Non-perturbative Effect on Fermionic DM Electromagnetic Dipole Moments

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arXiv: 2312.xxxxx

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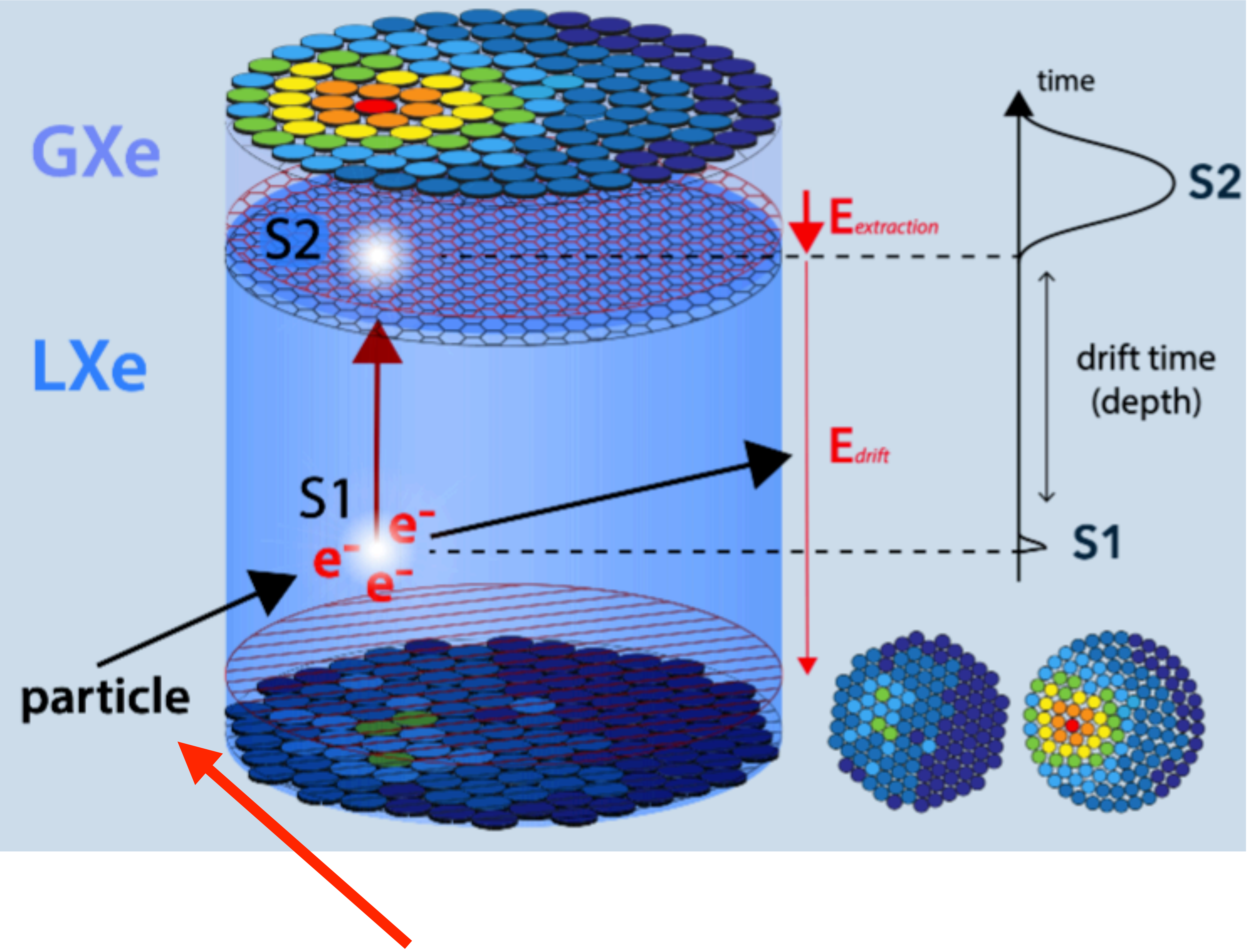
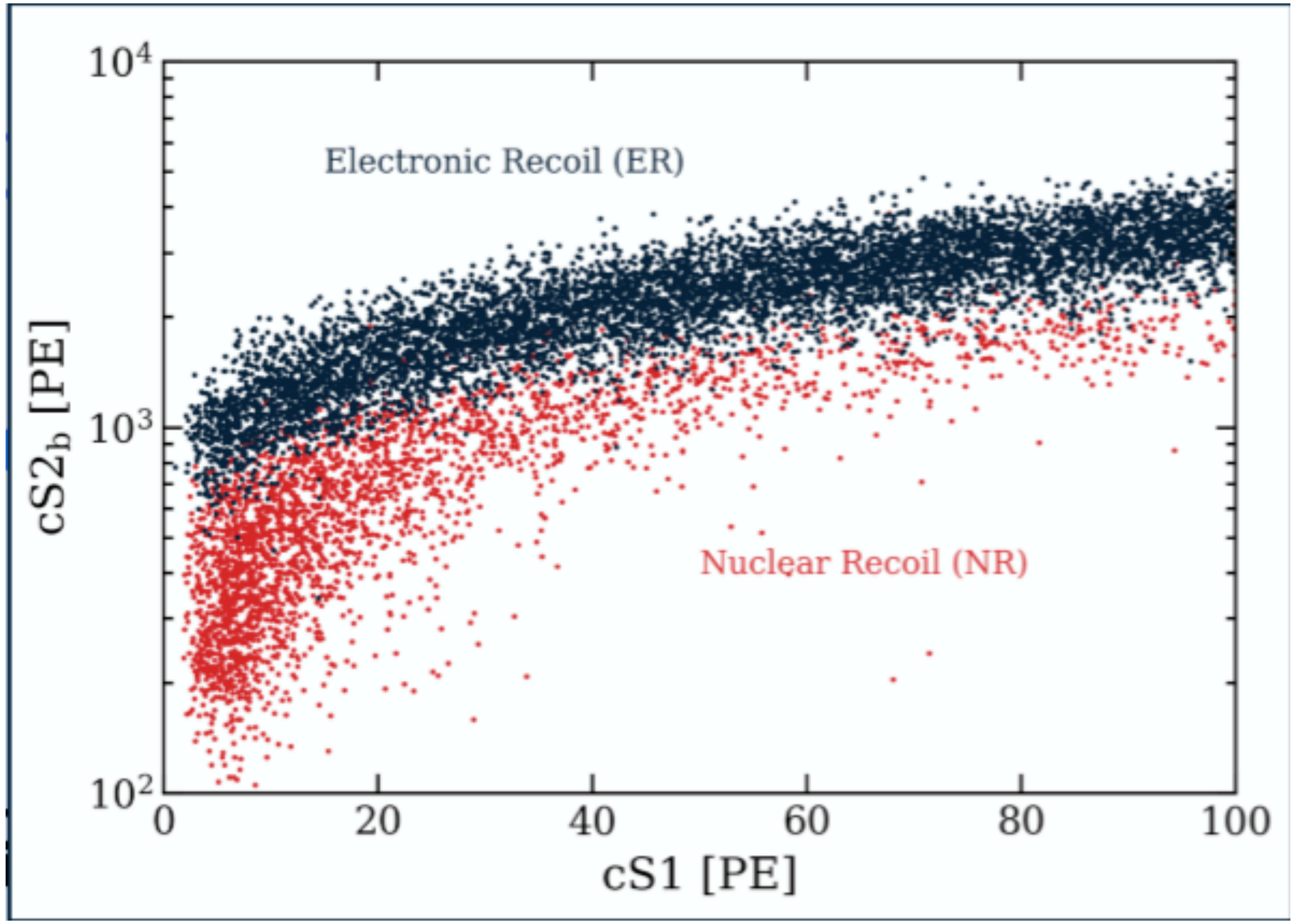
ER and NR signals at DM direct detection (DMDD) experiments

Two phase xenon detector

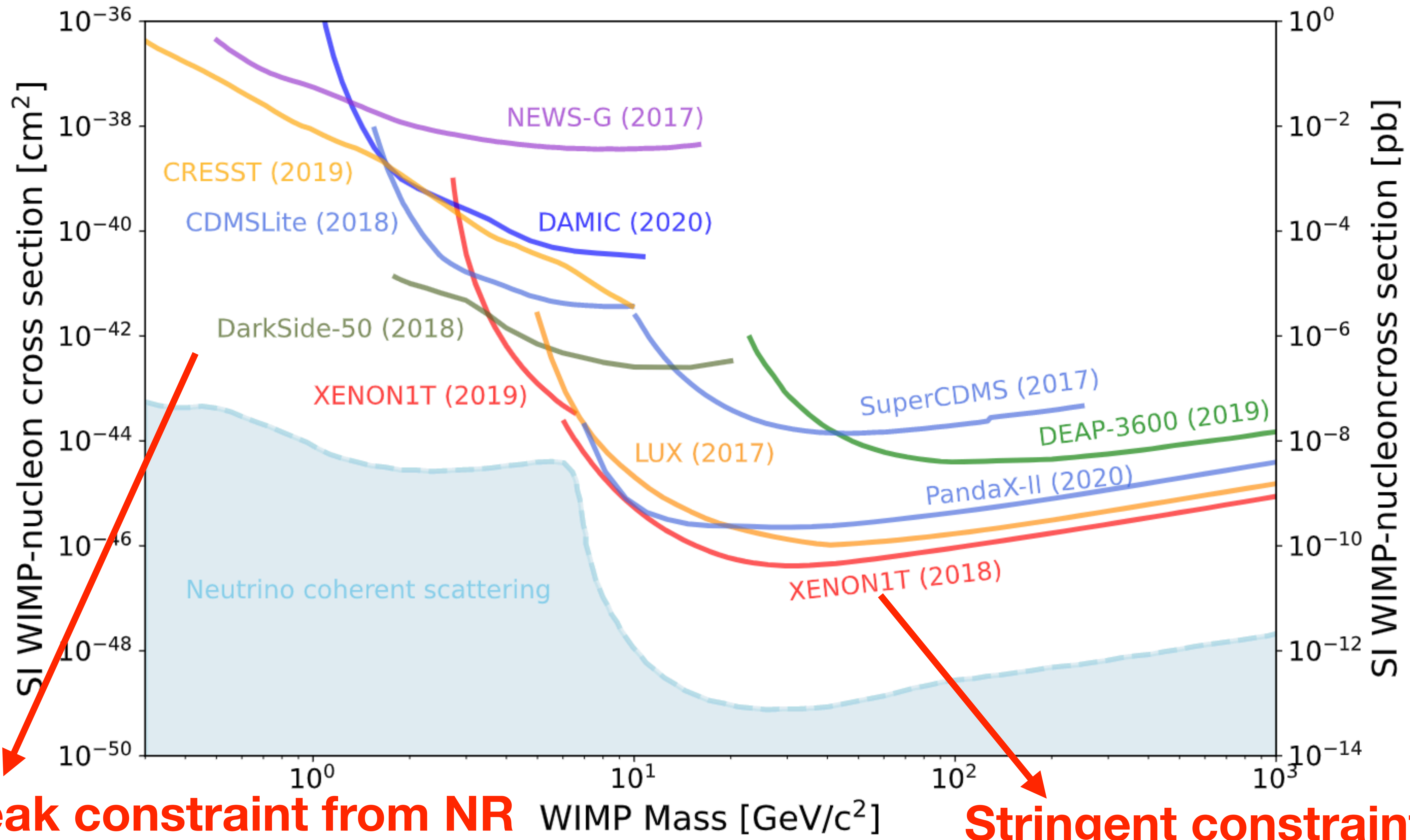




WIMP, $\rho \simeq 0.3\ \mathrm{GeV/cm^3}, v \simeq 10^{-3}c$

Talk of Evan Shockley, 2020

Current constraints on DM-nucleon interaction



Weak constraint from NR

Constrained by ER via DM-electron interaction

Stringent constraint

at $m_\chi \simeq m_{\rm Xe} \simeq 130$ GeV

PDG2020

DM-Nucleon operators for NR signal

$N = n, p$

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2\, \mathbb{1}_\chi \mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\, \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right), \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N\,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi\, (\vec{S}_N \cdot \vec{v}_\perp)\,, \qquad \mathcal{O}_8^N = (\vec{S}_\chi \cdot \vec{v}_\perp)\, \mathbb{1}_N\,,$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right), \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right),$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right),$$

$$\mathcal{O}_{13}^N = -\left(\vec{S}_\chi \cdot \vec{v}_\perp\right)\left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right), \qquad \mathcal{O}_{14}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}_\perp\right),$$

$$\mathcal{O}_{15}^N = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left((\vec{S}_N \times \vec{v}_\perp) \cdot \frac{\vec{q}}{m_N}\right)$$

Anand, Fitzpatrick, Haxton,1308.6288

DM-quark and DM-gluon EFT operators

Dim-6 operators

$$\mathcal{Q}_{1,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu q)\,, \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu q)\,,$$

$$\mathcal{Q}_{3,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu\gamma_5 q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q)\,,$$

Dim-7 operators

$$\mathcal{Q}_{1}^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi\chi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_{2}^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$

$$\mathcal{Q}_{3}^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,, \qquad \mathcal{Q}_{4}^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$

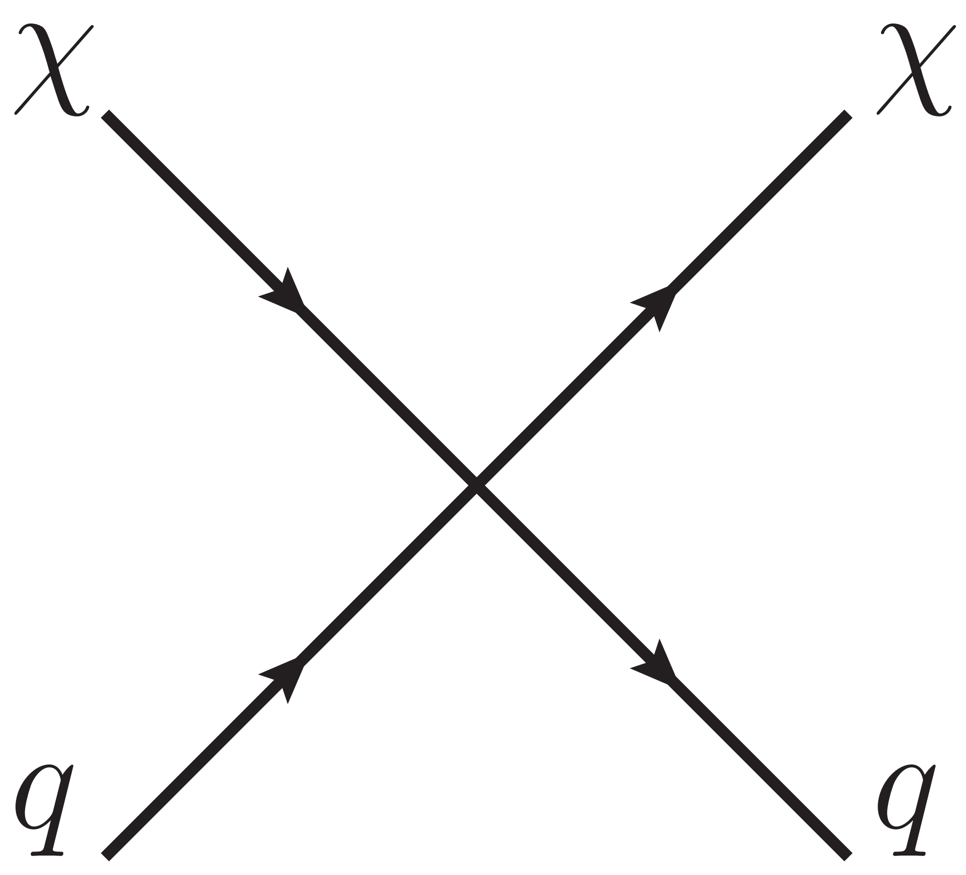
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\bar\chi\chi)(\bar q q)\,, \qquad \mathcal{Q}_{6,q}^{(7)} = m_q(\bar\chi i\gamma_5\chi)(\bar q q)\,,$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\bar\chi\chi)(\bar q i\gamma_5 q)\,, \qquad \mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi i\gamma_5\chi)(\bar q i\gamma_5 q)\,,$$

$$\mathcal{Q}_{9,q}^{(7)} = m_q(\bar\chi\sigma^{\mu\nu}\chi)(\bar q\sigma_{\mu\nu} q)\,, \qquad \mathcal{Q}_{10,q}^{(7)} = m_q(\bar\chi i\sigma^{\mu\nu}\gamma_5\chi)(\bar q\sigma_{\mu\nu} q)\,.$$

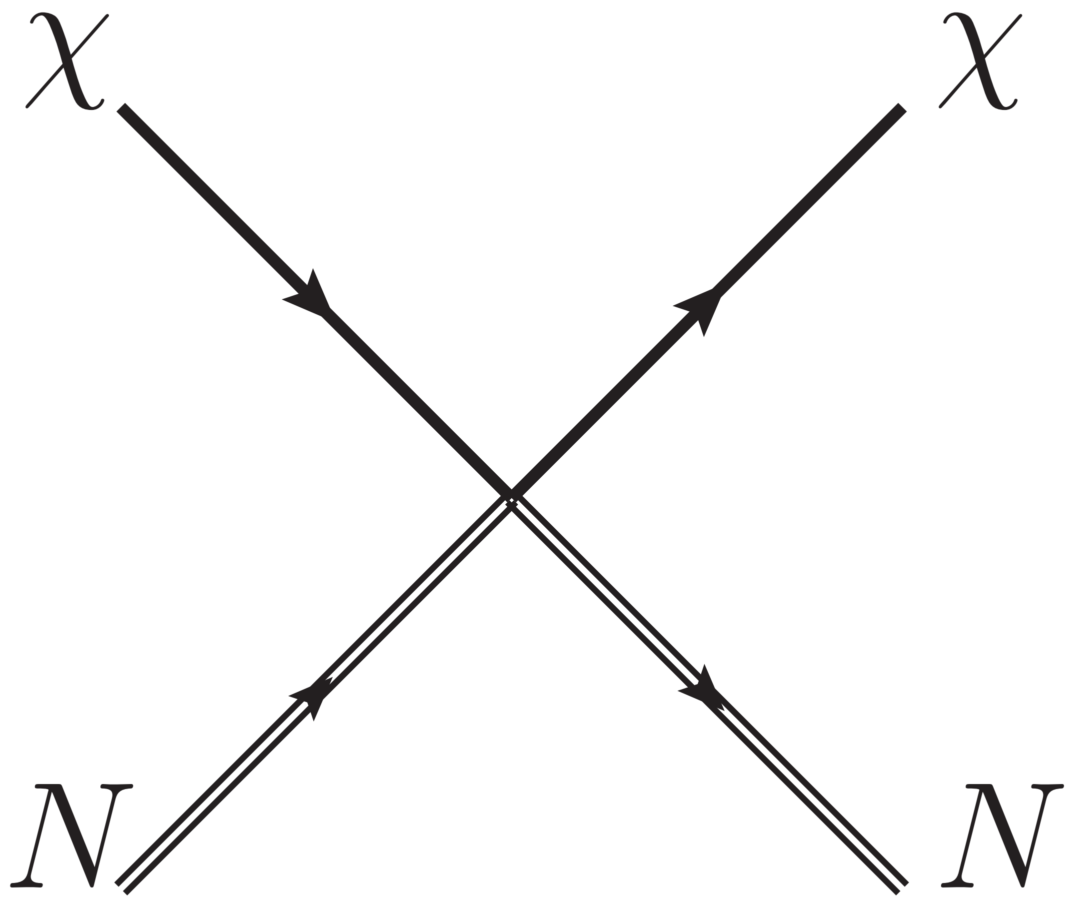
Bishara, Brod, Grinstein, Zupan, 1707.06998

Matching via ChPT



ChPT

$q_{\max} \lesssim 200\ \text{MeV} \ll \Lambda_\chi$ **at DMDD**



$$\mathcal{O}_{\chi q}^{\mathrm{T1}} \equiv m_q \left(\bar{\chi}\sigma^{\mu\nu}\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to 8F_{T,0}^{q/N}\mathcal{O}_4^N$$

$$\mathcal{O}_{\chi q}^{\mathrm{T2}} \equiv m_q \left(\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to \frac{-2m_N}{m_\chi}F_{T,0}^{q/N}\mathcal{O}_{10}^N + 2(F_{T,0}^{q/N} - F_{T,1}^{q/N})\mathcal{O}_{11}^N - 8F_{T,0}^{q/N}\mathcal{O}_{12}^N$$

Bishara, Brod, Grinstein, Zupan, 1707.06998

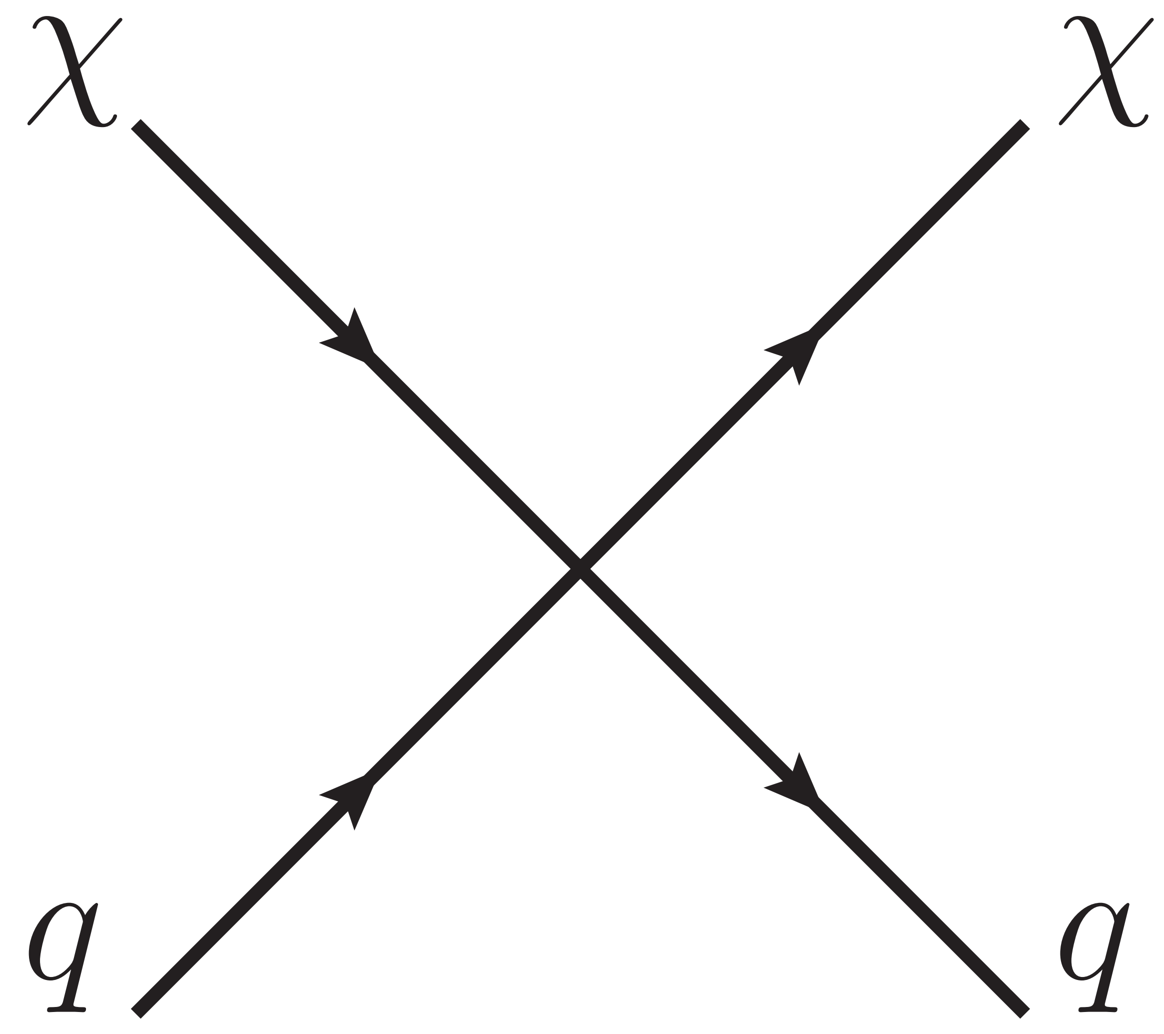
Induce DM dipole moments

MDM $\frac{\mu_\chi}{2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}$

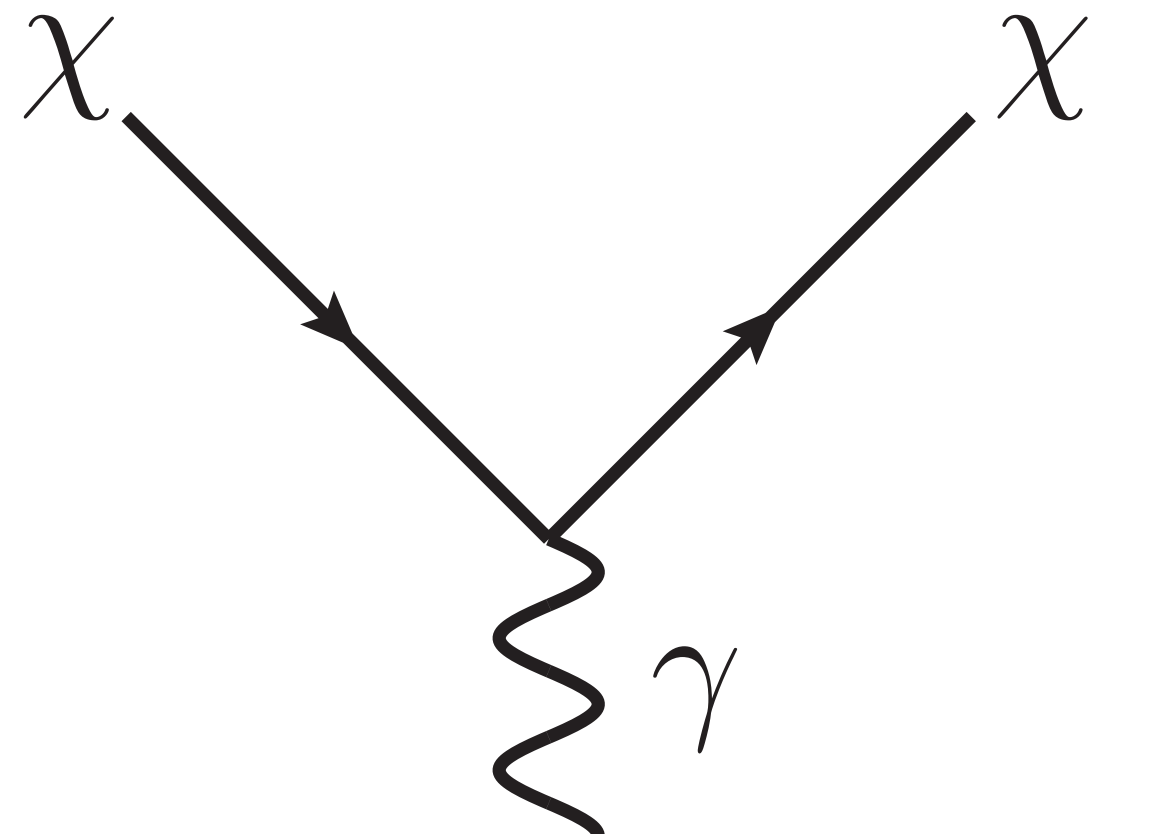
EDM $\frac{d_\chi}{2}(\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi)F_{\mu\nu}$

$$\mathcal{O}^{\rm T1}_{\chi q} = m_q\,(\bar{\chi}\sigma^{\mu\nu}\chi)\,(\bar{q}\sigma_{\mu\nu}q)$$

$$\mathcal{O}^{\rm T2}_{\chi q} = m_q\,(\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi)\,(\bar{q}\sigma_{\mu\nu}q)$$

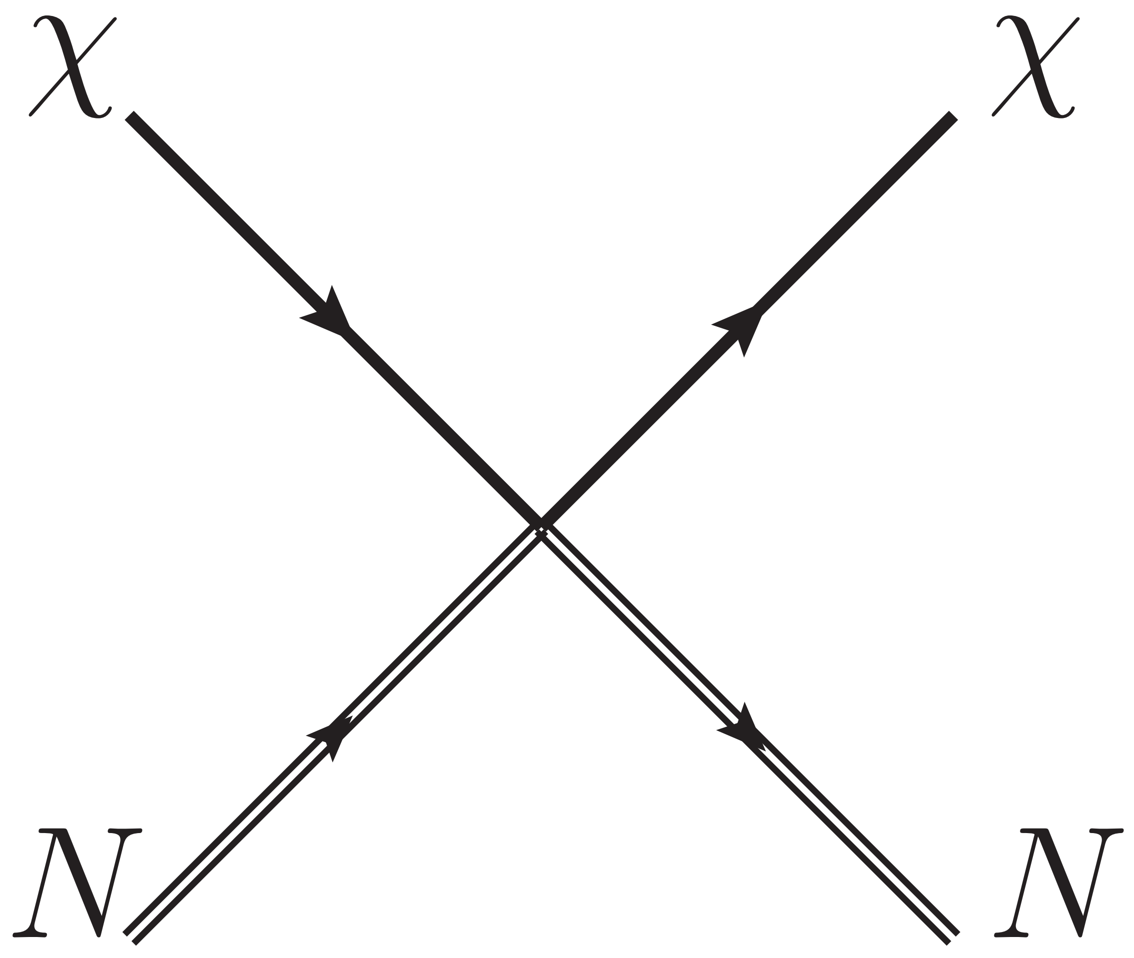


Matching



Long Distance

This work



Short Distance

$N = n, p$

Only this term is considered

in previous DMDD calculation

ChPT with tensor current

Cata & Mateu, 0705.2948

$$\mathscr{L}_{\rm ext} = \bar{q}\gamma_\mu(v^\mu + \gamma_5 a^\mu)q - \bar{q}(s + i\gamma_5 p)q + \bar{q}\sigma_{\mu\nu}\bar{t}^{\mu\nu}q$$

tensor current

$$\mathscr{L}_4^{\chi PT} = \Lambda_1 < t_+^{\mu\nu} f_{+\mu\nu} > \qquad \mathcal{O}(p^4)$$

$f_+^{\mu\nu}$: External field strength tensor

$t_+^{\mu\nu}$: External tensor current field

Non-perturbative effects in fermion electromagnetic moments

$t_+^{\mu\nu}$ with different external fermions

Dekens, Jenkins, Manohar, Stoffer, 1810.05675

$$\bar{\mu}\sigma^{\mu\nu}(\gamma_5)e\bar{q}\sigma_{\mu\nu}q \rightarrow \bar{\mu}\sigma^{\mu\nu}(\gamma_5)eF_{\mu\nu}$$

$\mu \rightarrow e\gamma$

Chen, Zheng, Zhang, 2206.13122

$$\bar{\nu}\sigma^{\mu\nu}(\gamma_5)\nu\bar{q}\sigma_{\mu\nu}q \rightarrow \bar{\nu}\sigma^{\mu\nu}(\gamma_5)\nu F_{\mu\nu}$$

Neutrino experiment

This work

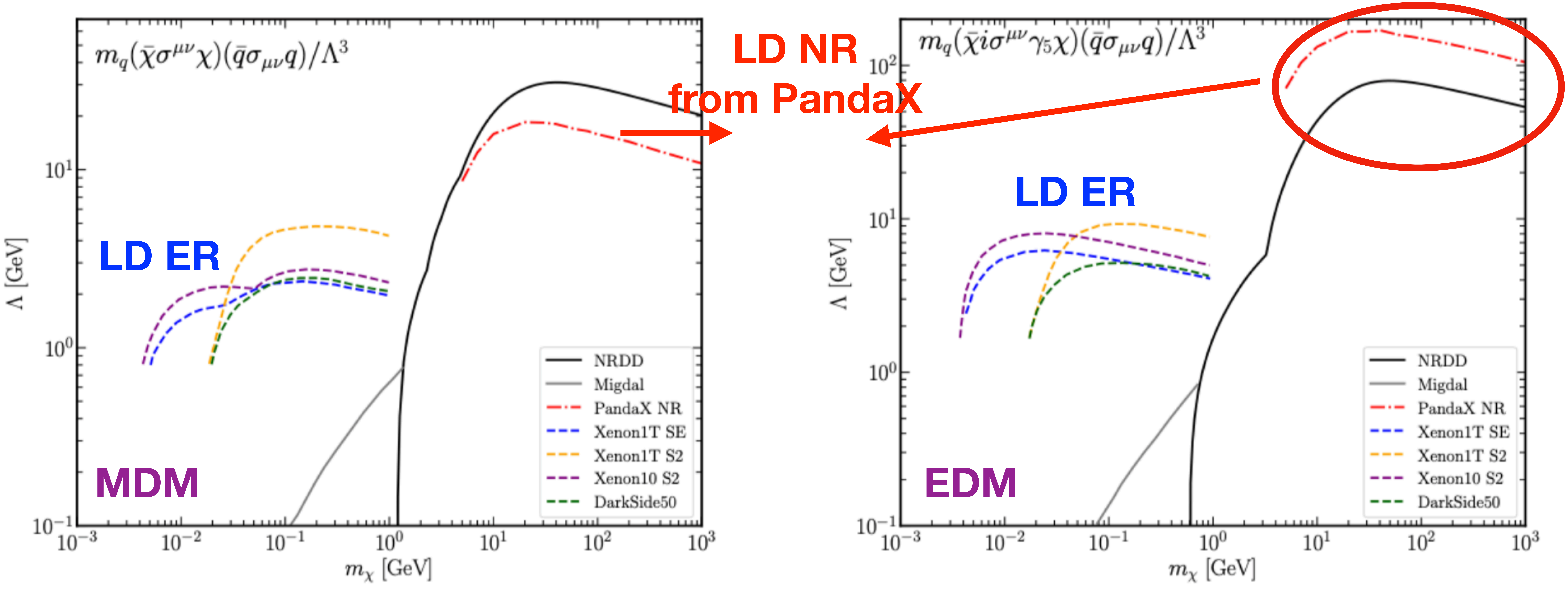
$$\bar{\chi}\sigma^{\mu\nu}(\gamma_5)\chi\bar{q}\sigma_{\mu\nu}q \rightarrow \bar{\chi}\sigma^{\mu\nu}(\gamma_5)\chi F_{\mu\nu}$$

DMDD


Quark level
Nucleon level
Nucleus level
DMDD
Long distance
Short distance
Electron recoil
Nuclear recoil
χ
q
γ
N
e−
Z

Convert constraints on DM dipole moments into constraints on DM-quark tensor operators

LD NR gives stronger constraint for EDM case



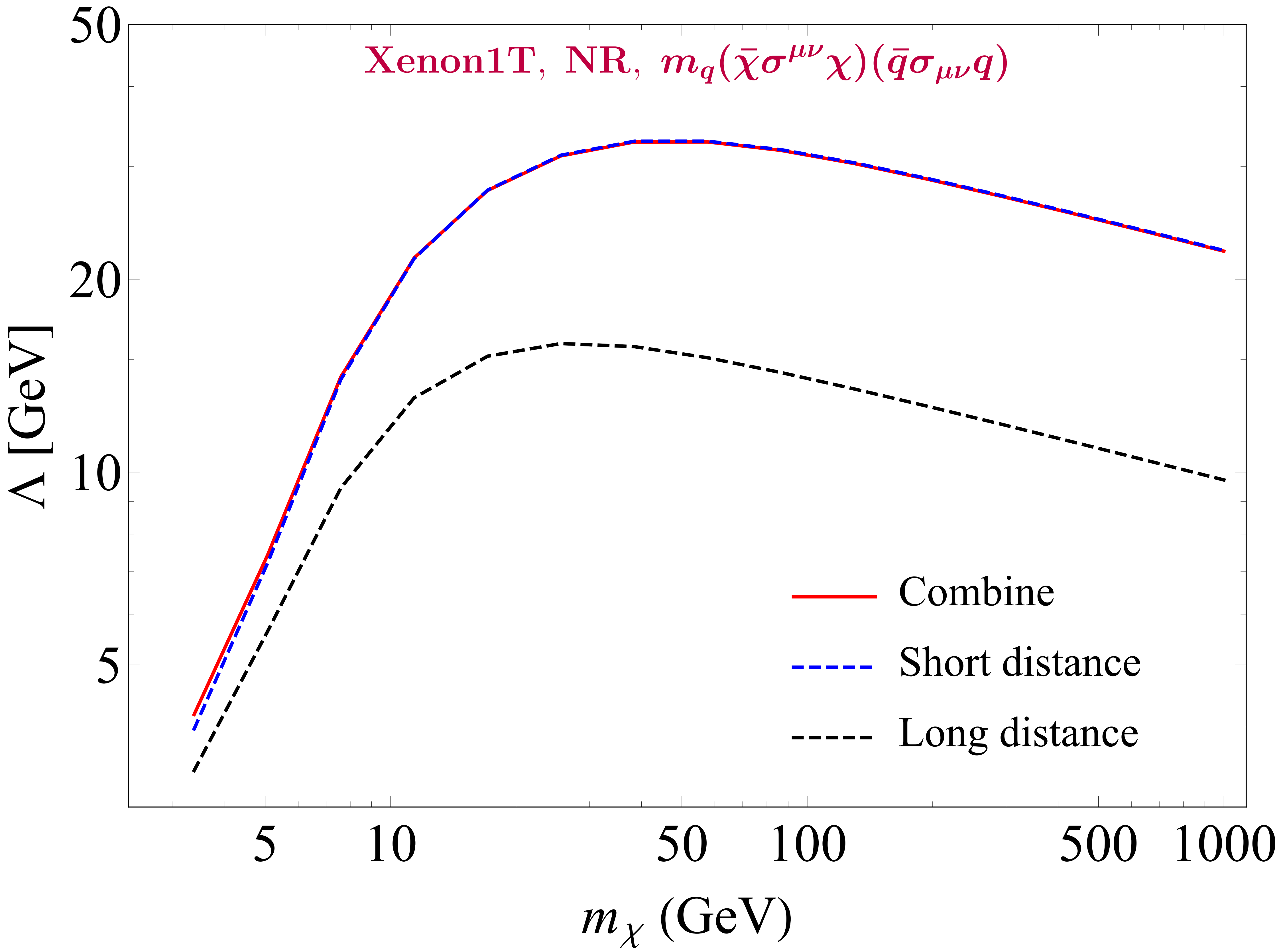
Constraints from LD ER are stronger than those from the Migdal effect

JL, YL, XM, HW, 2312.xxxxx

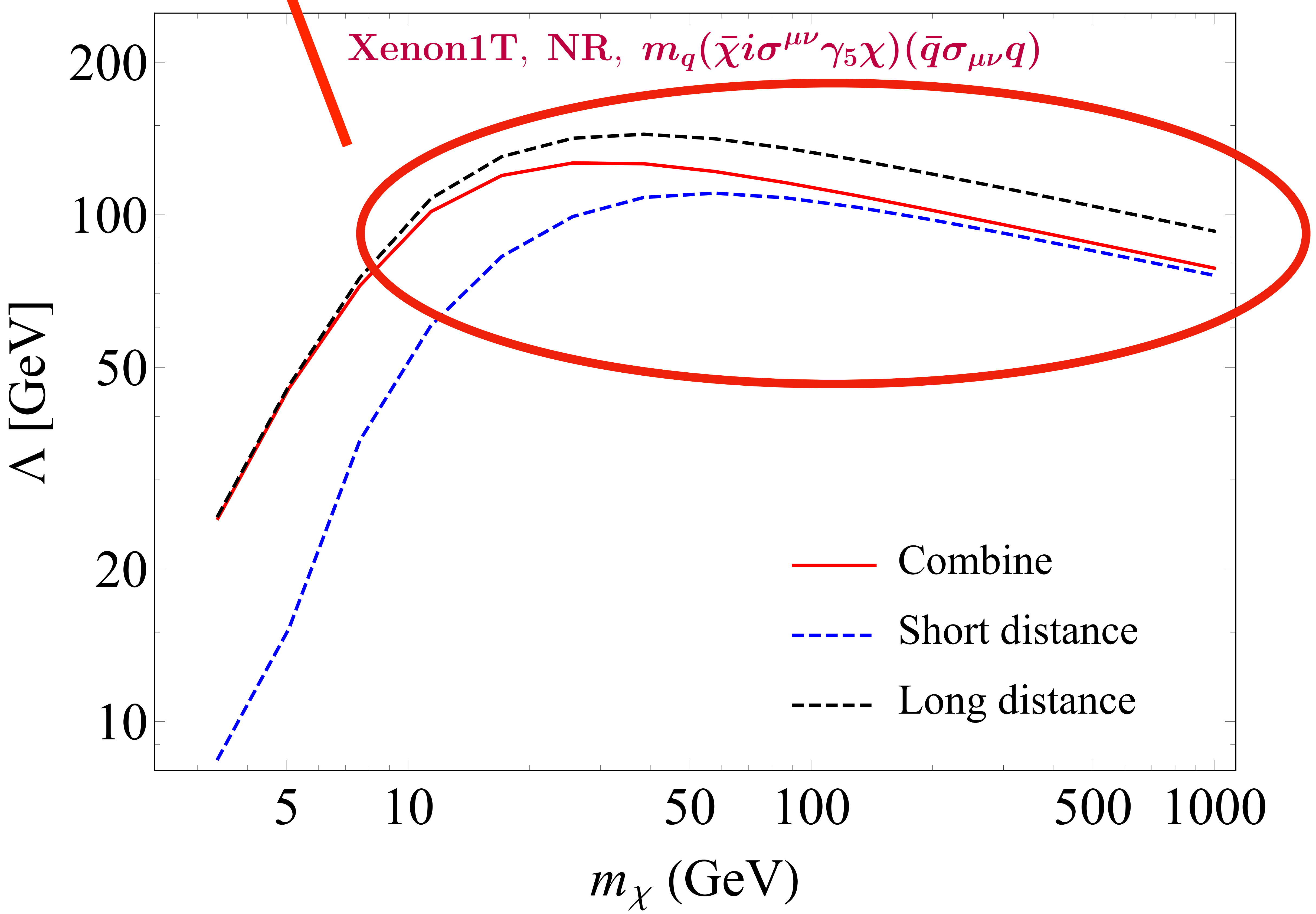
Interference effect for NR in high mass region

Obvious interference effect when $m_\chi \gtrsim 10$ GeV

MDM



EDM

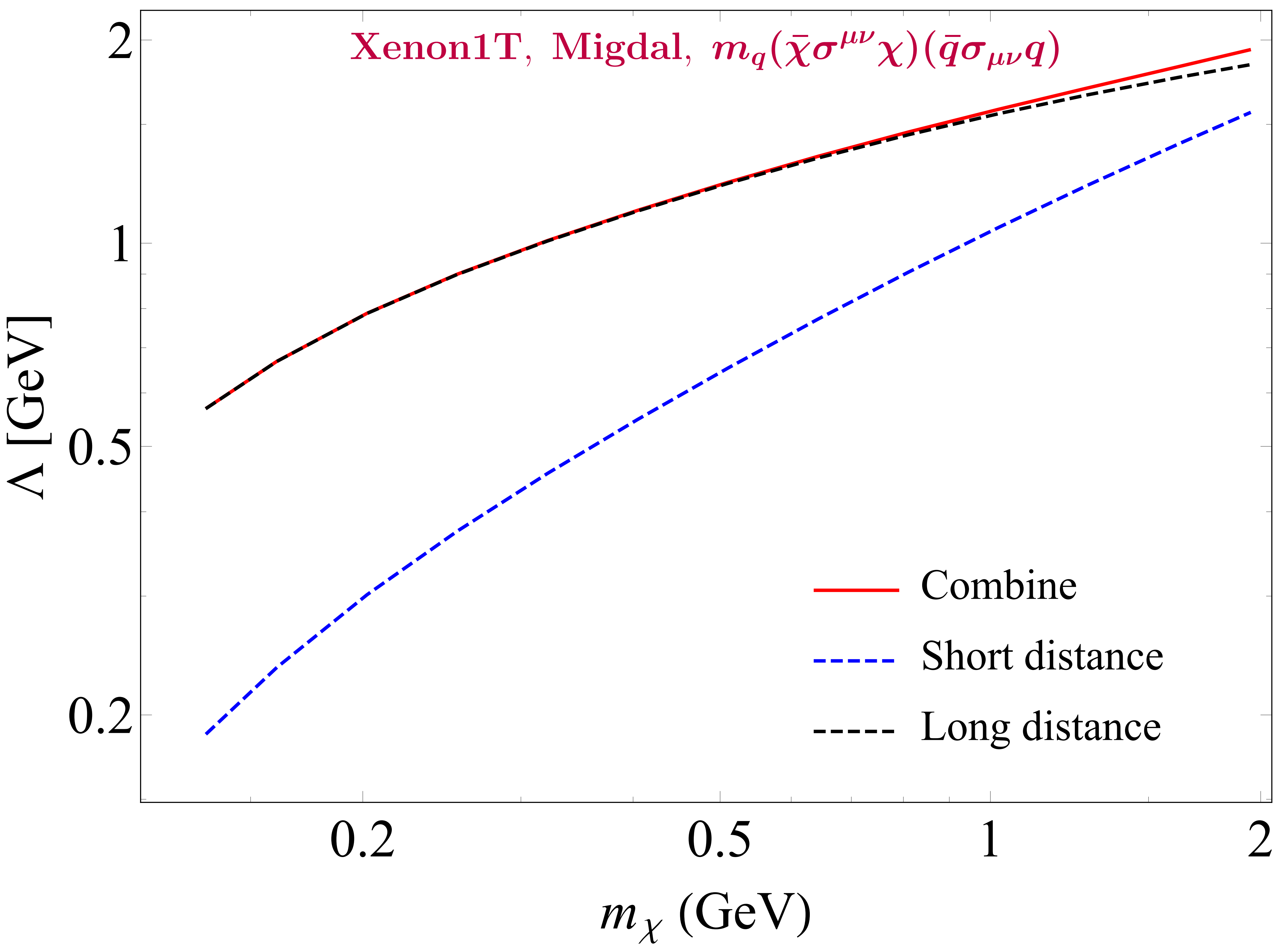


Long distance distribution dominates for EDM case

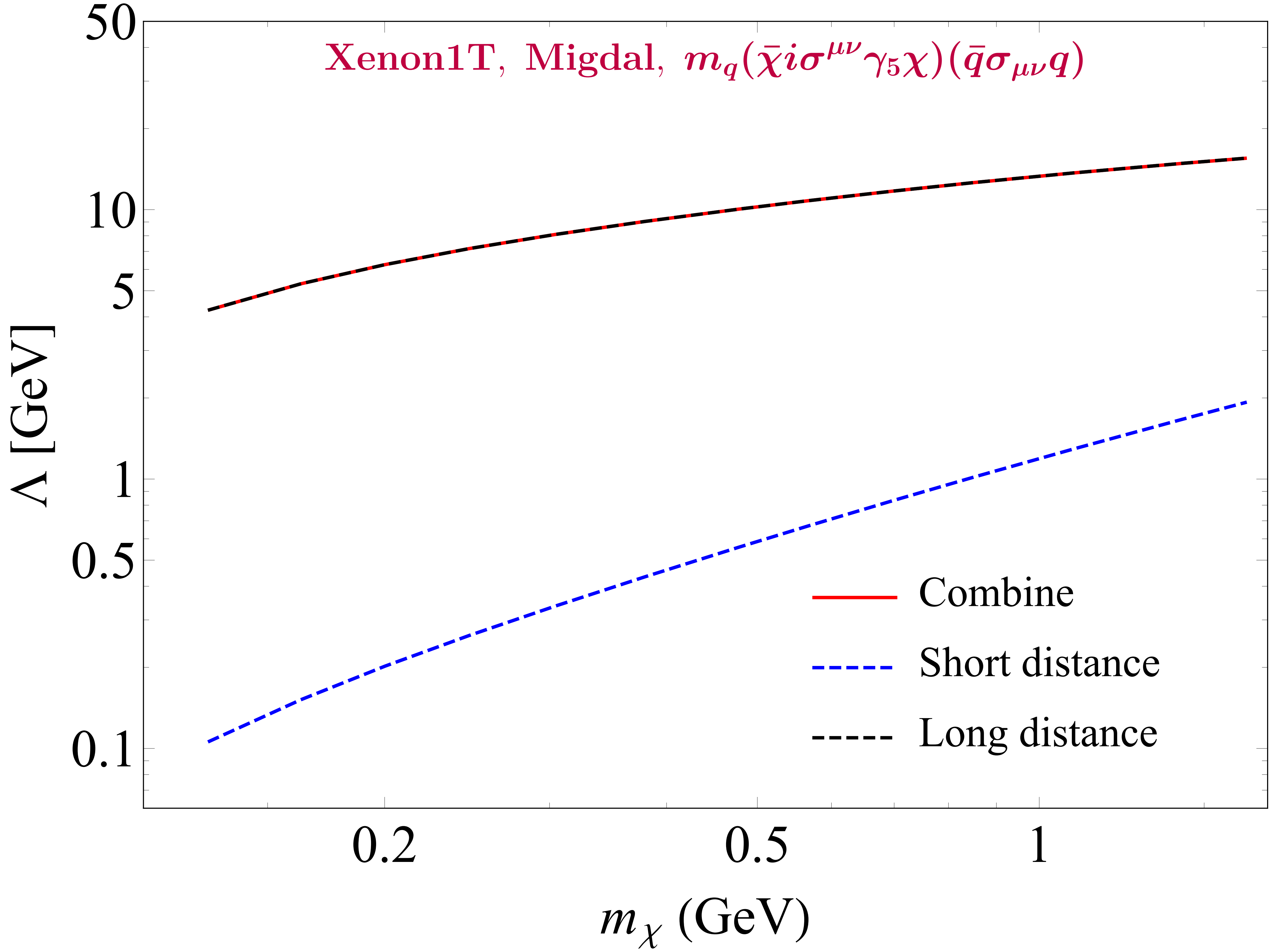
JL, YL, XM, HW, 2312.xxxxx

Interference effect for NR in low mass region

MDM



EDM



(1) The interference effect is not obvious

(2) Long-distance distribution dominates for both MDM and EDM cases

JL, YL, XM, HW, 2312.xxxxx

Constraints with only one flavor contribution

$$\mathcal{O}_{\chi q}^{\mathrm{T1}} = m_q \left(\bar{\chi}\sigma^{\mu\nu}\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right)$$

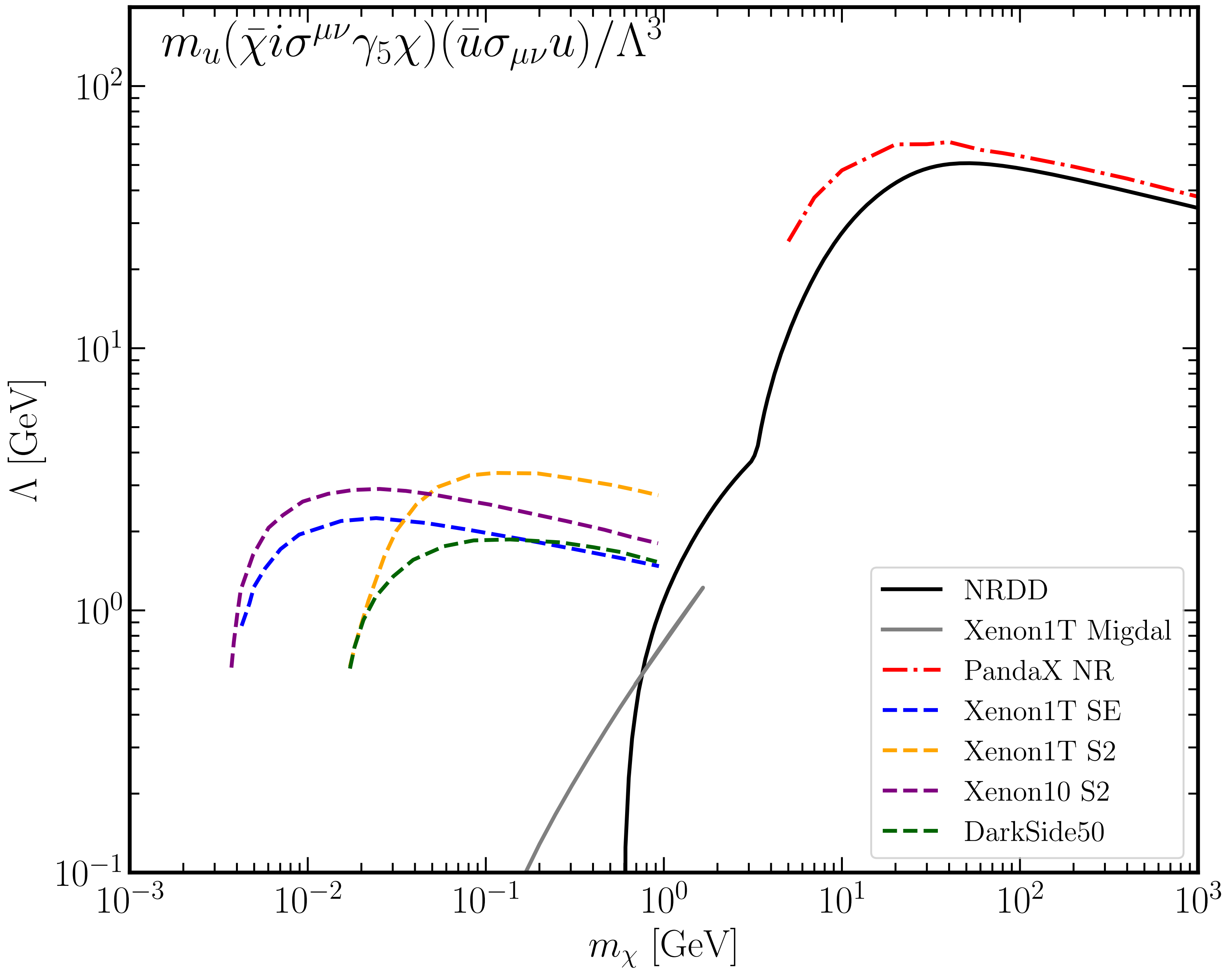
(1) Long distance dominates for MDM case with only s quark contribution

(2) Short distance distribution becomes weaker due to no valence strange quark in nucleons.

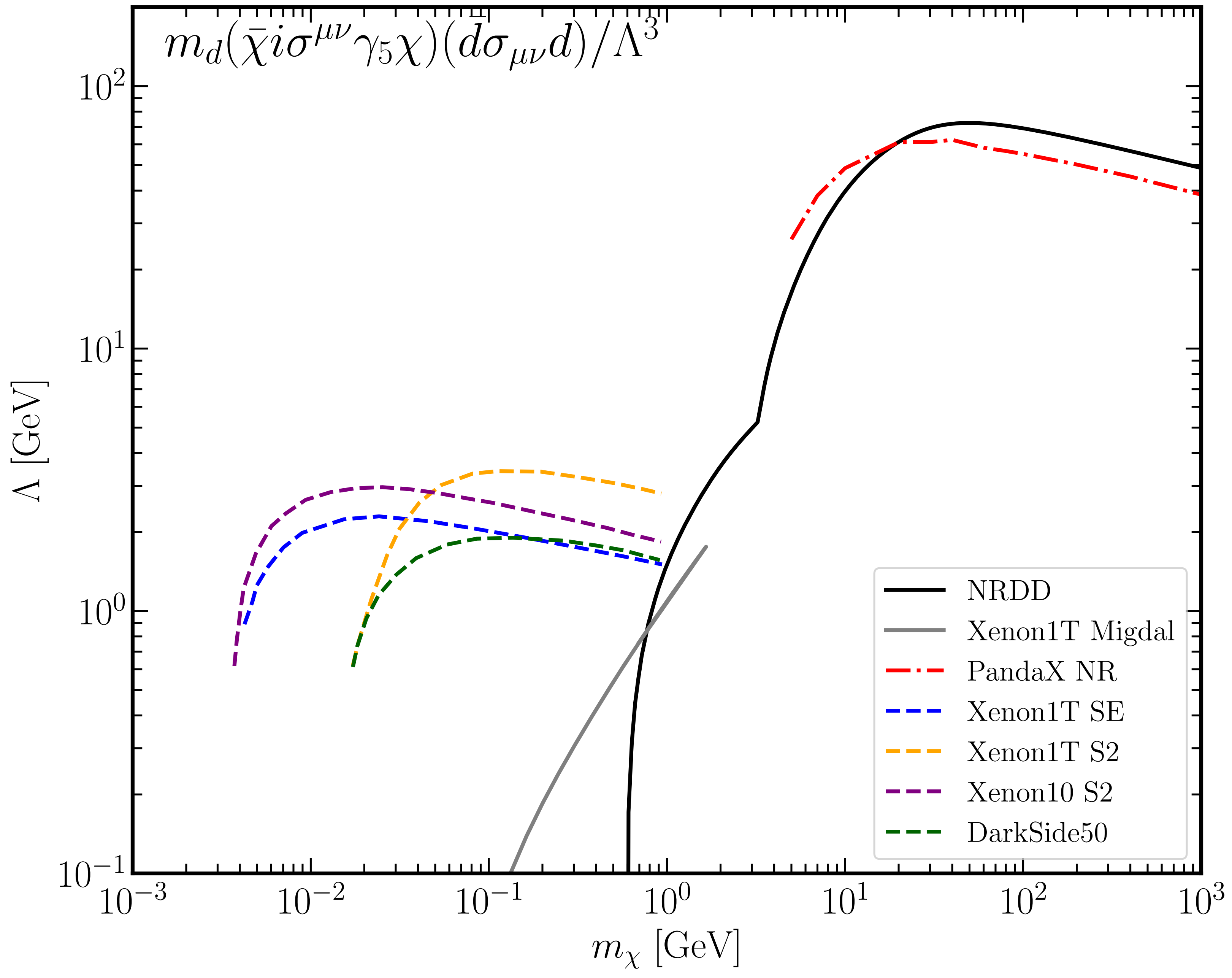
Constraints with only one flavor contribution

$$\mathcal{O}_{\chi q}^{\mathrm{T2}} = m_q \left(\bar{\chi} i \sigma^{\mu\nu} \gamma_5 \chi\right) \left(\bar{q} \sigma_{\mu\nu} q\right)$$

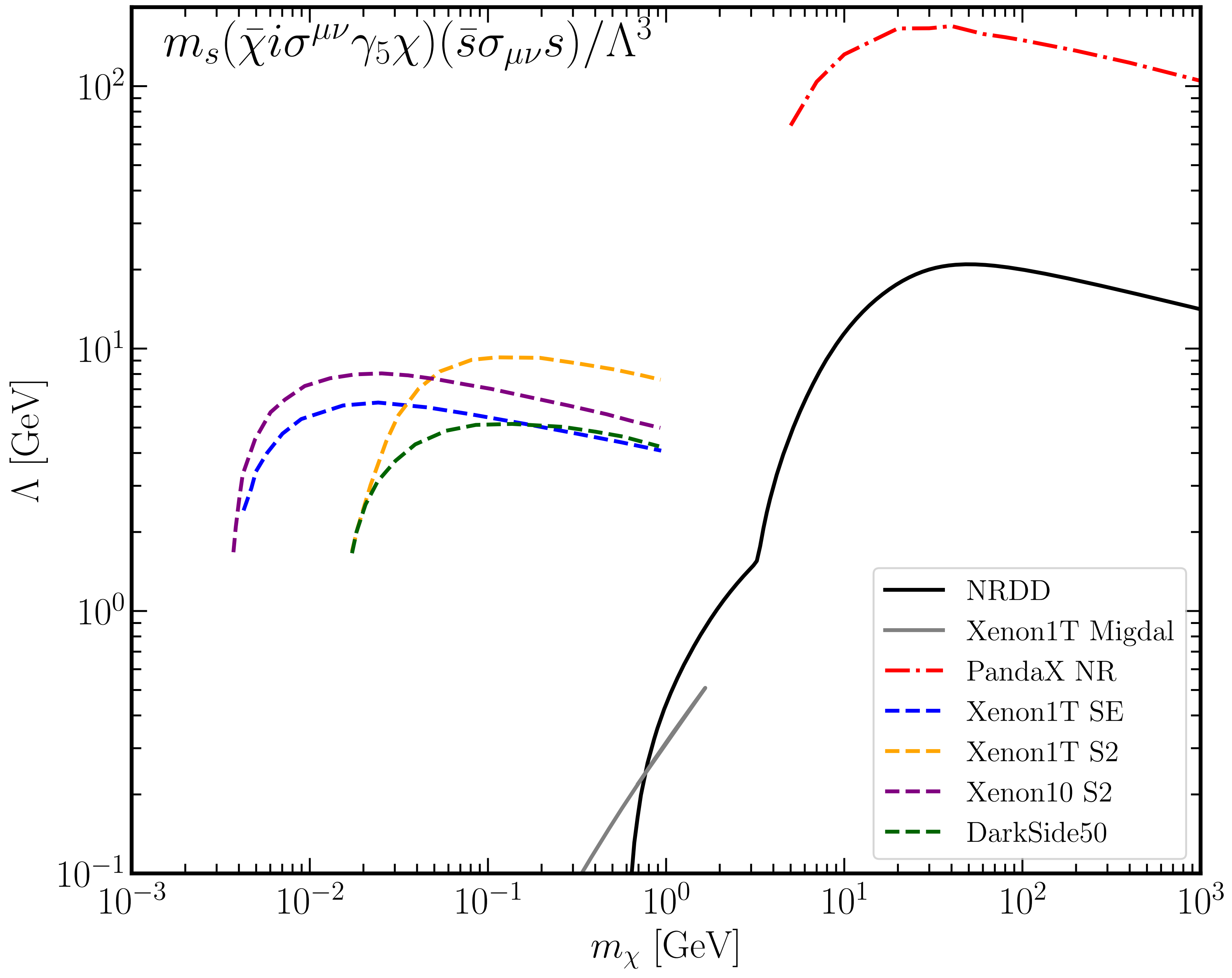
Up quark



Down quark



Strange quark



Conclusion

- By taking into the tensor current in ChPT, DM-quark tensor operators can induce DM electromagnetic dipole moment operators.
- In previous unconstrained low-mass regions, the DM-quark tensor operators receive constraints from electron recoil signals at DMDD experiments.
- For the DMDD constraints on DM-quark tensor operators from nuclear recoil signals, one has to consider both short-distance and long-distance contributions. The interference effect becomes significant for EDM case when $m_\chi \gtrsim 10\ \text{GeV}$.