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Direct detection and cosmological constraints of dark matter with dark dipoles

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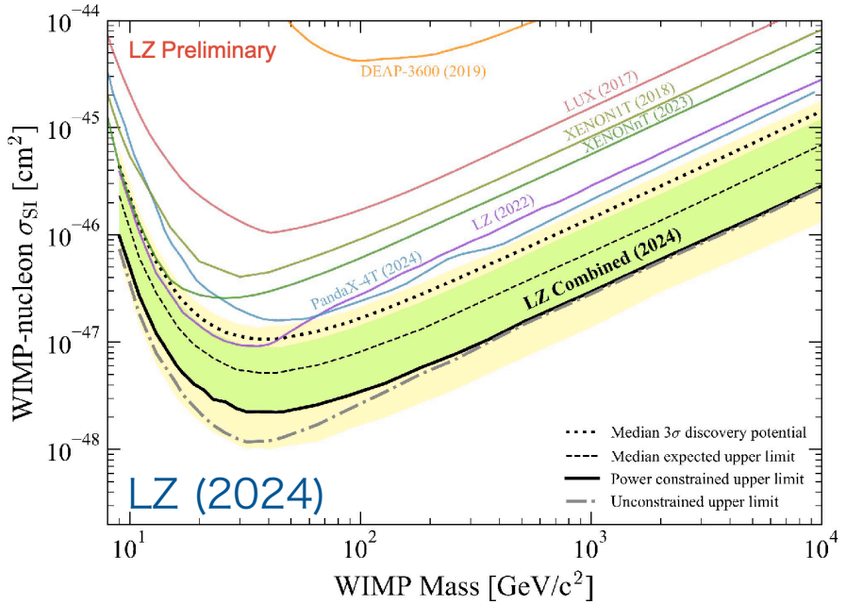
in collaborations with
J-C, Wang (Peking U. -> HKUST), S. Yuan (Peking U.) (JHEP 07 2026 138, 2602.06861)

SubGeV-to-GeV DM

Particle WIMPs face constraints from direct/indirect detection experiments

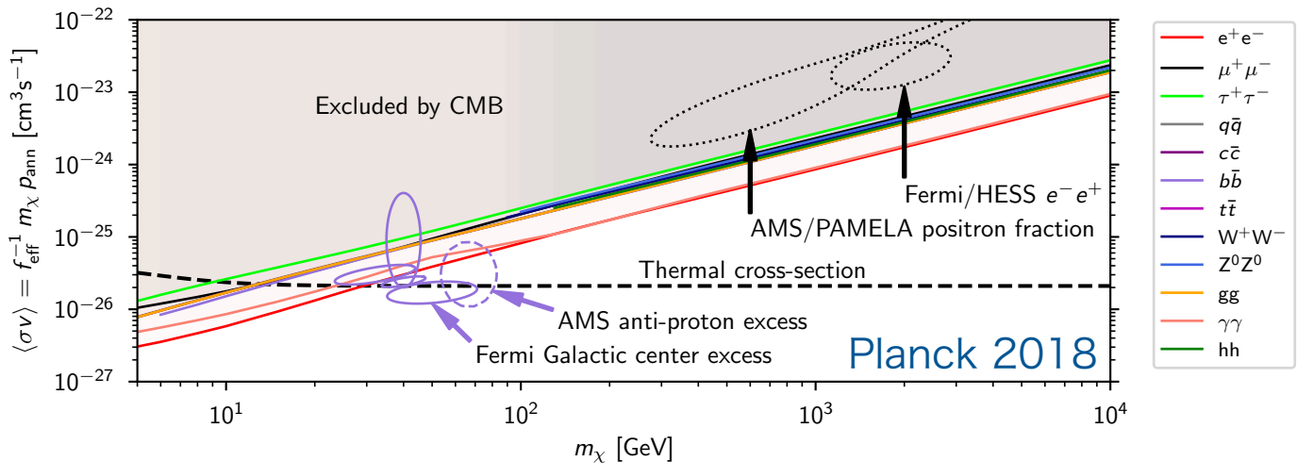
Several ways to escape from constraints have been proposed

- (sub-)GeV scale mass
- inelastic scattering
- velocity/momentum transfer suppression
- ...



(Sub-)GeV DM

- ✦ weaker constraints from Xe-based DD
- ✦ strong constraints on annihilation into SM particles (s-wave): cosmic-ray and CMB



Dark Dipole

Dirac Fermionic DM χ + Massive Vector-portal U(1) A':

$$\mathscr{L}_{\text{portal}} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$

DM-Portal Couplings

- DM charged under U(1)

  current coupling to A' $\quad \mathscr{L} \supset ie'A'_\mu\bar{\chi}\gamma^\mu\chi$

- DM neutral under U(1)

  no renormalizable coupling to A'

  possible couplings: **dipole interactions** $\quad \mathscr{L} \supset \frac{i}{2}d_\chi\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F'_{\mu\nu} + \frac{1}{2}\mu_\chi\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu}$

  Possible realizations:

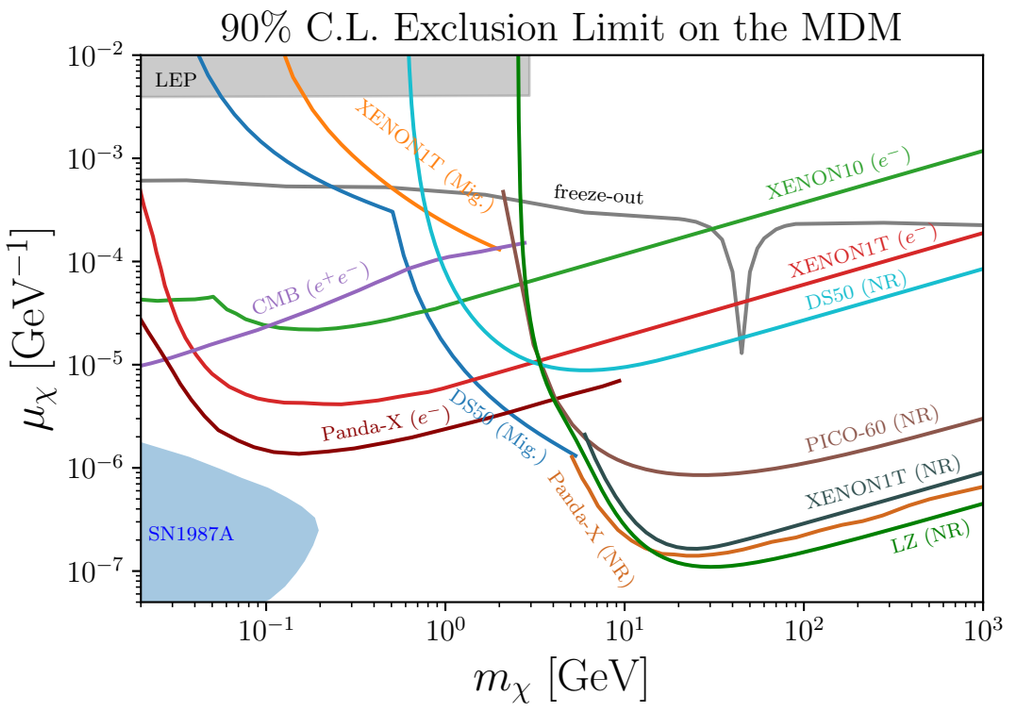
  - Dark neutrinos (via loop contributions)
  - Dark neutrons (dark strong dynamics)
  - etc

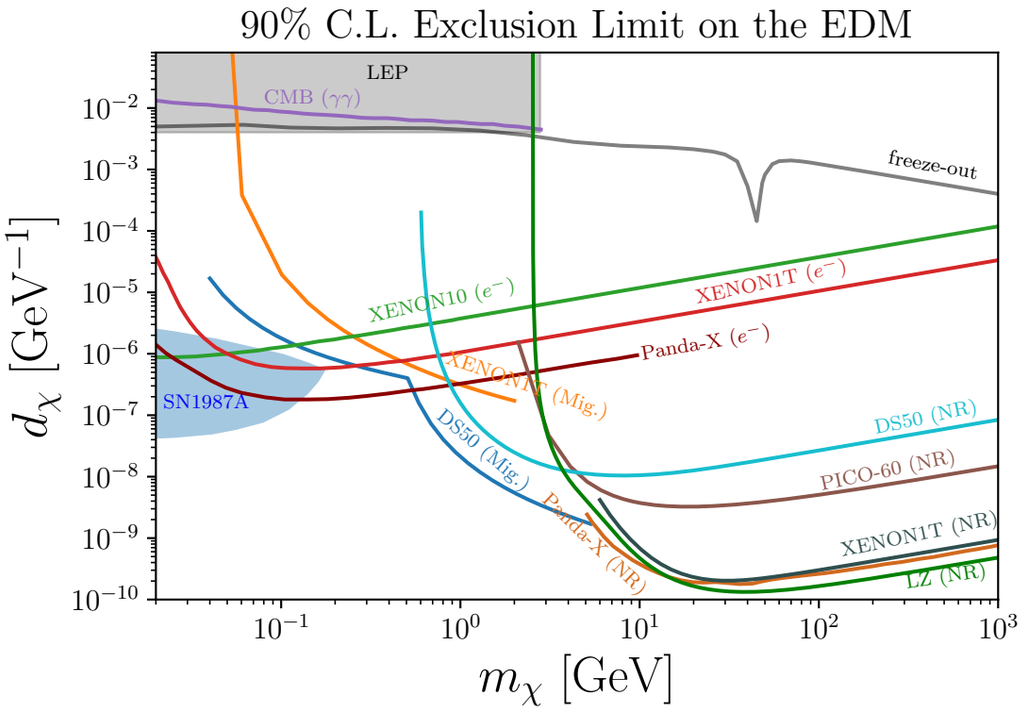
Electromagnetic dipoles

instead of dark dipoles

Sigurdson, Doran, Kurylov, Caldwell, Kamionkowski (2004)
Masso, Mohanty, Rao (2009)

$$\mathscr{L} \supset \frac{i}{2} d_\chi \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu} + \frac{1}{2} \mu_\chi \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu}$$





Ibarra, Reichard, Tomar (2024)

thermal DM with electromagnetic dipoles has been already covered

Annihilation and Scattering

Annihilation $\chi\bar{\chi} \to f\bar{f}$

$$\sigma_{\chi\bar{\chi}\to f\bar{f}} v \propto Q_f^2 \alpha \epsilon^2 \left(\frac{d_\chi^2 v^2}{12} + \mu_\chi^2 \right) \qquad m_\chi \lesssim m_{A'}$$

$$\sigma_{\chi\bar{\chi}\to \mathrm{had}} v = R(e^- e^+ \to \mathrm{had}) \sigma_{\chi\bar{\chi}\to\mu\bar{\mu}} v$$

Indirect detection (Late-time Cosmic-ray and CMB)

EDM contributes as p-wave, while MDM does as s-wave

cf.) $\chi\bar{\chi} \to A'A'$ (massless) $\qquad \sigma_{\chi\bar{\chi}\to A'A'} v \simeq \frac{m_\chi^2}{4\pi}(\mu_\chi^2 + d_\chi^2)^2$

Scattering $\chi f \to \chi f$ via dipole interactions

$$\sigma_{\chi f\to\chi f} = Q_f^2 \alpha \epsilon^2 \mu_{\chi f}^2 \frac{q^2}{(q^2 + m_{A'}^2)^2} \left[4d_\chi^2 + \mu_\chi^2 \left(1 - \frac{2m_f}{m_\chi} \right) \frac{q^2}{m_f^2} \right]$$

Direct detection

MDM is suppressed by momentum transfer q^2 than EDM

Constraints

DM with dark dipole interaction with $m_\chi \leq 10\,\mathrm{GeV}$

Direct Detection

- Nuclear recoil with argon detector (smaller NR threshold than Xe): DarkSide
- Electron recoil: XENON S2 etc...
- Silicon detector: SENSEI and DAMIC-M, ...

Existing Constraints

- Late-time energy injection, CMB and BBN constraints
- Cosmic-ray observations ($e^\pm$ and γ)

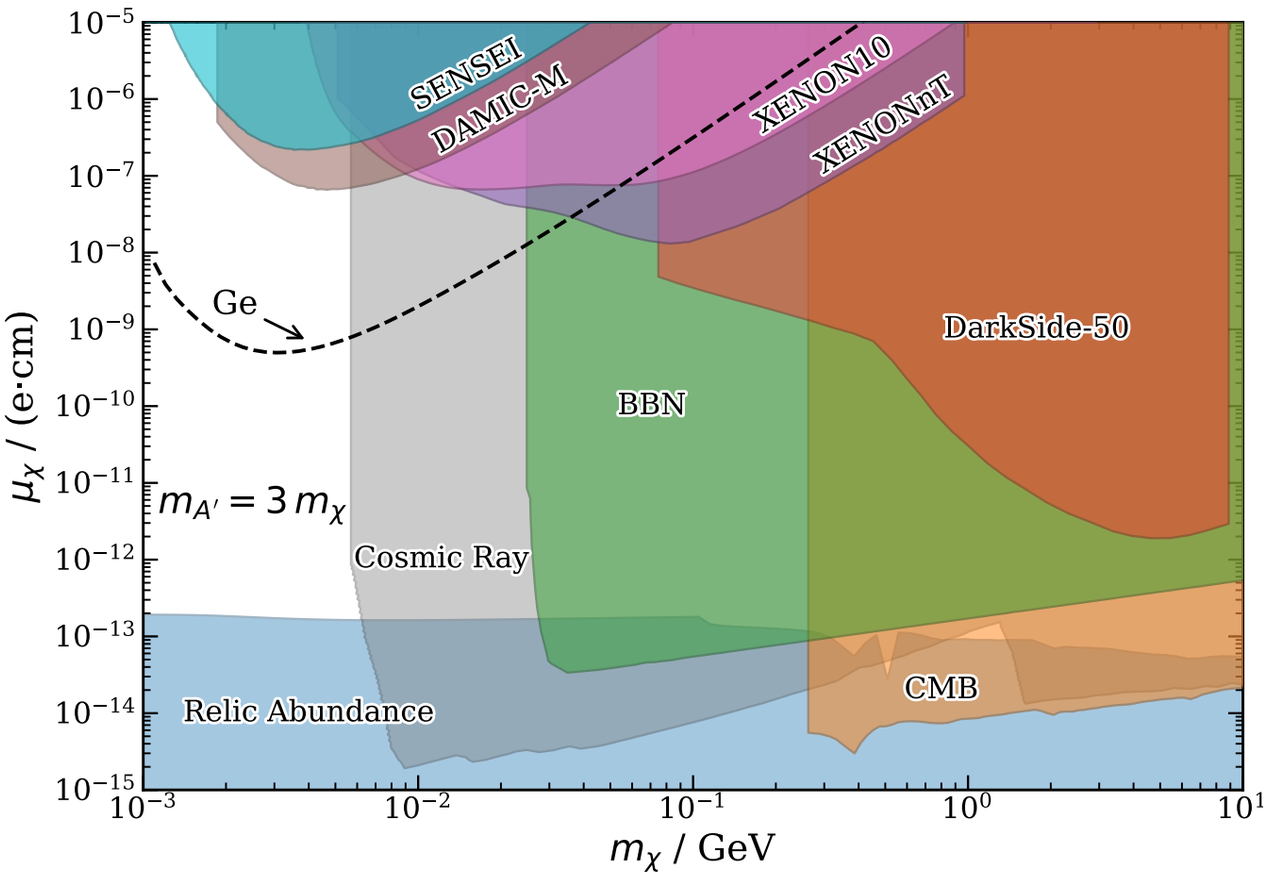
- Dark photon visible decay signals (collider, beam-dump, ...) for $m_{A'} < m_\chi$

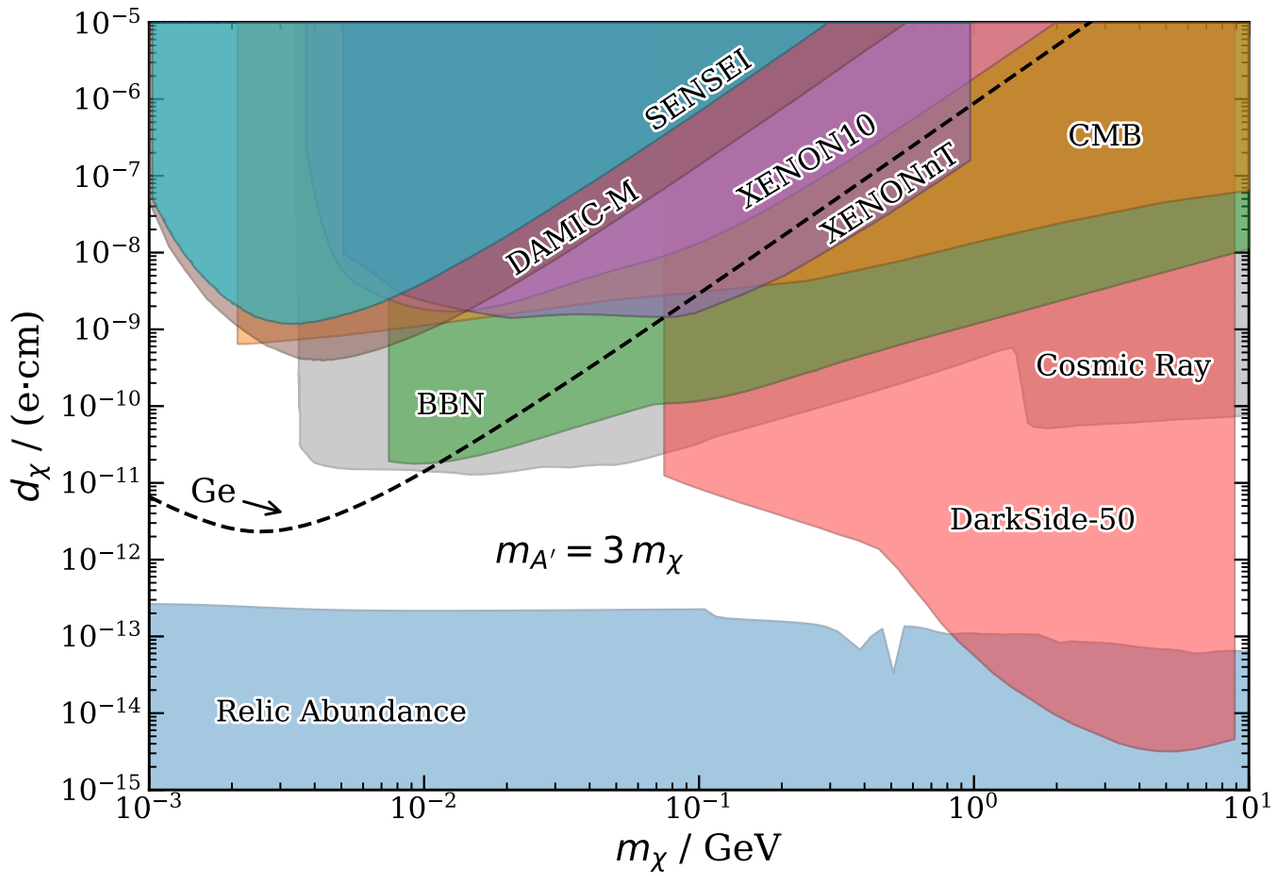
Direct detection Constraints

TK, Yuan, Wang (2026)

heavier mediator ($m_{A'} = 3m_\chi$)

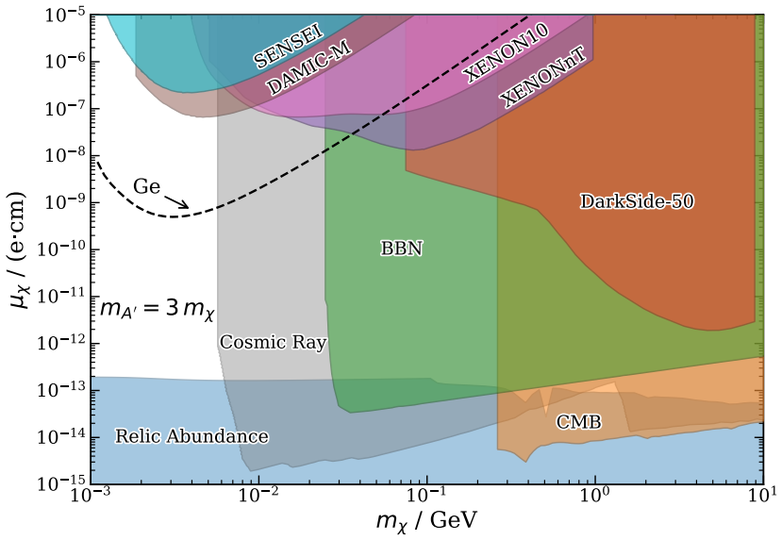
$\epsilon = 10^{-3}$

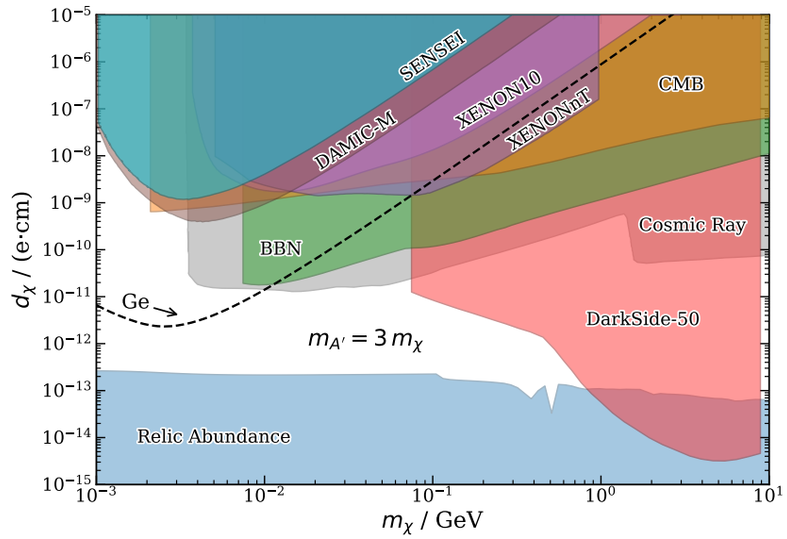




Allowed window: $m_\chi \lesssim 10\,\mathrm{MeV}$ for MDM and $m_\chi \lesssim 1\,\mathrm{GeV}$ for EDM

Implication for EFTs





Perturbative generation of dipole interactions (EFT)

$$\mu_\chi \sim \frac{c_\mu}{\Lambda}, \quad d_\chi \sim \frac{c_d}{\Lambda}$$

Cutoff scale $\mu_\chi, d_\chi \simeq 6 \times 10^{-15}\, e\,\mathrm{cm} \left(\frac{1\,\mathrm{GeV}}{\Lambda}\right)$

viable window: corresponding to $\Lambda \lesssim 10\,\mathrm{MeV}$ for $\epsilon = 10^{-3}$

Dependence on ϵ : $\mu_\chi, d_\chi \propto \epsilon^{-1}$

both annihilation and scattering cross sections prop to $\mu_\chi^2\epsilon^2, d_\chi^2\epsilon^2$

Dark Neutron-like States

DM = neutron-like fermionic composite particle in hidden confinement sector

A composite realization of Asymmetric DM

Ibe, Kamada, Nakano, Kobayashi (2018)
Ibe, TK, Kamada, Nakano, Kobayashi (2019)

"neutron-like": no current interaction to dark photon

$$\mathscr{L} \supset \frac{1}{2}\mu_\chi \bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu}$$

arises from MDM of dark quarks

Assume Bohr magneton scaling:

$$\mu_\chi = \frac{e'}{2m_\chi} \simeq 10^{-16}\, e\,\mathrm{cm}\left(\frac{1\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\alpha'}{\alpha}\right)^{1/2}$$

Dark Neutron-like States

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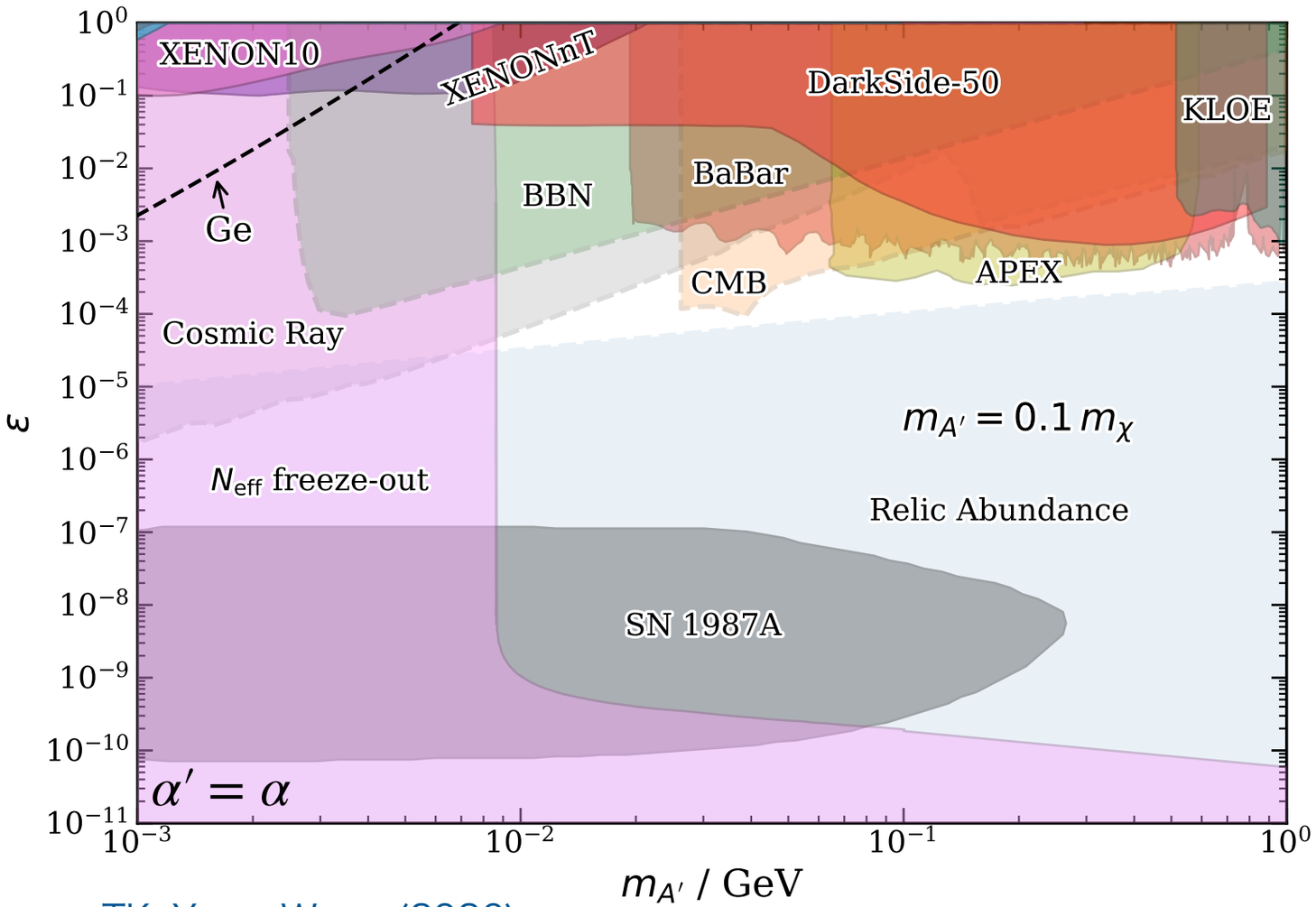


TK, Yuan, Wang (2026)

Lighter mediator:

Constraints on A' decay

- SN 1987A — Chang et al (2016)
- $N_{\rm eff}$ from CMB — Ibe et al (2020)
- Collider experiments

(beam-dump constraints not listed)

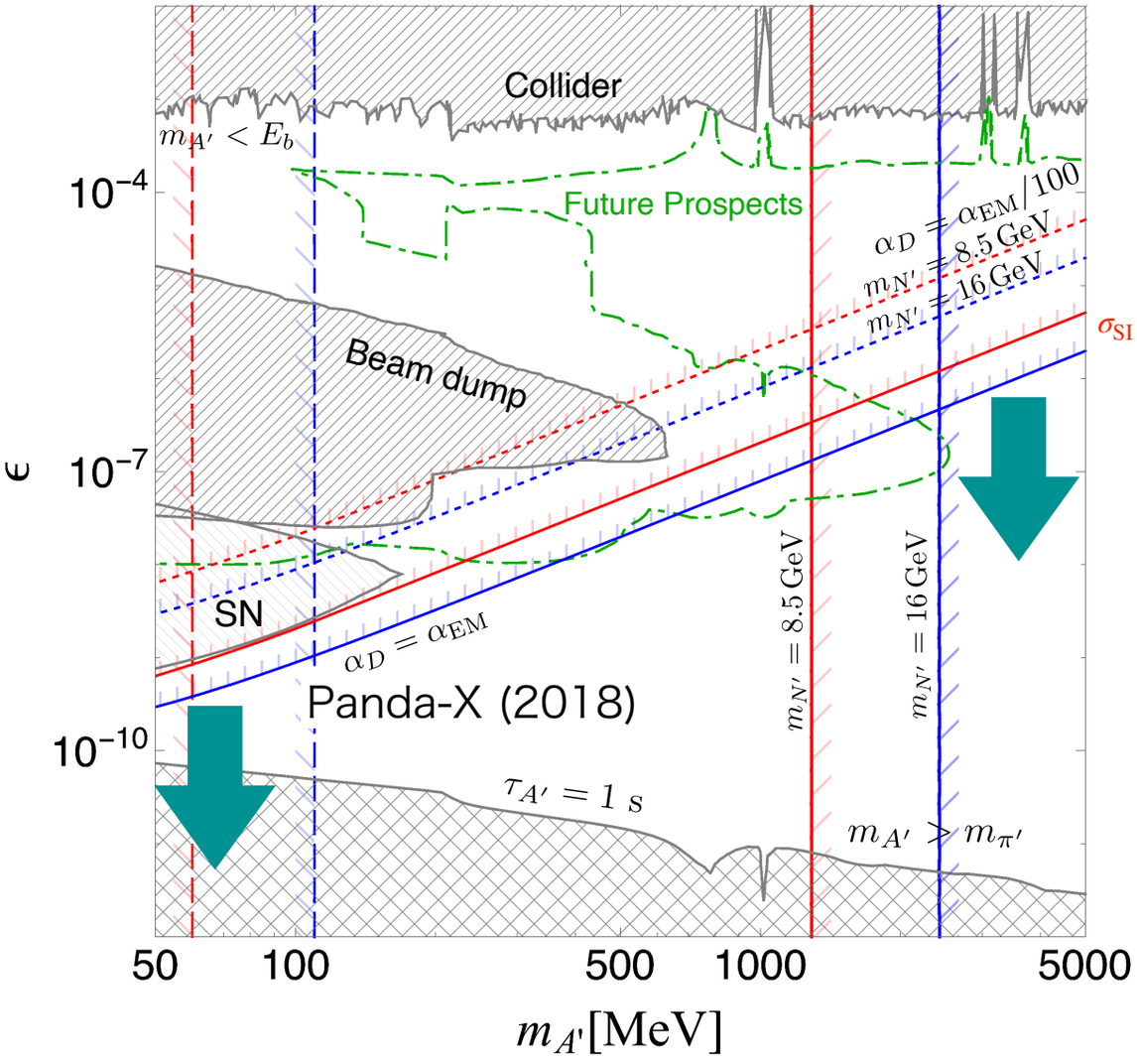
Composite ADM scenario:

No constraints from

- CMB/BBN/Cosmic Ray (late-time energy injection)
- Relic abundance

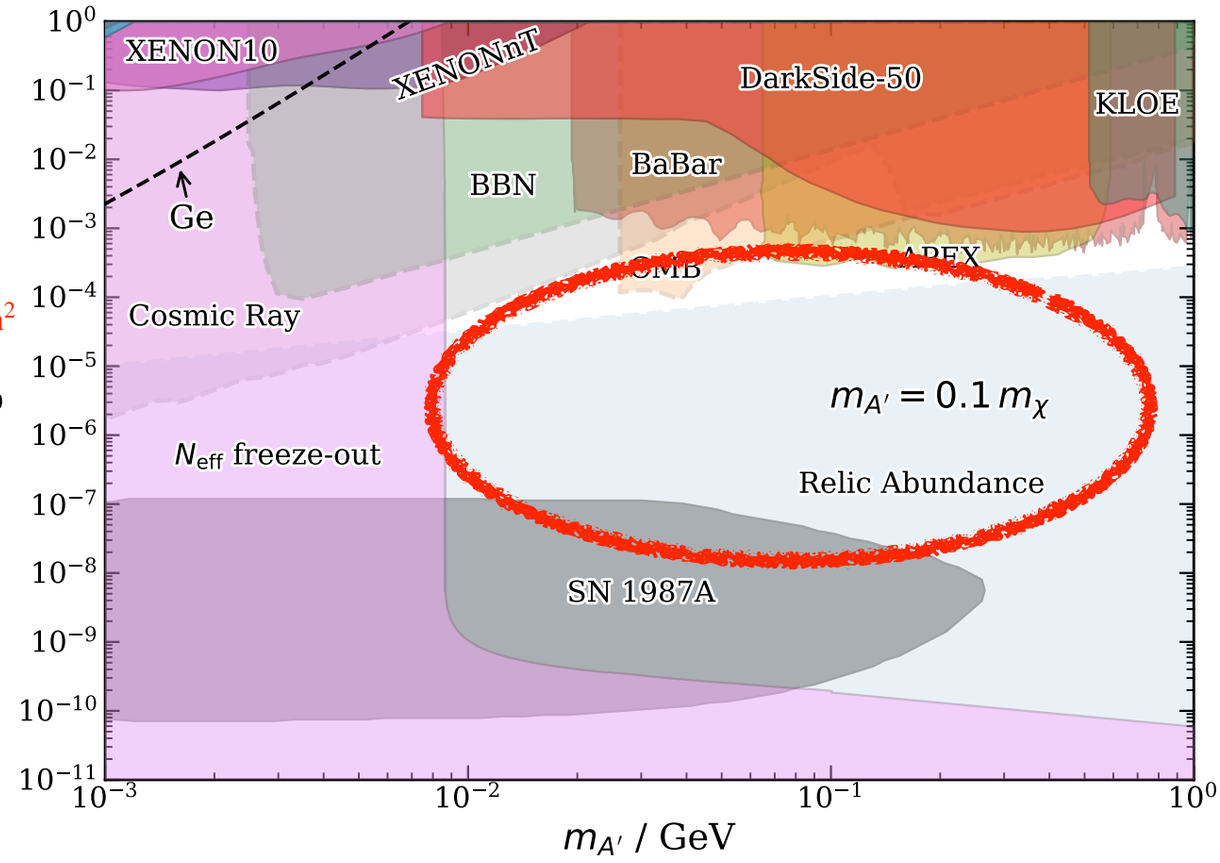
Comparison with Current-interaction

current interaction



$\sigma_{SI} > 10^{-44}\,\mathrm{cm}^2$

only dipole interaction



composite ADM realization

remains as viable setup for dark dipoles

Kamada, TK, Kim (2021)

fixed DM mass ~ 10GeV

Summary and Discussions

Dark Dipole Portal

- Alternative to current dark photon portal
- Such as neutral dark lepton or dark neutron realization

Phenomenology

- Thermal DM scenarios
  - limited viable parameter space (relic vs DD & ID constraints)
  - unrealistic dipole moments (in perturbative EFT realization)
- dark neutron like realization:
  - moderate $\epsilon \sim 10^{-4}$-10^{-6} (portal searches at Beam-dump/LLP at FPF etc)

Backup Slides

Cross section

Nuclear-recoil differential cross section

$$\frac{\mathrm{d}\sigma_0}{\mathrm{d}E_R} = \frac{\epsilon^2\alpha}{2}\left(\frac{q_T^2}{q_T^2+m_{A'}^2}\right)^2 \frac{m_T}{m_N^2}\frac{1}{v^2}\left\{\mu_\chi^2\left[\left(\frac{1}{m_\chi^2}-\frac{1}{\mu_{T\chi}^2}+\frac{4v^2}{q_T^2}\right)m_N^2 F_M^{(p,p)}(q_T^2)+4F_\Delta^{(p,p)}(q_T^2)\right.\right.$$

$$\left.\left.+\frac{1}{4}\sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma'}^{(N,N')}(q_T^2) - \sum_{N=p,n} 2g_N F_{\Sigma',\Delta}^{(N,p)}(q_T^2)\right] + 4d_\chi^2\frac{m_N^2}{q_T^2}F_M^{(p,p)}(q_T^2)\right\},$$

nuclear response function: $F_M^{(N,N')}, F_{\Sigma'}^{(N,N')}, F_{\Sigma''}^{(N,N')}, F_\Delta^{(N,N')}, F_{\Sigma',\Delta}^{(N,N')}$ (Anand, Fitzpatrick, Haxton (2021))

g-factor: g_N

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \frac{\mathrm{d}\sigma_0}{\mathrm{d}E_R}\sum_F |Z_{FI}|^2$$

$$\sum_F |Z_{FI}|^2 = |Z_{II}|^2 + \sum_{n,\ell,n',\ell'} p_{q_e}^d(n\ell \to n'\ell') + \sum_{n,\ell}\int \frac{\mathrm{d}E_e}{2\pi}\frac{\mathrm{d}}{\mathrm{d}E_e}p_{q_e}^c(n\ell \to E_e),$$

Cross section

DM-Electron differential cross section with ionization

$$\frac{\mathrm{d}\langle\sigma^i v\rangle}{\mathrm{d}\ln E_k} = \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\int \mathrm{d}q\, q\, |f_{\mathrm{ion}}^i(E_k, q)|^2\, |F_{\mathrm{DM}}(q)|^2 \eta(v_{\mathrm{min}})$$

$f_{\mathrm{ion}}^i(E_k, q)$ implemented in wimprate (and QEDark)

J. Aalbers, et al (2023), R. Essig, et al (2016)

Recoil Rate for ionization

$$\frac{R_{\mathrm{ion}}}{m_T} = \frac{n_{\mathrm{DM}}}{m_T}\frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\sum_i \int \mathrm{d}q\mathrm{d}E_k\, \frac{q}{E_k}\, |f_{\mathrm{ion}}^i(E_k, q)|^2\, |F_{\mathrm{DM}}(q)|^2 \eta(v_{\mathrm{min}})$$

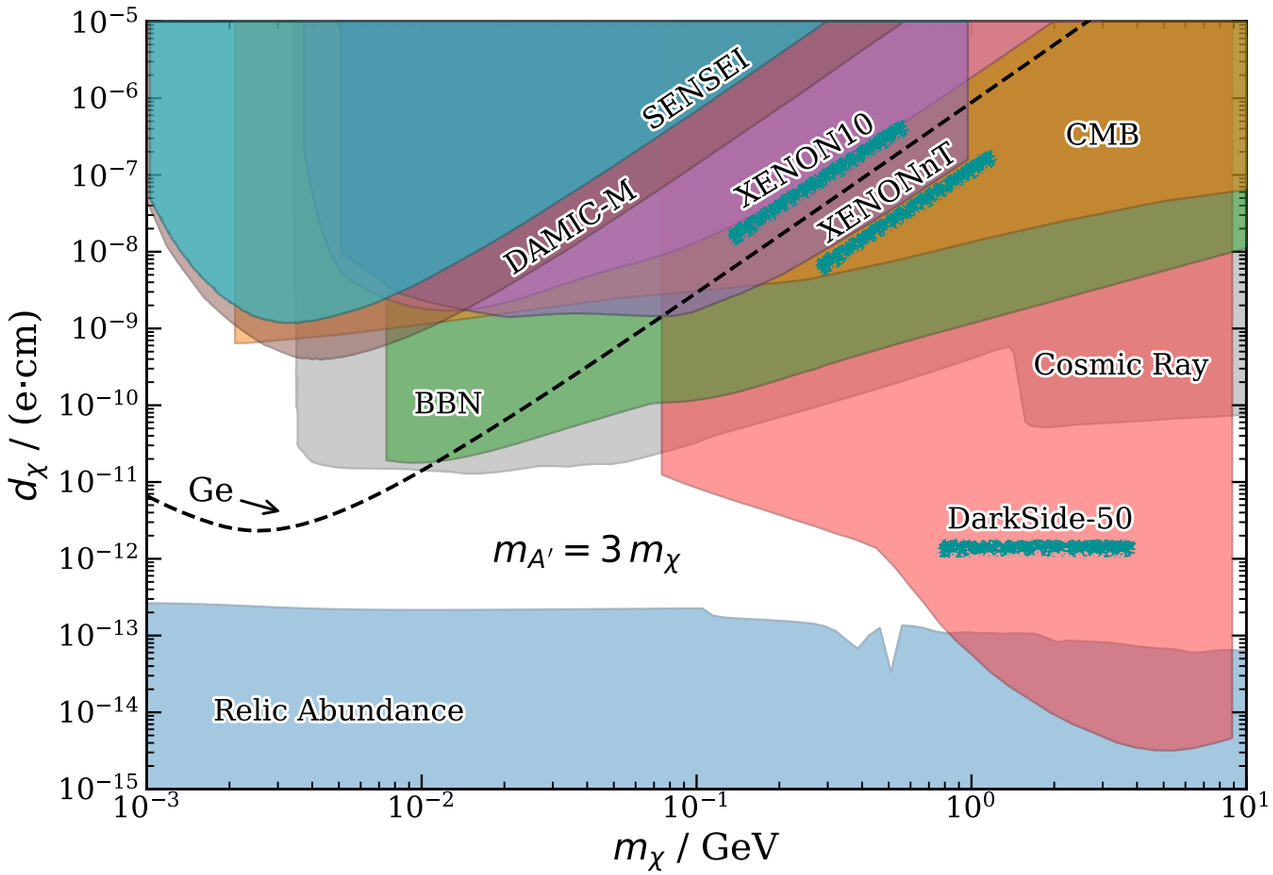
Recoil Rate on Semiconductor Detector

$$\frac{\mathrm{d}R_{\mathrm{crystal}}}{\mathrm{d}\ln E_e} = n_{\mathrm{DM}}\bar{\sigma}_e N_{\mathrm{cell}}\alpha\frac{m_e^2}{\mu_{\chi e}^2}\int \mathrm{d}\ln q \frac{E_e}{q}\, |f_{\mathrm{crystal}}(q, E_e)|^2\, |F_{\mathrm{DM}}(q)|^2 \eta(v_{\mathrm{min}})$$

Crystal Form Factor $f_{\mathrm{crystal}}(q, E_e)$

R. Essig, et al (2016, Dreyer, et al (2023))

Direct detection Constraints



DarkSide-50

DarkSide-50 (2023)

Liquid Argon Detector
Migdal + (S1+S2) analysis

XENON10, XENON100

R. Essig, et al (2016)

"S2-only" signal analysis
including multiple electron final states

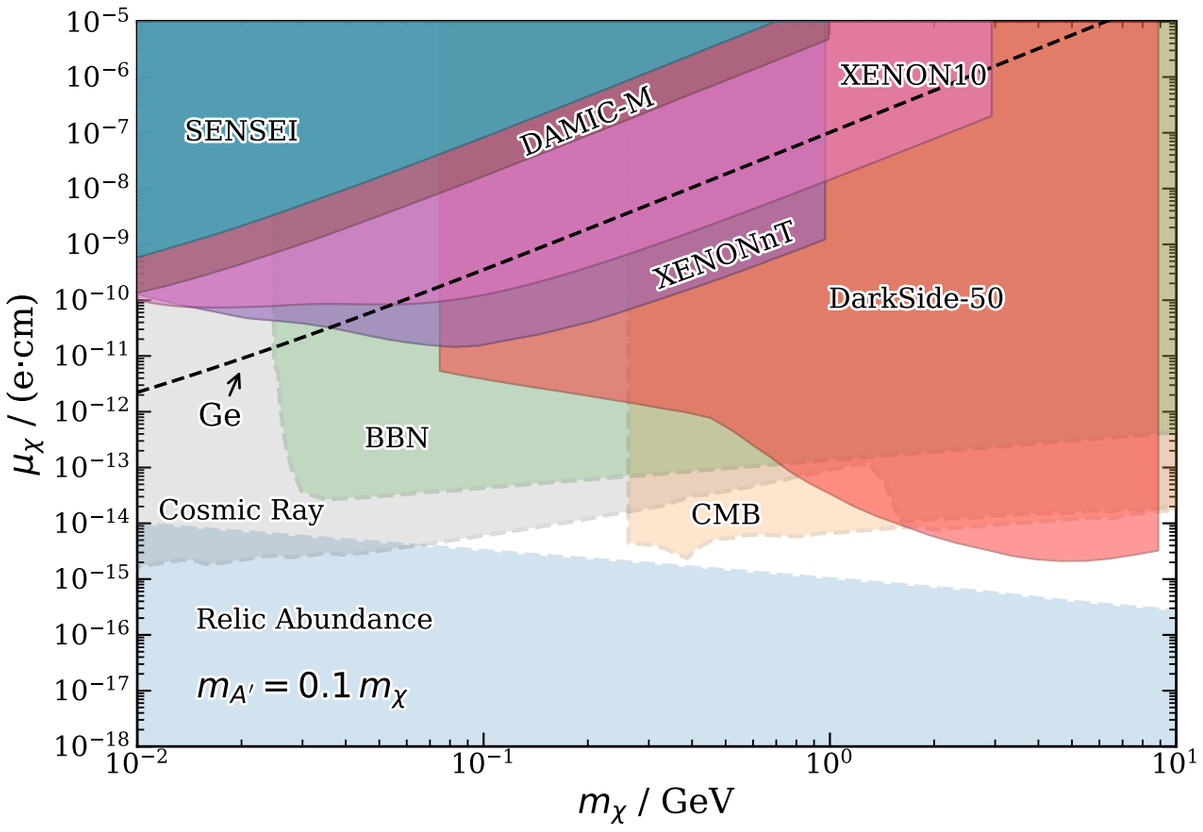
XENONnT

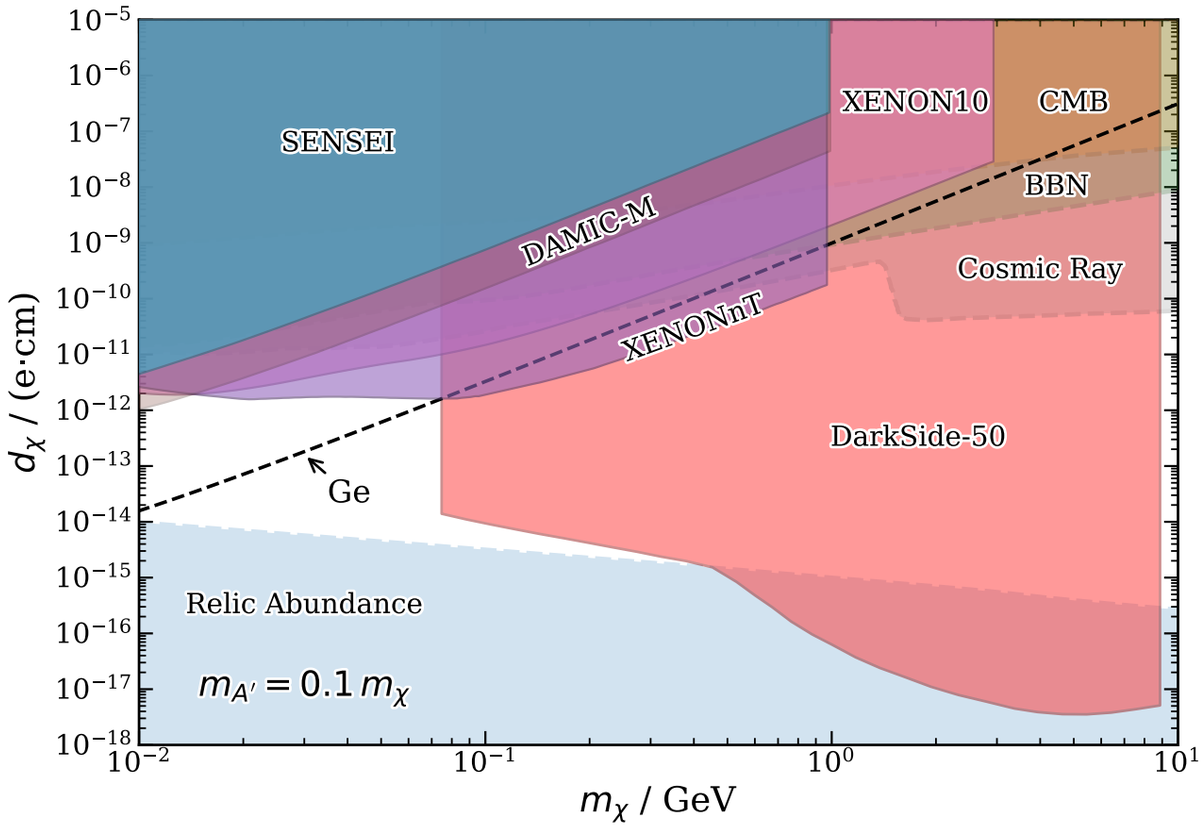
XENONnT (2024)

"S2-only" signal analysis

Direct detection Constraints

lighter mediator $\epsilon = 10^{-3}$





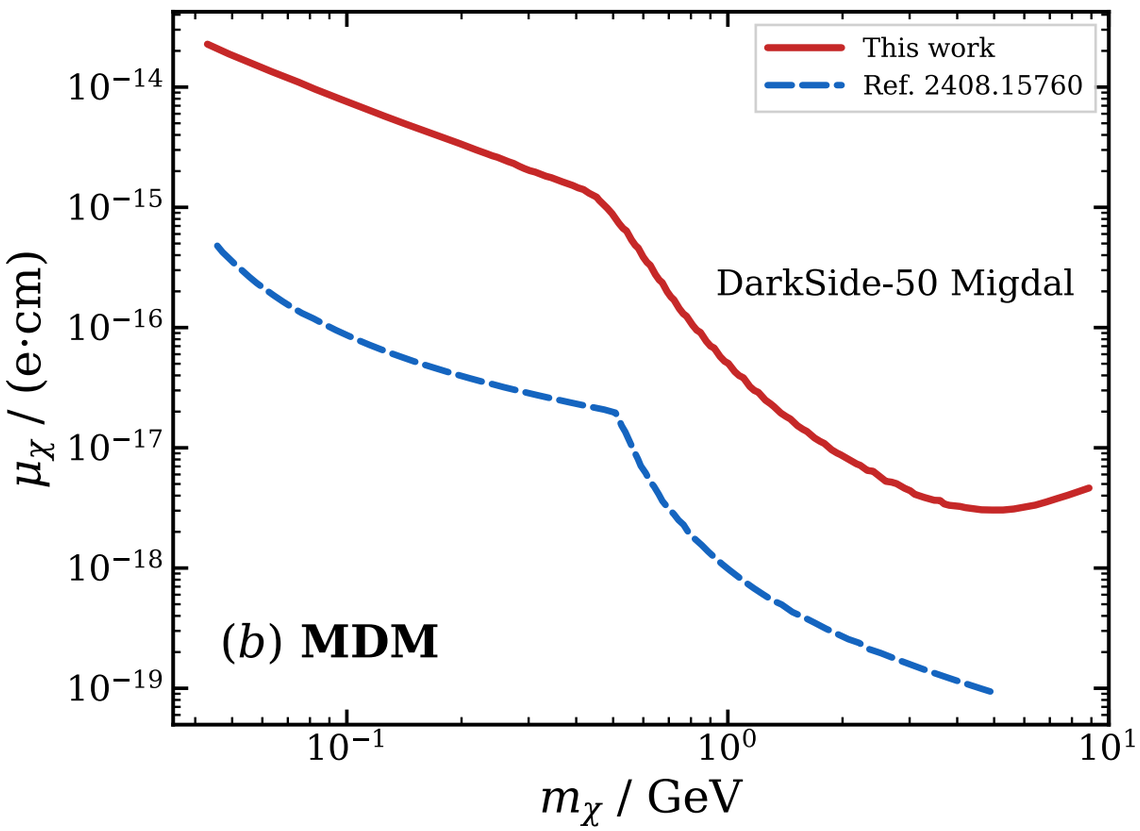
Allowed window: $m_\chi \gtrsim 100\,\mathrm{MeV}$ for MDM and $m_\chi \lesssim 100\,\mathrm{MeV}$ for EDM

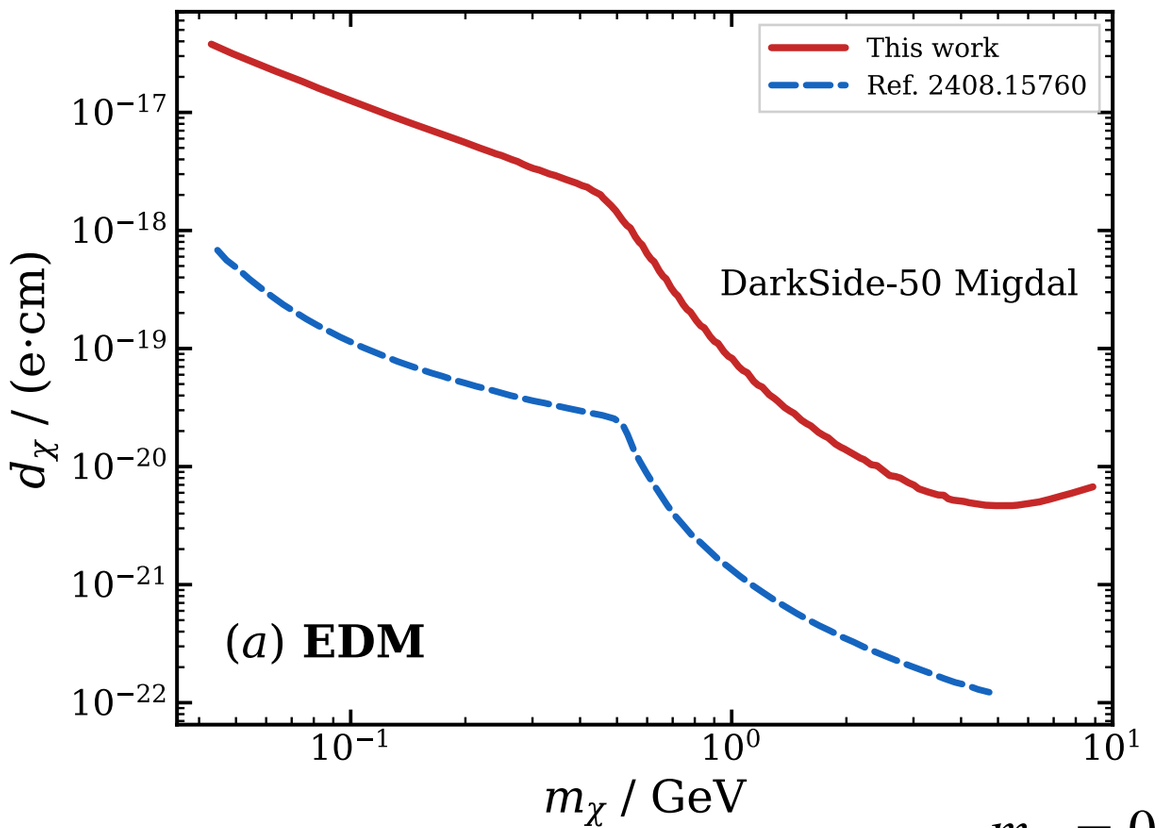
Once constraints on A' is taken into account,

most of parameter space of EDM case is closed

Comparison with Electromagnetic dipole DM

$\epsilon = 1$





$m_{A'} = 0.1 m_\chi$

Cross section further suppressed by mediator mass

Ibarra, Reichard, Tomar (2024)

$$\left(\frac{q^2}{q^2 + m_{A'}^2}\right) \simeq \left(\frac{q}{m_{A'}}\right)^2,$$