Earth and Celestial Bodies as Dark Matter Laboratories

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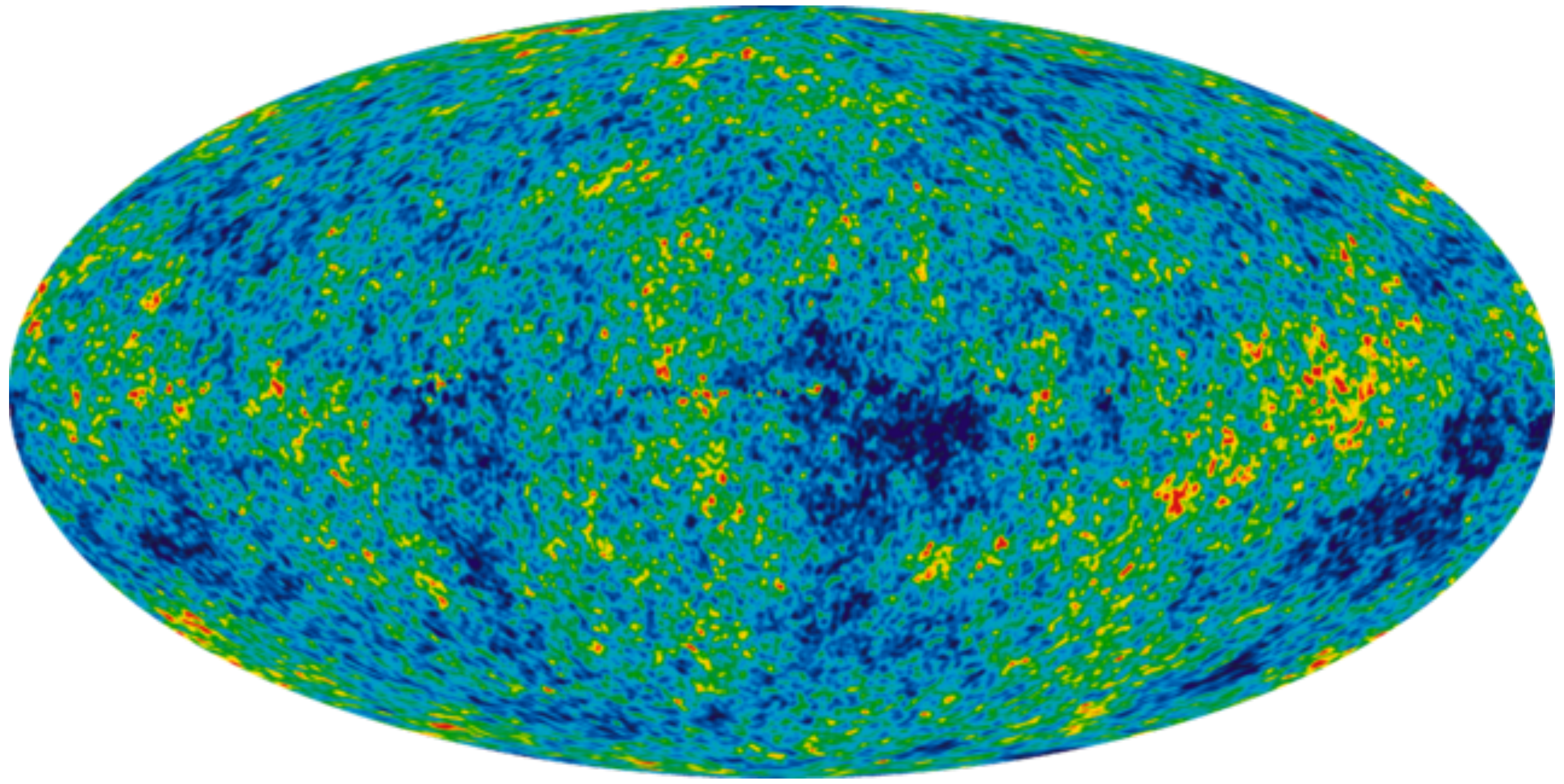
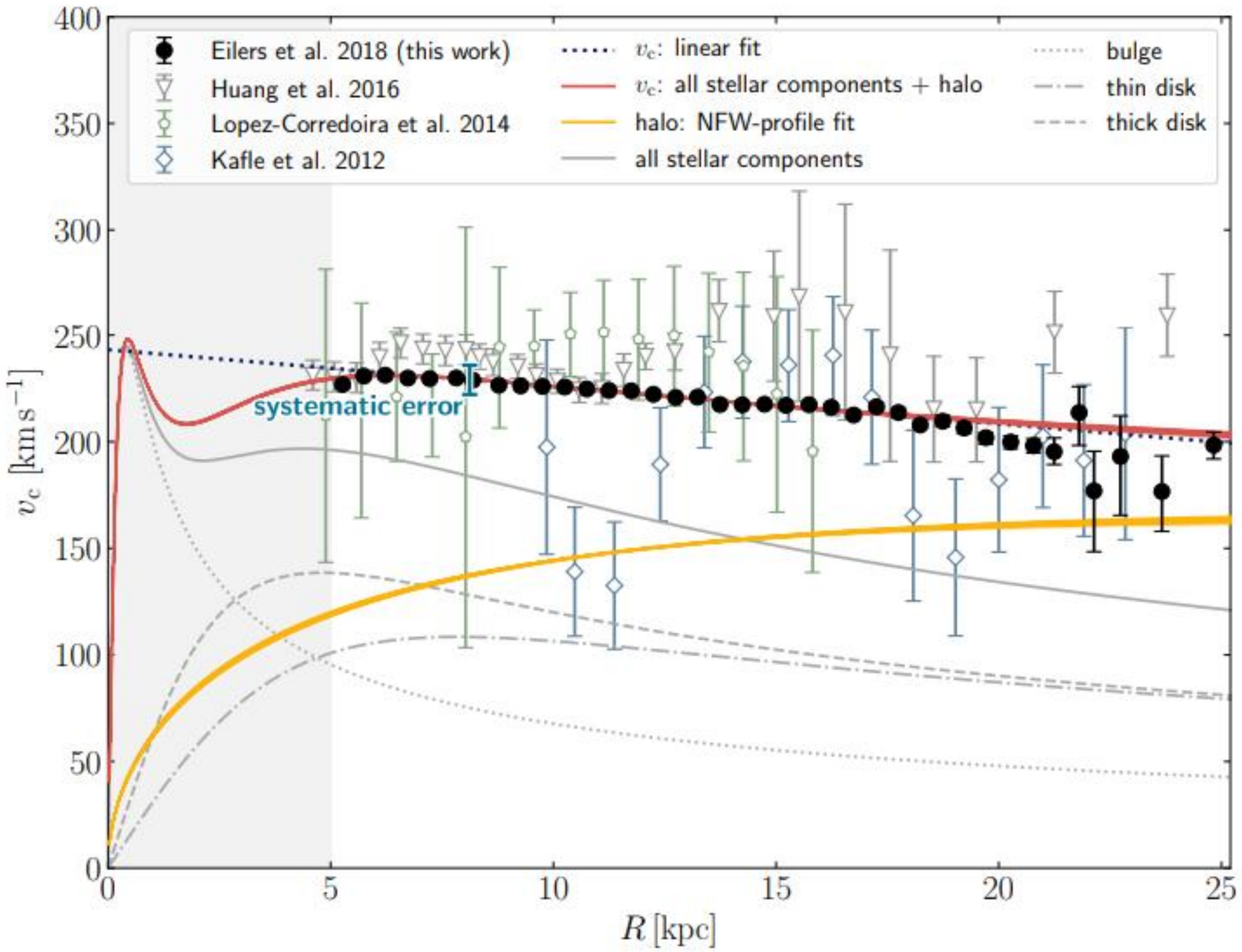
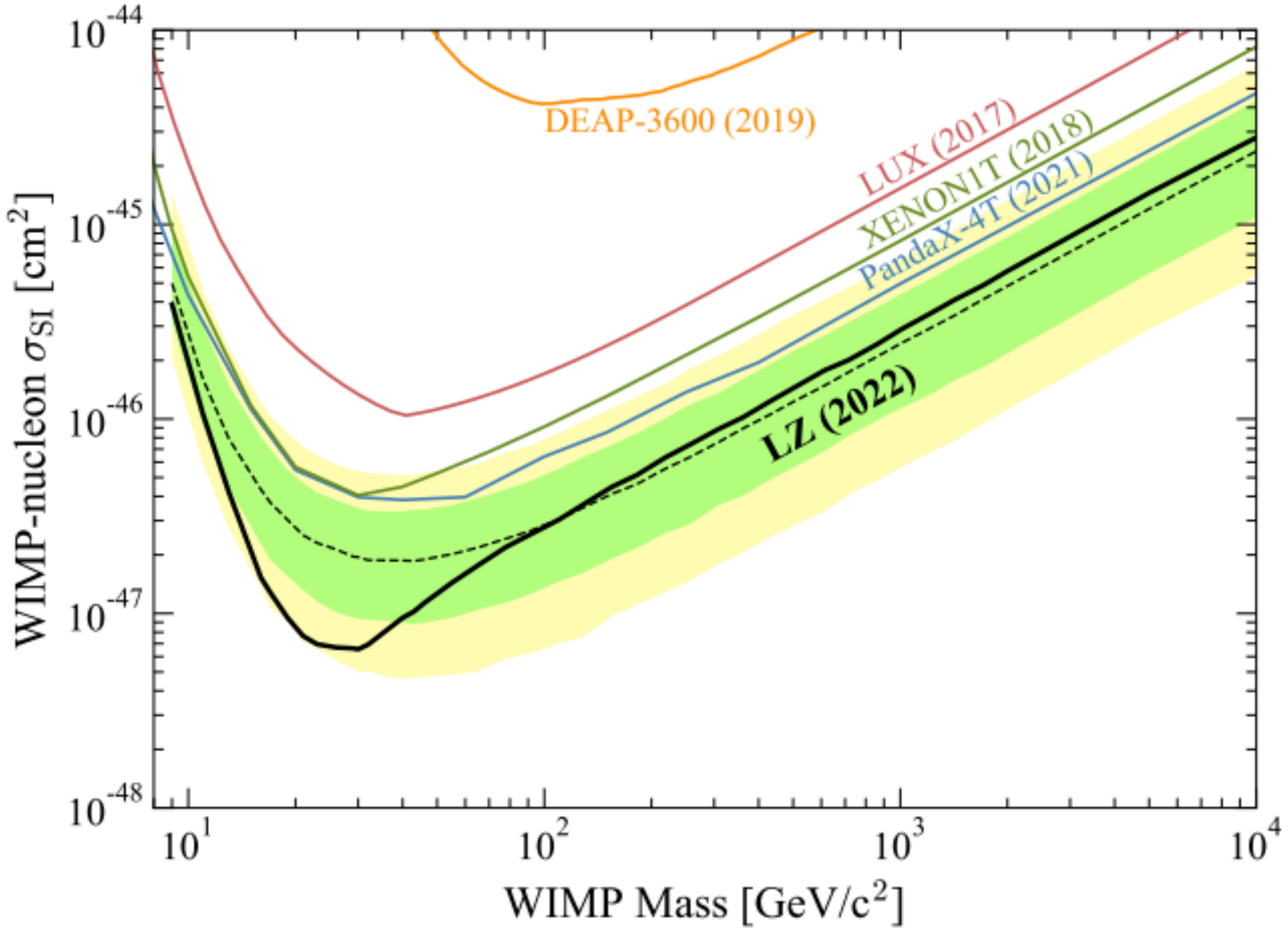




Ningqiang Song (songnq@itp.ac.cn)
Eilers *et al.*, 1810.09466

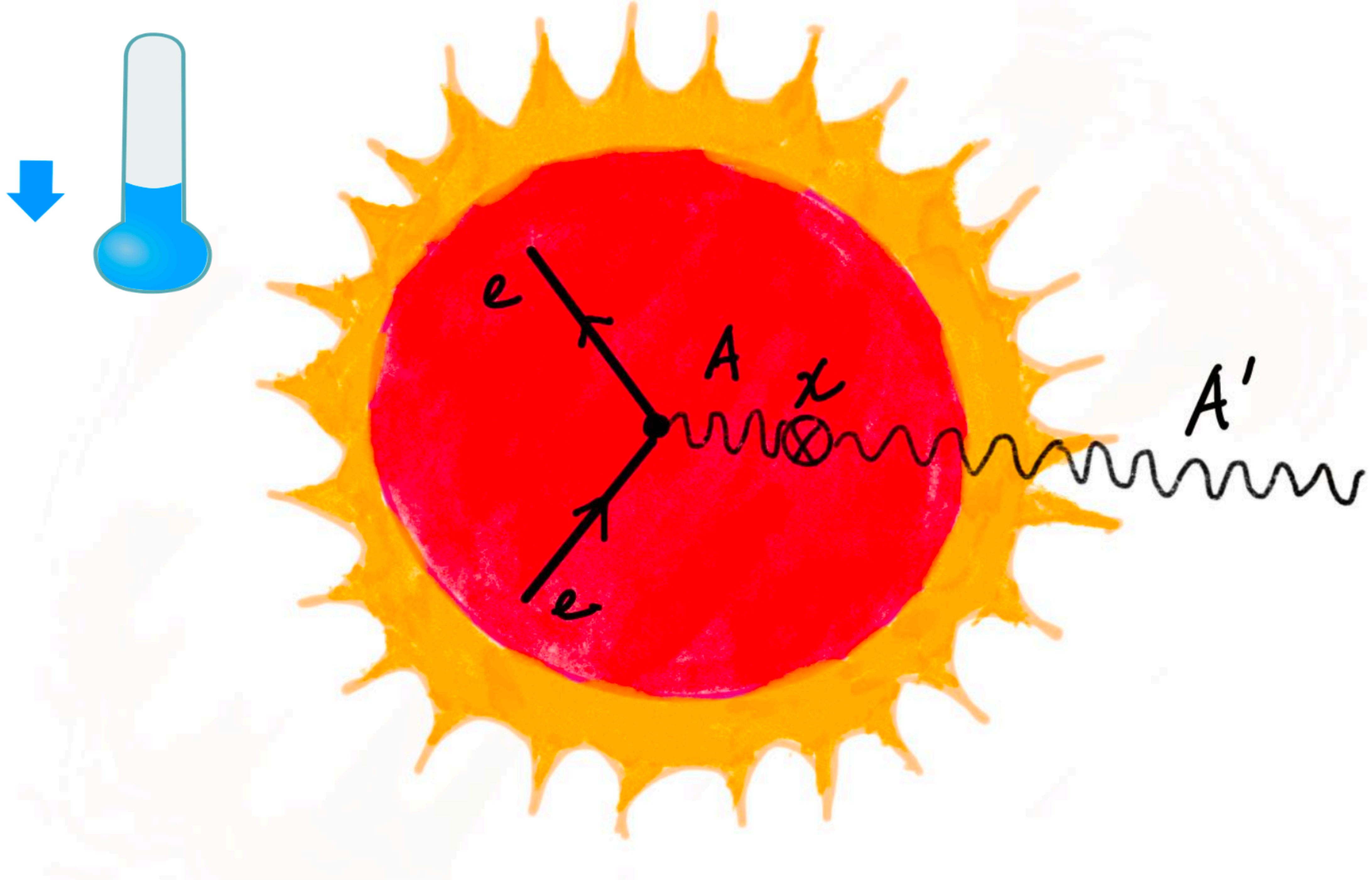
Why Celestial Bodies?



LZ 2207.03764
See also latest XENONnT 2303.14729

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

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

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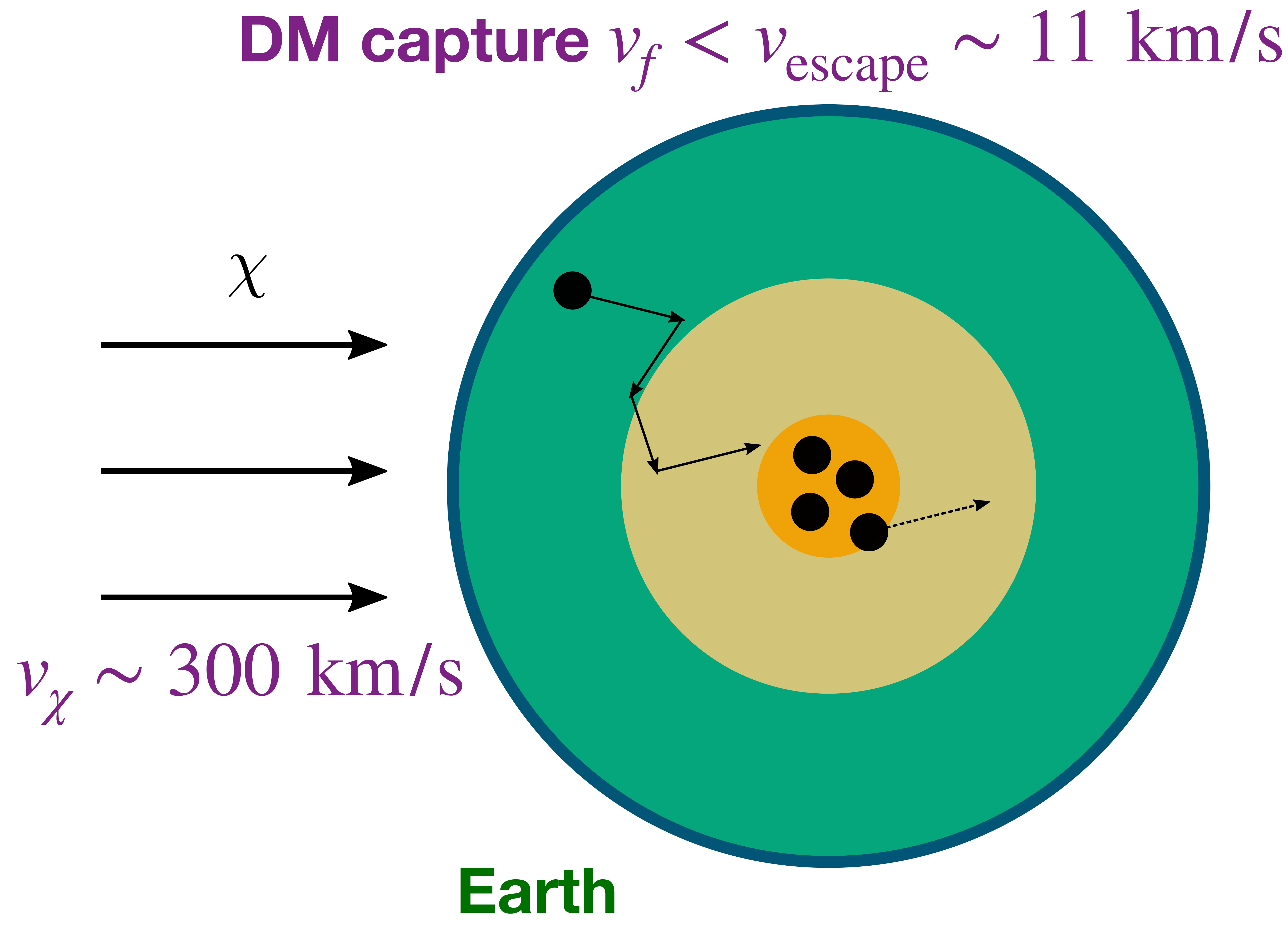
Dark Matter Stove

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

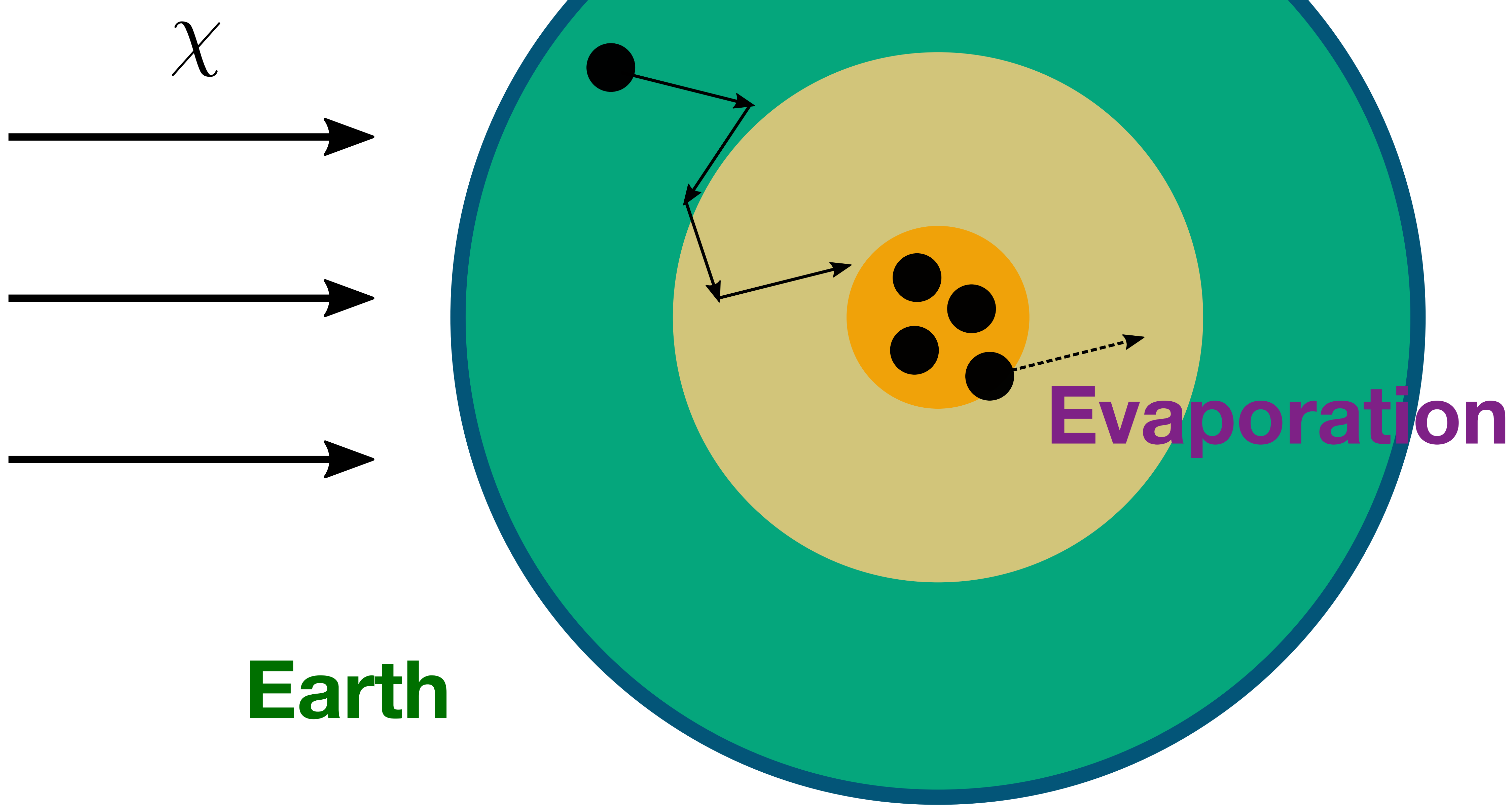
Earth Heating

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



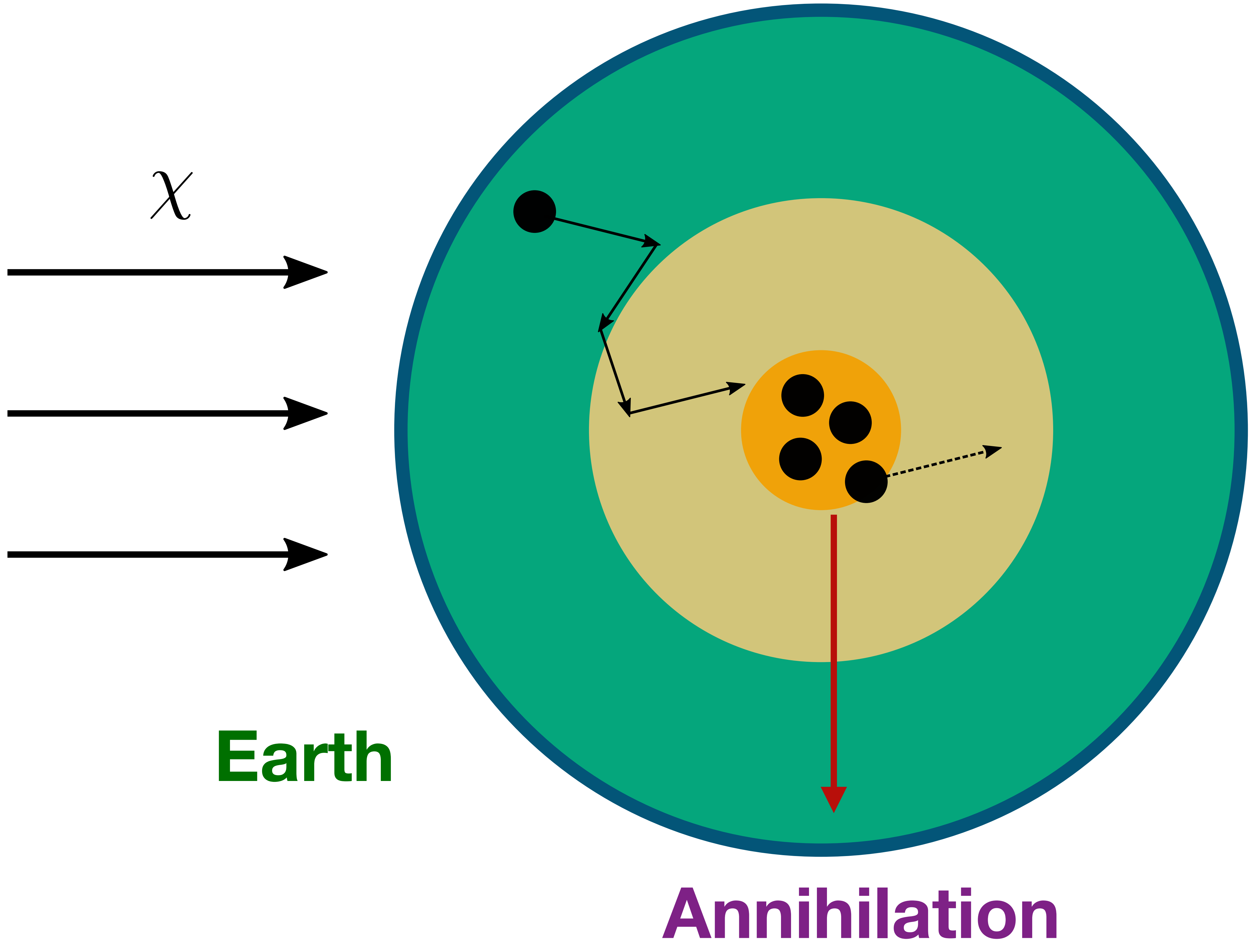
Earth Heating

- Dark matter scatters with Earth matter, slows down and gets trapped
- Dark matter scatters with thermal nuclei and escapes from the Earth



Earth Heating

- Dark matter scatters with Earth matter, slows down and gets trapped
- Dark matter scatters with thermal nuclei and escapes from the Earth
- Dark matter annihilate to Standard Model particles, heating the Earth



DM Heating $\lesssim$ 44 TW

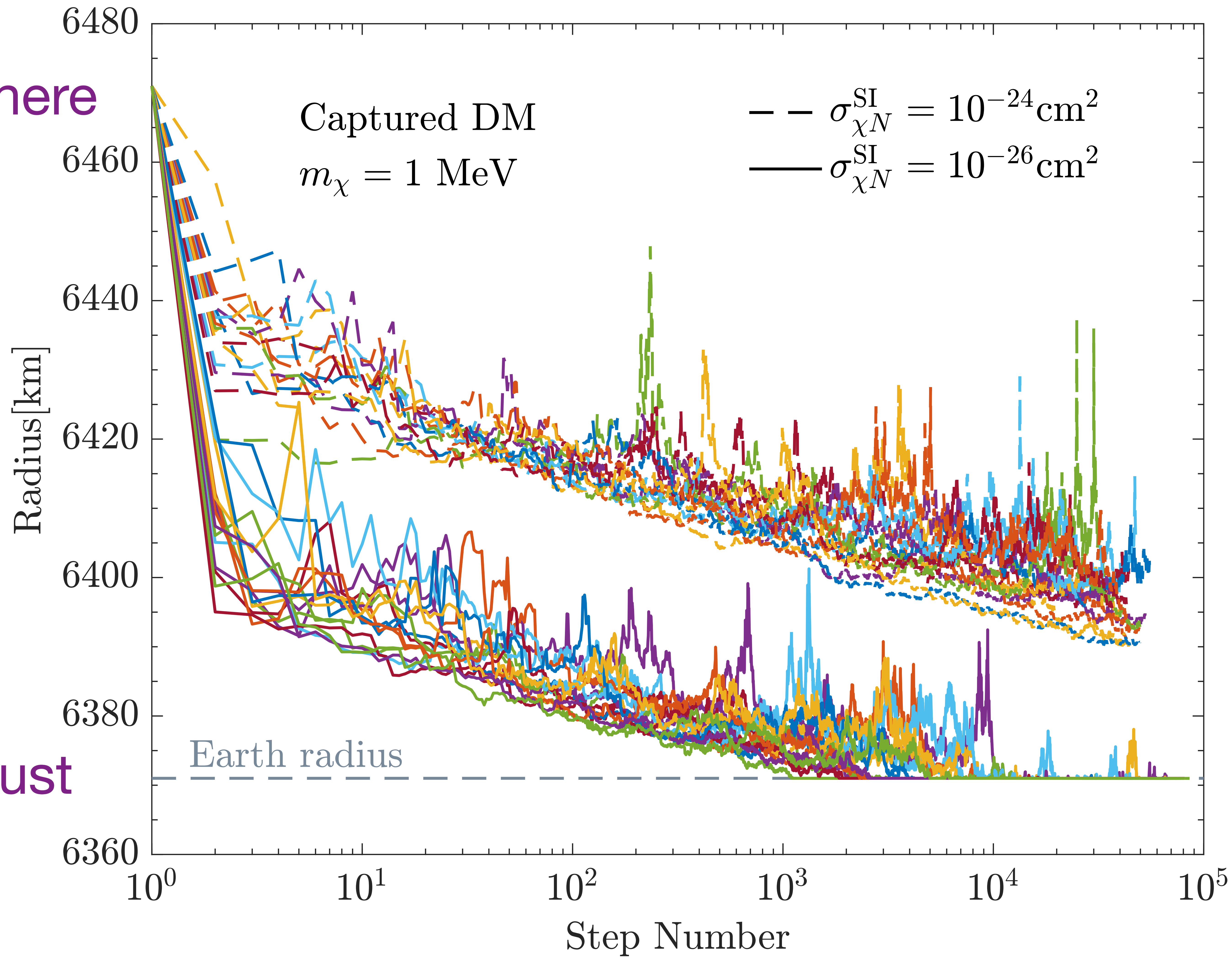
Kamland, Borexino
geoneutrino observation

Monte Carlo

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

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

Top of atmosphere



Top of Earth crust

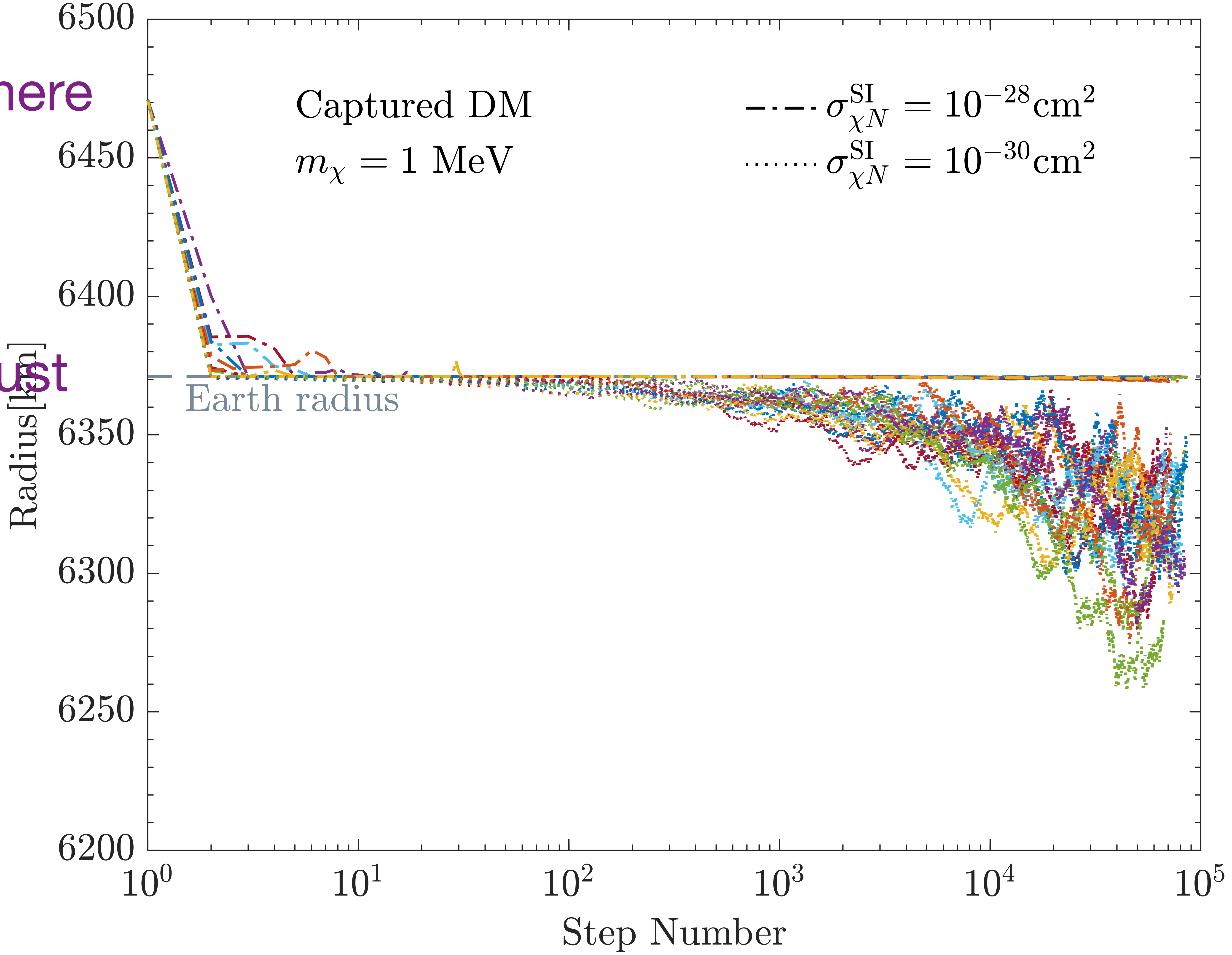
Number of scattering

Monte Carlo

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

Top of atmosphere

Top of Earth crust

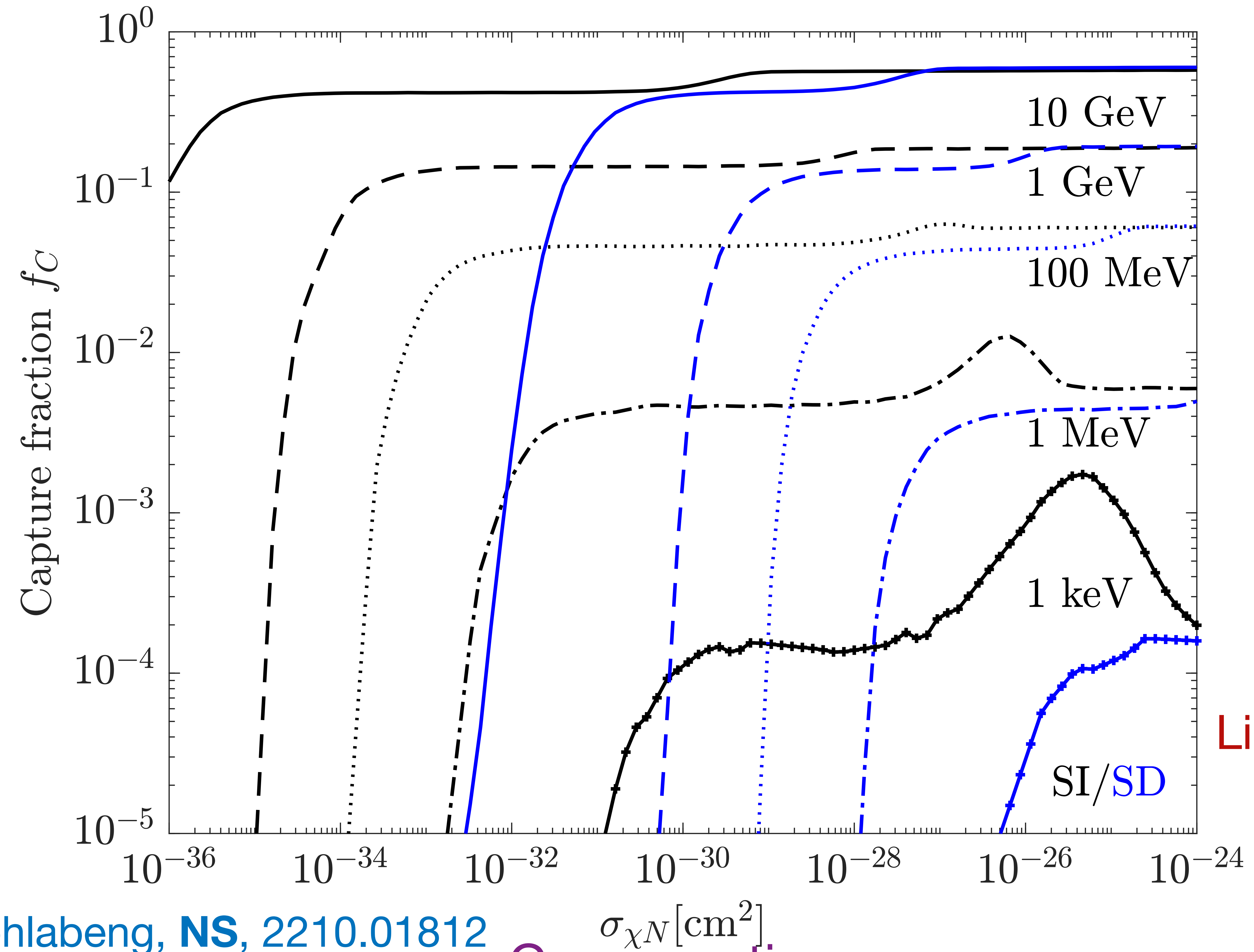


Number of scattering

Capture Fraction

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

Capture fraction



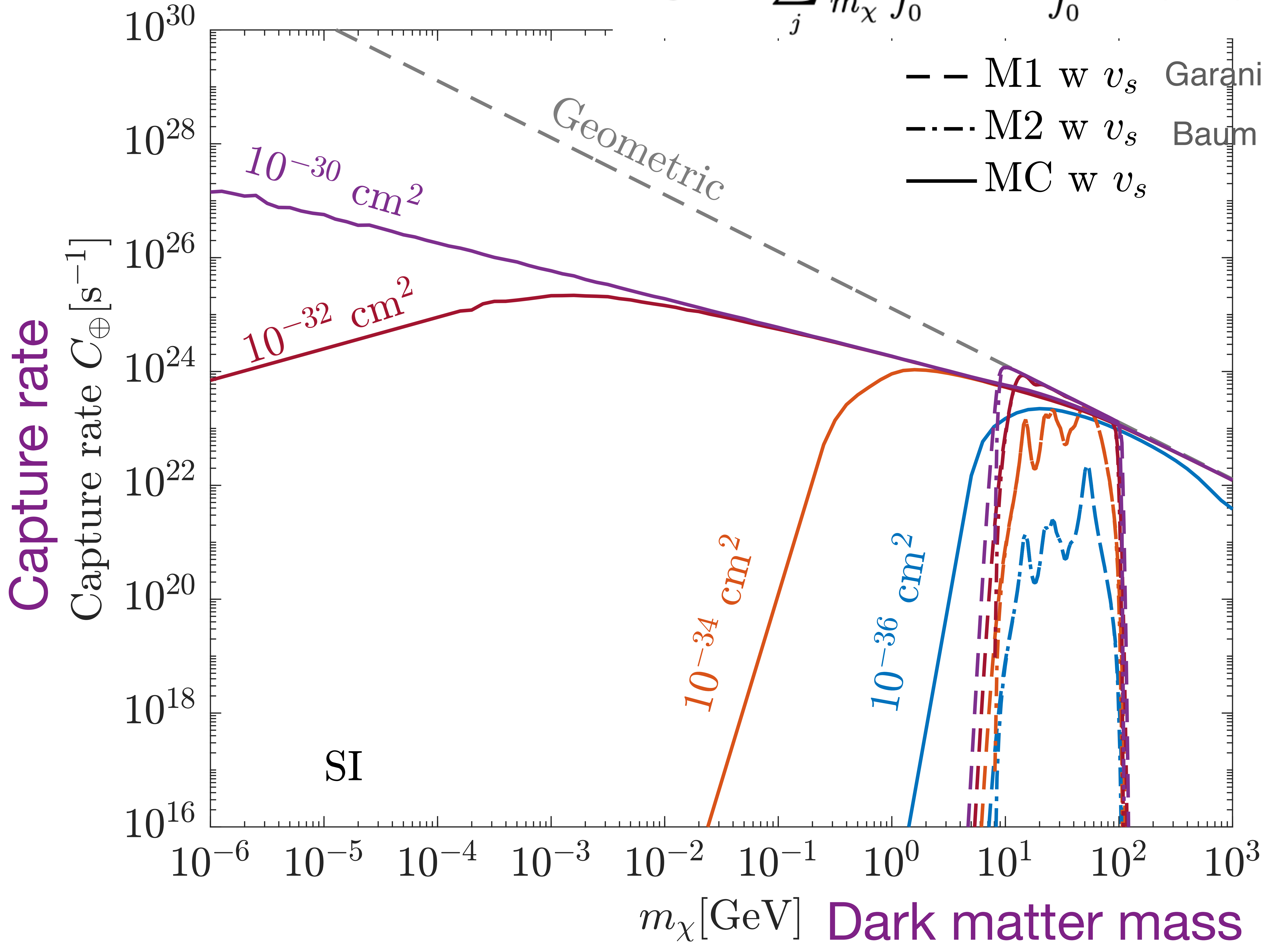
Lighter DM

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

Cross section

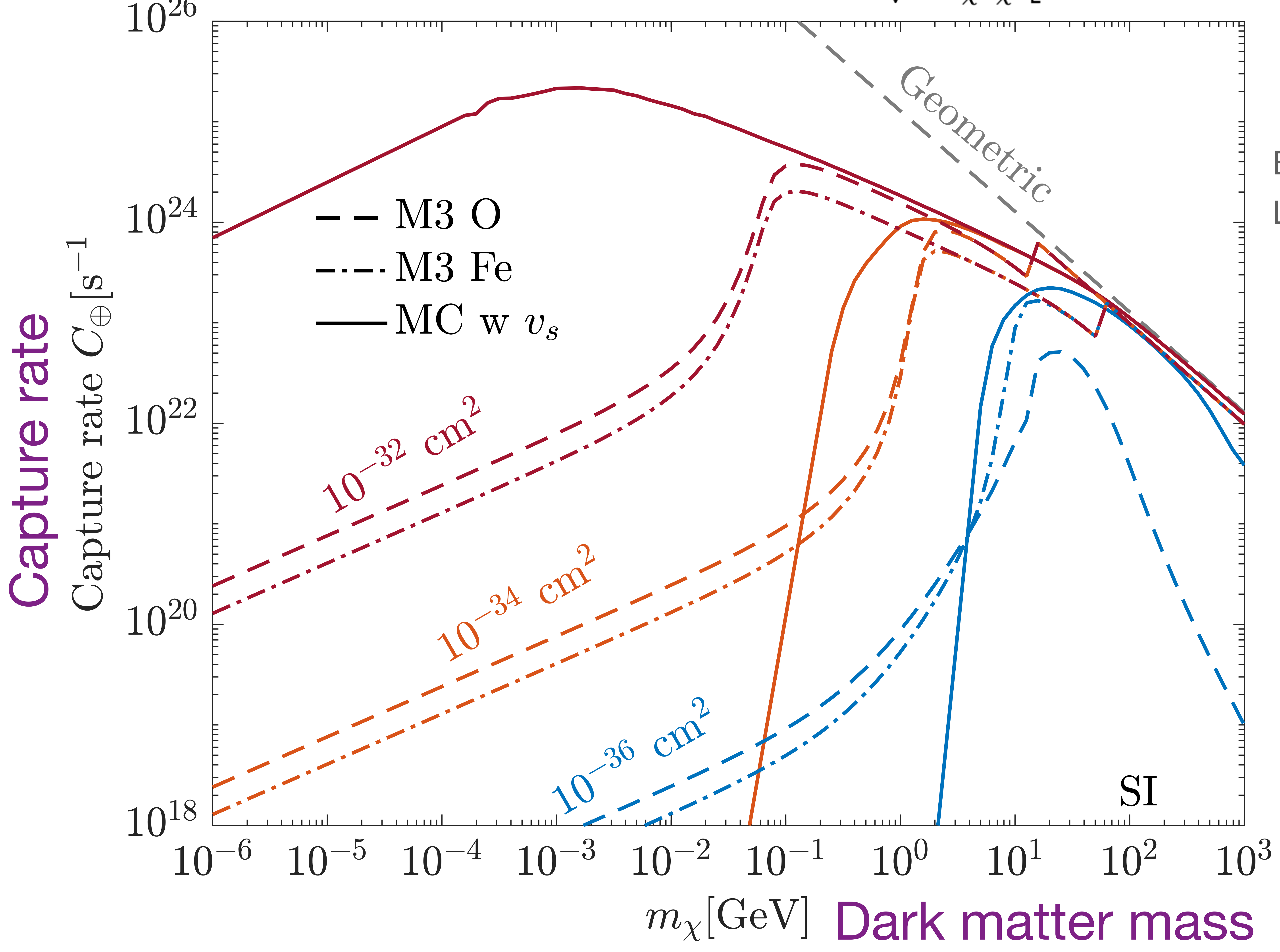
Monte Carlo vs Single Scatter

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



Monte Carlo vs Multi Scatter

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

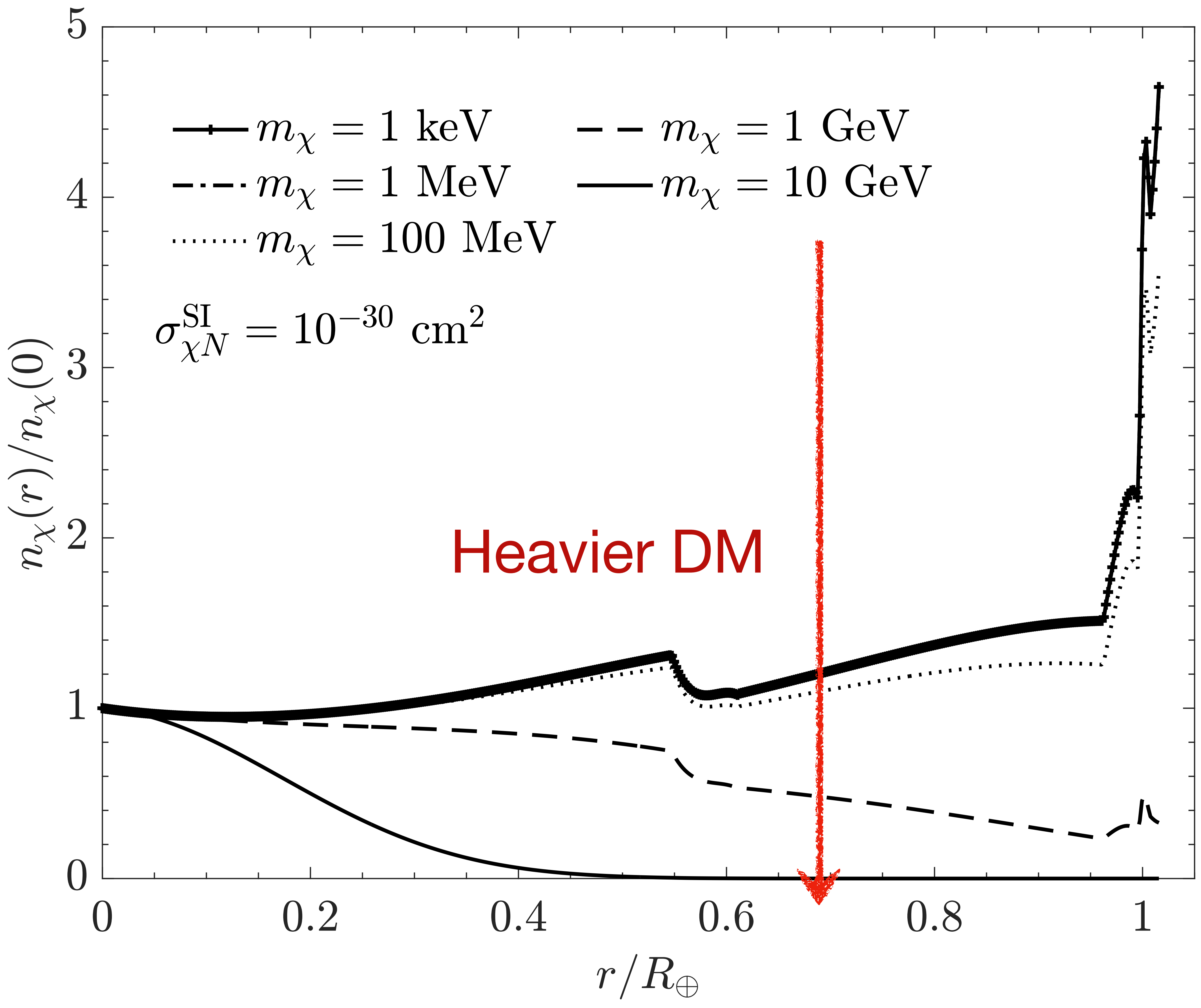


Bramante 1703.04043

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

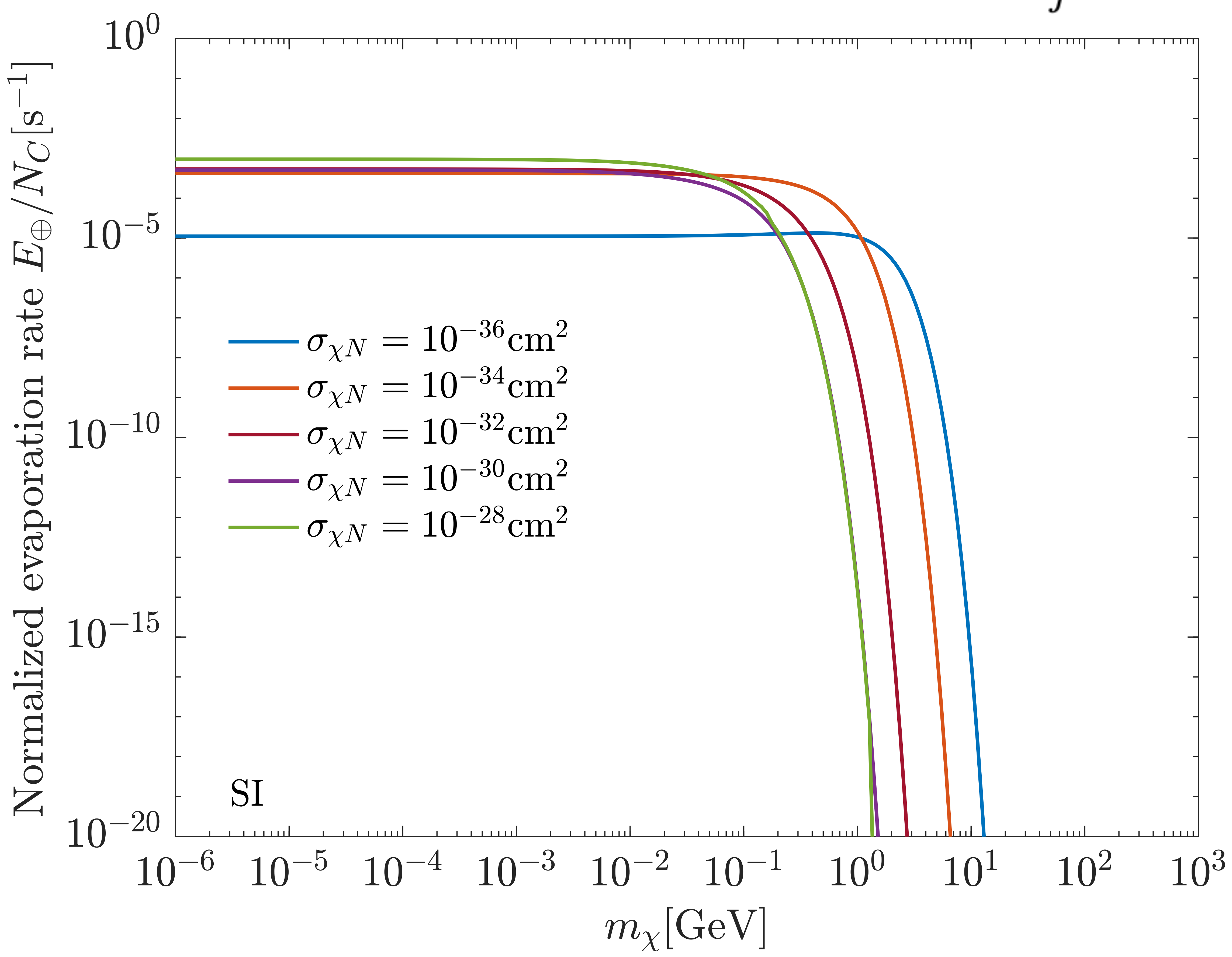
Garani 1702.02768

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 $$\Gamma_{\oplus}(t) = (1/2) A_{\oplus} N_C(t)^2$$

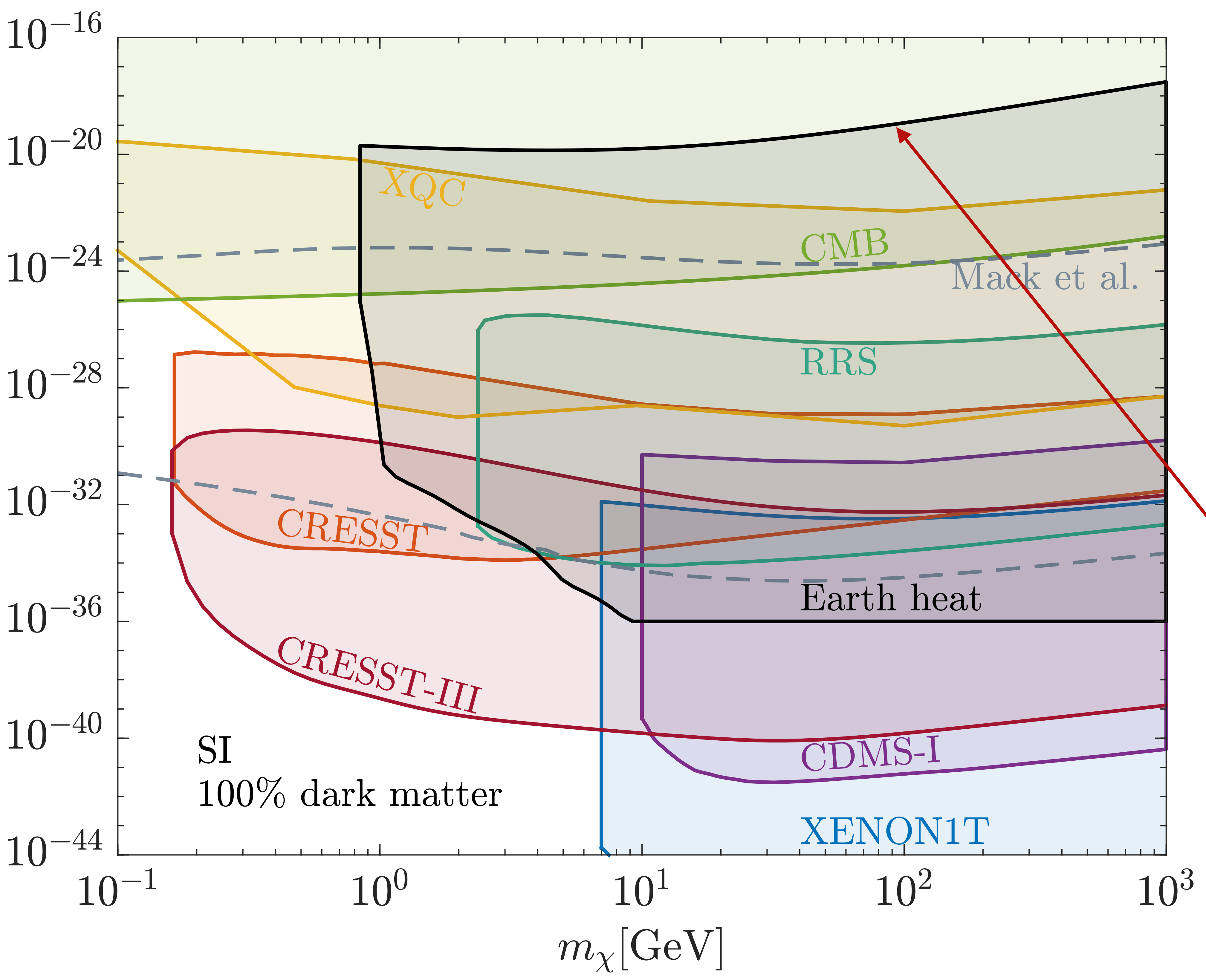
Capture Evaporation Annihilation

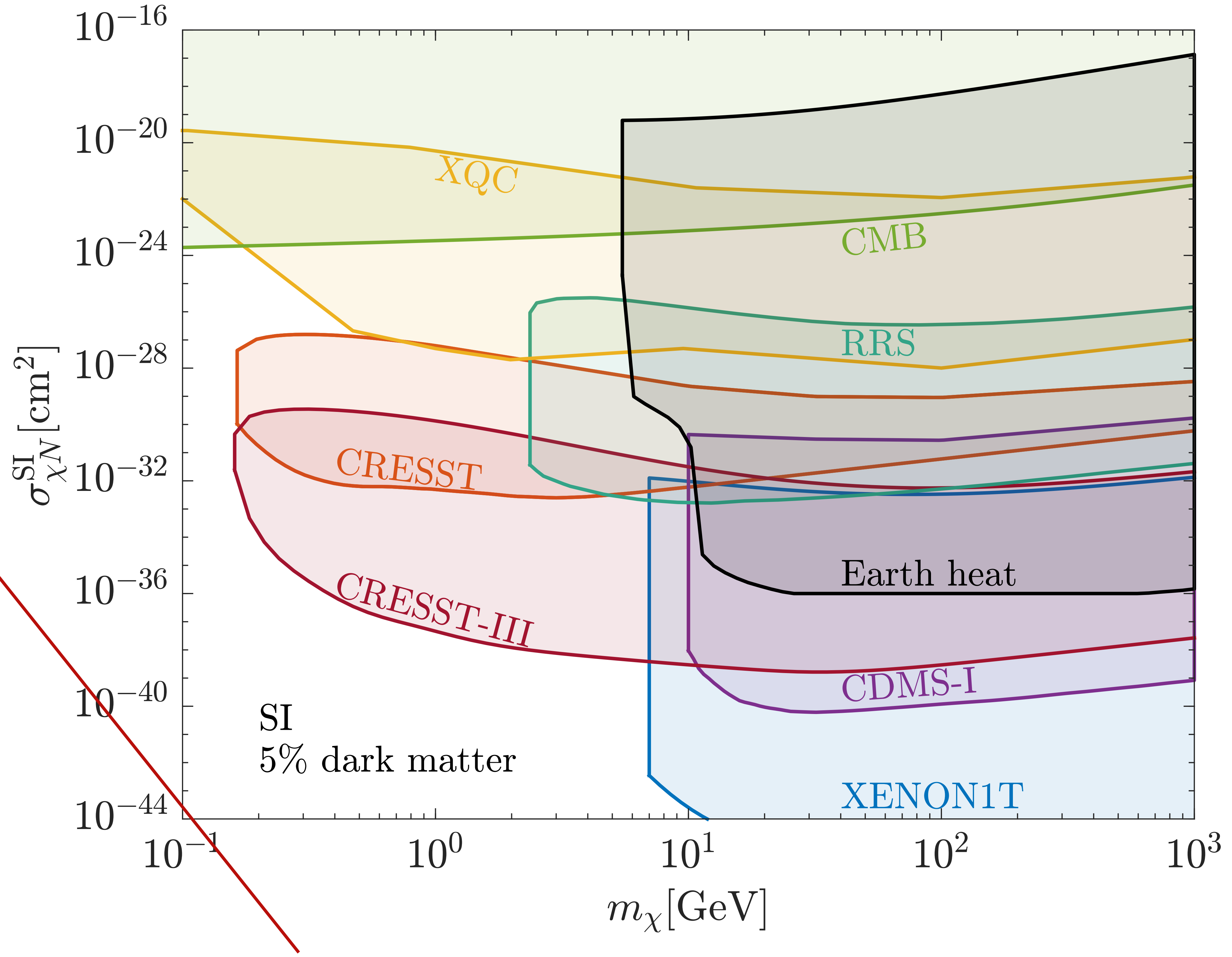
Earth Heating Constraints

DM Heating ≤ 44 TW

Spin-Independent 100%

Spin-Independent 5%





Cross section

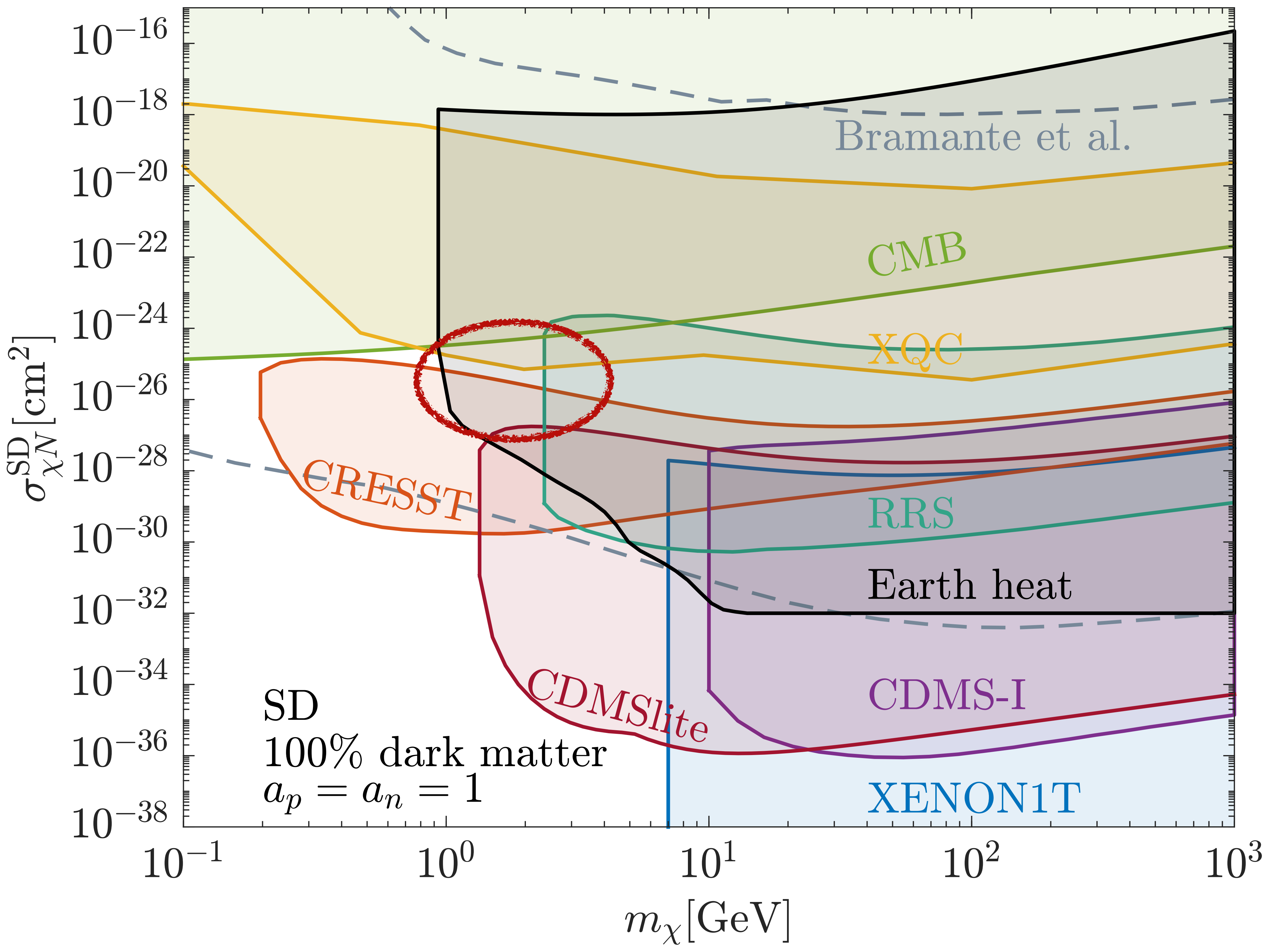
Dark matter mass

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

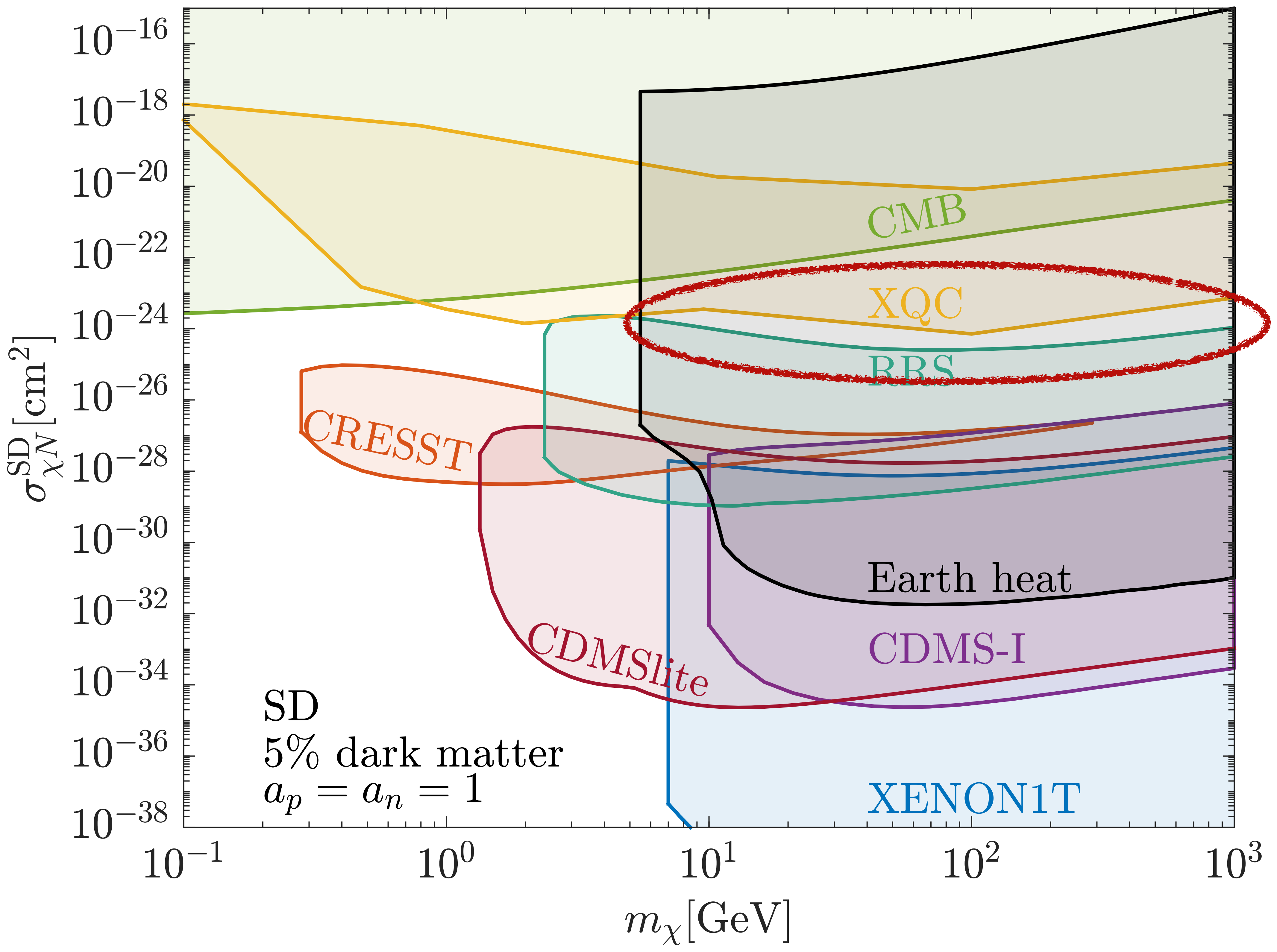
Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

Heating Constraints - Spin-Dependent

Spin-Dependent 100%



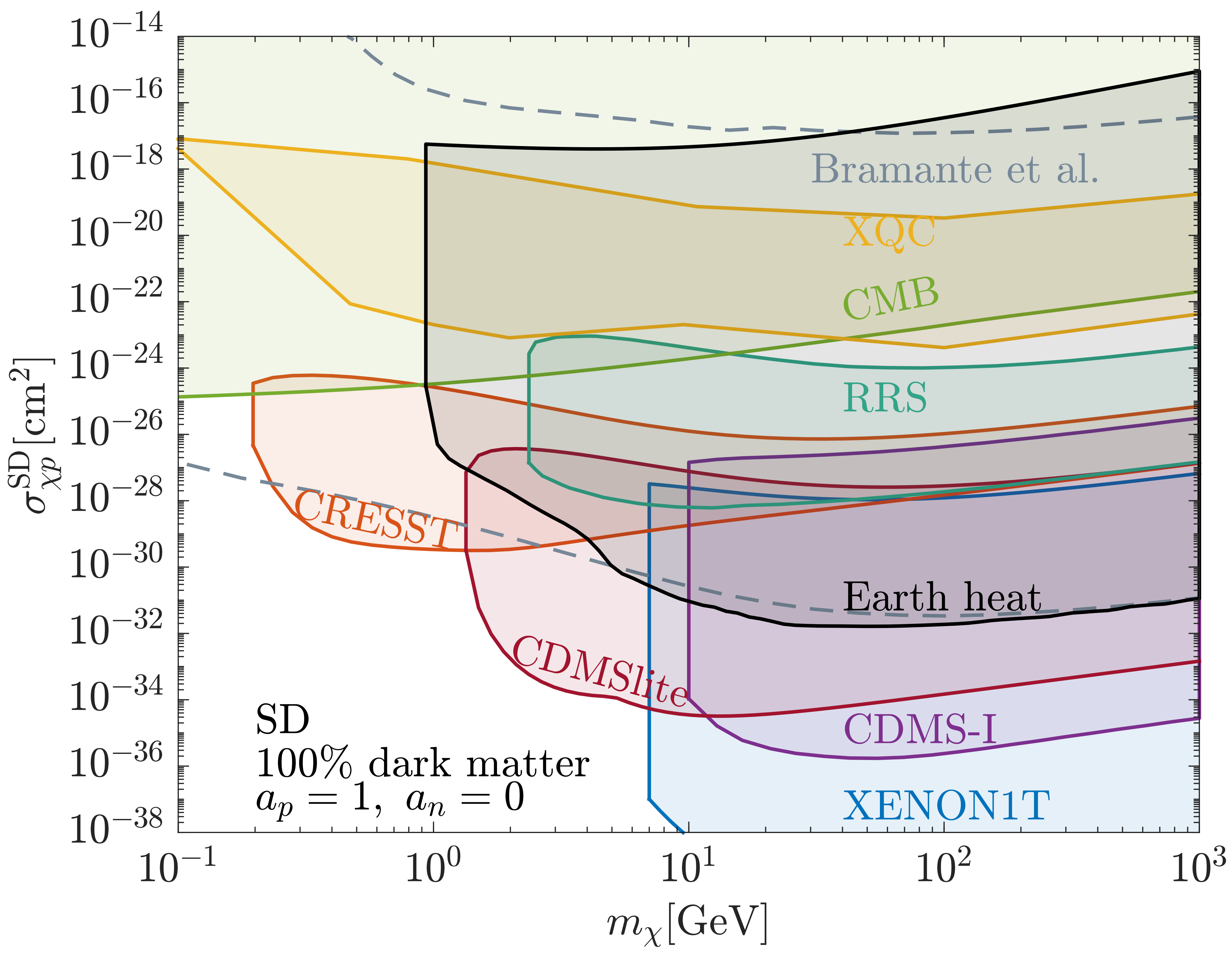
Spin-Dependent 5%



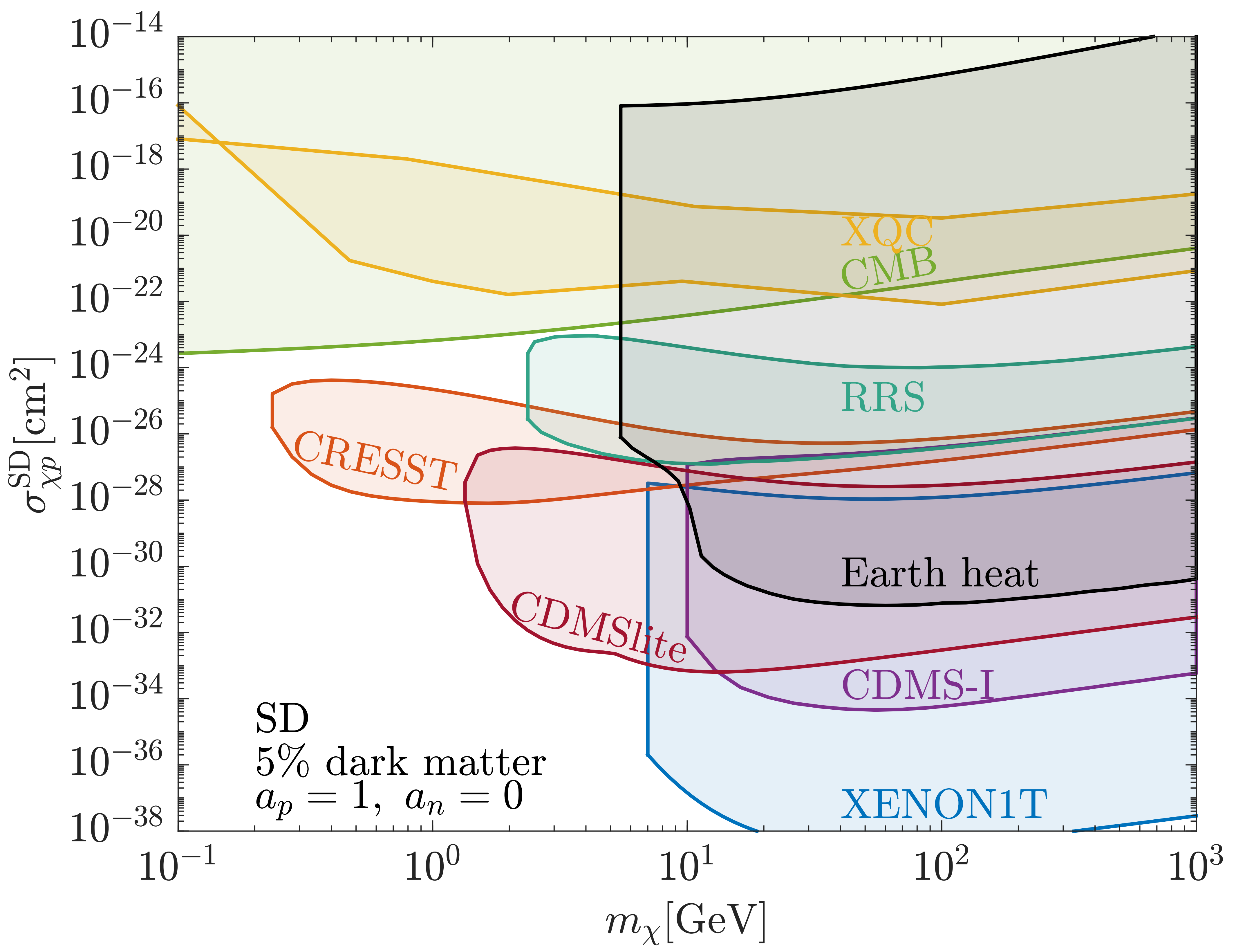
Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

Heating Constraints - Spin-Dependent

SD Proton-only 100%



SD Proton-only 5%



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

What Else?

Now

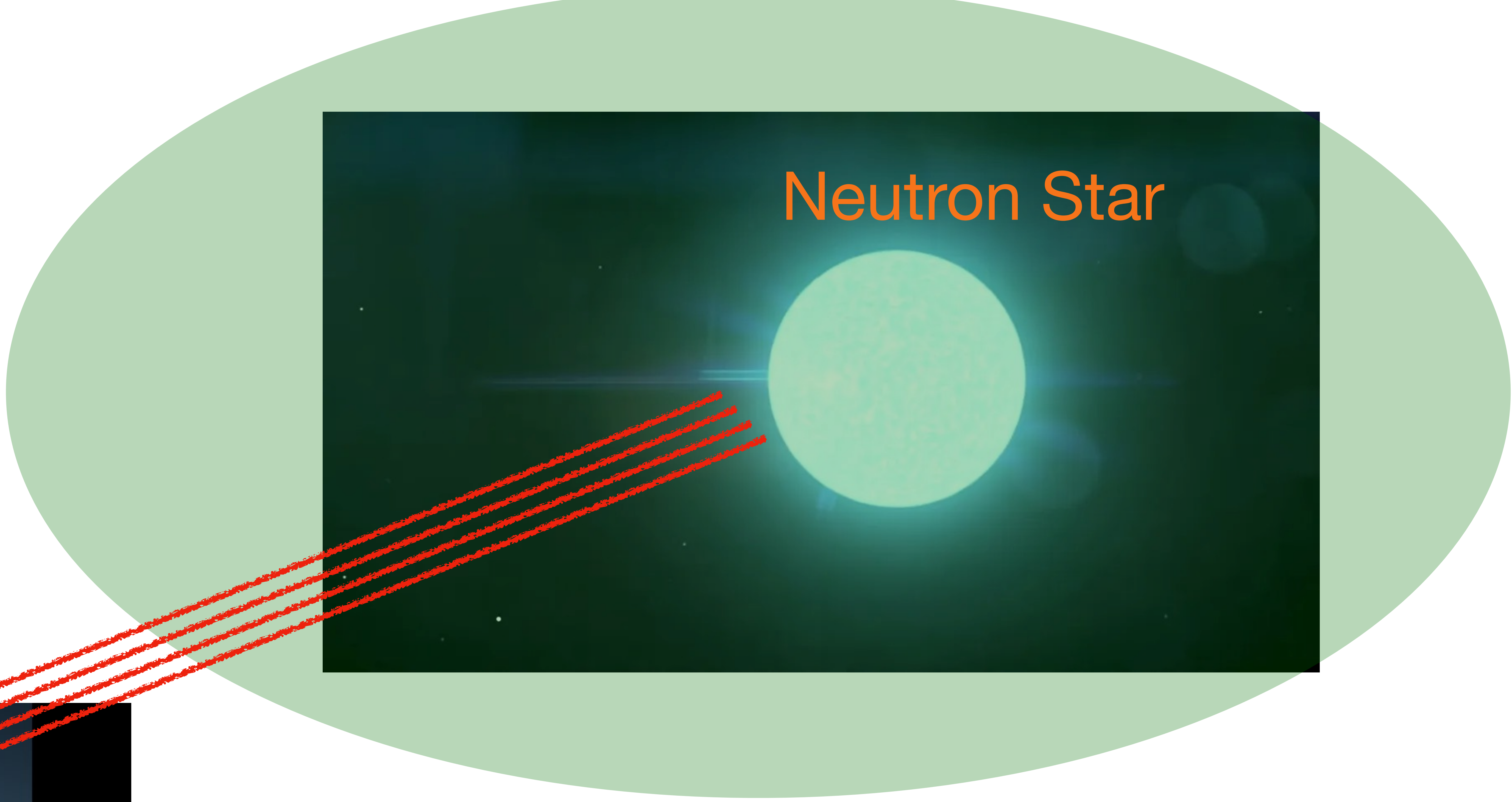
Something

Different

Credit:
ESO/M. Kornmesser

Radios From Stars

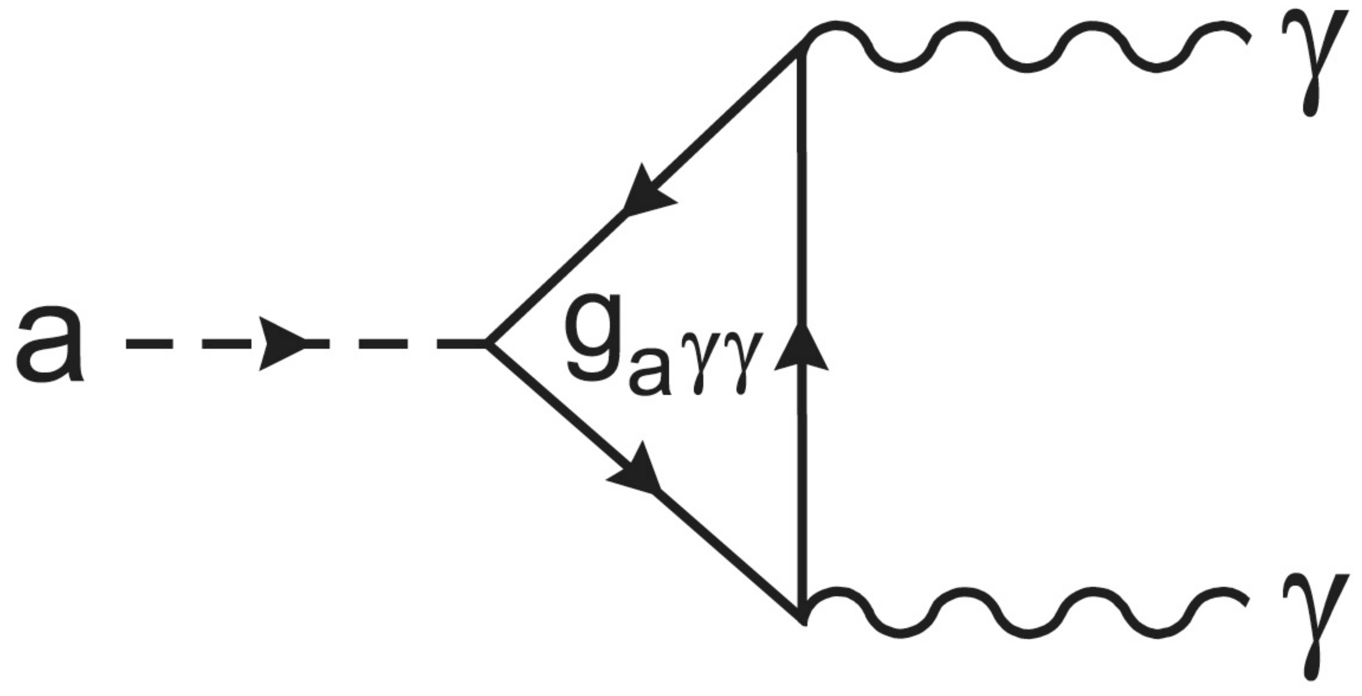
DM Halo



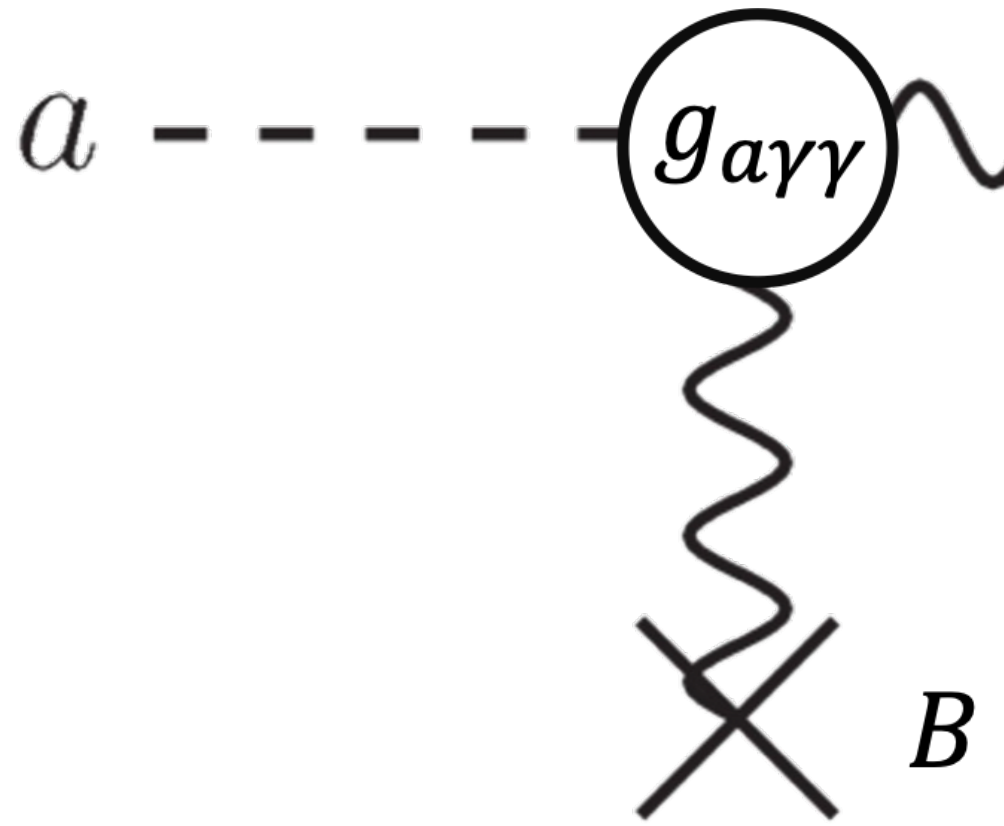
Radio Signals

Axion-Photon Conversion

- CP conserved in QCD $\Rightarrow$ axion
- $\mathscr{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Resonant conversion from axion to photon in plasma when $m_a \sim \omega_p$



$\omega^2 = k^2 + m_a^2$ $\qquad$ $\omega^2 \sim k^2 + \omega_p^2$



Plasma frequency
$\omega_p^2 = 4\pi\alpha n_e / m_e$

Axion Conversion in Neutron Star

- Magnetized neutron star atmosphere—magnetosphere

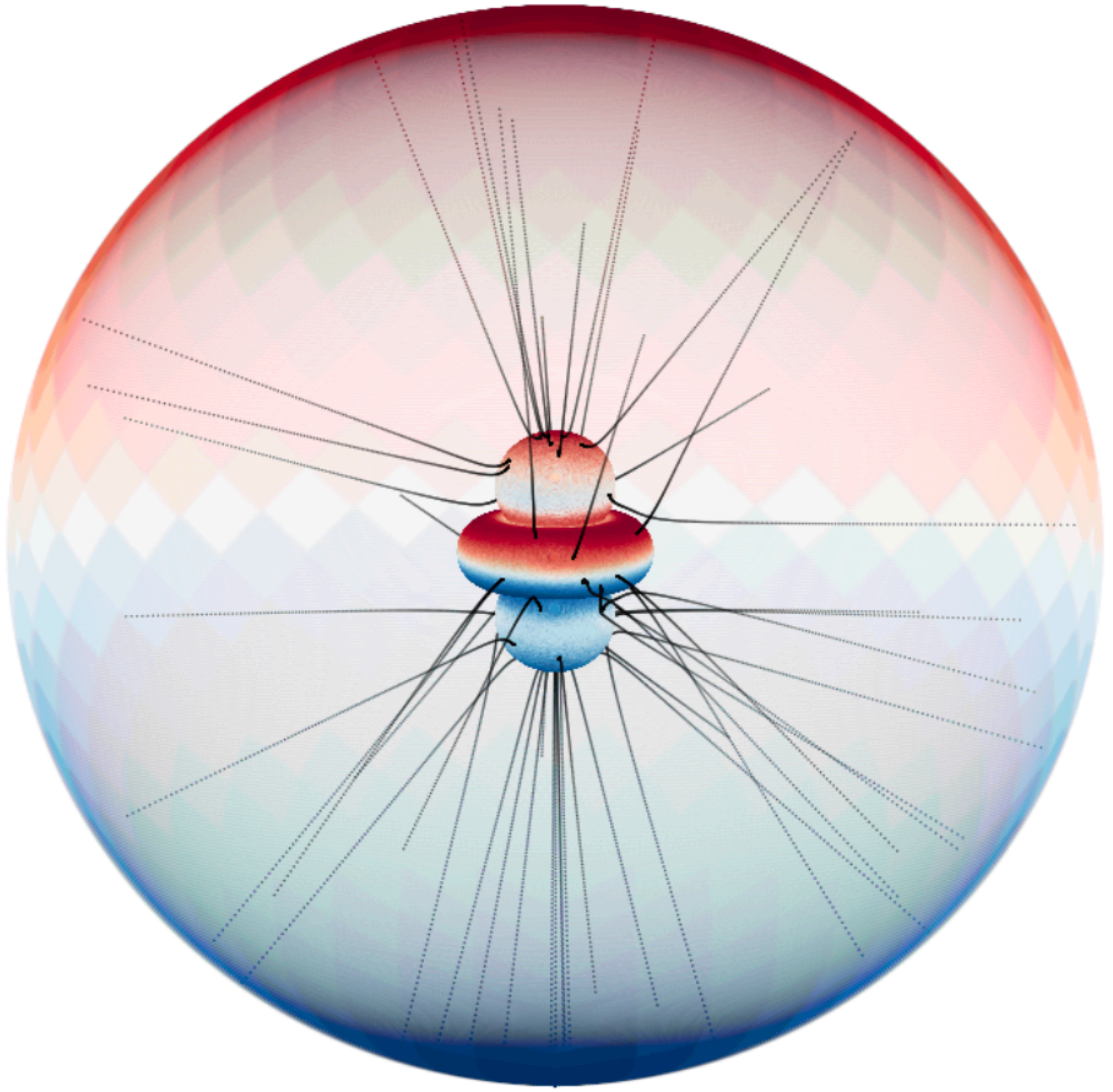
$$n_{\mathrm{GJ}}(\mathbf{r}_{\mathrm{NS}}) = \frac{2\boldsymbol{\Omega}\cdot\mathbf{B}_{\mathrm{NS}}}{e}\frac{1}{1-\Omega^2 r^2 \sin^2\theta_{\mathrm{NS}}}$$

- Conversion probability

$$p = \frac{g_{a\gamma\gamma}^2 B^2}{2k\,|\,\omega_p'\,|}\frac{\pi m_a^5}{(k^2+m_a^2\sin^2\theta)^2}\sin^2\theta$$

Hook et al 1804.03145

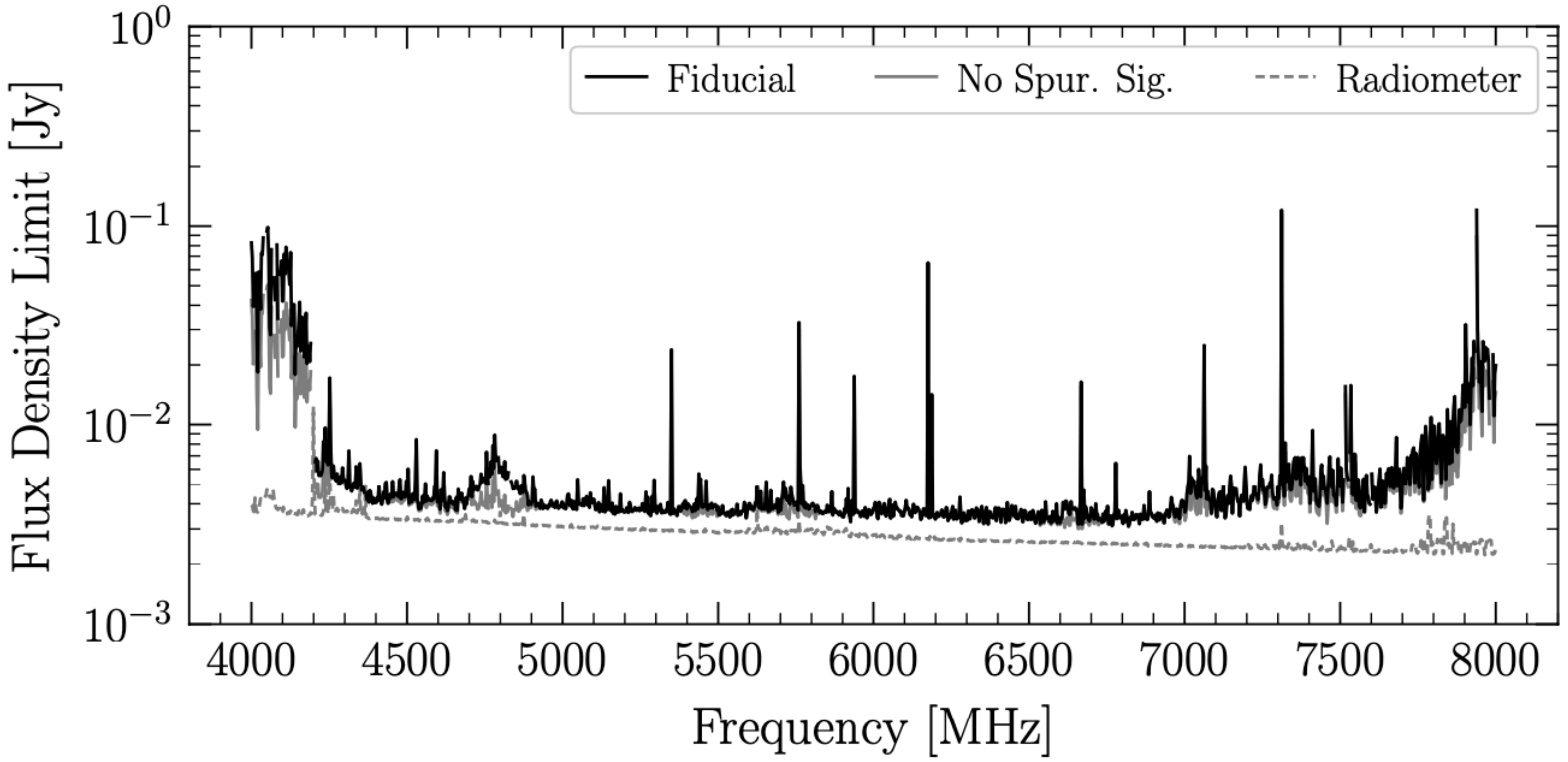
Millar et al 2107.07399

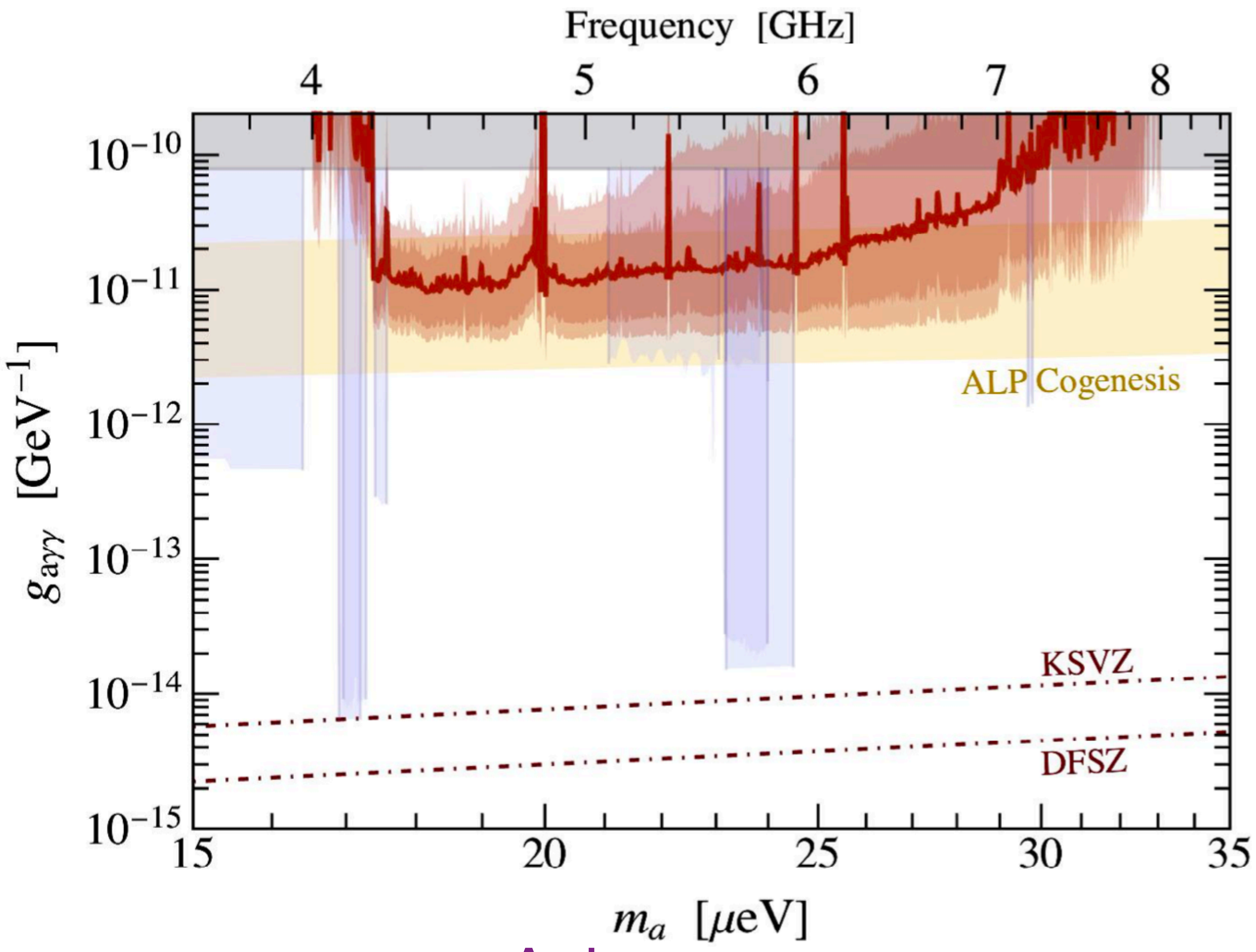


Witte et al 2104.07670

Radio Observation Constraint

Radio flux limit from the galactic center





Axion mass

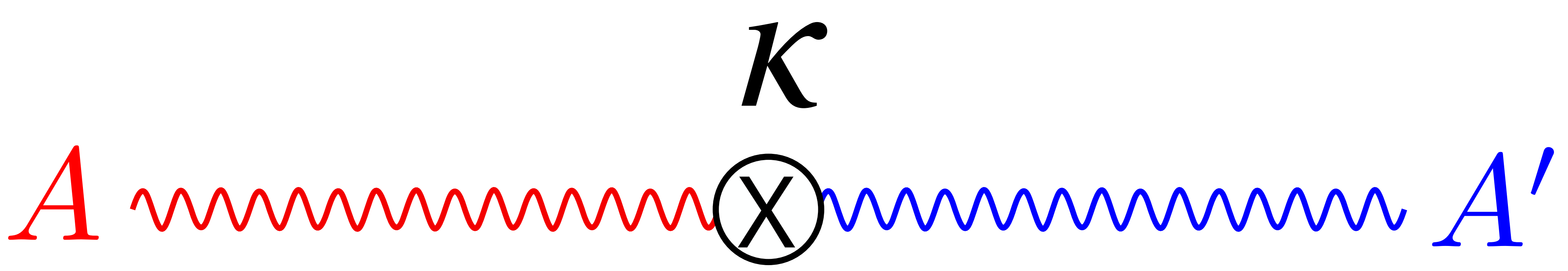
Foster et al 2202.08274

Dark Photon

Extra $U(1)$? $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

Pospelov' 2008
Ackerman, Buckley, Carrol, Kamionkowsk' 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\kappa F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - J^\mu A_\mu$$



$\omega^2 \sim k^2 + \omega_p^2$

$\omega^2 = k^2 + m_{A'}^2$

Resonant Dark Photon Conversion

- Resonant conversion from dark photon to photon in the magnetosphere of a neutron star when $m_{A'} \sim \omega_p$

No magnetic field need!

- Redefine $A_\mu \to A_\mu + \kappa A'_\mu$ to remove the mixing,

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - (A_\mu + \kappa A'_\mu)J^\mu$$

- Equation of motion

$$(\omega^2 + \nabla^2)\boldsymbol{A} - \nabla(\nabla \cdot \boldsymbol{A}) + \omega^2 (\boxed{\boldsymbol{\chi}^p} + \boxed{\boldsymbol{\chi}^{\mathrm{vac}}}) \cdot (\boldsymbol{A} + \kappa \boldsymbol{A}') = 0$$
$$(\omega^2 + \nabla^2)\boldsymbol{A}' - m_{A'}^2 \boldsymbol{A}' + \kappa\omega^2(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\mathrm{vac}}) \cdot \boldsymbol{A} = 0$$

$$\left[\omega^2 + \partial_z^2 + \omega^2 \begin{pmatrix} \boldsymbol{\chi}^p + \boldsymbol{\chi}^{\mathrm{vac}} - \mathcal{D}^2 & \kappa(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\mathrm{vac}}) \\ \kappa(\boldsymbol{\chi}^p + \boldsymbol{\chi}^{\mathrm{vac}}) & -m_{A'}^2/\omega^2 \end{pmatrix}\right] \begin{pmatrix} \boldsymbol{A} \\ \boldsymbol{A}' \end{pmatrix} = 0$$

$$\boldsymbol{\epsilon} = 1 + \boldsymbol{\chi}^p = R_\theta^{yz} \cdot \begin{pmatrix} \varepsilon & ig & 0 \\ -ig & \varepsilon & 0 \\ 0 & 0 & \eta \end{pmatrix} \cdot R_{-\theta}^{yz}$$

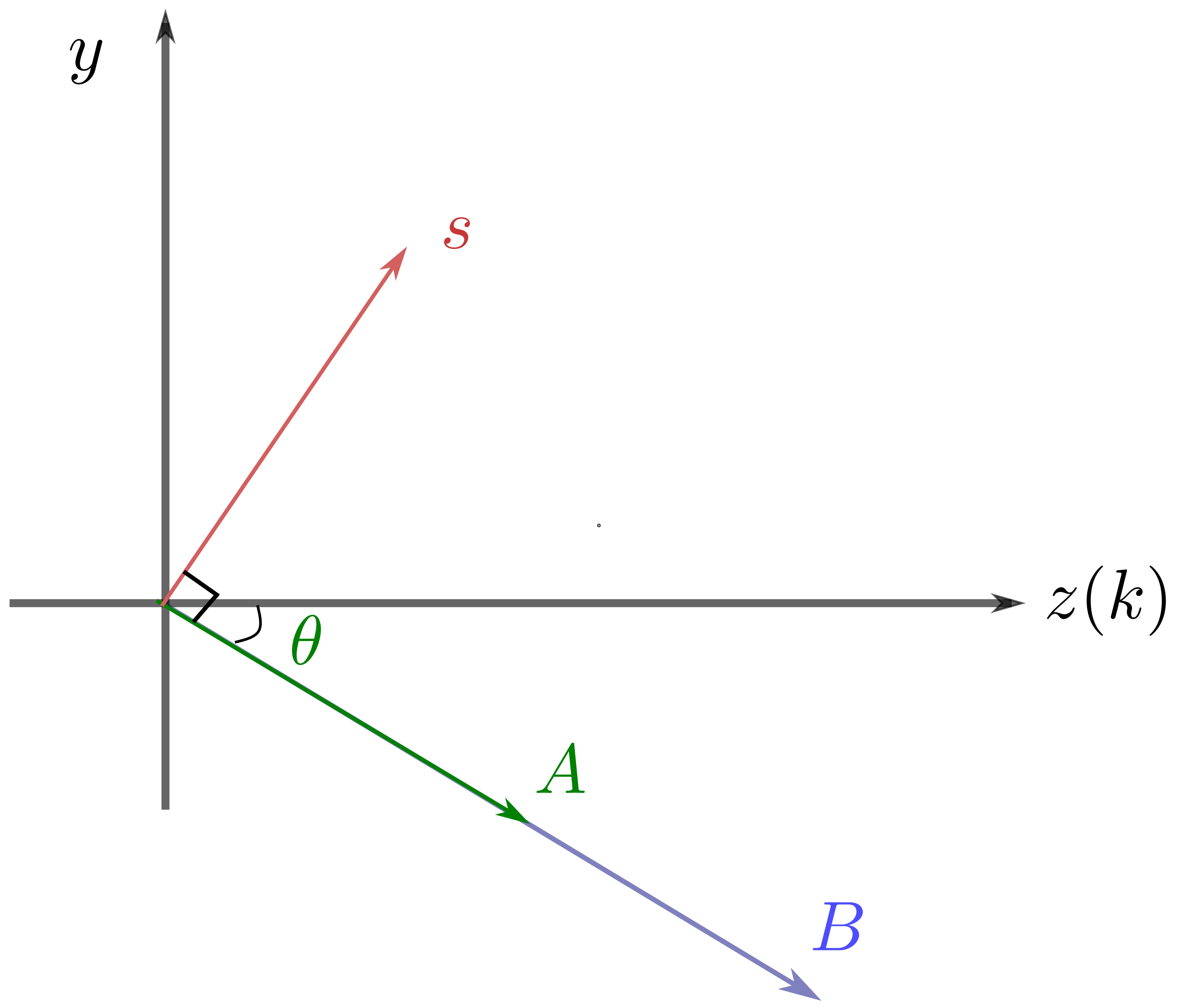
Resonant Dark Photon Conversion

$$(\omega^2 + \partial_z^2)A_x - \partial_x\partial_z A_z + \omega^2 a \bar{A}_x = 0\,,$$
$$(\omega^2 + \partial_z^2)A_y - \partial_y\partial_z A_z + \omega^2[(\eta' \sin^2\theta + a + q\sin\theta^2)\bar{A}_y - (\eta' + q)\cos\theta\sin\theta\bar{A}_z] = 0\,,$$
$$\omega^2 A_z - \partial_x\partial_z A_x - \partial_y\partial_z A_y + \omega^2[-(\eta' + q)\cos\theta\sin\theta\bar{A}_y + (\eta'\cos^2\theta + a + q\cos^2\theta)\bar{A}_z] = 0\,.$$

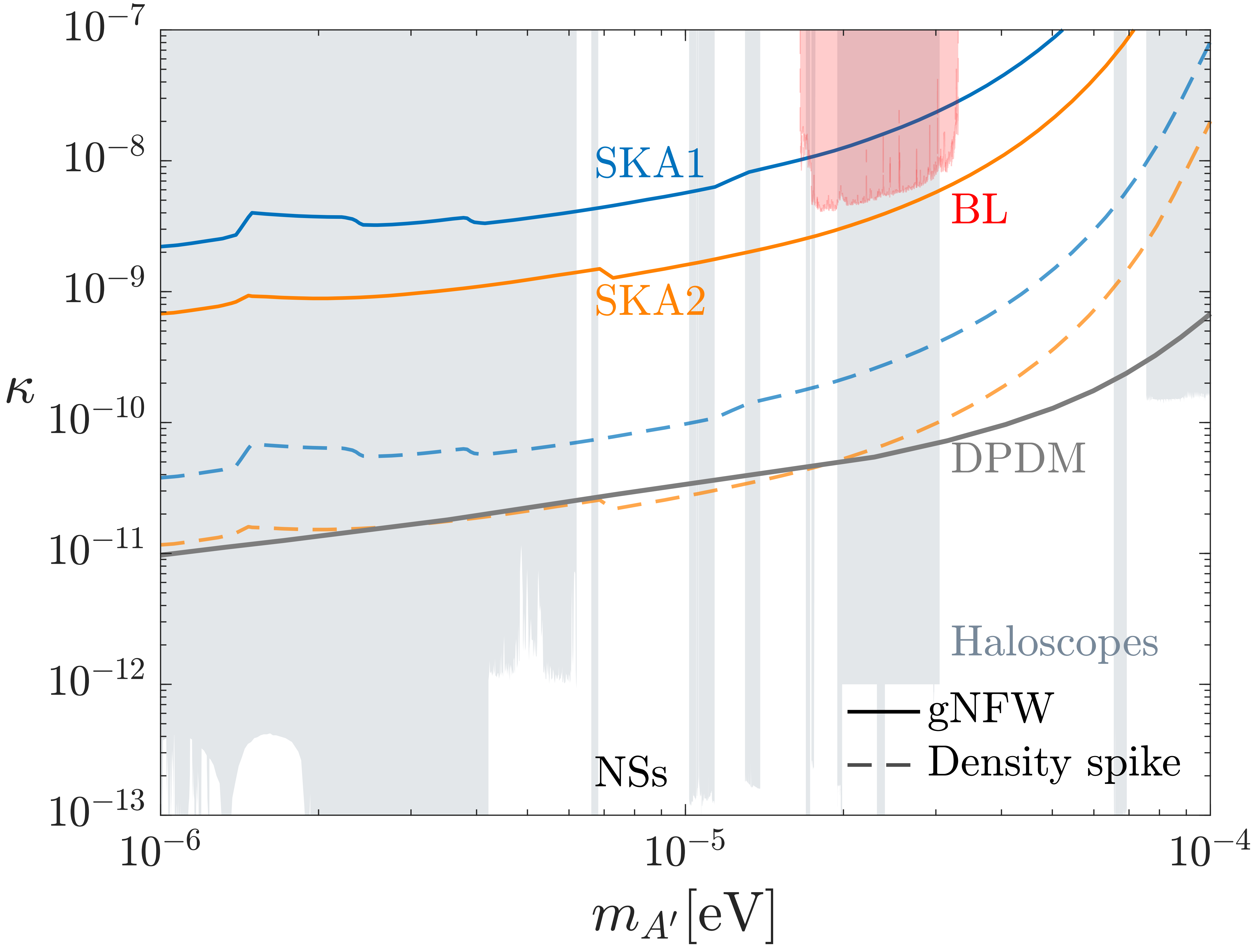
- Conversion probability

$$p \simeq \frac{|\tilde{A}_y|^2 + |\tilde{A}_z|^2}{|\tilde{A}'_x|^2 + |\tilde{A}'_y|^2 + |\tilde{A}'_z|^2} \simeq \frac{\pi\kappa^2\omega_p^3(m_{A'}^2\cos\theta - \omega_p^2\sin^3\theta)^2}{6km_{A'}^4\omega'_p\sin^2\theta}$$

- The converted photon has both transverse and longitudinal polarizations, and evolves in the direction that is perpendicular to the magnetic field



Sensitivities for Galactic Center Signals



Kinetic Mixing

Collection of neutron stars

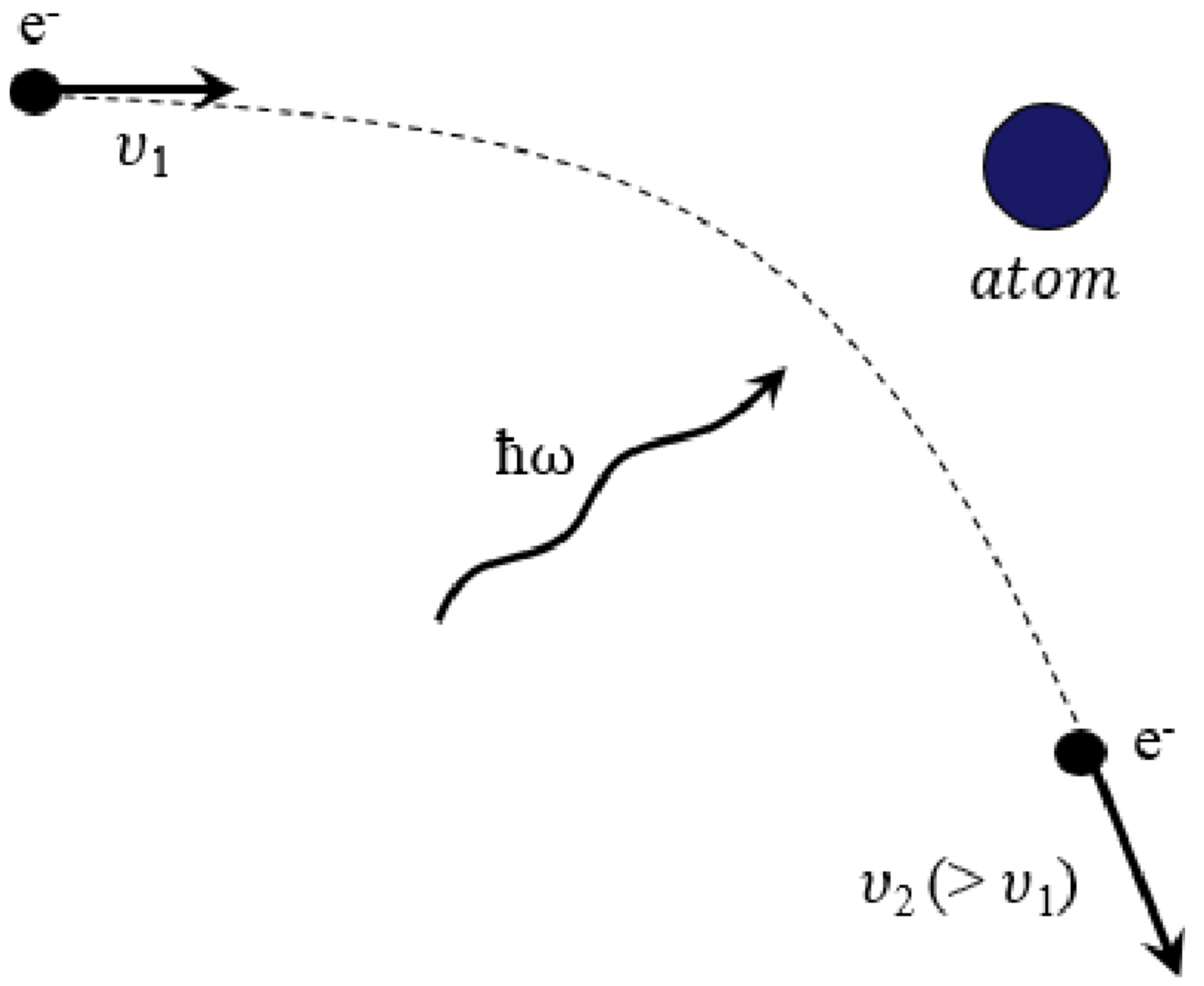
Dark Photon Mass

Edward Hardy, **NS**, 2212.09756

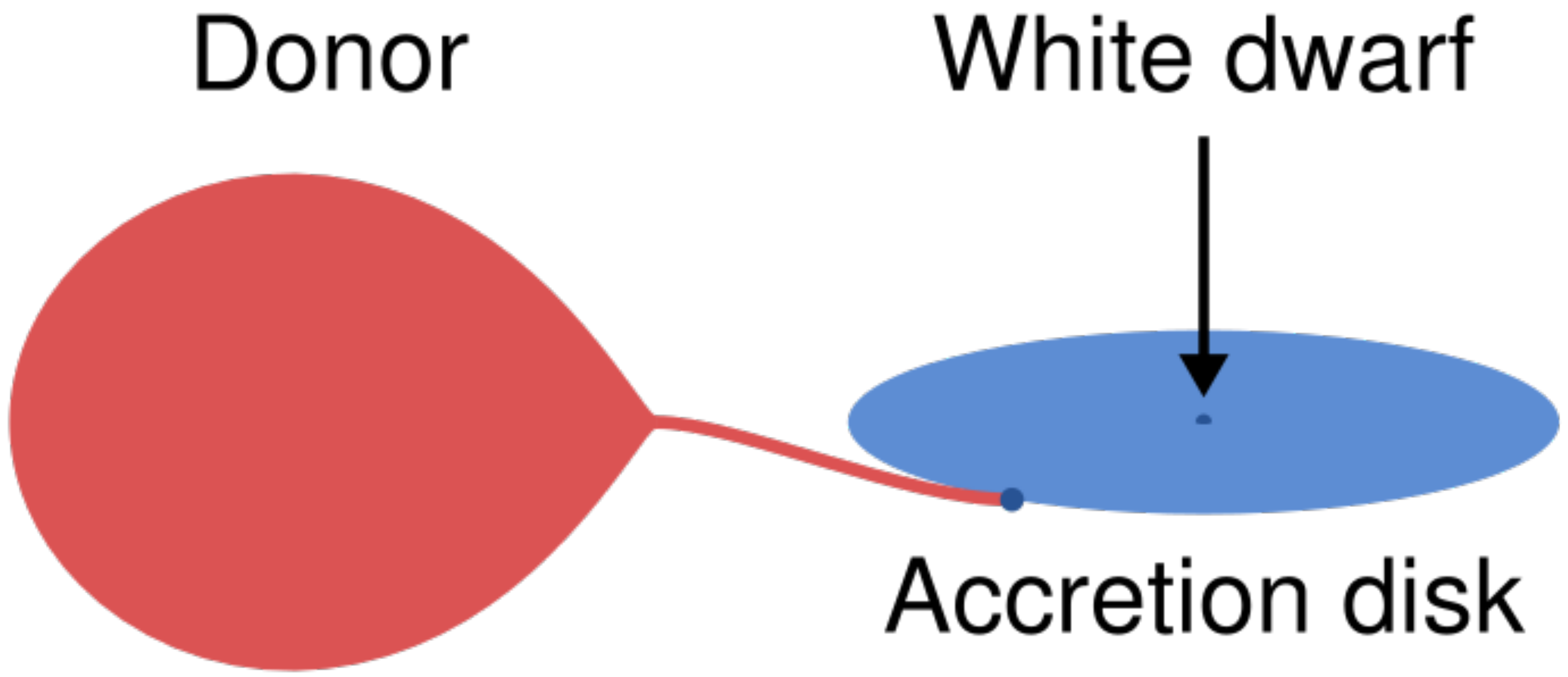
Criteria for Strong Conversion

- Strong magnetic field is NOT required
- Dense plasma ⇒ Larger dark photon mass
- High temperature ⇒ Less Inverse Bremsstrahlung absorption

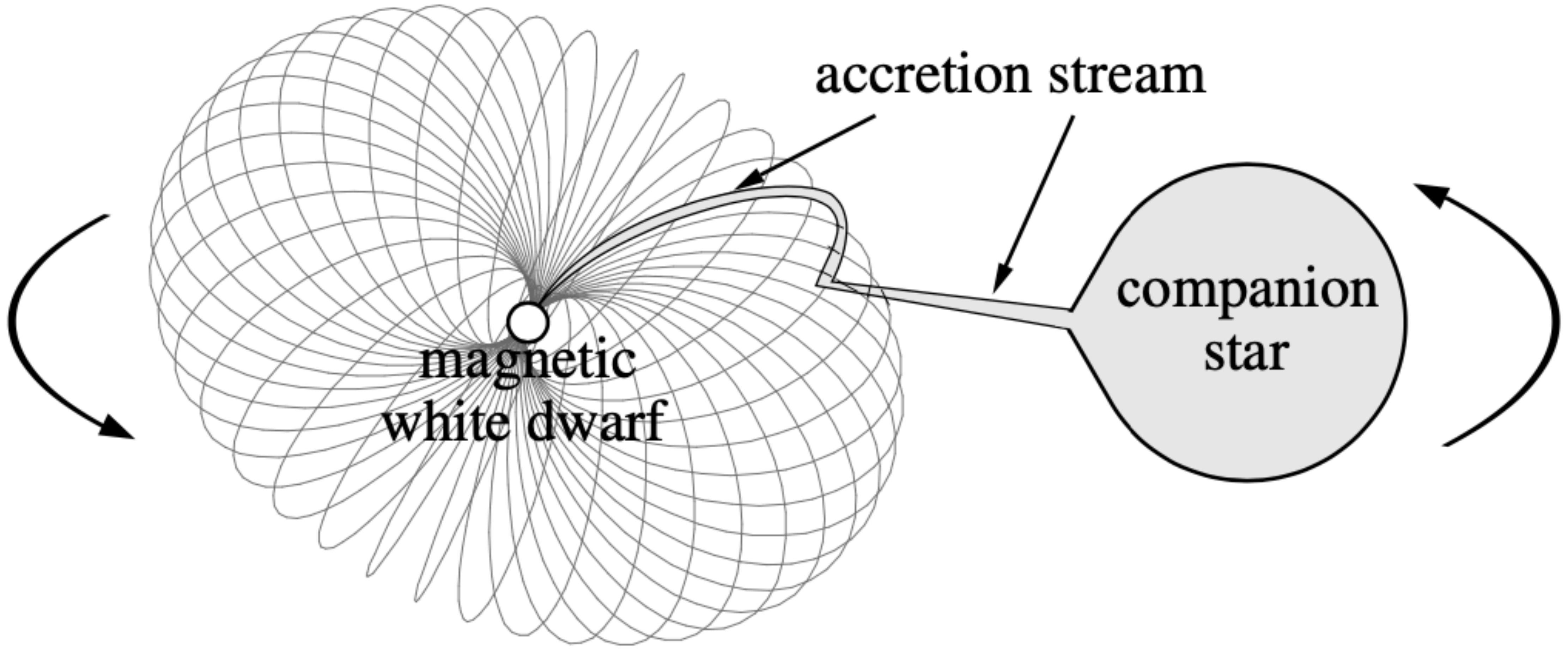
$$\Gamma_{\mathrm{IB}} = \frac{8\pi\alpha^3 n_e n_{\mathrm{ion}}}{3\omega^3 m_e^2}\sqrt{\frac{2\pi m_e}{T}}\ln\left(\frac{2T^2}{\omega_p^2}\right)\left(1-e^{-\omega/T}\right)$$



Accreting White Dwarf



Non-magnetic cataclysmic variable



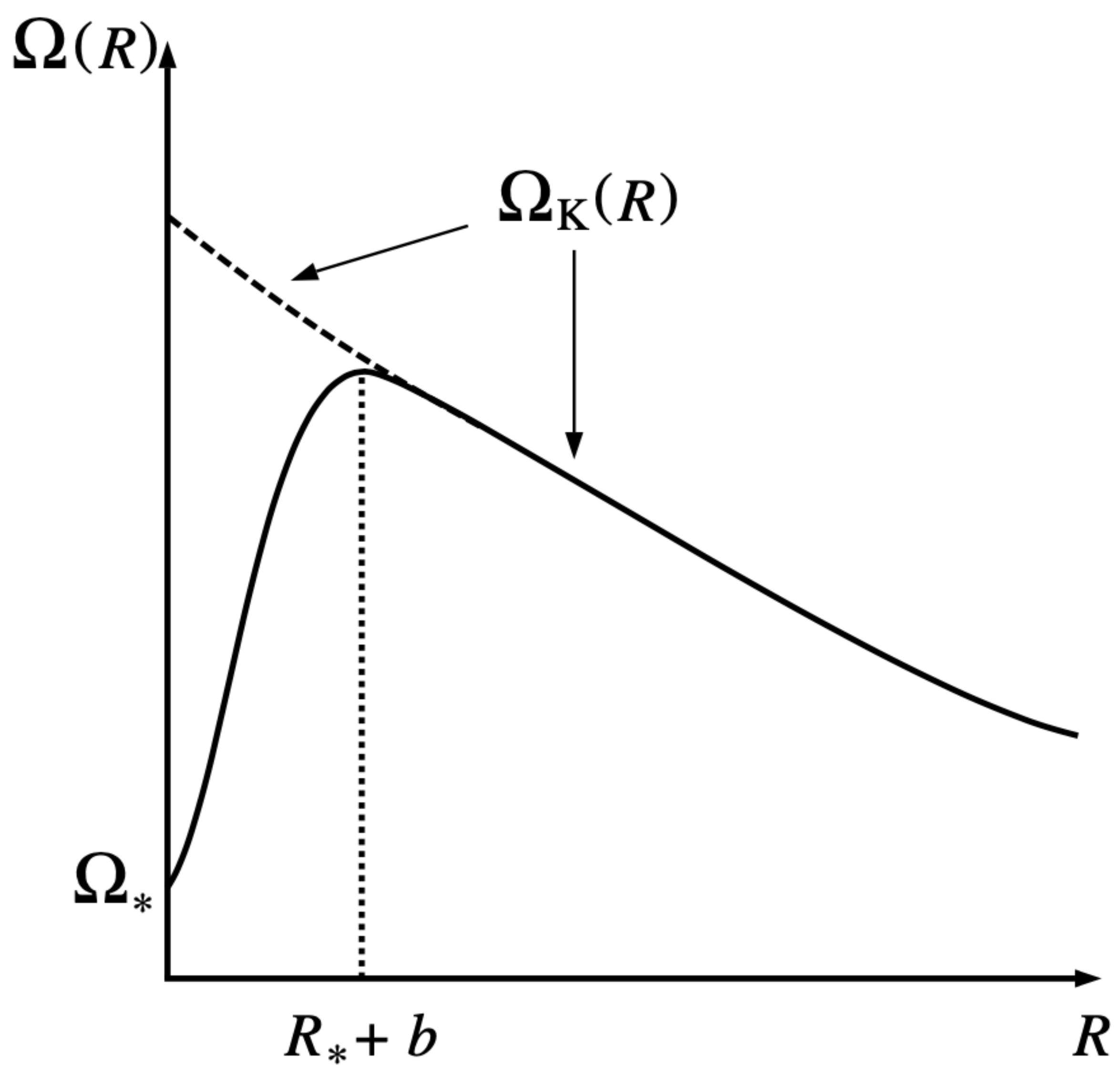
Magnetic cataclysmic variable

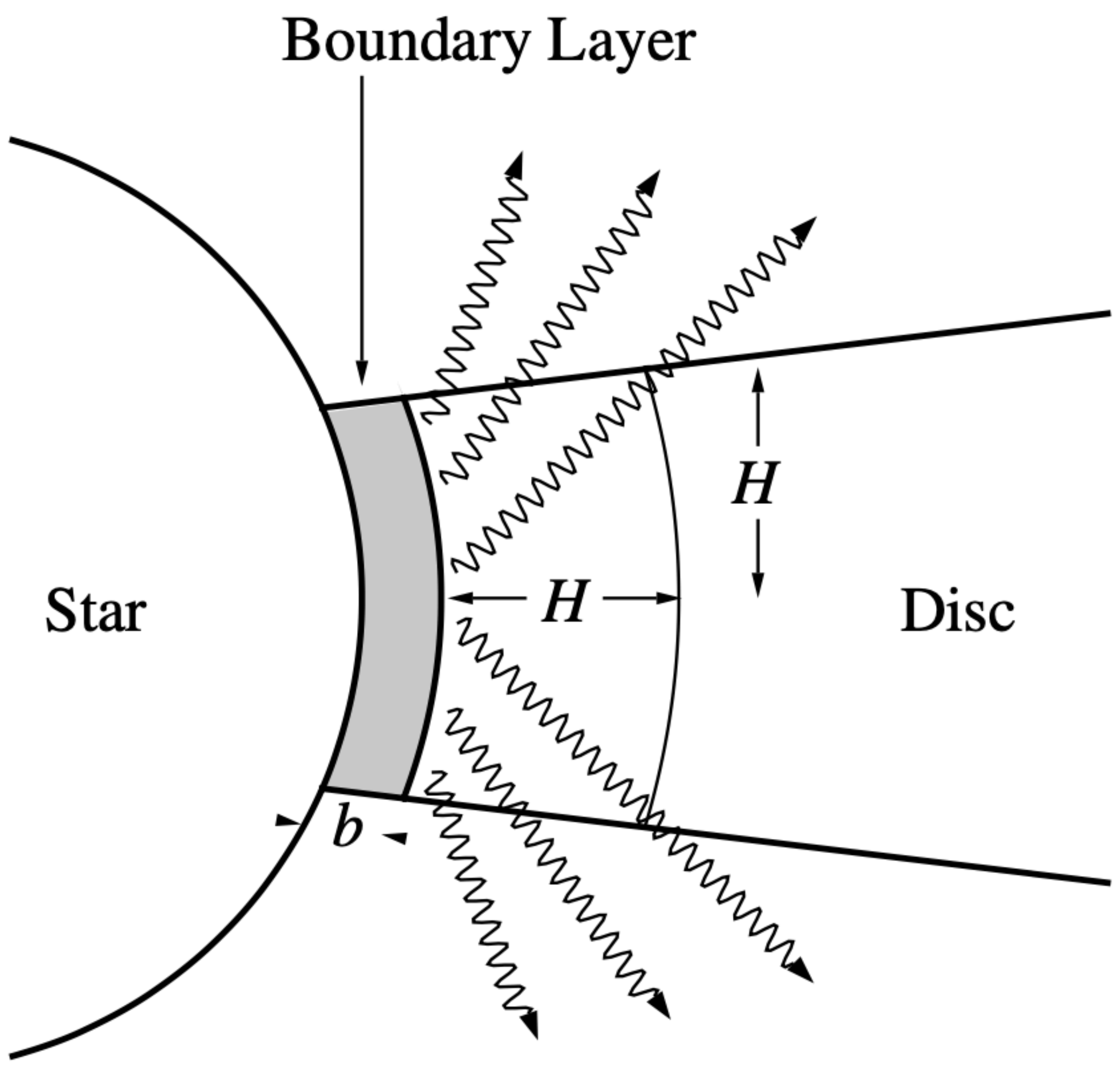
Non-magnetic Cataclysmic Variables

- The inner part of the disk decelerates and forms a hot boundary layer near the white dwarf surface

- High accretion rate ⇒ Black body emission from the optically-thick boundary layer

- Low accretion rate ⇒ Bremsstrahlung emission from the optically-thin boundary layer





Optically Thin Boundary Layer

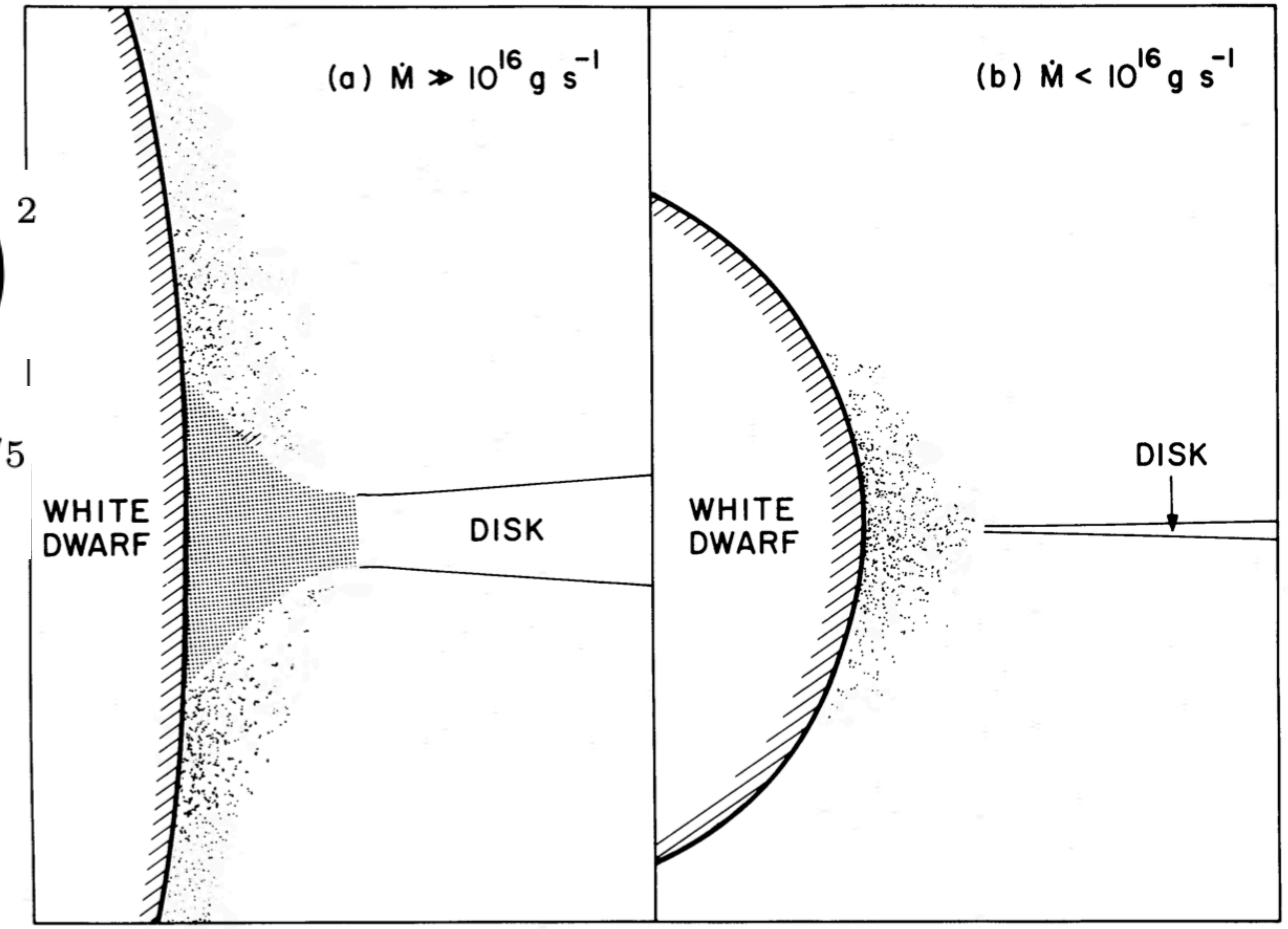
- Temperature $T \simeq \frac{3}{16}\frac{GM\mu m_p}{kR} \sim 10^8\ \mathrm{K}$

- Thickness $b \simeq 600\ \mathrm{km} \left(\frac{T_s}{10^8\ \mathrm{K}}\right)\left(\frac{M_{\mathrm{WD}}}{M_\odot}\right)\left(\frac{r_0}{0.01\ R_\odot}\right)^2$

- Height $H = 2\times 10^3\ \mathrm{km}\ \alpha_d^{-1/10}\dot{M}_{16}^{3/20}\left(\frac{r_0+b}{10^5\ \mathrm{km}}\right)^{9/8} f_r^{3/5}$

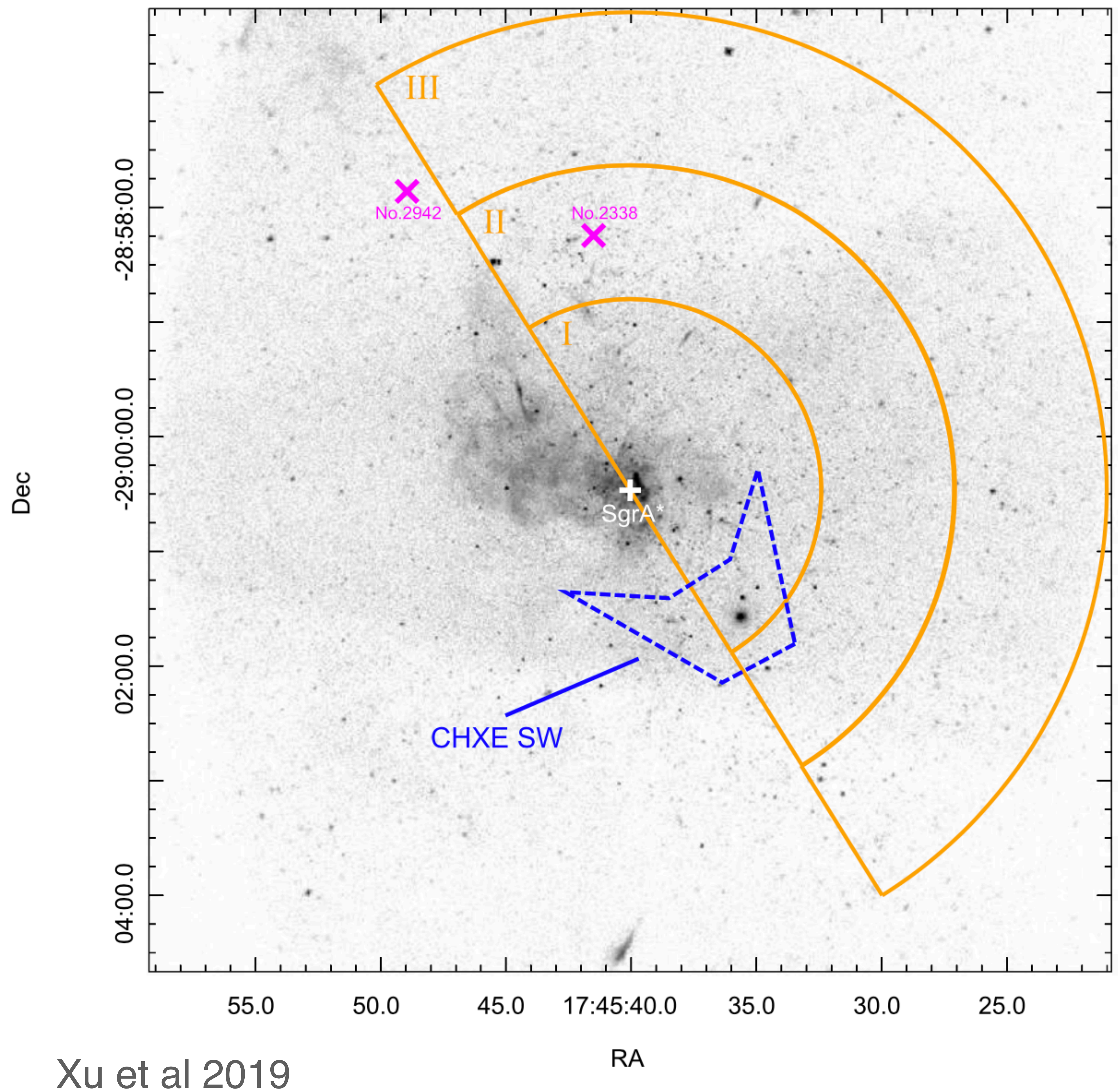
- Density profile

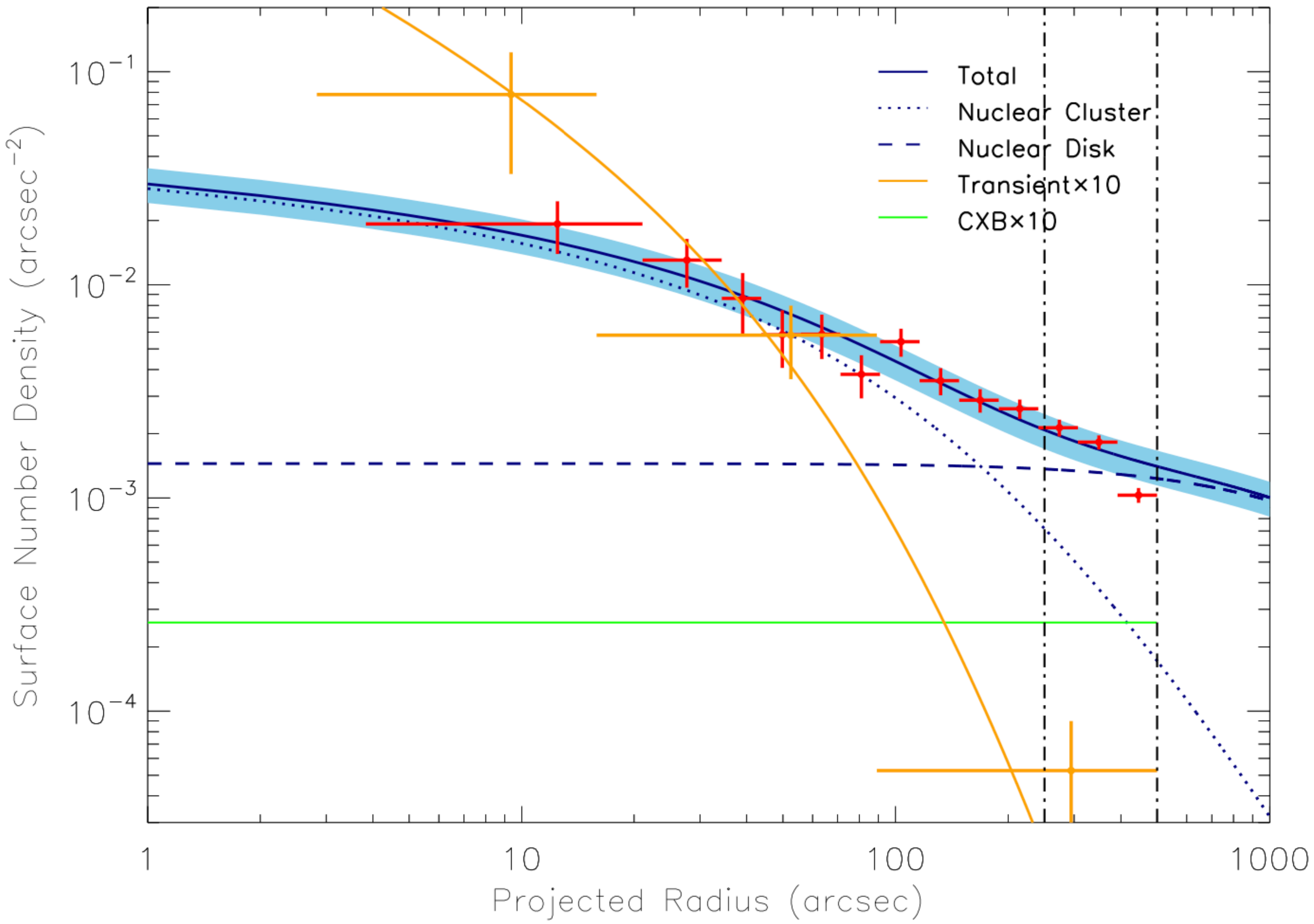
$$n_e = n_d \exp\left(1 - \frac{r-r_0}{b} - \frac{h^2}{H^2}\right)$$



Patterson et al 1985

X-ray Map in the Galactic Center

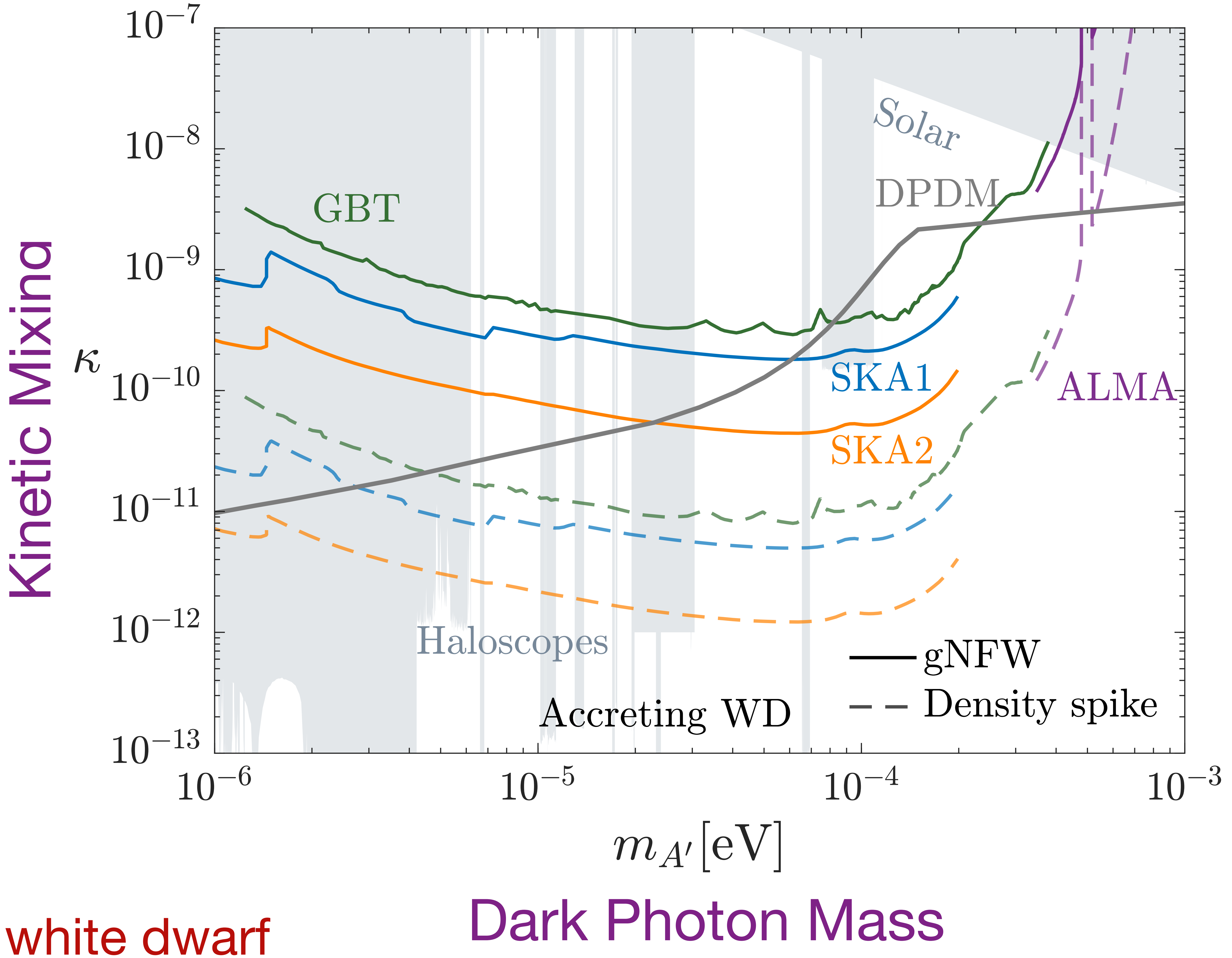




Xu et al 2019

Zhu et al 1802.05073

Sensitivities from Non-magnetic Cataclysmic Variable



Single accreting white dwarf

Edward Hardy, **NS**, 2212.09756

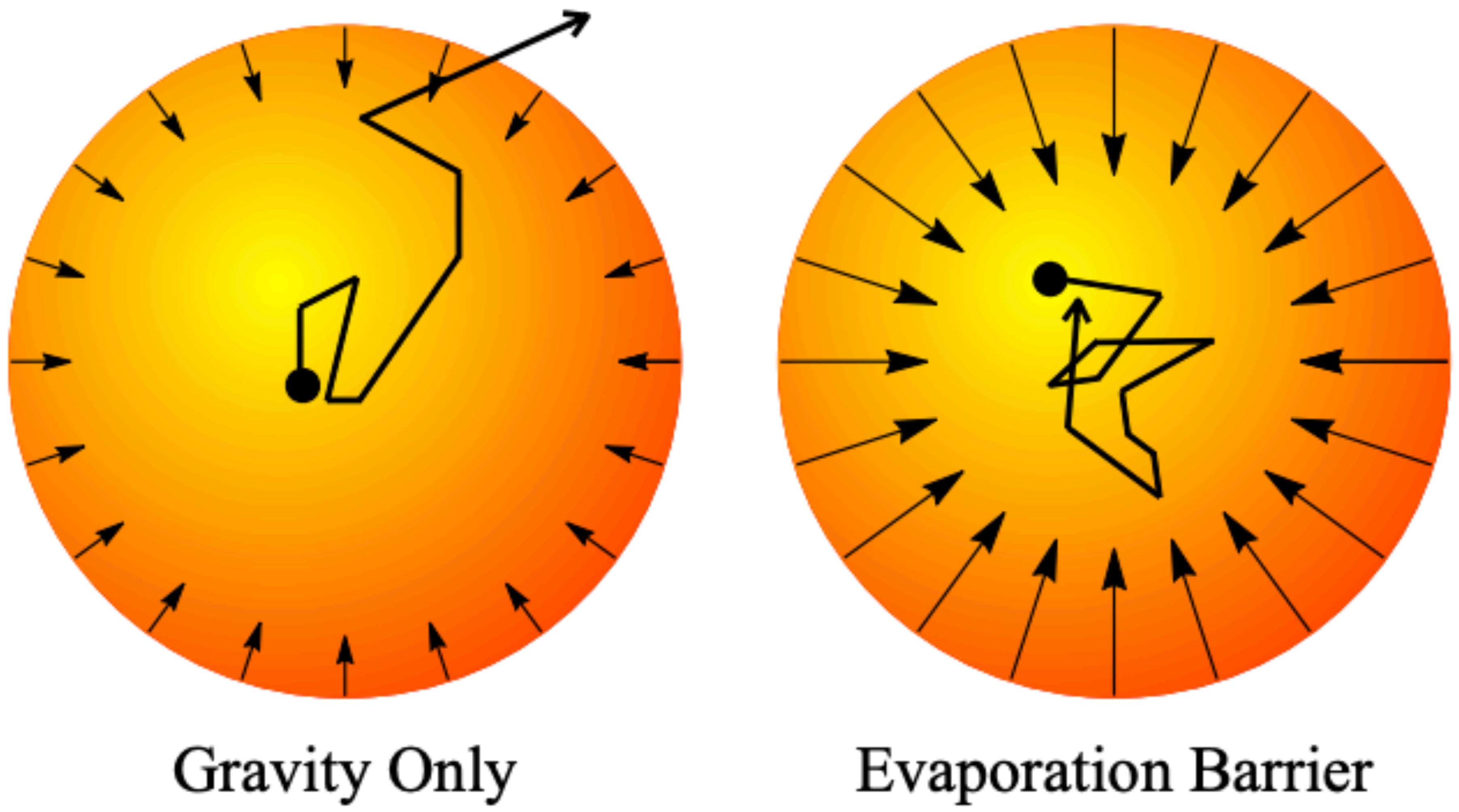
Summary

- Dark matter accumulation and Earth heating

- Dark photon conversion in celestial plasma

Future Directions

- Dark matter annihilation to neutrinos
- Dark matter-electron scattering, stay tuned
- Special types of interactions   Acevedo et al 2303.01516
- Full MC including annihilation and evaporation
- Direct detection of thermalized dark matter   Das et al 2210.09313



Future Directions

- Signals from compact star and dark photon star encounters

Gorghetto et al 2203.10100

- Magnetic cataclysmic variable, accreting neutron star and black holes

- Axion signal from such systems

Thank you!

Back up

Dark Photon

Extra $U(1)$? $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

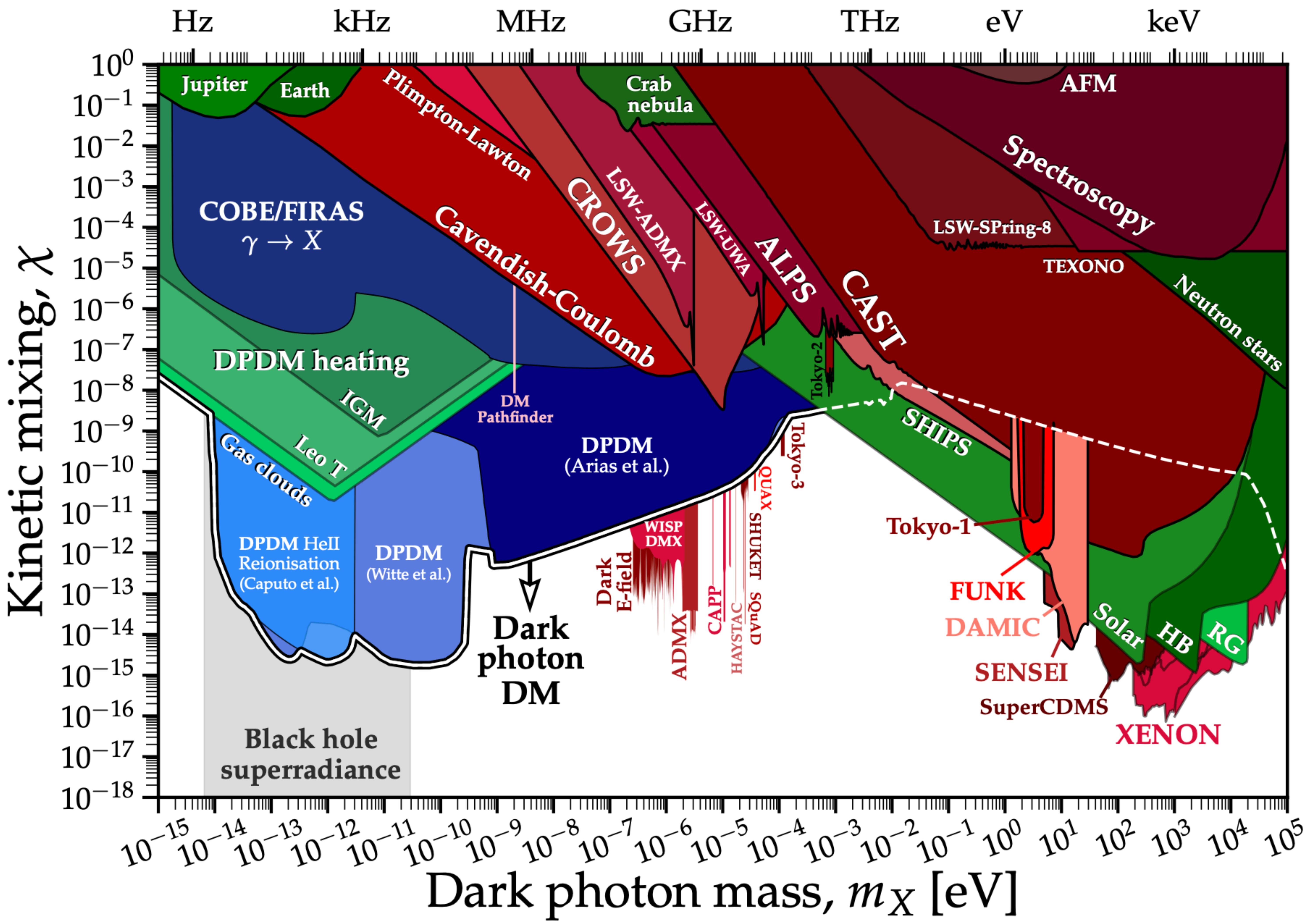
$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\kappa F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - J^\mu A_\mu$$

- Heavy states charged both SM and $U(1)'$
- String compactifications
- Production through misalignment, inflationary perturbation, etc

Pospelov' 2008
Ackerman, Buckley, Carrol, Kamionkowsk' 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

Graham et al 1504.02102

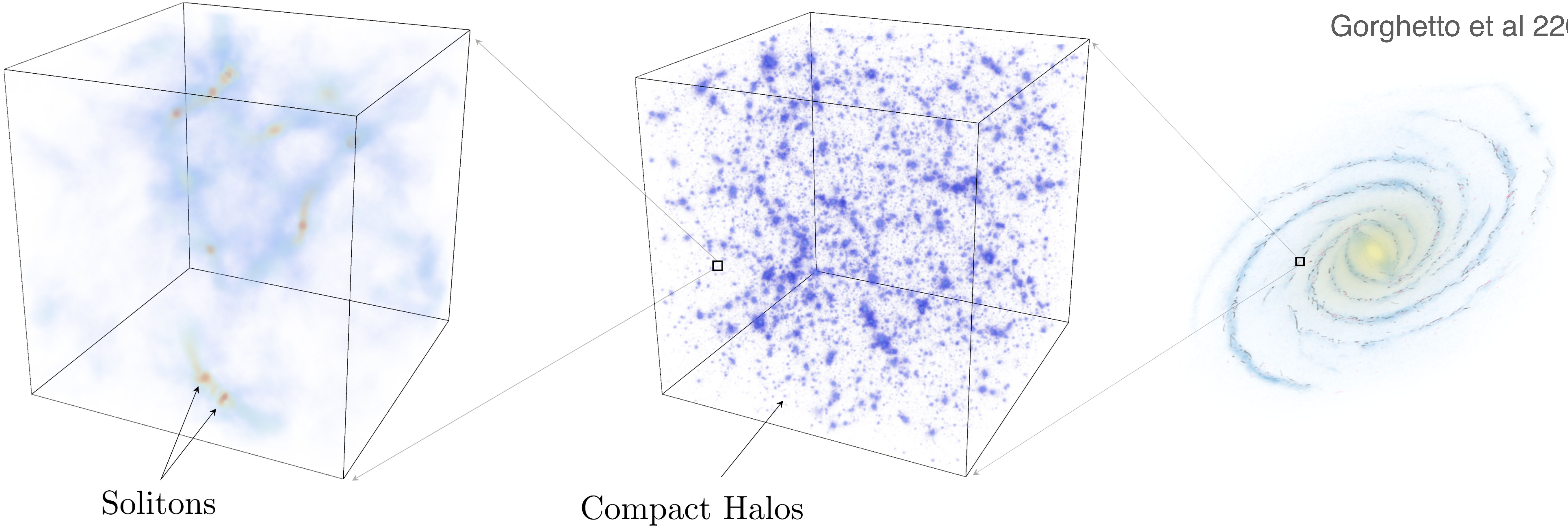
Dark Photon Constraints



Caputo et al 2105.04565

Dark Photon Stars

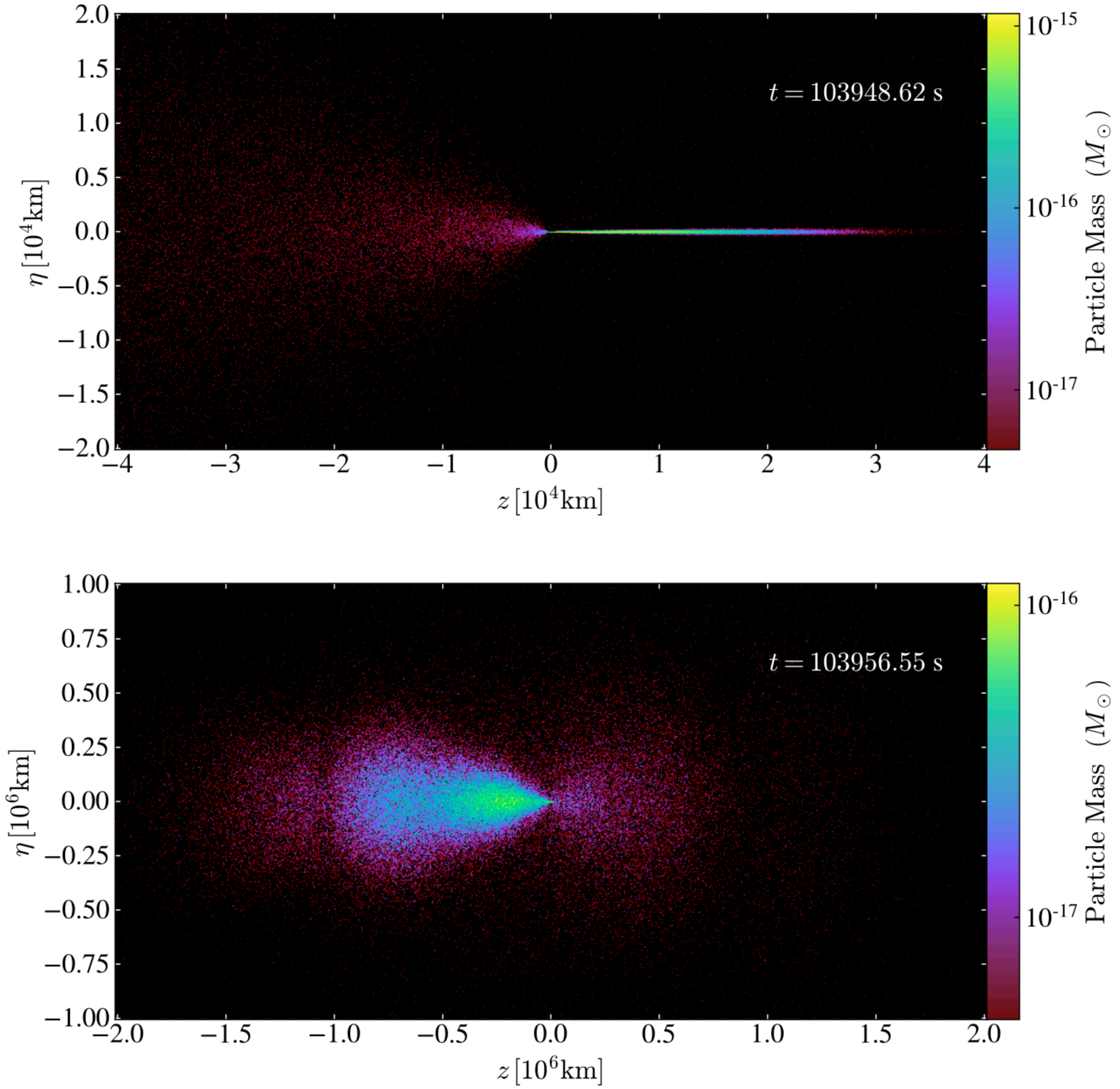
Gorghetto et al 2203.10100



$$\lambda_J = 4.6 \times 10^3 \ \mathrm{km} \left(\frac{\mathrm{eV}}{m_{A'}}\right)^{1/2} \left(\frac{M_J^{\mathrm{eq}}}{M}\right) \qquad M_J^{\mathrm{eq}} = 5.2 \times 10^{-23} M_\odot \left(\frac{\mathrm{eV}}{m_{A'}}\right)^{3/2}$$

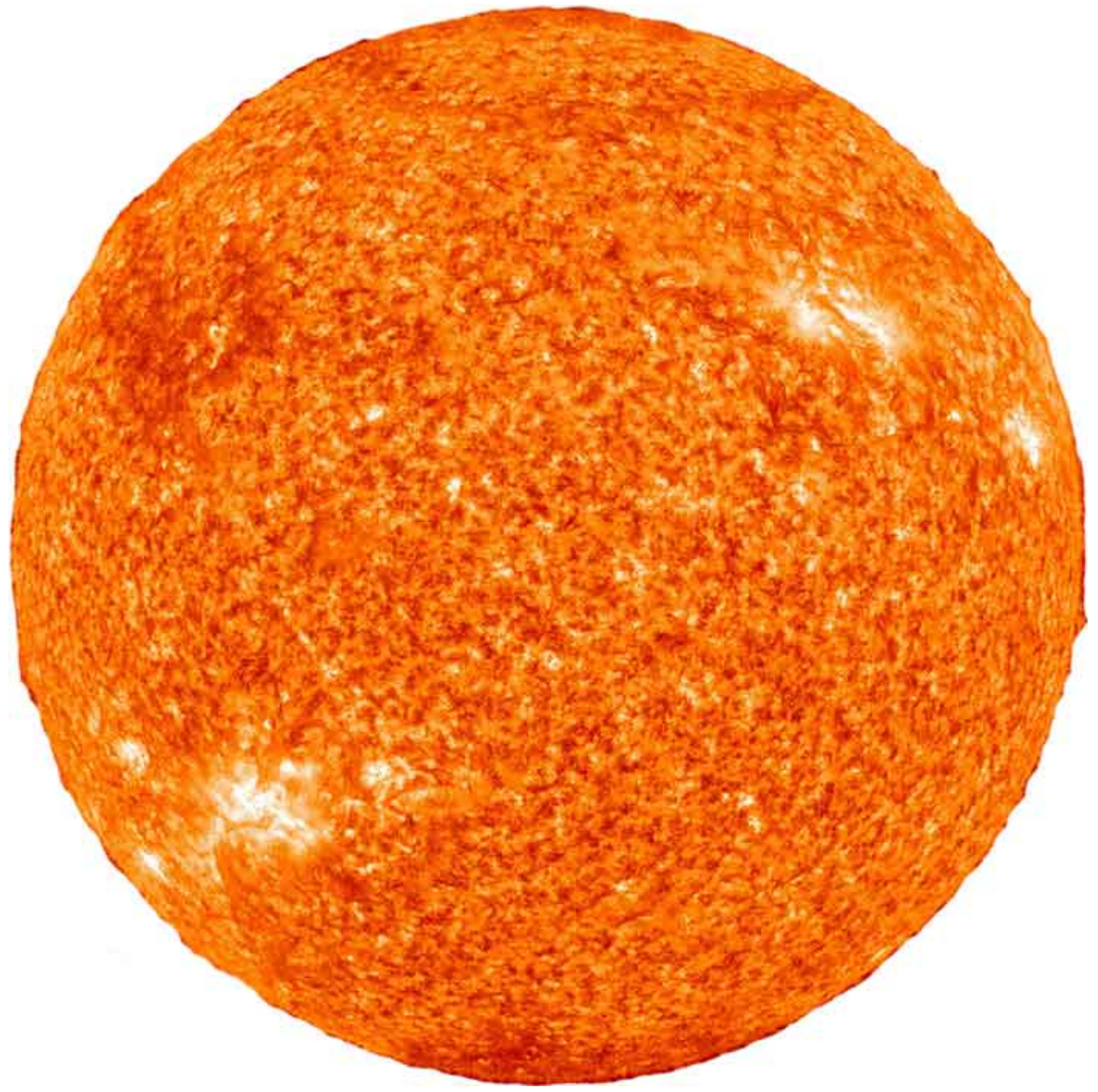
Signal from Dark Photon Star Encounters

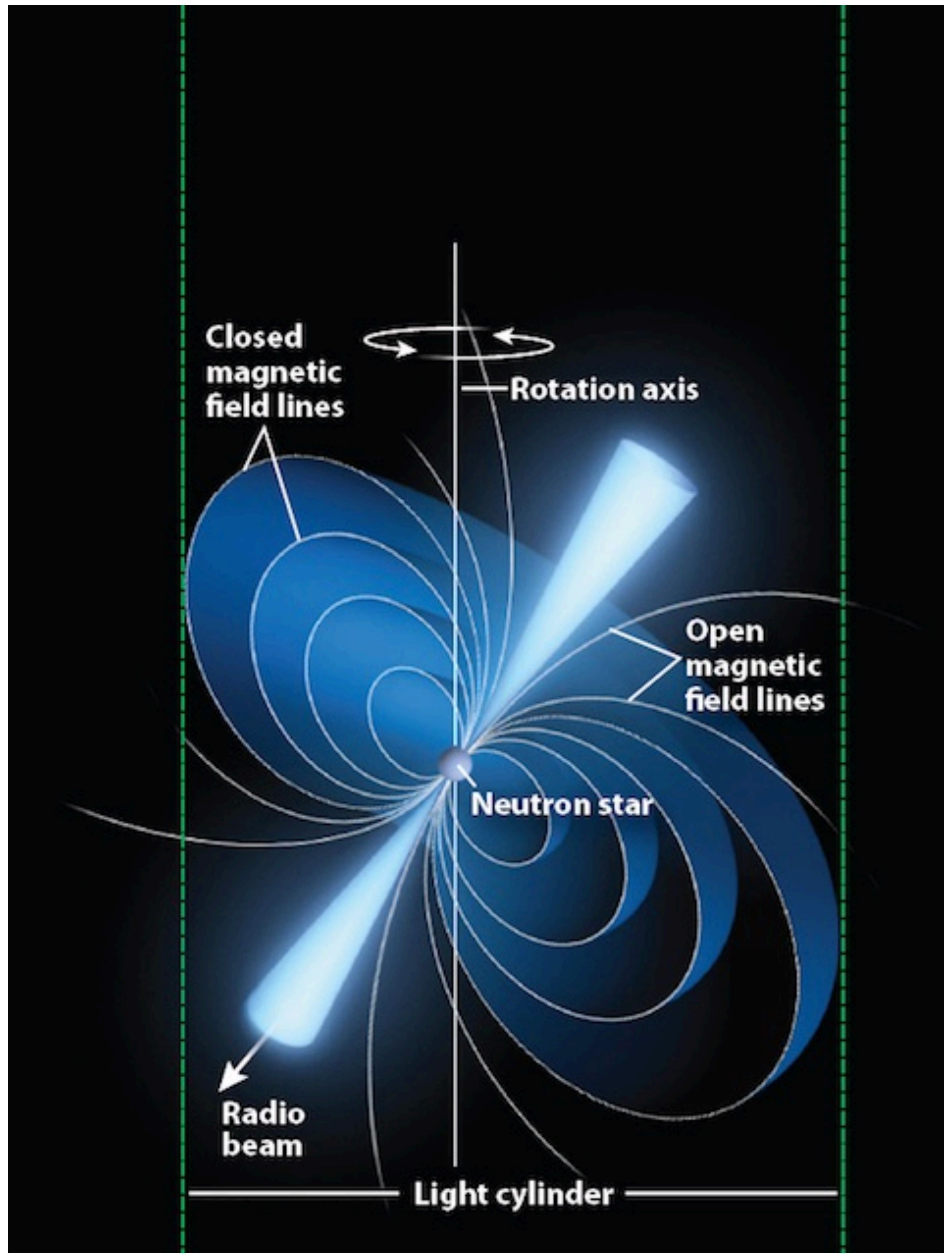
- Dark photon stars are tidally disrupted when colliding with neutron star or white dwarf
- Collision yields a transient signal which lasts a few days
- Density enhancement of around 10^6
- Small velocity dispersion
- More frequent encounter than Earth



Bai et al 2109.01222

Plasma frequencies





Solar Corona
$n_e \lesssim 10^{10}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 4 \times 10^{-6}\ \mathrm{eV}$
$f \lesssim \mathrm{GHz}$

Neutron Star Magnetosphere
$n_e \lesssim 10^{13}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 10^{-4}\ \mathrm{eV}$
$f \lesssim 24\ \mathrm{GHz}$

White Dwarf Corona
$n_e \lesssim 10^{17}\ \mathrm{cm}^{-3}$
$\omega_p \lesssim 10^{-2}\ \mathrm{eV}$
$f \lesssim 2400\ \mathrm{GHz}$

An et al 2010.15836

Signals from the Galactic Centre

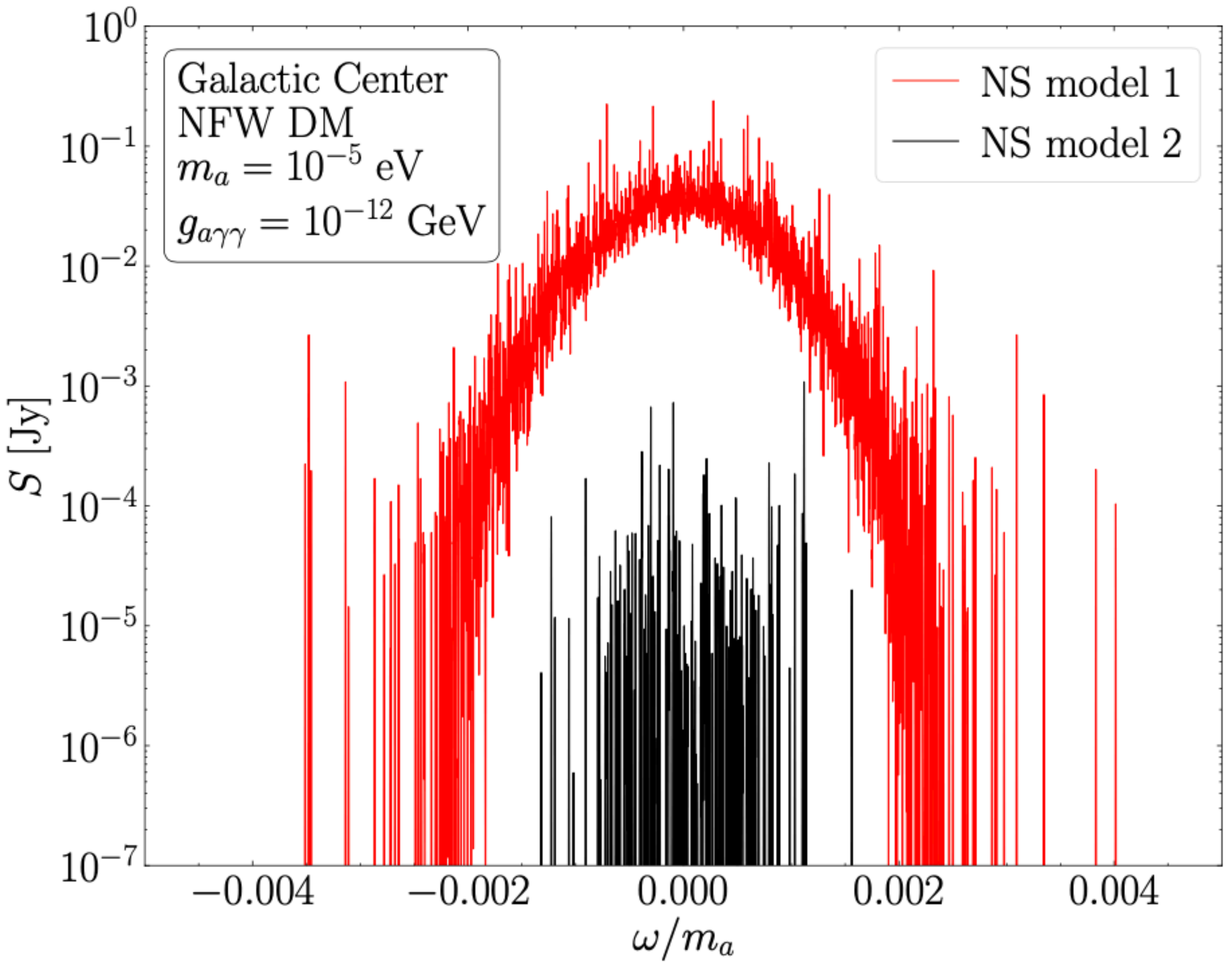
$$S_{\text{sig}} = \frac{1}{\mathscr{B}d^2}\frac{dP}{d\Omega} > S_{\text{min}}$$

Signals from a single star $\delta f/f \sim v^2 \sim 10^{-6}$

Signals from stellar population $\delta f/f \sim v \sim 10^{-3}$

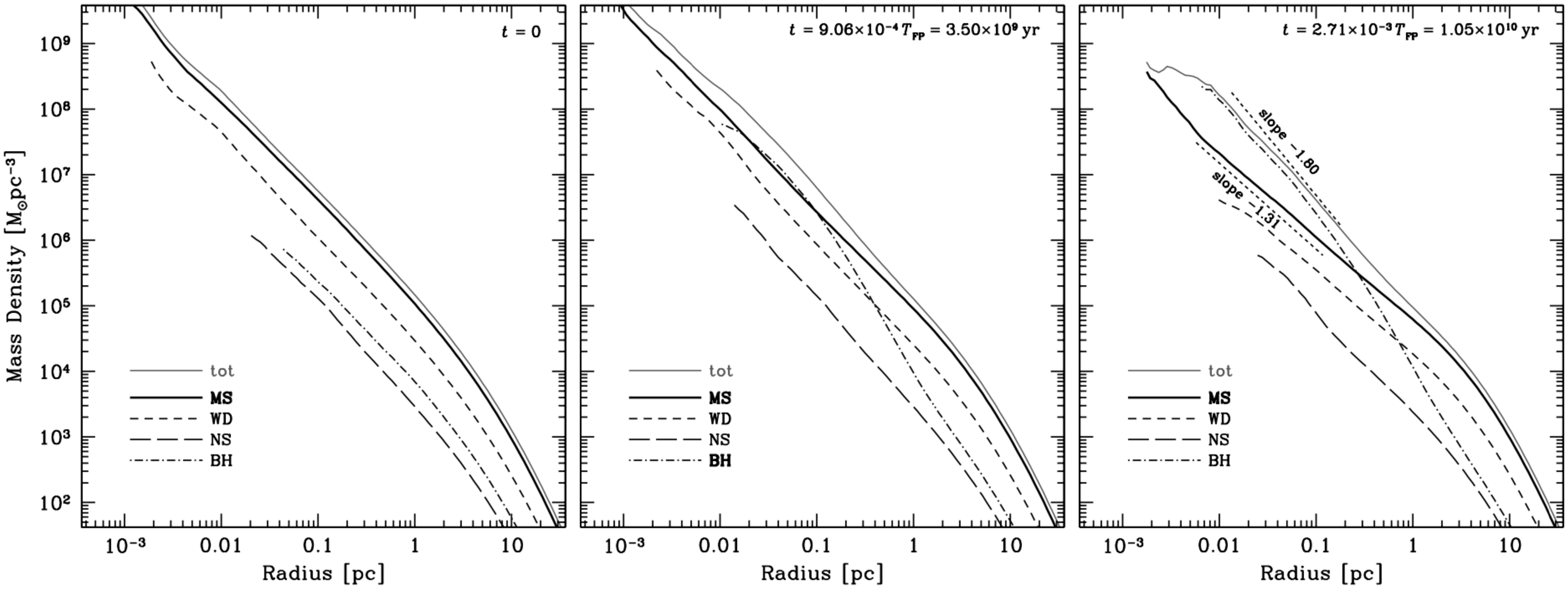
$$\omega_{\text{obs}} = \omega\sqrt{\frac{1 - v_{\text{l.o.s}}}{1 + v_{\text{l.o.s}}}}$$

Doppler shift can be important!



Safdi et al 1811.01020

Compact Stars in the Galactic Centre



Freitag et al 2006

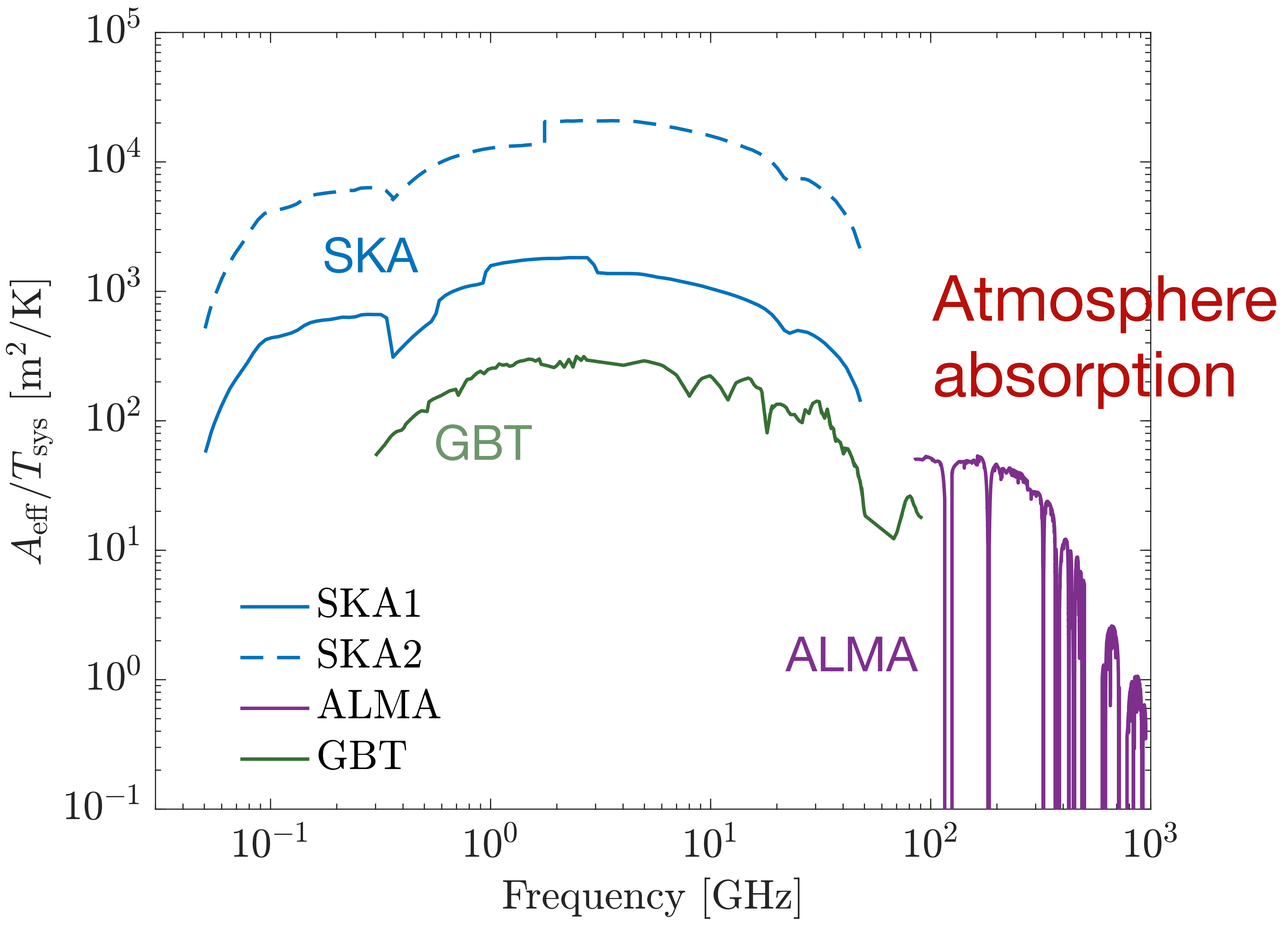
Radio Telescopes

Minimum detectable signal flux density

$$S_{\rm min} = \frac{\rm SEFD}{\eta\sqrt{n_{\rm pol}\mathscr{B}t_{\rm obs}}}$$

$$\mathrm{SEFD} = 2k_B\frac{T_{\rm sys}}{A_{\rm eff}} = 2.75\ \mathrm{Jy}\frac{1000\ \mathrm{m}^2/\mathrm{K}}{A_{\rm eff}/T_{\rm sys}}$$

$$S_{\rm sig} = \frac{1}{\mathscr{B}d^2}\frac{dP}{d\Omega} > S_{\rm min}$$



White Dwarf Atmosphere

Isotropic plasma ⇒ photon longitudinal polarization does not propagate, only transverse modes convert

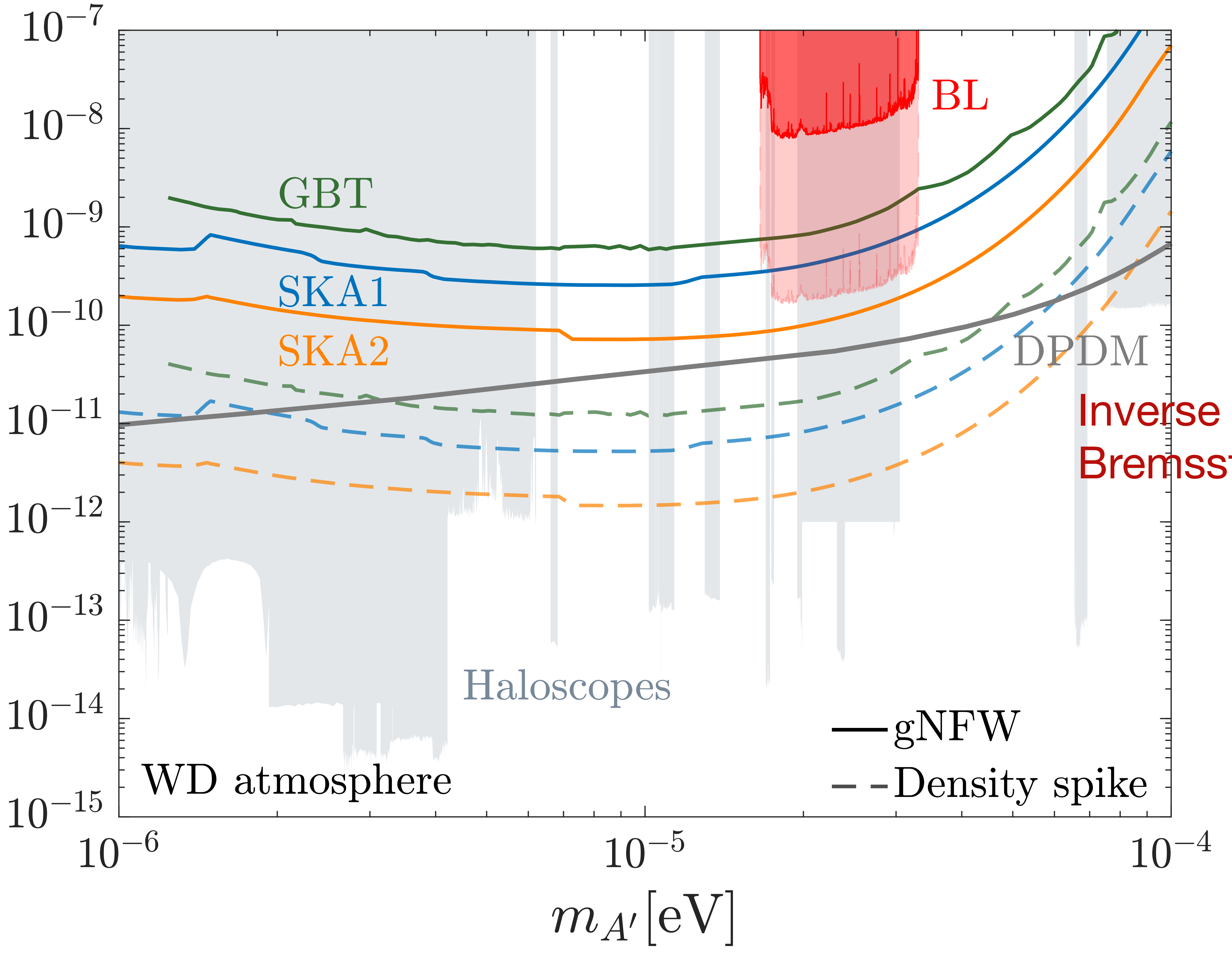
$$\left[-i\frac{d}{dr}+\frac{1}{2k}\begin{pmatrix} m_{A'}^2-\omega_p^2 & -\kappa\omega_p^2 \\ -\kappa\omega_p^2 & 0 \end{pmatrix}\right]\begin{pmatrix} \tilde{A} \\ \tilde{A}' \end{pmatrix}=0\,.$$

White Dwarf Atmosphere

- Pressure gradient balances gravity $l_a \simeq \frac{kT_a r_0^2}{GM_{\rm WD}\mu m_p} = 0.06\ \mathrm{km}\left(\frac{T_a}{10^4\ \mathrm{K}}\right)\left(\frac{M_{\rm WD}}{M_\odot}\right)\left(\frac{r_0}{0.01\ R_\odot}\right)^2$
- Exponential density profile $n_e(r) = n_0 e^{-\frac{r-r_0}{l_a}}$
- Conversion probability $p = \frac{2\pi}{3}\frac{\kappa^2 m_{A'}^2}{k} l_a$
- Radio emission power $\frac{d\mathcal{P}}{d\Omega} \simeq 2pr_c^2 \rho_{A'}(r_c) v_c$

$$T_a \sim 10^4 - 10^5\ \mathrm{K},\ n_0 \sim 10^{17}\ \mathrm{cm}^{-3}$$

Sensitivities from White Dwarf Atmosphere



Kinetic Mixing

Inverse Bremsstrahlung

Dark Photon Mass

Collection of white dwarfs

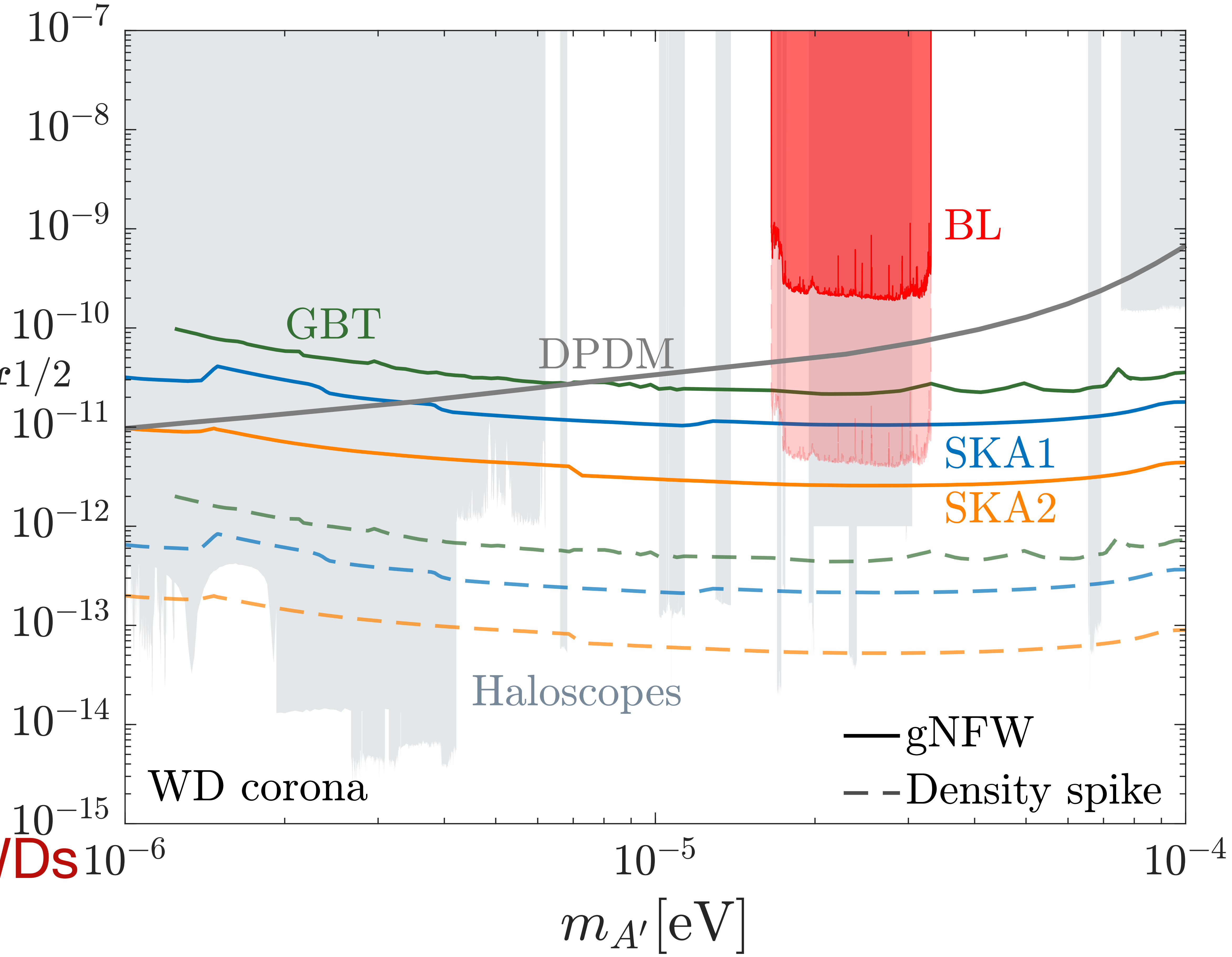
Edward Hardy, **NS**, 2212.09756

White Dwarf Corona?

- Higher temperature $10^6 - 10^7$ Kelvins $\Rightarrow$ less absorption
- Exponential density profile $n_e(r) = n_0 e^{-\frac{r - r_0}{l_a}}$
- No observational evidence for hot corona in isolated white dwarfs

$$T_a \sim 10^6 - 10^7 \text{ K}, n_0 \sim ?$$

Sensitivities from White Dwarf Corona

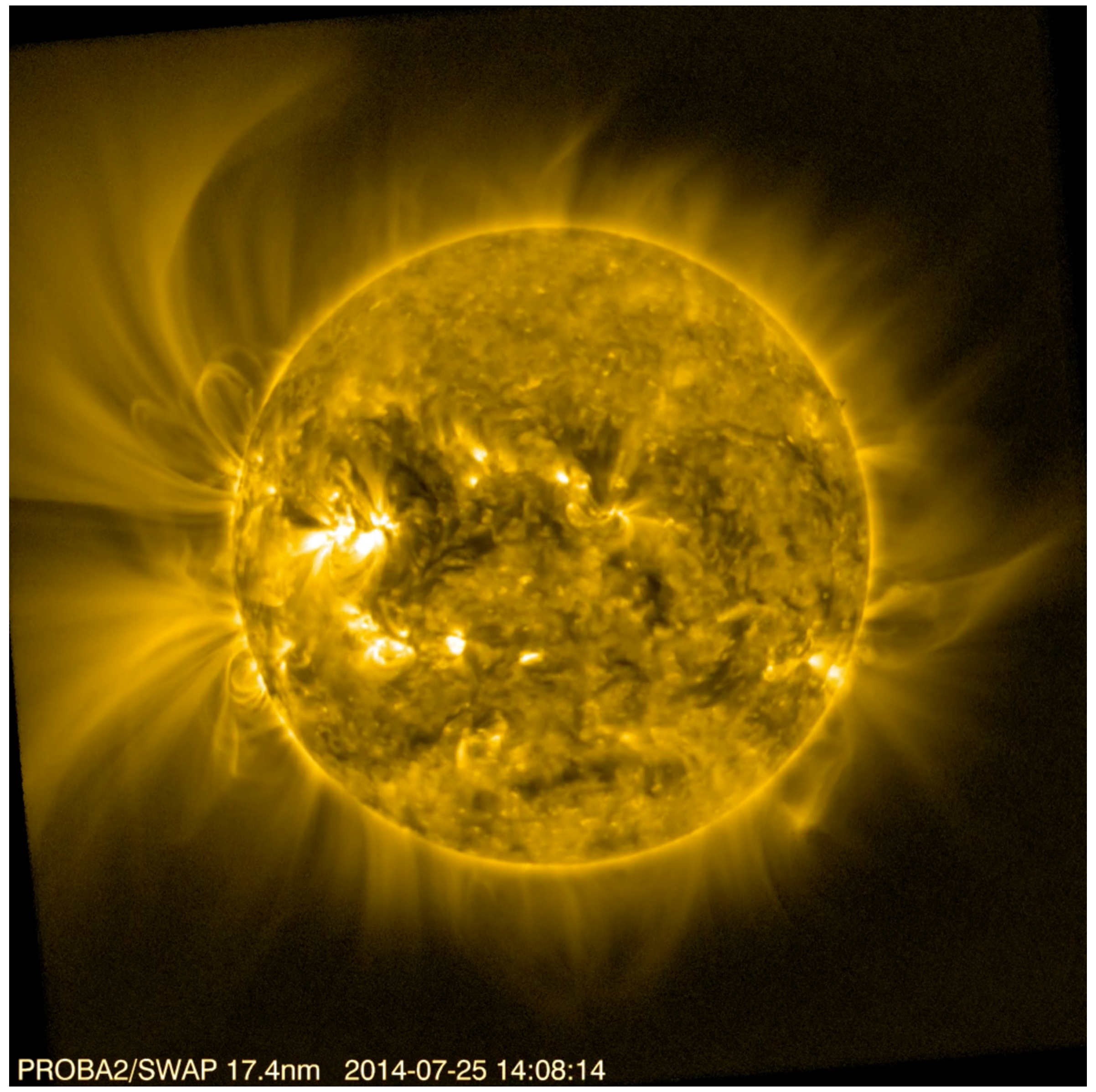


Kinetic Mixing

Fraction of WDs with corona

Dark Photon Mass

Collection of white dwarfs



Credit: ESA

Edward Hardy, **NS**, 2212.09756