The Timescales for Dark Matter heating of old Neutron Stars

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in collaboration with

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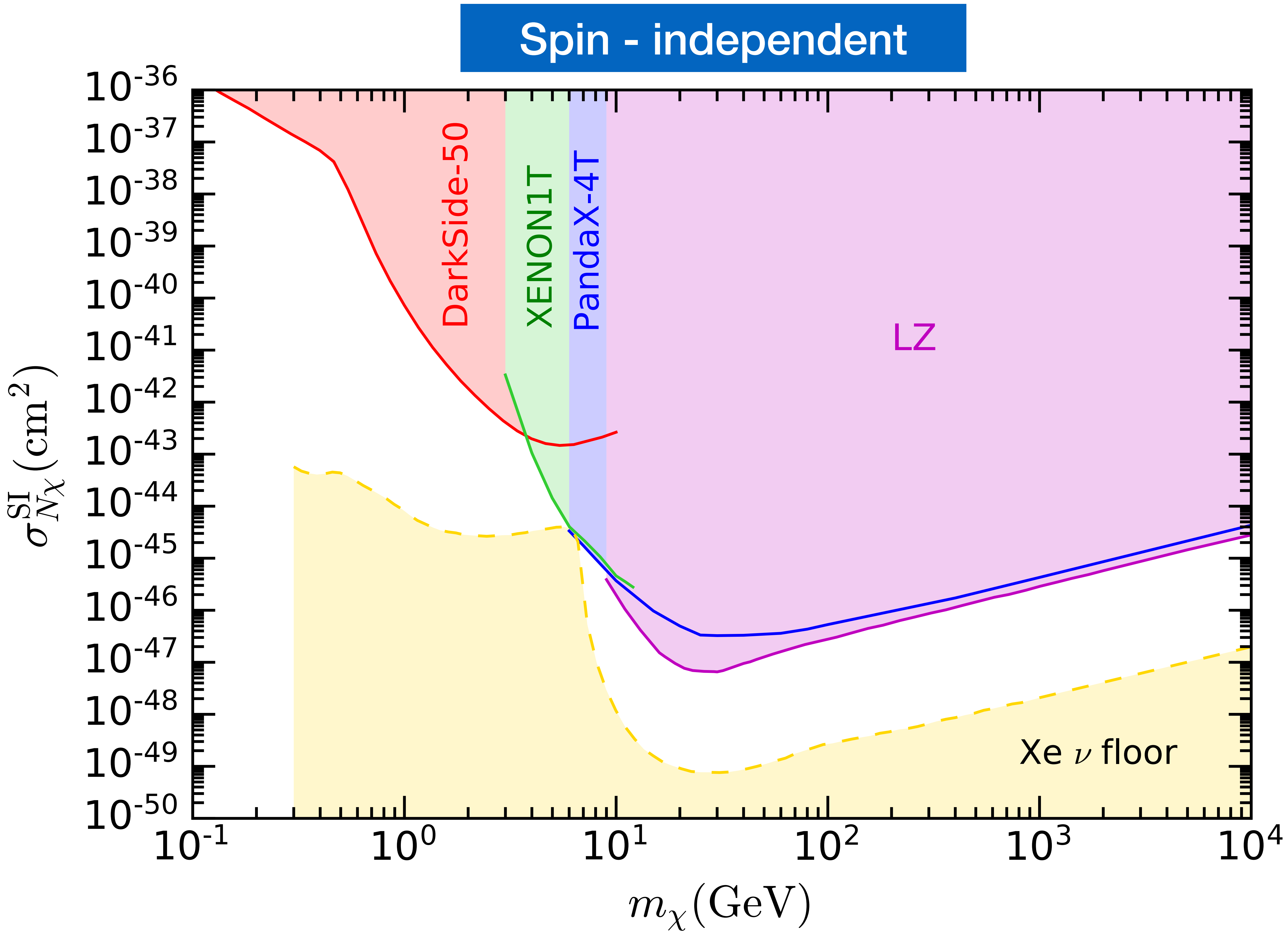
arXiv:2312.11892 (JCAP)

Fermilab

Introduction

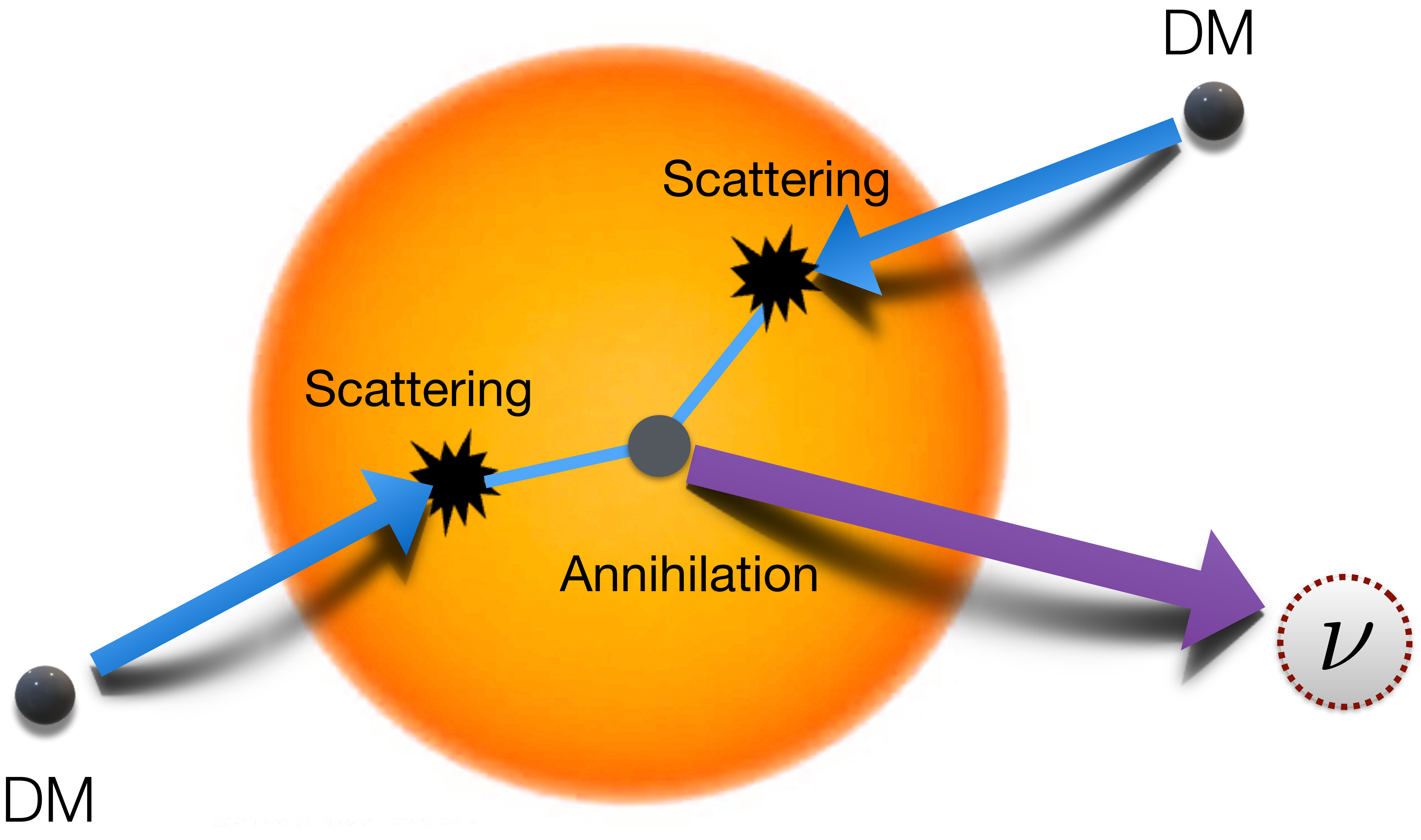
Direct Detection

- 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 and SD cross sections.



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

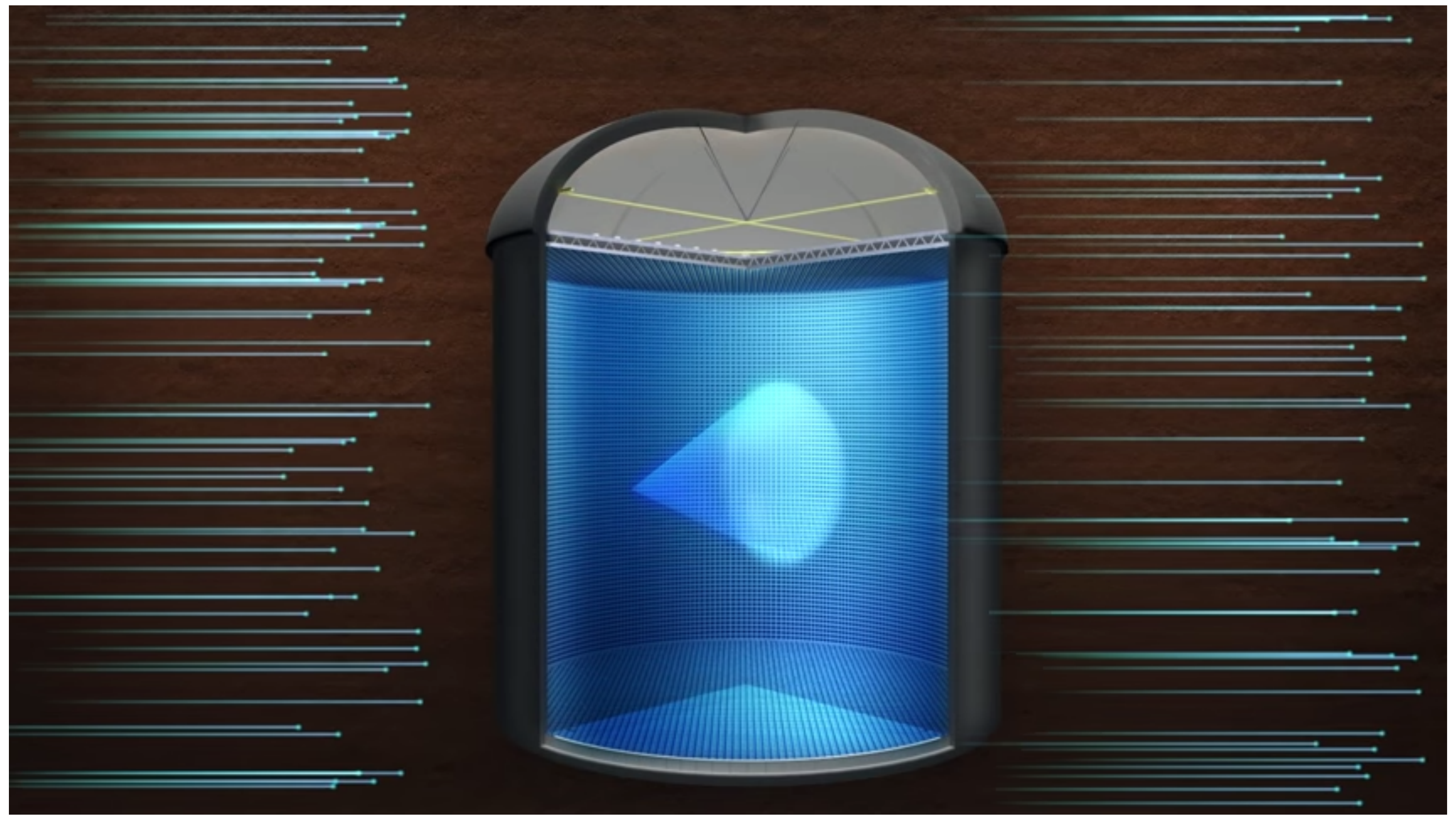
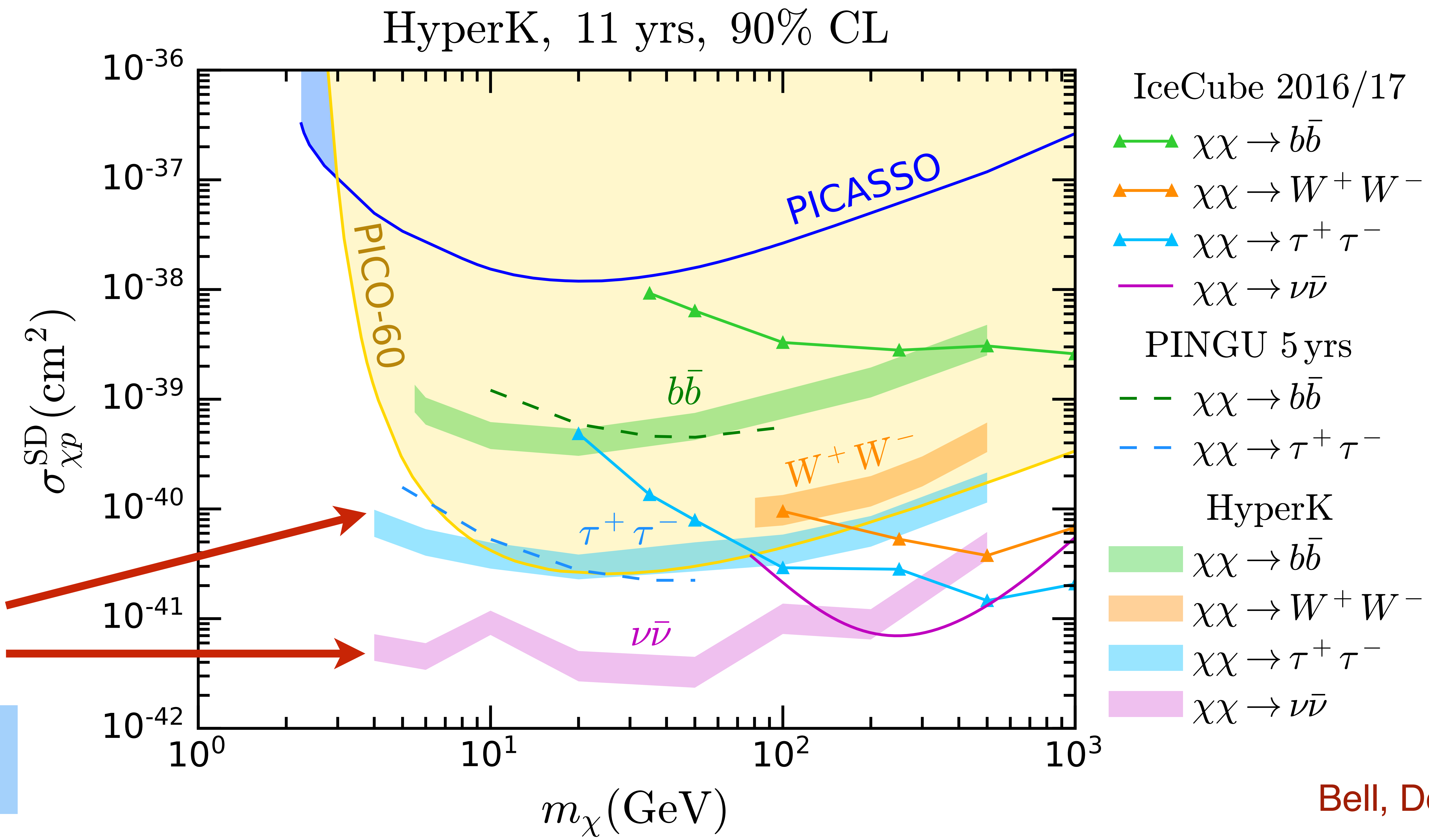


Image credit: Institute for Cosmic Ray Research,The University of Tokyo

Captured DM annihilating in the Sun

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

Spin - dependent



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

Bell, Dolan & SR arXiv: 2107.04216

Neutron Stars

- Neutron stars as DM probes Goldman & Nussinov 1989
- Higher density ➡ higher efficiency at capturing DM
- Capture probability order 1 for

$$\sigma_{n\chi} \sim \mathcal{O}(10^{-45} - 10^{-44}\mathrm{cm}^2)$$

- DM can heat up old, isolated, NSs in the local bubble

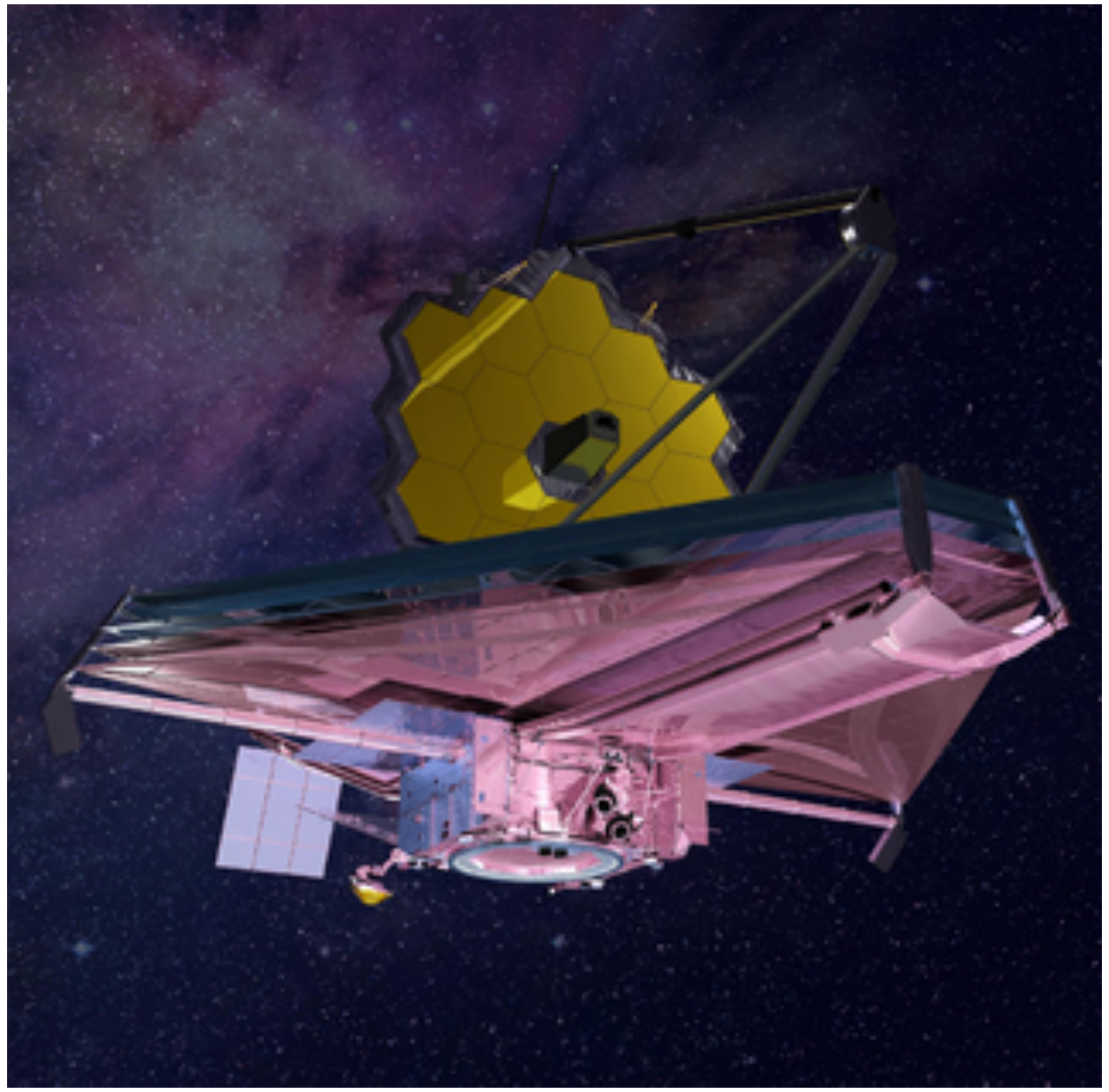
➡ Kinetic + annihilation heating

➡ Possibly within the reach of the JWST

Baryakhtar et al. arXiv:1704.01577

Chatterjee et al. arXiv: 2205.05048

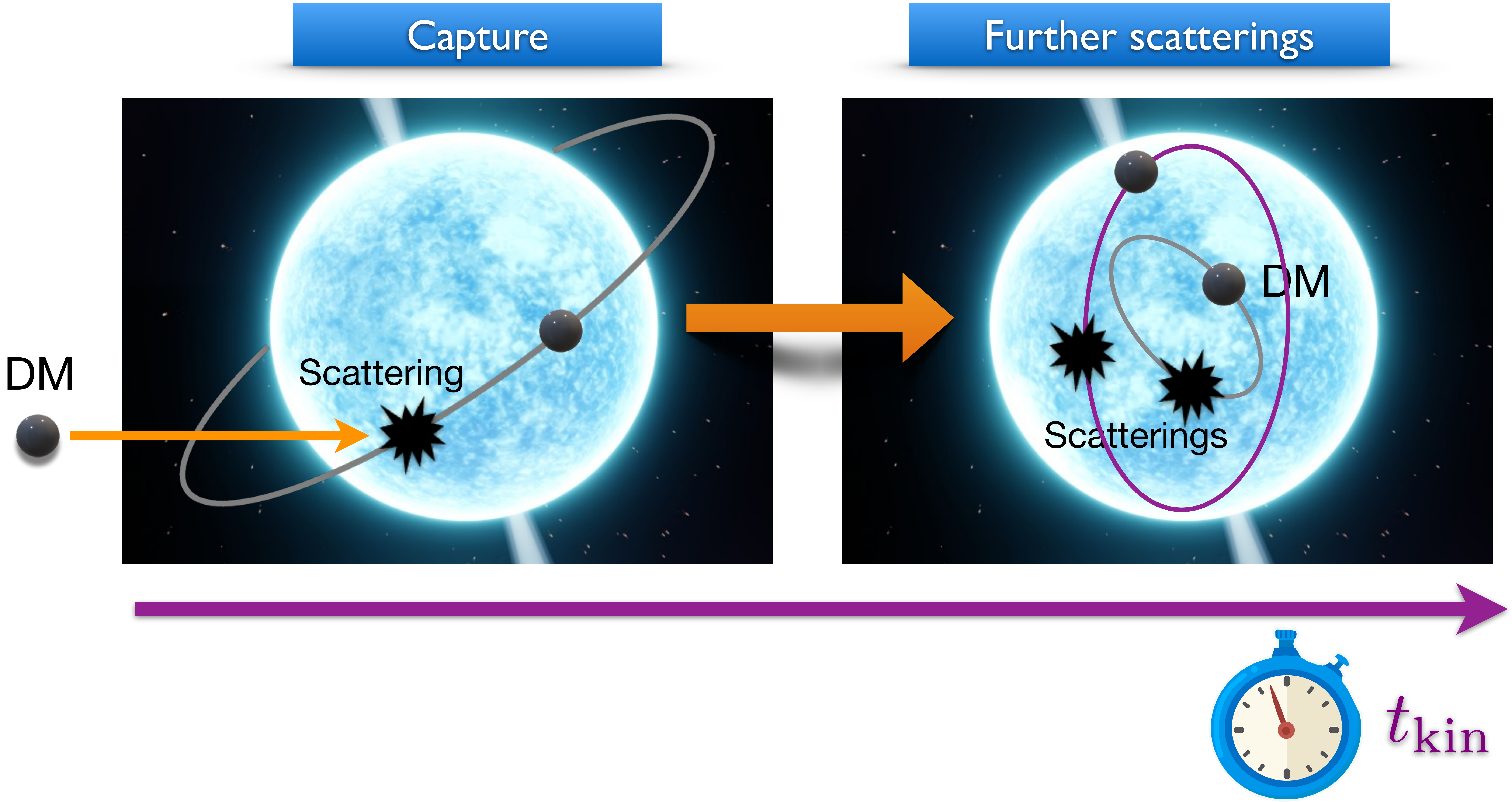
JWST (NIRcam)



1st

Timescale

DM kinetic heating

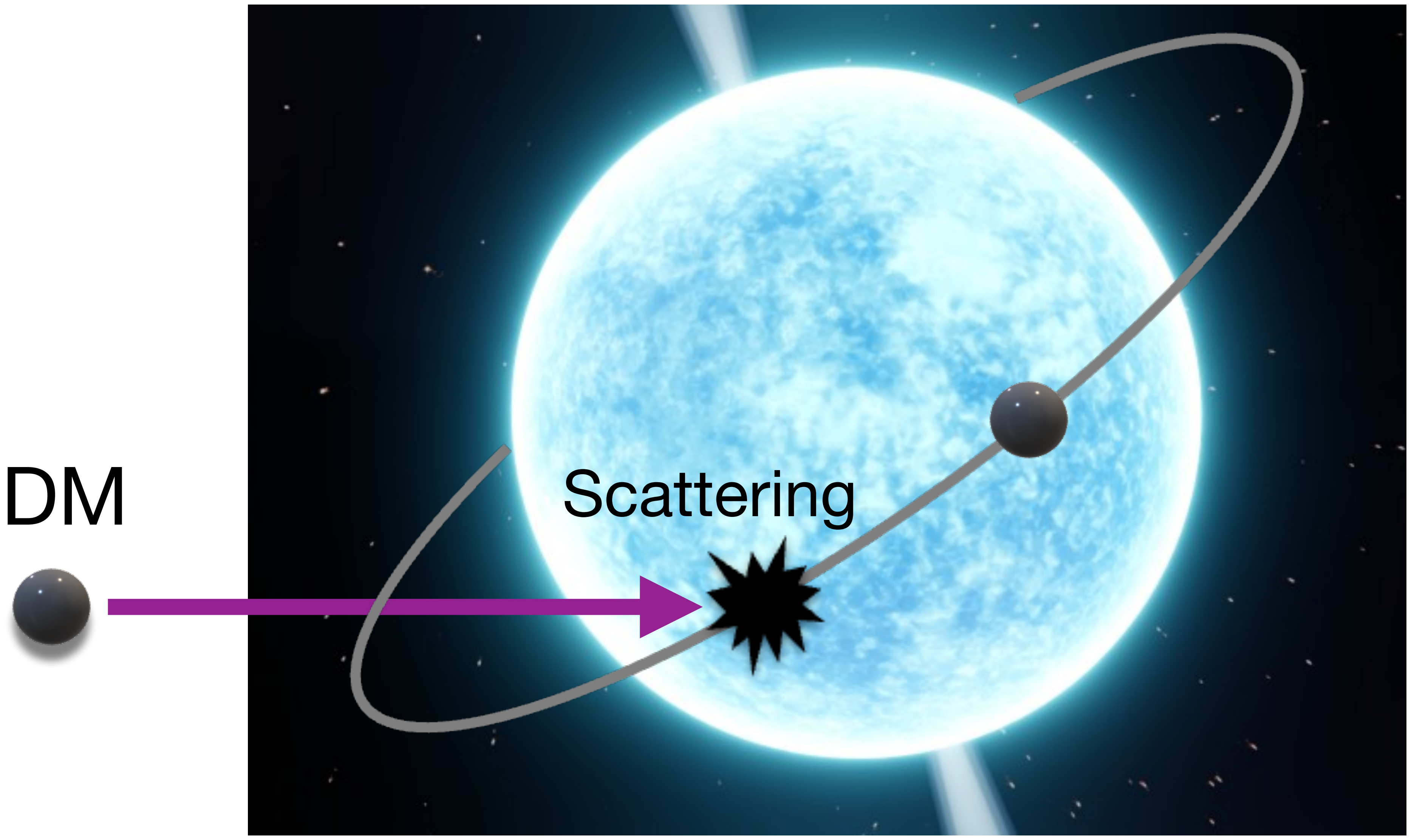


DM kinetic heating of Neutron Stars

- DM kinetic energy deposited through scatterings, including capture $\chi n \to \chi n$

➡ DM contribution to the star luminosity $L_\chi = \dot{E}_\chi^{\rm kin} = 4\pi\sigma_{SB} R_\star^2 T_{\chi,\rm kin}^4$

Capture



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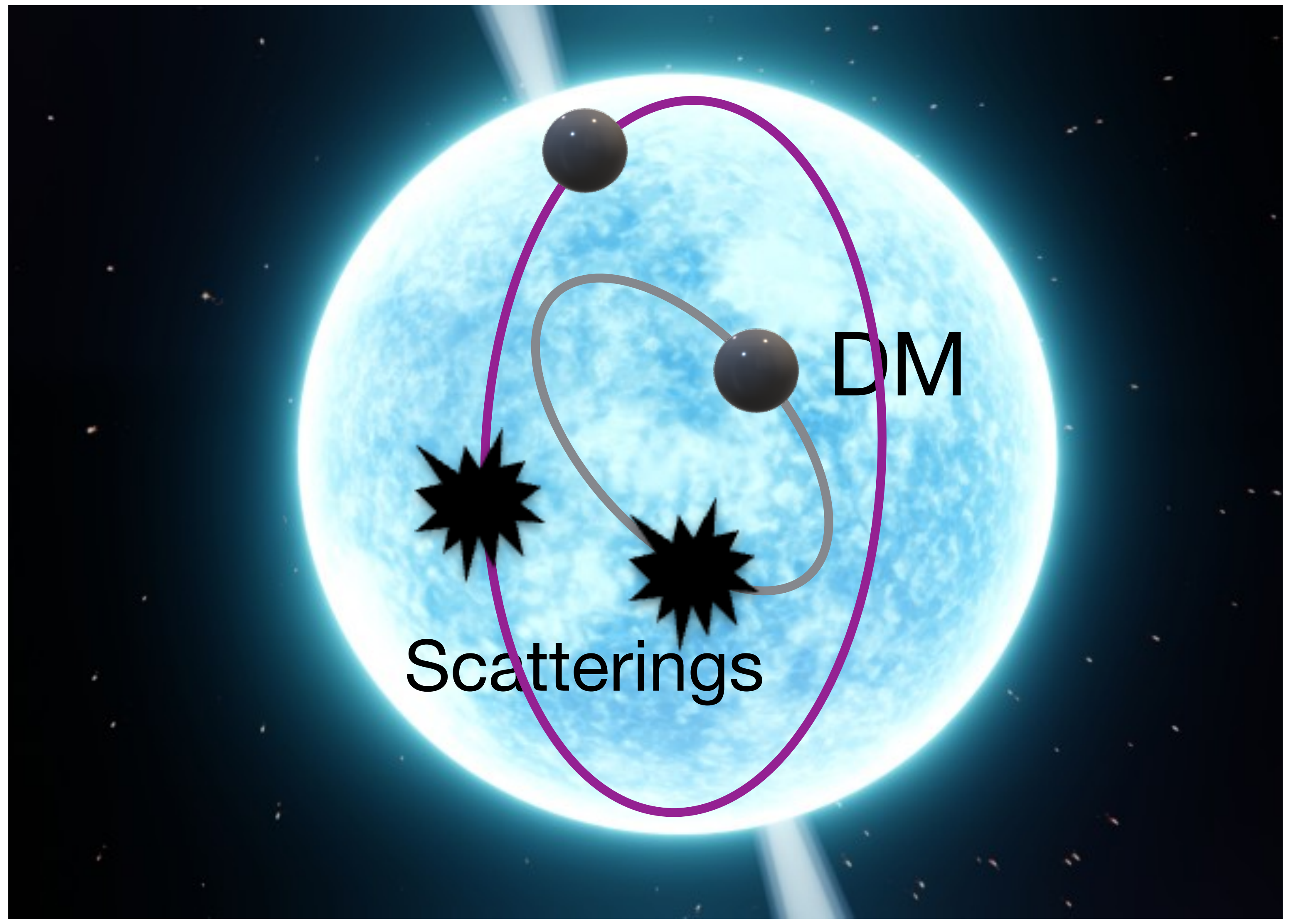
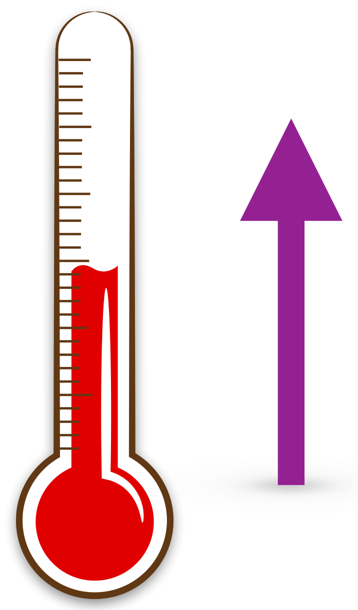
Further scatterings



➡ Maximal capture local NS $1.5\, M_\odot$

=



$T_{\chi,\rm kin}^\infty \sim 1850\,\rm K$

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
  - ➡ Degenerate targets

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

Capture rate

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

DM flux

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

Interaction rate

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

Relativistic kinematics

Pauli Blocking target initial and final states

Bell, Busoni, SR & Virgato, arXiv: 2004.14888, + Motta & Thomas, arXiv: 2012.08918

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

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

1. Nucleon couplings

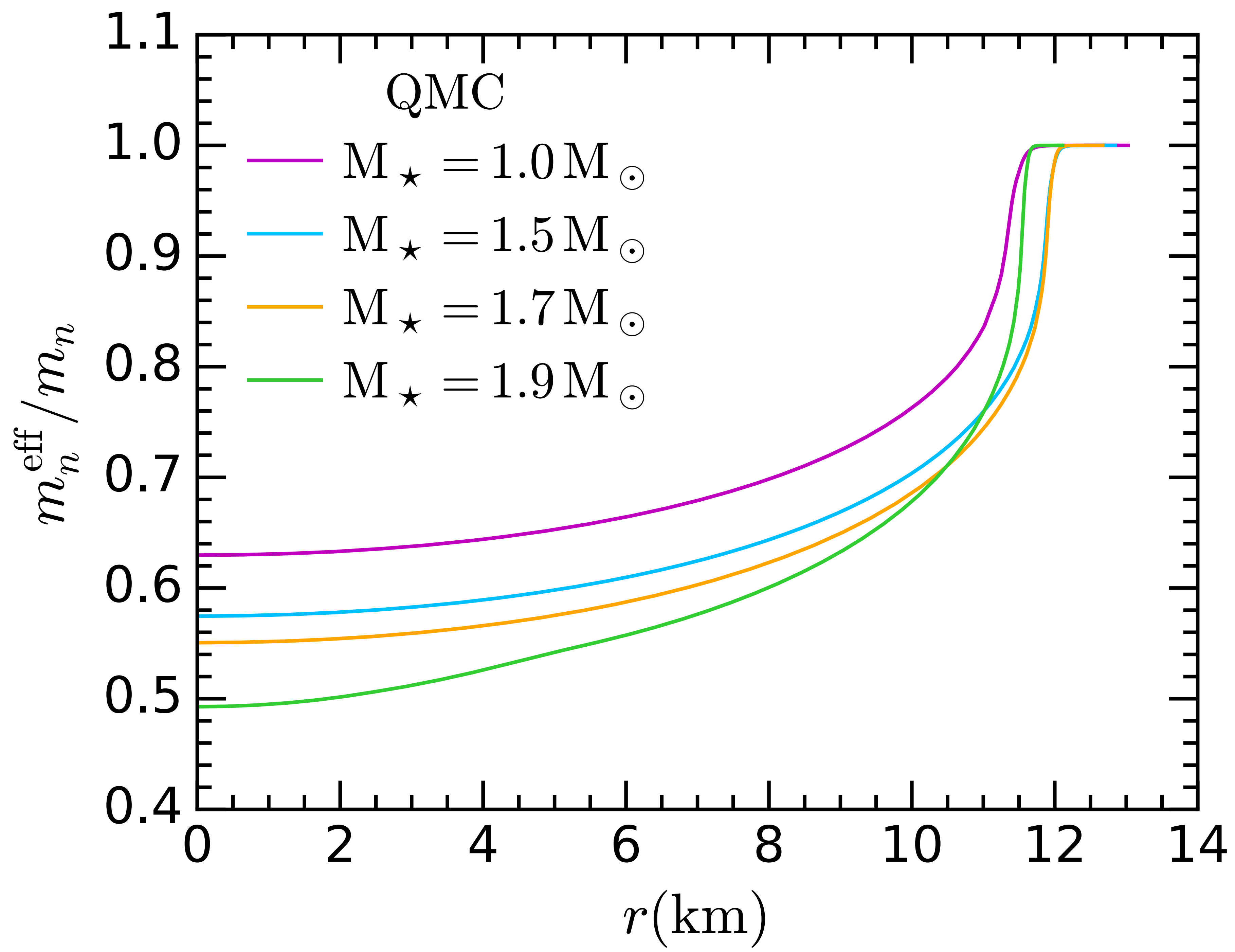
$$c_n(q) = \frac{c_n(0)}{(1 - q^2/Q_0^2)^2}$$

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

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

2. Nucleon effective mass

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

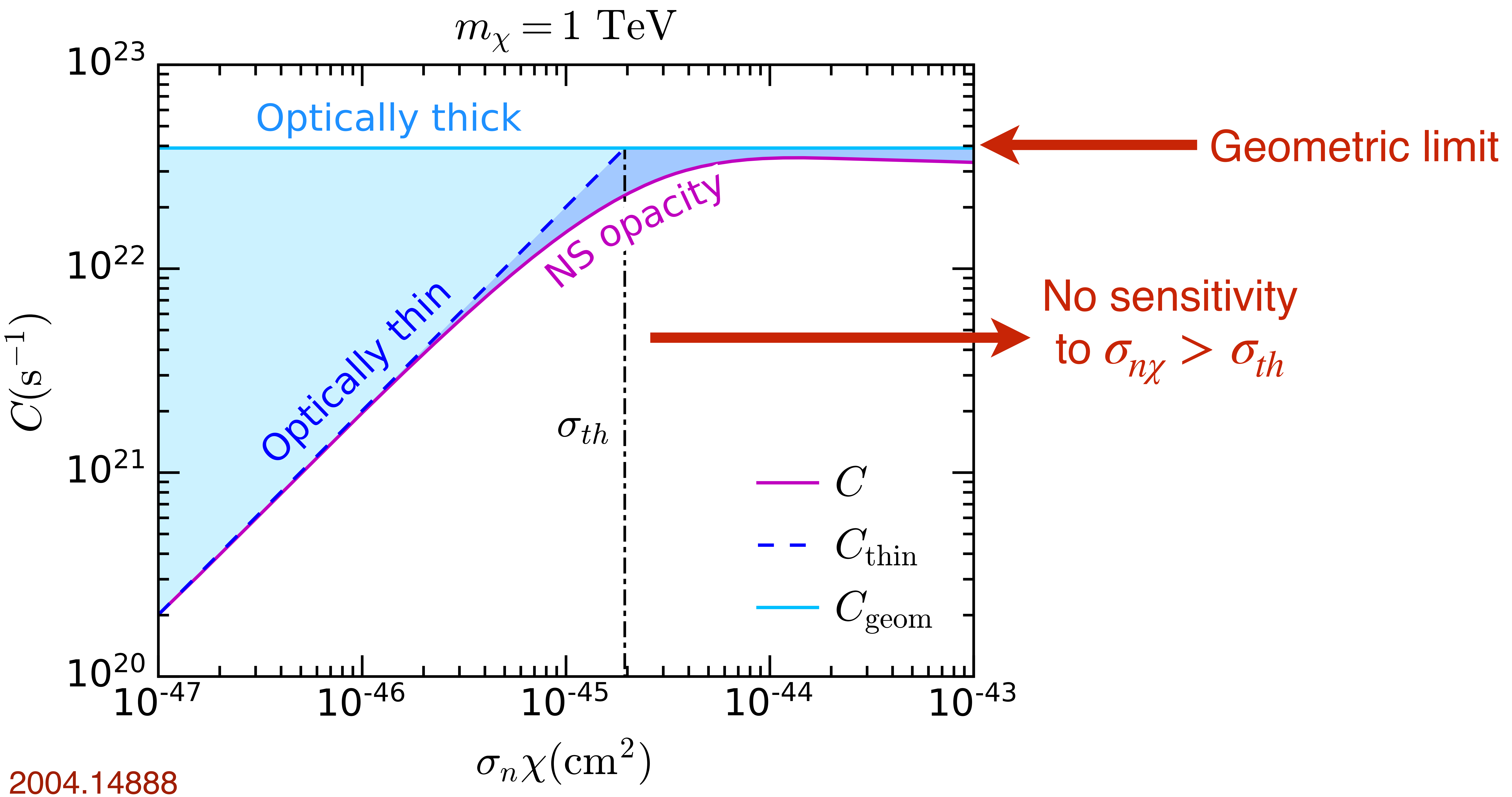


Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2012.08918

DM heating of Neutron Stars

NS sensitivity

- Maximal capture = geometric limit



Bell, Busoni, SR & Virgato, arXiv: 2004.14888

Scattering Operators for Fermionic DM

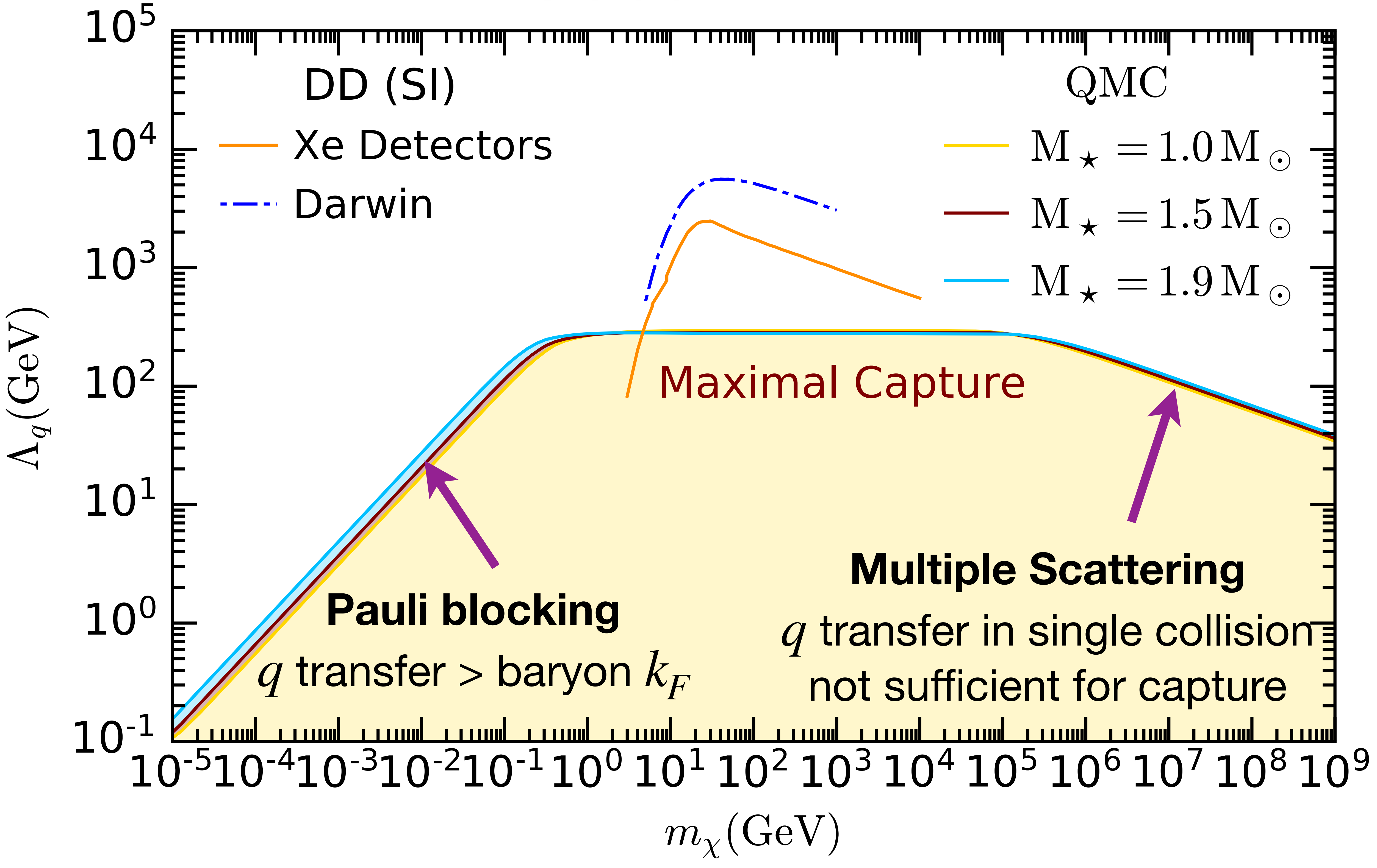
Operator	Coupling	Interaction	Momentum supressed	$\langle \sigma_{\rm ann} v \rangle$
$\bar\chi\chi\ \bar q q$	y_q/Λ^2	SI	✘	p-wave
$\bar\chi\gamma^5\chi\ \bar q q$	$i y_q/\Lambda^2$	SI	✔	s-wave
$\bar\chi\chi\ \bar q\gamma^5 q$	$i y_q/\Lambda^2$	SD	✔	p-wave
$\bar\chi\gamma^5\chi\ \bar q\gamma^5 q$	y_q/Λ^2	SD	✔	s-wave
$\bar\chi\gamma_\mu\chi\ \bar q\gamma^\mu q$	$1/\Lambda^2$	SI	✘	s-wave
$\bar\chi\gamma_\mu\gamma^5\chi\ \bar q\gamma^\mu q$	$1/\Lambda^2$	SI, SD	✔	p-wave
$\bar\chi\gamma_\mu\chi\ \bar q\gamma^\mu\gamma^5 q$	$1/\Lambda^2$	SD	✔	s-wave
$\bar\chi\gamma_\mu\gamma^5\chi\ \bar q\gamma^\mu\gamma^5 q$	$1/\Lambda^2$	SD	✘	s-wave
$\bar\chi\sigma_{\mu\nu}\chi\ \bar q\sigma^{\mu\nu} q$	$1/\Lambda^2$	SD	✘	s-wave
$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\ \bar q\sigma^{\mu\nu} q$	i/Λ^2	SI	✔	s-wave

NS sensitivity to DM-nucleon interactions

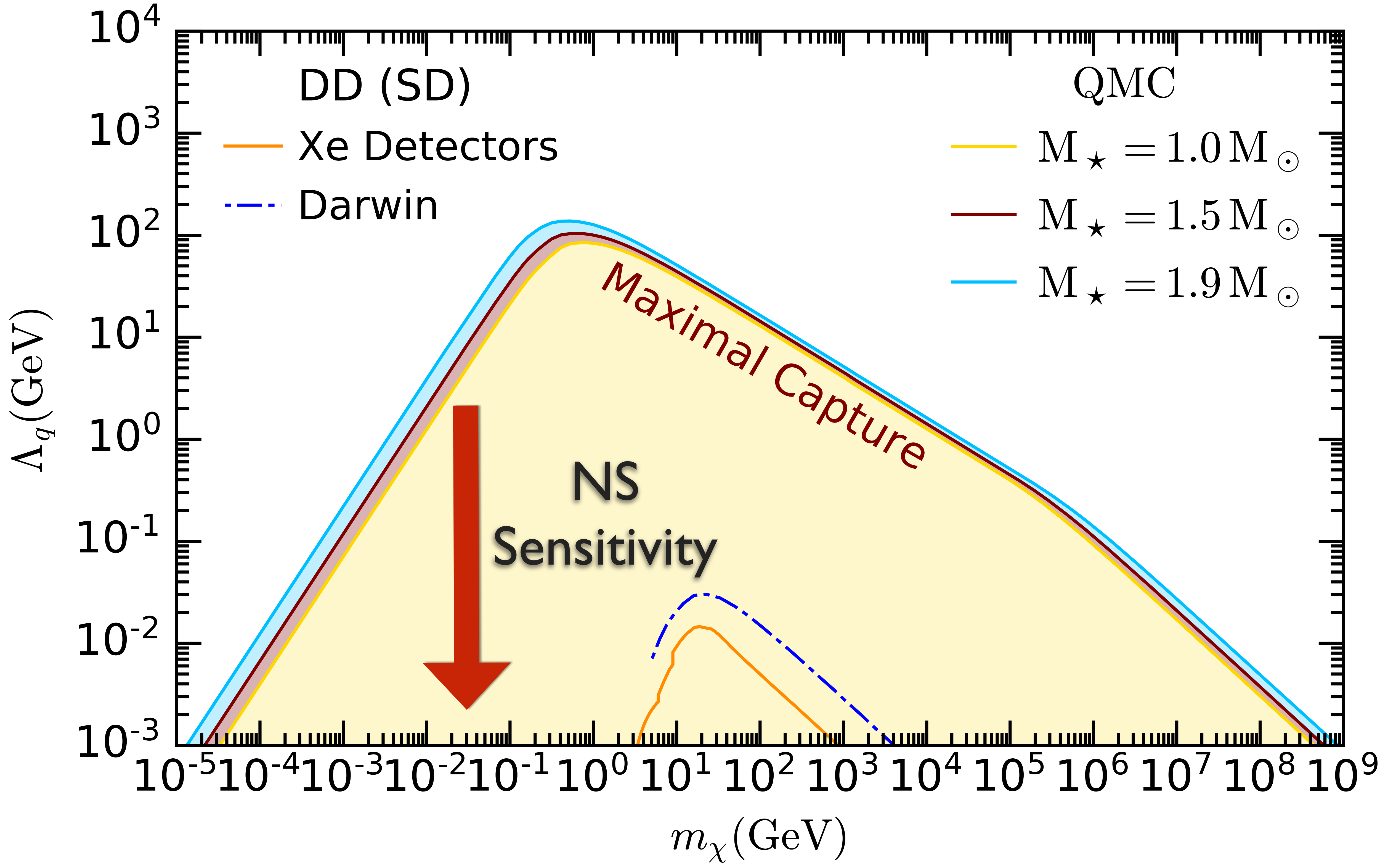
Maximal capture

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

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



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



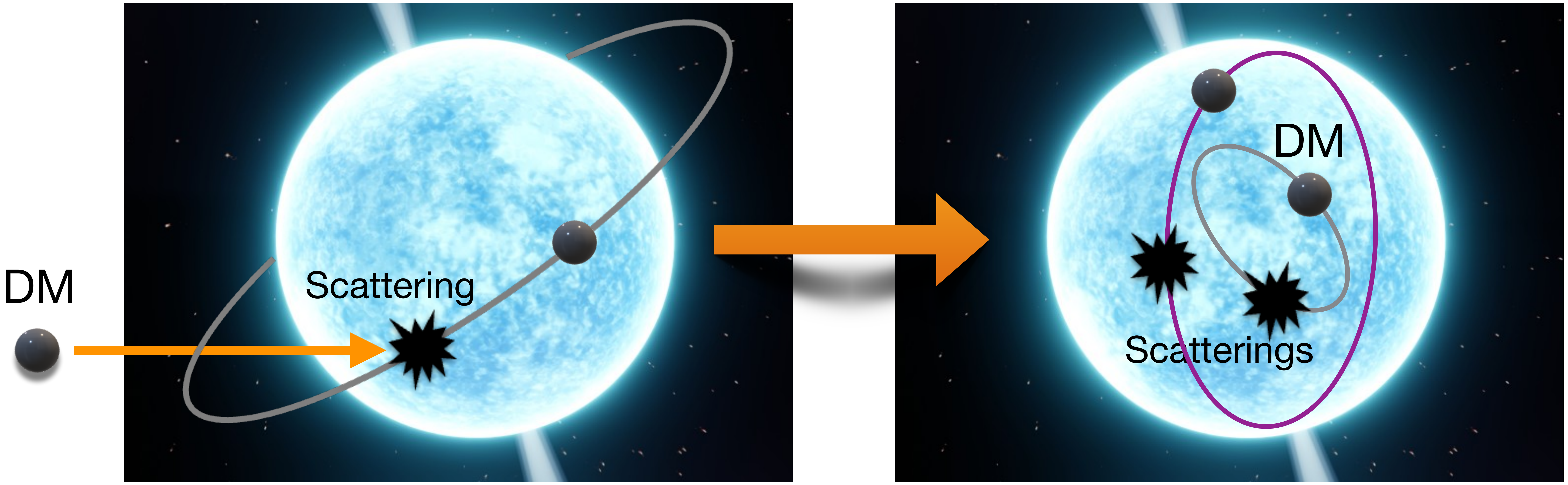
Anzuini, Bell, Busoni, Motta, SR, Thomas & Virgato, arXiv: 2108.02525

Neutron stars are sensitive to interactions that direct detection experiments will never be able to probe

next

Kinetic Heating Timescale

- Capture
- Further scatterings



- Sum of average time between collisions since capture till $K_N = 0.99 K_0$

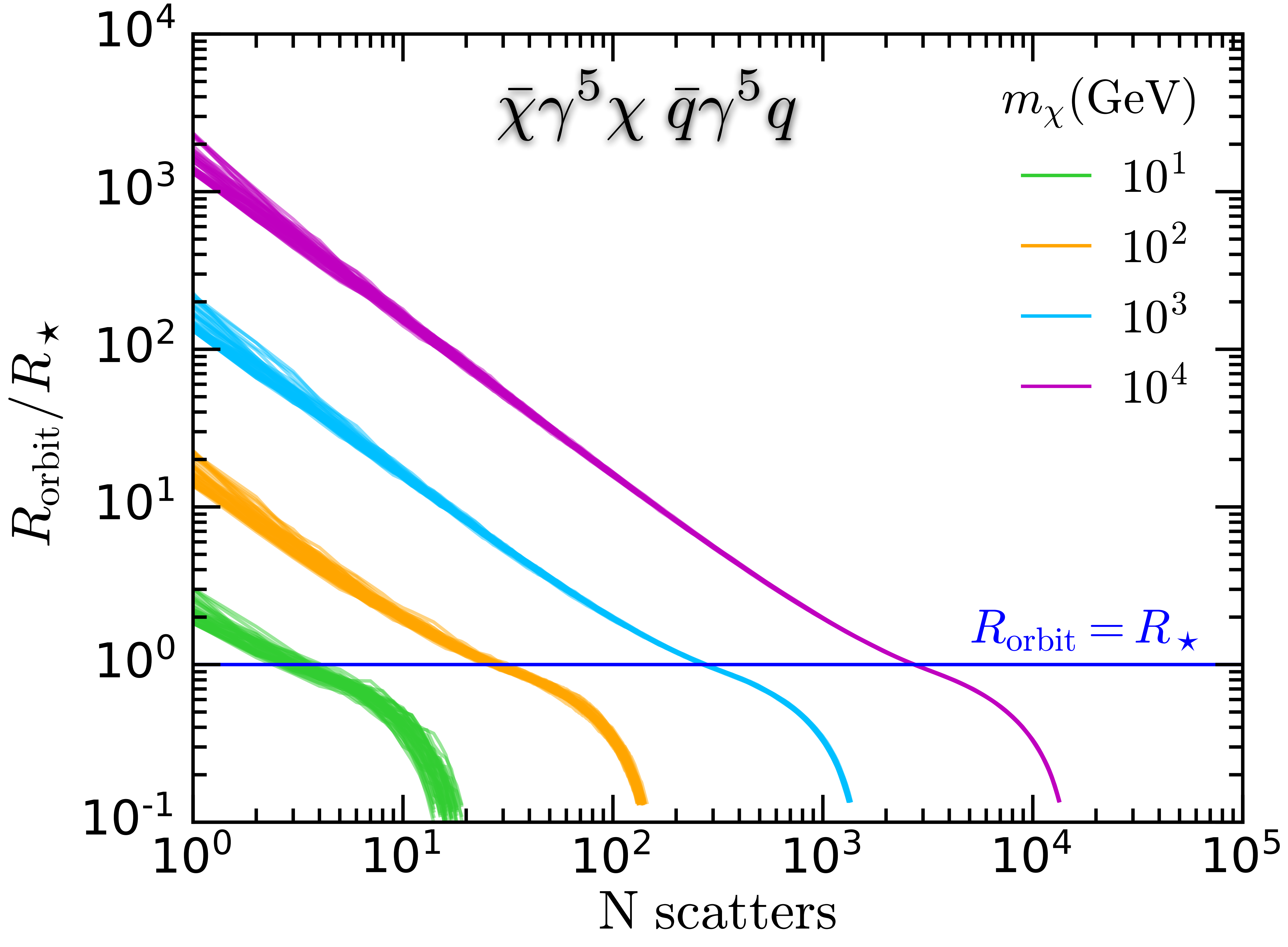
$$t_{\rm kin} \simeq \sum_{n=1}^{K_N = 0.99K_0} \frac{1}{\Gamma^-(K_n)}$$

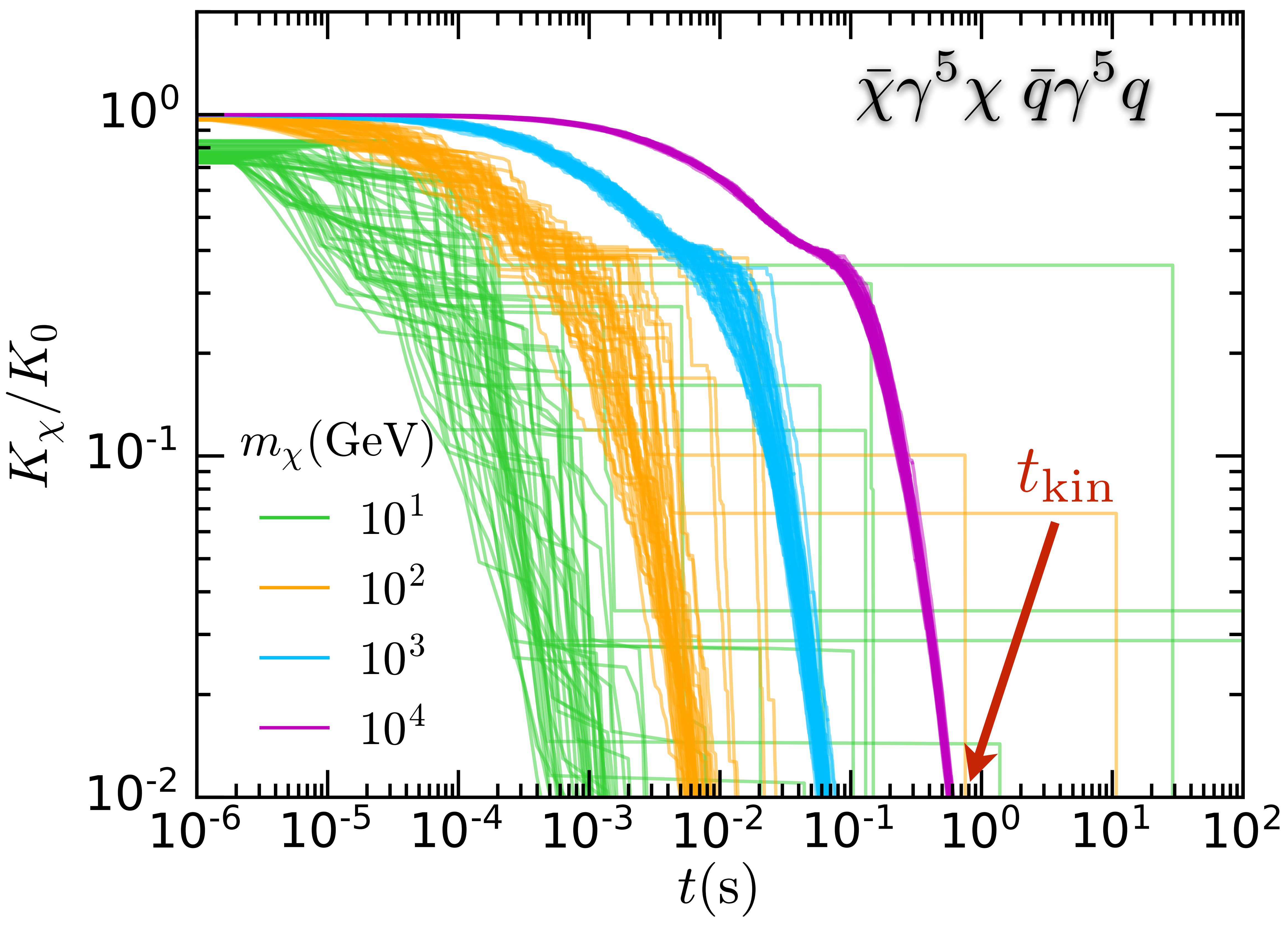
$$K_n = K_{N_1}\left(1 - \frac{\langle \Delta K_\chi \rangle}{K_\chi}\right)^n$$

Bell, Busoni, SR & Virgato, arXiv:2312.11892

Kinetic Heating Timescale

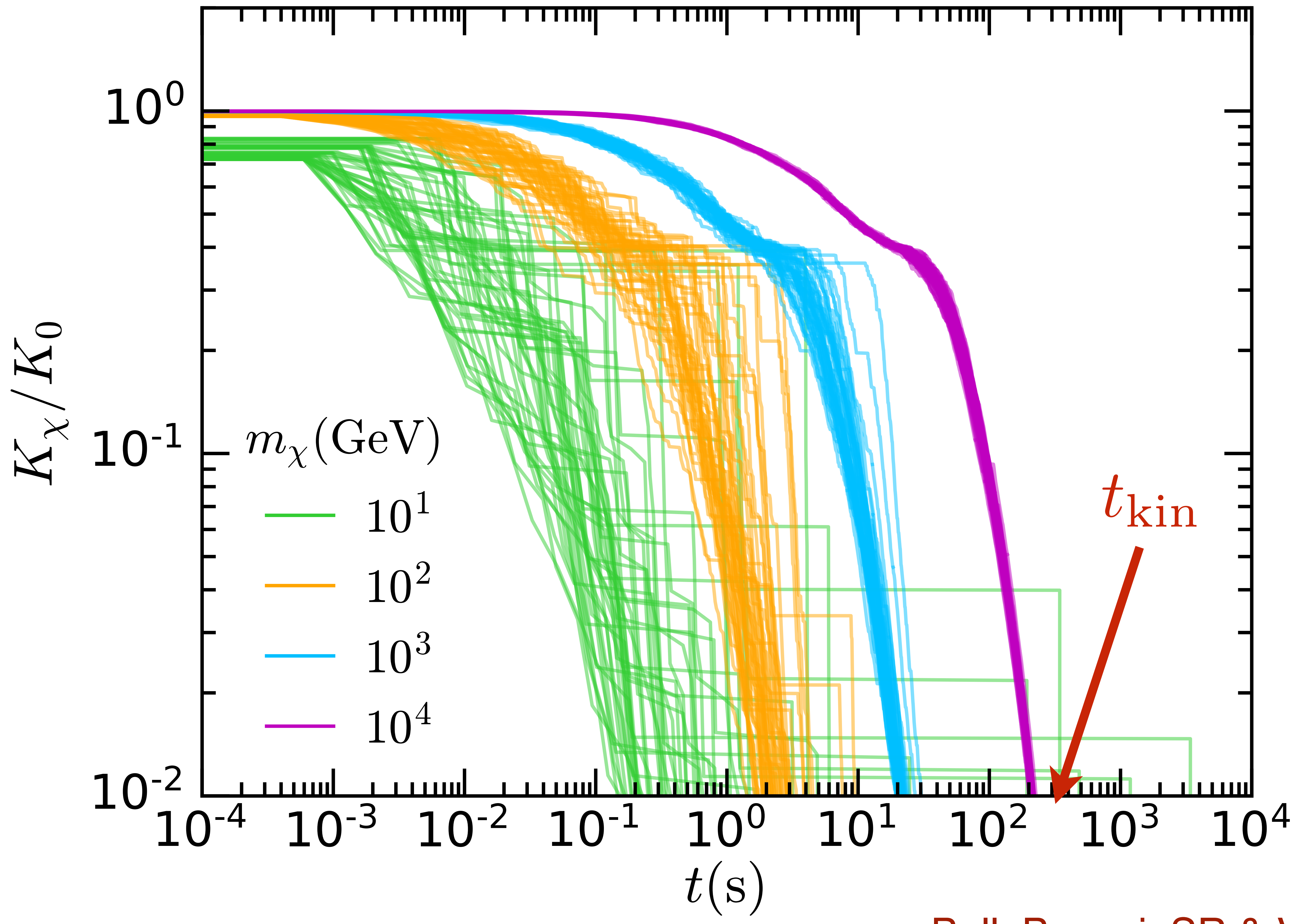
- Maximal Capture

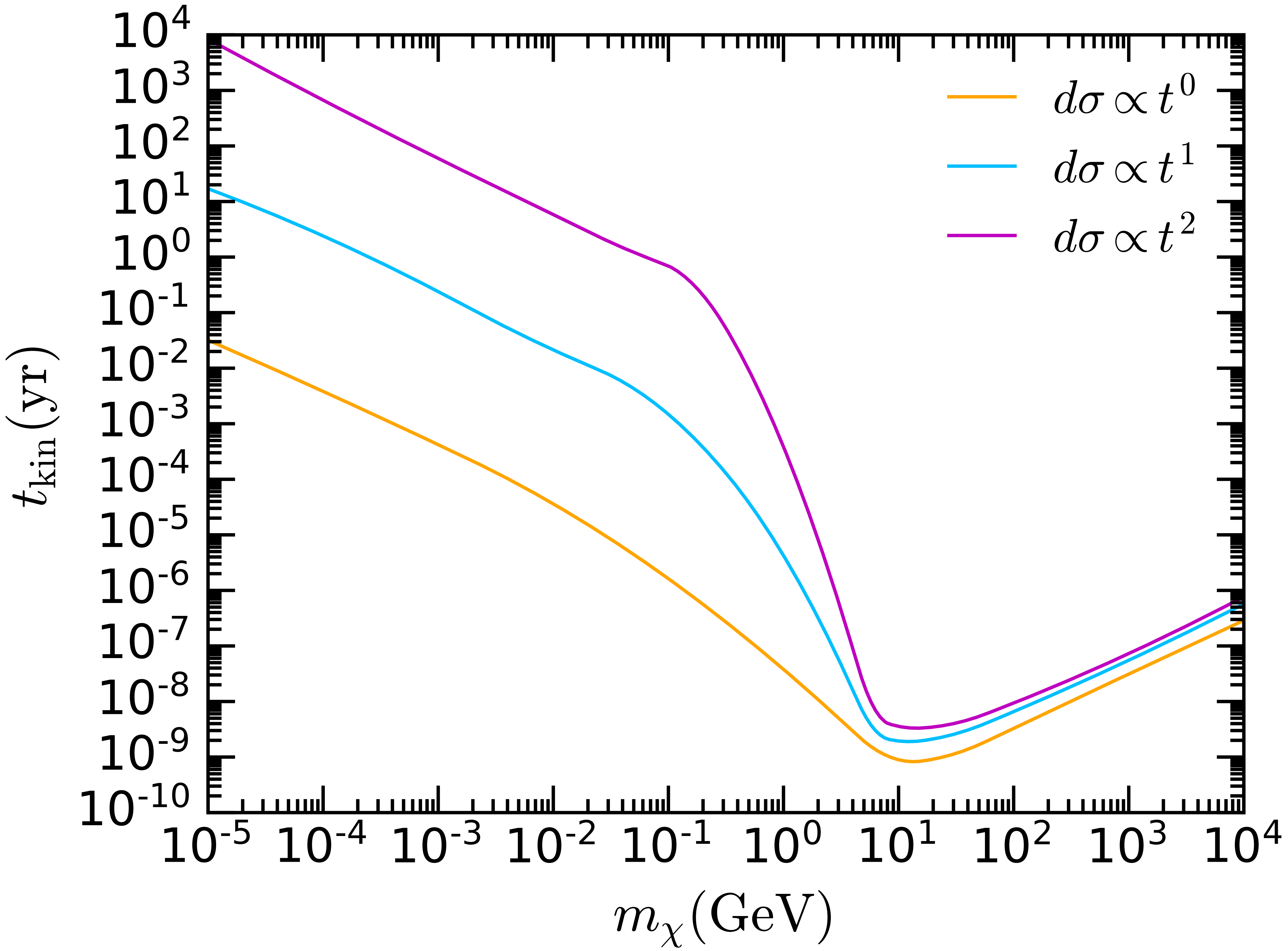




Kinetic Heating Timescale

- Depends on the cross section. E.g. $\sigma_{n\chi} = 10^{-45}\text{cm}^2$





Bell, Busoni, SR & Virgato, arXiv:2312.11892

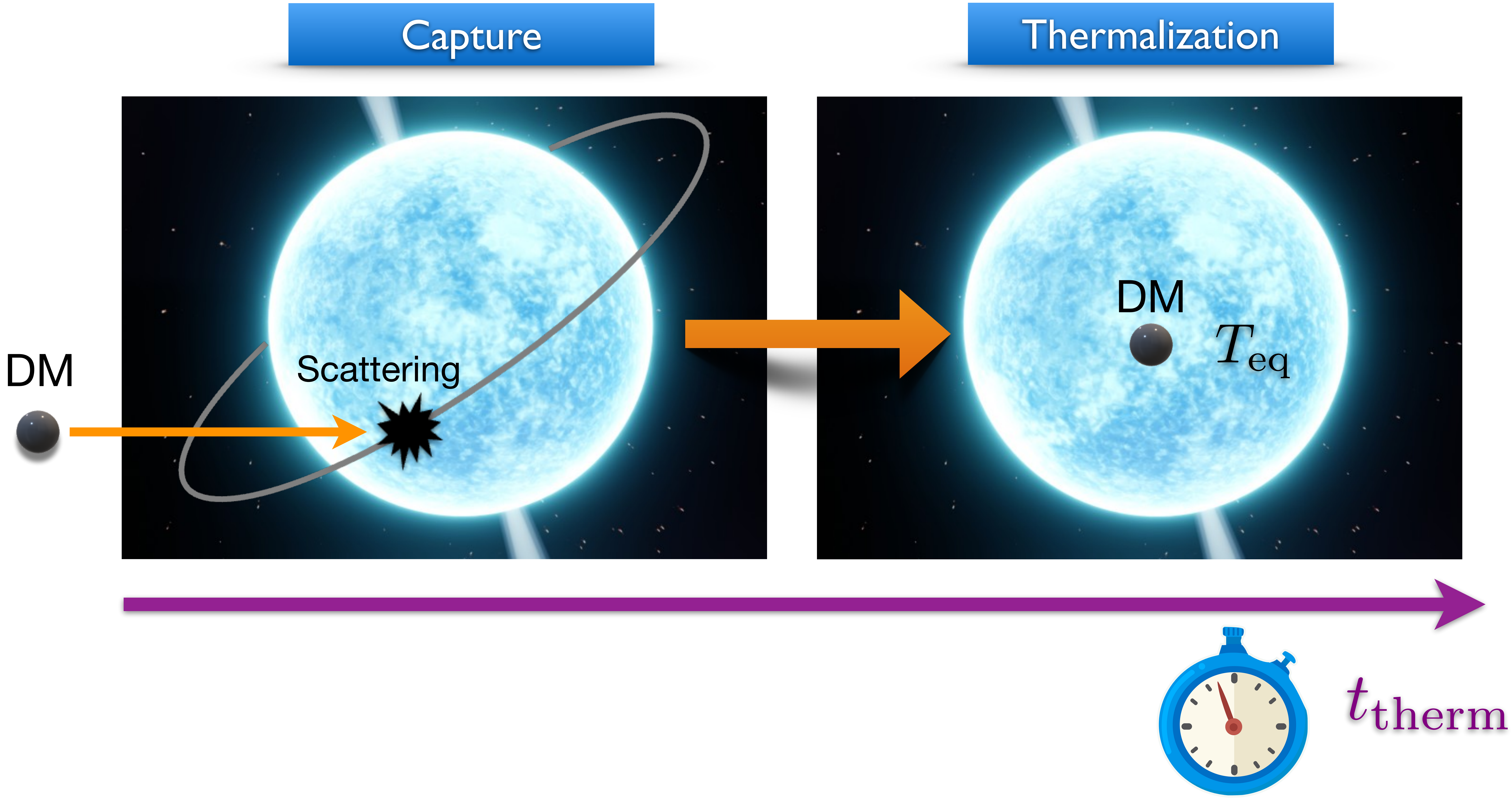
DM deposits its kinetic energy almost instantaneously for all types of interactions

next

2nd

Timescale

DM Thermalization



DM Thermalization in NSs

- After $N_1 + N_2$ scatterings DM reaches equilibrium temperature $T_{\rm eq}$

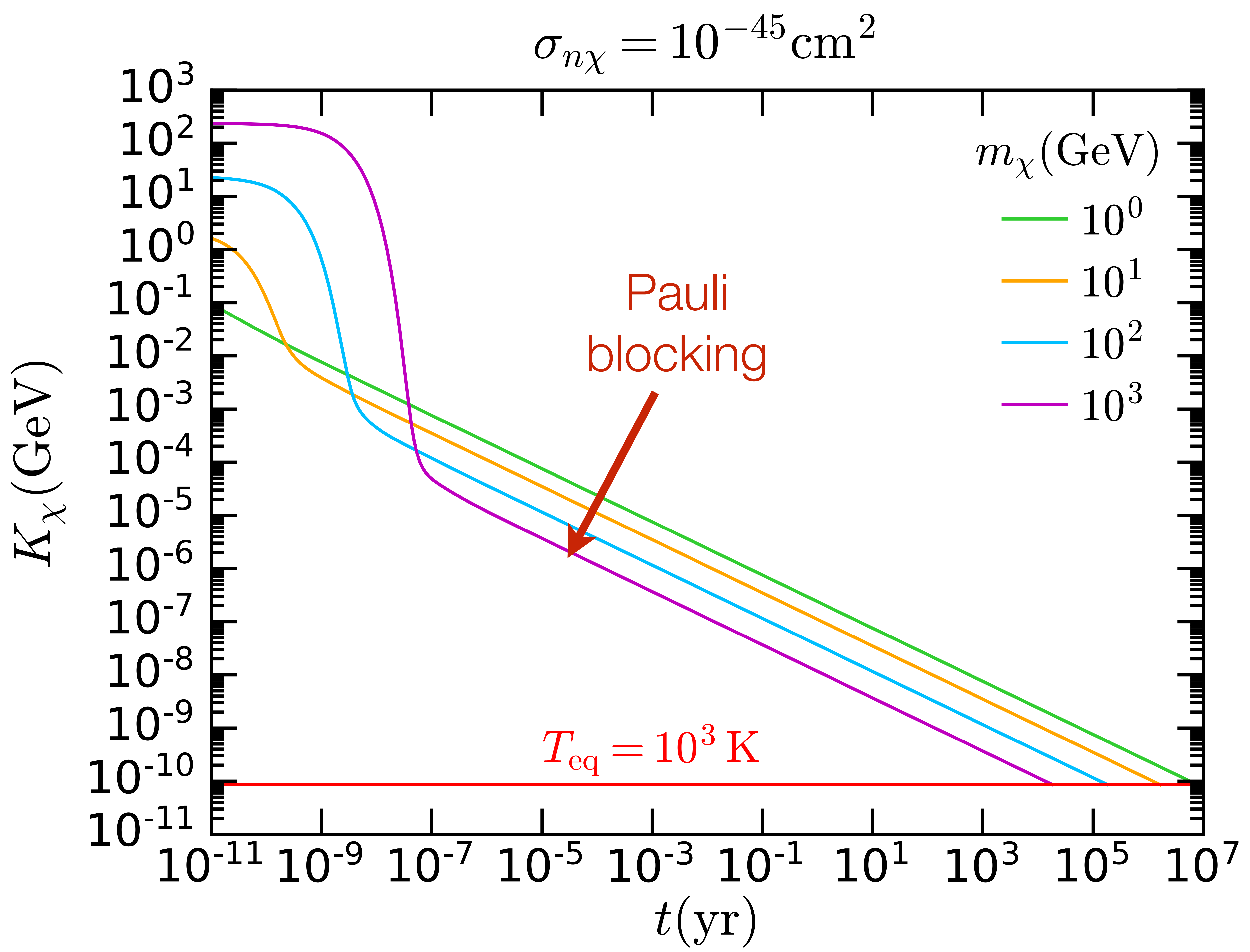
Capture | Orbit within NS | Thermalized

1st stage: N_1 scatterings

2nd stage: N_2 scatterings

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

DM Thermalization in NSs



- Last scatterings take longer to occur
  - E.g. m_χ = 1 TeV last 2 scatterings are $\mathcal{O}(1\,\text{kyr})$ apart
  - They dictate the value of t_{therm}

$$t_{\text{therm}} \simeq t_2^{\text{therm}} = \sum_{n=N_1}^{N_2} \frac{1}{\Gamma^-(K_n)}.$$

$$K_n = K_{N_1}\left(1 - \frac{\langle \Delta K_\chi \rangle}{K_\chi}\right)^n$$

DM Thermalization in NSs

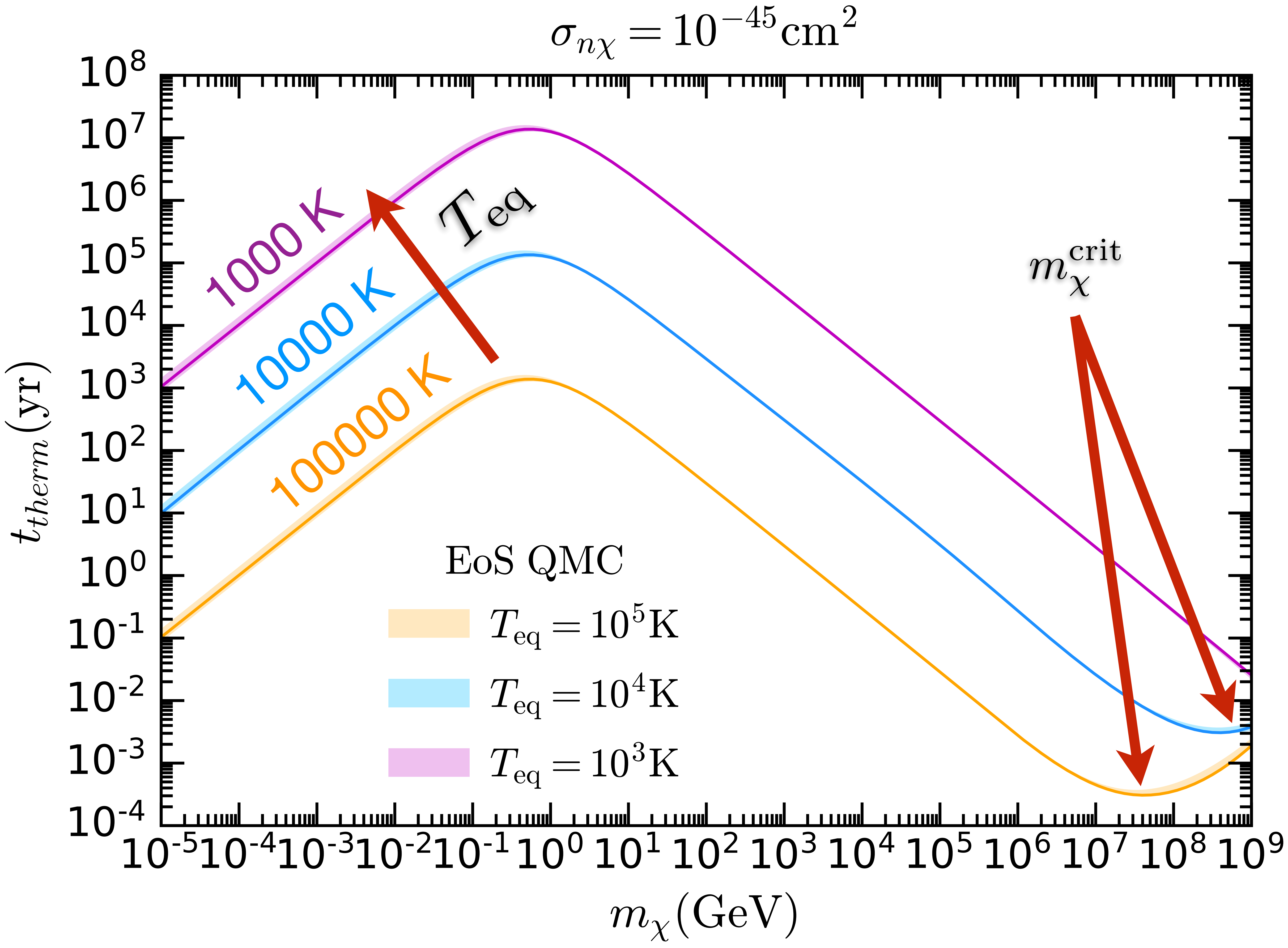
- We can define a critical mass above which Pauli blocking is never in effect

$$m_\chi^{\rm crit} \sim \frac{2\varepsilon_{F,n}(2m_n + \varepsilon_{F,n})}{T_{\rm eq}}$$

- Thermalization time for constant cross section

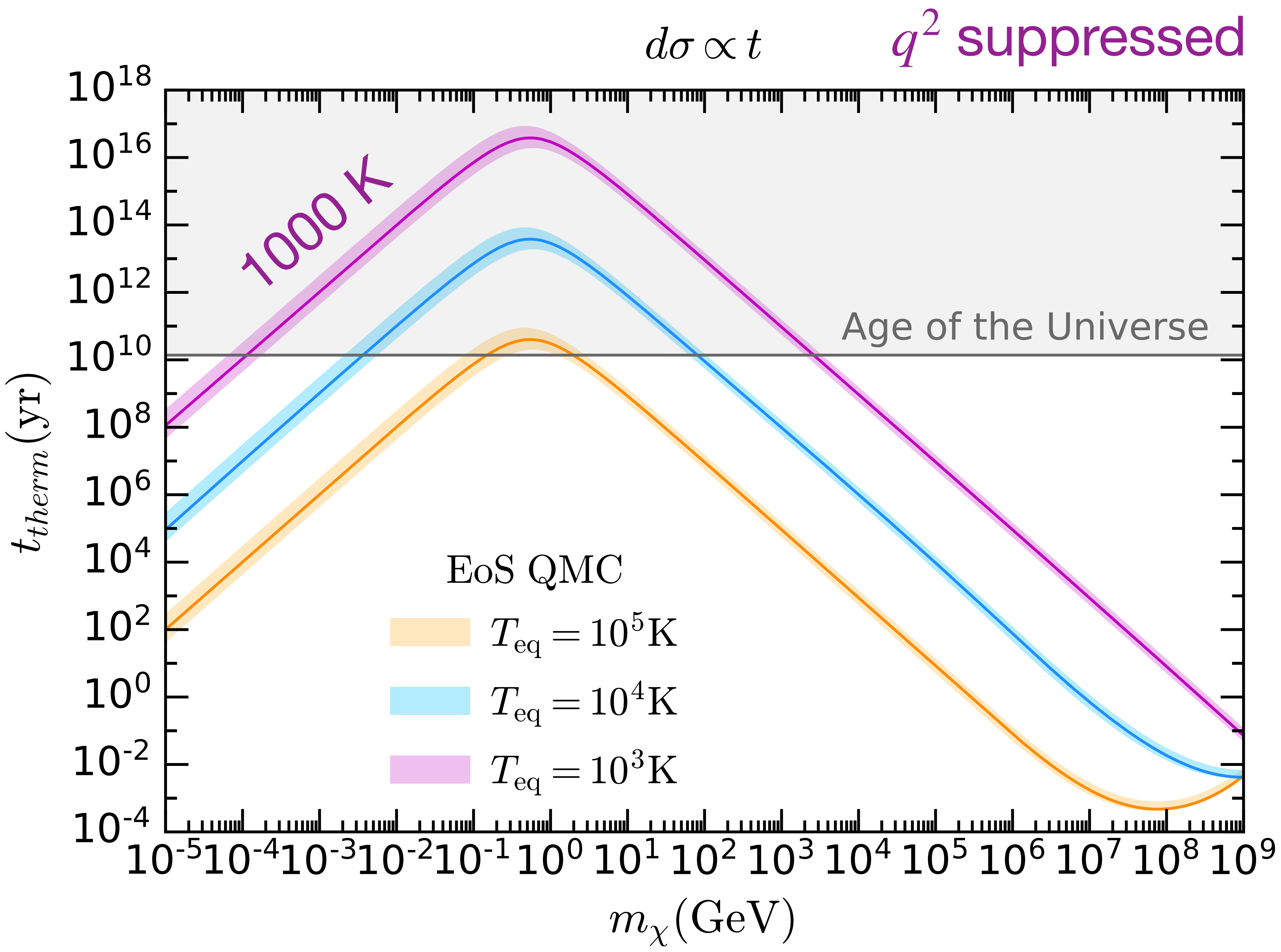
$$t_{\rm therm} \sim \frac{147}{16}\frac{\pi^2 m_\chi}{\left(m_i^{\rm eff}(0) + m_\chi\right)^2 \sigma_{i\chi} T_{\rm eq}^2}$$

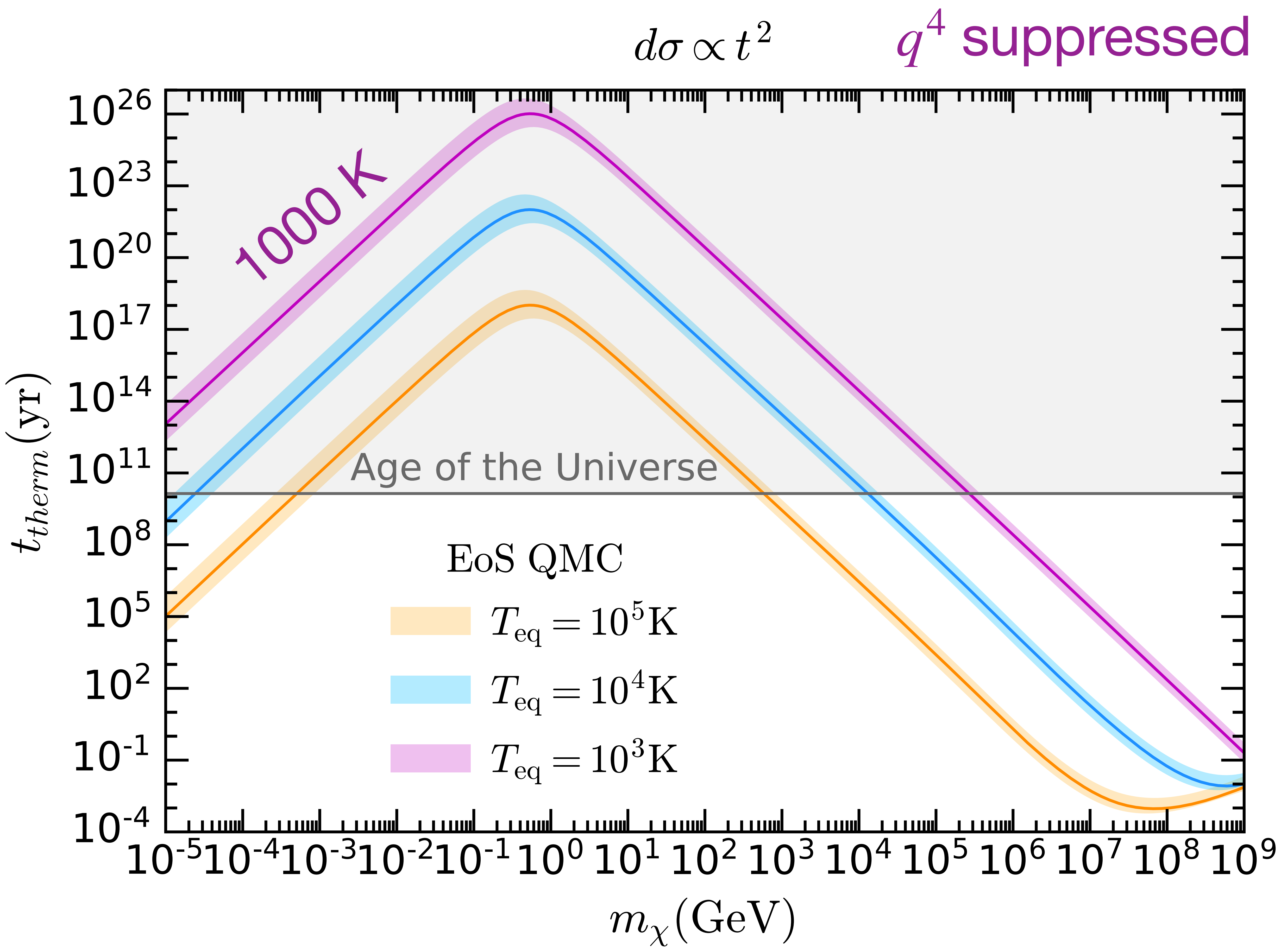
Bell, Busoni, SR & Virgato, arXiv:2312.11892



DM Thermalization in NSs

- Momentum suppressed interactions





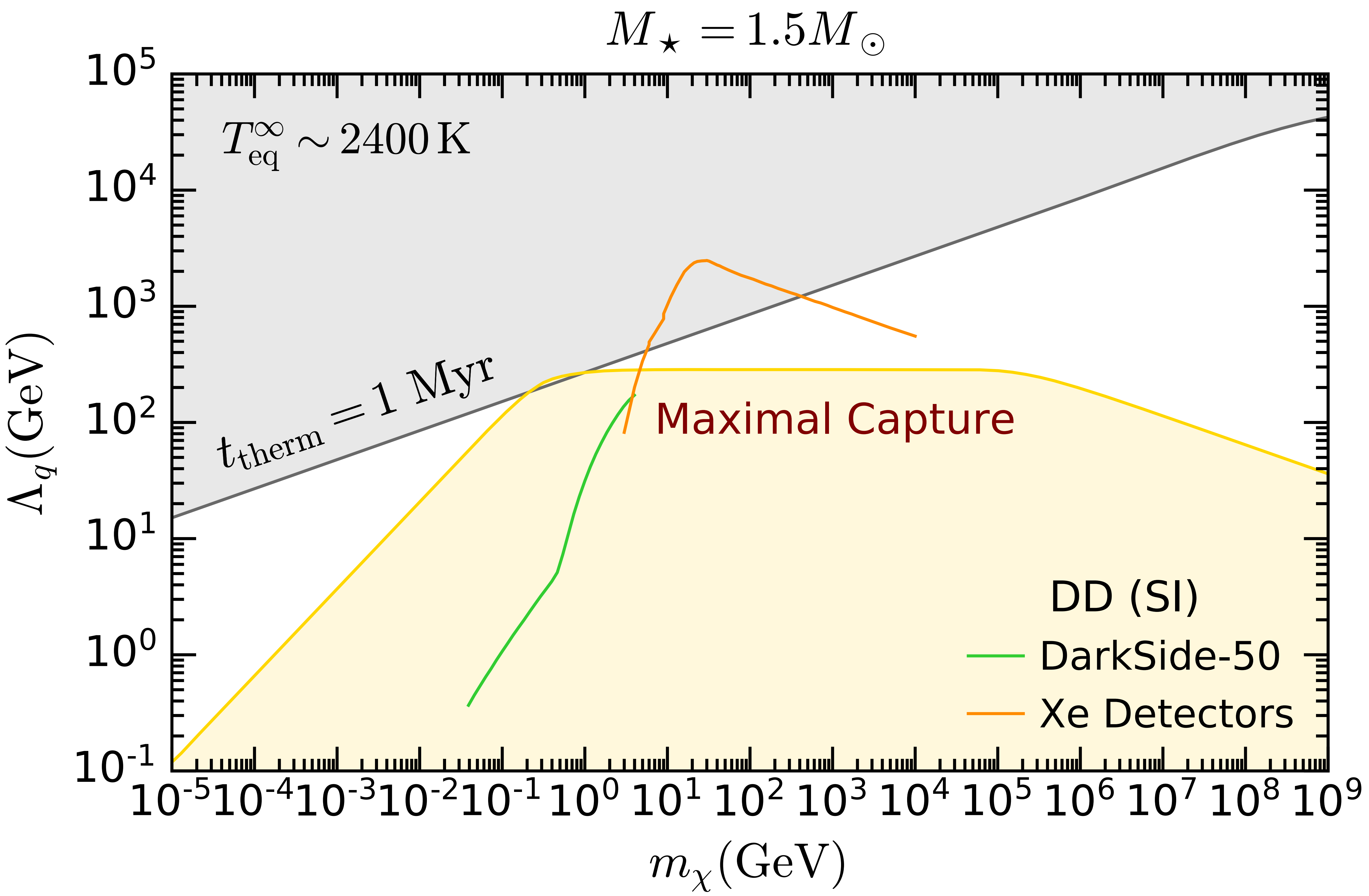
Bell, Busoni, SR & Virgato, arXiv:2312.11892

DM Thermalization in NSs

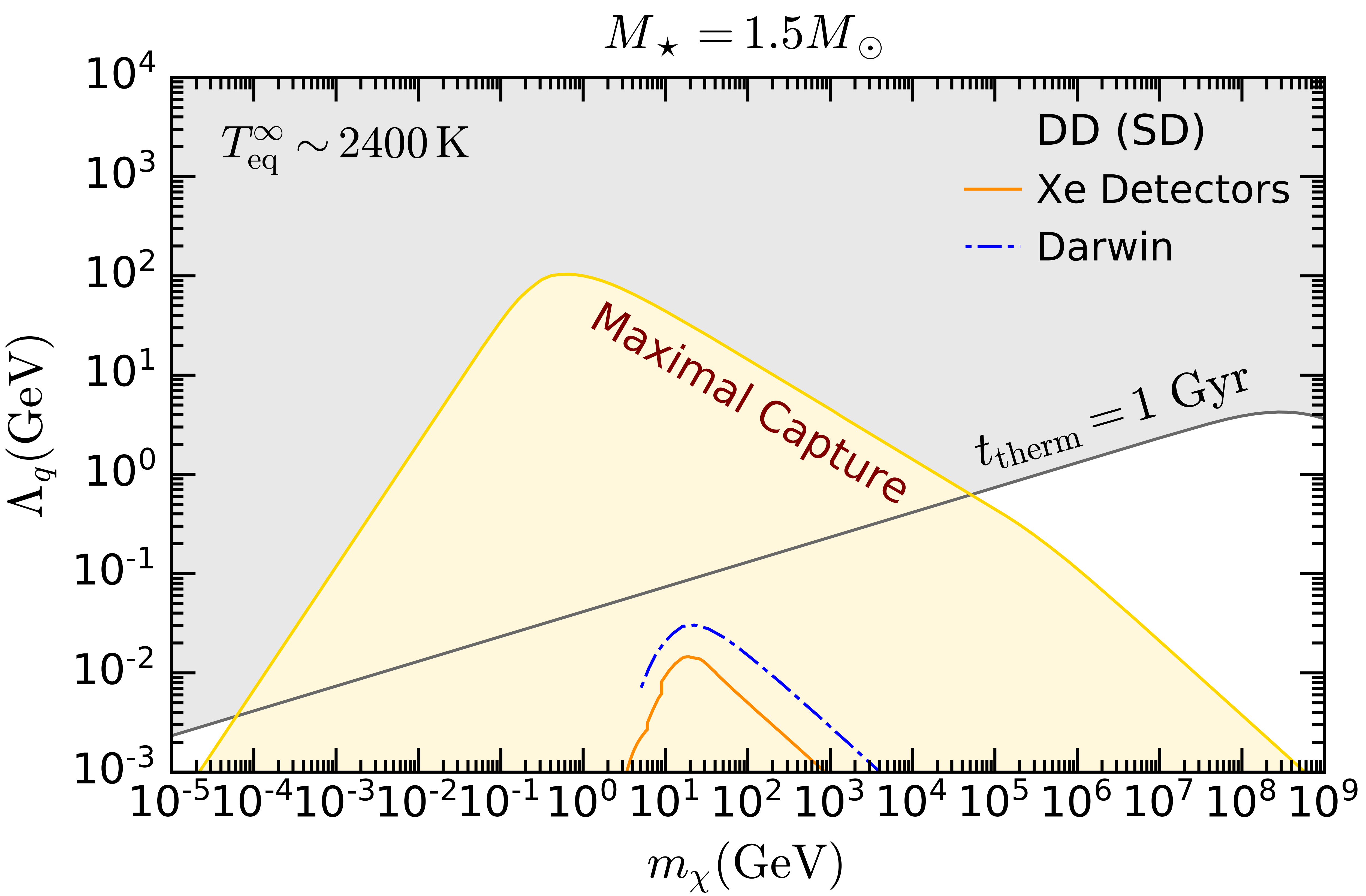
EFT operators

- Captured DM thermalizes 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



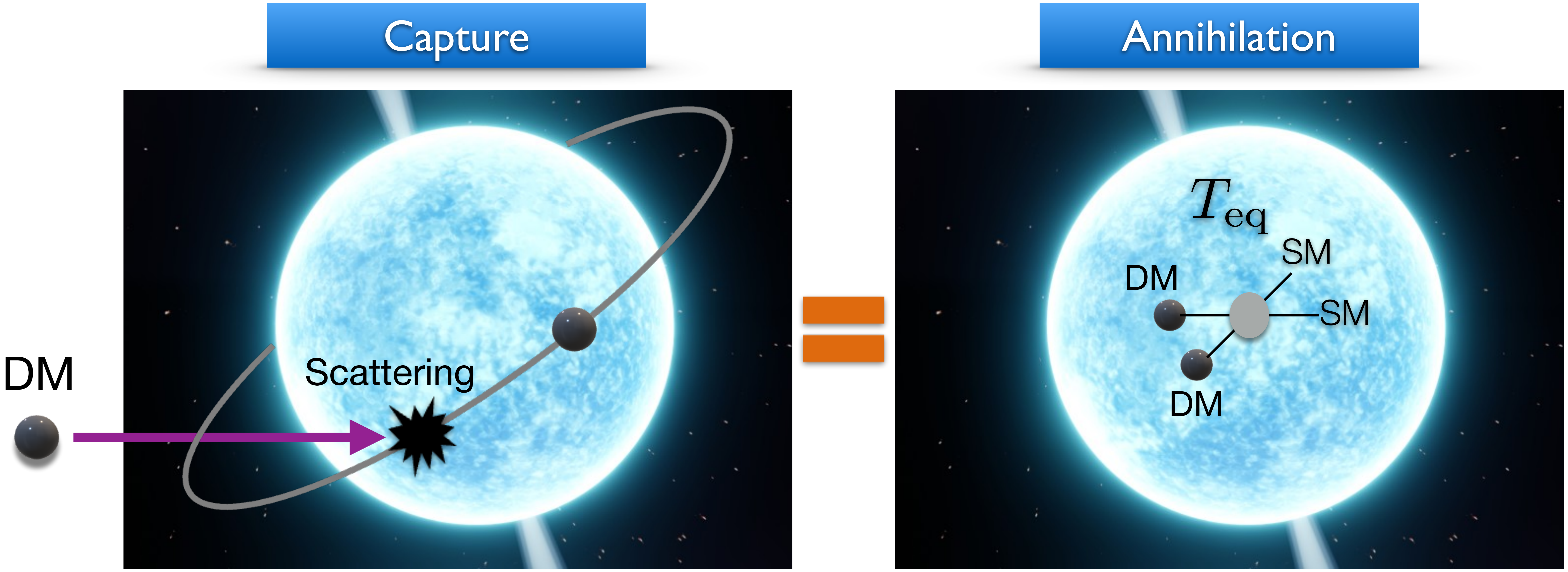
DM with momentum suppressed interactions will not be able to thermalize within the NS lifetime

next

3rd

Timescale

Capture-Annihilation Equilibrium



t_{eq}

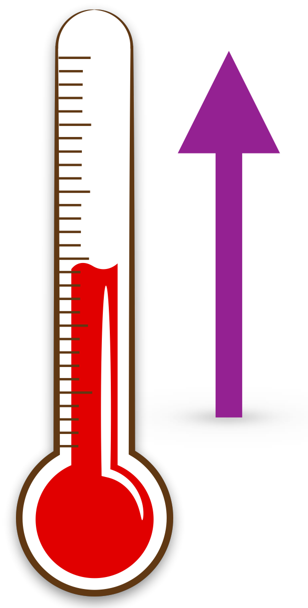
DM heating of Neutron Stars

- **Annihilation Heating** $\chi\bar{\chi} \to \mathrm{SM\ SM}$
- Total contribution to the NS luminosity $L_\chi = \dot{E}_\chi^{\mathrm{kin}} + \dot{E}_\chi^{\mathrm{ann}} = 4\pi\sigma_{SB} R_\star^2 T_\chi^4$

➡ Maximal capture local $1.5\, M_\odot$ NS

Only "detectable" in old (cold) neutron stars

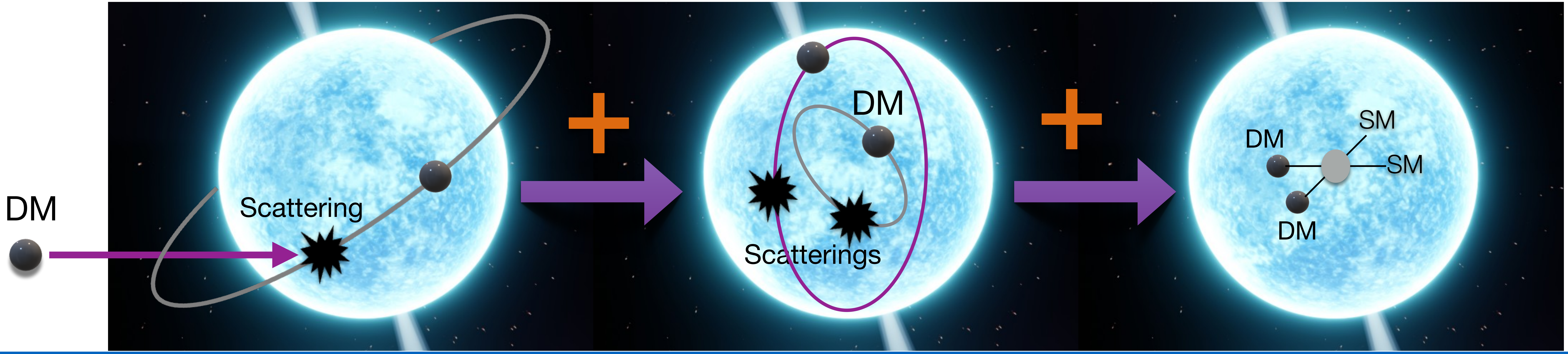
$T_\chi^\infty \sim 2400\,\mathrm{K}$



near IR
1 - 2 μm

Kinetic Heating

Annihilation Heating



Capture - Annihilation Equilibrium

Standard picture: Thermalized DM

- 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

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

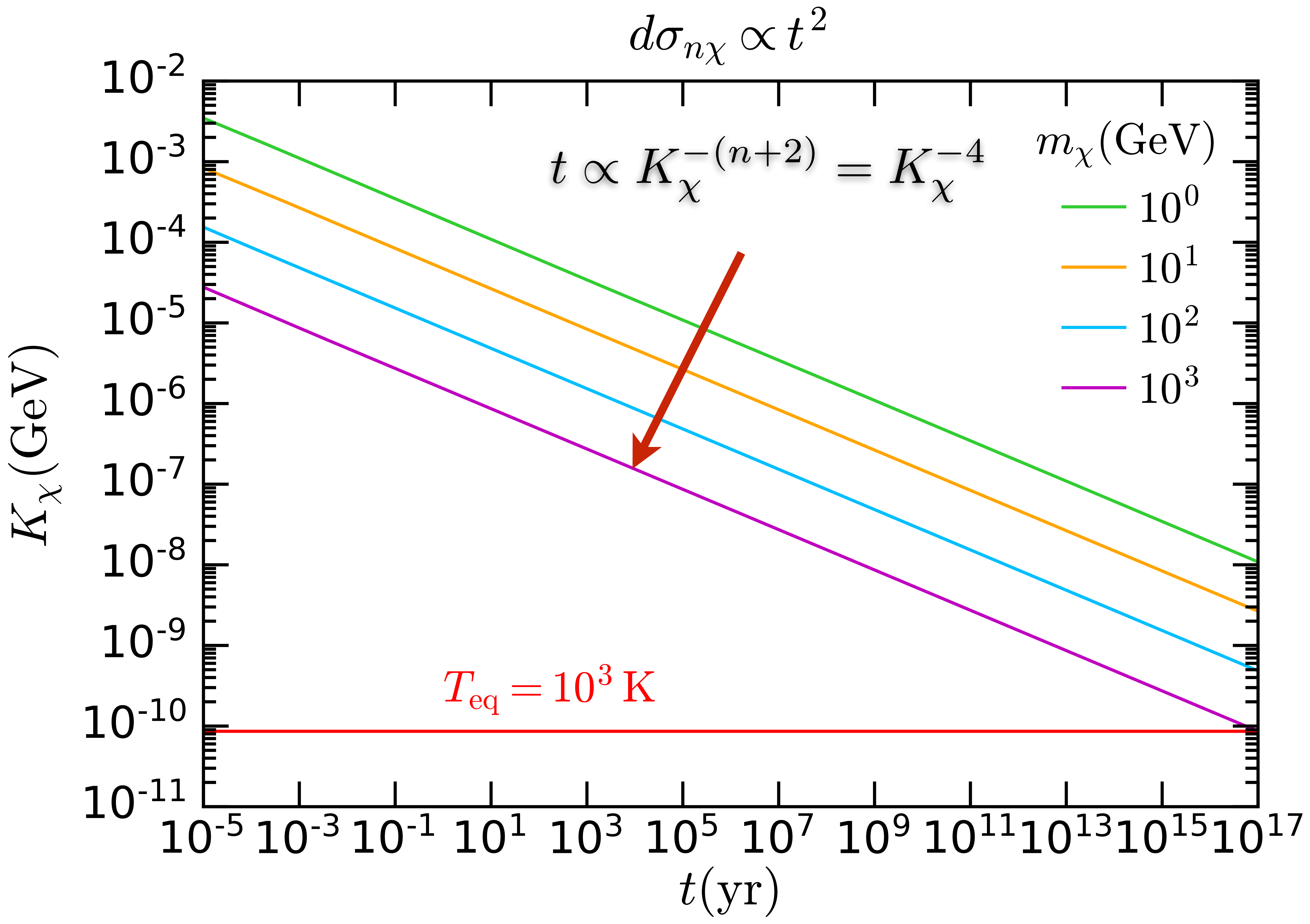
$$A \simeq \frac{\langle \sigma_{\text{ann}} v_\chi \rangle}{(2\pi)^{3/2} r_\chi^3}$$

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

Capture - Annihilation Equilibrium

Partially thermalized DM

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



➡ Lowest temperature the DM has reached

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

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

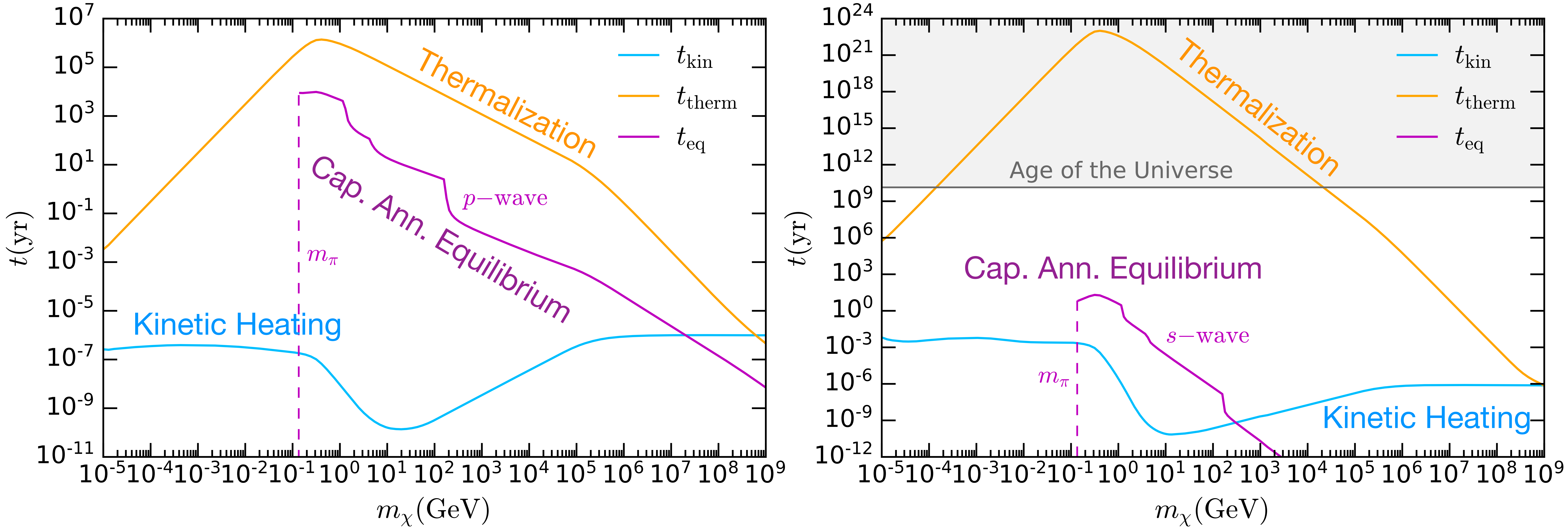
- Annihilation final states

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

Timescales for Maximal Capture

- Capture-annihilation equilibrium reached in ~1 yr (s-wave) up to 10 kyr (p-wave).

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



Bell, Busoni, SR & Virgato, arXiv:2312.11892

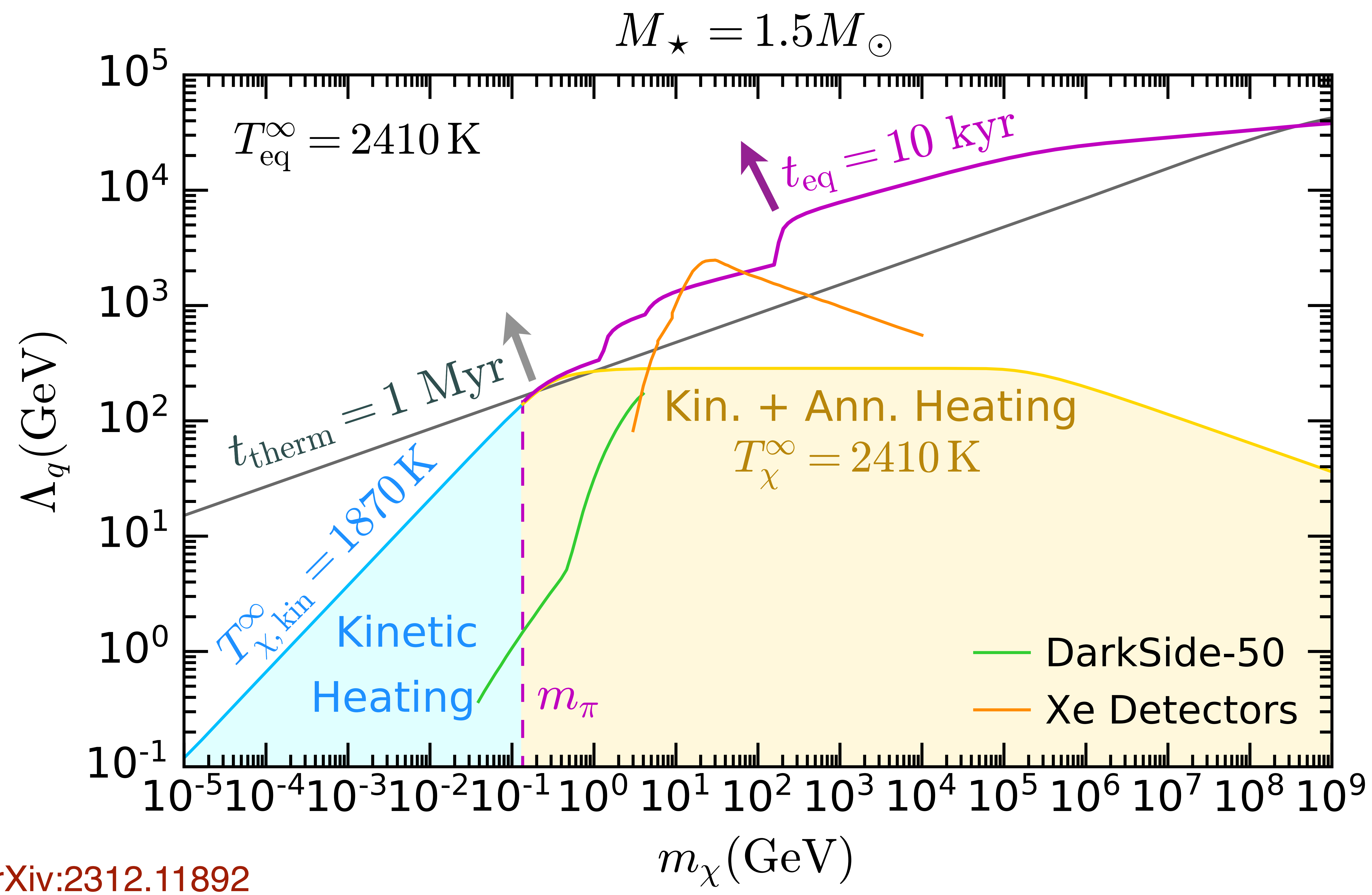
Capture - annihilation equilibrium can be reached without full thermalization for all type of interactions in a short time

next

DM-induced Heating of NSs

Maximal capture

- Both kinetic and annihilation heating can be realized $\bar{\chi}\chi\,\bar{q}q$ unsuppressed

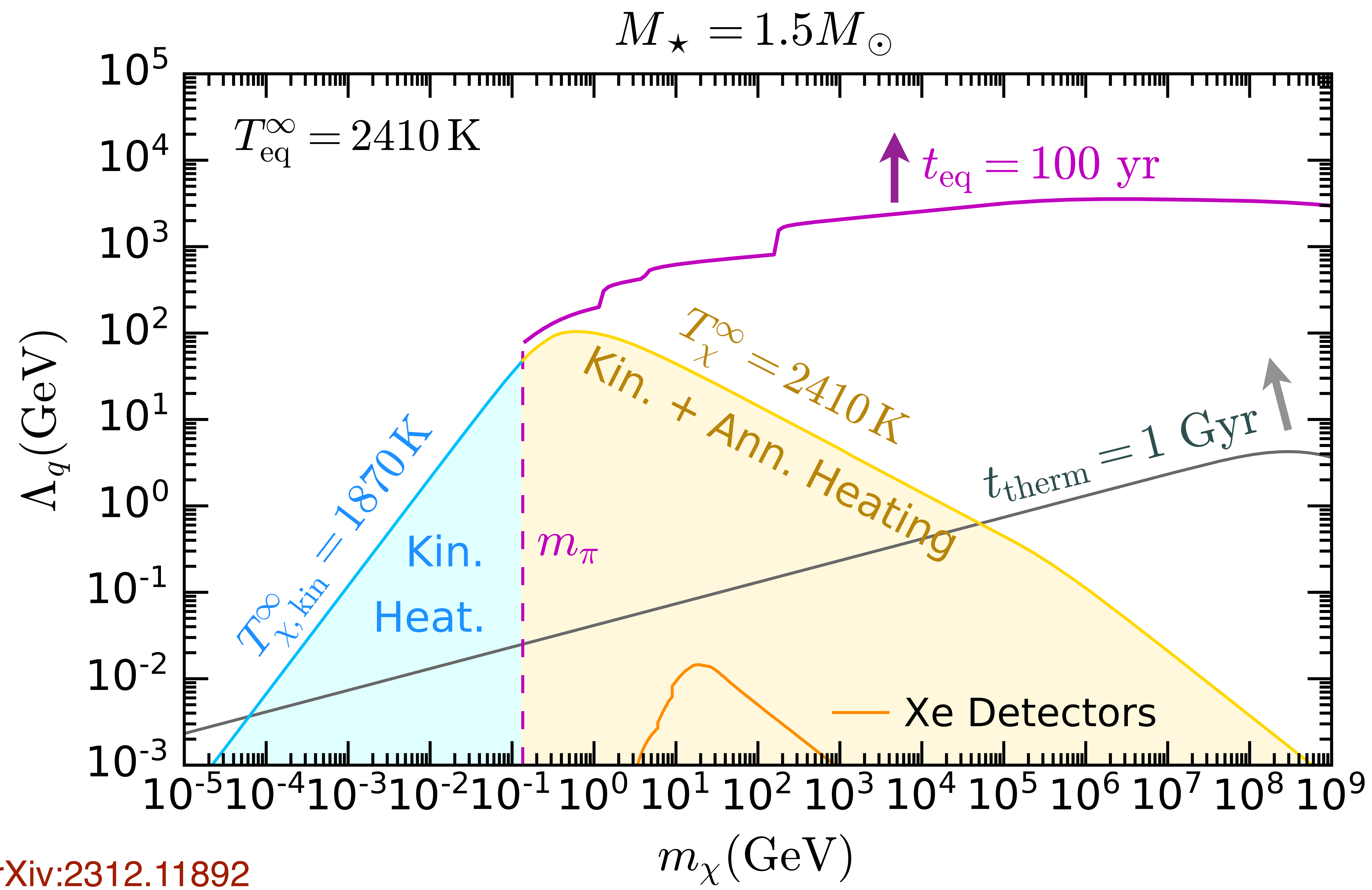


Bell, Busoni, SR & Virgato, arXiv:2312.11892

DM-induced Heating of NSs

Maximal capture

- Both kinetic and annihilation heating can be realized even for $\bar{\chi}\gamma^5\chi\ \bar{q}\gamma^5 q$ q^4 suppressed



Bell, Busoni, SR & Virgato, arXiv:2312.11892

Observation of old, isolated NSs could probe interactions for which direct detection experiments have no sensitivity

next

Summary

- Neutron stars could constrain different types of interactions, including those that are velocity and momentum suppressed.
- Captured DM would thermalize 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 10 kyr.
- Constraining DM interactions using DM-induced anomalous heating of neutron stars requires

➡ Observation of old (cold) neutron stars.

➡ Better understanding of the cooling process in neutron stars.

Thank you!