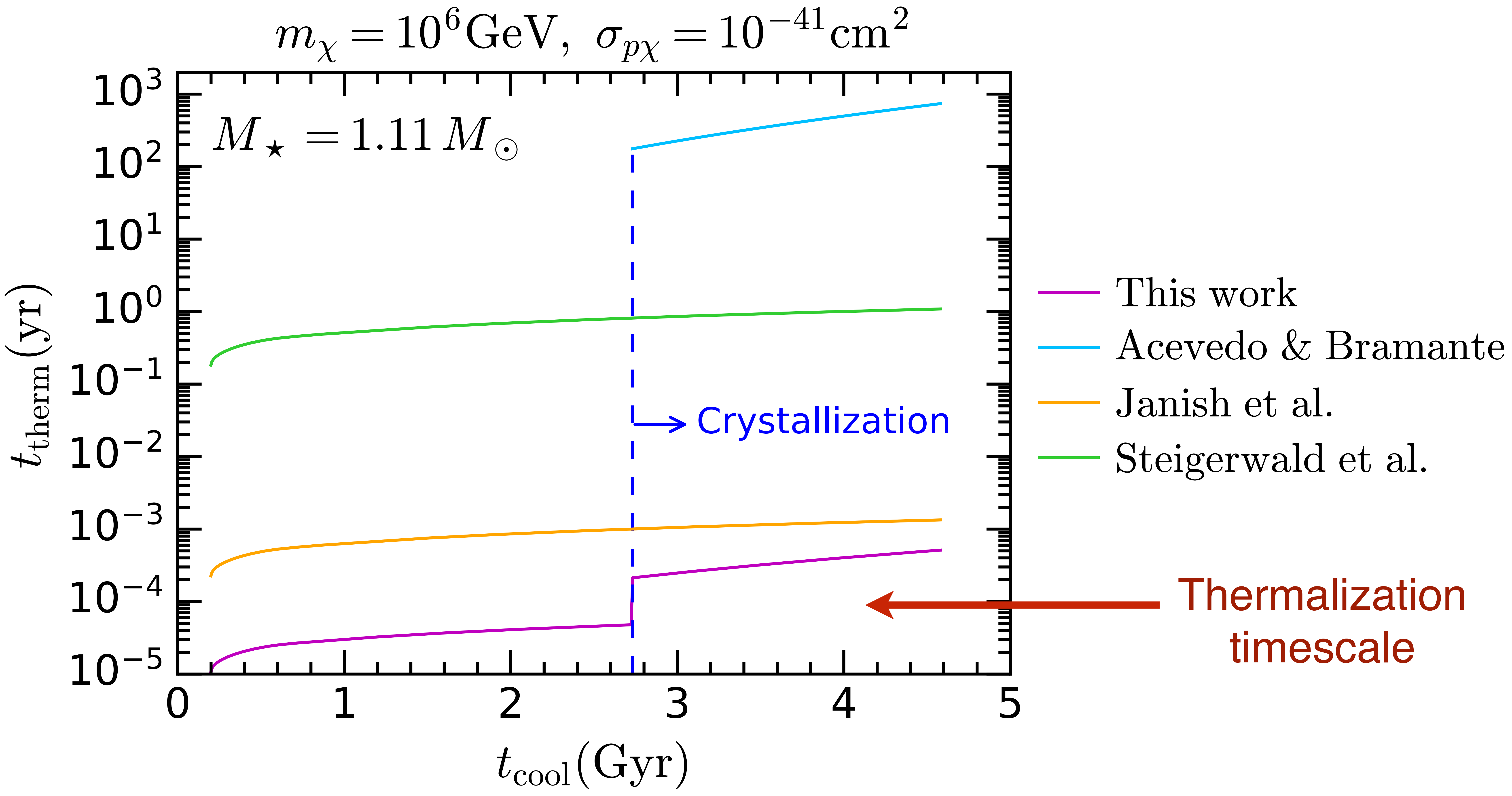
$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$ q^4 suppressed



Bell, Busoni, SR & Virgato, arXiv:2312.11892 (JCAP)

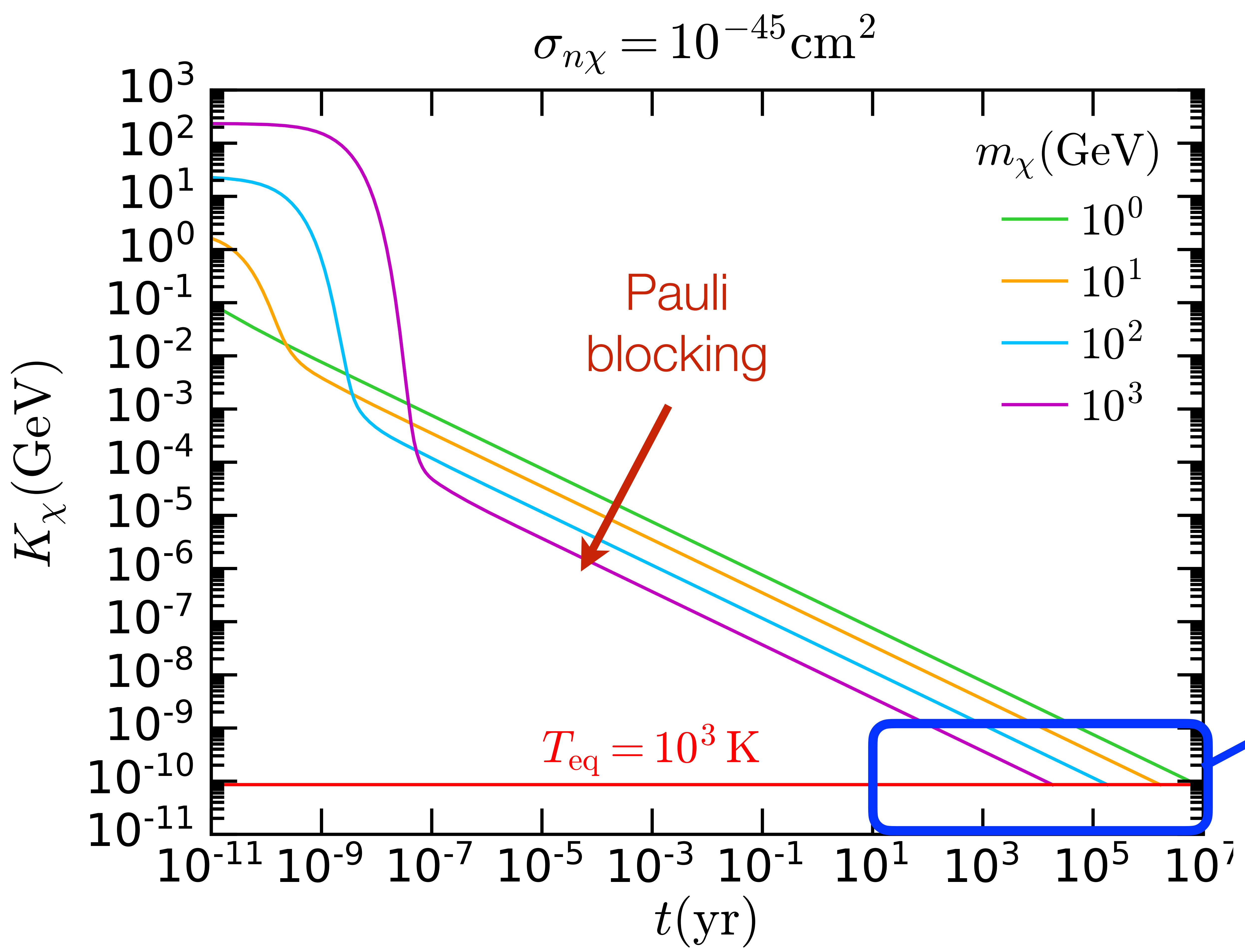
DM Thermalization in WDs

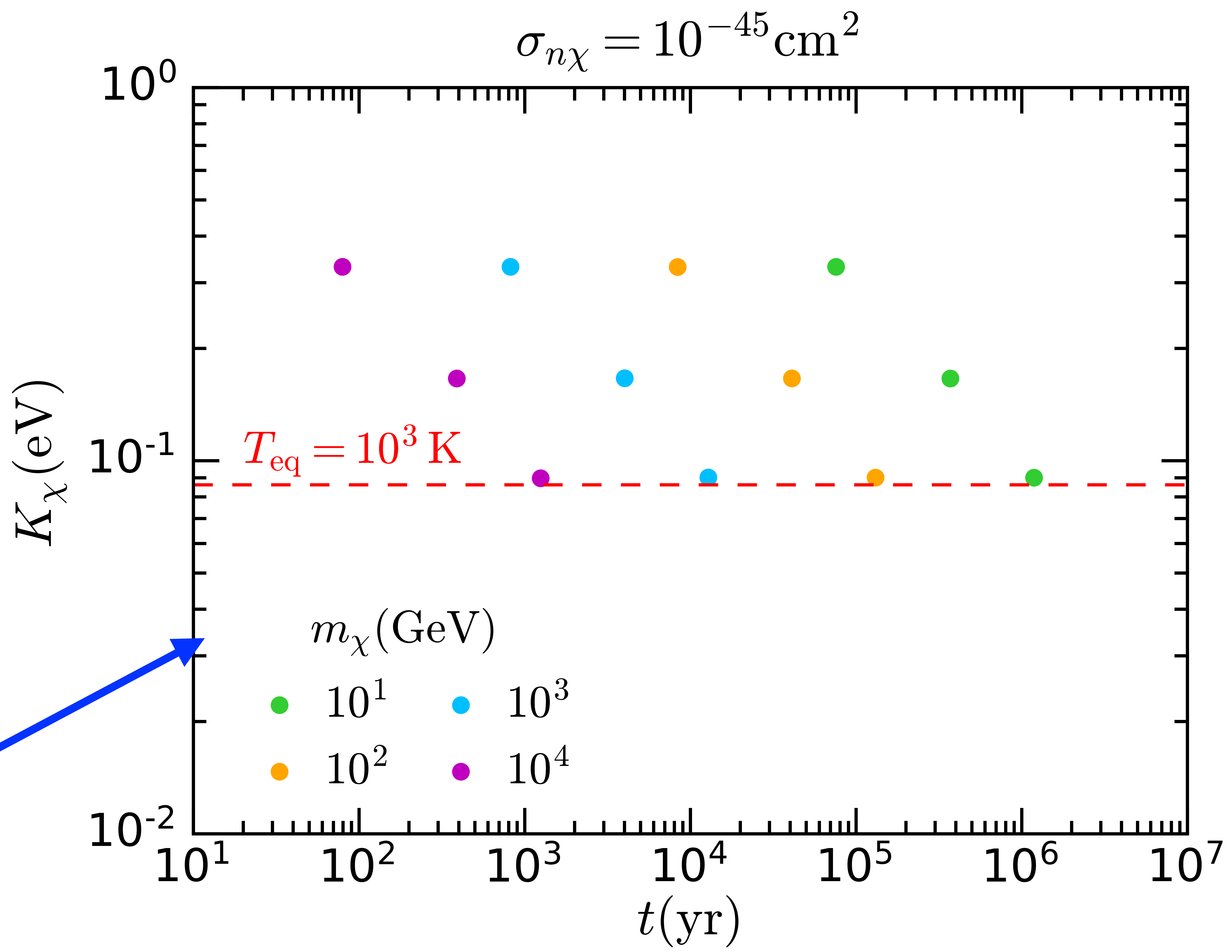
- Very short thermalization timescales



Bell, Busoni, SR & Virgato, arXiv: 2404.16272 (JCAP)

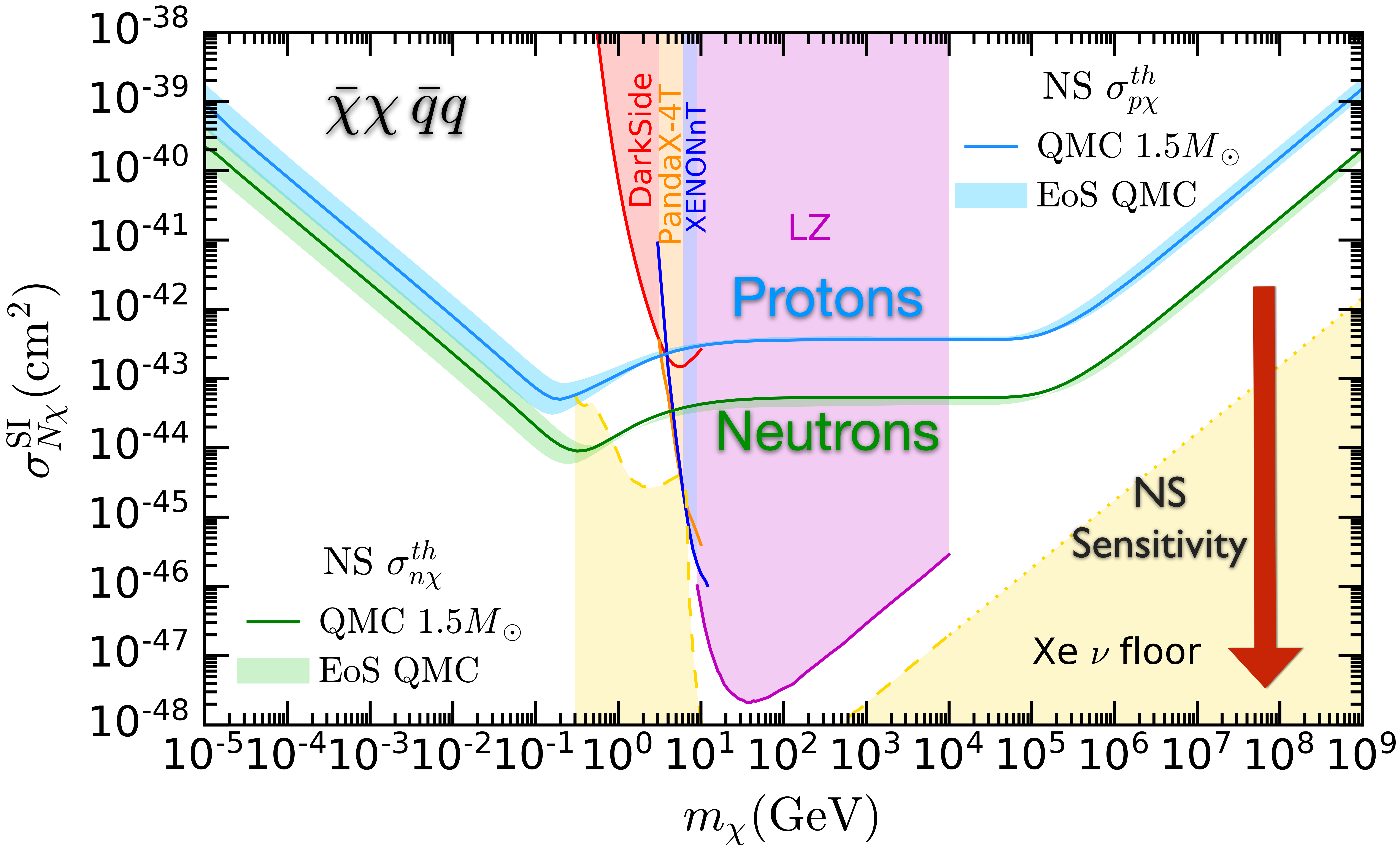
DM Thermalization in NSs





NS sensitivity to SI DM-nucleon scattering cross section

Signal: Anomalous heating



➡ Coldest NS observed

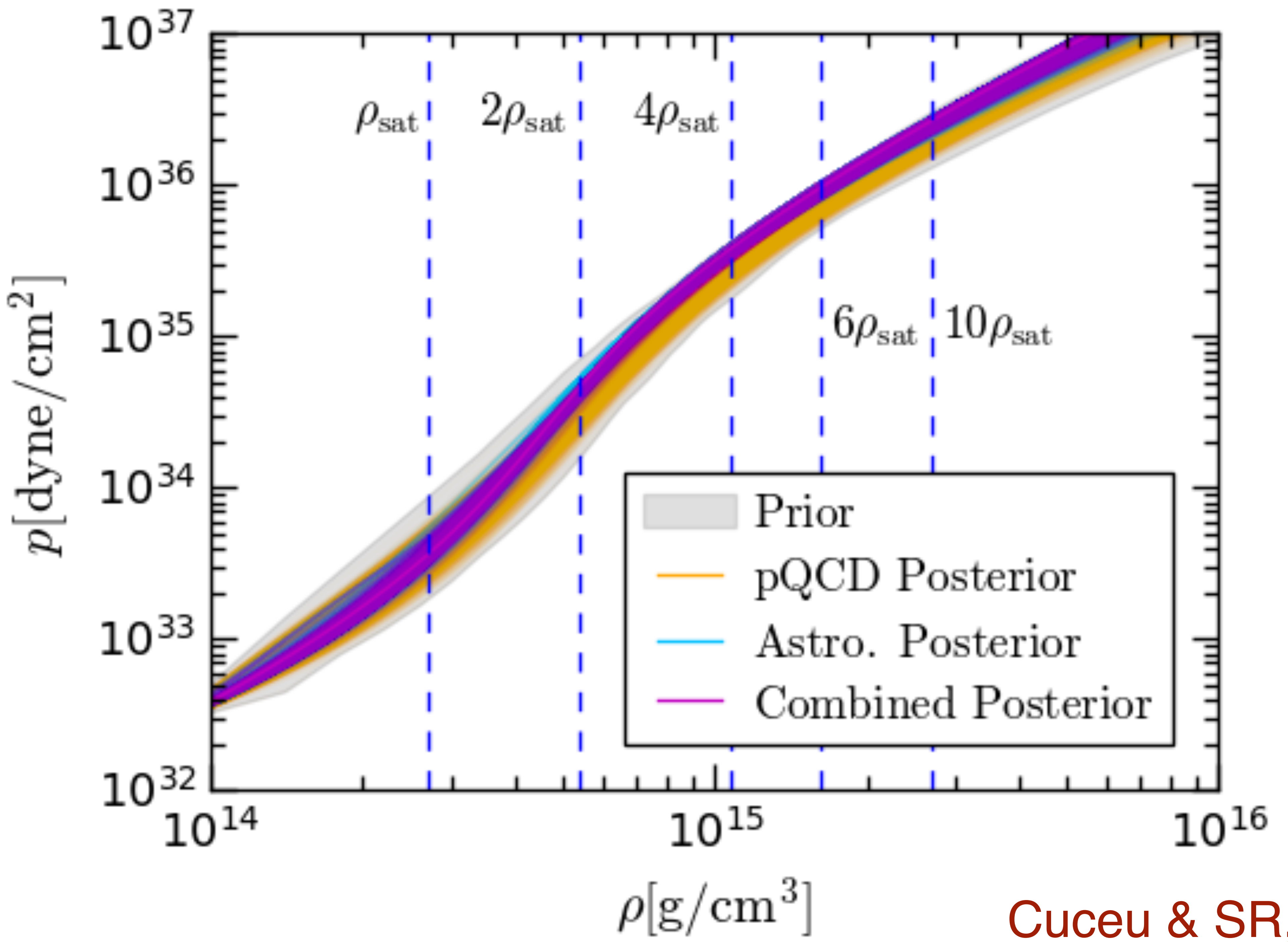
$T_{\mathrm{eff}} < 42000\,\mathrm{K}$

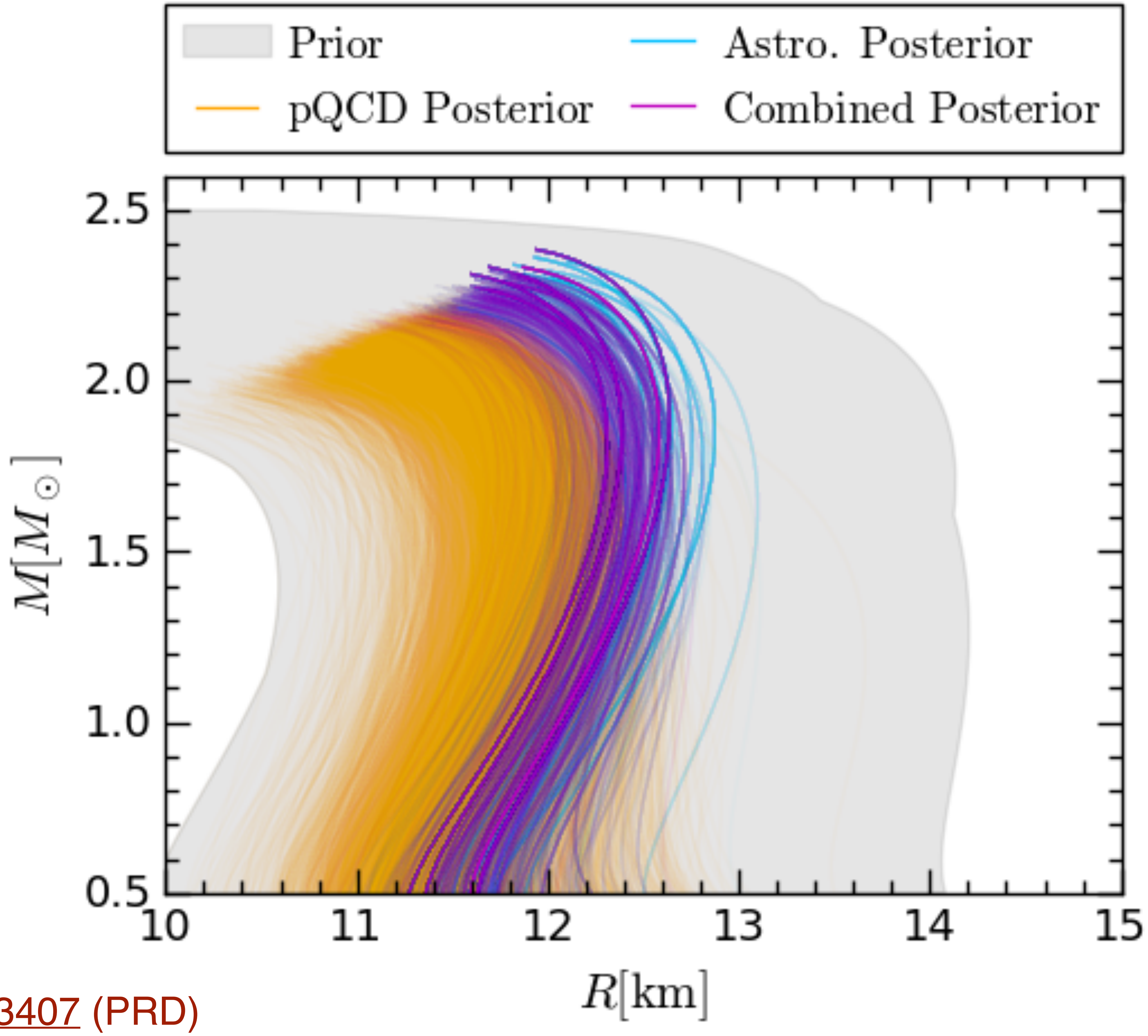
Guillot et al. arXiv: 1901.07998

Anzuini, Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525 (JCAP)

Uncertainties

- Equation of state of nuclear dense matter
  - ➡ Binary NS merger: GW170817
  - ➡ X-ray and radio observations
  - ➡ Perturbative QCD

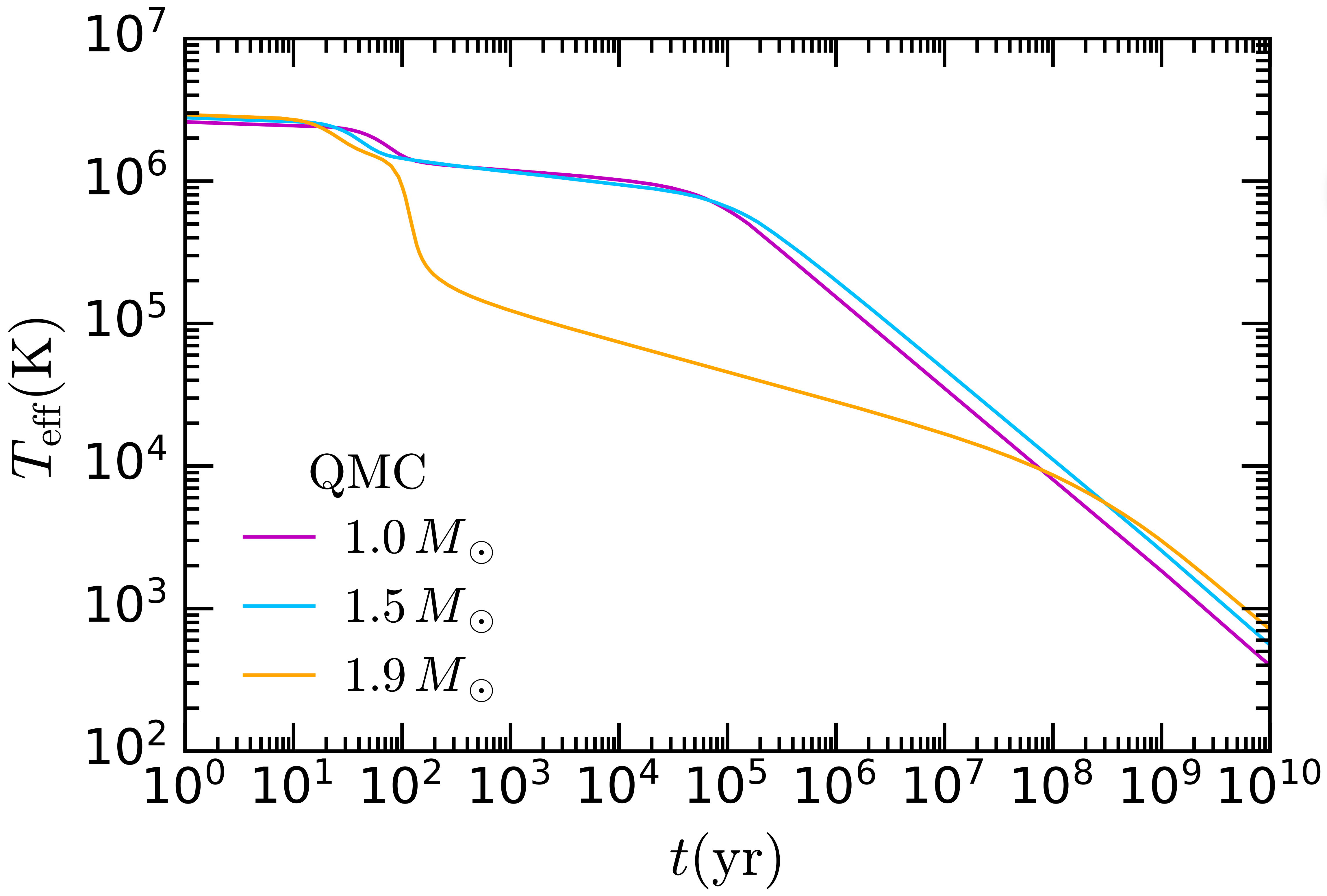


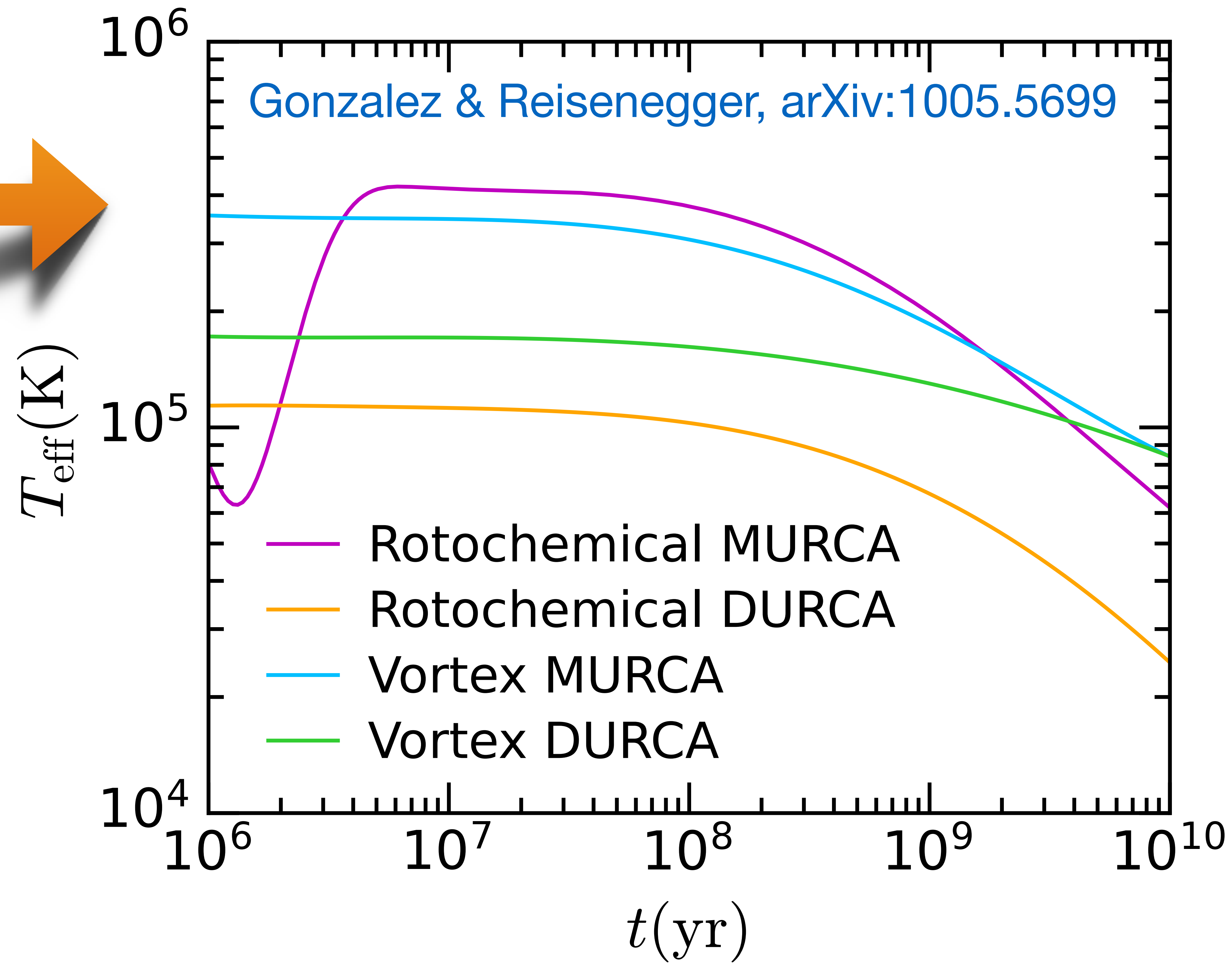


Cuceu & SR, arXiv: 2410.23407 (PRD)

Other sources of late NS heating

- Rotation induced heating (spin down)
  - ➡ Rotochemical heating Reisenegger astro-ph/9410035, Fernandez & Reisenegger astro-ph/0502116
  - ➡ Frictional motion of superfluid neutron vortices Alpar et al.1984, ApJ, 276, 325; Shibazaki & Lamb 1989; Larson & Link astro-ph/9810441



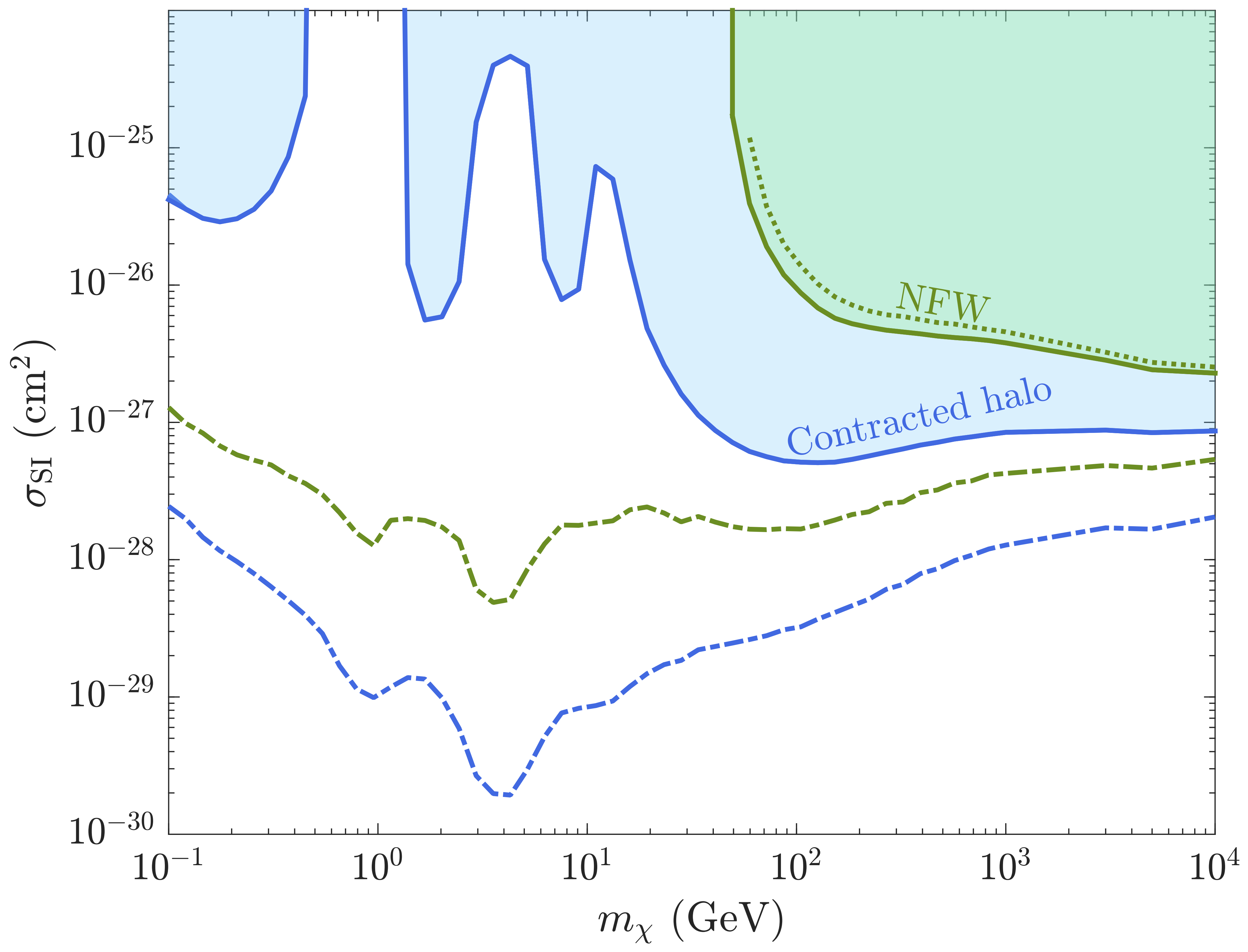


Tip of the Red Giant Branch

Annihilating DM

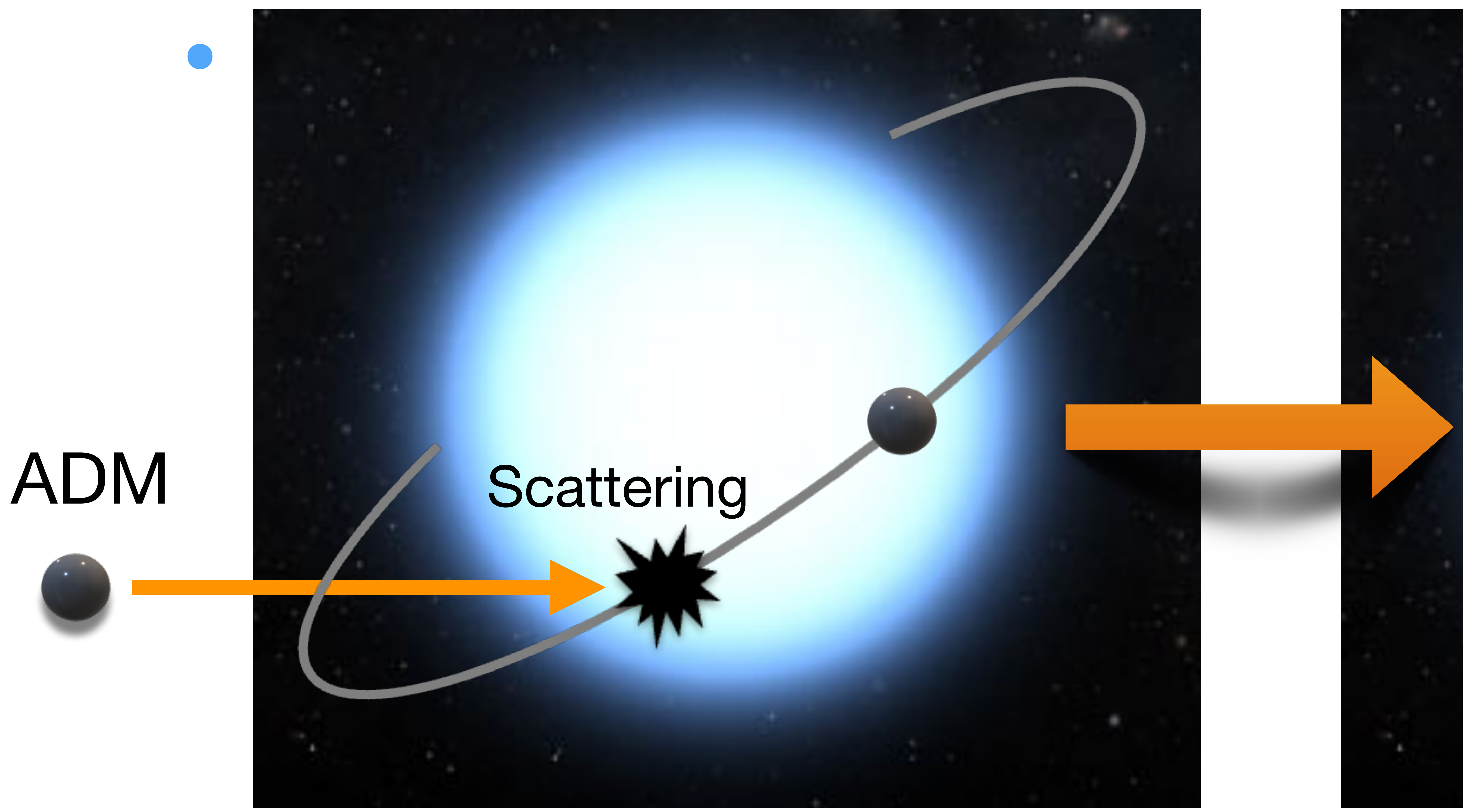
- 22 globular clusters with TRGB magnitude

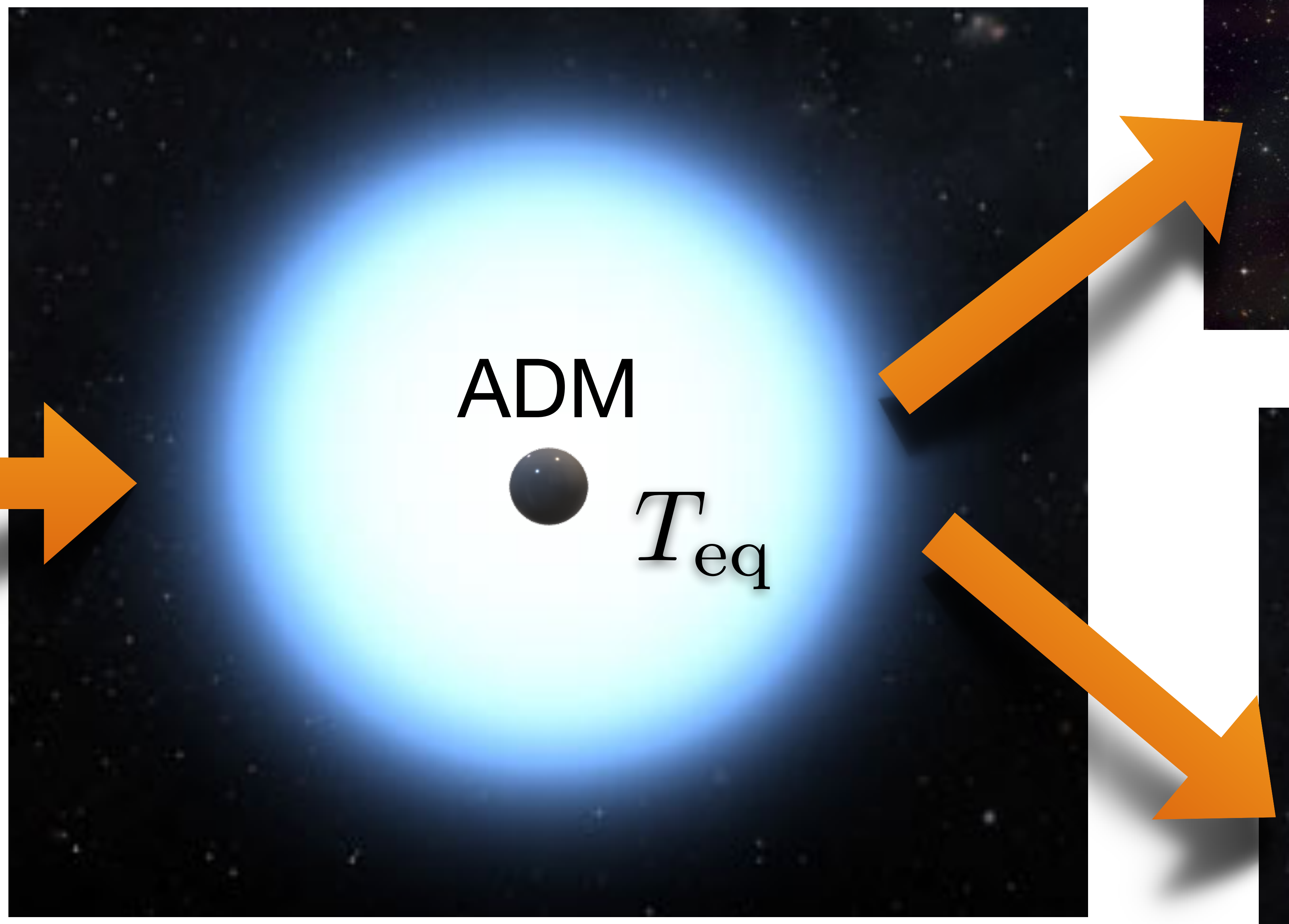
Hong & Vincent, arXiv:2407.08773

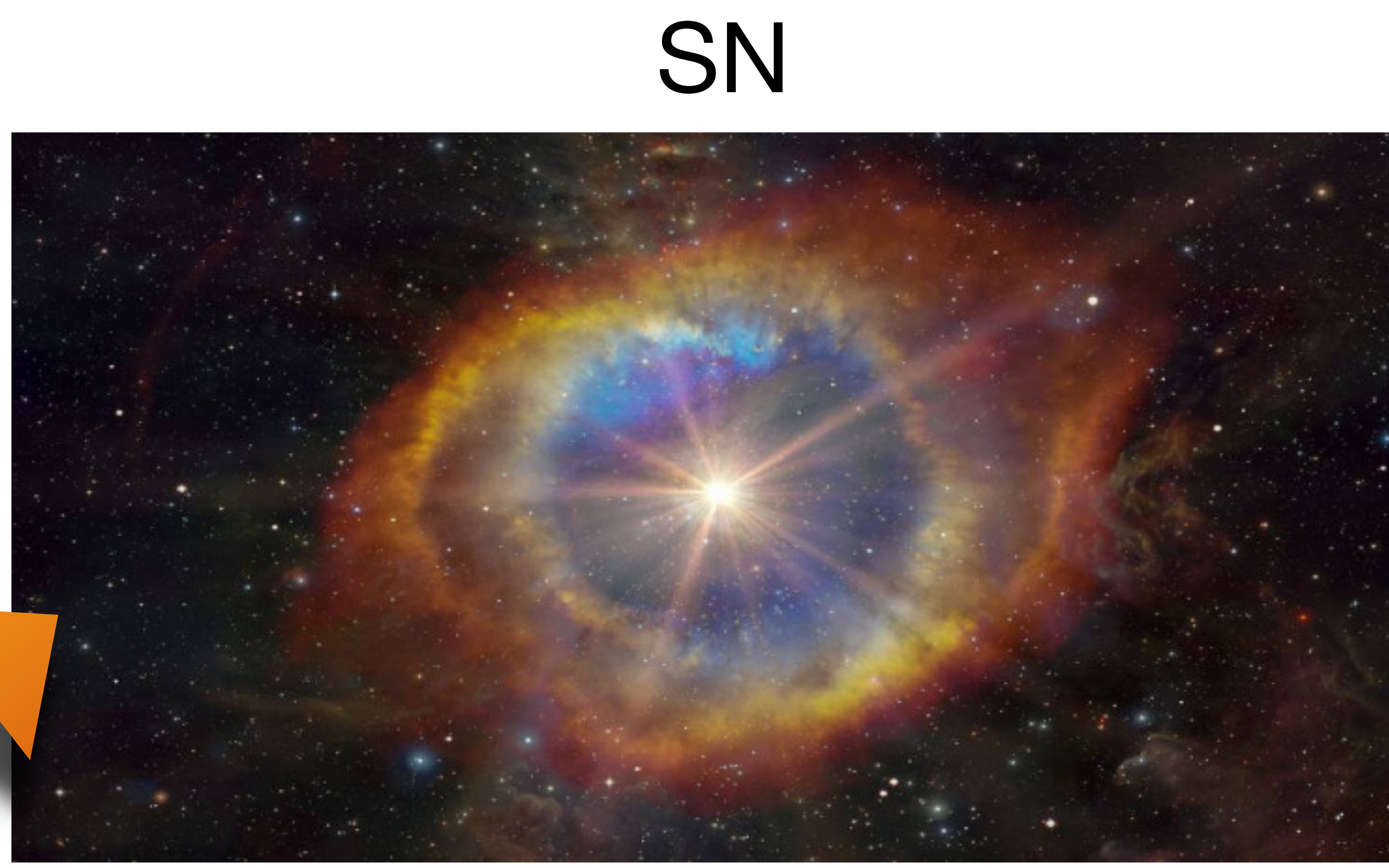


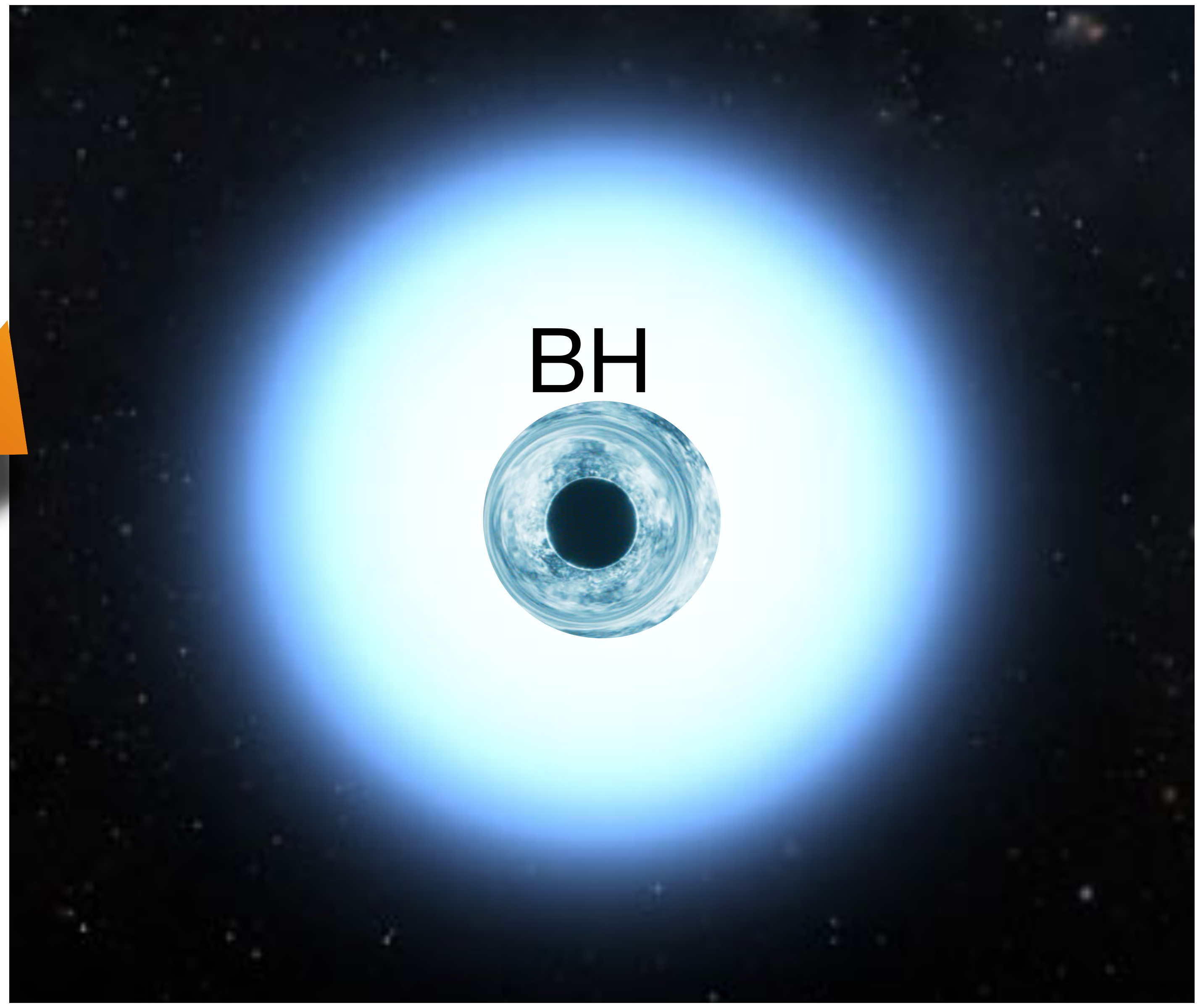
White Dwarf destruction by SN/BH formation

Asymmetric DM



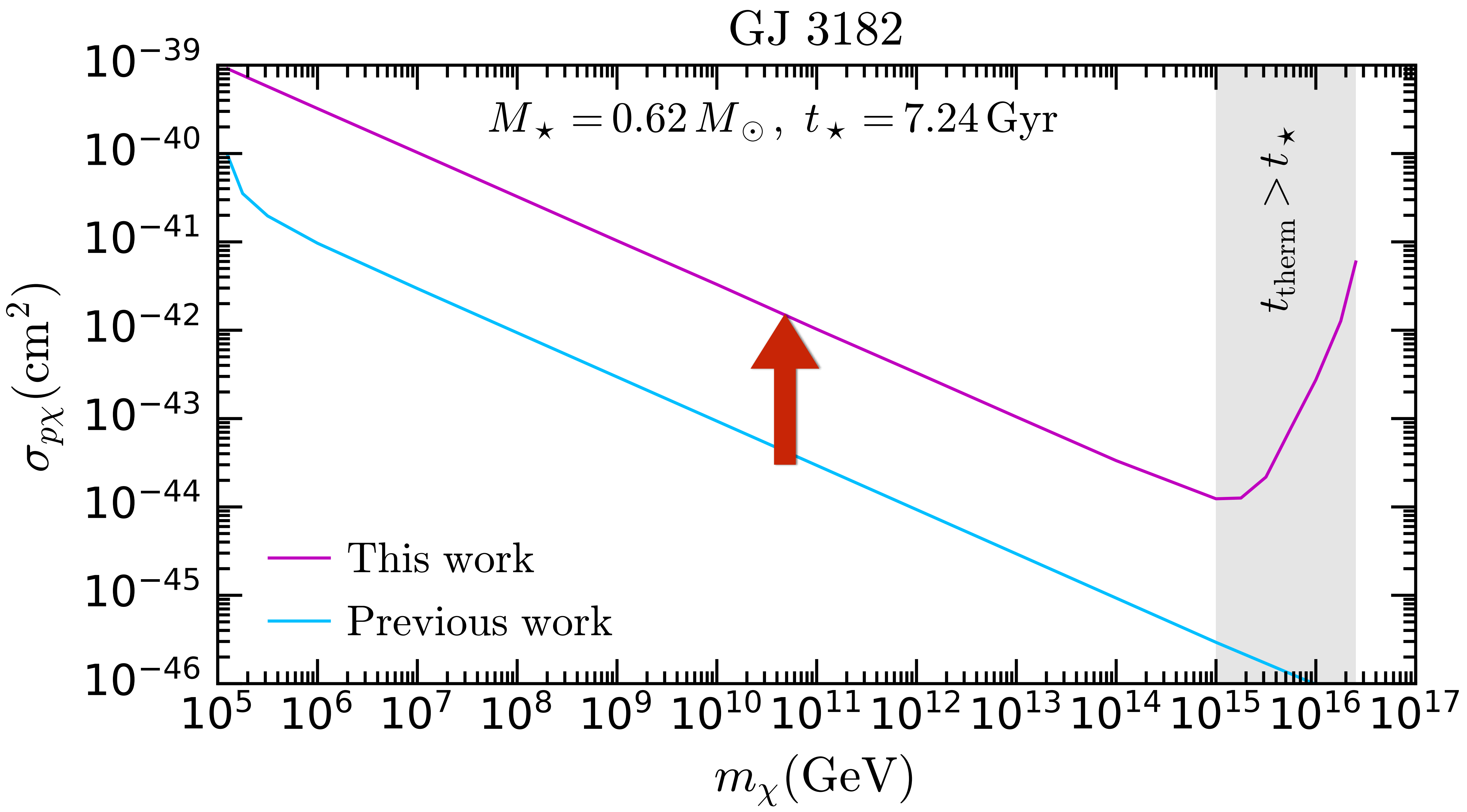


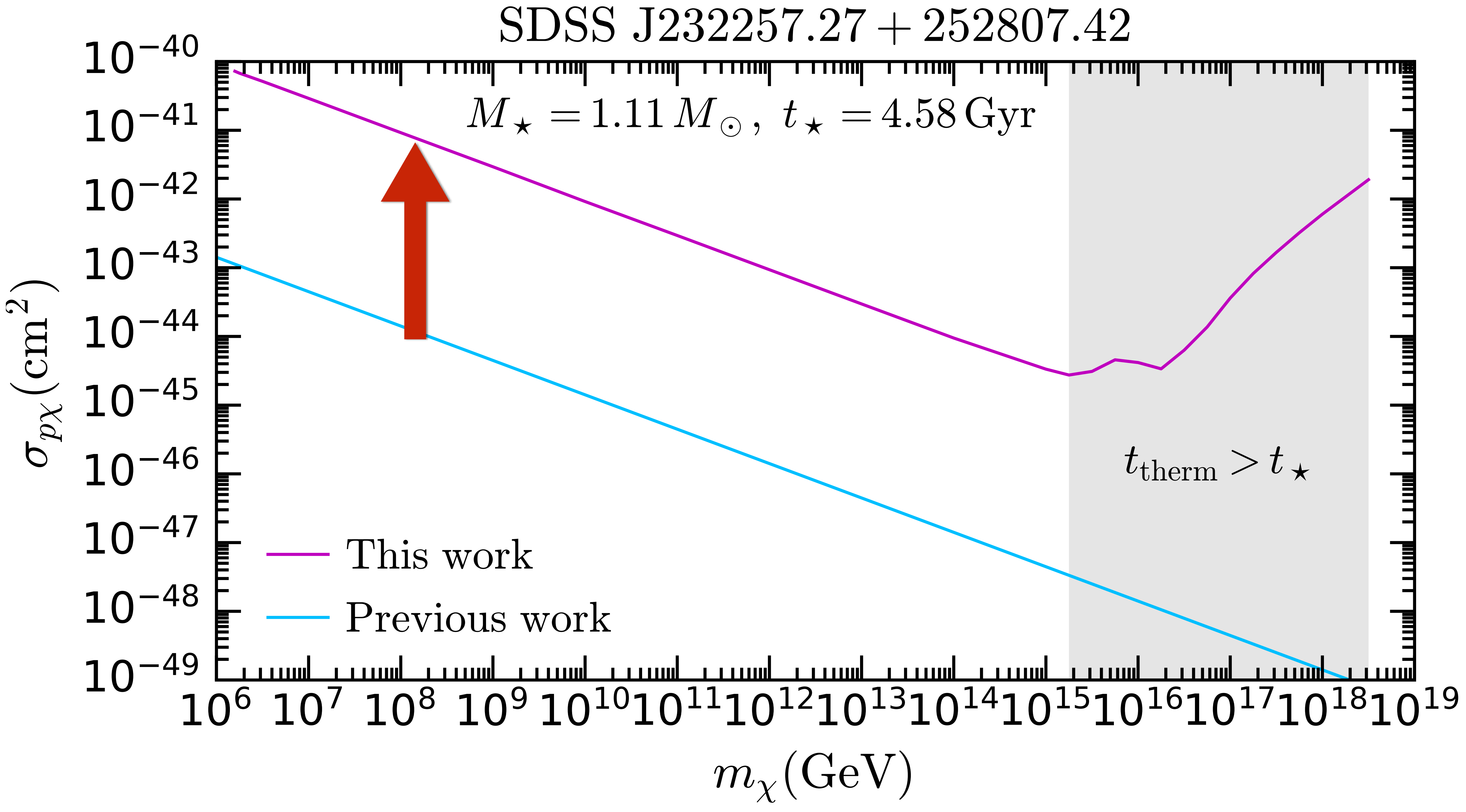




Bramante, arXiv:1505.07464
Graham et al., arXiv:1805.07381
Janish et al., arXiv:1905.00395
Acevedo & Bramante, arXiv:1904.11993
Steigerwald et al, arXiv:2203.09054

Self-gravitation





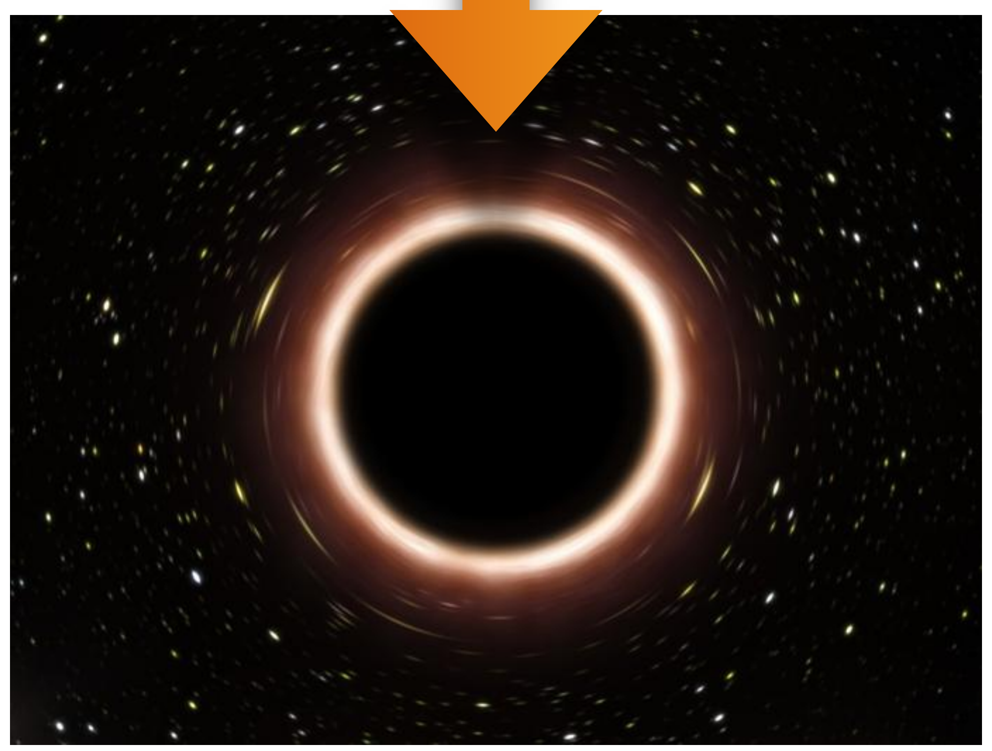
Bell, Busoni, SR & Virgato, arXiv: 2404.16272 (JCAP)

Neutron Star Destruction by BH formation

Asymmetric DM

Goldman & Nussinov, 1989
Kouvaris & Tinyakov, 2010, 2011
McDermott et al. 2011

NS destruction



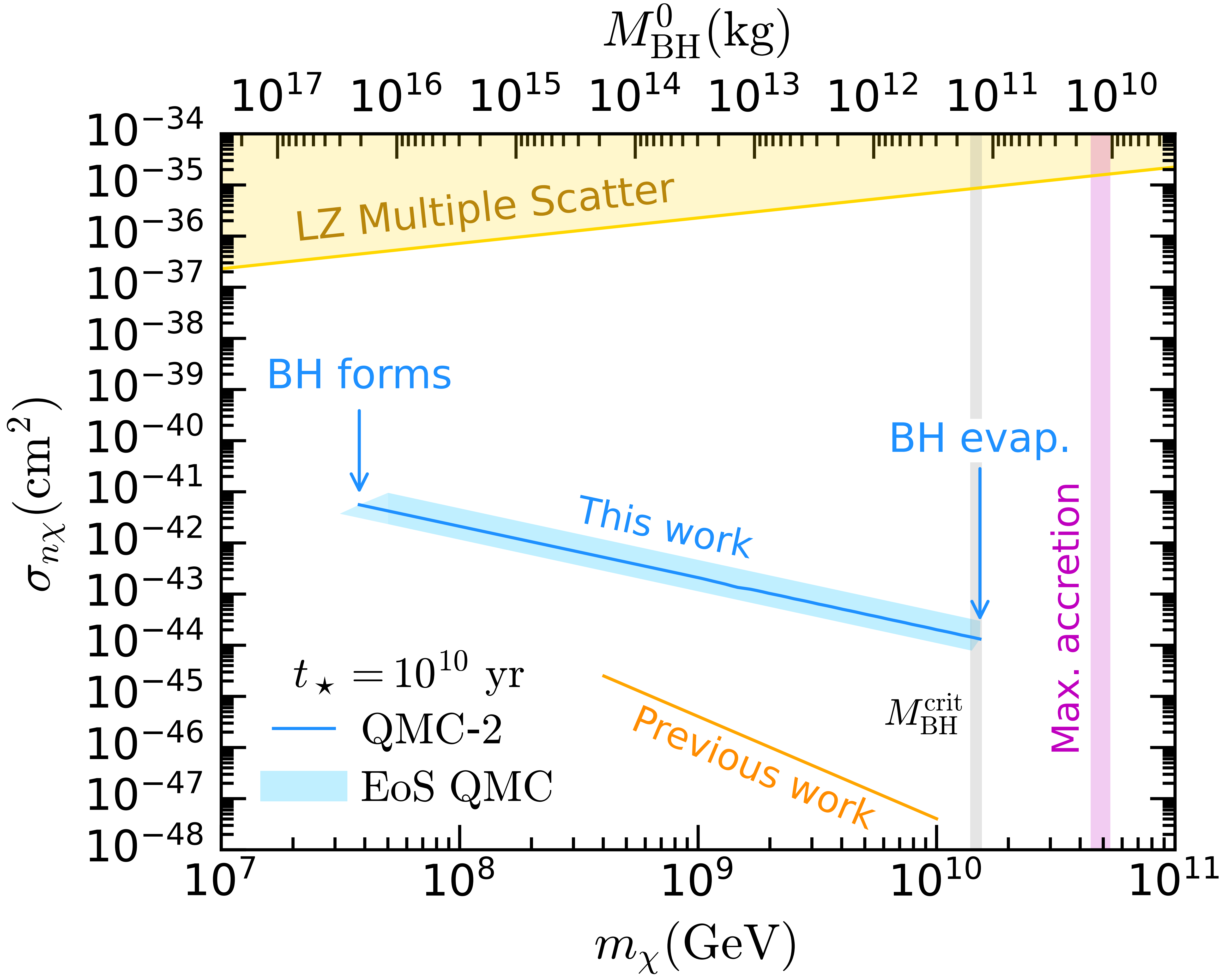
Neutron Star destruction by BH formation

Fermionic Asymmetric DM

- Local NS

$$t_\star = 10^{10}\,\mathrm{yr}$$

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



SR, Vatsyayan and Busoni, arXiv: 2507.22881

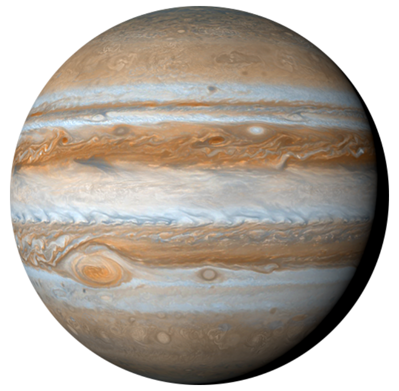
Summary

The Sun

$$\chi\chi \to \tau^+\tau^-, \nu\bar{\nu}$$

$$m_\chi \gtrsim 3\,\mathrm{GeV}$$

Jupiter



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

$$m_\chi \sim 1 - 3\,\mathrm{GeV}$$

Super-K/Hyper-K

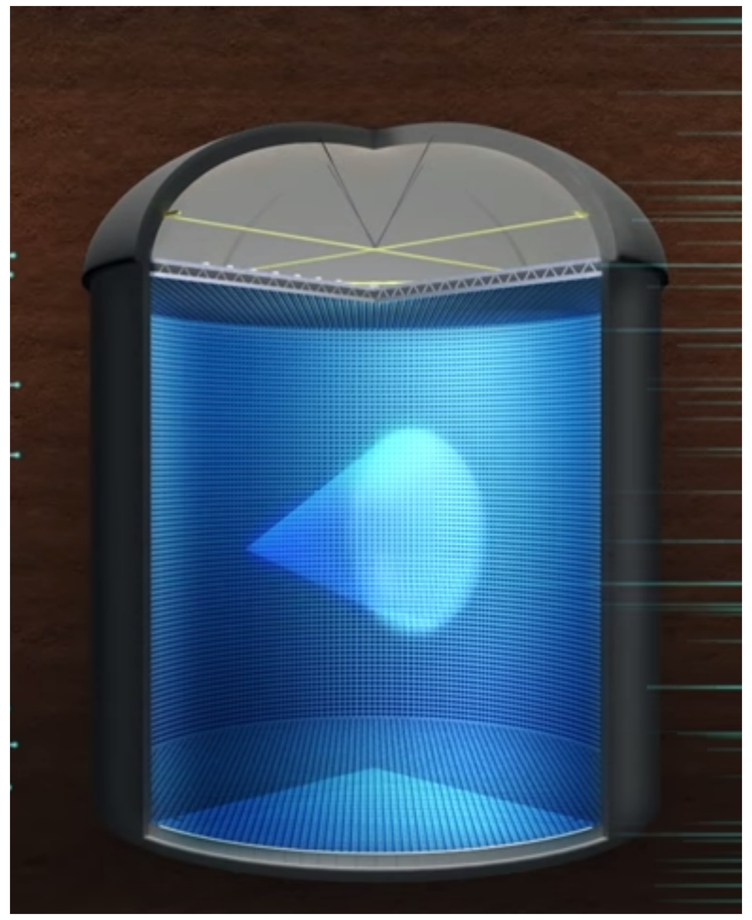
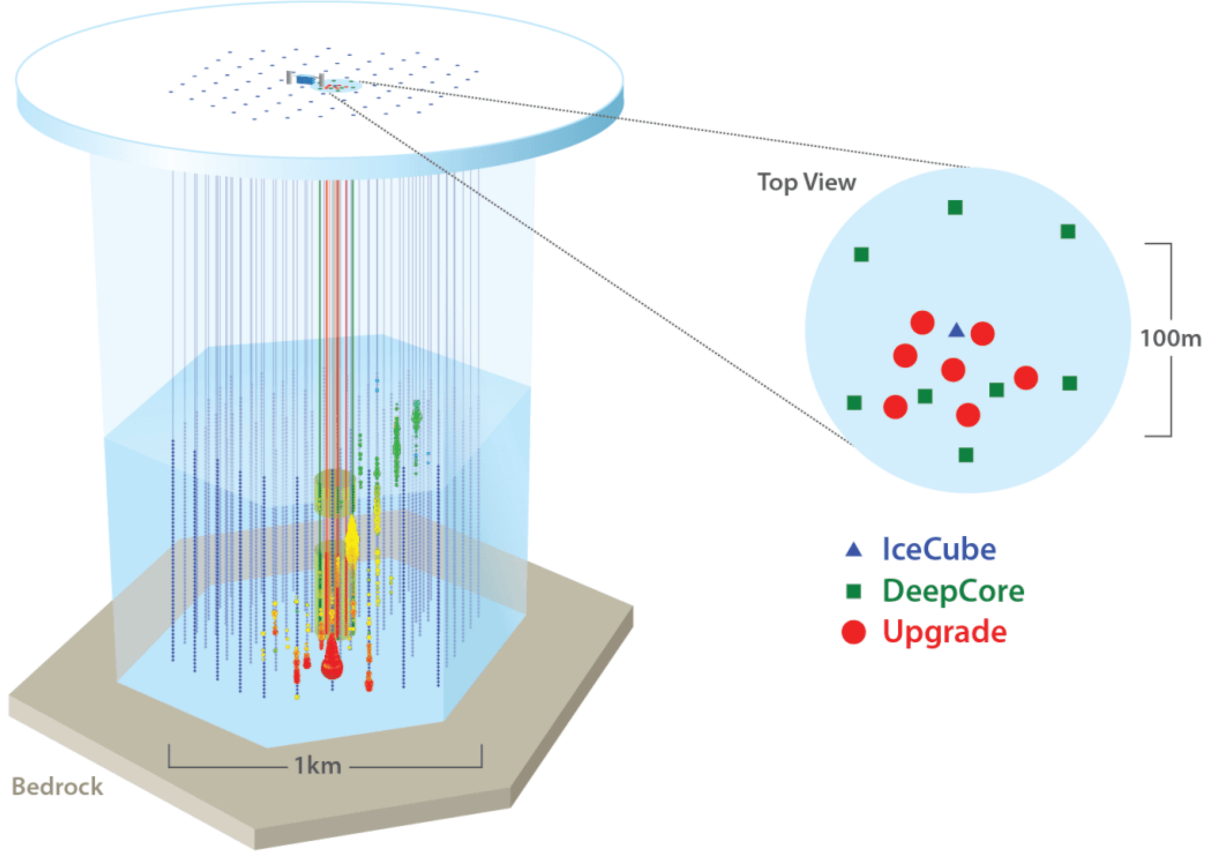


Image credit: Institute for Cosmic Ray Research,The University of Tokyo

IceCube/Upgrade



- Complimentary/competitive with direct detection experiments
- Spin dependent proton

➡ Neutrino detectors

➡ Long lived mediators Gamma ray telescopes

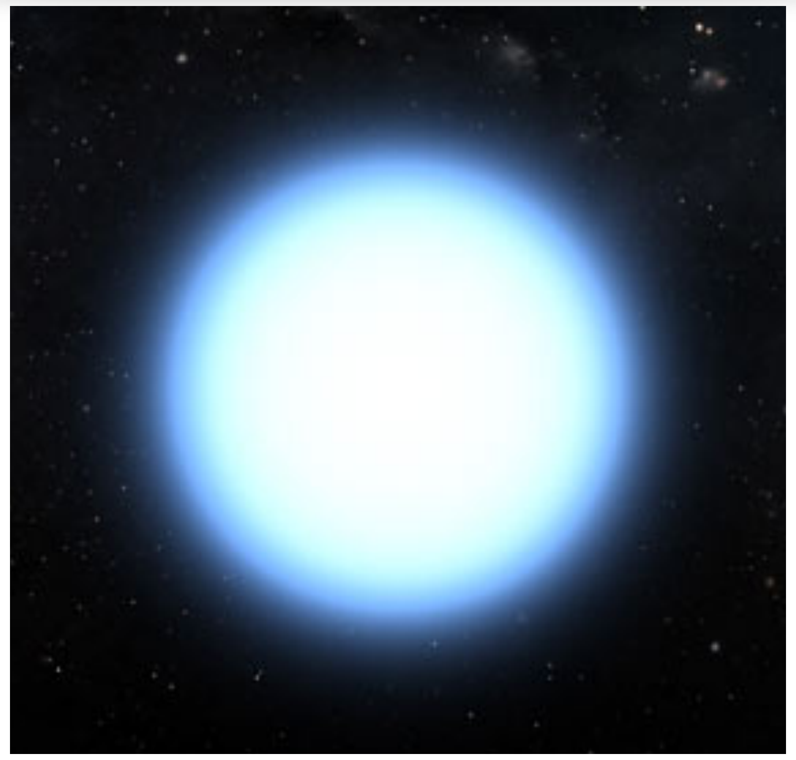
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Fermi-LAT

Summary

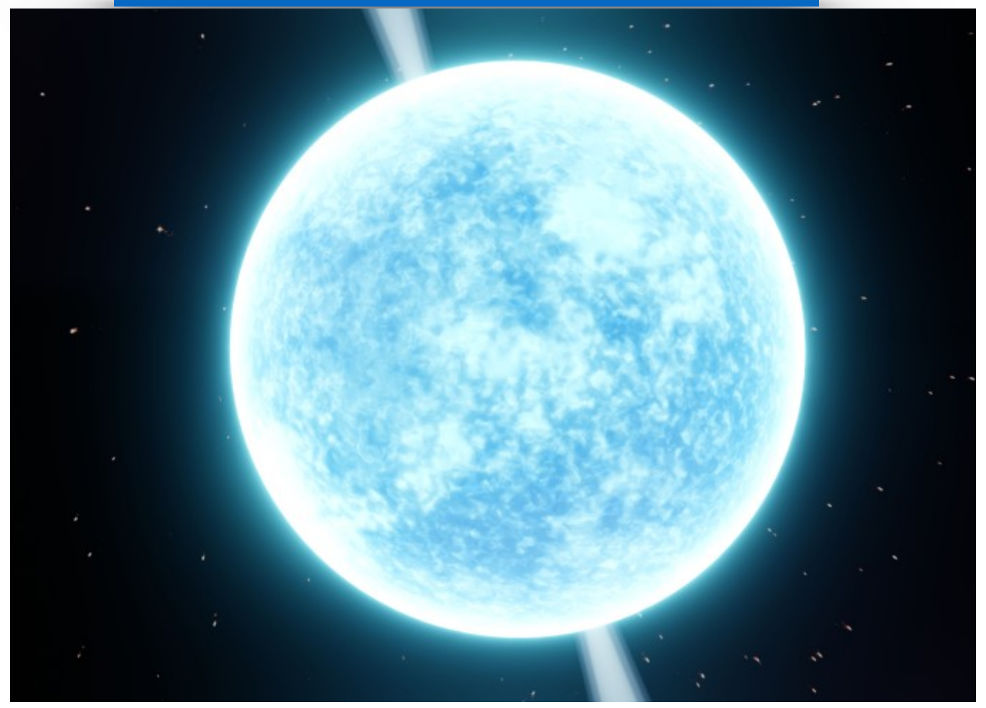
- Compact stars:
  - ➡ Signal: Increase in luminosity (heating)
  - ➡ Non-annihilating DM: star destruction

White Dwarfs



- Spin independent
- Heating: $\rho_\chi = \mathcal{O}(100\,\mathrm{GeV\,cm^{-3}})$
- $\chi\chi \rightarrow \phi\phi \rightarrow \gamma\gamma\gamma\gamma$ (CTA gamma rays)
- Local WD destruction (heavy DM)

Neutron Stars



- SI, SD
- Local NSs could probe sub-GeV regime
- Uncertainties in composition and cooling
- Local NS destruction (heavy DM)

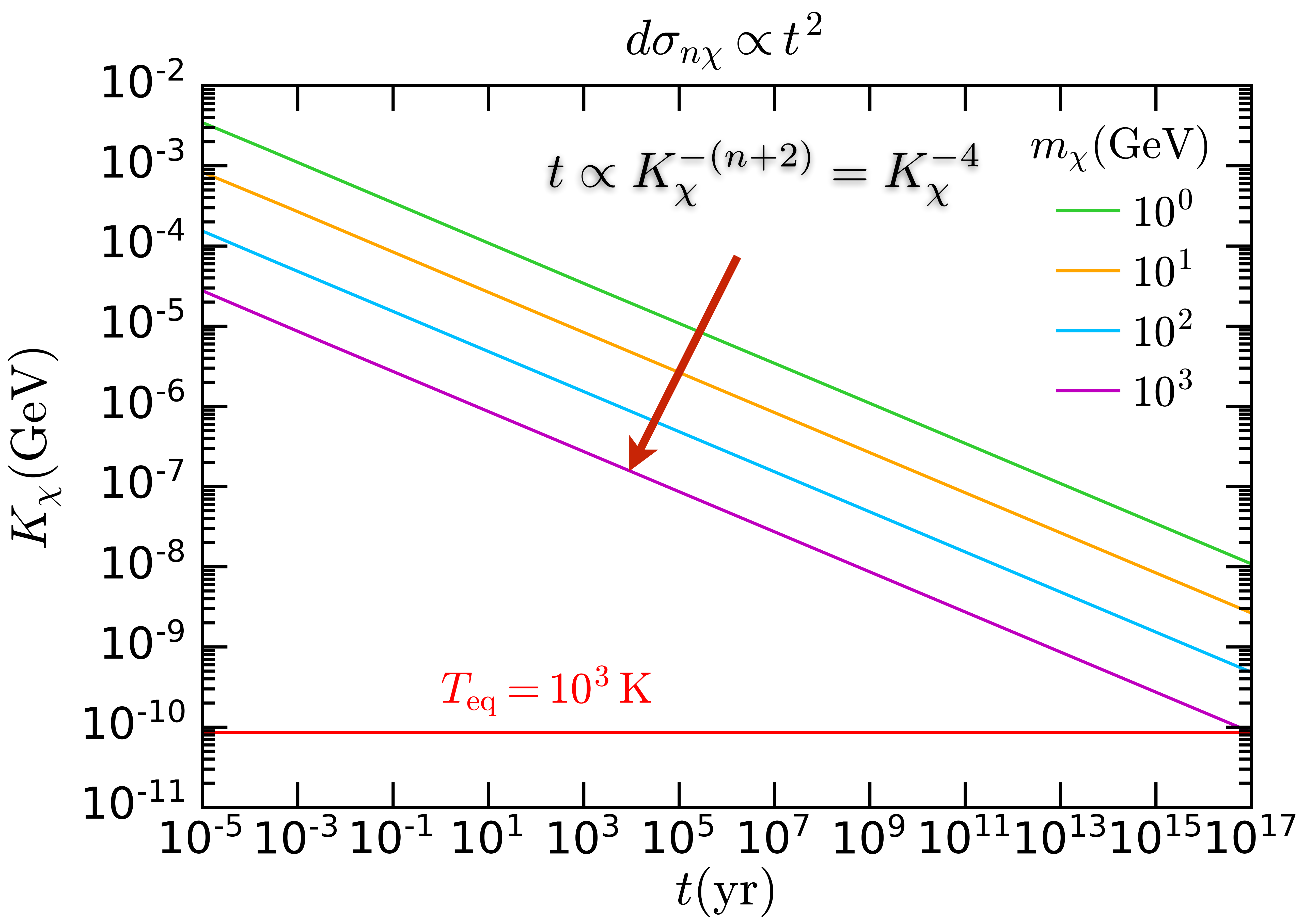
Thank you for your attention!

Backup

Capture - Annihilation Equilibrium

Partially thermalized DM

- If DM has not yet thermalized $t_\star < t_{\rm therm}$



➡ Lowest temperature the DM has reached

$$K_\chi \sim T_{\rm eq}\left(\frac{t_{\rm therm}+t_\star}{t_\star}\right)^{\frac{1}{2+n}}$$

$$t_{\rm eq} = \frac{1}{\sqrt{CA}}\left(\frac{t_{\rm therm}+t_\star}{t_\star}\right)^{\frac{\alpha}{2(2+n)}}$$

Bell, Busoni, SR & Virgato, arXiv:2312.11892