Troubles mounting for Multipolar Dark Matter

based on [arXiv: 2312.05131]
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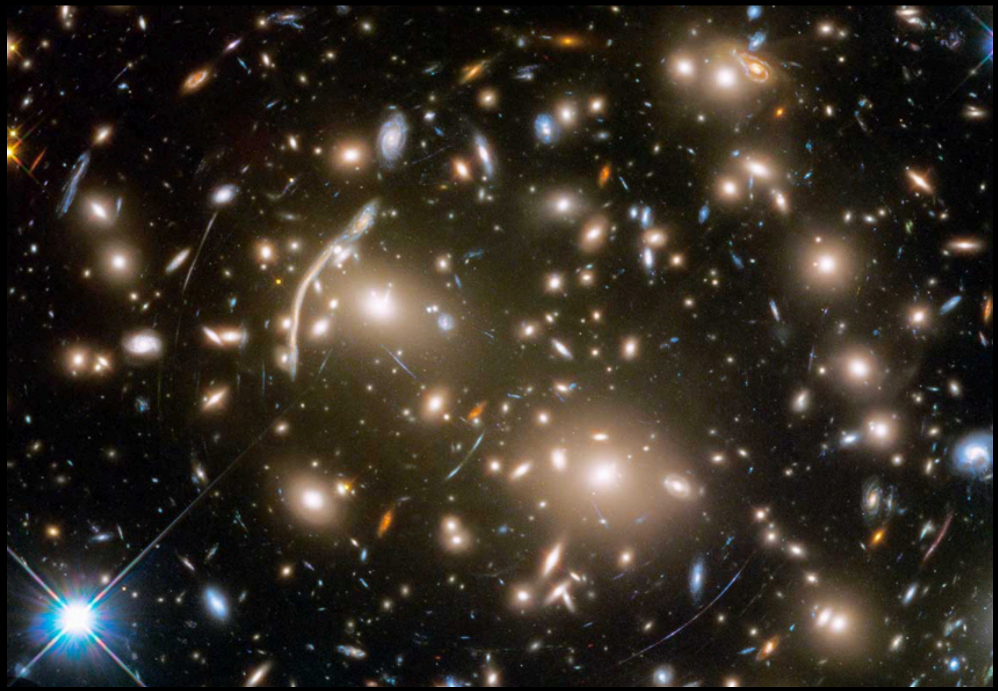
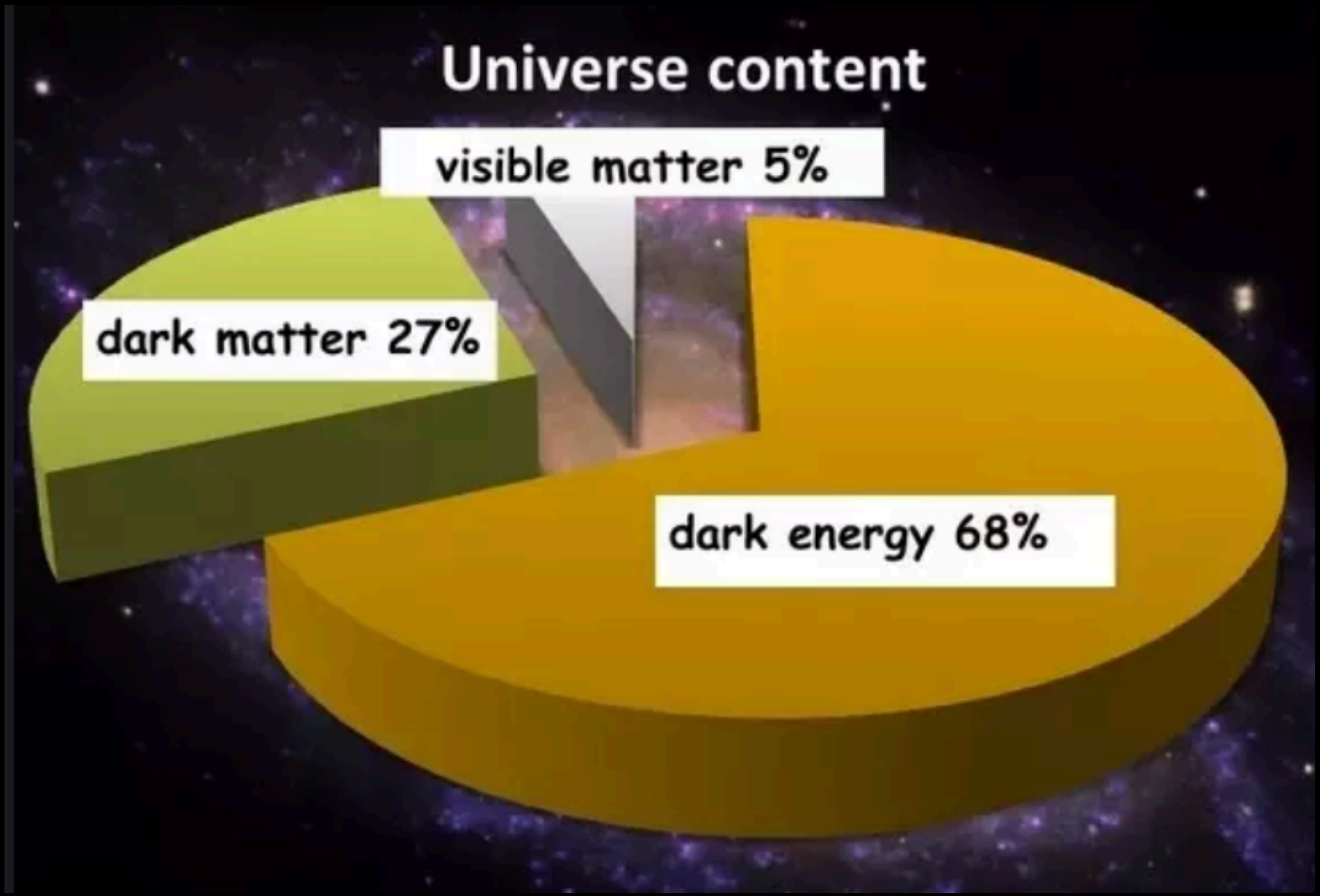
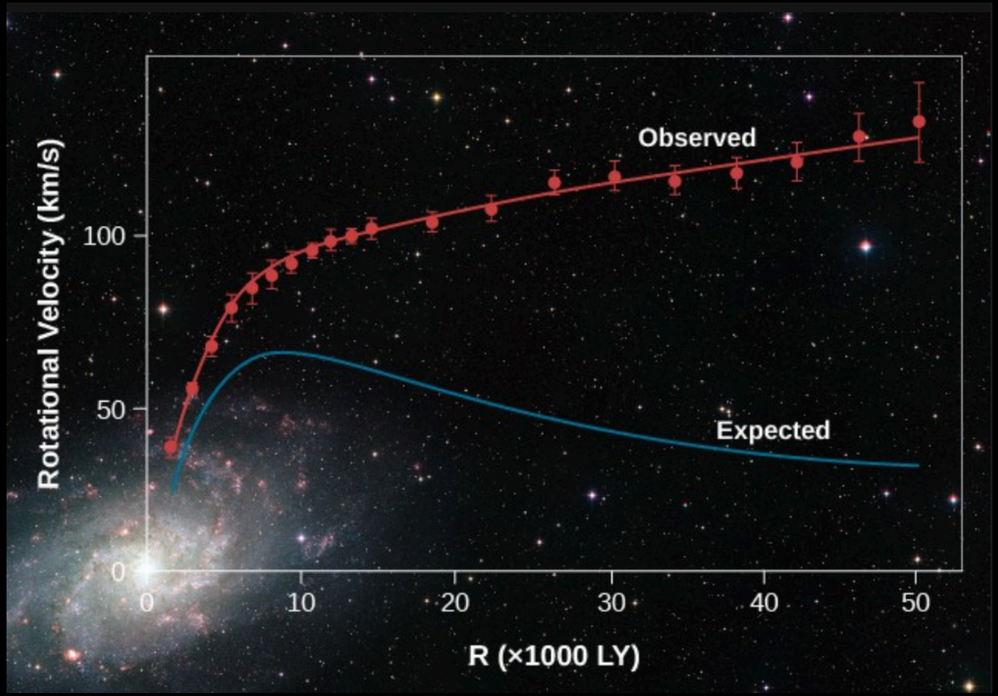
Firm evidences over decades

Rotation of Galaxies

Gravitational Lensing **CMB**







Velocity dispersions

Multipolar dark matter

- WIMP interact electromagnetically with ordinary matter, via an electric or magnetic dipole moment

- Contains derivative coupling → Rich phenomenology

- Pospelov and ter Veldhuris proposed another possible form of EM coupling to the DM

Anapole moment

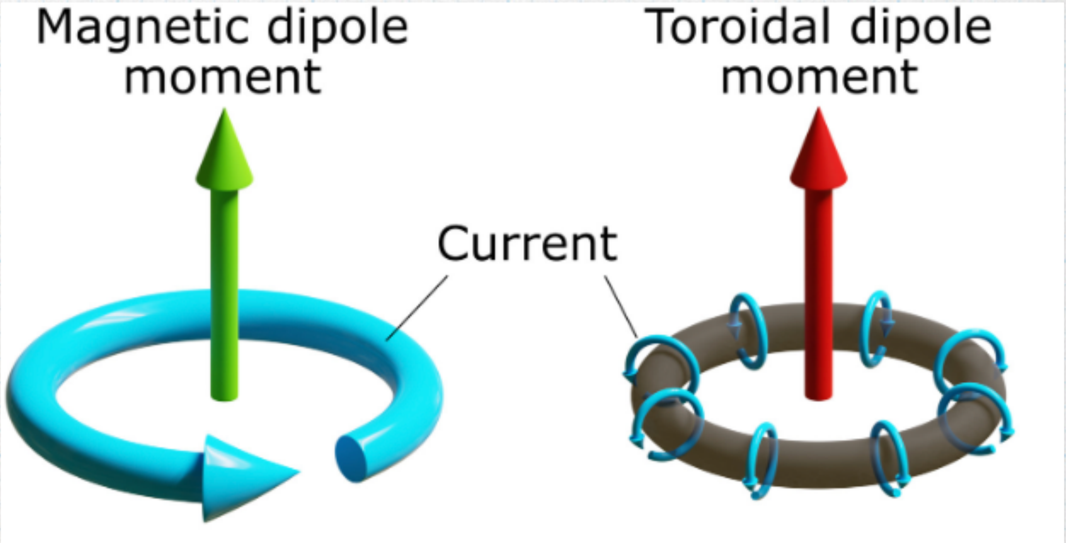
[M. Pospelov and T. Ter Veldhuris, Phys. Lett. B 480, 181 (2000)]

$$\mathscr{L}_{\text{anapole}} = \frac{1}{\Lambda_1^2}\bar{\chi}\gamma_\mu\gamma_5\chi\partial_\nu F^{\mu\nu}$$

EFT cut-off Scale

Majorana DM

EM field strength tensor



Relic density

Early universe

DM DM ⟺ SM SM → **DM "freezes-out"**

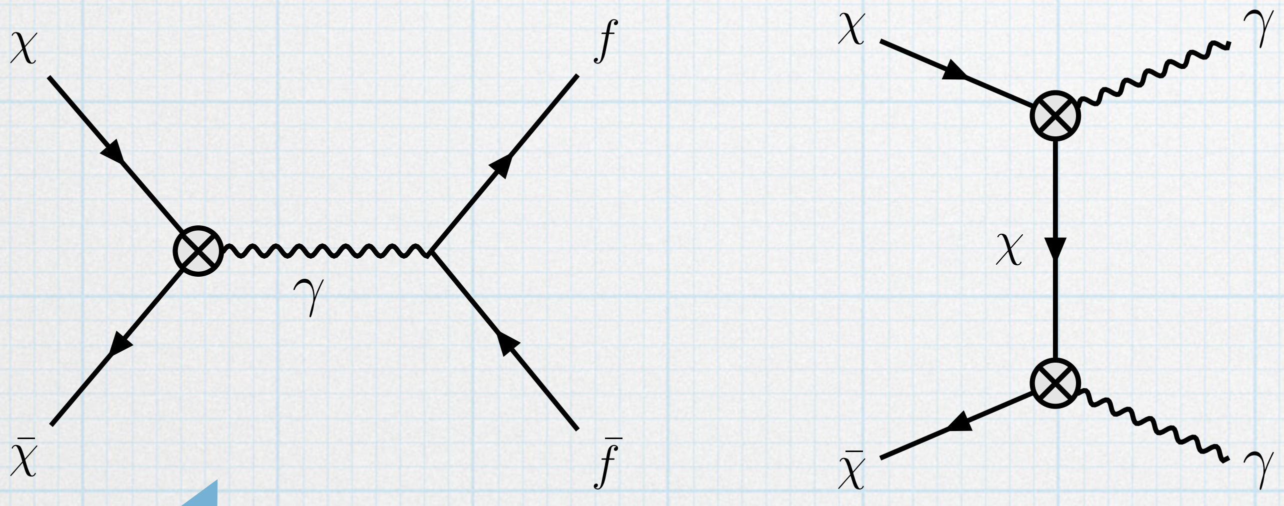
Thermal equilibrium

Universe cools down

Interactions stop

Boltzmann equation :

$$\frac{dY_\chi}{dz} = -\frac{zs\langle\sigma_{\mathrm{ann}}v\rangle}{H\left(m_\chi\right)}\left(Y_\chi^2 - Y_{\mathrm{eq}}^2\right)$$



(a)

(b)

Kinematically allowed but forbidden at tree level

$$\Omega h^2 \propto \frac{1}{\langle\sigma v\rangle}$$

$$\left(\frac{d\sigma_{\chi\bar{\chi}\to f\bar{f}}}{dt}\right)_{\mathrm{AP}} = \frac{1}{16\pi s\left(s-4m_\chi^2\right)} \times \frac{8\pi\alpha_e}{\Lambda_1^4}\left[2m_f^4 + 2m_\chi^4 + s^2 + 2st + 2t^2 - 4m_f^2\left(m_\chi^2+t\right) - 4m_\chi^2\left(s+t\right)\right],$$

Direct detection

DM particles scatter off the nuclei and recoil rates are measured in the detectors

Exposure time of the detector

Escape velocity

DM density

Velocity distribution profile

$$\frac{dR}{dE_{\rm nr}} = \frac{\eta_{\rm exp}}{m_k}\left(\frac{\rho_0}{m_\chi}\right)\int_{u_{\rm min}}^{u_{\rm esc}} du_\chi \, u_\chi \, f(u_\chi)\,\frac{d\sigma}{dE_{\rm nr}},$$

Differential recoil rate

DM mass

Target nucleus mass

Differential scattering cross section

Minimum velocity of DM to produce a recoil event

Recoil energy

$$u_{\rm min} = \sqrt{\frac{E_{\rm nr}\, m_T}{2\beta^2_{\chi,k}}},$$

Reduced mass

DM Capture

- A celestial body can attract DM in their gravitational well
- DM scatters with SM constituents → looses energy → Captured
- Accumulated DM annihilate → Increase stellar luminosity

  → Produce signal at earth based experiments

[W. H. Press, D. N. Spergel
Astrophys. J 296, 679-684 (1985)]

Advantage of Anapole DM in capture → Momentum dependant Interaction topology

DM velocity → Escape velocity

acceleretion due to

Gravitational boost

boosts the scattering cross-section

Heating signature inside neutron star

Neutron stars are extremely dense with $v_{\text{esc}} \approx 0.6c$

DM annihilate to SM → Annihilated products get trapped

↓

stellar heating

$$T \propto (f \times \rho_\chi)$$

Fraction of captured DM

DM density

$$f \propto \sigma$$

Scattering cross section

[Acevedo, Bramante, Leane,Raj JCAP03(2020)038]

Scattering with both **proton** ($1\,\%$) and **neutron**

Tree level coupling

Loop level coupling

Contributions are of the same order

Old NS can cool down to $\mathcal{O}$(2000K)

Can be explored by infrared tellscopes like JWST, TMT, E-ELT

Neutrinos from Sun

Annihilated products from **captured DM in Sun** → **escape** from Solar interior → produce ν signals at earth based observatories

Icecube

Fermi-LAT AMS

$$\frac{dN_\chi}{dt} = C_\odot - C_{\rm ann}\, N_\chi^2 - C_{\rm evap}\, N_\chi ,$$

No of DM particles Inside Sun

Capture

Annihilation

Evaporation

[IceCube collaboration Phys. Rev. Lett. 110, 131302 (2013)]

Neutrinos from Sun

$$C_\odot = \sum_k \left(\frac{\rho_0}{m_\chi}\right) \int_0^{R_\odot} 4\pi r^2\, dr$$

$$\times \int_0^{u_{\rm esc}} du_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi}\, w(r)\, \Omega_k^-(w),$$

Capture rate

Velocity of DM particle at a distance r from centre of sun

$$w(r) = \sqrt{u_\chi^2 + v_{\rm esc}^2(r)},$$

Velocity distribution of DM in the rest frame of Sun

Capture probability of DM with velocity $\omega(r)$ that interacts with nucleus

Differential ν flux reaching earth $\propto$ $\frac{1}{D^2}$, $\Gamma_{\rm ann}$, neutrino spectra per DM annihilation

Obtained using

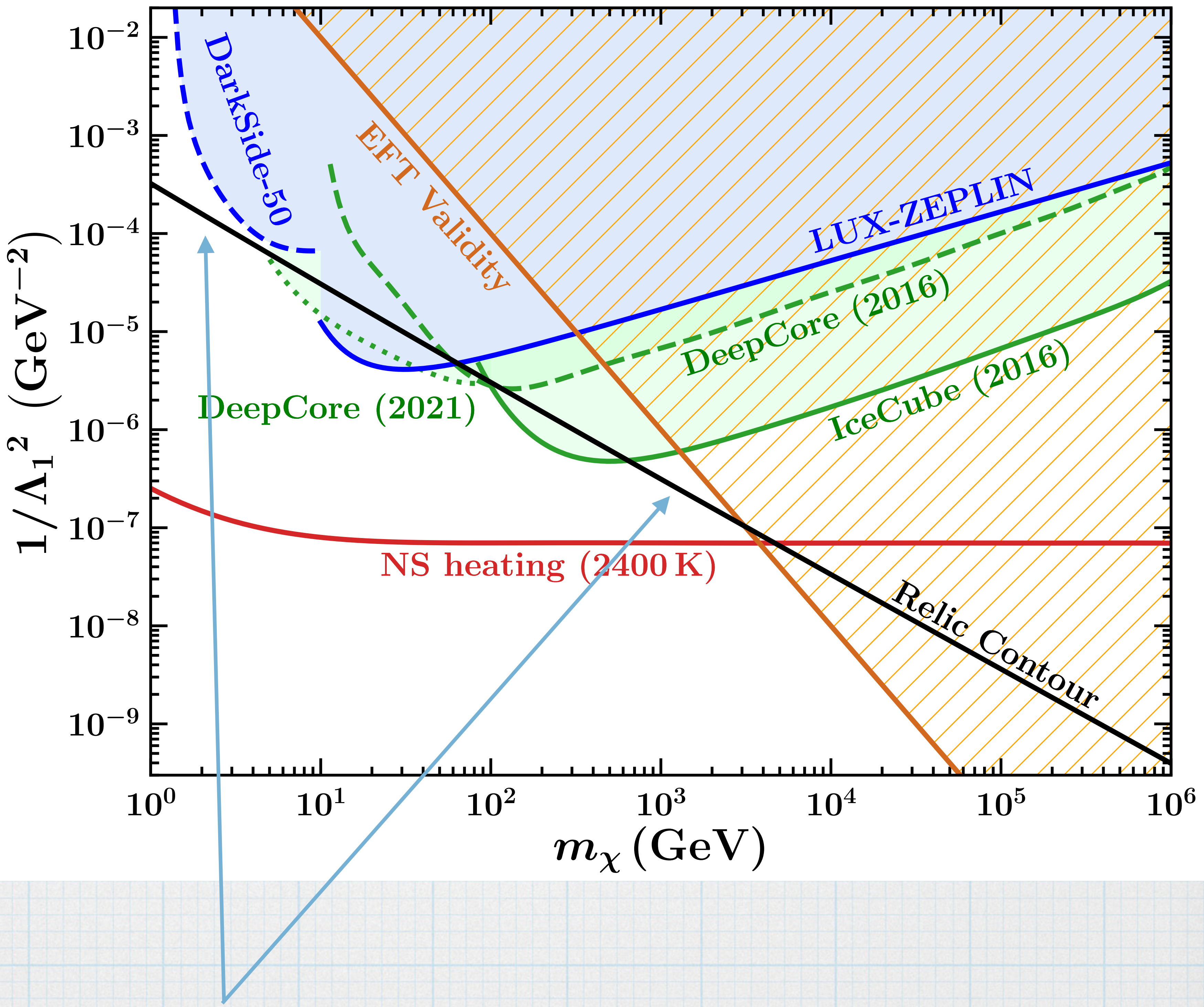
χaroν `nuSQuIDS`

Distance between Earth and Sun

Annihilation rate $\propto C_\odot$ (At equilibrium)

Anapole Dark Matter

- DM relic abundance Satisfies **planck 2018 data**
- EFT validity: $\Lambda \gg$ **Mass**
- Indirect detections From **Fermi-LAT, MAGIC, H.E.S.S** are subdominant



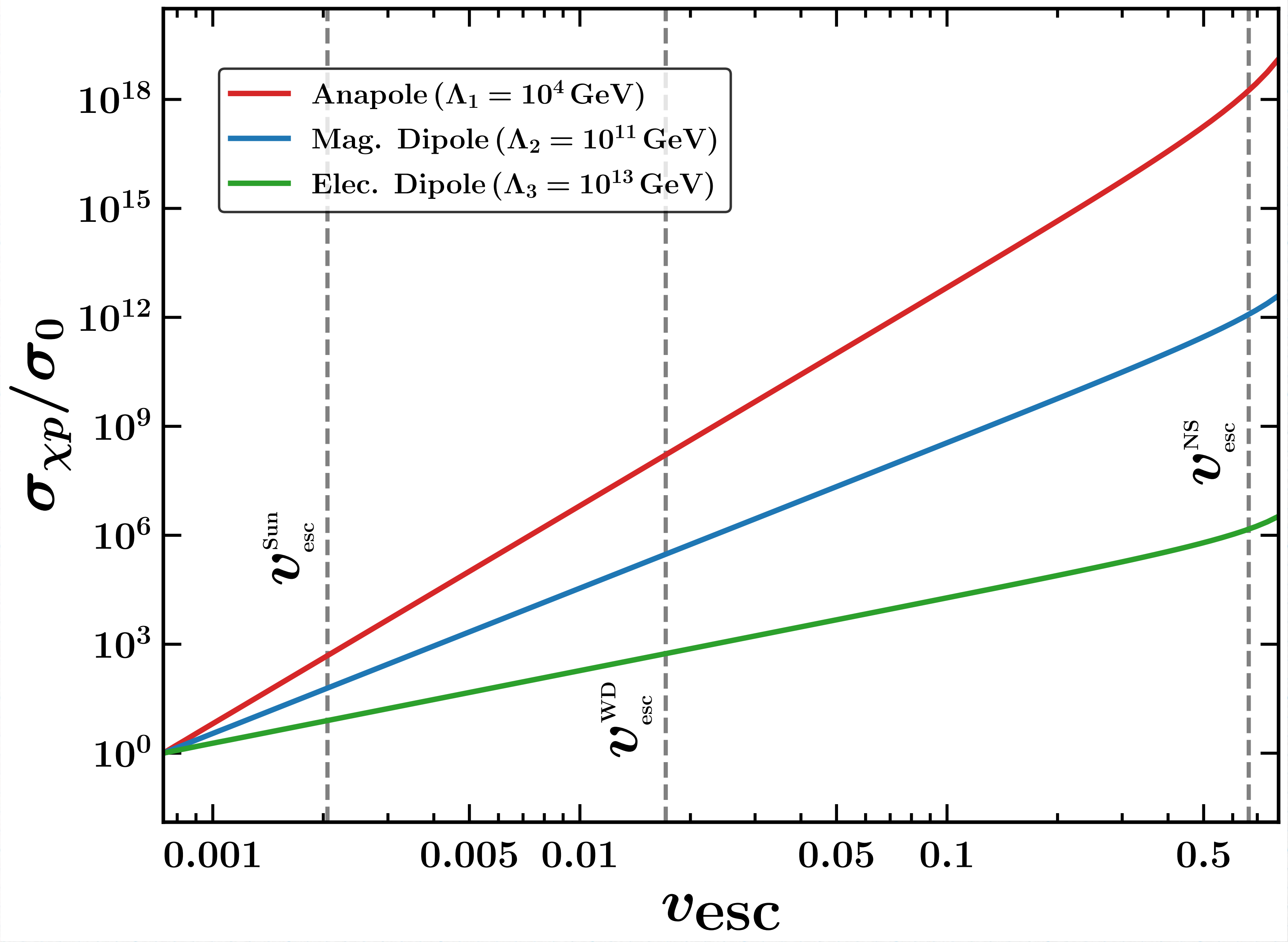
Allowed parameter space without the projected Limits from NS heating

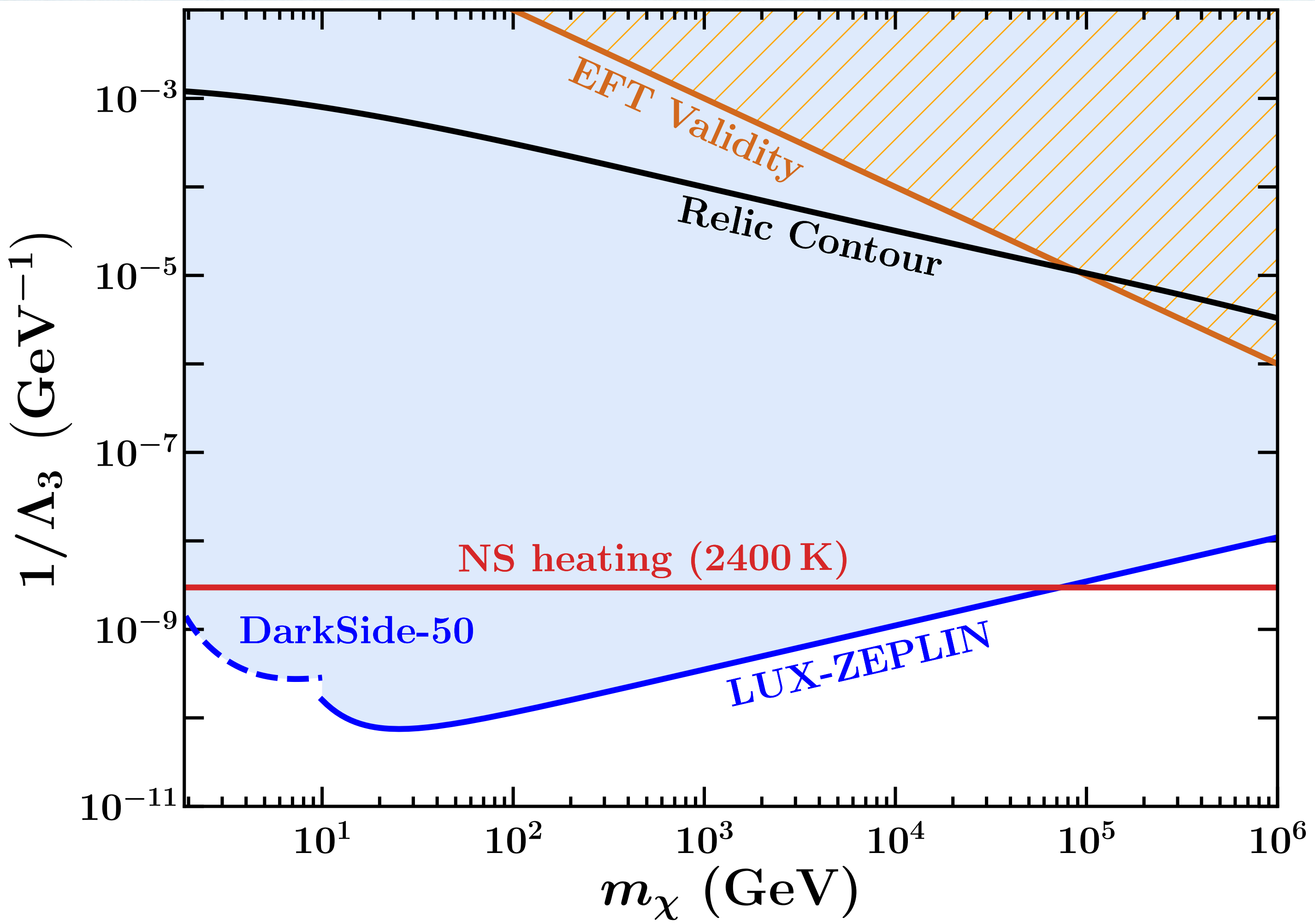
Effect of gravitational boosting in DM capture

- Monotonically increasing Cross-section with v_{esc}

- Enhancement is maximum In Anapole

- Large v_{esc} makes NS efficient in DM capture



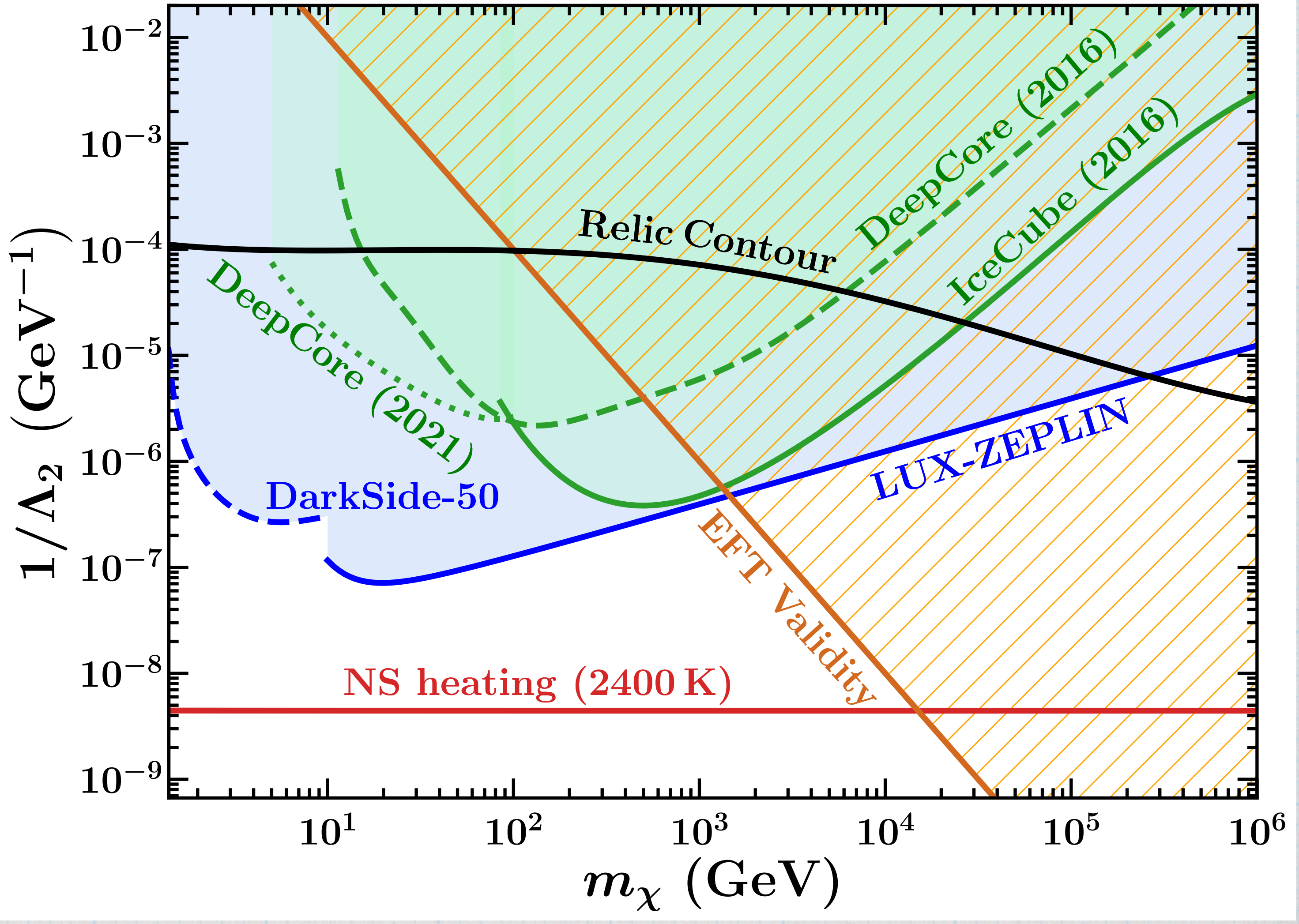


$$\mathcal{L}_{\text{dipole}} = \underbrace{\frac{1}{\Lambda_2}\bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}}_{\text{magnetic}} + \underbrace{\frac{i}{\Lambda_3}\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi F^{\mu\nu}}_{\text{electric}},$$

EDM

MDM

- Maximum parameter space is rulled out from direct detection
- At low mass region, NS put better constraints



Summary

- Derivative coupling, by enhancing the scattering rate, increase the DM capture rate in celestial bodies

- Updated direct detection and capture disfavour the viable parameter space in EDM and MDM

- A narrow window survives in Anapole that lies within the reach of JWST

Thank You!

Backup slides

$$\frac{dN}{dVdt} = \sigma v_{\mathbf{mol}} n_1 n_2 \rightarrow \text{Lorentz invariant}$$

MB statistics

$$f(E) \propto \exp(-E/T)$$

$$\langle \sigma v_{\text{Møl}} \rangle = \frac{\int \sigma v_{\text{Møl}} \, e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2}{\int e^{-E_1/T} e^{-E_2/T} \, d^3p_1 \, d^3p_2},$$

$$\downarrow$$

$$\langle \sigma v_{\text{Møl}} \rangle = \frac{1}{8m^4 T K_2^2(m/T)} \int_{4m^2}^{\infty} \sigma (s - 4m^2) \sqrt{s} \, K_1(\sqrt{s}/T) \, ds.$$

$$v_{\text{Møl}} = \left[|v_1 - v_2|^2 - |v_1 \times v_2|^2 \right]^{1/2}$$

$$v_1 = p_1/E_1 \qquad v_2 = p_2/E_2$$

- Obtained for MB statistics, applicable for all statistics for $T \leq 3m$

For larger nuclei scattering matrix element : $\mathcal{M}(q^2) = T(0)F(q^2).$

Coupling const for p and n

Spin for p and n

spin-dep

$$\overline{|\mathcal{M}(q^2)|^2} = \frac{J+1}{J}\left|(G_a^p + G_a^n)\langle S_p + S_n\rangle F^0_{\text{spin}}(q^2) + (G_a^p - G_a^n)\langle S_p - S_n\rangle F^1_{\text{spin}}(q^2)\right|^2.$$

spin-indep

$$\overline{|\mathcal{M}(q^2)|^2} = \left|ZG_s^p + NG_s^n\right|^2 \left|F_{\text{mass}}(q^2)\right|^2,$$

Form factor, generally Different for spin-dep And spin-indep interactions

For spin 1/2 **Majorana fermions** vector and tensor currents identically vanish.

Pieces that survive in the **non-relativistic limit:** $q^2 \ll m^2$

- Time like component of scalar current gives **spin- indep term** $\chi^\dagger\chi$
- space like axial current gives **spin dependent term** $\chi^\dagger\sigma\chi$

WIMP with spin s can interact with external E and B field

Magnetic dipole moment electric dipole moment

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S} - a\mathbf{j} \cdot \frac{\mathbf{S}}{S}$$

$$-\frac{1}{4S(2S-1)}\left[S_iS_j + S_jS_i - \frac{2}{3}\delta_{ij}S(S+1)\right]\left(Q\frac{\partial}{\partial x_i}E_j + M\frac{\partial}{\partial x_i}B_j\right) + ...$$

electric quadruple moment Magnetic quadruple moment

Anapole moment is the form factor that describes the contact interaction with the external current density → j

If spin of WIMP is zero, these moments do not exist and the interaction with the EM field is given by the charge radius r_D of the WIMP and the polarizabilities.

$$H = -\frac{1}{6}er_D^2\frac{\partial}{\partial x_i}E_i - \frac{1}{2}\chi_E E^2 - \frac{1}{2}\chi_B B^2 - \chi_{EB}\mathbf{E}\cdot\mathbf{B} + ...$$

Scattering cross-sections for NS heating calculation for Anapole

$$\left(\frac{d\sigma_{\chi p\to\chi p}}{d\,cos\theta}\right)_{\mathrm{AP}} = \frac{1}{32\pi s}\times\frac{8\pi\alpha_e}{\Lambda_1^4}\left[2\left(m_p^4+m_\chi^4\right)+2s^2 +2st+t^2-4m_p^2\left(m_\chi^2+s\right)-4m_\chi^2\left(s+t\right)\right]$$

$$\left(\frac{d\sigma_{\chi n\to\chi n}}{d\,cos\theta}\right)_{\mathrm{AP}} = \frac{1}{32\pi s}\times\frac{4\mu_n^2 t}{\Lambda_1^4}\left[m_n^2\left(2s+2t-6m_\chi^2\right) -m_n^4-\left(m_\chi^2-s\right)^2-st\right]$$

Majorana fermion → CPT self-conjugate → Cannot have EDM of MDM, since the interactions are CPT-odd

ADM is related to toroidal dipole moment corresponds to solenoid with joined end producing an azimuthal magnetic field

$$\Gamma_\mu(q) = F(q^2)\gamma_\mu + M(q^2)\sigma_{\mu\nu}q^\nu + E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + A(q^2)[q^2\gamma_\mu - \hat{q}q_\mu]\gamma_5$$

EM vertex Lorentz structure

Normal Magnetic

Anomalous Magnetic

Electric

Anapole (does not correspond to a certain multipole distribution)

$$H_{\text{int}} \propto -\mu(\boldsymbol{\sigma}\cdot\mathbf{B}) - d(\boldsymbol{\sigma}\cdot\mathbf{E}) - a(\boldsymbol{\sigma}\cdot\text{curl}\,\mathbf{B})\,.$$

Non-rel Limit

$$A(q^2) = T(q^2) + \frac{m_i^2 - m_f^2}{q^2 - \Delta m^2}[D(q^2) - D(\Delta m^2)]\,.$$

Anapole form factor

Toroidal dipole Form factor

static limit $(m_i = m_f)$