Detecting Rare Species of Dark Matter with Terrestrial Detectors

i) Phys. Rev. Lett. 131, 011005 (2023) [arXiv: 2303.03416]
ii) JCAP 01 029 (2024) [arXiv: 2309.10032]
iii) arXiv: 2402.03431

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N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER
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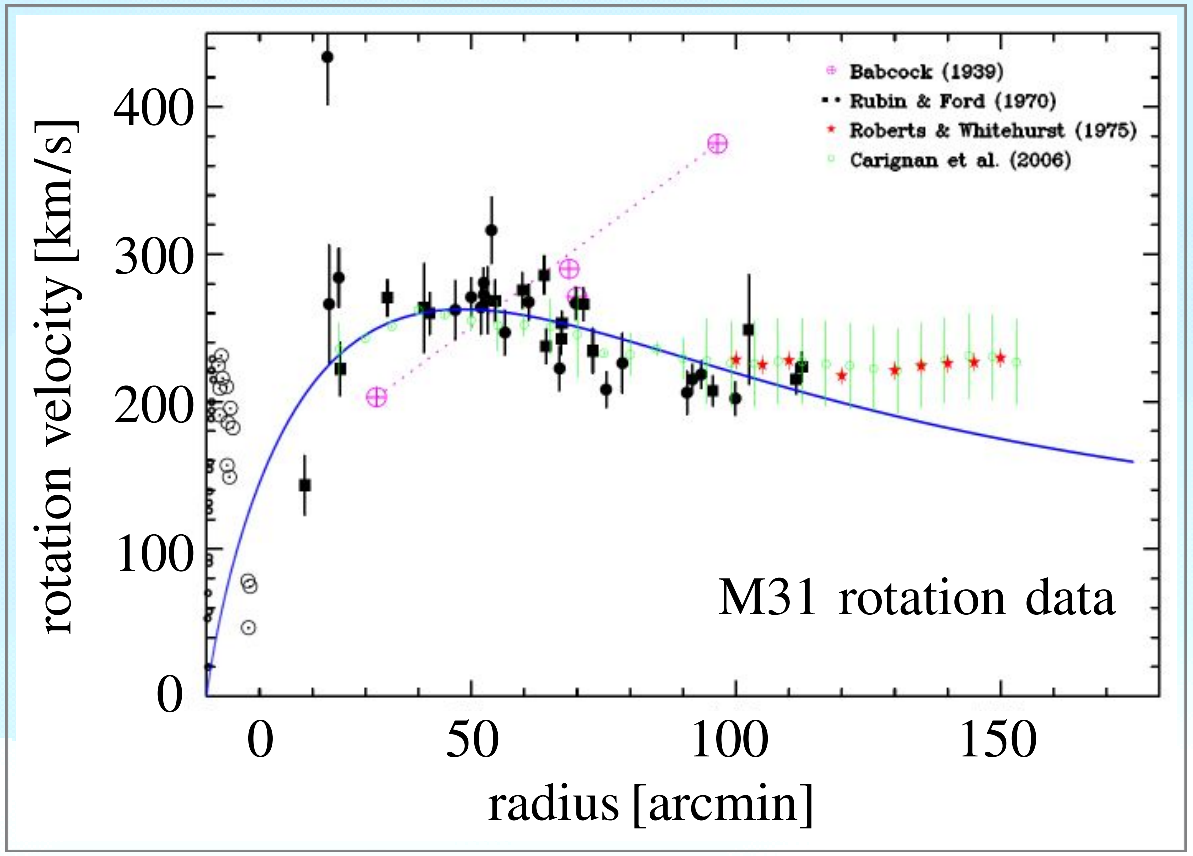
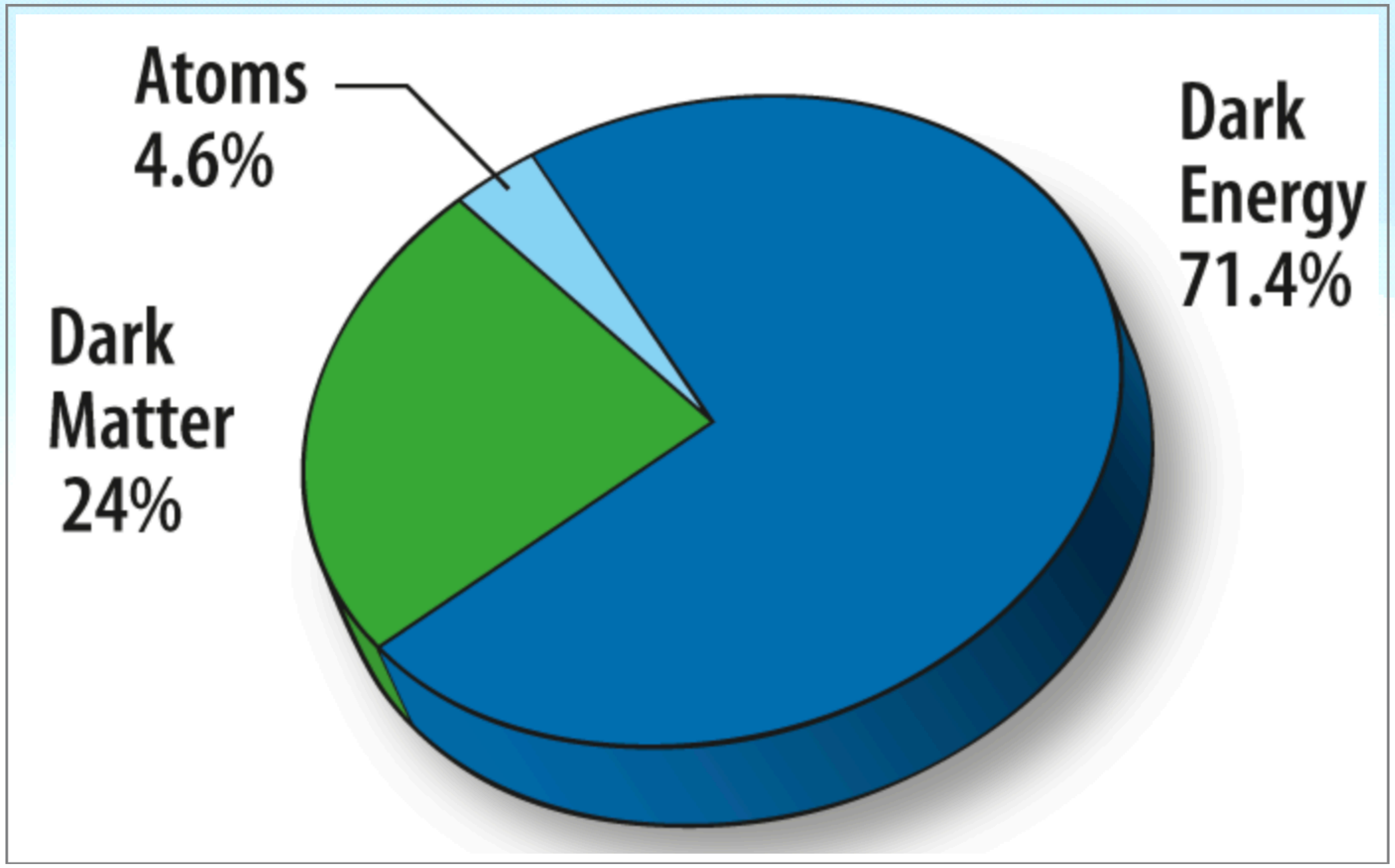
Physics & Astronomy

Dark Matter (DM)



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

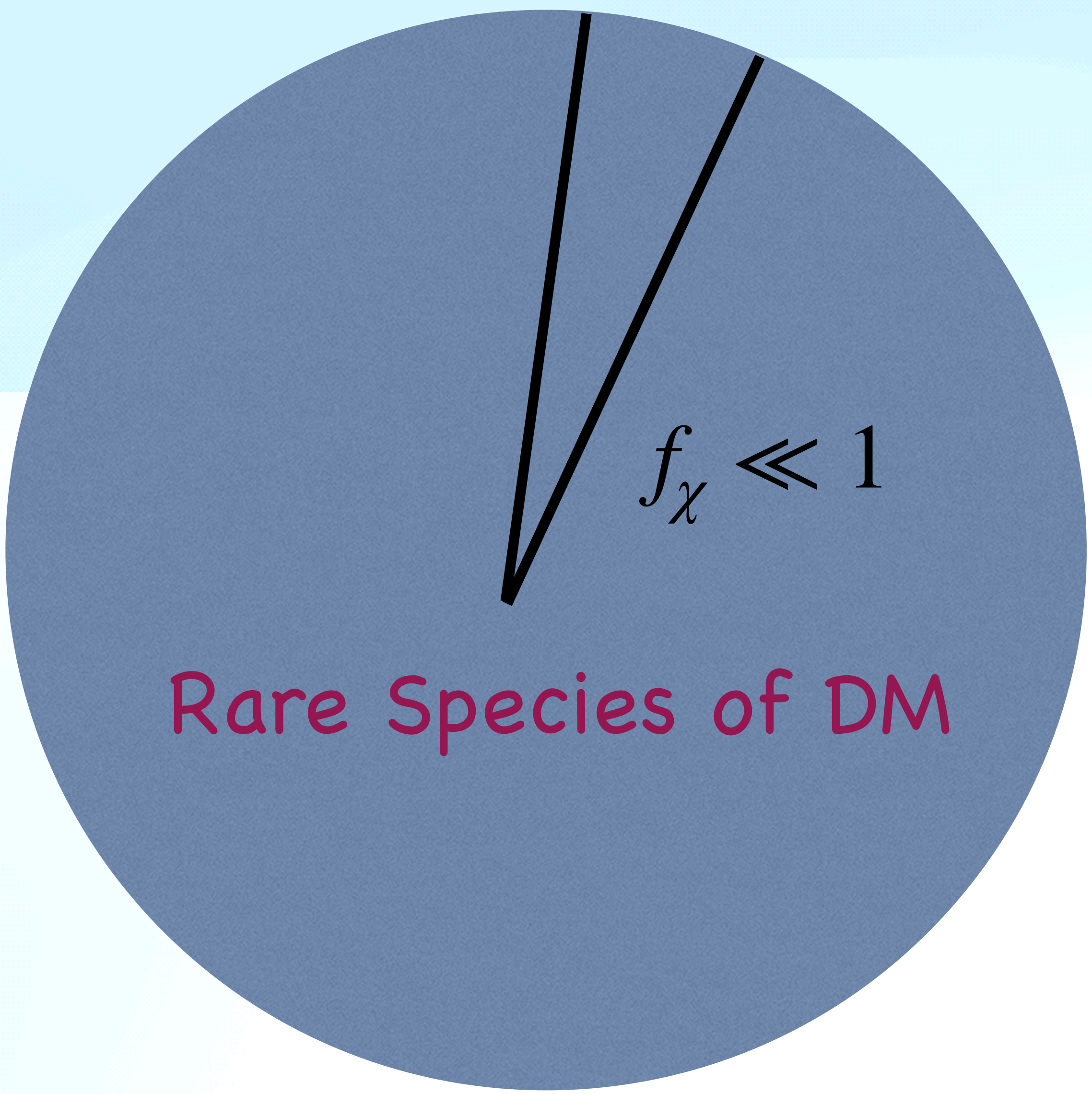


https://wmap.gsfc.nasa.gov/universe/uni_matter.html

- DM mass?
- DM interactions with baryons?

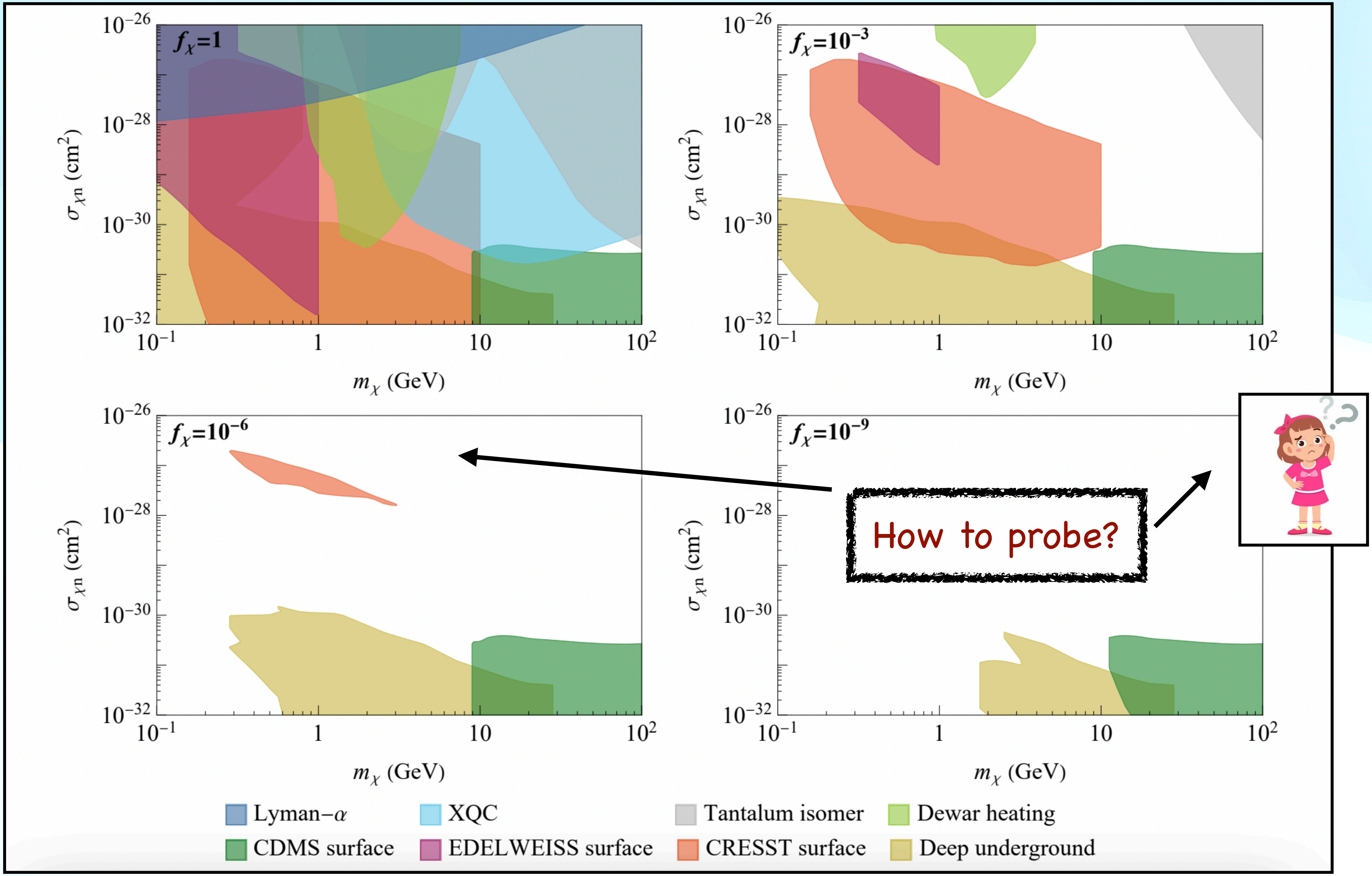
Strongly-interacting DM Component

- A sub-component of DM can be strongly interacting.



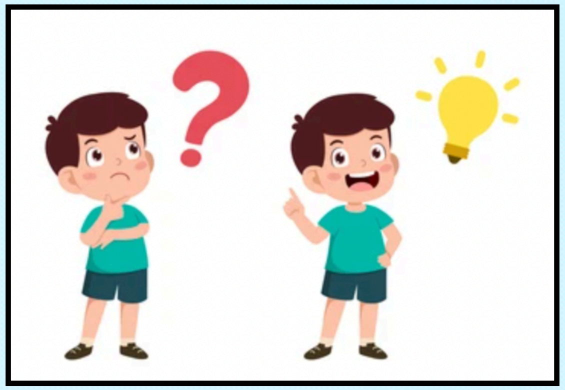
χ makes up a sub-component of the total DM energy budget.

Strongly-interacting DM Component



Mckeen et al [PRD, 2022]

Take Away



- "Earth-bound" DM provides a novel powerful probe.

The density of "Earth-bound DM" can be huge.

Annihilating DM

- Local annihilation inside any large-volume neutrino detectors (such as Super-Kamiokande)

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

- Neutrinos from annihilation of Earth-bound DM.

  Pospelov & Ray [JCAP, 2024]

Non-Annihilating DM

- Earth-bound DM can be up-scattered by fast neutrons inside the nuclear reactors, and subsequently detected.

(similar scheme as CEνNS)

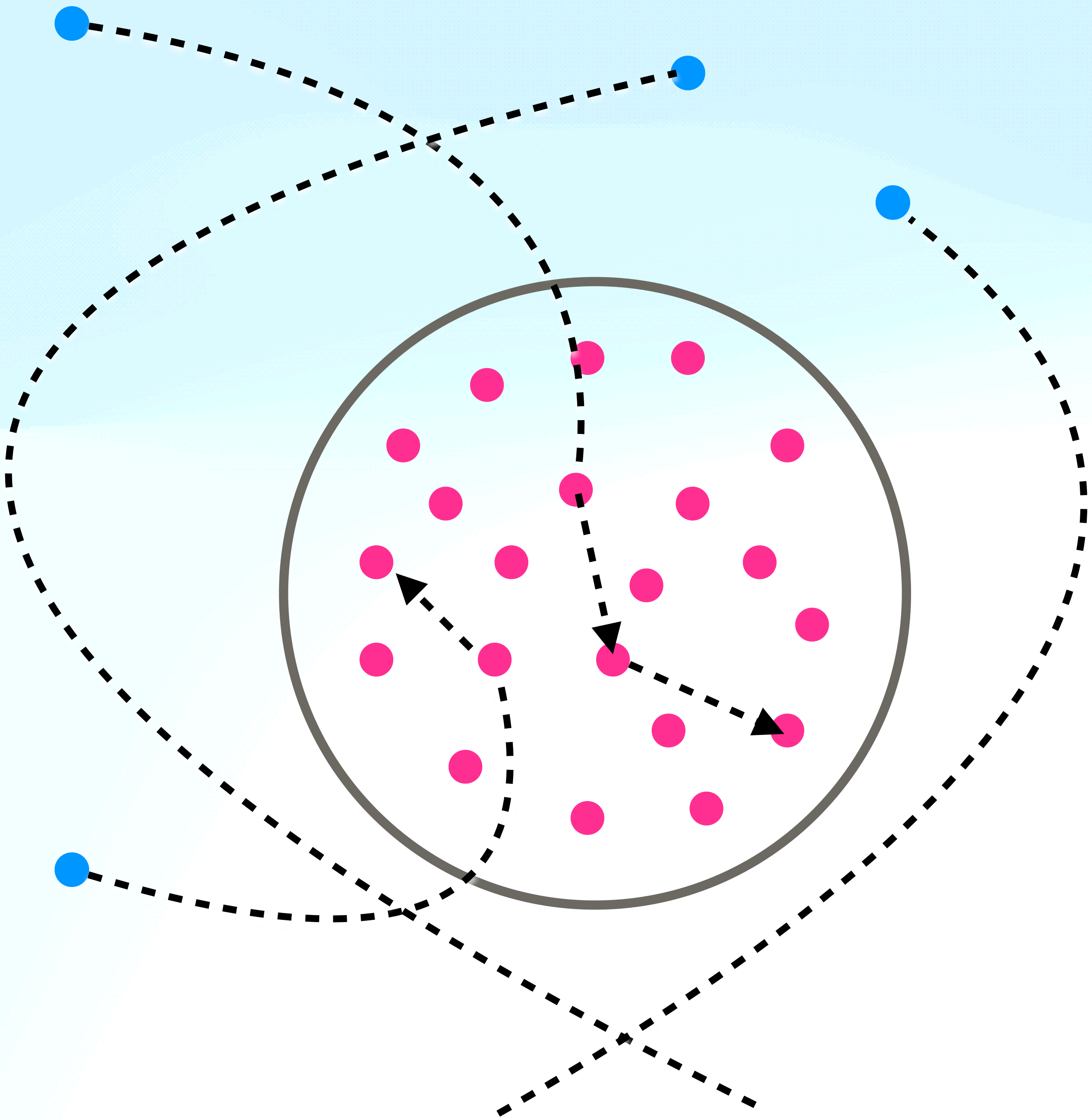
Ray, (with Ema, Pospelov)

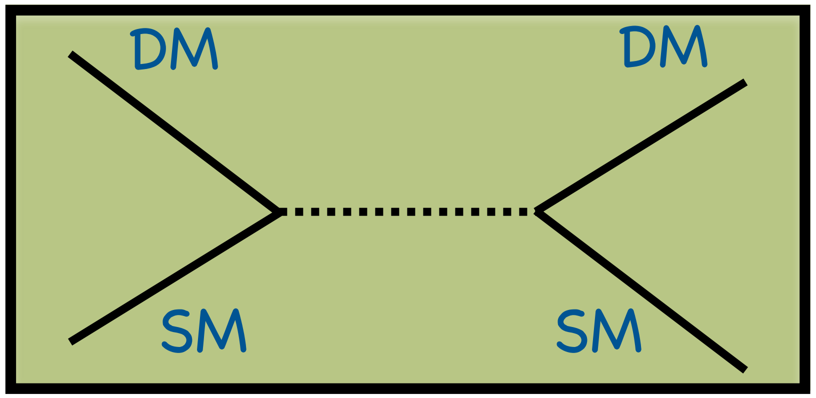
[2402.03431]

Earth-Bound DM

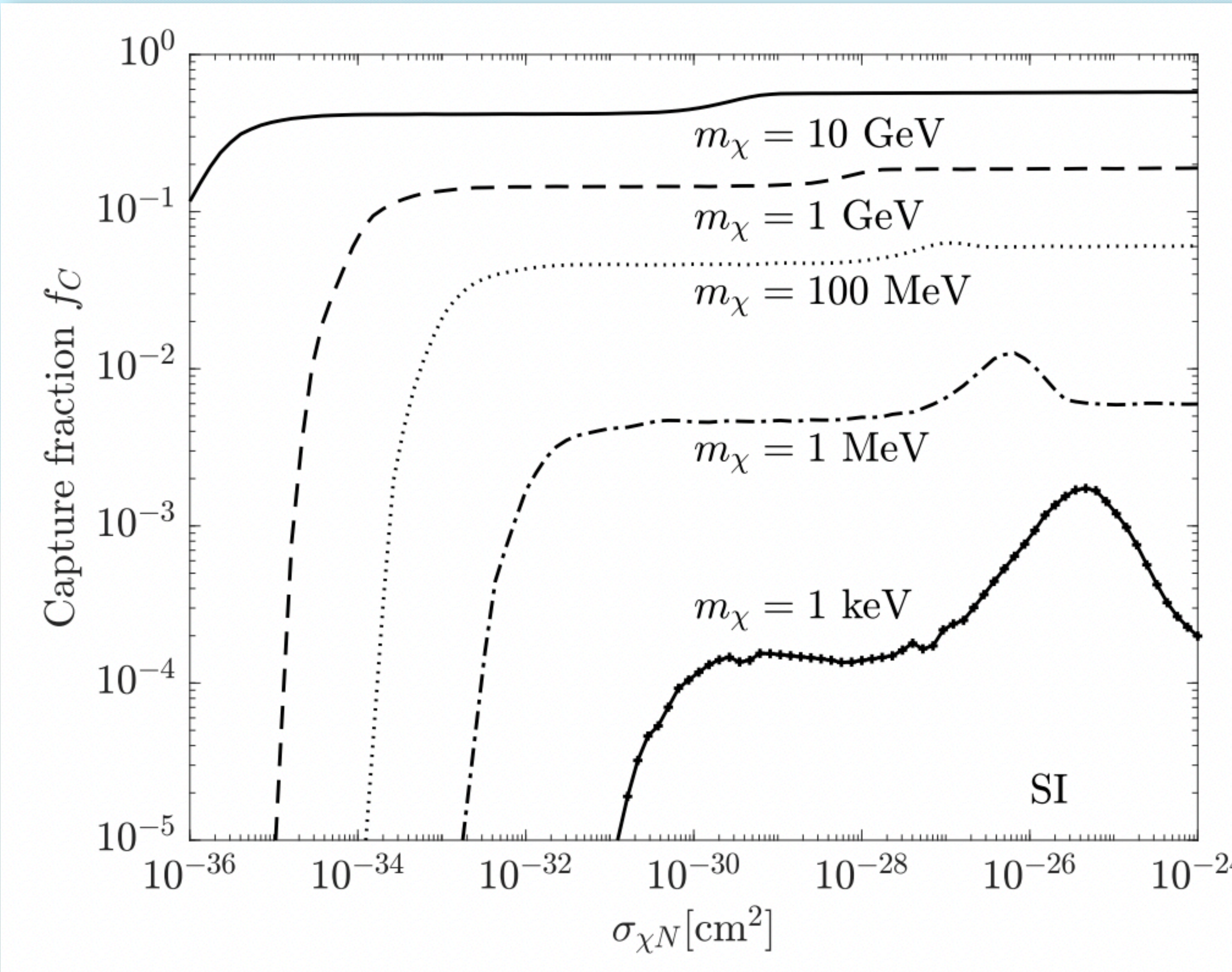
Press & Spergel (1985,ApJ), Gould (1987, ApJ),...

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





Earth-Bound DM



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

Bramante et al. (PRD, 2022)

Earth-Bound DM

- Lets do some estimate:

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

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

$f_\chi = 1$

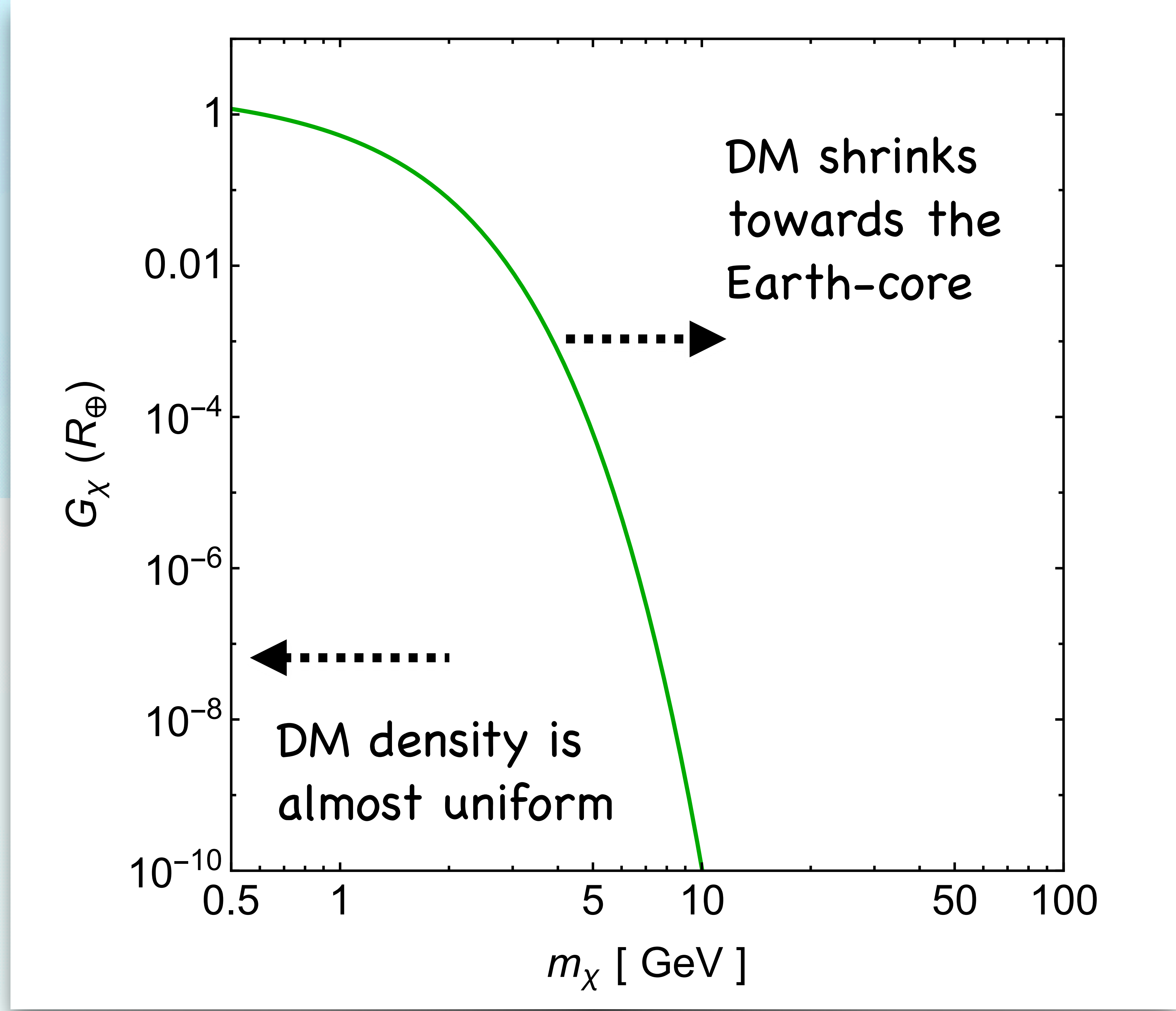
DM density (assuming they uniformly distribute over the Earth-volume)

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

$f_\chi = 1$

- 15 orders of magnitude larger than the Galactic DM 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:

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

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

Signal at Super-K

- Earth-bound DM, of mass GeV scale have an enormously large surface density.

- Their detection via scattering is almost impossible as they acquire very little amount kinetic energy (0.03 eV).

- How to detect them?

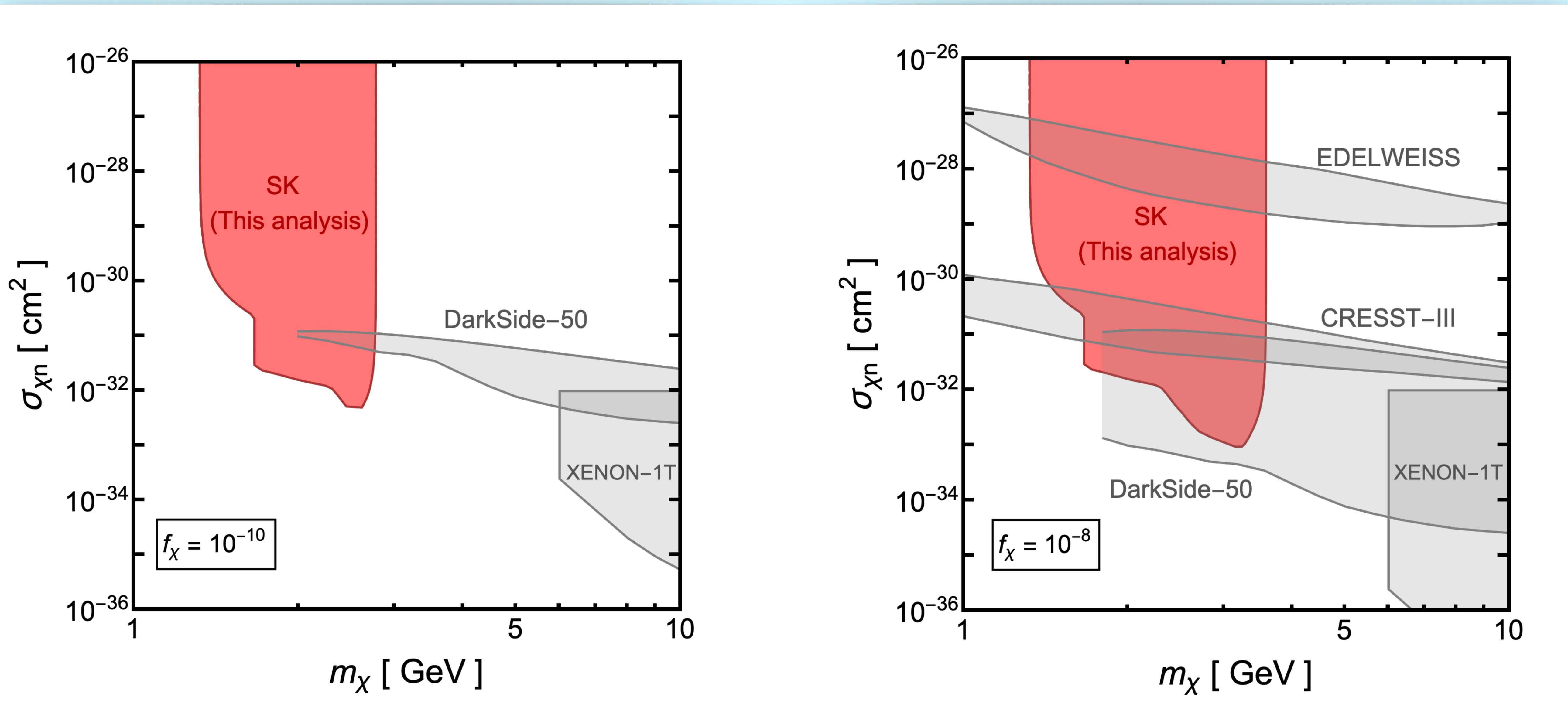
Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]

Our proposal: simply look at their annihilation signature inside large-volume detectors (annihilation is not limited to the tiny kinetic energy)!

Results

- Using existing di-nucleon annihilation searches at Super-K

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



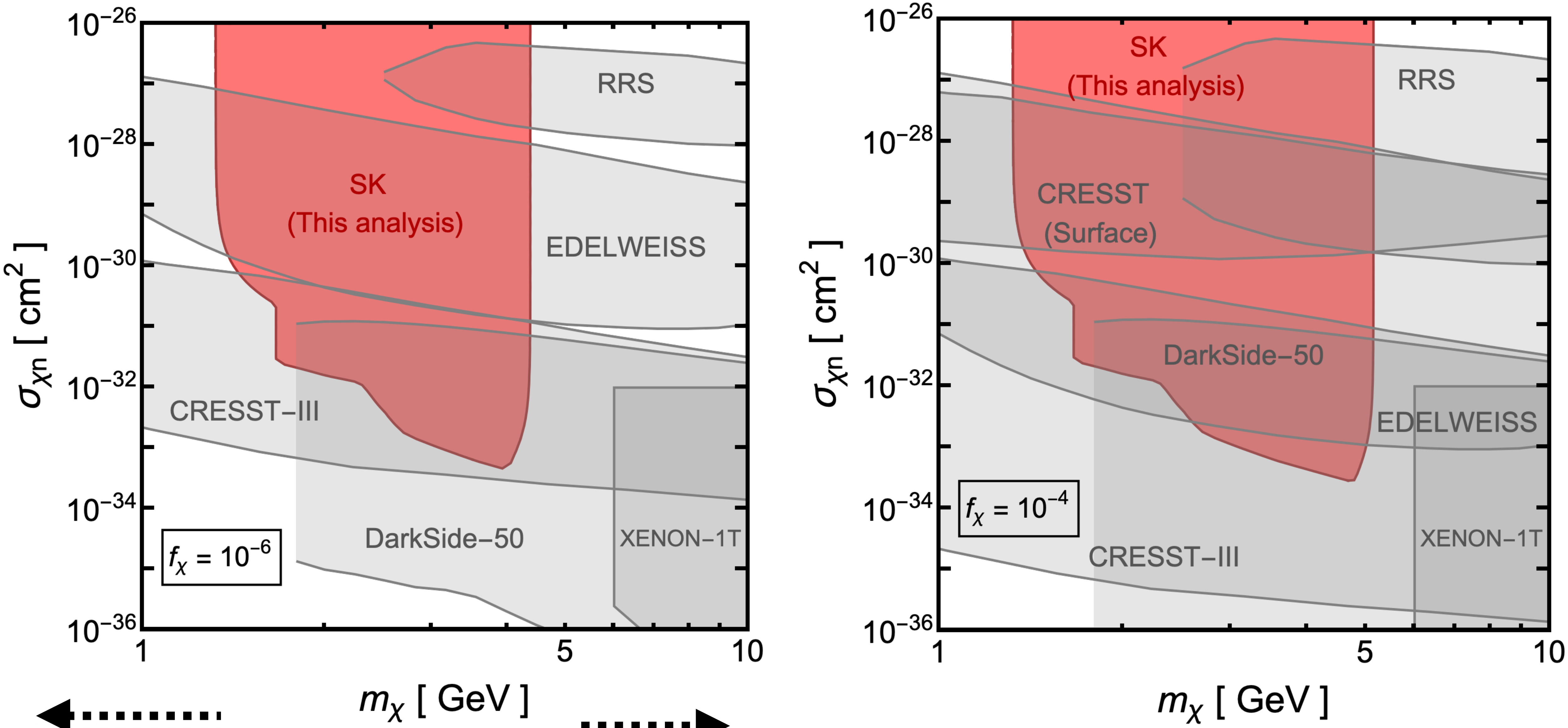
Evaporation

DM shrinks towards the Earth-core

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

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

Pospelov, Ritz, Voloshin (PLB, 2008)

Model

- We are interested in the following channel

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

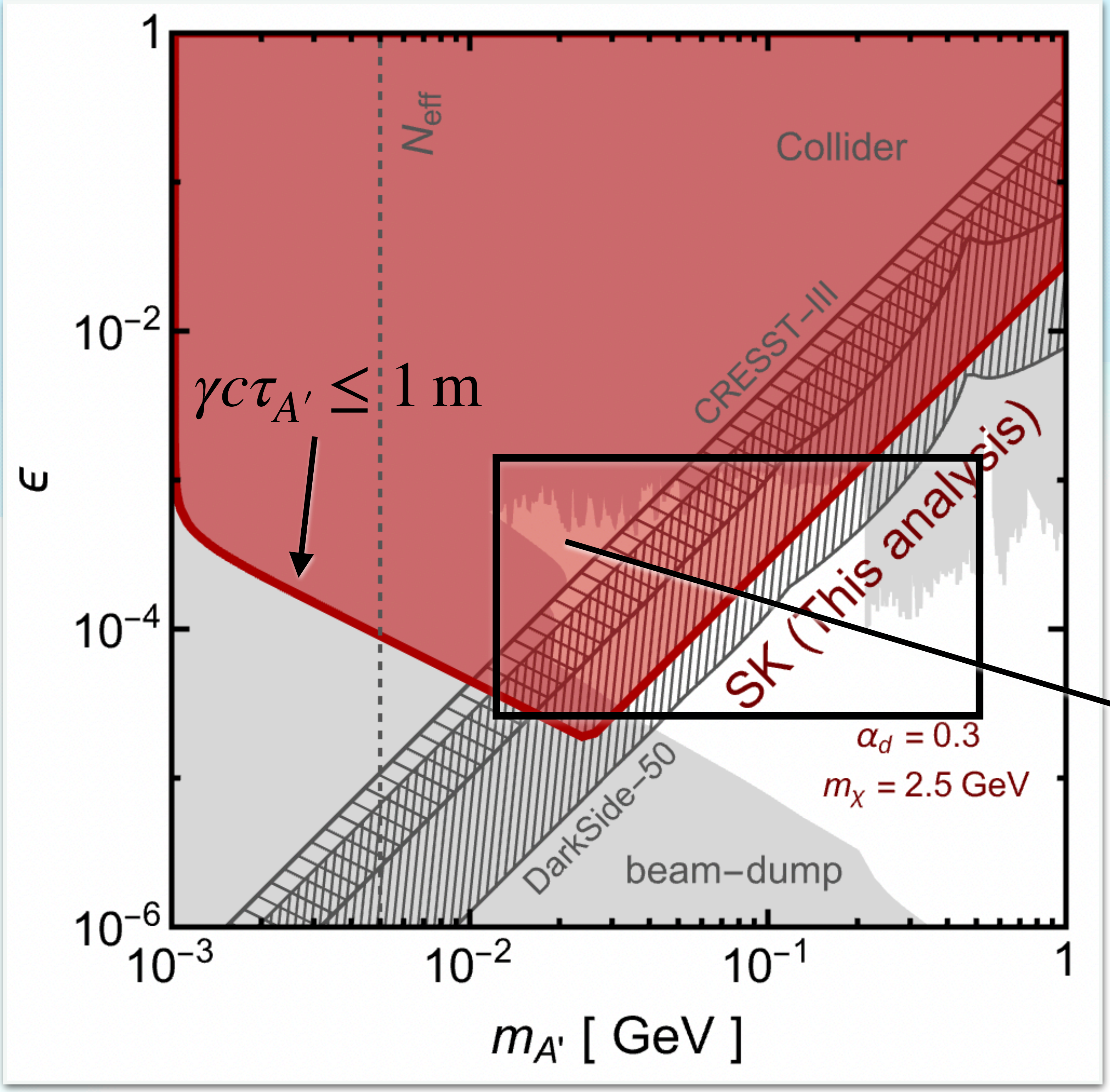
$$\langle \sigma v \rangle_{\text{ann}} = \frac{\pi \alpha_d^2}{m_\chi^2} \frac{\left(1 - m_{A'}^2/m_\chi^2\right)^{3/2}}{\left(1 - m_{A'}^2/4m_\chi^2\right)^2}$$

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

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

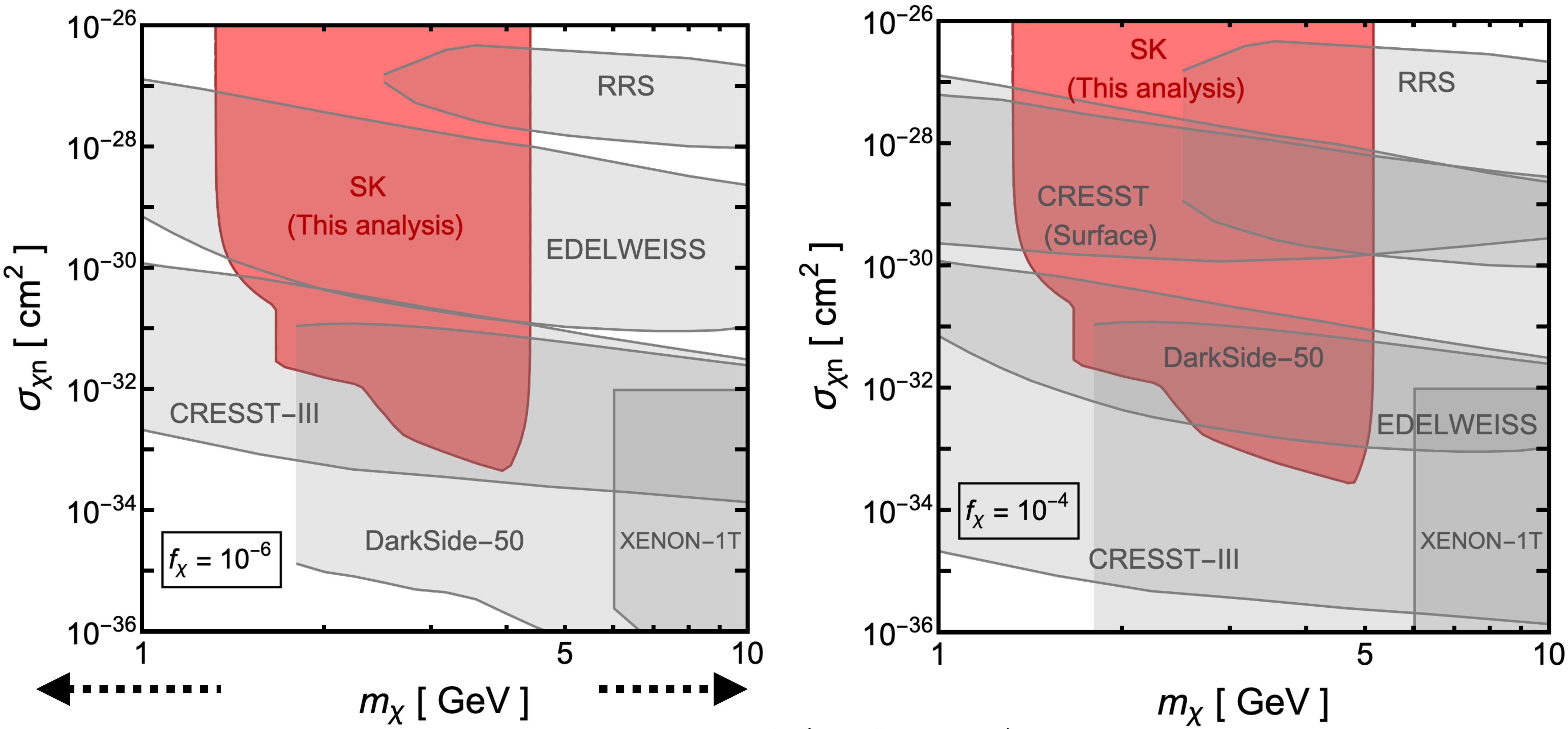
Results

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



Unprecedented sensitivity on parts of the parameter space.

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.

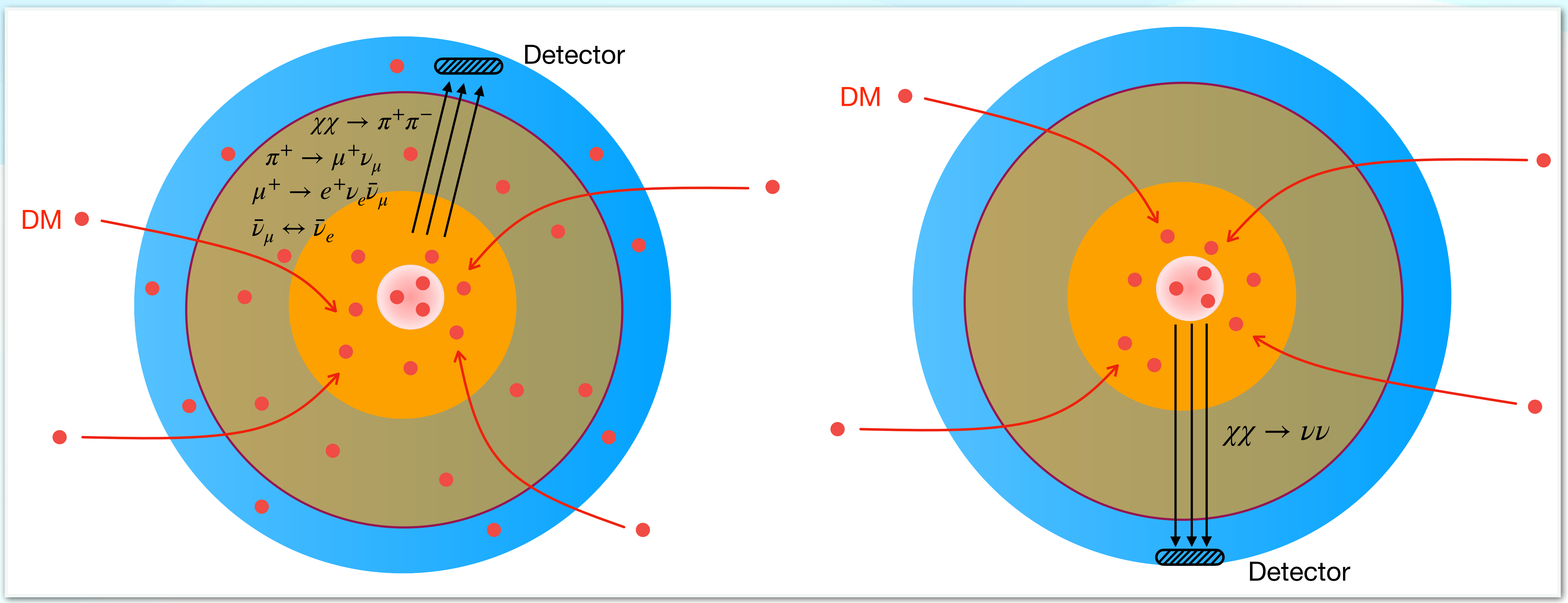
Pospelov & Ray [JCAP, 2024]

Neutrino Signal

- We consider two phenological scenarios:

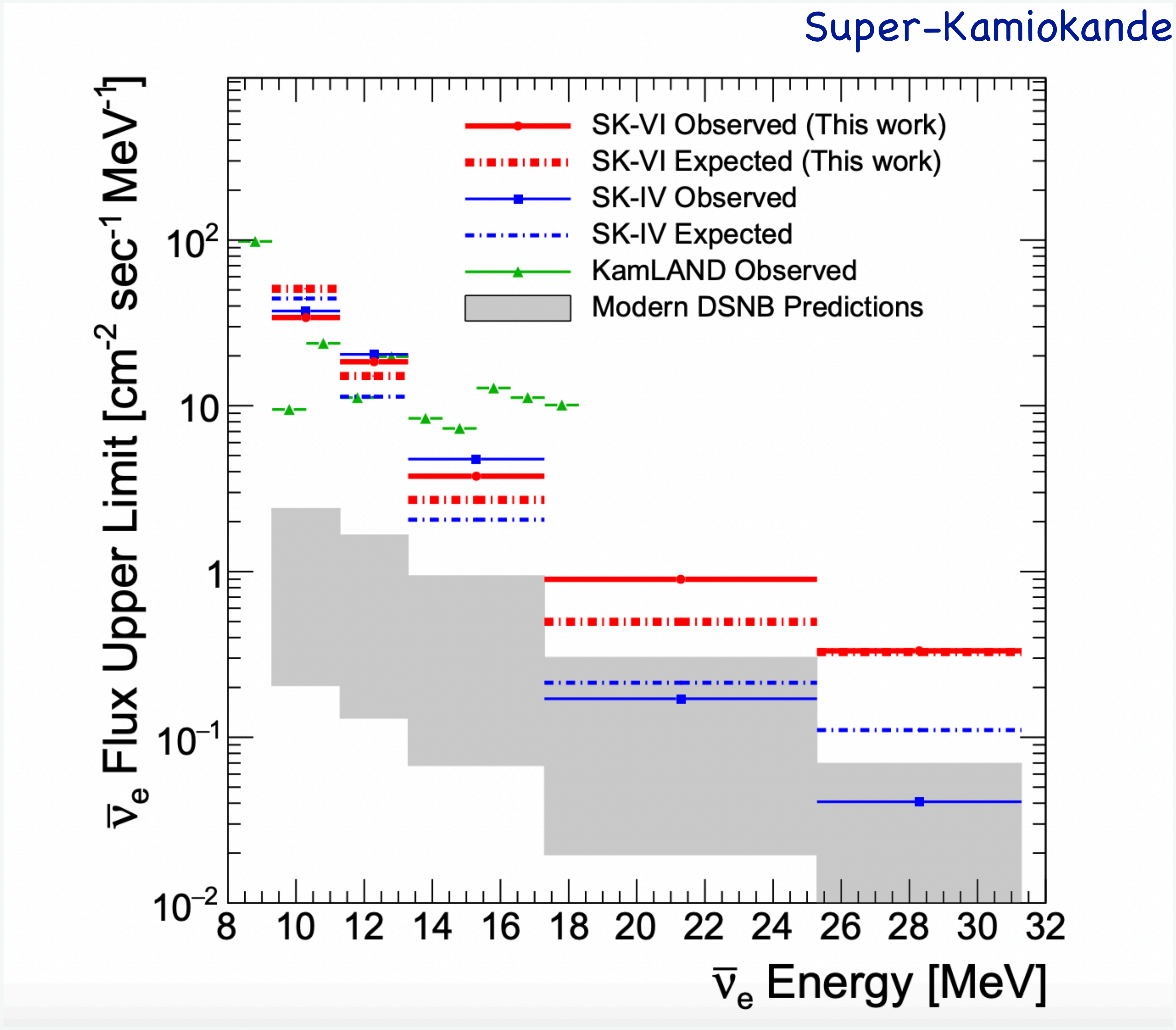
Lower energy neutrinos from the stopped pion decay

Higher energy neutrino lines from direct annihilation



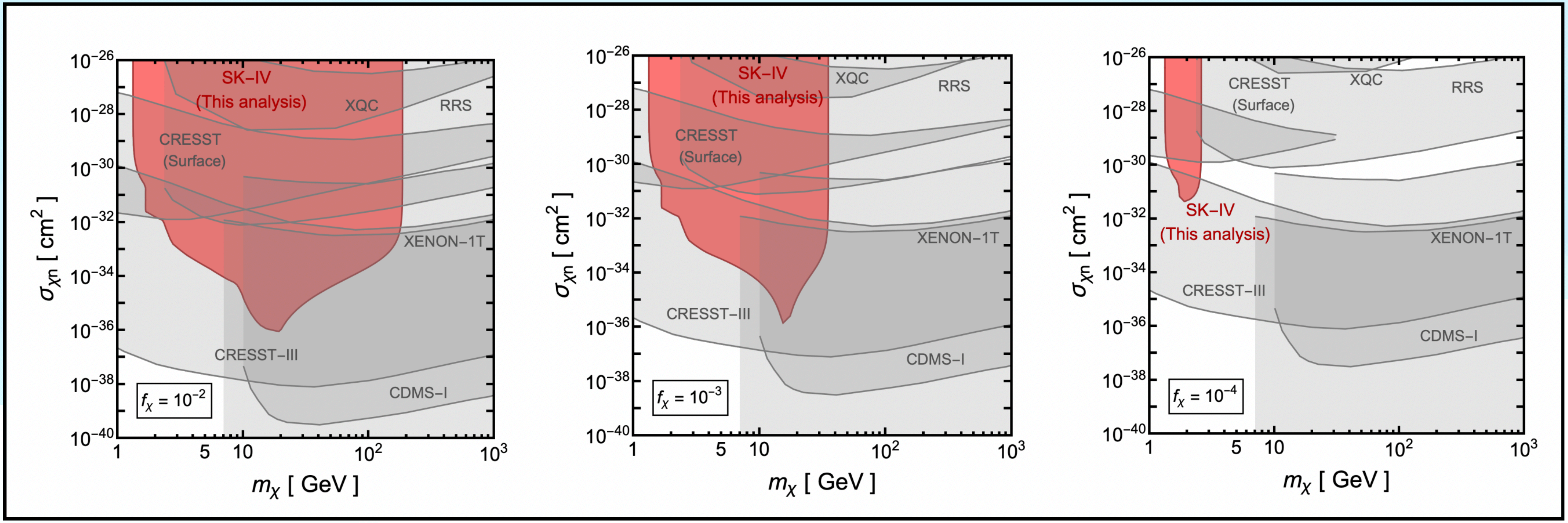
Low Energy Neutrinos

Super-Kamiokande (APJL, 2023)



Low Energy Neutrinos

Pospelov & Ray [JCAP, 2024]

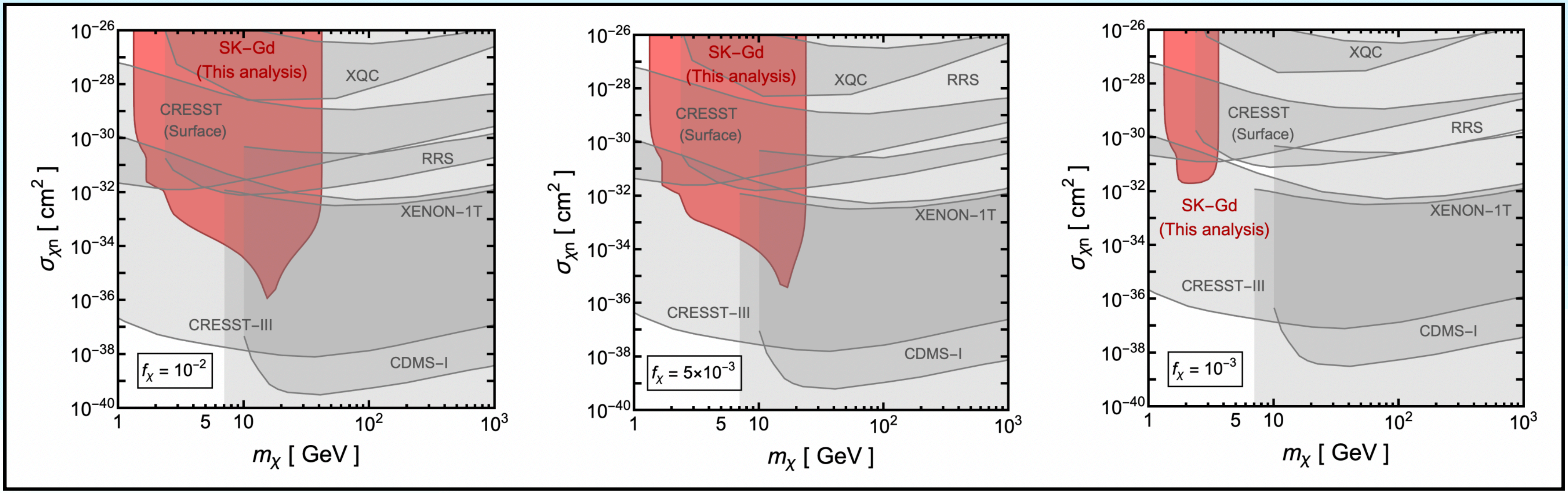


We use the Super-K DSNB search result with pure-water (22.5 kton × 2970 days) to derive the exclusion limits.

Super-Kamiokande (PRD, 2021)

Low Energy Neutrinos

Pospelov & Ray [JCAP, 2024]



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 (as compared to the pure-water limits) although the data is 5 times less.

High Energy Neutrinos

- DM annihilation directly to neutrinos yields a line at $E_\nu = m_\chi$

  high-energy neutrinos can also come from $\chi\chi \to W^+W^-, b\bar{b}, \tau\bar{\tau}$, giving a continuum spectra up to $E_\nu = m_\chi$ (or $\chi\chi \to A'A' \to 4\nu$).

- We search the "neutrino-line" signature in the IceCube DeepCore data with a total live-time of 6.75 years.

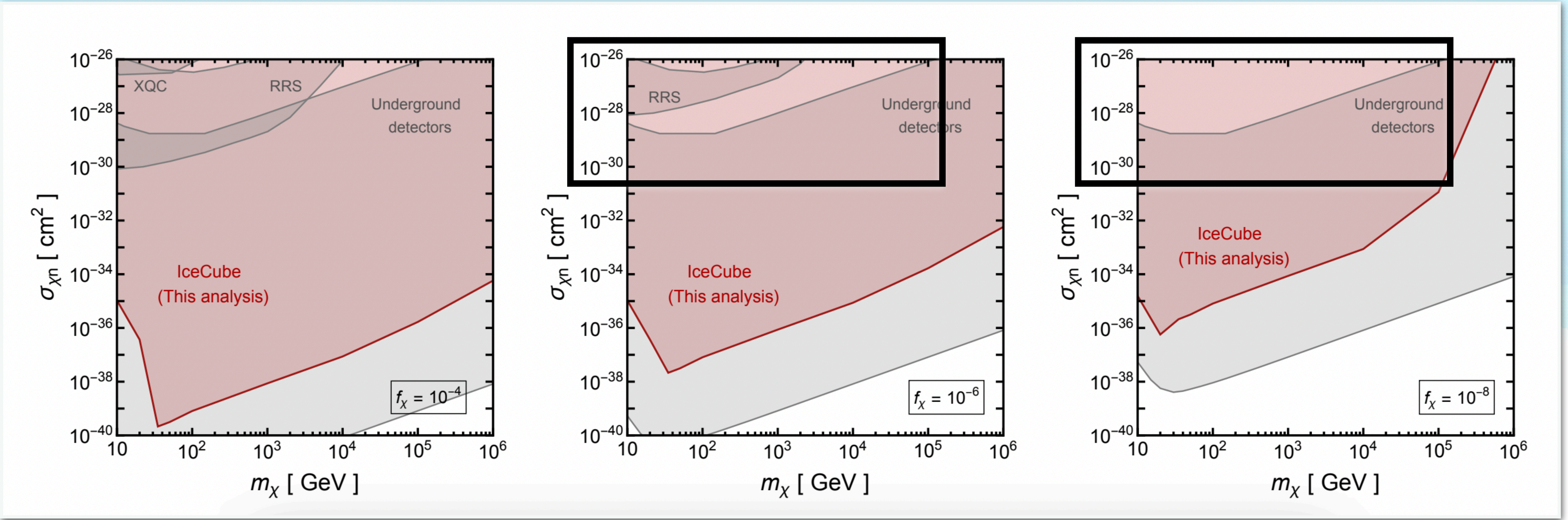
- We use the null-detection of the neutrino-line signature in the IceCube DeepCore data to derive the exclusions

Mass (GeV)	$\mathbf{b\bar{b}}$ $\Gamma_{\rm ann}$ [s^{-1}] $\times 10^{23}$	$\boldsymbol{\tau\ \bar{\tau}}$ $\Gamma_{\rm ann}$ [s^{-1}] $\times 10^{23}$	$\boldsymbol{\nu\bar{\nu}}$ $\Gamma_{\rm ann}$ [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)

High Energy Neutrinos

Pospelov & Ray [JCAP, 2024]



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

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.

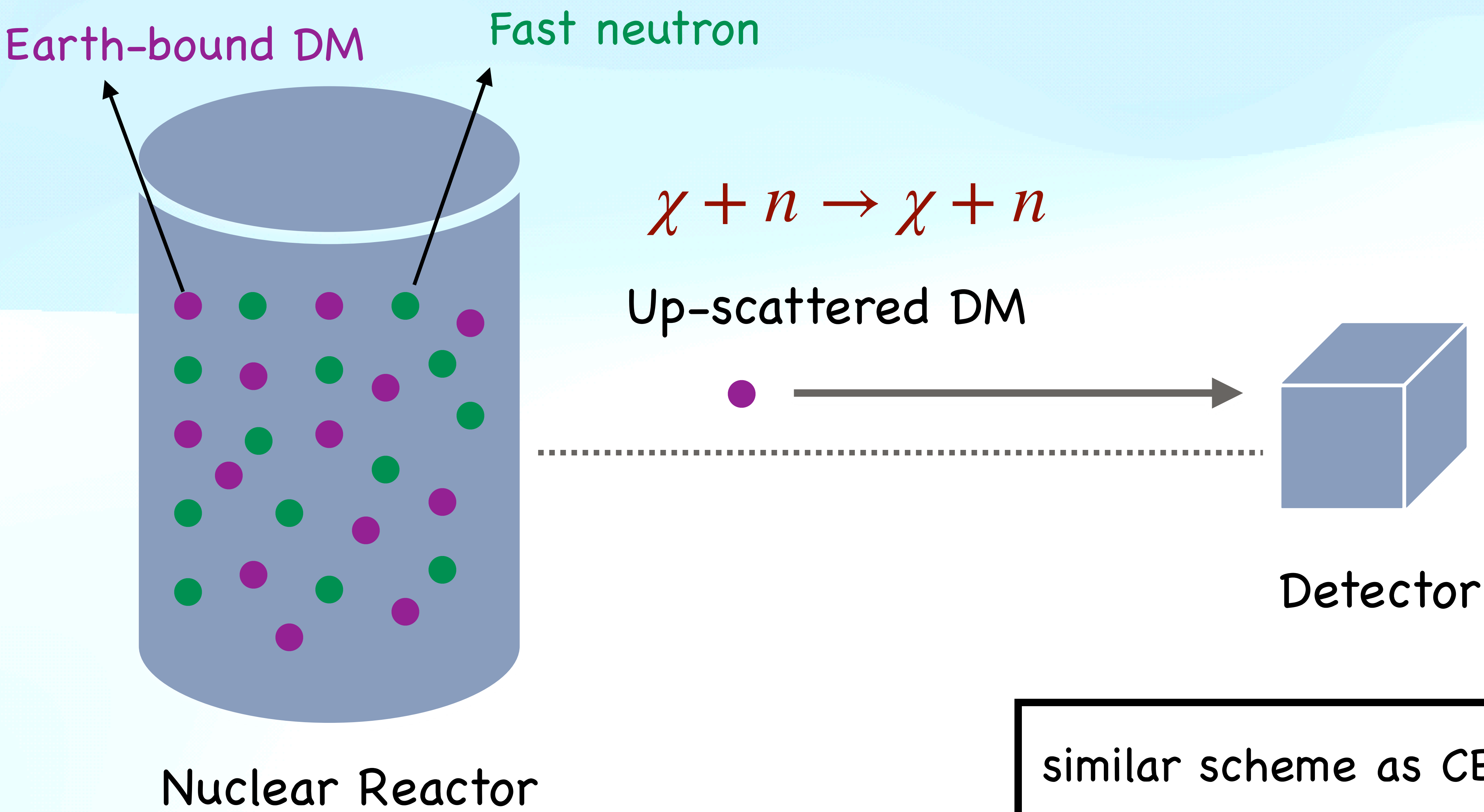
$$\phi_\oplus \sim \frac{\Gamma_{\rm cap}}{4\pi R_\oplus^2} \quad \text{and} \quad \phi_\odot \sim \frac{\Gamma_{\rm cap}}{4\pi D^2}$$

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 hence, has been studied over the past few decades.

Non-Annihilating DM

- Nuclear Reactors act as powerful probe of Earth-bound DM detection.



similar scheme as CEνNS detection

Ray, (with Ema, Pospelov) [2402.03431]

Non-Annihilating DM

- Accumulation of Earth-bound DM. ✓

- Distribution of Earth-bound DM. ✓

- Up-scattering of Earth-bound DM inside Nuclear Reactors by fast neutrons (typically of MeV energy).

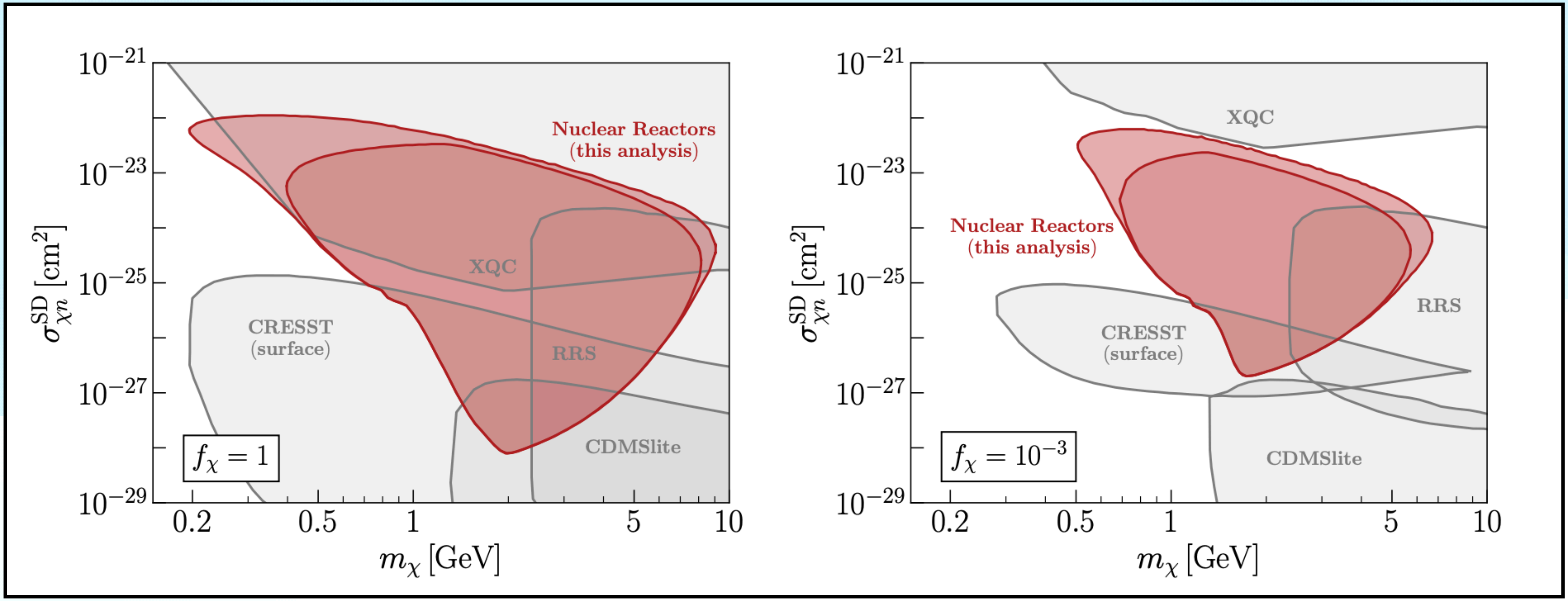
We use CONUS experiment setup for our analysis.

- Subsequent propagation through shielding and detection via scattering.

We use MC simulations for the propagation along with provide an analytical recipe.

Results

Ray, (with Ema, Pospelov) [2402.03431]

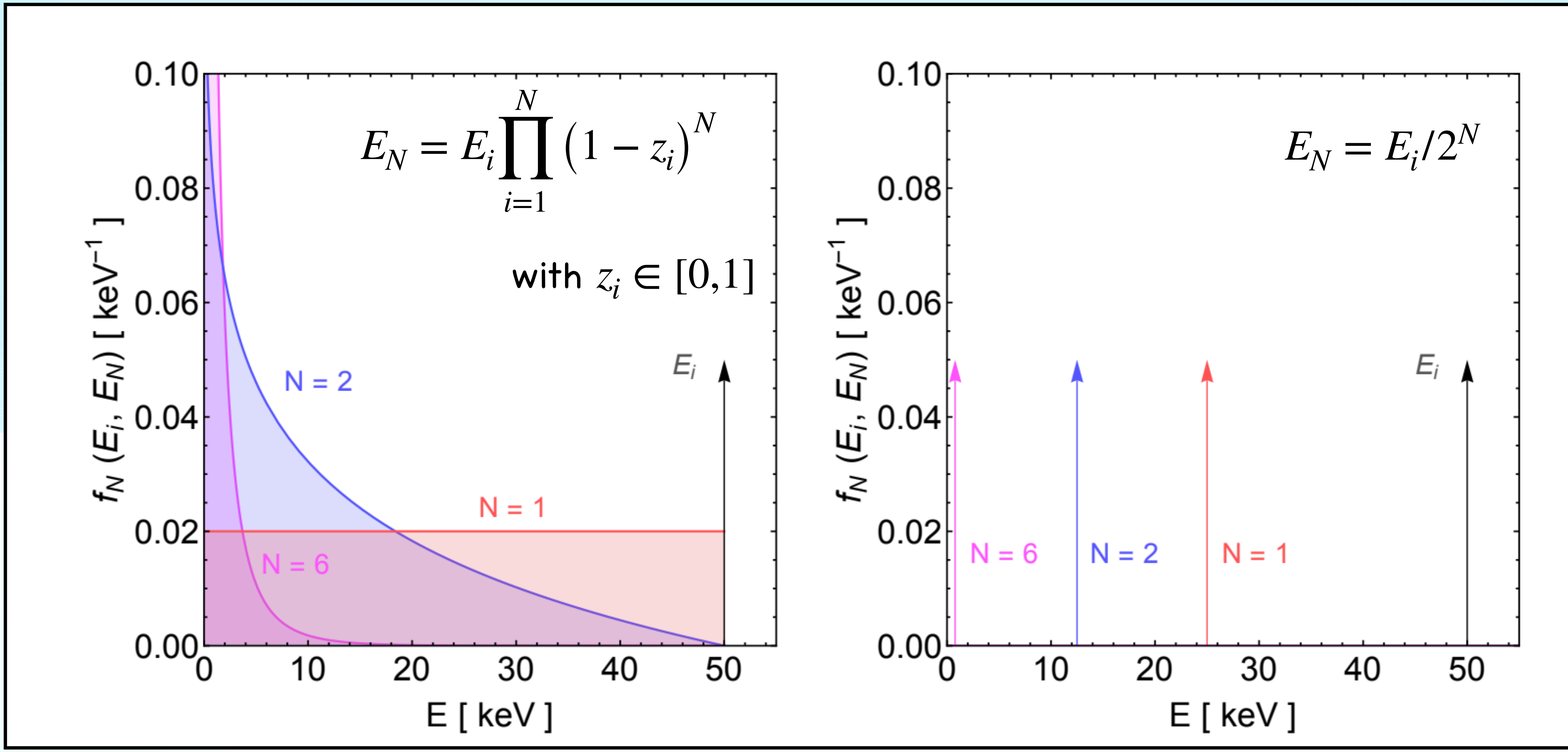


Smaller regions: includes only the DM particles which do not experience any collisions.

Bigger regions: includes the full multiple-scattering contributions.

Propagation of Up-scattered DM

Ray, (with Ema, Pospelov) [2402.03431]



Tail of the distribution is utterly important. Many previous studies (e.g., Bramante et al [PRD, 2017], Leane et al. [JCAP, 2022] etc) neglect this simple yet important point.

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!

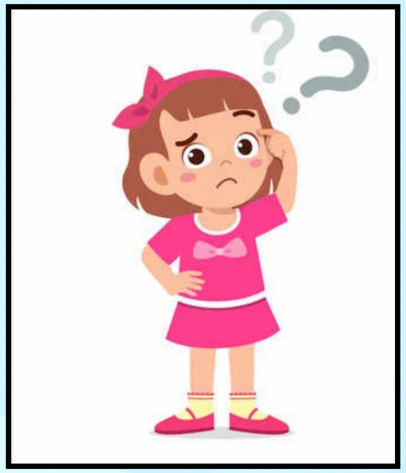
- Despite their prodigious abundance, their detection is extremely challenging as they acquire tiny amount of kinetic energy.

- Annihilation of such Earth-bound DM at large-volume neutrino detectors, provides a novel way for their detection and can be used to probe strongly-interacting DM component.

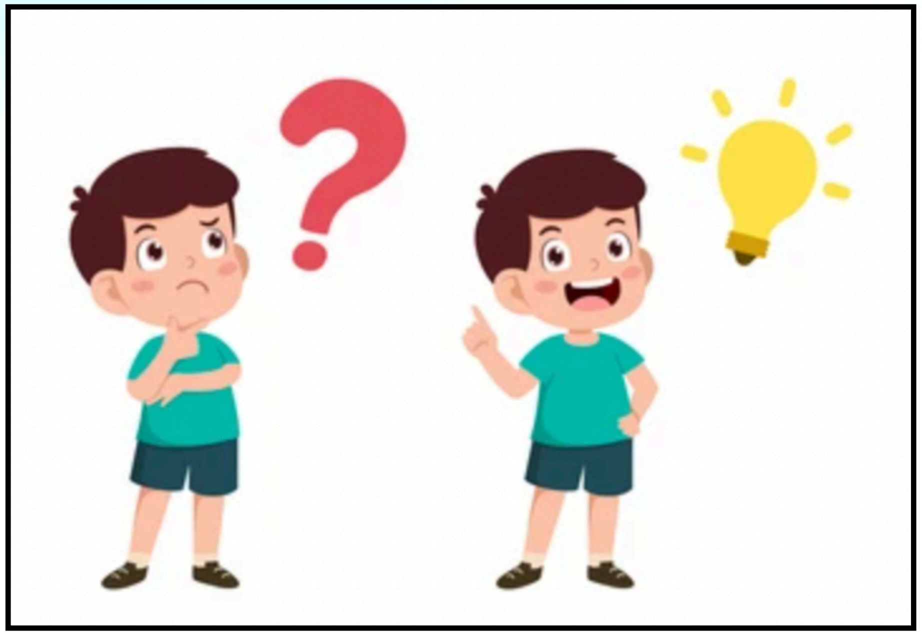
- If Earth-bound DM do not annihilate among themselves, up-scattering them inside nuclear reactors provides a powerful probe of their detection.

Conclusion

★ How to detect rare species of DM?



★ Look at the Earth-bound DM!

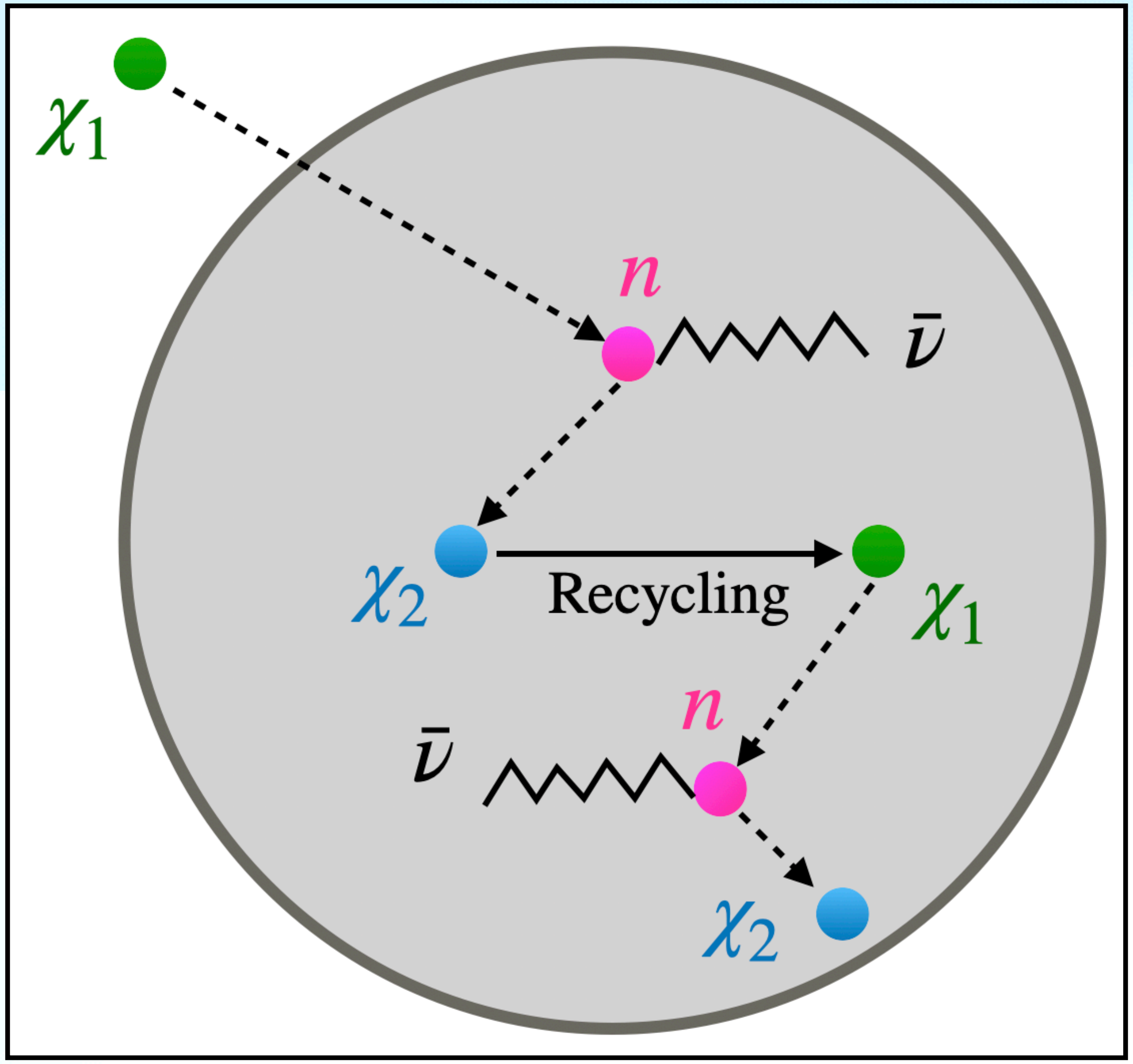


Questions & Comments: anupam.ray@berkeley.edu

What about the Major Portion?

- Major portion of the DM could be weakly-interacting, and can have baryon-number-violating interactions.

How to probe?



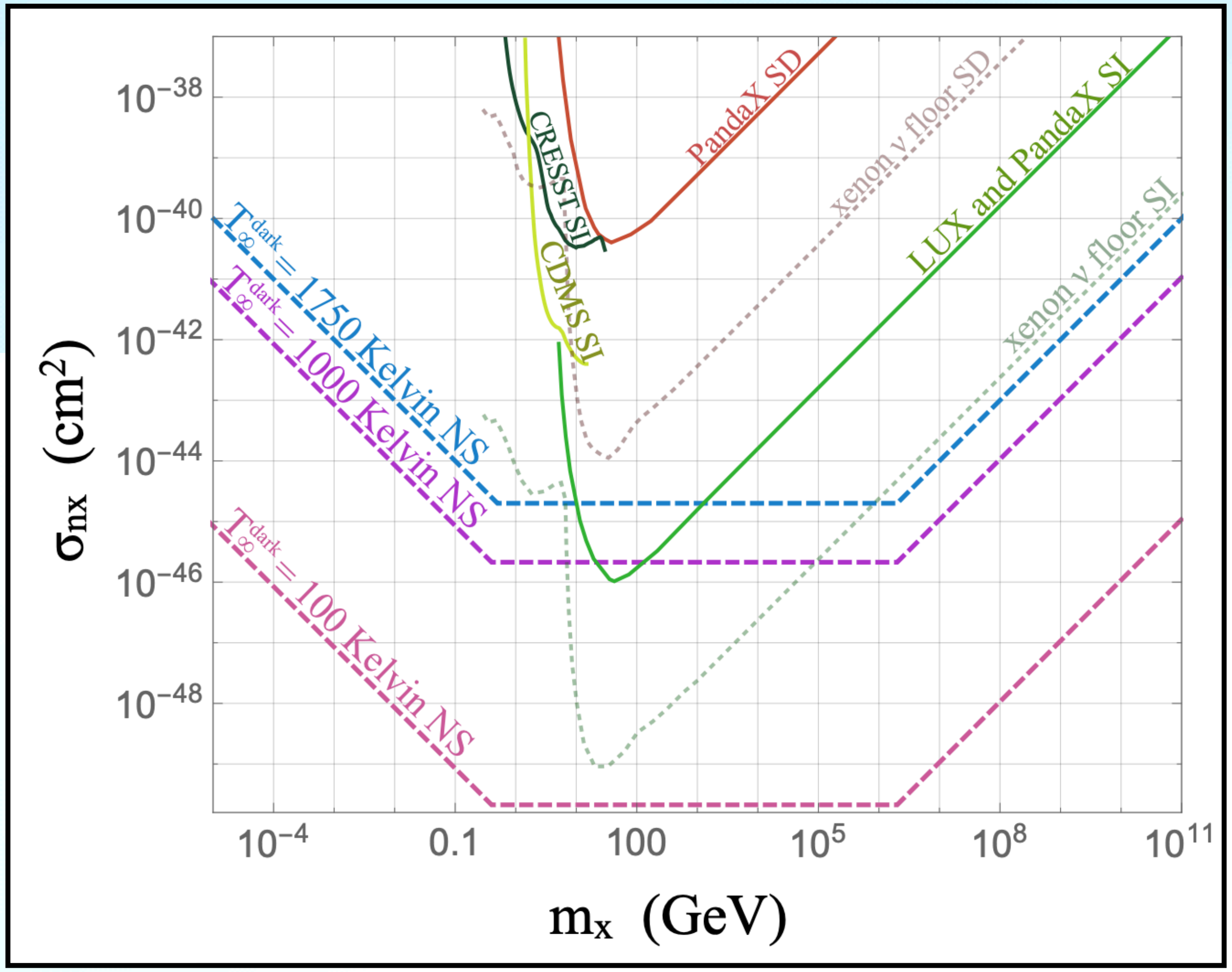
Ray, (with Ema, McGhee, Pospelov) [in prep.]

Leads to anomalous heating of cold Neutron Stars.

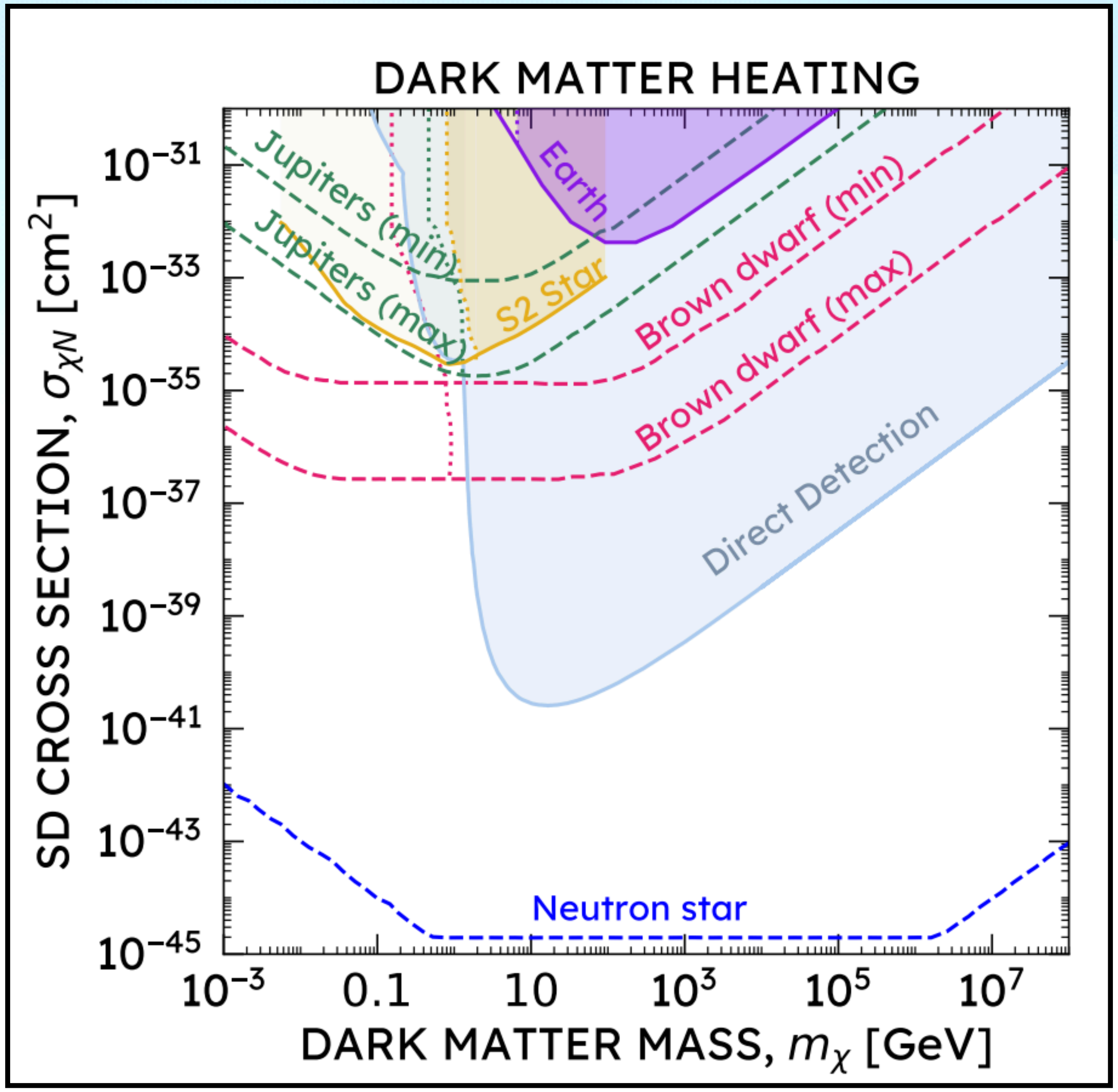
What about the Major Portion?

- Anomalous neutron star heating via captured DM annihilation (or via kinetic energy transfer).

Baryakhtar et al [PRL, 2017]



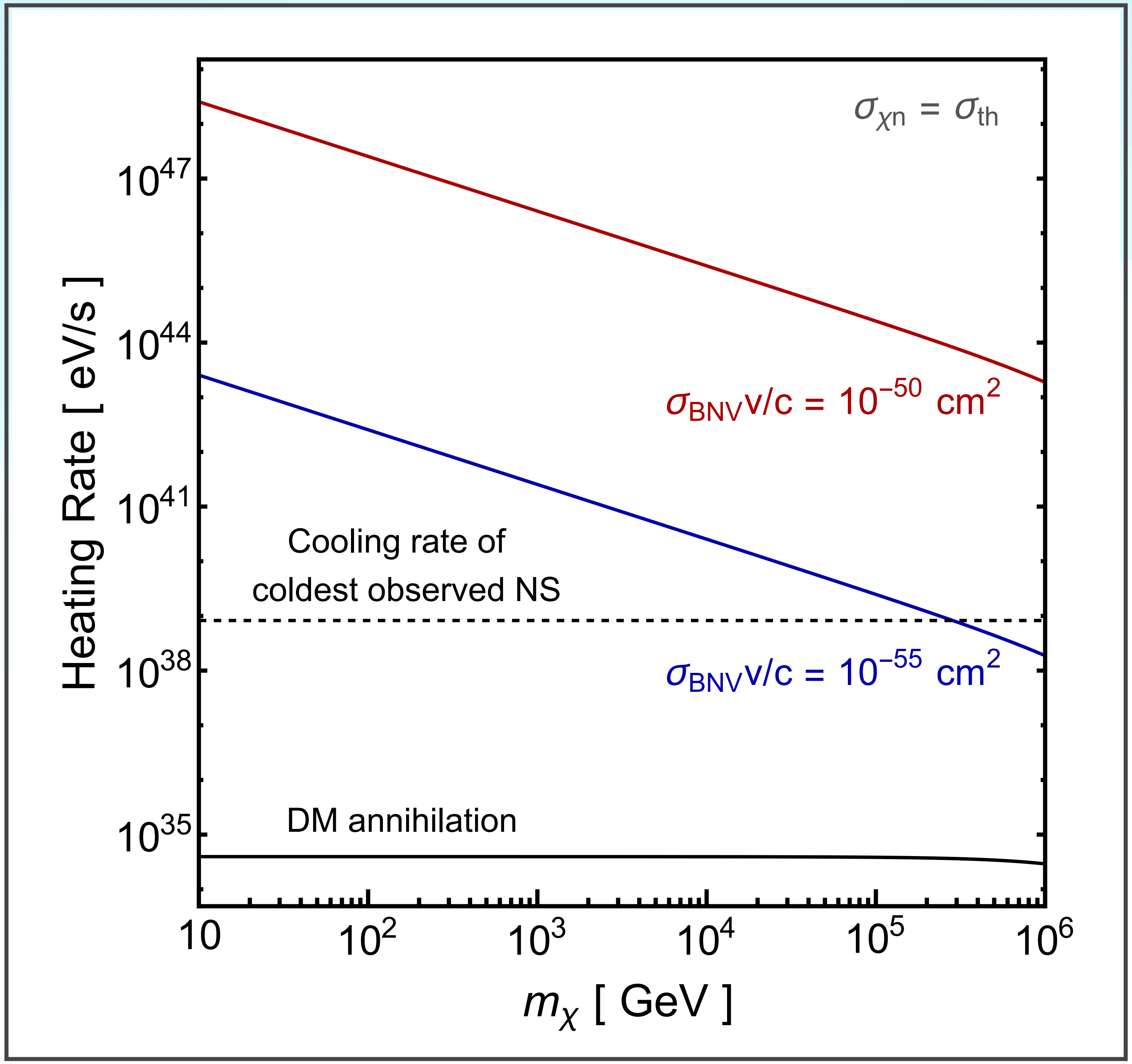
Leane et al [2405.05312]



Coldest NS so far seen has $T \sim 40{,}000\,K$ (significantly larger than these estimates!)

DM-induced BNV

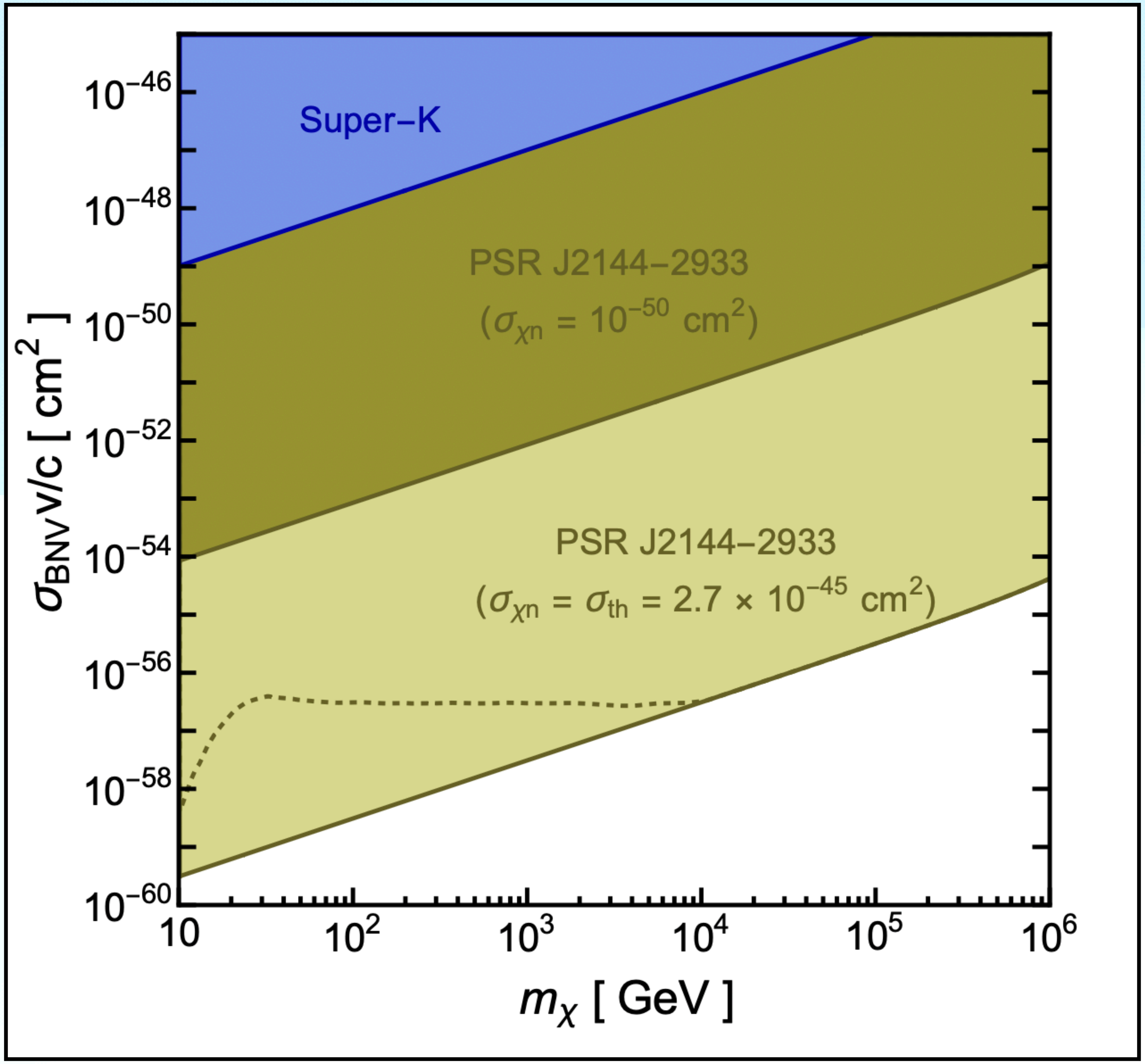
- Total amount of DM captured inside a neutron star is minuscule as compared to the total neutron mass.



Ray, (with Ema, McGhee, Pospelov) [in prep.]

DM-induced BNV

- How strong can DM-induced BNV interactions be?



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