Decoding the Mystery of Dark Matter with Celestial Objects

Anupam Ray

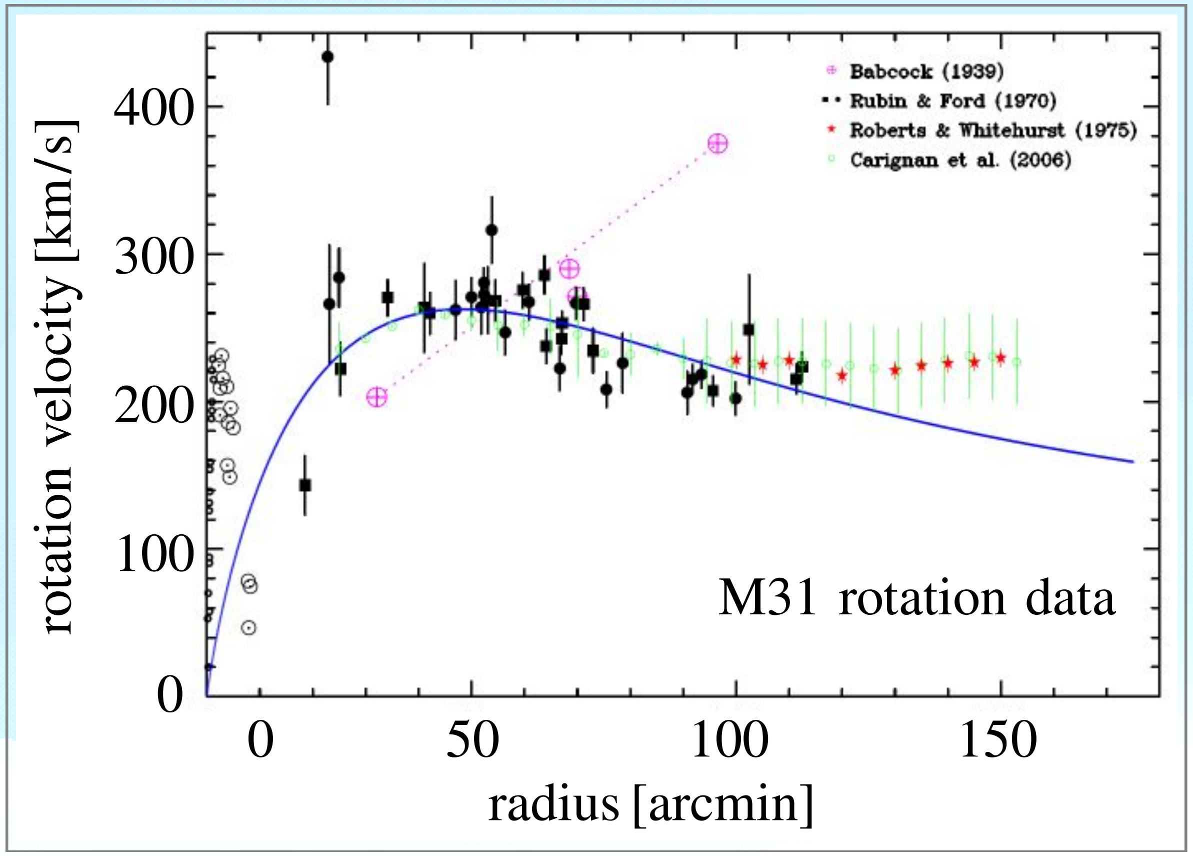
N3AS Fellow, UC Berkeley & University of Minnesota

CETUP* Workshop 2024
06.21.2024

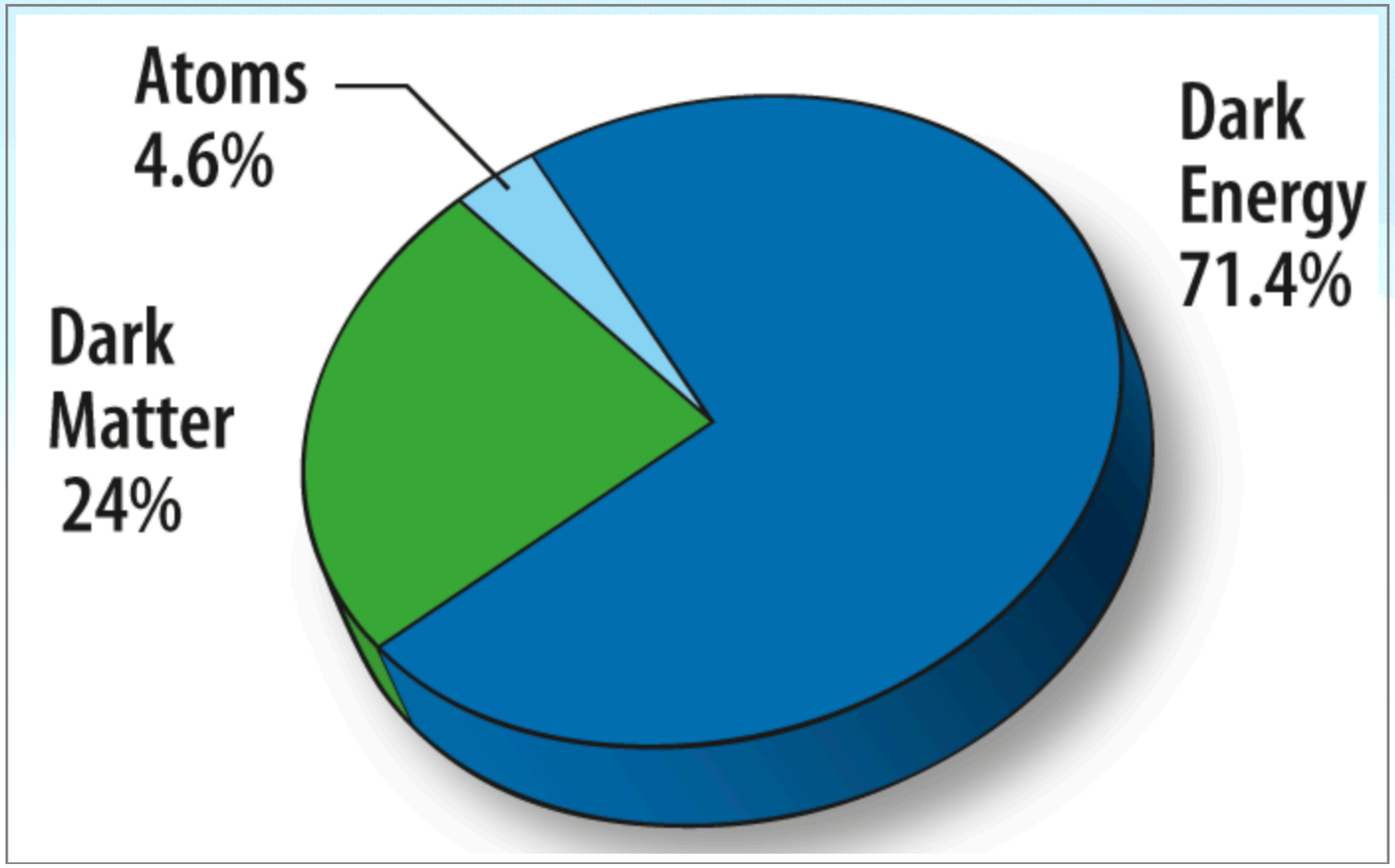
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER
NSF

THE INSTITUTE FOR UNDERGROUND SCIENCE AT SURF
CETUP* 2024

Dark Matter (DM)



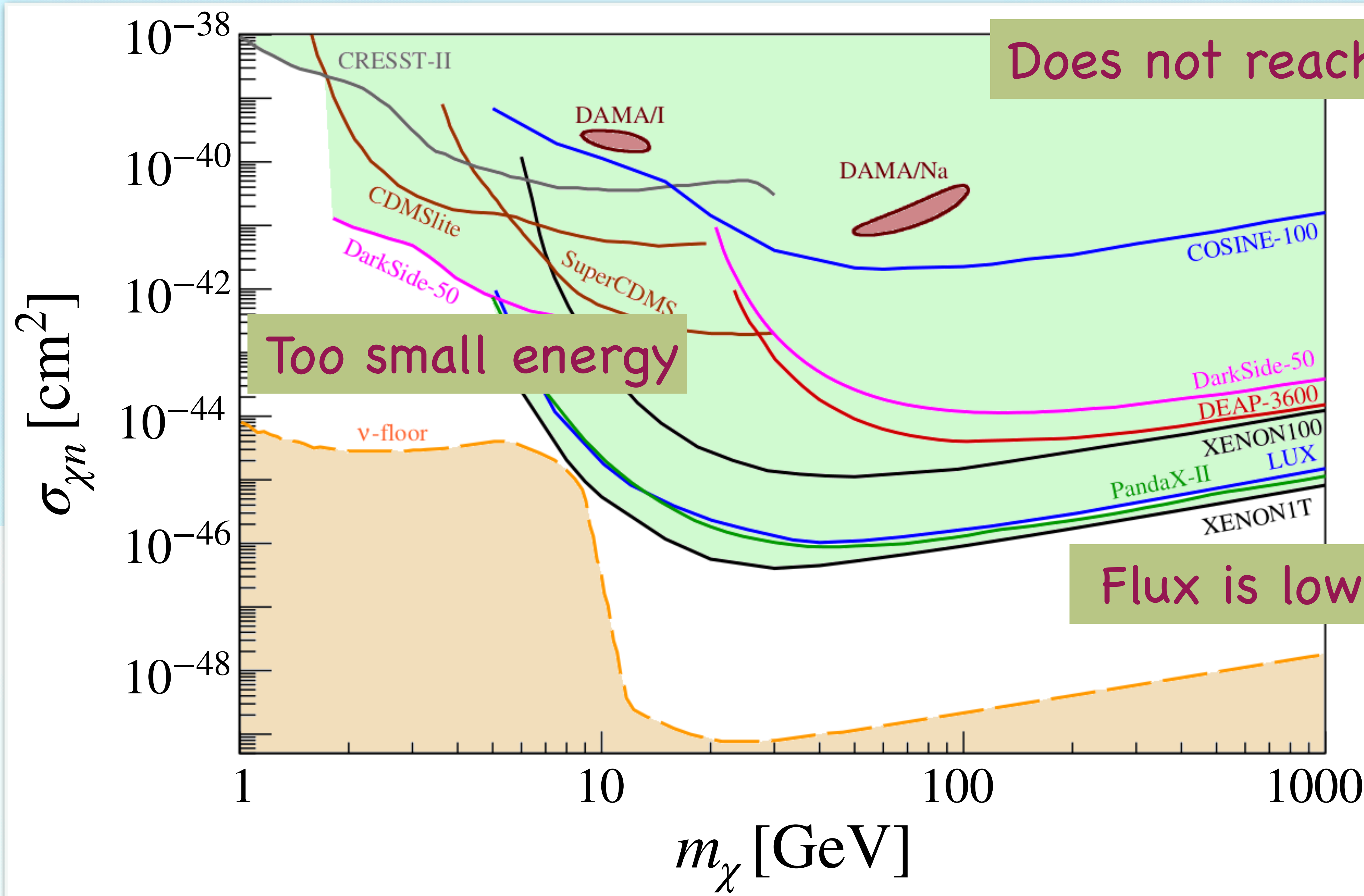
From: Bertone and Hooper, Rev. Mod. Physics (2016)



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

- DM mass?
- DM interactions with baryons?

Results: Underground Detectors



- Light DM, Heavy DM and Strongly-interacting DM

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

Take Away

- We show DM capture in celestial objects can provide significant sensitivity to these blind-spots.

  Which stellar object is the most optimal detector?

- Neutron Stars are the most optimal detectors for heavy dark matter searches — far more powerful than the direct detection experiments.

  The "effective" exposure of stellar objects are enormously larger as compared to the human-made experiments.

- In the strongly-interacting regime, Earth provides novel way to probe DM interactions.

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search

Open Access

Low Mass Black Holes from Dark Core Collapse

Basudeb Dasgupta, Ranjan Laha, and Anupam Ray
Phys. Rev. Lett. **126**, 141105 – Published 8 April 2021

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About Editorial Team

Can LIGO Detect Nonannihilating Dark Matter?

Sulagna Bhattacharya, Basudeb Dasgupta, Ranjan Laha, and Anupam Ray
Phys. Rev. Lett. **131**, 091401 – Published 29 August 2023

70

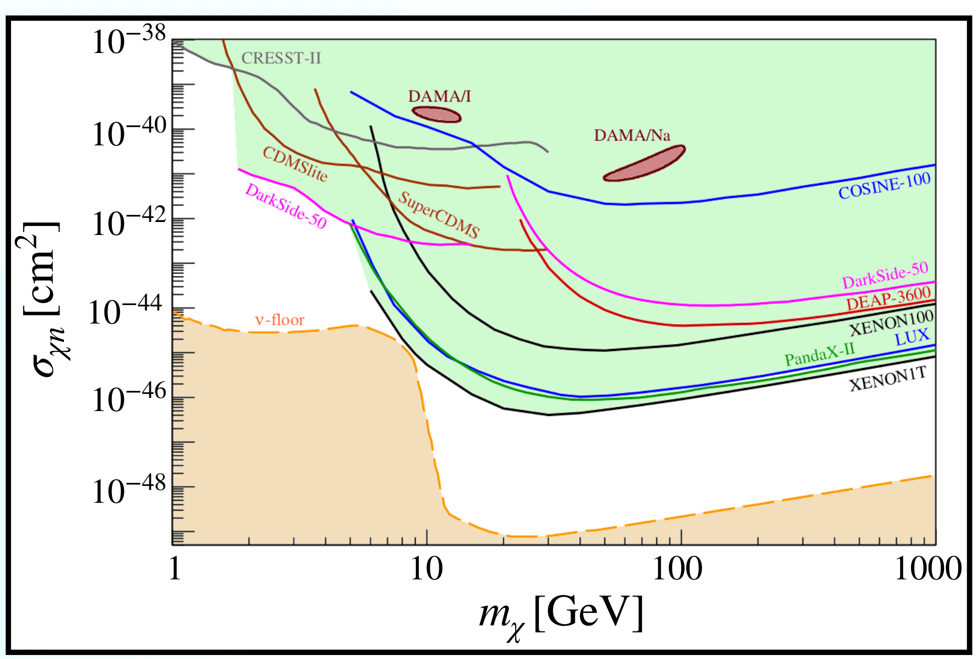
More

Weakly interacting Heavy DM

Neutron Stars as DM Detectors

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

Ray (with Dasgupta, Laha) [PRL, 2021]



Outline

- Gradual accumulation of heavy non-annihilating DM particles inside neutron stars can transmute them to comparably low mass BHs.

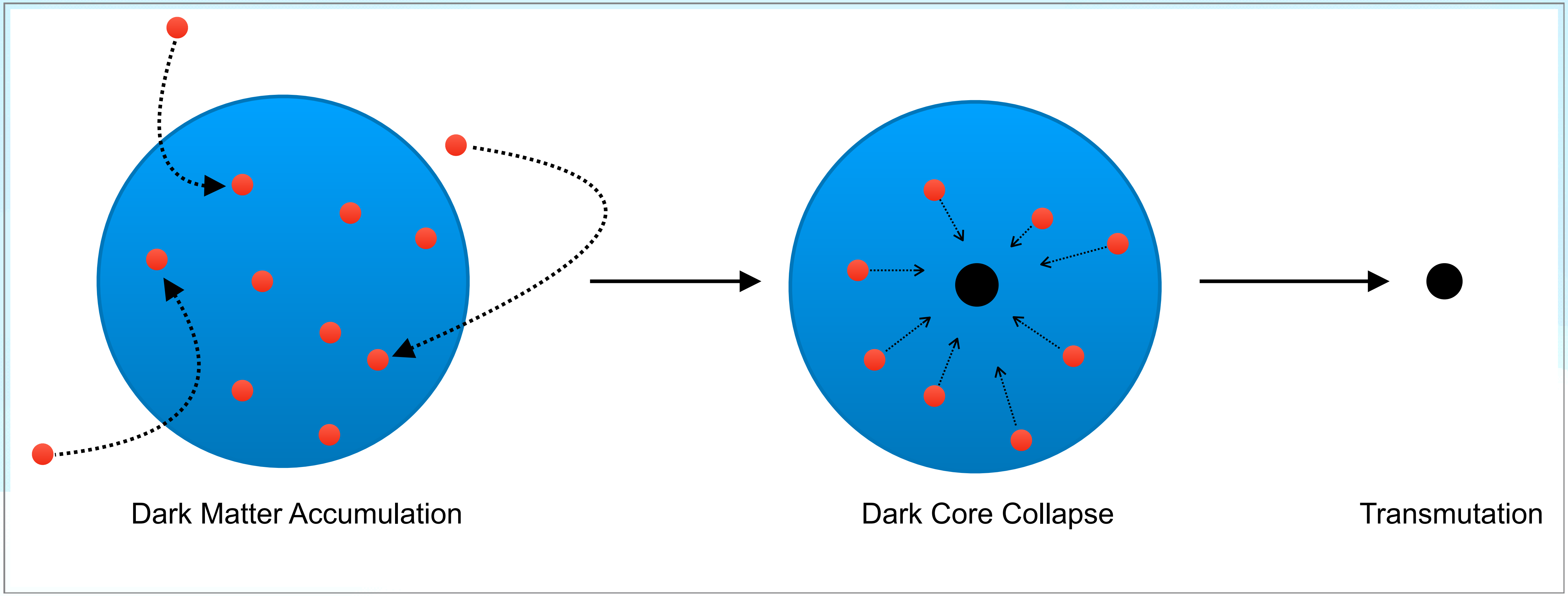
- These low mass transmuted BHs if in binaries can emit GW, detectable by current generation detectors, LVK.

- We explore GW emission from such BH binaries in the LVK data, and provide novel exclusions on DM parameters based on non-detection.

Note: Existence of isolated NSs also put significant exclusions on DM parameters.

See: Kouvaris et al. (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),...., Dasgupta, Gupta, **Ray** (JCAP 2020),...

DM-induced Collapse

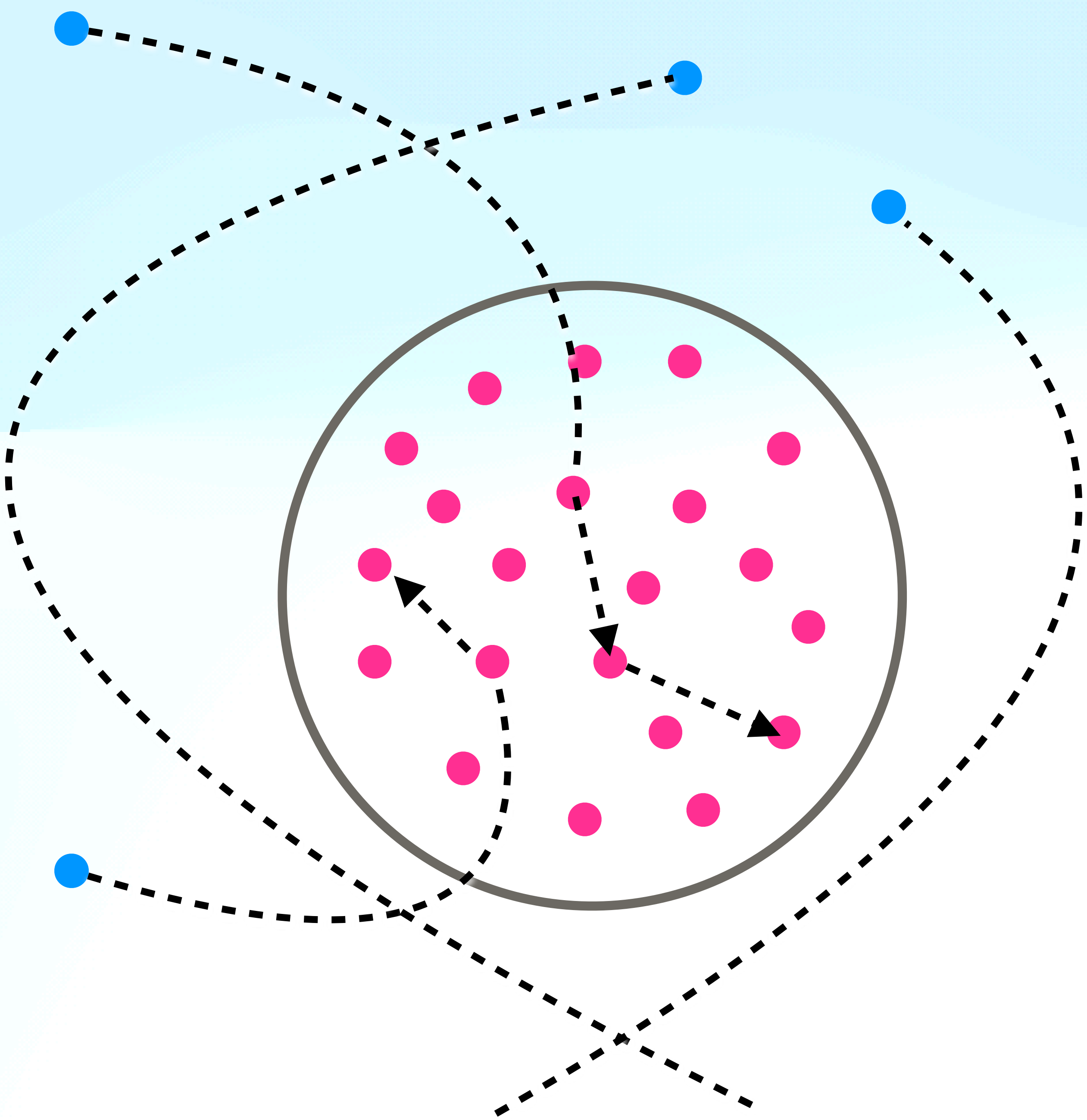


1. DM accumulation and its thermalisation
2. DM distribution
3. Dark Core Collapse
4. Growth of micro-BH and destruction of host

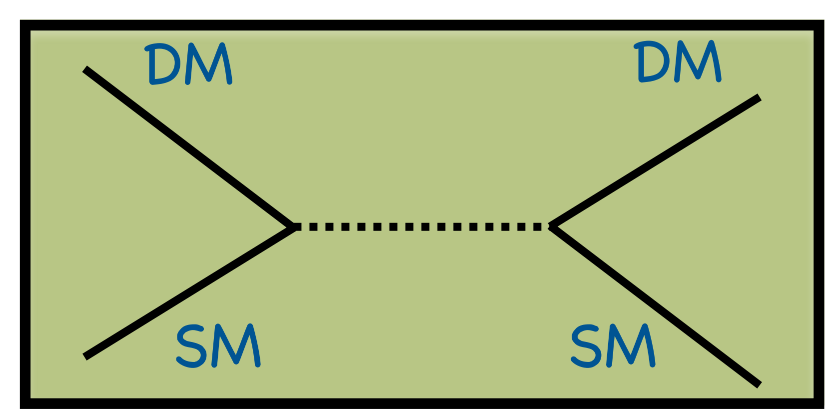
DM Accumulation

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)



DM Accumulation

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

- Rate of DM particles transiting:

$$C_{\rm geo} \sim \pi R^2 \times \frac{\rho_\chi}{m_\chi} \times \bar{v} \times \left(1 + \frac{3v_{\rm esc}^2}{2\bar{v}^2}\right)$$

For typical NS parameters, transit rate is $10^{20}\,{\rm s}^{-1}$ for $m_\chi = 10^5$ GeV

- Fraction of these transiting DM particles gets captured depending on DM-nucleon scattering cross-section.

Capture fraction (f_c) = $\dfrac{\sigma_{\chi n}}{\pi R^2/N_n}$

For $\sigma_{\chi n} = 10^{-45}$ cm^2 $\rightarrow f_c \sim 0.4$

(For Sun $\rightarrow f_c \sim 10^{-10}$)

*Capture rate scales linearly with compactness (M/R)

Distribution of Captured DM

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

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

- For heavy DM, the effect of gravity ($\sim m_\chi$) dominates over the diffusion processes ($\sim m_\chi^{-3/2}$), and they gravitate towards the stellar core.

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

For a typical NS, DM particles of mass 10^5 GeV settle within ~5 cm radius!

Dark Core Collapse

- The core density of the captured DM particles become tantalisingly larger, and eventually it collapses to a tiny BH at the center.

For a Gyr old NS, $\mathcal{O}(10^{36})$ number of DM particles of mass 10^5 GeV can settle within 5 cm radius!

(Increases further with larger DM mass).

Core density of $10^{39}\,\mathrm{GeV/cm^3}$

- Once the core density exceeds its critical threshold value, BH formation occurs.

bosonic/fermionic DM have different threshold.

Mass of the nascent BH is very small: $10^{-16}\,M_\odot$ for DM mass of 10^5 GeV and decreases with larger DM mass.

Growth of Nascent BH

- The micro BH accumulates matter from the host and also evaporates via Hawking radiation.

- For sufficiently small BH, accretion (M^2) becomes inefficient and Hawking evaporation dominates ($1/M^2$), ceasing the implosion.

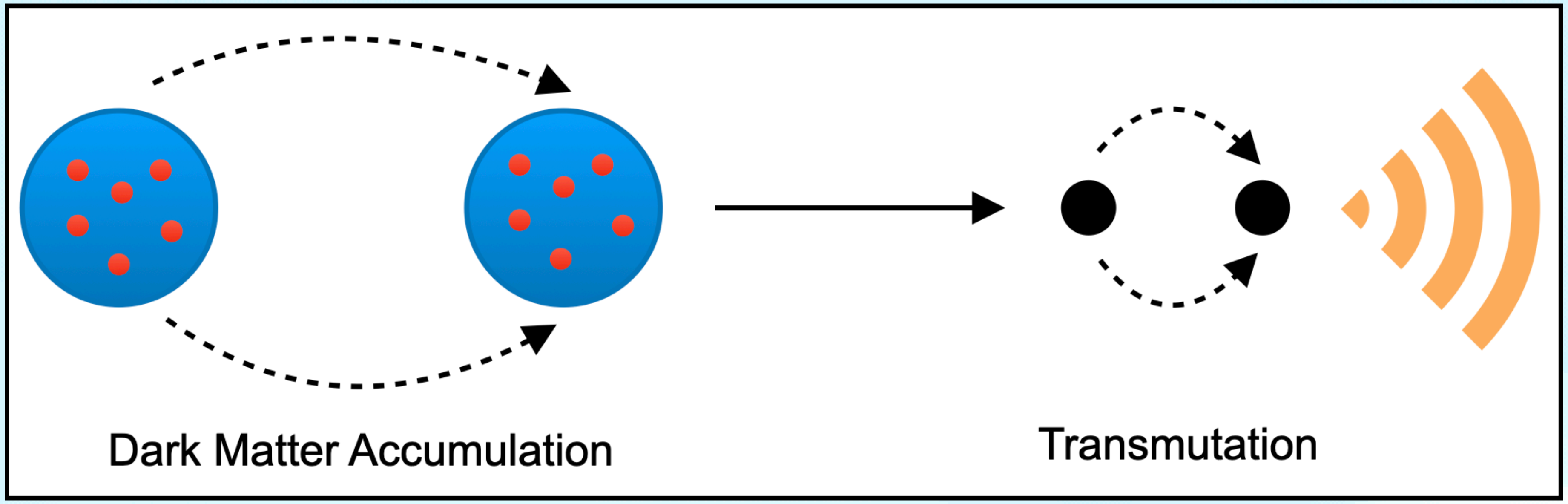
For micro-BHs smaller than $10^{-20}\,M_\odot$, Hawking evaporation dominates

$$\frac{dM_{\rm BH}}{dt} = \frac{4\pi\rho_{\rm core}G^2M_{\rm BH}^2}{c_s^3} - \frac{P\left(M_{\rm BH}\right)}{G^2M_{\rm BH}^2}$$

$P(M_{\rm BH})$: Page factor which takes into account the grey-body spectrum and importantly, the number of emitted SM species. It ranges from $1/74\pi$ to $1/1135\pi$.

Classical limit is $1/11360\pi$.

Summary



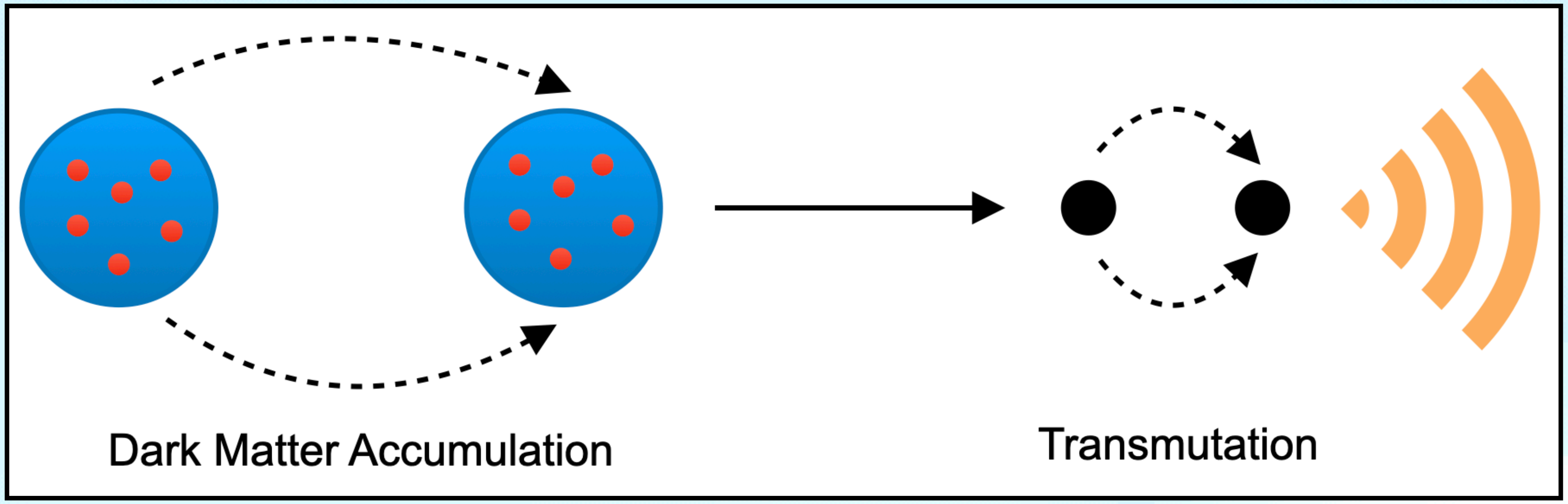
- Binary neutron stars can be transmuted to anomalously low mass binary BHs via gradual accumulation of non-annihilating DM.

Dasgupta, Laha, Ray (PRL, 2022)

- Non detection of such binary BHs in the existing GW data provide novel constraints on weakly-interacting heavy DM interactions.

Bhattacharya, Dasgupta, Laha, Ray (PRL, 2023)

TBH formation & Mergers



Kouvaris et al (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),...

- We track each progenitors (NS binaries) from their binary formation time till present day to compute the present day TBH merger rate.

Dasgupta, Laha, **Ray** (PRL, 2021)

Essentially, counting the number of NS binaries that undergoes a successful transmutation from its birth till the present day.

TBH formation & Mergers

- Transmutation time:

[Collapse time + Swallow time]

t_f : Binary formation time

t_0 = 13.79 Gyr = Present day

$$\tau_{\text{trans}} < t_0 - t_f$$

Depends on DM parameters (DM mass and DM-nucleon scattering cross-section)

- Normalization (number of progenitors) is fairly uncertain and needs to be statistically marginalised. Normalization is based on "few" observed BNS events by LVK.

TBH merger rate depends on DM mass and DM-nucleon scattering cross-section via transmutation time with an uncertain normalization parameter.

TBH Merger Rate

- TBH merger rate depends on:

i) Spatial distribution of Binary NS in the Galaxies.

(uniform distribution in 1d)

ii) DM density profile in the Galactic halos.

(NFW profile)

iii) Progenitor properties (mass, radius, core temperature of the progenitors).

(Typical NS parameters)

iv) Uncertain normalization parameter.

(10-1700 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ from LVK measurement)

Systematic exploration is required.

GW Data & Statistics

- We use the null-detection of low mass BH searches in the LVK data to infer constraints on non-annihilating DM interactions.

LVK 2212.01477, LVK (PRL 2018, 2019, 2022), Nitz & Wang (APJ 2021, PRL 2021),...

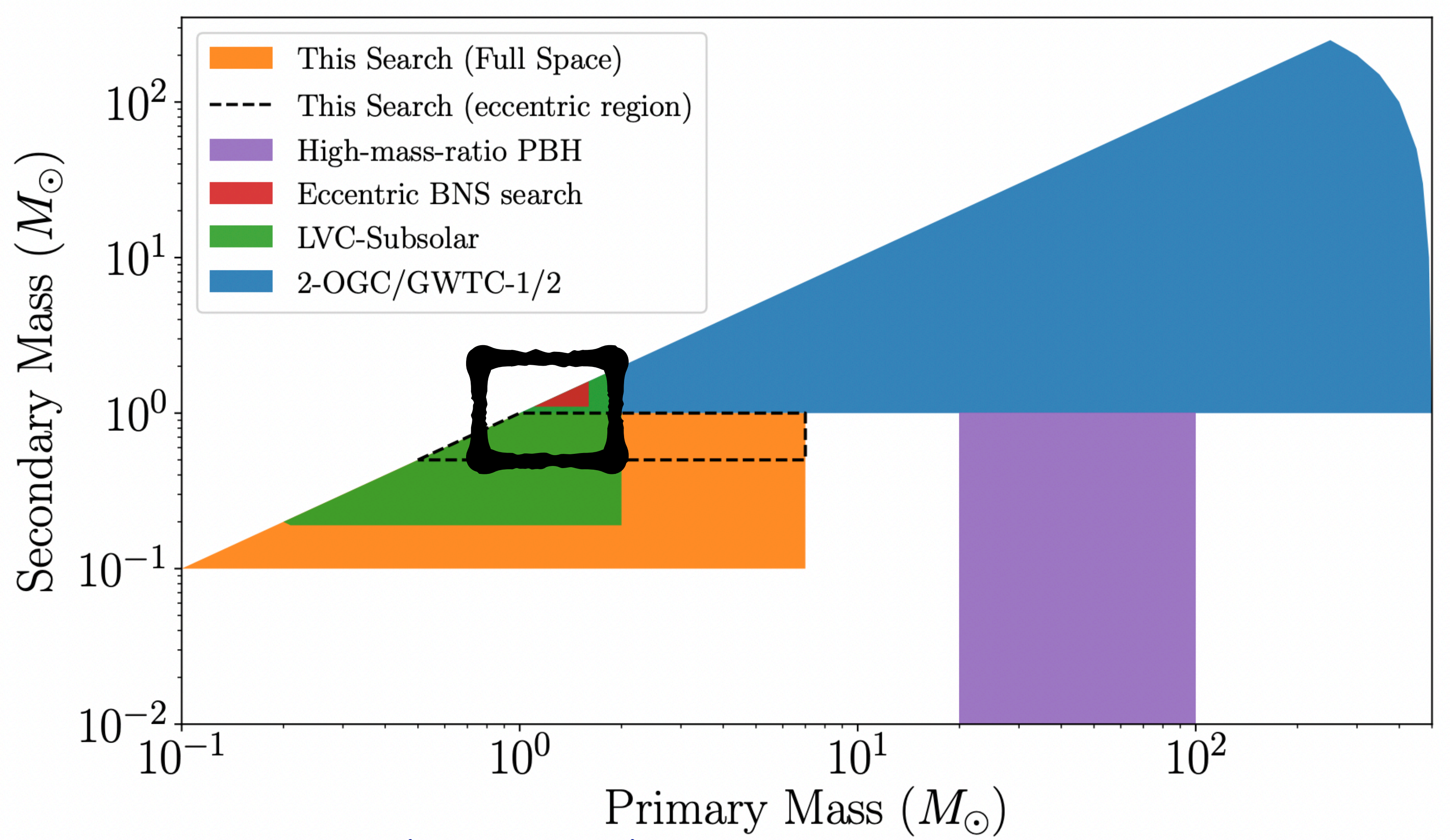


Fig: Nitz & Wang (APJ 2021)

GW Data & Statistics

- Merger rate upper limits:

LVK 2212.01477, LVK (PRL 2018, 2019, 2022), Nitz & Wang (APJ 2021, PRL 2021),...

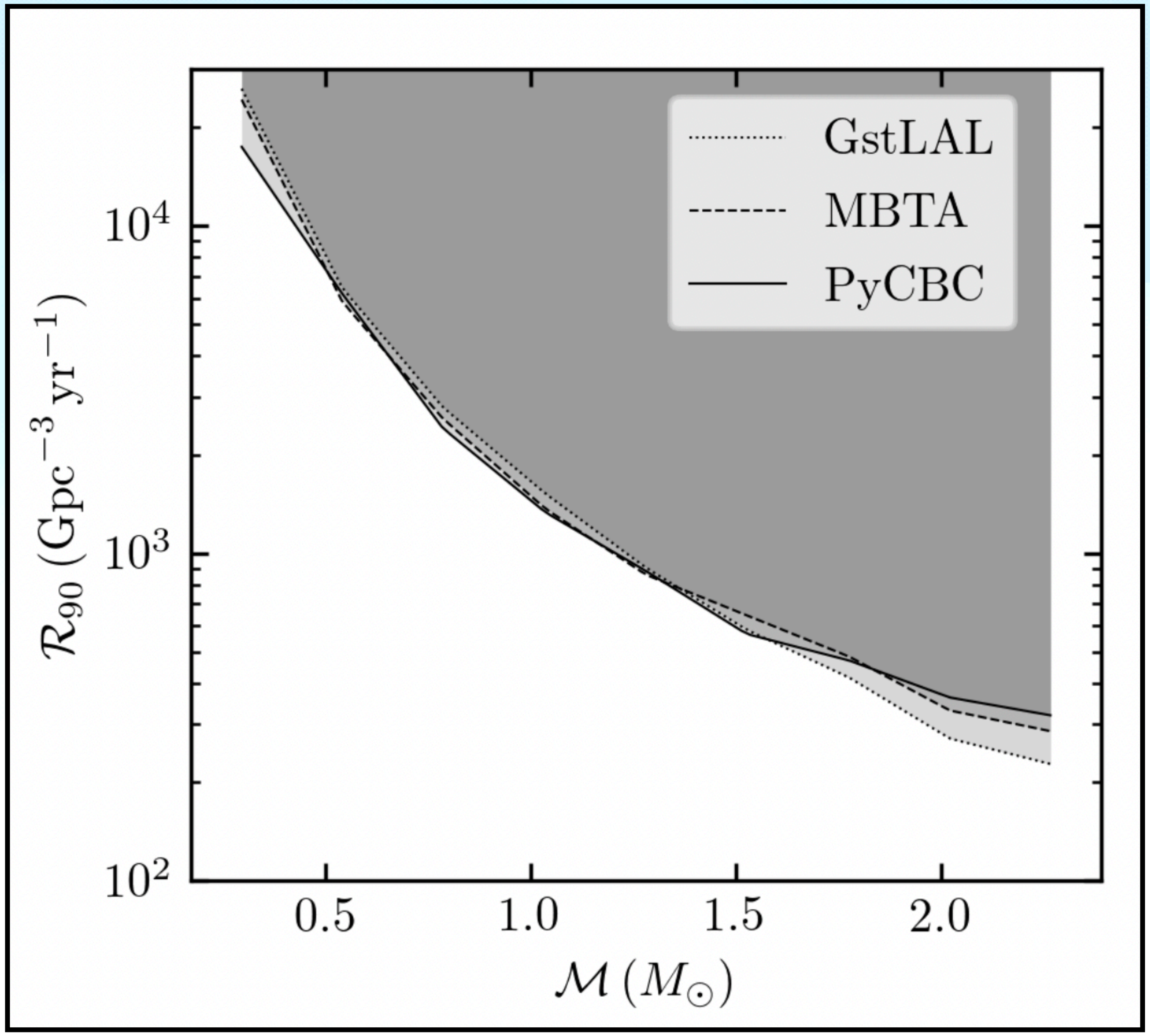


Fig: LVK (PRL 2021)

*These searches have recently been used to put constraints on PBHs as DM as well as an atomic DM model. For the first time, we use them to probe particle DM interactions.

GW Data & Statistics

- For 1.32 - 1.32 $M_\odot$ binary = Chirp mass of 1.15 $M_\odot$, LIGO collaboration (O3 run) provides a merger rate upper limit of $R_{90} = 389\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

LVK 2212.01477, LVK (PRL 2018, 2019, 2022), Nitz & Wang (PRL 2021),...

- Our "Conservative" exclusion limit:

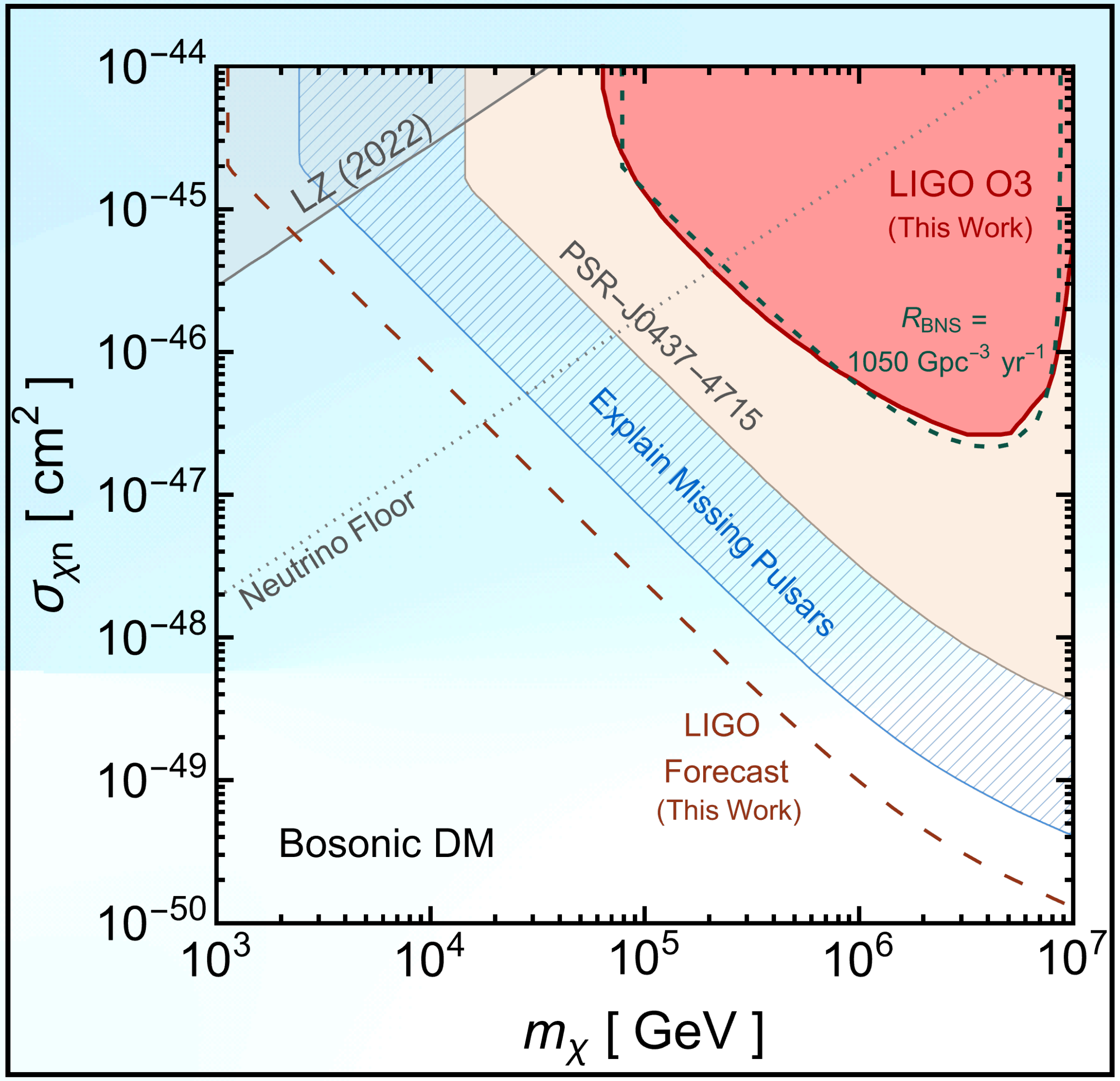
$$R_{\mathrm{TBH}}(z=0)\,[m_c = 1.15\,M_\odot] \leq 389\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

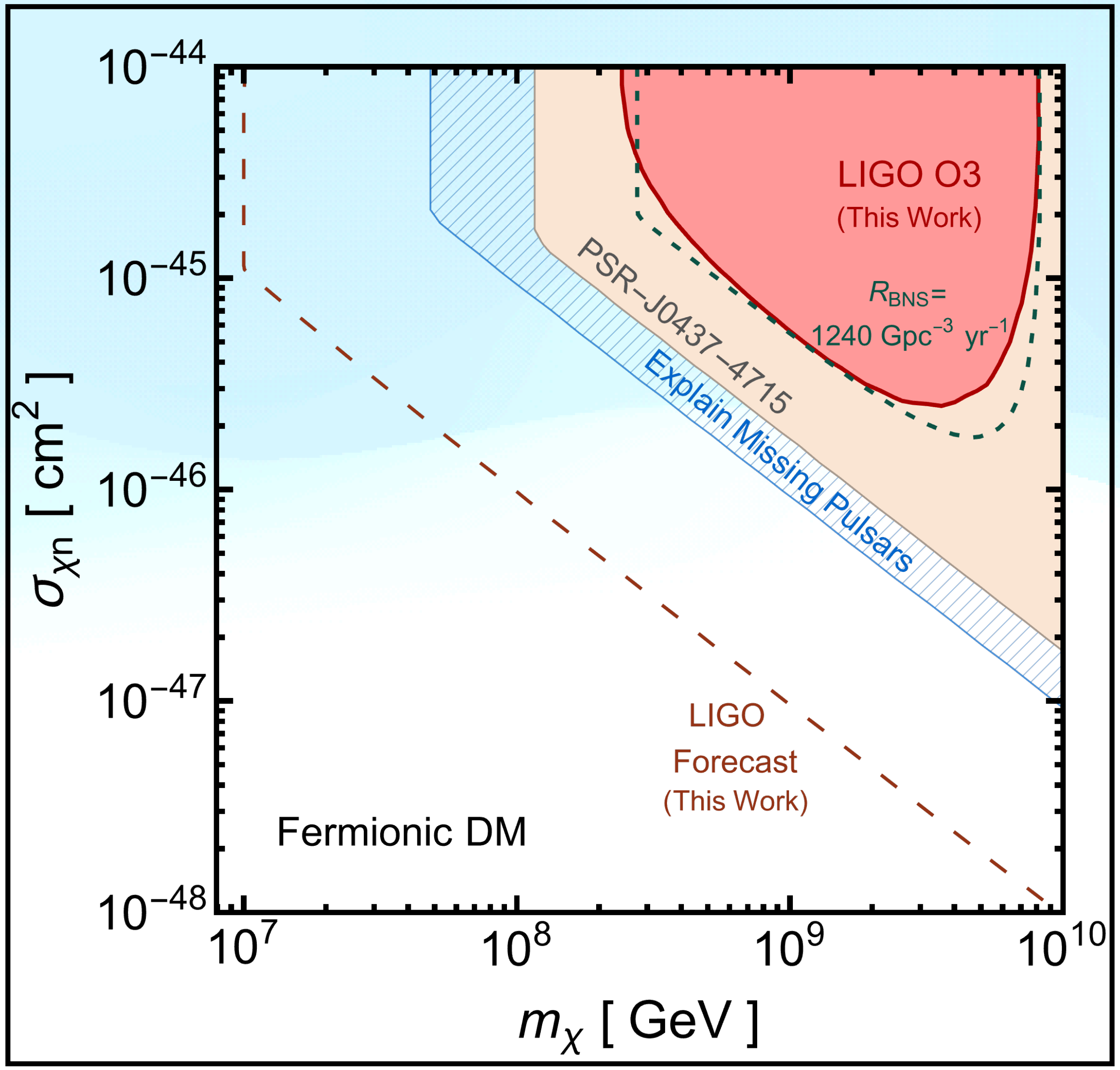
Chirp mass distribution of BNS is sharply peaked peaked at 1.15 $M_\odot$, which can be approximated as a Dirac-delta mass distribution.

Ozel & Freire (Ann. Review of Astronomy and Astrophysics, 2016)

Results

Bhattacharya, Dasgupta, Laha, **Ray** (PRL, 2023)





(Left) Bosonic DM

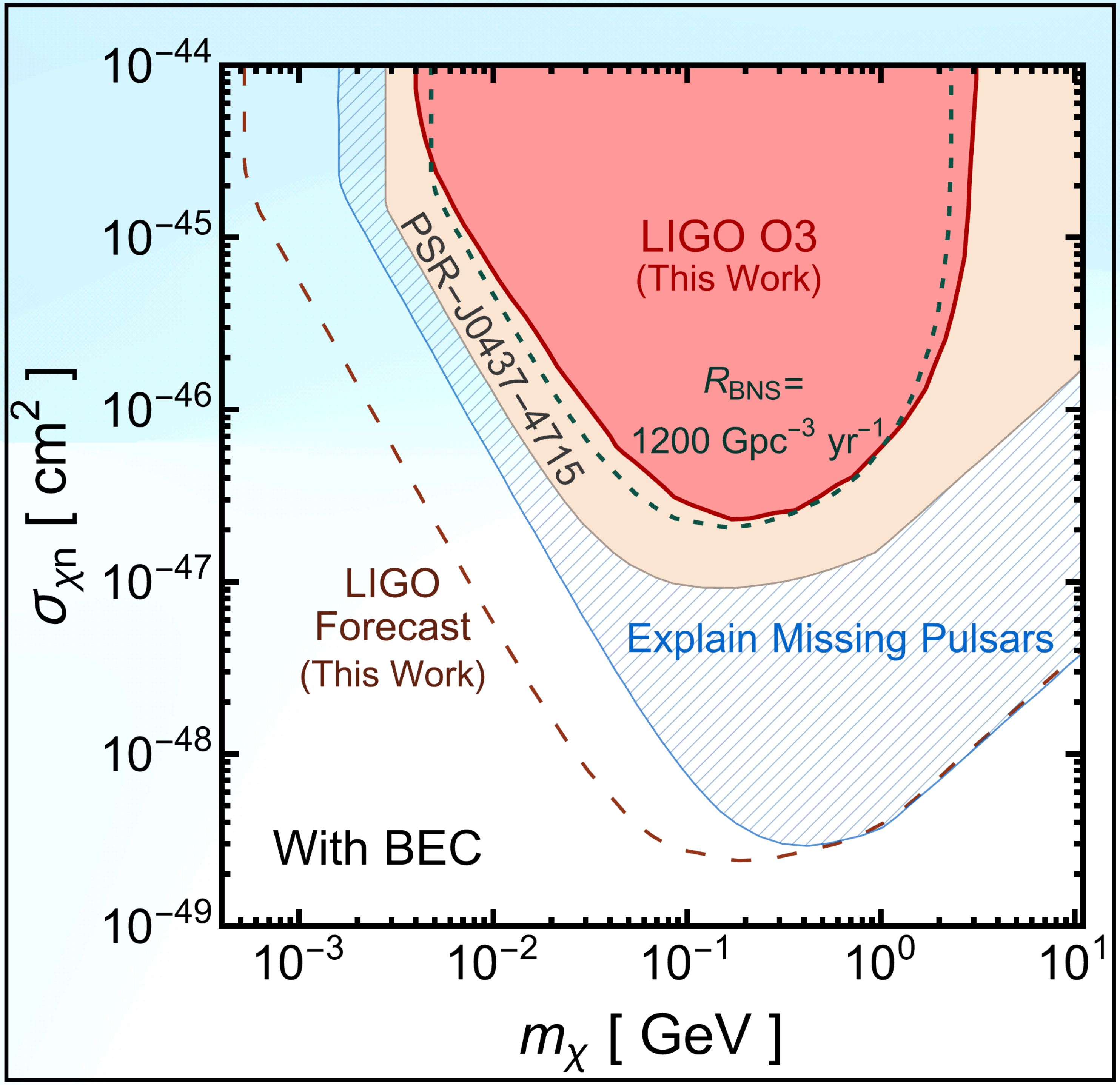
(Right) Fermionic DM

Heavier DM masses, the nascent BH becomes smaller, Hawking evaporation becomes significant, ceasing the TBH formation.

BEC Formation

- Bosonic DM can form a Bose-Einstein condensate inside NSs

Kouvaris et al (PRL 2012), McDermott et al. (PRD 2012), Garani et al. (JCAP 2018),...



Bhattacharya, Dasgupta, Laha, **Ray** (PRL, 2023)

GW-inferred constraints for a possible BEC formation scenario

Conclusion

- Existing GW detectors can be used to probe the particle nature of DM.

- For weakly interacting heavy DM, LIGO provides novel constraints on DM interactions, much more stringent as compared to the direct DM searches.

- Owing to a different systematics, GW-inferred exclusions has the potential to beat the EM-inferred exclusions, and covers parameter space well-below the neutrino floor.

(LZ 2022) (spin-independent) excludes DM-nucleon scattering cross-section of $2.8 \times 10^{-43}\,\mathrm{cm}^2$ for $m_\chi = 10^6\,\mathrm{GeV}$.

LIGO excludes DM-nucleon scattering cross-section of $2 \times 10^{-47}\,\mathrm{cm}^2$ for $m_\chi = 10^6\,\mathrm{GeV}$. **"Impossible"** to reach by these underground detectors!

What about Strongly-interacting regime?

- In the strongly-interacting regime, capture primarily occurs via multiple collisions.

- NSs are no longer optimal objects in this regime. Larger objects, such as, stars are ideal.

- Rate of DM particles transiting:

$$C_{\rm geo} \sim \pi R^2 \times \frac{\rho_\chi}{m_\chi} \times \bar{v} \times \left(1 + \frac{3v_{\rm esc}^2}{2\bar{v}^2}\right)$$

For typical NS parameters, transit rate is $10^{20}\,{\rm s}^{-1}$ for $m_\chi = 10^5$ GeV.

For Sun, transit rate is $10^{25}\,{\rm s}^{-1}$ for $m_\chi = 10^5$ GeV.

GW probe of Strongly-interacting DM

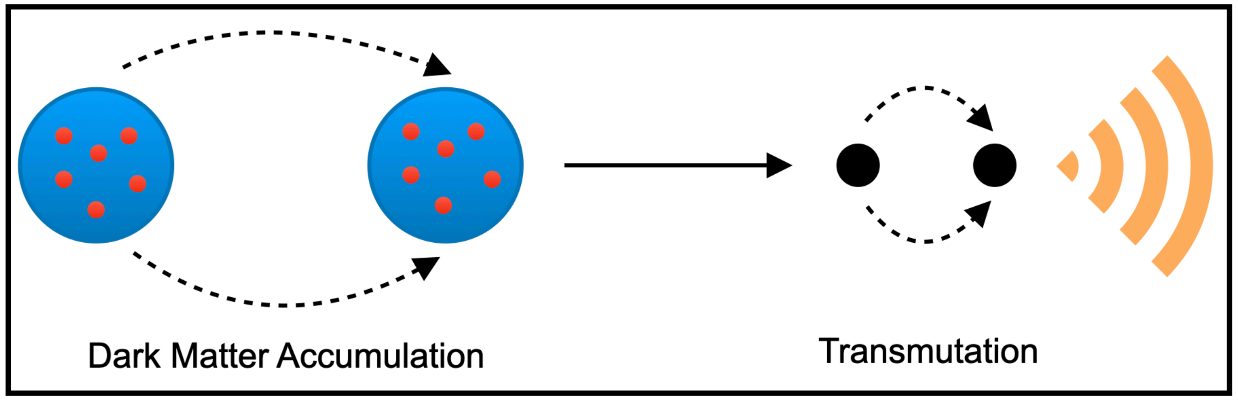
- We consider GW emission from binary Sun-like systems.

- Accumulation of heavy DM inside Sun like stars can also transmute them to comparable mass BHs.

Acevado et al. (JCAP, 2021), Ray (PRD, 2023)

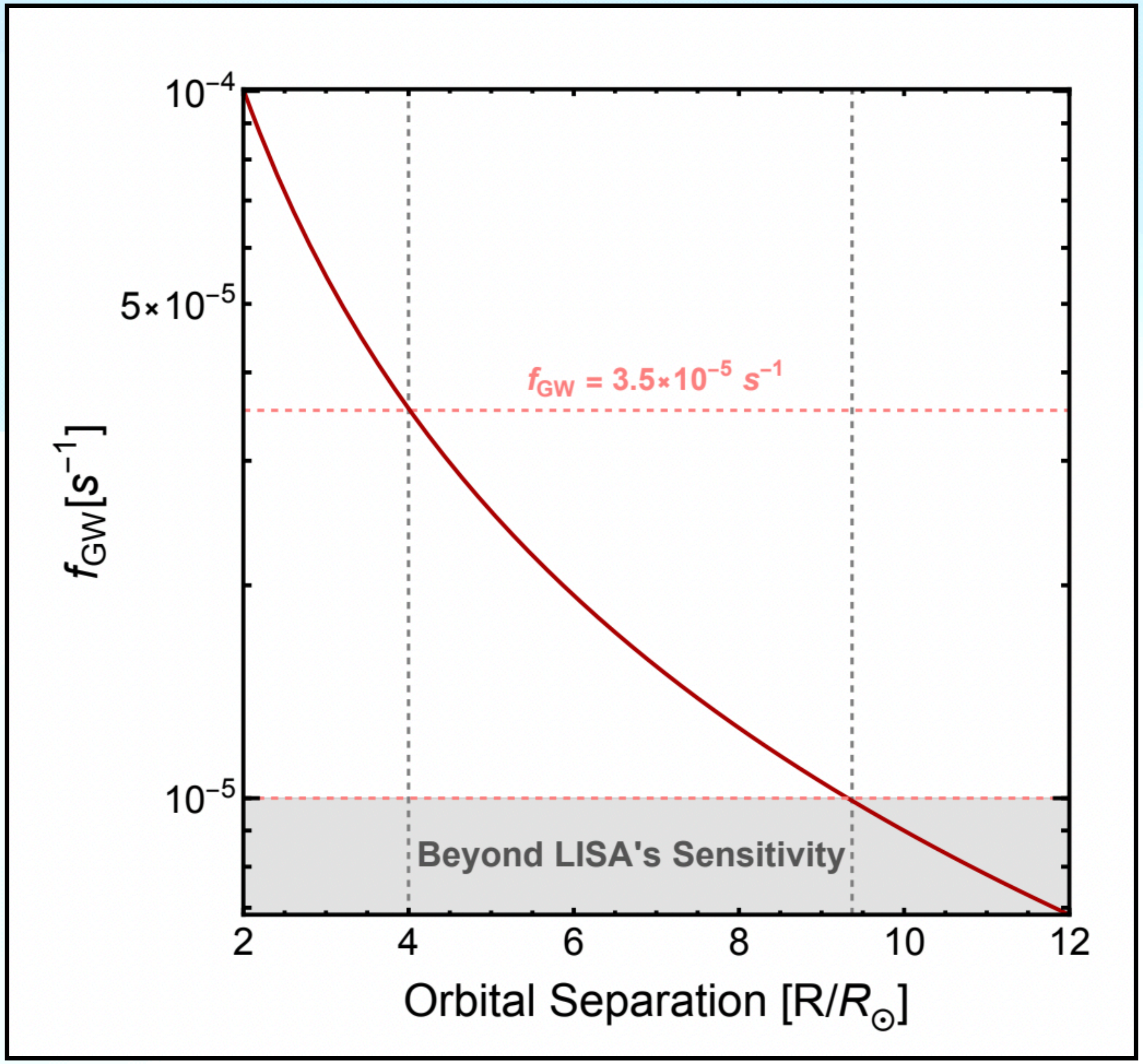
- If a Sun like binary is sufficiently close, the transmuted BHs in their inspiral phase can emit a quasi-monochromatic GW signal, commonly known as "Continuous GWs".

Ray (with Bhattacharya, Miller)
[2403.13886]



GW probe of Strongly-interacting DM

- Frequency of such Continuous GW signal is $\sim 10^{-5}$ Hz, detectable by space-based detectors, such as LISA.



$\dot{f}_{GW} \sim 10^{-23}\,\mathrm{Hz/s}$

↓

Monochromatic GW

Ray (with Bhattacharya, Miller) [2403.13886]

GW probe of Strongly-interacting DM

- We estimate the number of such transmuted BH binary in our Galaxy.

Number of Stars in our Galaxy is 200-400 billions.

20% of them are Sun-like stars → 40-80 billions.

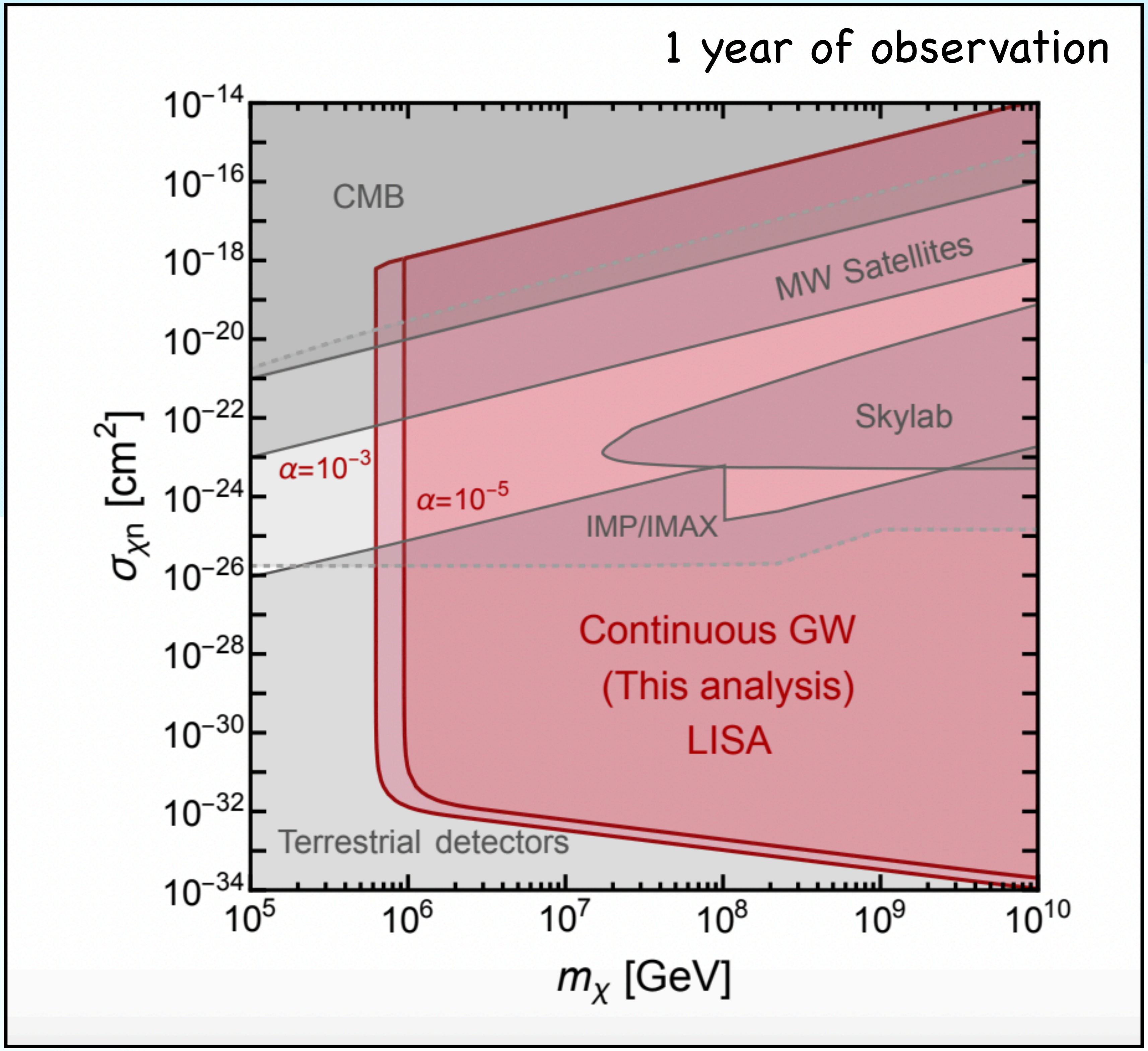
Among them a certain fraction forms close binary. Lets call it as "α".

(We take α as a free parameter since it is uncertain, and take values consistent with astrophysics.)

Moe et al (ApJ 2019 and references therein)

They can transmute if the transmutation time (which depends on DM parameters) is shorter than the available time.

GW probe of Strongly-interacting DM



First study on Continuous GW as a probe of particle DM.

For $\alpha \leq 10^{-6}$, one can use future detectors like BBO.

Ray (with Bhattacharya, Miller) [2403.13886]


PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press About Editoria

Open Access

Dark Matter Annihilation inside Large-Volume Neutrino Detectors

David McKeen, David E. Morrissey, Maxim Pospelov, Harikrishnan Ramani, and Anupam Ray
Phys. Rev. Lett. **131**, 011005 – Published 7 July 2023


Journal of Cosmology and Astroparticle Physics

PAPER • OPEN ACCESS

Neutrinos from Earth-bound dark matter annihilation

Maxim Pospelov[1,2] and Anupam Ray[1,3]
Published 12 January 2024 • © 2024 The Author(s)
Journal of Cosmology and Astroparticle Physics, Volume 2024, January 2024
Citation Maxim Pospelov and Anupam Ray JCAP01(2024)029
DOI 10.1088/1475-7516/2024/01/029

Article PDF

Article metrics
79 Total downloads
1
Share this article

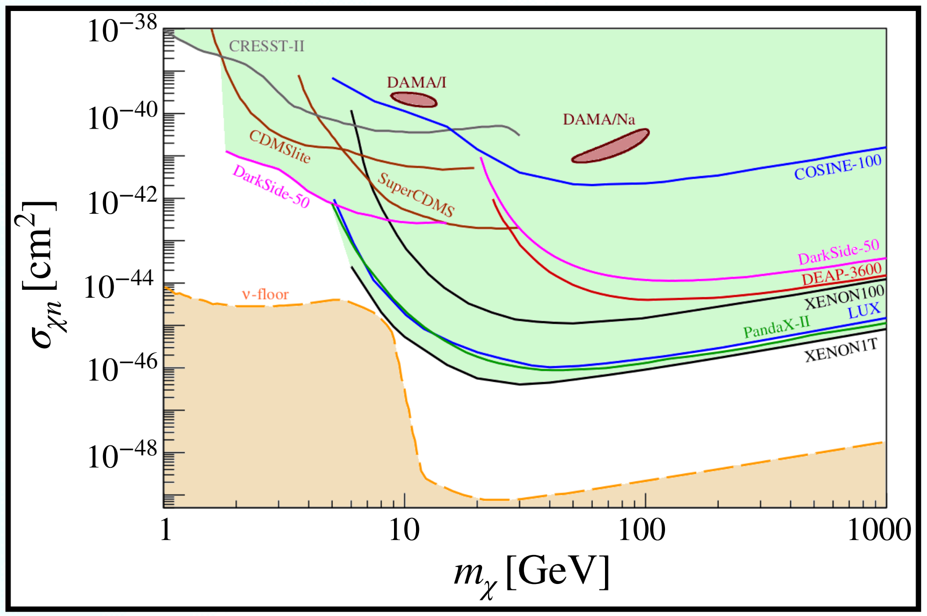
Strongly interacting DM Component

Earth as a novel DM Detector

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

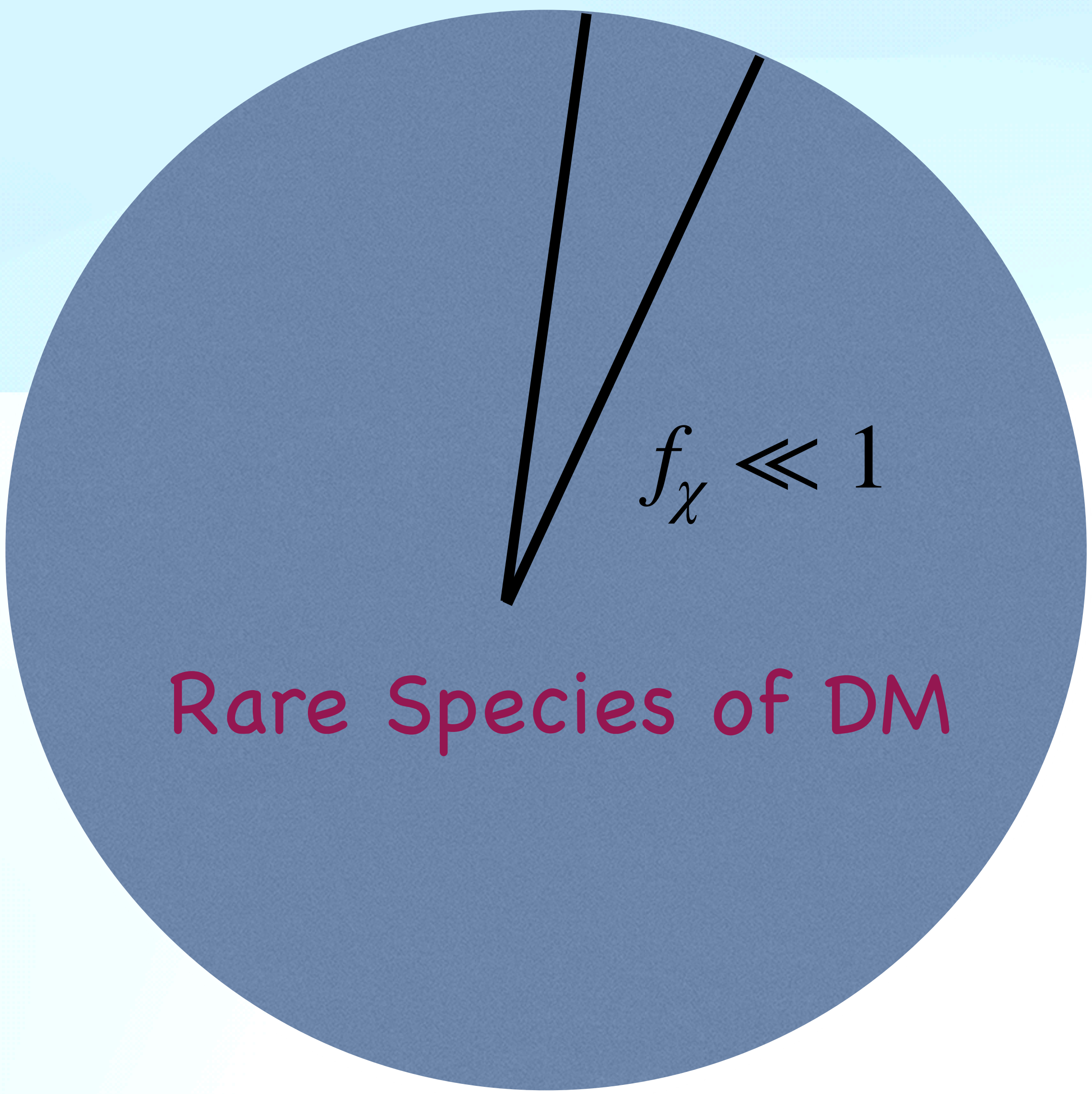
Ray (with Pospelov) [JCAP, 2024]

Ray (with Ema, Pospelov) [JHEP, in press]



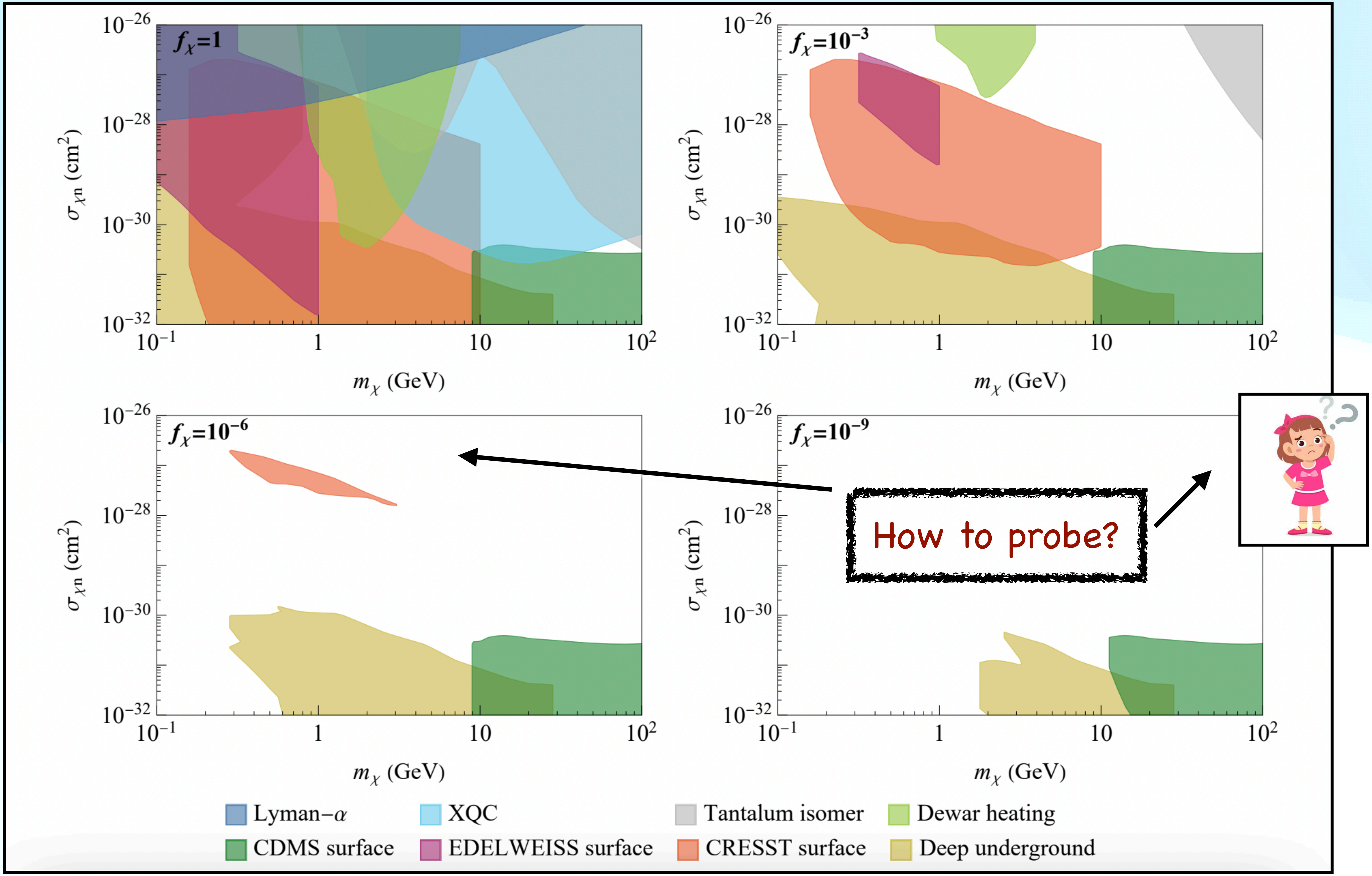
Strongly-interacting DM Component

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



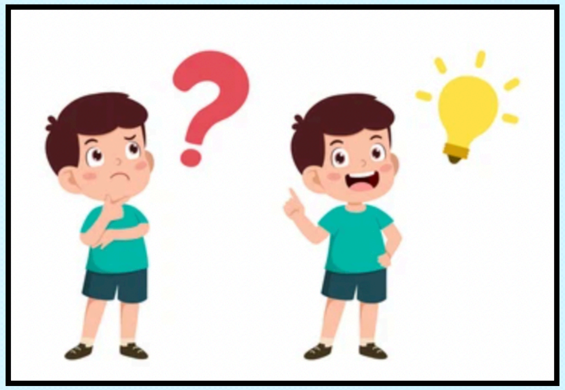
χ makes up a sub-component of the total DM energy budget.

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)

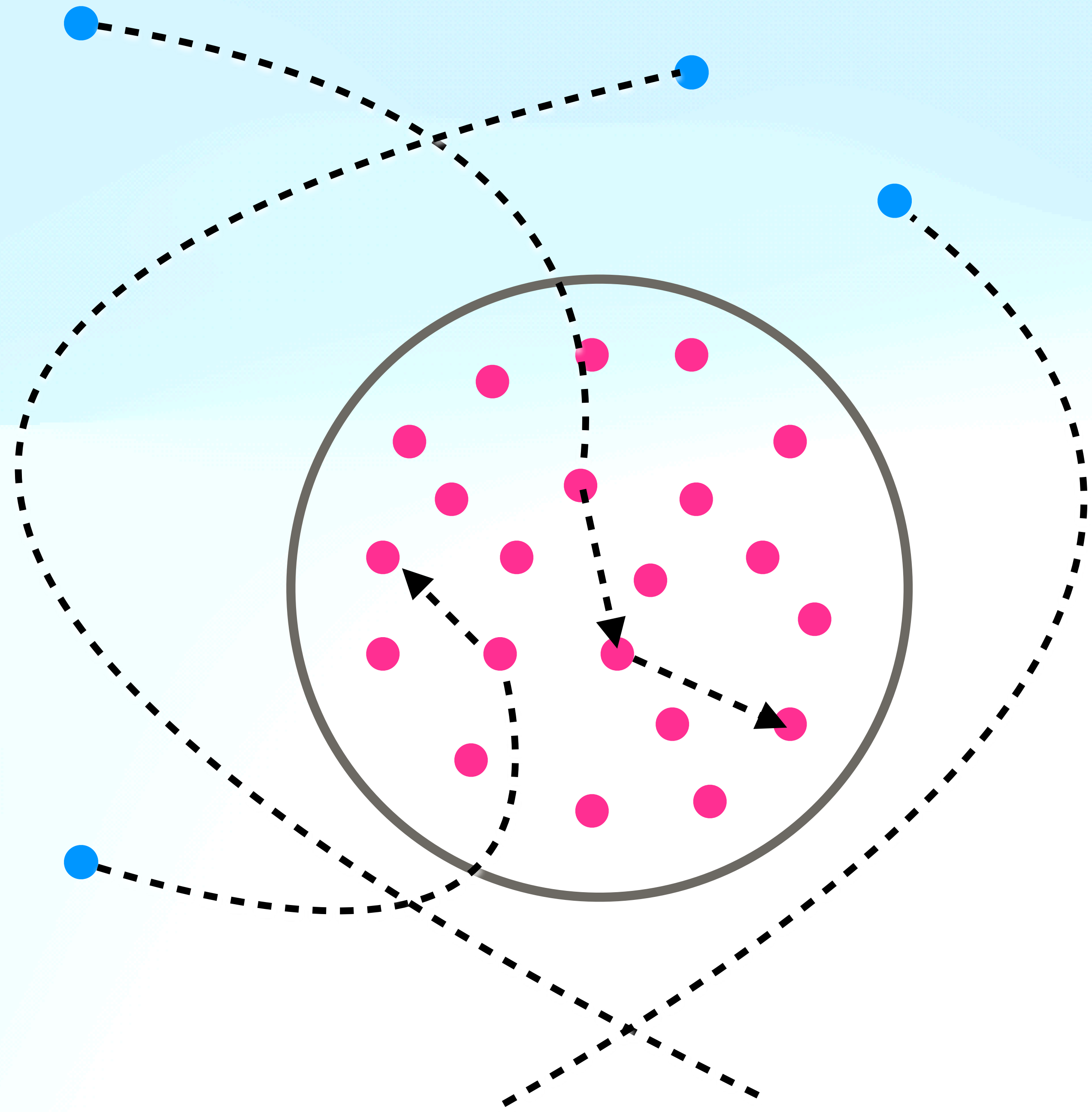
  Ray, (with Ema, Pospelov)

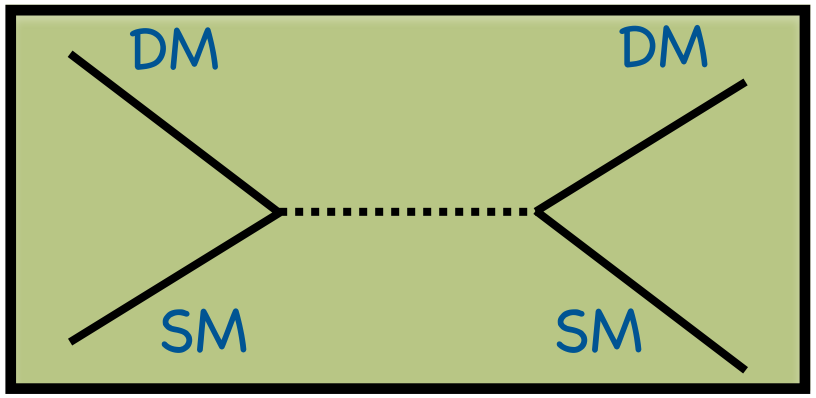
  [2402.03431]

Earth-Bound DM

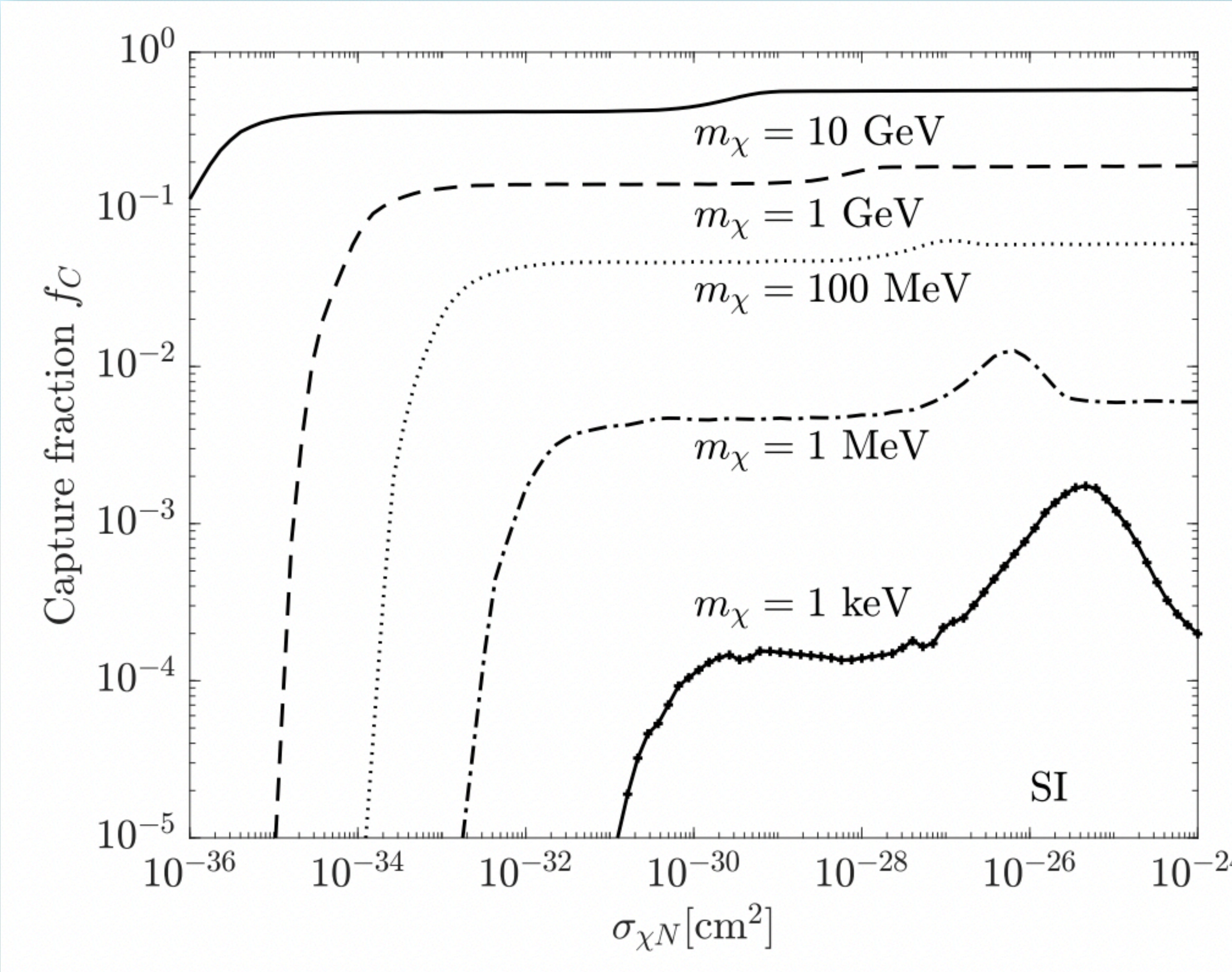
Press & Spergel (1985,ApJ), Gould (1987, ApJ),...

Small $\sigma_{\chi n}$ $\rightarrow$ single collision, large $\sigma_{\chi n}$ $\rightarrow$ 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 $\sigma_{\chi n} = 10^{-28}\,\mathrm{cm}^2$

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

$f_\chi = 1$

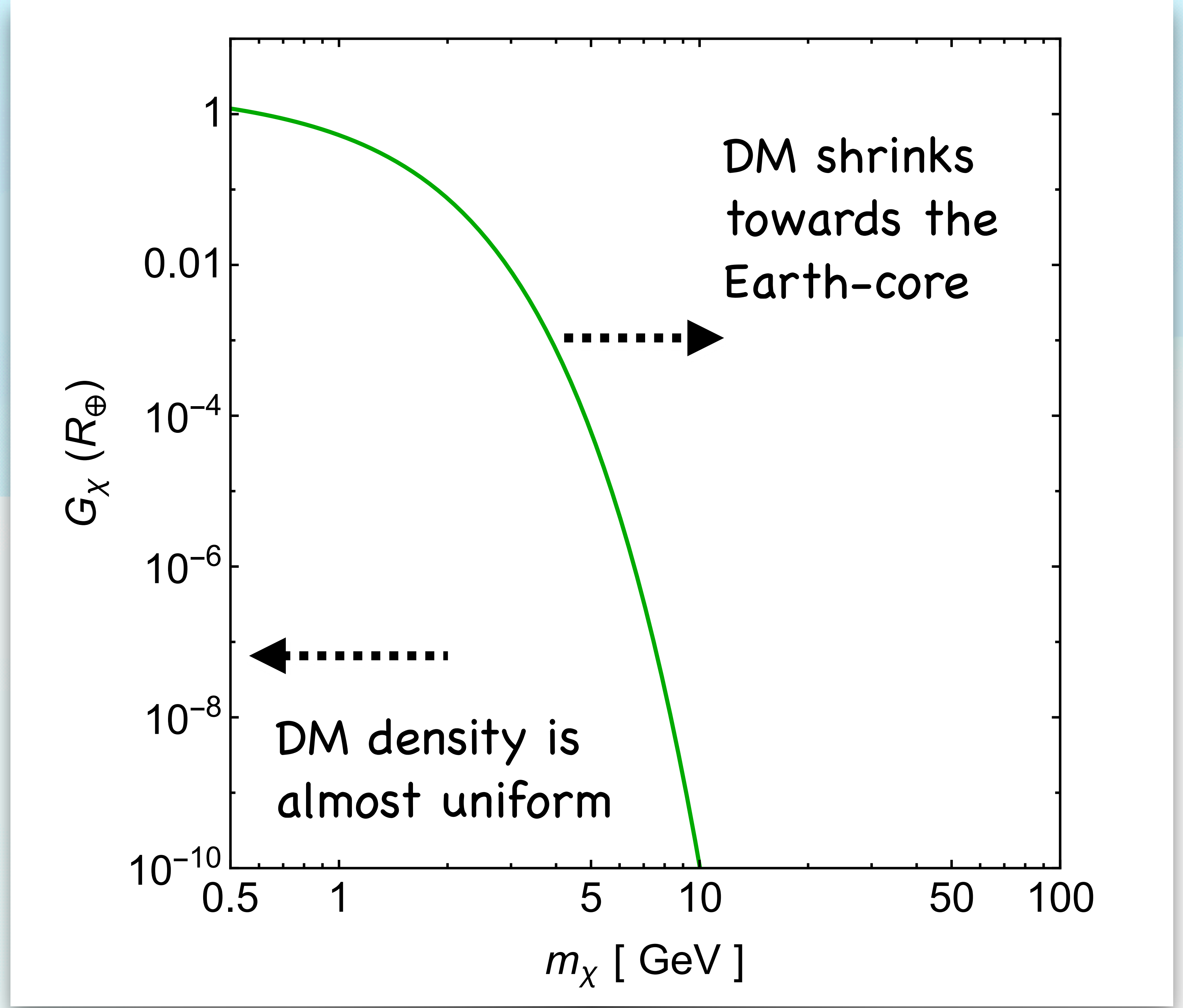
DM density (assuming they uniformly distribute over the Earth-volume)

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

$f_\chi = 1$

- 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?

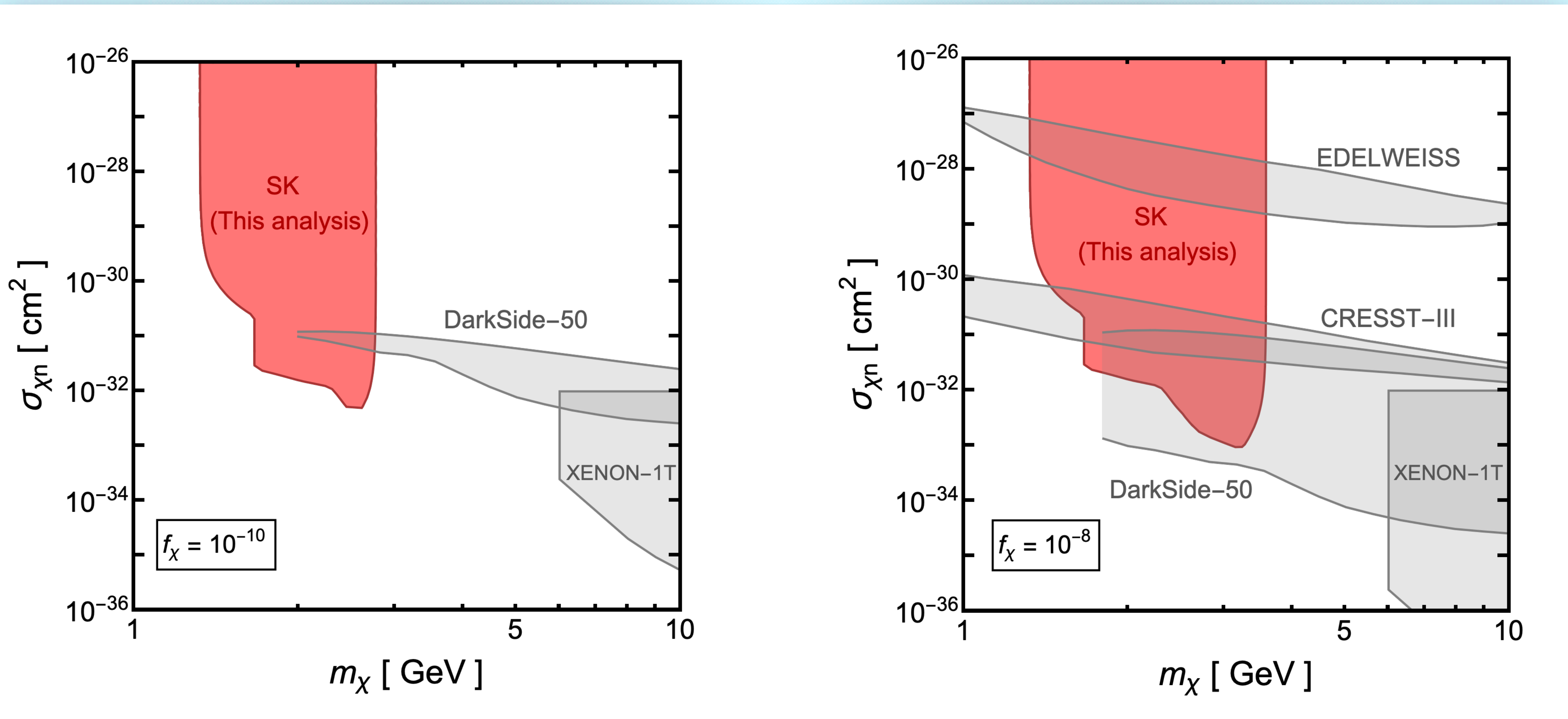
Ray, (with Mckeen, Morissey, Pospelov, Ramani) [PRL, 2023]

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]



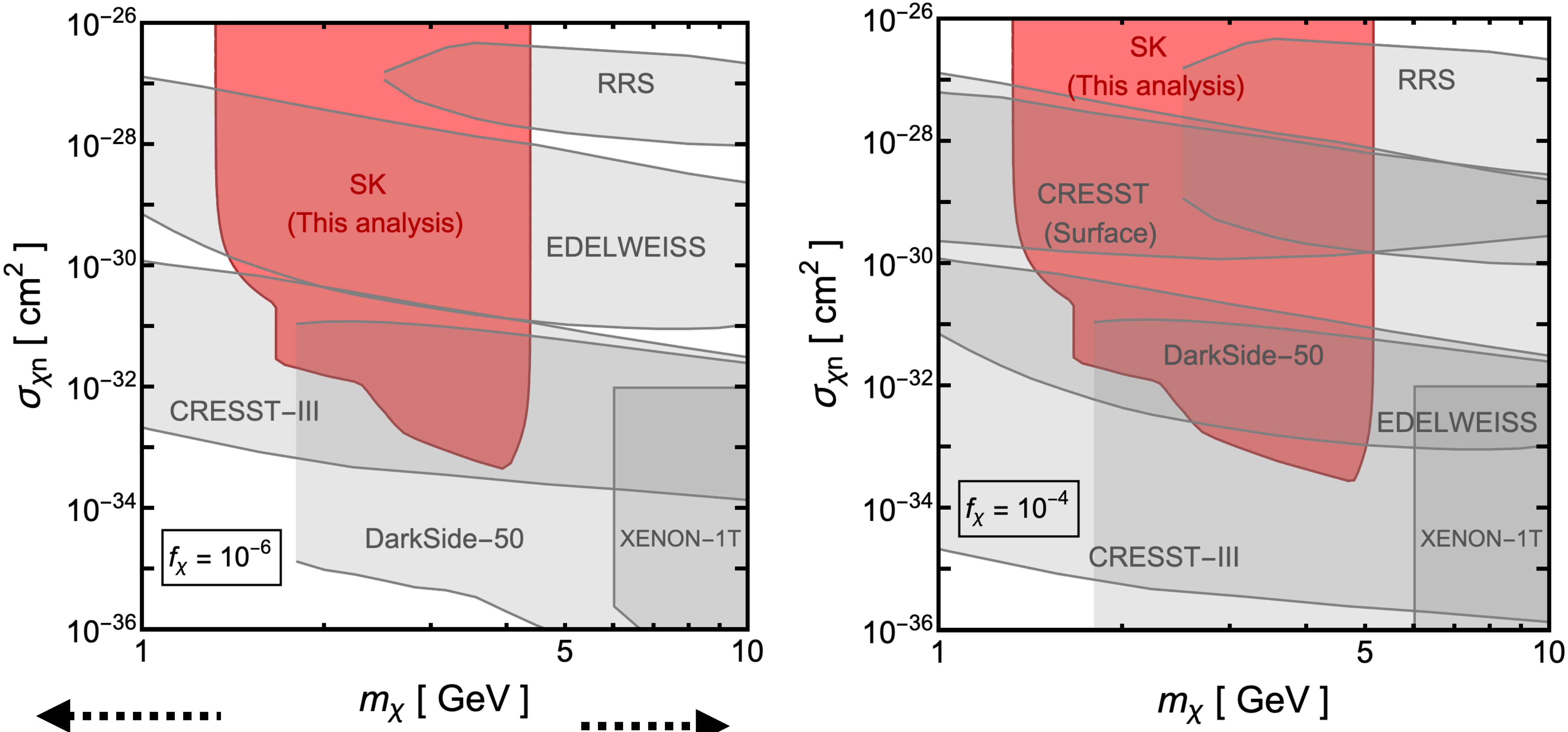
Evaporation

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

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

Pospelov, Ritz, Voloshin (PLB, 2008)

Model

- We are interested in the following channel

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

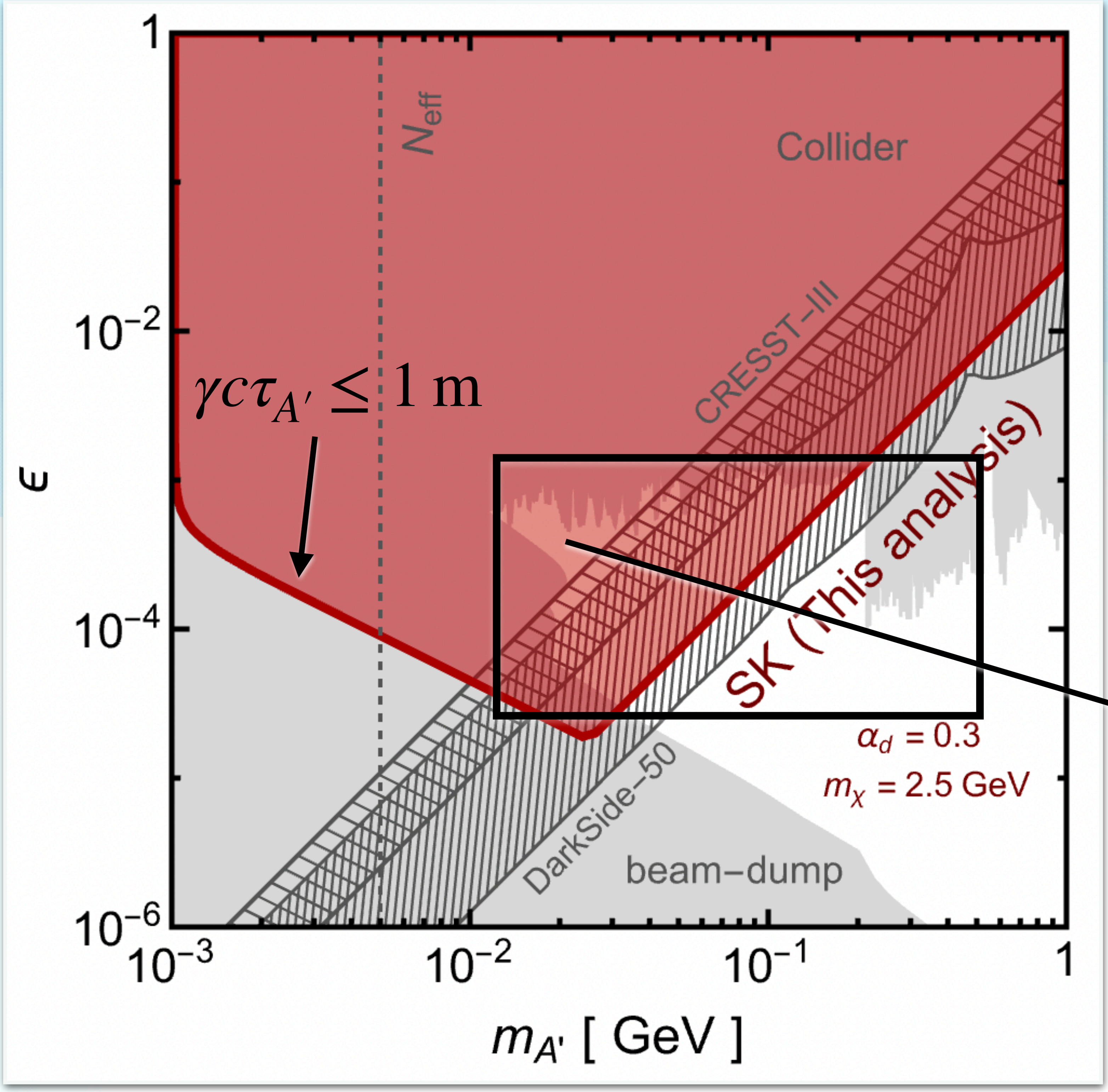
$$\langle \sigma v \rangle_{\rm ann} = \frac{\pi \alpha_d^2}{m_\chi^2} \frac{\left(1 - m_{A'}^2/m_\chi^2\right)^{3/2}}{\left(1 - m_{A'}^2/4m_\chi^2\right)^2}$$

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

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

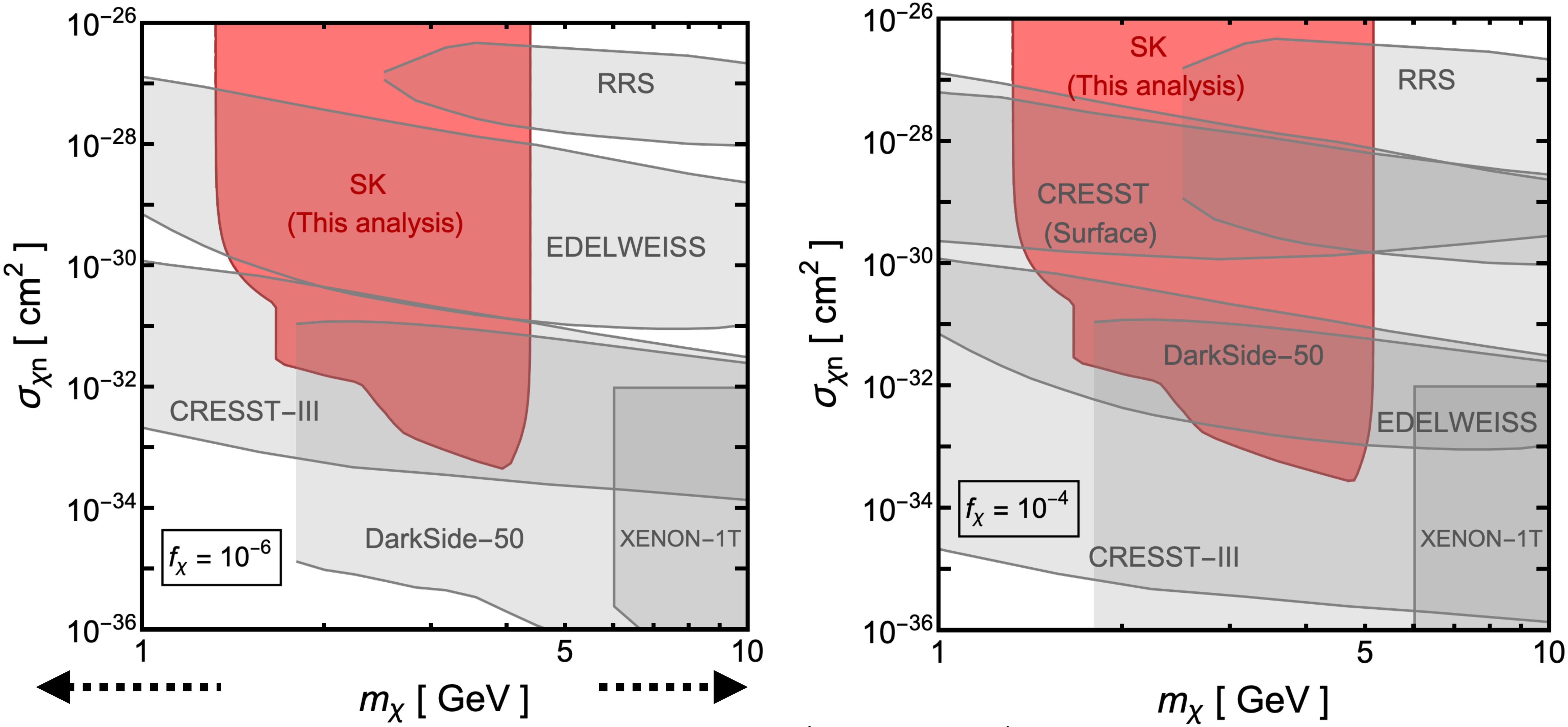
Results

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.

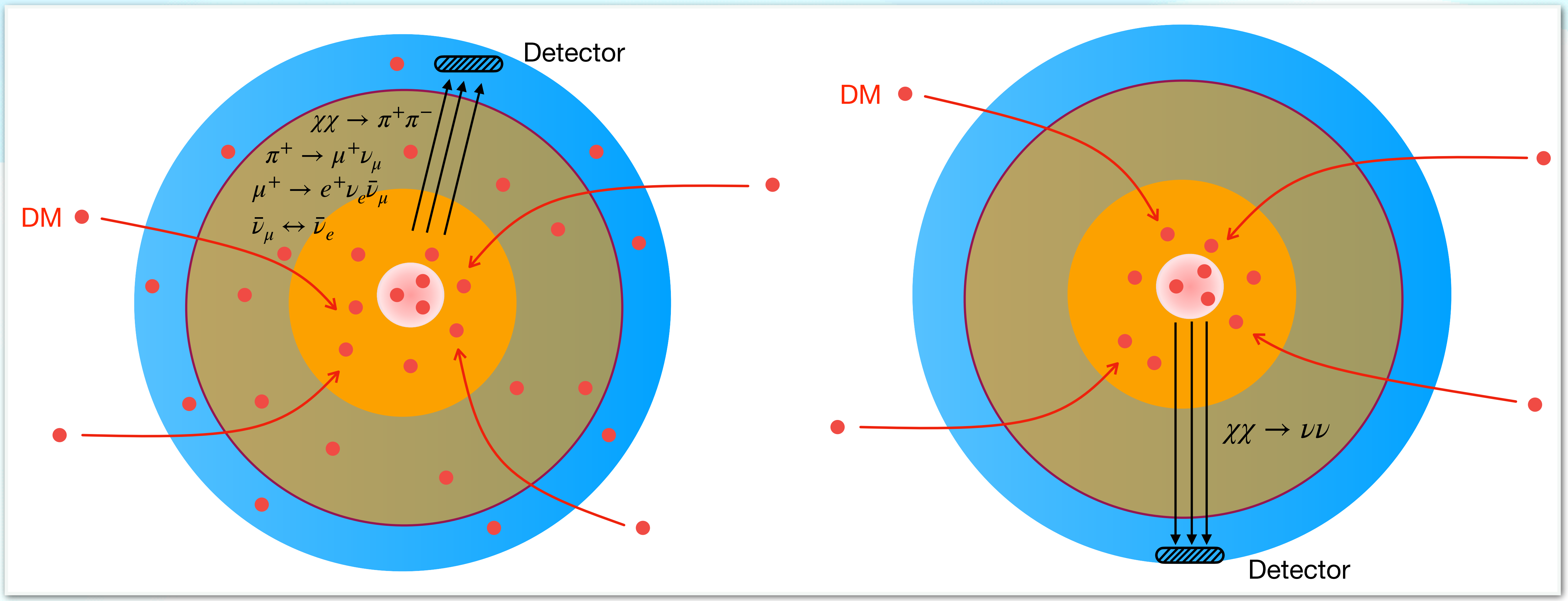
Pospelov & Ray [JCAP, 2024]

Neutrino Signal

- We consider two phenological scenarios:

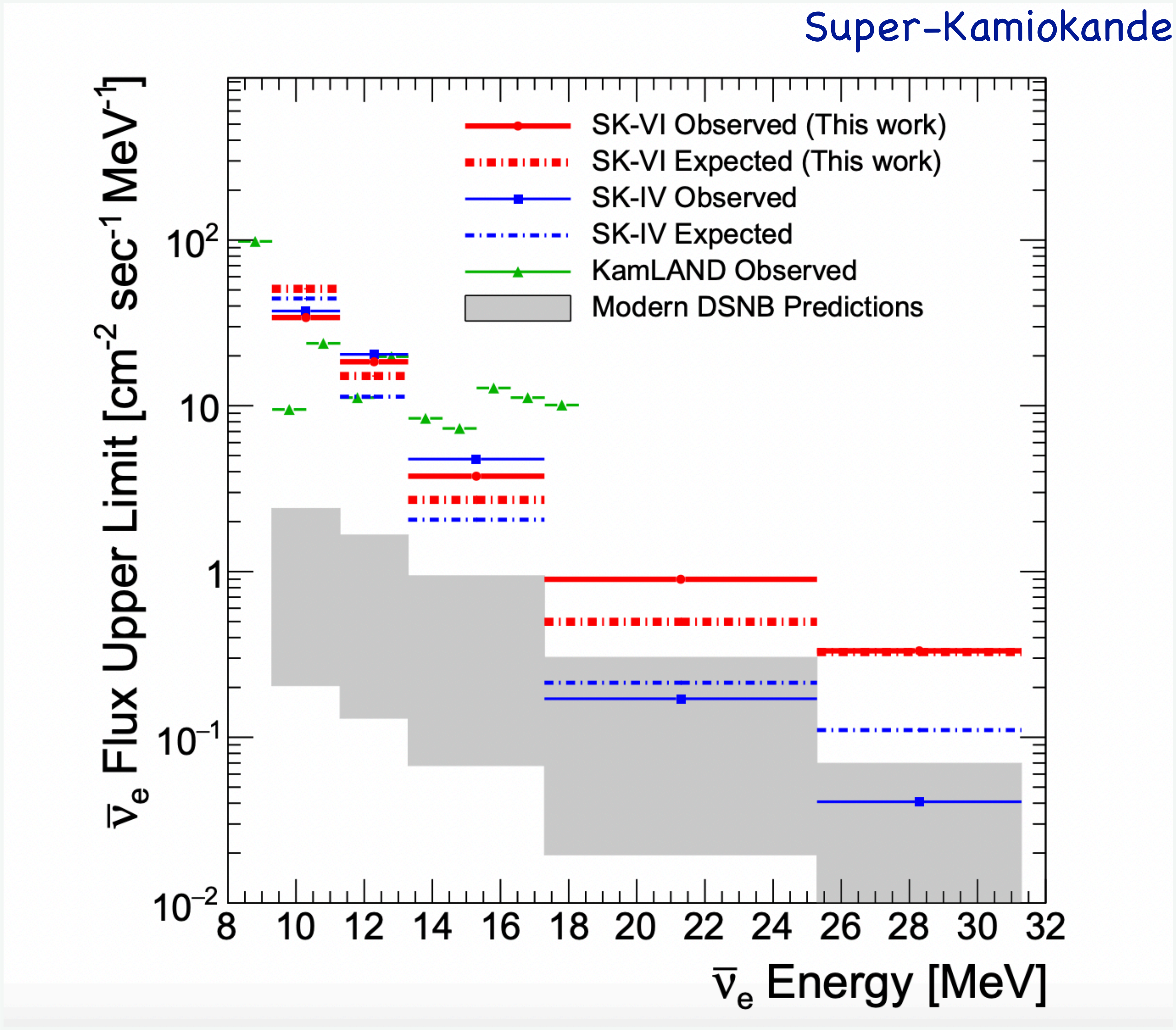
Lower energy neutrinos from the stopped pion decay

Higher energy neutrino lines from direct annihilation



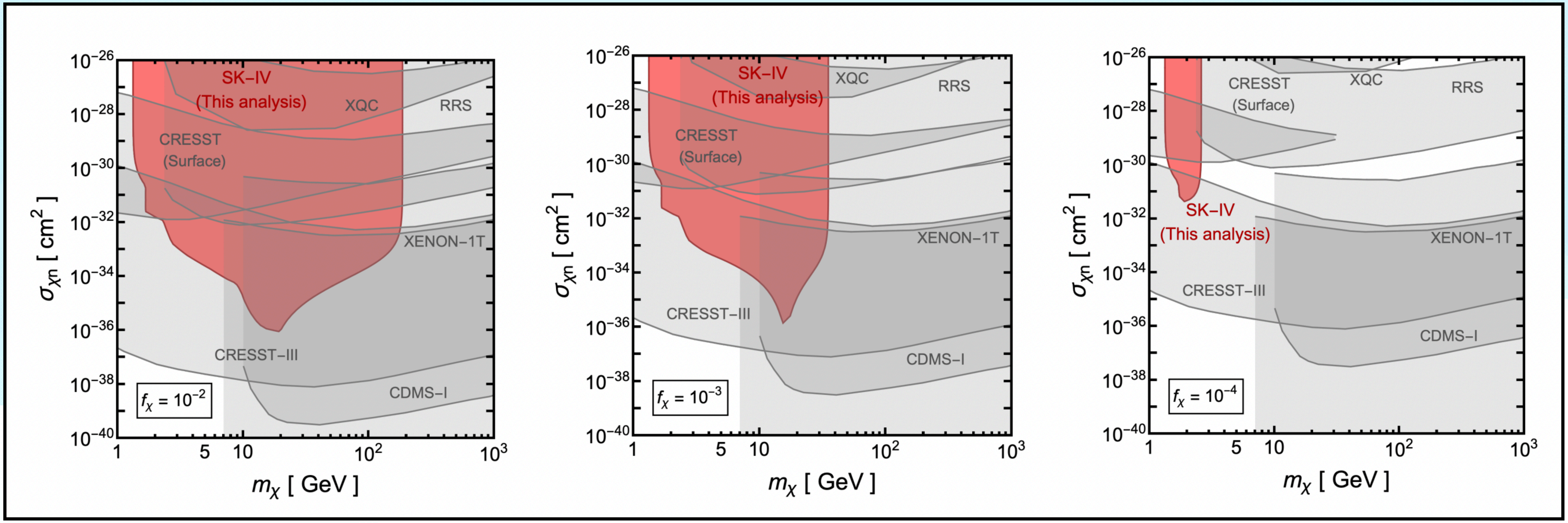
Low Energy Neutrinos

Super-Kamiokande (APJL, 2023)



Low Energy Neutrinos

Pospelov & Ray [JCAP, 2024]

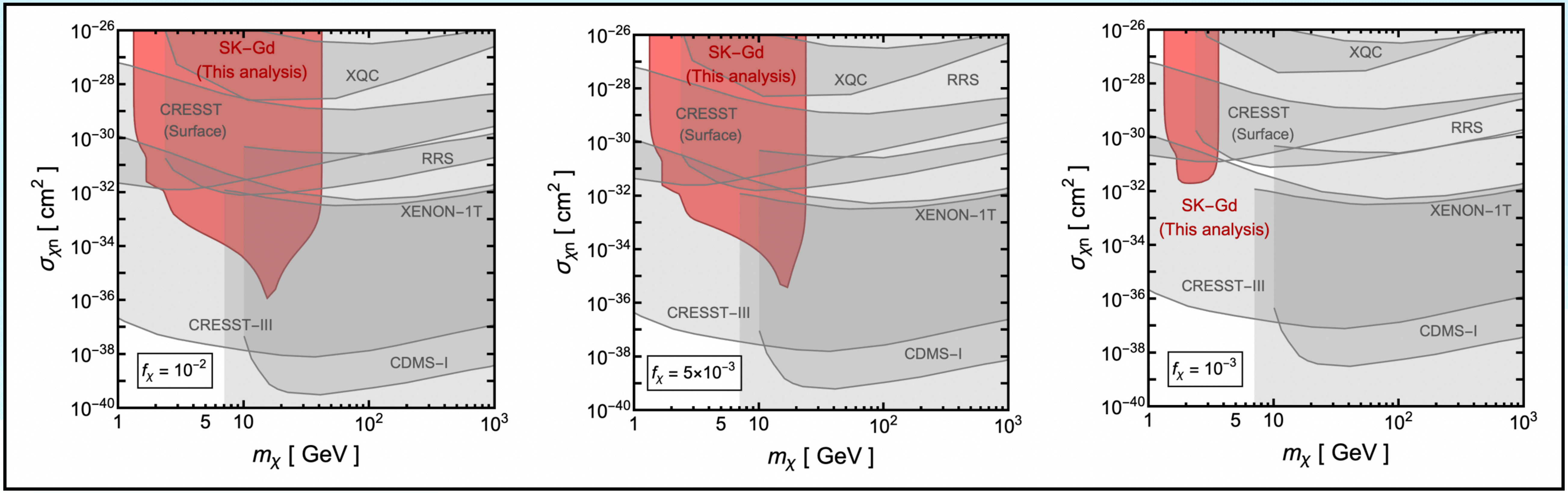


We use the Super-K DSNB search result with pure-water (22.5 kton × 2970 days) to derive the exclusion limits.

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.

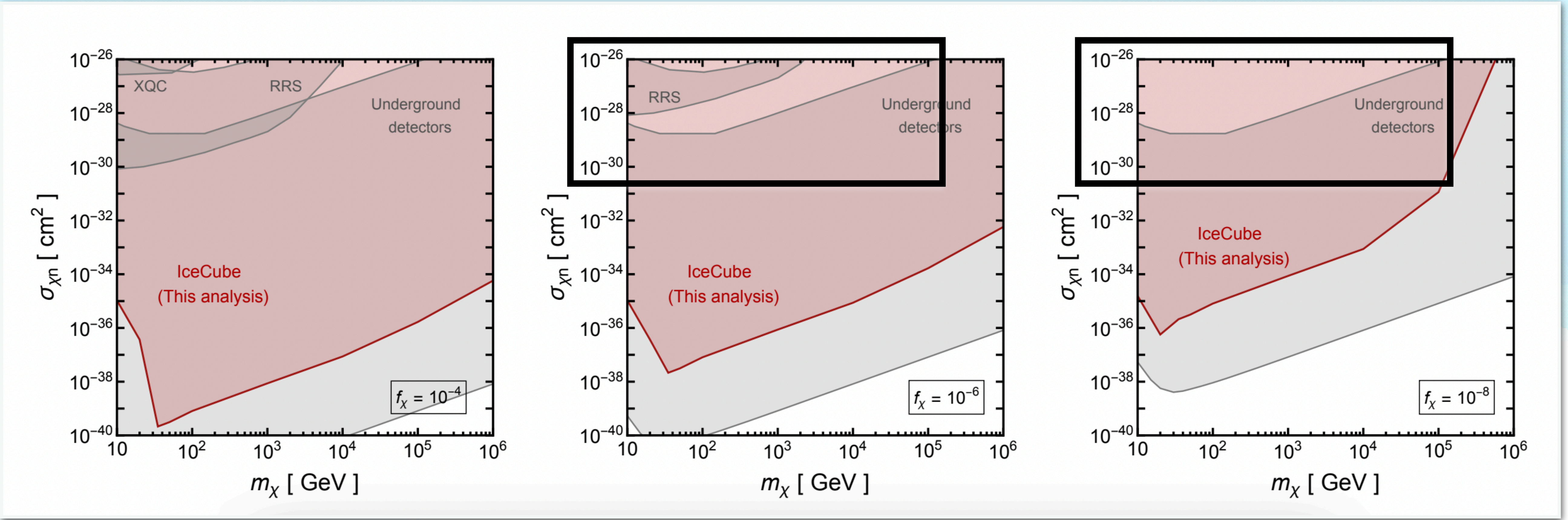
- We use the null-detection of the neutrino-line signature in the IceCube DeepCore data to derive the exclusions

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.

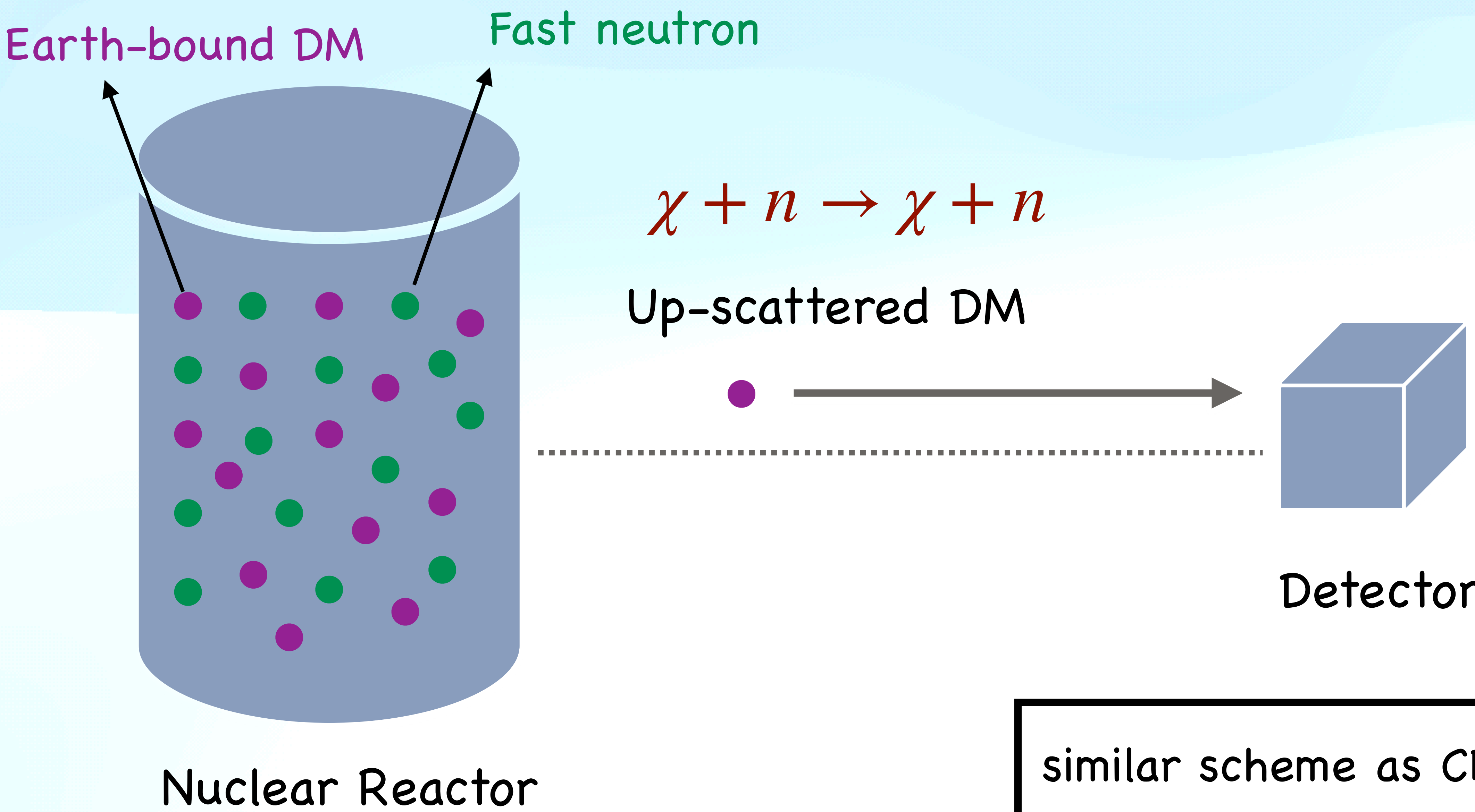
$$\phi_\oplus \sim \frac{\Gamma_{\rm cap}}{4\pi R_\oplus^2} \quad \text{and} \quad \phi_\odot \sim \frac{\Gamma_{\rm cap}}{4\pi D^2}$$

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).

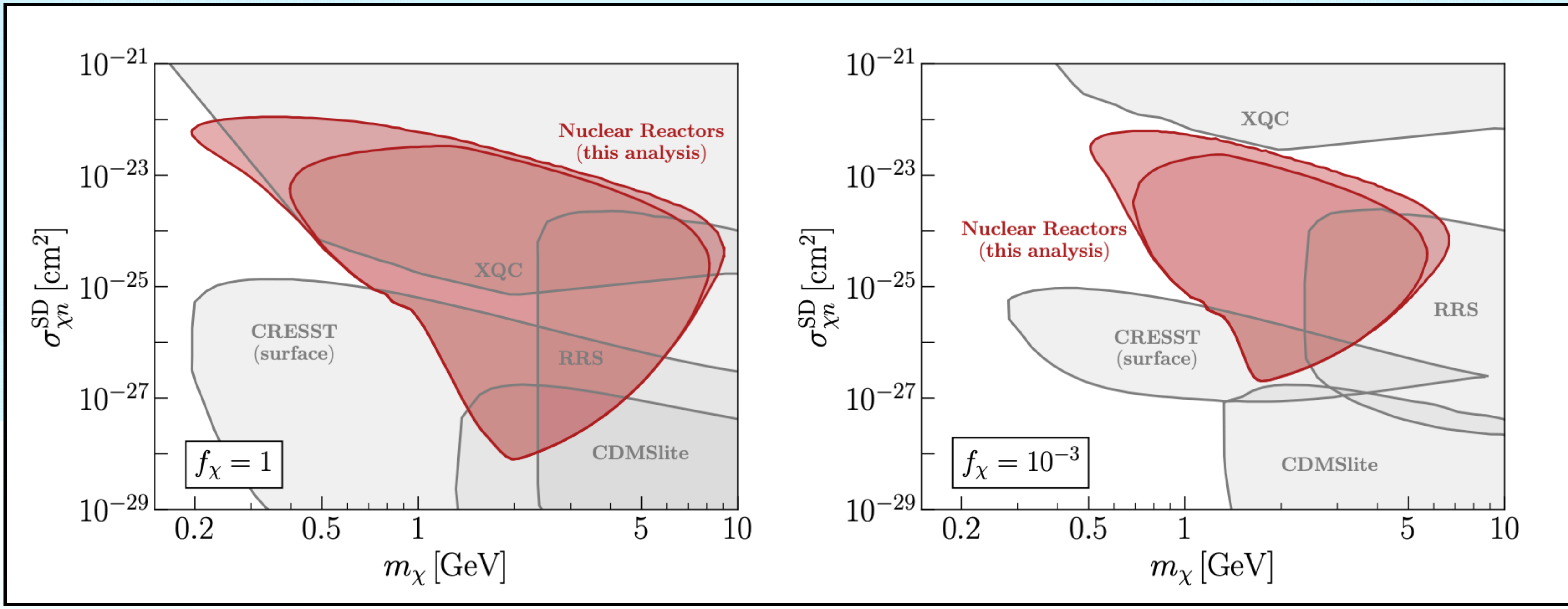
We use CONUS experiment setup for our analysis.

- 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]

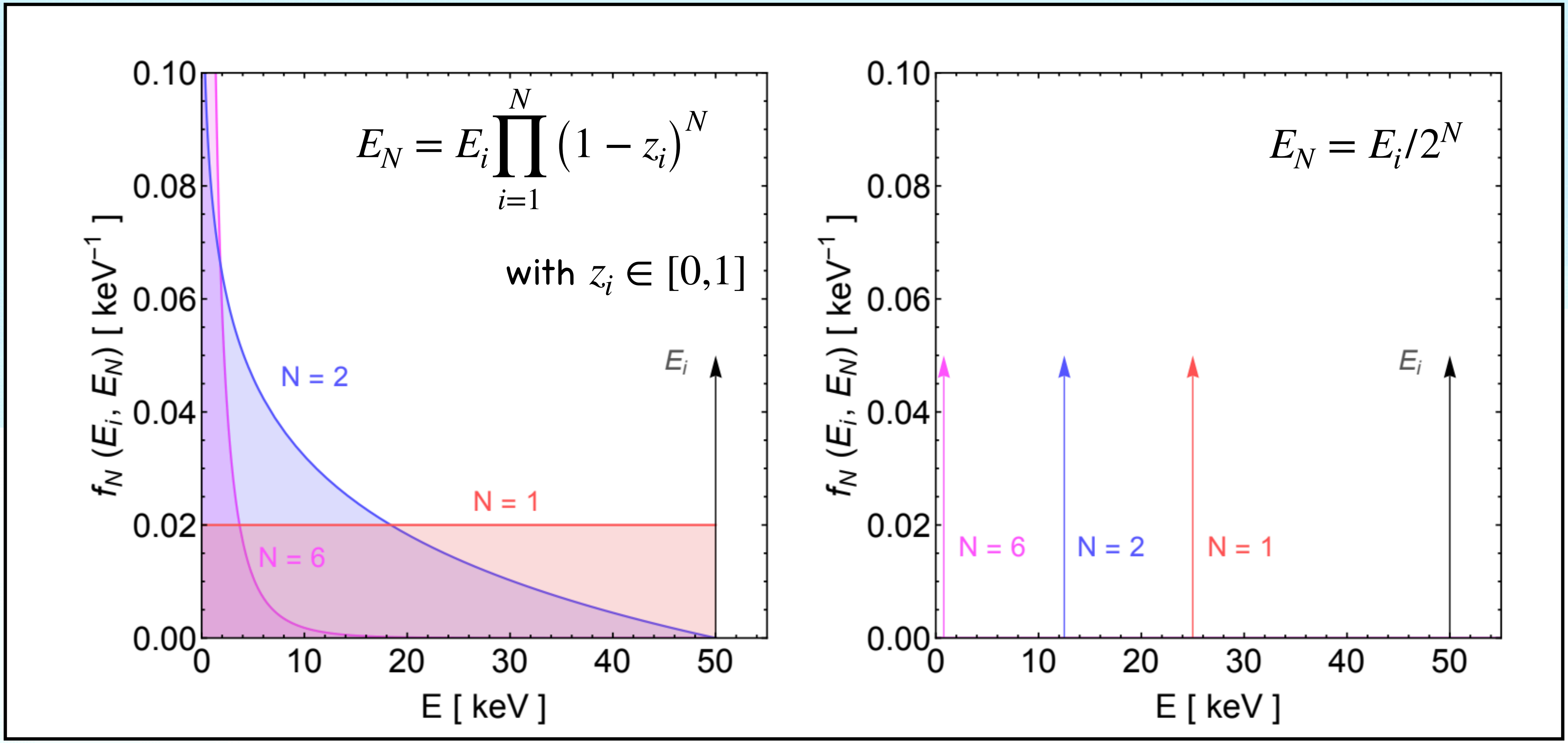


Smaller regions: includes only the DM particles which do not experience any collisions.

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!

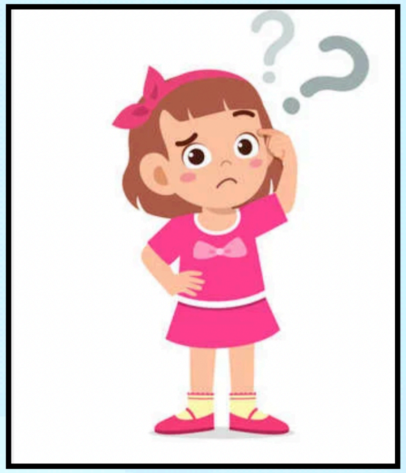
- Despite their prodigious abundance, their detection is extremely challenging as they acquire tiny amount of kinetic energy.

- 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.

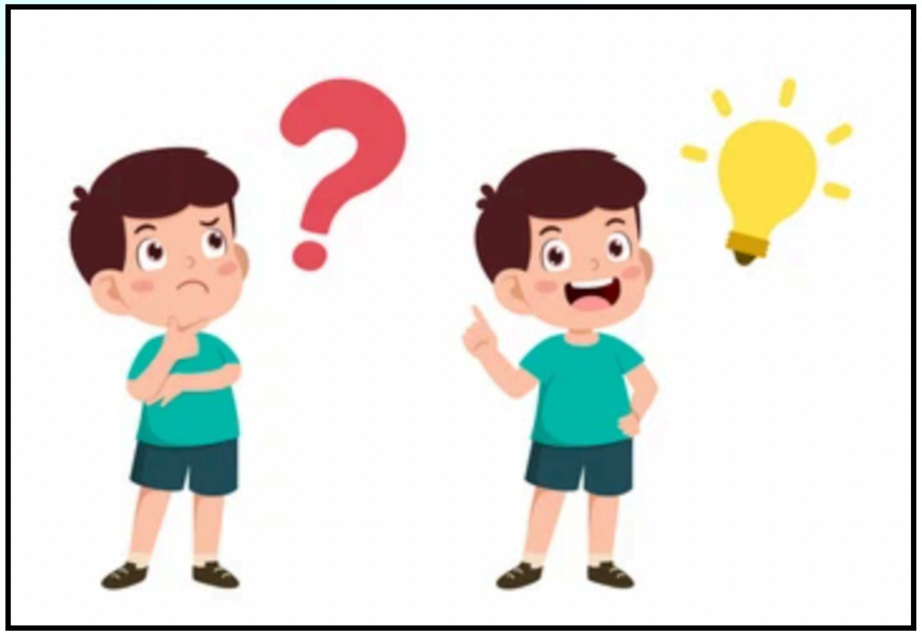
- If Earth-bound DM do not annihilate among themselves, up-scattering them inside nuclear reactors provides a powerful probe of their detection.

Conclusion

★ How to detect rare species of DM?



★ Look at the Earth-bound DM!



Questions & Comments: anupam.ray@berkeley.edu