

# Sino-Thai International Summer School on High Energy Physics and Astrophysics in 2026

## Overview of Dark Matter Candidates

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**July 15th, 2026**

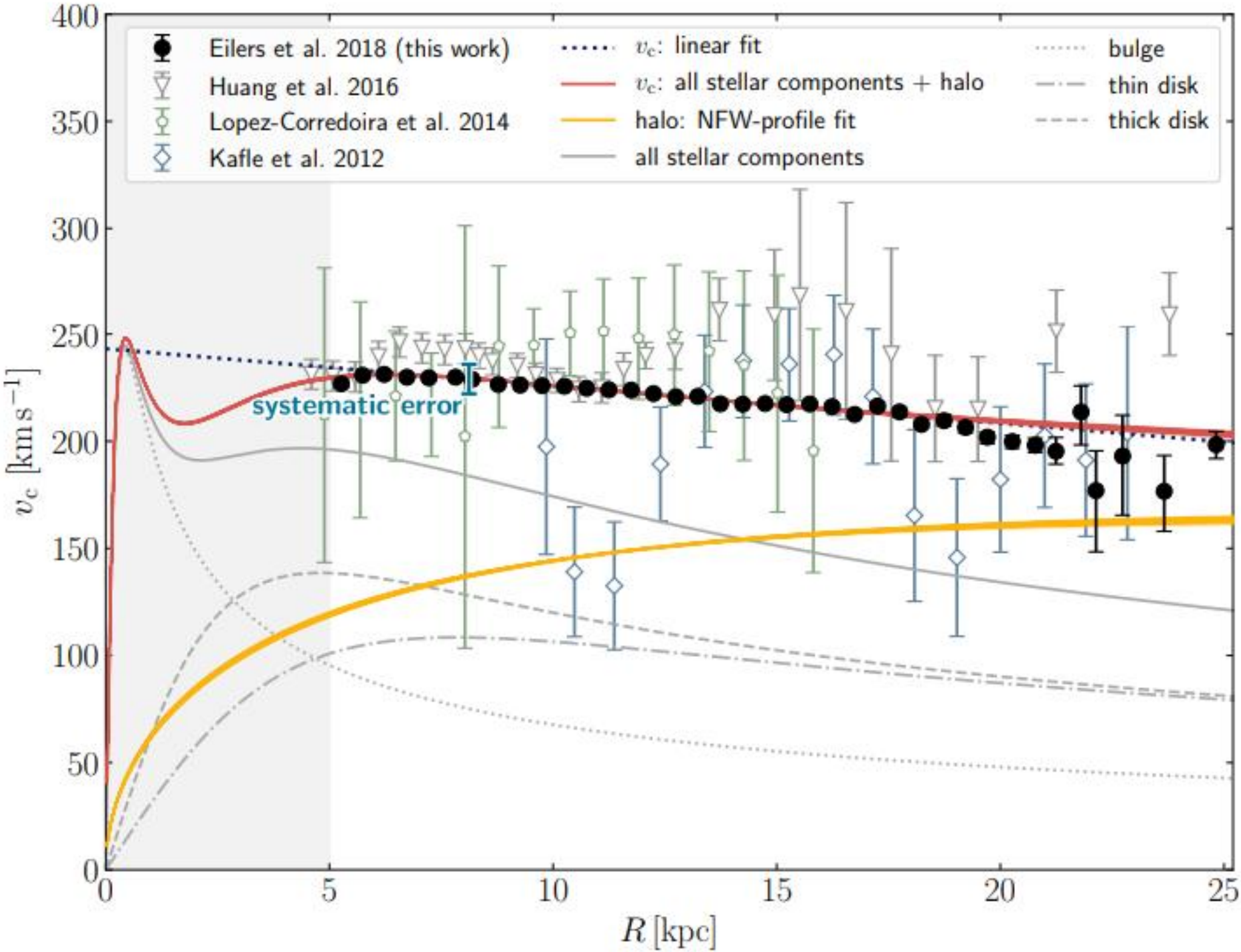
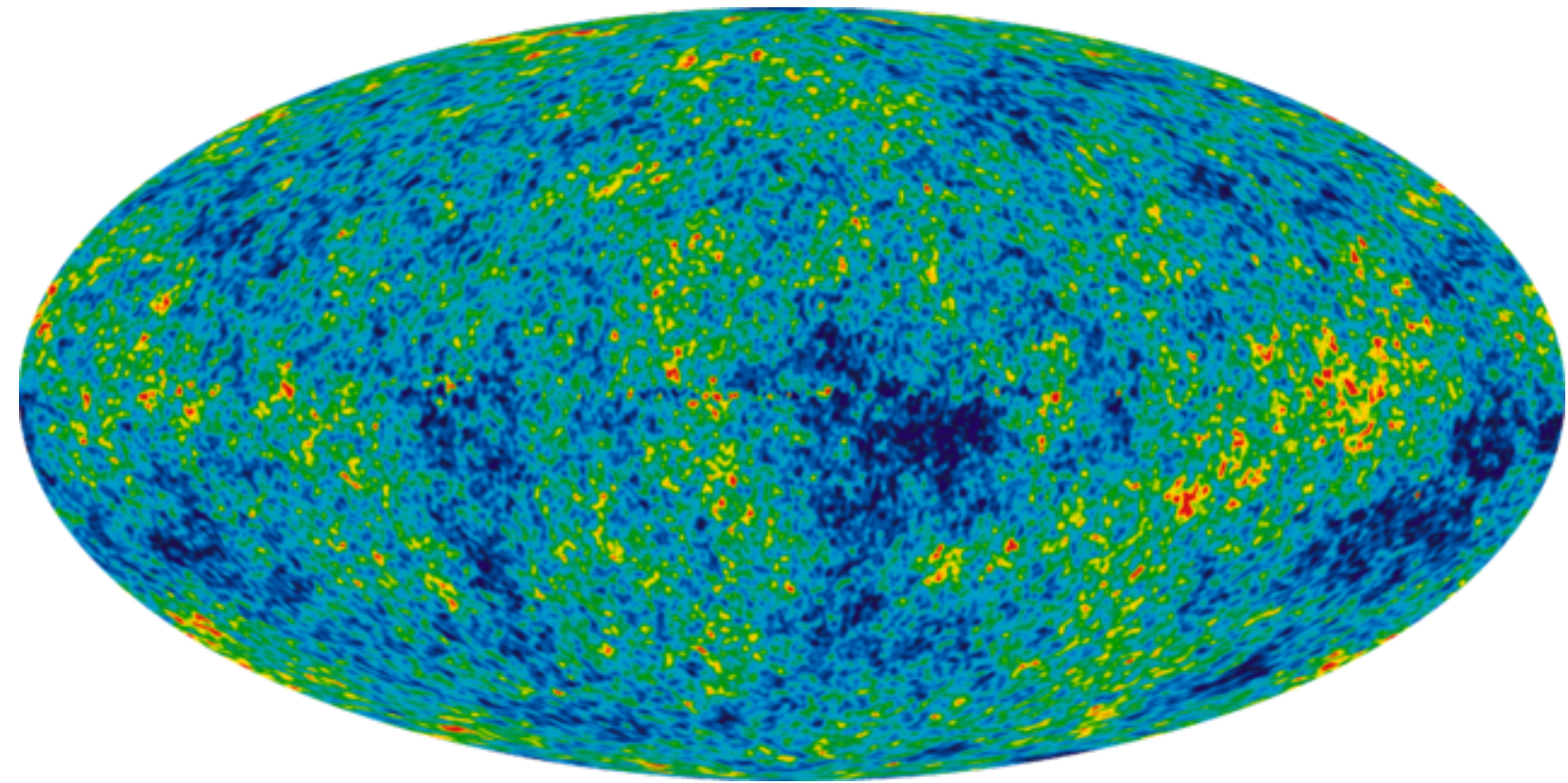


# Outline

- ❖ Introduction
- ❖ Particle-like dark matter
- ❖ Wave-like dark matter
- ❖ Primordial black hole as dark matter



# Evidence of Dark Matter

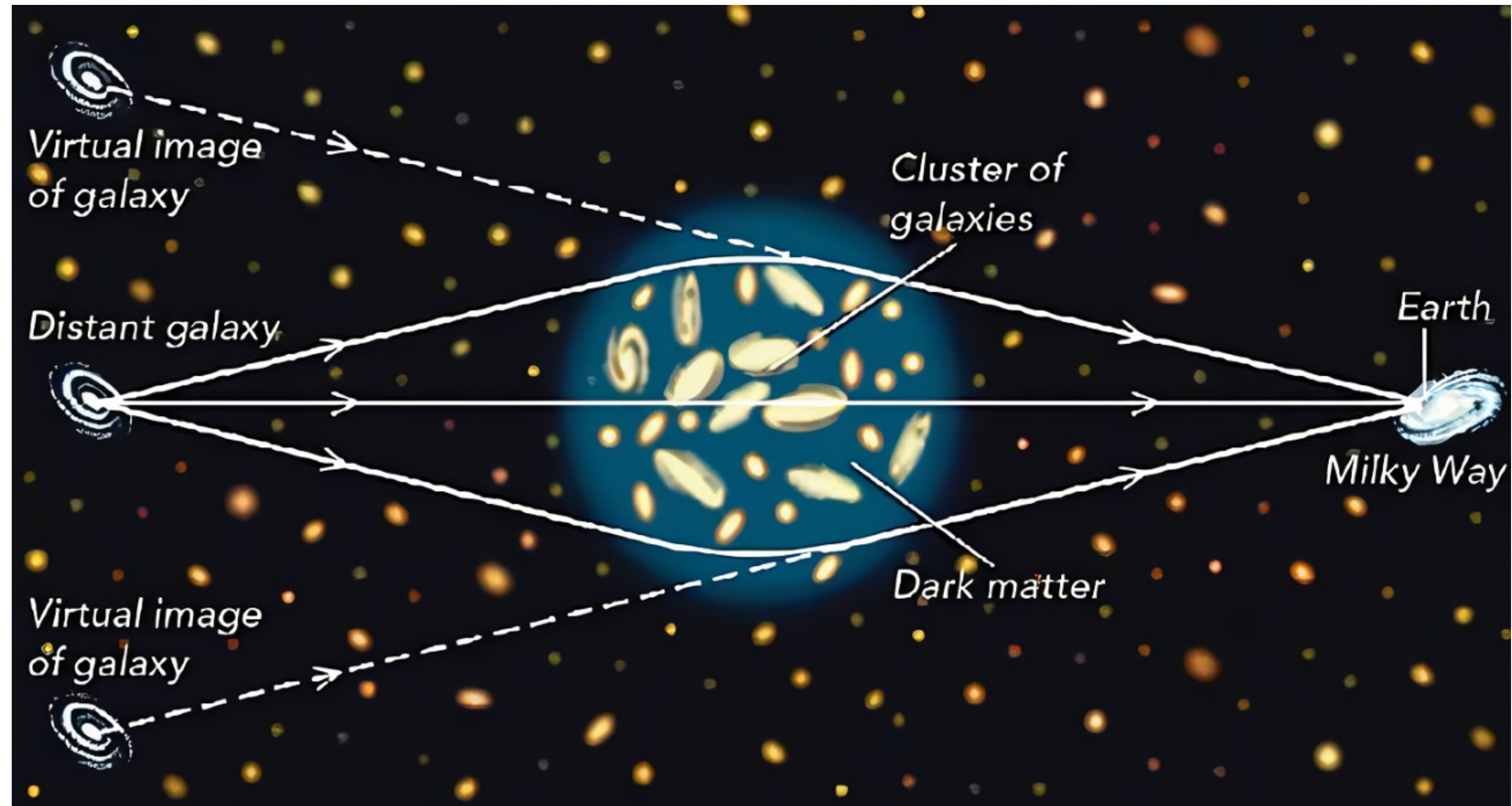




# Gravitational Lensing

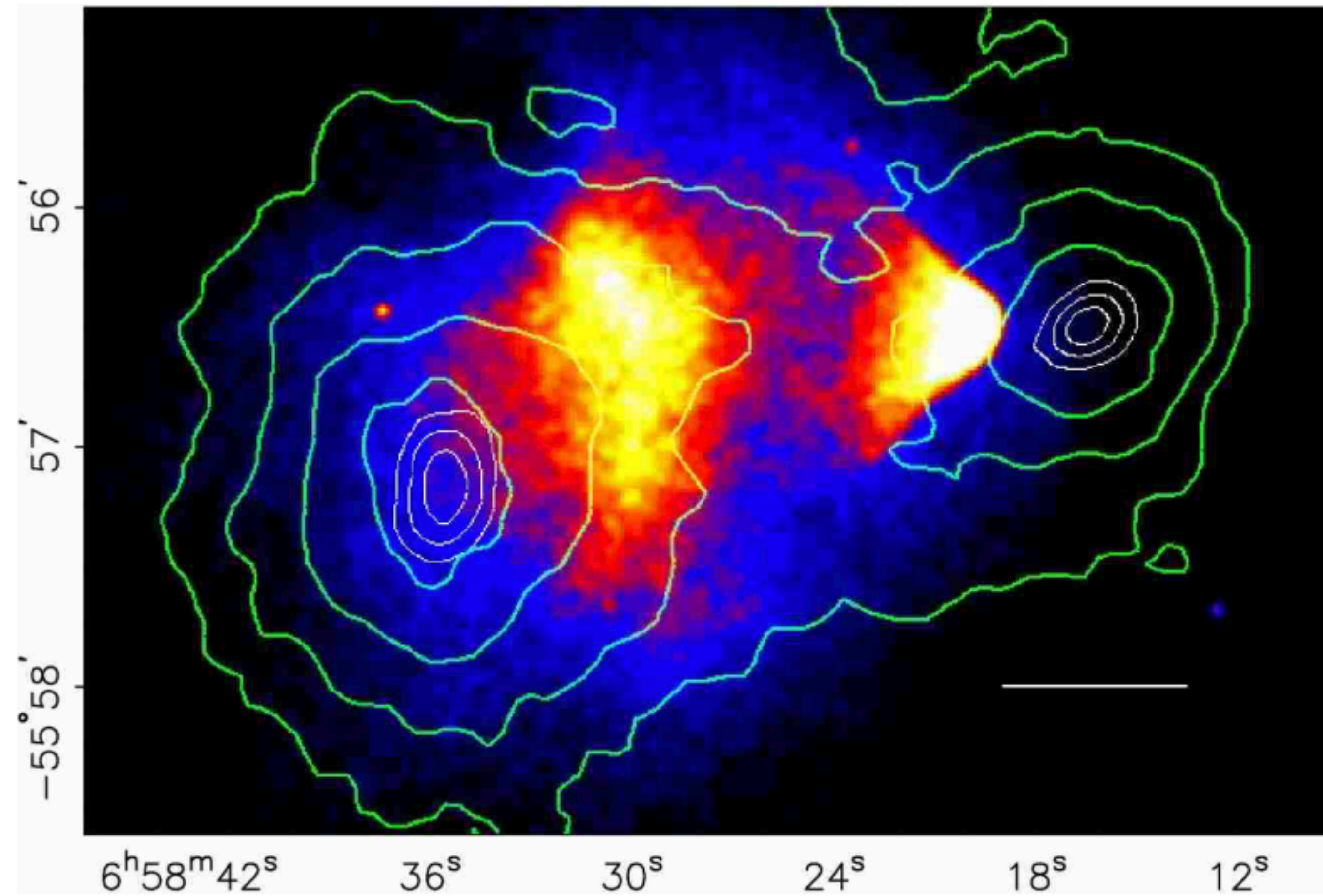


The image of distant galaxy is distorted by gravity of dark matter



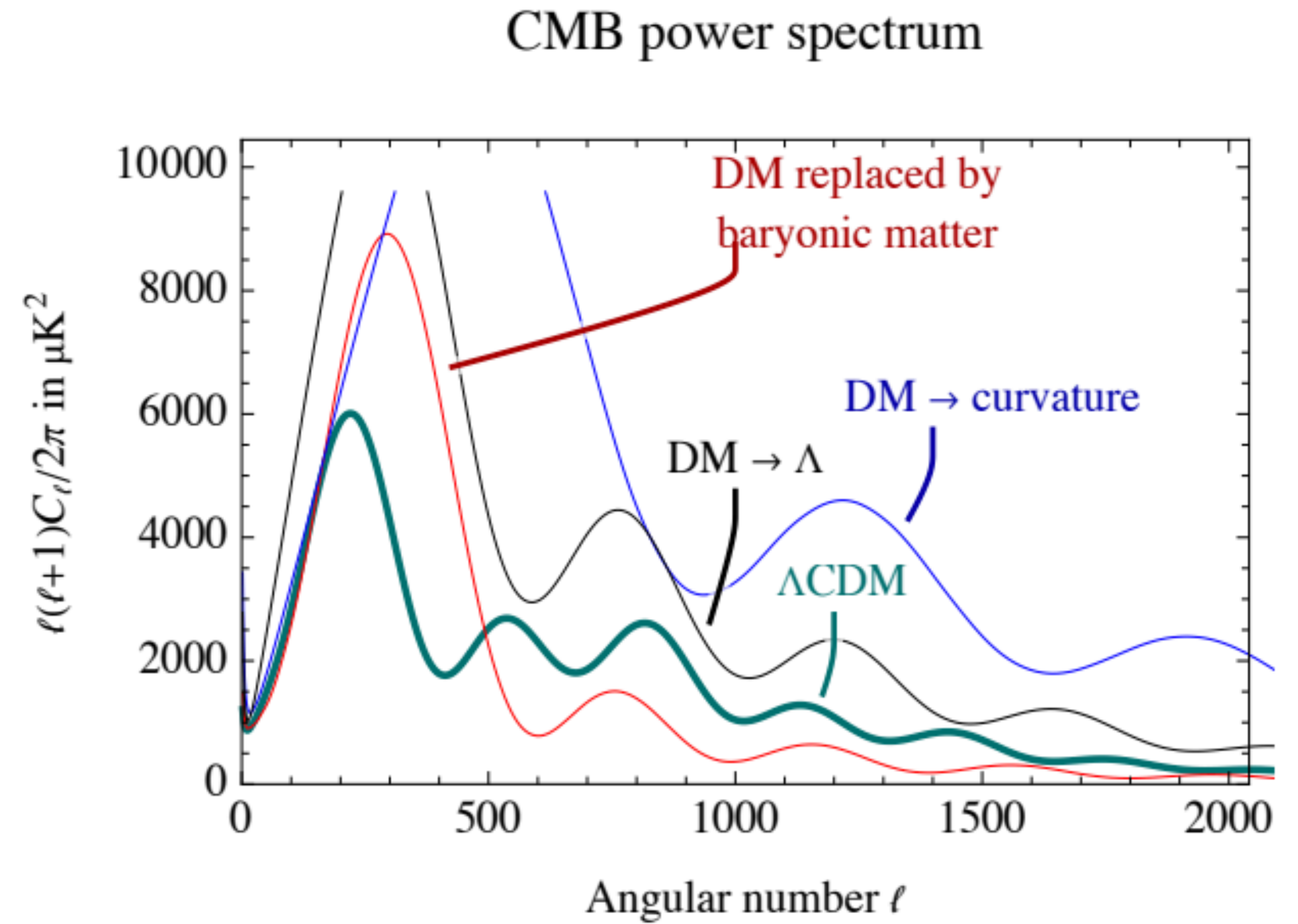
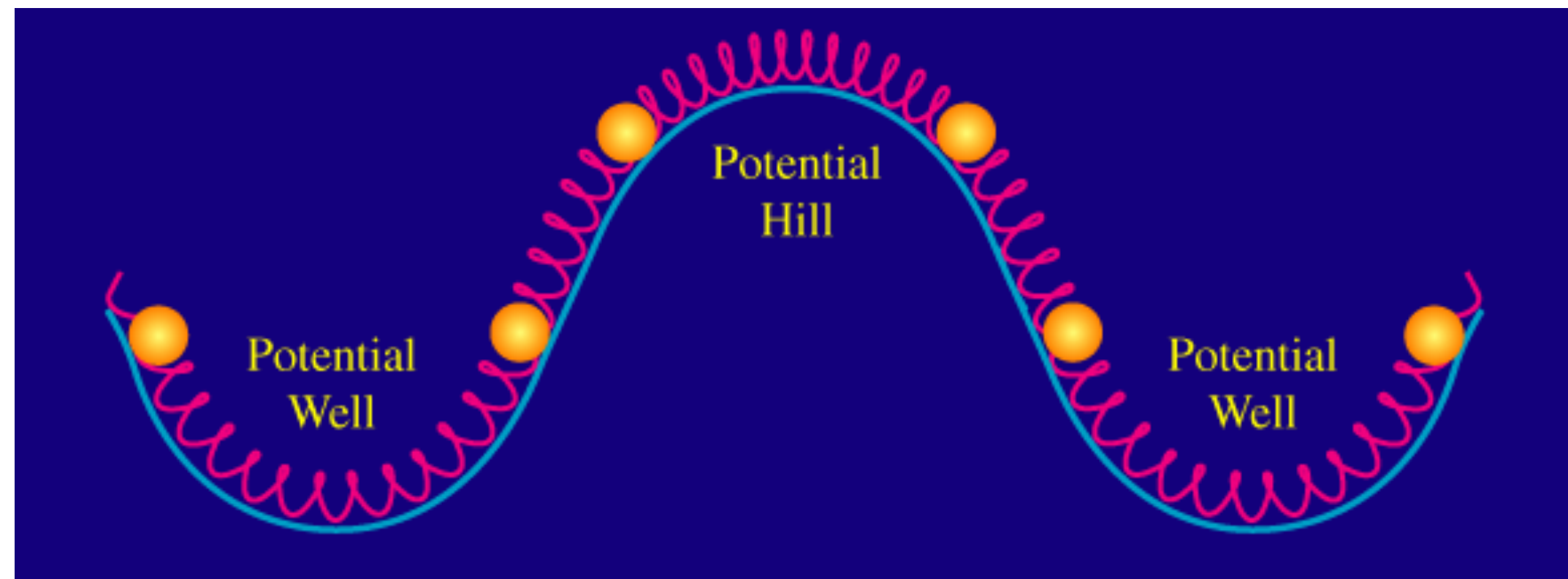


# The Bullet Cluster



Clowe *et al.*, arXiv:1612.03906

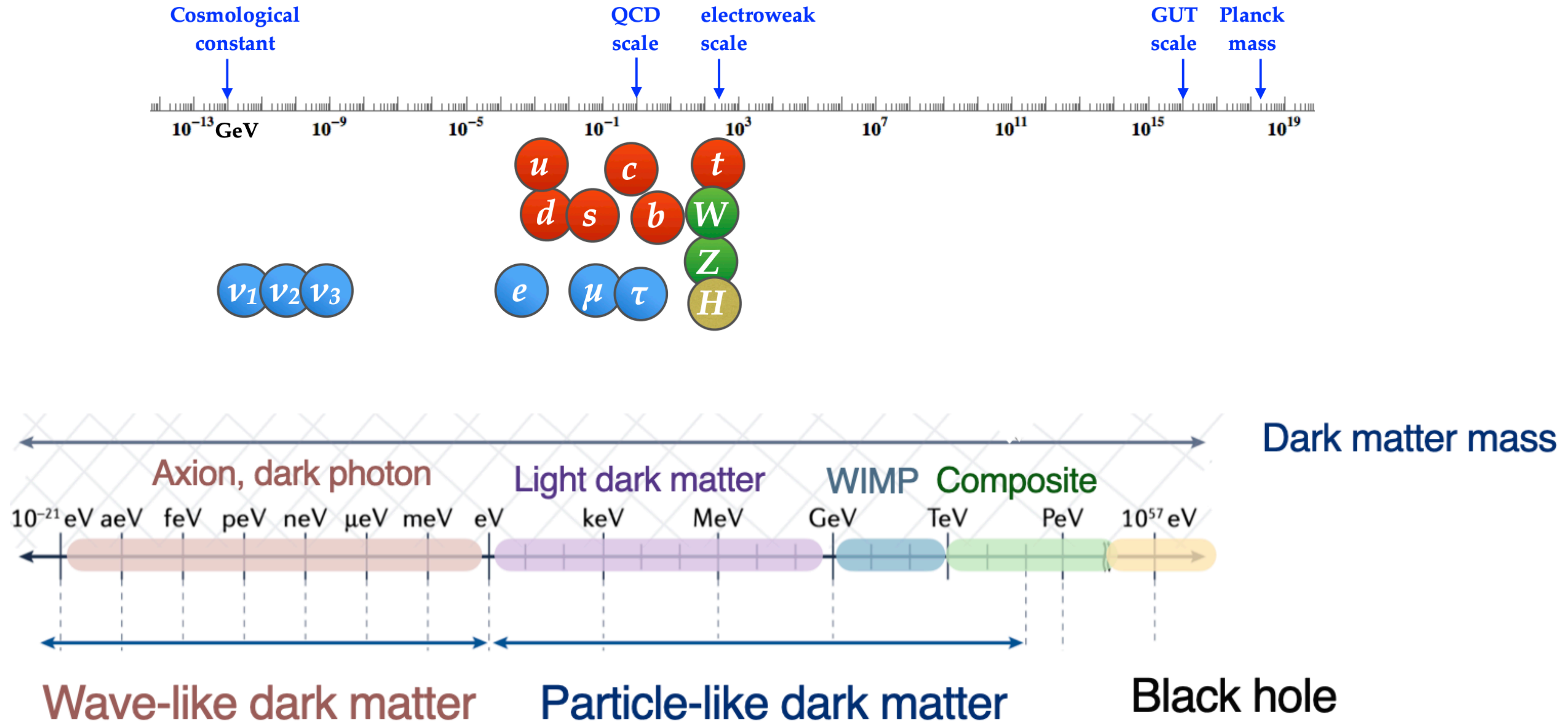
# Cosmic Microwave Background



Cirelli *et al.*, arXiv:2406.01705



# Dark Matter Candidates



*Nature Viewpoint, 4, 637-641*

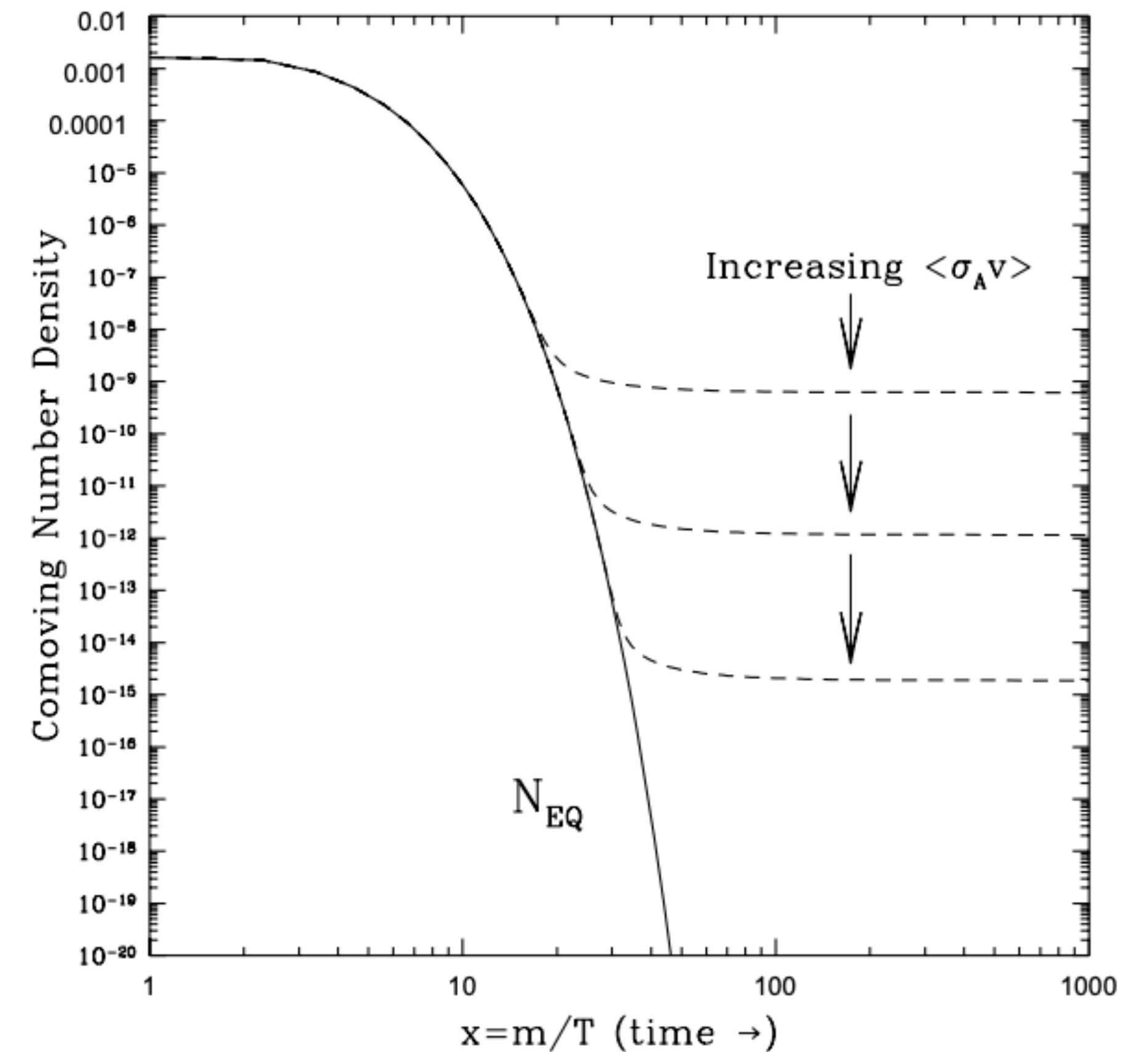
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# A “Standard” Cosmological History of Dark Matter

- Dark matter in **thermal equilibrium** with SM at high temperature
- As the Universe cools down, chemical equilibrium is **no longer** maintained when  $T < M_\chi$ , and the dark matter abundance drops exponentially
- The Universe expansion rate eventually exceeds the dark matter annihilation rate, and the comoving dark matter density “**freezes**”
- A **cold dark matter relic** is left over



Hooper, arxiv: 0901.4090

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$$

# Thermal Freeze-out

## Boltzmann equation of dark matter

$$\dot{n}(t) + 3H(t)n(t) = -\langle\sigma_{\chi\chi} v\rangle (n(t)^2 - n_{\text{eq}}(t)^2) .$$

expansion of the universe

DM annihilation

regeneration from the SM plasma

$$\frac{1}{a(t)^3} \frac{d}{dt} (n(t)a(t)^3) = -\langle\sigma_{\chi\chi} v\rangle (n(t)^2 - n_{\text{eq}}(t)^2)$$

$$\Leftrightarrow T(t)^3 \frac{d}{dt} \left( \frac{n(t)}{T(t)^3} \right) = -\langle\sigma_{\chi\chi} v\rangle (n(t)^2 - n_{\text{eq}}(t)^2)$$

$$\Leftrightarrow \frac{dY(t)}{dt} = -\langle\sigma_{\chi\chi} v\rangle T(t)^3 (Y(t)^2 - Y_{\text{eq}}(t)^2) \quad \text{with} \quad Y(t) := \frac{n(t)}{T^3} .$$



# Thermal Freeze-out

$$\dot{n}(t) + 3H(t)n(t) = -\langle\sigma_{\chi\chi} v\rangle \left( n(t)^2 - n_{\text{eq}}(t)^2 \right) .$$

## Radiation domination

$$\begin{aligned} \frac{1}{2t} \stackrel{\text{Eq. (1.31)}}{=} H \stackrel{\text{Eq. (1.47)}}{=} \frac{H(x=1)}{x^2} &\Leftrightarrow x = \sqrt{2tH(x=1)} \\ &\Leftrightarrow \frac{dx}{dt} = \frac{2H(x=1)}{2\sqrt{2tH(x=1)}} = \frac{H(x=1)}{x}, \quad x = m_\chi/T \end{aligned}$$

$$\begin{aligned} \frac{dY(x)}{dx} &= \frac{x}{H(x=1)} \frac{dY(t)}{dt} \\ &= -\langle\sigma_{\chi\chi} v\rangle \frac{x}{H(x=1)} \frac{m_\chi^3}{x^3} (Y(x)^2 - Y_{\text{eq}}(x)^2) \\ &= -\frac{\lambda(x)}{x^2} (Y(x)^2 - Y_{\text{eq}}(x)^2) \quad \text{with} \quad \lambda(x) := \frac{m_\chi^3 \langle\sigma_{\chi\chi} v\rangle}{H(x=1)} = \frac{\sqrt{90} M_{\text{Pl}} m_\chi}{\pi \sqrt{g_{\text{eff}}}} \langle\sigma_{\chi\chi} v\rangle(x) . \end{aligned}$$

# Thermal Freeze-out

$$\dot{n}(t) + 3H(t)n(t) = -\langle\sigma_{\chi\chi} v\rangle (n(t)^2 - n_{\text{eq}}(t)^2) .$$

$$\frac{1}{Y(x'_{\text{dec}})} - \frac{1}{Y(x_{\text{dec}})} = \bar{Y}(x'_{\text{dec}}) - \bar{Y}(x_{\text{dec}}) = -\frac{\bar{\lambda}}{x_{\text{dec}}'^{3/2}} + \frac{\bar{\lambda}}{x_{\text{dec}}^{3/2}} . \quad x = m_{\chi}/T$$

At late time  $T' \ll T, x' \gg x, Y' \ll Y$

$$\frac{1}{Y(x'_{\text{dec}})} = \frac{\bar{\lambda}}{x_{\text{dec}}^{3/2}} \quad \Leftrightarrow \quad Y(x'_{\text{dec}}) = \frac{m_{\chi}^3 \langle\sigma_{\chi\chi} v\rangle}{H(x=1)} = \frac{x_{\text{dec}}}{\lambda(x_{\text{dec}})} \stackrel{\text{Eq. (3.24)}}{=} x_{\text{dec}} \frac{\pi \sqrt{g_{\text{eff}}}}{\sqrt{90} M_{\text{Pl}} m_{\chi}} \frac{1}{\langle\sigma_{\chi\chi} v\rangle} .$$

$$\rho_{\chi}(T_0) = m_{\chi} n_{\chi}(T_0)$$

$$= m_{\chi} Y(x'_{\text{dec}}) T_{\text{dec}}'^3 \left( \frac{a(T'_{\text{dec}})}{a(T_0)} \right)^3 \stackrel{\text{Eq. (3.11)}}{=} m_{\chi} Y(x'_{\text{dec}}) T_0^3 \frac{g_{\text{eff}}(T_0)}{g_{\text{eff}}(T'_{\text{dec}})} = m_{\chi} \frac{Y(x'_{\text{dec}}) T_0^3}{28} .$$



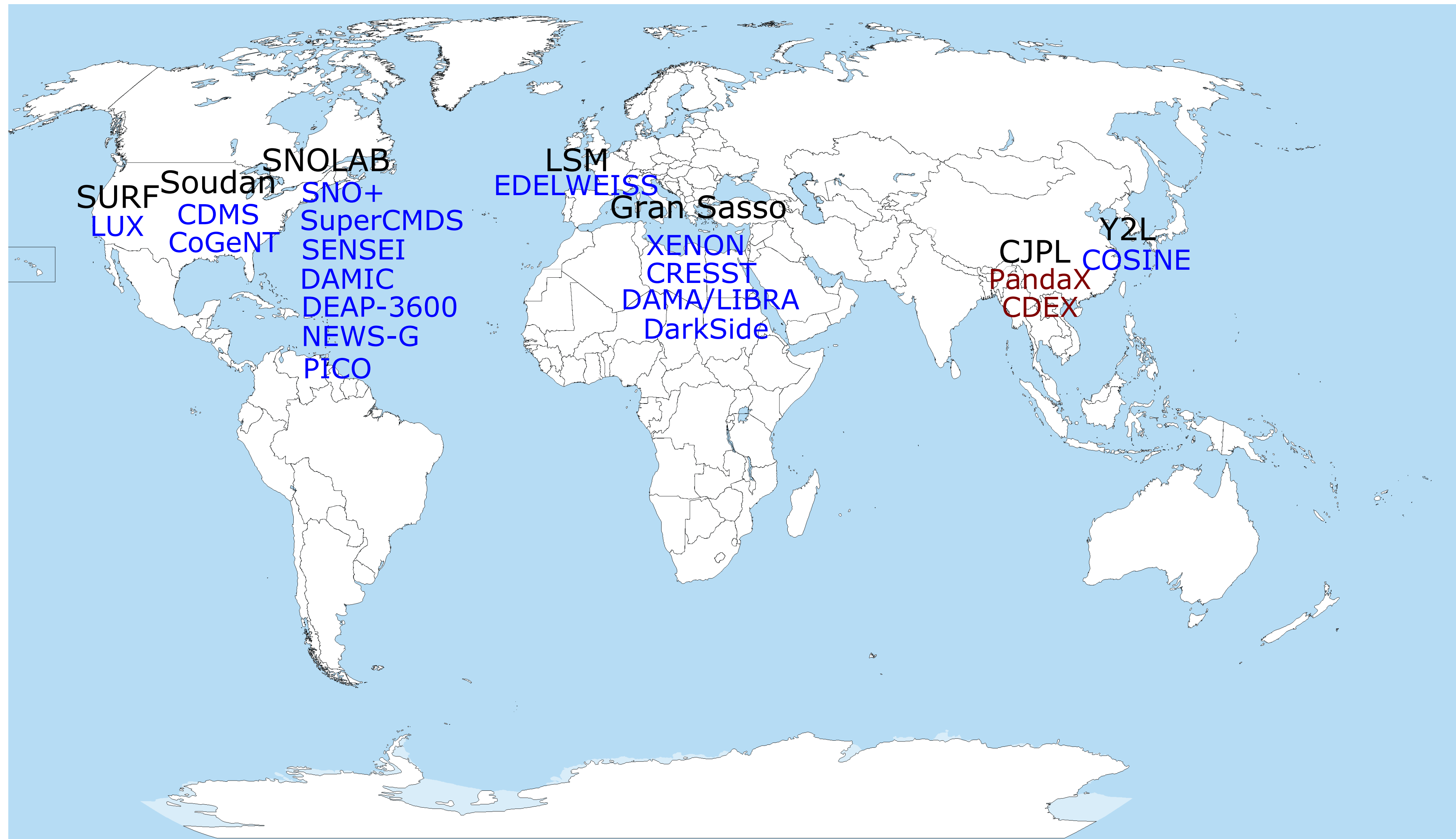
# Thermal Freeze-out

$$\boxed{\dot{n}(t) + 3H(t)n(t) = -\langle\sigma_{\chi\chi} v\rangle (n(t)^2 - n_{\text{eq}}(t)^2)}.$$

$$\begin{aligned}\rho_{\chi}(T_0) &= m_{\chi} n_{\chi}(T_0) \\ &= m_{\chi} Y(x'_{\text{dec}}) T_{\text{dec}}'^3 \left( \frac{a(T'_{\text{dec}})}{a(T_0)} \right)^3 \stackrel{\text{Eq. (3.11)}}{=} m_{\chi} Y(x'_{\text{dec}}) T_0^3 \frac{g_{\text{eff}}(T_0)}{g_{\text{eff}}(T'_{\text{dec}})} = m_{\chi} \frac{Y(x'_{\text{dec}}) T_0^3}{28}.\end{aligned}$$

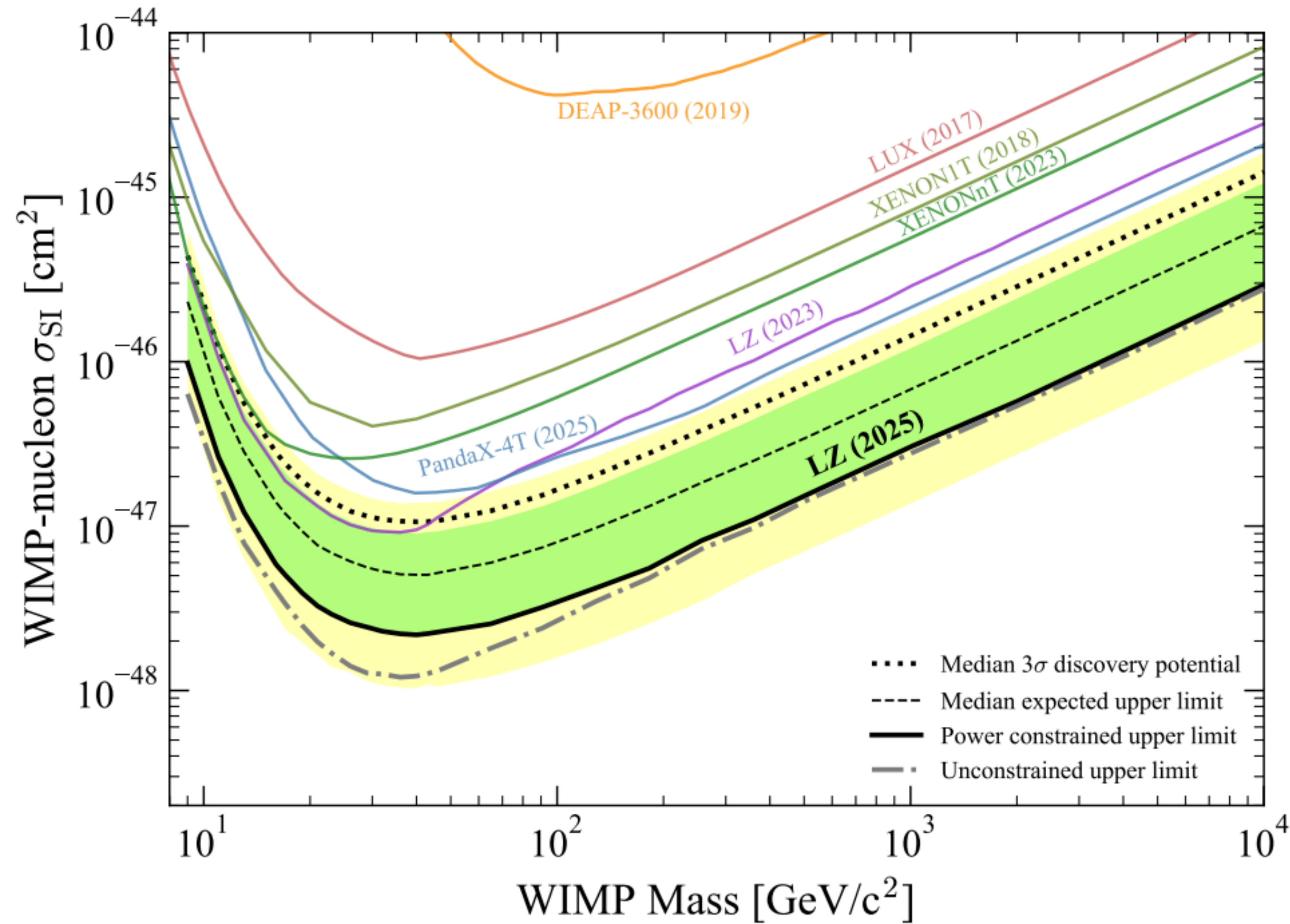
$$\begin{aligned}\Omega_{\chi} h^2 &= m_{\chi} \frac{Y(x'_{\text{dec}}) T_0^3}{28} \frac{h^2}{3M_{\text{Pl}}^2 H_0^2} \\ &= \frac{h^2 \pi \sqrt{g_{\text{eff}}}}{28 \sqrt{90} M_{\text{Pl}}} \frac{x_{\text{dec}}}{\langle\sigma_{\chi\chi} v\rangle} \frac{T_0^3}{3M_{\text{Pl}}^2 H_0^2} \quad \Omega_{\chi} h^2 \approx 0.12 \frac{x_{\text{dec}}}{23} \frac{\sqrt{g_{\text{eff}}}}{10} \frac{1.7 \cdot 10^{-9} \text{GeV}^{-2}}{\langle\sigma_{\chi\chi} v\rangle} \approx 0.12 \frac{x_{\text{dec}}}{23} \frac{\sqrt{g_{\text{eff}}}}{10} \frac{2.04 \cdot 10^{-26} \text{cm}^3/\text{s}}{\langle\sigma_{\chi\chi} v\rangle} \\ &= \frac{h^2 \pi \sqrt{g_{\text{eff}}}}{28 \sqrt{90} M_{\text{Pl}}} \frac{x_{\text{dec}}}{\langle\sigma_{\chi\chi} v\rangle} \frac{(2.4 \cdot 10^{-4})^3}{(2.5 \cdot 10^{-3})^4} \frac{1}{\text{eV}}\end{aligned}$$

See, e.g. Bauer and Plehn, arxiv: 1705.01987

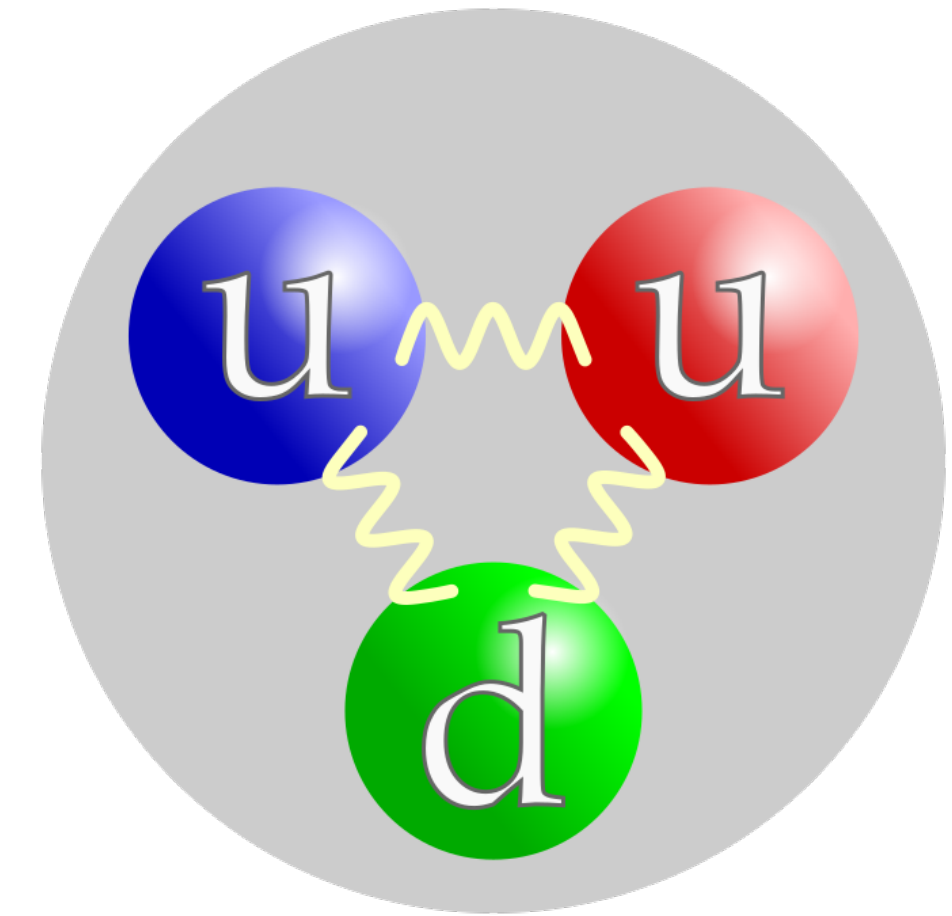




# Constraints on WIMP Dark Matter



How???



$$\sigma_p \sim 10^{-25} \text{ cm}^2$$

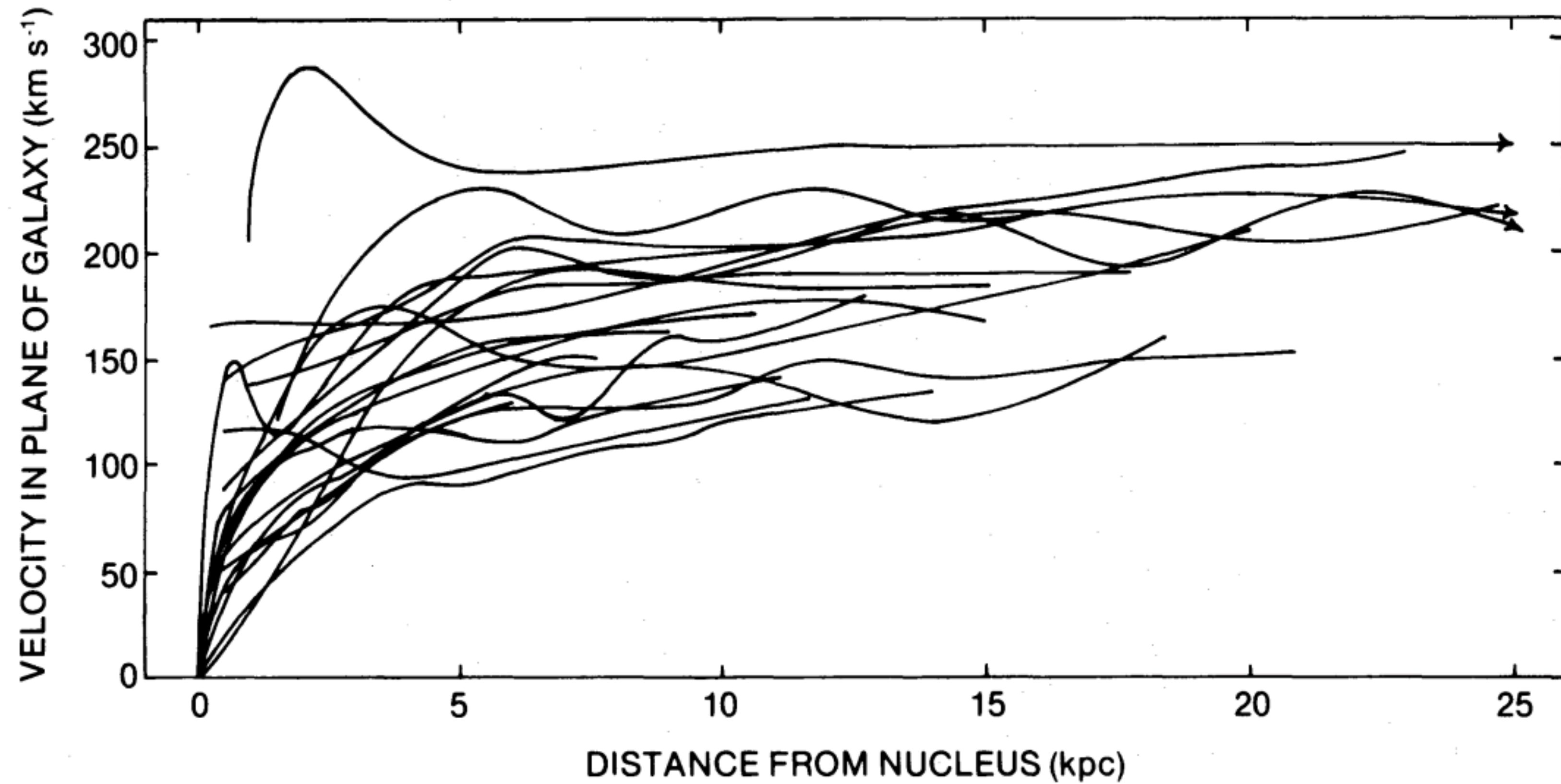
LZ 2207.03764

XENONnT 2303.14729

PandaX-4t 2408.00664

LZ 2410.17036

# Dark Matter Distribution

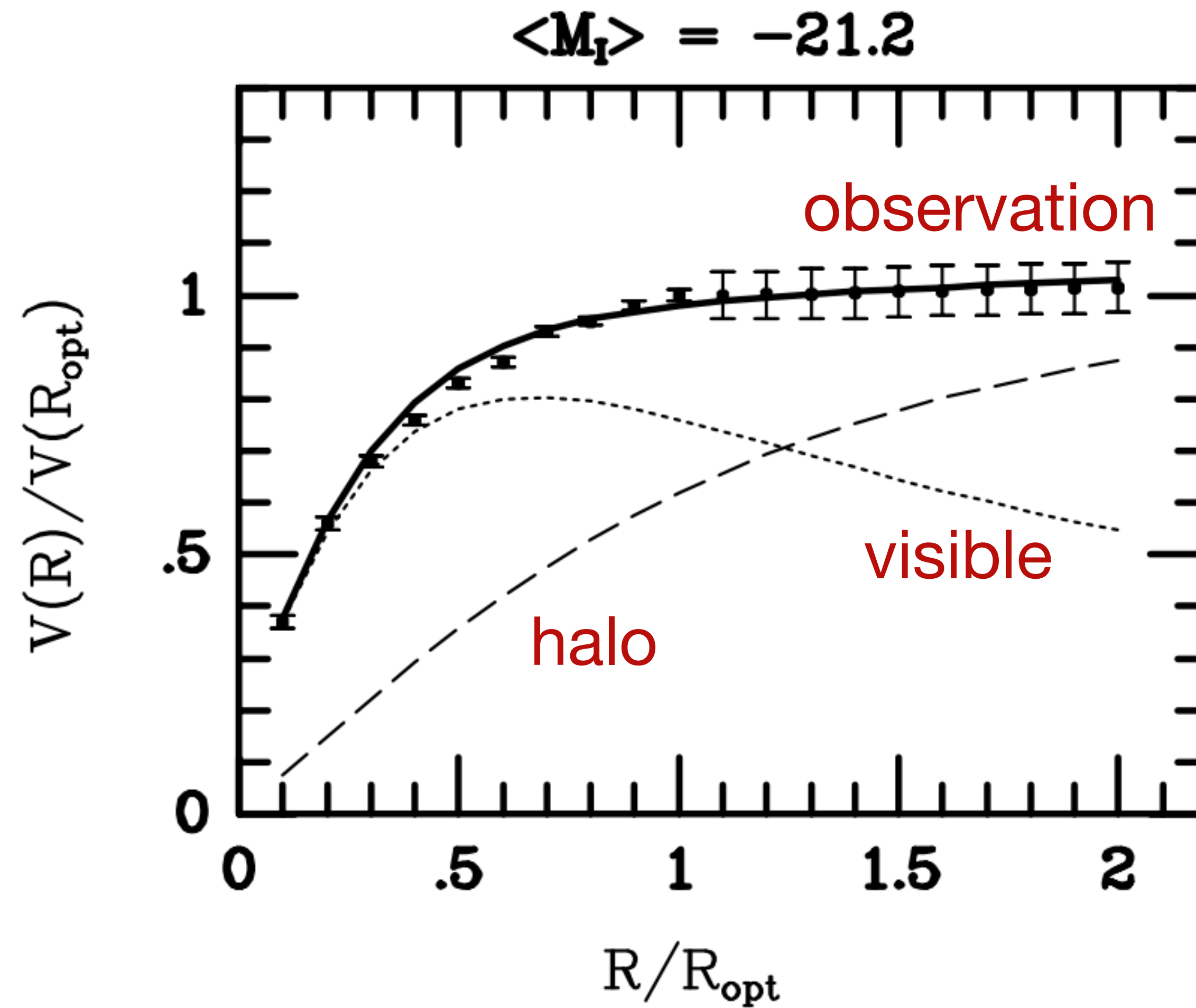


Rotation curves of spiral galaxies

Rubin et al, Astrophys. J. 1980



# Dark Matter Distribution



$$v_c(r) = \sqrt{\frac{GM}{r}}$$

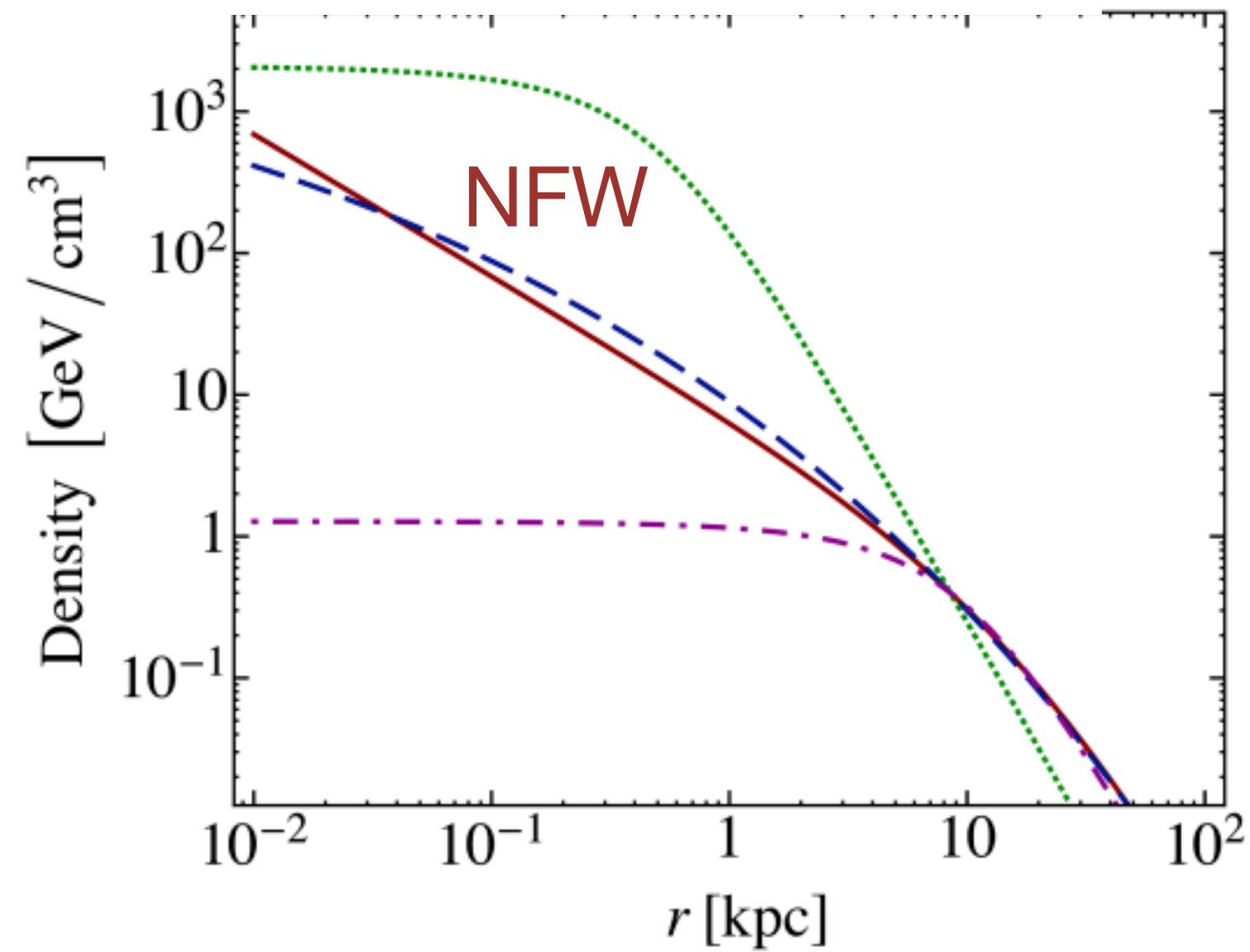
Persic et al MNRAS 1996

# Dark Matter Distribution

$$\mathbf{L}[f] = \mathbf{C}[f]$$

$$\frac{\partial f}{\partial t} + \dot{\mathbf{x}} \frac{\partial f}{\partial \mathbf{x}} + \dot{\mathbf{v}} \frac{\partial f}{\partial \mathbf{v}} = 0$$

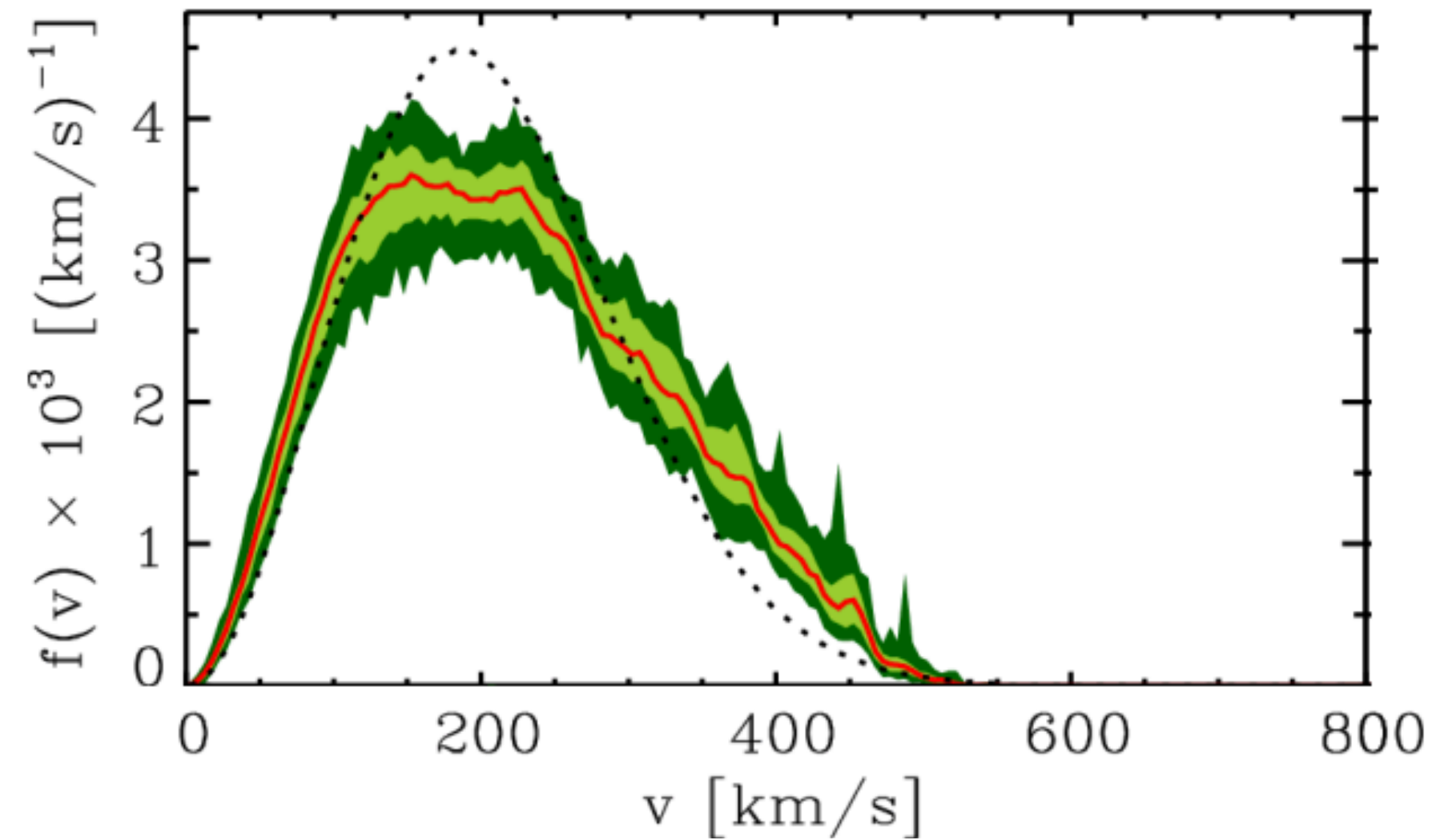
Cohen et al, 1307. 4082



Navarro-Frenk-White (NFW)

Einasto

Burkert



$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{r/r_s (1 + r/r_s)^2}$$

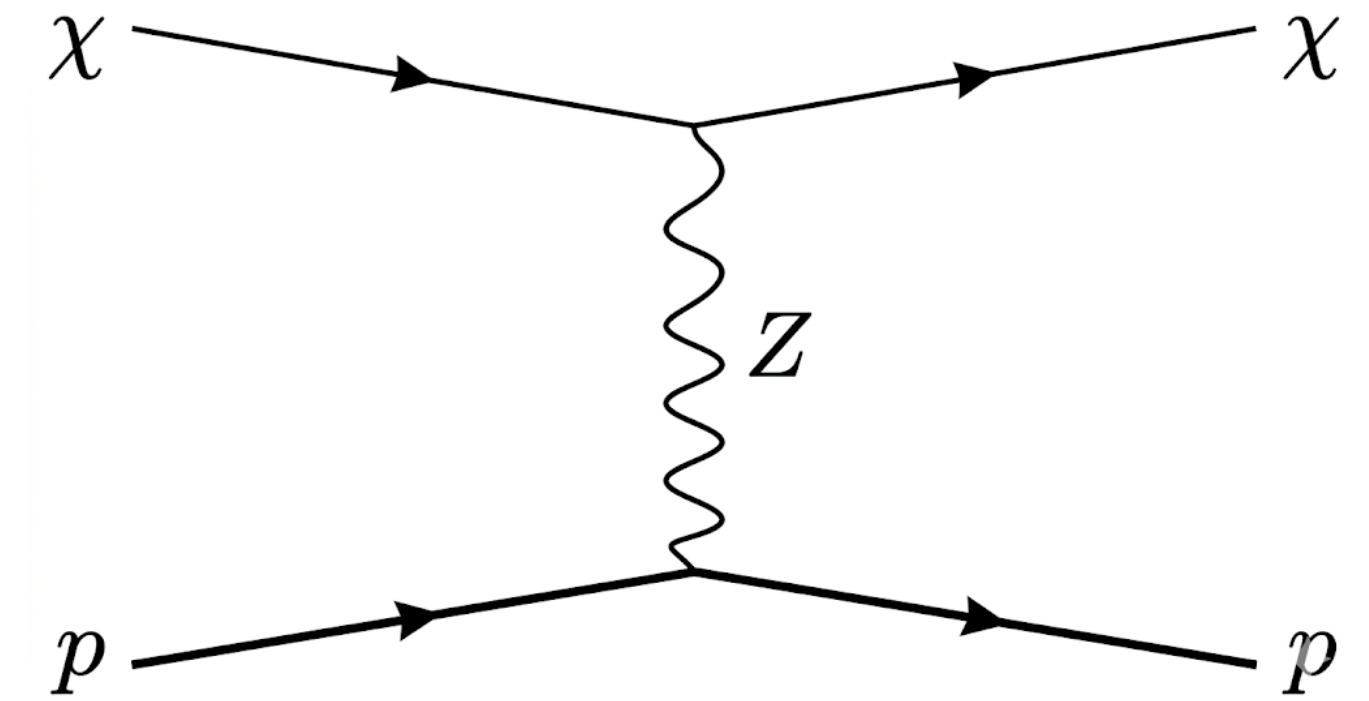
$$\rho_{\text{Ein}}(r) = \rho_0 \exp \left[ -\frac{2}{\gamma} \left( \left( \frac{r}{r_s} \right)^\gamma - 1 \right) \right]$$

$$\rho_{\text{Burk}}(r) = \frac{\rho_0}{(1 + r/r_s)(1 + (r/r_s)^2)}$$



# Dark Matter Scattering Cross Section

Dark matter scatters through the Z boson mediator

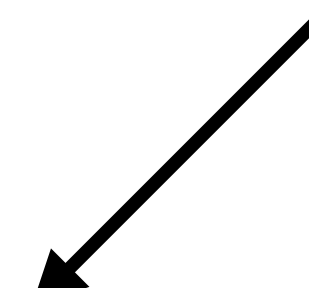


$$\sigma_{\chi N} = \frac{g^4 m_\chi^2 m_N^2}{4\pi(m_\chi + m_N)^2} \frac{(Zf_p + (A - Z)f_n)^2}{m_Z^4} F^2(E_R)$$

$$\sigma_{\chi p} = \frac{g^4 m_\chi^2 m_p^2}{4\pi(m_\chi + m_p)^2} \frac{1}{m_Z^4}$$

$$\sigma_{\chi N} = \sigma_{\chi p} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \frac{(Zf_p + (A - Z)f_n)^2}{f_p^2} F^2(E_R) \sim A^4 \sigma_{\chi p}$$

form factor



# The Scattering Rate

$$\Gamma = n\sigma v$$

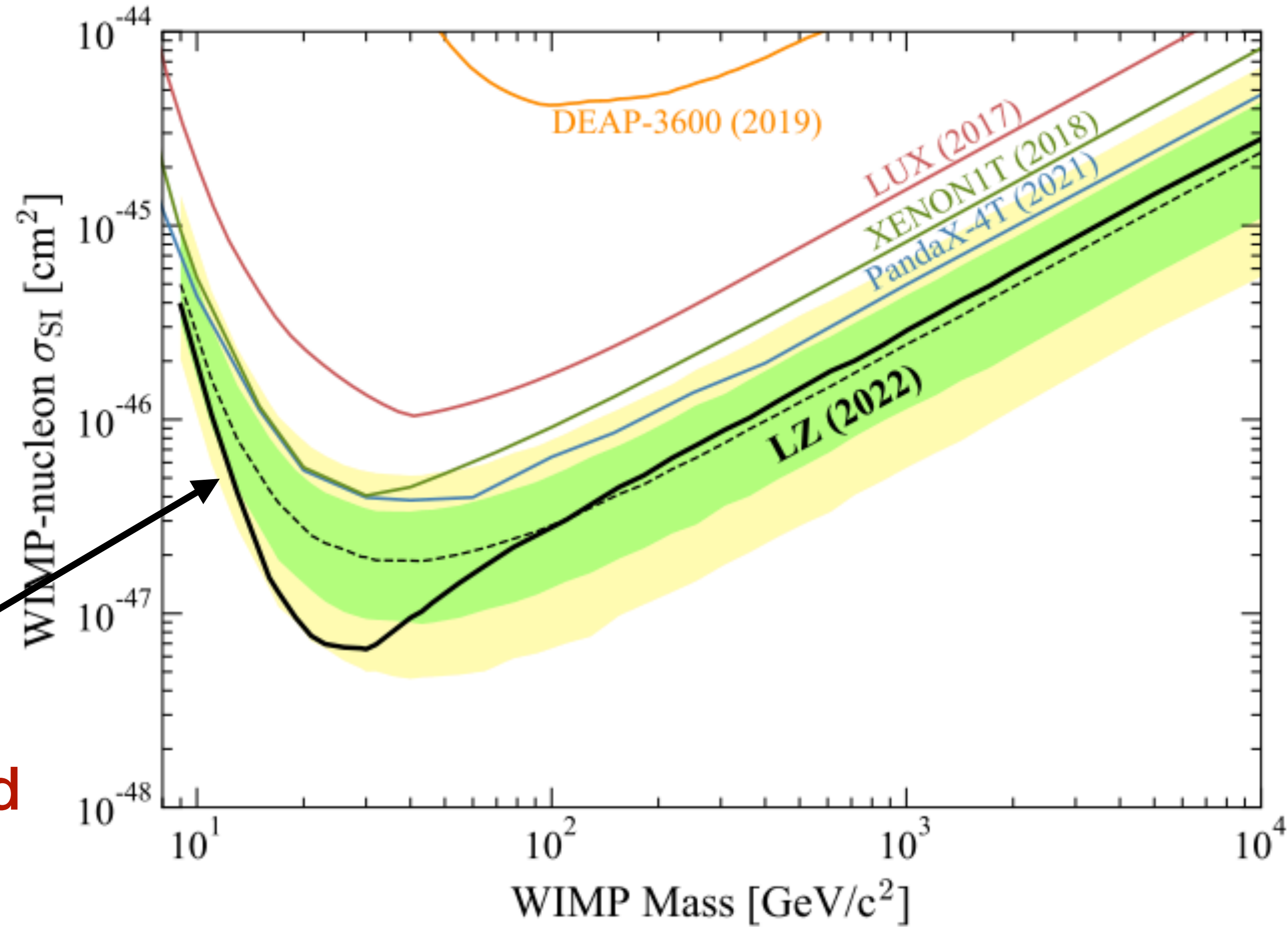
number of target nuclei

detection efficiency

$$N_{\text{exp}} = \sum_i N_i T \frac{\rho_\chi}{m_\chi} \int u_f f(u_f) du_f \int \frac{d\sigma_i}{dE_R} \epsilon(E_R) dE_R$$

dark matter velocity distribution

# Constraints on WIMP Dark Matter

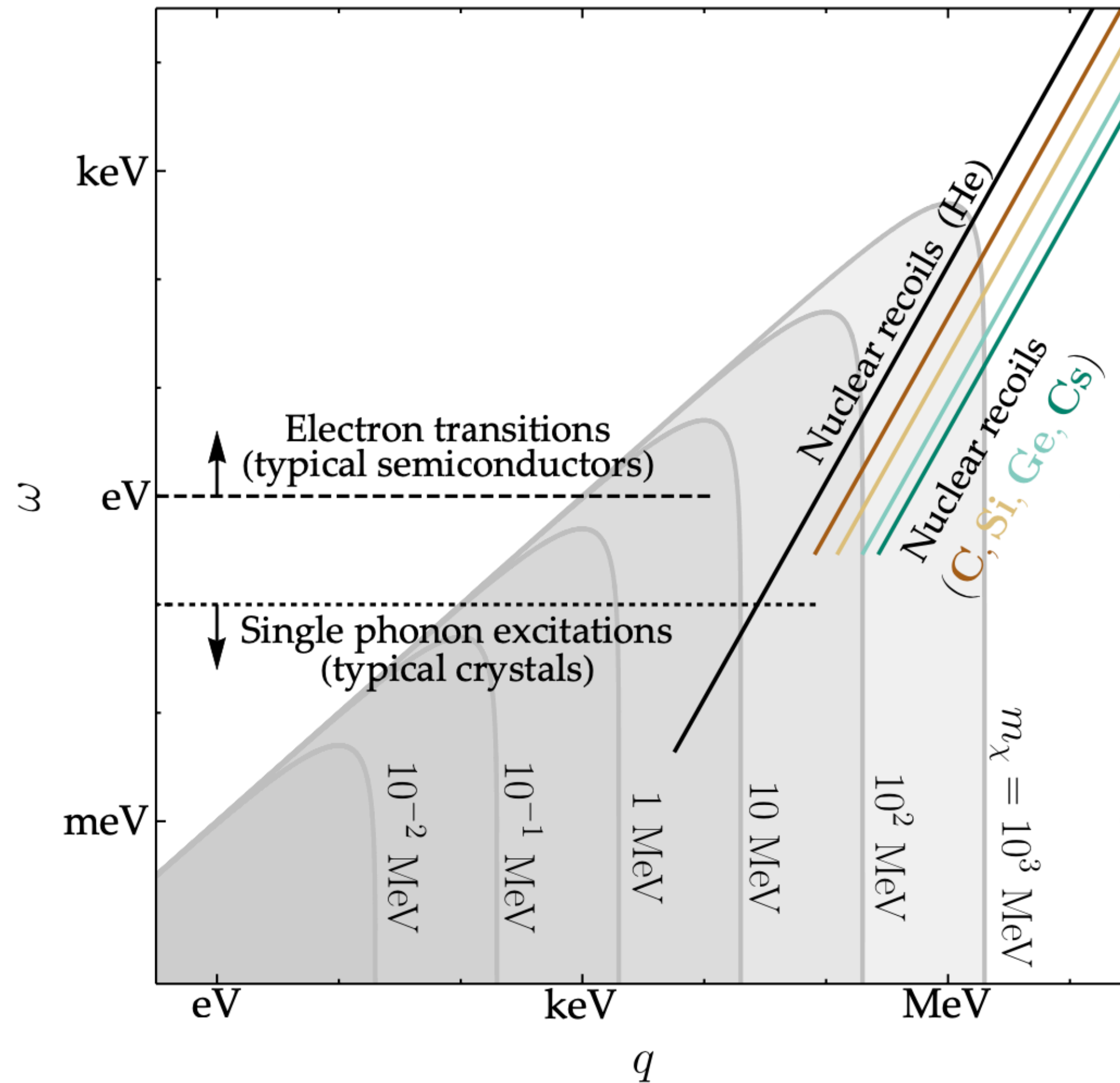


Limited by the  
detection threshold

How to overcome the detection threshold?



# Kinematics of Light Dark Matter



Trickle et al, arXiv: 1910.08092

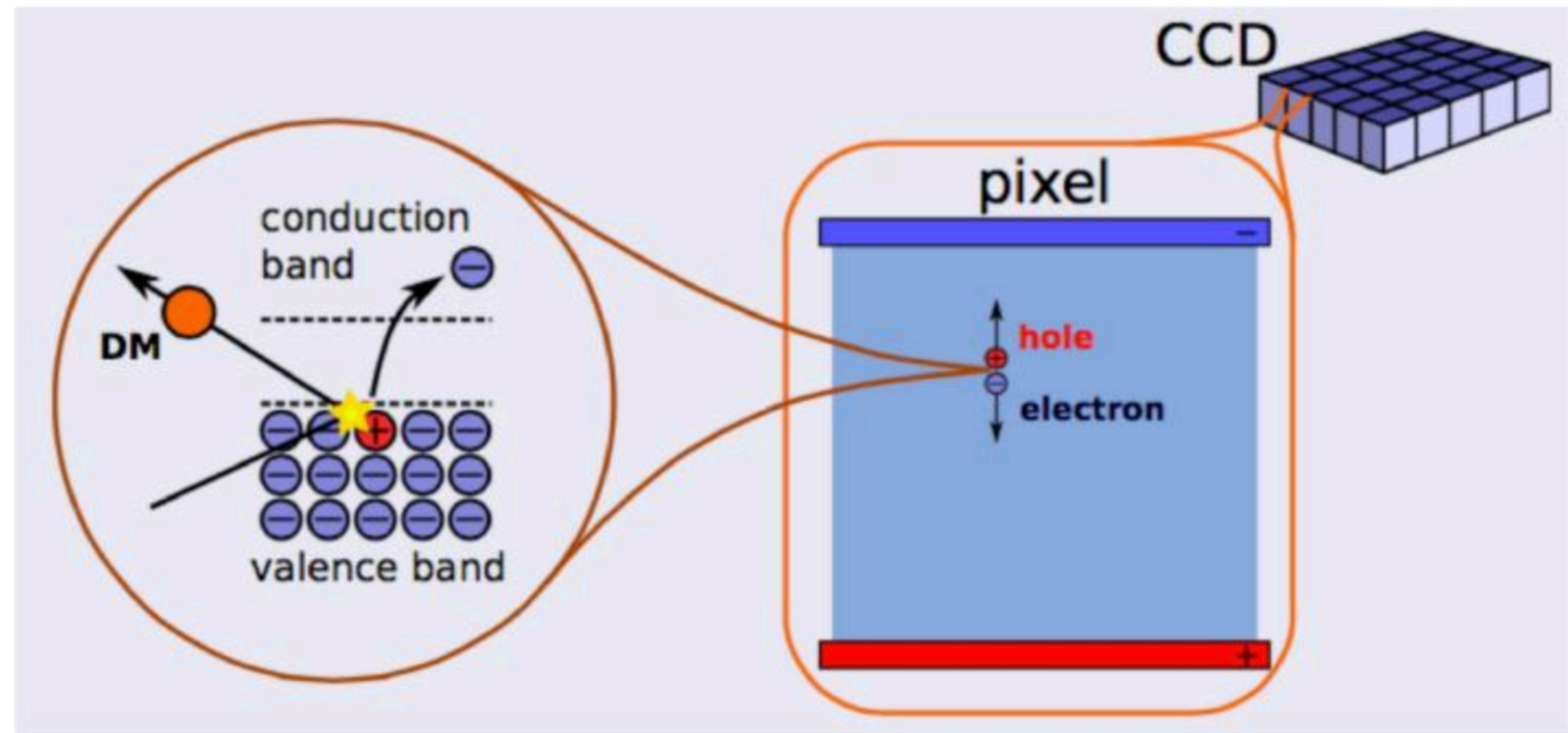
- The maximum dark matter energy deposition depends on its mass
- The energy deposition reduces for lower mass dark matter

$$\omega_{\mathbf{q}} = \frac{1}{2}m_{\chi}v^2 - \frac{(m_{\chi}\mathbf{v} - \mathbf{q})^2}{2m_{\chi}} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_{\chi}}$$

$$\omega \leq E_k \sim m_{\text{DM}}v^2 \sim 10^{-6}m_{\text{DM}}$$

**Look for electron recoil instead!**

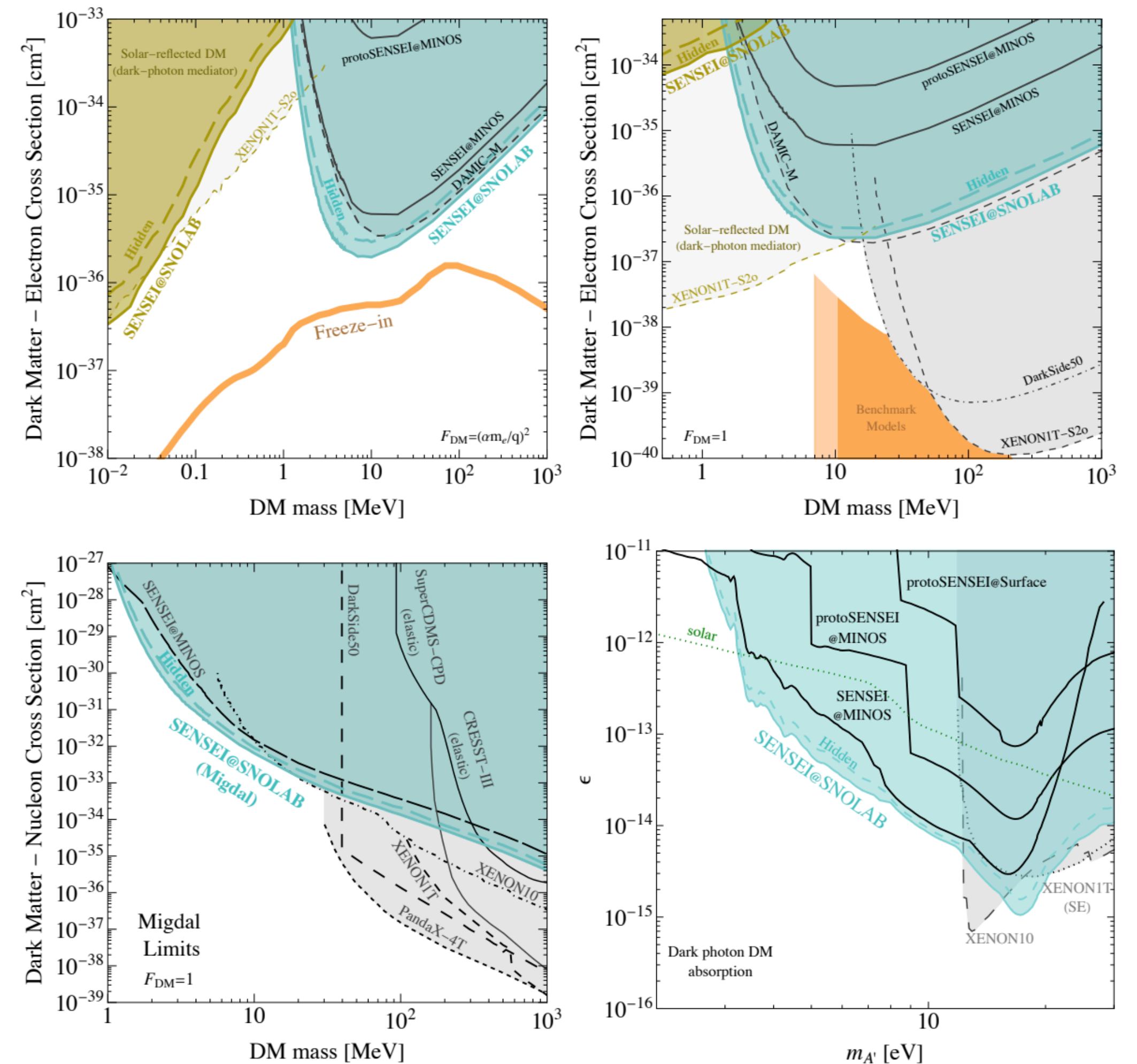
# SENSEI/CDEX



Yonit Hochberg

**Electron-hole pair from ionization**

**Charge only**



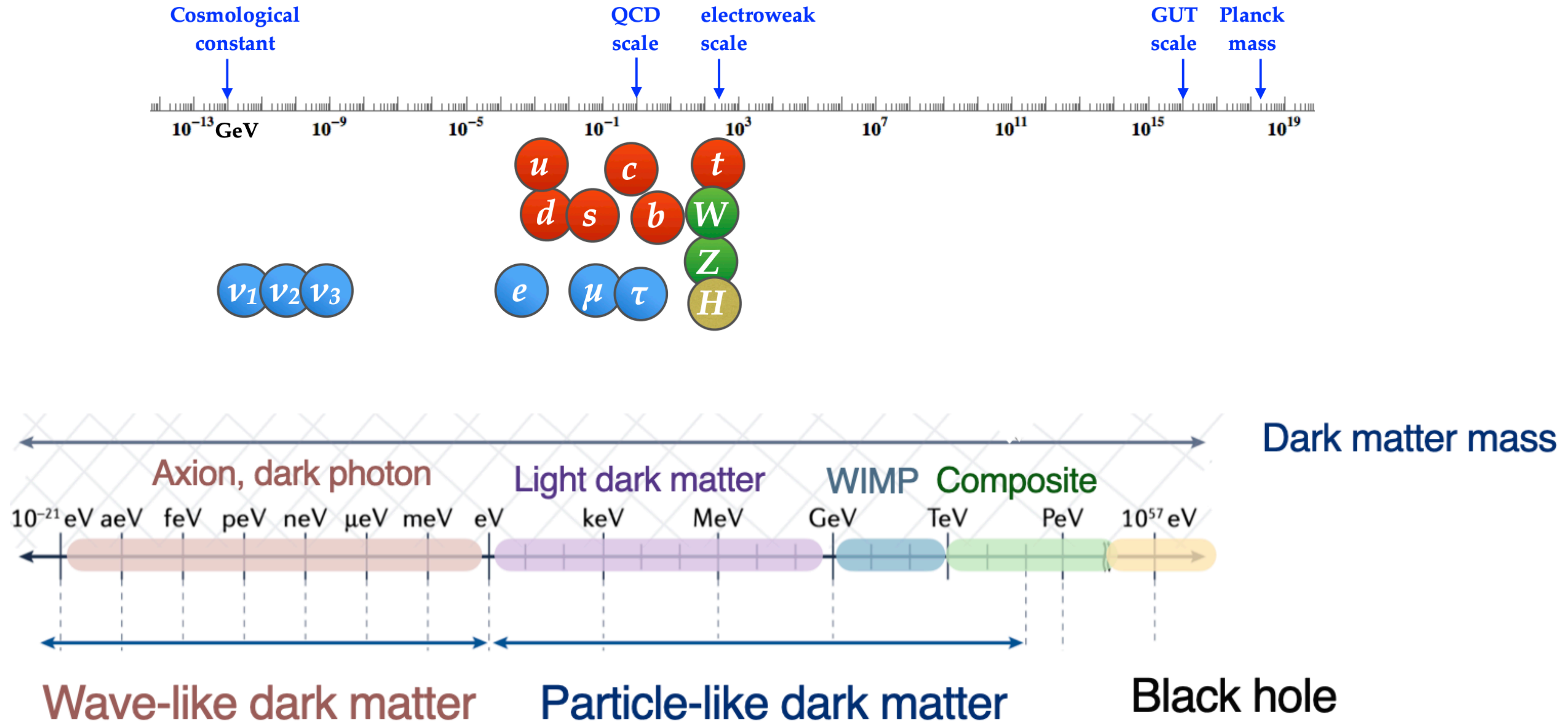
SENSEI@SNOLAB

$E_{th} \sim \text{eV}$

2312.13342



# Dark Matter Candidates



*Nature Viewpoint, 4, 637-641*



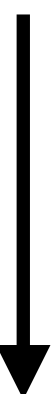
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# The Strong CP Problem

The QCD theta-term

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a,$$


$$F_{\mu\nu} \tilde{F}^{\mu\nu} \propto \vec{E} \cdot \vec{B}$$

# The Strong CP Problem

The QCD theta-term

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a$$



$$F_{\mu\nu} \tilde{F}^{\mu\nu} \propto \vec{E} \cdot \vec{B}$$

E: even under time reversal (T/CP)

B: odd under time reversal (T/CP)

$G\tilde{G}$  violates CP conservation



# The Strong CP Problem

The QCD theta-term  $\mathcal{L} = \mathcal{L}_{\text{SM}} - \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a$

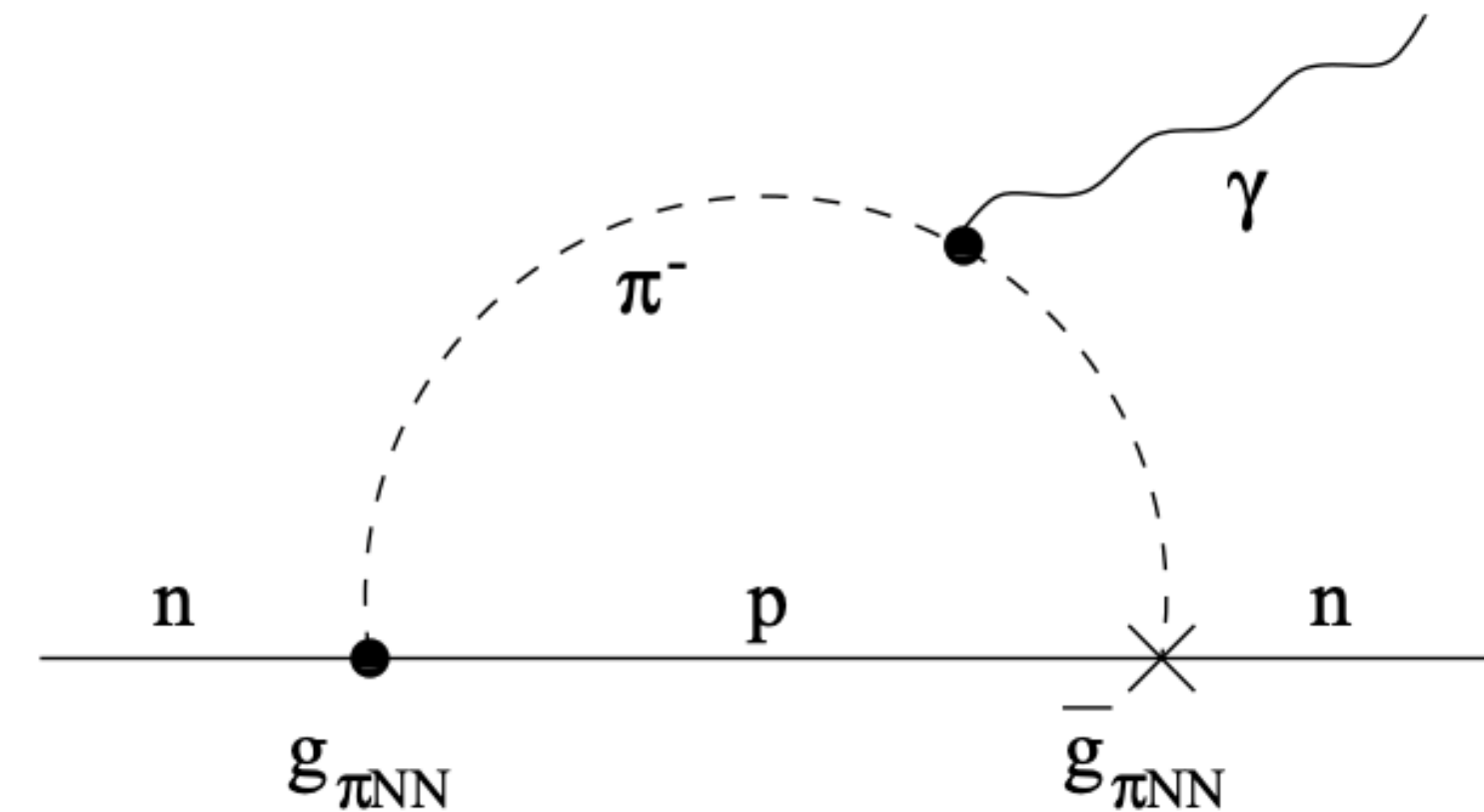
$G\tilde{G}$  violates CP conservation

Theoretical prediction of neutron EDM

$$d_n \approx \bar{\theta} e m_\pi^2 / m_N^3 \approx 10^{-16} \bar{\theta} e \text{ cm.}$$

Experimental measurement

$$|d_n| \lesssim 1.8 \cdot 10^{-26} e \text{ cm}$$

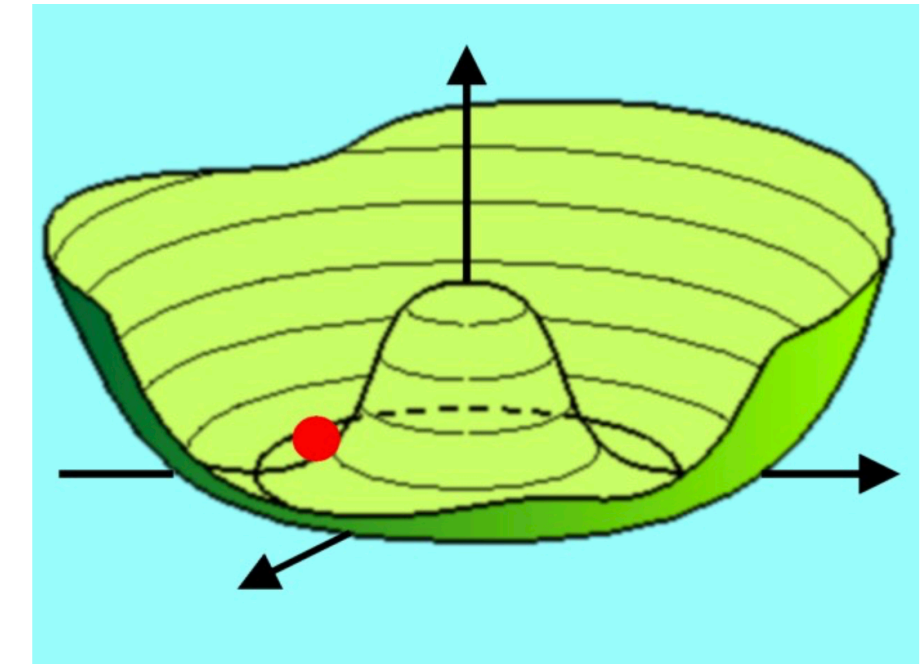


Pospelov et al, arXiv: hep-ph/9908508

Crewther et al, 1979

# The Strong CP Problem

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2} \partial^\mu a \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{v_{\text{PQ}}} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

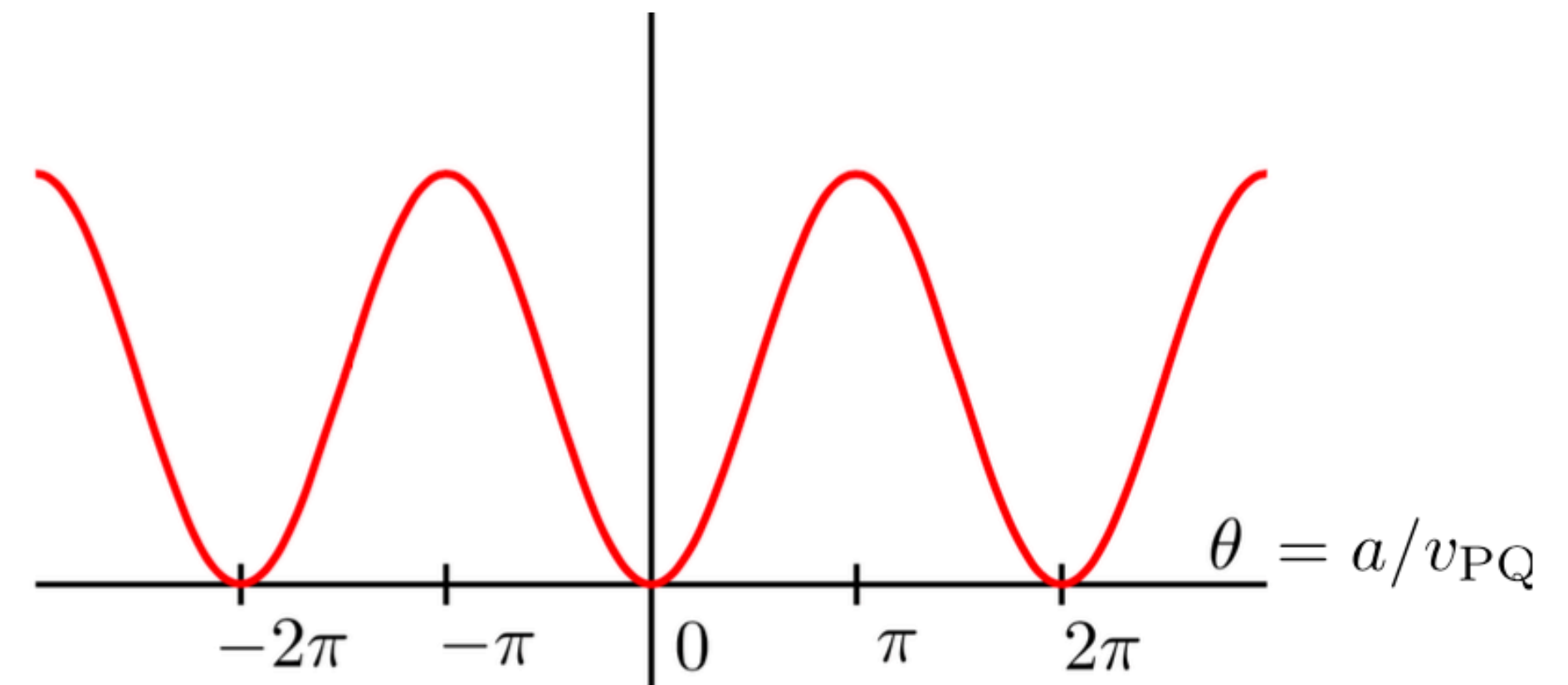


Di Vecchia et al, 1980

Leutwyler et al, 1992]

$$V(\theta) = m_\pi^2 f_\pi^2 \left( 1 - \frac{\sqrt{1 + z^2 + 2z \cos \theta}}{1 + z} \right)$$

$z \equiv m_u/m_d \approx 1/2$



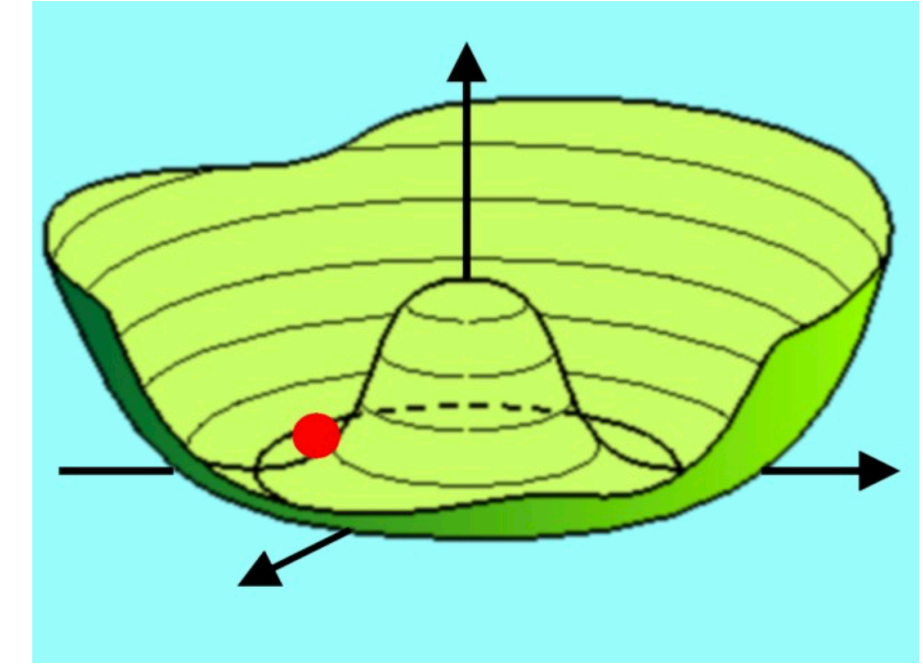
Promote  $\theta$  to a dynamical field

Credit: Ringwald

$$\langle \theta(x) \rangle = 0 \Rightarrow \text{nEDM vanishes}$$

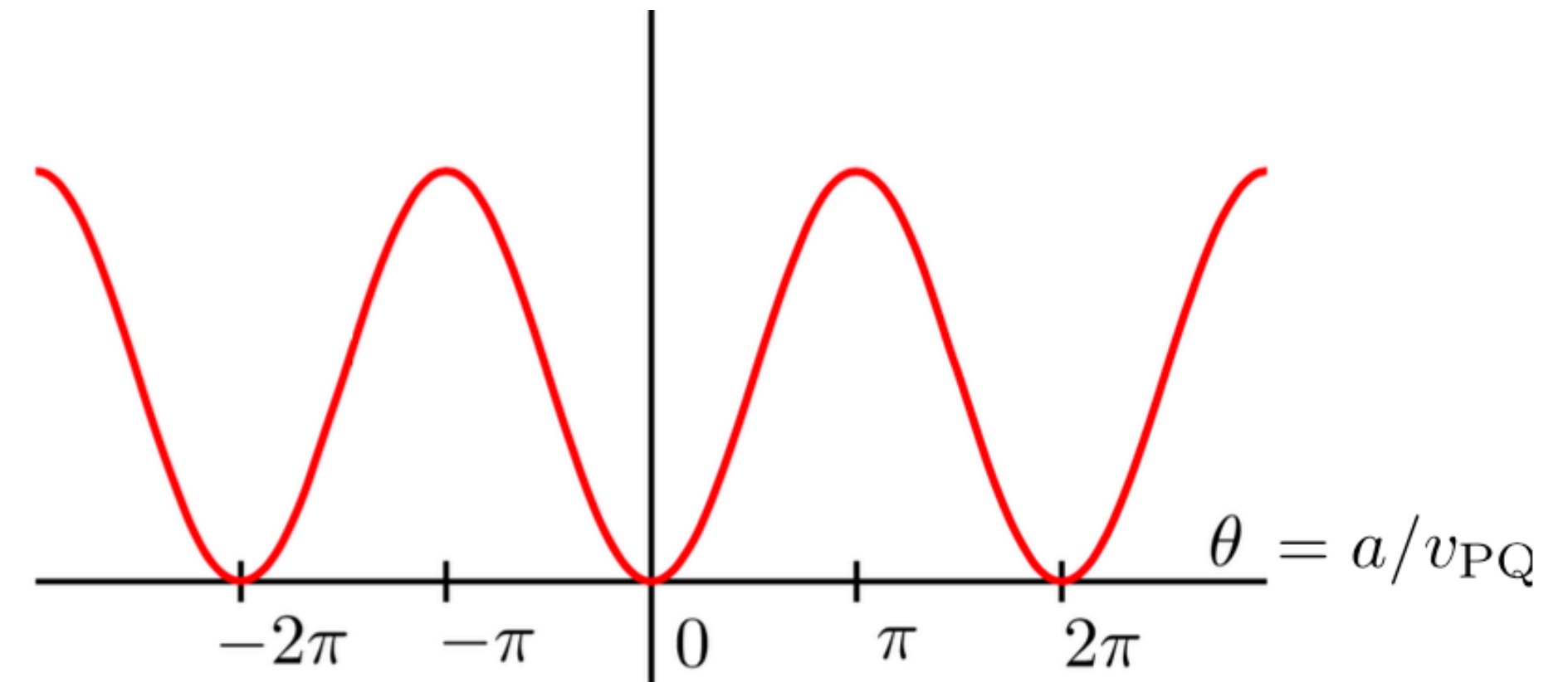
# The Strong CP Problem

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2} \partial^\mu a \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{v_{\text{PQ}}} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$



$$V(\theta) = m_\pi^2 f_\pi^2 \left( 1 - \frac{\sqrt{1 + z^2 + 2z \cos \theta}}{1 + z} \right)$$

$z \equiv m_u/m_d \approx 1/2$



$$m_a = \frac{\sqrt{V''(0)}}{v_{\text{PQ}}} = \frac{\sqrt{z}}{1 + z} \frac{m_\pi f_\pi}{v_{\text{PQ}}} \approx 6 \mu\text{eV} \left( \frac{10^{12} \text{ GeV}}{v_{\text{PQ}}} \right)$$



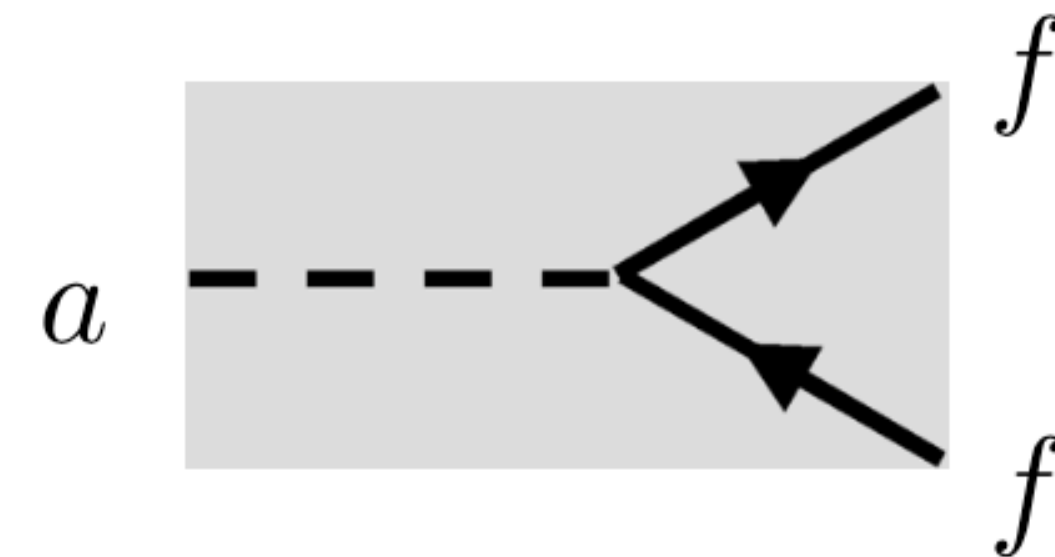
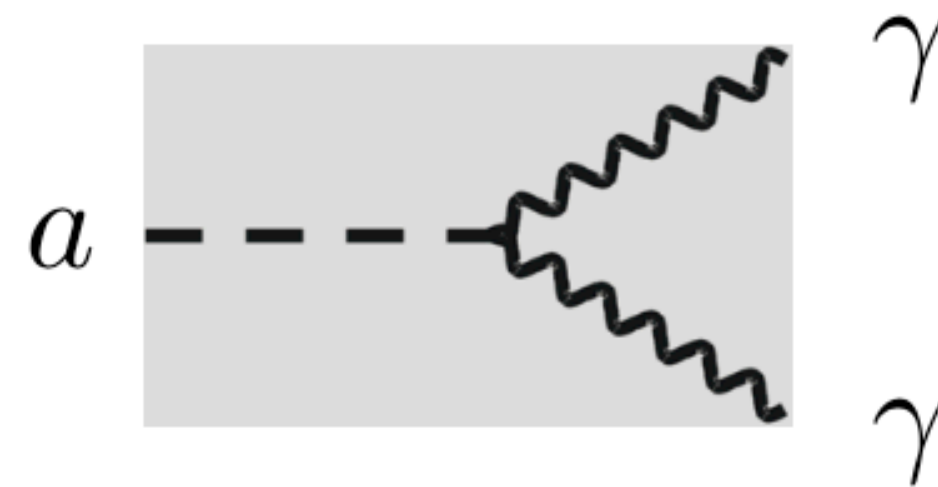
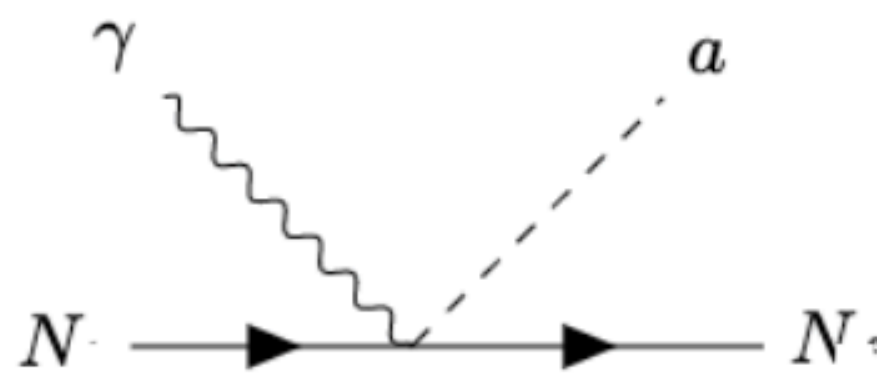
# The Effective Axion Coupling

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{i}{2} \frac{eC_{\text{NEDM}}}{f_a} a \bar{\psi}_N \sigma_{\mu\nu} \gamma_5 \psi_N F^{\mu\nu} + C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} C_{af} \frac{\partial_\mu a}{f_a} \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

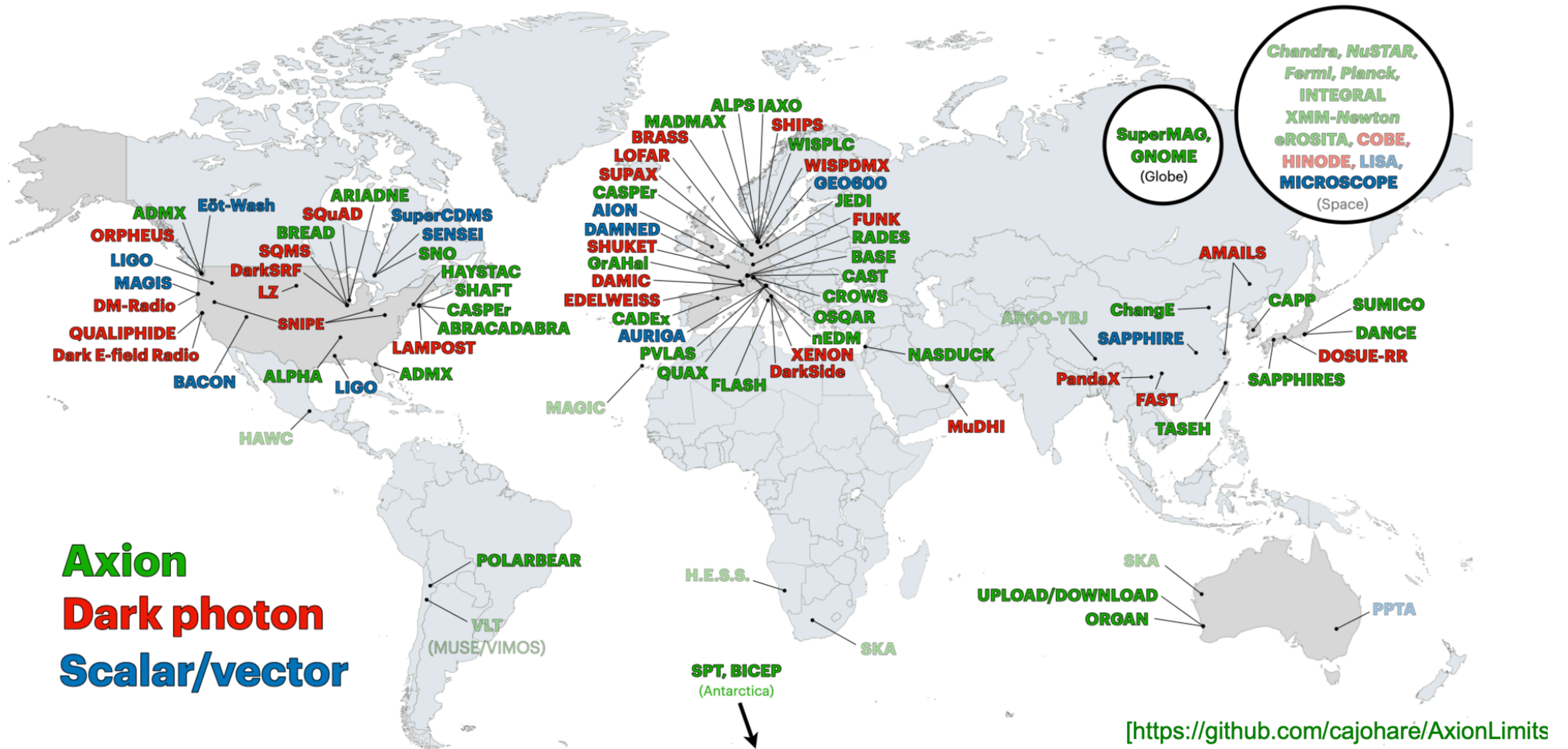
axion-nucleon coupling

axion-photon coupling

axion-fermion coupling



# The Axion Experiments



# The Misalignment Mechanism

A simple real scalar field

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 + \mathcal{L}_I$$

$$S = \int d^4x \sqrt{-g} \left( \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right)$$

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0.$$



# The Misalignment Mechanism

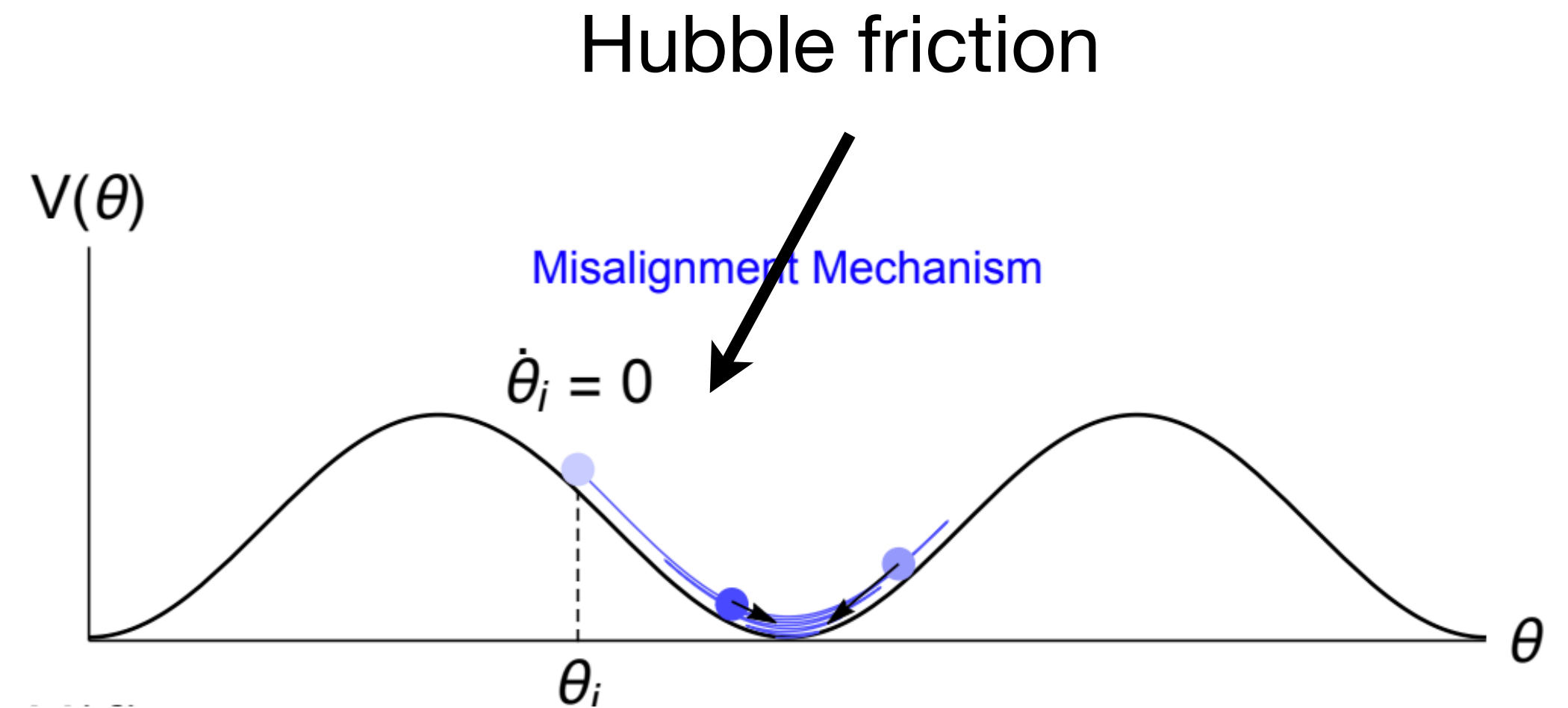
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$$S = \int d^4x \sqrt{-g} \left( \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right)$$

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0.$$

$$H \ll m_\phi \quad \phi \simeq \phi_1 \left( \frac{m_1 a_1^3}{m_\phi a^3} \right)^{1/2} \cos \left( \int_{t_1}^t m_\phi dt \right)$$

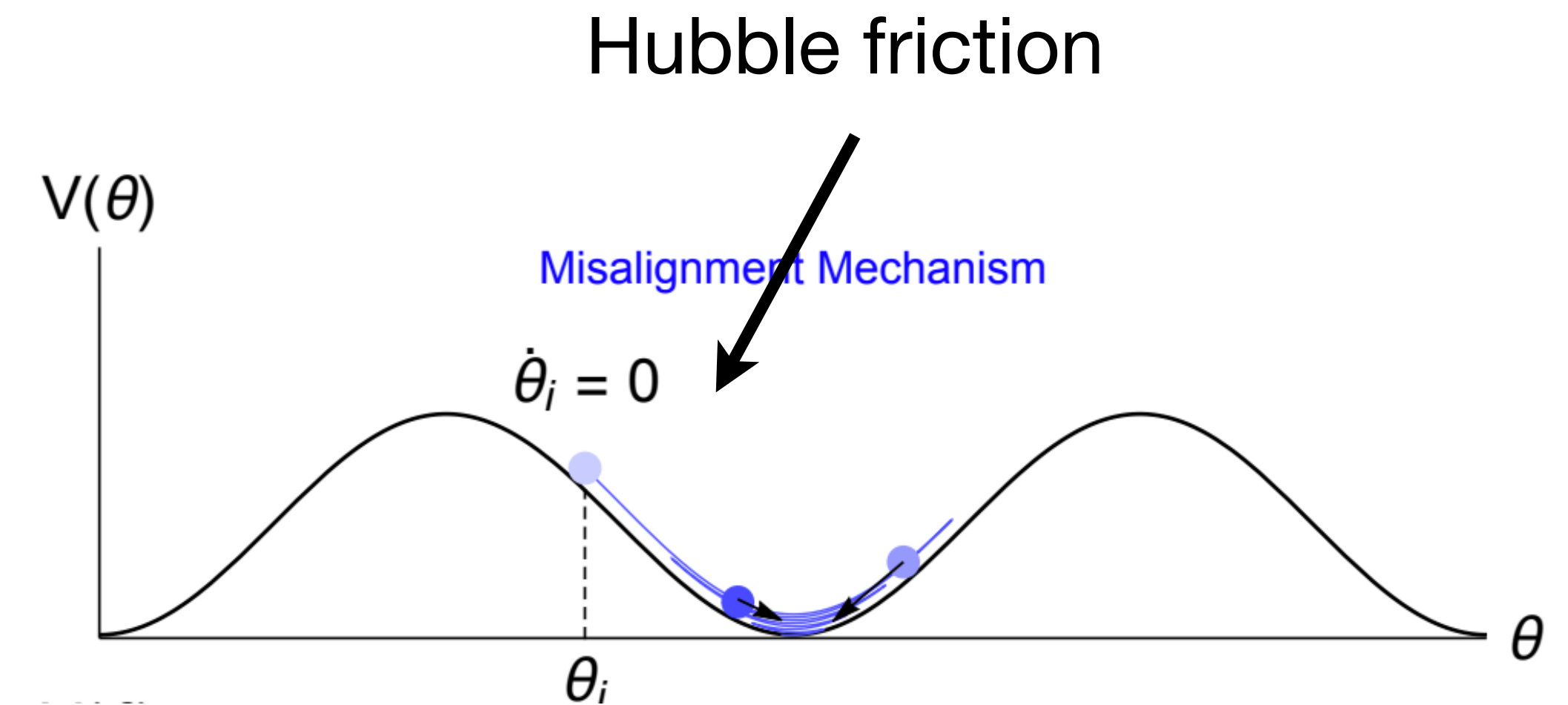
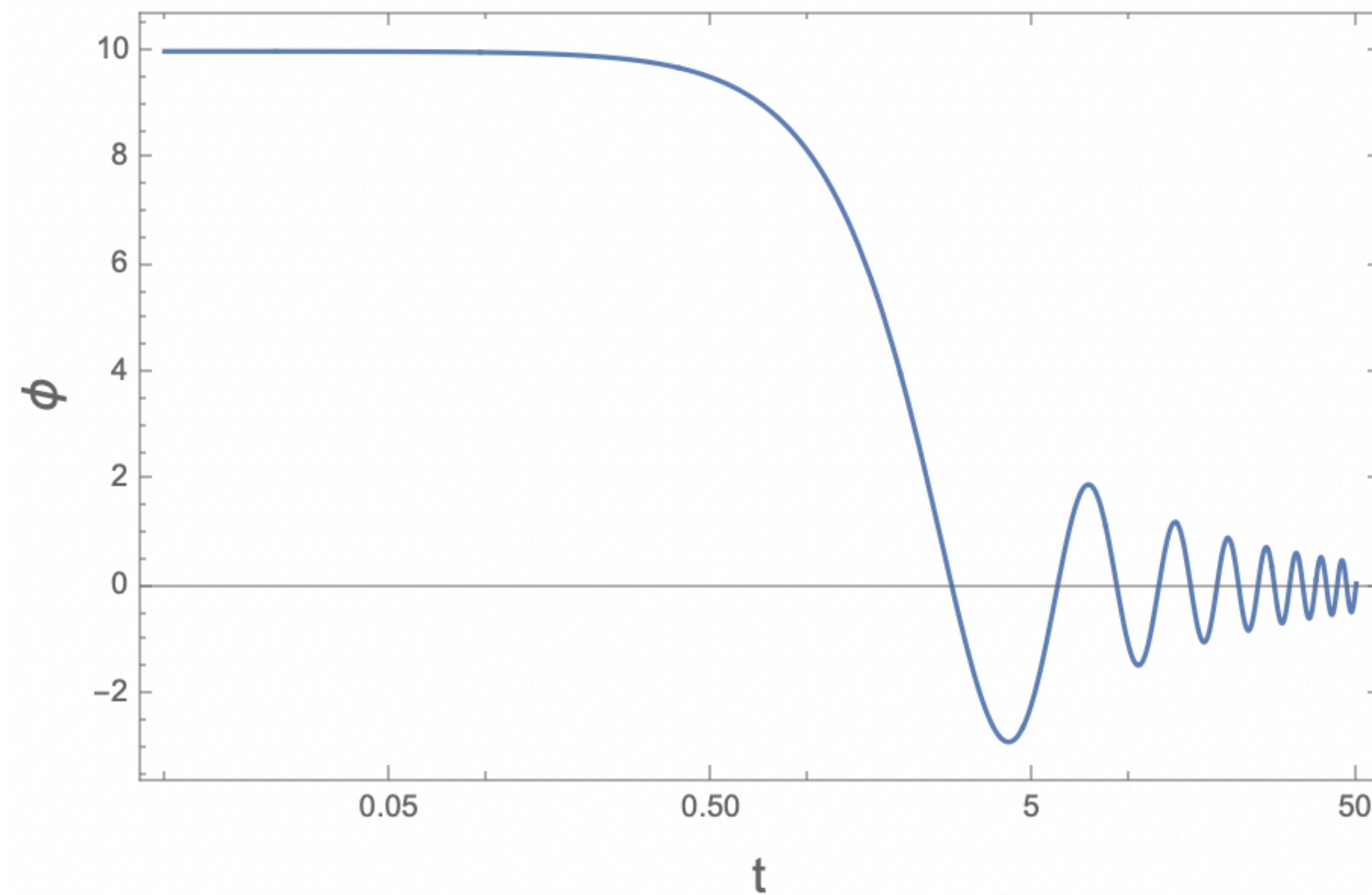


$H \gg m_\phi$ , the field is frozen

$H \ll m_\phi$ , the field oscillates

# The Misalignment Mechanism

$$H \ll m_\phi \quad \phi \simeq \phi_1 \left( \frac{m_1 a_1^3}{m_\phi a^3} \right)^{1/2} \cos \left( \int_{t_1}^t m_\phi dt \right)$$



$H \gg m_\phi$ , the field is frozen

$H \ll m_\phi$ , the field oscillates

# The Misalignment Mechanism

$$H \ll m_\phi \quad \phi \simeq \phi_1 \left( \frac{m_1 a_1^3}{m_\phi a^3} \right)^{1/2} \cos \left( \int_{t_1}^t m_\phi dt \right)$$

$$\mathcal{A}(t) = \dot{\phi}_1 (m_1 a_1^3 / m_\phi a^3)^{1/2}$$

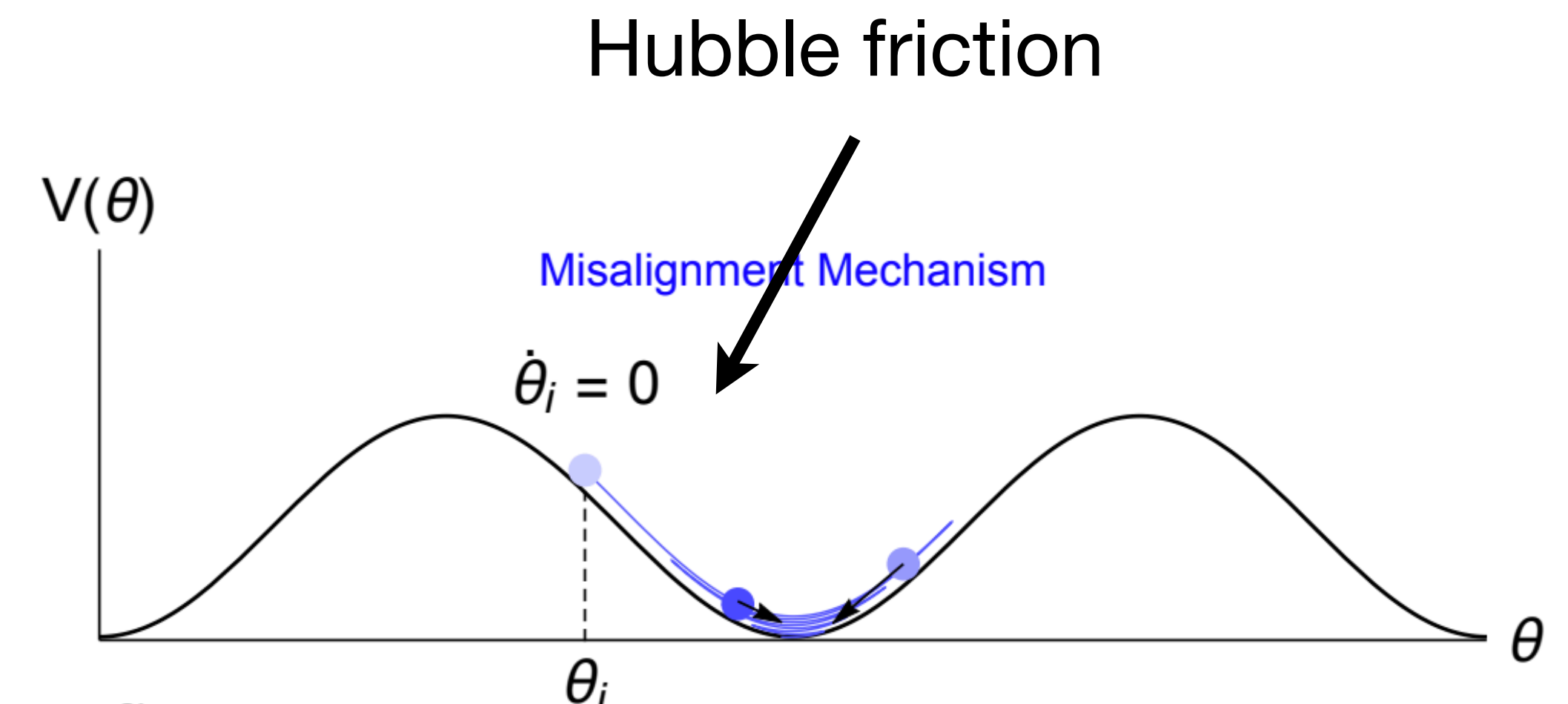
$$\rho_\phi = \frac{1}{2} \dot{\phi}^2 + \frac{1}{2} m_\phi^2 \phi^2 = \frac{1}{2} m_\phi^2 \mathcal{A}^2 + \dots$$

$$p_\phi = \frac{1}{2} \dot{\phi}^2 - \frac{1}{2} m_\phi^2 \phi^2 = -\frac{1}{2} m_\phi^2 \mathcal{A}^2 \cos(2\alpha) - \mathcal{A} \dot{\mathcal{A}} m_\phi \sin(2\alpha) + \dot{\mathcal{A}}^2 \cos^2(\alpha)$$

$$\langle p_\phi \rangle = \langle \dot{\mathcal{A}}^2 \cos^2(\alpha) \rangle = \frac{1}{2} \dot{\mathcal{A}}^2$$

$$w = \langle p \rangle / \langle \rho \rangle \simeq 0$$

The oscillating field behaves like matter



$H \gg m_\phi$ , the field is frozen

$H \ll m_\phi$ , the field oscillates



# The Misalignment Mechanism

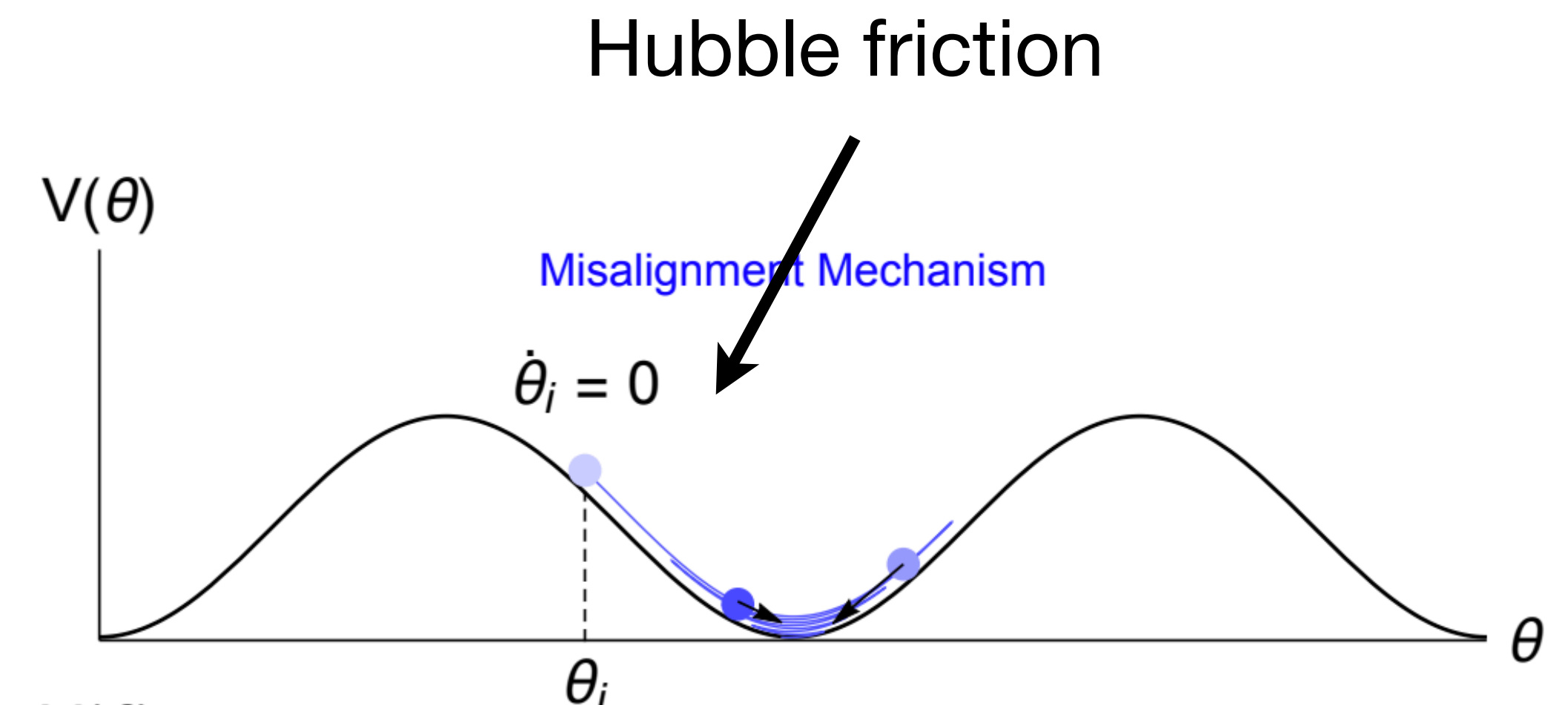
$$H \ll m_\phi \quad \phi \simeq \phi_1 \left( \frac{m_1 a_1^3}{m_\phi a^3} \right)^{1/2} \cos \left( \int_{t_1}^t m_\phi dt \right)$$

$$\mathcal{A}(t) = \dot{\phi}_1 (m_1 a_1^3 / m_\phi a^3)^{1/2}$$

$$\rho_\phi = \frac{1}{2} \dot{\phi}^2 + \frac{1}{2} m_\phi^2 \phi^2 = \frac{1}{2} m_\phi^2 \mathcal{A}^2 + \dots$$

$$N = \rho a^3 / m_\phi = \frac{1}{2} m_1 a_1^3 \phi_1^2$$

$$\rho_\phi(t_0) = m_0 \frac{N}{a_0^3} \simeq \frac{1}{2} m_0 m_1 \phi_1^2 \left( \frac{a_1}{a_0} \right)^3$$



$H \gg m_\phi$ , the field is frozen

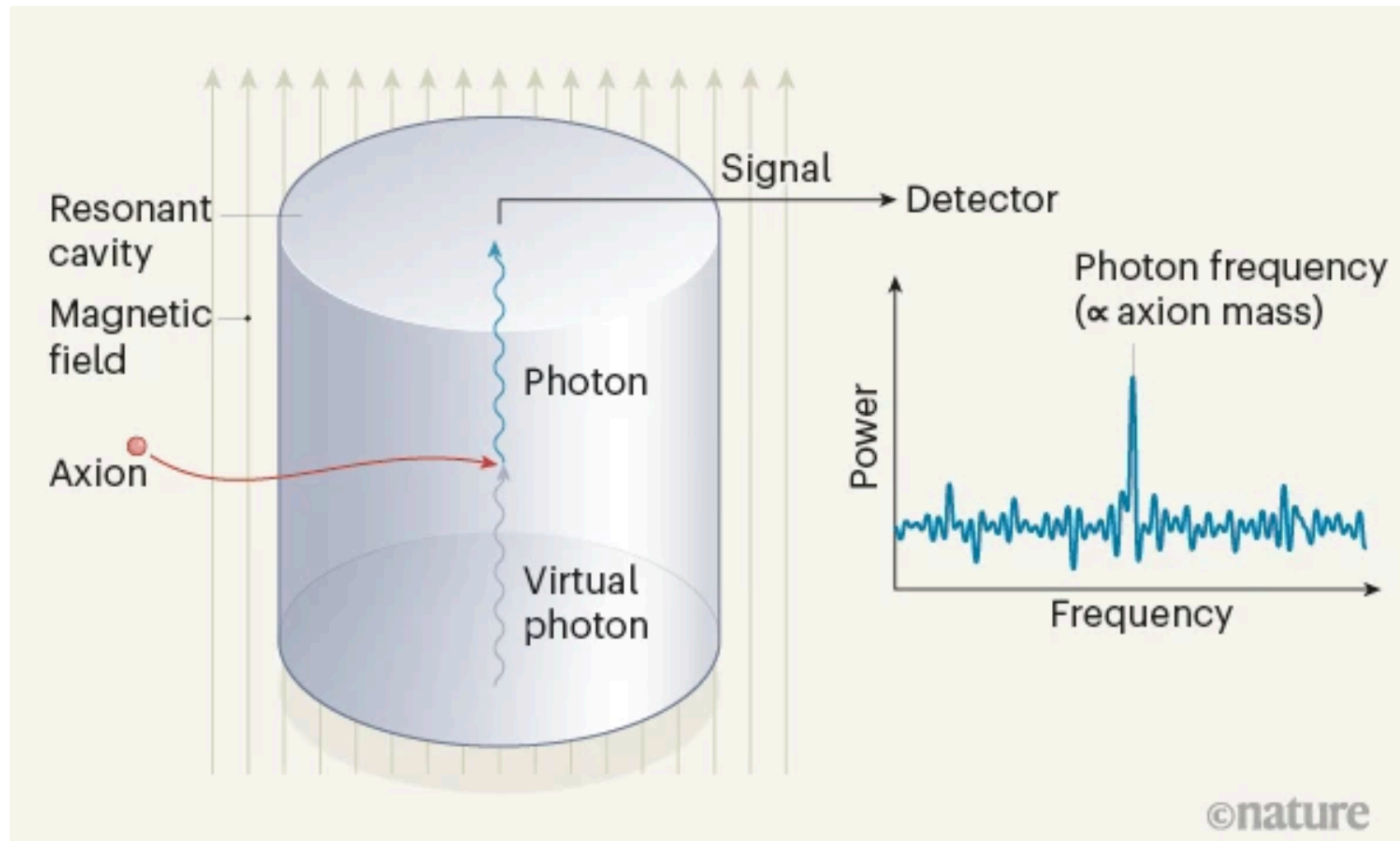
$H \ll m_\phi$ , the field oscillates

The oscillating field behaves like matter

See e.g. Arias et al, arXiv: 1201.5902

# The Axion Haloscope

Sikivie, 1983



Irastorza, Nature, 2021

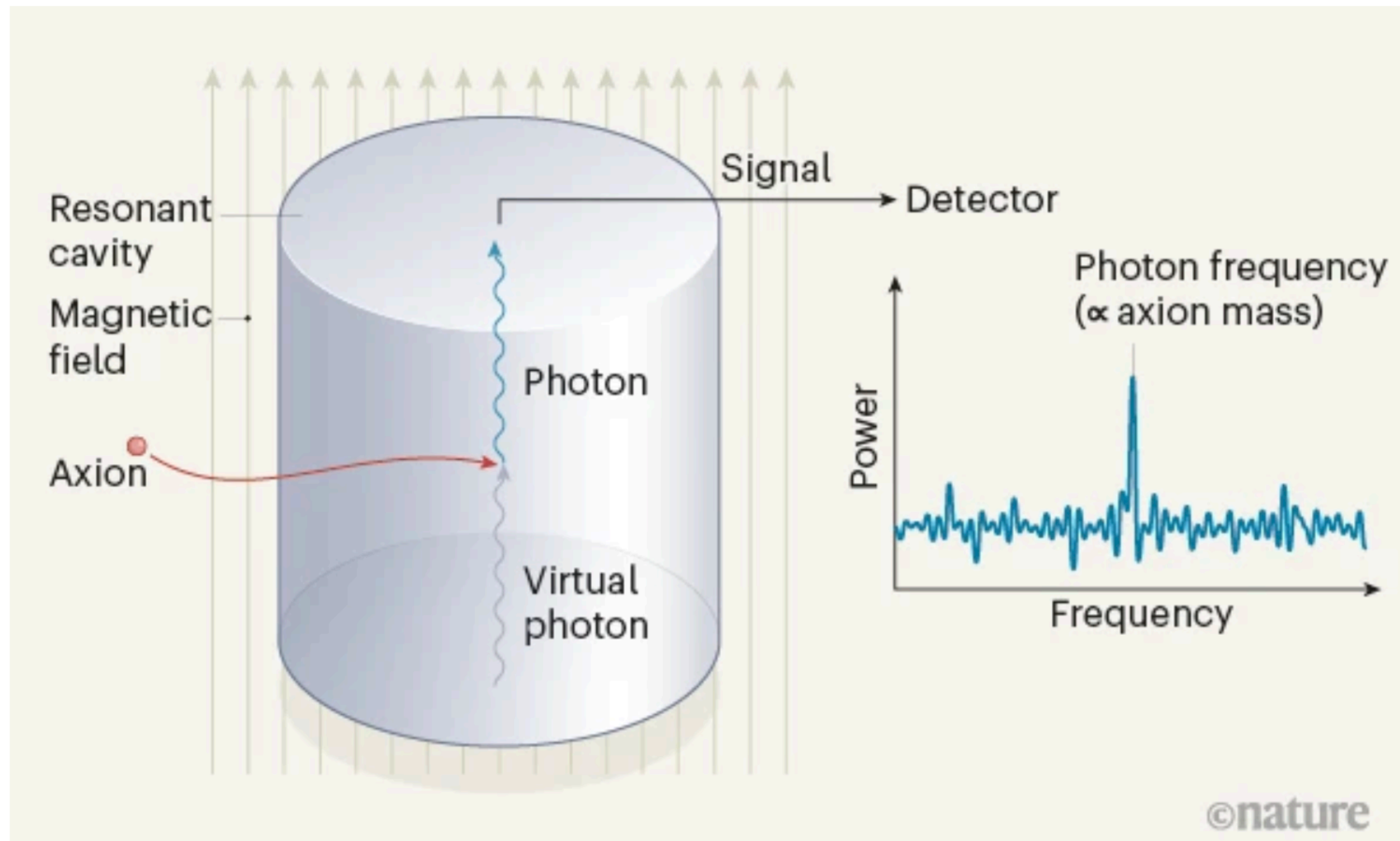
$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

$$g_{a\gamma\gamma} a(t, x) \mathbf{B}_0 \cdot \mathbf{E}$$

$$\ddot{\mathbf{E}} - \nabla^2 \mathbf{E} = g_{a\gamma\gamma} \ddot{a}(t) \mathbf{B}_0$$

Axion could convert to photons in the cavity when applying strong magnetic field

# The Axion Haloscope



Irastorza, Nature, 2021

$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Sikivie, 1983

$$P_{\text{out}} \sim g_{a\gamma}^2 \rho_a B_0^2 V Q$$

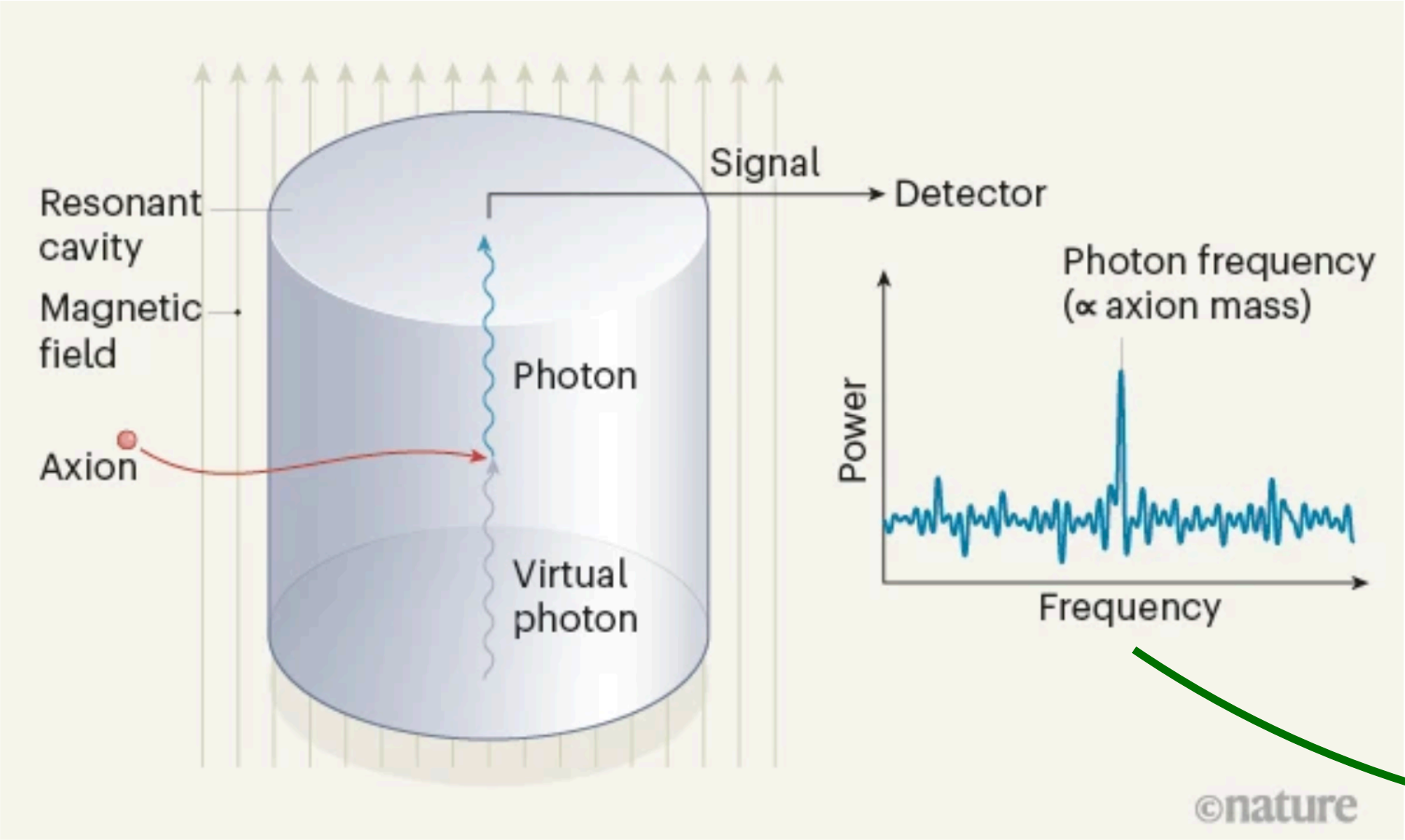
Quality factor  $\sim 10^5$

Axion could convert to photons in the cavity when applying strong magnetic field

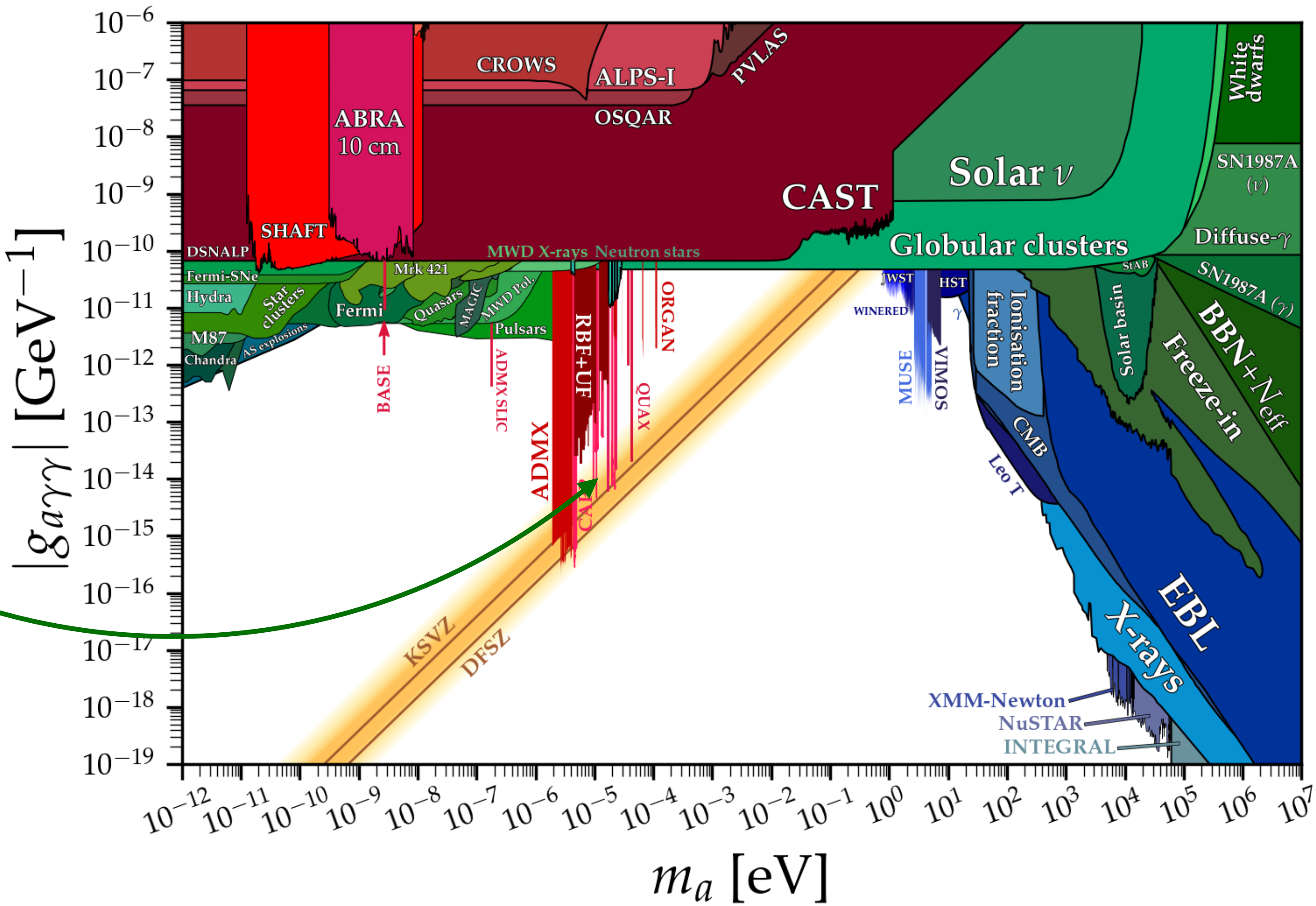


# Dark Matter Haloscopes

<https://raw.githubusercontent.com/cajohare/AxionLimits>



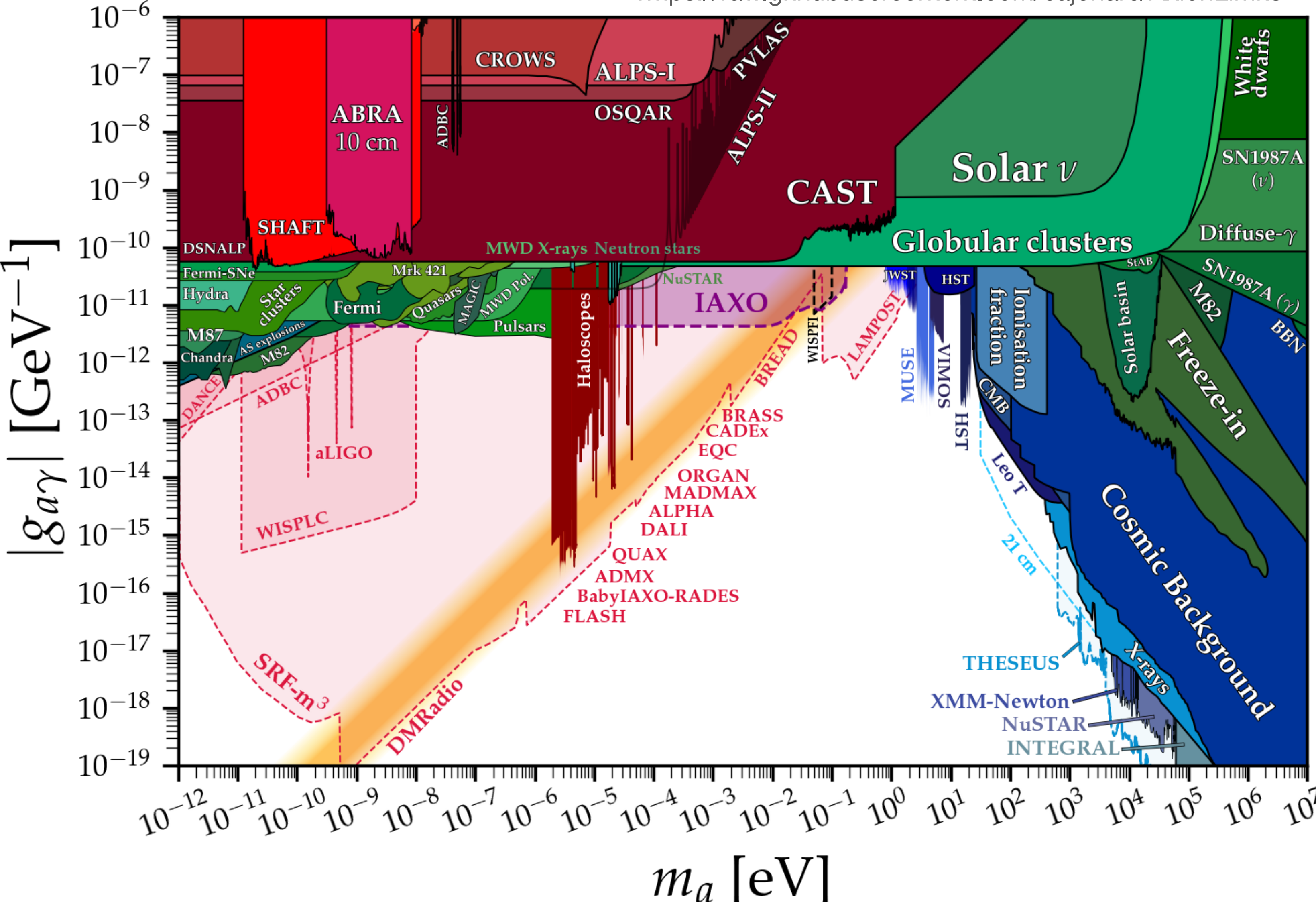
Irastorza, Nature 2021





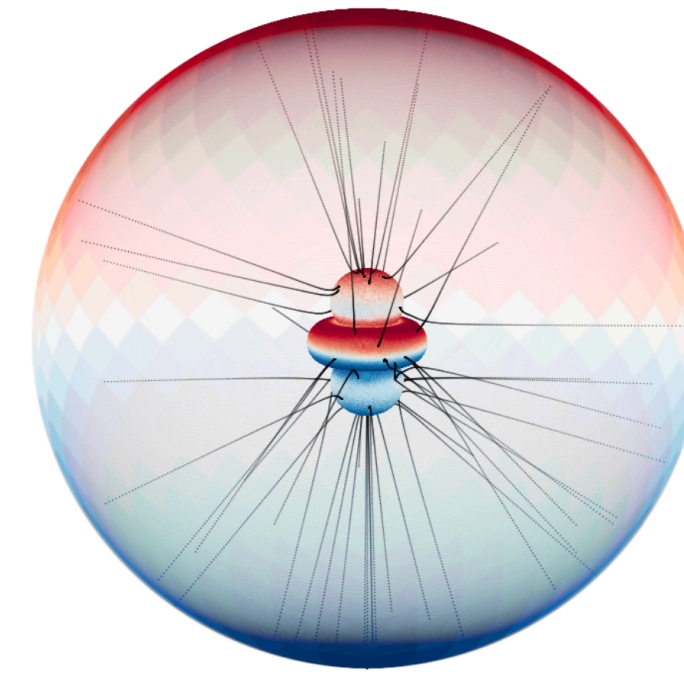
# Future Dark Matter Haloscopes

<https://raw.githubusercontent.com/cajohare/AxionLimits>

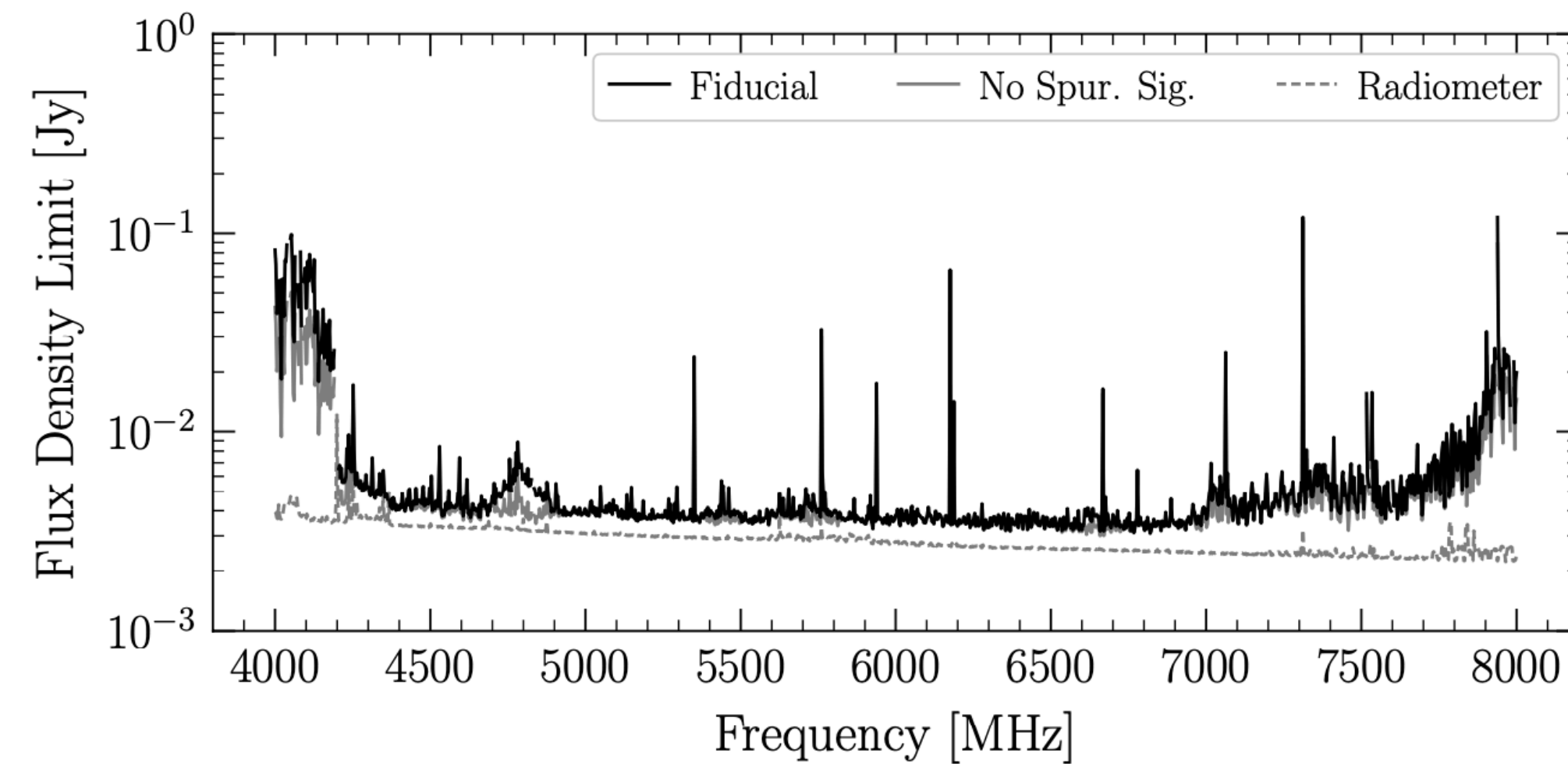




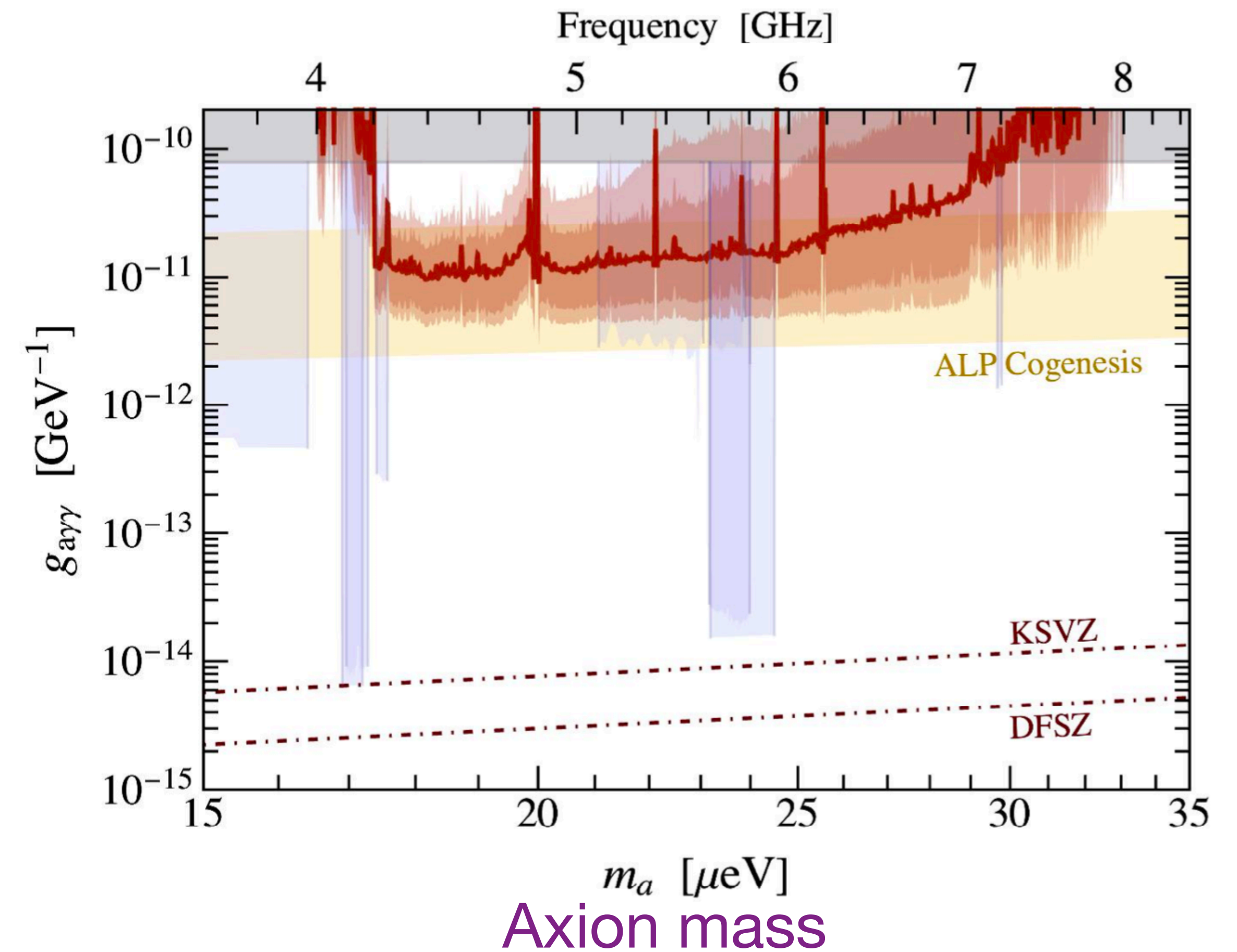
# Radio Observation Constraint



## Radio flux limit from the galactic center

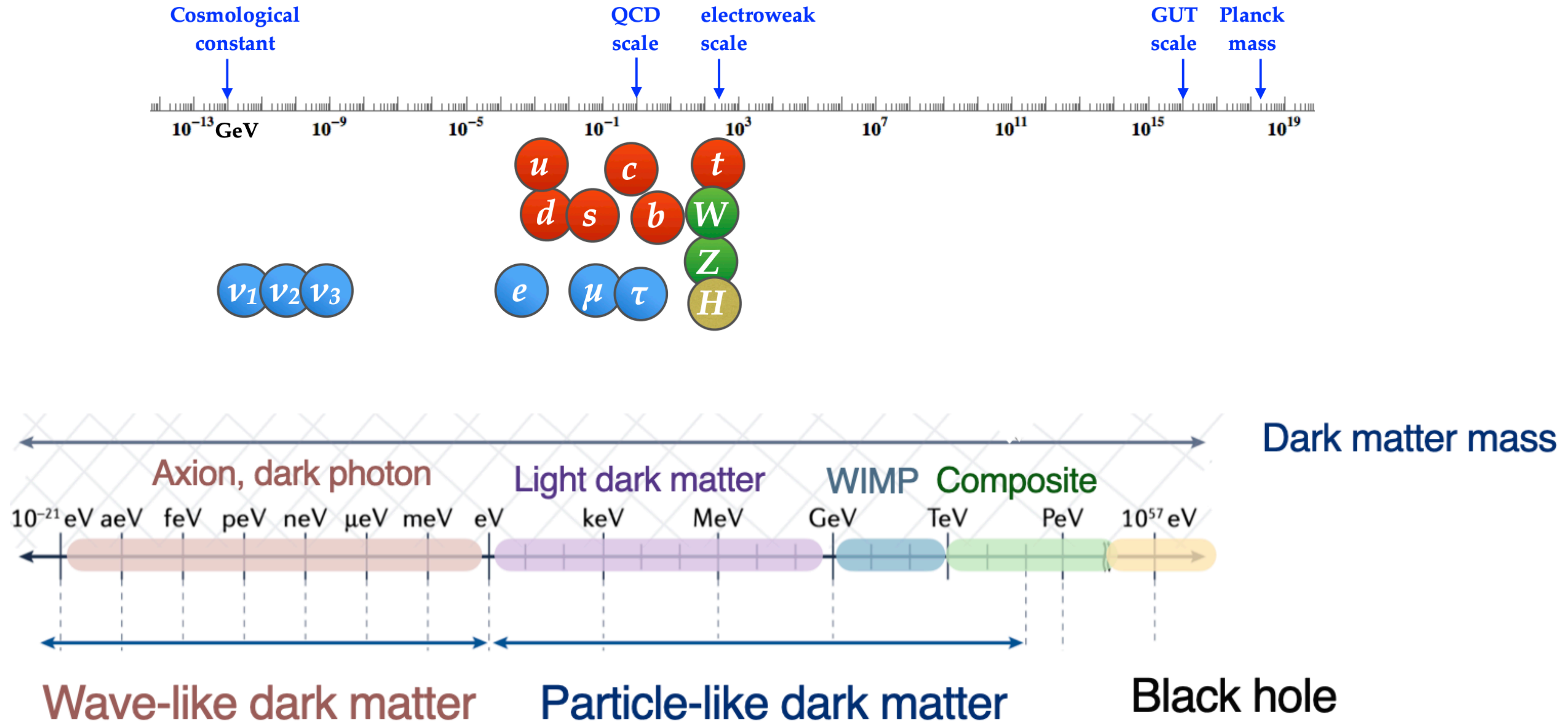


Foster et al 2202.08274





# Dark Matter Candidates



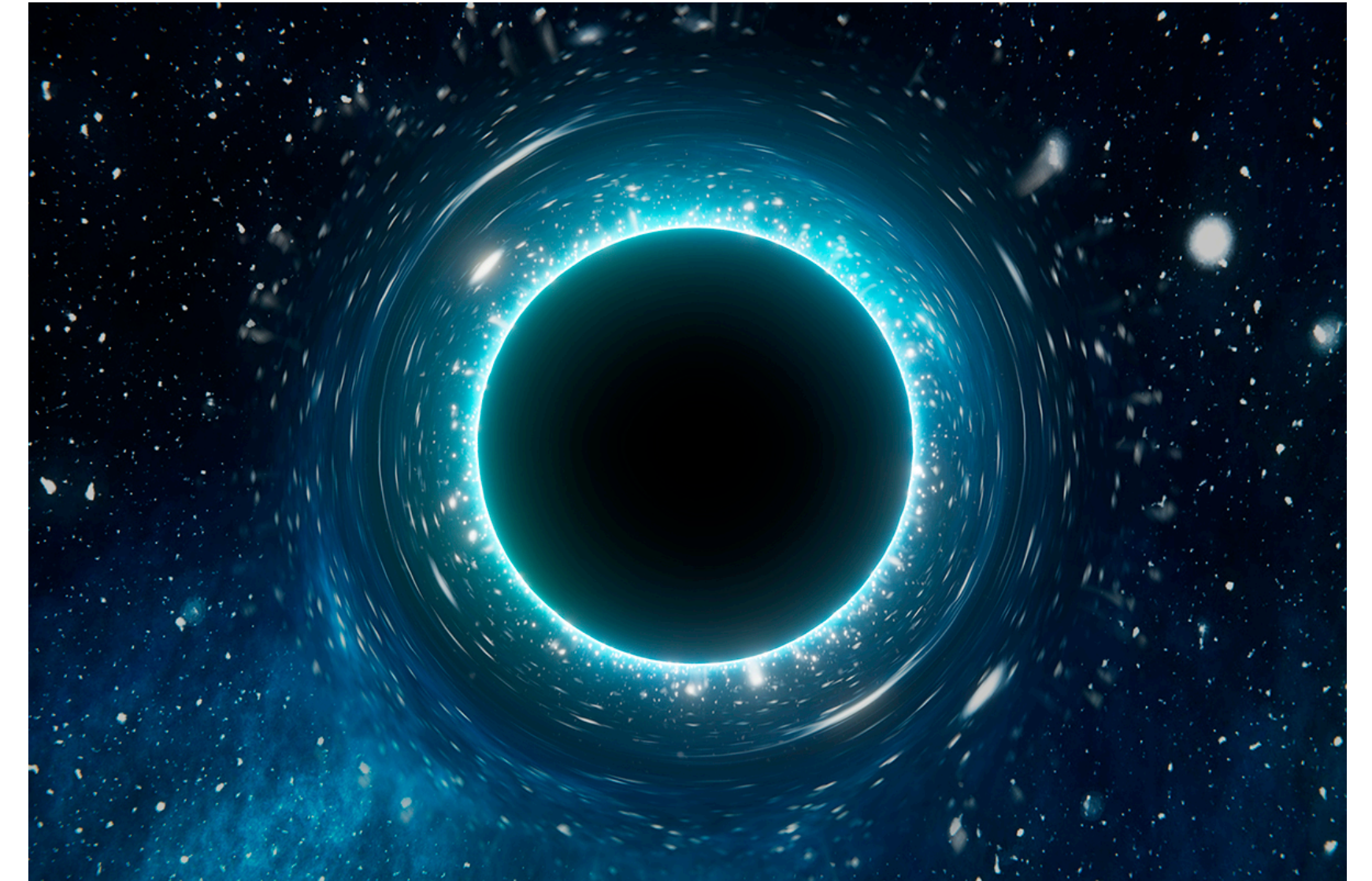
*Nature Viewpoint, 4, 637-641*

# Outline

- ❖ Introduction
- ❖ Particle-like dark matter
- ❖ Wave-like dark matter
- ❖ Primordial black hole as dark matter

# Primordial Black Hole Dark Matter

- Primordial perturbations reenter the horizon, if the overdensity is larger than the critical value,  $\delta > \delta_c$ , the overdense regions may collapse into black holes





# Primordial Black Hole Dark Matter

- Primordial perturbations reenter the horizon, if the overdensity is larger than the critical value,  $\delta > \delta_c$ , the overdense regions may collapse into black holes

$$M_{\text{PBH}}(k) = \gamma \frac{4\pi}{3} \rho H^{-3} \Big|_{k=aH}$$

$$M_{\text{PBH}}(k) \sim 5 \times 10^{15} \text{g} \left( \frac{g_{\star,0}}{g_{\star,i}} \right)^{\frac{1}{6}} \left( \frac{10^{15} \text{Mpc}^{-1}}{k} \right)^2$$

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Initial BH fraction  $\beta(M_{\text{PBH}}) = \frac{\rho_{\text{PBH},i}}{\rho_{\text{total},i}}$

$$\beta(M_{\text{PBH}}) = \frac{\Omega_{\text{PBH},0}(M_{\text{PBH}})}{\Omega_{r,0}^{\frac{3}{4}} \gamma^{\frac{1}{2}}} \left( \frac{g_{\star,i}}{g_{\star,0}} \right)^{\frac{1}{4}} \left( \frac{M_{\text{PBH}}}{M_{H0}} \right)^{\frac{1}{2}}$$

$$f_{\text{PBH}} = \frac{\beta(M_{\text{PBH}}) \Omega_{r,0}^{\frac{3}{4}} \gamma^{\frac{1}{2}}}{\Omega_{\text{CDM},0}} \left( \frac{g_{\star,i}}{g_{\star,0}} \right)^{-\frac{1}{4}} \left( \frac{M_{\text{PBH}}}{M_{H0}} \right)^{-\frac{1}{2}}$$

# Primordial Black Hole Dark Matter

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Initial BH fraction  $\beta(M_{\text{PBH}}) = \frac{\rho_{\text{PBH},i}}{\rho_{\text{total},i}}$

$$\beta(M_{\text{PBH}}) = \text{Erfc} \left( \frac{\delta_c}{\sqrt{2}\sigma(R)} \right)$$

$$\sigma^2(R) = \int \tilde{W}^2(kR) \mathcal{P}_\delta(k) \frac{dk}{k}$$

$$\mathcal{P}_\delta(k) = 4 \left( \frac{1+w}{5+3w} \right)^2 \mathcal{P}_{\mathcal{R}}(k)$$



# Primordial Black Hole Dark Matter

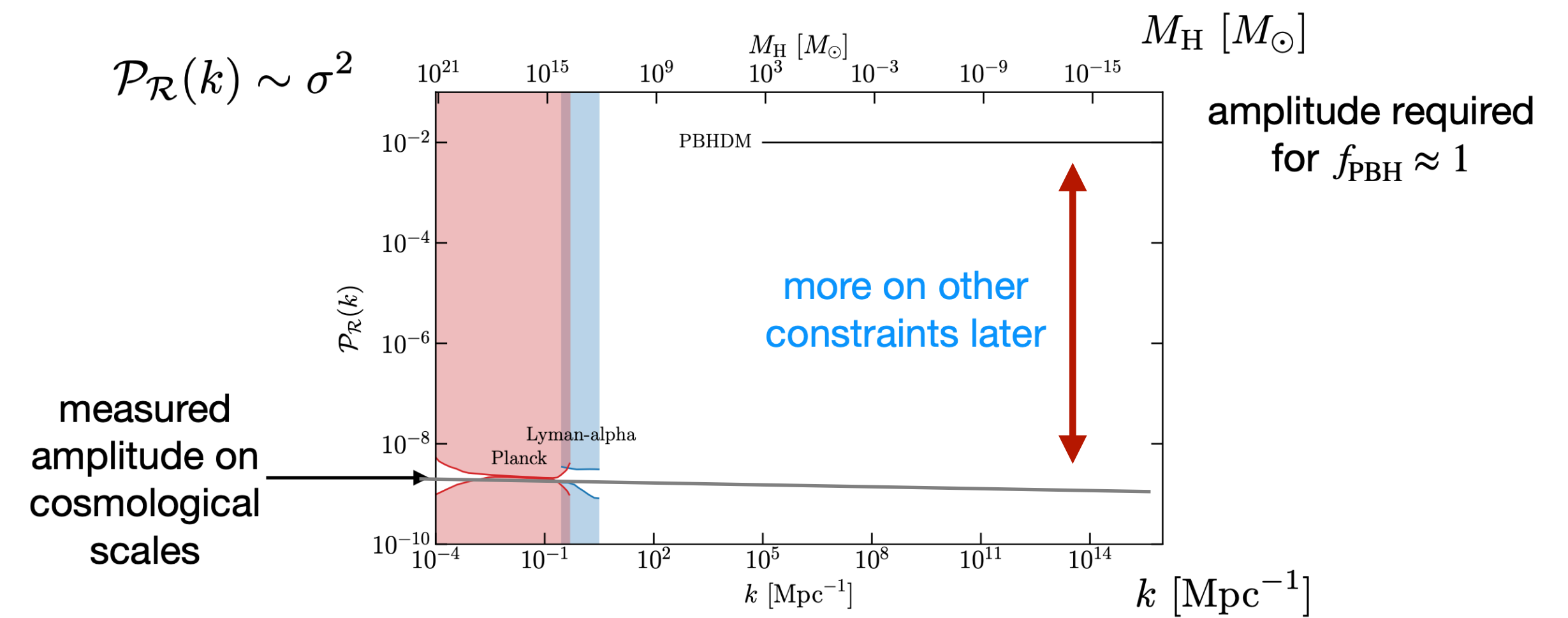
- Primordial perturbations reenter the horizon, if the overdensity is larger than the critical value,  $\delta > \delta_c$ , the overdense regions may **collapse into black holes**

$$M_{\text{PBH}}(k) \sim 5 \times 10^{15} \text{g} \left( \frac{g_{\star,0}}{g_{\star,i}} \right)^{\frac{1}{6}} \left( \frac{10^{15} \text{Mpc}^{-1}}{k} \right)^2$$

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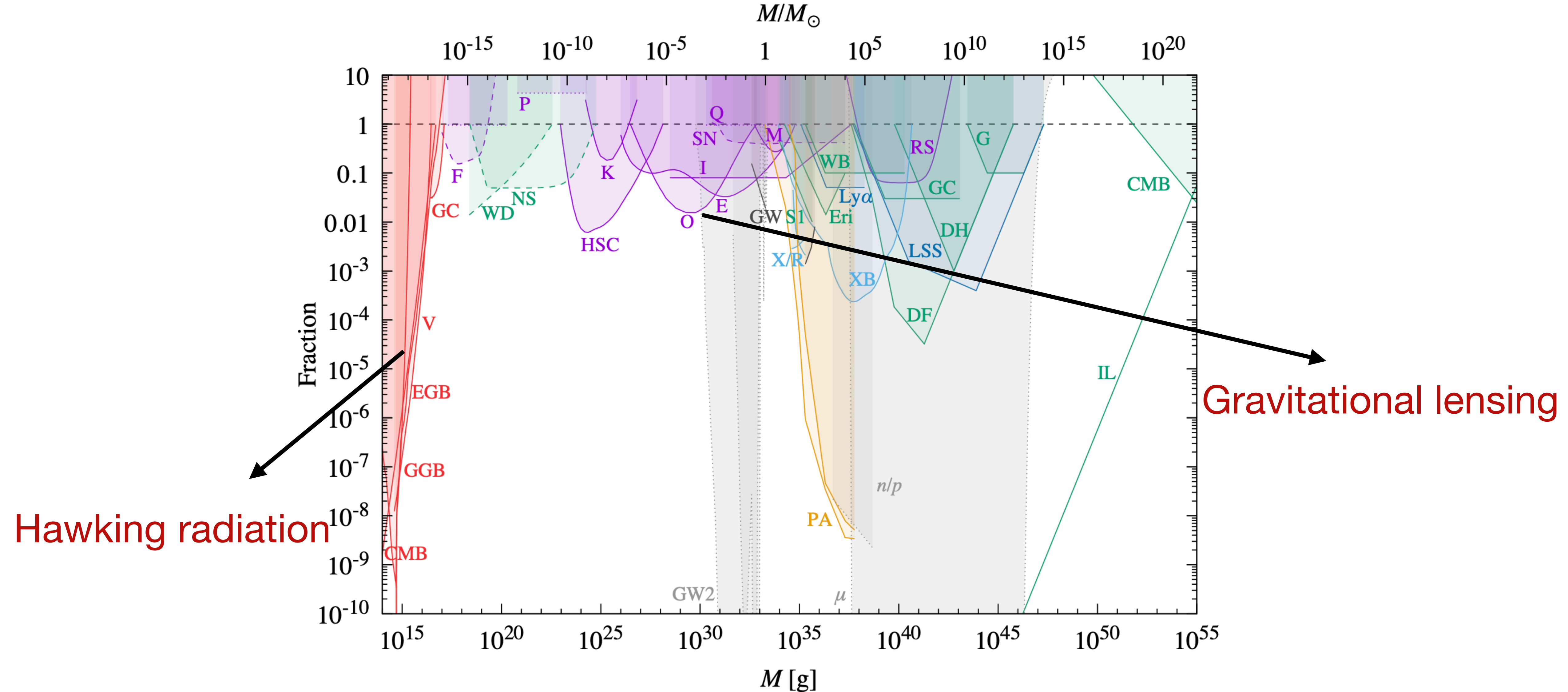
At  $k \sim 0.05 \text{ Mpc}^{-1}$ ,  $P_R \sim 2.1 \times 10^{-9}$ , much less than the requirement  $\mathcal{O}(10^{-2})$ , curvature perturbation needed!



See e.g. arXiv:2208.14279

# Constraints on PBH Dark Matter

Carr, Kohri, Sendouda, Yokoyama, arXiv:2002.12778



# Summary

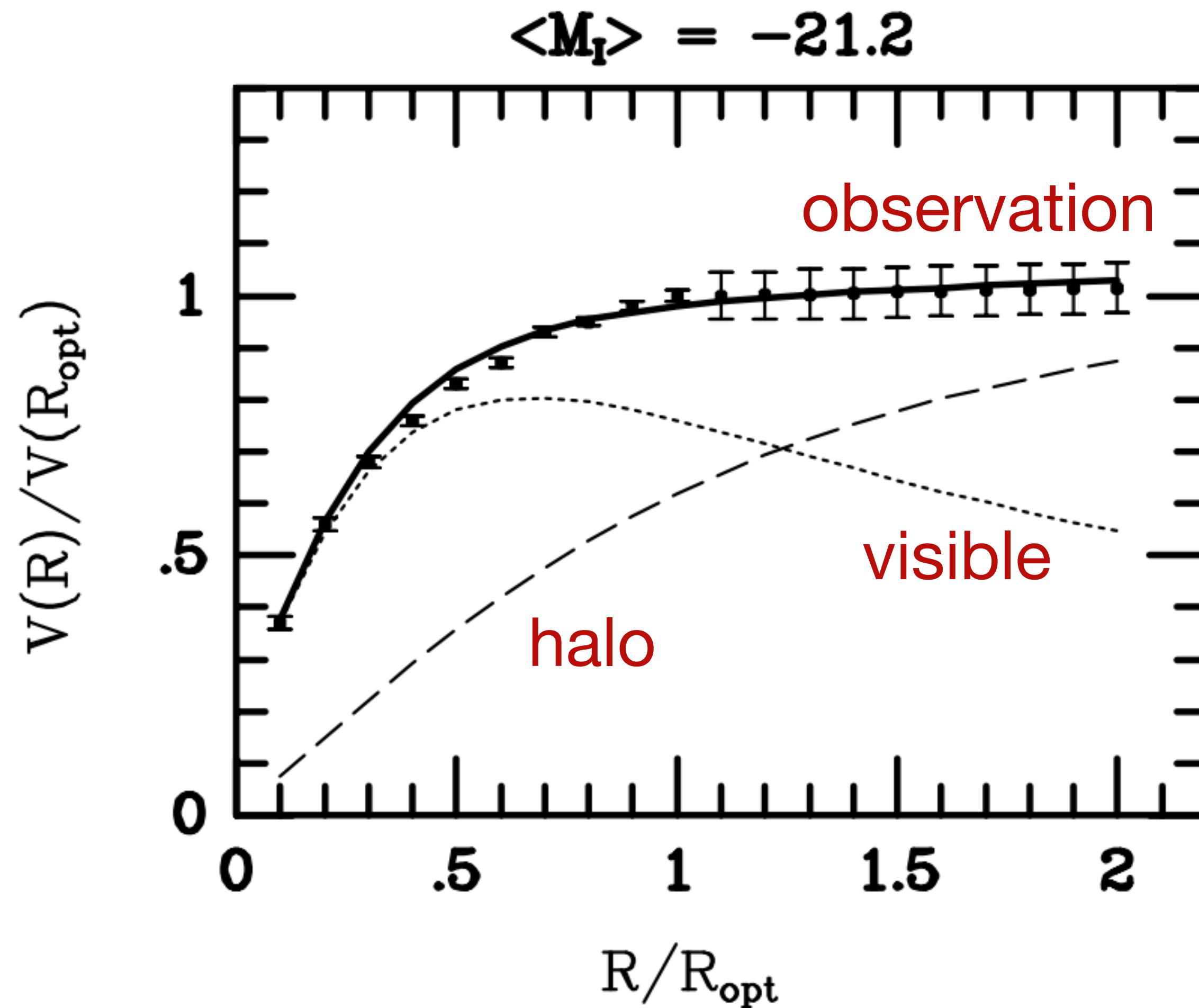
- ❖ Introduction
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# Thanks

# Back up

# Dark Matter Distribution



Persic et al MNRAS 1996

## Milky Way

$$M_{\text{halo}} \sim 10^{12} M_{\odot}$$

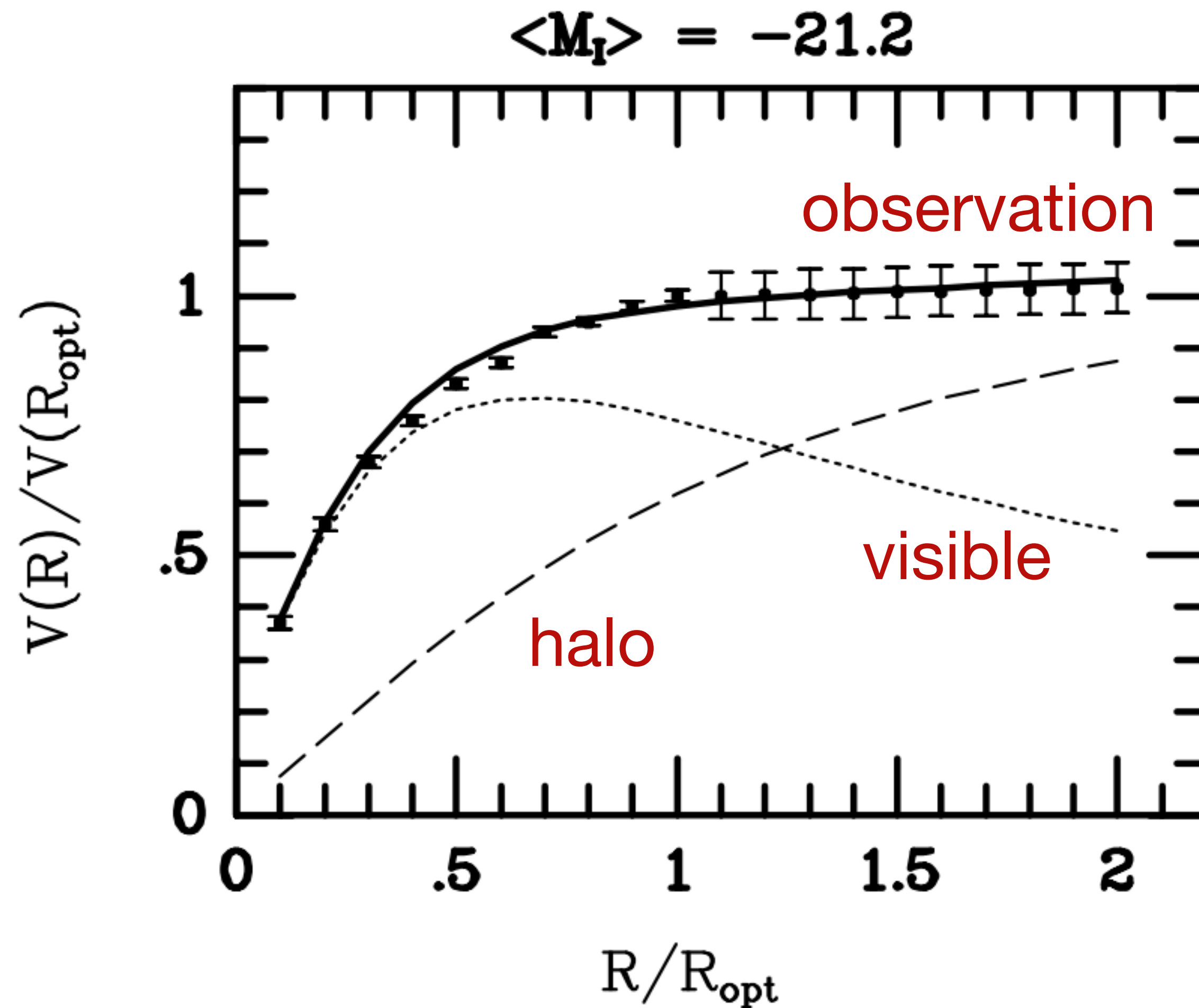
$$\rho_0 \sim 0.3 \text{ GeV/cm}^3$$

$$M_{\text{halo}} \sim 4\pi \int_0^{R_{\text{halo}}} dr r^2 \rho(r) \longrightarrow R_{\text{halo}} ??$$

$$\langle v \rangle \sim \sqrt{\frac{GM_{\text{halo}}}{R_{\text{halo}}}} \quad ??$$



# Dark Matter Distribution



Persic et al MNRAS 1996

## Milky Way

$$M_{\text{halo}} \sim 10^{12} M_{\odot}$$

$$\rho_0 \sim 0.3 \text{ GeV/cm}^3$$

$$M_{\text{halo}} \sim 4\pi \int_0^{R_{\text{halo}}} dr r^2 \rho(r) \longrightarrow R_{\text{halo}} \sim 100 \text{ kpc}$$

$$\langle v \rangle \sim \sqrt{\frac{GM_{\text{halo}}}{R_{\text{halo}}}} \sim 200 \text{ km/s}$$

# Dark Matter Distribution

Boltzmann equation of the phase space

$$\mathbf{L}[f] = \mathbf{C}[f]$$

$$\frac{\partial f}{\partial t} + \dot{\mathbf{x}} \frac{\partial f}{\partial \mathbf{x}} + \dot{\mathbf{v}} \frac{\partial f}{\partial \mathbf{v}} = 0 \quad \leftarrow \text{assuming DM is collisionless}$$

# Dark Matter Distribution

## Boltzmann equation of the phase space

Binney, Galactic Dynamics

$$\mathbf{L}[f] = \mathbf{C}[f]$$

$$\frac{\partial f}{\partial t} + \dot{\mathbf{x}} \frac{\partial f}{\partial \mathbf{x}} + \dot{\mathbf{v}} \frac{\partial f}{\partial \mathbf{v}} = 0$$

**Jeans theorem** *Any steady-state solution of the collisionless Boltzmann equation depends on the phase-space coordinates only through integrals of motion in the given potential, and any function of the integrals yields a steady-state solution of the collisionless Boltzmann equation.*

$$f(\mathbf{x}, \mathbf{v}) = f(\mathcal{E})$$

$$\mathcal{E} = \Psi - \frac{1}{2}v^2$$

Let's guess!

$$f(\mathcal{E}) \propto e^{\mathcal{E}}$$



# Dark Matter Distribution

Boltzmann equation of the phase space

$$\mathbf{L}[f] = \mathbf{C}[f] \qquad f(\mathbf{x}, \mathbf{v}) = f(\mathcal{E}) \qquad \mathcal{E} = \Psi - \frac{1}{2}v^2$$

$$\frac{\partial f}{\partial t} + \dot{\mathbf{x}} \frac{\partial f}{\partial \mathbf{x}} + \dot{\mathbf{v}} \frac{\partial f}{\partial \mathbf{v}} = 0 \qquad f(\mathcal{E}) \propto e^{\mathcal{E}}$$

$$\rho \propto \int_0^\infty dv v^2 f(v) = \int_0^\infty dv v^2 \exp\left(\frac{\Psi - v^2/2}{\sigma^2}\right) \propto e^{\Psi/\sigma^2}$$

# Dark Matter Distribution

Boltzmann equation of the phase space

$$\mathbf{L}[f] = \mathbf{C}[f] \qquad f(\mathbf{x}, \mathbf{v}) = f(\mathcal{E}) \qquad \mathcal{E} = \Psi - \frac{1}{2}v^2$$

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$$\nabla^2 \Psi = -4\pi G \rho \longrightarrow \rho(r) = \frac{\sigma^2}{2\pi G r^2} \qquad \rho(r) \propto 1/r^2$$

# Dark Matter Distribution

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$$M_{\text{halo}} \sim 4\pi \int_0^{R_{\text{halo}}} dr r^2 \rho(r) \longrightarrow R_{\text{halo}}$$

$$\langle v \rangle \sim \sqrt{\frac{GM_{\text{halo}}}{R_{\text{halo}}}}$$

$$M(r) = \frac{2\sigma^2 r}{G}$$

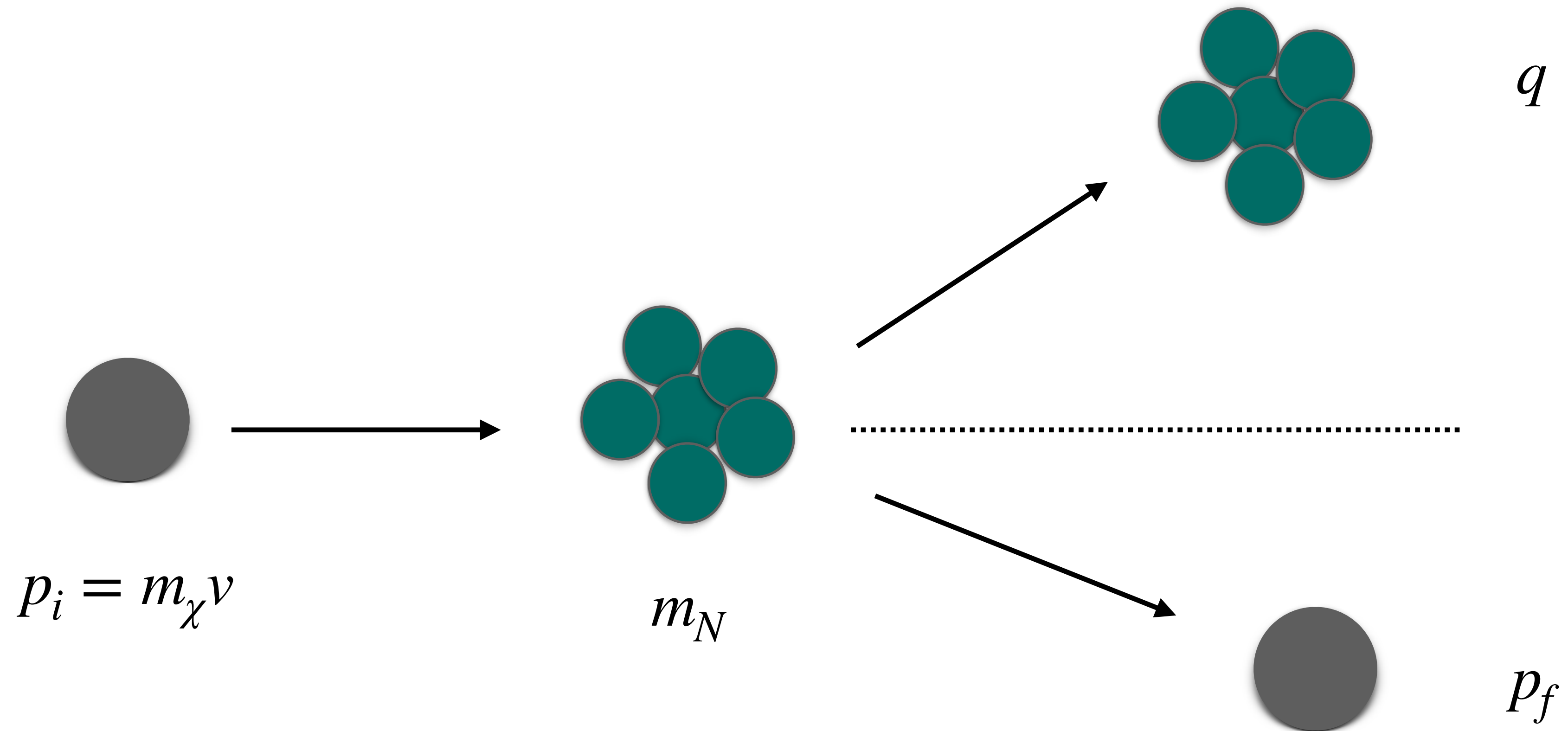
$$v_0 = v_c = \sqrt{2}\sigma$$

Maxwell-Boltzmann distribution

$$f \sim \frac{1}{(\pi v_0)^{3/2}} e^{-v^2/v_0^2}$$

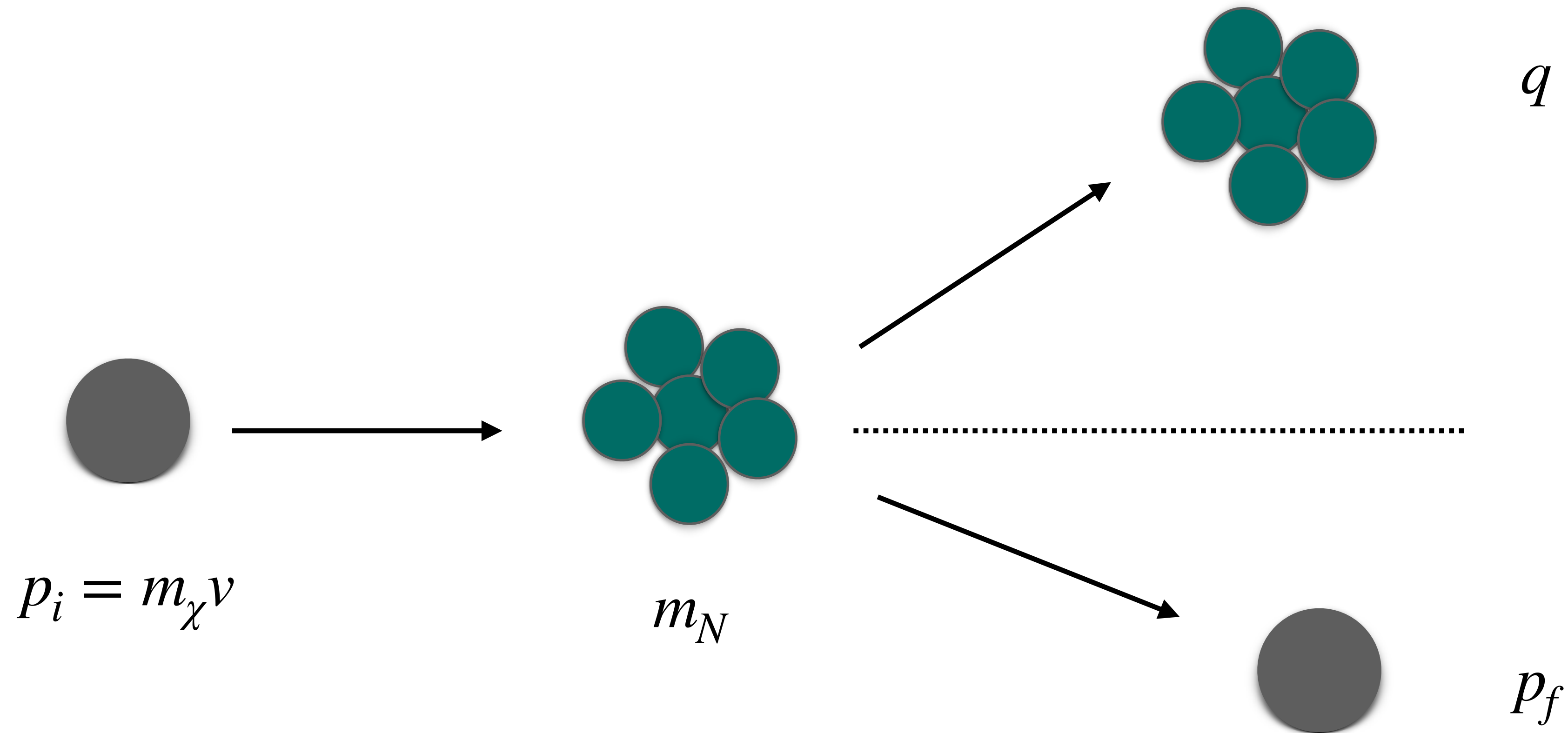


# Exercise: Kinematics



Recoil energy of the nucleus?

# Kinematics



$$q = 2\mu_{\chi N} v \cos \theta$$

$$v \sim 300 \text{ km/s} \sim 10^{-3} c$$

$$\mu_{\chi N} = \frac{m_\chi m_N}{m_\chi + m_N} \sim m_N \quad \text{if } m_\chi \gg m_N$$

$$E_R \sim 50 \text{ keV} \quad \text{if } m_N \sim 50 \text{ GeV}$$

# The Form Factors

$$\sigma_{\chi N} = \sigma_{\chi p} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \frac{(Zf_p + (A - Z)f_n)^2}{f_p^2} F^2(E_R)$$

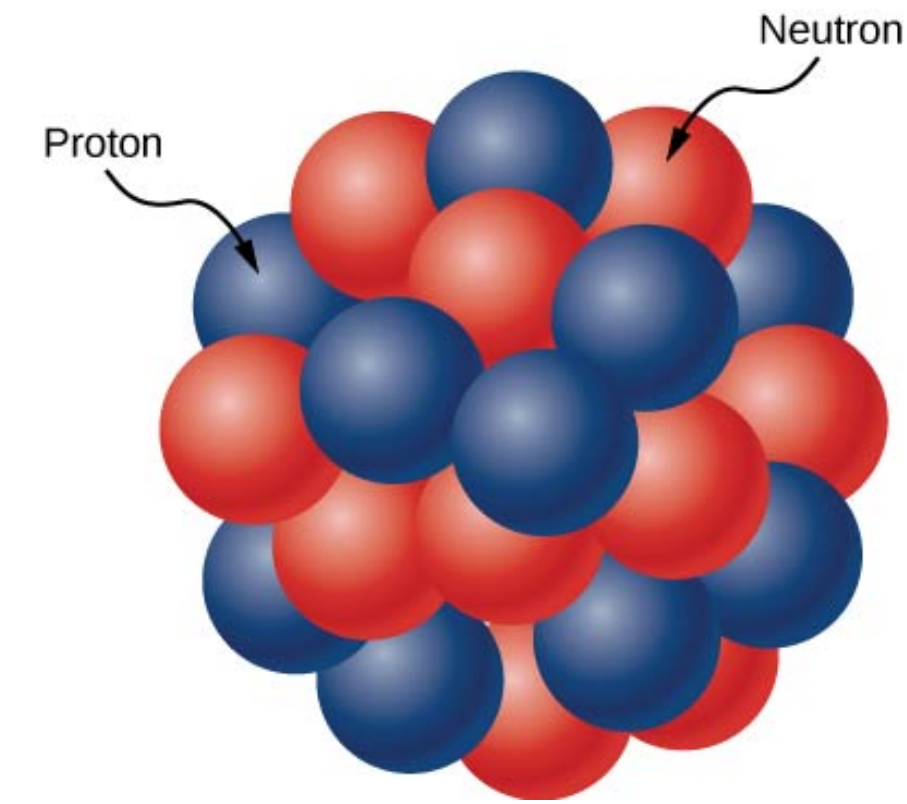
$$F(q) = \frac{1}{M} \int \rho_{\text{mass}}(r) e^{-i\mathbf{q} \cdot \mathbf{r}} d^3r :$$

$$\rho_U(r) = \begin{cases} \frac{3Ze}{4\pi R^3}, & r < R, \\ 0, & r > R, \end{cases}$$

assuming constant nucleon density distribution

$$F(q) = \frac{3j_1(qR)}{qR} e^{-(qs)^2/2}$$

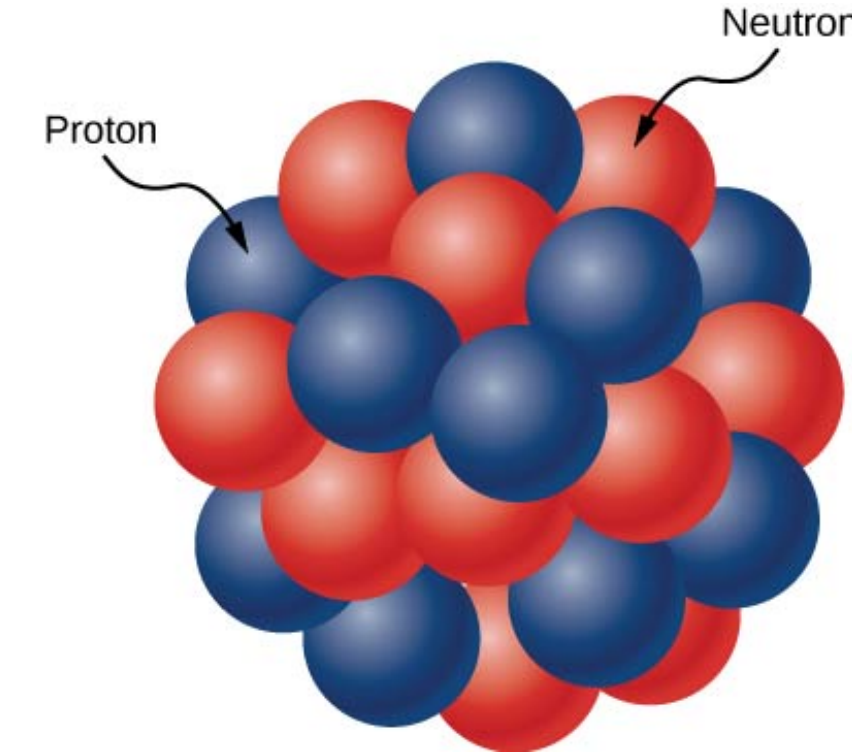
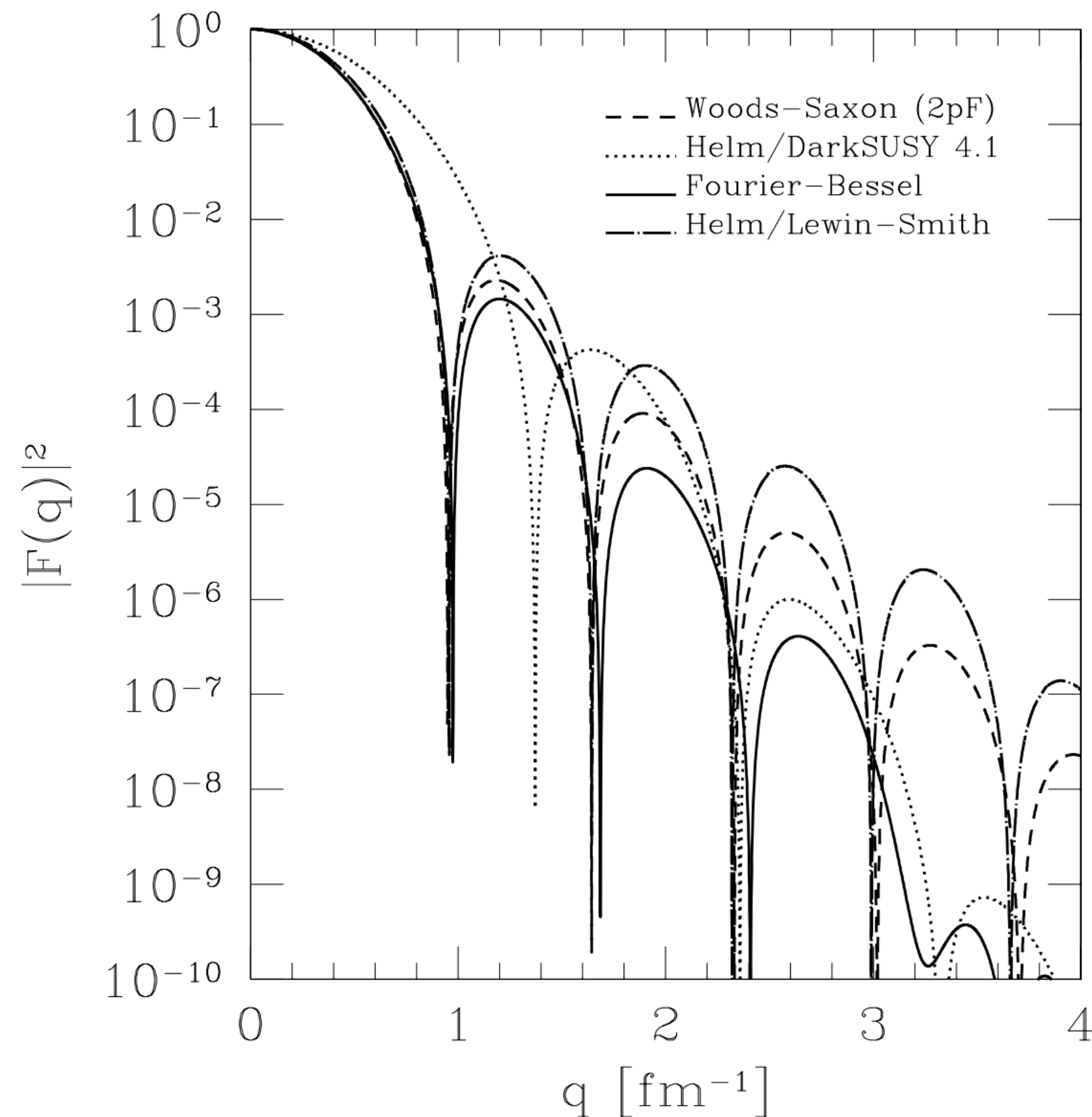
$$j_1(x) = \frac{\sin x}{x^2} - \frac{\cos x}{x}$$





# The Form Factors

$$F(q) = \frac{3j_1(qR)}{qR} e^{-(qs)^2/2}$$



The form factor measures how coherent it is to scatter with the nucleons in the nucleus

Duda et al, hep-ph/0608035

# Spin-dependent Form Factors

Spin-independent  $\mathcal{O}_{SI} = (\bar{\chi}\gamma_{\mu}\chi)(\bar{q}\gamma^{\mu}q)$

Spin-dependent  $\mathcal{O}_{SD} = (\bar{\chi}\gamma_{\mu}\gamma_5\chi)(\bar{q}\gamma^{\mu}\gamma_5q)$

$$\sigma_{j,0}^{SD} = \left(\frac{\mu_{A_j}}{\mu_N}\right)^2 S_{J_j} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2 \sigma_{\chi N}^{SD} \quad N = n, p$$

$$S_A(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q).$$

$$S_A(0) = \frac{(2J+1)(J+1)}{4\pi J} \times |(a_0 + a'_1)\langle \mathbf{S}_p \rangle + (a_0 - a'_1)\langle \mathbf{S}_n \rangle|^2$$

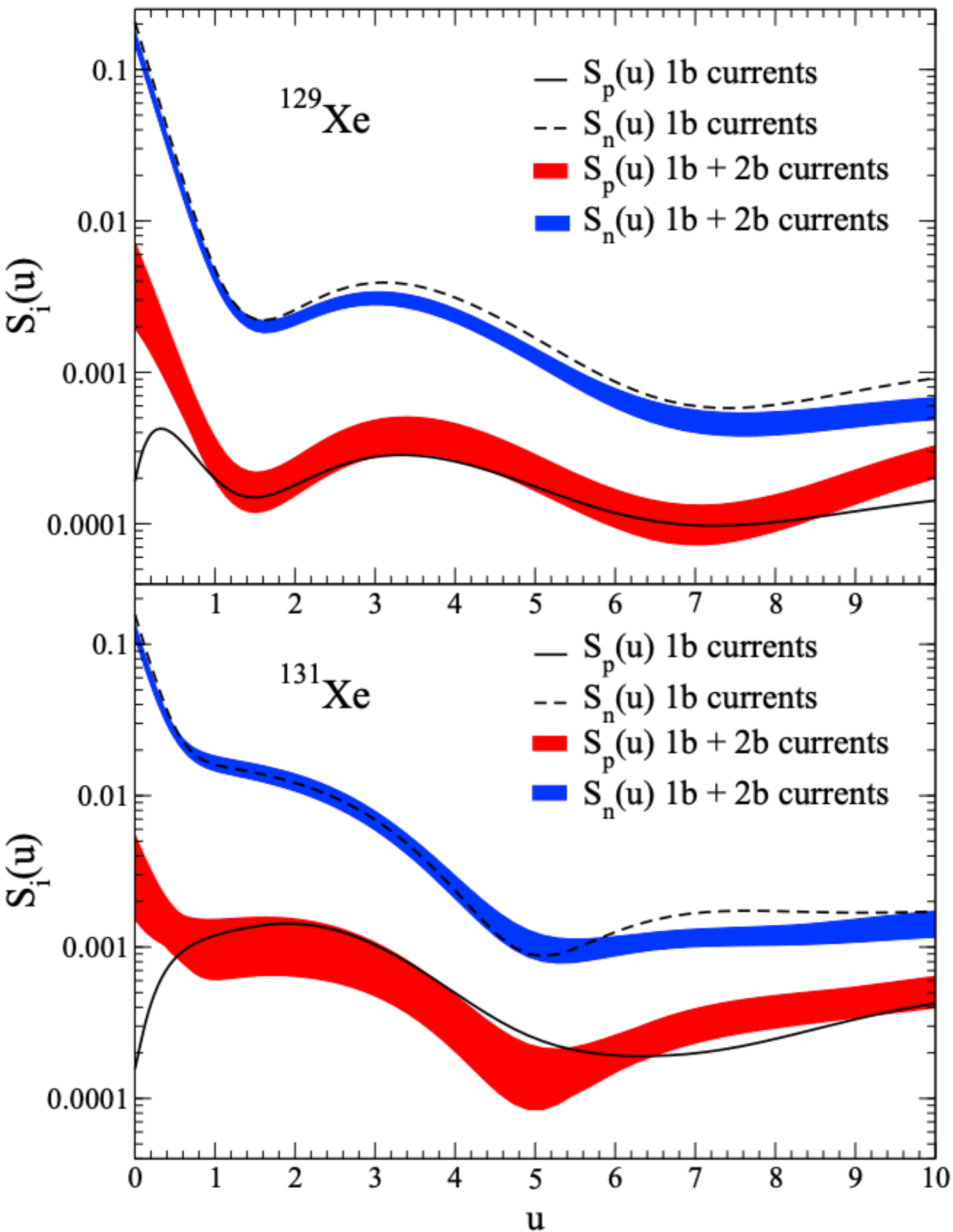
$$\sigma_{\chi A}^{SD} \sim A^2 \sigma_{\chi p}^{SD}$$

# Spin-dependent Form Factors

$$S_A(q) = a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q).$$

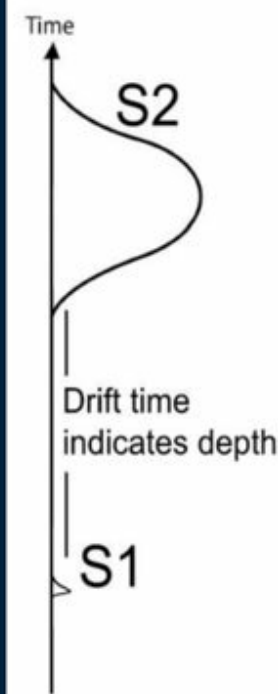
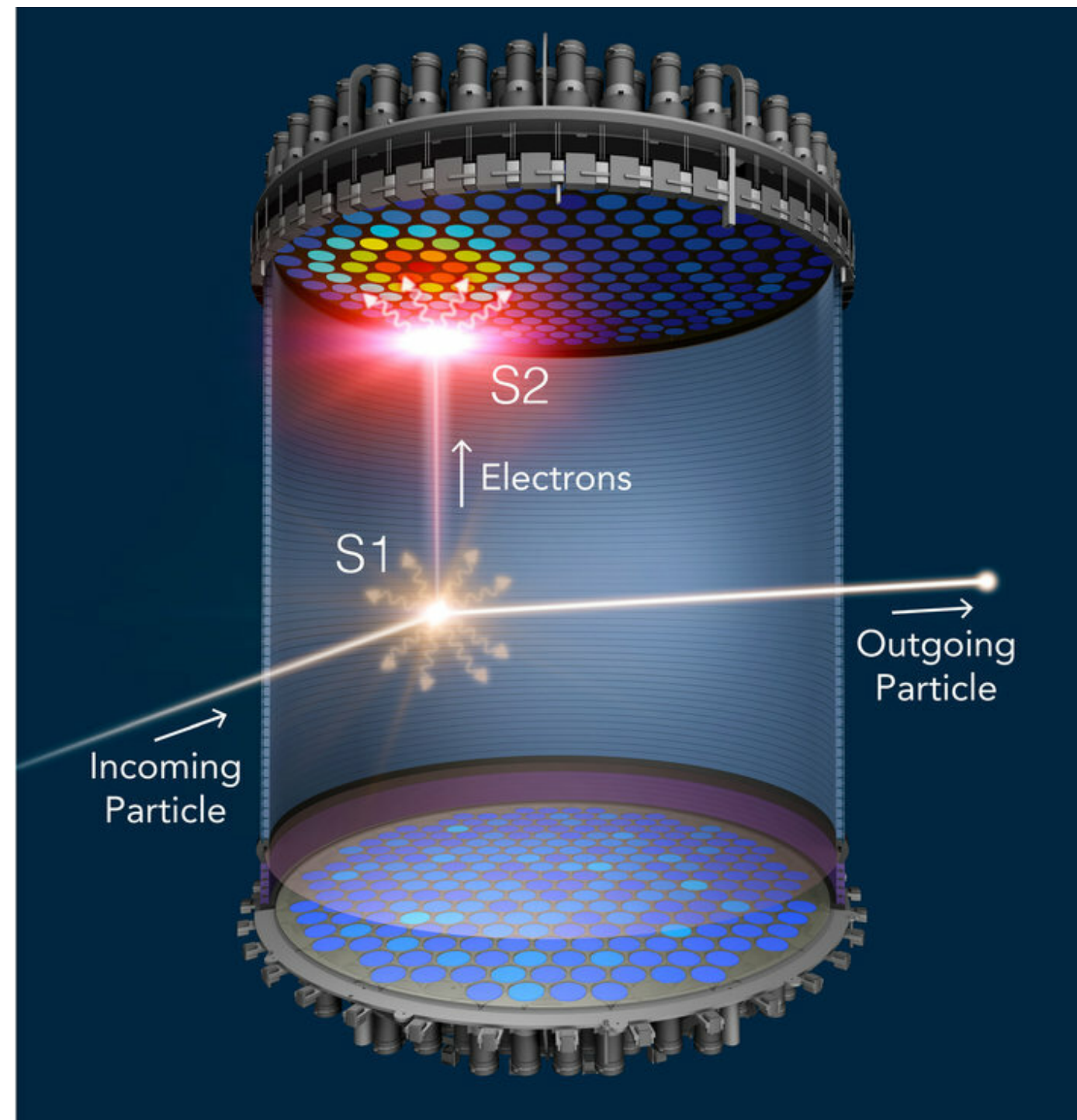
$$S_A(0) = \frac{(2J+1)(J+1)}{4\pi J} \times |(a_0 + a'_1)\langle \mathbf{S}_p \rangle + (a_0 - a'_1)\langle \mathbf{S}_n \rangle|^2$$

|                       | <sup>129</sup> Xe              |                                | <sup>131</sup> Xe              |                                | <sup>127</sup> I               |                                | <sup>73</sup> Ge               |                                | <sup>29</sup> Si               |                                | <sup>27</sup> Al               |                                | <sup>23</sup> Na               |                                | <sup>19</sup> F                |                                |
|-----------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
|                       | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ | $\langle \mathbf{S}_n \rangle$ | $\langle \mathbf{S}_p \rangle$ |
| This work<br>(Int. 1) | 0.329                          | 0.010                          | -0.272                         | -0.009                         | 0.031                          | 0.342                          | 0.439                          | 0.031                          | 0.156                          | 0.016                          | 0.038                          | 0.326                          | 0.024                          | 0.224                          | -0.002                         | 0.478                          |
| [20] (Bonn A)         | 0.359                          | 0.028                          | -0.227                         | -0.009                         | 0.075                          | 0.309                          |                                |                                |                                |                                |                                |                                | 0.020                          | 0.248                          |                                |                                |
| [20] (Nijm. II)       | 0.300                          | 0.013                          | -0.217                         | -0.012                         | 0.064                          | 0.354                          |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |
| [18]                  |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |
| [17]                  |                                |                                |                                |                                |                                |                                | 0.468                          | 0.011                          | 0.13                           | -0.002                         |                                |                                |                                |                                |                                |                                |
| [19]                  |                                |                                |                                |                                |                                |                                | 0.378                          | 0.030                          |                                |                                |                                |                                |                                |                                |                                |                                |
| [23]                  | 0.273                          | -0.002                         | -0.125                         | -7·10 <sup>-4</sup>            | 0.030                          | 0.418                          |                                |                                |                                |                                |                                |                                |                                |                                |                                |                                |
| [22]                  |                                |                                |                                |                                | 0.038                          | 0.330                          | 0.407                          | 0.005                          |                                |                                |                                |                                | 0.020                          | 0.248                          |                                |                                |
| [21]                  |                                |                                |                                |                                |                                |                                |                                |                                | 0.133                          | -0.002                         |                                |                                | 0.020                          | 0.248                          | -0.009                         | 0.475                          |
| [13]                  | 0.248                          | 0.007                          | -0.199                         | -0.005                         | 0.066                          | 0.264                          | 0.475                          | 0.008                          |                                |                                |                                |                                | 0.020                          | 0.248                          | -0.009                         | 0.475                          |





# Xenon Experiments



## The PANDAX Experiment

Ge - Counting station

Storage Cylinders with Gas Xenon

Xe - Detector



Tireless Collaborator

- Particle interacts and produces the prompt scintillation signal (S1), and the electrons drifted to the top generate the delayed scintillation signal (S2)
- The ratio of S1 and S2 can be used to distinguish different particles, or electron vs nuclear recoil



# Inelastic Dark Matter

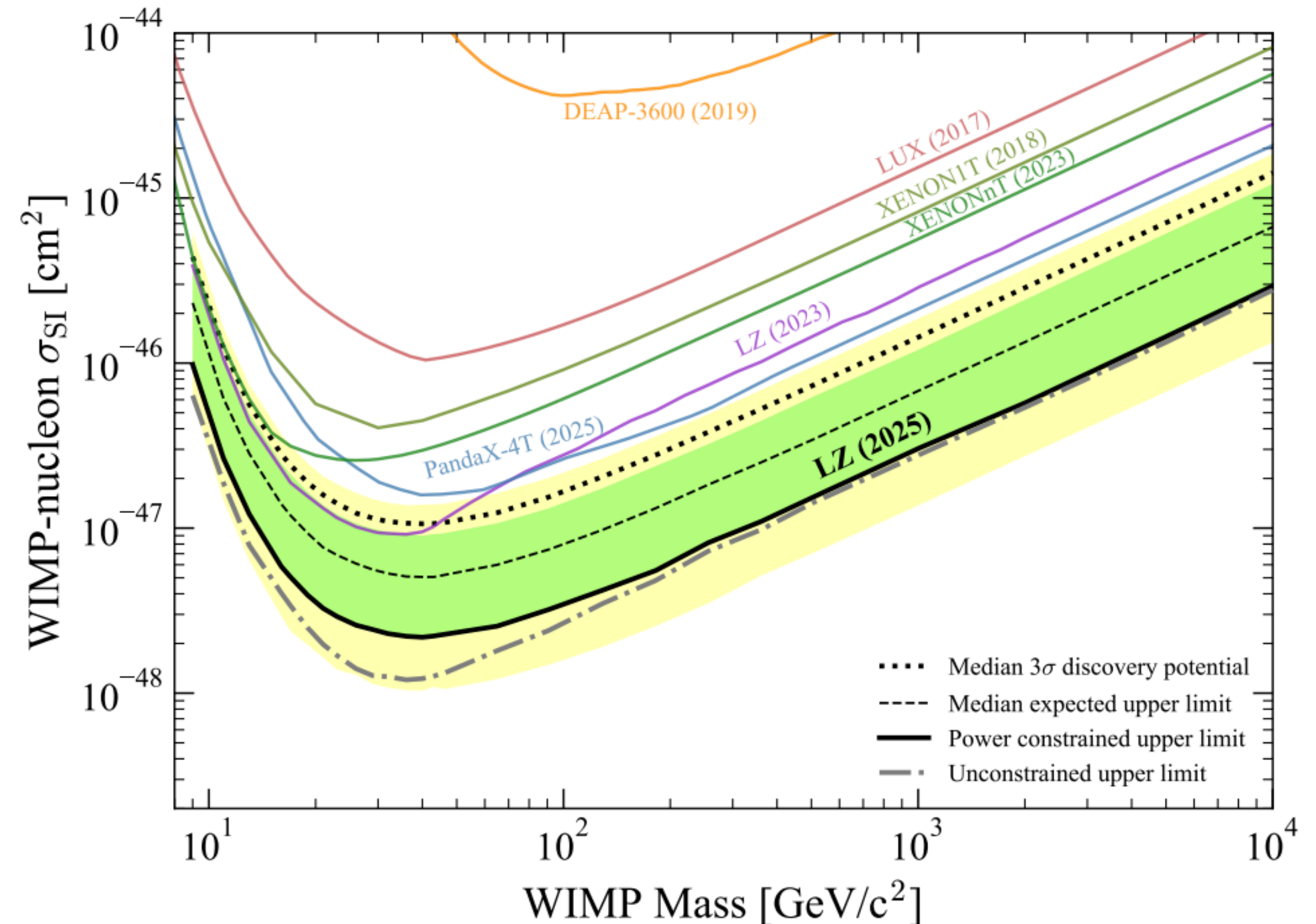
# The WIMP Miracle?

- Dark matter with weak interactions freezes out to the correct relic abundance
- Dark matter scatters through the Z boson mediator

$$\sigma_{\chi p} = \frac{g^4 m_\chi^2 m_p^2}{4\pi(m_\chi + m_p)^2 m_Z^4} \sim 10^{-39} \text{ cm}^2$$

Are there ways around?

$$\Omega h^2 \simeq \left( \frac{3 \times 10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle} \right)$$





Feb 22, 2019, 02:00am EST | 57,704 views

# The 'WIMP Miracle' Hope For Dark Matter Is Dead



**Ethan Siegel** Senior Contributor

**Starts With A Bang** Contributor Group ⓘ

Science

*The Universe is out there, waiting for you to discover it.*

## WIMPs on Death Row

Posted on July 21, 2016 by woit

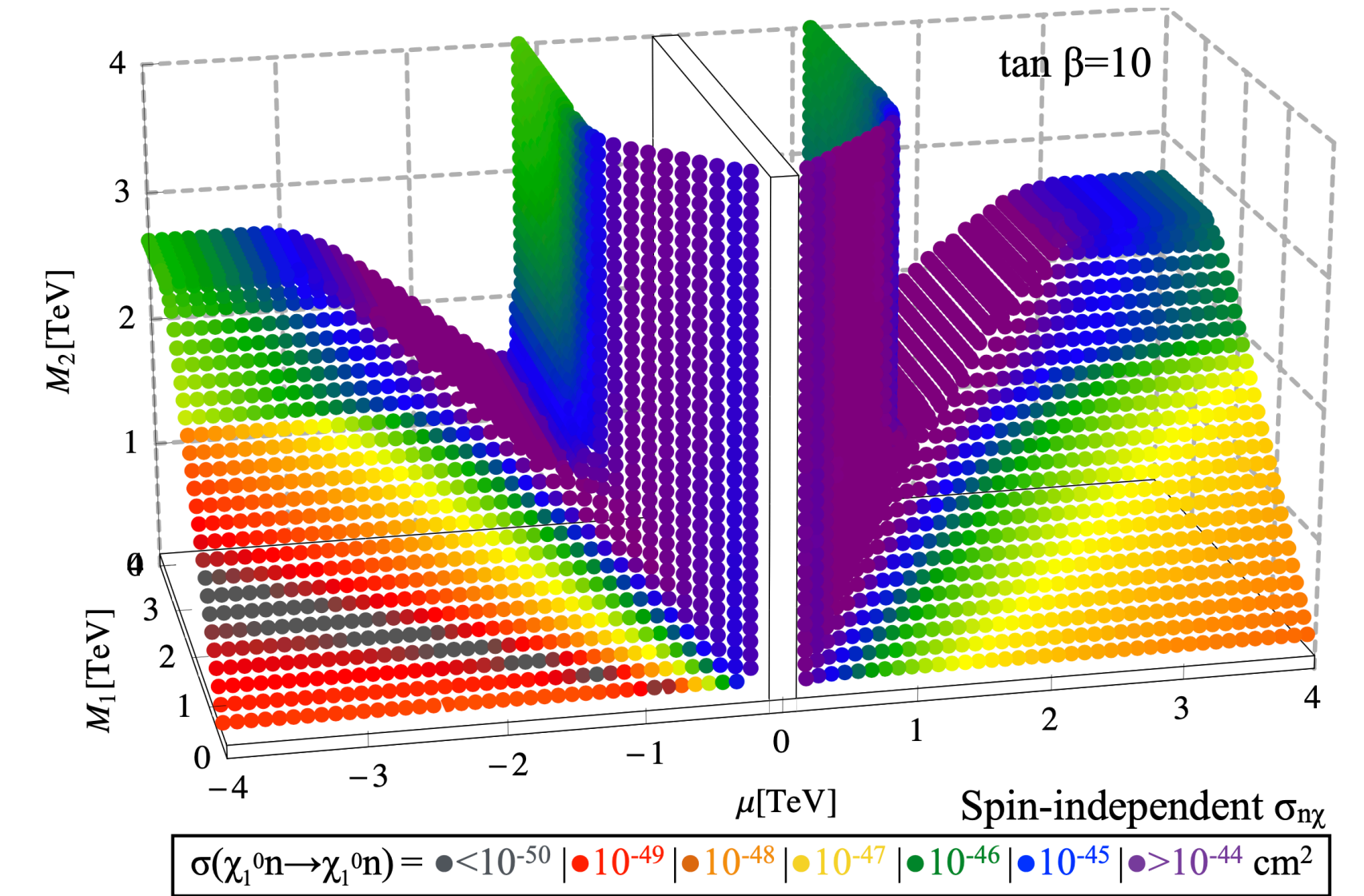
One of the main arguments given for the idea of supersymmetric extensions of the standard model has been what SUSY enthusiasts call the “WIMP Miracle” (WIMP=Weakly Interacting Massive Particle). This is the claim that such SUSY models include a stable very massive weakly interacting particle that could provide an explanation for dark matter.

# Inelastic Dark Matter

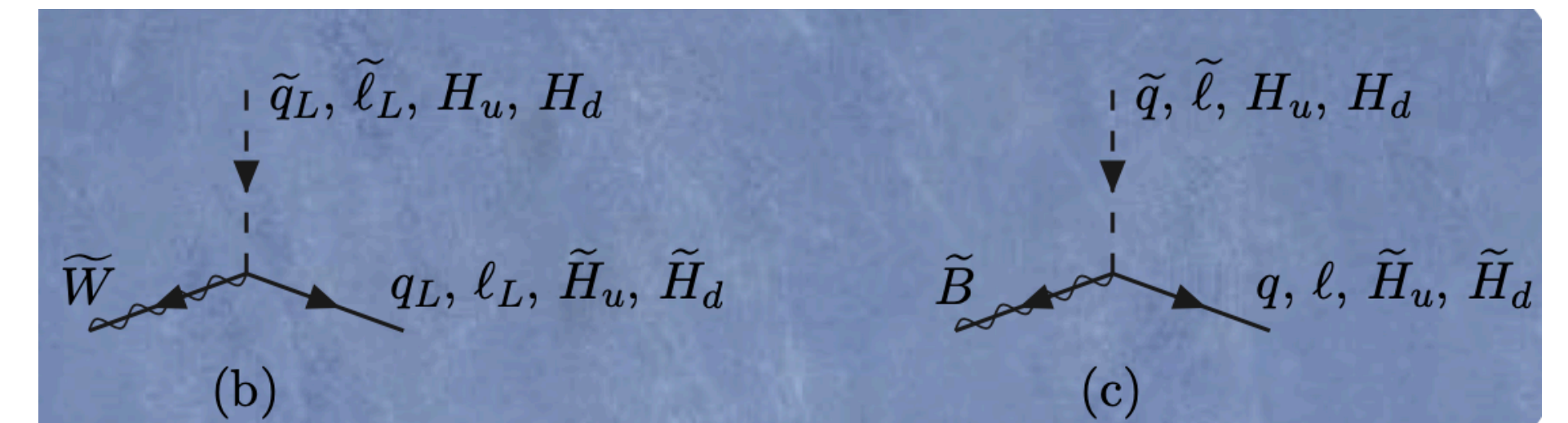
- Off-diagonal mass term  $\begin{pmatrix} M & \nu \\ \nu & M \end{pmatrix}$
- After diagonalization  $M_{\chi_1} = M + \nu$ ,  $M_{\chi_2} = M - \nu$
- $\delta \equiv M_{\chi_2} - M_{\chi_1} \ll M_\chi$
- Example: dark photon-mediated DM

$$\mathcal{L} \supset \bar{\psi}(iD_\mu \gamma^\mu - m_\psi)\psi + (y\phi\bar{\psi}^T C^{-1}\psi + h.c.)$$

Bramante, **NS**, PRL/2006.14089  
 Batell, Pospelov, Ritz, 0903.3396



Neutralino DM, see Bramante et al,  
 1510.03460, 1412.4789



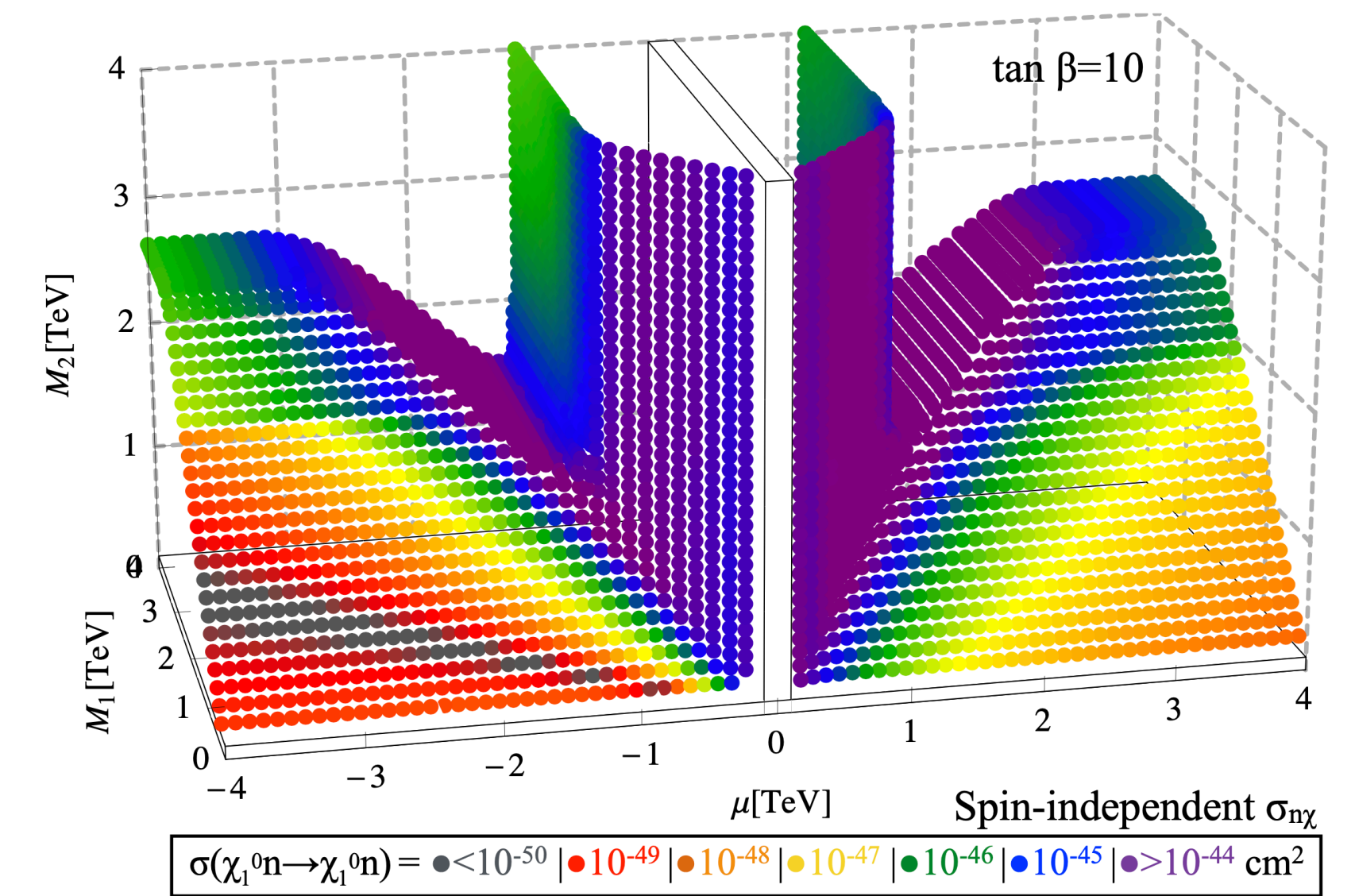


# Inelastic Dark Matter

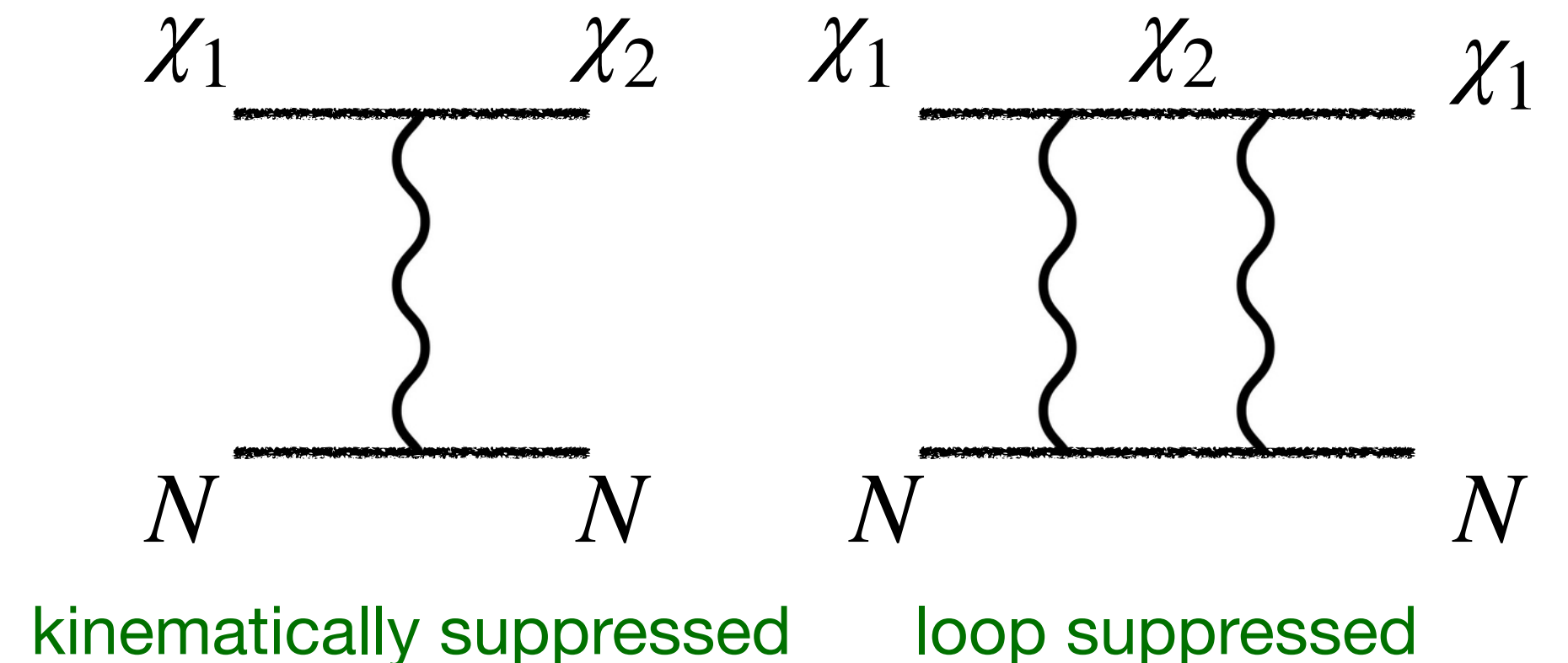
- Off-diagonal mass term  $\begin{pmatrix} M & \nu \\ \nu & M \end{pmatrix}$
- After diagonalization  $M_{\chi_1} = M + \nu$ ,  $M_{\chi_2} = M - \nu$
- $\delta \equiv M_{\chi_2} - M_{\chi_1} \ll M_\chi$
- Example: dark photon-mediated DM

$$\mathcal{L} \supset \bar{\psi}(iD_\mu \gamma^\mu - m_\psi)\psi + (y\phi\bar{\psi}^T C^{-1}\psi + h.c.)$$

Bramante, **NS**, PRL/2006.14089  
 Batell, Pospelov, Ritz, 0903.3396



Neutralino DM, see Bramante et al,  
 1510.03460, 1412.4789





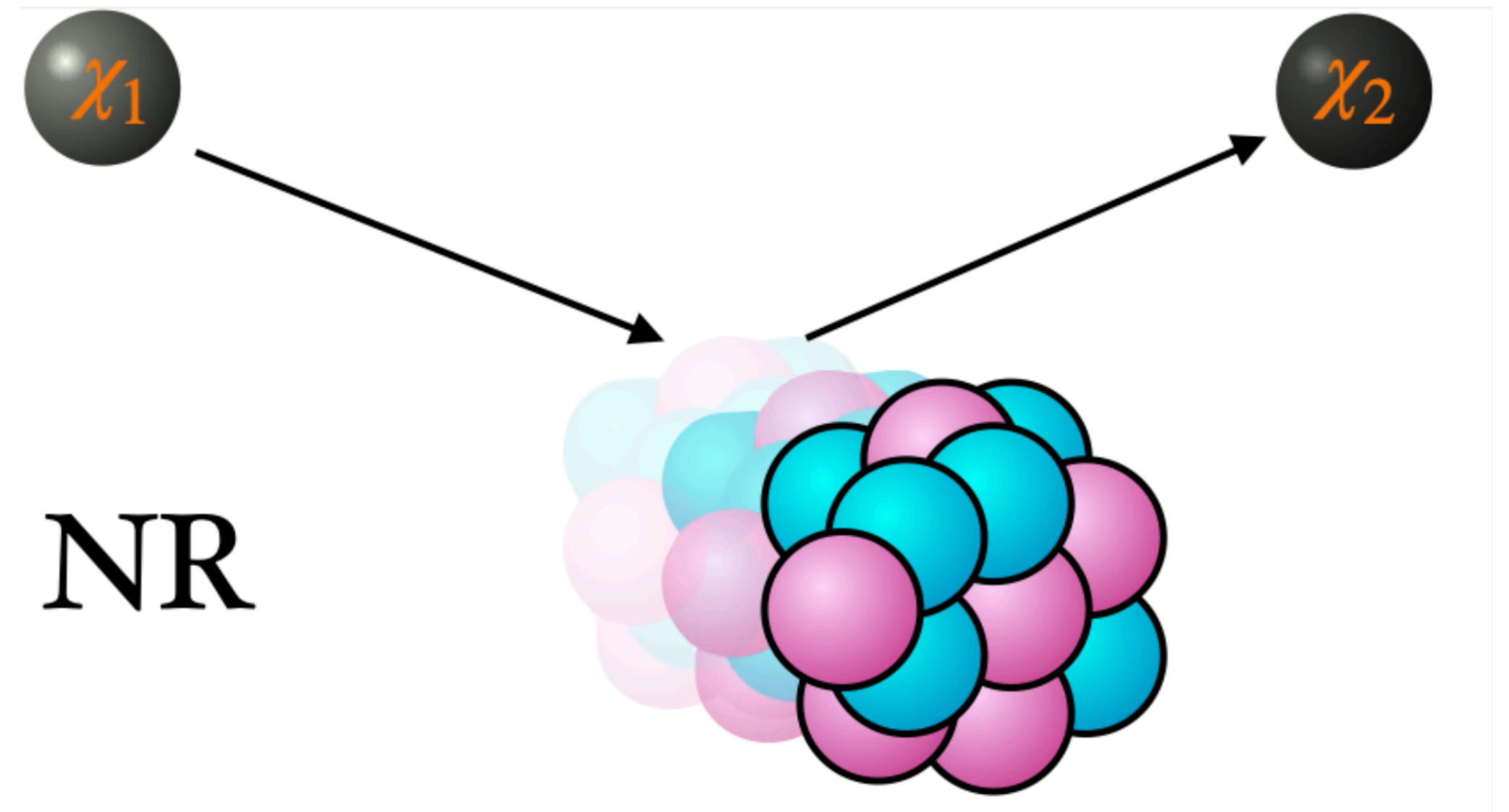
# Homework Exercise: Kinematics in Nuclear Recoil

- $$\frac{\vec{q}_i^2}{2M_{\chi_1}} = \frac{\vec{q}_f^2}{2M_{\chi_2}} + \frac{\vec{q}^2}{2M_A} + \delta$$

- $$q_{\min/\max} = \mu_{\chi A} v \left[ 1 \mp \sqrt{1 - 2 \frac{\delta}{\mu_{\chi A} v^2}} \right]$$

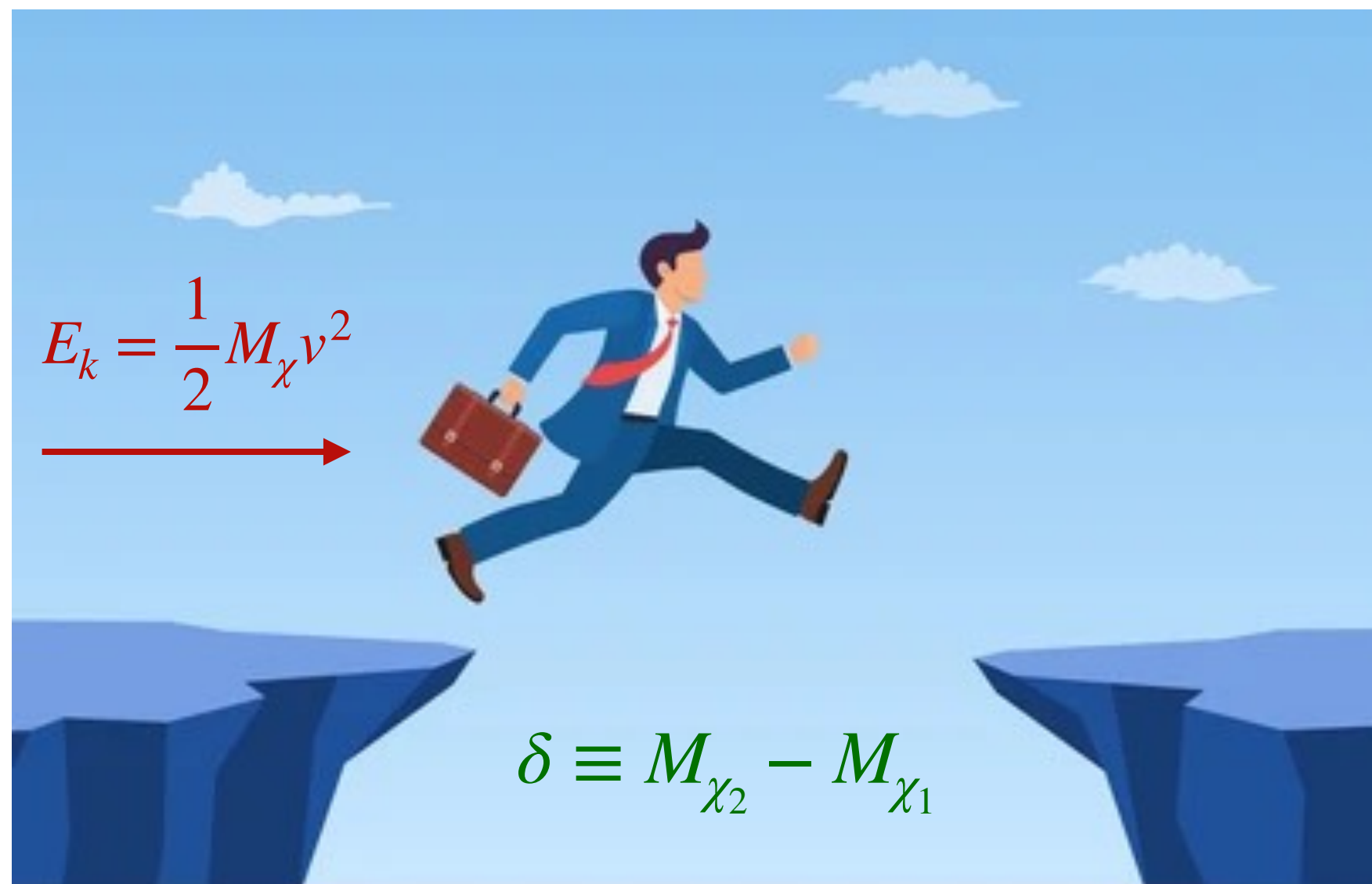
- Minimum velocity  $v_{\min} = \sqrt{2 \frac{\delta}{\mu_{\chi A}}}$

$$\delta \equiv M_{\chi_2} - M_{\chi_1}$$

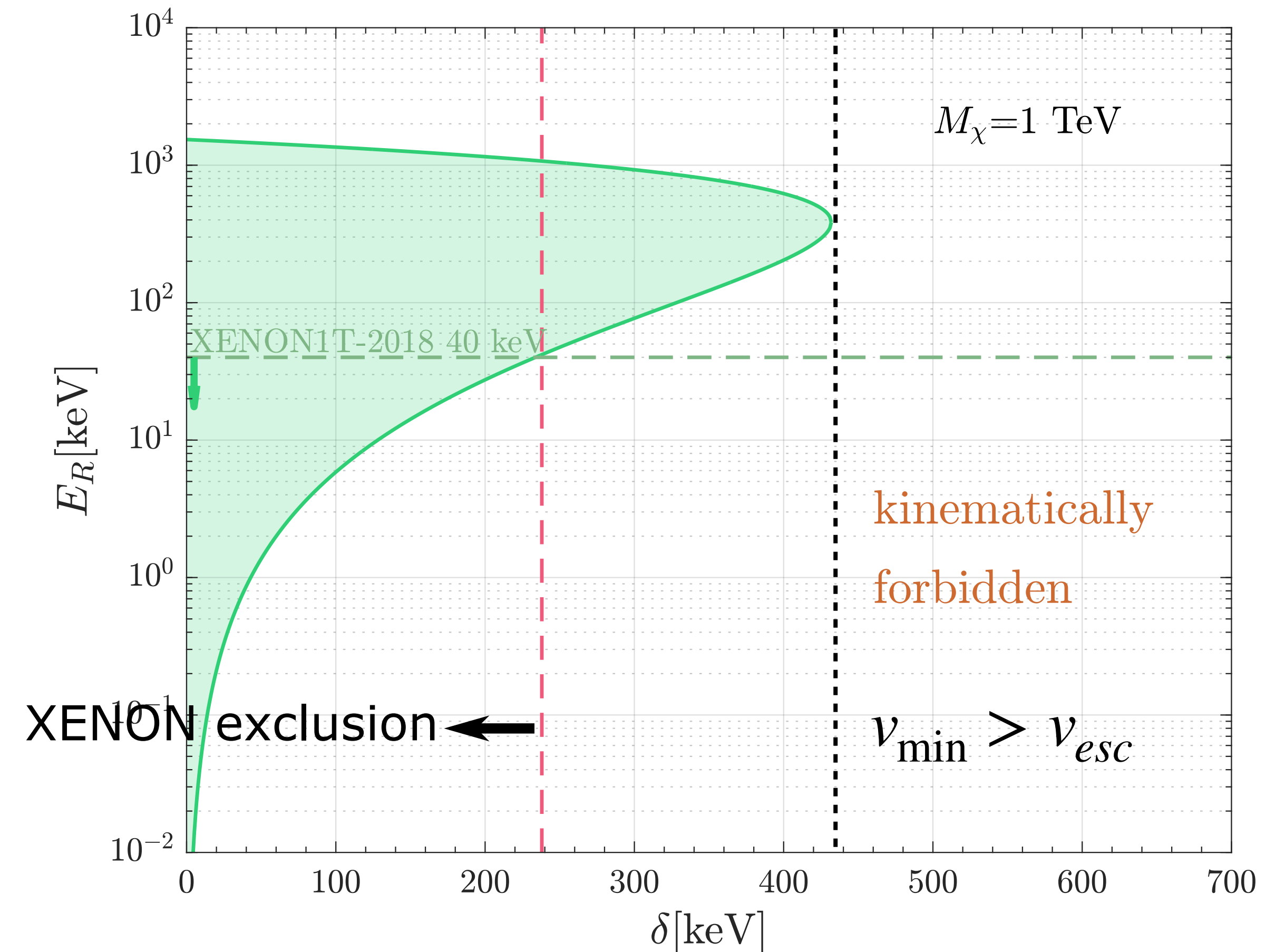


# Why not XENON

- Xenon not heavy enough
- Xenon experiments only sensitive to low energy deposition ( $E_R \lesssim 40$  keV)



shutterstock.com · 1808704210

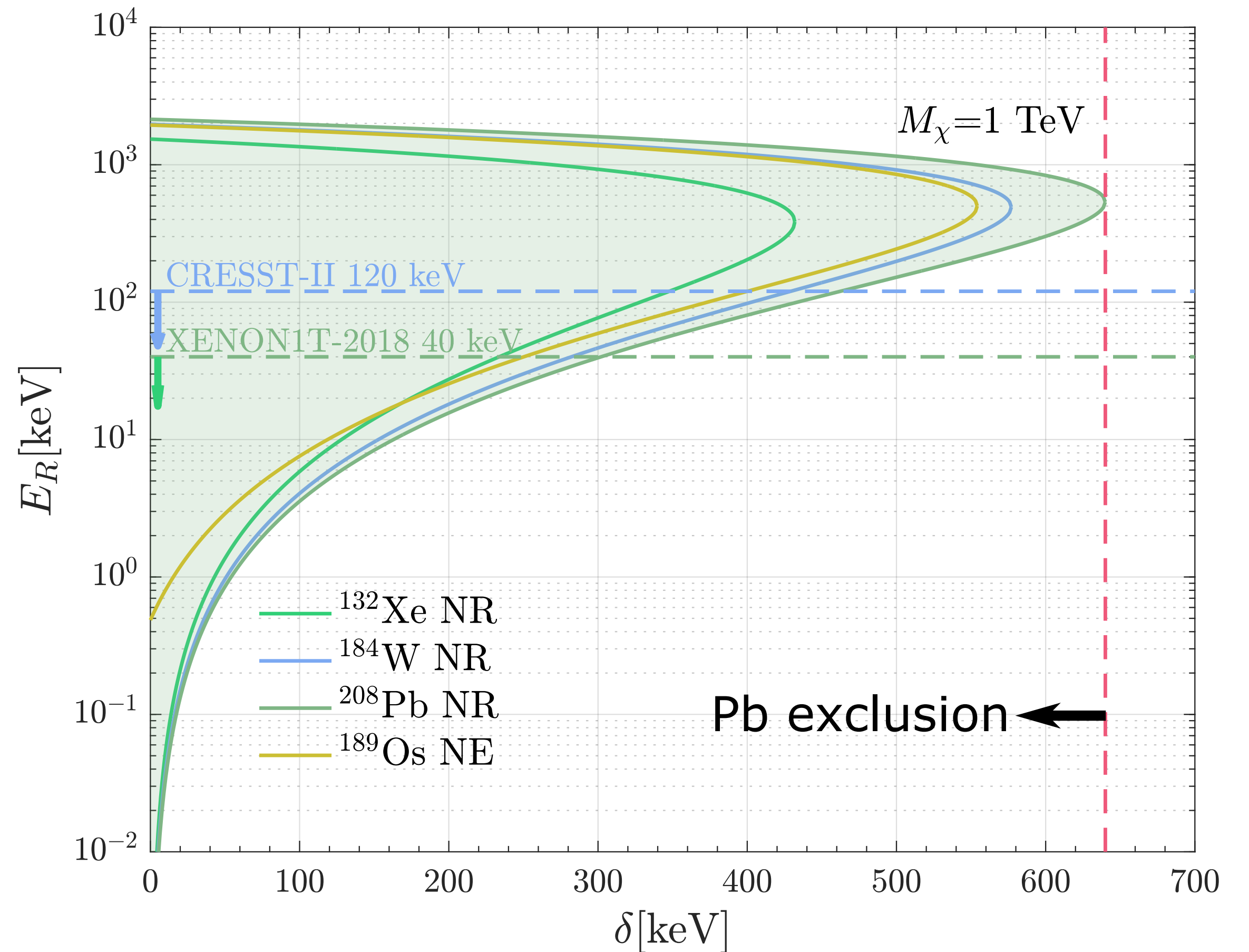


# Two Criteria

- Heavy nuclear target
- High energy deposition acceptance

$$\delta_{\max} = \frac{1}{2} \mu_{\chi A} (v_e + v_{esc})^2$$

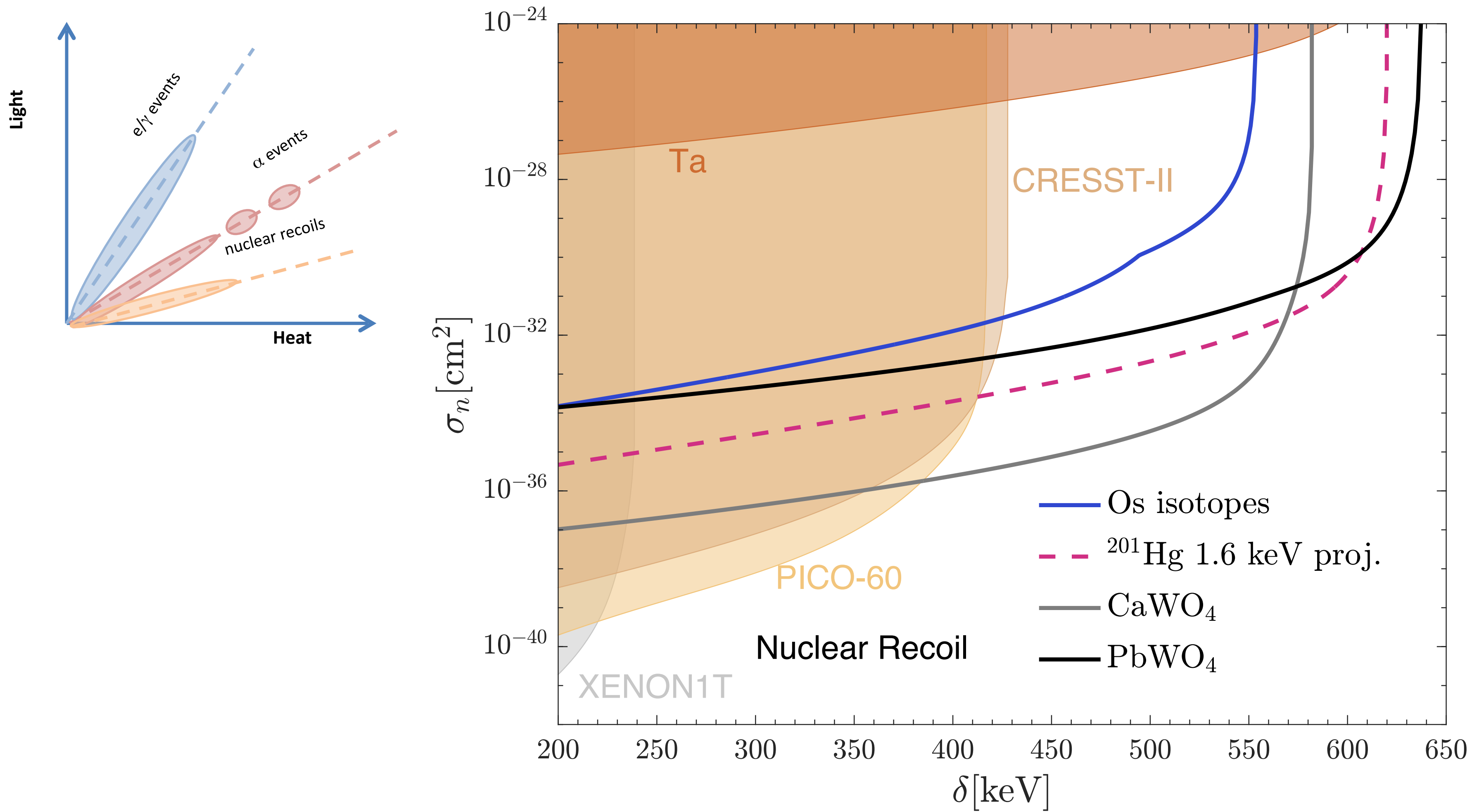
Target nuclei with  $A \sim 200$



NS, Nagorny, Vincent, PRD/2104.09517



# Nuclear Recoil with Scintillating Bolometer

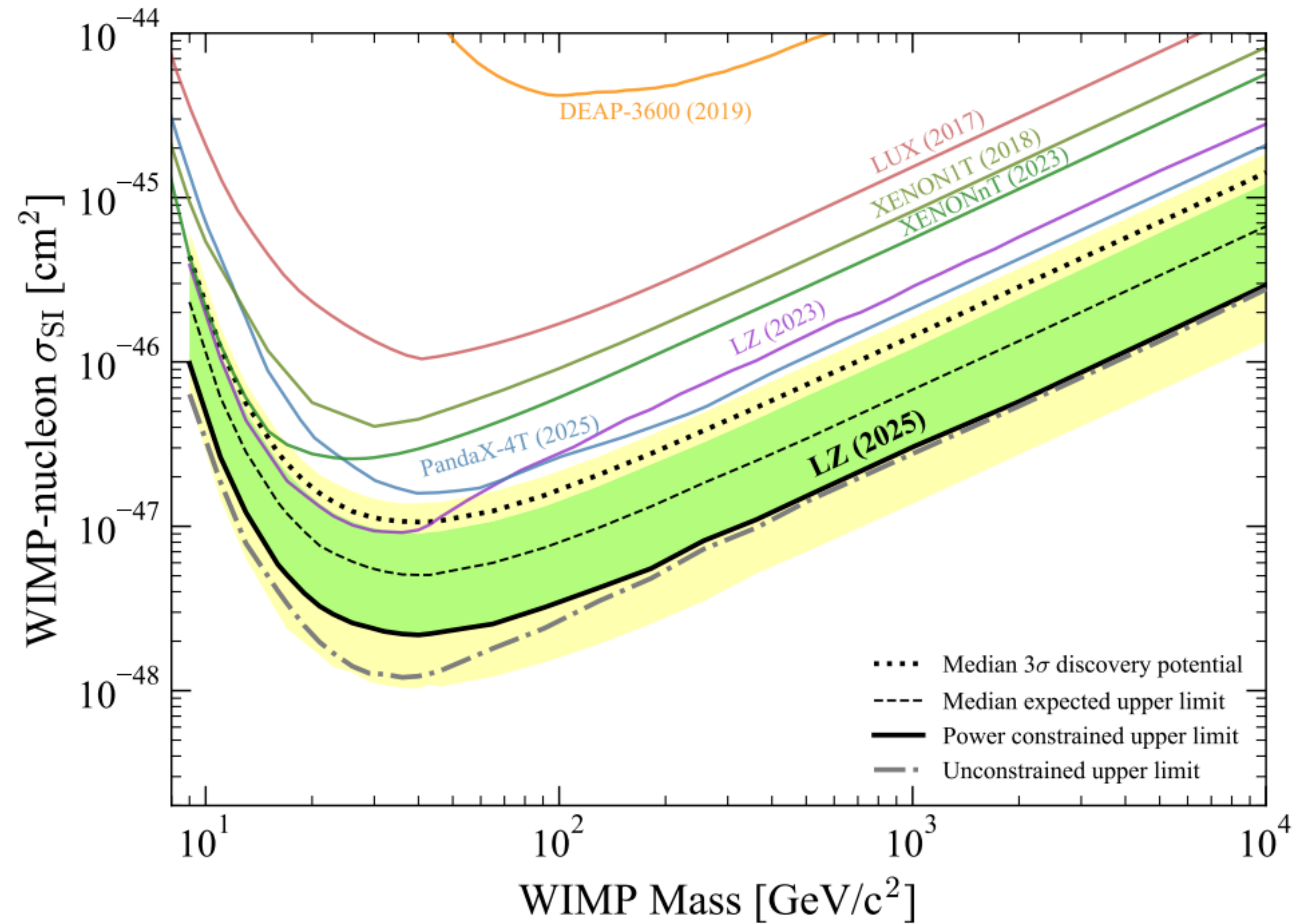


$$M_\chi = 1 \text{ TeV}$$

NS, Nagorny, Vincent, PRD/2104.09517

# Strongly Interacting Dark Matter

Are the above all excluded???

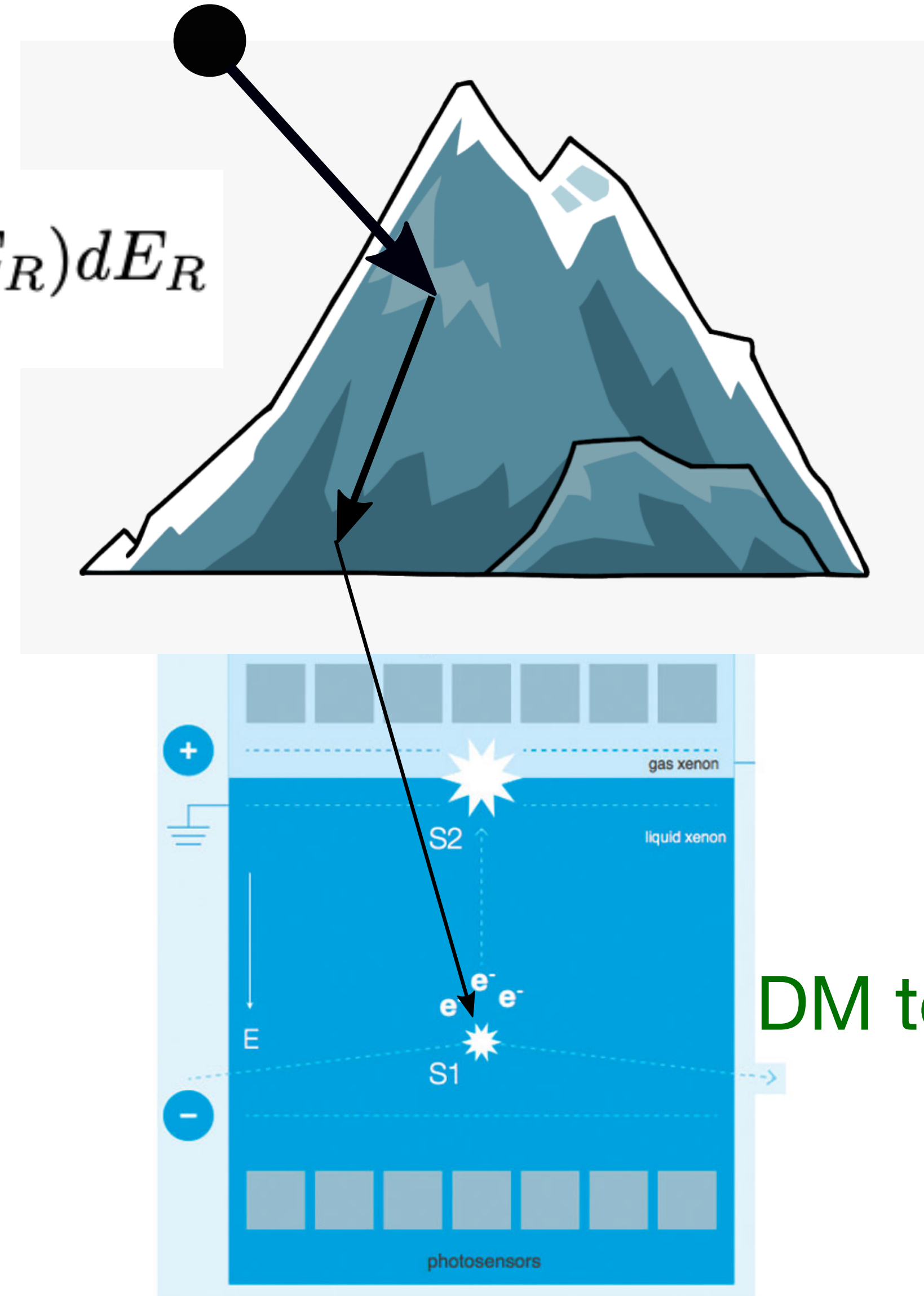




# Overburden

$$N_{\text{exp}} = \sum_i N_i T \frac{\rho_\chi}{m_\chi} \int u_f f(u_f) du_f \int \frac{d\sigma_i}{dE_R} \epsilon(E_R) dE_R$$

dark matter velocity distribution



Dark matter velocity distribution at the underground detector could be different from the halo

# Overburden

$$\begin{aligned}\tilde{f}(\mathbf{v}_f) d^3\mathbf{v}_f &= f(\mathbf{v}_i) d^3\mathbf{v}_i \\ \Rightarrow \tilde{f}(\mathbf{v}_f) v_f^2 dv_f d\hat{\mathbf{v}}_f^2 &= f(\mathbf{v}_i) v_i^2 dv_i d\hat{\mathbf{v}}_f^2 \\ \Rightarrow \tilde{f}(\mathbf{v}_f) &= f(\mathbf{v}_i) \left( \frac{v_i^2}{v_f^2} \right) \frac{dv_i}{dv_f},\end{aligned}$$

$$\frac{d\langle E_\chi \rangle}{dt} = - \sum_i n_i(\mathbf{r}) \langle E_R \rangle_i \sigma_i(v) v, \quad \langle E_R \rangle_i = \frac{1}{\sigma_i(v)} \int_0^{E_i^{\max}} E_R \frac{d\sigma_i}{dE_R} dE_R.$$

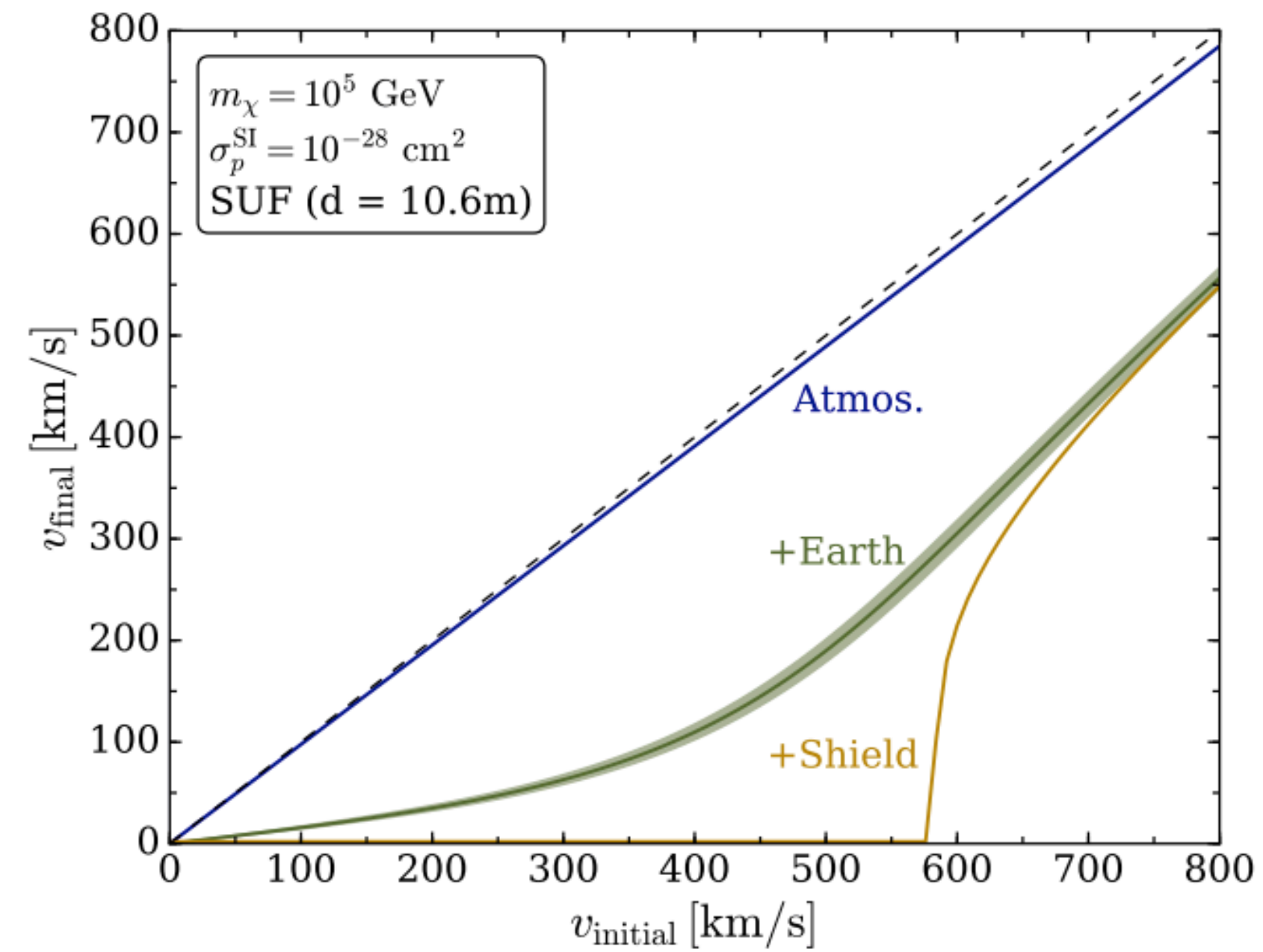
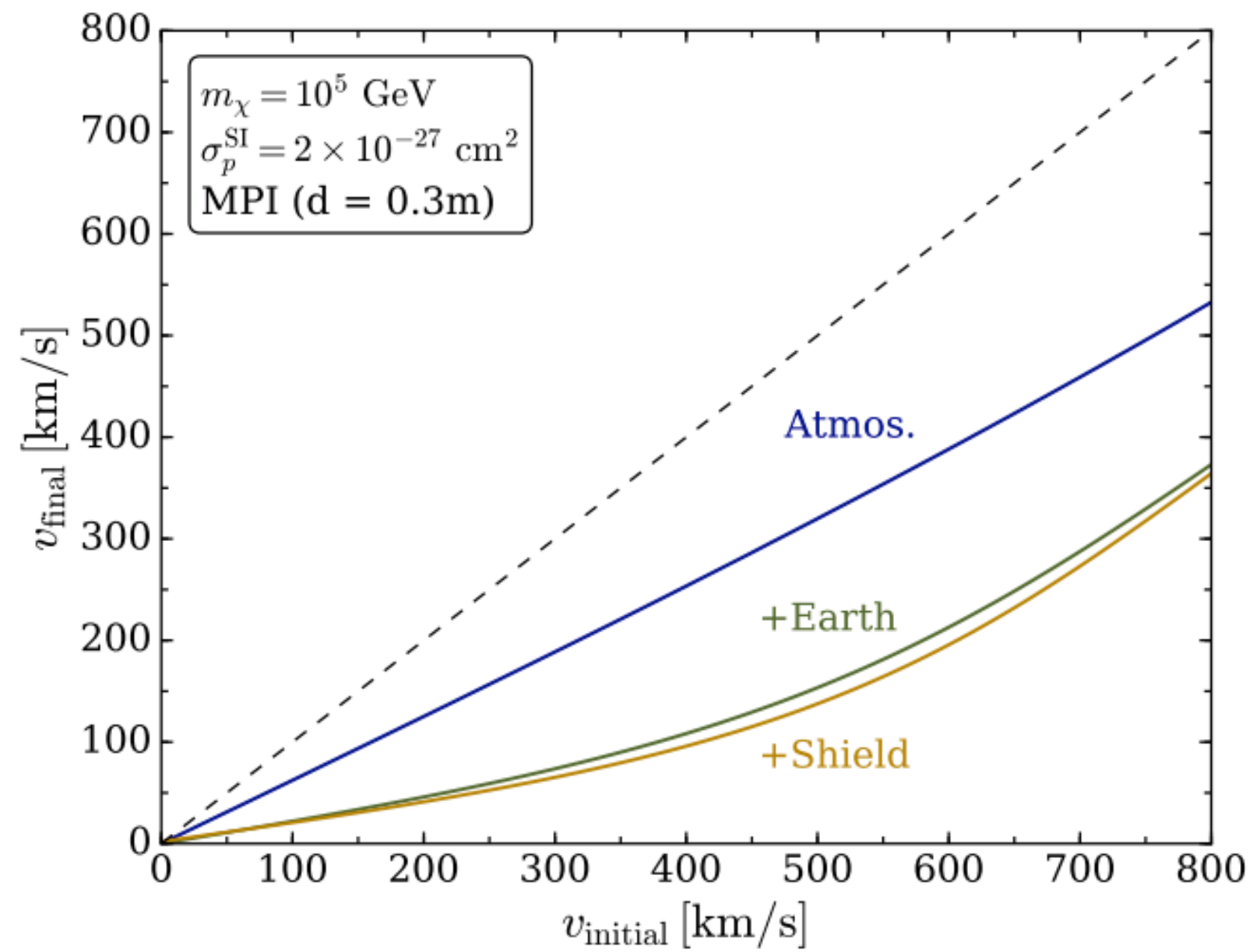
$$N_{\text{scat}} = \sum_i n_i \sigma_i L \approx 500 \left( \frac{\sigma_p^{\text{SI}}}{10^{-28} \text{ cm}^2} \right) \left( \frac{D}{\text{m}} \right)$$

$$\begin{aligned}\frac{dv}{dD} &= - \frac{v}{m_\chi \mu_{\chi p}^2} \sigma_p^{\text{SI}} \sum_i^{\text{species}} n_i(\mathbf{r}) \frac{\mu_{\chi i}^4}{m_i} A_i^2 C_i(m_\chi, v) \\ &\approx -m_p v \left( \frac{\sigma_p^{\text{SI}}}{m_\chi} \right) \sum_i^{\text{species}} n_i(\mathbf{r}) A_i^5 C_i(m_\chi \rightarrow \infty, v),\end{aligned}$$

# Overburden

$$\frac{dv}{dD} = -\frac{v}{m_\chi \mu_{\chi p}^2} \sigma_p^{\text{SI}} \sum_i^{\text{species}} n_i(\mathbf{r}) \frac{\mu_{\chi i}^4}{m_i} A_i^2 C_i(m_\chi, v)$$

$$\approx -m_p v \left( \frac{\sigma_p^{\text{SI}}}{m_\chi} \right) \sum_i^{\text{species}} n_i(\mathbf{r}) A_i^5 C_i(m_\chi \rightarrow \infty, v),$$

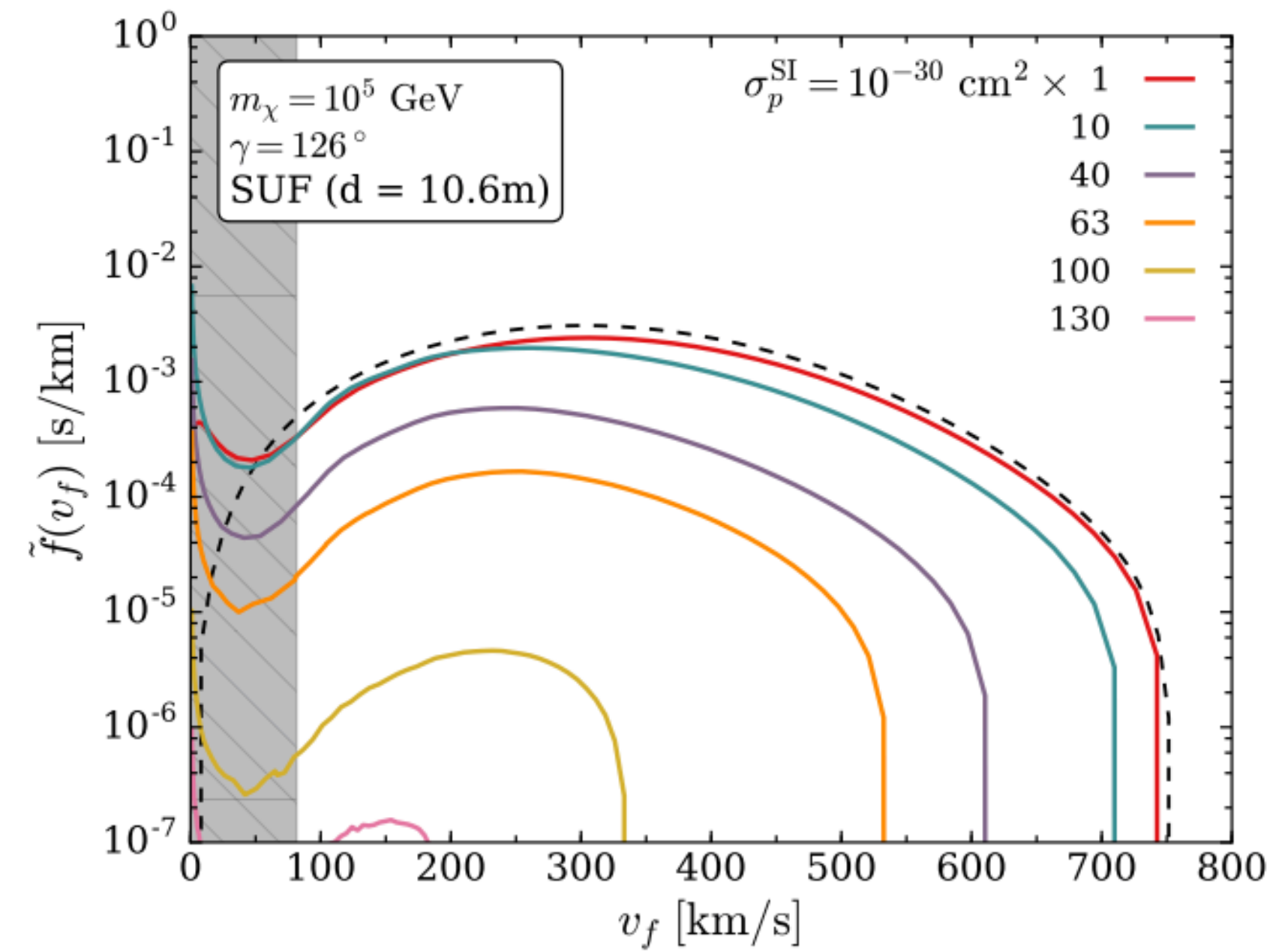
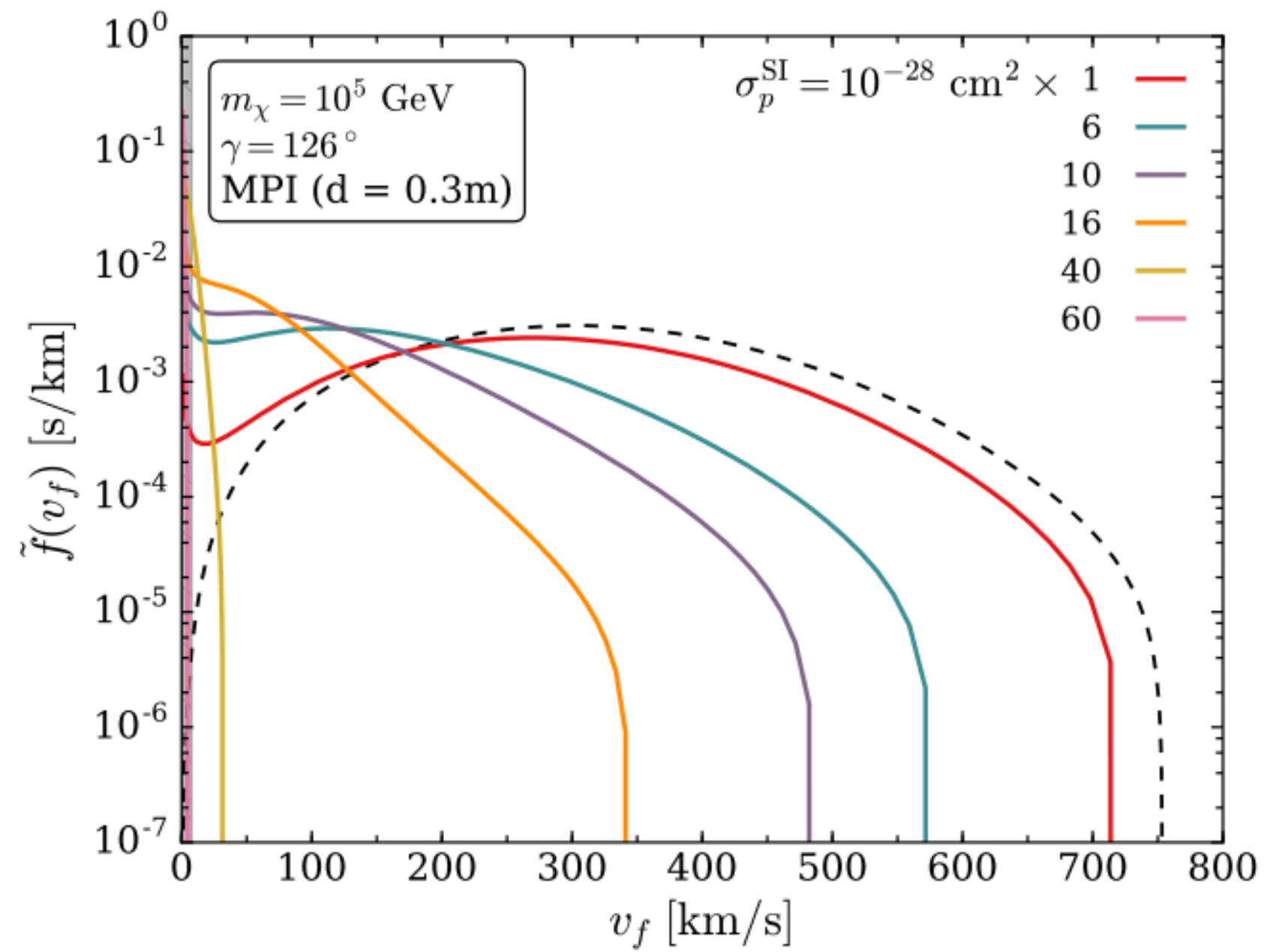




# Overburden

$$\frac{dv}{dD} = -\frac{v}{m_\chi \mu_{\chi p}^2} \sigma_p^{\text{SI}} \sum_i^{\text{species}} n_i(\mathbf{r}) \frac{\mu_{\chi i}^4}{m_i} A_i^2 C_i(m_\chi, v)$$

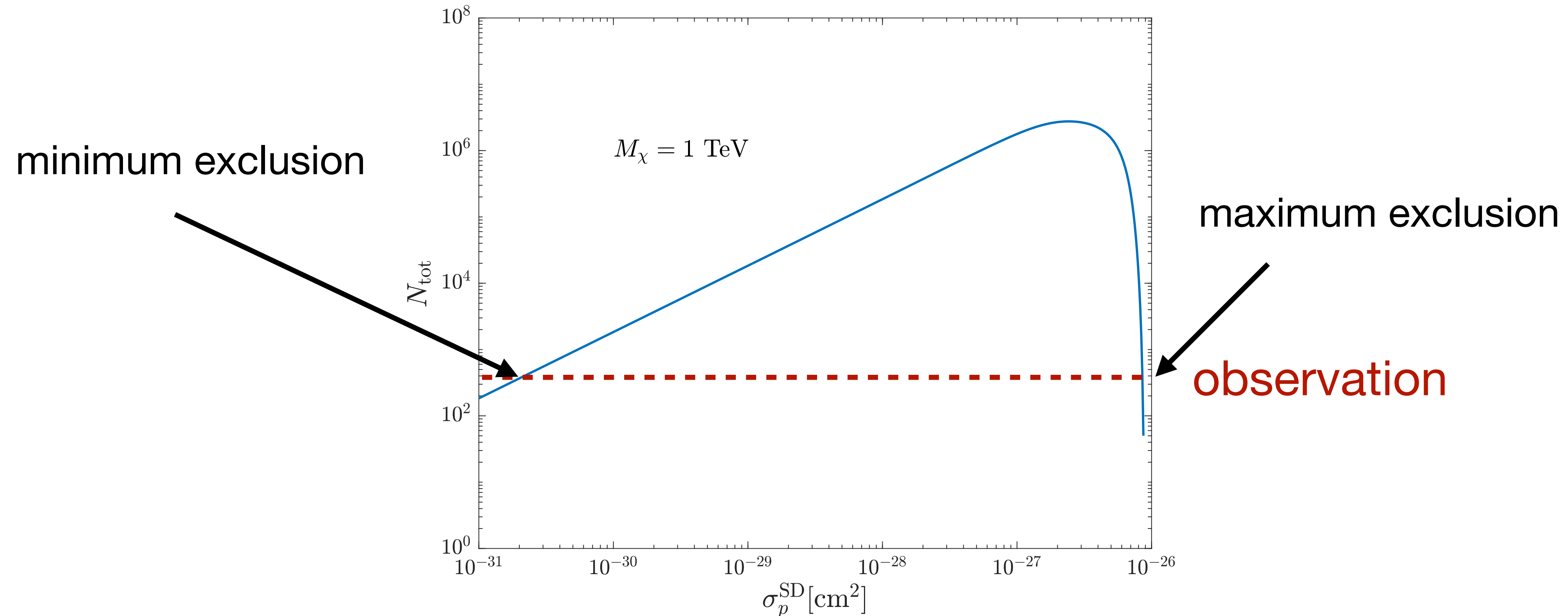
$$\approx -m_p v \left( \frac{\sigma_p^{\text{SI}}}{m_\chi} \right) \sum_i^{\text{species}} n_i(\mathbf{r}) A_i^5 C_i(m_\chi \rightarrow \infty, v),$$



# Overburden

$$N_{\text{exp}} = \sum_i N_i T \frac{\rho_\chi}{m_\chi} \int u_f f(u_f) du_f \int \frac{d\sigma_i}{dE_R} \epsilon(E_R) dE_R$$

dark matter velocity distribution

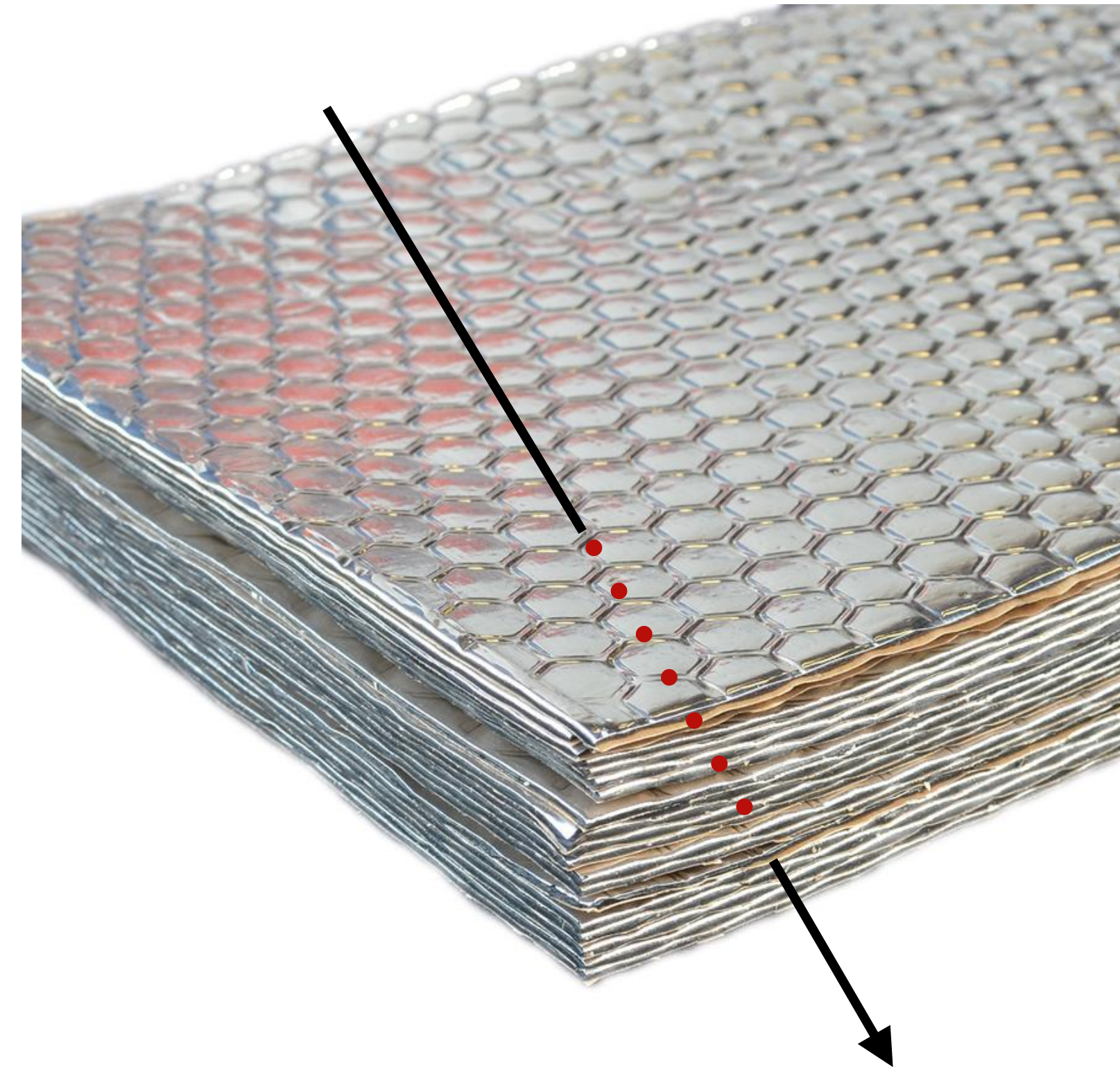




# Skylab and Ohya



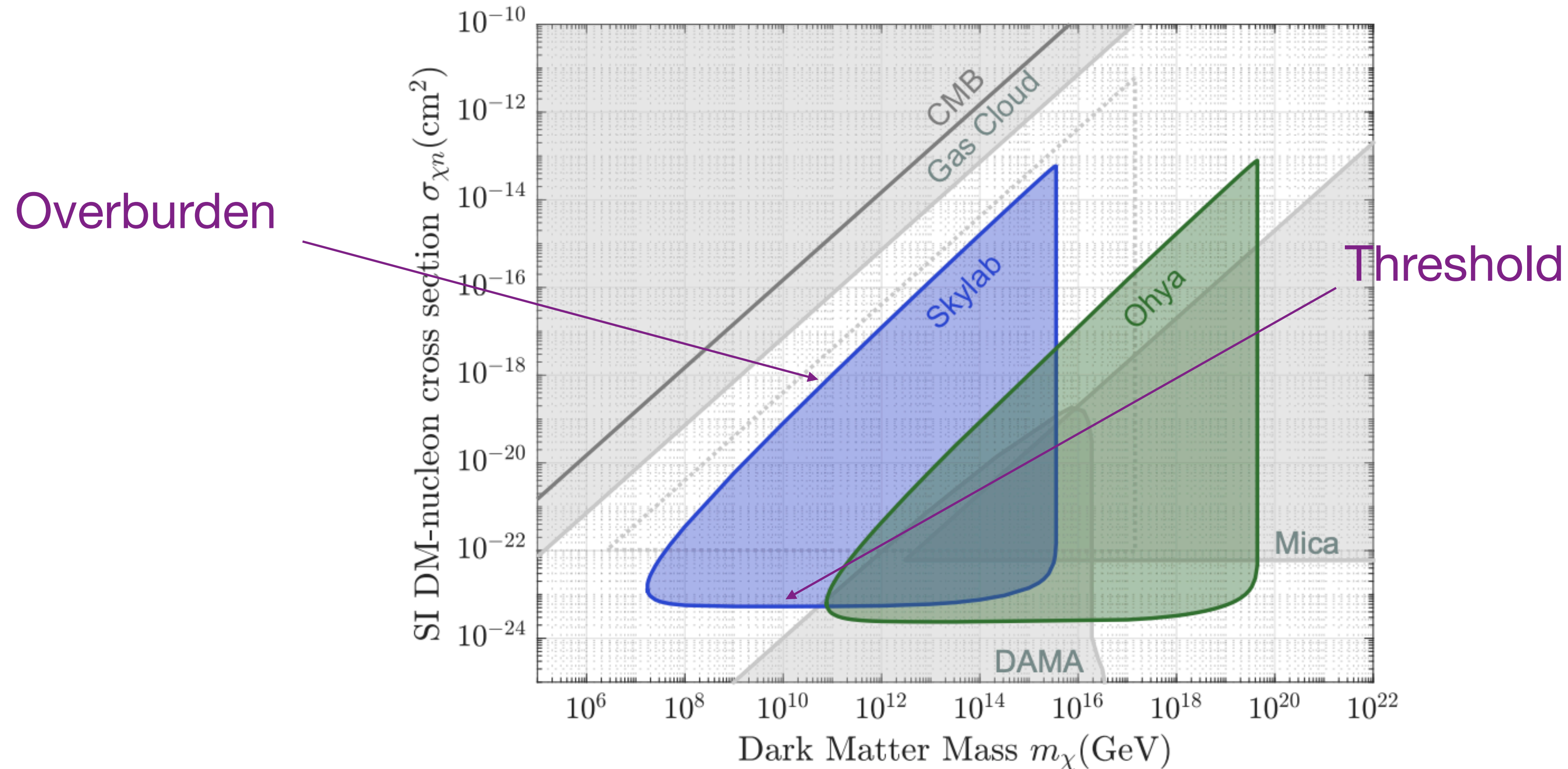
Etching holes





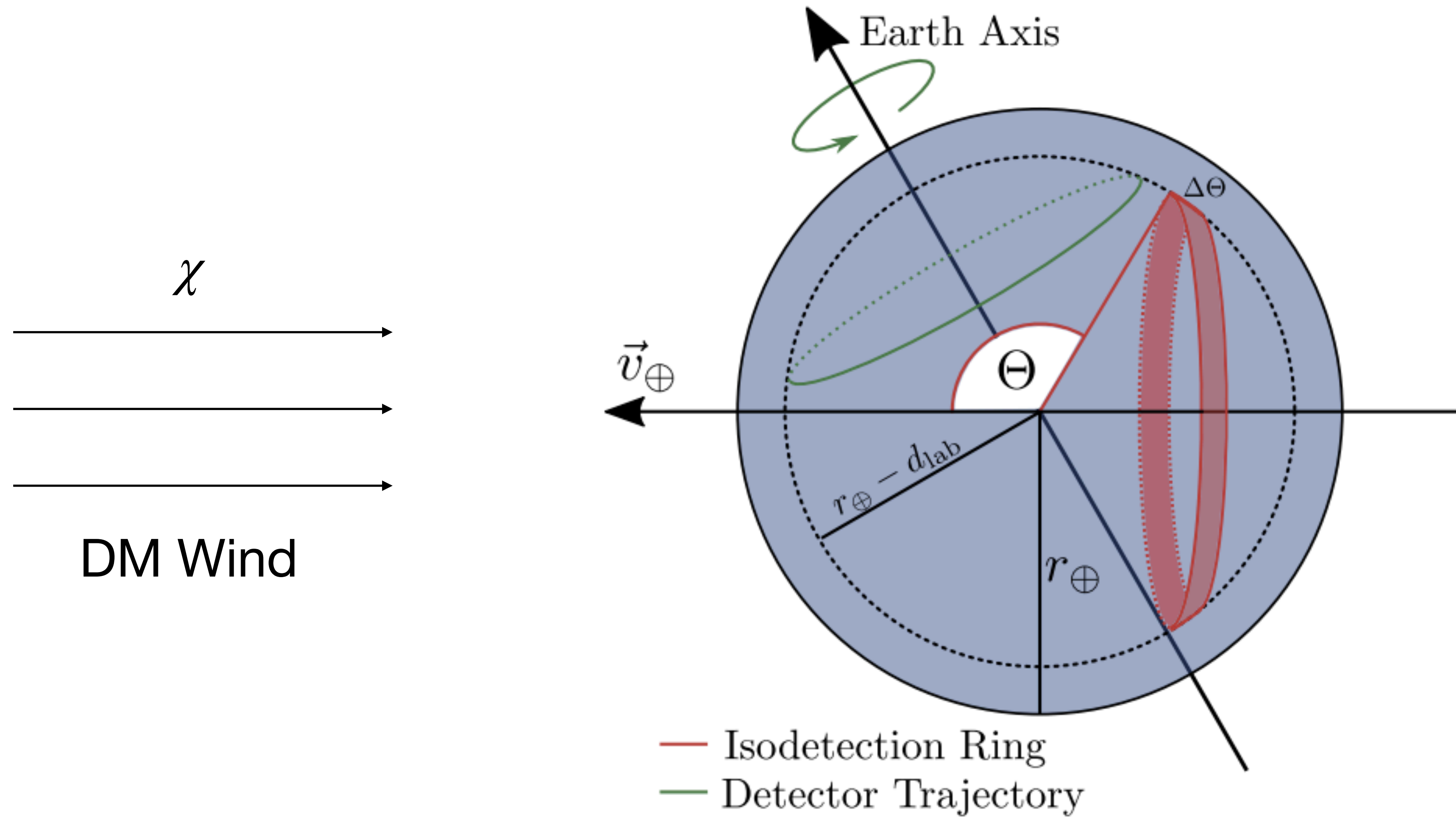
# Constraints on Multiple Scattering Dark Matter

$$\left. \frac{dE}{dx} \right|_{th} = \frac{2E_i}{m_\chi} \left( \sum_{A \subset D} \frac{\mu_{\chi A}^2}{m_A} n_A \sigma_{\chi A} \right) \exp \left[ \frac{-2}{m_\chi} \left( x_O \sum_{A \subset O} n_A \frac{\mu_{\chi A}^2}{m_A} \sigma_{\chi A} + x_D \sum_{A \subset D} n_A \frac{\mu_{\chi A}^2}{m_A} \sigma_{\chi A} \right) \right]$$



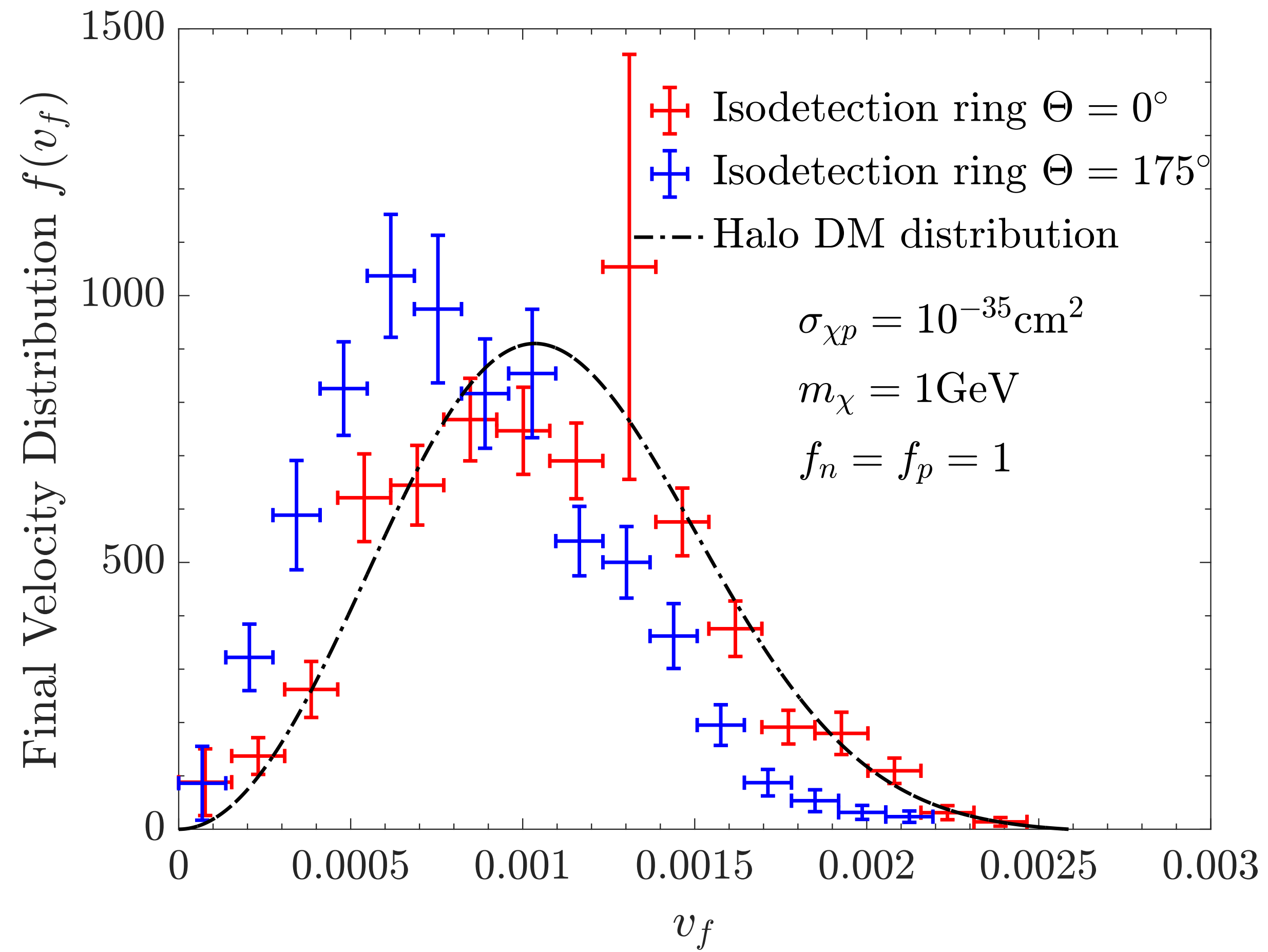
Bhoonah, Bramante, Courtman, **NS**, PRD/2012.13406

# Daily Modulation



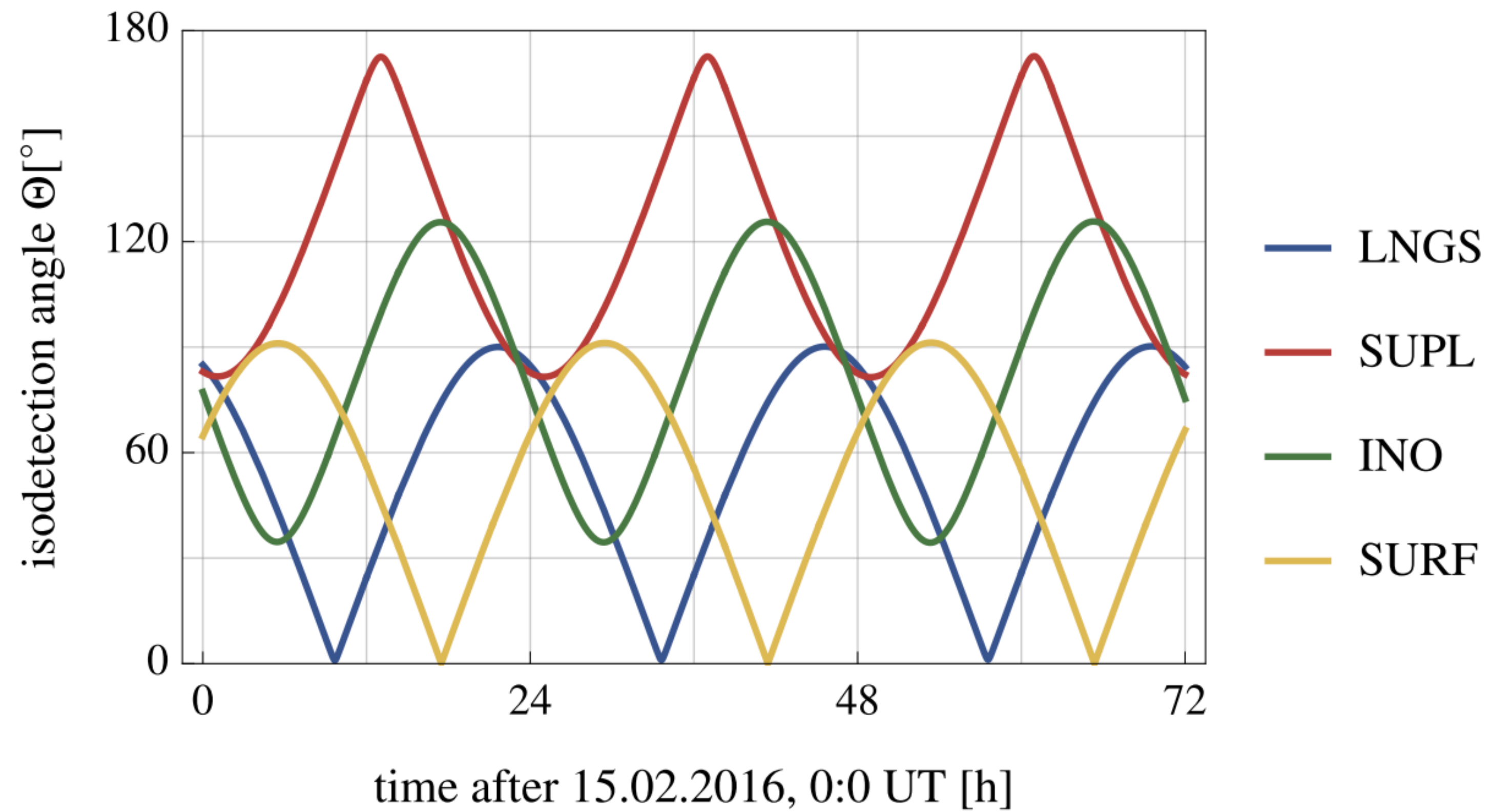
Emken, Kouvaris 1706.02249

# Daily Modulation



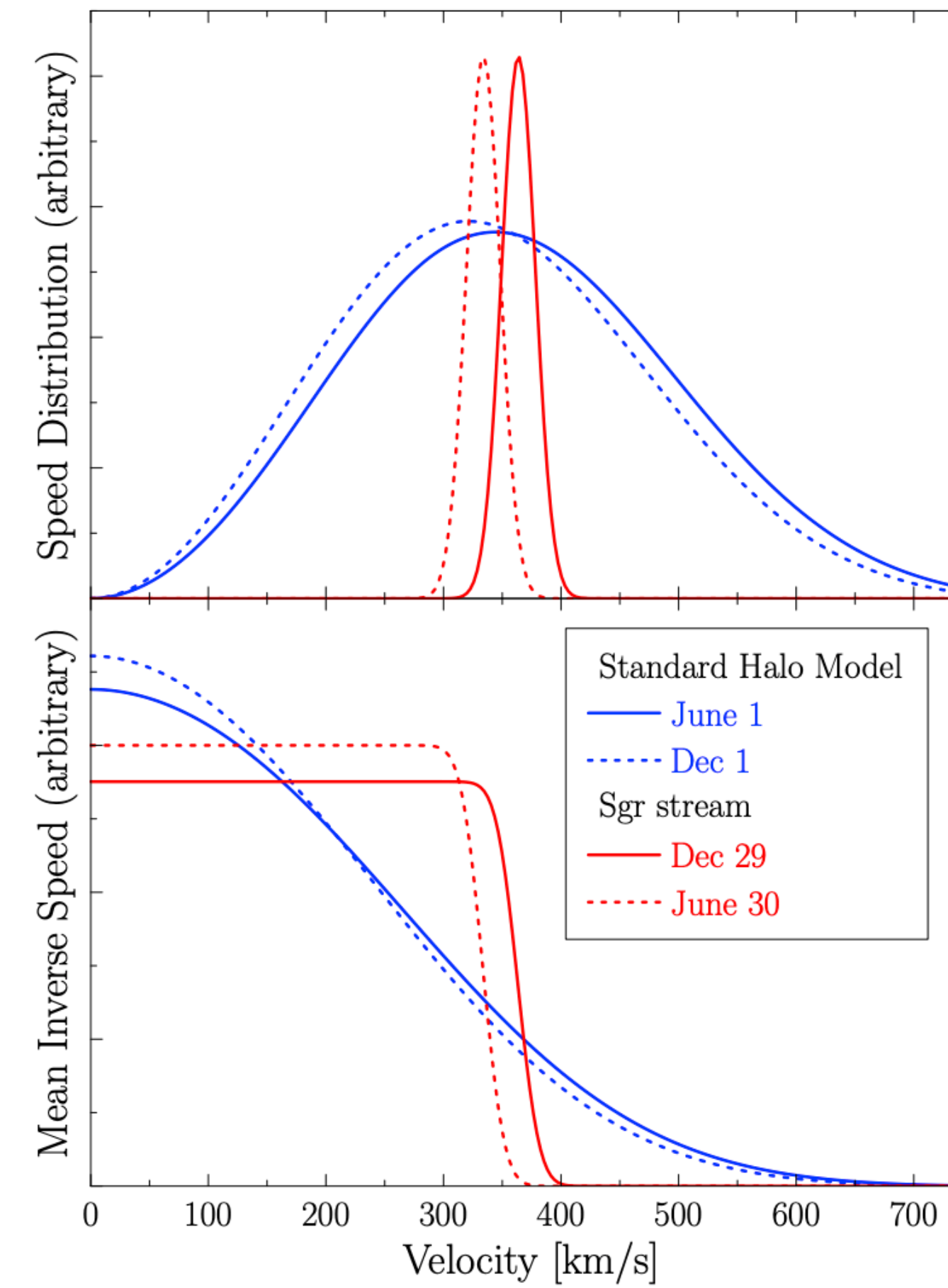
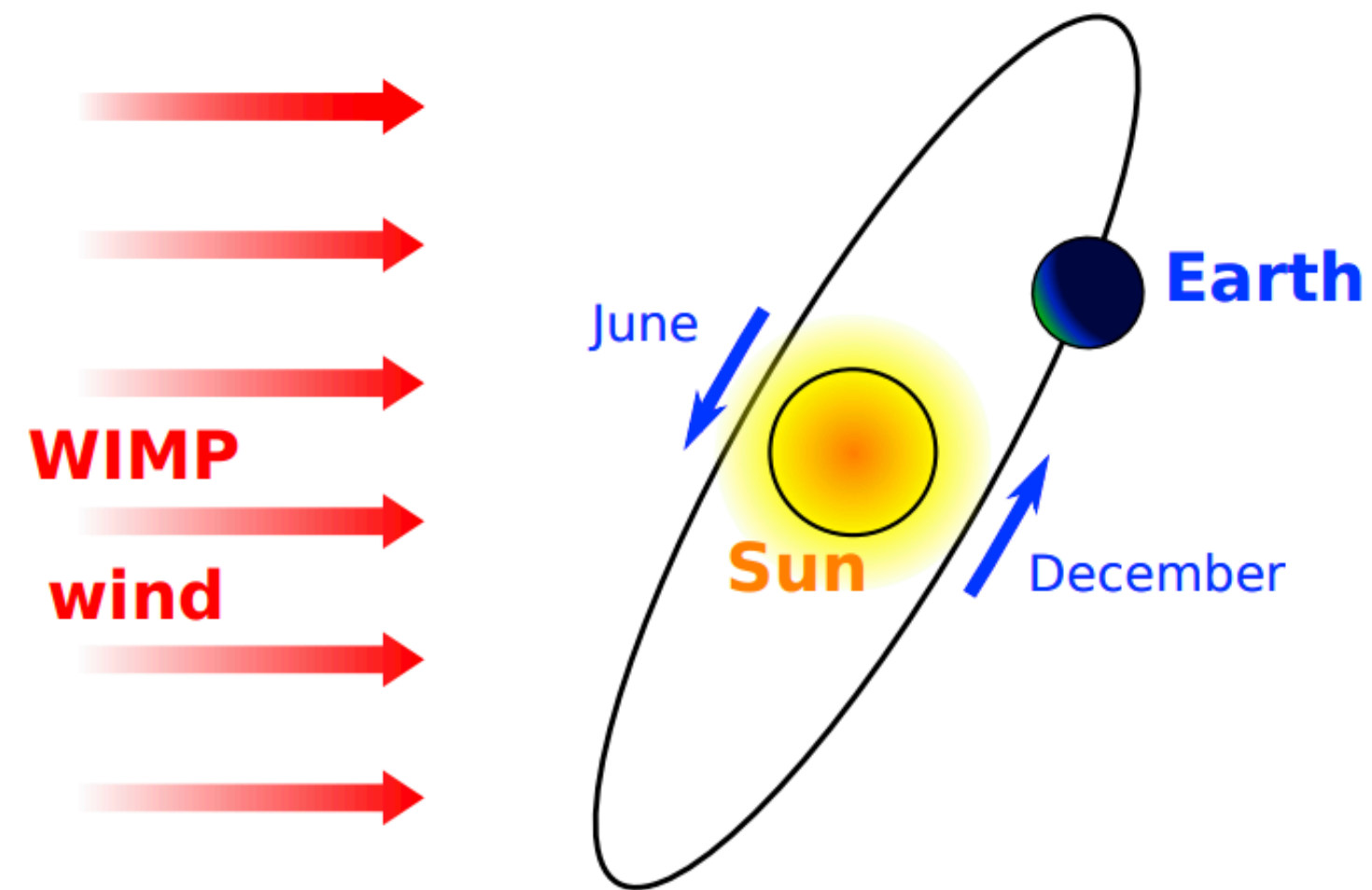


# Daily Modulation



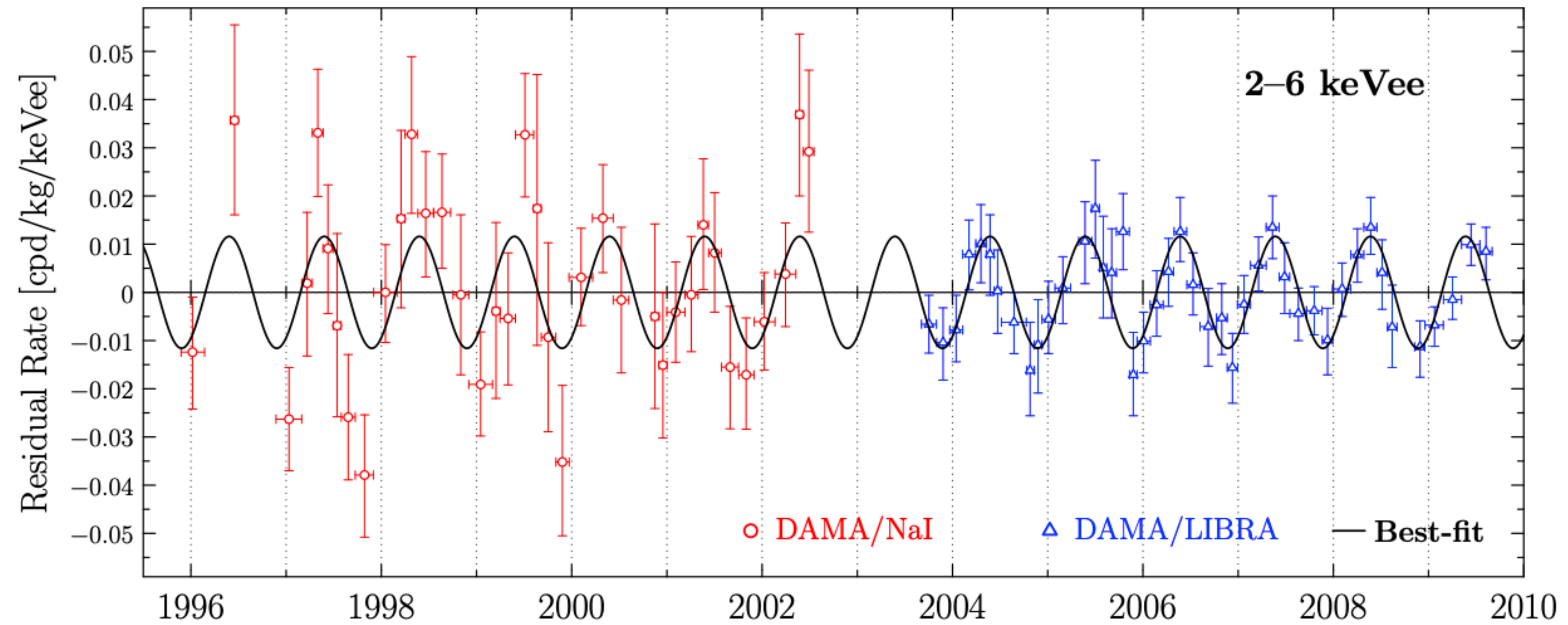
Emken, Kouvaris 1706.02249

# Annual Modulation



Freese *et al.*, arXiv:1209.3339

# The DAMA Experiment



Freese *et al.*, arXiv:1209.3339

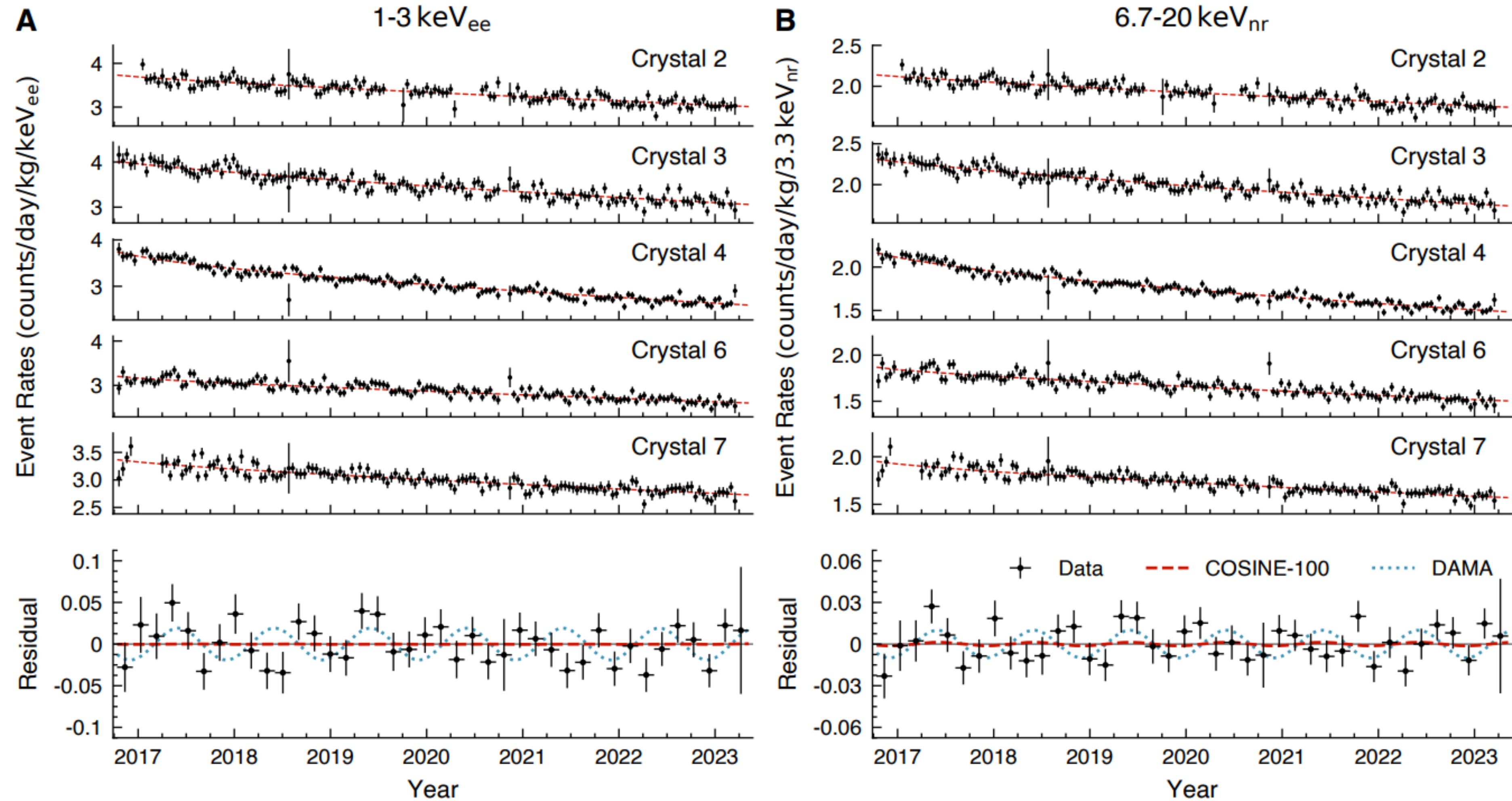


# The COSINE-100 Experiment

## COSINE-100 Full Dataset Challenges the Annual Modulation Signal of DAMA/LIBRA

For over 25 years, the DAMA/LIBRA collaboration has claimed to observe an annual modulation signal, suggesting the existence of dark matter interactions. However, no other experiments have replicated their result using different detector materials. To address this puzzle, the COSINE-100 collaboration conducted a model-independent test using 106 kg of sodium iodide as detectors, the same target material as DAMA/LIBRA. Analyzing data collected over 6.4 years, with improved energy calibration and time-dependent background description, we found no evidence of an annual modulation signal, challenging the DAMA/LIBRA result with a confidence level greater than  $3\sigma$ . This finding represents a significant step toward resolving the long-standing debate surrounding DAMA/LIBRA's dark matter claim, indicating that the observed modulation is unlikely to be caused by dark matter interactions.

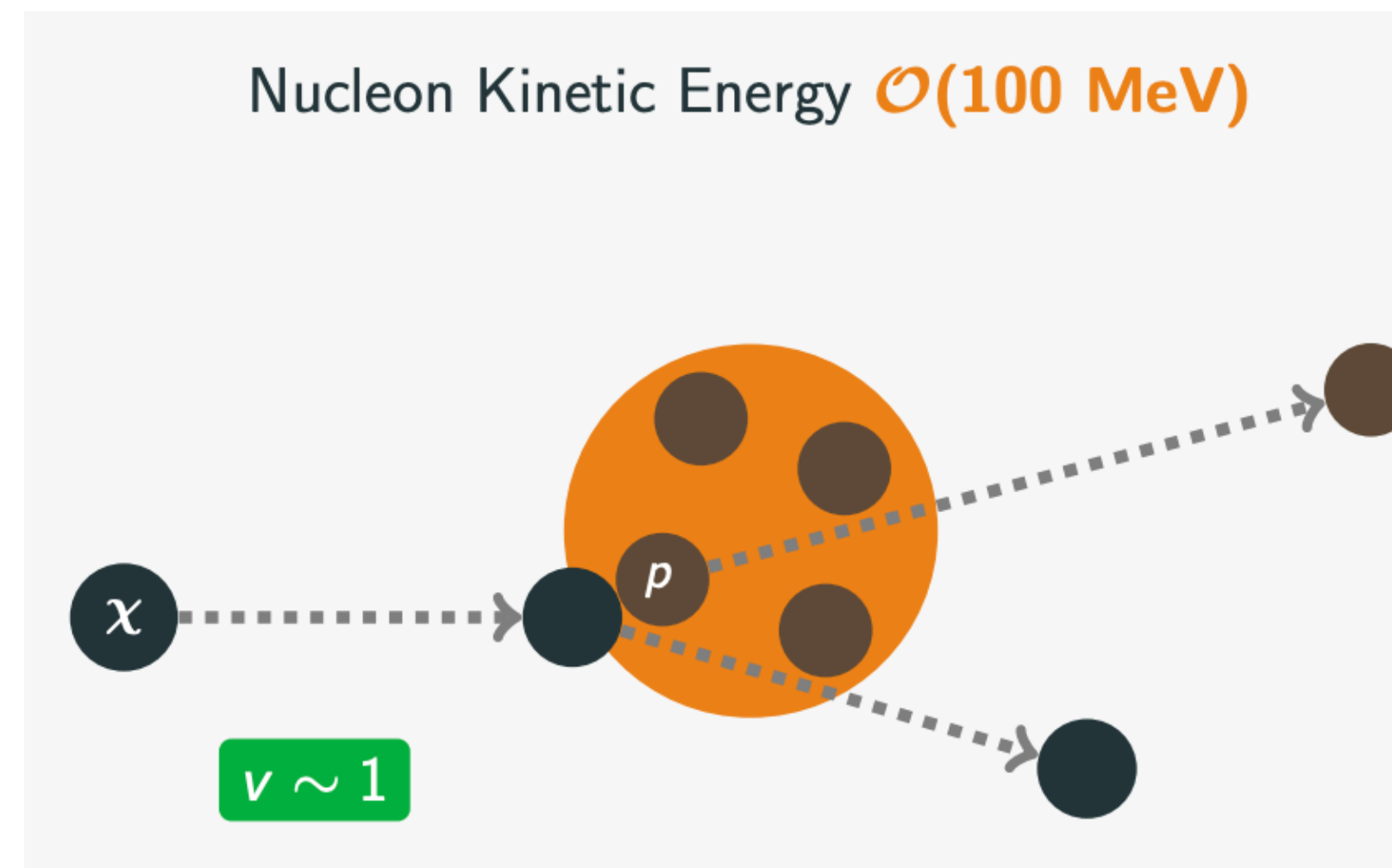
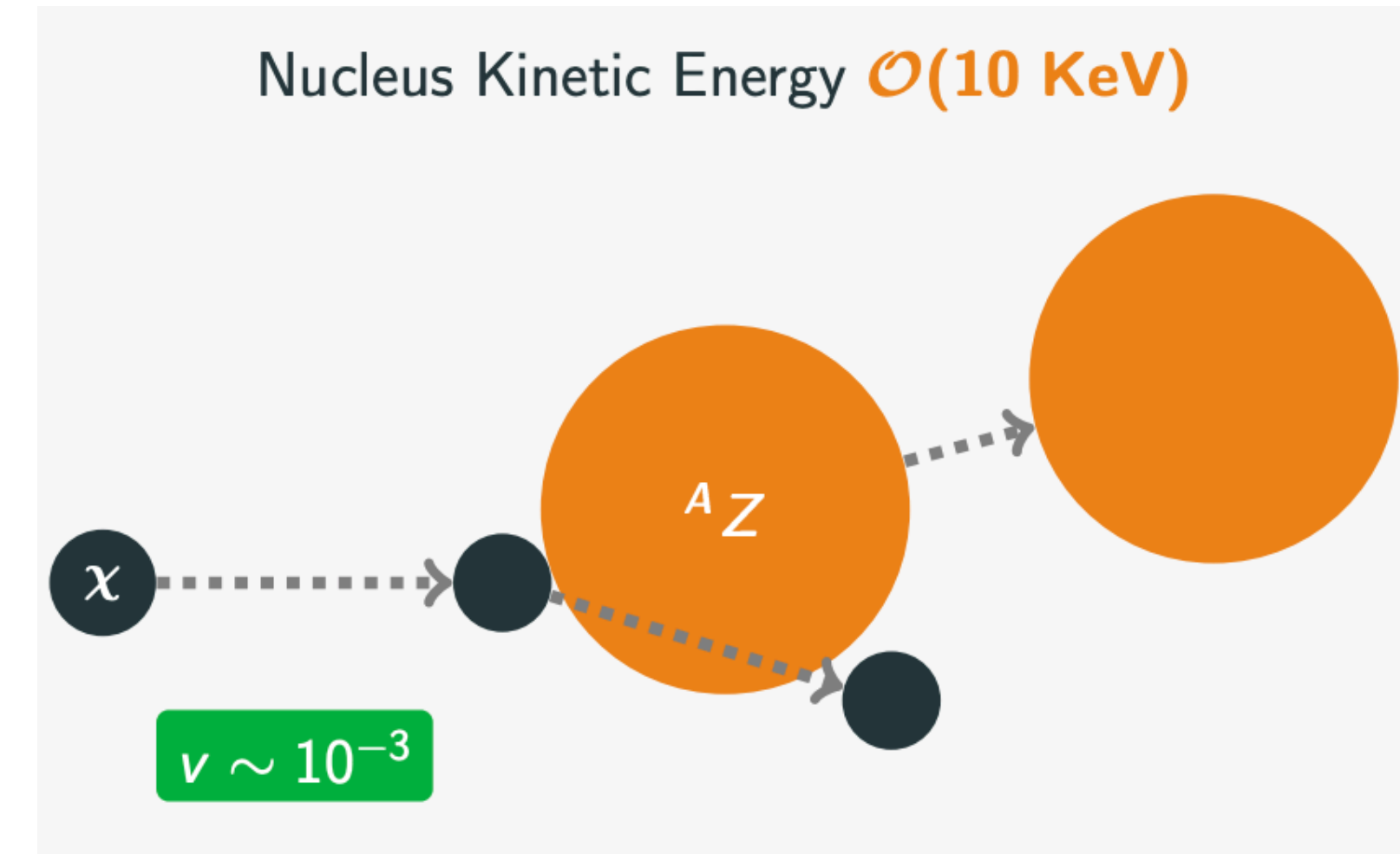
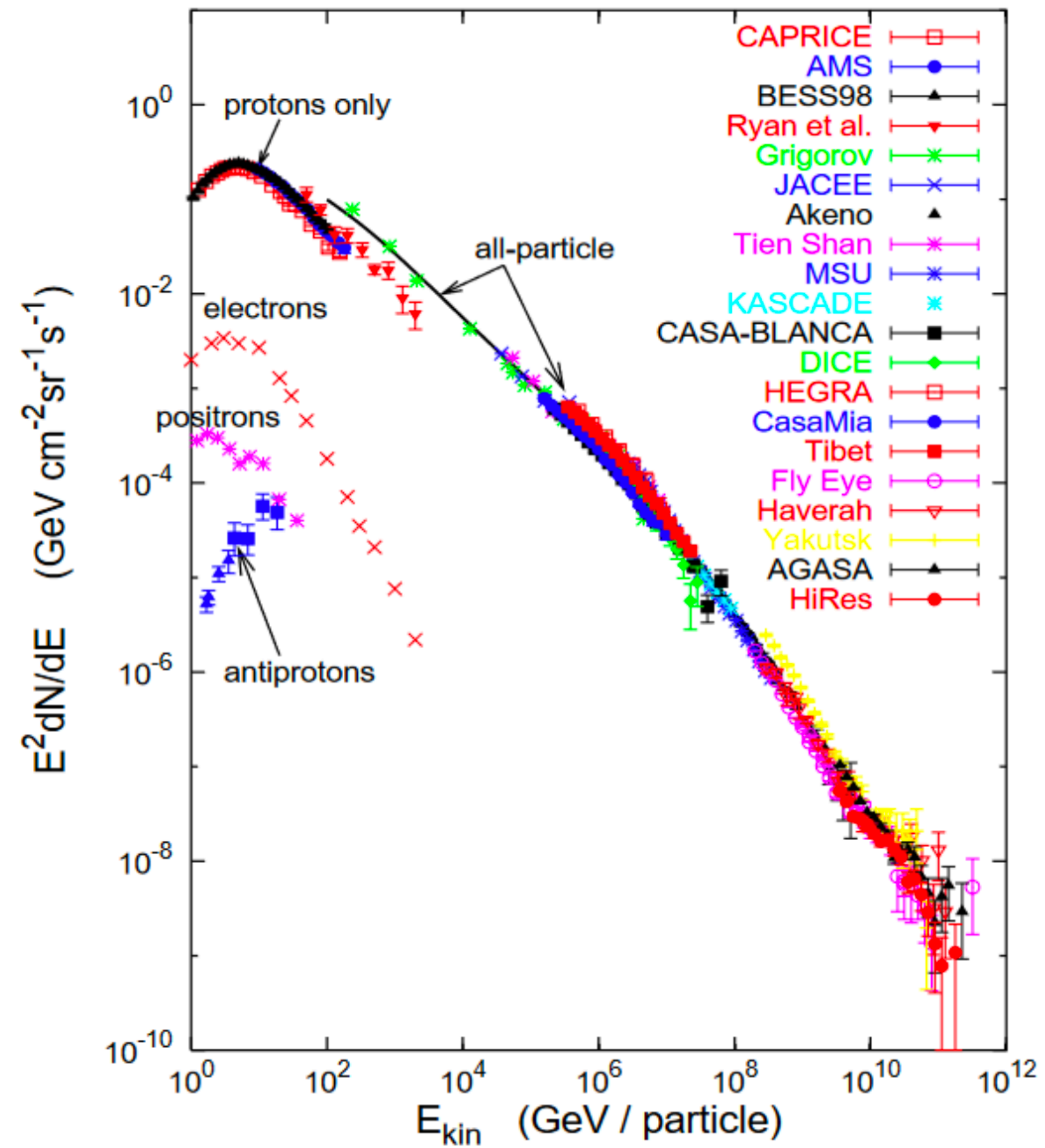
# The COSINE-100 Experiment



COSINE-100 collaboration, arXiv:2409.13226



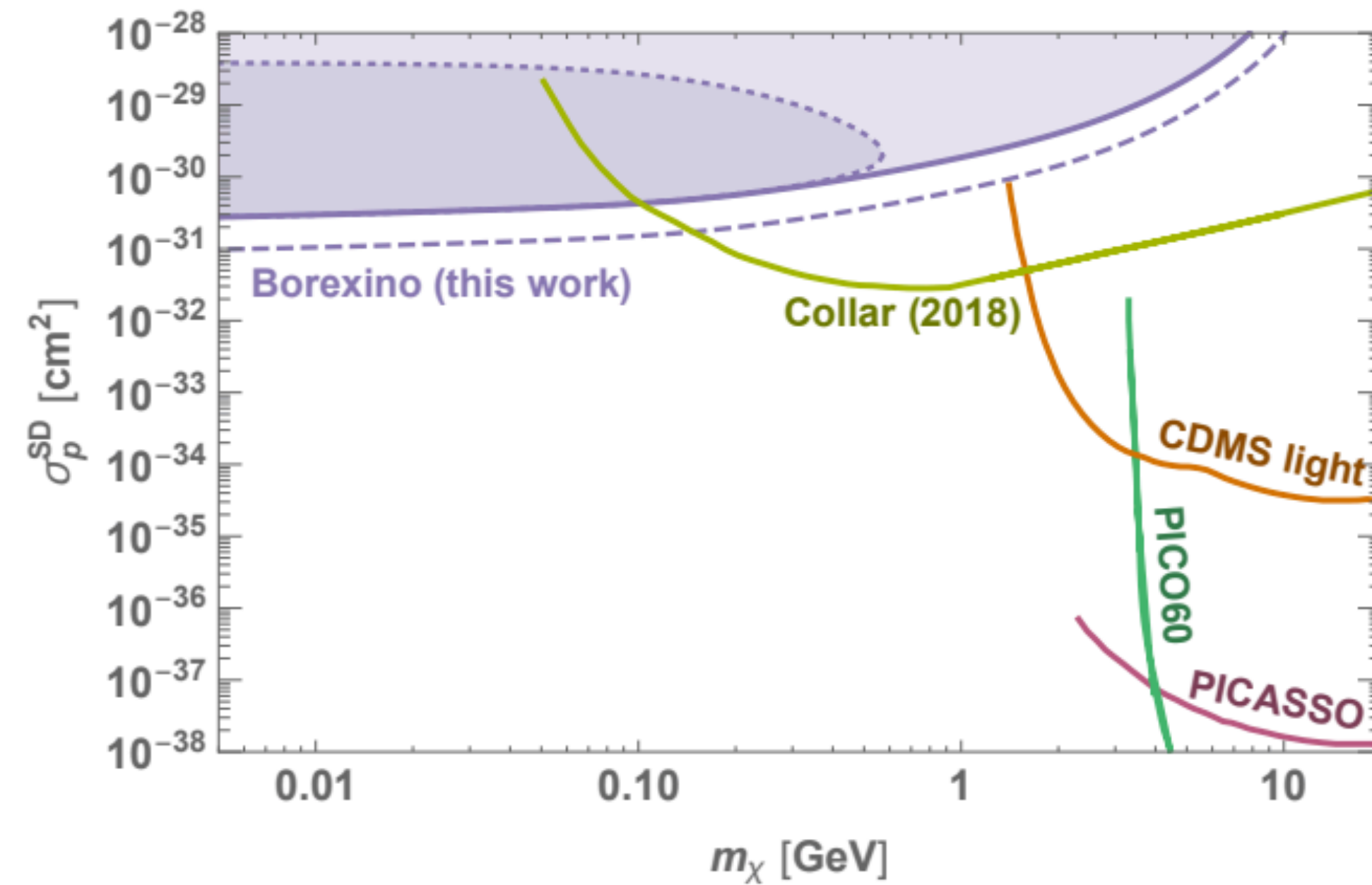
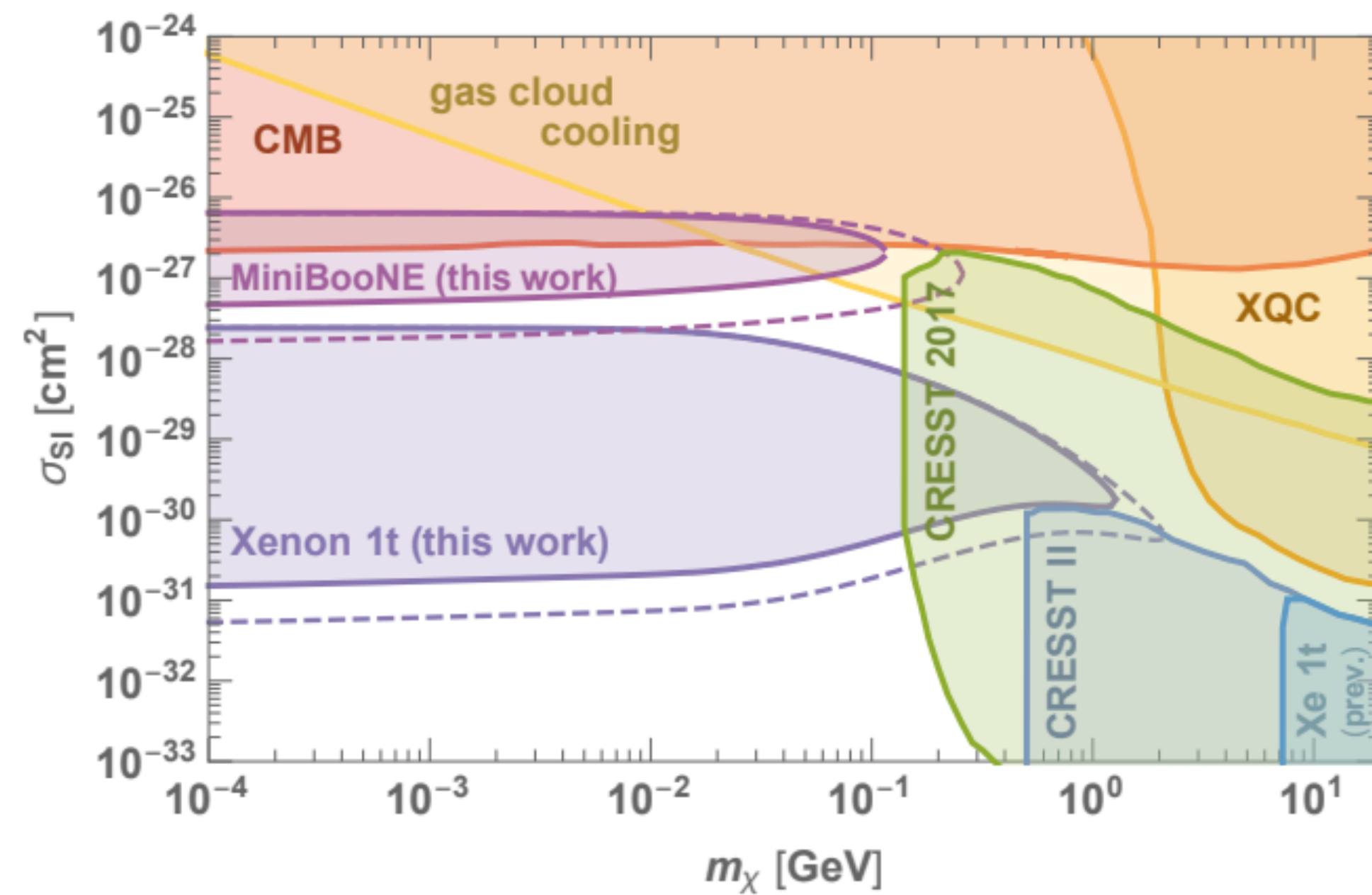
# Cosmic Rays



Credit: Joshua Berger



# Cosmic Ray Boosted Dark Matter: Constraints



Bringmann et al, arXiv:1810.10543

# Cosmic Ray Boosted Dark Matter: Kinematics

Kinematics:

$$T_\chi = T_\chi^{\max} \frac{1 - \cos \theta}{2}, \quad T_\chi^{\max} = \frac{T_i^2 + 2m_i T_i}{T_i + (m_i + m_\chi)^2 / (2m_\chi)}$$

$$T_i^{\min} = \left( \frac{T_\chi}{2} - m_i \right) \left[ 1 \pm \sqrt{1 + \frac{2T_\chi}{m_\chi} \frac{(m_i + m_\chi)^2}{(2m_i - T_\chi)^2}} \right],$$

# Cosmic Ray Boosted Dark Matter: Boost

Kinematics:

$$T_\chi = T_\chi^{\max} \frac{1 - \cos \theta}{2}, \quad T_\chi^{\max} = \frac{T_i^2 + 2m_i T_i}{T_i + (m_i + m_\chi)^2 / (2m_\chi)}$$

$$T_i^{\min} = \left( \frac{T_\chi}{2} - m_i \right) \left[ 1 \pm \sqrt{1 + \frac{2T_\chi}{m_\chi} \frac{(m_i + m_\chi)^2}{(2m_i - T_\chi)^2}} \right],$$

$$d\Gamma_{\text{CR}_i \rightarrow \chi} = \sigma_{\chi i} \times \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i^{\text{LIS}}}{dT_i} dT_i dV$$

$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{\text{l.o.s.}} d\ell \sigma_{\chi i} \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i} \frac{\rho_\chi^{\text{local}}}{m_\chi} \frac{d\Phi_i^{\text{LIS}}}{dT_i} D_{\text{eff}}$$

$$\frac{d\Phi_\chi}{dT_\chi} = \int_0^\infty dT_i \frac{d\Phi_\chi}{dT_i} \frac{1}{T_\chi^{\max}(T_i)} \Theta [T_\chi^{\max}(T_i) - T_\chi]$$



# Cosmic Ray Boosted Dark Matter: Boost

Kinematics:

$$T_\chi = T_\chi^{\max} \frac{1 - \cos \theta}{2}, \quad T_\chi^{\max} = \frac{T_i^2 + 2m_i T_i}{T_i + (m_i + m_\chi)^2 / (2m_\chi)}$$

$$T_i^{\min} = \left( \frac{T_\chi}{2} - m_i \right) \left[ 1 \pm \sqrt{1 + \frac{2T_\chi}{m_\chi} \frac{(m_i + m_\chi)^2}{(2m_i - T_\chi)^2}} \right],$$

$$d\Gamma_{\text{CR}_i \rightarrow \chi} = \sigma_{\chi i} \times \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i^{\text{LIS}}}{dT_i} dT_i dV$$

$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{\text{l.o.s.}} d\ell \sigma_{\chi i} \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i} \frac{\rho_\chi^{\text{local}}}{m_\chi} \frac{d\Phi_i^{\text{LIS}}}{dT_i} D_{\text{eff}}$$

$$\frac{d\Phi_\chi}{dT_\chi} = \int_0^\infty dT_i \frac{d\Phi_\chi}{dT_i} \frac{1}{T_\chi^{\max}(T_i)} \Theta [T_\chi^{\max}(T_i) - T_\chi]$$

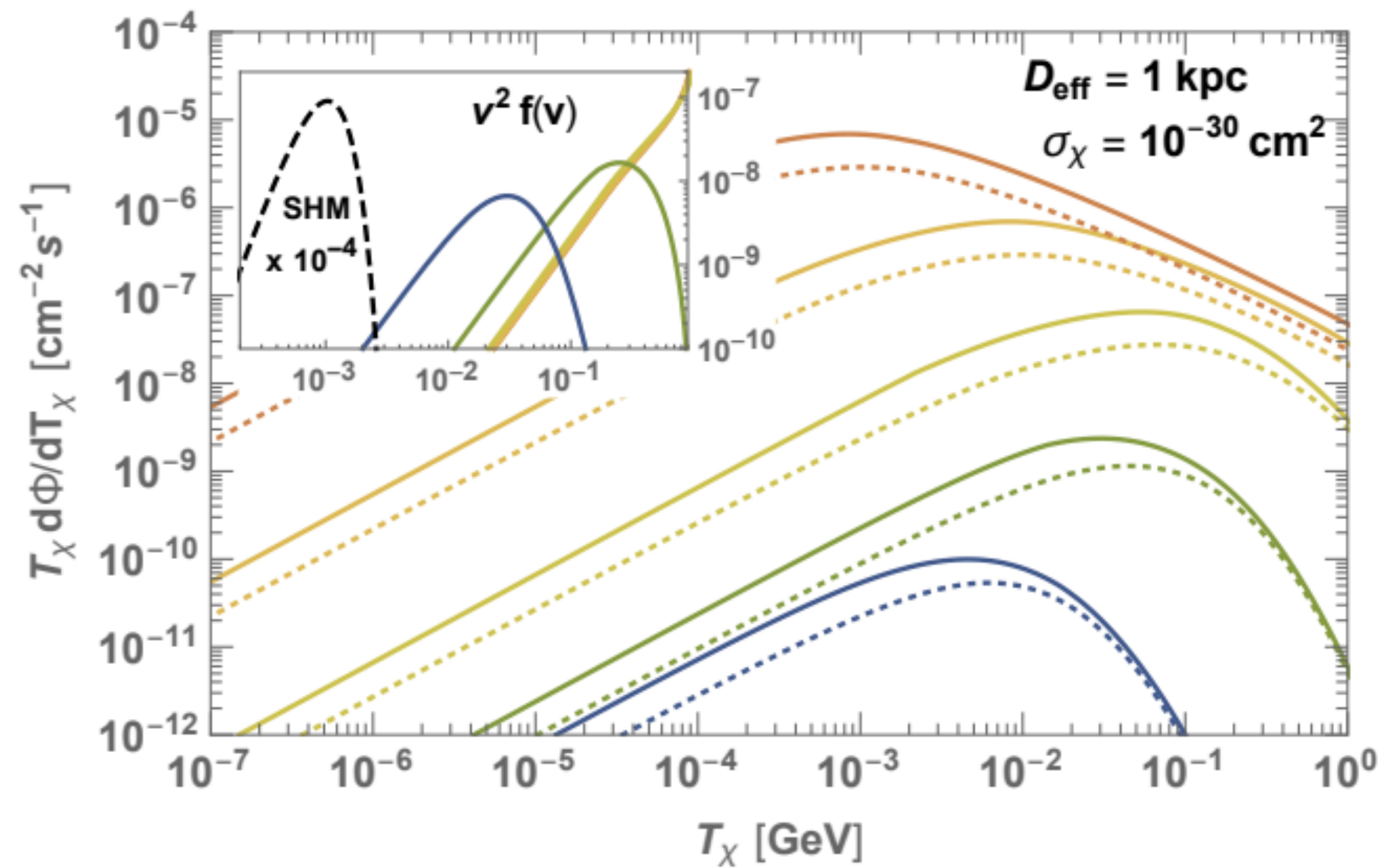
Hadronic elastic  
scattering form factor

$$G_i(Q^2) = 1 / (1 + Q^2 / \Lambda_i^2)^2, \quad \frac{d\sigma_{\chi i}}{d\Omega} = \left. \frac{d\sigma_{\chi i}}{d\Omega} \right|_{Q^2=0} G_i^2(2m_\chi T_\chi)$$

# Cosmic Ray Boosted Dark Matter: Spectrum

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\text{eff}} \frac{\rho_\chi^{\text{local}}}{m_\chi} \times$$

$$\times \sum_i \sigma_{\chi i}^0 G_i^2(2m_\chi T_\chi) \int_{T_i^{\text{min}}}^\infty dT_i \frac{d\Phi_i^{\text{LIS}}/dT_i}{T_\chi^{\text{max}}(T_i)}$$



Bringmann et al, arXiv:1810.10543

# Cosmic Ray Boosted Dark Matter: Detection

Attenuation

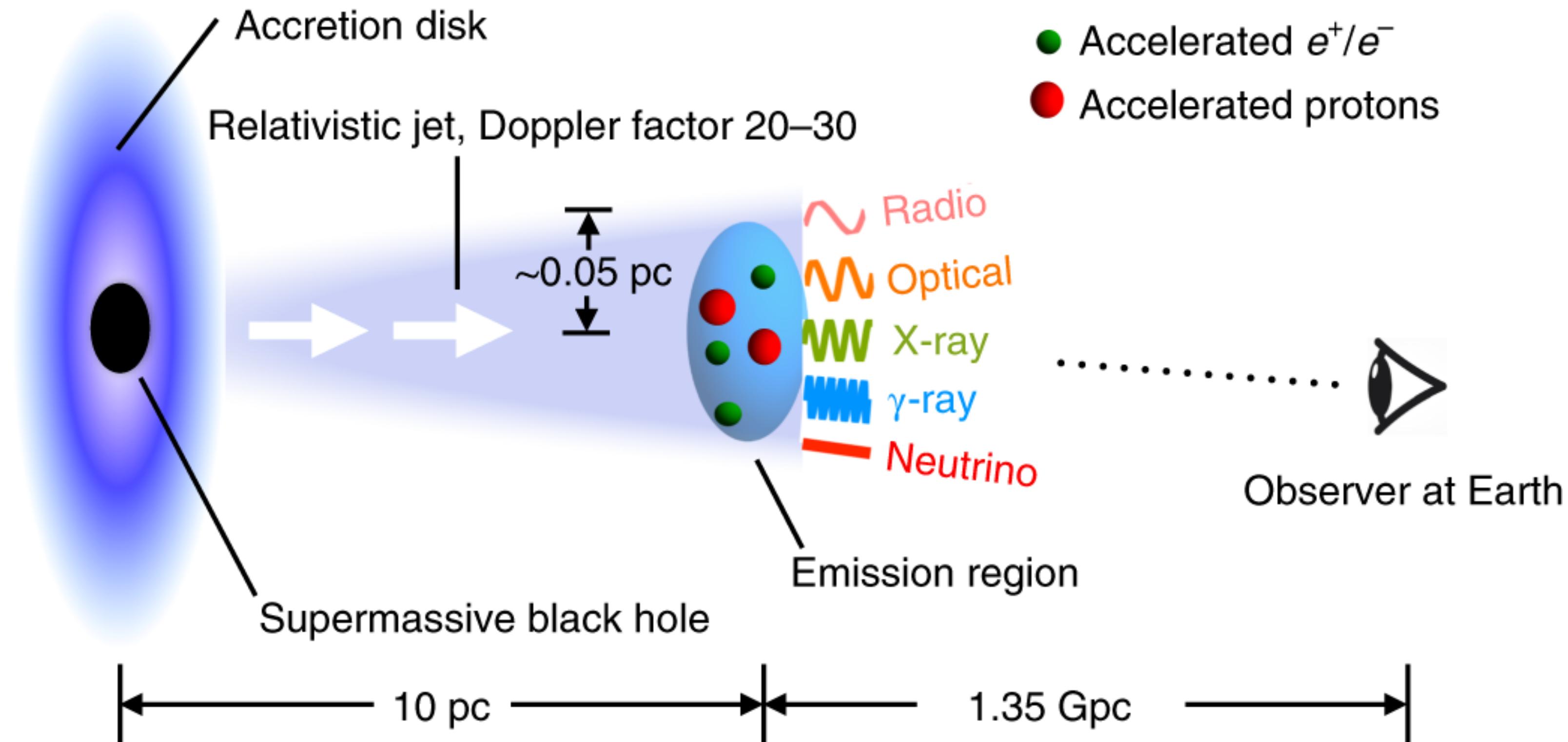
$$\frac{dT_{DM}}{dx} = - \sum_N n_N \int_0^{T_r^{\max}} \frac{d\sigma_{\chi N}}{dT_r} T_r dT_r$$

Detection

$$\frac{d\Gamma_N}{dT_N} = \sigma_{\chi N}^0 G_N^2(2m_N T_N) \int_{T_\chi(T_\chi^z, \min)}^\infty \frac{dT_\chi}{T_{r,N}^{\max}(T_\chi^z)} \frac{d\Phi_\chi}{dT_\chi}$$



# Blazar Boosted Dark Matter

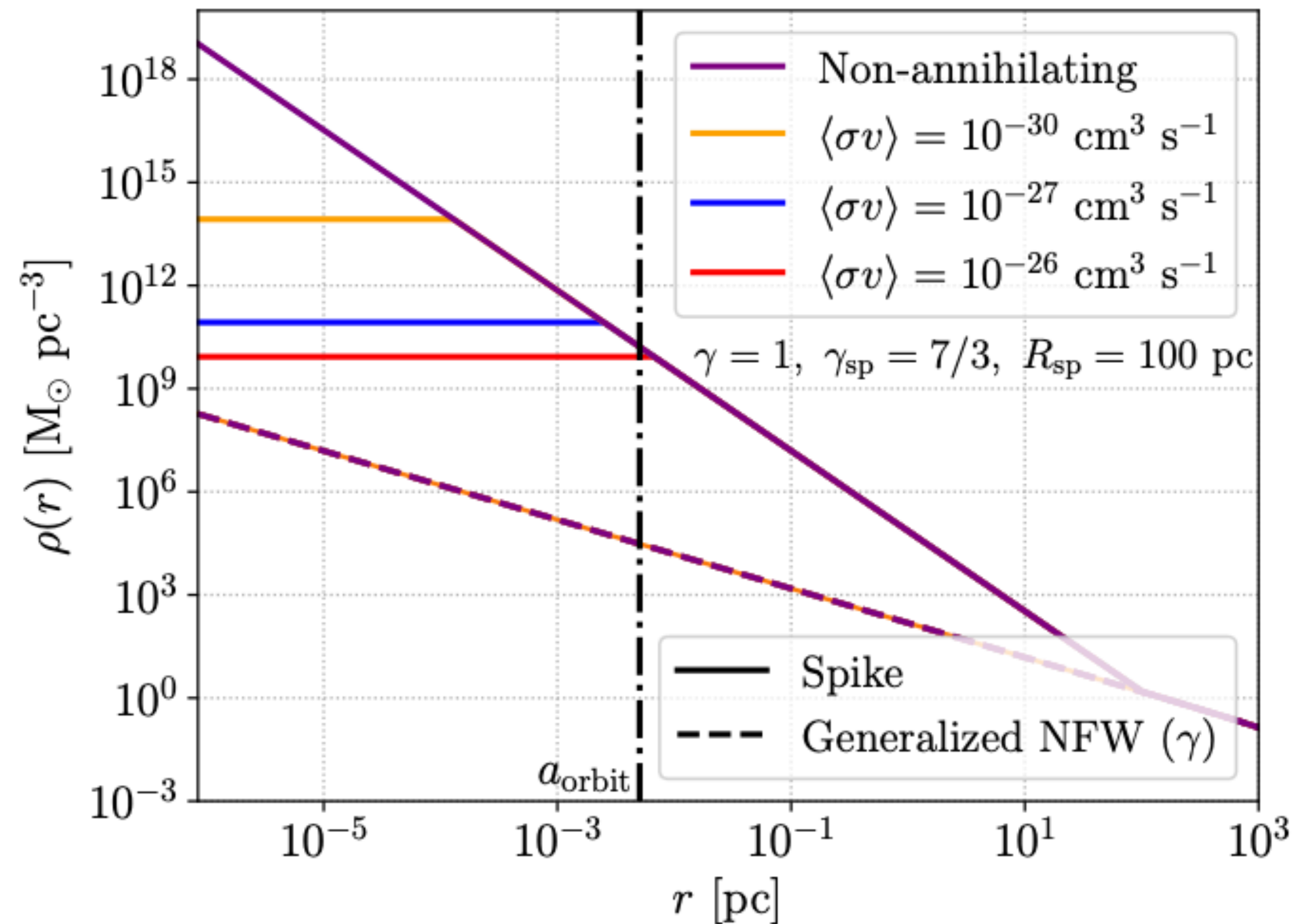


$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$p + p \rightarrow n_\pi [\pi^0 + \pi^+ + \pi^-]$$

Gao et al, Nature Astronomy, 2019

# A Dark Matter Spike?



Lacroix, arXiv: 1801.01308

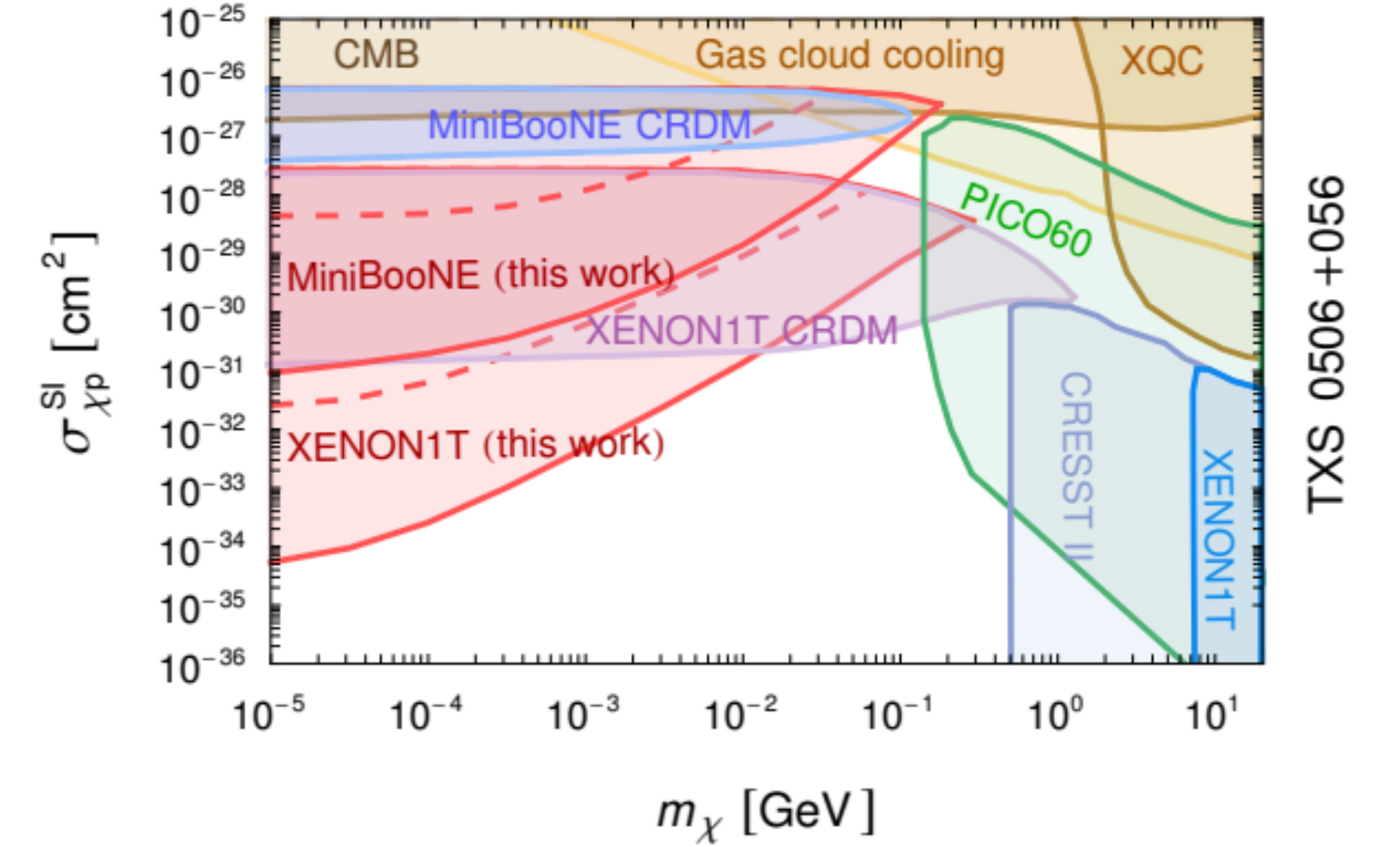
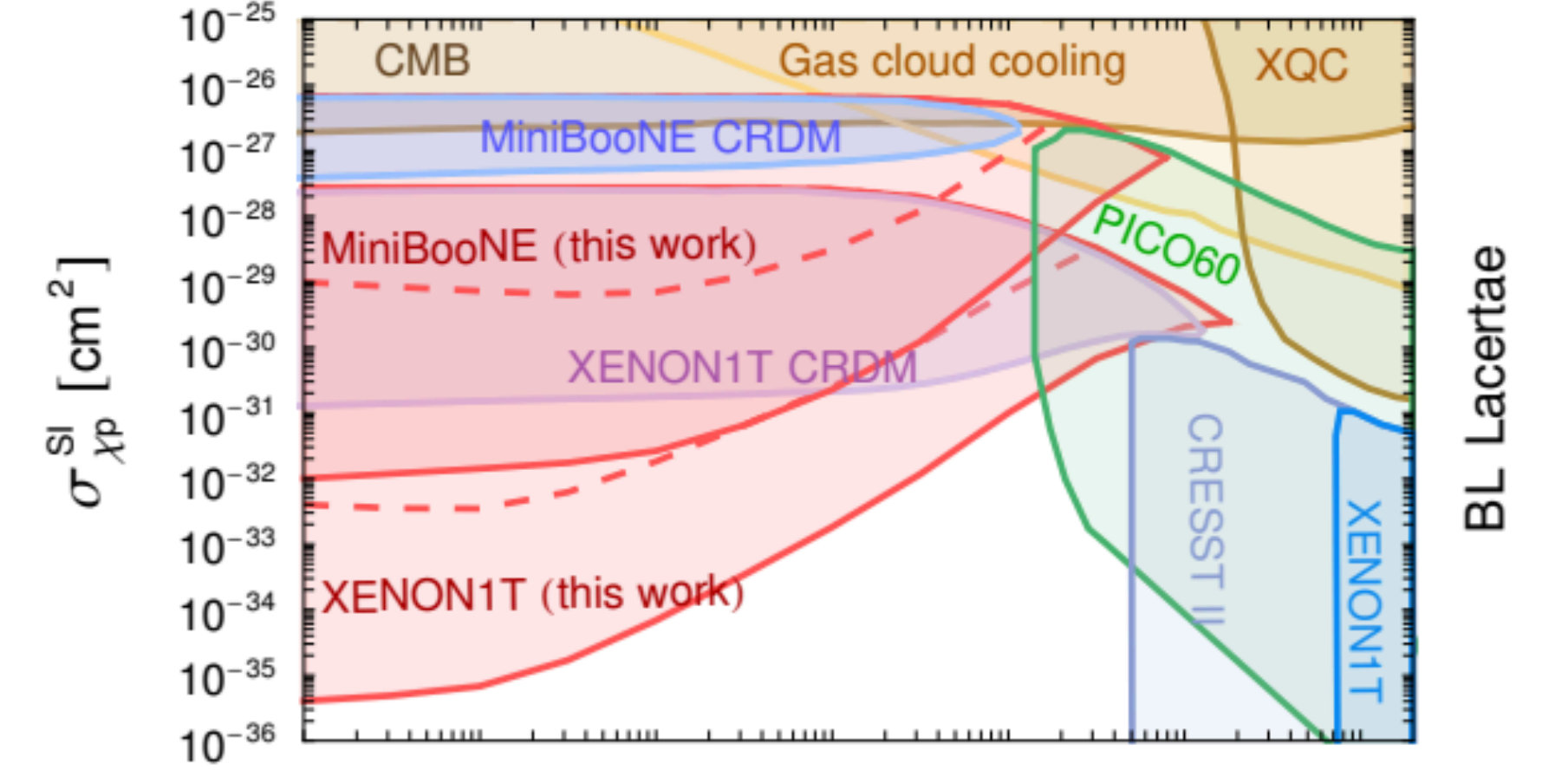
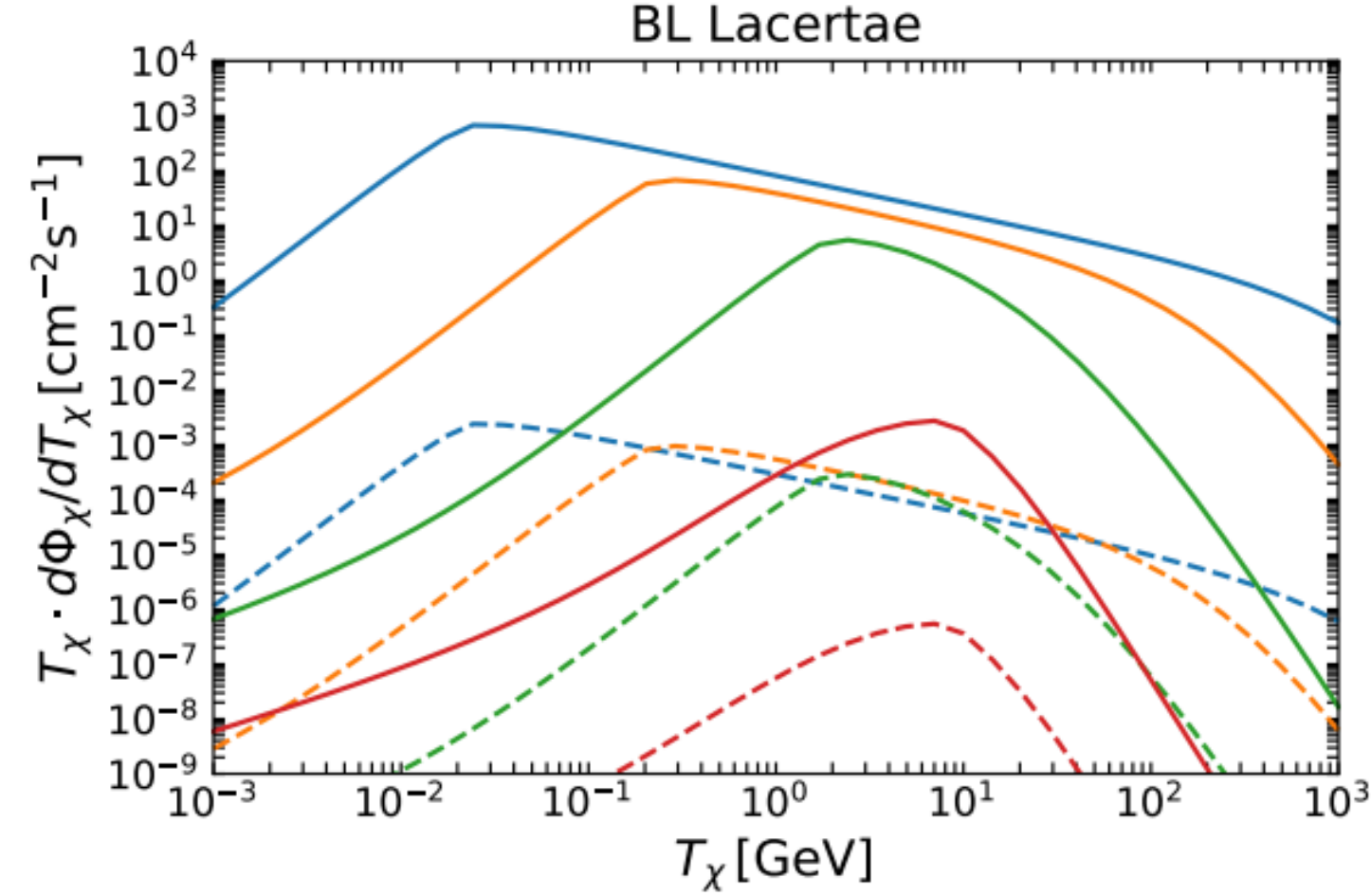
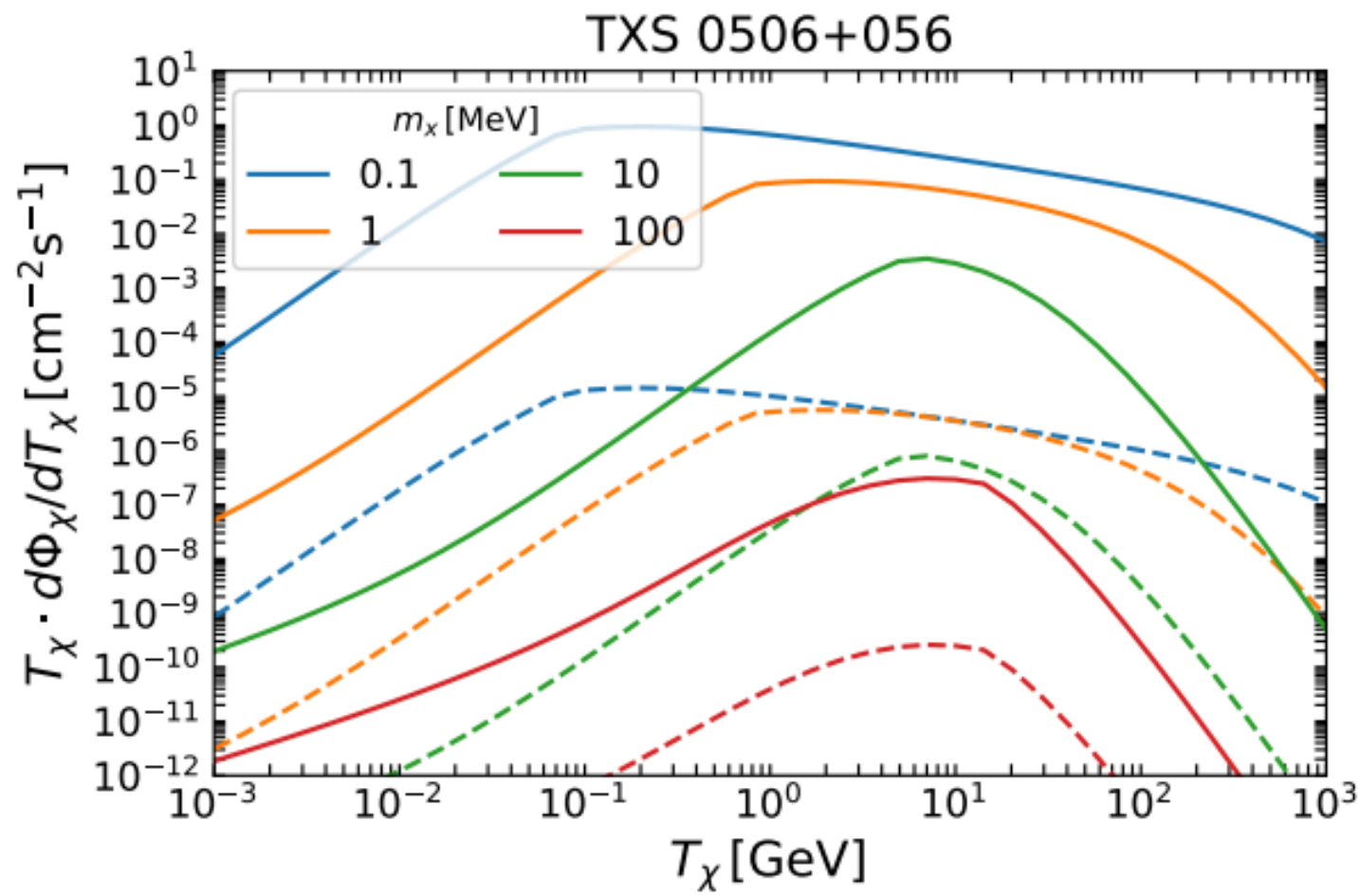
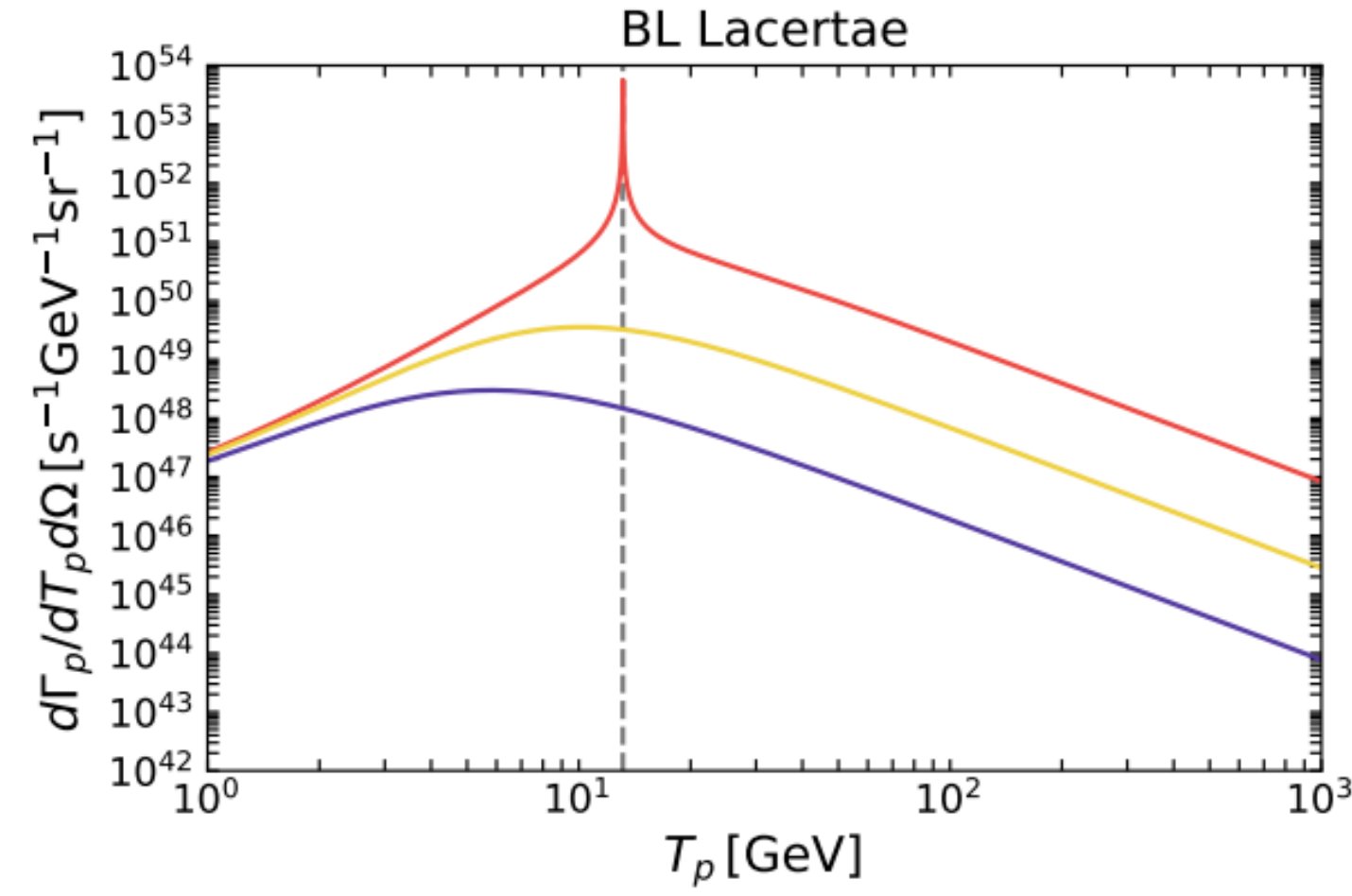
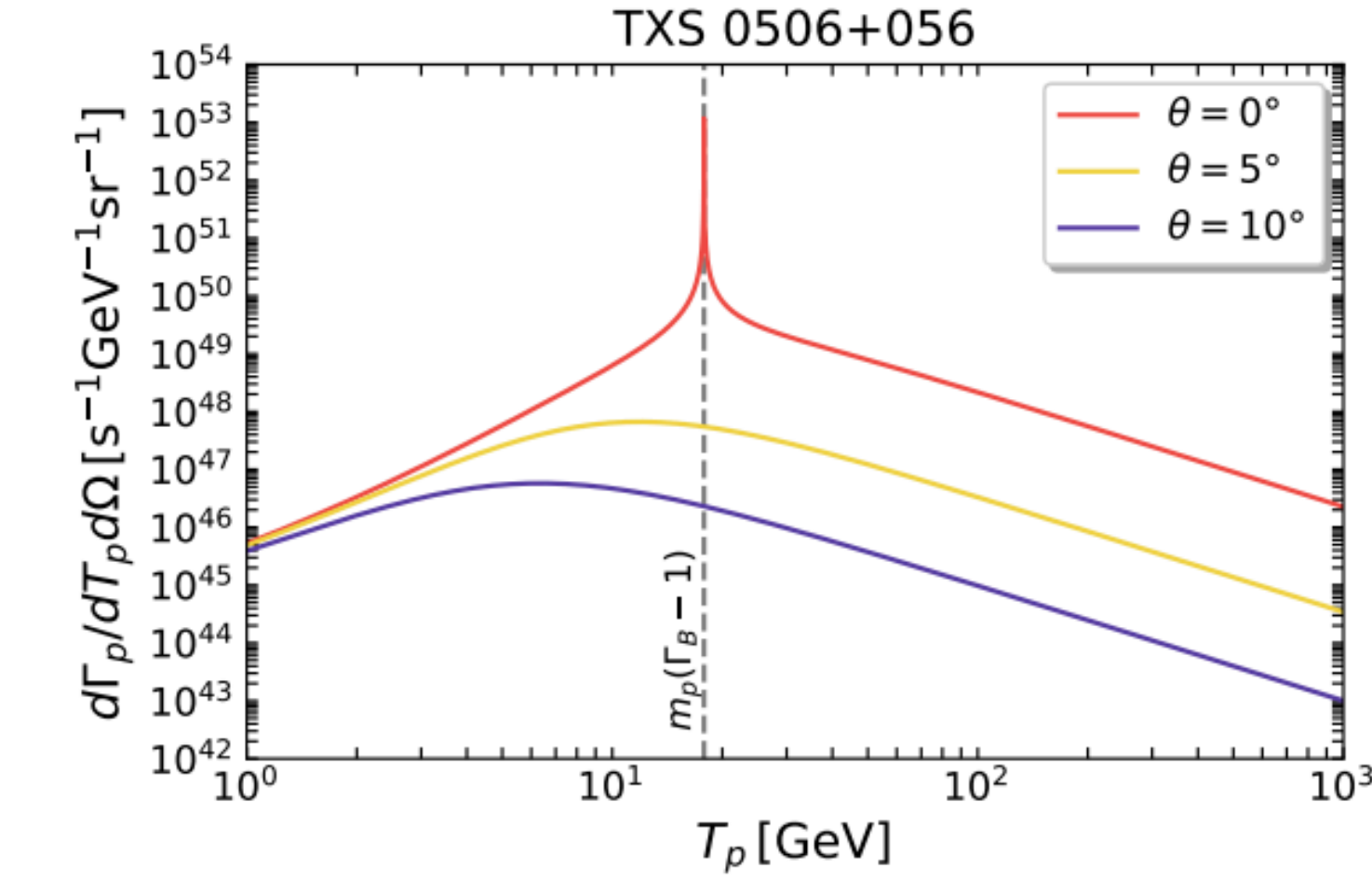
$$\rho(r) = \begin{cases} 0 & r < 2R_S \\ \rho_{\text{halo}}(R_{\text{sp}}) \left( \frac{r}{R_{\text{sp}}} \right)^{-\gamma_{\text{sp}}} & 2R_S \leq r < R_{\text{sp}} \\ \rho_{\text{halo}}(r) & r \geq R_{\text{sp}}, \end{cases}$$

$$\rho_{\text{halo}}(r) = \rho_s \left( \frac{r}{r_s} \right)^{-\gamma} \left( 1 + \frac{r}{r_s} \right)^{\gamma-3},$$

Spike inside, NFW outside



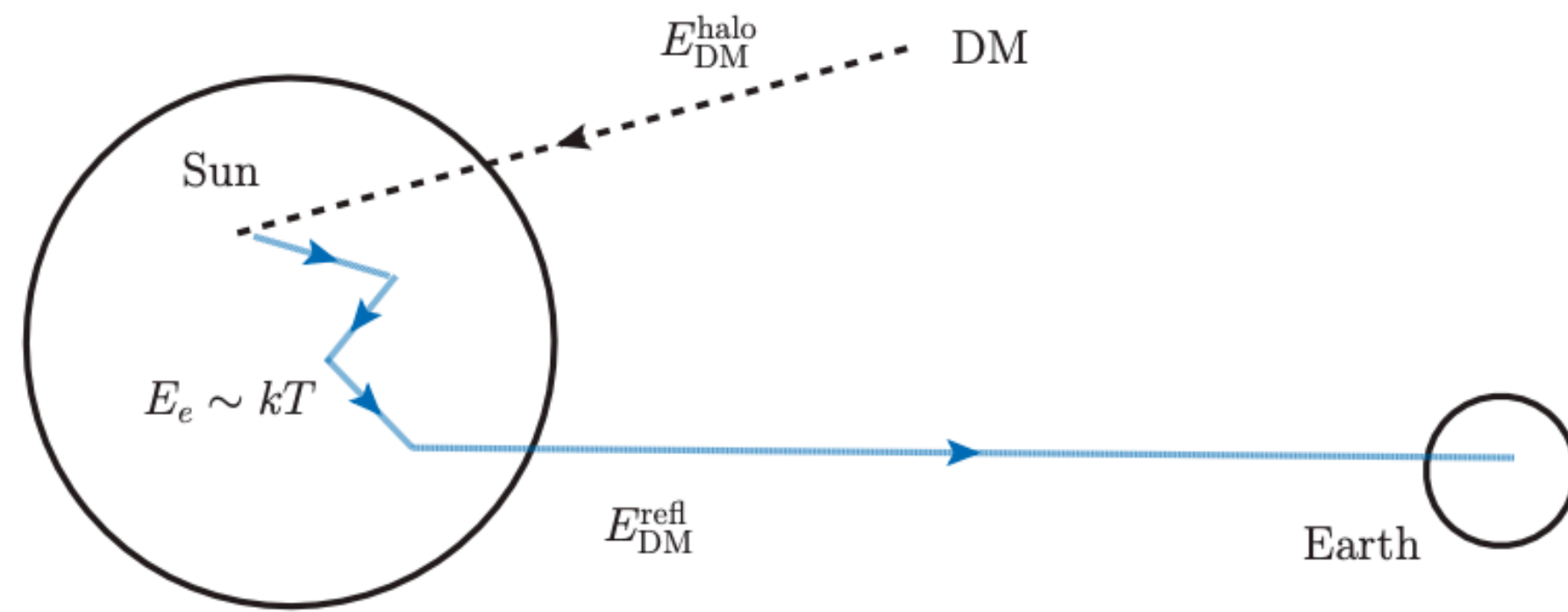
# Blazar Boosted Dark Matter



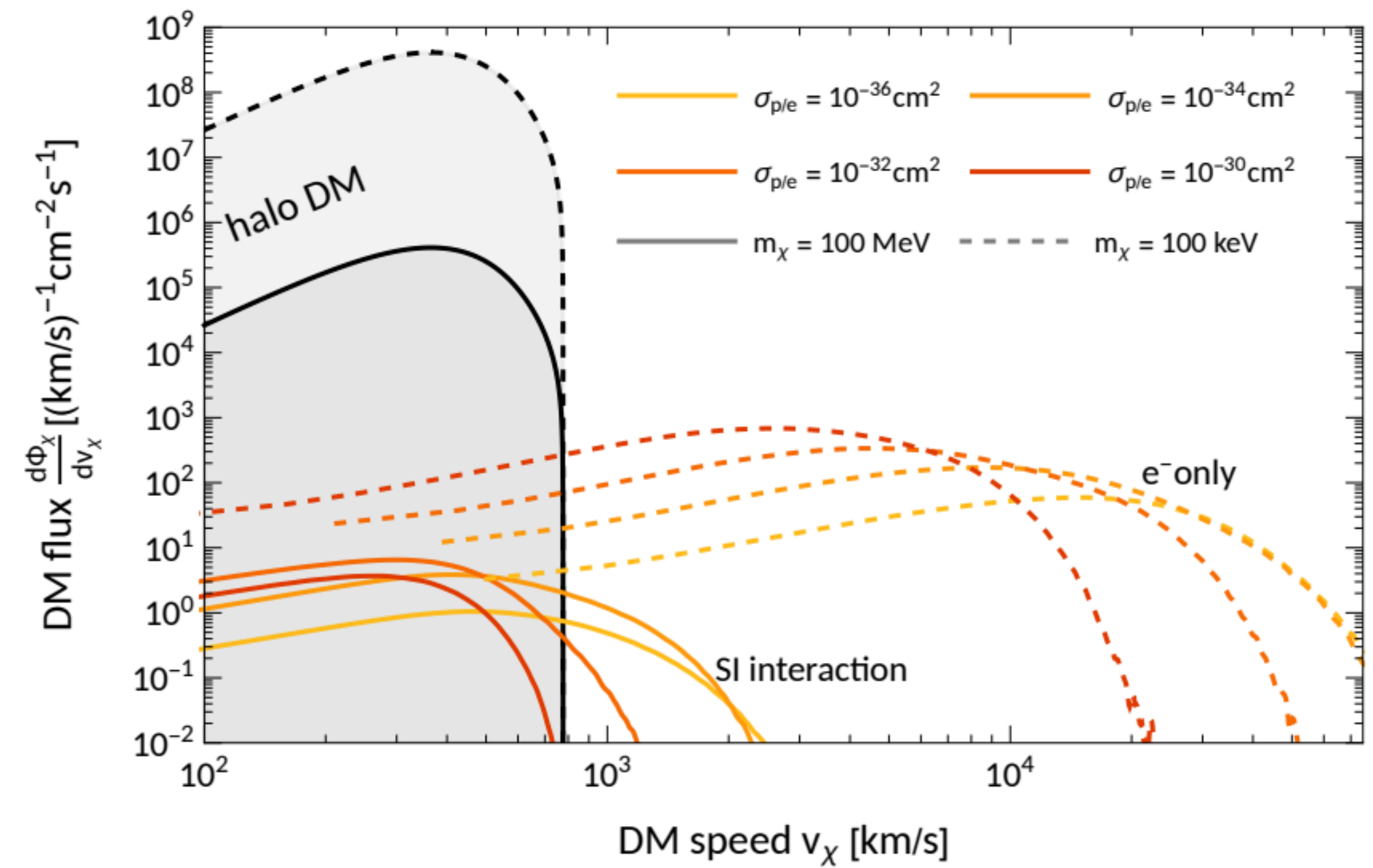
Wang et al, arXiv: 2111.13644



# Solar Reflected Dark Matter



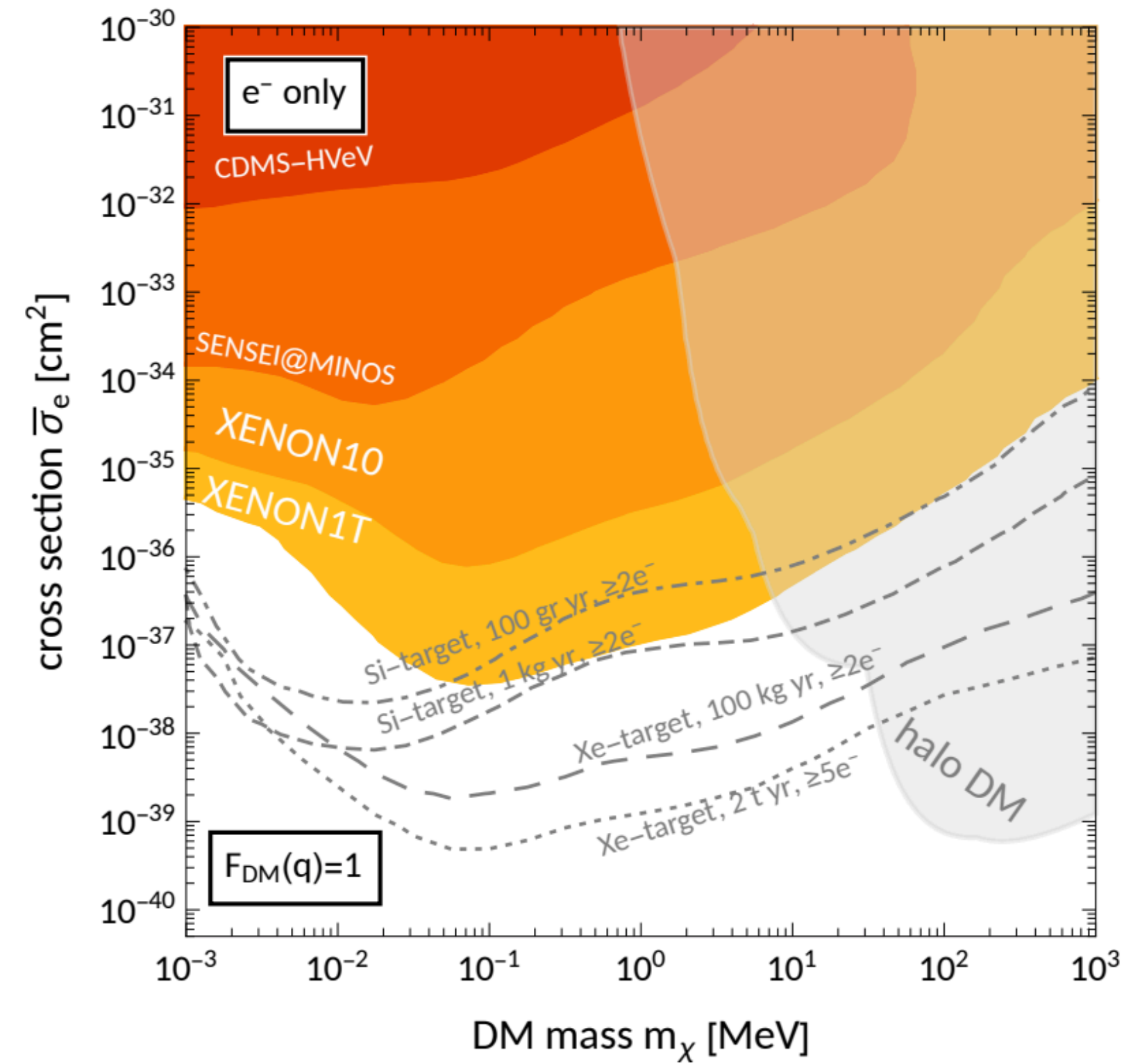
Need dedicated simulations!



Emken, arXiv: 2102.12483

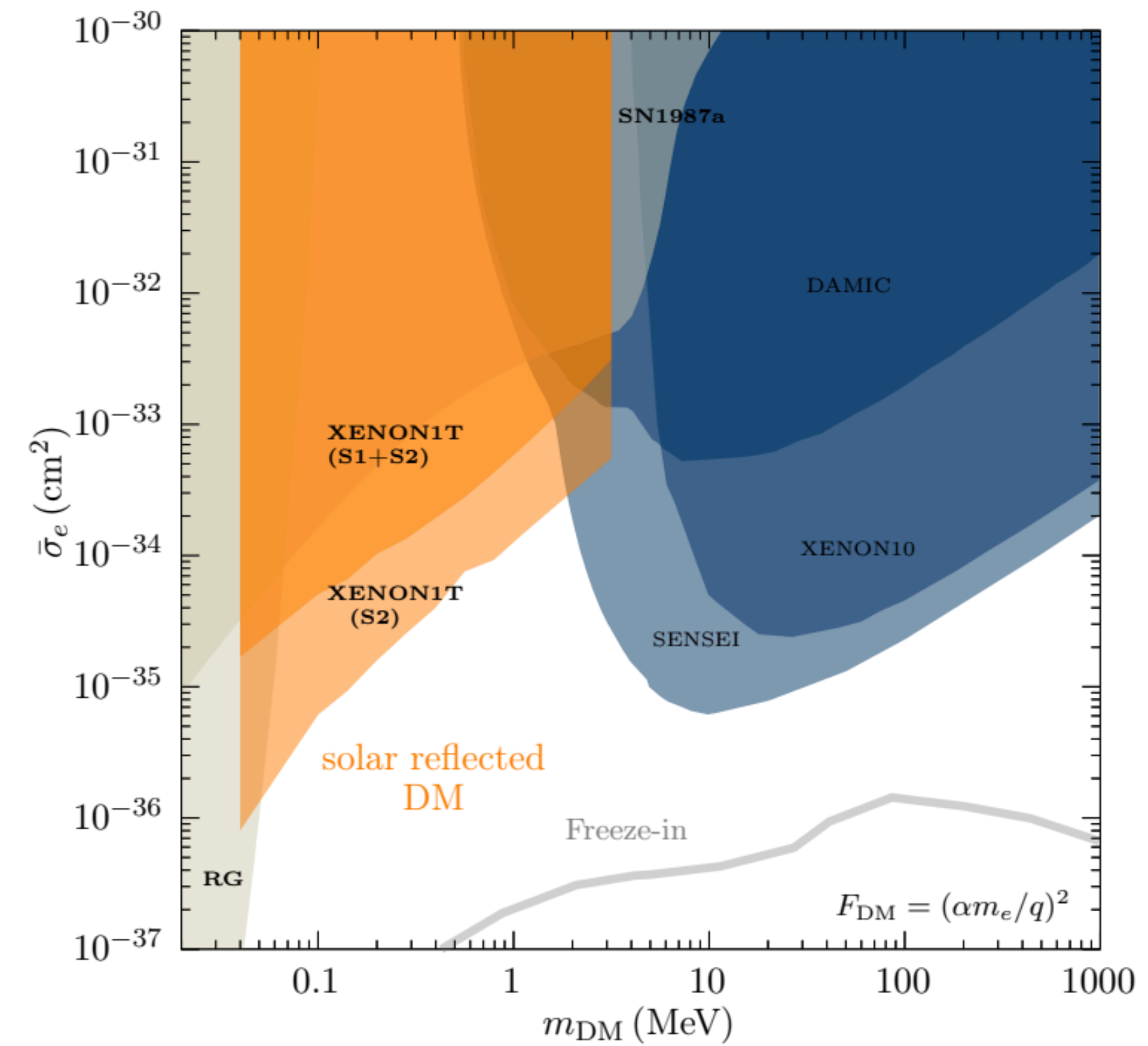
# Solar Reflected Dark Matter

Heavy mediator



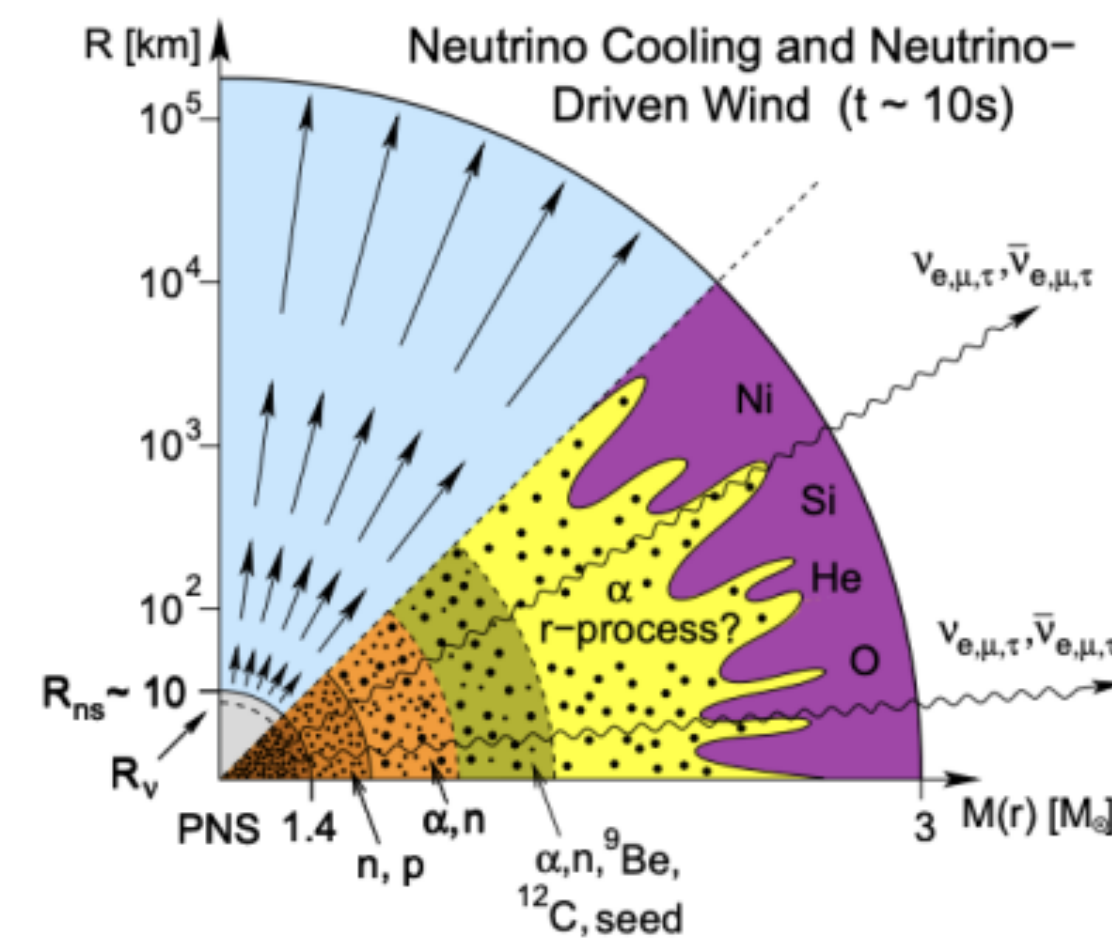
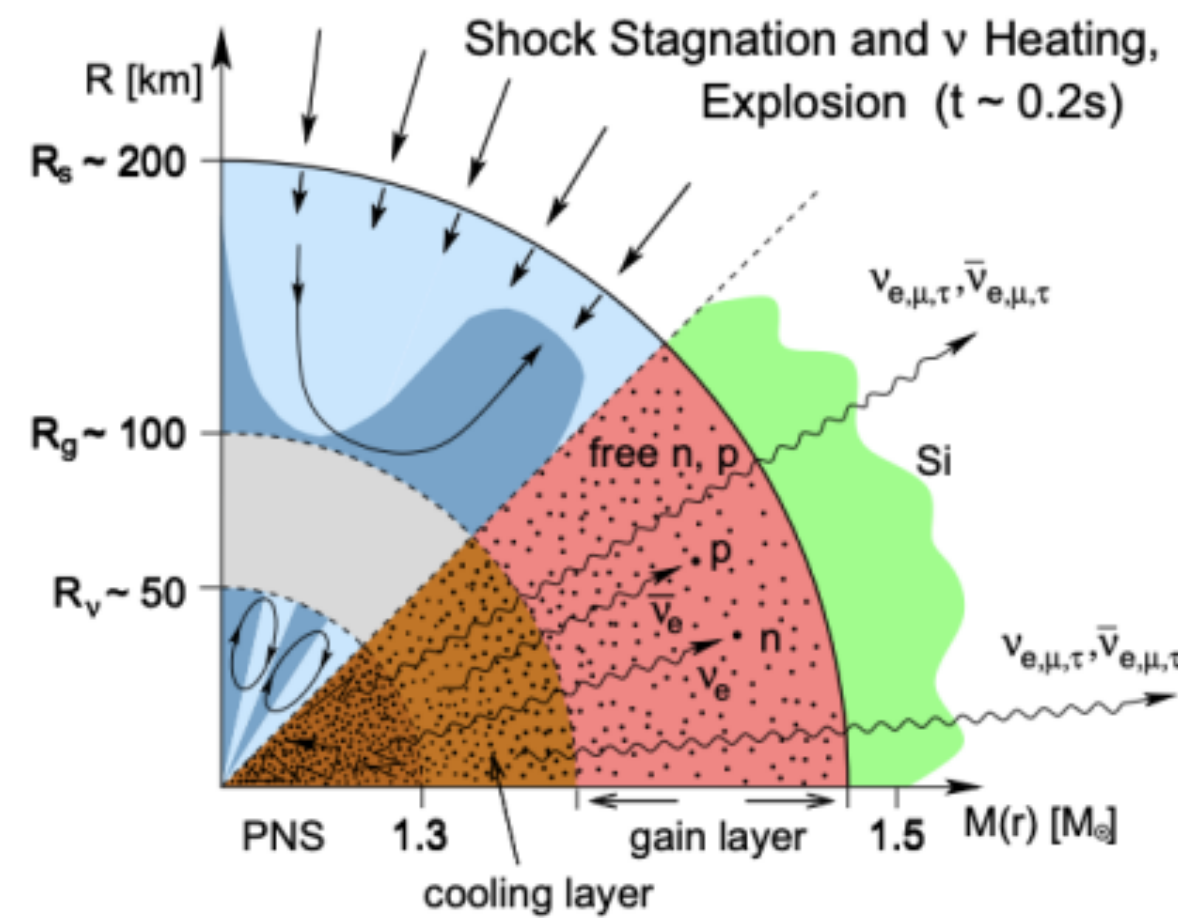
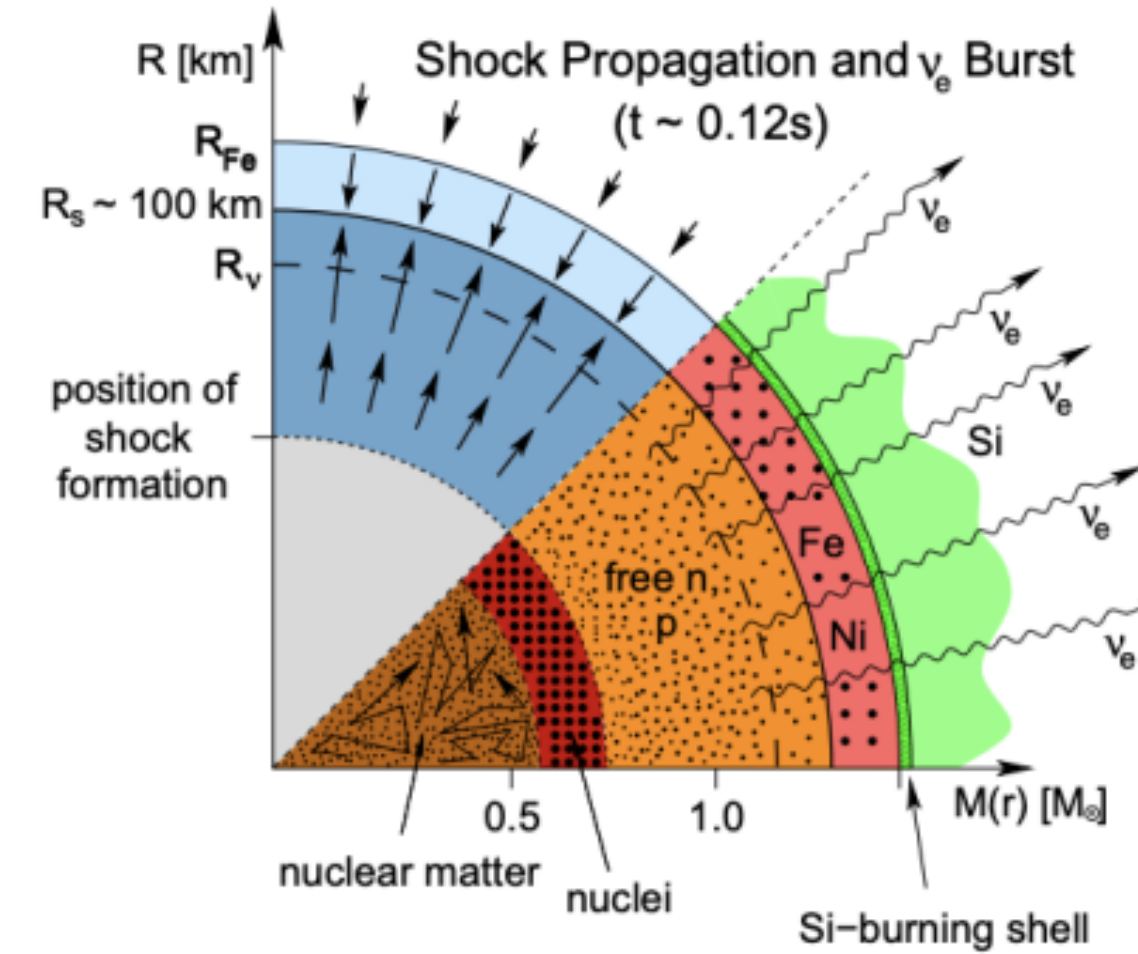
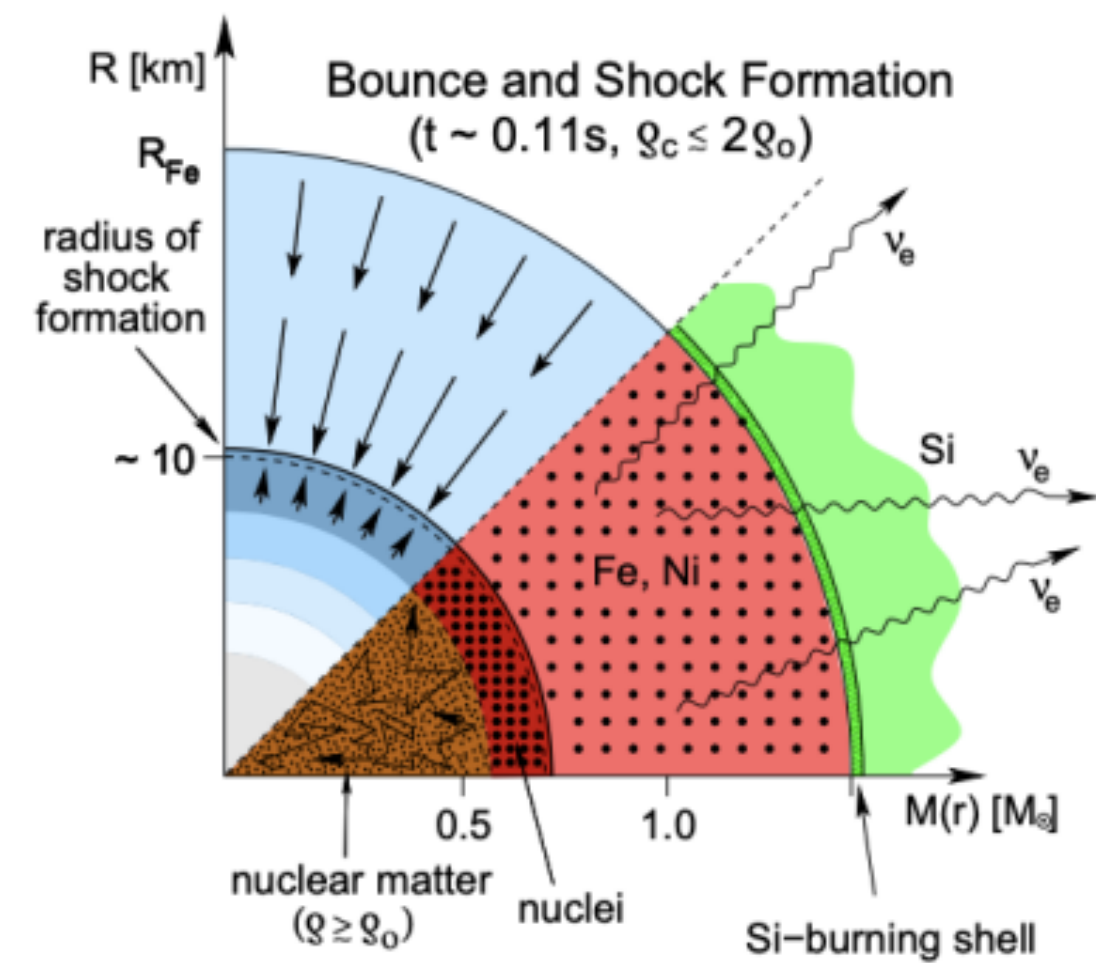
Emken, arXiv: 2102.12483

Light mediator



An et al, arXiv: 2108.10332

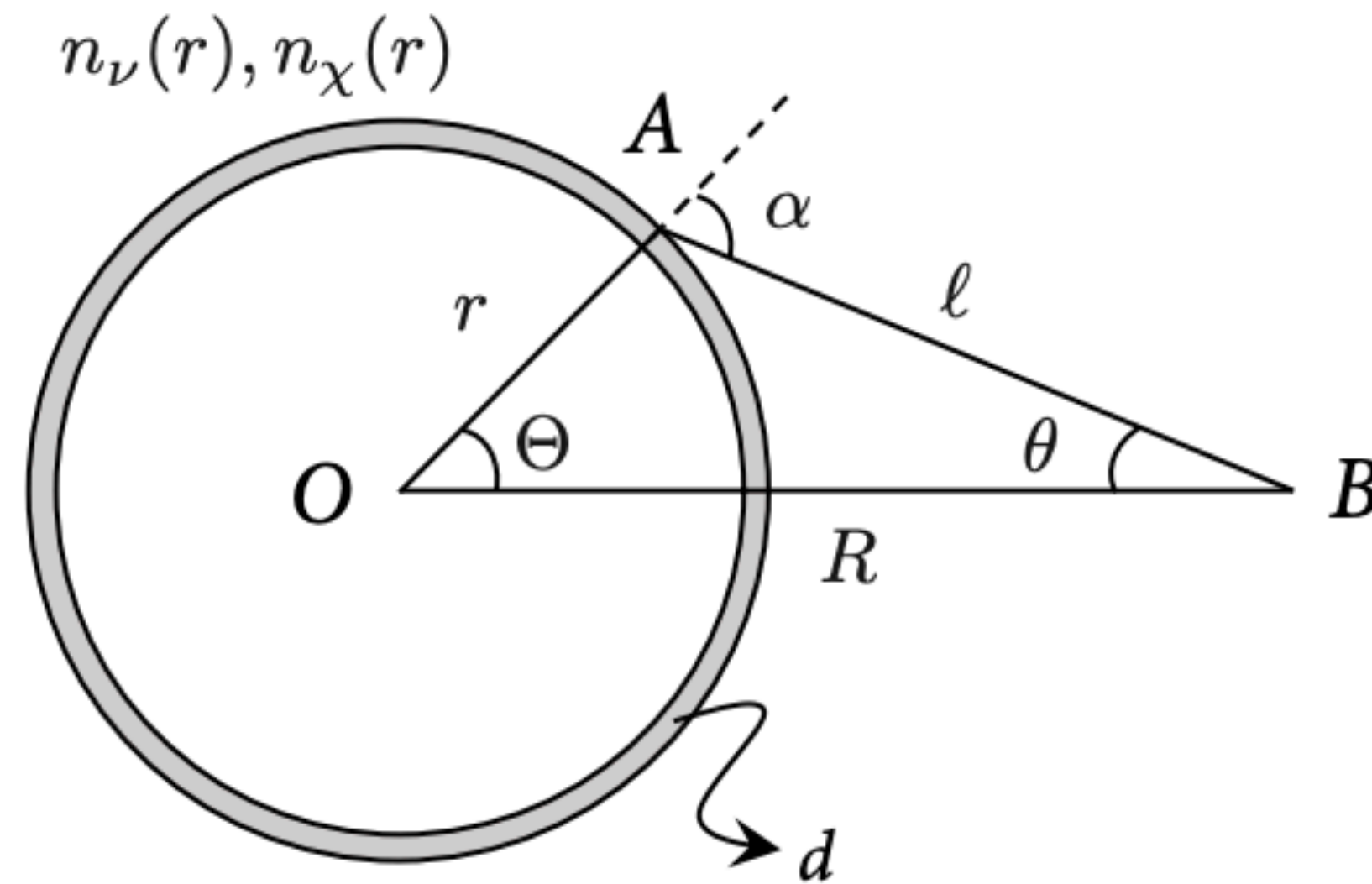
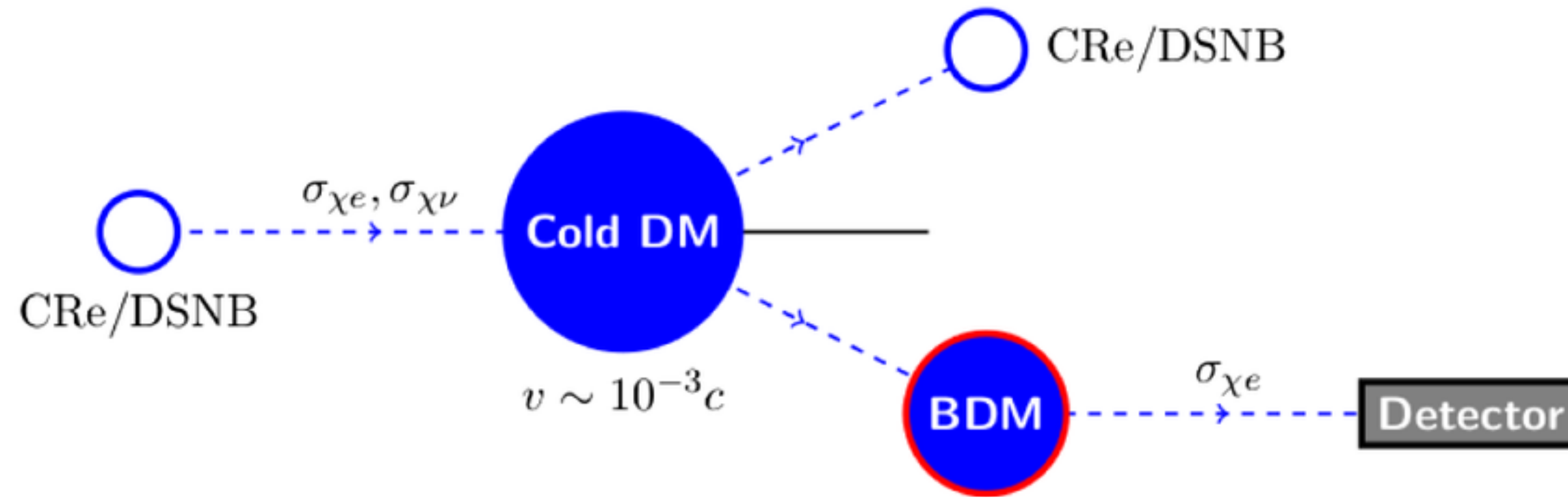
# Supernova Neutrino Boosted Dark Matter



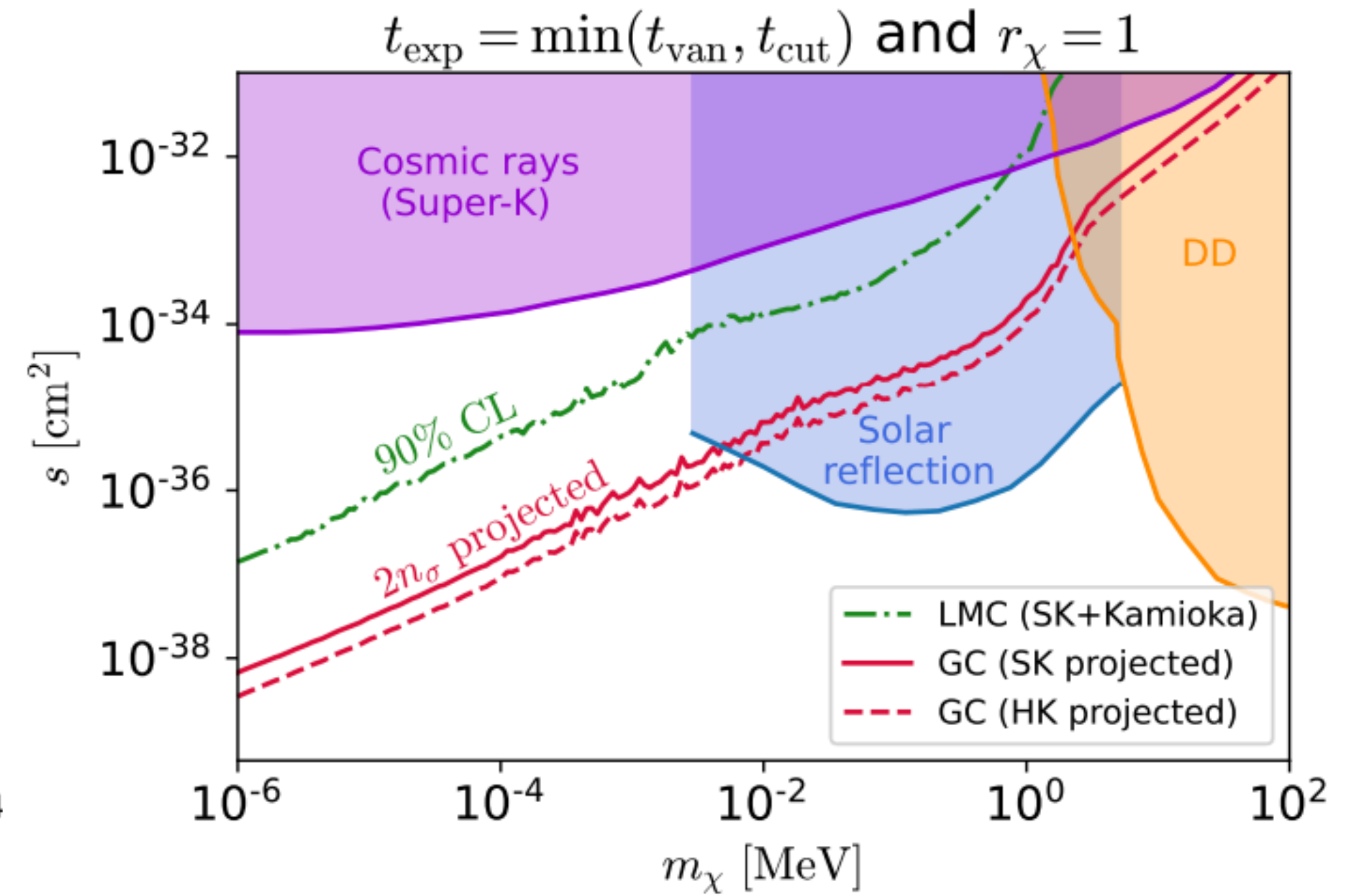
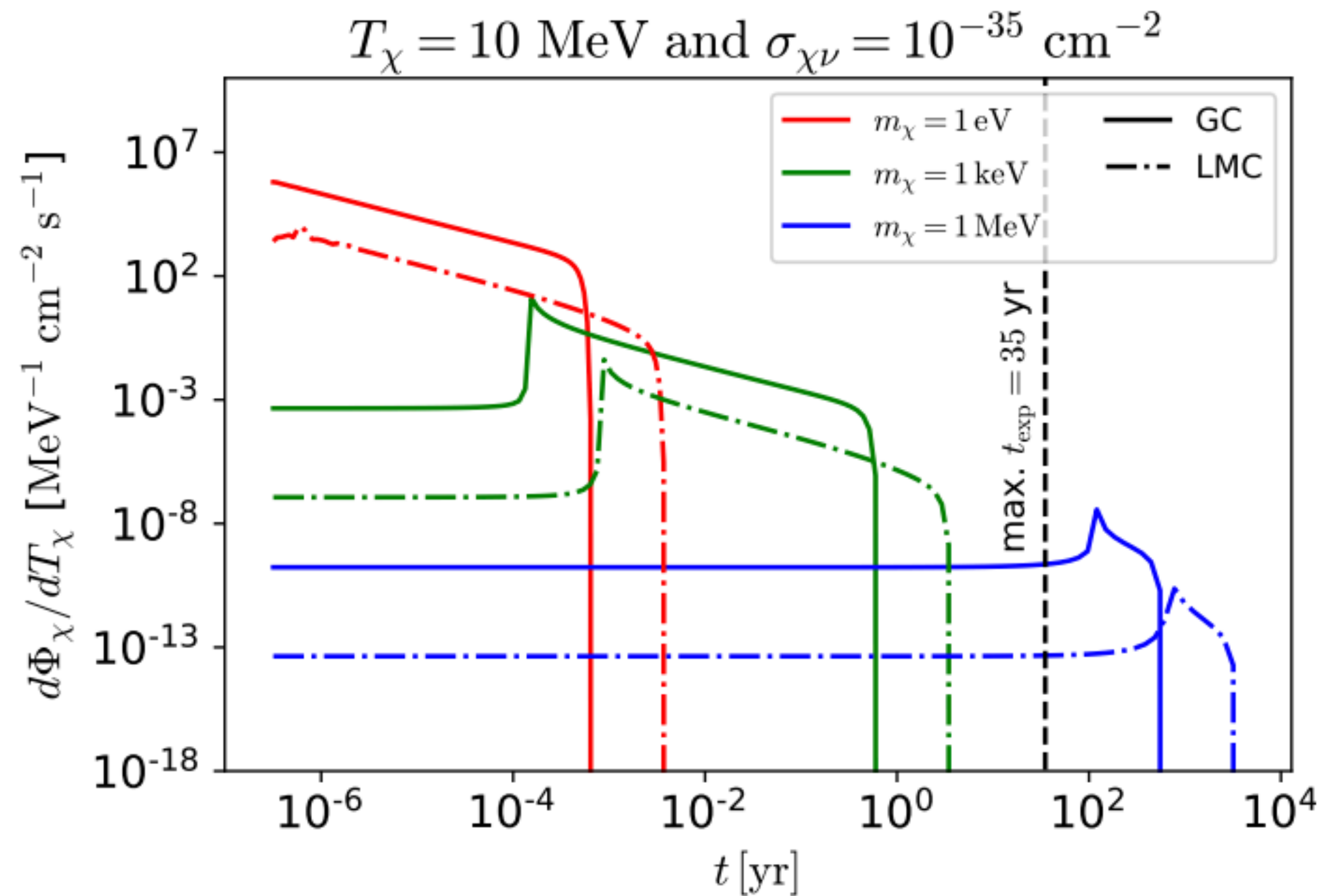
Janka et al, arXiv: astro-ph/0612072



# Supernova Neutrino Boosted Dark Matter



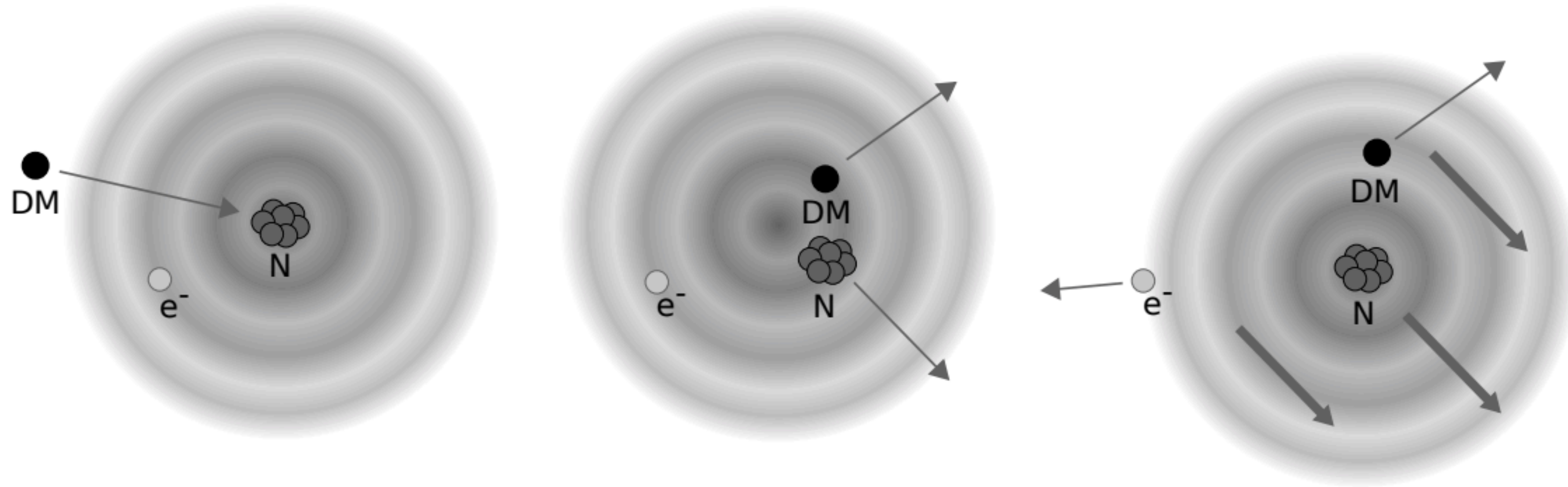
# Supernova Neutrino Boosted Dark Matter



Lin et al, arXiv: 2206.06864

See also Lin et al, arXiv: 2404.08528

# Migdal Effect

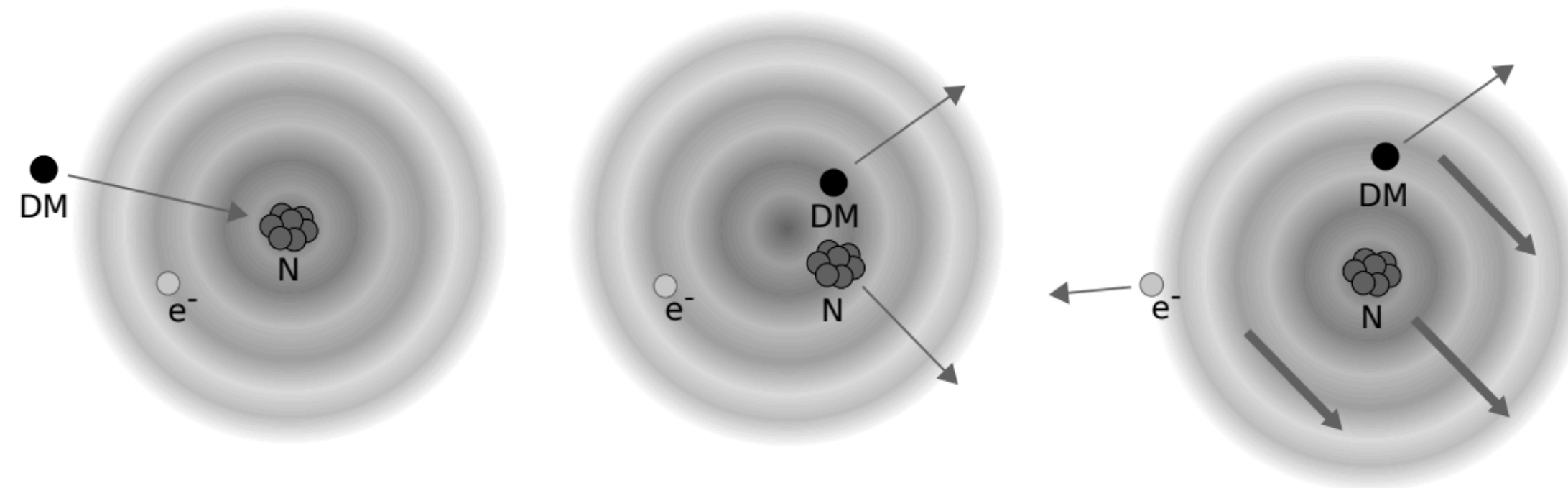


The nuclear gets recoil, but the electron cloud is left behind



# Migdal Effect

The nuclear gets recoil, but the electron cloud is left behind

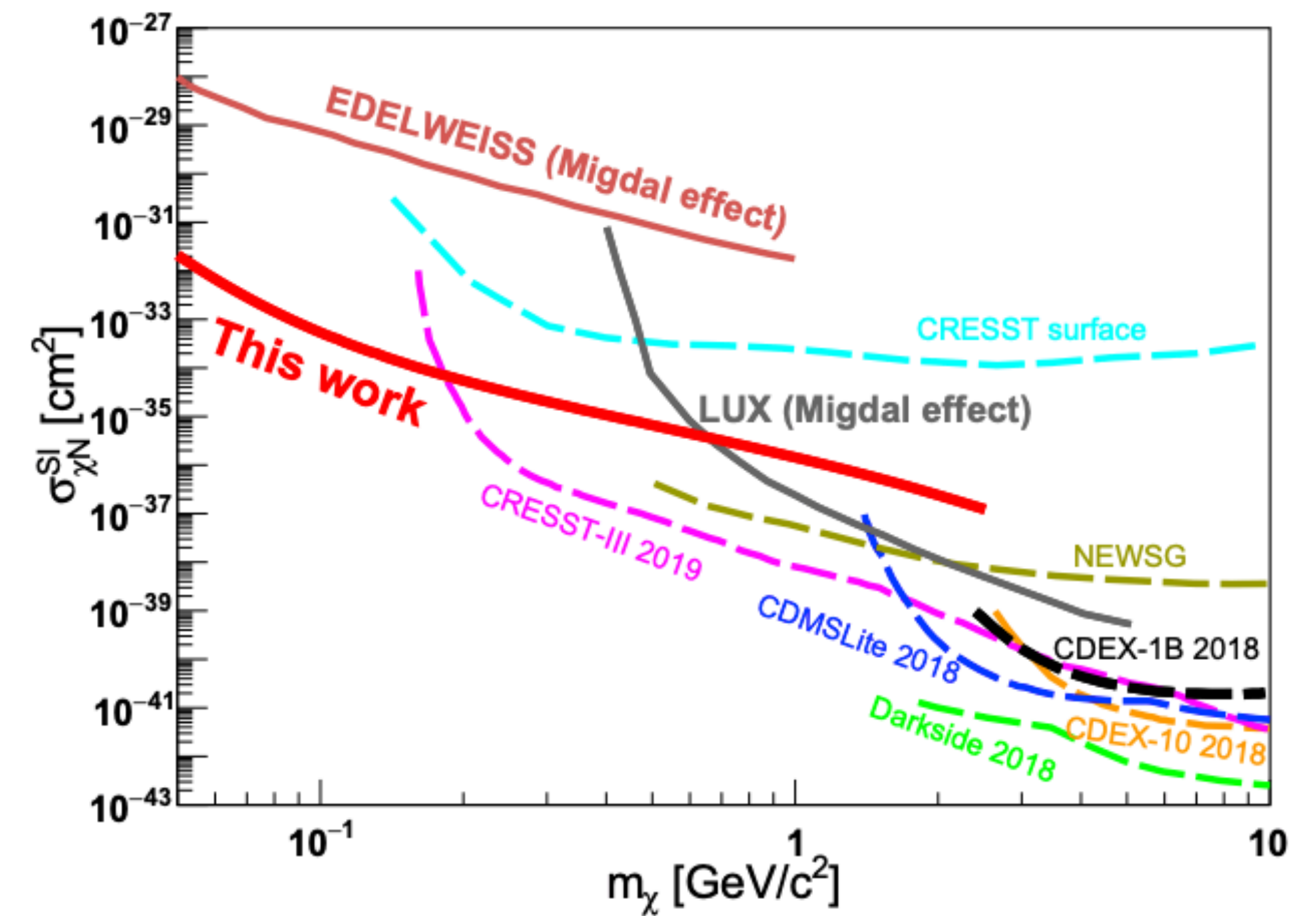
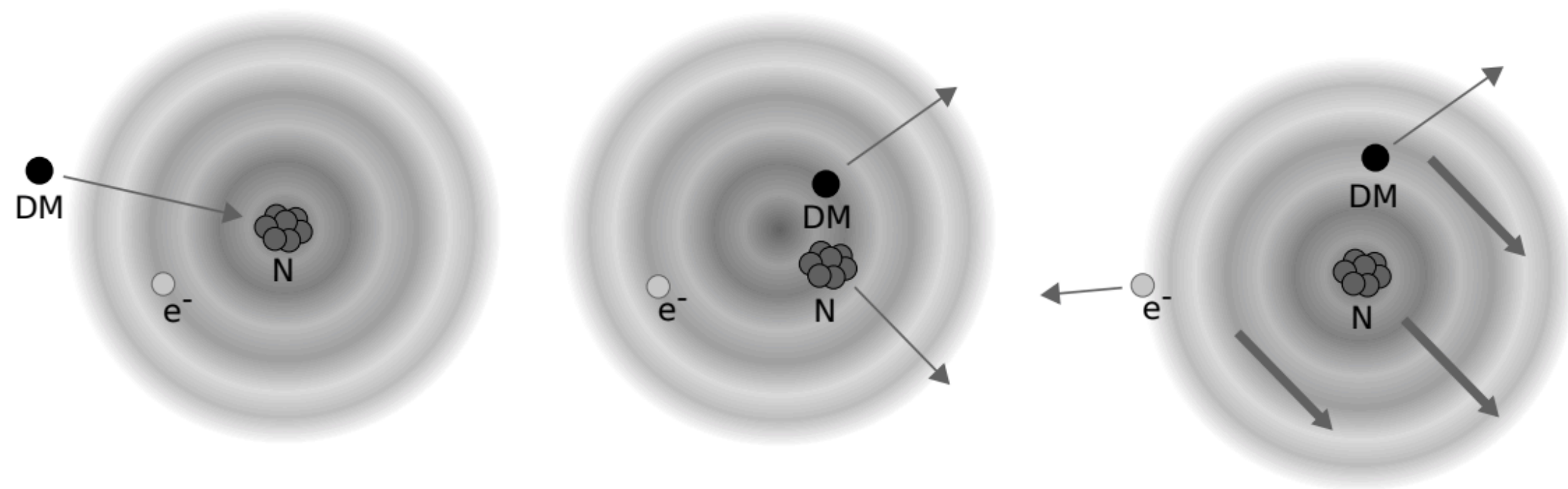


$$\frac{d^3 R_{\text{ion}}}{dE_R dE_e dv} = \frac{d^2 R_{\text{nr}}}{dE_R dv} \times |Z_{\text{ion}}(E_R, E_e)|^2$$

$$|Z_{\text{ion}}(E_R, E_e)|^2 = \sum_{nl} \frac{1}{2\pi} \frac{dp_{q_e}^c(nl \rightarrow E_e)}{dE_e}$$

# Migdal Effect

The nuclear gets recoil, but the electron cloud is left behind



CDEX collaboration, arXiv: 1905.00354

# Migdal Effect

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## Direct observation of the Migdal effect induced by neutron bombardment

[Difan Yi](#), [Qian Liu](#) , [Shi Chen](#), [Chunlai Dong](#), [Huanbo Feng](#), [Chaosong Gao](#), [Wenqian Huang](#), [Xinmei Jing](#), [Lingquan Kong](#), [Jin Li](#), [Peirong Li](#), [Enwei Liang](#), [Ruiting Ma](#), [Chenguang Su](#), [Liangliang Su](#), [Junwei Sun](#), [Dong Wang](#), [Junrun Wang](#), [Zheng Wei](#), [Zeen Yao](#), [Yunlinchen Yu](#), [Yu Zhang](#), [Shiqiang Zhou](#), [Zhuo Zhou](#), [Bin Zhu](#), [Jie Zuo](#), [Hongbang Liu](#) , [Xiangming Sun](#) , [Lei Wu](#)  & [Yangheng Zheng](#) 

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### Abstract

The search for dark matter focuses now on hypothetical light particles with masses ranging from MeV to GeV (refs. [1,2,3,4,5,6,7,8,9,10,11,12](#)). These particles would leave very faint signals experimentally. A potential avenue for enhancing experimental sensitivity to light matter relies on the Migdal effect<sup>[13,14,15](#)</sup>, which involves the detectable ejection of electrons following the instantaneous accelerations of atoms colliding with neutral dark matter. However, although the Migdal effect could be equally generated in controlled experiments with neutral projectiles, a direct experimental observation of this effect is missing, casting doubt on the reliability of detection experiments relying on this effect. Here we report the direct observation of the Migdal effect in neutron–nucleus collisions, achieving a statistical significance of 5 standard deviations, which rests on 6 candidate events selected out of almost 10<sup>6</sup> recorded events. Our experiments have determined the ratio of the Migdal cross-section to the nuclear recoil cross-section to be  $4.9^{+2.6}_{-1.9} \times 10^{-5}$ , in which nuclear recoils exceed 35 keVee and electron recoils span 5–10 keV. These findings are consistent with theoretical predictions. This work resolves a long-standing gap in experimental validation, which not only strengthens the theoretical foundation of the Migdal effect but also paves the way for its application in light dark matter detection.



# Electron Recoil

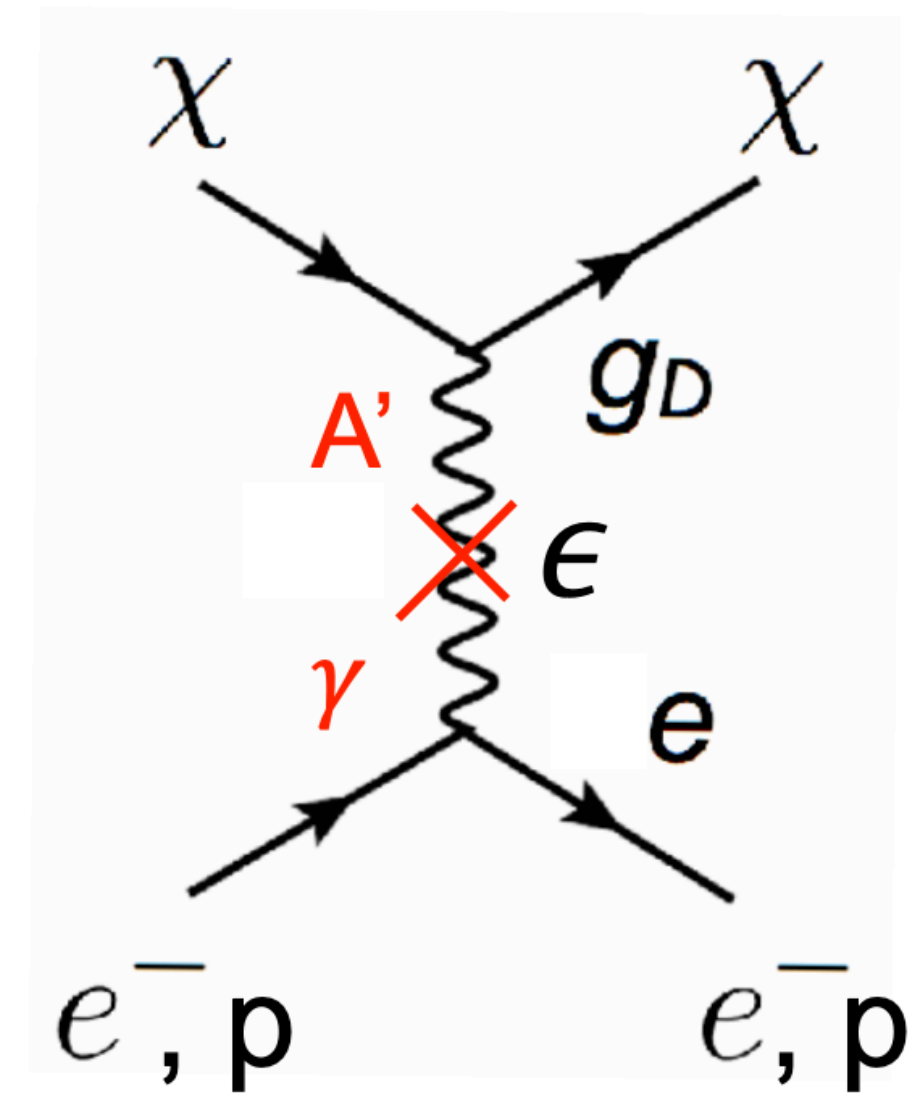
$$v > v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}$$

$$\bar{\sigma}_e = \frac{16\pi\mu_{\chi e}^2\alpha\epsilon^2\alpha_D}{(m_{A'}^2 + \alpha^2 m_e^2)^2} \simeq \begin{cases} \frac{16\pi\mu_{\chi e}^2\alpha\epsilon^2\alpha_D}{m_{A'}^4}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2\alpha\epsilon^2\alpha_D}{(\alpha m_e)^4}, & m_{A'} \ll \alpha m_e \end{cases},$$

$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2} \simeq \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}, & m_{A'} \ll \alpha m_e \end{cases}$$

Essig et al, arXiv: 1509.01598

Essig et al, arXiv: 1108.5383



# Electron Recoil

$$v > v_{min} = \frac{\Delta E_B + E_R}{q} + \frac{q}{2m_\chi}$$

$$\bar{\sigma}_e \equiv \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2} \overline{|\mathcal{M}_{\chi e}(q)|^2} \Big|_{q^2=\alpha^2 m_e^2},$$

$$\overline{|\mathcal{M}_{\chi e}(q)|^2} = \overline{|\mathcal{M}_{\chi e}(q)|^2} \Big|_{q^2=\alpha^2 m_e^2} \times |F_{\text{DM}}(q)|^2$$

$$\frac{d\langle \sigma_{ion}^i v \rangle}{d \ln E_R} = \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2} \int q dq |f_{ion}^i(k', q)|^2 |F_{\text{DM}}(q)|^2 \eta(v_{\min})$$

Essig et al, arXiv: 1509.01598

Essig et al, arXiv: 1108.5383

# Electron Recoil

$$\frac{dR^{ER}}{dE_e} = \boxed{\bar{\sigma}_e} \boxed{\frac{\rho_\chi}{M_\chi} \frac{1}{8\mu_{e\chi}^2}} \int \boxed{q dq} \boxed{|F_{DM}(q)|^2} \boxed{|f_{n,l}^{ion}(q, E_e)|^2} \boxed{\eta(v_{min})}$$

**Rate scales linearly with DM-electron cross section** (purple arrow pointing to  $\bar{\sigma}_e$ )

**Properties of the DM** (green arrow pointing to  $\frac{\rho_\chi}{M_\chi} \frac{1}{8\mu_{e\chi}^2}$ )

**DM Form Factor**  
 • Choice of DM interaction mediator (red arrow pointing to  $|F_{DM}(q)|^2$ )

**Integral over momentum transfer** (yellow arrow pointing to  $q dq$ )

**ionization form factor** (blue arrow pointing to  $|f_{n,l}^{ion}(q, E_e)|^2$ )

$$|f_{n,l}^{ion}(q, E_e)|^2 = \frac{k'^3}{4\pi^3} \sum_{n,l} |\langle \psi_{E_e} | e^{-i \sum_\alpha \mathbf{q} \cdot \mathbf{x}^\alpha} | \psi_{n,l} \rangle|^2$$

**Dependence on DM velocity** (orange arrow pointing to  $\eta(v_{min})$ )

Credit: Paolo Privitera



For sub-GeV dark matter,  $m_\chi \ll m_N$

$$q_{\max} = 2m_\chi v \sim \text{MeV} \quad v \sim 300 \text{ km/s} \sim 10^{-3}c$$

$$E_{R, \max} \sim 10 \text{ eV} \quad \text{for } m_\chi = 300 \text{ MeV} \text{ scattering on oxygen}$$

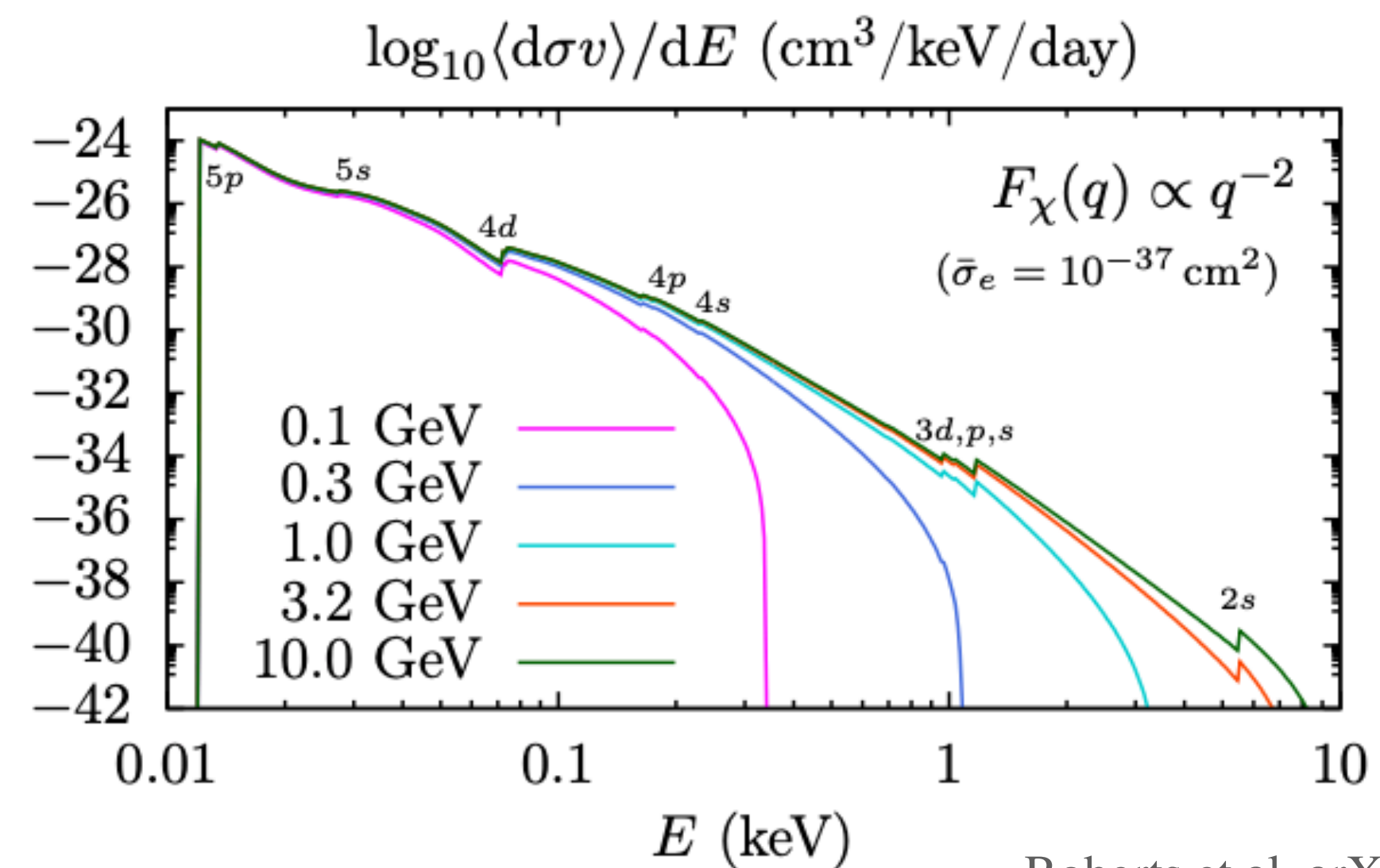
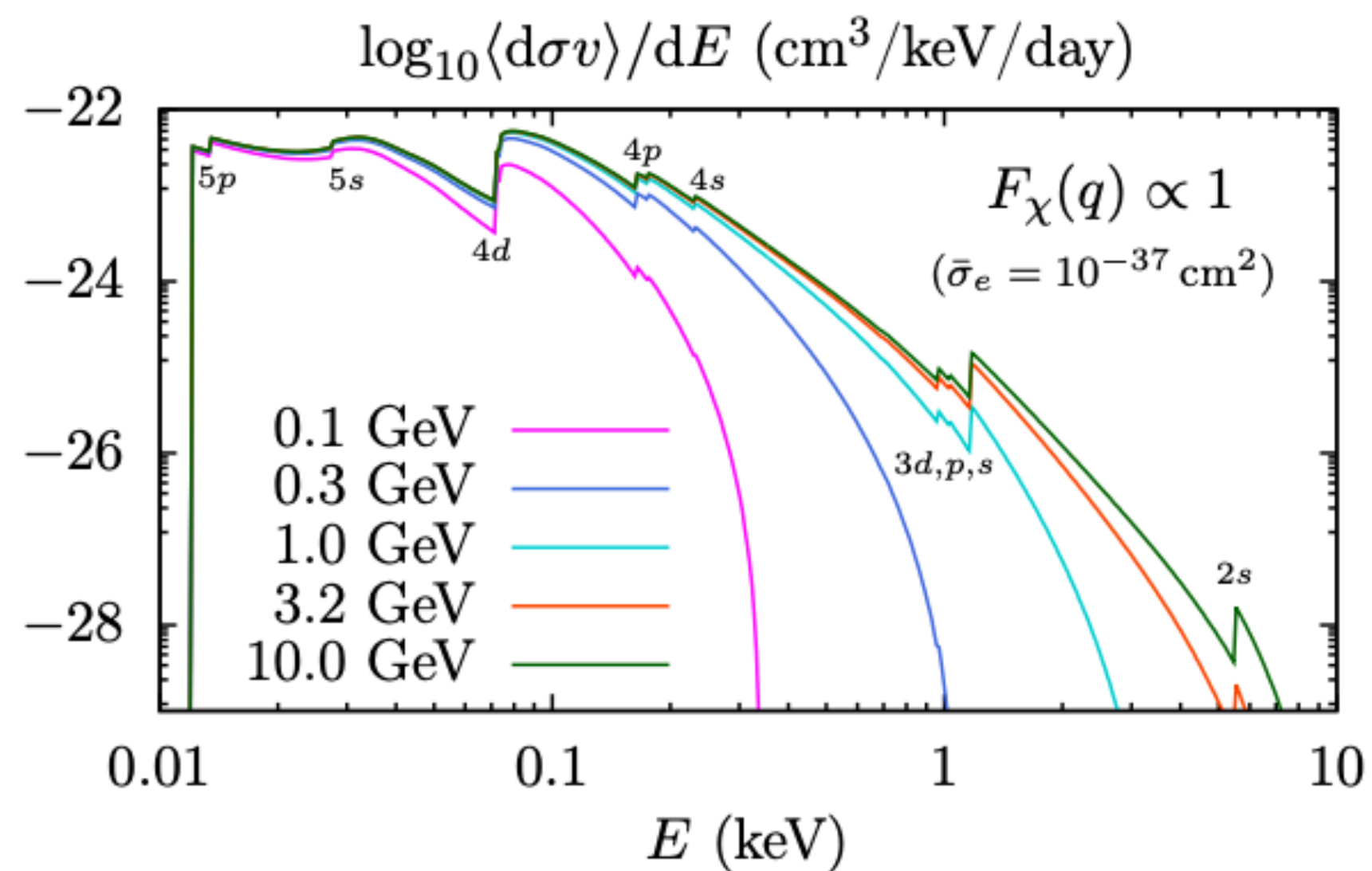
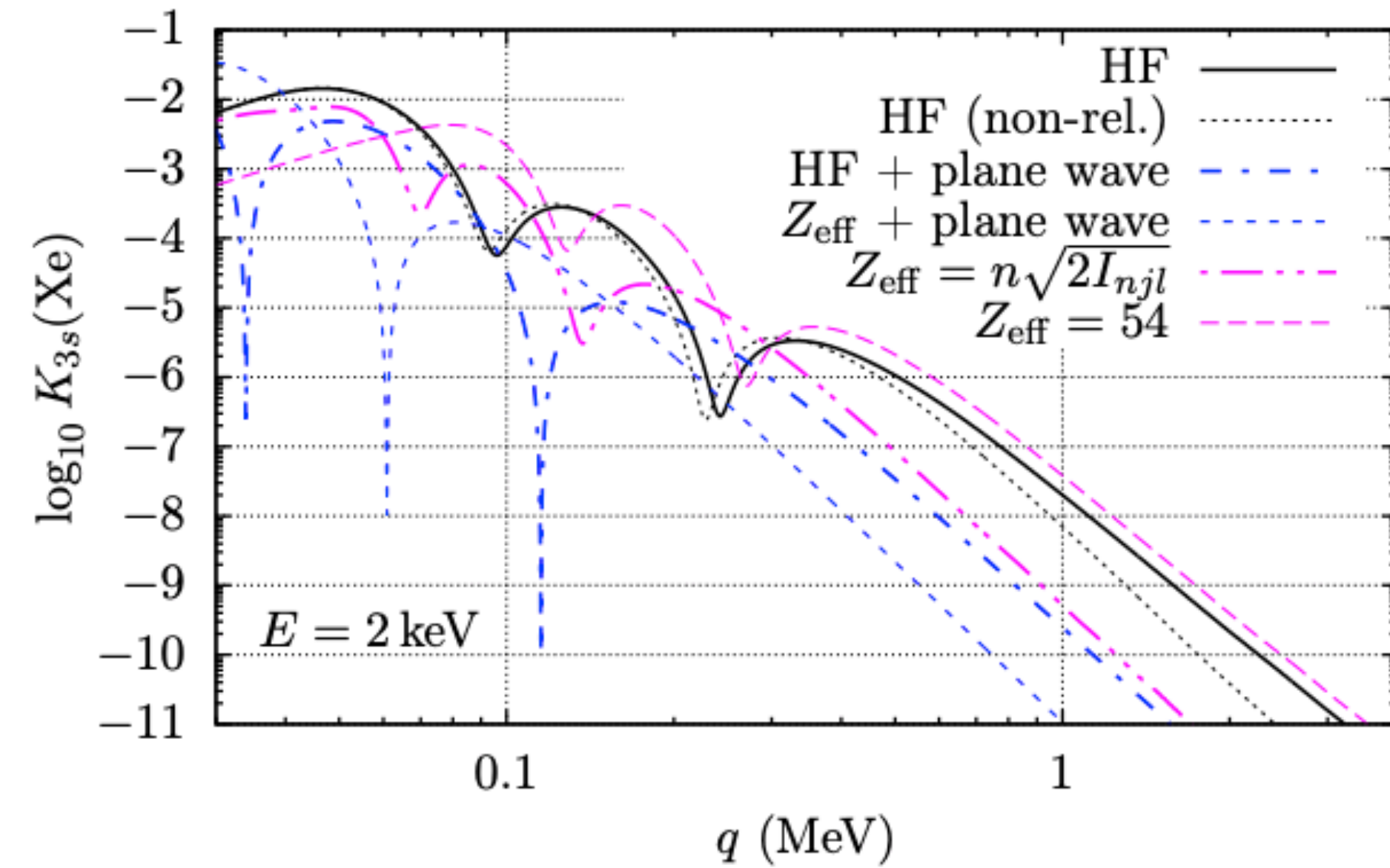
$$E_{R, \max} \ll E_{k, \chi}$$

**Detecting sub-GeV dark matter using nuclear recoil is difficult!**

# The Form Factors for Electron Recoil

## Liquid noble

$$|f_{ion}^i(k', q)|^2 = \frac{2k'^3}{(2\pi)^3} \sum_{\text{degen. states}} \left| \int d^3x \tilde{\psi}_{k'l'm'}^*(\mathbf{x}) \psi_i(\mathbf{x}) e^{i\mathbf{q} \cdot \mathbf{x}} \right|^2$$

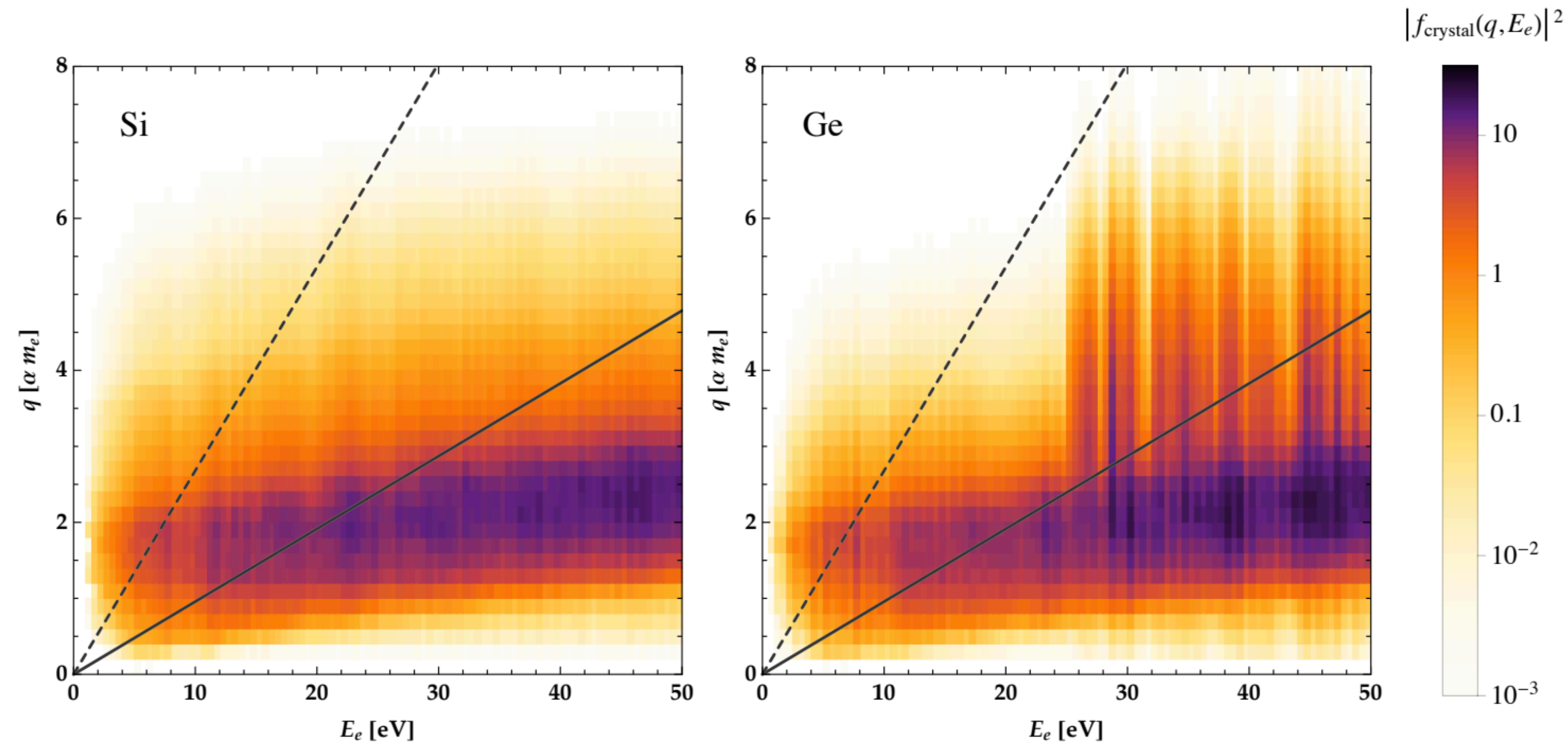


# The Form Factors for Electron Recoil

## Semiconductor

$$\psi_{i\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{\vec{G}} u_i(\vec{k} + \vec{G}) e^{i(\vec{k} + \vec{G}) \cdot \vec{x}}$$

$$|f_{\text{crystal}}(q, E_e)|^2 = \frac{2\pi^2 (\alpha m_e^2 V_{\text{cell}})^{-1}}{E_e} \sum_{i i'} \int_{\text{BZ}} \frac{V_{\text{cell}} d^3 k}{(2\pi)^3} \frac{V_{\text{cell}} d^3 k'}{(2\pi)^3} \times \\ E_e \delta(E_e - E_{i'\vec{k}'} + E_{i\vec{k}}) \sum_{\vec{G}} q \delta(q - |\vec{k}' - \vec{k} + \vec{G}|) |f_{[i\vec{k}, i'\vec{k}', \vec{G}]}|^2$$



Essig et al, arXiv: 1509.01598



# An Alternative Way

$$\text{Im} \left( -\frac{1}{\epsilon(\mathbf{q}, \omega)} \right) = \frac{\pi e^2}{q^2} \sum_f |\langle f | \hat{\rho}(\mathbf{q}) | 0 \rangle|^2 \delta(\omega_f - \omega)$$

$$R = \frac{1}{\rho_T} \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{\mu_{\chi e}^2} \frac{\pi}{\alpha_{em}} \int d^3v f_\chi(v) \int \frac{d^3\mathbf{k}}{(2\pi)^3} k^2 |F_{DM}(k)|^2 \int \frac{d\omega}{2\pi} \frac{1}{1 - e^{-\beta\omega}} \text{Im} \left[ \frac{-1}{\epsilon_L(\omega, \mathbf{k})} \right] \delta \left( \omega + \frac{k^2}{2m_\chi} - \mathbf{k} \cdot \mathbf{v} \right)$$

- Dark matter that couples to charge density is similar to light
- Including the contribution from plasmons
- Can be determined experimentally with light response

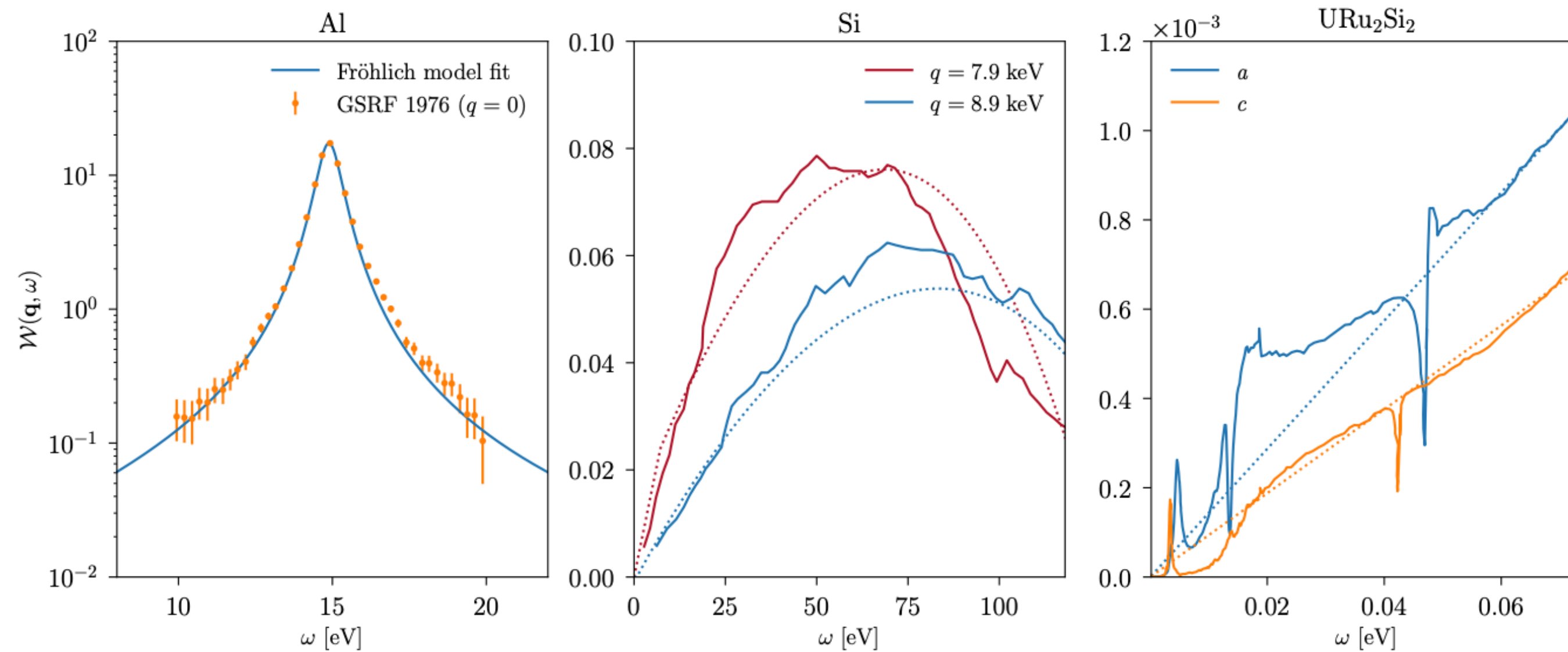
Hochberg et al, arXiv: 2101.08263

Knapen et al, arXiv: 2101.08275

# The Dielectric Function

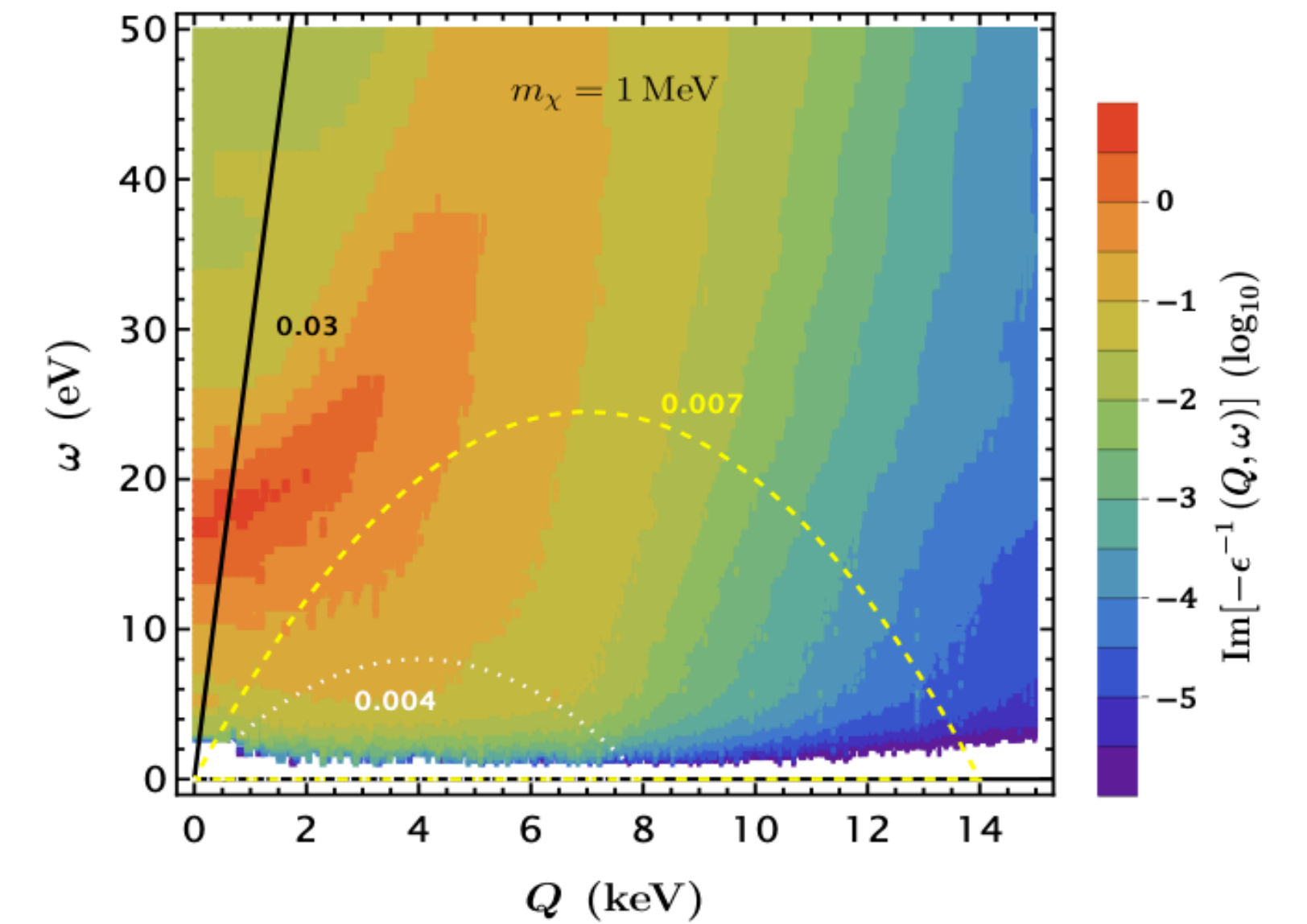
$$\text{Im} \left( -\frac{1}{\epsilon(\mathbf{q}, \omega)} \right) = \frac{\pi e^2}{q^2} \sum_f |\langle f | \hat{\rho}(\mathbf{q}) | 0 \rangle|^2 \delta(\omega_f - \omega)$$

$$R = \frac{1}{\rho_T} \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{\mu_{\chi e}^2} \frac{\pi}{\alpha_{em}} \int d^3v f_\chi(v) \int \frac{d^3\mathbf{k}}{(2\pi)^3} k^2 |F_{DM}(k)|^2 \int \frac{d\omega}{2\pi} \frac{1}{1 - e^{-\beta\omega}} \text{Im} \left[ \frac{-1}{\epsilon_L(\omega, \mathbf{k})} \right] \delta \left( \omega + \frac{k^2}{2m_\chi} - \mathbf{k} \cdot \mathbf{v} \right)$$



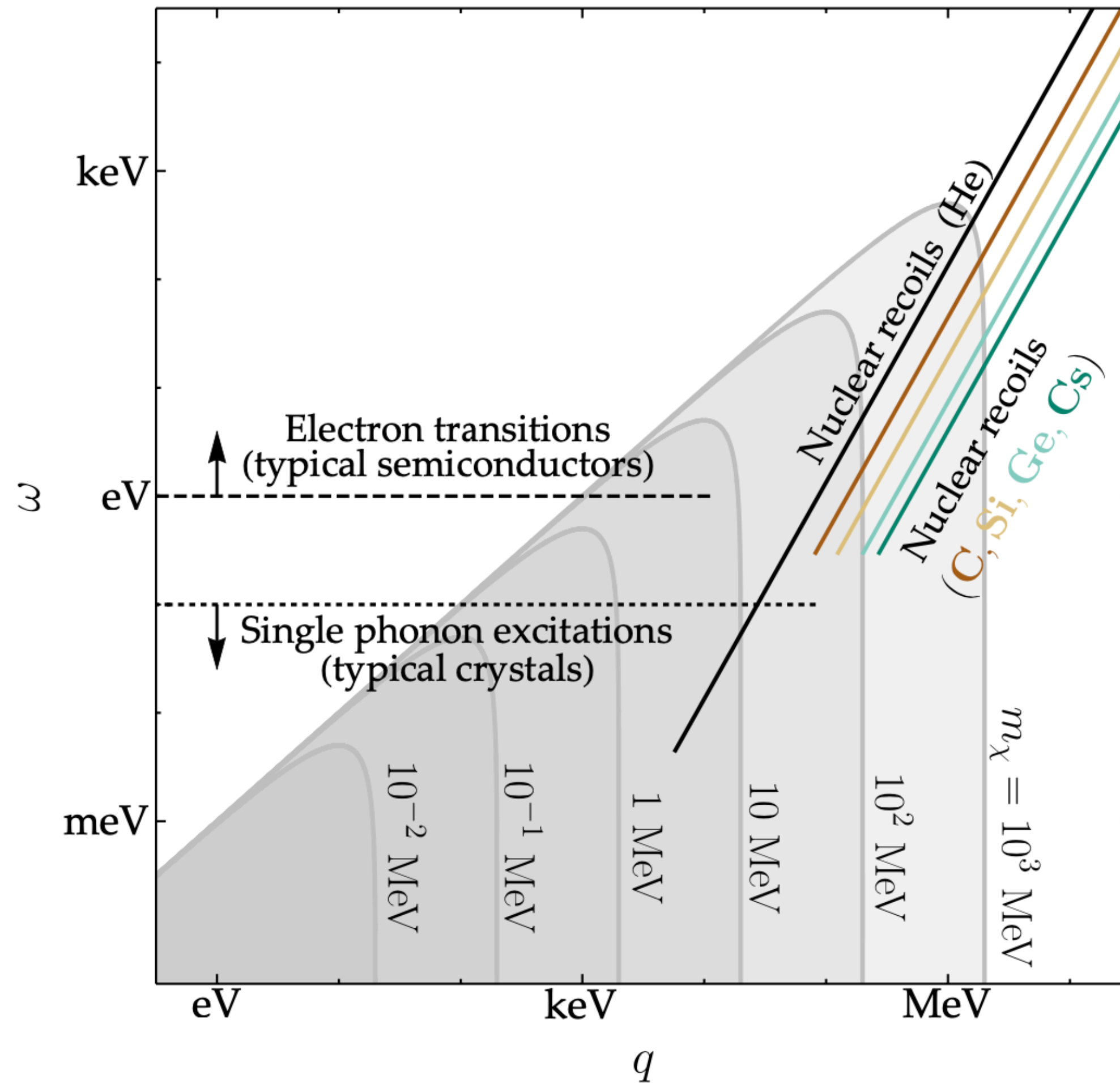
Hochberg et al, arXiv: 2101.08263

Knapen et al, arXiv: 2101.08275



Liang et al, arXiv: 2401.11971

# Kinematics of Light Dark Matter



Trickle et al, arXiv: 1910.08092

- The maximum dark matter energy deposition depends on its mass
- The energy deposition reduces for lower mass dark matter

$$\omega_{\mathbf{q}} = \frac{1}{2}m_{\chi}v^2 - \frac{(m_{\chi}\mathbf{v} - \mathbf{q})^2}{2m_{\chi}} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_{\chi}}$$

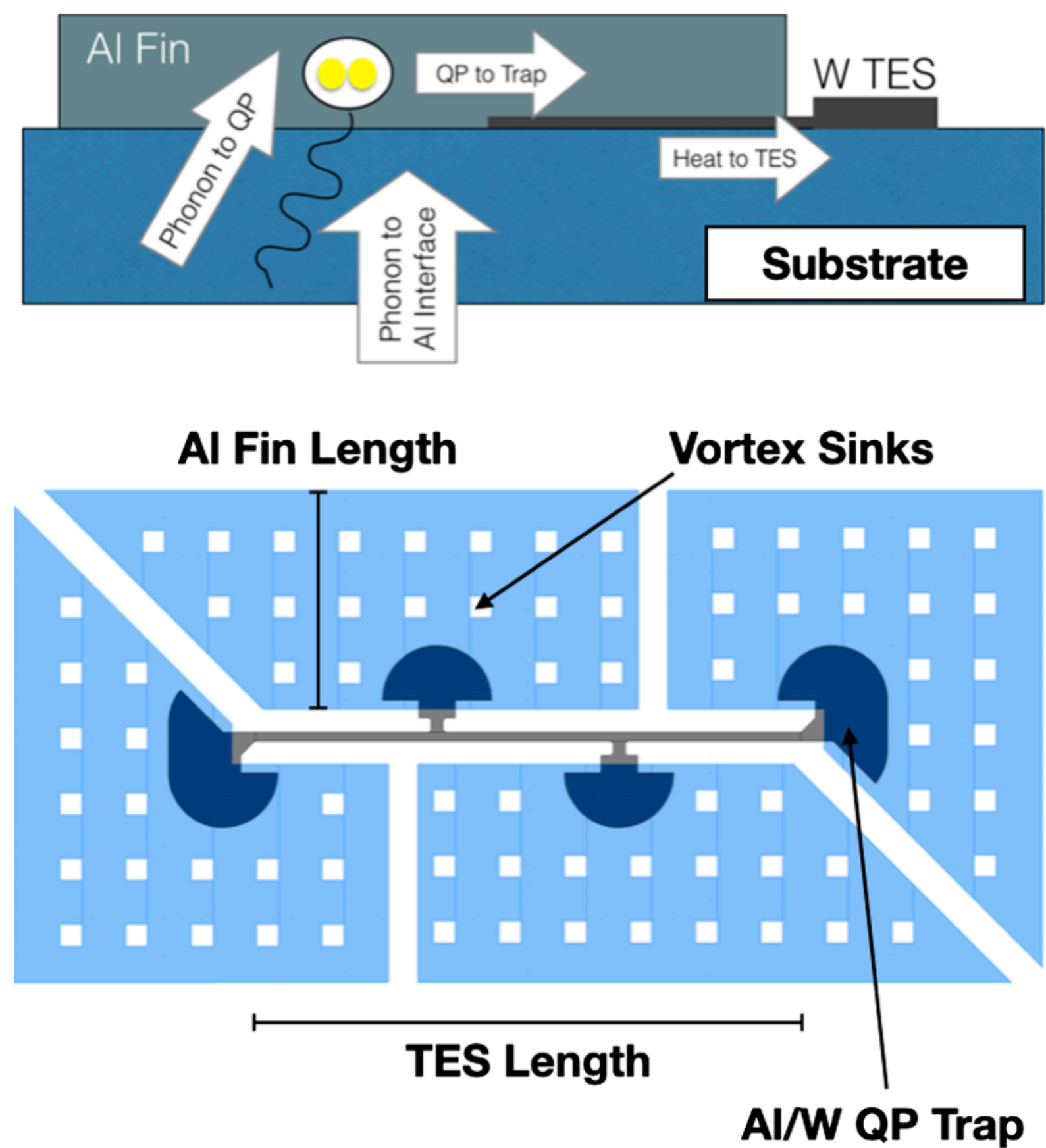
$$\omega \leq E_k \sim m_{\text{DM}}v^2 \sim 10^{-6}m_{\text{DM}}$$

**Look for phonon excitation!**

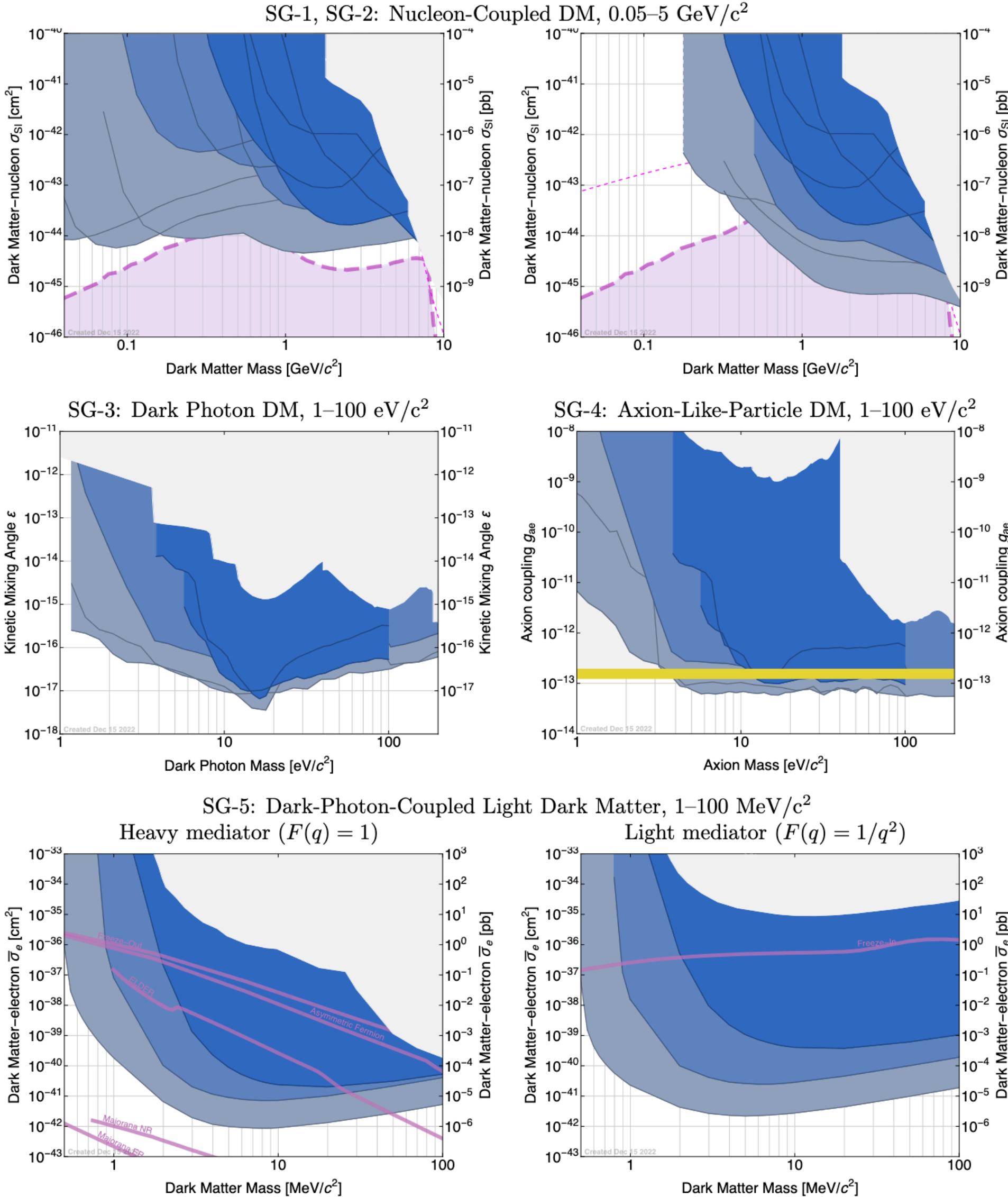


# SuperCDMS

PRD 104,032010 2021



SuperCDMS-CPD **phonon+charge**



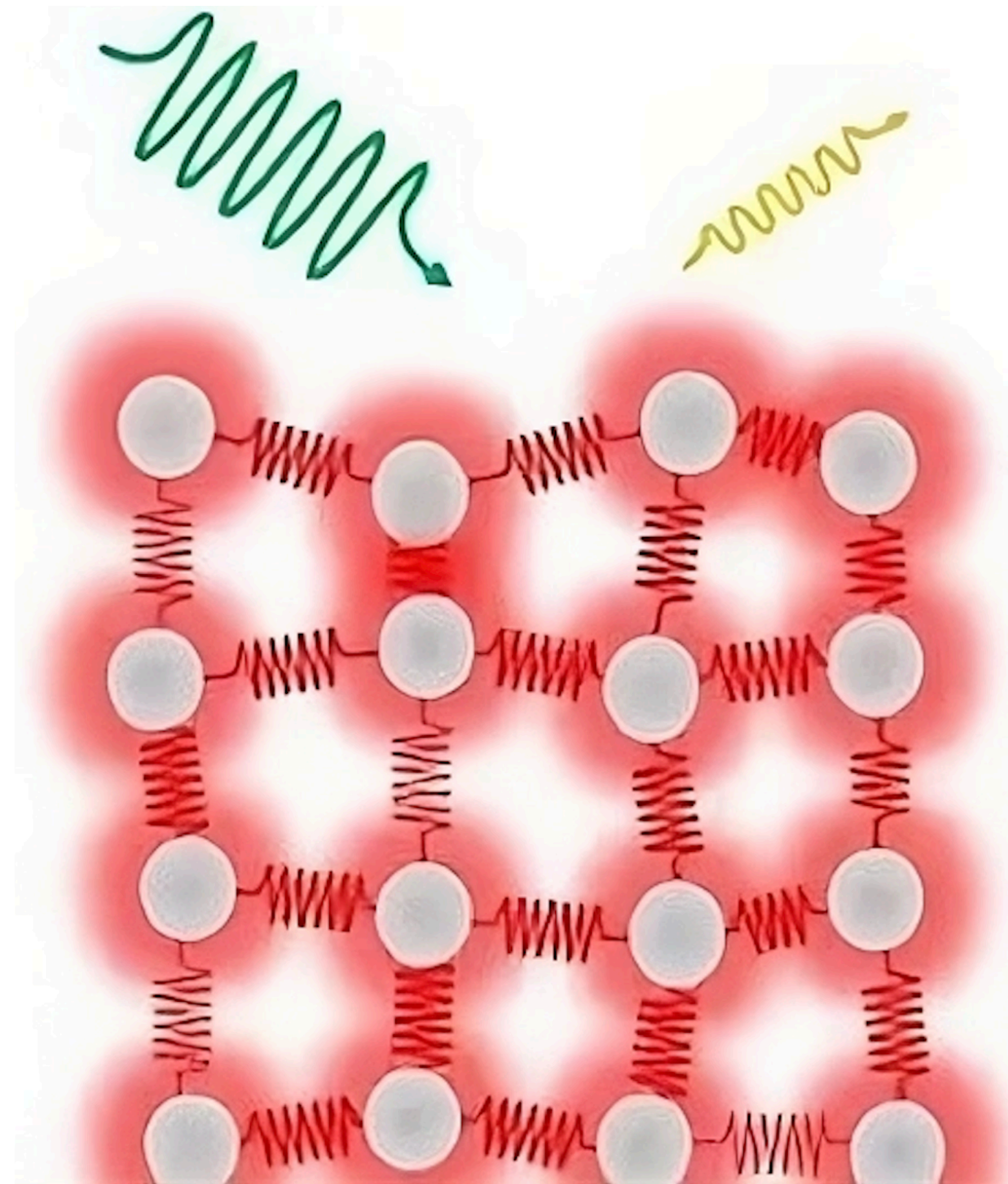
SuperCDMS@SNOLab

$E_{th} \sim \text{eV}$  2203.08463

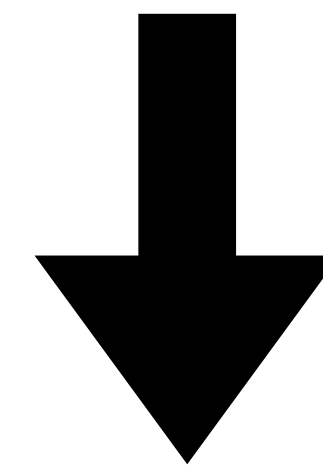
# The Phonons

dark matter

phonon



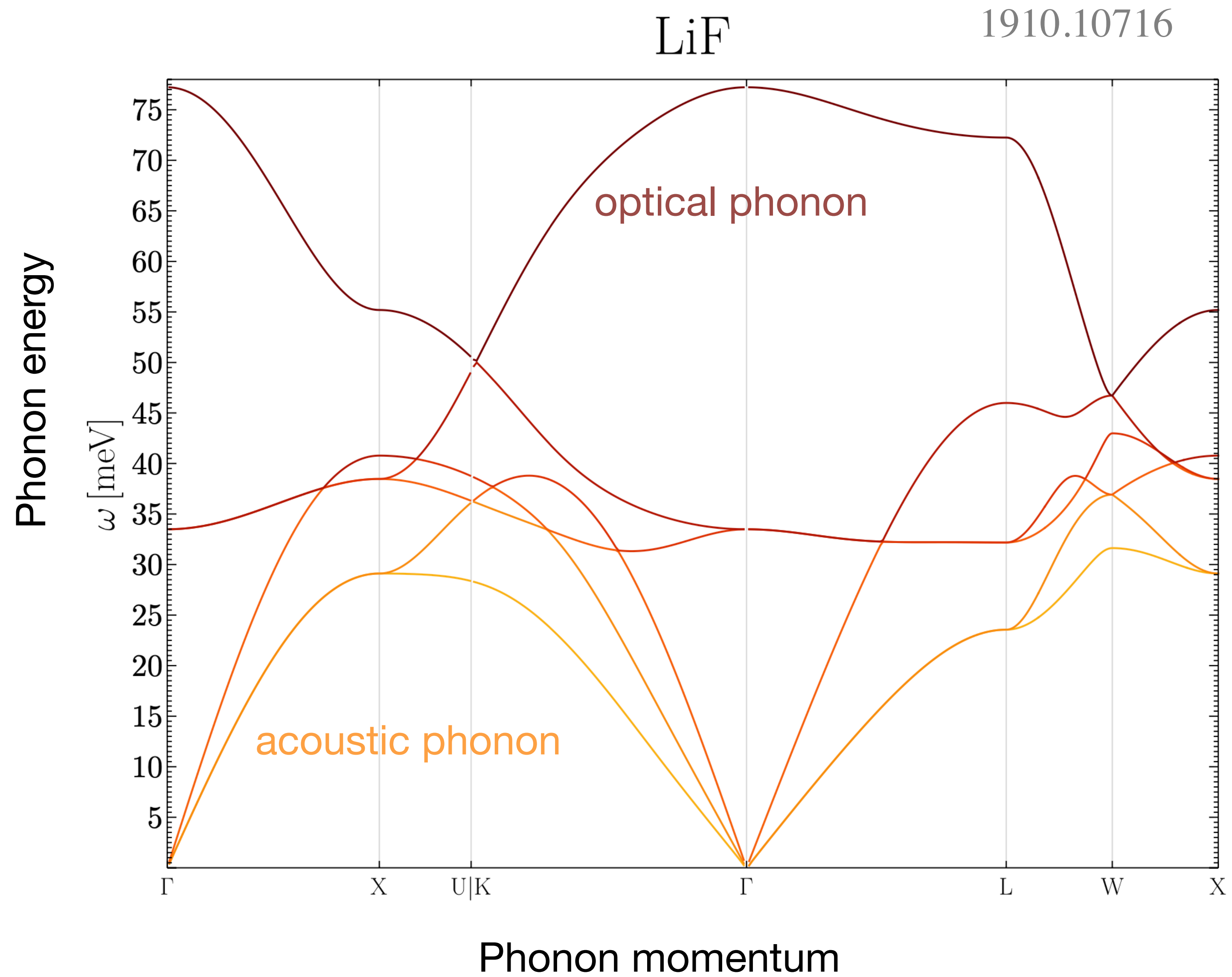
Light dark matter  $\frac{1}{q} > \text{lattice spacing}$



phonon excitation



# The Phonons





# Dark Matter Scattering Rate

See also: 1910.08092, 2009.13534

$$\Gamma(\mathbf{v}) = V \int \frac{d^3q}{(2\pi)^3} \sum_f |\langle \mathbf{p}', f | \delta \hat{H} | \mathbf{p}, i \rangle|^2 2\pi \delta(E_f - E_i - \omega_{\mathbf{q}})$$

$$R = \frac{1}{\rho_T} \frac{\rho_\chi}{m_\chi} \int d^3v f_\chi(\mathbf{v}) \Gamma(\mathbf{v})$$

$$R = \frac{1}{m_{\text{cell}}} \frac{\rho_\chi}{m_\chi} \frac{\pi \bar{\sigma}}{2\mu^2} \int \frac{d^3q}{(2\pi)^3} \mathcal{F}_{\text{med}}^2(q) \sum_\nu \frac{1}{\omega_{\nu,\mathbf{k}}} \left| \sum_j \frac{e^{-W_j(\mathbf{q})}}{\sqrt{m_j}} e^{i\mathbf{G} \cdot \mathbf{x}_j^0} (\mathbf{Y}_j \cdot \boldsymbol{\epsilon}_{\nu,\mathbf{k},j}^*) \right|^2 g(\mathbf{q}, \omega_{\nu,\mathbf{k}})$$

Cell mass

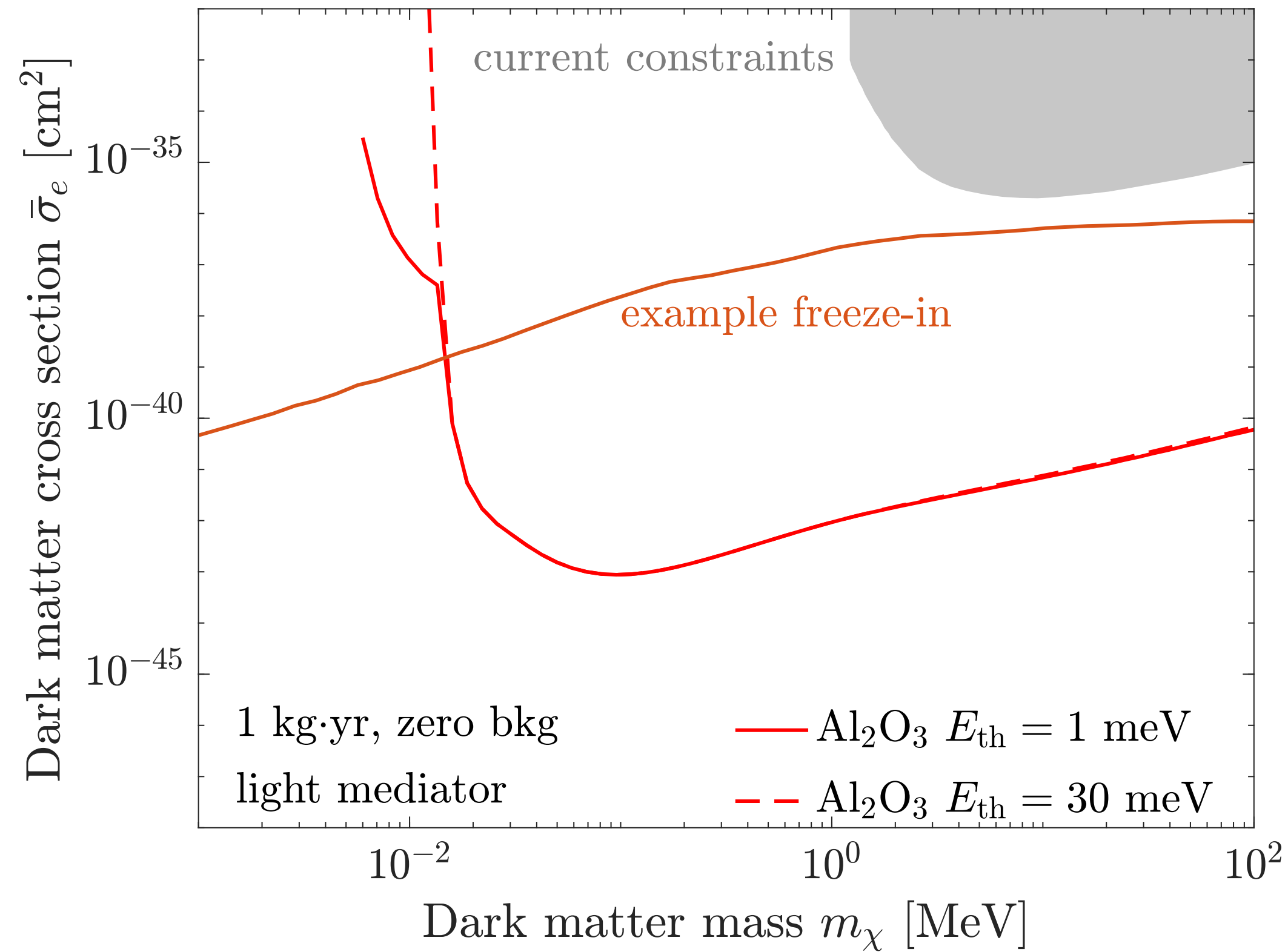
Mediator form factor

Phonon eigen energy

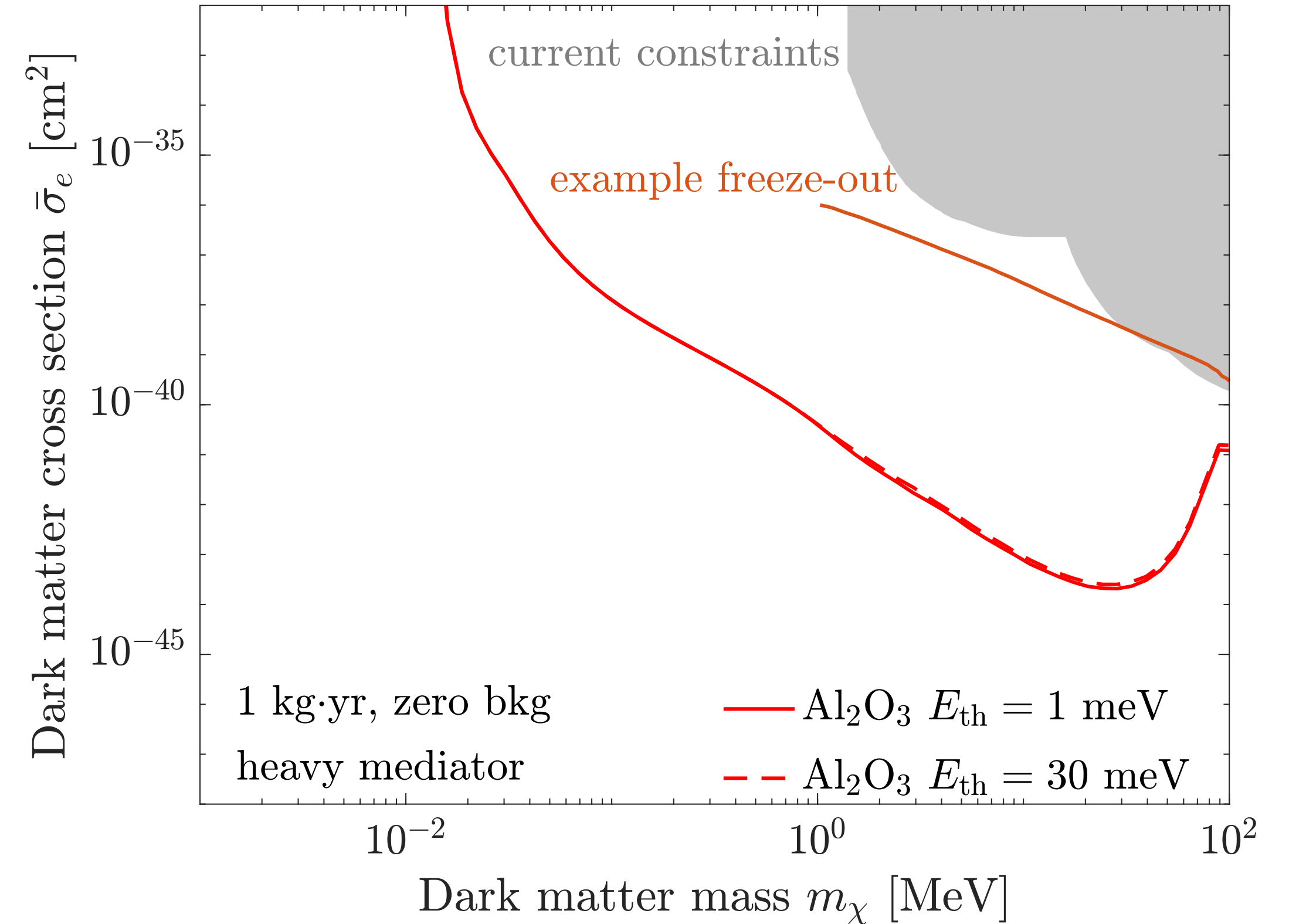
Material response

Dark matter velocity integral

# Sensitivity to Light Dark Matter



**Light mediator**  $F_{\text{med}} = \frac{(\alpha m_e)^2}{q^2}$



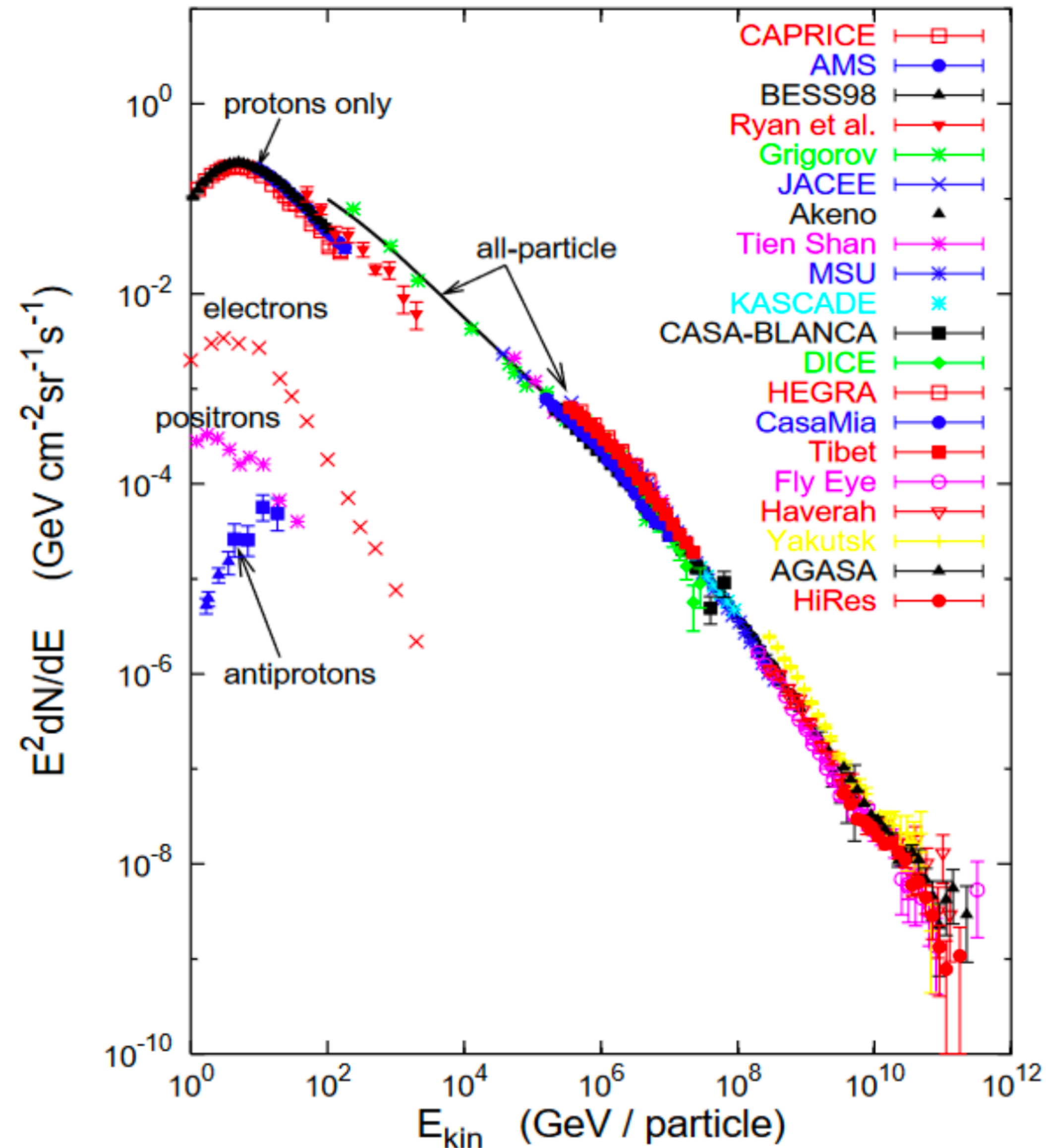
**Heavy mediator**  $F_{\text{med}} = 1$

# Atmospheric Dark Matter



# Boosted Dark Matter from Cosmic Rays in the Atmosphere

- Heavy neutral leptons
- Hadrophilic dark matter
- Axion-like particles
- Long-lived neutralinos
- Monopoles
- Dark photon
- Millicharged particles
- ...



# Dark Photon Kinetic Mixing

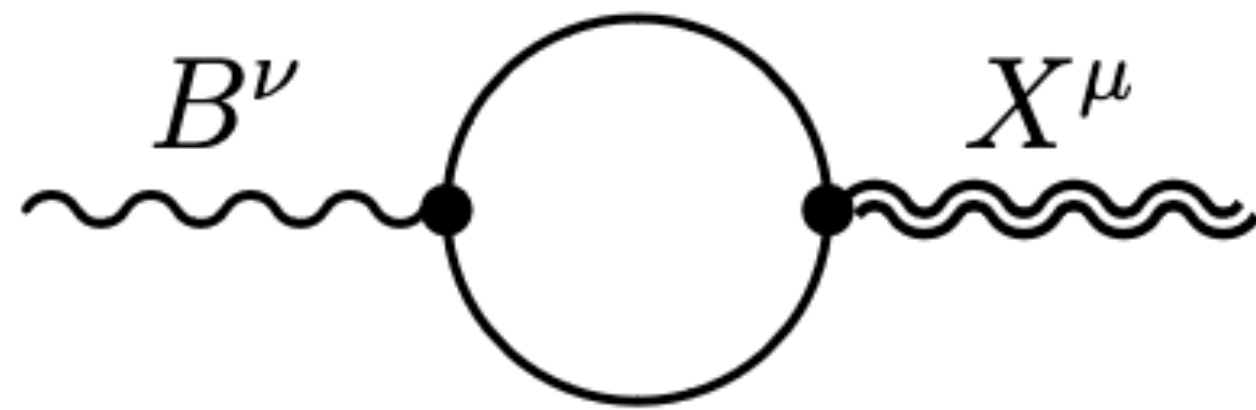
Extra  $U(1)$ ?  $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

Pospelov' 2008

Ackerman, Buckley, Carrol, Kamionkowski' 2008

Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\epsilon \mathbf{F}_{\mu\nu} \mathbf{F}'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) - J^\mu A_\mu$$



$$\epsilon = -\frac{g' g_X}{16\pi^2} \sum_i Y_i q_i \ln \frac{M_i^2}{\mu^2} \sim 10^{-1} - 10^{-3}$$

# Millicharge Particles

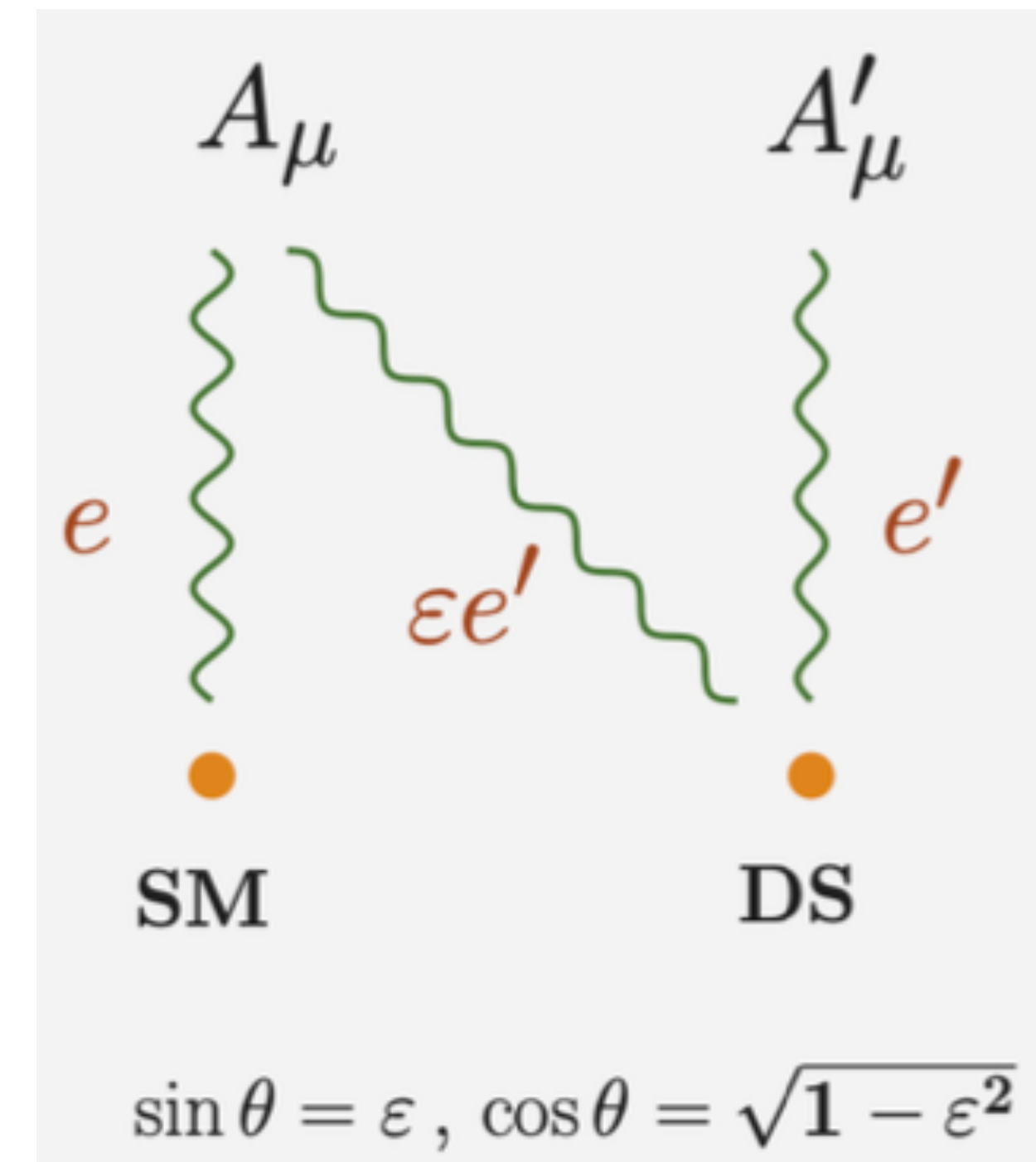
Massless dark photon  $\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$

$$\mathcal{L} = e J_\mu A_b^\mu + e' J'_\mu A_a^\mu$$

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}' &= \left[ \frac{e' \cos\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e \left( \sin\theta - \frac{\varepsilon \cos\theta}{\sqrt{1-\varepsilon^2}} \right) J_\mu \right] A'^\mu \\ &+ \left[ -\frac{e' \sin\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e \left( \cos\theta + \frac{\varepsilon \sin\theta}{\sqrt{1-\varepsilon^2}} \right) J_\mu \right] A^\mu \end{aligned}$$

$$\boxed{\mathcal{L}' = e' J'_\mu A'^\mu + \left[ -\frac{e' \varepsilon}{\sqrt{1-\varepsilon^2}} J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}} J_\mu \right] A^\mu}$$





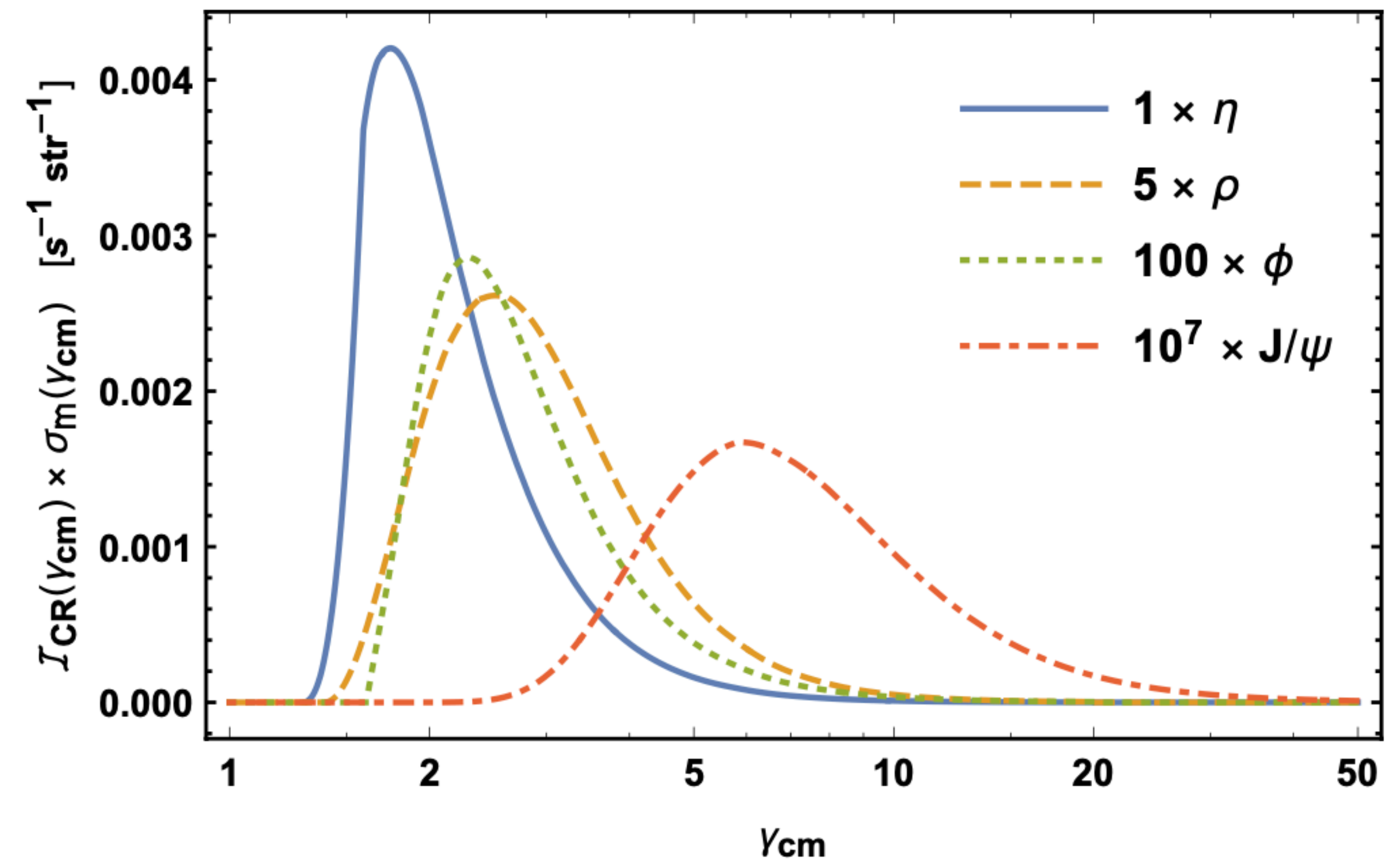
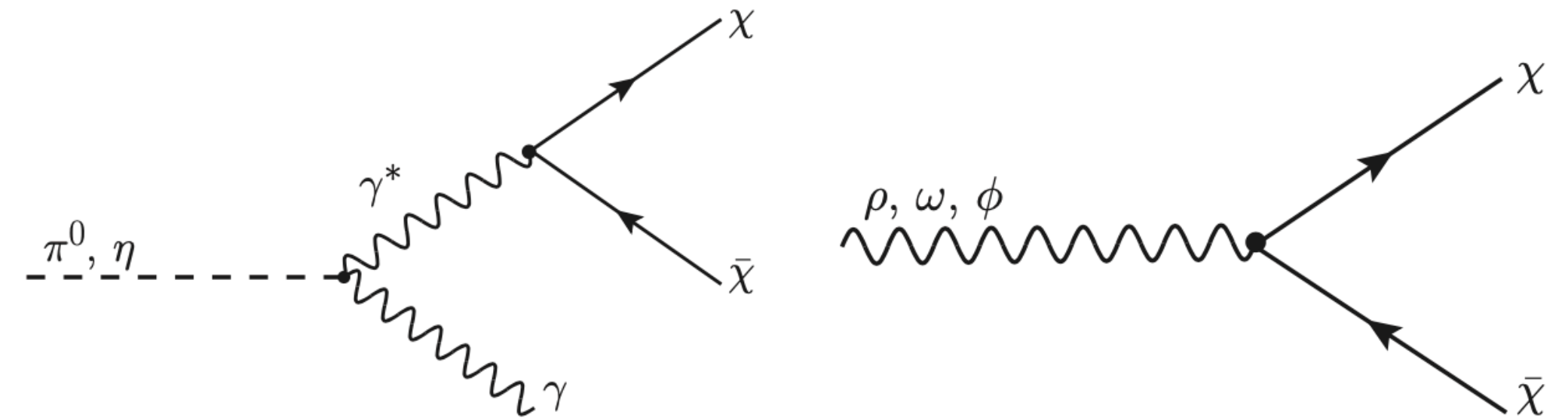
# Millicharge Particles from Light Meson Decay

$$\Phi_m(\gamma_m) = \Omega_{\text{eff}} \int \mathcal{I}_{\text{CR}}(\gamma_{\text{cm}}) \frac{\sigma_m(\gamma_{\text{cm}})}{\sigma_{\text{in}}(\gamma_{\text{cm}})} P(\gamma_m | \gamma_{\text{cm}}) d\gamma_{\text{cm}}$$

$$\gamma_{\text{cm}} = \frac{1}{2} \sqrt{s} / m_p$$

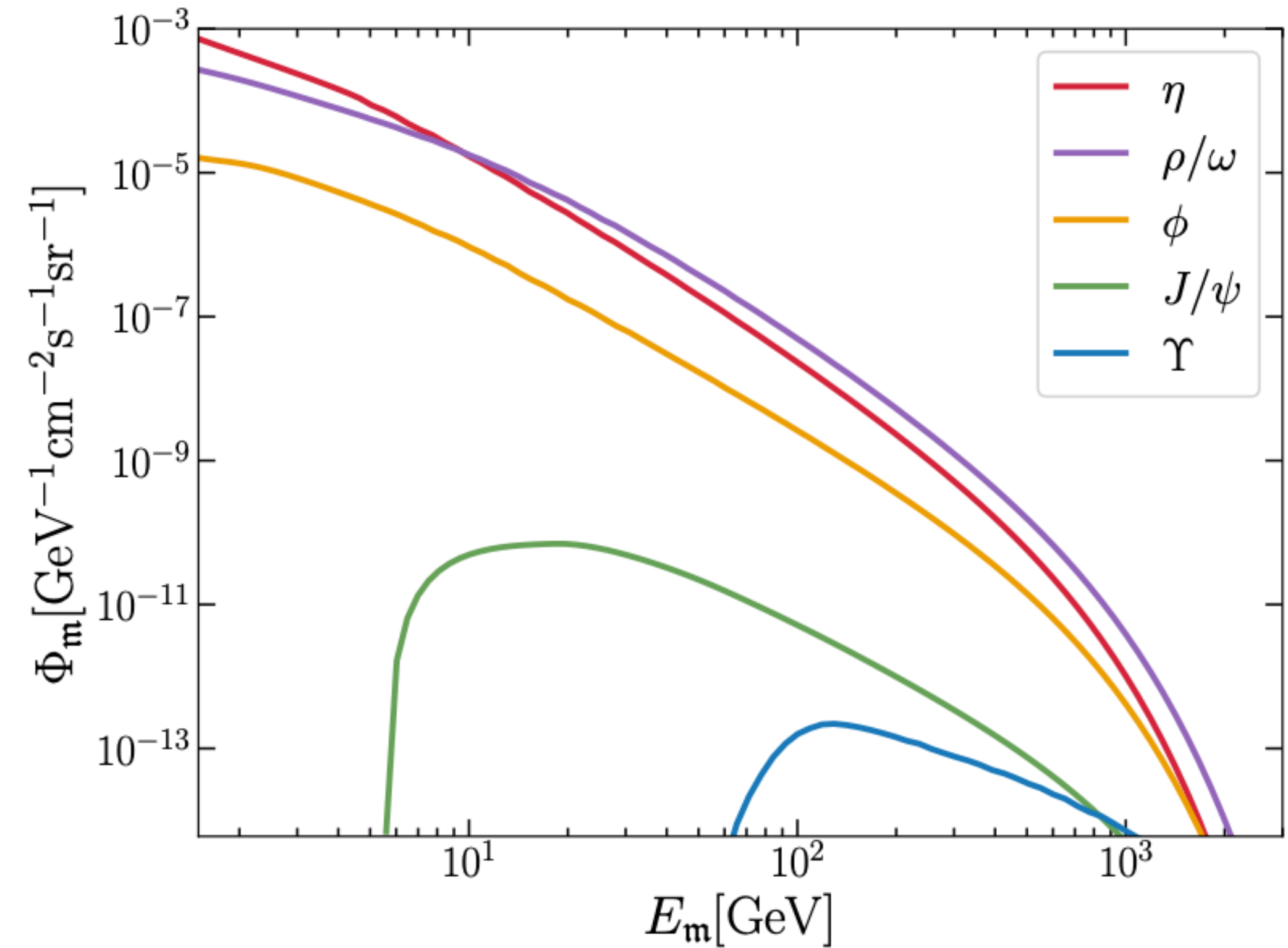
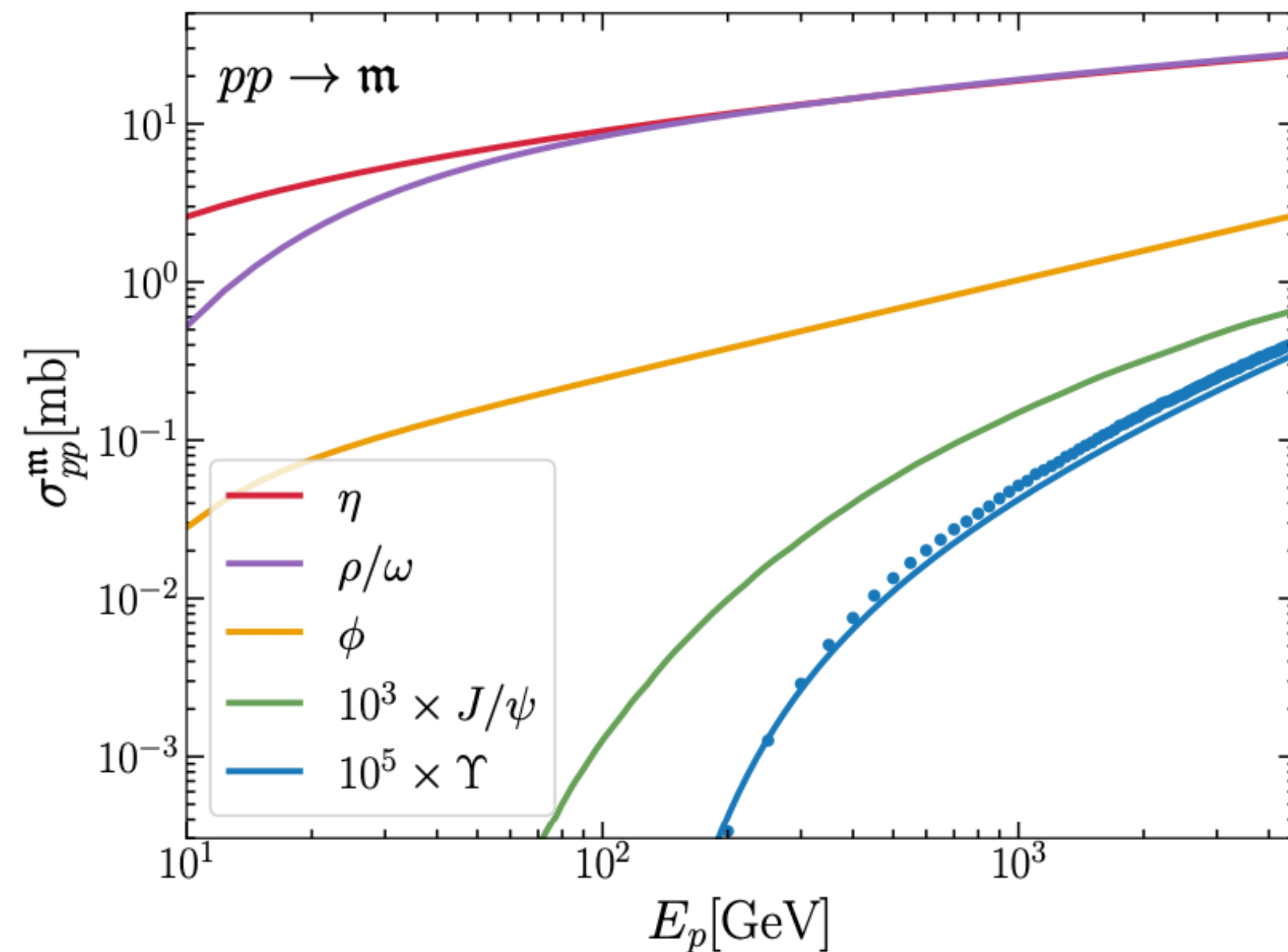
$$P(\gamma_m | \gamma_{\text{cm}}) \approx \sum_{\alpha} \frac{1}{\sigma_m} \times \frac{d\sigma_m}{dx_F} \times \frac{dx_F^{(\alpha)}}{d\gamma_m}$$

Plestid et al PRD/2002.11732



# Millicharge Particles from Upsilon Meson Decay

Pythia8 simulations



Wu, Hardy, **NS**, PRD/2406.01668

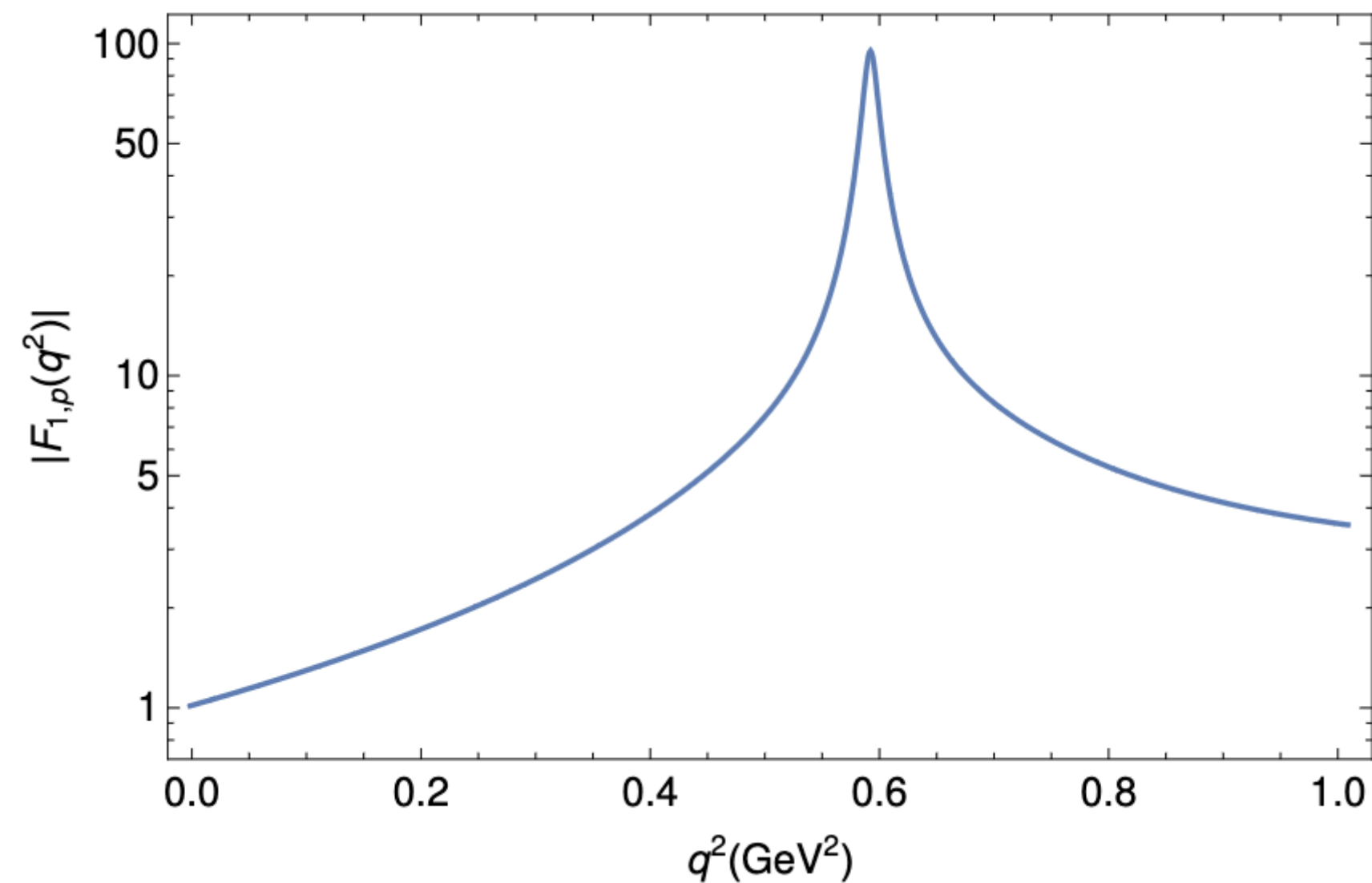
# Millicharge Particles from Proton Bremsstrahlung

Fermi-Weizsacker-Williams (FWW) approximation with the splitting-kernel approach

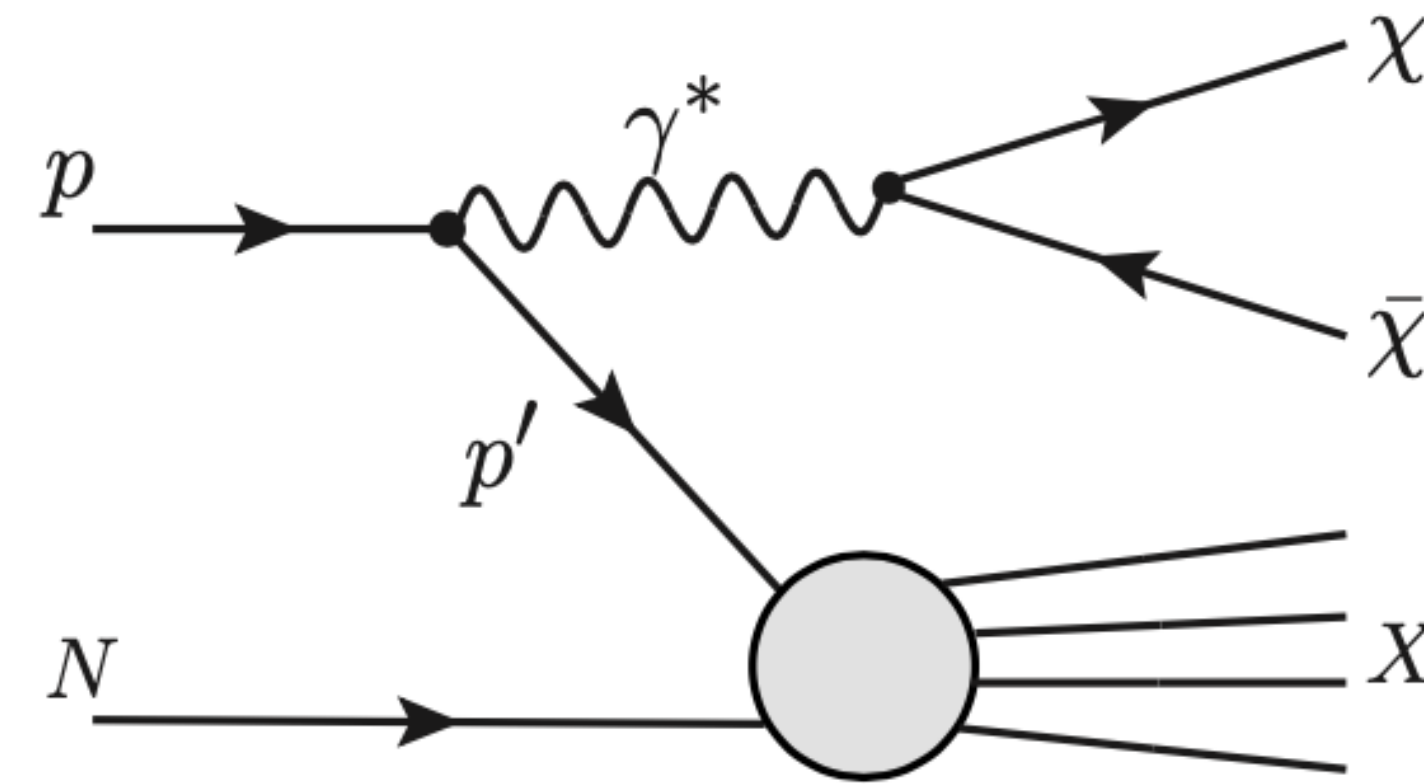
$$d\sigma^{\text{PB}}(s) \simeq d\mathcal{P}_{p \rightarrow \gamma^* p'} \times \sigma_{pN}(s')$$

$$\frac{d^2 \mathcal{P}_{p \rightarrow \gamma^* p}^{\text{FWW}}}{dE_k d\cos\theta_k} = |\mathbf{J}(z, p_T^2)| \frac{d^2 \mathcal{P}_{p \rightarrow \gamma^* p}^{\text{FWW}}}{dz dp_T^2} = |\mathbf{J}(z, p_T^2)| |F_V(k)|^2 \omega(z, p_T^2)$$

Kernel EM form factor



deNiverville et al PRD/1609.01770



$$\Phi_{\chi}^{\text{PB}} = \int dE_p \Phi_p \frac{\epsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1 - \frac{4m_{\chi}^2}{k^2}} \left( 1 + \frac{2m_{\chi}^2}{k^2} \right) \\ \times \int dE_k \frac{1}{\sigma_{vN}} \frac{d\sigma^{\text{PB}}}{dE_k} \frac{\Theta(E_{\chi} - E_{\min}) \Theta(E_{\max} - E_{\chi})}{E_{\max} - E_{\min}}$$

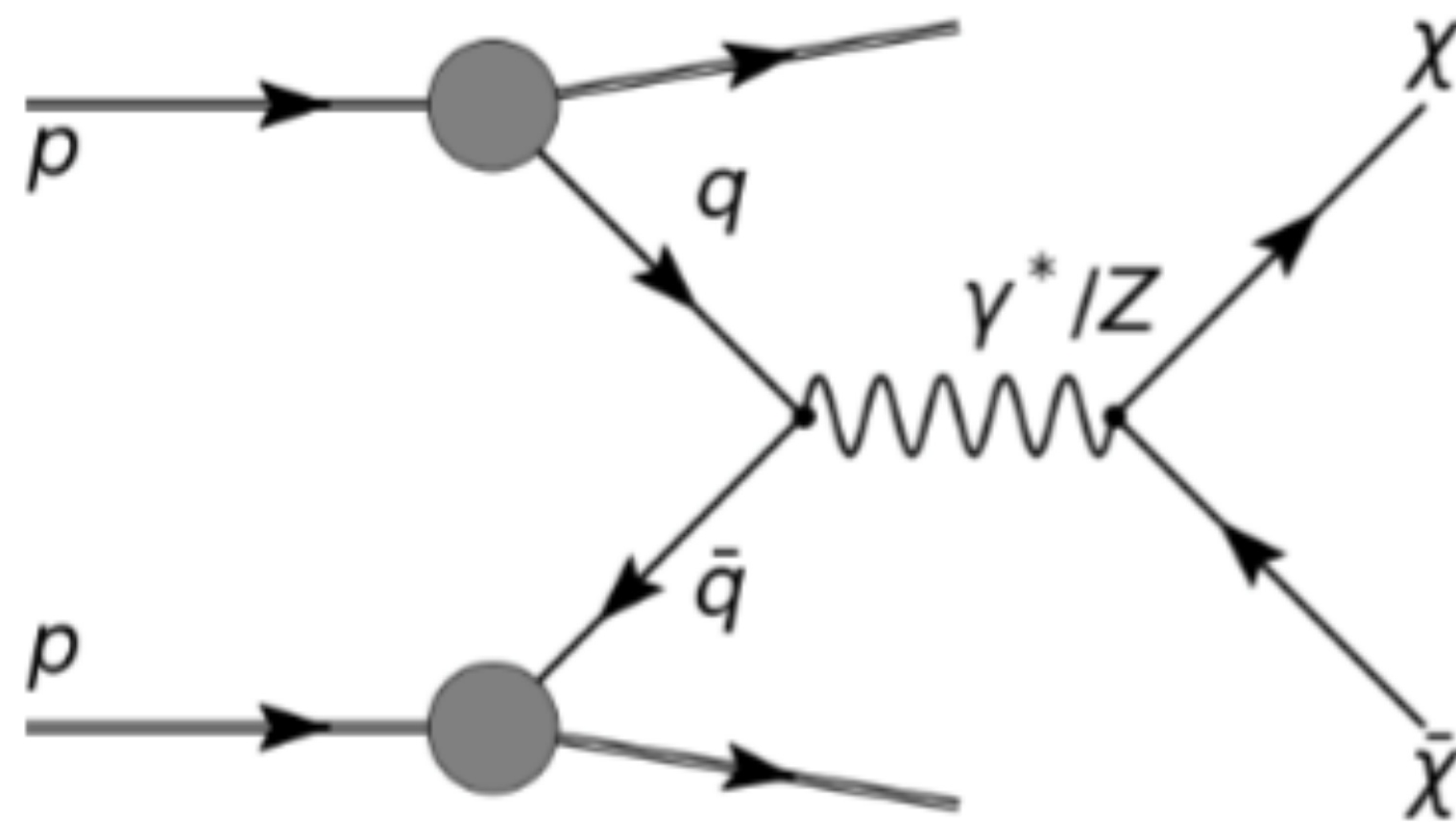
Du et al arXiv: 2211.11469

Du et al arXiv: 2308.05607

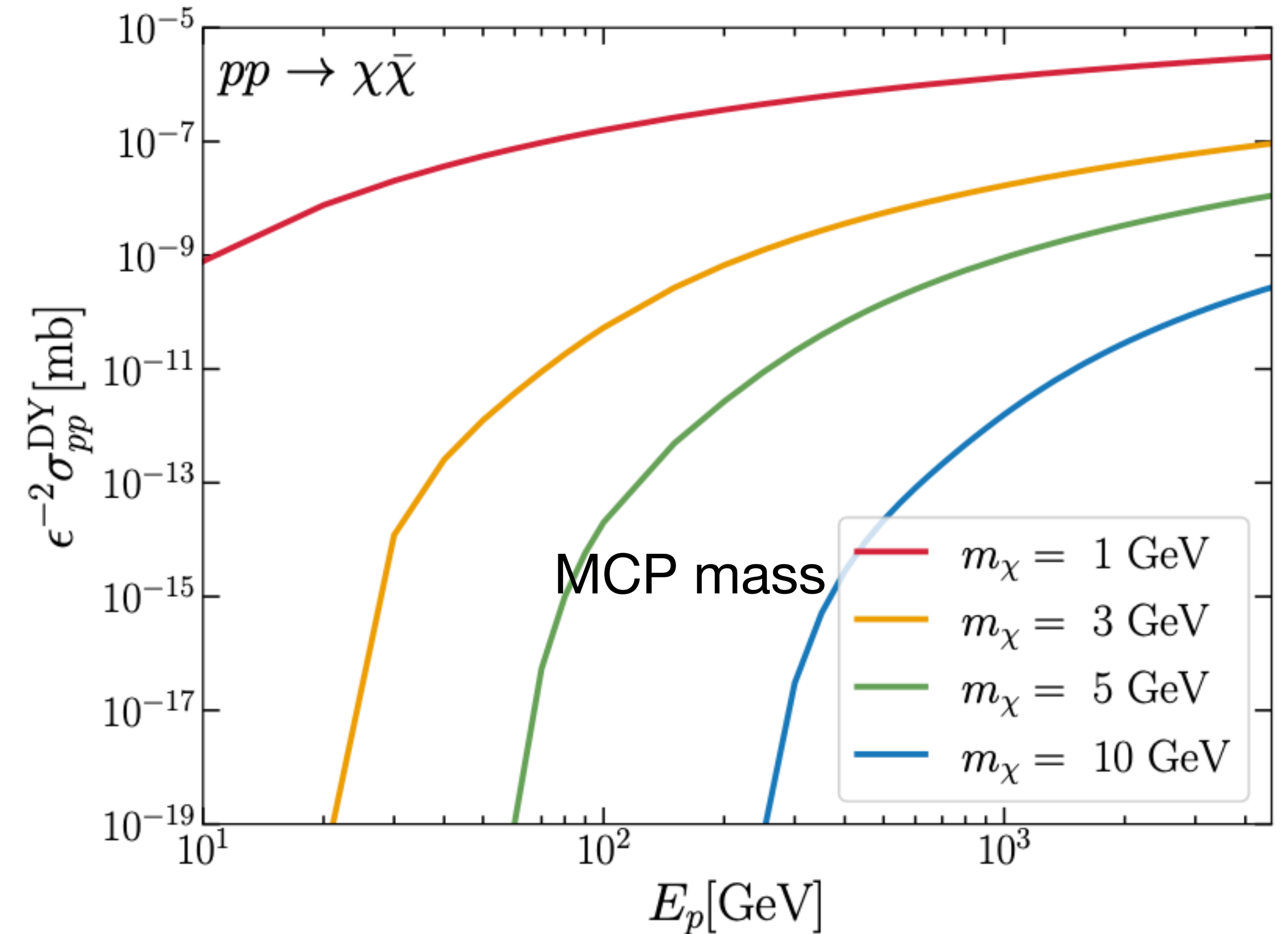


# Millicharge Particles from Drell-Yan Process

Madgraph simulations



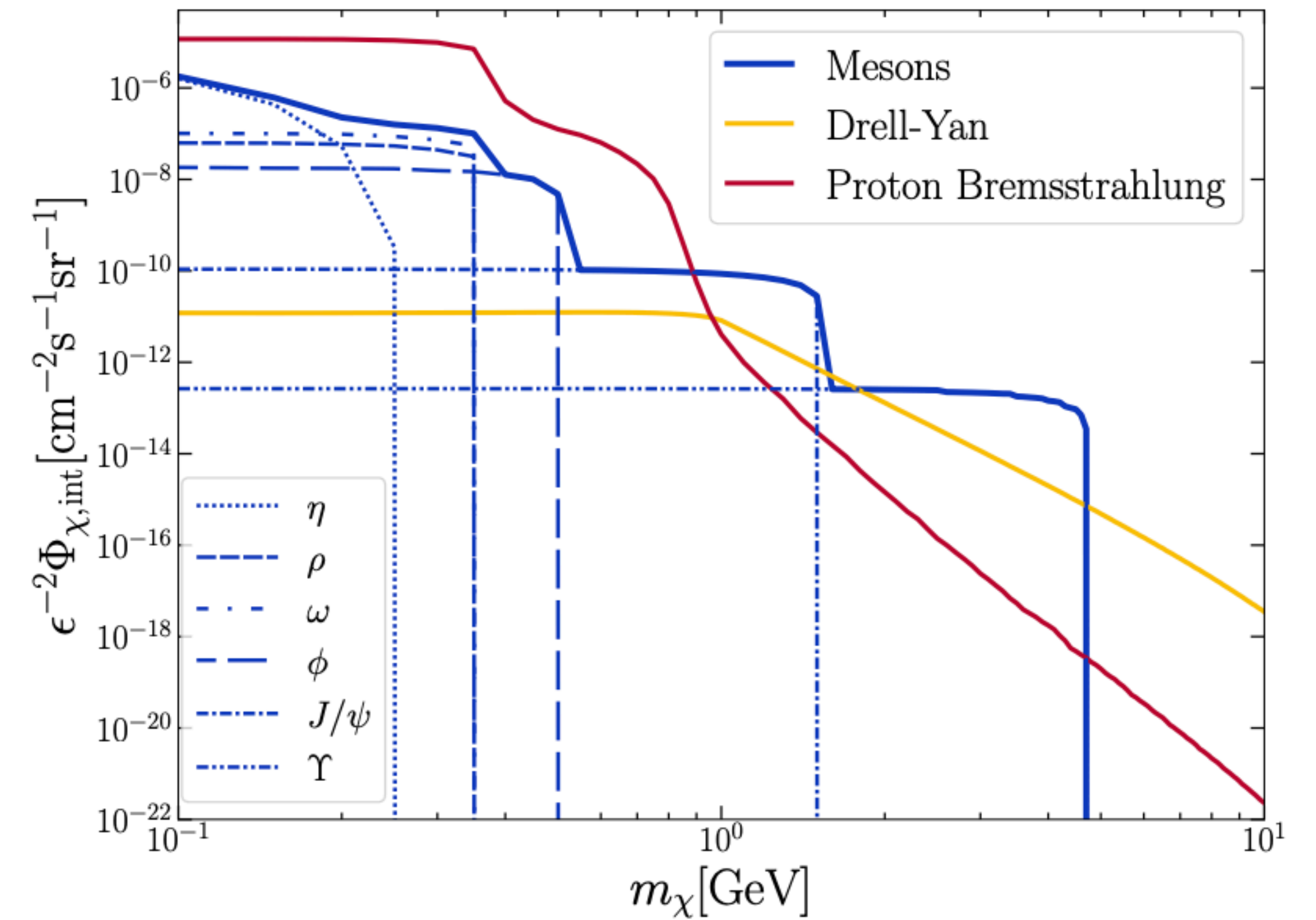
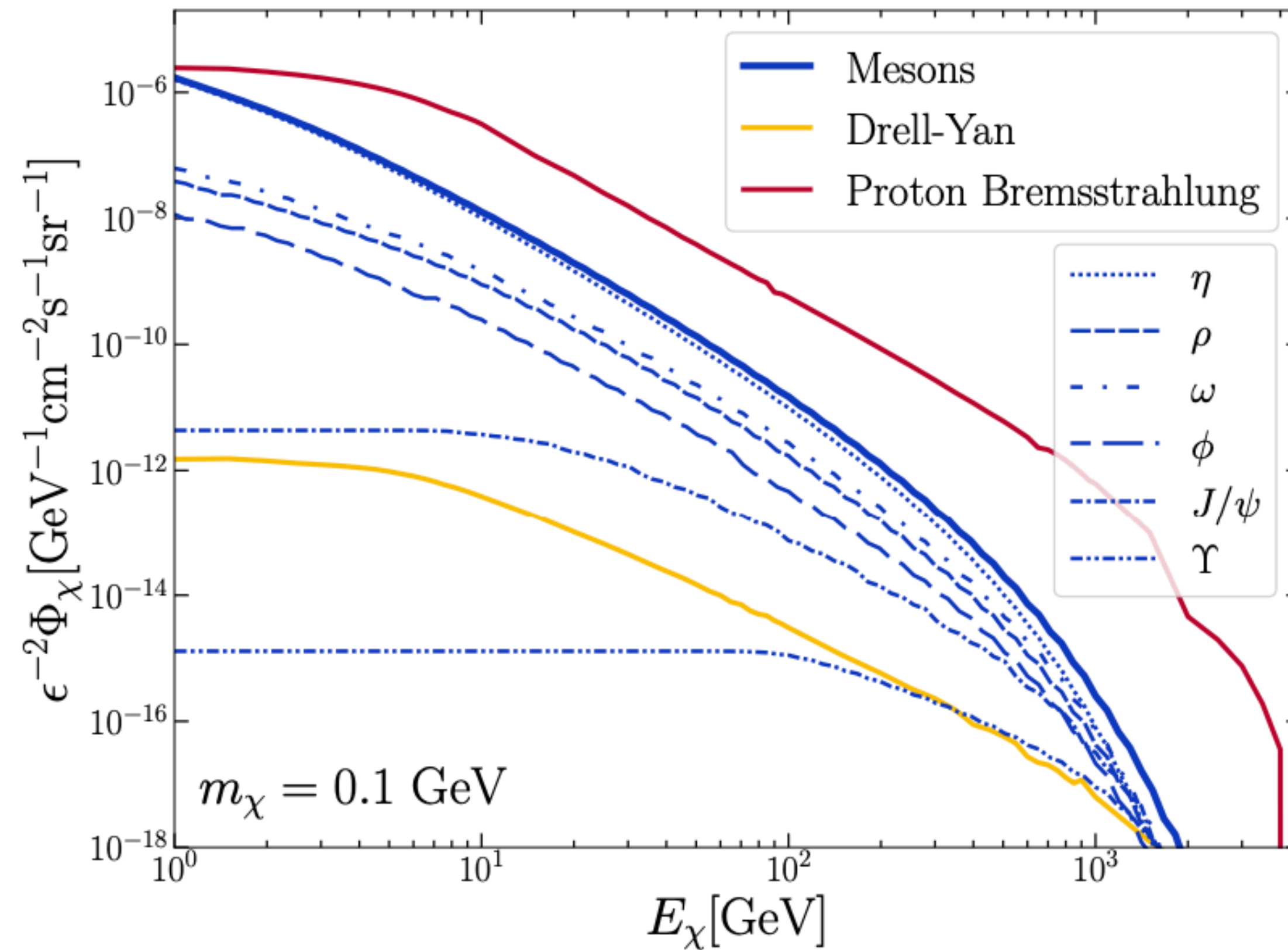
Wu, Hardy, **NS**, PRD/2406.01668



$$\hat{\sigma} (q(p_1) \bar{q}(p_2) \rightarrow l^+ l^-) = \frac{4\pi\alpha^2}{3\hat{s}} \frac{1}{N_c} Q_q^2$$

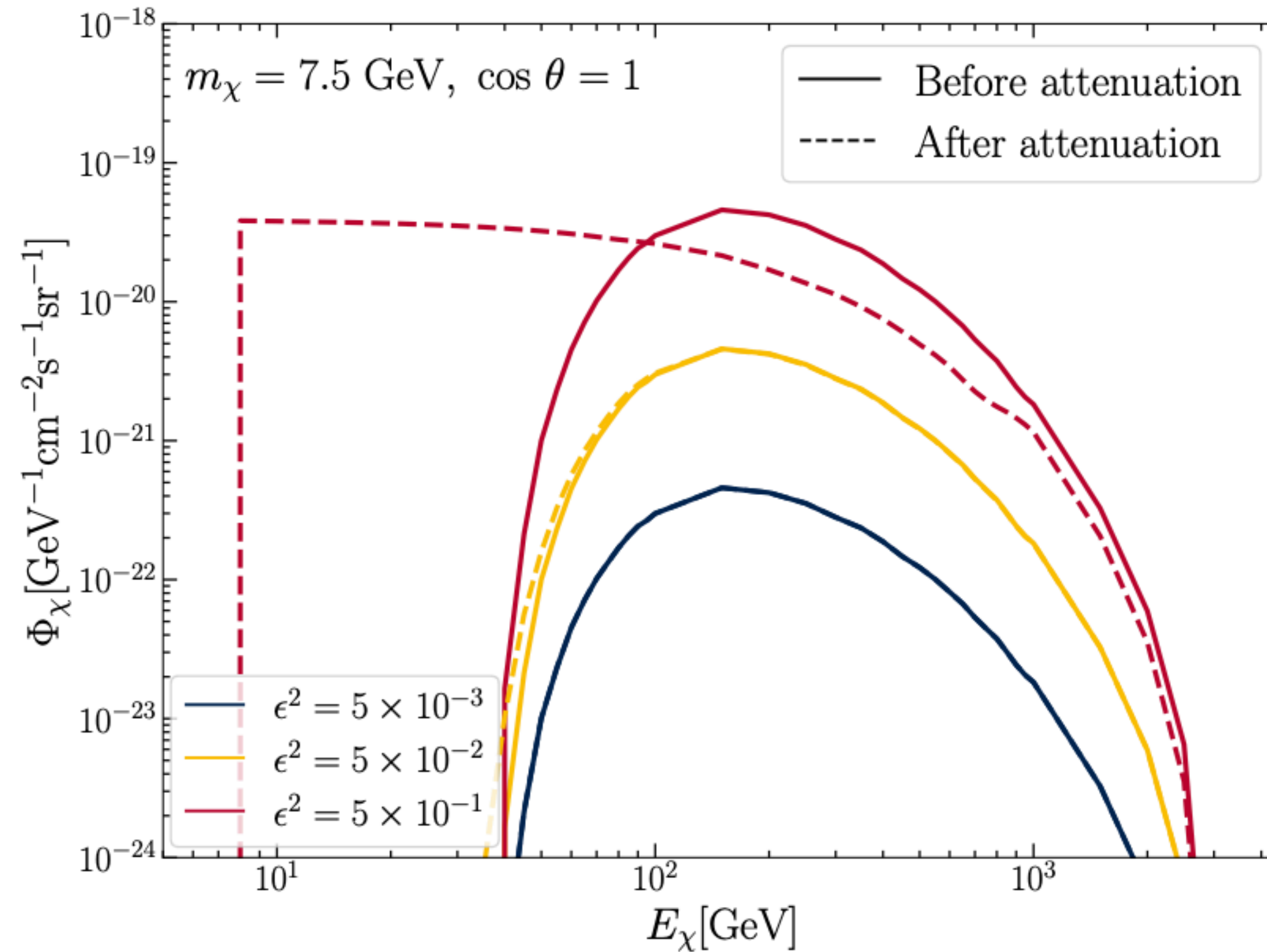
# Millicharge Particles Flux

Meson decay+Proton Bremsstrahlung+Drell-Yan



# Earth Attenuation

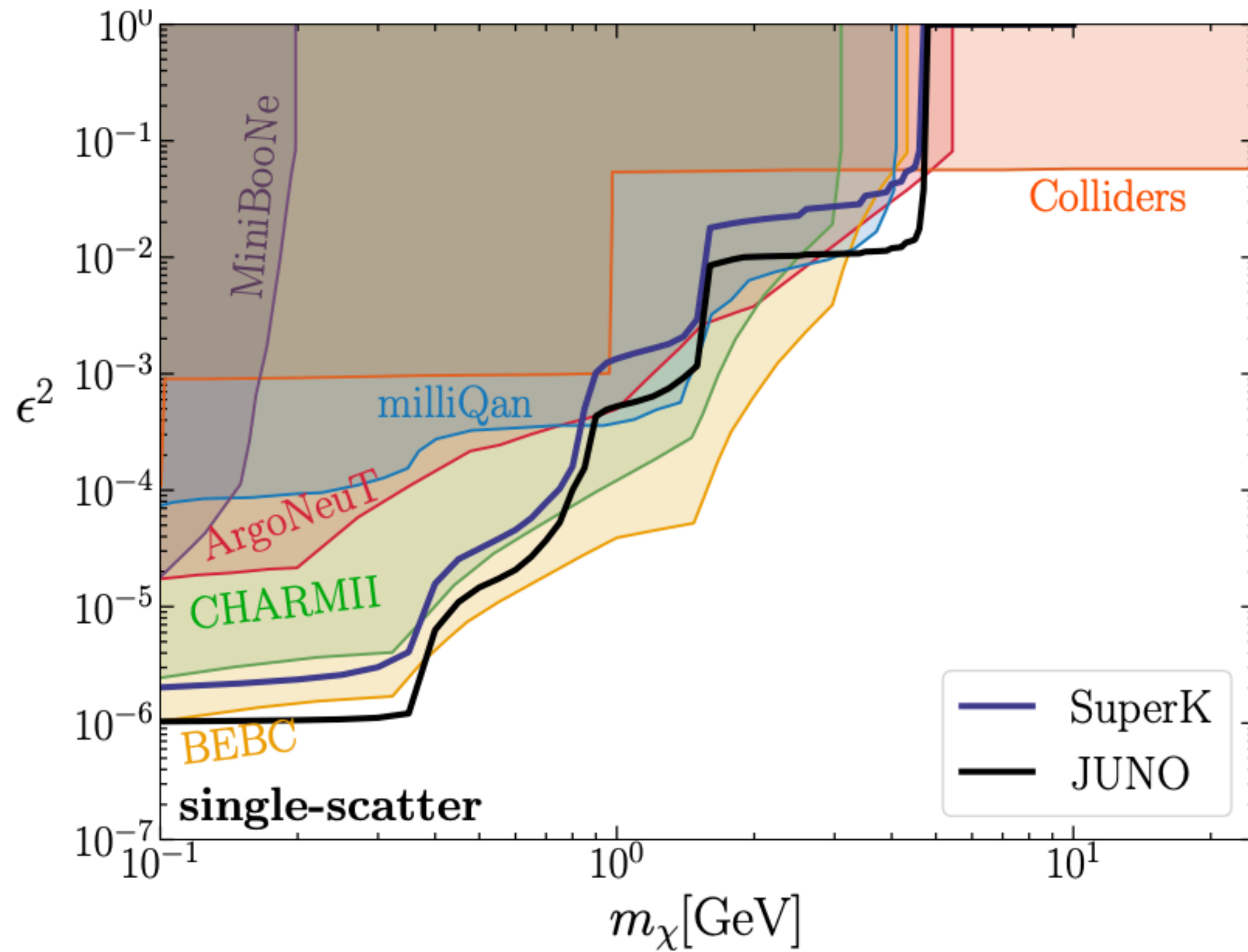
$$-\frac{dE}{dX} = \varepsilon^2 \left( a_{\text{ion.}} + b_{\text{el.-brem.}} \varepsilon^2 E + b_{\text{inel.-brem.}} E + b_{\text{pair}} E + b_{\text{photo-had.}} E \right) \approx \varepsilon^2 (a + bE)$$



For  $\epsilon^2 \gtrsim 10^{-2}$ , the down-going flux becomes significantly attenuated



# Single Scatter Constraint



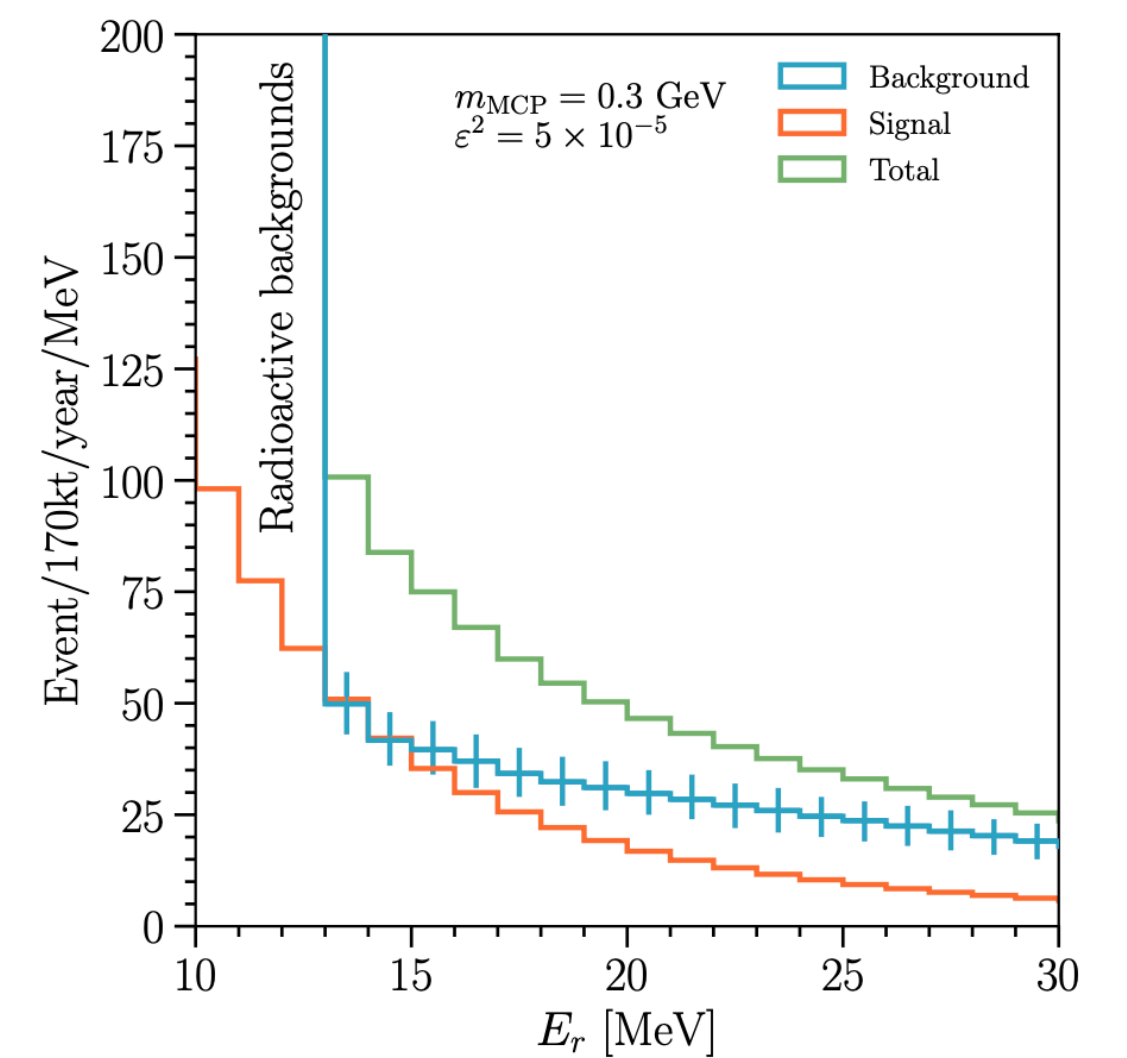
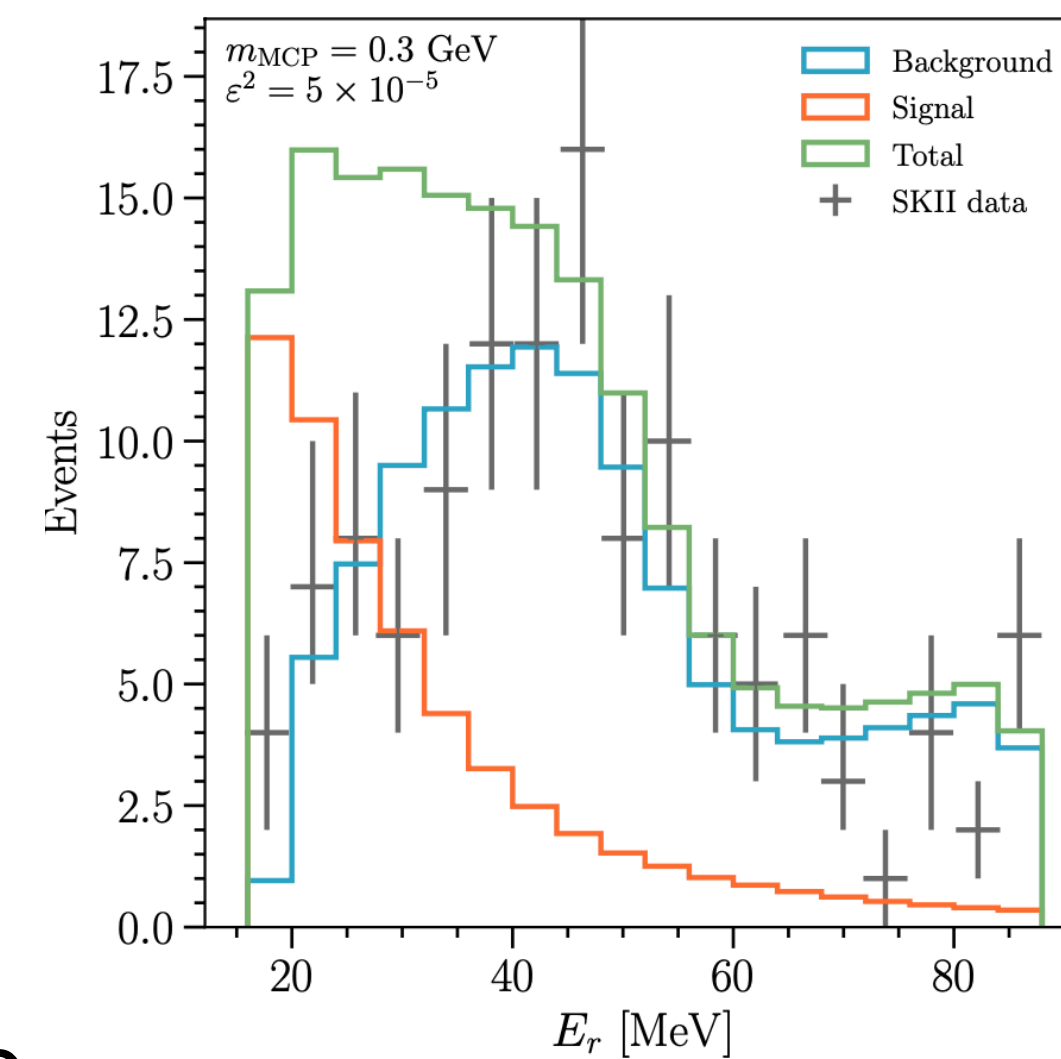
Assuming JUNO 10 MeV threshold+170 kton·yr exposure

Wu, Hardy, [NS](#), PRD/2406.01668

$$\frac{d\sigma_{\chi e}}{dE_r} = \pi\epsilon^2\alpha^2 \frac{(E_r^2 + 2E_\chi^2)m_e - ((2E_\chi + m_e)m_e + m_\chi^2) E}{E_r^2 m_e^2 (E_\chi^2 - m_\chi^2)}$$

$$d\sigma_{\chi e}/dE_r \propto 1/E_r^2$$

$$\sigma_{\chi e} \simeq \frac{\pi\alpha_{EM}\epsilon^2}{m_e T_{\min}} = 2.6 \times 10^{-25} \epsilon^2 \text{ cm}^2 \frac{\text{MeV}}{T_{\min}}$$



Arguelles et al JHEP/2104.13924

# Multiple Scatter Constraint

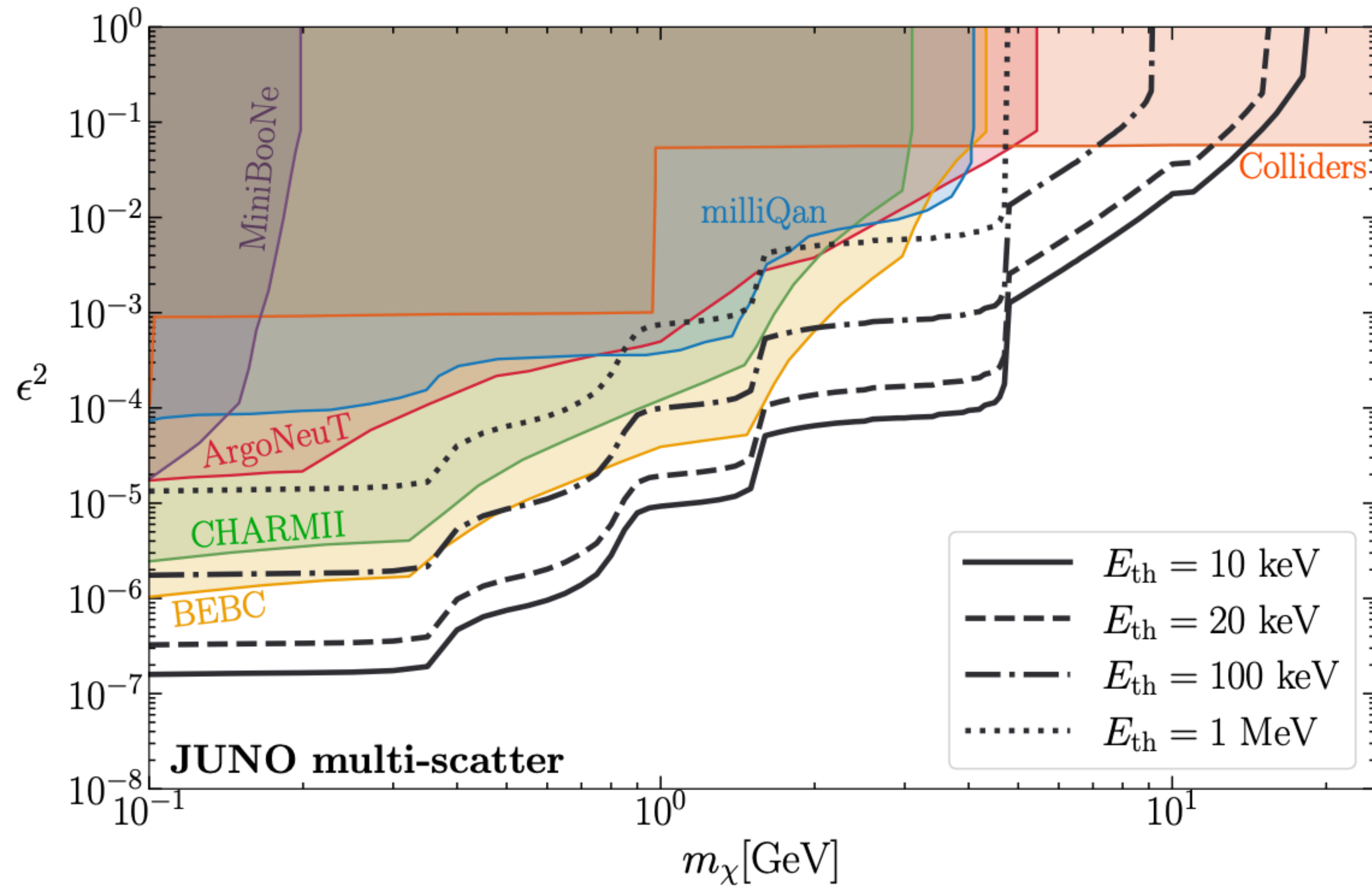
Single scatter probability  $P_1 = 1 - \exp\left(-\frac{L_D}{\lambda(T_{\min})}\right)$

Multiple scatter probability  $P_{n \geq 2}(T_{\min}) = 1 - \exp\left(-\frac{L_D}{\lambda}\right) \left(1 + \frac{L_D}{\lambda}\right)$

Number of observed events  $N_{\text{multi}} = N_{\text{single}} P_{n \geq 2}(T_{\min, \text{multi}}) / P_1(T_{\min, \text{single}})$

$$N_{\text{single}}(m_\chi, \epsilon) = N_e T \int_{E_{i, \min}}^{E_{i, \max}} dE_r \epsilon_D(E_r) \times \int dE_\chi d\Omega \Phi_\chi^D(E_\chi, \Omega) \frac{d\sigma_{\chi e}}{dE_r}$$

# Multiple Scatter Constraint



Assuming JUNO 170 kton·yr exposure

Wu, Hardy, [NS](#), PRD/2406.01668



# Contributions from Inelastic Scattering

Elastic scattering

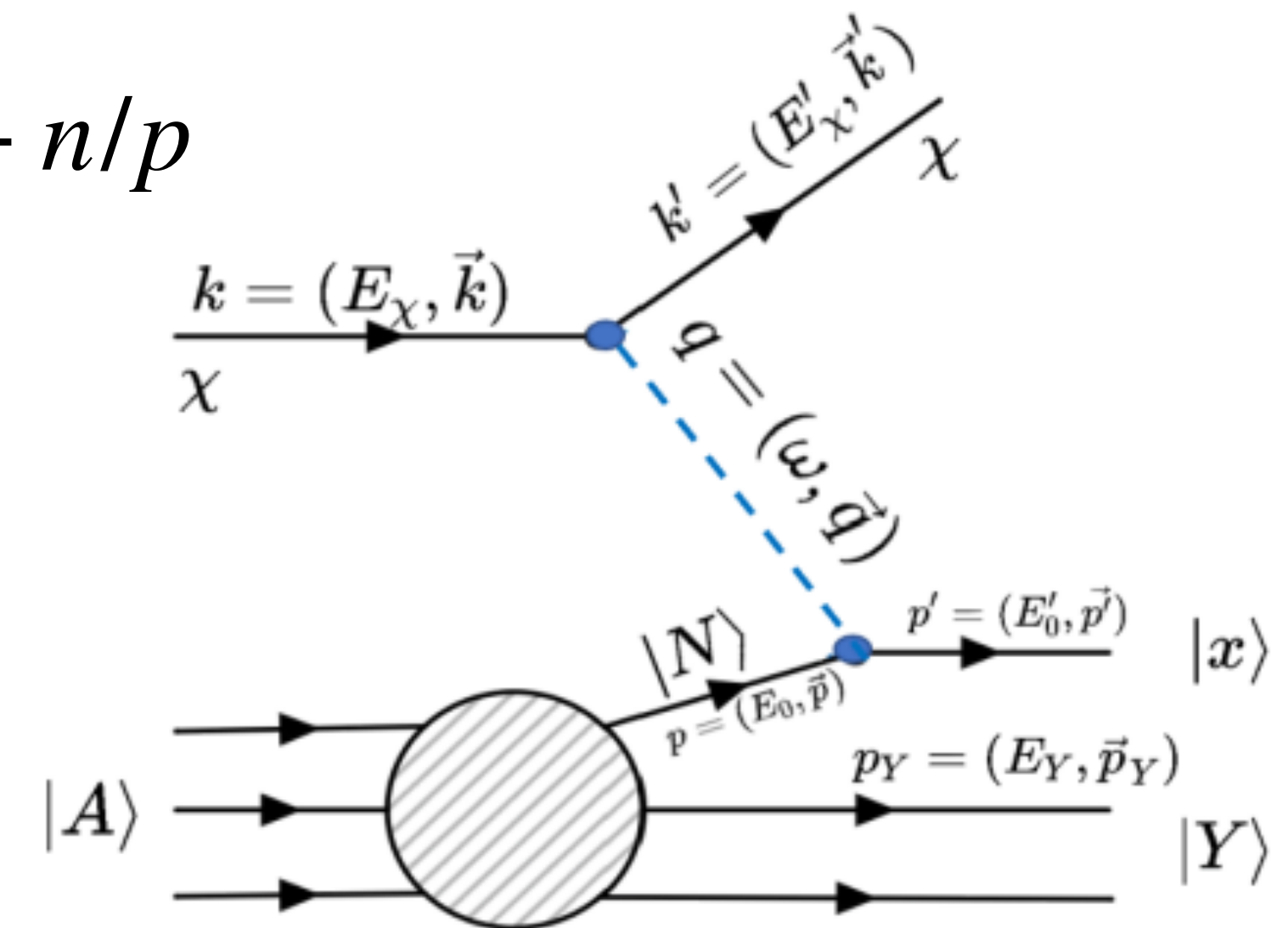
$$\chi + A \rightarrow \chi + A$$

$$\frac{d\sigma_{\text{ES}}}{dE_R} = \frac{\bar{\sigma}_n A^2 m_S^4 F^2(E_R)}{32\mu_n^2 m_A (2m_A E_R + m_S^2)^2 (E_\chi^2 - m_\chi^2)} \times (4m_\chi^2 + 2m_A E_R)(4m_A^2 + 2m_A E_R),$$

Quasi-elastic scattering

$$\chi + A \rightarrow \chi + (A - 1) + n/p$$

$$\frac{d\sigma_{\text{QE}}}{dE'_\chi d\Omega} = \frac{\bar{\sigma}_n m_S^4}{16\pi\mu_n^2} \frac{|\vec{k}'|}{|\vec{k}|} \frac{\chi_S W_S}{(Q^2 + m_S^2)^2},$$



Deep inelastic scattering

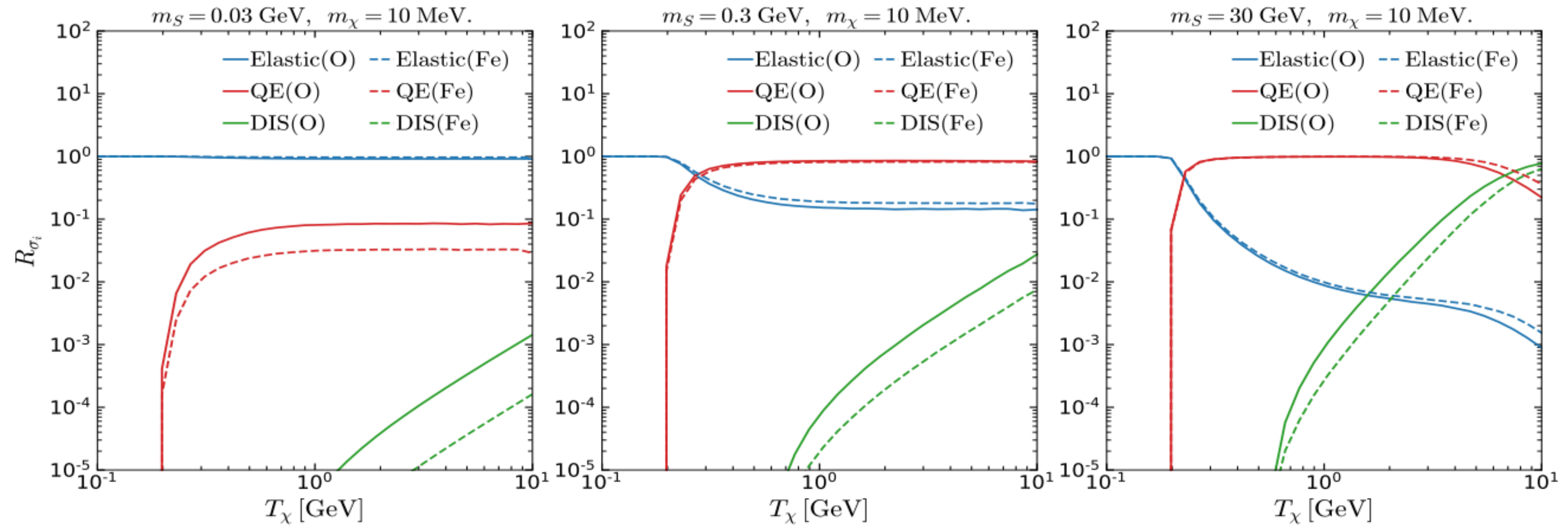
$$\chi + A \rightarrow \chi + X$$

$$\begin{aligned} d\sigma_{\text{DIS}} &= \frac{d\nu dQ^2}{64\pi m_A^2 \nu (E_\chi^2 - m_\chi^2)} \int_0^1 \frac{f(\xi)}{\xi} d\xi |\overline{\mathcal{M}(\xi)}|^2 \delta(\xi - x) \\ &= \sum_q \frac{g_\chi^2 g_q^2 (4m_\chi^2 + Q^2)(4m_q^2 + Q^2) d\nu dQ^2}{32\pi m_A Q^2 (E_\chi^2 - m_\chi^2)(Q^2 + m_S^2)^2} f_{q/A}(x, Q^2), \end{aligned}$$

Su et al, arXiv: 2212.02286

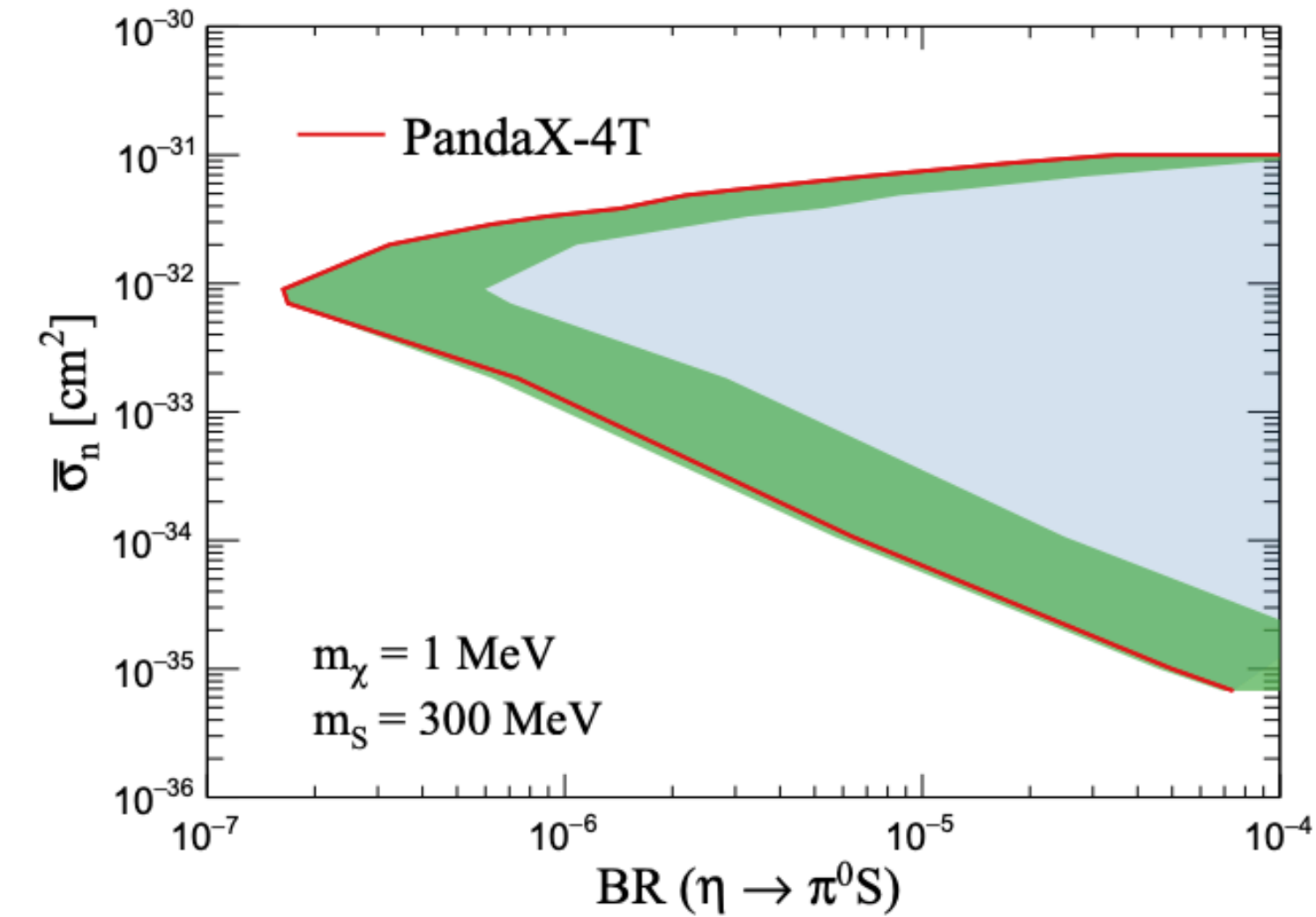
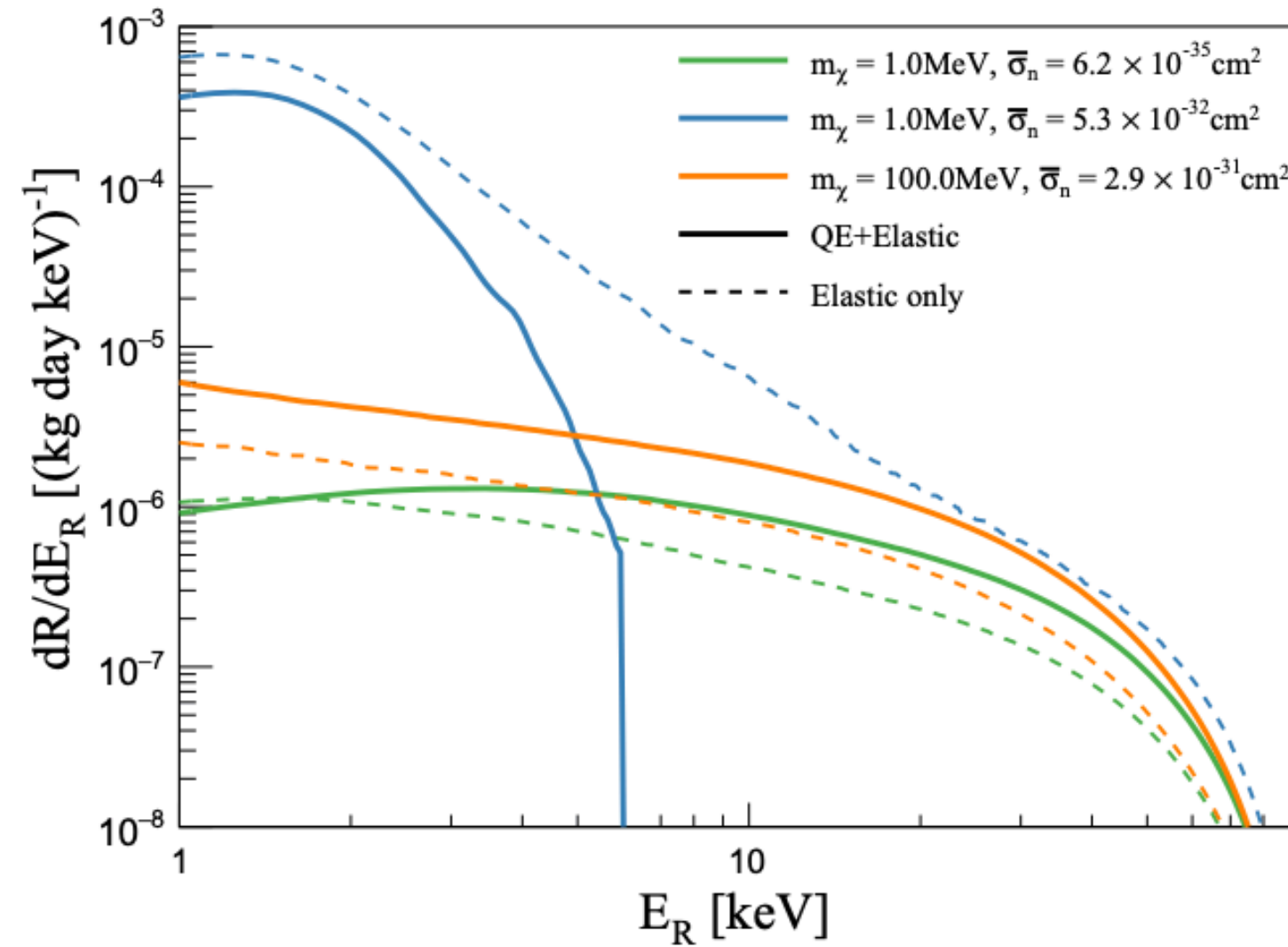
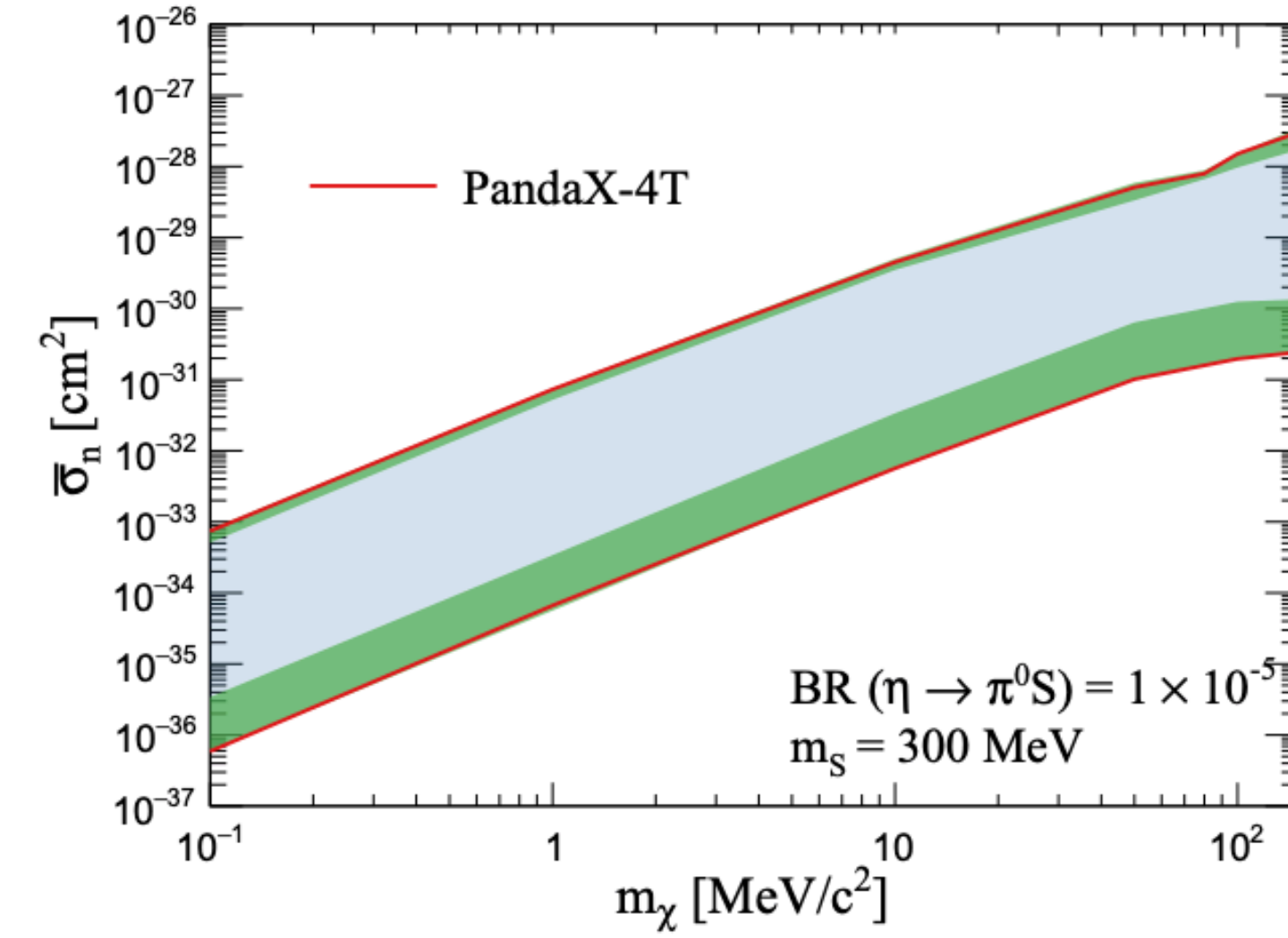
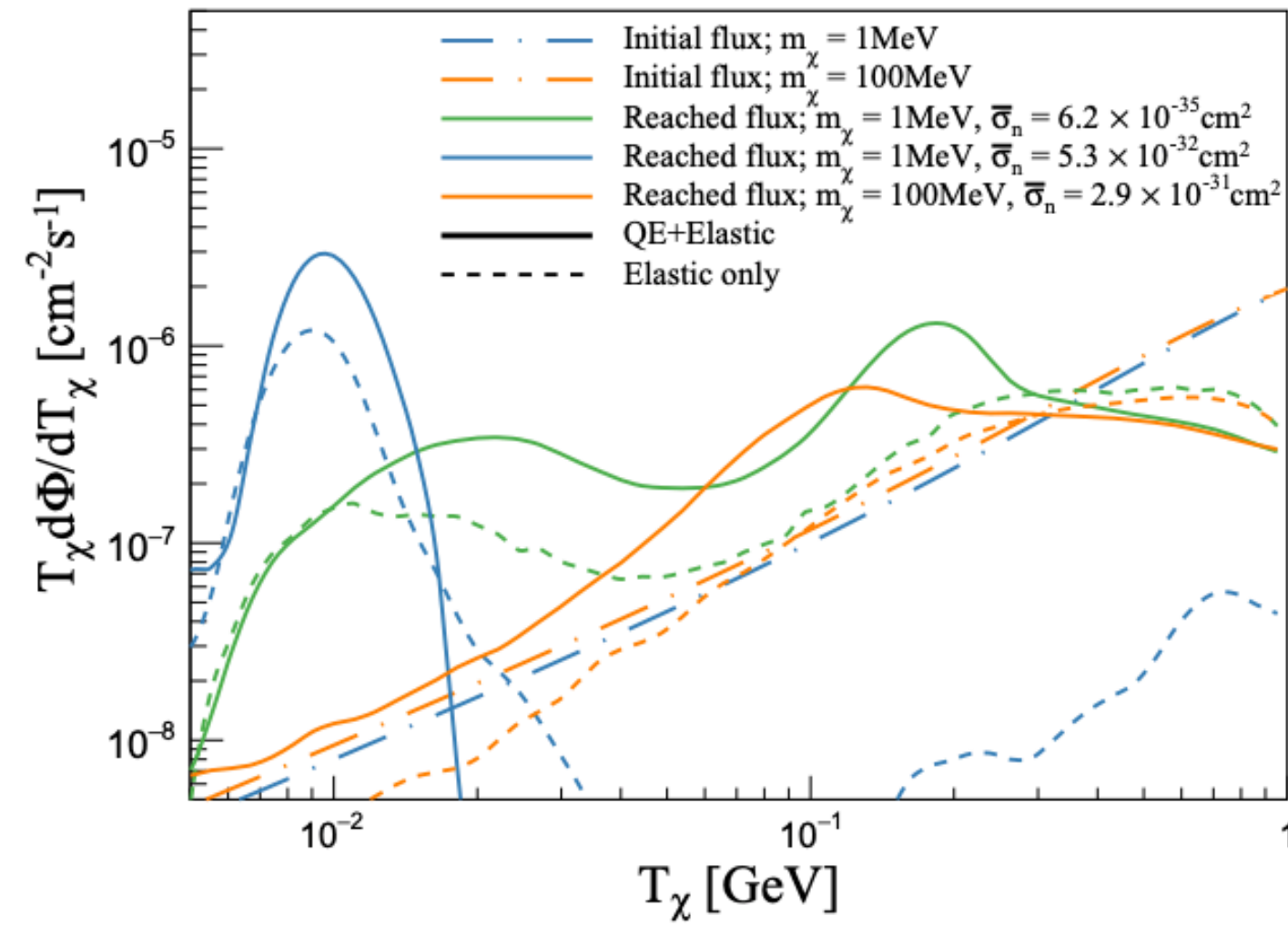
# Contributions from Inelastic Scattering

$$R_{\sigma_i} = \frac{\sigma_i}{\sigma_{tot}}$$



# New Limits from PandaX

PandaX Collaboration, arXiv: 2301.03010

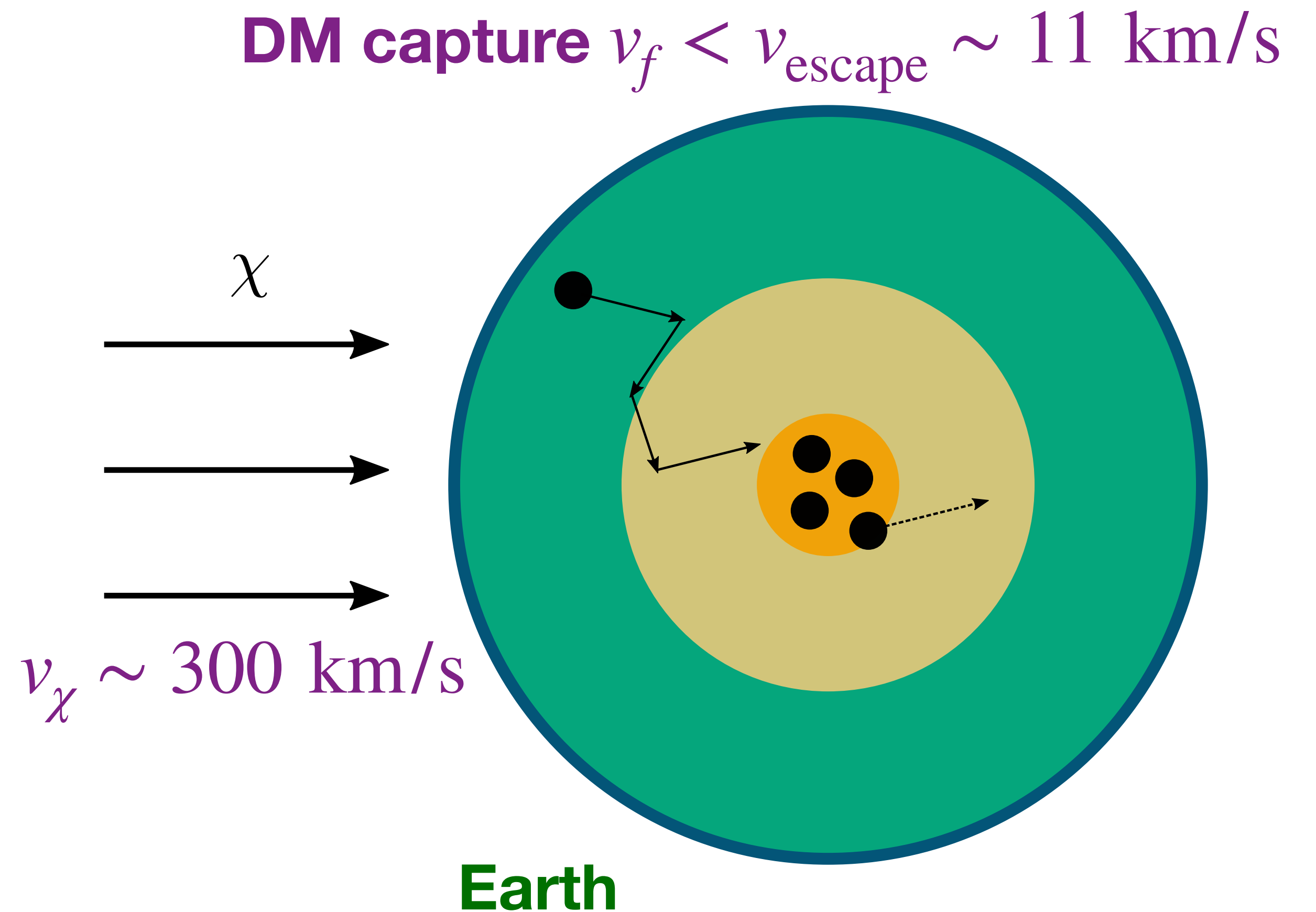




# Dark Matter Capture

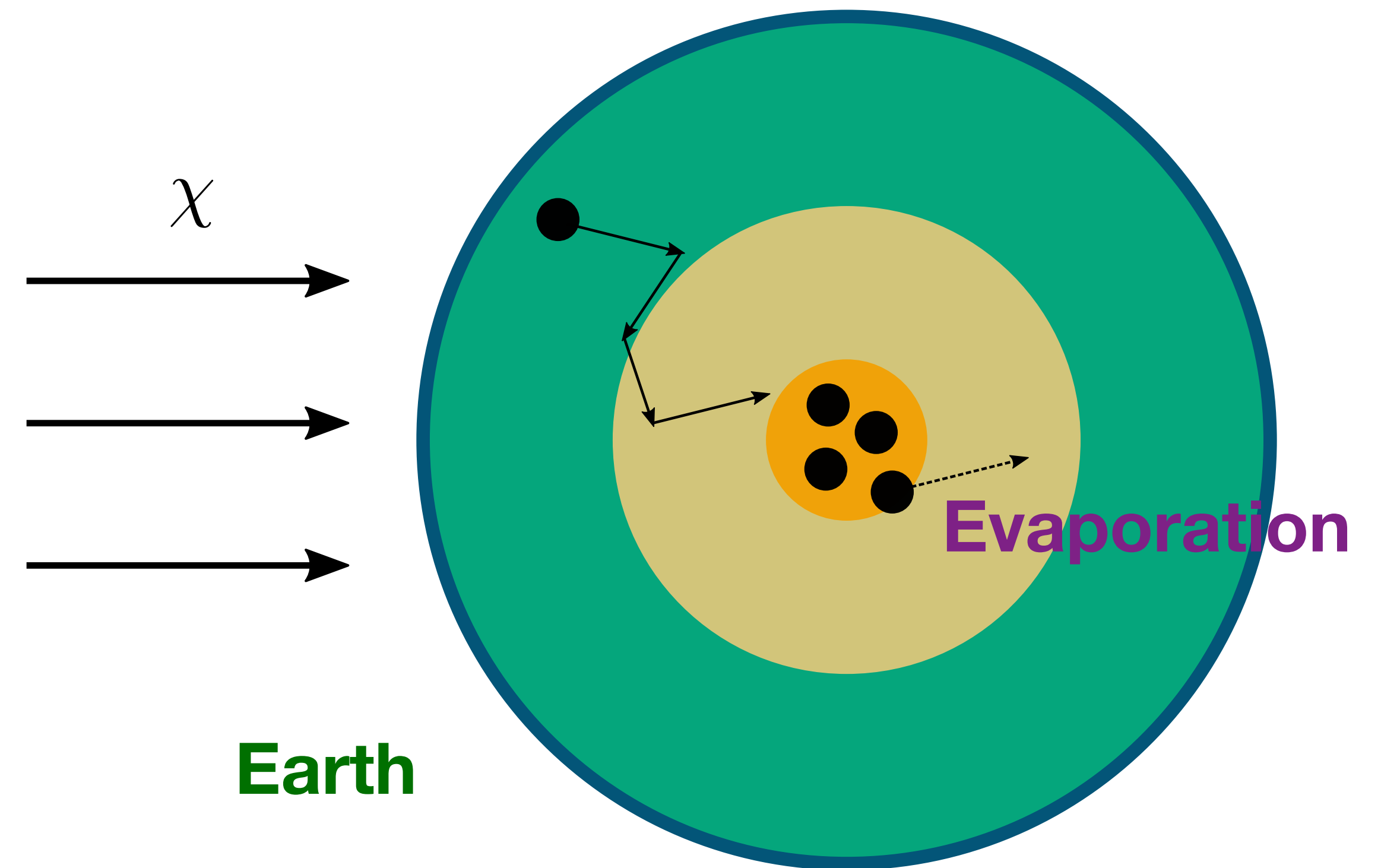
# Earth Heating

- 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



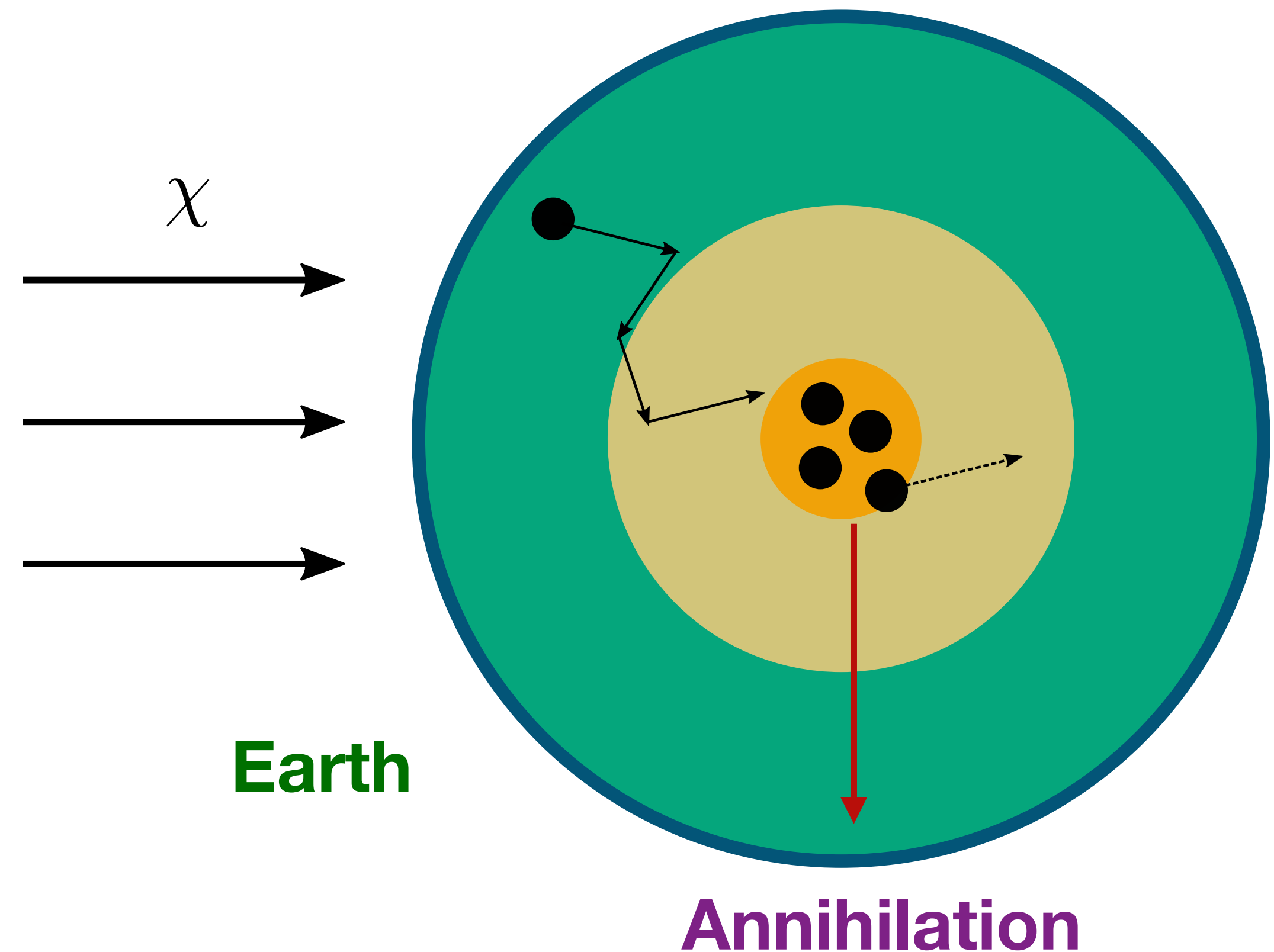


# Earth Heating

- 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  $\leq 44$  TW

Kamland, Borexino  
geoneutrino observation

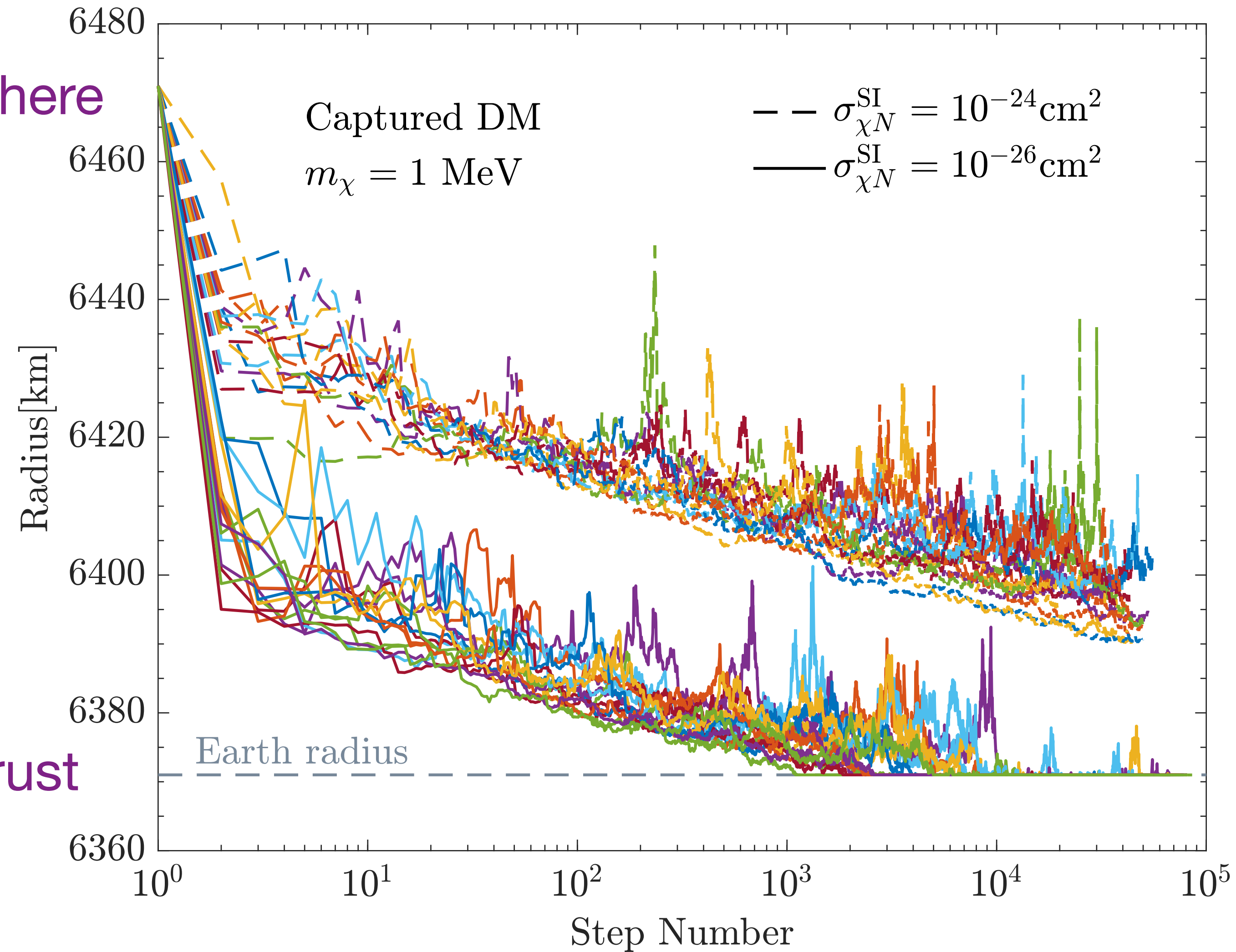


# Monte Carlo

DaMaSCUS\_EarthCapture

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

Top of atmosphere



See also DaMaSCUS

<https://github.com/temken/DaMaSCUS>

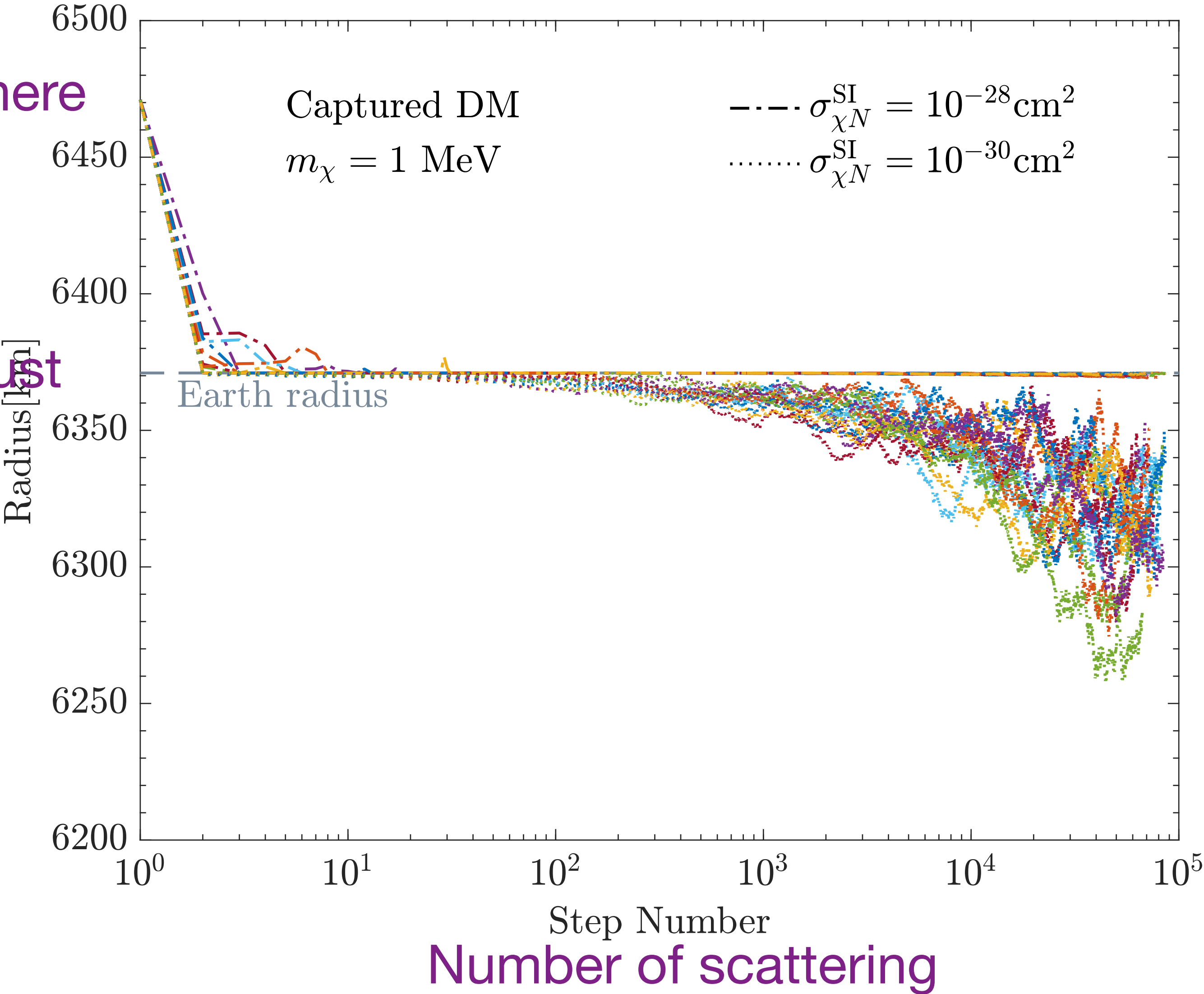
Top of Earth crust

# Monte Carlo

DaMaSCUS\_EarthCapture  
<https://github.com/songningqiang/DaMaSCUS-EarthCapture>

Top of atmosphere

Top of Earth crust

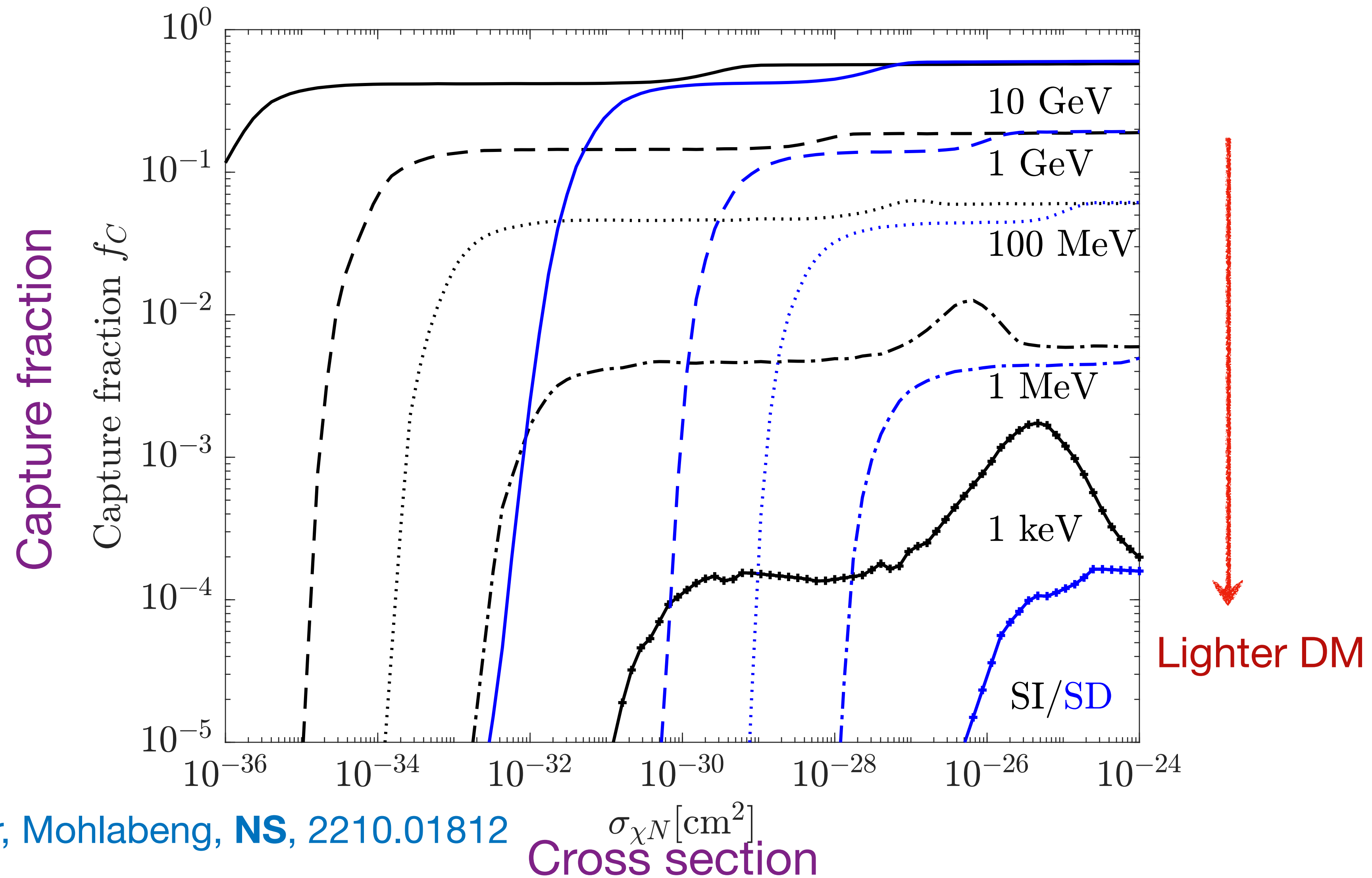




# Capture Fraction

DaMaSCUS\_EarthCapture

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

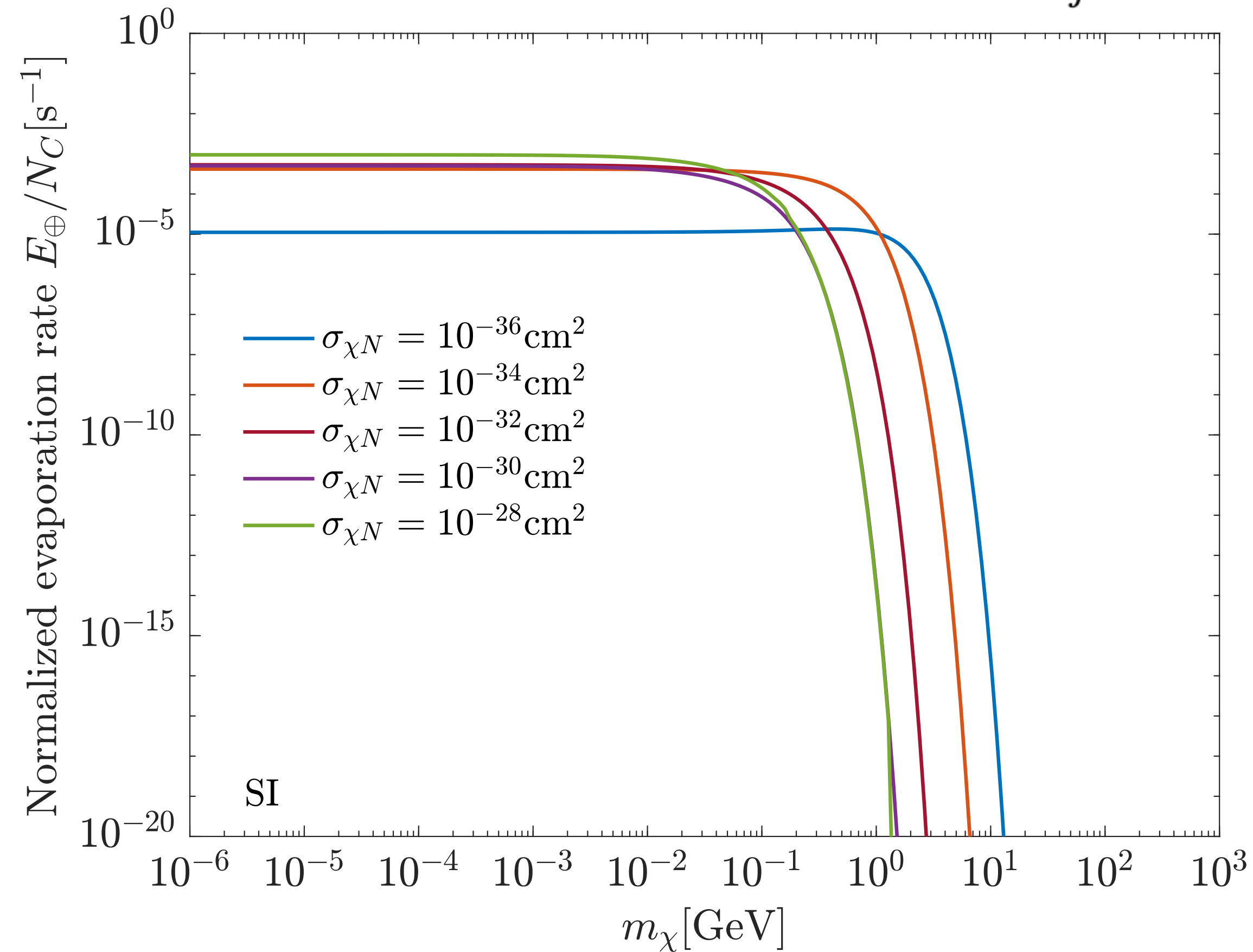


Bramante, Kumar, Mohlabeng, **NS**, 2210.01812

$\sigma_{\chi N} [\text{cm}^2]$   
Cross section

# Dark Matter Evaporation

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



Multi scatter

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

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

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

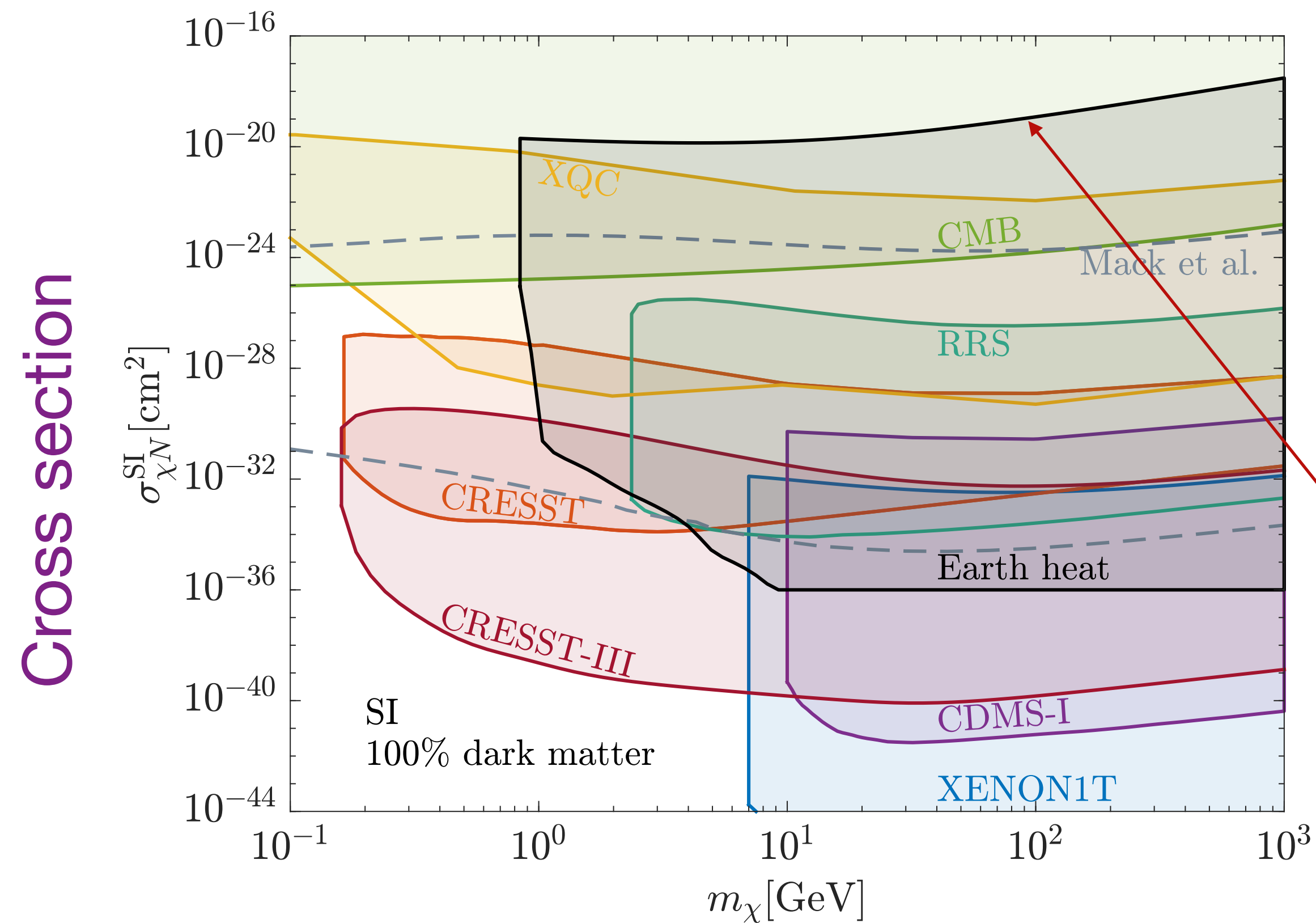
$$\Gamma_{\oplus}(t) = (1/2) A_{\oplus} N_C(t)^2$$

Capture   Evaporation   Annihilation



# Earth Heating Constraints

Spin-Independent 100%

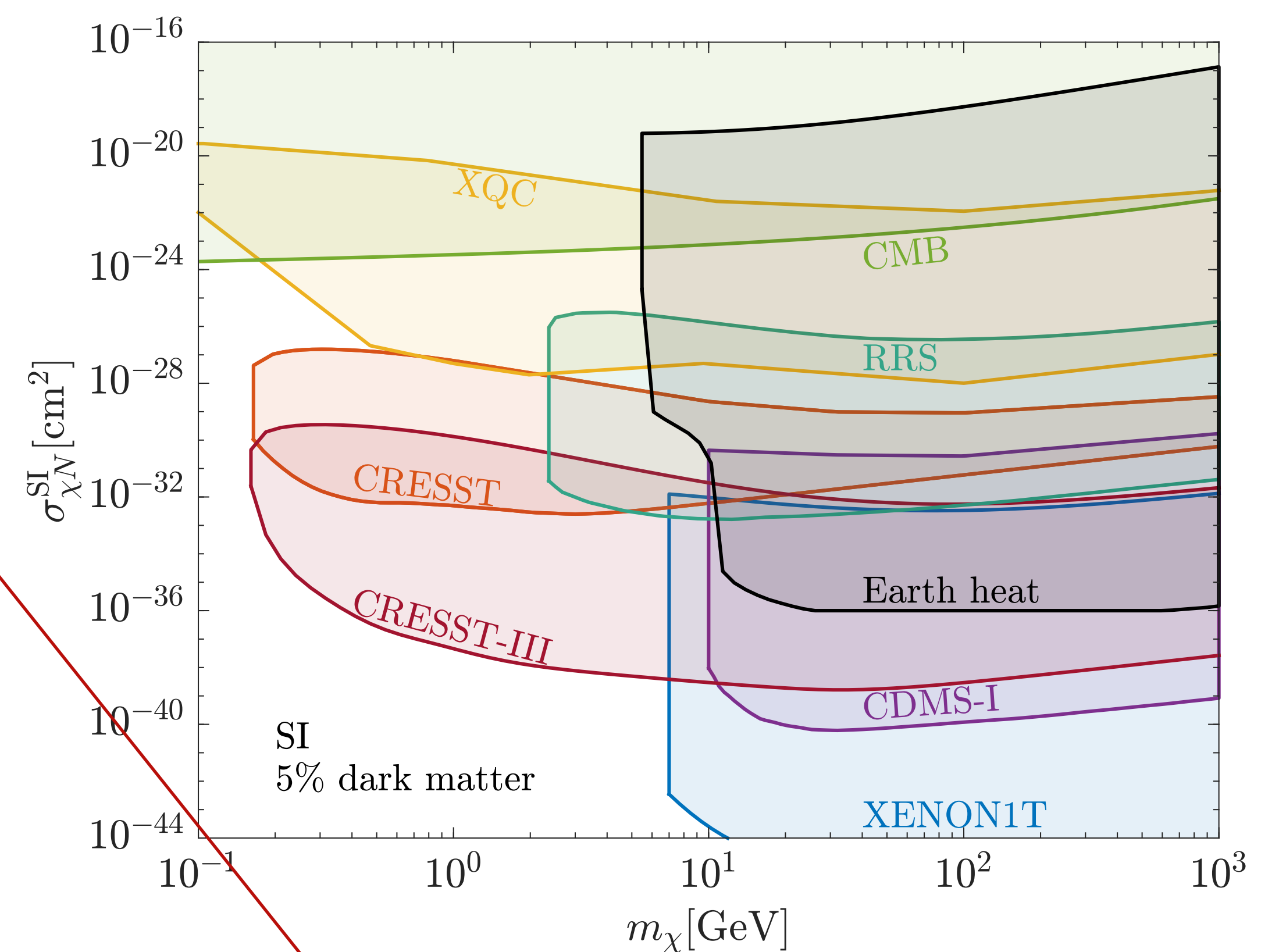


Dark matter mass

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

DM Heating  $\leq 44$  TW

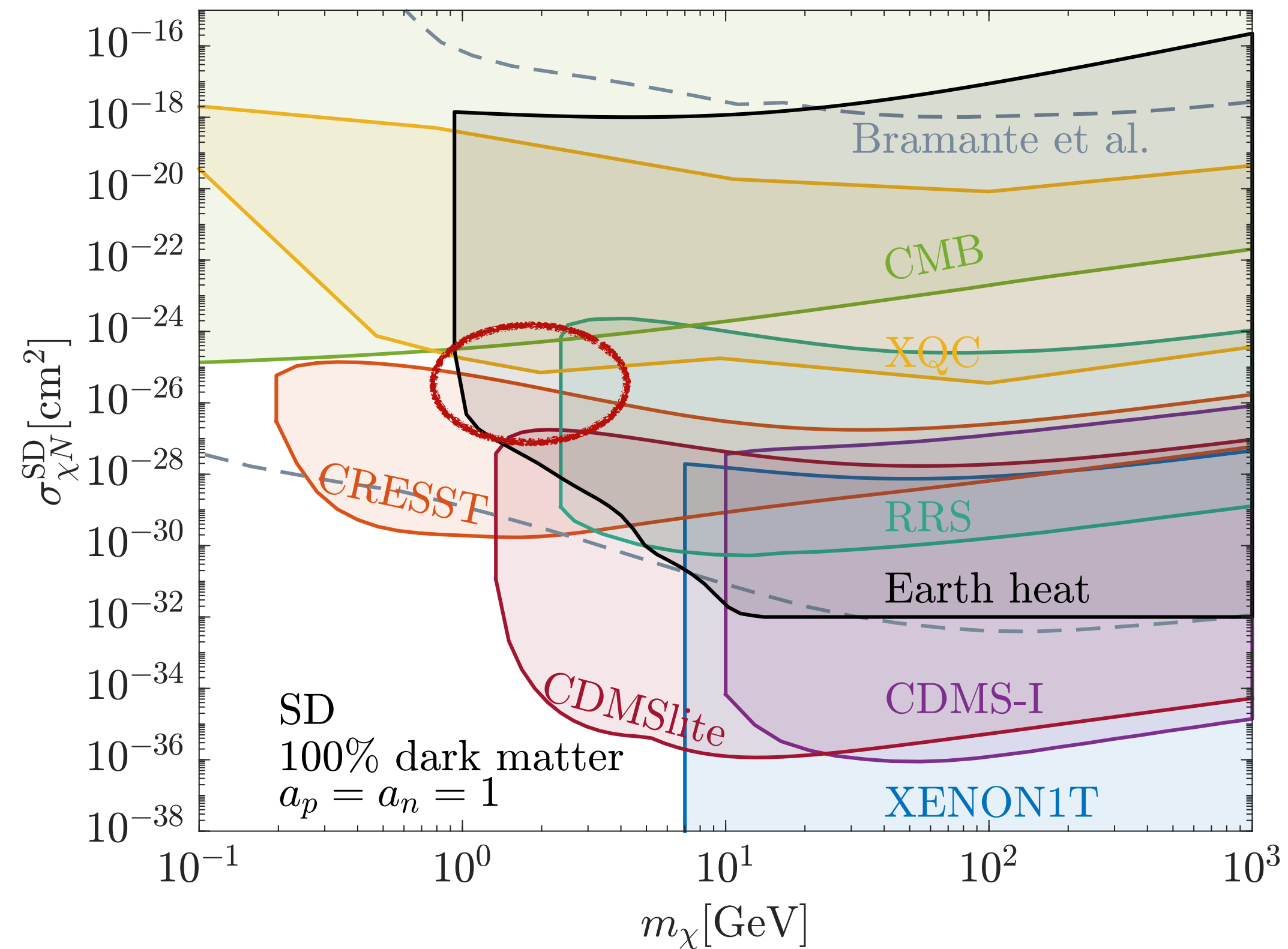
Spin-Independent 5%



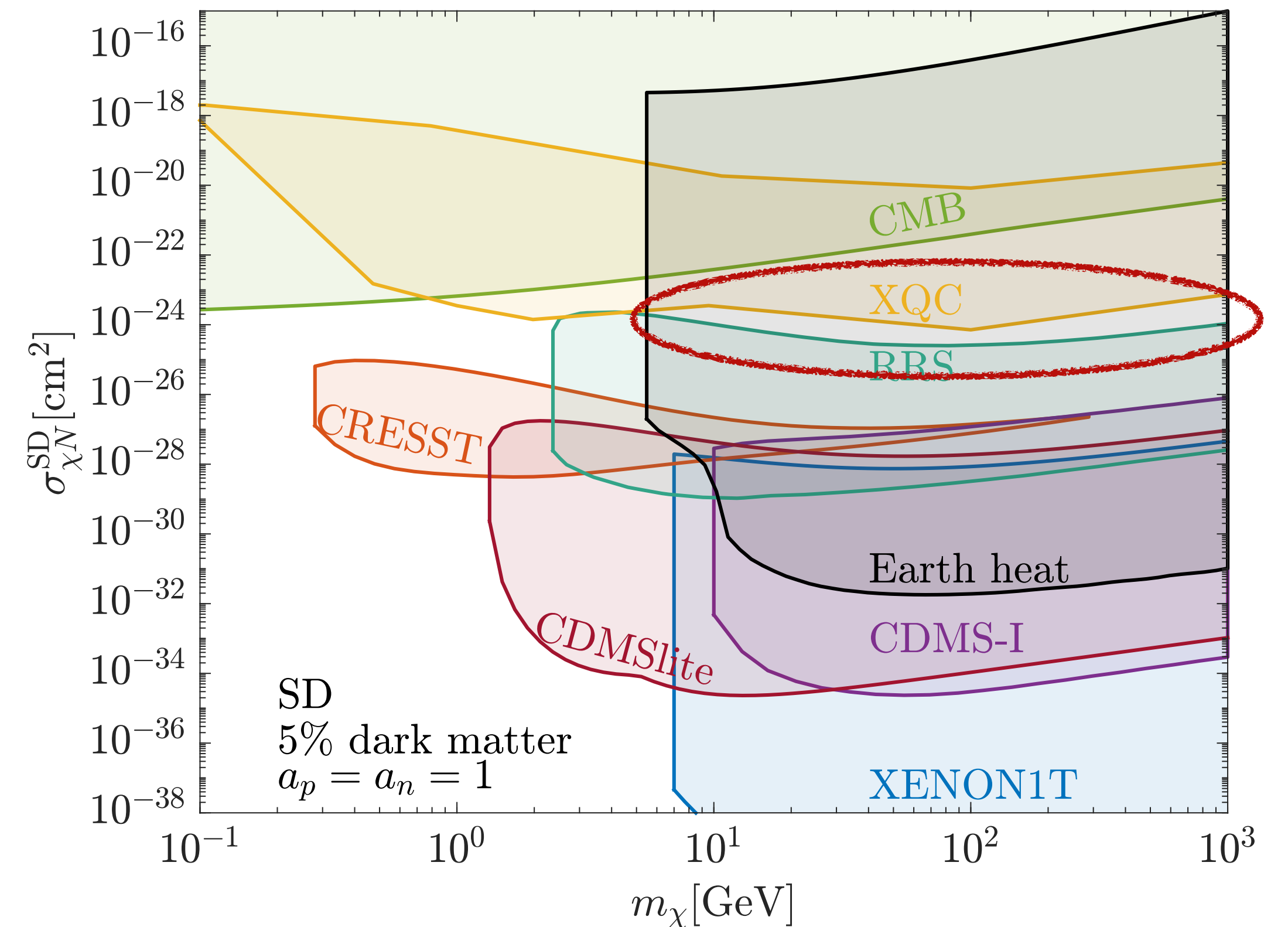
Less than 10% DM annihilation  
when drifting down to Earth crust

# Heating Constraints - Spin-Dependent

Spin-Dependent 100%



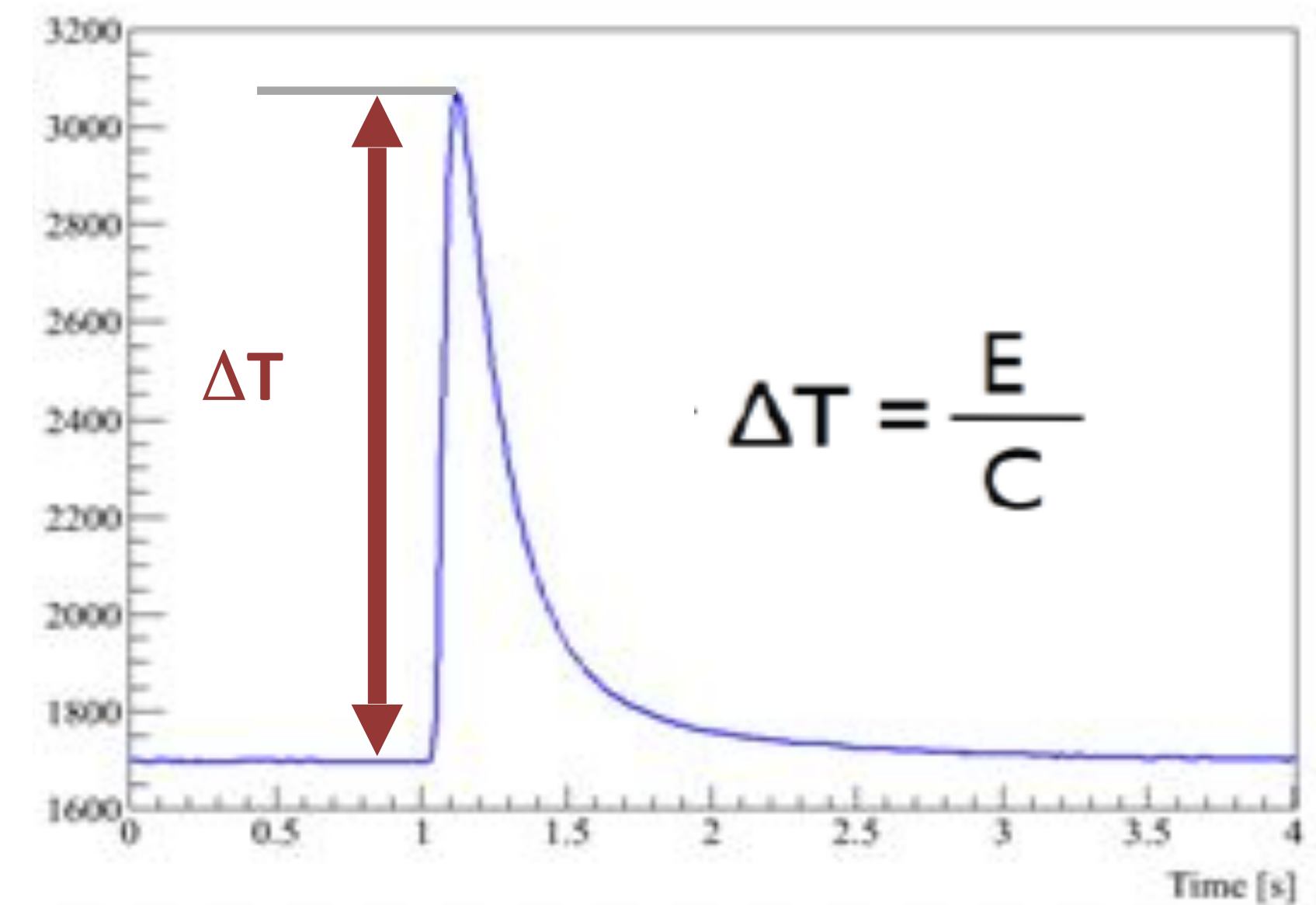
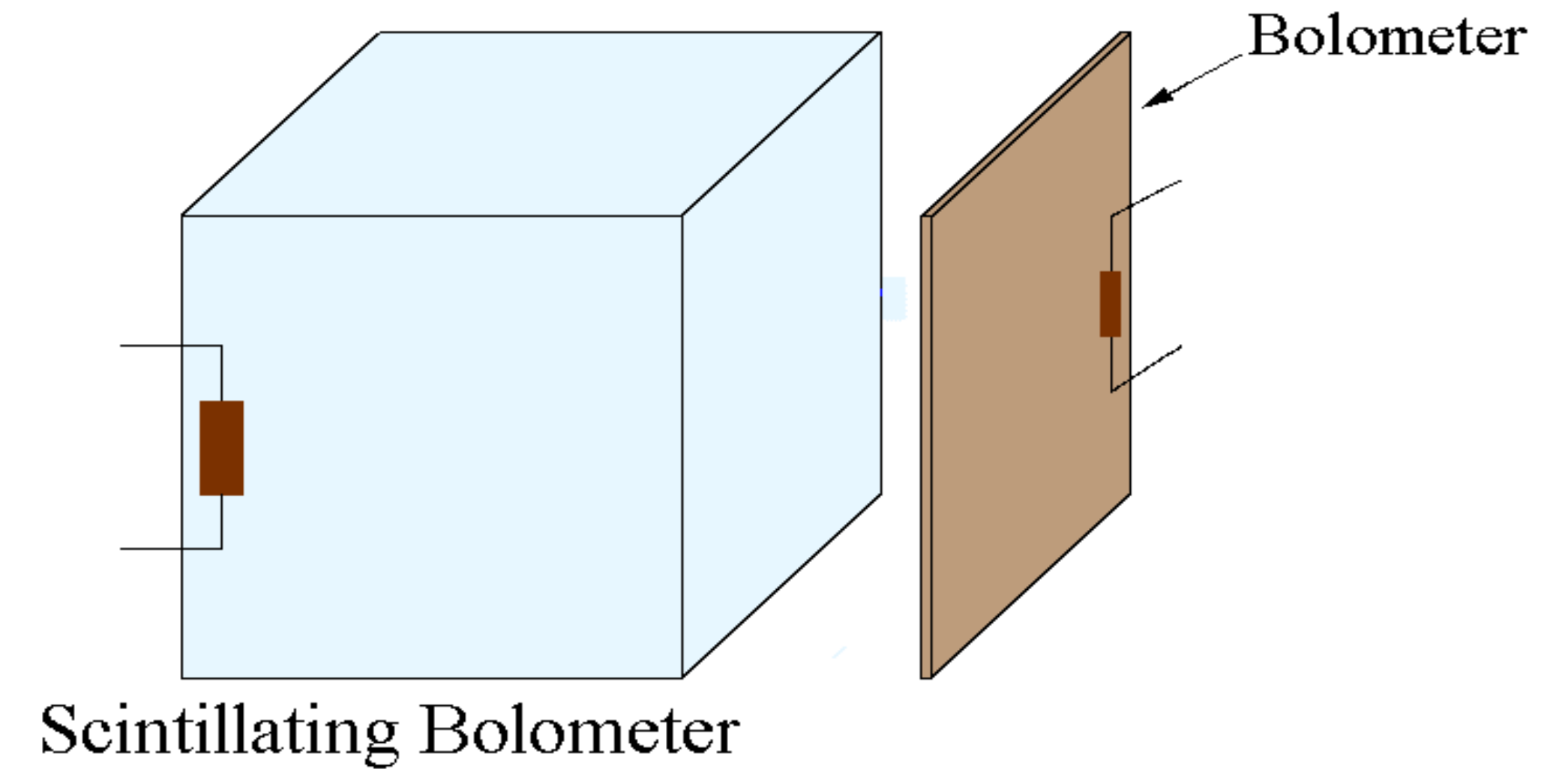
Spin-Dependent 5%



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

# Scintillating Bolometers

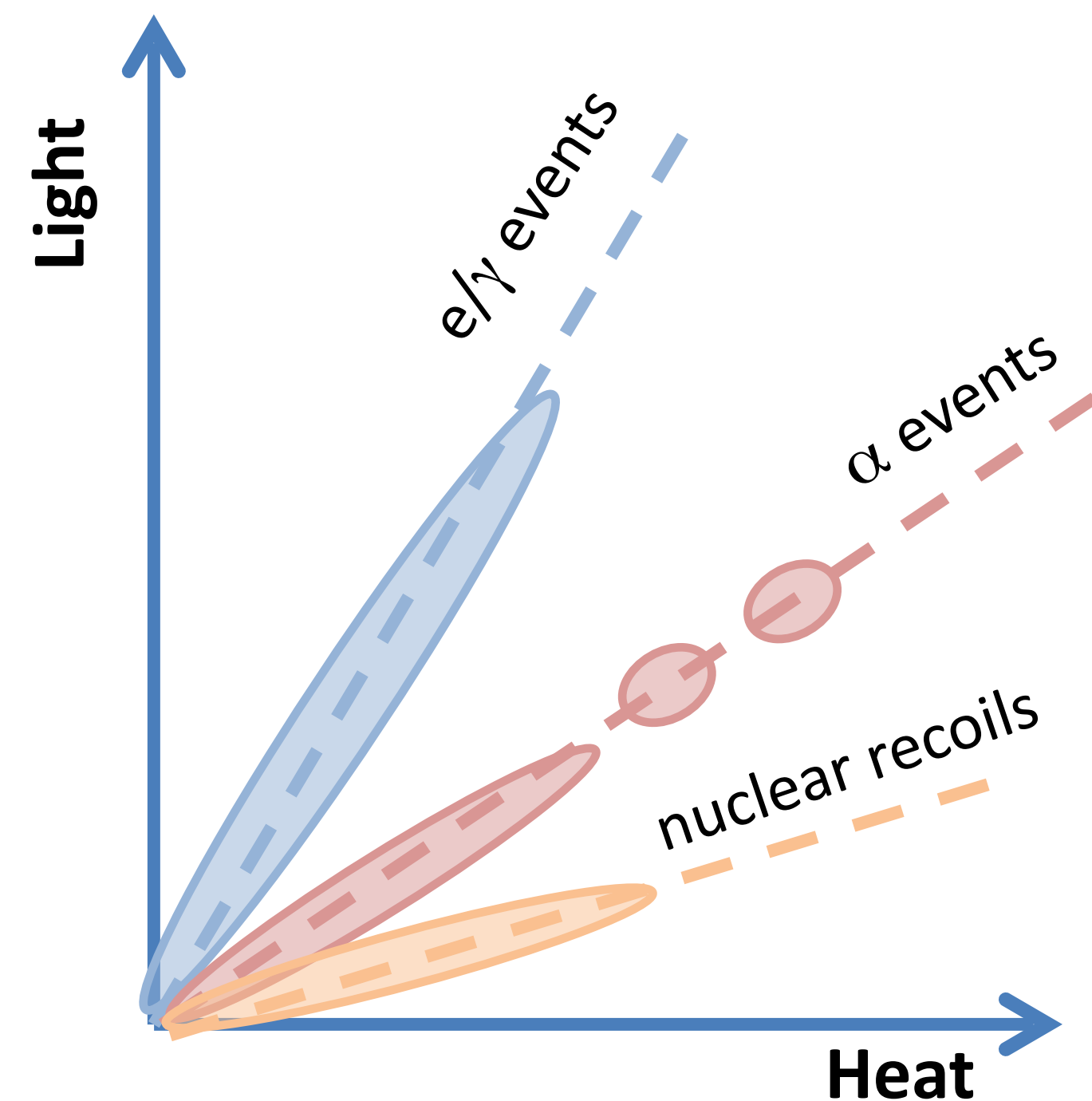
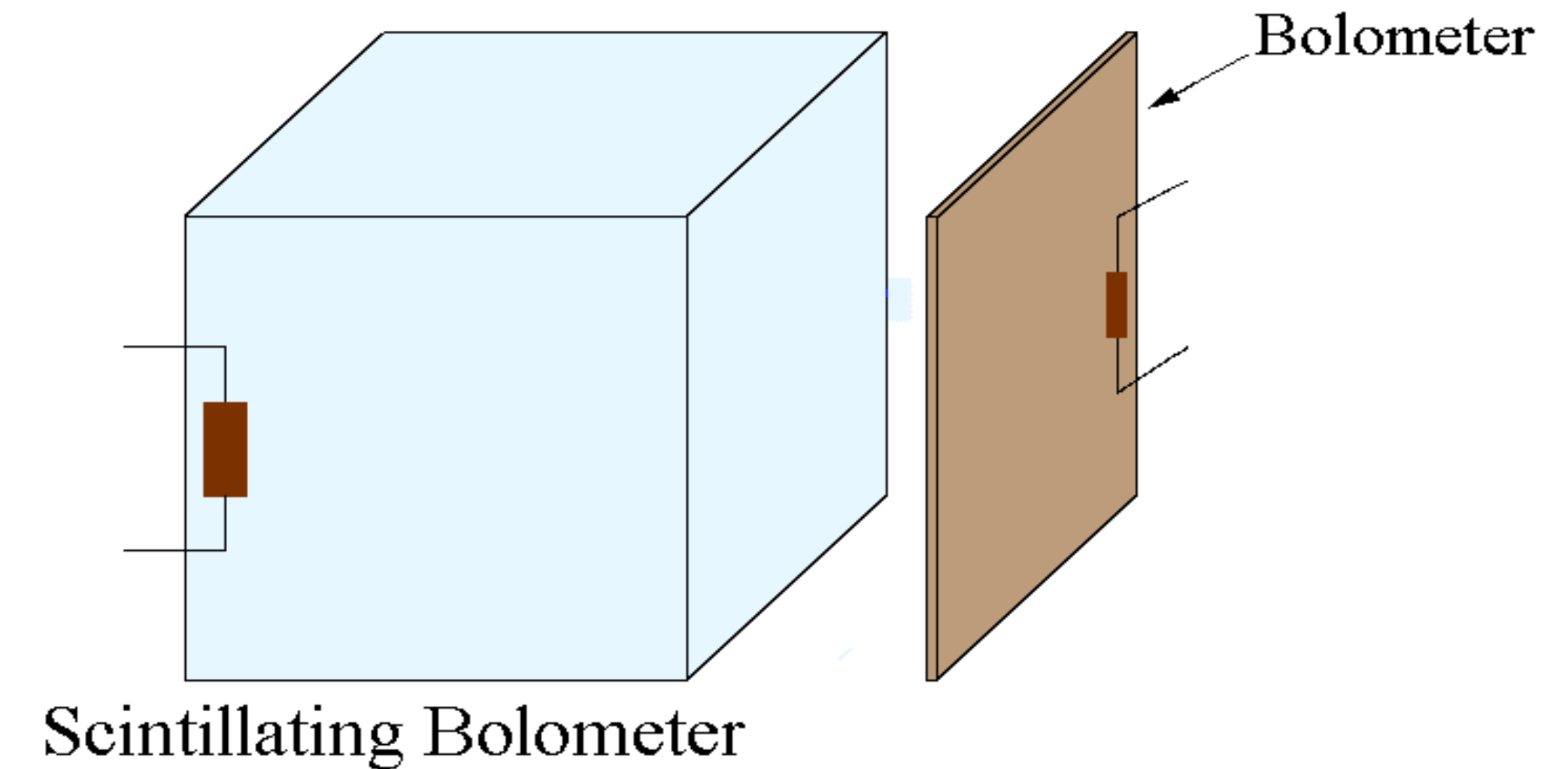
- Simultaneous double readout of **heat (H)** and **scintillation light (L)**





# Scintillating Bolometers

- Simultaneous double readout of **heat (H)** and **scintillation light (L)**
- Fraction of the deposited energy is converted into a scintillation (up to 25%)
- effective discrimination of  $e/\gamma$  from  $\alpha$  events/DM by the difference in L/H ratio



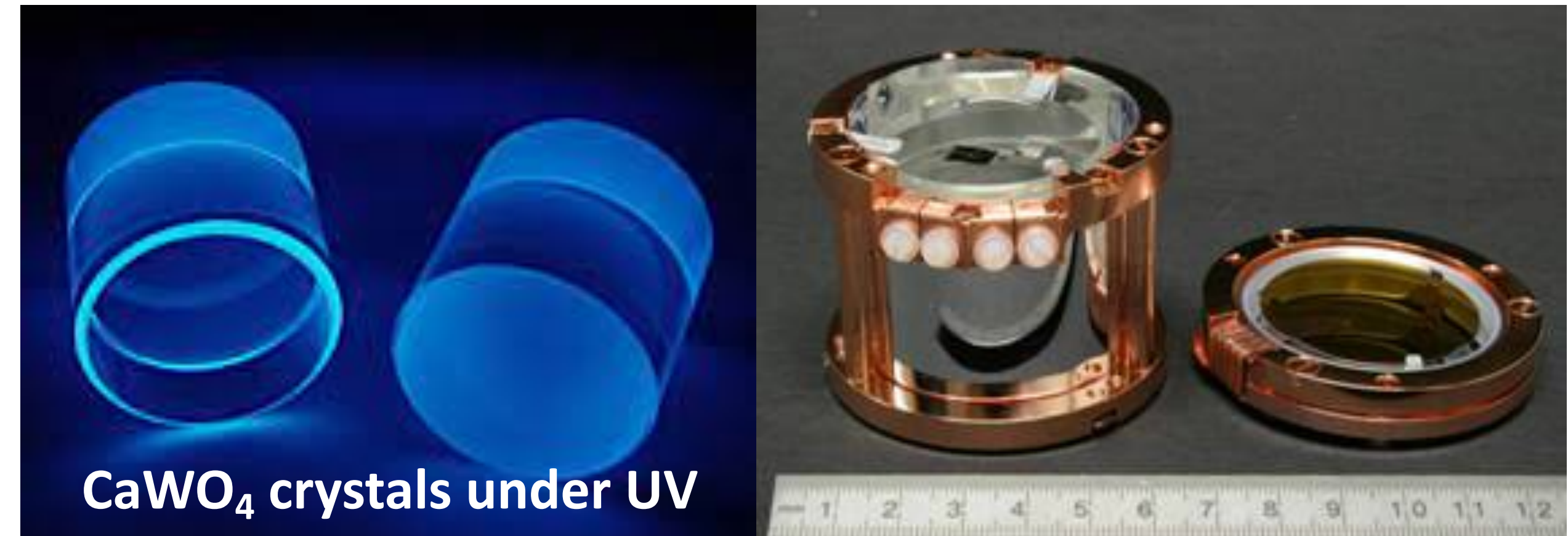
# CaWO<sub>4</sub> Scintillating Bolometer

Detector module with CaWO<sub>4</sub>

300 g

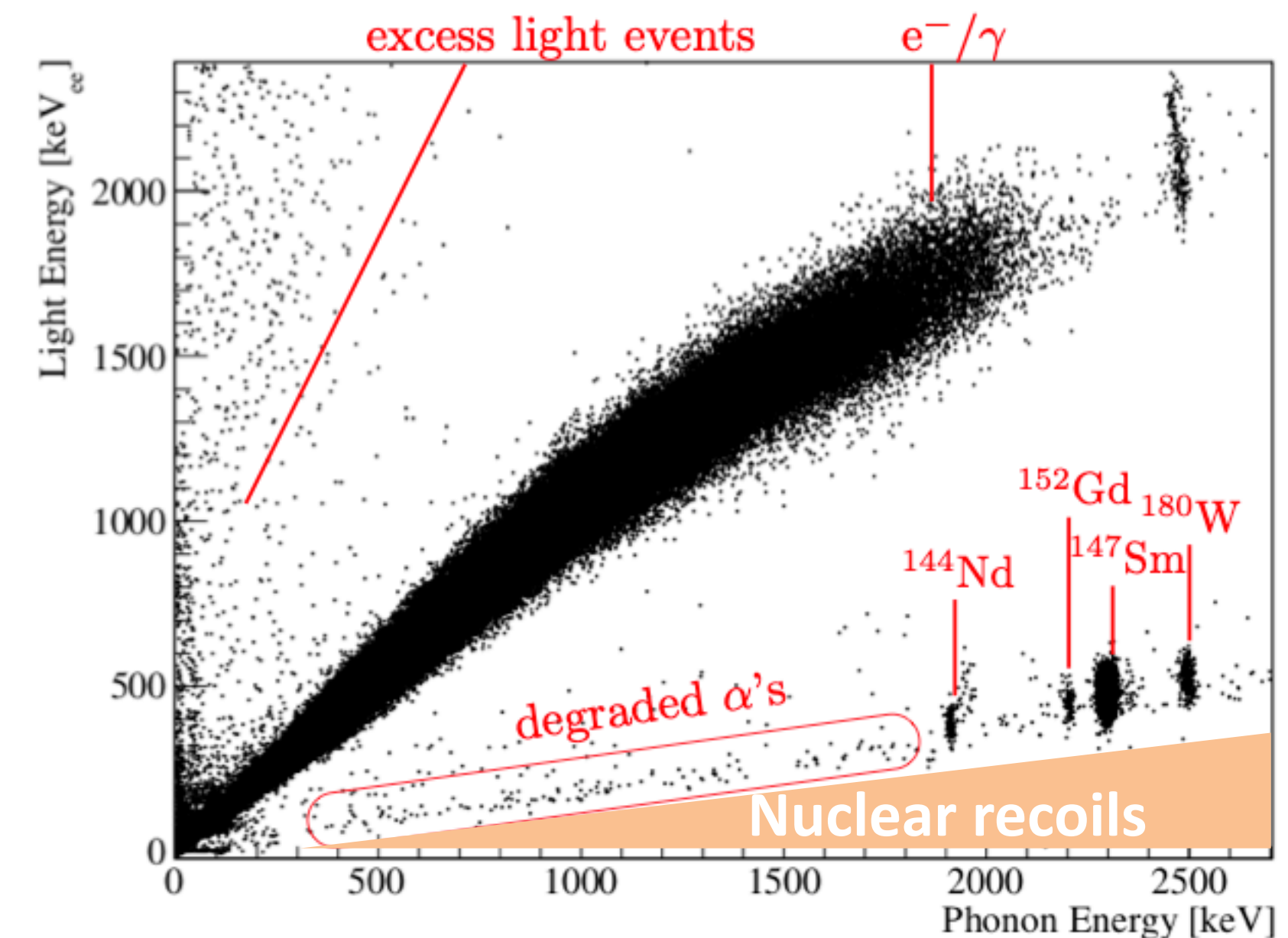
∅40×40 mm<sup>3</sup>

- Simultaneous double readout of **heat (H)** and **scintillation light (L)**
- Fraction of the deposited energy is converted into a scintillation (up to 25%)
- Effective discrimination of e/γ from α events/DM by the difference in L/H ratio



*Credit: CRESST Collaboration*

**90.1 kg·days**



Munster *et al.*, arXiv:1403.5114

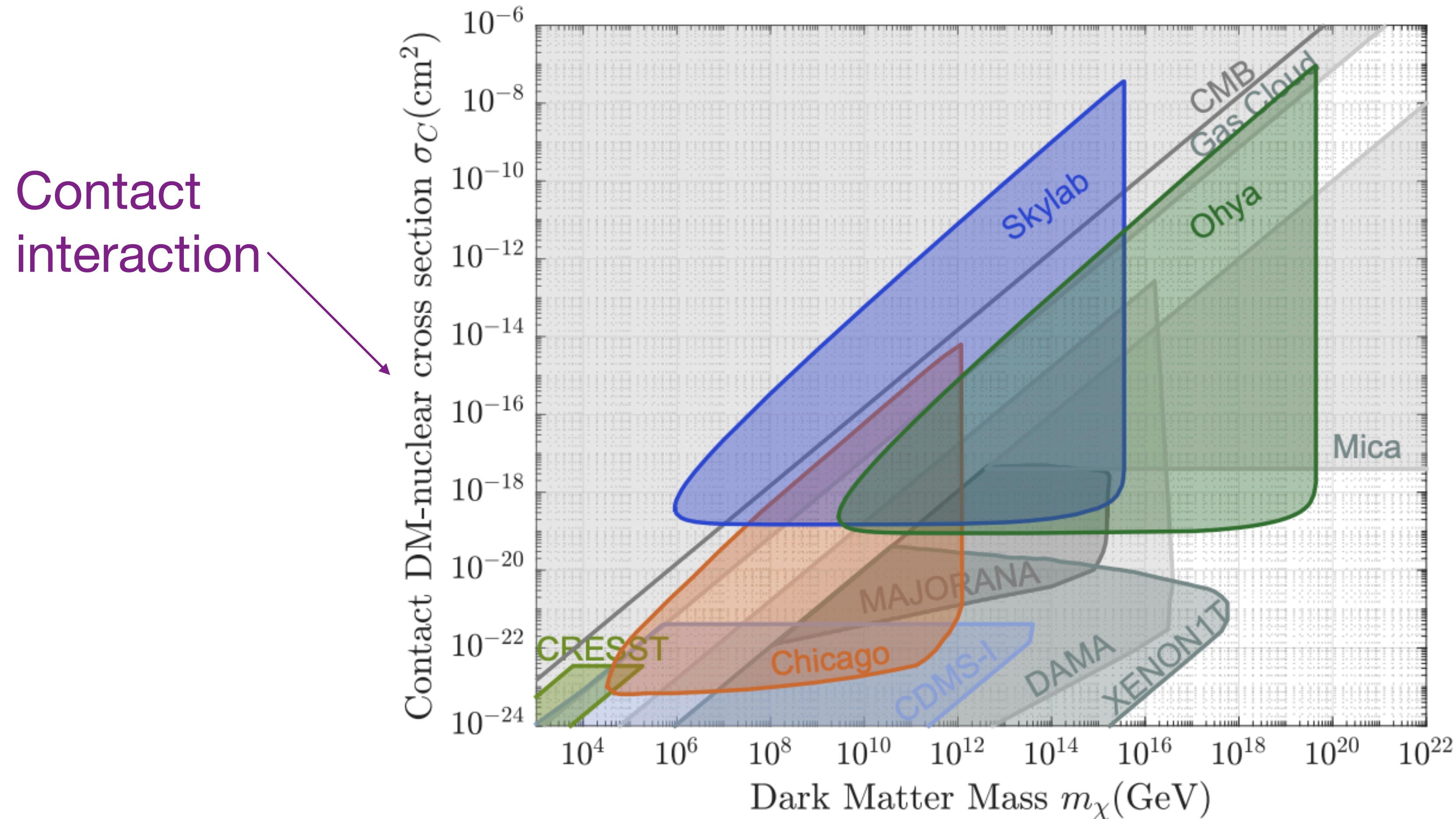
# Skylab and Ohya

|                                 | Skylab                                    | Ohya                                     |
|---------------------------------|-------------------------------------------|------------------------------------------|
| Area A                          | $1.17 \text{ m}^2$                        | $2442 \text{ m}^2$                       |
| Duration t                      | 0.70 yr                                   | 2.1 yr                                   |
| Zenith cutoff angle             | $\theta_D = 60^\circ$                     | $\theta_D = 18.4^\circ$                  |
| Detector material               | 0.25 mm thick Lexan<br>$\times 32$ sheets | 1.59 mm thick CR-39<br>$\times 4$ sheets |
| Detector density                | $1.2 \text{ g cm}^{-3}$ Lexan             | $1.3 \text{ g cm}^{-3}$ CR-39            |
| Detector length at $\theta_D$   | 1.6 cm                                    | 0.66 cm                                  |
| Overburden density              | $2.7 \text{ g cm}^{-3}$ Aluminum          | $2.7 \text{ g cm}^{-3}$ Rock             |
| Overburden length at $\theta_D$ | 0.74 cm                                   | 39 m                                     |



# Constraints on Multiple Scattering Dark Matter

$$\left. \frac{dE}{dx} \right|_{th} = \frac{2E_i}{m_\chi} \left( \sum_{A \subset D} \frac{\mu_{\chi A}^2}{m_A} n_A \sigma_{\chi A} \right) \exp \left[ \frac{-2}{m_\chi} \left( x_O \sum_{A \subset O} n_A \frac{\mu_{\chi A}^2}{m_A} \sigma_{\chi A} + x_D \sum_{A \subset D} n_A \frac{\mu_{\chi A}^2}{m_A} \sigma_{\chi A} \right) \right]$$



Bhoonah, Bramante, Courtman, **NS**, PRD/2012.13406

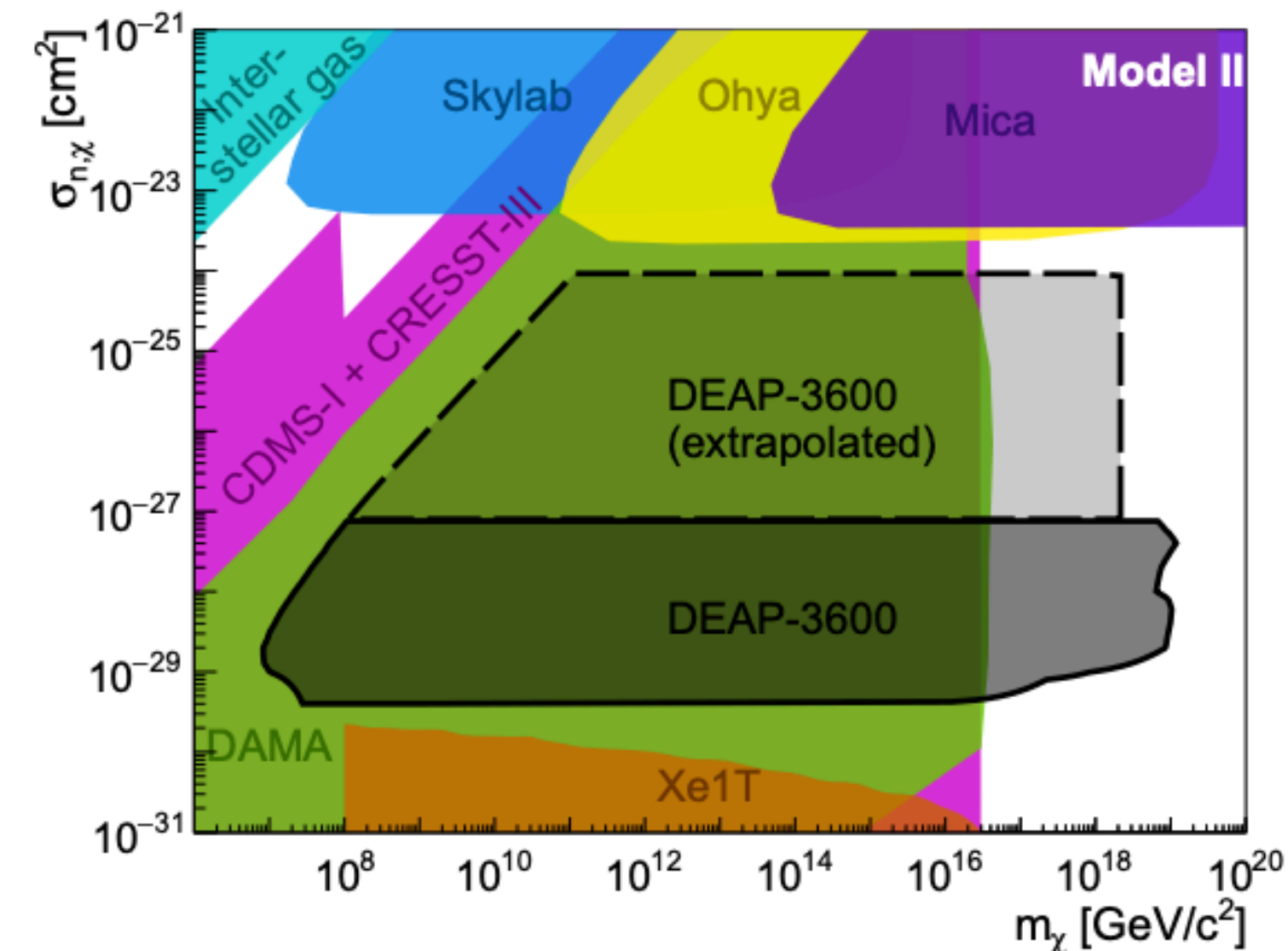
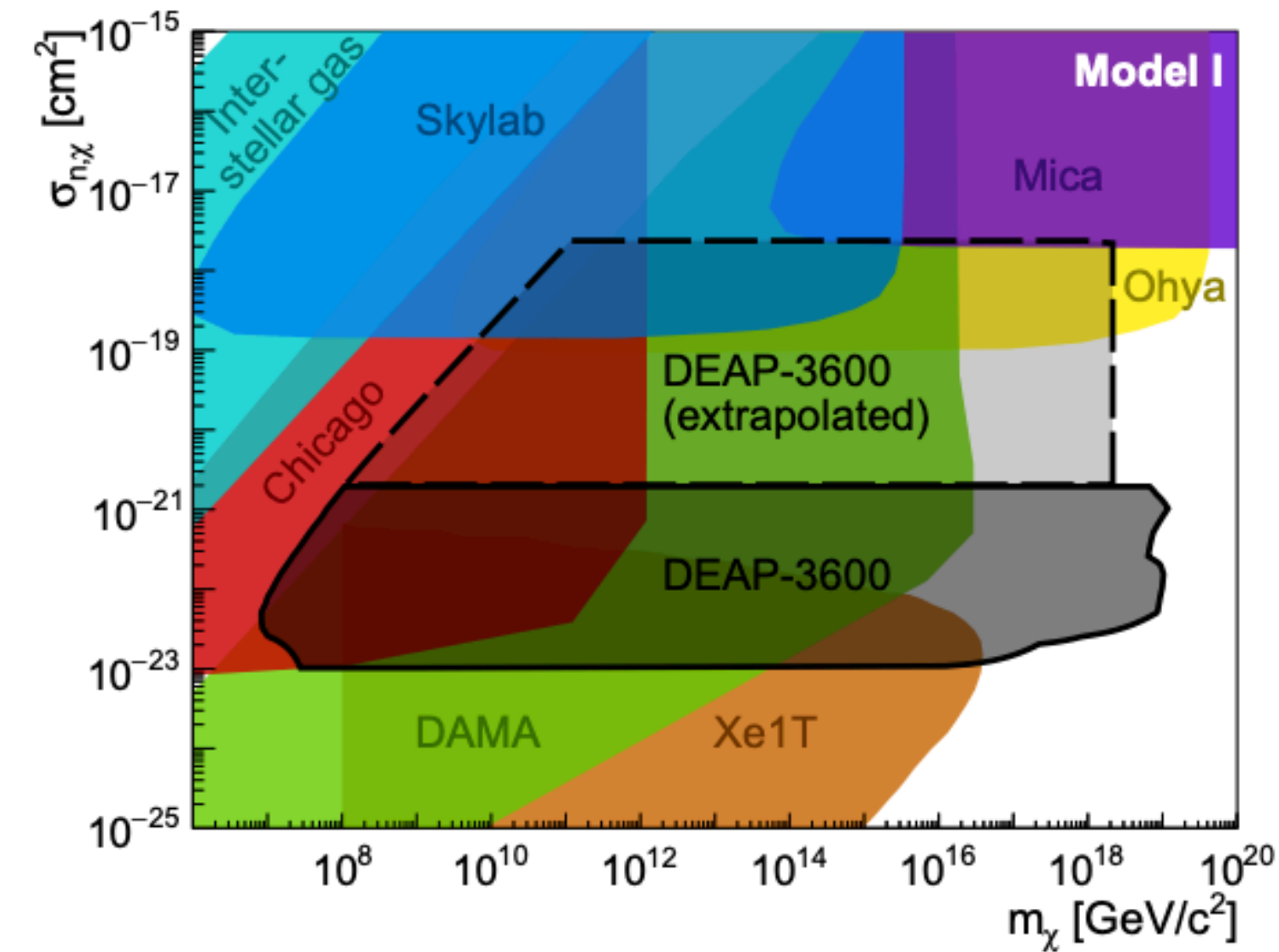
# Multiple Scatter Dark Matter

$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R} |F_T(q)|^2$$

$$\begin{aligned} \frac{d\sigma_{T\chi}}{dE_R} &= \frac{d\sigma_{n\chi}}{dE_R} \left( \frac{\mu_{T\chi}}{\mu_{n\chi}} \right)^2 A^2 |F_T(q)|^2 \\ &\simeq \frac{d\sigma_{n\chi}}{dE_R} A^4 |F_T(q)|^2, \end{aligned}$$

Dark matter may even scatter multiple times in the detector!

DEAP collaboration, arXiv:2108.09405



# Isospin-violating Dark Matter

Isospin-independent interaction

$$\sigma_j \simeq \frac{\mu_{A_j}^2}{\mu_N^2} A^2 \sigma_0$$

Isospin-violating interaction

$$\sigma_j \simeq \frac{\mu_{A_j}^2}{\mu_N^2} f_{\text{IV}}^2 \sigma_0$$

$$f_{\text{IV}} \equiv f_p Z_j + f_n (A_j - Z_j)$$



# Reduced Detector Response

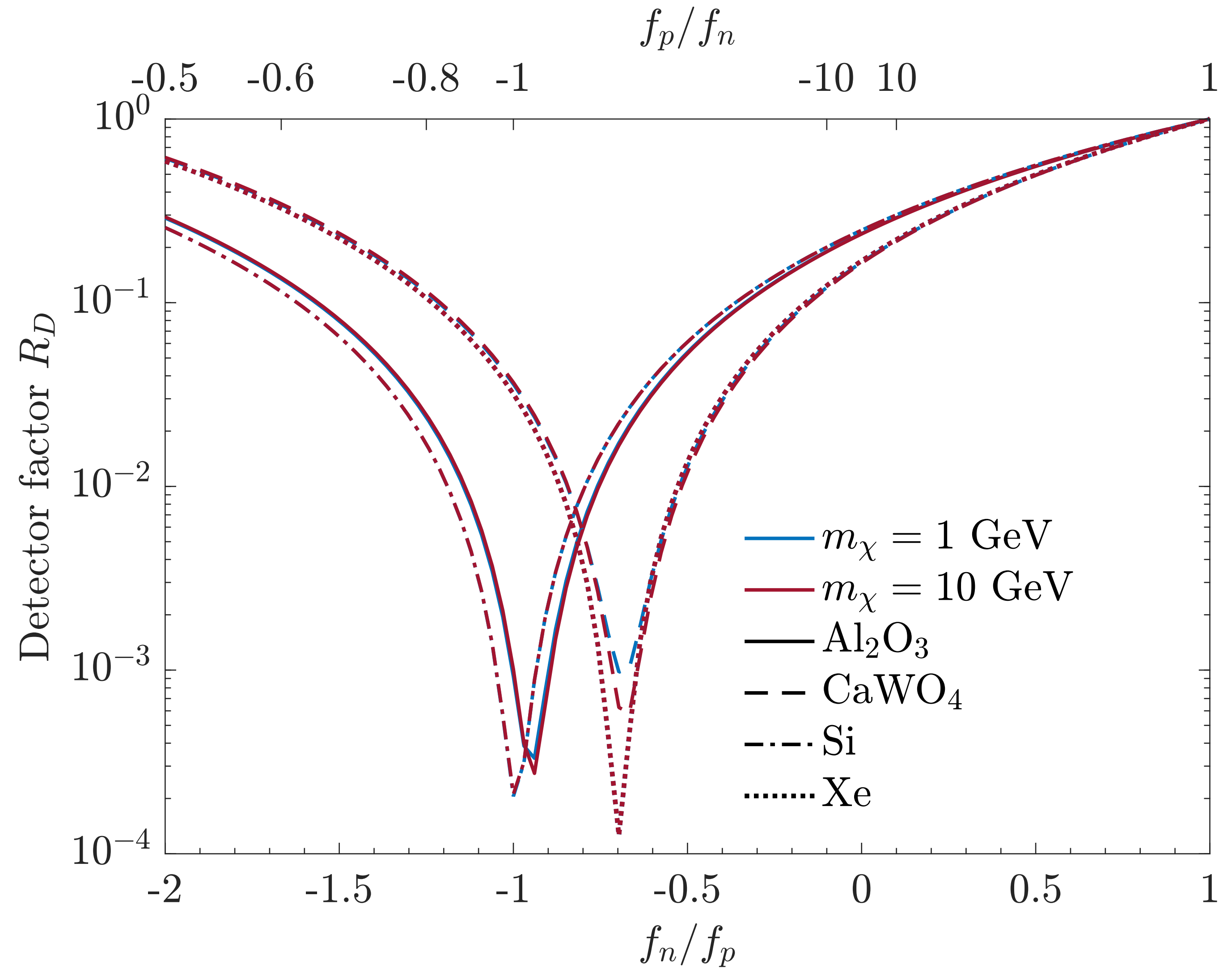
SI

$$\sigma_j \simeq \frac{\mu_{A_j}^2}{\mu_N^2} A^2 \sigma_0$$

IVDM

$$\sigma_j \simeq \frac{\mu_{A_j}^2}{\mu_N^2} f_{\text{IV}}^2 \sigma_0$$

$$R_\sigma = \frac{\sum_j N_j \mu_{A_j}^2 f_{\text{IV}}^2}{\sum_j N_j \mu_{A_j}^2 A_j^2}$$



# Reduced Overburden

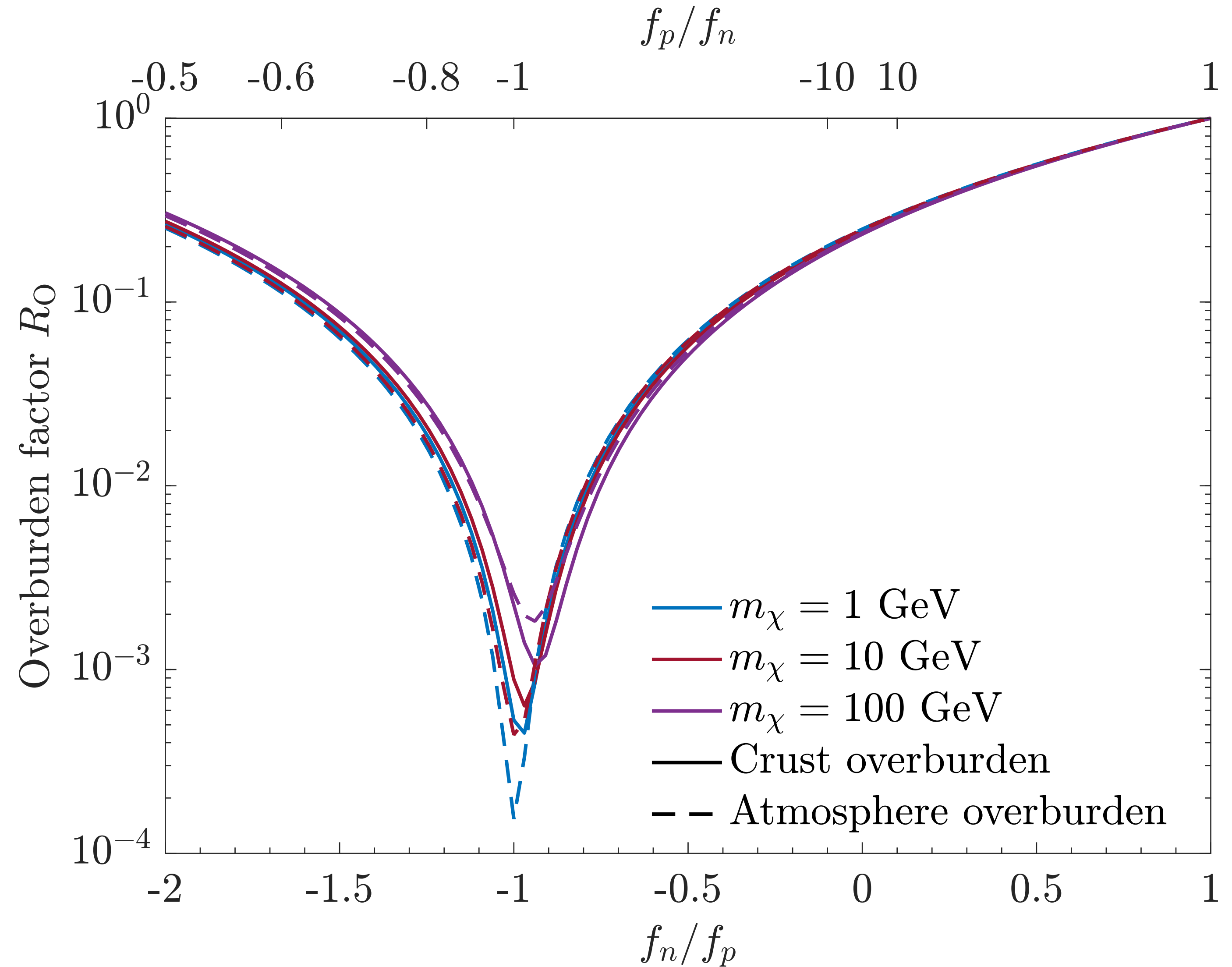
SI

$$\sigma_j \simeq \frac{\mu_{A_j}^2}{\mu_N^2} A^2 \sigma_0$$

IVDM

$$\sigma_j \simeq \frac{\mu_{A_j}^2}{\mu_N^2} f_{\text{IV}}^2 \sigma_0$$

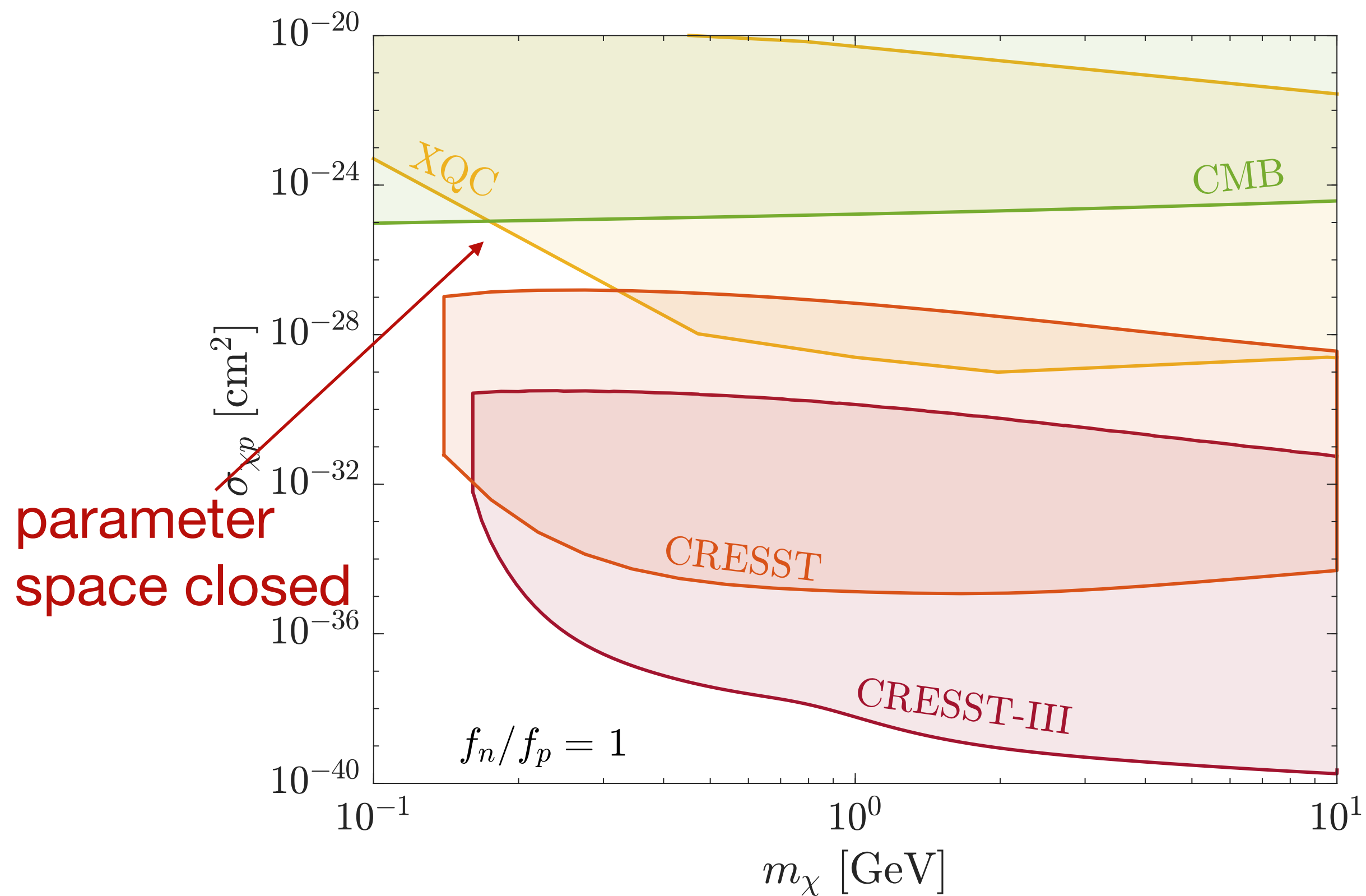
$$R_{\text{OF}} = \frac{\sum_j n_j \mu_{A_j}^4 f_{\text{IV}}^2 / m_{A_j}}{\sum_j n_j \mu_{A_j}^4 A_j^2 / m_{A_j}}$$



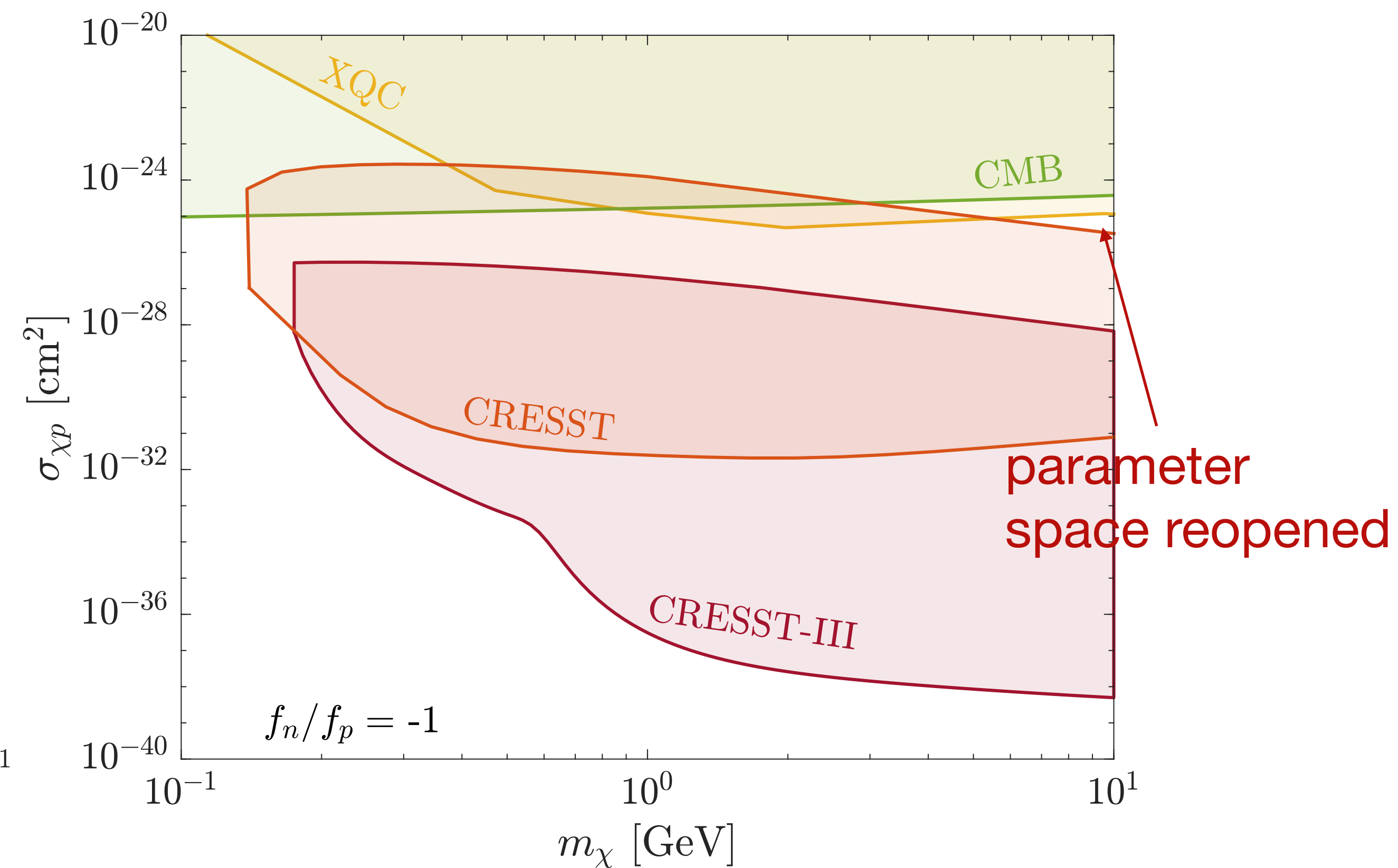
# Constraints on Isospin-violating Dark Matter

## Coupling to protons

### Isospin conserving

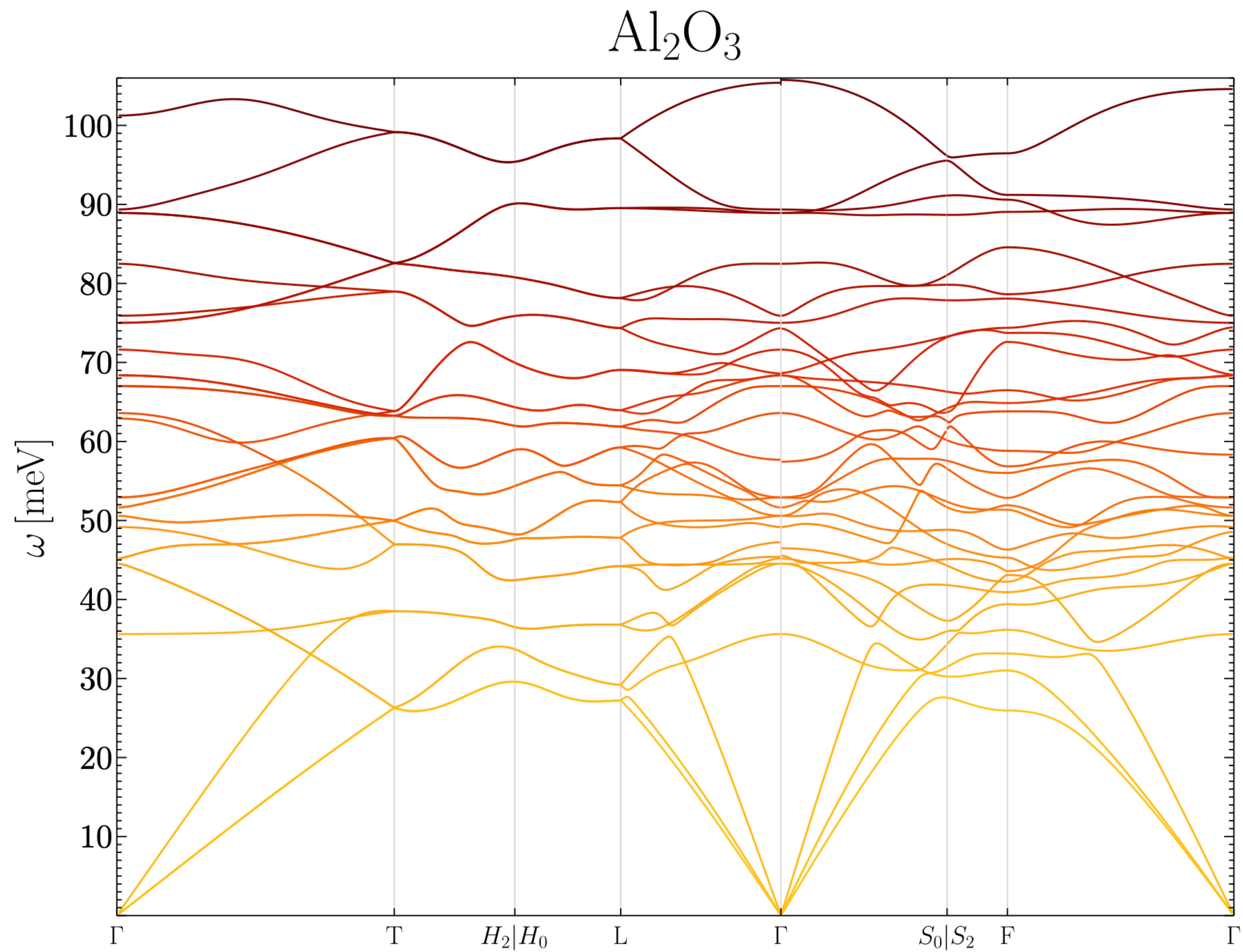


### Isospin violating





# Phonon Structure of Sapphire



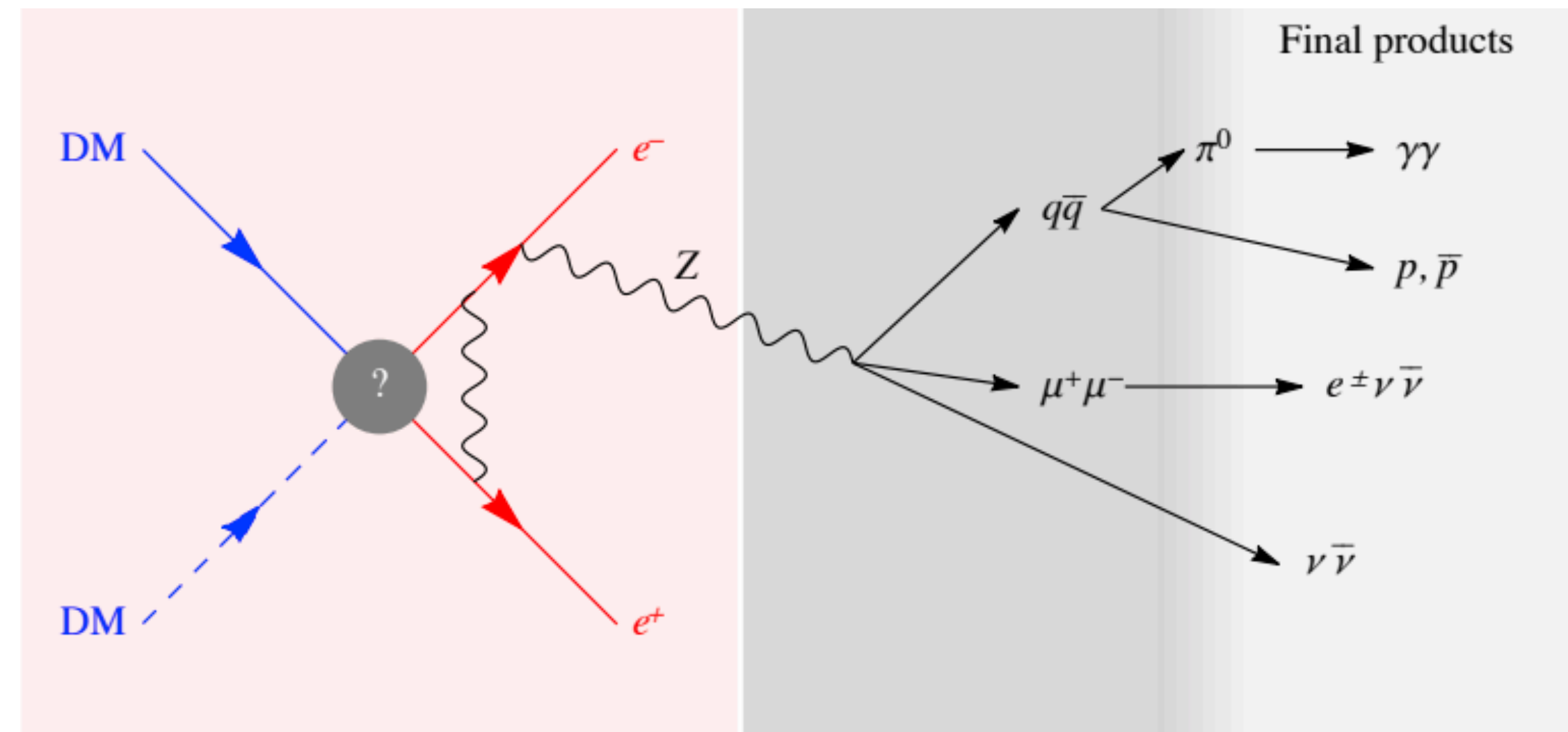
# Indirect Detection

# The Gamma Signal

$$\frac{dN_\gamma}{dEdtdV} = \left( \frac{dN_\gamma}{dE} \right)_0 \frac{A}{4\pi r^2} \times \left\{ \frac{\frac{1}{2} \langle \sigma v_{\text{rel}} \rangle n(\vec{r})^2}{\frac{n(\vec{r})}{\tau}} \right. \quad \begin{array}{l} \text{annihilation} \\ \text{decay} \end{array}$$

detector area

dark matter properties



See e.g. Tracy Slatyer, arXiv: 1710.05137



# The Gamma Signal

$$\frac{dN_\gamma}{dE dt d\Omega} = \frac{A}{4\pi} \left( \frac{dN_\gamma}{dE} \right)_0 \times \begin{cases} \frac{\langle \sigma v_{\text{rel}} \rangle}{2m_{\text{DM}}^2} \int_0^\infty \rho(\vec{r})^2 dr & \text{annihilation} \\ \frac{1}{m_{\text{DM}} \tau} \int_0^\infty dr \rho(\vec{r}) & \text{decay} \end{cases}$$

**Integrate along the line of sight**

# The Gamma Signal

$$\frac{dN_\gamma}{dE dt} = \frac{A}{4\pi} \left( \frac{dN_\gamma}{dE} \right)_0 \times \begin{cases} \frac{\langle \sigma v_{\text{rel}} \rangle}{2m_{\text{DM}}^2} \int dr d\Omega \rho(\vec{r})^2 & \text{annihilation} \\ \frac{1}{m_{\text{DM}} \tau} \int_0^\infty dr d\Omega \rho(\vec{r}) & \text{decay} \end{cases}$$

Integrate over the solid angle

# The Gamma Signal

$$\frac{1}{A} \frac{dN_\gamma}{dE dt} = \frac{\langle \sigma v_{\text{rel}} \rangle}{m_{\text{DM}}^2} \left( \frac{dN_\gamma}{dE} \right)_0 J_{\text{ann}}$$

only particle physics

only dark matter distribution

$$J_{\text{ann}} \equiv \frac{1}{8\pi} \int dr d\Omega \rho(\vec{r})^2,$$



# The Extragalactic Gamma Signal

$$\frac{dN}{dEdV_0} = \int_{\infty}^0 dz \frac{dt}{dz} \frac{dN_{\gamma}(z)}{dE} \frac{\langle \sigma v_{\text{rel}} \rangle}{2} n(z)^2 \frac{dV_z}{dV_0}$$

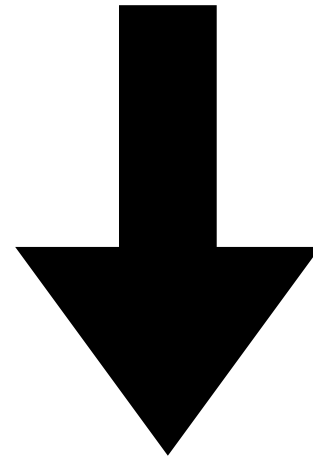
physical volume

comoving volume

The diagram illustrates the relationship between physical and comoving volumes in the equation. An arrow labeled 'physical volume' points from the text to the  $\frac{dV_z}{dV_0}$  term in the equation. Another arrow labeled 'comoving volume' points from the text to the  $\frac{dV_z}{dV_0}$  term. The equation itself is centered on the slide.

# The Extragalactic Gamma Signal

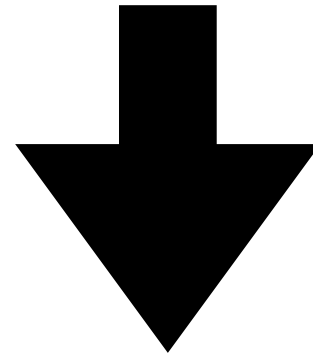
$$\frac{dN}{dEdV_0} = \int_{-\infty}^0 dz \frac{dt}{dz} \frac{dN_{\gamma}(z)}{dE} \frac{\langle \sigma v_{\text{rel}} \rangle}{2} n(z)^2 \frac{dV_z}{dV_0}$$



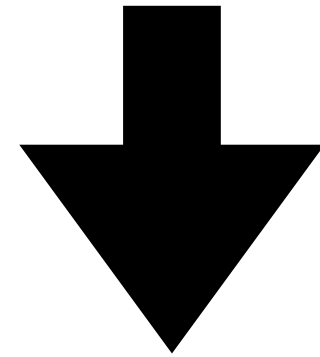
$$\frac{dN}{dEdV_0} = \int_0^{\infty} dz \frac{(1+z)^3}{H(z)} \rho(z=0)^2 \left[ \left( \frac{dN_{\gamma}}{dE'} \right)_0 \bigg|_{E'=E(1+z)} \frac{\langle \sigma v_{\text{rel}} \rangle}{2m_{\text{DM}}^2} \right]$$

# The Extragalactic Gamma Signal

$$\frac{dN}{dEdV_0} = \int_{-\infty}^0 dz \frac{dt}{dz} \frac{dN_{\gamma}(z)}{dE} \frac{\langle \sigma v_{\text{rel}} \rangle}{2} n(z)^2 \frac{dV_z}{dV_0}$$



$$\frac{dN}{dEdV_0} = \int_0^{\infty} dz \frac{(1+z)^3}{H(z)} \rho(z=0)^2 \left[ \left( \frac{dN_{\gamma}}{dE'} \right)_0 \bigg|_{E'=E(1+z)} \frac{\langle \sigma v_{\text{rel}} \rangle}{2m_{\text{DM}}^2} \right]$$



$$\frac{dN_{\gamma}}{dEdAdt} = \int \frac{d\Omega}{4\pi} \int dz \left( \frac{dN_{\gamma}}{dE'} \right)_0 \bigg|_{E'=E(1+z)} \frac{1}{H(z)(1+z)^3} \times \begin{cases} \frac{\langle \sigma v_{\text{rel}} \rangle}{2m_{\text{DM}}^2} \rho(z, \theta, \phi)^2 & \text{annihilation} \\ \frac{1}{m_{\text{DM}} \tau} \rho(z, \theta, \phi) & \text{decay} \end{cases}$$

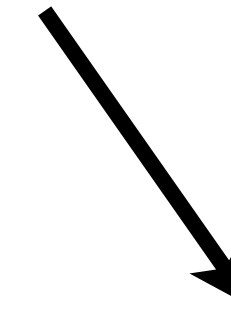


# The Extragalactic Gamma Signal

More rigorously,

$$\frac{d\Phi_{\text{EG}\gamma}(E_\gamma)}{dE_\gamma} = c \frac{1}{E_\gamma} \int_0^\infty dz' \frac{1}{H(z')(1+z')^4} j_{\text{EG}\gamma}(E'_\gamma, z') e^{-\tau(E_\gamma, z')}$$

attenuation

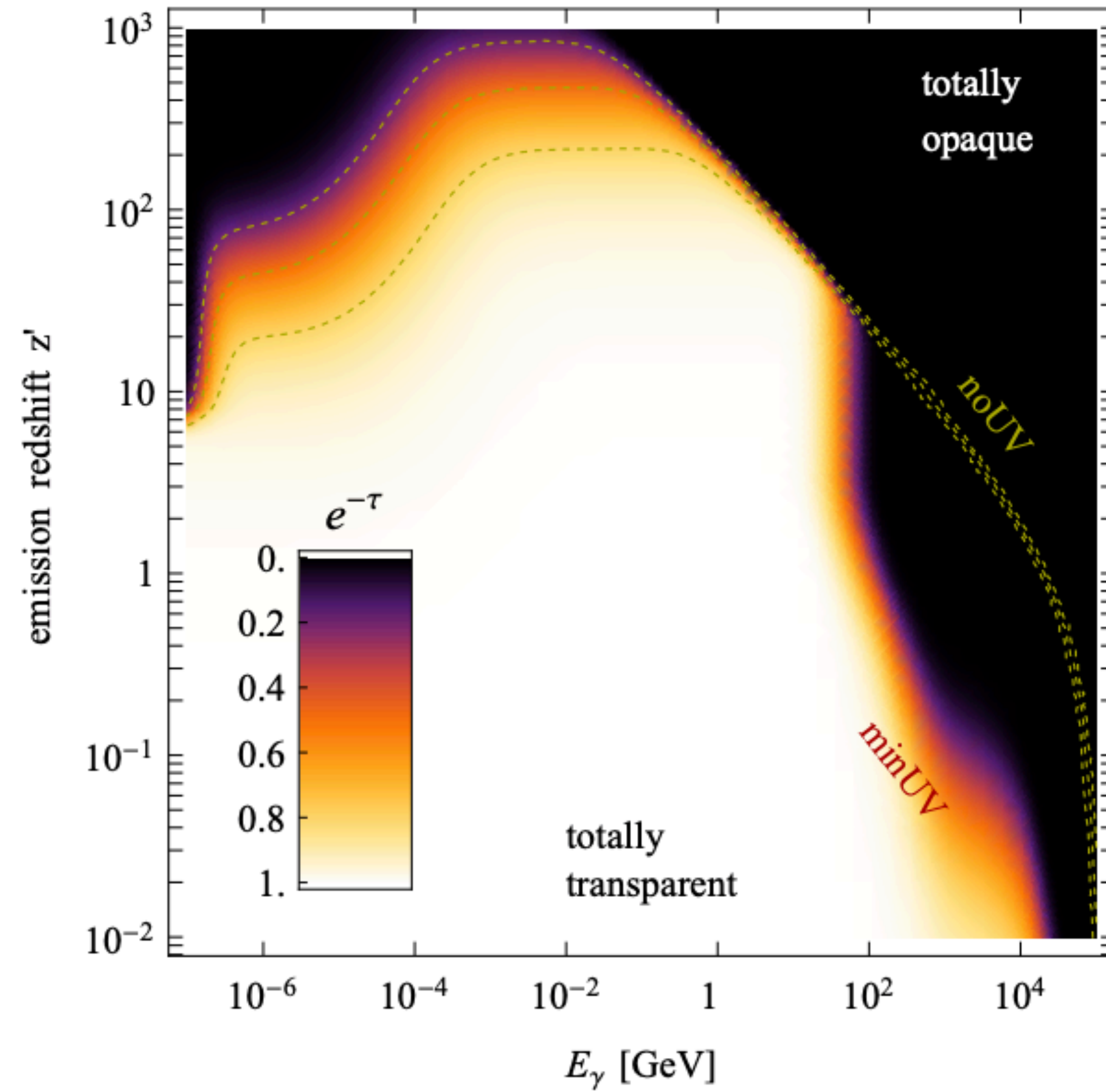
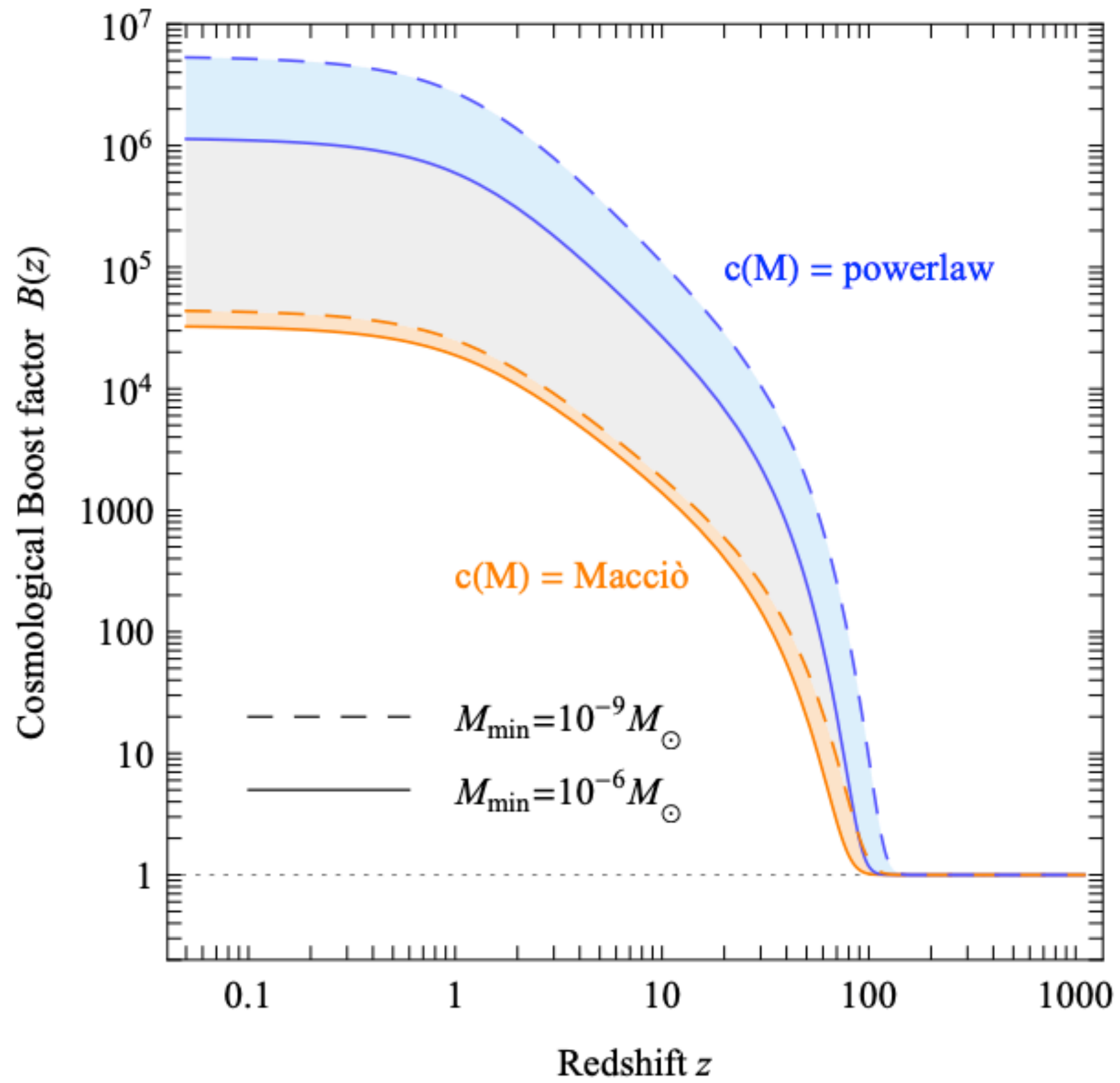


$$j_{\text{EG}\gamma}^{\text{prompt}}(E'_\gamma, z') = E'_\gamma \begin{cases} \frac{1}{2} B(z') \left( \frac{\bar{\rho}(z')}{M_{\text{DM}}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE_\gamma}(E'_\gamma) & \text{(annihilation)} \\ \frac{\bar{\rho}(z')}{M_{\text{DM}}} \sum_f \Gamma_f \frac{dN_\gamma^f}{dE_\gamma}(E'_\gamma) & \text{(decay)} \end{cases}$$

Clustering effect

$$B(z, M_{\text{min}}) = 1 + \frac{\Delta_c}{3\bar{\rho}_{m,0}} \int_{M_{\text{min}}}^\infty dM M \frac{dn}{dM}(M, z) f[c(M, z)]$$

# The Extragalactic Gamma Signal



Cirelli et al, arXiv: 1012.4515

# Constraints from CMB

$$\left. \frac{d^2 E}{dV dt} \right|_{\text{inj}} = \frac{f_{\bullet} f_{\text{e.m.}} \rho_c \Omega_{\text{CDM}} (1+z)^3}{M_i} \frac{dM}{dt}$$

Fraction of BH energy  
injection as  $e^{\pm}$  and  $\gamma$

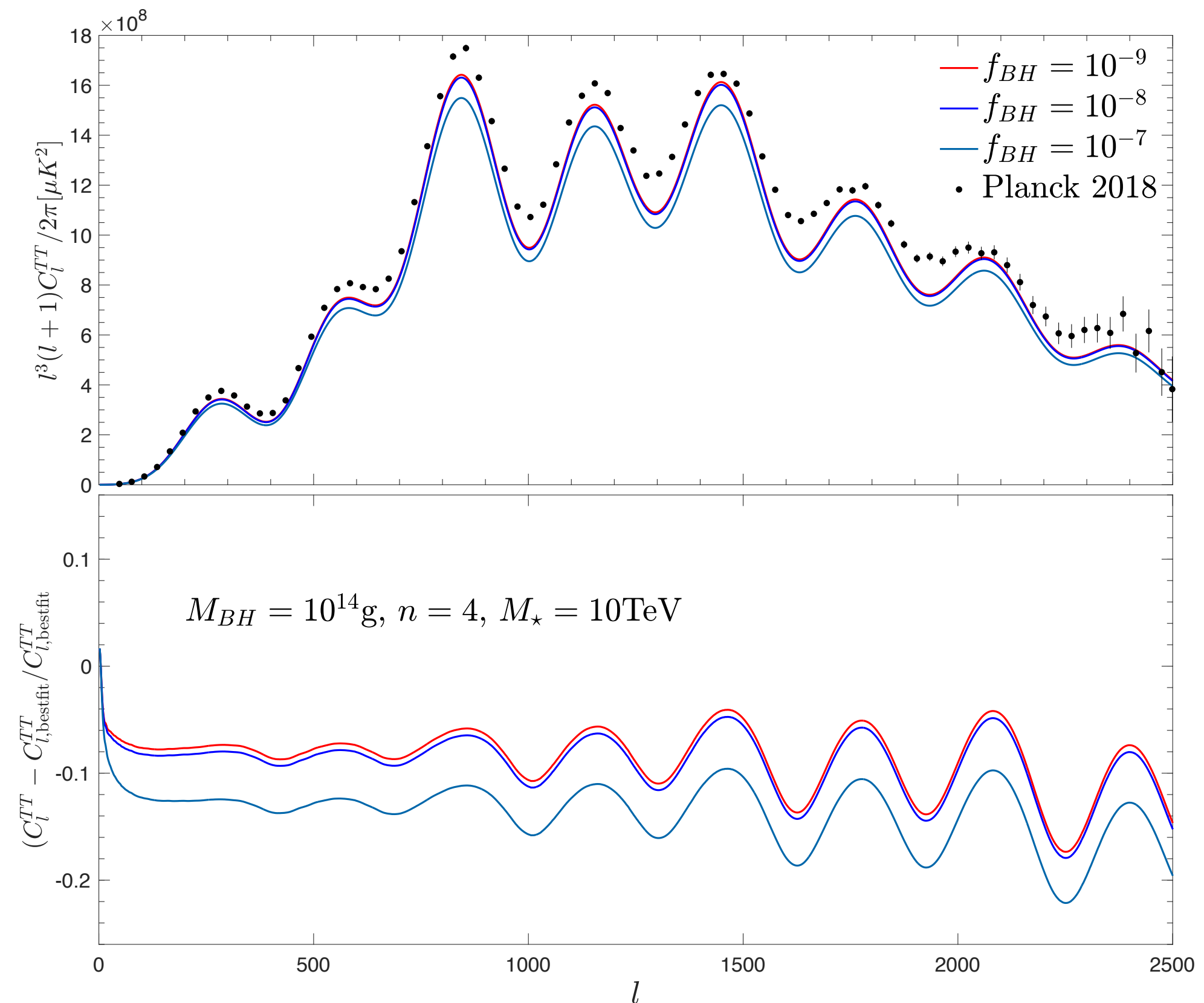
$$\left. \frac{d^2 E}{dV dt} \right|_{\text{dep,c}}(z) = h_c(z) \left. \frac{d^2 E}{dV dt} \right|_{\text{inj}}(z)$$

The injected energy is then deposited at different redshift  $z$ , in the form of ionization, excitation of the Lyman- $\alpha$  transition and heating of the intergalactic medium



# Constraints from CMB

- BH evaporation during and after recombination leads to high energy electrons and photons, which rescatter CMB photons, **suppressing the angular power spectrum on small scales**
- Polarized Thomson scattering **enhances EE power spectrum at lower multipoles**



Planck 2018 high- $l$  TT,TE, EE+low- $l$  TT, EE+Planck lensing

Friedlander, Mack, **NS**, Schon, Vincent, PRD/2201.11761

# Galactic Gamma Ray

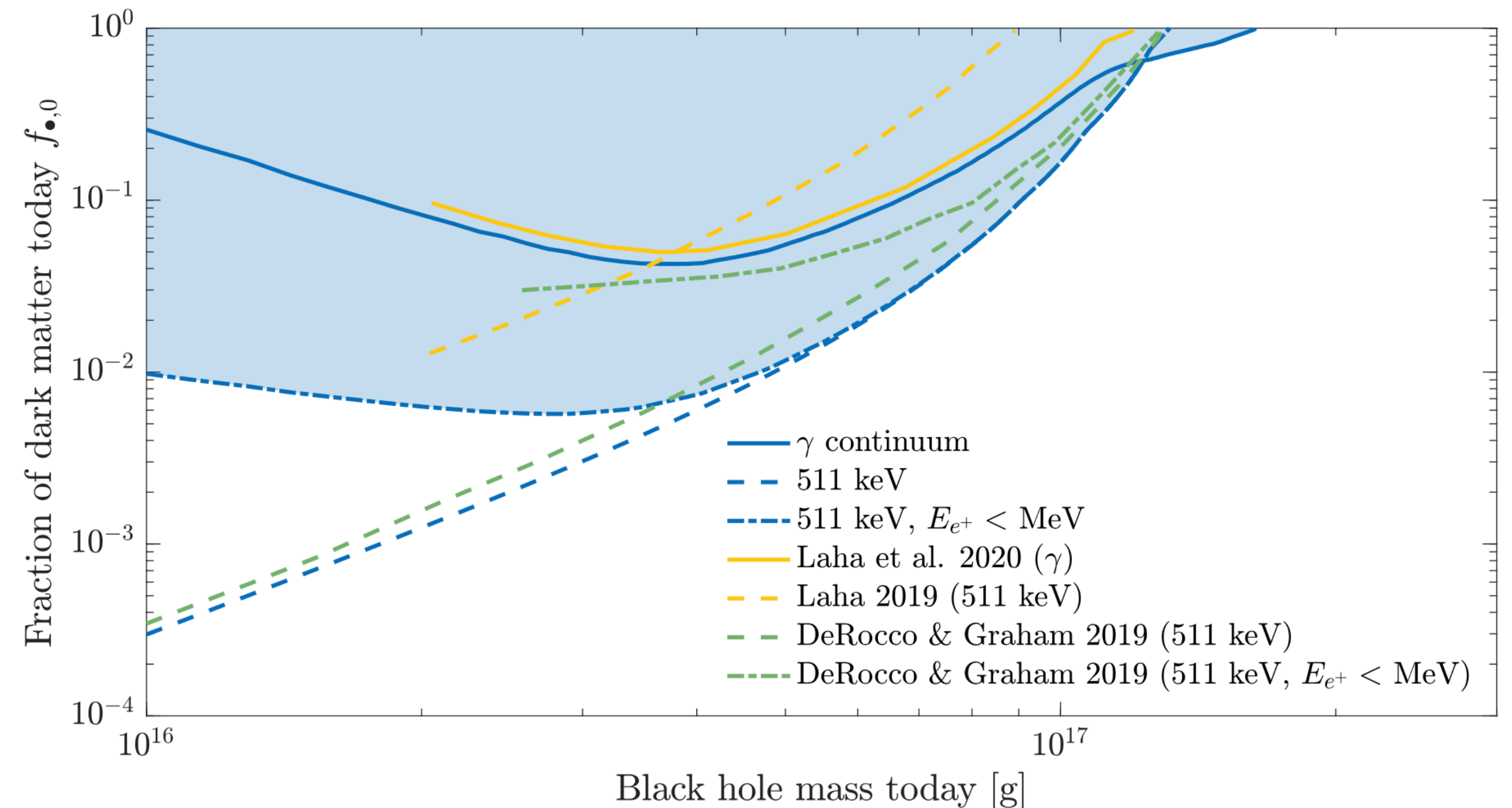
$$\frac{d\Phi_\gamma}{dEd\Omega} = \frac{1}{4\pi} \frac{dN}{dEdt} \frac{f_{\bullet,0}}{M} \frac{1}{\Delta\Omega} \mathcal{D}(\Omega),$$

$$\mathcal{D}(\Omega) \equiv \int_{\text{l.o.s.} \Delta\Omega} \rho_{DM}(\vec{x}) d\Omega dx,$$

$$\frac{d\Phi_{511}}{d\Omega} = 2(1 - 0.75f_P) \frac{dN_{e^+}}{dt} \frac{1}{4\pi} \frac{1}{M} \frac{1}{\Delta\Omega} \mathcal{D}(\Omega)$$

fraction of positronium

25% annihilation to 2 gamma,  
75% to 3 gamma



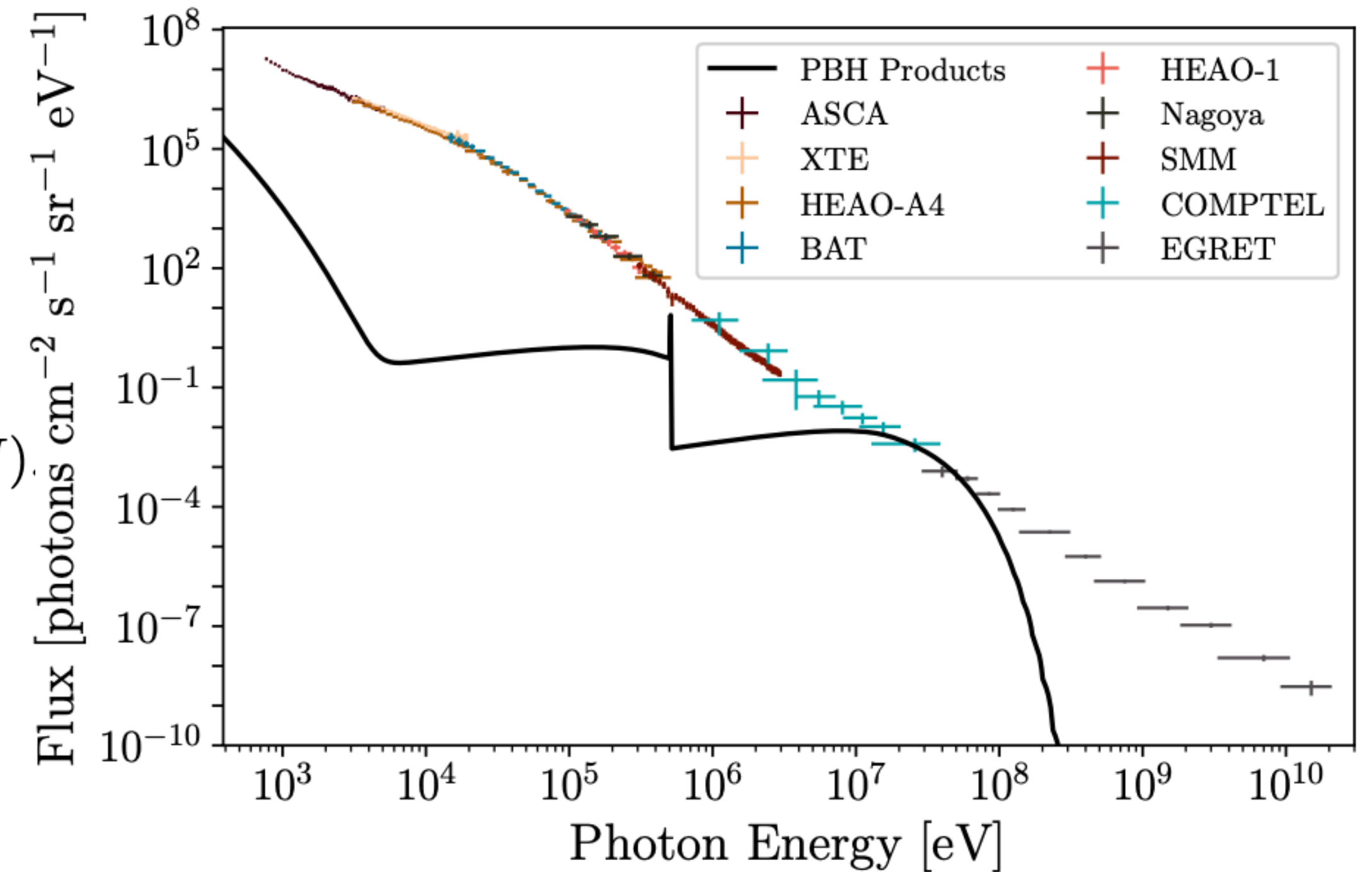
Friedlander, Mack, **NS**, Schon, Vincent, PRD/2201.11761

# Isotropic Gamma Ray Background

$$\frac{d^2 N_\gamma}{dE dt}(E, M) = \frac{d^2 N_{\gamma, \text{evap}}}{dE dt}(E, M) + \frac{d^2 N_{\gamma, \text{pos}}}{dE dt}(E, M) + \frac{d^2 N_{\gamma, \text{ics}}}{dE dt}(E, M)$$

direct evaporation
positron annihilation

Inverse Compton scattering

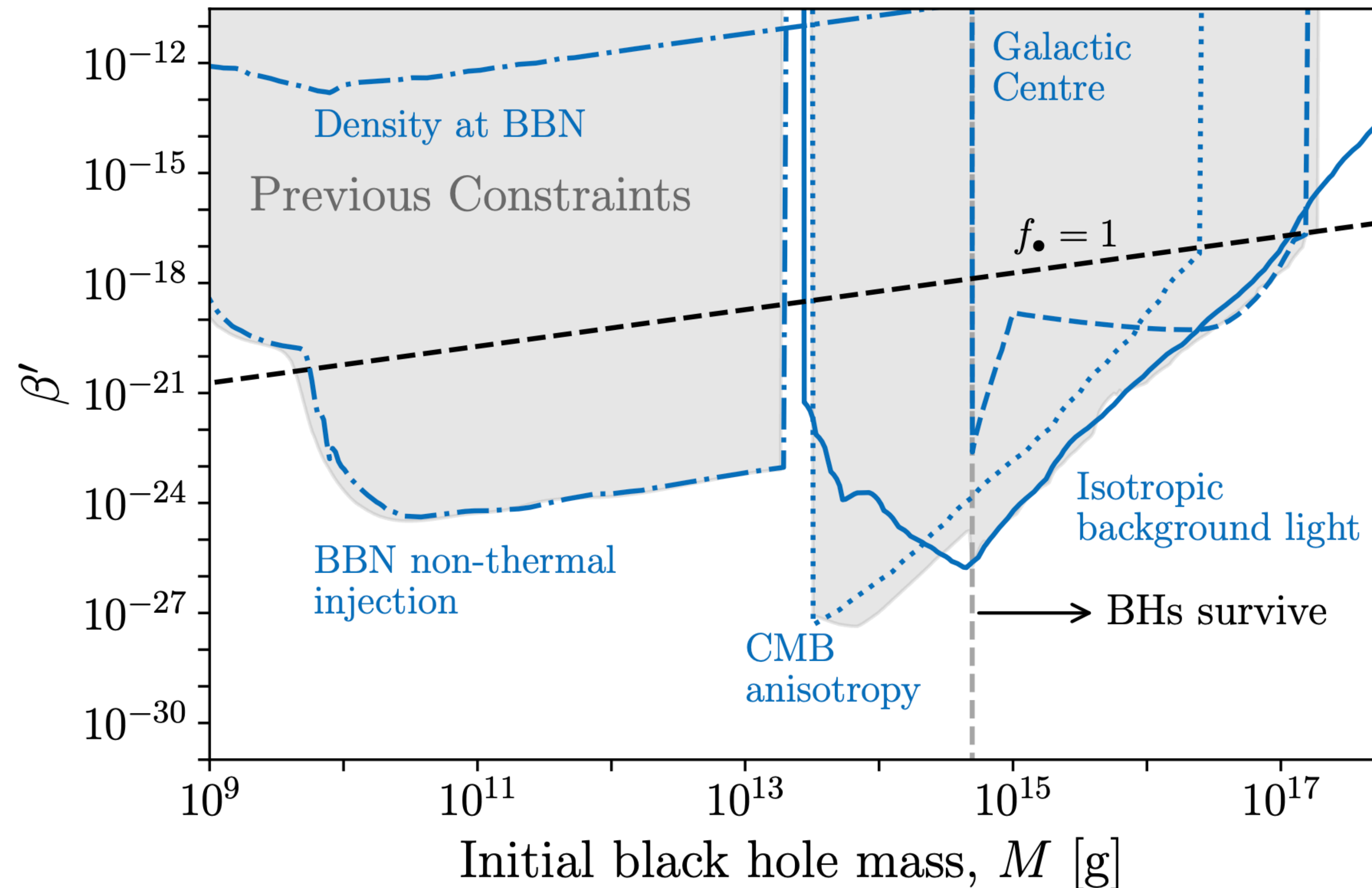




# A Snapshot of 4D BH Constraints

CosmoLED

<https://github.com/songningqiang/CosmoLED>

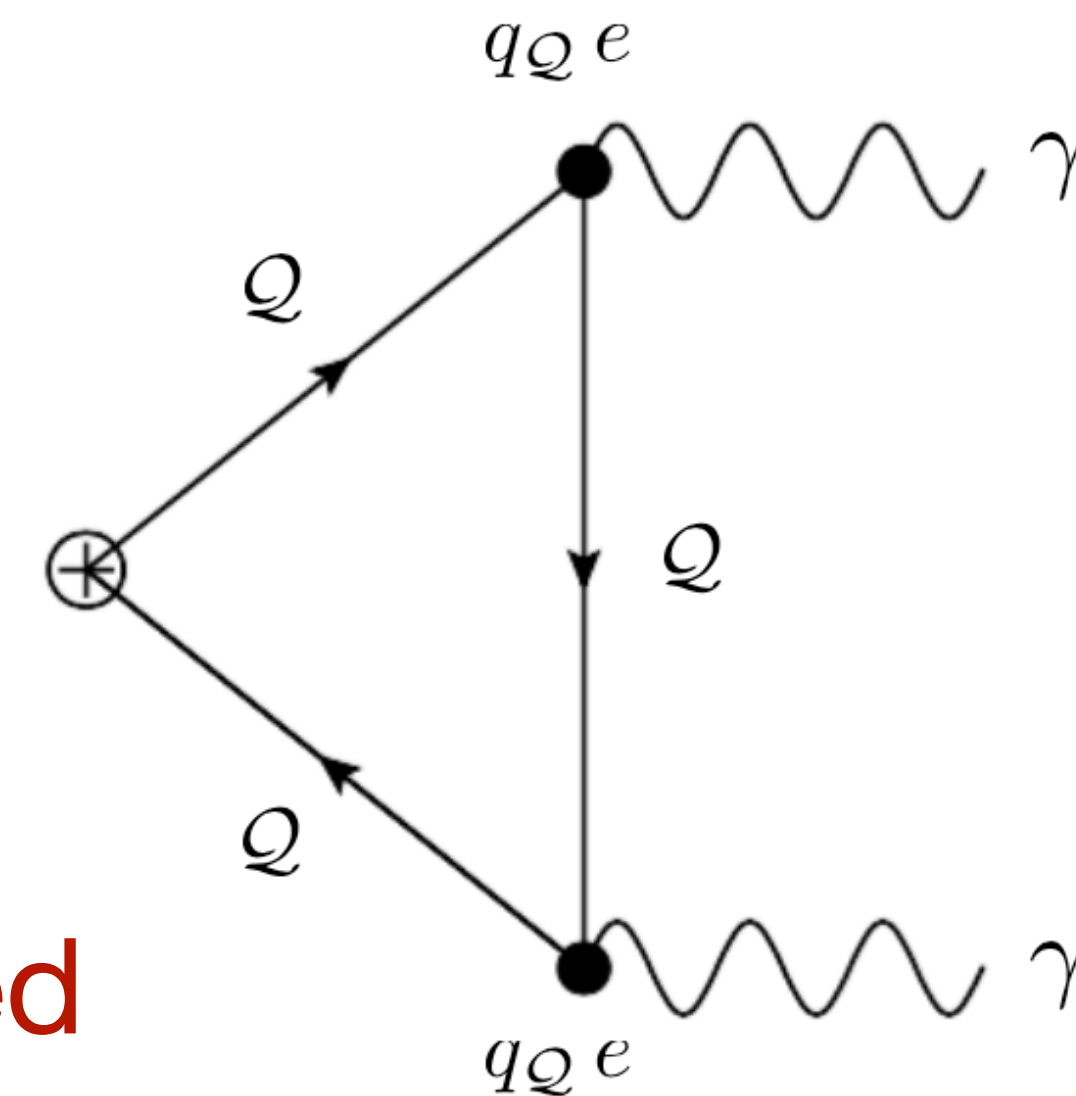


# The Effective Axion Coupling

$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{i}{2} \frac{e C_{\text{NEDM}}}{f_a} a \bar{\psi}_N \sigma_{\mu\nu} \gamma_5 \psi_N F^{\mu\nu} + C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} C_{af} \frac{\partial_\mu a}{f_a} \bar{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

$$g_{a\gamma\gamma} \equiv \frac{\alpha}{2\pi f_a} C_{a\gamma} \simeq \frac{\alpha}{2\pi f_\pi} \frac{m_a}{m_\pi} \frac{1+z}{\sqrt{z}} \left( \frac{E_Q}{N_Q} - \frac{2}{3} \frac{4+z}{1+z} \right)$$

Kaplan, 1985  
Srednicki et al, 1985



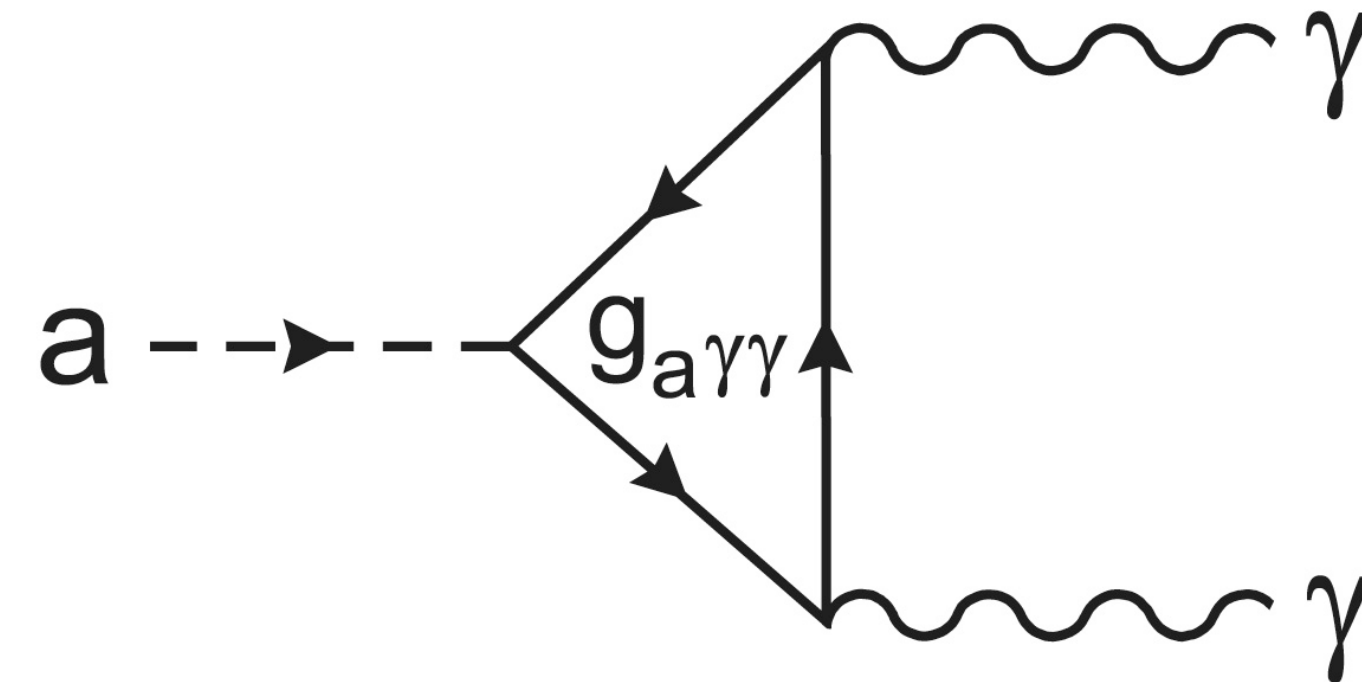
The QCD axion mass and coupling is tightly coupled

# Axion-photon Conversion



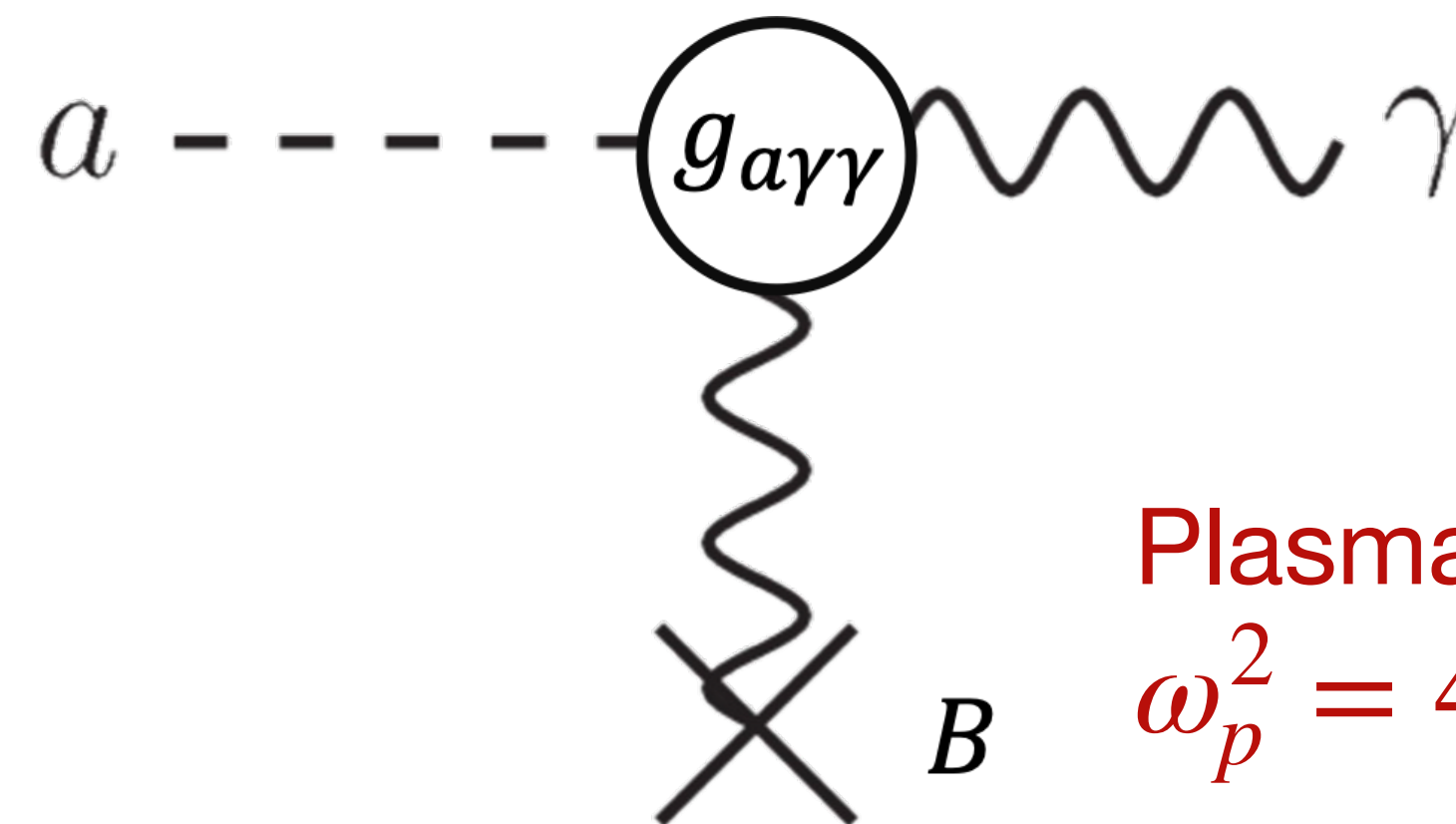
# Axion-photon Conversion

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



$$\omega^2 = k^2 + m_a^2$$

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



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

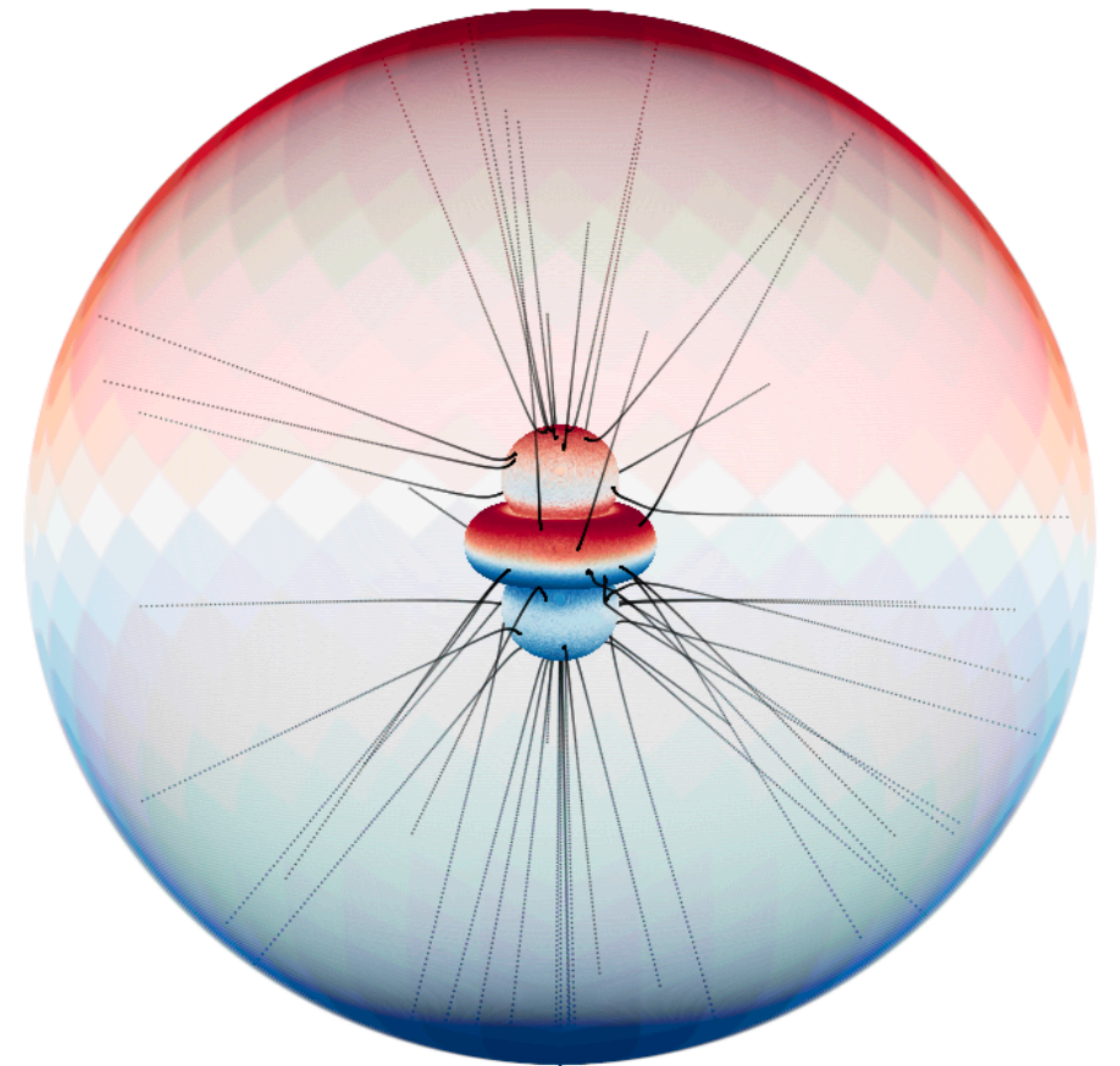


# Axion Conversion around Neutron Star

- Magnetized neutron star atmosphere—magnetosphere

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

$$B_z = \frac{B_0}{2} \left( \frac{r_0}{r} \right)^3 [3 \cos \theta \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} - \cos \theta_m]$$



Witte et al 2104.07670

# Homework Exercise: Axion Conversion around Neutron Star

$$\begin{aligned} -\partial_t^2 a + \nabla^2 a &= m_a^2 a - g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}, \\ -\nabla^2 \mathbf{E} + \nabla(\nabla \cdot \mathbf{E}) &= \omega^2 \mathbf{D} + \omega^2 g_{a\gamma\gamma} a \mathbf{B}, \end{aligned}$$

$$\left[ -i \frac{d}{dr} + \frac{1}{2k} \begin{pmatrix} m_a^2 - \xi \omega_p^2 & \Delta_B \\ \Delta_B & 0 \end{pmatrix} \right] \begin{pmatrix} \tilde{A}_{\parallel} \\ \tilde{a} \end{pmatrix} = 0,$$

$$\xi = \frac{\sin^2 \tilde{\theta}}{1 - \frac{\omega_p^2}{\omega^2} \cos^2 \tilde{\theta}}, \quad \Delta_B = B g_{a\gamma\gamma} m_a \frac{\xi}{\sin \tilde{\theta}},$$

$$p_{a\gamma}^{\infty} \approx \frac{1}{2v_c} g_{a\gamma\gamma}^2 B(r_c)^2 L^2$$

$$\frac{d\mathcal{P}(\theta, \theta_m t)}{d\Omega} \approx 2 \times p_{a\gamma}^{\infty} \rho_{\text{DM}}^{r_c} v_c r_c^2,$$

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

$$B_z = \frac{B_0}{2} \left( \frac{r_0}{r} \right)^3 [3 \cos \theta \hat{\mathbf{m}} \cdot \hat{\mathbf{r}} - \cos \theta_m]$$

$$\mathbf{D} = R_{\tilde{\theta}}^{yz} \cdot \begin{pmatrix} \epsilon & ig & 0 \\ -ig & \epsilon & 0 \\ 0 & 0 & \eta \end{pmatrix} \cdot R_{-\tilde{\theta}}^{yz} \cdot \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix},$$

$$-\partial_z^2 \begin{pmatrix} E_y \\ a \end{pmatrix} = \begin{pmatrix} \frac{\omega^2 - \omega_p^2}{1 - \frac{\omega_p^2}{\omega^2} \cos^2 \tilde{\theta}} & \frac{g_{a\gamma\gamma} B_t \omega^2}{1 - \frac{\omega_p^2}{\omega^2} \cos^2 \tilde{\theta}} \\ \frac{g_{a\gamma\gamma} B_t}{1 - \frac{\omega_p^2}{\omega^2} \cos^2 \tilde{\theta}} & \omega^2 - m_a^2 \end{pmatrix} \cdot \begin{pmatrix} E_y \\ a \end{pmatrix},$$

$$\rho_{\text{DM}}^{r_c} = \rho_{\text{DM}}^{\infty} \frac{2}{\sqrt{\pi}} \frac{1}{v_0} \sqrt{\frac{2GM_{\text{NS}}}{r_c}} + \dots.$$

Hook et al 1804.03145

Millar et al 2107.07399

Witte et al 2104.07670



# Axion Conversion in Neutron Star

- Magnetized neutron star atmosphere—magnetosphere

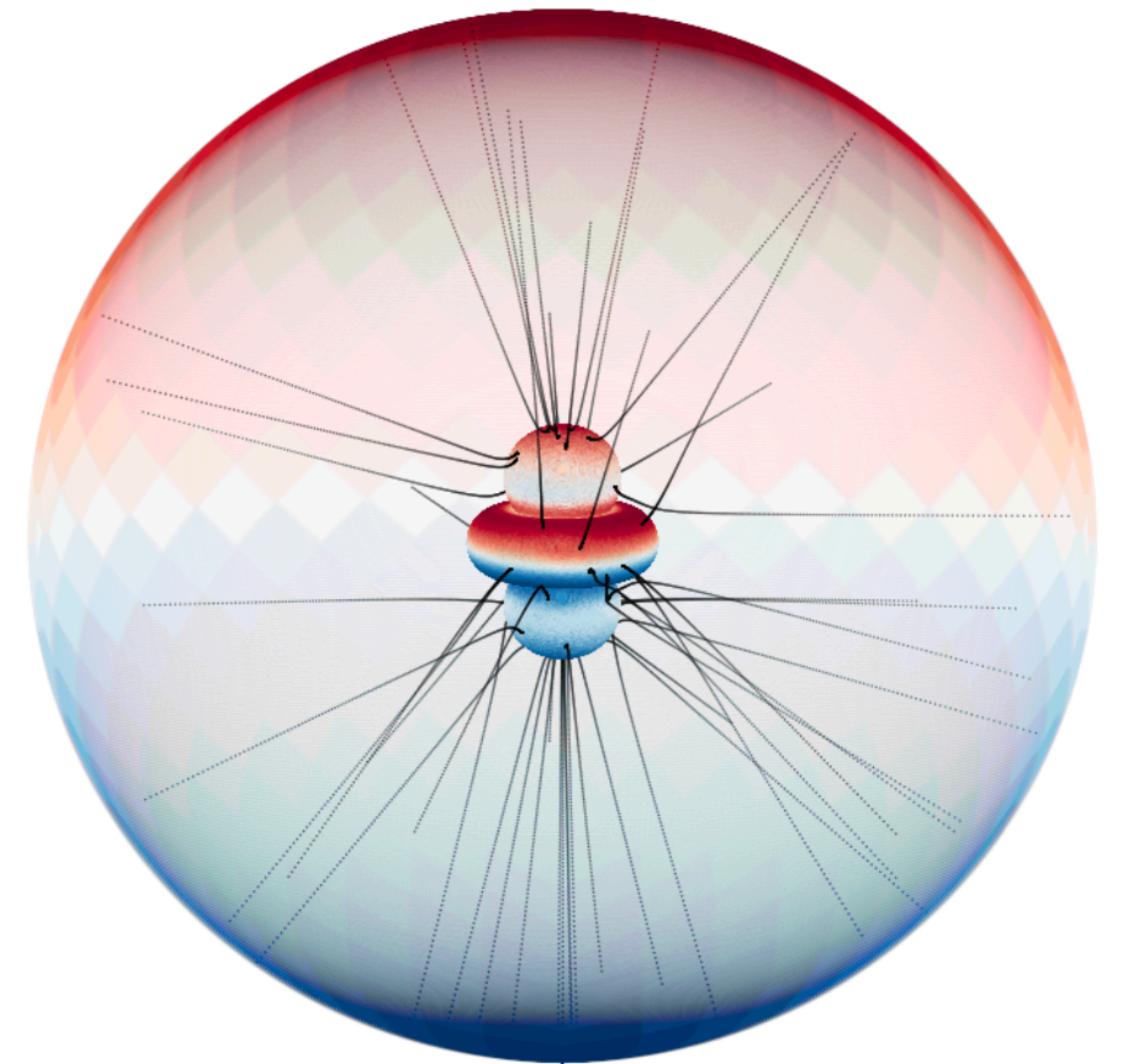
$$n_{\text{GJ}}(\mathbf{r}_{\text{NS}}) = \frac{2\mathbf{\Omega} \cdot \mathbf{B}_{\text{NS}}}{e} \frac{1}{1 - \Omega^2 r^2 \sin^2 \theta_{\text{NS}}}$$

- 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

# Signals from the Galactic Centre

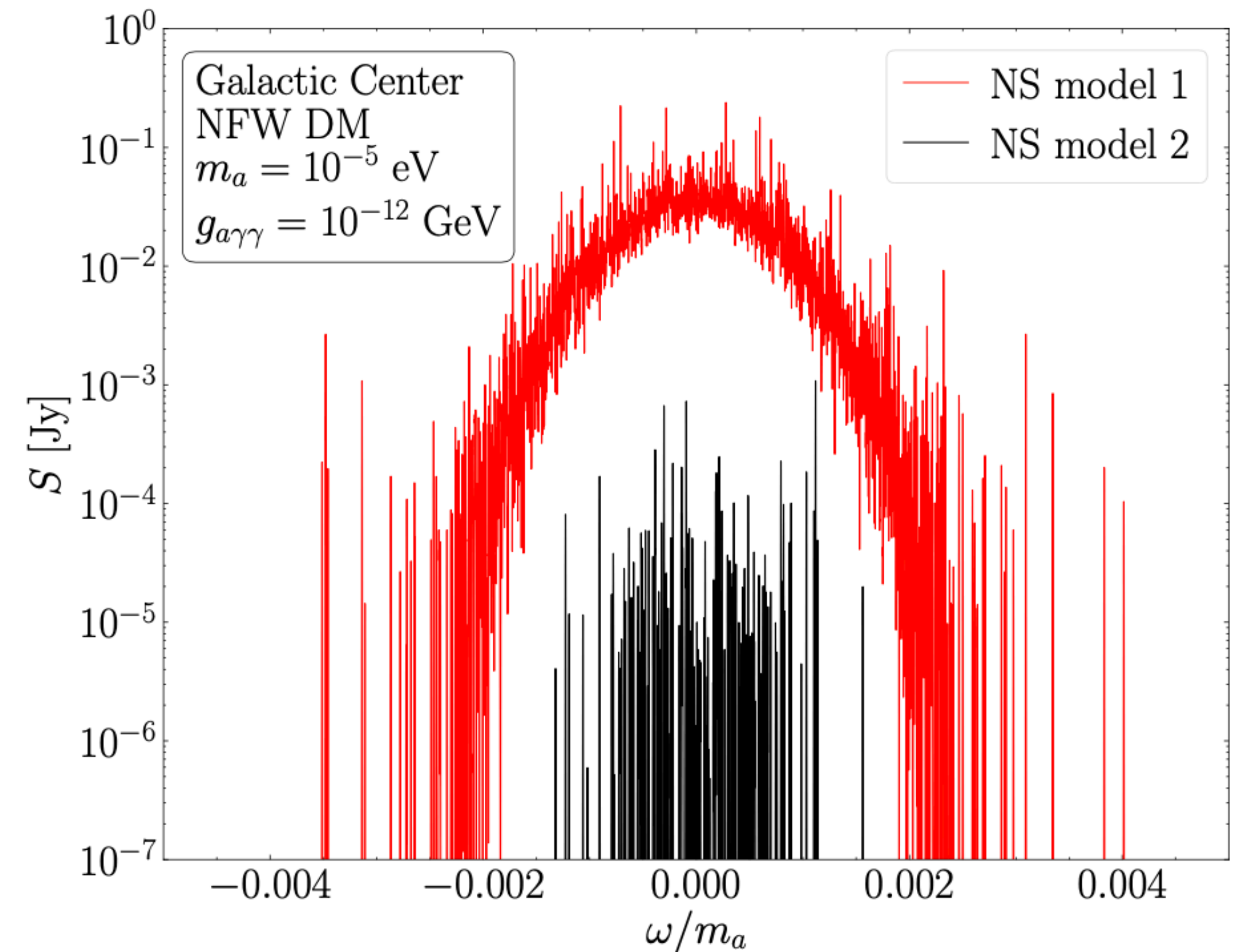
$$S_{\text{sig}} = \frac{1}{\mathcal{B}d^2} \frac{dP}{d\Omega} > S_{\text{min}}$$

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!



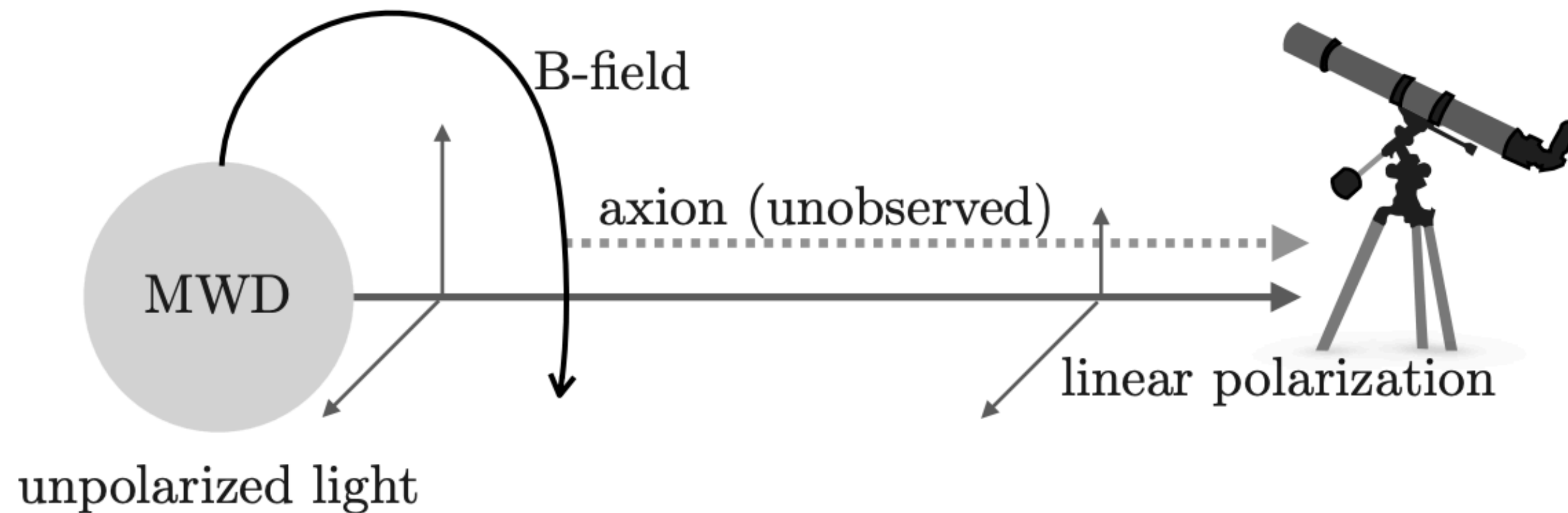
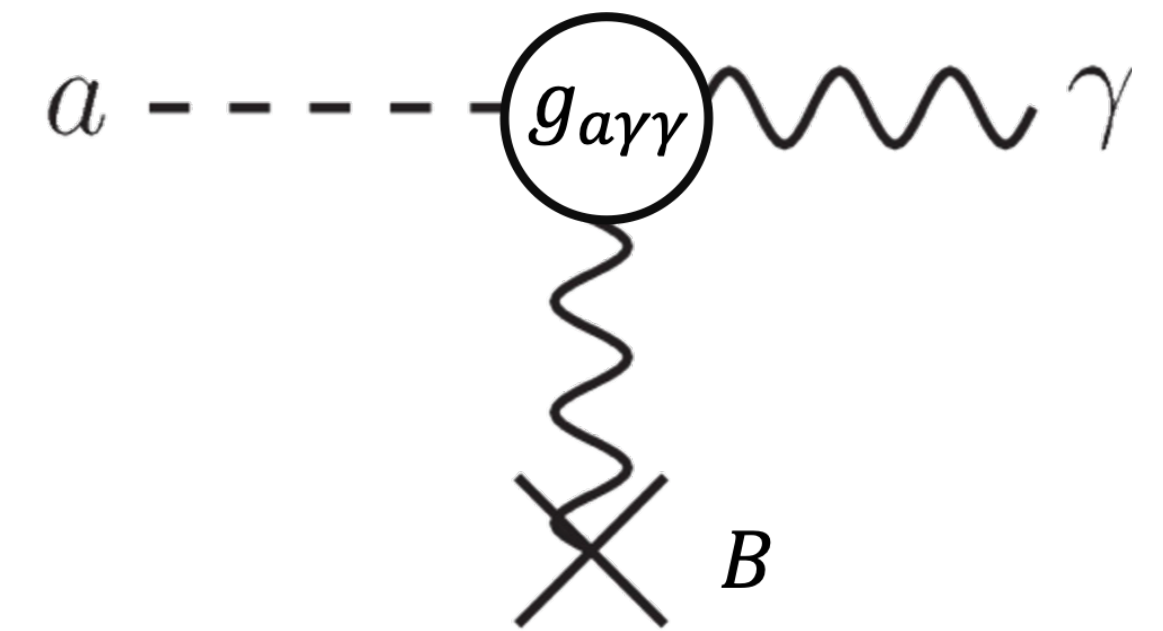
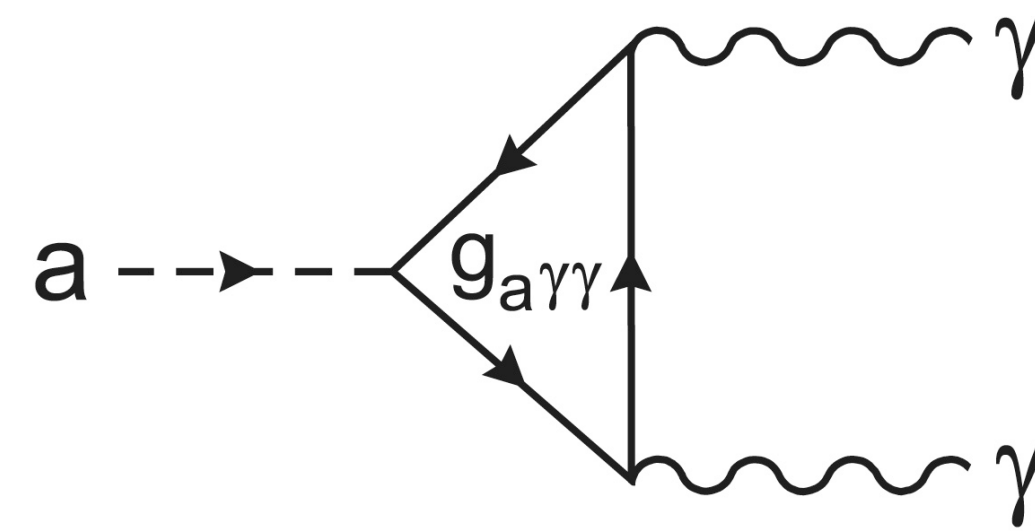
Safdi et al 1811.01020



# Optical Polarization Signal

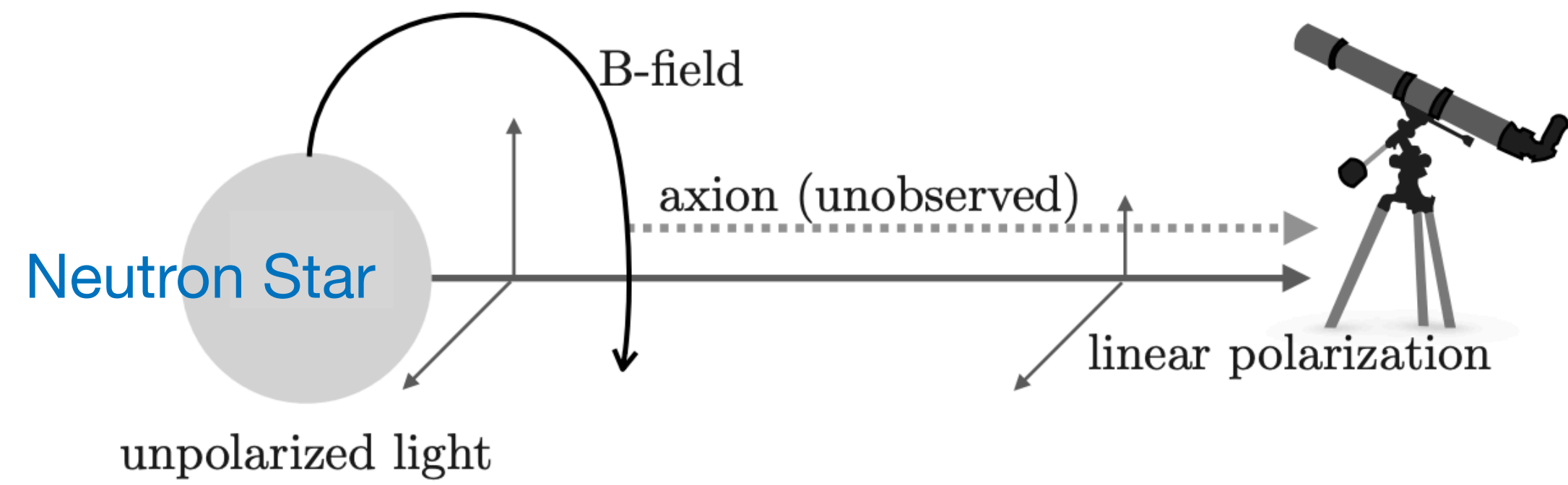
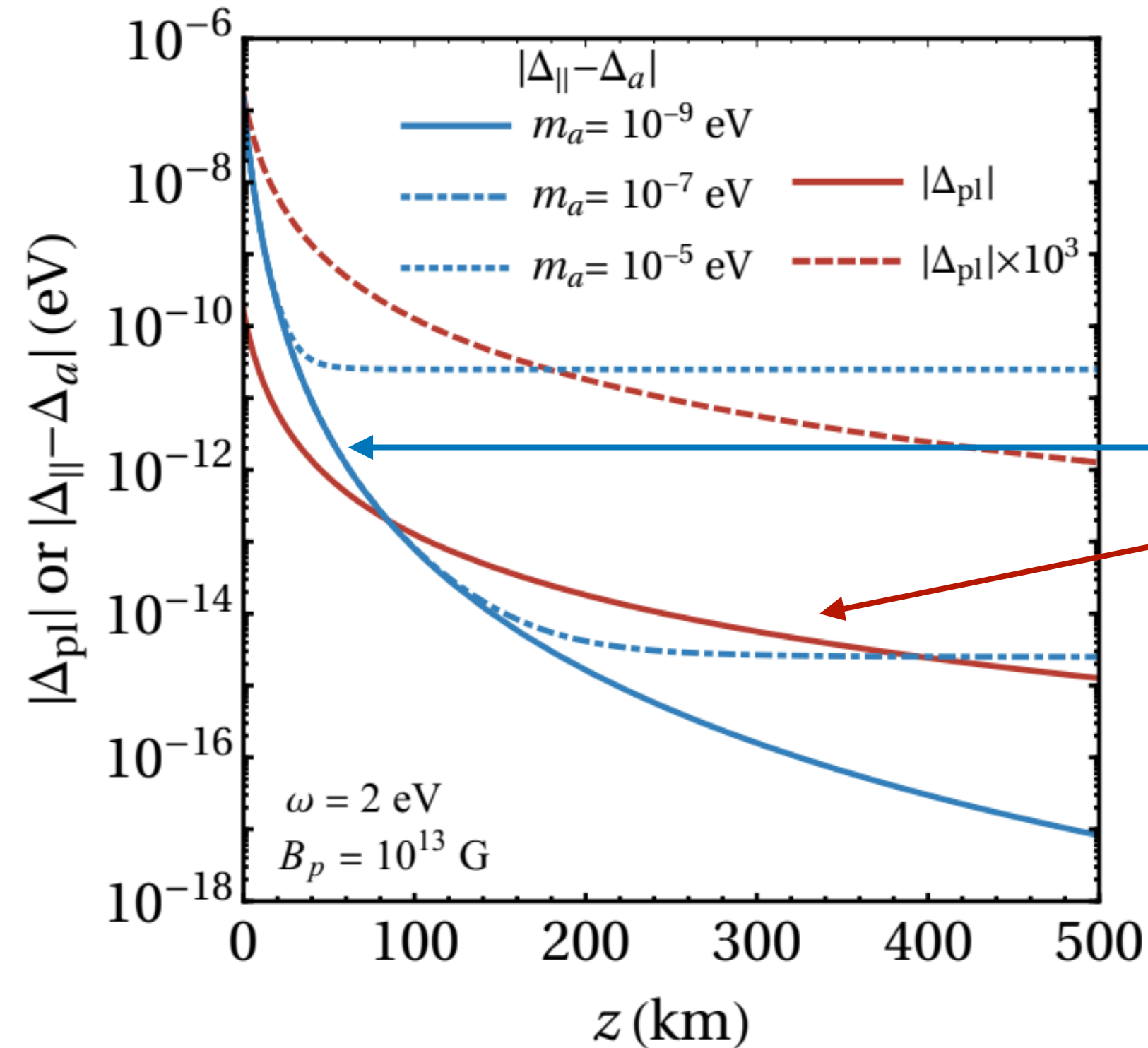
- CP conserved in QCD  $\Rightarrow$  axion

- $\mathcal{L}_{a\gamma\gamma} = \frac{1}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$



- Photon only converts to axion in the direction parallel to magnetic field, inducing polarization signals

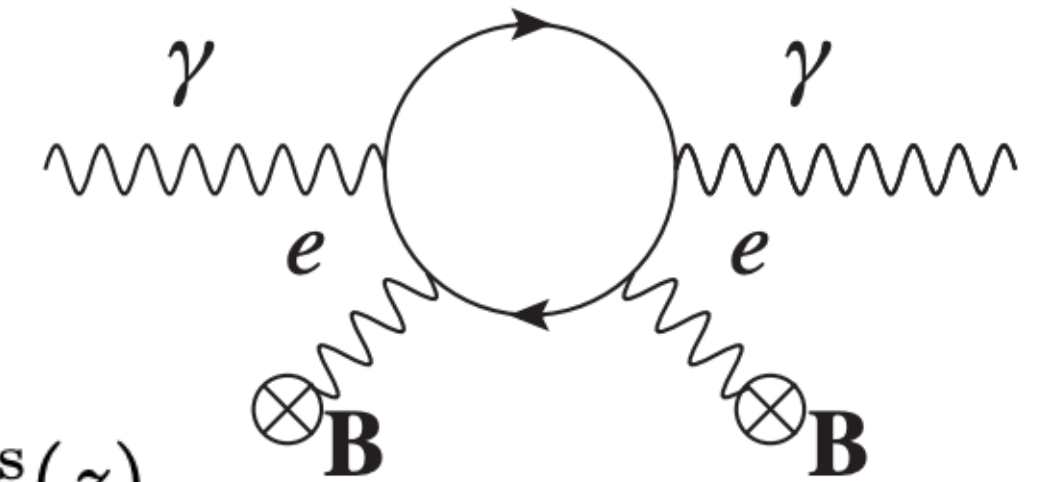
# Optical Polarization Signal



$$\Delta_{||} + \Delta_{pl} - \Delta_a = 0$$

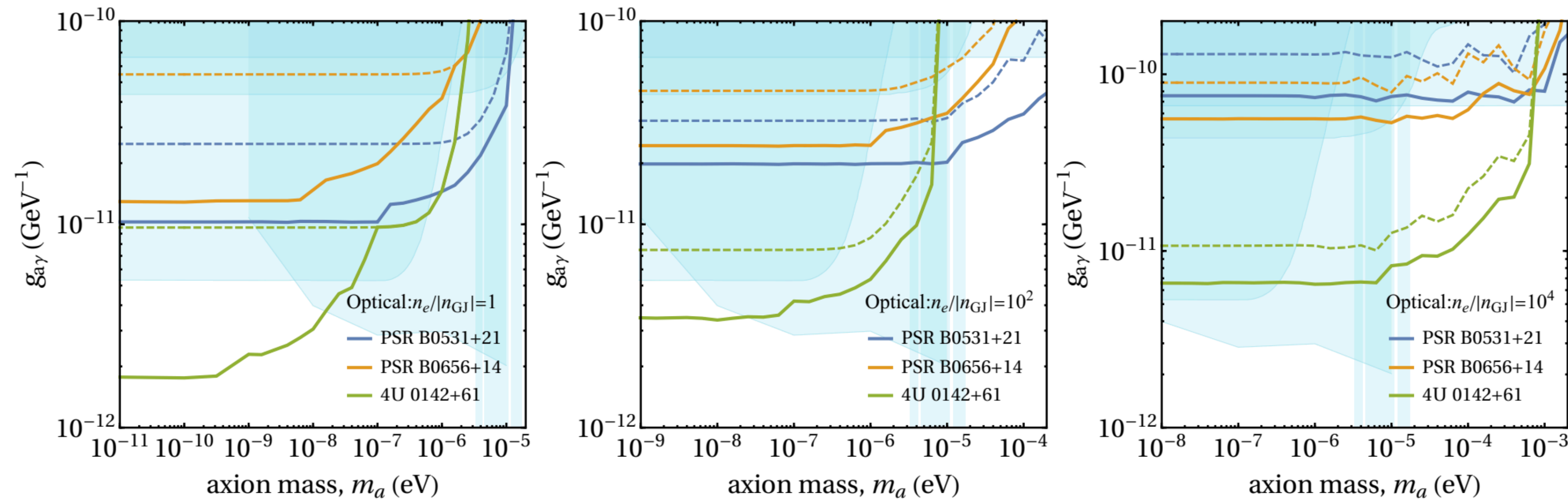
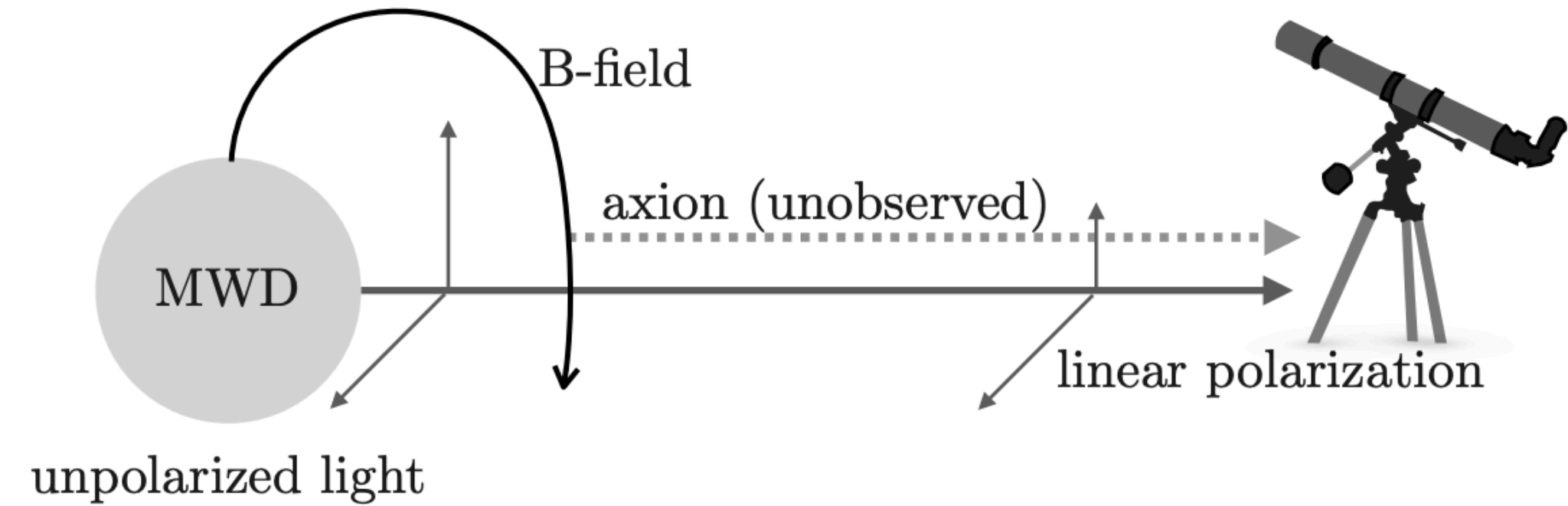
$$\Pi_L(z) = \frac{I_{\perp}(z) - (1 - P_{\gamma \rightarrow a}^{\text{res}})I_{||}^{\text{nonres}}(z)}{I_{\perp}(z) + (1 - P_{\gamma \rightarrow a}^{\text{res}})I_{||}^{\text{nonres}}(z)}$$

$$\approx \frac{P_{\gamma \rightarrow a}^{\text{res}} + 2|\text{Re}(A_{||,2})|}{2 - (P_{\gamma \rightarrow a}^{\text{res}} + 2|\text{Re}(A_{||,2})|)},$$



- Photon only converts to axion in the direction parallel to magnetic field, inducing polarization signals
- Resonant conversion occurs when vacuum polarization matches plasma

# Optical Polarization Signal



- Photon only converts to axion in the direction parallel to magnetic field, inducing polarization signals
- Optical polarization signals from neutron stars could place the most stringent limits

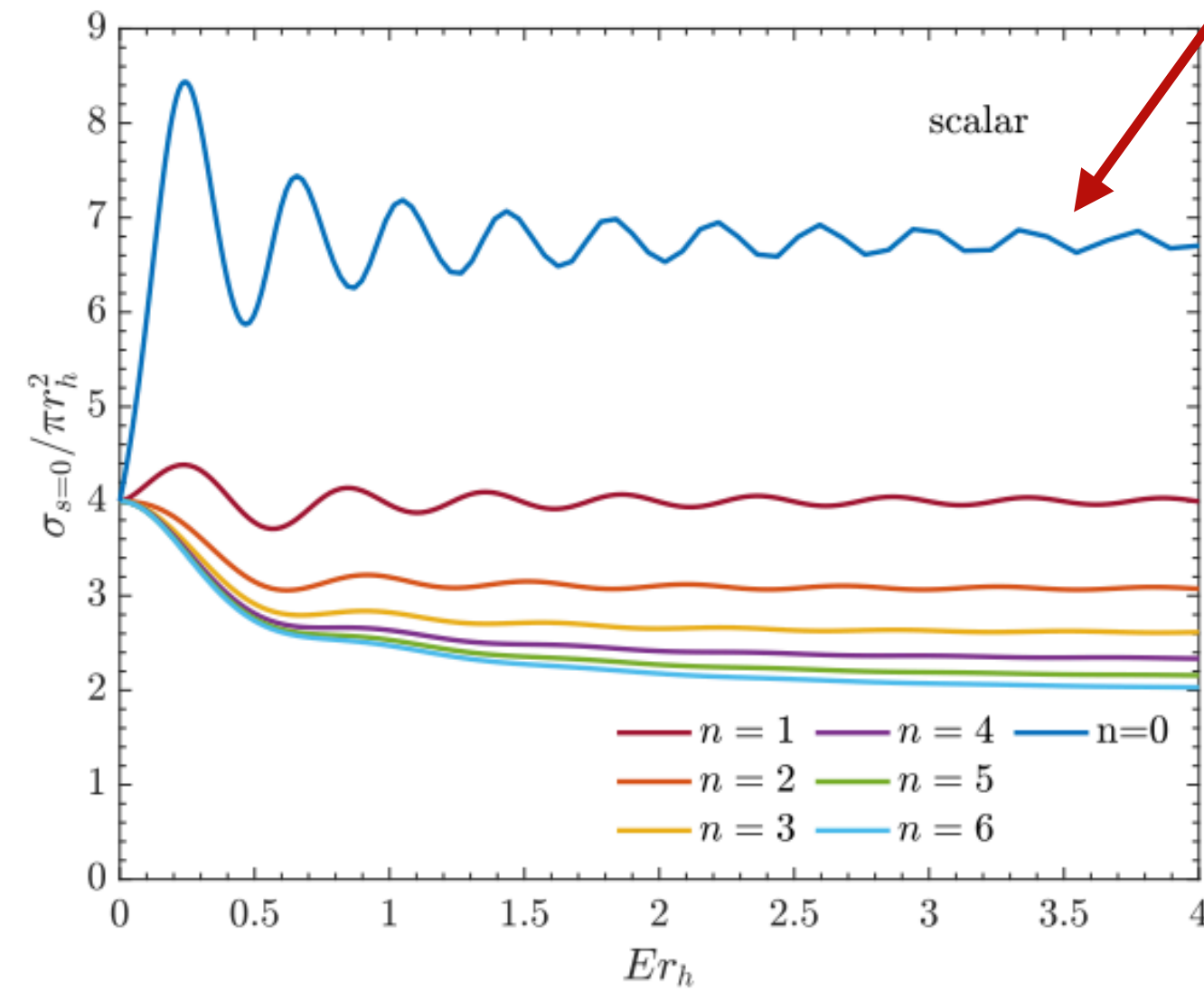


# Greybody spectra

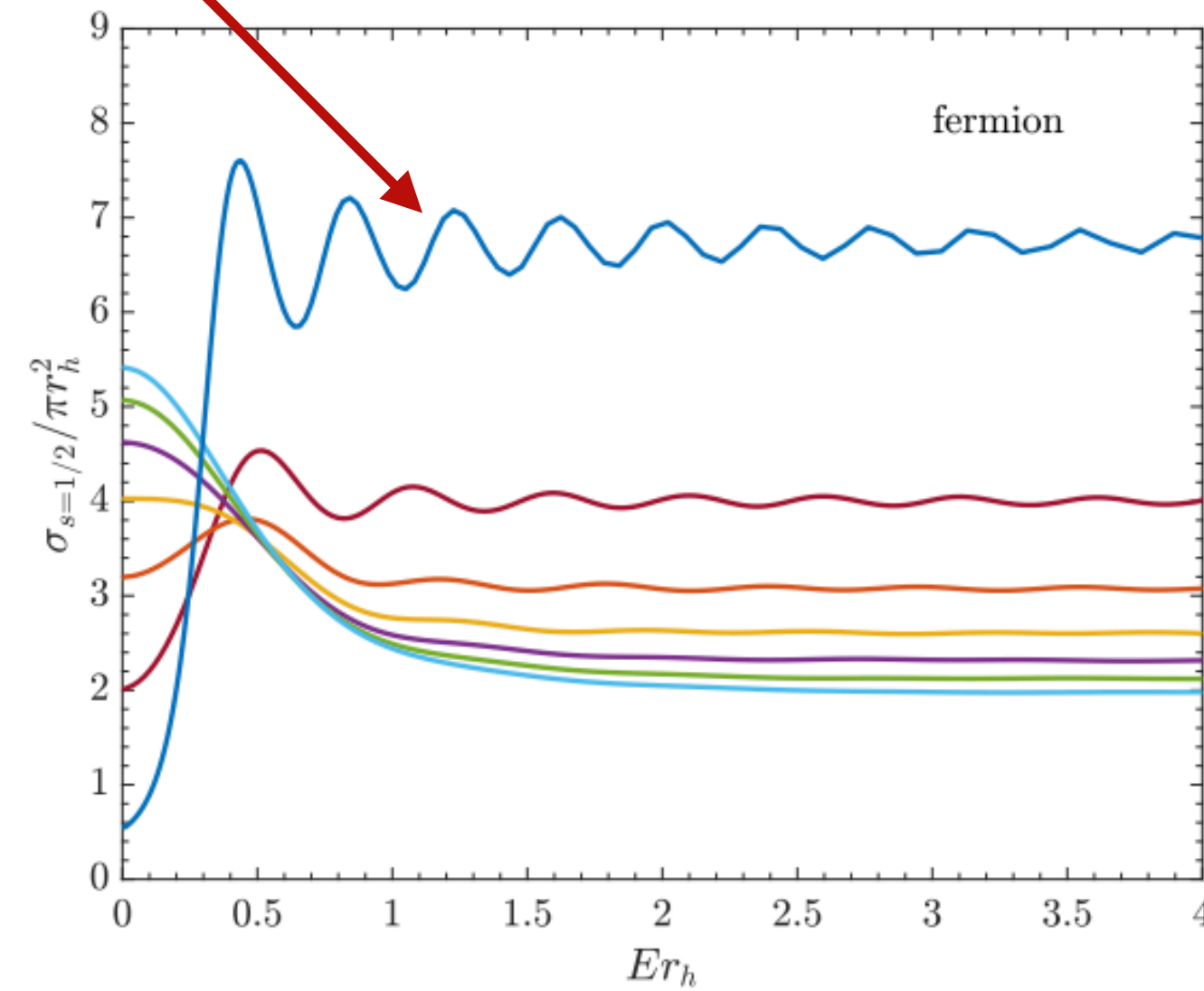
4D BHs

$$-\frac{dM_{\bullet \rightarrow i}}{dt} = \frac{g_i}{2\pi^2} \int \frac{E \sigma_i(r_h E)}{\exp(E/T_H) \mp 1} p^2 dp$$

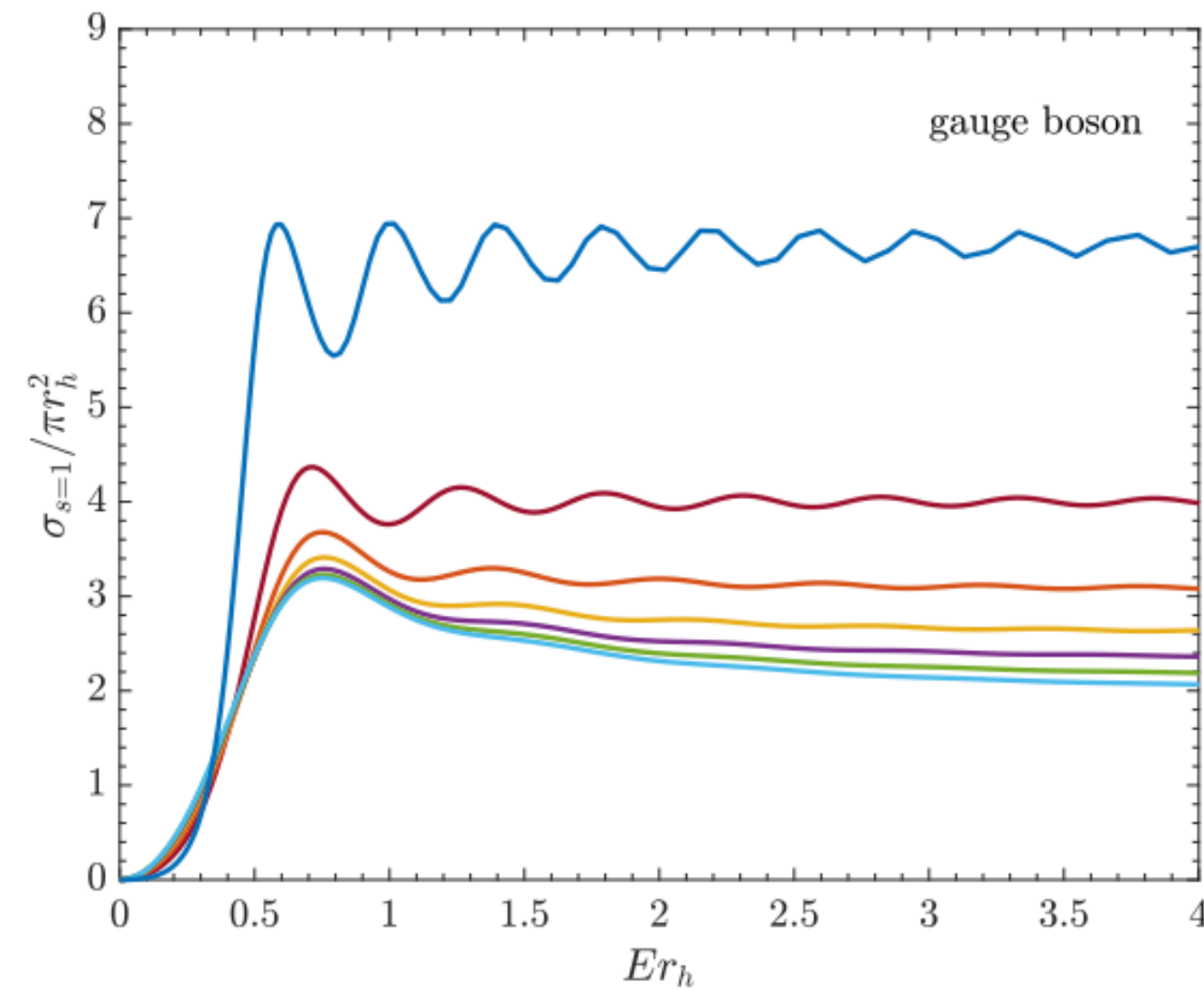
Scalar



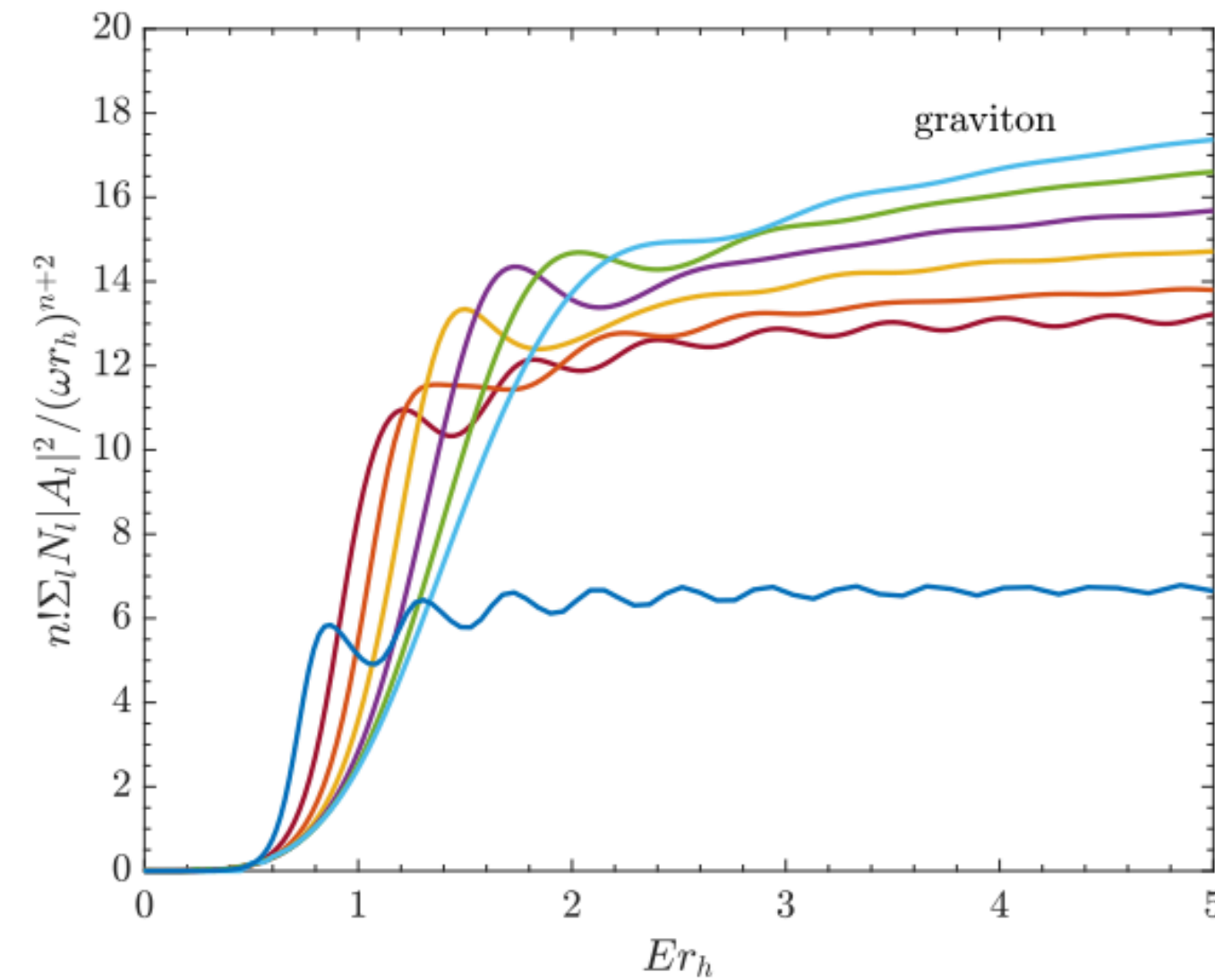
Fermion



Vector



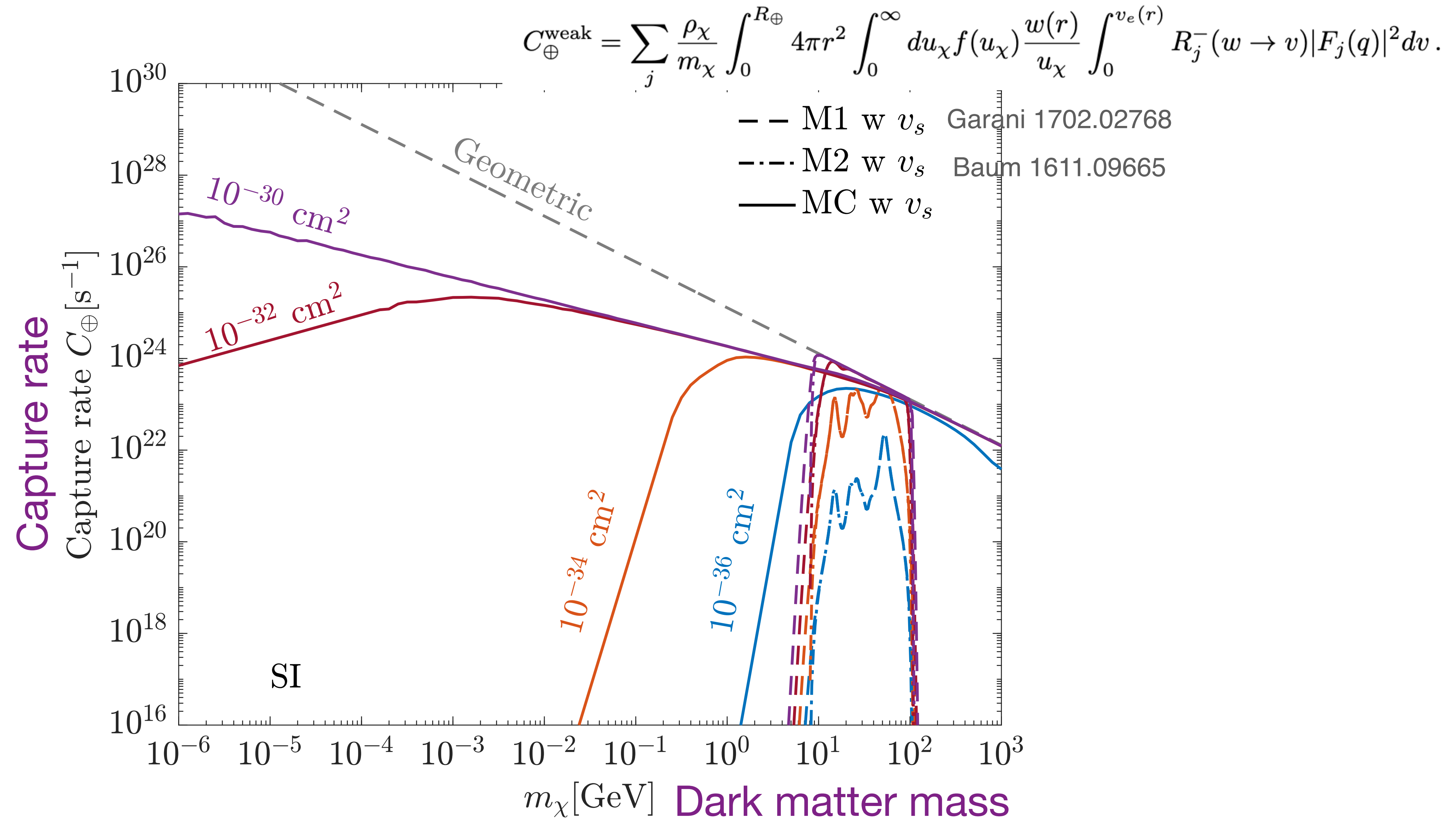
Graviton



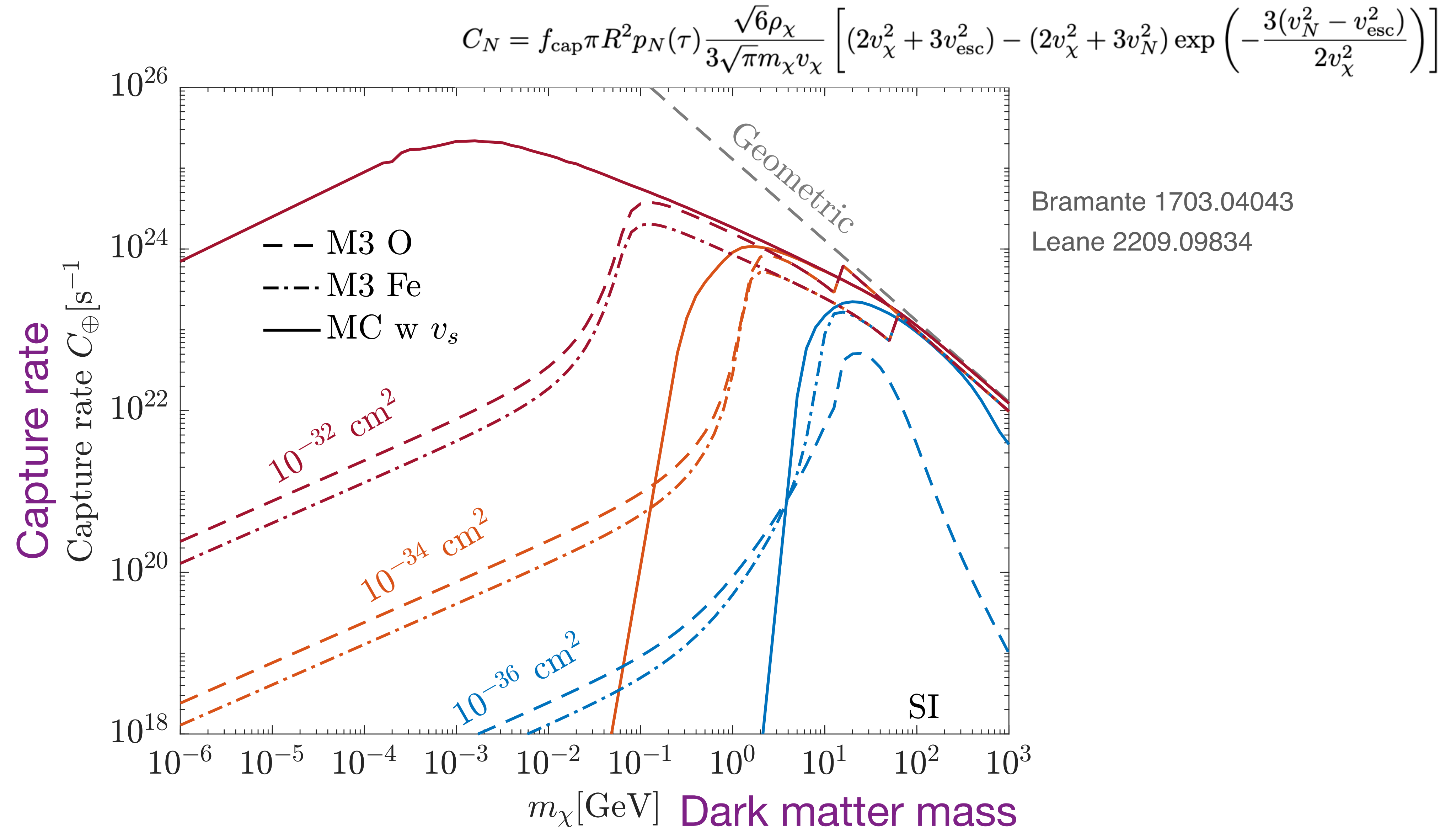
Energy



# Monte Carlo vs Single Scatter

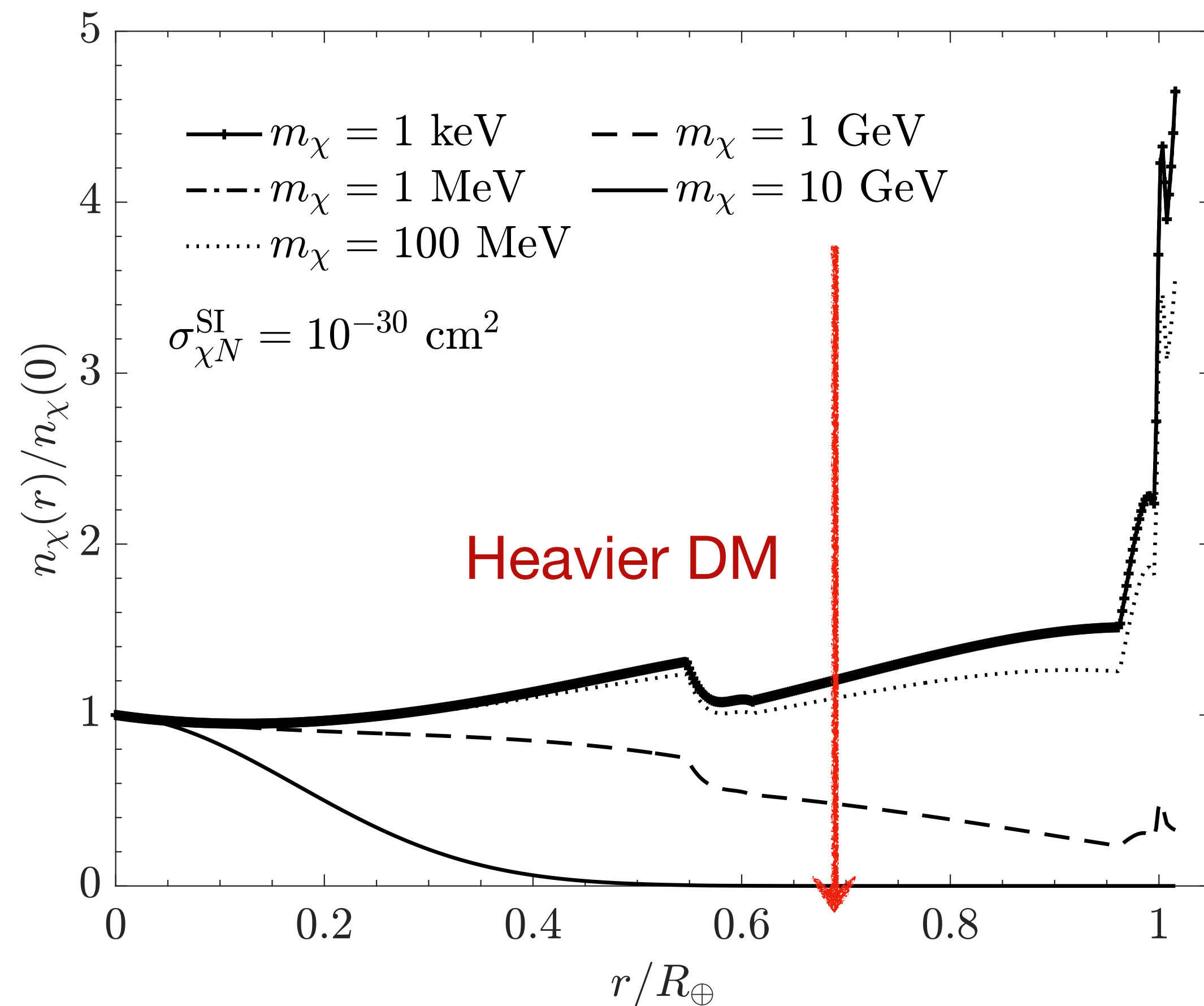


# Monte Carlo vs Multi Scatter



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

Garani 1702.02768

Heavier dark matter sinks down, lighter dark matter float

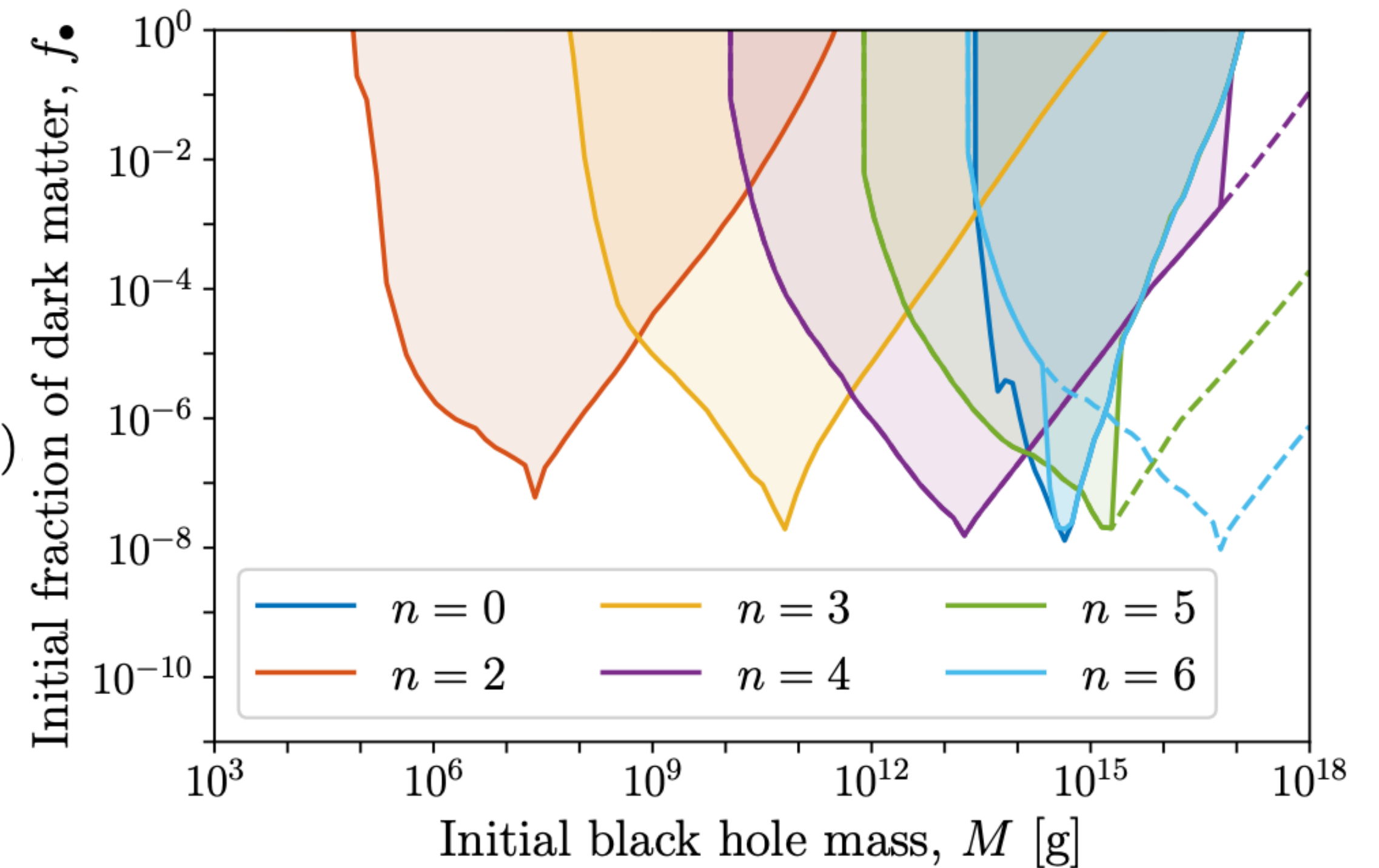


# Isotropic Gamma Ray Background

$$\frac{d^2 N_\gamma}{dE dt}(E, M) = \frac{d^2 N_{\gamma, \text{evap}}}{dE dt}(E, M) + \frac{d^2 N_{\gamma, \text{pos}}}{dE dt}(E, M) + \frac{d^2 N_{\gamma, \text{ics}}}{dE dt}(E, M)$$

direct evaporation
positron annihilation

Inverse Compton scattering



Friedlander, Mack, **NS**, Schon, Vincent, PRD/2201.11761



# Dark Photon

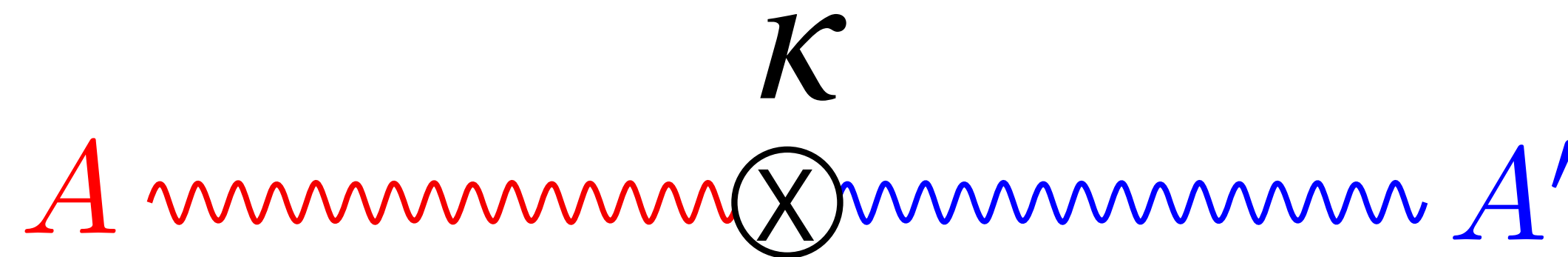
Extra  $U(1)$ ?  $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

Pospelov' 2008

Ackerman, Buckley, Carrol, Kamionkowski' 2008

Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

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



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

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

# 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  $A_\mu \rightarrow A_\mu + \kappa A'_\mu$  to remove the mixing,

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

- Equation of motion

$$\begin{aligned} (\omega^2 + \nabla^2)\mathbf{A} - \nabla(\nabla \cdot \mathbf{A}) + \omega^2(\chi^p + \chi^{\text{vac}}) \cdot (\mathbf{A} + \kappa\mathbf{A}') &= 0 \\ (\omega^2 + \nabla^2)\mathbf{A}' - m_{A'}^2\mathbf{A}' + \kappa\omega^2(\chi^p + \chi^{\text{vac}}) \cdot \mathbf{A} &= 0 \end{aligned}$$

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

# Resonant Dark Photon Conversion

$$(\omega^2 + \partial_z^2)A_x - \partial_x \partial_z A_z + \omega^2 a \bar{A}_x = 0,$$

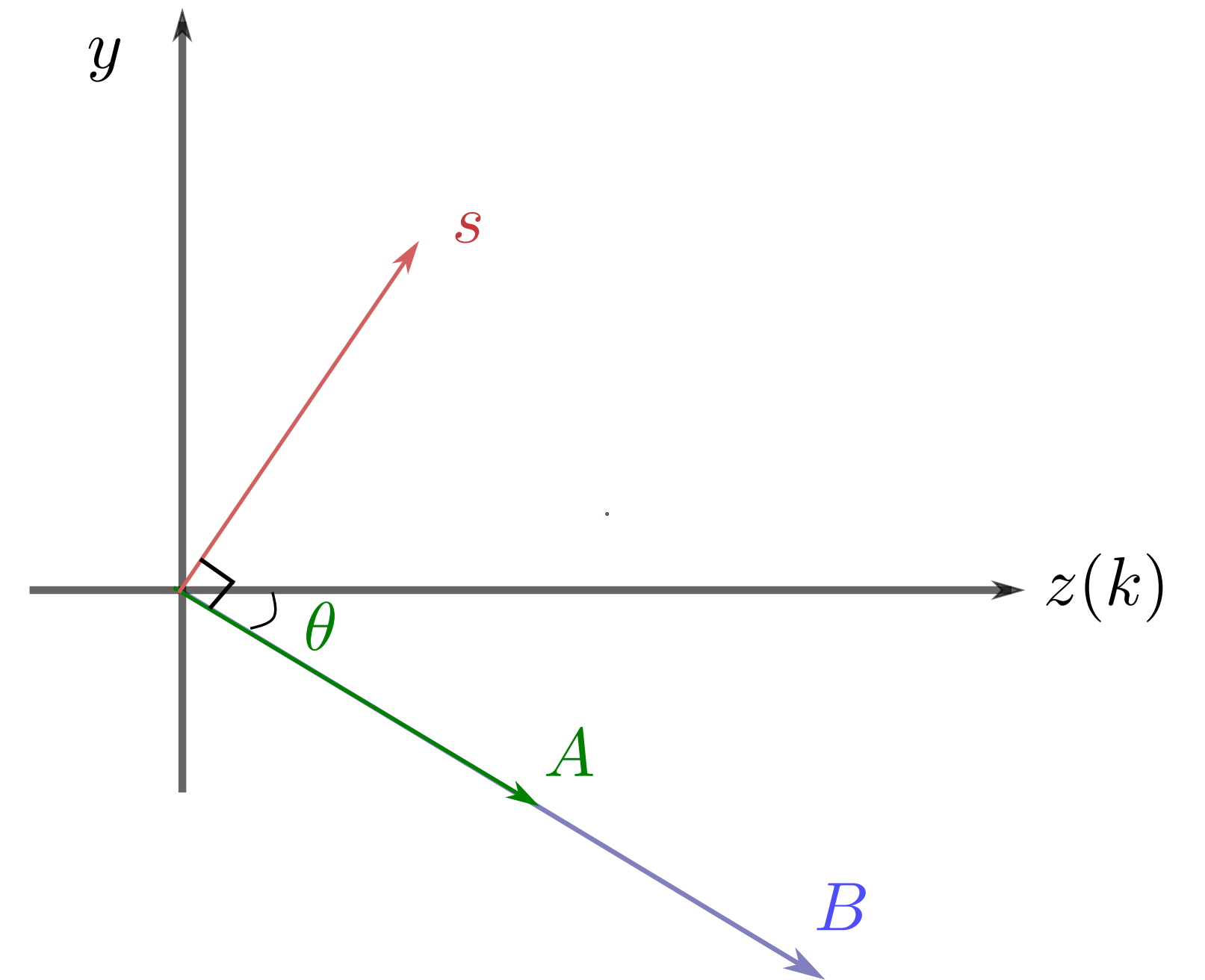
$$(\omega^2 + \partial_z^2)A_y - \partial_y \partial_z A_z + \omega^2 [(\eta' \sin^2 \theta + a + q \sin \theta^2) \bar{A}_y - (\eta' + q) \cos \theta \sin \theta \bar{A}_z] = 0,$$

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

- Conversion probability

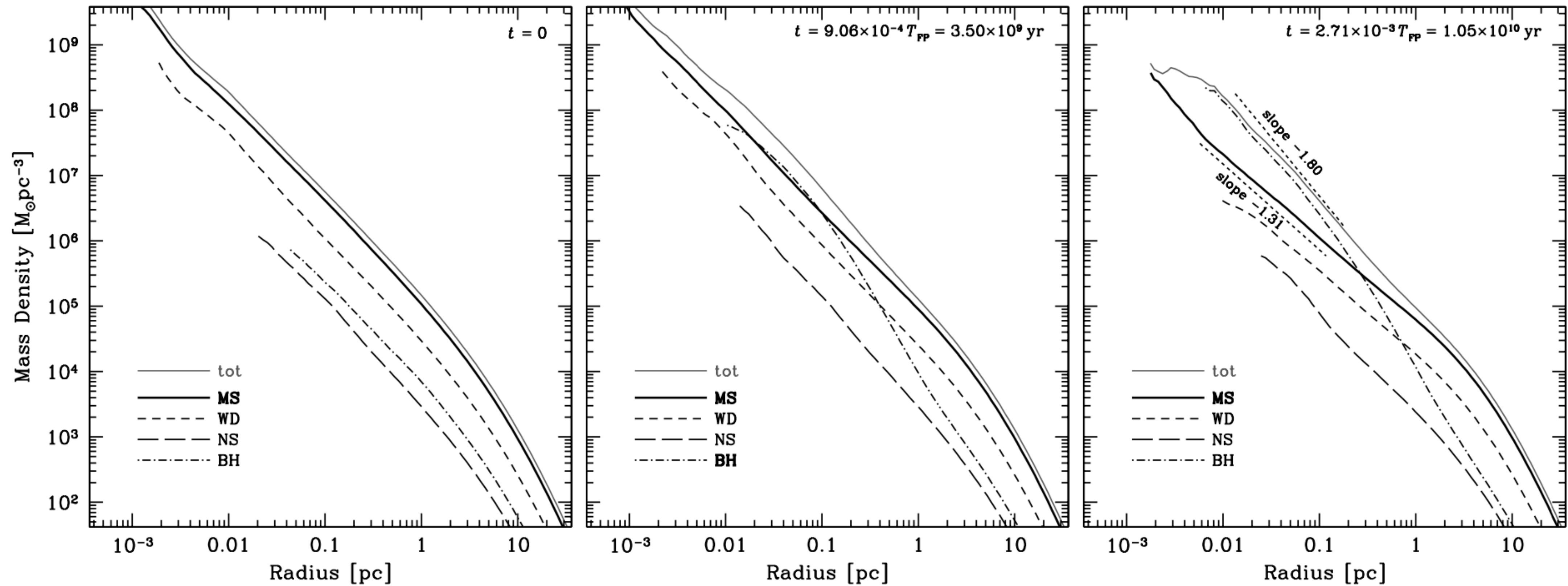
$$p \simeq \frac{|\tilde{A}_y|^2 + |\tilde{A}_z|^2}{|\tilde{A}'_x|^2 + |\tilde{A}'_y|^2 + |\tilde{A}'_z|^2} \simeq \frac{\pi \kappa^2 \omega_p^3 (m_A^2 \cos \theta - \omega_p^2 \sin^3 \theta)^2}{6 k m_A^4 \omega_p' \sin^2 \theta}$$

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





# Compact Stars in the Galactic Centre



Freitag et al 2006



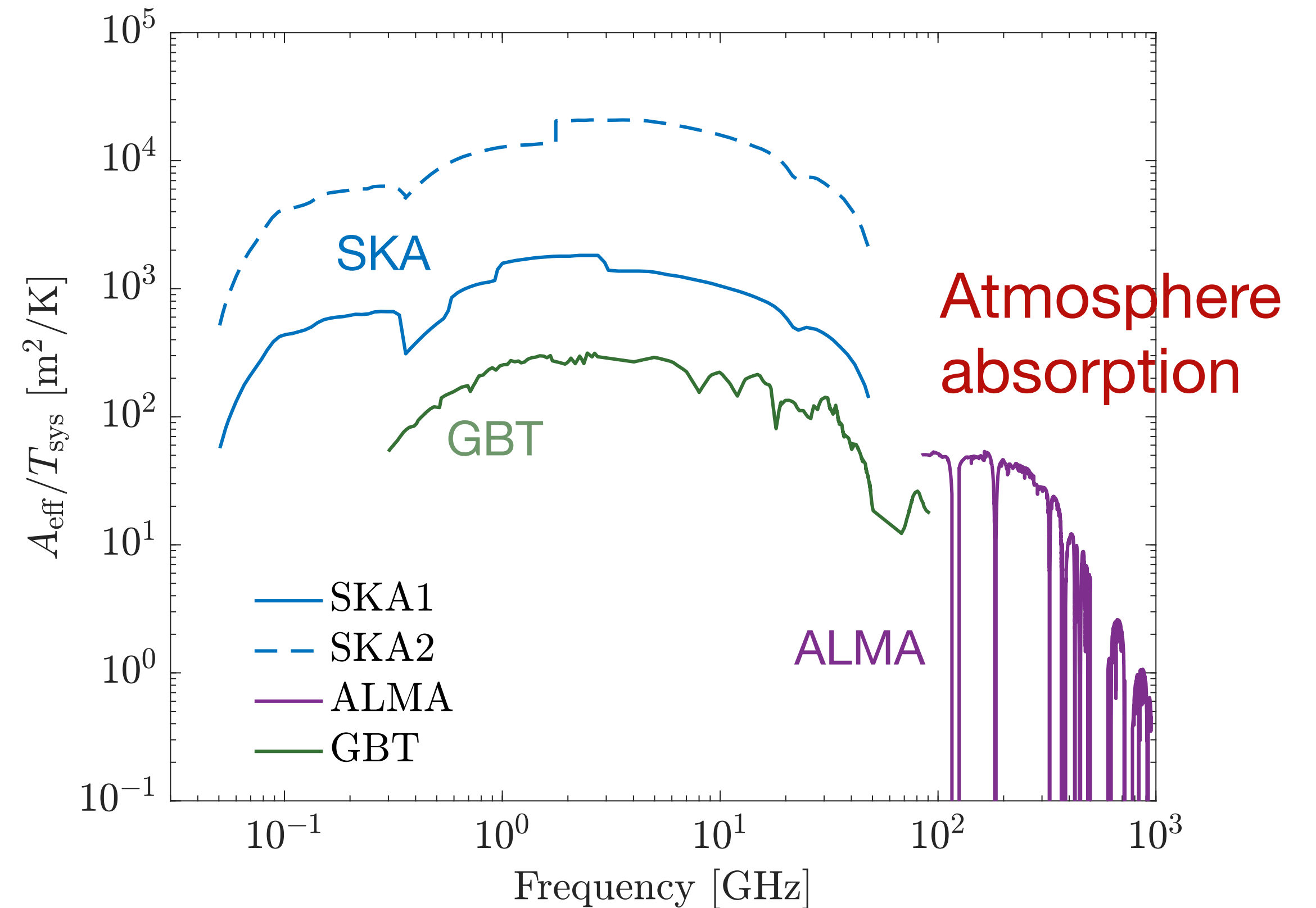
# Radio Telescopes

Minimum detectable signal flux density

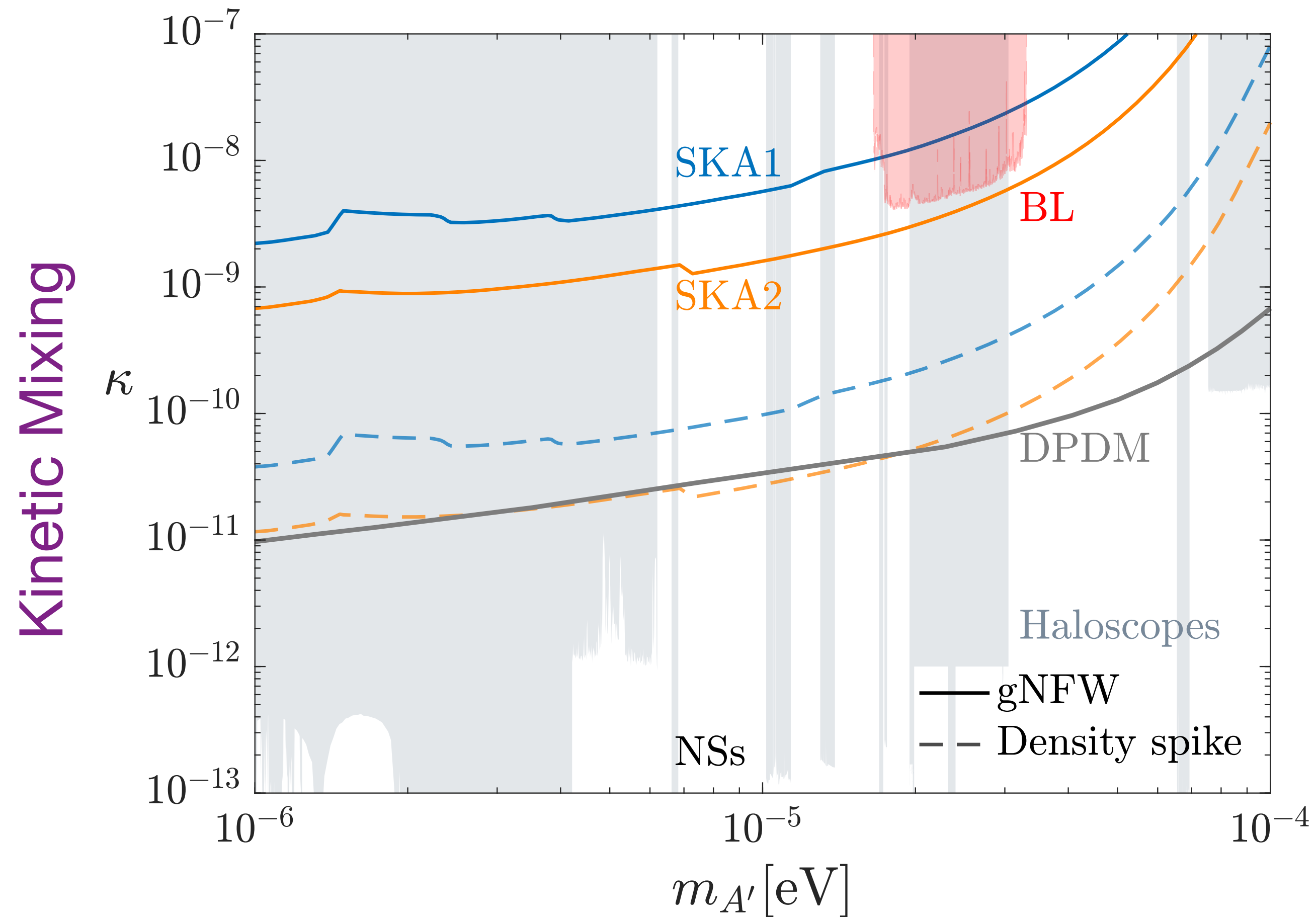
$$S_{\min} = \frac{\text{SEFD}}{\eta \sqrt{n_{\text{pol}} \mathcal{B} t_{\text{obs}}}}$$

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

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



# Sensitivities for Galactic Center Signals



Collection of neutron stars

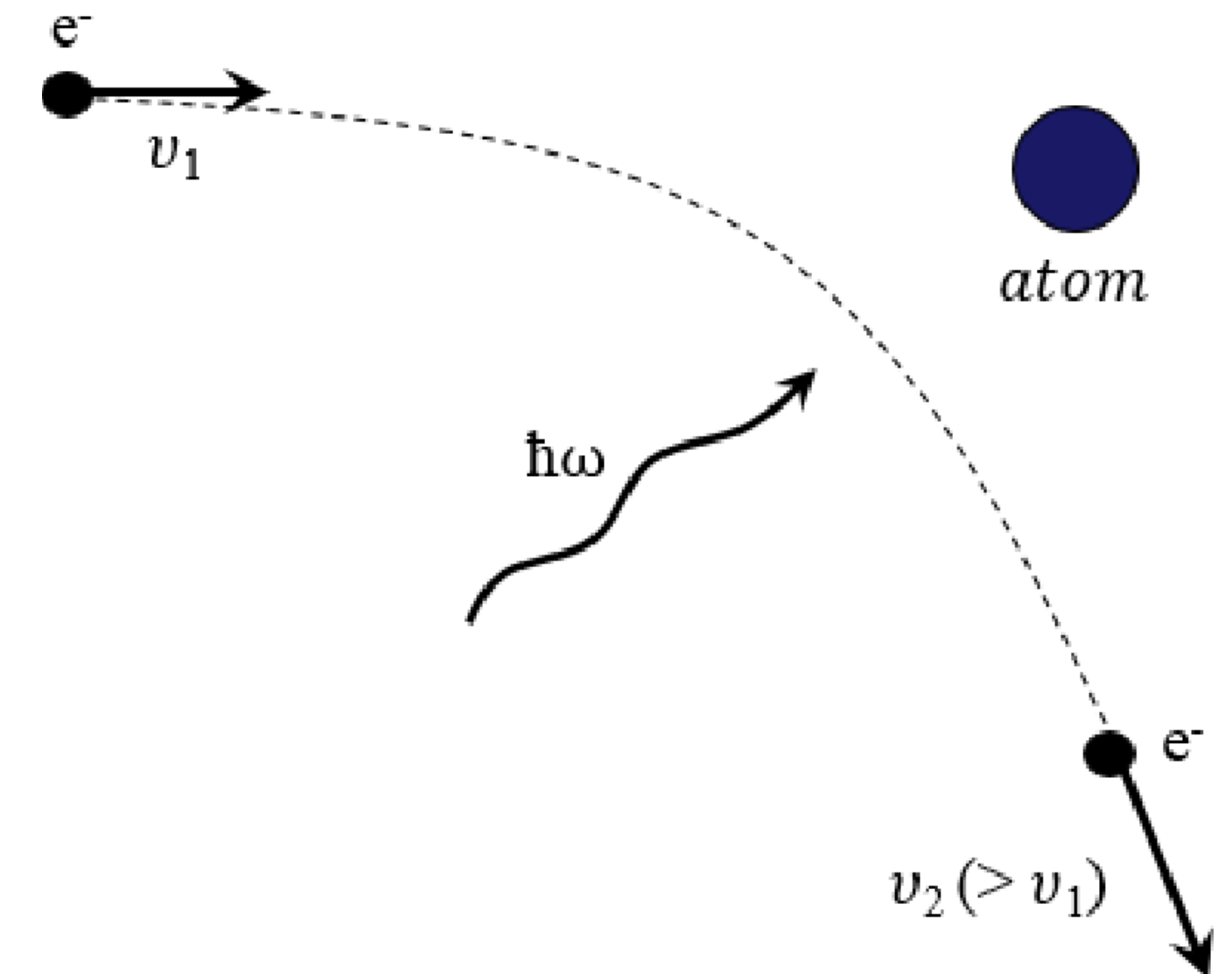
Dark Photon Mass

Edward Hardy, **NS**, 2212.09756

# Criteria for Strong Conversion

- Strong magnetic field is **NOT** required
- **Dense plasma**  $\Rightarrow$  Larger dark photon mass
- **High temperature**  $\Rightarrow$  Less Inverse Bremsstrahlung absorption

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





# White Dwarf Atmosphere

Isotropic plasma  $\Rightarrow$  photon longitudinal polarization does not propagate, only transverse modes convert

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

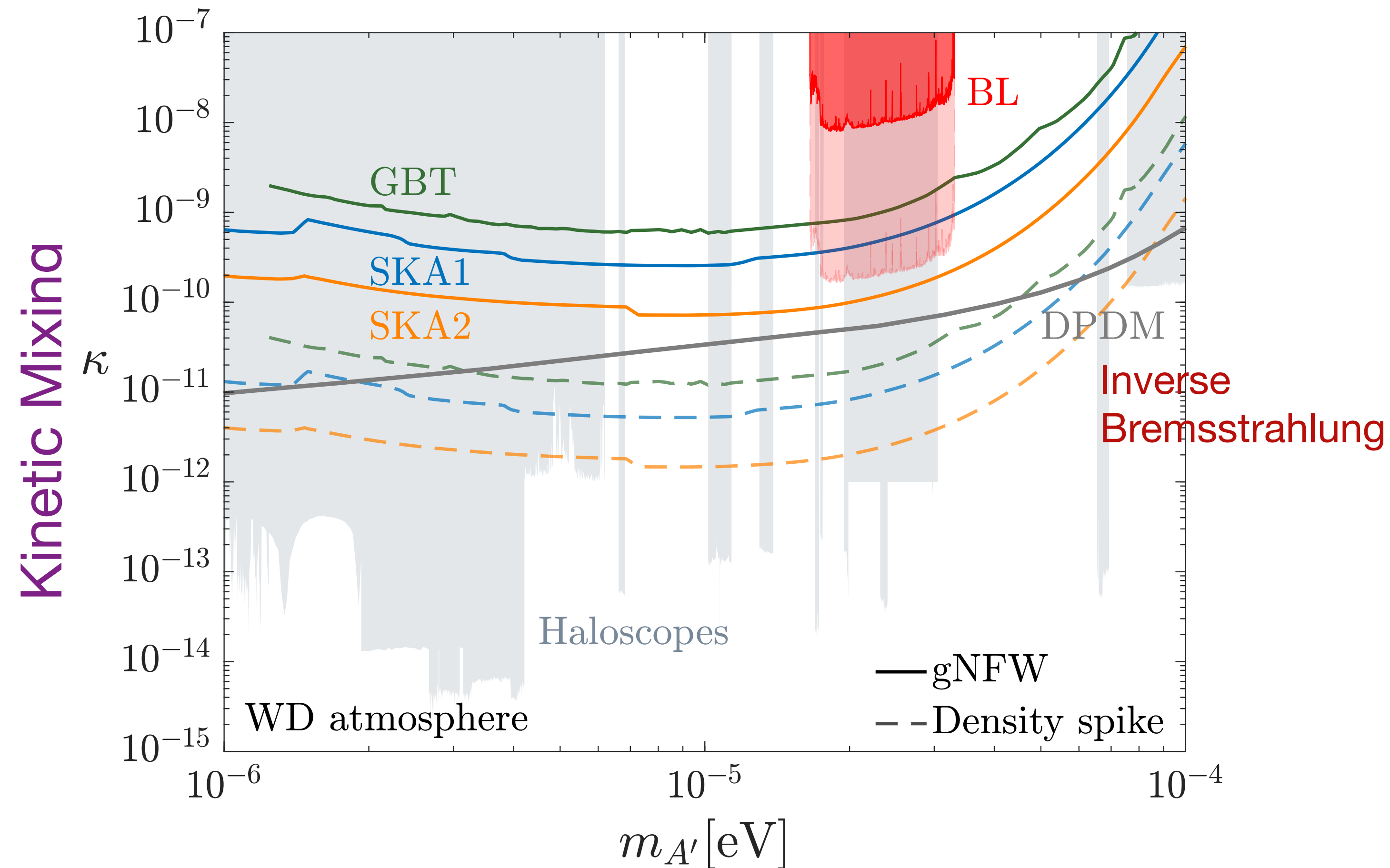


# White Dwarf Atmosphere

- Pressure gradient balances gravity  $l_a \simeq \frac{kT_a r_0^2}{GM_{\text{WD}} \mu m_p} = 0.06 \text{ km} \left( \frac{T_a}{10^4 \text{ K}} \right) \left( \frac{M_{\text{WD}}}{M_\odot} \right) \left( \frac{r_0}{0.01 R_\odot} \right)^2$
- **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  $\frac{d\mathcal{P}}{d\Omega} \simeq 2pr_c^2 \rho_{A'}(r_c) v_c$

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

# Sensitivities from White Dwarf Atmosphere



Collection of white dwarfs

Dark Photon Mass

Edward Hardy, **NS**, 2212.09756

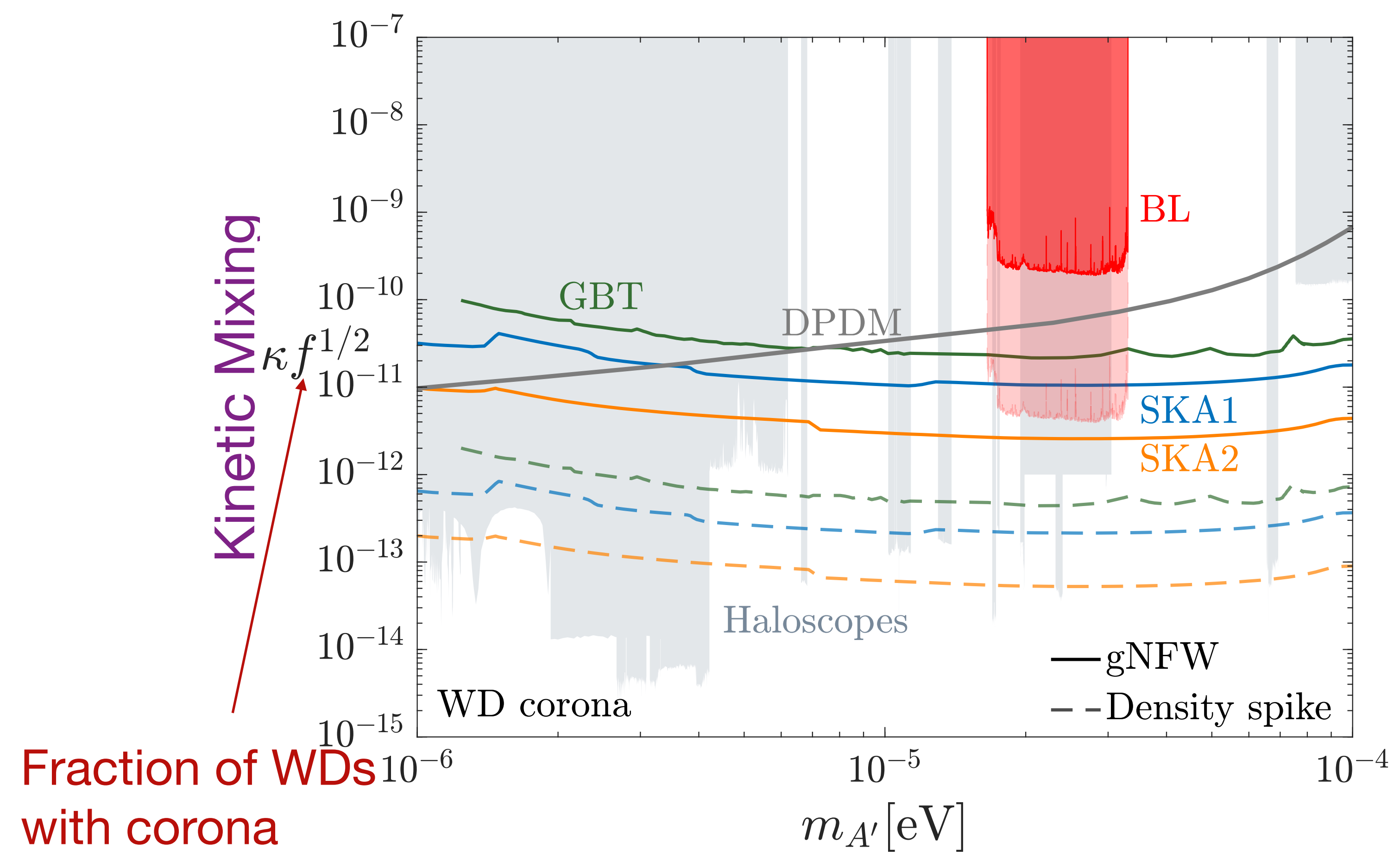
# White Dwarf Corona?

- 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

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



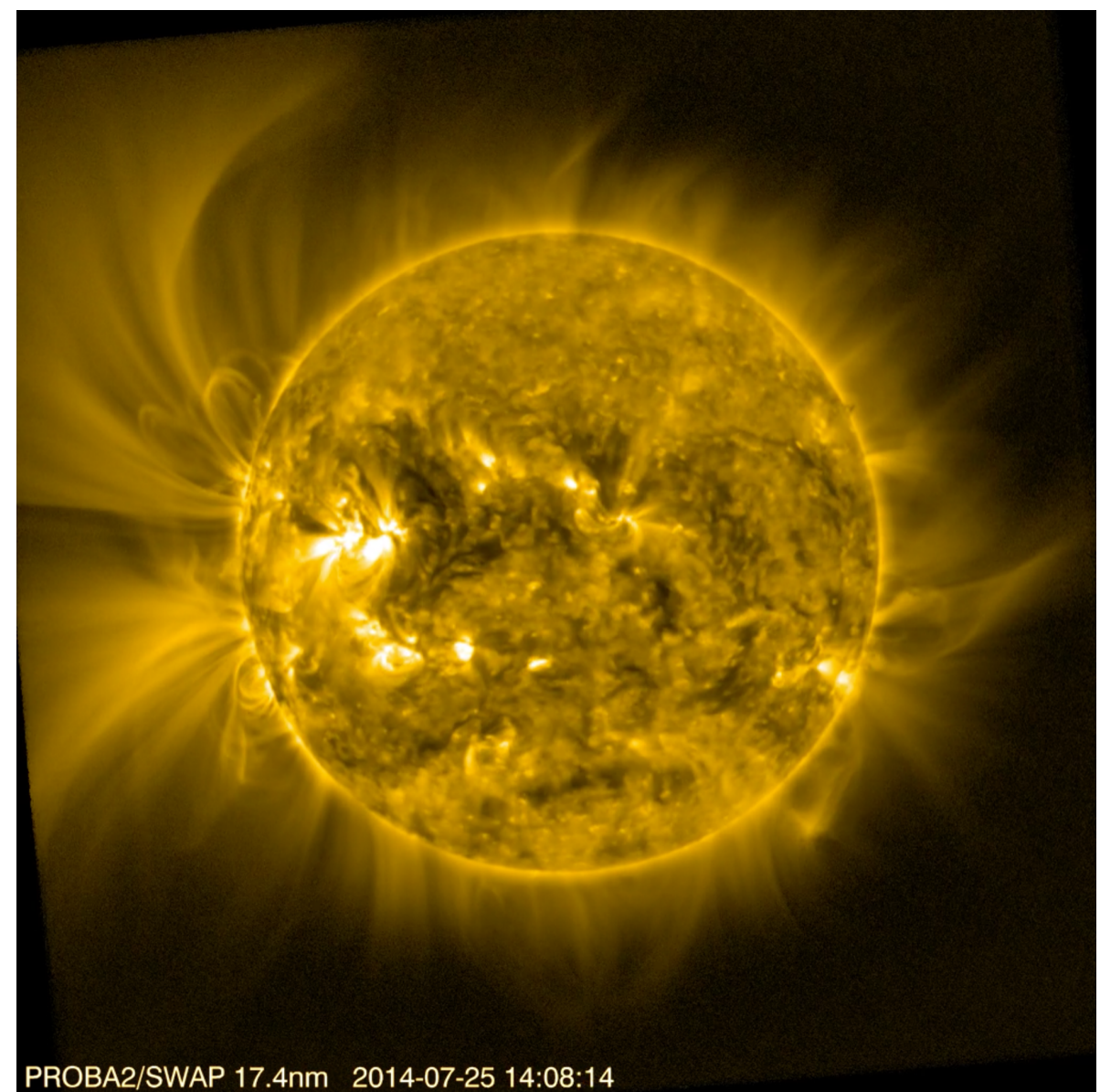
# Sensitivities from White Dwarf Corona



Fraction of WDs  
with corona

Collection of white dwarfs

Dark Photon Mass

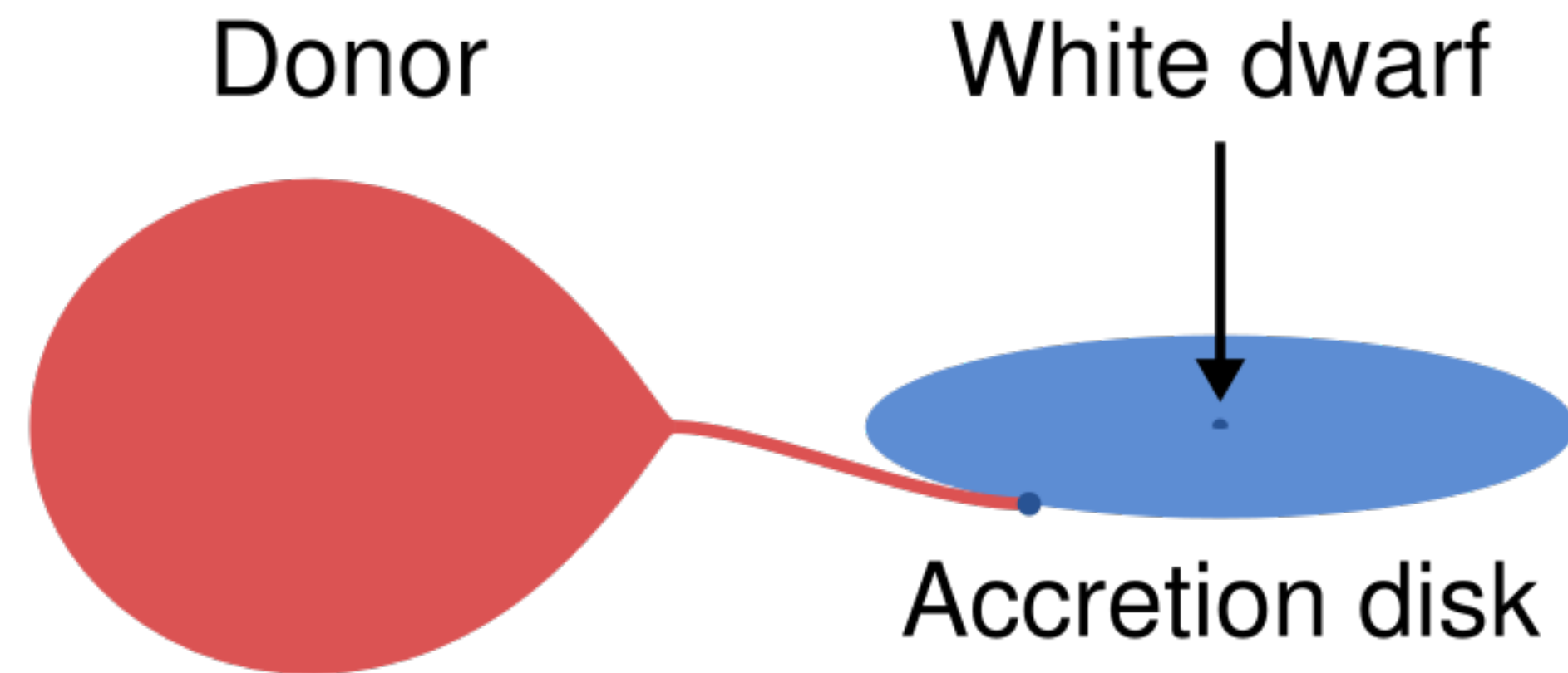


Credit: ESA

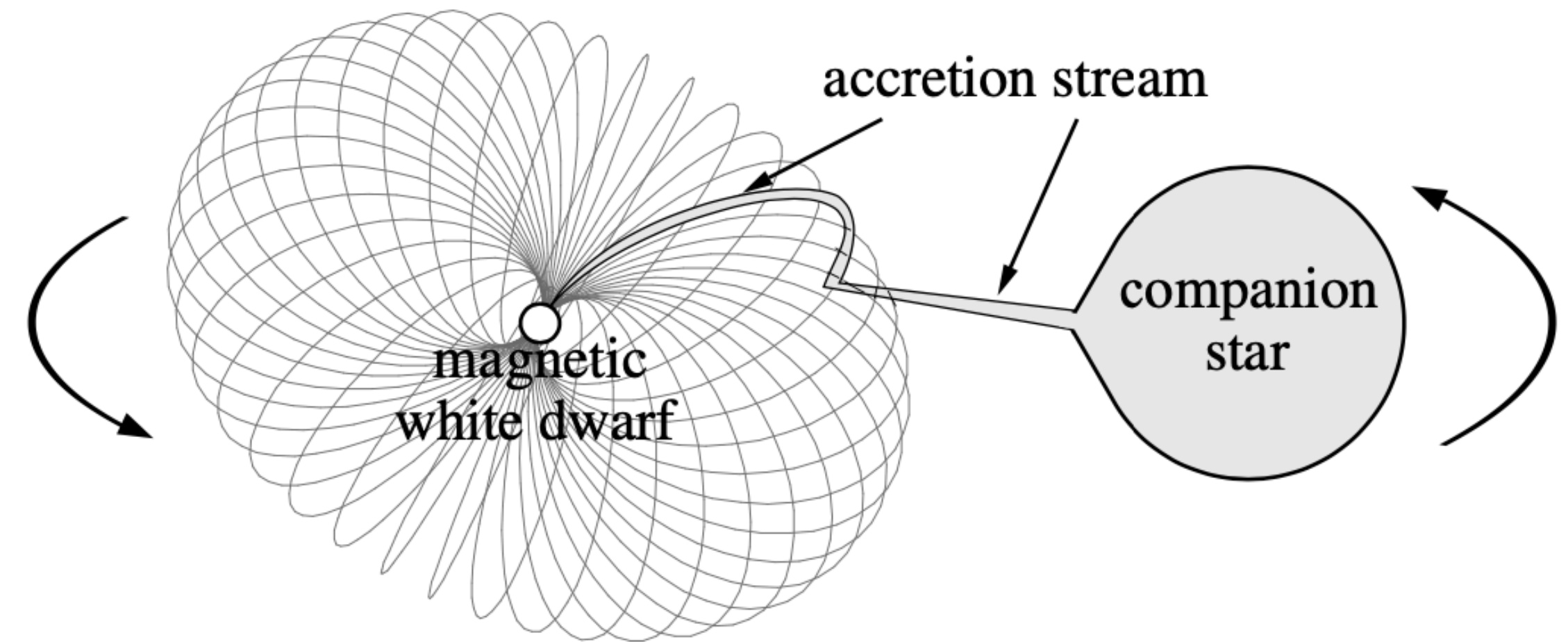
Edward Hardy, **NS**, 2212.09756



# Accreting White Dwarf



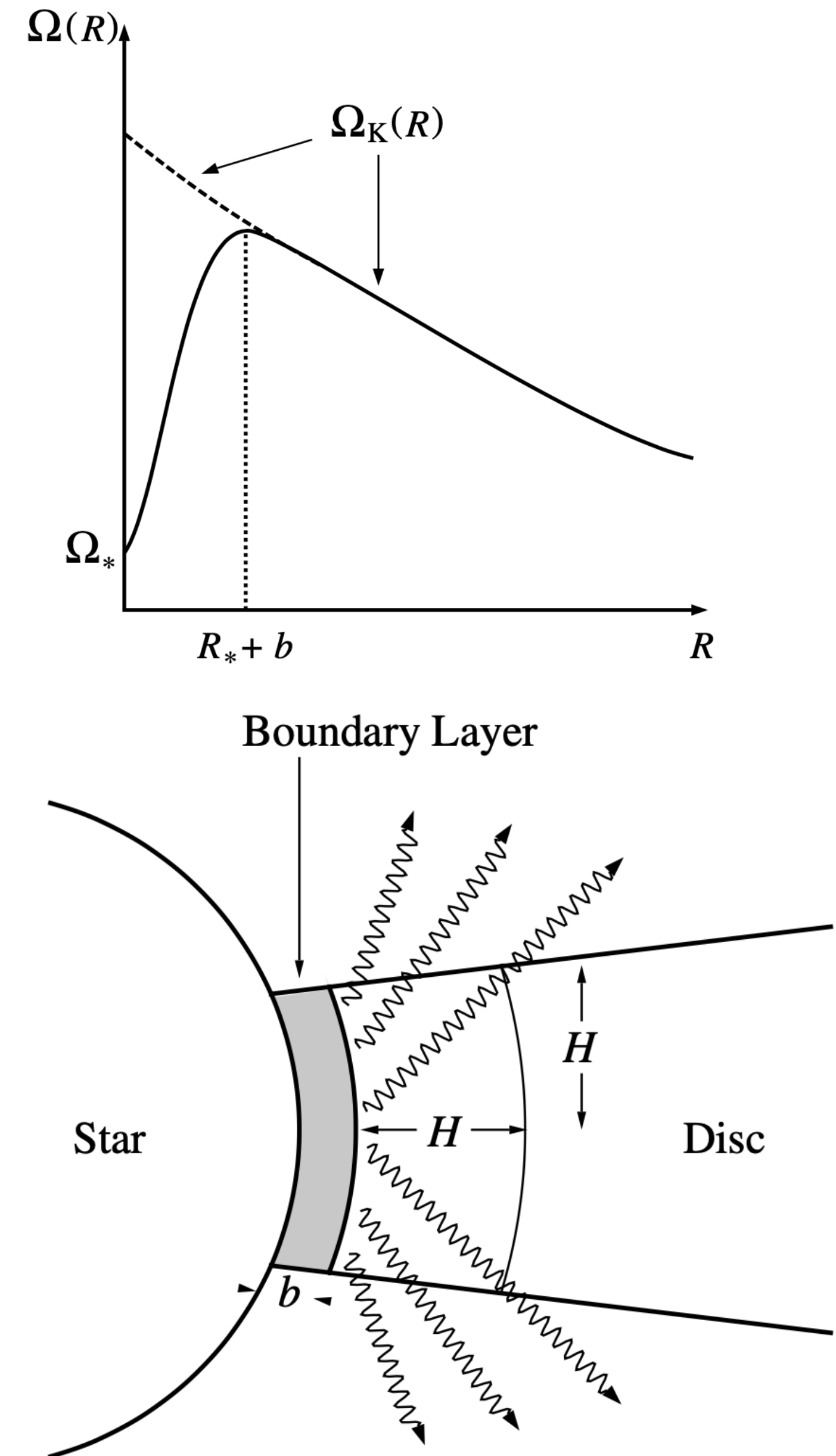
Non-magnetic cataclysmic variable



Magnetic cataclysmic variable

# Non-magnetic Cataclysmic Variables

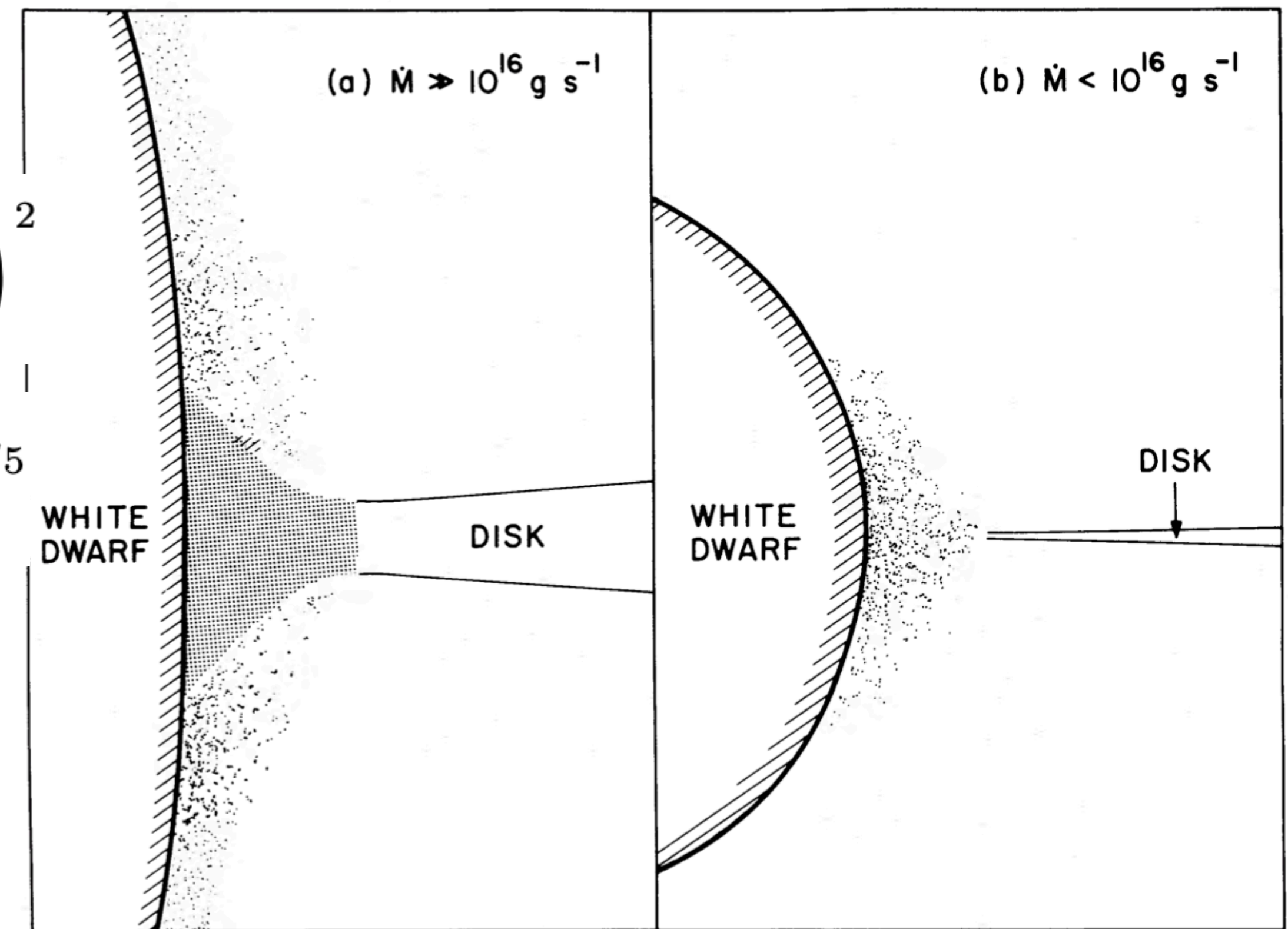
- The inner part of the disk **decelerates** and forms a **hot boundary layer** near the white dwarf surface
- High accretion rate  $\Rightarrow$  **Black body** emission from the **optically-thick** boundary layer
- Low accretion rate  $\Rightarrow$  **Bremsstrahlung** emission from the **optically-thin** boundary layer



# Optically Thin Boundary Layer

- Temperature  $T \simeq \frac{3}{16} \frac{GM\mu m_p}{kR} \sim 10^8 \text{ K}$
- Thickness  $b \simeq 600 \text{ km} \left( \frac{T_s}{10^8 \text{ K}} \right) \left( \frac{M_{\text{WD}}}{M_\odot} \right) \left( \frac{r_0}{0.01 R_\odot} \right)^2$
- Height  $H = 2 \times 10^3 \text{ km} \alpha_d^{-1/10} \dot{M}_{16}^{3/20} \left( \frac{r_0 + b}{10^5 \text{ km}} \right)^{9/8} f_r^{3/5}$
- Density profile

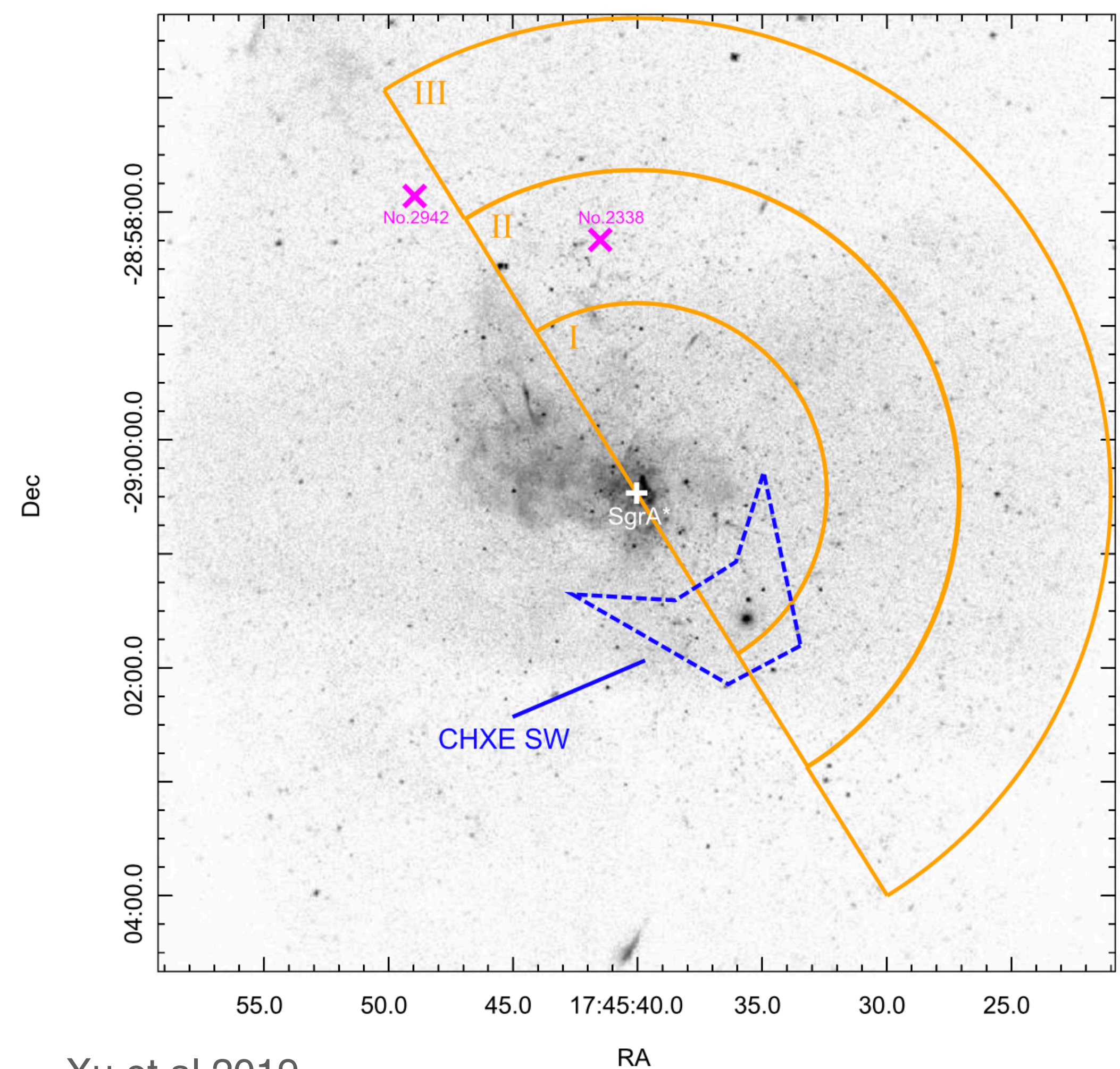
$$n_e = n_d \exp \left( 1 - \frac{r - r_0}{b} - \frac{h^2}{H^2} \right)$$



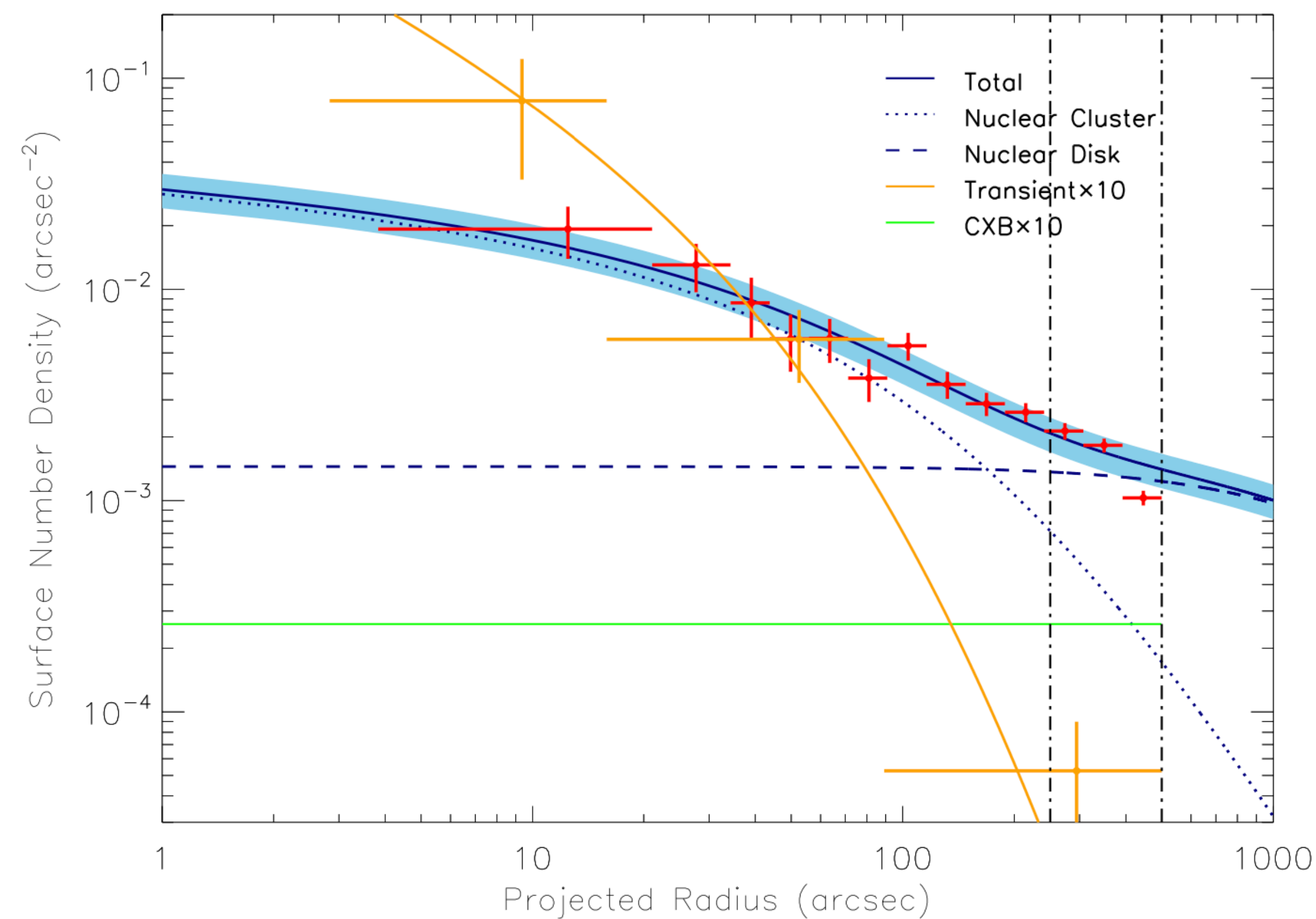
Patterson et al 1985



# X-ray Map in the Galactic Center



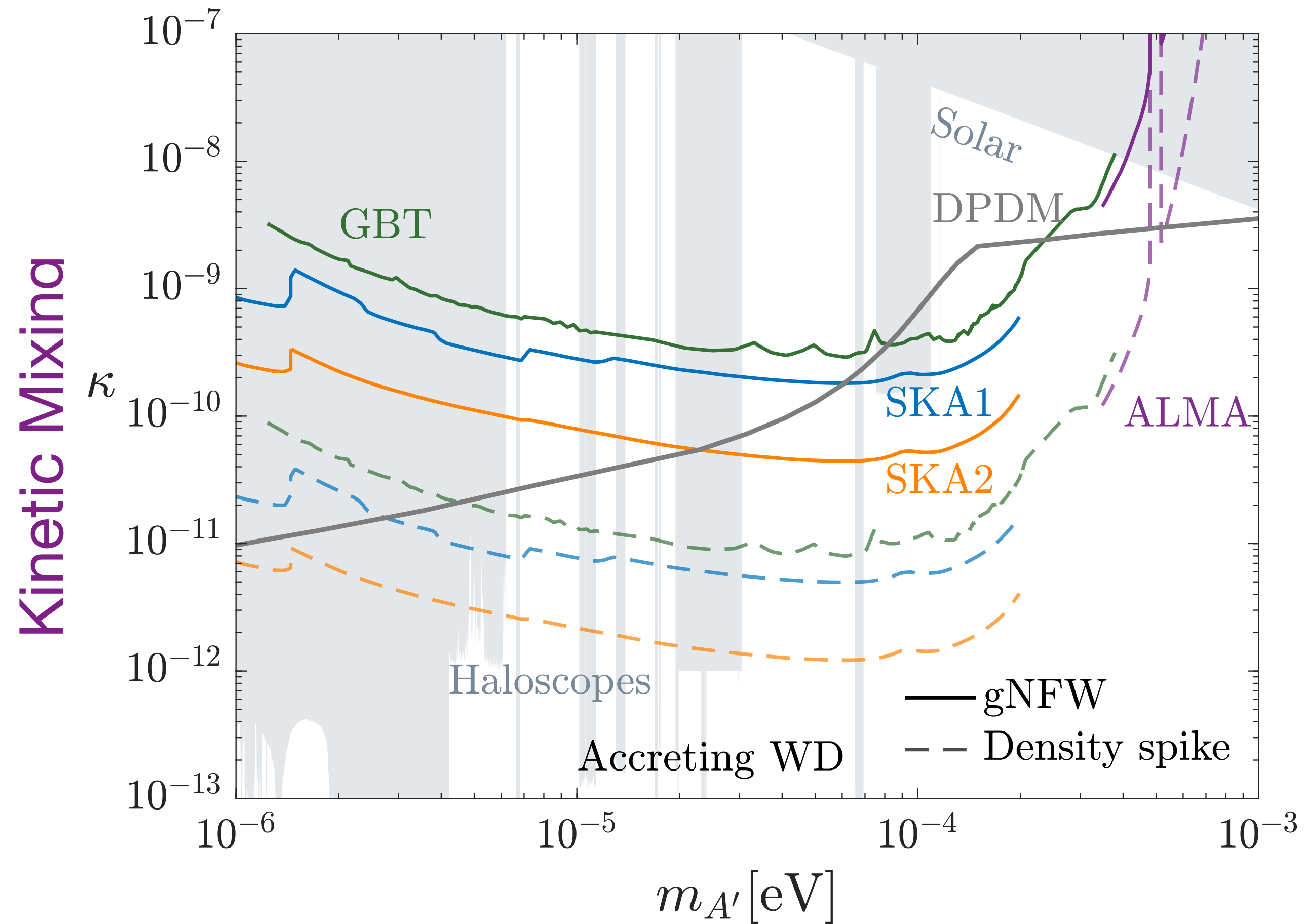
Xu et al 2019



Zhu et al 1802.05073



# Sensitivities from Non-magnetic Cataclysmic Variable



Single accreting white dwarf

Dark Photon Mass

Edward Hardy, **NS**, 2212.09756