Photon-mediated interactions in BULLKID-DM

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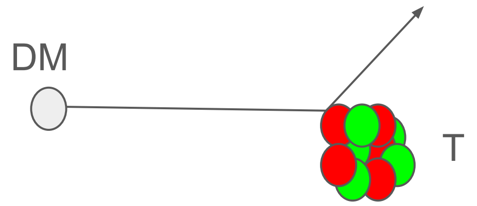
Dark matter-nucleon interactions

- We consider a 2 → 2 scattering between a Dark Matter particle χ and a nucleon *N* in a target nucleus T



- It is not ruled out the possibility of DM coupling to electromagnetic radiation
- Photon-mediated DM-nucleon interaction
  - DM couples to the photon and then interacts with the nucleons
  - DM exchanges photons with the nucleus, long range interaction

Dark matter-nucleon interactions: electromagnetic multipoles

- Interaction spin ½ DM with the photon

$$\mathcal{L}_{\rm int} = \epsilon_\chi e \overline{\chi}\gamma^\mu \chi A_\mu + \frac{\mu_\chi}{2}\overline{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{d_\chi}{2} i\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} + c_A\overline{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + b_\chi\overline{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}$$

millicharge | magnetic dipole moment | electric dipole moment | anapole moment | charge radius

- If the momentum transfer and the relative velocity are small, the most general interaction lagrangian is

$$\mathcal{L} = \sum_i c_i \mathcal{O}_i$$

- With non-relativistic effective field theory operators $\mathcal{O}_i$

Non-Relativistic Effective Field Theory (NREFT)

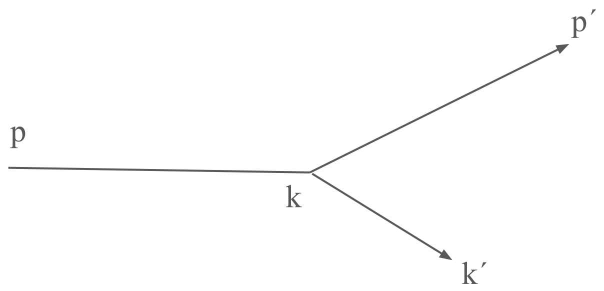
- Developed for elastic scattering in direct detection
- Identify DM-nucleus response functions to characterize DM
- The momentum transfer is

$$q = p - p' = k' - k$$

- Galilean invariance and Hermiticity
- Effective operators are four-field operators of the form

$$\mathcal{L} = \chi \mathcal{O}_\chi \chi N \mathcal{O}_N N$$

- q^2 is a completely invariant scalar that depends only on DM kinematic quantities



NREFT

- DM spin ½ there are 4 Galilean invariants and 15 operators

$$\mathbf{S}_N,\ \mathbf{S}_\chi,\ i\mathbf{q},\ \mathbf{v}^\perp = \mathbf{v} + \frac{\mathbf{q}}{2\mu_N}$$

$$\mathcal{O}_1 \equiv 1_\chi 1_N,$$

$$\mathcal{O}_3 \equiv i\mathbf{S}_N \cdot \left(\frac{\mathbf{q}}{m_N} \times \mathbf{v}^\perp\right),$$

$$\mathcal{O}_4 \equiv \mathbf{S}_\chi \cdot \mathbf{S}_N,$$

$$\mathcal{O}_5 \equiv i\mathbf{S}_\chi \cdot \left(\frac{\mathbf{q}}{m_N} \times \mathbf{v}^\perp\right),$$

$$\mathcal{O}_6 \equiv \left(\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N}\right)\left(\mathbf{S}_N \cdot \frac{\mathbf{q}}{m_N}\right),$$

$$\mathcal{O}_7 \equiv \mathbf{S}_N \cdot \mathbf{v}^\perp,$$

$$\mathcal{O}_8 \equiv \mathbf{S}_\chi \cdot \mathbf{v}^\perp,$$

$$\mathcal{O}_9 \equiv i\mathbf{S}_\chi \cdot \left(\mathbf{S}_N \times \frac{\mathbf{q}}{m_N}\right),$$

$$\mathcal{O}_{10} \equiv i\mathbf{S}_N \cdot \frac{\mathbf{q}}{m_N},$$

$$\mathcal{O}_{11} \equiv i\mathbf{S}_\chi \cdot \frac{\mathbf{q}}{m_N},$$

$$\mathcal{O}_{12} \equiv \mathbf{v}^\perp \cdot \left(\mathbf{S}_\chi \times \mathbf{S}_N\right),$$

$$\mathcal{O}_{13} \equiv i\left(\mathbf{S}_\chi \cdot \mathbf{v}^\perp\right)\left(\mathbf{S}_N \cdot \frac{\mathbf{q}}{m_N}\right),$$

$$\mathcal{O}_{14} \equiv i\left(\mathbf{S}_\chi \cdot \frac{q}{m_N}\right)\left(\mathbf{S}_N \cdot \mathbf{v}^\perp\right),$$

$$\mathcal{O}_{15} \equiv \left(\mathbf{S}_\chi \frac{\mathbf{q}}{m_N}\right)\left(\mathbf{S}_N \cdot \left[\frac{\mathbf{q}}{m_N} \times \mathbf{v}^\perp\right]\right)$$

NREFT

- It is of some interest to study the electromagnetic interactions
  - Millicharge

$$\mathcal{L}_{\mathcal{M}} = e\epsilon_\chi A_\mu \overline{\chi}\gamma^\mu \chi \quad \rightarrow \quad \mathcal{O}_{\mathcal{M}} = e^2 \epsilon_\chi \frac{1}{q^2}\mathcal{O}_1$$

  - Magnetic dipole moment

$$\mathcal{L}_{\mathcal{MD}} = \frac{\mu_\chi}{2}\overline{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} \quad \rightarrow \quad \mathcal{O}_{\mathcal{MD}} = e\mu_\chi \sum_{N=n,p}\left[\frac{1}{2m_\chi}\mathcal{O}_1 + 2\frac{m_N}{q^2}\mathcal{O}_5 + g_N\left(\frac{1}{m_N}\mathcal{O}_4 - \frac{2m_N}{q^2}\mathcal{O}_6\right)\right]$$

  - Electric dipole moment

$$\mathcal{L}_{\mathcal{ED}} = \frac{d_\chi}{2}i\overline{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} \quad \rightarrow \quad \mathcal{O}_{\mathcal{ED}} = 2ed_\chi \frac{m_N}{q^2}\mathcal{O}_{11}$$

  - Anapole moment

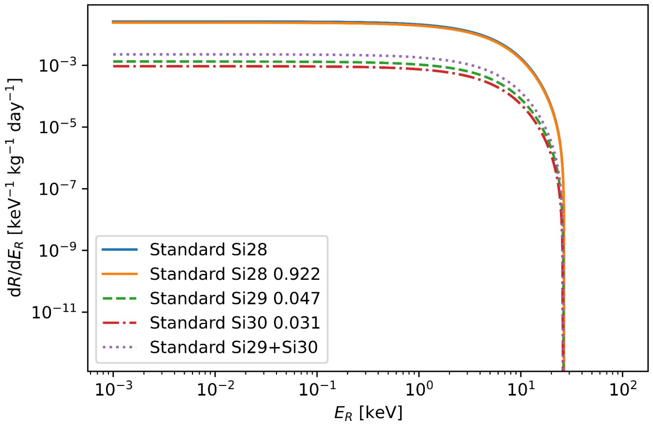
$$\mathcal{L}_{\mathcal{A}} = c_{\mathcal{A}}\overline{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} \quad \rightarrow \quad \mathcal{O}_{\mathcal{A}} = c_{\mathcal{A}}\left(2e\mathcal{O}_8 + [g_p + g_n]\mathcal{O}_9\right)$$

  - Charge radius

$$\mathcal{L}_{\mathcal{CR}} = b_\chi\overline{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu} \quad \rightarrow \quad \mathcal{O}_{\mathcal{CR}} = eb_\chi\mathcal{O}_1$$

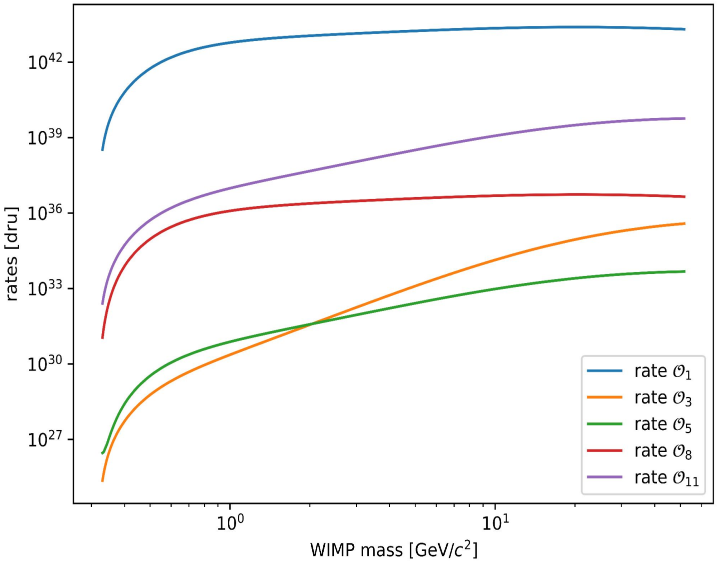
WIMpy

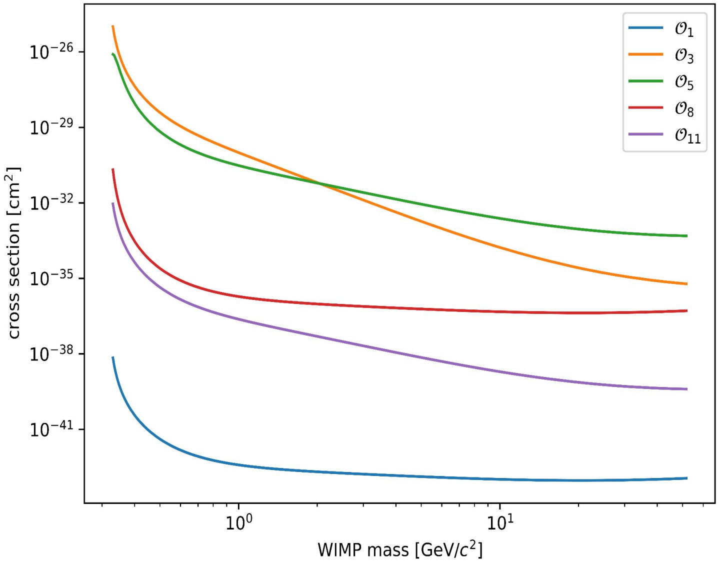
- WIMpy_NREFT is a python code developed by B. J. Kavanah & T. Edwards for calculating DM-Nucleus scattering rates in the framework of NREFT (https://github.com/bradkav/WIMpy_NREFT)
- Current version supports operators for spin 0, ½ and 1 DM as well as millicharge, anapole moment and magnetic dipole moment DM
- For BULLKID, we have considered that our target mass is pure ^{28}Si
  - Nuclear structure functions for ^{29}Si and ^{30}Si are not available in the NREFT framework



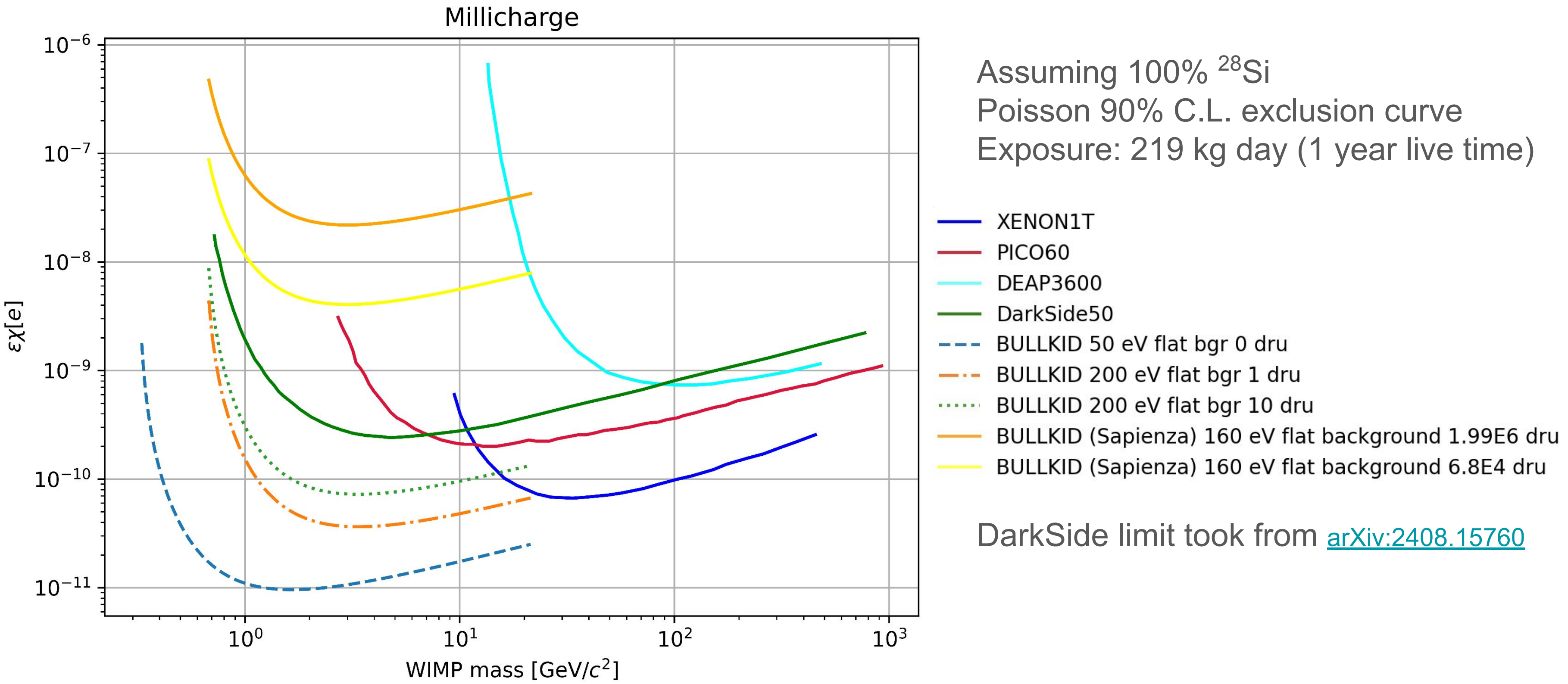
BULLKID-DM Sensitivity (NREFT)

- BULLKID is sensitive to spin-dependent operators (4.7% ^{29}Si) but for the analysis in WIMpy we cannot study them now
  - Operator 3 is sensitive to spin-orbit coupling rather than nuclear spin





BULLKID-DM Sensitivity (NREFT) without Migdal



Assuming 100% ^{28}Si
Poisson 90% C.L. exclusion curve
Exposure: 219 kg day (1 year live time)

DarkSide limit took from arXiv:2408.15760

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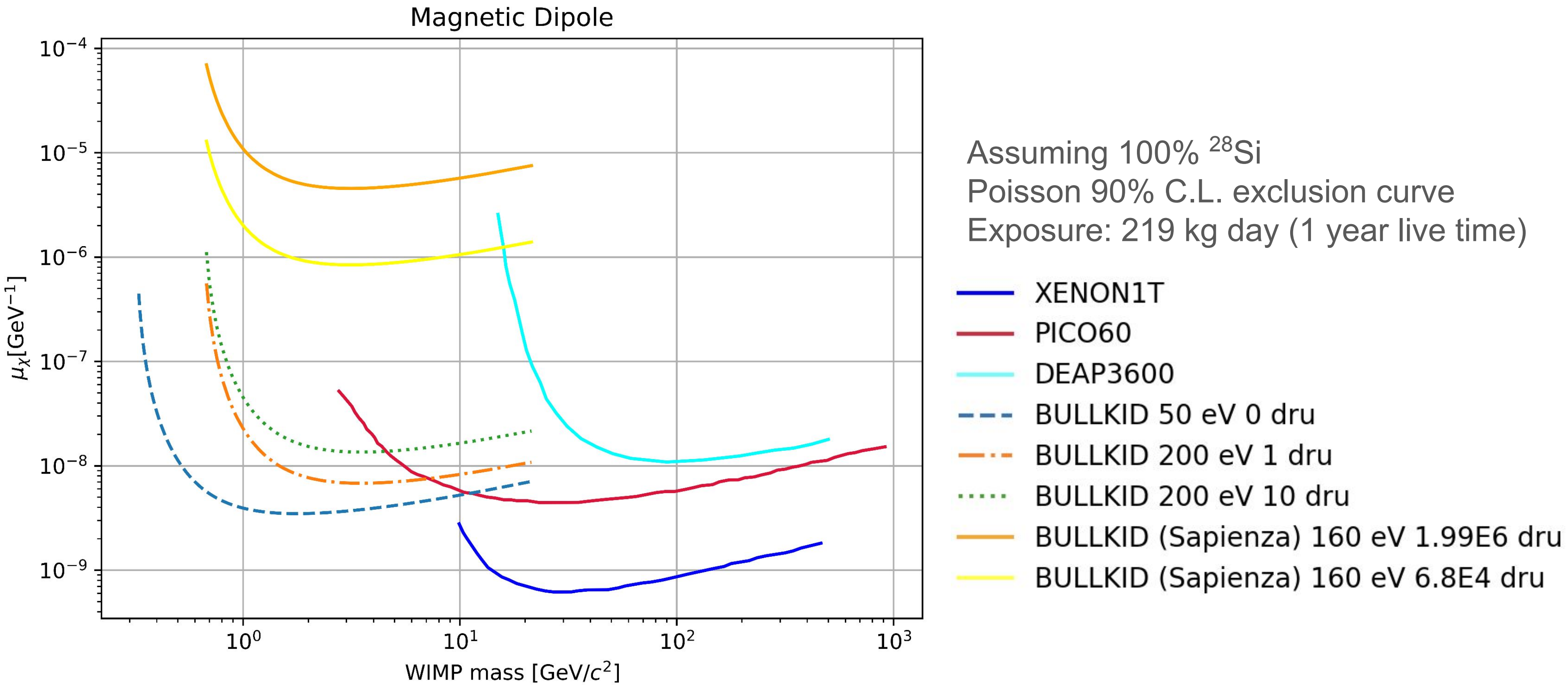

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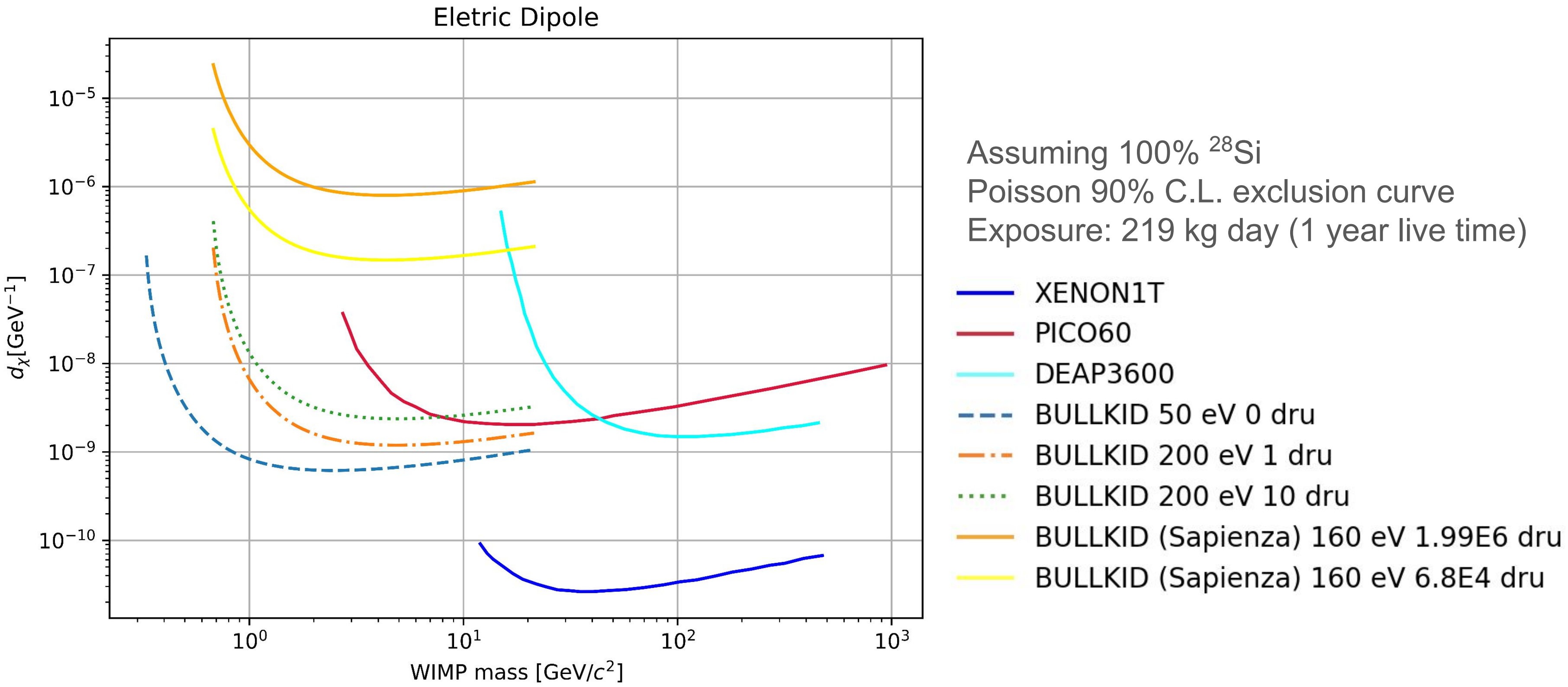

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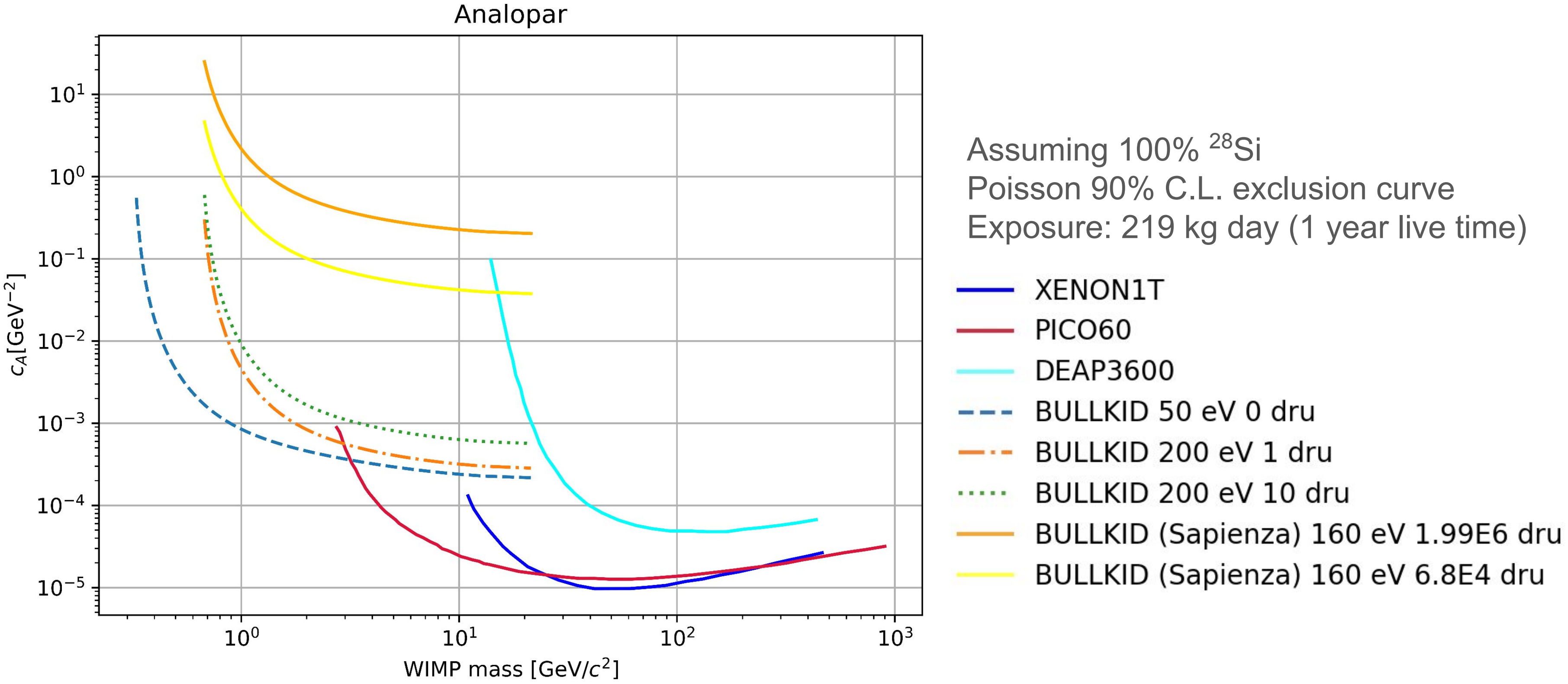

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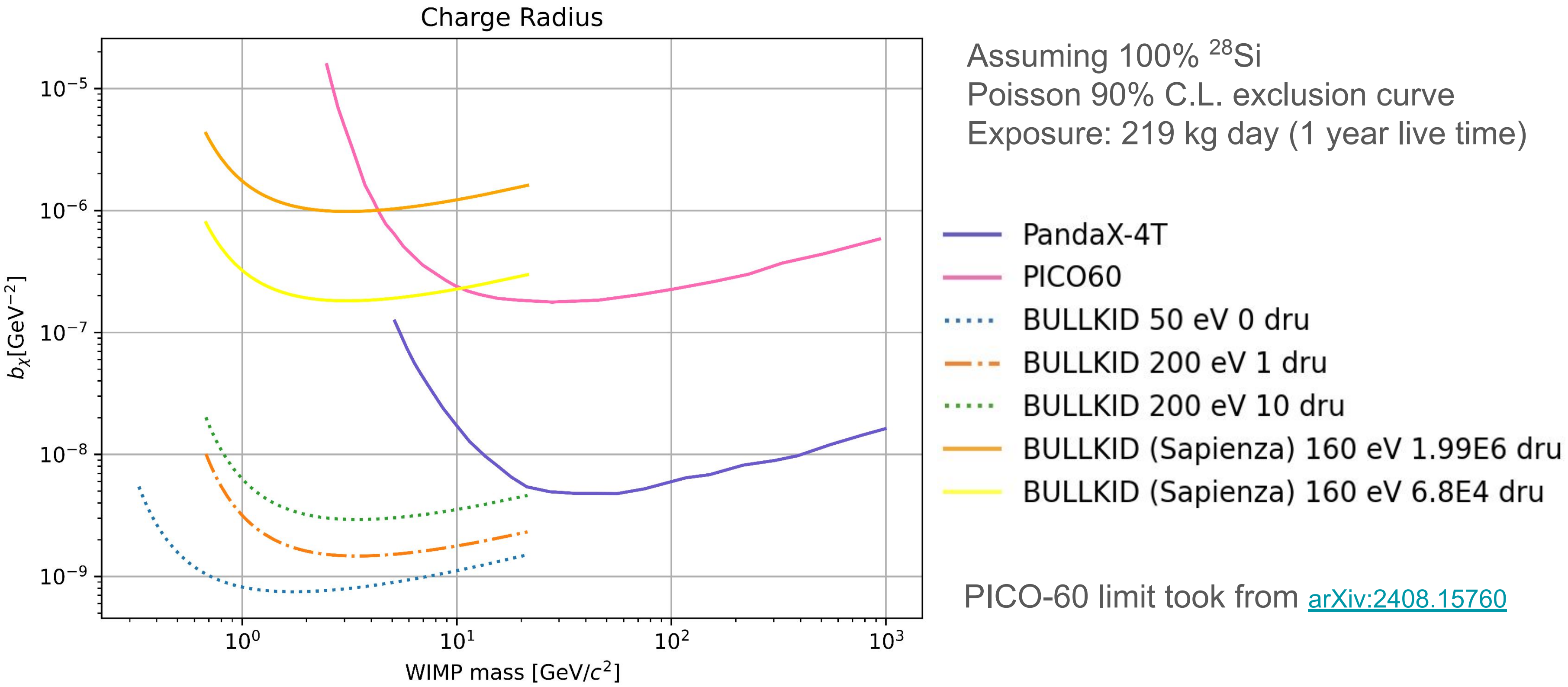

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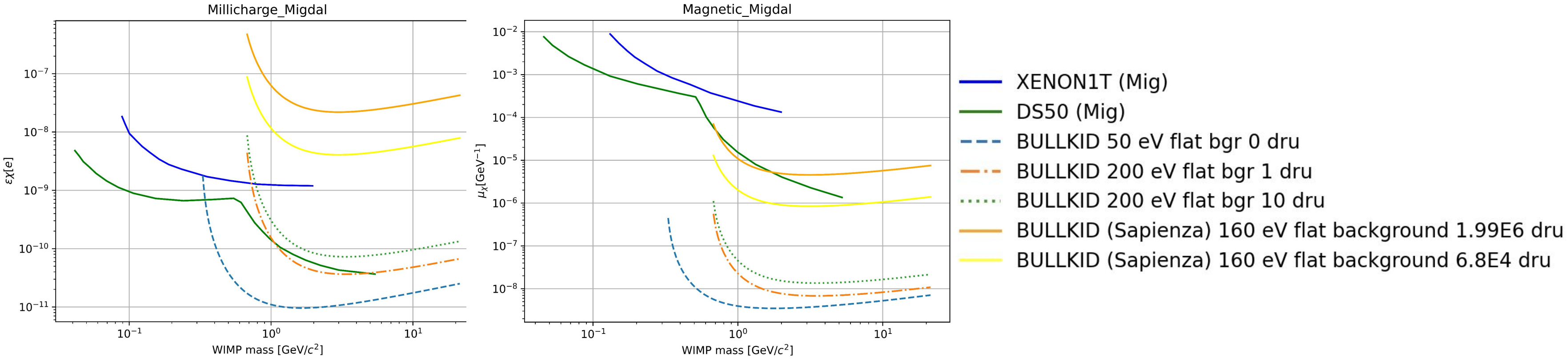
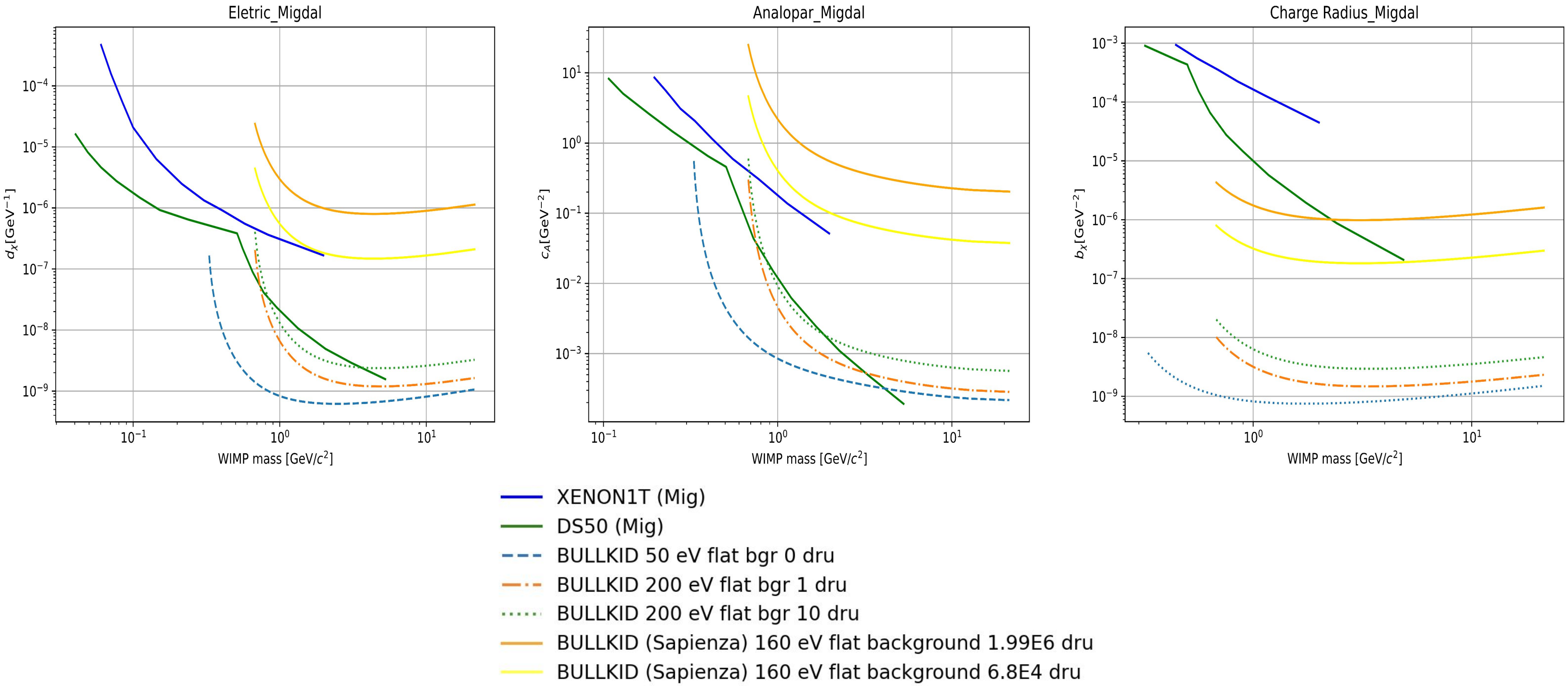
PICO-60 limit took from arXiv:2408.15760

BULLKID-DM (NREFT) Migdal

- Many Collaborations have been extending the range of their limits for Spin-Dependent (SD) and Spin-Independent through Migdal effect
- Some authors are considering Migdal effect to put limits for the electromagnetic properties of DM



BULLKID-DM (NREFT) Migdal



Next steps

- Study how to include the spin-dependent operators in the NREFT framework
  - other codes, estimations on the nuclear structure functions for ^{29}Si and ^{30}Si
- Consider electron and nuclear recoils
- Check Migdal effect for BULLKID
- Aim for a publication
  - Surface and sensitivity limits

Further readings

- NREFT
  - A. Liam Fitzpatrick *et al* JCAP02(2013)004 (arXiv:1203.3542v3)
  - E. Del Nobile, Lect. Notes Phys. 996 (2022) (arXiv:2104.12785v1)
- PICO-60 and XENON1T exclusion limits NREFT
  - PICO Collaboration, Phys. Rev. D 106, 042004(2022) (arXiv:2204.10340v1)
- DEAP-3600 exclusion limits NREFT
  - DEAP Collaboration, Phys. Rev. D 102, 082001 (2020) (arXiv:2005.14667v3)
- PandaX-4T exclusion limits NREFT
  - PandaX Collaboration, Nature 618, 47–50 (2023)
- Migdal in semiconductors
  - Knapen S. *et al* Phys. Rev. Lett. 127,081805 (arXiv:2011.09496)