Interactions of relativistic dark matter with nuclei and implications for light dark matter detection

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Based on 2504.16996 with Richie Diurba (University of Bern)

Forskningsrådet

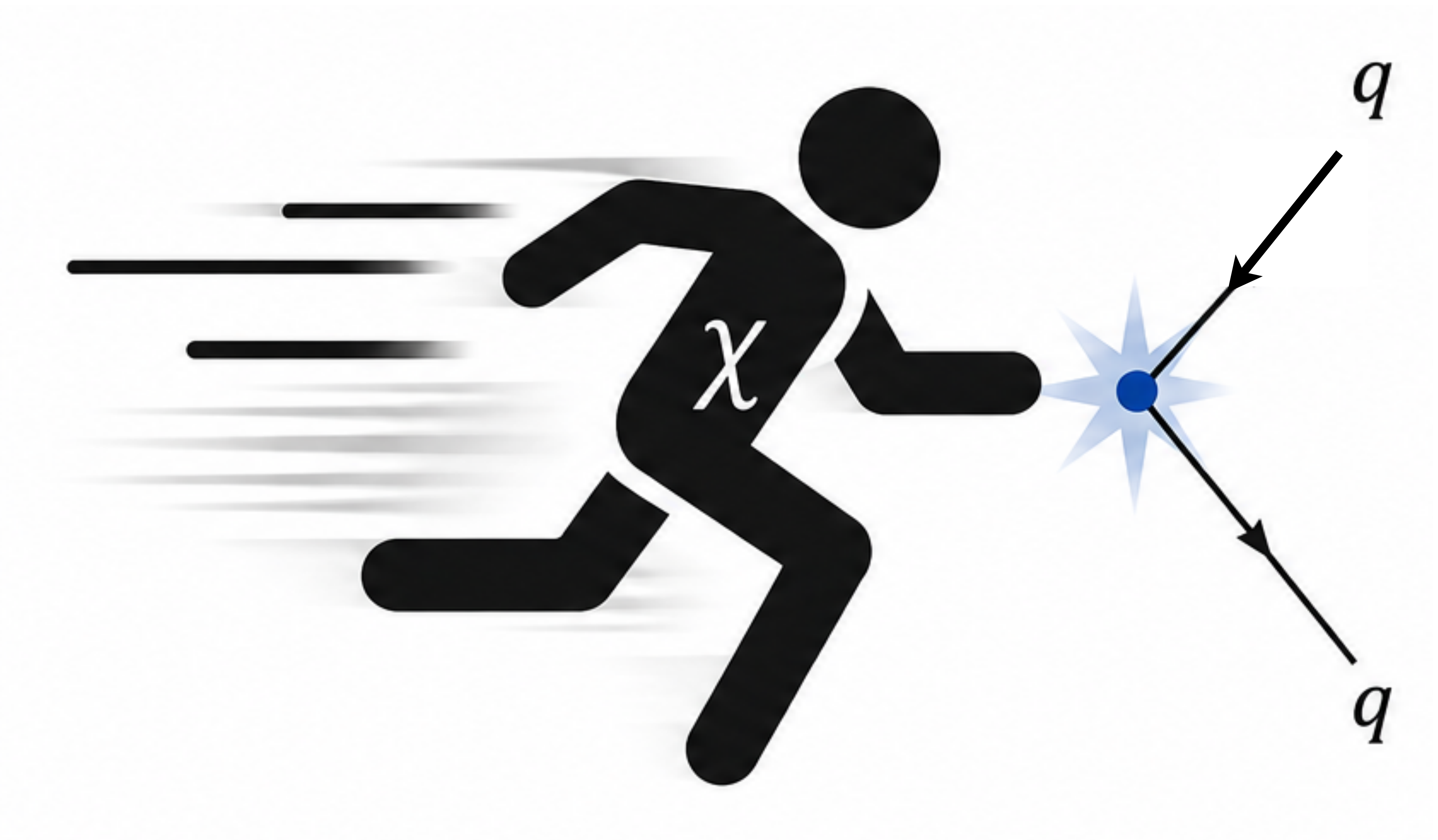
Outline

1. Weak points of “traditional” dark matter direct detection

2. “Advantages” of accelerated dark matter*

   - Example: sensitivity of DUNE to cosmic-ray up-scattered dark matter

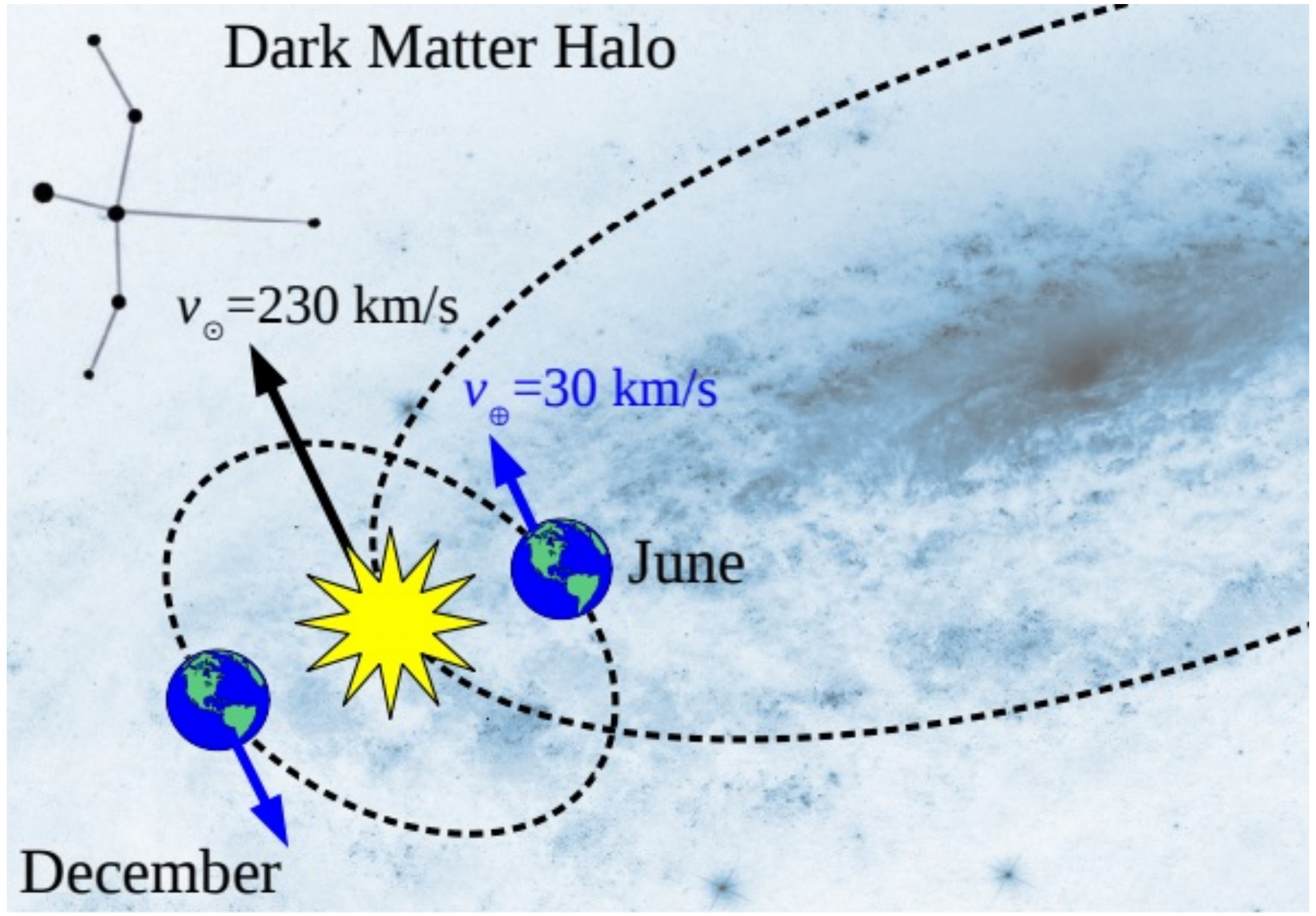
   - Outlook



***See also talks by Pedro De la Torre Luque, Branden Aitken, Dimitrios Papoulias**

[ChatGPT]

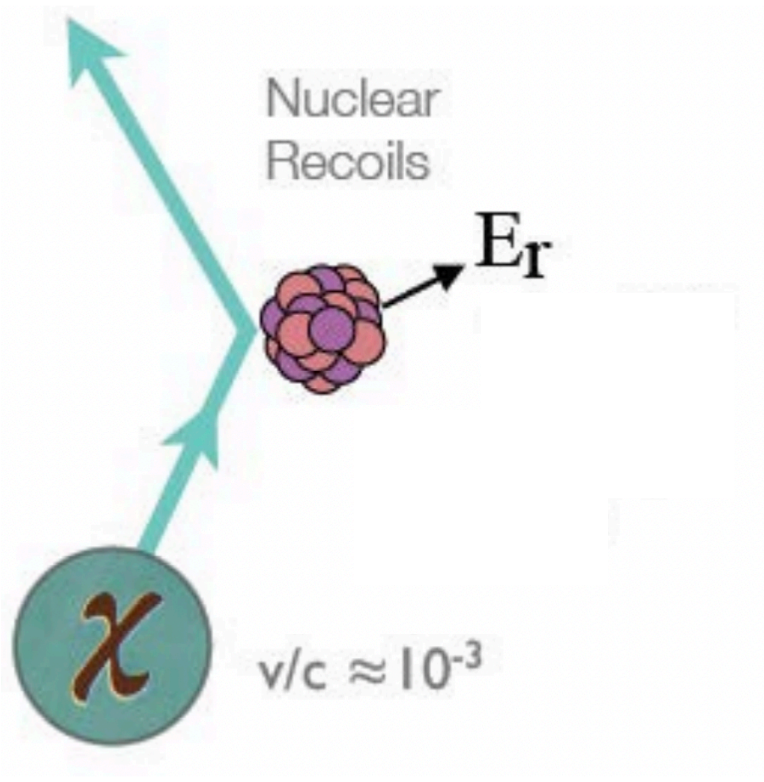
Direct detection of dark matter



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

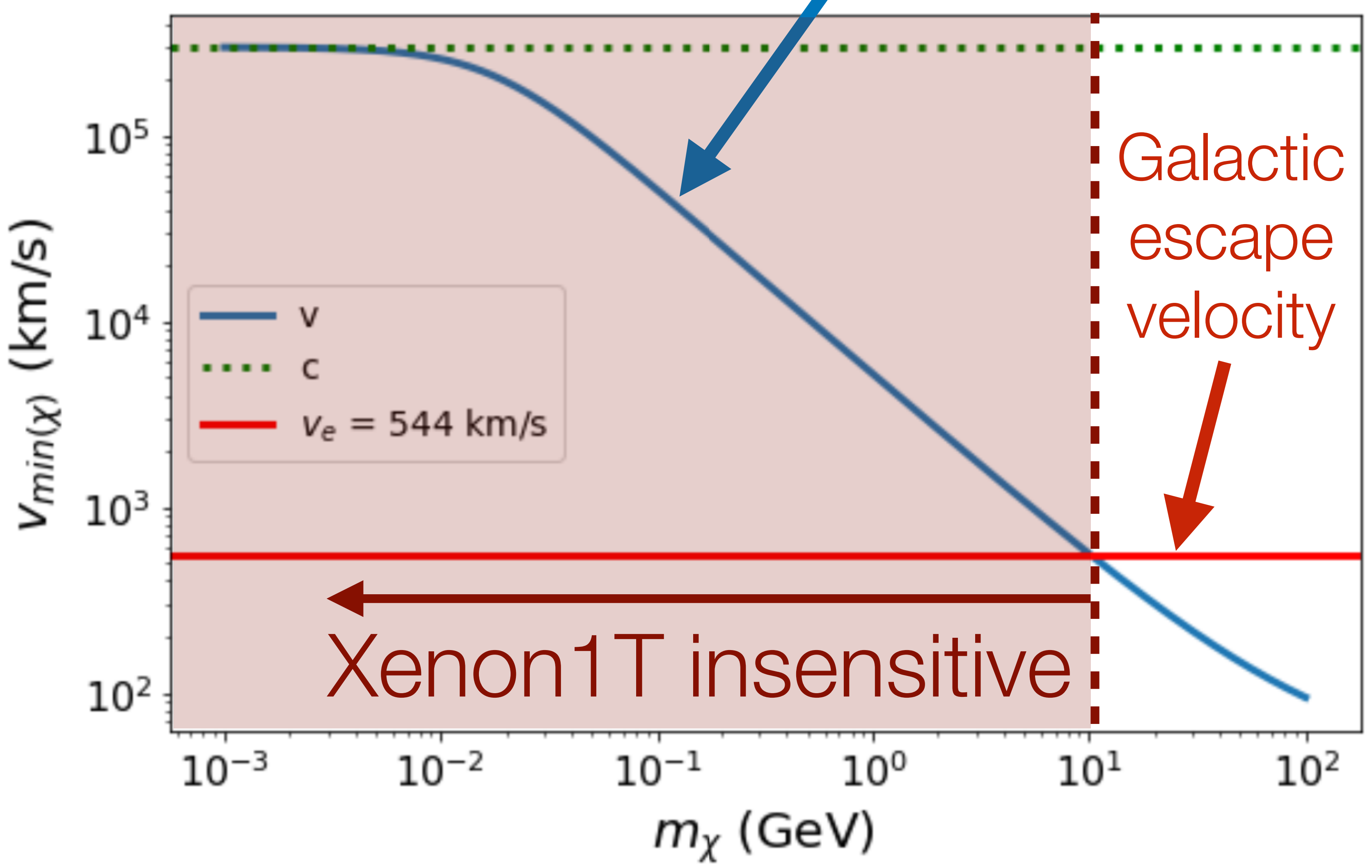
$\Rightarrow$ Scattering with nuclei via coherent elastic scattering expected

Direct detection of light dark matter?

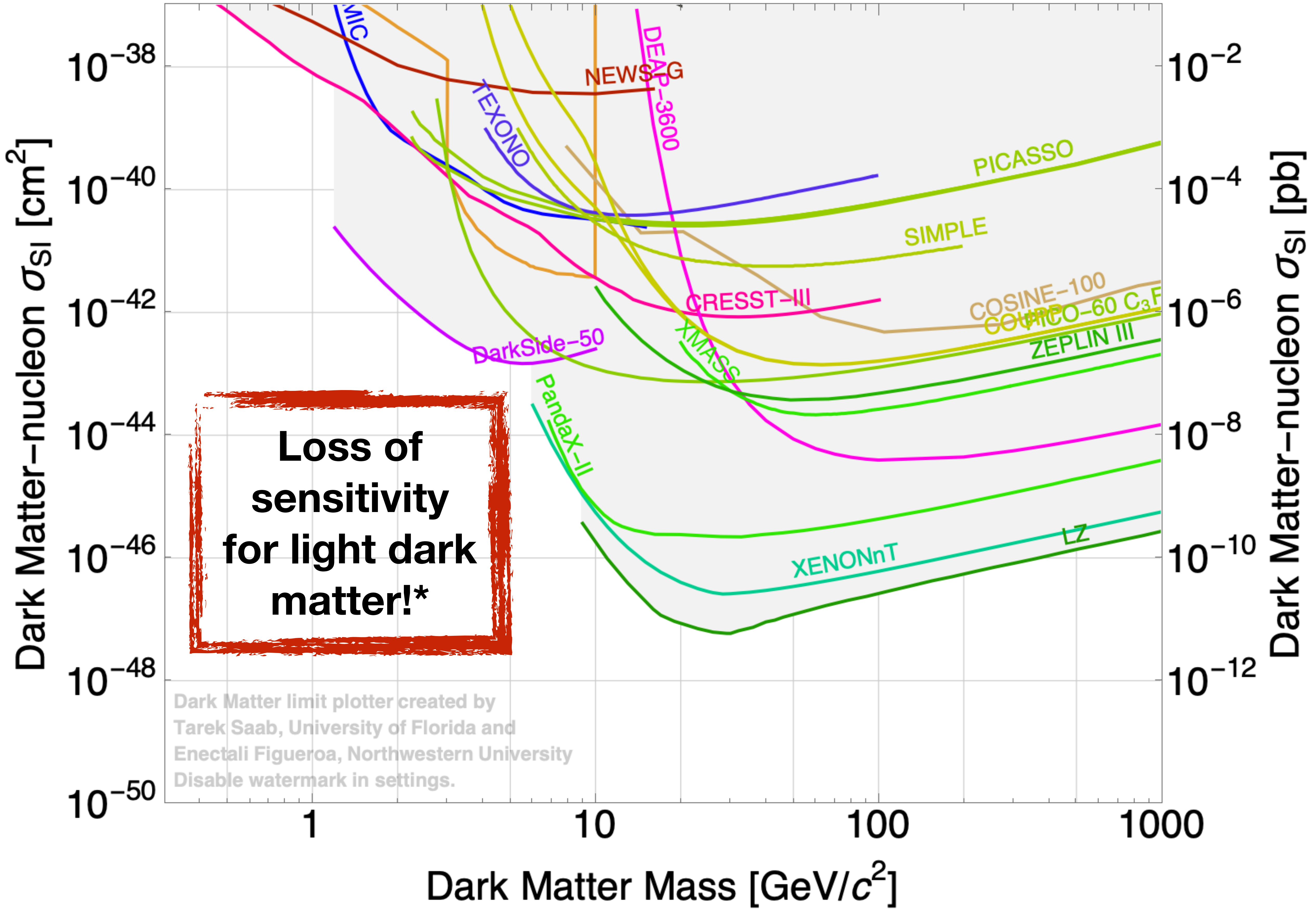


Example: Xenon1T threshold
for nucleus recoil energy:
$E_r \gtrsim 5$ keV

⇒ Minimal dark matter
velocity to trigger
detectable nuclear recoil



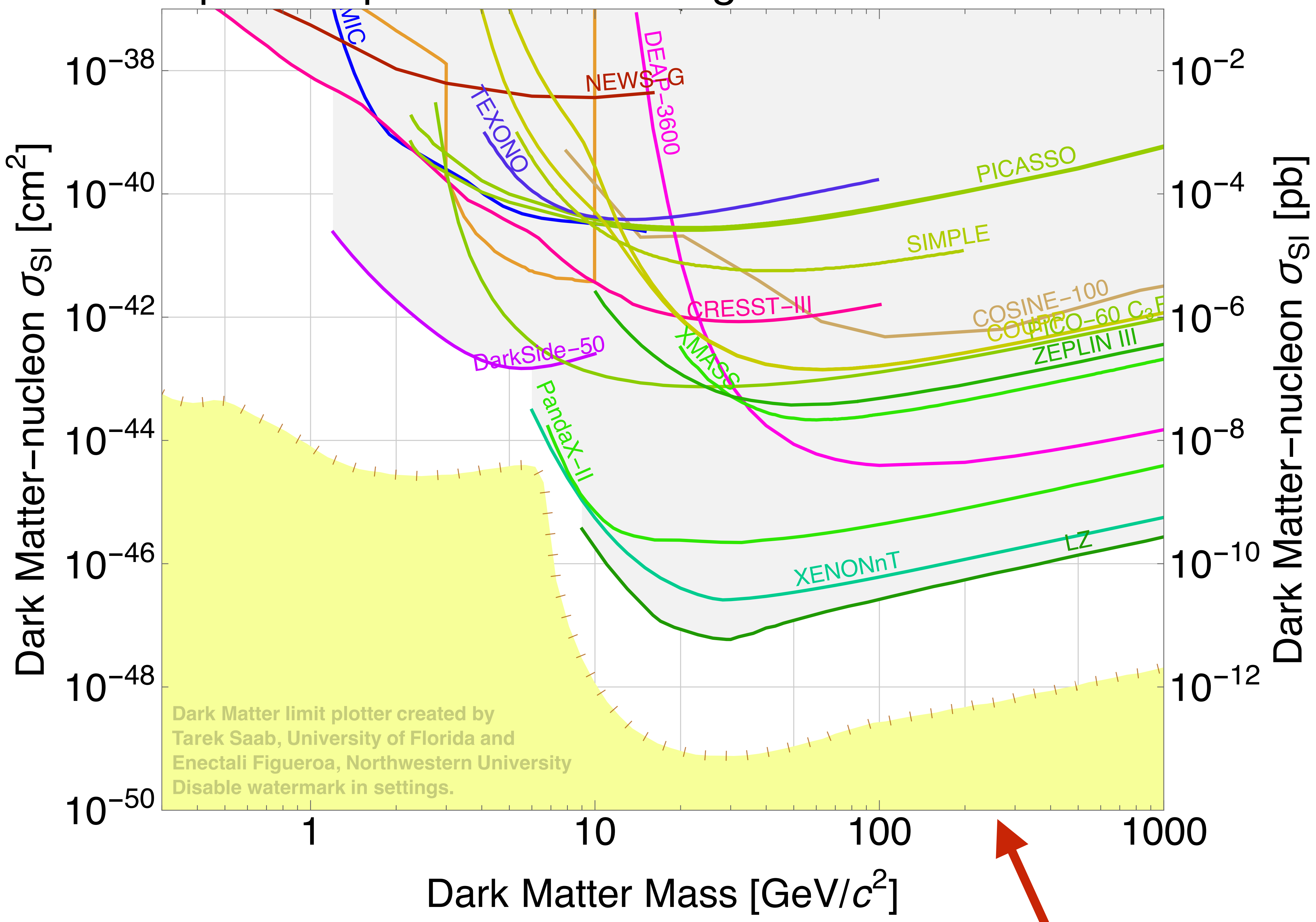
[Master's thesis by Gailyn Monroe]



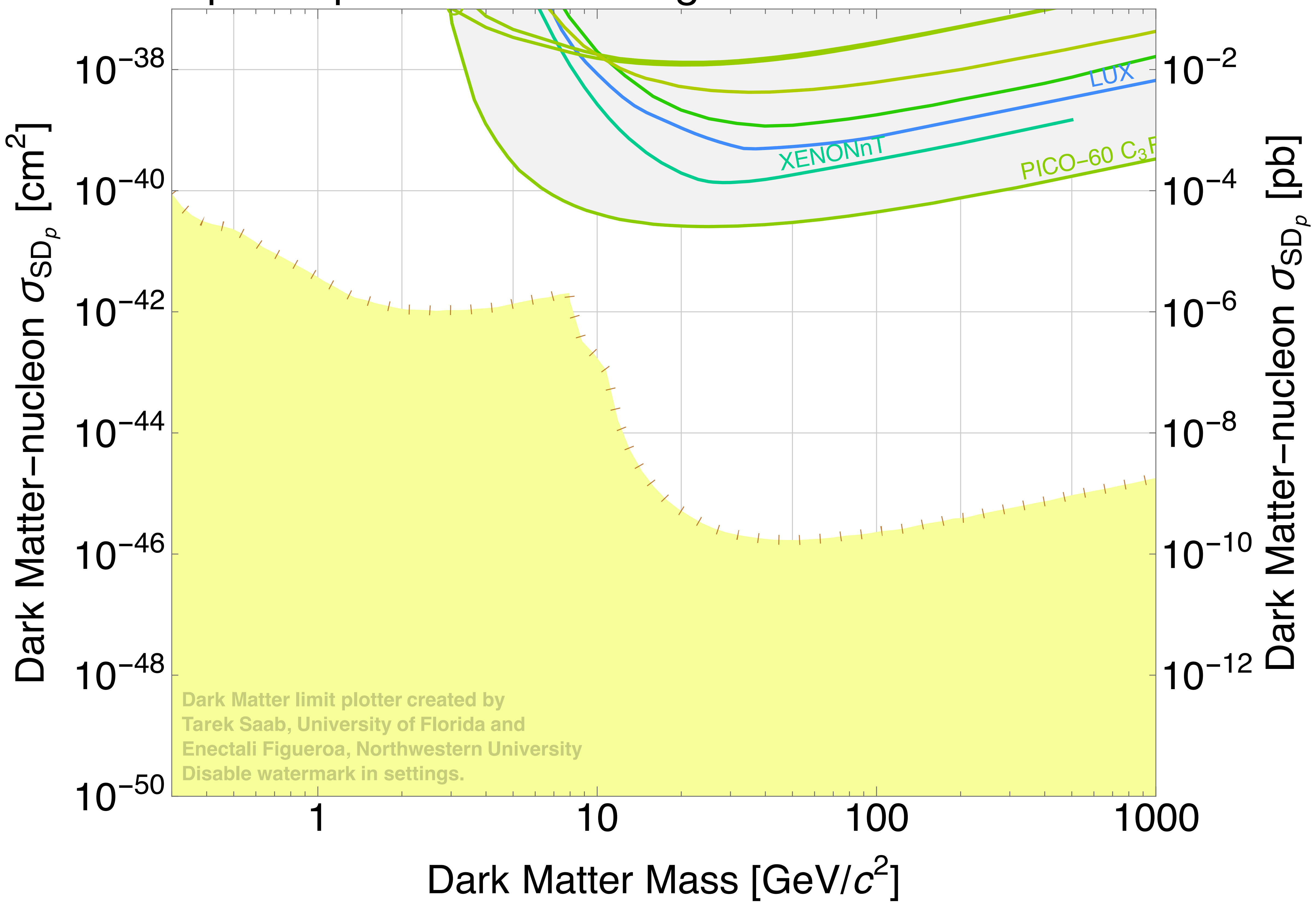
*See many exciting talks at this conference addressing direct detection of sub-GeV dark matter!

Direct detection: model dependence

Spin-independent scattering



Spin-dependent scattering



Coherent elastic scattering in spin-independent case:

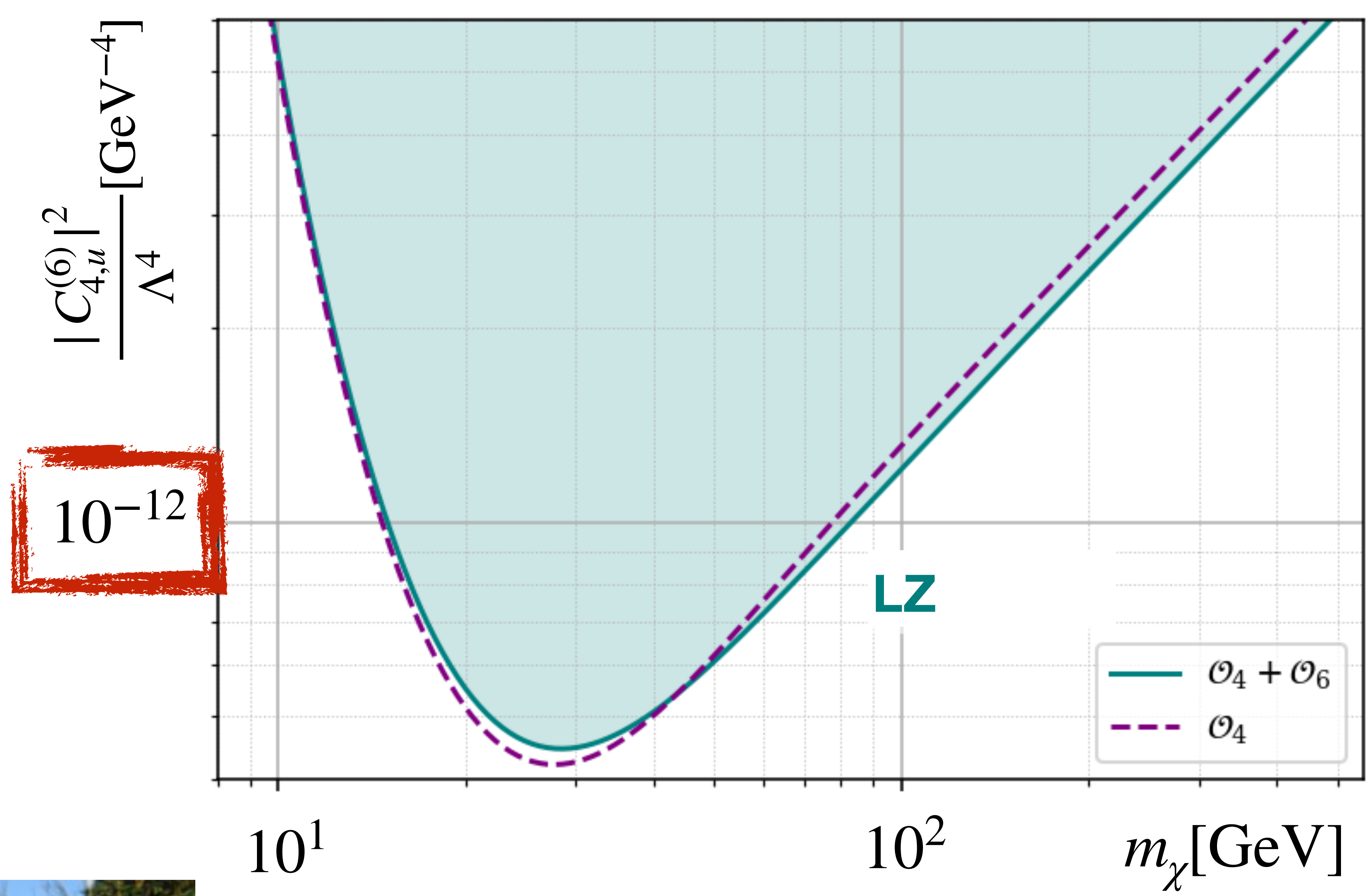
$\sigma_{\chi A} \propto A^2 \frac{\mu_{\chi A}^2}{\mu_{\chi p}^2} \sigma_{\mathrm{SI}} \Rightarrow$ strong bounds on σ_{SI} when using heavy nuclei

No enhancement by A^2 for spin-dependent interactions $\Rightarrow$ weaker bounds on σ_{SD}

Direct detection: model dependence

NB: Velocity-suppressed interactions

$$Q^{(6)}_{4,q} = \frac{C^{(6)}_{4,q}}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q) = \text{“Standard” SD interactions}$$



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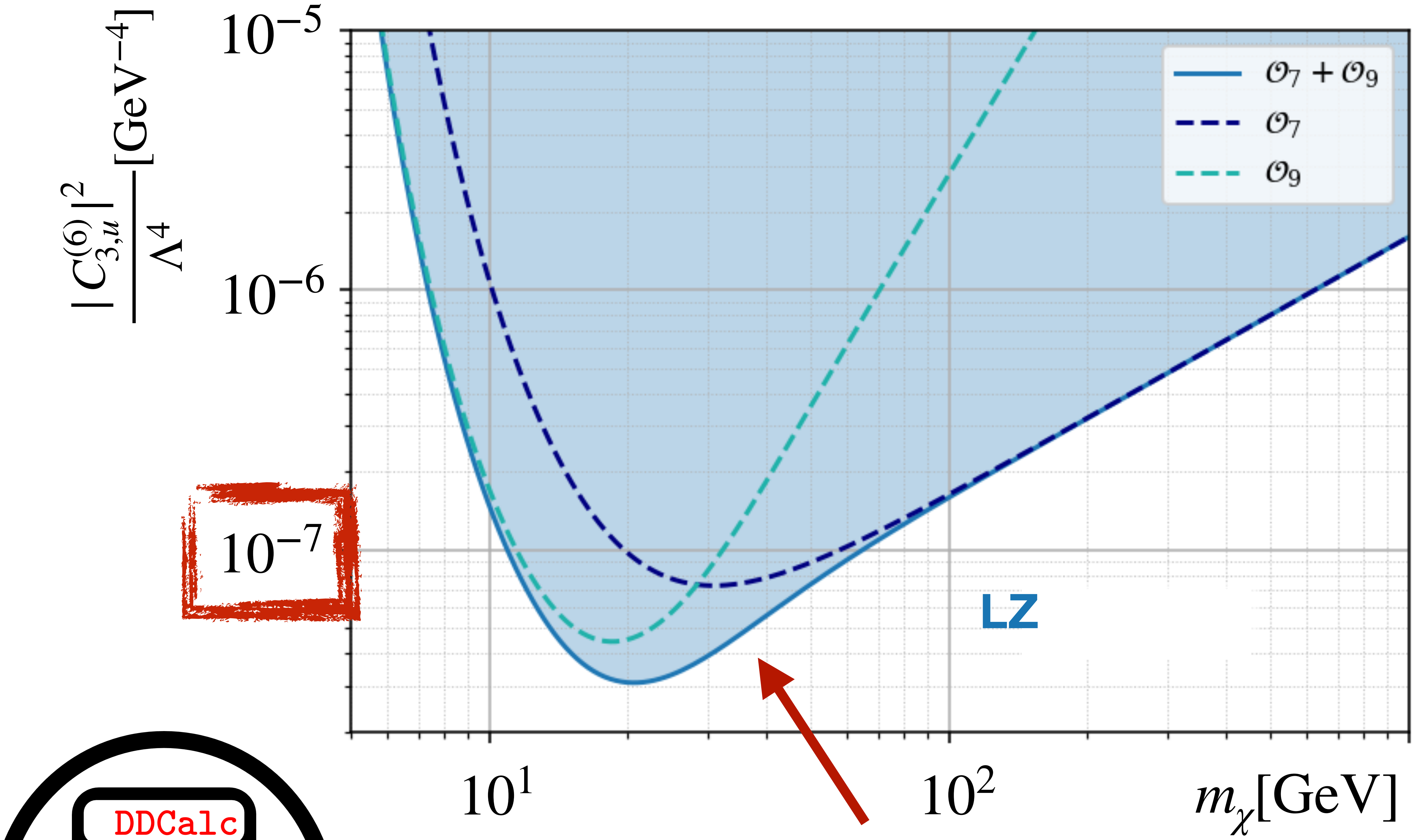


Yet weaker bounds!*

[Bachelor’s thesis by Victoria Falao]

[GAMBIT DM workgroup, DDCalc: 1705.07920]

[LZ: 2207.03764]

*Loop contributions not included

Direct detection: model dependence

NB: Velocity-suppressed interactions

- Some types of interactions may be further suppressed due to dependence of low-energy scattering with nucleons on DM velocity or transferred momentum!

$$Q_{4,q}^{(6)} = \frac{C_{4,q}^{(6)}}{\Lambda^2}(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q) \xrightarrow{\text{Low energy}} \mathcal{O}_4^N = \mathbf{S}_\chi \cdot \mathbf{S}_N \quad \& \quad \mathcal{O}_6^N = \left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}\right)\left(\mathbf{S}_N \cdot \frac{\mathbf{q}}{m_N}\right)$$

"Standard" SD interaction, present even at vanishing relative DM-nucleon velocity

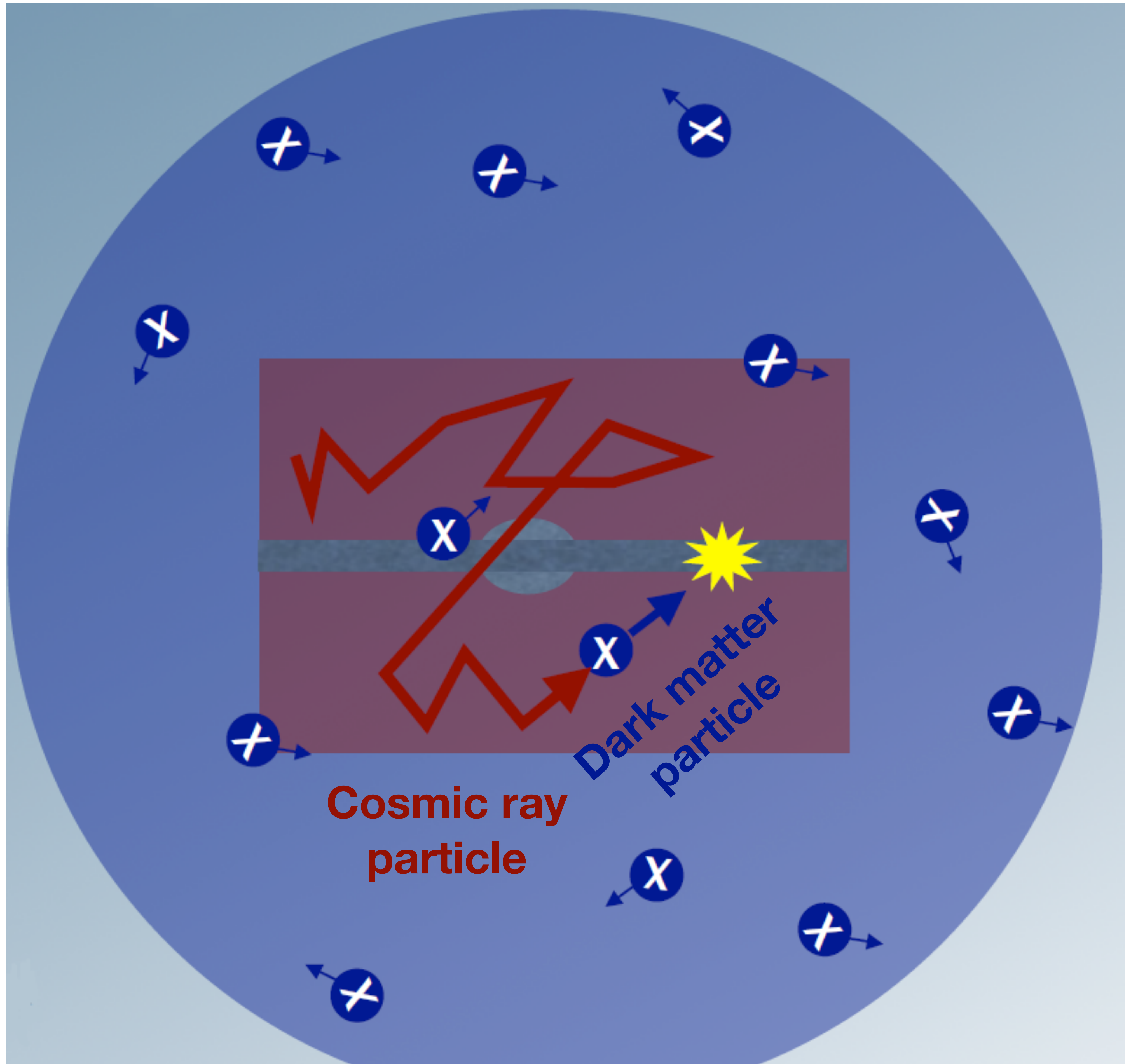
$$Q_{3,q}^{(6)} = \frac{C_{4,q}^{(6)}}{\Lambda^2}(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu\gamma_5 q) \xrightarrow{\text{Low energy}} \mathcal{O}_7^N = 1_\chi\left(\mathbf{S}_N \cdot \mathbf{v}_\perp\right) \quad \& \quad \mathcal{O}_9^N = \mathbf{S}_\chi \cdot \left(\frac{i\mathbf{q}}{m_N} \times \mathbf{S}_N\right)$$

[Bishara, Brod, Grinstein, Zupan: **DirectDM**: a tool for dark matter direct detection, 1708.02678]

Suppression by relative velocity or transferred momentum

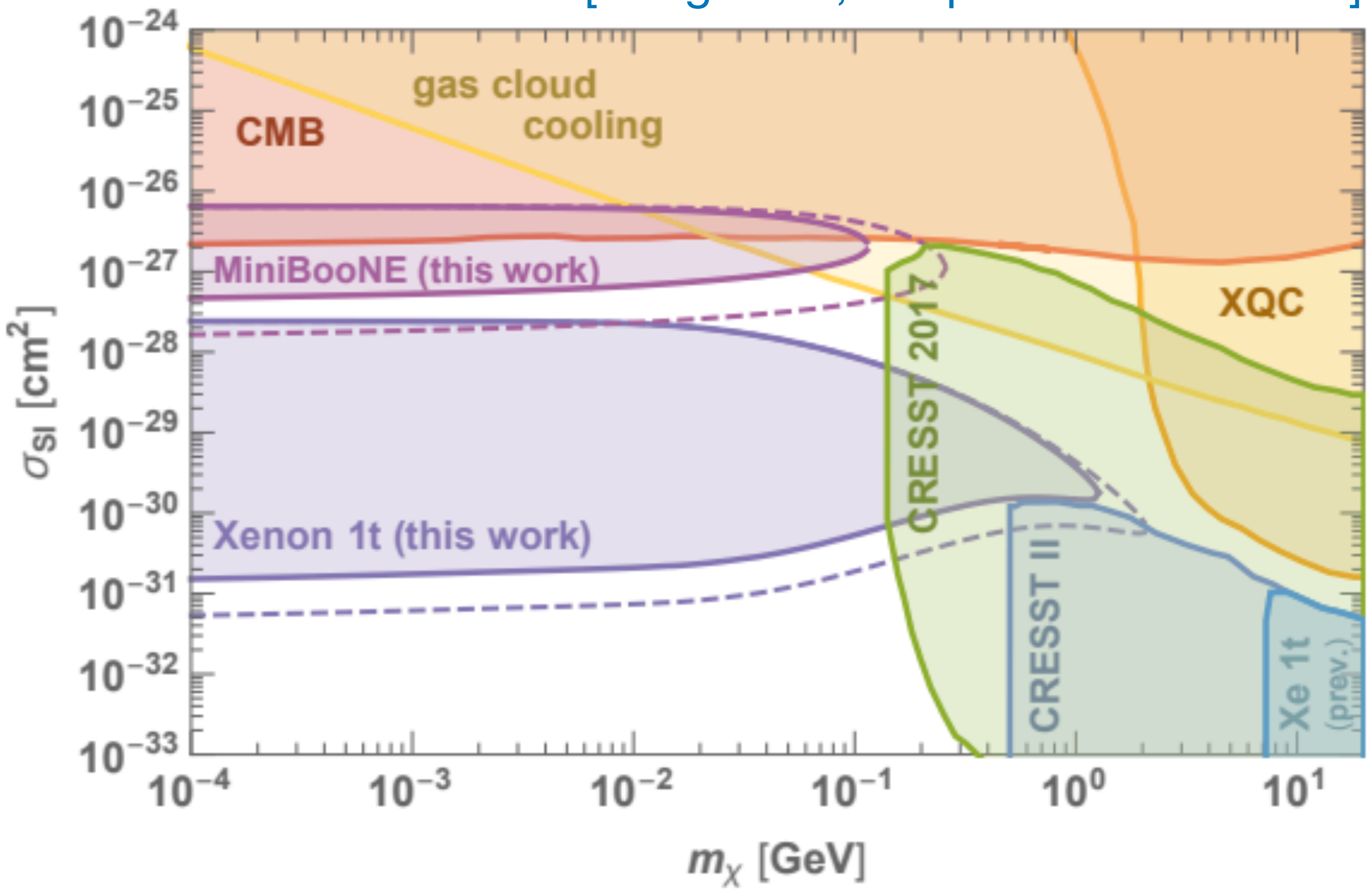
Accelerated dark matter $\Rightarrow$ sensitivity to lighter particles & less "punishment" for spin-dependent or velocity suppressed interactions!

Cosmic-ray up-scattered dark matter



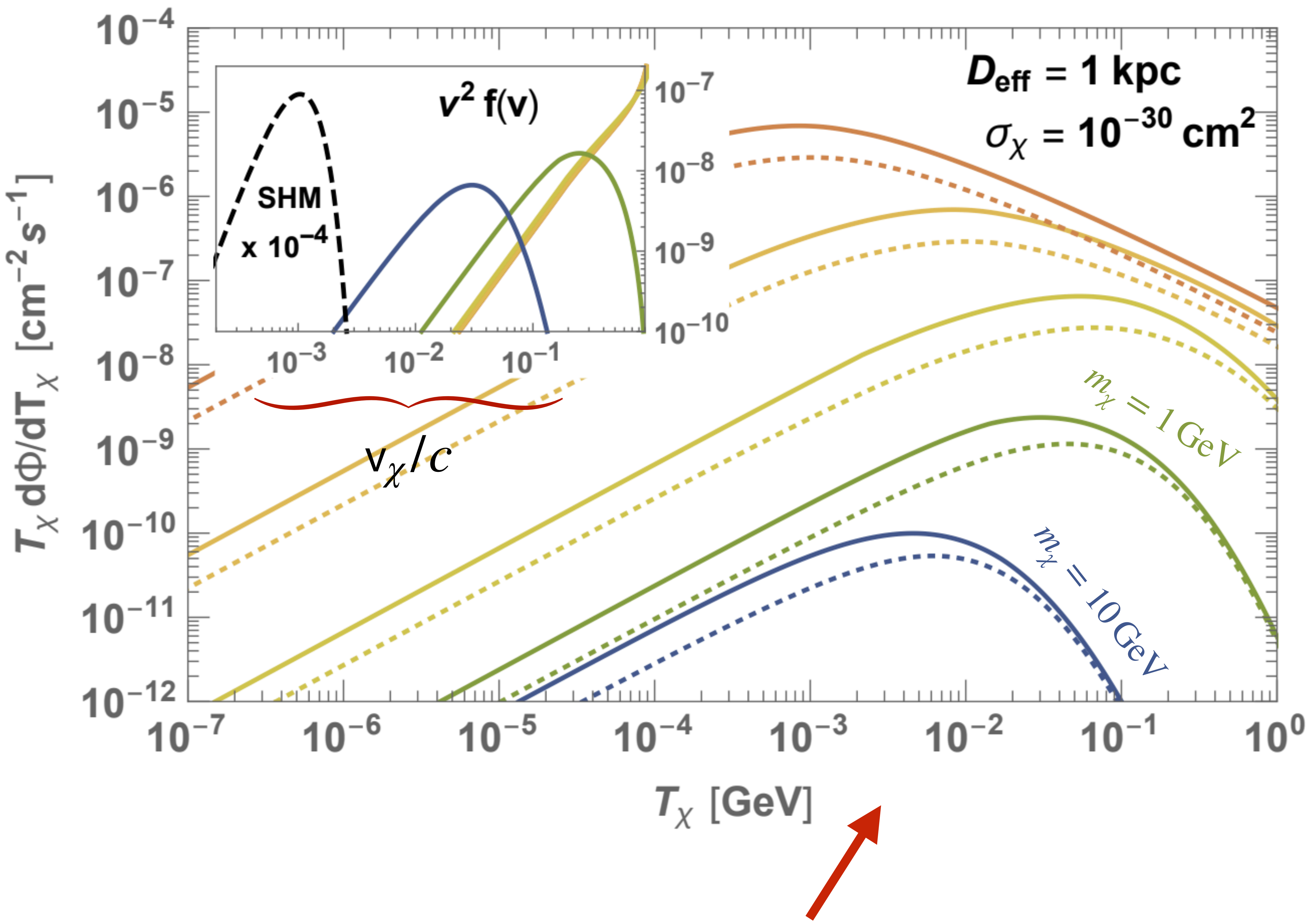
Credit: T. Bringmann

[Bringmann, Pospelov: 1810.10543]

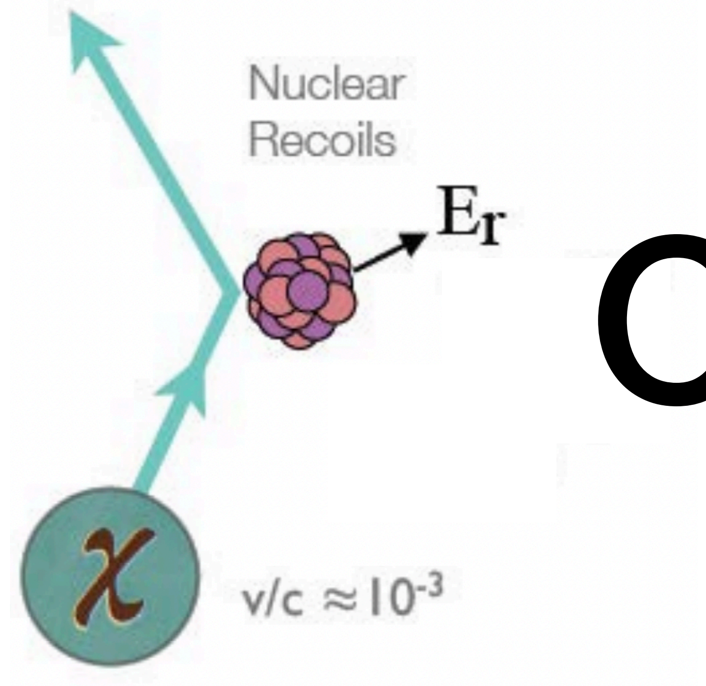


Increased dark matter kinetic energy ⇒ lighter dark matter can be probed by direct detection experiments like Xenon 1t!

Cosmic-ray up-scattered dark matter

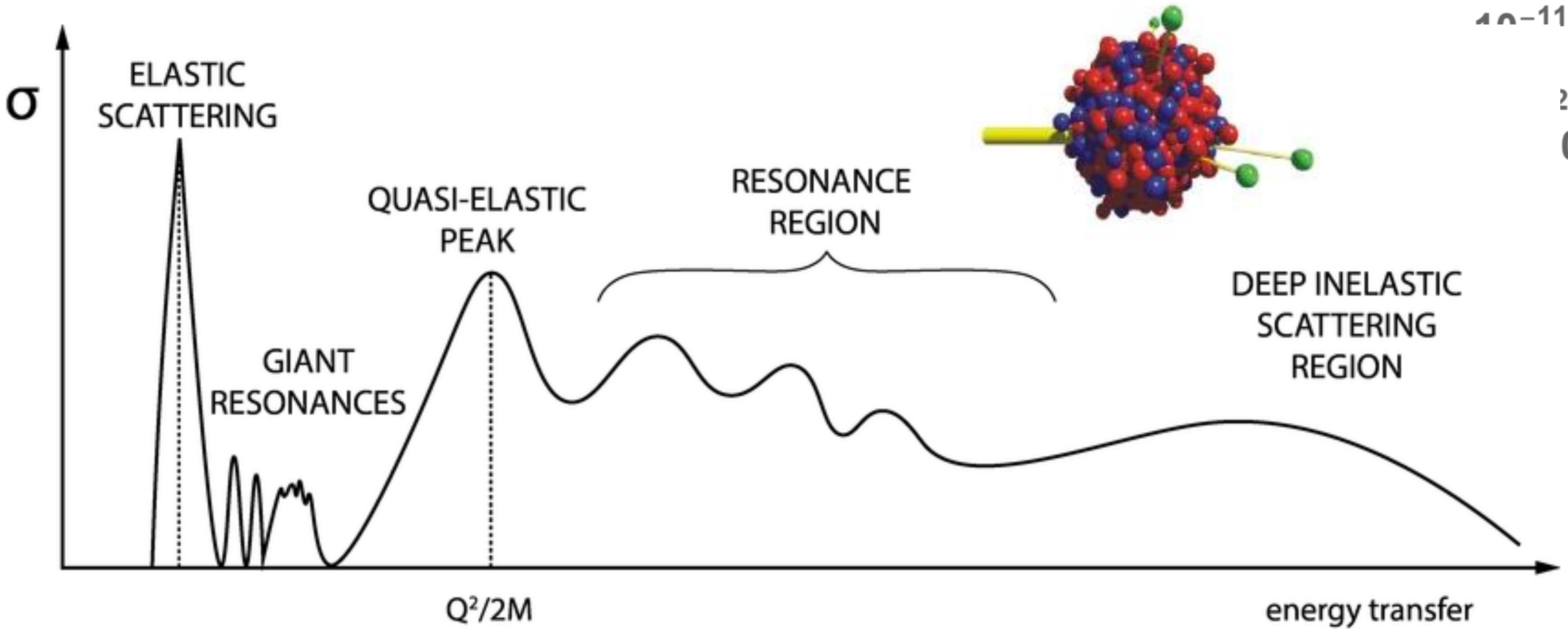


Up-scattered dark matter flux coming to Earth
[Bringmann, Pospelov: 1810.10543]

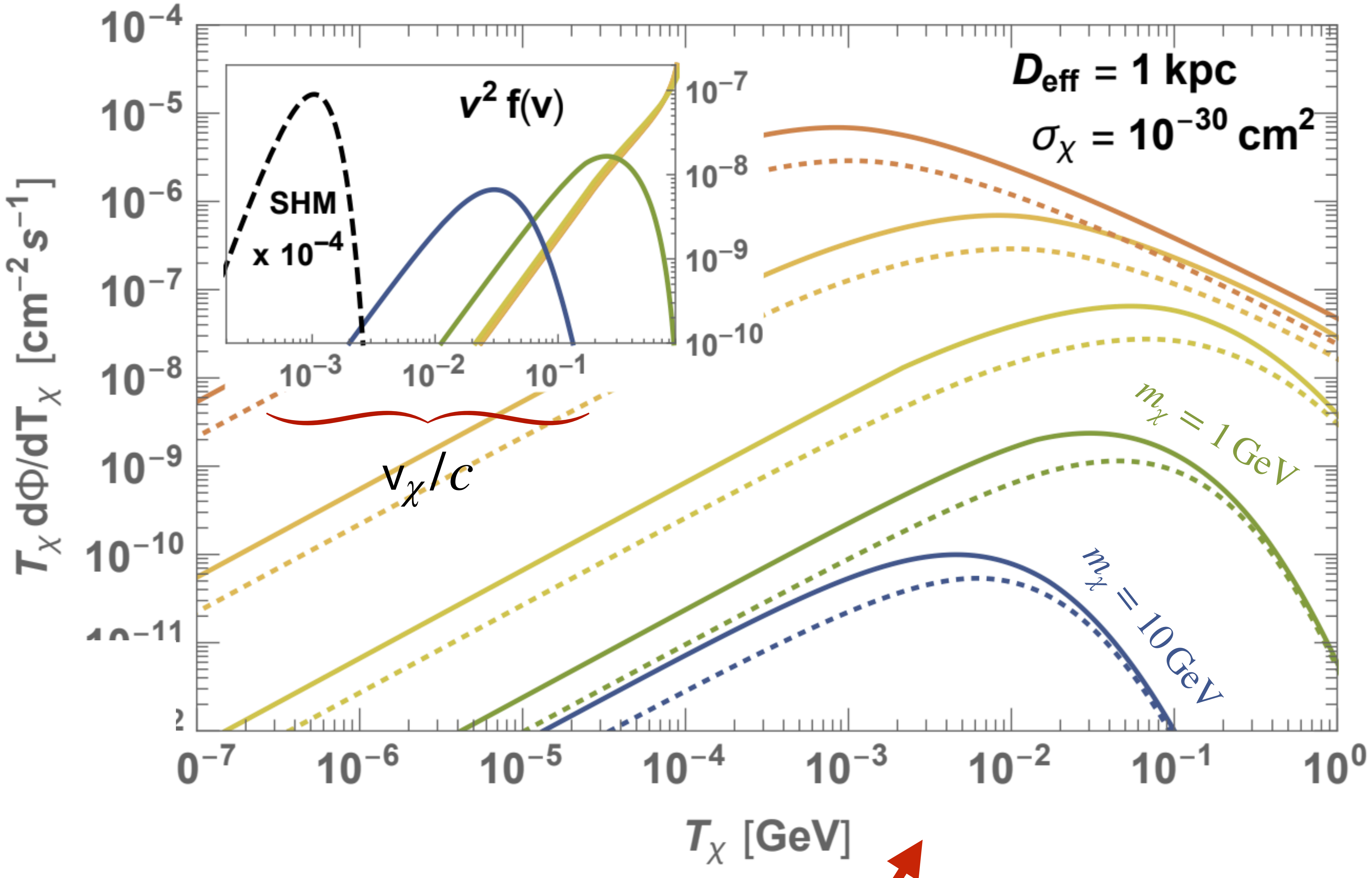


Cosmic-ray up-scattered dark matter

- Direct detection experiments are tuned to "slow" halo dark matter
- Particles with $\mathcal{O}$(GeV) kinetic energies can induce other processes that are detectable in neutrino experiments!



Credit: GiBUU, [Sobczyk et al.: 10.22323/1.369.0009]



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

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

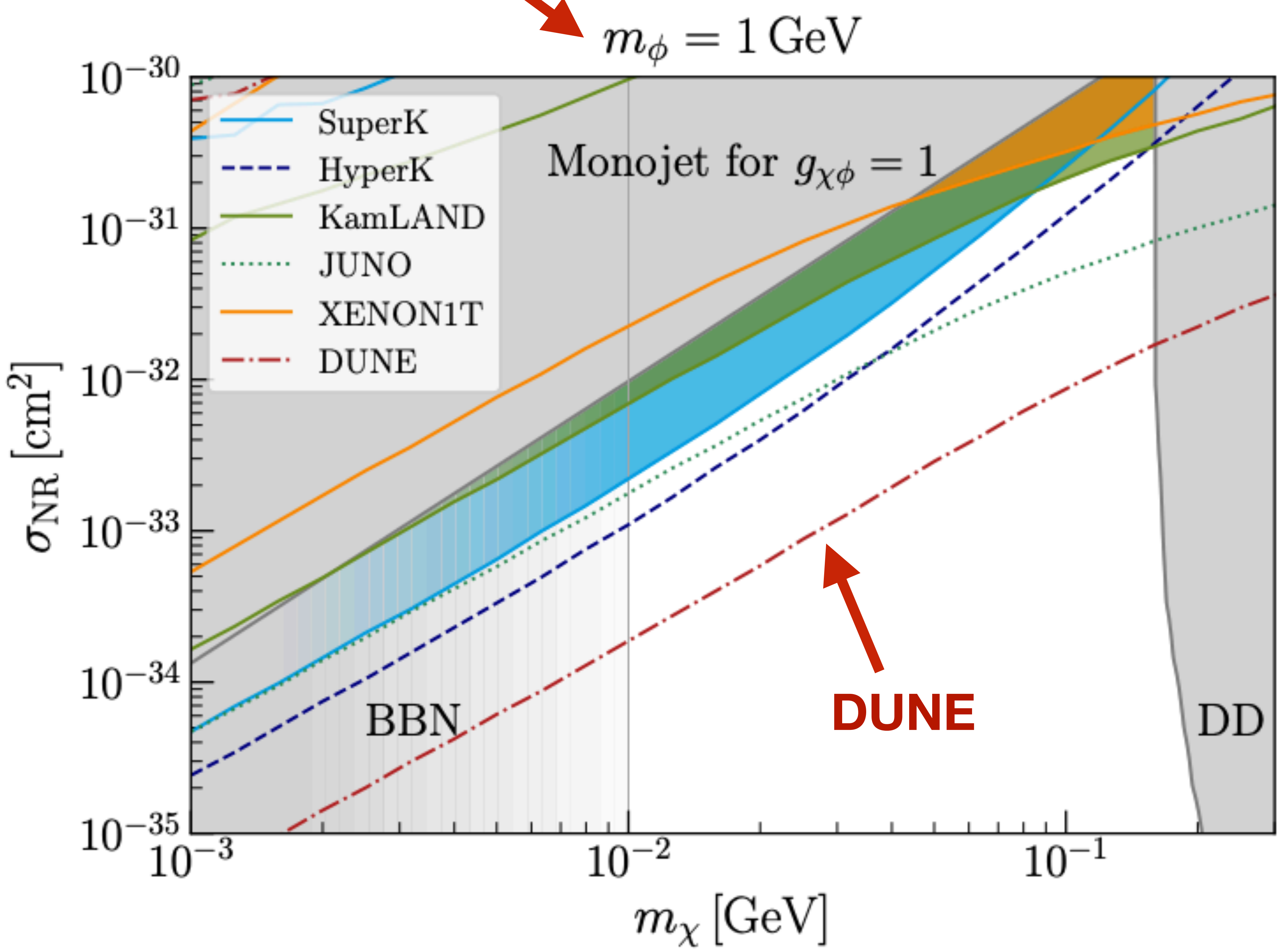
DUNE sensitivity predicted in [Ema, Sala, Sato: 2011.01939]:

- 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!

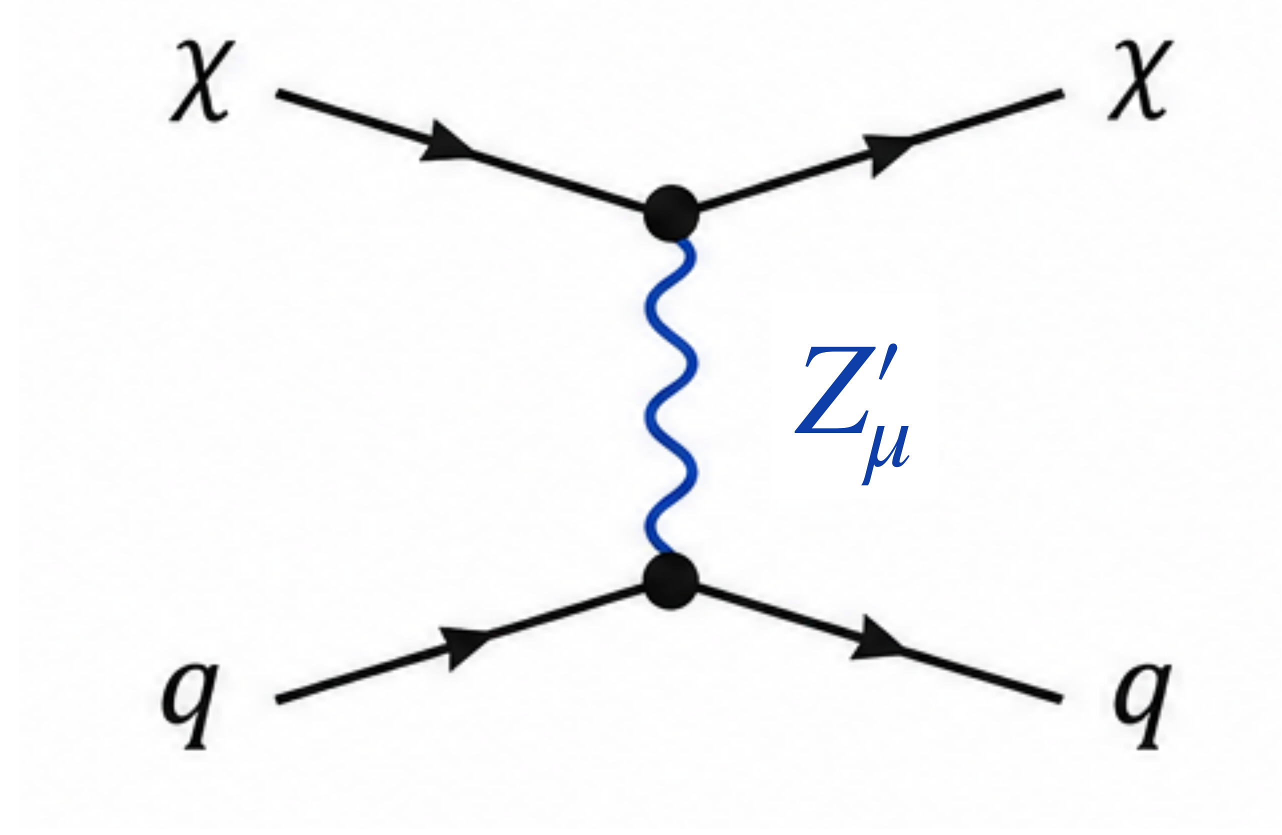
Scalar mediator

[Ema, Sala, Sato: 2011.01939]



Benchmark model: massive Z' mediator

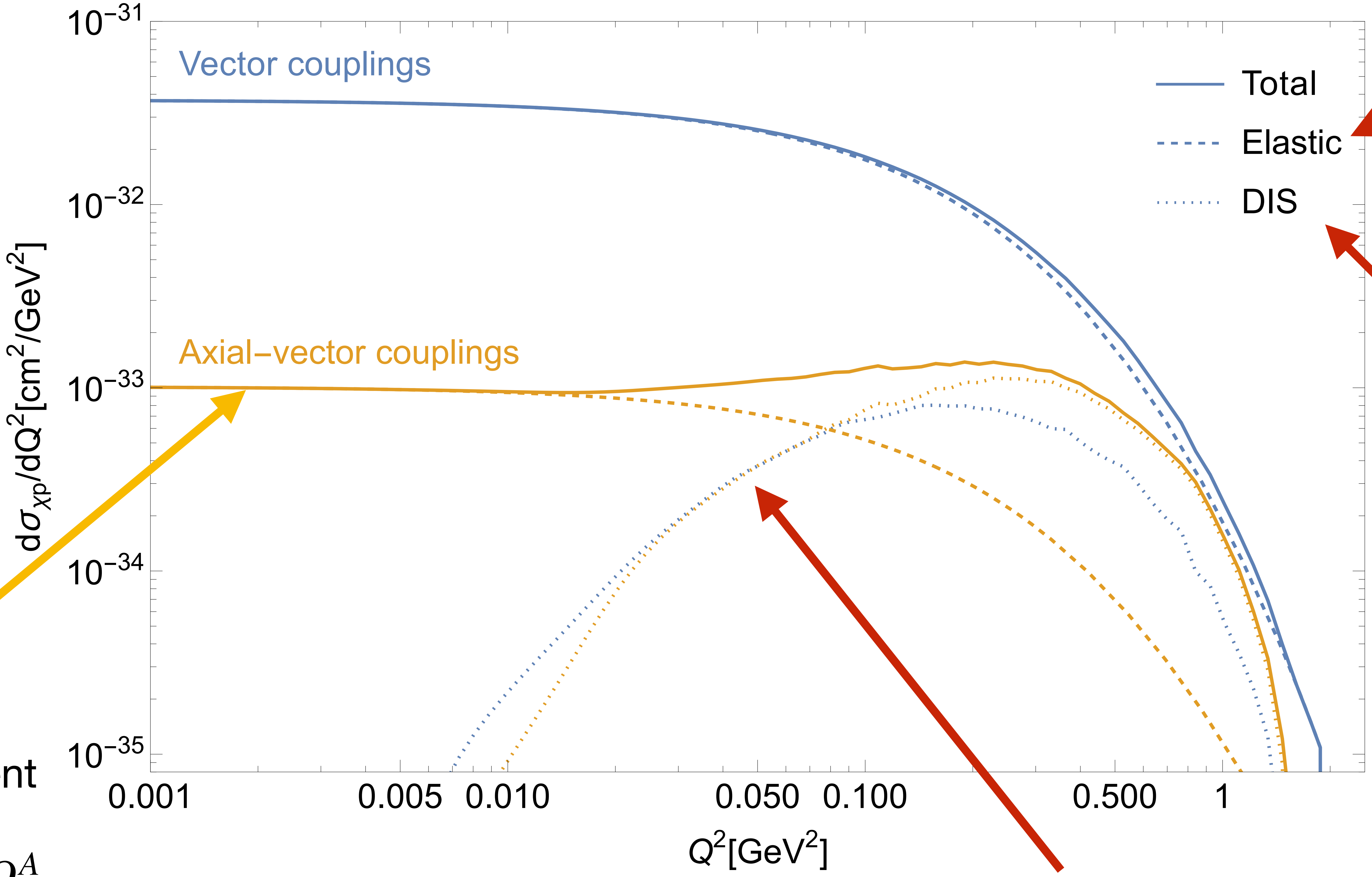
- Motivation: implemented in GENIE boosted DM module [Berger: 1812.05616]
- Both dark matter particles and Standard Model quarks charged under $U(1)_D$:
- Vector couplings ↔ SI: $\mathscr{L}_{\chi,\text{int}} = g_{Z'}\, Q^V_\chi\, Z'_\mu\, \bar{\chi}\, \gamma^\mu \chi\,, \;\; \mathscr{L}_{q,\text{int}} = g_{Z'}\, Q^V_q\, Z'_\mu\, \bar{q}\, \gamma^\mu q$
  $U(1)_B$: $Q^V_q = 1,\ \forall q$ (less constrained than "dark photon" with $Q^V_q = Q^{\text{em}}_q$)
- Axial-vector couplings ↔ SD:
  $\mathscr{L}_{\chi,\text{int}} = g_{Z'}\, Q^A_\chi\, Z'_\mu\, \bar{\chi}\, \gamma^\mu \gamma_5 \chi\,, \;\; \mathscr{L}_{q,\text{int}} = g_{Z'}\, Q^A_q\, Z'_\mu\, \bar{q}\, \gamma^\mu \gamma_5 q$



Dark-matter-proton cross section

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

$m_{Z'}$=1GeV, m_χ=1GeV, T_χ=1GeV



Calculated analytically, agrees with the GENIE output

Numerical calculation by GENIE [Berger: 1812.05616]

Relative suppression of the elastic contribution for axial-vector couplings due to different nucleon form factors:

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

“DIS” contribution comparable for vector and axial-vector cases

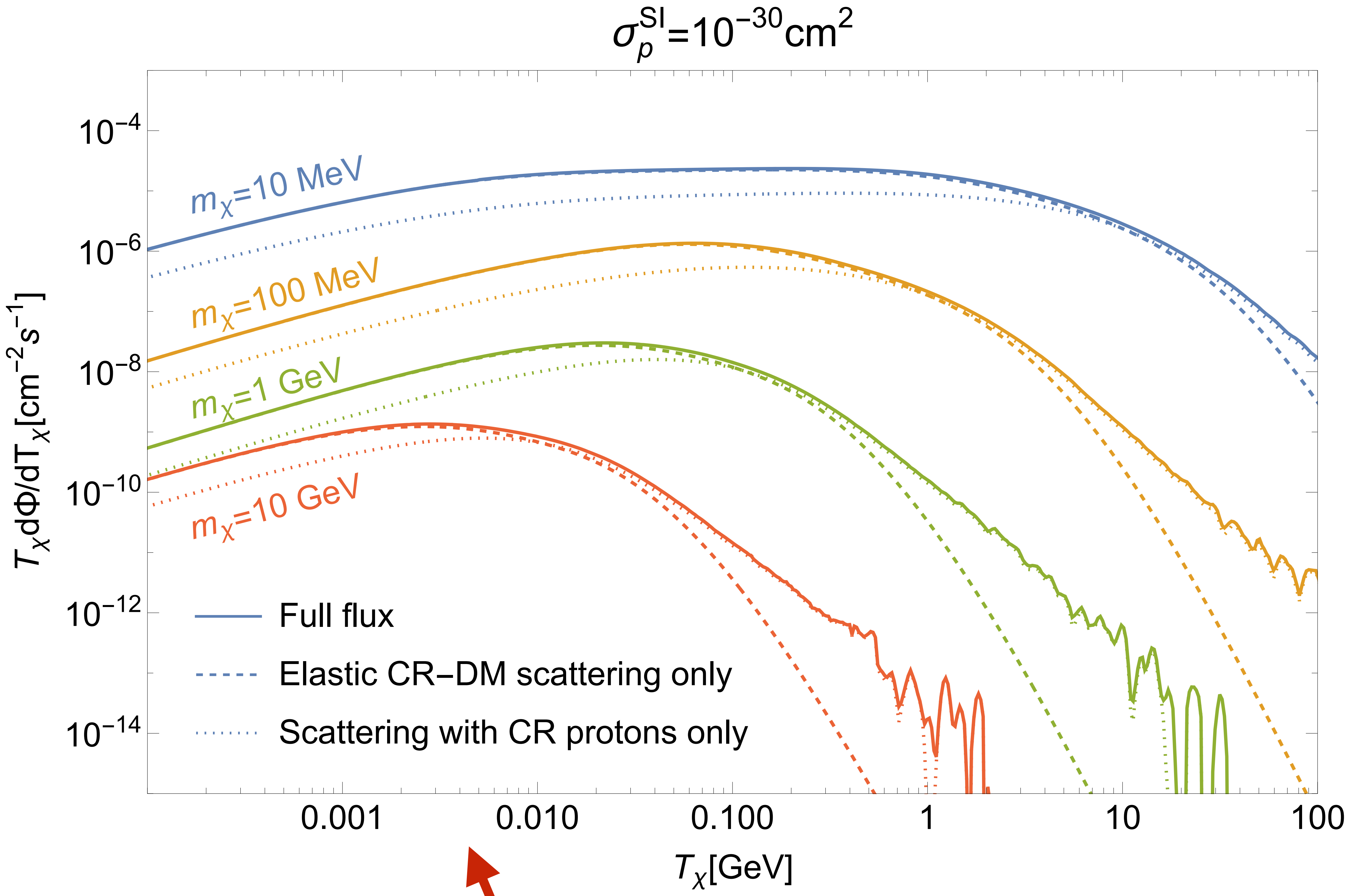
(NB: at low Q^2, GENIE employs parton distribution functions extrapolated using the Bodek-Yang model)

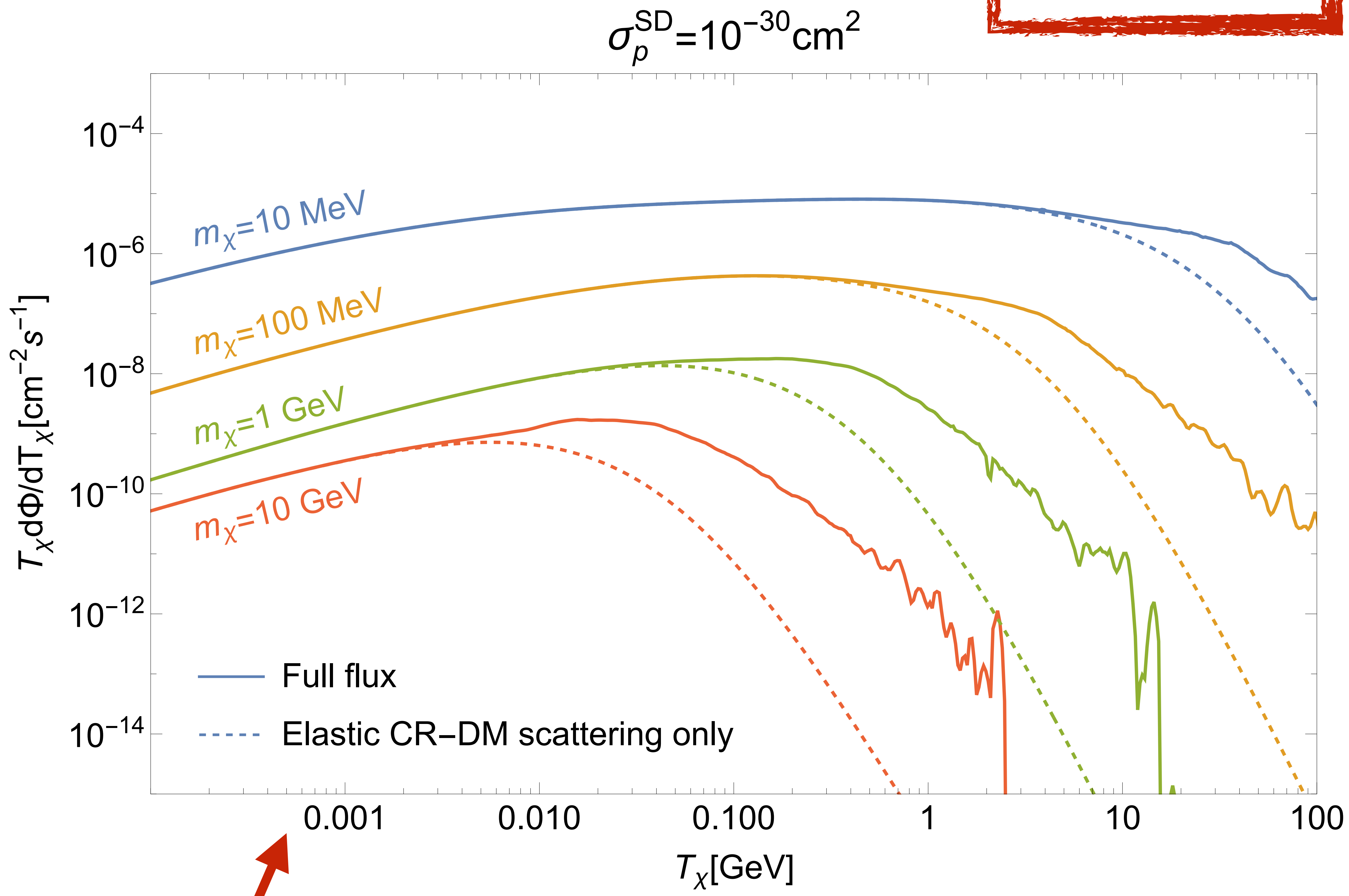
CRDM flux coming to Earth

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

Plots produced by

DarkSUSY



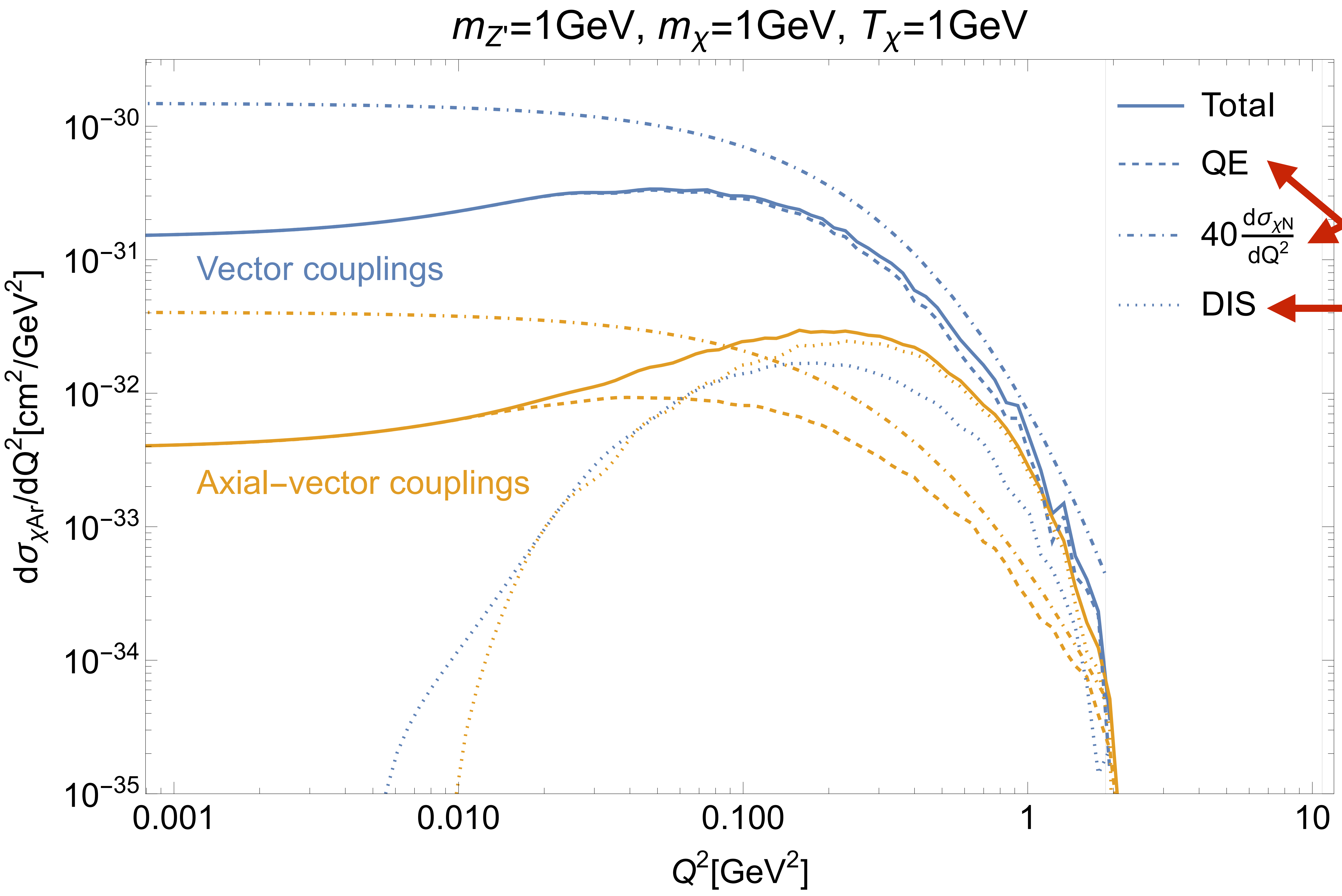


Vector couplings: $\sigma^p_{\mathrm{SI}} = \dfrac{g^4_{Z'}(Q^V_\chi)^2(3Q^V_q)^2\mu^2_{\chi p}}{\pi\, m^4_{Z'}}$

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

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

Dark-matter-argon cross section



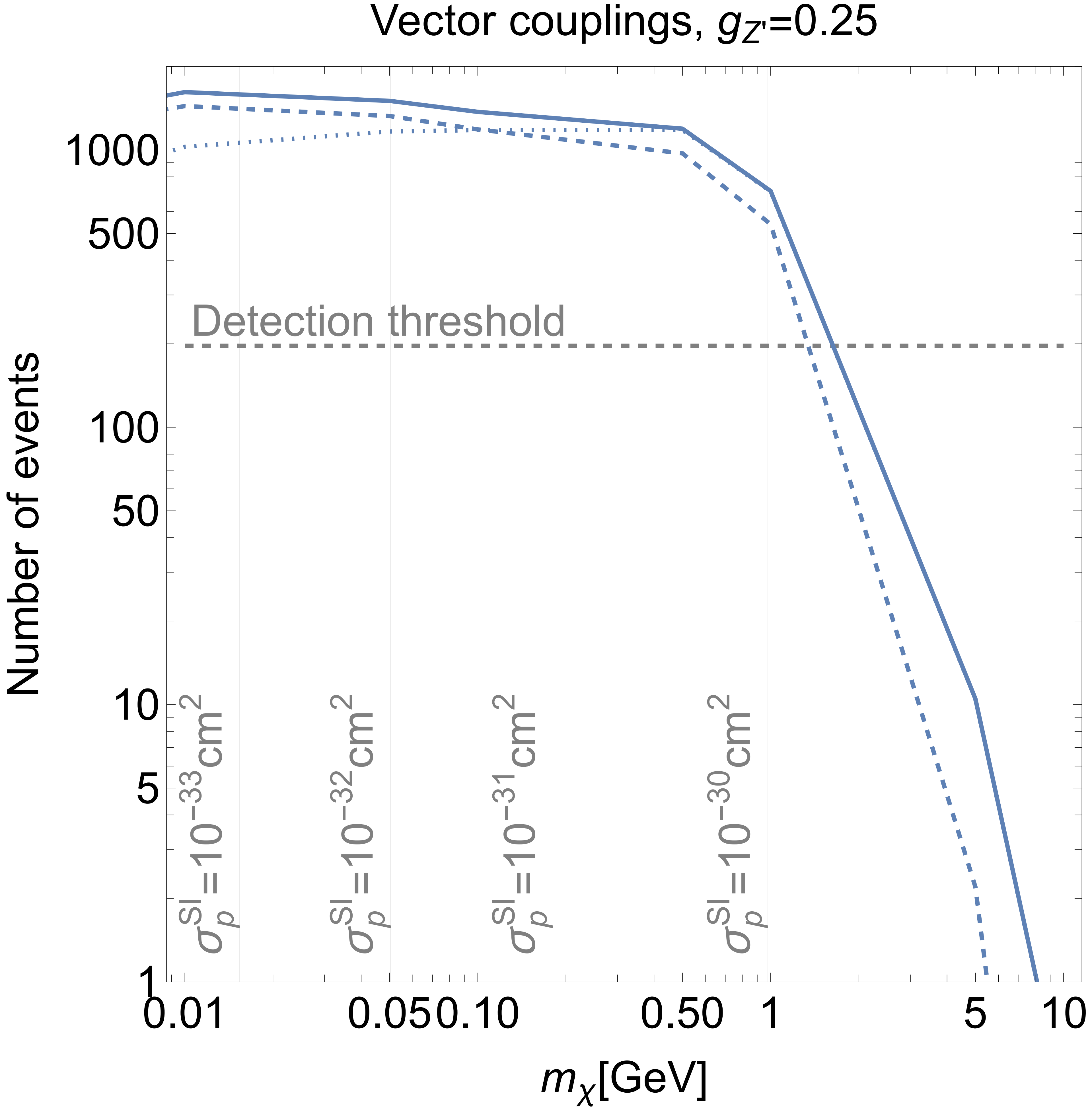
Rough analytic estimate of the QE contribution

Numerical calculation by GENIE [Berger: 1812.05616]

Expected number of events in DUNE

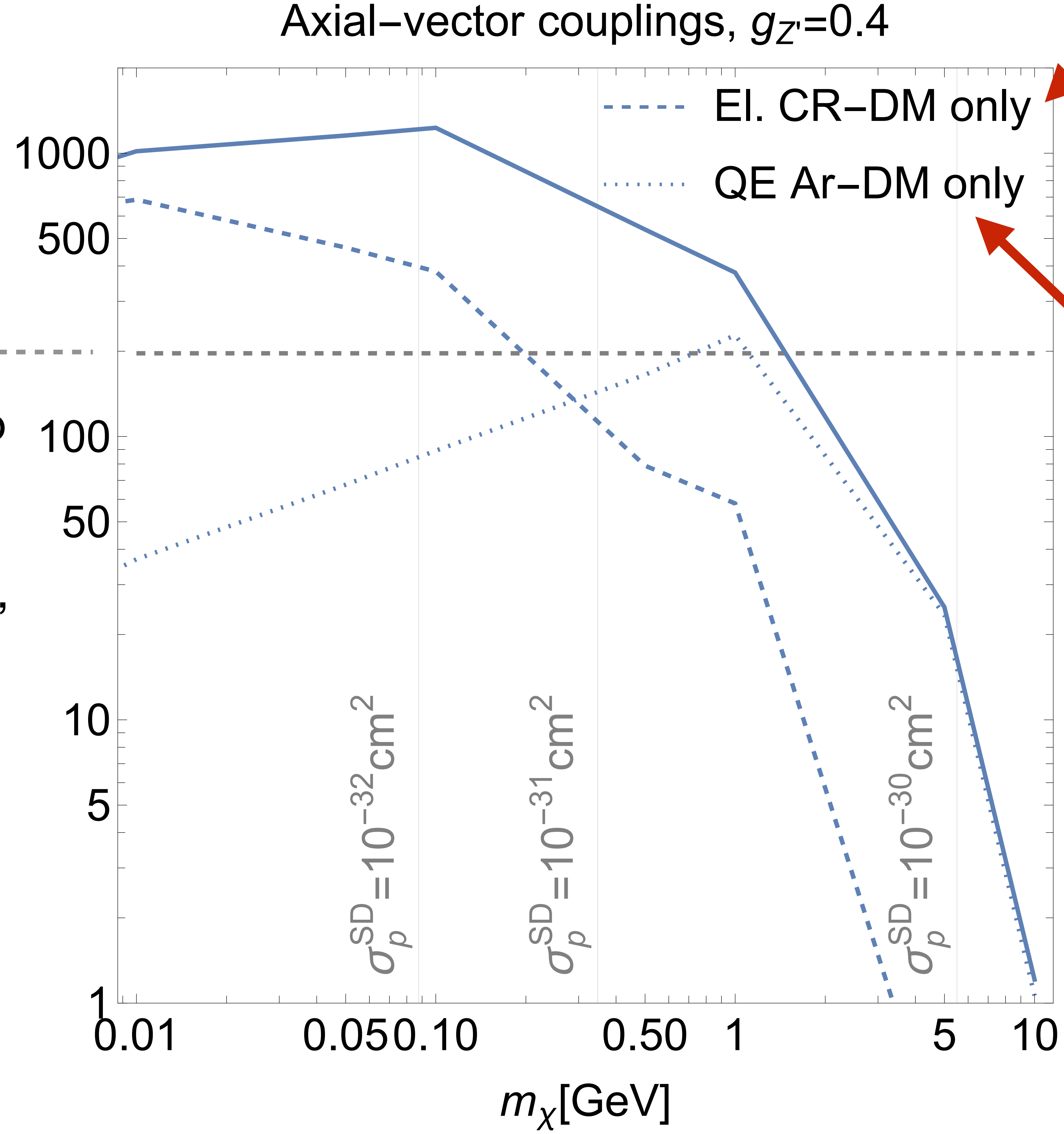
- Inclusion of DIS enhances considerably the event rate for SD case

Without inelastic interactions in DM up-scattering



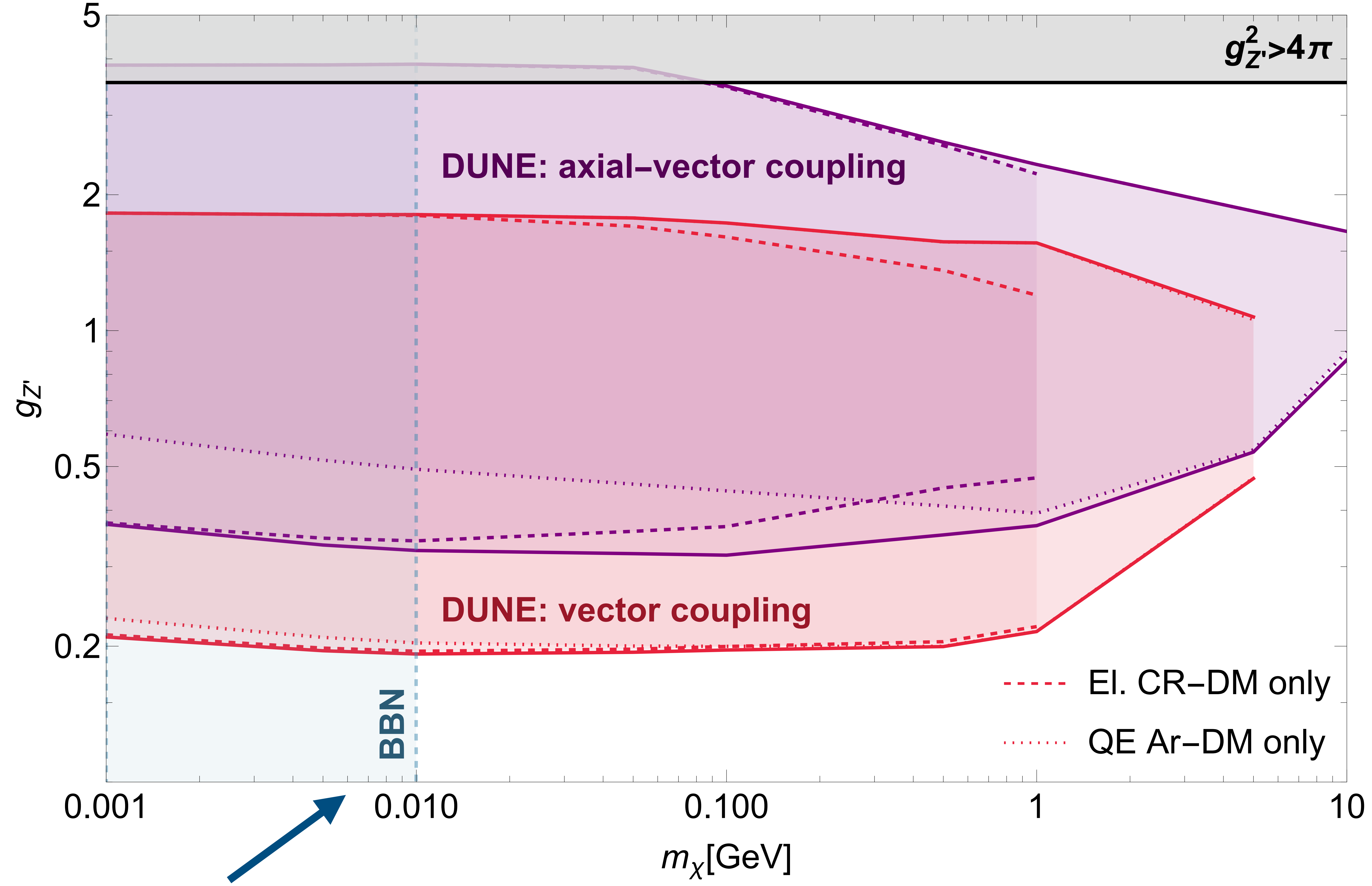
DUNE sensitivity at 2σ level

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



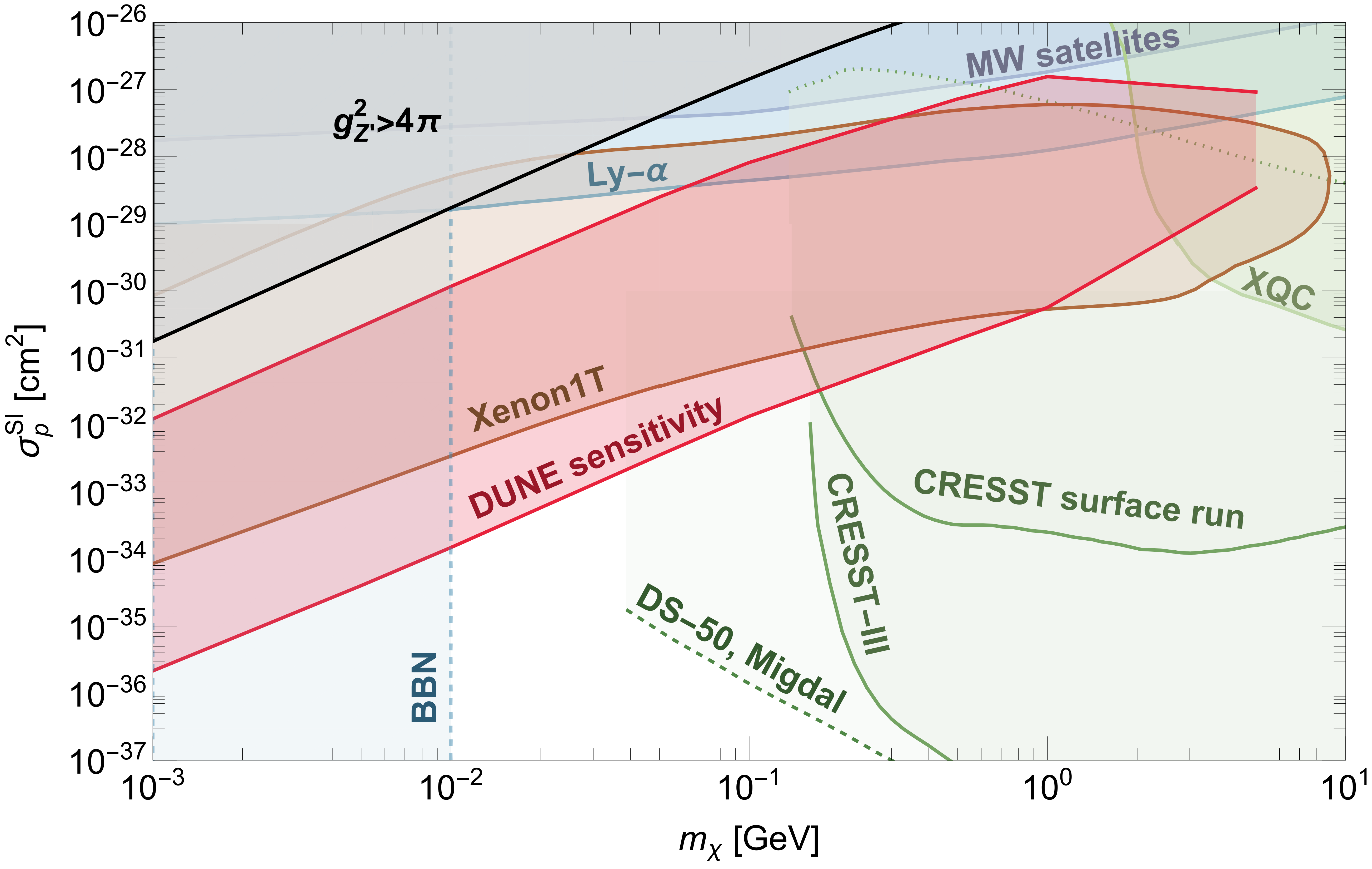
Without DIS in detection

Results



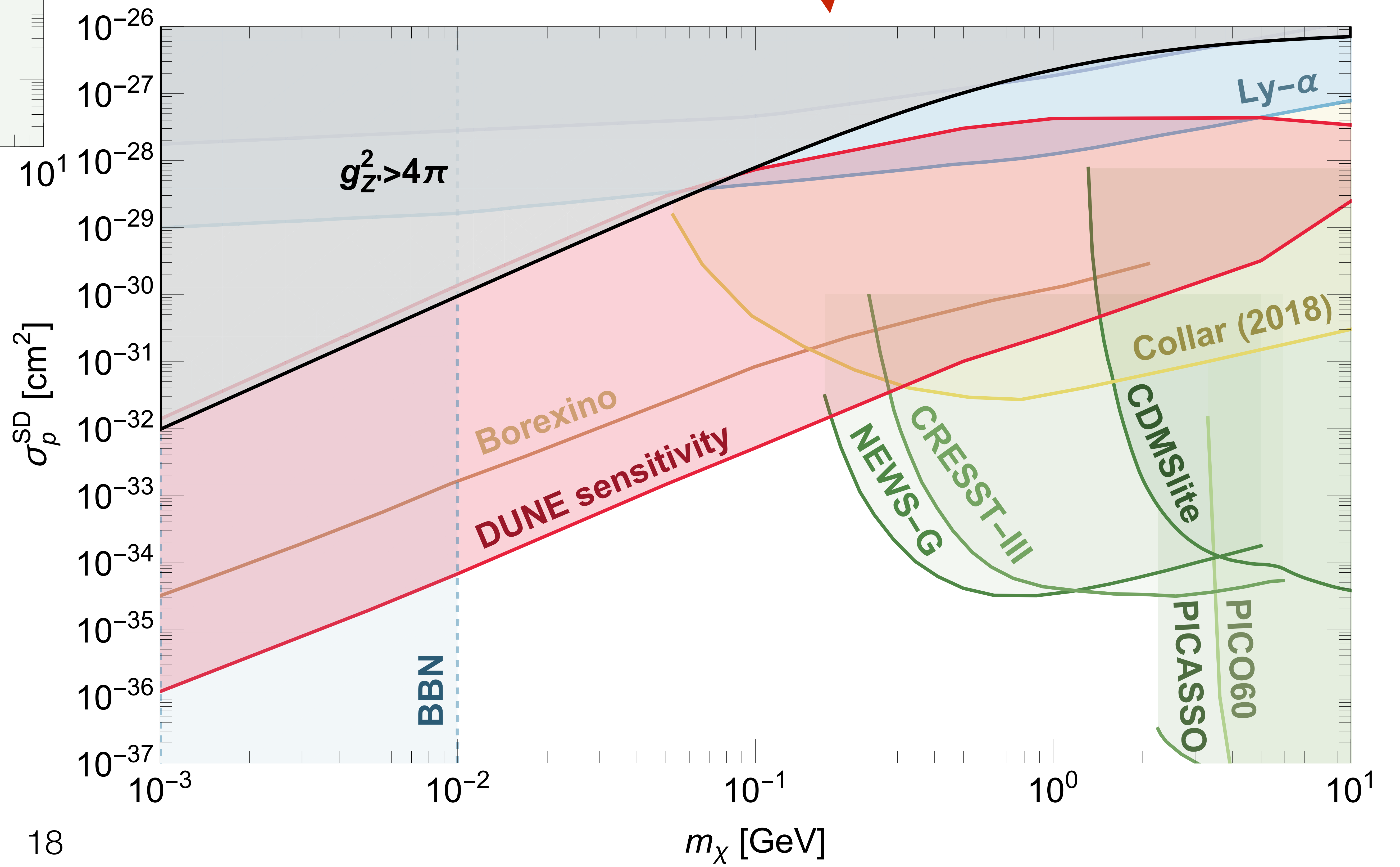
BBN constraints on extra light degrees of freedom thermalised with SM plasma
[Krnjaic: 1908.00007]

Results



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

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



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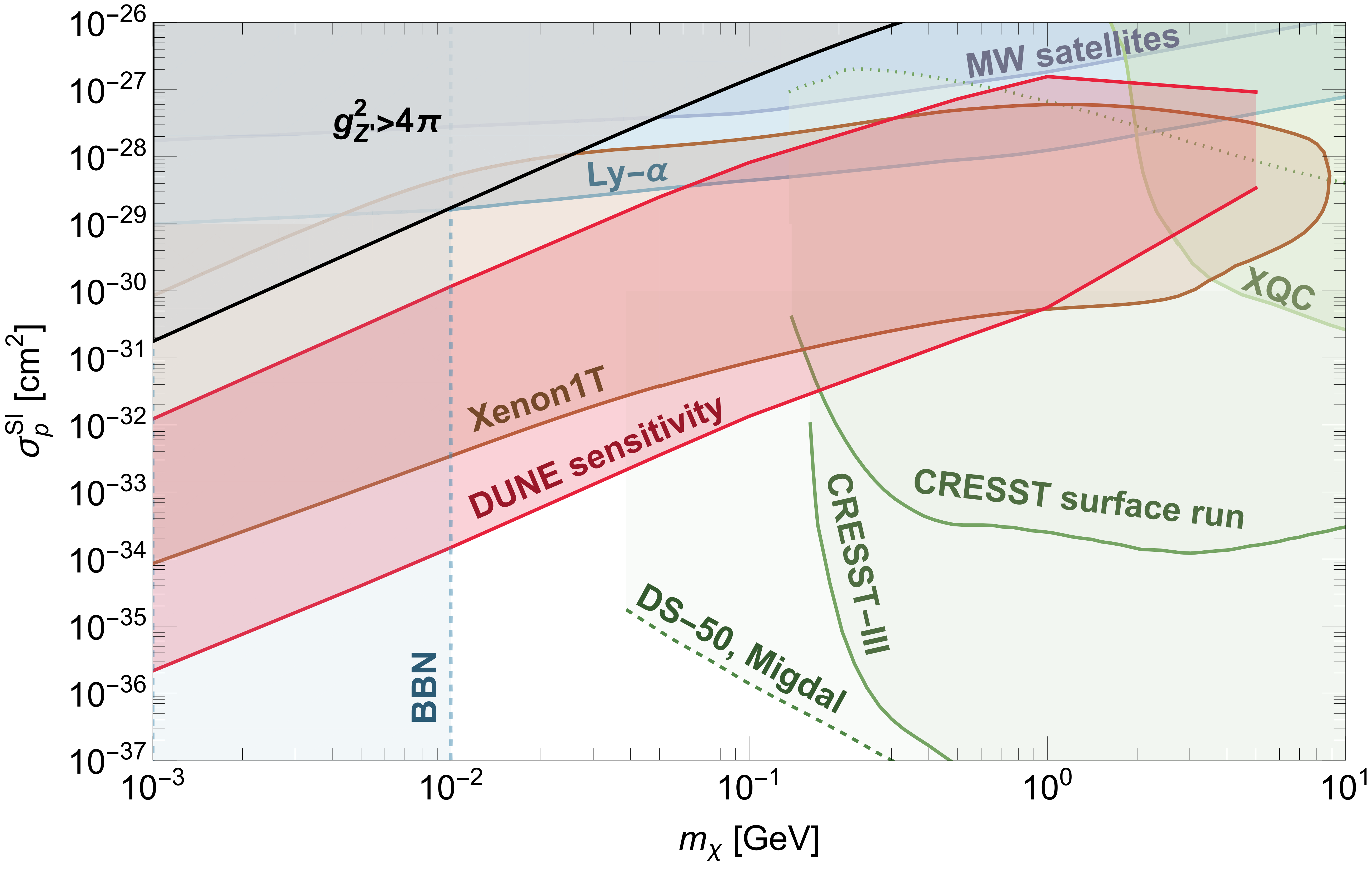

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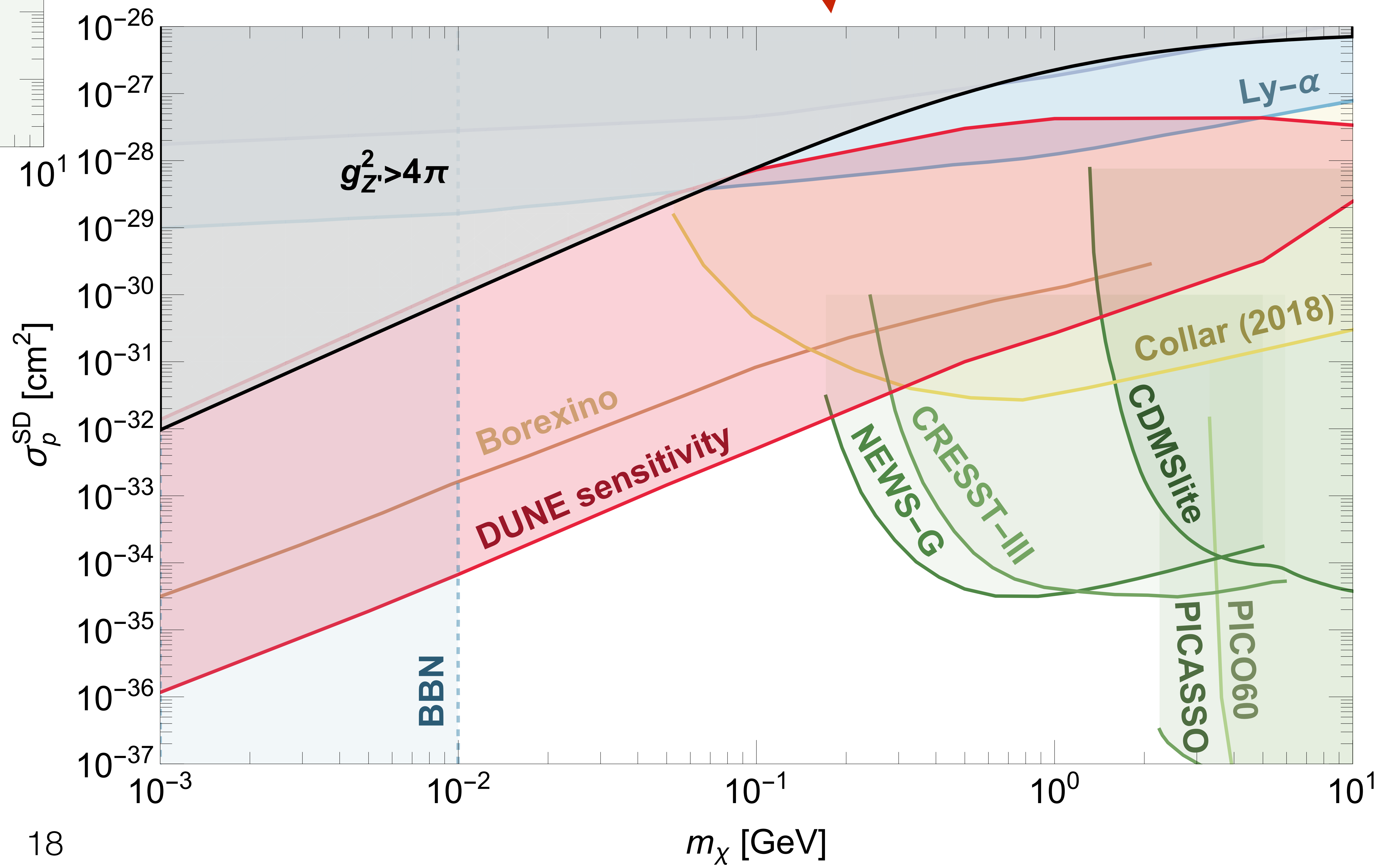
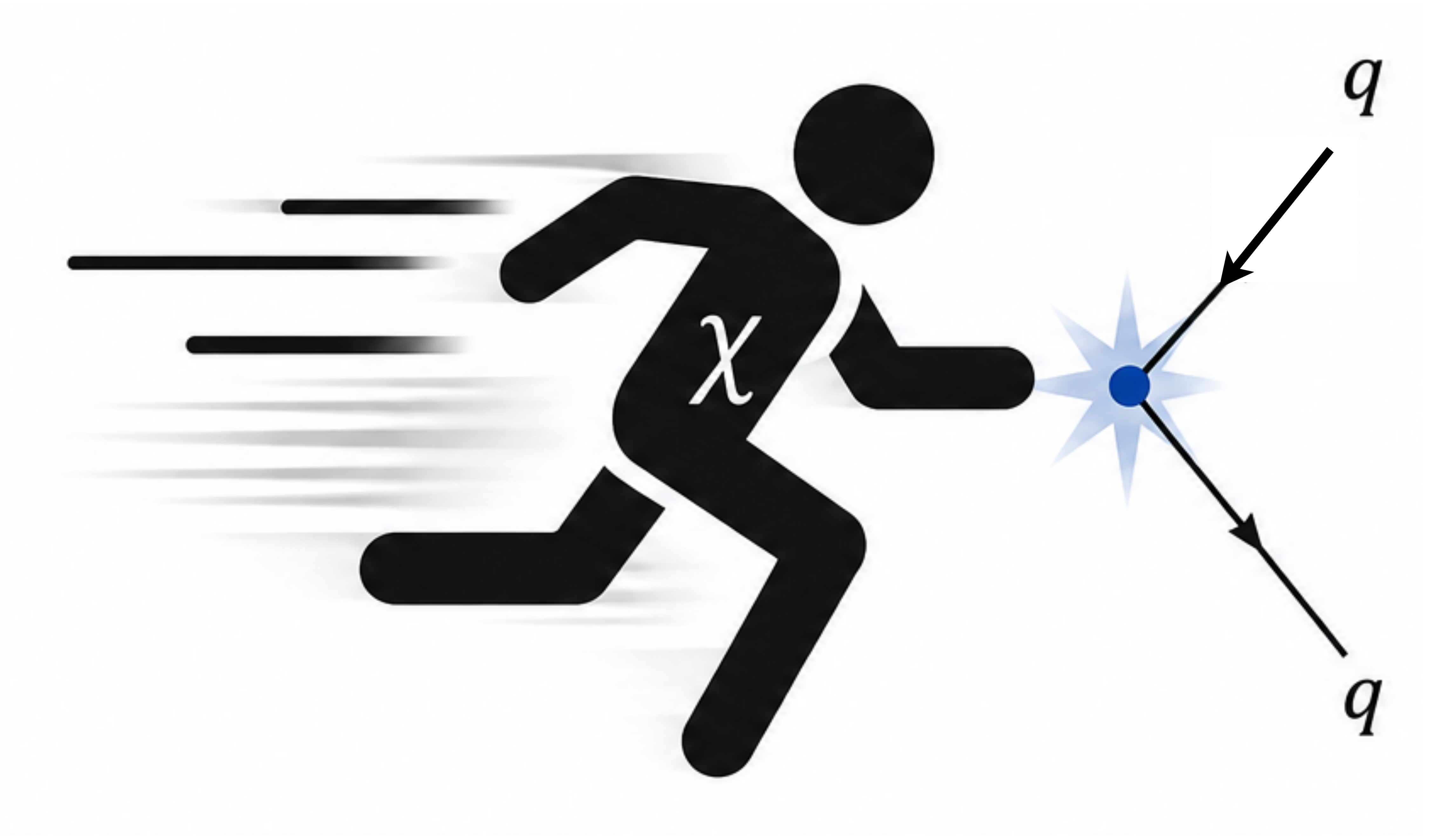


But… Further model-dependent constraints on Z' mediators from meson decays, by collider experiments, feasibility of UV completion etc.

Way forward?

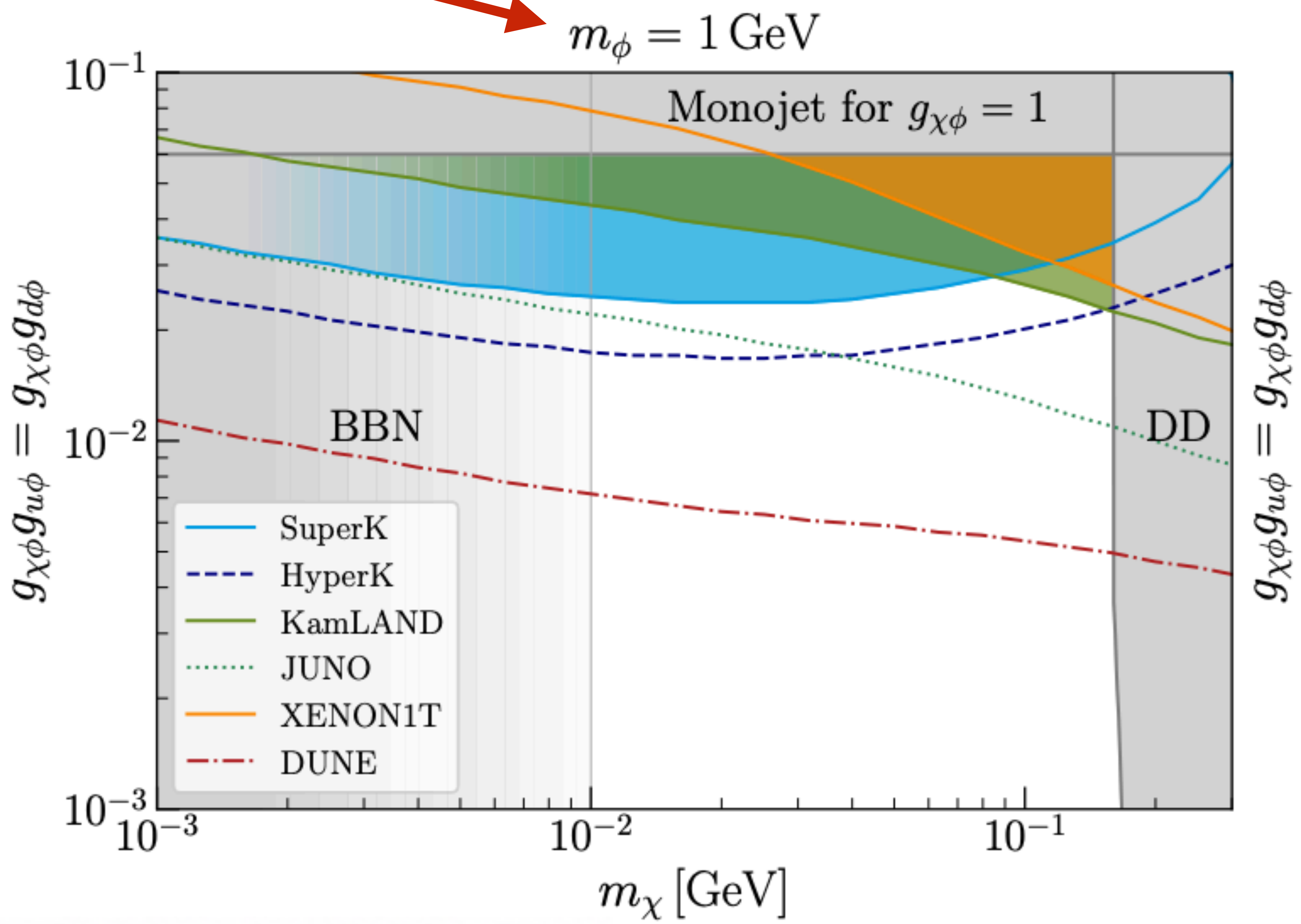


[ChatGPT]

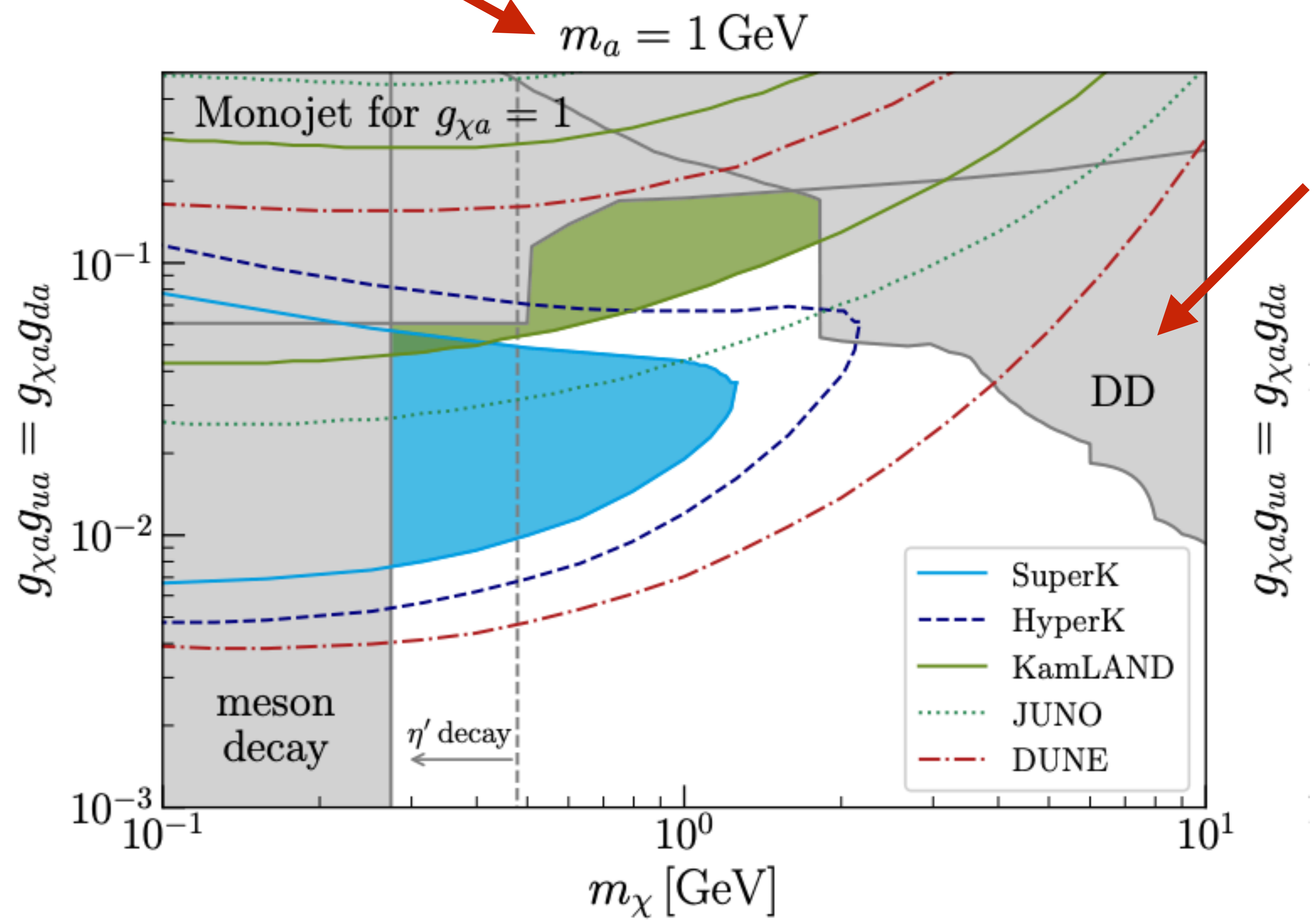
(Pseudo)scalar mediators more favourable?

[Ema, Sala, Sato: 2011.01939]

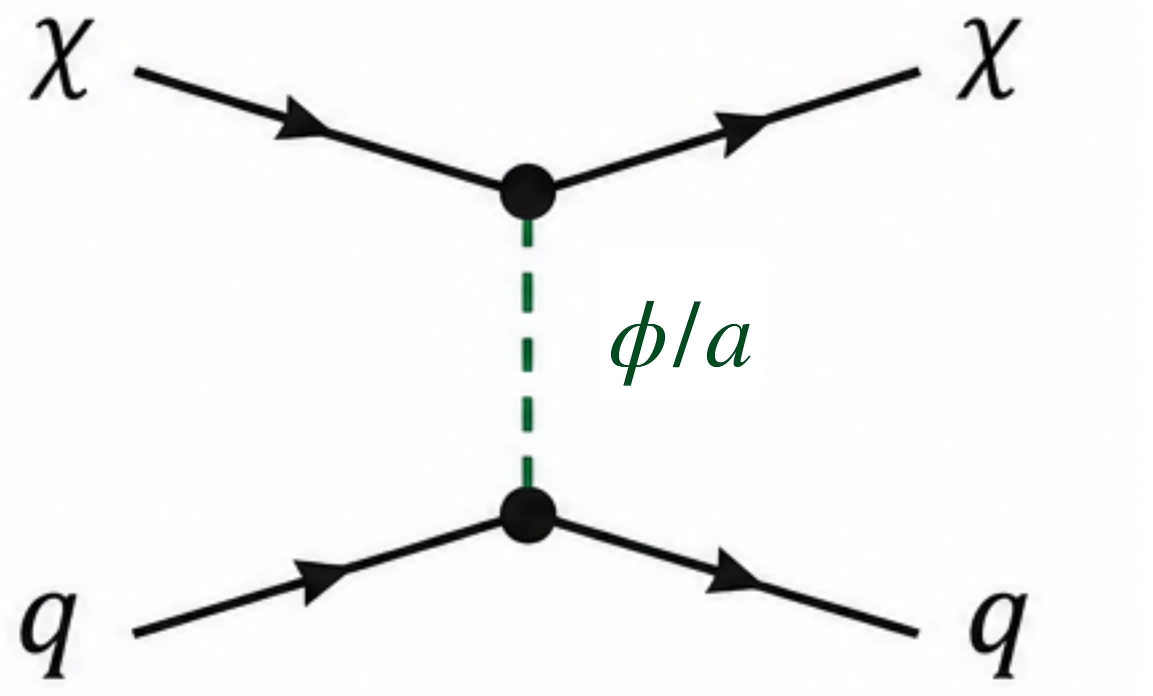
Scalar mediator



Pseudo-scalar mediator



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



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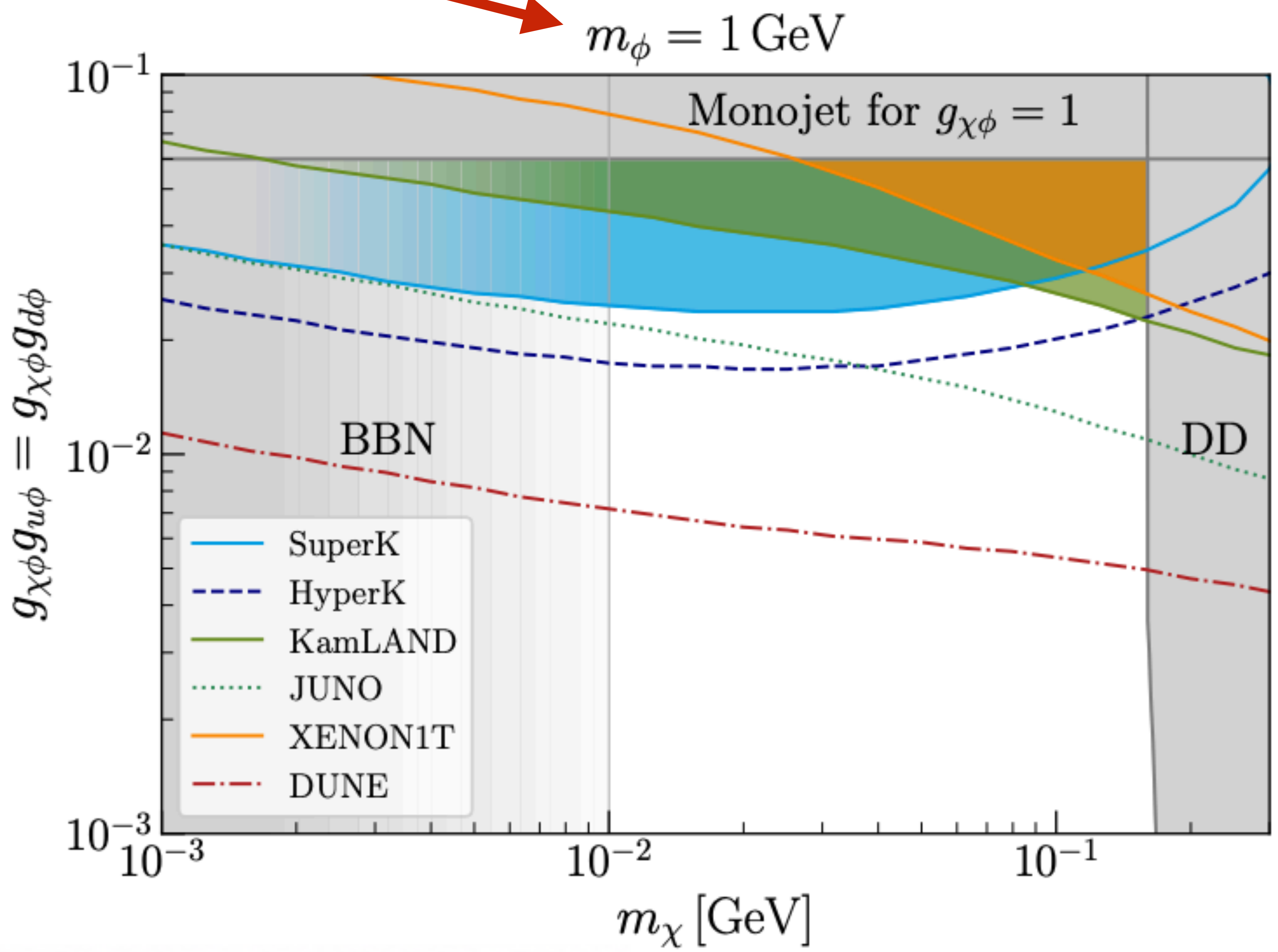
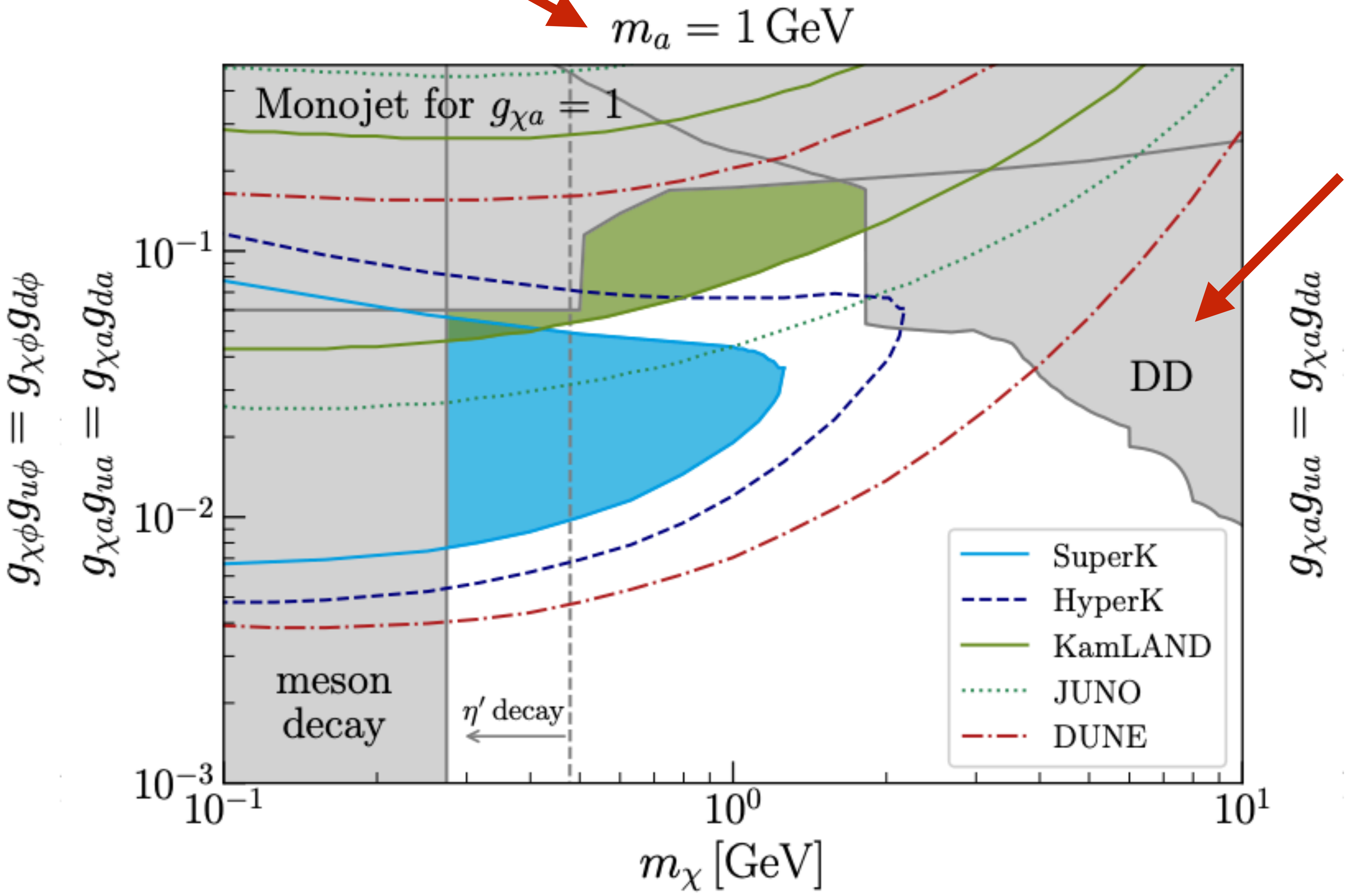


Pseudo-scalar mediator



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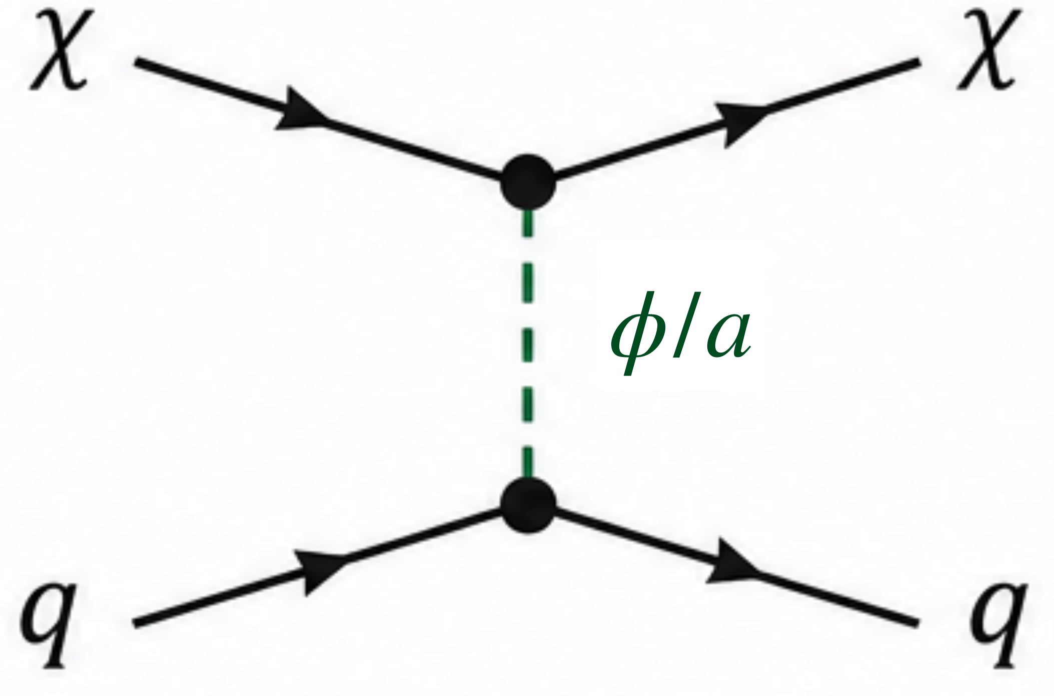


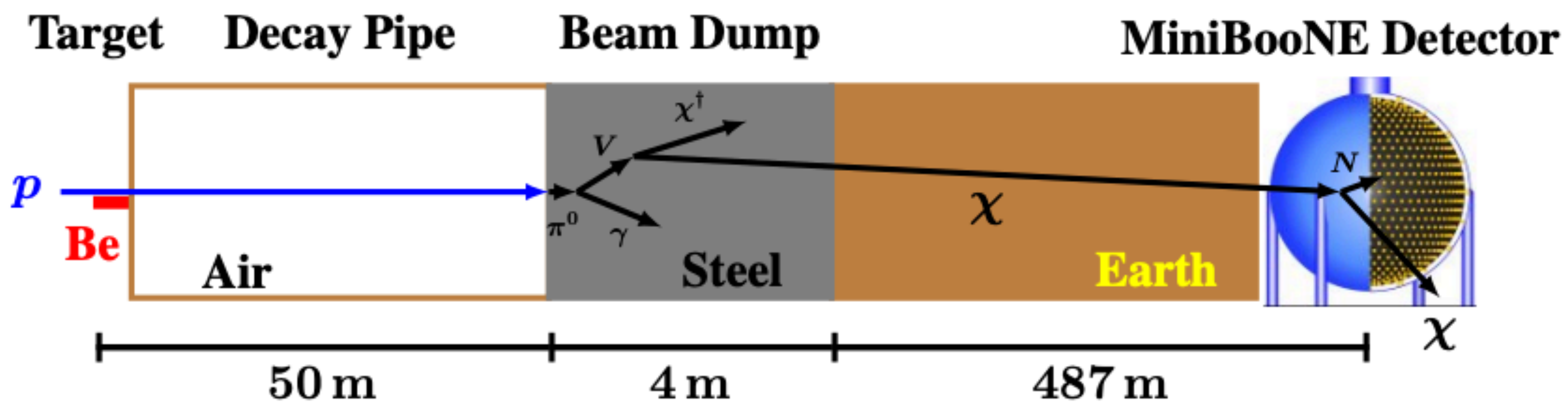
But numerical implementation of inelastic dark matter-nucleus cross sections missing as far as I know & nucleon form factors not known very well!*

*see talk by Jose Manuel Alarcón

Other mechanisms for accelerating dark matter?

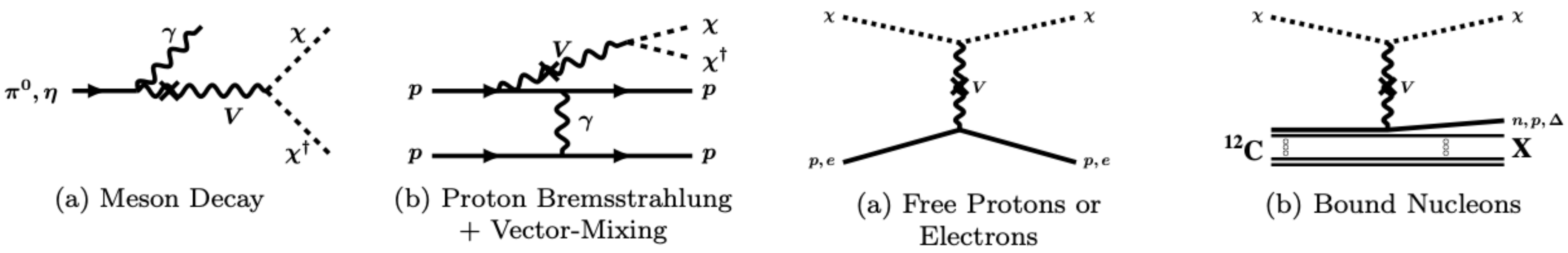
Relativistic dark matter can be produced in beam dumps and later detected!

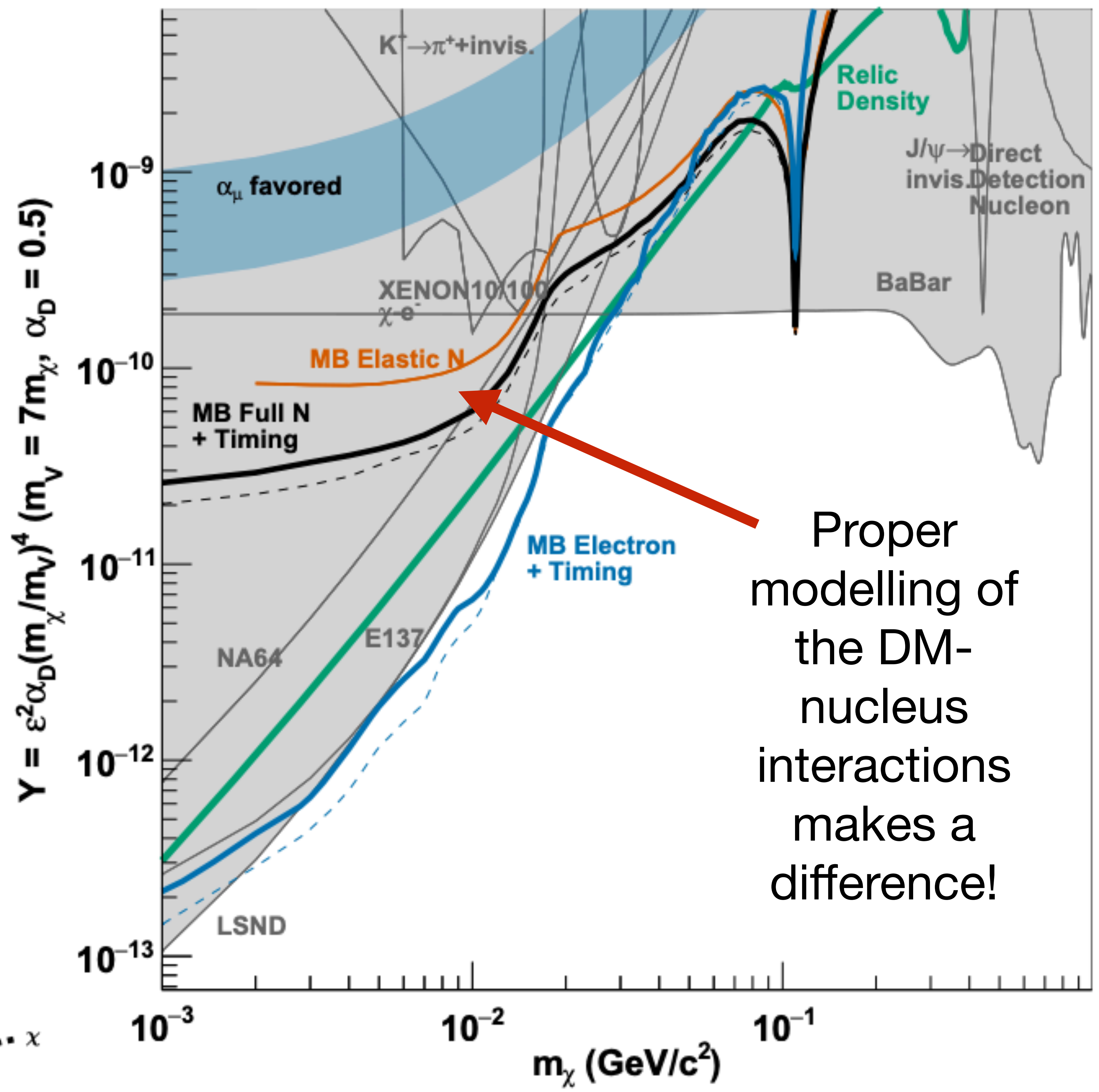
[MiniBooNE-DM Collaboration: 1807.06137]



Dark matter production:

Dark matter detection:





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

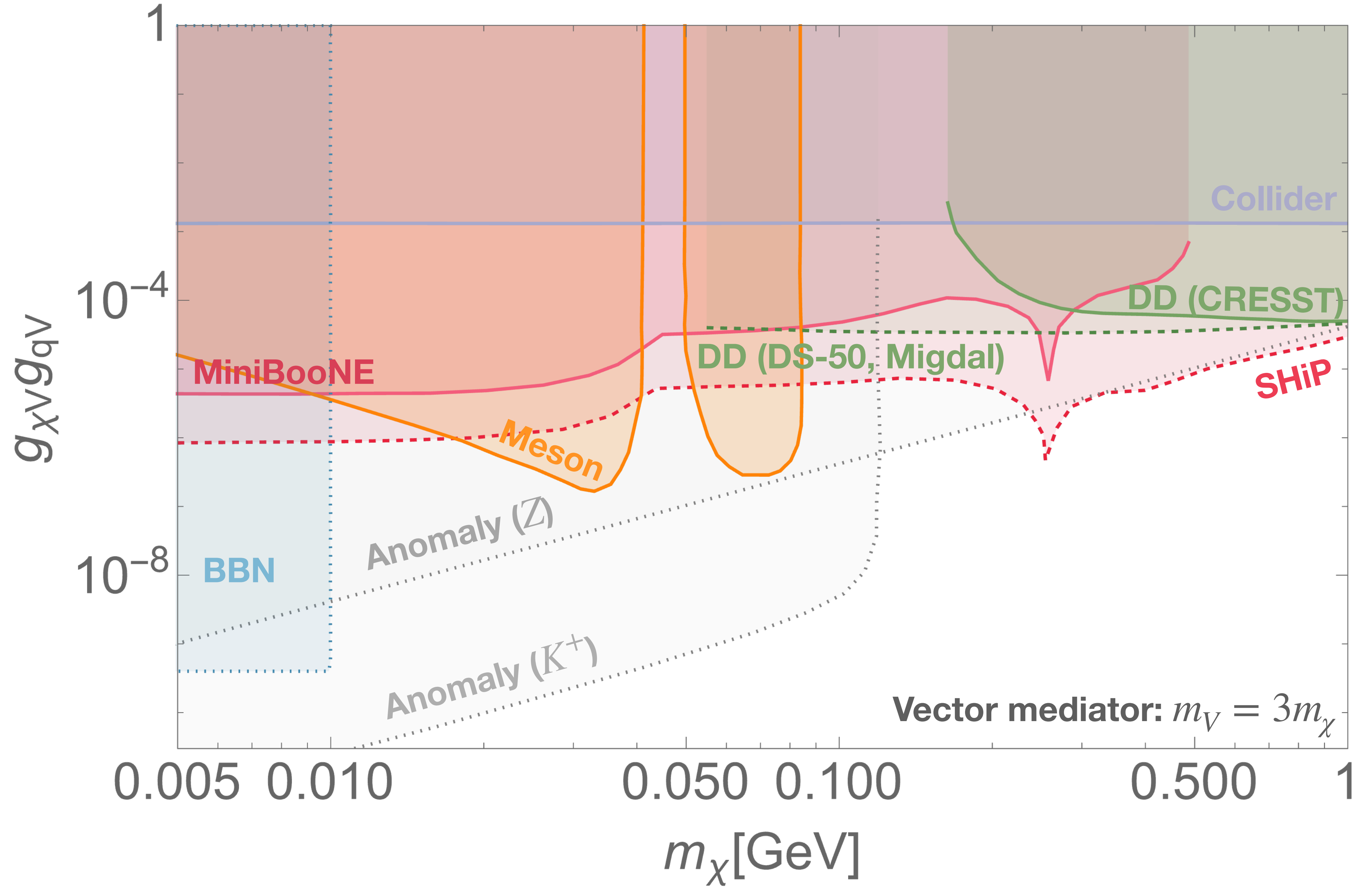
Proper modelling of the DM-nucleus interactions makes a difference!

Other mechanisms for accelerating dark matter?

Relativistic dark matter can be produced in beam dumps and later detected!

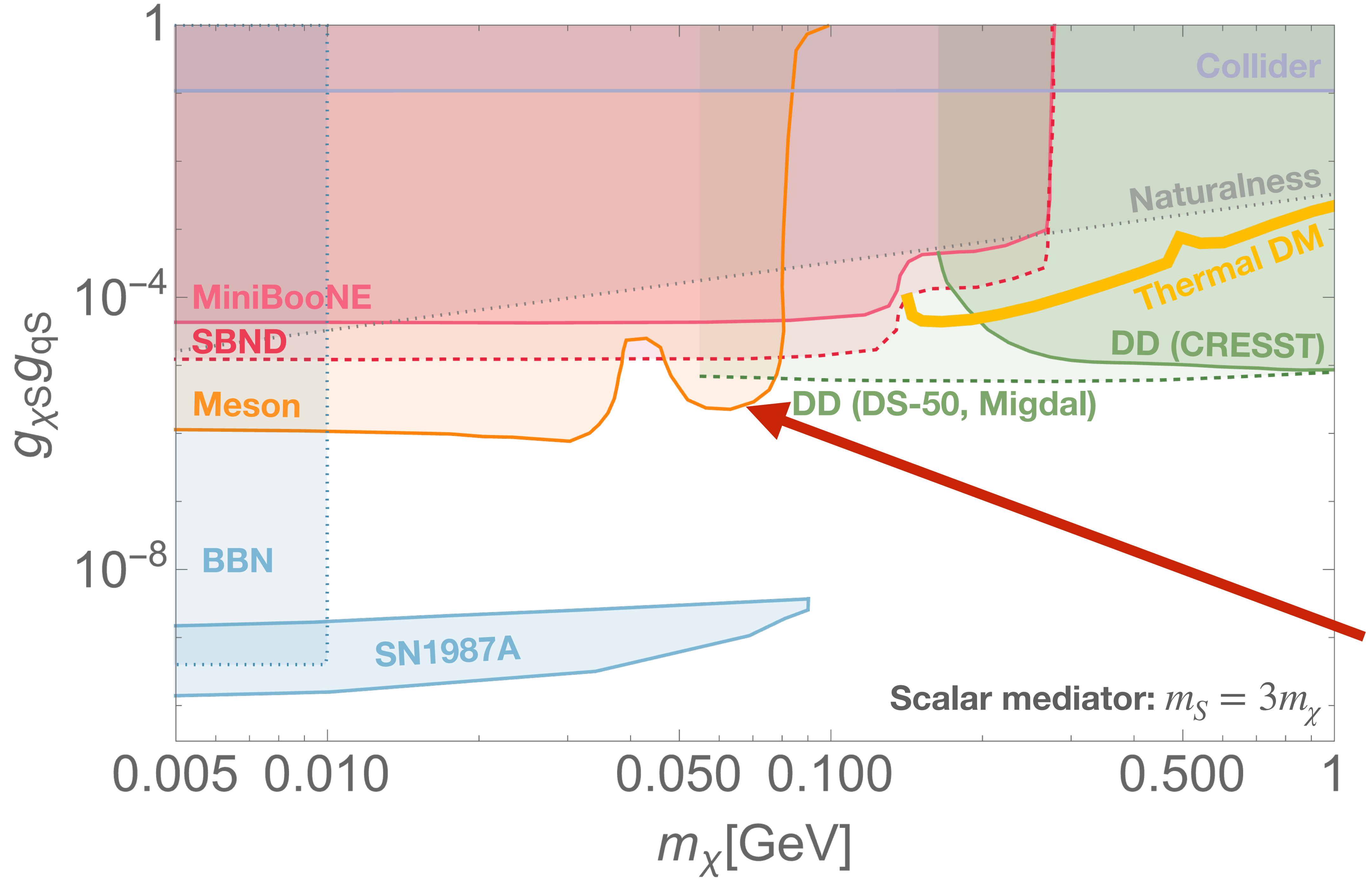
$U(1)_B$ vector meson

[deNiverville, Chen, Pospelov, Ritz: 1609.01770]



u-phylic scalar mediator

[Batell, Freitas, Ismailand, Mckeen: 1812.05103]



Meson decay bounds are model dependent (sensitive to couplings of individual quarks)

Leading bounds on invisibly decaying mediators can be obtained by SHiP* or SBND!**

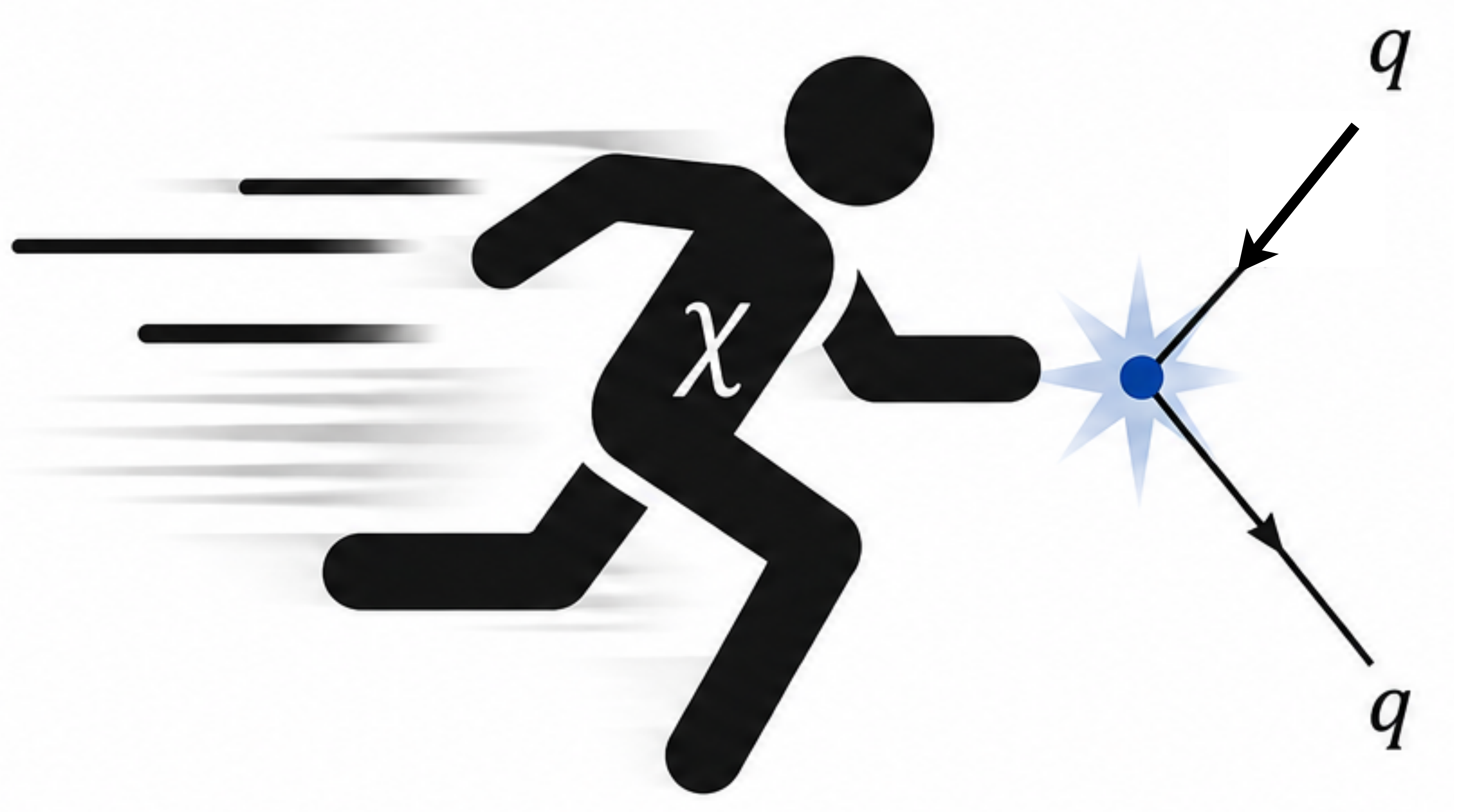
* depending on the detector design

* SHiP talk by Richard Jacobsson on Thursday!

** if beam dump run performed

Conclusions

- Accelerated dark particles can be probed by neutrino detectors like DUNE
  - ✴ Sensitivity to sub-GeV dark matter
  - ✴ Based on scattering with nucleons or partons ⇒ comparable bounds for SI and SD interactions
- Interactions of “fast” dark matter with nuclei harder to model, tools for scalar/pseudoscalar mediators missing as far as I know. NB: relevant also for non-standard neutrino interactions [Kopp, Rocco, Tabrizi: 2401.07902]
- Further promising setups where accelerated dark matter could be detected?



Conclusions

- Accelerated dark particles can be probed by neutrino detectors like DUNE

    - Sensitivity to sub-GeV dark matter

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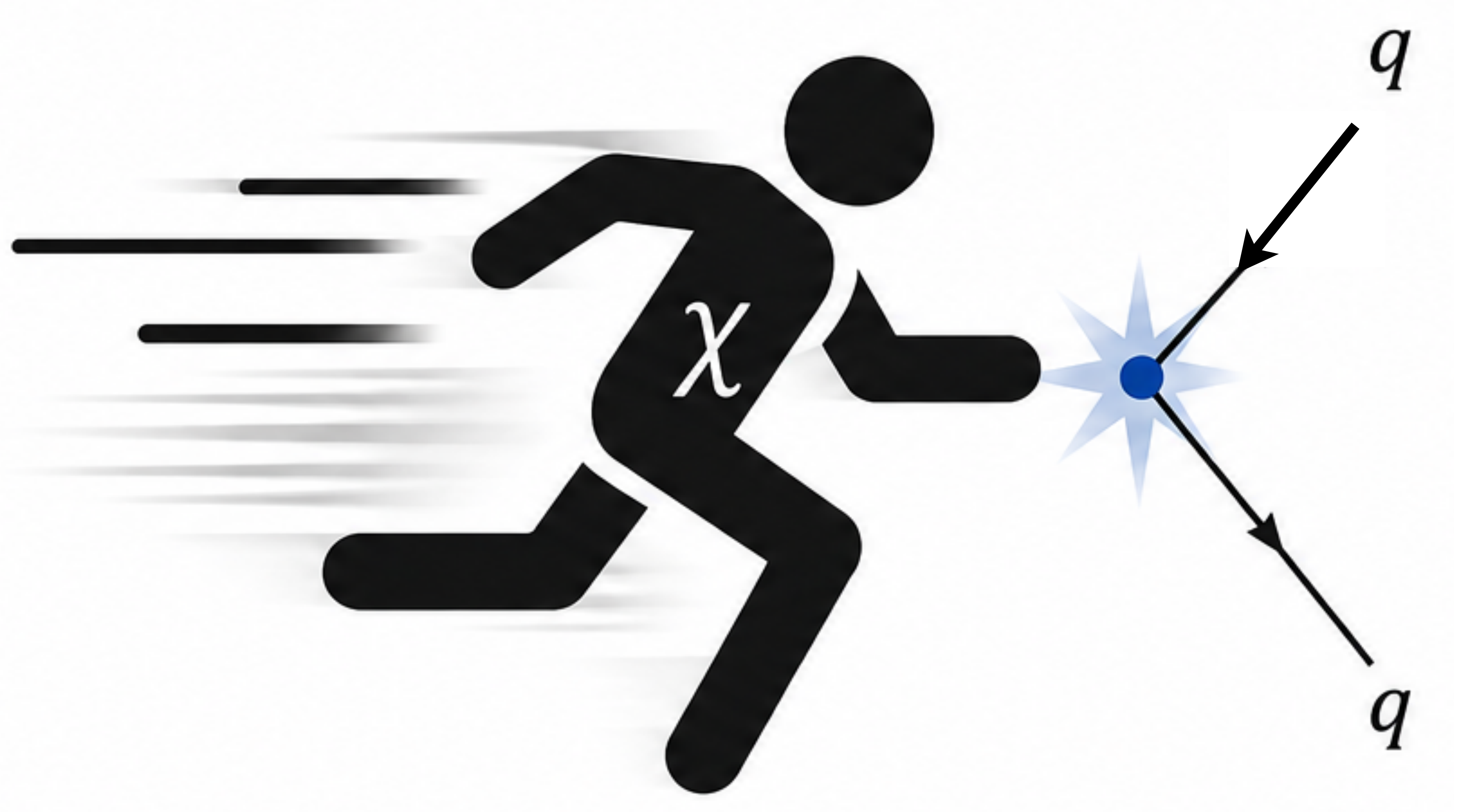


Thank you for attention!

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 particle mass ⇒ irrelevant for neutrino NC scattering. Related to F_A by Ward identities.

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.

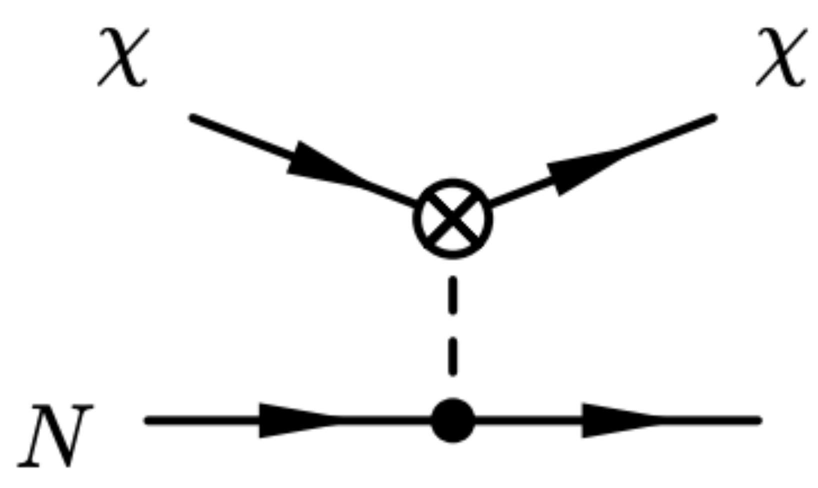
$$\frac{F_P^{u|N} - F_P^{d|N}}{F_A^{u|N} - F_A^{d|N}} = \frac{4\,M_N^2}{M_\pi^2 + Q^2}, \qquad \frac{F_P^{u|N} + F_P^{d|N} - 2\,F_P^{s|N}}{F_A^{u|N} + F_A^{d|N} - 2\,F_A^{s|N}} = \frac{4\,M_N^2}{M_\eta^2 + Q^2}. \tag{33}$$

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

This does not correspond to the structure expected from chiral perturbation theory, $F_P^{s|N}$ should include a non-vanishing contribution by the η pole

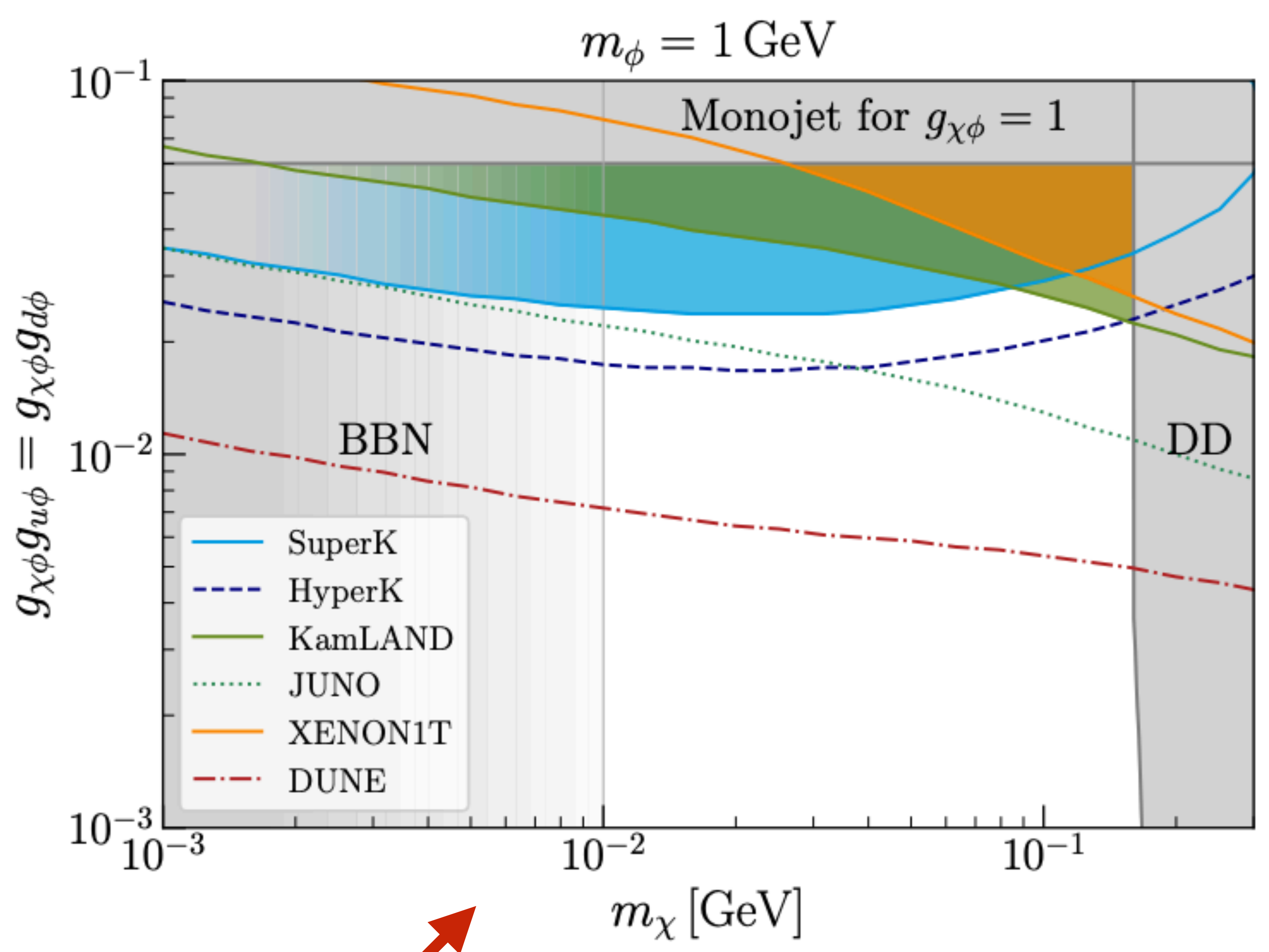
[Bishara et al.: 1707.06998]
[Hoferichter et al.: 2007.08529]

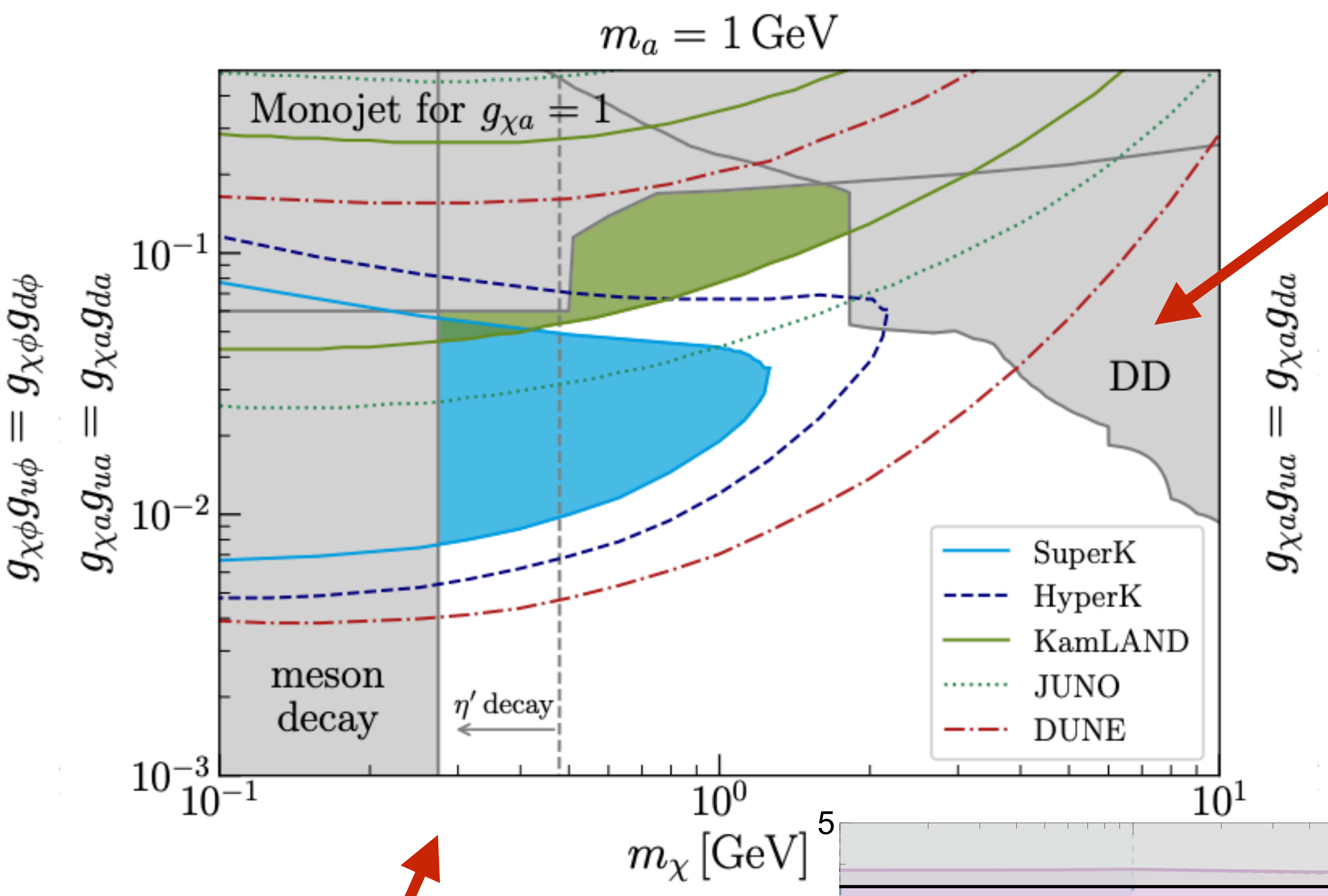
NB: For a lattice study, see, e.g., [Alexandrou et al.:1705.03399].
In the $u - d$ channel, the pion pole indeed reproduced. Nonzero value of $F_P^{s|N}$ observed.



Scalar mediator more favourable?

[Ema, Sala, Sato: 2011.01939]





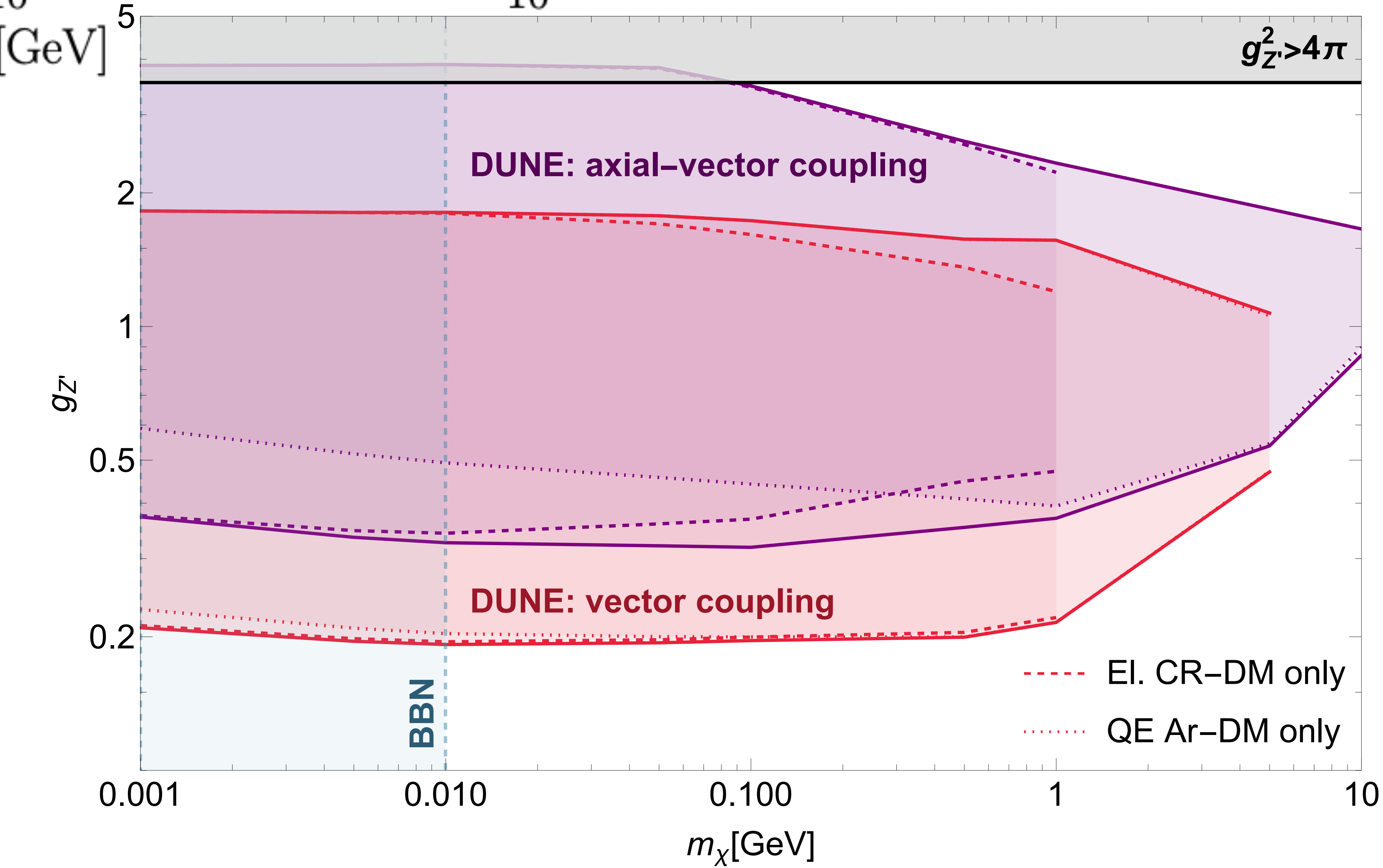
NB: Direct detection limits much weaker for pseudo-scalar case due to velocity-suppressed low-energy interactions!

Scalar mediator

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

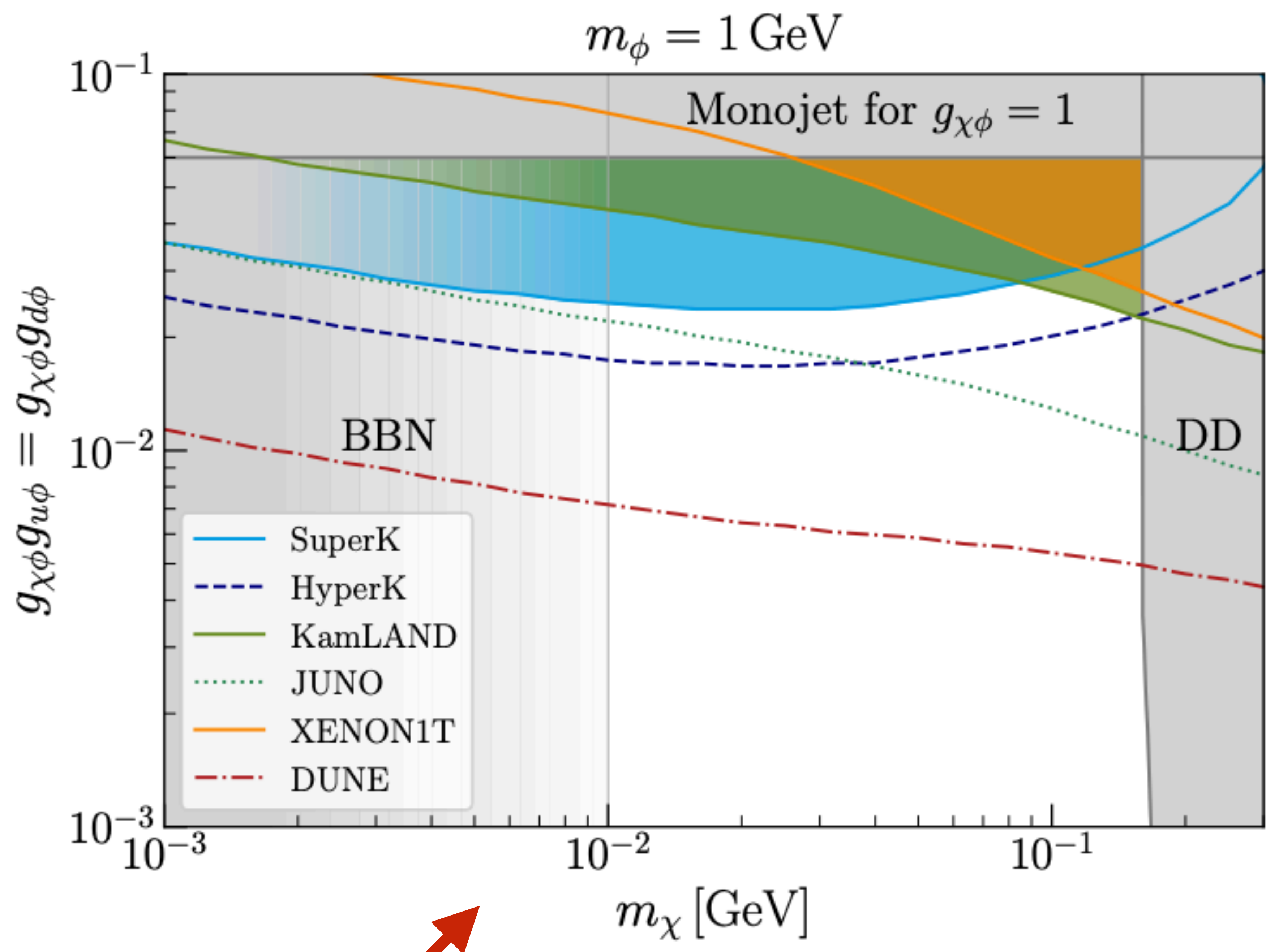
Pseudo-scalar mediator

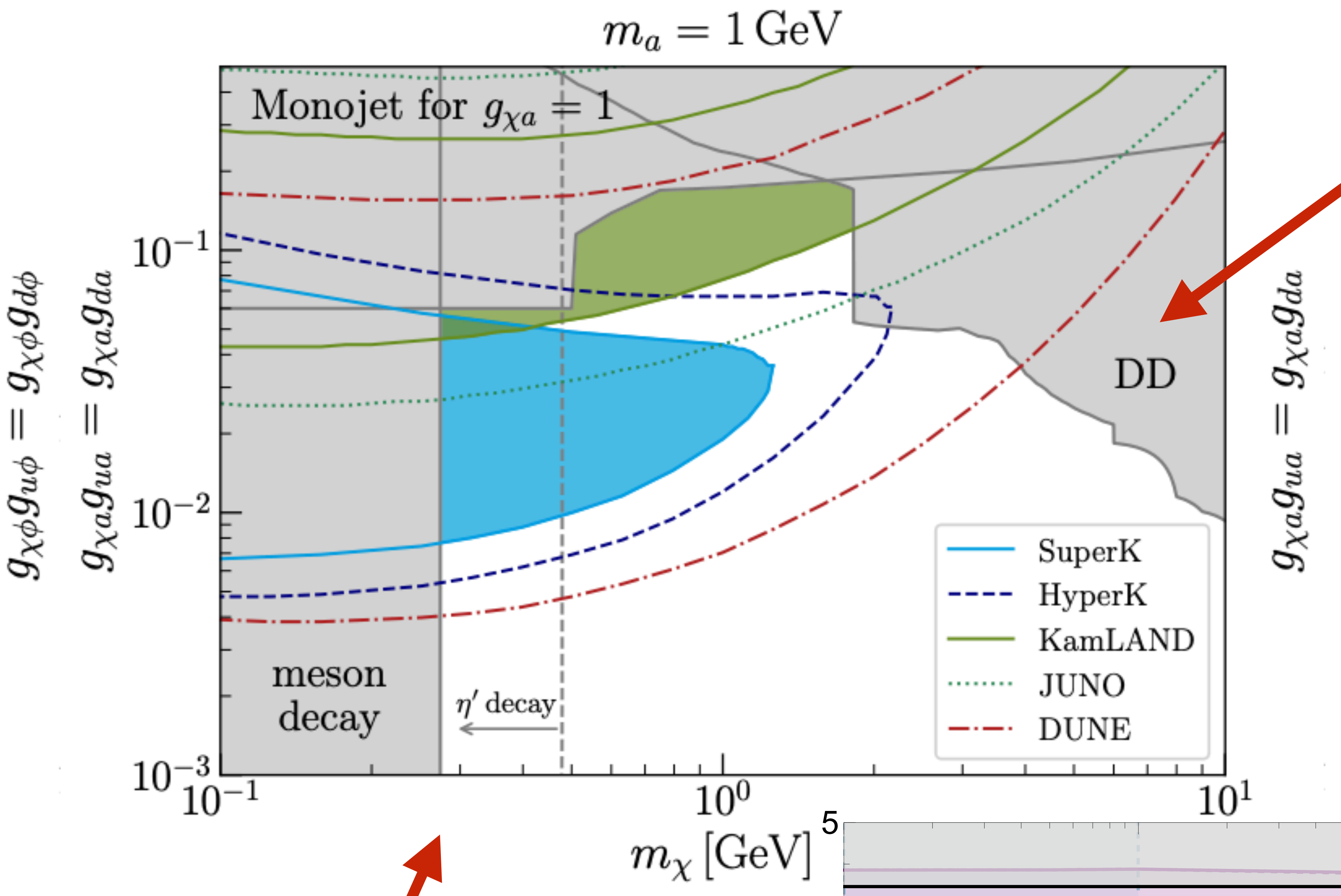
$$g_{Na} = g_a \underbrace{\frac{2 m_N}{m_u + m_d} h_{u+d}}_{\sim 120}$$



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!

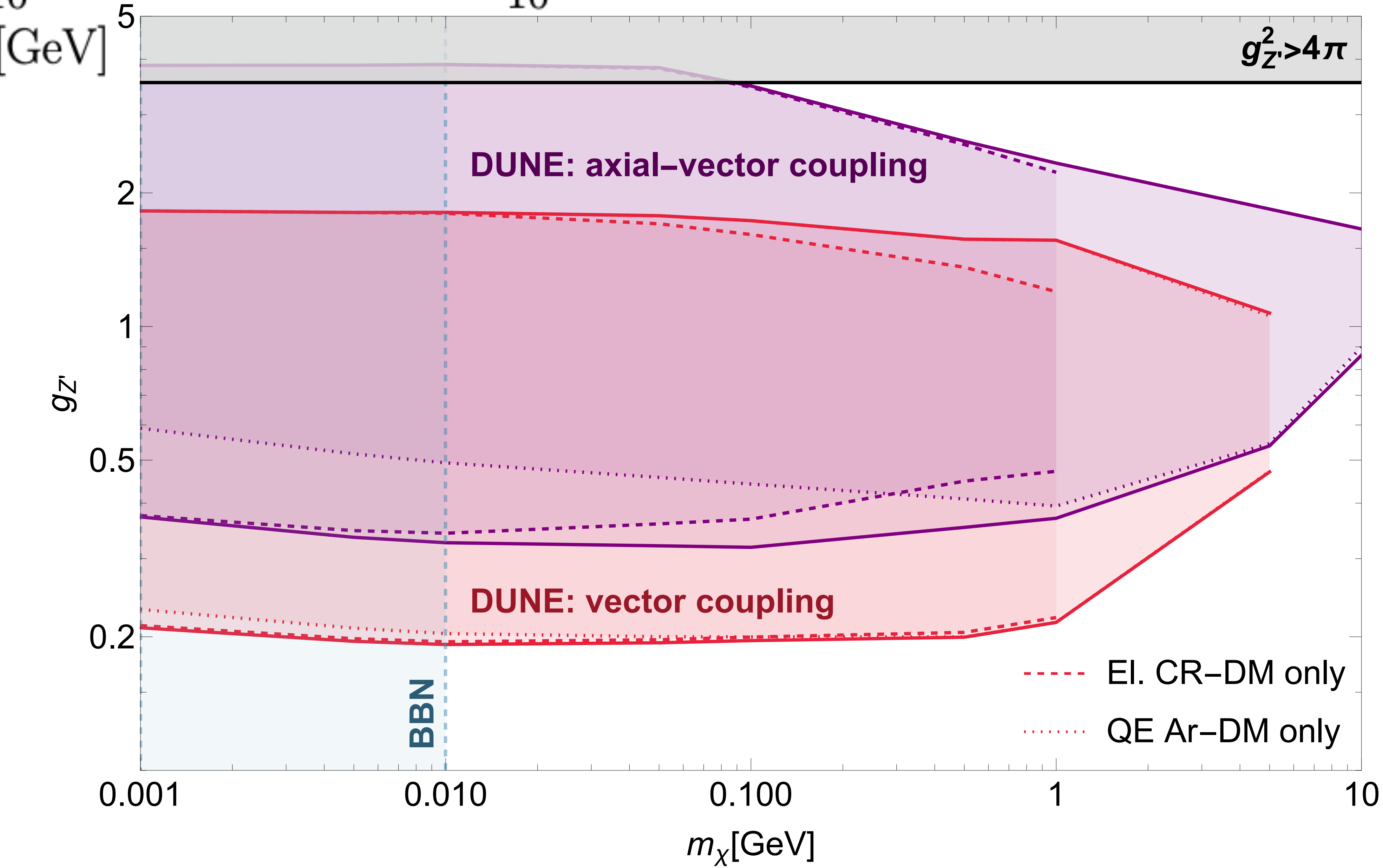
Scalar mediator

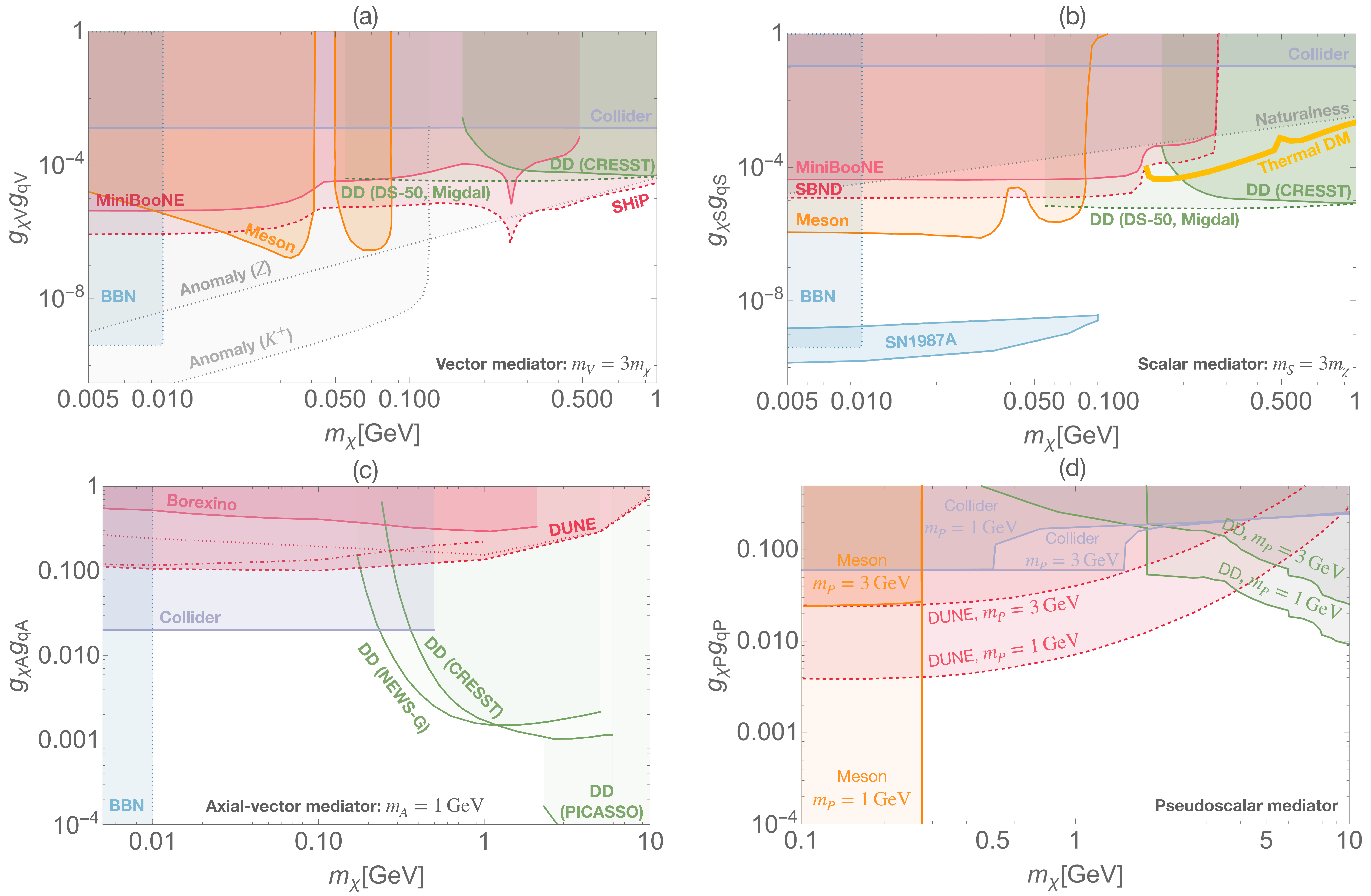
$$g_{N\phi} = g_\phi \underbrace{\left(\frac{m_N}{m_u} f_u^N + \frac{m_N}{m_d} f_d^N\right)}_{\sim 30}$$

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

Pseudo-scalar mediator

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

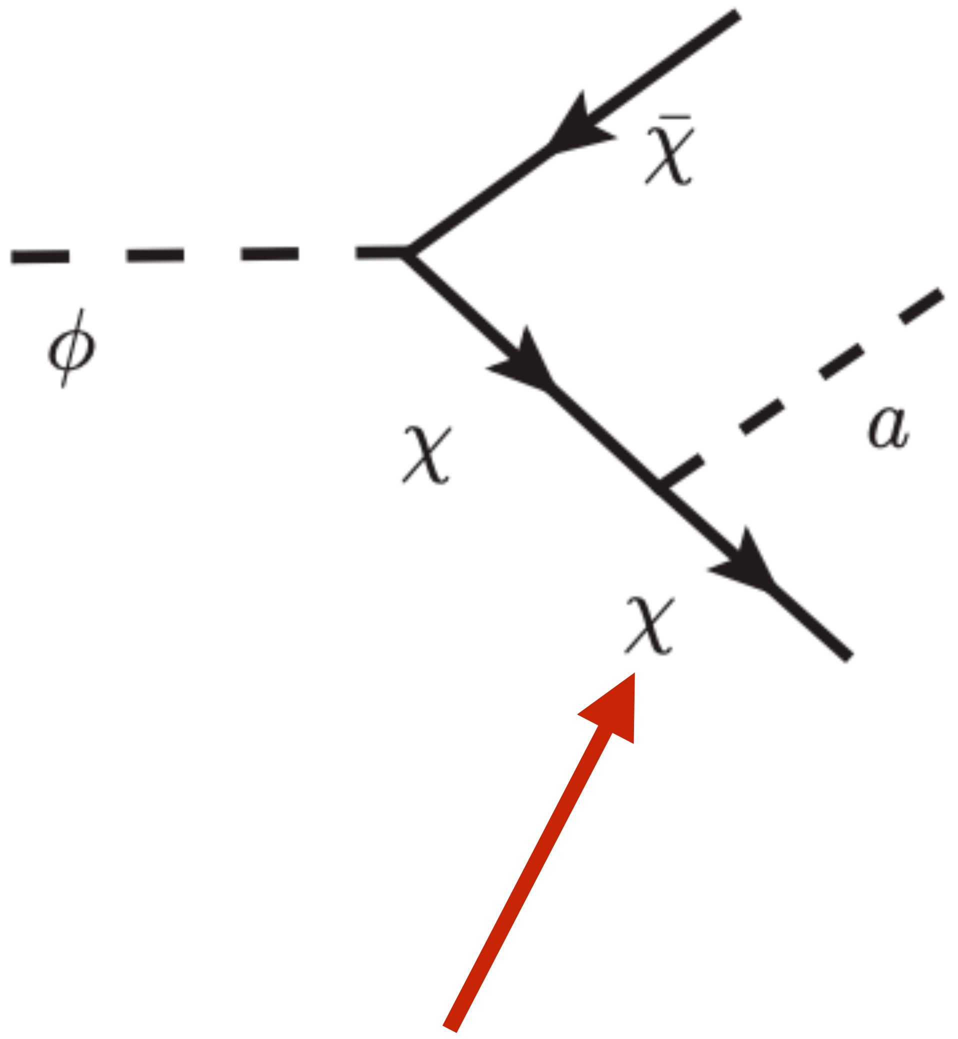




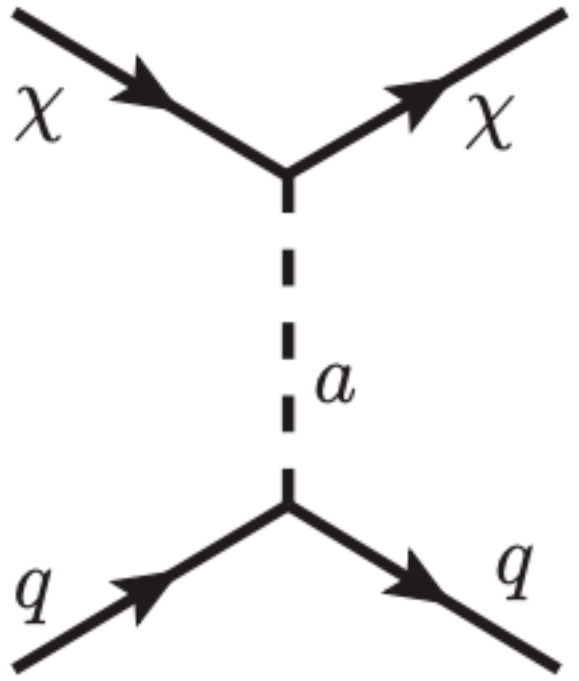
(a)
Collider
DD (CRESST)
DD (DS-50, Migdal)
MiniBooNE
SHiP
Meson
BBN
Anomaly (Z)
Anomaly (K^+)
Vector mediator: $m_V = 3m_\chi$
$g_{\chi V}g_{qV}$
m_χ[GeV]
(b)
Collider
Naturalness
Thermal DM
MiniBooNE
SBND
Meson
DD (CRESST)
DD (DS-50, Migdal)
BBN
SN1987A
Scalar mediator: $m_S = 3m_\chi$
$g_{\chi S}g_{qS}$
m_χ[GeV]
(c)
Borexino
DUNE
Collider
DD (NEWS-G)
DD (CRESST)
DD (PICASSO)
BBN
Axial-vector mediator: $m_A = 1\,\mathrm{GeV}$
$g_{\chi A}g_{qA}$
m_χ[GeV]
(d)
Collider $m_P = 1\,\mathrm{GeV}$
Collider $m_P = 3\,\mathrm{GeV}$
Meson $m_P = 3\,\mathrm{GeV}$
DUNE, $m_P = 3\,\mathrm{GeV}$
DUNE, $m_P = 1\,\mathrm{GeV}$
DD, $m_P = 3\,\mathrm{GeV}$
DD, $m_P = 1\,\mathrm{GeV}$
Meson $m_P = 1\,\mathrm{GeV}$
Pseudoscalar mediator
$g_{\chi P}g_{qP}$
m_χ[GeV]

Accelerated dark particles

Another example: 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]

[Snowmass (2013): 1401.6077]