Optimal anti-ferromagnets for light dark matter detection

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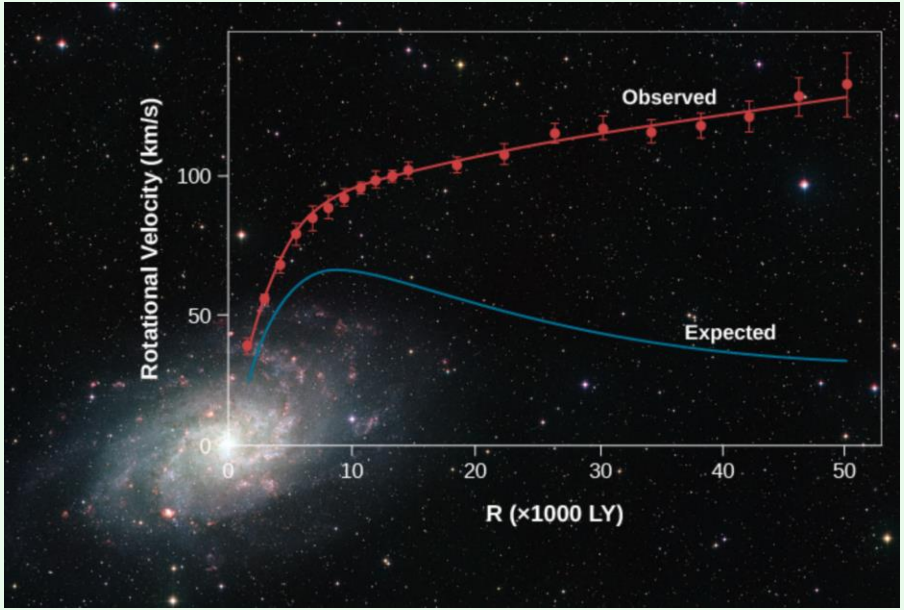
Based on the work with Angelo Esposito (arXiv: 2210.13516)

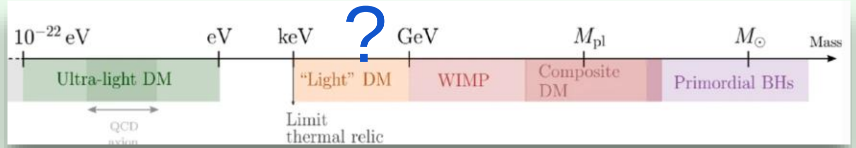
Dark Matter

Accounts for almost 85 % of mass



Spans over wide range of masses ⟶ Need variety of detection techniques

- * Primordial black hole mergers
- * Gamma rays from annihilation
- * CMB polarization rotation



- * Conversion in magnetic field
- * Light shining through walls
- * Nuclear spin precession
- * Mechanical sensors

- * Multi-tonne liquid noble elements
- * Bubble chambers
- * Cryogenic calorimeters
- * CCDs

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Sub-GeV Dark matter

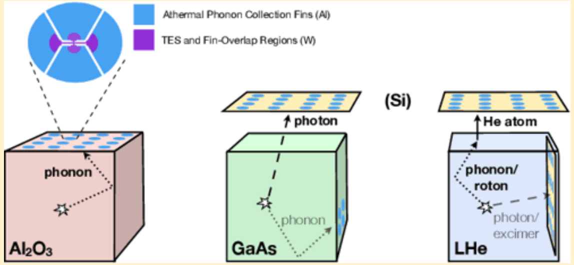
$M \sim$ keV - GeV $\Longrightarrow$ $E \sim$ meV - keV

Condensed matter systems provide an ideal platform $\Longrightarrow$

* Semiconductors
* Narrow-gap materials
* Organic crystals
* Superconductors

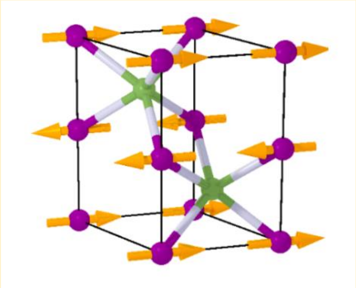
Collective excitations in condensed matter systems ~ O(meV). Ideal for the O(keV) dark matter.

E.g. Phonons in solids, superfluid helium.



TESSERACT Dark Matter Project

Magnons in anti-ferromagnets (This work)



Effective field theory

But many-body physics is hard …… Multiple scales in the problem !!

EFT ??

Anti-ferromagnets spontaneously break a host of spacetime and internal symmetries $\longrightarrow$ gapless degrees of freedom (magnons).

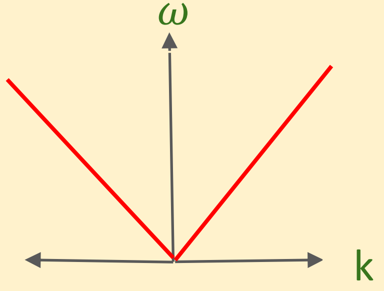
$$L_\chi = \frac{c_6}{2}(\partial_t \chi^a)^2 - \frac{c_7}{2}(\partial_i \chi^a)^2 + \ldots$$

Straightforward to include higher dim. Operators, explicit symmetry breaking terms within a well defined power counting scheme.

Why anti-ferromagnets ?

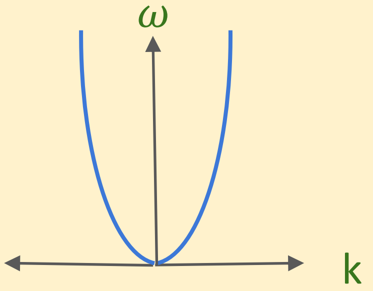
Better reach for spin-dependent interactions.

$L \supset f(q)\, \boldsymbol{S}_{DM} . \delta\boldsymbol{\rho}_s$ (magnons) , $f(q)\, \boldsymbol{S}_{DM} . \boldsymbol{\nabla}\delta\rho$ (phonons)



Two Type-I goldstone in anti-ferromagnets : $\omega \sim c\ k$

Max. $\omega \sim 4\, E\, y\, (1-y)\, ; \quad y = \frac{c}{v}$ optimal $c \sim 0.5\, v$



Single Type-II goldstone in ferromagnets : $\omega \sim \frac{k^2}{2m}$

Max. $\omega \sim 4\, E\, \frac{x}{(1+x)^2}\, ; \qquad x = \frac{m}{M} \quad , m \sim\ O(MeV)$

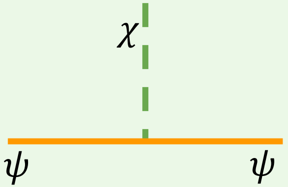
Allows multi-magnon emission in anti-ferromagnets.

Put everything together…

$$\mathcal{L}_{\psi}^{\mathrm{m.d.}} = -\frac{4 g_\psi g_e}{\Lambda_\psi m_e}\left(\psi_{\mathrm{nr}}^{\dagger}\frac{\sigma^i}{2}\psi_{\mathrm{nr}}\right)\left(\delta^{ij} - \frac{\nabla^i \nabla^j}{\nabla^2}\right)\left(e_{\mathrm{nr}}^{\dagger}\frac{\sigma^j}{2}e_{\mathrm{nr}}\right)$$

S^j — IR →

$$\rho_s^i = c_6 \delta^{ia}\chi^a + c_6 \delta^{i3}\epsilon^{ab}\dot{\chi}^a \chi^b$$



Compute decay rates $\Gamma(v_\psi)$

⇩

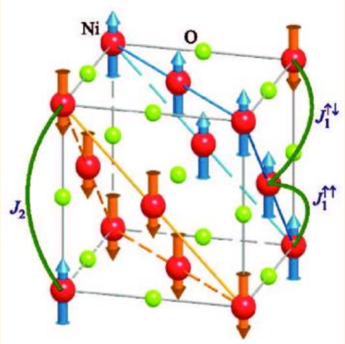
# of events per kilogram of year exposure.

DM velocity distribution

$$R = \frac{\rho_\chi}{\rho_T m_\chi}\int d^3 v_\chi f(v_\chi)\Gamma(v_\chi)$$

Matching

But c_6 needs to be determined ⟶ Use a matching procedure



“UV” theory = Heisenberg model

$$\mathcal{H} = \sum_{ij} J_{ij} \vec{S}_i . \vec{S}_j$$

Neutron scattering cross-section

EFT

$$\frac{d^2\sigma}{d\Omega\, dE'} = V(\gamma r_0)^2 \frac{k'}{k} c_6 \frac{1+\hat{q}_z^2}{4} \omega(q) \delta\big(E' - E - \omega(q)\big)$$

Heisenberg model

$$\left(\frac{d^2\sigma}{d\Omega\, dE'}\right)^{(\pm)} = r_0^2 \frac{k'}{k} \{\tfrac{1}{2} gF(\boldsymbol{\kappa})\}^2 \tfrac{1}{4}(1+\tilde{\kappa}_z^2) \exp\{-2W(\boldsymbol{\kappa})\} \frac{(2\pi)^3}{Nv_0}$$

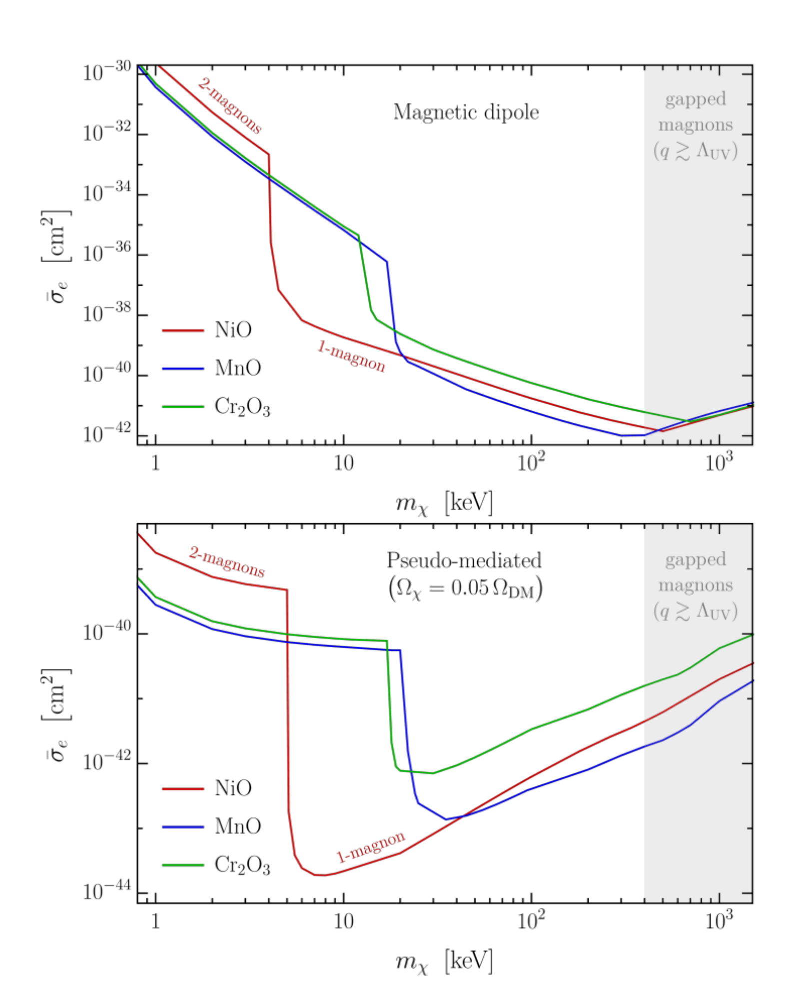
$$\times \sum_{a=0,1} \sum_{\mathbf{q},\boldsymbol{\tau}} (n_{\mathbf{q},a} + \tfrac{1}{2} \pm \tfrac{1}{2})\, \delta(\hbar\omega_{\mathbf{q},a} \mp \hbar\omega)\, \delta(\boldsymbol{\kappa} \mp \mathbf{q} - \boldsymbol{\tau}) \{u_{\mathbf{q}}^2 + v_{\mathbf{q}}^2 + 2u_{\mathbf{q}}v_{\mathbf{q}} \cos \boldsymbol{\rho} \cdot \boldsymbol{\tau}\}.$$

Cross-Section

Compute the DM-electron cross section $\boldsymbol{\sigma_e}$.

For NiO, $c \sim v$ and therefore has the best mass reach (O(keV)) for single magnon.

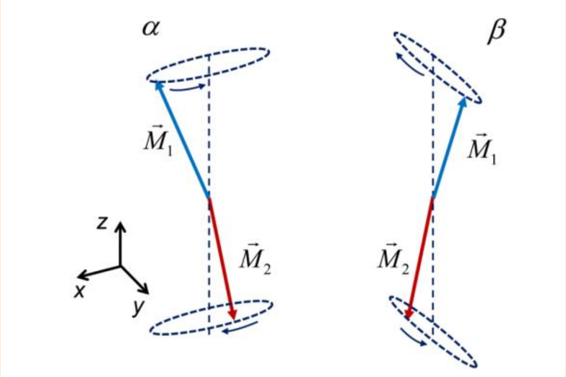
Two magnon rates have O(keV) reach for all cases.

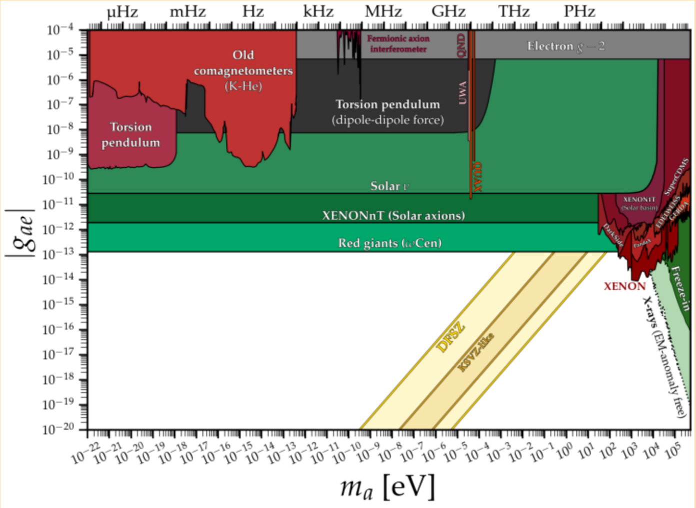


Axions

Can also hunt for axion and axion like particles via the electron coupling $L \supset \frac{g_{aee}}{f_a} \vec{\nabla} a \cdot \vec{S}_e$

$\omega \sim m_a \,, k \sim m_a v_a \ll m_a$ ⟹ couples to the zero modes of the antiferromagnet ~ THz resonance





Reproduced from https://cajohare.github.io/AxionLimits/docs/ae.html

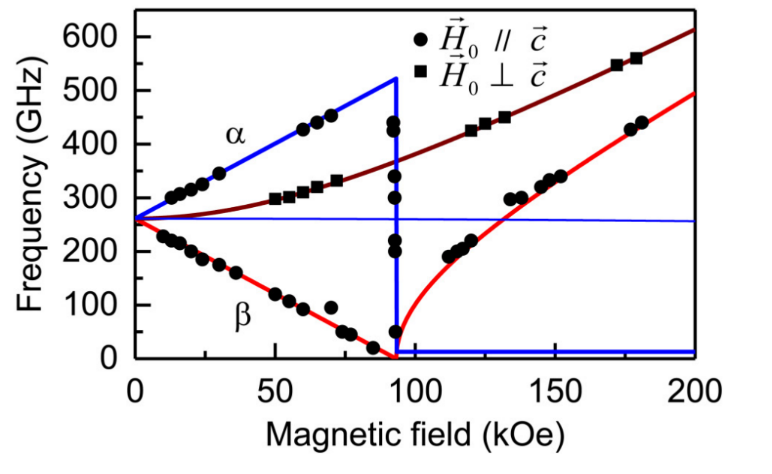
Include effects of anisotropy ⟶ gapped magnons. Can be tuned using a B field.

$$\mathcal{L}^{(2)}_{AFM} = \frac{c_6}{2}\dot{\chi}^a\dot{\chi}^a - \frac{c_2}{2}\partial_i\chi^a\partial^i\chi^a - \frac{c_3}{2}\chi^a\chi^a + c_6\,\mu B_3\,\epsilon_{ab}\chi^a\dot{\chi}^b$$

Two gapped modes with linear B dependence.

$$\omega_{\pm} = \frac{c_3}{c_6} \pm \mu\, B$$

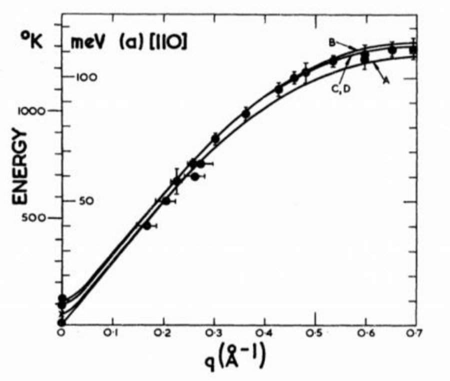
Compute rates for exciting a single mode. Can be used to constrain g_{aee} beyond astrophysical limits for long lived magnons.



Conclusions

- Anti-ferromagnets can probe spin-dependent interactions down to O(keV) masses.
- Allow for multi-magnon emission which can be utilized as background discrimination.
- Can also be utilized to look axions and axion like particles.
- EFT’s provide an effective and simple computational tool in a complicated many body setting.

“Light” Dark Matter



- Typical magnon energies ~ 1-100 meV

Start with some well-motivated UV models ; Interactions mediated by a scalar or vector ;

Magnetic dipole DM →

$$\mathcal{L}_{\psi}^{\text{m.d.}} = \frac{g_\psi}{\Lambda_\psi} V_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi + g_e V_\mu \bar{e}\gamma^\mu e$$

Pseudo-mediated DM →

$$\mathcal{L}_{\chi}^{\text{p.m.}} = g_\psi \phi\, \bar{\psi}\psi + g_e \phi\, i\, \bar{e}\gamma^5 e$$