Searching for Light Accelerated Dark Matter

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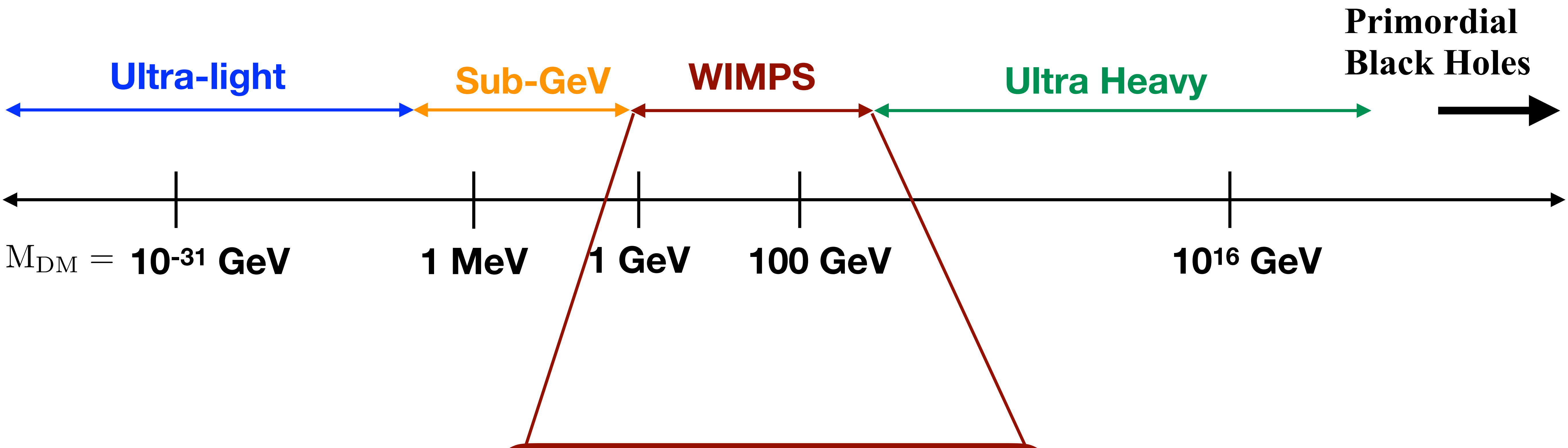
FLASY 2024

SFU

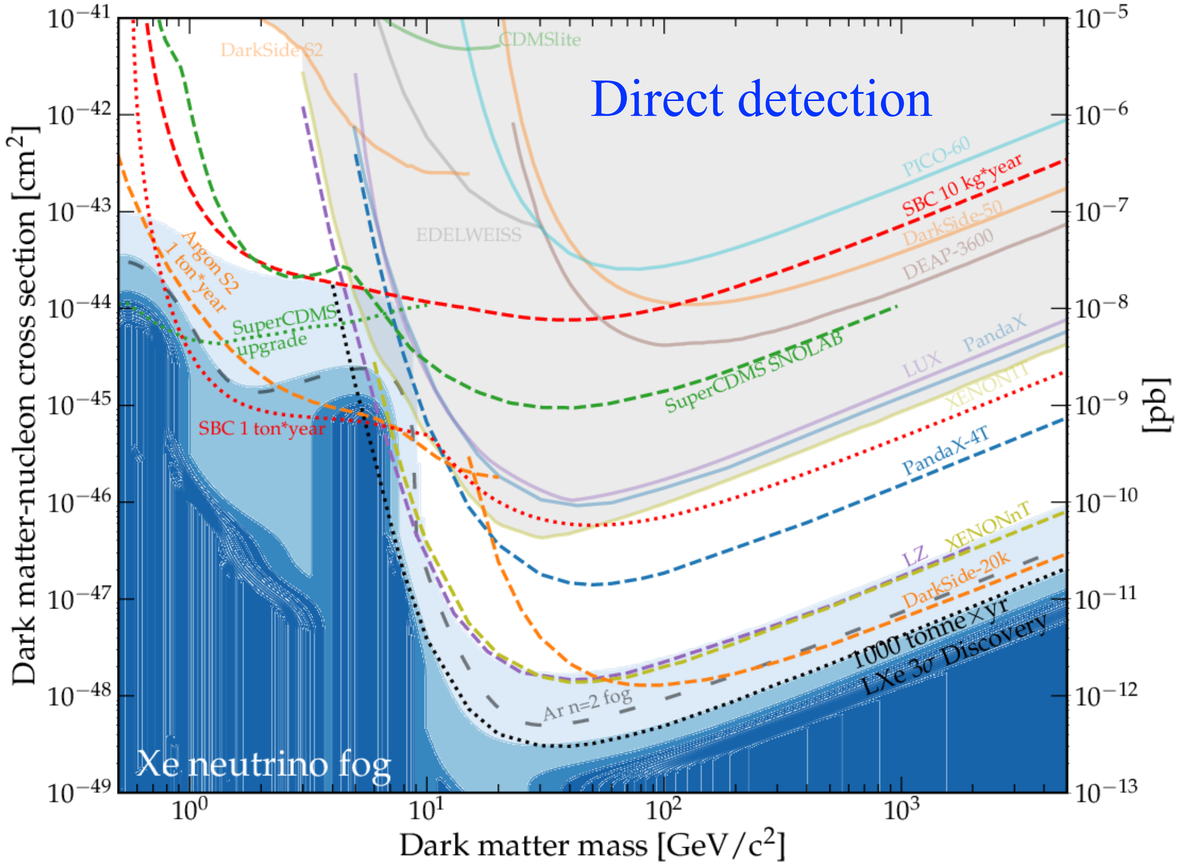
Range of DM possibilities is VAST



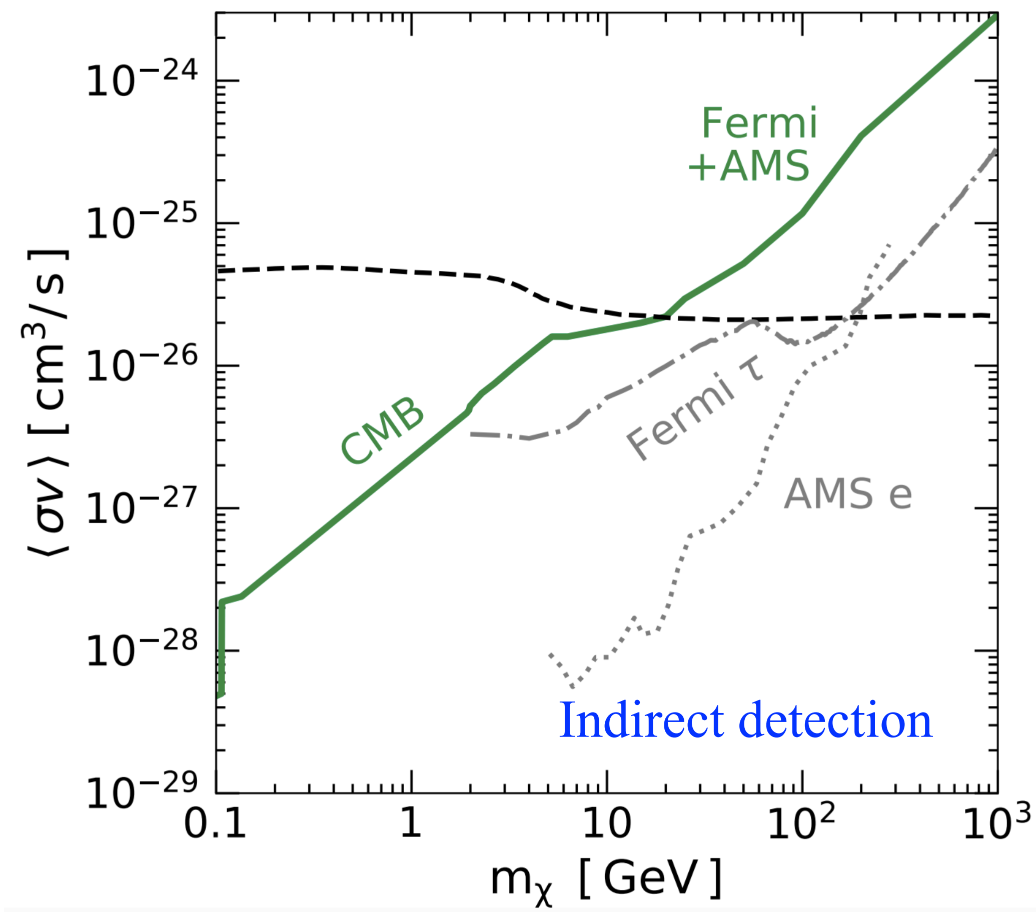
For the last decades, searches have been focussed on this region of space

WIMP Hypothesis is very motivated

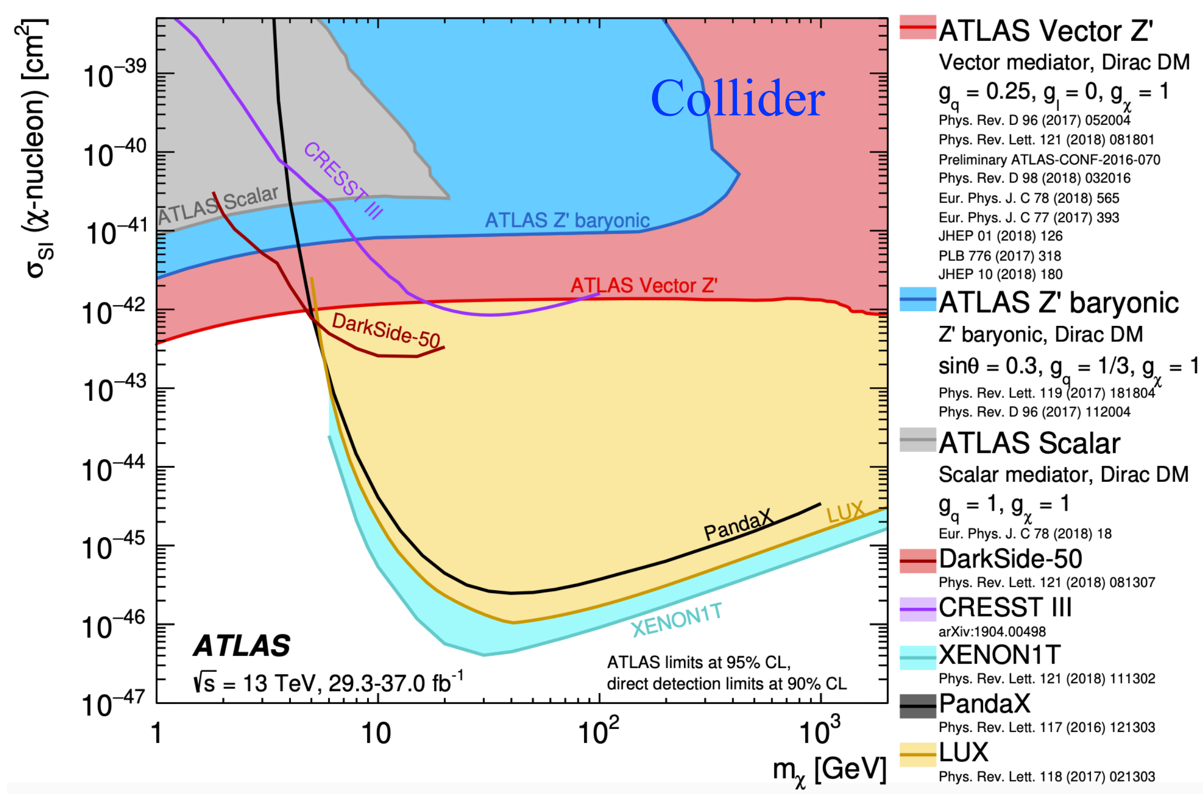
Searching for Decades



Akerib et al, arXiv: 2203.08084

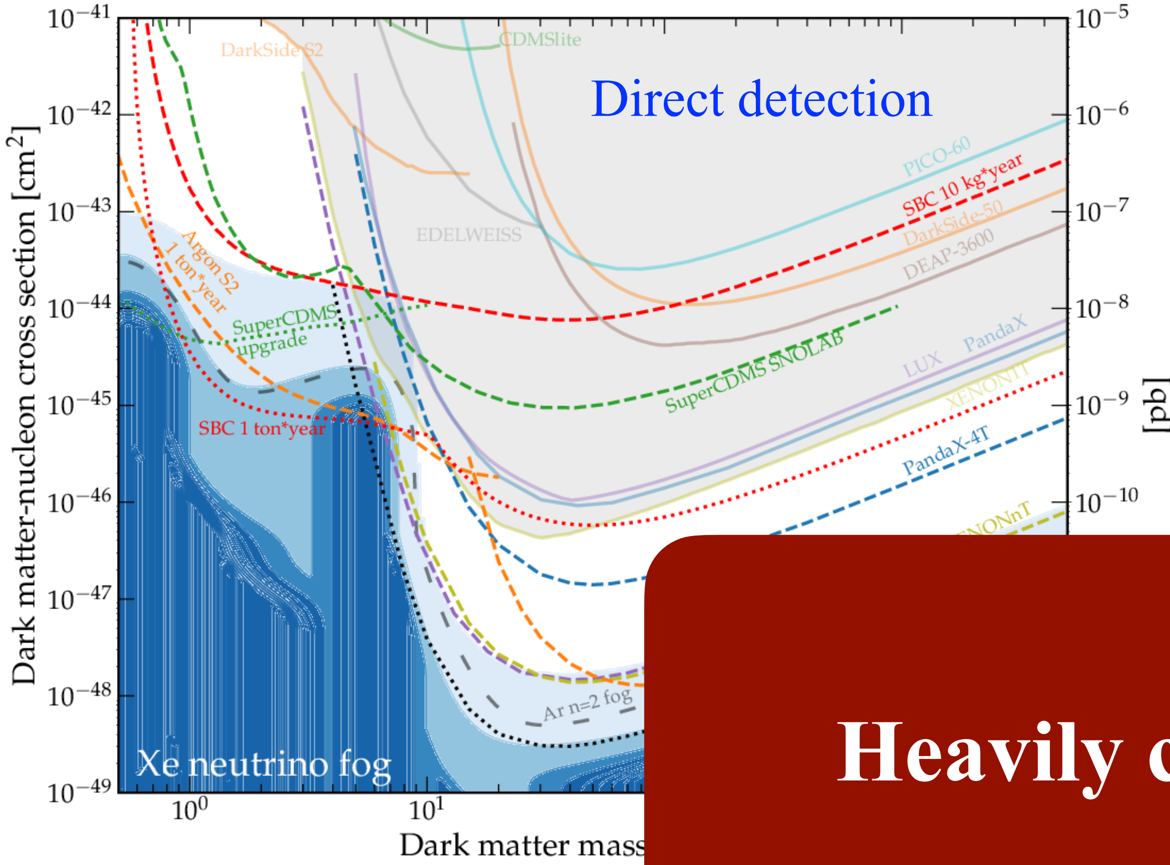


Leane et al, Phys.Rev.D 98 (2018) 2

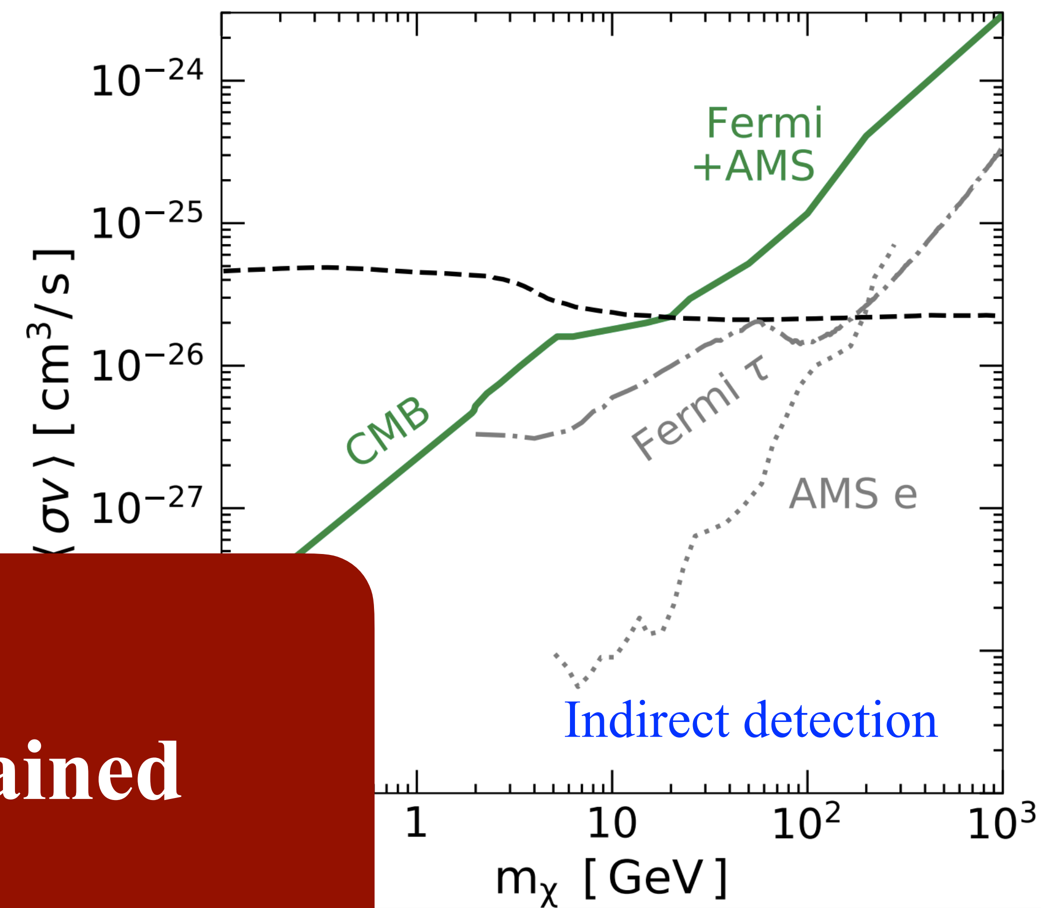


ATLAS Collaboration JHEP05(2019)142

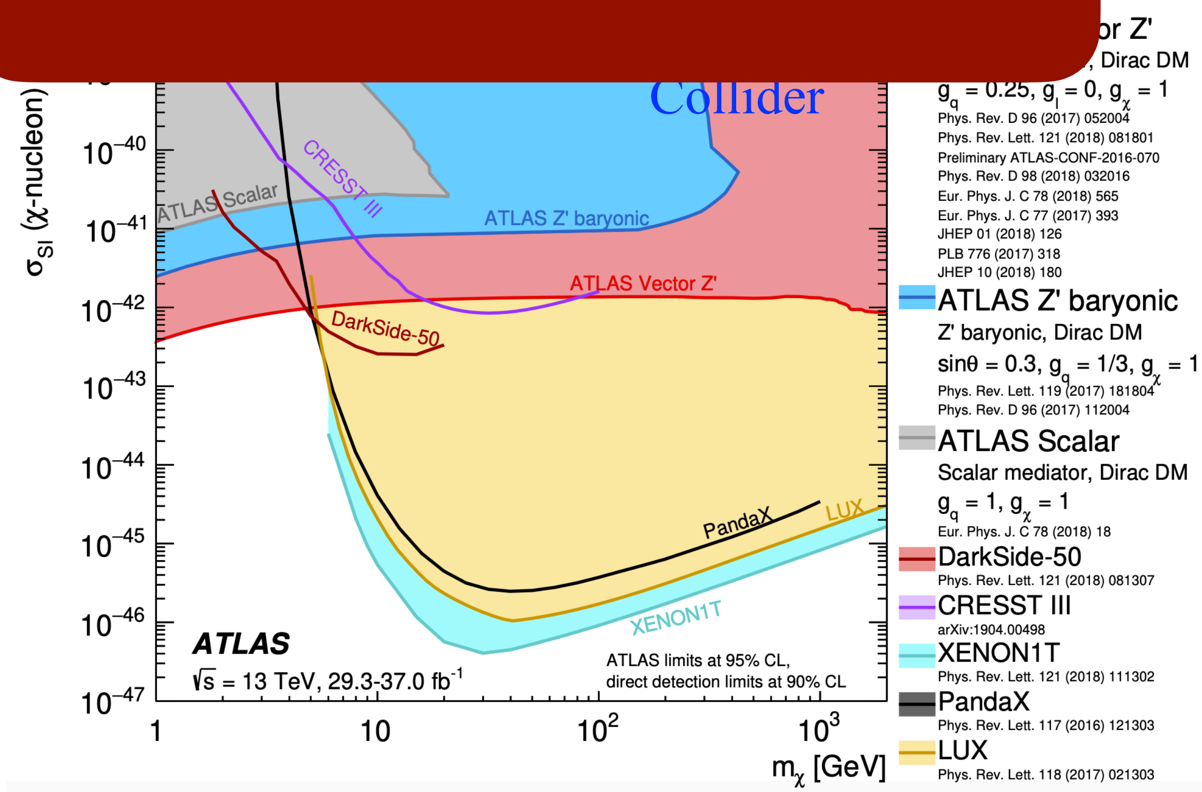
Searching for Decades



Akerib et al, arXiv: 2203.08084



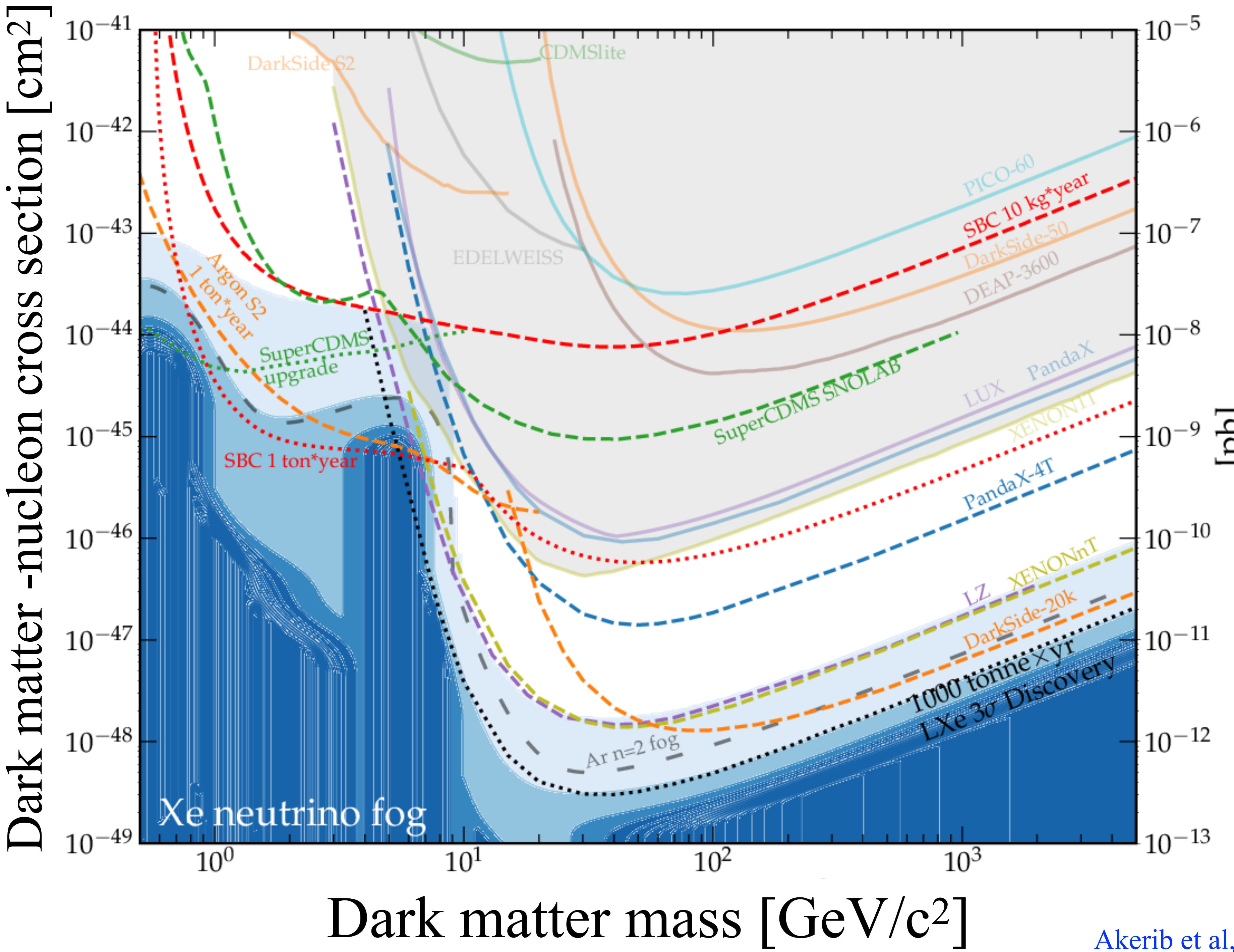
Leane et al, Phys.Rev.D 98 (2018) 2



ATLAS Collaboration JHEP05(2019)142

Heavily constrained

Current status of DM direct detection



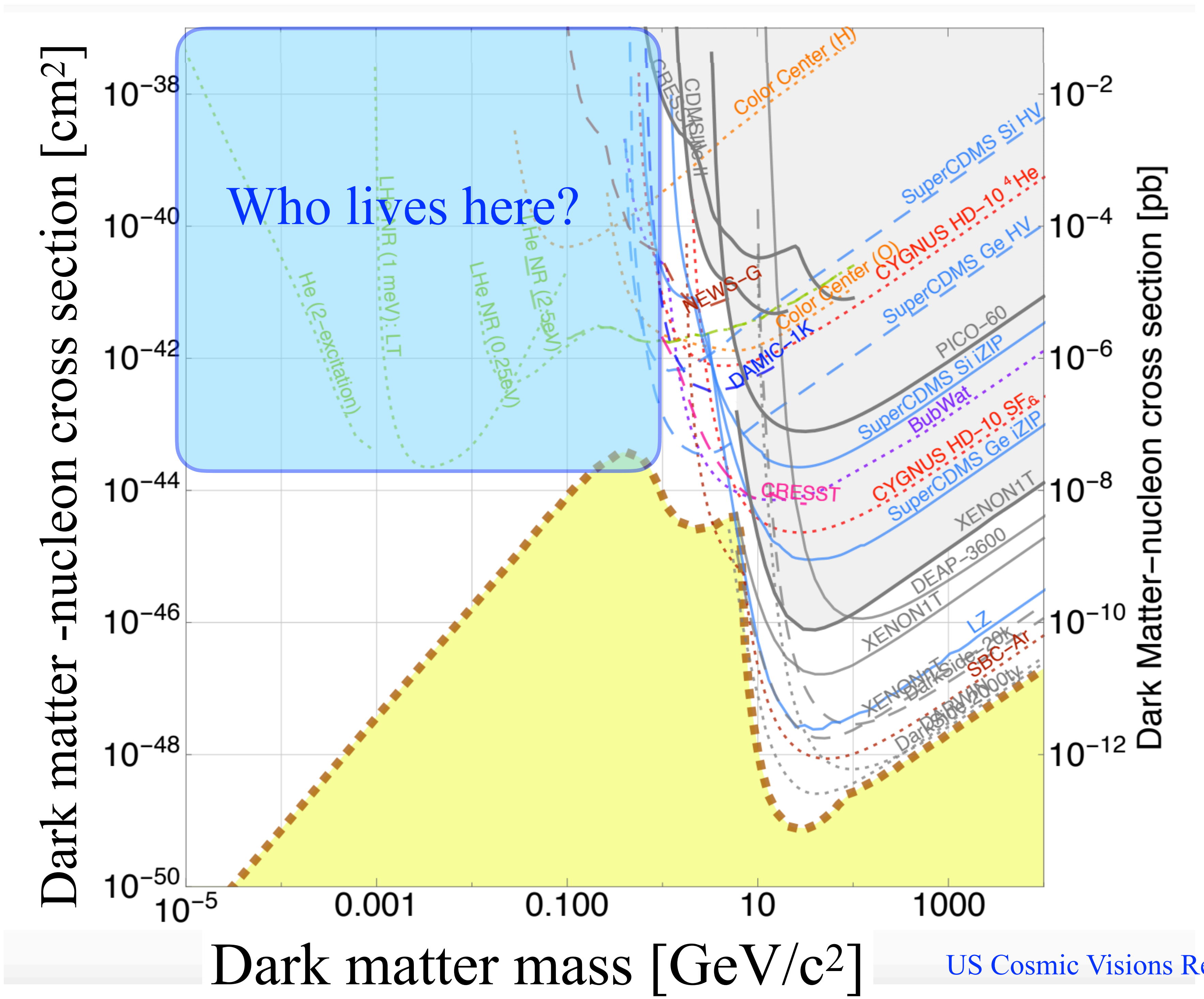
Akerib et al, **arXiv: 2203.08084**

Very little parameter space left in *traditional* WIMP mass range (1 GeV - 100 TeV)

Larger detectors gives us more sensitivity, but "Neutrino Floor/fog" may be challenging

WIMPs remain highly motivated

We are compelled to move beyond the WIMP scale



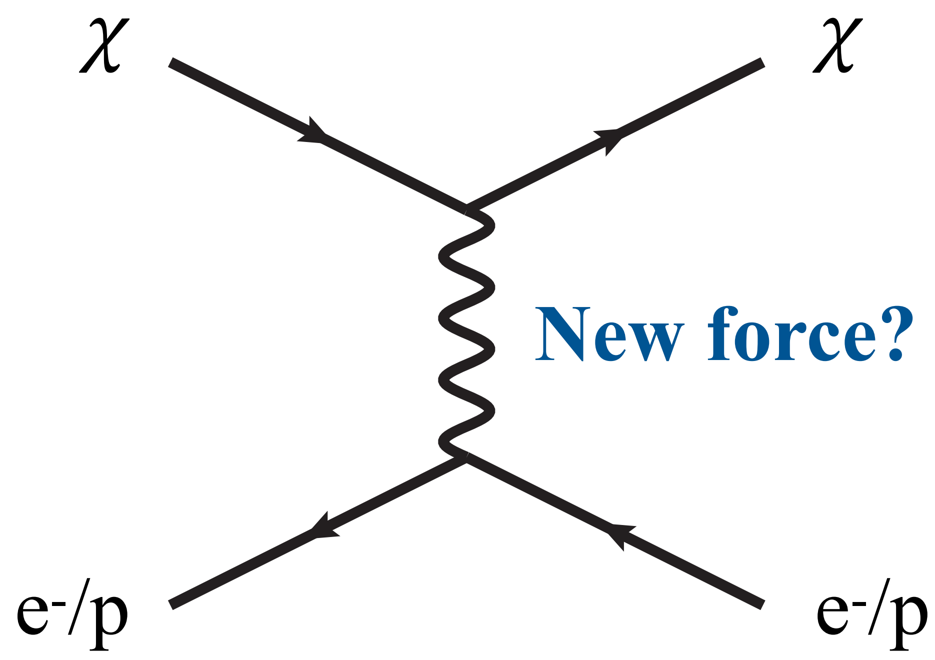
US Cosmic Visions Report, **arXiv:1707.04591**

Many opportunities to explore here

Low mass (sub-GeV) DM searches are:

1. Complementary to WIMP searches

2. Very well motivated:



e.g. low mass DM coupled through new hidden sector mediator presents a good target to understand DM production in the early universe

- Thermal freeze-out
- Freeze-in
- Asymmetric

Big stumbling block is that light DM is **invisible** to current WIMP searches

Many nuclear recoil experiments have ~ keV recoil thresholds

Recoil energy caused by galactic DM with v ~ 10^{-3} c

$$E_{nr} \sim \frac{\mu_{xN}^2 v^2}{m_N}$$

$$\sim 2.5 \text{ eV} \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

$$\ll \text{keV}$$

To probe lower masses need very low threshold nuclear recoil detectors

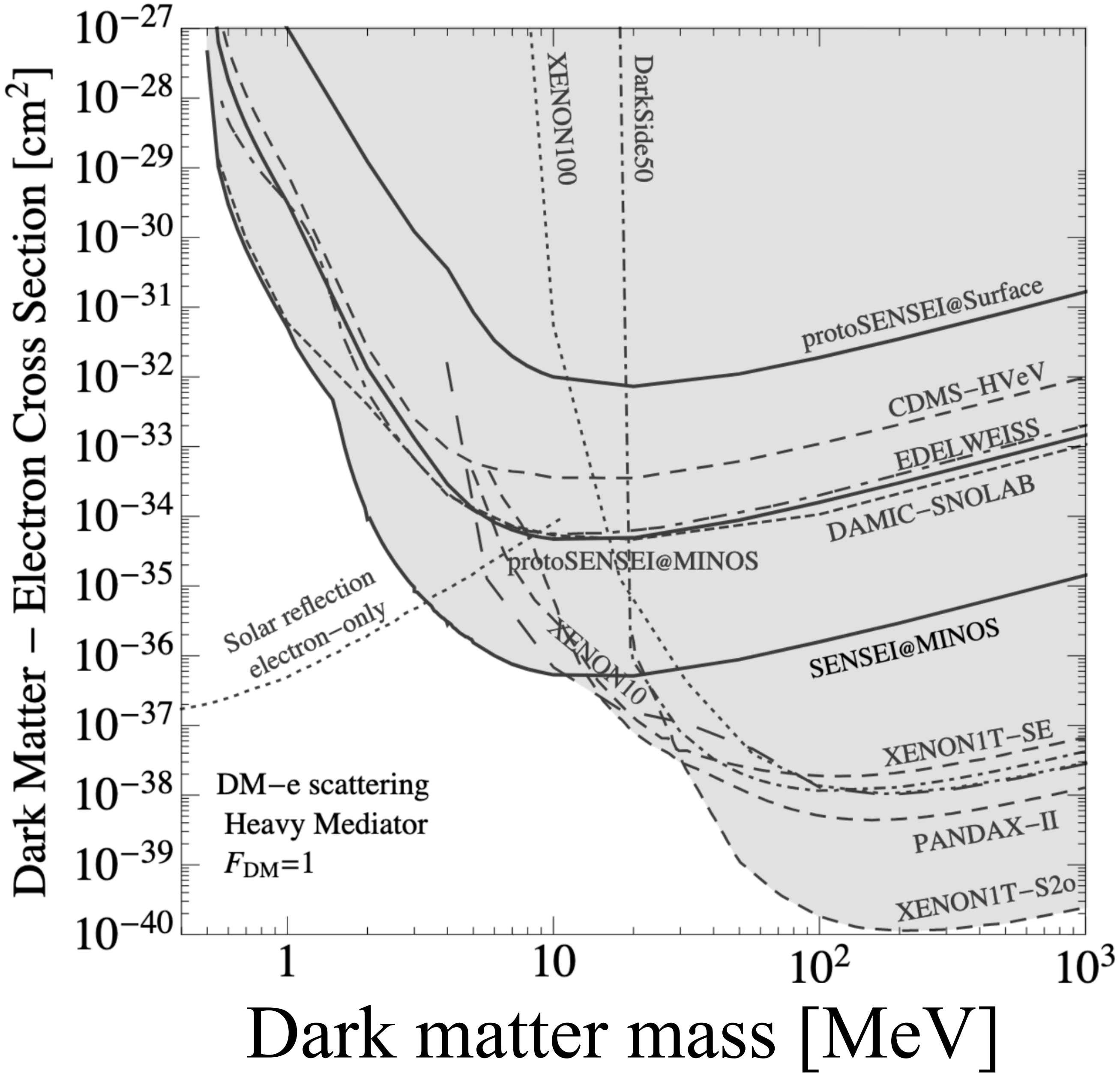
or

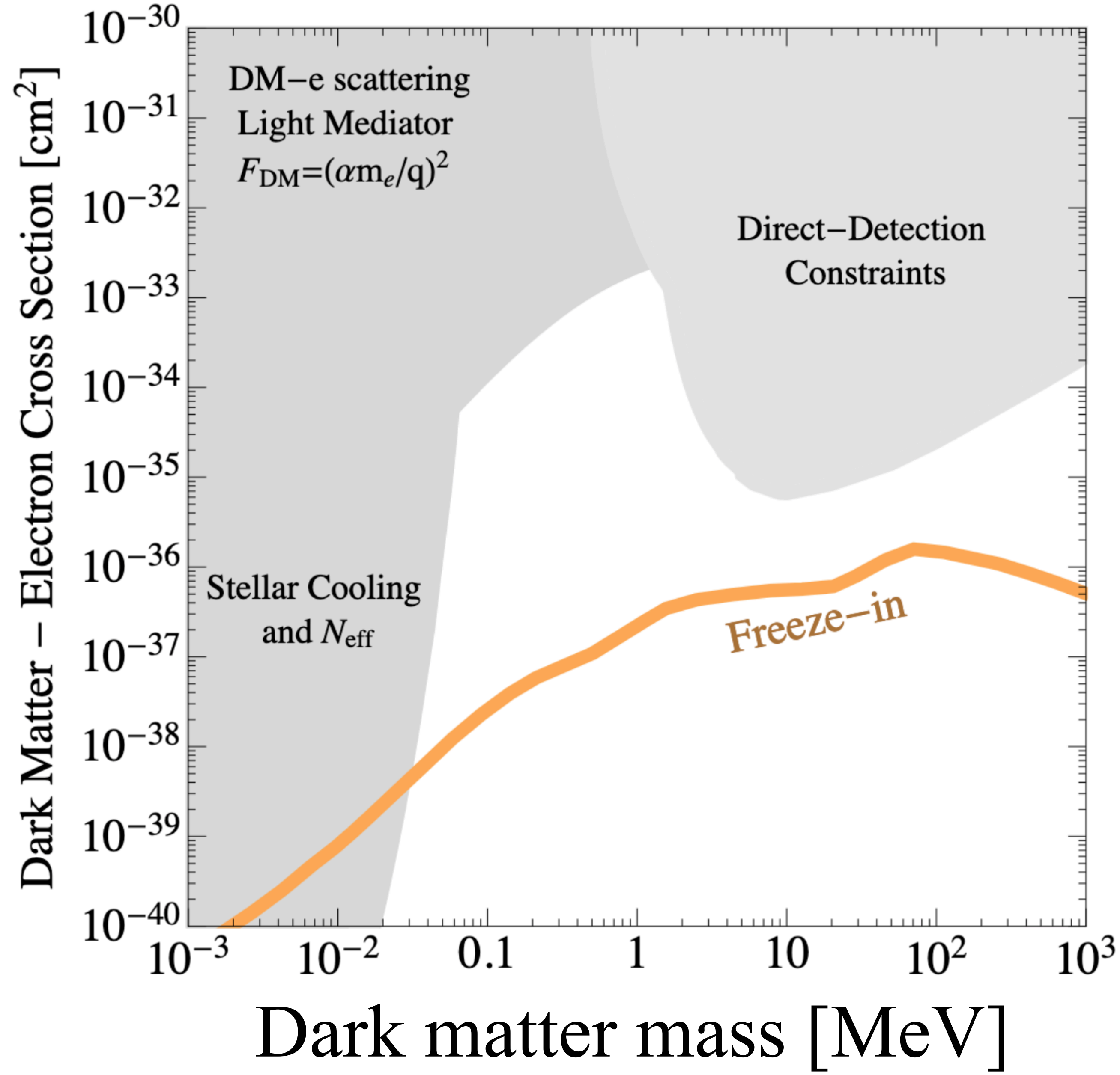
Other ways to maximize energy transfer to the target

Look for DM hitting lighter target to maximize energy transfer

Dark matter - electron scattering

Current searches include:
- Large volume noble liquid detectors
- Small scale semi - conductor detectors





Essig et al, **arXiv: 2203.08297**

Complementary way to maximize energy transfer to target is

Fast moving/accelerated dark matter

- Energy transferred to nucleus

$$E_{nr} \sim 50 \text{ keV} \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right) \left(\frac{v}{0.1}\right)^2$$

- Max energy transferred to electron

$$E_{er} \lesssim 2 \text{ MeV} \left(\frac{m_\chi}{500 \text{ MeV}}\right) \left(\frac{v}{0.1}\right)^2$$

These are above ~ keV threshold energies in **current dark matter detectors** & actually **some large neutrino detectors**

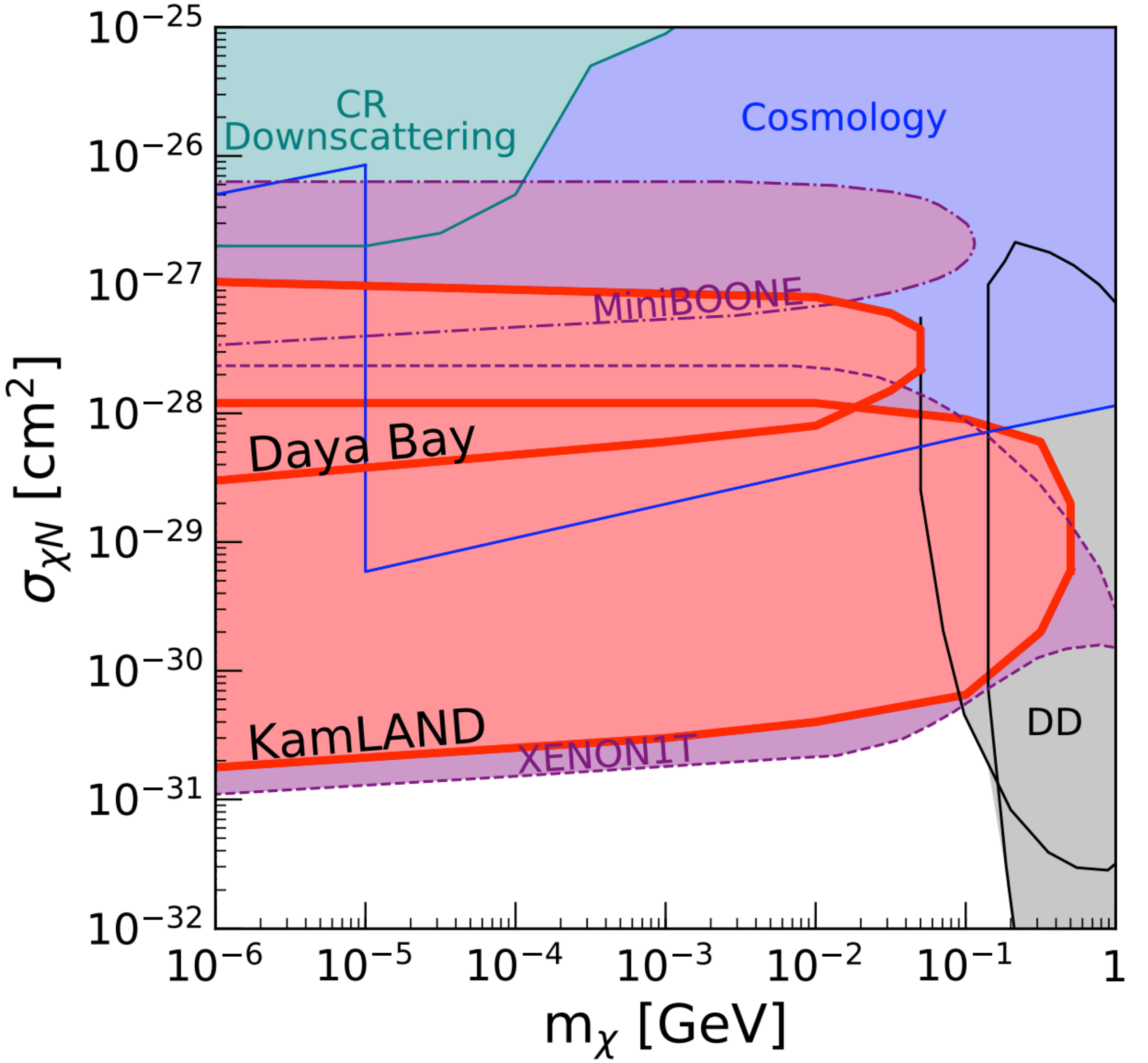
But, galactic DM has to be **non-relativistic**

Accelerated DM must be small subcomponent total halo DM

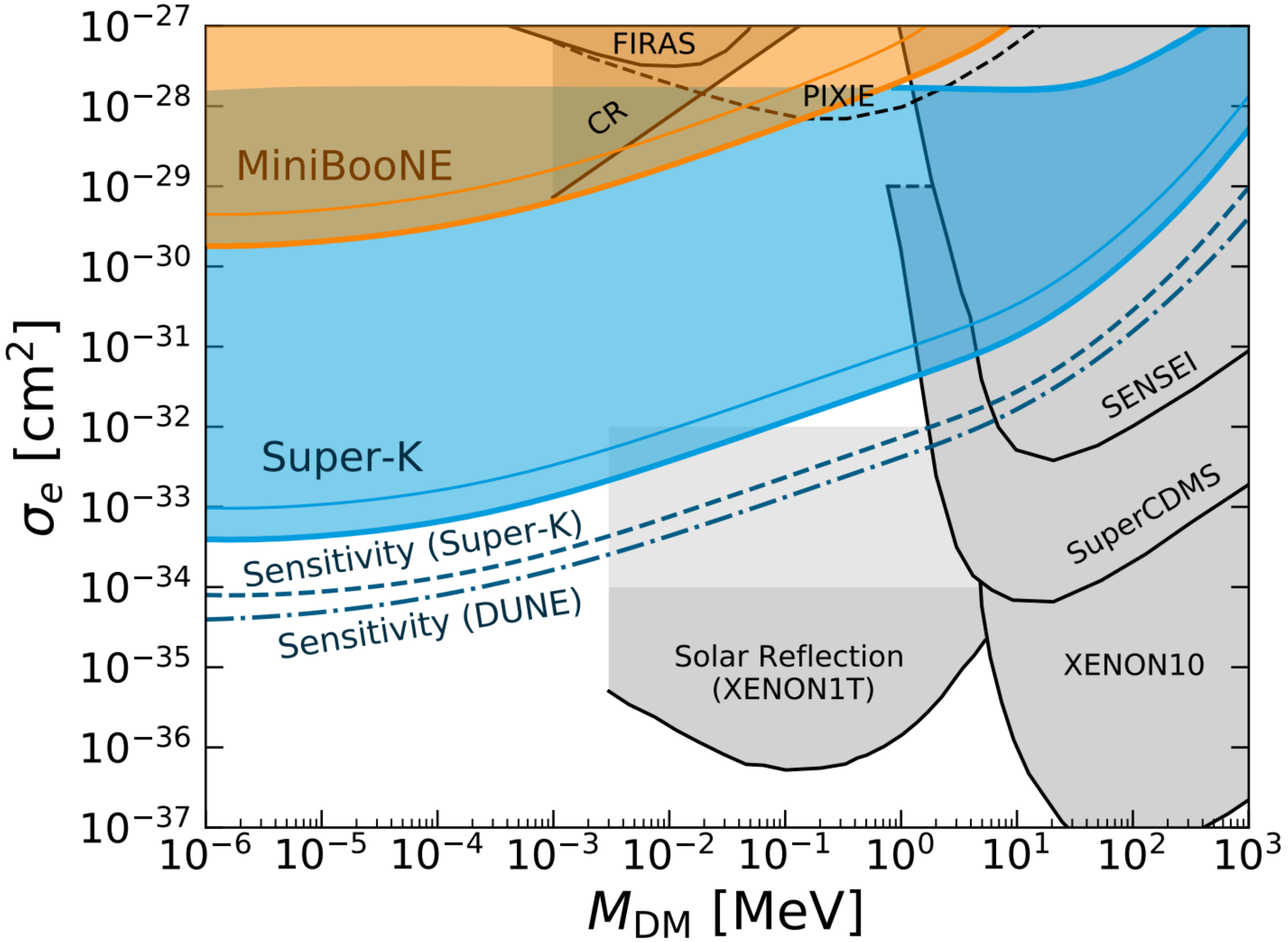
Many ways to get accelerated dark matter

Cosmic ray accelerated dark matter

- High energy CR can scatter off DM moving at v~10^{-3} c
- CR transfers energy to DM, accelerating it
- Accelerated DM reaches earth and scatters in detectors



Cappiello, Beacom : **Phys.Rev. D100 (2019) 10, 103011**



Ema, Sala, Sato : **Phys.Rev. Lett 122 (2019) 19, 181802**

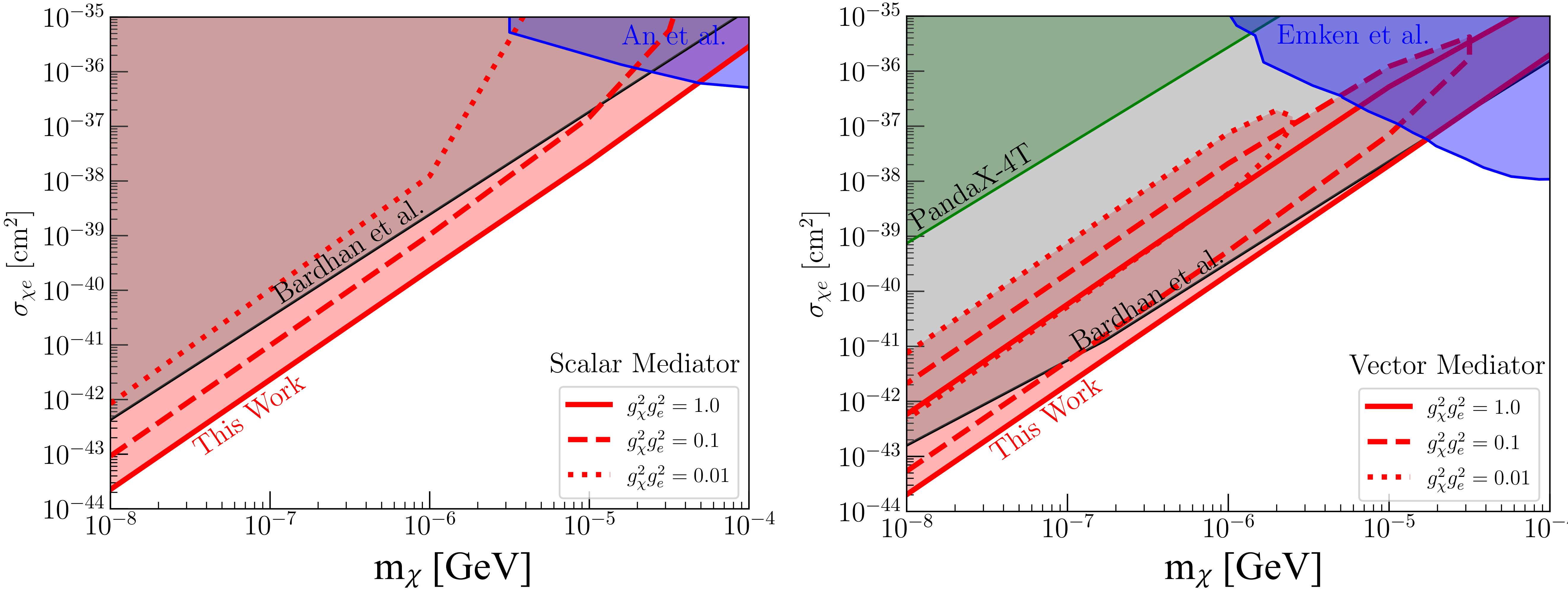
Cappiello, Ng, Beacom : **Phys.Rev. D99 (2019) 6, 063004**

Dent et al : **Phys.Rev. D101 (2020) 11, 116007**

Krnjaic, McDermott : **Phys.Rev. D101 (2020) 12, 123022** + many others

We can probe even lighter DM particles using **IceCube** low energy data

DM - electron scattering

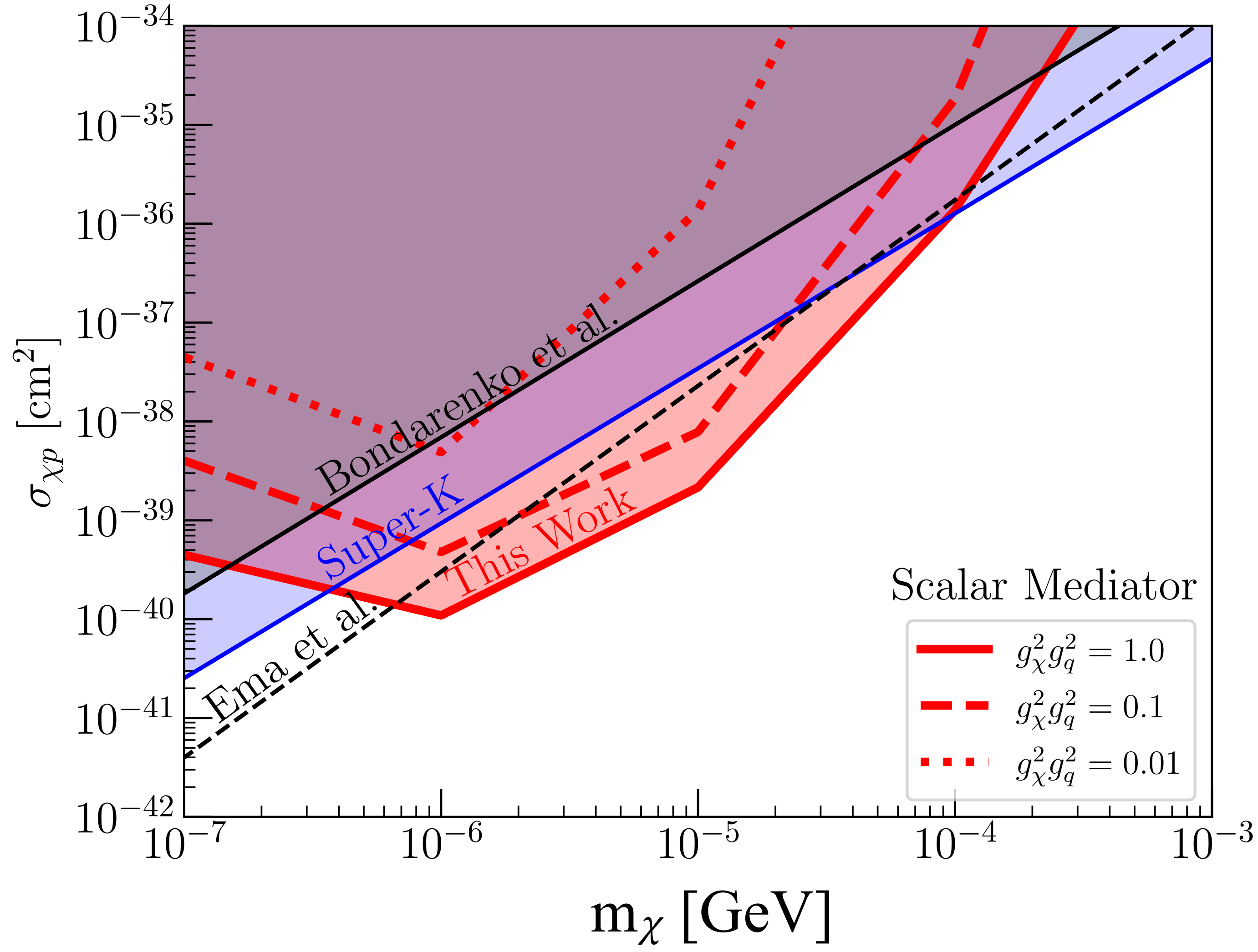


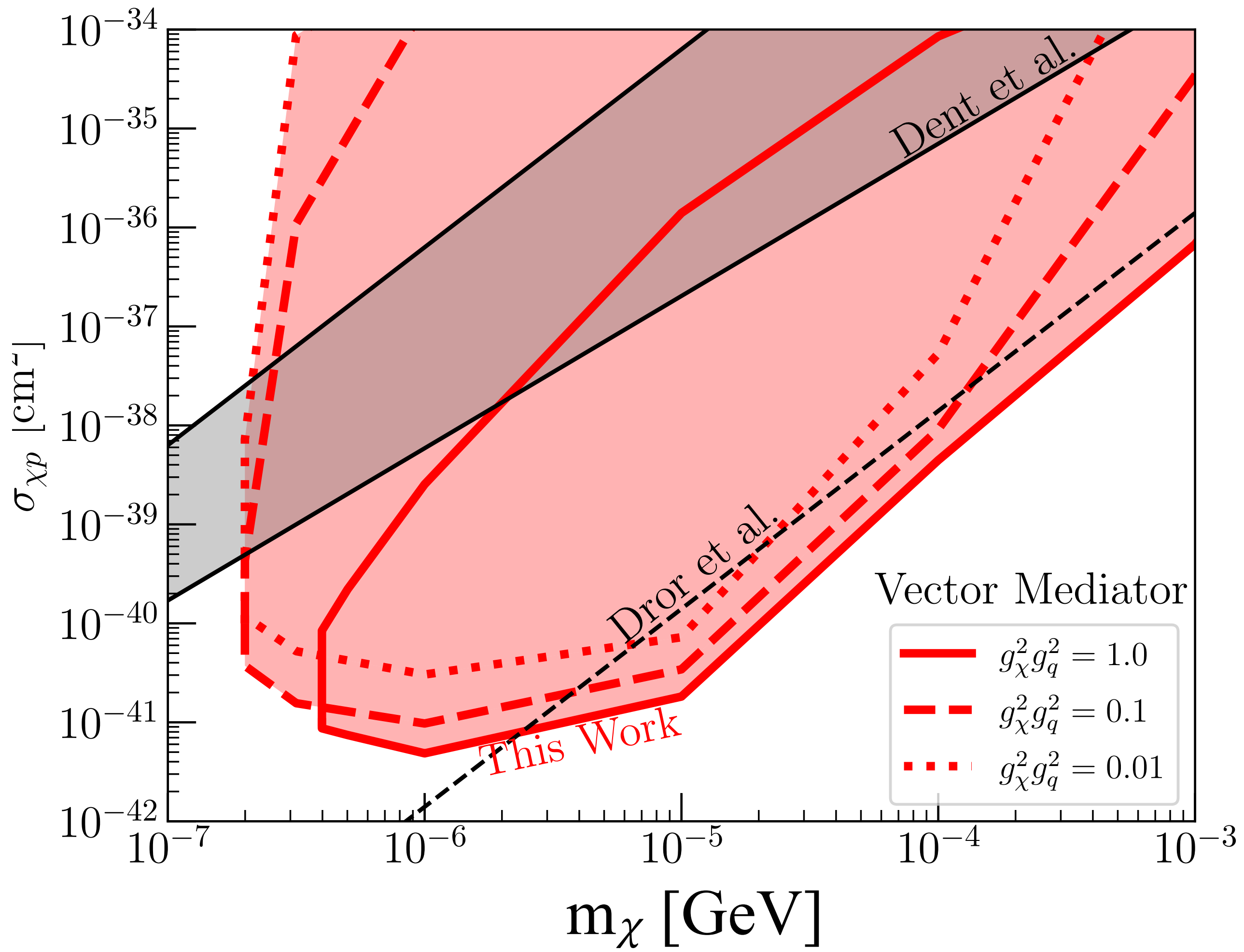
Cappiello, Liu, **Mohlabeng** & Vincent: **arXiv 2405.00086**

We can probe even lighter DM particles using **IceCube** low energy data

DM - nucleon scattering

(including elastic & deep inelastic scattering)

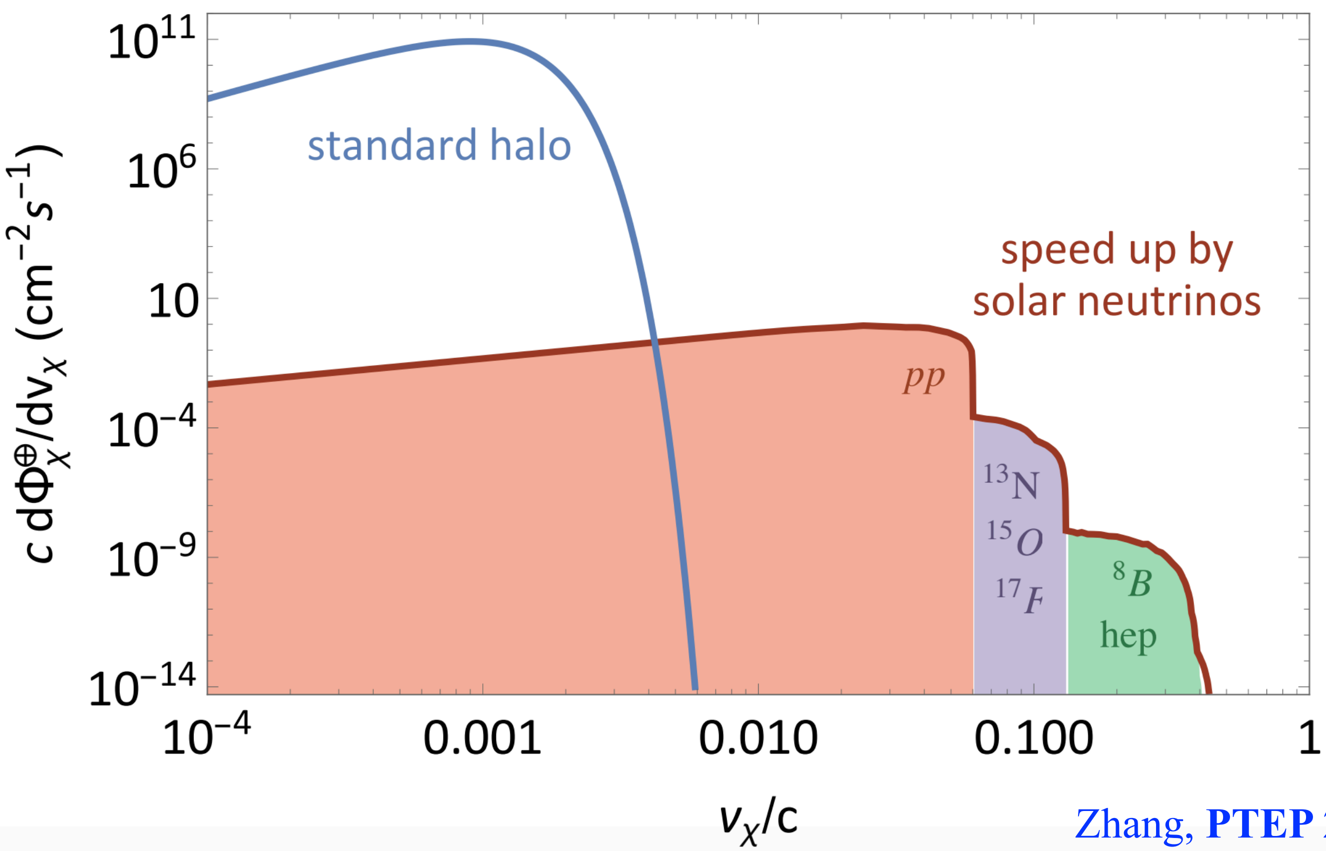


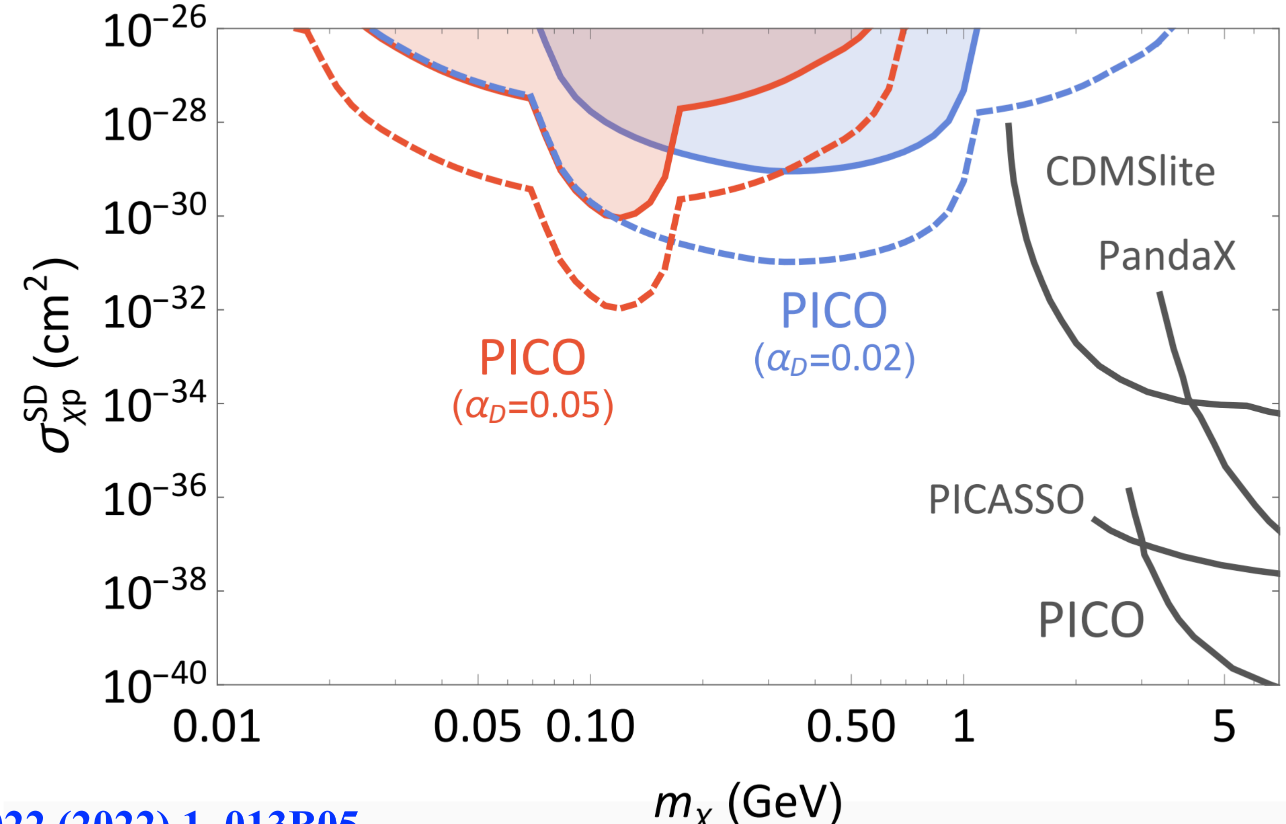


Cappiello, Liu, **Mohlabeng** & Vincent: **arXiv 2405.00086**

Neutrino accelerated dark matter

- e.g. Solar neutrinos can scatter off DM moving at v~10^{-3} c
- After interaction, DM obtains velocity: $v_\chi \sim \frac{2E_\nu}{m_\chi} cos\theta$
- DM enters detector, transferring to target energy : $E_{nr} \lesssim \frac{2E_\nu^2}{m_N}$





Zhang, **PTEP 2022 (2022) 1, 013B05**

Cosmic neutrino upscattering: Jho et al, **arXiv: 2101.11262**

DSNB neutrino upscattering: Das, Sen, **Phys.Rev.D 104 (2021) 7, 075029**

Other interesting mechanisms

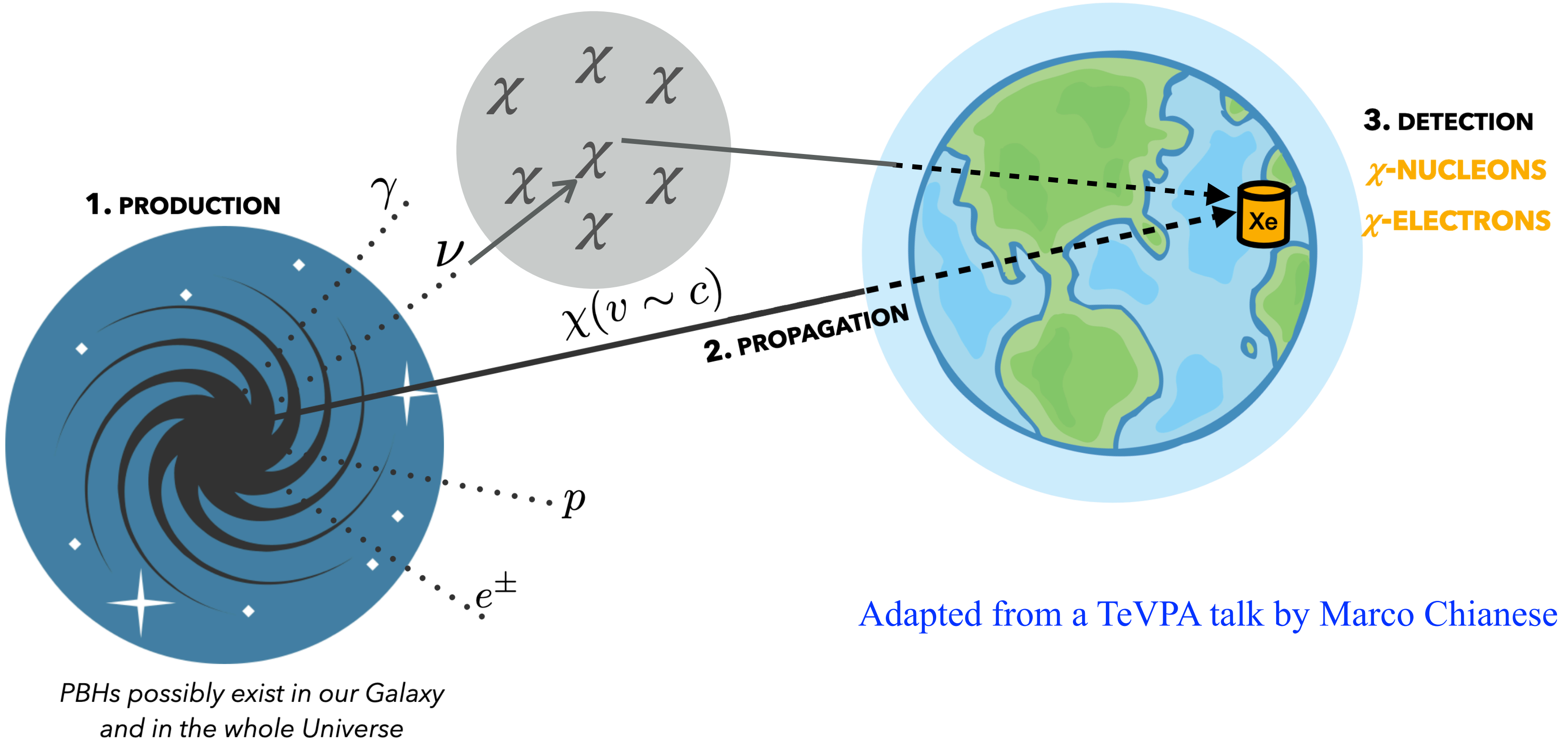
Accelerated DM from evaporating primordial black holes:

Calabrese et al, **Phys. Rev. D (105) 2022 2**

Calabrese et al, **Phys. Rev. D (105) 2022 10**

Neutrinos from evaporating primordial black holes accelerate DM:

Chao et al, **arXiv: 2108.05608**



Adapted from a TeVPA talk by Marco Chianese

Accelerated DM from supernova shockwaves:

Cappiello et al, **Phys. Rev. D (107) 2023 3, 035003**

+ many others

A different mechanism (doesn't depend on accelerating SM particle flux)

Dark sector may be non-minimal, i.e. more than one stable DM state

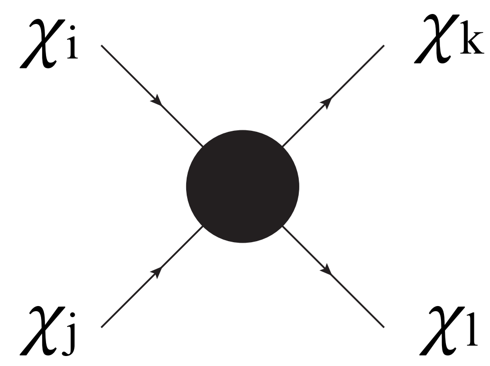
Generic feature of any non-minimal dark sector: small fraction of DM today may be relativistic/semi-relativistic

Sources:

- **Assisted Freeze-out**:

  $\chi_i \chi_j \to \chi_k \chi_l$

  with $\chi_i \chi_j > \chi_k \chi_l$

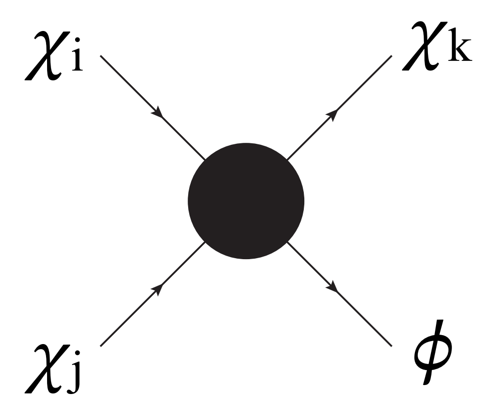


Belanger and Park : **JCAP 03 (2012) 038**

- **Semi-annihilation**:

  $\chi_i \chi_j \to \chi_k \phi$

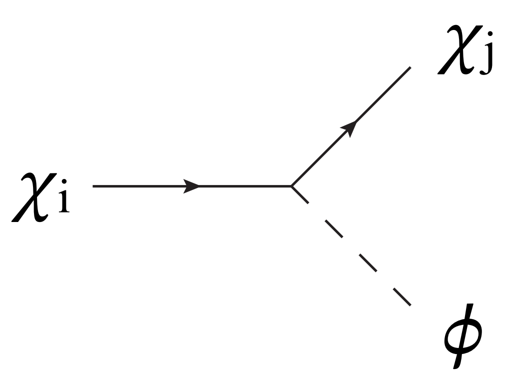
  , Z_3 DM symmetry



D'Eramo and Thaler : **JHEP 06 (2010) 109**

- **Decay**:

  $\chi_i \to \chi_j \phi$



Tucker-Smith & Weiner: **Phys.Rev. D64 (2001) 043502**

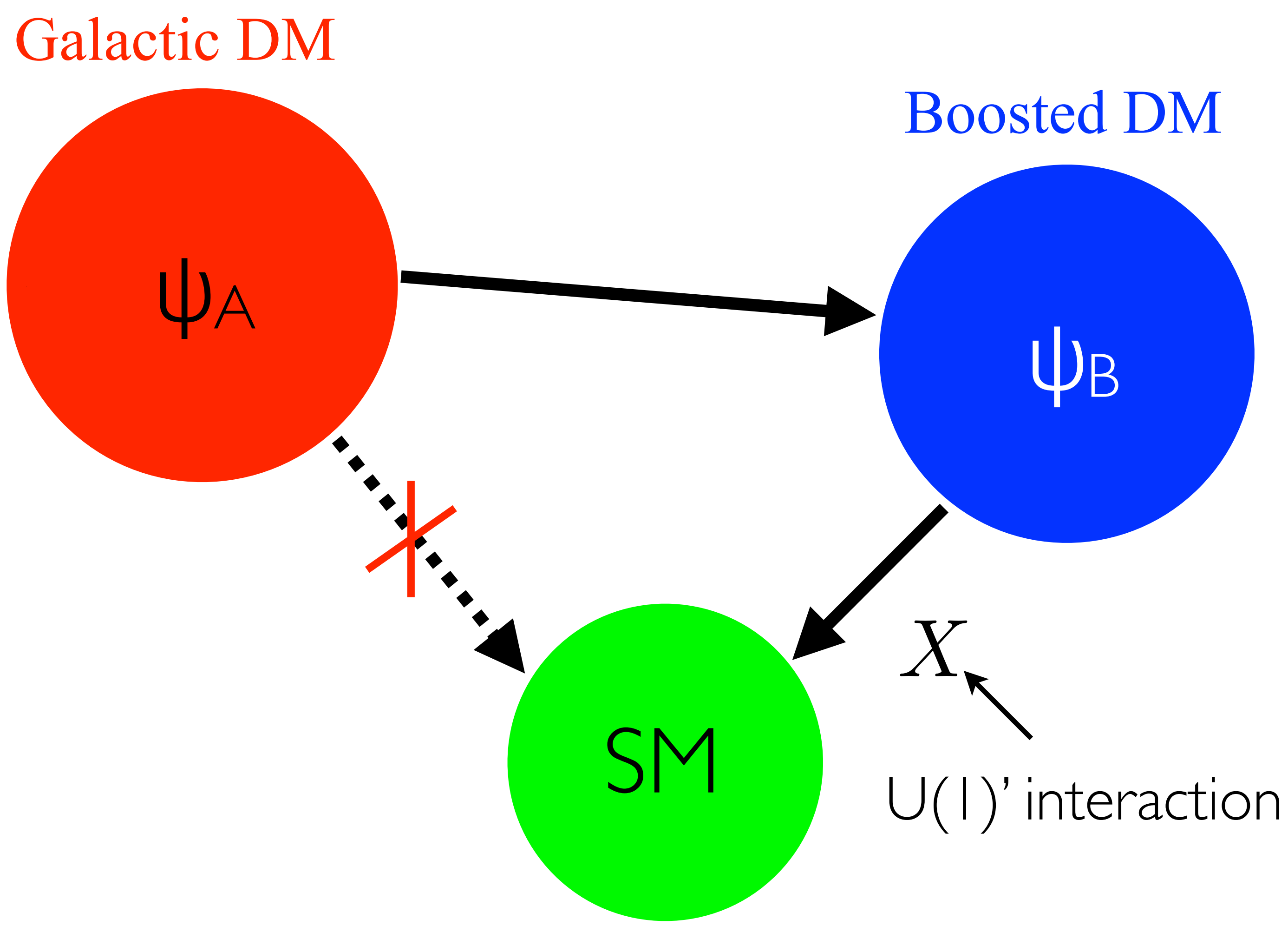
Mohlabeng : **Phys.Rev. D99 (2019) 11, 115001**

\+ **many others**

Boosted dark matter

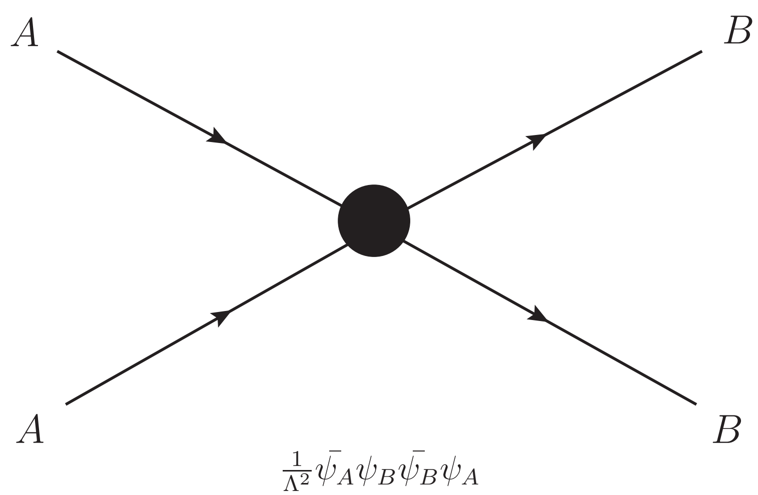
- Two stable DM particle, ψ_A & ψ_B with $m_A > m_B$ $(eg. U(1)' \otimes U(1)'')$

For example:



- ψ_A is the dominant DM component and has no direct coupling to SM

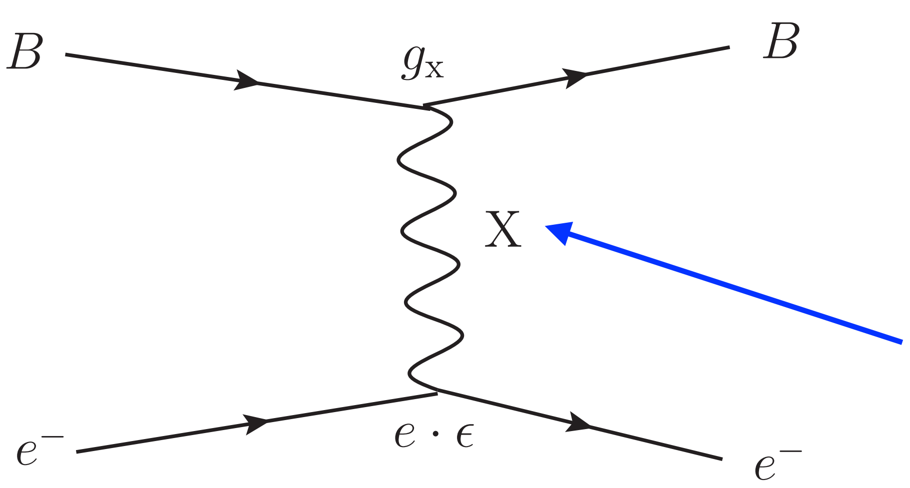
- ψ_B is sub-dominant and couples to SM through new force



$$\frac{1}{\Lambda^2}\overline{\chi}_A\chi_B\overline{\chi}_B\chi_A$$

- ‘A’ particles self-annihilate producing accelerated ‘B’ particles with boost factor

$$\gamma = m_A/m_B$$



- boosted DM particles travel to Earth and scatter with SM in the detector

- Interacts through some light mediator particle X

Agashe, et al : **JCAP 10 (2014) 062**

Alhazmi, Kim, Kong, **Mohlabeng**, Park, Shin: **JHEP 05 (2021) 055**

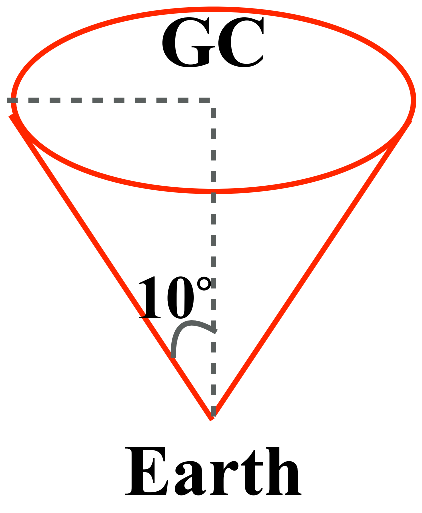
Necib et al: **Phys.Rev. D95 (2017) 7, 075018**

Dutta et al: **JHEP 01 (2022) 144**

Kim et al: **JHEP 07 (2020) 057** **+ many others**

Boosted dark matter from the Galactic Center

Annihilation of A to boosted B in the Galactic Center



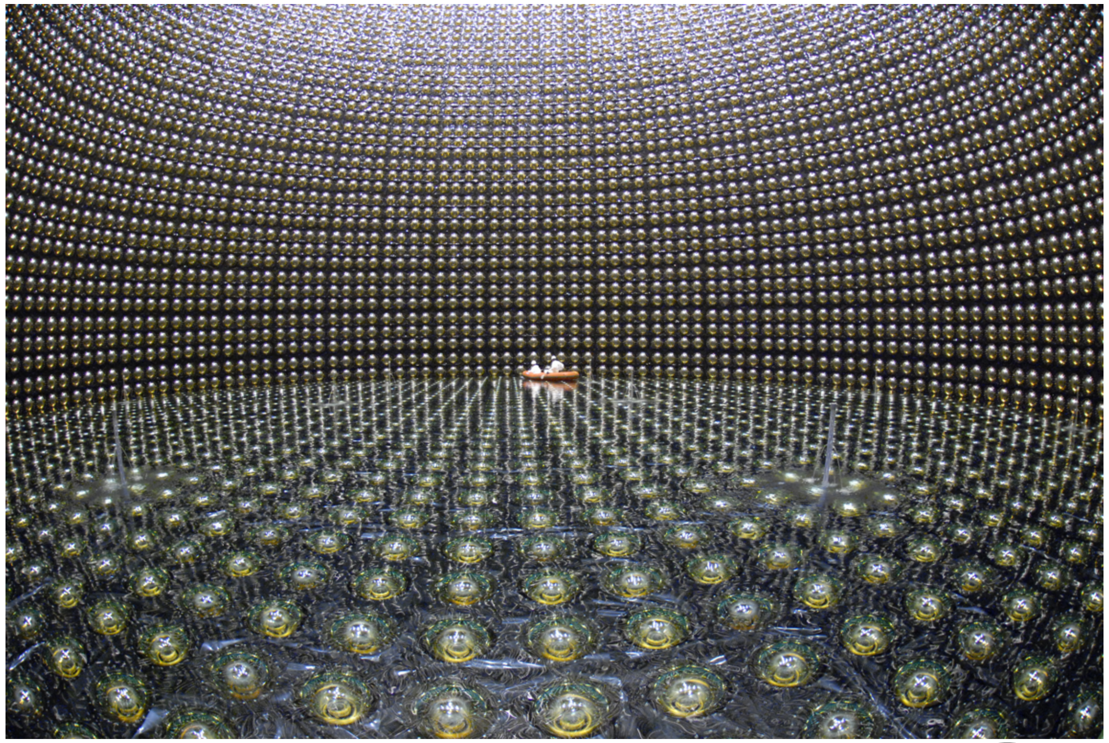
Flux: NFW profile + 10° cone around GC

$$\Phi_{GC}^{10^\circ} = 9.9 \times 10^{-8} cm^{-2} s^{-1} \left(\frac{< \sigma_{A\bar{A}\to B\bar{B}} v >}{5 \times 10^{-26} cm^3/s} \right) \left(\frac{20 GeV}{m_A} \right)^2$$

Lower flux means we need large volume detectors for sensitivity

Neutrino detectors: Super-K, Hyper-K, Ice-Cube, DUNE

Dark matter detectors: XENON1T, DarkSide



Focus on electron scattering

For nucleon scattering:

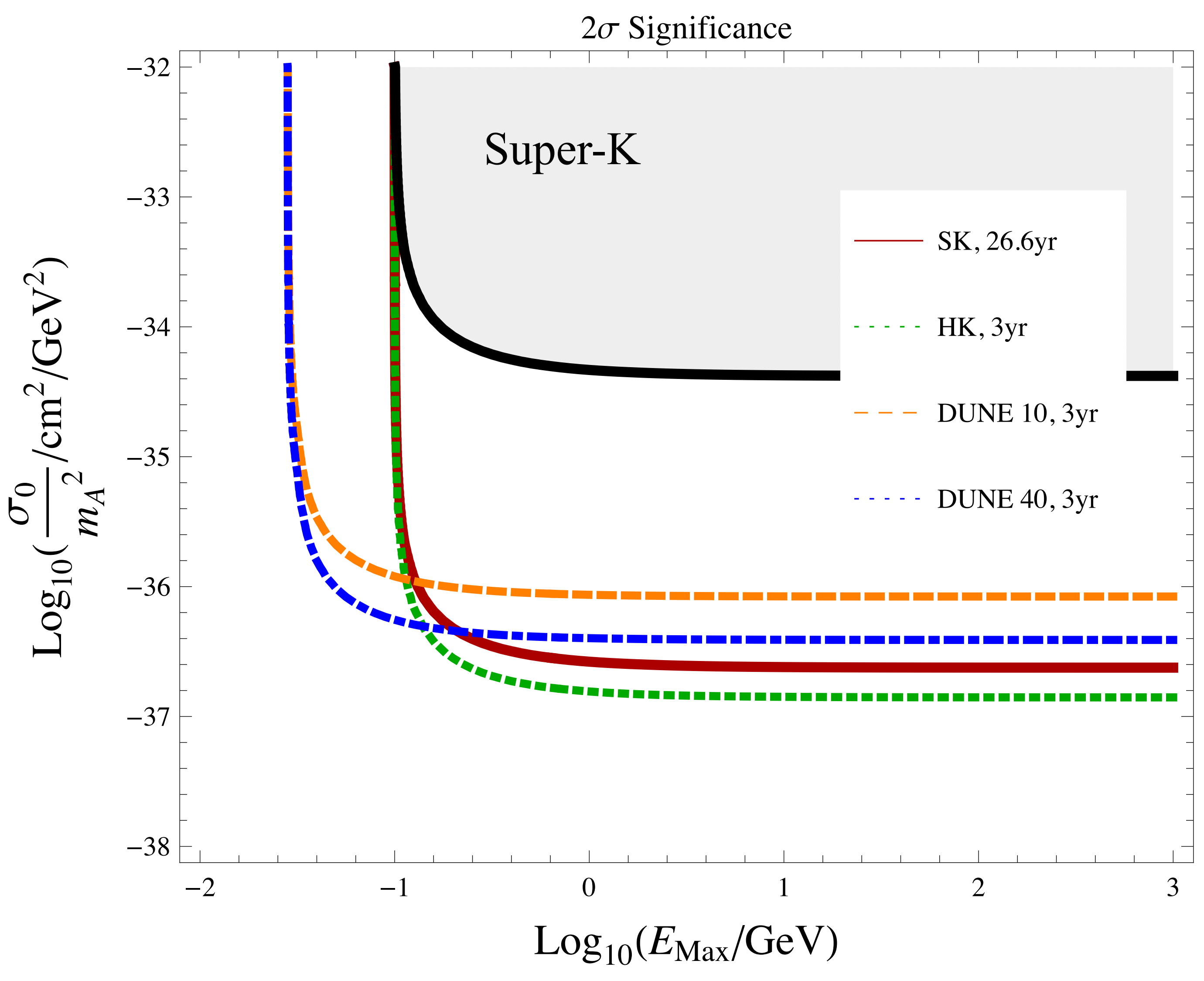
Berger et al, **Phys.Rev.D 103 (2021) 9, 095012**

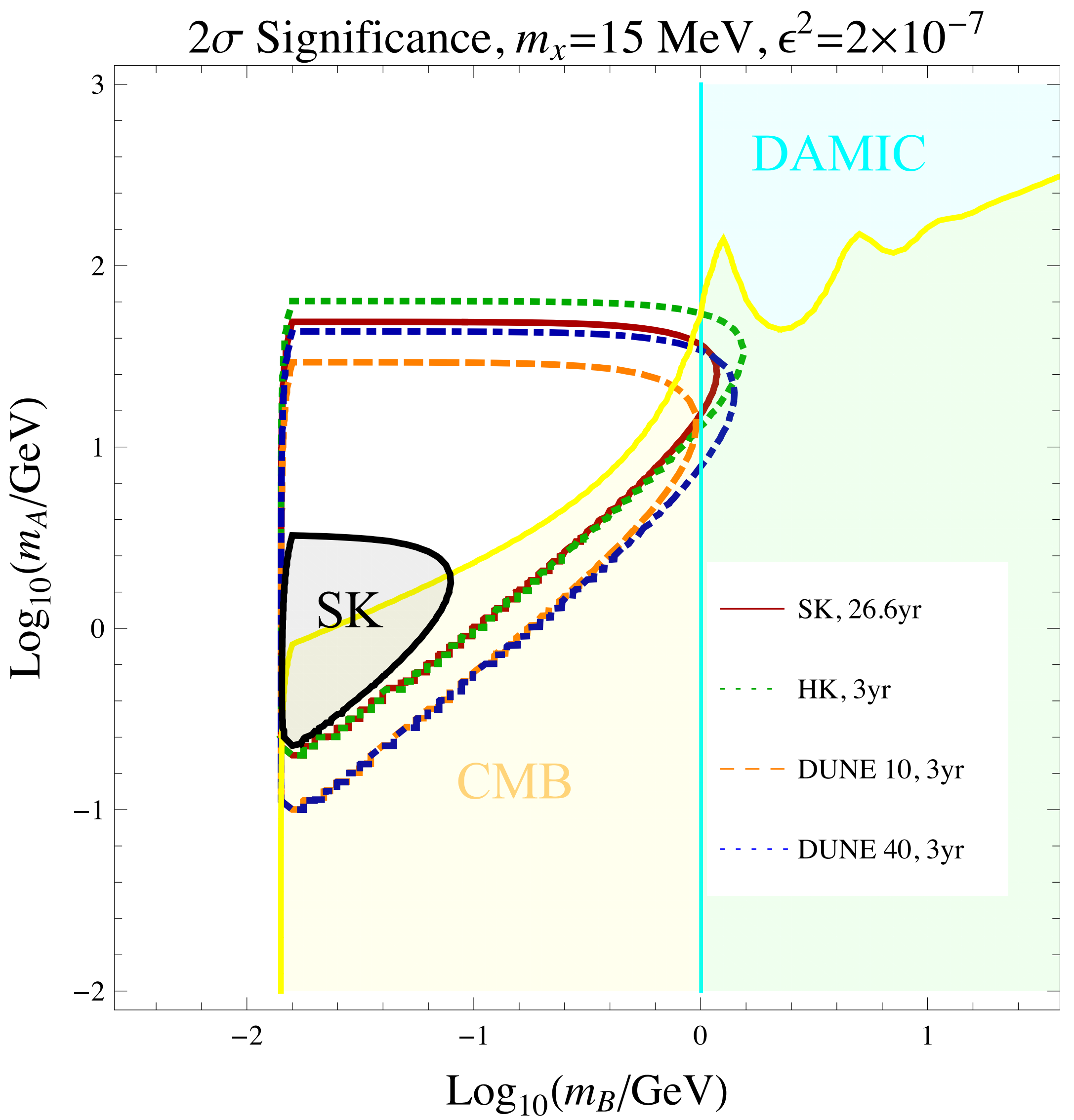
Boosted DM from the Galactic Center

$$N_{sig} = \Delta T\ N_{target}\,\Phi^{10^\circ}_{GC}\int_{E_{thres}}^{E_{max}} dE_e \frac{d\sigma_{Be^-\to Be^-}}{dE_e}$$

2σ sensitivity:

$$S^{\theta_{res}} = \frac{N_{sig}}{\sqrt{N_{BG}^{\theta_{res}}}}$$





Alhazmi, Kong, Mohlabeng, Park: **JHEP 04 (2017) 158**

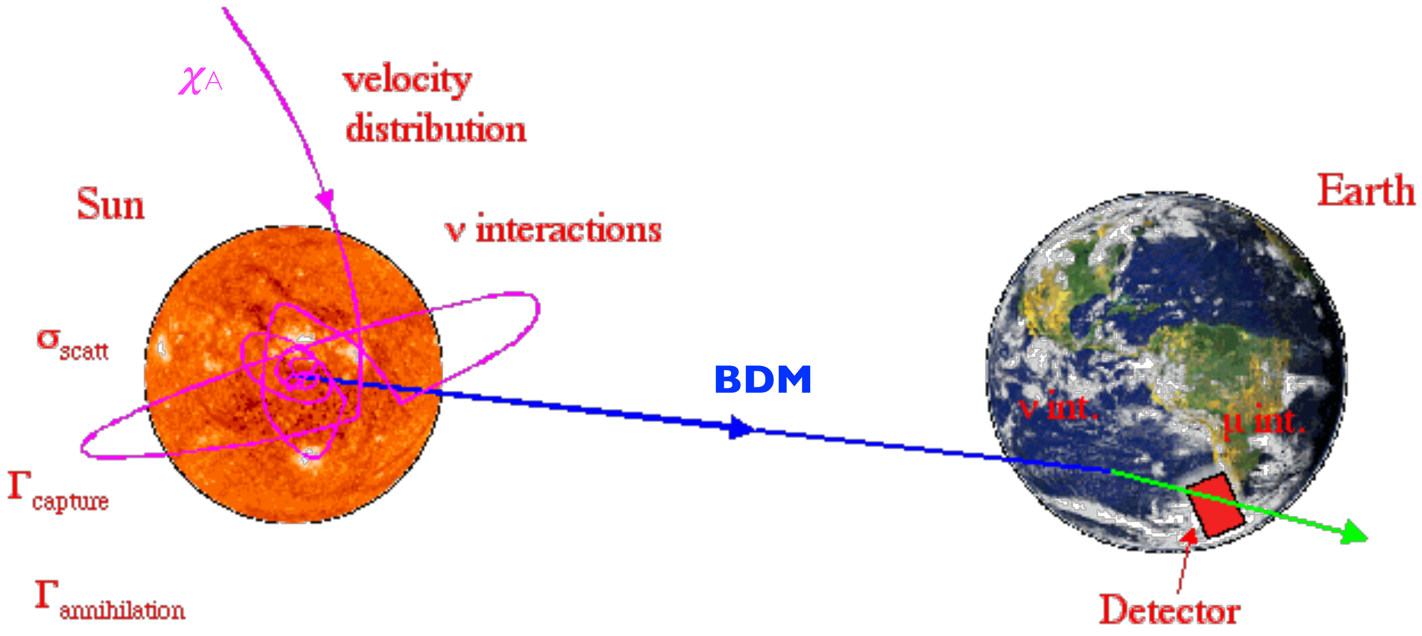
Boosted DM from the Sun

χ_A can get captured in the Sun and annihilate to χ_B

χ_B travel to earth and scatter in the detector

The Sun is a point-like source so we don't consider an observation angle

Including self-interactions enhances the capture rate in the Sun



Kong, Mohlabeng, Park: **Phys. Lett. B 743 (2015) 256-266**

Berger et al: **JCAP 02 (2015) 005**

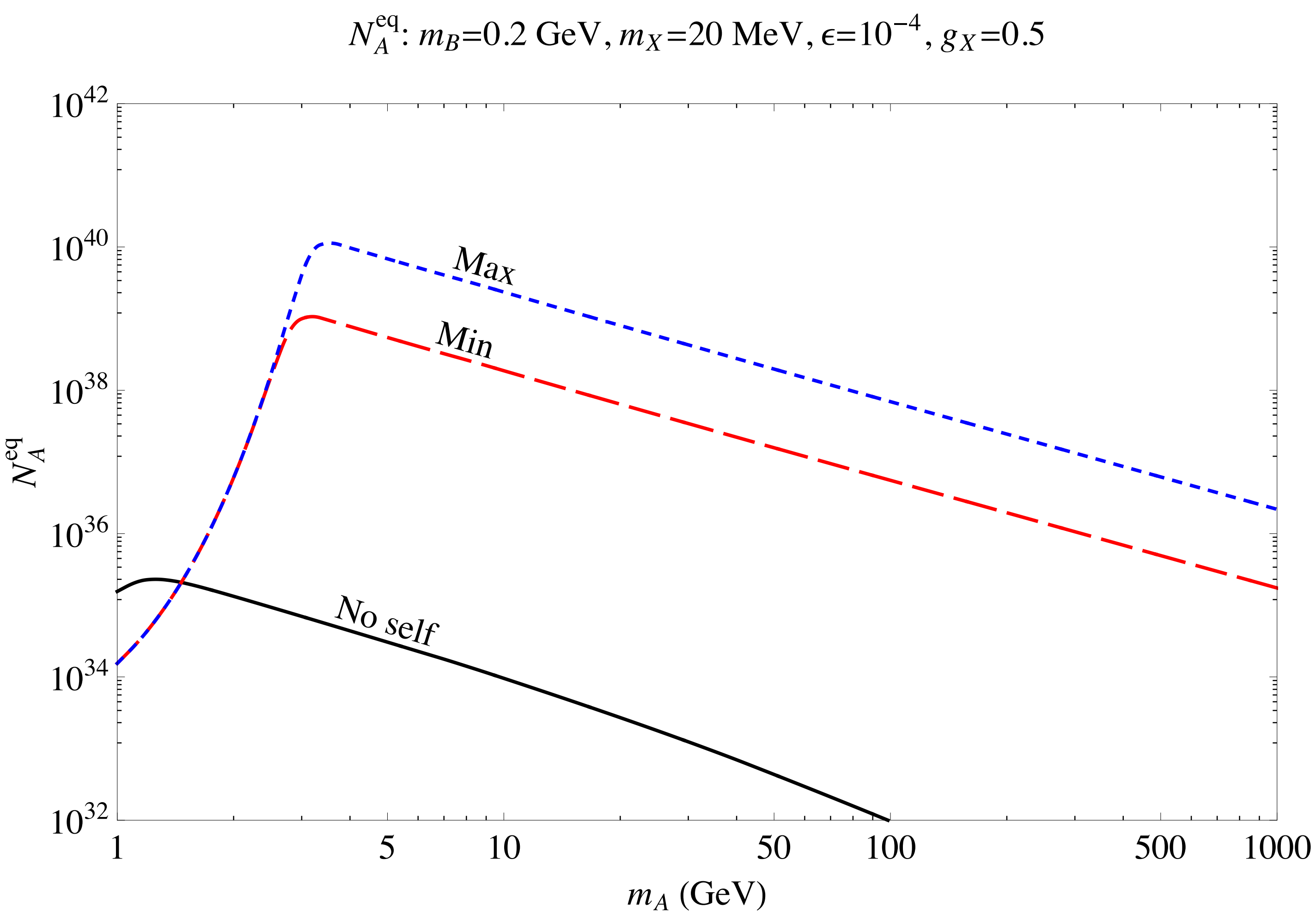
Alhazmi, Kong, Mohlabeng, Park: **JHEP 04 (2017) 158**

Bhattacharya et al: **JCAP 05 (2017) 002**

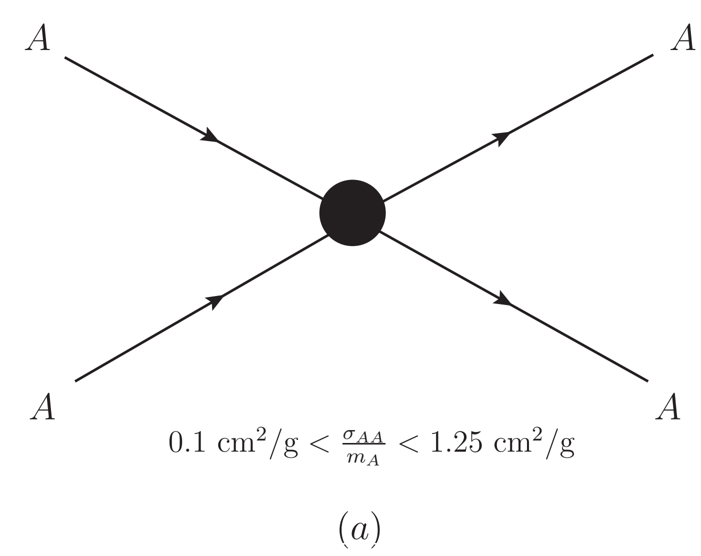
Boosted DM from the Sun

Time evolution of ψ_A number density in the Sun is

$$\frac{dN_\chi}{dt} = C_c + (C_s - C_e)N_\chi - (C_a + C_{se})N_\chi^2$$



Importance of self-interactions overlooked before



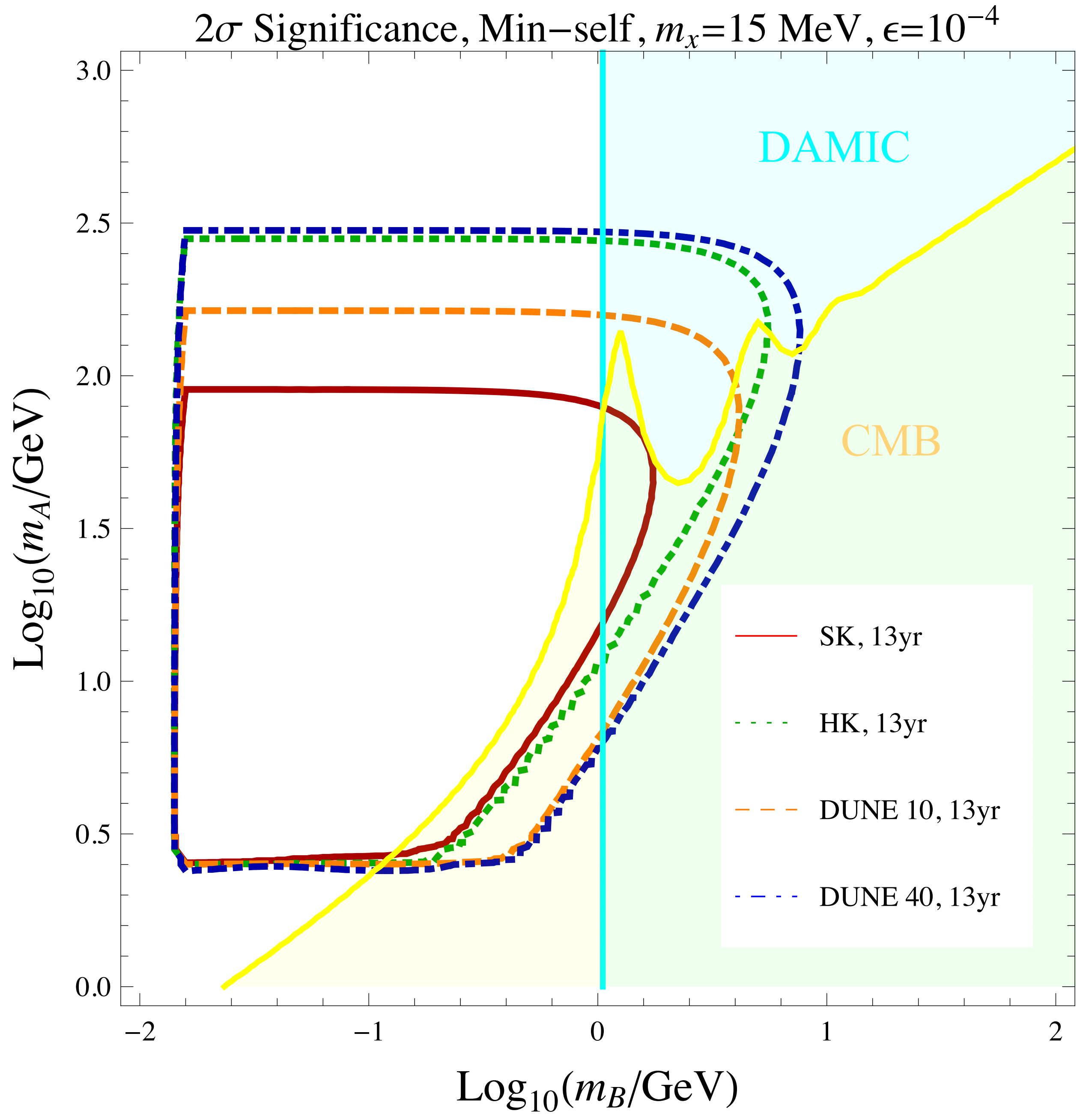
min $0.1\ \mathrm{cm}^2/g < \frac{\sigma_{AA}}{m_A} < 1.25\ \mathrm{cm}^2/g$ max

Kong, Mohlabeng, Park: **Phys. Lett. B 743 (2015) 256-266**

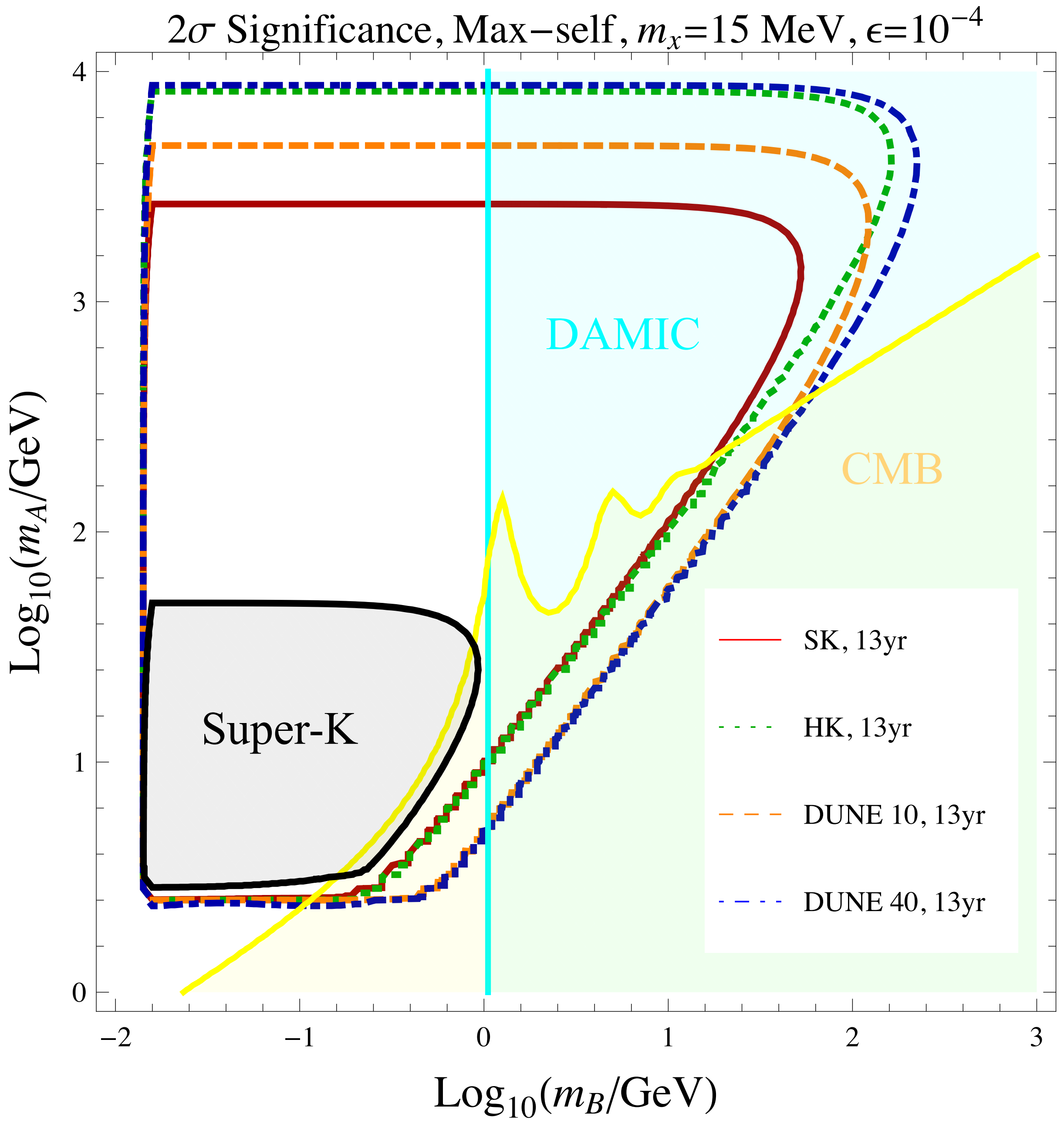
Alhazmi, Kong, Mohlabeng, Park: **JHEP 04 (2017) 158**

Boosted DM from the Sun

90% CL, Min-self



90% CL, Max-self



Alhazmi, Kong, Mohlabeng, Park: **JHEP 04 (2017) 158**

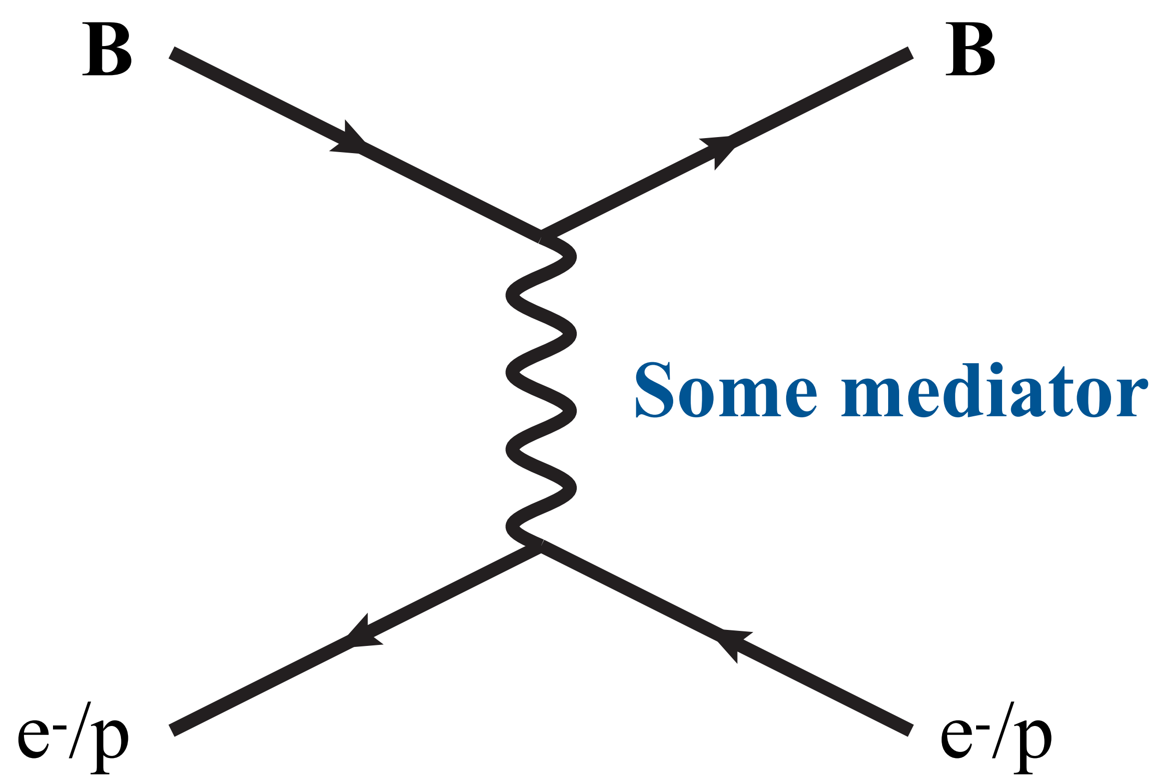
Boosted DM at direct detection experiments

- Large volume DD experiments can look for lower A masses

XENON1T
DarkSide
…

} Lower threshold than neutrino detectors

Scattering with either nucleon or electrons



Focus on electron scattering

To obtain recoil rates in neutrino experiments:

$$N_{sig} = \Phi_B \sigma_{Be} N_e^{eff} t_{exp}$$

However, it is important to include atomic effects related to DM - e scattering

$$\frac{dN_{sig}}{dE_{eR}} = \Phi_B t_{exp} N_{Xe} \frac{d\sigma_{Be} v_{rel}}{dE_{eR}}$$

Includes important atomic effects

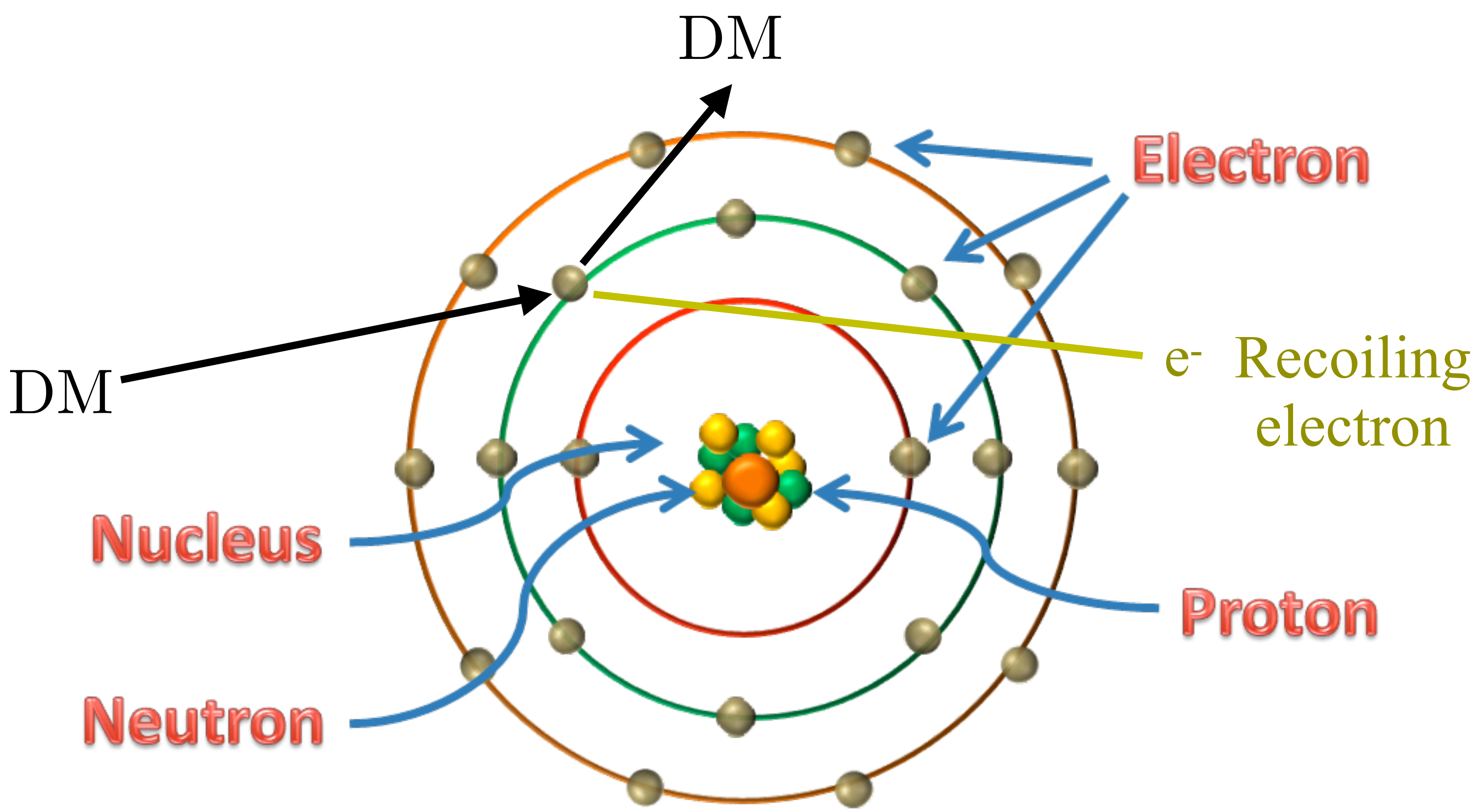
Differential scattering cross-section

Ionization form factor

$$\frac{d\sigma_{Be} v_{rel}}{dE_{eR}} = \frac{1}{64\pi} \frac{1 - v_{rel}^2}{v_{rel}} \frac{1}{m_B^2 E_{eR}(2m_e + E_{eR})(m_e - |E_{nl}^B|)} \int_{q_{min}}^{q_{max}} dq\ q\ |\mathcal{M}|^2\ \overbrace{|f_{ion}(E_{eR}, q)|^2}$$

- Bound electrons have non-negligible momentum dependence & Ionization function takes into account

- Electrons are bound in different orbitals with binding energies, ionization function accounts mom transfer required to ionize electron from these orbitals



free electron wave-function

bound electron wave-function

$$|f_{ion}(E_{eR}, q)|^2 = \frac{2k'^{\,3}}{(2\pi)^3} \int dr^3 \psi^*_{ef}(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} \psi_{ei}(\mathbf{r})$$

Different functions considered

Plane - Wave: - bound electron wave function is described by **Roothaan-Hartree-Fock** wavefunctions

Bunge et al: **Atom. Data Nucl. Data Tabl. 53 (1993) 113-162**

- Outgoing electron wave function is described by **plane wave**

$$f^{PW}_{e_i \to e_f}(\mathbf{q}) = \int d^3\mathbf{r}\; e^{-i\mathbf{k}'\cdot\mathbf{r}}\; e^{i\mathbf{q}\cdot\mathbf{r}} \psi_{nlm}(\mathbf{r})$$

Essig et al: **Phys. Rev. D 85 (2012) 076007**

Kopp et al: **Phys. Rev. D 80 (2009) 083502**

Cao et al: Chin**. Phys. C 45 (2021) 4, 045002**

+ many others

Relativistic ionization function: - bound and ionized electron wave functions are obtained by solving relativistic Dirac equation

i.e. solve $\hat{h}\psi_{nk} = E_{nk}\psi_{nk}$

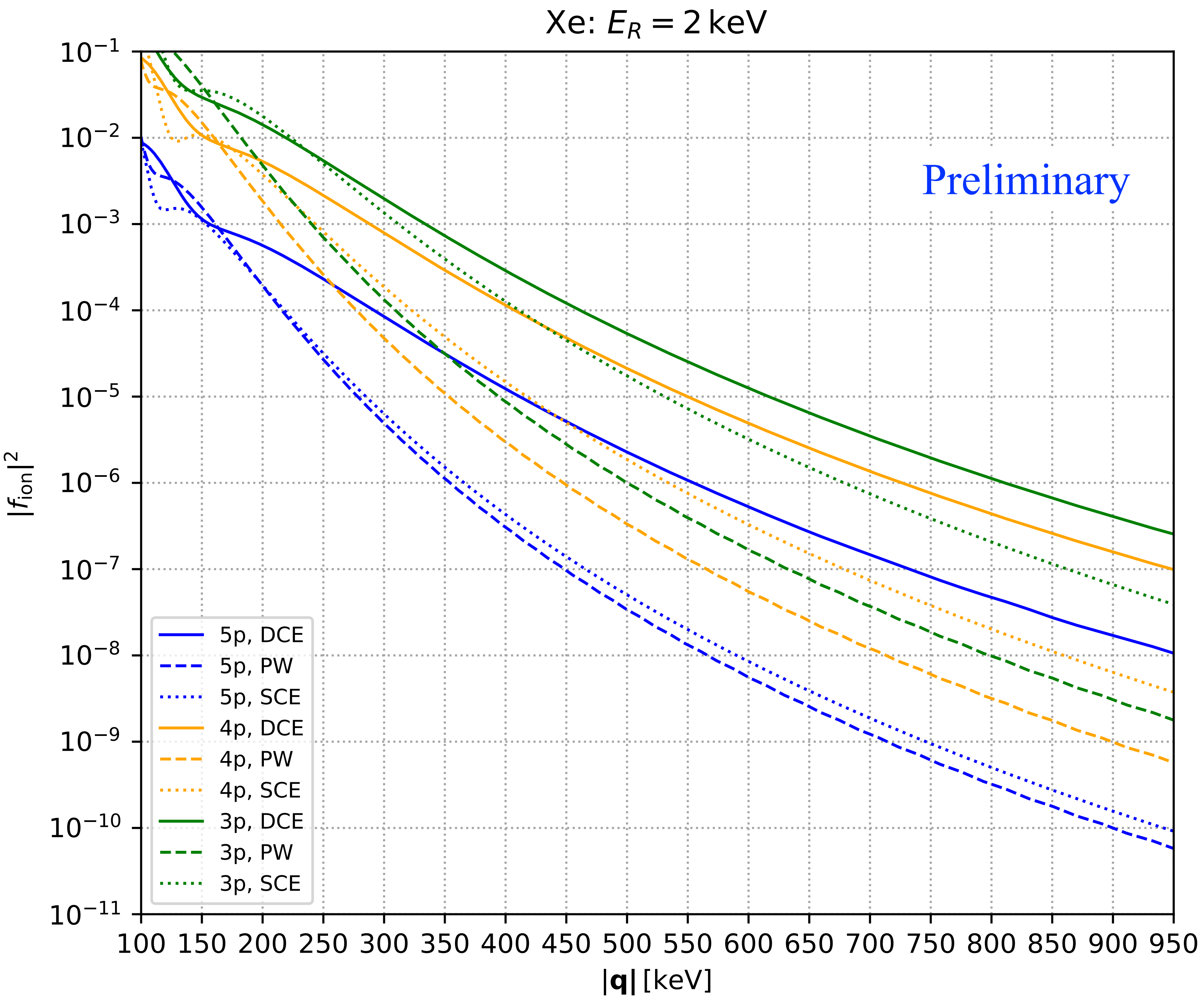
With Hamiltonian $\hat{h} = \alpha.\mathbf{p} + m_e(\beta - 1) + V_{eff}(r)$

Roberts et al: **Phys. Rev. D 93 (2016) 115037**

Roberts, Flambaum: **Phys. Rev. D 100 (2019) 063017**

- accounts for Lorentz structure of DM - e interactions

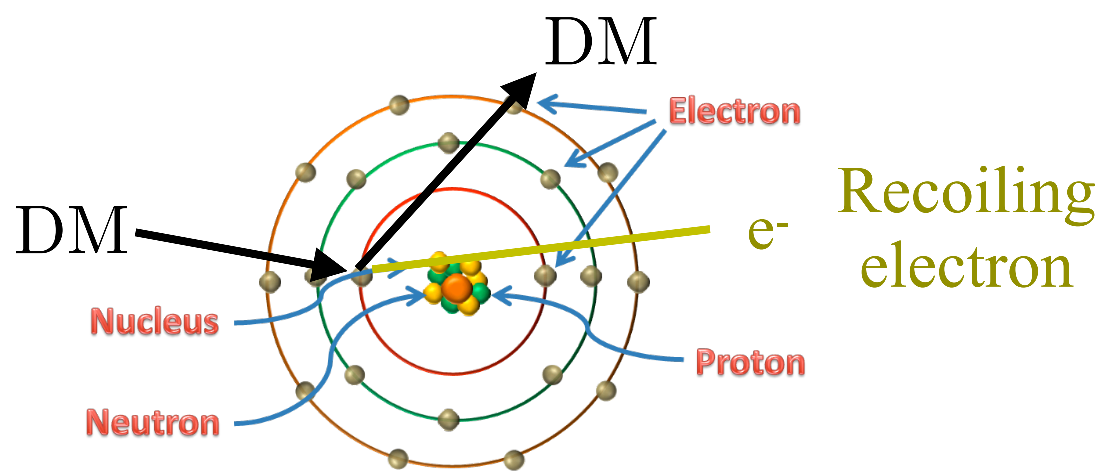
At high momentum transfer, relativistic & PW are different

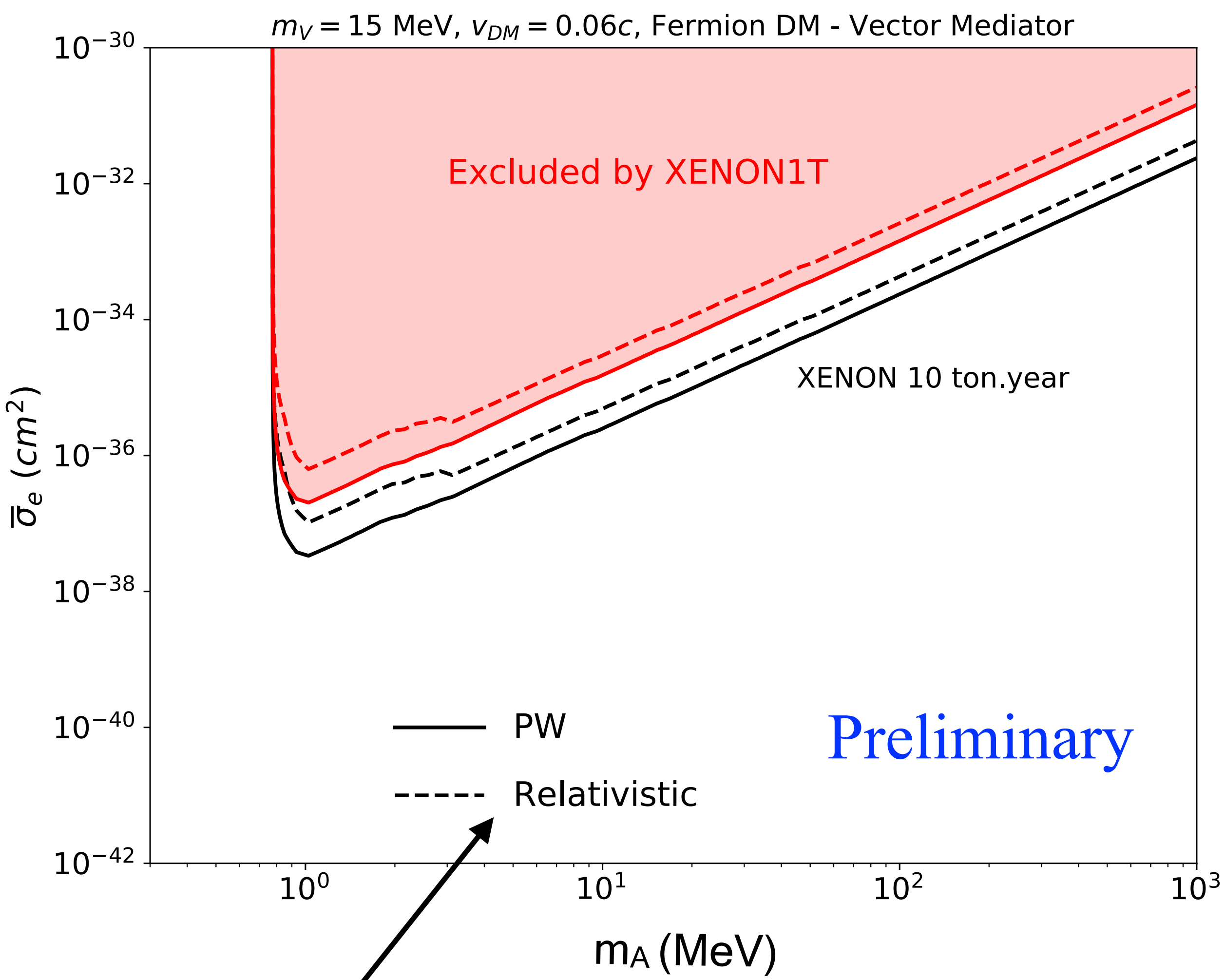


Alhazmi, Kim, Kong, Mohlabeng, Park, Shin: **In Progress**

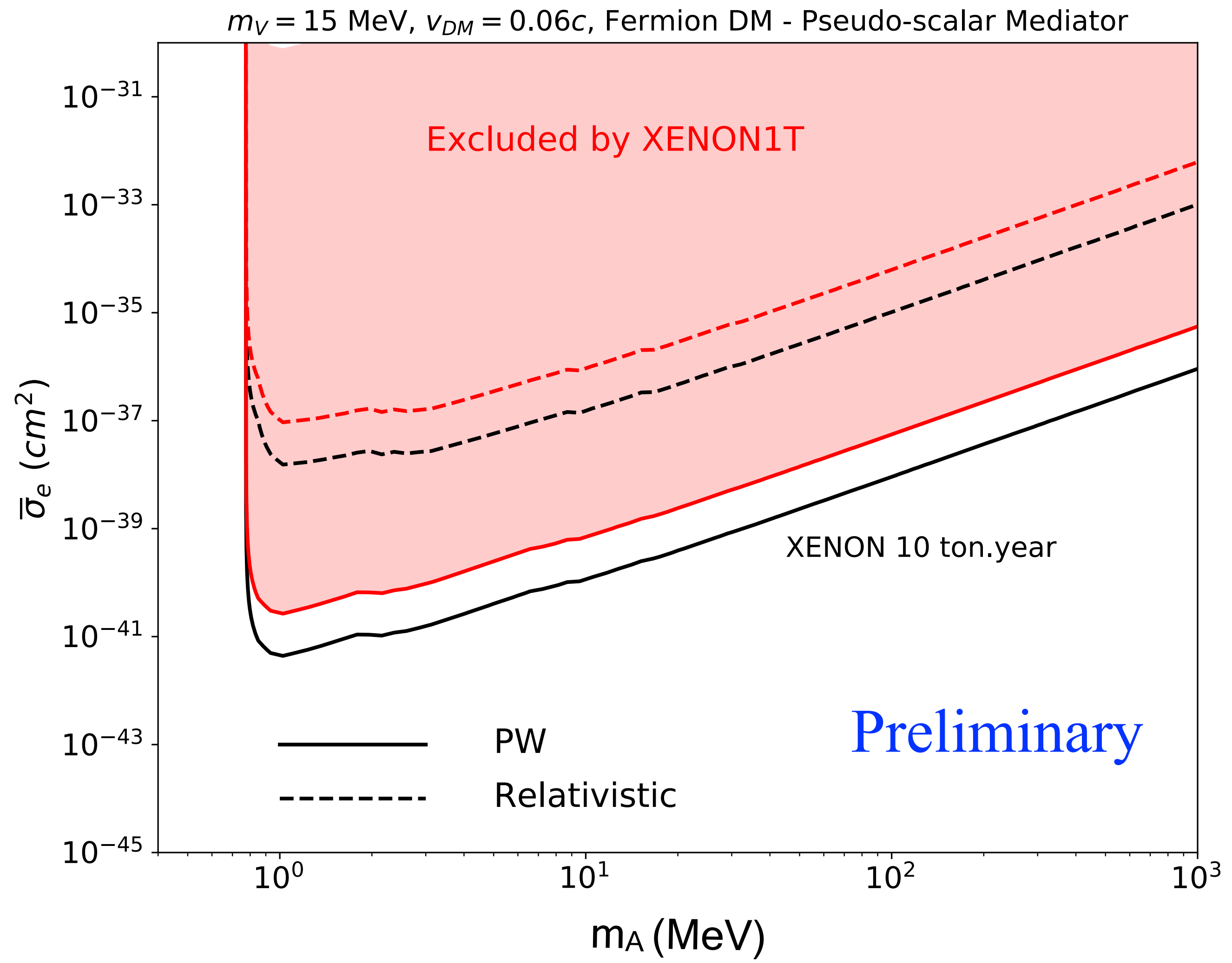
What are the Ionization effects of boosted DM?

Can these pin-point the underlying model?





Ionization form factors



Alhazmi, Kim, Kong, Mohlabeng, Park, Shin: **In Progress**

Summary

- Accelerated DM is interesting phenomenological prospect

- Can give striking signals at large volume neutrino & DM detectors

- Atomic & nuclear effects can be important for accelerated DM scattering

- **Accelerated DM can open up a whole new world of possibilities**

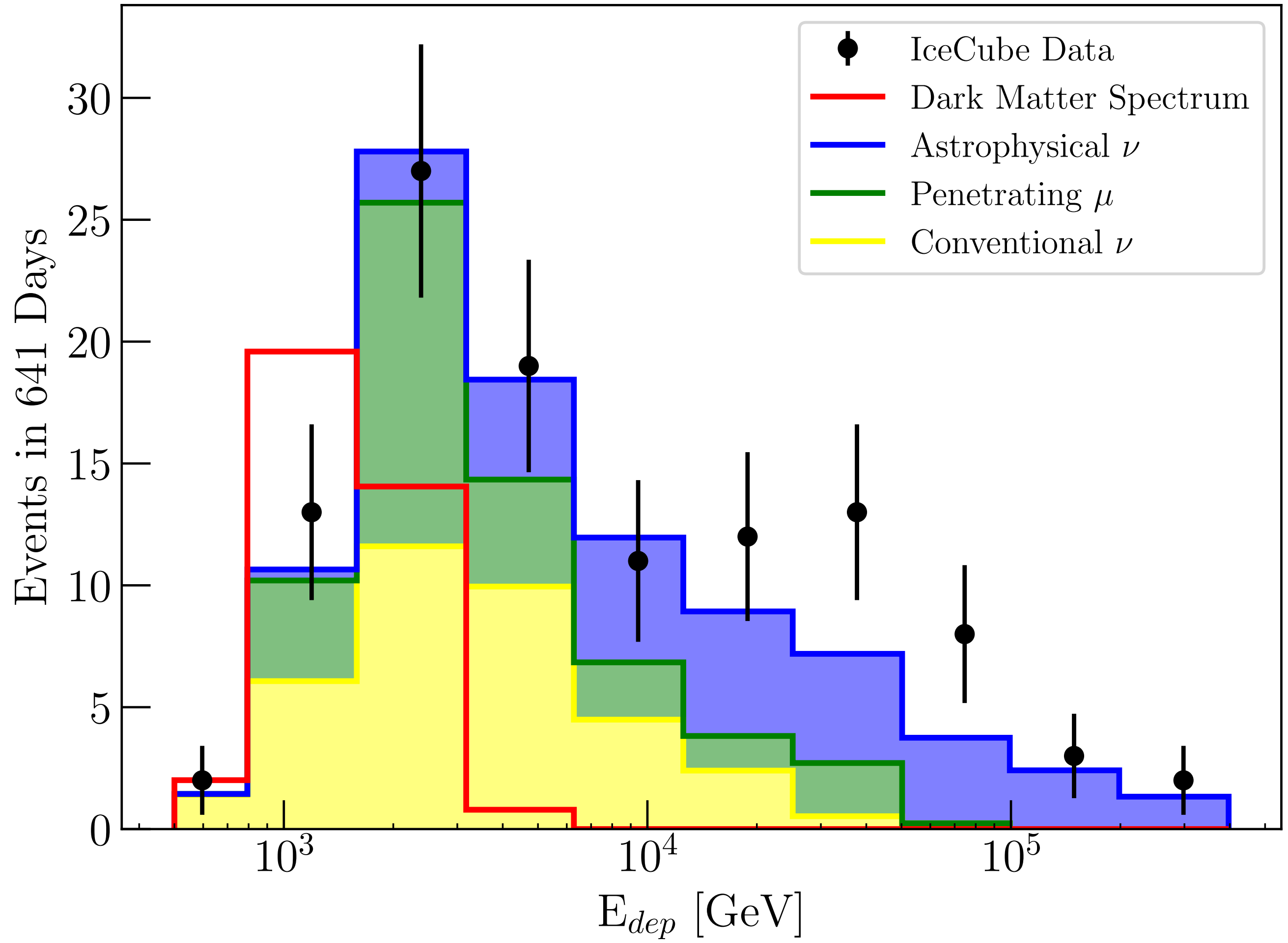
- **What are the possible astrophysical & cosmological signatures/ constraints?**

- **Are there any implications from flavor specific models?**

Thank you

Extra slides

Fits to low energy **IceCube** data



Vector mediator with $m_\chi = 1$ keV, $g_\chi g_e = 1$ & $m_z = 1.16$ GeV

BDM relic abundance

Annihilation processes (s-wave): $\chi_A \overline{\chi}_A \to \chi_B \overline{\chi}_B, \;\; \chi_B \overline{\chi}_B \to XX$

Coupled Boltzmann Eqn:

$$\frac{dn_A}{dt} + 3Hn_A = -\frac{1}{2} < \sigma_{A\overline{A}\to B\overline{B}} v > \left(n_A^2 - \frac{(n_A^{eq})^2}{(n_B^{eq})^2} n_B^2 \right)$$

$$\frac{dn_B}{dt} + 3Hn_B = -\frac{1}{2} < \sigma_{B\overline{B}\to XX} v > \left(n_B^2 - n_B^2 \right) - \frac{1}{2} < \sigma_{A\overline{A}\to B\overline{B}} v > \left(n_B^2 - \frac{(n_B^{eq})^2}{(n_A^{eq})^2} n_A^2 \right)$$

χ_A and χ_B decouple when $<\sigma_{B\overline{B}\to XX} v> \;\gg\; < \sigma_{A\overline{A}\to B\overline{B}} v >$

and $\Omega_A h^2 \gg \Omega_B h^2$

$$\Omega_A h^2 \sim 0.2 \left(\frac{5 \times 10^{-26} cm^3/s}{< \sigma_{A\overline{A}\to B\overline{B}} v >} \right) \longrightarrow < \sigma_{A\overline{A}\to B\overline{B}} v > \sim 5 \times 10^{-26} \; cm^3/s \left(\frac{m_A}{20GeV} \right)^2 \left(\frac{250GeV}{\Lambda} \right)^4$$

Background Reduction

Largest background for GC search is atmospheric neutrinos

Good angular resolution helps with background reduction

$$\theta_C \sim \max\{10^\circ, \theta_{res}\}$$

For the Sun

$$\theta_C \sim \theta_{res}$$

$$\frac{N_{BG}^{\theta_C}}{\Delta T} = \frac{1-\cos\theta_C}{2}\frac{N_{BG}^{allsky}}{\Delta T}$$

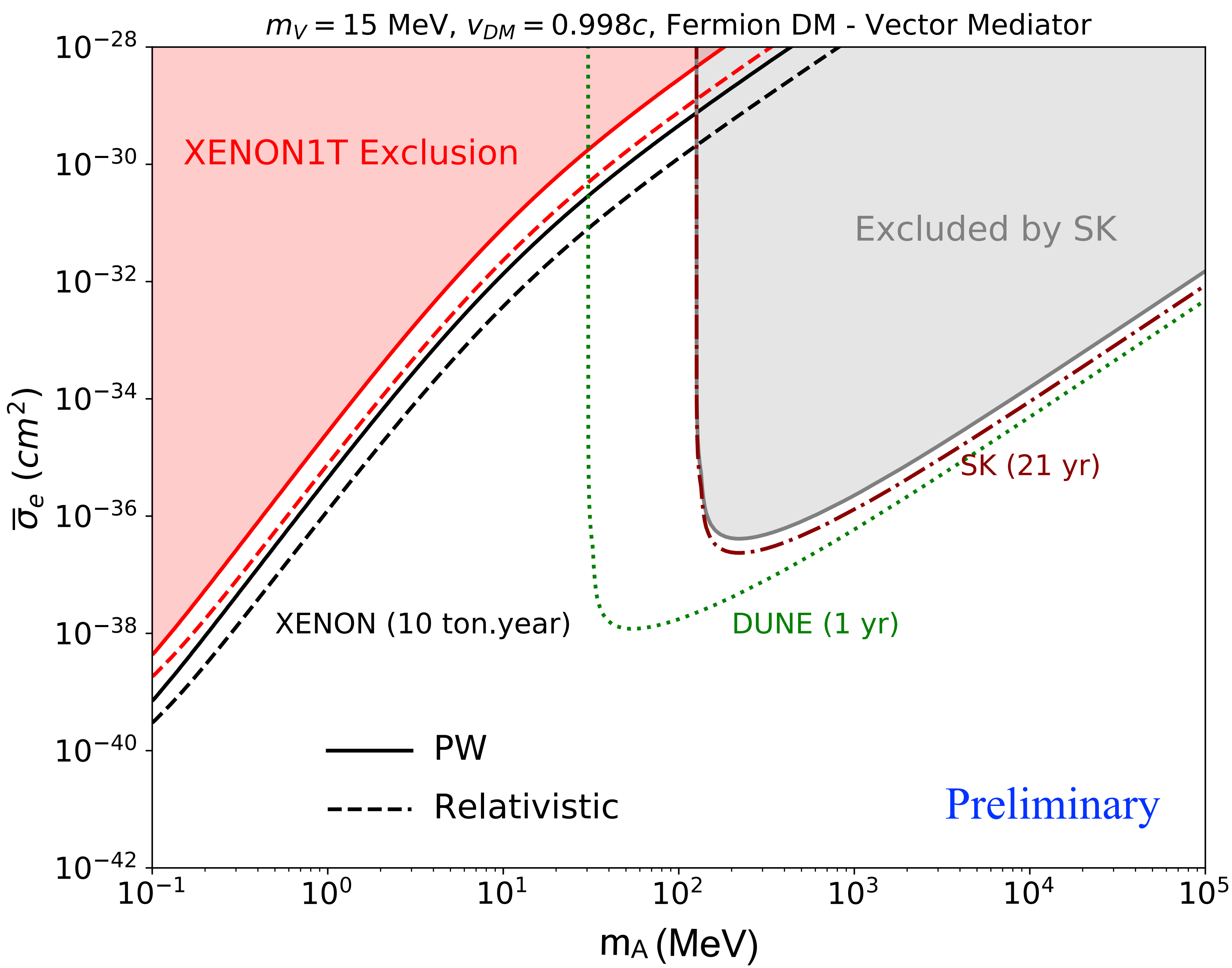
Experiment	Volume (MTon)	Ethres(GeV)	res(deg)
Super-K	0.0224	0.1	3
Hyper-K	0.56	0.1	3
PINGU	0.5	1	23
DUNE	0.04	0.03	1

Background Events

$$\frac{N_{BG}^{\theta_C}}{\Delta T} = \#\ \text{events/yr}$$

	DUNE 10	DUNE 40	SK	HK
GC	1 with 10°	4 with 10°	7.01 with 10°	174 with 10°
Sun	0.01 with 1°	0.04 with 1°	0.632 with 3°	15.7 with 3°

At higher velocities



Alhazmi, Kim, Kong, Mohlabeng, Park, Shin: **In Progress**