Interactions of accelerated dark matter with nuclei: what can we learn from neutrinos?

Helena Kolešová (University of Stavanger)

Joint work with James Alvey, Torsten Bringmann and Richie Diurba
ArXiv: 2209.03360, 2504.16996

Forskningsrådet
Universitetet i Stavanger

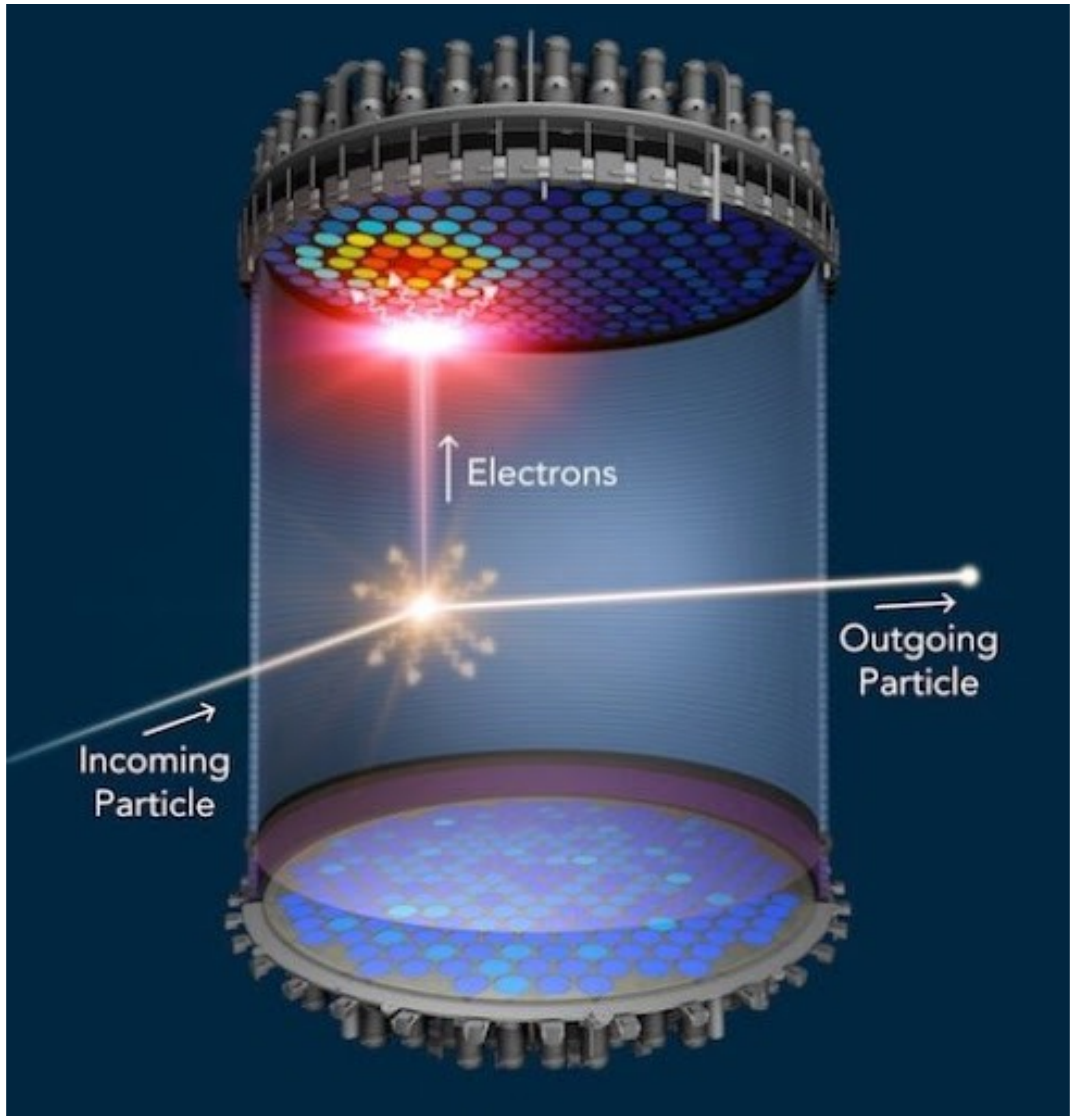
Outline

1. Dark matter detection: typically via coherent elastic scattering (↔ CEνNs)

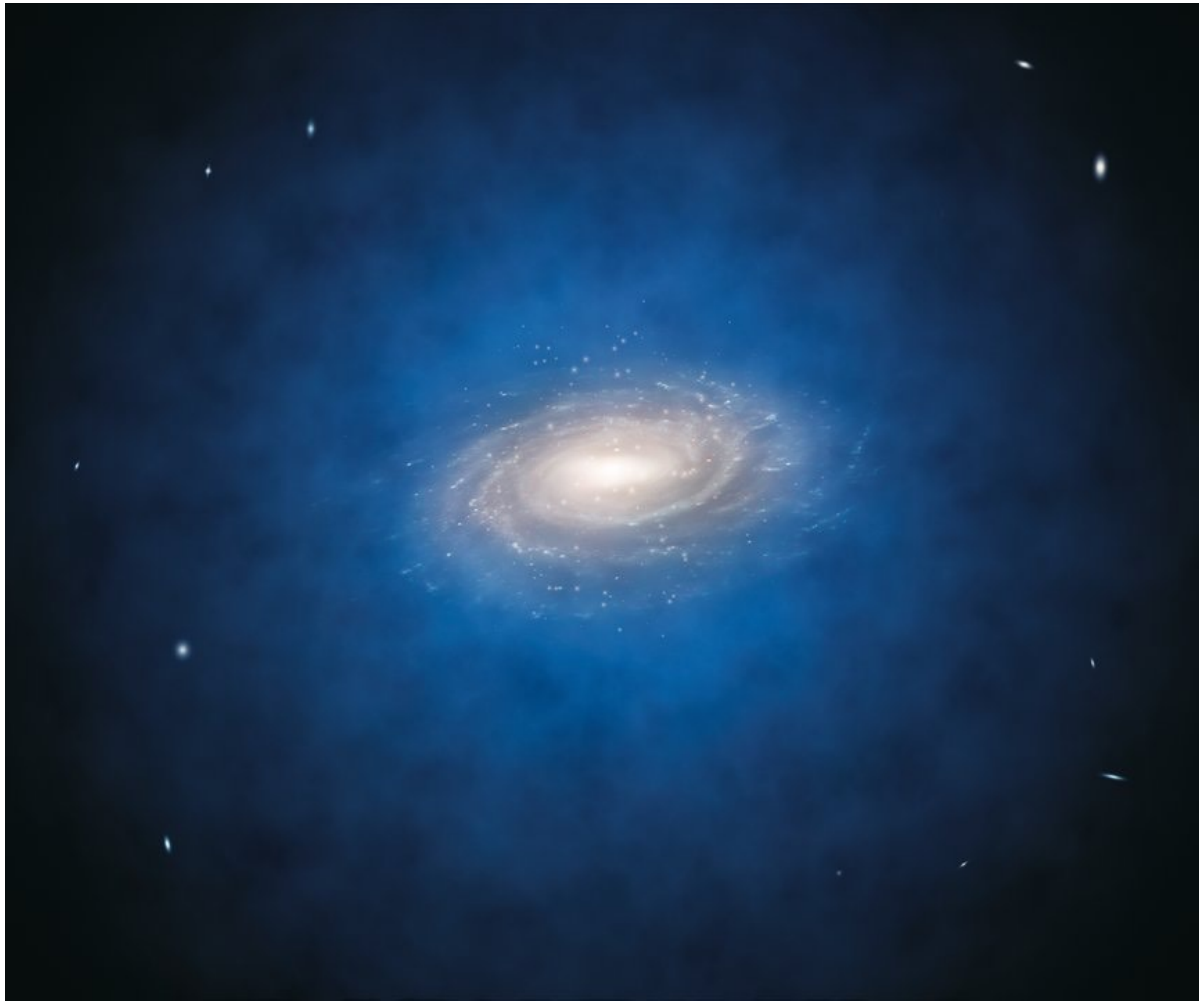
2. Accelerated dark matter: detection via "QE" scattering, resonance production, DIS (↔ accelerator, atmospheric, astrophysical neutrinos)

3. Modelling of dark-matter-nucleus interactions

4. Example: cosmic-ray up-scattered dark matter



“Direct detection” of dark matter



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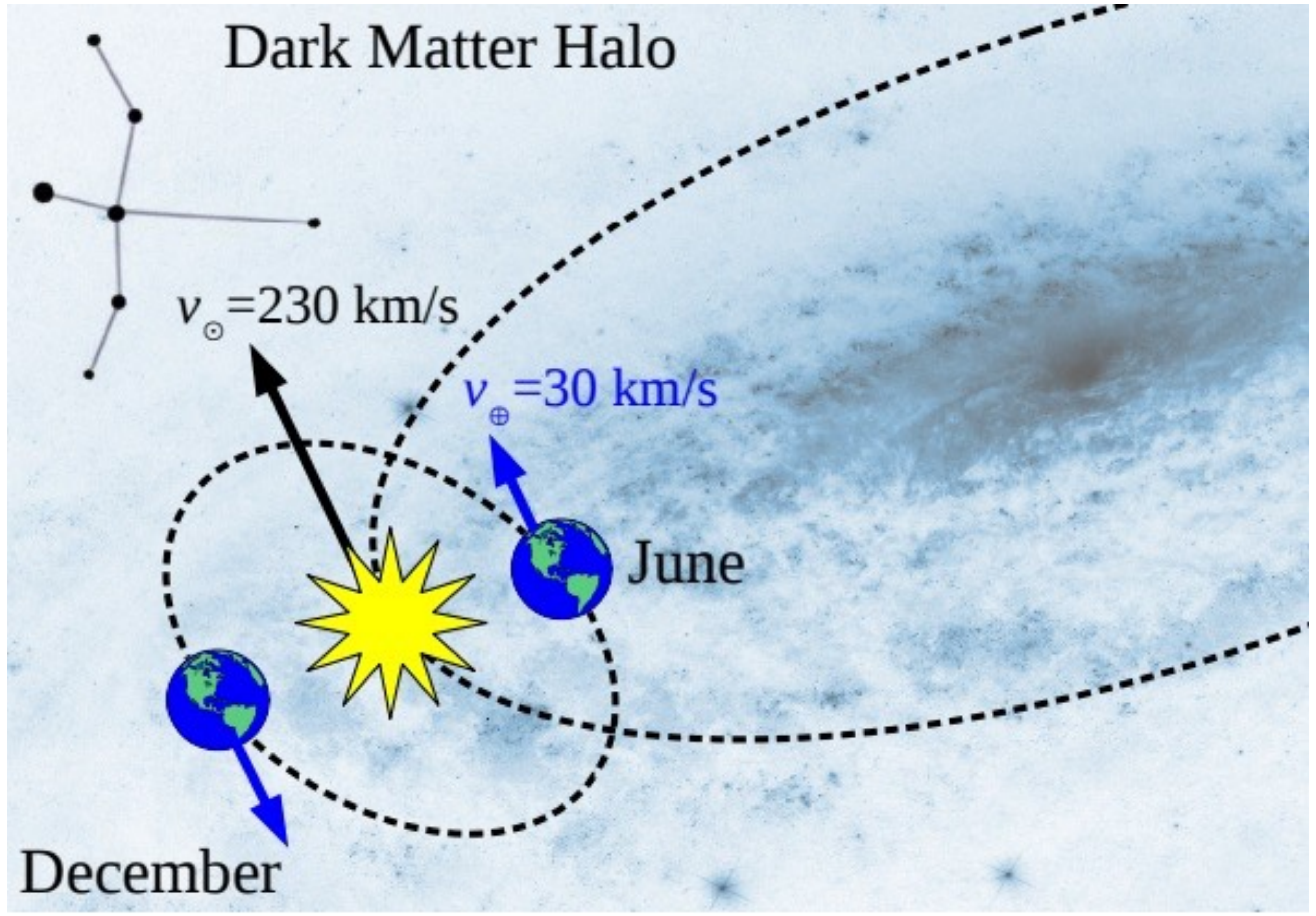
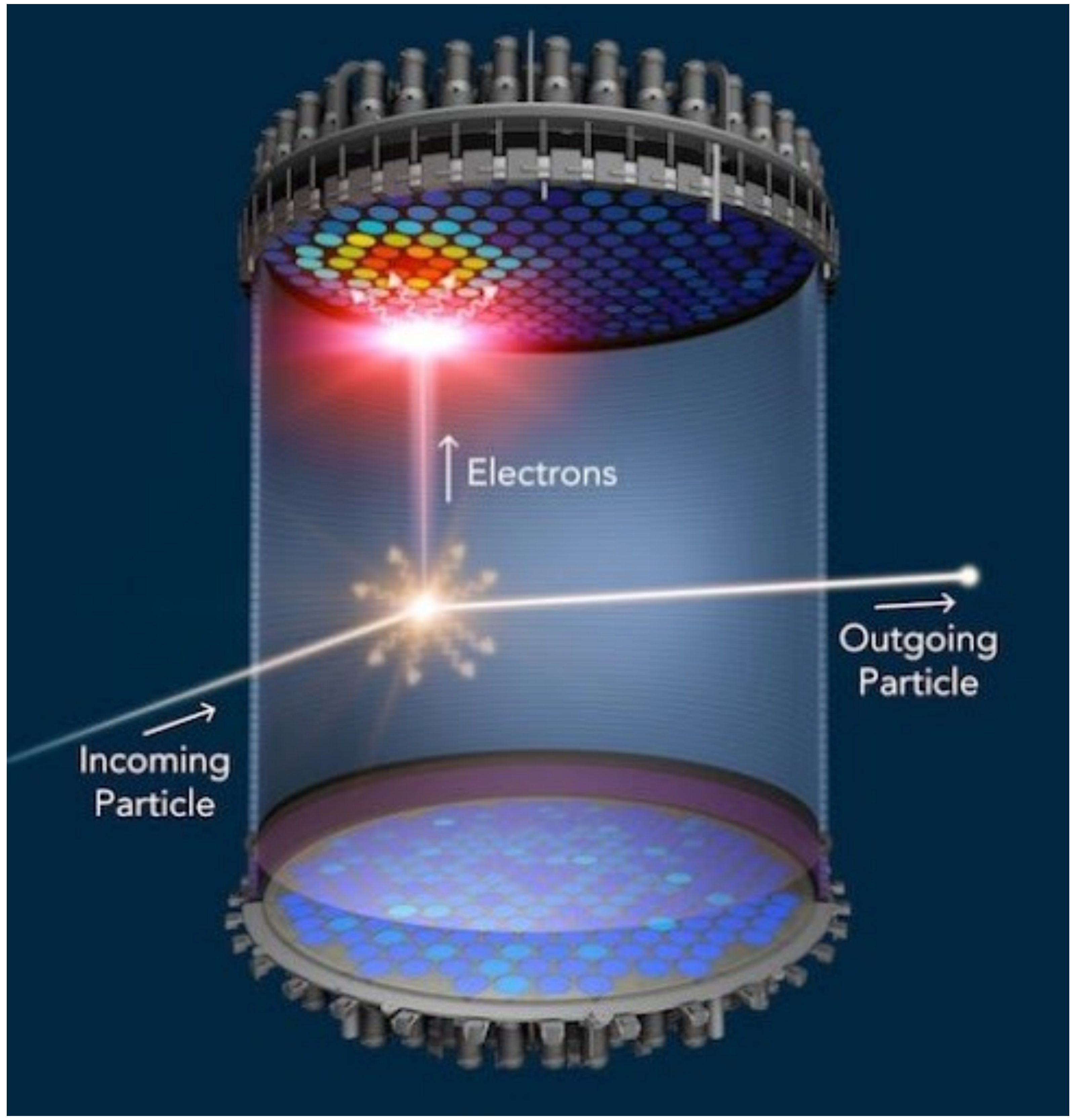


- Relative velocity of dark matter particles with respect to Earth ~ 200 km/s $\sim 10^{-3}\,c$

“Direct detection” of dark matter

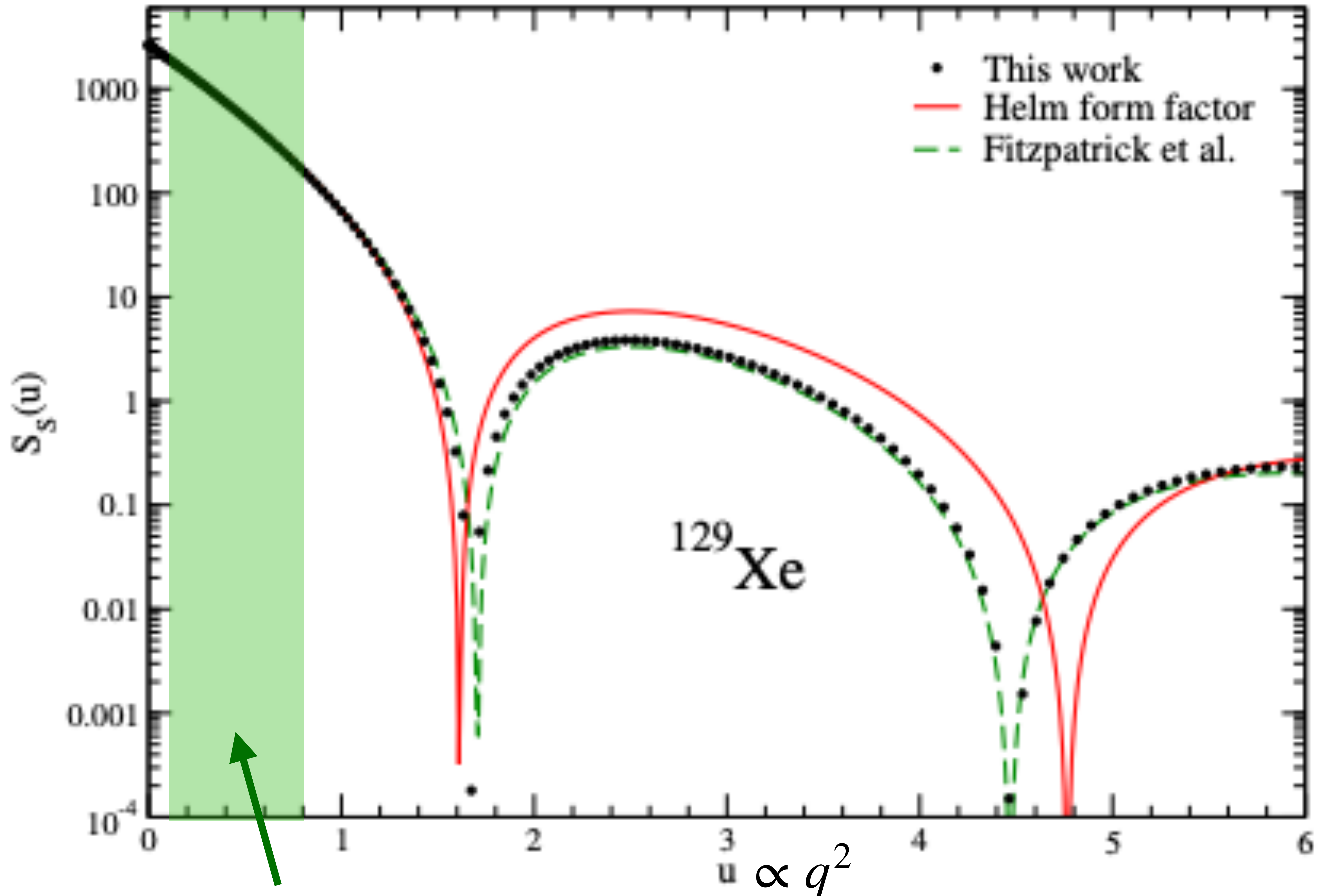


- Relative velocity of dark matter particles with respect to Earth ~ 200 km/s $\sim 10^{-3}\,c$

⇒ Scattering with nuclei in direct detection experiments via coherent elastic scattering

NB: Modeling of coherent elastic cross section

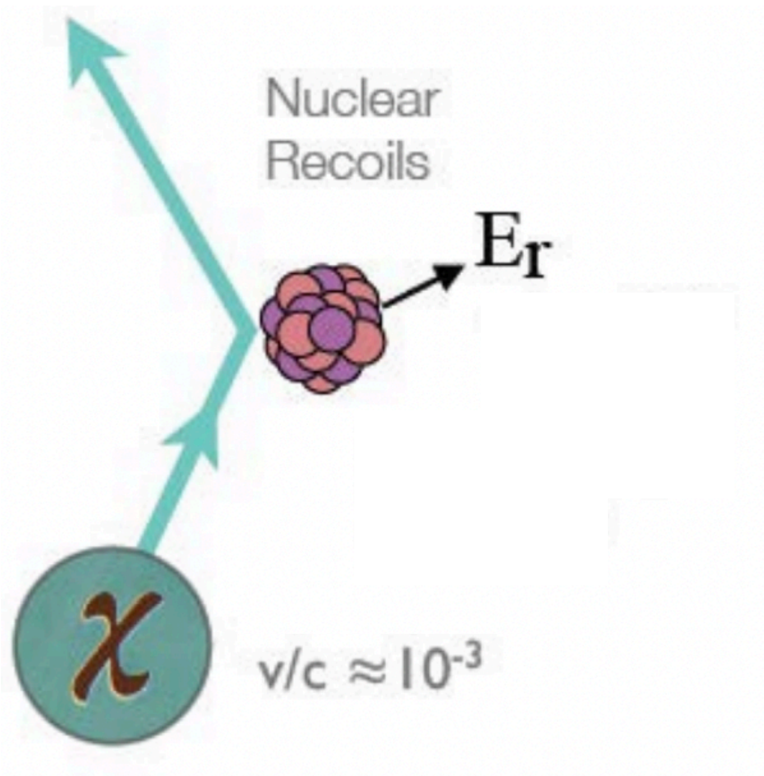
[Vietze et al.: 1412.6091]



Range of q^2 probed by Xenon1T experiment

- $d\sigma/dq^2 \propto S(q)$ - nuclear structure factors/form factors
- Typical recoil energies of the nuclei detectable in direct detection experiments: $\mathcal{O}(\text{keV}) - \mathcal{O}(10\,\text{keV})$

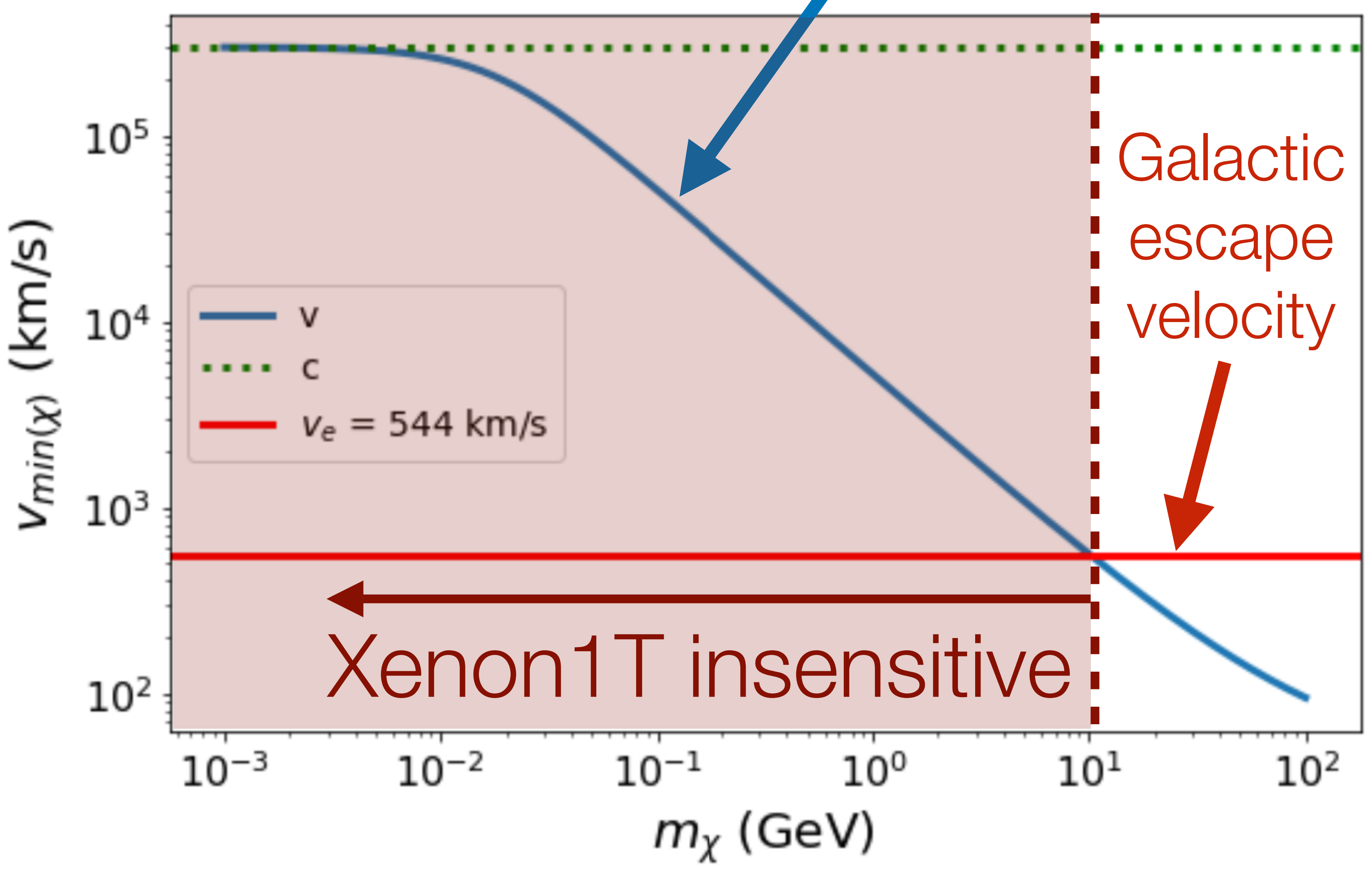
Direct detection of light dark matter?

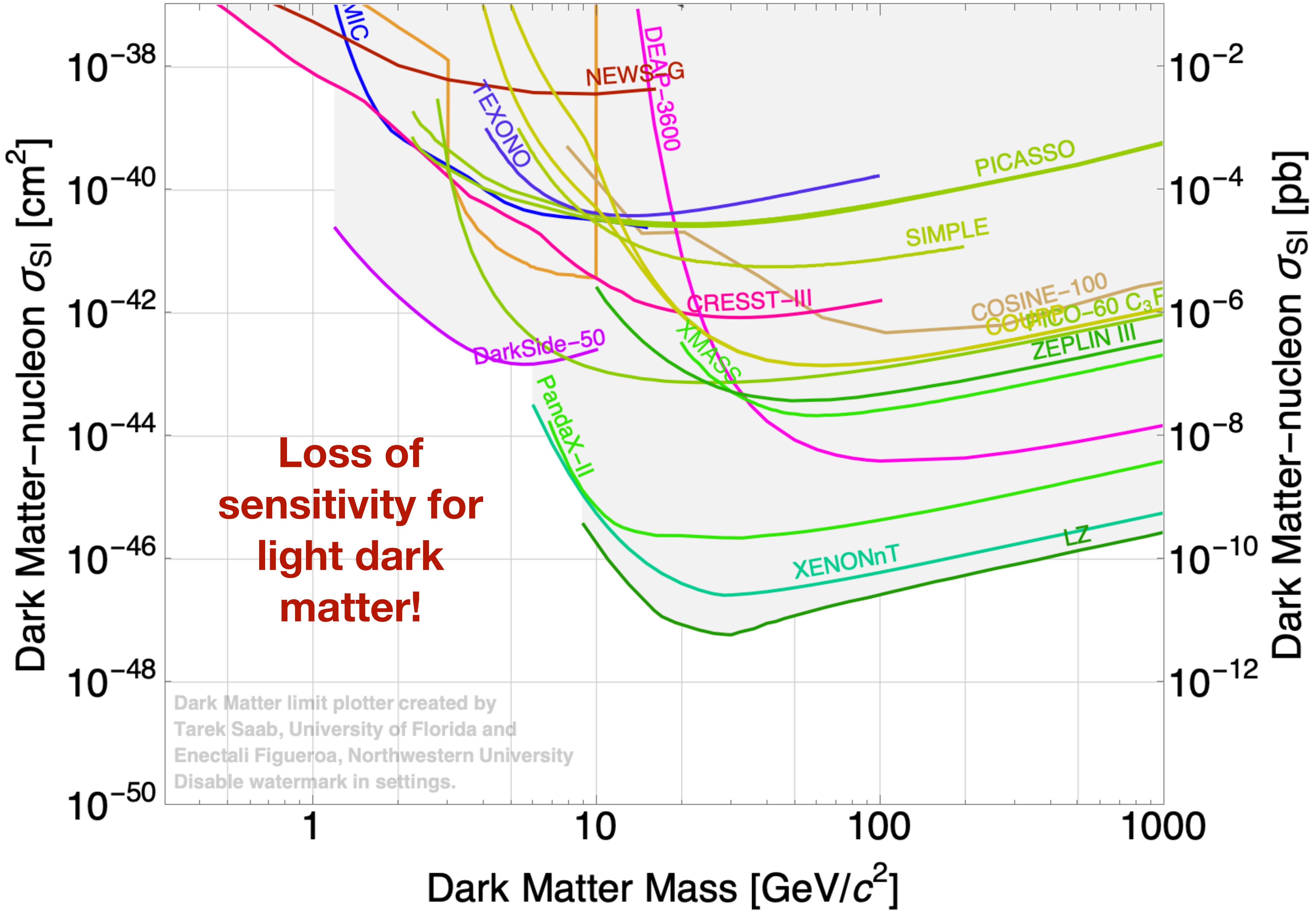


Example: Xenon1T threshold for nucleus recoil energy:

$E_r \gtrsim 5$ keV

⇒ Minimal dark matter velocity to trigger detectable nuclear recoil





Direct detection: model dependence

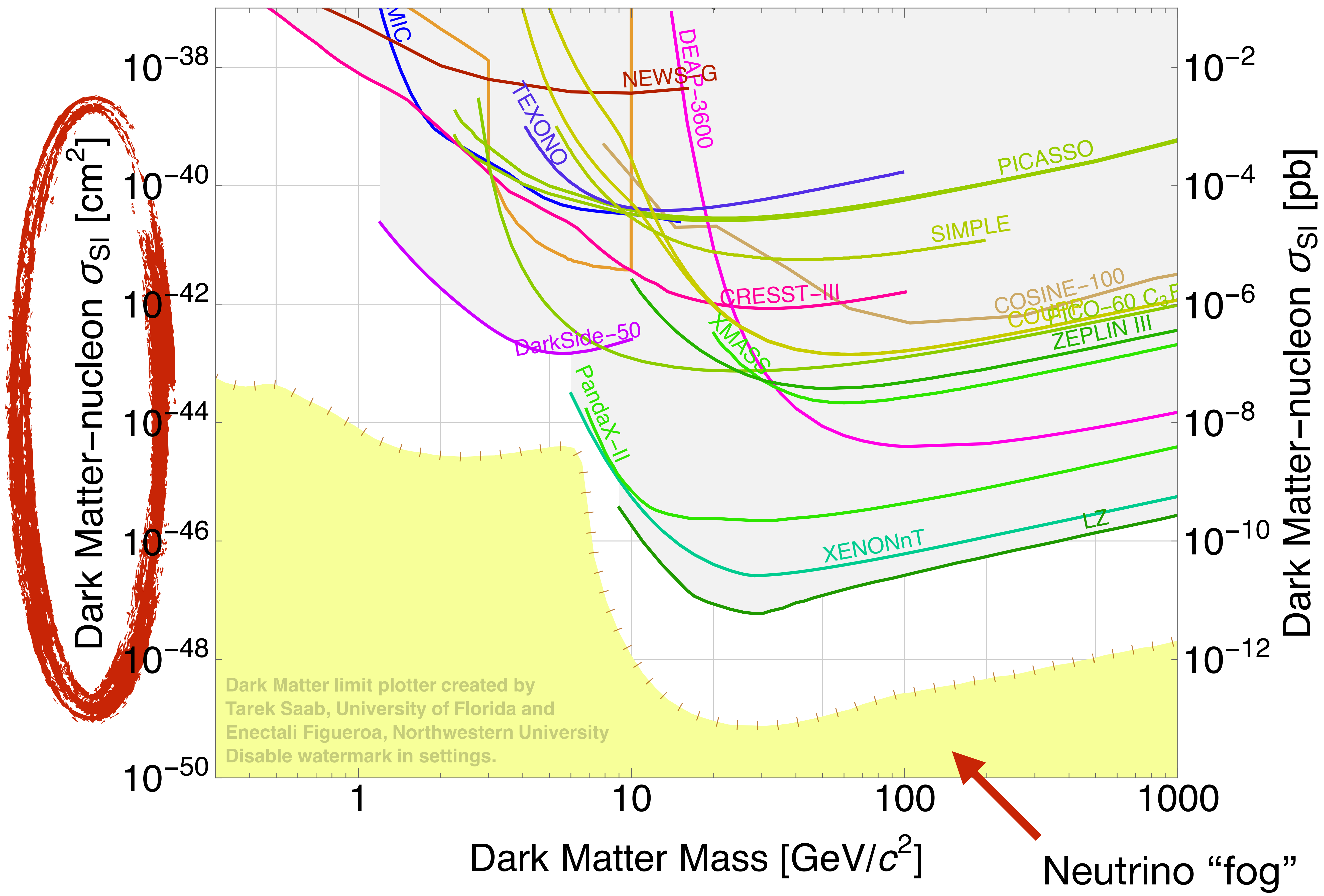
Spin-independent interactions

- Coherently enhanced:

$$\sigma_{\chi A} \propto A^2 \frac{\mu_{\chi A}^2}{\mu_{\chi p}^2} \sigma_{SI}$$

(cross sections in non-relativistic limit)

- Realised, e.g., for DM-quark interaction via scalar or vector mediator

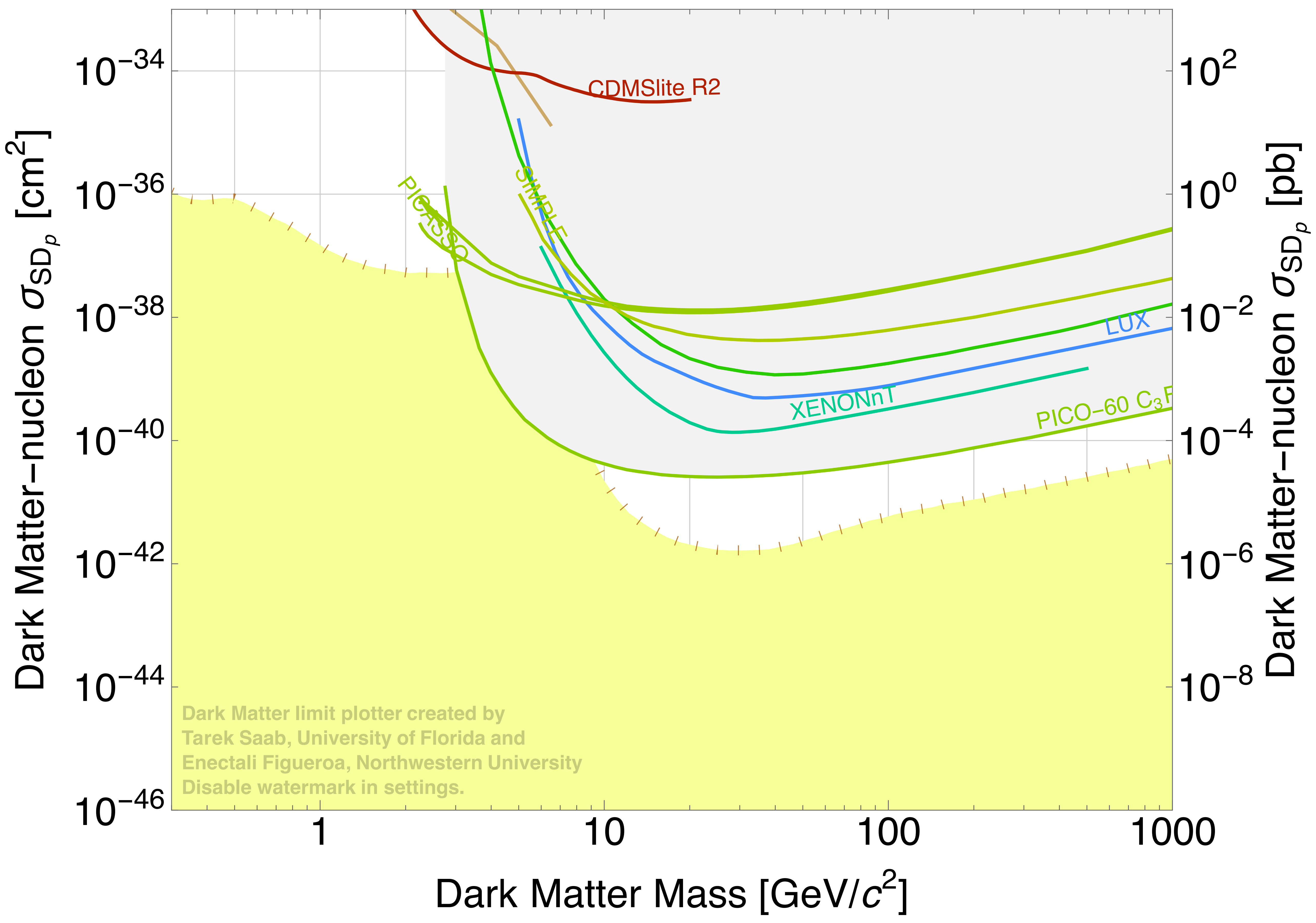


Neutrino “fog”

Direct detection: model dependence

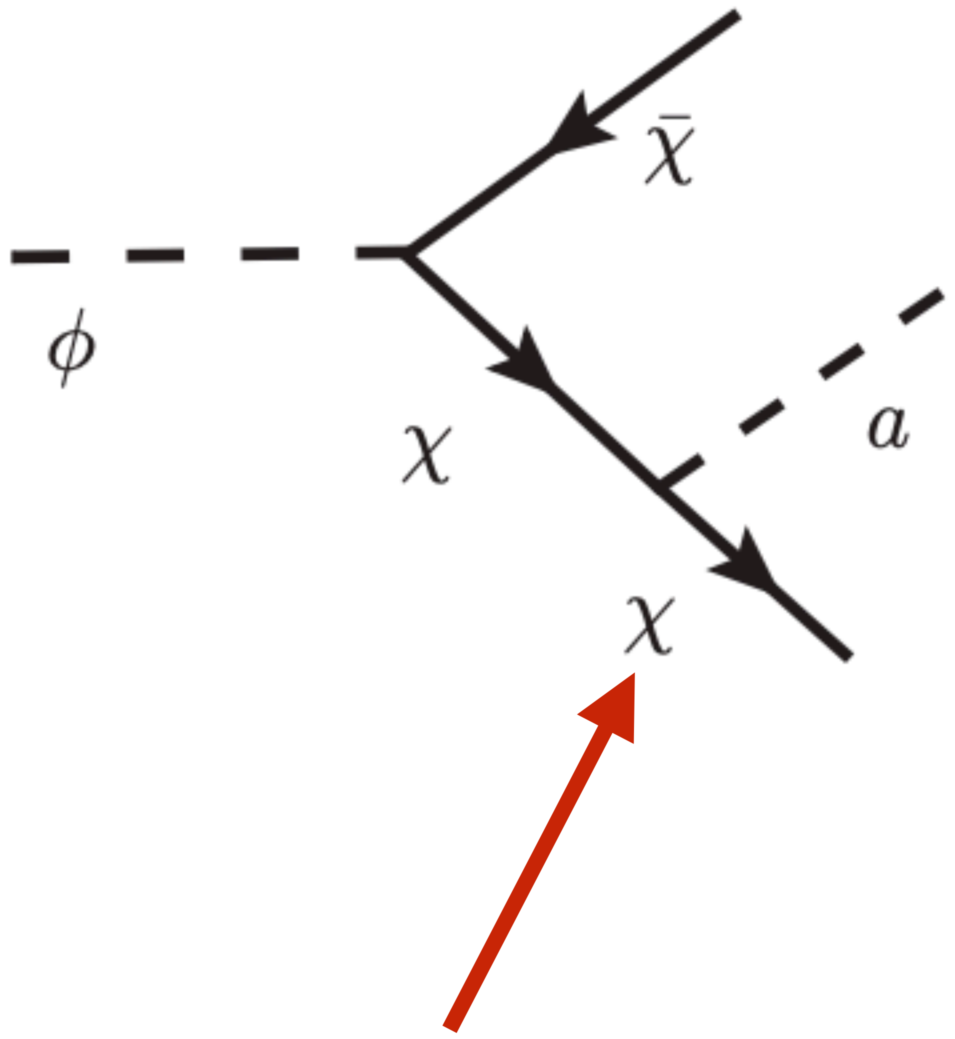
Spin-dependent interactions

- No A^2 enhancement, depend on the spin structure of the nucleus
- Realised, e.g., for DM-quark interaction via mediator with axial-vector couplings
- Much weaker constraints!

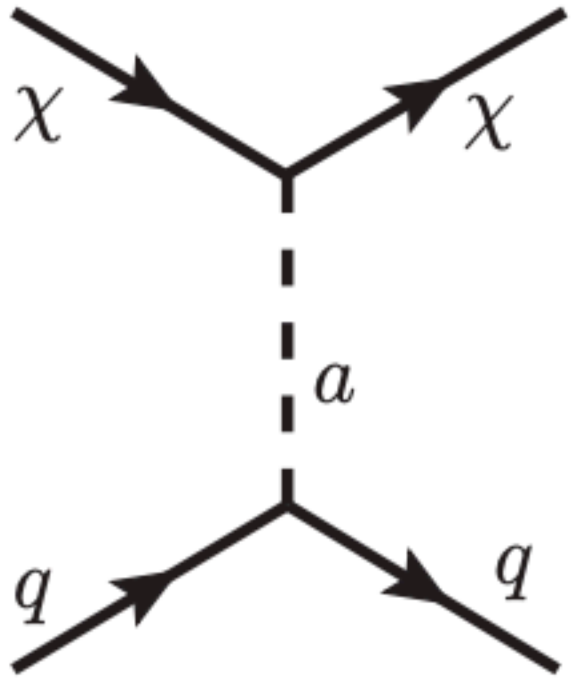


Accelerated dark particles

Example 1: Boosted dark particles from decays of heavy dark matter



Boosted dark fermion



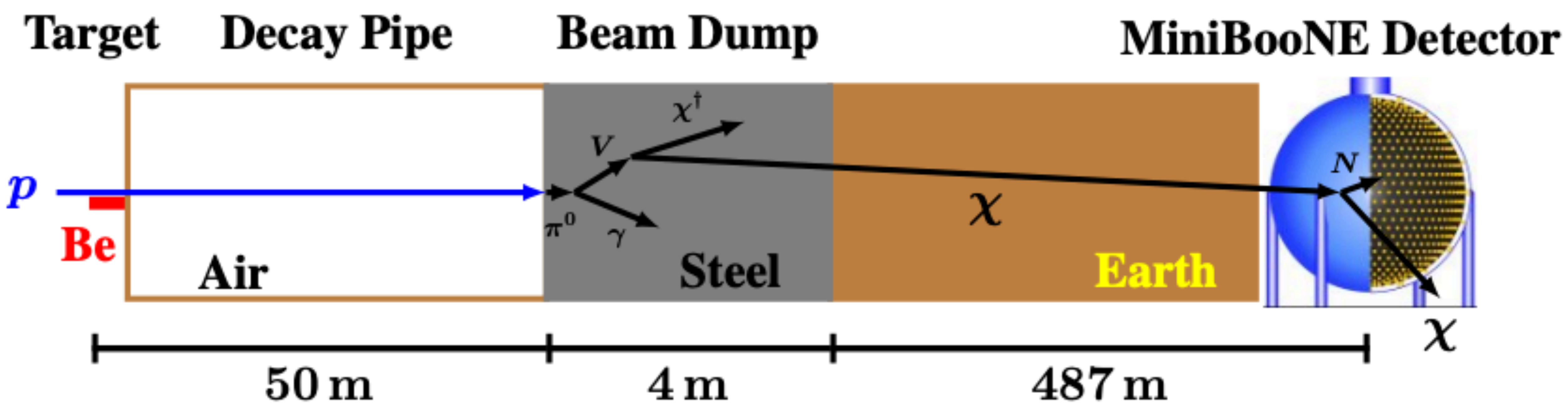
Interaction with quarks: boosted dark particles can mimic astrophysical neutrino events in IceCUBE if $m_\phi \sim \mathcal{O}$(PeV)

[Kopp, Liu, Wang: 1503.02669]

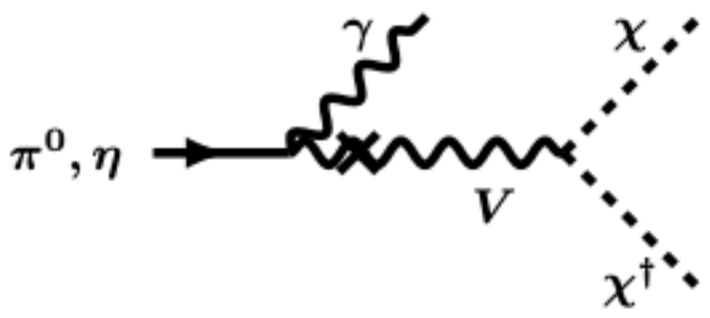
Accelerated dark particles

Example 2: Dark matter produced in beam dump

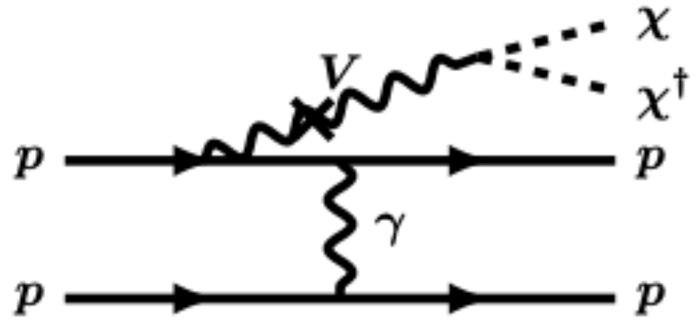
[MiniBooNE-DM Collaboration: 1807.06137]



Dark matter production:

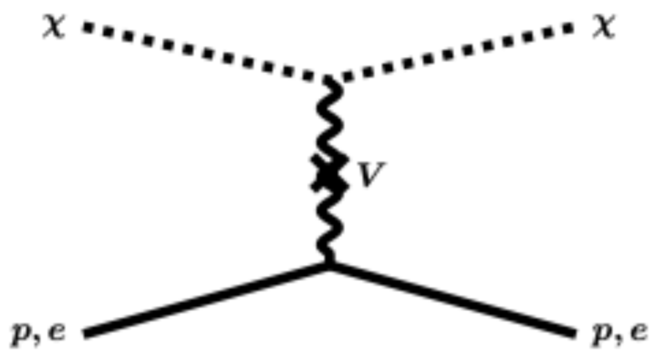


(a) Meson Decay

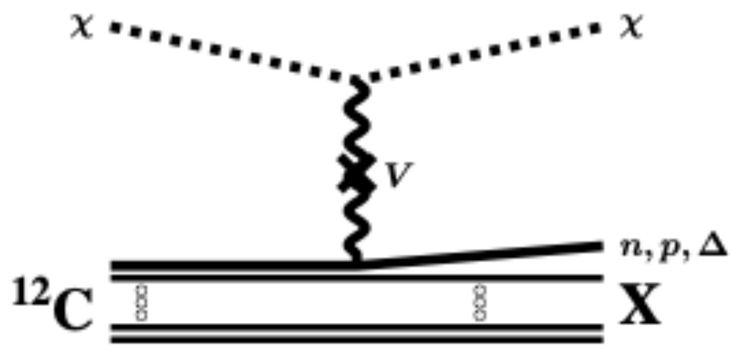


(b) Proton Bremsstrahlung + Vector-Mixing

Dark matter detection:



(a) Free Protons or Electrons

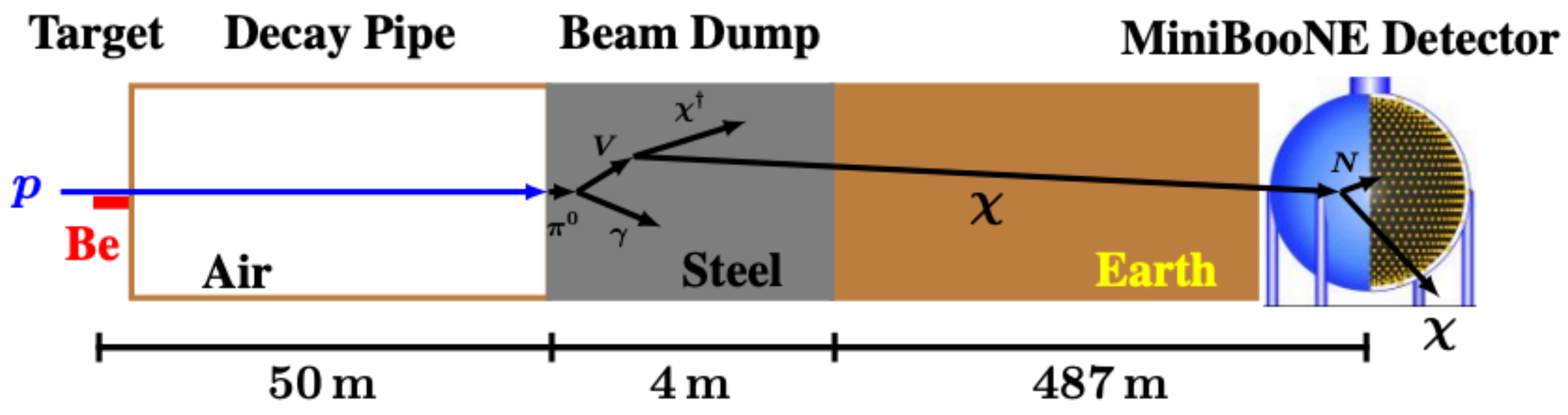


(b) Bound Nucleons

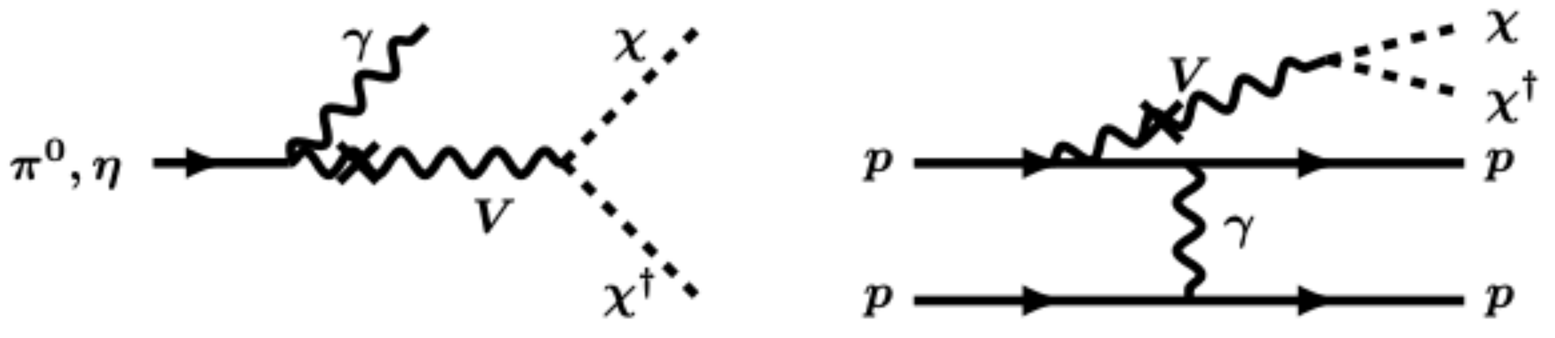
Accelerated dark particles

Example 2: Dark matter produced in beam dump

[MiniBooNE-DM Collaboration: 1807.06137]



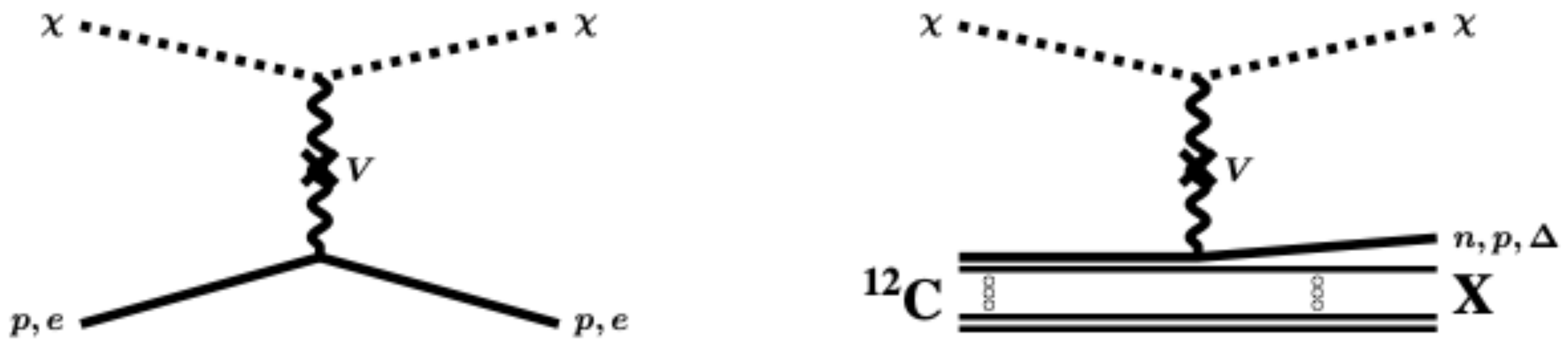
Dark matter production:



(a) Meson Decay

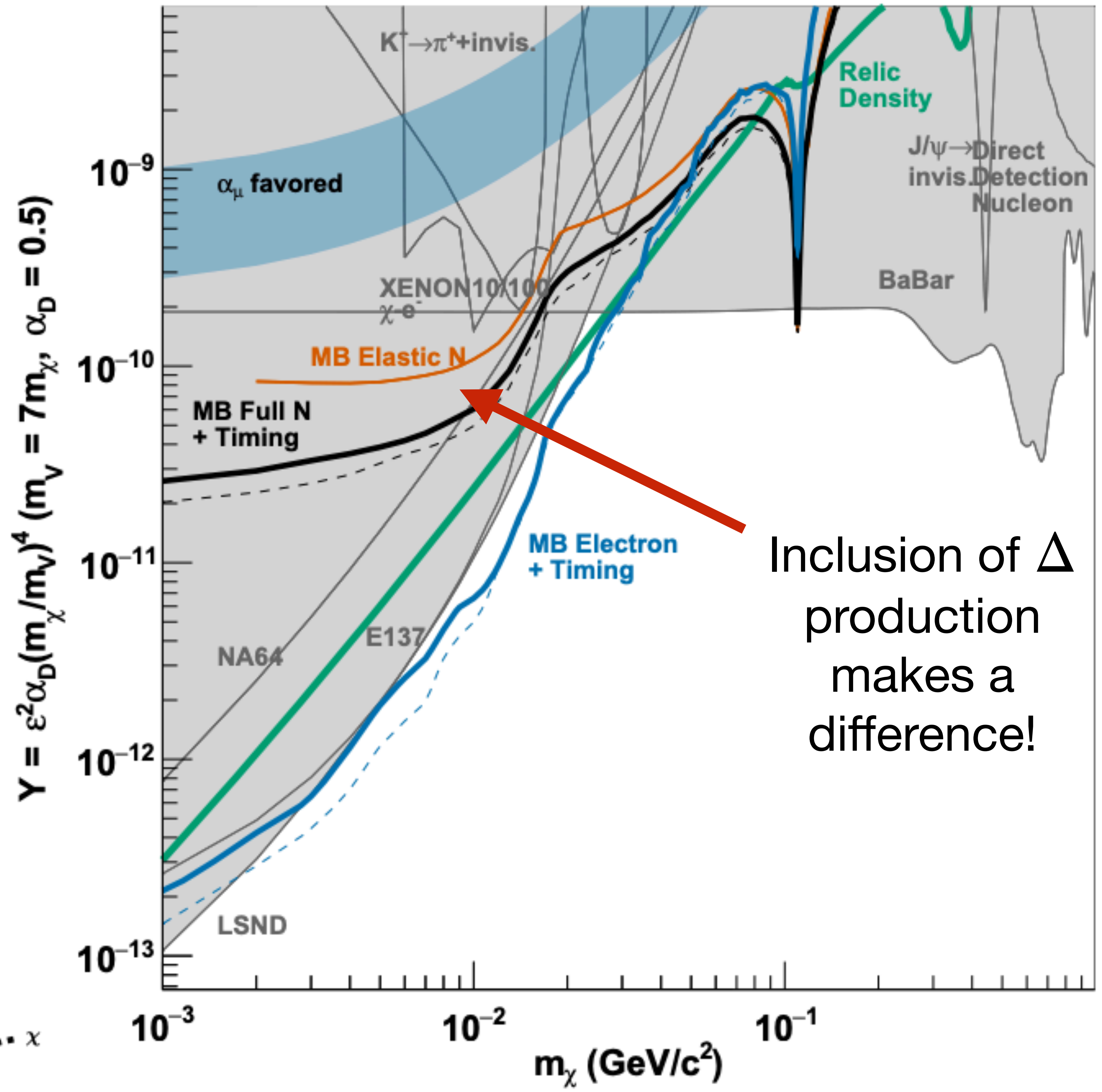
(b) Proton Bremsstrahlung + Vector-Mixing

Dark matter detection:



(a) Free Protons or Electrons

(b) Bound Nucleons

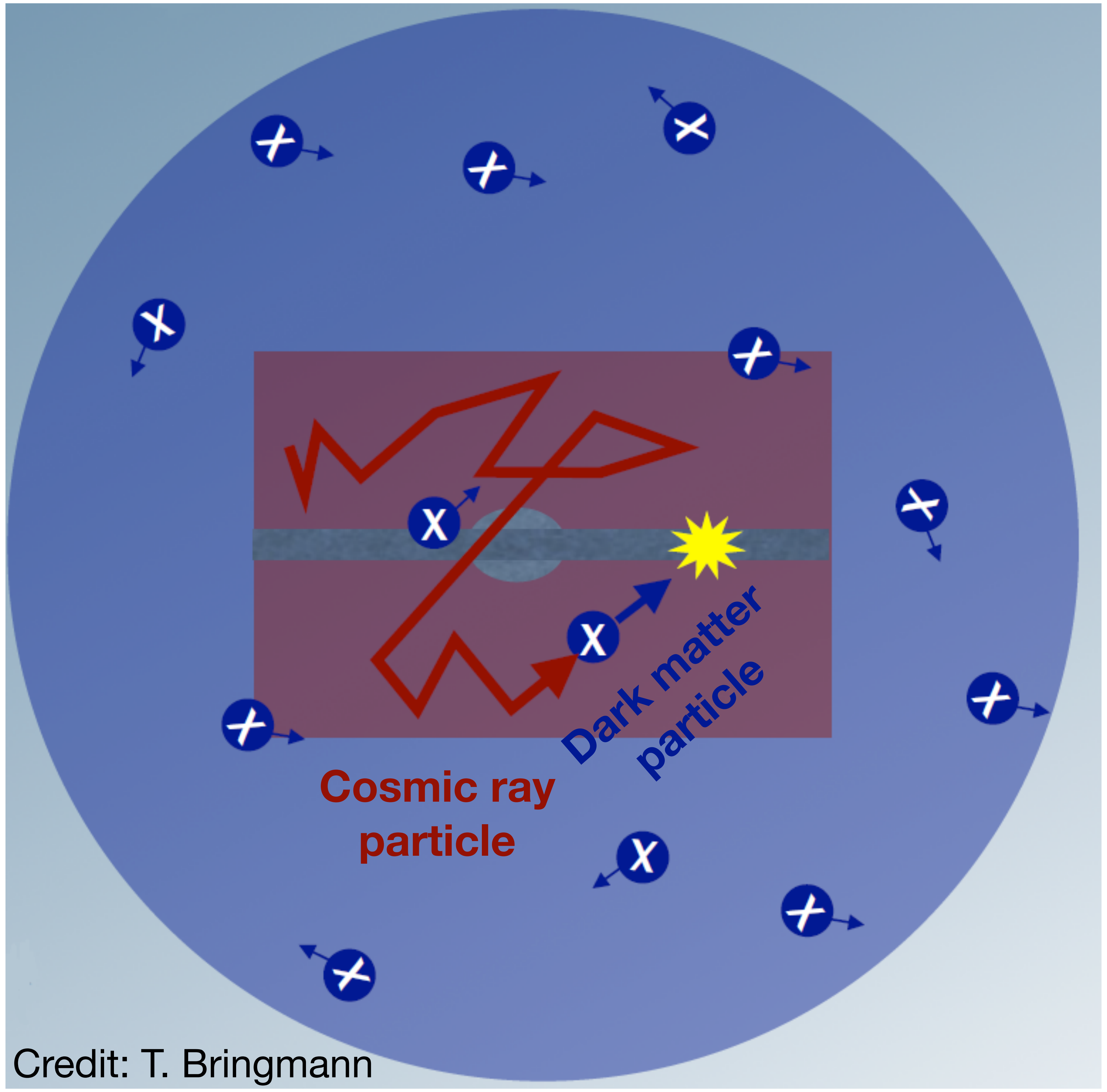


(b) vector portal ($\alpha_D = 0.5, m_V = 7m_\chi$)

Inclusion of Δ production makes a difference!

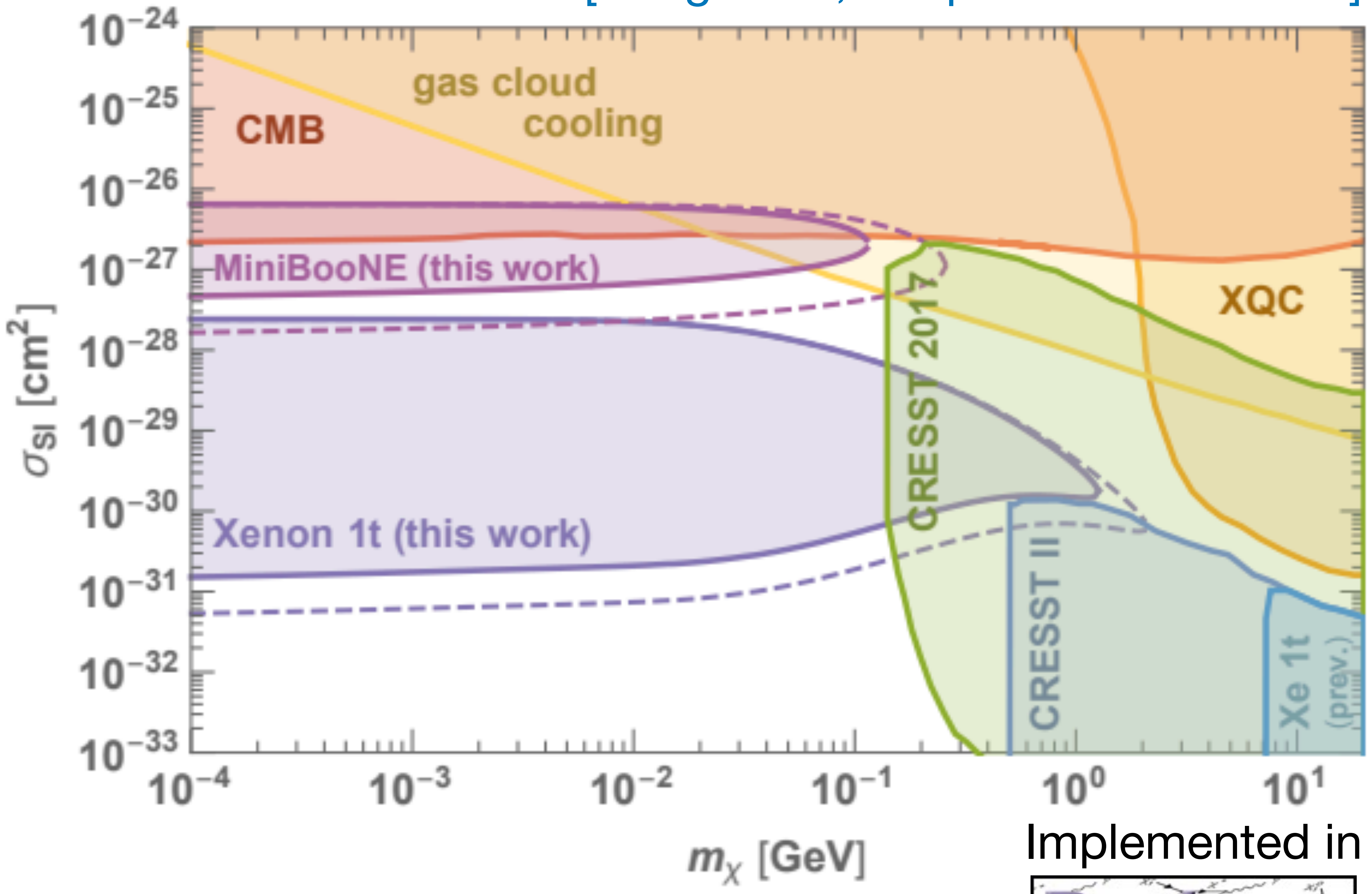
Accelerated dark particles

Example 3: Cosmic-ray up-scattered dark matter (CRDM)



Credit: T. Bringmann

[Bringmann, Pospelov: 1810.10543]

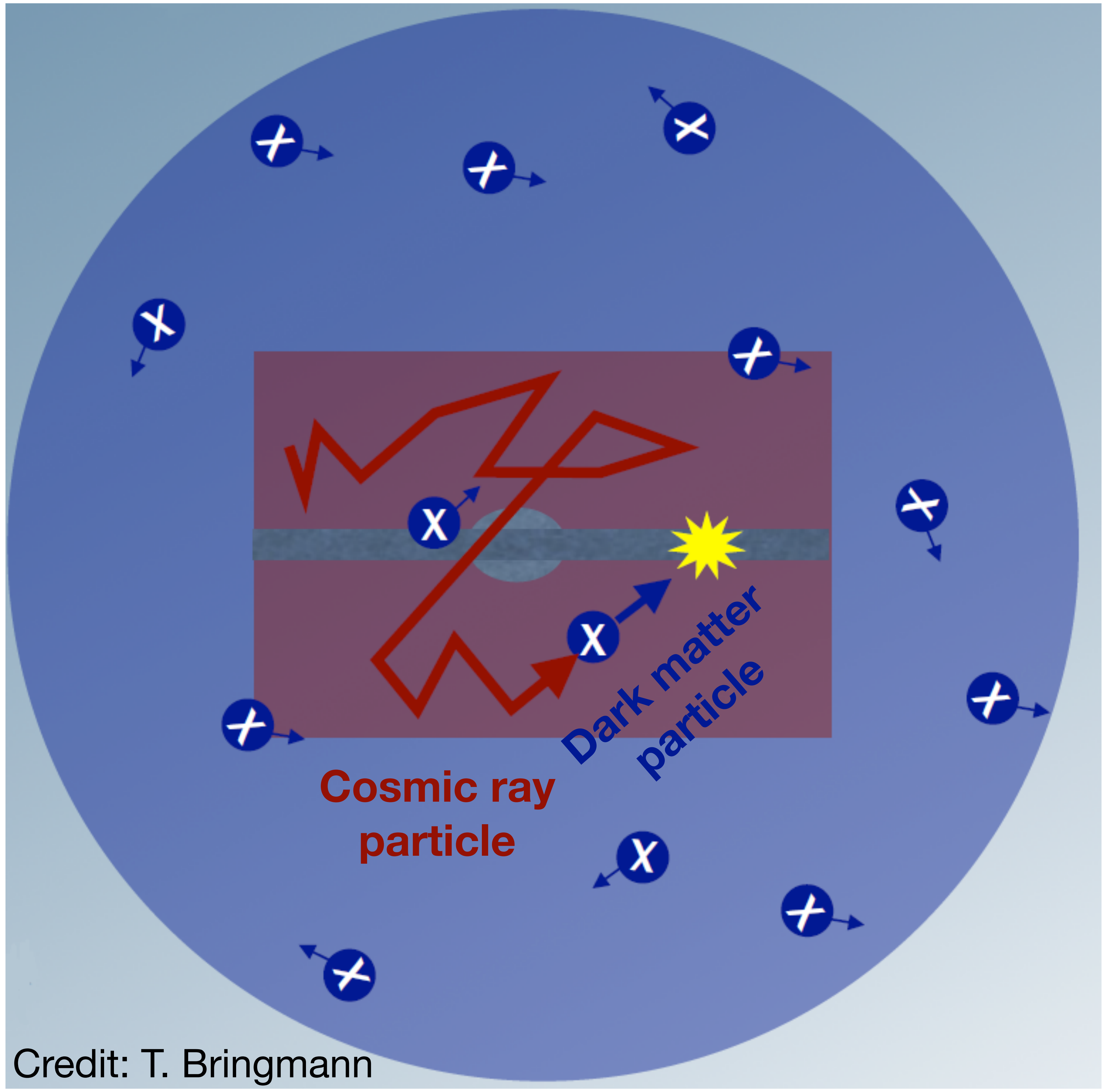


Implemented in DarkSUSY

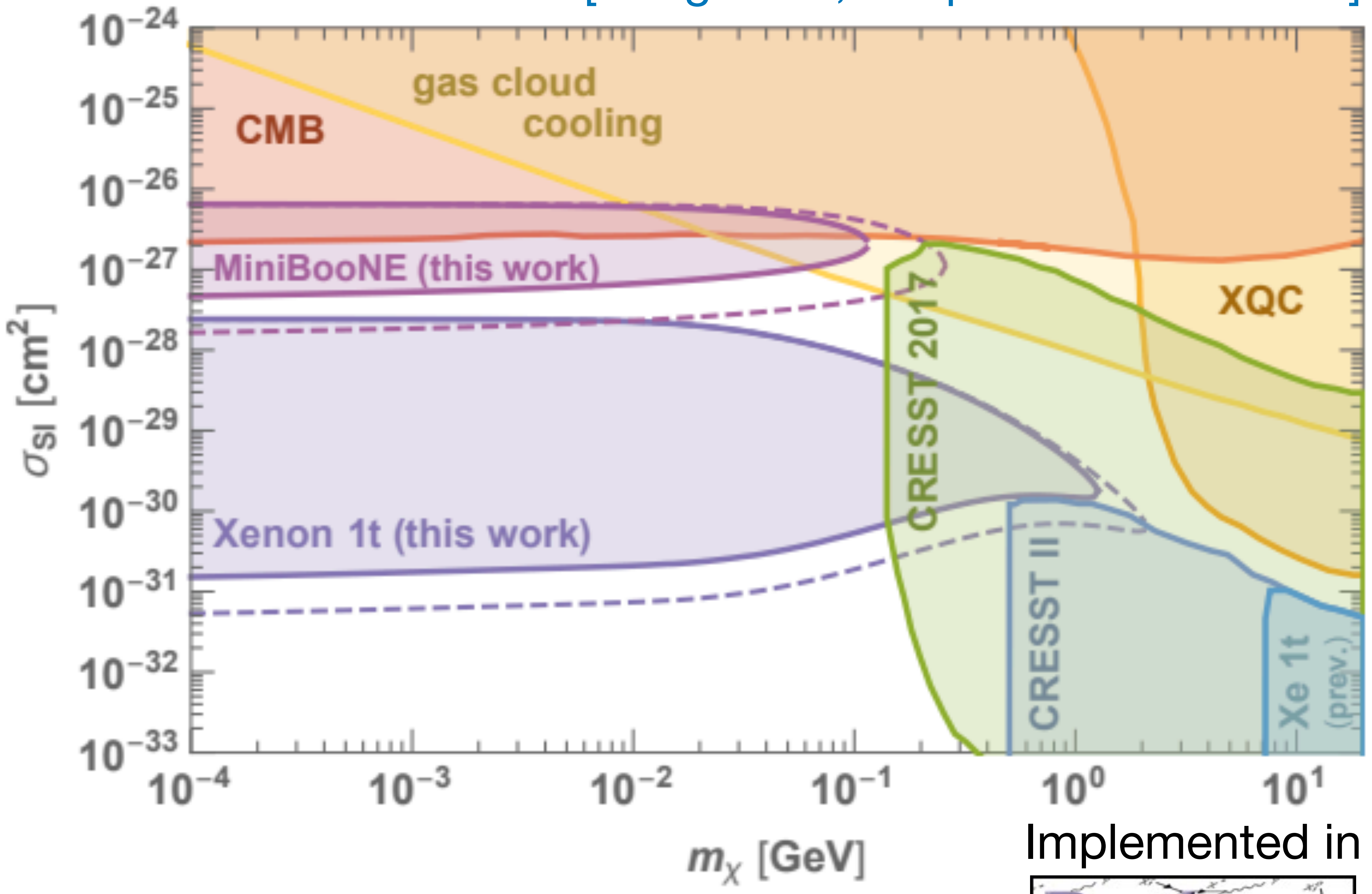
Accelerated dark particles

Example 3: Cosmic-ray up-scattered dark matter (CRDM)

Running example for this talk!

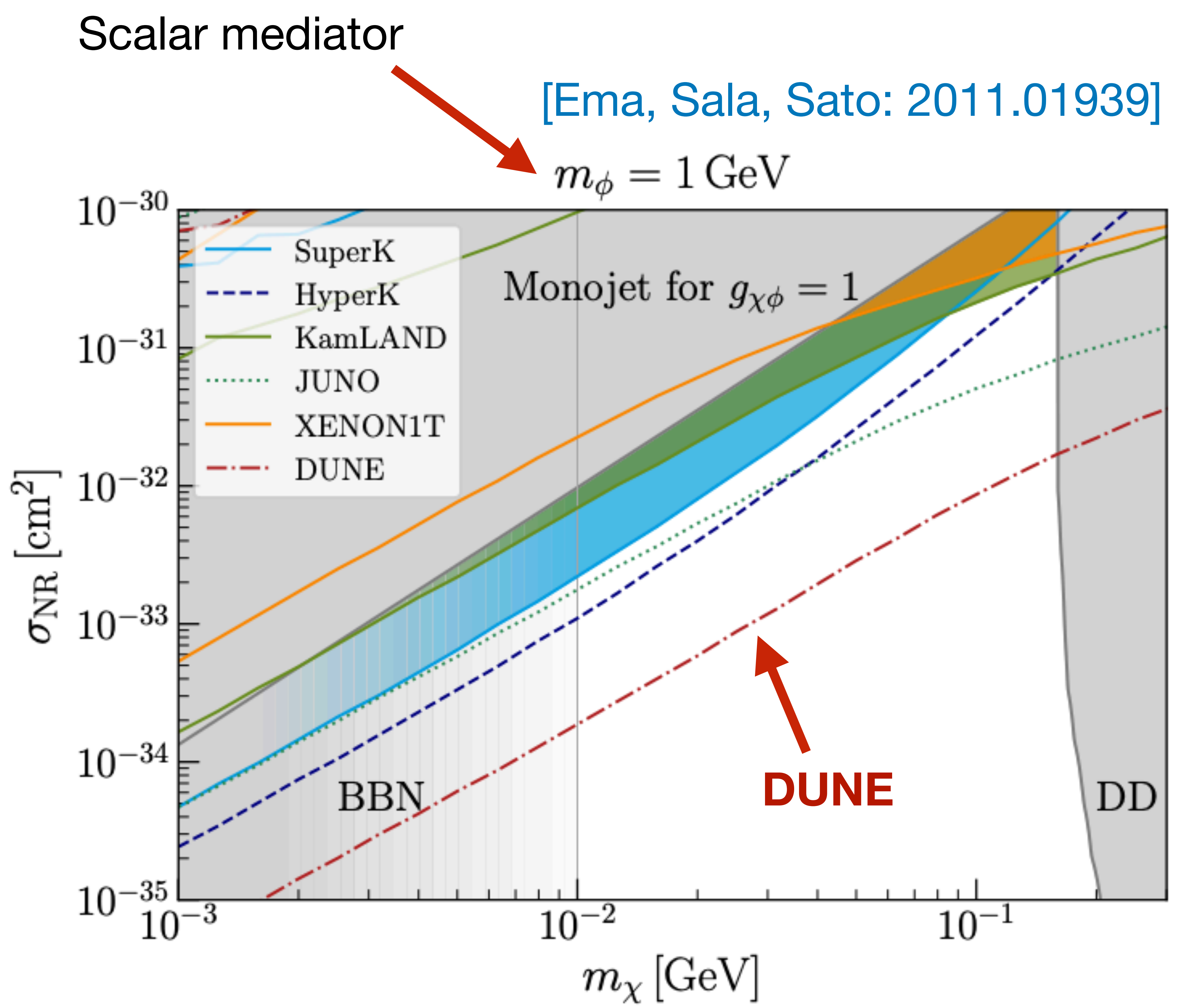


[Bringmann, Pospelov: 1810.10543]



Implemented in DarkSUSY

Cosmic-ray up-scattered dark matter probed also by neutrino experiments!



Cosmic-ray up-scattered dark matter probed also by neutrino experiments!

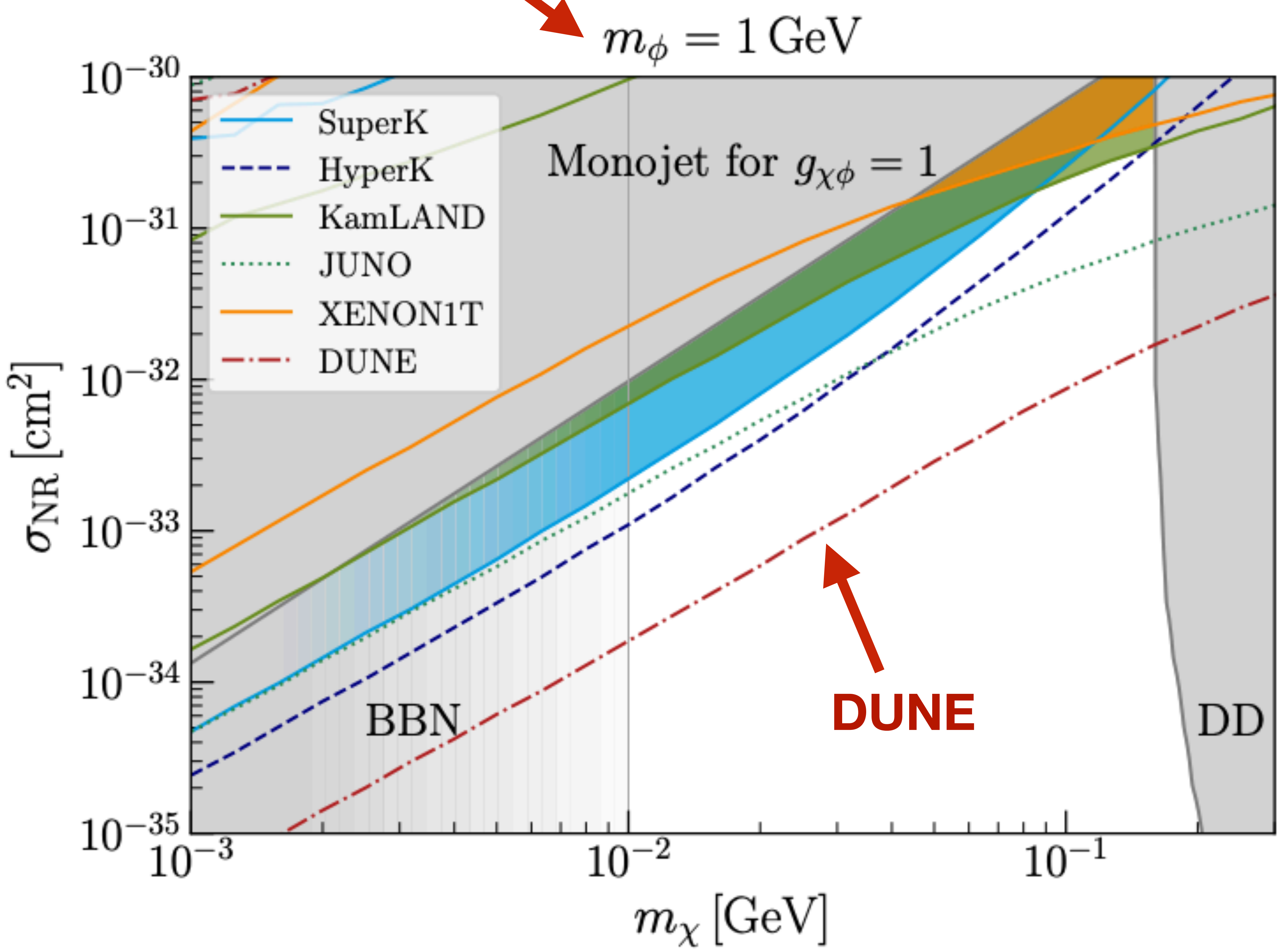
DUNE sensitivity:

- Detection modelled as elastic scattering off free nucleons in the detector
- Background by atmospheric neutrinos not considered
- Only elastic scattering considered for up-scattering by cosmic rays

We tried to improve on these points!

Scalar mediator

[Ema, Sala, Sato: 2011.01939]



Benchmark model: massive Z’ mediator

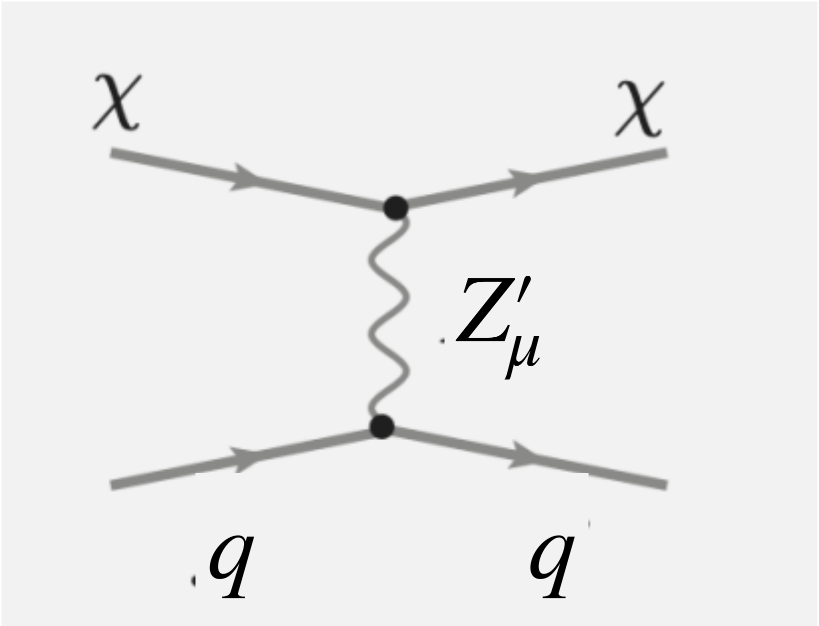
- Motivation: implemented in GENIE boosted DM module [Berger: 1812.05616]

- Both dark matter particles and Standard Model quarks charged under $U(1)_D$:

$$\mathscr{L}_{\chi,\mathrm{int}} = g_{Z'} Z'_\mu \bar{\chi} \gamma^\mu \left(Q_\chi^L P_L + Q_\chi^R P_R \right) \chi \qquad \mathscr{L}_{q,\mathrm{int}} = g_{Z'} Z'_\mu \bar{q} \gamma^\mu \left(Q_q^L P_L + Q_q^R P_R \right) q$$

- Vector couplings: $Q_\chi^L = Q_\chi^R \equiv Q_\chi^V , \quad Q_q^L = Q_q^R \equiv Q_q^V$

(Dark photon: $Q_q^V = Q_q^{\mathrm{em}}$, or $U(1)_B$: Q_q^V equal for all quarks)



- Axial-vector couplings: $-Q_\chi^L = Q_\chi^R \equiv Q_\chi^A , \quad - Q_q^L = Q_q^R \equiv Q_q^A$

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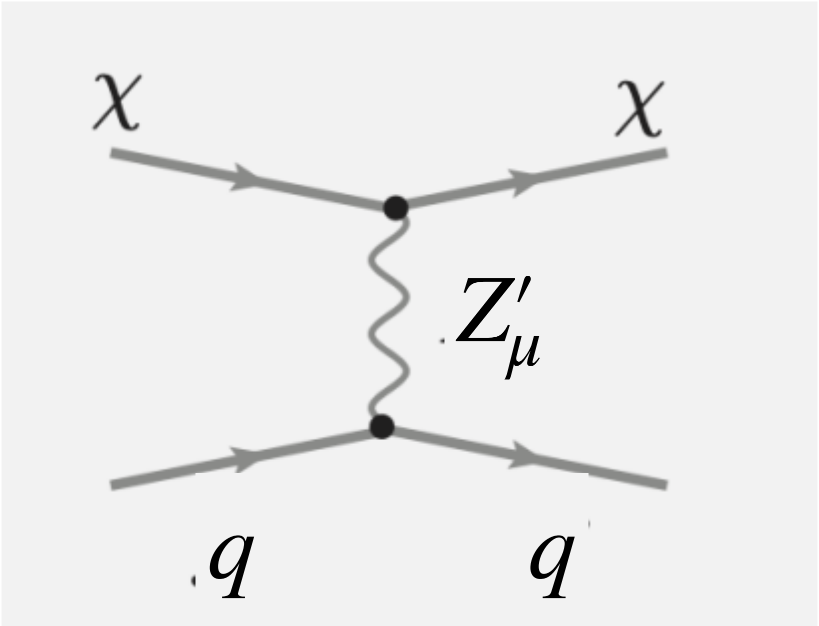

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- Axial-vector couplings: $-Q^L_\chi = Q^R_\chi \equiv Q^A_\chi , \quad -Q^L_q = Q^R_q \equiv Q^A_q$

Dark matter scattering with nucleons

- Dark-matter-proton elastic scattering important for up-scattering by cosmic rays
- Need for nucleon form factors!

Well known, enter electromagnetic interactions

$$\langle N(p')|\bar{q}\gamma^\mu q|N(p)\rangle = \bar{u}(p')\left(F_1^{q|N}(Q^2)\,\gamma^\mu + F_2^{q|N}(Q^2)\frac{i\,q_\nu\sigma^{\mu\nu}}{2m_N}\right)u(p)$$

$$\langle N(p')|\bar{q}\gamma^\mu\gamma^5 q|N(p)\rangle = \bar{u}(p')\left(F_A^{q|N}(Q^2)\,\gamma^\mu\gamma^5 + F_P^{q|N}(Q^2)\frac{q^\mu}{2m_N}\gamma^5\right)u(p)$$

Somewhat known, enters neutrino interactions

Corresponding contribution to cross section suppressed by scattering particle mass ⇒ irrelevant for neutrinos, not so well known?

NB: Pseudo-scalar form factor

[Berger: 1812.05616]

Thus far, I have neglected the pseudoscalar form factor. For the isospin octet form factors corresponding to the π and η, these can be predicted by the assumption of PCAC and the dominance of the lowest meson pole. For the pion-like isospin current, there is some data indicating that this assumption holds. The other combinations are very difficult to access within the SM. There has been some lattice study of this, with mixed results particularly for the pion.

$$\frac{F_P^{u|N} - F_P^{d|N}}{F_A^{u|N} - F_A^{d|N}} = \frac{4\,M_N^2}{M_\pi^2 + Q^2}, \qquad \frac{F_P^{u|N} + F_P^{d|N} - 2\,F_P^{s|N}}{F_A^{u|N} + F_A^{d|N} - 2\,F_A^{s|N}} = \frac{4\,M_N^2}{M_\eta^2 + Q^2}. \tag{33}$$

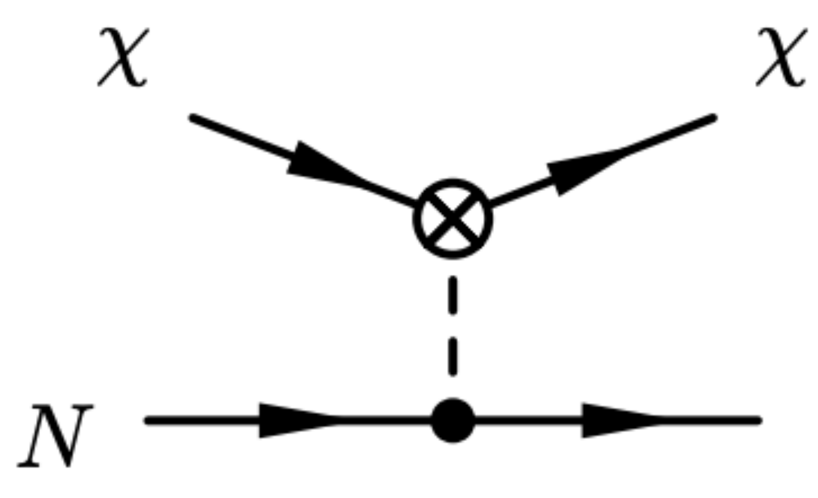
I then assume that the contribution of the strange quark is small, allowing for a solution for the two non-vanishing pseudoscalar form factors.

$$F_P^{u/d|p} = \frac{2m_p^2}{(1 + Q^2/M_A^2)^2} \left(\pm \frac{\Delta u - \Delta d}{m_\pi^2 + Q^2} + \frac{\Delta u + \Delta d - 2\Delta s}{m_\eta^2 + Q^2} \right)$$

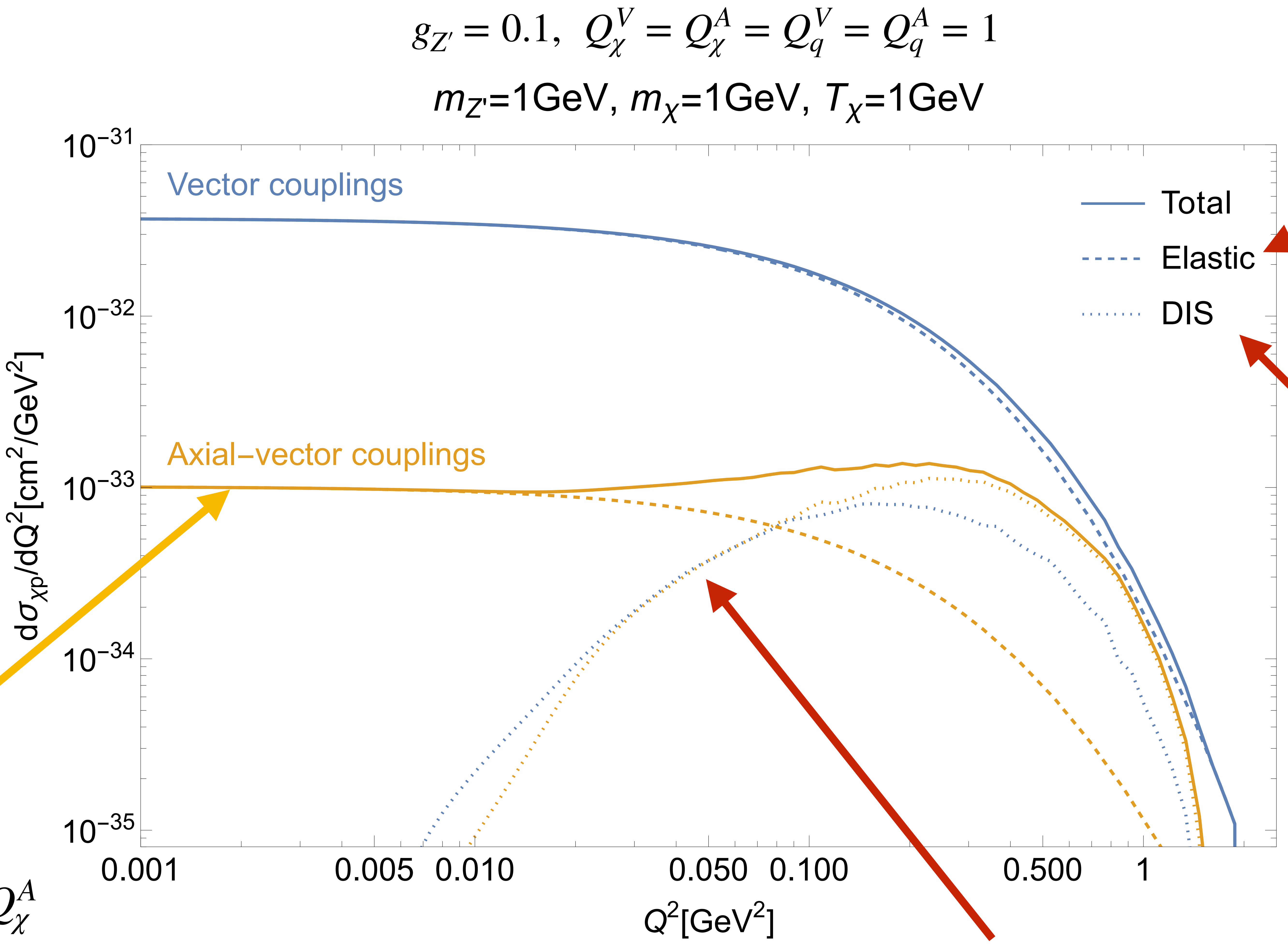
Used in [Berger: 1812.05616]

This structure can be found using chiral perturbation t

[Bishara et al.: 1707.06998]



Dark-matter-proton cross section



Calculated analytically, agrees with the GENIE output

Numerical calculation by GENIE [Berger: 1812.05616]

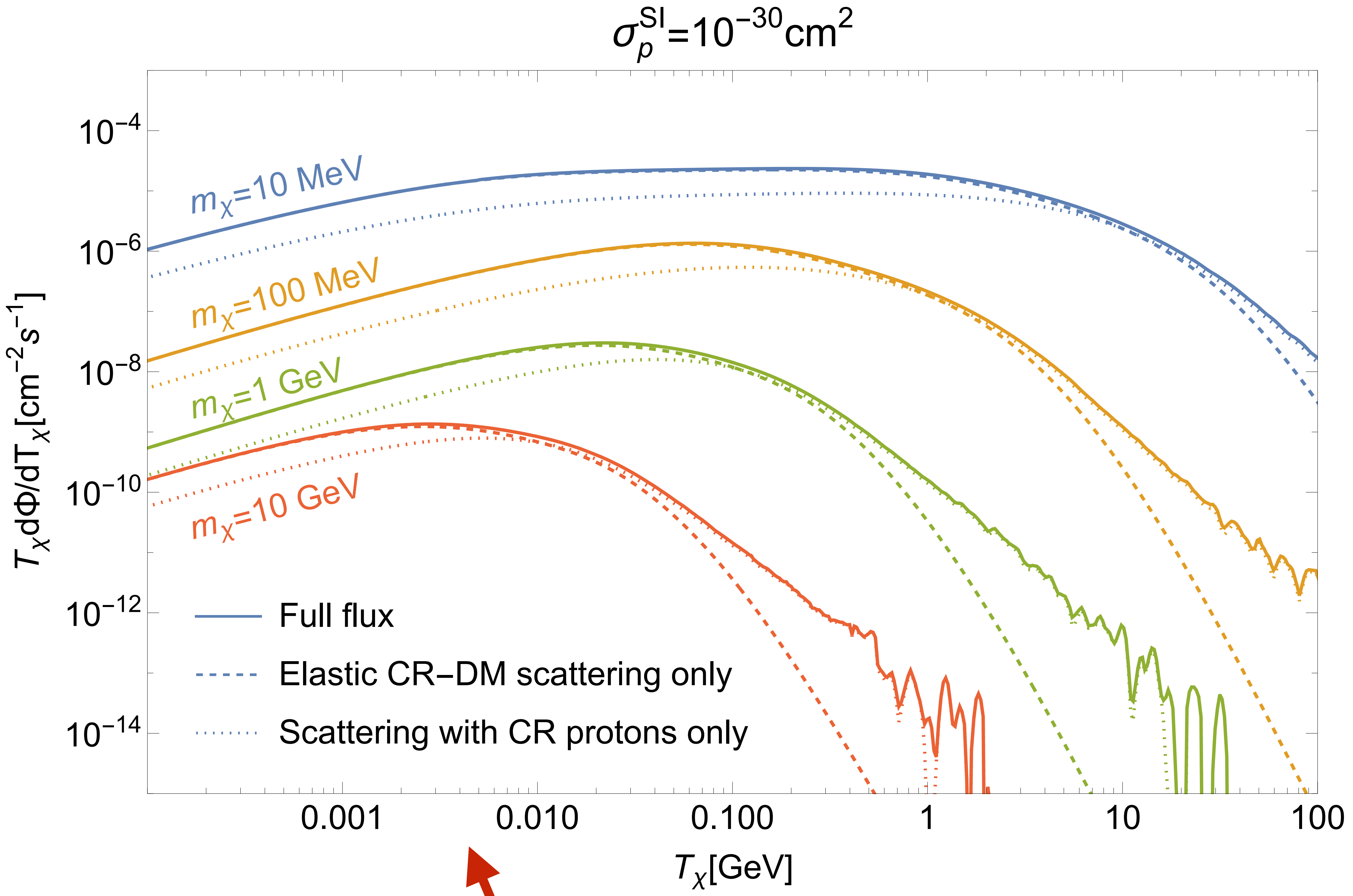
Relative suppression of the elastic contribution for axial-vector couplings since

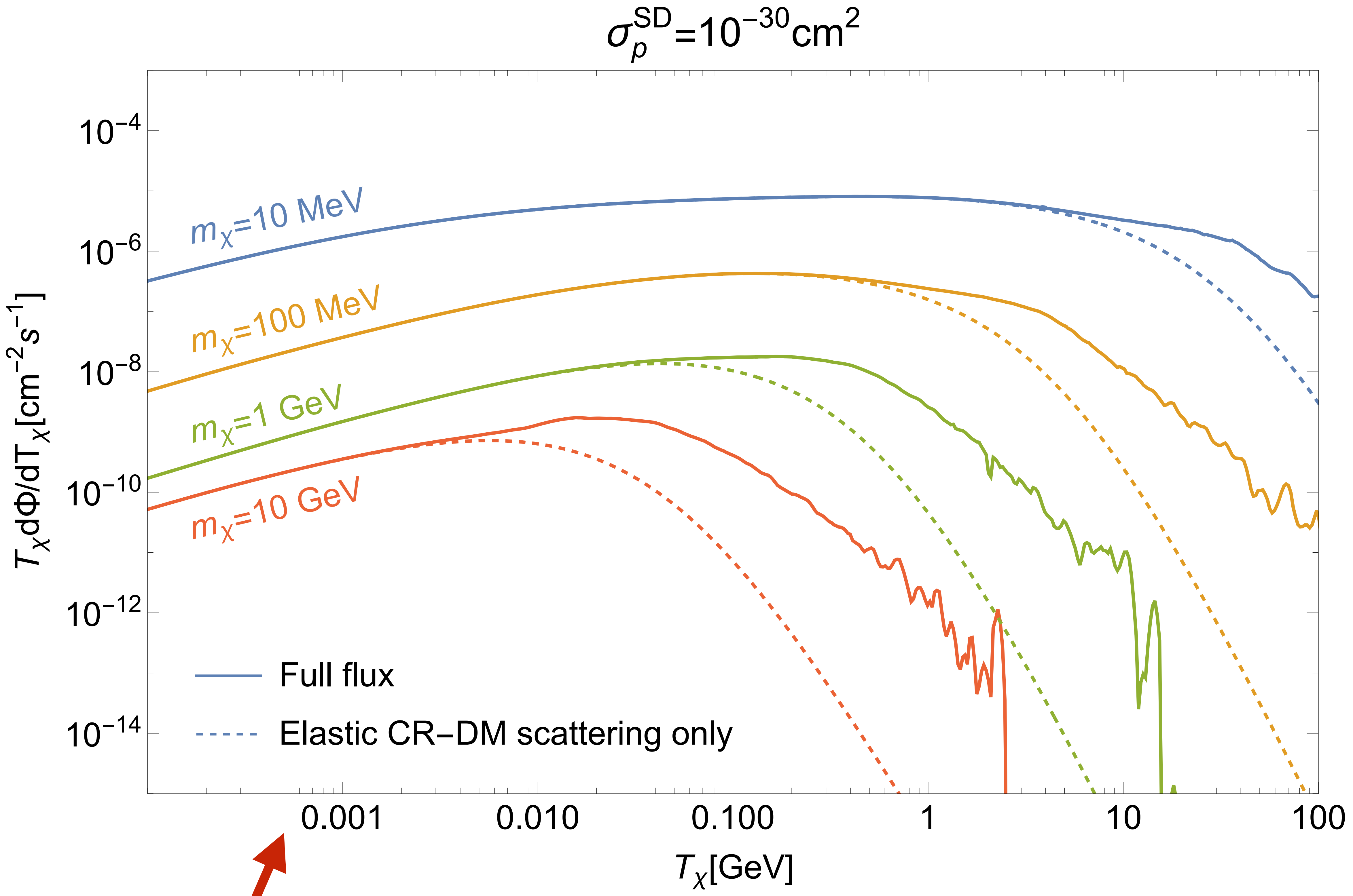
$$F_1^p(0) = 3Q_\chi^V \ll F_A^p(0) \approx 0.4\, Q_\chi^A$$

DIS contribution comparable for vector and axial-vector cases

CRDM flux coming to Earth

- Dark matter acceleration to larger T_χ mostly due to cosmic-ray protons
- Inelastic scattering enhances considerably the flux at largest DM kinetic energies

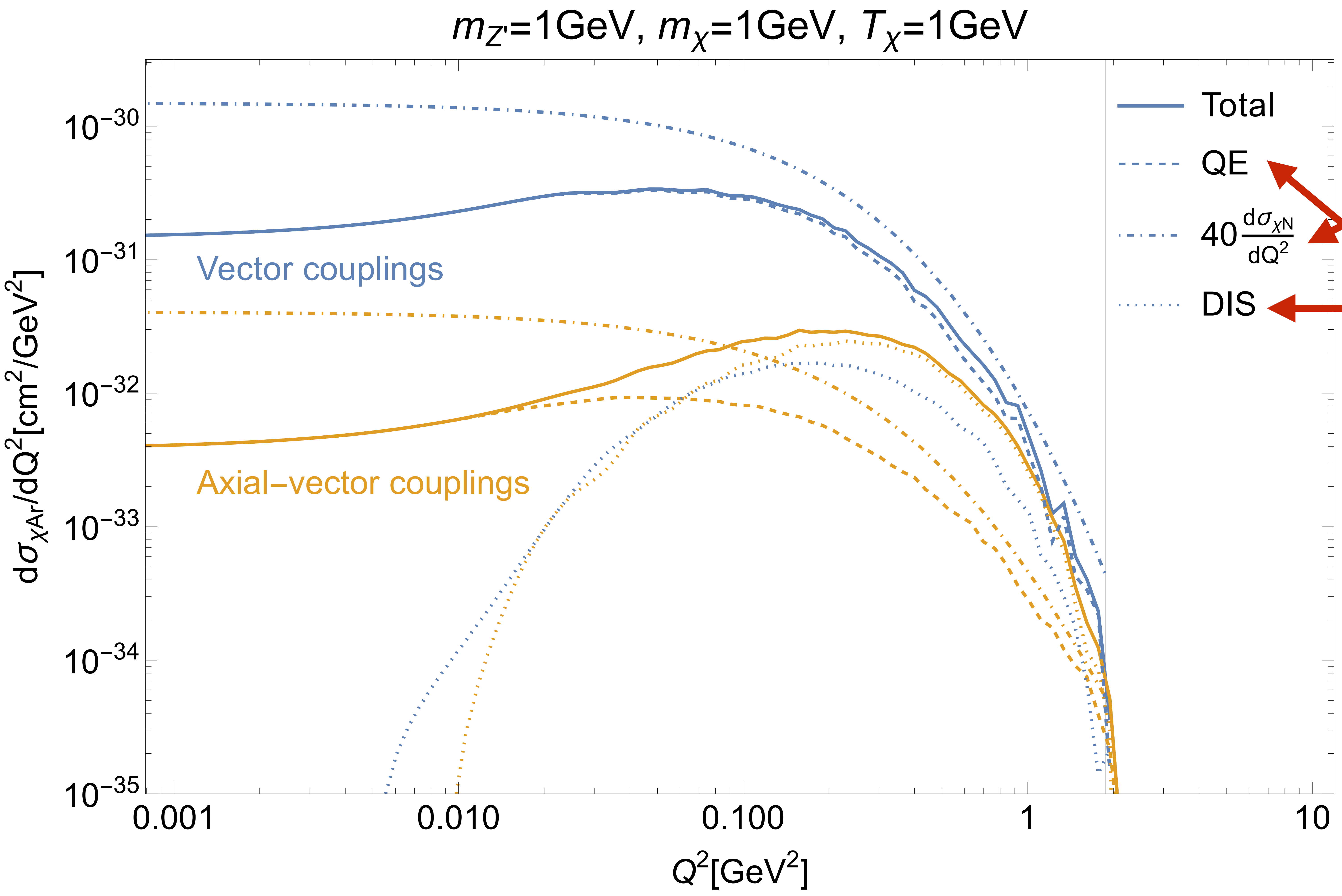




Vector couplings: $\sigma^p_{\rm SI} = \dfrac{g^4_{Z'}(Q^V_\chi)^2(3Q^V_q)^2\mu^2_{\chi p}}{\pi m^4_{Z'}}$

Axial-vector couplings: $\sigma^p_{\rm SD} = \dfrac{3g^4_{Z'}(Q^A_\chi)^2 F^p_A(0)^2\mu^2_{p\chi}}{\pi m^4_{Z'}}$

Dark-matter-argon cross section

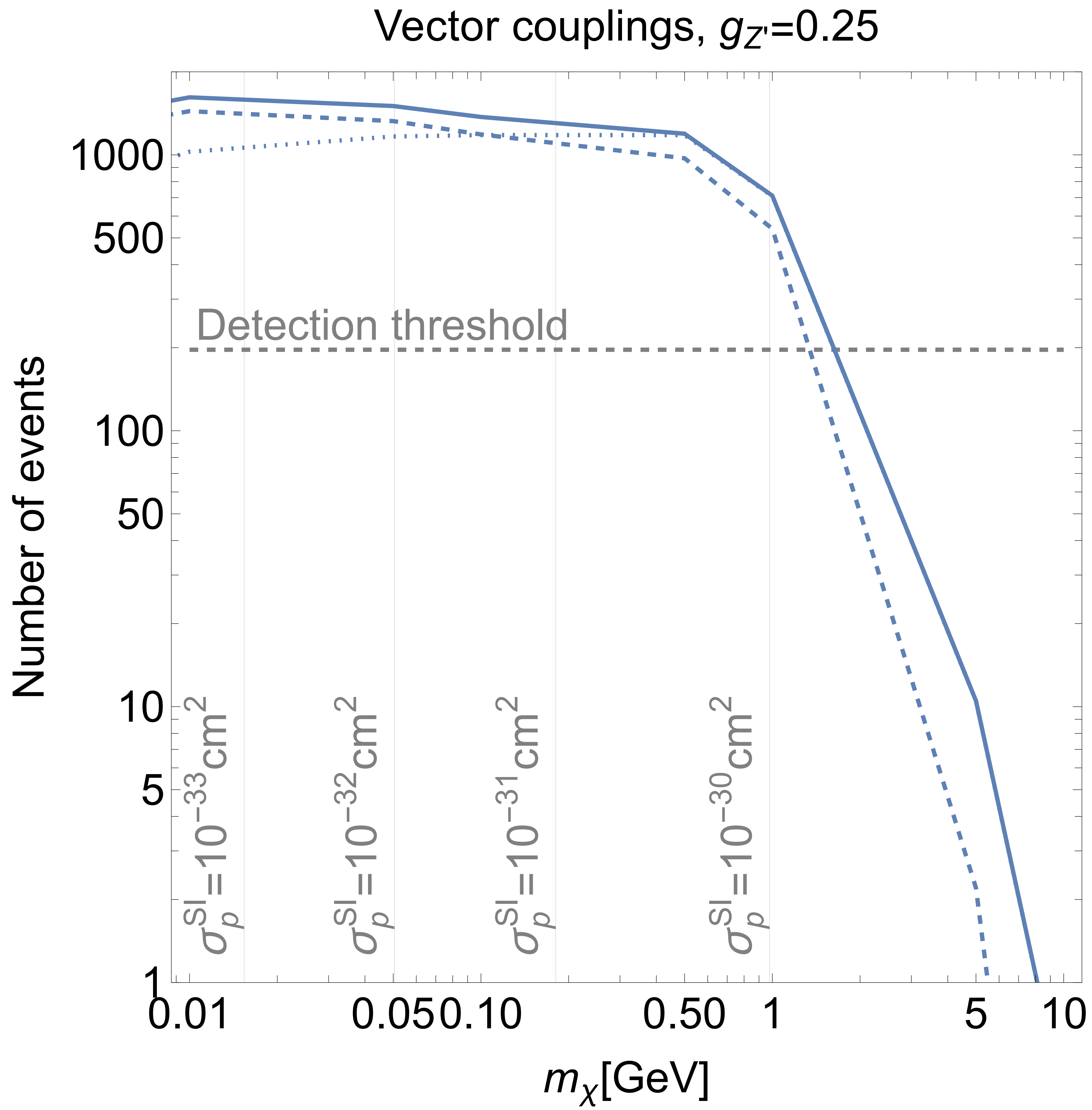


Rough analytic estimate of the QE contribution

Numerical calculation by GENIE [Berger: 1812.05616]

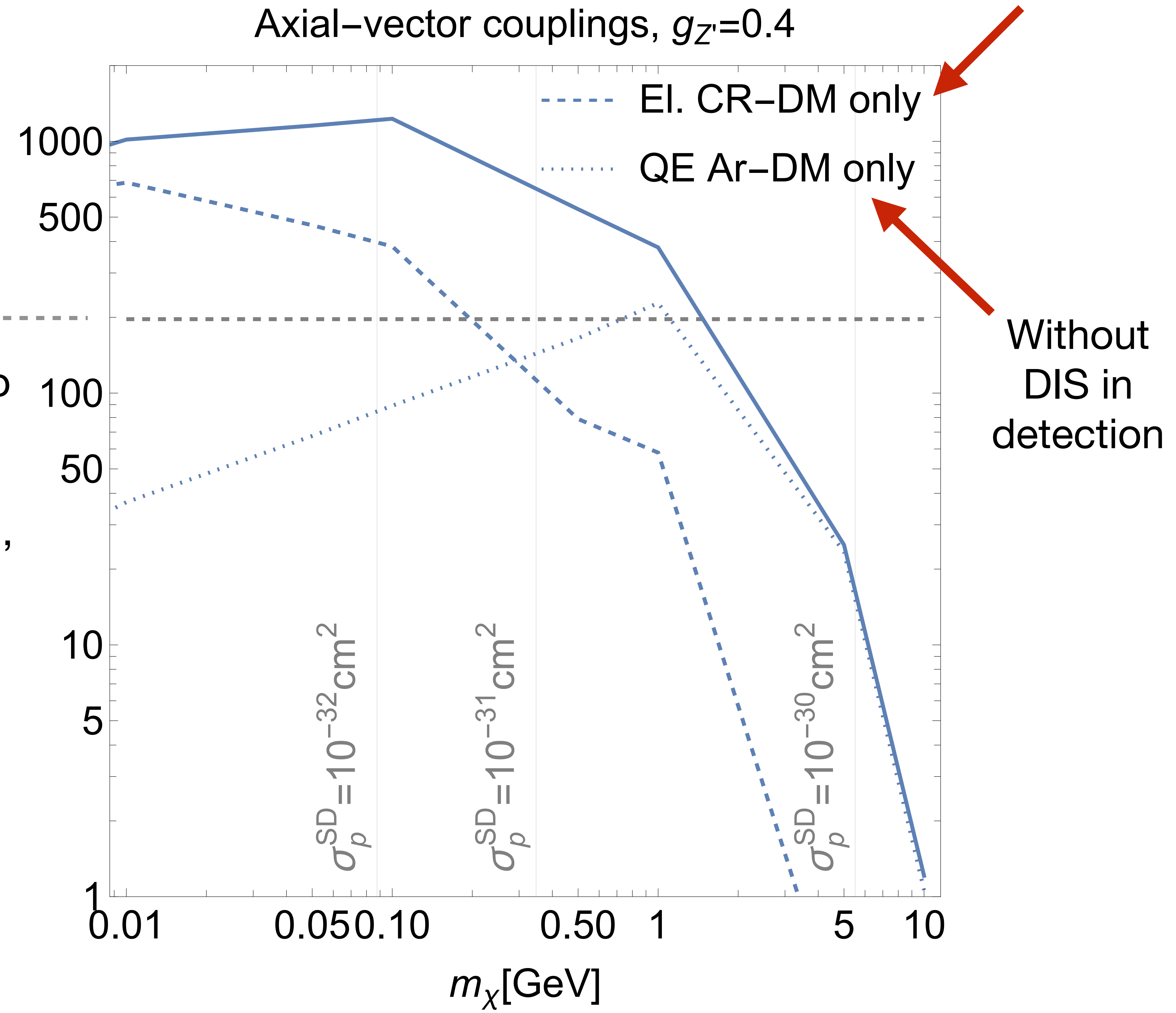
Dark matter scattering with nucleons/nuclei

- DIS plays a role for dark matter detection in DUNE

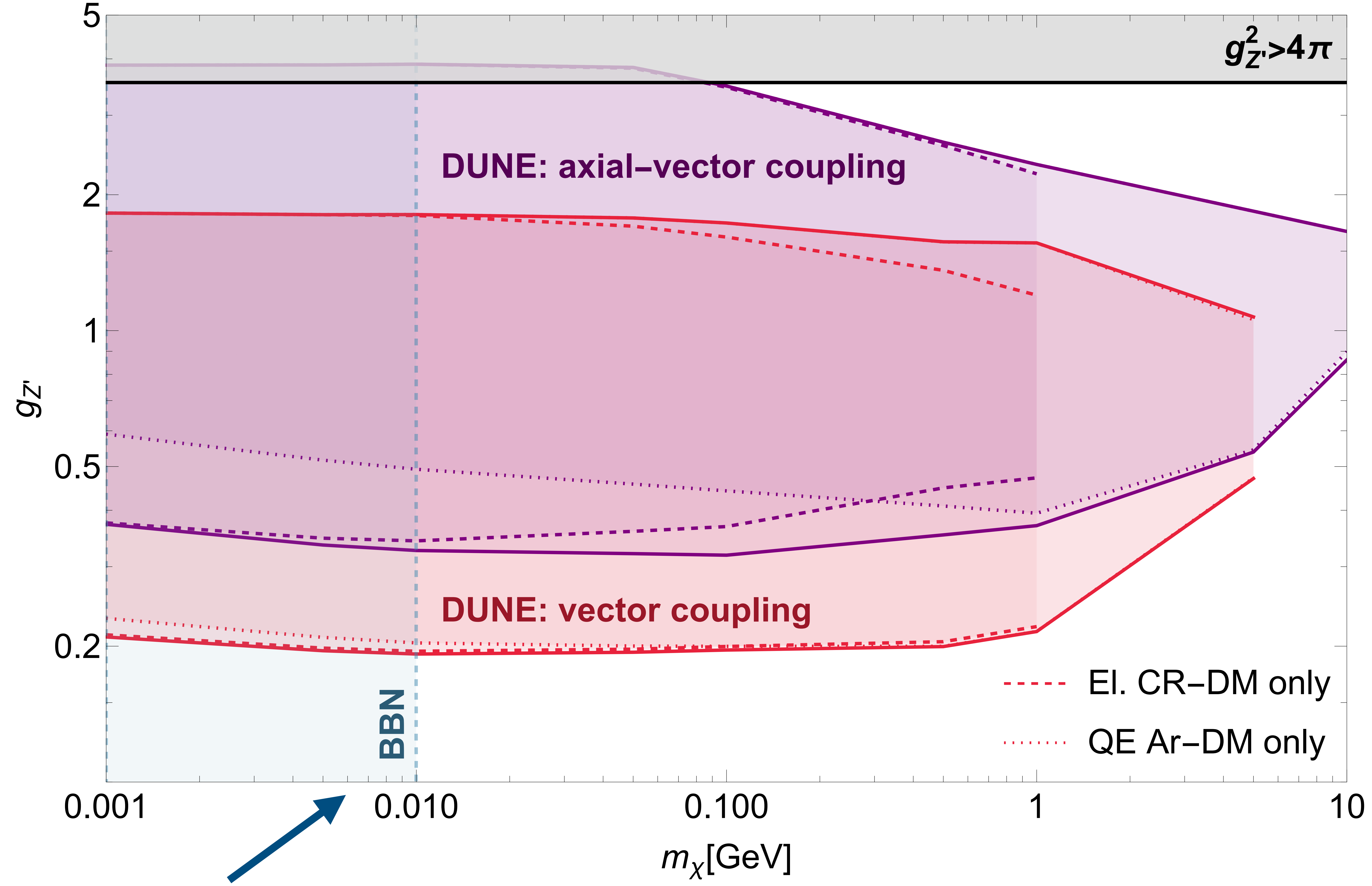


DUNE sensitivity at 2σ level

(Atmospheric neutrino background estimated based on fluxes by Honda et al., only statistical uncertainties considered)

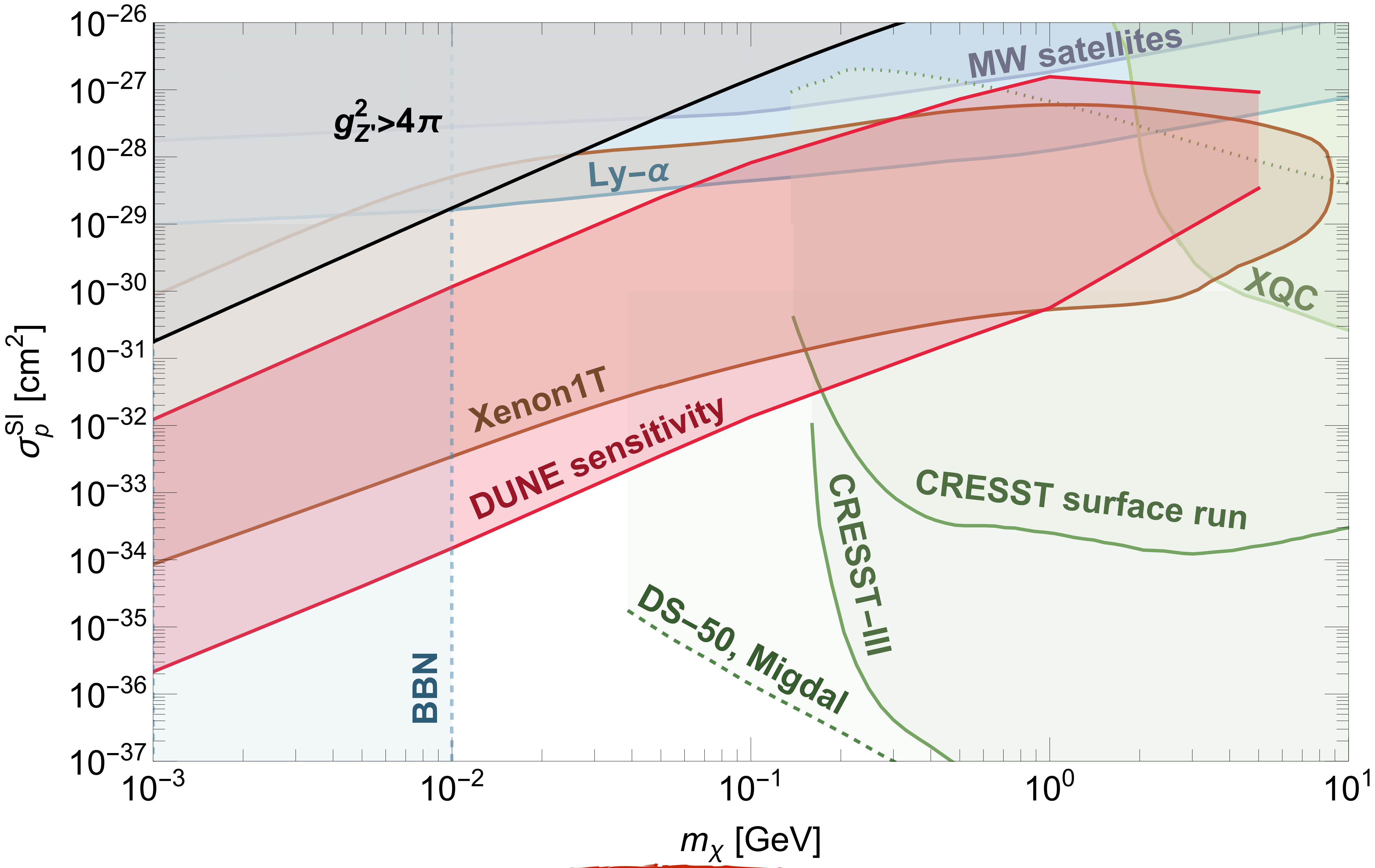


Results



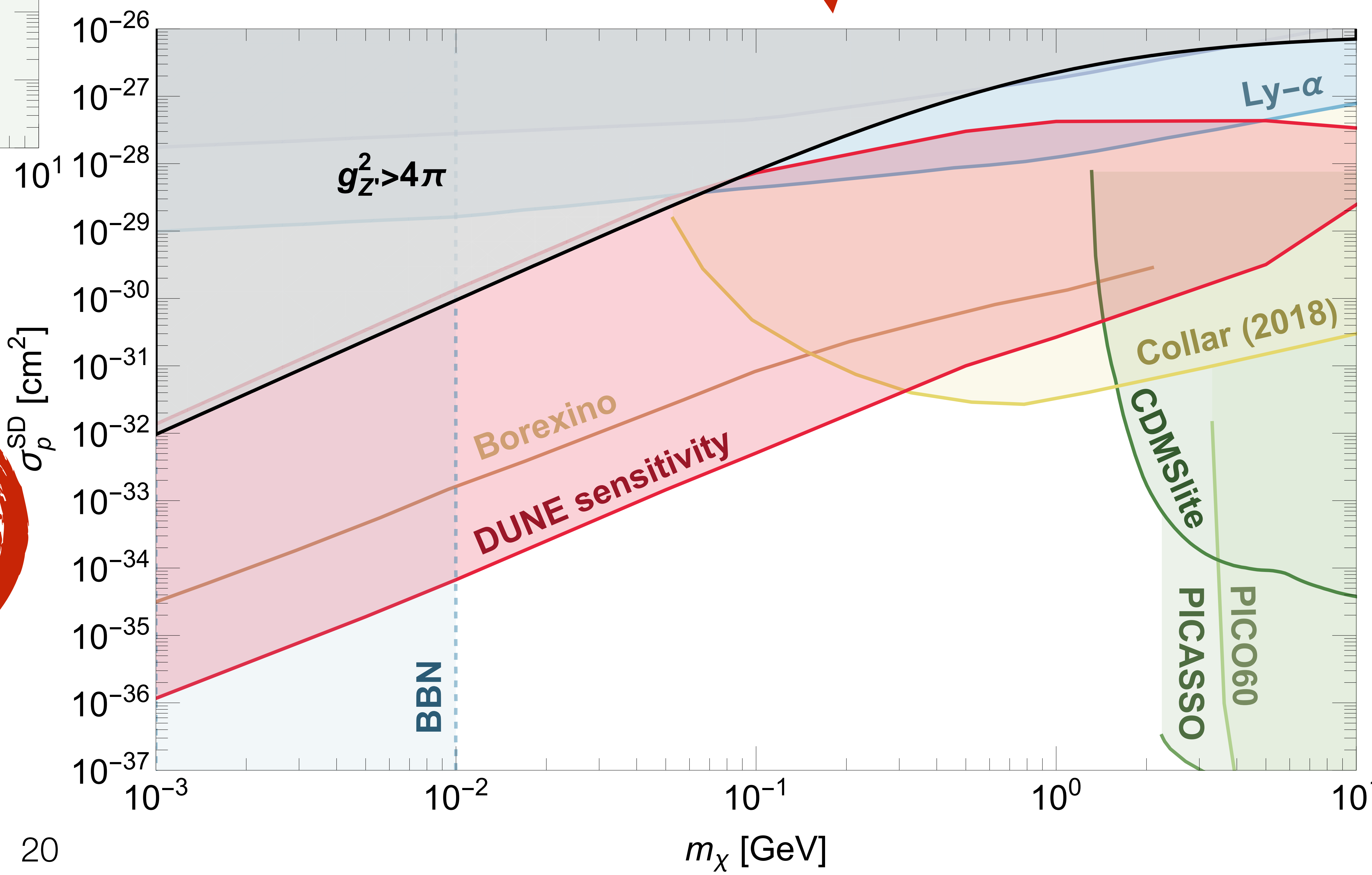
BBN constraints on extra light degrees of freedom thermalised with SM plasma
[Krnjaic: 1908.00007]

Results



Vector couplings

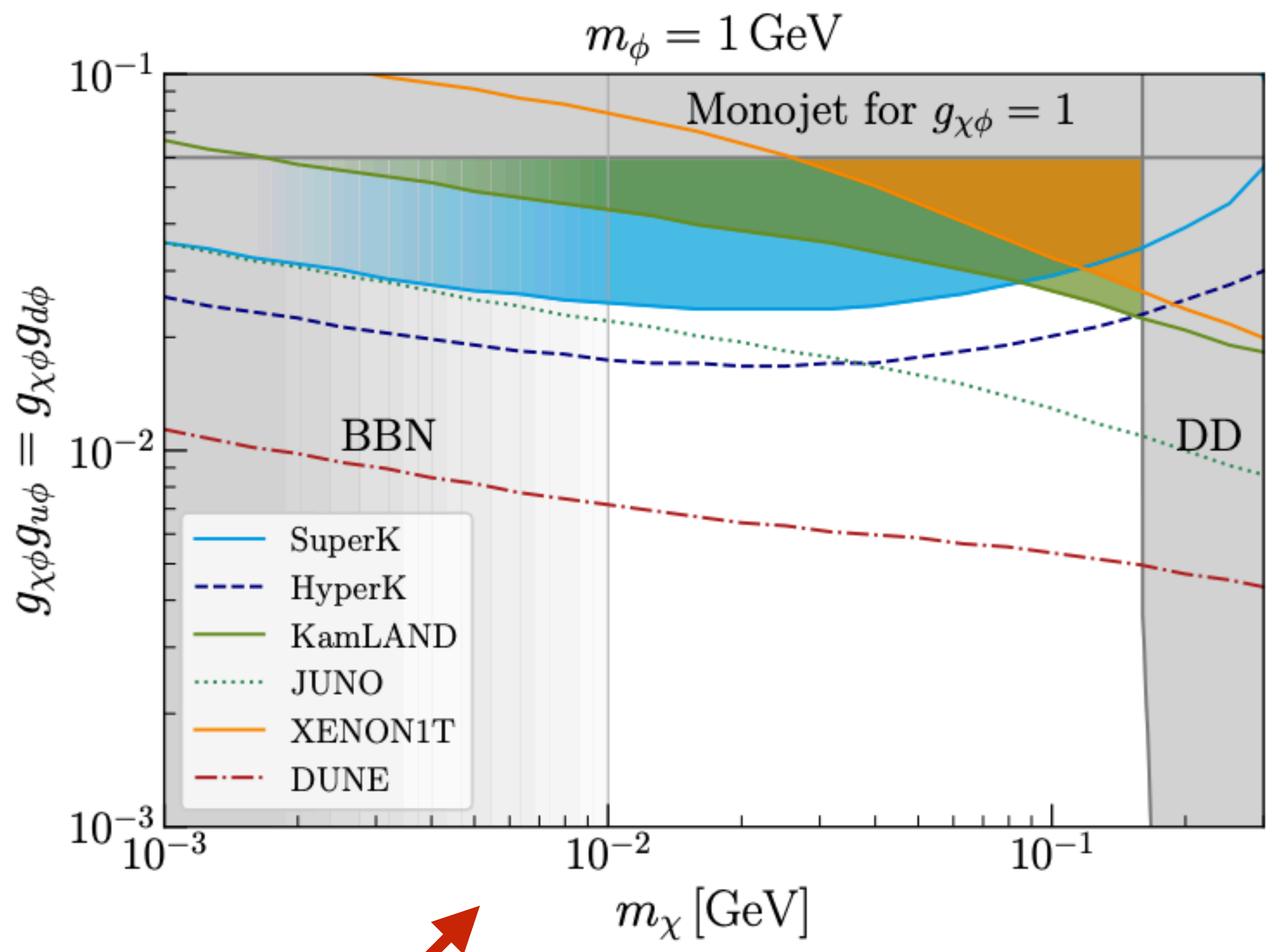
Axial-vector couplings:

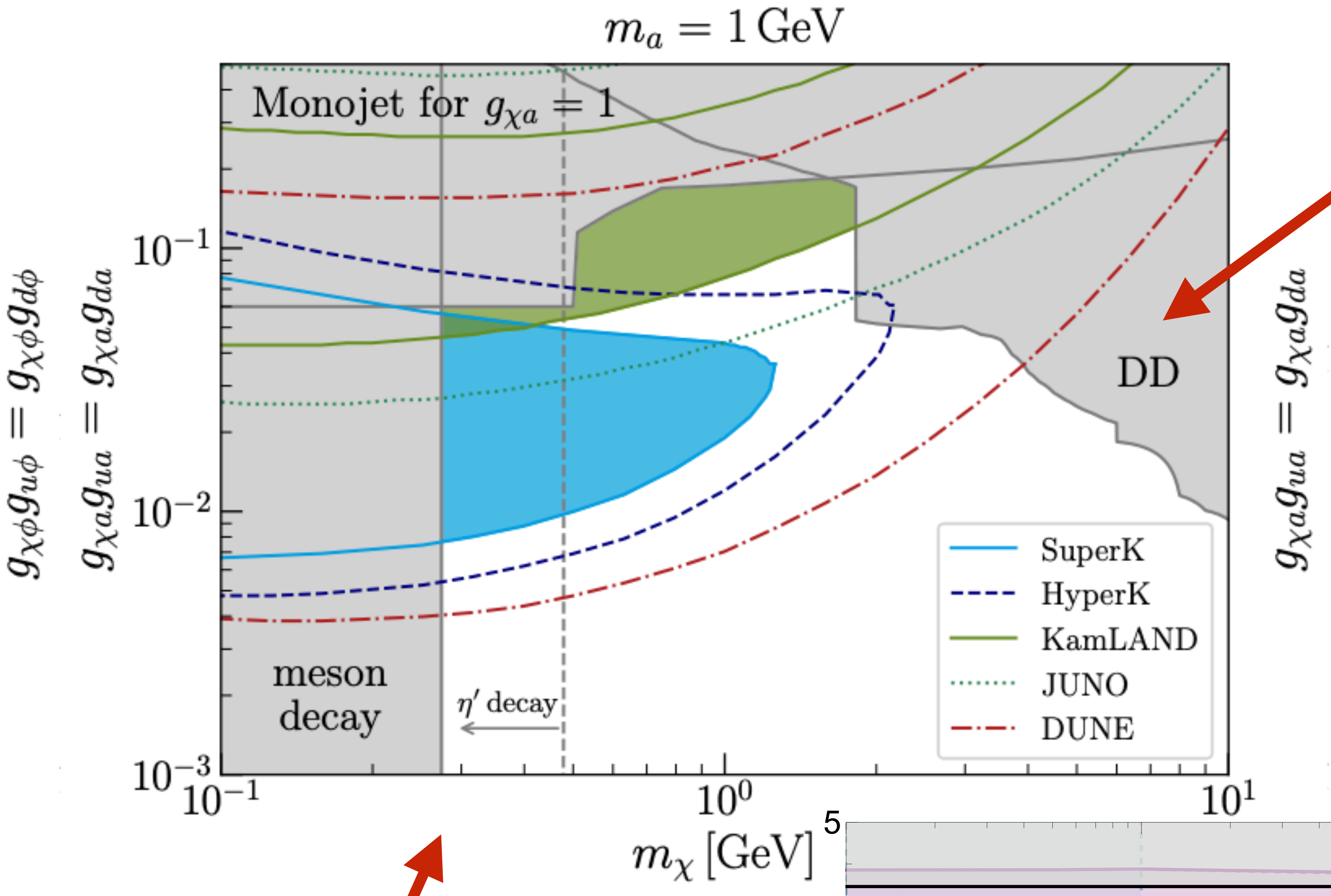


But… Further model-dependent constraints on Z' mediators from meson decays, by collider experiments, feasibility of UV completion etc.!

Scalar mediator more favourable?

[Ema, Sala, Sato: 2011.01939]





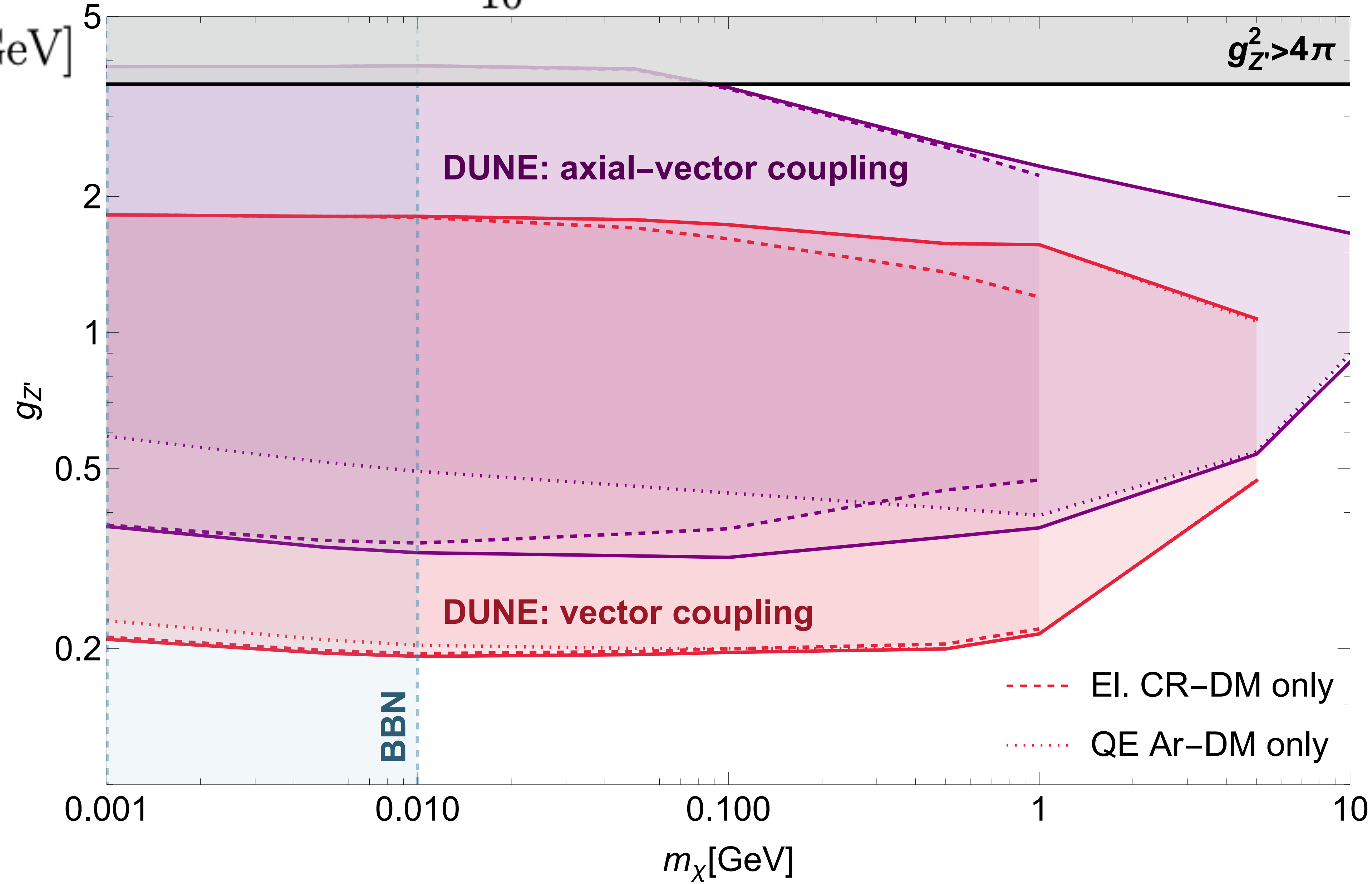
NB: Direct detection limits much weaker for pseudo-scalar case due to velocity-suppressed low-energy interactions!

Scalar mediator

$$g_{N\phi} = g_\phi \underbrace{\left(\frac{m_N}{m_u}f_u^N + \frac{m_N}{m_d}f_d^N\right)}_{\sim 30}$$

Pseudo-scalar mediator

$$g_{Na} = g_a \underbrace{\frac{2m_N}{m_u + m_d}h_{u+d}}_{\sim 120}$$



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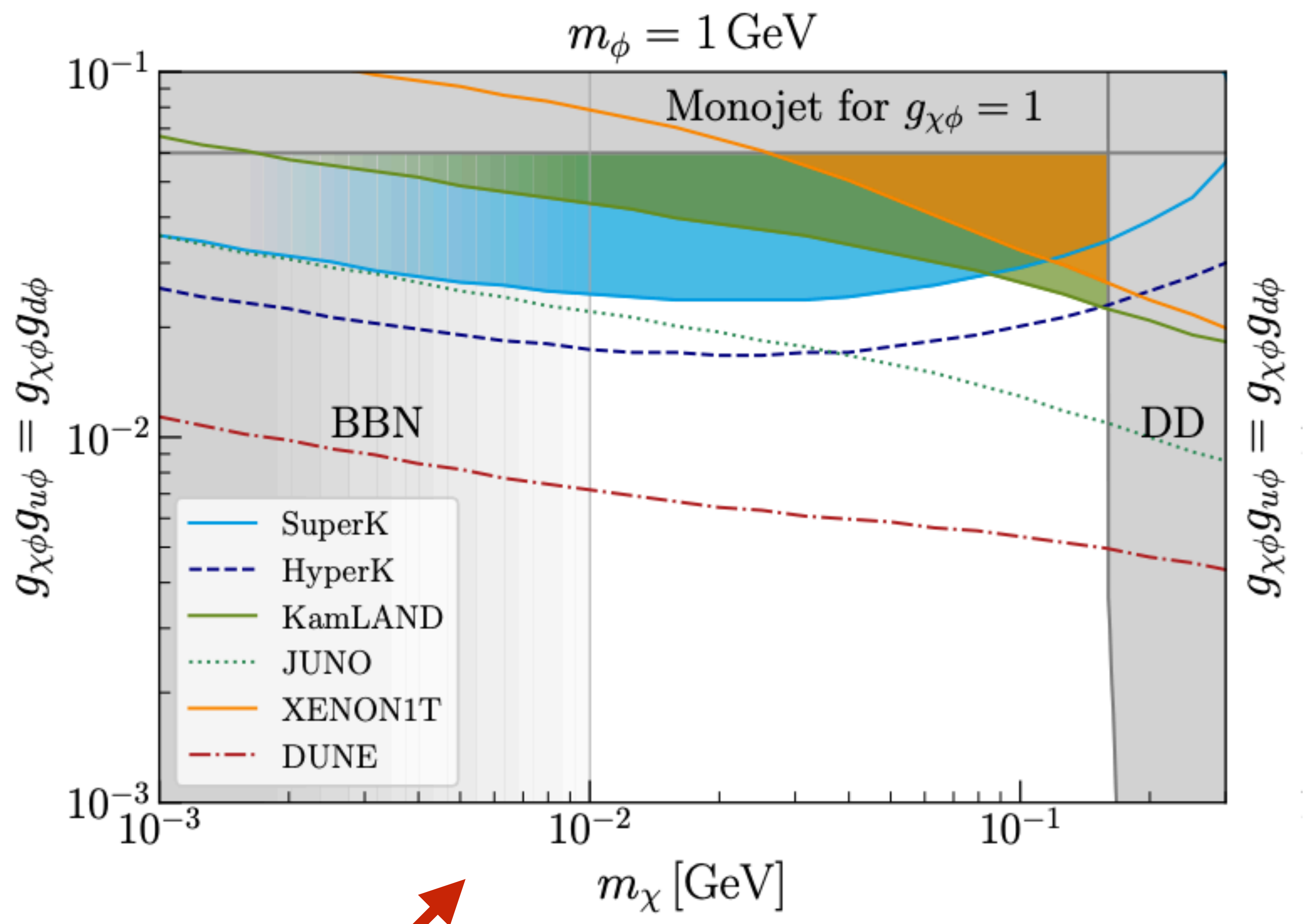

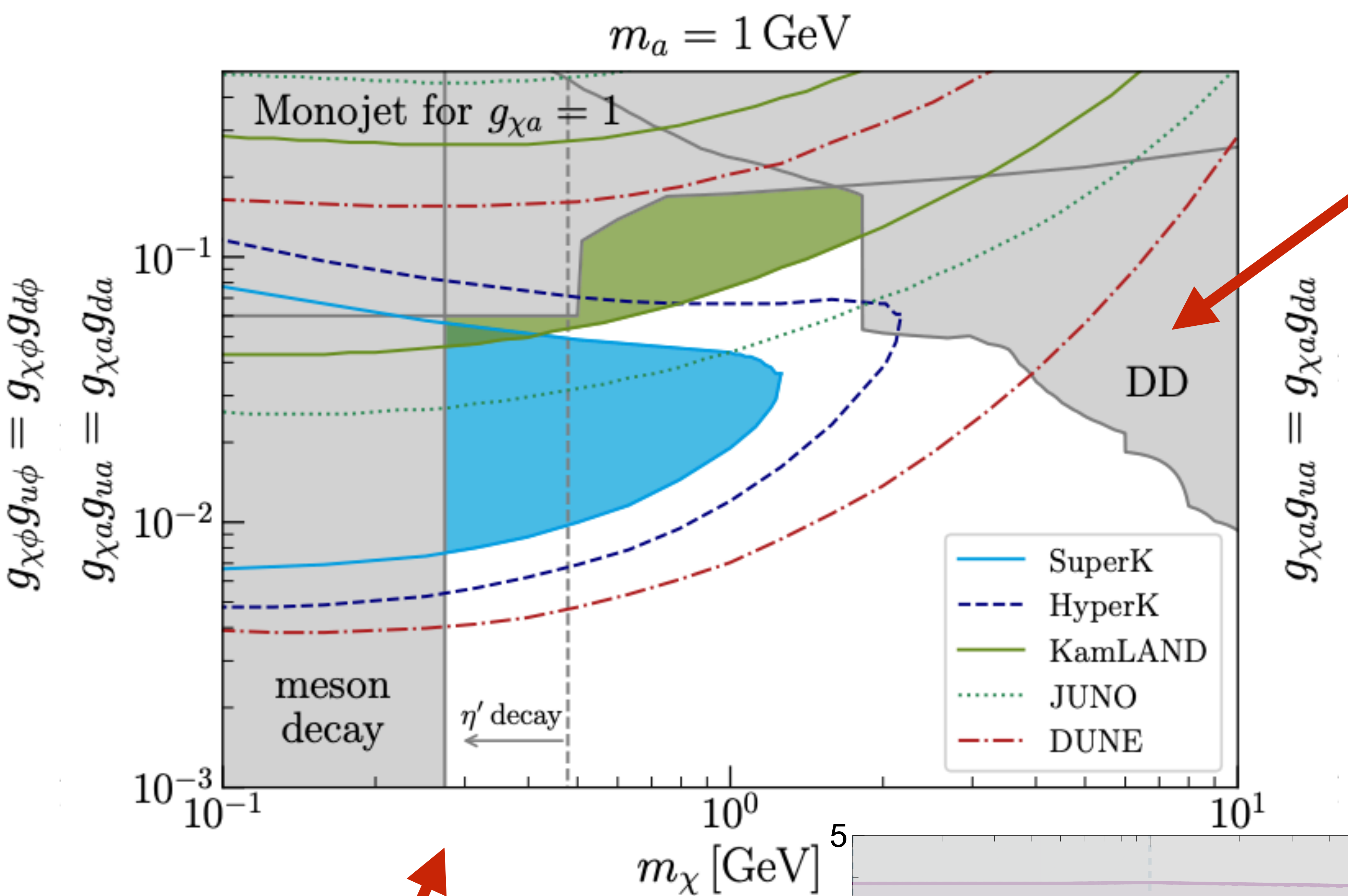

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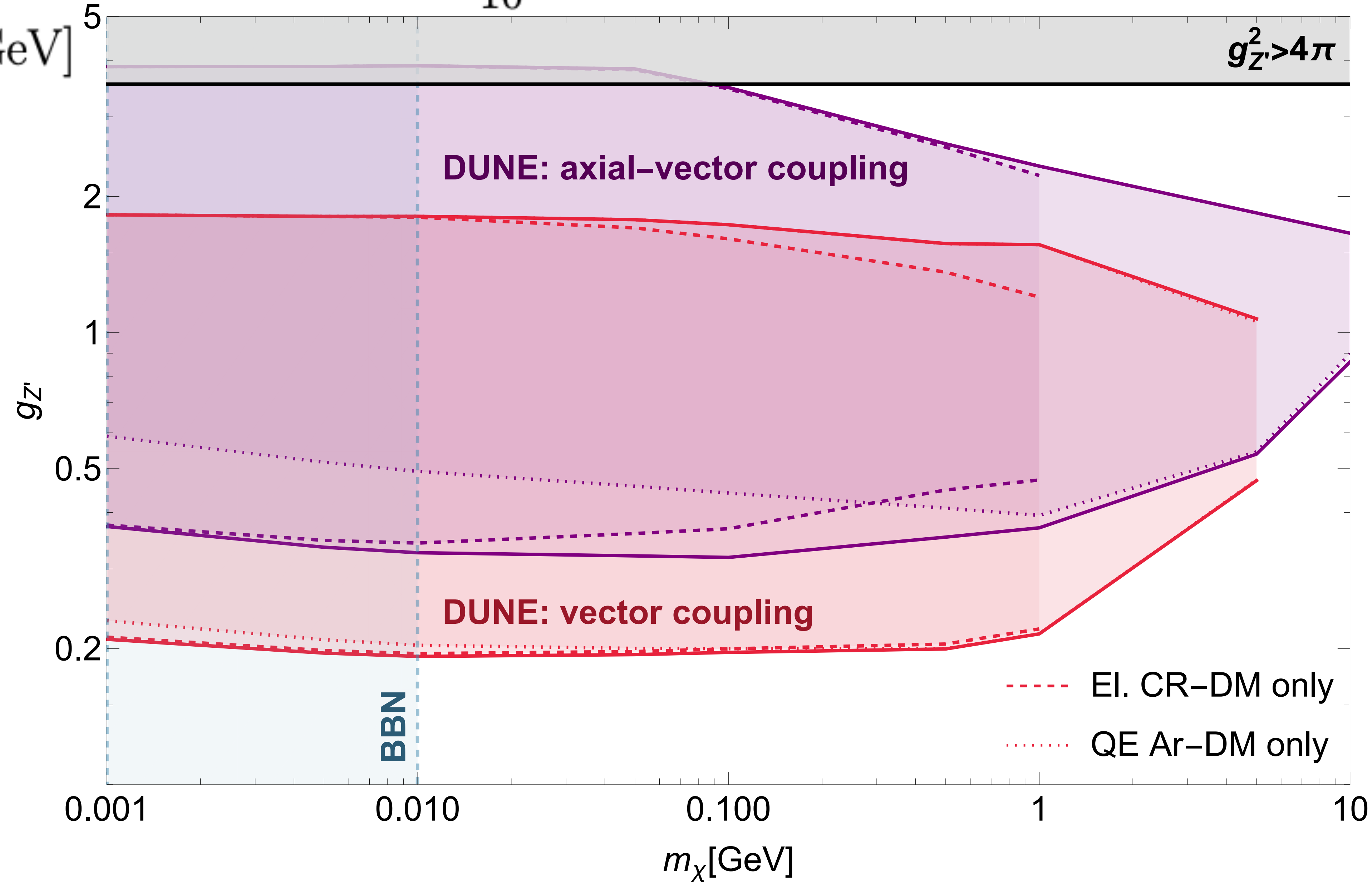
Scalar mediator

$$g_{N\phi} = g_\phi \underbrace{\left(\frac{m_N}{m_u} f_u^N + \frac{m_N}{m_d} f_d^N \right)}_{\sim 30}$$

But numerical implementation of full dark matter-nucleus cross sections missing as far as I know! (ACHILLES?)

Pseudo-scalar mediator

$$g_{Na} = g_a \underbrace{\frac{2 m_N}{m_u + m_d} h_{u+d}}_{\sim 120}$$



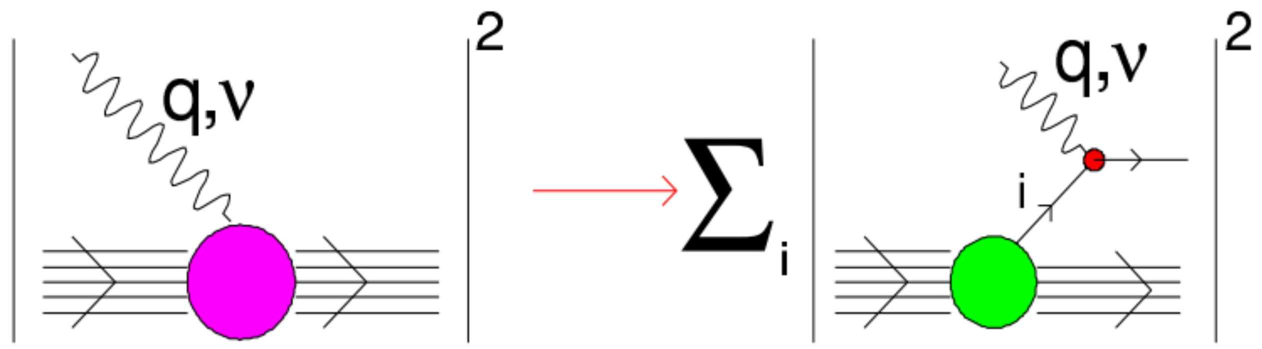
NB: Work with impulse approximation?

Used in the context of boosted dark matter in
[Su, Wu, (Zhou,) Zhu.: 2212.02286, 2308.02204]

B. The impulse approximation

The main assumptions underlying the impulse approximation (IA) scheme are that i) as the spatial resolution of a probe delivering momentum $\mathbf{q}$ is $\sim 1/|\mathbf{q}|$, at large enough $|\mathbf{q}|$ the target nucleus is seen by the probe as a collection of individual nucleons and ii) the particles produced at the interaction vertex and the recoiling (A − 1)-nucleon system evolve indipendently of one another, which amounts to neglecting *both* statistical correlations due to Pauli blocking and dynamical Final State Interactions (FSI), i.e. rescattering processes driven by strong interactions.

In the IA regime the scattering process off a nuclear target reduces to the incoherent sum of elementary processes involving only one nucleon, as schematically illustrated in Fig. 1.



[Benhar et al.: hep-ph/0506116]

Nuclear spectral function, calculated within nuclear many-body theory in [Benhar et al.: hep-ph/0506116]

$$\frac{d\sigma_{IA}}{d\Omega_{e'}dE_{e'}} = \int d^3p\, dE\, \boxed{P(\mathbf{p},E)} \left[Z \frac{d\sigma_{ep}}{d\Omega_{e'}dE_{e'}} + (A-Z)\frac{d\sigma_{en}}{d\Omega_{e'}dE_{e'}} \right] \delta(\nu - E + m - E_x),$$

Conclusions

1. Dark matter detection: typically via coherent elastic scattering (↔ CEνNs)
   - Light dark matter difficult
   - Sensitivity strongly depends on the type of dark matter interactions
2. Accelerated dark matter: detection via "QE" scattering, resonance production, DIS (↔ accelerator, atmospheric, astrophysical neutrinos)
   - Detection of lighter dark particles possible
   - Sensitivity to different types of dark matter interactions
   - Tools for modelling of inelastic interactions needed! Input for nucleon form factors missing?

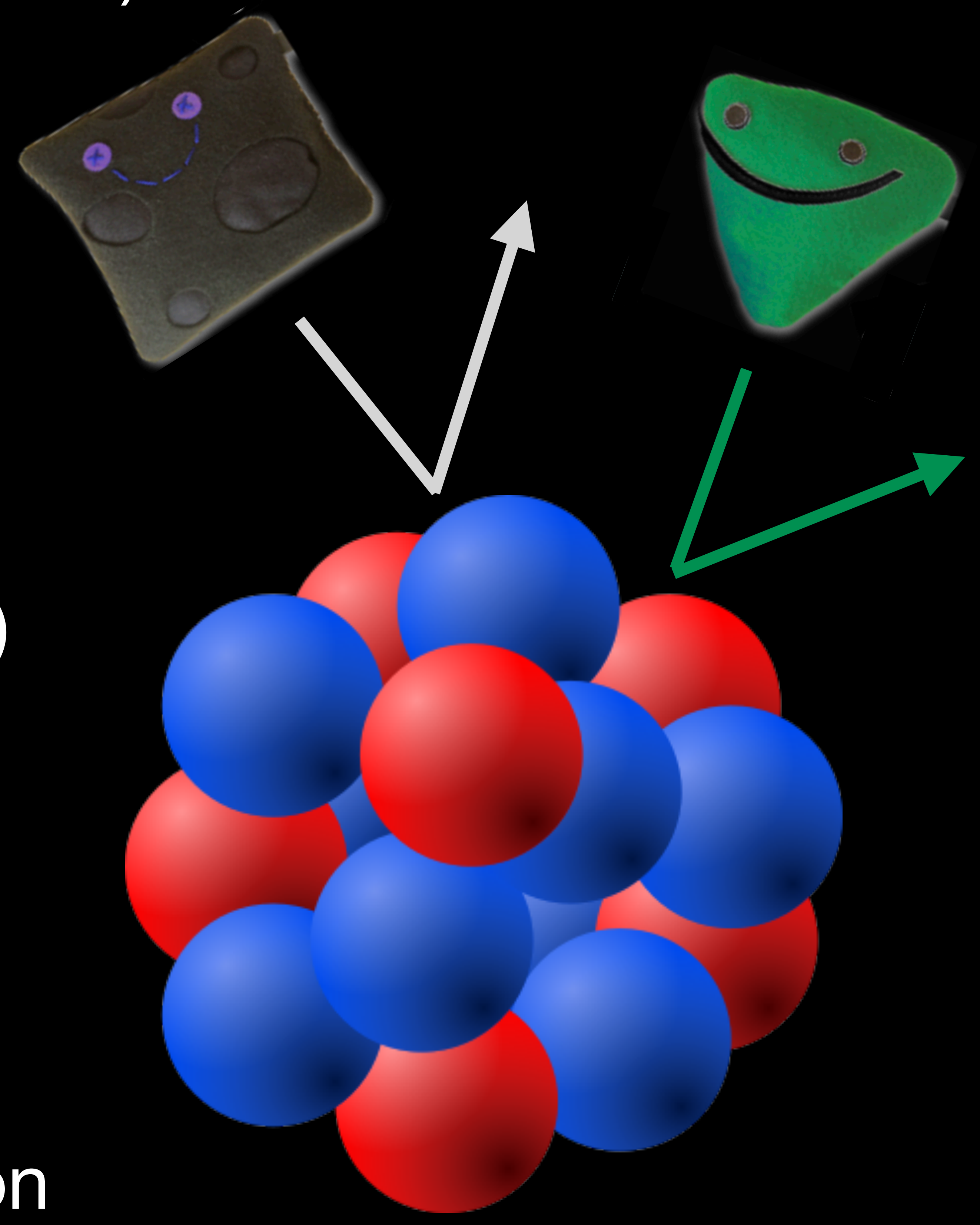


Image credit: Wikipedia, Quarkonia meet Dark Matter

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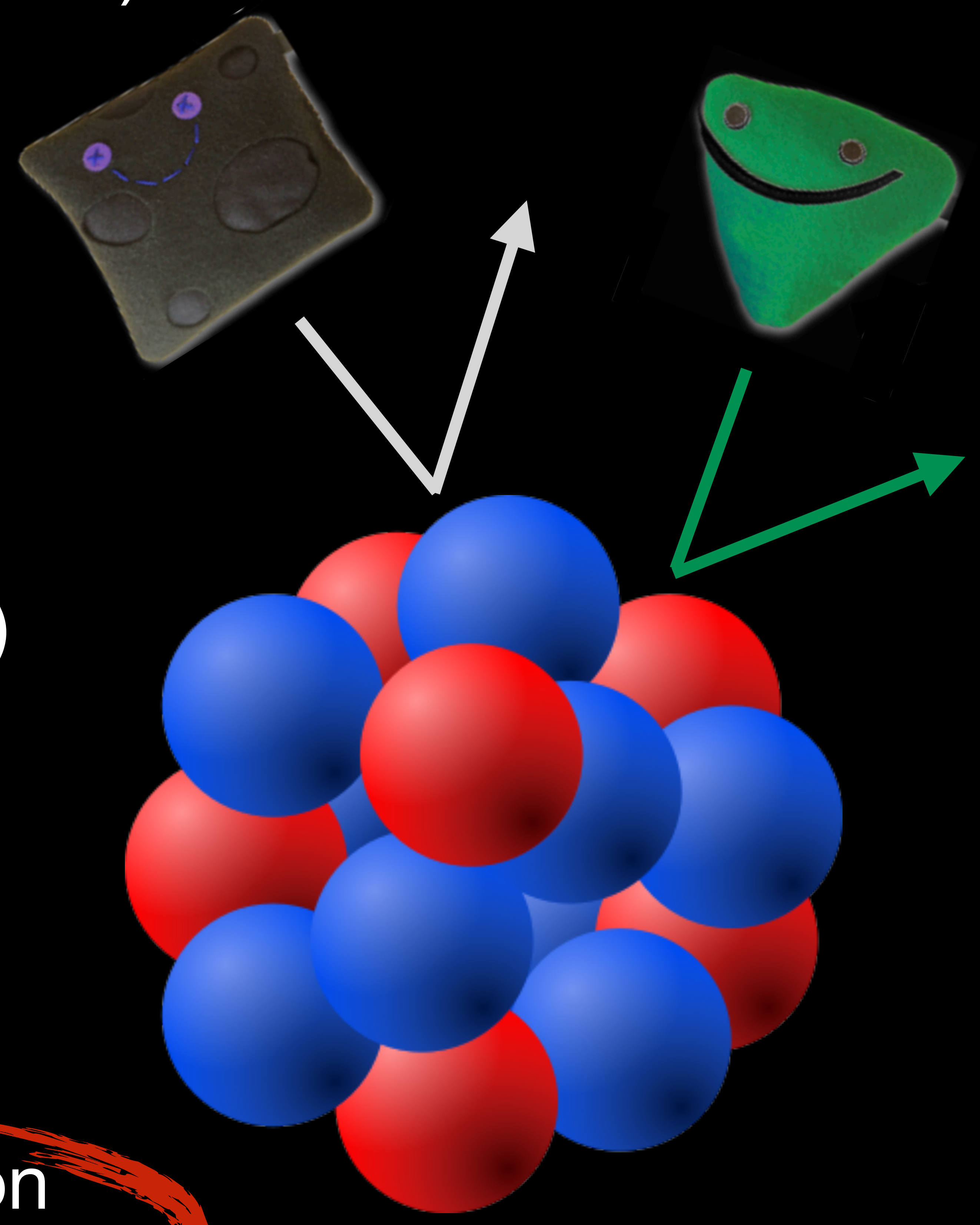


Looking forward to talking to you more! Thanks for listening!

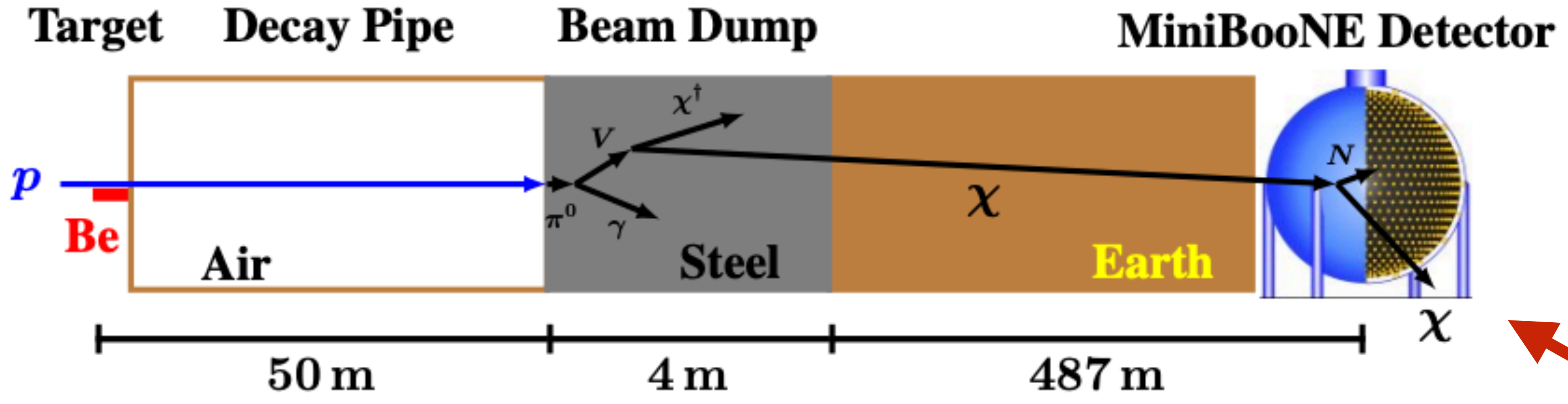
Image credit: Wikipedia, Quarkonia meet Dark Matter

Accelerated dark particles

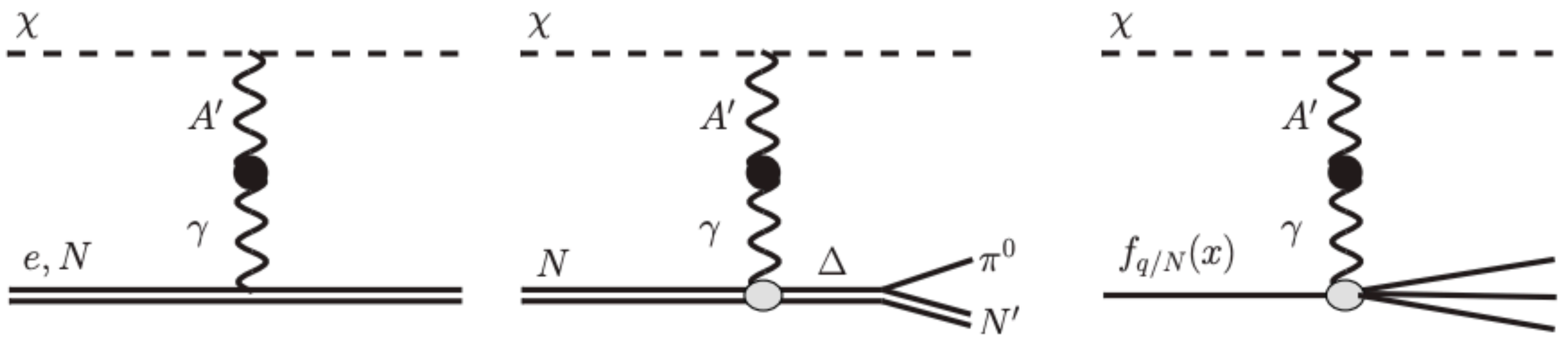
Example 2: Dark matter produced in beam dump

[deNiverville et al.: 1609.01770]:

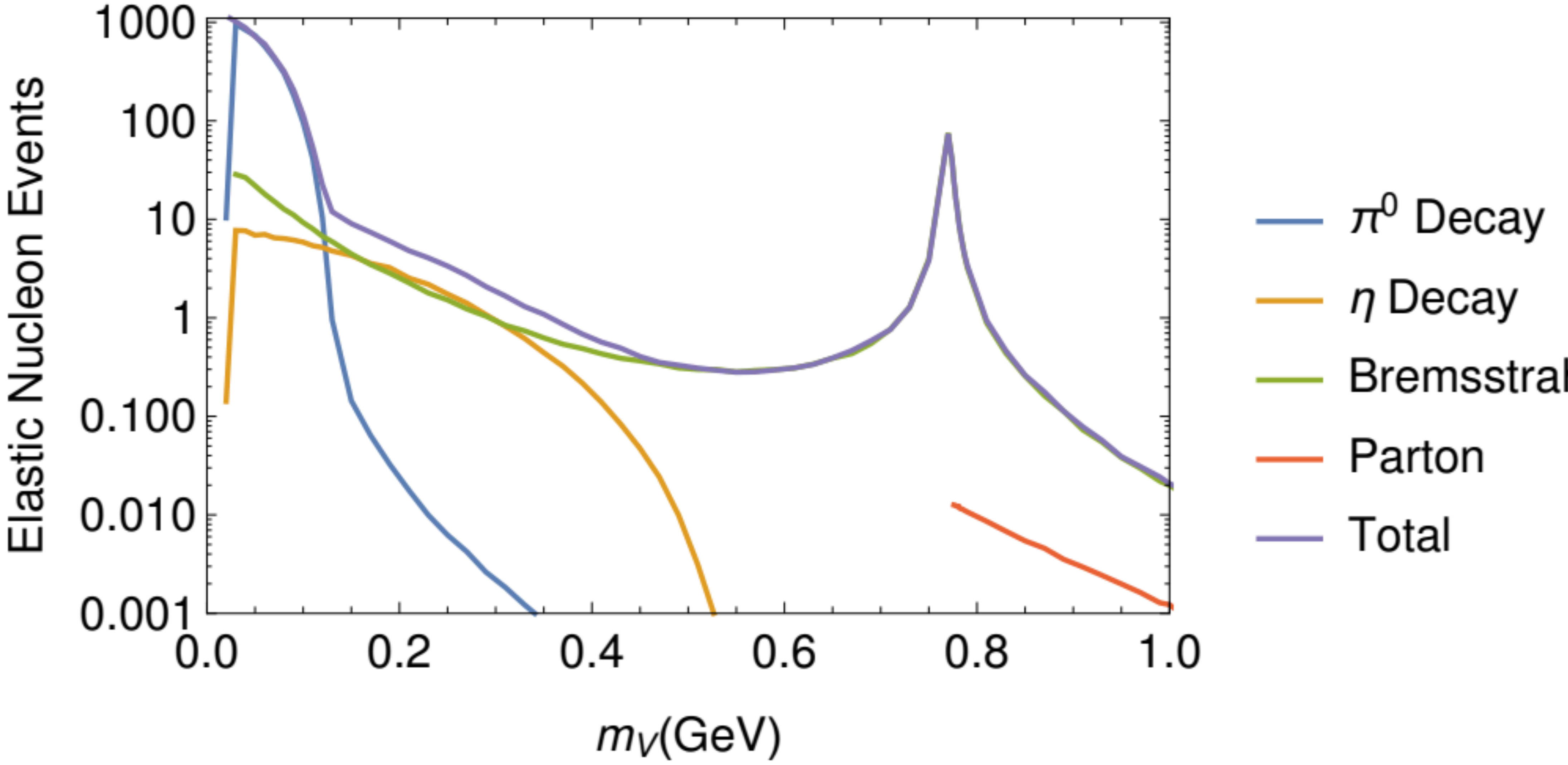
- Also sensitivities by other experiments (SBND, SHiP, T2K),
- BdNMC tool for simulation of DM production and detection



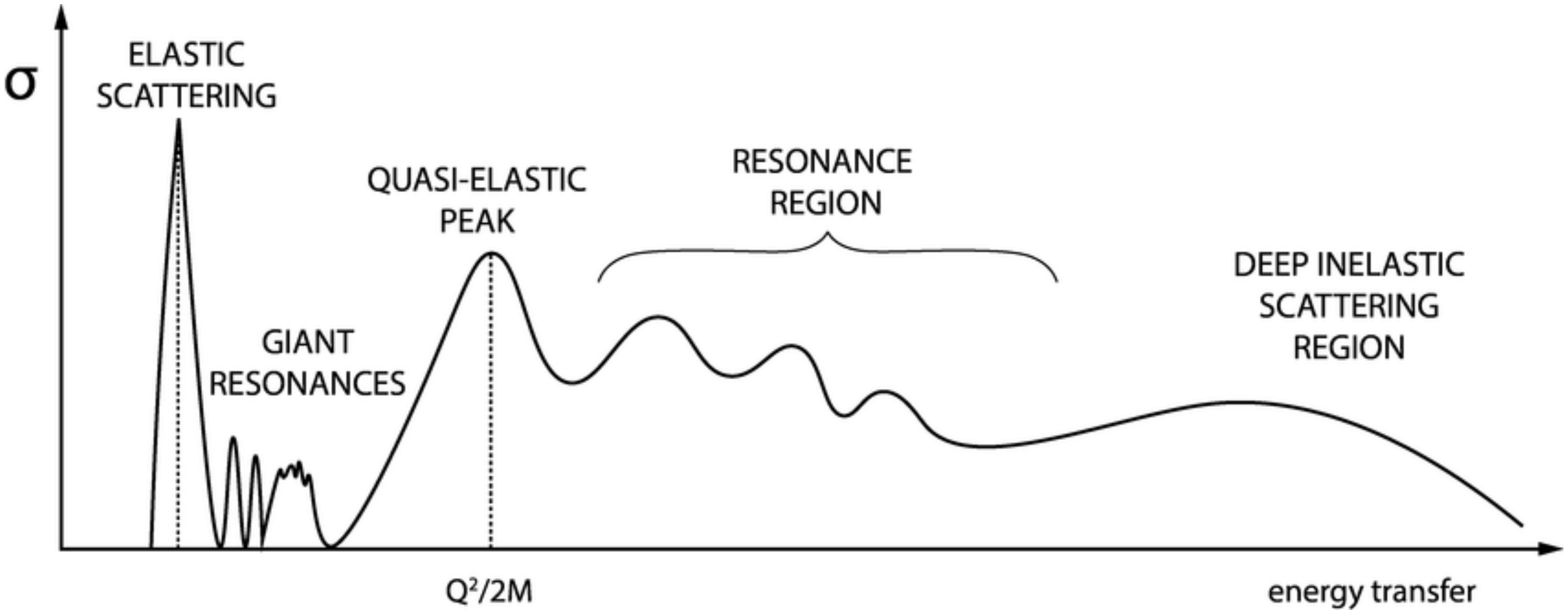
Dark matter detection:



Number of elastic nucleon events for different DM production channels:



Enhanced at $m_V \sim m_\rho$ due to resonant vector meson mixing



[Sobczyk et al.: 10.22323/1.369.0009]

[Snowmass (2013): 1401.6077]