# Direct Detection of Low Mass Fast Moving Dark Matter

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**JHEP 05 (2021) 055 & arXiv:22XX.XXXX**

**Mitchell Conference**

24 May 2022

# Outline

1. Current status of dark matter direct detection.

2. Motivation for low mass fast moving dark matter

3. Specific e.g. Boosted dark matter

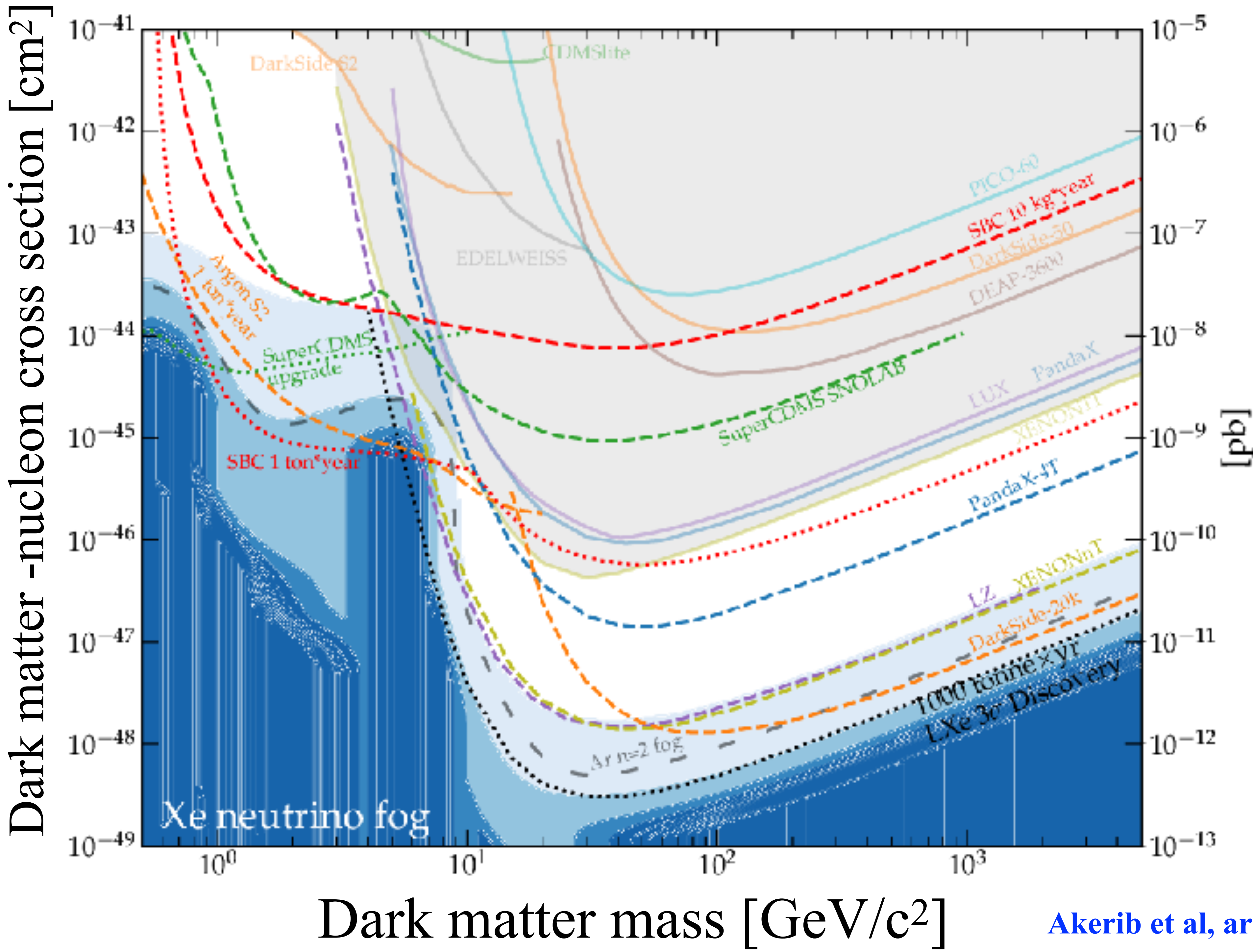
   - Boosted dark matter - electron scattering

   - Atomic effects

     i.e Atom ionization form-factors important when calculating rates & setting limits

4. Conclusion and outlook

# Current status of DM direct detection



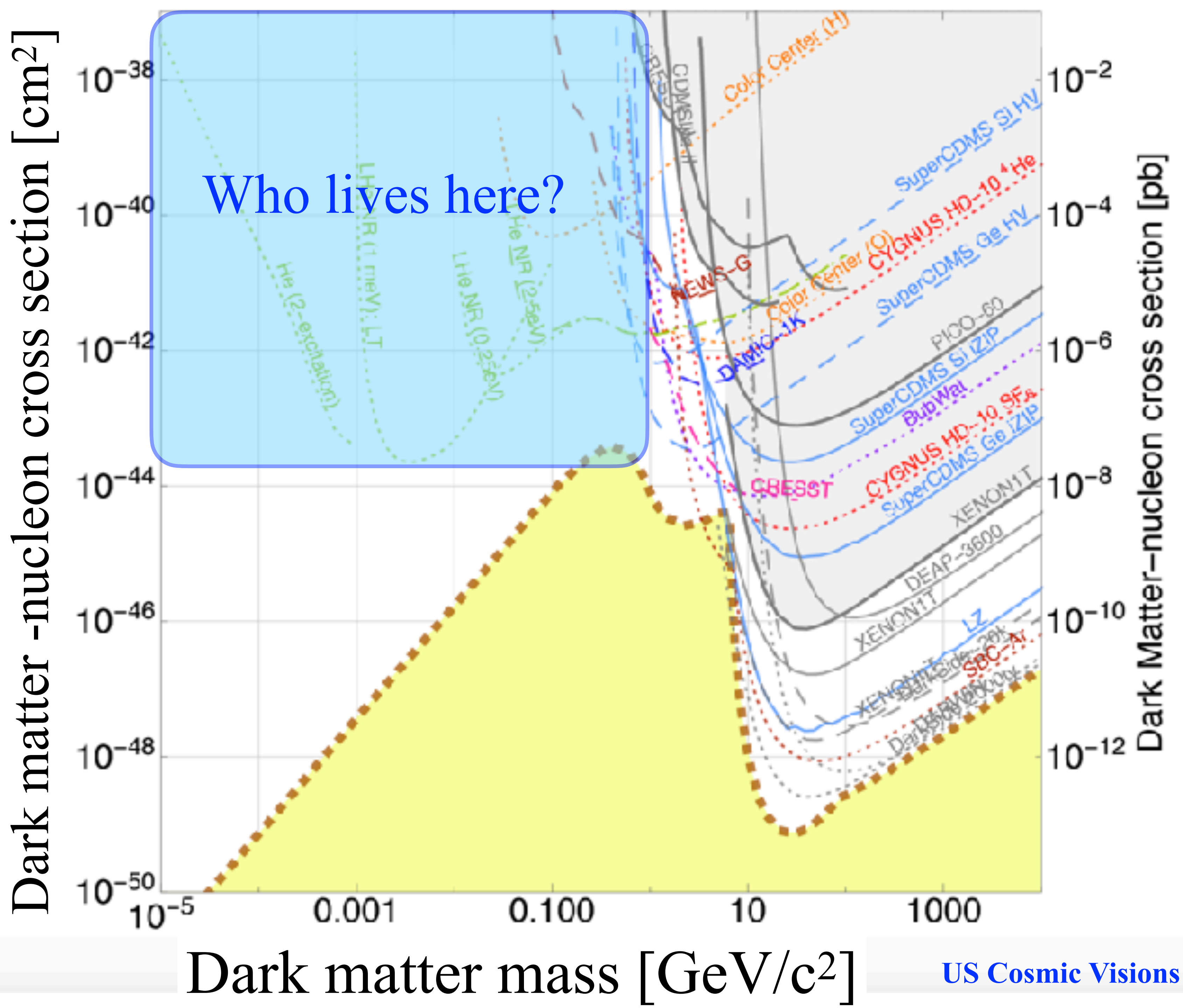

**Akerib et al, arXiv: 2203.08084**

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



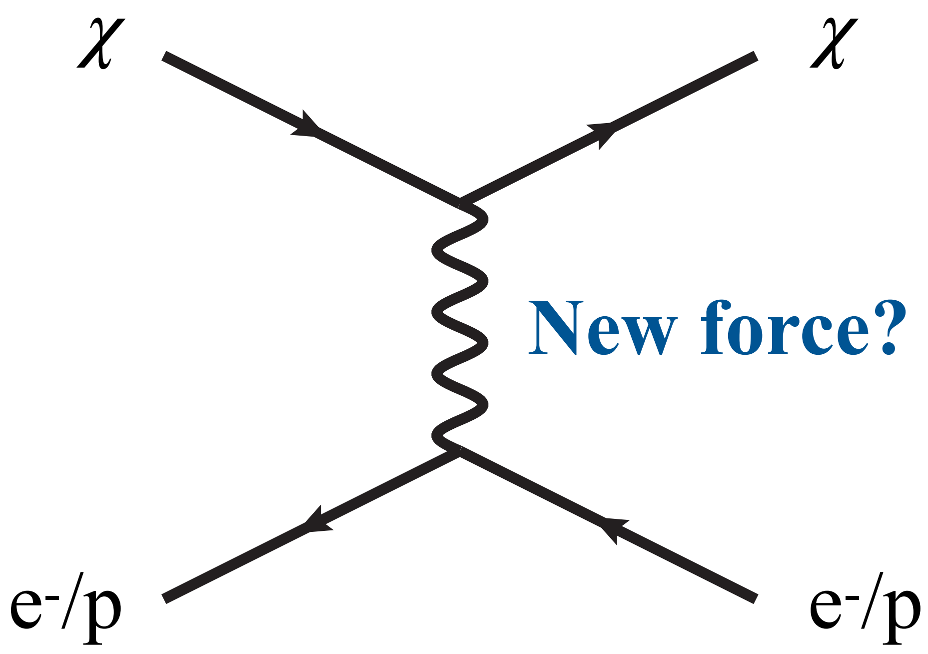

US Cosmic Visions Report, arXiv:1707.04591

Many opportunities to explore here

Low mass (sub-GeV) DM searches are:

1. Complementary to WIMP searches

2. Very well motivated:



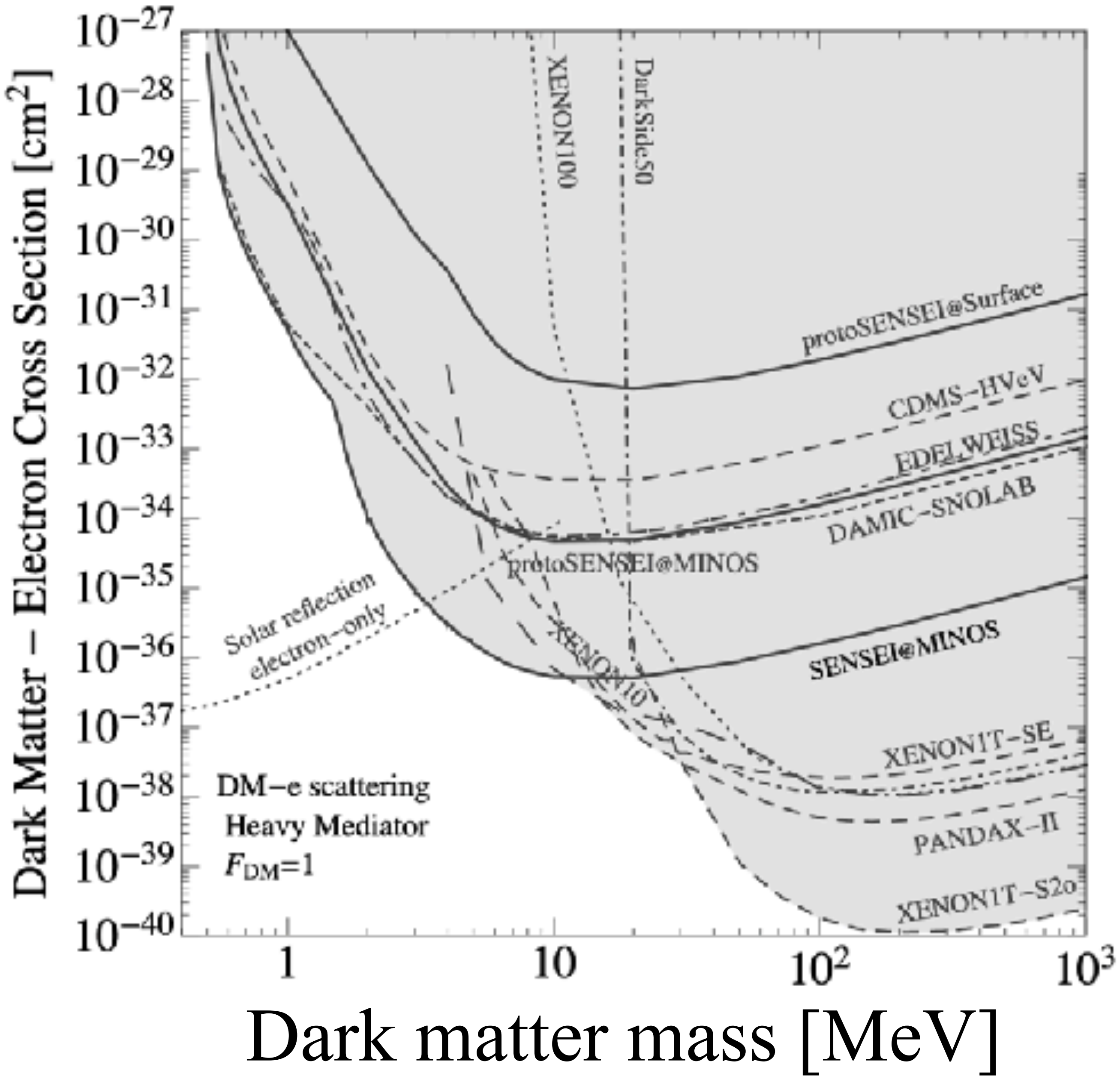

e.g. low mass DM coupled through new hidden sector mediator presents a good target to understanding DM production in the early universe

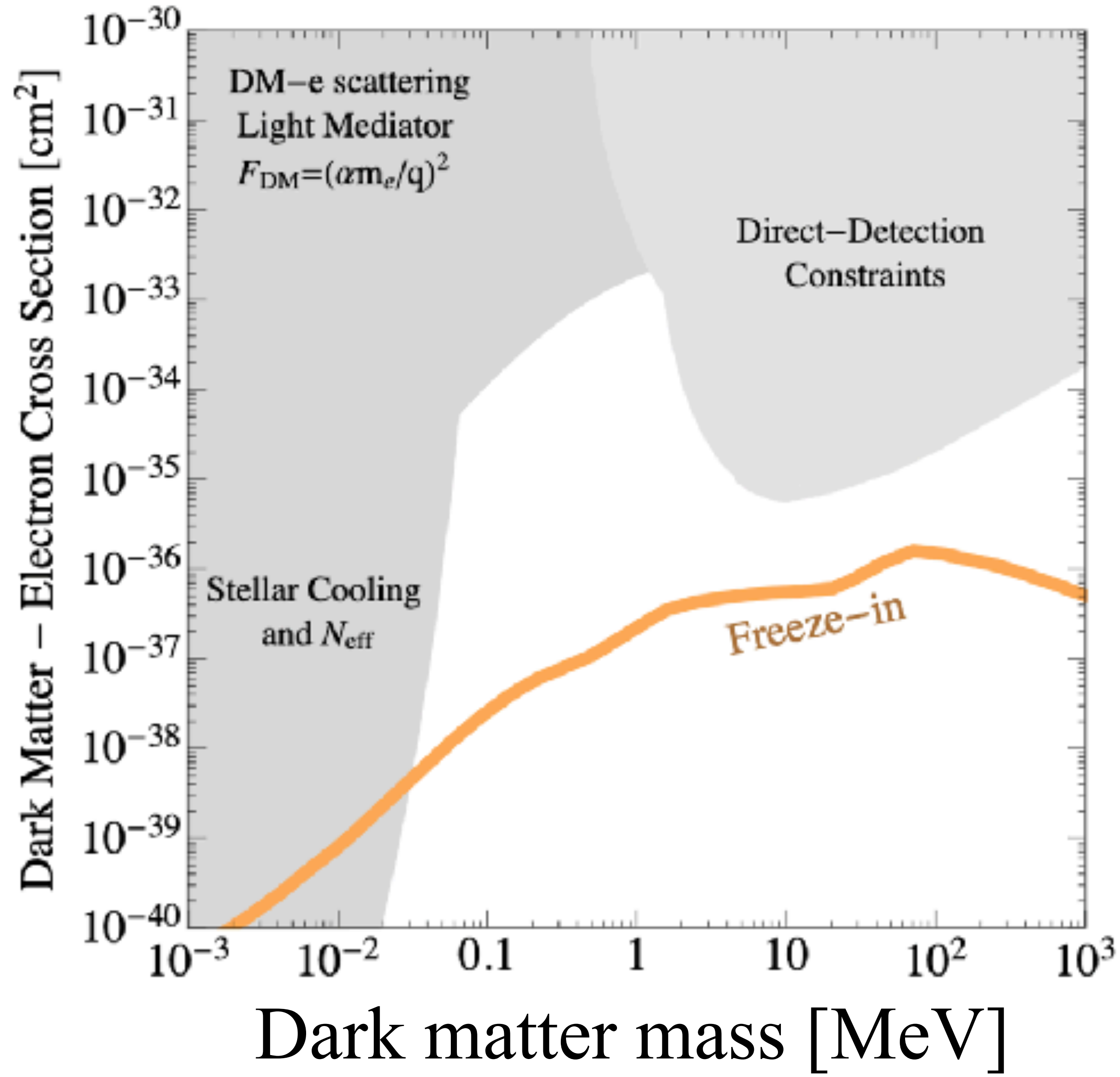
- Thermal freeze-out
- Freeze-in
- Asymmetric

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

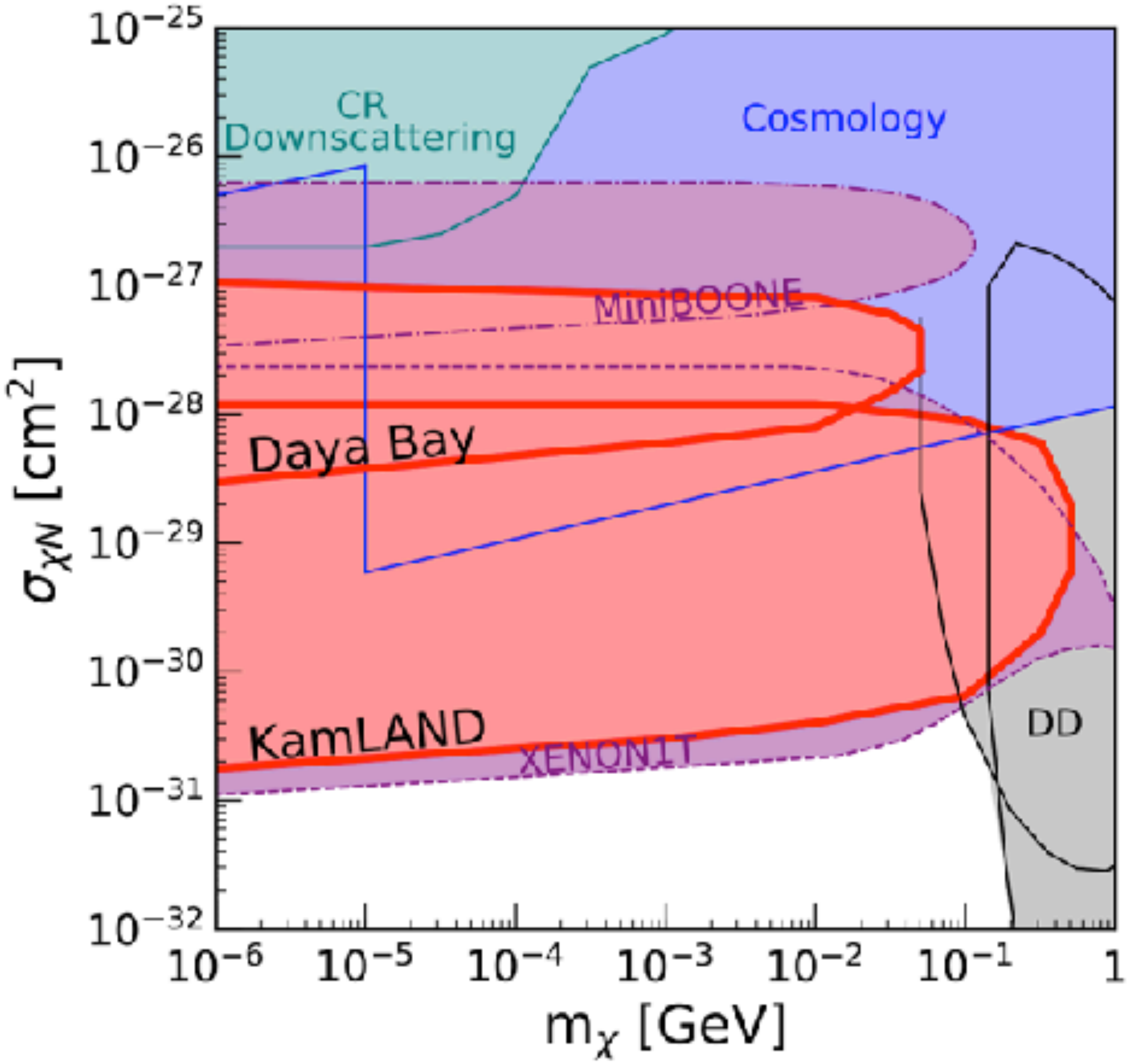
## Many ways to get accelerated dark matter

# Cosmic ray accelerated dark matter

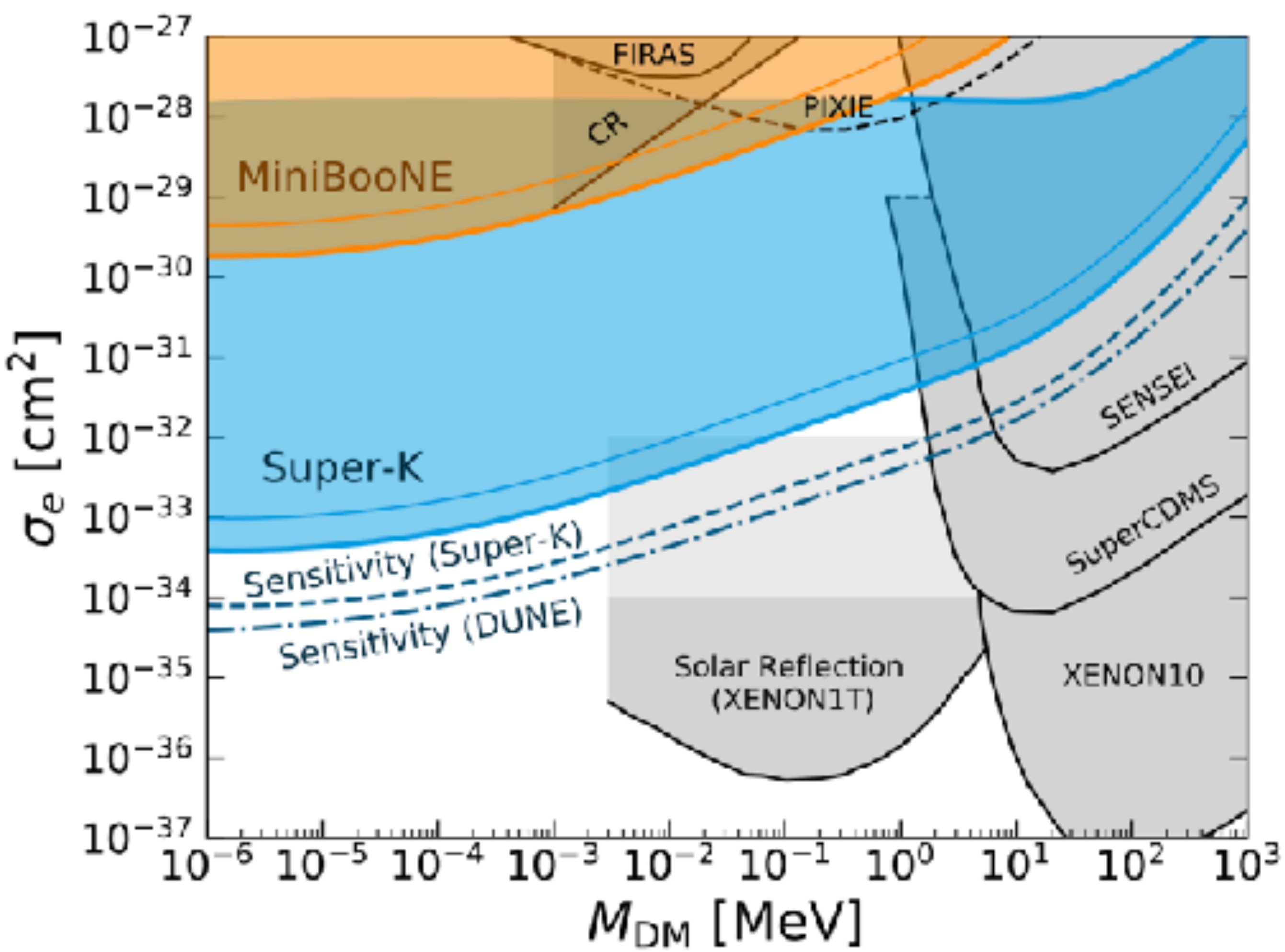
- High energy CR can scatter off DM moving at $v \sim 10^{-3}$ c

- 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**

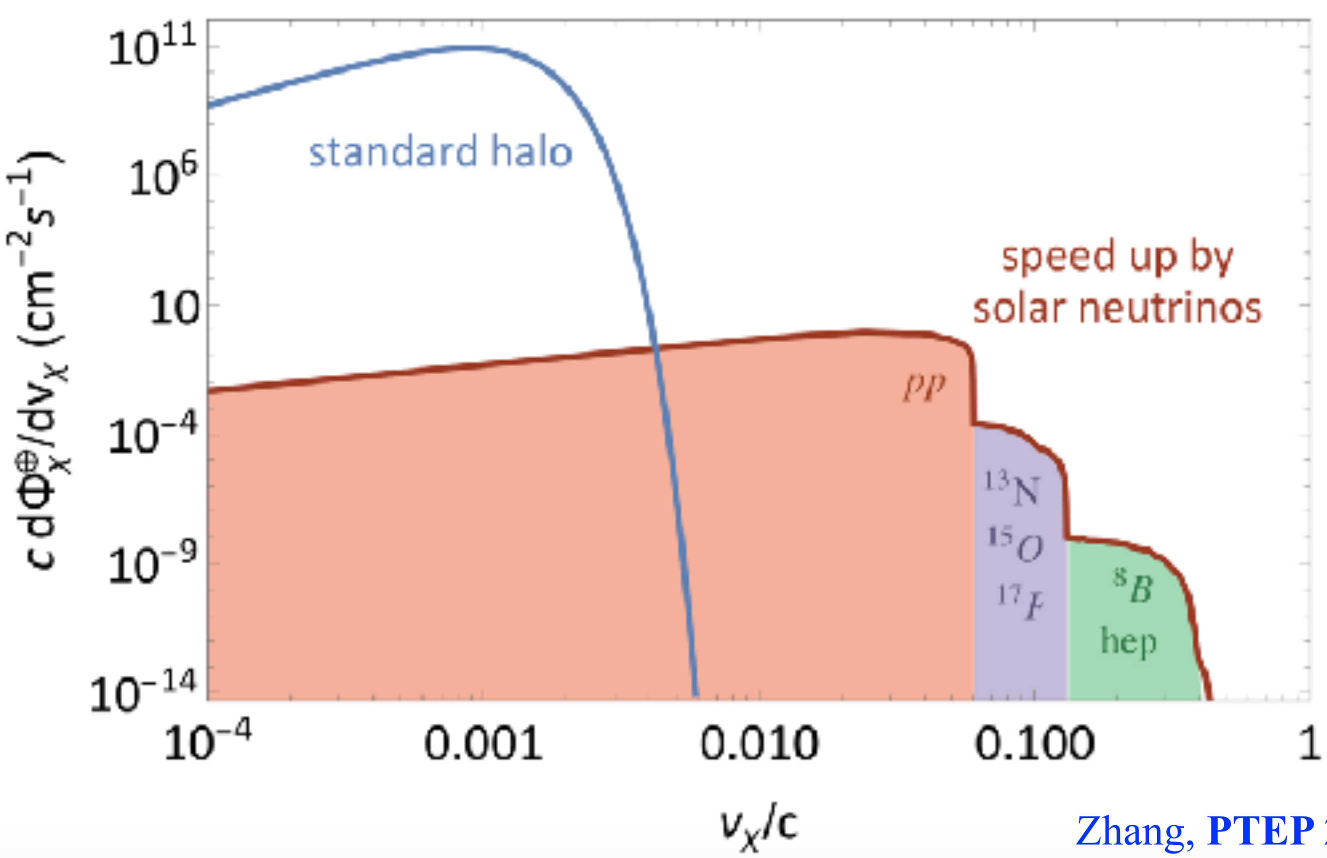
Krnjaic, McDermott : **Phys.Rev. D101 (2020) 12, 123022** + many others

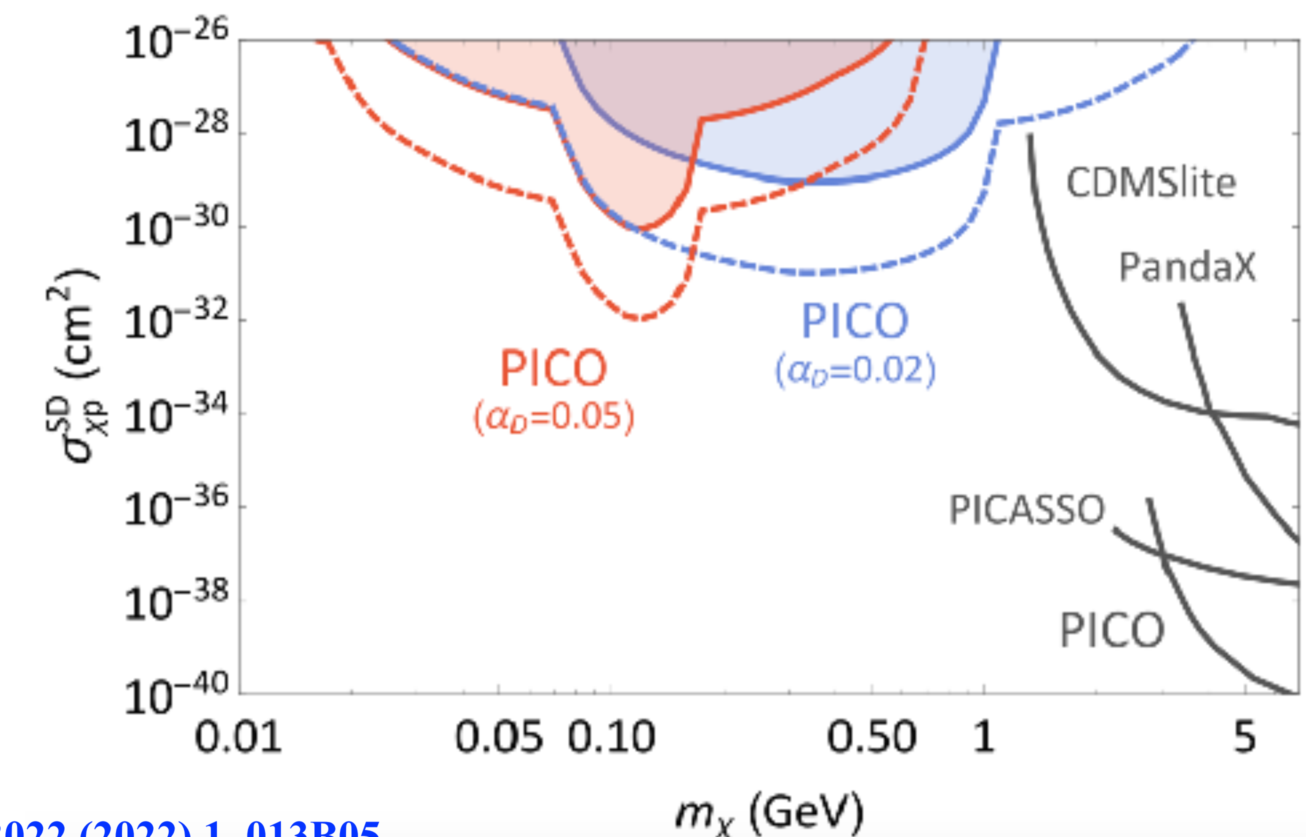
# Neutrino accelerated dark matter

- e.g. Solar neutrinos can scatter off DM moving at $v \sim 10^{-3}$ c

- After interaction, DM obtains velocity: $v_\chi \sim \dfrac{2E_\nu}{m_\chi} cos\theta$

- DM enters detector, transferring to target energy : $E_{nr} \lesssim \dfrac{2E_\nu^2}{m_N}$




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**

Primordial Black hole neutrino upscattering:

Chao et al, **arXiv: 2108.05608**

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

# A different mechanism…

Consider non-minimal Dark sector

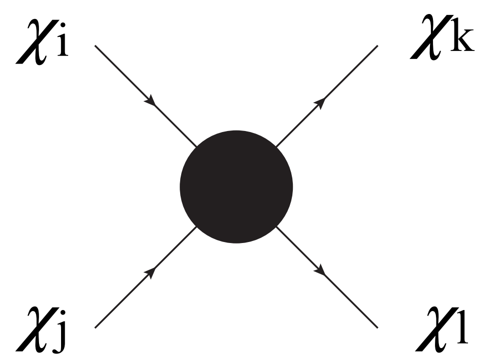
**Generic feature** of any non-minimal dark sector: small fraction of DM today may be relativistic/semi-relativistic

## Sources:

- **Assisted Freeze-out**:

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

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

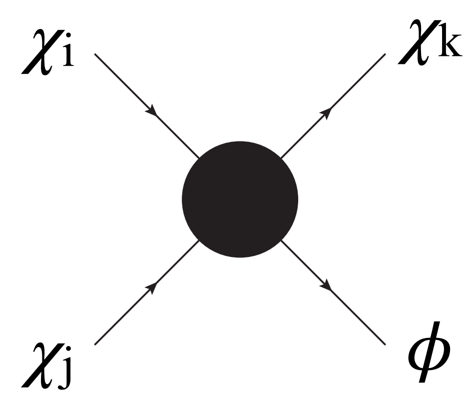



Belanger and Park : **JCAP 03 (2012) 038**

- **Semi-annihilation**:

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

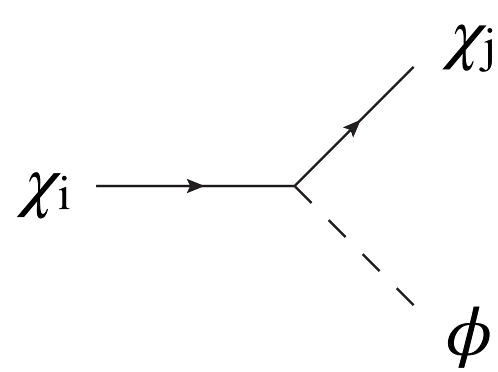
  , $Z_3$ DM symmetry




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

- **Decay**: (e.g inelastic DM)

  $\chi_i \to \chi_j \phi$



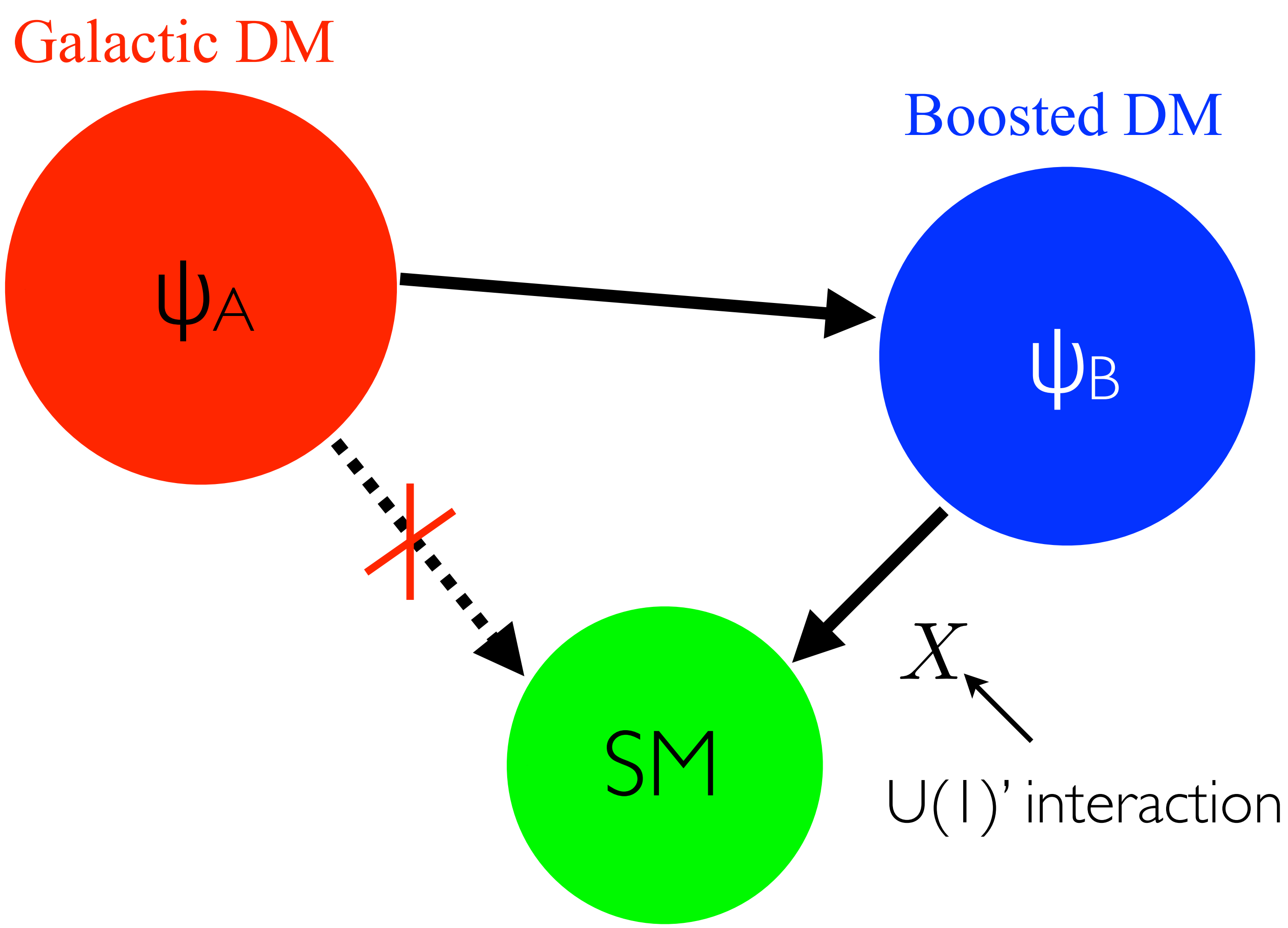

Tucker-Smith & Weiner: **Phys.Rev. D64 (2001) 043502**

+ **many others**

# Boosted dark matter

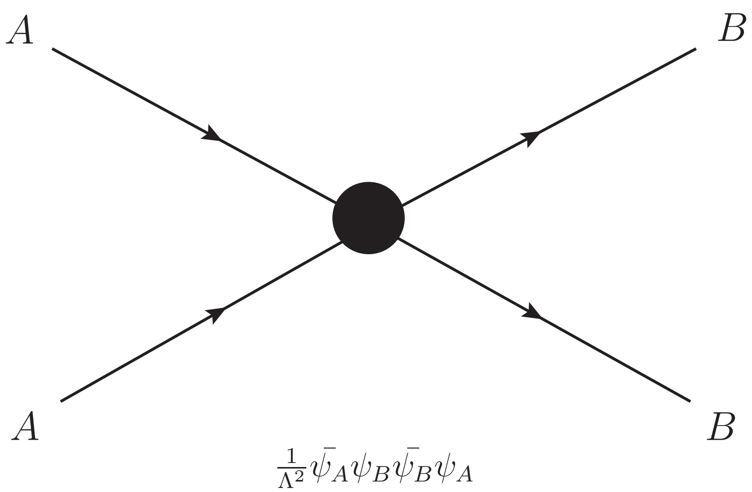
- Two stable DM particle, $\psi_A$ & $\psi_B$ with $m_A > m_B$ $(eg. U(1)' \otimes U(1)'')$

**For example:**




- $\psi_A$ is the dominant DM component and has no direct coupling to SM

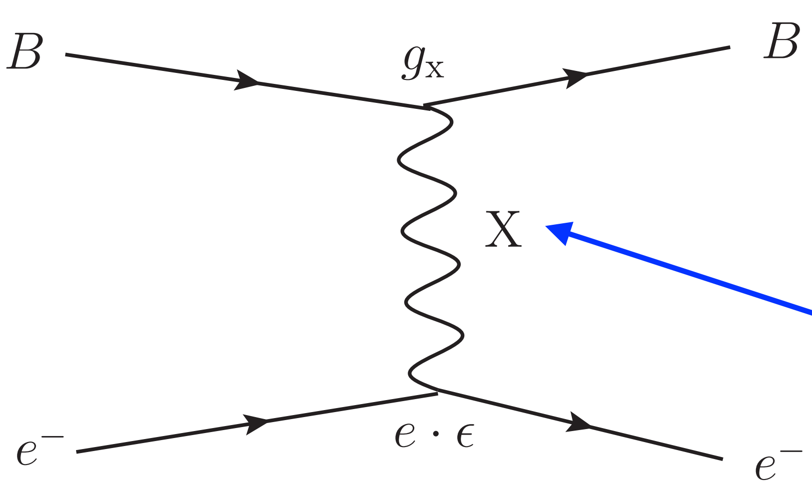
- $\psi_B$ is sub-dominant and couples to SM through new force




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

- '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**

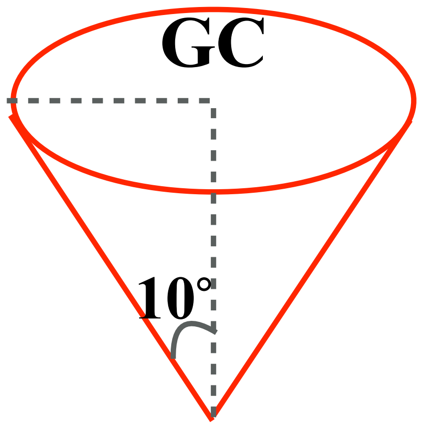
Necib et al: **Phys.Rev. D95 (2017) 7, 075018**

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

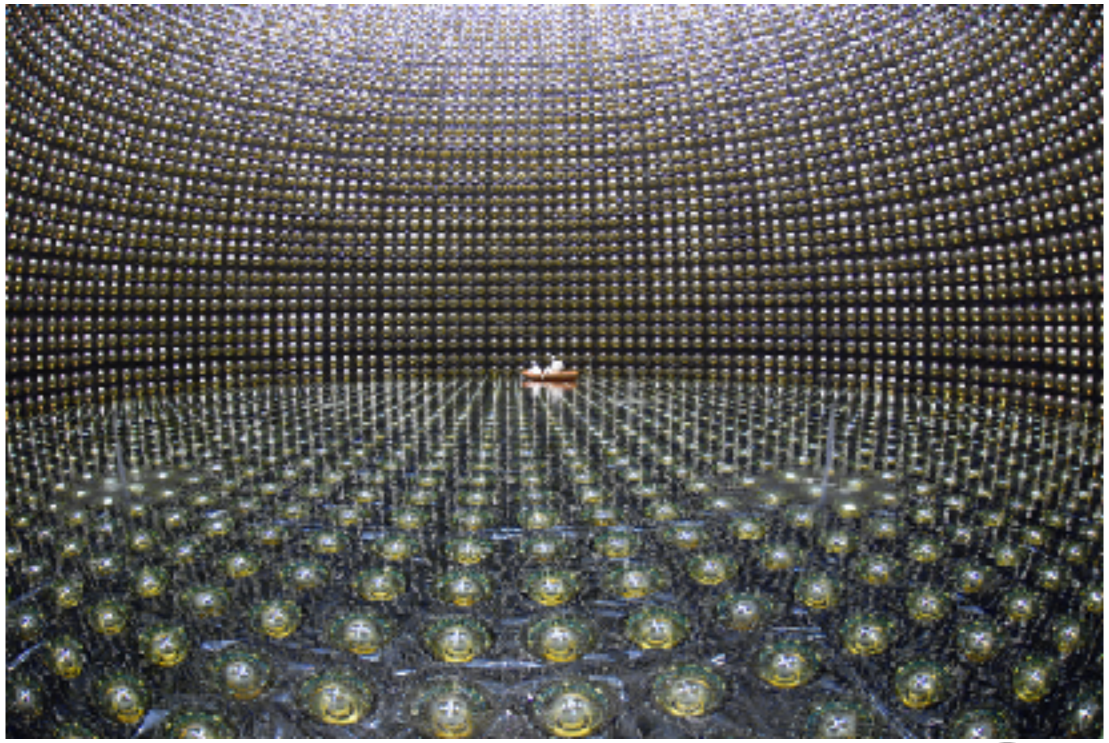
**Neutrino detectors:** Super-K, Hyper-K, Ice-Cube, DUNE

**Dark matter detectors:** XENON1T, DarkSide

Focus on electron scattering

For nucleon scattering:

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

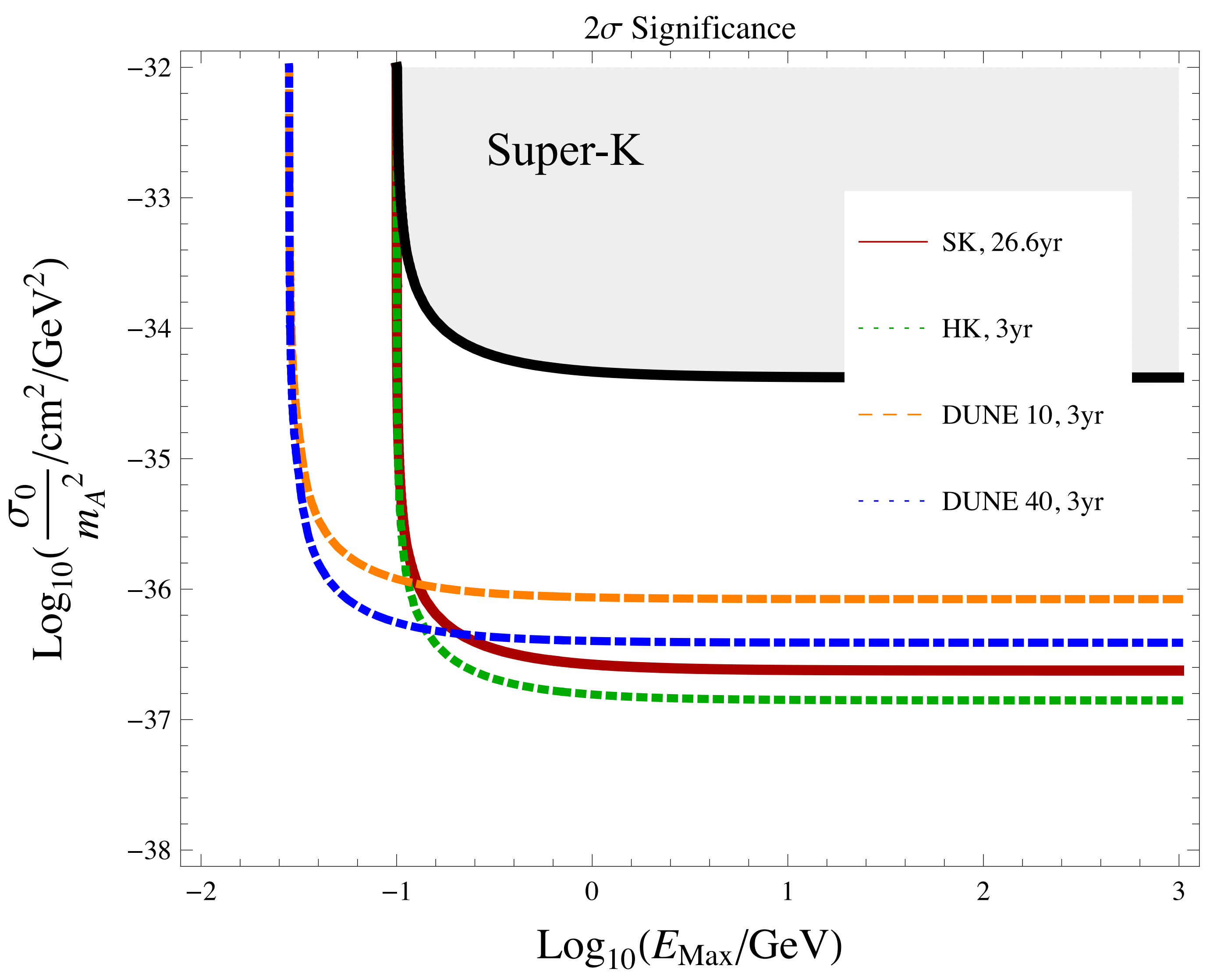


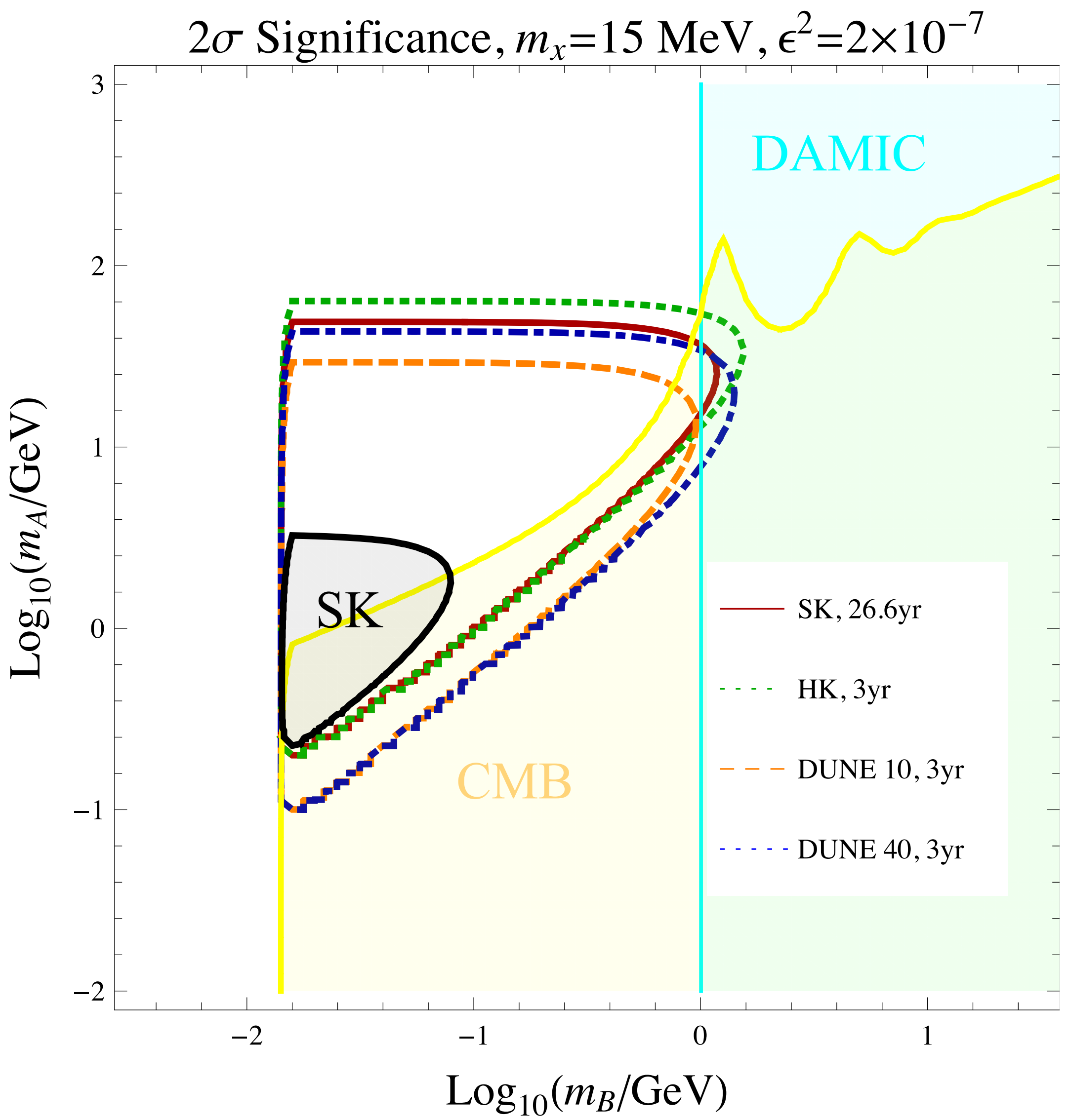
# Boosted DM from the Galactic Center

2$\sigma$ sensitivity:

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

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




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

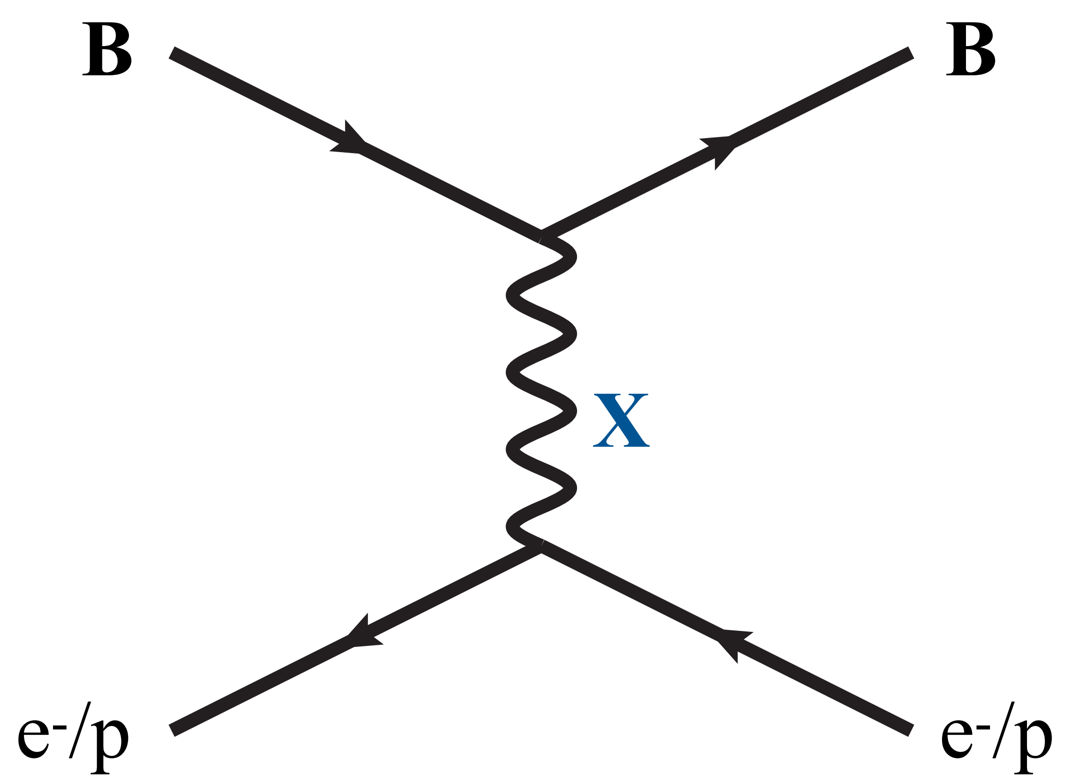
# Direct DM detector search for GC BDM

- Large volume DD experiments can look for lower A masses

XENON1T
DarkSide
…

Lower threshold than neutrino detectors

Scattering with either nucleon or electrons

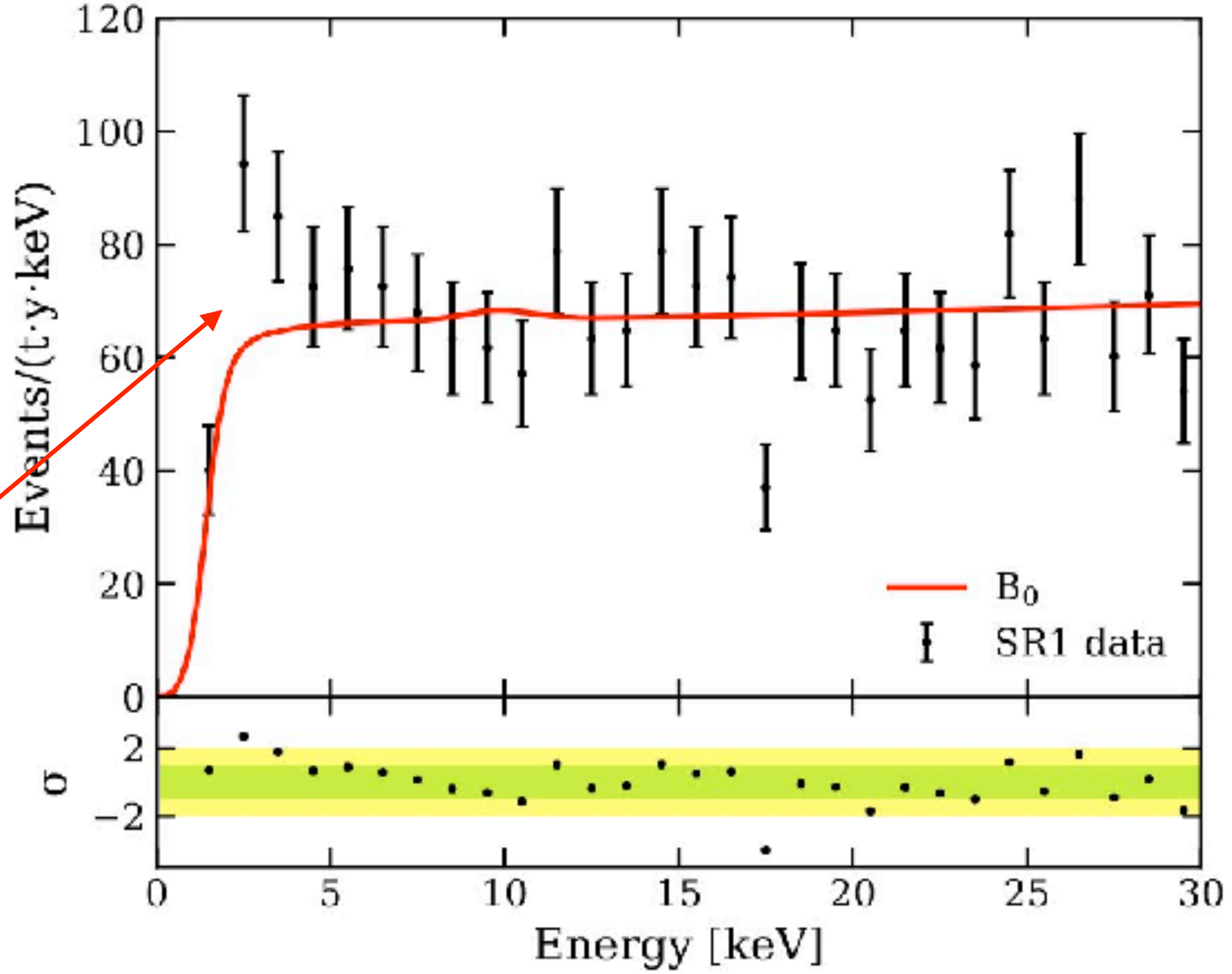



Focus on electron scattering

# Direct DM detector search for GC BDM

Recently, XENON1T reported an excess of electron scattering events

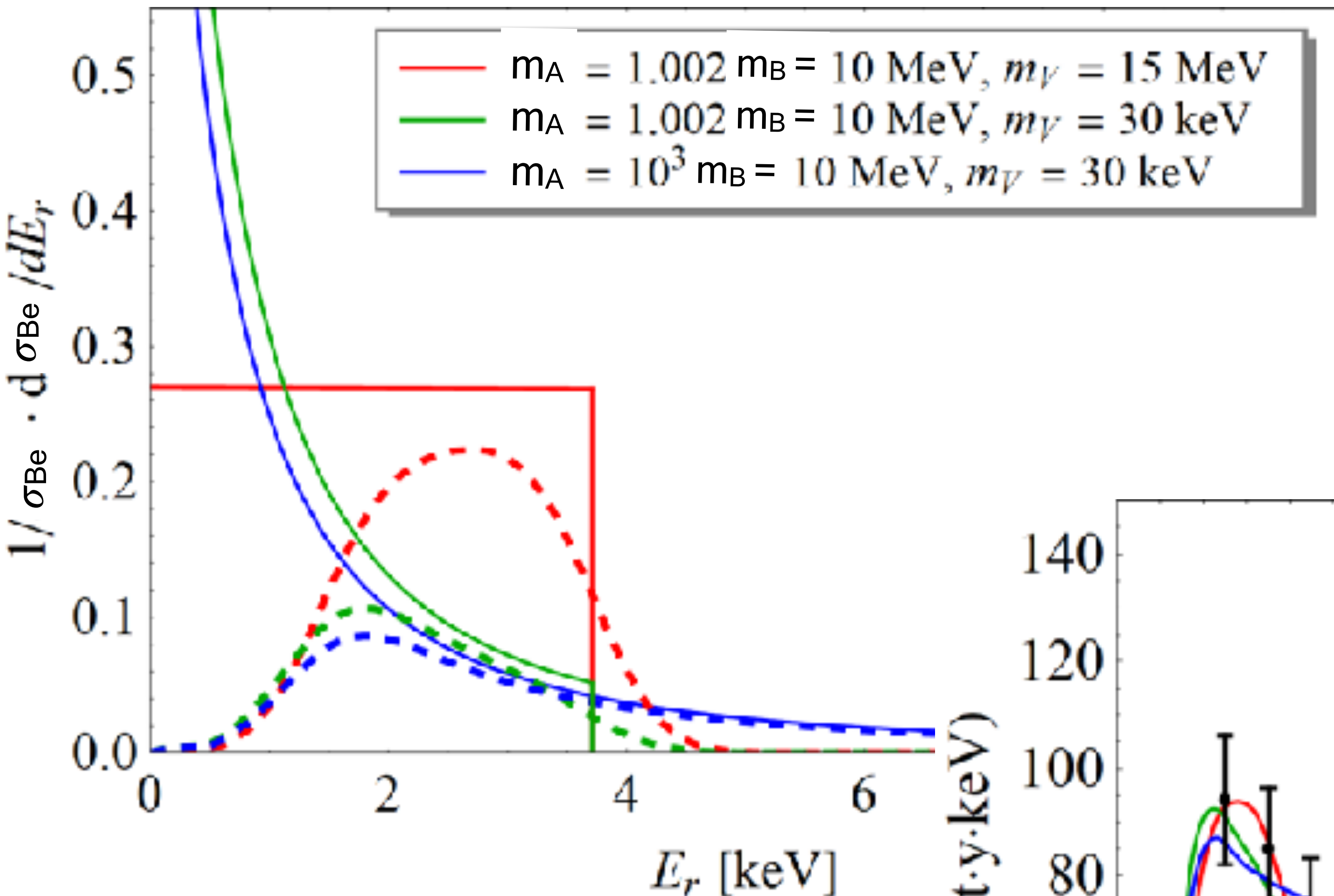
Excess at ~2-3 keV recoil energies




XENON1T collaboration: **Phys. Rev. D102 (2020) 7, 072004**

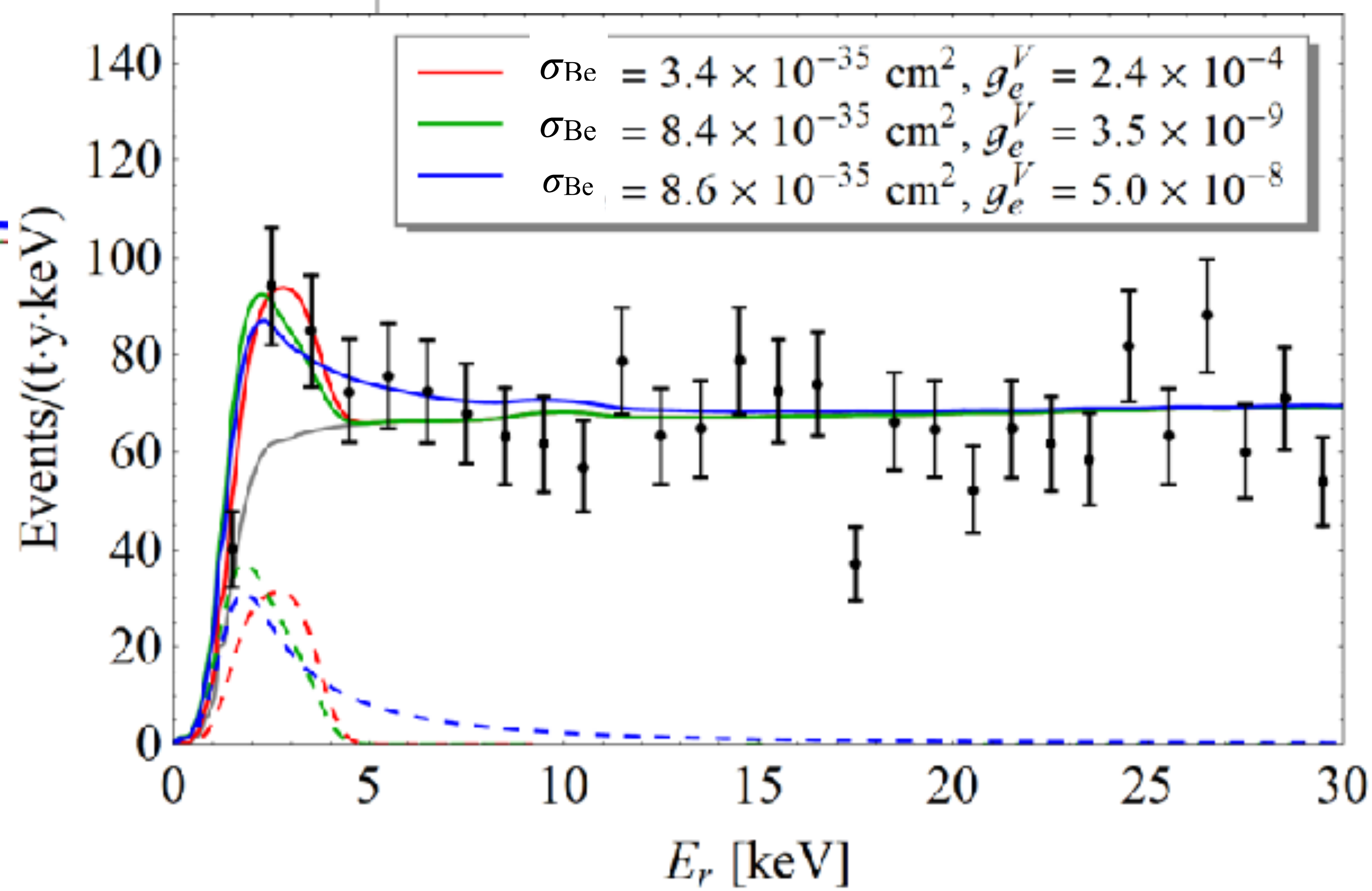
BDM framework can explain excess

# For Fermion DM with a vector mediator




$$v_B = \sqrt{1 - \frac{m_B^2}{m_A^2}}$$

$\sim 0.06$c




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

Recoil rates:

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

BDM flux

Scattering cross-section

Effective # of electrons

exposure time

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

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

# of Xenon atoms in volume

Differential scattering cross-section

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

- Bound electrons have non-negligible momentum dependence

- Ionization function takes into account electron momentum dependence

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

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

free electron wave-function

bound electron wave-function

- 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

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

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

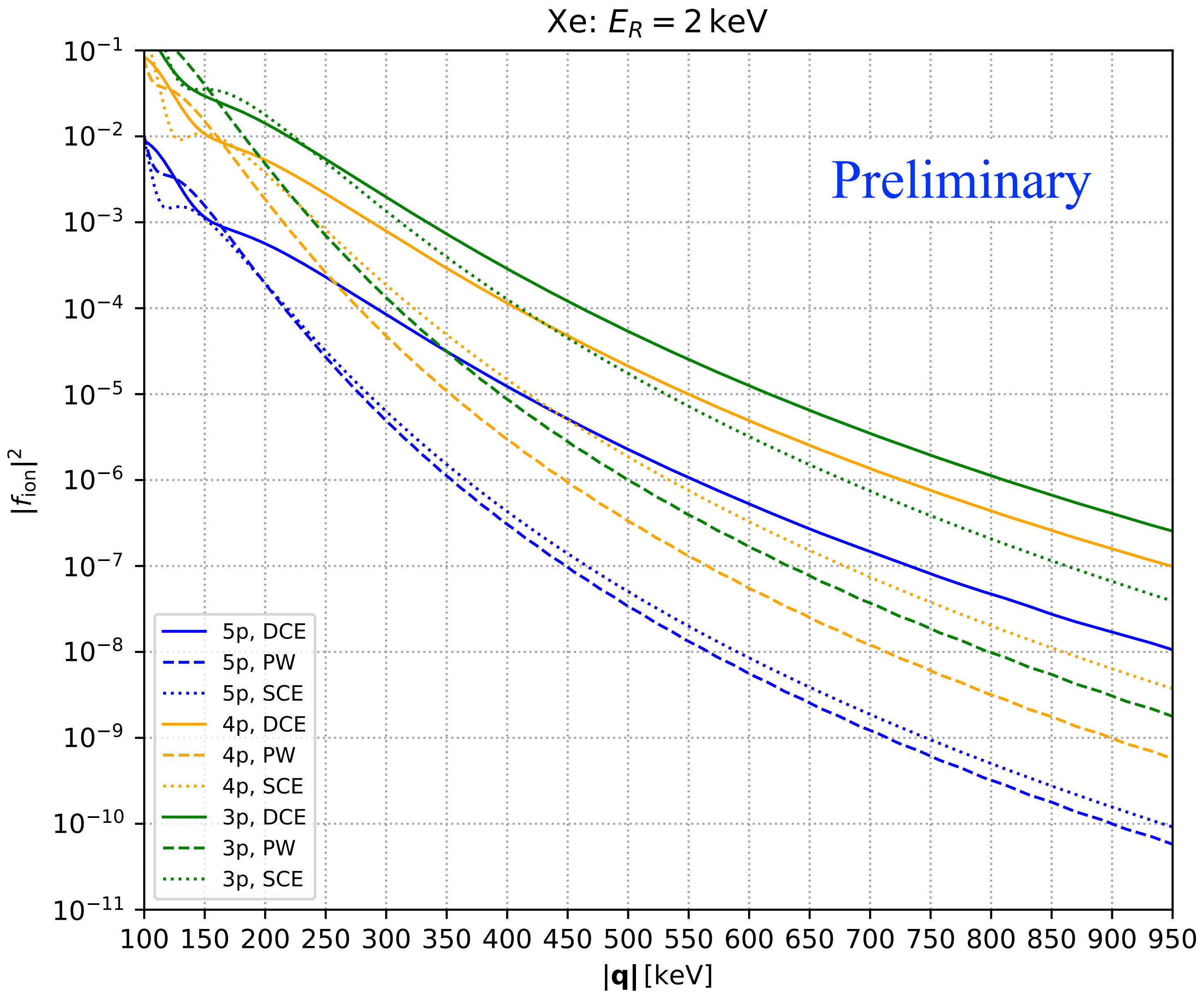
Cao et al: Chin**. Phys. C 45 (2021) 4, 045002** + many others

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

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

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

- accounts for Lorentz structure of DM - e interactions




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

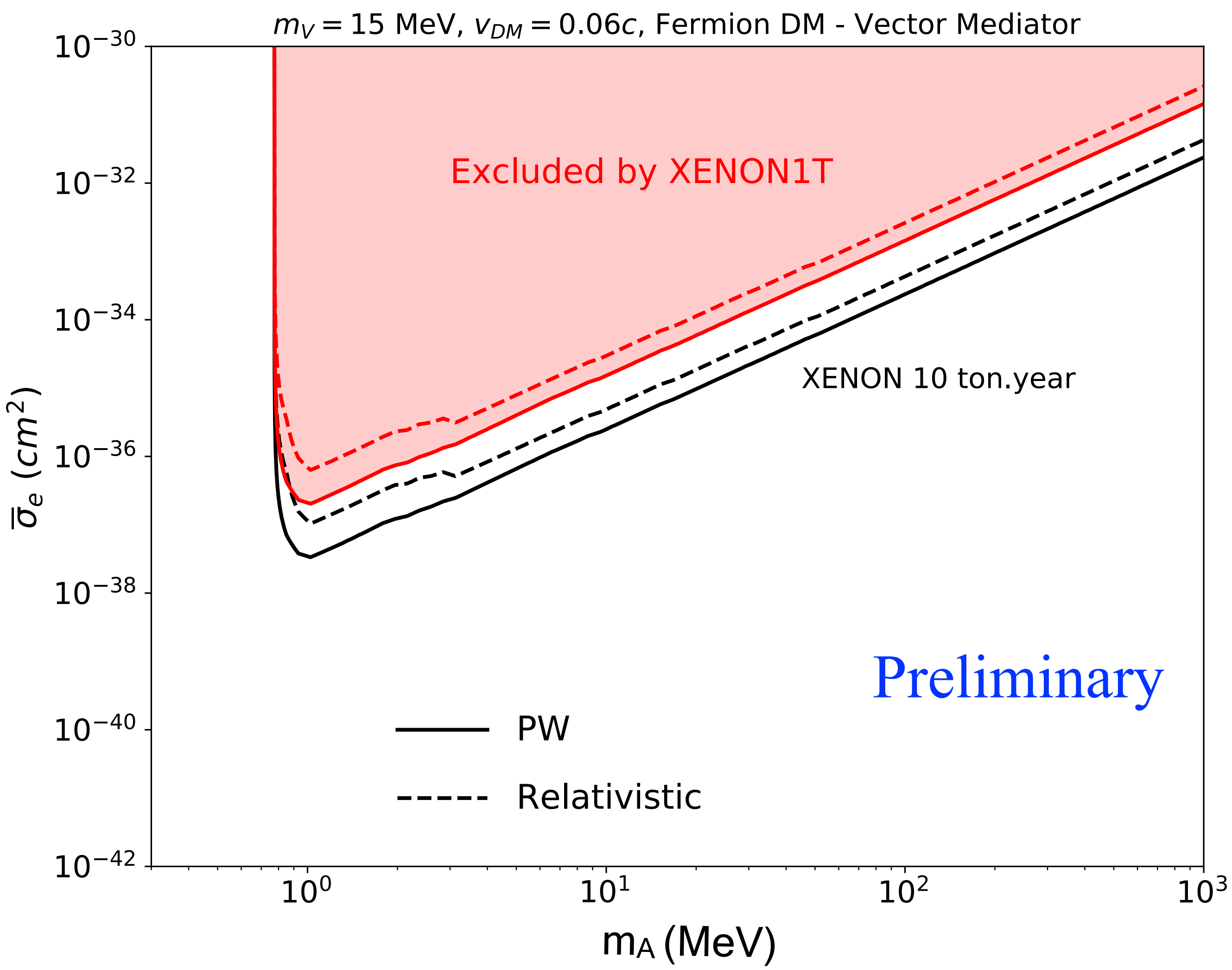
Roberts, Flambaum: **Phys. Rev. D 100 (2019) 063017**

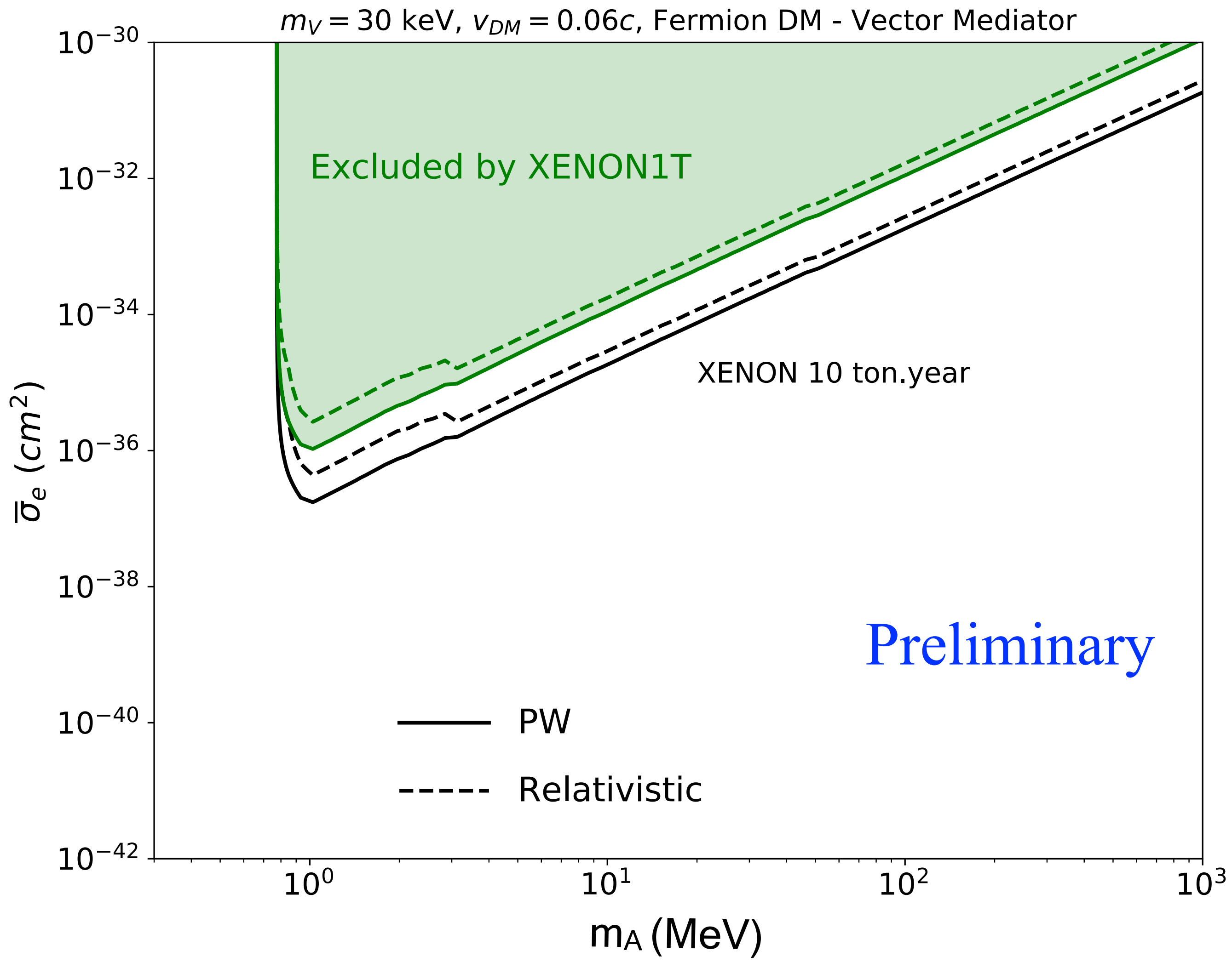
At high momentum transfer, relativistic & PW are different

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

# Some Limit plots

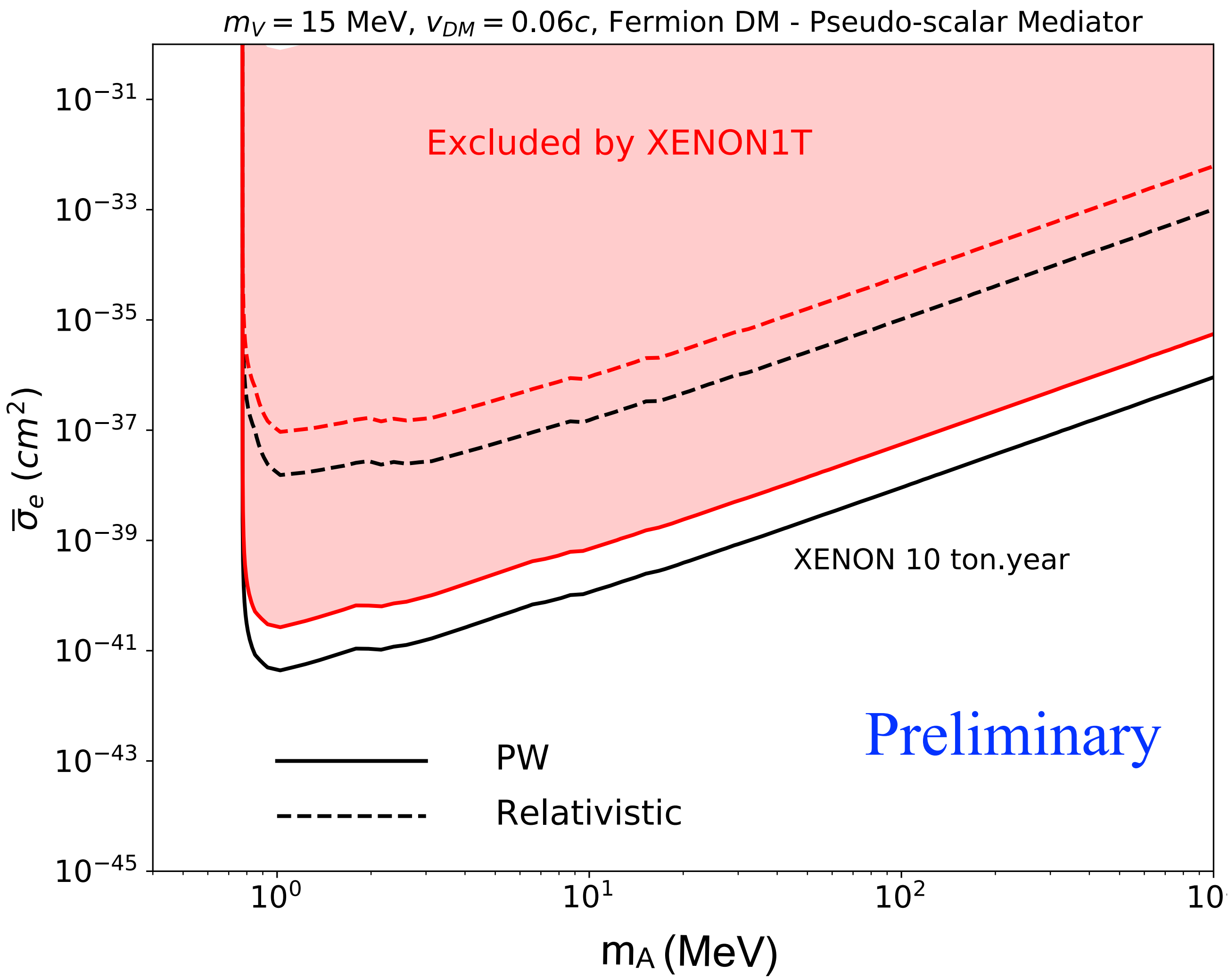
## Fermion Dark Matter with a vector mediator

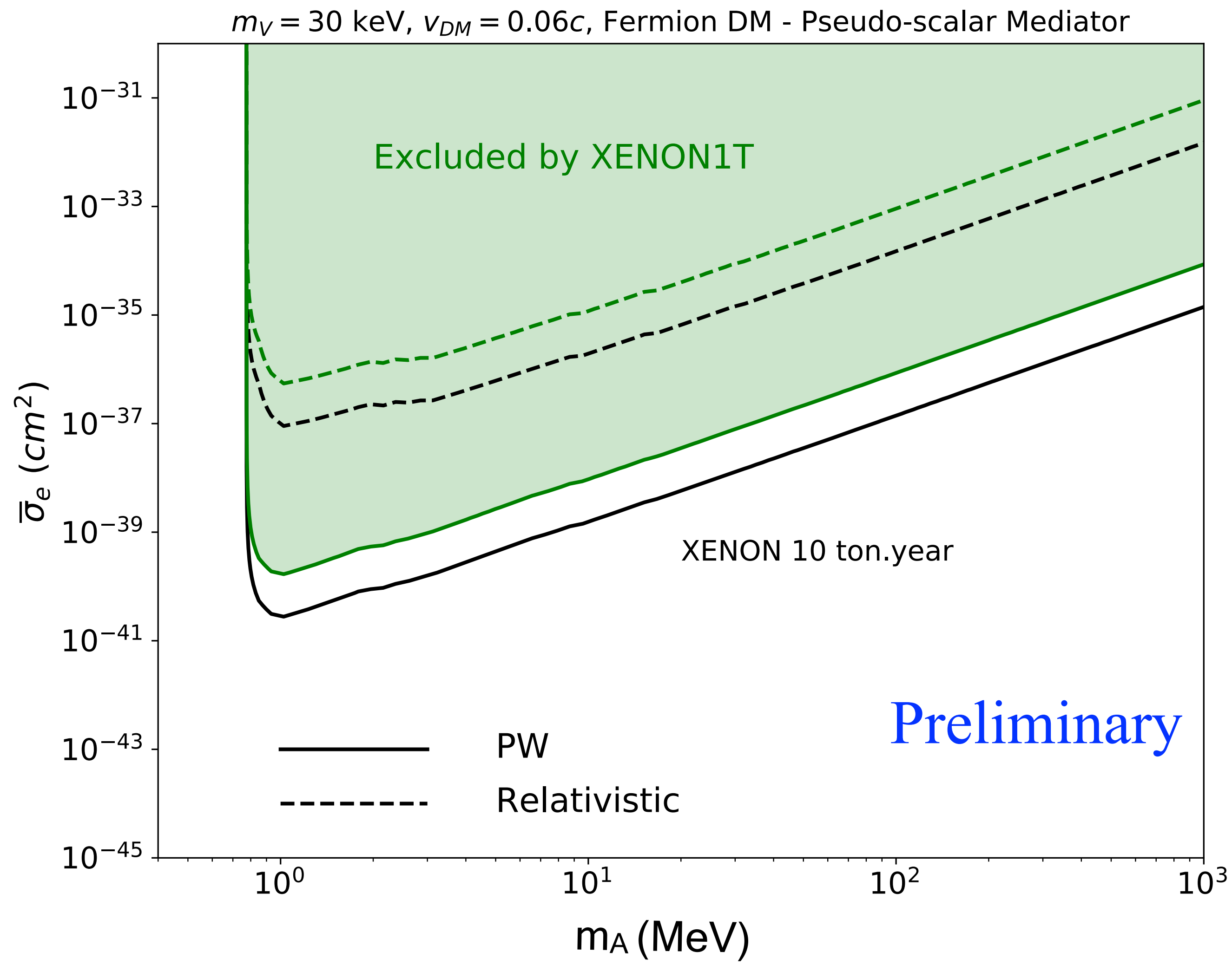



Alhazmi, Kim, Kong, Mohlabeng, Park, Shin: **In Progress**

# Fermion Dark Matter with a pseudo-scalar mediator




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

# Outlook

Accelerated DM is interesting phenomenological prospect

Can give striking signals at large volume neutrino detectors

Can explain excess seen at direct detection experiment: XENON1T

Atomic effects can be important for very fast moving DM

Ongoing work, need to include other limits

Xenon100, Xenon10, Darkside50, Super-K, BBN?

Working on examining ionization effects from other accelerated DM scenarios

Cosmic-ray up-scattered DM

Neutrino up-scattered DM

Thank you

Back UP

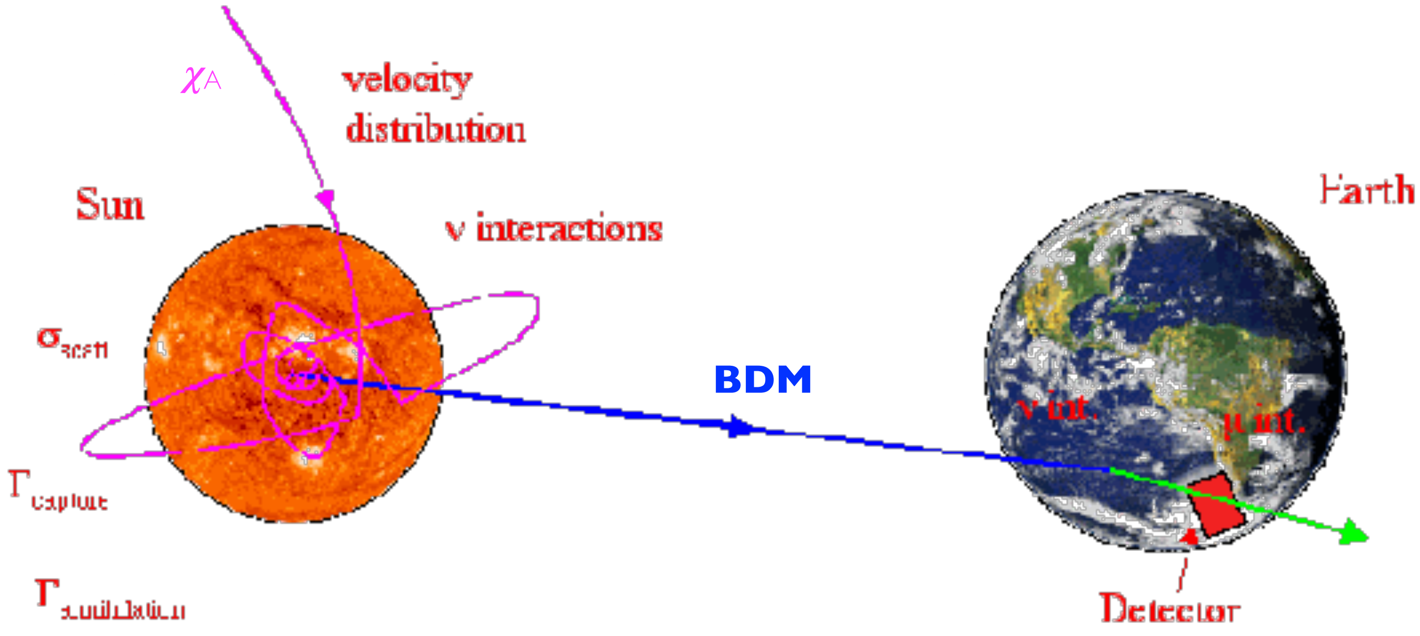
## What about a point source closer to us, i.e. The Sun?

$\chi_A$ can get captured in the Sun and annihilate to $\chi_B$

$\chi_B$ 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 $\chi_A$ number density in the Sun is

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

***Cc***: capture rate by nuclei inside Sun

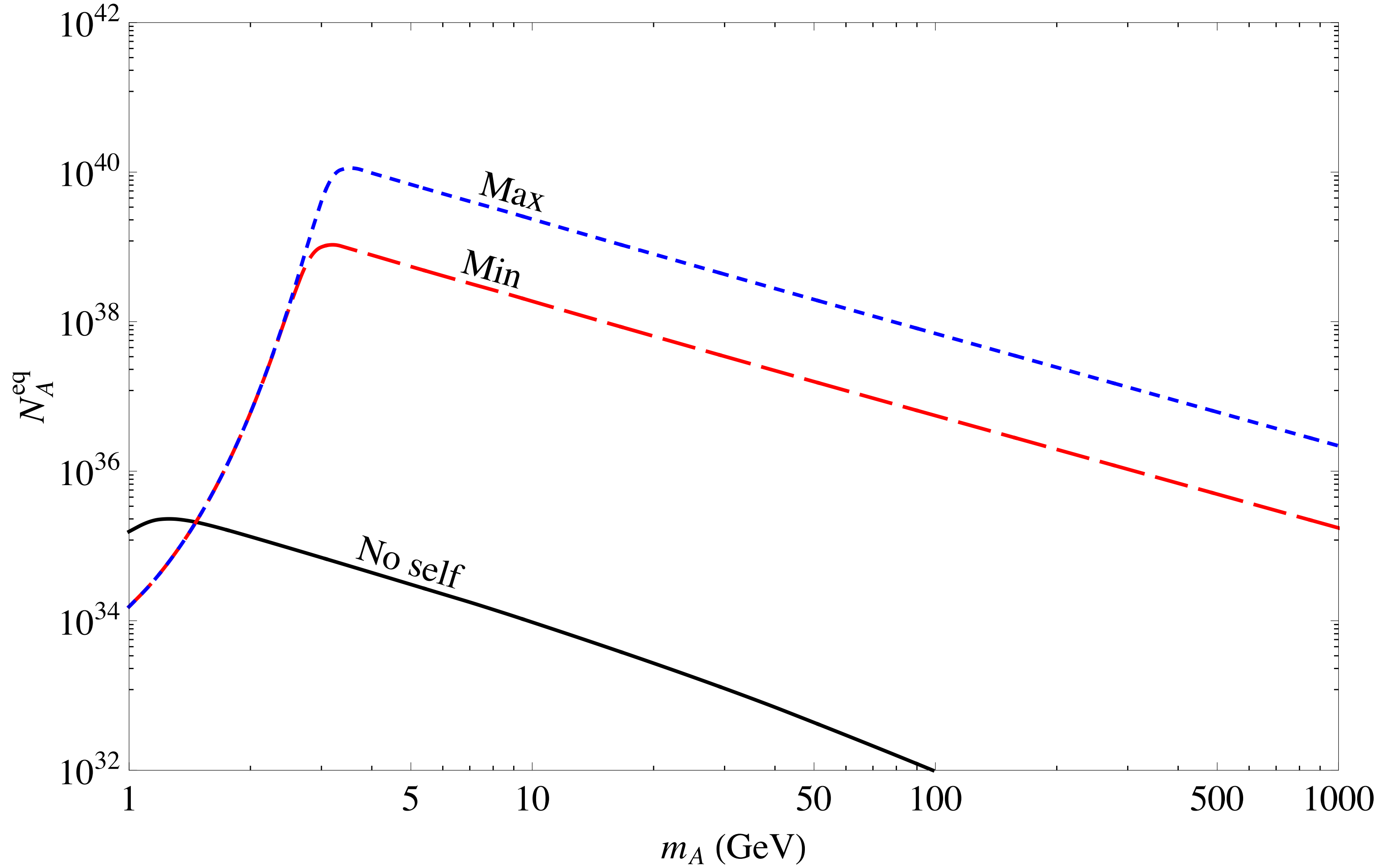
***Cs***: capture rate by DM already captured in Sun

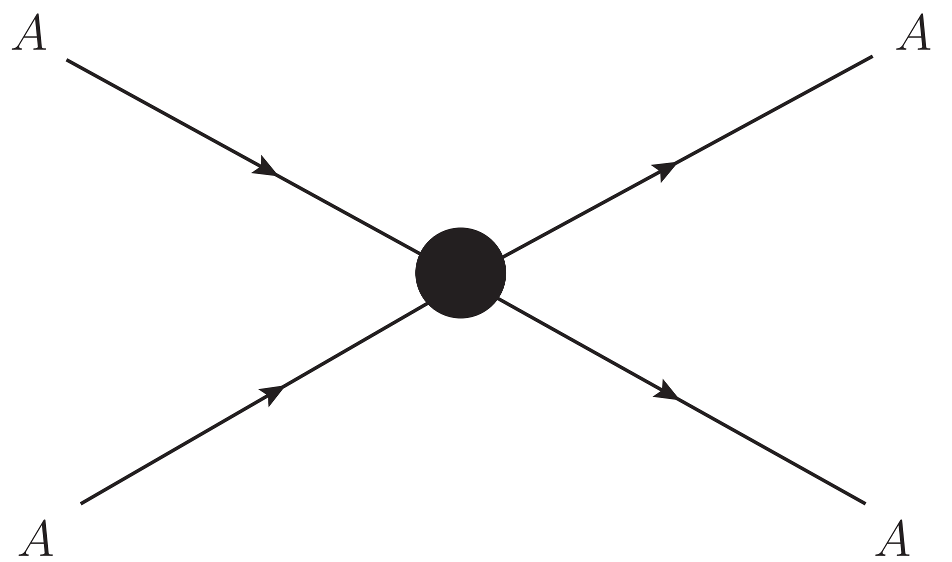
***Ce***: Evaporation rate due to DM-nuclei scattering

***Cse***: evaporation rate due to DM-self interaction

***Ca***: annihilation rate

# Importance of Self-interaction



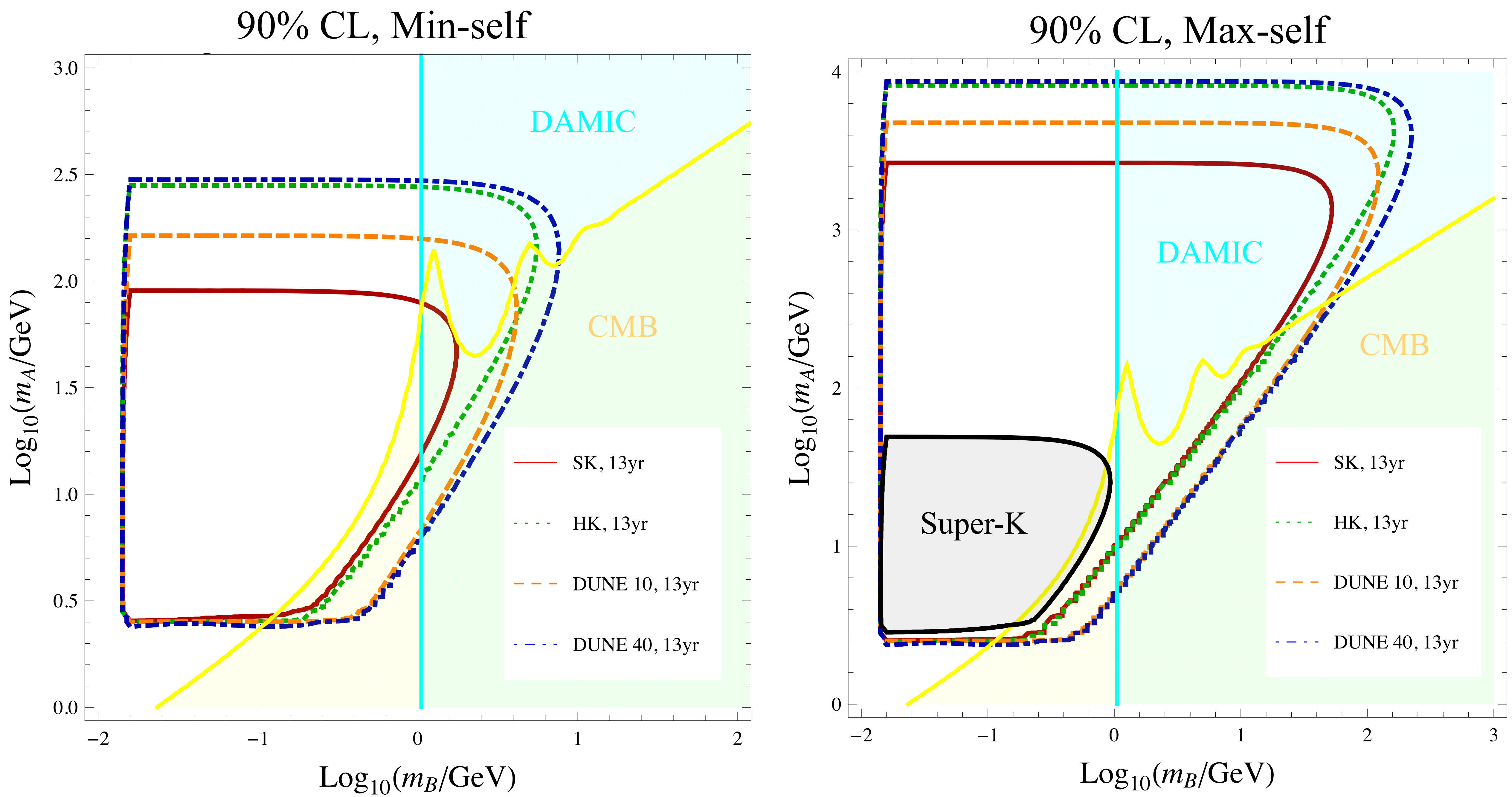




Kong, Mohlabeng, Park: **Phys. Lett. B 743 (2015) 256-266**

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

min

max




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

**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:

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

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

$\chi_A$ and $\chi_B$ 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

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

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

**For the Sun**

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

| 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° |

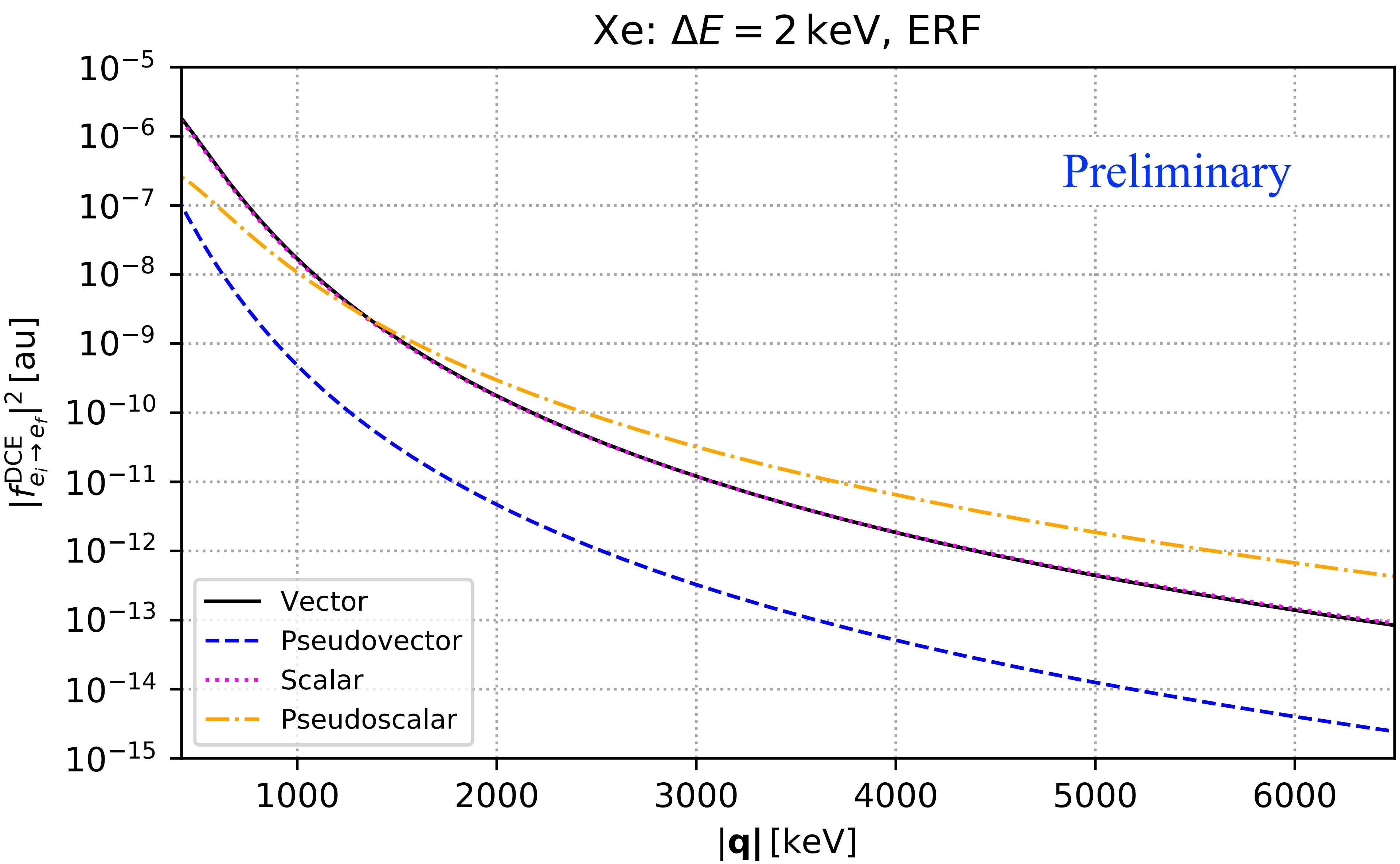
## Shape of BDM plots

Top edge - DM number density, hence flux of B particles

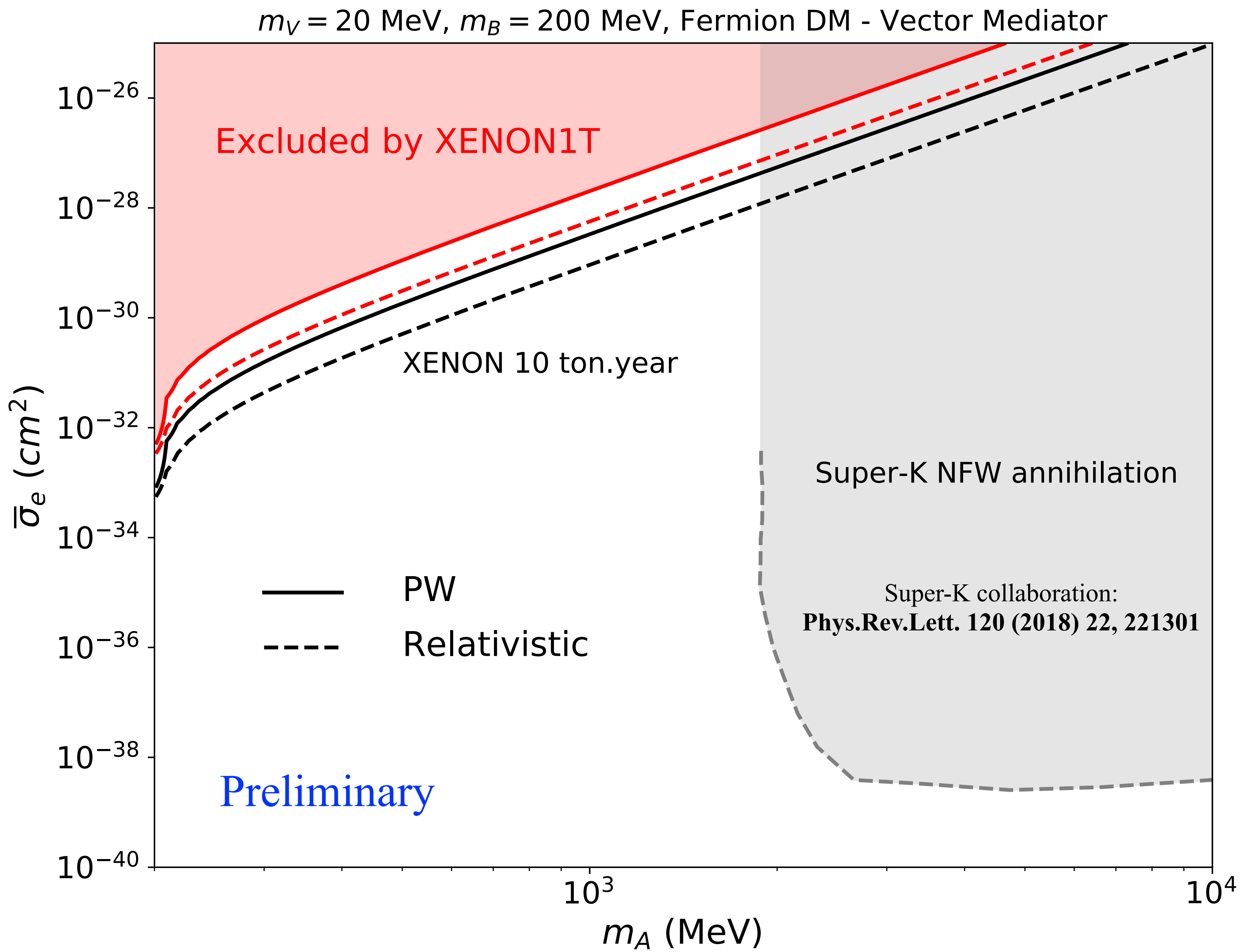
left edge - B > X

Bottom edge - Evaporation inside sun

right edge - kinematic effect where Emax > Ethres




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

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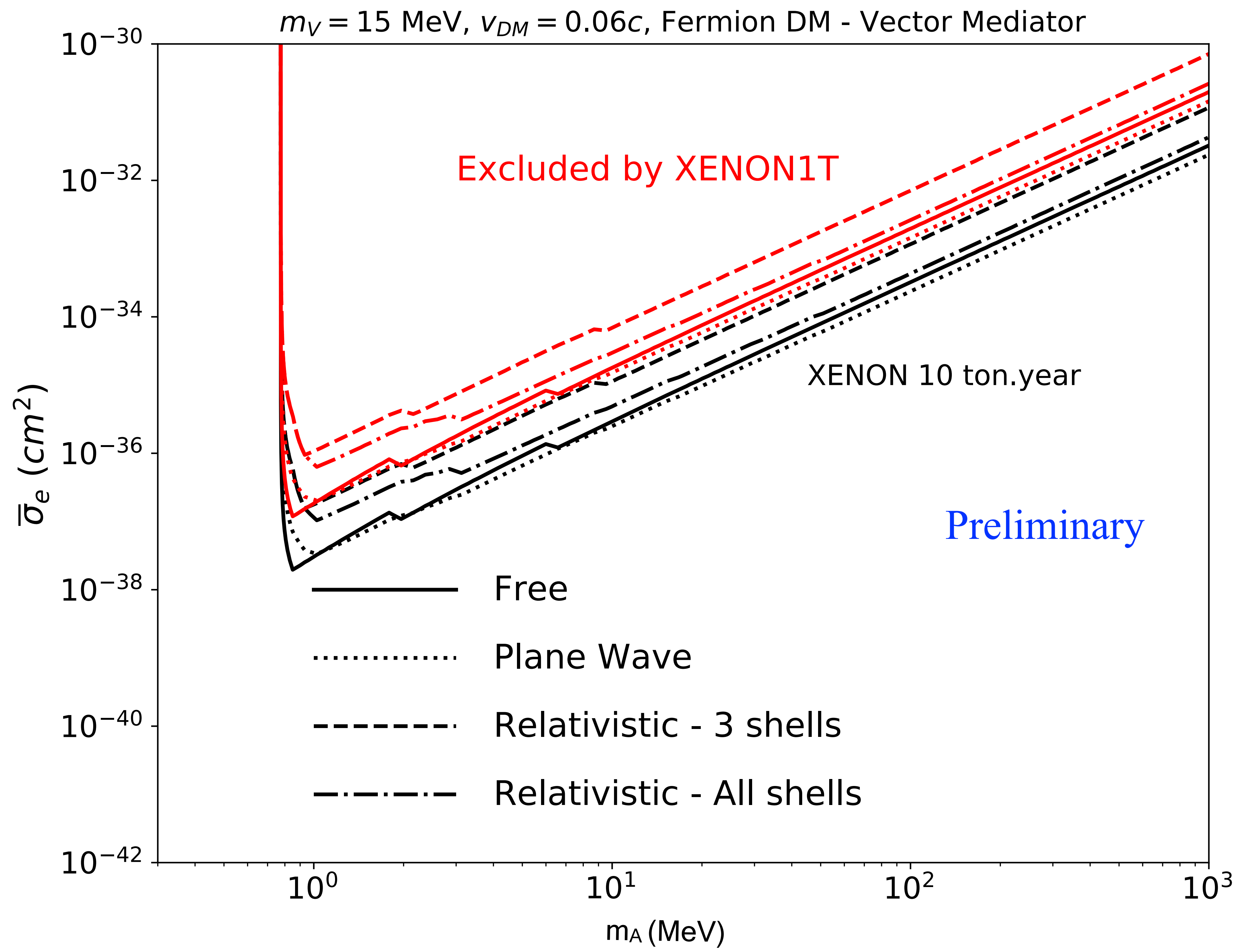


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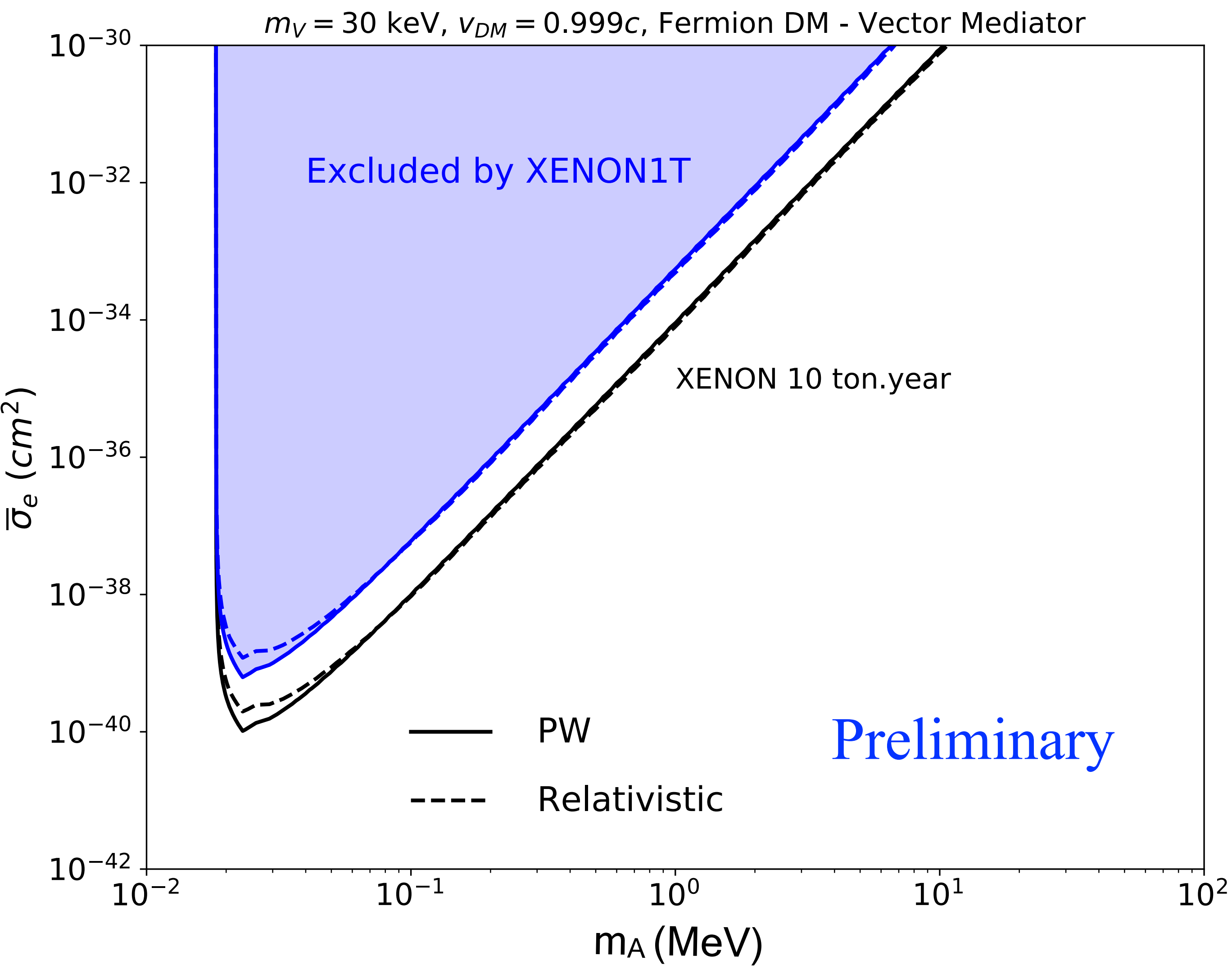
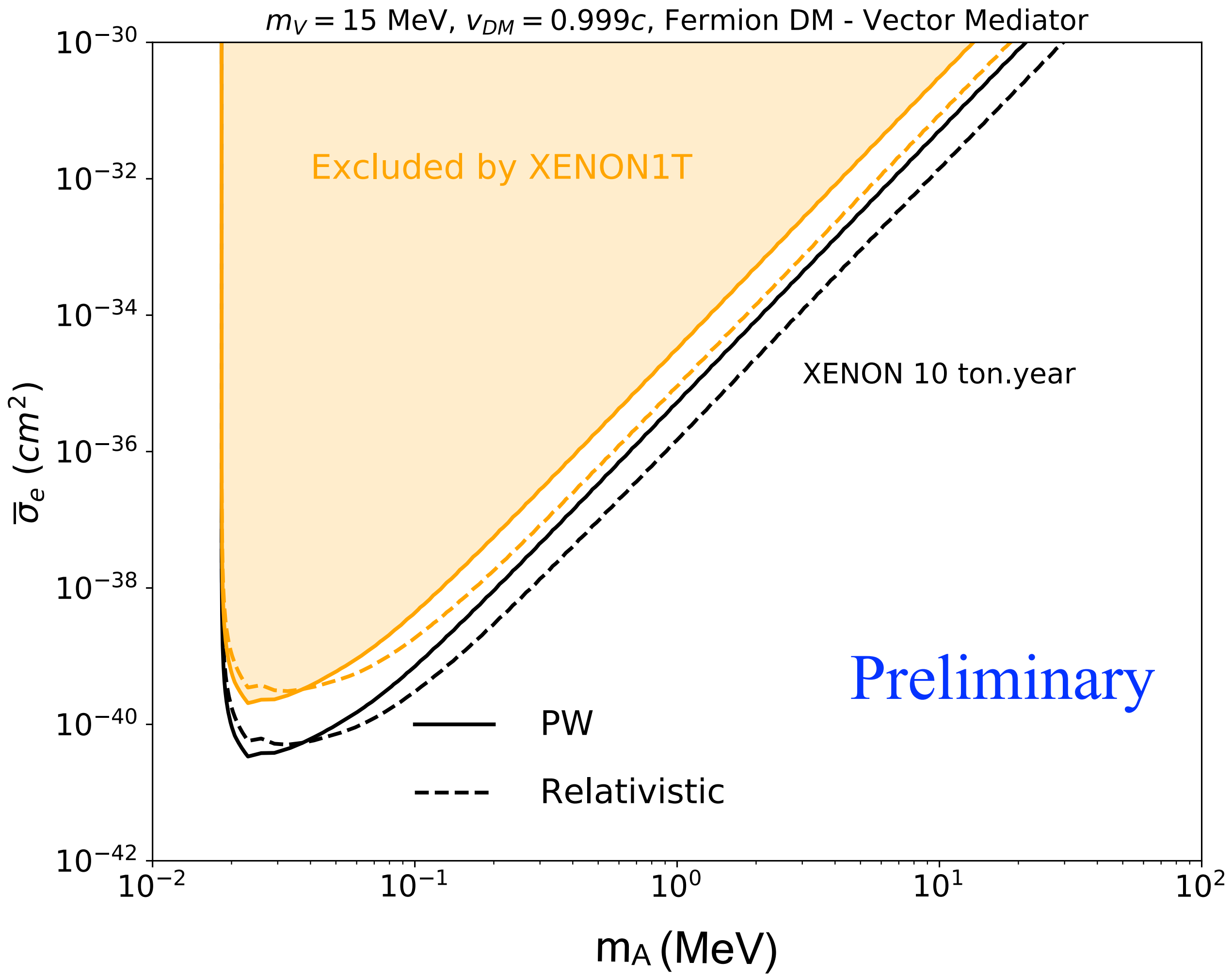
# Fermion Dark Matter with a vector mediator




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