Dark Matter Capture, Thermalisation and Annihilation in Neutron Stars

Sandra Robles

Fermi National Accelerator Laboratory

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in collaboration with

Nicole F. Bell, Giorgio Busoni, Michael Virgato, Anthony W. Thomas, & Theo F. Motta

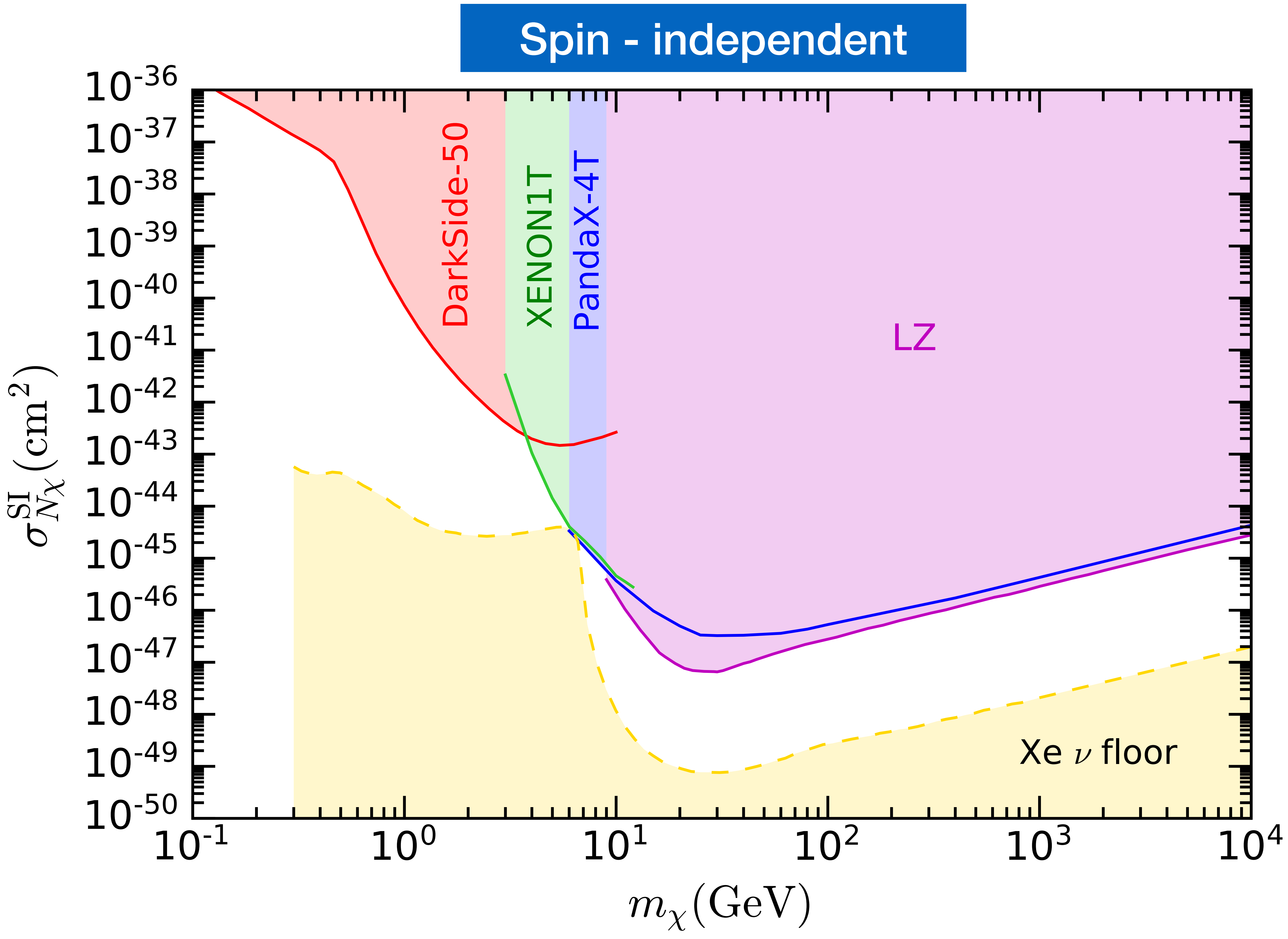
arXiv:2004.14888 (JCAP), arXiv:2010.13257 (JCAP), arXiv:2012.08918 (PRL), arXiv: 2108.02525 (JCAP), arXiv:23XX.XXXX

Fermilab

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.



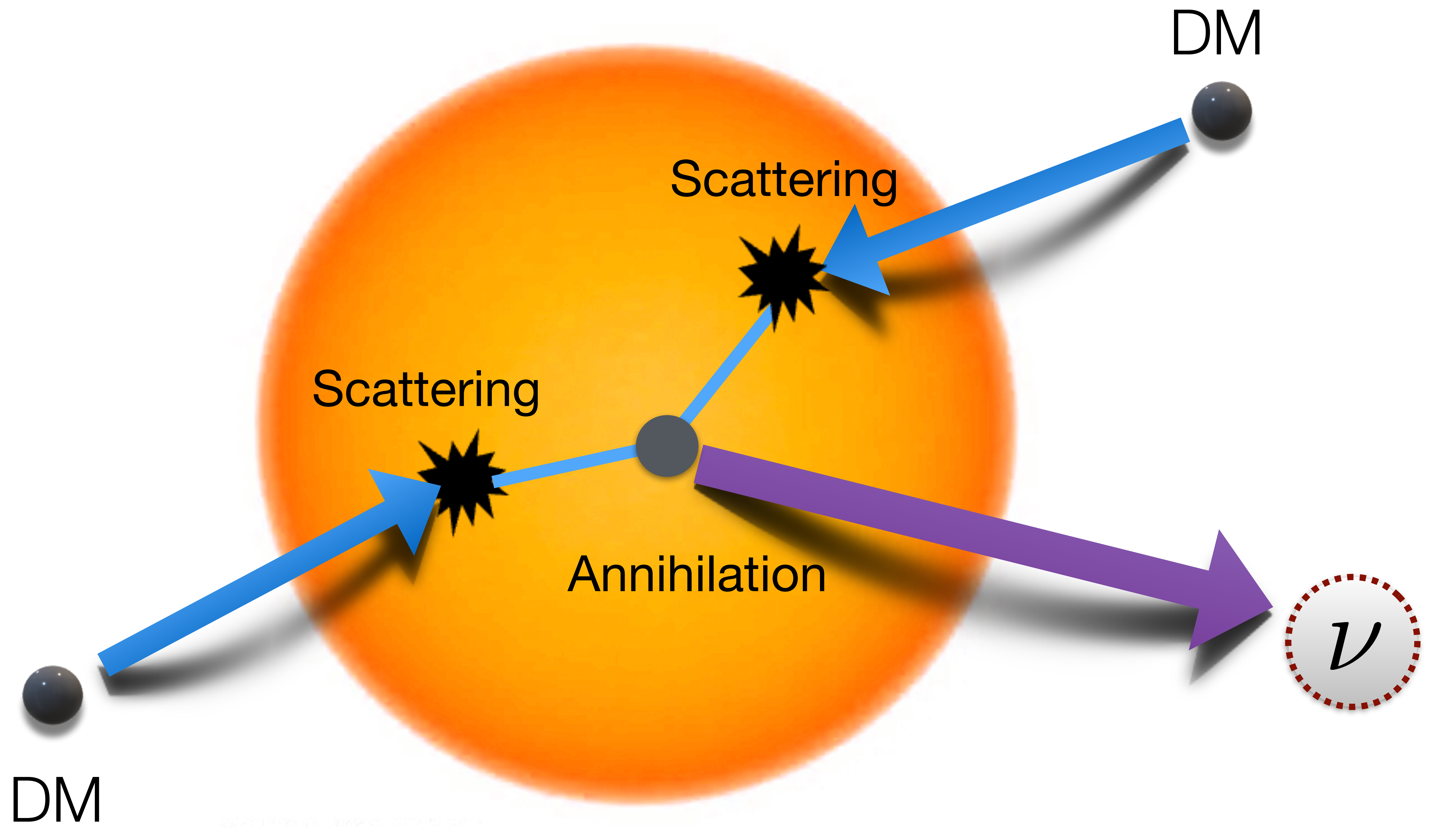
Introduction

Direct Detection

- Much weaker sensitivity to spin-dependent interactions.

DM Capture in the Sun

- DM scatters, loses energy, becomes gravitationally bound to the Sun. Gould 1987
- Accumulates and annihilates in the centre of 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).



SuperK

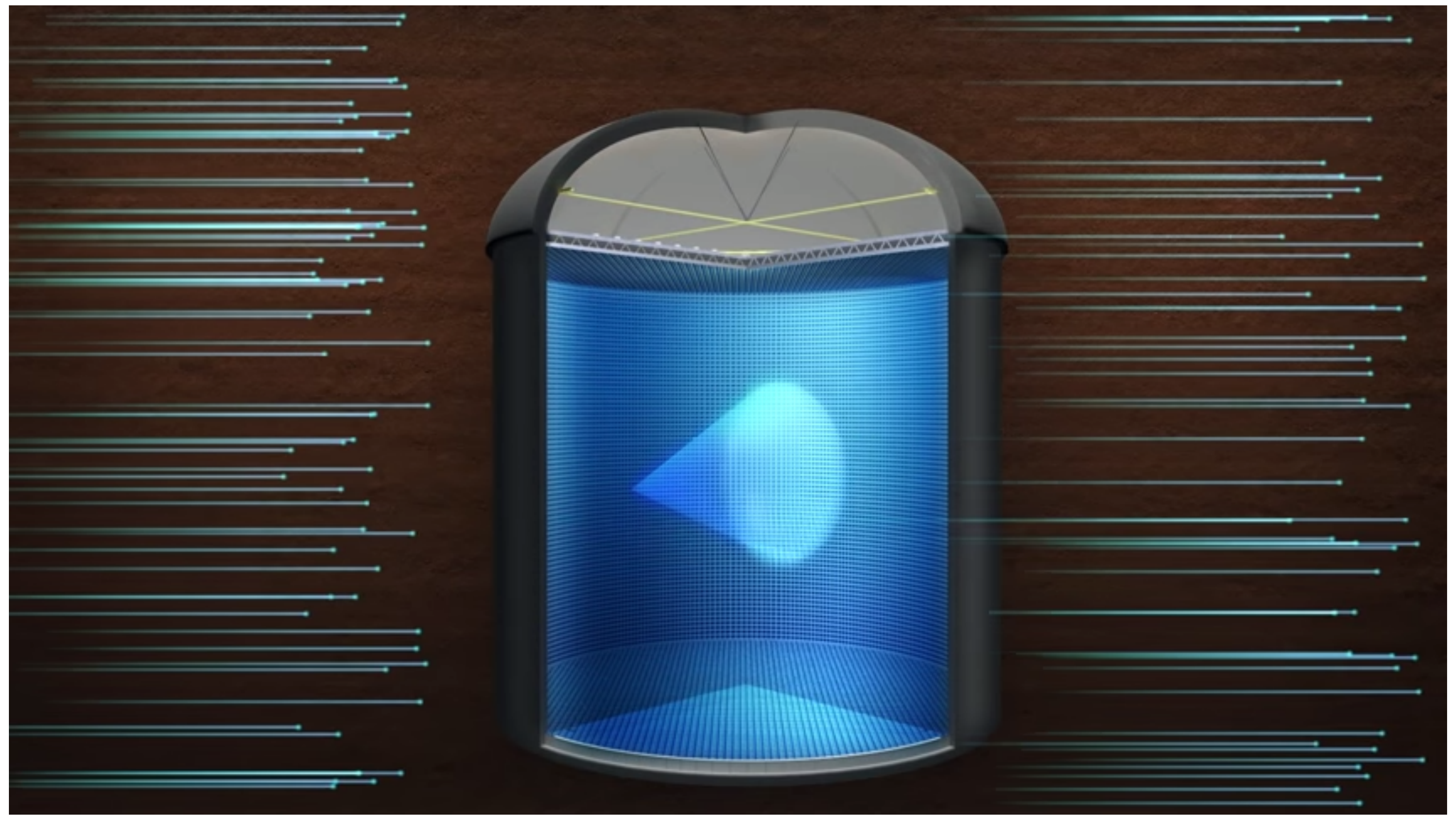
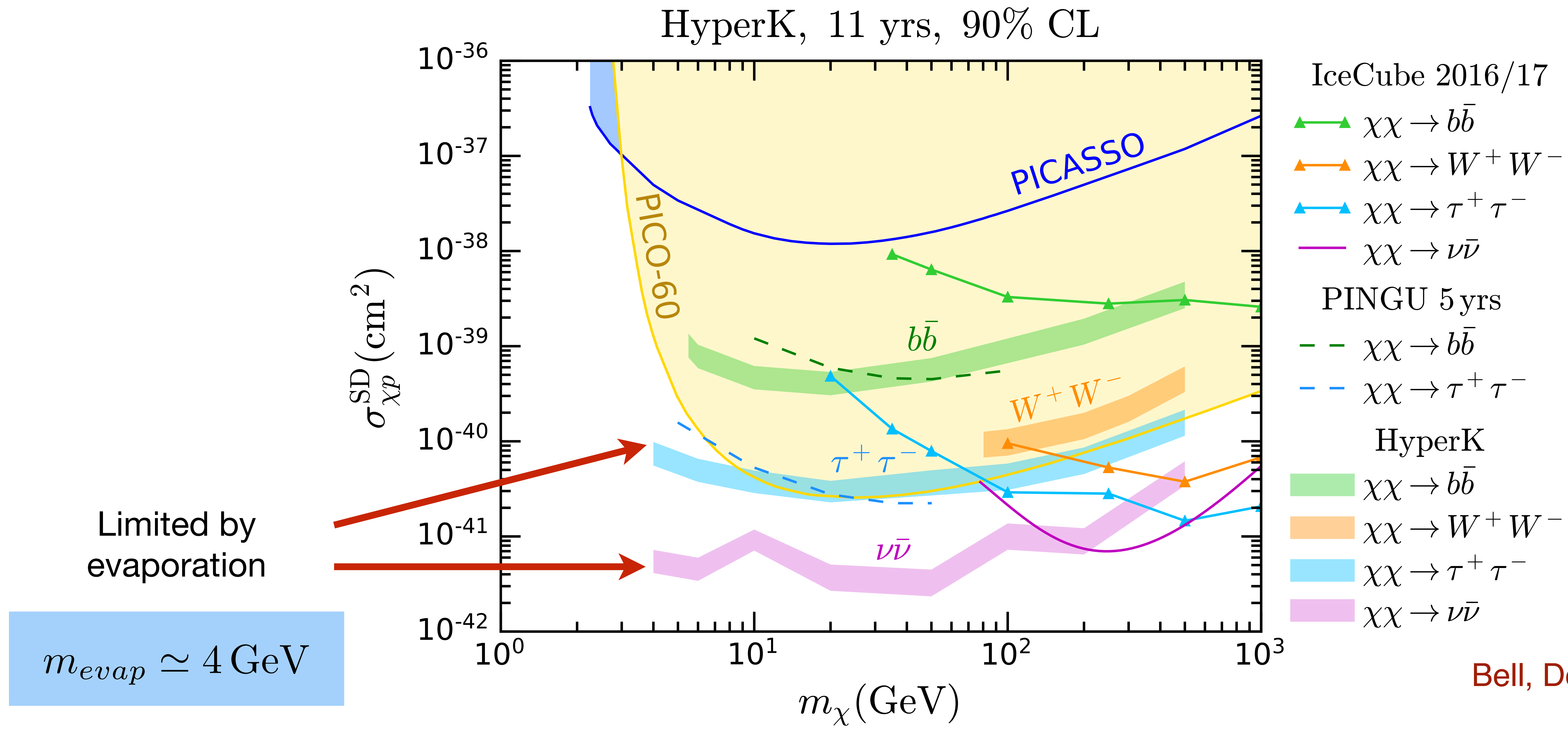


Image credit: Institute for Cosmic Ray Research,The University of Tokyo

Captured DM annihilating in the Sun

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

Spin - dependent

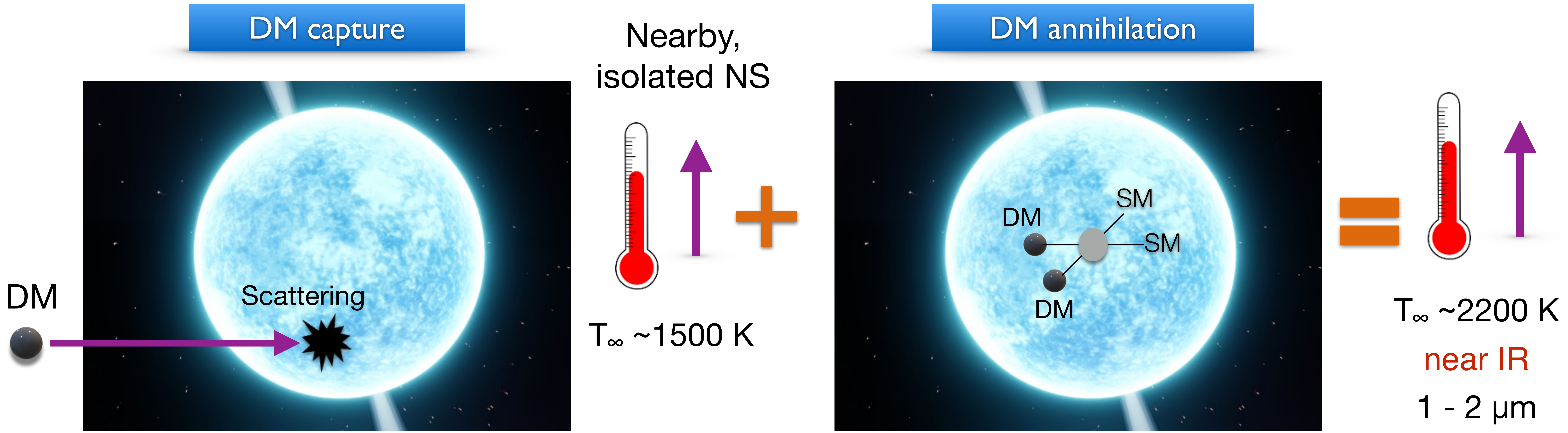


Bell, Dolan & SR arXiv: 2107.04216

DM capture in Neutron Stars

- Extremely efficient at capturing DM, capture probability order 1 for $\sigma_{n\chi} \sim \mathcal{O}(10^{-45} - 10^{-44} \mathrm{cm}^2)$
- Capture plus subsequent annihilation can heat up local NSs (10 pc) Baryakhtar et al. arXiv:1704.01577 (PRL)

➡ Possible detection with JWST NIRCam (SNR = 5) Chatterjee et al. arXiv: 2205.05048



Neutrons Stars

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

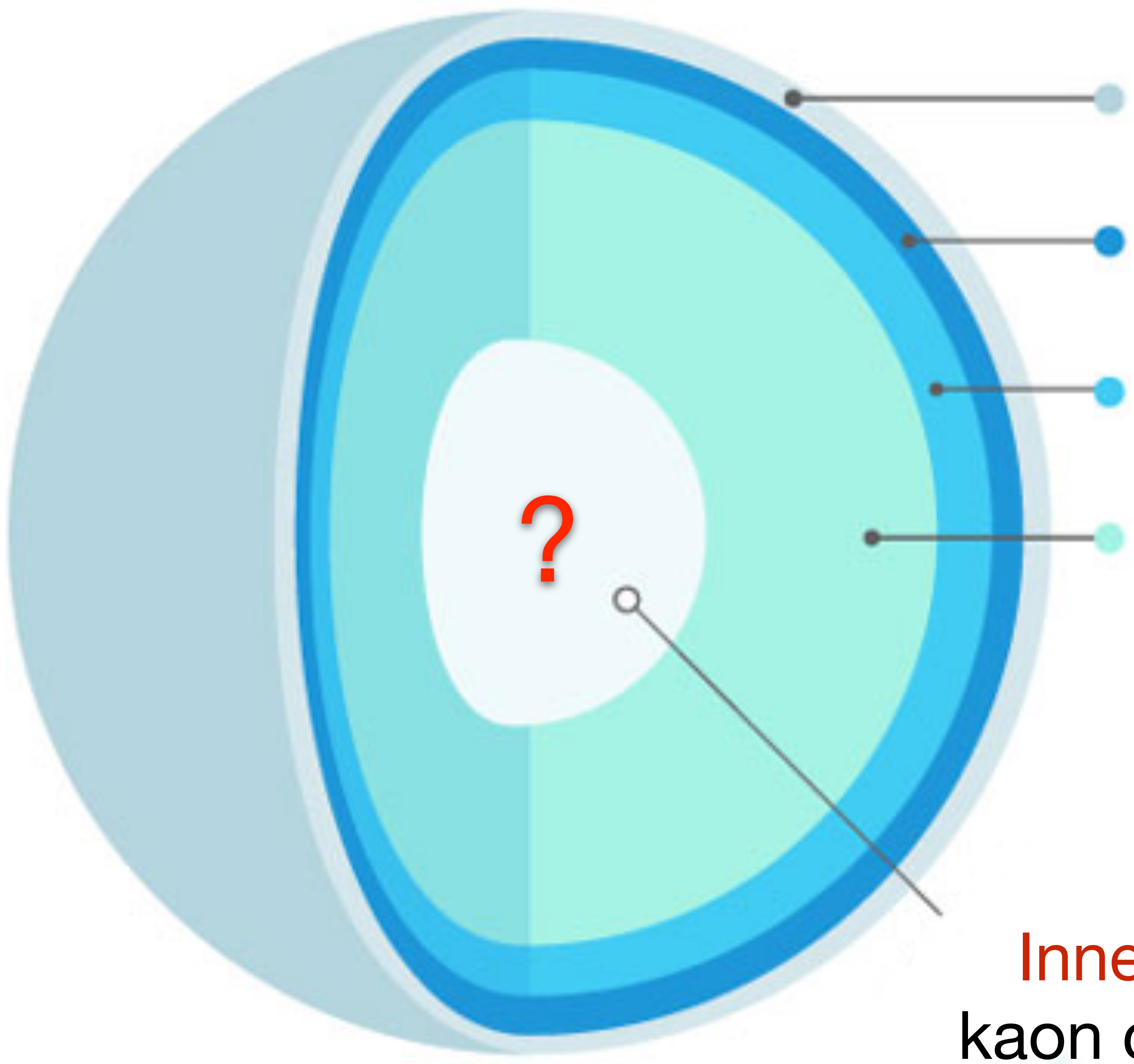


Image Credit: Feryal Özel

Equation of State (EoS)

$$P = P(\rho)$$

- APR
- BSk
- QMC
- SLy, …

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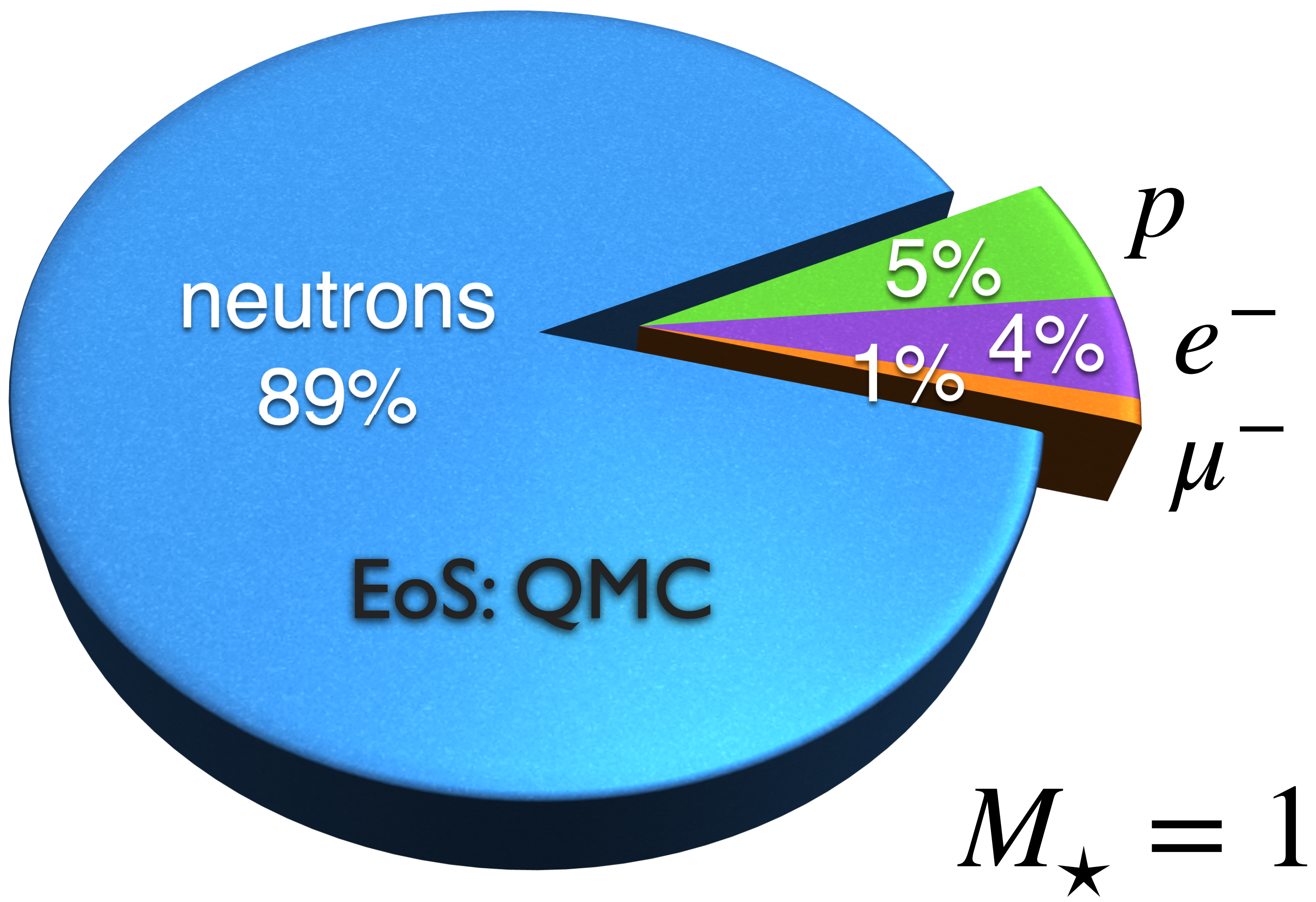
Hydrostatic Equilibrium

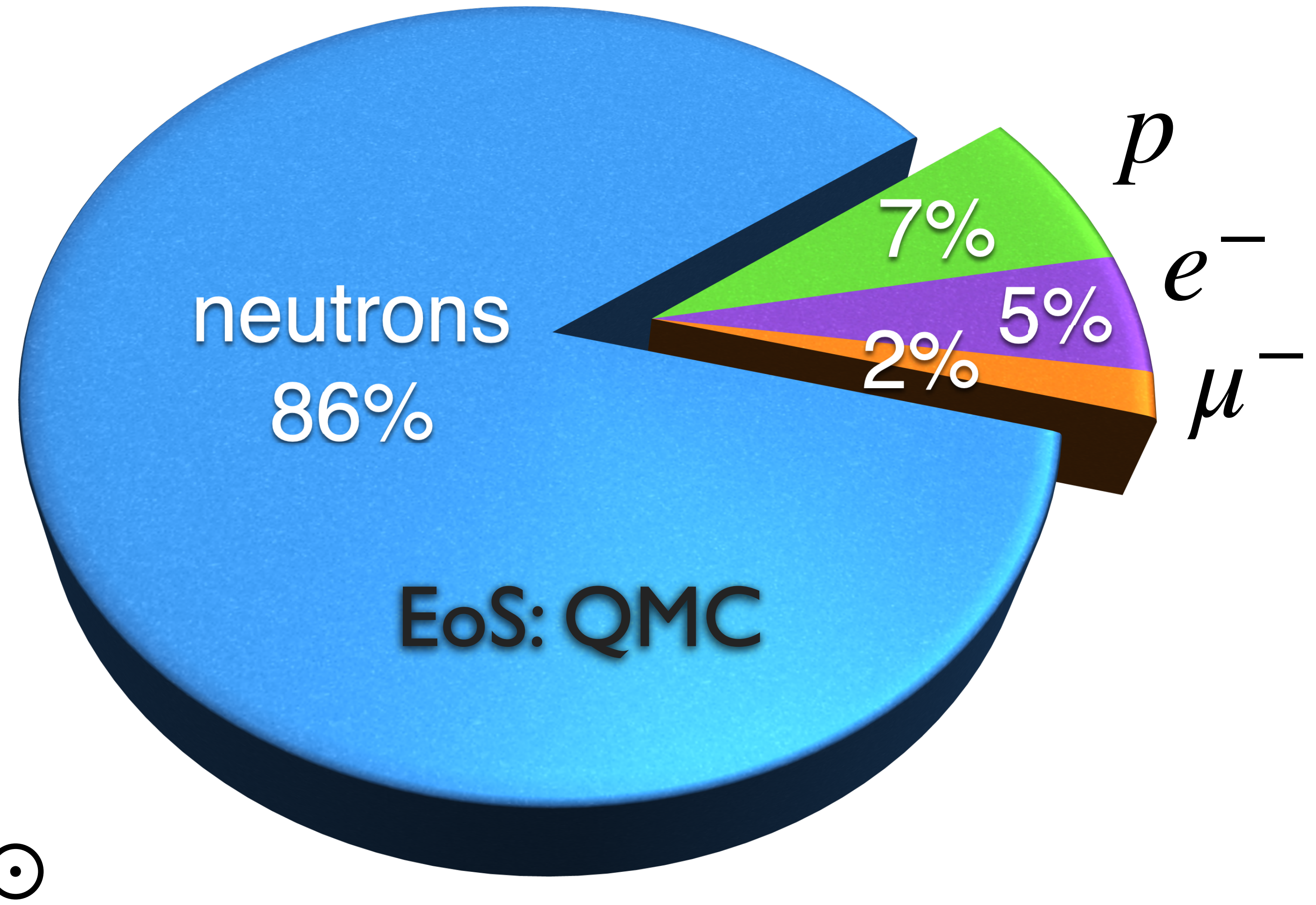
- Tolman-Oppenheimer-Volkoff (TOV) equations

DM capture in Neutron Stars

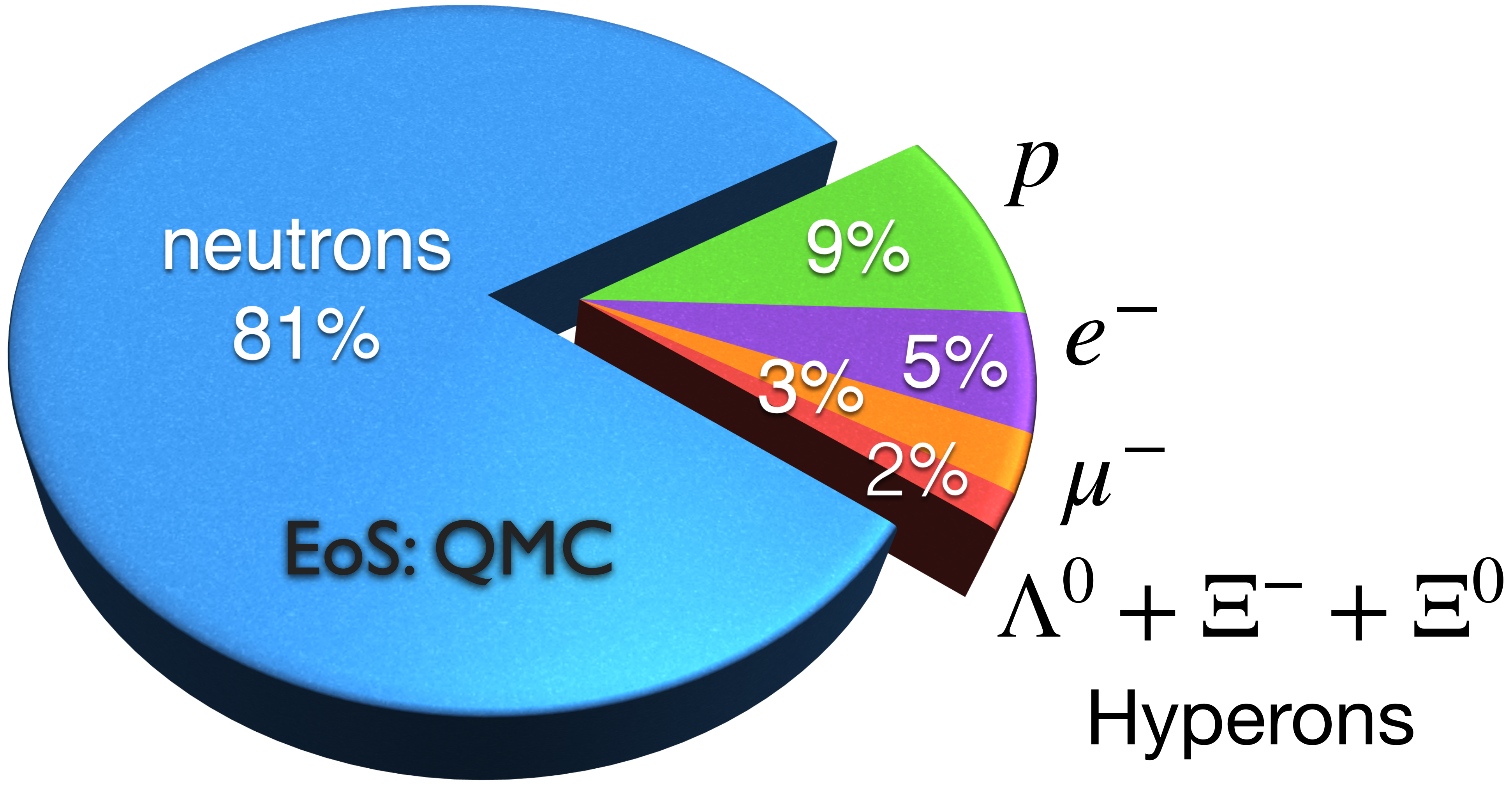
$M_\star = 1\, M_\odot$



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



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



Targets

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

DM capture in Neutron Stars

Scattering off a Fermi gas of interacting baryons

- Different kinematic regime from DM capture in the Sun.

➡ DM accelerated to quasi-relativistic speeds

➡ TOV equations and Schwarzchild metric

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

DM flux

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

Capture rate

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

Interaction 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

Pauli Blocking target initial and final states

Bell, Busoni, SR & Virgato, arXiv: 2004.14888

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

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

Nucleon couplings

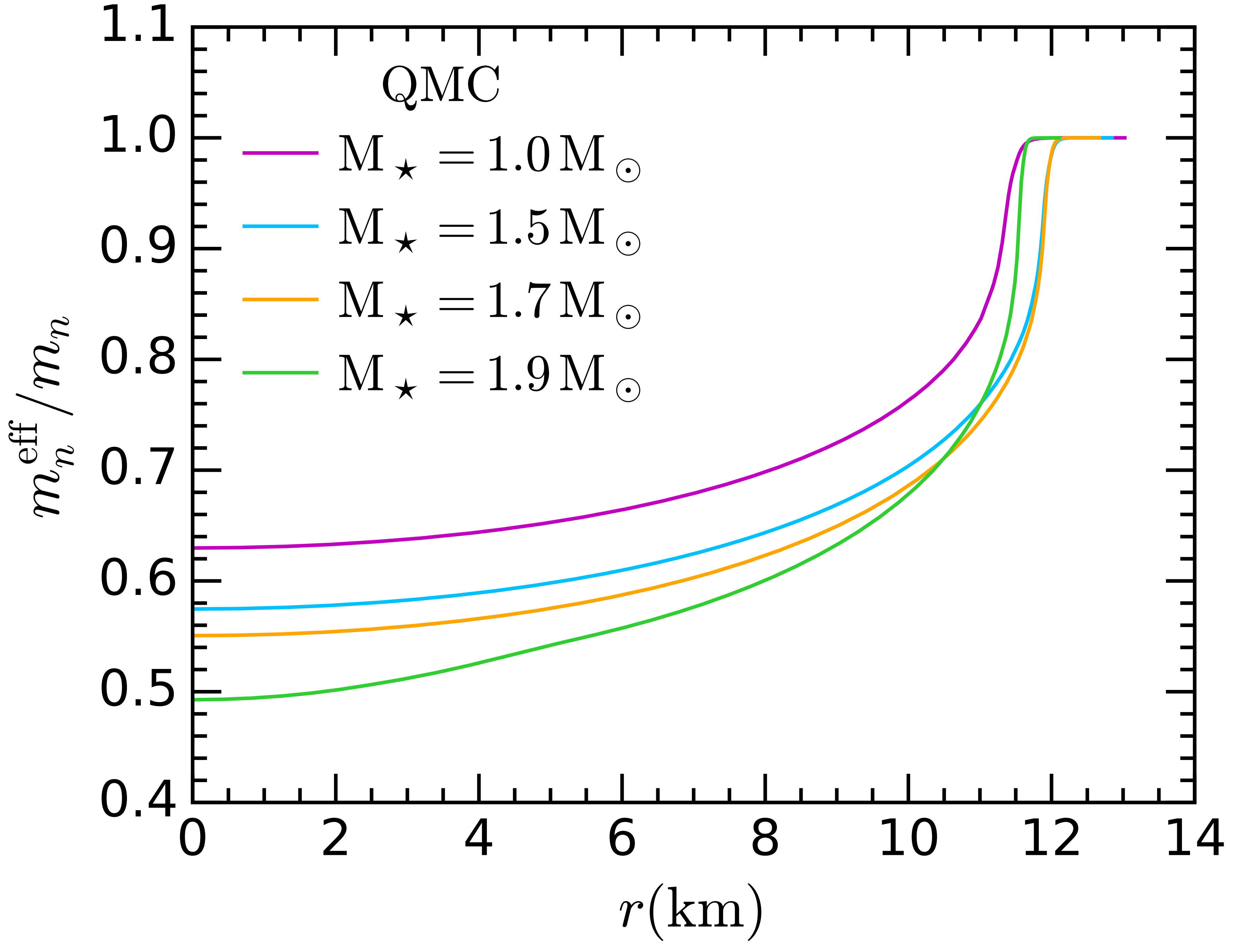
$$c_n(q) = \frac{c_n(0)}{(1-q^2/Q_0^2)^2}$$

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

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

Nucleon effective mass

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



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

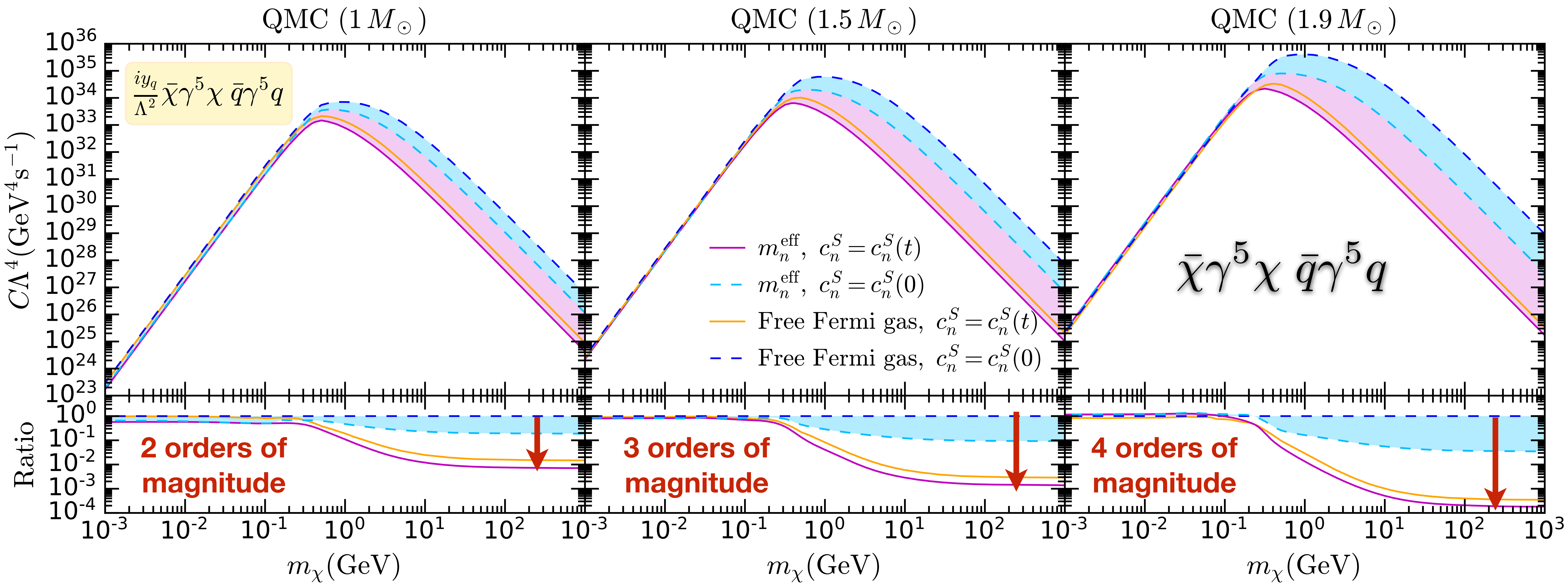
Scattering Operators for Fermionic DM

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-neutron capture rate in NSs

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

Suppression of the capture rate



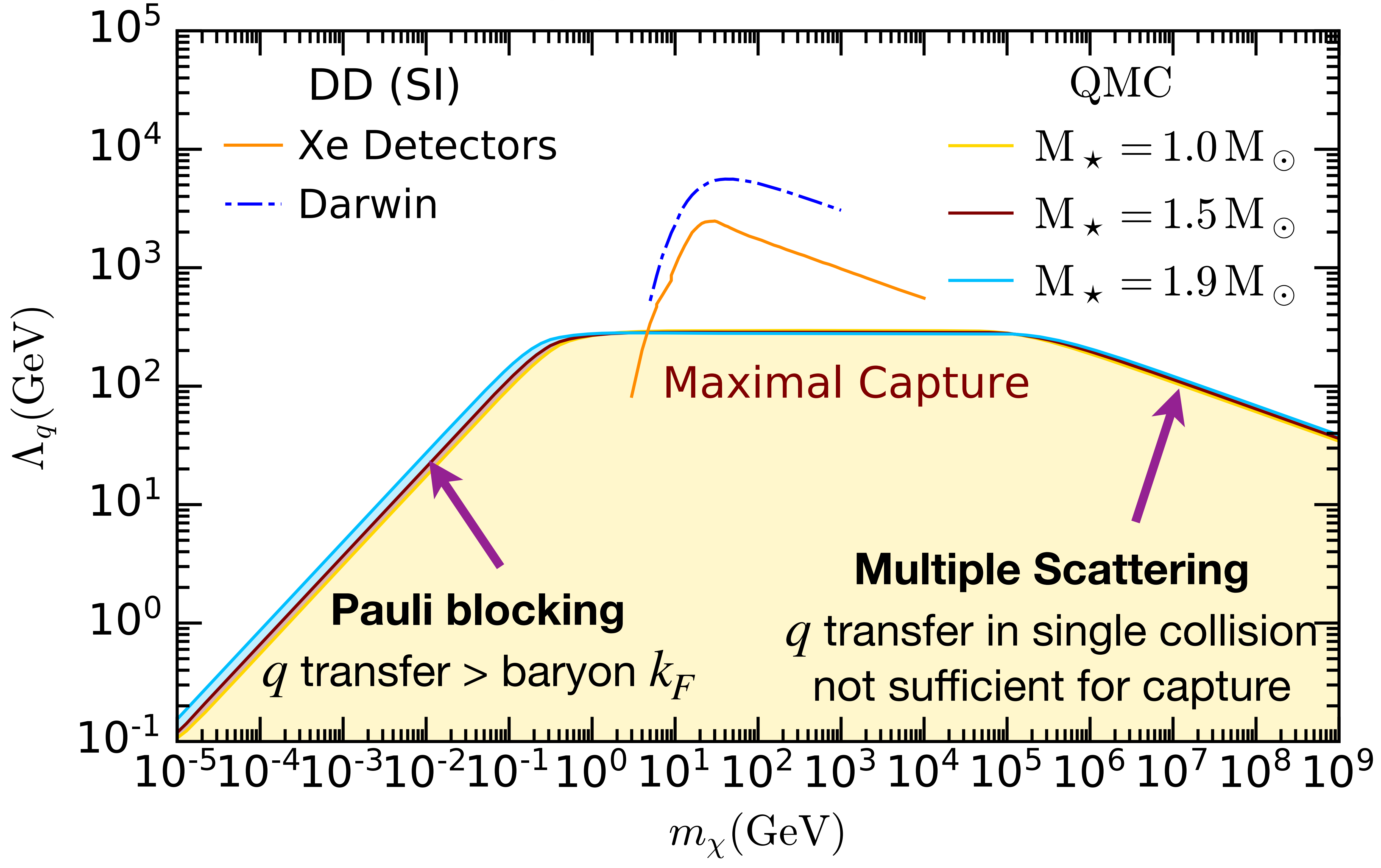
Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918, arXiv: 2108.02525

NS sensitivity to DM-nucleon interactions

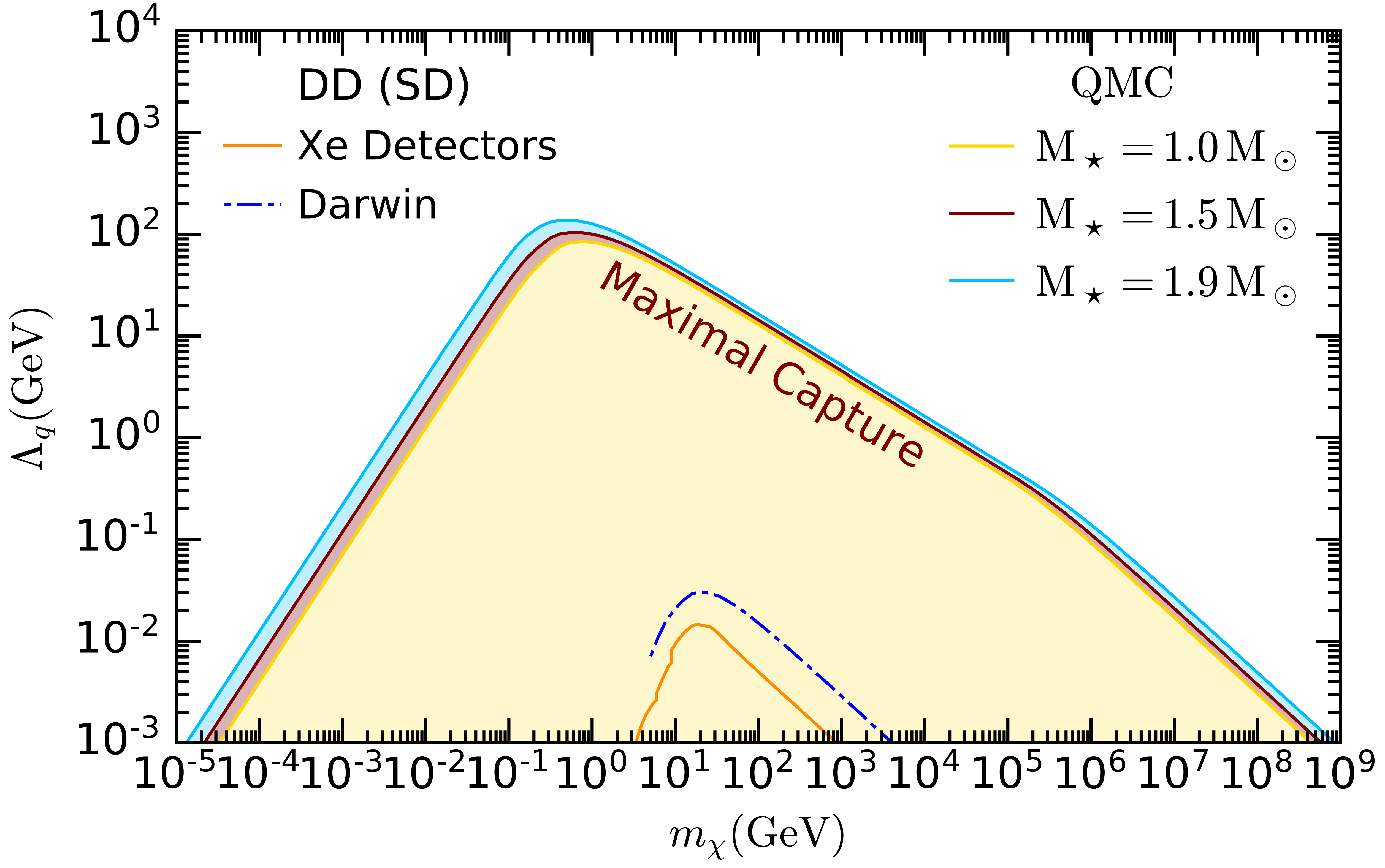
EFT operators

$$\sigma_{i\chi} \propto \Lambda_q^{-4}$$

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

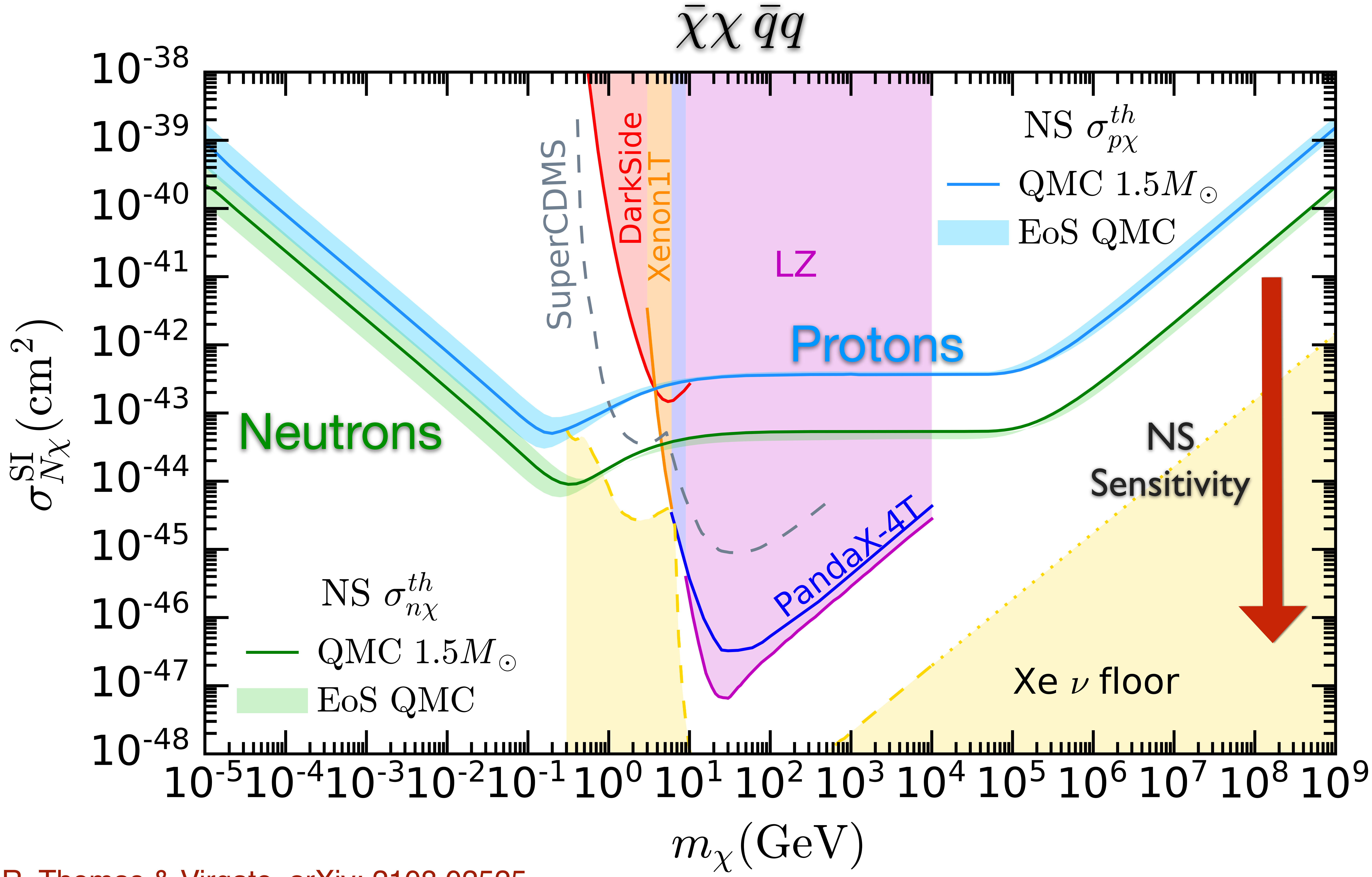


$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$ q^4 suppressed



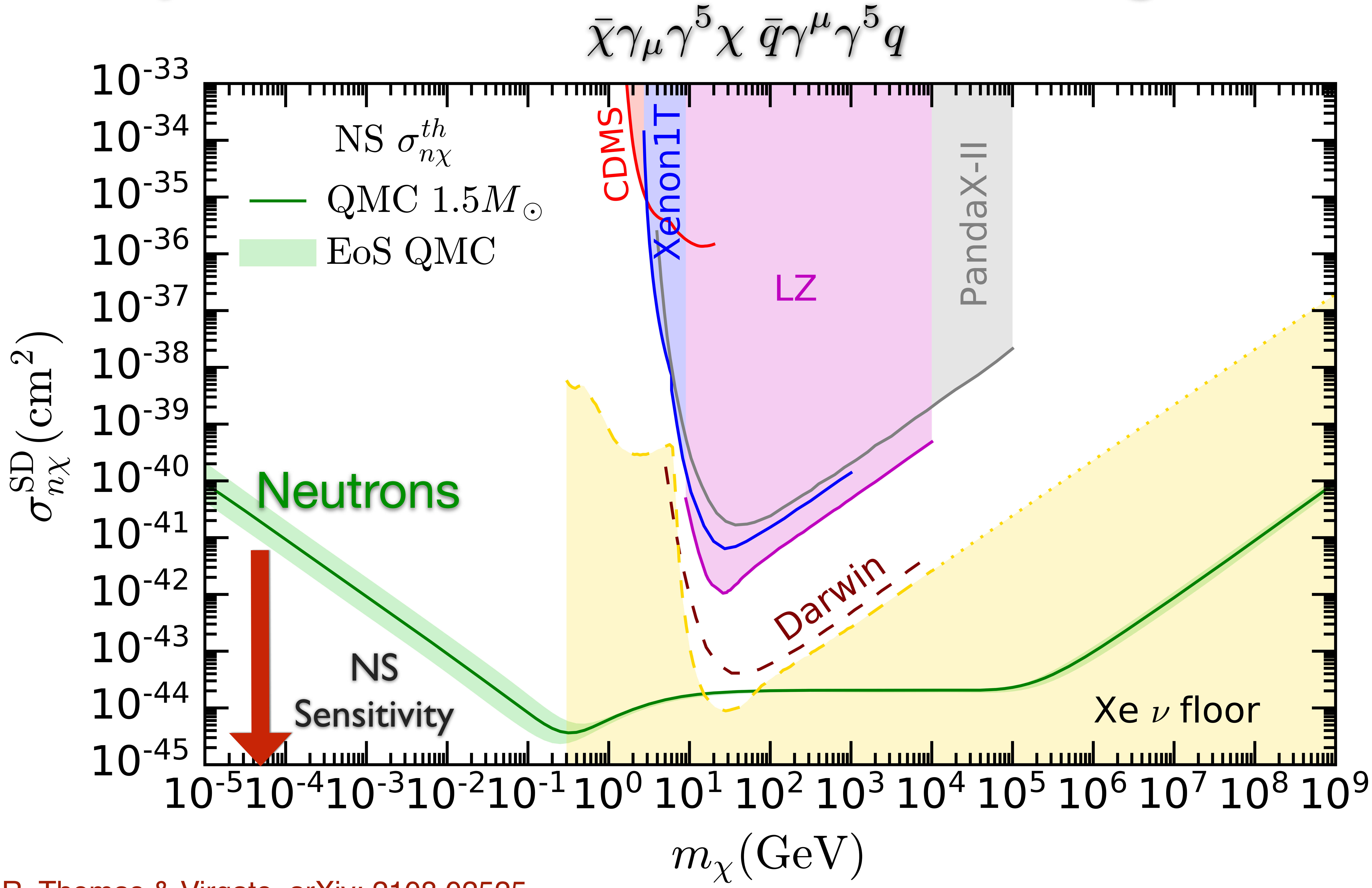
Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525

NS sensitivity to SI DM-nucleon scattering cross section



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

NS sensitivity to SD DM-neutron scattering cross section



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

DM Thermalisation in NSs

- Capture
- Further scatterings
- Thermalised

1st stage: N_1 scatterings

2nd stage: N_2 scatterings

$$t_1^{\rm therm} \ll t_2^{\rm therm}$$

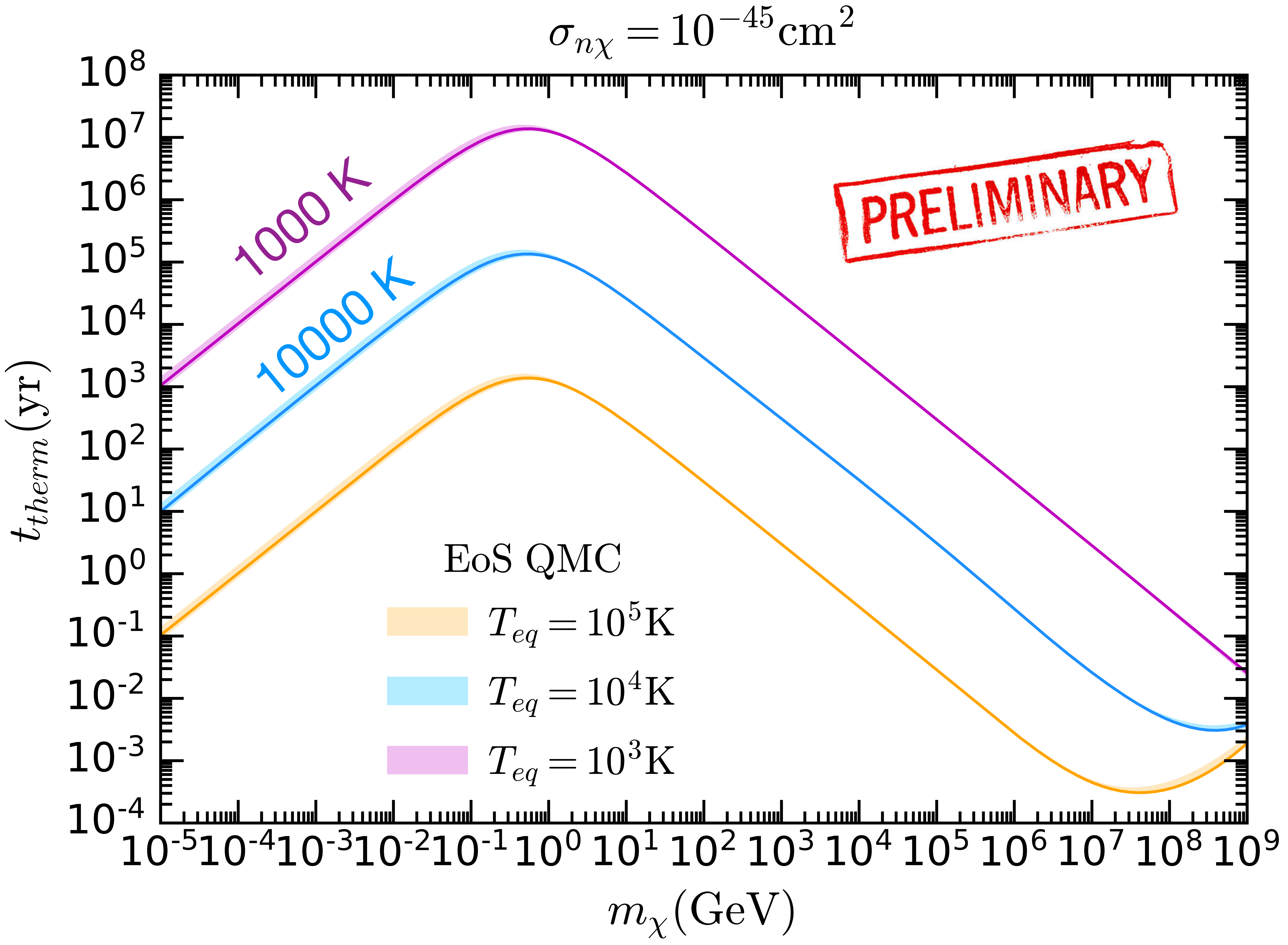
$$t_{\rm therm} \simeq t_2^{\rm therm}$$

DM Thermalisation in NSs

- After $N_1 + N_2$ scatterings DM reaches equilibrium temperature $T_{\rm eq}$
- Thermalisation time (Pauli Blocking)
  - ➡ Sum of average time between collisions
  - ➡ Final energy transfer = $T_{\rm eq}$

$$t_{\rm therm} \simeq \sum_{n=N_1}^{N_2} \frac{1}{\Gamma^{-}(K_n)}.$$

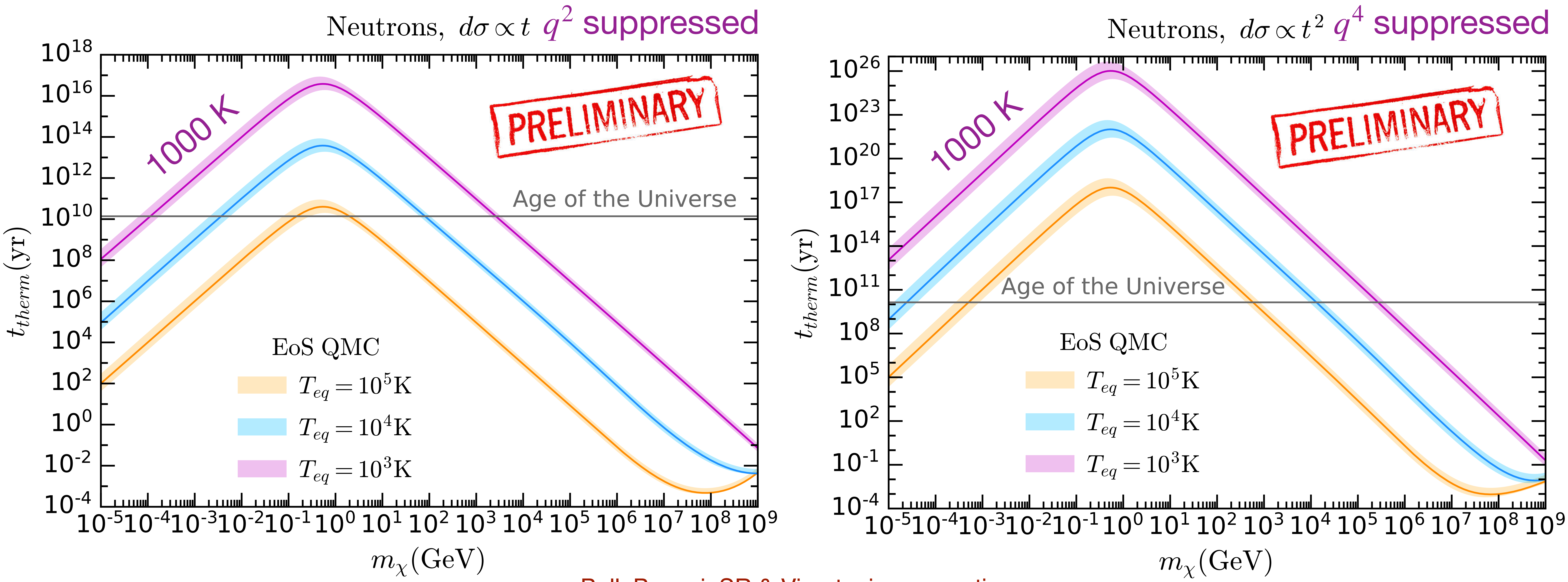
Bertoni, Nelson & Reddy, arXiv: 1309.1721



Bell, Busoni, SR & Virgato, in preparation

DM Thermalisation in NSs

- Momentum suppressed interactions



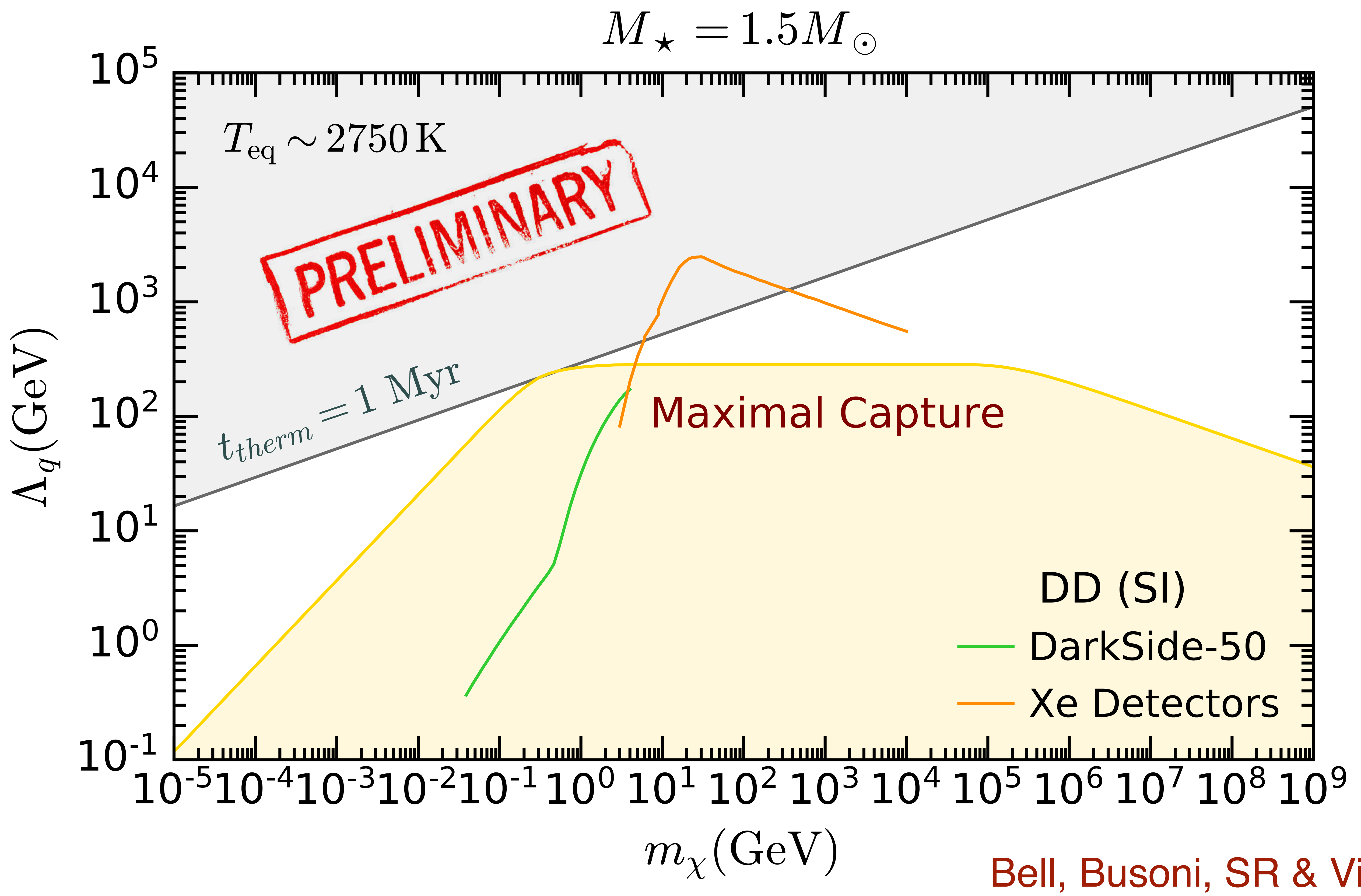
Bell, Busoni, SR & Virgato, in preparation

DM Thermalisation in NSs

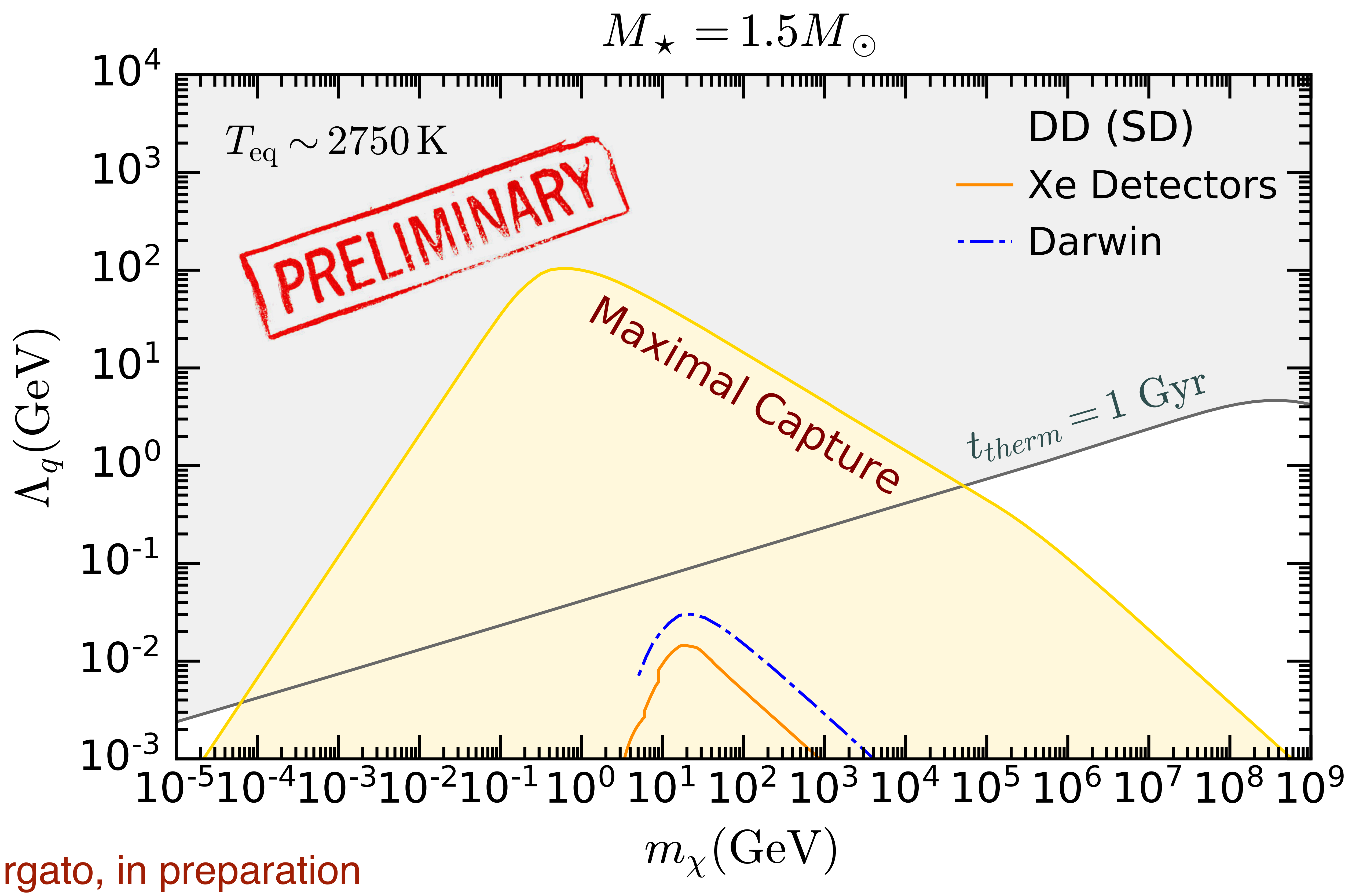
EFT operators

- Captured DM thermalises in ~ 1 Myr (unsuppressed interactions)

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



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



Bell, Busoni, SR & Virgato, in preparation

Capture and Annihilation Equilibrium

- Number of accumulated DM particles depends on the capture, evaporation and annihilation rates

$$\frac{dN_\chi}{dt} = C - EN_\chi - AN_\chi^2$$

Annihilation rate: $\Gamma_{ann} = \frac{1}{2} AN_\chi^2$

- When evaporation is negligible $m_\chi \gtrsim m_{evap}$

$$m_{evap} \sim \mathcal{O}(10\text{eV})$$

Bell, Busoni, SR & Virgato, arXiv: 2010.13257

$$N_\chi(t) = \sqrt{\frac{C}{A}} \tanh\left(\frac{t}{t_{eq}}\right)$$

where

$$t_{eq} = \frac{1}{\sqrt{CA}}$$

$$A \simeq \frac{\langle \sigma_{\text{ann}} v_\chi \rangle}{(2\pi)^{3/2} r_\chi^3}$$

- If $t \gg t_{eq}$ → $\Gamma_{ann} = \frac{1}{2} C(\sigma)$ capture - annihilation equilibrium

DM Annihilation in NSs

- If DM has not yet thermalized

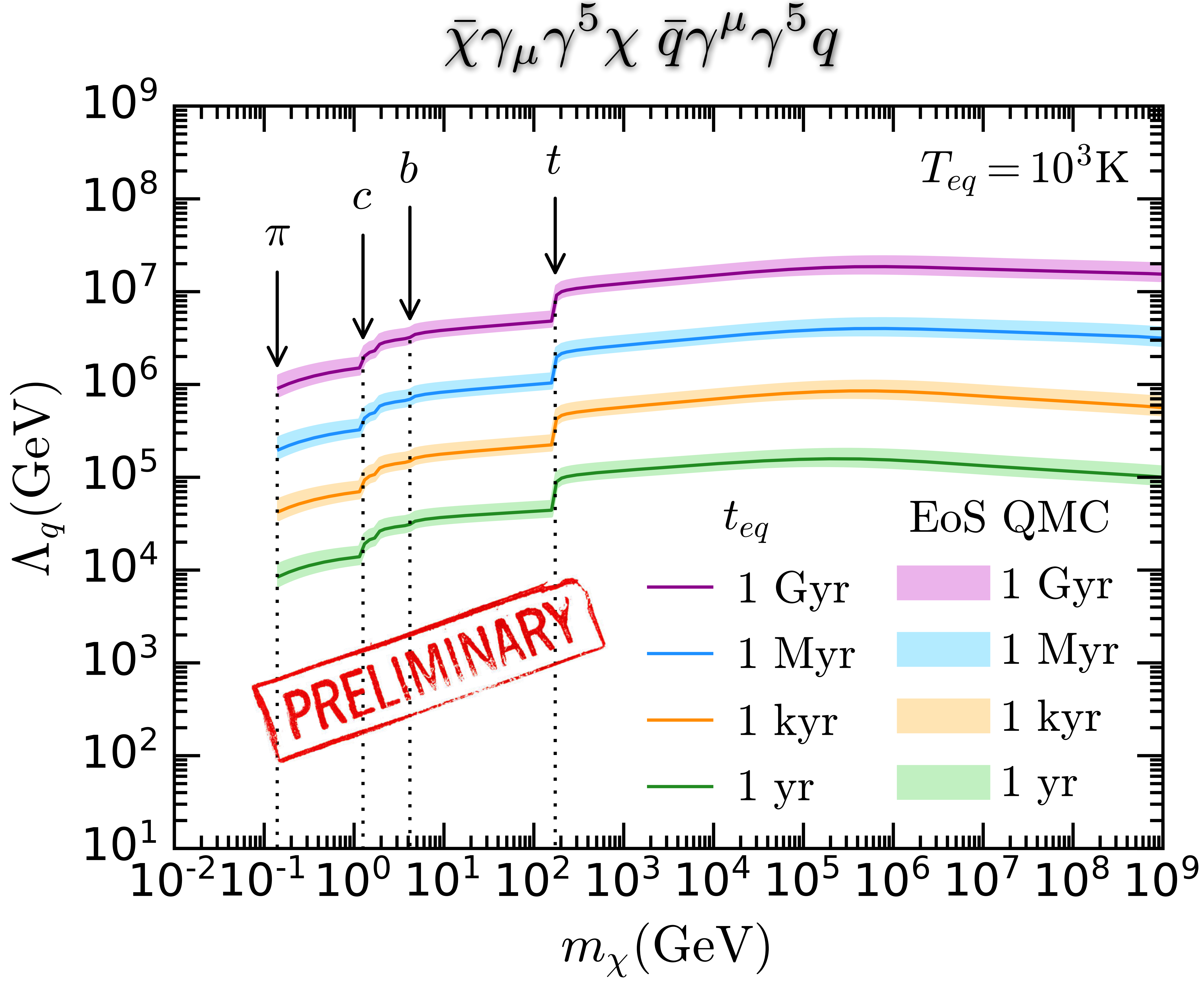
$$t_{\rm eq} = \frac{1}{\sqrt{CA}}\left(\frac{t_{\rm therm}+t}{t}\right)^{\frac{\alpha}{2(2+n)}}$$

- Annihilation final states

$$\chi\chi \to t\bar{t}, b\bar{b}, c\bar{c}, \pi^+\pi^-$$

- Annihilation to leptons
  - ➡ Model dependent
  - ➡ Pauli blocked

Bell, Busoni, SR & Virgato, in preparation

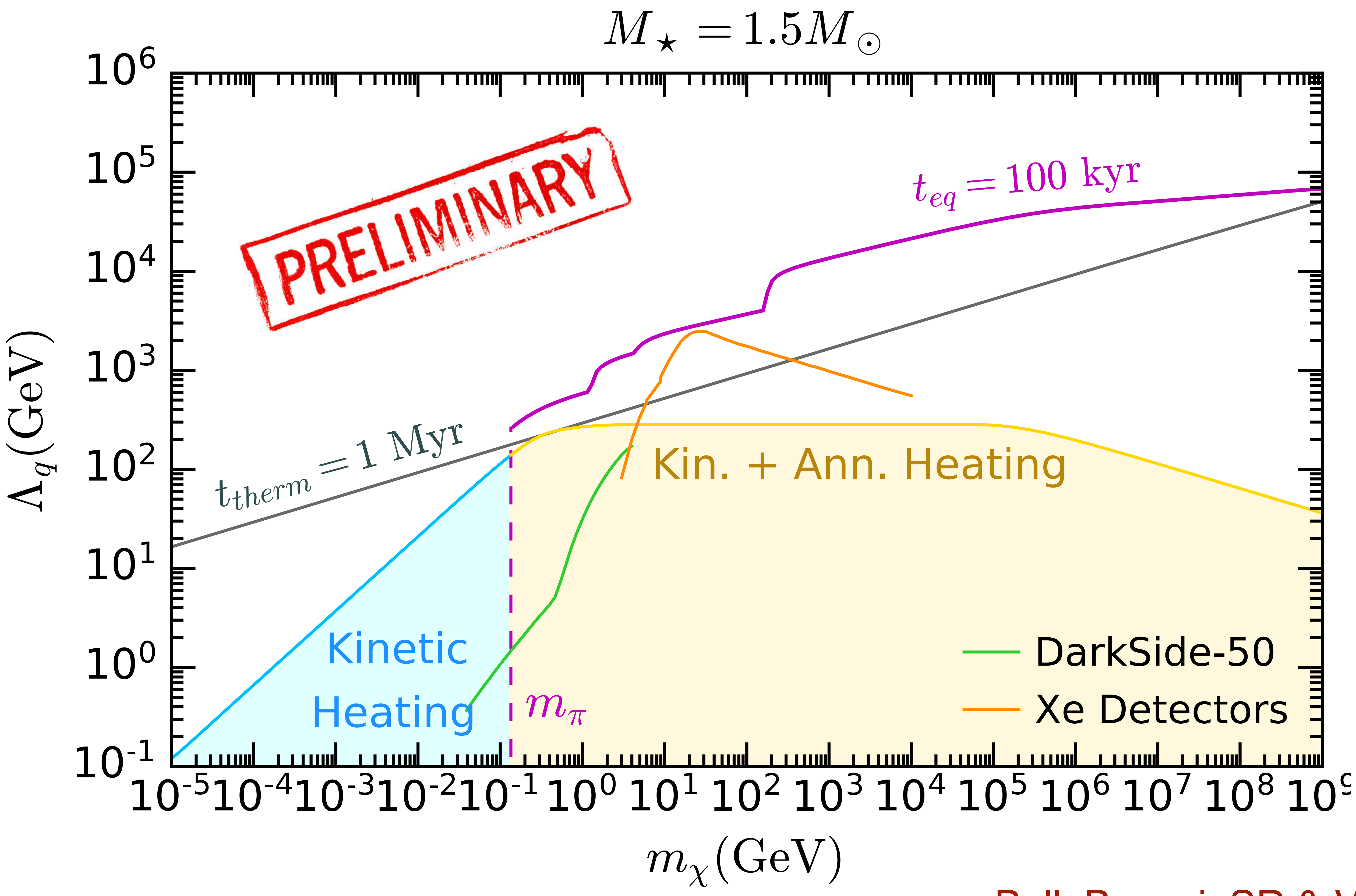


DM-induced Heating of NSs

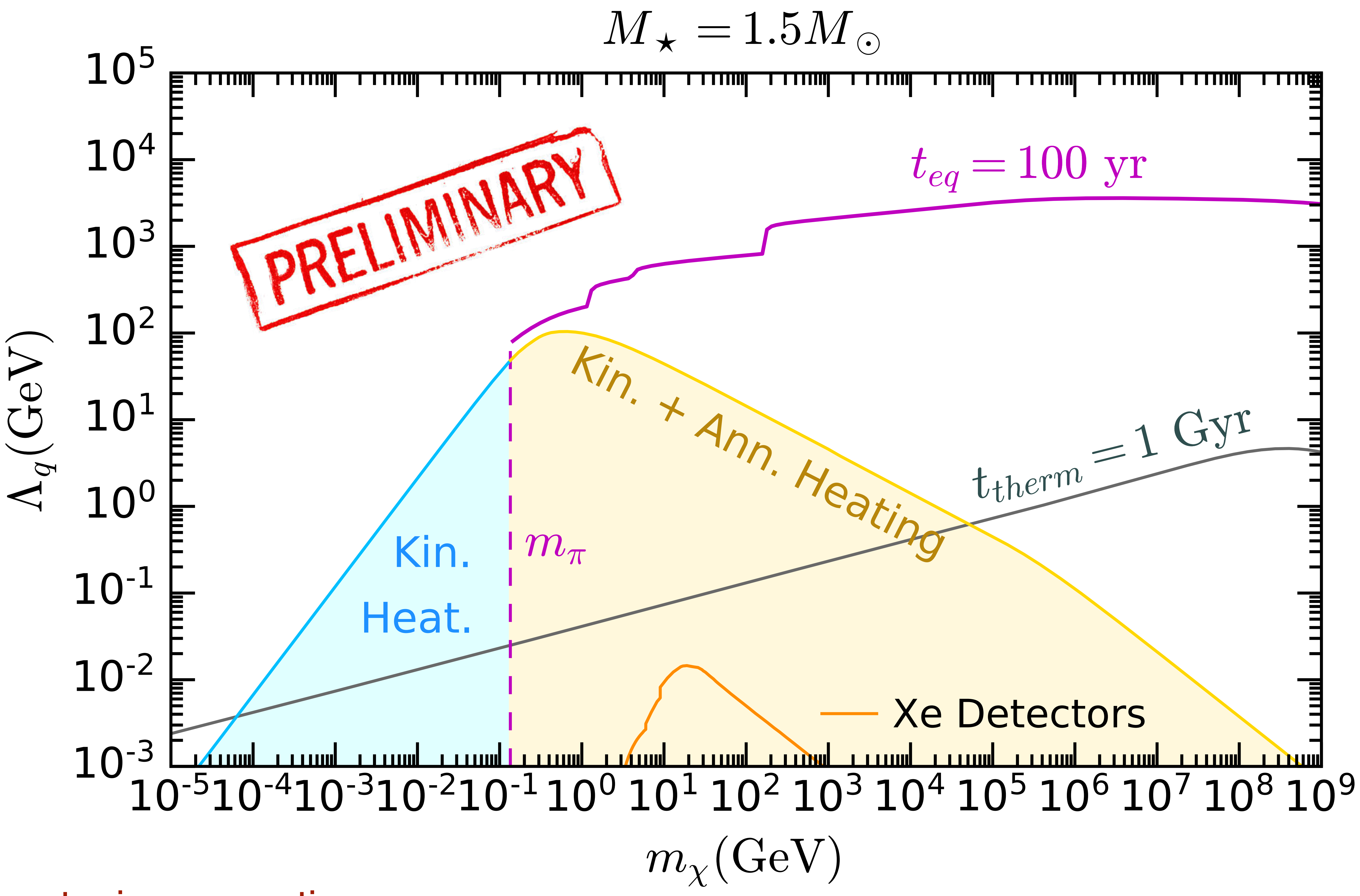
EFT operators

- 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, in preparation

Summary

- Improved calculation of the DM capture in neutron stars for (non-)relativistic, degenerate targets.

  ➡ Strong interactions in NSs require treatment beyond the free Fermi gas approximation.

- Neutron stars could constrain different types of interactions, including those that are velocity and momentum suppressed.
- Captured DM would thermalise in ~ 1 Myr (unsuppressed interactions), momentum suppressed operators will need longer than the age of the Universe.
- Capture-annihilation equilibrium reached for all interactions in ~1 yr up to 100 kyr.
- Constraining DM interactions using DM-induced anomalous heating of neutron stars require

  ➡ Observation of old (cold) neutron stars.

  ➡ Better understanding of the cooling process in neutron stars.

Thank you for your attention!