The Celestial Dark Matter Calorimeter

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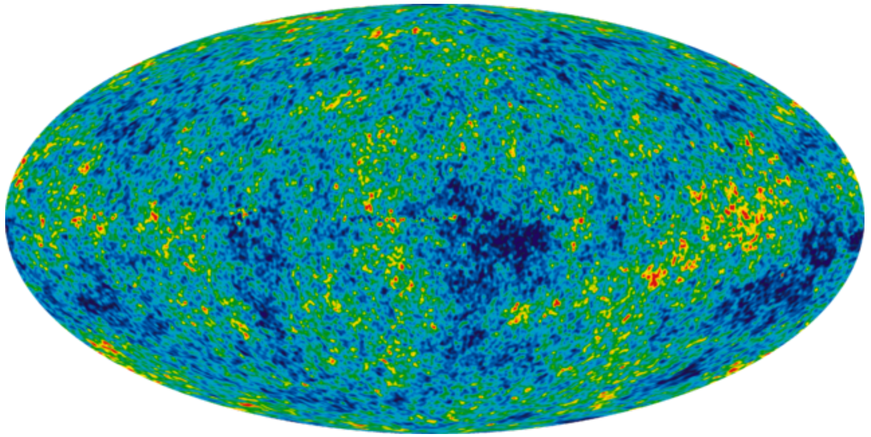
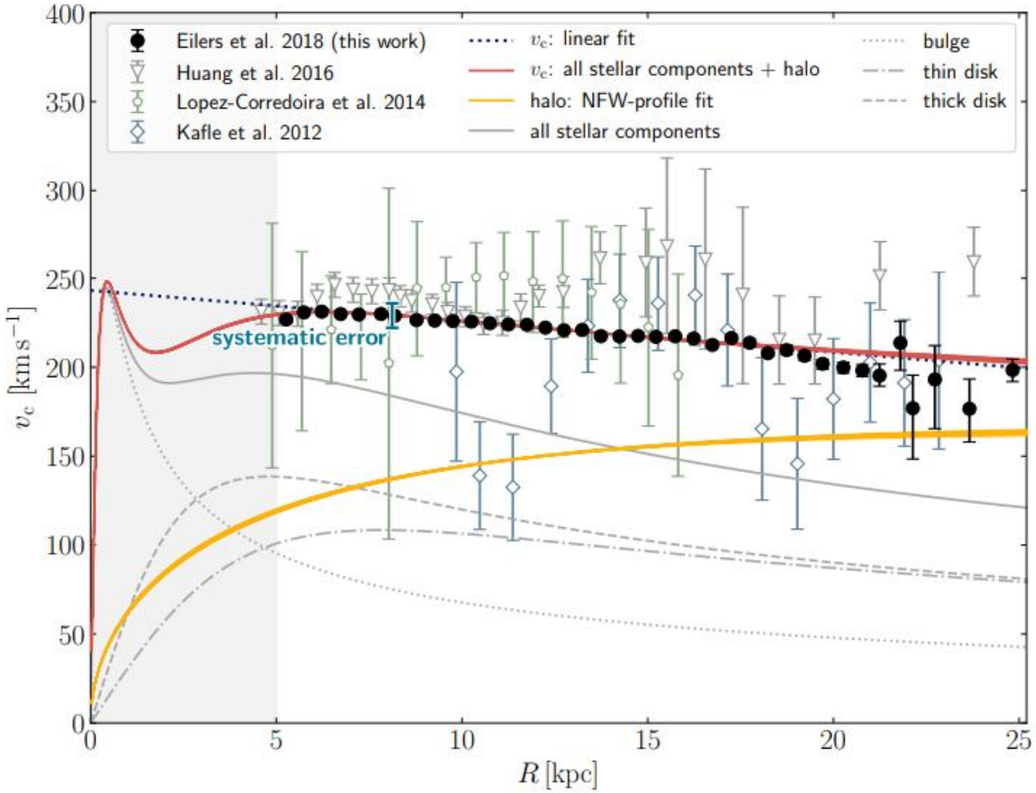
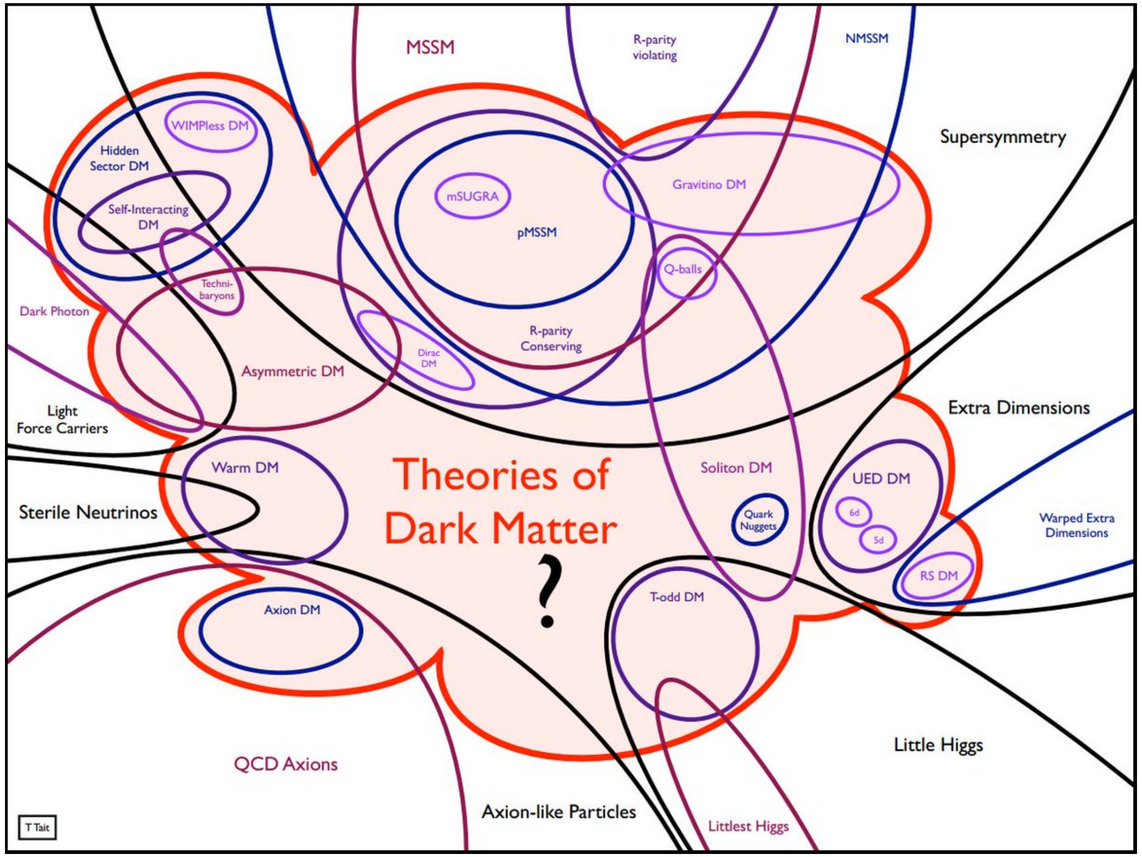
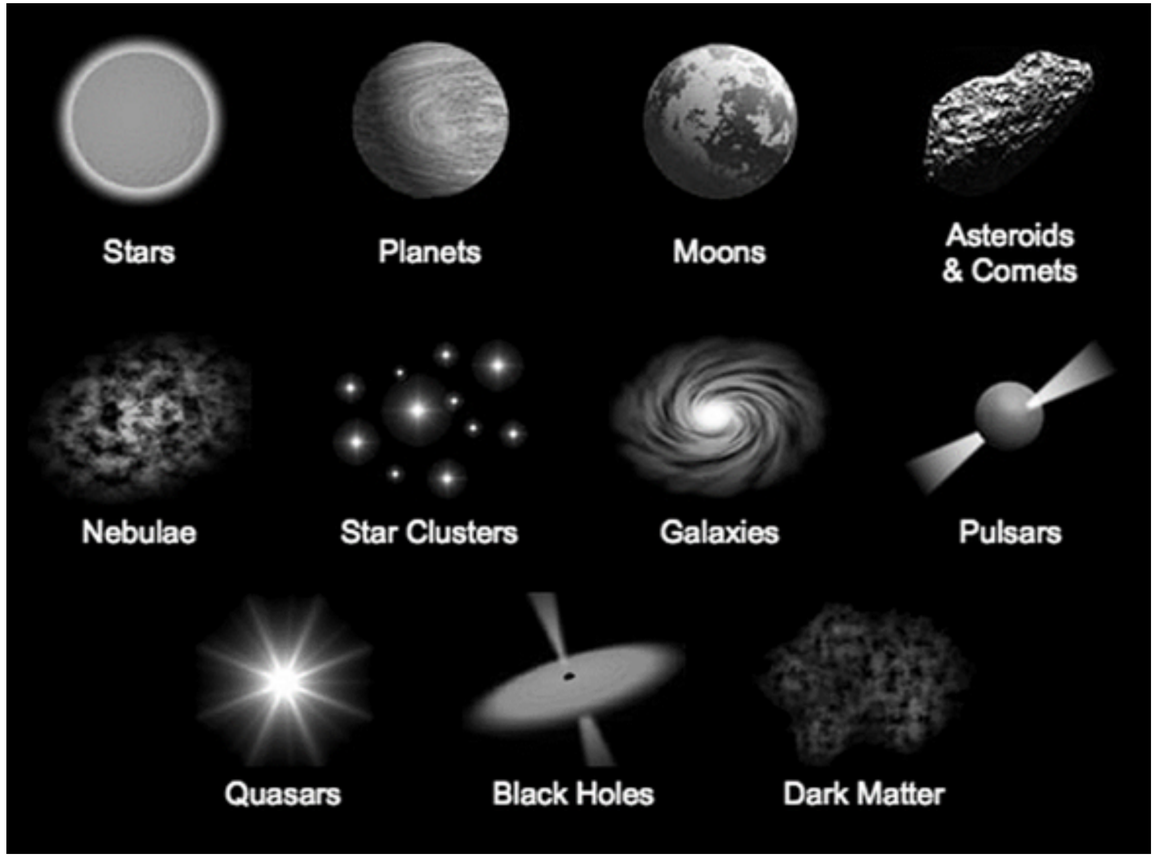
Galaxy Cluster MACS J0025.4−1222
Hubble Space Telescope ACS/WFC
Chandra X-ray Observatory
Near Infrared ▪ Hubble
Visible ▪ Hubble
X-ray ▪ Chandra
Dark Matter Map
1.5 million light-years
460 kiloparsecs
70"
E
N




Eilers et al. 2018 (this work)
Huang et al. 2016
Lopez-Corredoira et al. 2014
Kafle et al. 2012
v_c: linear fit
v_c: all stellar components + halo
halo: NFW-profile fit
all stellar components
bulge
thin disk
thick disk
systematic error
v_c [km s^{-1}]
R [kpc]
0
50
100
150
200
250
300
350
400
0
5
10
15
20
25

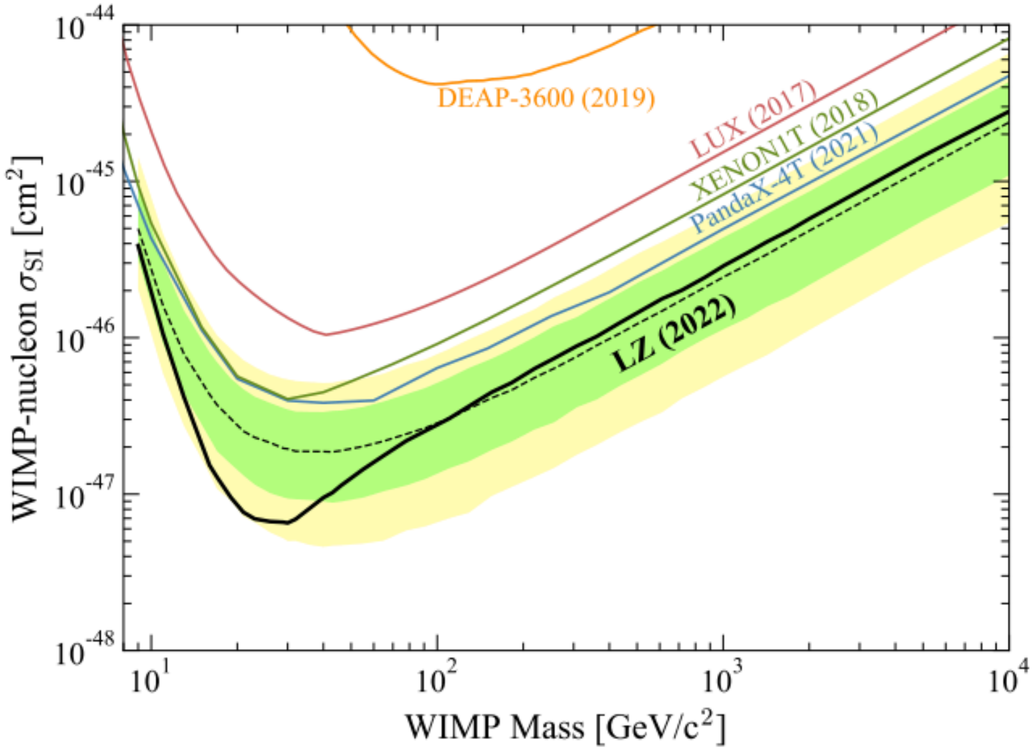
Light vs Dark





Credit: Leslie J Rosenberg

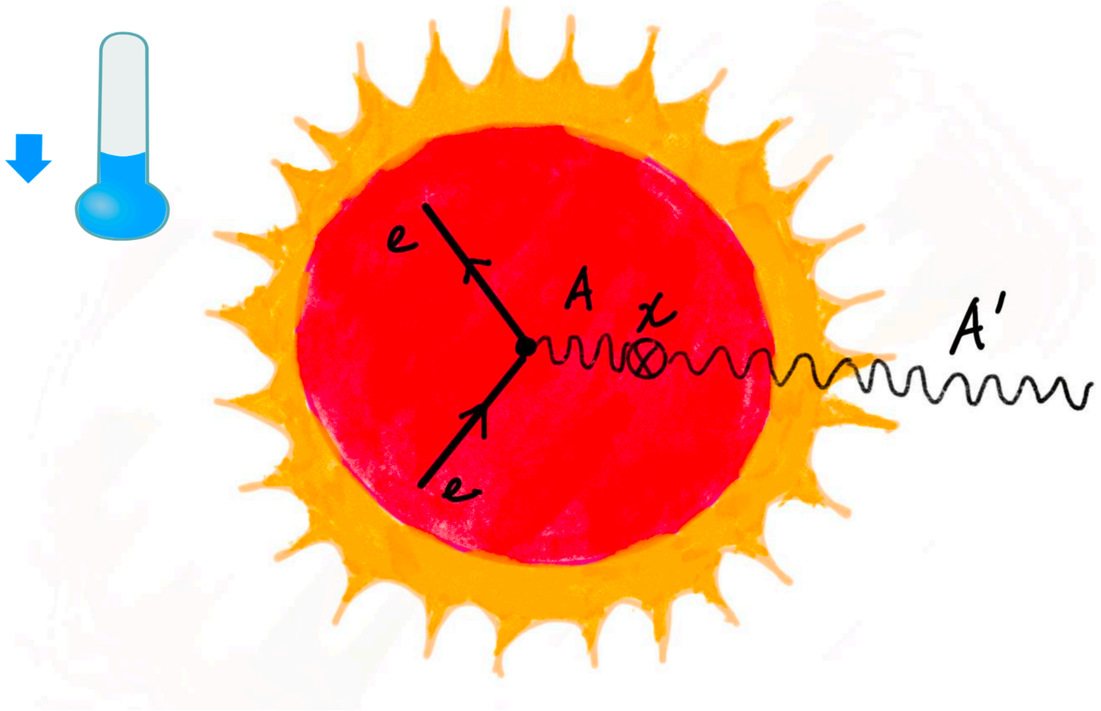
Why Celestial Bodies?



- Greater dark matter density
- Special environment: high temperature, high gravity
- Multi-messenger, multi-frequency observations available

LZ 2207.03764
See also latest XENONnT 2303.14729

Dark Matter Fridge



Dark particles that dissipate star energy

Raffelt 1996, 1999, Chang 2018

- Excess cooling of supernova
- Stellar evolution Luzio 2109.10368
- BH superradiance Arvanitaki 2009, 2010

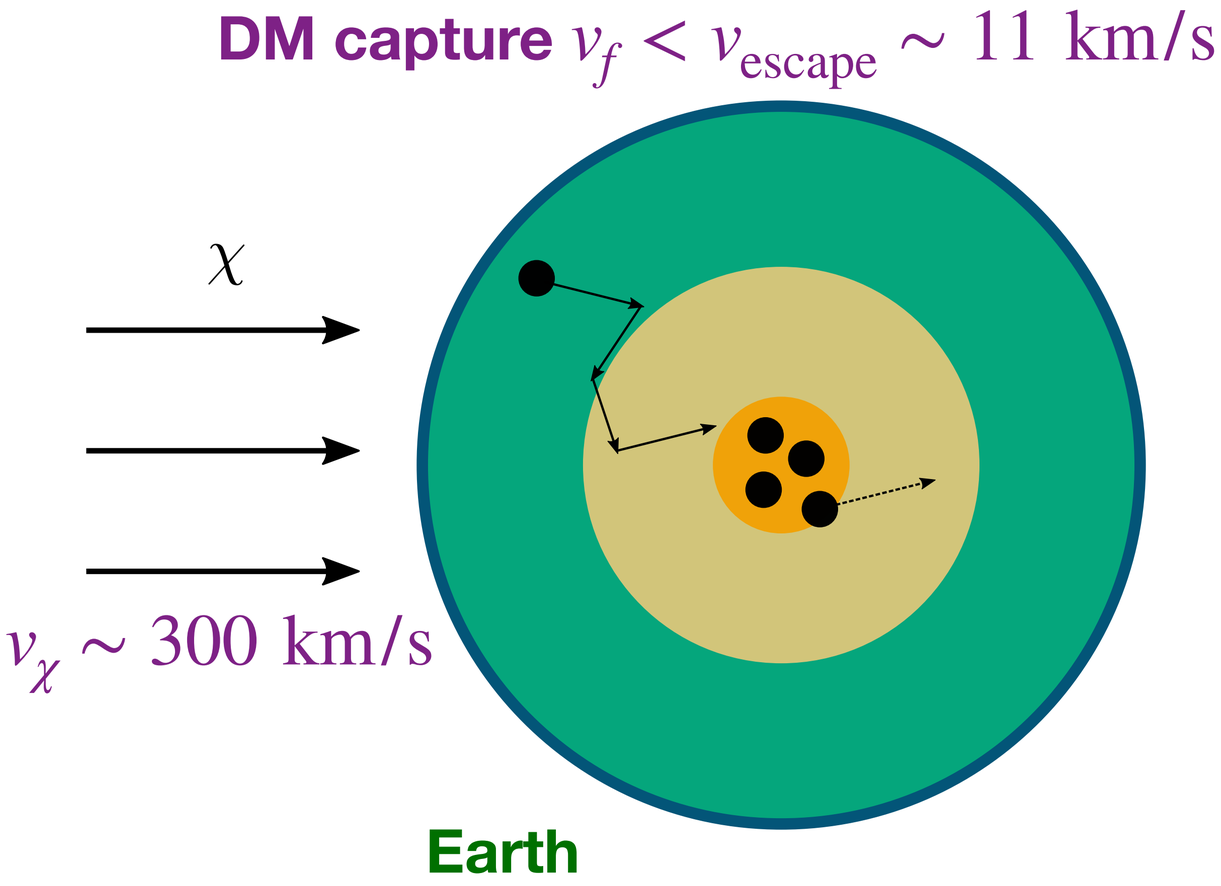
Dark Matter Stove

Dark matter heating of the astrophysical environments

- Increase star temperature/luminosity Baryakhtar 1704.01577
- Collapse into BHs Goldman1989, Bertone 0709.1485
- Triggered explosion of white dwarfs Fayet 2006, Smirnov 2022
- Heating of gas Bhoonah 1806.06857, 2010.07240

Earth Heating

- Dark matter scatters with Earth matter, slows down and gets trapped



Earth Heating

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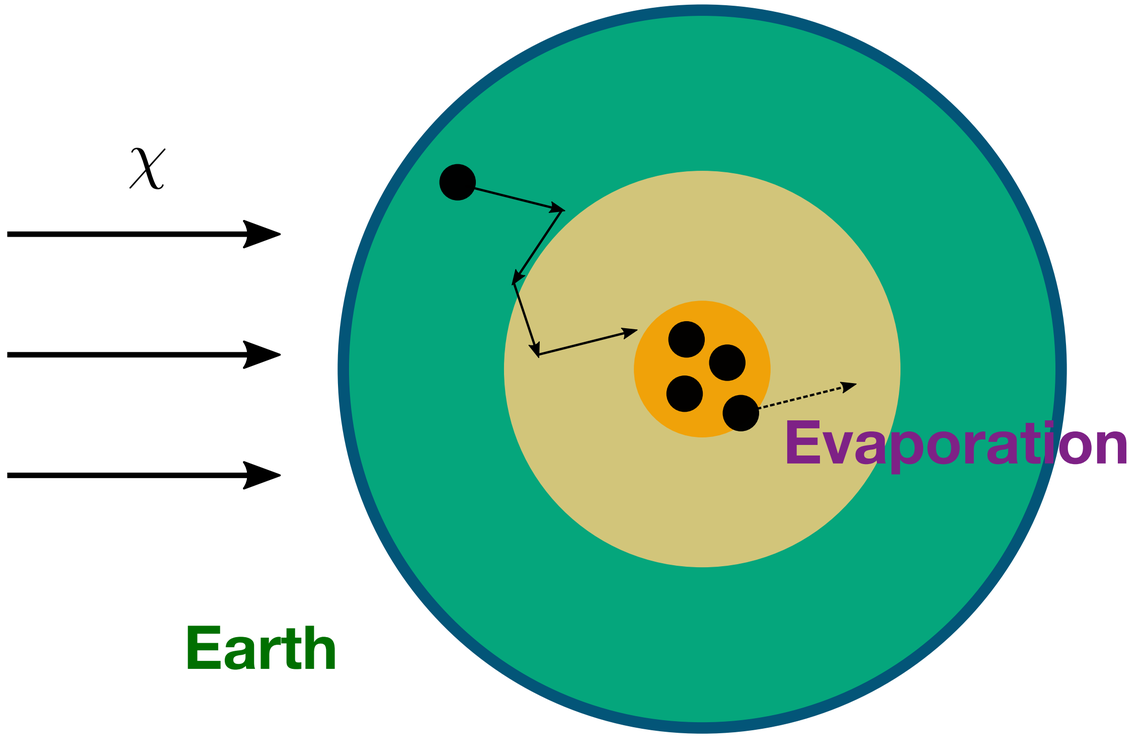
- Dark matter scatters with thermal nuclei and escapes from the Earth



Earth Heating

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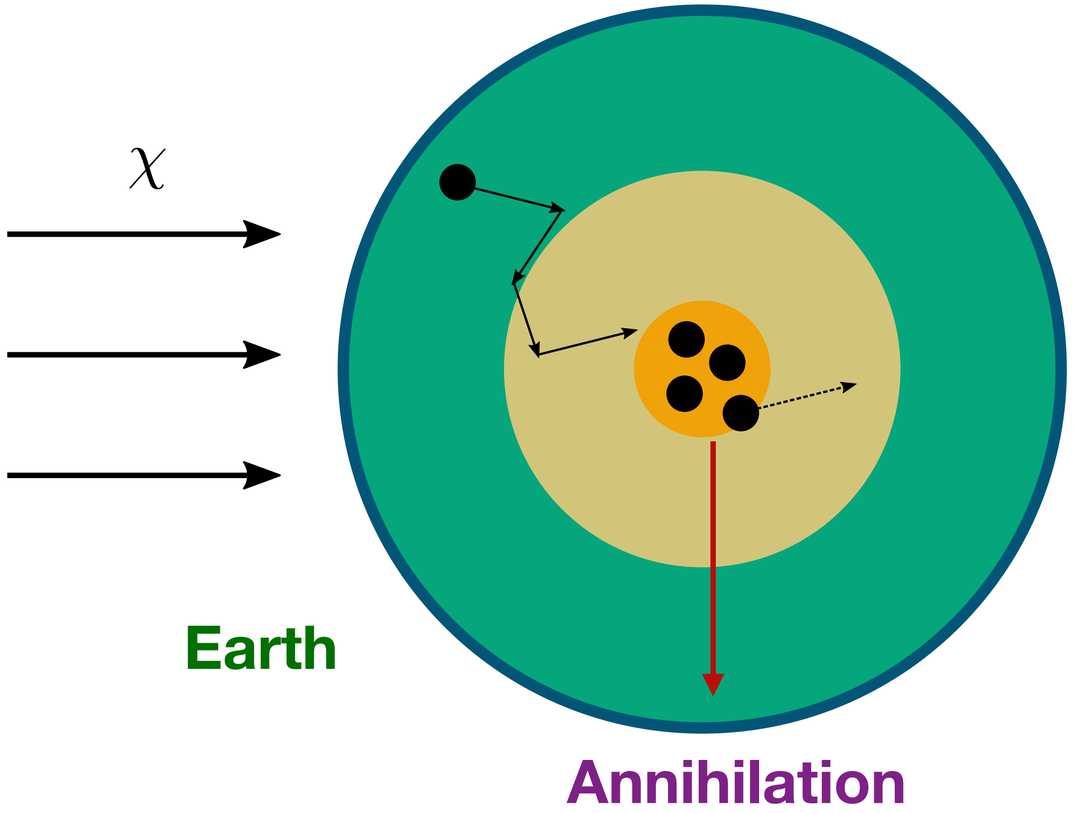

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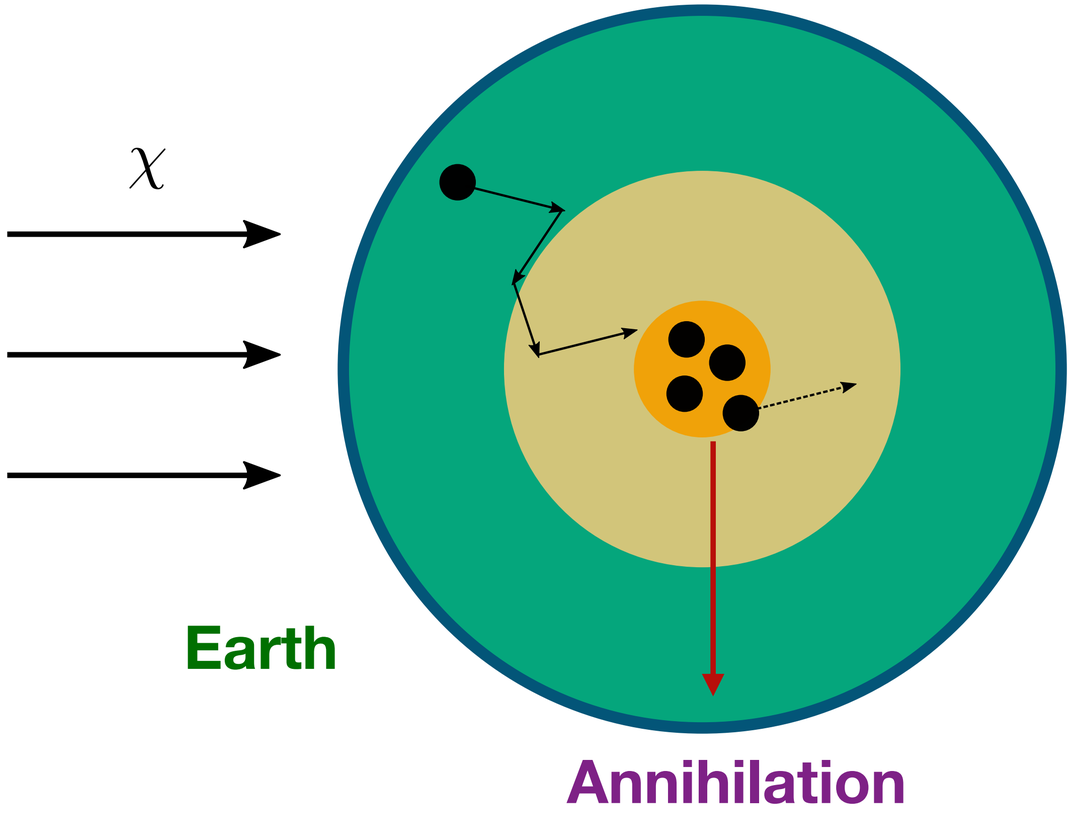


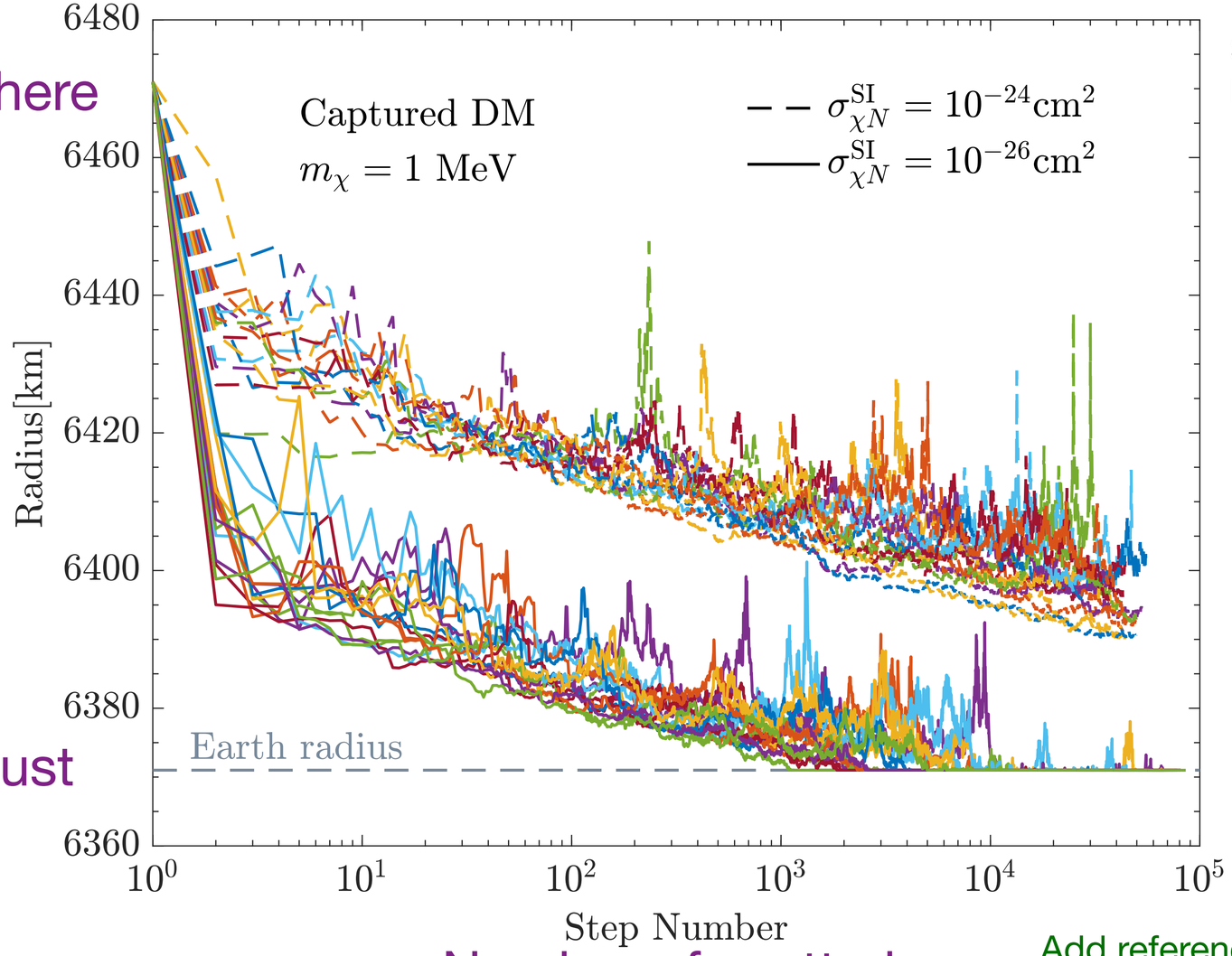
DM Heating $\leq$ 44 TW

Kamland, Borexino geoneutrino observation

Monte Carlo

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

Top of atmosphere



Top of Earth crust

Number of scattering

See also DaMaSCUS
https://github.com/temken/DaMaSCUS

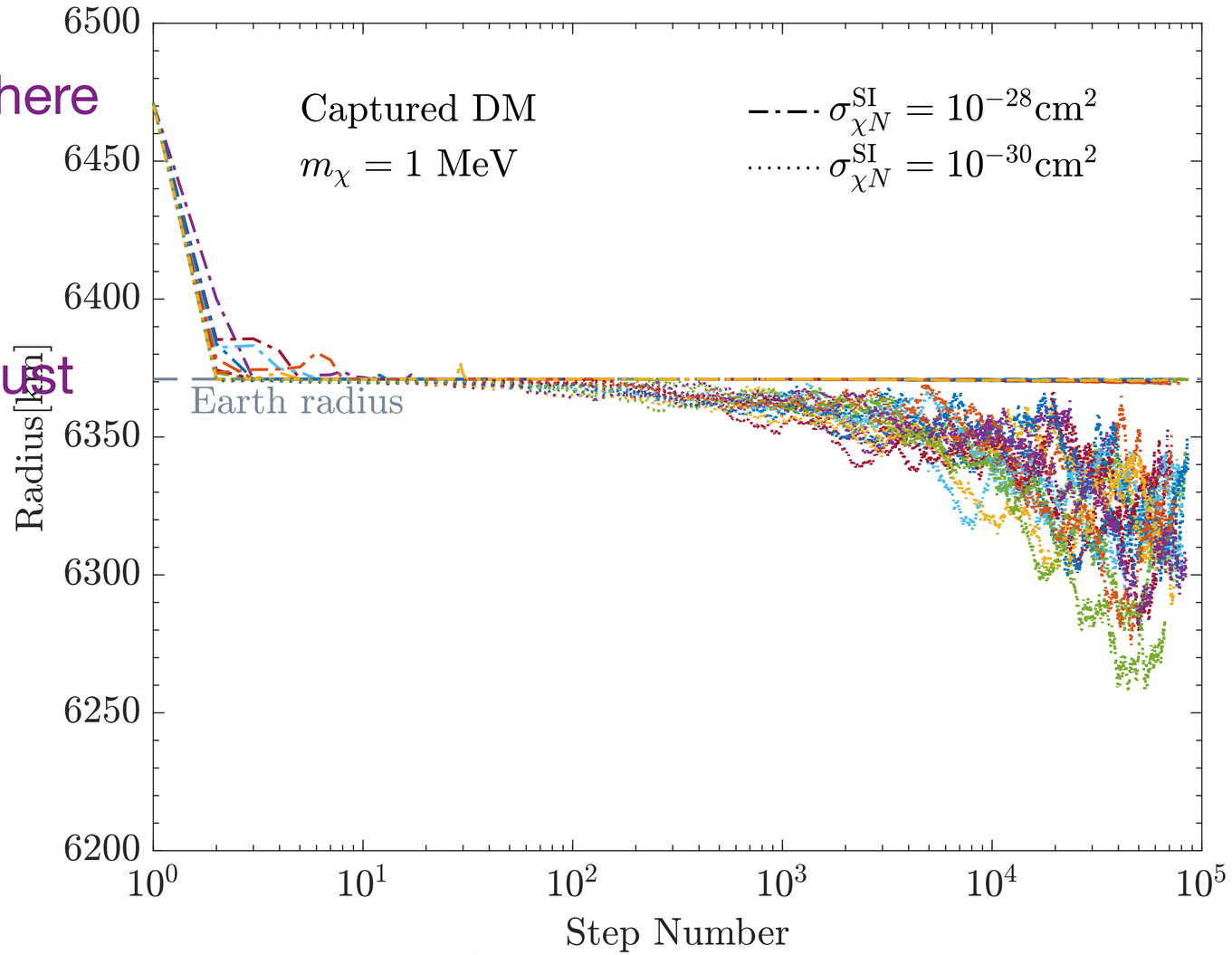
Add reference to DaMaSCUS

Monte Carlo

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

Top of atmosphere

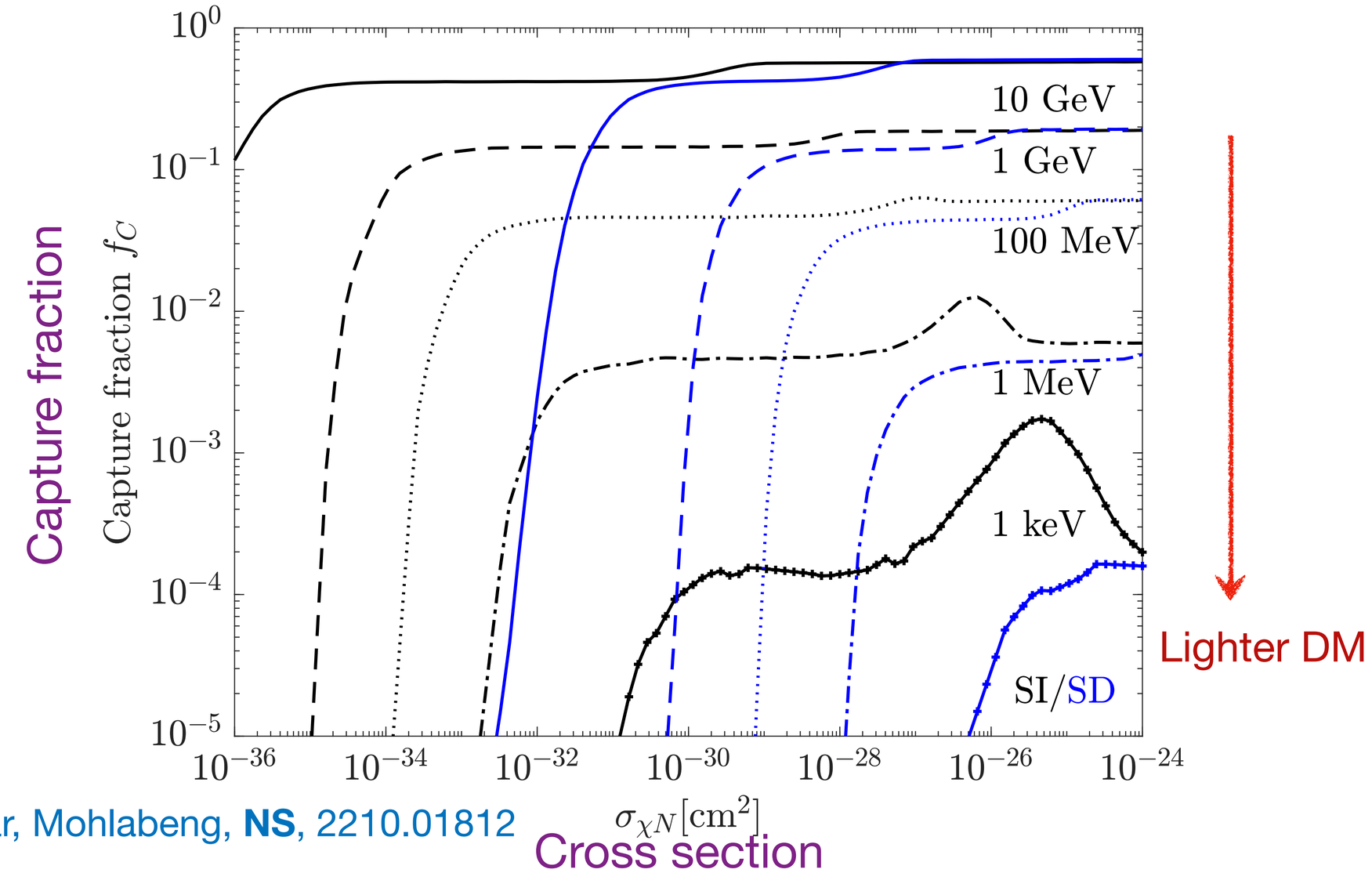
Top of Earth crust



Number of scattering

Capture Fraction

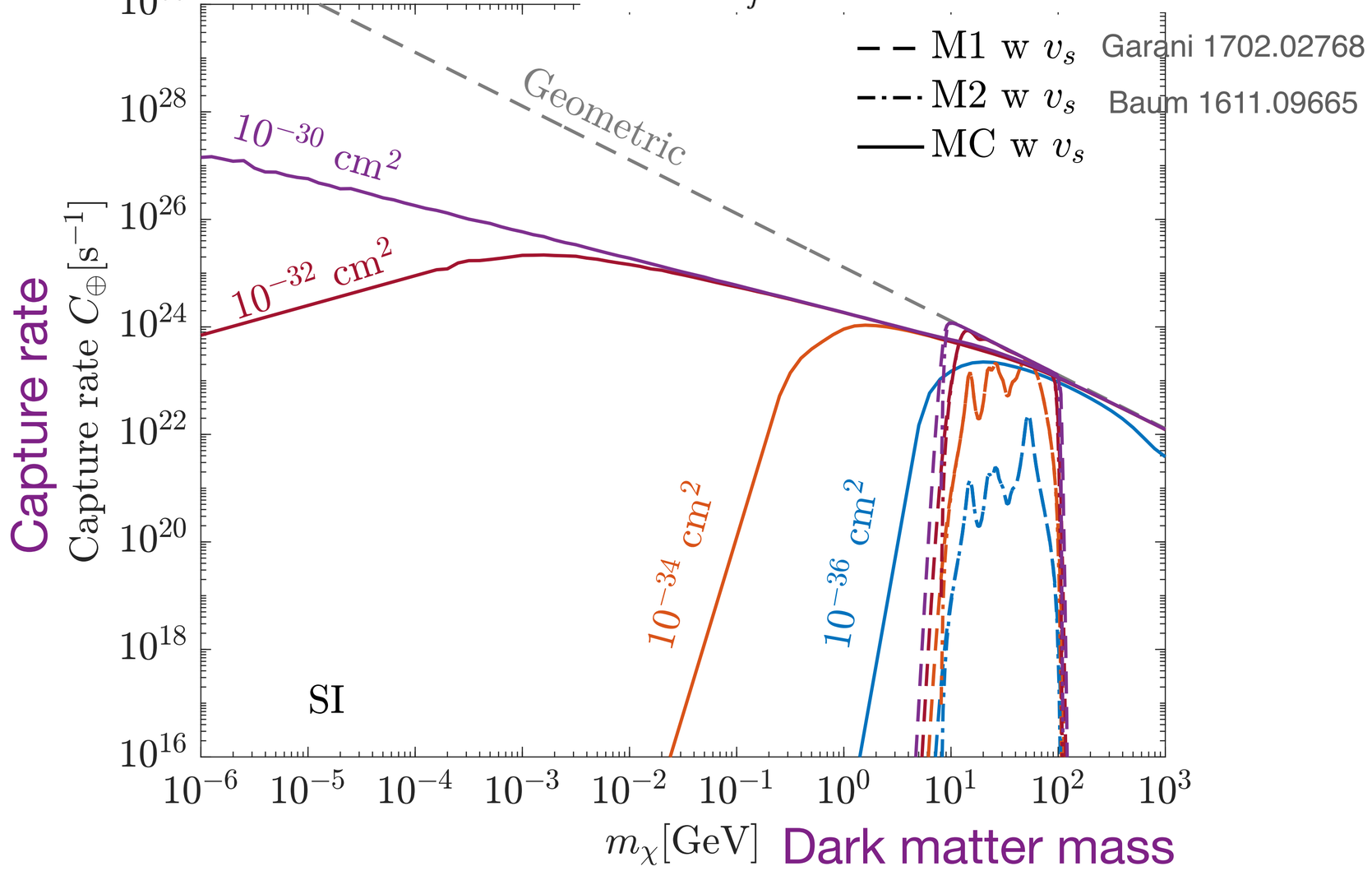
DaMaSCUS_EarthCapture
https://github.com/songningqiang/DaMaSCUS-EarthCapture



Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

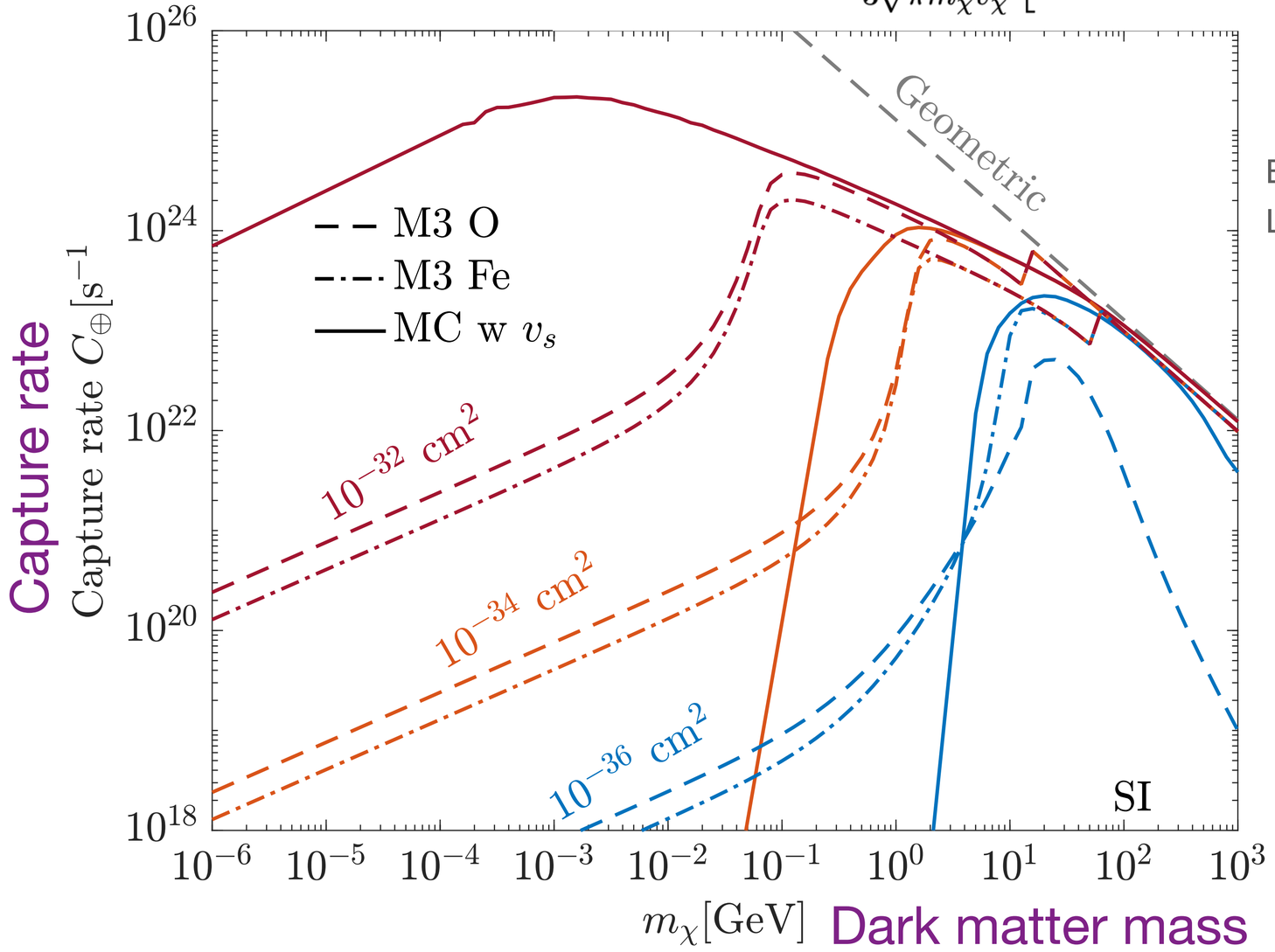
Monte Carlo vs Single Scatter

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



Monte Carlo vs Multi Scatter

$$C_N = f_{\rm cap}\pi R^2 p_N(\tau)\frac{\sqrt{6}\rho_\chi}{3\sqrt{\pi}m_\chi v_\chi}\left[(2v_\chi^2+3v_{\rm esc}^2)-(2v_\chi^2+3v_N^2)\exp\left(-\frac{3(v_N^2-v_{\rm esc}^2)}{2v_\chi^2}\right)\right]$$

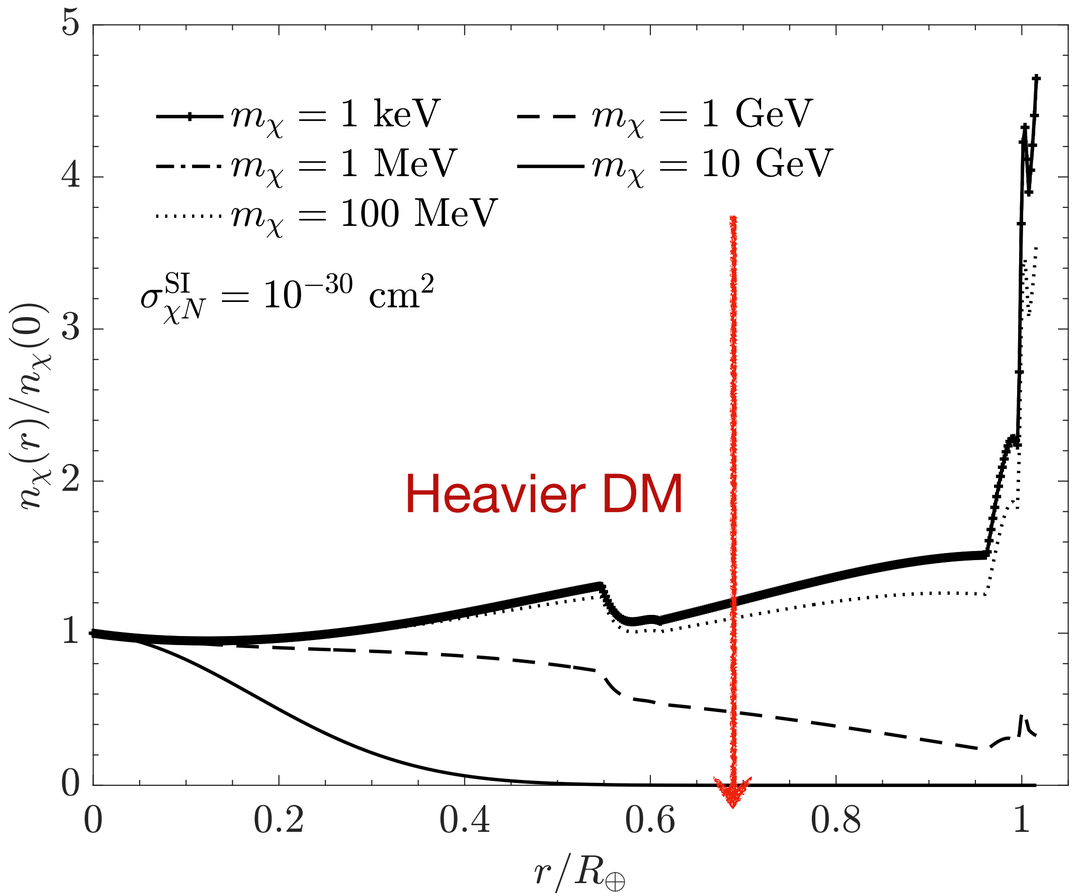


Bramante 1703.04043

Leane 2209.09834

Dark Matter Distribution

$$\frac{n_\chi(r)}{n_\chi(0)} = \left(\frac{T_\oplus(r)}{T_\oplus(0)}\right)^{3/2} \exp\left(-\int_0^r \left[\alpha(r')\frac{dT_\oplus(r')}{dr'} + m_\chi \frac{d\phi(r')}{dr'}\right] T_\oplus^{-1} dr'\right)$$

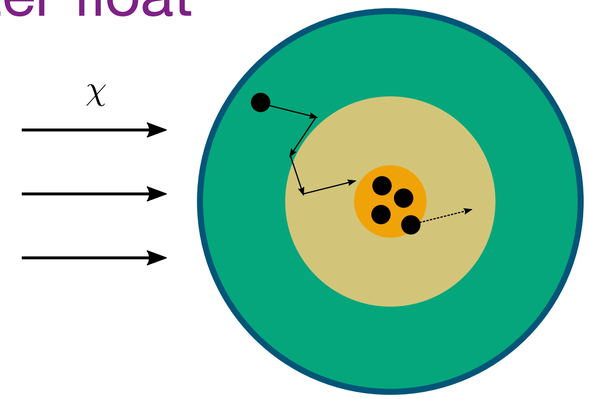


Normalized radius

When $\sigma_{\chi N}^{\rm SI} \gtrsim 10^{-36}$ cm^2, dark matter thermalizes with local environment due to frequent scattering

Garani 1702.02768

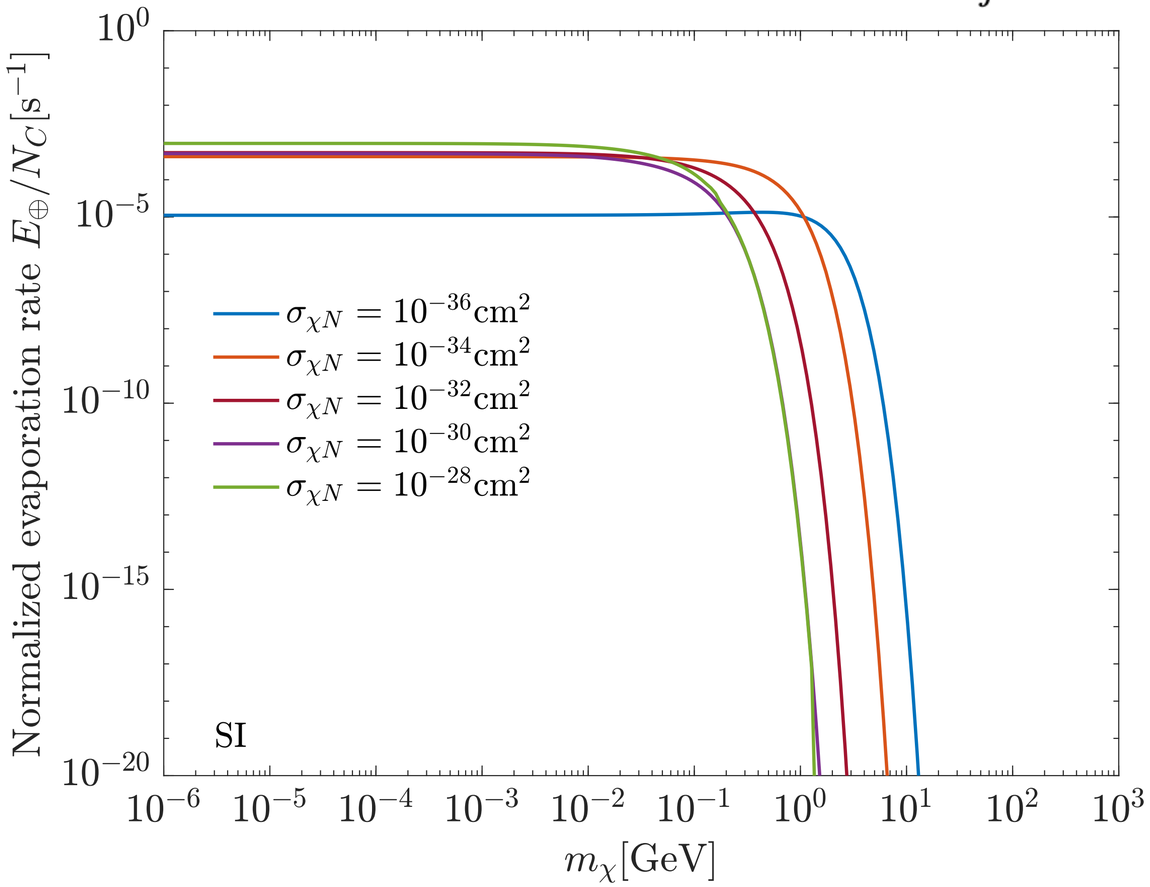
Heavier dark matter sinks down, lighter dark matter float



Dark Matter Evaporation

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

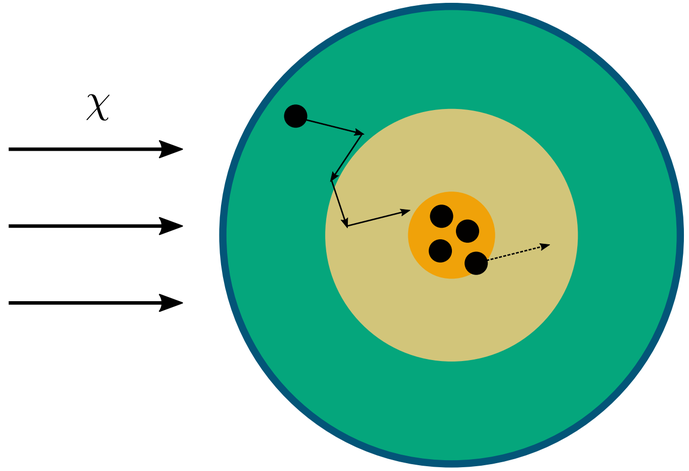
Multi scatter



Dark matter mass

Dark matter scatters with thermal nuclei and escapes from the Earth

Garani 1702.02768



Dark Matter Annihilation

Assuming dark matter annihilates to SM final states

Normalized annihilation rate $$A_\oplus = \frac{\langle \sigma v \rangle_{\chi\chi}}{N_C^2} \int_0^{R_{\oplus,\mathrm{atm}}} n_\chi^2 4\pi r^2 dr$$ $$\langle \sigma v \rangle_{\chi\chi} \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

DM in the Earth $$\frac{dN_C}{dt} = C_\oplus - \left(\frac{E_\oplus}{N_C}\right) N_C - A_\oplus N_C^2$$

Total annihilation rate $$\Gamma_\oplus(t) = (1/2) A_\oplus N_C(t)^2$$

Capture Evaporation Annihilation

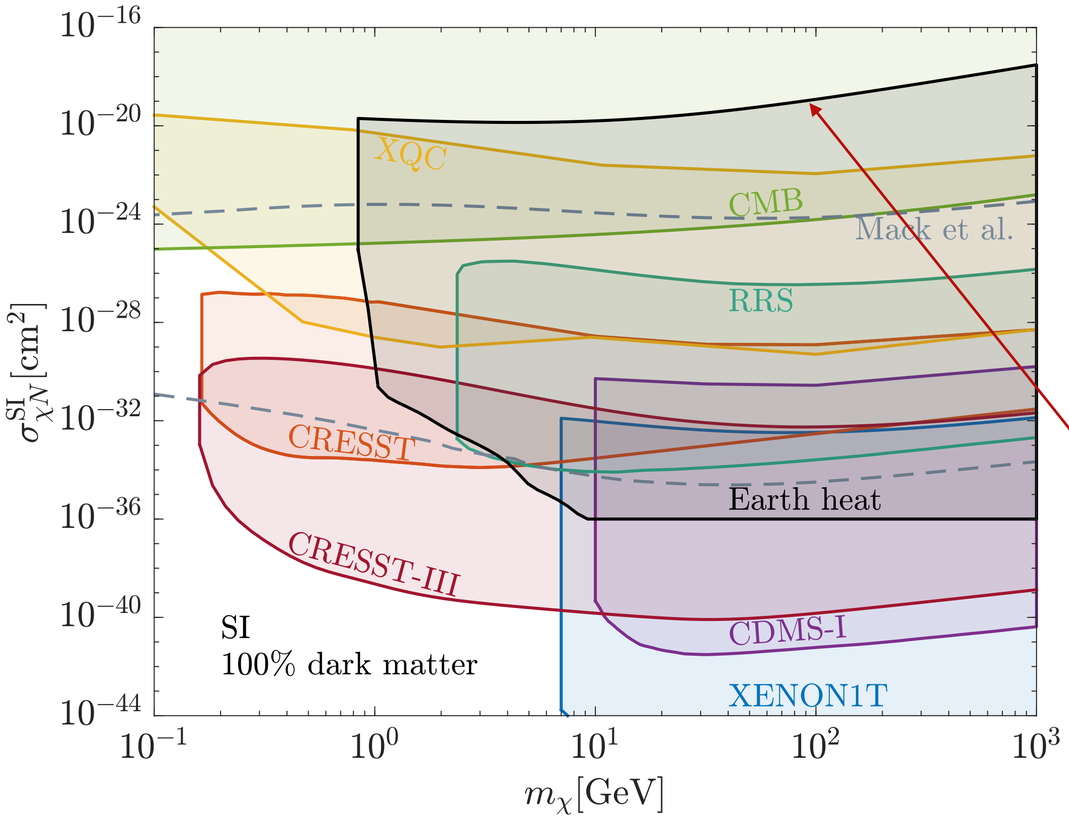
Earth Heating Constraints

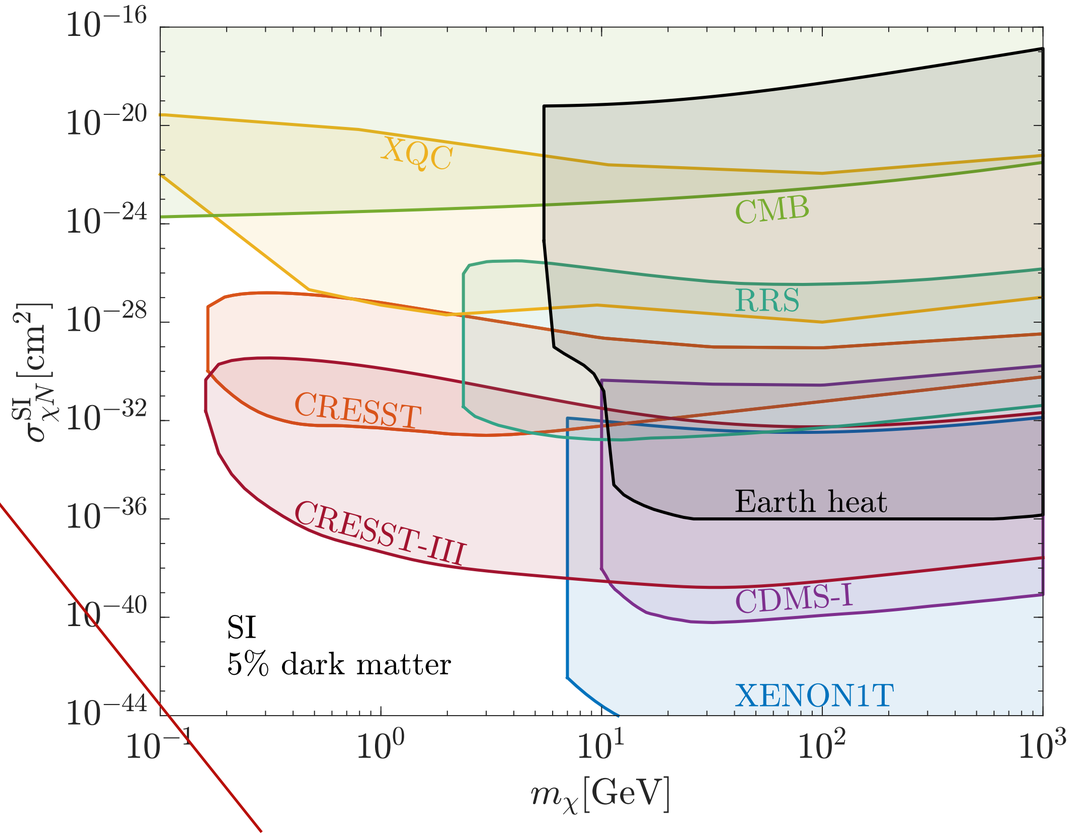
DM Heating $\leq$ 44 TW

Spin-Independent 100%

Spin-Independent 5%

Cross section





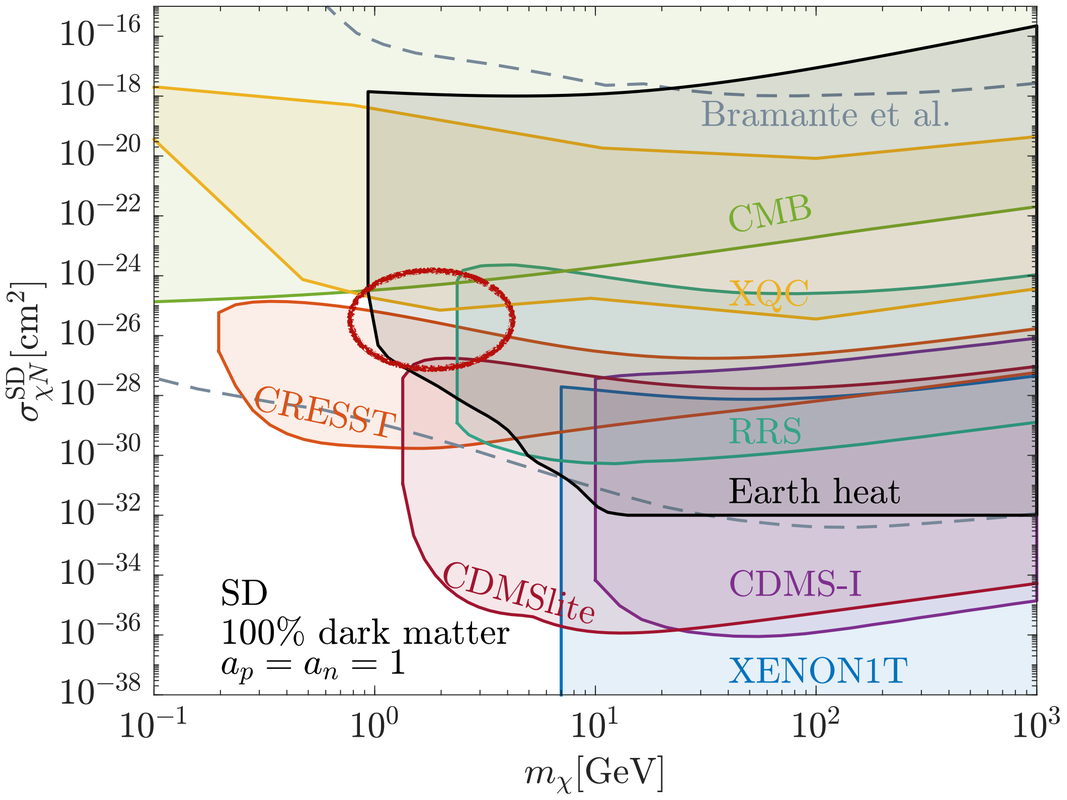
Dark matter mass

Less than 10% DM annihilation when drifting down to Earth crust

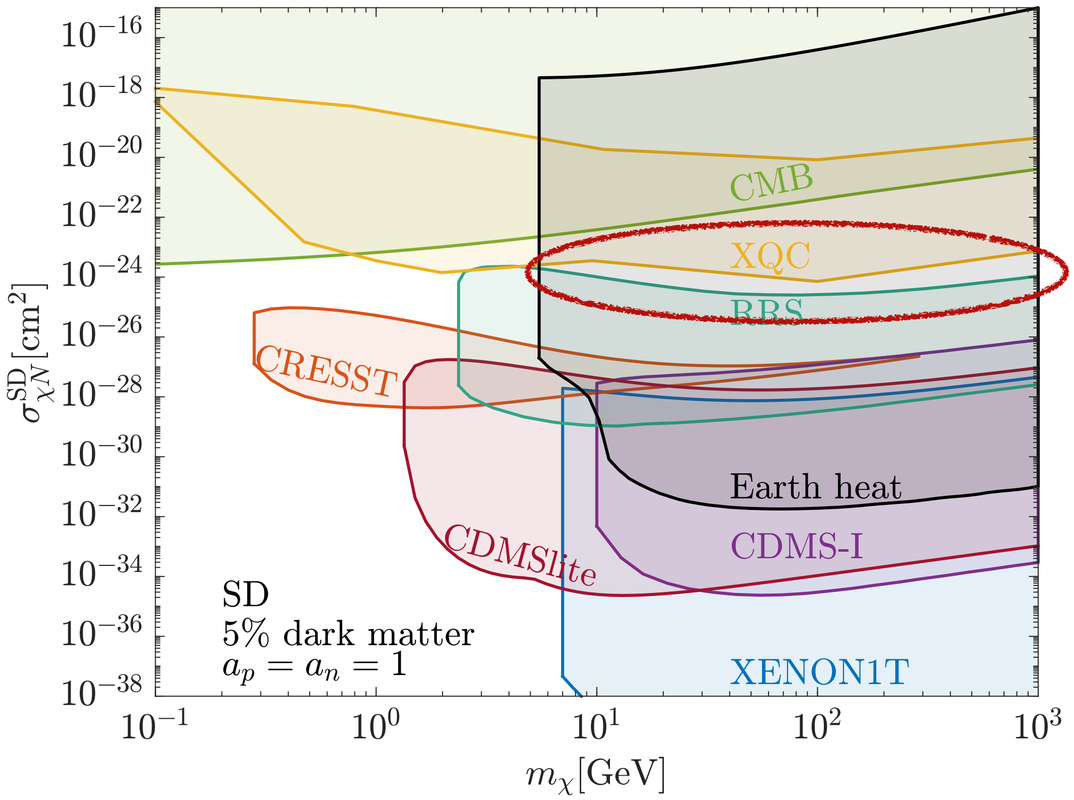
Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

Heating Constraints - Spin-Dependent

Spin-Dependent 100%



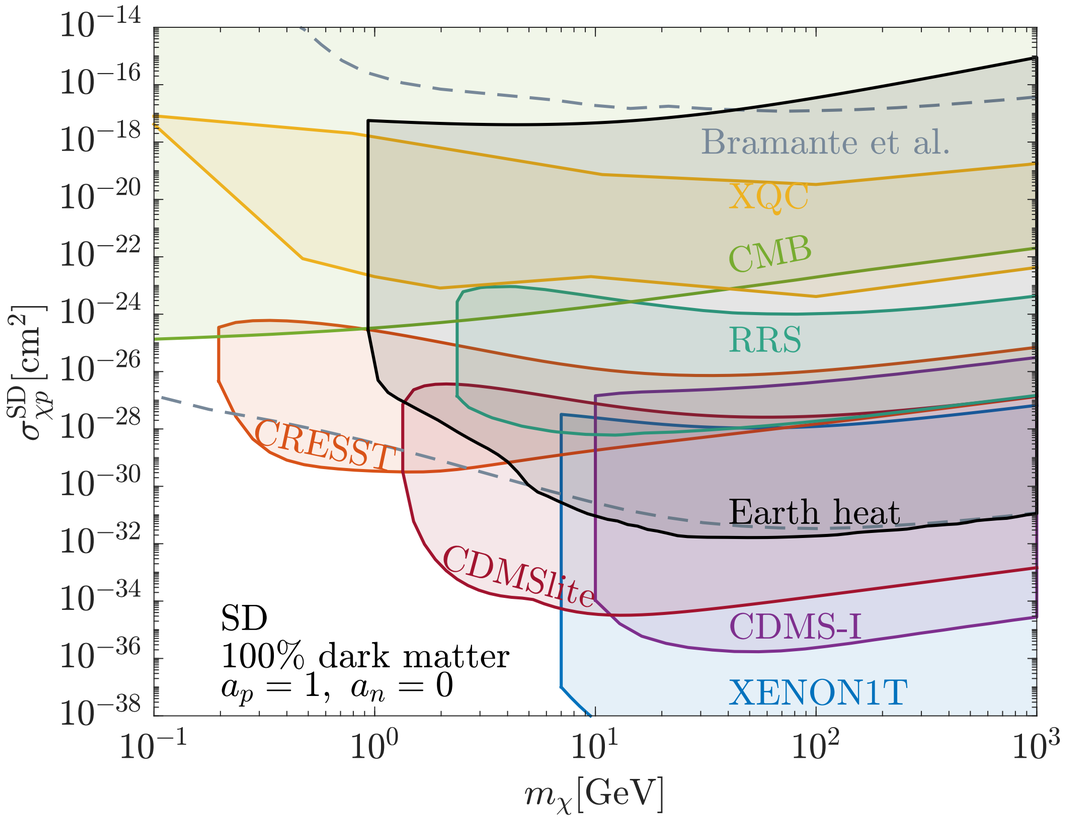
Spin-Dependent 5%



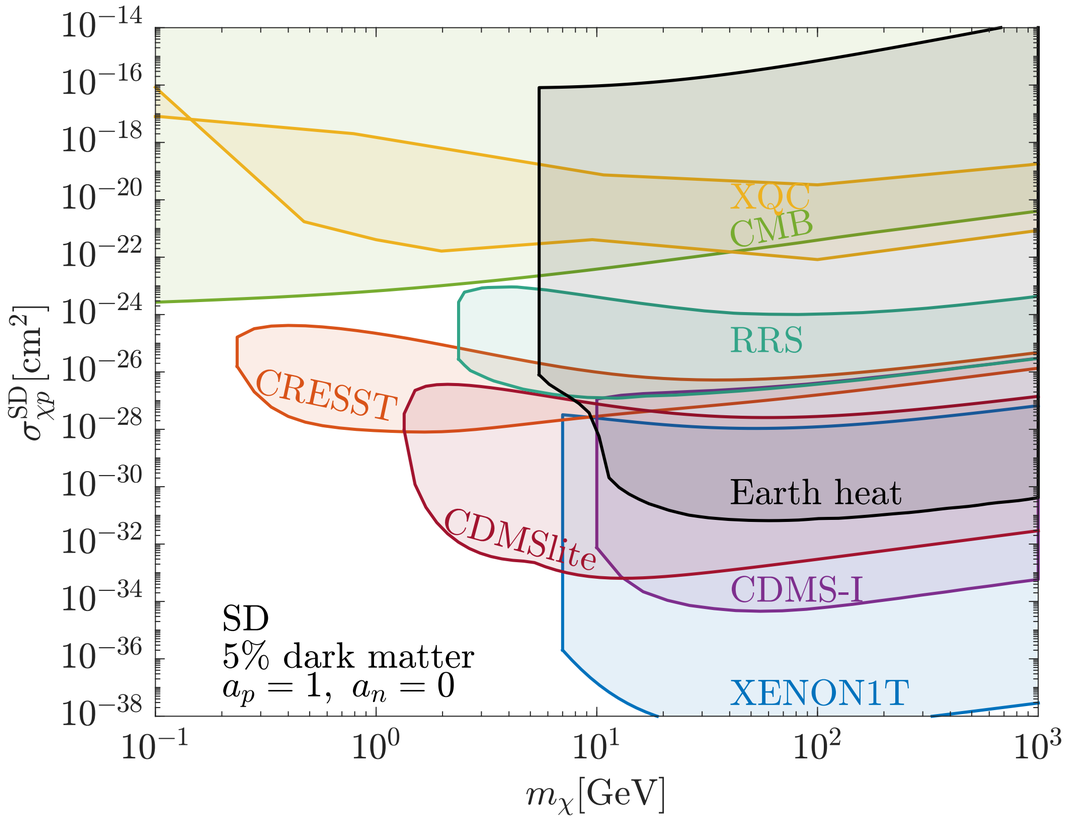
Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

Heating Constraints - Spin-Dependent

SD Proton-only 100%



SD Proton-only 5%



Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

Future Directions

- Dark matter annihilation to neutrinos
- Dark matter-electron scattering, stay tuned
- Special types of interactions
- Full MC including annihilation and evaporation
- Direct detection of thermalized dark matter Das et al 2210.09313

Thank you!