Optimal anti-ferromagnets for light dark matter detection

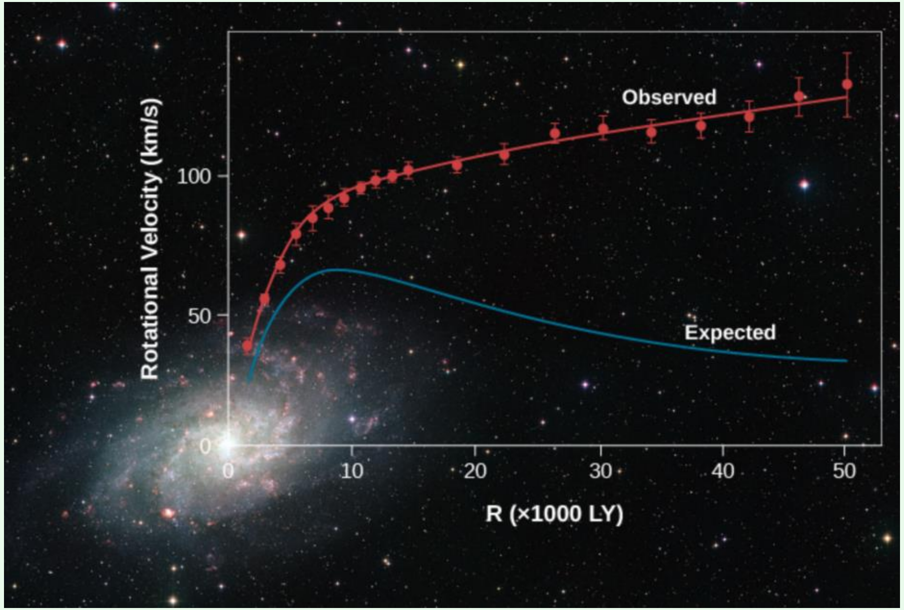
Shashin Pavaskar
University of Illinois at Urbana-Champaign

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

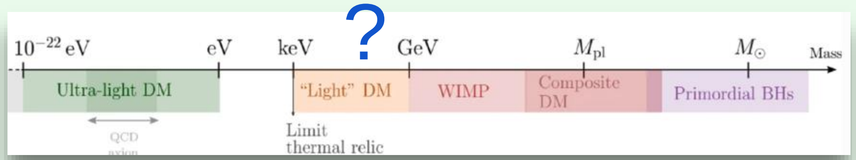
Dark Matter

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

Sub-GeV Dark matter

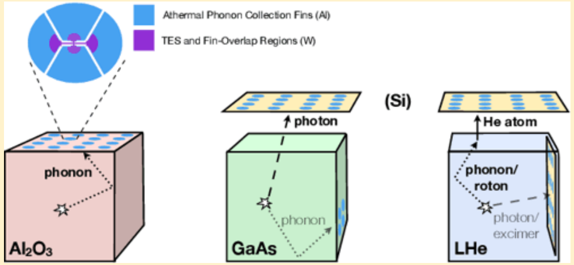
M ~ keV - GeV ⟹ **E** ~ meV - keV

Condensed matter systems provide an ideal platform ⟹

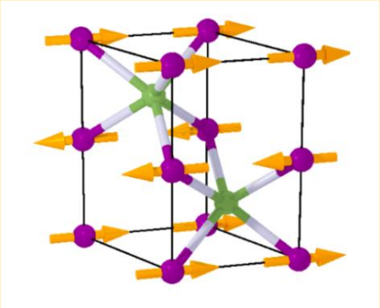
* Semiconductors
* Narrow-gap materials
* Organic crystals
* Superconductors

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

E.g. Phonons in solids, superfluid helium.



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 → gapless degrees of freedom (magnons).

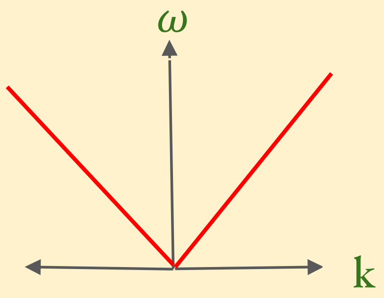
$$L_\chi = \frac{c_6}{2}(\partial_t \chi^a)^2 - \frac{c_7}{2}(\partial_i \chi^a)^2 + \ldots$$

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

Why anti-ferromagnets ?

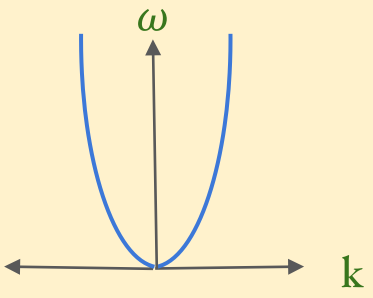
Better reach for spin-dependent interactions.

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



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

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



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

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

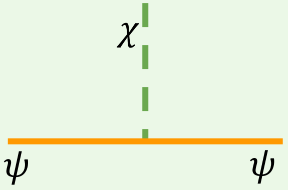
Allows multi-magnon emission in anti-ferromagnets.

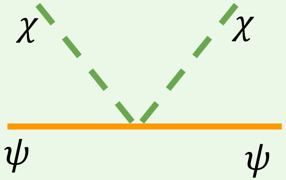
Put everything together...

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

$\boldsymbol{S}^j$ — IR →

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





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

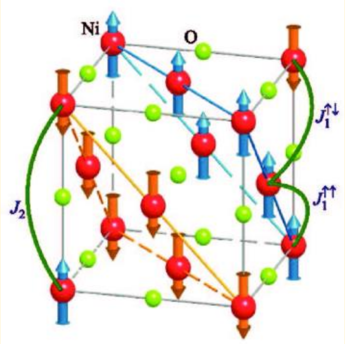
↓

# 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

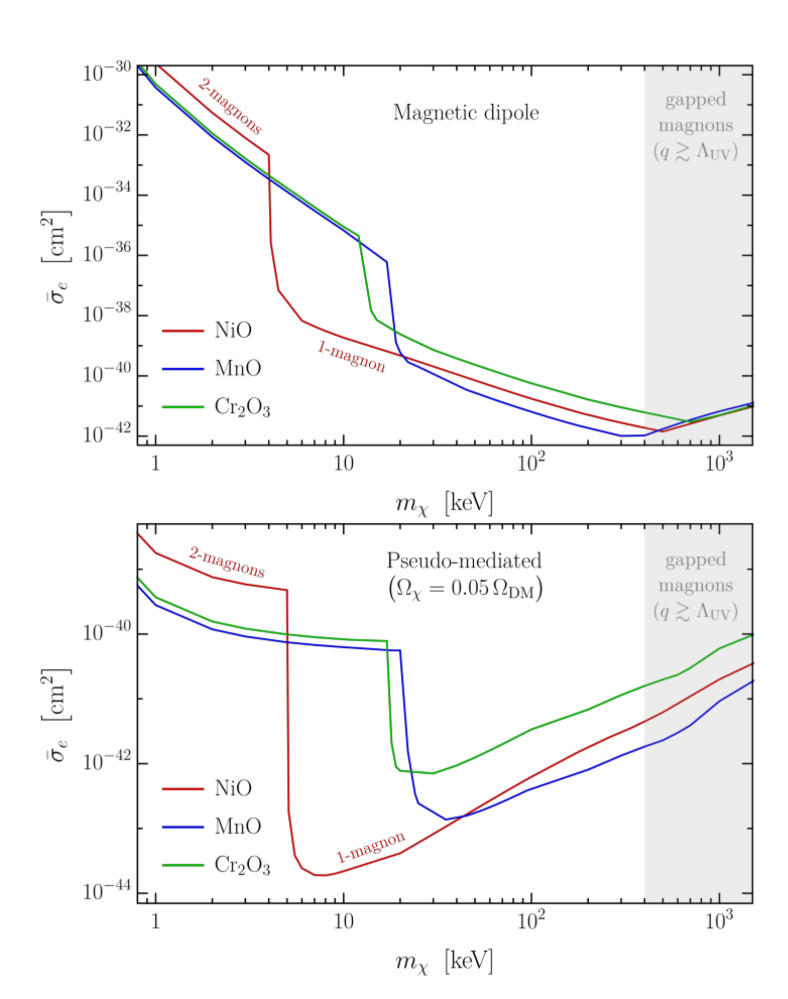
$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\, \mathrm{d}E'}\right)^{(\pm)} = r_0^2 \frac{k'}{k} \{\tfrac{1}{2} g F(\boldsymbol{\kappa})\}^2 \tfrac{1}{4}(1+\tilde{\kappa}_z^2) \exp\{-2W(\boldsymbol{\kappa})\} \frac{(2\pi)^3}{N v_0}$$
$$\times \sum_{a=0,1} \sum_{\mathbf{q},\boldsymbol{\tau}} (n_{\mathbf{q},a} + \tfrac{1}{2} \pm \tfrac{1}{2})\, \delta(\hbar\omega_{\mathbf{q},a} \mp \hbar\omega)\, \delta(\boldsymbol{\kappa} \mp \mathbf{q} - \boldsymbol{\tau}) \{u_{\mathbf{q}}^2 + v_{\mathbf{q}}^2 + 2u_{\mathbf{q}} v_{\mathbf{q}} \cos \boldsymbol{\rho} \cdot \boldsymbol{\tau}\}.$$

Cross-Section

Compute the DM-electron cross section σ_e.

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

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



Conclusions

Anti-ferromagnets can probe spin-dependent interactions down to O(keV) masses.

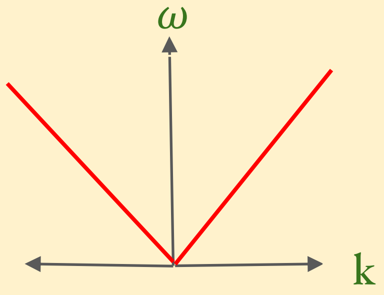
Allow for multi-magnon emission which can be utilized as background discrimination.

EFT's provide an effective and simple computational tool in a complicated many body setting.

Backup

Better reach for spin-dependent interactions.

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



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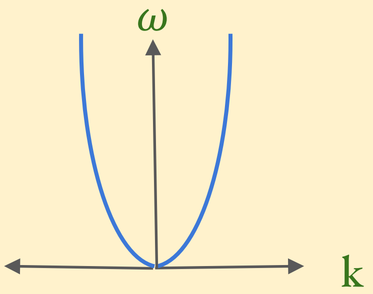
Max. $\omega \sim$ E ; optimal $c \sim v$

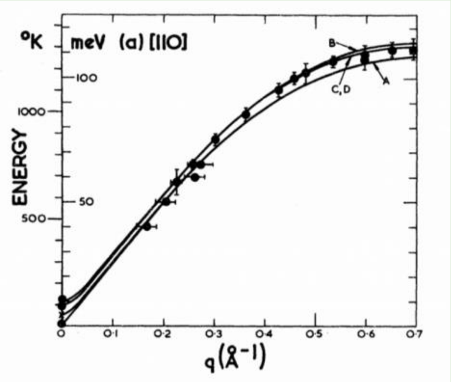


Single Type-II goldstone in ferromagnets : $\omega \sim \frac{k^2}{2m}$

Max. $\omega <<$ E ; $m \sim O(MeV)$

Allows multi-magnon emission in anti-ferromagnets.

"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 →

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