Fermionic dark matter-quark tensor operators in direct detection experiments

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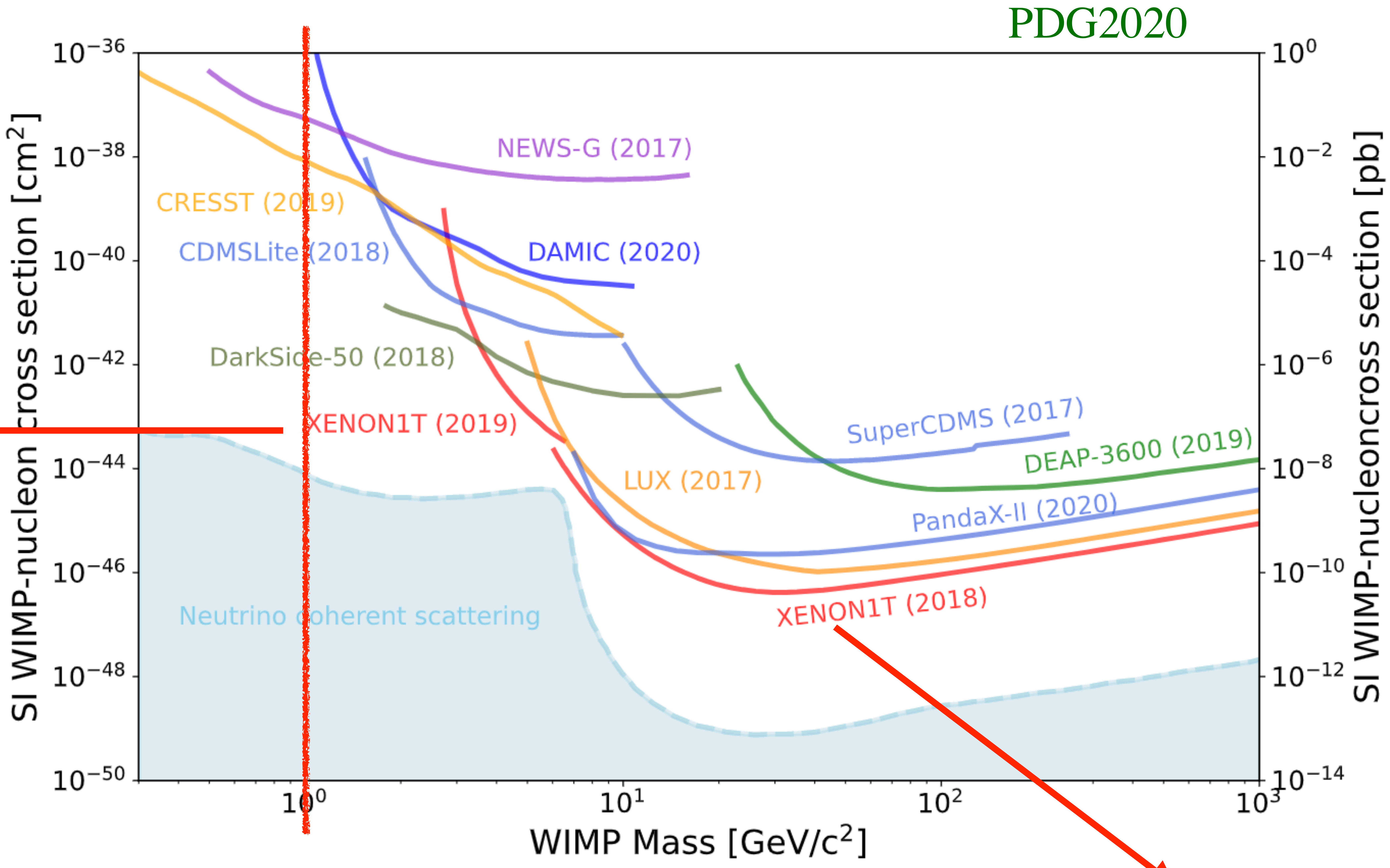
2024.10.14 苏州

Constraints on DM-nucleus interaction



Weak constraint at sub-GeV region

Migdal effect
DM-electron

Stringent constraints at $m_\chi \simeq m_{\rm Xe} \simeq 100$ GeV

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

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\bar{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$

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

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

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

This talk

Tensor operators

Bishara, Brod, Grinstein, Zupan, 1707.06998

DM-nucleon NR operators

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

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

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

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

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

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

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

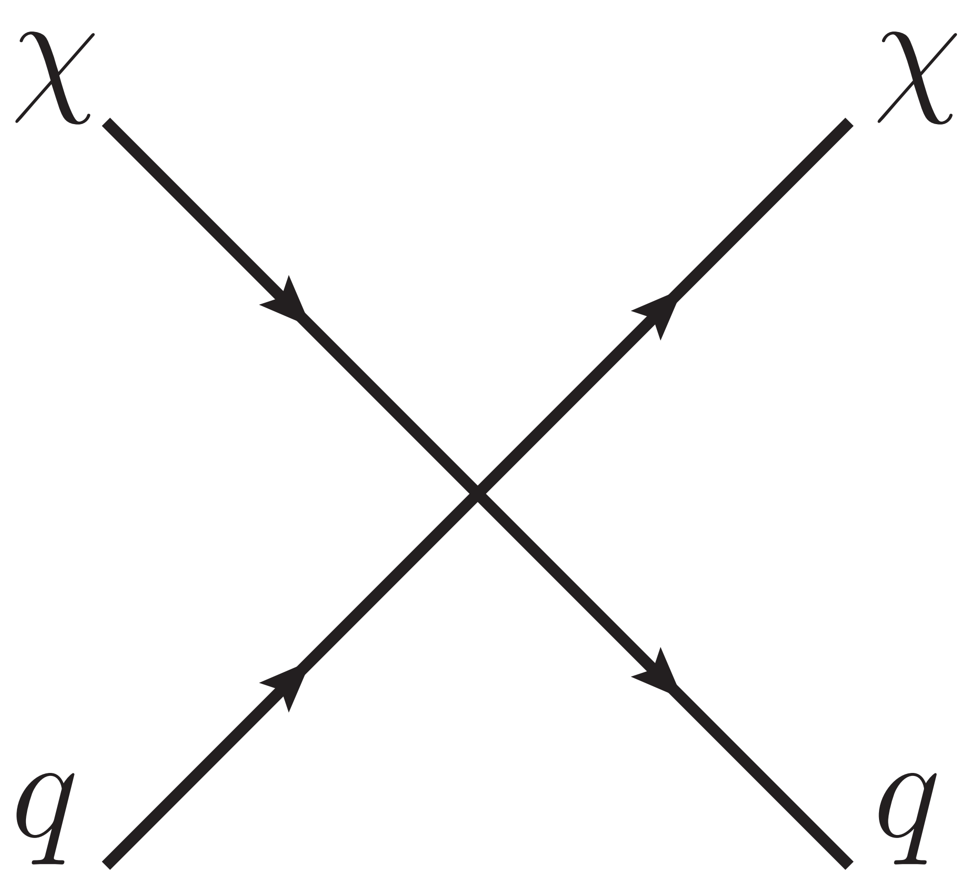
$$\mathcal{O}_{15}^N = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\left(\vec{S}_N \times \vec{v}_\perp\right) \cdot \frac{\vec{q}}{m_N}\right)$$

$\mathcal{O}(q^2 v)$

$N = n, p$

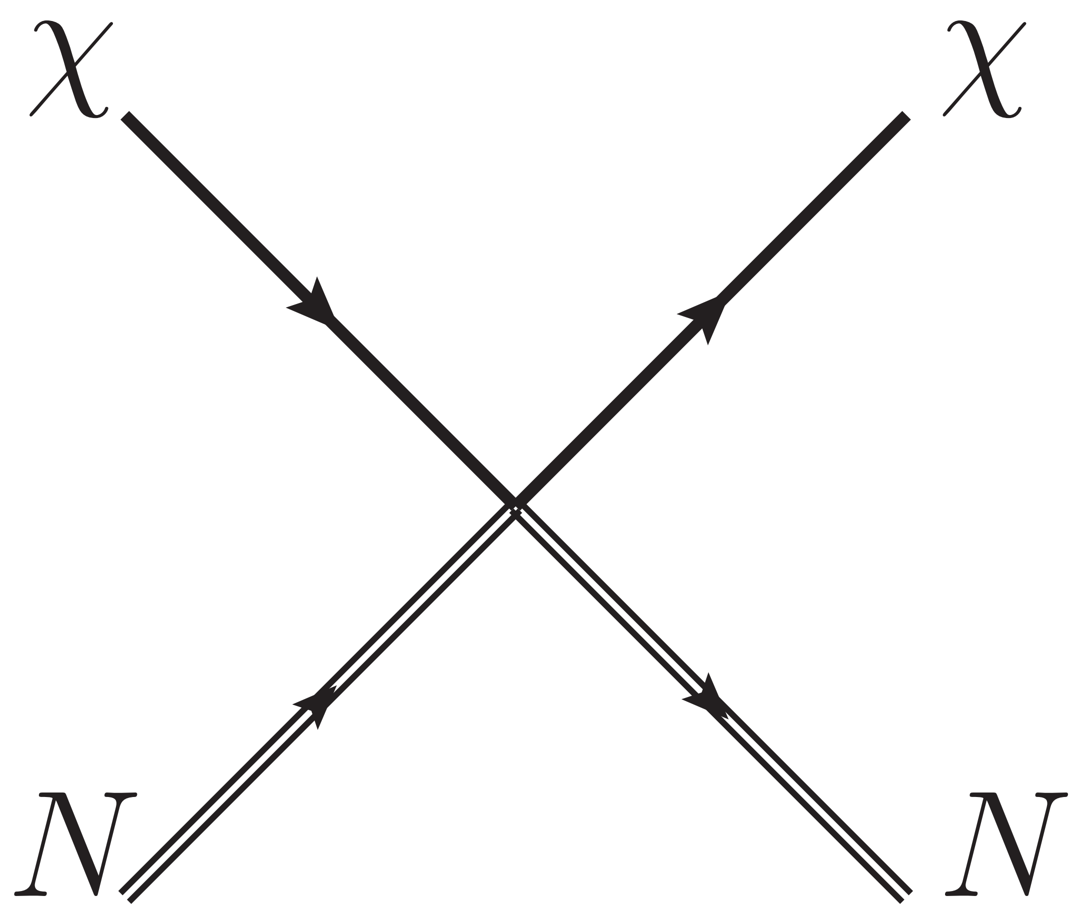
Anand, Fitzpatrick, Haxton, 1308.6288

Matching to DM-nucleon operators via χPT



χPT

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



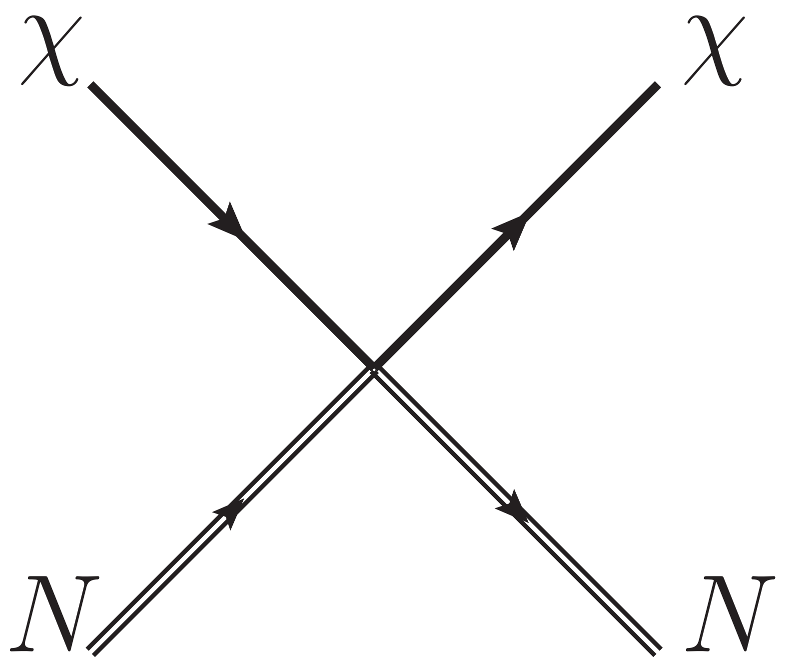
Bishara, Brod, Grinstein, Zupan, 1707.06998

$$\mathcal{O}^{\rm T1}_{\chi q} \equiv m_q \left(\bar{\chi}\sigma^{\mu\nu}\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to 8F^{q/N}_{T,0}\mathcal{O}^N_4$$

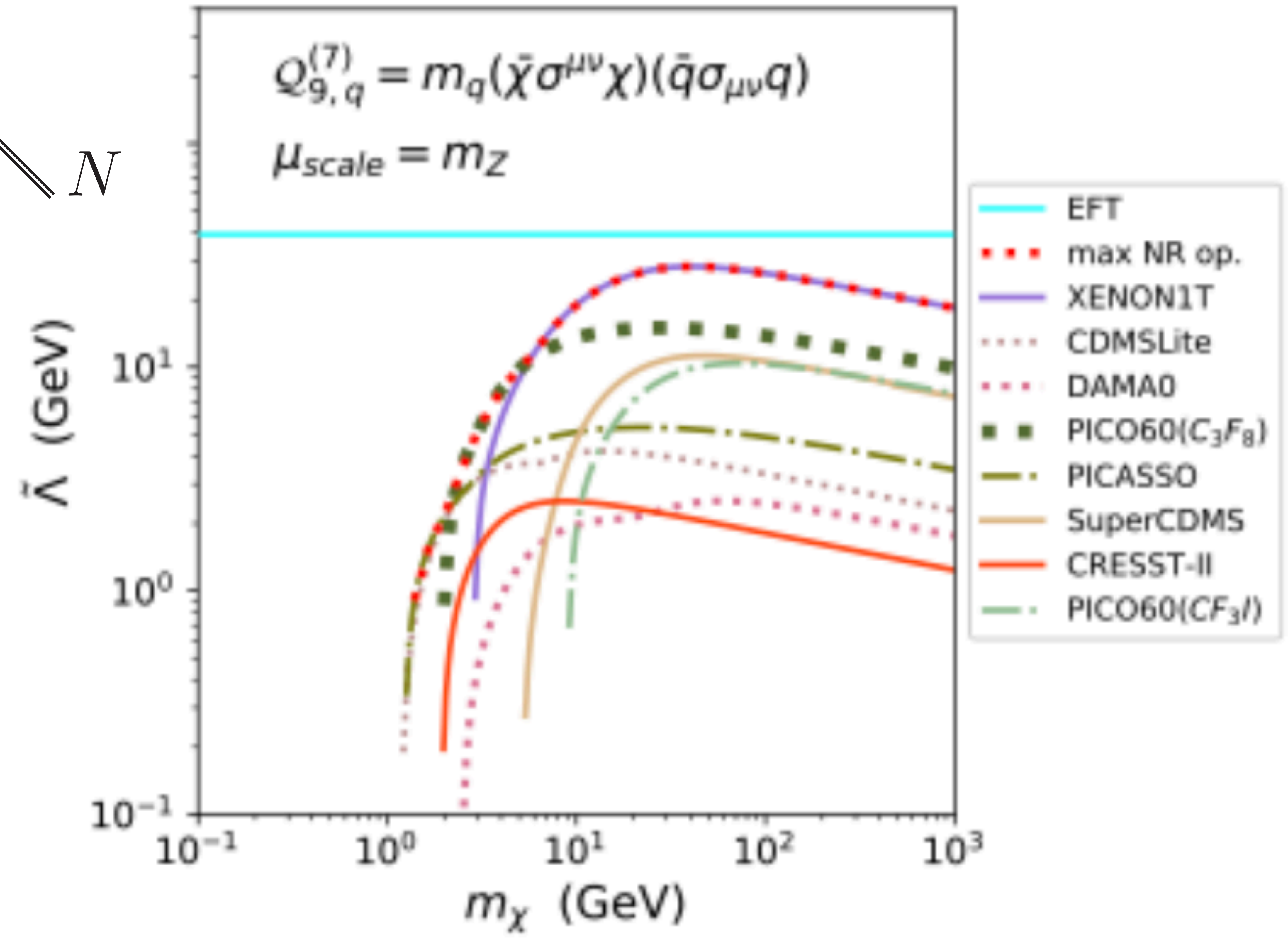
$$\mathcal{O}^{\rm T2}_{\chi q} \equiv m_q \left(\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to \frac{-2m_N}{m_\chi}F^{q/N}_{T,0}\mathcal{O}^N_{10} + 2(F^{q/N}_{T,0} - F^{q/N}_{T,1})\mathcal{O}^N_{11} - 8F^{q/N}_{T,0}\mathcal{O}^N_{12}$$

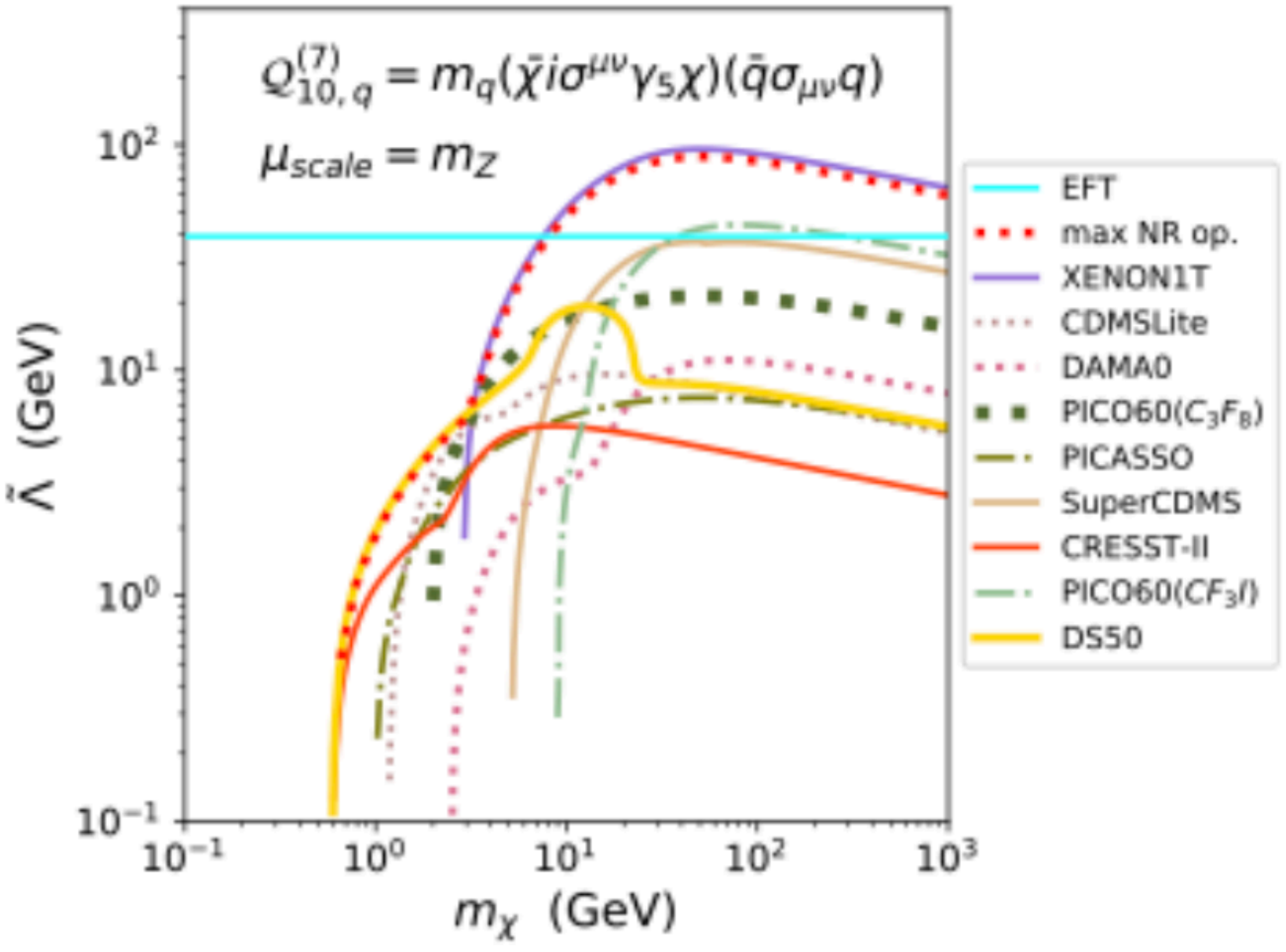
DM-quark tensor operators —**LO**→ **DM-nucleon operators**

Constraints on tensor operators from nucleus recoil



Kang, Scopel, Tomar, Yoon, 1810.00607





Weak constraints at sub-GeV region

χPT with tensor source

$$\mathcal{O}^{\mathrm{T1}}_{\chi q} \equiv m_q \left(\bar{\chi}\sigma^{\mu\nu}\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to 8F^{q/N}_{T,0}\mathcal{O}^N_4$$

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

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \overline{q_L} l_\mu \gamma^\mu q_L + \overline{q_R} r_\mu \gamma^\mu q_R - \left[\overline{q_R}(s + ip)q_L - \overline{q_R} t^{\mu\nu}\sigma_{\mu\nu} q_L + \text{ h.c. }\right],$$

$$\mathcal{L}^{(4)}_{\chi\mathrm{PT}} = \Lambda_1 < t^{\mu\nu}_+ f_{+\mu\nu} > \qquad \mathcal{O}(p^4)$$

Cata & Mateu, 0705.2948

$$t^{\mu\nu}_+ = u^\dagger t^{\mu\nu} u^\dagger + u t^{\mu\nu\dagger} u$$

$$f^{\mu\nu}_+ = u F^{\mu\nu}_L u^\dagger + u^\dagger F^{\mu\nu}_R u$$

$$F^{\mu\nu}_L = \partial^\mu l^\nu - \partial^\nu l^\mu - i[l^\mu, l^\nu], \quad F^{\mu\nu}_R = \partial^\mu r^\nu - \partial^\nu r^\mu - i[r^\mu, r^\nu].$$

u : meson fileds

Induce DM dipole moments from tensor operators

$$\mathcal{L}_{\chi\mathrm{PT}}^{(4)} = \Lambda_1 < t_+^{\mu\nu} f_{+\mu\nu} >$$

$$l_\mu = r_\mu = -eA_\mu \,\mathrm{diag}(Q_u, Q_d, Q_s),$$

SM photon

$$(\bar{t}^{\mu\nu})_{qq} = C_{\chi q}^{\mathrm{T1}} m_q (\bar{\chi}\sigma^{\mu\nu}\chi) + C_{\chi q}^{\mathrm{T2}} m_q (\bar{\chi} i\sigma^{\mu\nu}\gamma_5\chi)$$

$u \to 1$

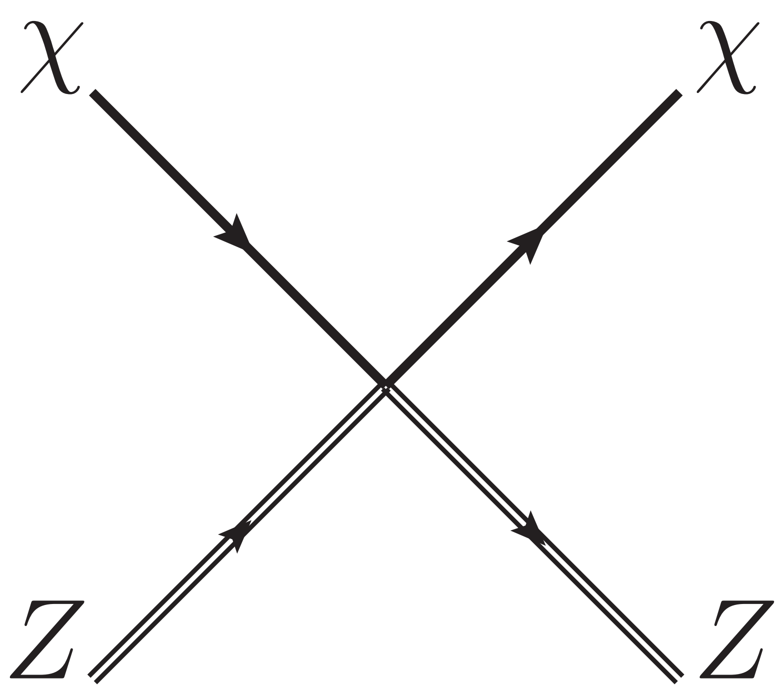
$$\mathcal{L}_{\chi\mathrm{PT}}^{(4)} \supset \frac{\mu_\chi}{2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu} + \frac{d_\chi}{2}(\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi)F_{\mu\nu},$$

$$\mu_\chi = -\frac{ec_T\Lambda_\chi}{12\pi^2}\left(\sum_q 3Q_q C_{\chi q}^{\mathrm{T1}} m_q\right) \qquad d_\chi = -\frac{ec_T\Lambda_\chi}{12\pi^2}\left(\sum_q 3Q_q C_{\chi q}^{\mathrm{T2}} m_q\right)$$

JL, Liao, Ma, Wang, 2401.05005


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

Recalculate DM-nucleus scattering

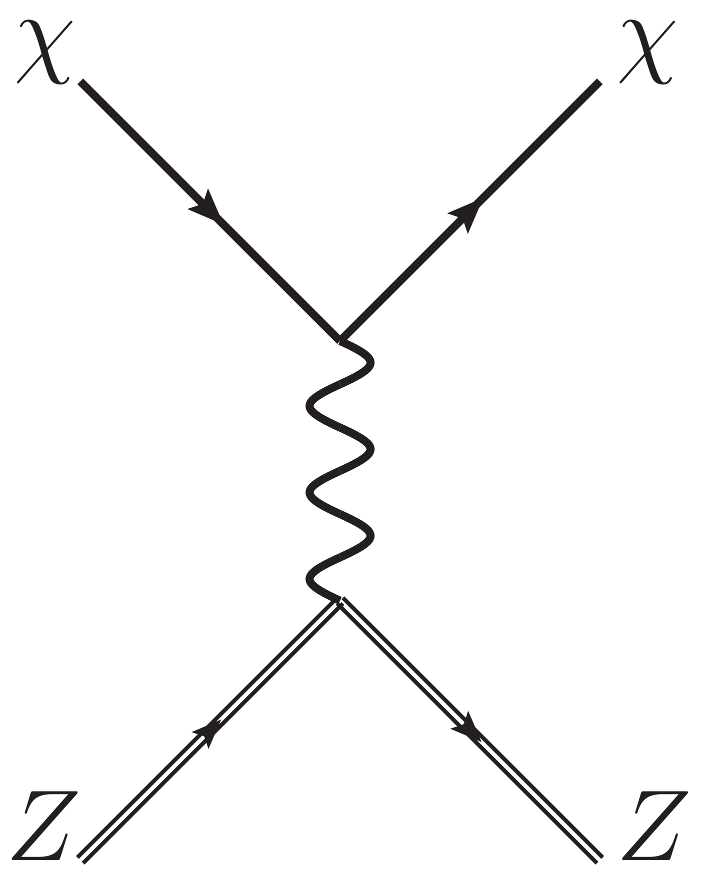


$$m_q\left(\bar{\chi} i\sigma^{\mu\nu}\gamma_5\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to \frac{-2m_N}{m_\chi}F^{q/N}_{T,0}\mathcal{O}^N_{10} + 2(F^{q/N}_{T,0} - F^{q/N}_{T,1})\mathcal{O}^N_{11} - 8F^{q/N}_{T,0}\mathcal{O}^N_{12}$$

$$m_q\left(\bar{\chi}\sigma^{\mu\nu}\chi\right)\left(\bar{q}\sigma_{\mu\nu}q\right) \to 8F^{q/N}_{T,0}\mathcal{O}^N_4$$

Short distance

+



This work

Long distance

$$\frac{d_\chi}{2}(\bar{\chi} i\sigma^{\mu\nu}\gamma_5\chi)F_{\mu\nu} \to -8\frac{m_\chi m_N}{\mathbf{q}^2}ed_\chi Q_N\mathcal{O}^N_{11}$$

$$\frac{\mu_\chi}{2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu} \to -2e\mu_\chi\left[m_N Q_N\mathcal{O}^N_1 + 4\frac{m_\chi m_N}{\mathbf{q}^2}Q_N\mathcal{O}^N_5 + 2m_\chi g_N\left(\mathcal{O}^N_4 - \frac{\mathcal{O}^N_6}{\mathbf{q}^2}\right)\right]$$

The LD contribution is enhanced at low $\mathbf{q}^2$

Recalculate DM-nucleus scattering

DM-nucleus elastic scattering

$$\frac{dR_{\mathtt{NR}}}{dE_R} = \frac{\rho_\chi}{m_\chi}\frac{1}{m_A}\int_{v_{\min}(E_R)}^{v_{\max}} dv F(v) v \frac{d\sigma_T}{dE_R}(v, E_R)$$

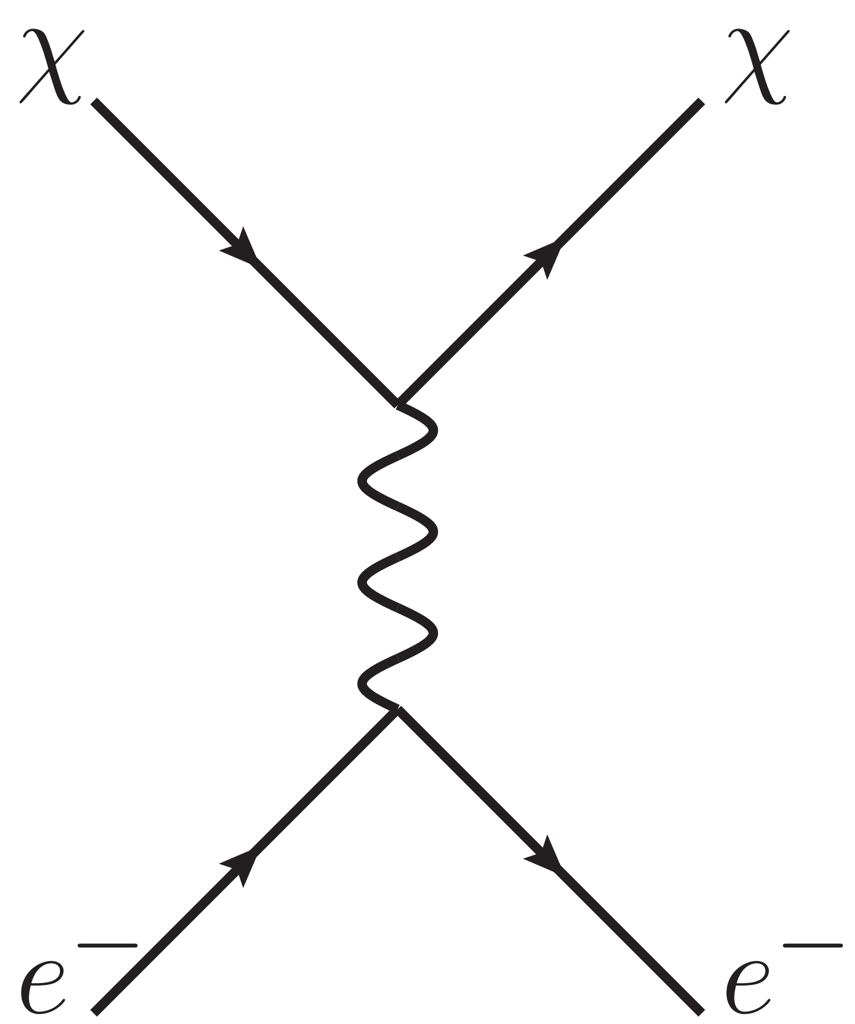
Migdal effect

$$\frac{dR_{\mathtt{Migdal}}}{dE_{\rm det}} = \frac{\rho_\chi}{m_\chi}\frac{1}{m_A}\int_0^{E_R^{\max}} dE_R \int_{v_{\min}}^{v_{\max}} dv F(v) v \frac{d\sigma_T}{dE_R}(v, E_R)\,|Z_{\rm ion}(E_R, E_{\rm EM})|^2$$

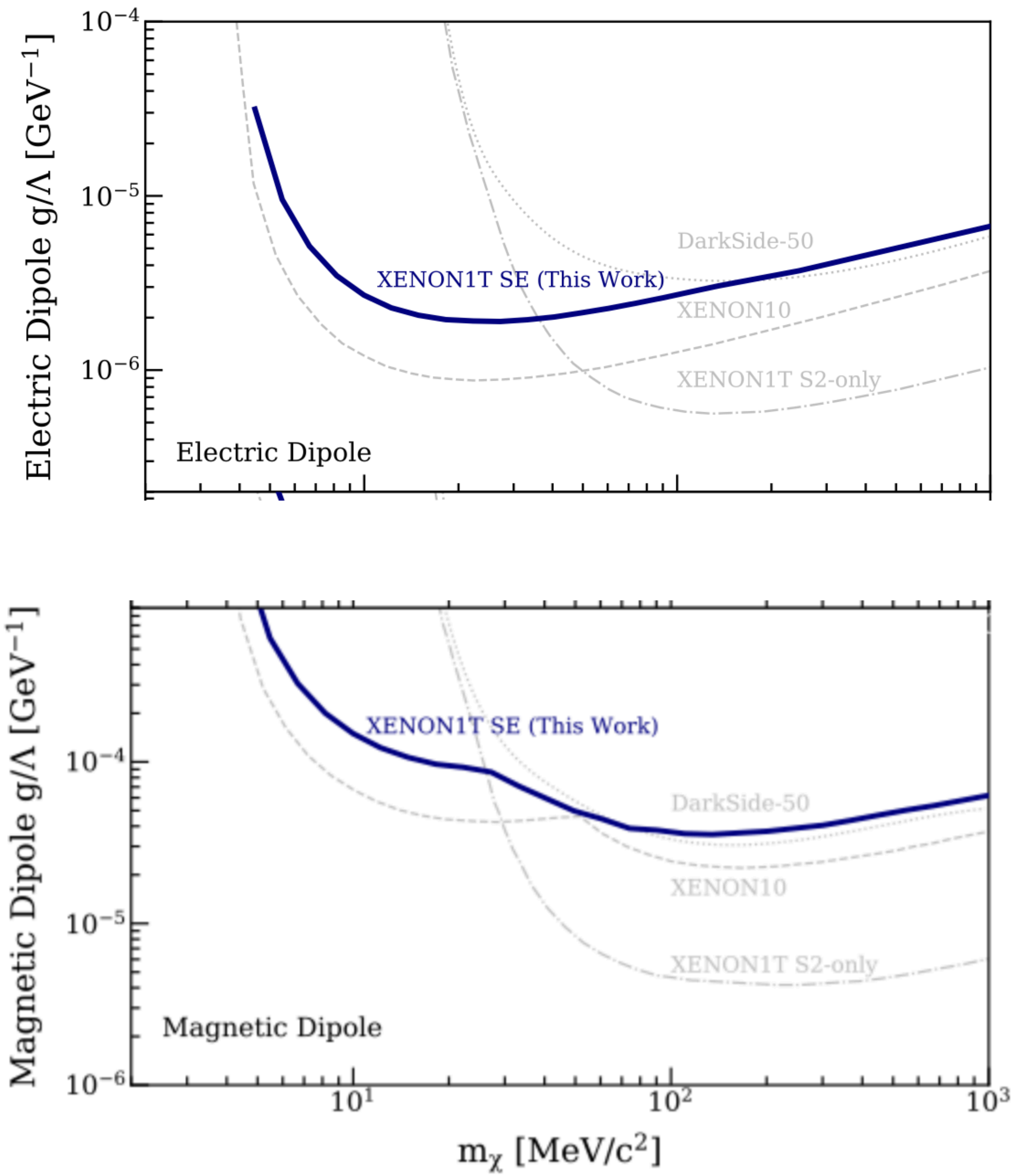
Same DM-nucleus scattering differential cross-section

(LD+SD)

Constraints from DM-electron scattering



XENON Collaboration, 2112.12116



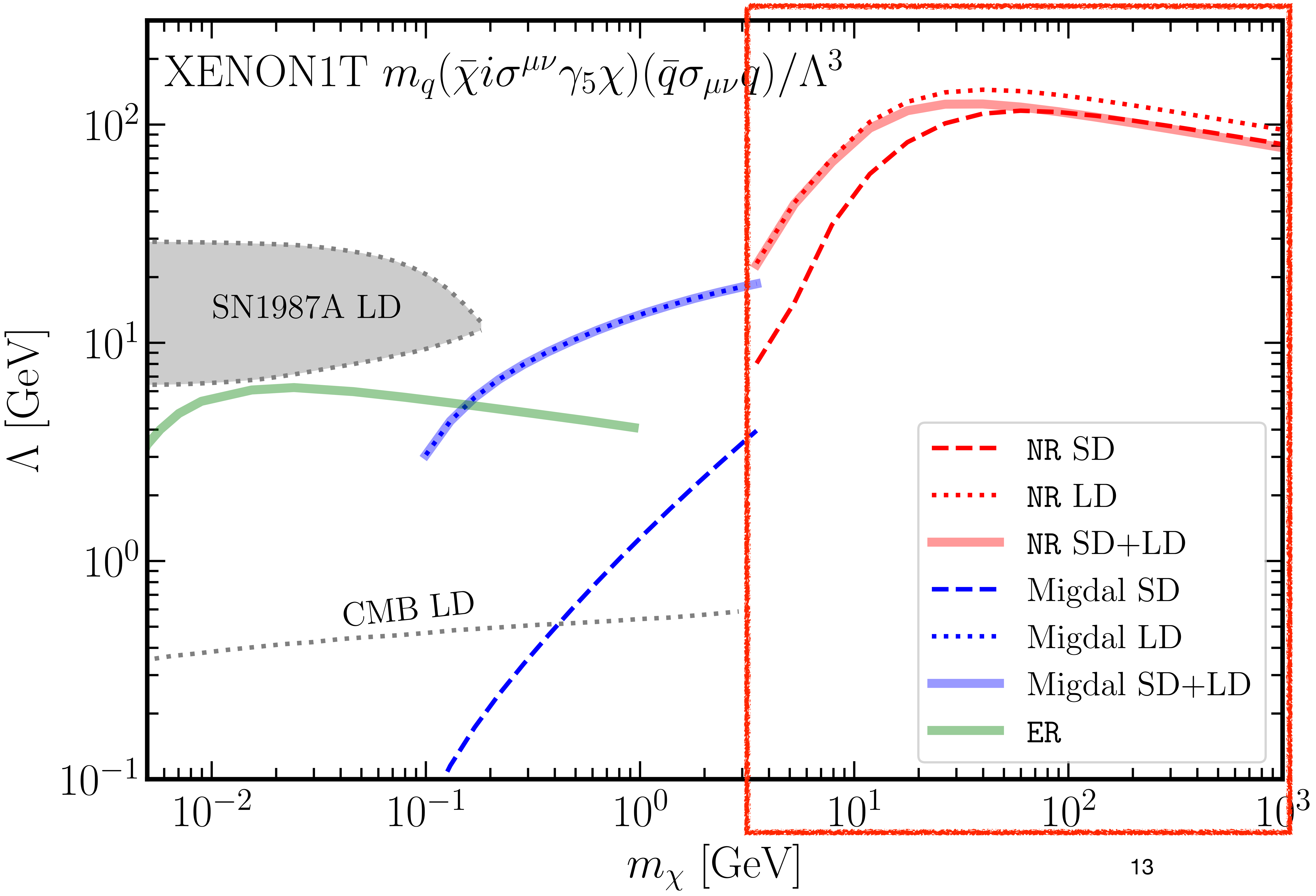
$$\frac{2g}{\Lambda} = d_\chi = -\frac{ec_T\Lambda_\chi}{12\pi^2}\left(\sum_q 3Q_q C^{\mathrm{T2}}_{\chi q} m_q\right)$$

$$\frac{g}{2\Lambda} = \mu_\chi = -\frac{ec_T\Lambda_\chi}{12\pi^2}\left(\sum_q 3Q_q C^{\mathrm{T1}}_{\chi q} m_q\right)$$

Recalculate XENON1T constraints

$4\ \text{GeV} \lesssim m_\chi \lesssim 1\ \text{TeV}$

DM-nucleus elastic scattering



LD contribution is slightly larger than SD contribution

↓

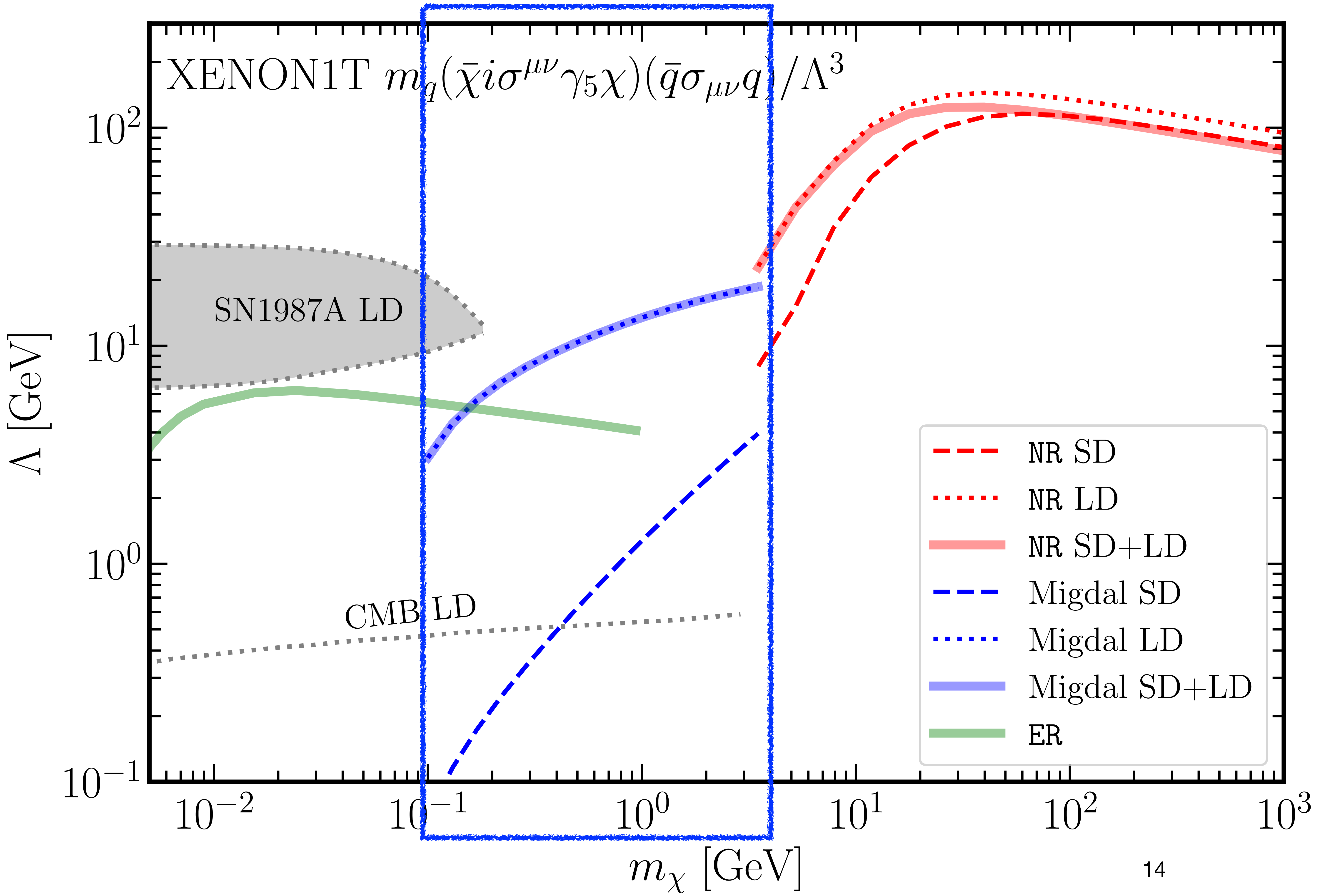
Destructive interference

JL, Liao, Ma, Wang, 2401.05005

Recalculate XENON1T constraints

$0.1 \text{ GeV} \lesssim m_\chi \lesssim 4 \text{ GeV}$

Migdal effect



LD contribution is much larger stronger than SD contribution

↓

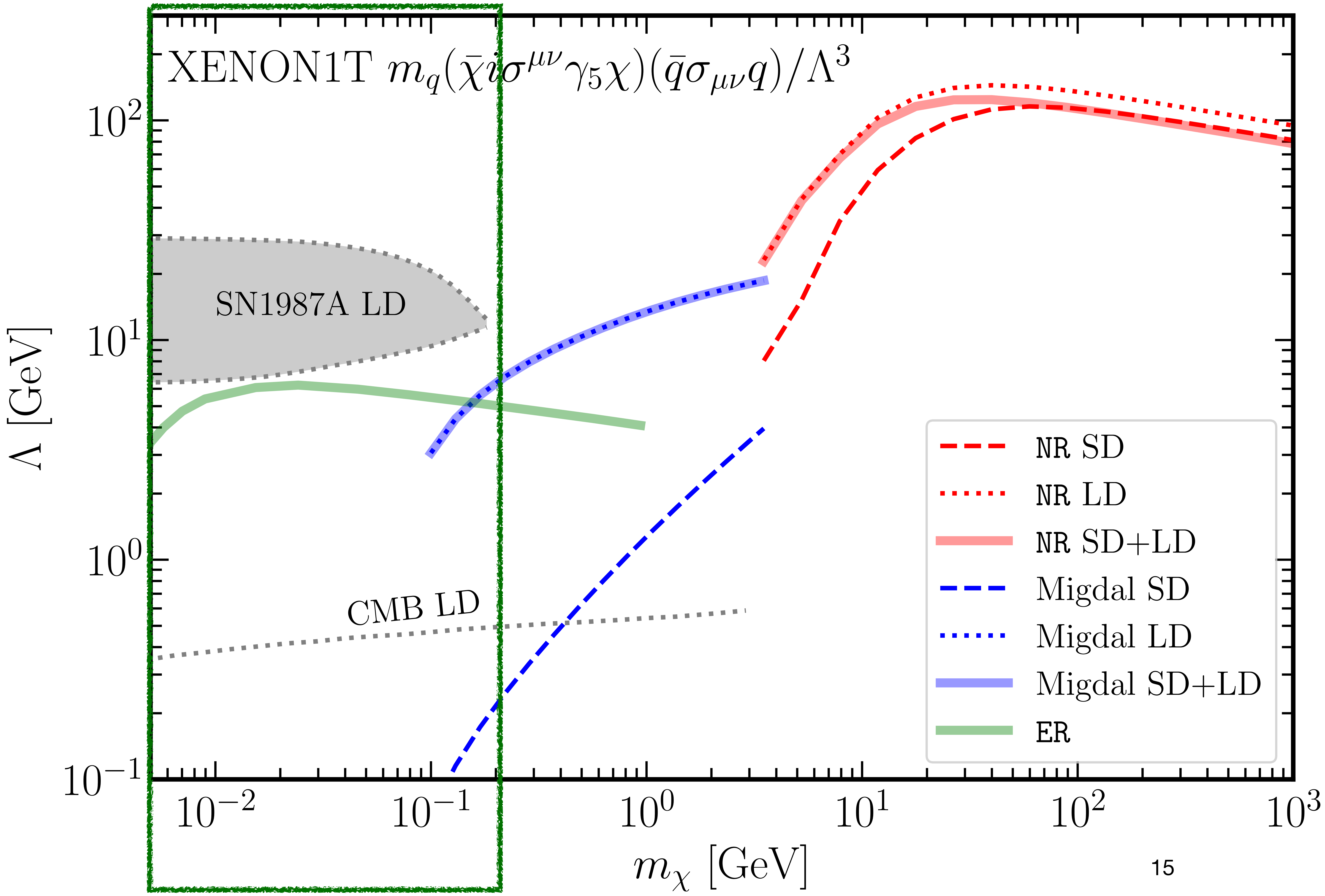
Enhance the constraint by about one order of magnitude

JL, Liao, Ma, Wang, 2401.05005

Recalculate XENON1T constraints

$5\ \text{MeV} \lesssim m_\chi \lesssim 0.2\ \text{GeV}$

DM-electron scattering



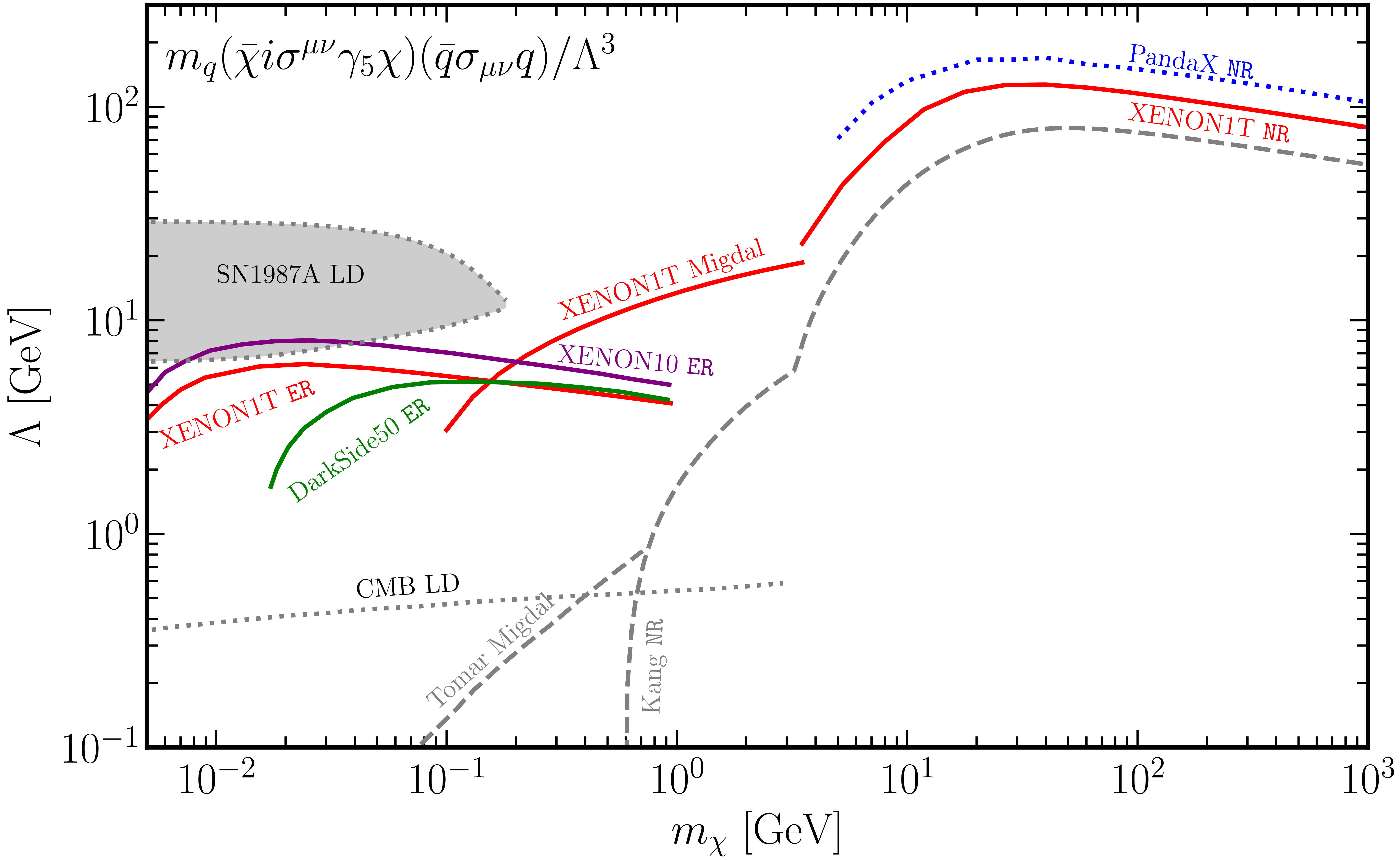
Only LD contribution

↓

Extend the constraint down to 5 MeV

JL, Liao, Ma, Wang, 2401.05005

Comprehensive constraints



JL, Liao, Ma, Wang, 2401.05005

Summary

- By taking into the tensor current in χPT, 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 obvious for EDM case when $m_\chi \gtrsim 10\ \mathrm{GeV}$.

A more systematic investigation of other types of DM-quark operators within χPT

Backup

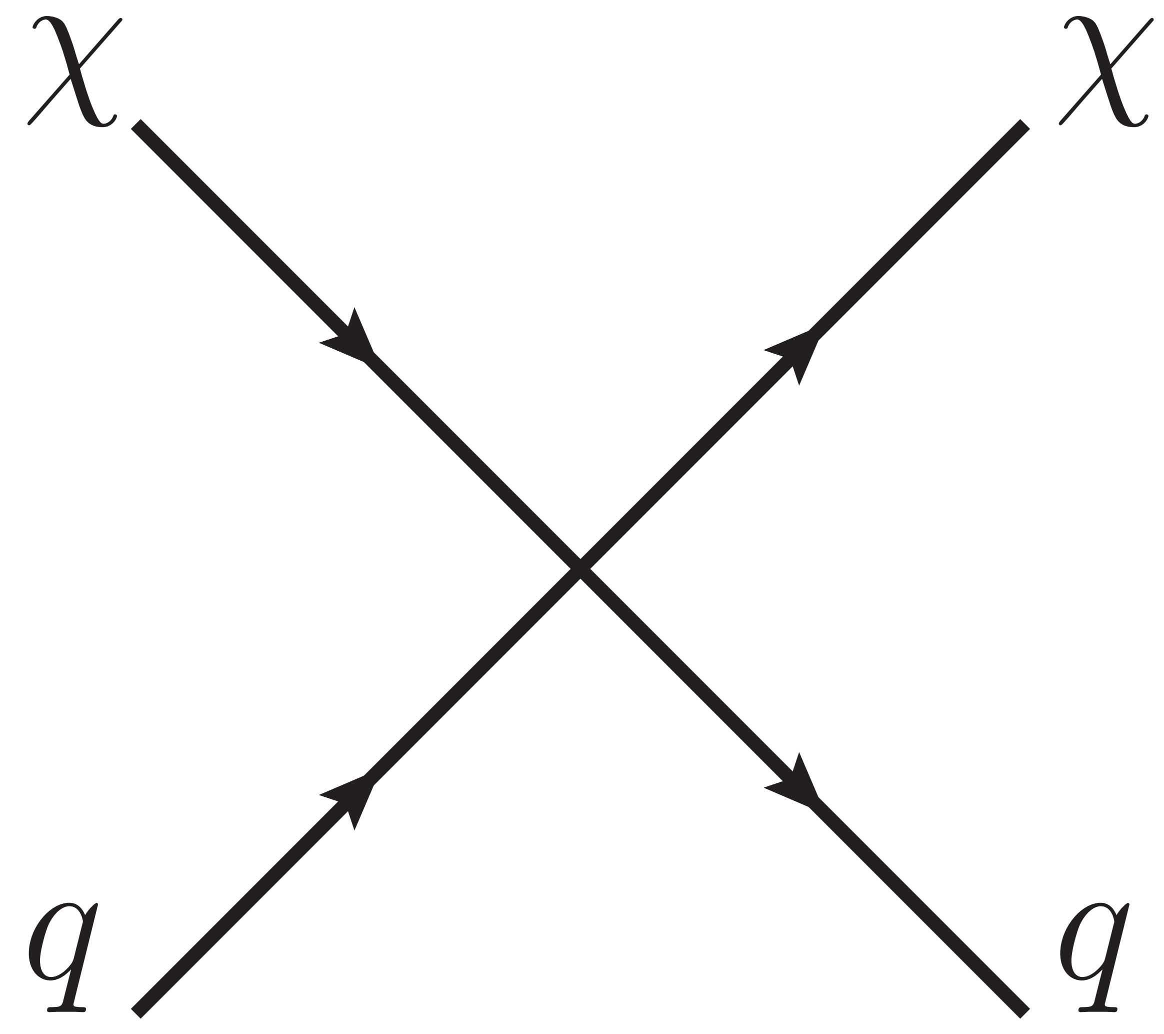
Comprehensive matching

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

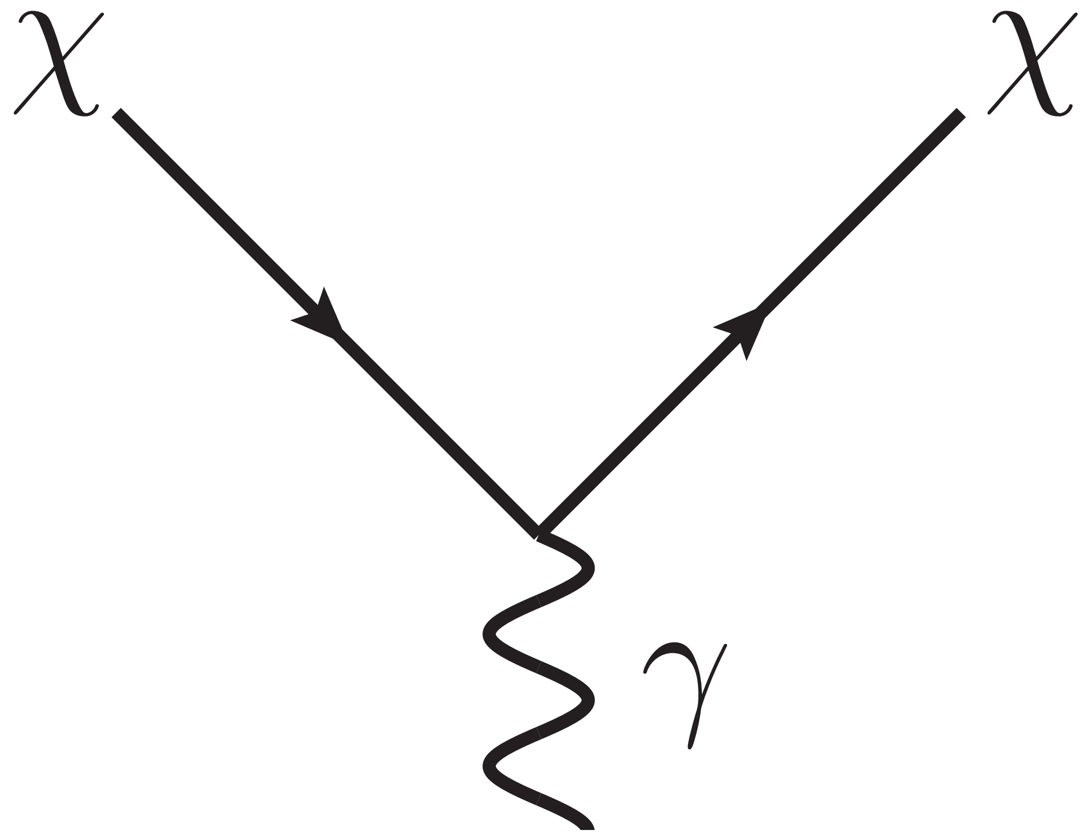
EDM $\frac{d_\chi}{2}(\bar{\chi}i\sigma^{\mu\nu}\gamma_5\chi)F_{\mu\nu}$

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

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

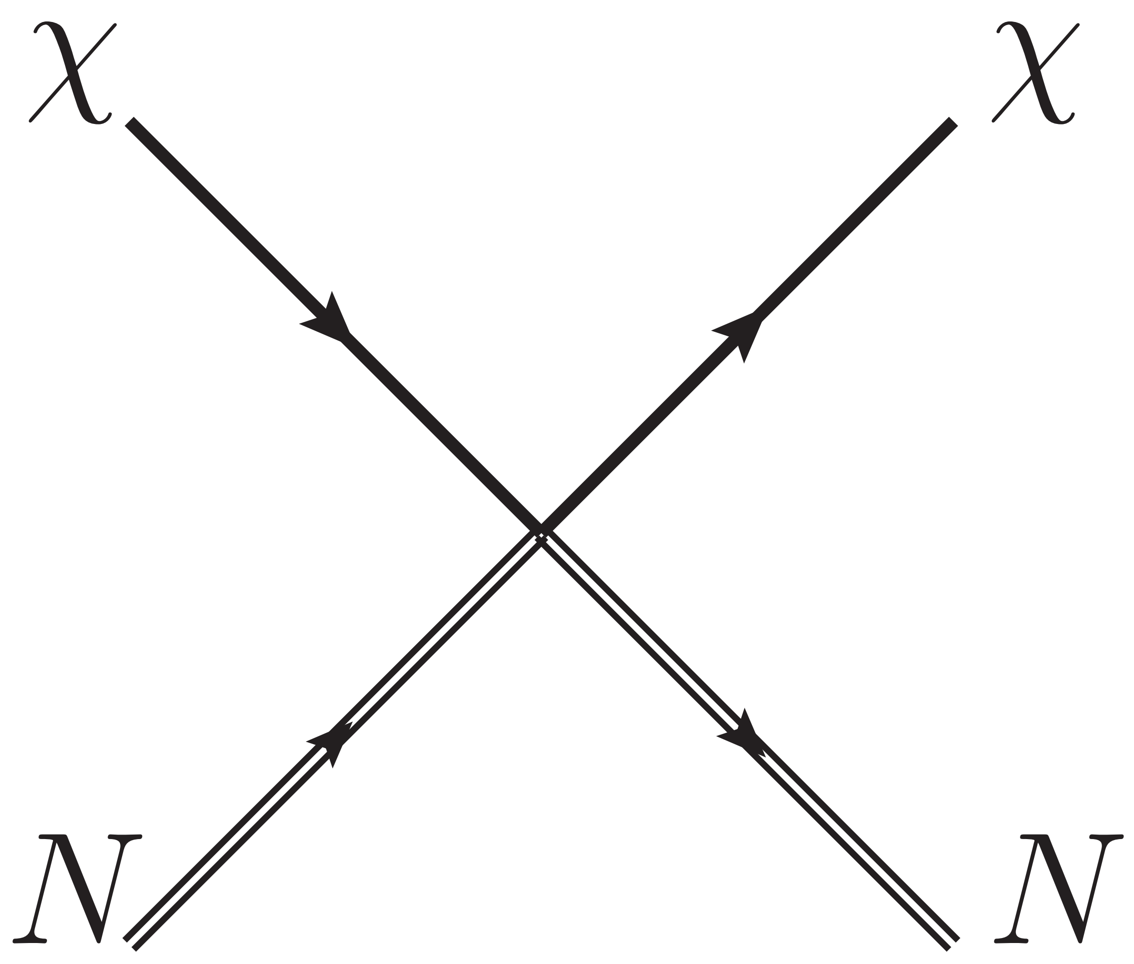


Matching



Long Distance

This work



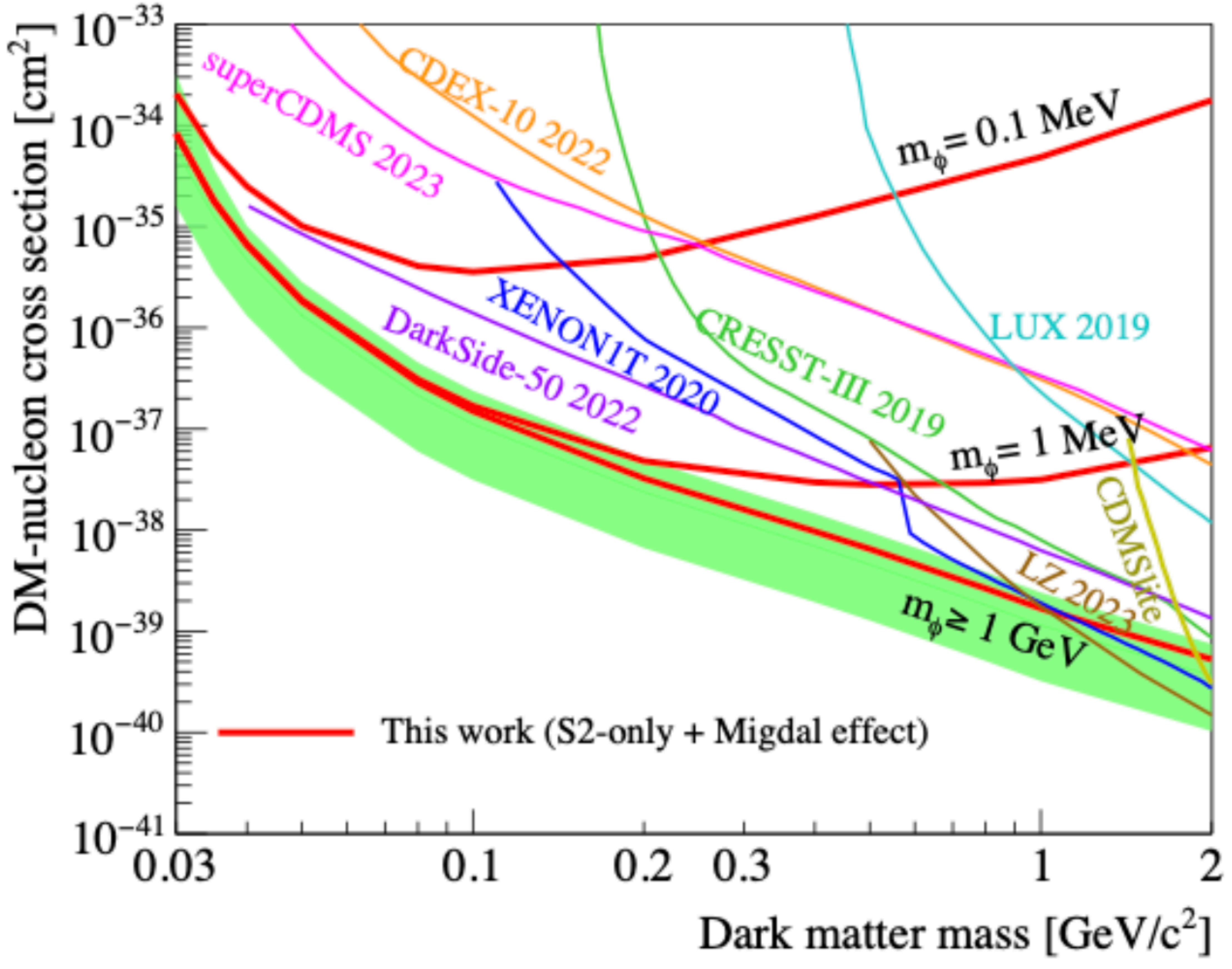
$N = n, p$

Short Distance

Only this term is considered in previous DMDD calculation

The Migdal effect and DM-electron scattering

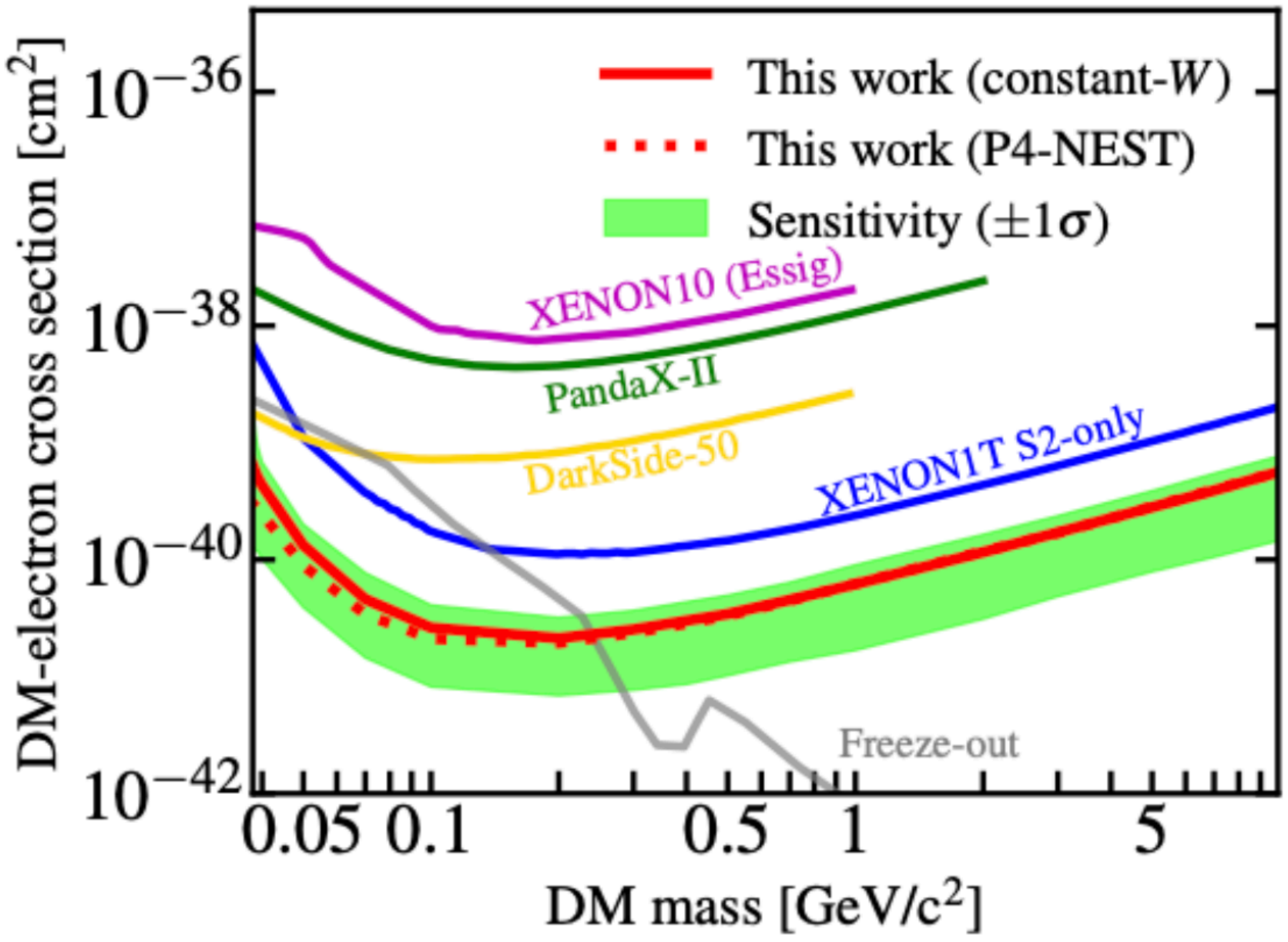
PandaX Collaboration, 2308.01540



Migdal effect

$30 \text{ MeV} \lesssim m_\chi \lesssim 2 \text{ GeV}$

PandaX Collaboration, 2212.10067

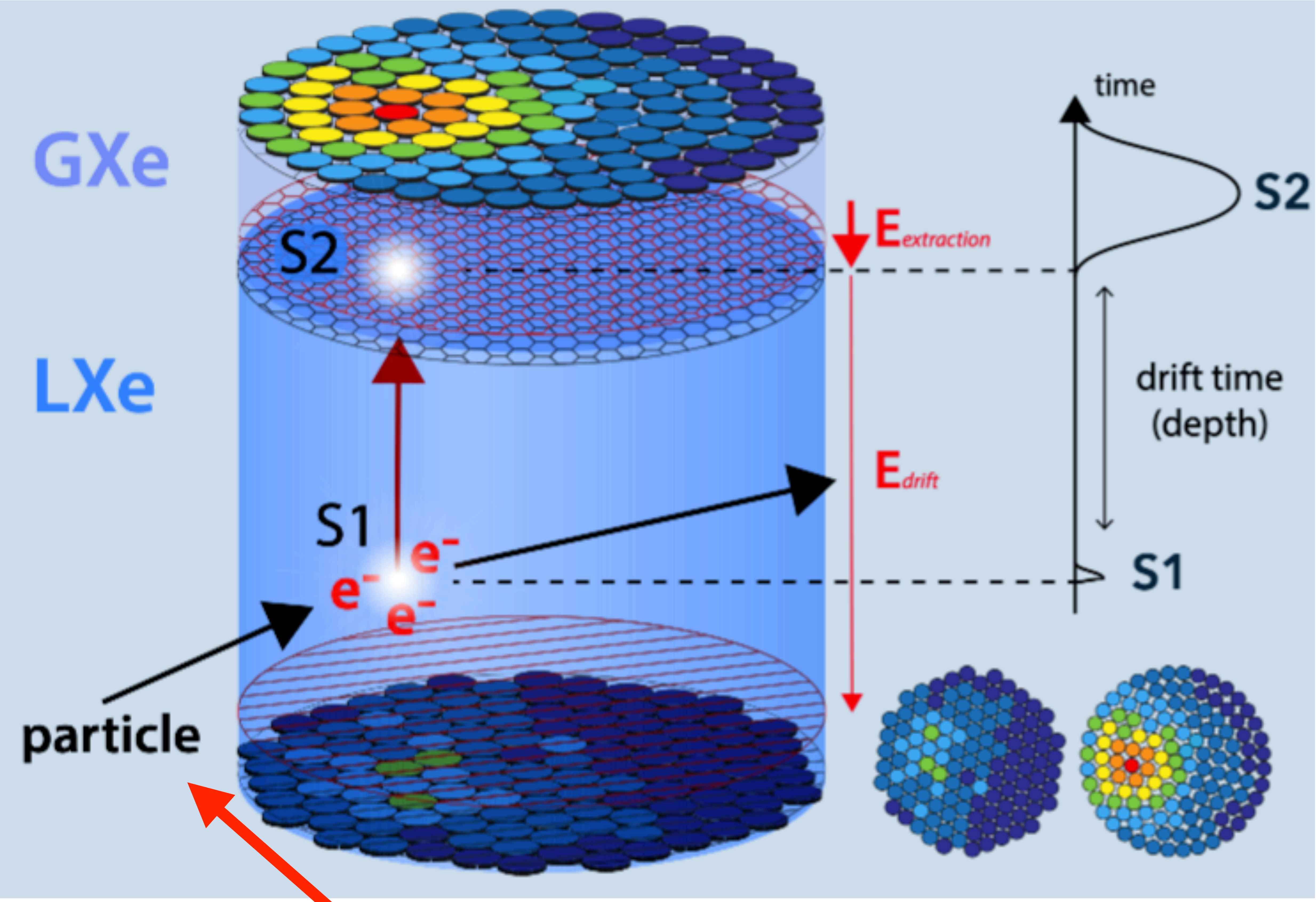


DM-electron

Down to ~ 5 MeV

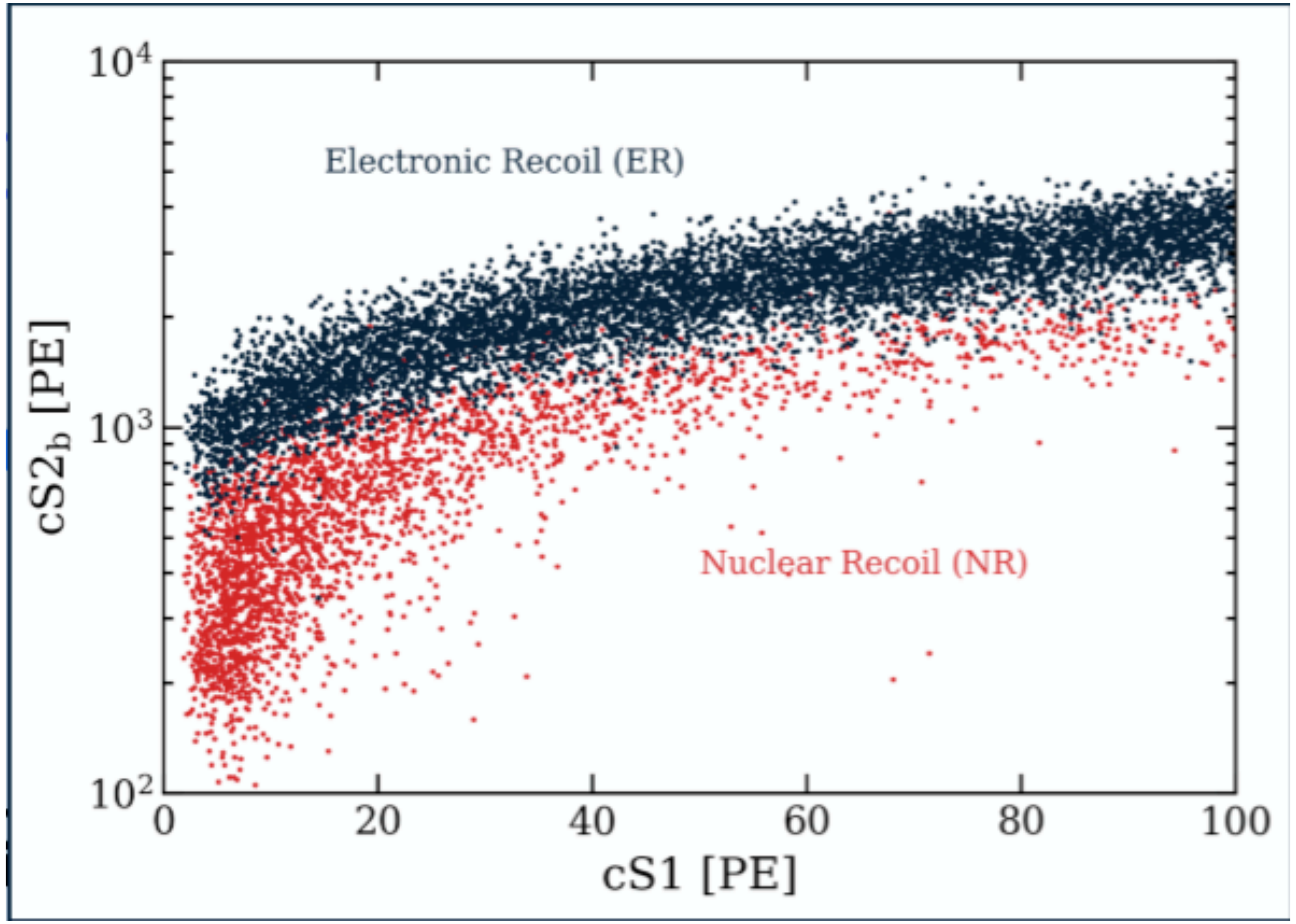
ER and NR signals at DMDD experiments

Dual-phase time projection chamber



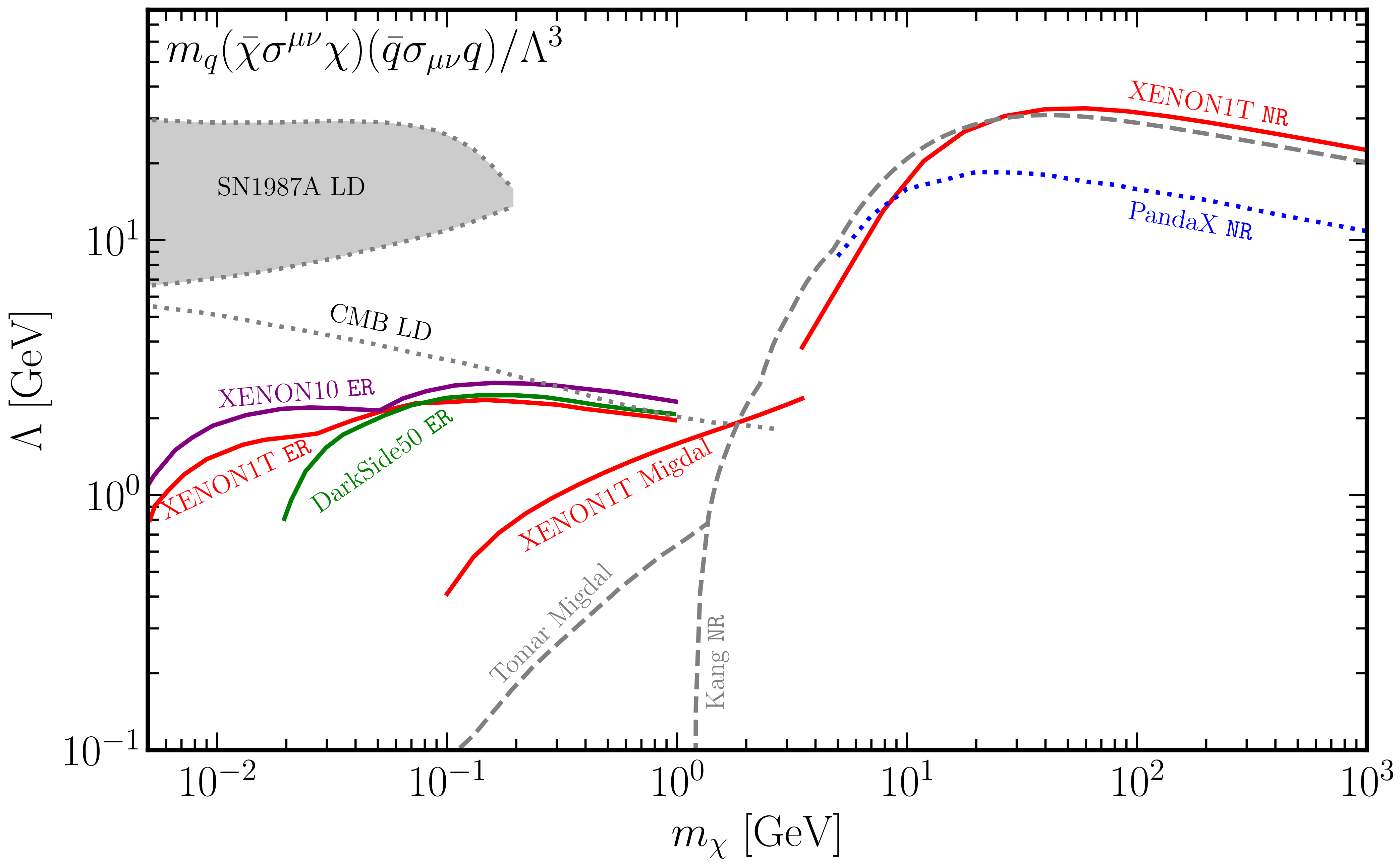
WIMP, $\rho \simeq 0.3\ \mathrm{GeV/cm^3}, v \simeq 10^{-3}c$

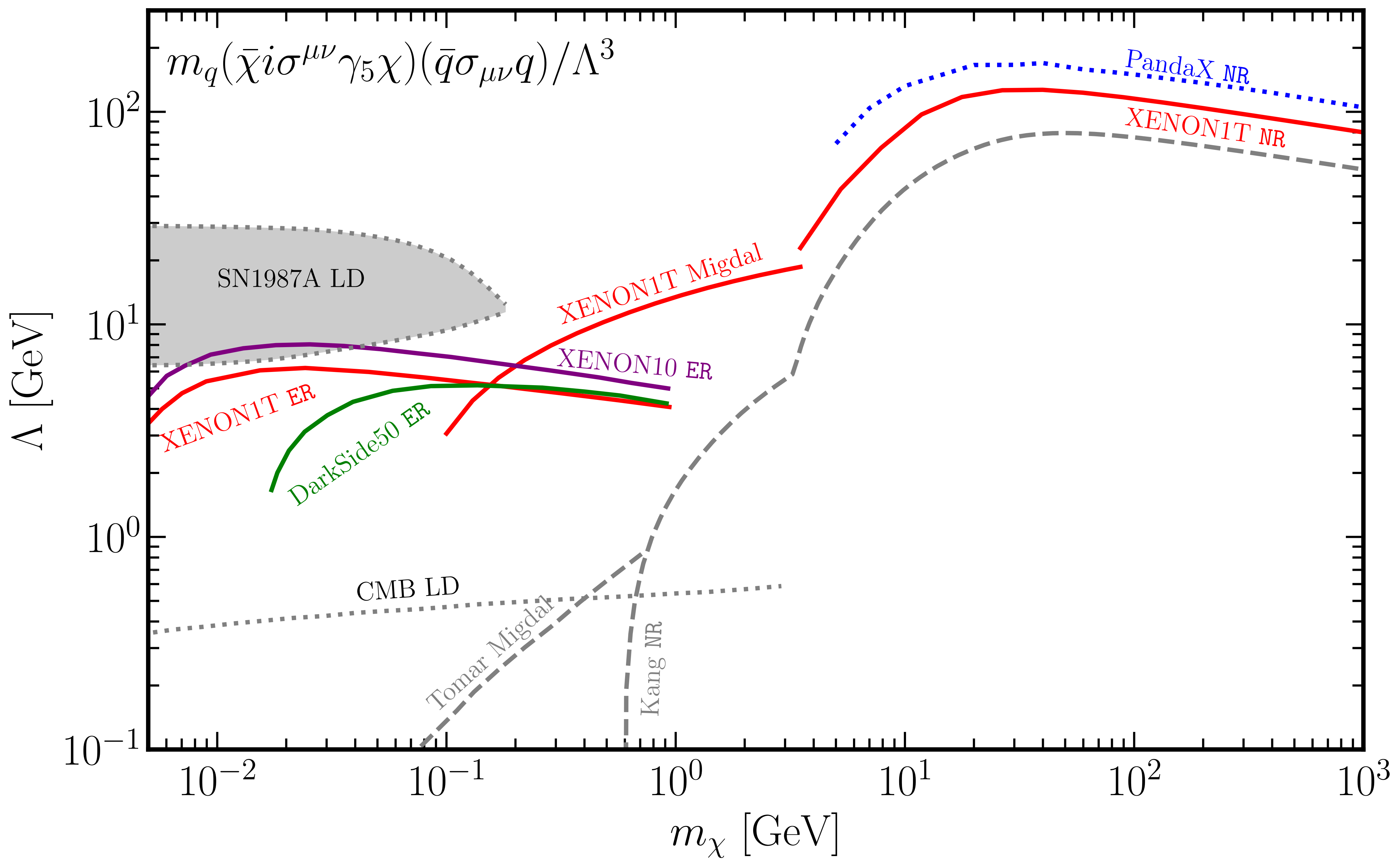
Separate ER and NR signals



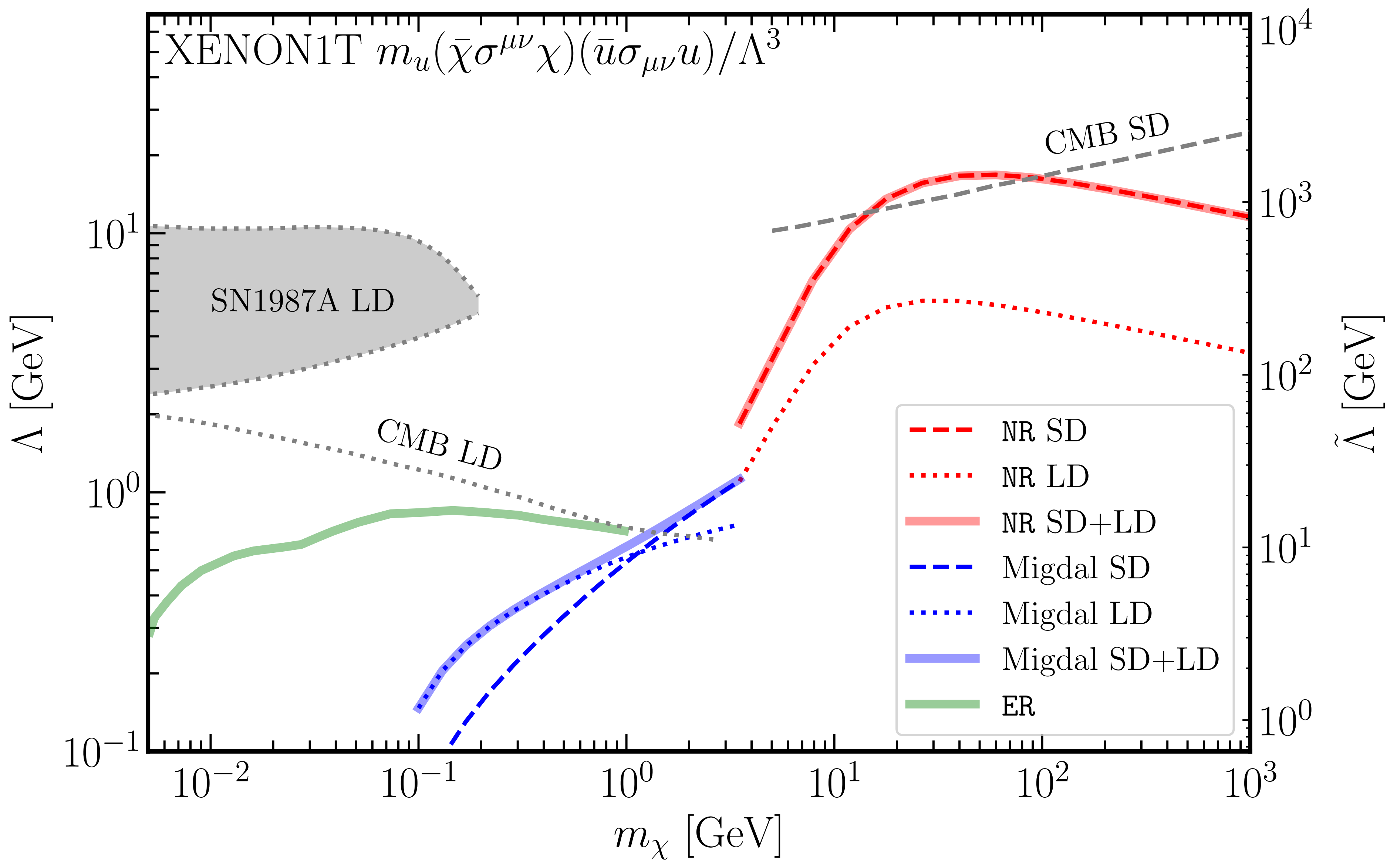
Talk of Evan Shockley, 2020

Constraints on EDM and MDM operators

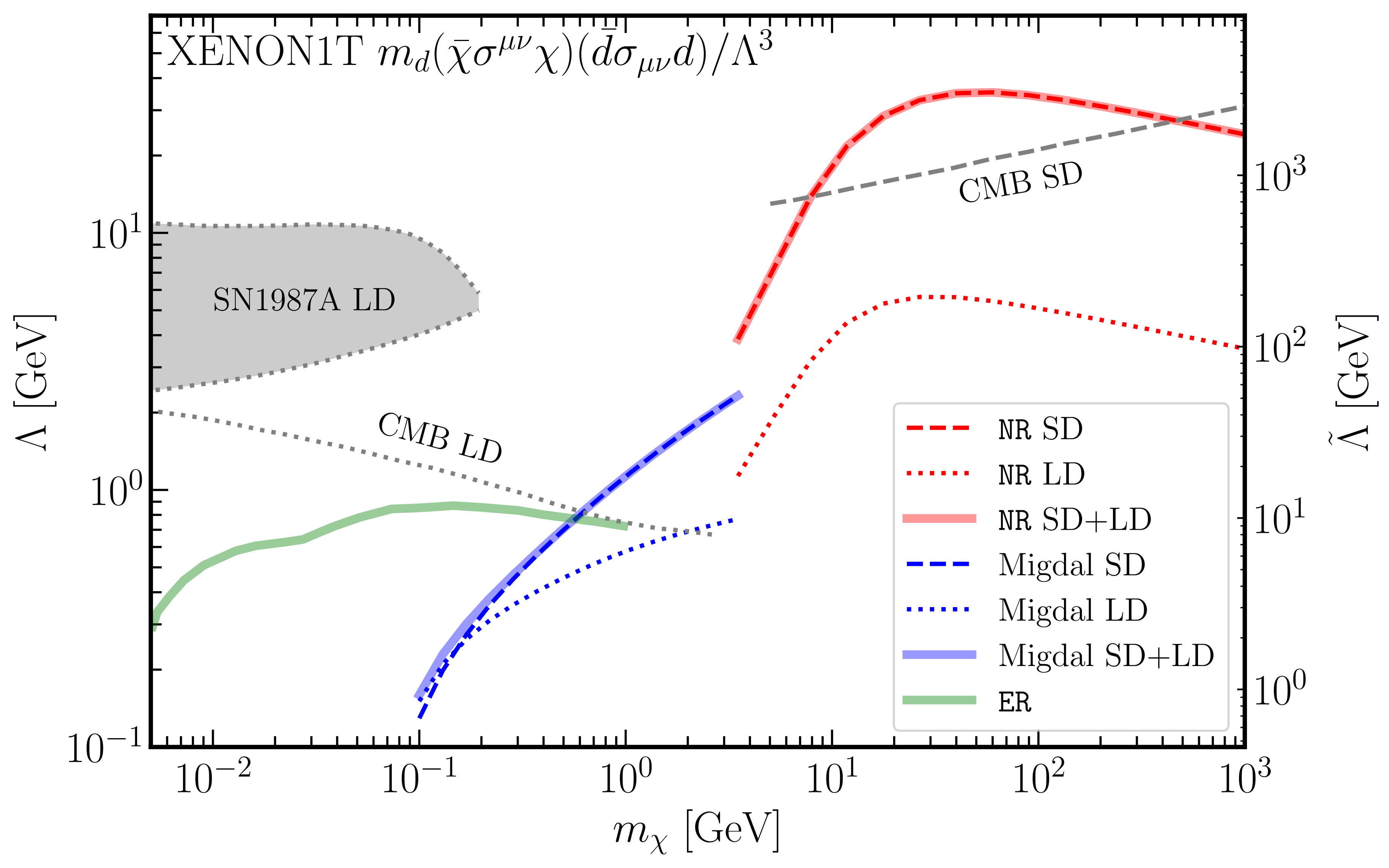


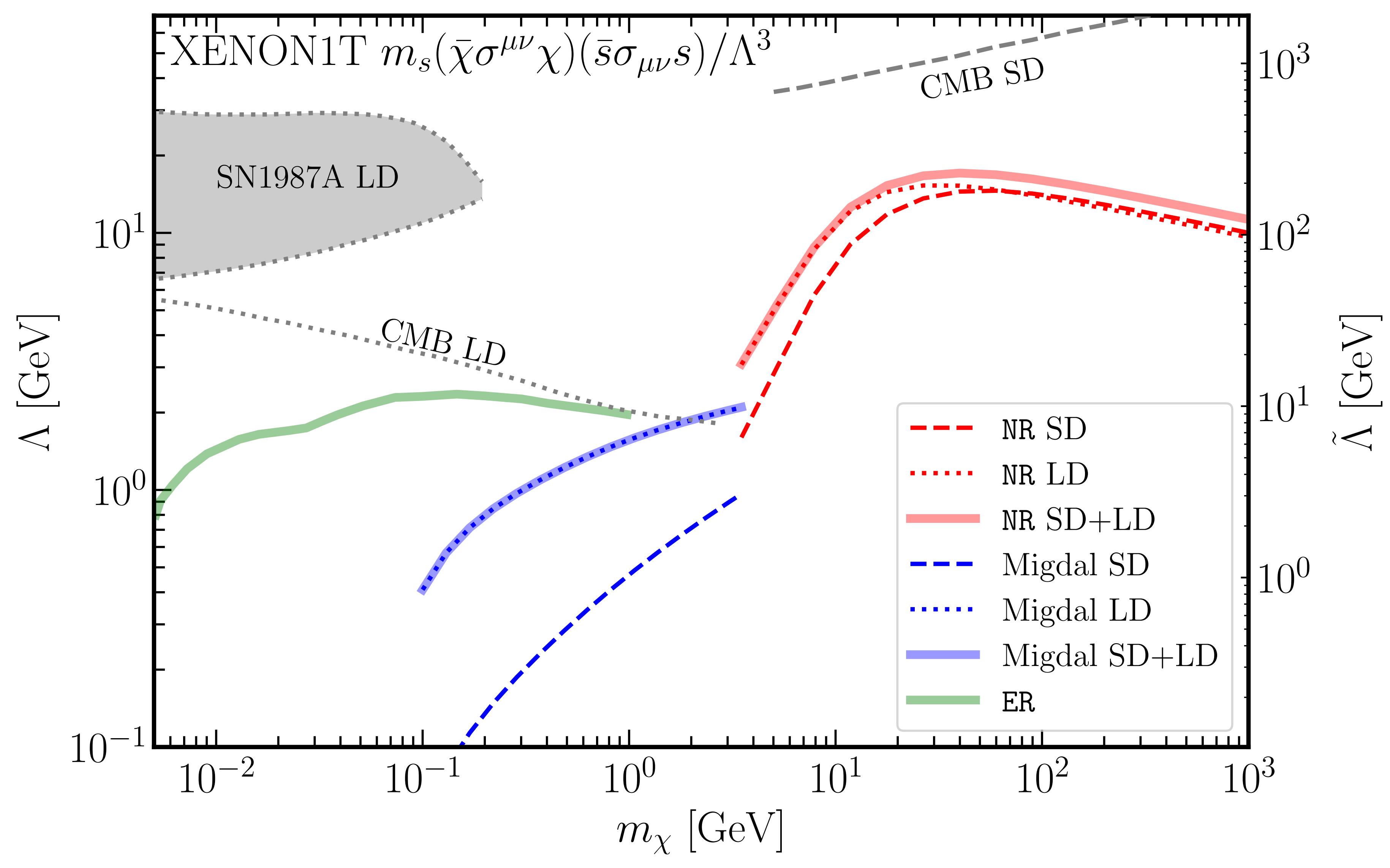


Constraints on MDM operators with specific flavor

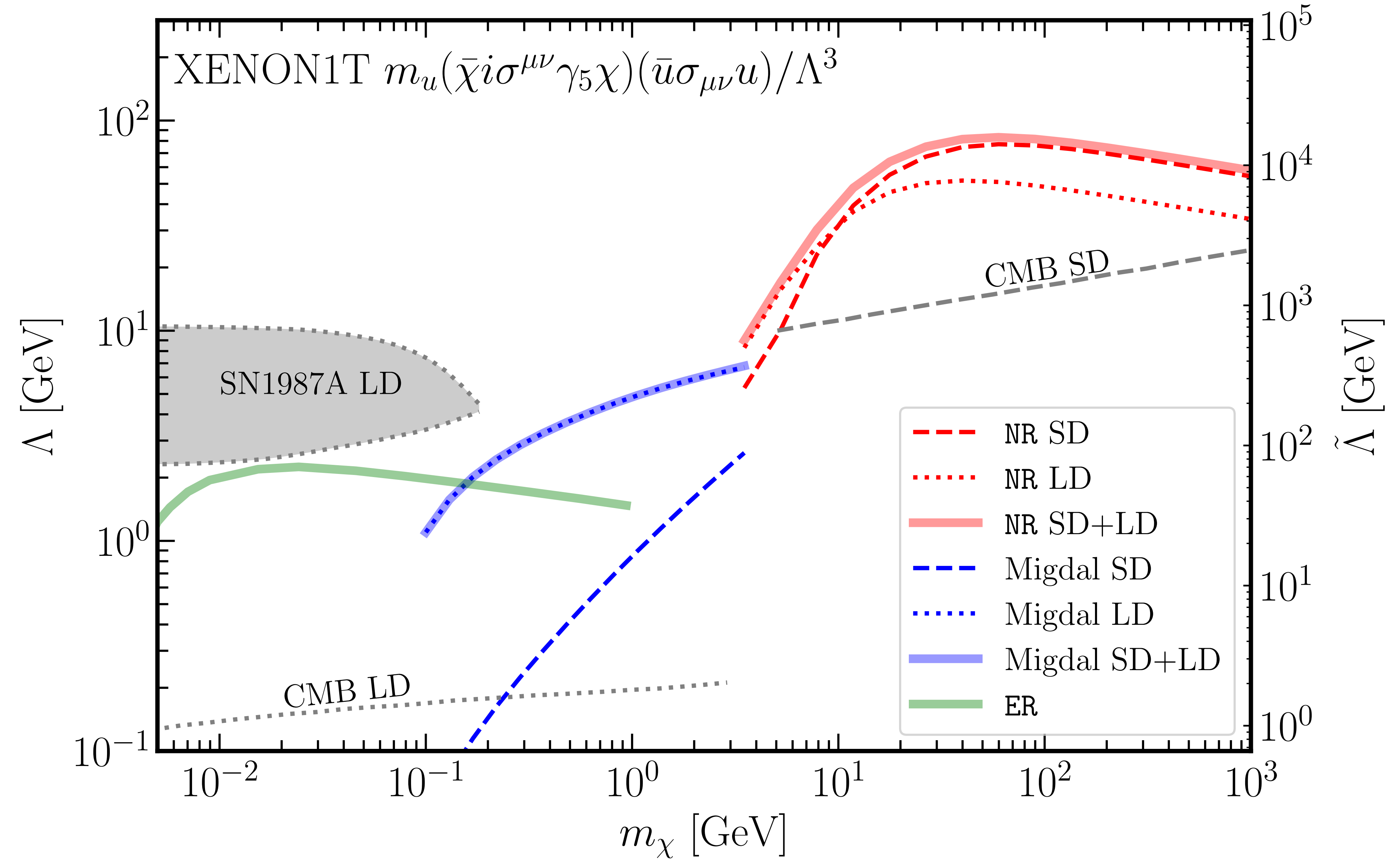


$$\tilde{\Lambda} = \Lambda\sqrt{\Lambda/m_q}$$





Constraints on EDM operators with specific flavor



$$\tilde{\Lambda} = \Lambda\sqrt{\Lambda/m_q}$$