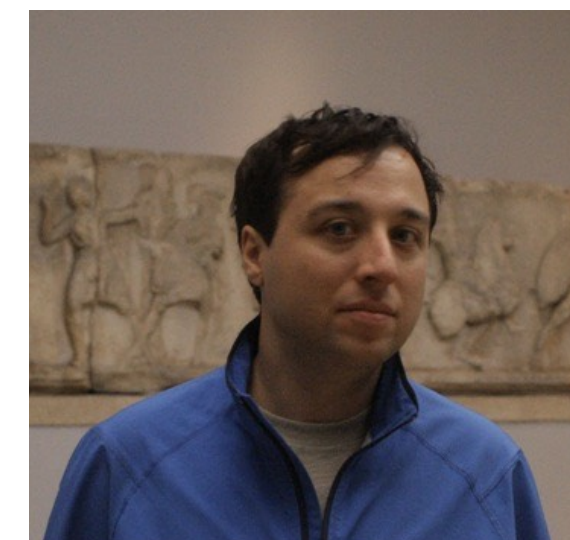


Interactions of accelerated dark matter with nuclei and implications for DUNE

Helena Kolešová (University of Stavanger)



[Alvey, Bringmann, HK: 2209.03360],

[Diurba, HK: 2504.16996]

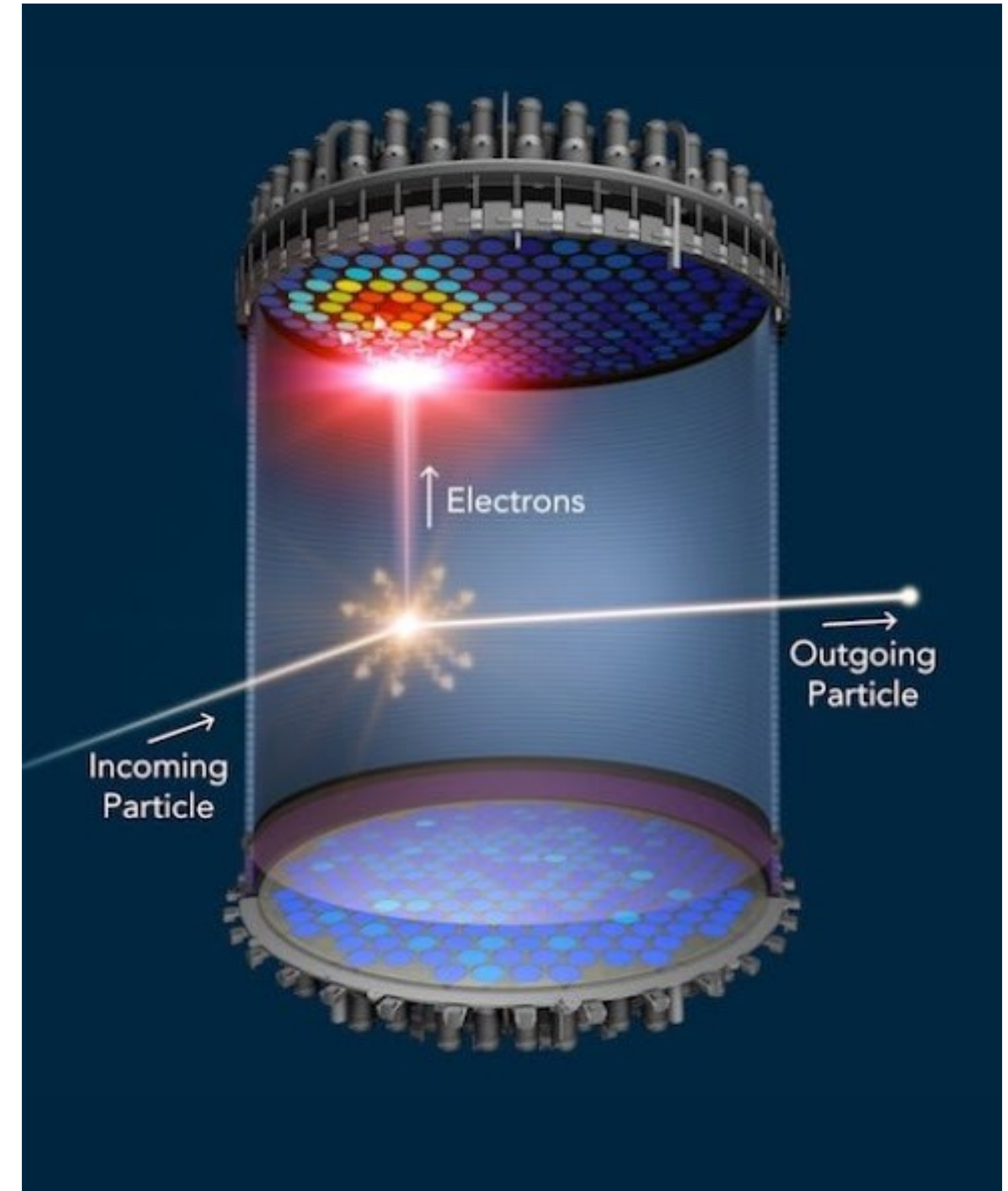
Outline

1. “Traditional” dark matter direct detection:

- Sub-GeV dark matter difficult
- Probed region model dependent

2. Cosmic-ray up-scattered dark matter:

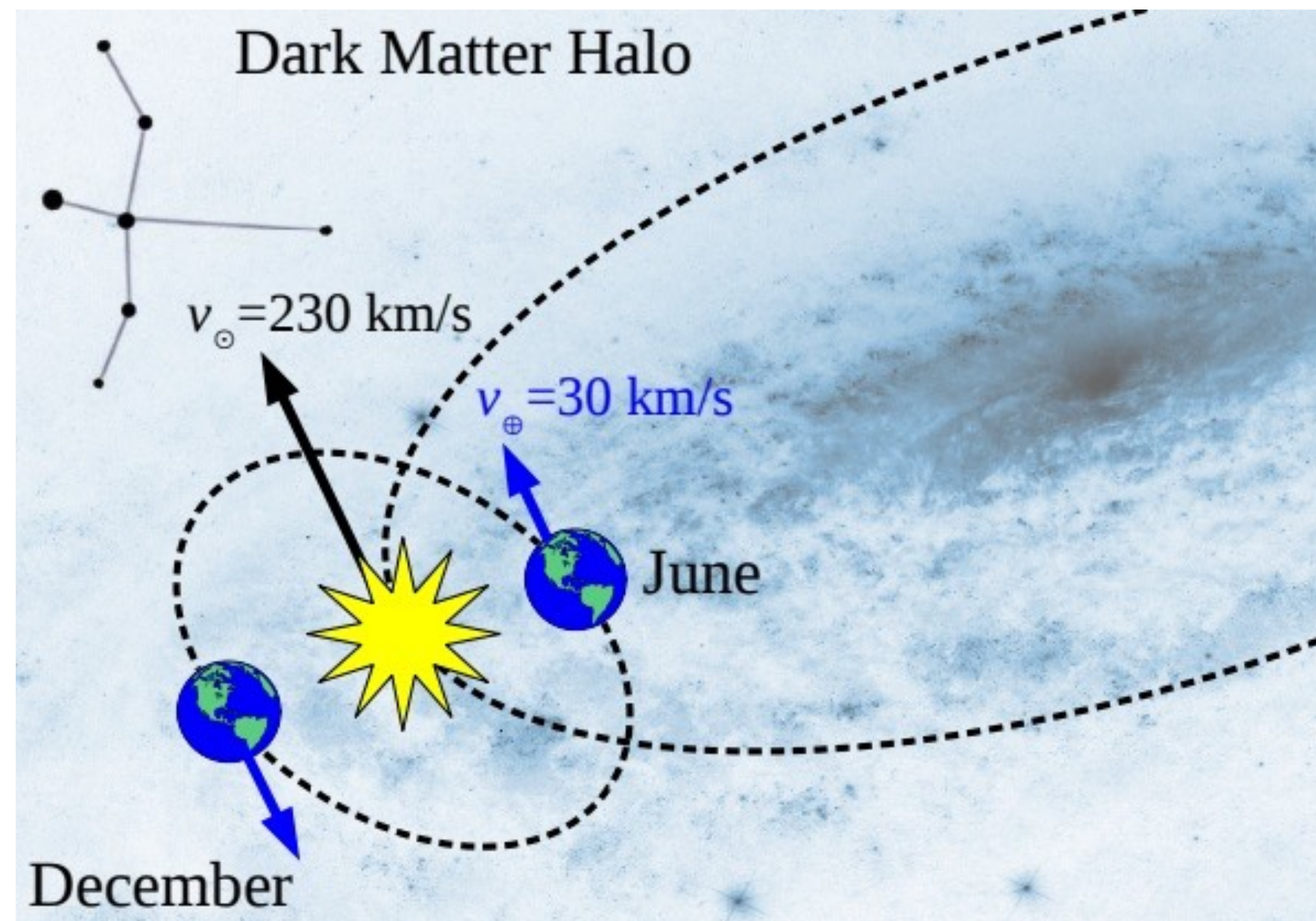
- Light dark matter can be probed by direct detection and neutrino experiments
- Neutrino experiments are similarly sensitive to different dark matter models



“Direct detection” of dark matter

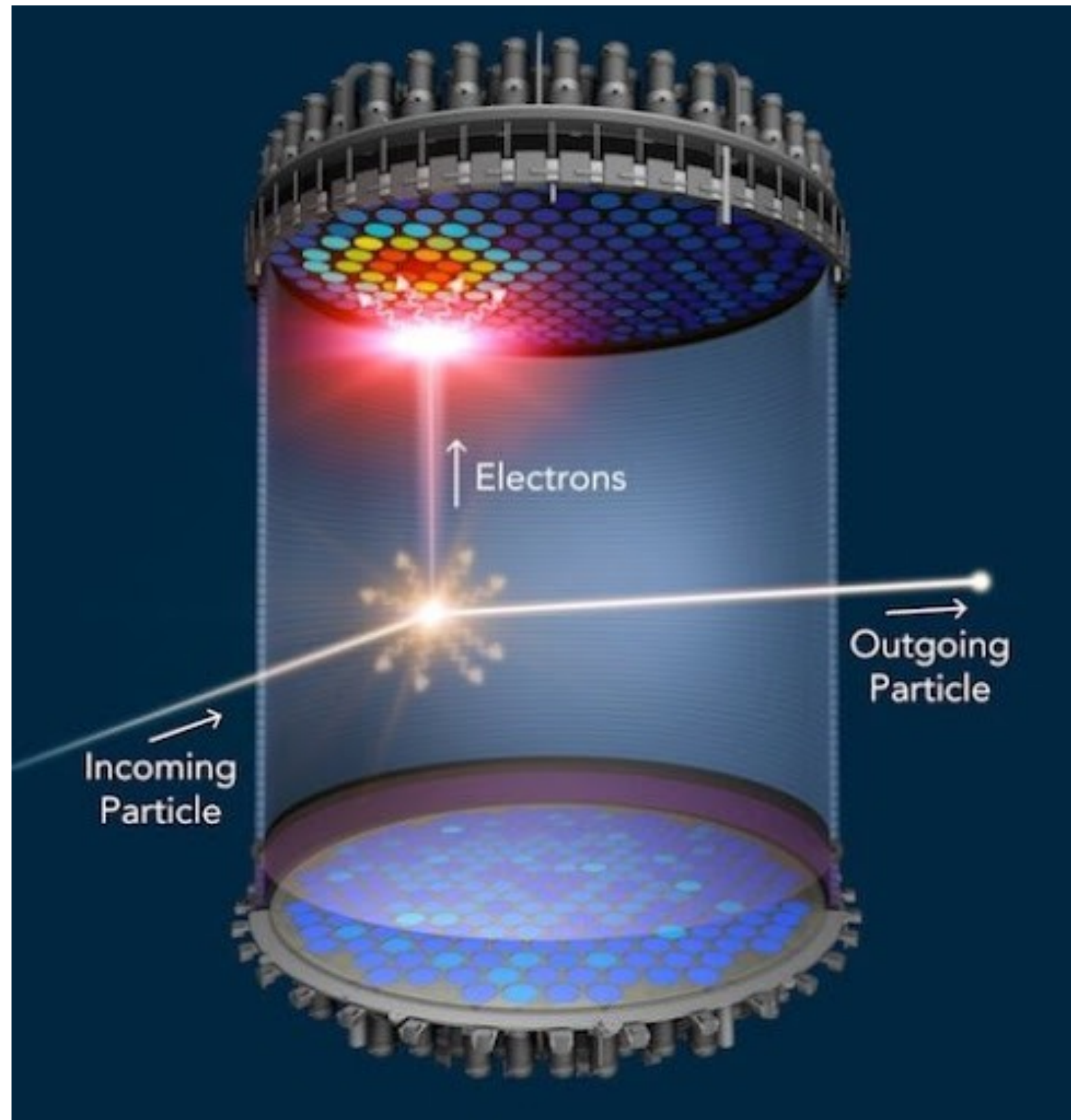


“Direct detection” of dark matter



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

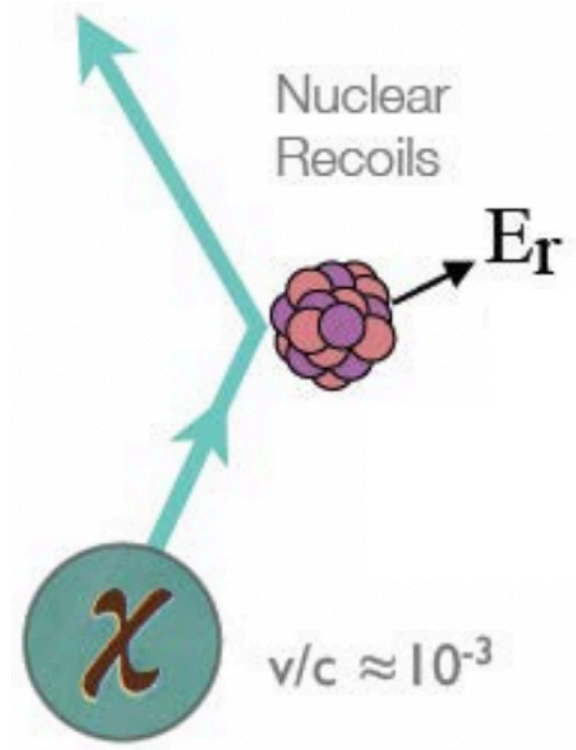
“Direct detection” of dark matter



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

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

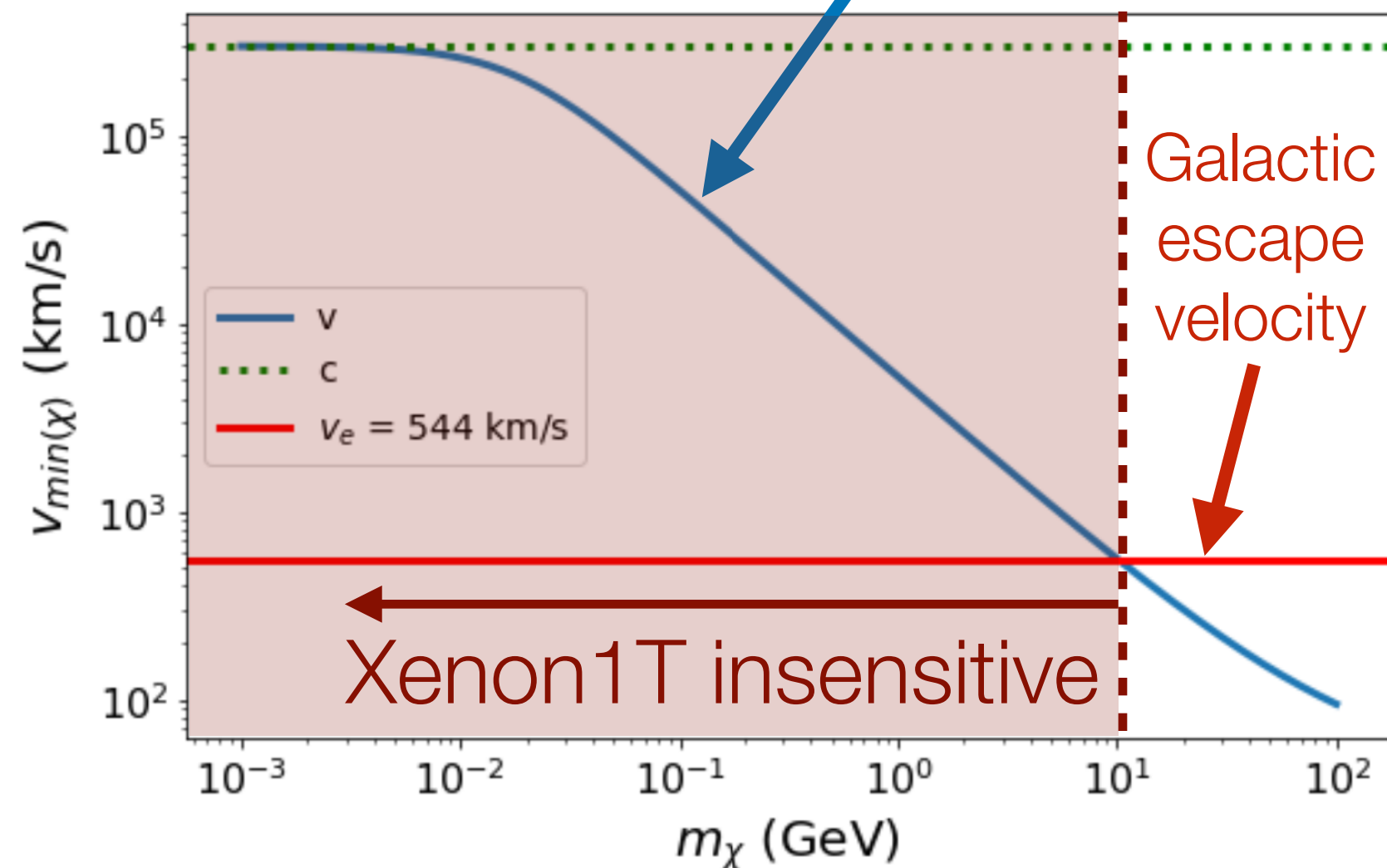
Direct detection of light dark matter?



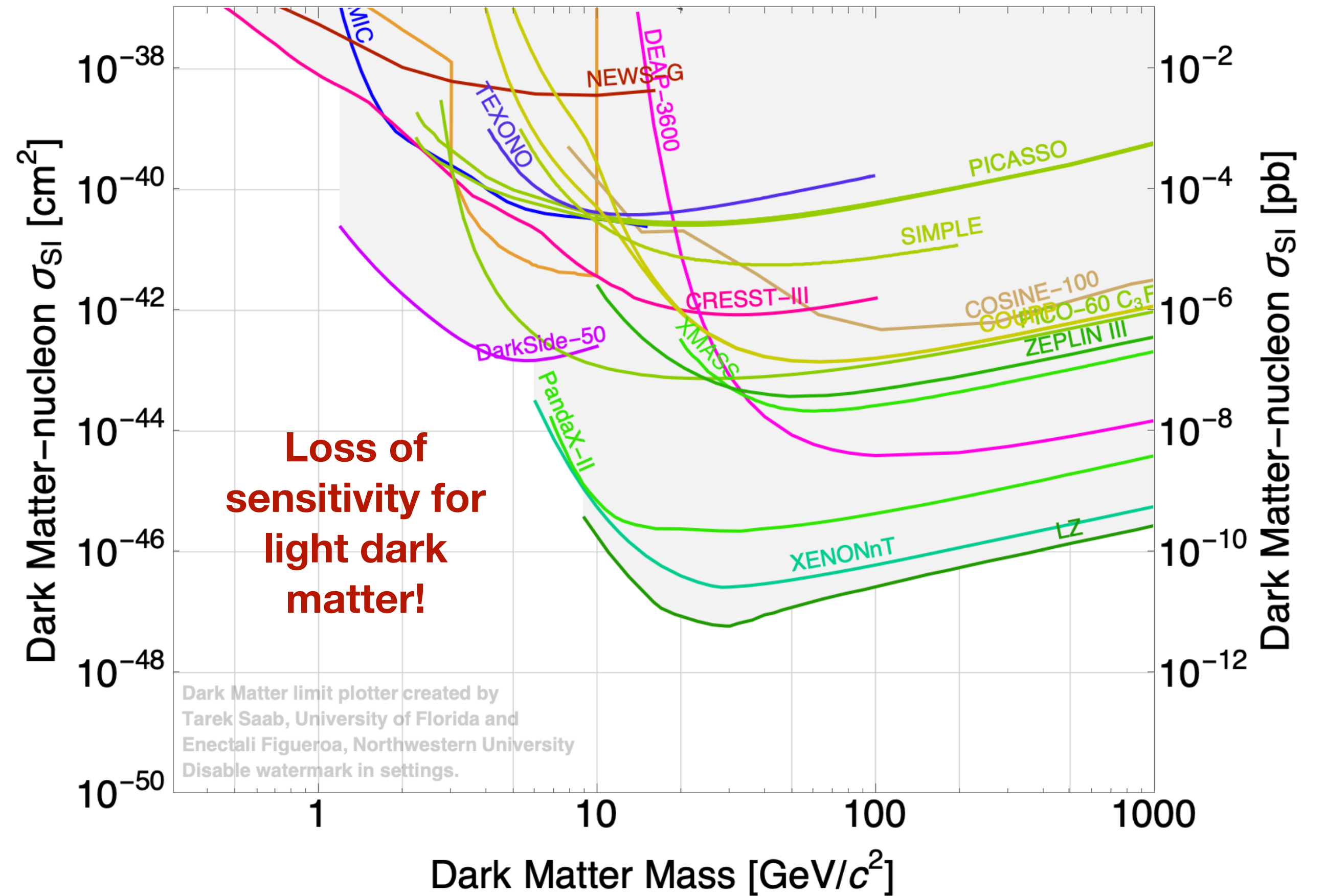
Example: Xenon1T threshold for nucleus recoil energy:

$$E_r \gtrsim 5 \text{ keV}$$

⇒ Minimal dark matter velocity to trigger detectable nuclear recoil



Credit: Gailyn Monroe



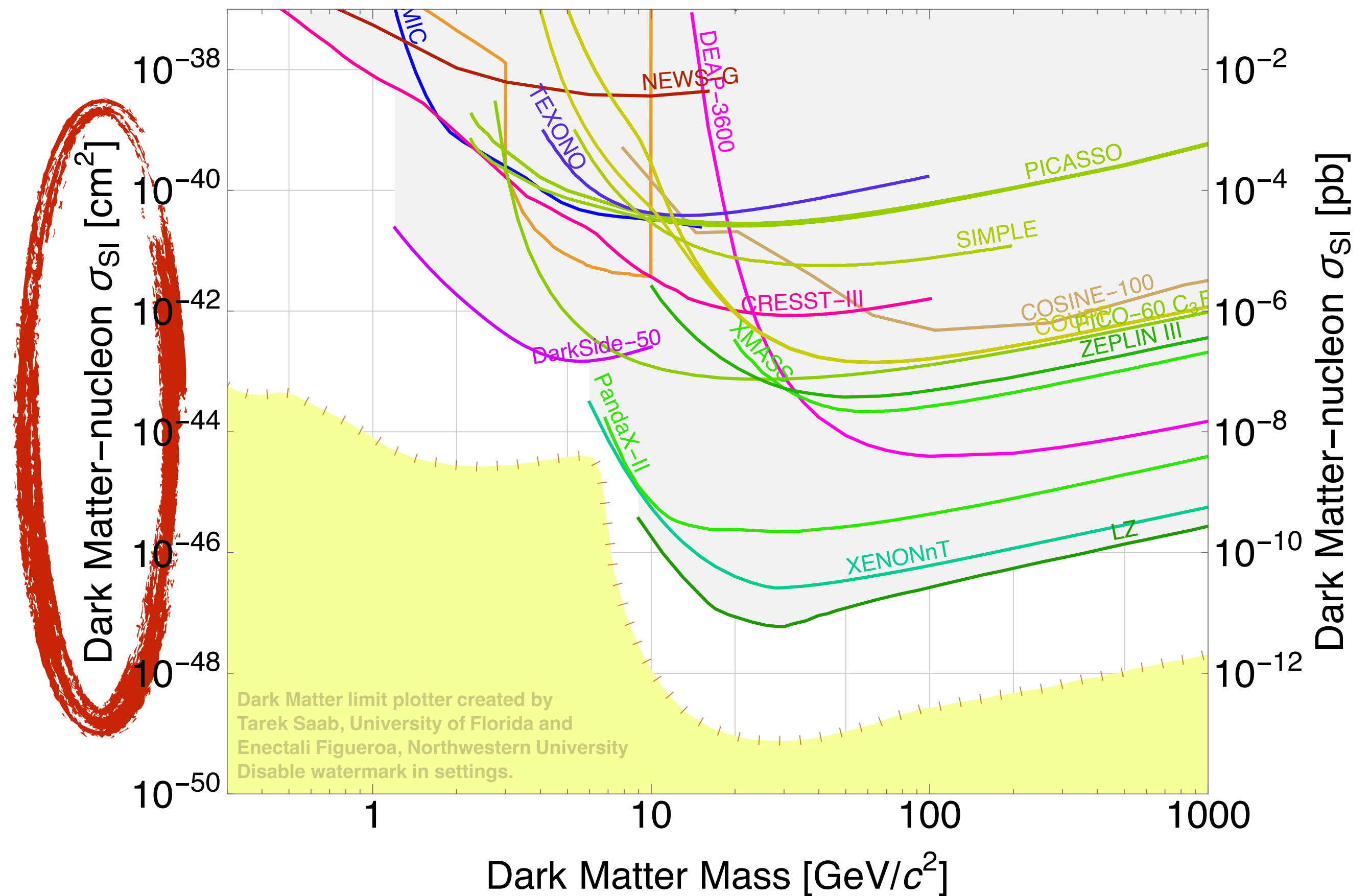
Direct detection: model dependence

Spin-independent interactions

- Coherently enhanced:

$$\sigma_{\chi A} \propto A^2 \frac{\mu_{\chi A}^2}{\mu_{\chi p}^2} \sigma_{SI} \quad \text{(cross sections in non-relativistic limit)}$$

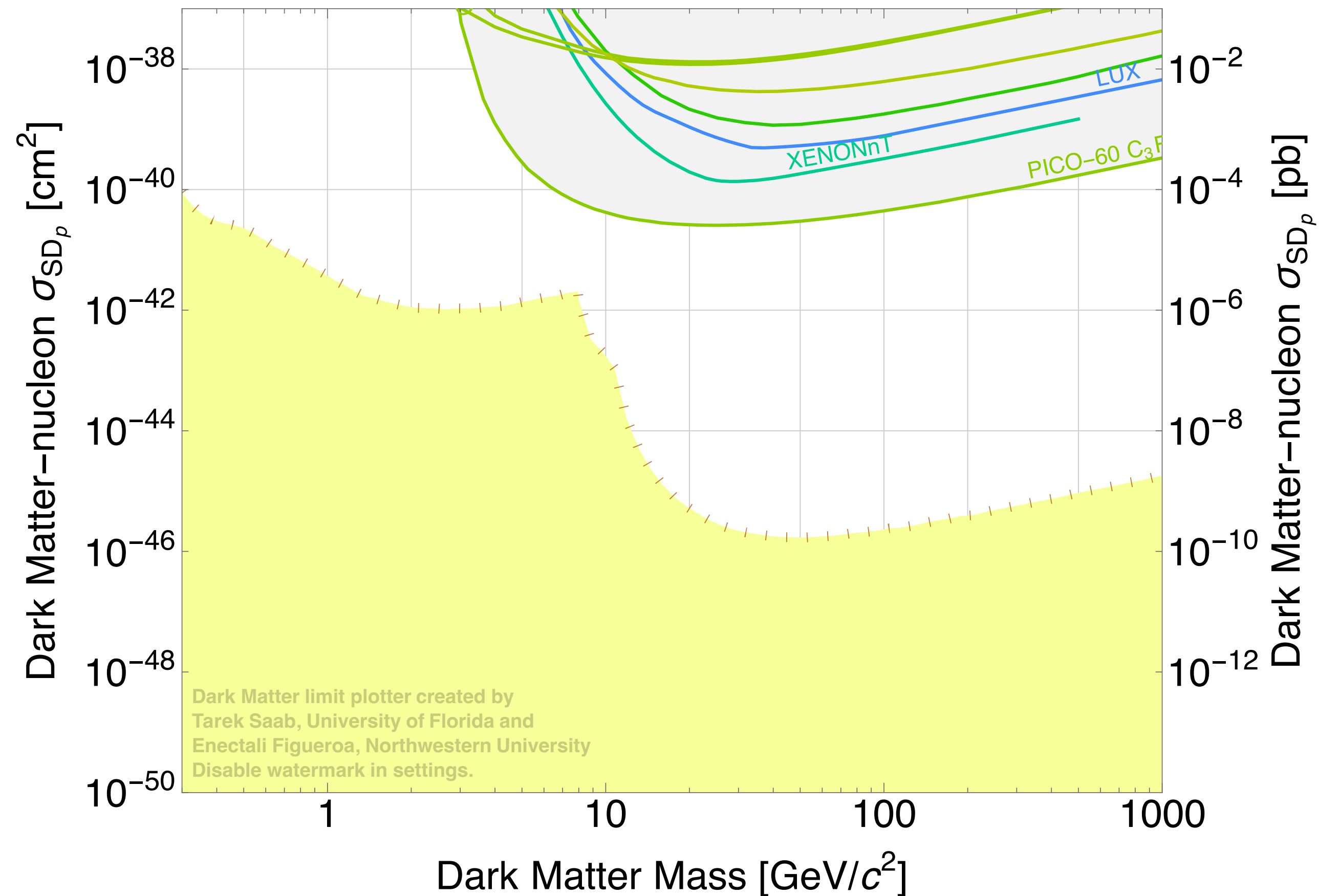
- Realised, e.g., for DM-quark interaction via scalar or vector mediator



Direct detection: model dependence

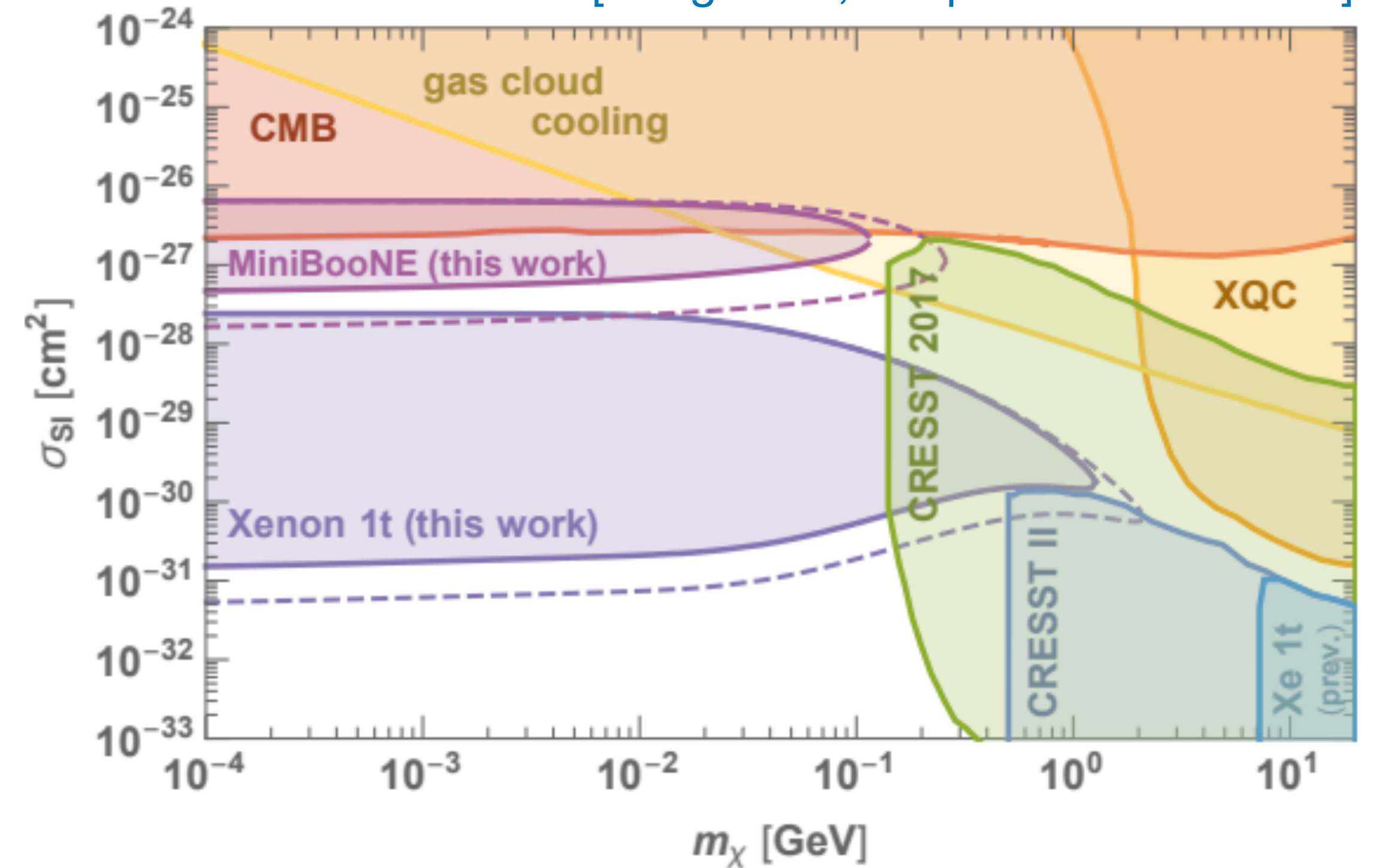
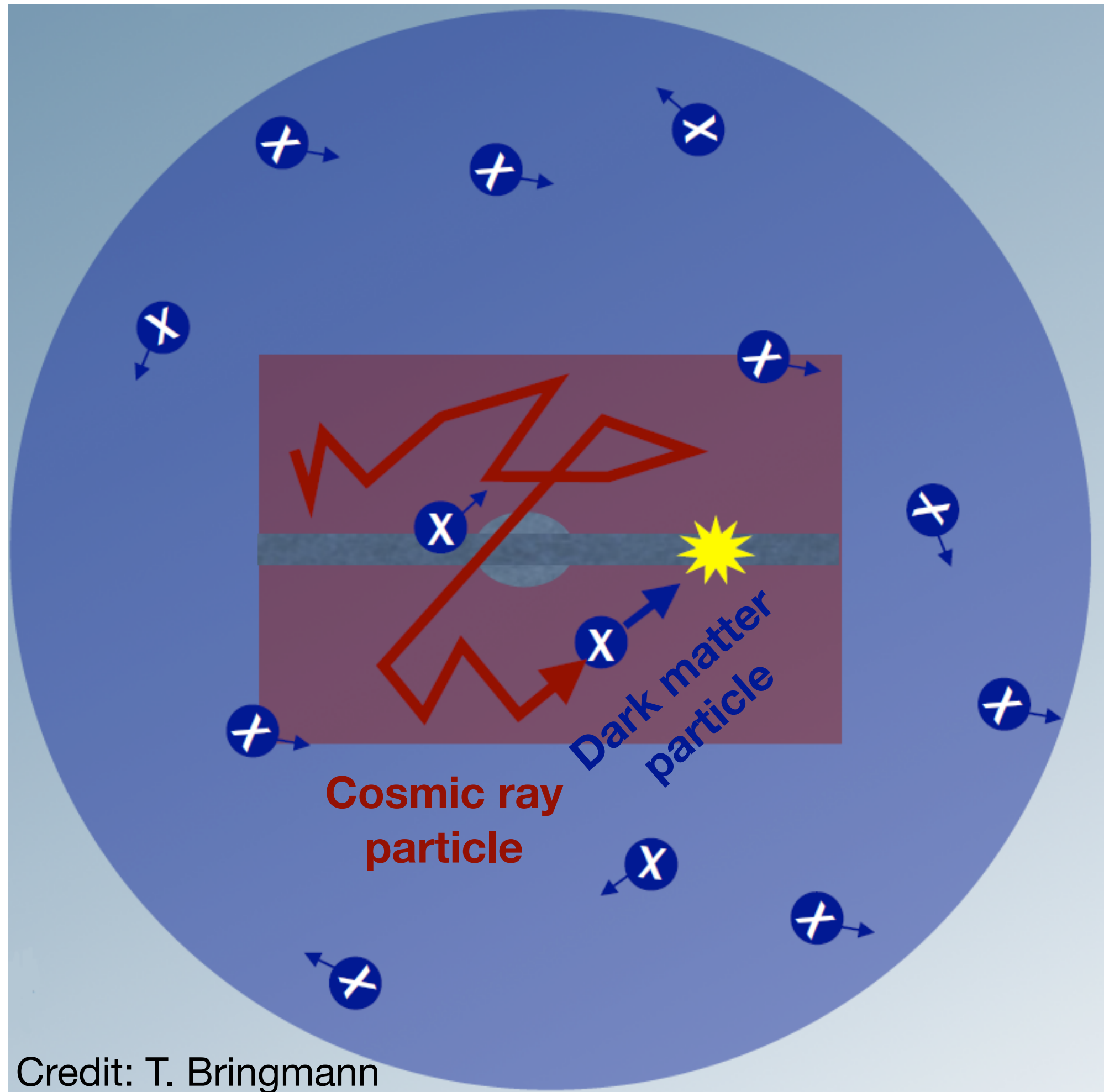
Spin-dependent interactions

- 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!



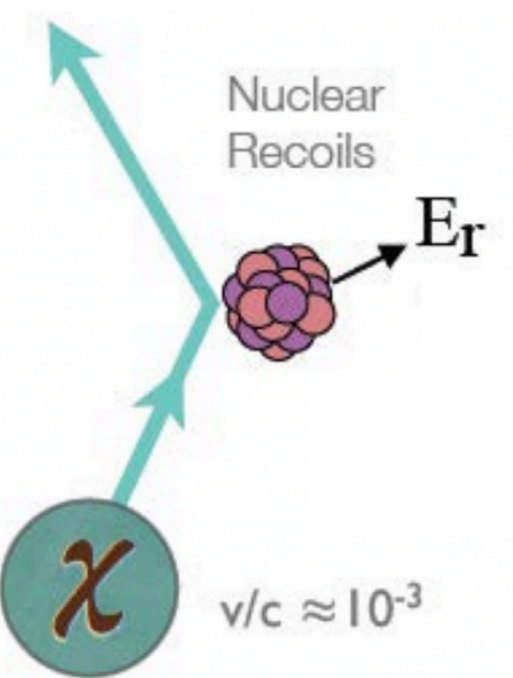
Cosmic-ray up-scattered dark matter

[Bringmann, Pospelov: 1810.10543]

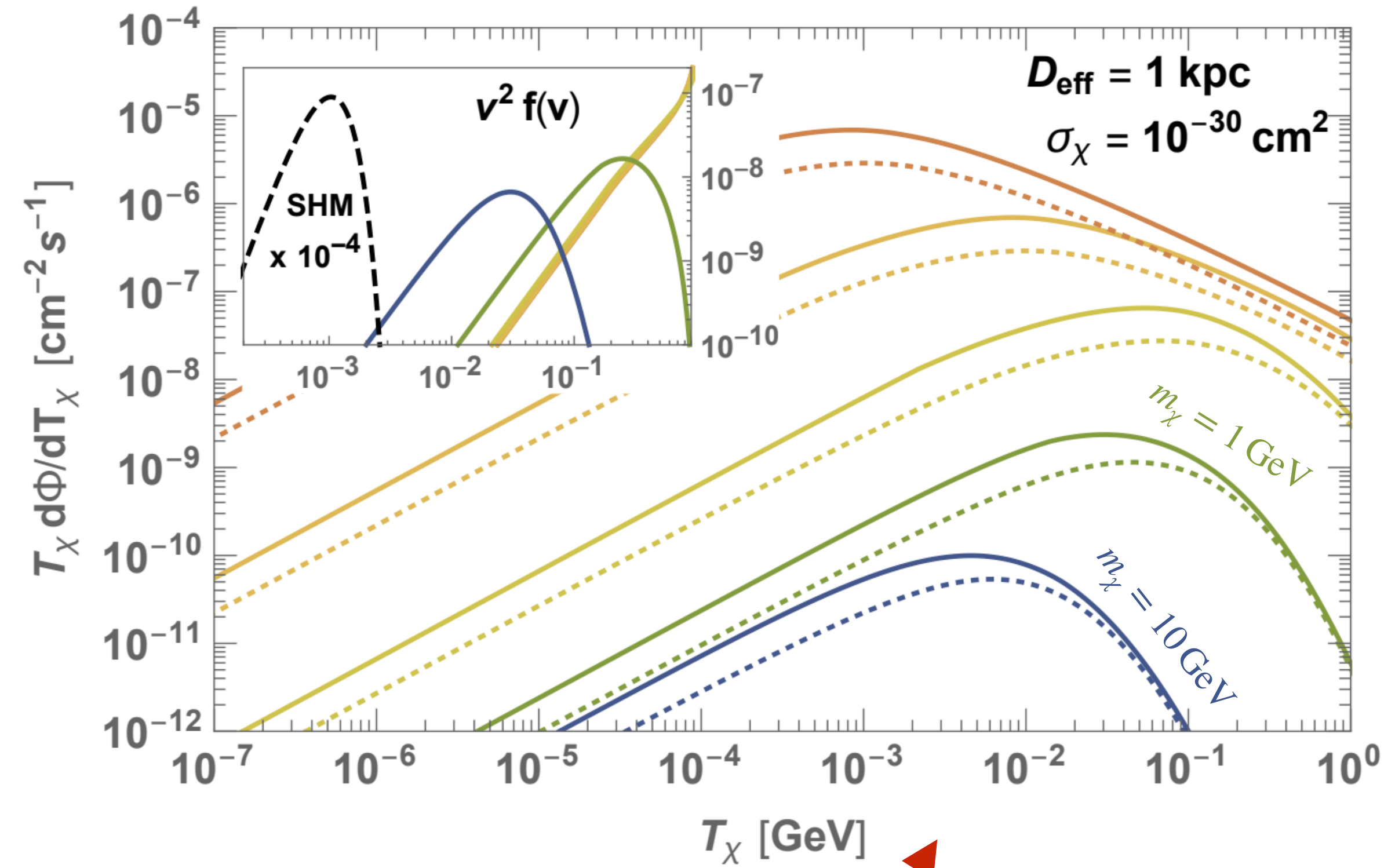
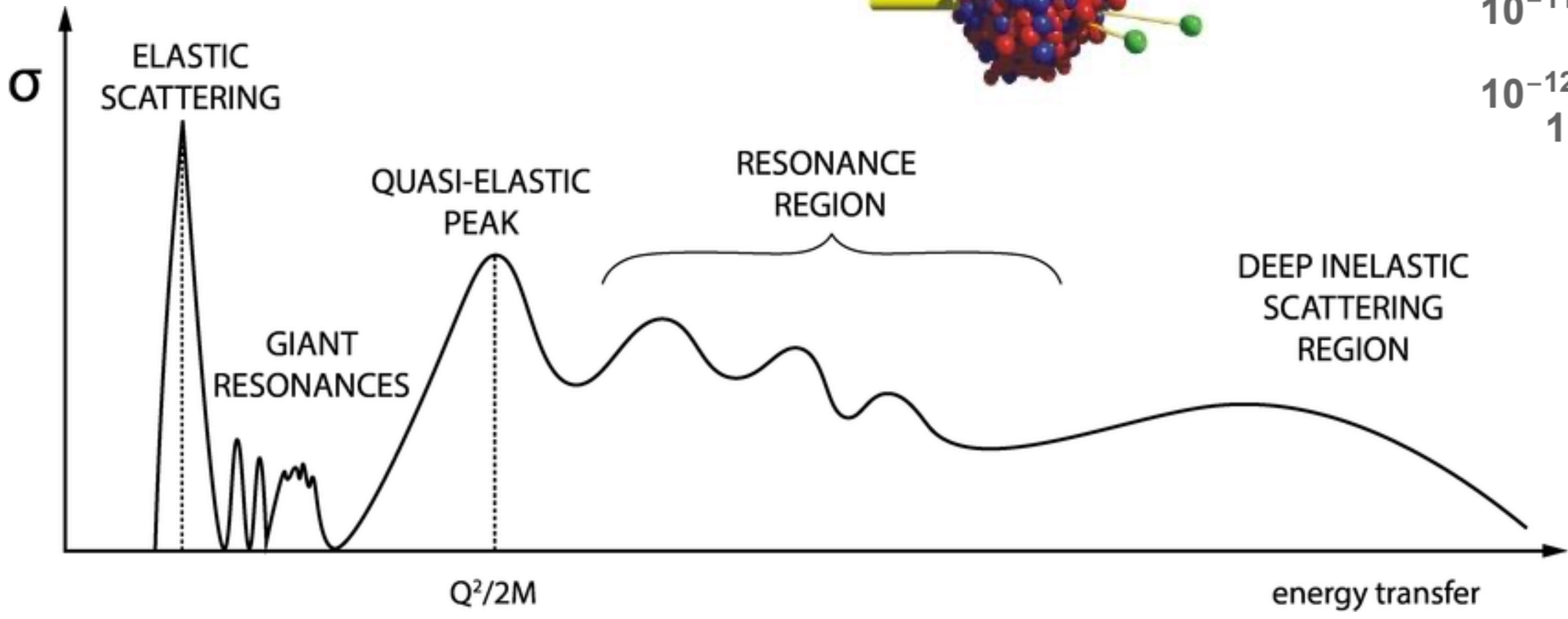
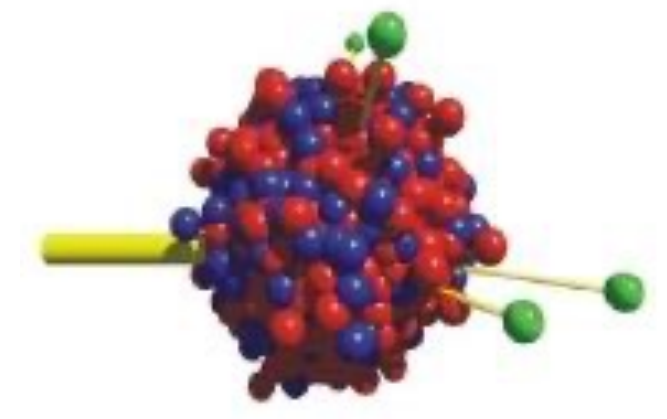


Increased dark matter kinetic energy \Rightarrow lighter dark matter can be probed by direct detection experiments like Xenon 1t!

Cosmic-ray up-scattered dark matter in neutrino experiments?

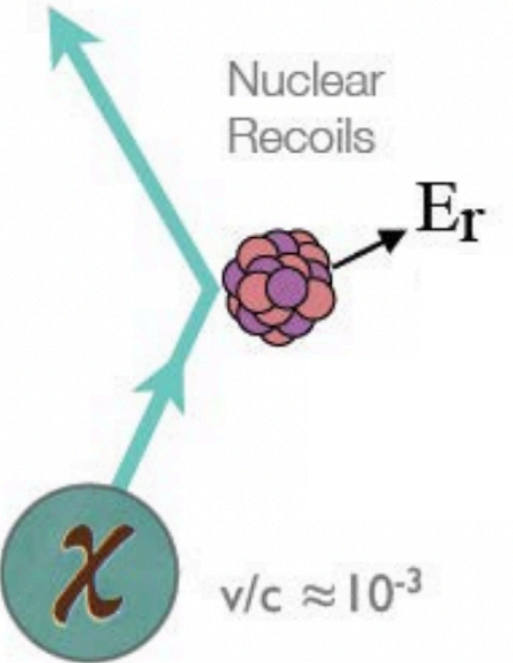


- Direct detection experiments are tuned to halo dark matter (e.g., Xenon 1T is sensitive to coherent elastic scattering with $E_r = 5-50$ keV)
- Particles with $\mathcal{O}(\text{GeV})$ kinetic energies can induce other processes!

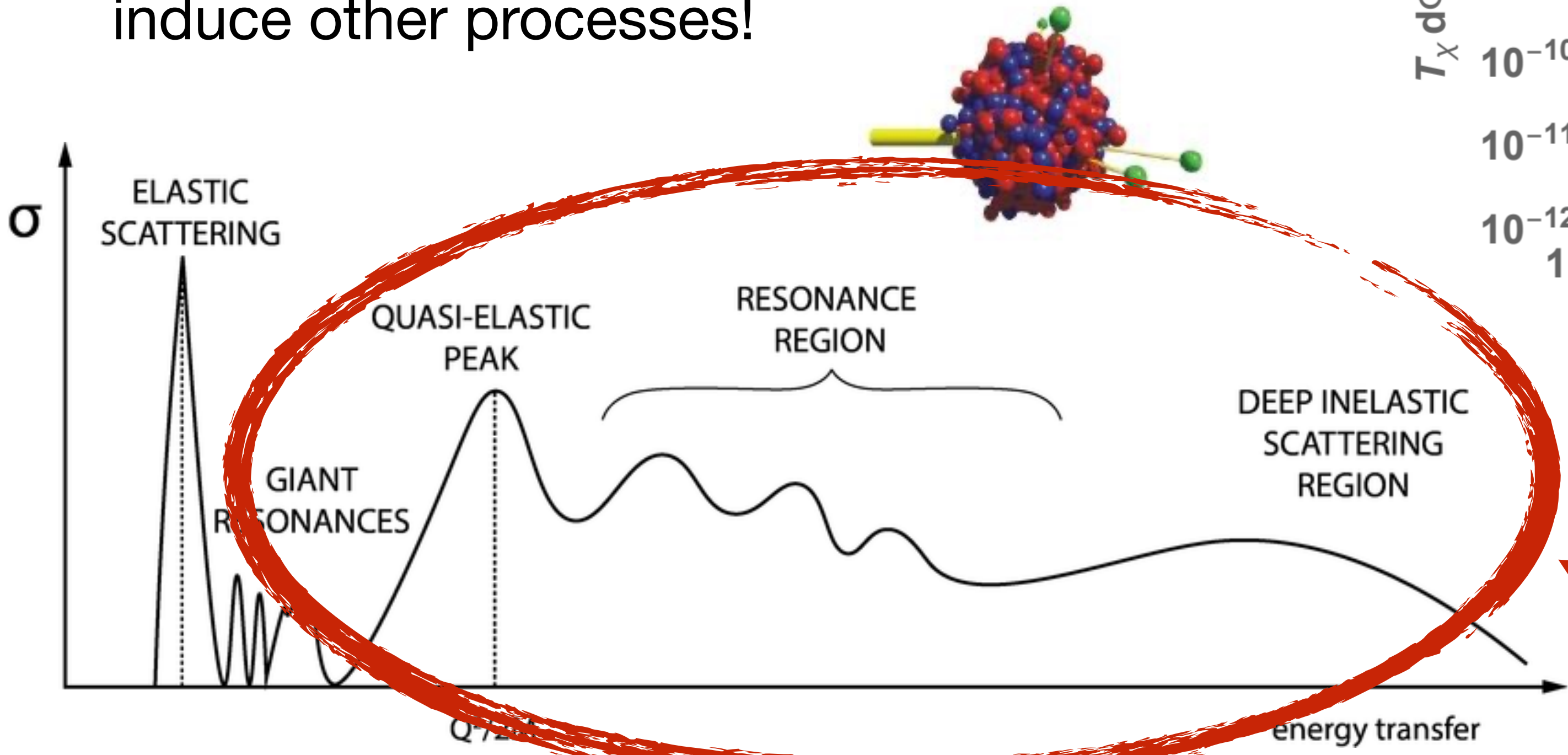
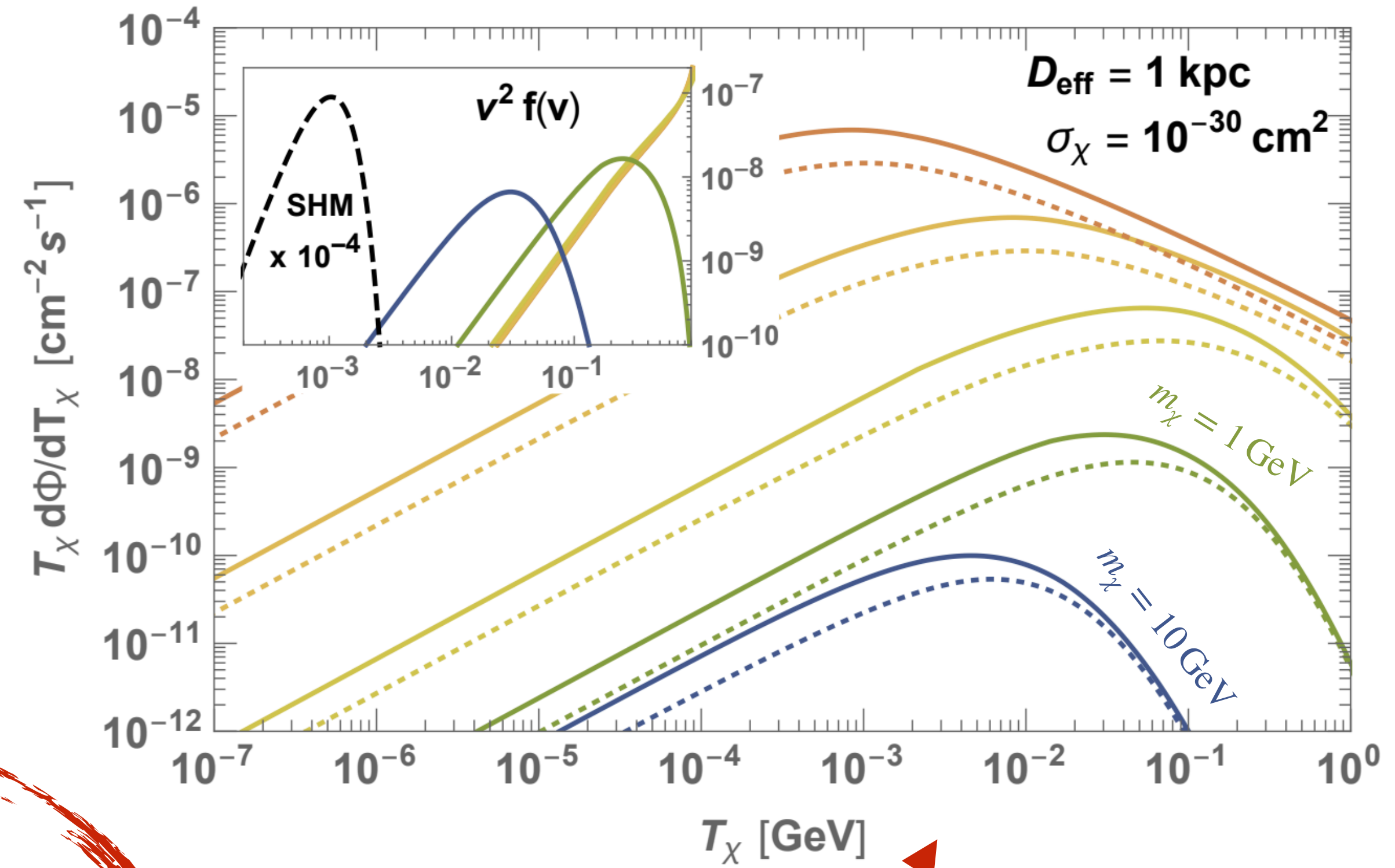


Up-scattered dark matter flux coming to Earth
[\[Bringmann, Pospelov: 1810.10543\]](#)

Cosmic-ray up-scattered dark matter in neutrino experiments?



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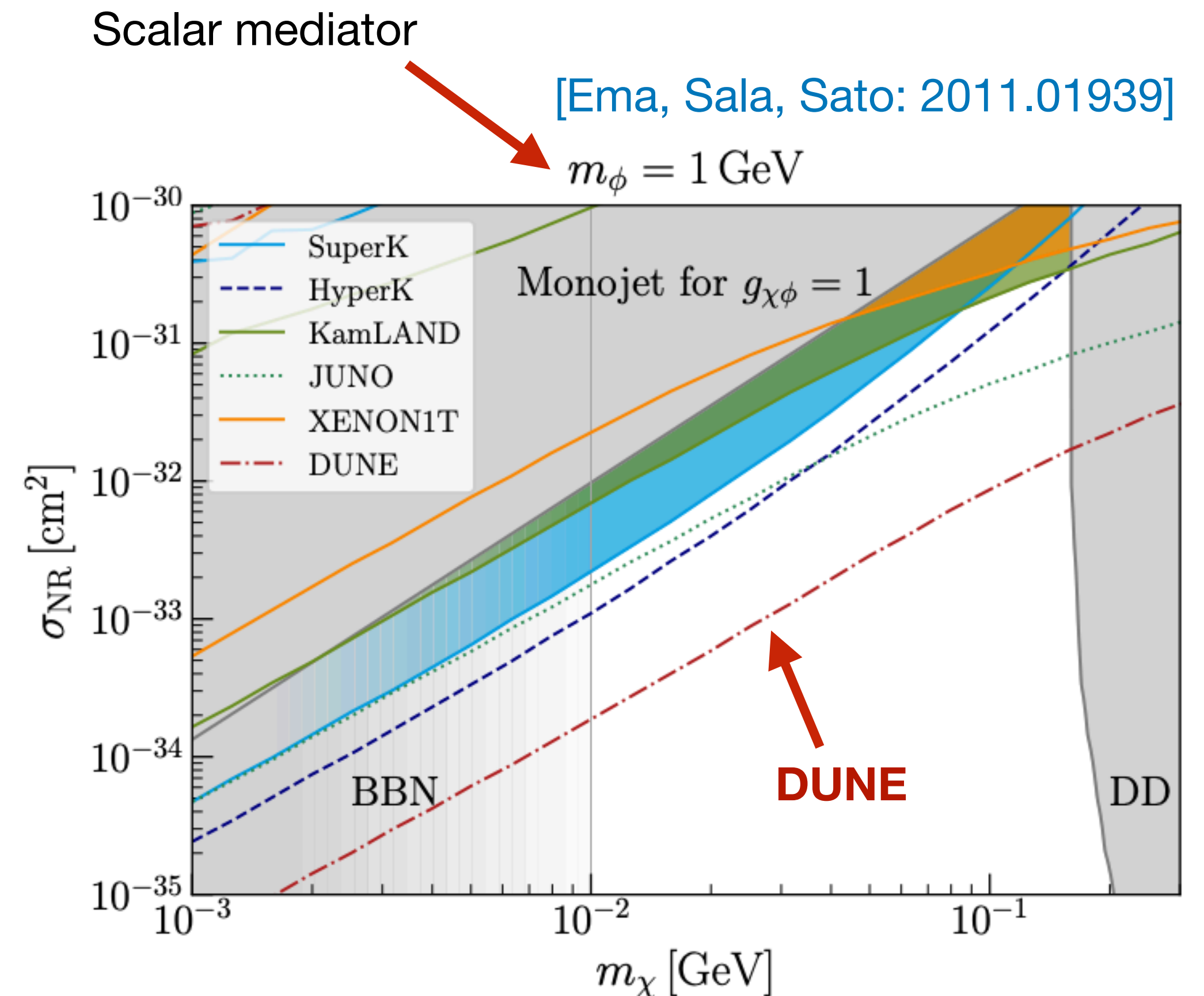
Observable in neutrino experiments like DUNE!

Cosmic-ray up-scattered dark matter in neutrino experiments?

DUNE sensitivity predicted in
[Ema, Sala, Sato: 2011.01939]:

- 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!



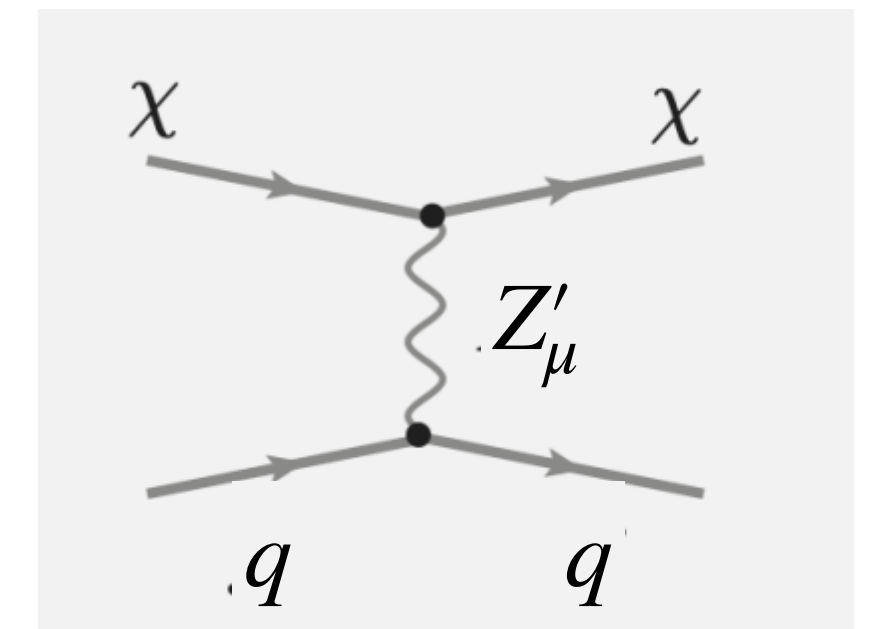
Benchmark model: massive Z' mediator

- Motivation: implemented in GENIE boosted DM module [[Berger: 1812.05616](#)]
- Both dark matter particles and Standard Model quarks charged under $U(1)_D$:

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

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

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



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

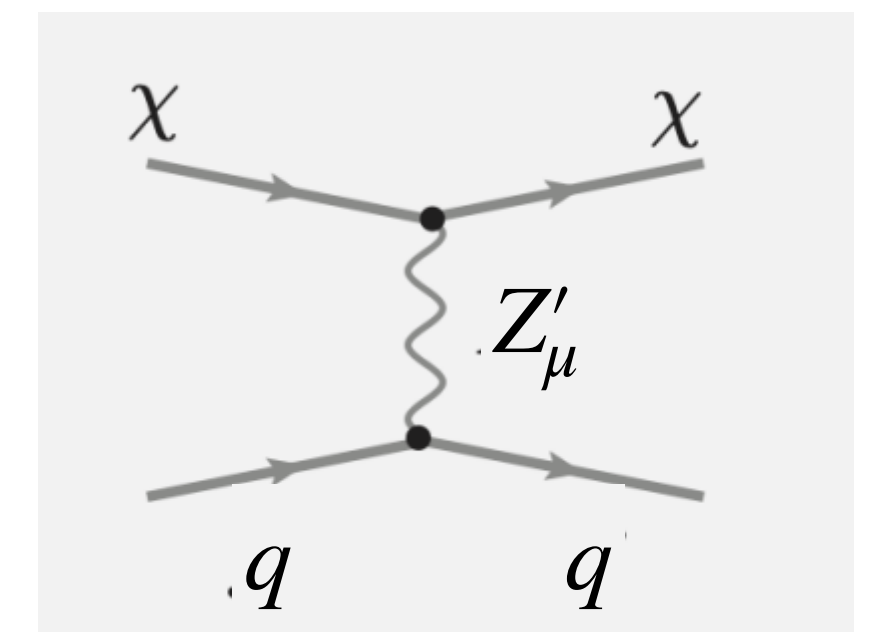
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Dark matter scattering with nucleons

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

Well known, enter
electromagnetic
interactions

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

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

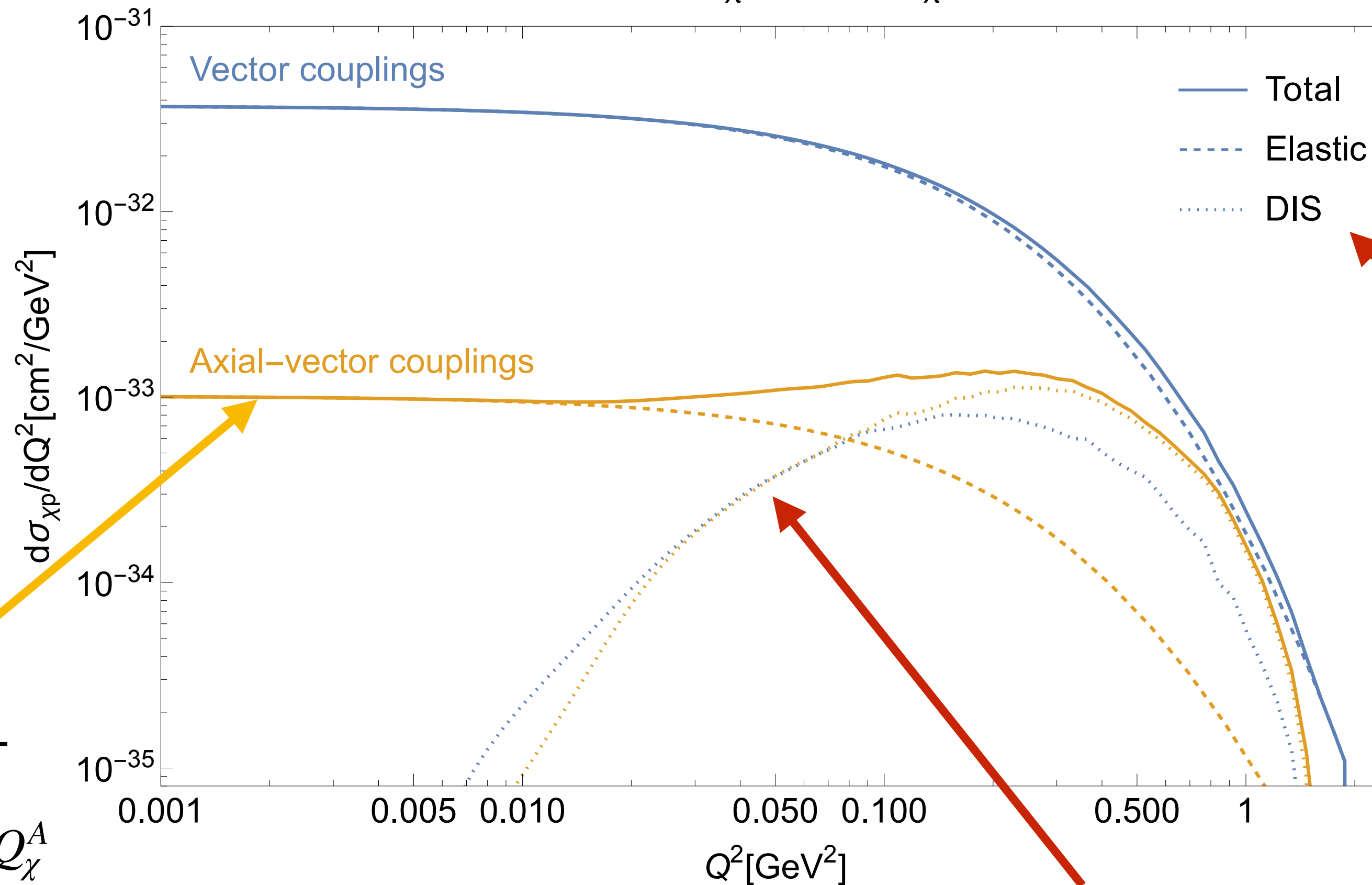
Somewhat known,
enters neutrino
interactions

Corresponding contribution to cross section
suppressed by scattering particle mass \Rightarrow
irrelevant for neutrinos, not known very well!

Dark-matter-proton cross section

$$g_{Z'} = 0.1, \quad Q_\chi^V = Q_\chi^A = Q_q^V = Q_q^A = 1$$

$$m_{Z'} = 1\text{GeV}, \quad m_\chi = 1\text{GeV}, \quad T_\chi = 1\text{GeV}$$



Calculated
analytically, agrees
with the GENIE output

Numerical calculation
by GENIE
[Berger: 1812.05616]

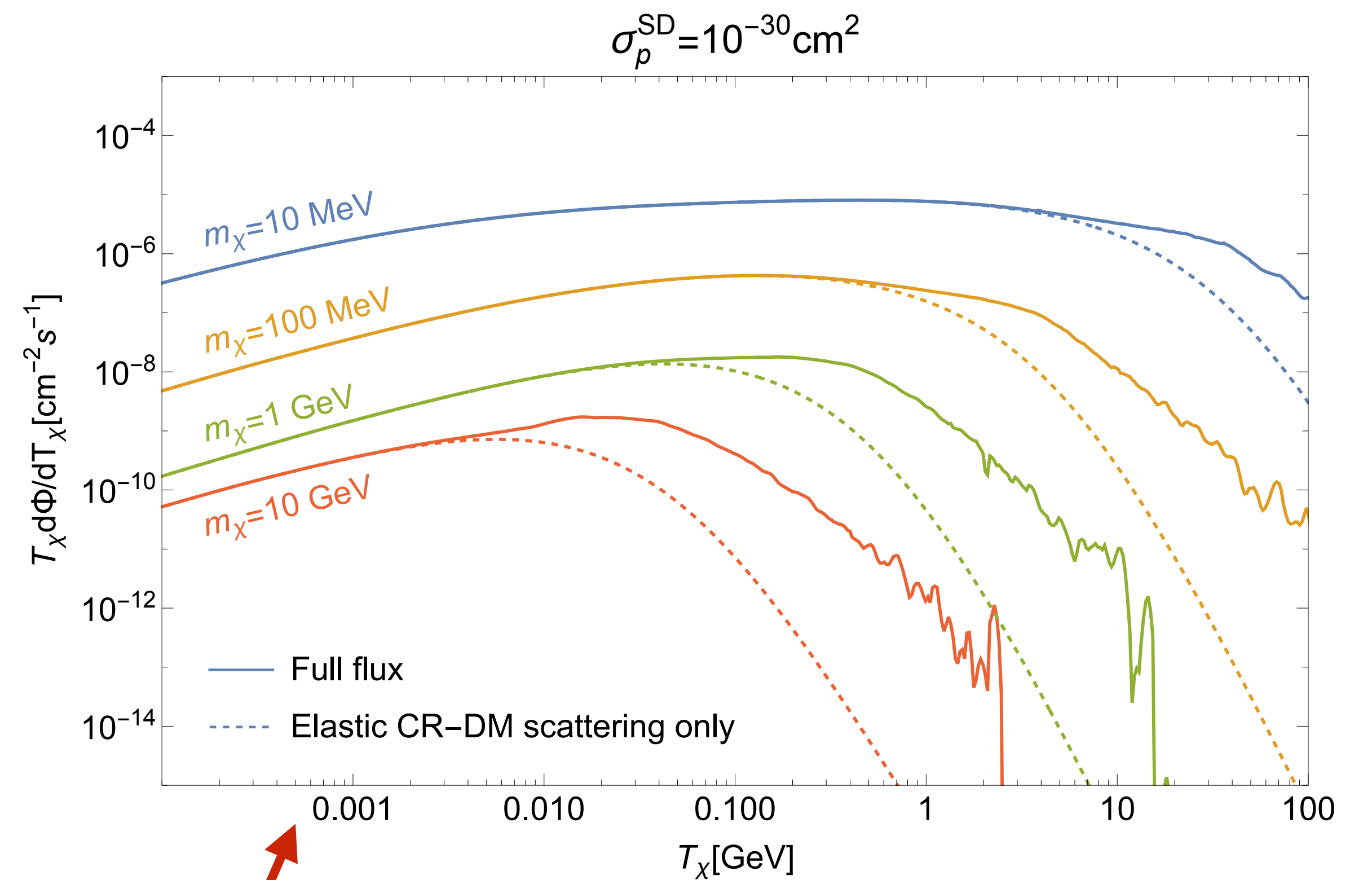
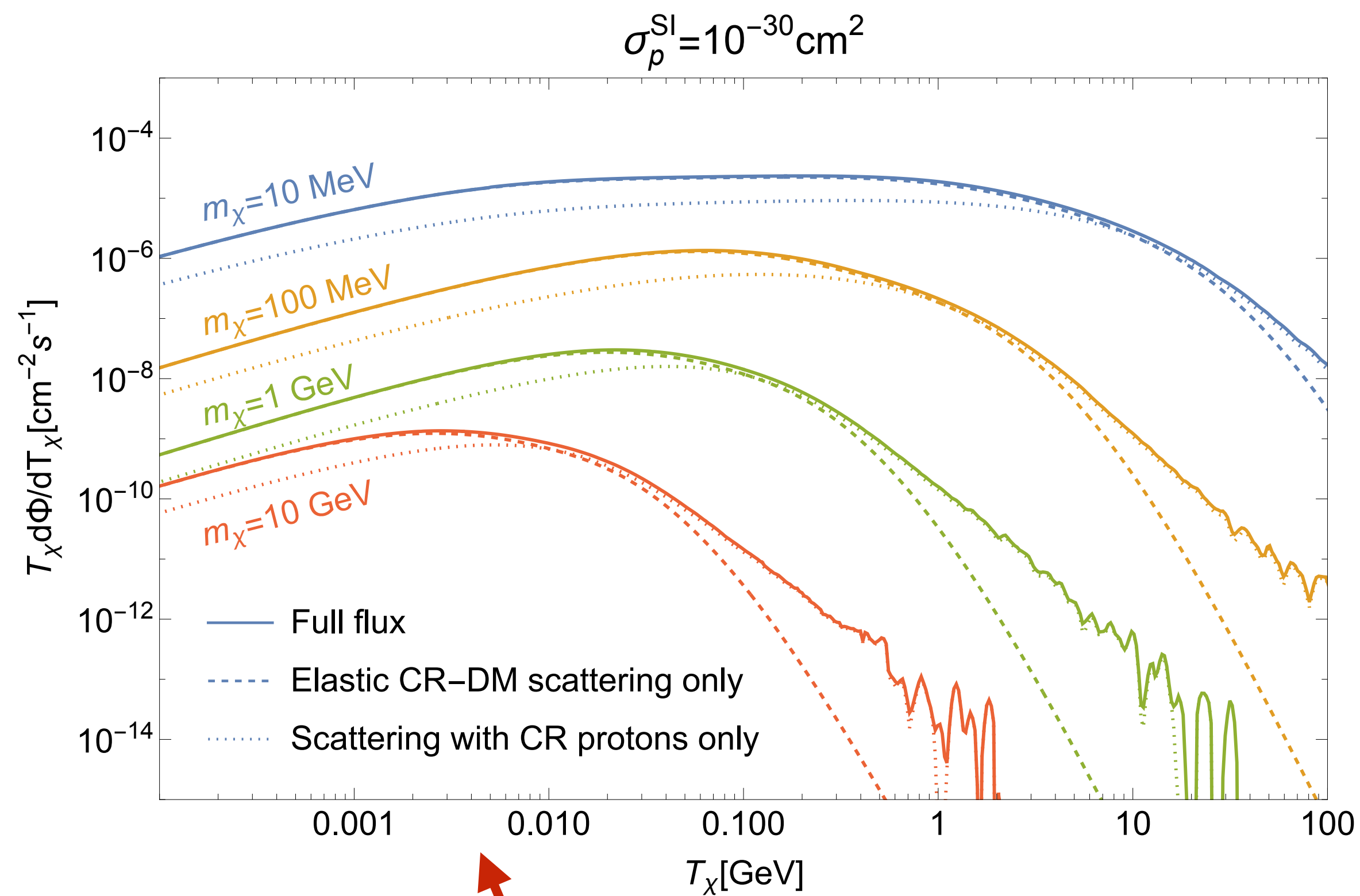
Relative suppression of the
elastic contribution for axial-
vector couplings since

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

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

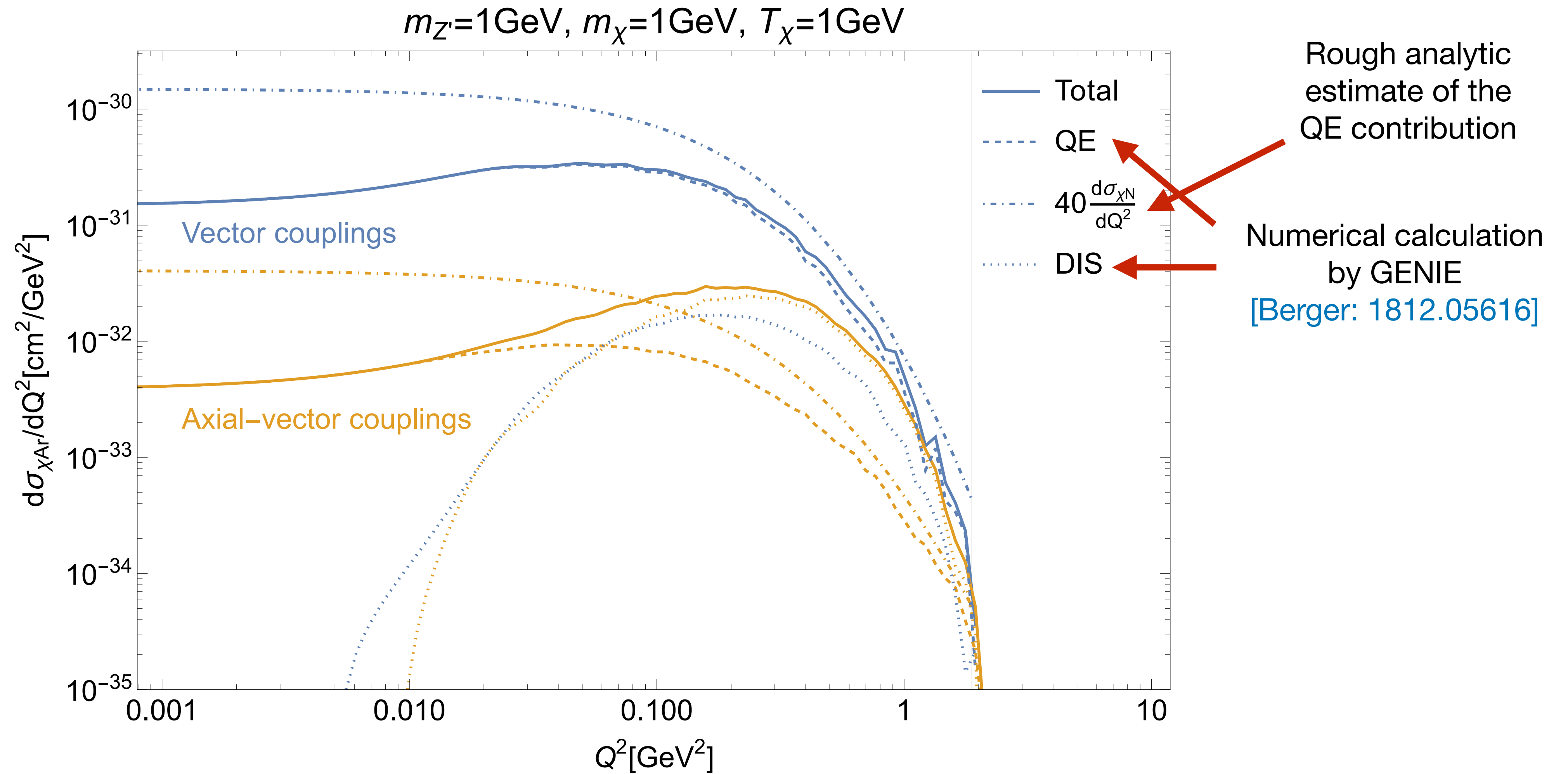


$(m_{Z'} = 1 \text{ GeV})$

Vector couplings: $\sigma_{\text{SI}}^p = \frac{g_{Z'}^4 (Q_\chi^V)^2 (3Q_q^V)^2 \mu_{\chi p}^2}{\pi m_{Z'}^4}$

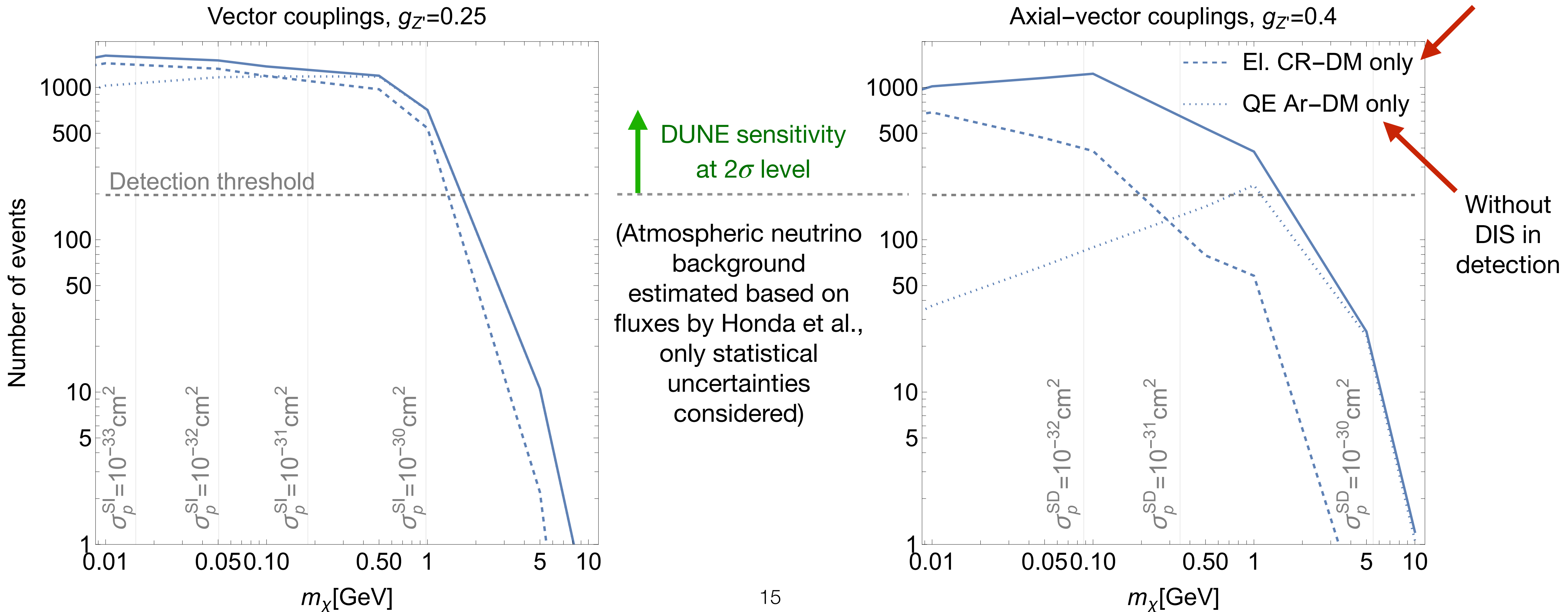
Axial-vector couplings: $\sigma_{\text{SD}}^p = \frac{3g_{Z'}^4 (Q_\chi^A)^2 F_A^p(0)^2 \mu_{\chi p}^2}{\pi m_{Z'}^4}$

Dark-matter-argon cross section

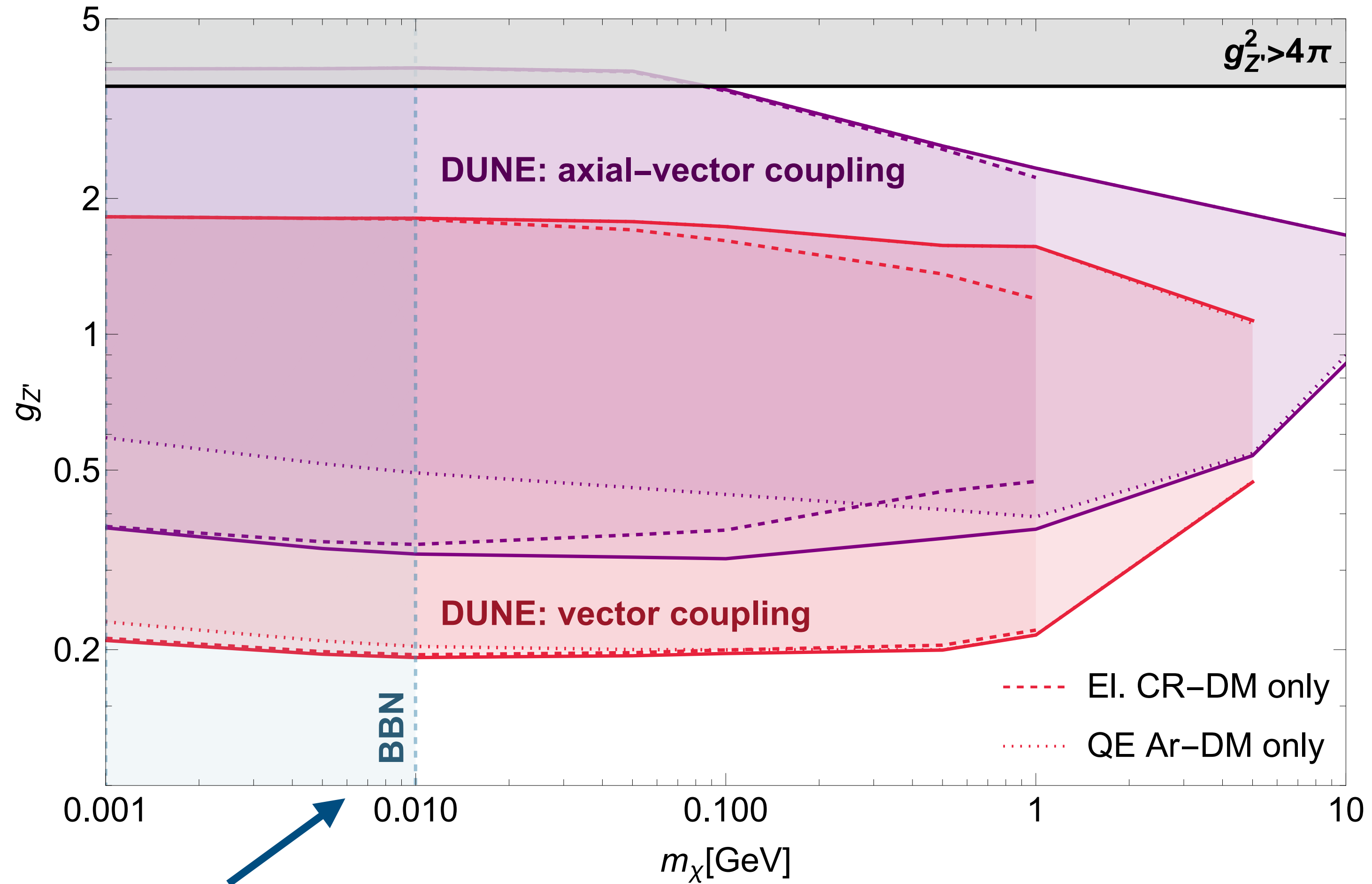


Dark matter scattering with nucleons/nuclei

- DIS plays a role for dark matter detection in DUNE

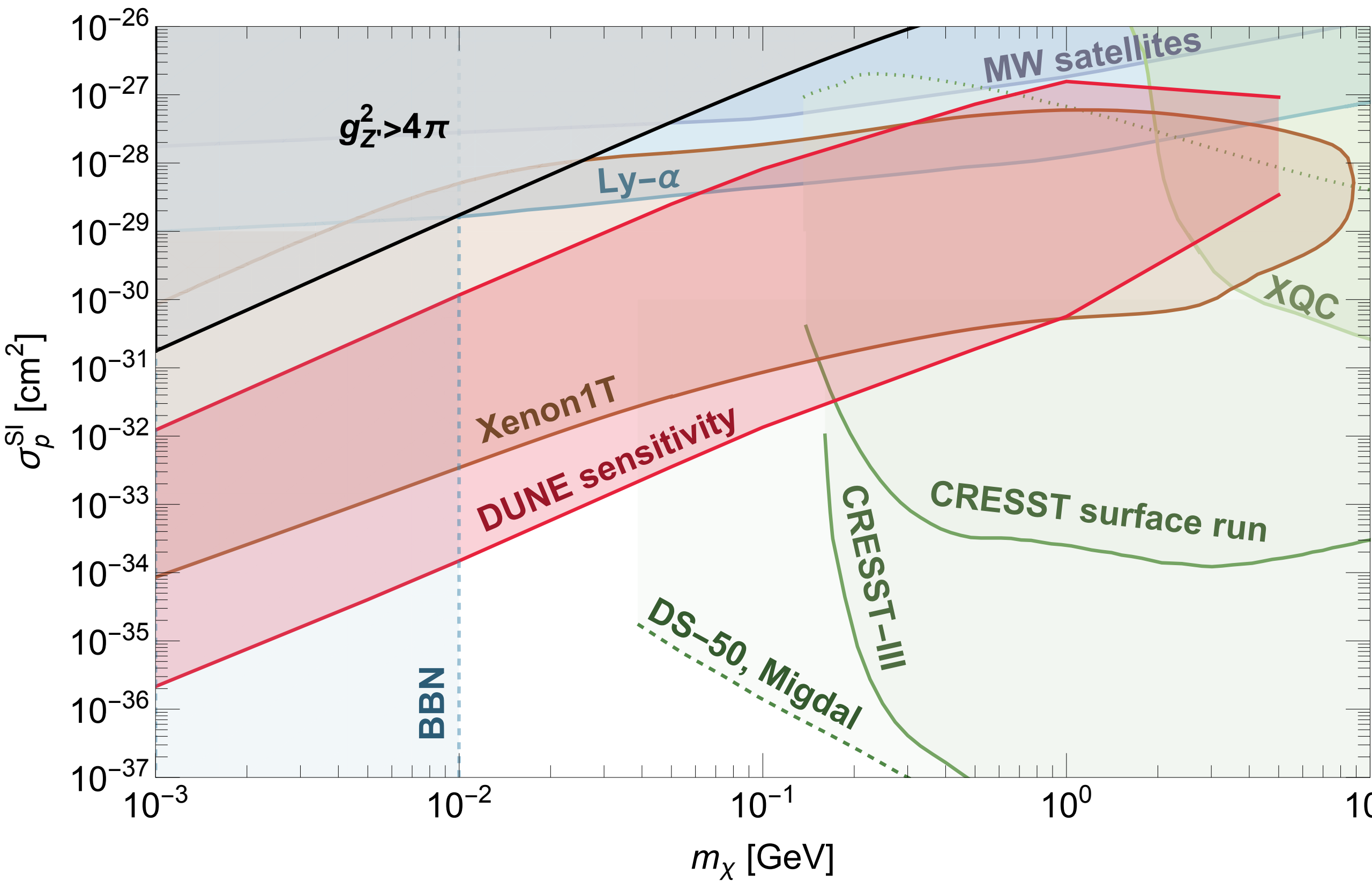


Results



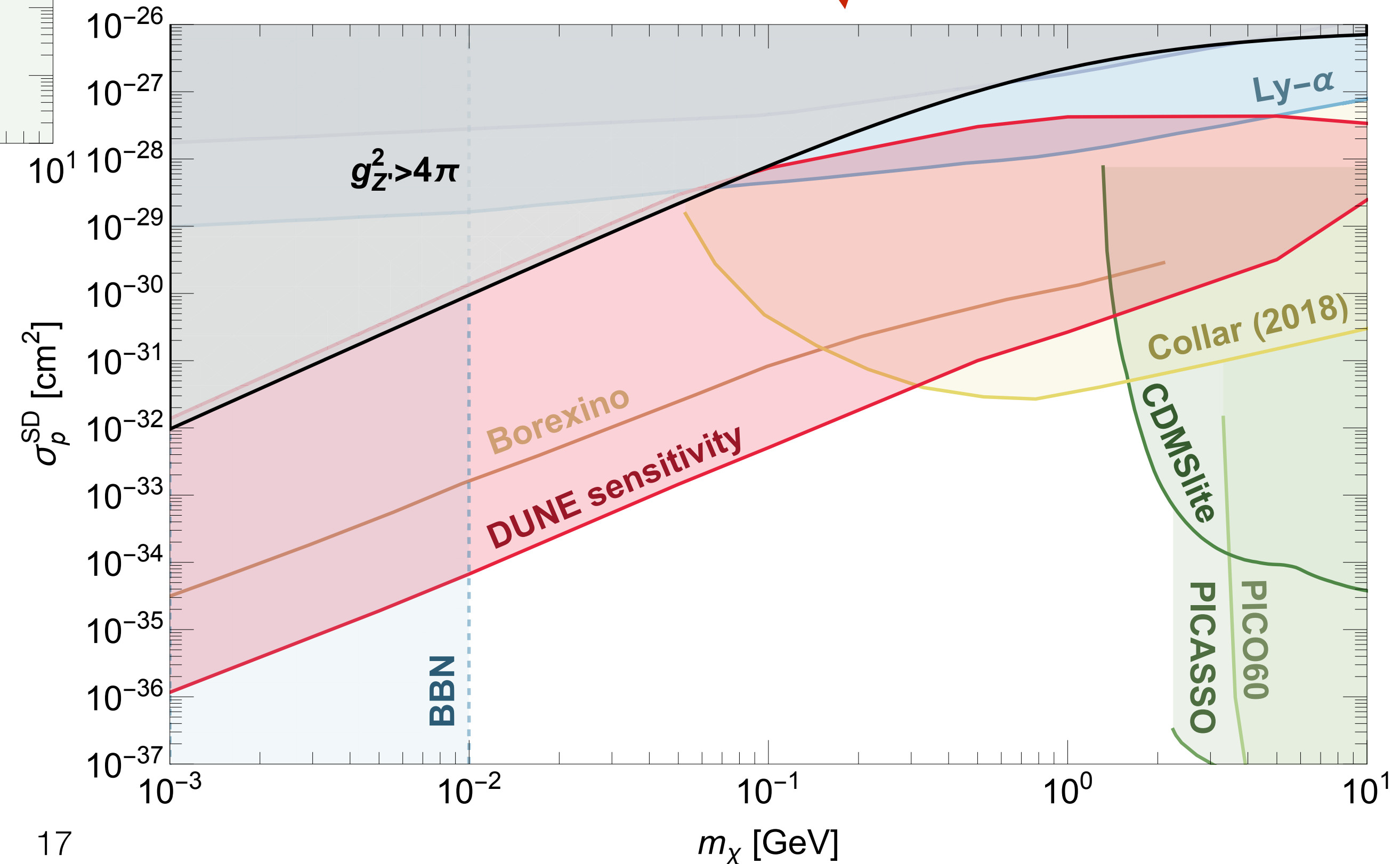
BBN constraints on extra light degrees of freedom thermalised with SM plasma
[Krnjaic: 1908.00007]

Results



Vector couplings, $m_{Z'} = 1 \text{ GeV}$

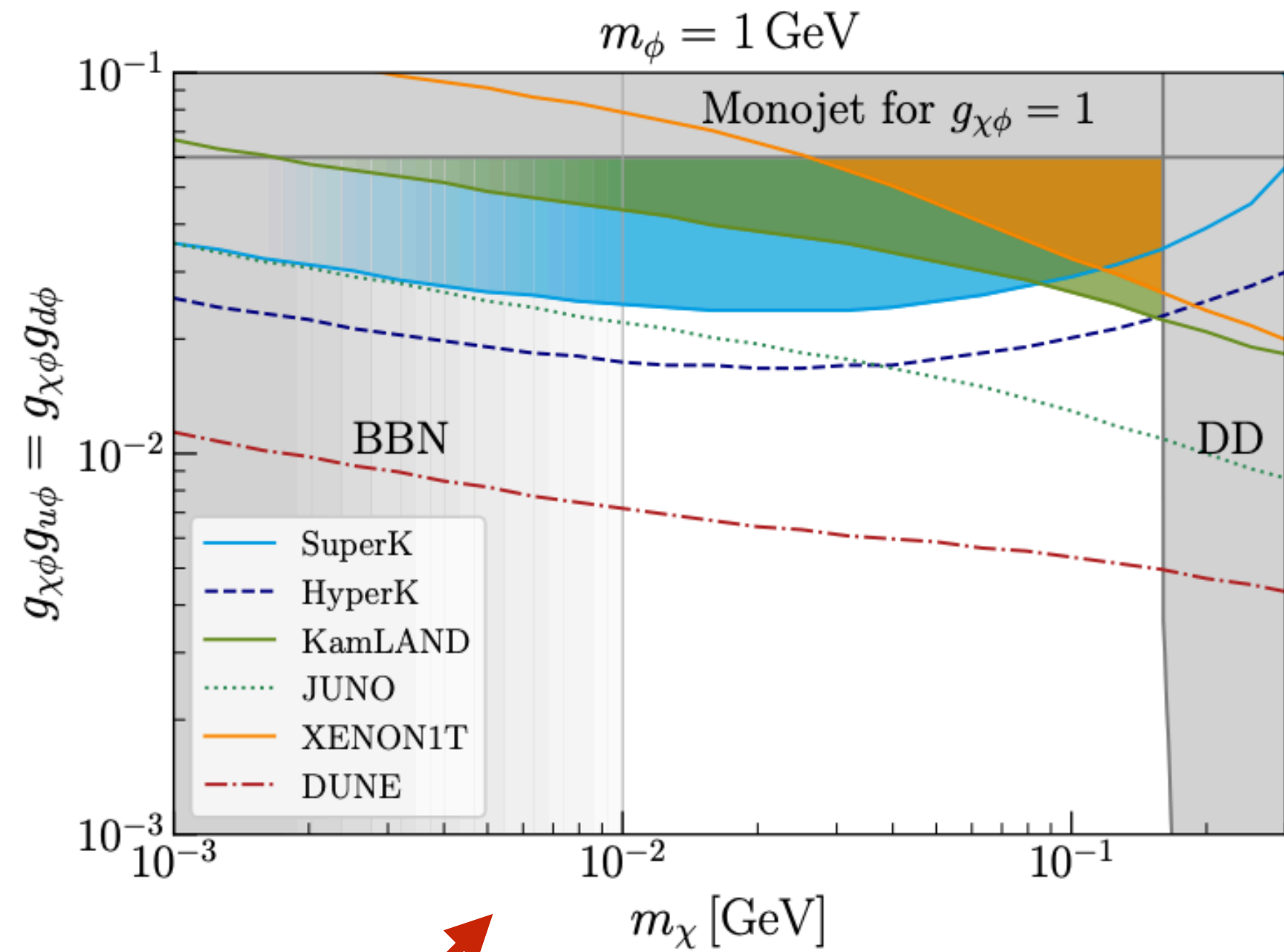
Axial-vector couplings, $m_{Z'} = 1 \text{ GeV}$



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

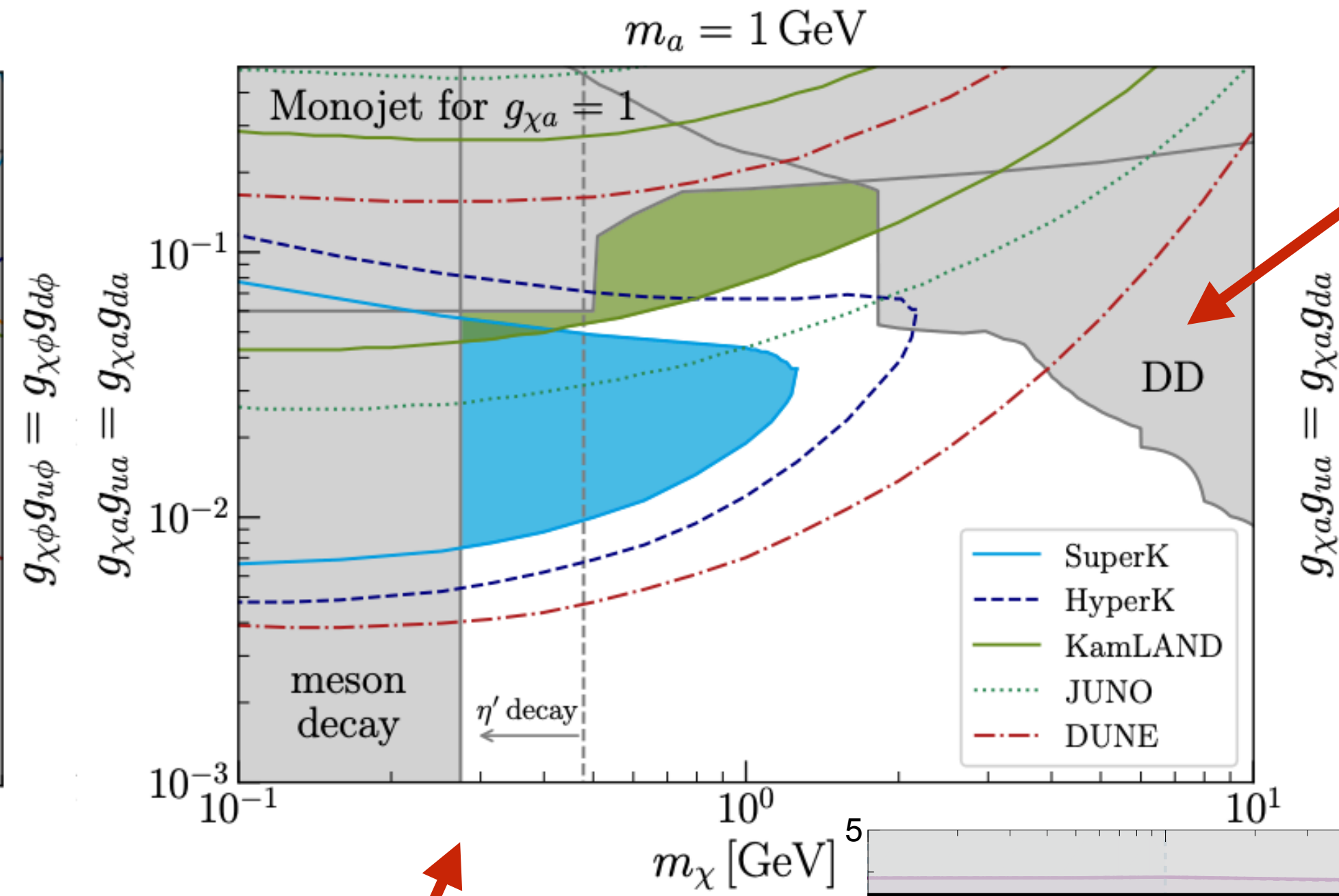
Scalar mediator more favourable?

[Ema, Sala, Sato: 2011.01939]



Scalar mediator

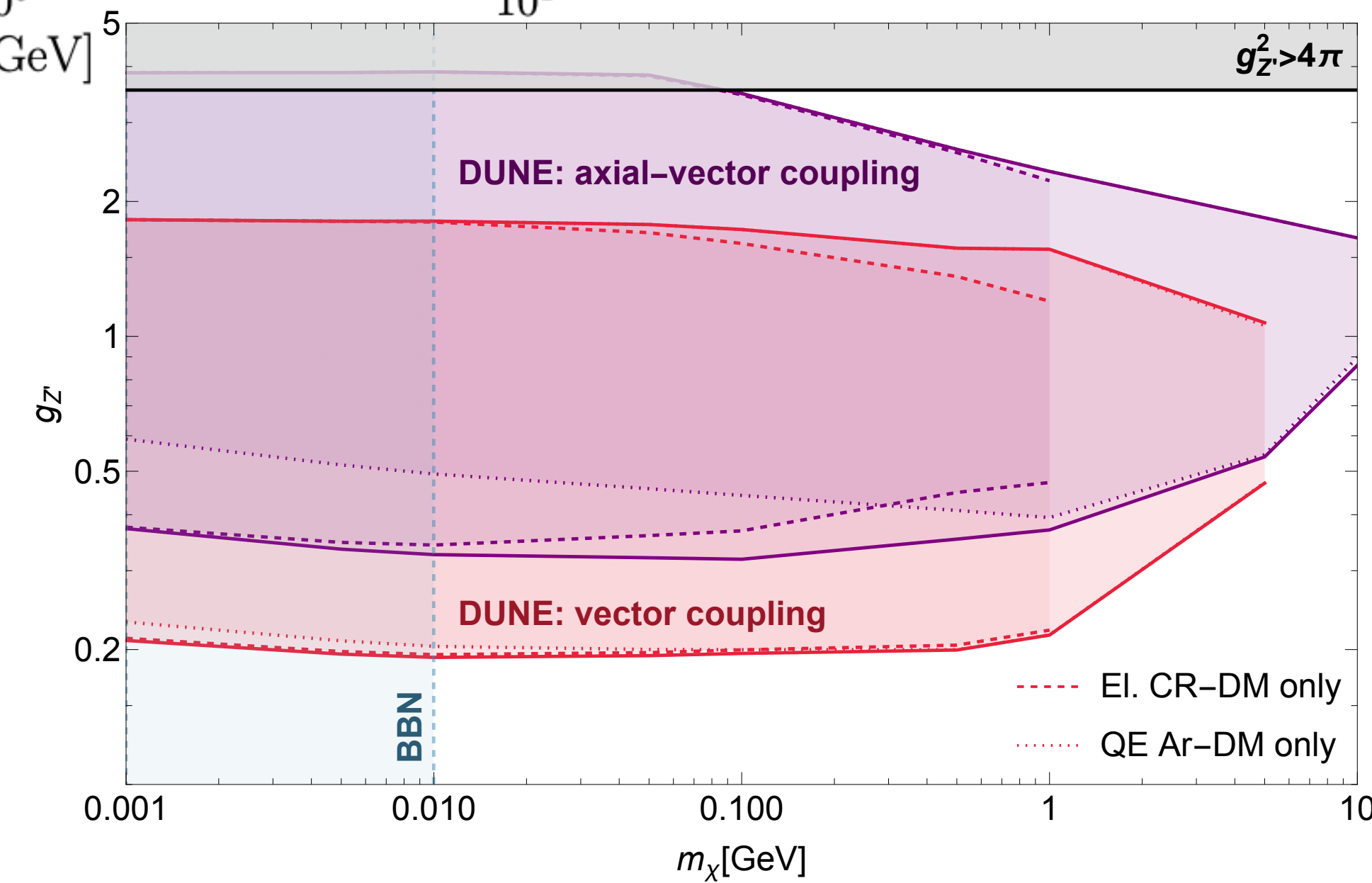
$$g_{N\phi} = g_{\phi} \underbrace{\left(\frac{m_N}{m_u} f_u^N + \frac{m_N}{m_d} f_d^N \right)}_{\sim 30}$$



Pseudo-scalar mediator

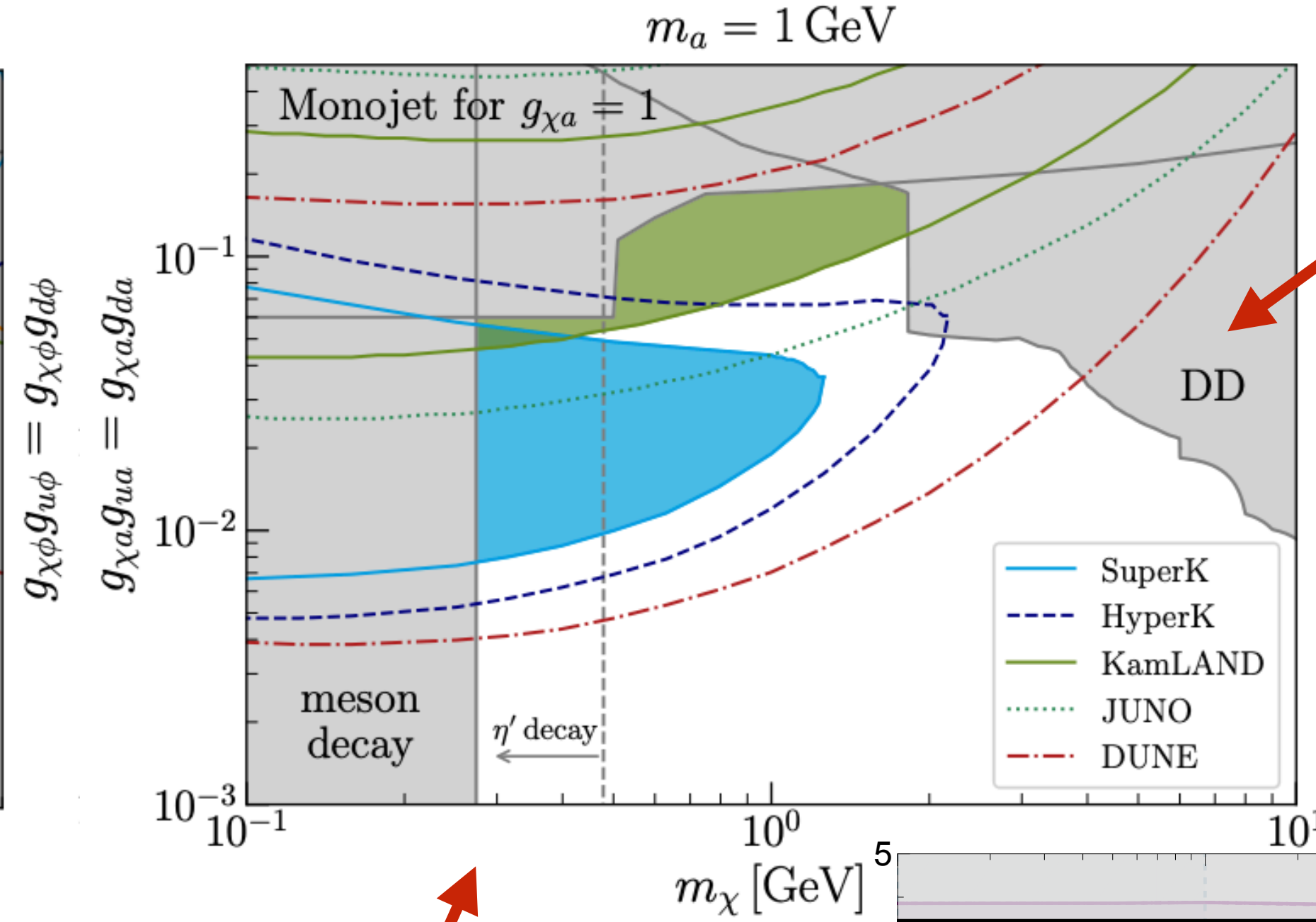
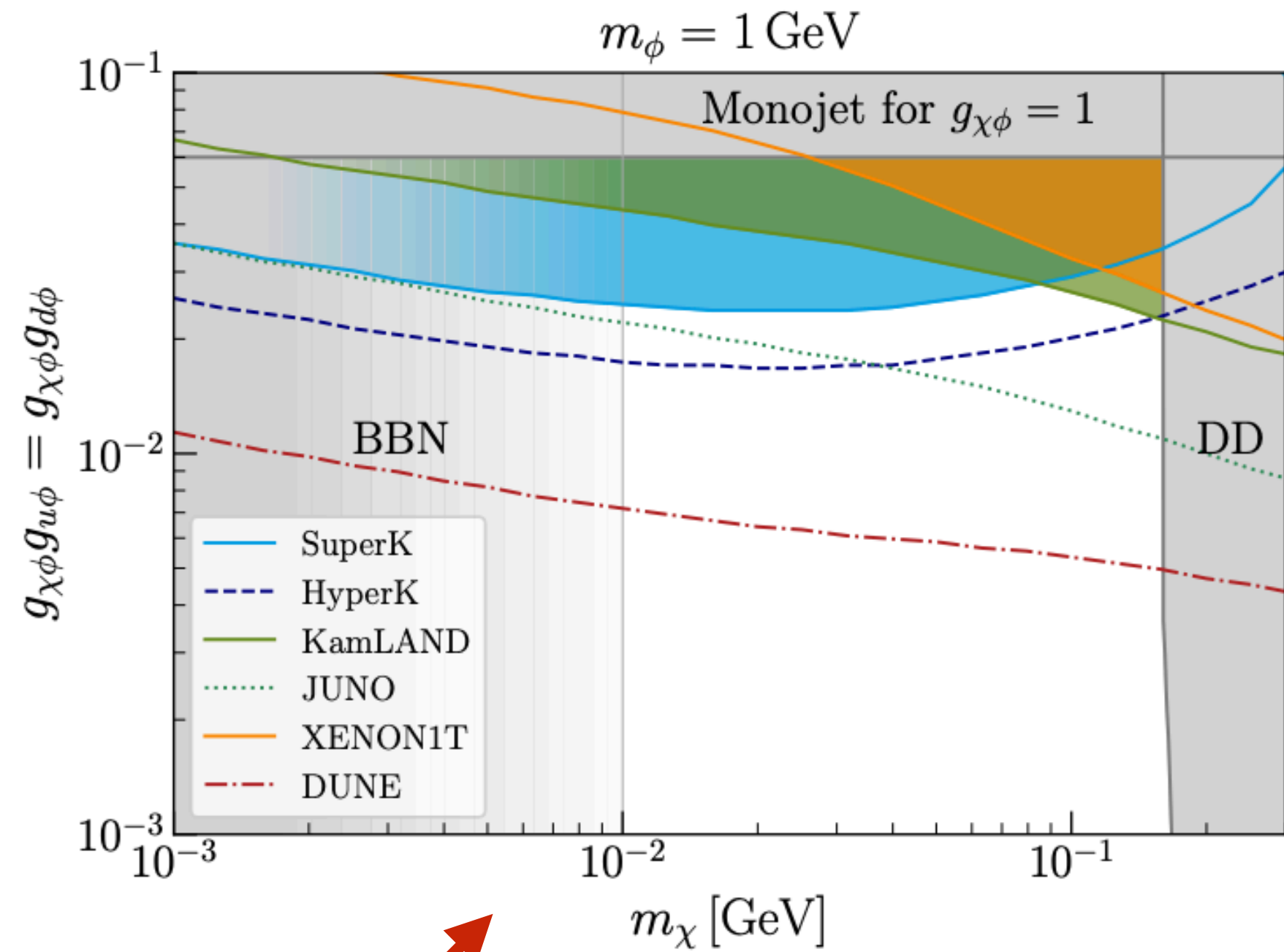
$$g_{Na} = g_a \underbrace{\frac{2m_N}{m_u + m_d} h_{u+d}}_{\sim 120}$$

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



Scalar mediator more favourable?

[Ema, Sala, Sato: 2011.01939]



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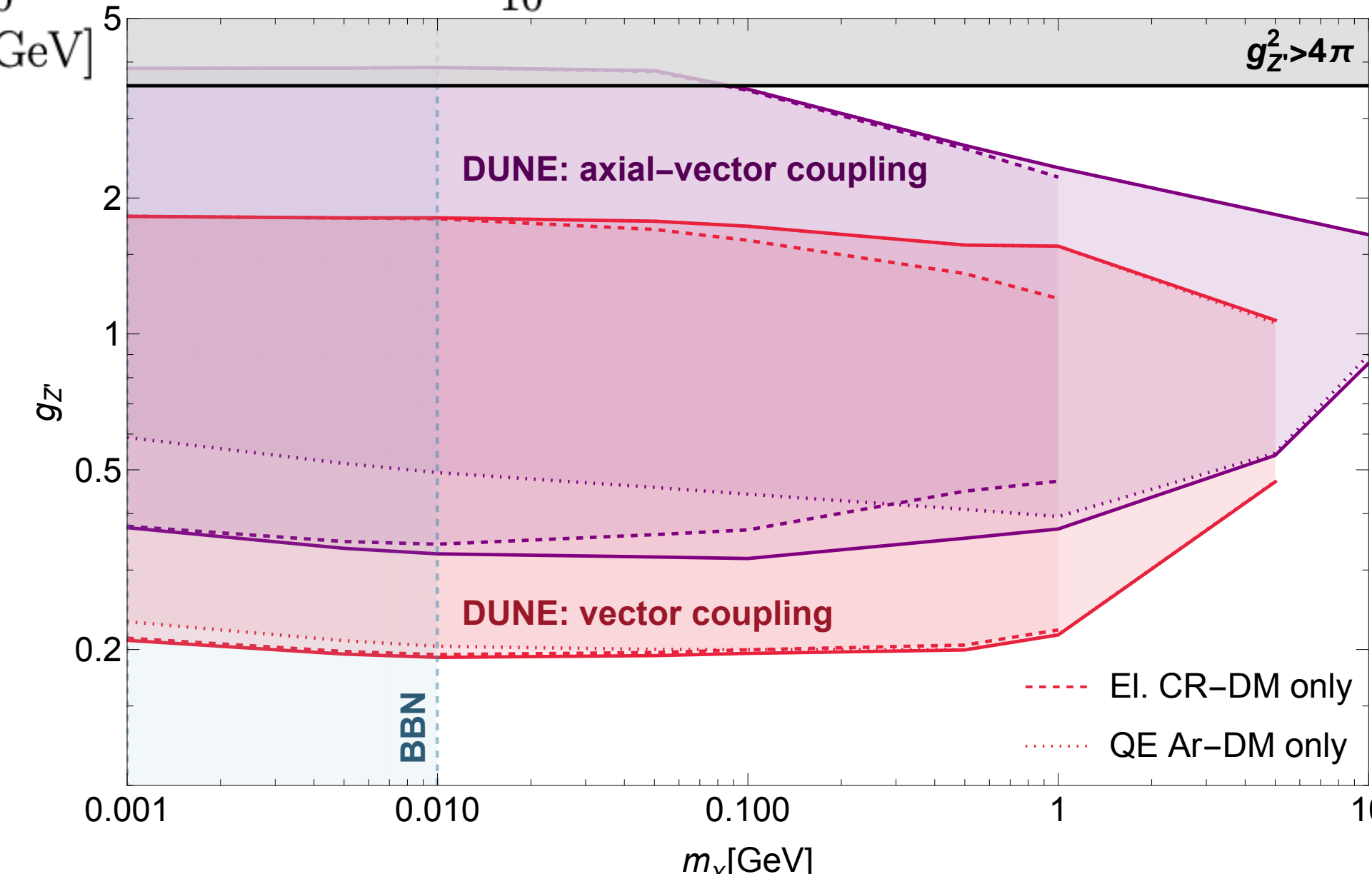
Scalar mediator

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

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

Pseudo-scalar mediator

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



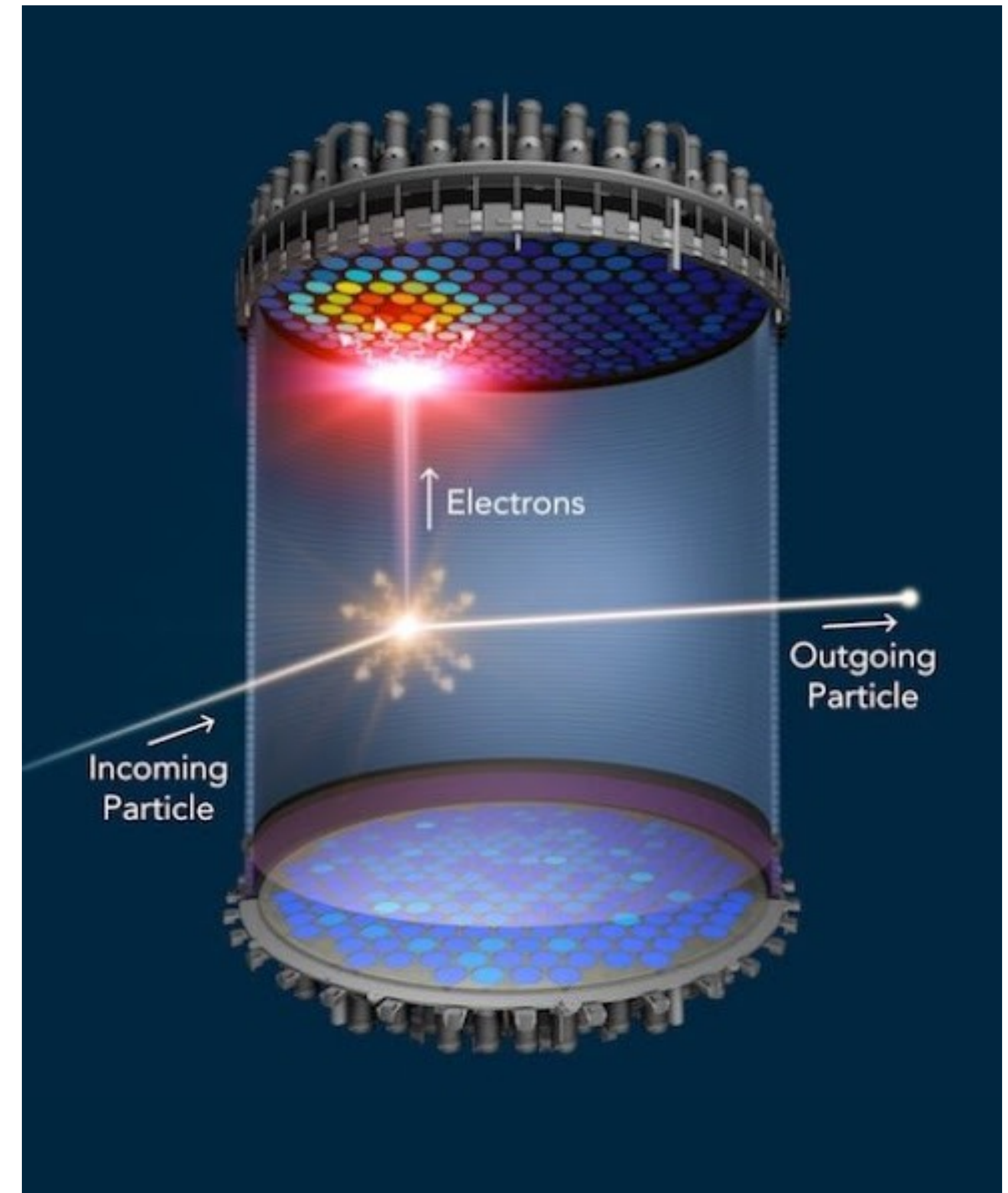
Conclusions

1. “Traditional” dark matter direct detection:

- Sub-GeV dark matter difficult
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2. Cosmic-ray up-scattered dark matter:

- Light dark matter can be probed by direct detection and neutrino experiments
- Neutrino experiments are similarly sensitive to different dark matter models



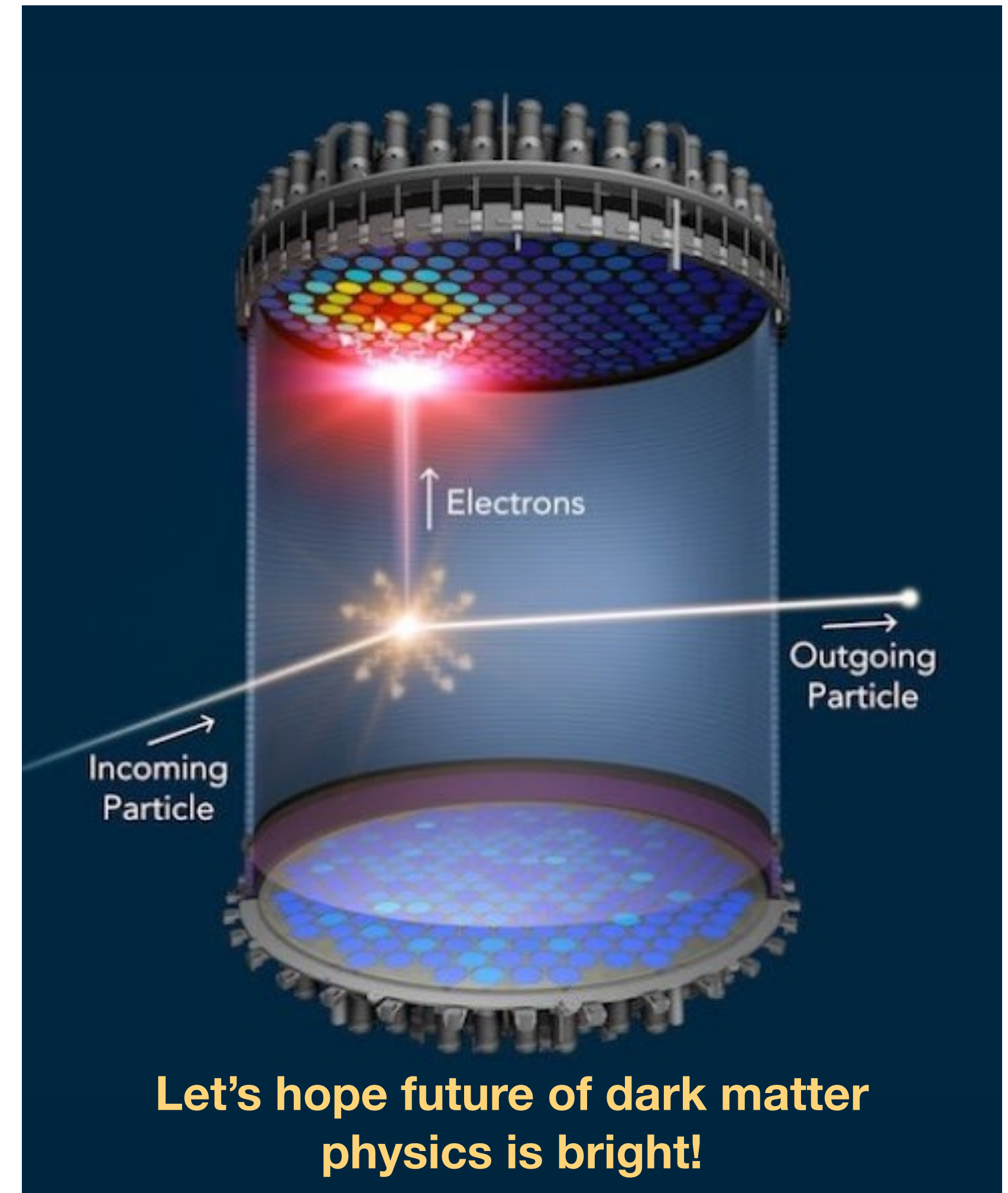
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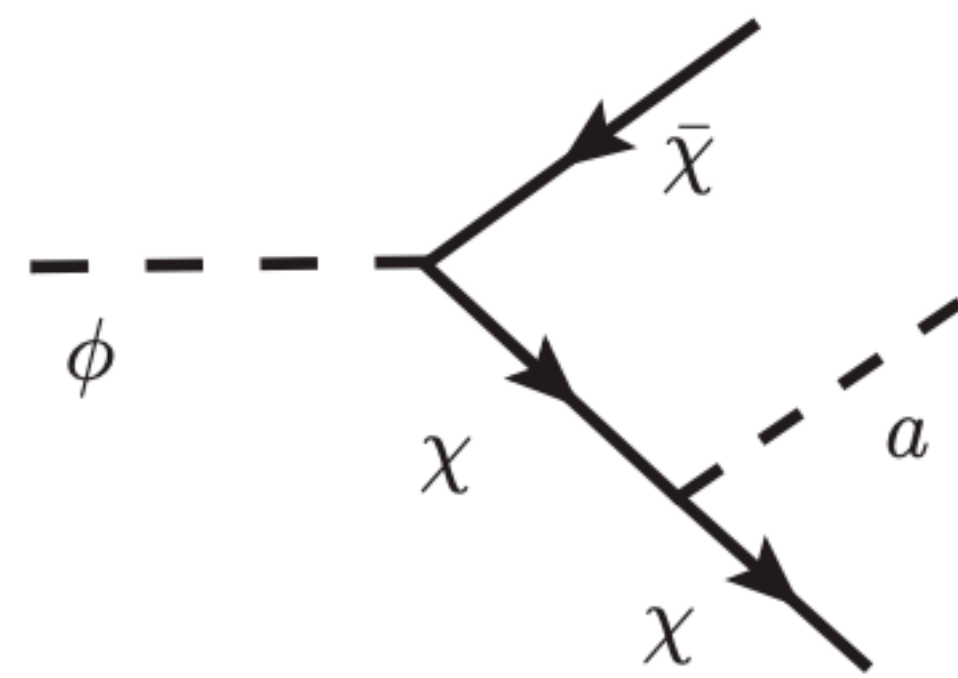
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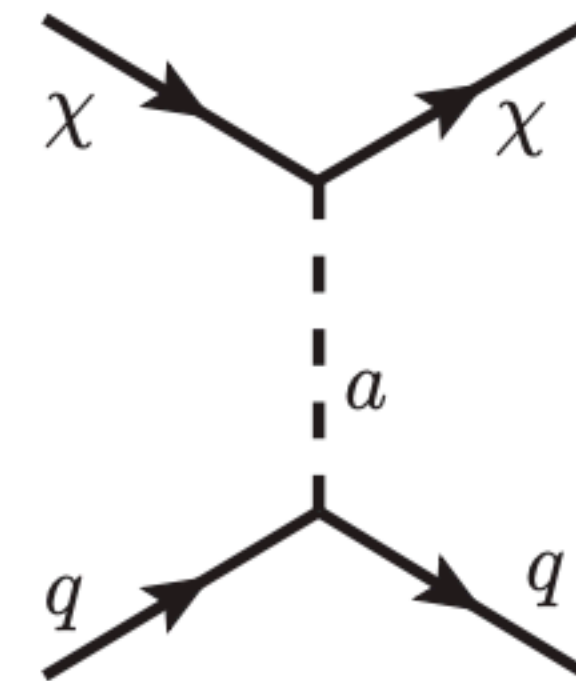
Thanks for your attention!

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

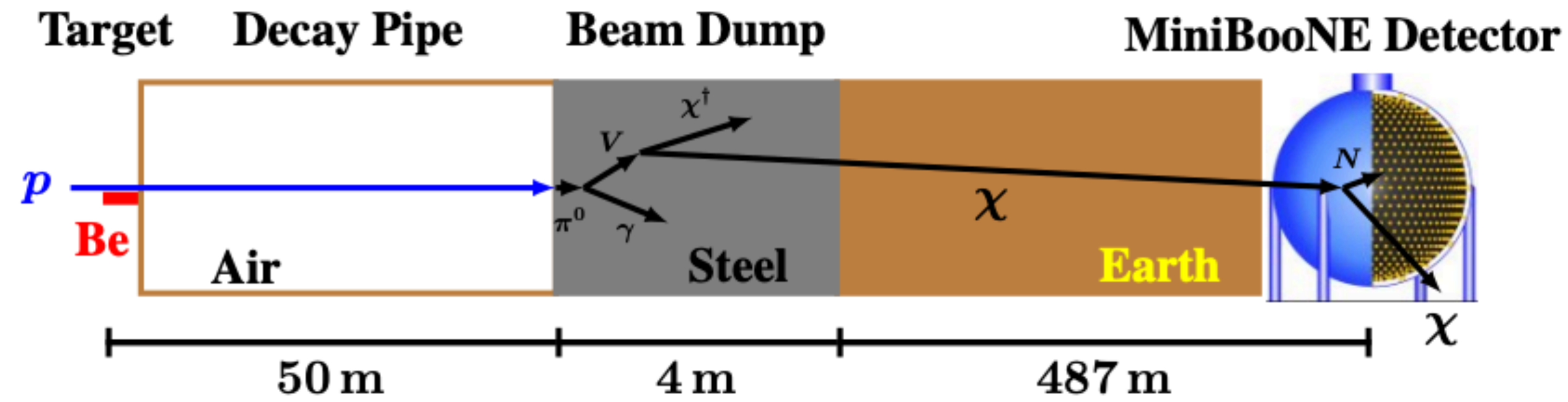
$$m_\phi \sim \mathcal{O}(\text{PeV})$$

[Kopp, Liu, Wang: 1503.02669]

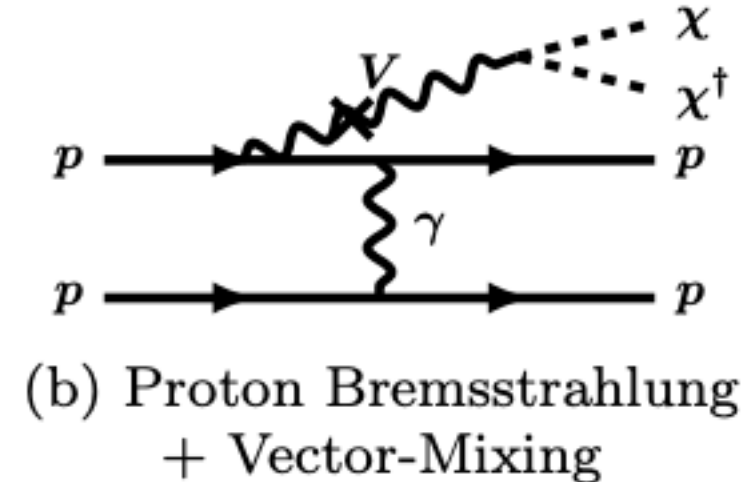
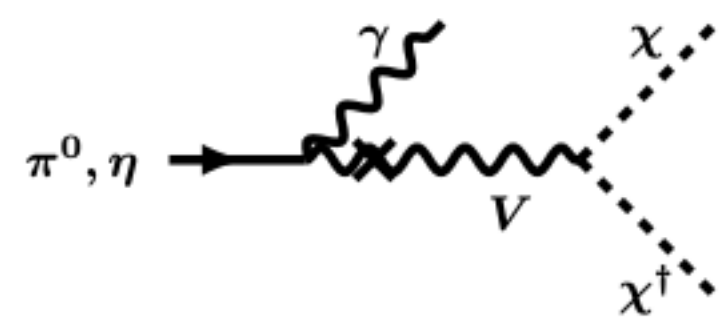
Accelerated dark particles

Example 2: Dark matter produced in beam dump

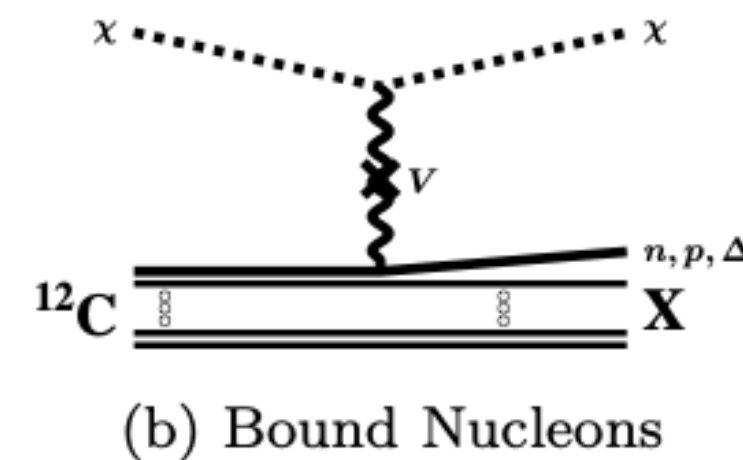
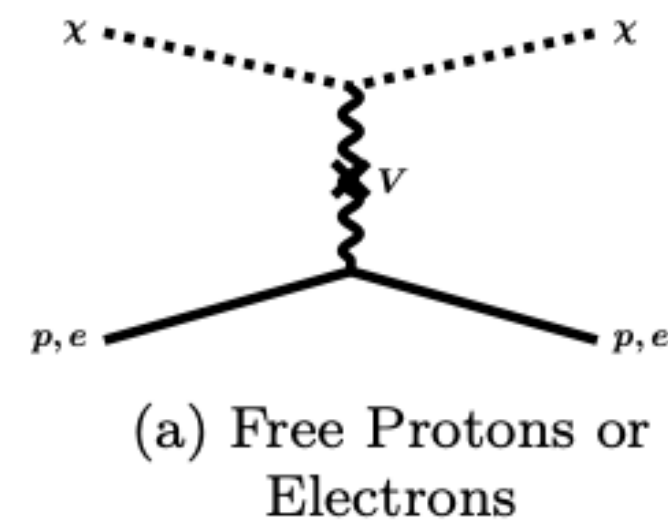
[MiniBooNE-DM Collaboration: 1807.06137]



Dark matter production:



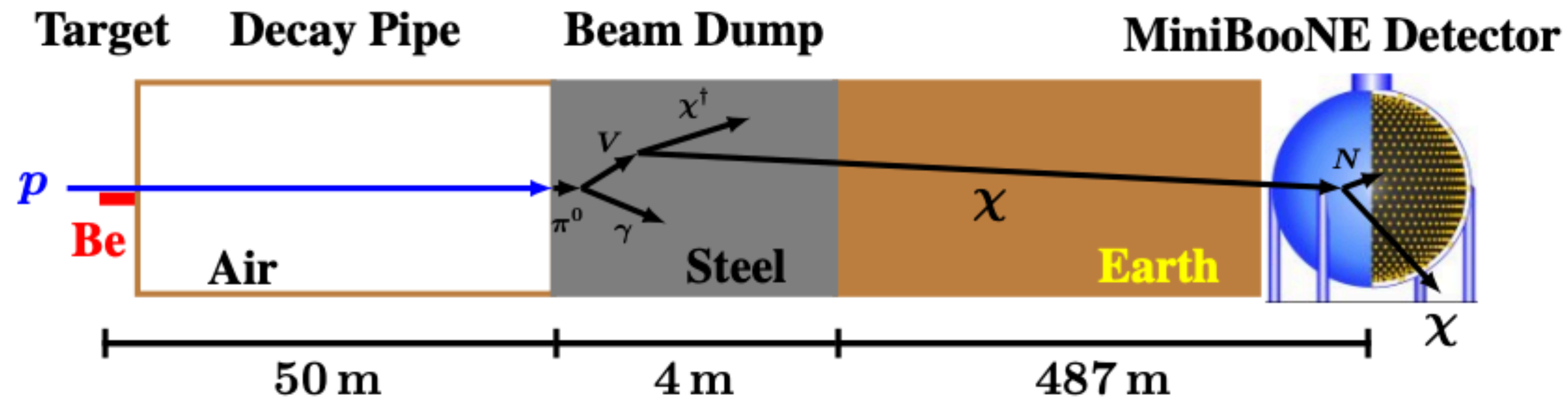
Dark matter detection:



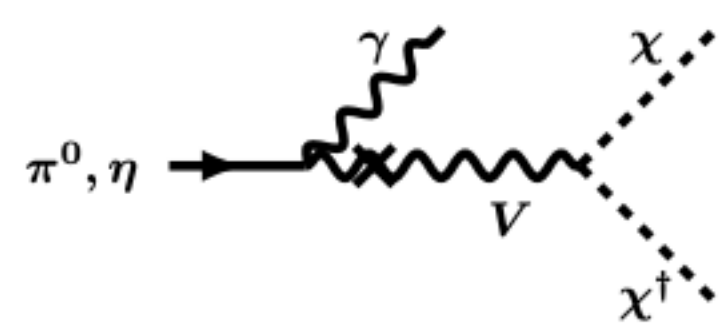
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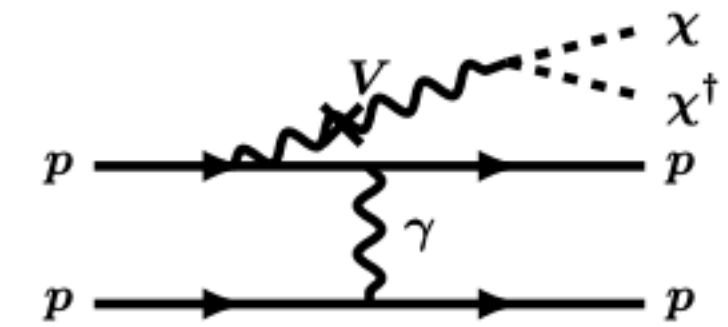
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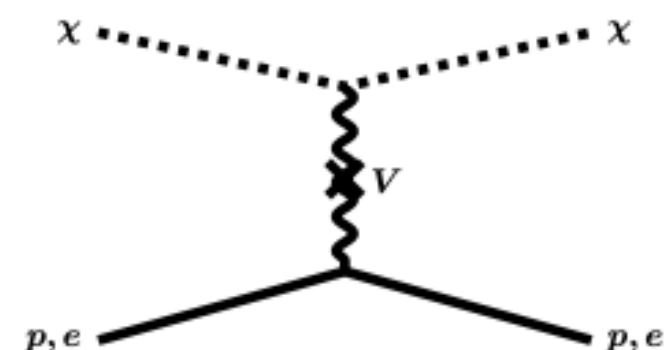


(a) Meson Decay

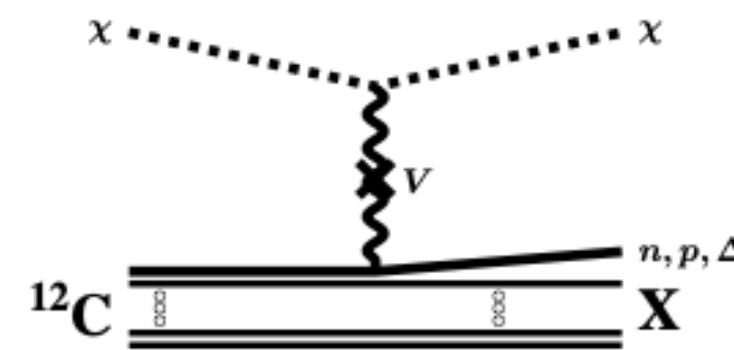


(b) Proton Bremsstrahlung + Vector-Mixing

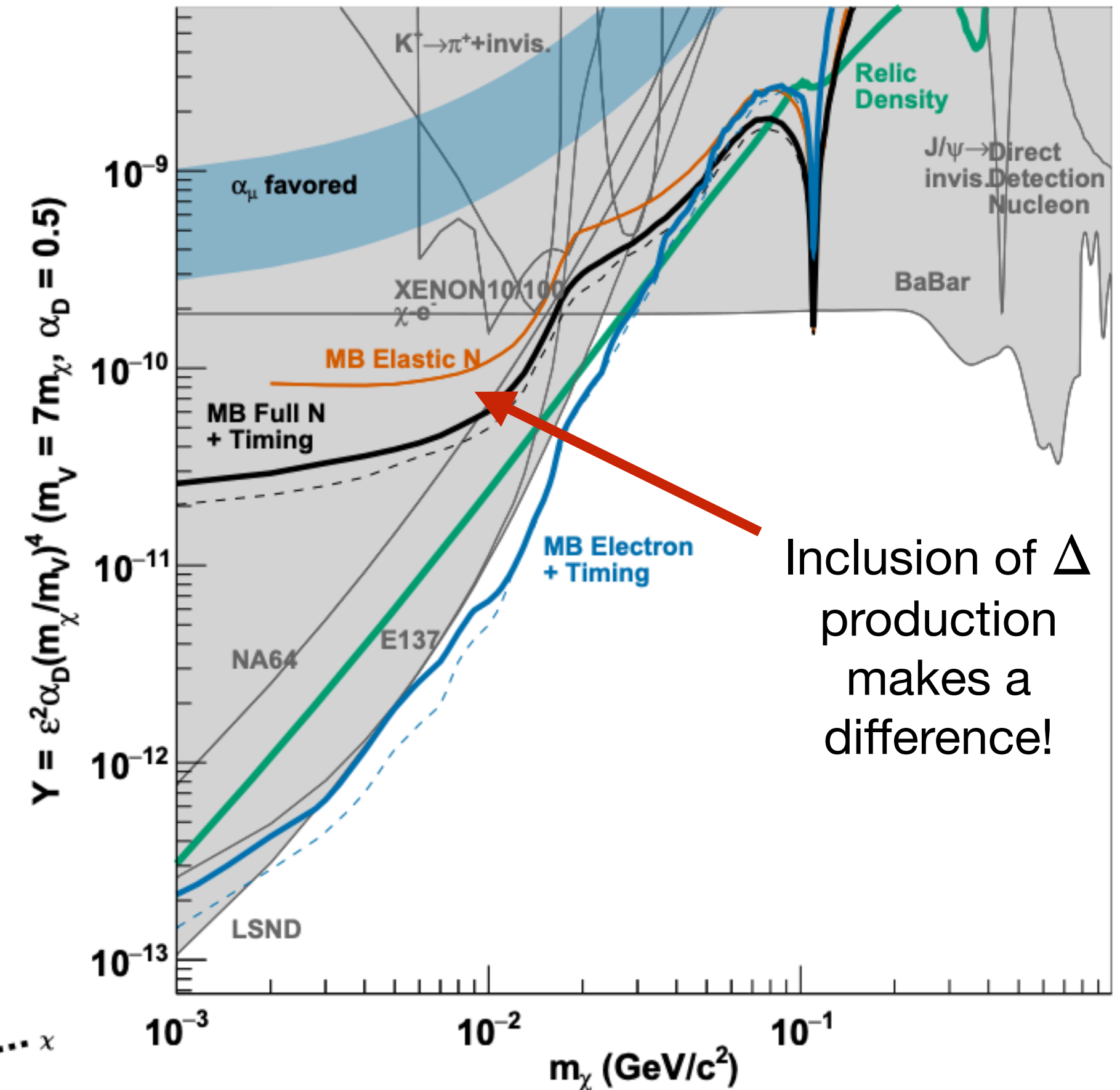
Dark matter detection:



(a) Free Protons or Electrons



(b) Bound Nucleons



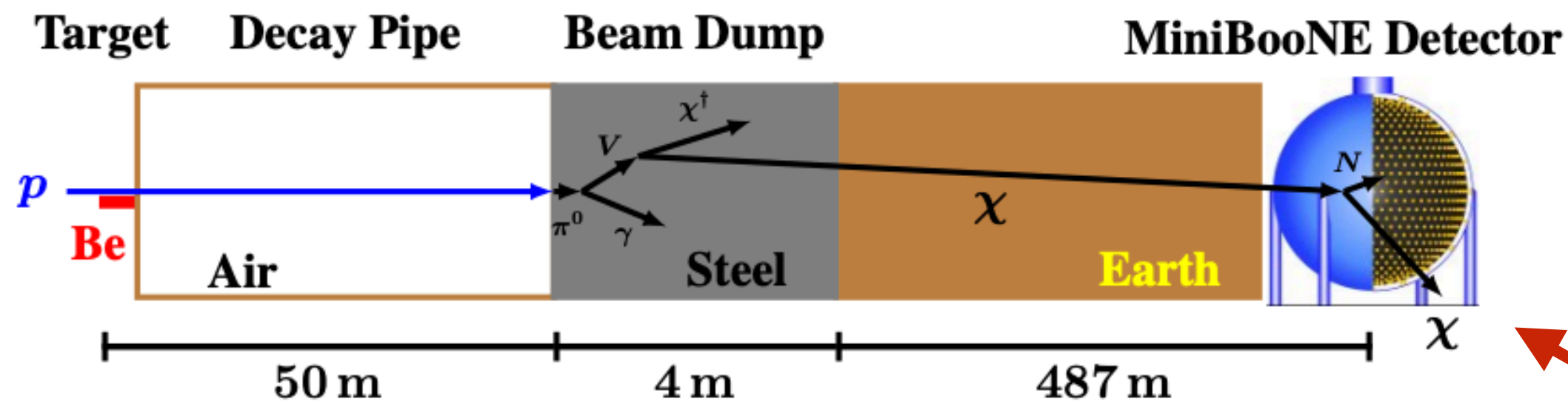
(b) vector portal ($\alpha_D = 0.5, m_V = 7m_\chi$)

Accelerated dark particles

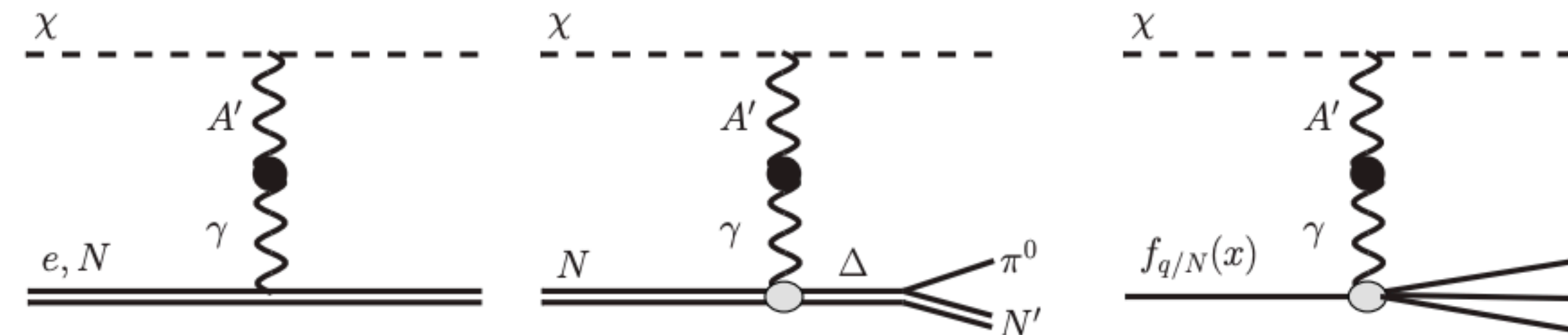
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[deNiverville et al.: 1609.01770]:

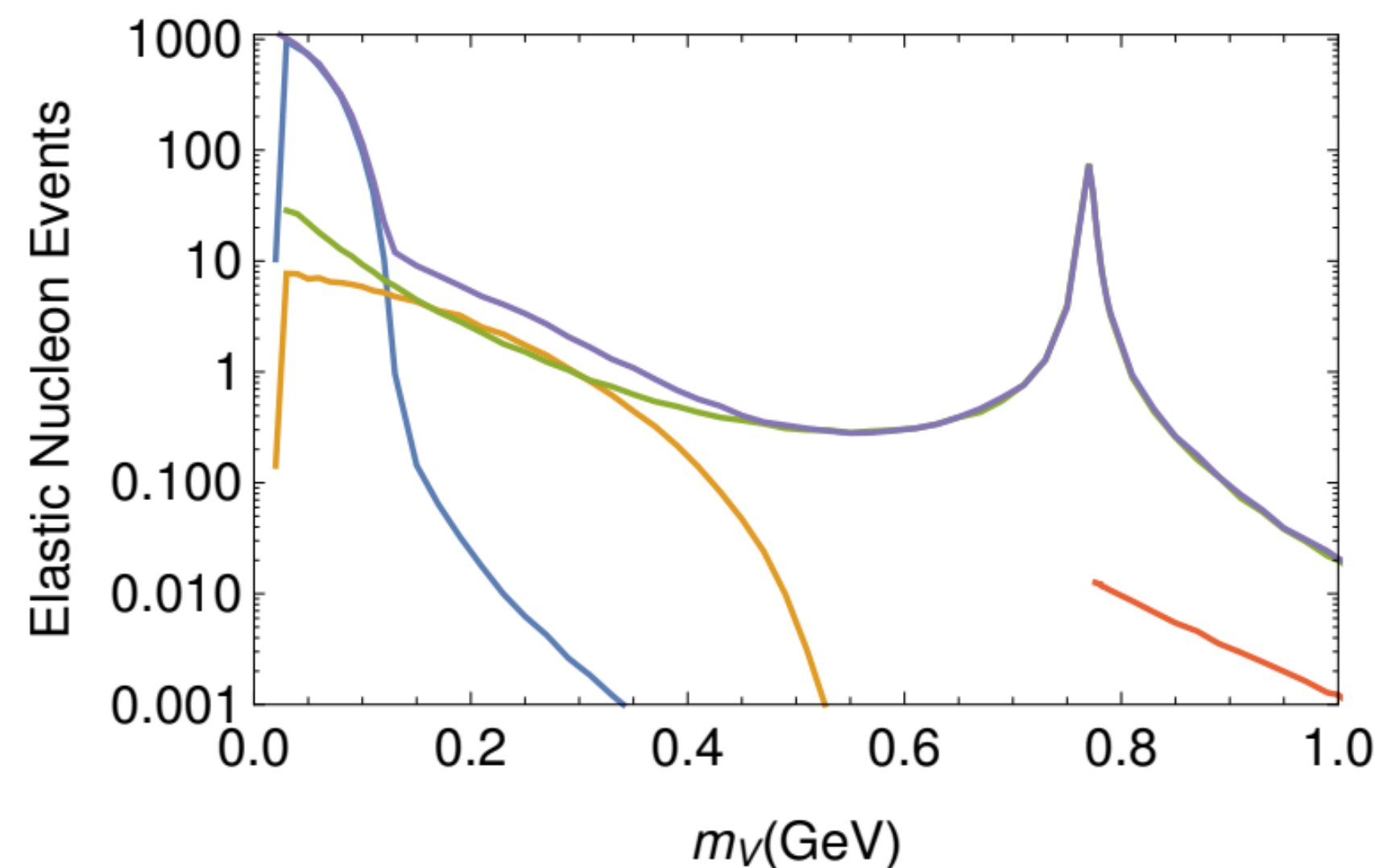
- Also sensitivities by other experiments (SBND, SHiP, T2K),
- BdNMC tool for simulation of DM production and detection



Dark matter detection:



Number of elastic nucleon events for different DM production channels:



- π^0 Decay
- η Decay
- Bremsstrahlung
- Parton
- Total

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

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.

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

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

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

Used in [Berger: 1812.05616]

This structure can be found using chiral perturbation theory [Bishara et al.: 1707.06998]

