Direct Detection of Low Mass Fast Moving Dark Matter

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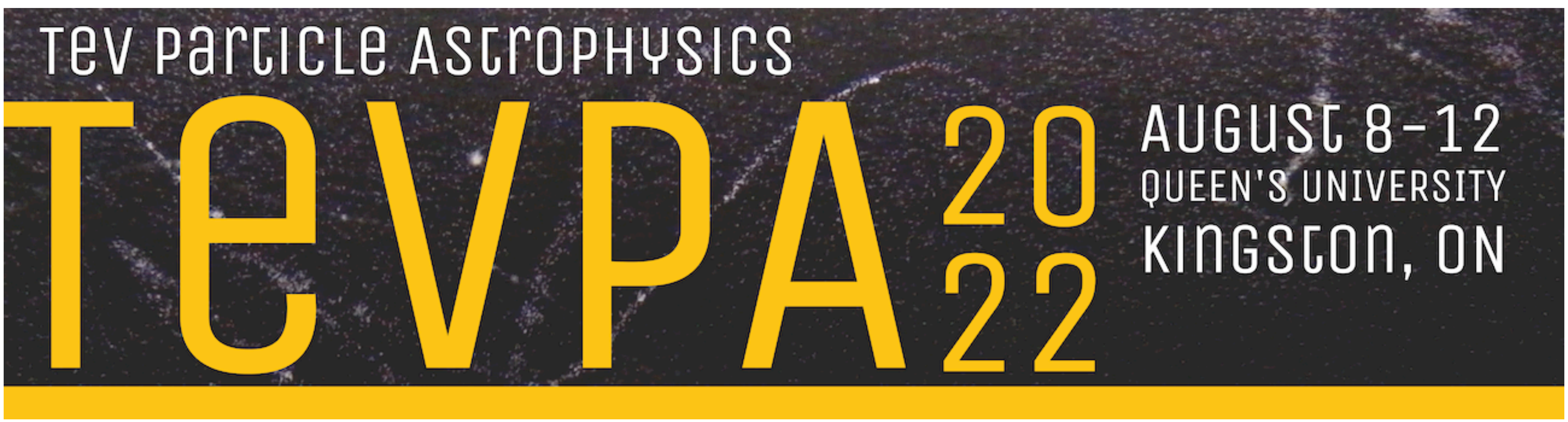
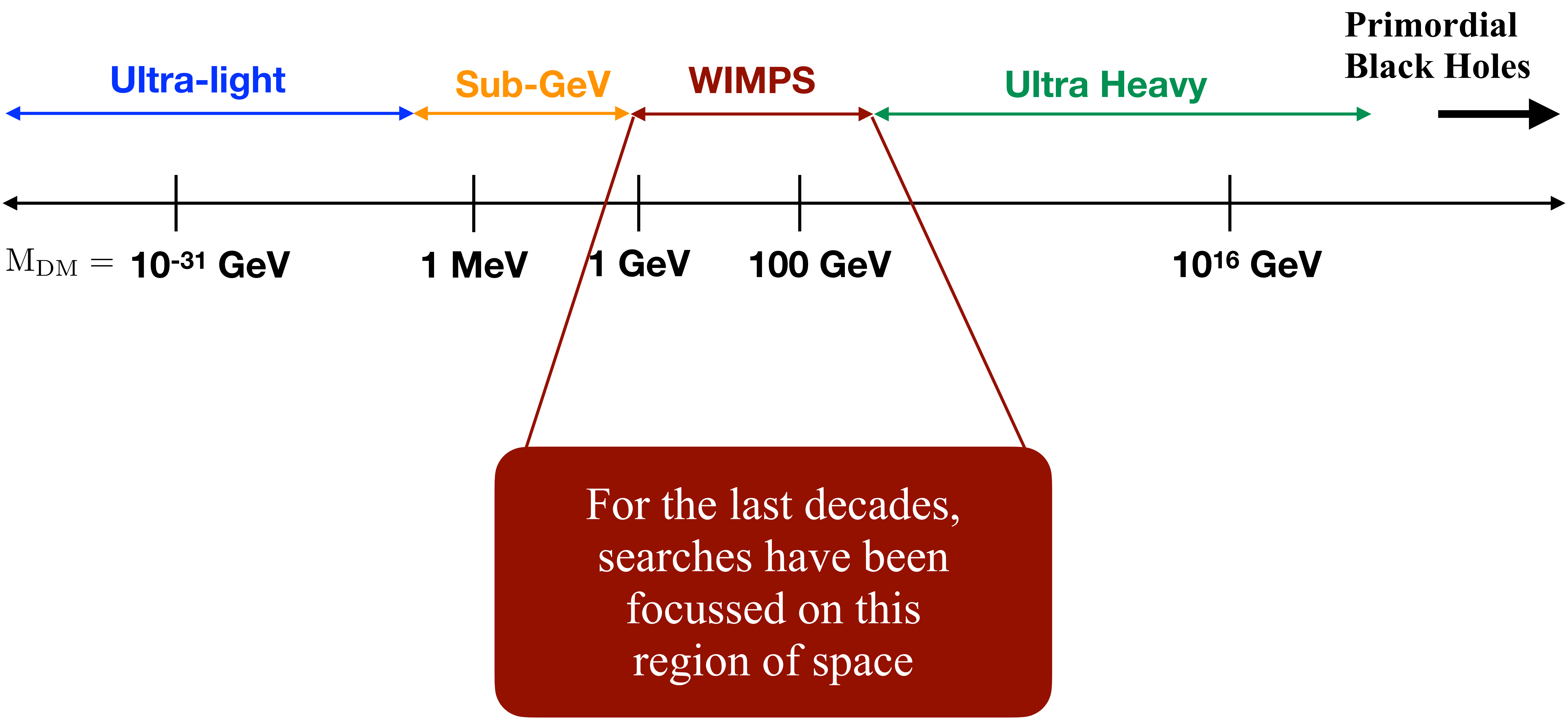


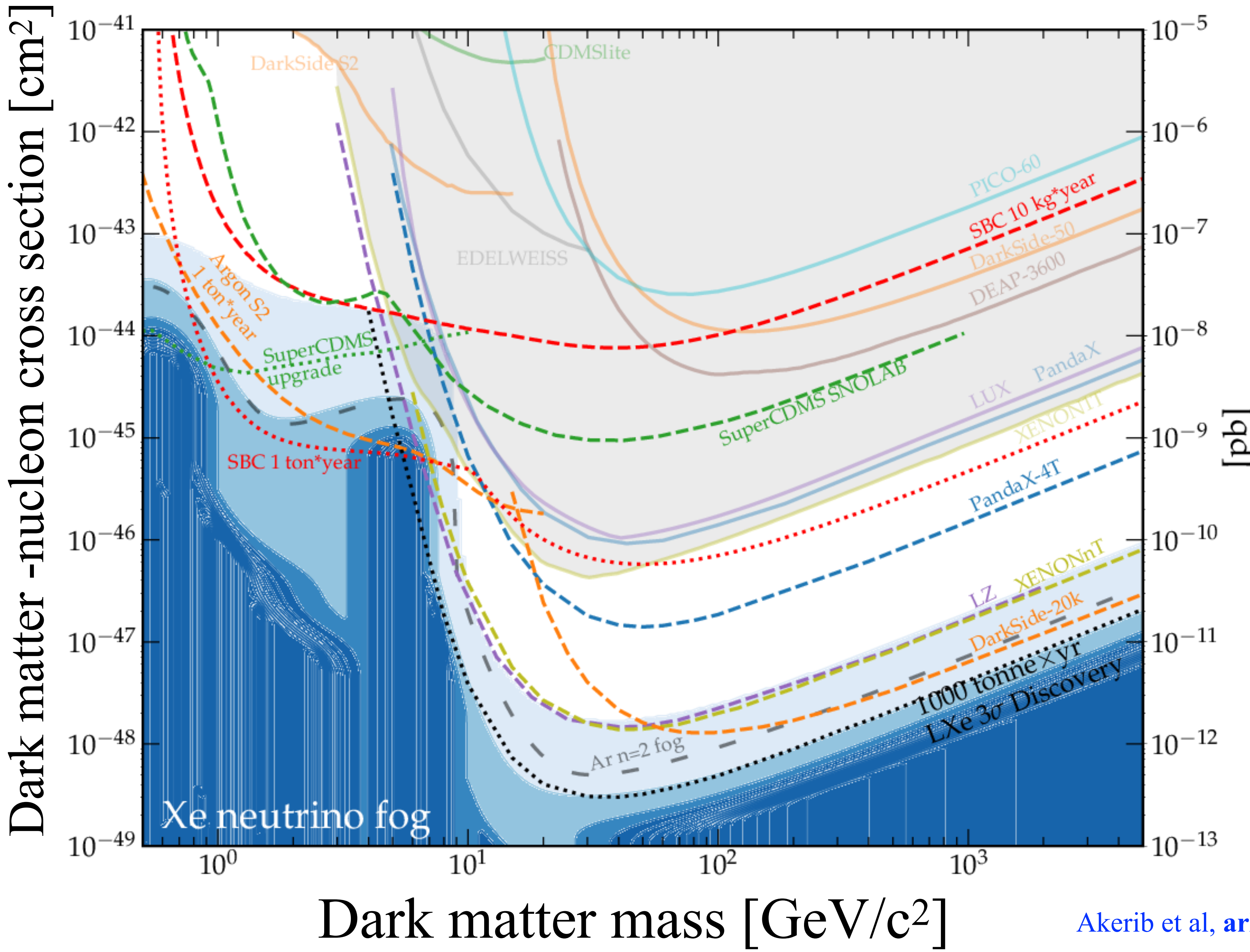
10 August 2022

Range of DM possibilities is VAST



WIMP Hypothesis is very motivated

Current status of DM direct detection



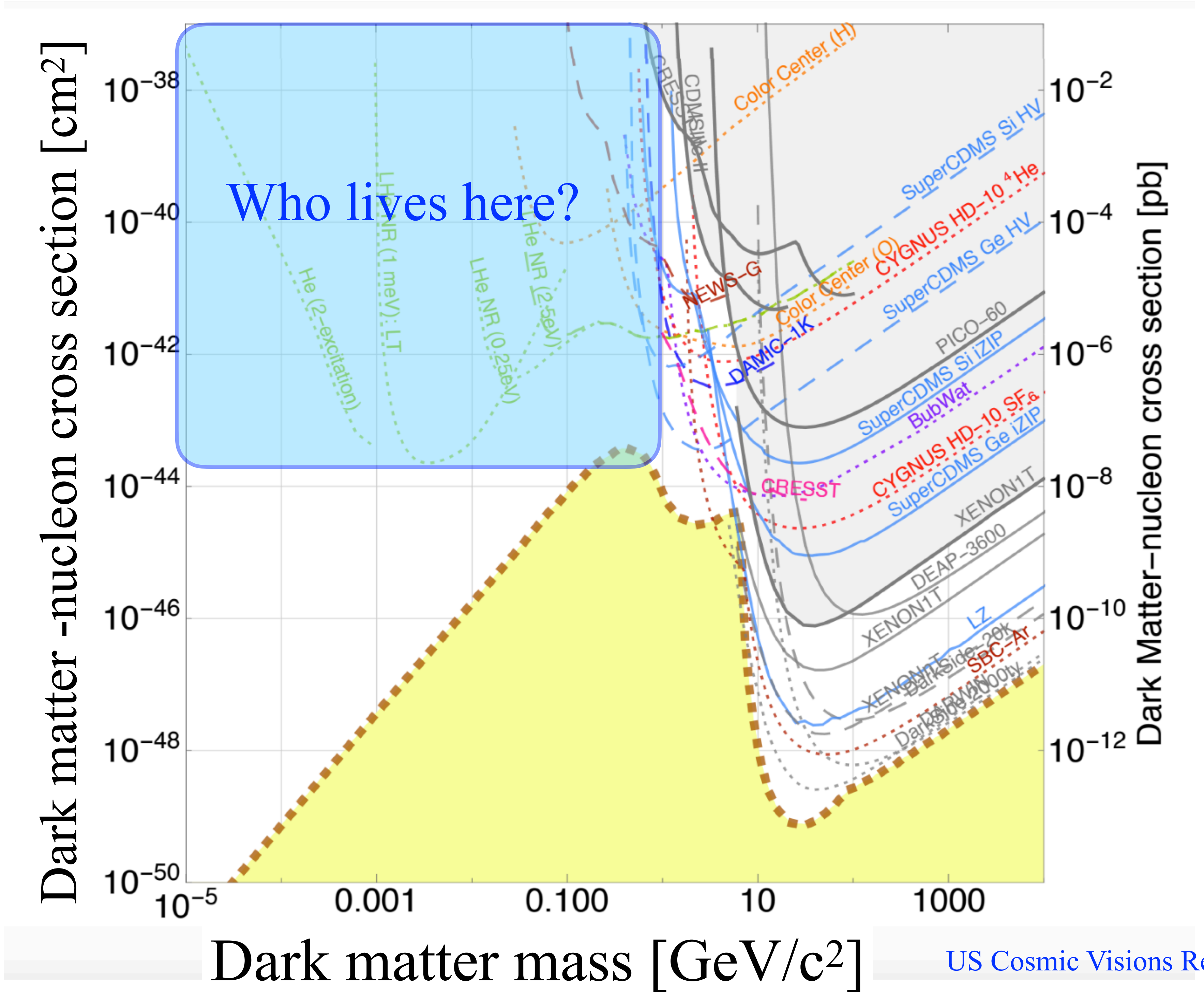
Akerib et al, **arXiv: 2203.08084**

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



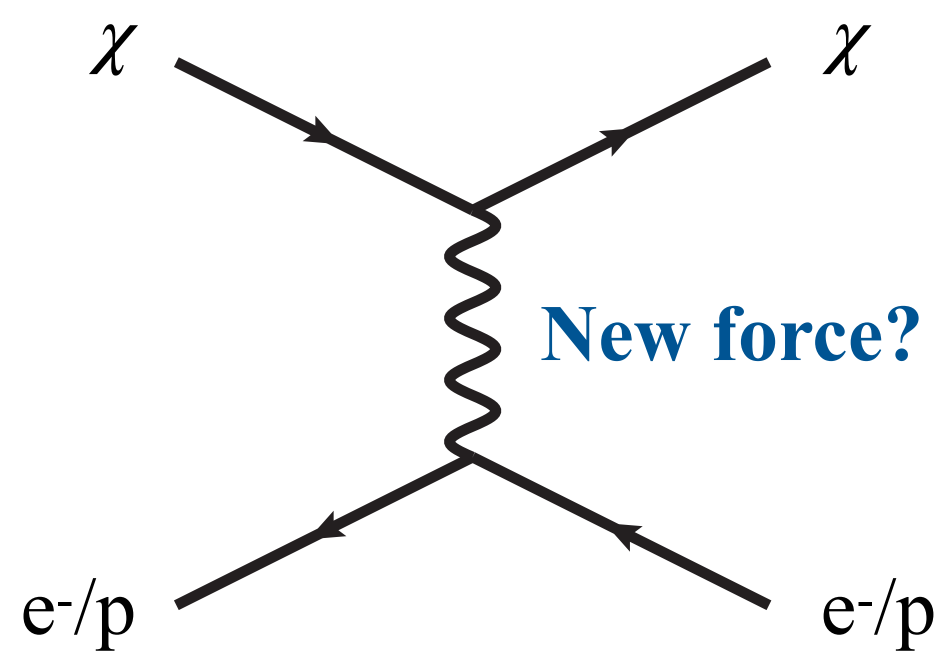
US Cosmic Visions Report, **arXiv:1707.04591**

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

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

$$\sim 19 \text{ eV} \left(\frac{m_\chi}{500 \text{ MeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

$$\ll \text{keV}$$

To probe lower masses need very low threshold nuclear recoil detectors

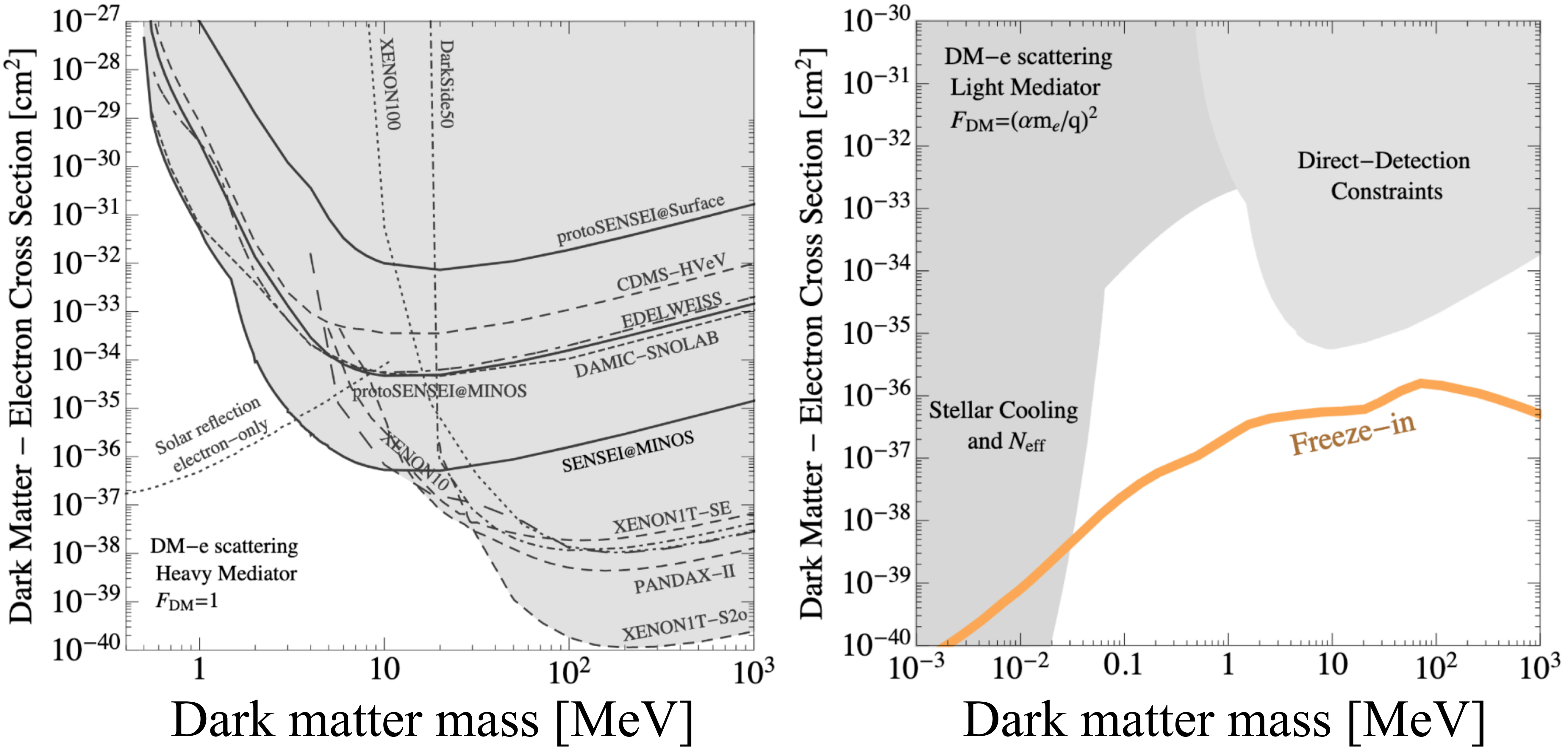
or

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

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

- Max energy transferred to electron

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

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

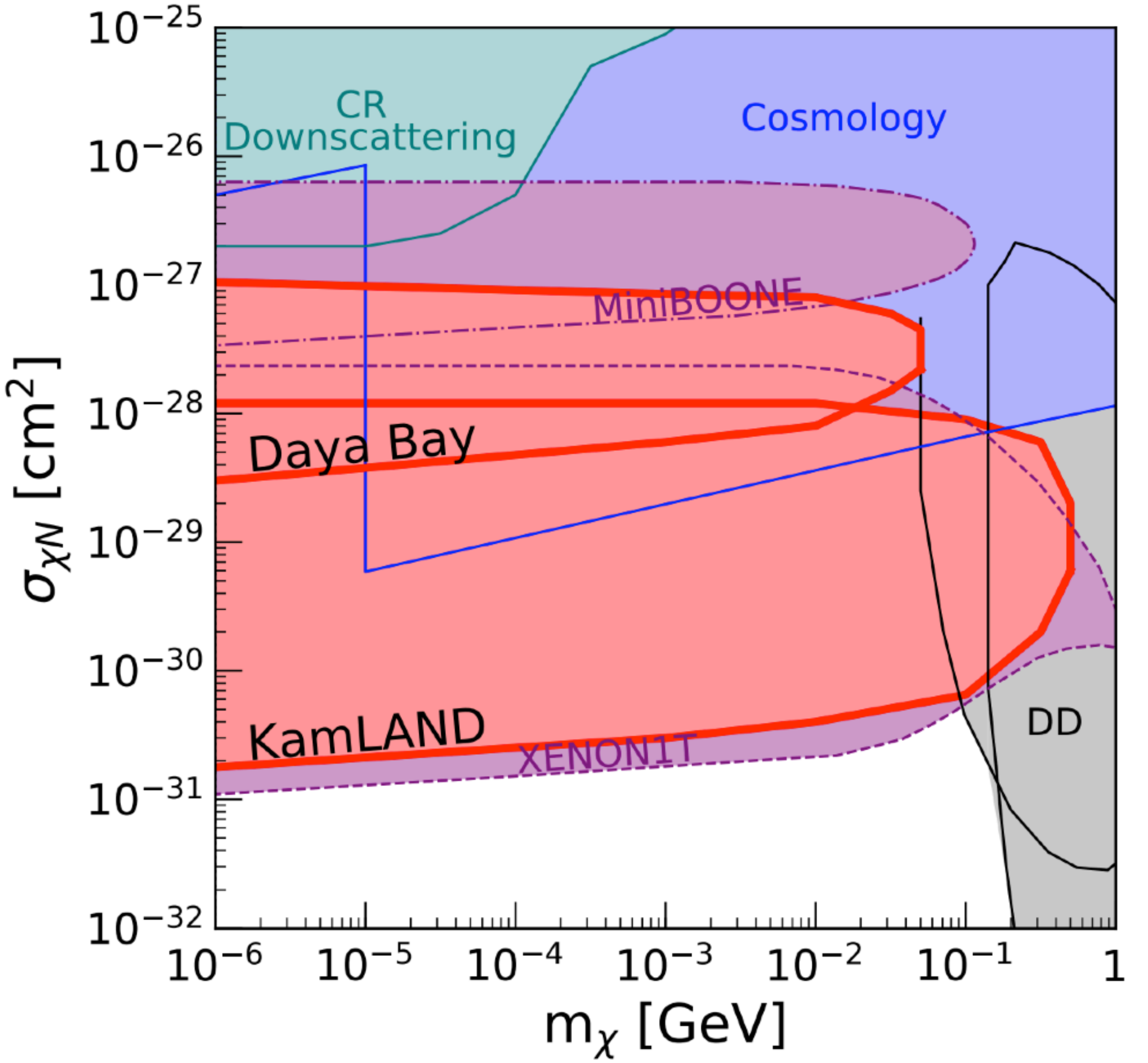
Many ways to get accelerated dark matter

Cosmic ray accelerated dark matter

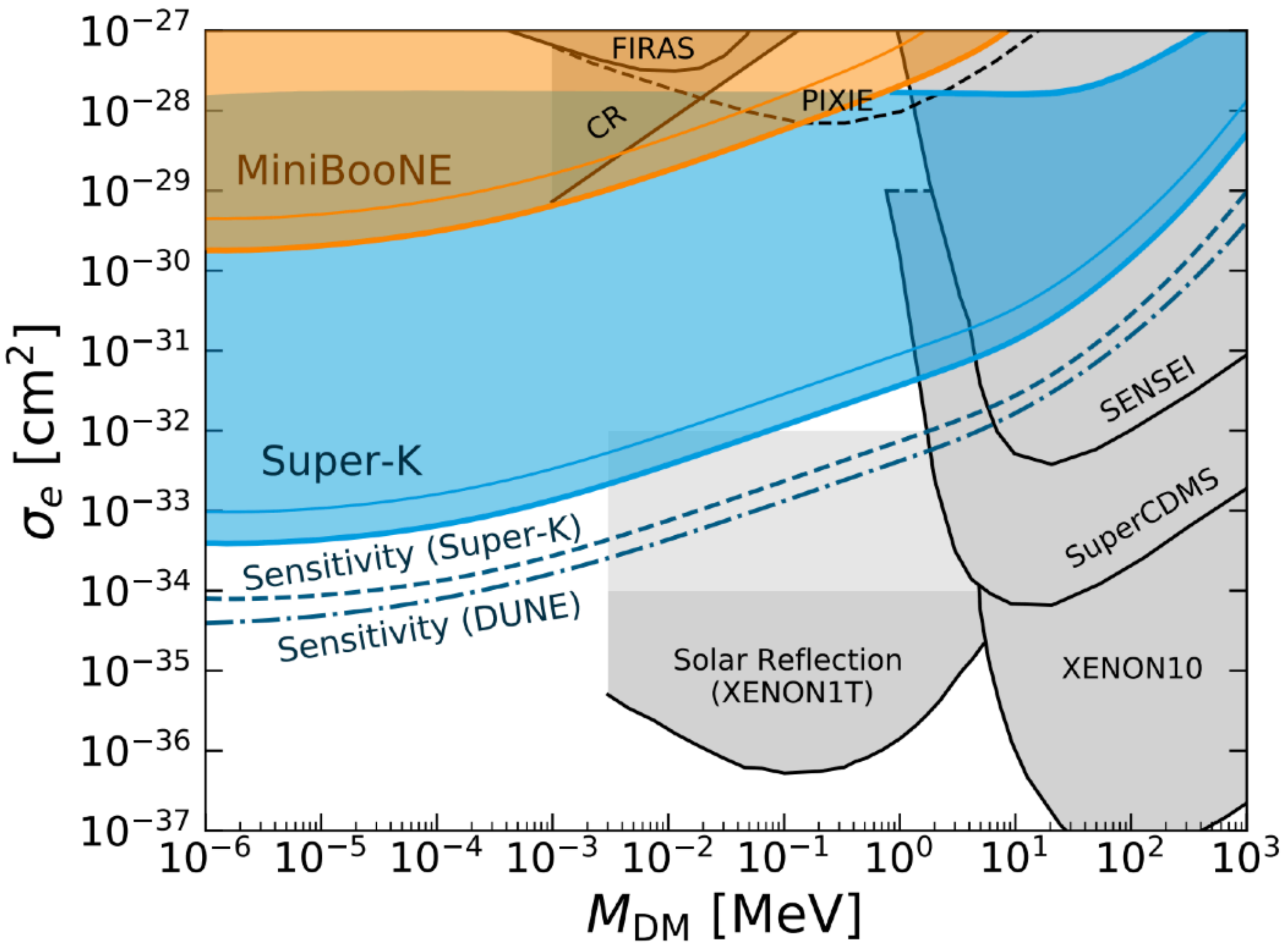
- High energy CR can scatter off DM moving at v~10^{-3} c

- 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**

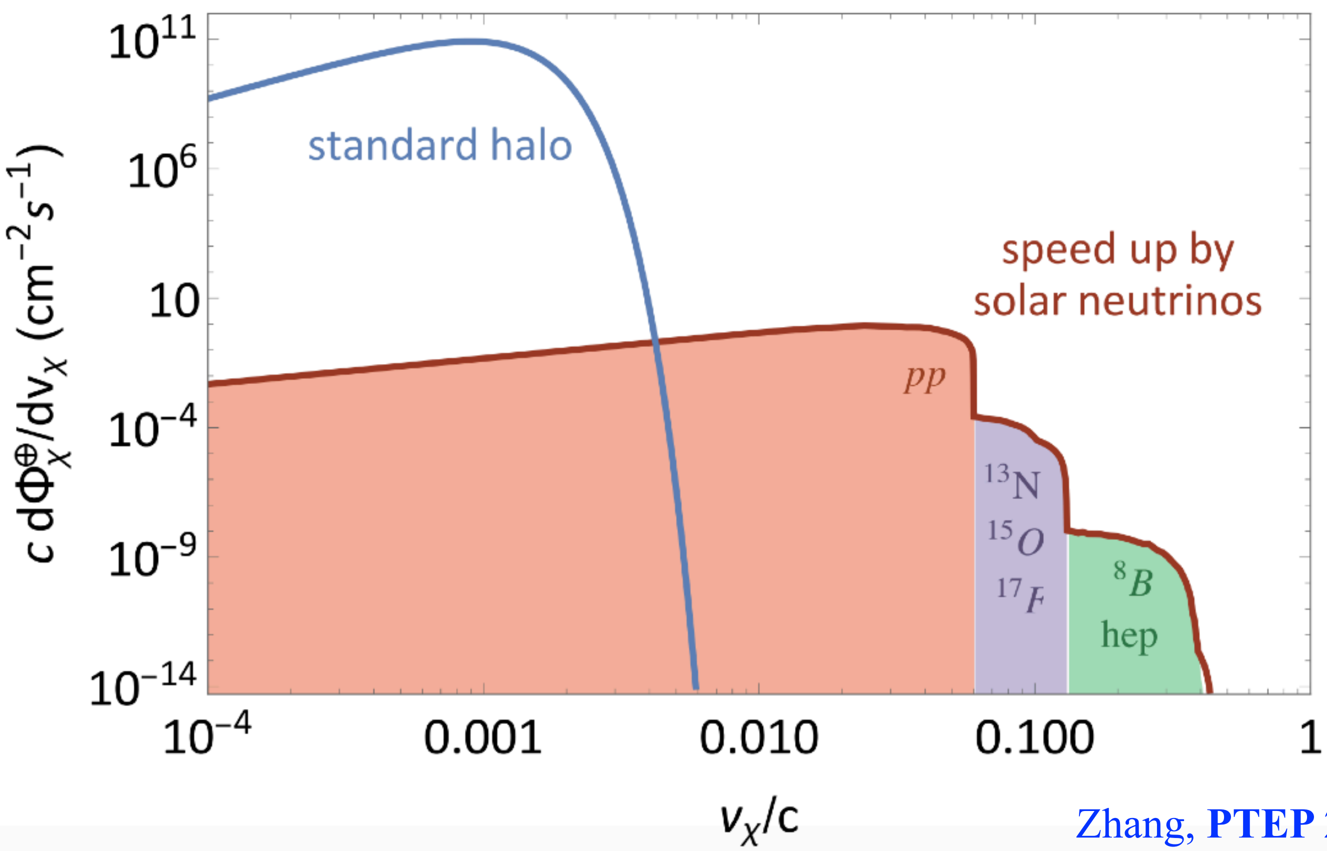
Krnjaic, McDermott : **Phys.Rev. D101 (2020) 12, 123022** + many others

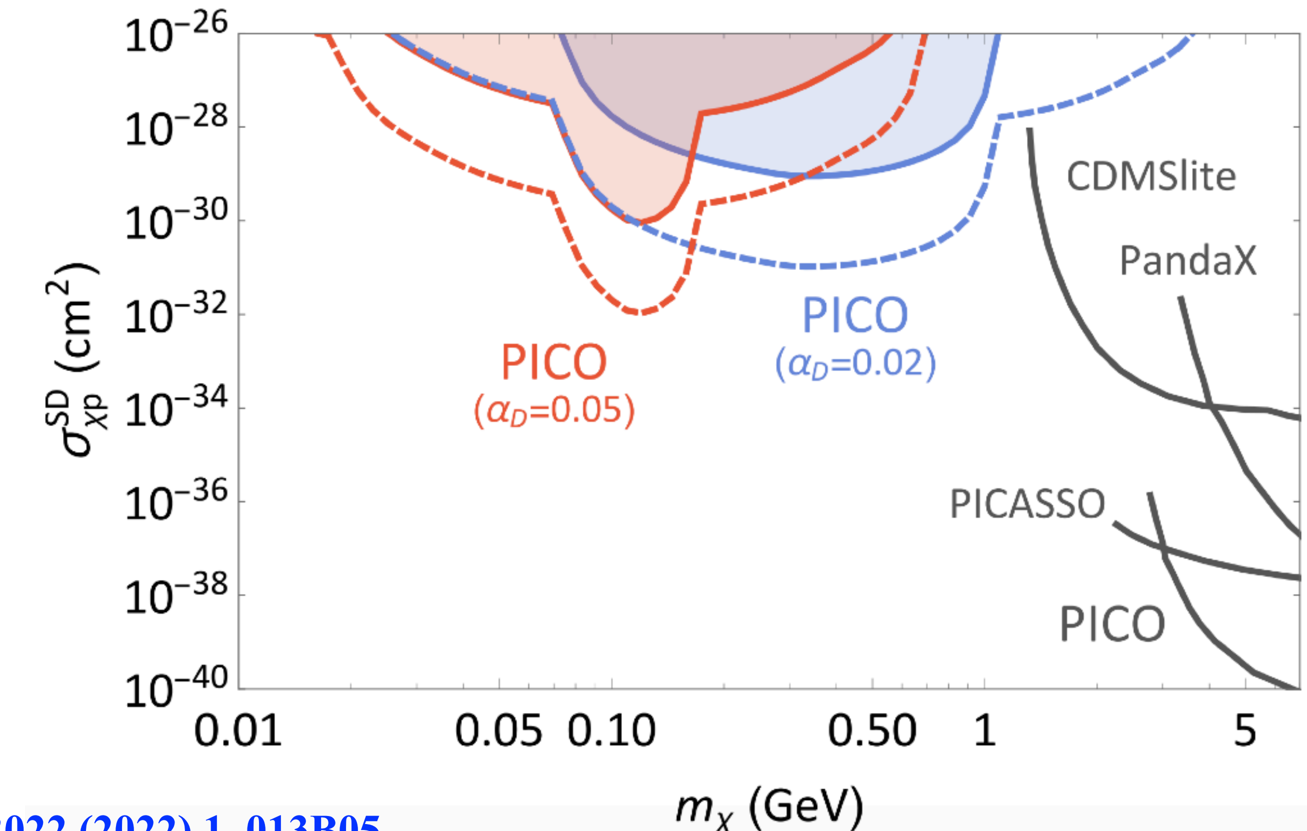
Neutrino accelerated dark matter

- 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** **See talk by Jong-Chul Park**

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

Other interesting mechanisms

Accelerated DM from evaporating primordial black holes:

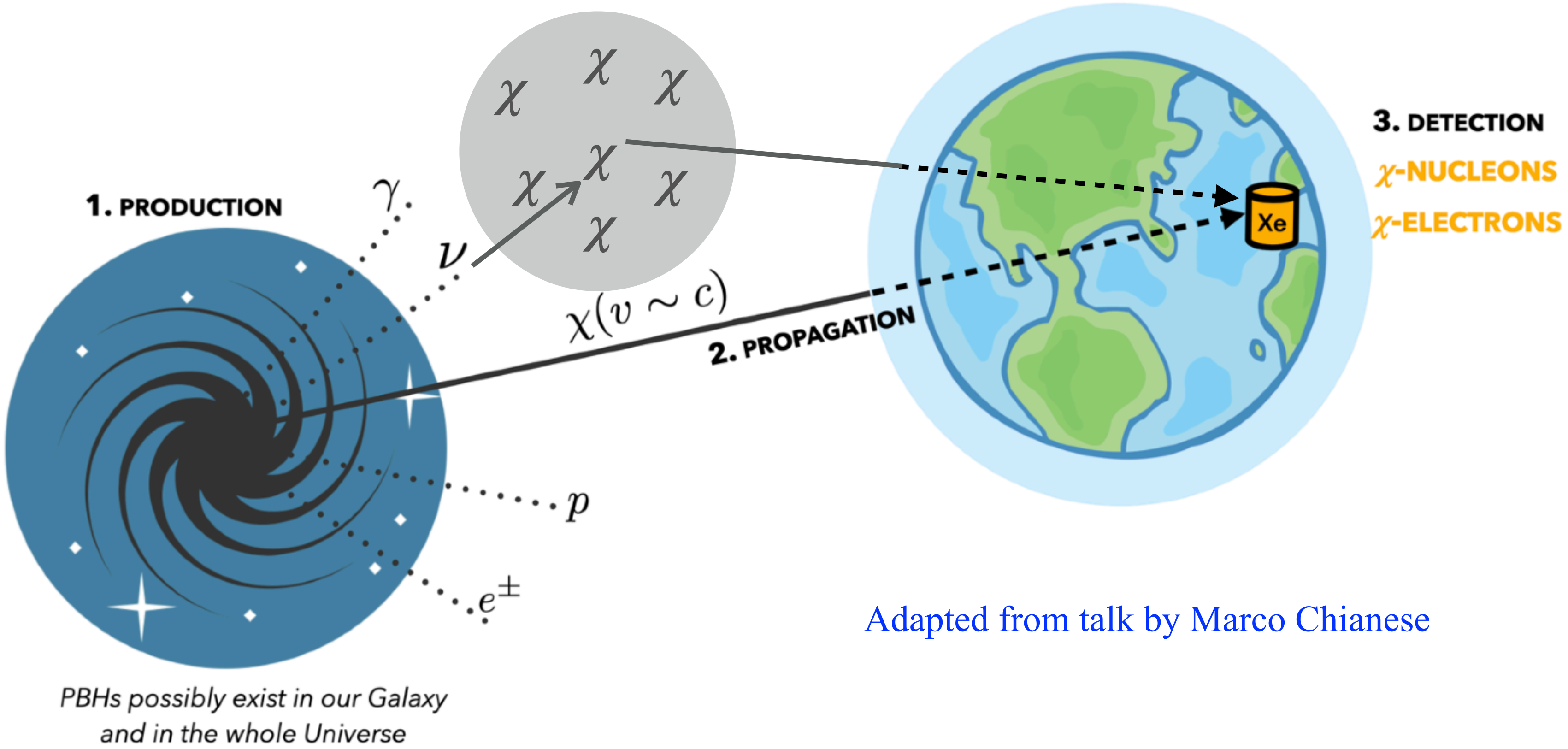
Calabrese et al, **Phys. Rev. D (105) 2022 2**

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

See talk by Marco Chianese

Neutrinos from evaporating primordial black holes accelerate DM:

Chao et al, **arXiv: 2108.05608**



Adapted from talk by Marco Chianese

Accelerated DM from supernova shockwaves: **See talk by Chris Cappiello**

+ many others

A different mechanism…

Consider non-minimal Dark sector

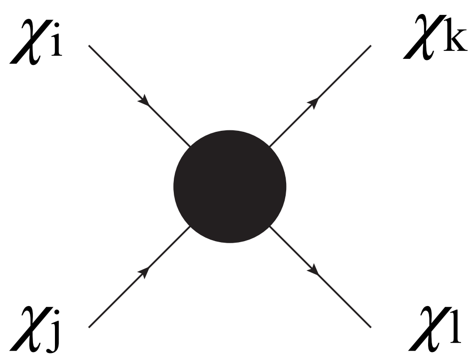
Generic feature of any non-minimal dark sector: small fraction of DM today may be relativistic/semi-relativistic

Sources:

- **Assisted Freeze-out**:

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

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



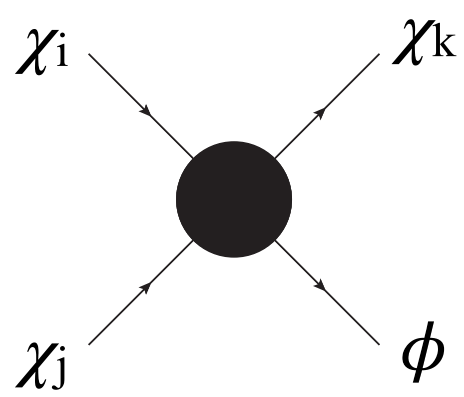
Belanger and Park : **JCAP 03 (2012) 038**

See talk by Seodong Shin

- **Semi-annihilation**:

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

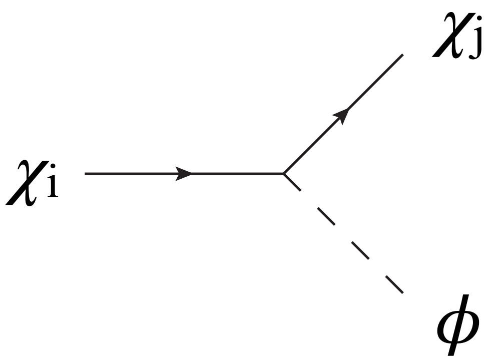
  , Z_3 DM symmetry



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

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

  $\chi_i \to \chi_j \phi$



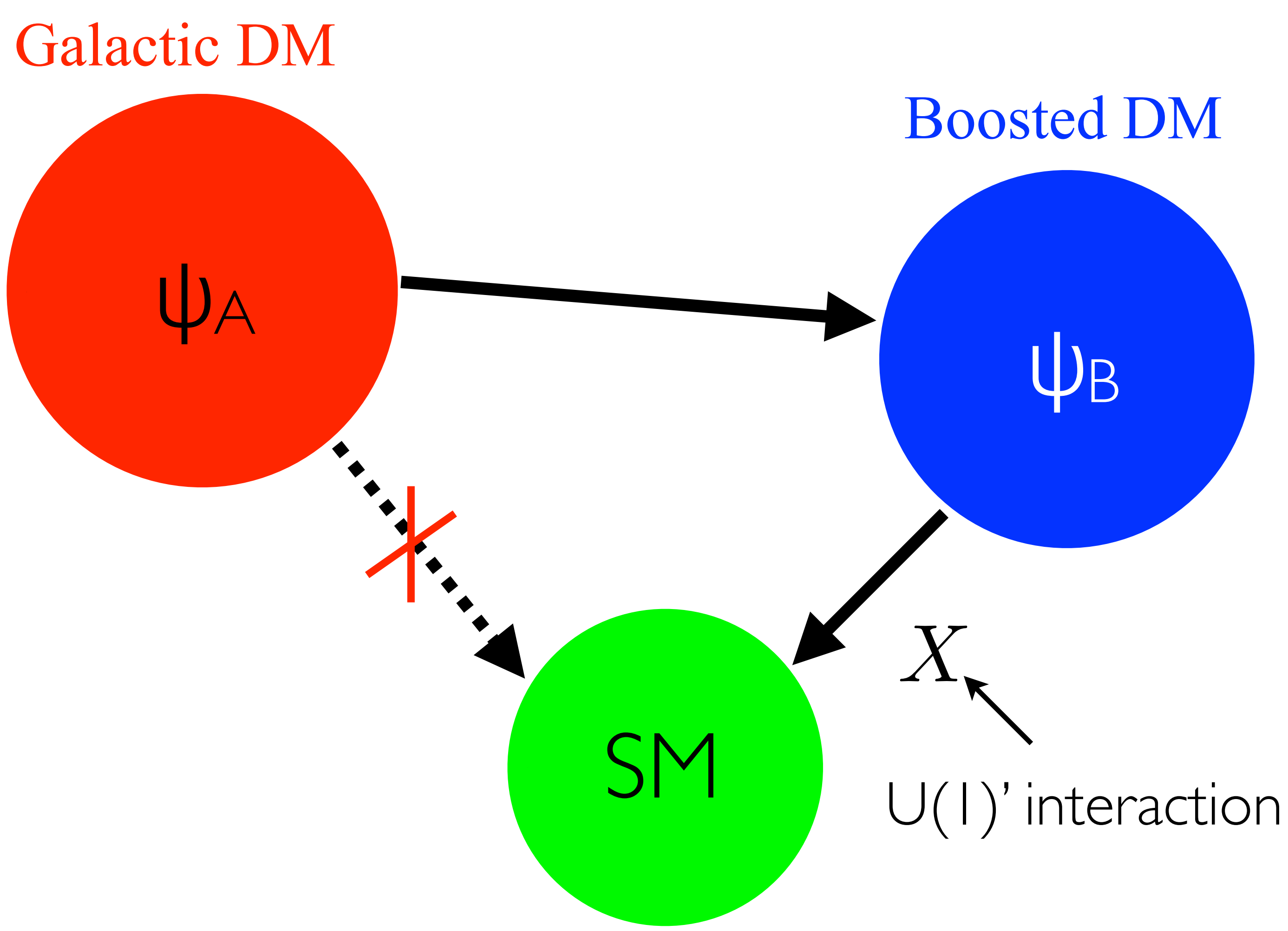
Tucker-Smith & Weiner: **Phys.Rev. D64 (2001) 043502**

+ **many others**

Boosted dark matter

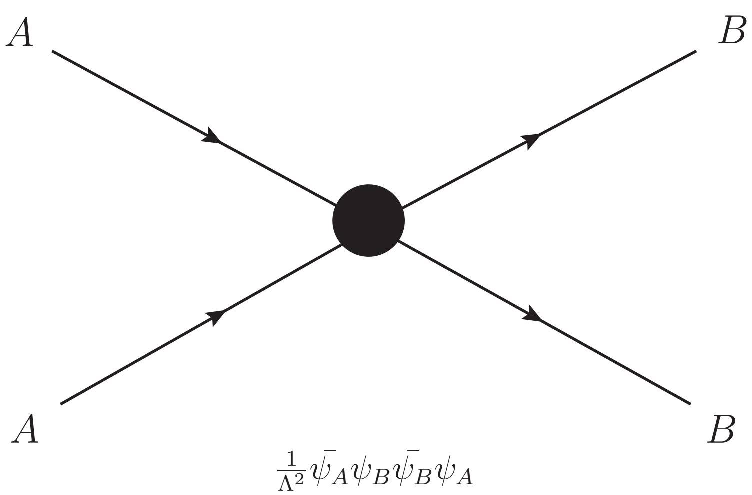
- Two stable DM particle, ψ_A & ψ_B with $m_A > m_B$ $(eg. U(1)' \otimes U(1)'')$

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

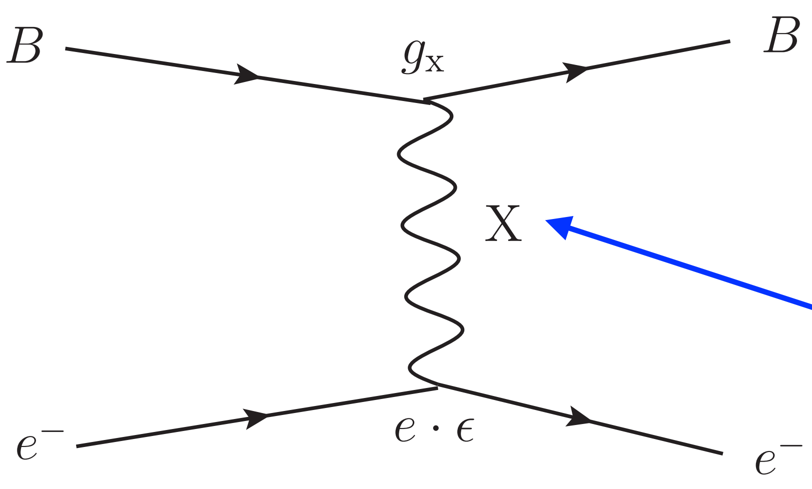


$$\frac{1}{\Lambda^2}\overline{\chi}_A\chi_B\overline{\chi}_B\chi_A$$

- '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**

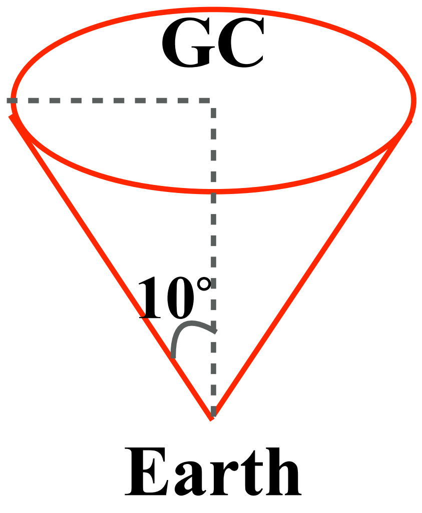
Alhazmi, Kim, Kong, **Mohlabeng**, Park, Shin: **JHEP 05 (2021) 055**

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

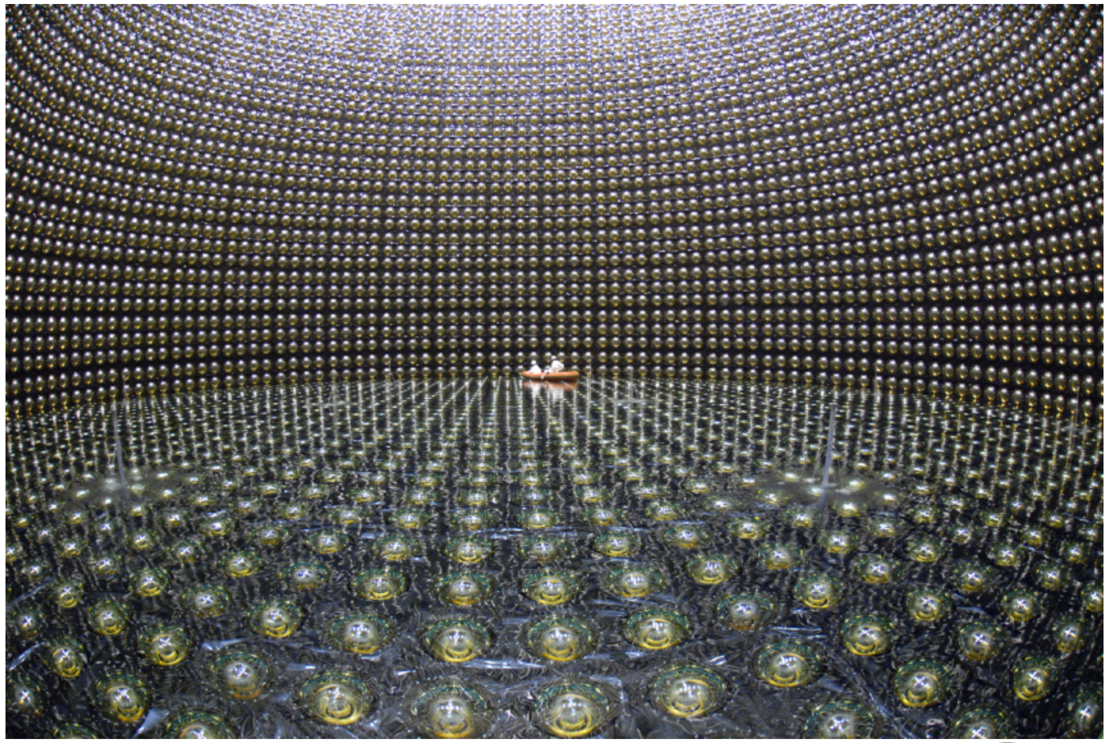
Flux: NFW profile + 10° cone around GC

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

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:

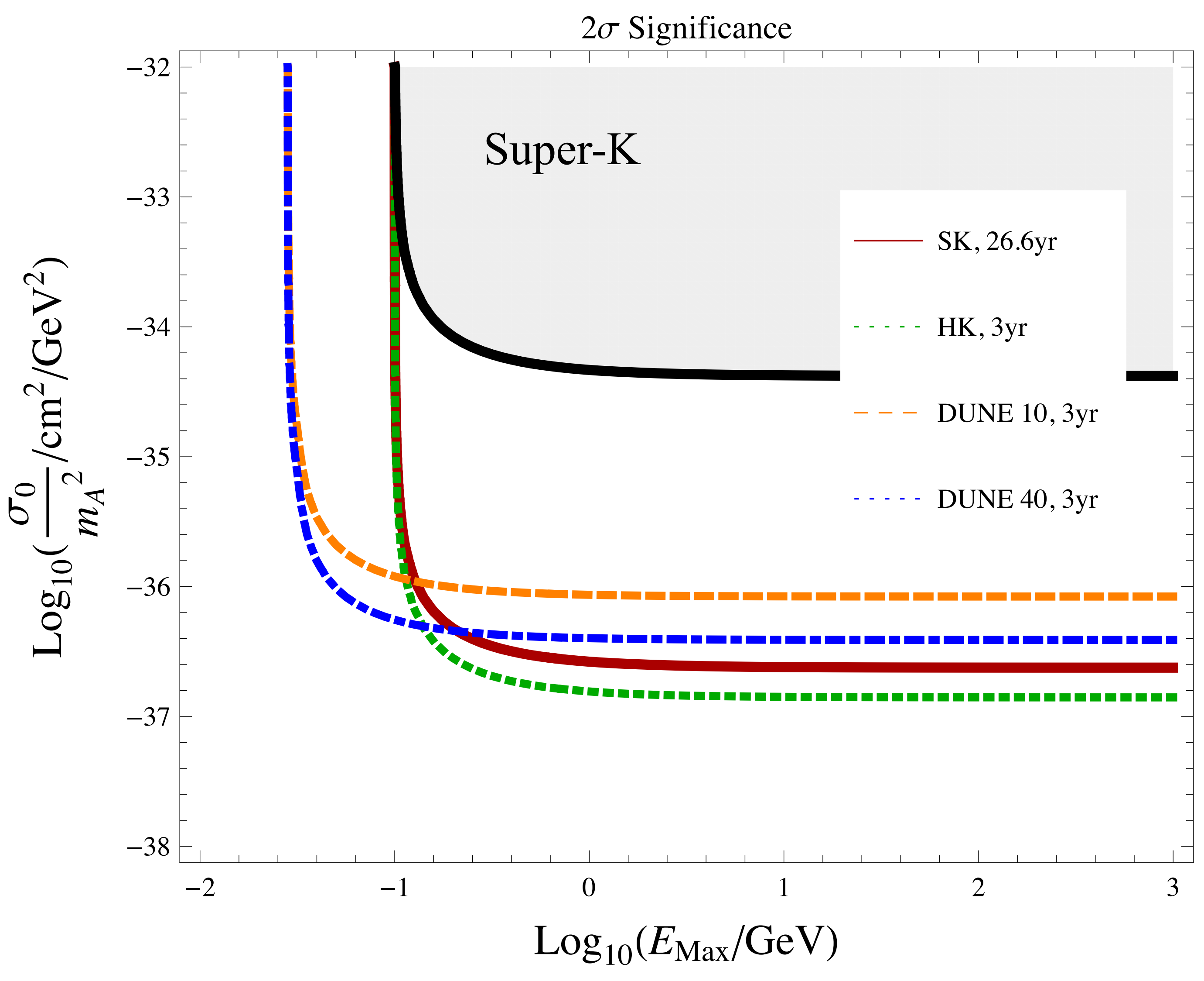
Berger et al, **Phys.Rev.D 103 (2021) 9, 095012**

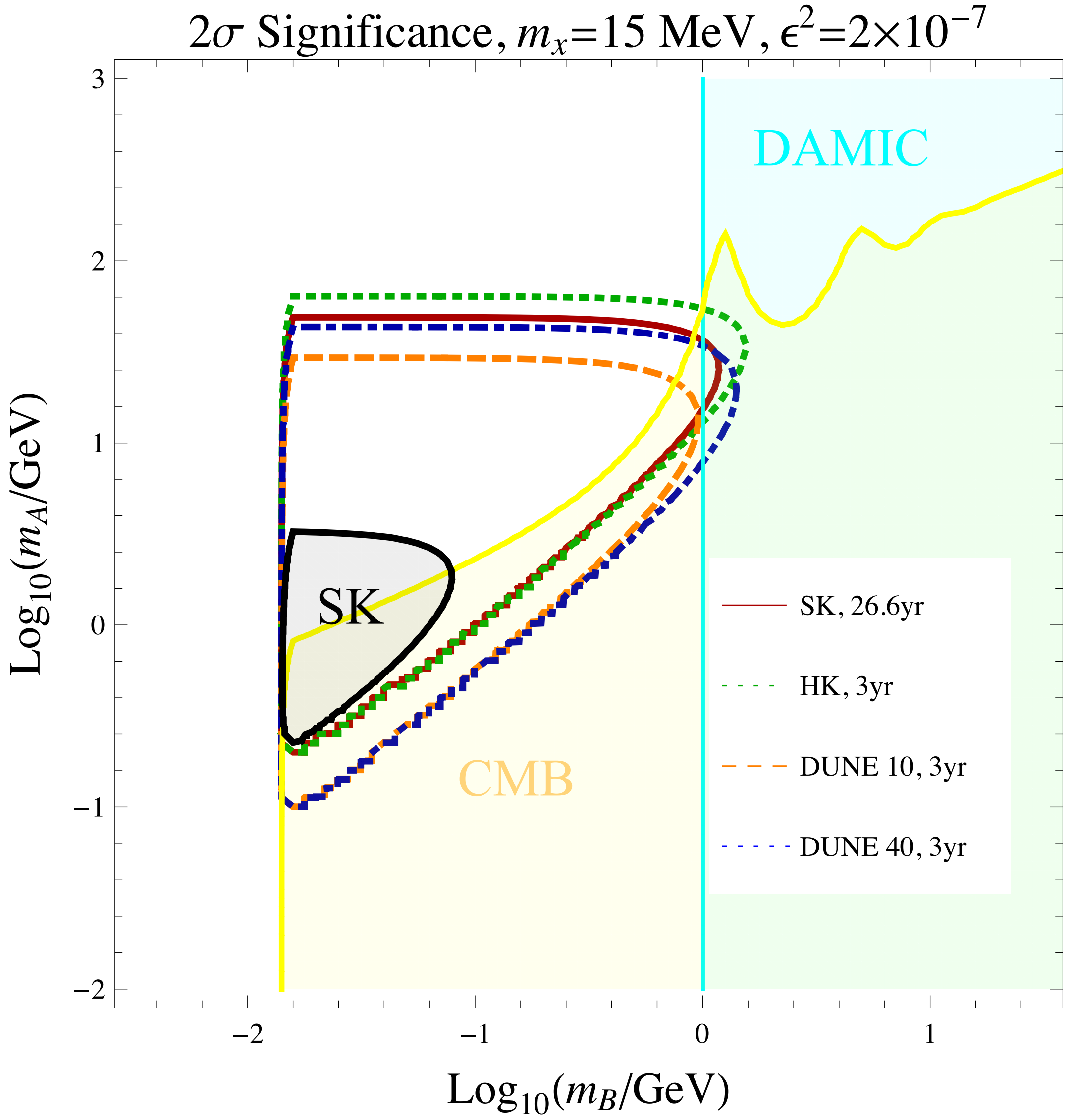
Boosted DM from the Galactic Center

2σ sensitivity:

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

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





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

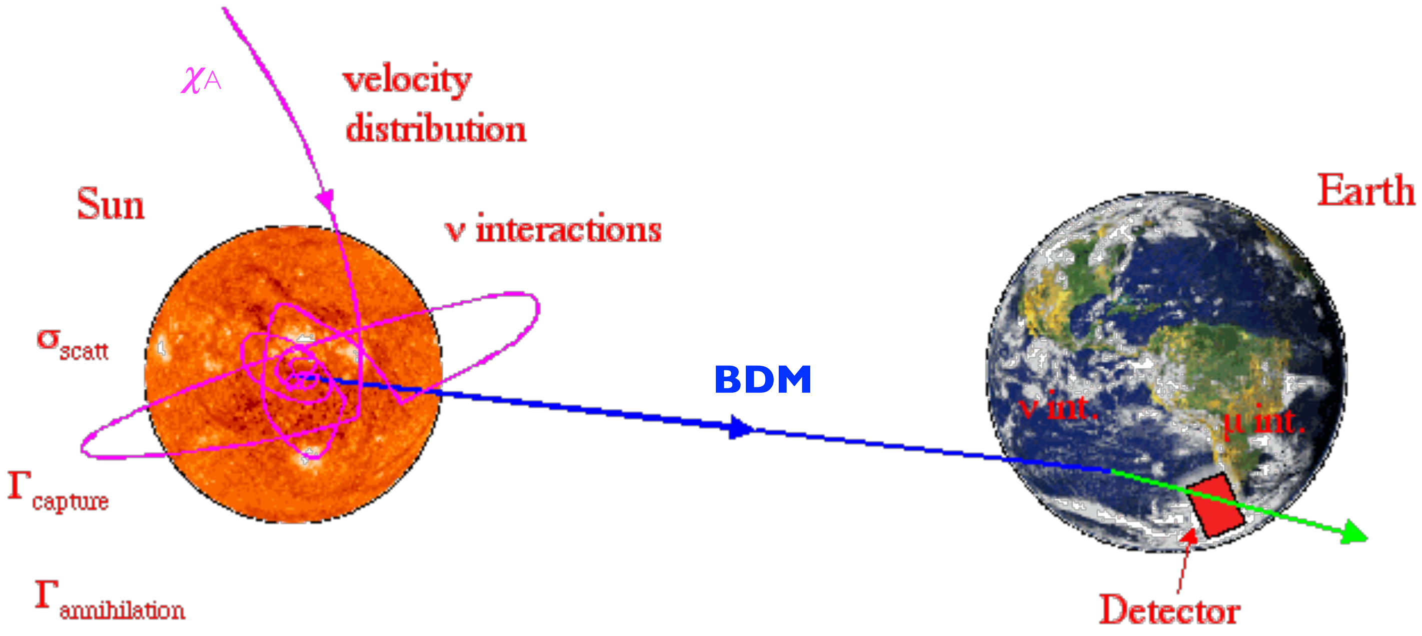
Boosted DM from the Sun

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 χ_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

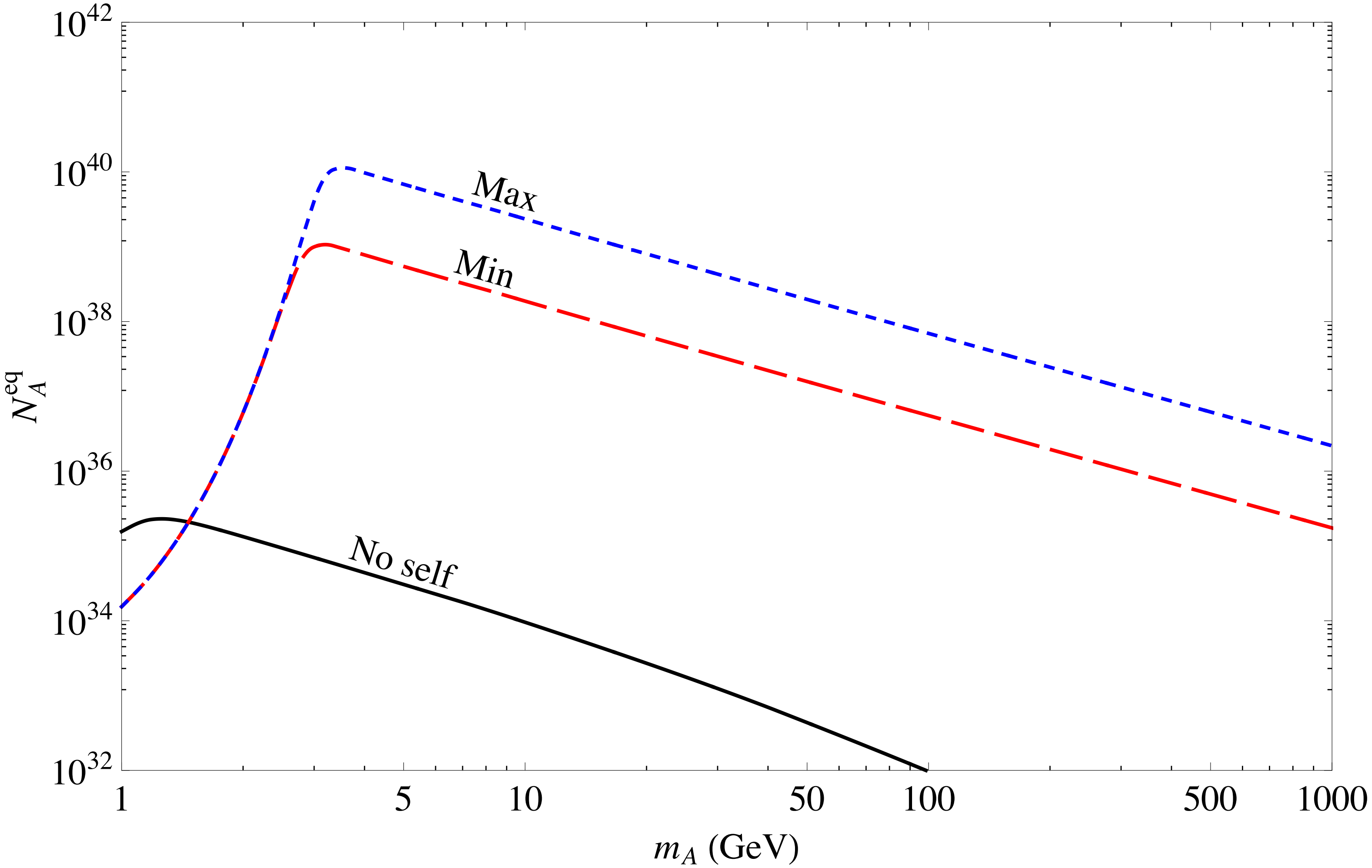
Cs: capture rate by DM already captured in Sun

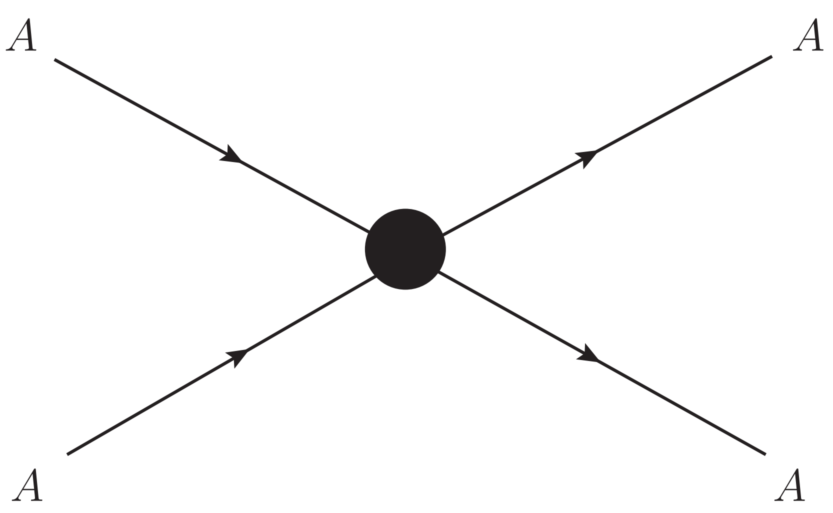
Ce: Evaporation rate due to DM-nuclei scattering

Cse: evaporation rate due to DM-self interaction

Ca: annihilation rate

Importance of DM Self-interactions





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

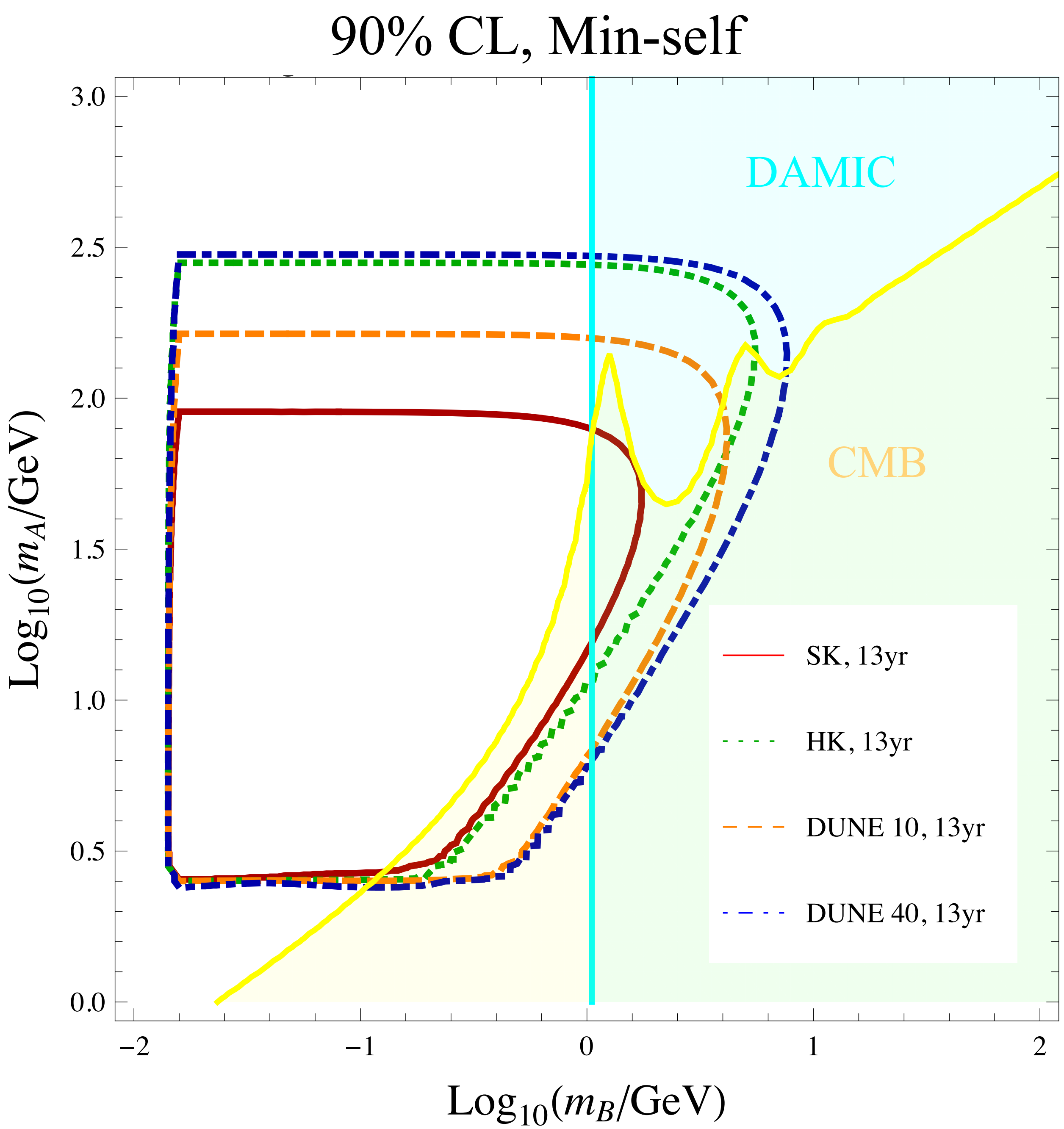
Kinematics of dwarf spheroidal galaxies

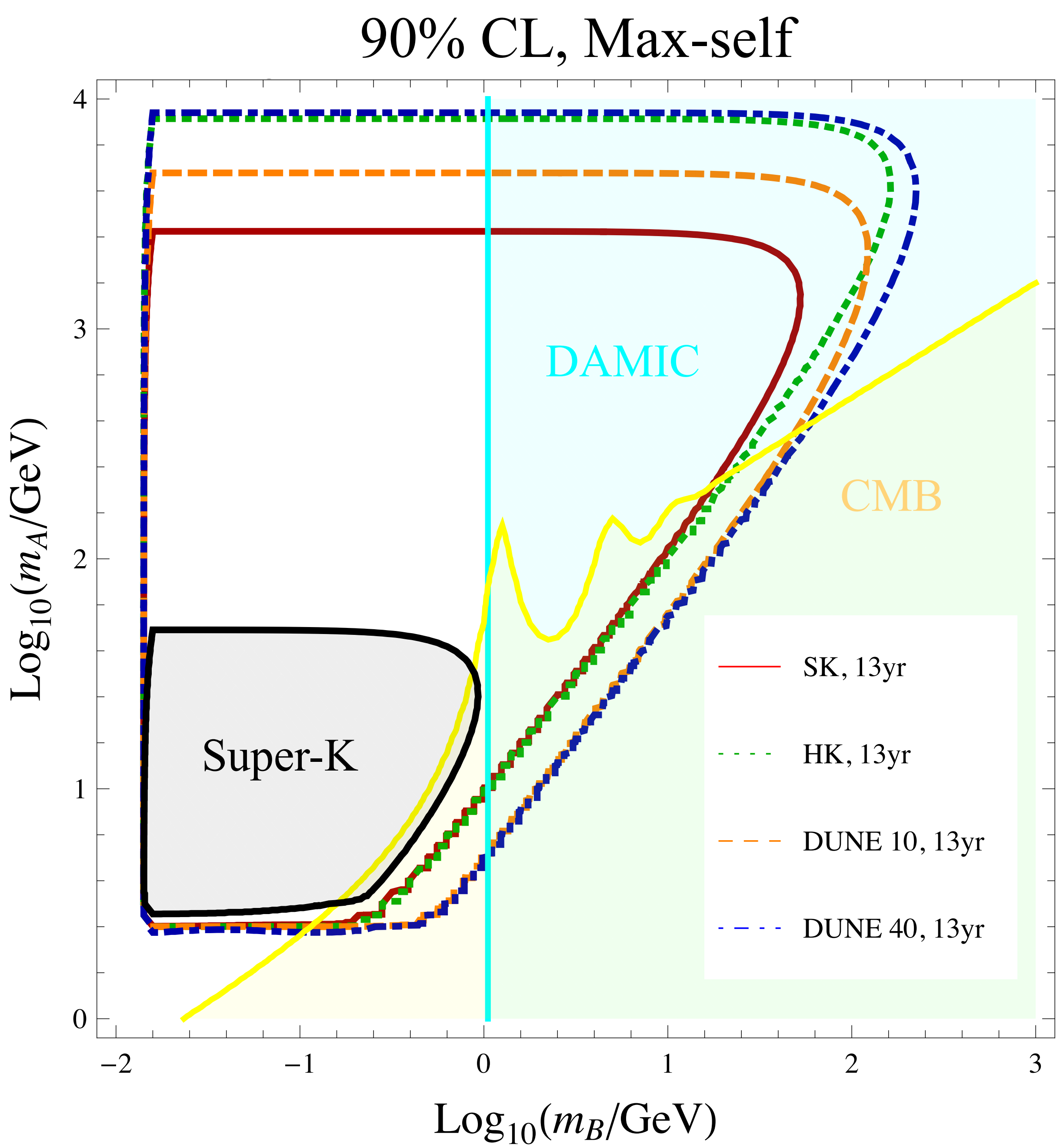
$$0.1\ \mathrm{cm}^2/g < \frac{\sigma_{AA}}{m_A} < 1.25\ \mathrm{cm}^2/g$$

min

max

Matter distribution of bullet cluster





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

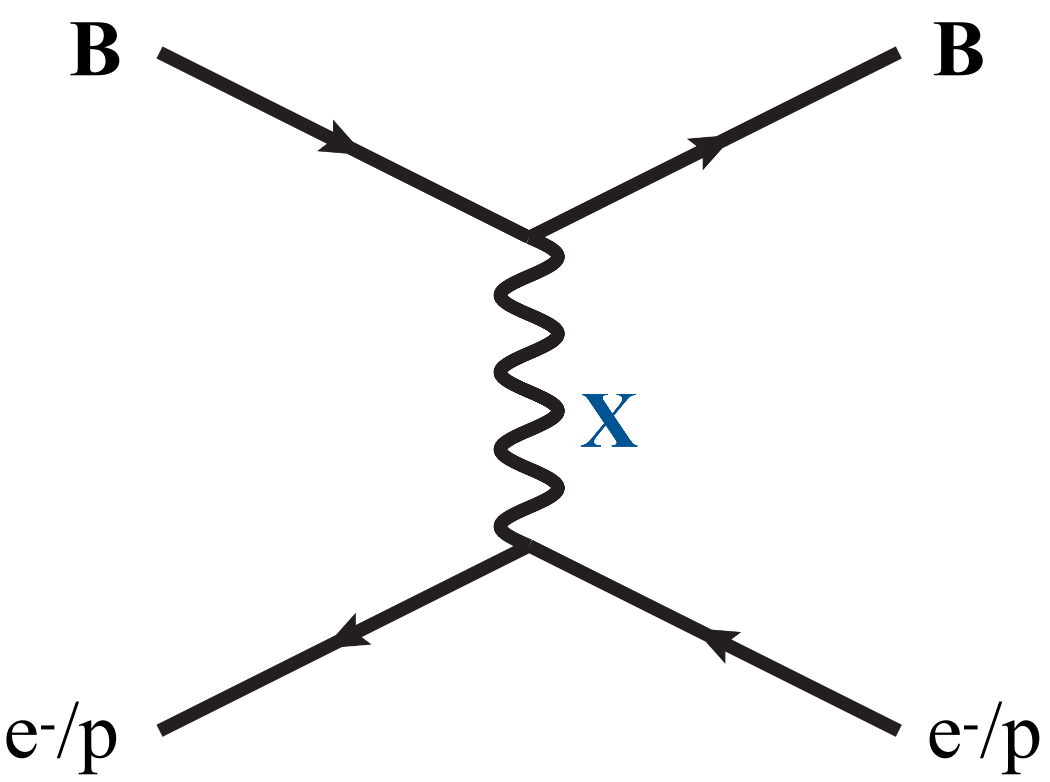
Boosted DM at direct detection experiments

- 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:

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

BDM flux

Scattering cross-section

Effective # of electrons

exposure time

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

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

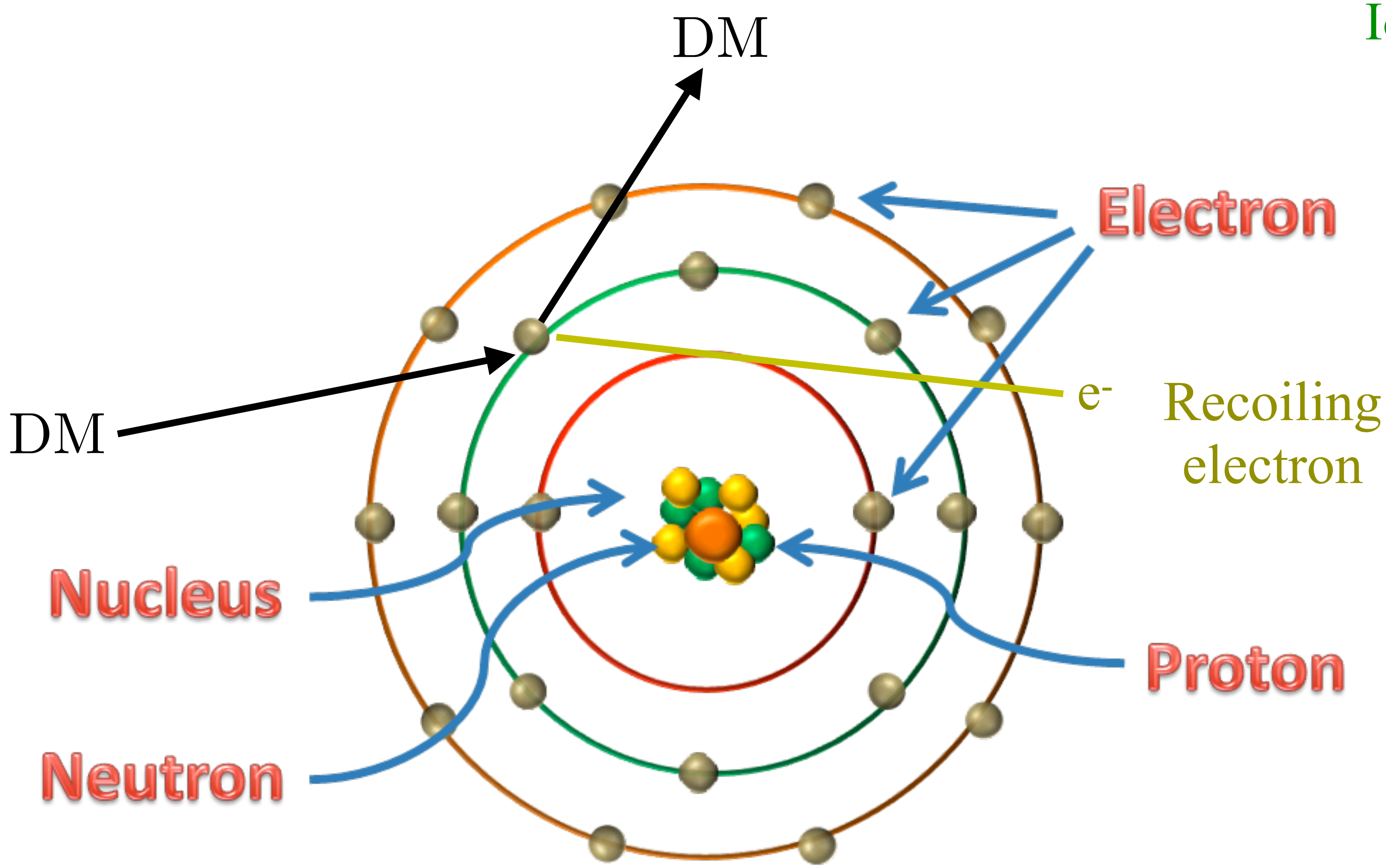
# of Xenon atoms in volume

Differential scattering cross-section

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

Ionization effects:

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



- 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**

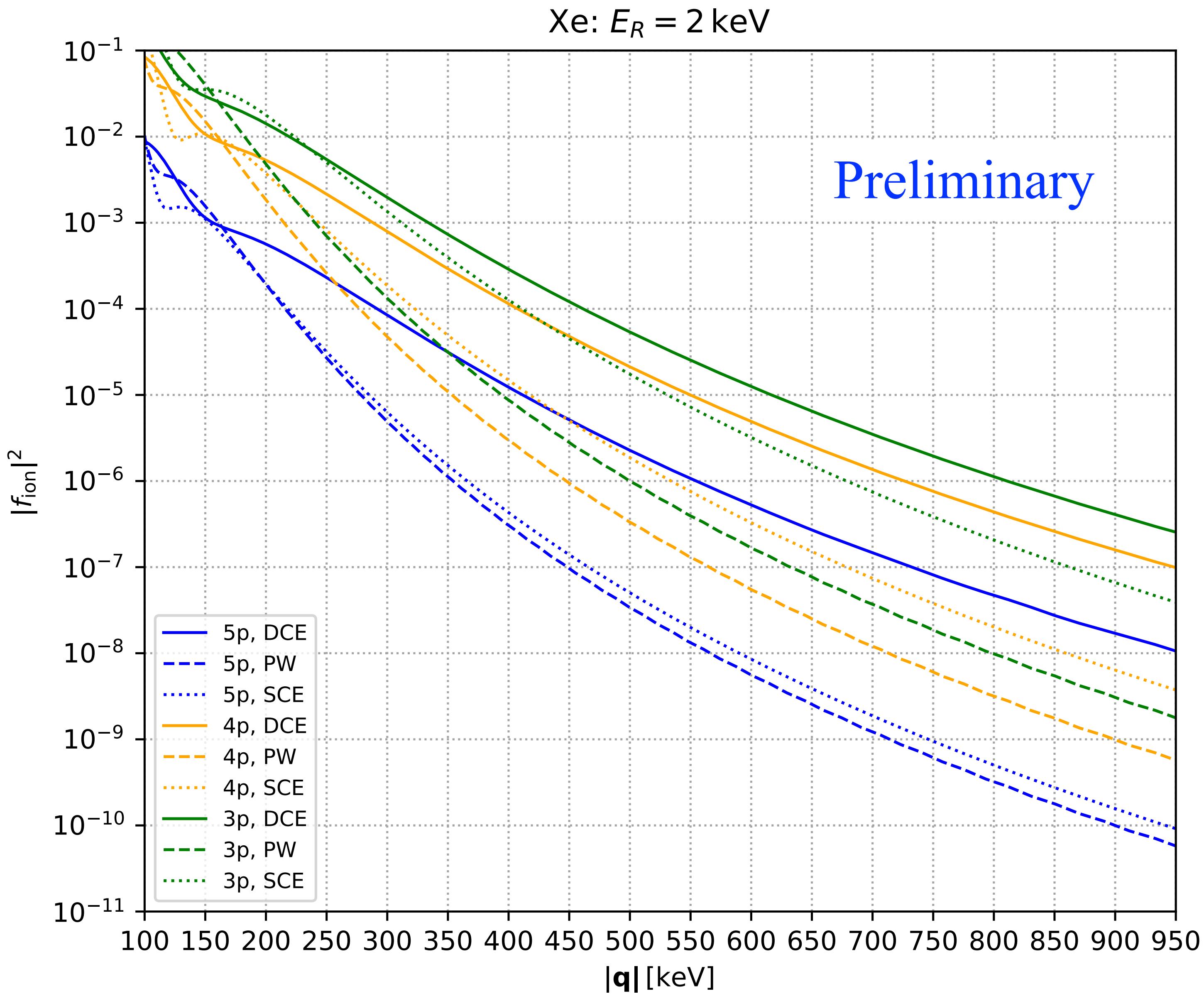
Cao et al: Chin**. Phys. C 45 (2021) 4, 045002** + many others

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**

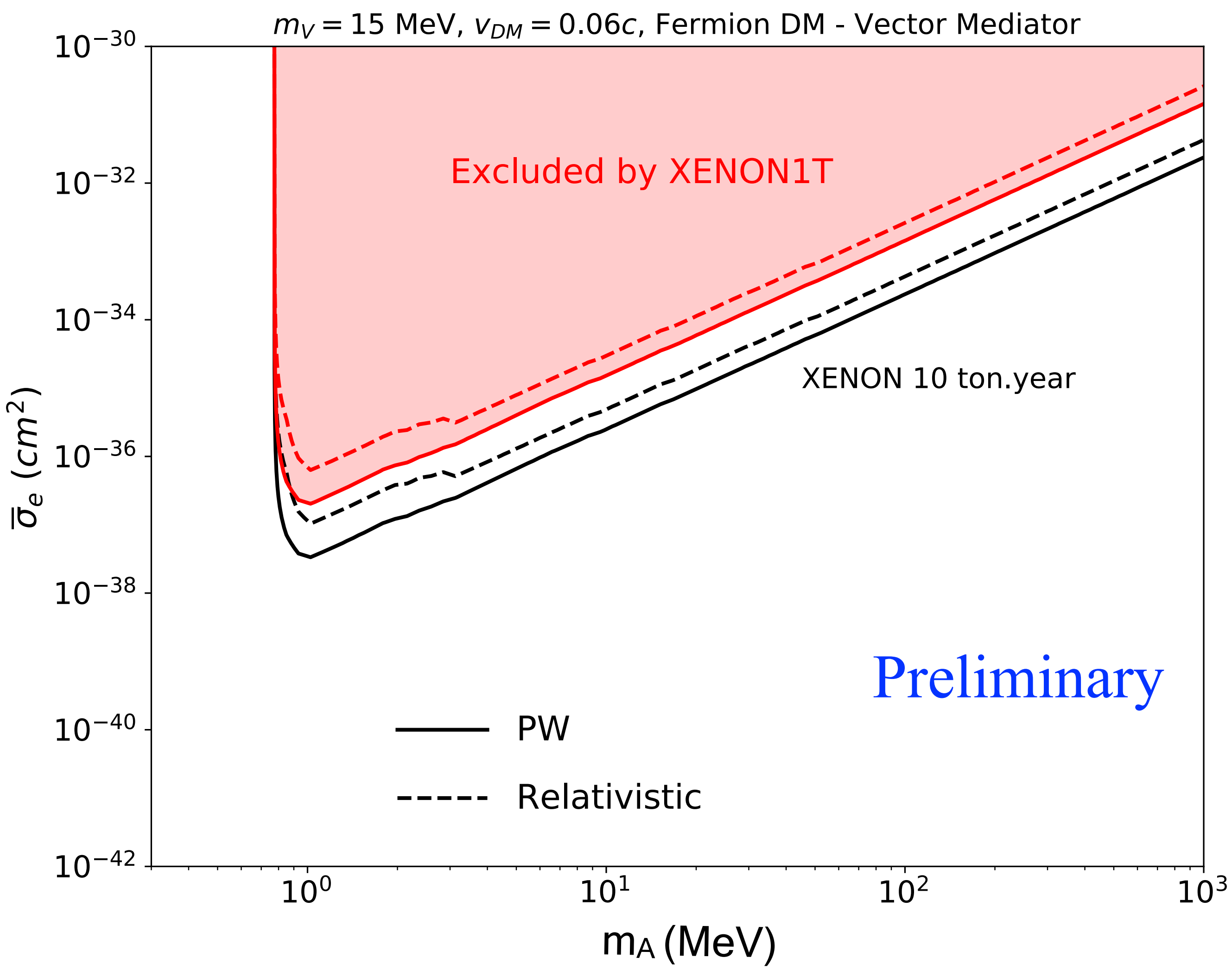
Roberts, Flambaum: **Phys. Rev. D 100 (2019) 063017**

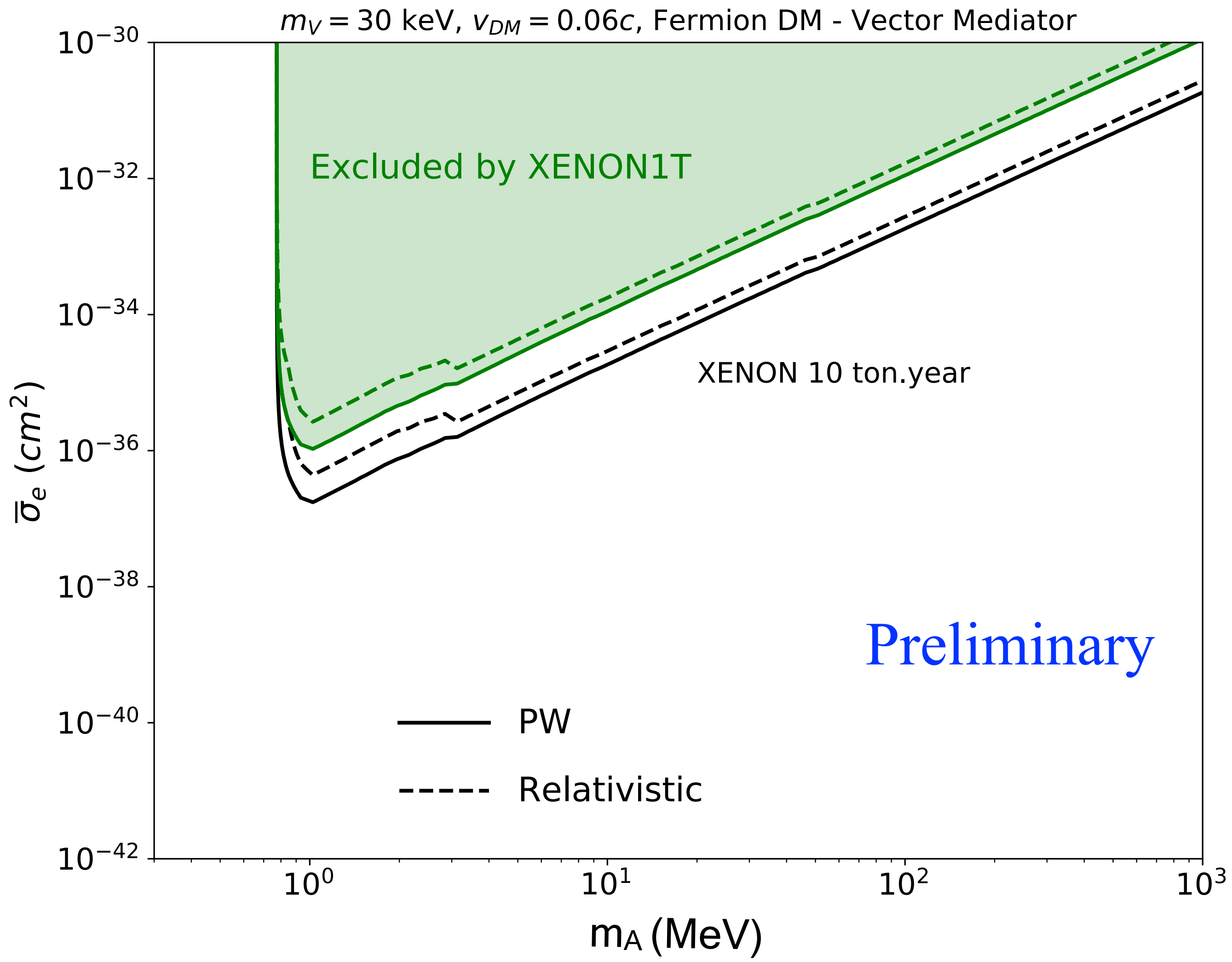
At high momentum transfer, relativistic & PW are different

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

Some Limit plots

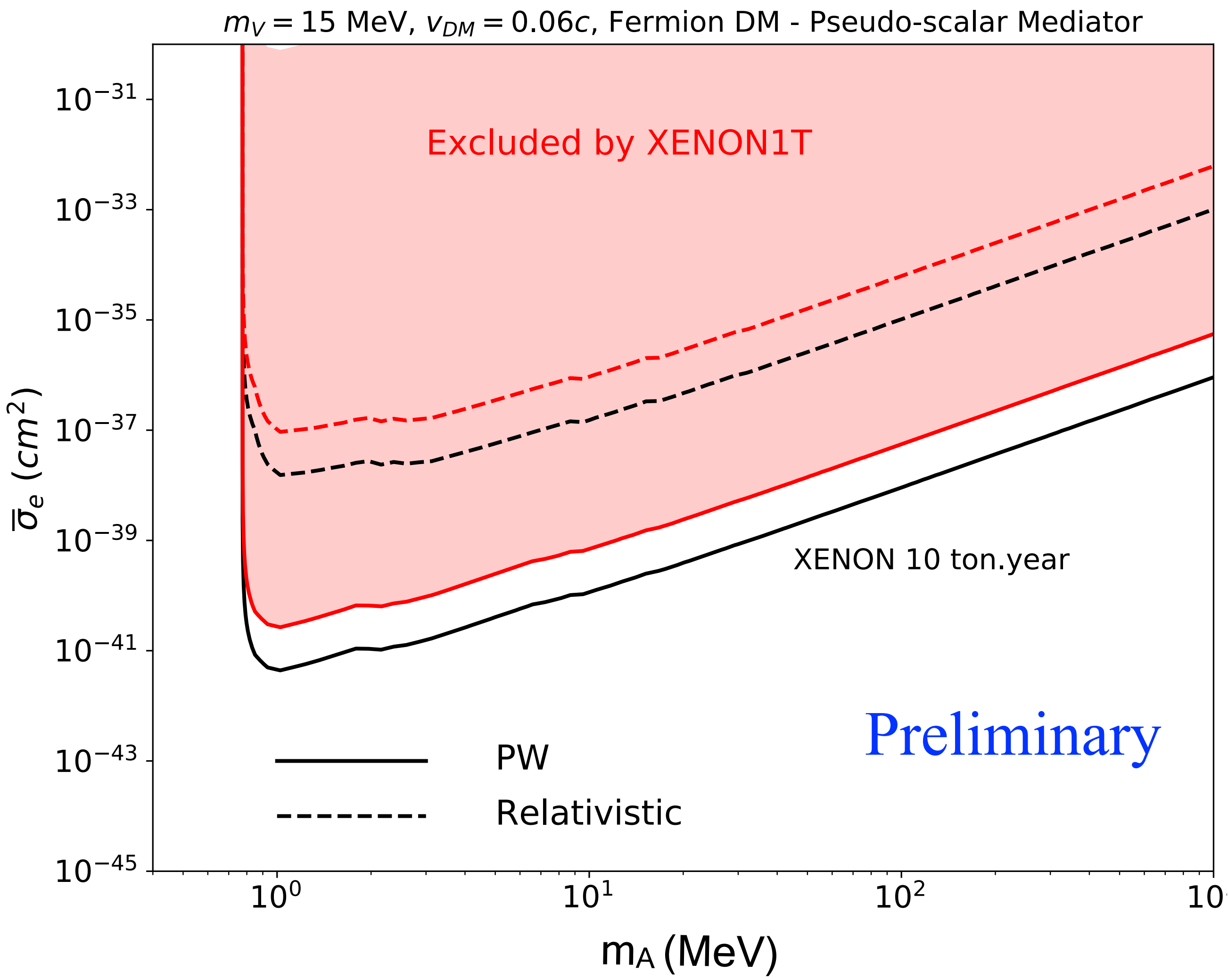
Fermion Dark Matter with a vector mediator

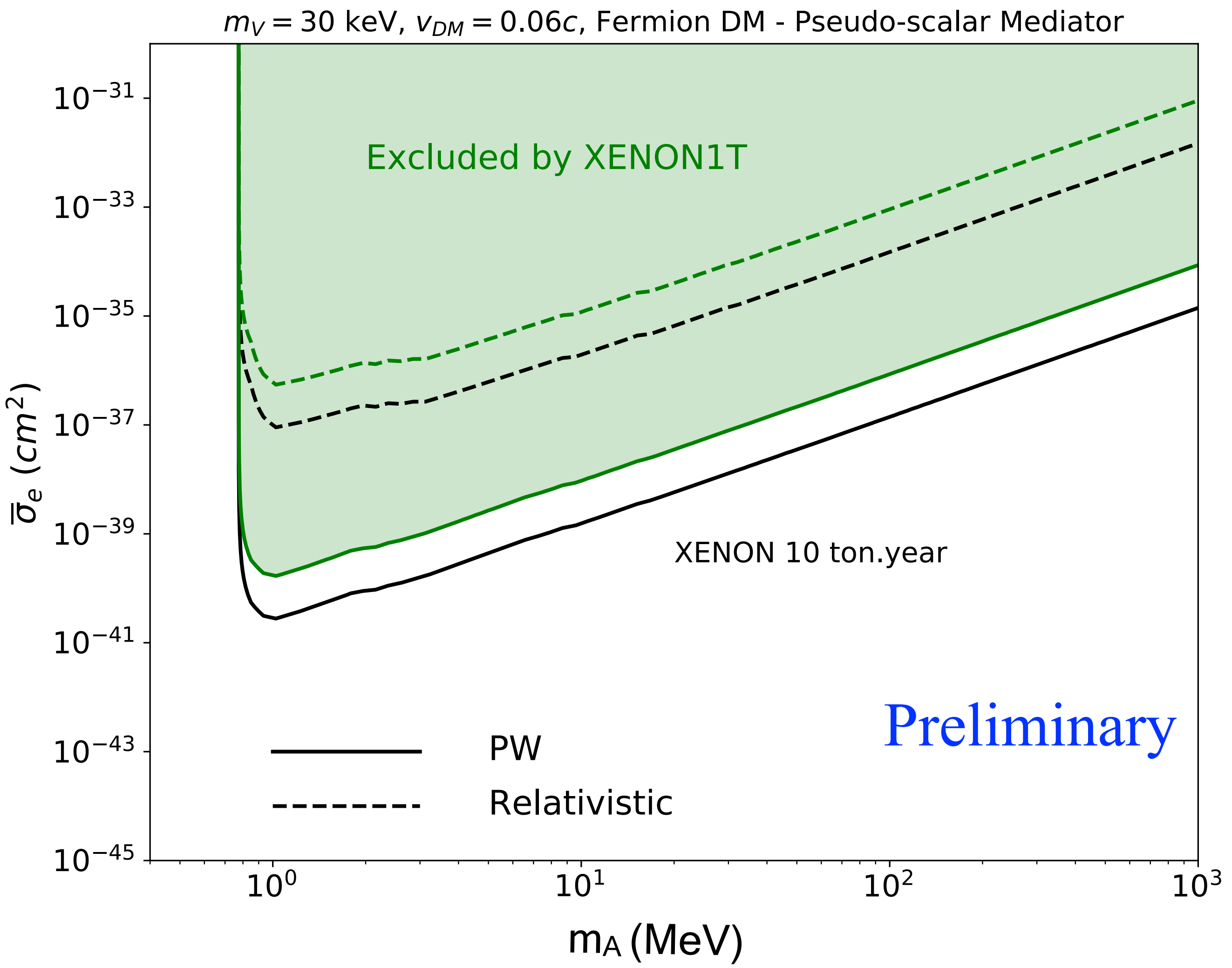




Alhazmi, Kim, Kong, Mohlabeng, Park, Shin: **In Progress**

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 produce interesting signals in direct detection experiments

Atomic effects can be important for accelerated DM-e scattering

Need to be careful when considering atomic effects

Ongoing work, need to include other limits

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

Working on examining ionization effects from general accelerated DM scenarios

Cosmic-ray up-scattered DM

Neutrino up-scattered DM + others

Thank you