Terrestrial Planet Probes of Low Mass Dark Matter

Gopolang (Gopi) Mohlabeng

University of California, Irvine

+ J. Bramante, J. Kumar, N. Raj & N. Song

based on

arXiv: 2210.01812

BNL HEP Theory Seminar

02 February 2023

What to expect in this talk

- Current status of dark matter searches

- Celestial bodies as laboratories for DM physics

- Multi-scatter capture and evaporation of low mass DM in Earth

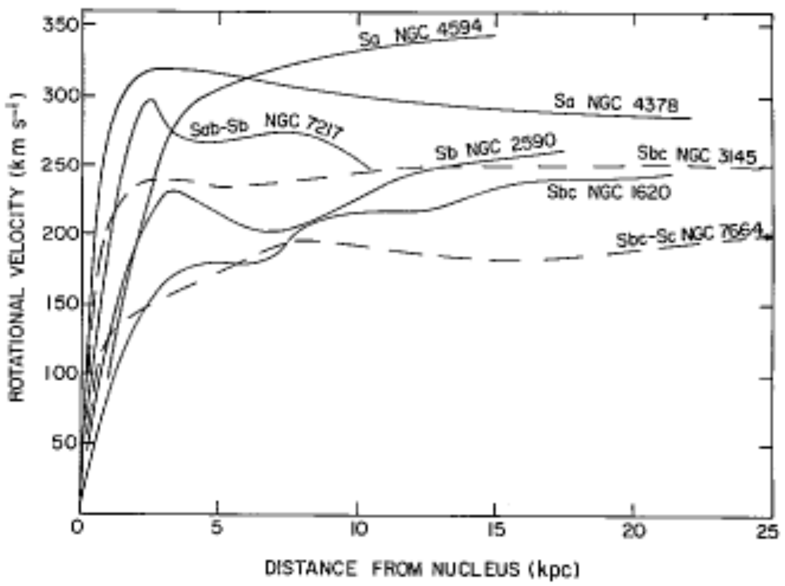
- Discuss improved direct detection & Earth heating constraints

- Conclusions

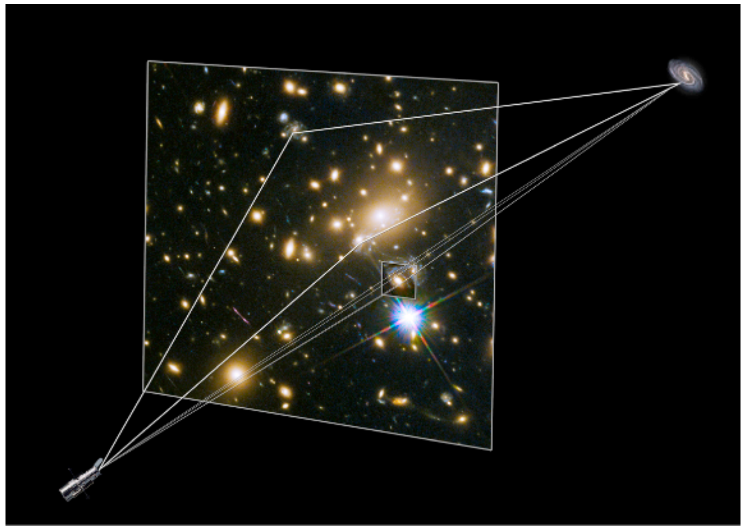
We know dark matter exists

Astronomy & Cosmology tell us

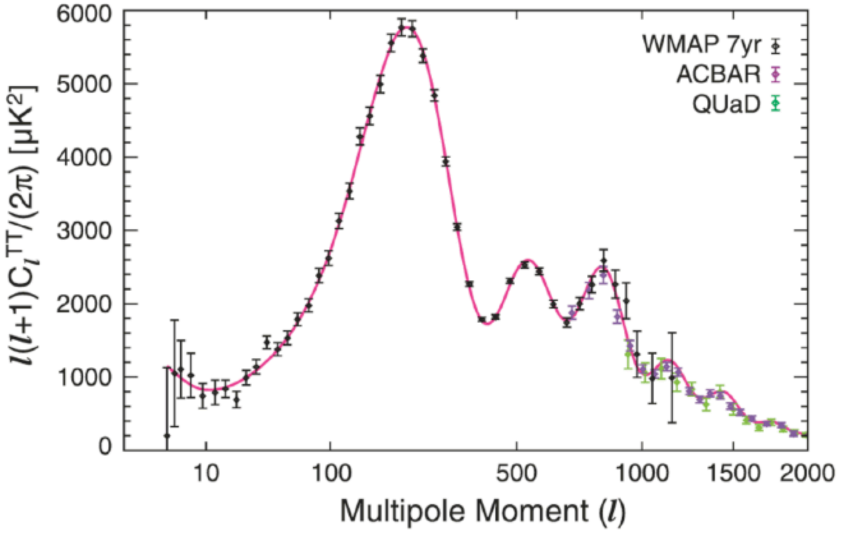
1. Rotation Curves



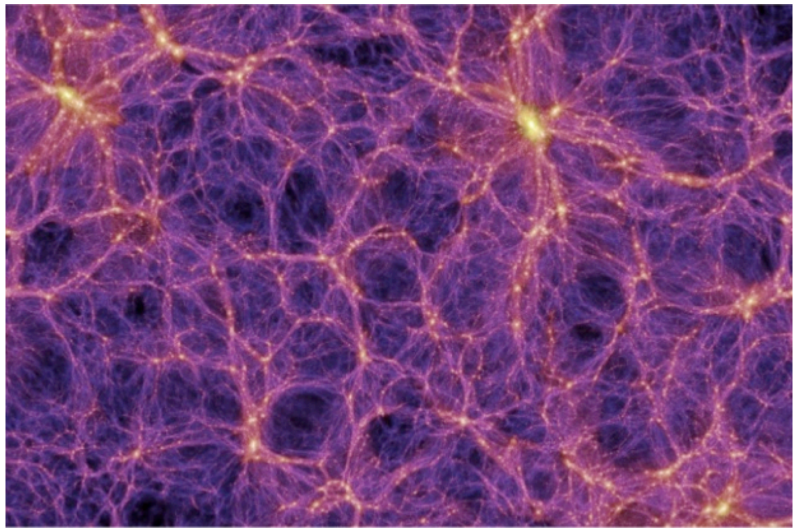
2. Gravitational Lensing



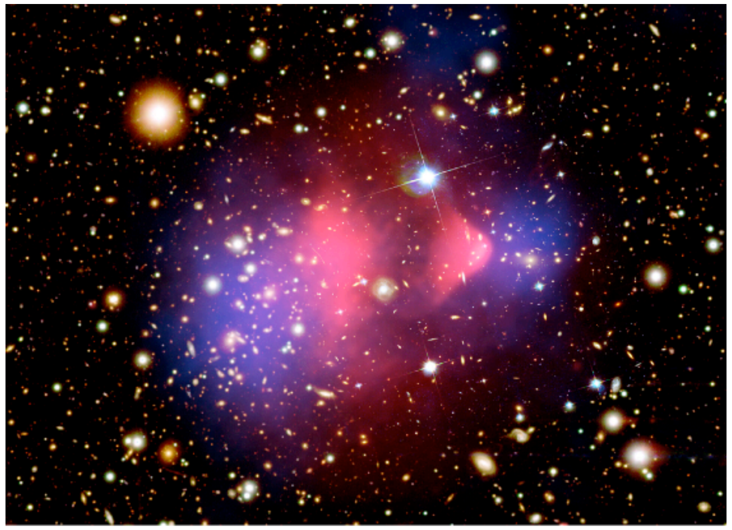
3. CMB Acoustic Peaks



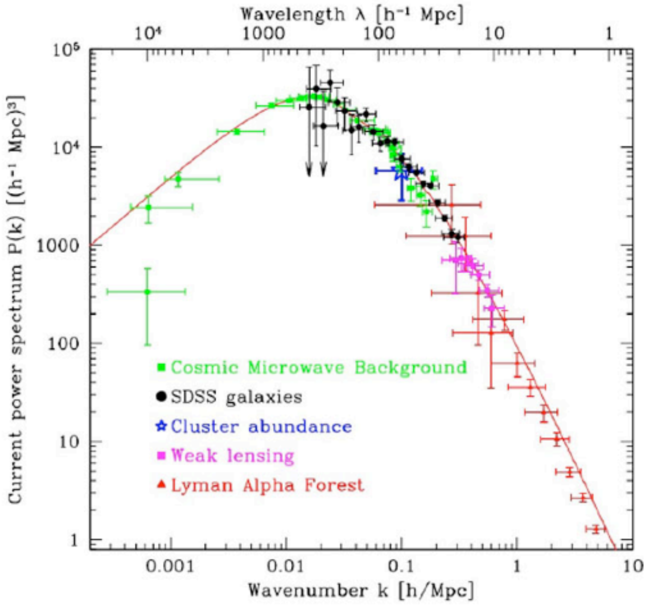
4. Large Scale Structure



5. Galaxy/Cluster Collisions

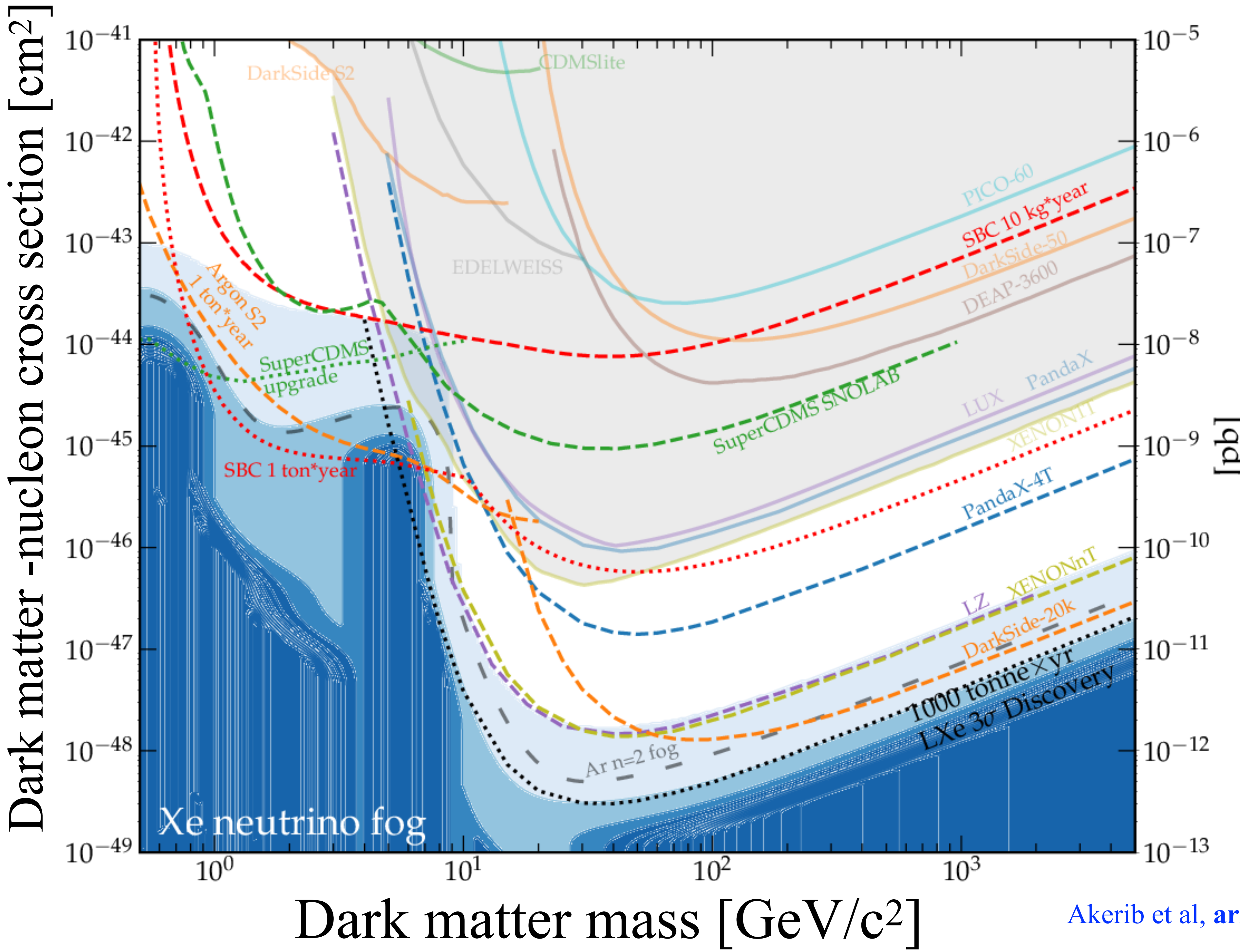


6. Matter Power Spectrum



Images: adapted from K. Mack

Current status of dark matter searches

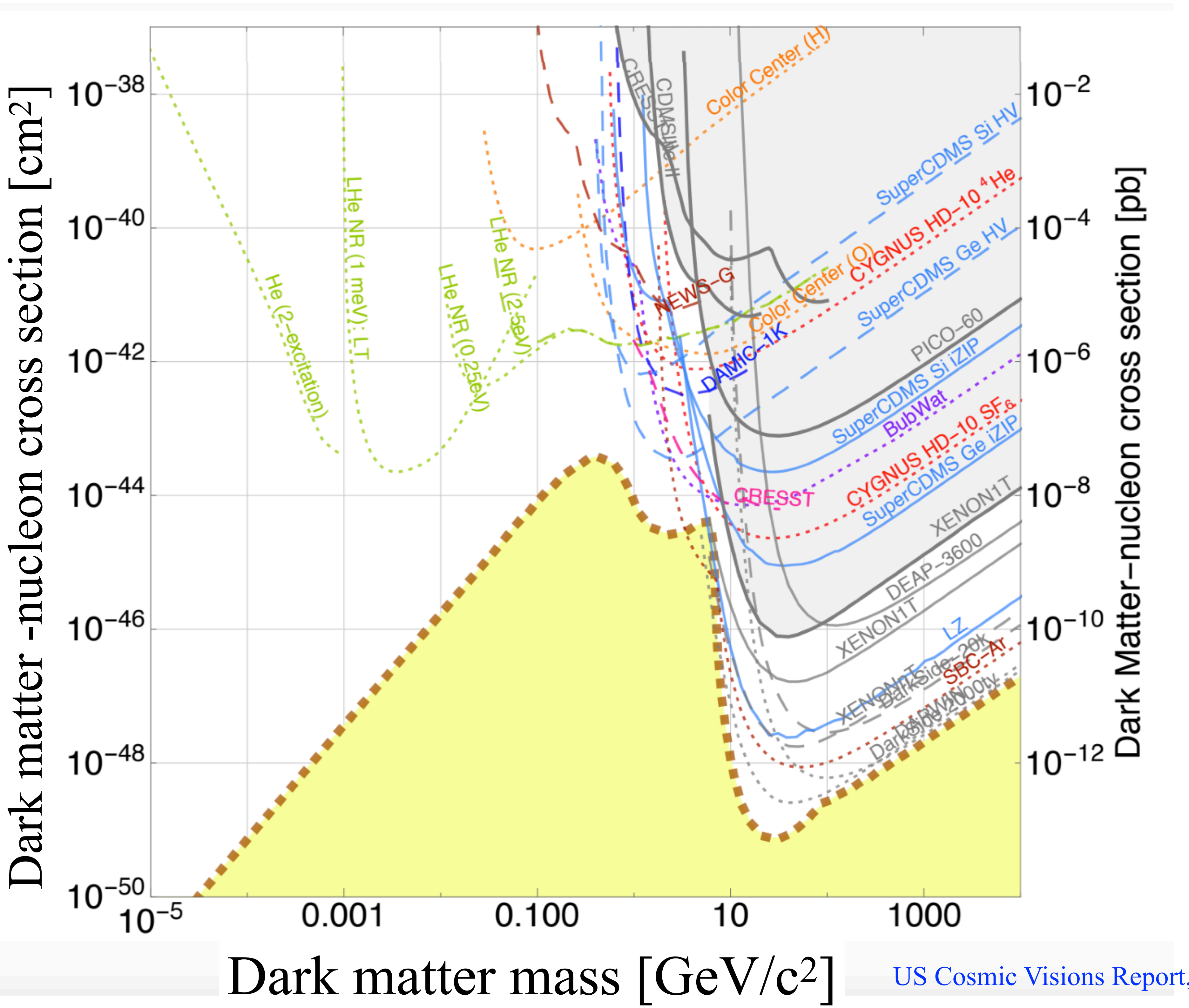


Akerib et al, **arXiv: 2203.08084**

Very little parameter space left in *traditional* WIMP mass range (1 GeV - 100 TeV)

Larger detectors gives us more sensitivity, but "Neutrino Floor/fog" may be challenging

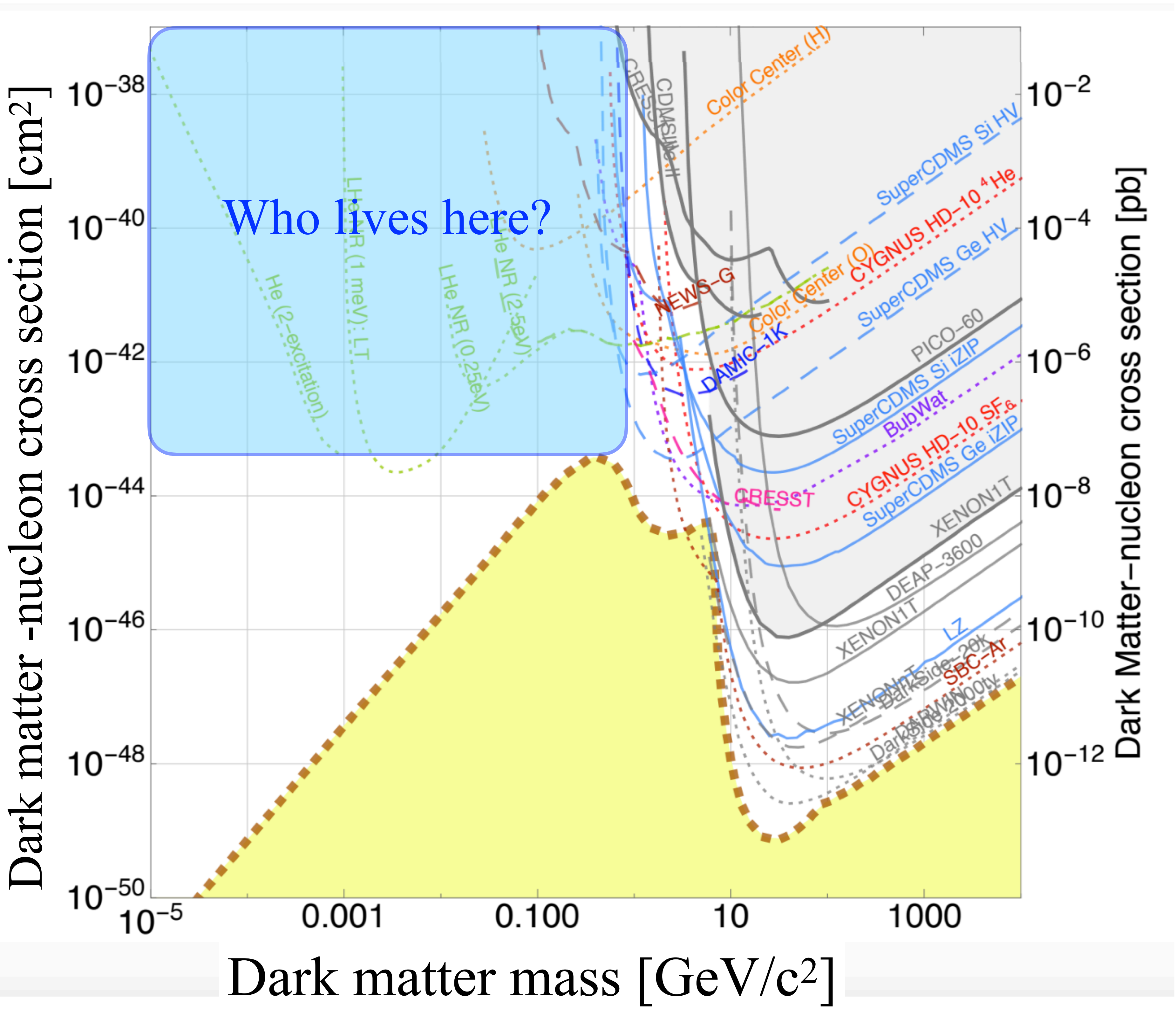
Looking towards lower dark matter masses



US Cosmic Visions Report, **arXiv:1707.04591**

Parameter space opens up in the sub-GeV region

Seems like many opportunities to explore here

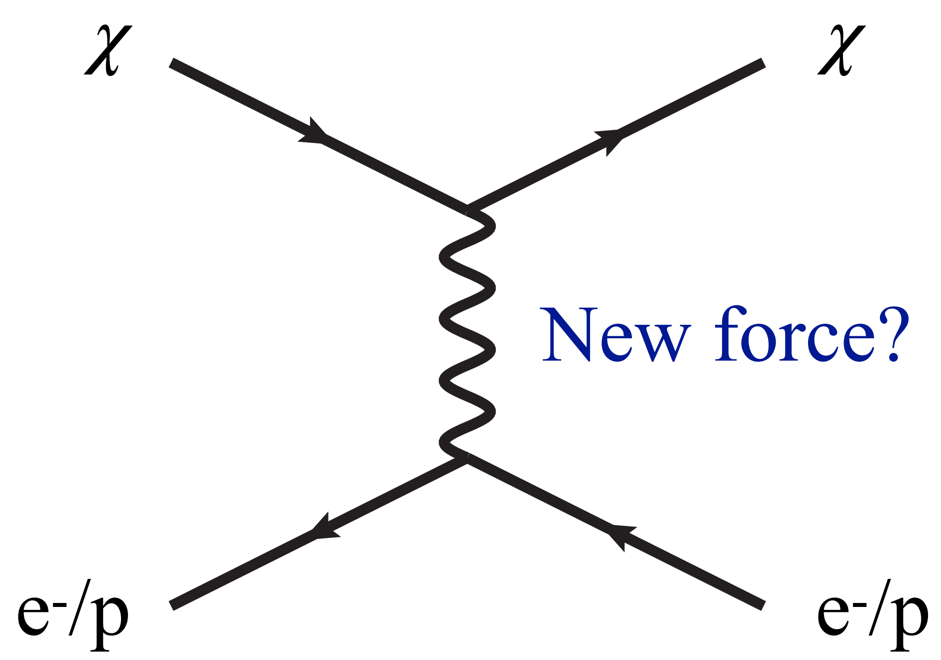


US Cosmic Visions Report, **arXiv:1707.04591**

Sub-GeV DM searches are:

1. Complementary to WIMP searches

2. Very well motivated:



e.g. low mass DM coupled through hidden sector mediator presents a good target to understanding DM production in the early universe

- Thermal freeze-out   - Freeze-in   - Asymmetric   …

Big stumbling block: light DM is invisible to current WIMP searches

Many nuclear recoil experiments have ~ keV recoil thresholds

Recoil energy caused by galactic DM with v ~ 10^{-3} c

$$E_{nr} \sim \frac{\mu_{xN}^2 v^2}{m_N}$$

$$\sim 19 \text{ eV} \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

$$\ll \text{keV}$$

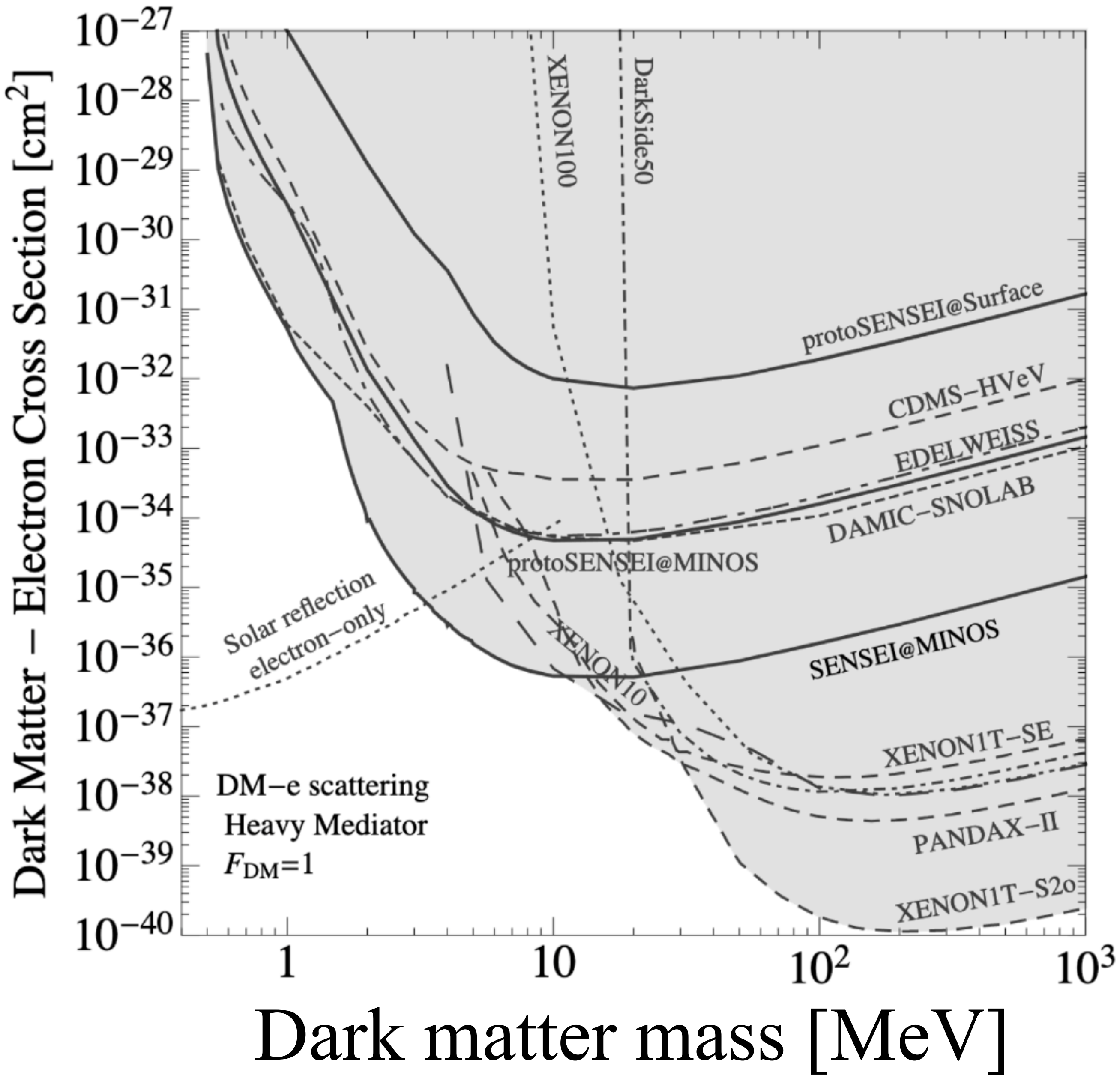
To probe lower masses need very low threshold nuclear recoil detectors

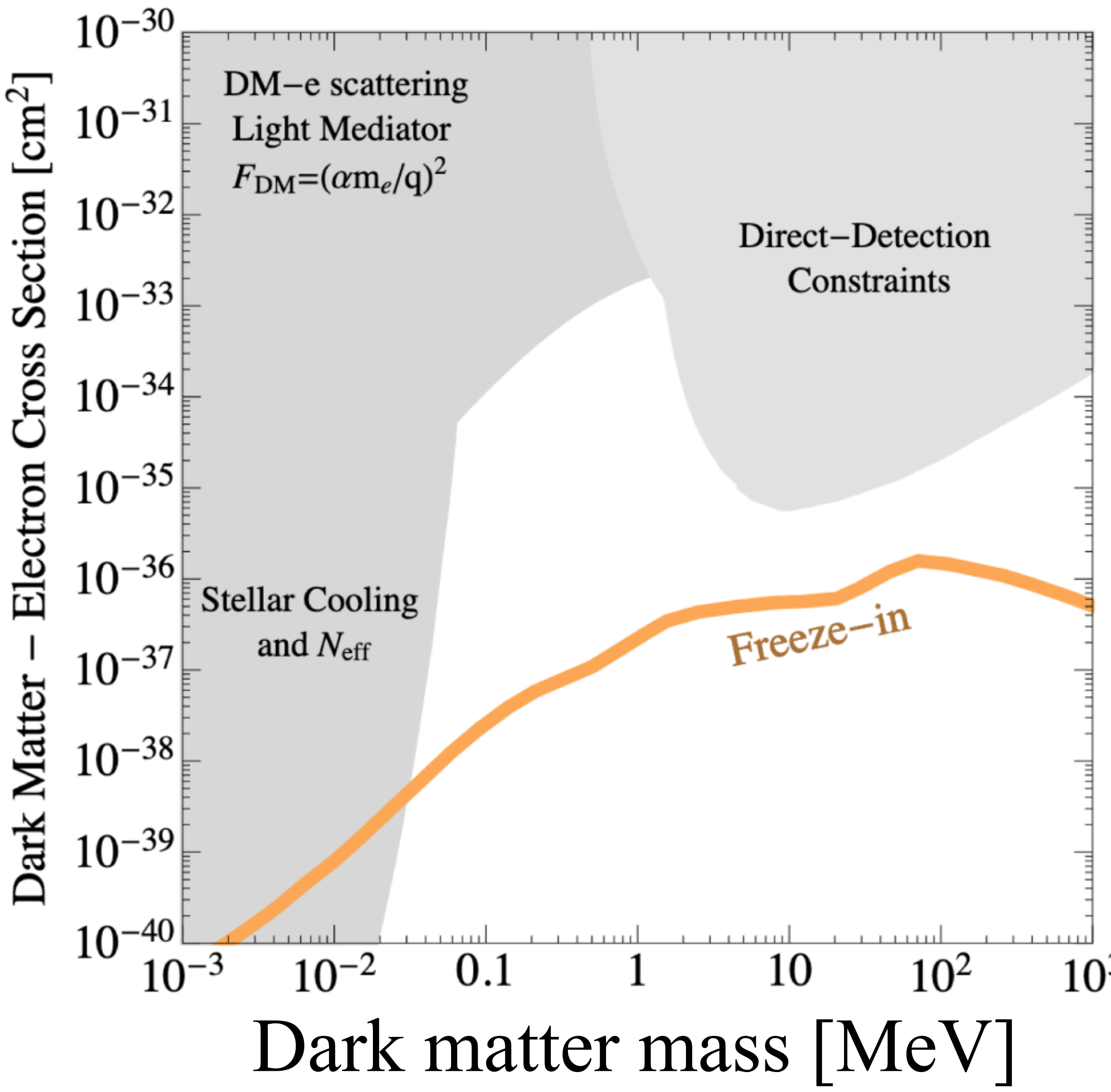
or

New range of detection strategies

Obvious direction: dark matter-electron scattering

Current searches include:
- Large volume noble liquid detectors
- Small scale semi-conductor detectors



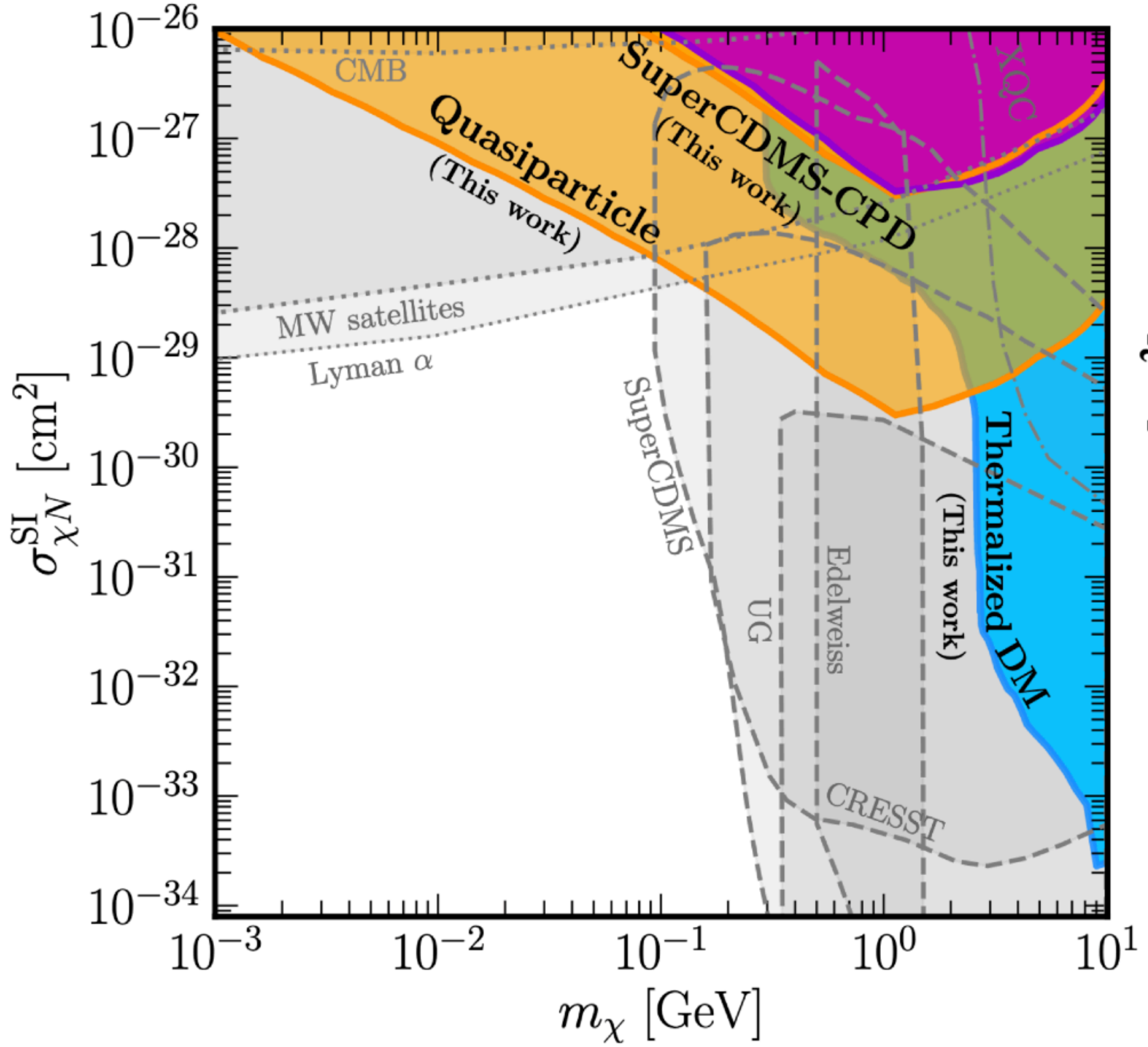


Essig et al, **arXiv: 2203.08297**

What about nuclear/nucleon scattering?

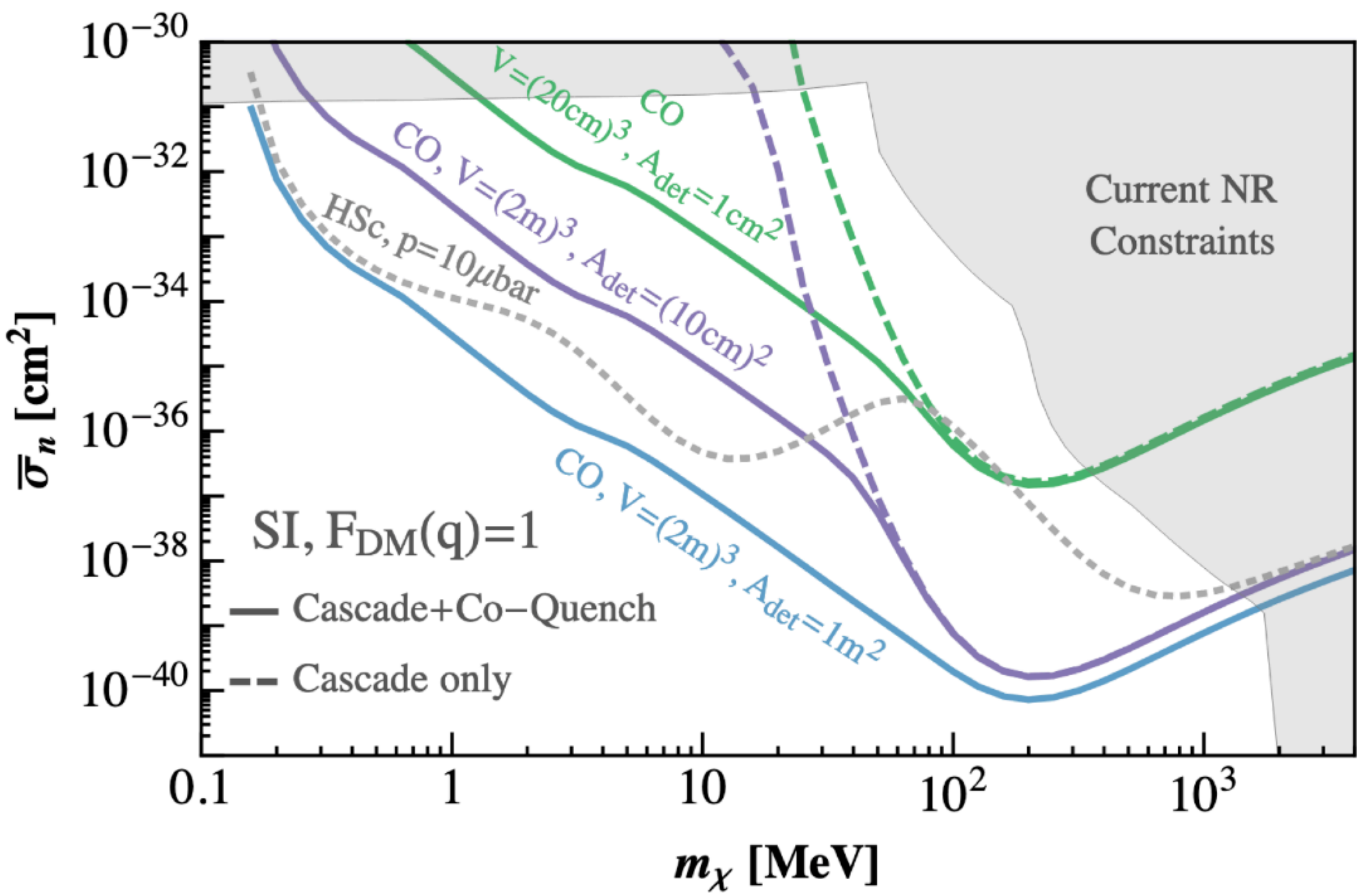
Build new detectors that can reduce thresholds & probe lower masses

e.g. Single Quasiparticle Devices



Das et al, **arXiv: 2210.09313**

e.g. Molecular excitations



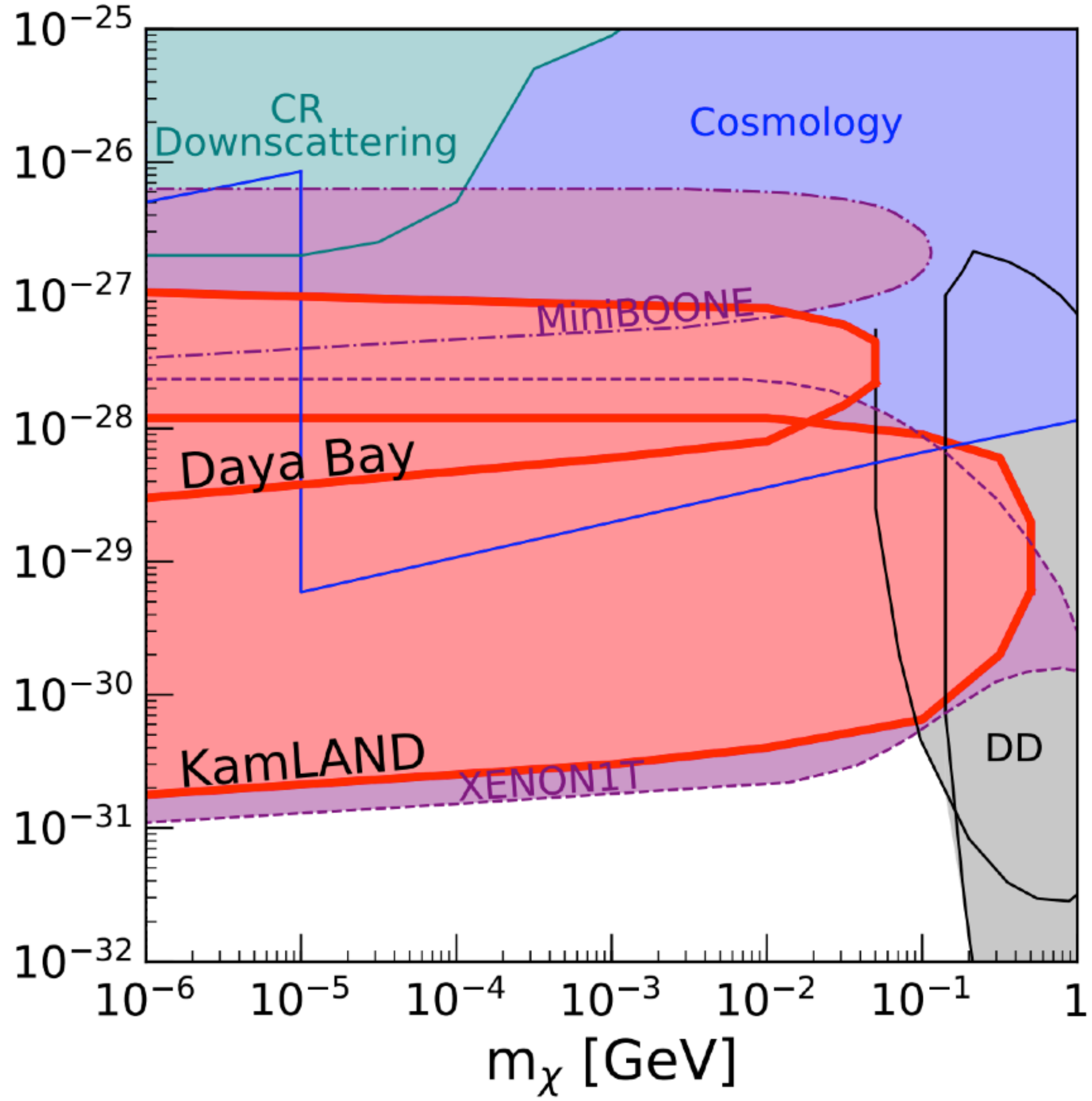
Essig et al: **Phys.Rev. Research 1, (2019) 033105**

Require new detector R&D and are for the future

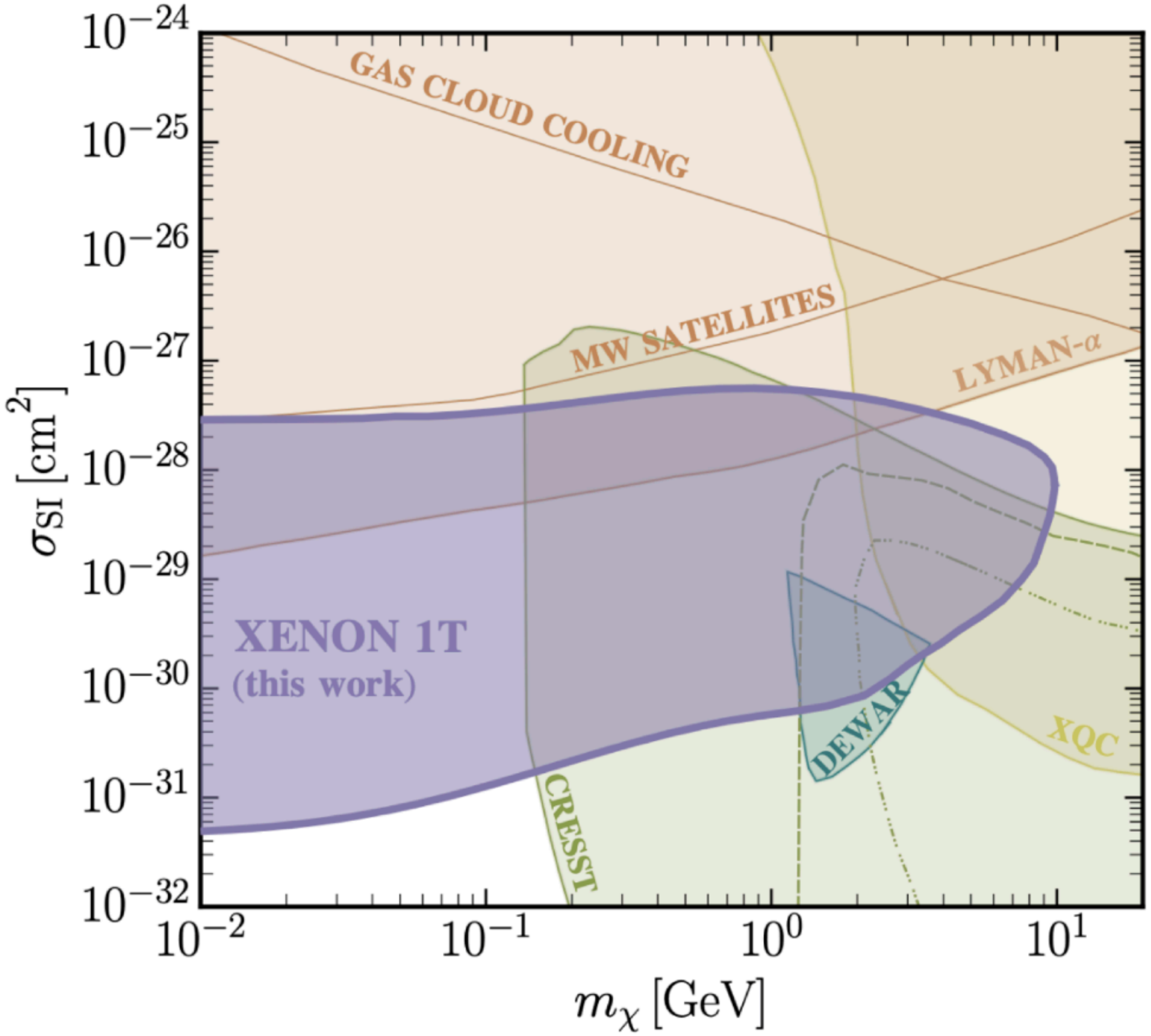
Can also probe lower masses by considering accelerated DM

Fast moving, low mass DM can deposit energy larger than detector threshold in existing experiments

E.g. Cosmic ray - up scattered DM



Cappiello, Beacom : **Phys.Rev. D100 (2019) 10, 103011**



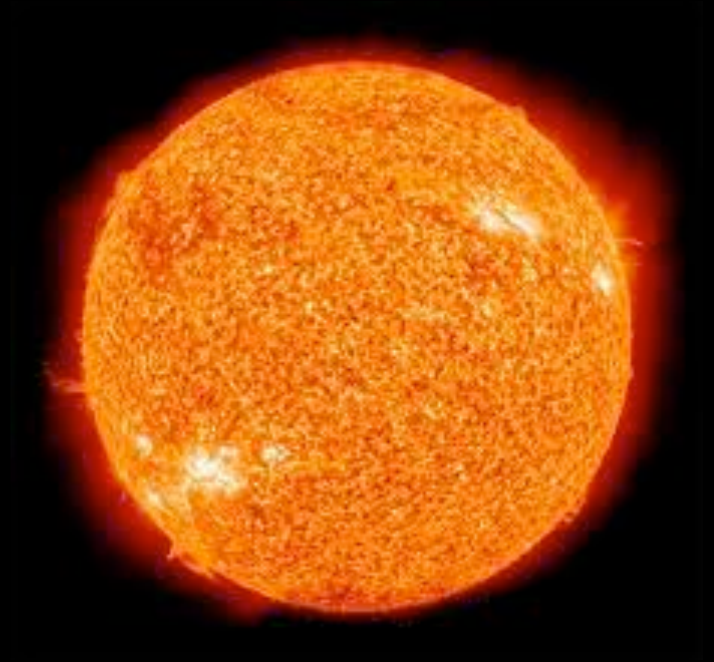
Alvey et al: **JHEP 01 (2023) 123**

Usually depend on flux of fast moving SM particles

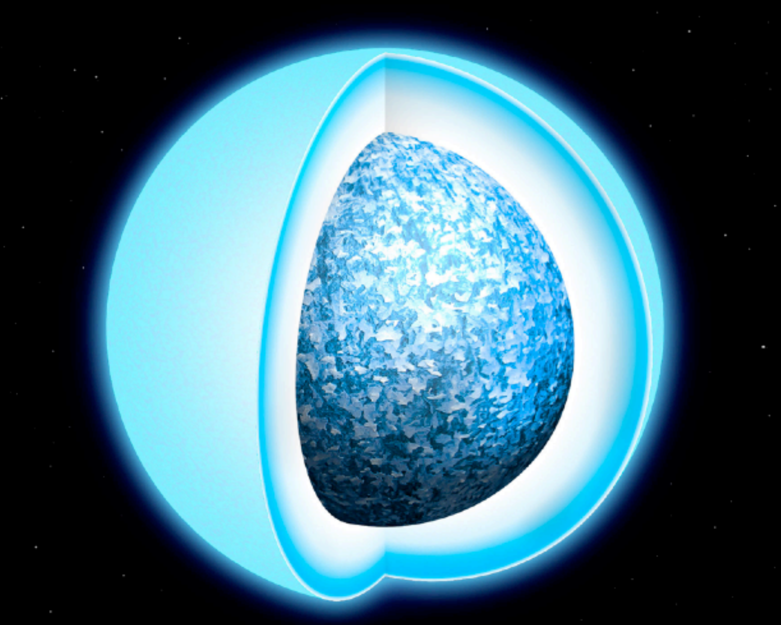
Astrophysical objects can also be laboratories for DM

Planets

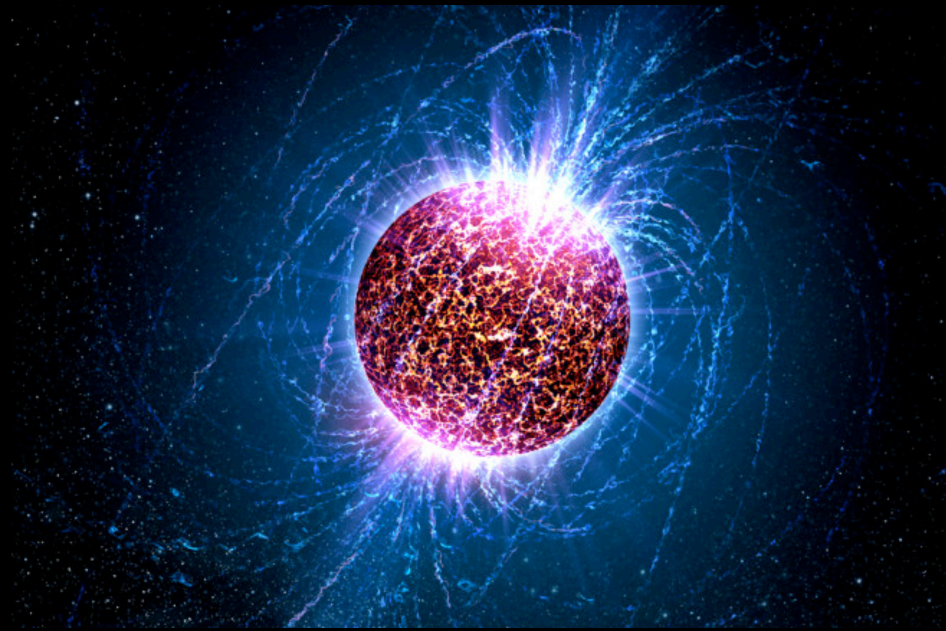
Brown dwarfs



main sequence stars



White dwarfs



Neutron Stars

Other compact objects

Why compact object searches for low mass DM?

- Great for attracting and accreting DM $\Longrightarrow$ higher DM densities

  E.g. DM capture in stars or planets and accumulation over lifetime of the body

- Higher flux of DM annihilation products $\Longrightarrow$ more experimental sensitivity

  E.g. DM annihilation into SM or new physics & detection on Earth

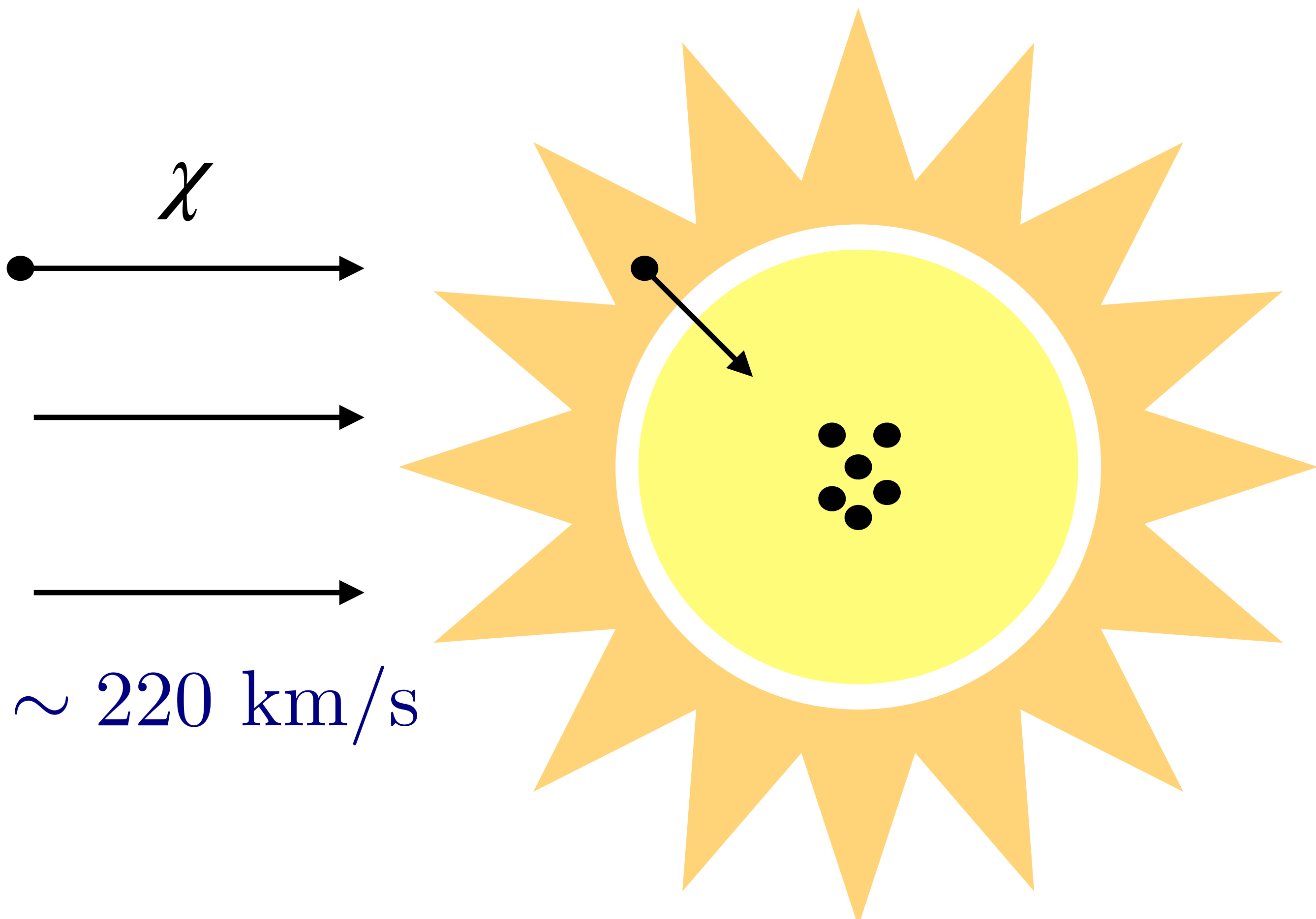
- Statistics: large number of astrophysical bodies, higher chance of DM accumulation

  E.g. DM capture & annihilation in exoplanets

- Used to set constraints

  E.g. Stellar cooling & planetary heating

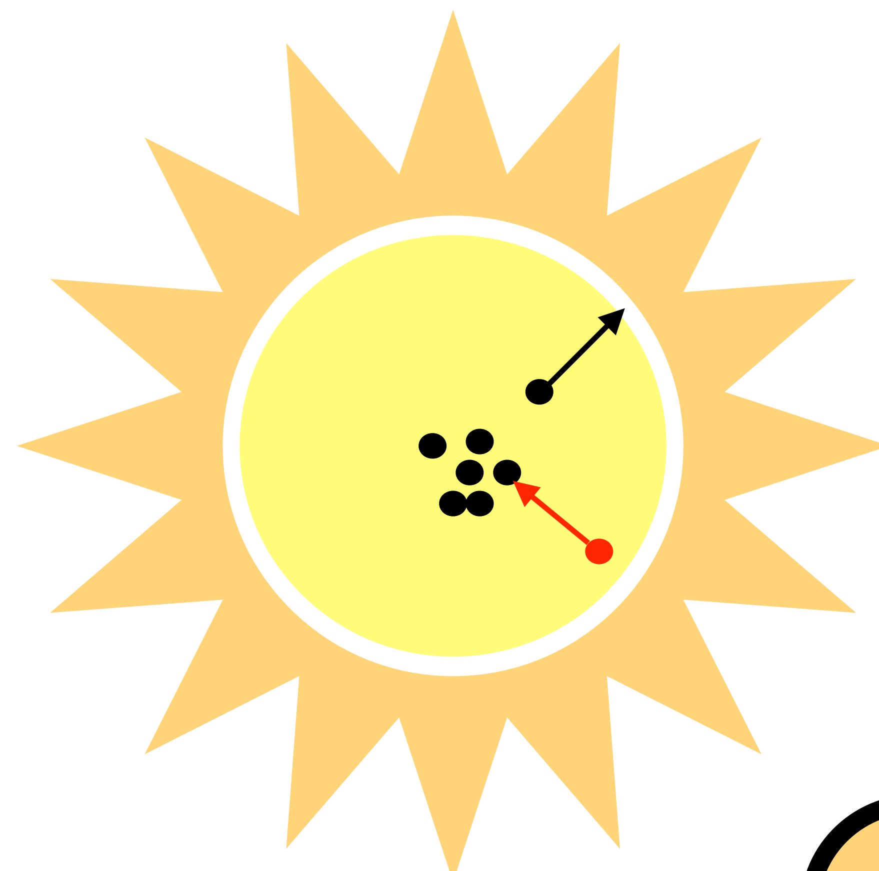
Standard framework for DM capture and evaporation in bodies like the Sun



$v_\chi \sim 220$ km/s

DM **captured** by scattering with solar material and

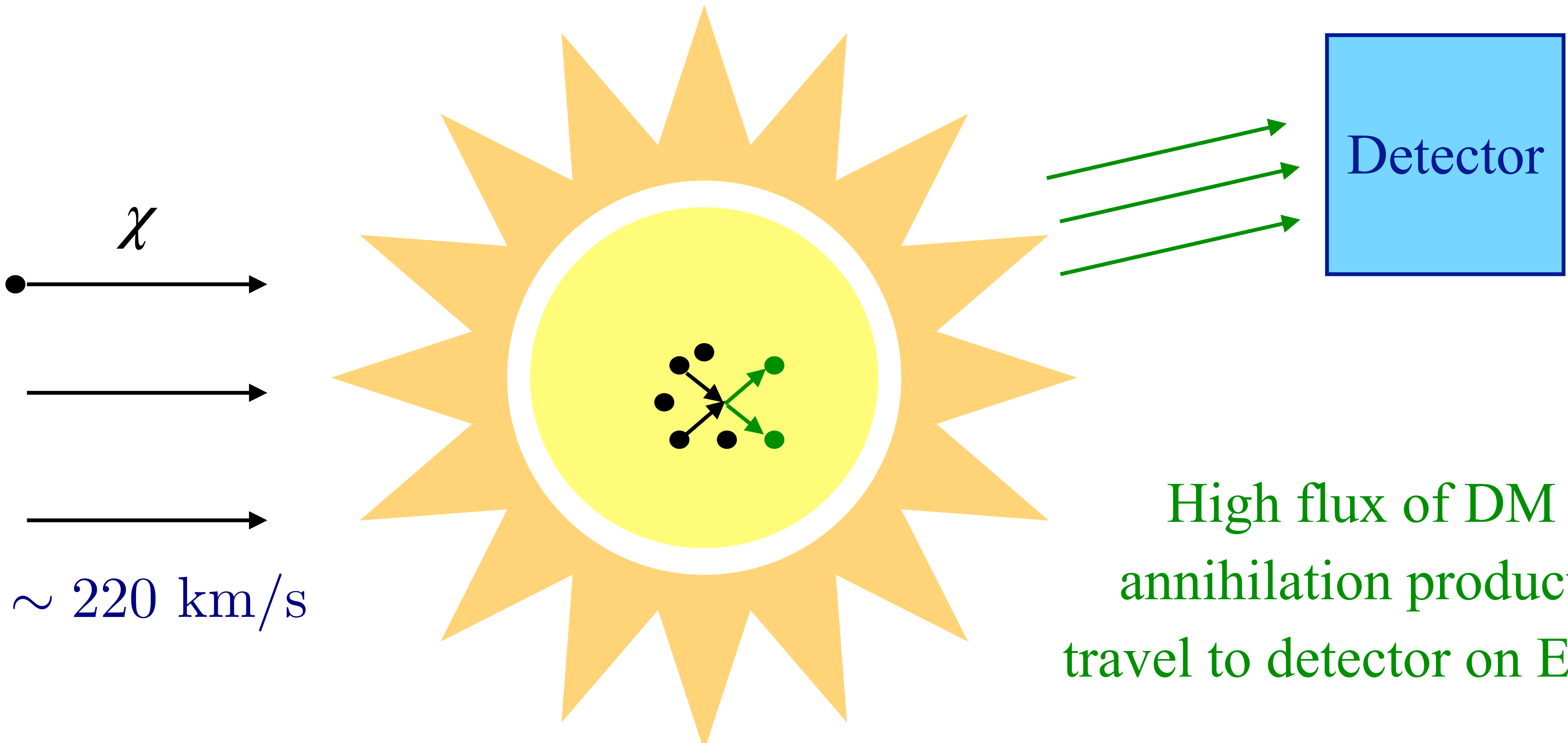
$$v_\chi^f \; < \; v_{esc}^{\odot}$$



SM particles with solar thermal motion scatter with DM causing **evaporation**

$$v_\chi^f \; > \; v_{esc}^{\odot}$$

Assuming thermal equilibrium, over Sun's lifetime DM has accumulated in solar core resulting in high number densities



High flux of DM annihilation products travel to detector on Earth

DM number density

$$\frac{dN_\chi}{dt} = C_c - C_e N_\chi - C_a N_\chi^2$$

Capture rate — Evaporation rate — Annihilation rate

Very large body of work

Sun

WIMPs, Gould: **Astrophys. J. 321 (1987) 560**

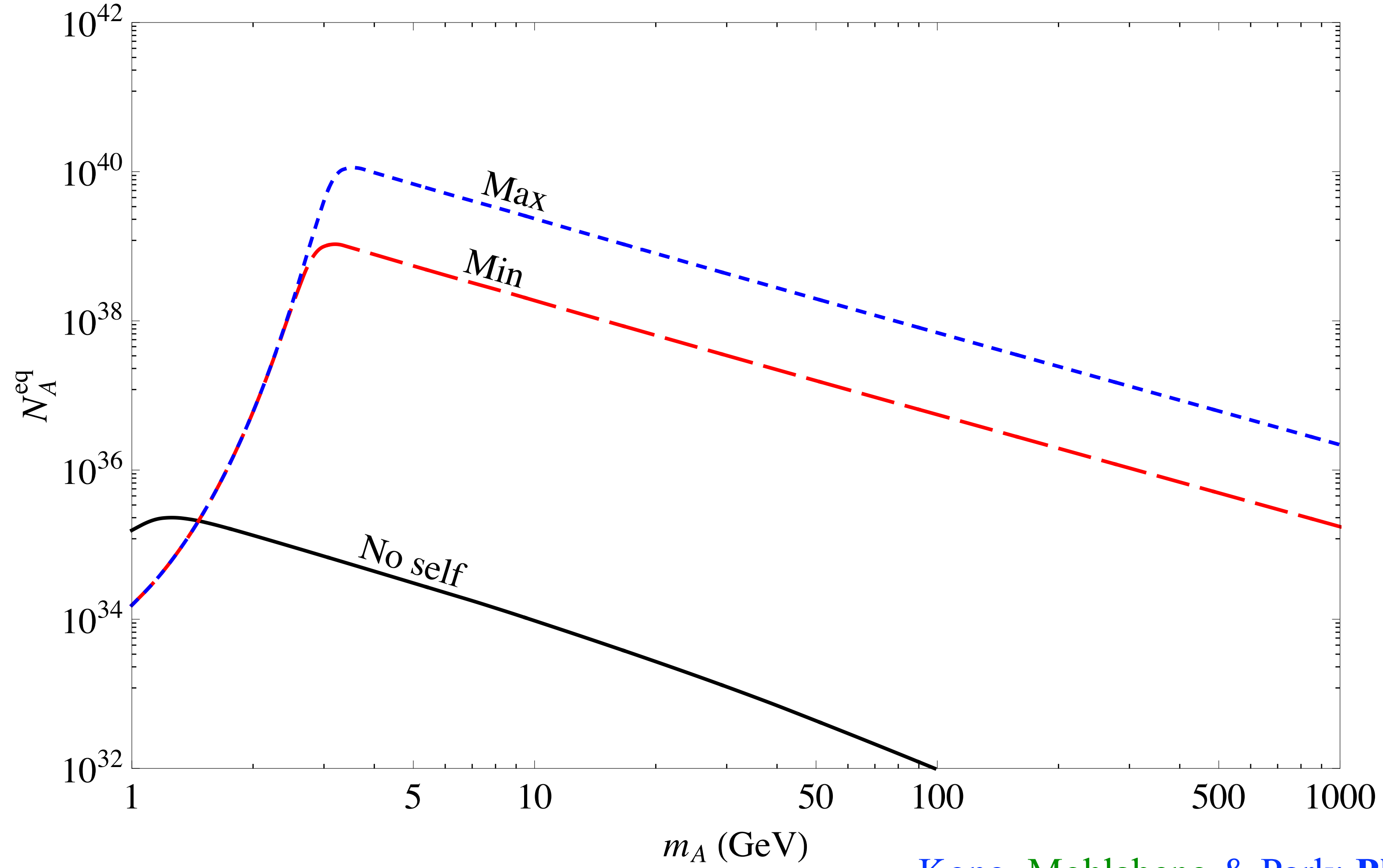
WIMPs with self interaction, Zentner: **Phys. Rev. D80 (2009) 063501**

Annihilation to dark photons, Feng et al: **Phys. Rev. D93 (2016) 115036** + many others

Multi-component boosted DM in the Sun

$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_{se} + C_a)N_\chi^2$$

self-interactions



$$0.1\ \mathrm{cm}^2/g < \frac{\sigma_{AA}}{m_A} < 1.25\ \mathrm{cm}^2/g$$

min max

Kong, Mohlabeng & Park: **Phys. Lett. B 743 (2015)**

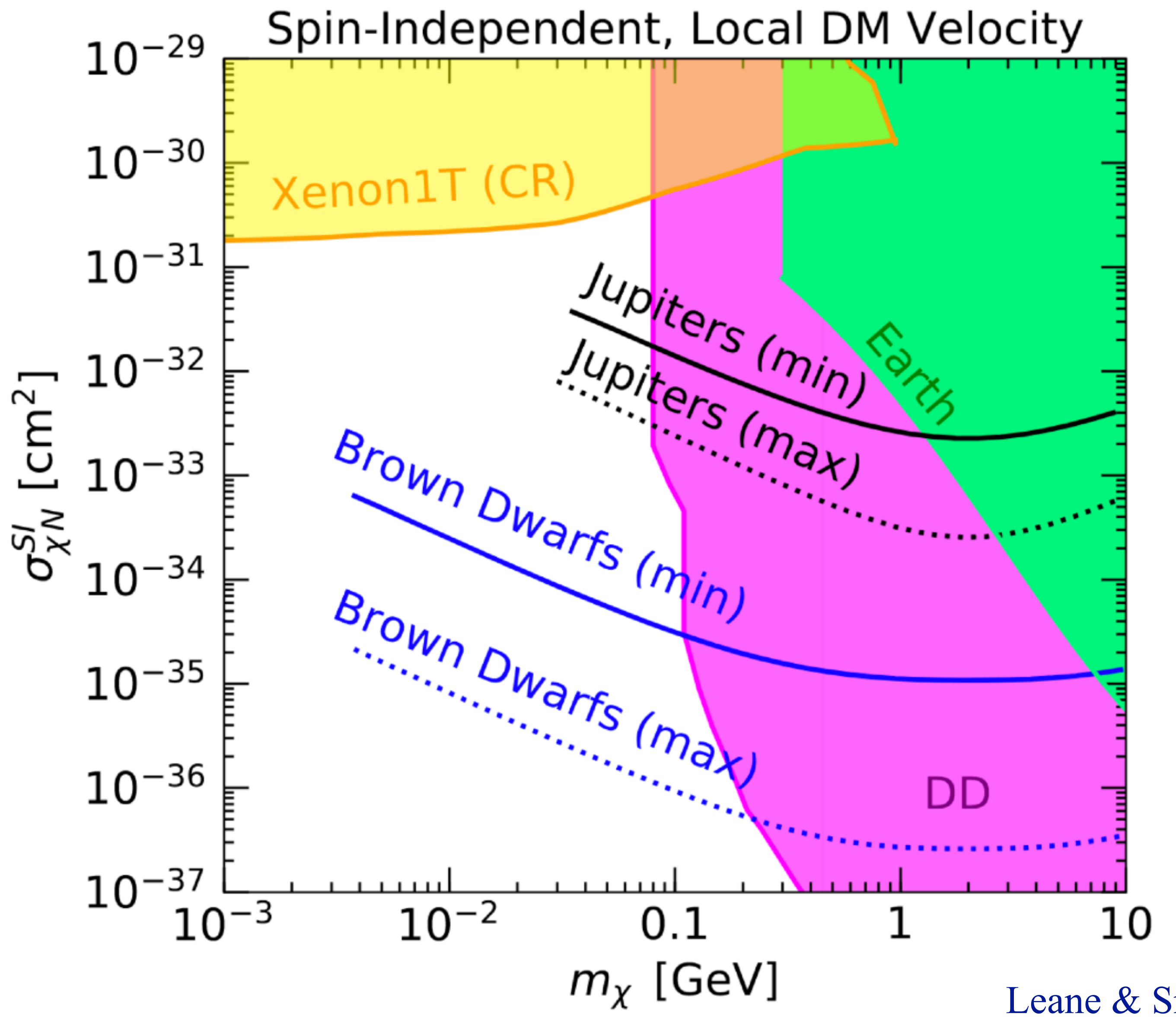
Earth & other Planets

WIMPs in the Earth, Gould: **Phys. Lett. B 671 (2009)**

Dark photons from Earth center, Feng et al: **Phys. Rev. D93 (2016) 015014**

DM in Uranus & Jupiter-like planets, Adler: **Phys. Lett. B 671 (2009)** + many others

Exoplanet search for Sub-GeV DM



Leane & Smirnov: **Phys. Rev. Lett. 126 (2021)**

Other compact Objects

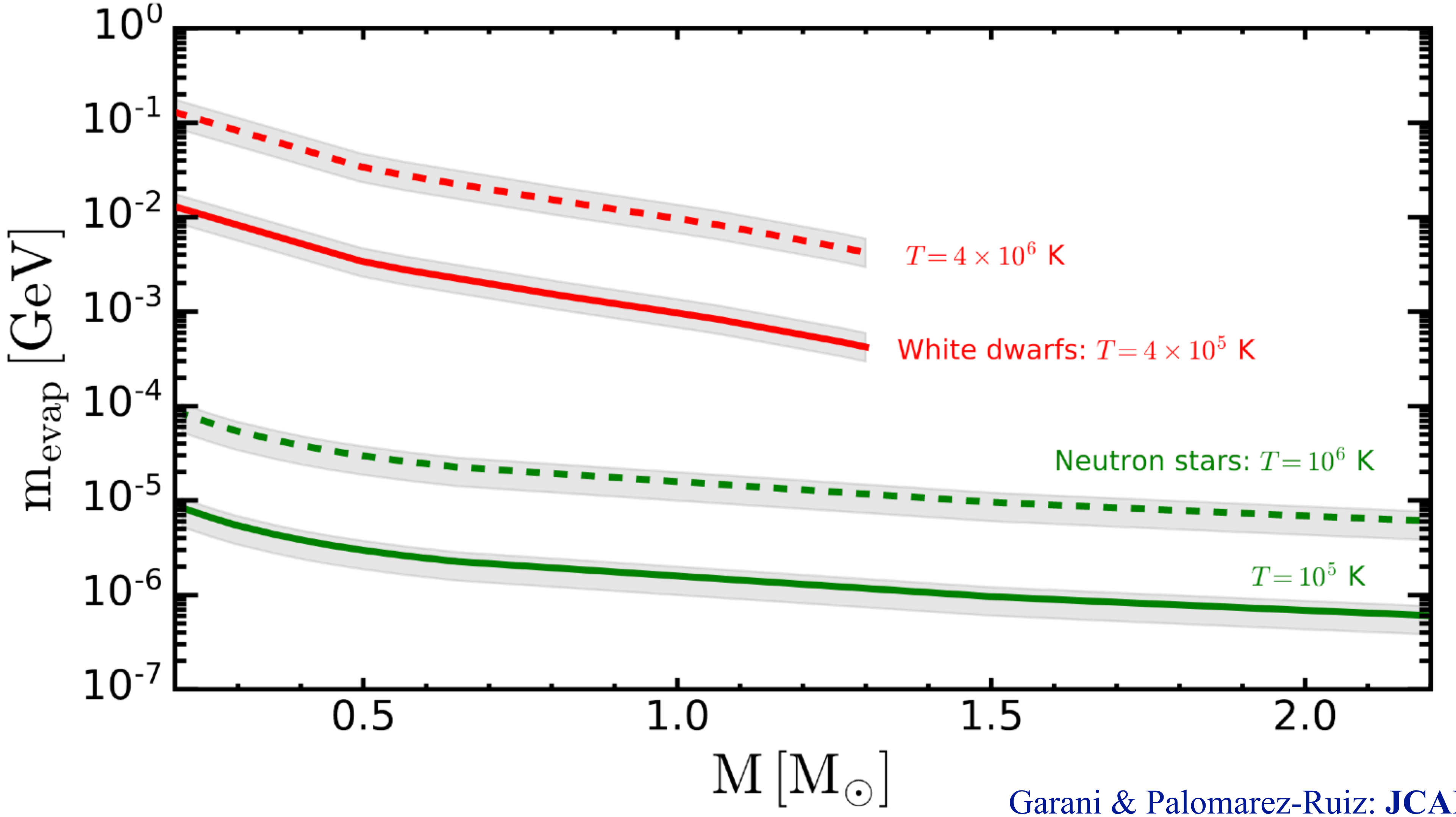
Capture in Neutron stars, Guver et al: **JCAP 05 (2014) 013**

Relativistic DM capture in Neutron stars, Joglekaar et al: **Phys. Rev. D 102 (2020) 123002**

DM capture in white dwarfs, Bell et al: **JCAP 10 (2021) 083**

DM trigger for white dwarf explosion, Smirnov et al: **arXiv 2211.00013** + many others

General evaporation from celestial bodies



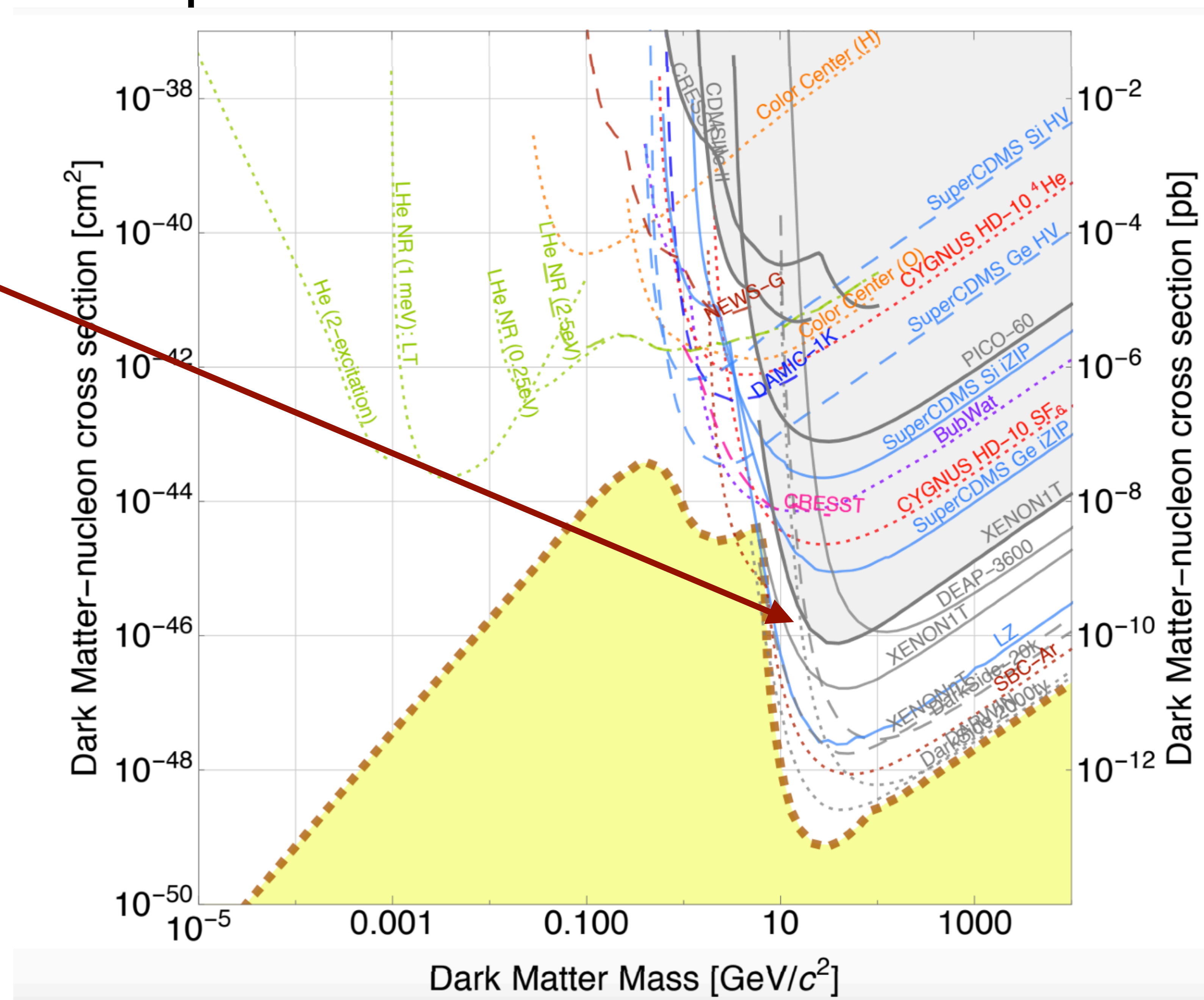
Garani & Palomarez-Ruiz: **JCAP 05 (2022) 042**

- Many of the existing studies expand on WIMP DM capture

- Main assumption: weak interactions $\Longrightarrow$ single scatter capture/evaporation

- Also due to current direct detection constraints in WIMP mass region

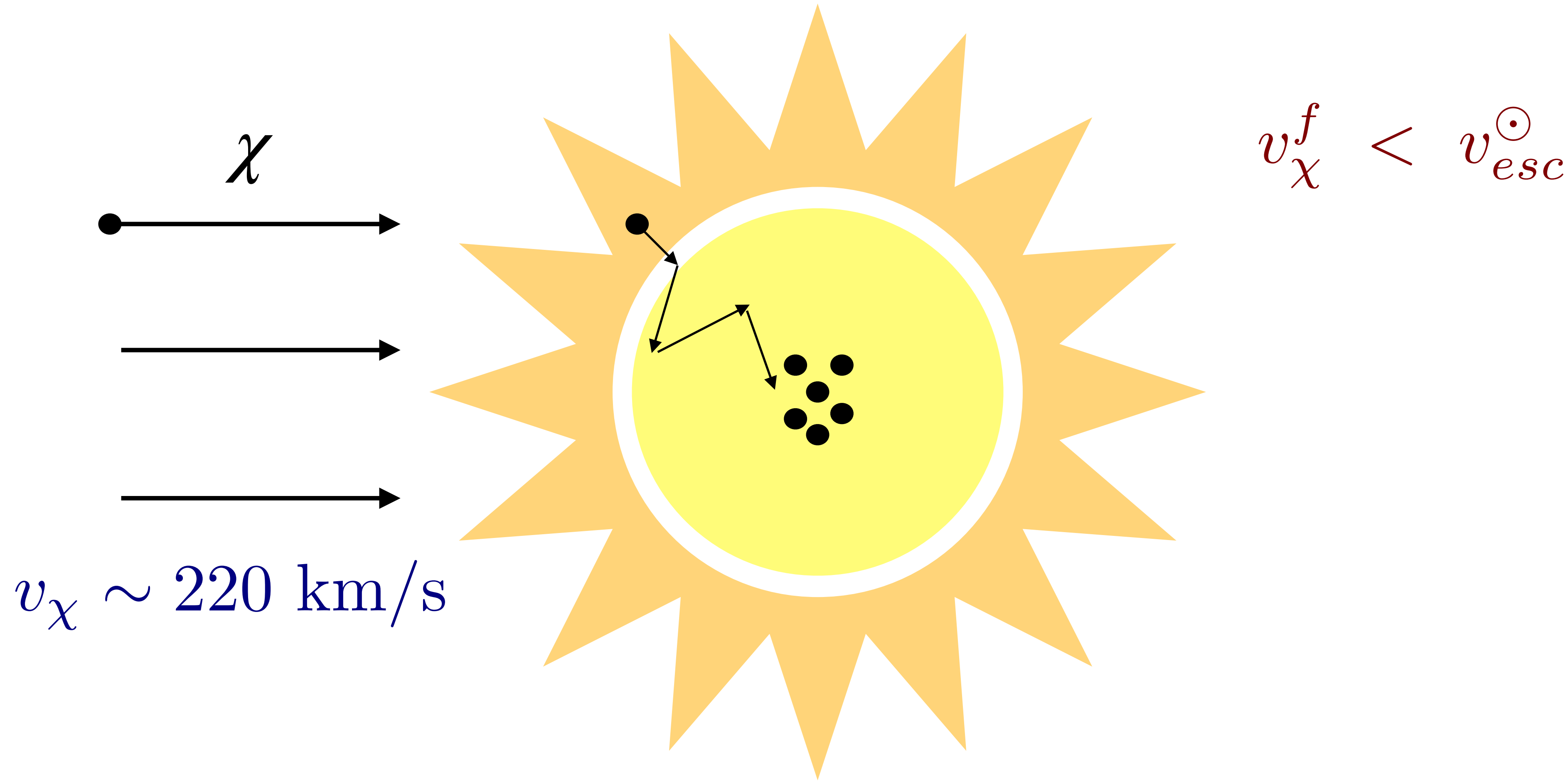
$\Longrightarrow$ Optically thin limit



US Cosmic Visions Report, **arXiv:1707.04591**

Away from the WIMP region, large cross-sections not ruled out $\Longrightarrow$ **multi-scatter** capture/evaporation is possible

We call this the **Optically thick regime**



Earth, Gould: **Astrophys. J. 387 (1992) 21**

Sun, Garani & Palomarez-Ruiz: **JCAP 05 (2017) 007**

Baum et al: **Phys. Rev. D 95 (2017) 043007**

Stars, Bramante et al: **Phys. Rev. D 96 (2017) 063002**

White dwarfs, Dasgupta et al: **JCAP 08 (2019) 018**

+ others

Focus of this talk is revisiting **multi-scatter** capture in Earth

- Focus on low mass DM

- Revisit Earth heating limit in the optically thick regime

- More detailed Monte Carlo simulation for multi-scatter capture in the Earth

- Improved bounds on low mass DM-nucleus/nucleon scattering for spin (in)dependent scattering

DM number density in Earth

Solve differential equation for DM number:

$$\frac{dN_\chi}{dt} = C_\oplus - \left(\frac{E_\oplus}{N_\chi}\right) N_\chi - A_\oplus N_\chi^2$$

Total DM annihilation rate:

$$\Gamma_\oplus = (1/2) A_\oplus N_\chi(t)^2$$

- DM captured through multiple interactions with nuclei
- Captured DM thermalizes with SM and is in local thermal equilibrium
- DM in LTE evaporates from earth or annihilates

DM Capture in Earth

Full analytic multi-scatter capture rate calculation doesn't exist

Analytical approximation:

Interpolation between single scatter capture rate and Earth's geometric capture rate

$$C_{\oplus}^{\rm geom} = \pi R_{\oplus,atm}^2 \sqrt{\frac{8}{3\pi}} \frac{\rho_\chi v_d}{m_\chi} \left(1 + \frac{3v_e^2(R_{\oplus,atm})}{v_d^2}\right) \xi$$

Single scatter capture

$$C_{\oplus}^{\rm weak} = \sum_j \frac{\rho_\chi}{m_\chi} \int_0^{R_\oplus} 4\pi r^2 \int_0^\infty du_\chi f(u_\chi) \frac{w(r)}{u_\chi} \int_0^{v_e(r)} R_j^-(w \to v) |F_j(q)|^2 dv$$

Multi scatter capture (approximation)

$$C_\oplus = C_\oplus^{\rm weak}(1 - \exp(-C_\oplus^{\rm geom}/C_\oplus^{\rm weak}))$$

Garani & Palomarez-Ruiz: **JCAP 05 (2017) 007**

Baum et al: **Phys. Rev. D 95 (2017) 043007**

Monte-Carlo Simulation:

- If DM heavier or lighter than nuclei, kinetic energy in scatter is small & DM can scatter multiple times before getting captured

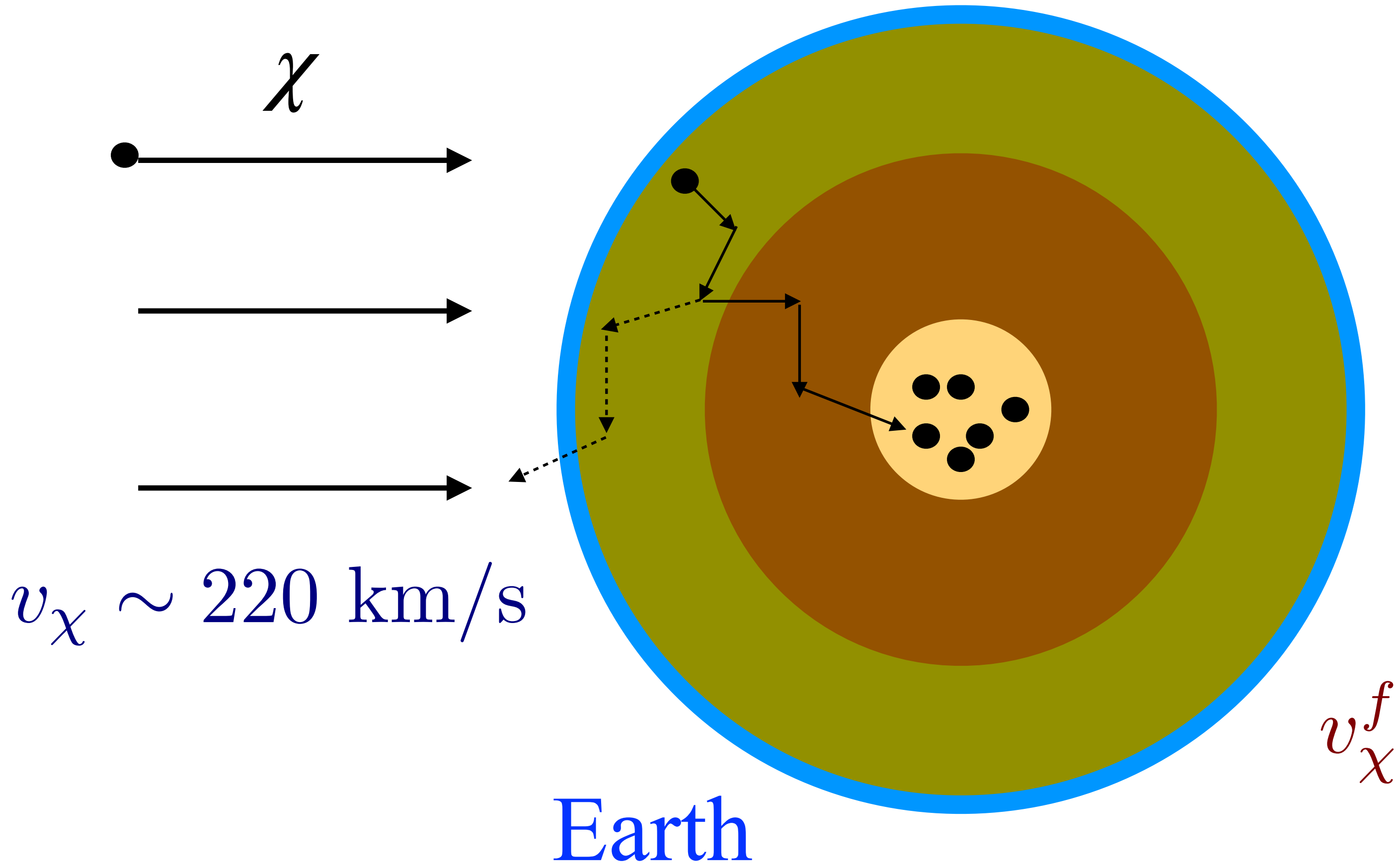
- Light DM can change direction & velocity after scattering, leading to a **Ping-Pong effect,** capture is not guaranteed

- Even if light DM interacts very strongly with nuclei, it may still be reflected away & not captured → suppressed capture

We simulate particles by drawing from DM velocity distribution, including escape velocity from Earth & Sun

$$v_\chi^i = \sqrt{u_\chi^2 + v_e^2(R_{\oplus,atm}) + v_s^2}$$

We calculate scattering probability given mean free path through length L in Earth



$$P = 1 - \exp\left(-\int_0^L dx/\lambda(x)\right)$$

Determine final velocity of particle after scattering

$v_\chi^f < v_e(R_{\oplus,atm})$ Captured

$v_\chi^f > v_e(R_{\oplus,atm})$ Not Captured

Properly model all the different layers in the Earth

DaMaSCUS-EarthCapture code

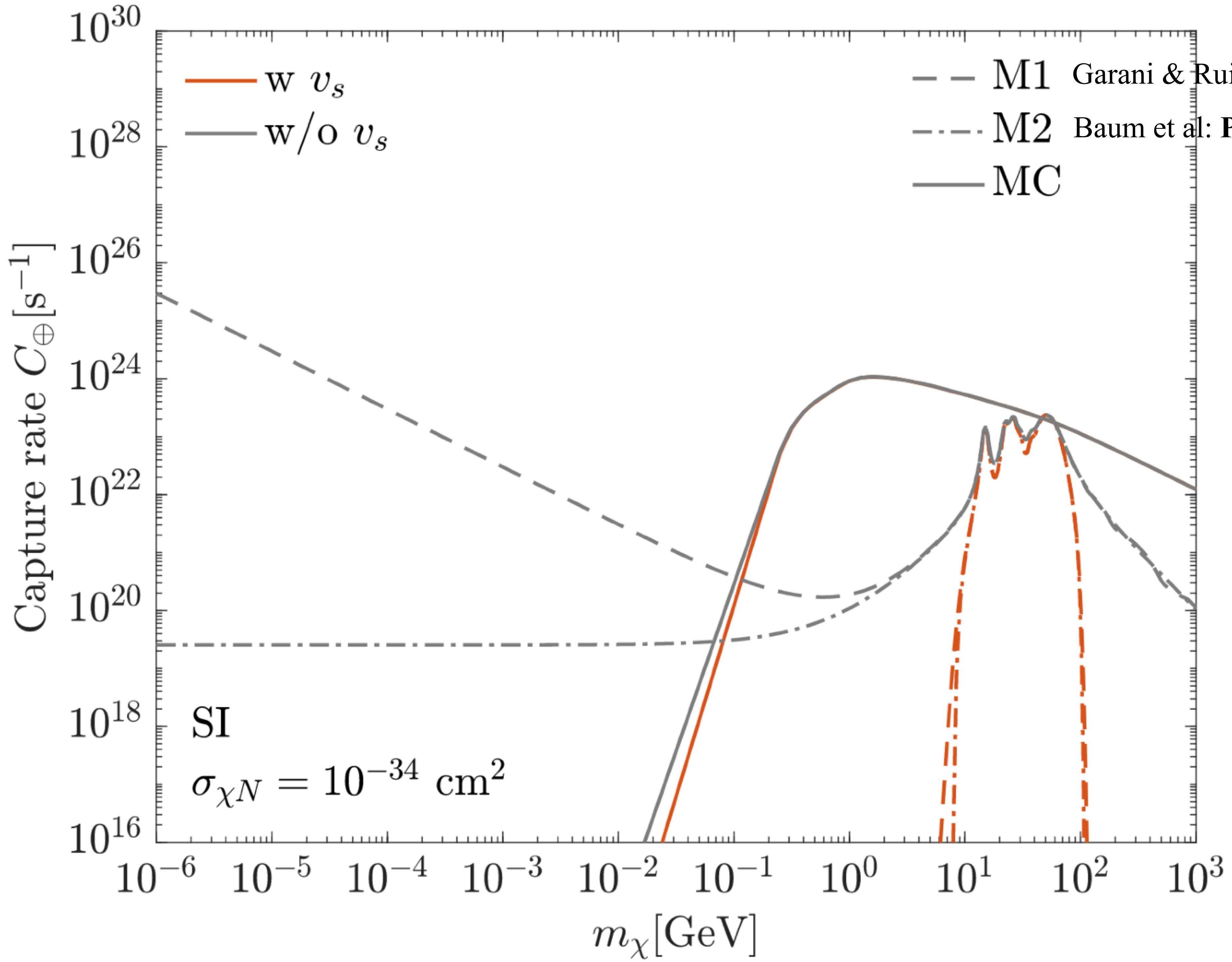
https://github.com/songningqiang/DaMaSCUS-EarthCapture

DaMaSCUS

Emken & Kouvaris: **JCAP 10 (2017) 031**

Monte-Carlo vs Analytic approx

$$C_{\oplus}^{\rm weak} = \sum_j \frac{\rho_\chi}{m_\chi} \int_0^{R_\oplus} 4\pi r^2 \int_0^\infty du_\chi f(u_\chi) \frac{w(r)}{u_\chi} \int_0^{v_e(r)} R_j^-(w \to v)|F_j(q)|^2 dv$$



Garani & Ruiz: **JCAP 05 (2017) 007**

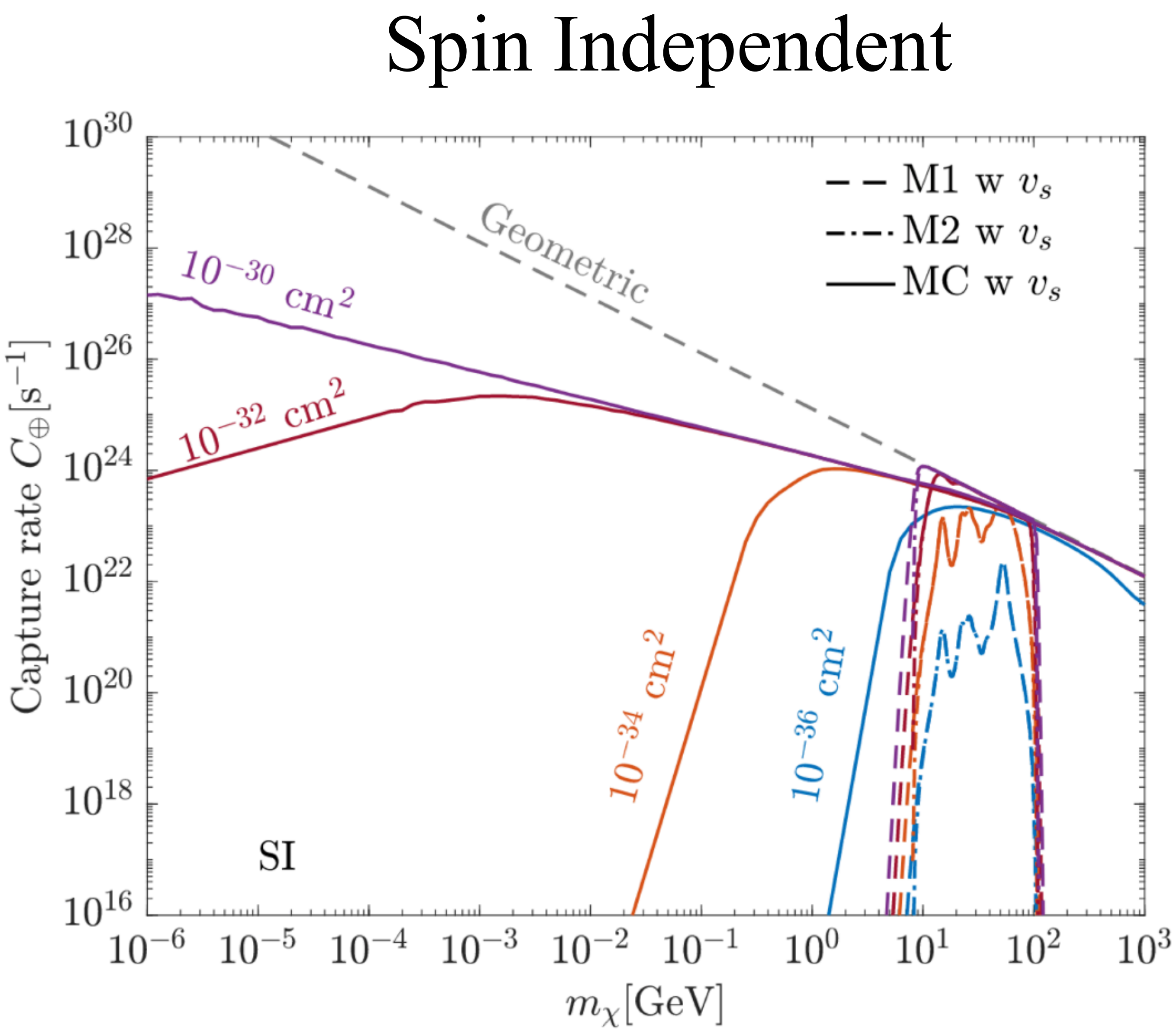
Baum et al: **Phys. Rev. D 95 (2017) 043007**

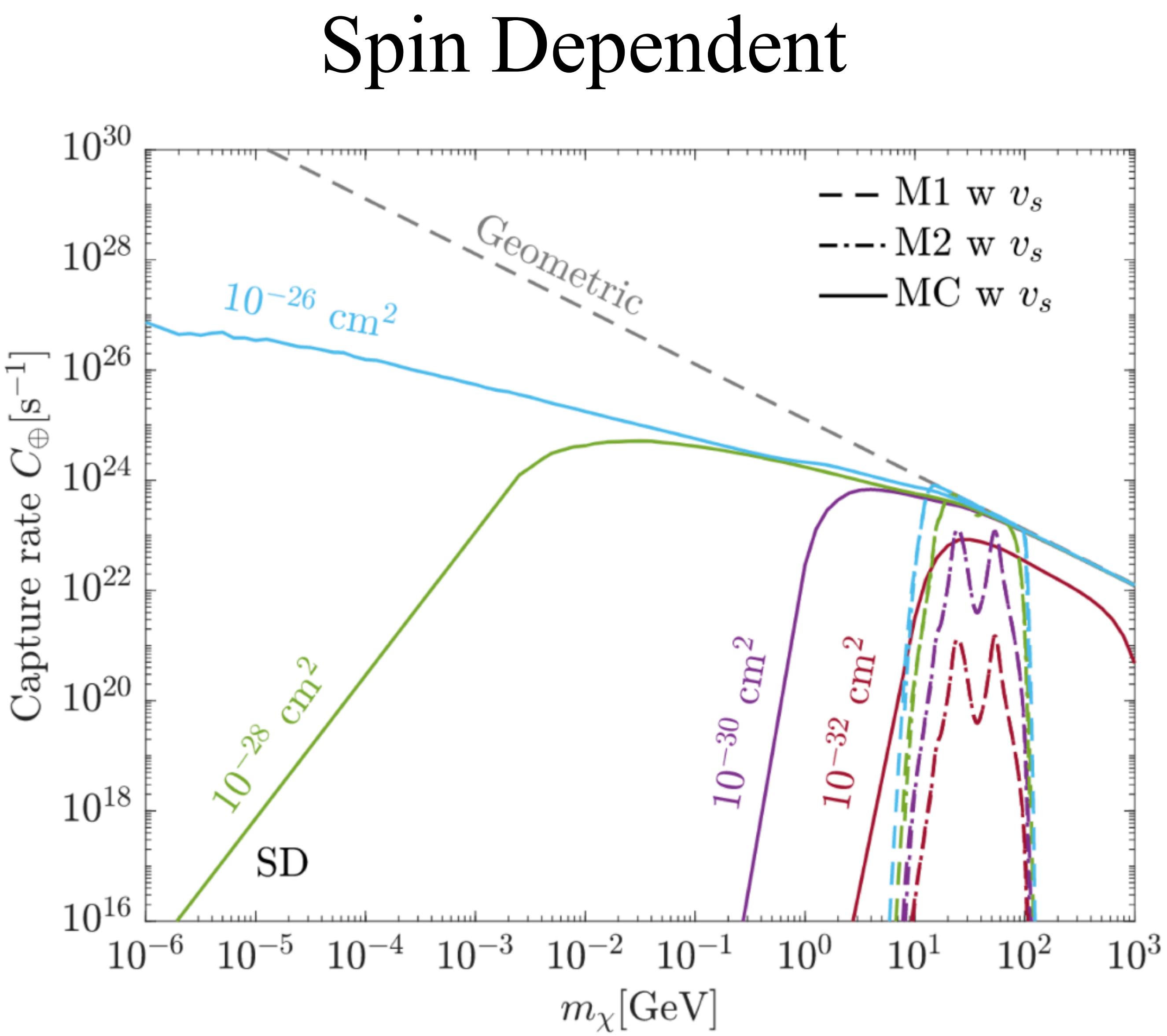
$v_s = 42.2$ km/s

Solar escape velocity

Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

DM Capture rate in the Earth

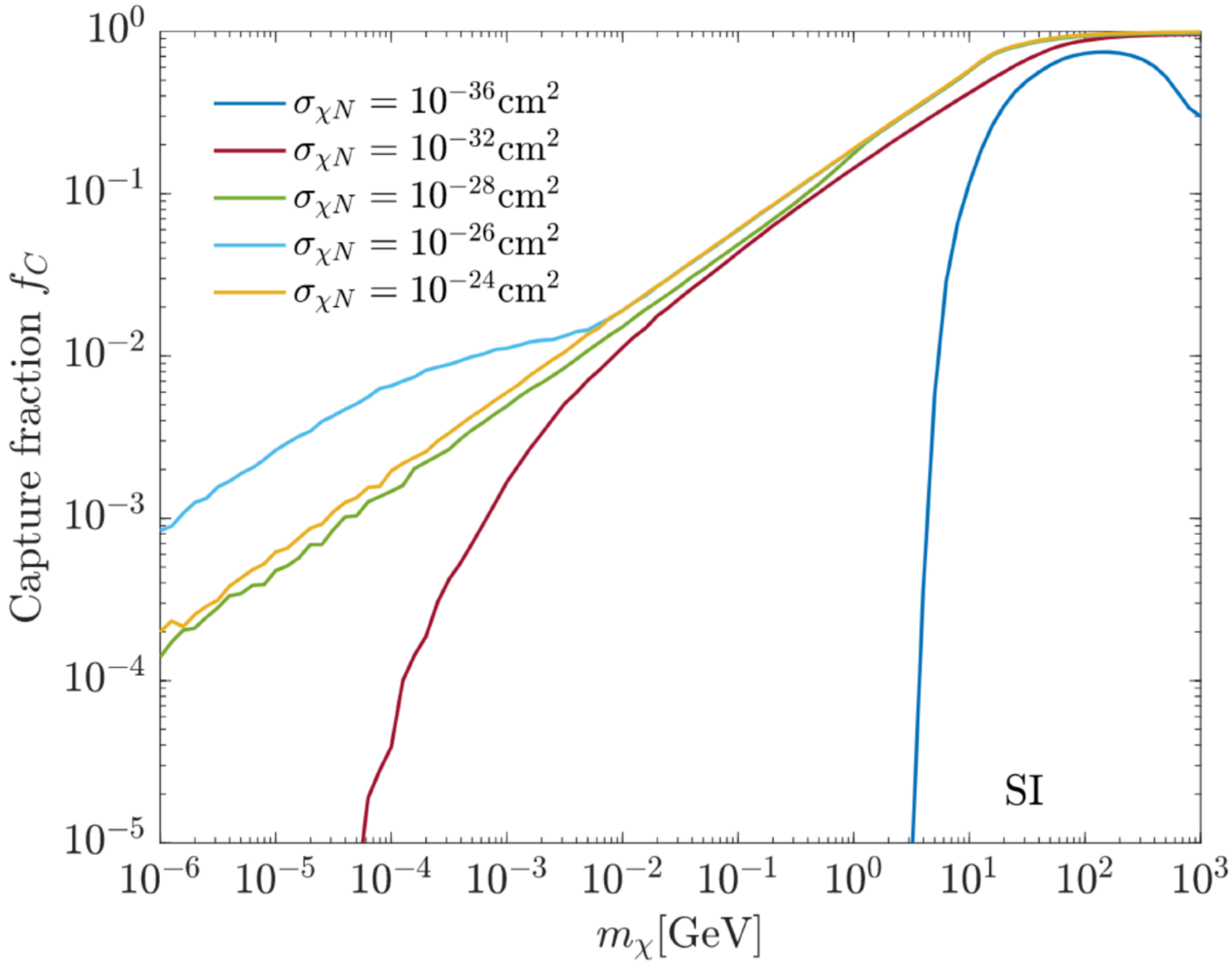




Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

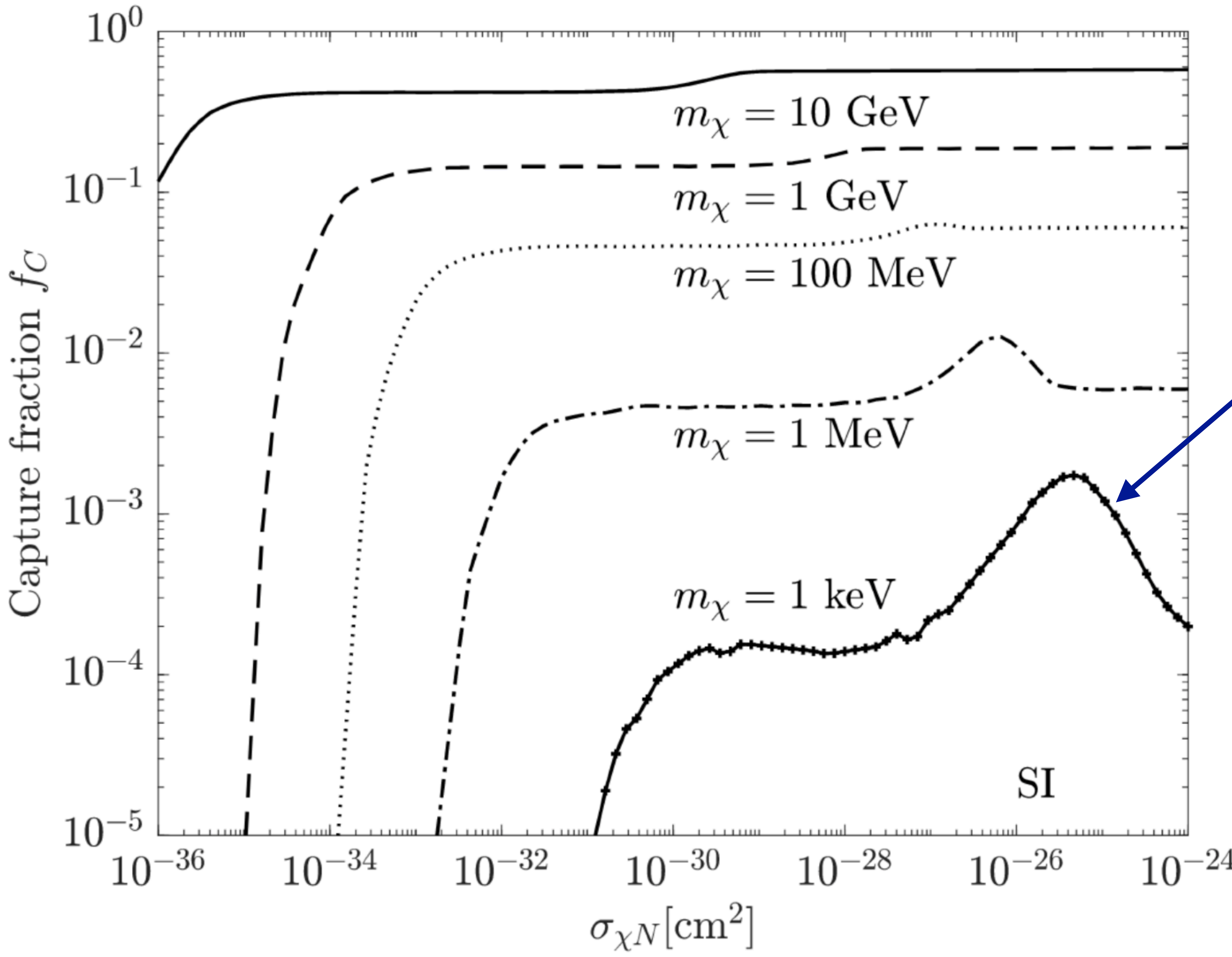
Capture saturates at Earth geometric cross-section & suppressed for smaller cross-sections

DM Capture fraction from MC



Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

DM Capture fraction from MC

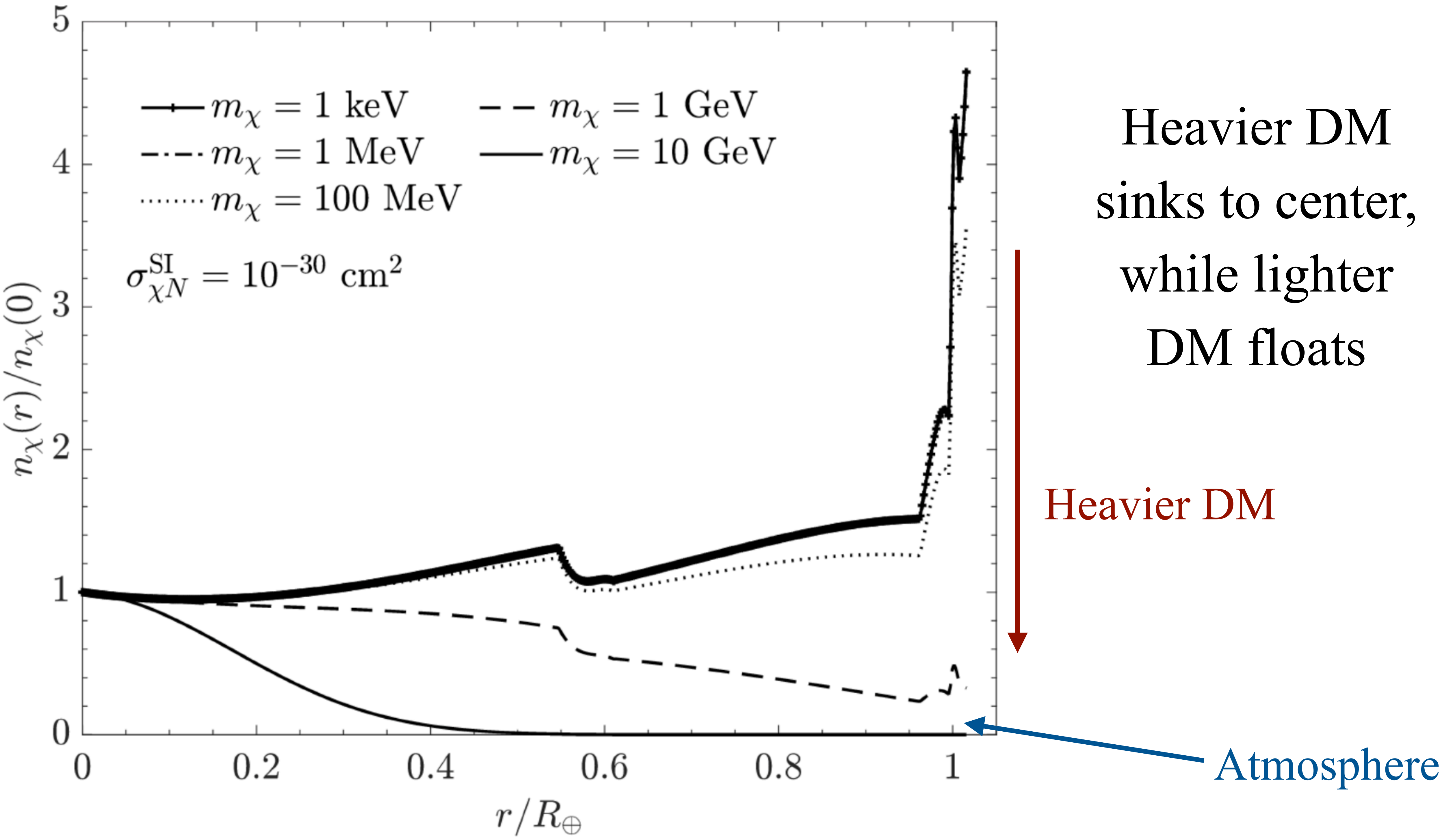


Summing all DM trajectories

Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

DM profile in Earth from multi scattering capture

Normalized distribution assuming local thermal equilibrium



Heavier DM sinks to center, while lighter DM floats

Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

DM Evaporation from the Earth

- Due to thermal motion of nuclei, DM scattering with nuclei can evaporate from Earth

$$E_{\oplus} = \sum_j \int_0^{R_{\oplus}} 4\pi r^2 n_\chi(r) s(r) dr \int_0^{v_e(r)} 4\pi u_\chi^2 f_{\oplus}(u_\chi, r) du_\chi \int_{v_e(r)}^{\infty} R_j^+(u_\chi \to v) dv$$

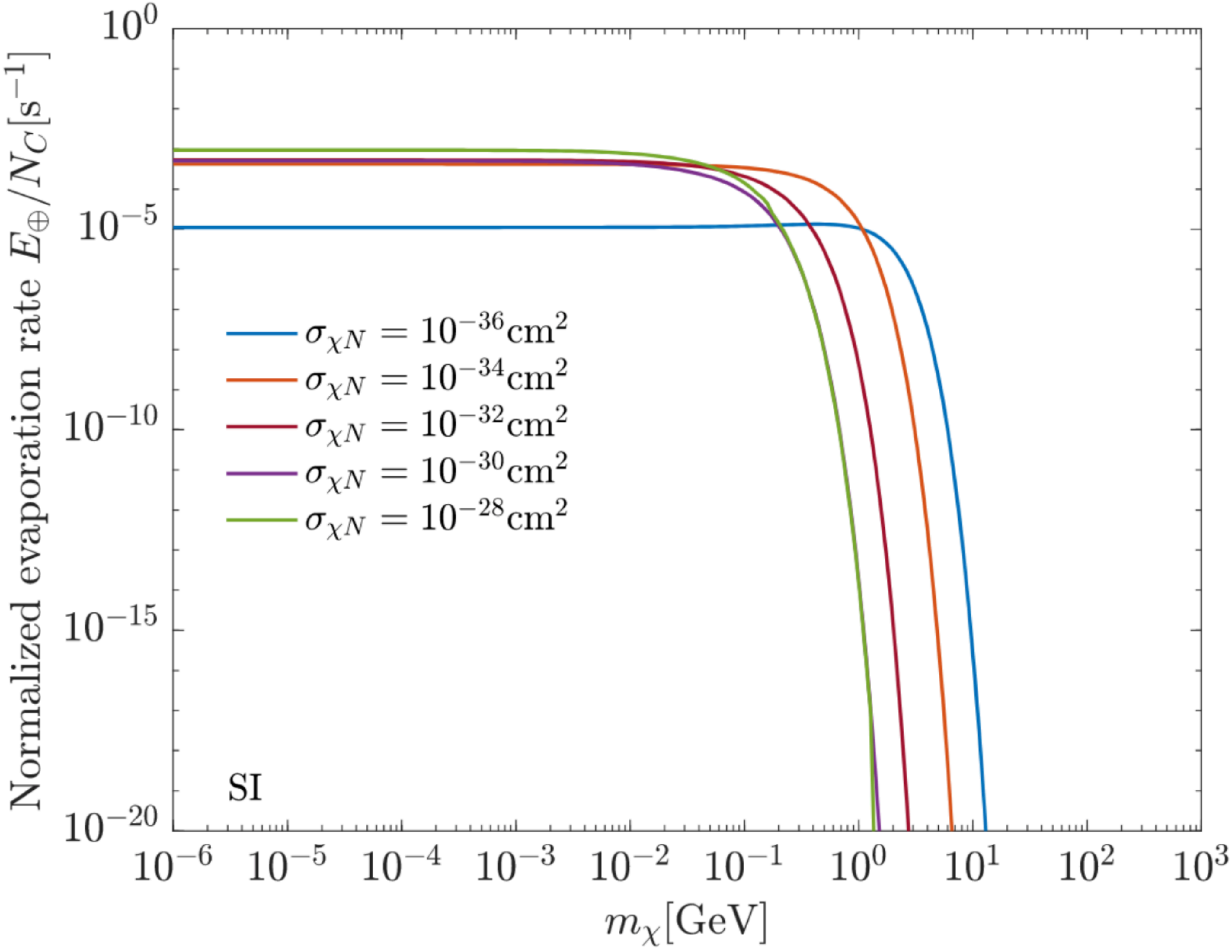
- DM may not evaporate after scattering multiple times on its way out

$$s(r) = \eta_{ang}\eta_{mult} \exp(-\tau(r))$$

Angular trajectory of particle

Optical depth through Earth

DM Evaporation from the Earth



Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

DM Annihilation & Earth heating

After enough DM has accumulated, it will annihilate

$$A_{\oplus} = \langle \sigma v \rangle_{\chi\chi} \int_0^{R_{\oplus}} n_{\chi}^2 4\pi r^2 dr \left(\int_0^{R_{\oplus}} 4\pi r^2 dr \right)^{-2}$$

$$\langle \sigma v \rangle_{\chi\chi} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

Total annihilation rate: $\Gamma_{\oplus} = (1/2) A_{\oplus} N_{\chi}(t)^2$

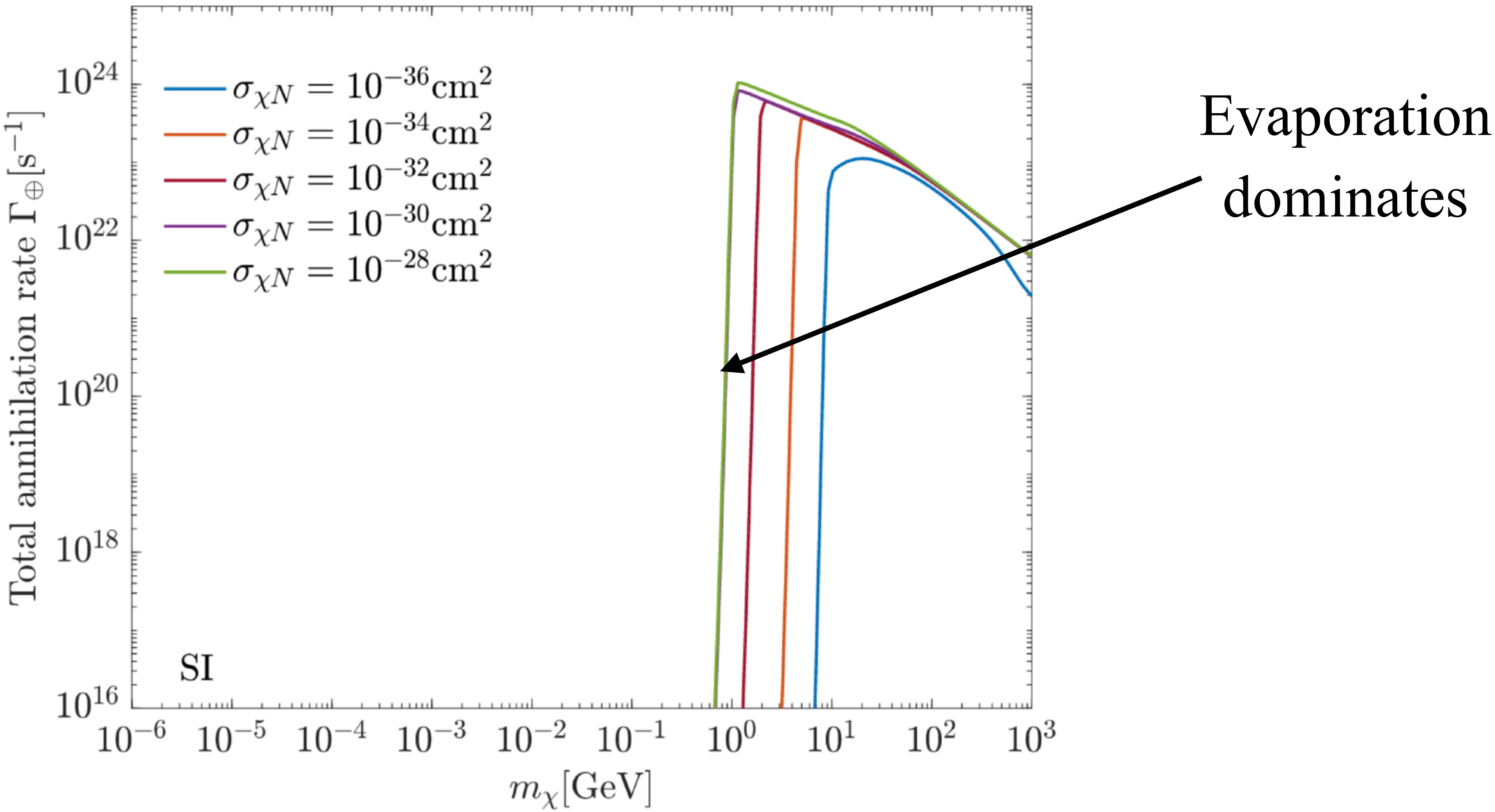
DM annihilating to SM final states can contribute to Earth heating

Total power produced by Earth $\leq$ 44 TW

Beardsmore & Cull, **Cambridge University Press, 2001**

Power produced from DM annihilation must be smaller than 44 TW

Places limit on DM-nucleus scattering cross-section

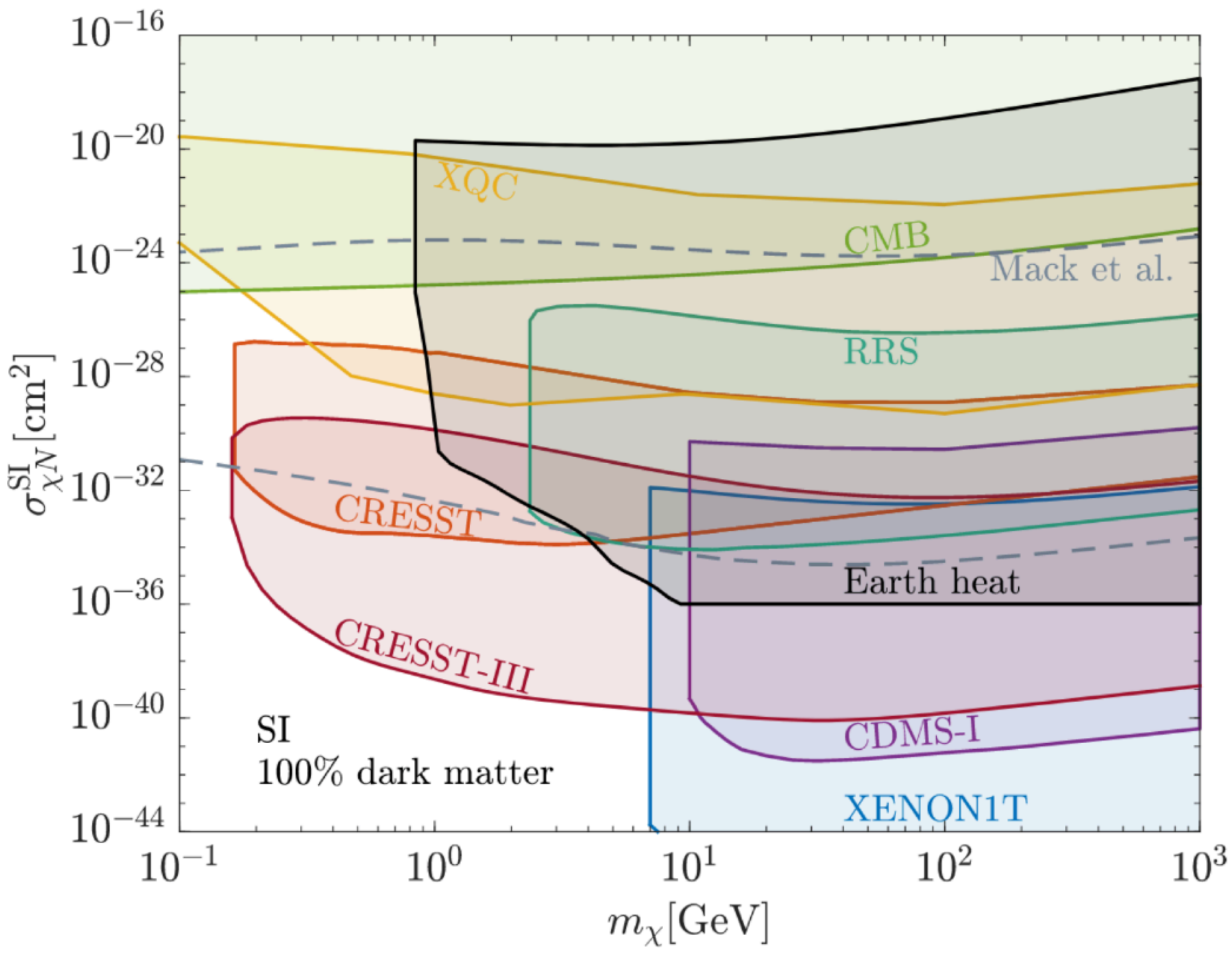


Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

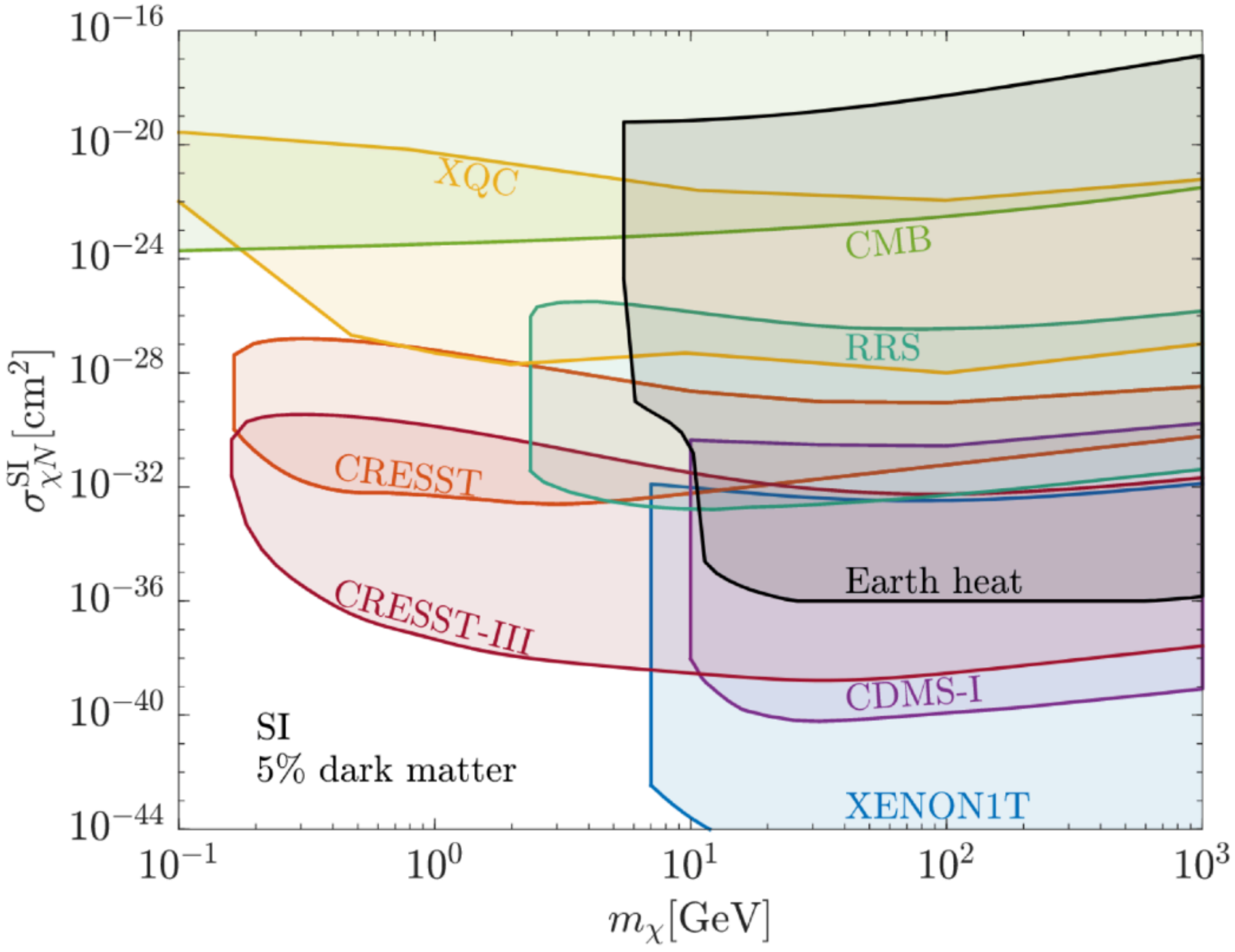
Direct detection constraints

Spin-Independent

100% DM density



5% DM density

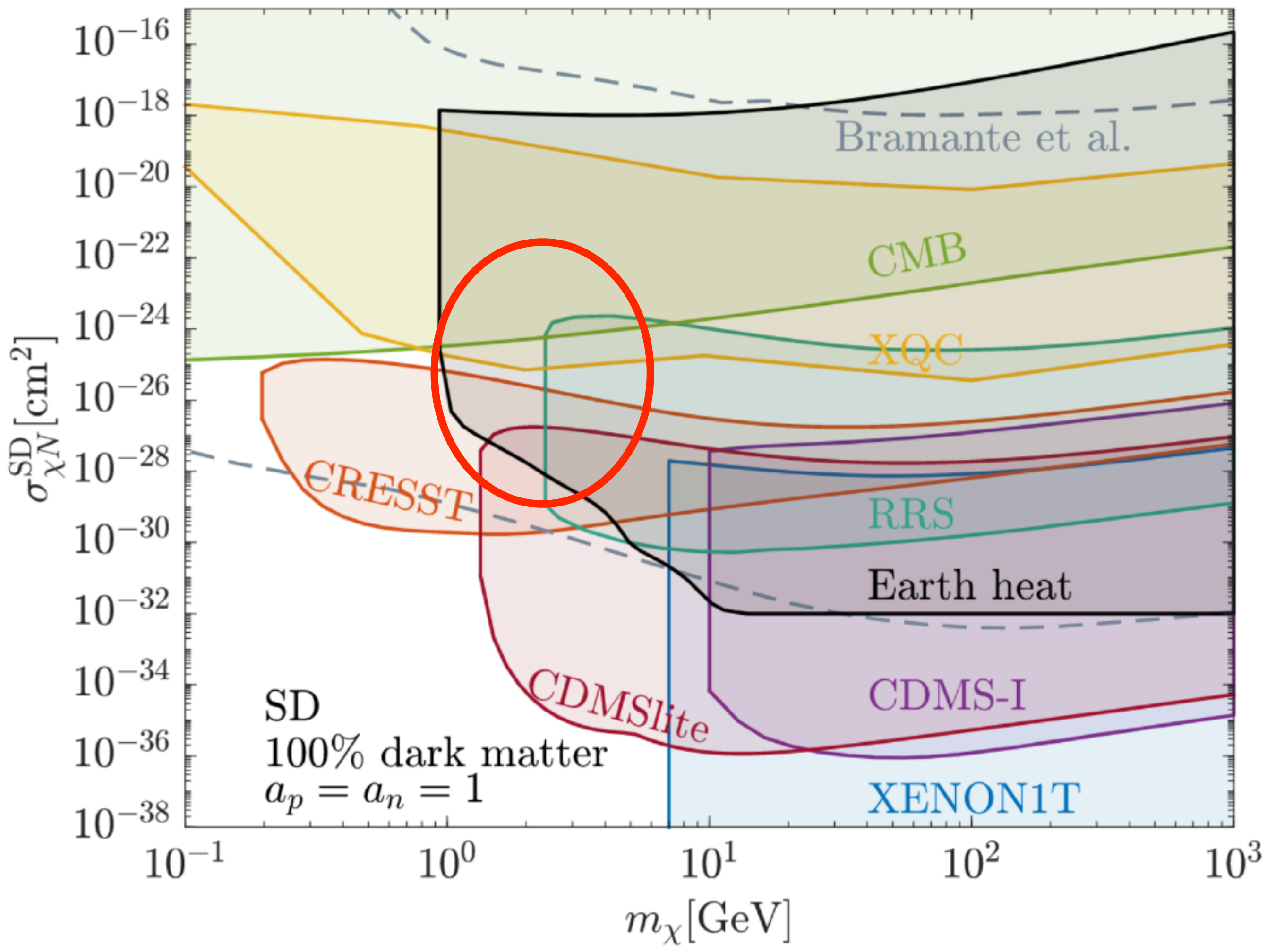


Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

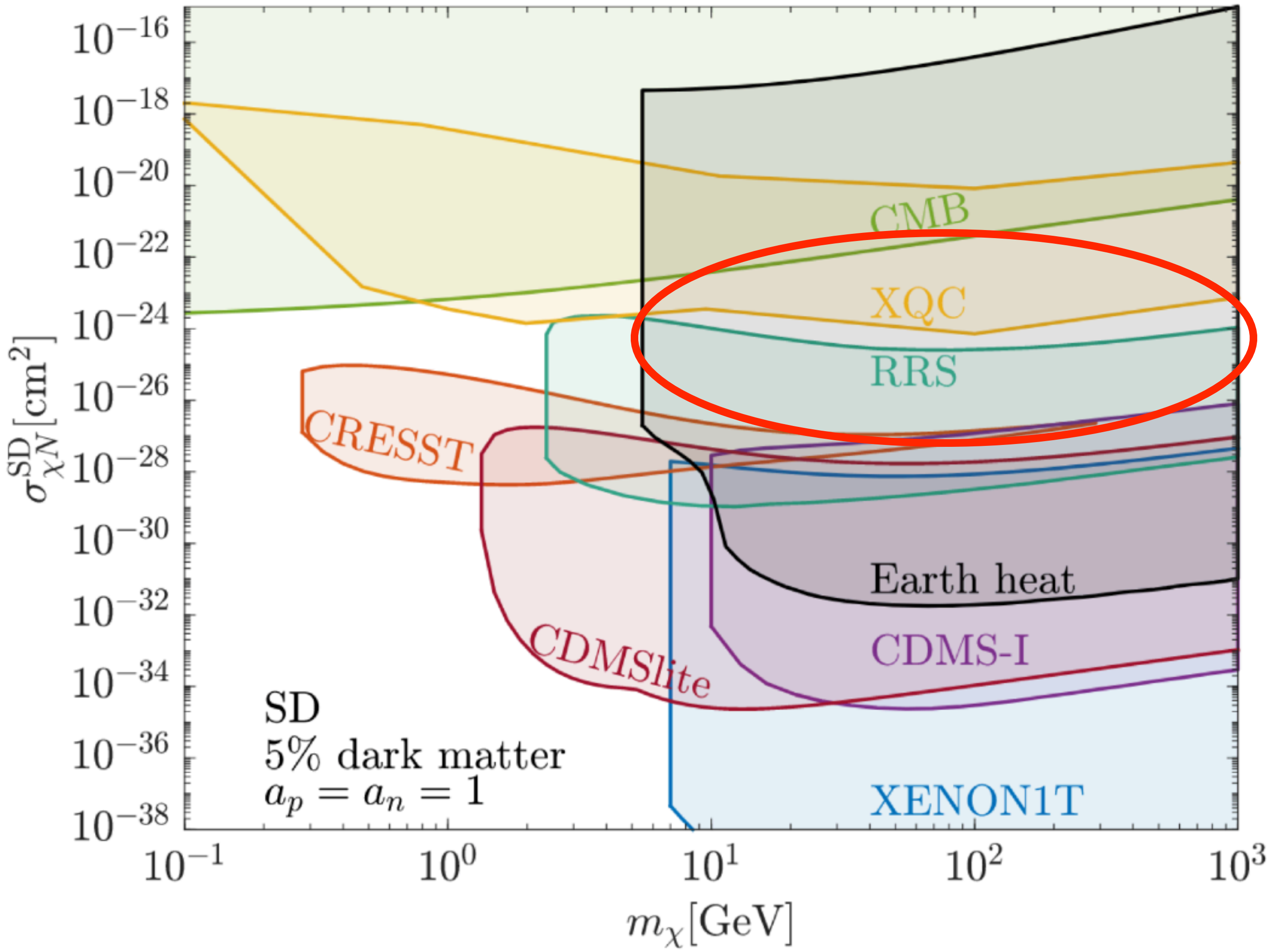
Direct detection constraints

Spin-Dependent

100% DM density



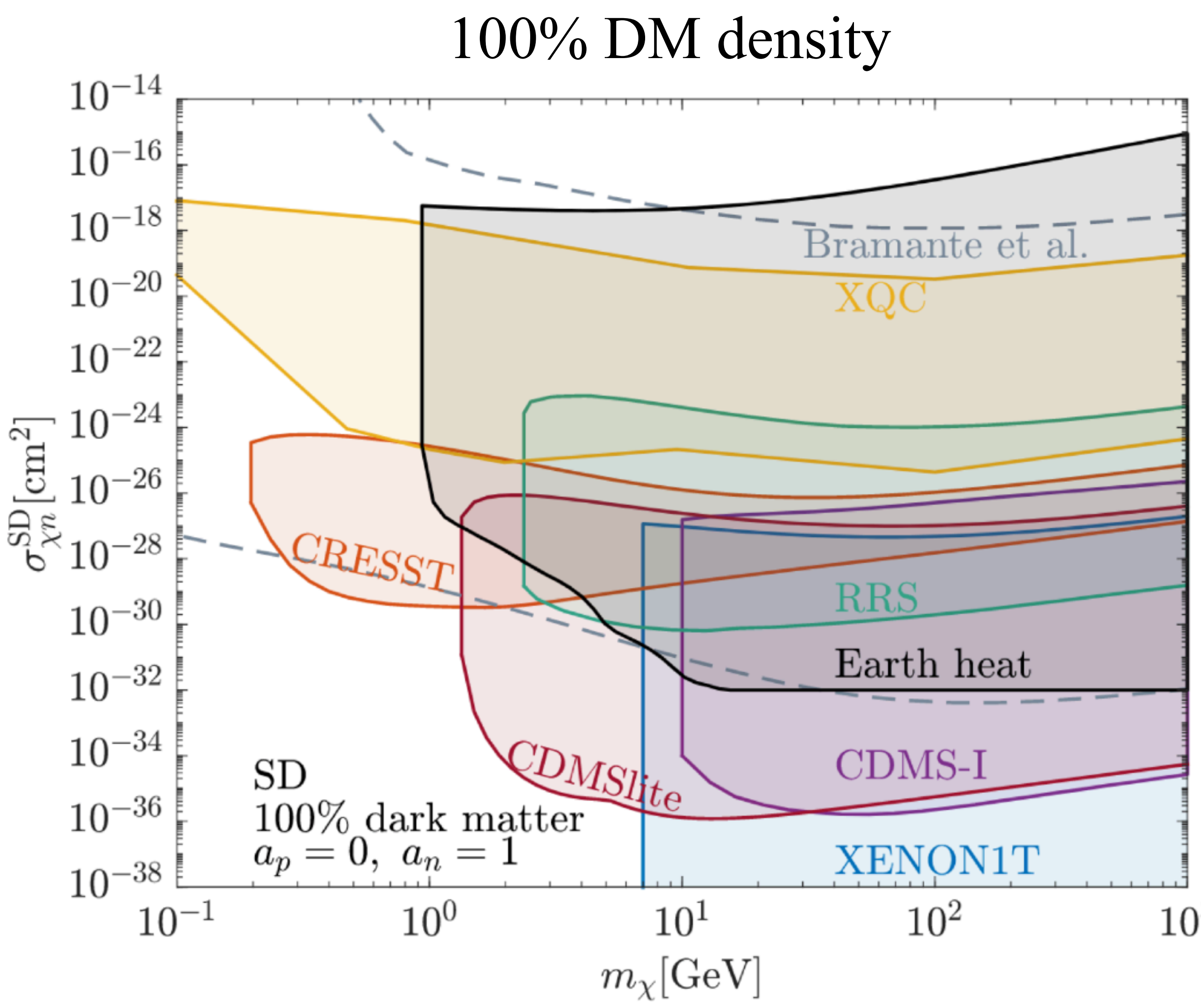
5% DM density

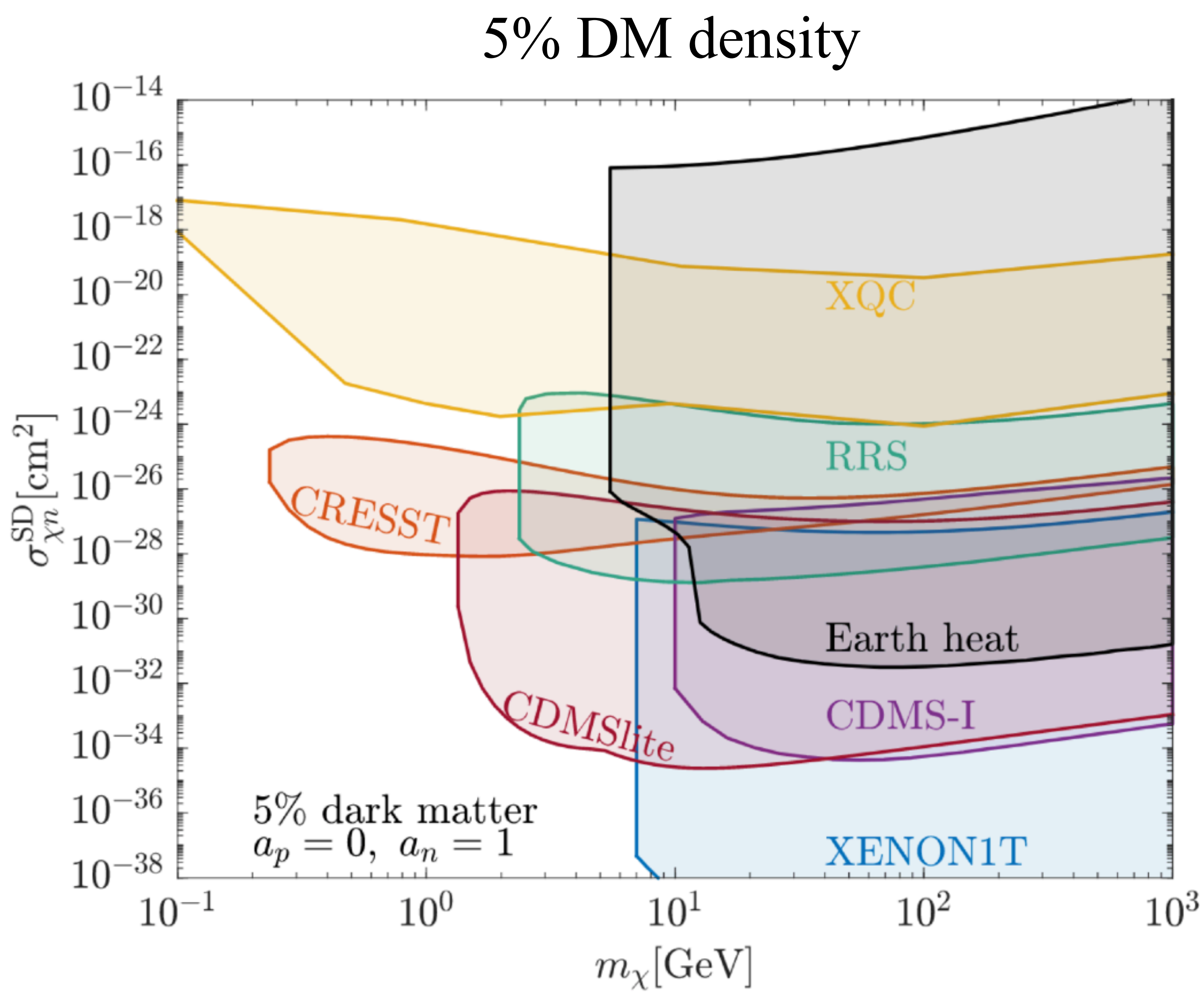


Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

Direct detection constraints

Spin-Dependent neutron only





Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**

Conclusions

- Search for DM is ramping up

- Many opportunities in low mass DM region

- Celestial bodies are good laboratories for low mass DM

- We focussed on capture/evaporation in strong interaction limit

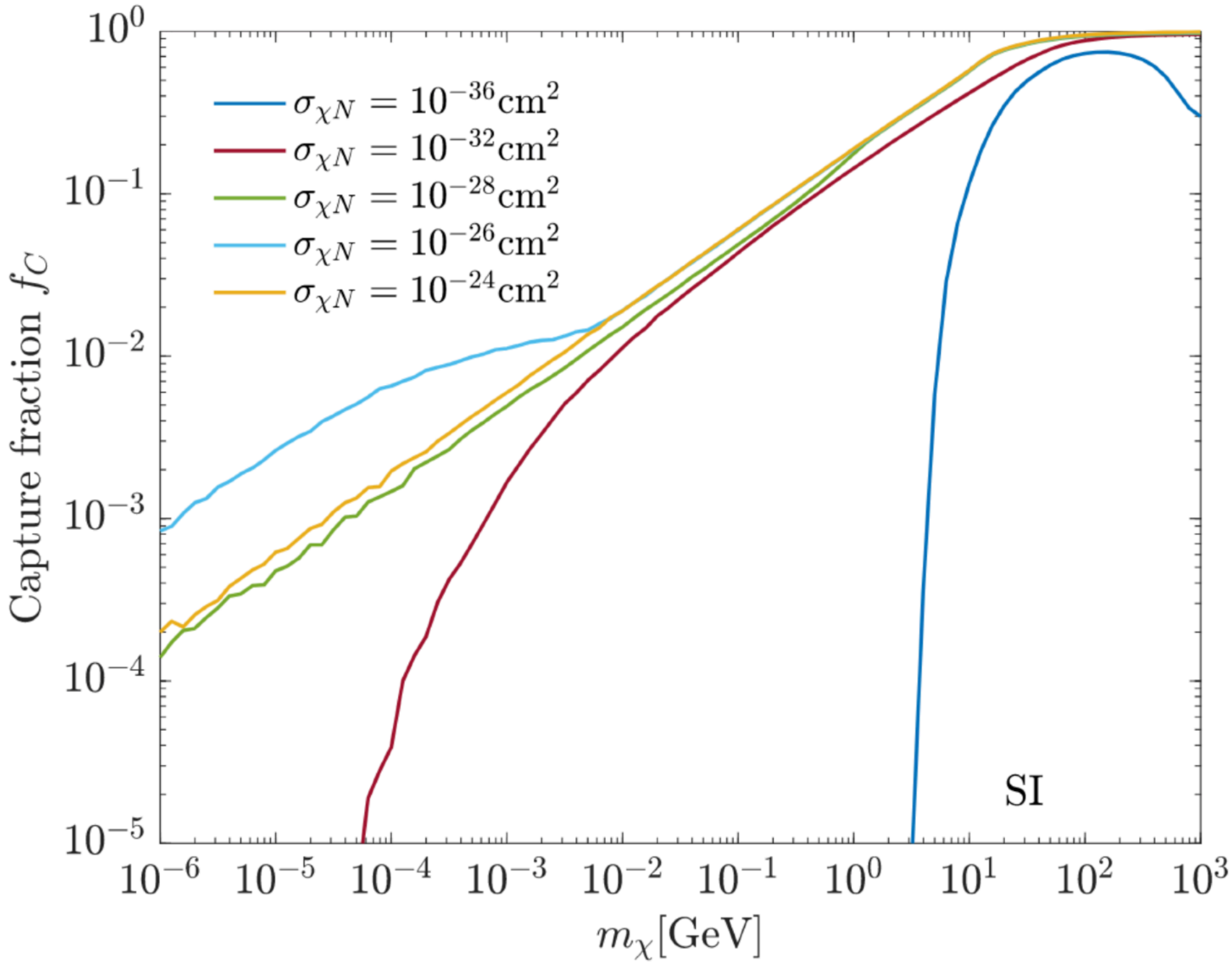
- After careful treatment in the Earth, we recast DD and Earth heating limits on DM - nucleus/nucleon scattering cross-section

Thank you

Back Up

DM Capture fraction from MC

$$C_{\oplus}^{MC} = f_C C_{\oplus}^{geom}$$



Bramante, Kumar, Mohlabeng, Raj & Song, **arXiv: 2210.01812**