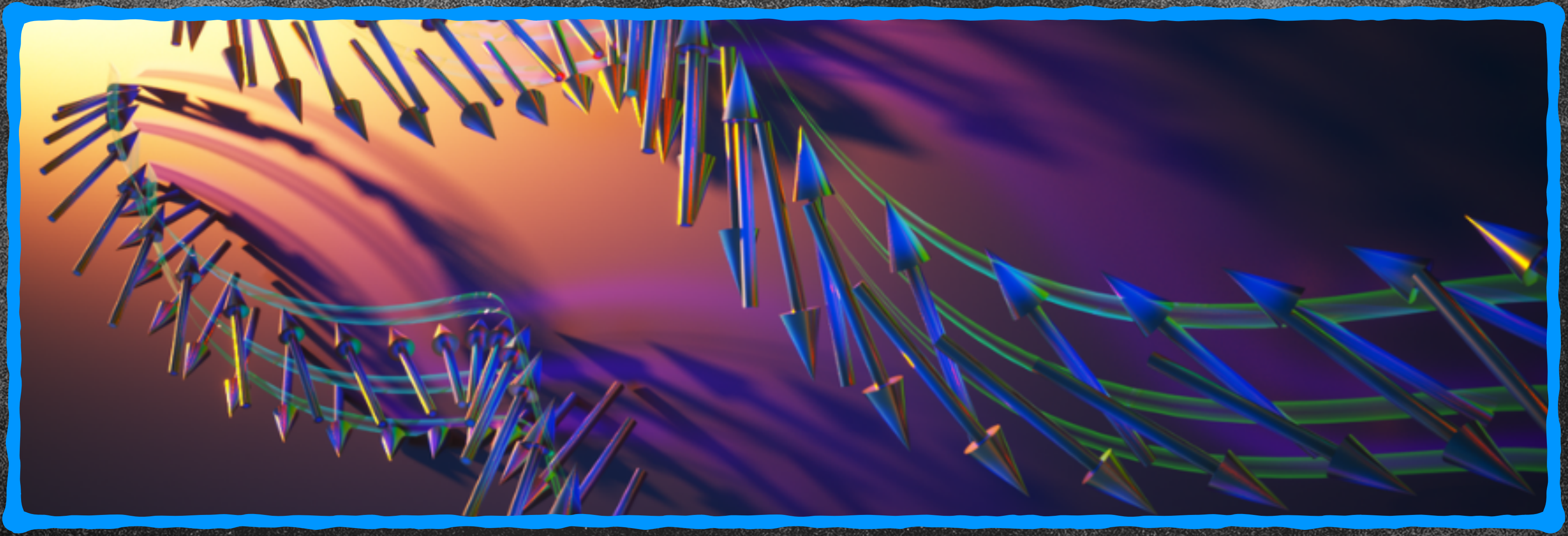
HUNTING AXION DARK MATTER WITH ANTI-FERROMAGNETS

Pier Giuseppe Catinari



Based on 2411.11971, 2411.09761
with A. Esposito and S. Pavaskar

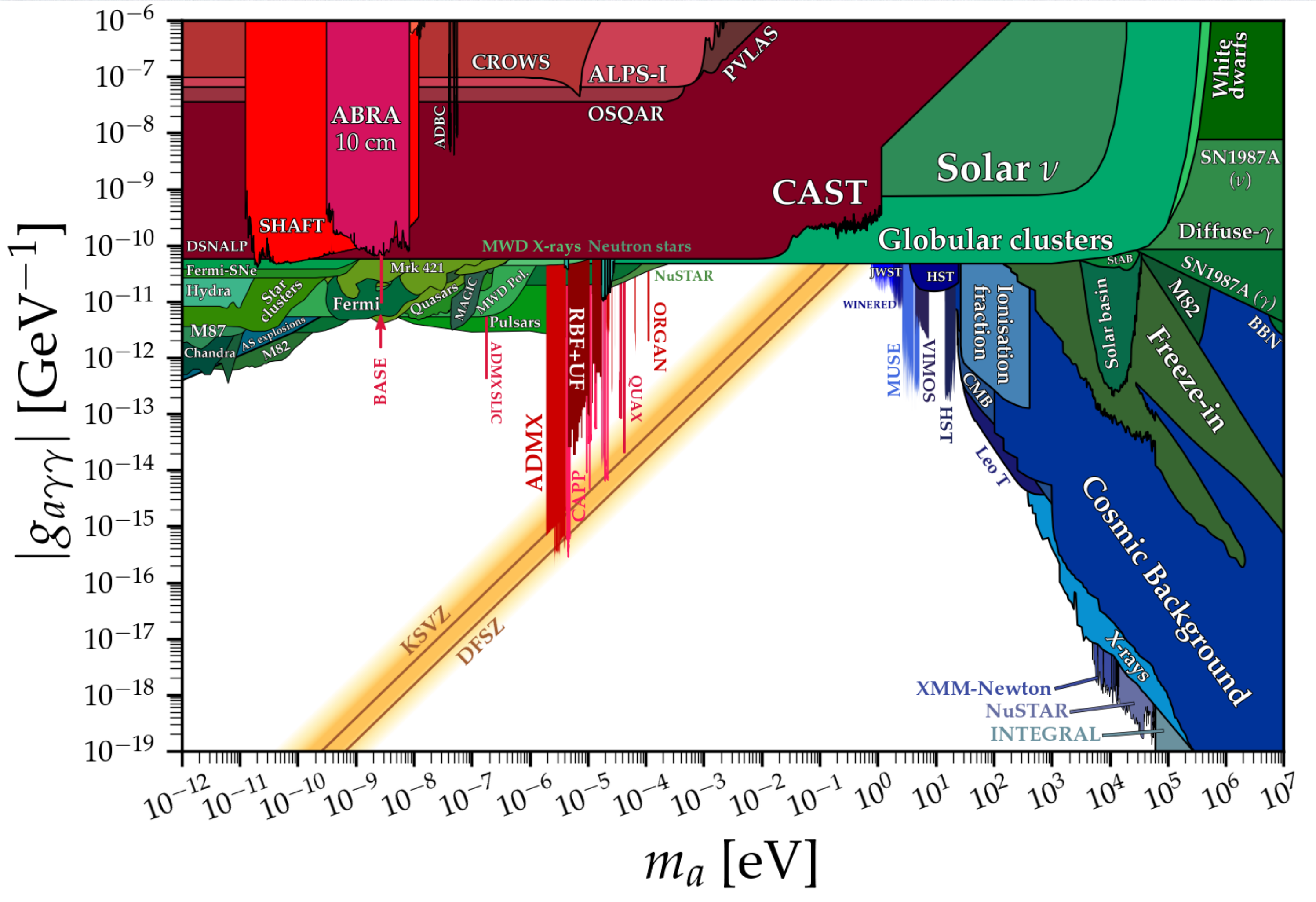
SAPIENZA
UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma

TPPC 2024 theory retreat, Abetone

The experimental landscape

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



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

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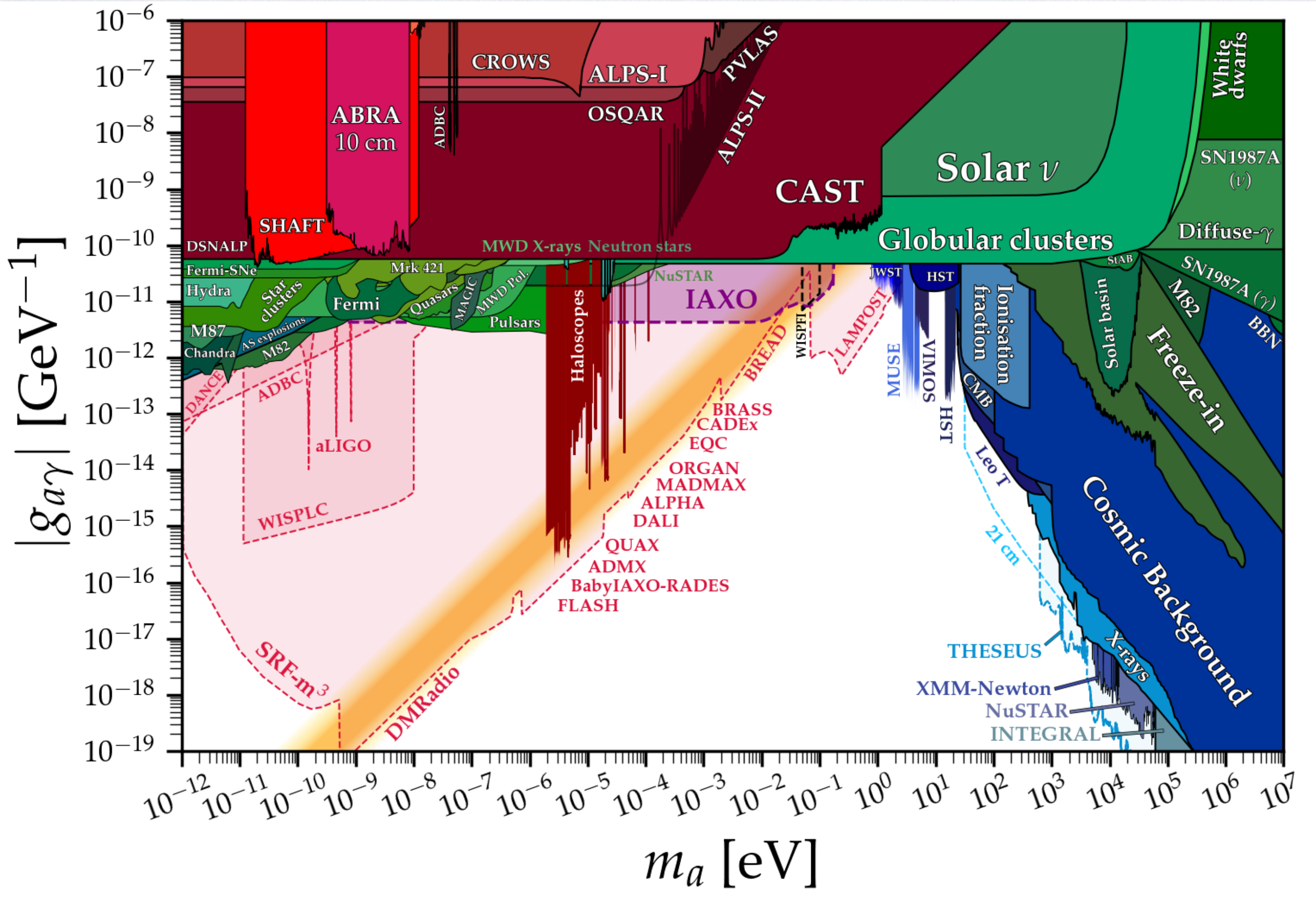
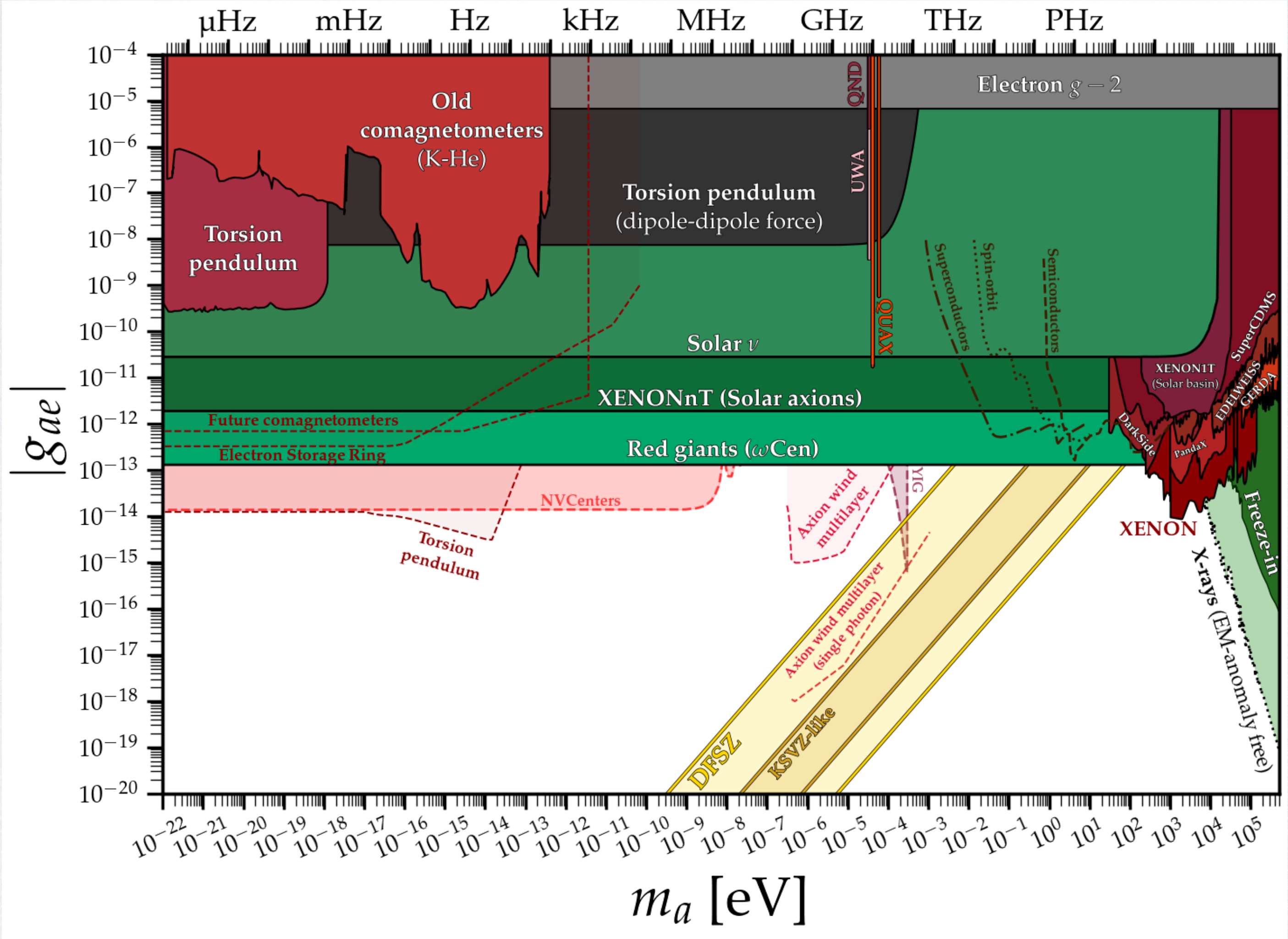


$$\mathscr{L}_a \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

The experimental landscape

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



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

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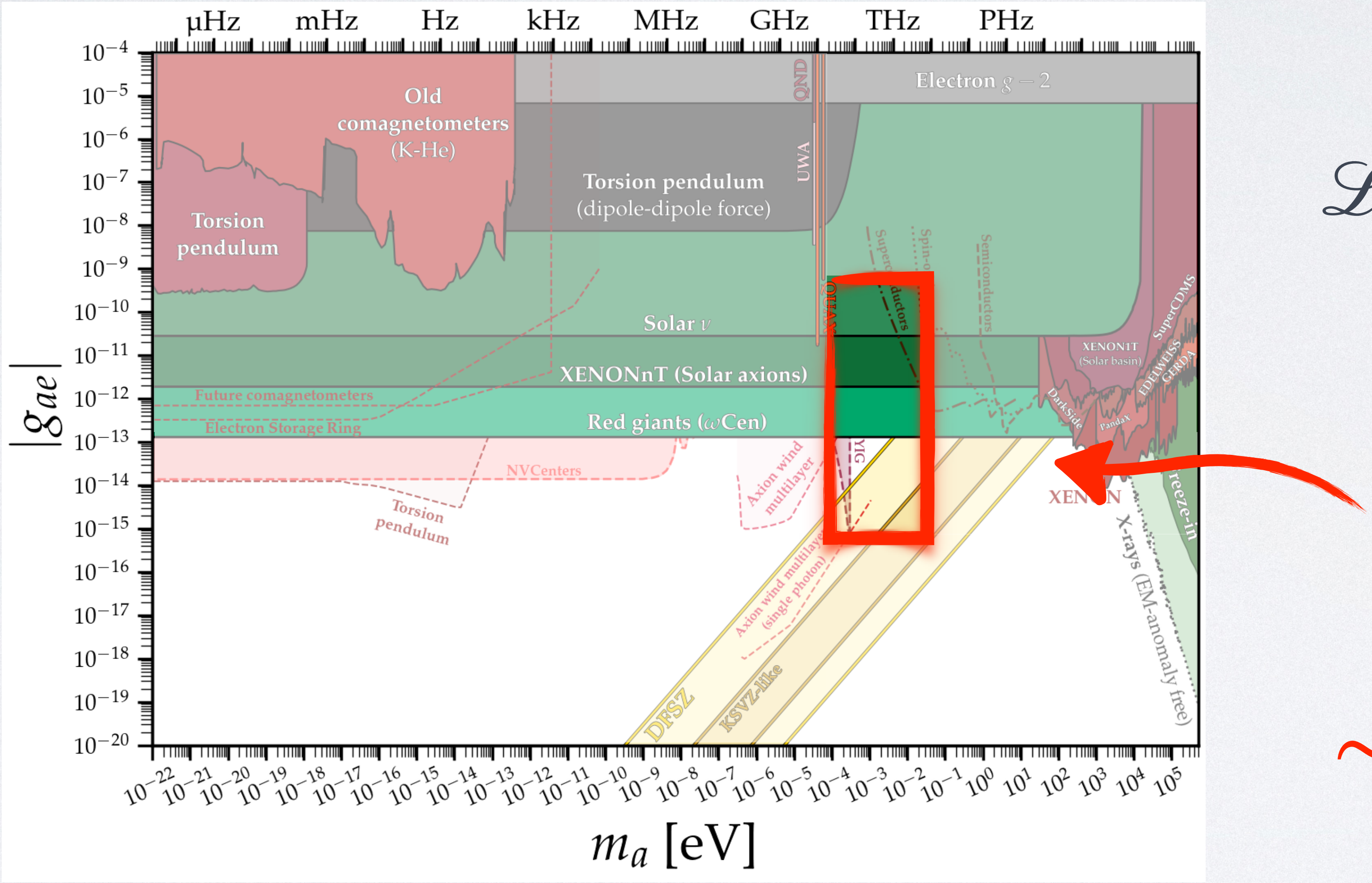


$$\mathscr{L}_a \supset \frac{g_{ae}}{2m_e}\partial_\mu a\ \bar{e}\gamma^\mu\gamma_5 e$$

Almost unconstrained window for

$$\sim (0.1 \div 10)\ \mathrm{meV}$$

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]

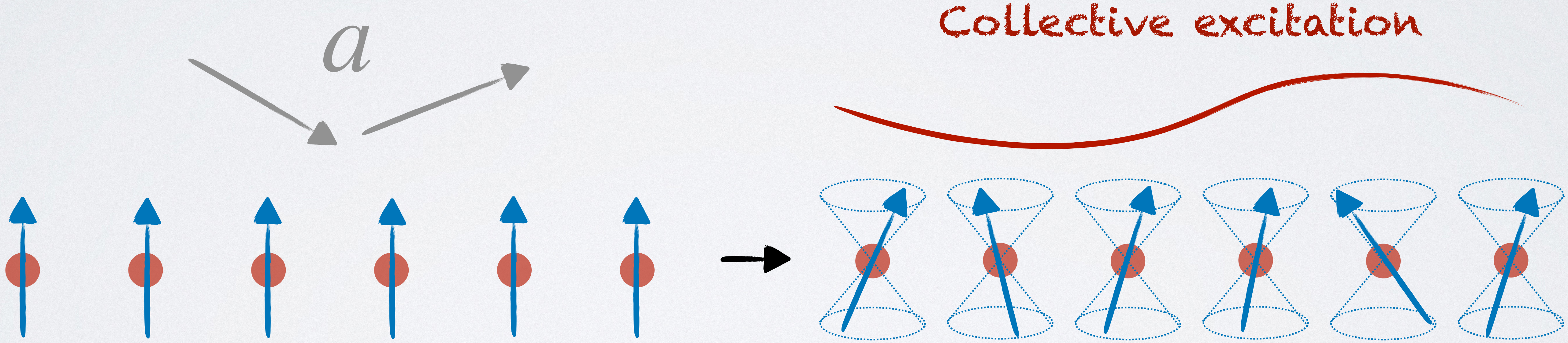
Setup

- We can use collective excitations of anti-ferromagnets to probe axion-electron coupling g_{ae}

- Idea

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

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



- How can we describe collective excitations in antiferromagnets?

Collective excitations in HEP

- All phases of matter spontaneously break spacetime and internal symmetries

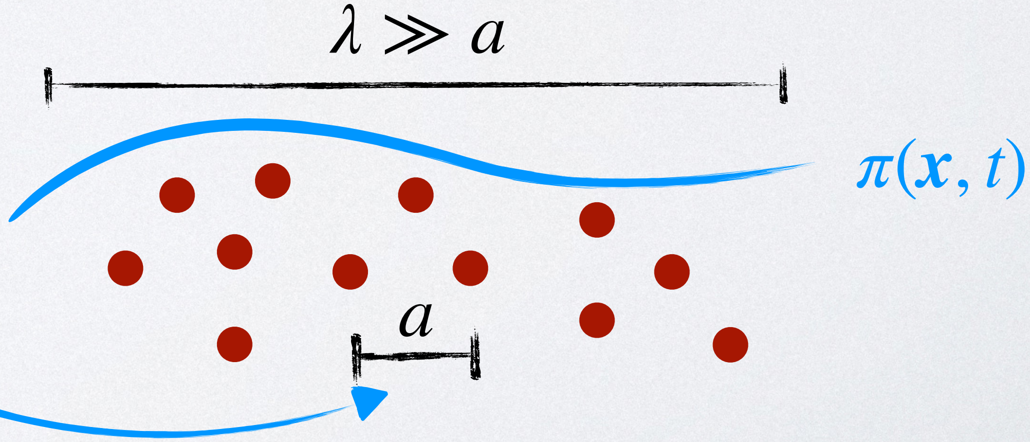
Goldstone's theorem

spontaneously broken symmetries ⟷ Existence of soft modes π

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

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

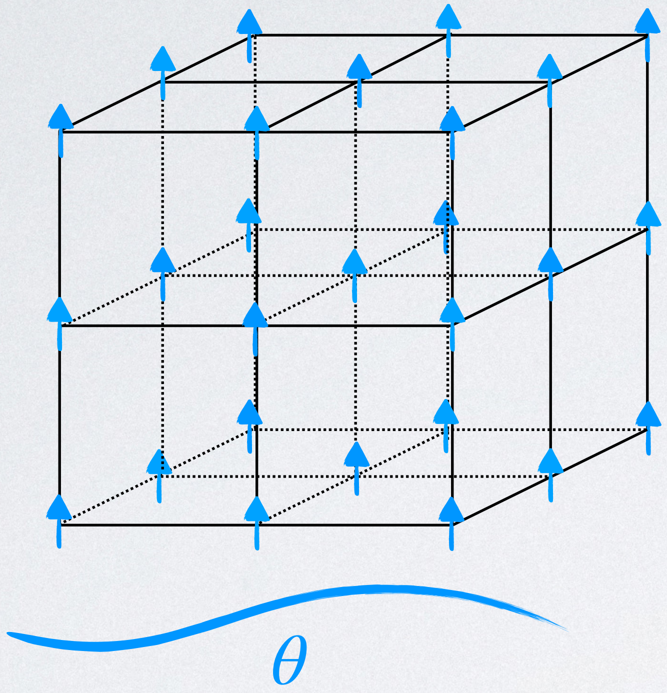
The complicated microphysics is encoded in the $g_{n,m}$ s



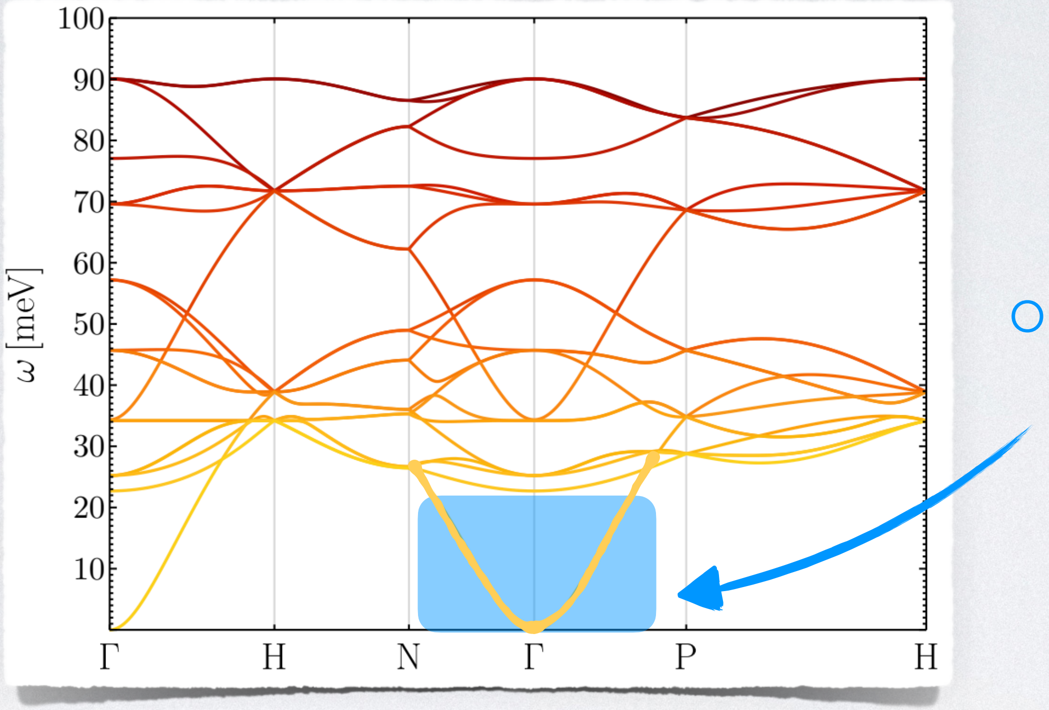
Why antiferromagnets?

- First was proposed to use ferromagnets

[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256;
Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]



Type B NGB

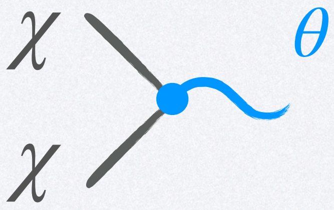


For $m_\chi \lesssim 10\,\mathrm{MeV}$
only gapless magnons

$$\omega \simeq \frac{q^2}{2m_\theta}\,,$$

$$m_\theta \sim \mathrm{MeV}$$

- One magnon emission



$$\omega_{\max} = 4T_\chi \frac{m_\theta/m_\chi}{(1+m_\theta/m_\chi)^2}\;,\; m_\theta \simeq 1\mathrm{MeV} \longrightarrow$$

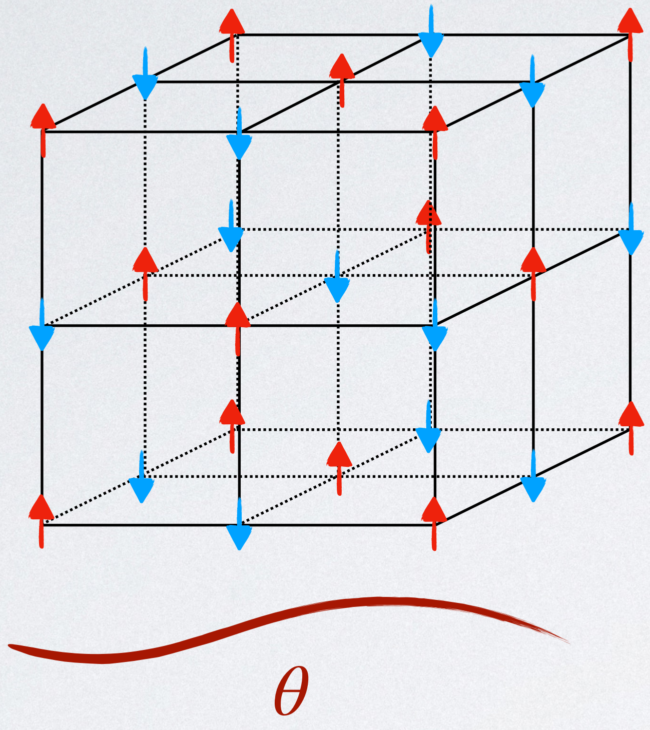
★Not efficient for $m_\chi < 1\,\mathrm{MeV}$

★Narrowband channel

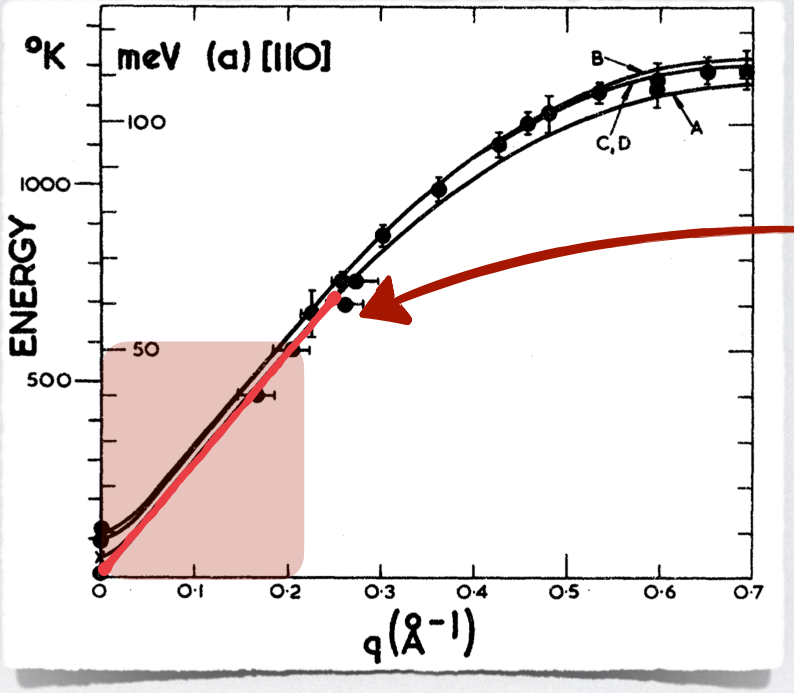
Why antiferromagnets?

- An optimal class of materials turns out to be anti-ferromagnets

[Esposito, Pavaskar, PRD 2023 — 2210.13516]



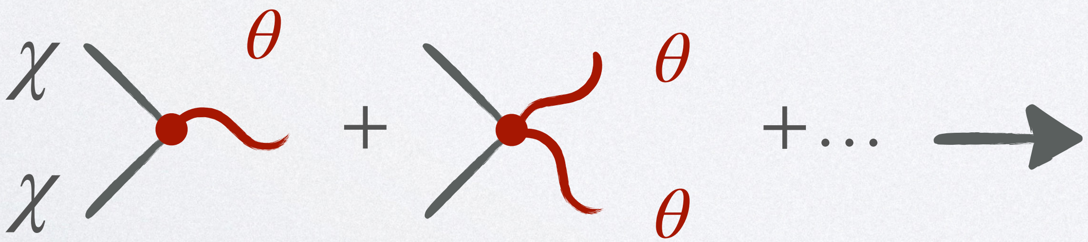
Type A NGB



For gapless modes

$\omega(q) = v_\theta\, q$

- For one magnon emission $\omega_{\max} = 4T_\chi\, v_\theta/v_{\rm DM}\,(1-v_\theta/v_{\rm DM})$
- Multi-magnon processes are allowed



★ Optimal antiferromagnets totally absorb $T_{\rm DM}$

★ Narrow- and broadband channels

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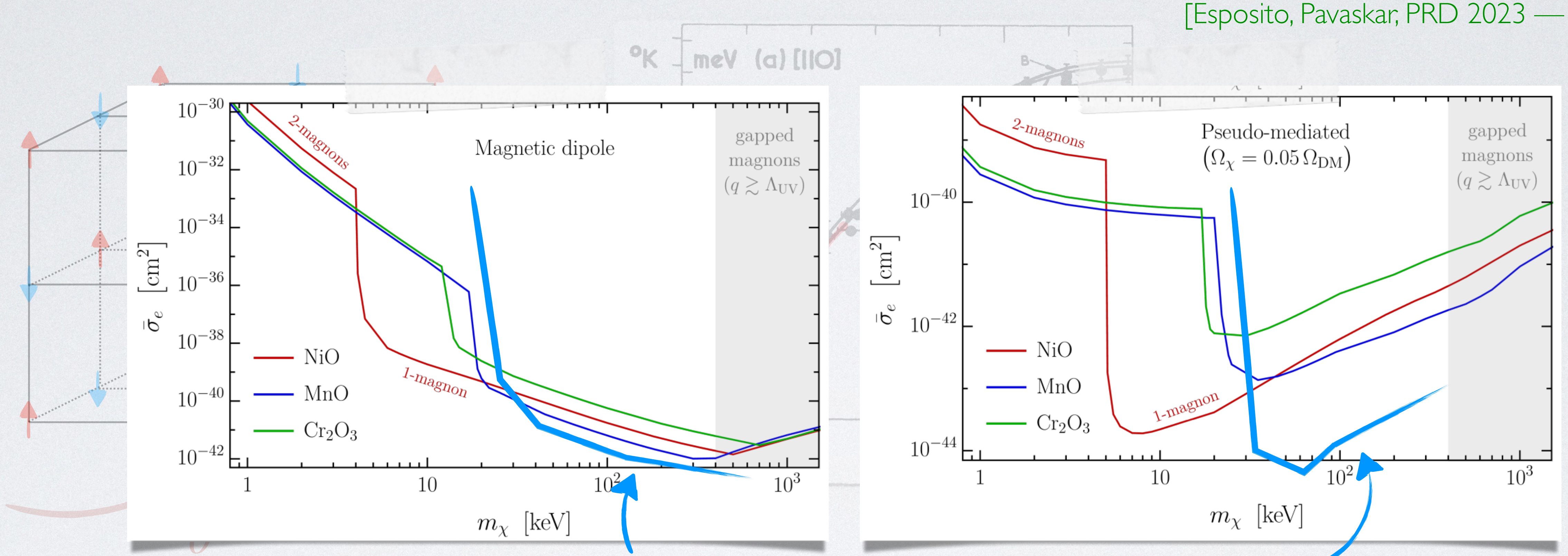
[Esposito, Pavaskar, PRD 2023 — 2210.13516]

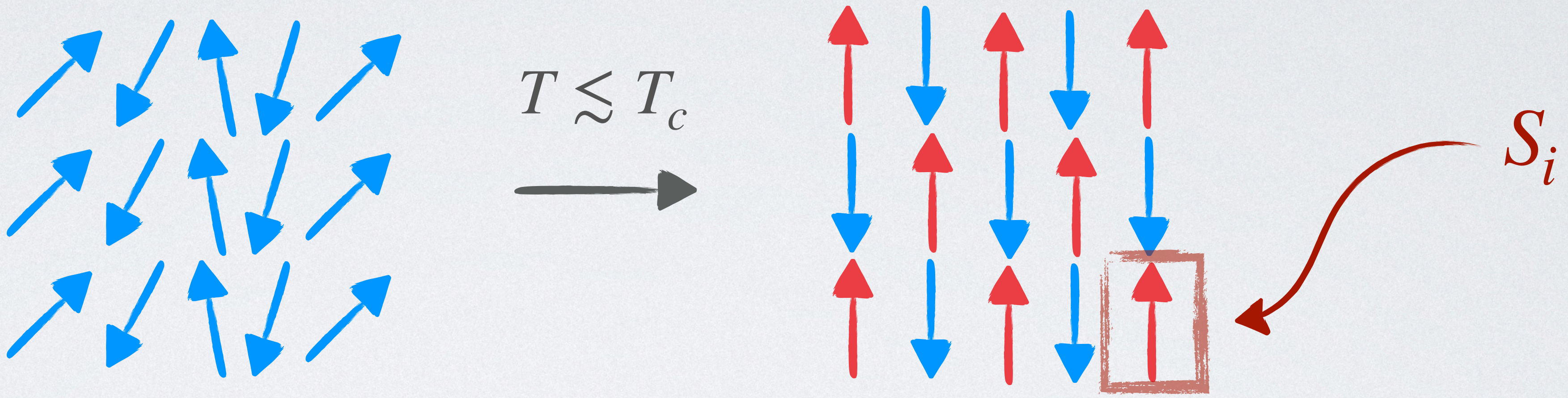


Ferromagnets (1-magnon)

Optimal anti-ferrmagnets (NiO) are ideal targets for light dark matter searches

Magnons EFT

- Antiferromagnets (AF) spontaneously break internal spin symmetry



$$\langle \mathcal{N} \rangle = \sum_i (-)^i S_i \neq 0 \longrightarrow SO(3)_{\text{int}} \to SO(2)_{\text{int}}$$

Magnons EFT

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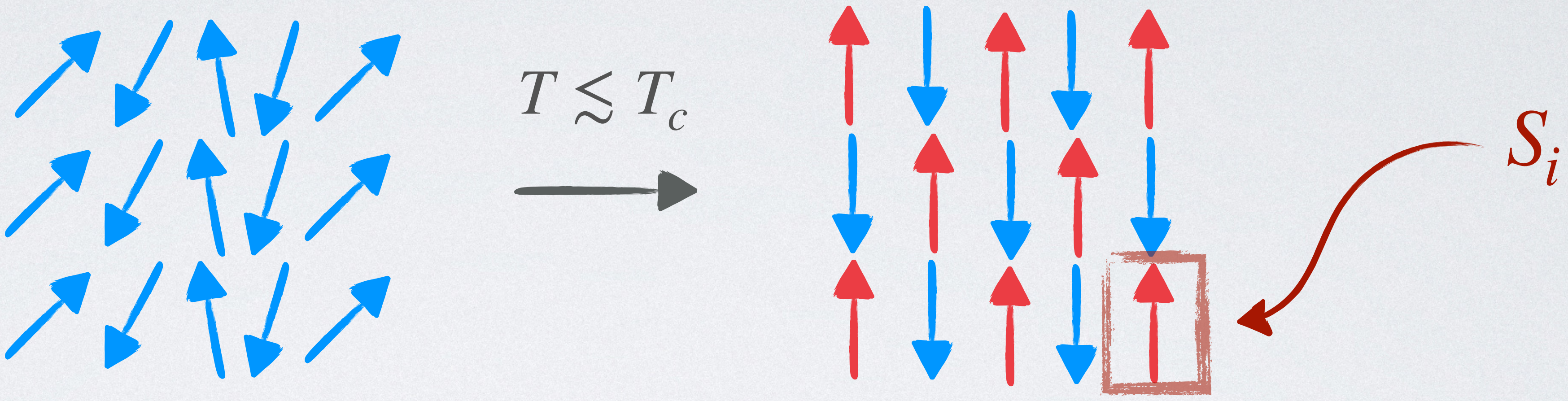

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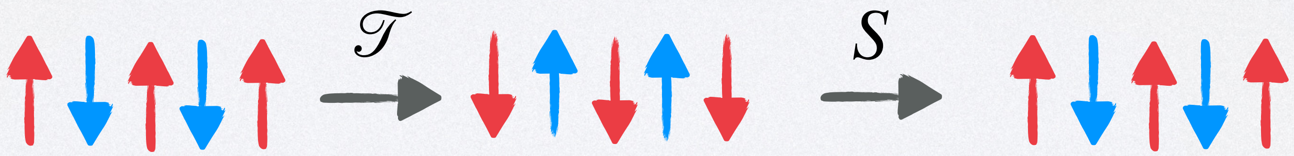
- AF are invariant under time reversal $\mathcal{T}$ + shift of one lattice site S



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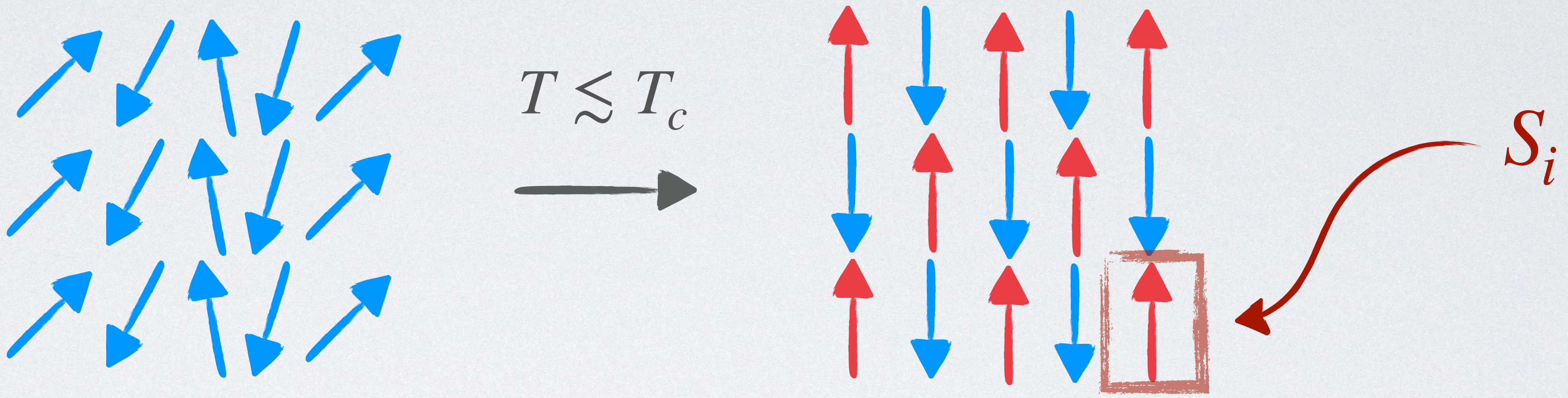

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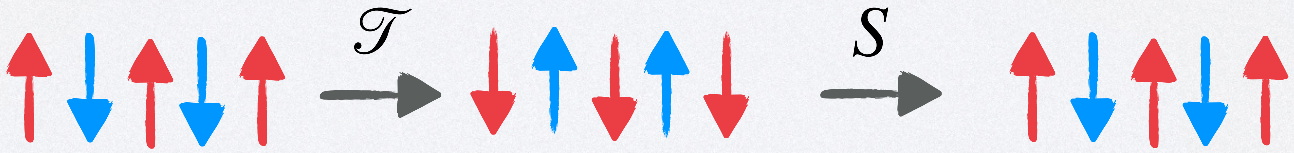

- At low energies, AF are described by an EFT that is invariant under SO(3) and not manifestly Lorentz-invariant

Magnons EFT

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

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

magnon fields

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magnon fields

- At the lowest order in the derivative expansion

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

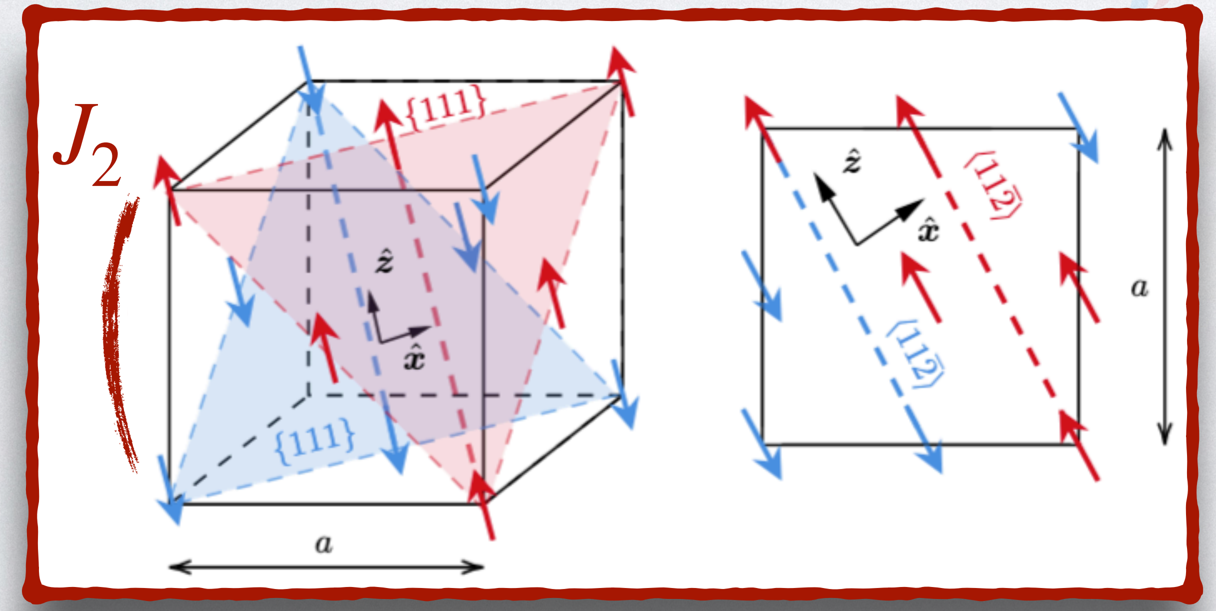
  - v_θ from dispersion relations
  - c_1 from nuclear scattering

$\sigma_n \propto c_1$

Magnons are gapless

Magnons EFT

- The phenomenology of NiO is, however, richer than this. Specifically, its magnon modes actually present a small but non-zero gap.
- This is due to the anisotropies, which *explicitly* break SO(3) symmetry [**PGC**, Esposito, Pavaskar, 2411.09761]



$\hat{z}$: easy axis (direction of magnetization)

$\hat{x}$: hard axis (⊥ to ferromagnetic planes)

UV $$H_{\text{tot}} = H_0 + \sum_i D_x \left(S_i^x\right)^2 - \sum_i D_z \left(S_i^z\right)^2 ,$$

Spurion analysis

IR $$\mathscr{L}_{\text{tot}} = \mathscr{L}_0 + c_1 \left[\lambda_z \hat{n}_z^2 - \lambda_x \hat{n}_x^2 \right]$$

Matched with the parameters of the microscopic Hamiltonian:

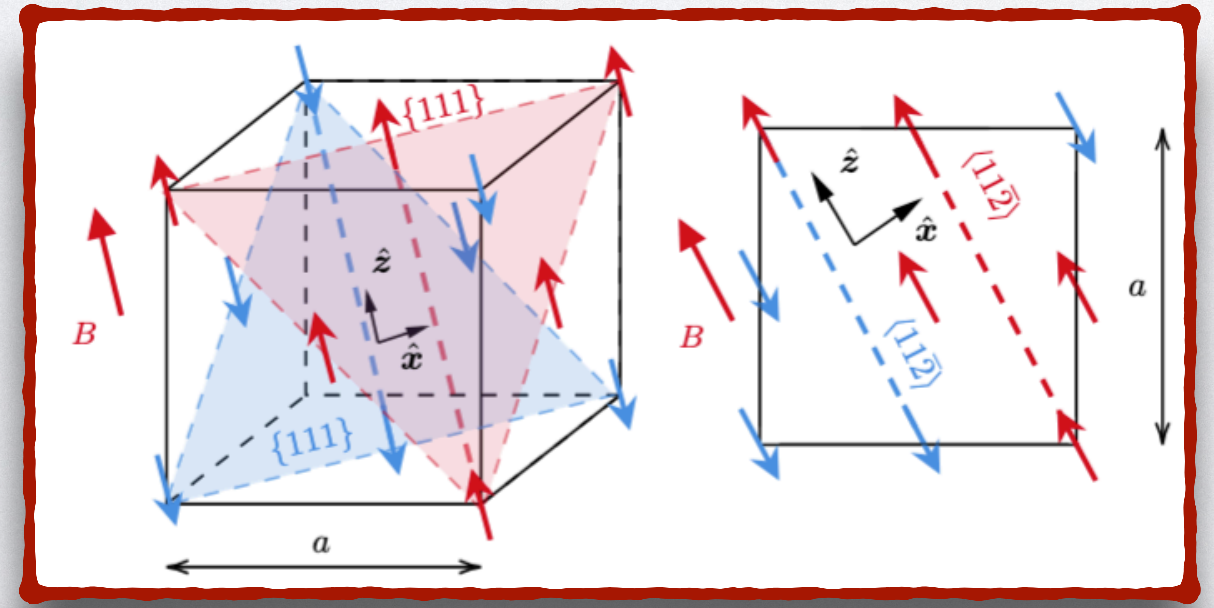
$$\lambda_x = 4 S^2 z J_2 D_x , \quad \lambda_z = 4 S^2 z J_2 D_z$$

Magnons EFT

- Explicit breaking effects → gap
- We can vary the gaps placing the NiO sample in an external magnetic field

$$\partial_t\hat{\boldsymbol{n}} \to \partial_t\hat{\boldsymbol{n}} + \mu\boldsymbol{B}\times\hat{\boldsymbol{n}} \;\rightarrow\; \mathscr{L} = \frac{c_1}{2}\left[(\partial_t\hat{\boldsymbol{n}} + \mu\boldsymbol{B}\times\hat{\boldsymbol{n}})^2 - v_\theta^2(\nabla_i\hat{\boldsymbol{n}})^2\right] + \mathscr{L}_{\text{anis}}$$

like working at finite density [Nicolis, Piazza, PRL 2013 - 1204.1570]



$$\boldsymbol{B} = B\,\hat{z}$$

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⟶ minimize the Hamiltonian [**PGC**, Esposito, Pavaskar, 2411.09761]

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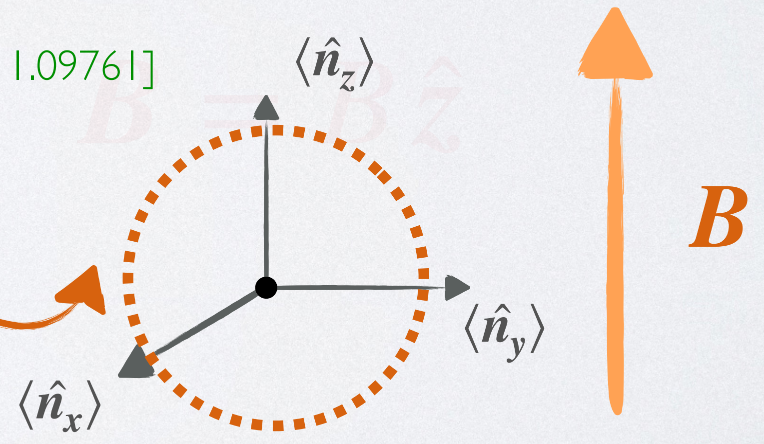
$$\mathscr{H}\Big|_{\text{stat., homog.}} = \frac{c_1}{2}\left[(\mu^2 B^2 - 2\lambda_z)\hat{n}_z^2 + 2\lambda_x \hat{n}_x^2\right]$$



$$\hat{\boldsymbol{n}}_x + \hat{\boldsymbol{n}}_y + \hat{\boldsymbol{n}}_z = 1$$

Magnons EFT

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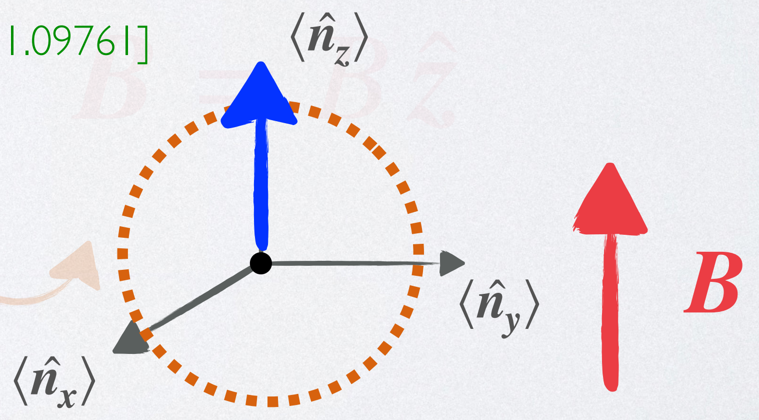
$$\mu^2 B^2 < 2\lambda_z \equiv \mu^2 B^2_{\text{s.f.}}$$



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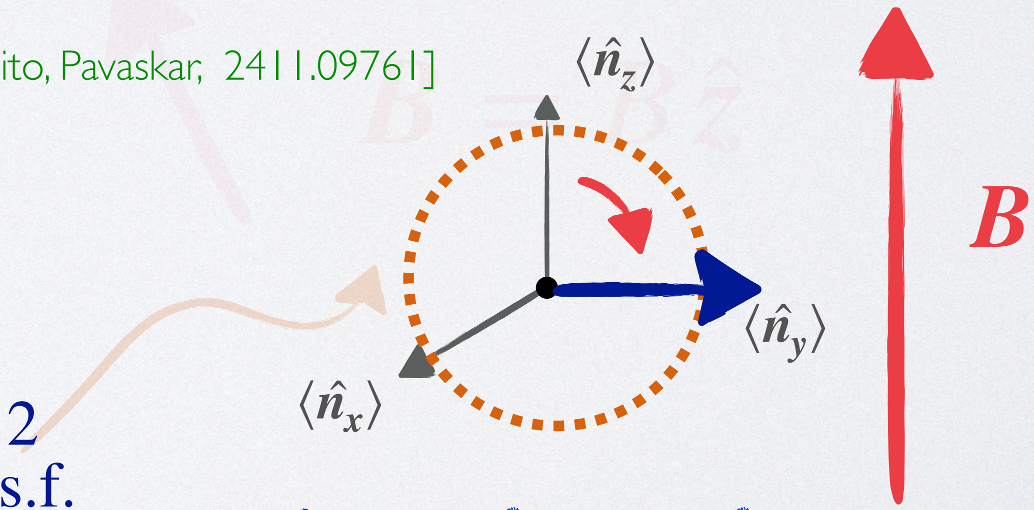
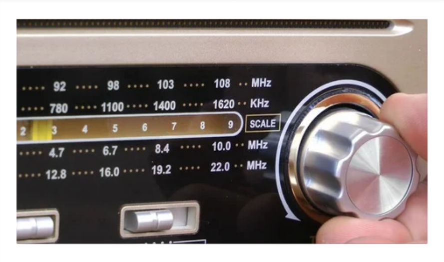


phase transition

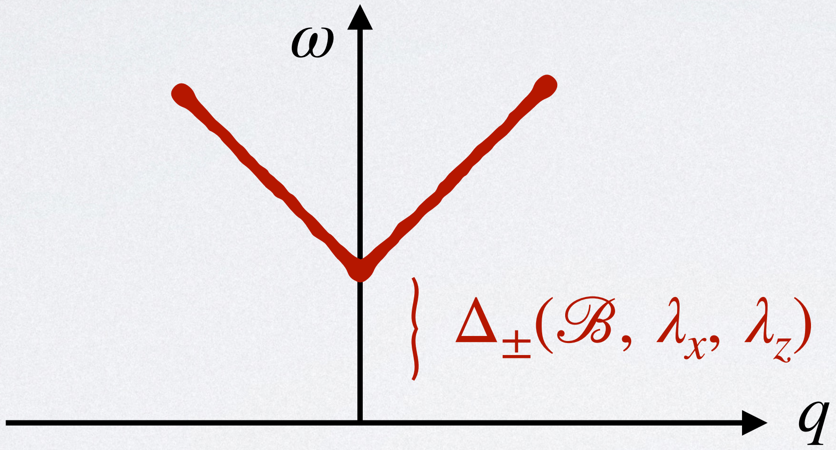
Magnons EFT

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

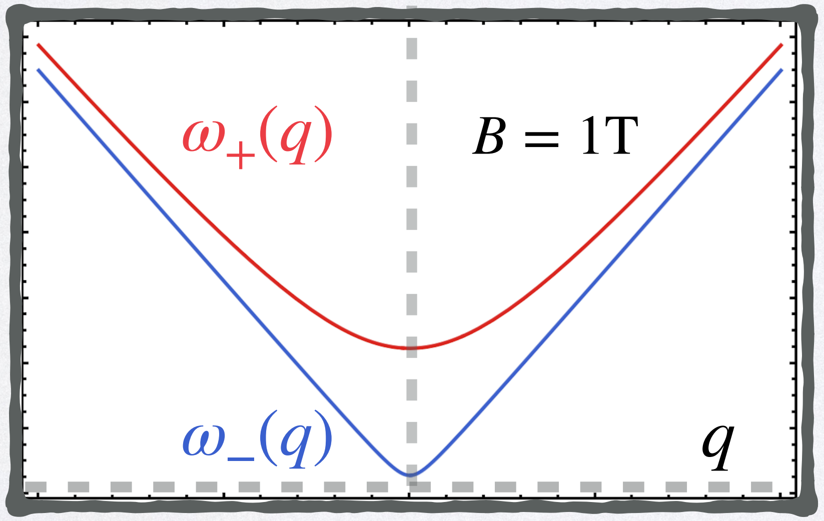
computing the spectrum of $\mathscr{L}_{\text{EFT}}$ one finds two modes:



$\mathscr{B}$



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



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

Magnons EFT (quantization)

- $\mathscr{L}_{\text{EFT}}$ contains one temporal derivative of the magnon field

$$\mathscr{L}_{\text{EFT}} \supset -\mu B \epsilon^{ab} \dot{\theta}^a \theta^b$$

$\longrightarrow$ not possible to diagonalize $\mathscr{L}_{EFT}$ by a *local* field redefinition

- Introduce overlap functions

[Esposito, Geoffray, Melia, PRD 2020 — 2006.05429]
[Chehung, Helset, Parra-Martinez, JHEP 2022 — 2111.03045]
[Hui , Kourkoulou, Nicolis, Podo, et al., JHEP 2023 — 2312.08440]

$$\langle 0 | \theta^a(\boldsymbol{x}, t) | \alpha = \pm, \boldsymbol{q} \rangle \not\propto \delta^a_\alpha$$

$$\langle 0 | \theta^a(\boldsymbol{x}, t) | \alpha = \pm, \boldsymbol{q} \rangle = e^{-i\omega_\alpha t + i\boldsymbol{q}\cdot\boldsymbol{x}} Z^a_\alpha(\boldsymbol{q})$$

labels
physical
states

$Z^a_\alpha \not\propto \delta^a_\alpha$

like a tetrad

meV QCD axion DM absorption with NiO

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

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

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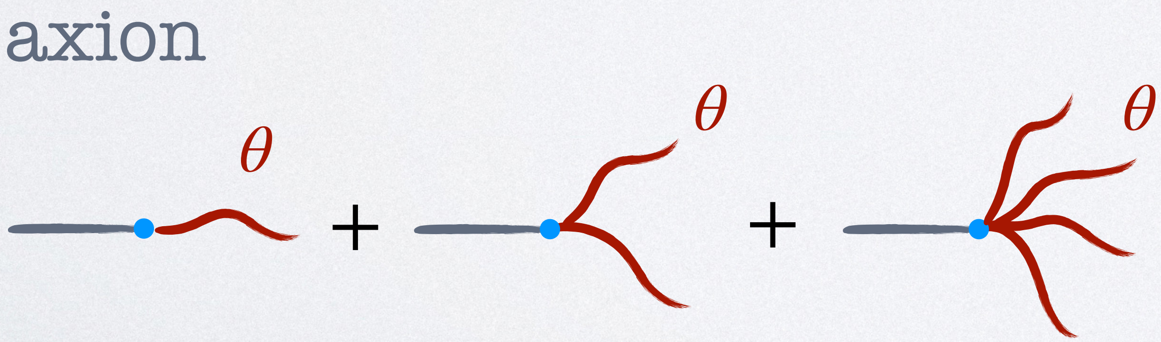
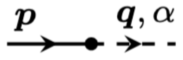
- The spin density is easily computed as the SO(3) Noether current in the EFT

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

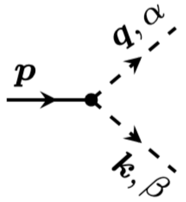
1-magnon

2-magnons



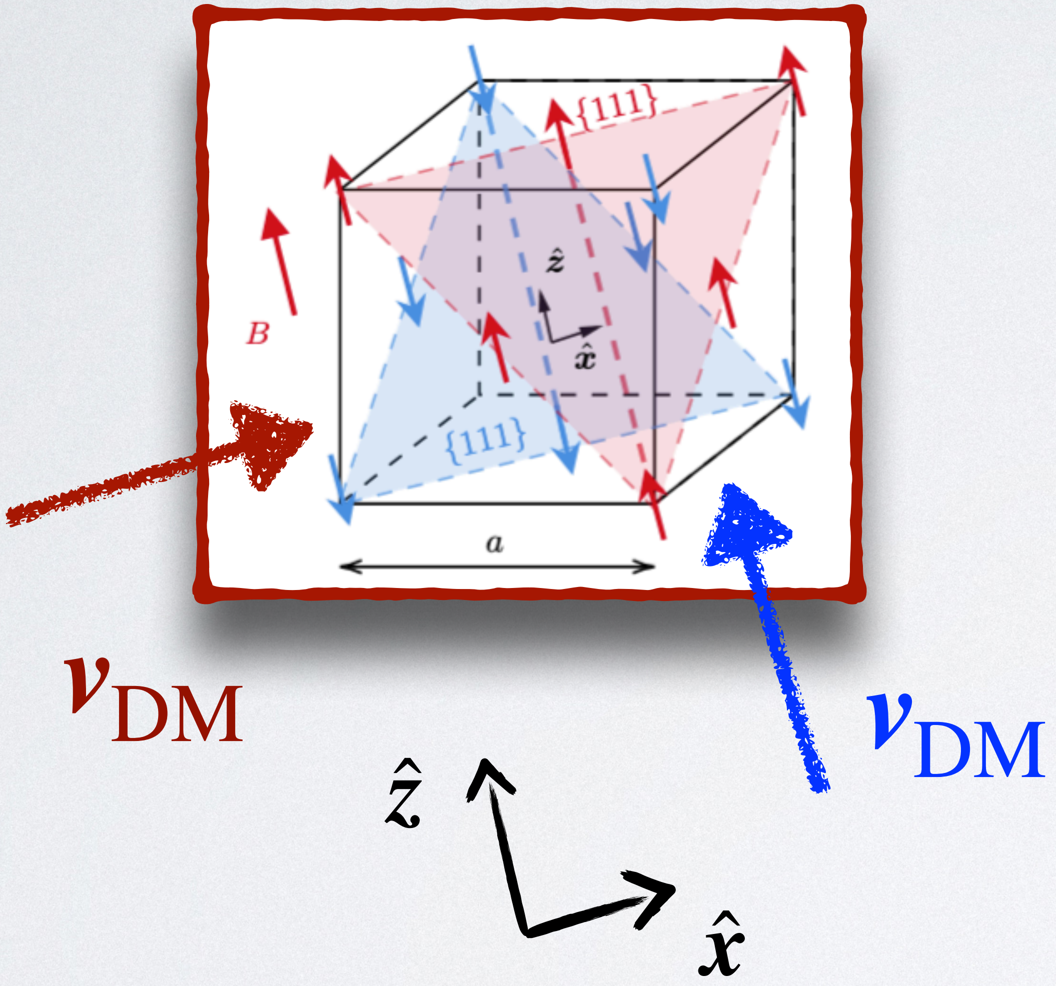


$$= i\frac{g_{aee}\sqrt{c_1}}{m_e}p_a\left[i\omega_{q,\alpha}\mathcal{Z}^a_{q,\alpha} + \mu B\epsilon^{ab}\mathcal{Z}^b_{q,\alpha}\right]^*,$$

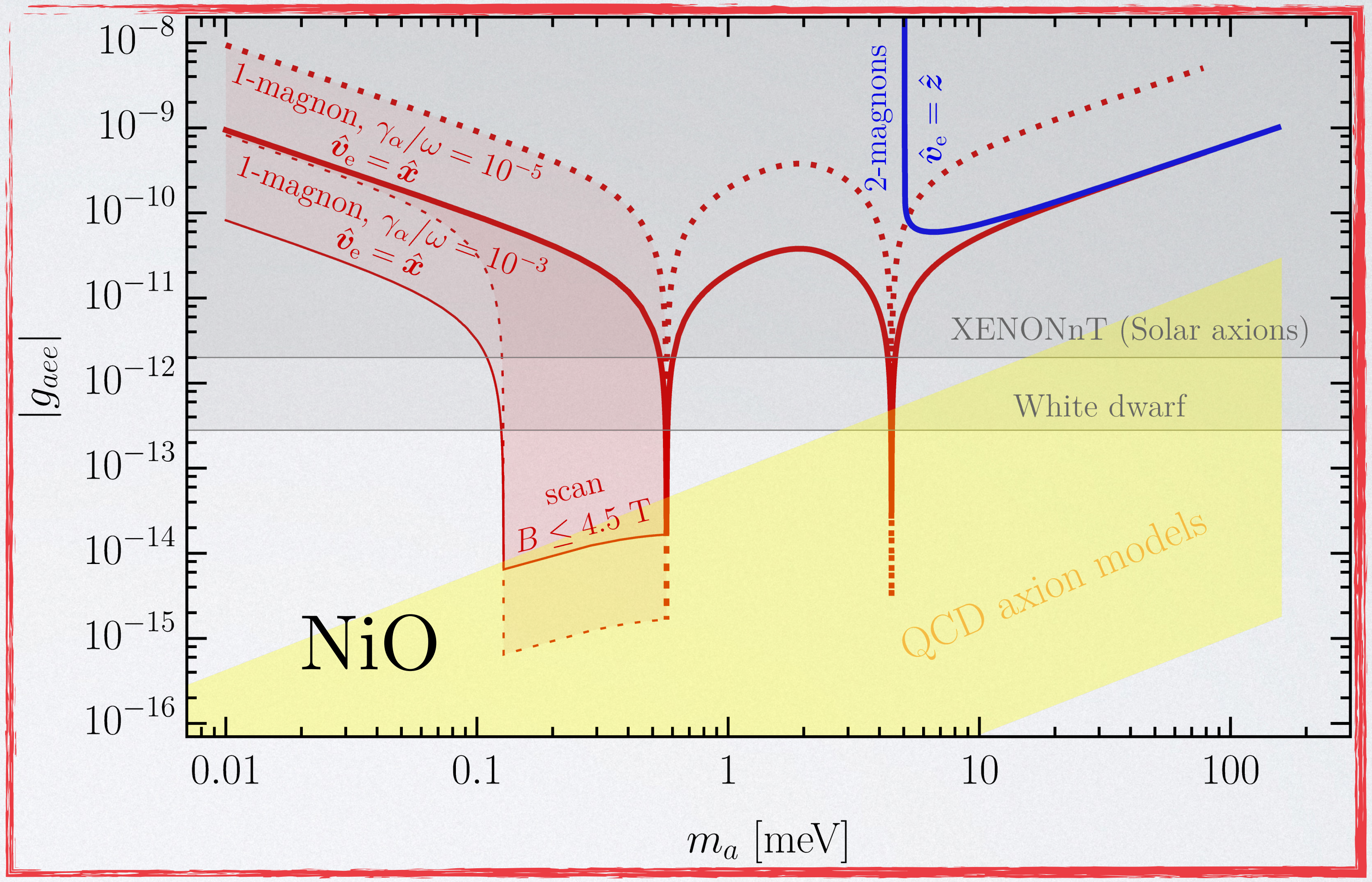


$$= i\,\frac{g_{aee}}{m_e}\,p_z\Big[i\left(\omega_{q,\alpha} - \omega_{k,\beta}\right)\epsilon^{ab}\mathcal{Z}^a_{q,\alpha}\mathcal{Z}^b_{k,\beta} + 2\mu B\mathcal{Z}^a_{q,\alpha}\mathcal{Z}^b_{k,\beta}\Big]^*,$$

meV QCD axion DM absorption with NiO



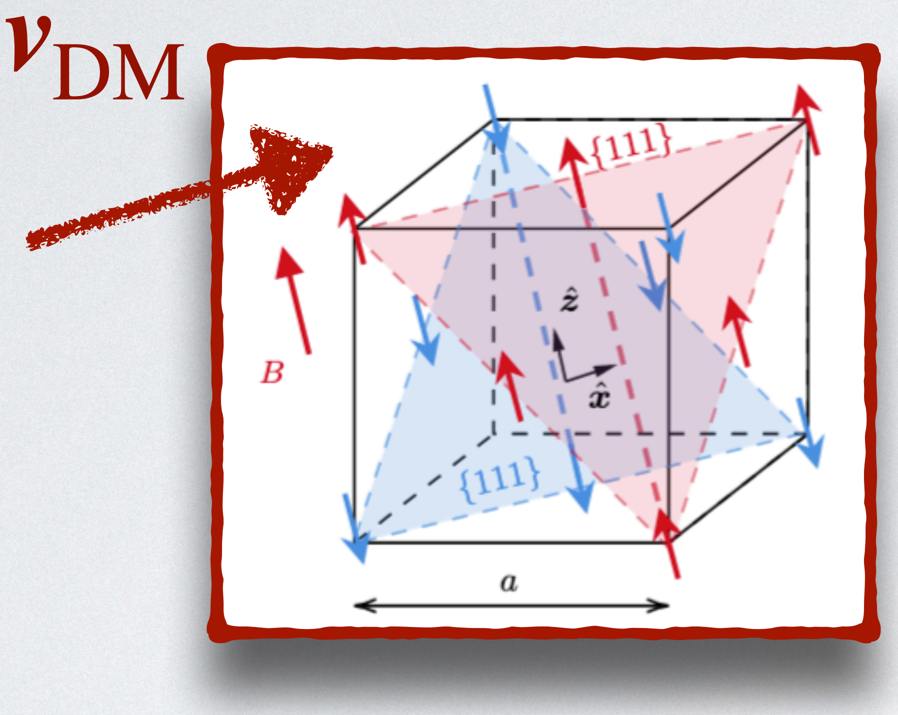
1Kg year exposure

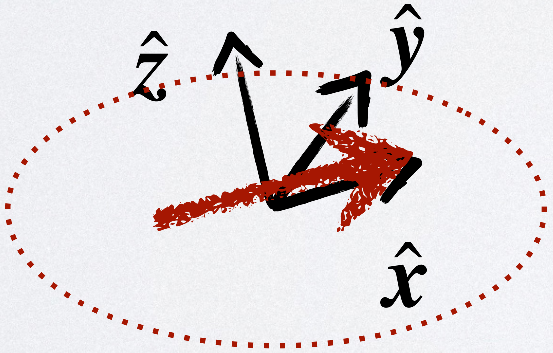


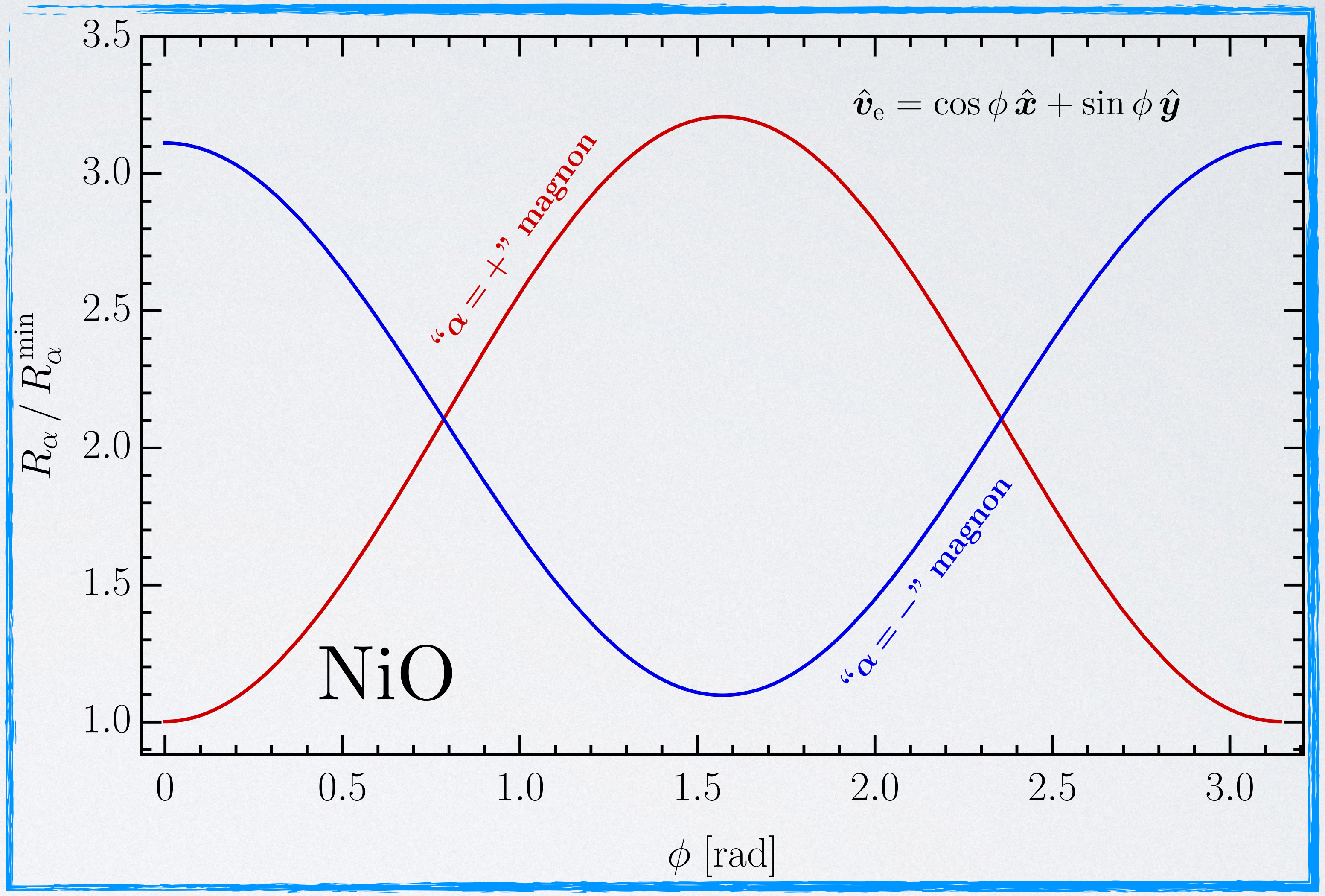
$$R(\hat{v}_e) = \frac{\rho_a}{\rho_T m_a} \int d^3v\, f(|\vec{v} + \vec{v}_e|)\, \Gamma(\vec{v})$$

Truncated Maxwell-Boltzmann
with dispersion
$v_0 = 230$ km/s

meV QCD axion DM absorption with NiO







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

Outlook

- Etra sources of breaking: strain effects?
- Extra modes to take into account?
- Observables (cavities, wave-guides)?

Thank you for the attention!