# LOW ENERGY AVENUES FOR SUB-MEV DARK MATTER SEARCHES

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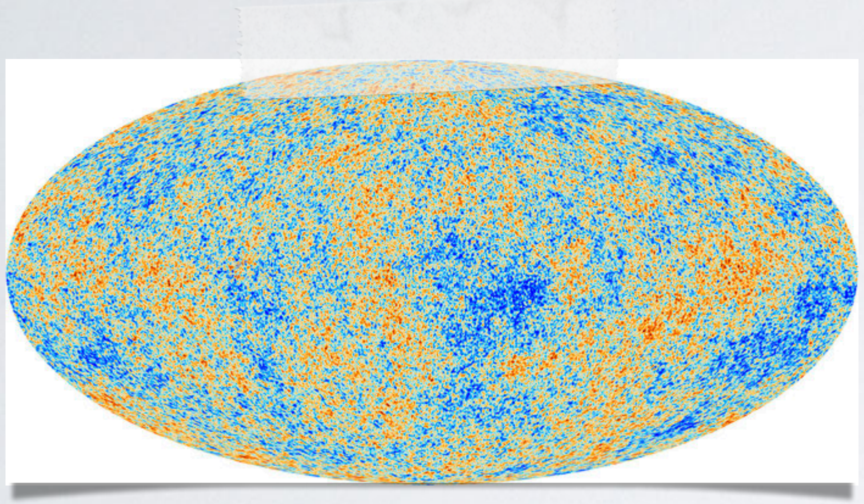
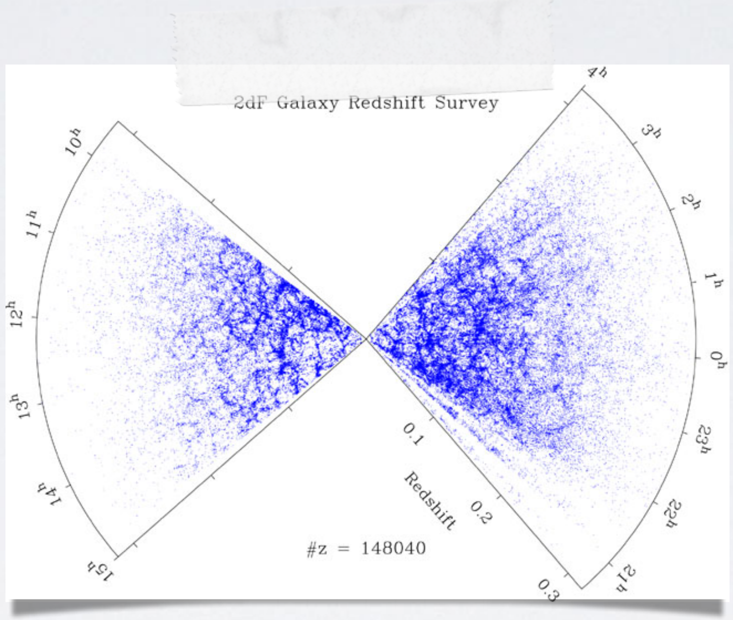
# OUTLINE

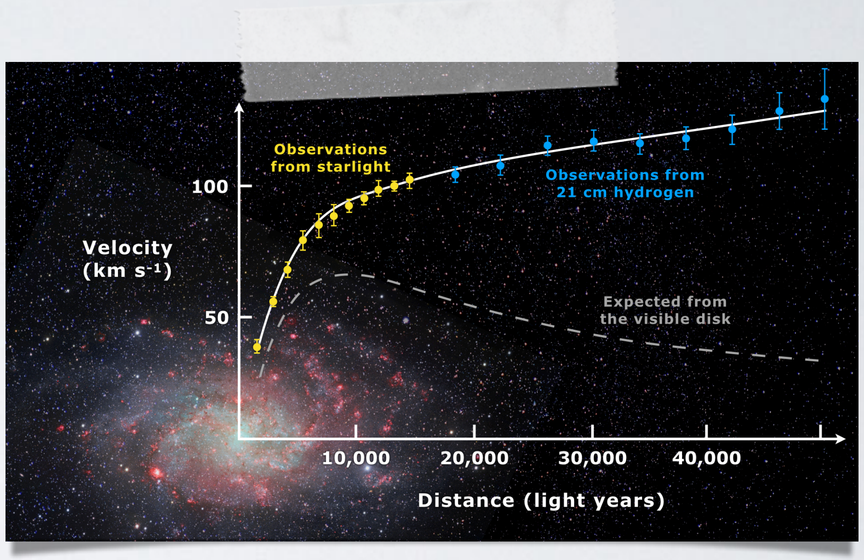
- Searching for light dark matter:
  - challenges and opportunities
  - intro to spontaneously broken spacetime symmetries
- Ideas for sub-MeV dark matter detection:
  - superfluid He-4
  - anti-ferromagnets
- Outlook

# SUB-MEV DARK MATTER

- Most of the matter ( $\sim 80\,\%$ ) that interacts gravitationally is dark



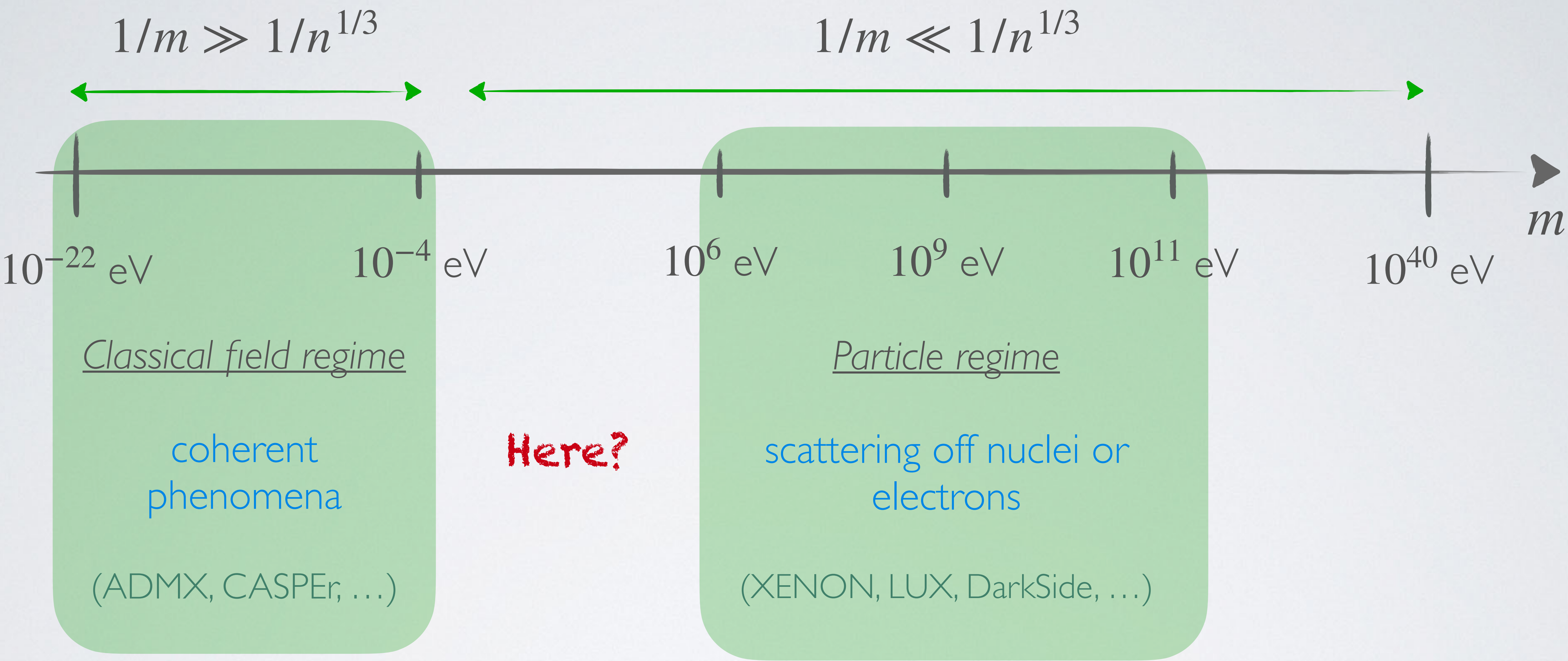




- One of the strongest evidences for physics beyond the Standard Model

- However… huge possible mass range → detection techniques vary widely depending on the dark matter mass

# SUB-MEV DARK MATTER



$1/m \gg 1/n^{1/3}$

$1/m \ll 1/n^{1/3}$

$10^{-22}$ eV

$10^{-4}$ eV

$10^{6}$ eV

$10^{9}$ eV

$10^{11}$ eV

$10^{40}$ eV

$m$

*Classical field regime*

coherent phenomena

(ADMX, CASPEr, …)

Here?

*Particle regime*

scattering off nuclei or electrons

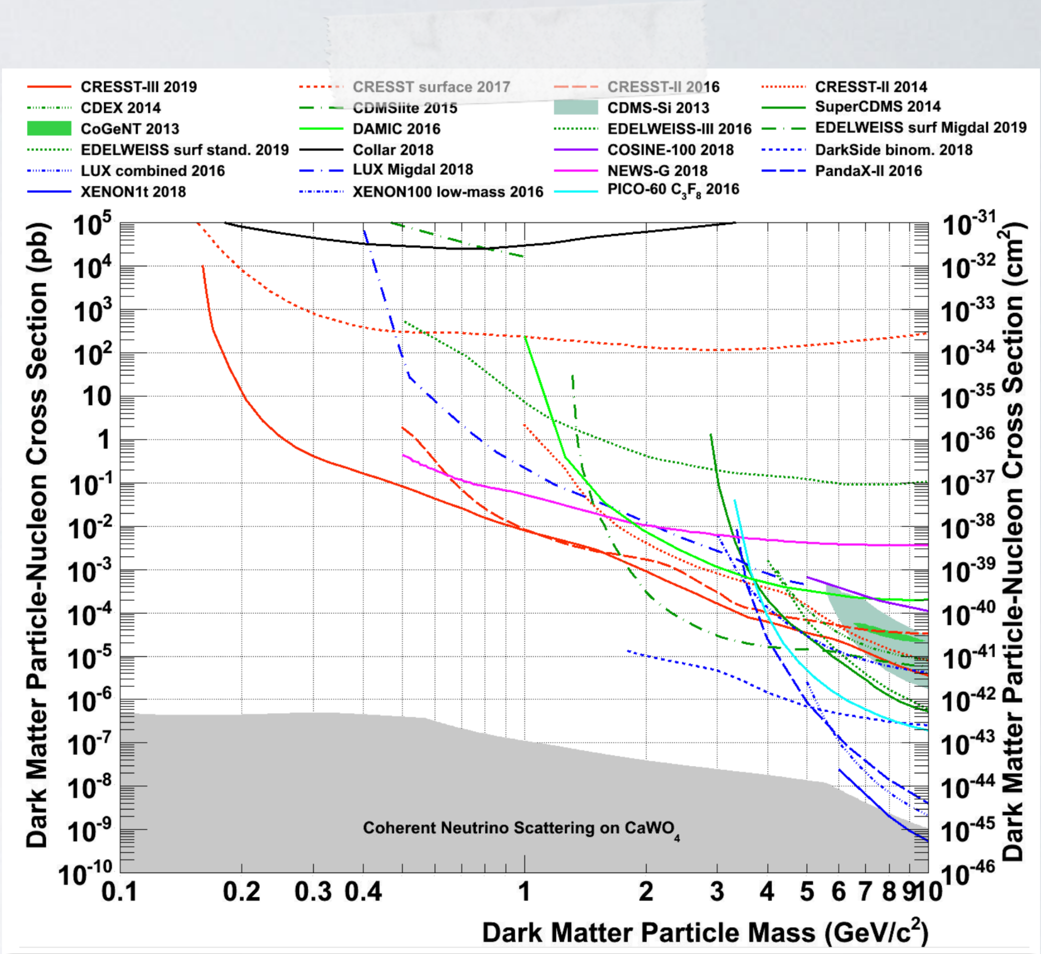
(XENON, LUX, DarkSide, …)

- Dark matter is a particle but too light for elastic recoil
- Need new materials and/or observables

# SUB-MEV DARK MATTER

- For an elastic scattering, it must be

$$E_T = \frac{m_\chi/m_T}{(1+m_\chi/m_T)^2}\,E_\chi \gtrsim E_{threshold}$$



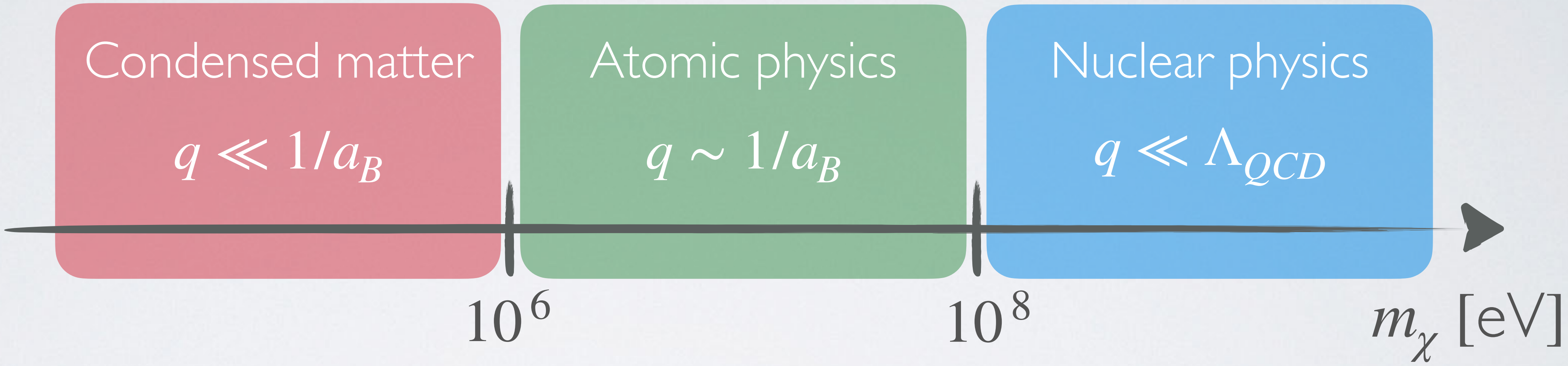
[CRESST — PRD 2019, 1904.00498]

- For $m_\chi \lesssim 1$ MeV elastic scattering off nuclei or electrons is very inefficient

- To evade this we must look into inelastic processes → one possibility are collective excitations

# NASTY STUFF

- For light dark matter one needs to delve into the condensed matter world



Condensed matter

$q \ll 1/a_B$

Atomic physics

$q \sim 1/a_B$

Nuclear physics

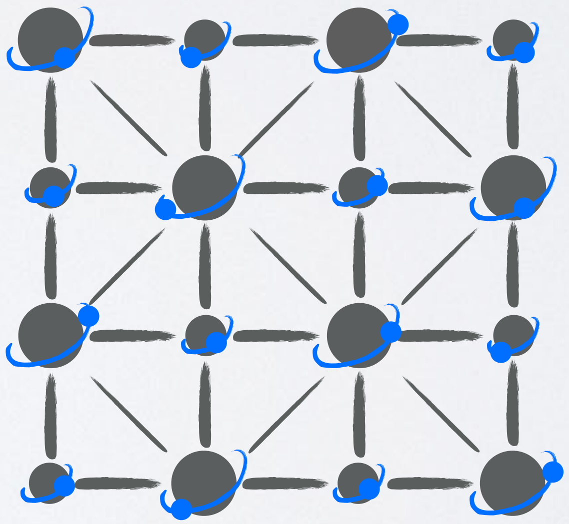
$q \ll \Lambda_{QCD}$

$10^6$

$10^8$

$m_\chi$ [eV]

- Must account for the complicated many-body physics (correlations, strong coupling, …)



- Need theoretical tools that allow to solve or bypass these problems

# COLLECTIVE MODES IN HEP

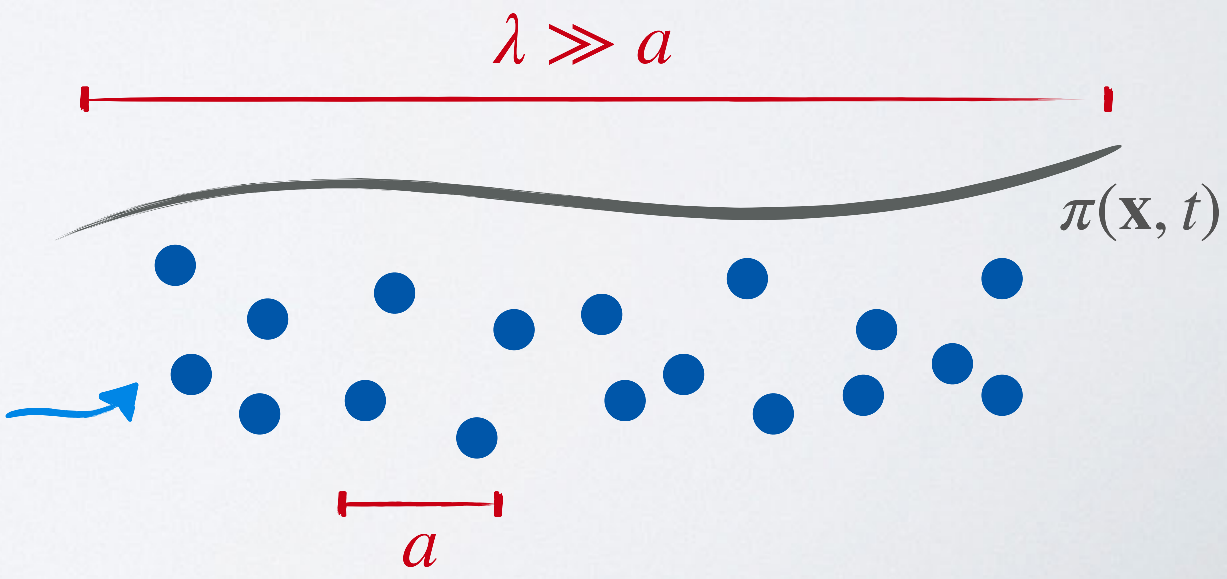
- All phases of matter spontaneously break spacetime and (maybe) internal symmetries

Goldstone's theorem

Spontaneous symm. breaking ⟷ existence of soft modes

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

$$\mathscr{L}_{EFT}[\pi, \partial] \sim \sum_{n,m} g_{n,m} \partial^n \pi^m$$



complicated microscopic physics encoded here

# COLLECTIVE MODES IN HEP

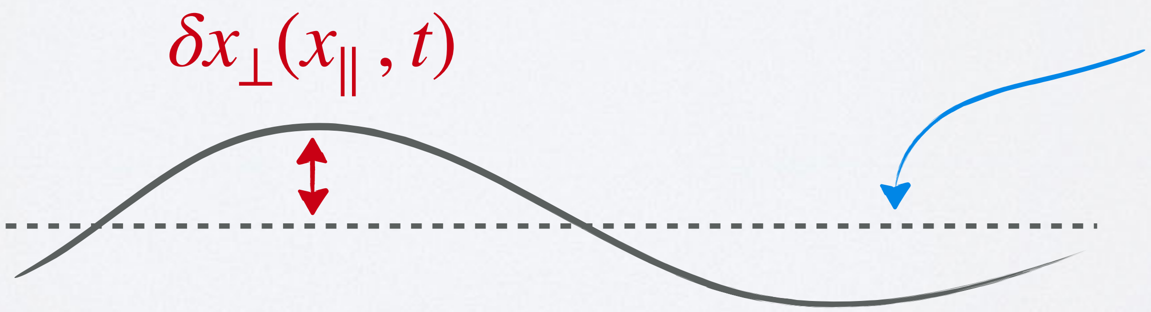
- Goldstone's theorem for spontaneously broken spacetime symmetries is less constraining

| Unbroken spacetime symm. | Broken spacetime symm. |
|---|---|
| num$(\pi) = $ dim$(G/H)$ | num$(\pi) \leq$ dim$(G/H)$ |
| $\omega(\mathbf{q}) = \lvert\mathbf{q}\rvert$ | $\omega(\mathbf{q}) \neq \lvert\mathbf{q}\rvert$ |
| Manifest Poincaré invariance | Non-manifest Poincaré invariance |

- Simple example: string in 2D

only one Goldstone:

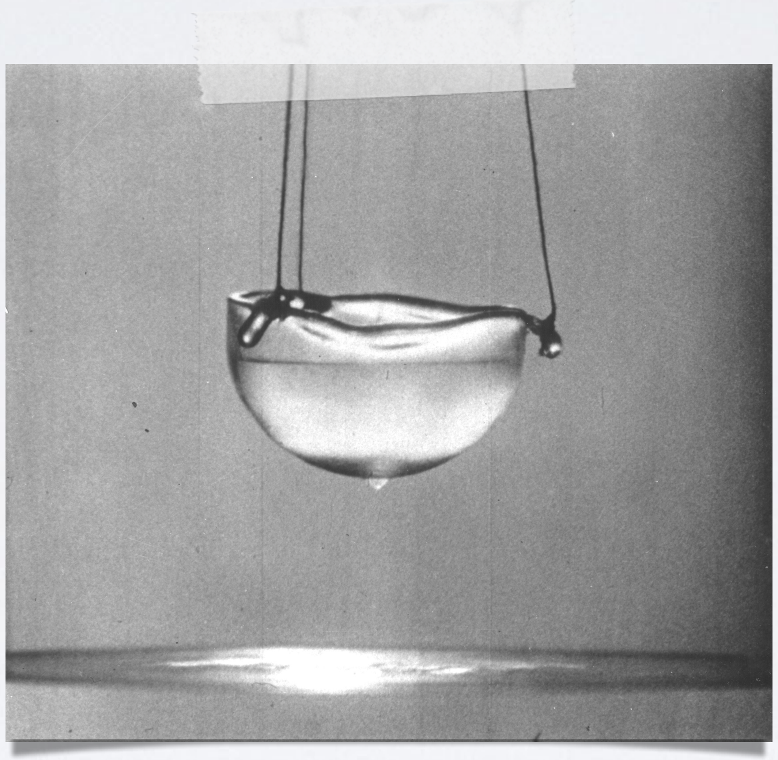
$$\omega(\mathbf{q}) = c_s\,\lvert\mathbf{q}\rvert$$



3 broken generators:

$$K_\perp, P_\perp, J$$

# Superfluid $^4$He



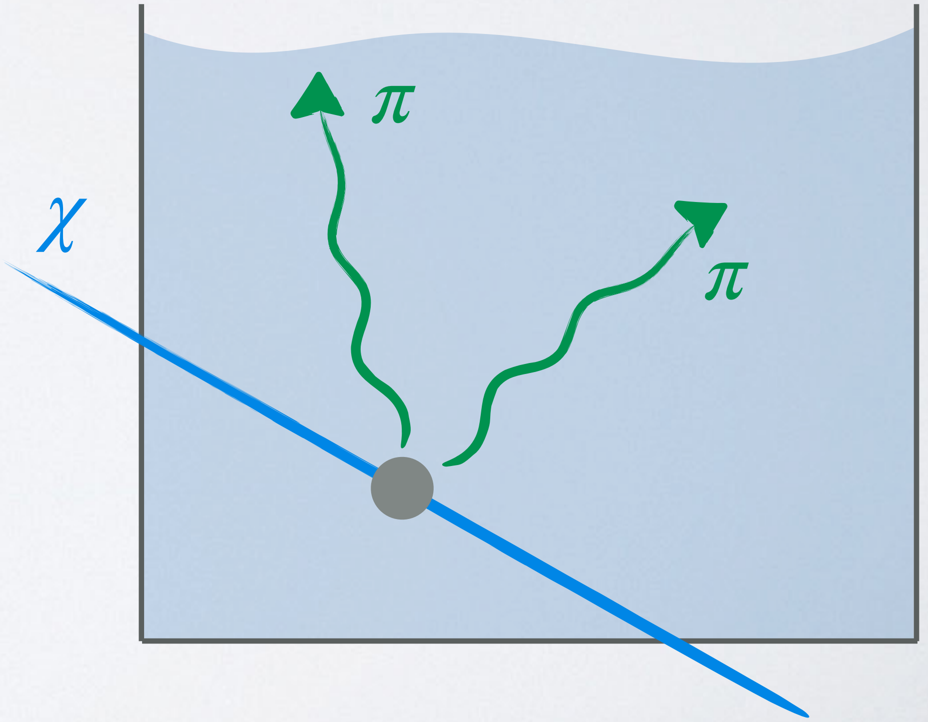
# SUPERFLUID $^4$He

- Superfluid $^4$He is an interesting target to probe dark matter with spin-independent interactions

  1. $E_{ion} \simeq 25$ eV → low electronic background
  2. High radiopurity
  3. Multi-phonon processes allow to probe down to $m_\chi \sim \mathcal{O}(\text{keV})$

- Idea: look for events where the dark matter produces more than one phonon

[Guo, McKinsey – PRD 2013, 1302.0534; Schutz, Zurek – PRL 2016, 1604.08206; Knapen, Lin, Zurek – PRD 2017, 1611.06228; Acanfora, **AE**, Polosa – EPJC 2019, 1902.02361; Caputo, **AE**, Polosa – PRD 2019, 1907.10635; Baym et al. – PRD 2021, 2005.08824; Caputo, **AE**, Piccini, Polosa, Rossi – PRD 2021, 2012.01432; Matchev et al. – JHEP 2022, 2108.07275; You et al. – 2208.14474]



# SUPERFLUID $^4$He

- $^4$He is microscopically strongly coupled → multi-phonon emission rate is hard to compute

*standard way*

atomic Hamiltonian, $H_{UV}$

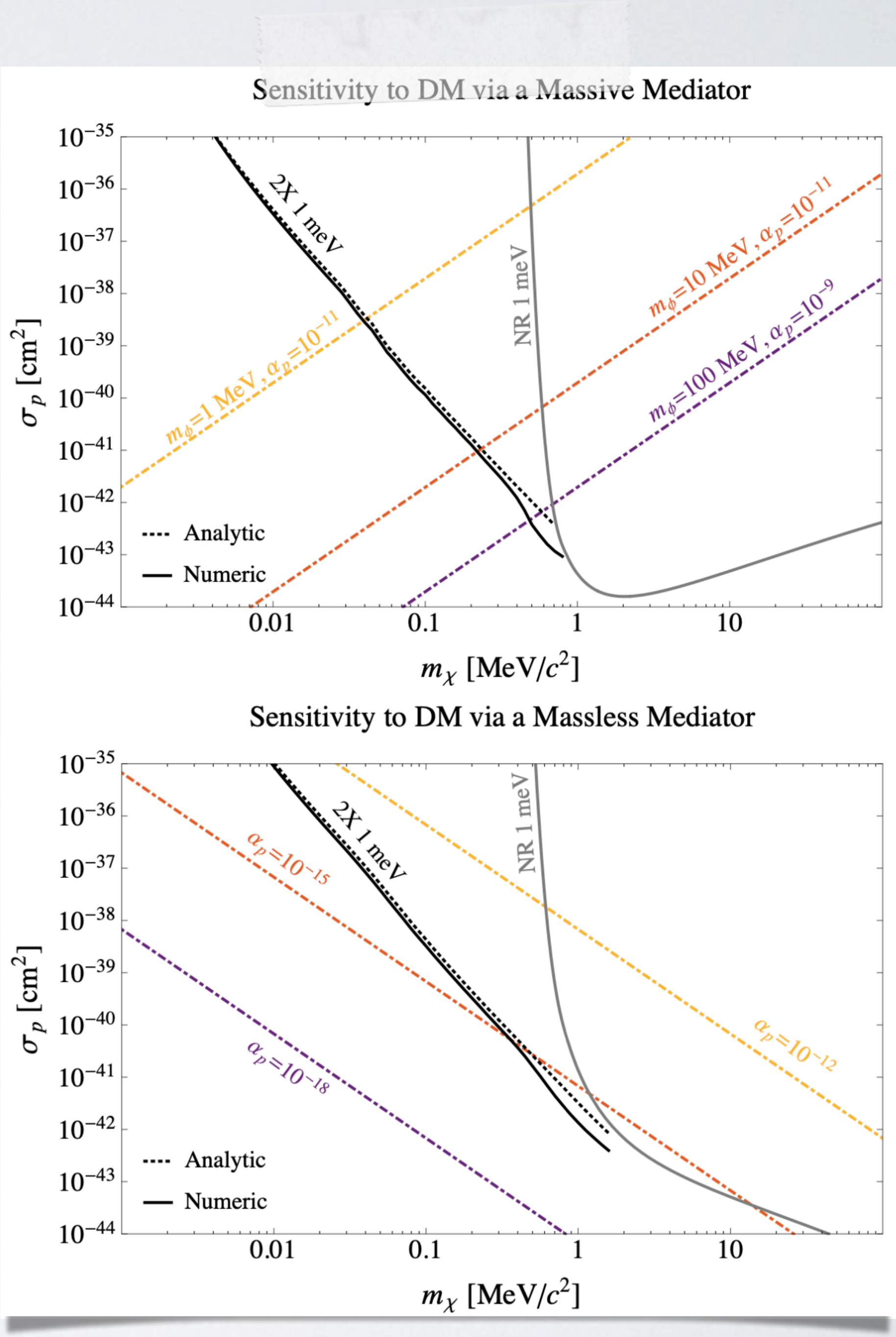
↓

clever ansatz for the condensate w.f.

↓

extrapolation of the structure factor

$$\frac{d\Gamma}{d\omega\, dq} = \frac{\rho_{He}\, \sigma_{\chi n}\, q}{2 m_\chi\, m_{He}\, p_i}\, S(q,\omega)$$



[Schutz, Zurek – PRL 2016, 1604.08206; Knapen, Lin, Zurek – PRD 2017, 1611.06228; Baym et al. – PRD 2021, 2005.08824]

# SUPERFLUID $^4$He

- Alternatively, the symmetry breaking pattern of a superfluid:

$$\cancel{\mathbf{K}}\,,\ \cancel{H}\,,\ \mathbf{P}\,,\ \mathbf{J}\,,\ \cancel{Q} \quad \longrightarrow \quad \mathbf{P}\,,\ \mathbf{J}\,,\ \bar{H} = H - \mu Q$$

- Realized by a real scalar field

$$\psi(x) \xrightarrow{Q} \psi(x) + a \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

[see, e.g., Son — hep-th/0204199; Nicolis, Piazza — JHEP 2012, 1112.5174]

- Gapless phonon = Goldstone → low energy EFT:

$$\mathscr{L}_{EFT} = P\left(\sqrt{\partial_\mu \psi \partial^\mu \psi}\right)$$

$$\sim \dot{\pi}^2 - c_s^2 (\nabla \pi)^2 + \lambda \dot{\pi} (\nabla \pi)^2 + \lambda' \dot{\pi}^3 + \dots$$

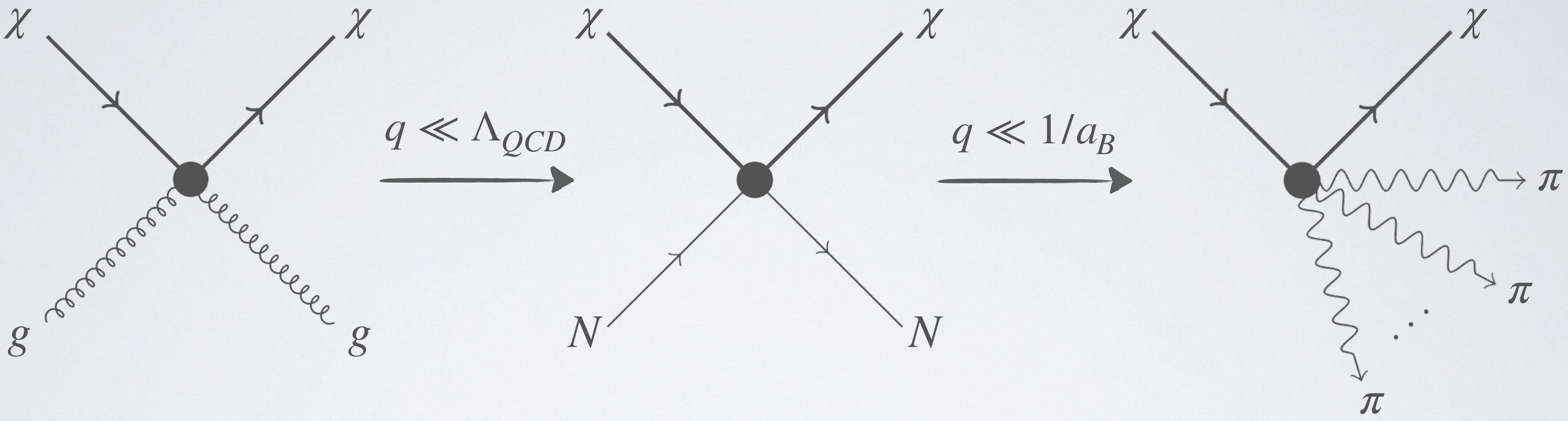
effective coefficients are given by the equation of state:

$$P \equiv P(\mu)$$

[see, e.g., Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361]

# DM-PHONON INTERACTION

- At low energies, dark matter couples to the *number density field*



$\mathscr{L}_{int} \sim |\chi|^2 G_{\mu\nu}G^{\mu\nu}$ $\mathscr{L}_{int} \sim |\chi|^2 \bar{N}N$ $\mathscr{L}_{int} \sim |\chi|^2 n(\pi)$

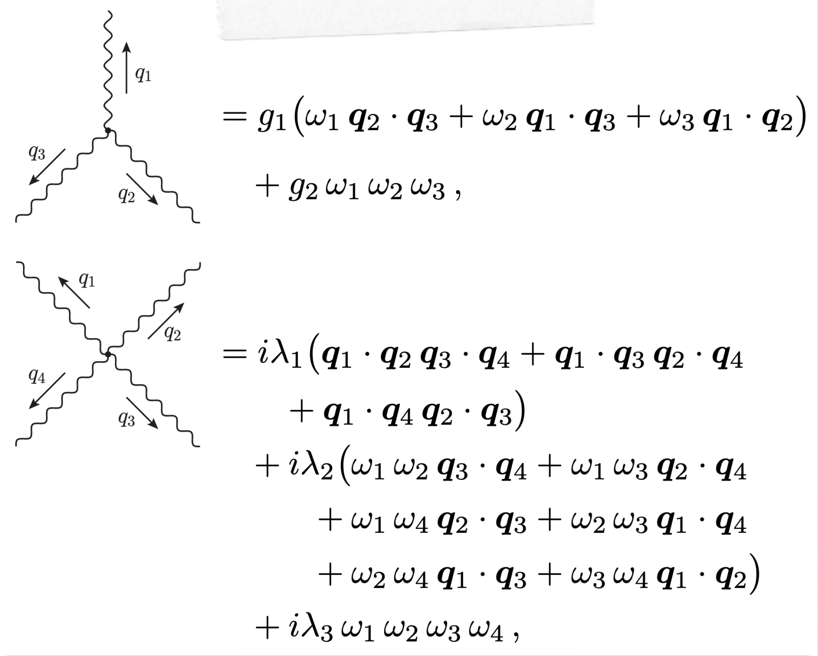
- Obtain from the $U(1)$ Noether current within the EFT

$$\mathscr{L}_{int} = G_\chi m_\chi |\chi|^2 J^0 \sim |\chi|^2 \left( g\dot{\pi} + g'\dot{\pi}^2 + g''(\nabla\pi)^2 + \dots \right)$$

`[see, e.g., Acanfora, AE, Polosa — EPJC 2019, 1902.02361]`

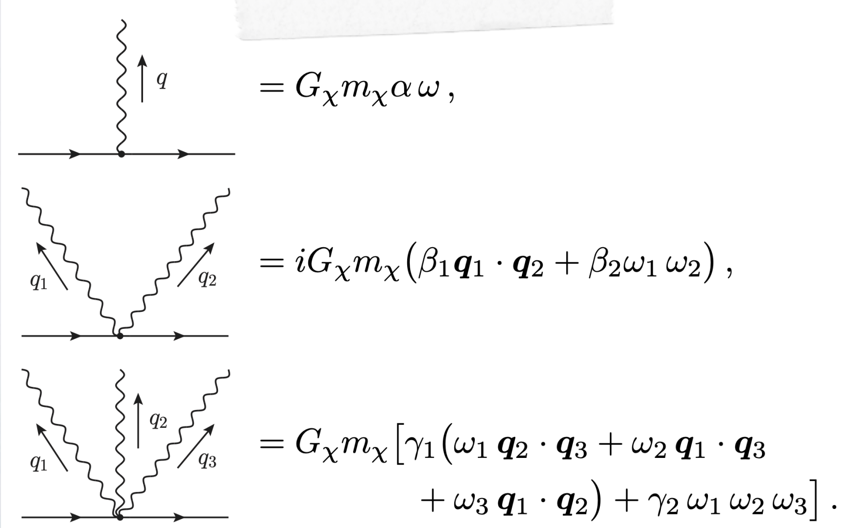
# IDEAL REACH

- We can now use standard QFT methods to compute event rates



$$= g_1\left(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\right) + g_2\, \omega_1\, \omega_2\, \omega_3\,,$$

$$\begin{aligned} &= i\lambda_1\big(\boldsymbol{q}_1\cdot\boldsymbol{q}_2\, \boldsymbol{q}_3\cdot\boldsymbol{q}_4 + \boldsymbol{q}_1\cdot\boldsymbol{q}_3\, \boldsymbol{q}_2\cdot\boldsymbol{q}_4 \\ &\qquad + \boldsymbol{q}_1\cdot\boldsymbol{q}_4\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3\big) \\ &\quad + i\lambda_2\big(\omega_1\,\omega_2\, \boldsymbol{q}_3\cdot\boldsymbol{q}_4 + \omega_1\,\omega_3\, \boldsymbol{q}_2\cdot\boldsymbol{q}_4 \\ &\qquad + \omega_1\,\omega_4\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\,\omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_4 \\ &\qquad + \omega_2\,\omega_4\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\,\omega_4\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) \\ &\quad + i\lambda_3\, \omega_1\, \omega_2\, \omega_3\, \omega_4\,, \end{aligned}$$

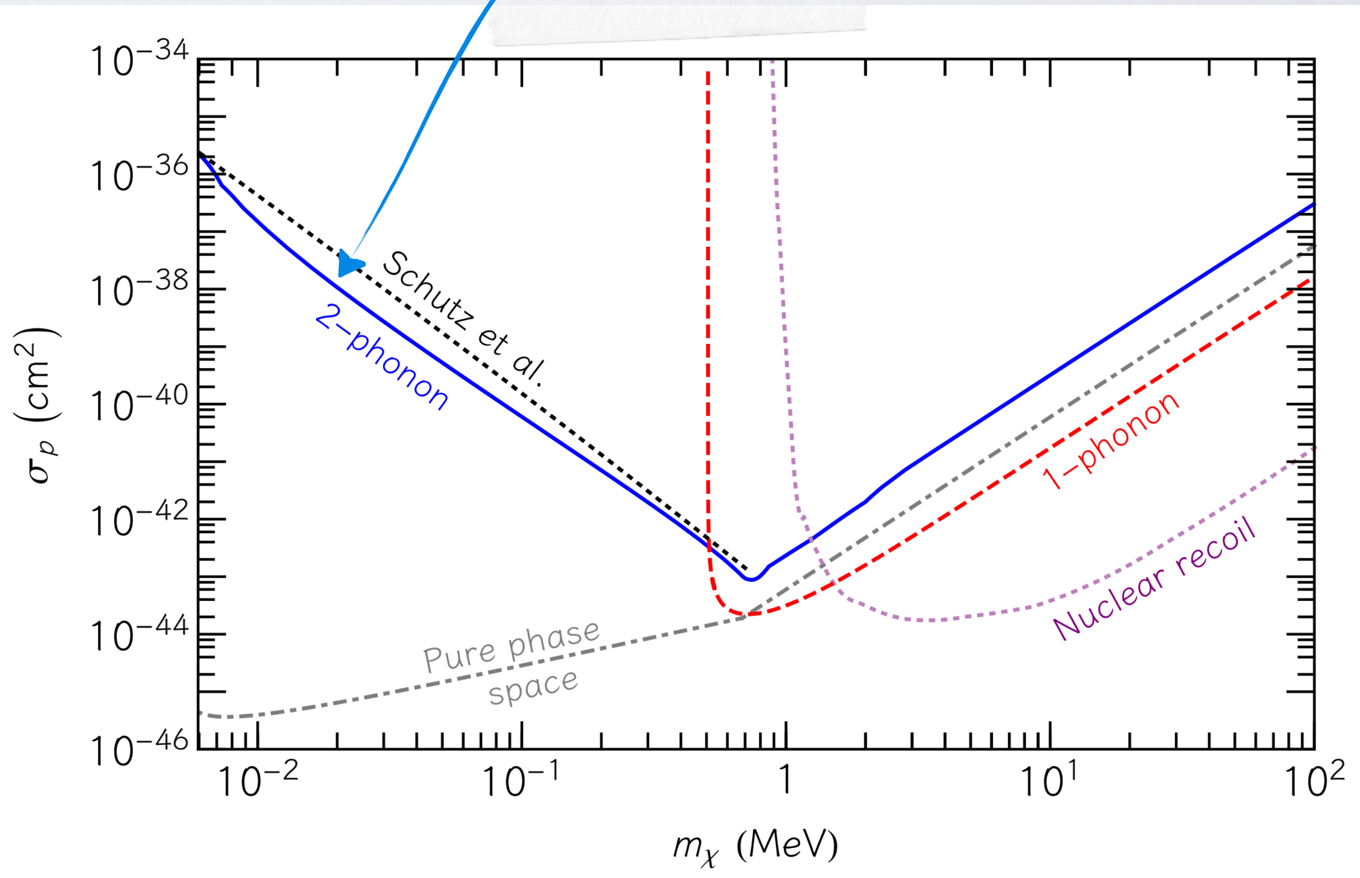


$$= G_\chi m_\chi \alpha\, \omega\,,$$

$$= iG_\chi m_\chi\left(\beta_1 \boldsymbol{q}_1\cdot\boldsymbol{q}_2 + \beta_2 \omega_1\, \omega_2\right),$$

$$\begin{aligned} &= G_\chi m_\chi\big[\gamma_1\big(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 \\ &\qquad + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) + \gamma_2\, \omega_1\, \omega_2\, \omega_3\big]\,. \end{aligned}$$

revise results obtained with traditional methods

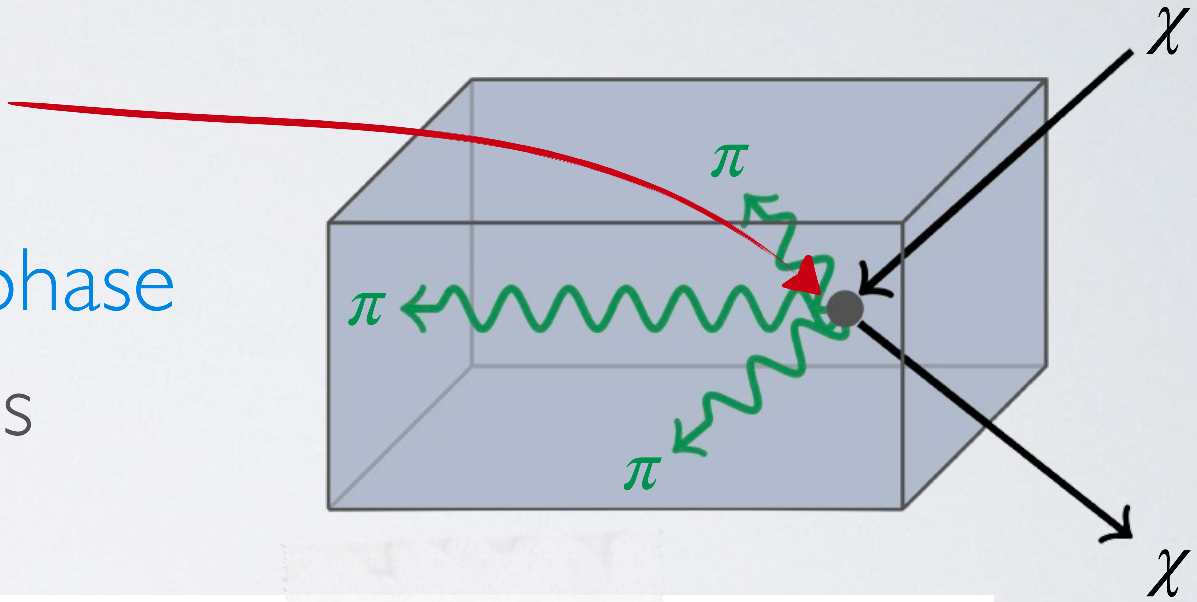


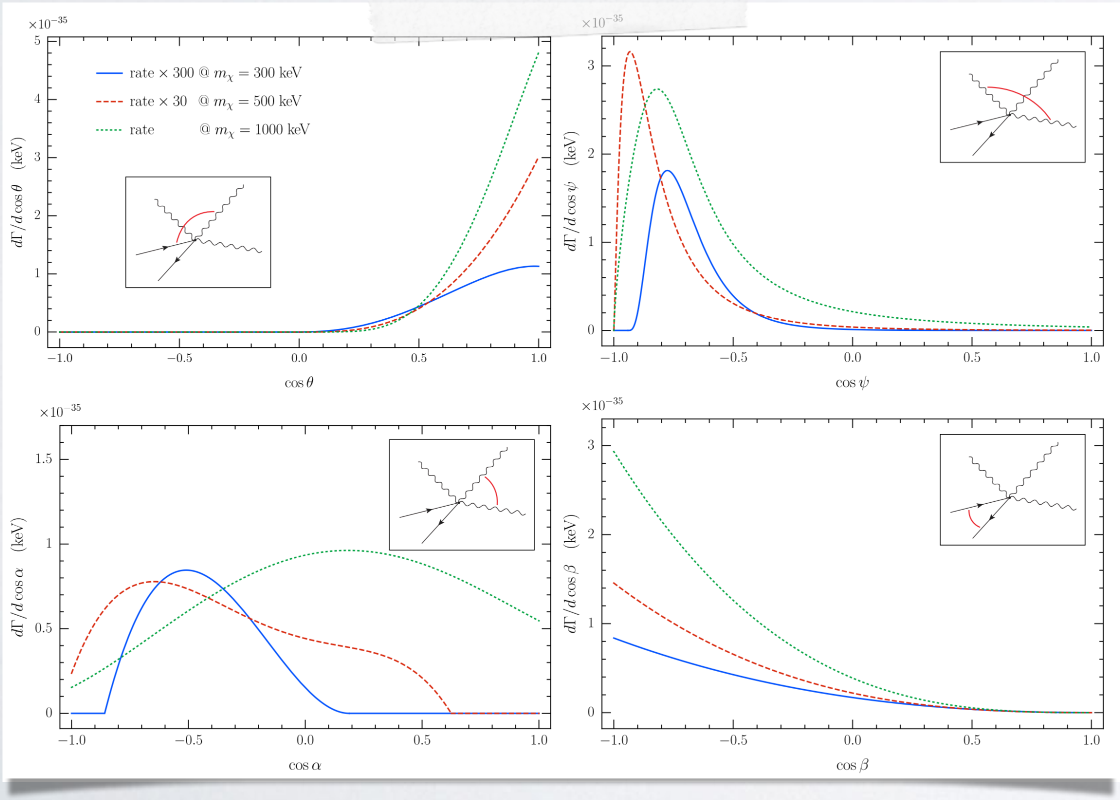
[Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361;
Caputo, **AE**, Polosa — PRD 2019, 1907.10635]

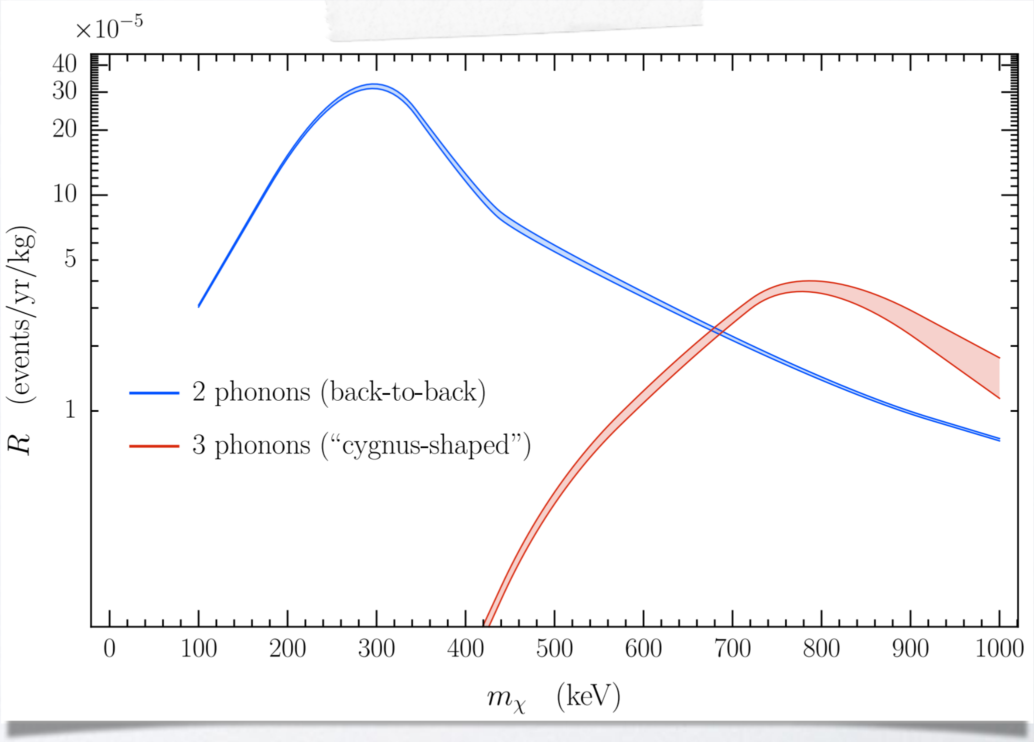
# DIRECTIONALITY

- EFT allows to also study more complicated, directional signals
- Complicated non-Lorentz invariant phase space computed with MC techniques

impossible with traditional methods,
but very simple within EFT

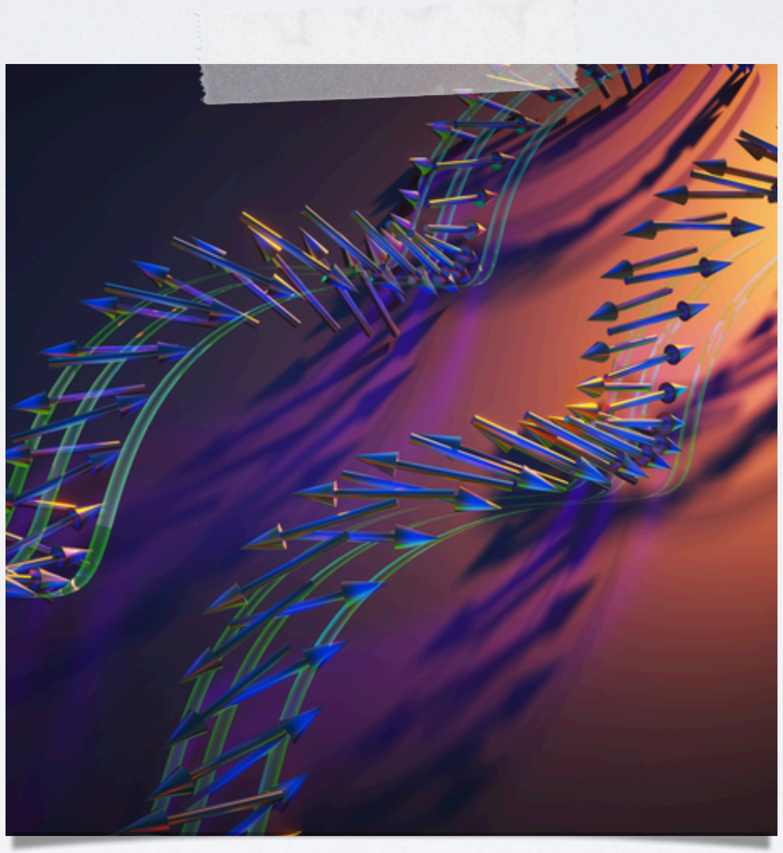






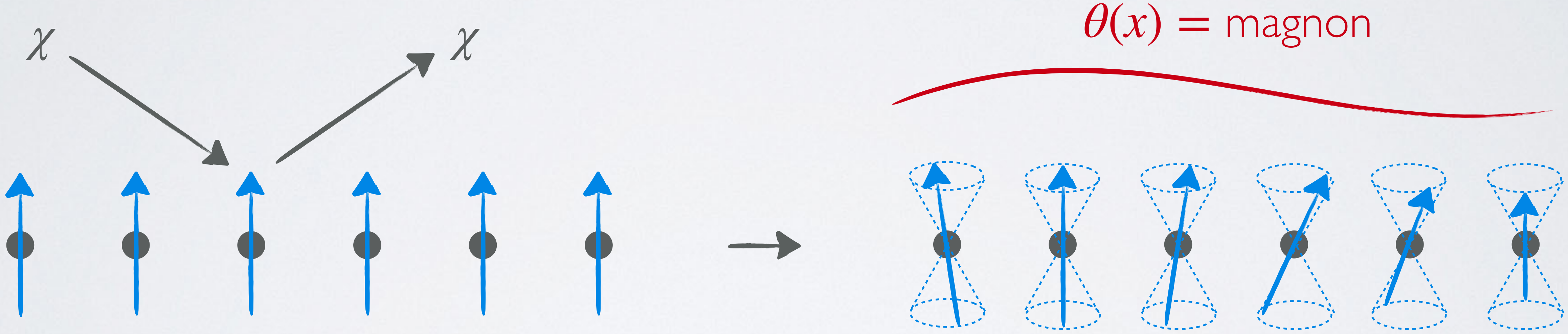
[Caputo, **AE**, Piccini, Polosa, Rossi – PRD 2021, 2012.01432]

# Anti-ferromagnets



# (ANTI-)FERROMAGNETS

- How about dark matter with spin-*dependent* interactions?
- A possibility is to look for the interaction between dark matter and spin-ordered systems



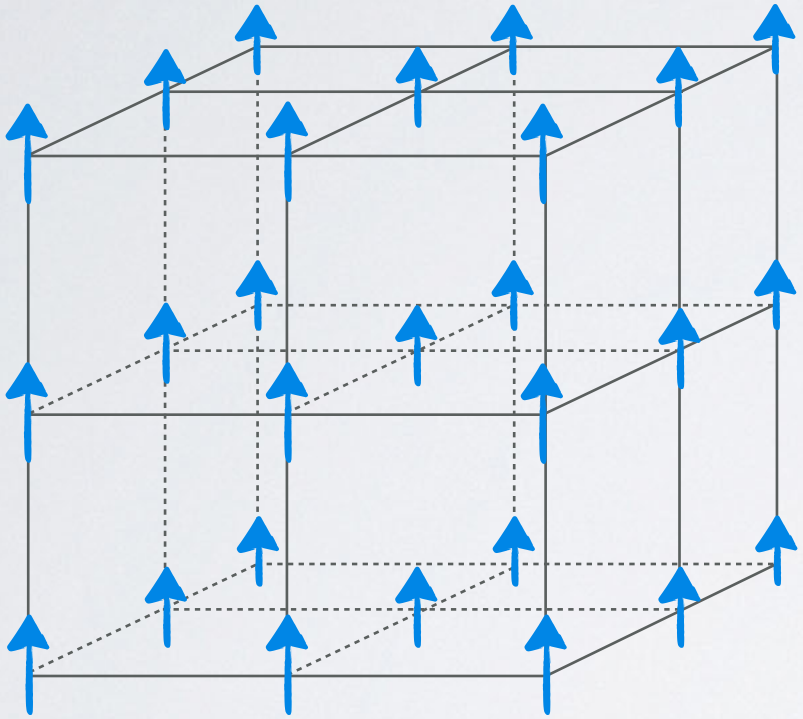
- Ways to detect few magnons have already been proposed and under development (TES, MKID, quantum sensors)

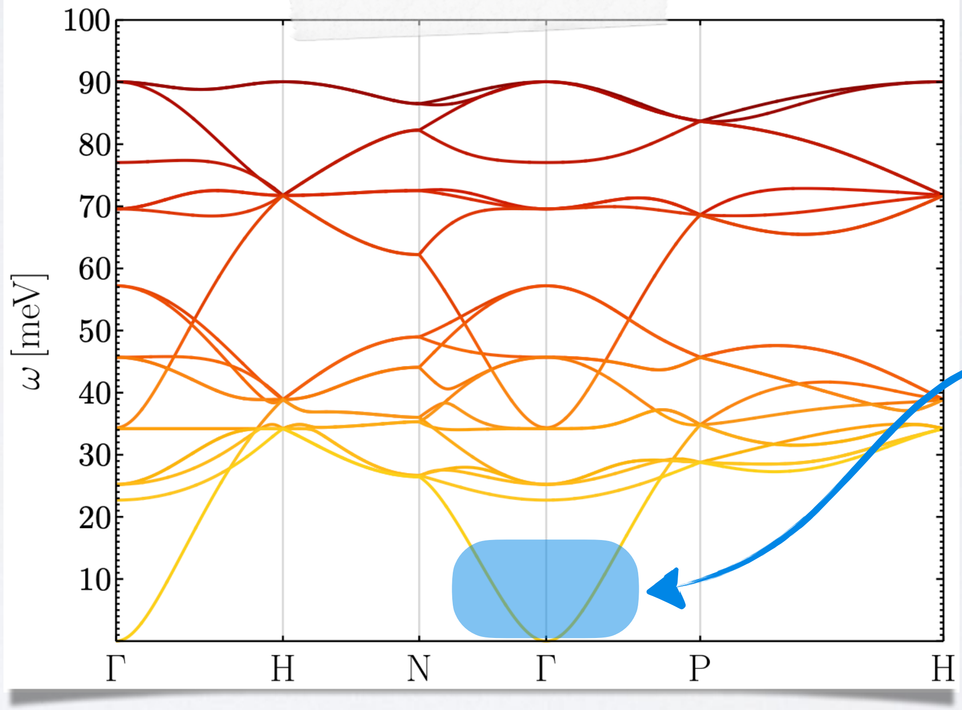
[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Lachance-Quirion et al. — Science Advances 2017; Lachance-Quirion et al. — Science 2020]

# FERROMAGNETS

- First 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]





for $m_\chi \lesssim 10$ MeV only

gapless magnons

$\omega(q) = q^2/(2m_\theta)$

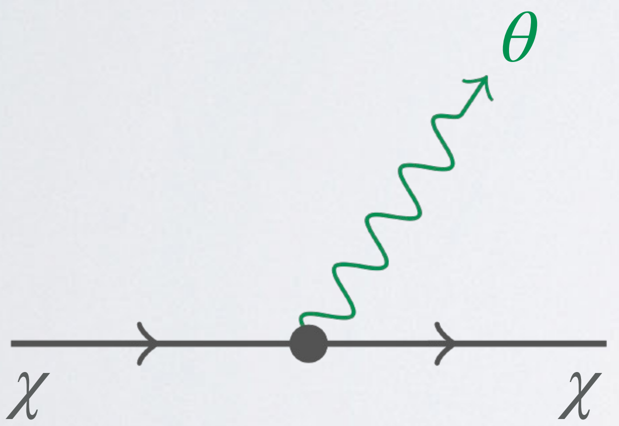
- Conservation of magnetization → only one magnon emitted

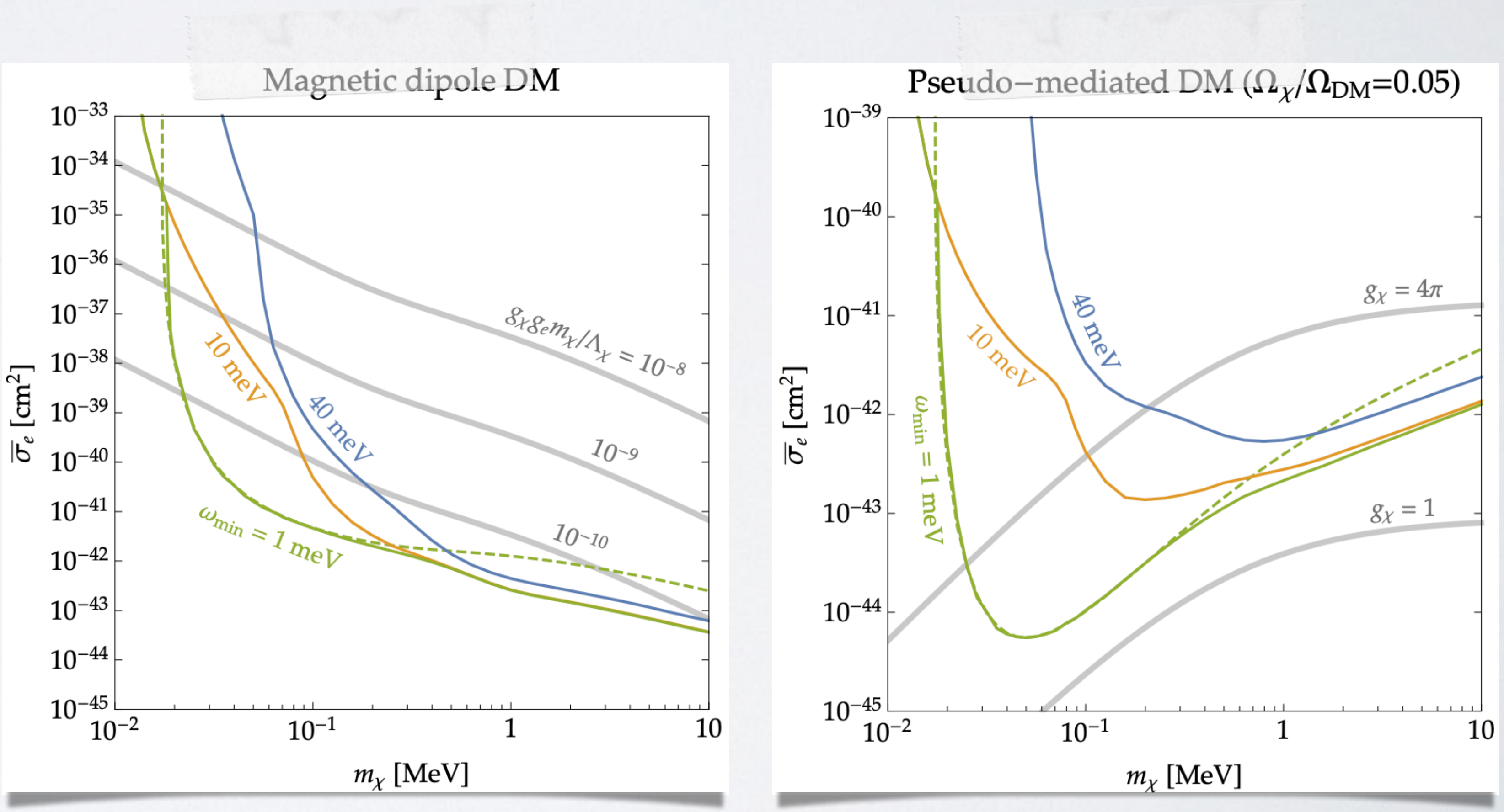
$$\omega_{max} = E_\chi \frac{4\, m_\theta/m_\chi}{(1+m_\theta/m_\chi)^2}$$ with $m_\theta \sim 1$ MeV → inefficient for $m_\chi \lesssim 1$ MeV

# FERROMAGNETS

- Compute the magnon emission rate
- Traditional approach: quantize the Heisenberg model

$$H = \frac{1}{2}\sum_{\ell,\ell'}^{N}\sum_{j,j'}^{n} J_{\ell\ell' jj'}\,\mathbf{S}_{\ell j}\cdot\mathbf{S}_{\ell' j'} \to \sum_{\nu=1}^{n}\sum_{\mathbf{q}\in 1BZ} \omega_{\nu,\mathbf{q}}\, b^{\dagger}_{\nu,\mathbf{q}}\, b_{\nu,\mathbf{q}}$$

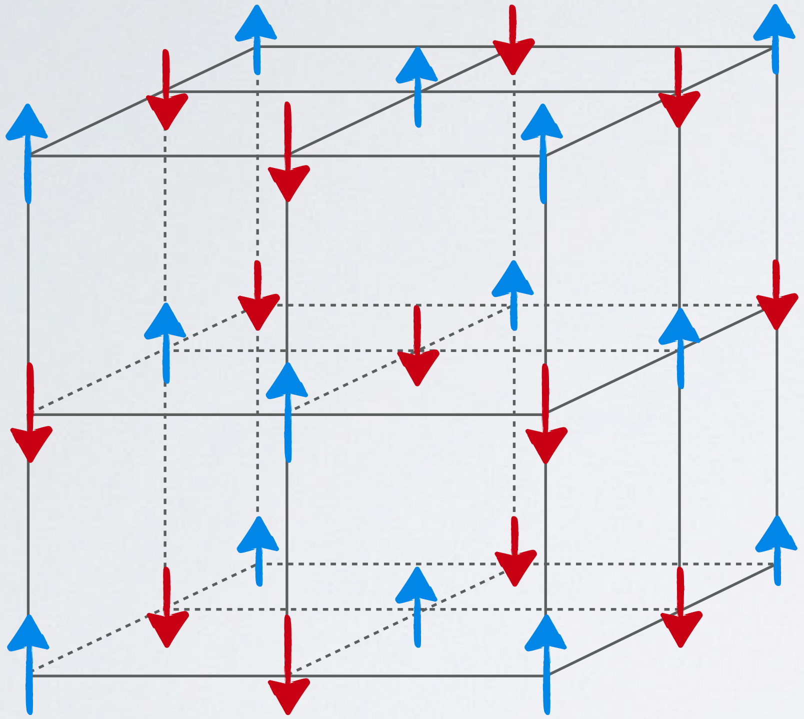


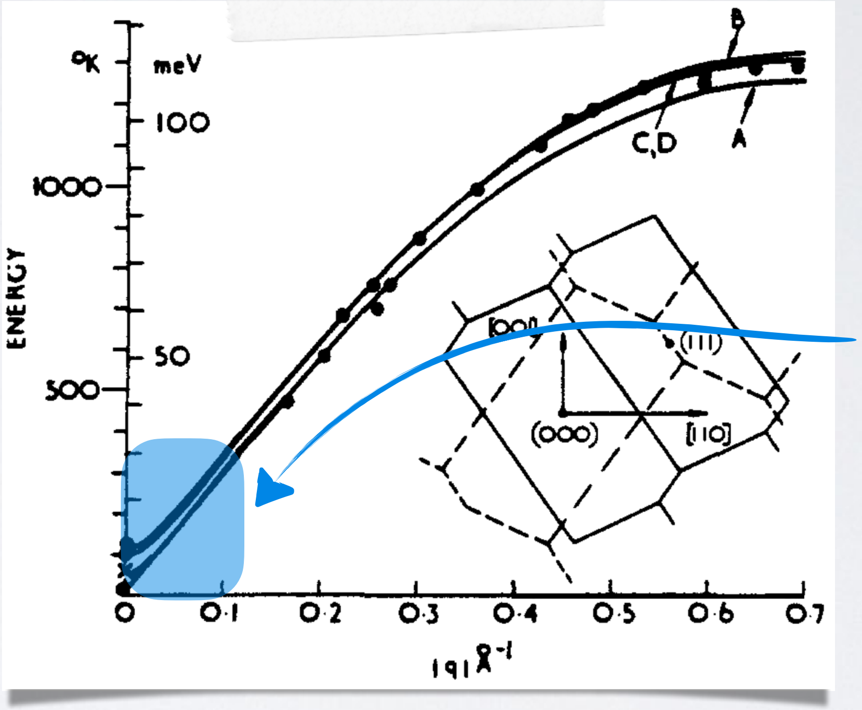


[Trickle, Zhang, Zurek — PRL 2020, 1905.13744]

# ANTI-FERROMAGNETS

- A better class of materials turns out to be anti-ferromagnets





gapless magnons have

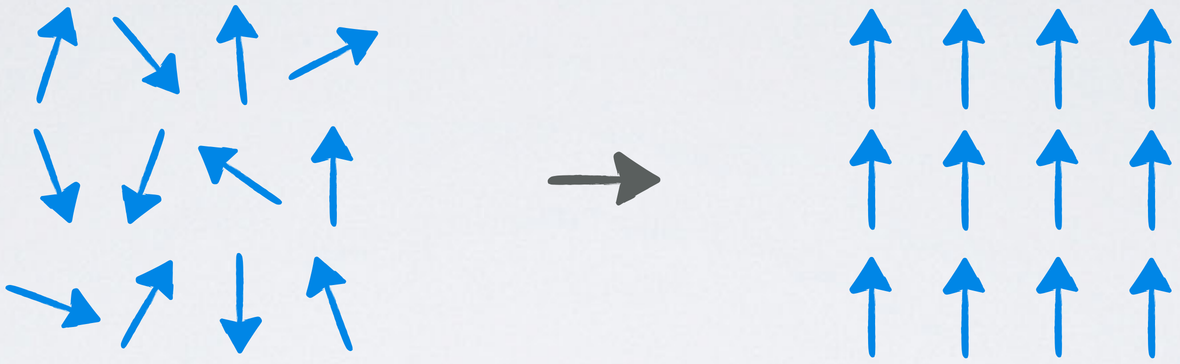
$$\omega(q) = v_\theta\, q$$

- Can always emit more than one magnon → multi-magnon emission allow to probe down to $m_\chi \sim 1$ keV
- Nickel-oxide has $v_\theta \simeq v_\chi$ → very efficient at absorbing dark matter energy

[**AE**, Pavaskar — PRD (2023), 2210.13516]

# ANTI-FERROMAGNETS

- Anti-ferromagnet spontaneously break internal spin symmetry



$SO(3)$ $SO(2)$

Gapless magnon = Goldstone

↓

from dispersion relation and neutron scattering

Write a low energy EFT: $\mathscr{L}_{EFT} = \frac{c_1}{2}\dot{\mathbf{n}}^2 - \frac{c_2}{2}(\partial_i \mathbf{n})^2$

[Pavaskar, Penco, Rothstein — SciPost Phys. (2022), 2112.13873; **AE**, Pavaskar — PRD (2023), 2210.13516]

↓

Bypass standard difficulties in computing multi-magnon processes

[Dyson — Phys. Rev. 1956]

# DM-MAGNON INTERACTION

- As for $^4$He, at low energies dark matter couples to *spin density field*
- Two benchmark models:

$$\mathscr{L}_{int}^{m.d.} \sim V_{\mu\nu}\,\bar{\chi}\sigma^{\mu\nu}\chi + V_\mu\,\bar{e}\gamma^\mu e$$

[e.g., Sigurdson et al. — PRD 2004, astro-ph/0406355; Chang, Weiner, Yavin — PRD 2010, 1007.4200]

$$\mathscr{L}_{int}^{p.m.} \sim \phi\,\bar{\chi}\chi + \phi\,\bar{e}i\gamma^5 e$$

[e.g., Banks, Fortin, Thomas — 1007.5515; Bagnasco, Dine, Thomas — PLB 1994, hep-ph/9310290]

- At low energies:

$$\mathscr{L}_{int}^{m.d.} \to \chi^\dagger\sigma^i\chi\left(\delta^{ij} - \nabla^{-2}\nabla^i\nabla^j\right)\, s_i$$

$$\mathscr{L}_{int}^{p.m.} \to \chi^\dagger\chi\nabla^{-2}\nabla\cdot\mathbf{s}$$

spin current

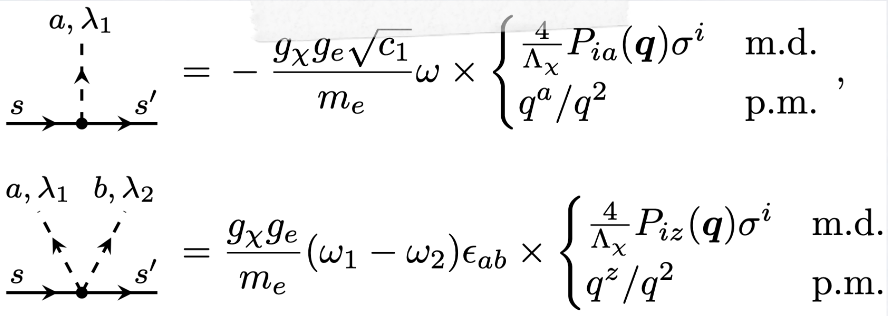
- Spin current easily obtained from EFT:

$$s_i = c_1\,(\mathbf{n}\times\dot{\mathbf{n}})_i = c_1\left(\delta_{ia}\theta^a + \delta_{i3}\epsilon_{ab}\theta^a\dot{\theta}^b + \dots\right)$$

# IDEAL REACH

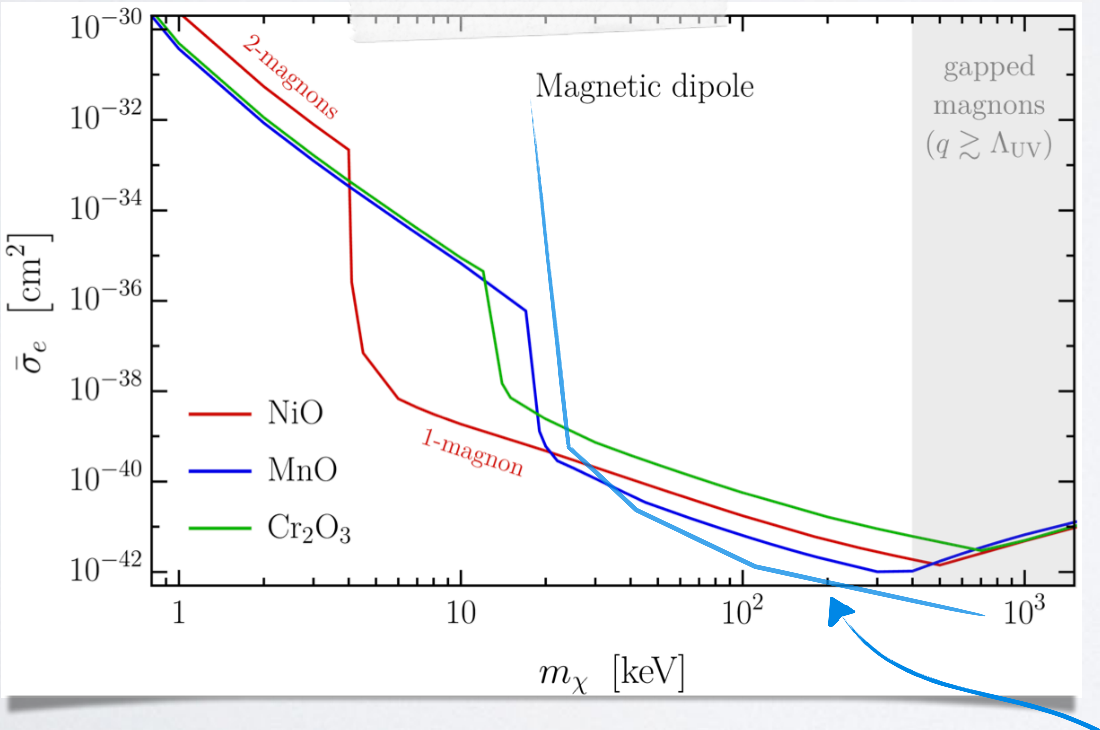
- Just like before, use standard QFT methods to compute event rates

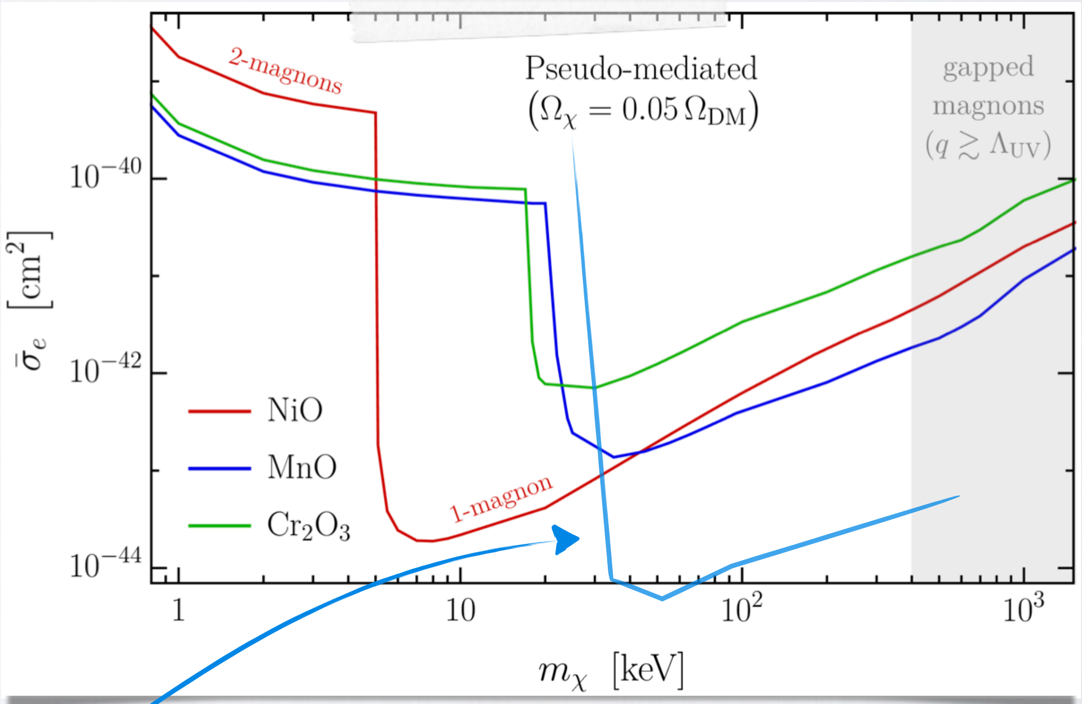
`[AE, Pavaskar — PRD (2023), 2210.13516]`



$$= -\frac{g_\chi g_e \sqrt{c_1}}{m_e}\omega \times \begin{cases} \frac{4}{\Lambda_\chi} P_{ia}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^a/q^2 & \text{p.m.} \end{cases},$$

$$= \frac{g_\chi g_e}{m_e}(\omega_1 - \omega_2)\epsilon_{ab} \times \begin{cases} \frac{4}{\Lambda_\chi} P_{iz}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^z/q^2 & \text{p.m.} \end{cases}$$





ferromagnets

# OUTLOOK

- The search for sub-MeV dark matter requires new ideas
- One must delve in the condensed matter world
- Very active field with plenty of exciting ideas
- Plethora of condensed matter phenomena can be an asset… but we must find a way of efficiently incorporating it in the particle physics language
- A lot of work left to do!

Thank you for the attention!