Hunting axion dark matter with anti-ferromagnets

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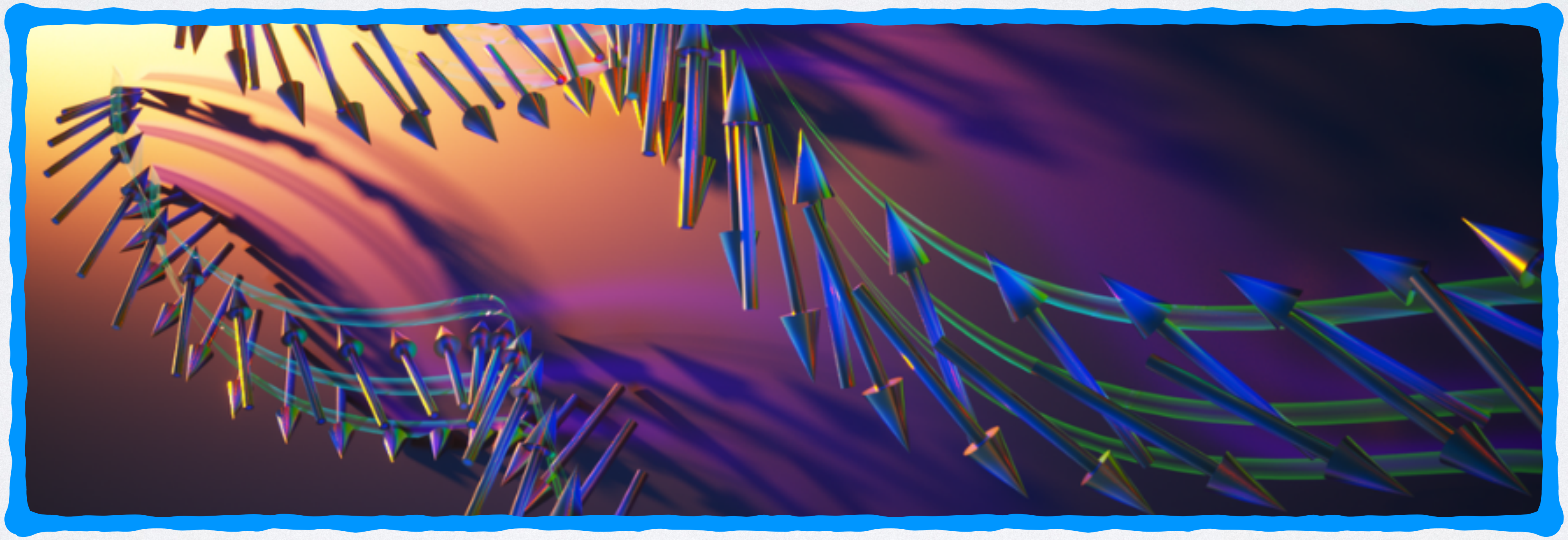
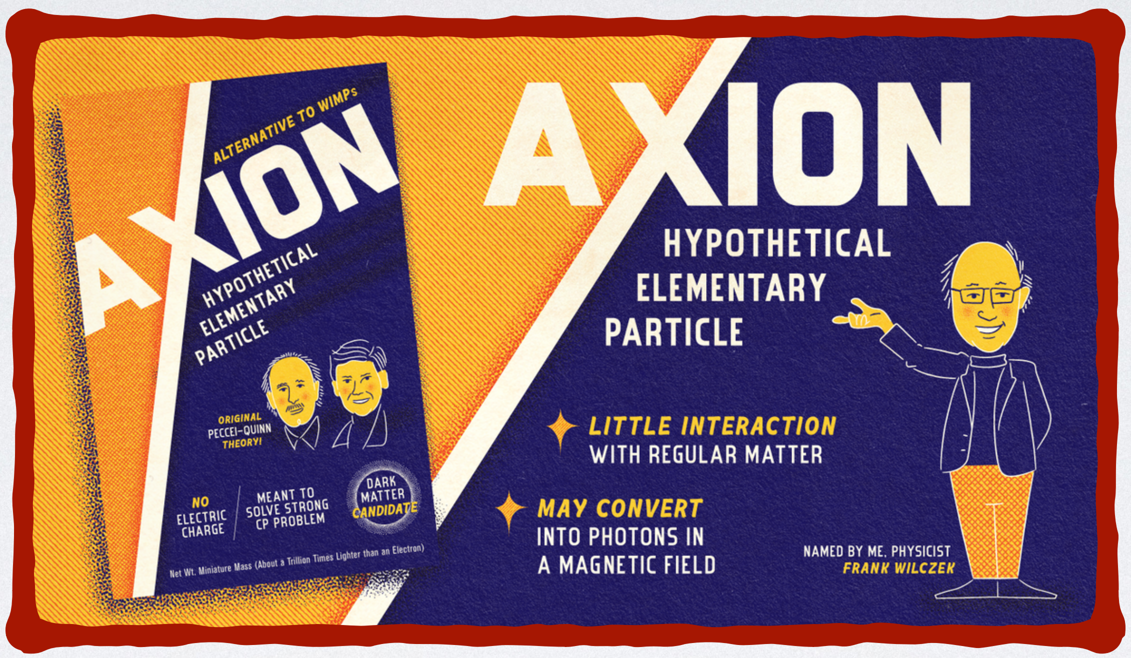


based on 2411.09761, 2411.11971 with Angelo Esposito and Shashin Pavaskar

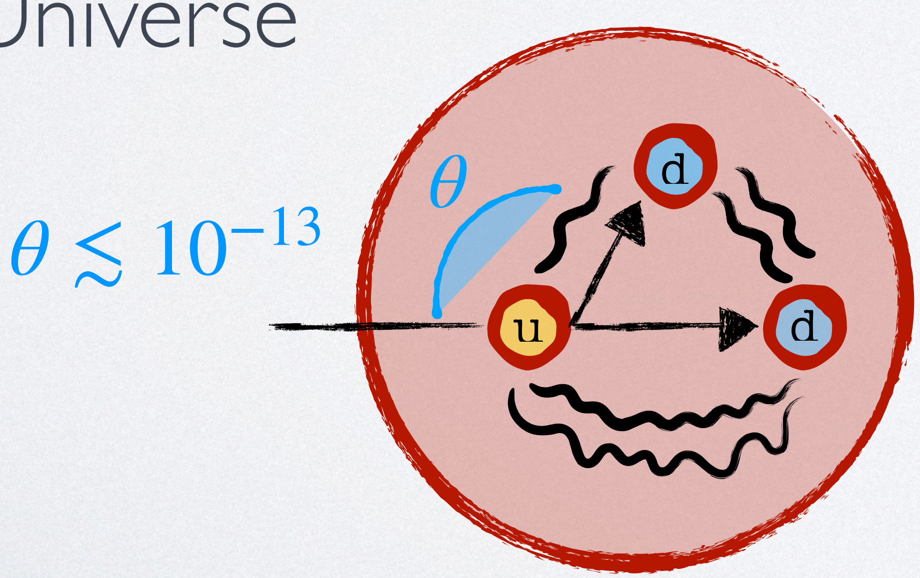
Cortona, May 20th 2025

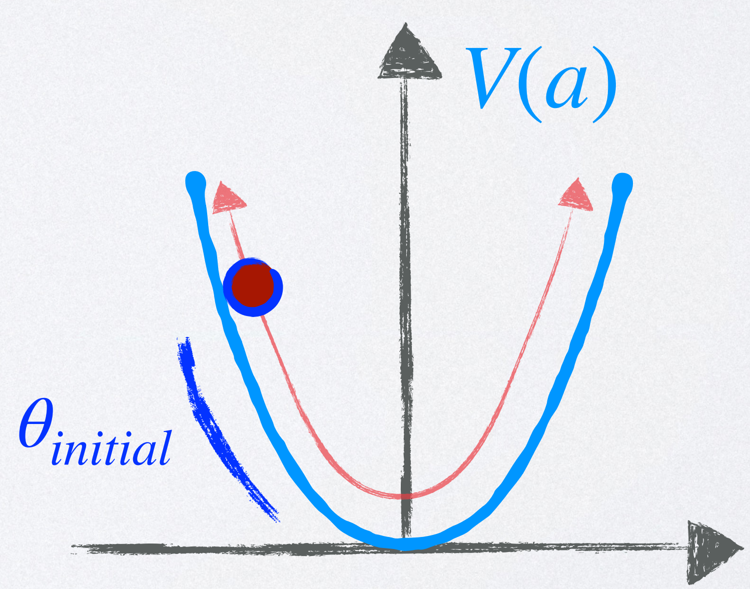
QCD axion

- The QCD axion is a very well motivated BSM particle.



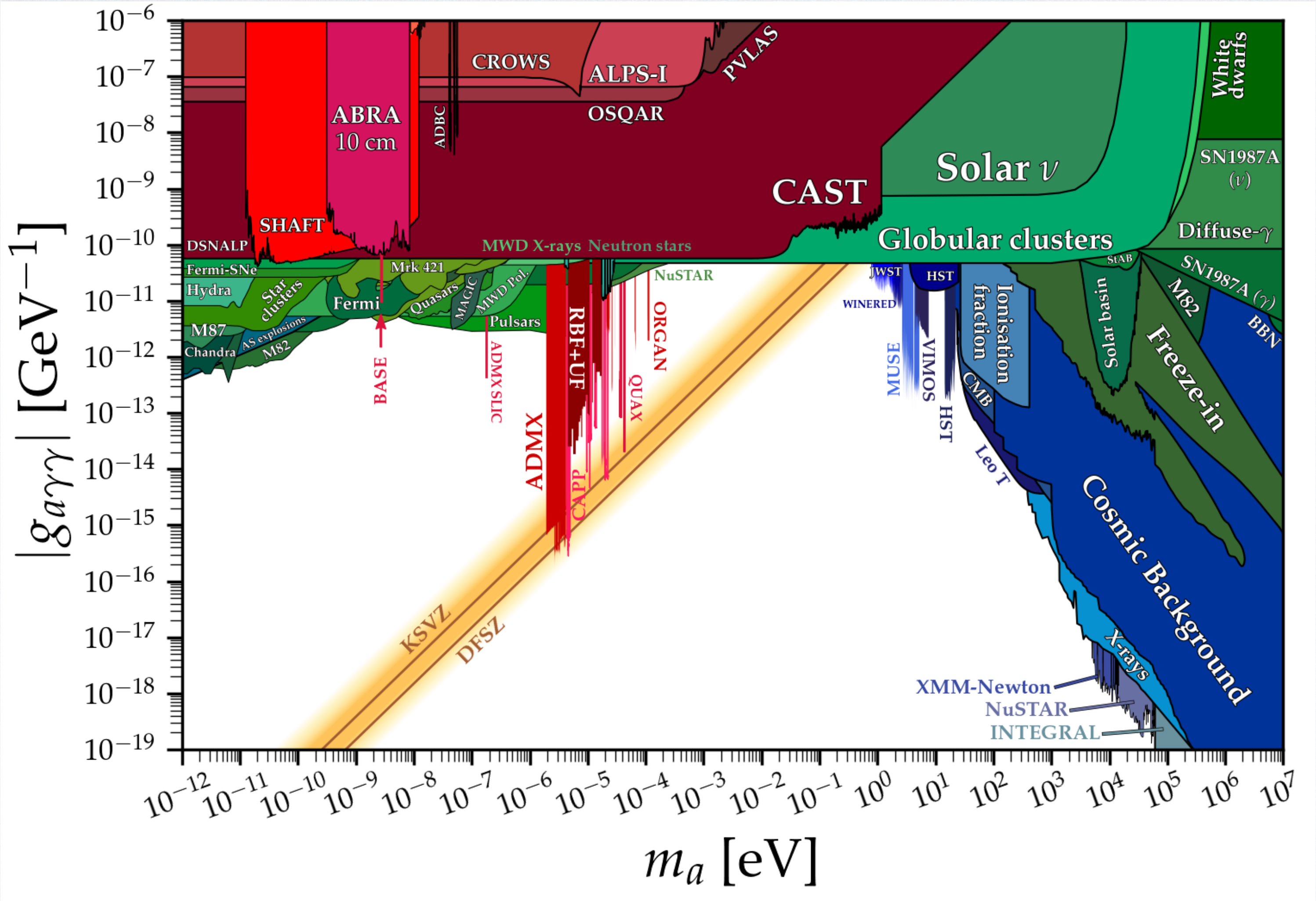
- Explains the smallness of θ and can constitute DM in our Universe





Experimental landscape

- Many ongoing experiments, prototypes and ideas to probe the axion-photon coupling $g_{\alpha\gamma}$



$$\mathscr{L}_a \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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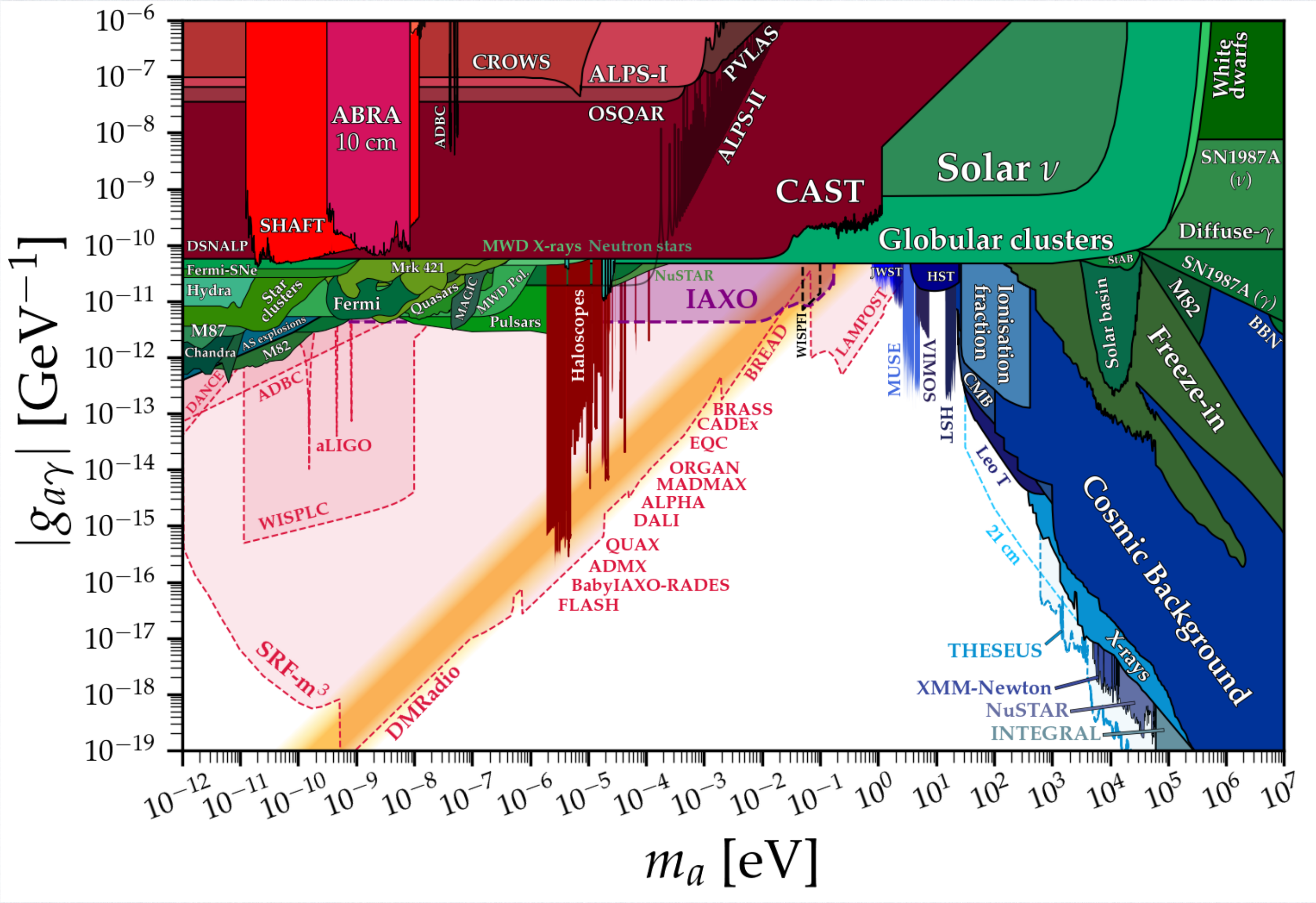

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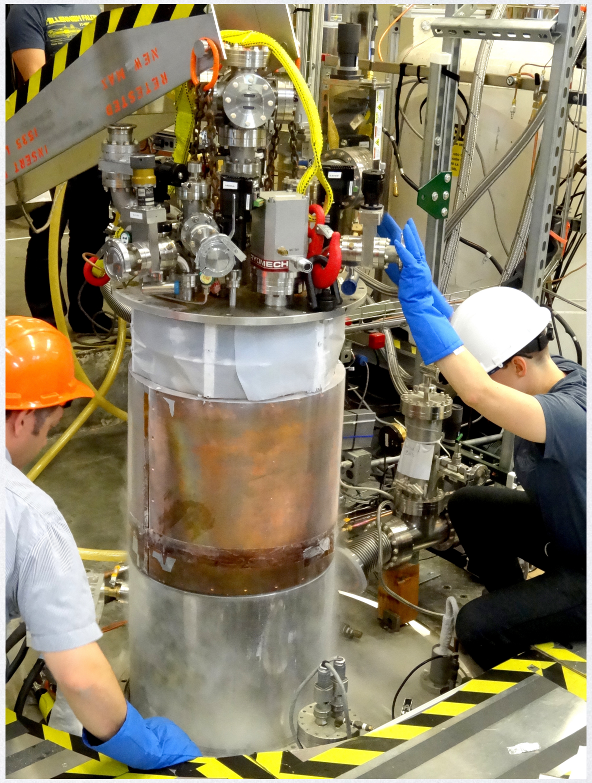

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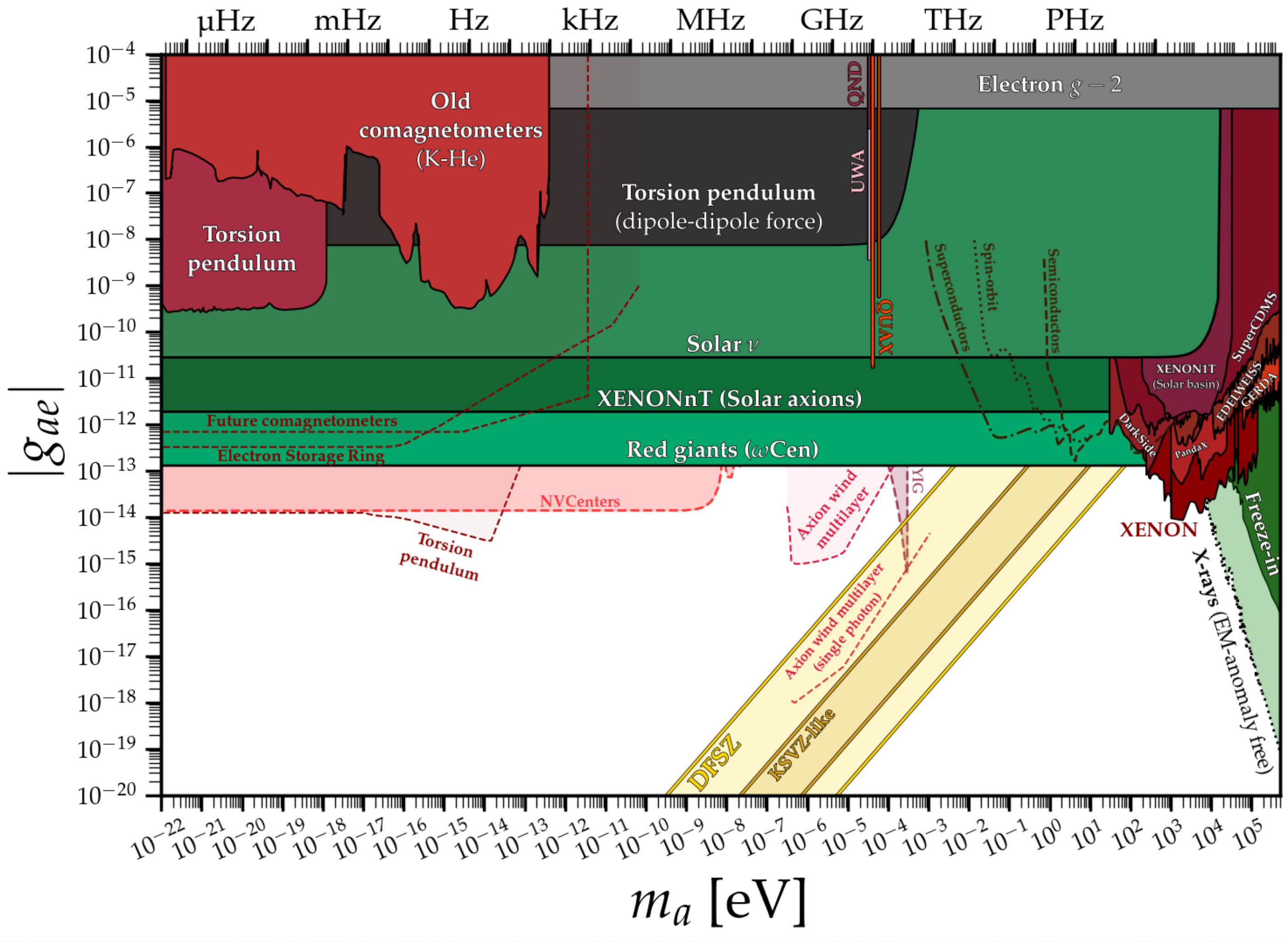
- Experimental program for axion-electron coupling g_{ae} is less developed ⟶ new ideas to probe unexplored regions



$$\mathcal{L}_a \supset \frac{g_{ae}}{2m_e}\partial_\mu a\, \bar{e}\gamma^\mu\gamma_5 e$$

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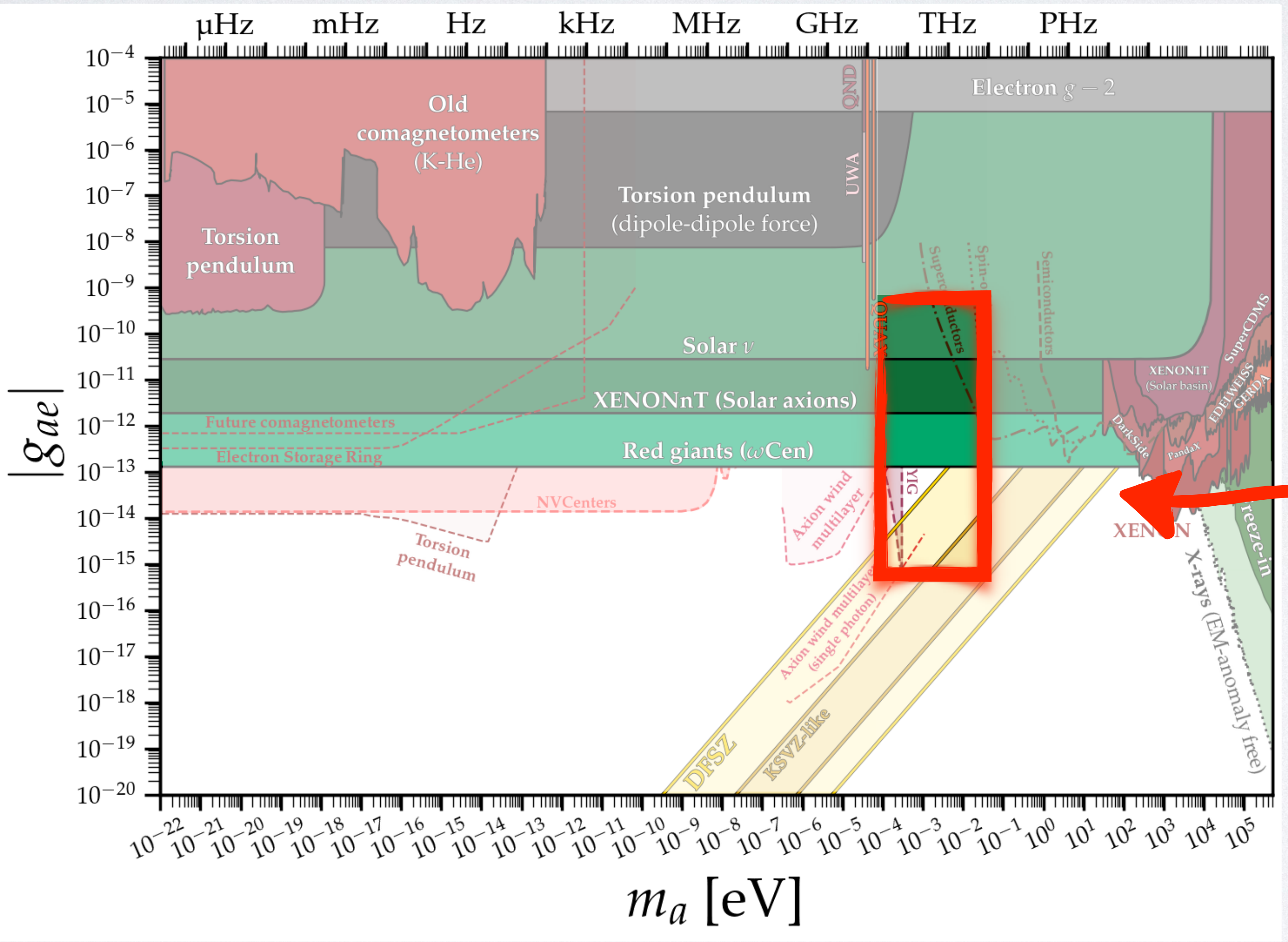


$$\mathcal{L}_a \supset \frac{g_{ae}}{2m_e}\,\partial_\mu a\;\bar{e}\gamma^\mu\gamma_5 e$$

Almost unconstrained window for

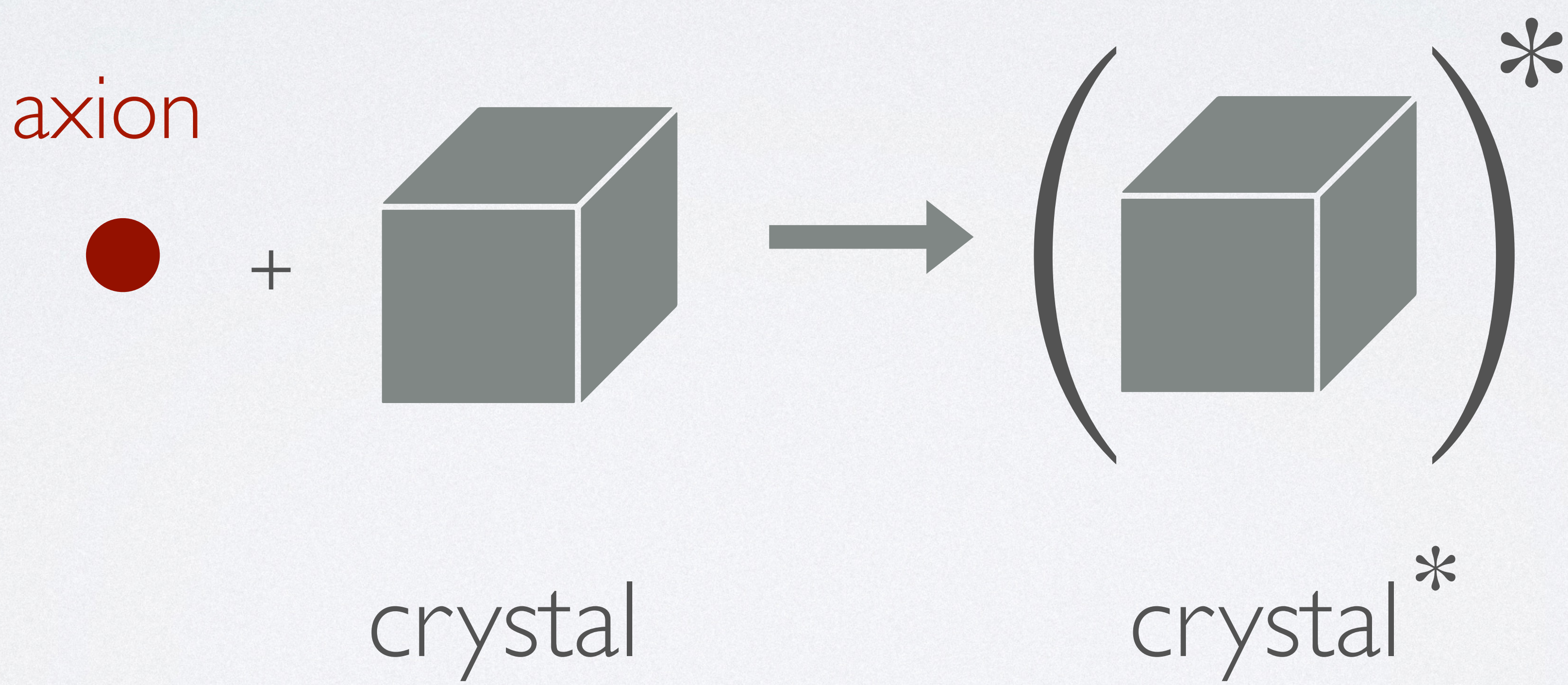
$\sim (0.1 \div 10)$ meV

For similar mass ranges see also
[Chigusa et al. — PRD 2020, 2001.10666,
Mitridate et al. — PRD 2020, 2005.10256,
Berlin et al. — JHEP 2024, 2312.11601]

Antiferromagnets

- We can use collective excitations of (anti-)ferromagnets to probe dark matter with spin-dependent interactions.

- Idea



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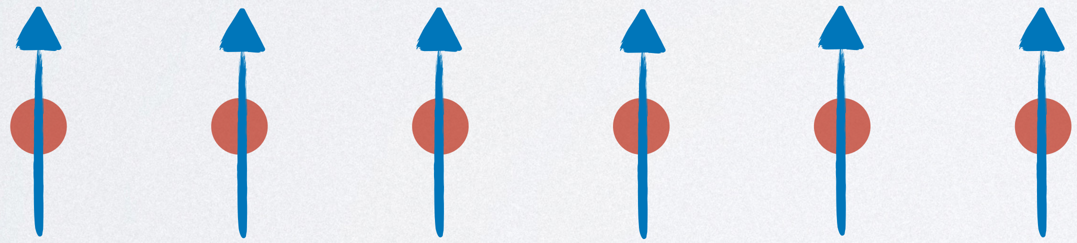

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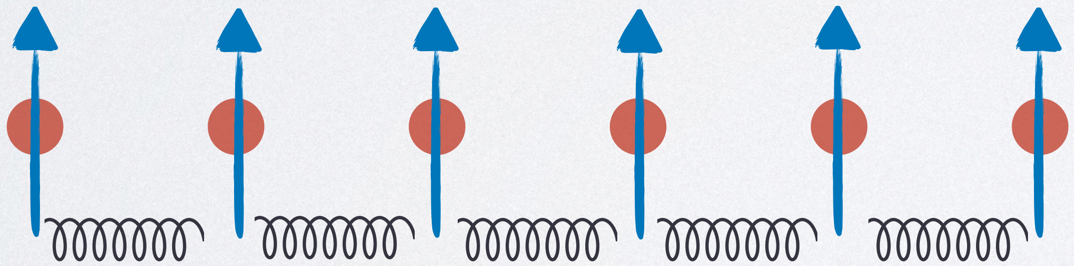

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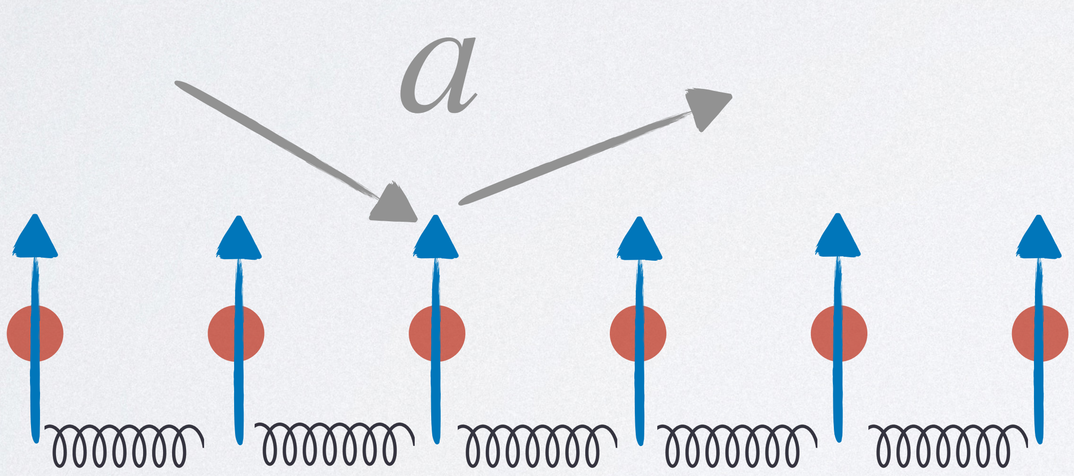

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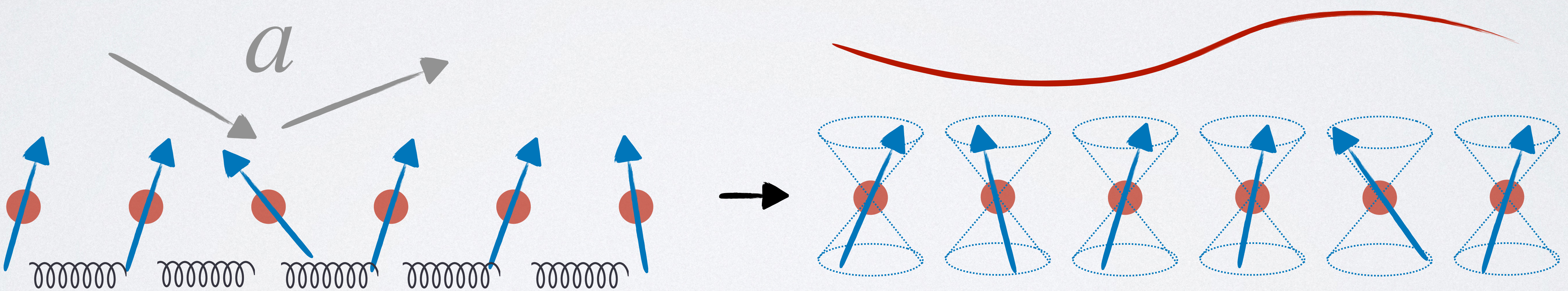
$$\mathscr{L}_a \supset \frac{g_{ae}}{2m_e} \partial_\mu a \; \bar{e}\gamma^\mu\gamma_5 e$$

$\theta(\mathbf{x}, t) = \text{magnon}$

Collective excitation



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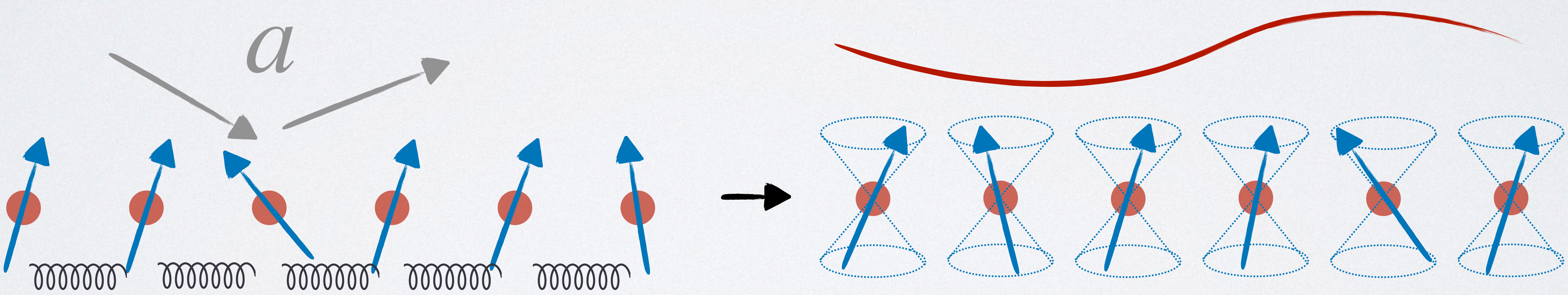
Collective excitation



- How can we describe collective excitations in antiferromagnets?

Collective excitations à la HEP

- All phases of matter spontaneously break spacetime and internal symmetries

Goldstone's theorem

spontaneously broken symmetries ⟷ Existence of soft modes π

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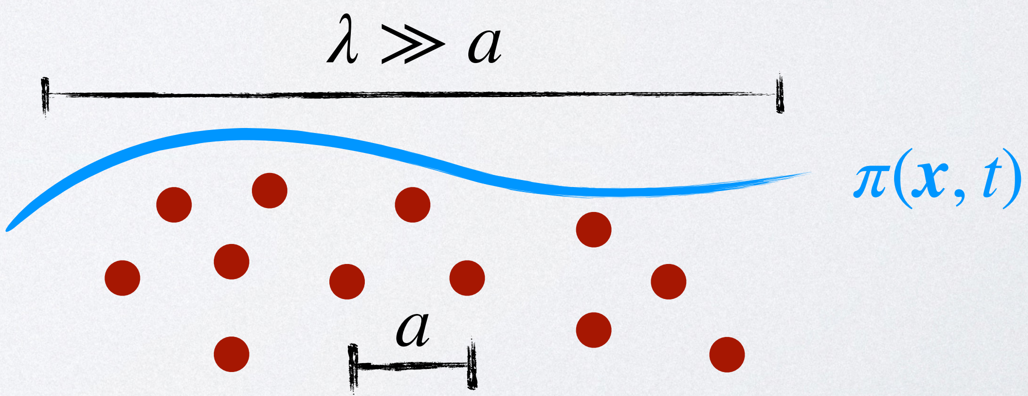
- At low energies, the system can be described by an EFT of Goldstones, organized in a derivative expansion

$$\mathscr{L}_{\mathrm{EFT}}(\pi, \partial\pi) \simeq \sum_{n,m} g_{n,m}(\pi, \partial\pi)\, \partial^n \pi^m$$



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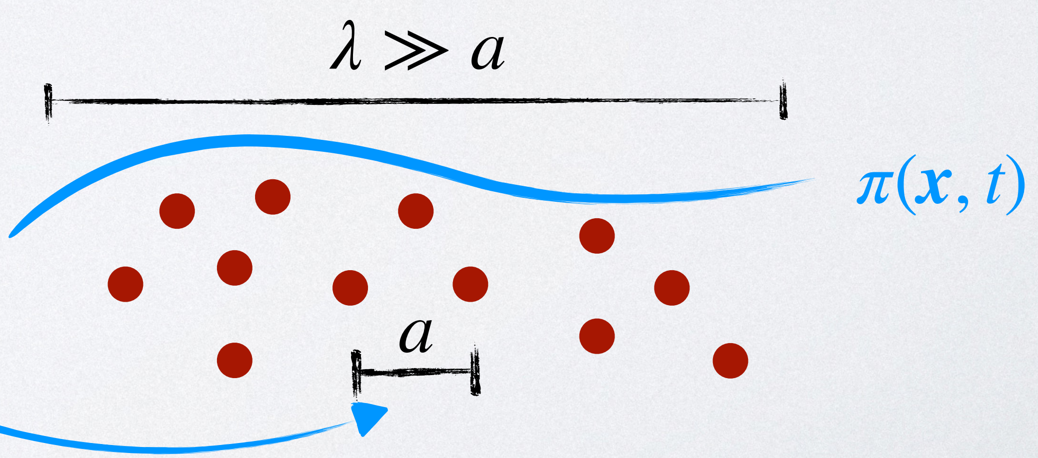
The complicated microphysics is encoded in the $g_{n,m}$ s



Magnons EFT

- Similarly to the non-linear σ model, we can parametrize the fluctuations around the vacuum as [Esposito, Pavaskar, PRD 2023 — 2210.13516]

$$\hat{\boldsymbol{n}}_{\mathrm{I}}(\boldsymbol{x}, t) = \left[e^{iJ_1 \theta^1(\mathbf{x},t) + iJ_2 \theta^2(\mathbf{x},t)} \hat{z} \right]_I \xrightarrow{SO(3)_{\text{int}}} R^J_{\ I} \cdot \hat{\boldsymbol{n}}_J(\boldsymbol{x}, t) \,, \quad \sum_I (\hat{\boldsymbol{n}}_I)^2 = 1$$

magnon fields

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magnon fields

- At the lowest order in the derivative expansion, the most general Lagrangian density invariant under the internal SO(3)

$$\mathscr{L}_0 = \frac{c_1}{2}\left[\partial_t\hat{\boldsymbol{n}}^I\partial_t\hat{\boldsymbol{n}}_I - v_\theta^2\left(\nabla_i\hat{\boldsymbol{n}}^I\right)\left(\nabla_i\hat{\boldsymbol{n}}_I\right)\right] \equiv \frac{c_1}{2}\left[(\partial_t\hat{\boldsymbol{n}})^2 - v_\theta^2(\nabla_i\hat{\boldsymbol{n}})^2\right]$$

v_θ from dispersion relations

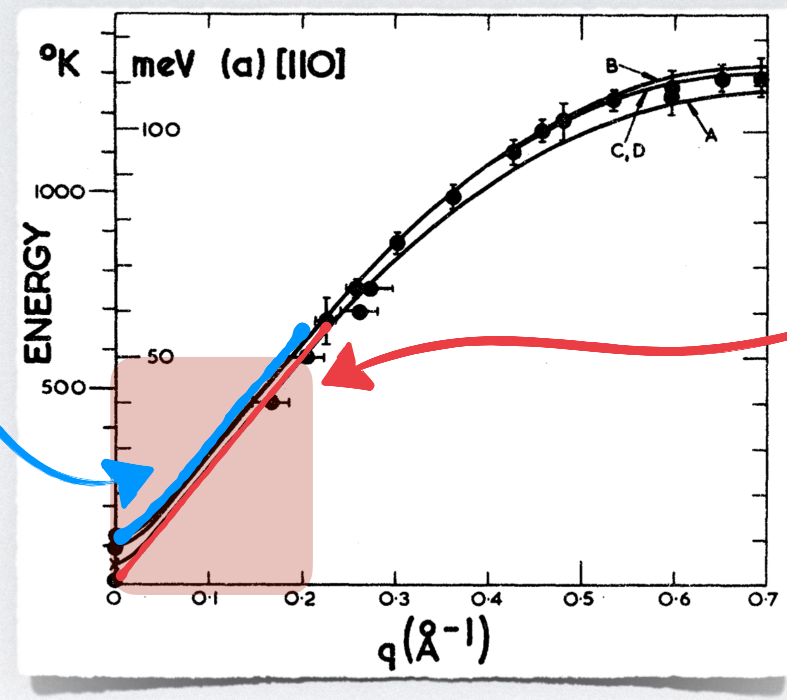
c_1 from nuclear scattering

$\sigma_n \propto c_1$

Magnons EFT

- The phenomenology of NiO is, however, richer than this. Specifically, its magnon modes actually present a small but non-zero gap.

pseudo-Goldstones
(like πs with massive quarks)



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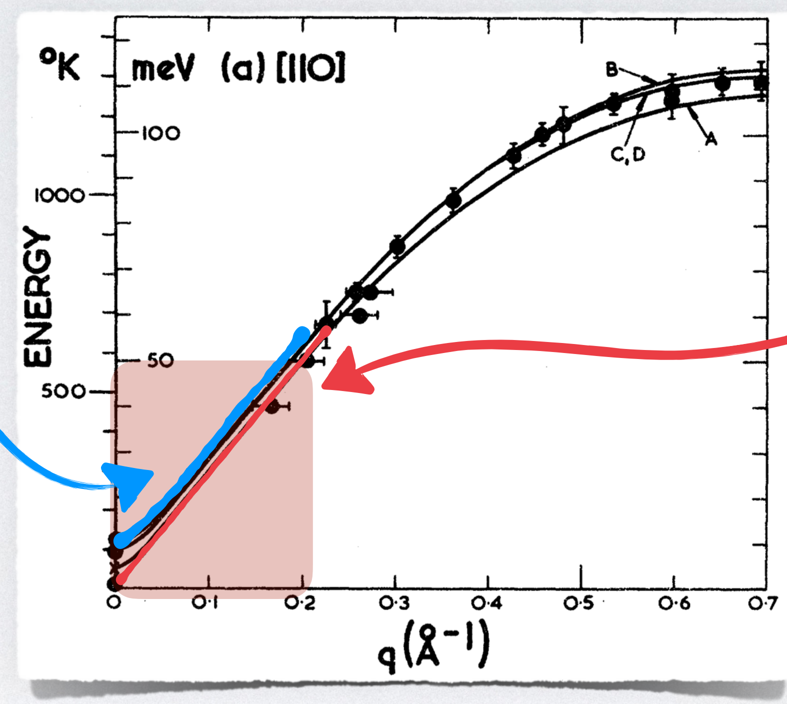
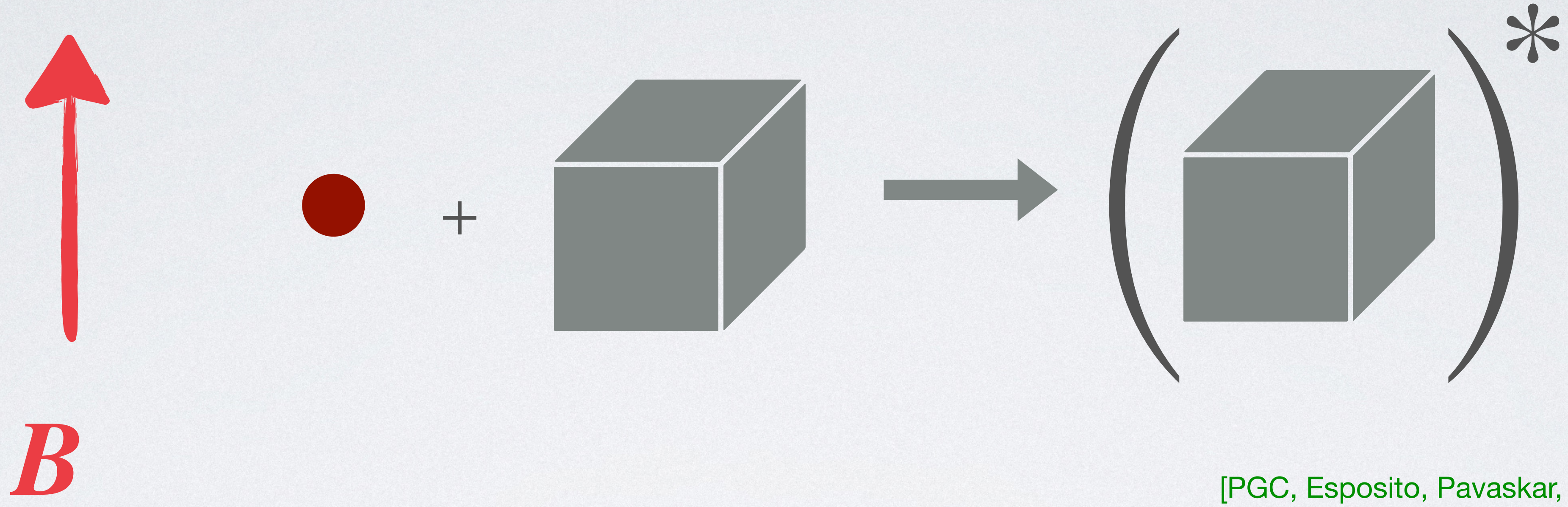


gapless Goldstone

- The gap depends on
  - Crystalline structure (*anisotropies* λ)
  - External *magnetic* fields $\boldsymbol{B}$

$$\Delta = \Delta(\lambda, B)$$

Magnons EFT



[PGC, Esposito, Pavaskar, 2411.11971]

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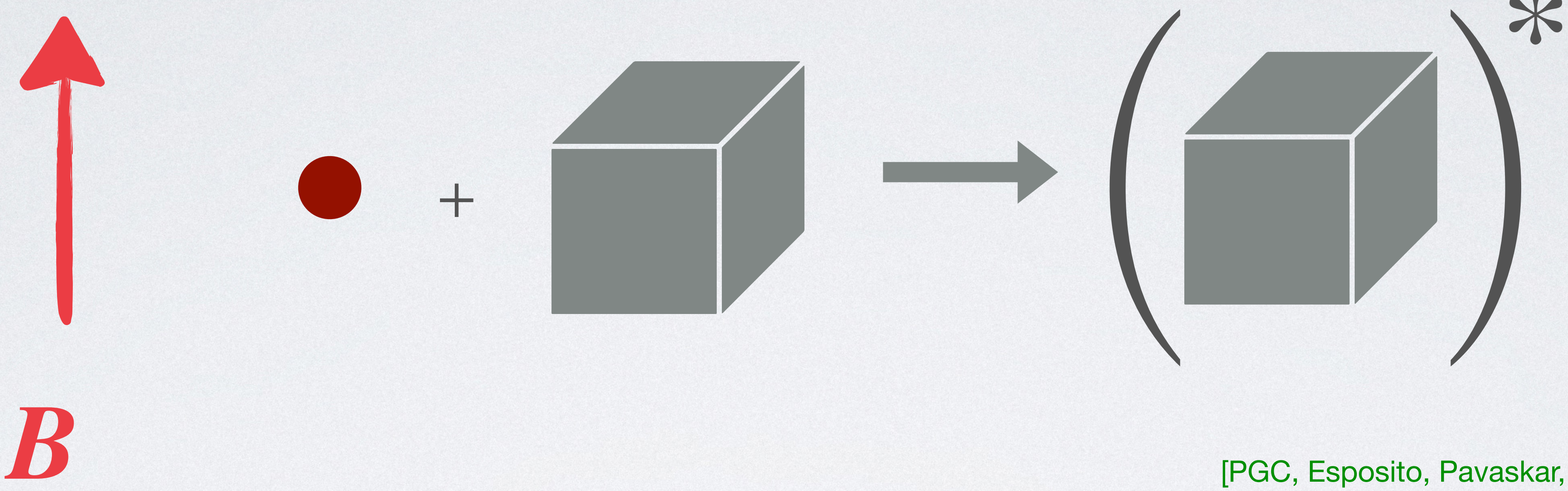

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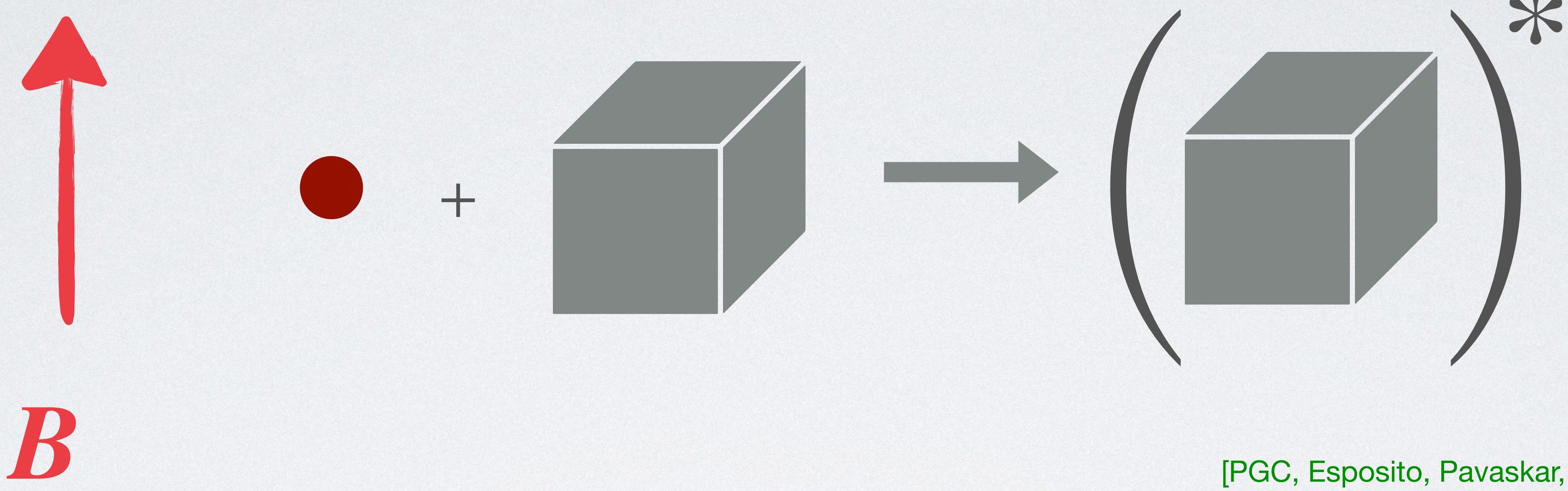
conservation of energy

$$m_a = \omega_\theta(p = m_a v_a)$$

Magnons EFT



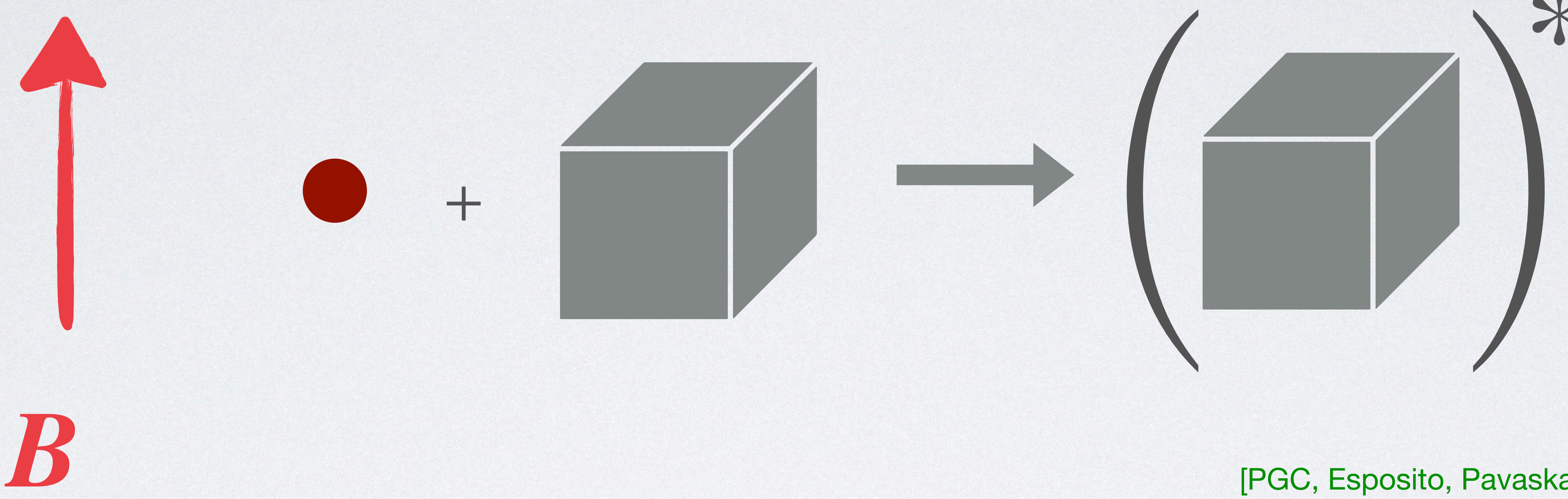
[PGC, Esposito, Pavaskar, 2411.11971]

conservation of energy

$$\Delta(\lambda, B) = m_a \left(1 - m_a v_a^2 v_\theta^2\right)$$

Different points to match energy conservation!

Magnons EFT



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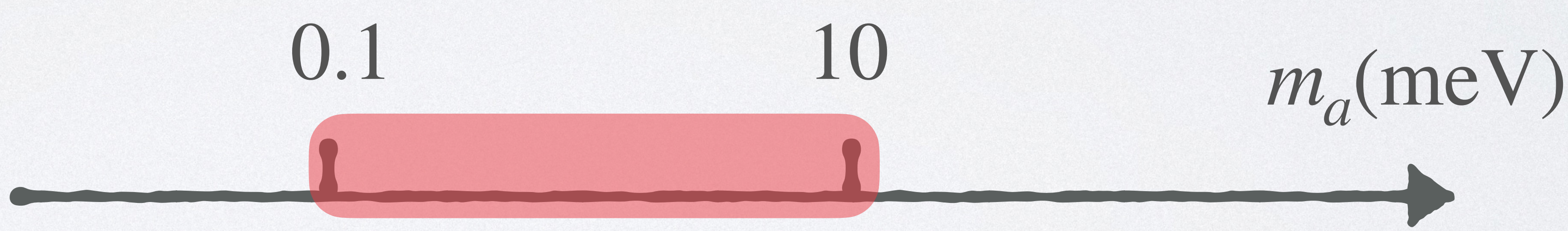

Magnons full EFT

- For small magnetic fields, i.e. $\boldsymbol{B} < \boldsymbol{B}_{\text{s.f.}}$, then [PGC, Esposito, Pavaskar, 2411.09761, 2411.11971]

$$\hat{\boldsymbol{n}}_I(\boldsymbol{x}, t) = \left[\exp\left(iS_a\theta^a\right)\hat{\boldsymbol{z}}\right]_I$$

$$\mathscr{L}_{\text{EFT}} = \frac{c_1}{2}\left[\left(\dot{\theta}^a - \mu B \epsilon^{ab}\theta^b\right)^2 - v_\theta^2\left(\nabla\theta^a\right)^2 - 2\lambda_z\left(\theta^a\right)^2 - 2\lambda_x\delta^{a2}\delta^{b2}\theta^a\theta^b + \mathcal{O}\left(\theta^4\right)\right]$$

$$a, b = 1,2$$

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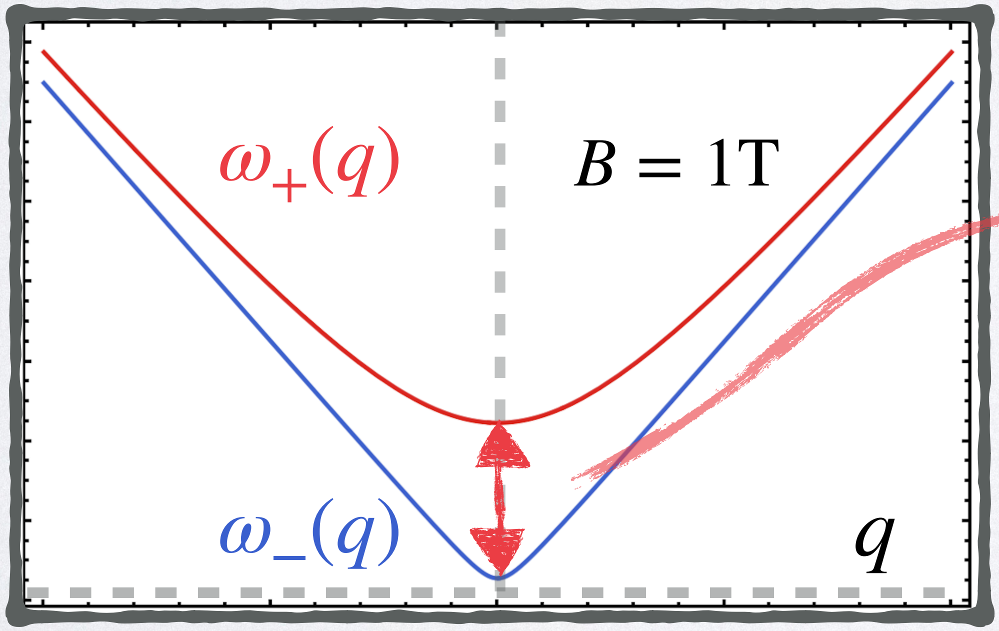
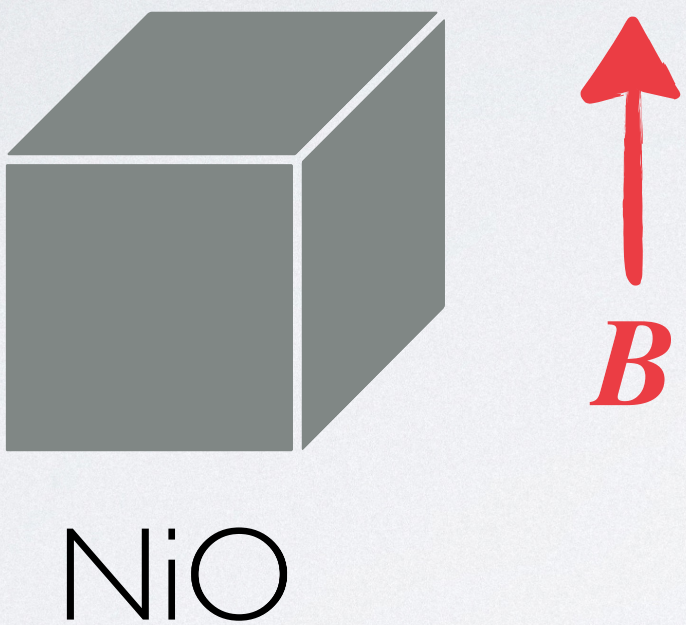
- Computing the spectrum of $\mathscr{L}_{\rm EFT}$ one finds two modes:

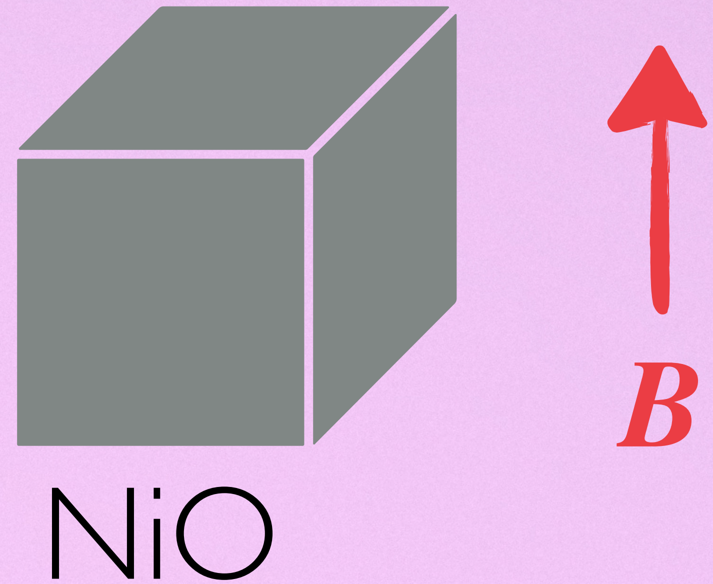


$$\omega^2_{\alpha=\pm}(\boldsymbol{q}) = \mu^2B^2 + \lambda_x + 2\lambda_z + v_\theta^2\boldsymbol{q}^2 \pm\sqrt{4\mu^2B^2(\lambda_x + 2\lambda_z + v_\theta^2\boldsymbol{q}^2) + \lambda_x^2}$$

$$\omega_\pm(\boldsymbol{q} = 0)\Big|_{B=0} \simeq \text{meV}$$

meV QCD axion DM absorption with NiO





axion DM background

$$\mathscr{L}_a \supset \frac{g_{ae}}{2m_e} \partial_\mu a \, \bar{e}\gamma^\mu\gamma_5 e$$

meV QCD axion DM absorption with NiO

- NR limit + selection of the right d.o.f. [PGC, Esposito, Pavaskar, 2411.11971]

$$\mathcal{L}_{\rm a} \supset \frac{g_{aee}}{2m_e}\partial_\mu a\ \bar{e}\gamma^\mu\gamma_5 e \xrightarrow{\rm NR} \frac{g_{aee}}{m_e}\nabla a \cdot \left(e^\dagger_{\rm nr}\frac{\boldsymbol{\sigma}}{2}e_{\rm nr}\right) \xrightarrow{\rm IR} \frac{g_{aee}}{m_e}\vec{\nabla} a \cdot \vec{s}$$

$\vec{s}(\theta)$ spin density

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$\vec{s}(\theta)$ spin density

- The spin density is easily computed as the SO(3) Noether current in the EFT

$$s^I = c_1\Big[\big(\partial_t\hat{\boldsymbol{n}}\times\hat{\boldsymbol{n}}\big)^I + \mu(\boldsymbol{B}\cdot\hat{\boldsymbol{n}})\,\hat{n}^I\Big] \simeq c_1\Big[\delta^{Ia}\big(\dot{\theta}^a - \mu B\epsilon^{ab}\theta^b\big) - \delta^{I3}\theta^a\big(\epsilon^{ab}\dot{\theta}^b + \gamma B\theta^a\big) + \dots\Big]$$

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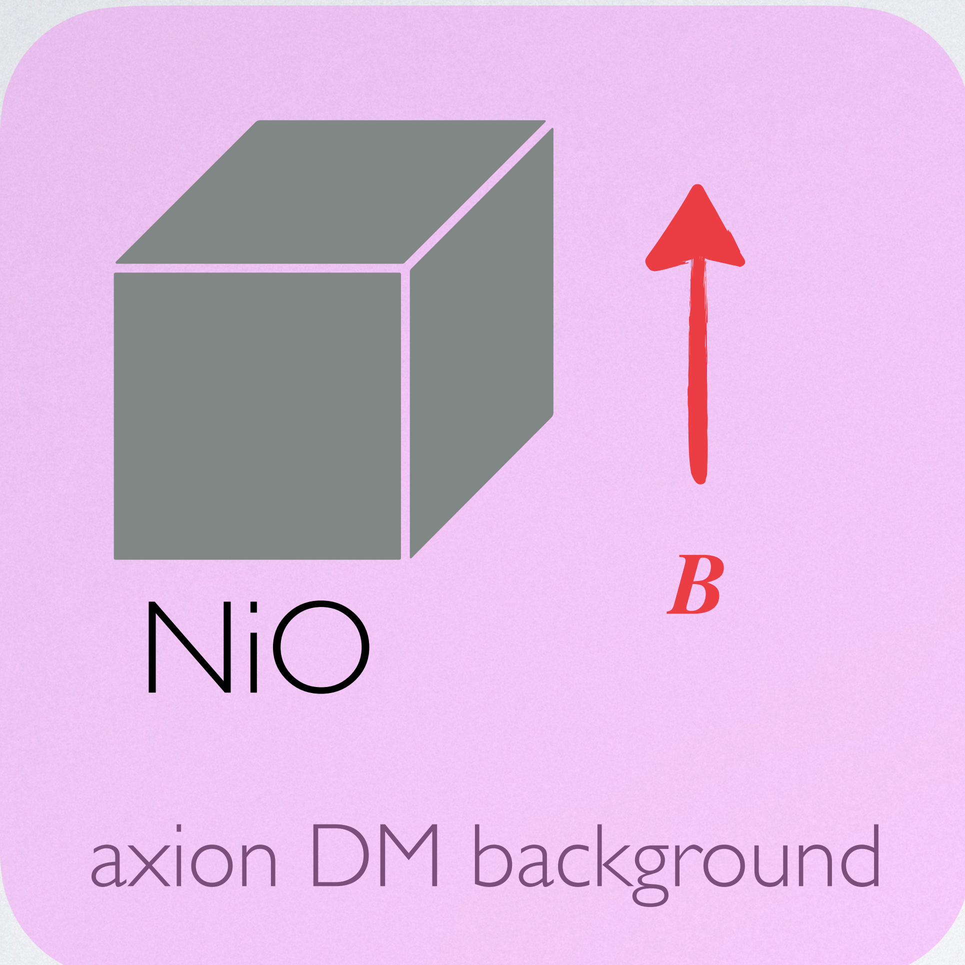
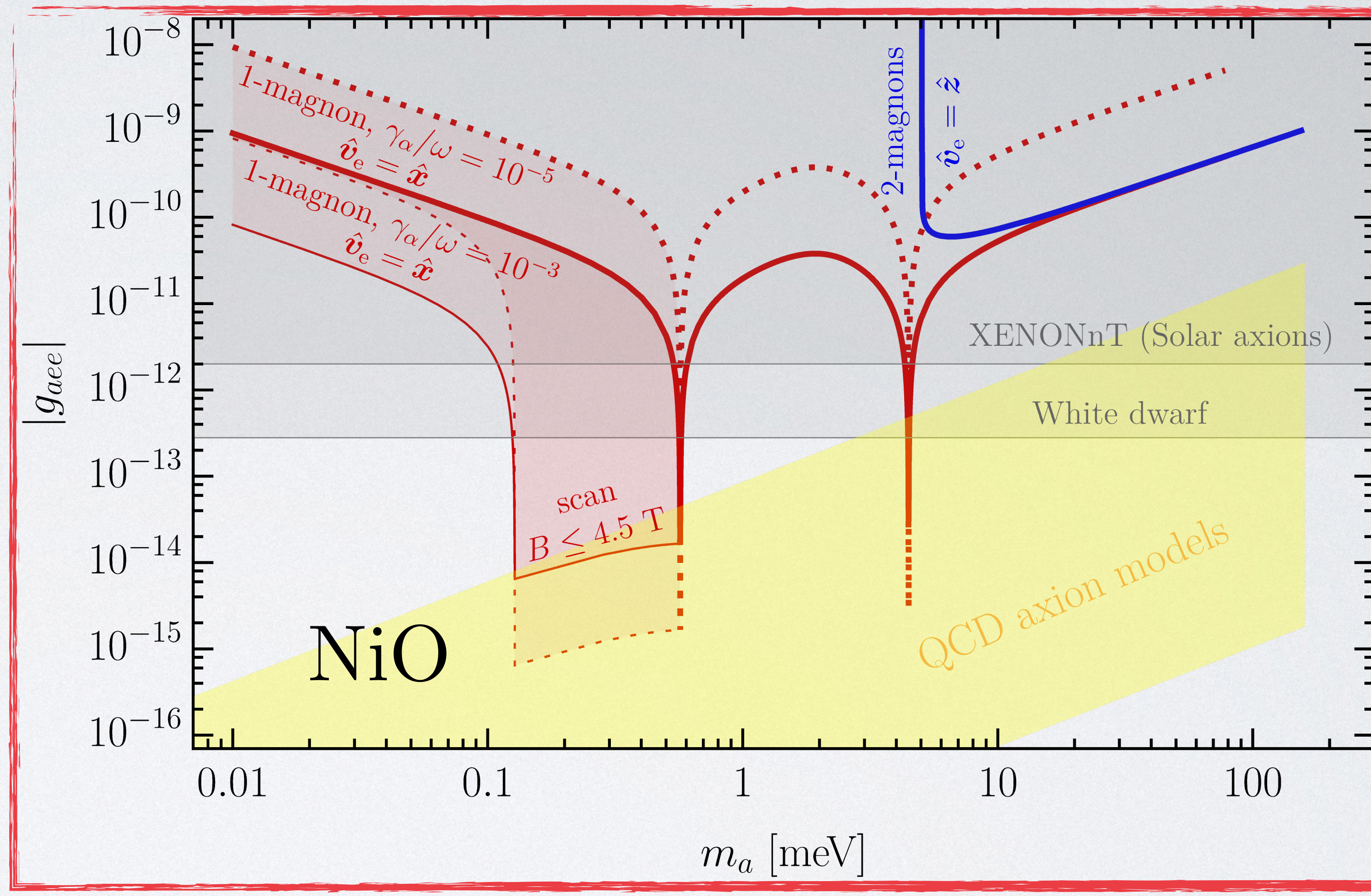
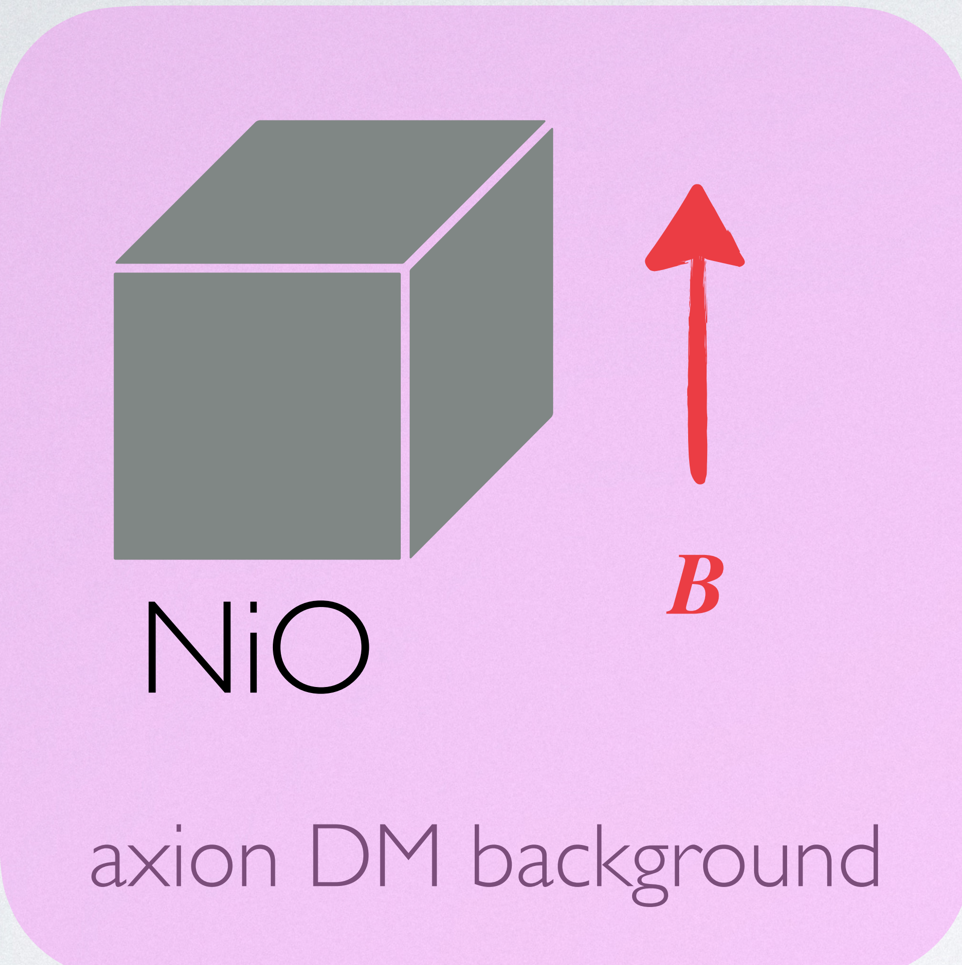


1Kg year exposure



$$R(\hat{v}_e) = \frac{\rho_a}{\rho_T m_a} \int d^3v \, f(|\vec{v} + \vec{v_e}|) \, \Gamma(\vec{v})$$

meV QCD axion DM absorption with NiO



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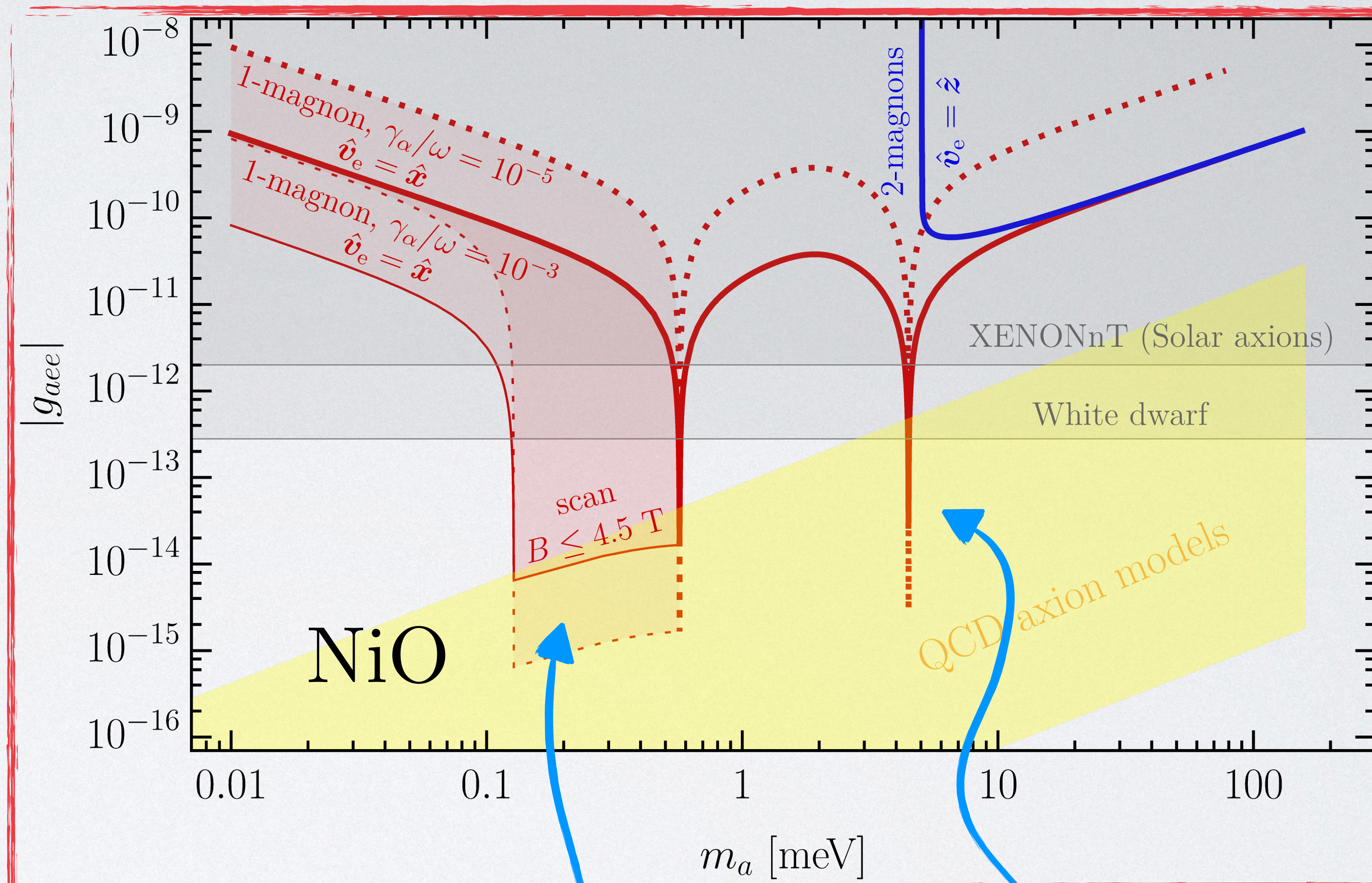

B-field scan

higher magnon branch

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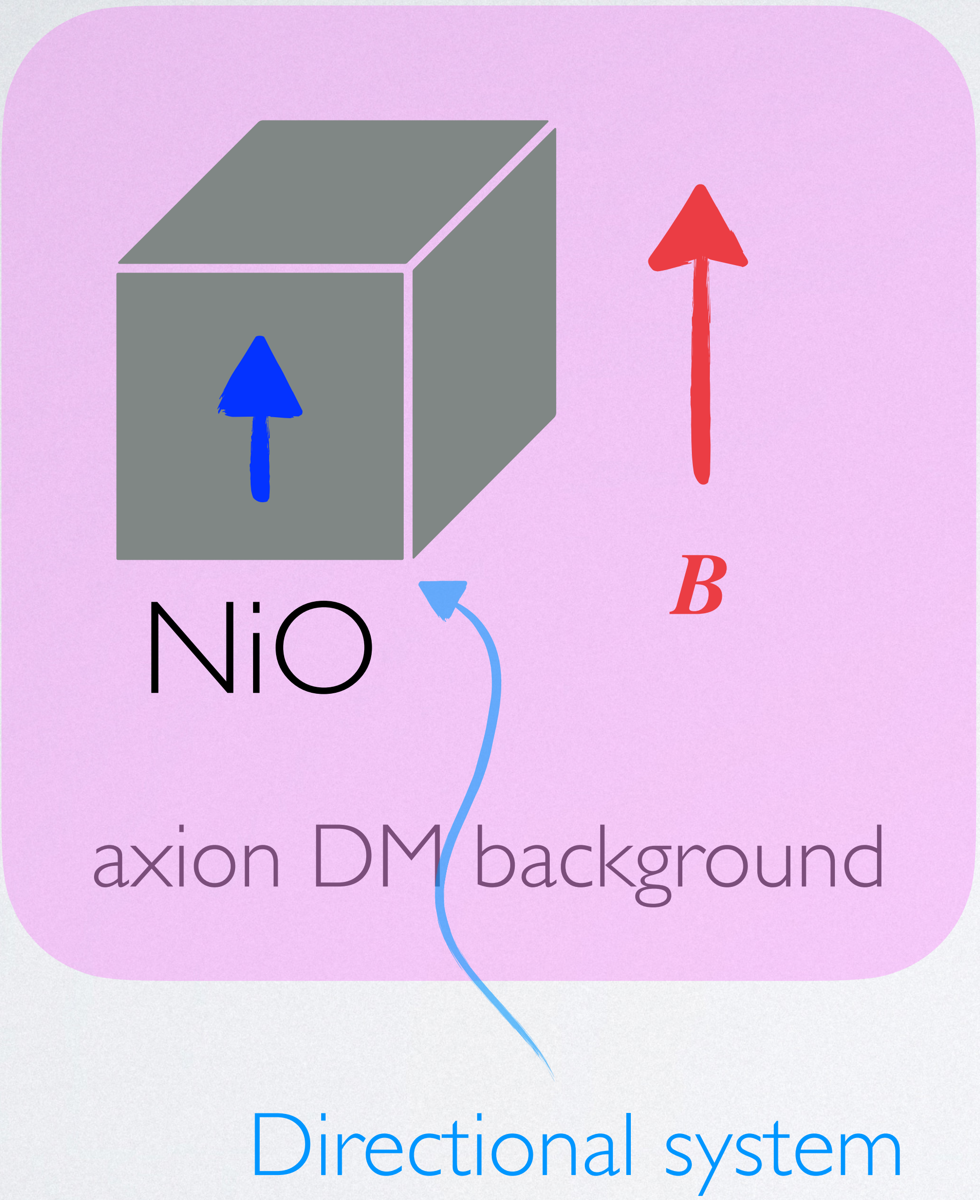
meV QCD axion DM absorption with NiO



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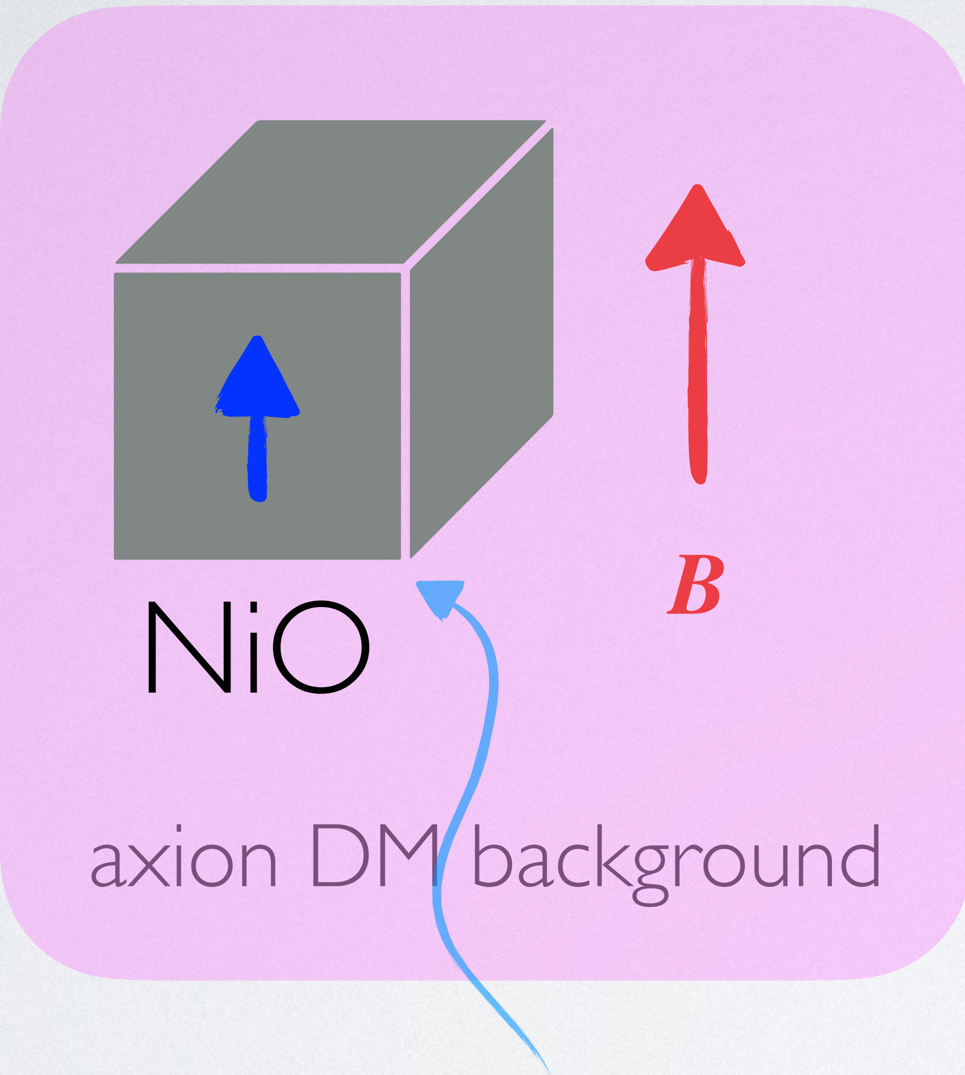
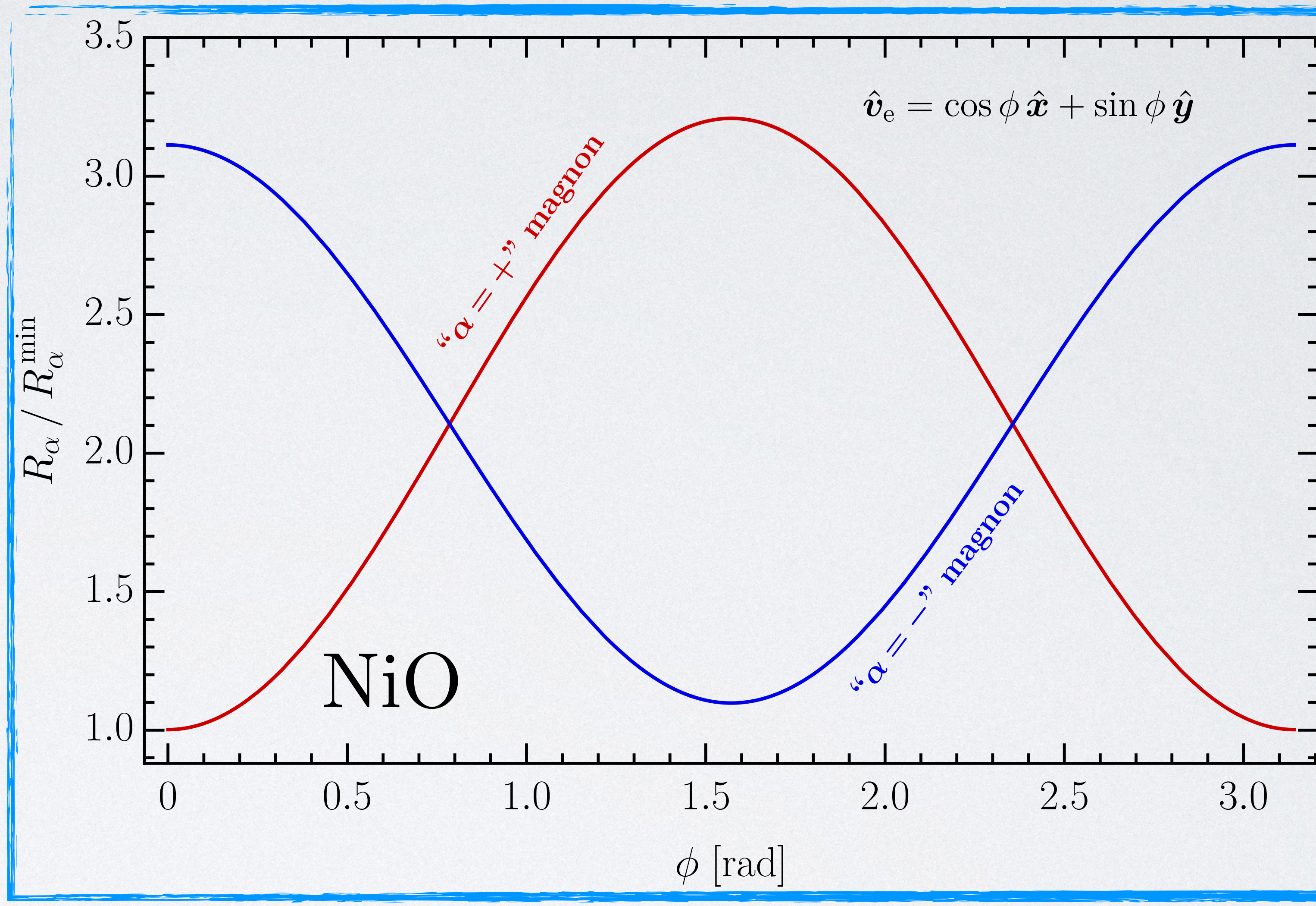


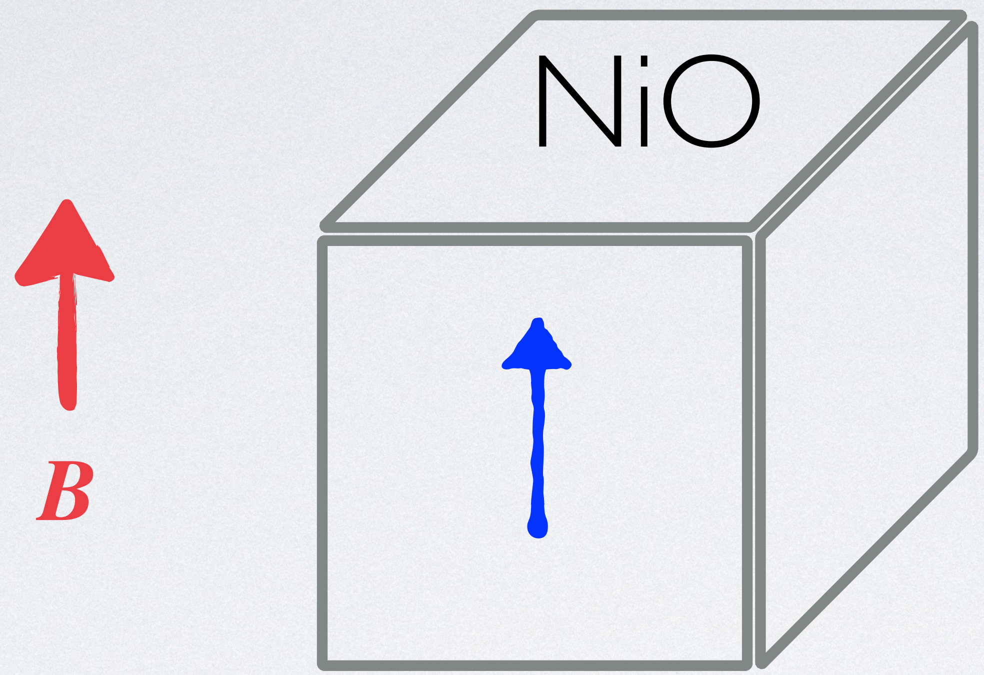


Directional system

Efficient strategy to discriminate
between signal and background ~300 % directionality

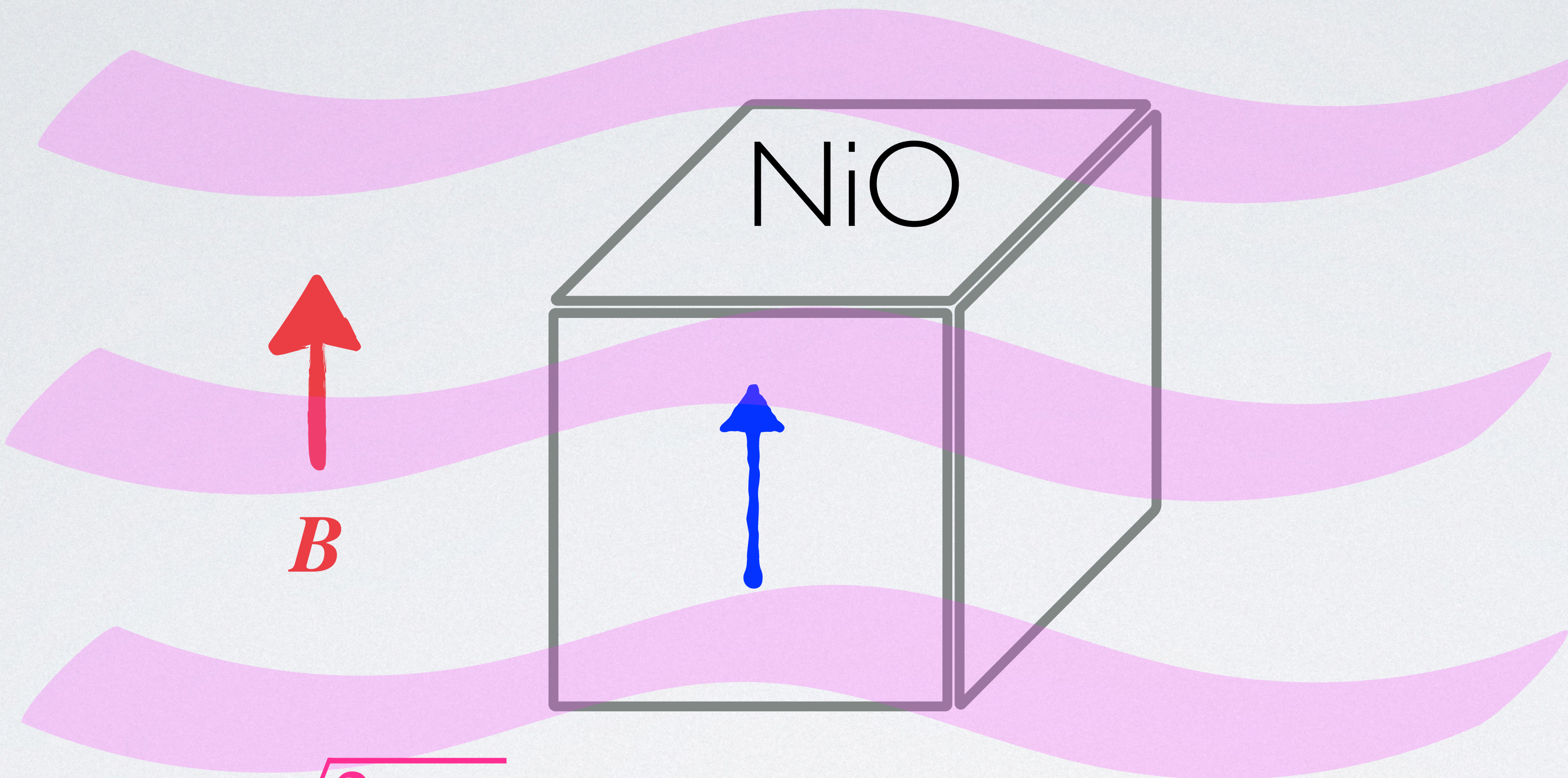
Observables?

WORK IN PROGRESS



Observables?

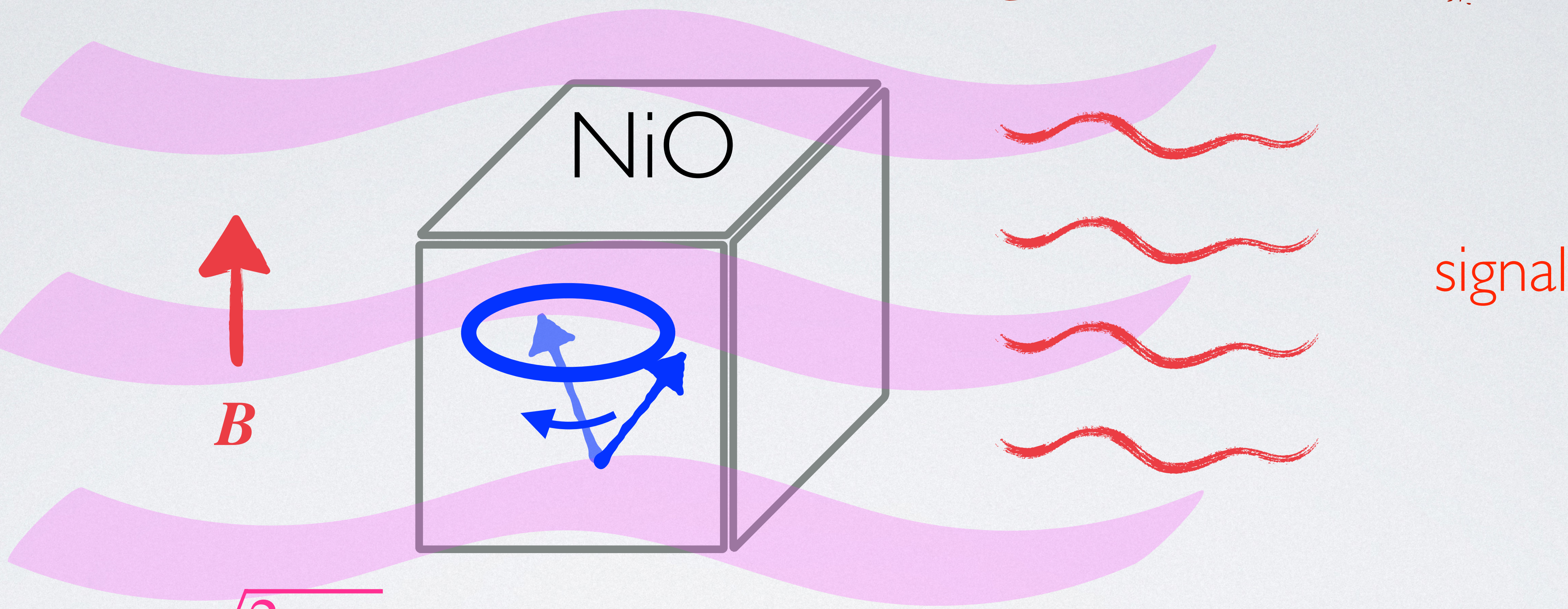
WORK IN PROGRESS



$$a(\boldsymbol{x}, t) = \frac{\sqrt{2\rho_{DM}}}{m_a} \sin(m_a t)$$

Observables?

WORK IN PROGRESS



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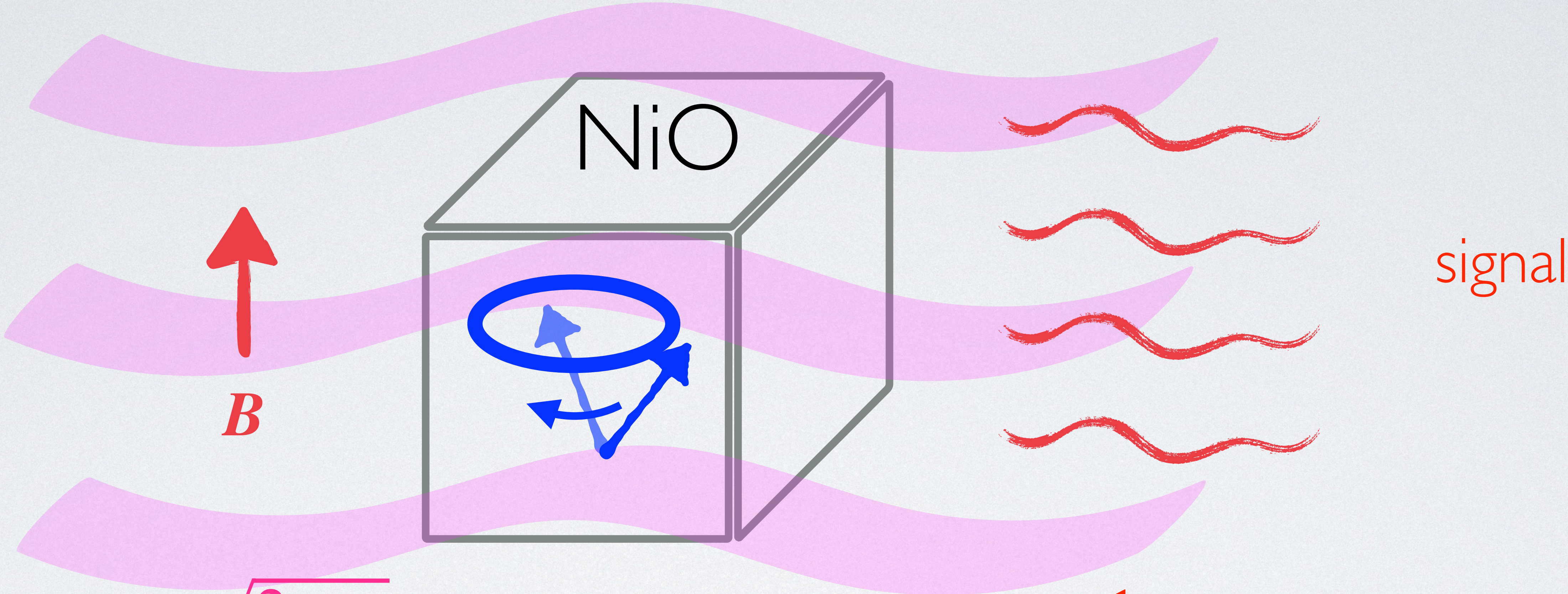

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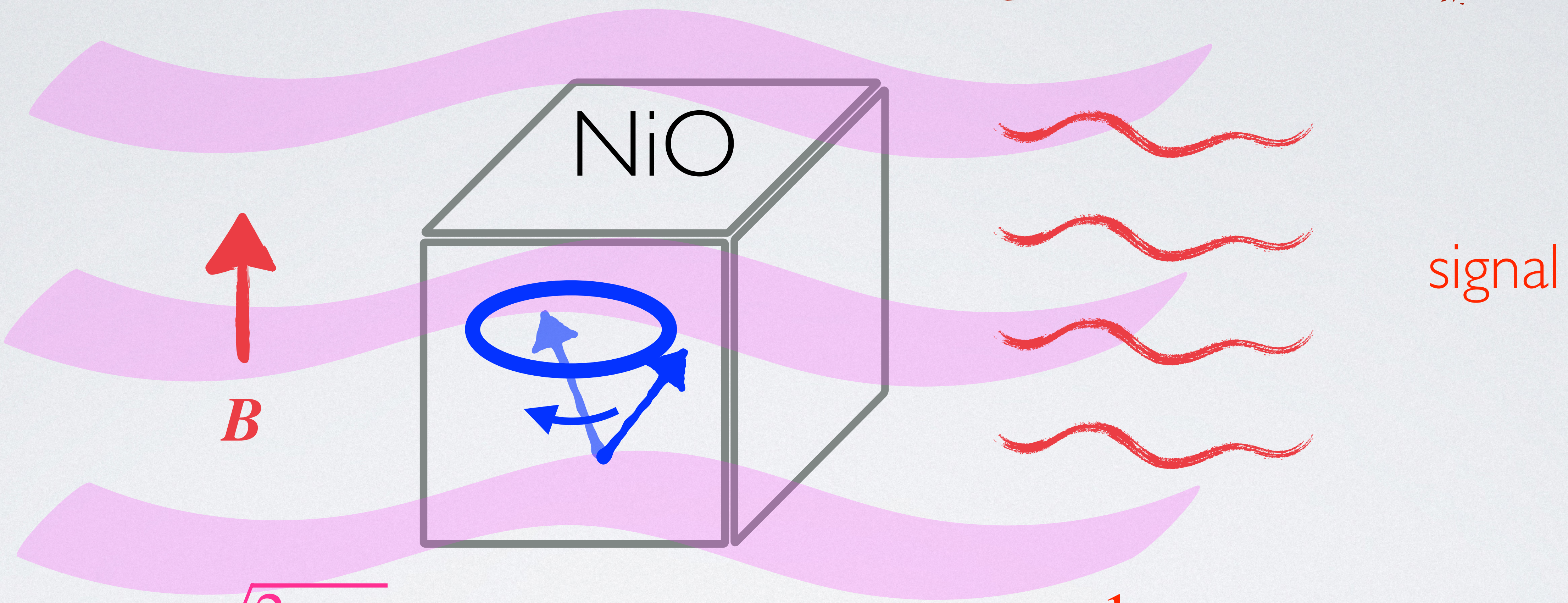
$$\delta B \propto \mu c_1 \frac{1}{\gamma_\theta \Delta} \frac{g_{aee}}{m_e} v_{DM}^3 \lambda^{3/2} a(\mathbf{x}, t)$$

Observables?

WORK IN PROGRESS



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- How to enhance this tiny signal?

★ SQUID?

★ Magnetic Haloscope?

Thank you for the attention!