Detecting Rare Species of Dark Matter with Large-volume Neutrino Detectors

i) Phys. Rev. Lett. 131, 011005 (2023) [arXiv: 2303.03416]
ii) arXiv: 2309.10032

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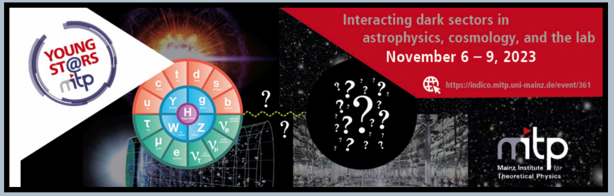
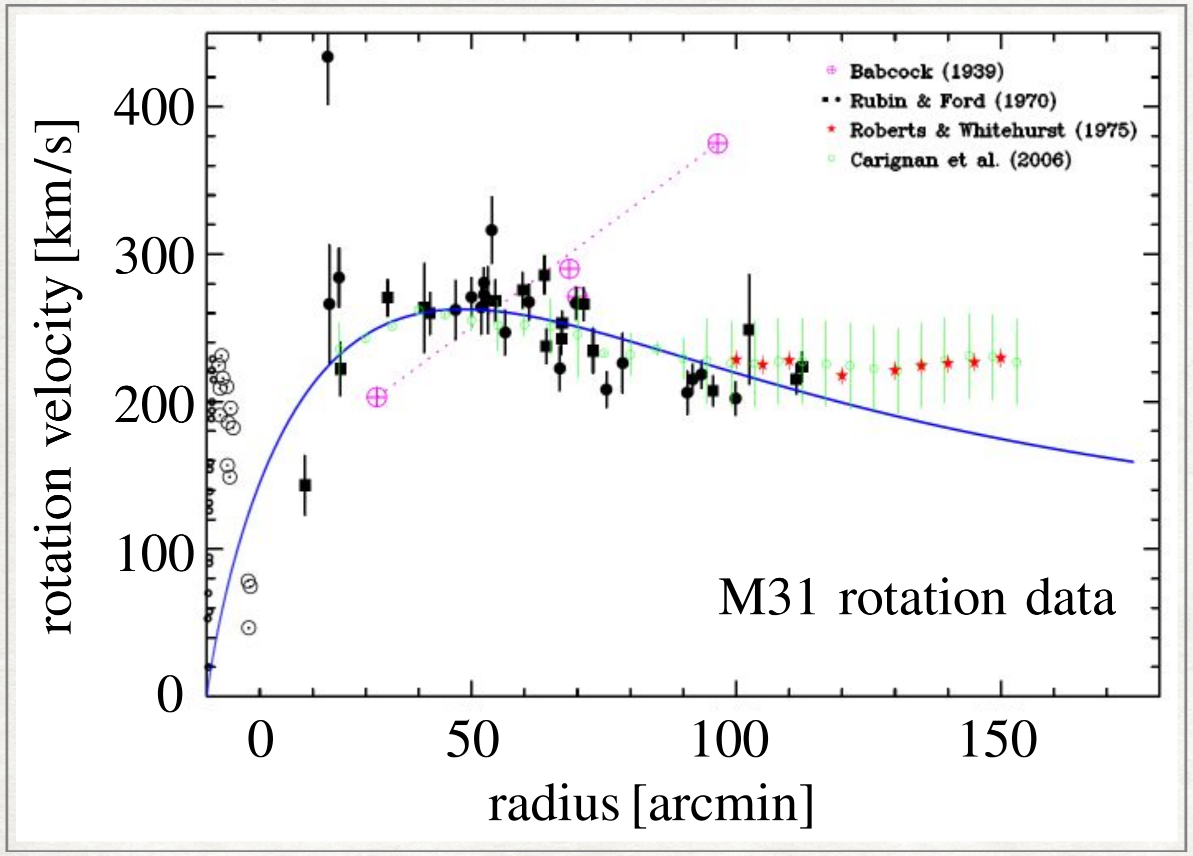
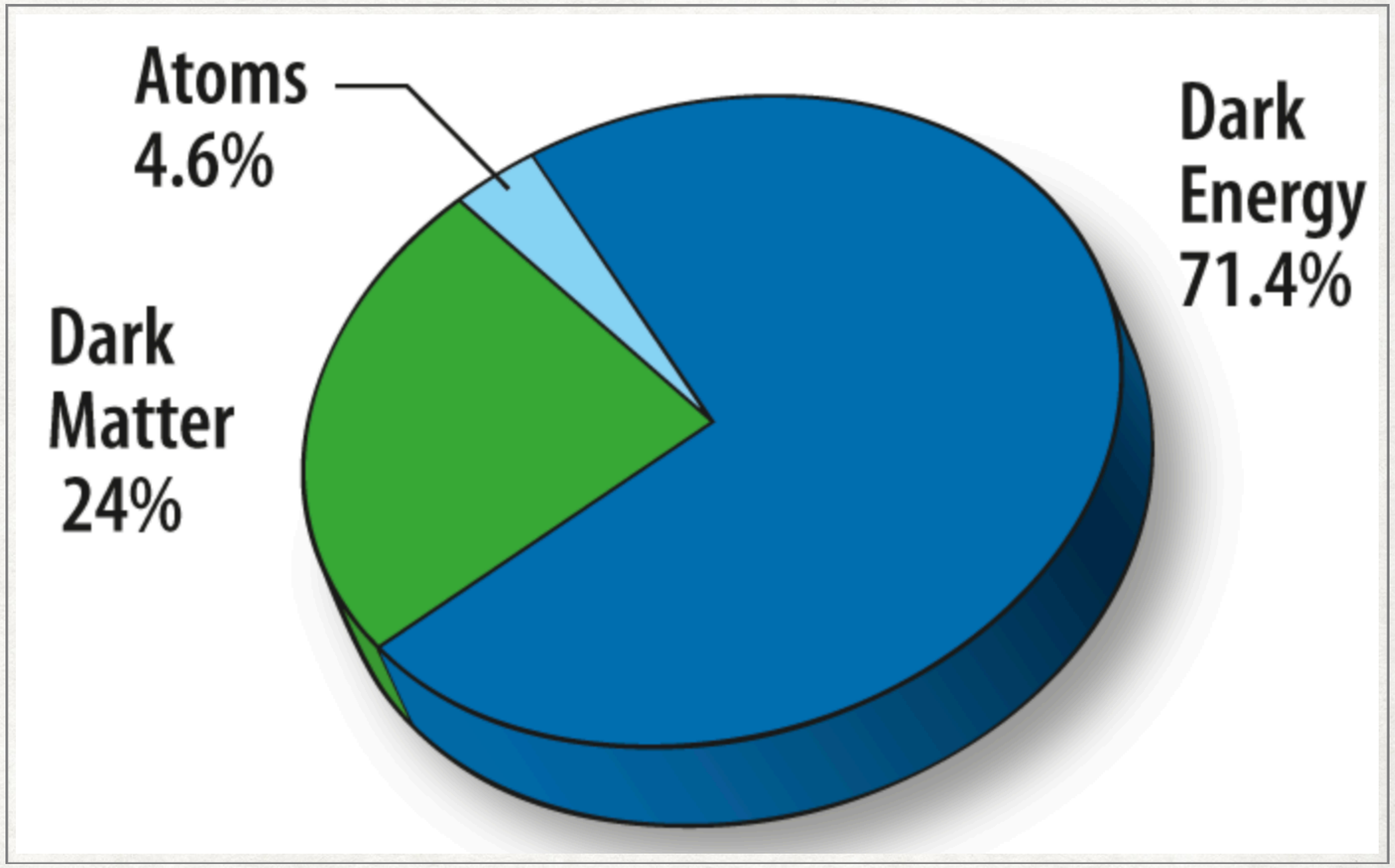


Dark Matter (DM)



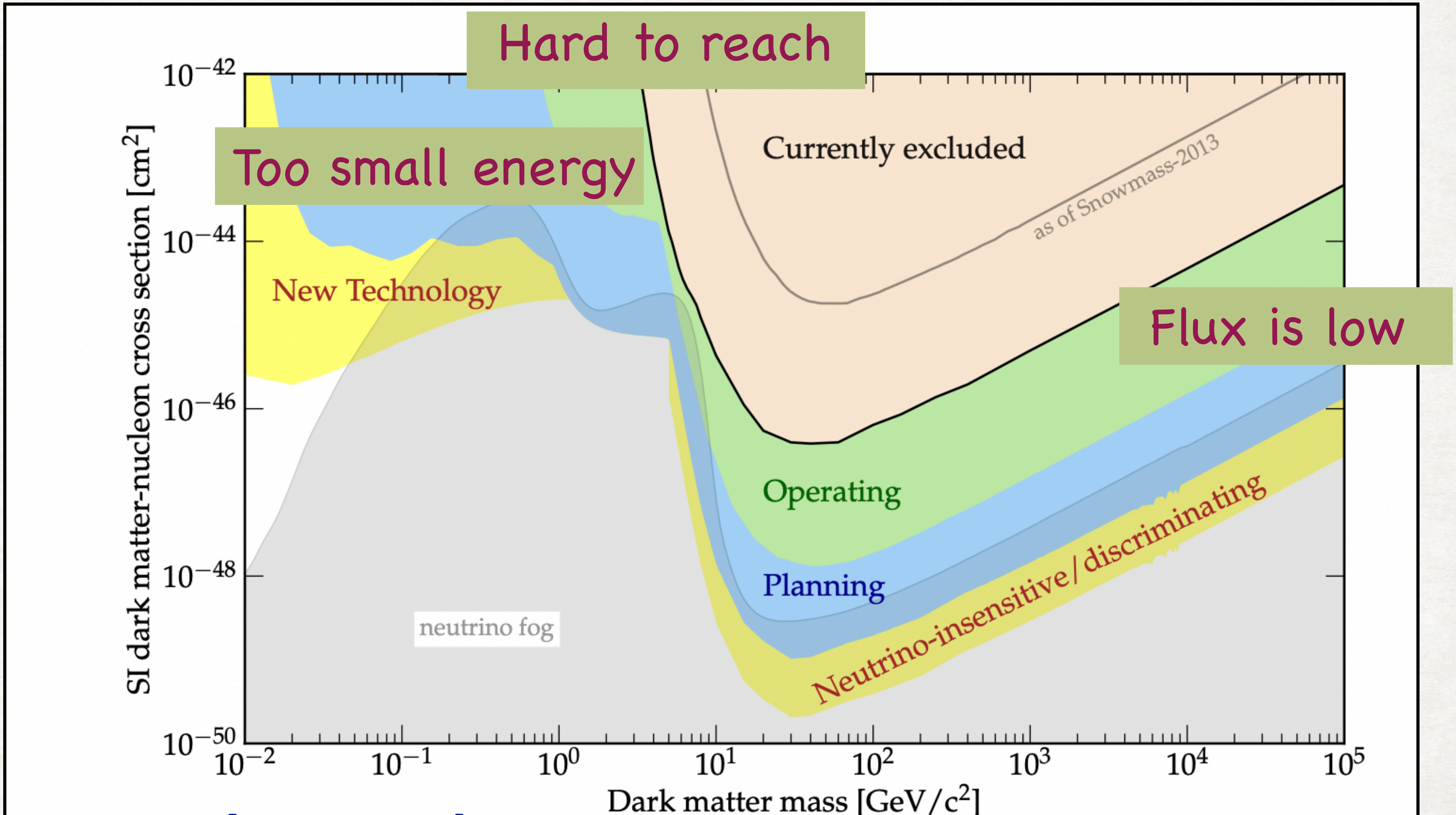
From: Bertone and Hooper, Rev. Mod. Physics (2016)



https://wmap.gsfc.nasa.gov/universe/uni_matter.html

- DM mass?
- DM interactions with baryons?

Direct Detection: Blindspots

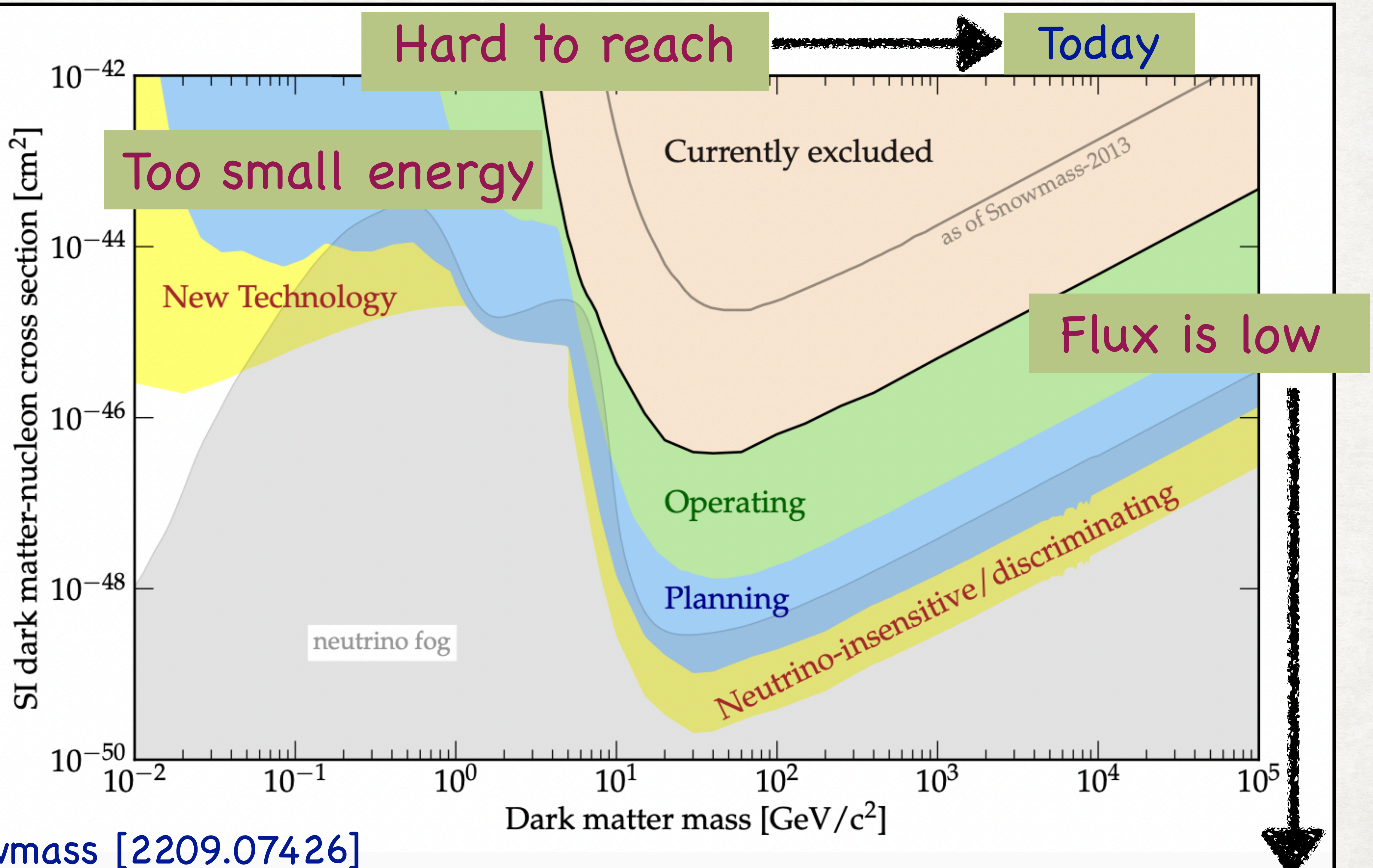


Snowmass [2209.07426]

- Light DM, Heavy DM and Strongly-interacting DM

— "3" Blind-spots to the underground detectors.

Direct Detection: Blindspots

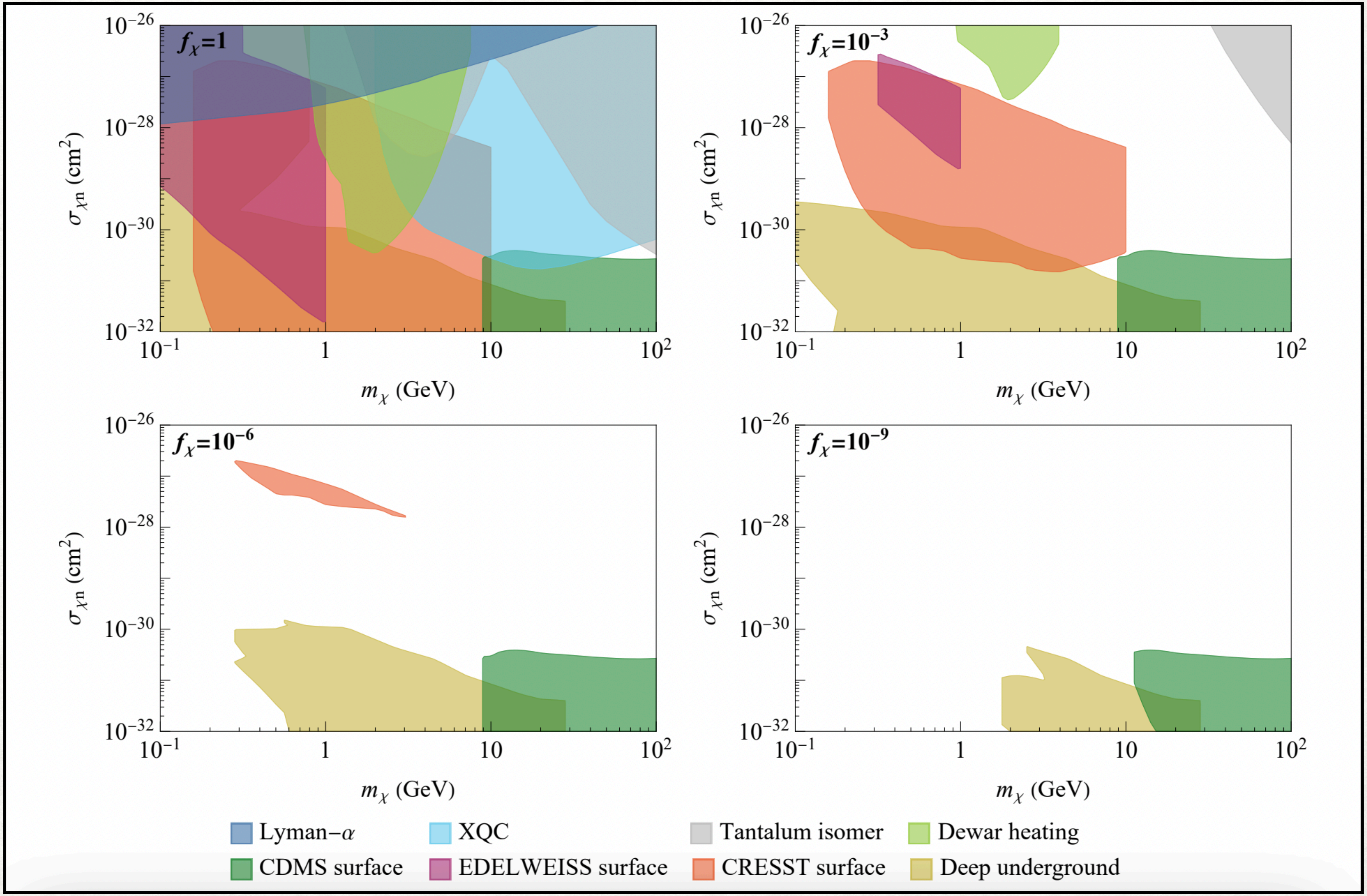


Snowmass [2209.07426]

EM/GW observations of compact objects

Ray (with Bhattacharya, Dasgupta, Laha) [PRL, 2023]

Strongly-interacting DM Component



Mckeen et al [PRD,2022]

Summary

- Earth accumulates significant number of DM particles from the Galactic halo, leading to a DM density up to 15 orders of magnitude larger than the Galactic DM density!

"Earth-bound DM"

- Local annihilation of Earth-bound DM particles inside any large-volume neutrino detectors (such as Super-Kamiokande) provides unprecedented sensitivity to strongly-interacting DM component.

Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]

- Neutrinos from annihilation of Earth-bound DM from the center of the Earth provide yet another probe of strongly-interacting DM component.

Pospelov & Ray [2309.10032]

Outline

- Earth-bound DM and their accumulation.

- Distribution of Earth-bound DM.

- Earth-bound DM at Super-Kamiokande.

  Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]

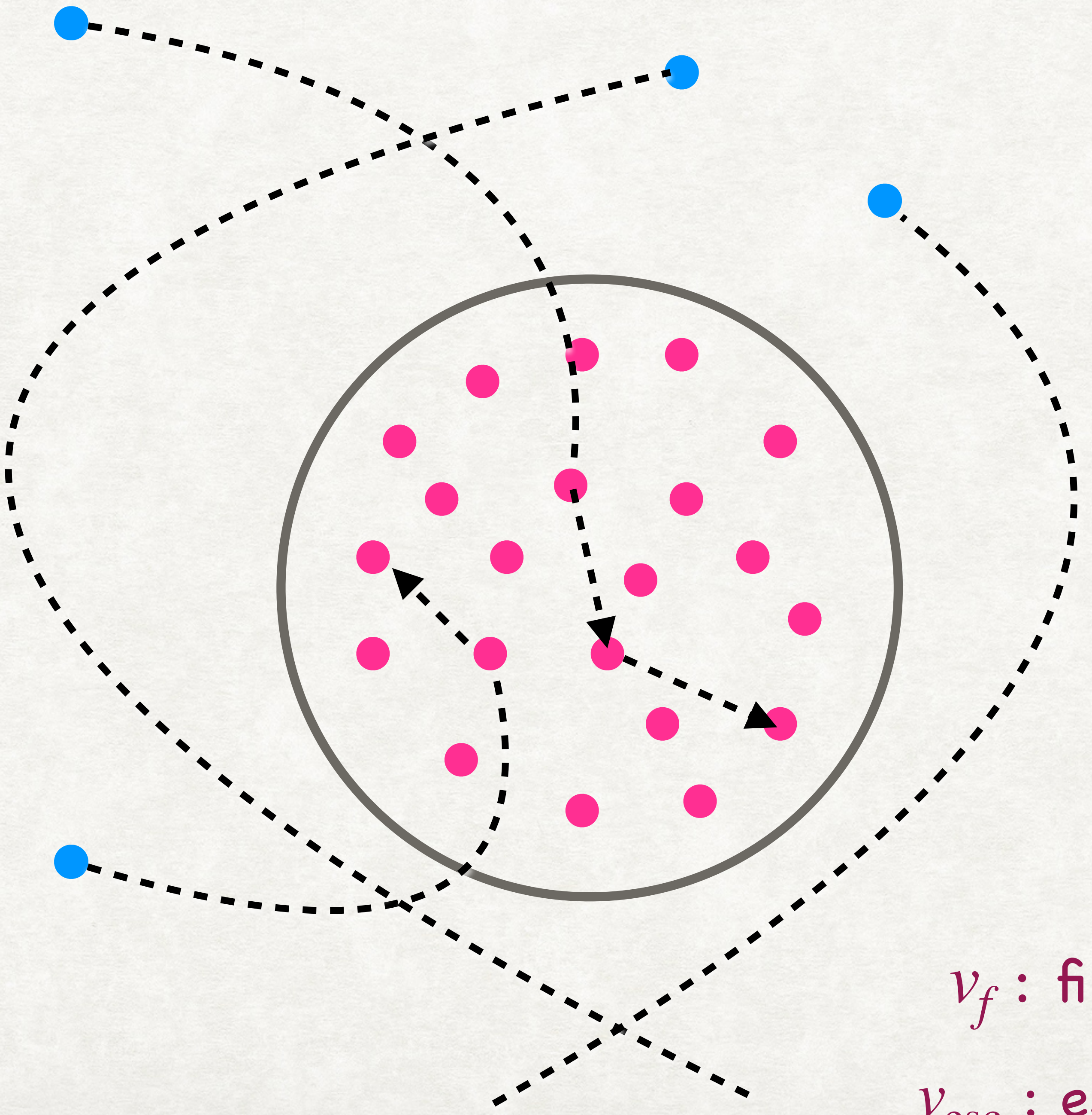
- Earth-bound DM annihilation to neutrinos.

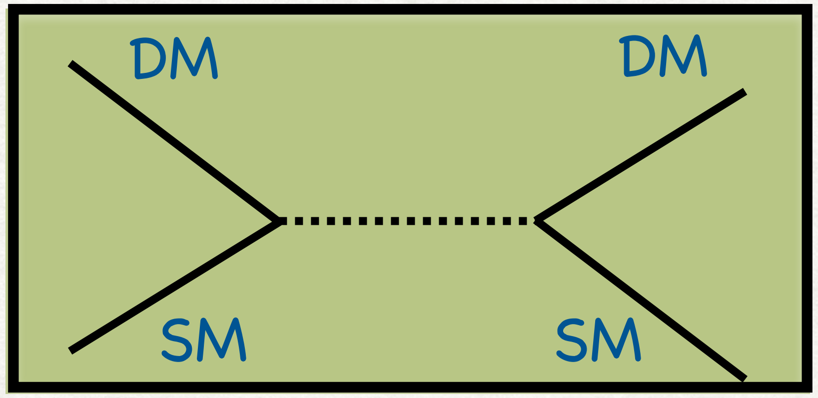
  Pospelov & Ray [2309.10032]

DM Accretion in Stellar Objects

Press & Spergel (1985,ApJ), Gould (1987, ApJ),...

Small $\sigma_{\chi n} \rightarrow$ single collision, large $\sigma_{\chi n} \rightarrow$ multiple collisions.





$v_f \leq v_{esc}$ (captured)

v_f : final velocity of the DM particles

$v_{\rm esc}$: escape velocity of the stellar object

DM accretion in stellar objects

- Number of DM particles that passes through:

$$C_{\rm geo} = \frac{\rho_\chi}{m_\chi} \pi R^2 \int \frac{f(u)du}{u} (u^2 + v_{\rm esc}^2)$$

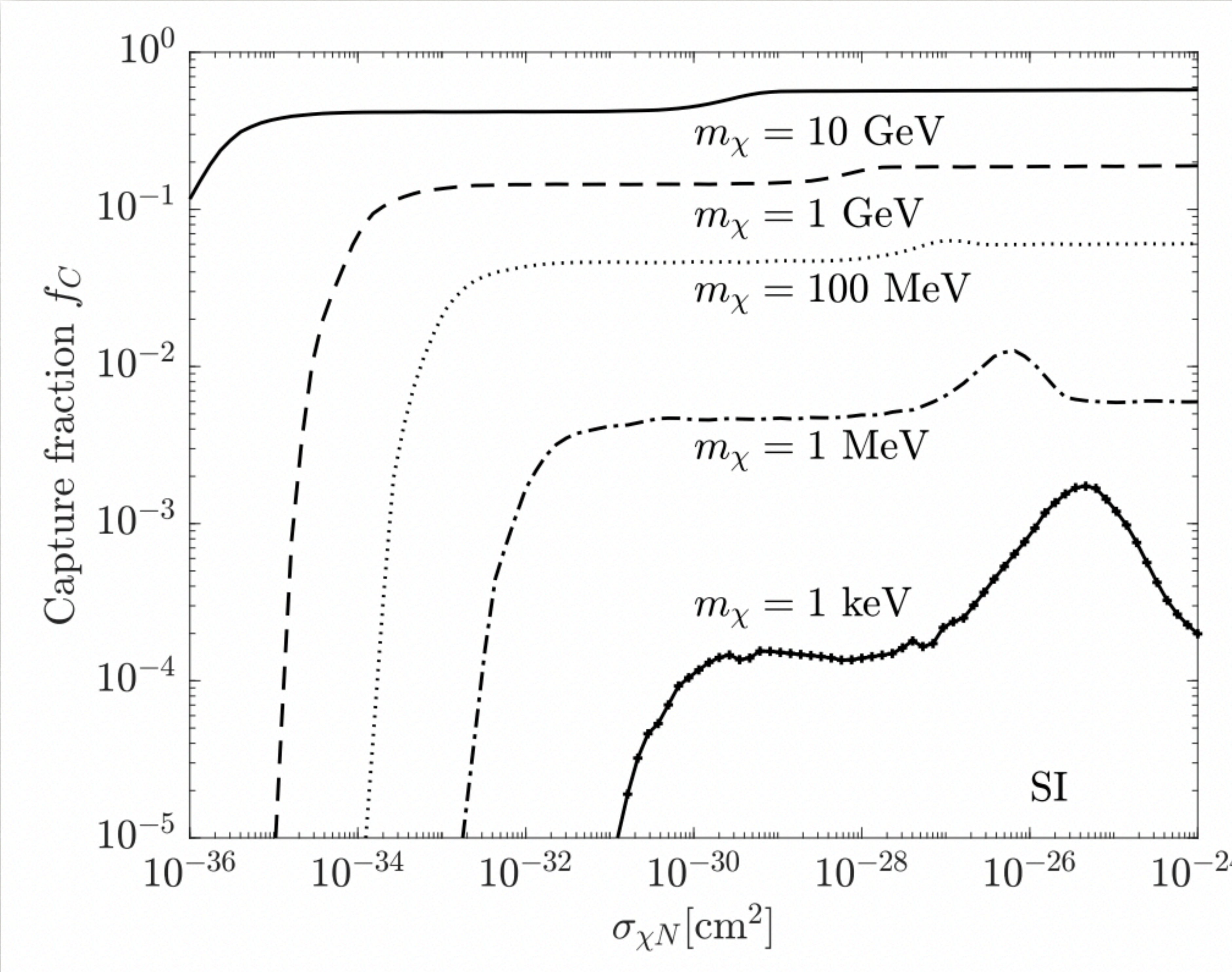
- A fraction of them gets captured depending on DM-nucleon interaction strength and DM mass.

$$\Gamma_{\rm cap} = f_c \times C_{\rm geo}$$

$$f_c \left(\sigma_{\chi n}, m_\chi \right)$$

Neufeld et al (2018, APJ), Bramante et al. (2022, PRD)...

DM accretion in stellar objects



$$f_c\left(\sigma_{\chi n}, m_\chi\right)$$

Bramante et al. (2022, PRD)

DM accretion in stellar objects

- Lets do some estimate:

For DM mass of 1 GeV and $\sigma_{\chi n} = 10^{-28}\,\mathrm{cm}^2$

$$C_{\rm geo} = 1.3 \times 10^{25}\,\mathrm{s}^{-1} \quad \text{and} \quad f_c \sim 0.1$$

f_χ = 1

DM density (assuming they uniformly distribute over the Earth-volume)

$$\rho_\chi = m_\chi \frac{f_c \times C_{\rm geo} \times t_\oplus}{V_\oplus} \sim 3 \times 10^{14}\,\mathrm{GeV/cm^3}$$

f_χ = 1

- 15 orders of magnitude larger than the Galactic DM density!

DM Distribution in Stellar Objects

- DM distribution inside the celestial objects depends on the effects of diffusion and gravity.

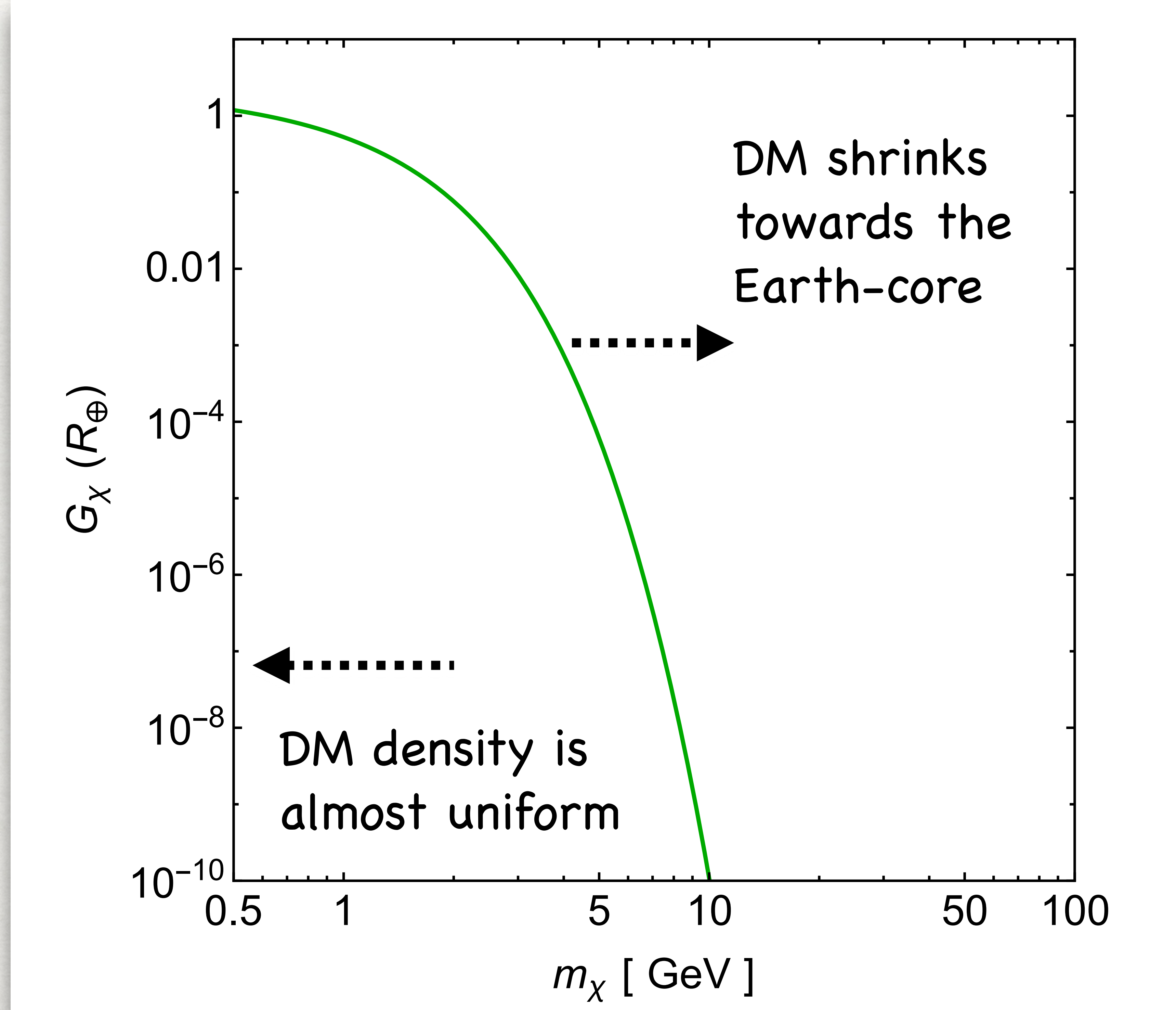
Gould and Raffelt (1990, APJ), ..., Leane et al (2209.09834)

$$\frac{\nabla n_\chi(r)}{n_\chi(r)} + (\kappa+1)\frac{\nabla T(r)}{T(r)} + \frac{m_\chi g(r)}{T(r)} = \frac{\Phi}{n_\chi(r) D_{\chi n}(r)} \frac{R_\oplus^2}{r^2}$$

- For heavy DM, the effect of gravity dominates over the diffusion processes, and they shrink towards the stellar core.

- For light DM, the distribution is almost uniform, leading to a huge surface density.

DM Distribution in Stellar Objects



- Dimensionless profile function:

$$G_\chi(R_\oplus) = \frac{n_\chi(R_\oplus)V_\oplus}{N_\chi}$$

- For uniform DM density:

$$G_\chi(R_\oplus) = 1$$

DM Evaporation

- Light DM can get thermal kick and escape the Earth-volume, commonly known as "Evaporation".

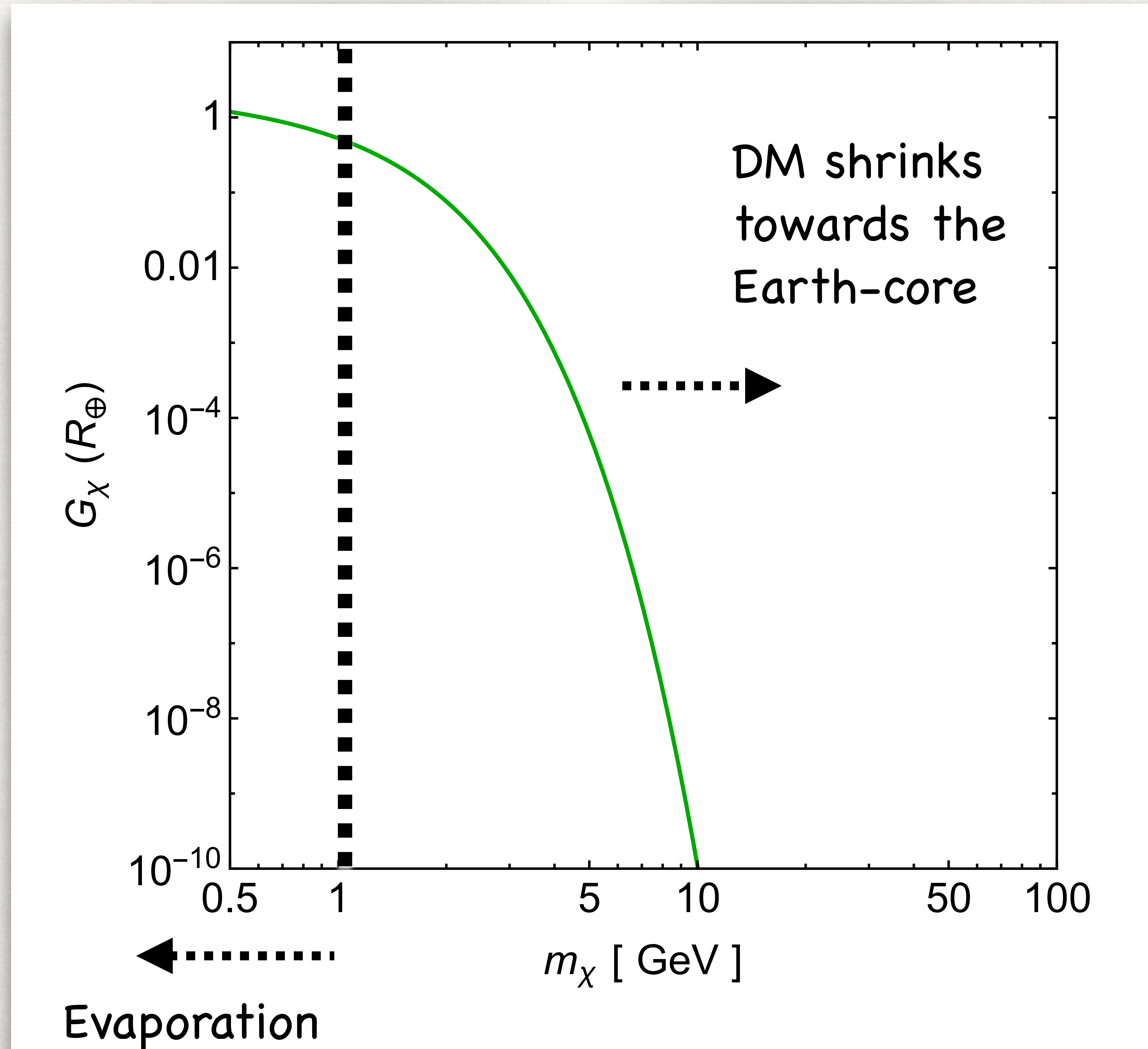
Gould (1990, APJ), …, Garani and Ruiz (JCAP, 2017, 2021),…

- In the strongly-interacting regime, evaporation primarily occurs from the Earth-surface (in the standard weakly interacting regime, evaporation occurs mostly from core).

Surface temperature is ~20 smaller than the core-temperature, this leads to smaller evaporation mass for large $\sigma_{\chi n}$.

- We found evaporation does not allow to retain $m_\chi \lesssim 1$ GeV (irrespective of DM-nucleon scattering cross-section).

DM Distribution in Stellar Objects



- Dimensionless profile function:

$$G_\chi(R_\oplus) = \frac{n_\chi(R_\oplus) V_\oplus}{N_\chi}$$

- For uniform DM density:

$$G_\chi(R_\oplus) = 1$$

Signal at SK

- Earth-bound DM, of mass GeV scale are present in a copious amount inside any large-volume detectors (for example Super-K).

- Their detection via scattering is almost impossible as they acquire very little amount kinetic energy (0.03 eV), much lower than the detection threshold of typical DM detectors.

Recently, Das, Kurinsky, and Leane [2210.09313] have proposed their detection via "futuristic" low-threshold quantum detectors.

Our proposal: simply look at their annihilation signature (as the annihilation channel is not limited to the tiny kinetic energy)!

Signal at SK

- For DM mass of 2 GeV, and large $\sigma_{\chi n}$ (say $\sigma_{\chi n} = 10^{-28}\,\mathrm{cm}^2$), annihilation rate inside Super-K is quite huge.

$$\Gamma_{\rm ann}^{\rm SK} = n_\chi^2(R_\oplus)\langle\sigma v\rangle_{\rm ann} V_{\rm SK}$$

$$\Gamma_{\rm ann}^{\rm SK} = n_\chi^2(R_\oplus)\langle\sigma v\rangle_{\rm ann} V_{\rm SK} \sim 2\times 10^{11}\,\mathrm{yr}^{-1} \qquad f_\chi = 1$$

- Given the relevant energy range of annihilations, we use the di-nucleon analysis (n+n $\rightarrow 2\pi^0 \rightarrow 4\gamma$) performed by Super-K.

background-free identification with an efficiency of ~ 10%

Super-Kamiokande (PRD, 2015)

Results

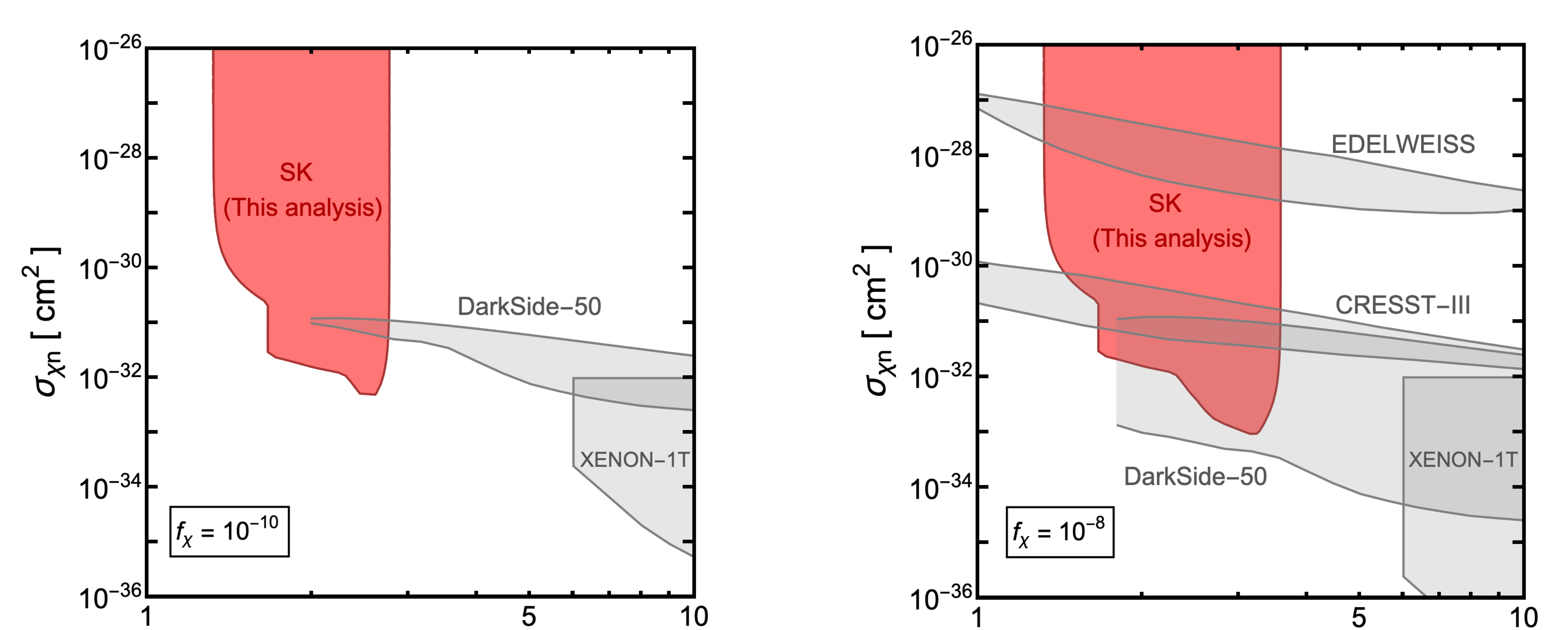
- Exclusion limits are simply derived:

$$\epsilon \times \Gamma_{\rm ann}^{\rm SK} \times t_{\rm obs} \leq 3$$

$\epsilon \sim 10\%$

$t_{\rm obs} = 4581.5$ days

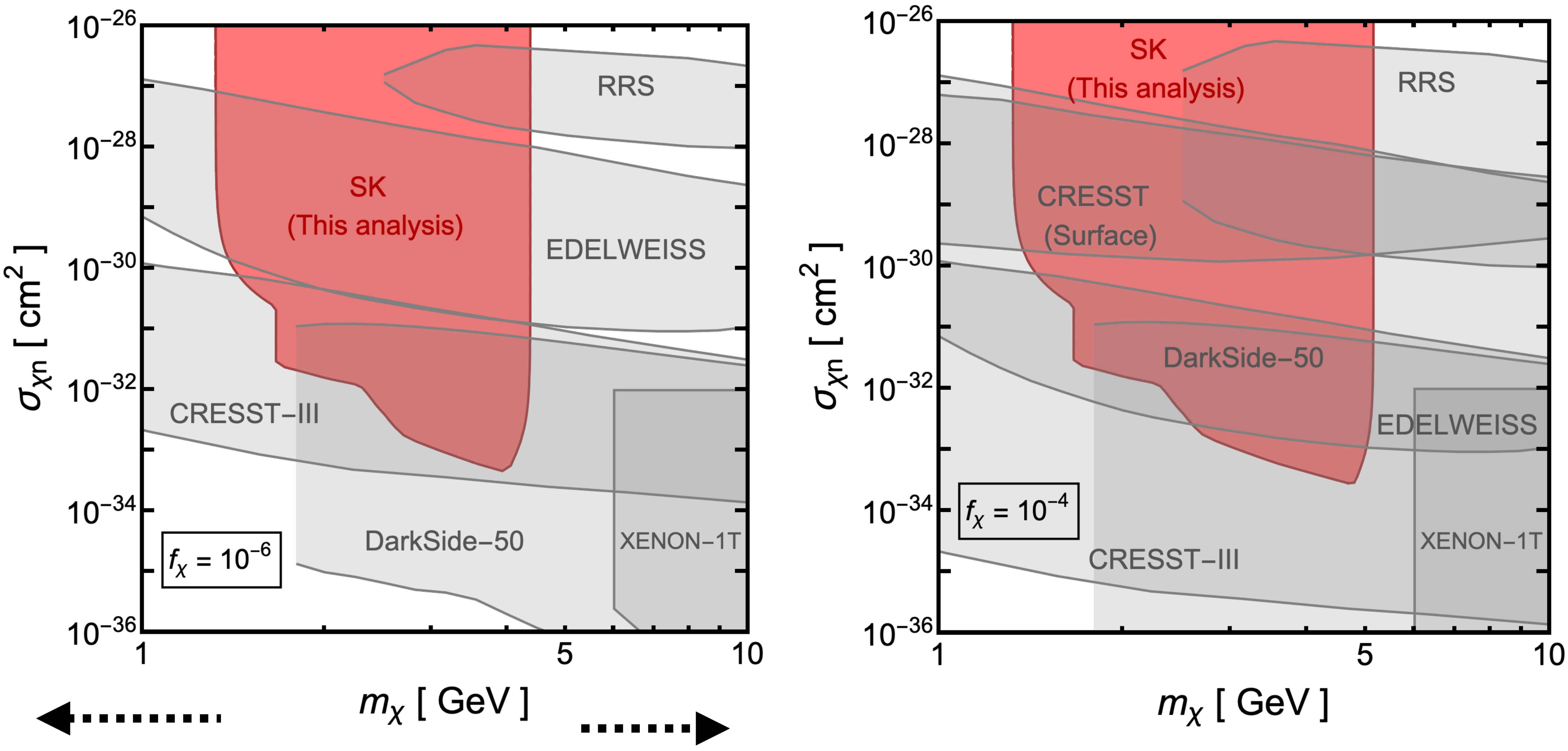
Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]



Up to $f_\chi = 10^{-10}$

Results

Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]



Evaporation

DM shrinks towards the Earth-core

Model

- Let's illustrate our result in a concrete phenomenological model.

$$\mathscr{L} = -\frac{1}{4}\left(F'_{\mu\nu}\right)^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{A'}^2\left(A'_\mu\right)^2 + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi$$

χ : Dirac fermion which can couple to a dark photon A'

- The perturbative cross section for χ to scatter on a nucleus (Z, A) is related to the model parameters

$$\sigma_{\chi A} = \frac{16\pi Z^2 \alpha \alpha_d \epsilon^2 \mu_{\chi A}^2}{m_{A'}^4}$$

Pospelov, Ritz, Voloshin (PLB, 2008)

Model

- We are interested in the following channel

$$\chi\bar{\chi} \rightarrow A'A' \quad \text{with } A' \rightarrow \text{SM + SM (say } e^+ + e^-)$$

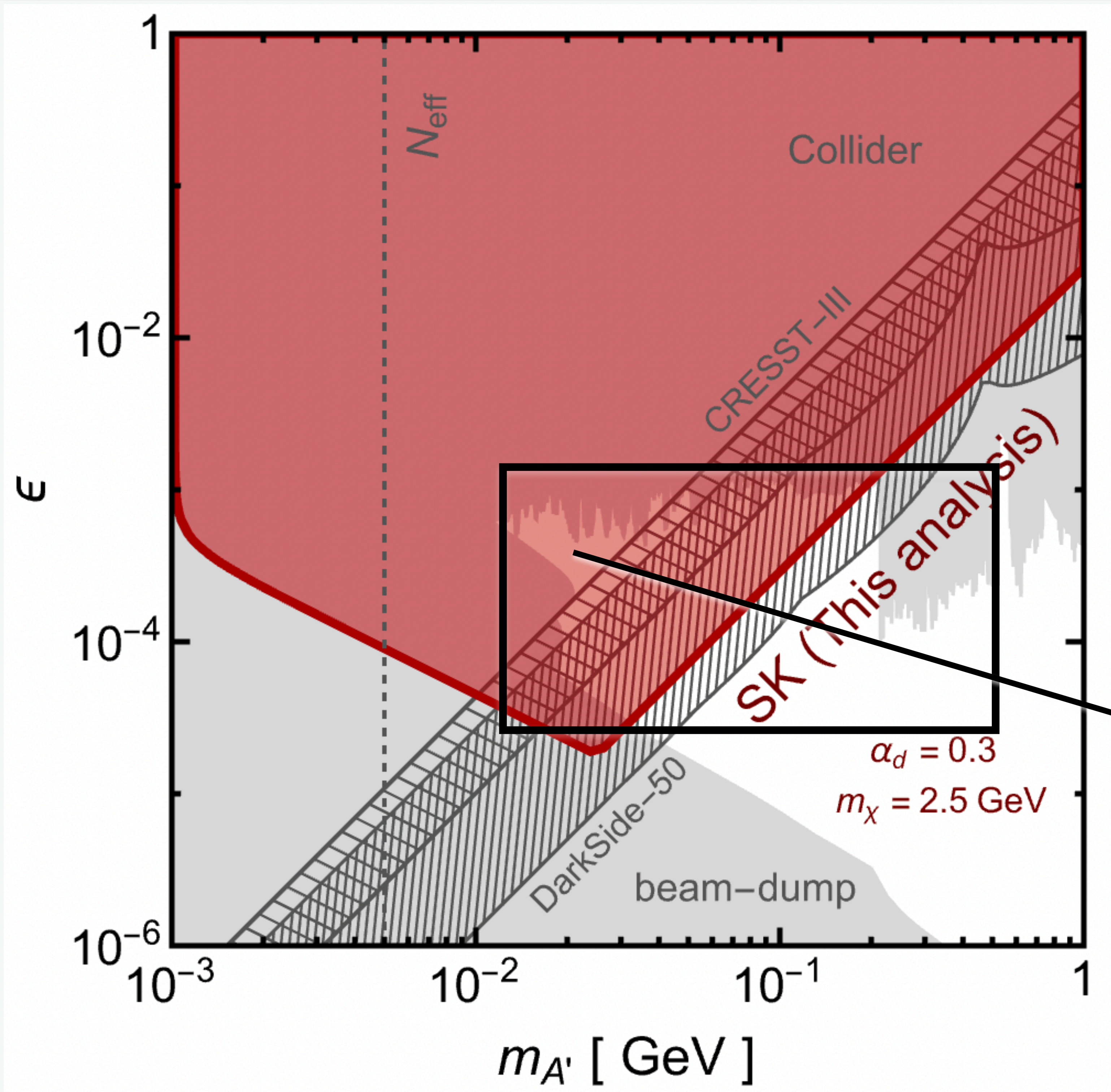
$$\langle \sigma v \rangle_{\text{ann}} = \frac{\pi \alpha_d^2}{m_\chi^2} \frac{\left(1 - m_{A'}^2/m_\chi^2\right)^{3/2}}{\left(1 - m_{A'}^2/4m_\chi^2\right)^2}$$

$$\Gamma_{A'} = \frac{1}{3} \alpha \epsilon^2 m_{A'} \left(1 + \frac{2m_e^2}{m_{A'}^2}\right) \left(1 - \frac{4m_e^2}{m_{A'}^2}\right)^{1/2}$$

- To ensure the decay within the Super-K fiducial volume, we restrict the decay length $\gamma c \tau_{A'} \leq 1\,\text{m}$.

Results

Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]



Unprecedented sensitivity on parts of the parameter space.

Summary

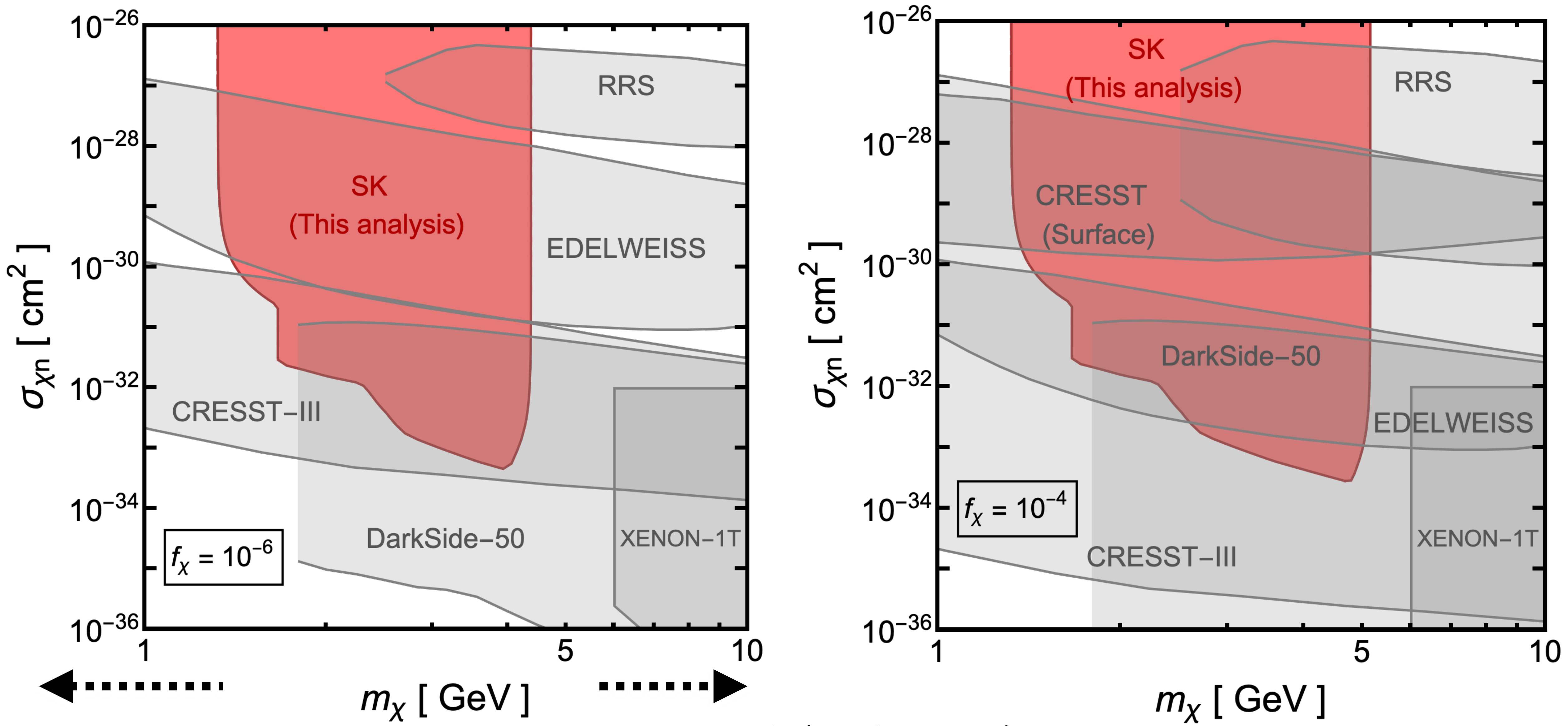
- Earth accumulates significant number of DM particles from the Galactic halo, leading to a DM density 15 orders of magnitude larger than the Galactic DM density!

- Despite their prodigious abundance, their detection is extremely challenging as they have tiny amount of kinetic energy.

- We propose a novel detection scheme of such Earth-bound DM based on their local annihilation signature at large-volume neutrino detectors, such as, Super-K.

- Using di-nucleon annihilation searches at Super-K, we provide unprecedented sensitivity to the DM parameters.

What about heavy DM?



Evaporation

(Can not be improved)

DM shrinks towards the Earth-core

(Can be improved)

Neutrino Signal

- Earth-bound DM if sufficiently heavy, shrinks towards the core, leading to a negligible surface density.

gravity dominates over the diffusion processes

- Annihilation to neutrinos can occur at the Earth-core, if Earth-bound DM if sufficiently heavy. Since the number density is huge, annihilation rate is also fairly large.

- Neutrinos, because of their feeble interactions, can reach detectors like Super-K, IceCube-DeepCore, and searching these annihilated neutrinos can provide sensitivity to DM interactions.

Pospelov & Ray [2309.10032]

Earth as the most optimal detector

- Earth accumulates fewer number of DM particles as compared to the Sun.

(by a factor of $\sim R_\oplus^2/R_\odot^2$)

$$\Gamma_{\rm cap} = f_c \frac{\rho_\chi}{m_\chi} \pi R^2 \int \frac{f(u)du}{u}(u^2 + v_{\rm esc}^2)$$

- But, for Earth-bound DM, distance to the detector is far less.

$$\phi_\oplus \sim \frac{\Gamma_{\rm cap}}{4\pi R_\oplus^2} \quad \text{and} \quad \phi_\odot \sim \frac{\Gamma_{\rm cap}}{4\pi D^2}$$

Flux for Earth-bound DM is ~ 4000 larger than the neutrino flux from Sun.

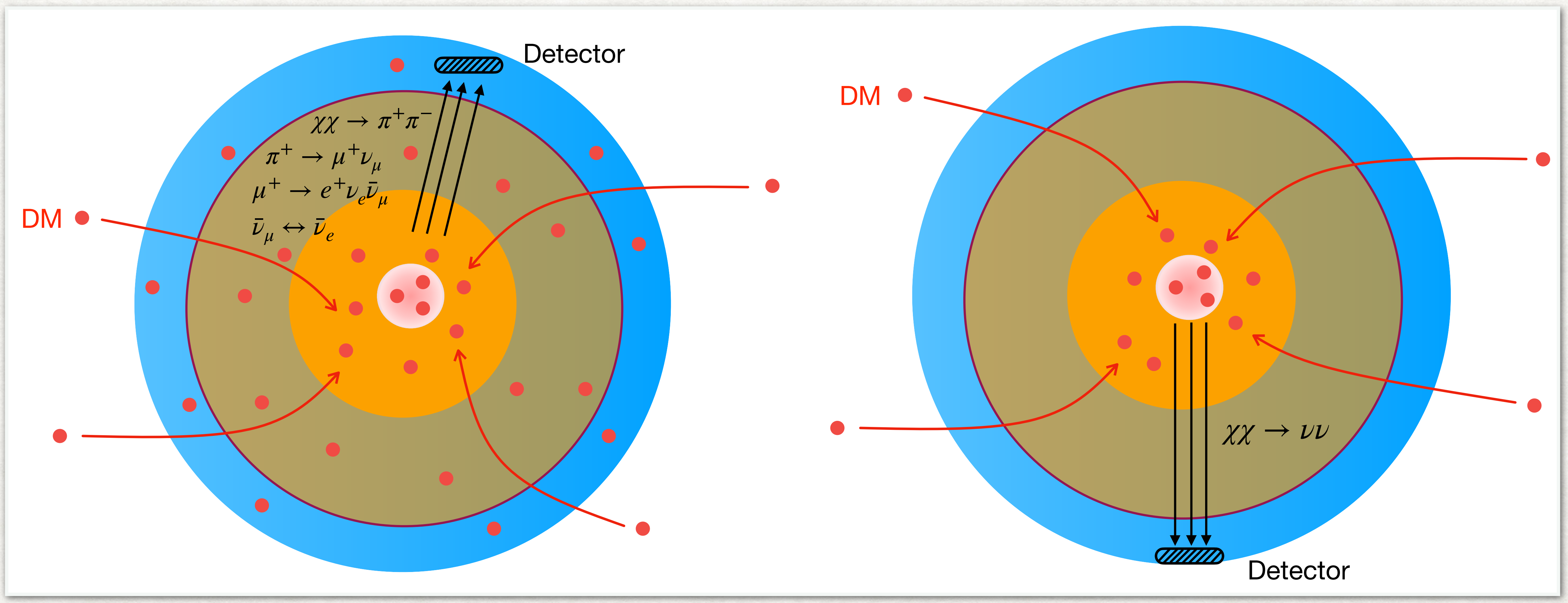
This is quite different from standard weakly-interacting paradigm where Sun is the most-optimal detector, and therefore, has been studied over the past few decades.

Neutrino Signal

- We consider two phenological scenarios:

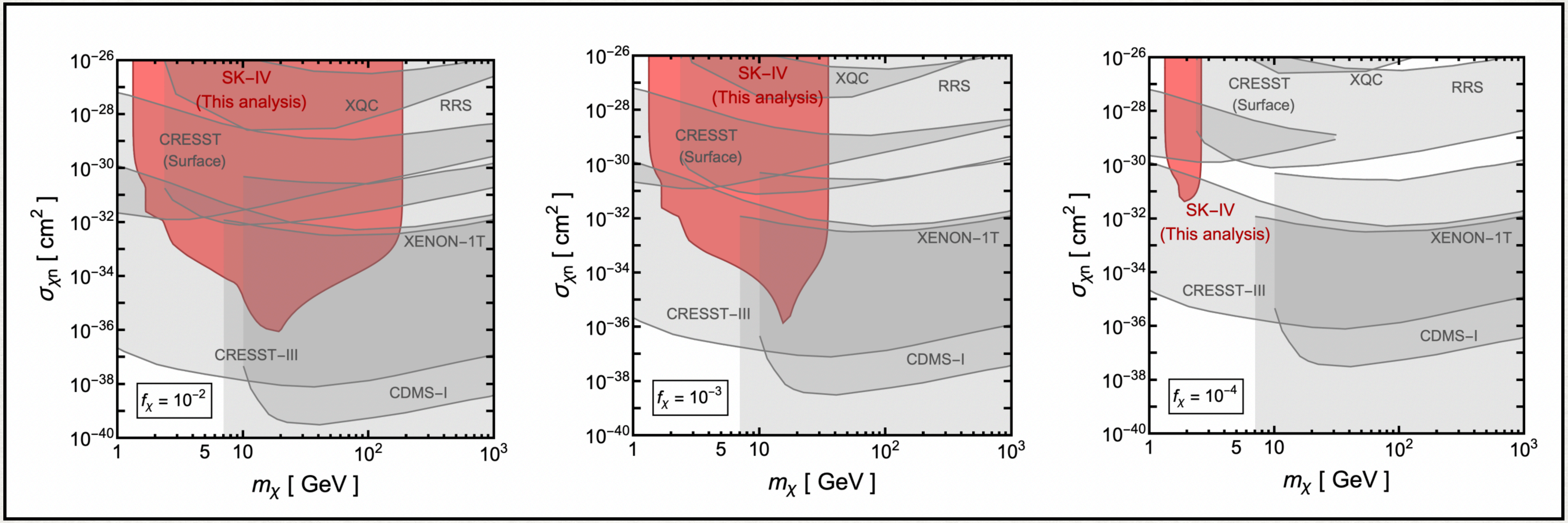
Lower energy neutrinos from the stopped pion decay

Higher energy neutrino lines from direct annihilation



Low Energy Neutrinos

Pospelov & Ray [2309.10032]

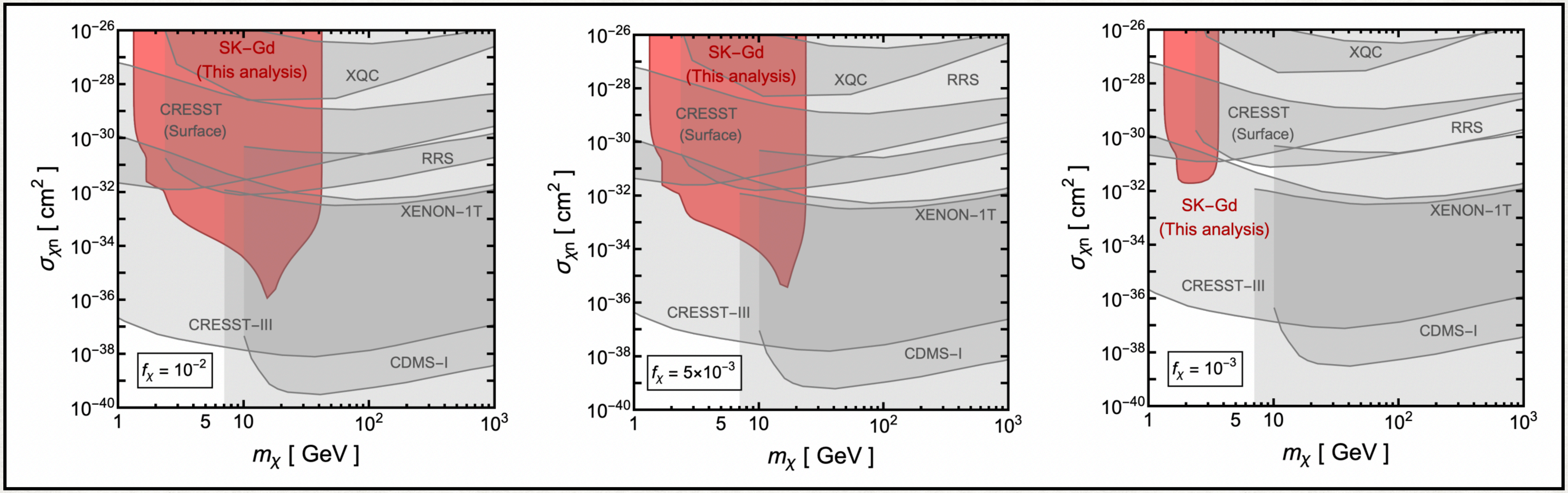


We use the Super-K DSNB search result with pure-water (22.5 kton × 2970 days) to derive the exclusion limits.

Super-Kamiokande (PRD, 2021)

Low Energy Neutrinos

Pospelov & Ray [2309.10032]



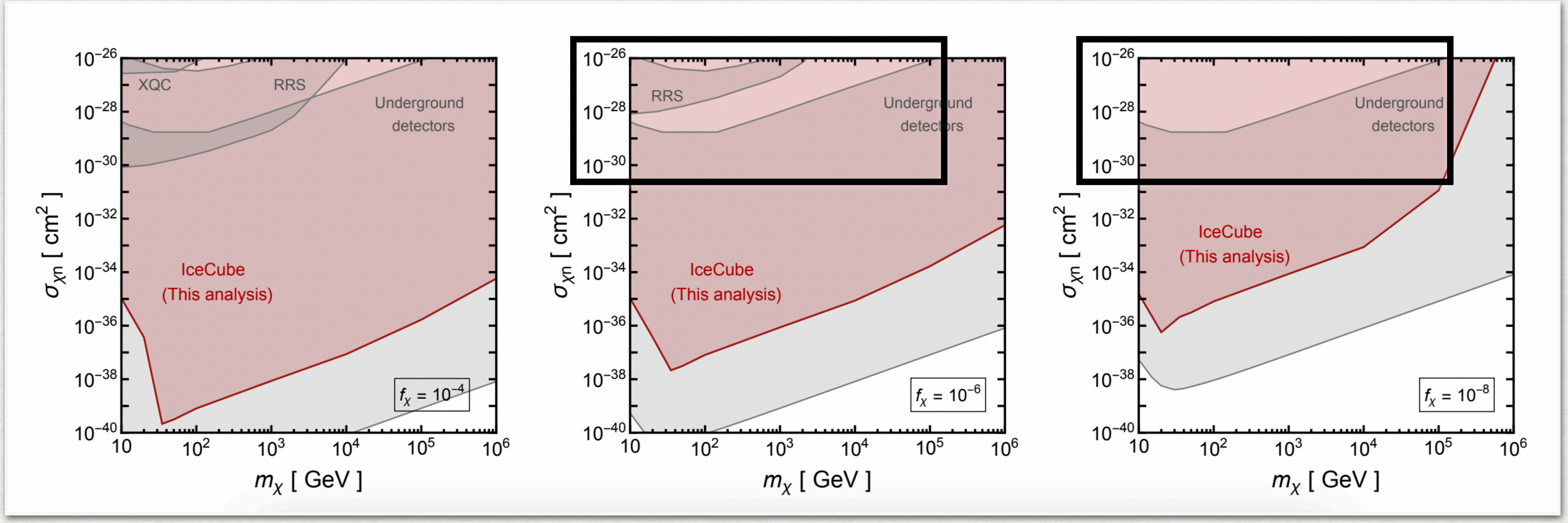
We use the Super-K DSNB search result with 0.01 wt% gadolinium loaded water (22.5 kton × 552.2 days) to derive the exclusion limits

Super-Kamiokande (APJL, 2023)

*Gd-loaded water gives competitive limit although the data is 5 times less.

High Energy Neutrinos

Pospelov & Ray [2309.10032]



We probe up to $f_\chi \geq 10^{-8}$ for sufficiently heavy Earth-bound DM.

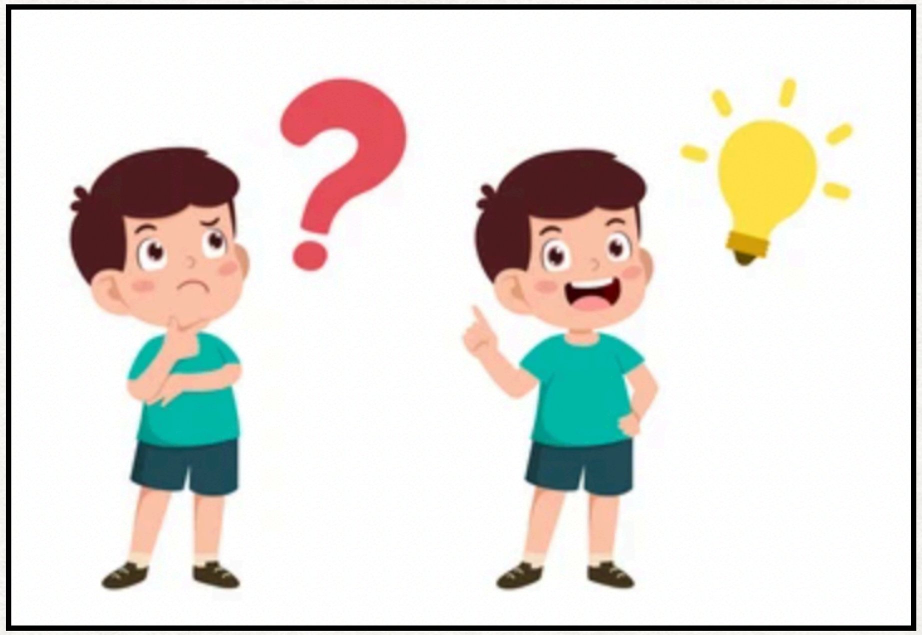
Mass (GeV)	$b\bar{b}$ $\Gamma_{\rm ann}$ [s^{-1}] $\times 10^{23}$	$\tau\bar{\tau}$ $\Gamma_{\rm ann}$ [s^{-1}] $\times 10^{23}$	$\nu\bar{\nu}$ $\Gamma_{\rm ann}$ [s^{-1}] $\times 10^{23}$
5	139	139.3	
10	396	7.0	1.37
20	29.7	0.97	0.27
35	7.41	0.22	0.09
50	3.51	0.096	0.05
100	1.39	0.038	0.027

IceCube (PRD,2022)

Conclusion

★ How to detect rare species of DM?

★ Look at the annihilation of Earth-bound DM!



Thanks!

Questions & Comments: anupam.ray@berkeley.edu