Anapole Dark Matter: A View from the Top

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DM electromagnetic form factors

- Milli-charge $\epsilon e \bar{\chi} \gamma^\mu \chi A_\mu$
- Electric dipole moment $\frac{id}{2} \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu}$
- Magnetic dipole moment $\frac{\mu}{2} \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu}$
- Anapole moment $\frac{A}{2} \bar{\chi} \gamma^\mu \gamma^5 \chi \partial^\nu F_{\mu\nu}$
- Charge radius $b \bar{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}$

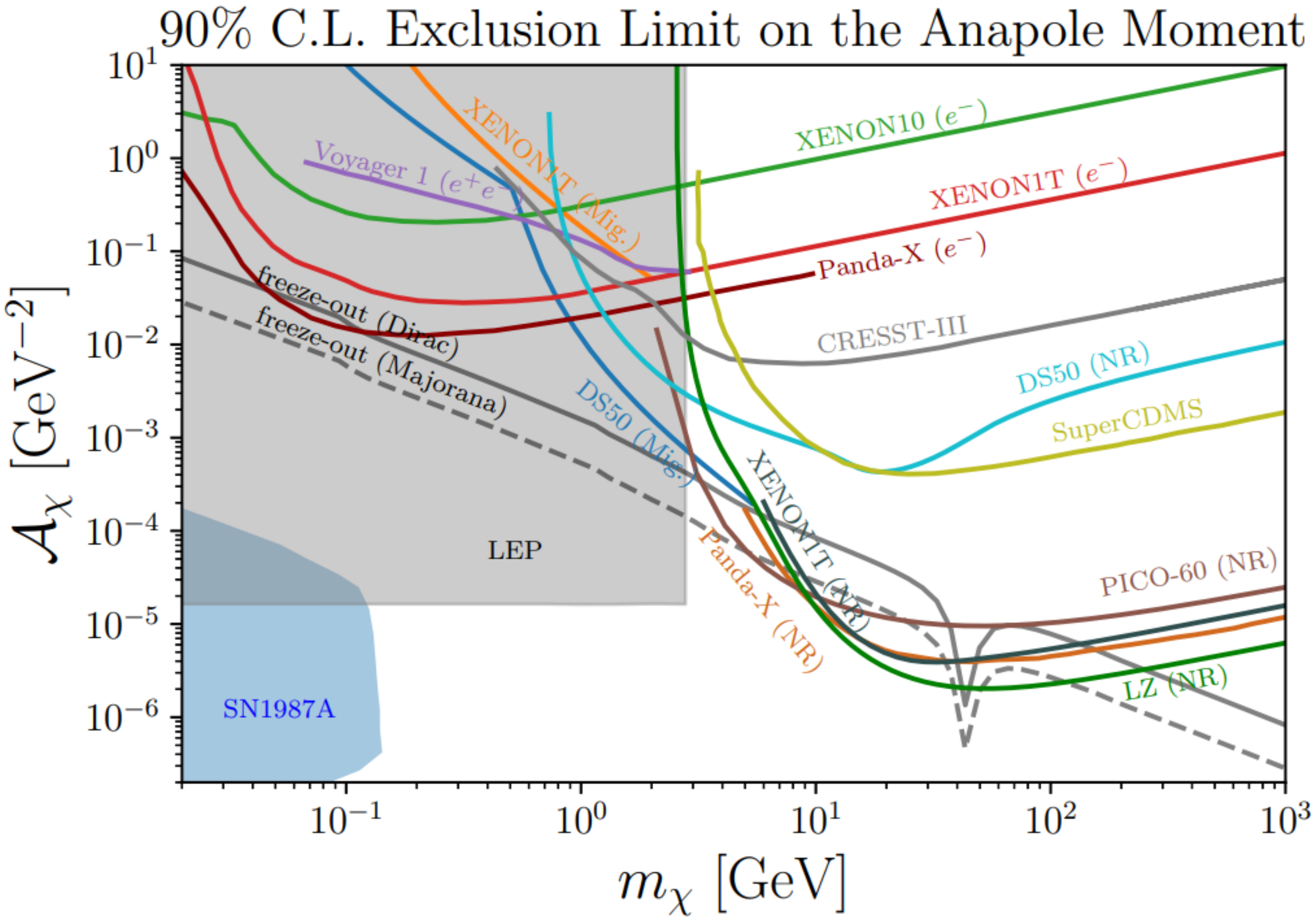
Anapole moment

$$\mathcal{L}_{\mathrm{anapole}} = \frac{\mathcal{A}}{2}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

- Only electromagnetic form factor allowed for Majorana χ.
- No coupling to on-shell photons, only the EM current.
- P-violating, CP-conserving.
- Much less detectable than electric and magnetic dipole moments.
- Dimension-6 operator: $\mathcal{A}$ is dimensionful, $\sim g/\Lambda^2$.
- Leads to p-wave annihilation to charged SM fermions.

Anapole DM freeze-out and constraints

- Anapole-mediated annihilation to SM fermions allows for thermal freeze-out. (Ho & Scherrer, 2012)
- Below $\sim 1\ \mathrm{GeV}$, LEP searches for $e^+e^- \to \gamma\bar{\chi}\chi$ rule out the freeze-out line.
  (Chu, Pradler & Semmelrock, 2019)
- Up to $100\ \mathrm{GeV}$, nuclear recoil direct detection covers it as well.
  (Ibarra, Reichard & Tomar, 2024)



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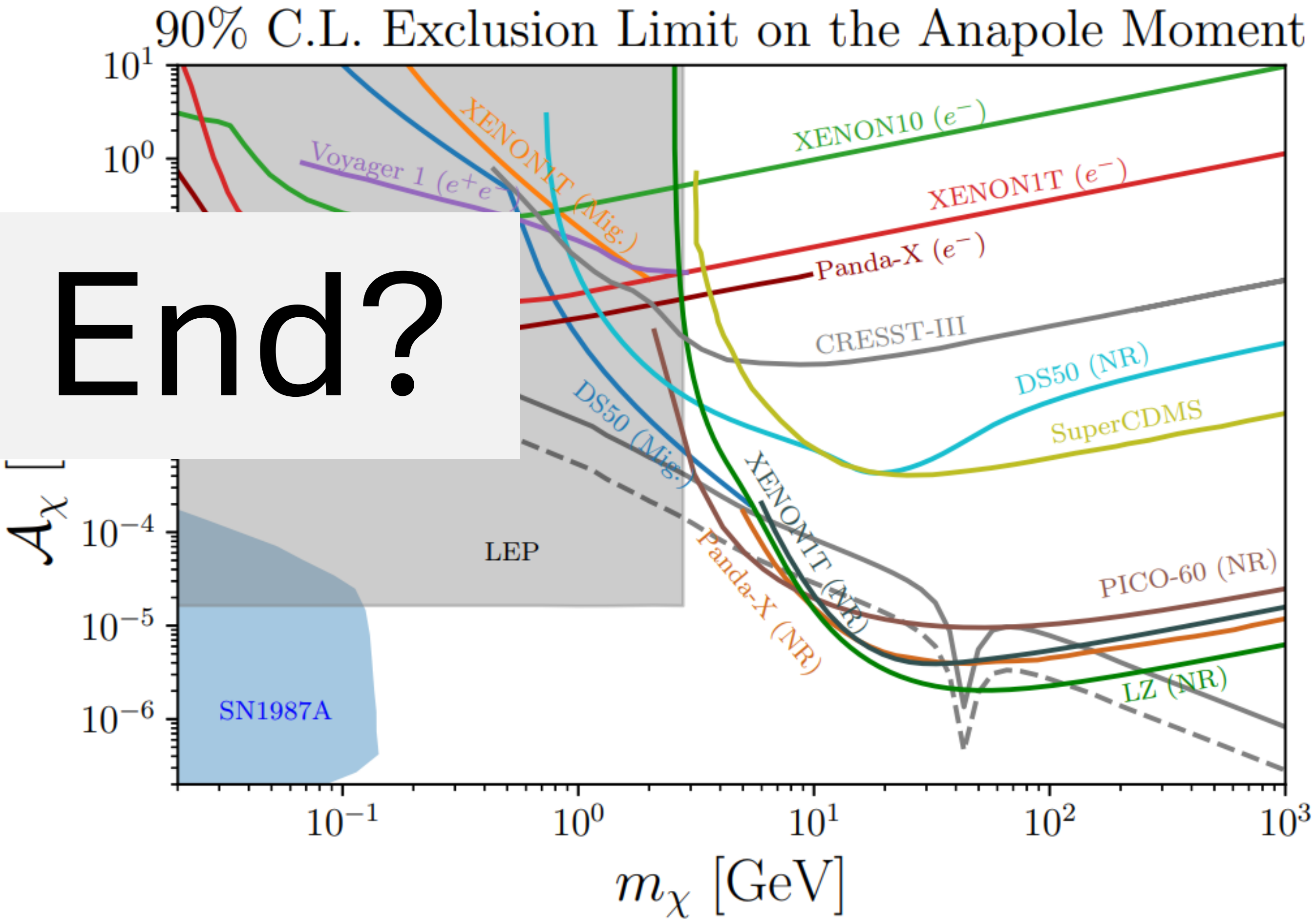
The End?



(Ibarra, Reichard and Tomar, 2024)

“From the top”: UV Completions

- What renormalizable models give rise to an anapole moment?
- Do they have the same production mechanism/thermal history?
- Can constraints on the UV model surpass constraints on the anapole moment?

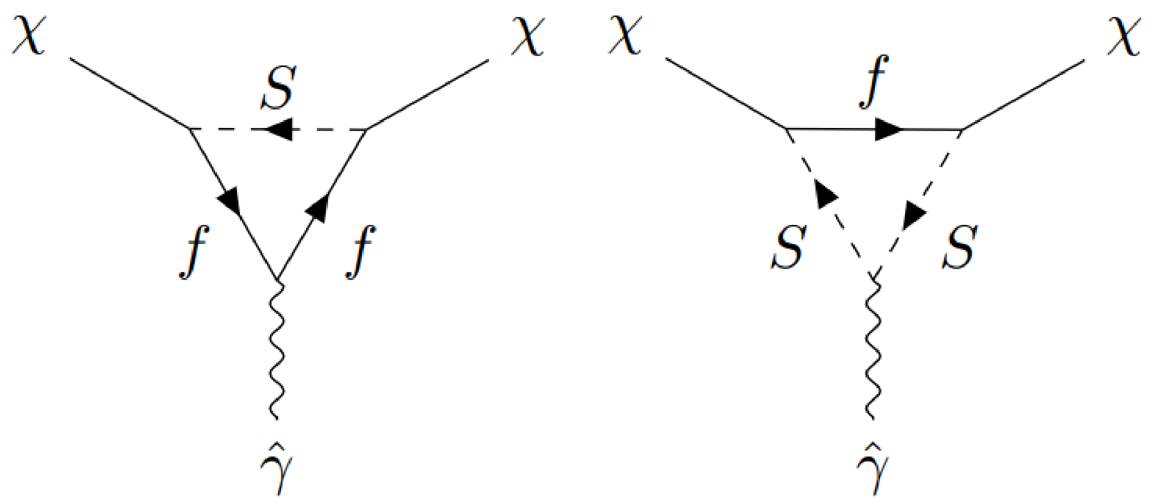
Generating anapole moment at loop level

$$\mathcal{L}_{AS} = \bar{\chi}[c_L P_L + c_R P_R] S^* f + \text{h.c.}$$

- Yukawa coupling of χ to charged* scalar S and fermion f.

- For heavy $M \equiv m_S \sim m_f$,

$$\mathcal{A} \approx \frac{eQ_{f,S}}{192\pi^2 M^2} \left(|c_L|^2 - |c_R|^2\right)$$



*or milli-charged

A (not exhaustive) list

- f is a SM particle (e.g. μ or τ). χ neutralino-like, S sfermion-like.
  - Constraints from collider searches.
  - Freeze-out controlled by Yukawa-mediated $\chi\chi \to \bar{f}f$ annihilation, not anapole moment.

- f and S both new heavy, EM-charged states.
  - Anapole controls freeze-out.

- f and S charged under $U(1)_{\mathrm{D}}$ that kinetically mixes with photon, yields milli-charge under $U(1)_{\mathrm{EM}}$.
  - Constraints from MCPs and ΔN_{eff}.
  - Alternative production mechanism: IR freeze-in of dark sector (Berlin, Chang & Trickle 2025).

- f and S milli-charged, no dark photon. “Pure milli-charge”.
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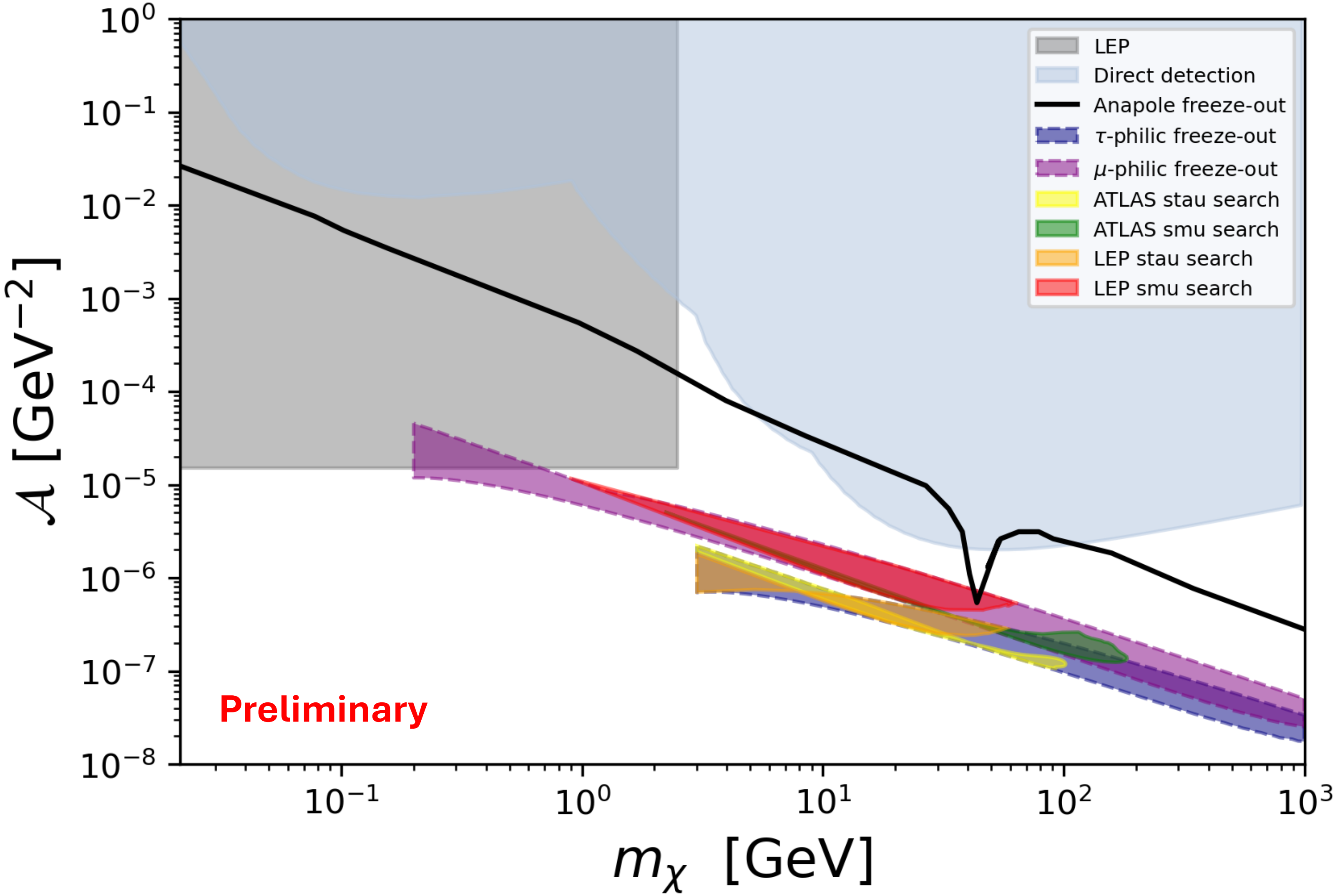
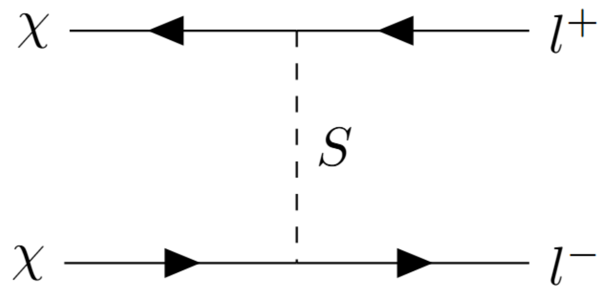
Leptophilic DM

AKA Bino DM

Leptophilic freeze-out





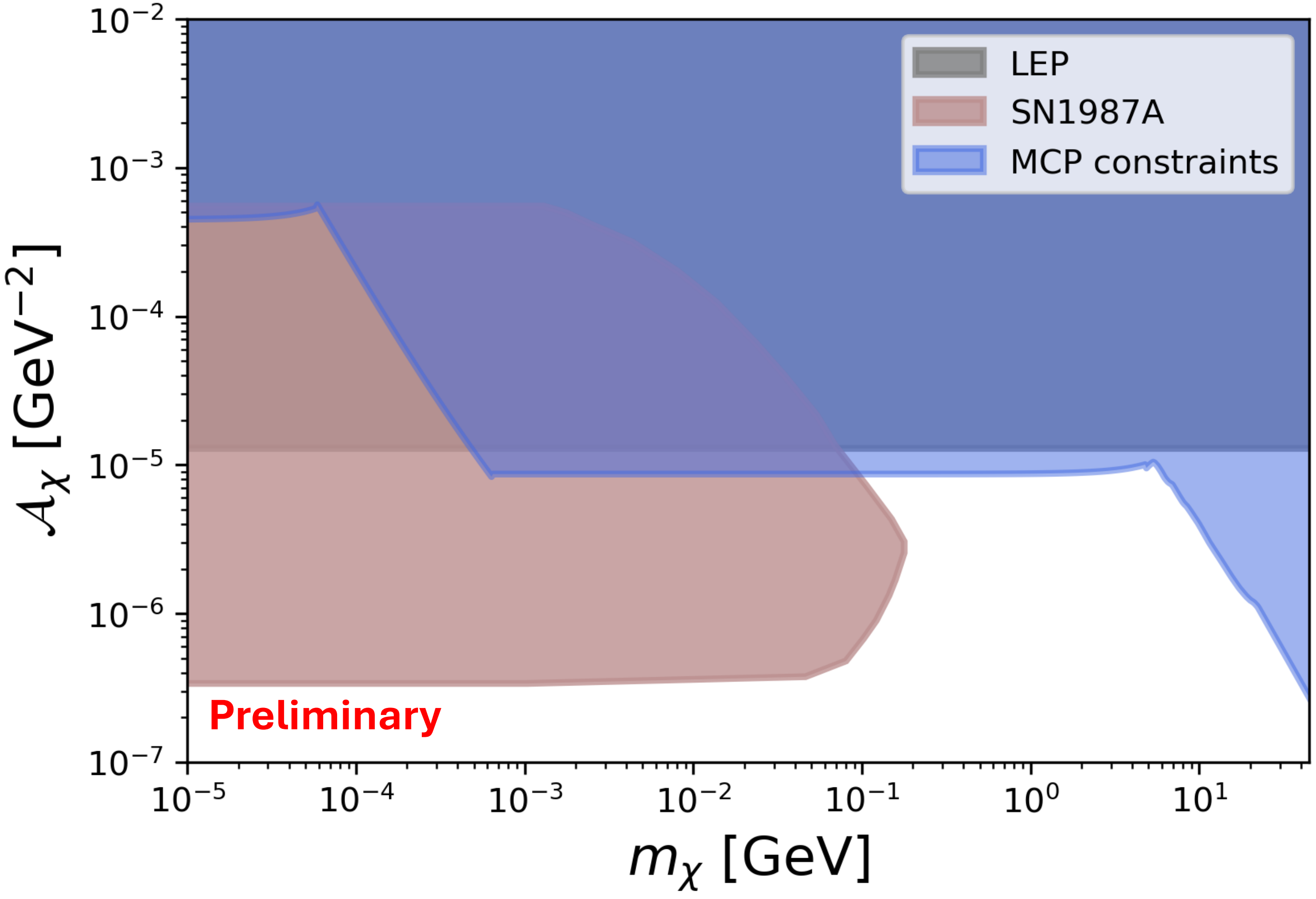
- Freeze-out band lies below anapole line and direct detection constraints*.
- Collider searches partially cover parameter space out to ~ 100 GeV .

*Caveat: co-annihilations when $m_S \sim m_\chi$.

Milli-charged particles

Milli-charged particles: Conservative bounds

- For each m_χ, take the MCP mass and milli-charge that yield the **largest** anapole moment, while consistent with MCP constraints.
- Current MCP constraints beat anapole constraints above ~ 0.1 GeV .
- Yukawa coupling set to $\sqrt{4\pi}$.

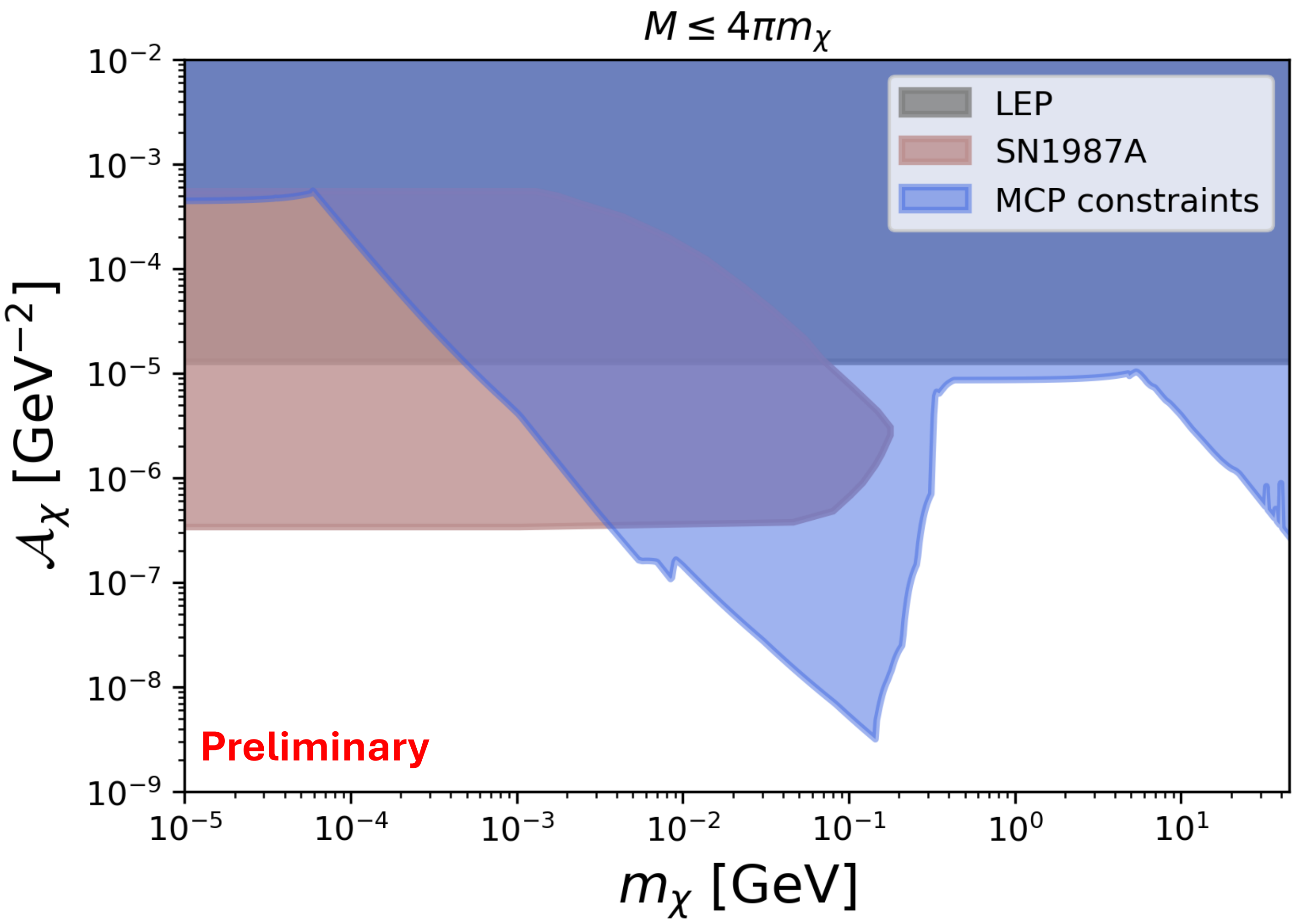


Slightly less conservative bounds

- No fine-tuning:

  Require that $m_\chi \geq \frac{y^2}{16\pi^2} M$.

- Strengthens constraint from MeV to 100 MeV.

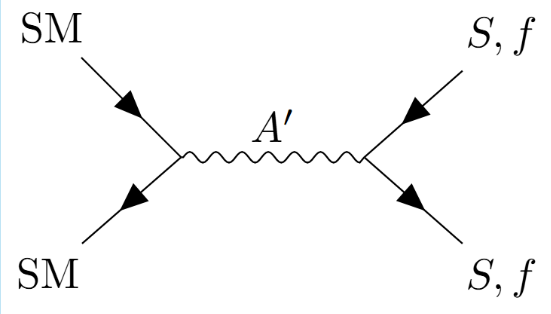


Dark sector freeze-in

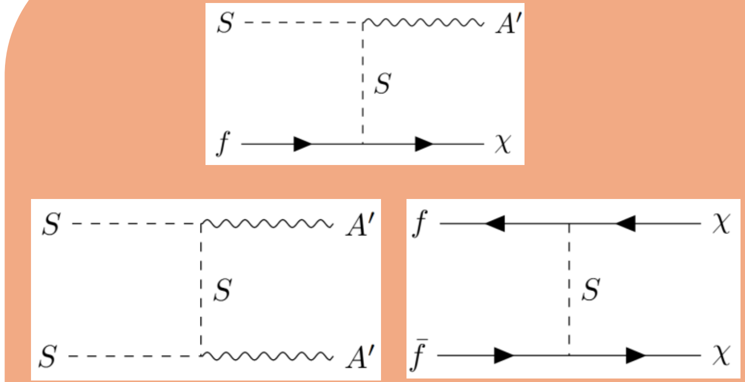
See Berlin, Chang & Trickle 2025 for details w/ magnetic dipole moment

- Milli-charged S and f.
- Kinetically mixed dark photon.
- Yukawa allows anapole moment for χ.

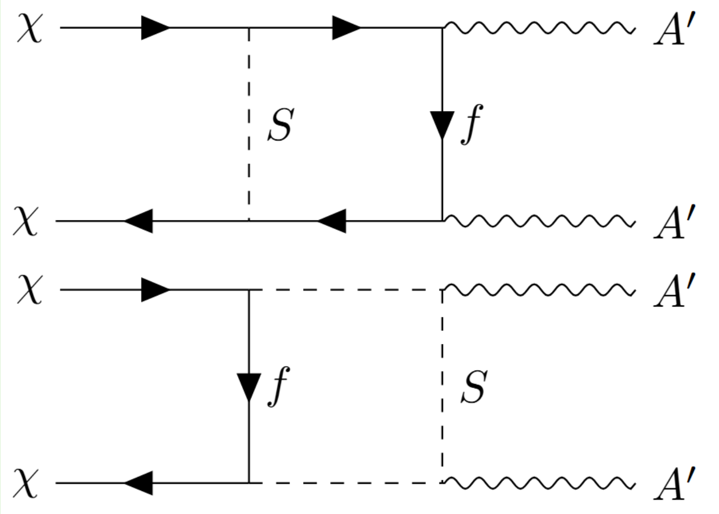
$$\mathcal{L} = \mathcal{L}_{SM} \boxed{- \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}} + \boxed{|D'_\mu S|^2 - m_S^2 |S|^2}$$
$$+ \boxed{\bar{f}(i\not{D}' - m_f) f} + \bar{\chi}(i\not{\partial} - m_\chi)\chi + \boxed{\bar{\chi}[c_L P_L + c_R P_R] S^* f} + \text{h.c.}$$



MCPs freeze in through kinetic mixing portal.



Dark sector thermalizes to temperature below SM, MCPs freeze out.



DM freezes out to dark photons.

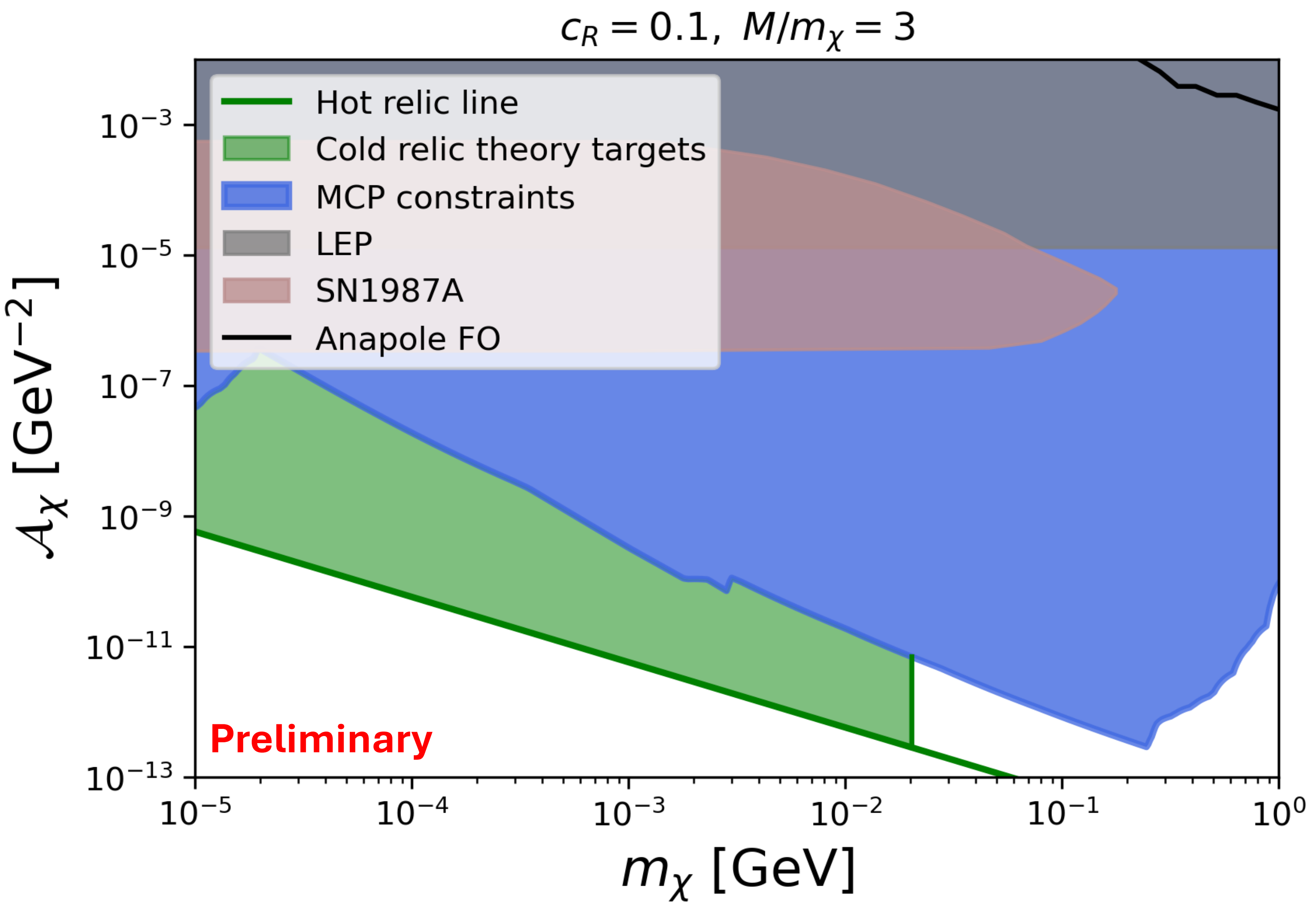
Even less conservative bounds, and freeze-in region

- Range of theory targets (Sorry, Gordan!)
- Hot relic line:

$$\mathcal{A}_{HR} \approx 3\times10^{-9}\ \mathrm{GeV}^{-2}\,|c_R|^2 \left(\frac{\mathrm{MeV}}{m_\chi}\right)\left(\frac{M}{m_\chi}\right)^{-3/2}$$

- Largest allowed m_χ with perturbative dark gauge coupling:

$$m_\chi \lessapprox (50\ \mathrm{GeV})c_R^2 \left(\frac{m_\chi}{M}\right)^4 \sqrt{g_s^*(m_\chi/10)}$$



Conclusions

- Going beyond EFT is worth it!
- Signatures of UV physics are often much more constraining than anapole operator itself.
- Assuming EFT operator controls production mechanism is often incorrect.
- There are viable theory targets for sub-GeV DM with anapole moment, not currently ruled out.