NEW FRONTIERS IN SUB-MEV DARK MATTER SEARCHES

Angelo Esposito

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

"The low-energy frontier of particle physics", LNF Feb. 11th 2025

SUB-MEV DARK MATTER

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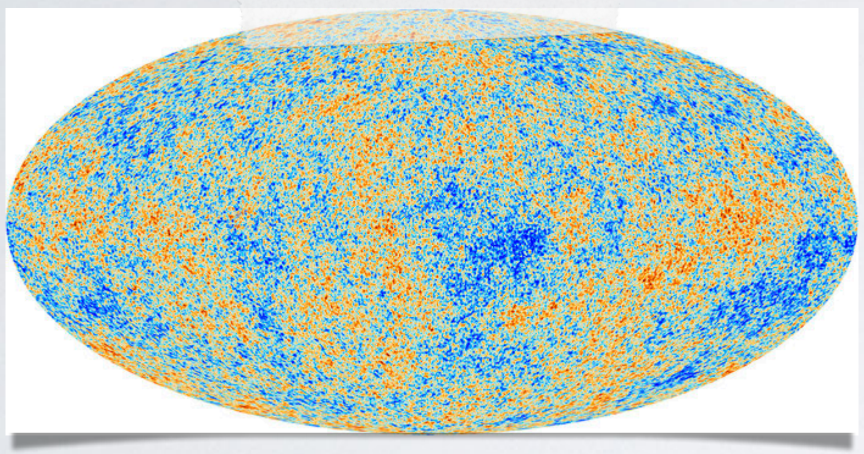

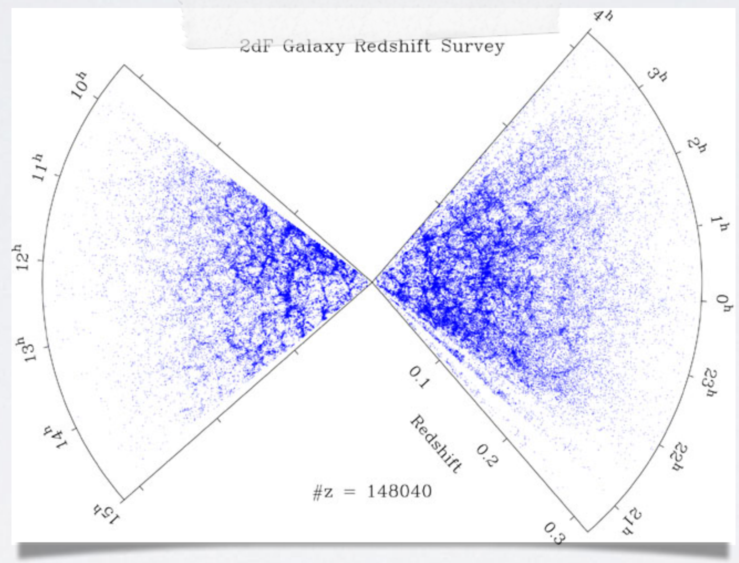

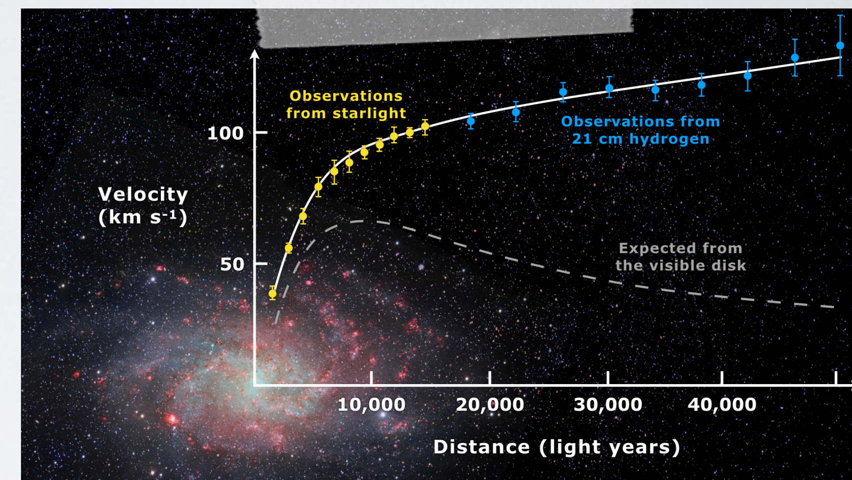

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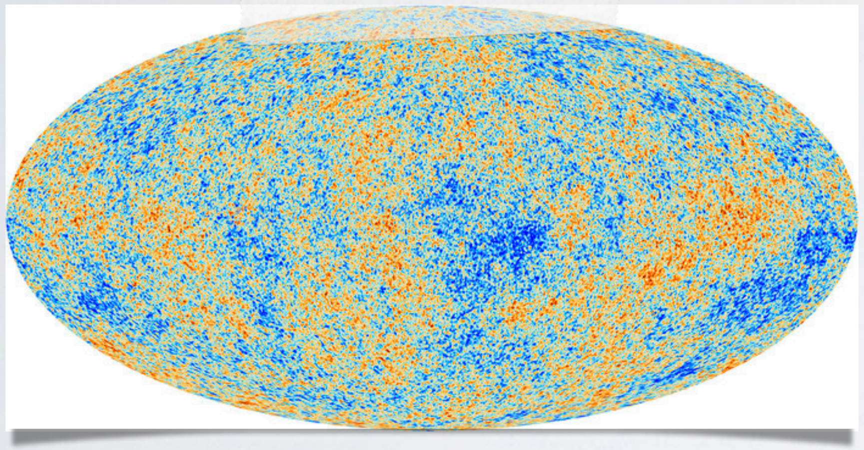

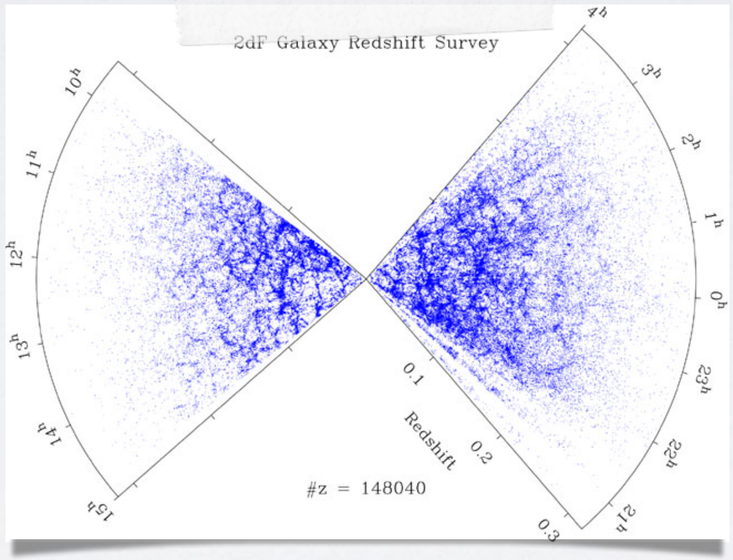

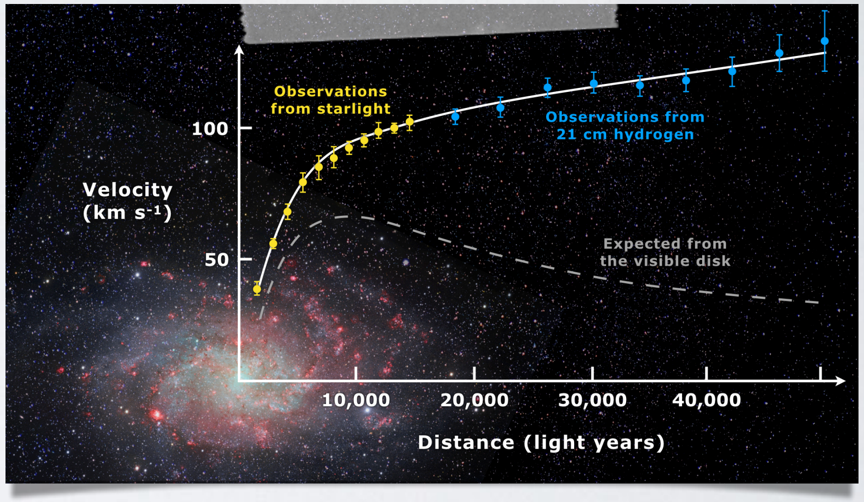

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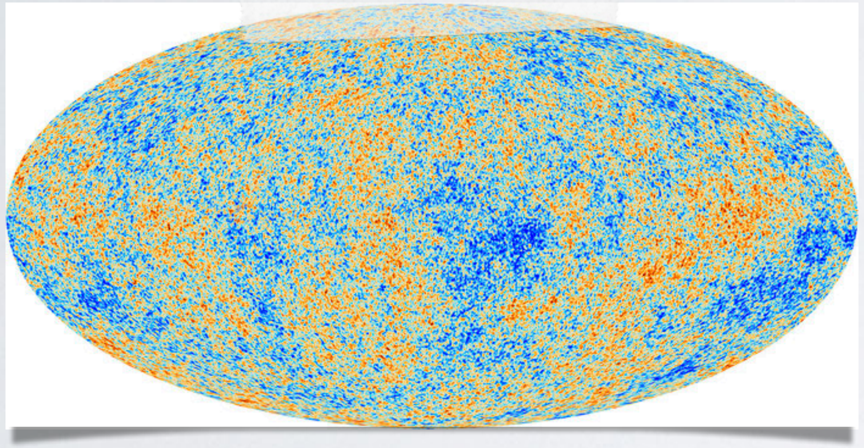

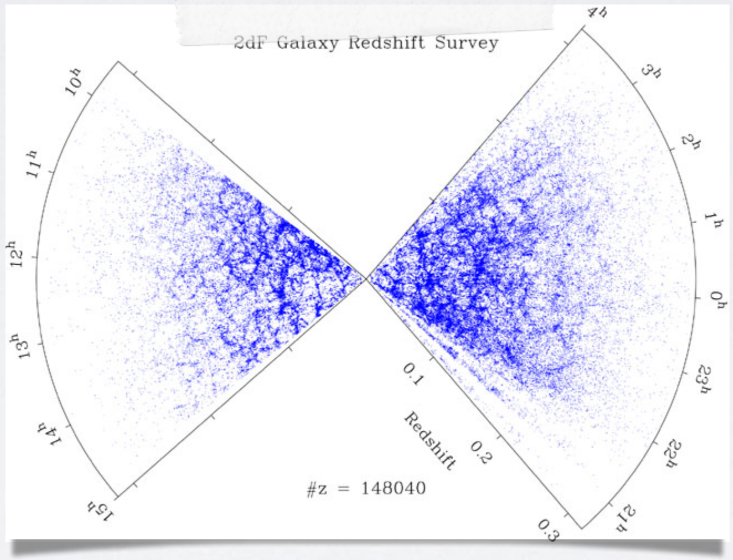

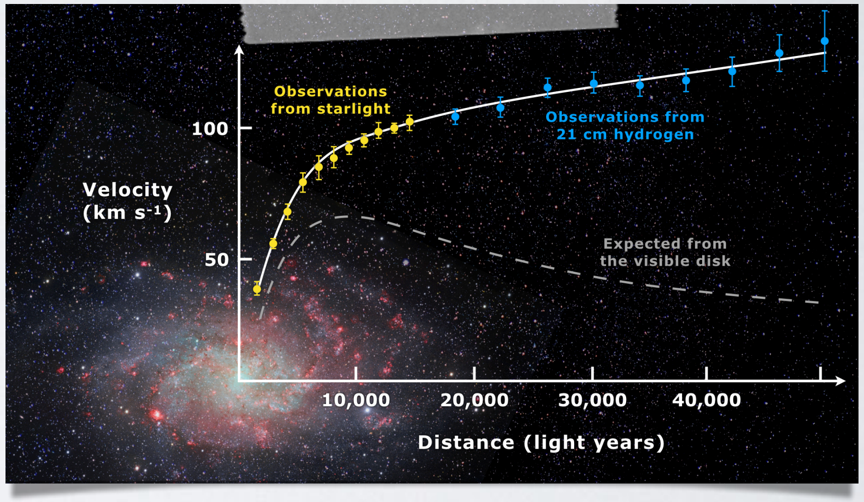

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- However… huge possible mass range → detection techniques vary widely depending on the dark matter mass

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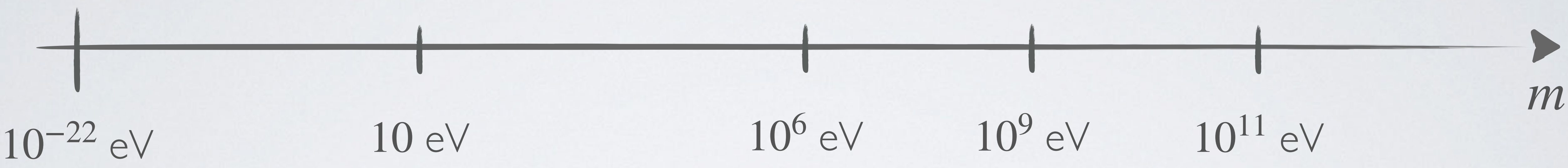

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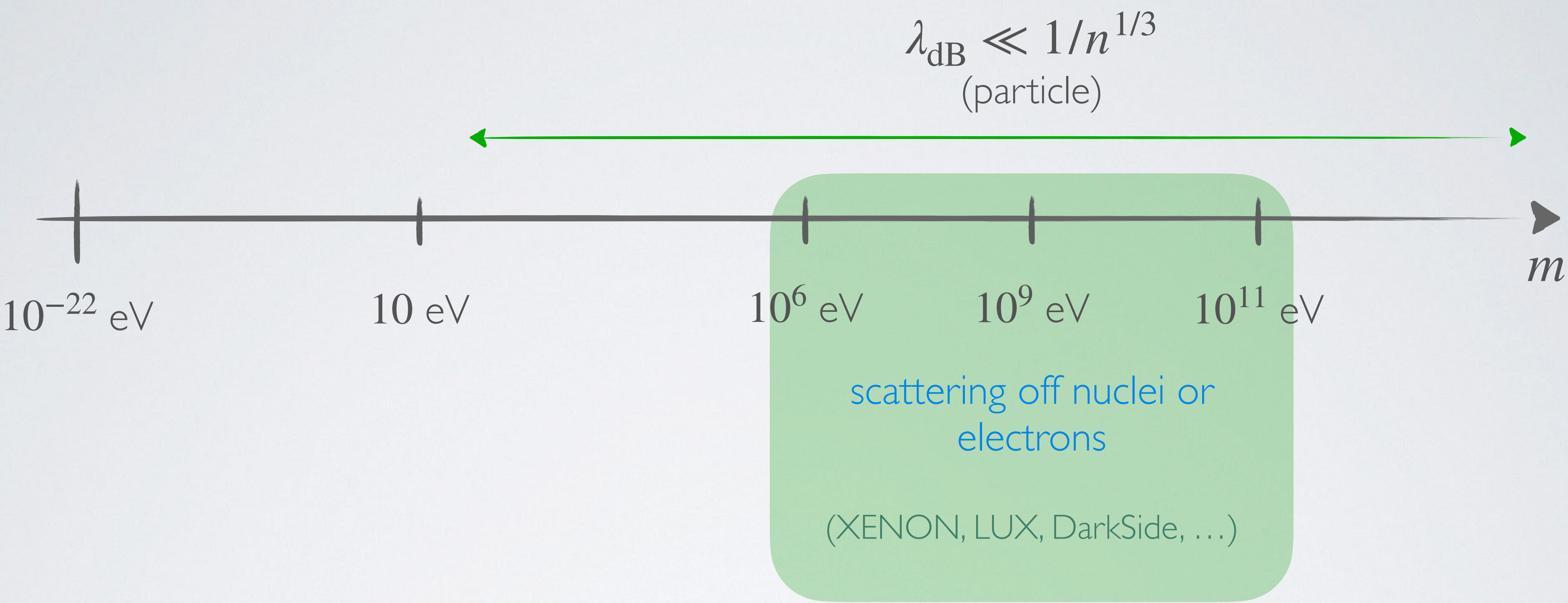

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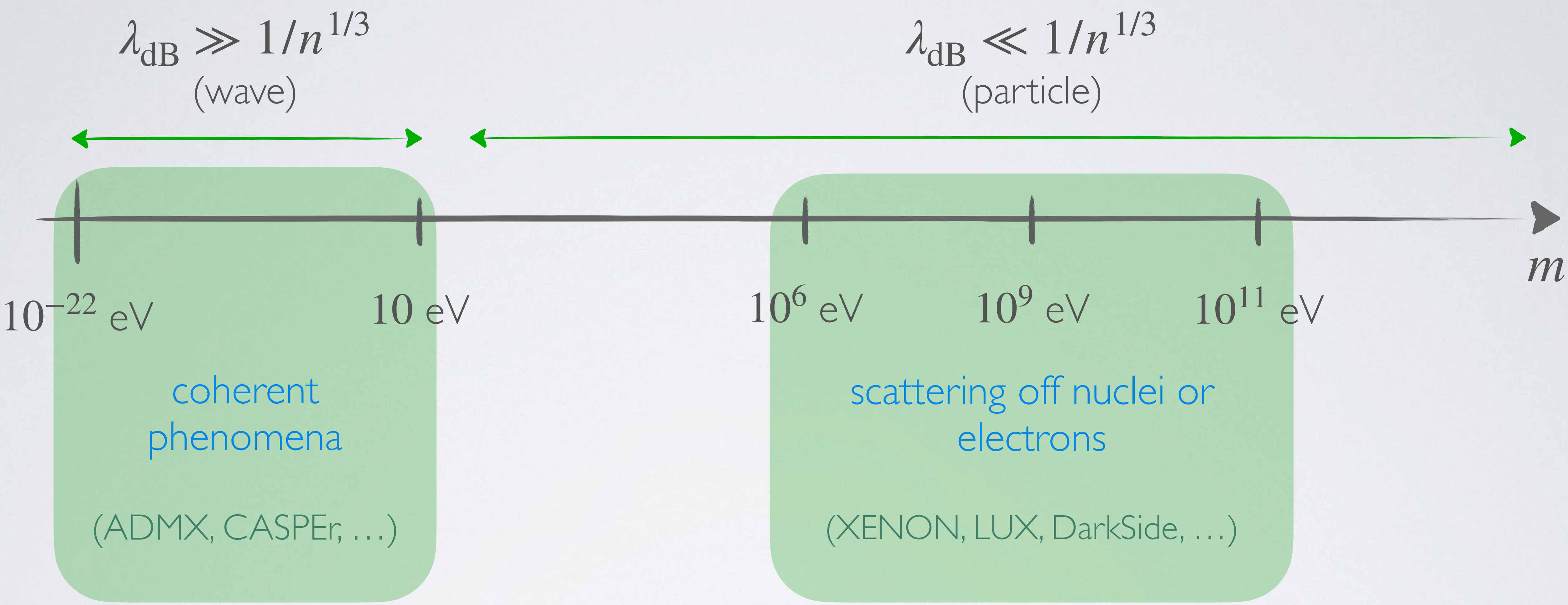

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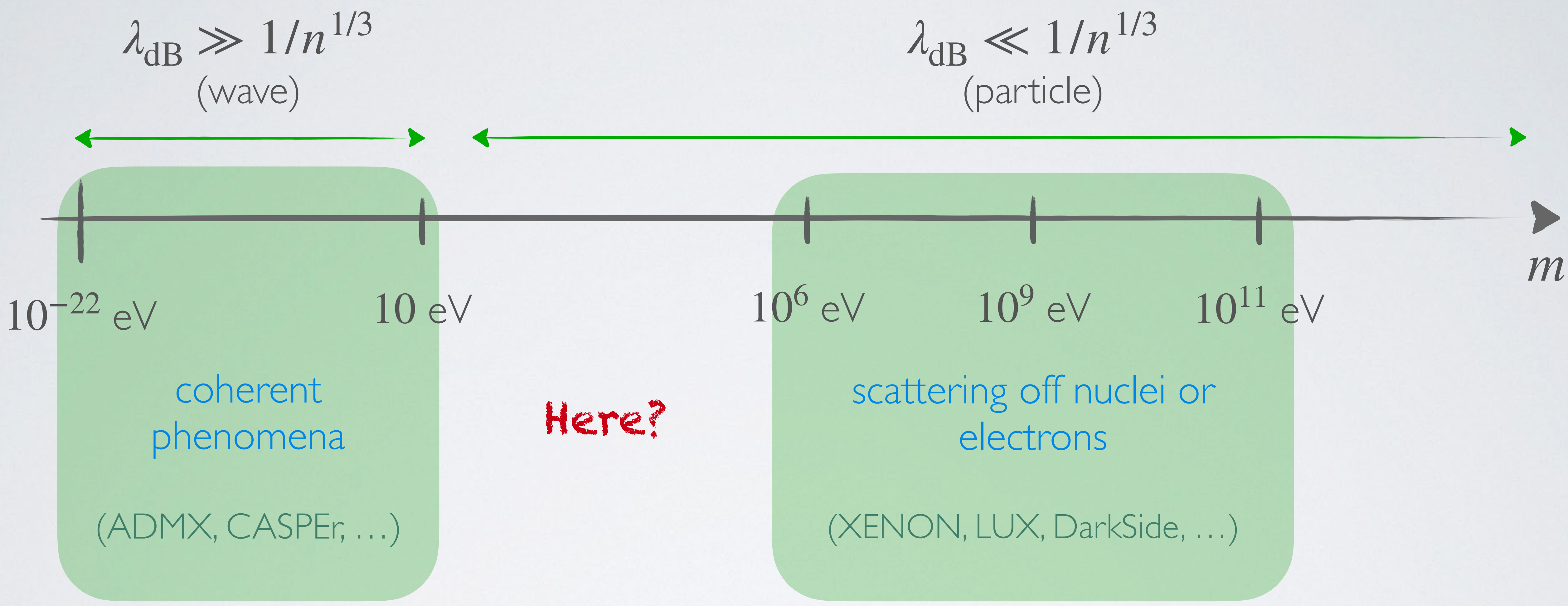

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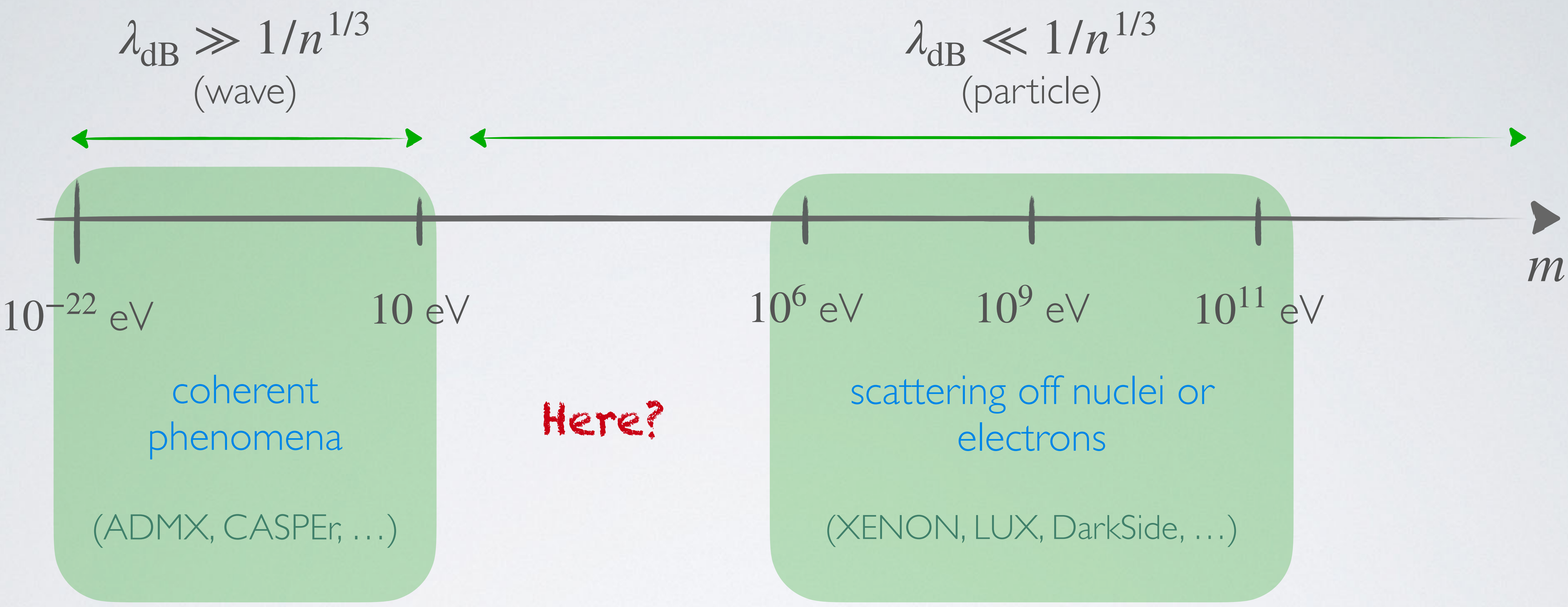

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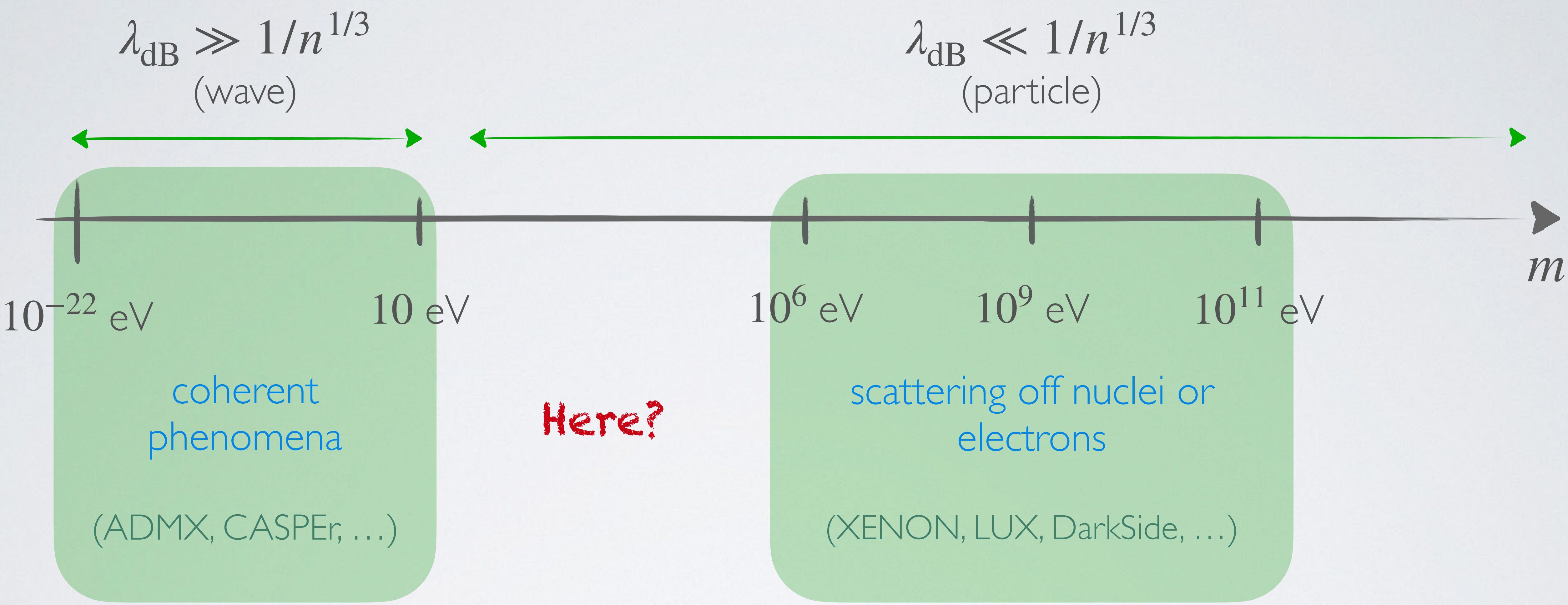

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- Need new materials and/or observables

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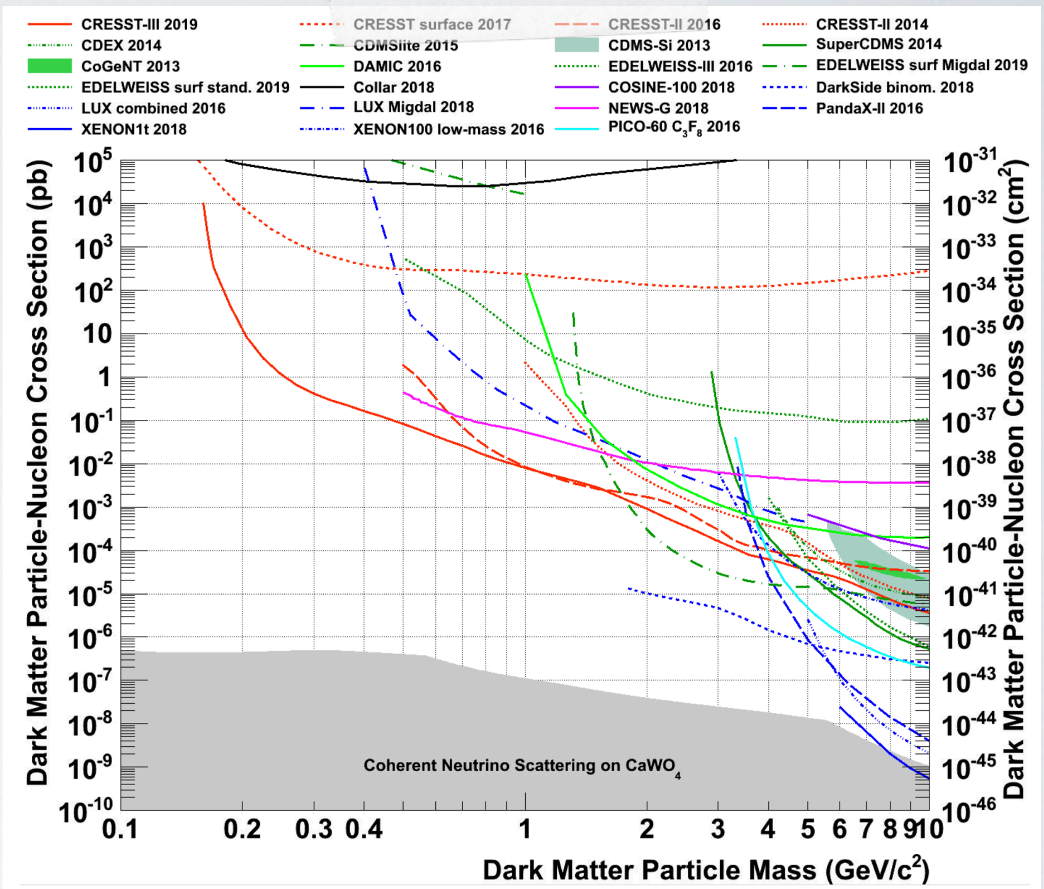

[CRESST — PRD 2019, 1904.00498]

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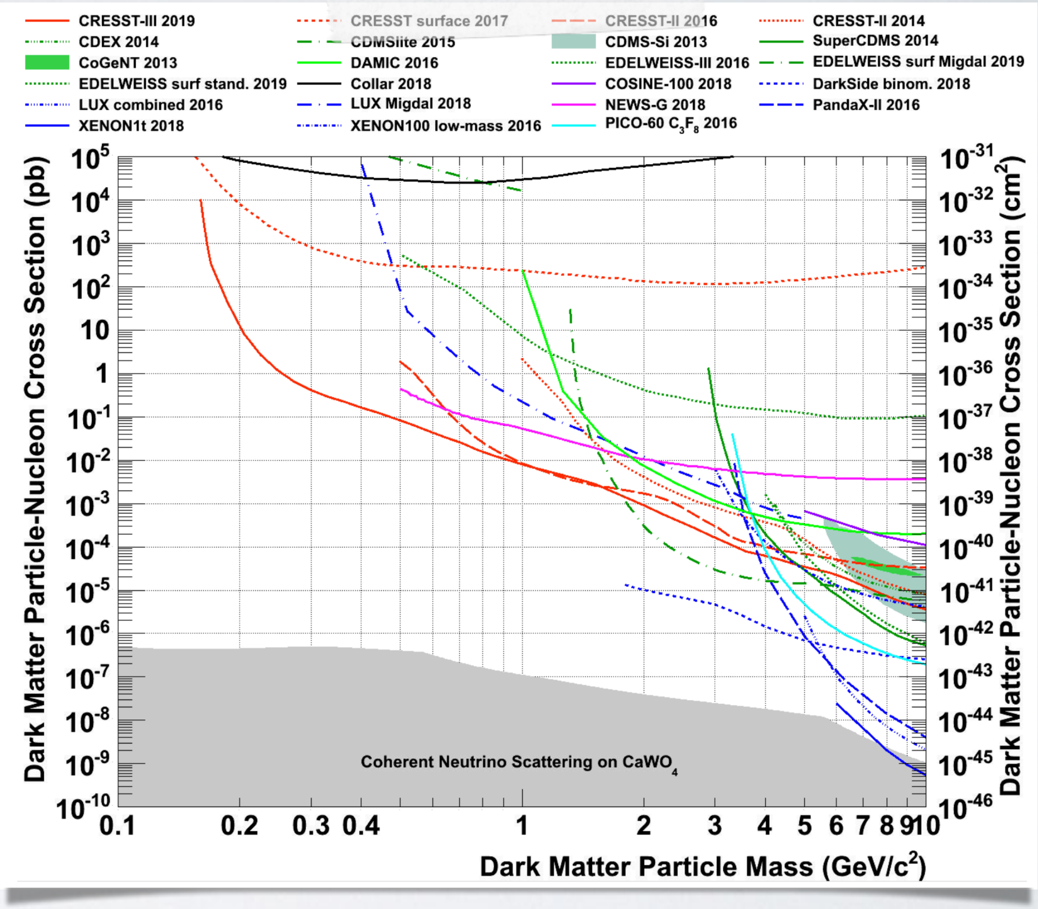

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- To evade this we must look into inelastic processes $\rightarrow$ one possibility are collective excitations

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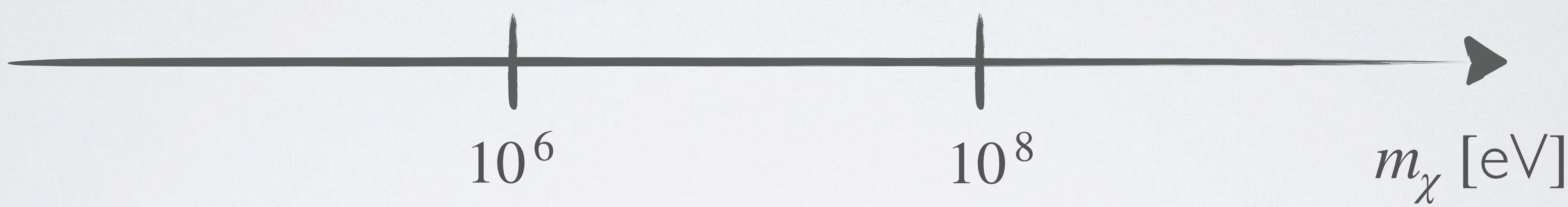

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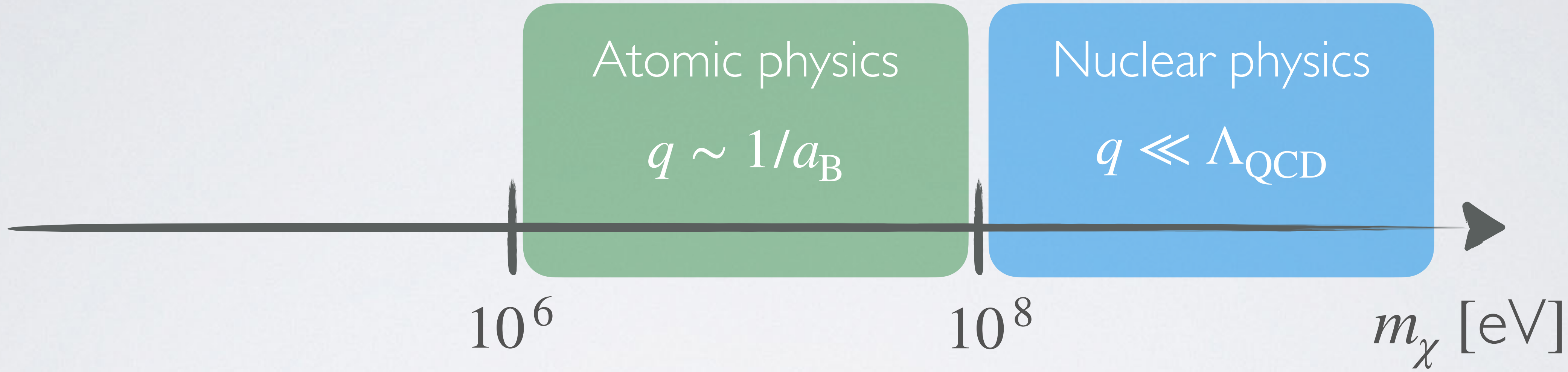

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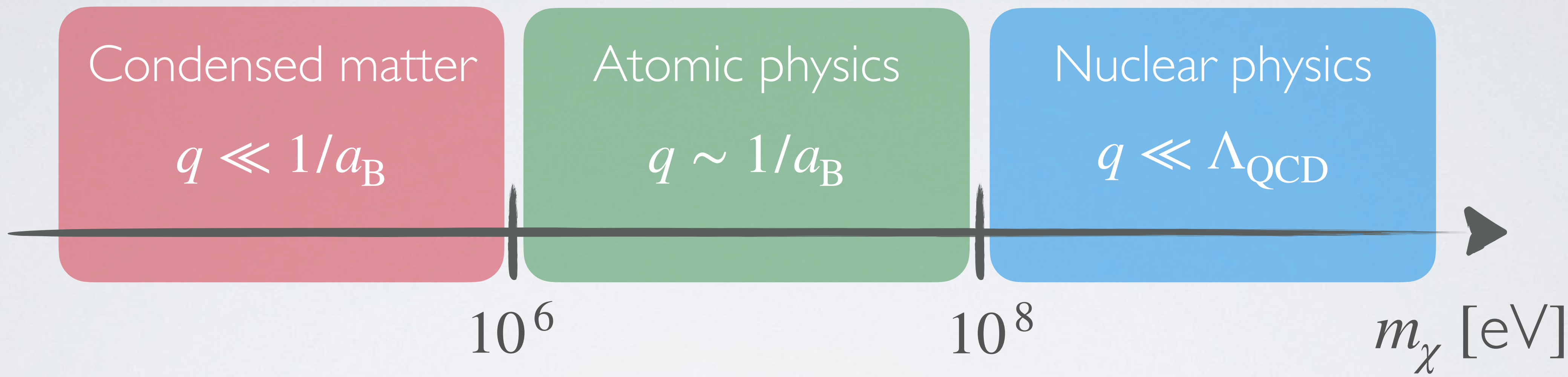

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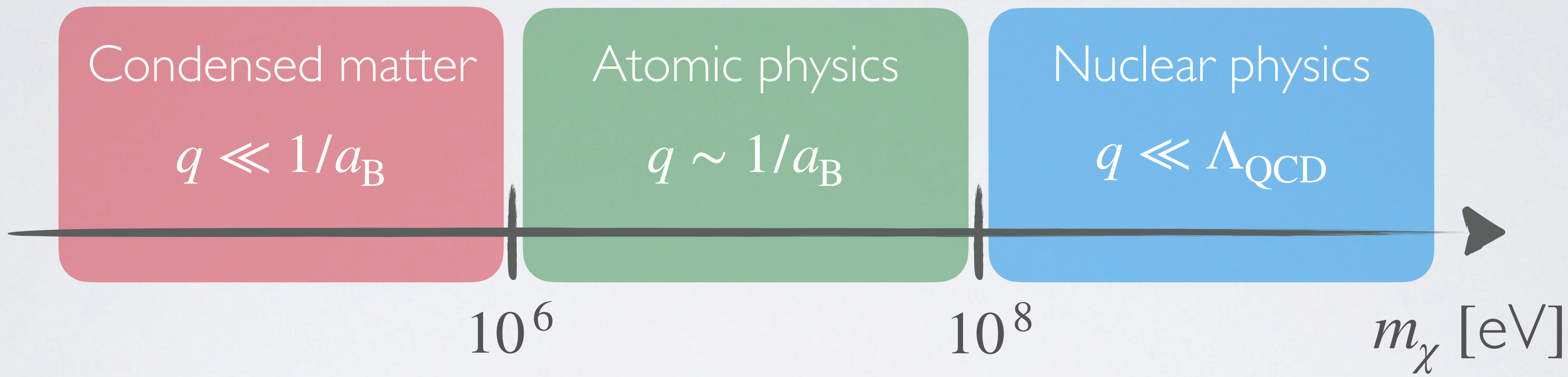

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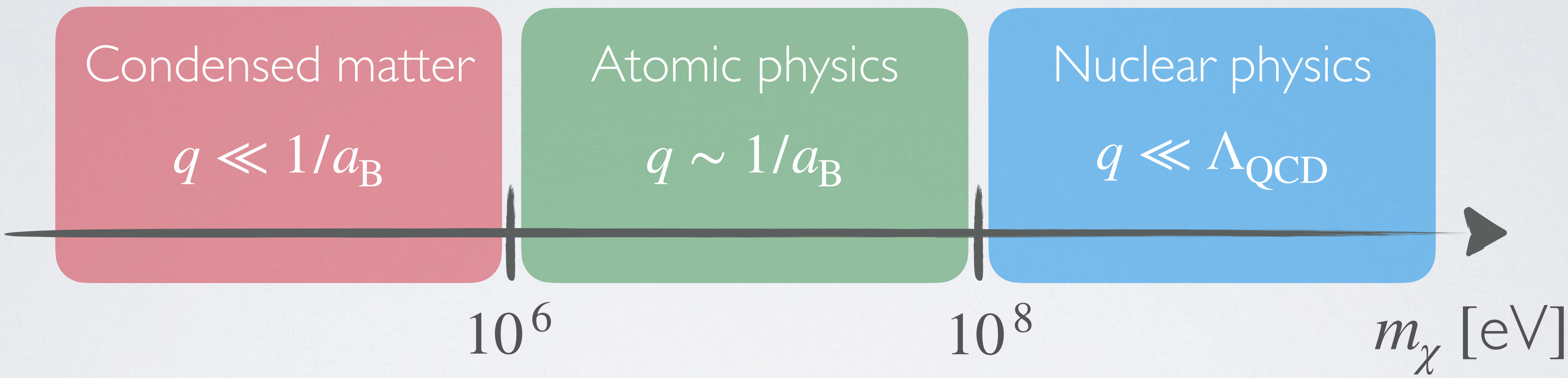

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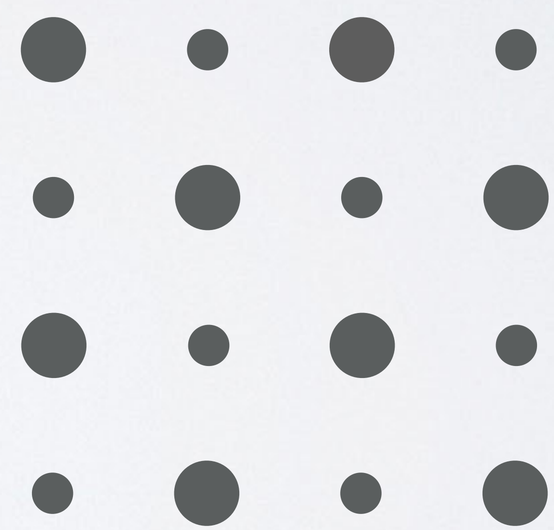

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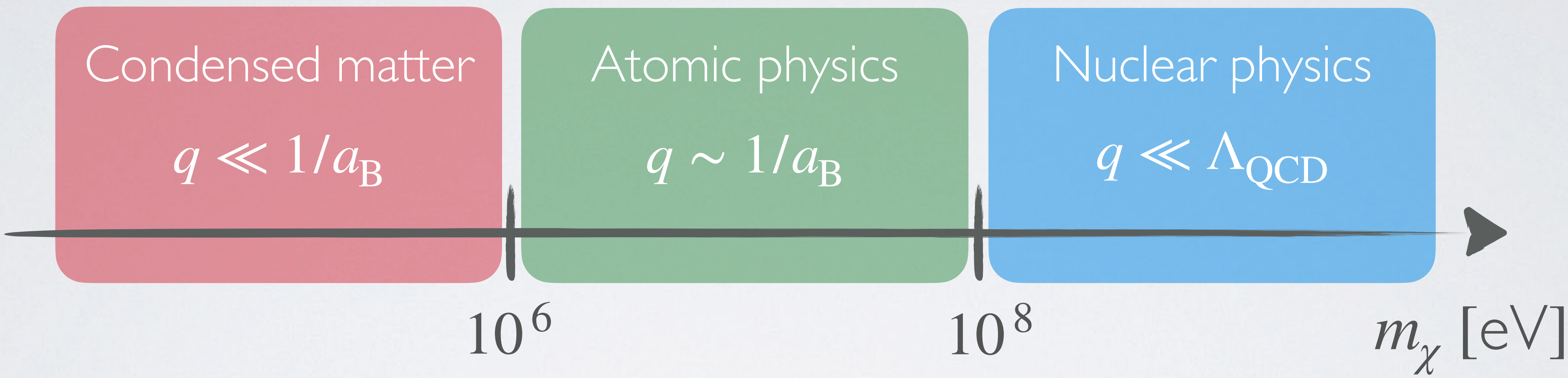

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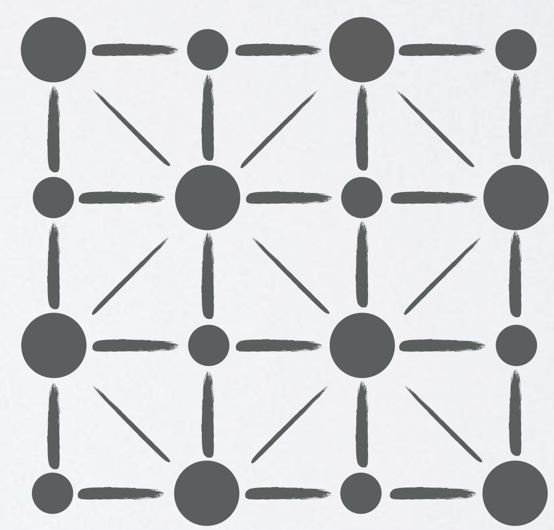

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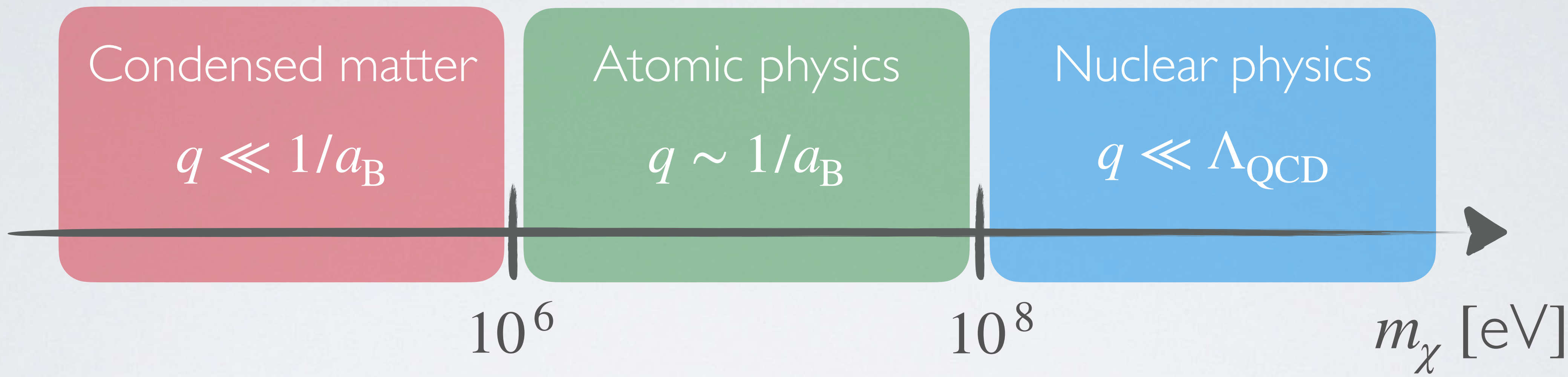

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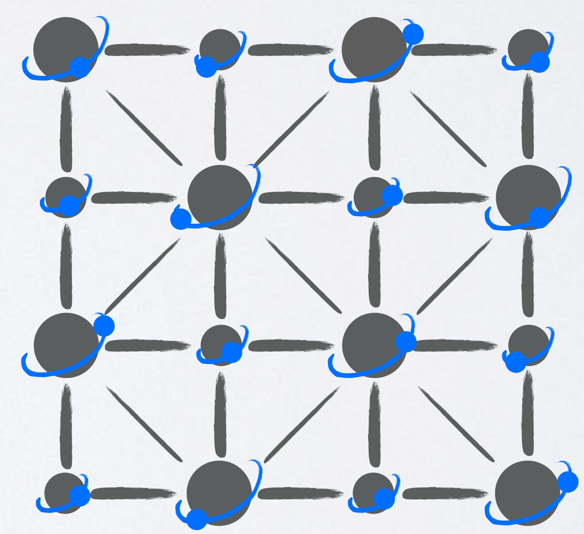

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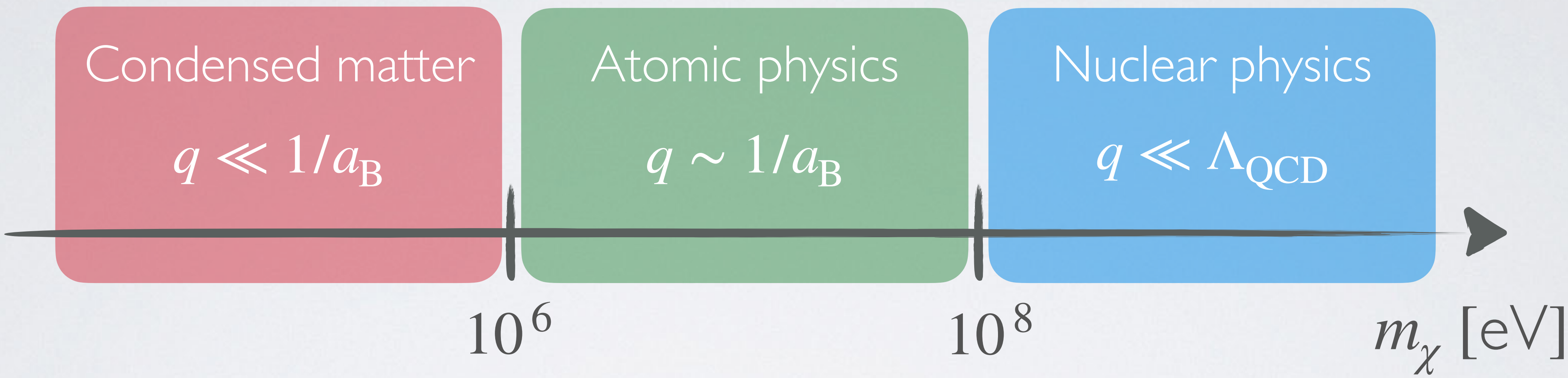

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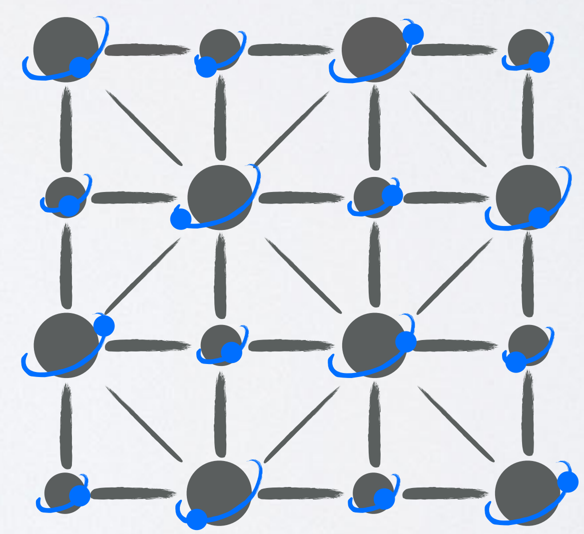

- Need theoretical tools that allow to solve or bypass these problems

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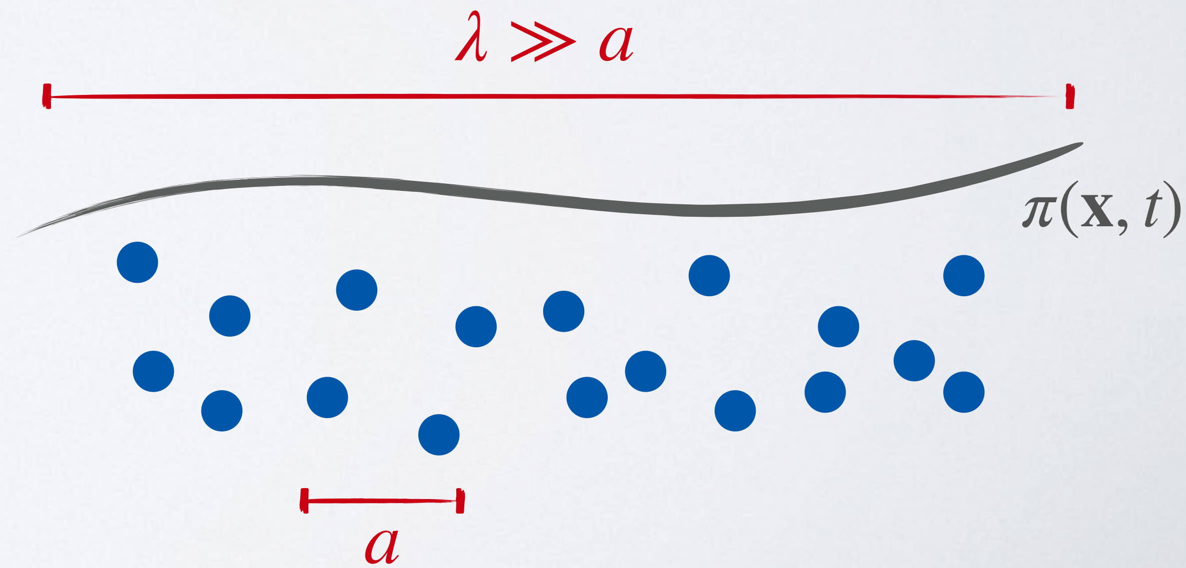

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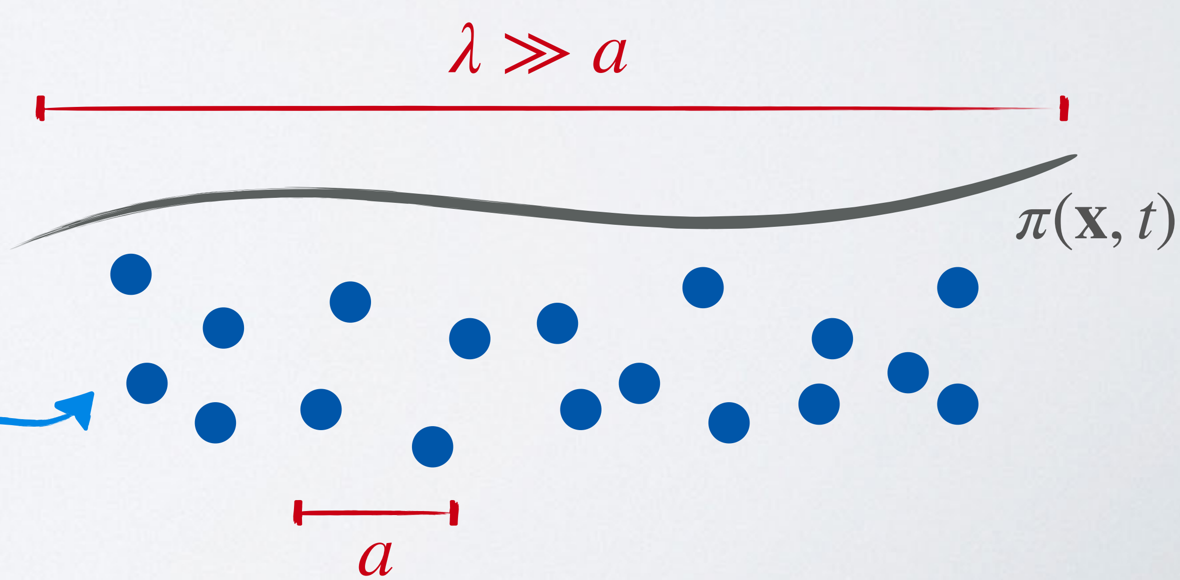
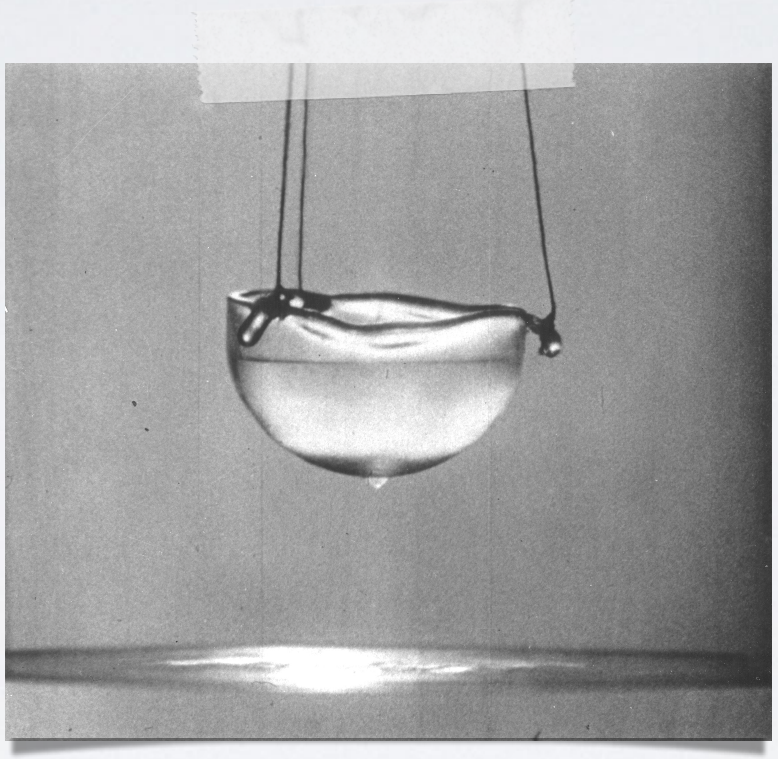


Spin-independent interactions: superfluid ^{4}He



[w/ Acanforo, Caputo, Geoffray, Piccinini, Polosa, Rossi, Sun]

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[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]

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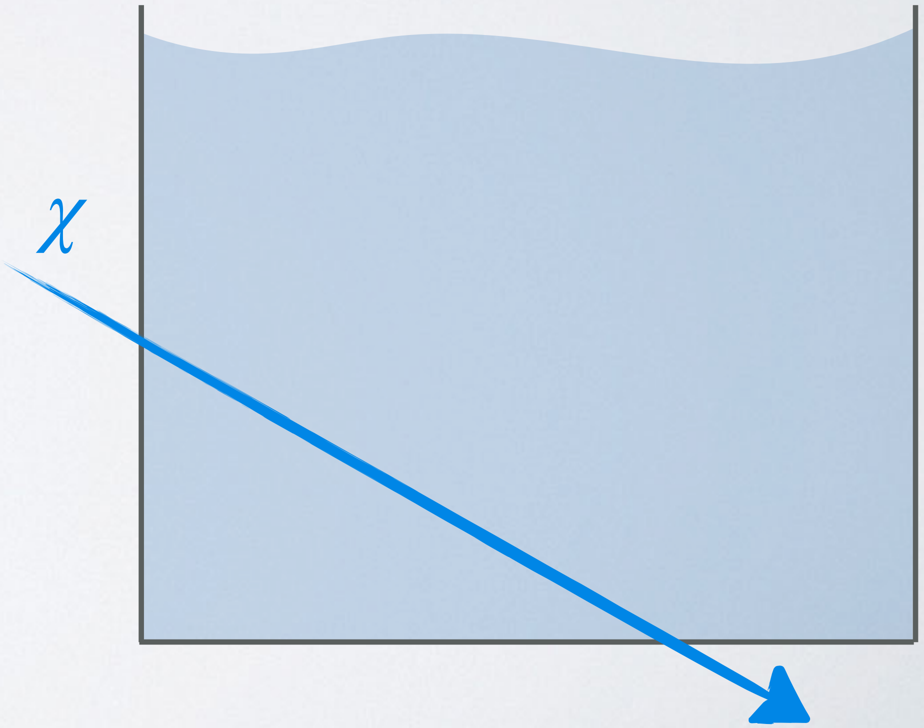

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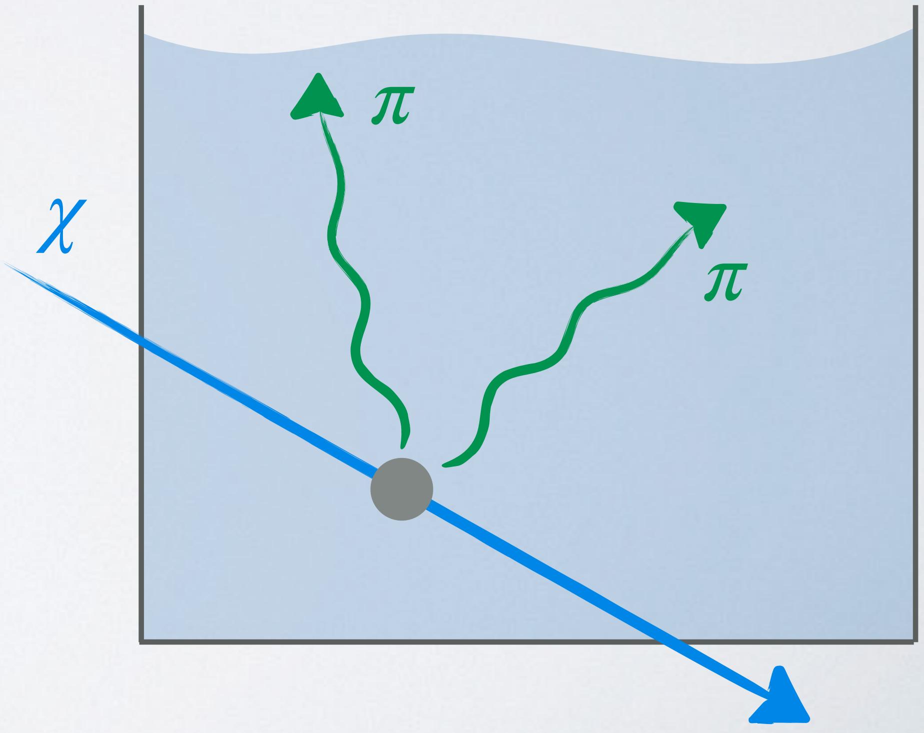

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- Not enough modes to lose energy/momentum into

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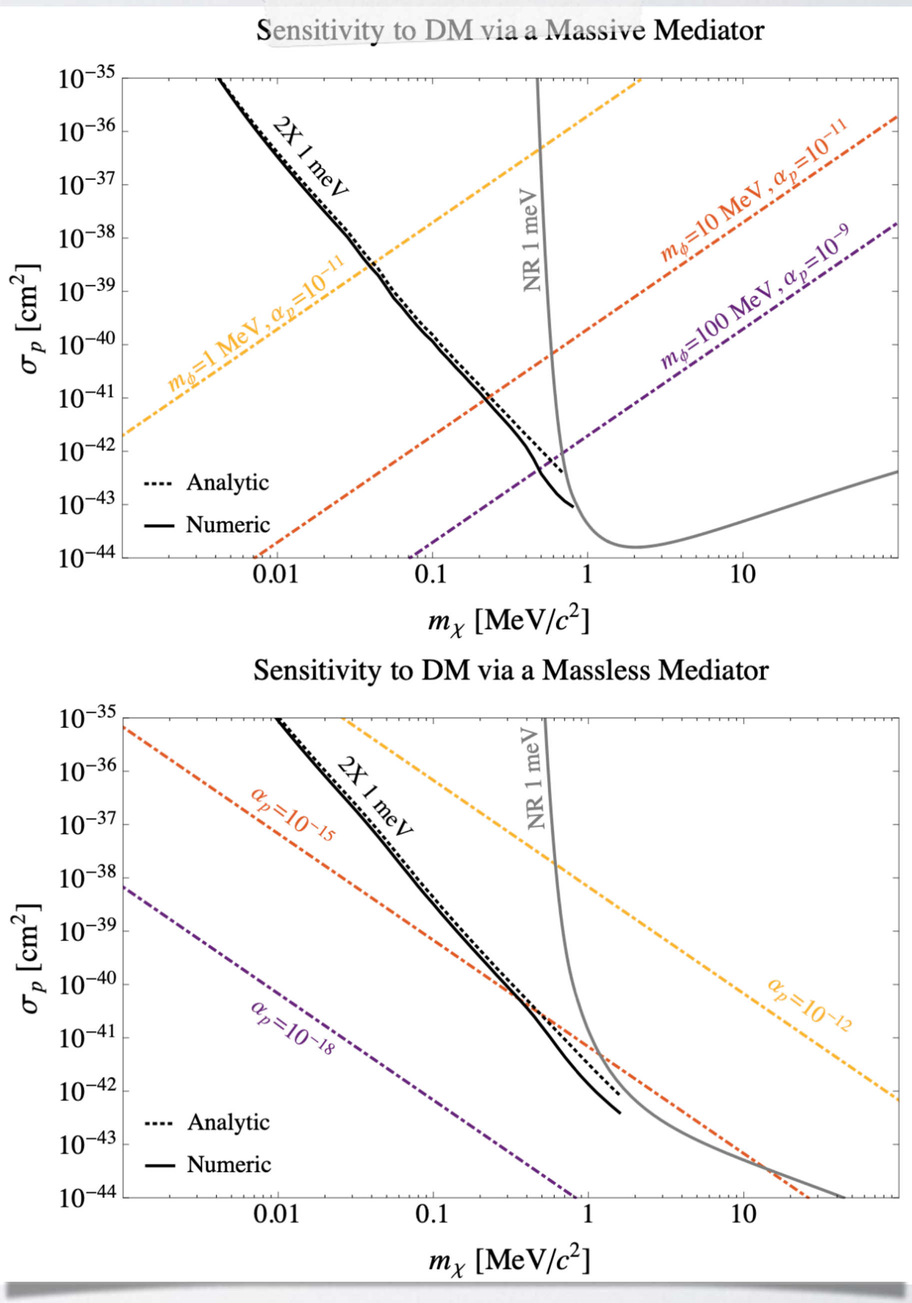

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$$\mathscr{L}_{\rm EFT} \sim \dot{\pi}^2 - c_s^2\left(\nabla\pi\right)^2 + \lambda\dot{\pi}\left(\nabla\pi\right)^2 + \lambda'\dot{\pi}^3 + \ldots$$

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

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

$$\mathscr{L}_{\rm EFT} \sim \dot{\pi}^2 - c_s^2 \left(\nabla\pi\right)^2 + \lambda\dot{\pi}\left(\nabla\pi\right)^2 + \lambda'\dot{\pi}^3 + \dots$$

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

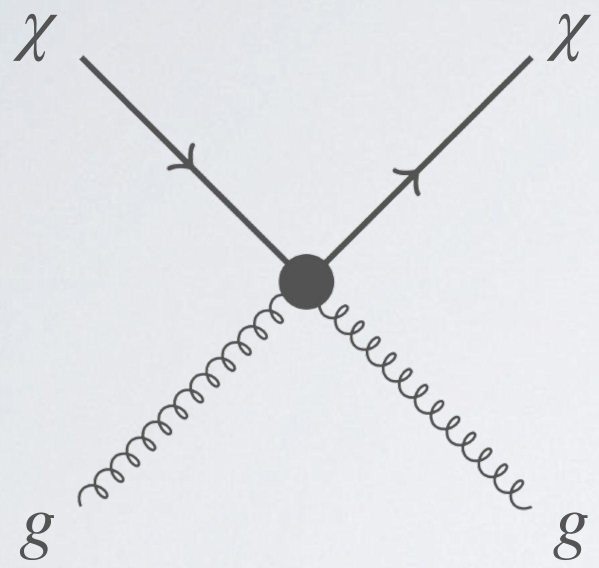
effective coefficients are given by the equation of state:

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

DM-PHONON INTERACTION

DM-PHONON INTERACTION

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



$$\mathscr{L}_{\text{int}} \sim |\chi|^2 \, \mathrm{tr}\, G_{\mu\nu} G^{\mu\nu}$$

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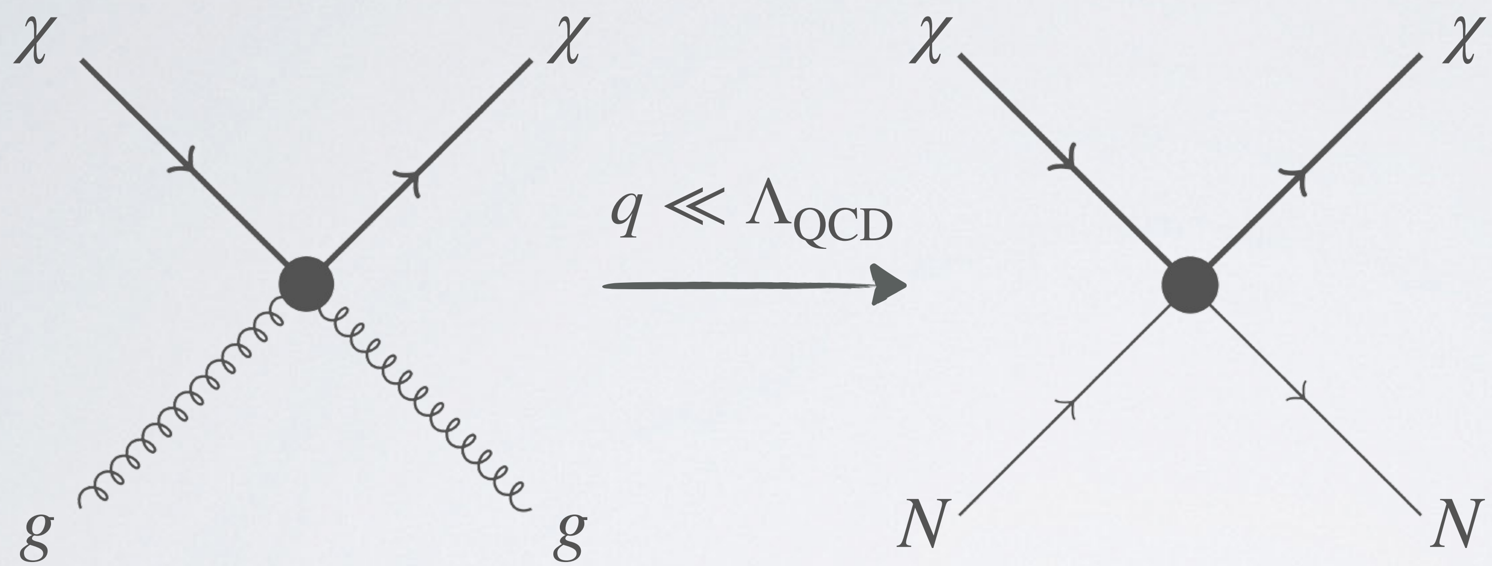

$\mathscr{L}_{\rm int} \sim |\chi|^2 \, \mathrm{tr}\, G_{\mu\nu} G^{\mu\nu}$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2 \, \bar{N} N$

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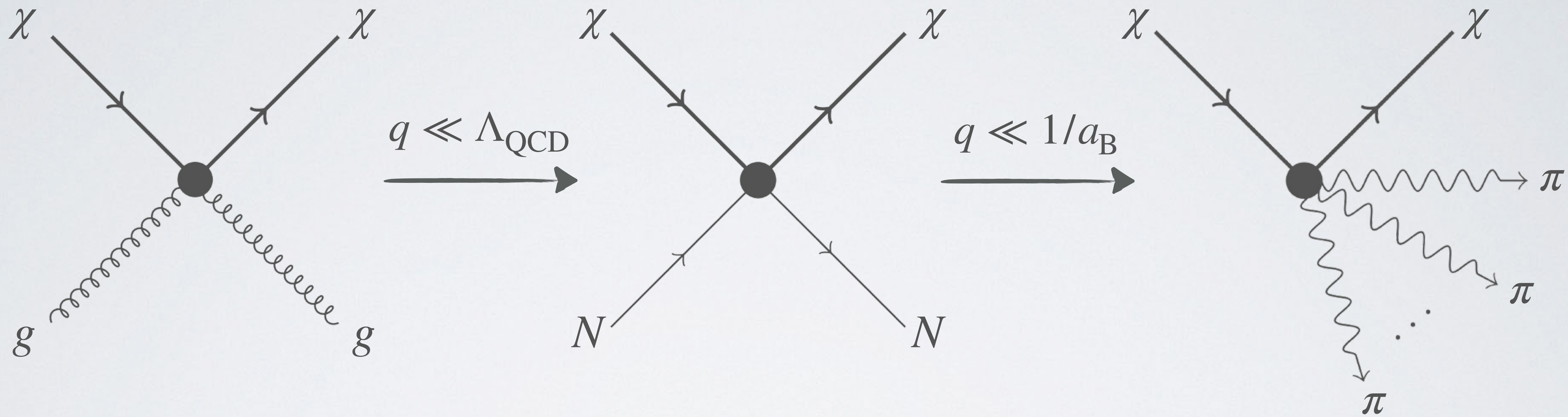

$\mathscr{L}_{\rm int} \sim |\chi|^2 \, {\rm tr}\, G_{\mu\nu} G^{\mu\nu}$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2 \bar{N} N$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2 \, n(\pi)$

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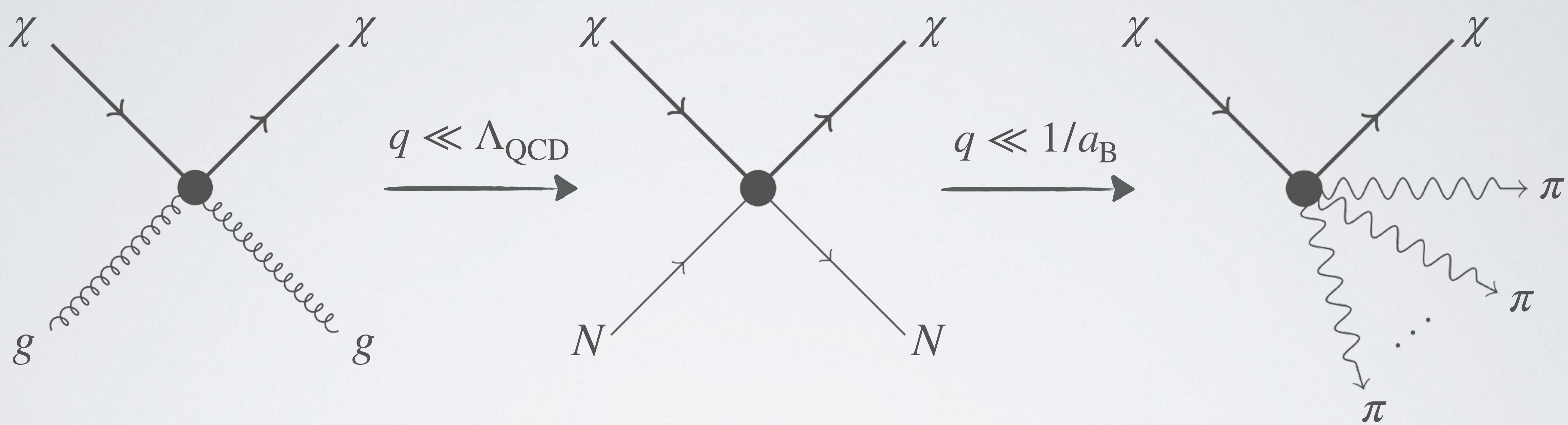

$\mathscr{L}_{\rm int} \sim |\chi|^2 \, {\rm tr}\, G_{\mu\nu} G^{\mu\nu}$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2 \bar{N} N$ $\qquad$ $\mathscr{L}_{\rm int} \sim |\chi|^2 n(\pi)$

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

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

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

IDEAL REACH

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

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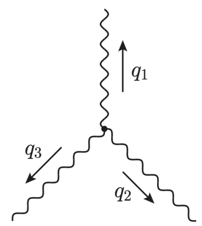
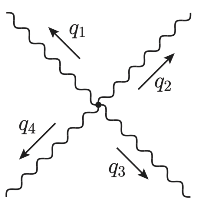
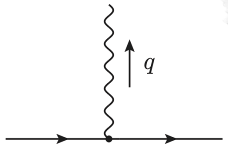


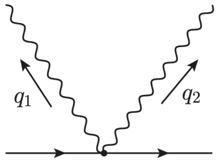
$$= g_1 \big(\omega_1\, \boldsymbol{q}_2 \cdot \boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1 \cdot \boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1 \cdot \boldsymbol{q}_2\big) + g_2\, \omega_1\, \omega_2\, \omega_3\,,$$



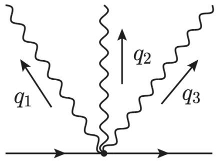
$$\begin{aligned} = i\lambda_1 \big(&\boldsymbol{q}_1 \cdot \boldsymbol{q}_2\, \boldsymbol{q}_3 \cdot \boldsymbol{q}_4 + \boldsymbol{q}_1 \cdot \boldsymbol{q}_3\, \boldsymbol{q}_2 \cdot \boldsymbol{q}_4 \\ &+ \boldsymbol{q}_1 \cdot \boldsymbol{q}_4\, \boldsymbol{q}_2 \cdot \boldsymbol{q}_3\big) \\ +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



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



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



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

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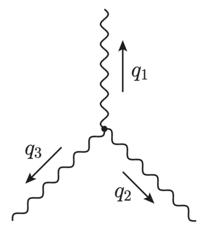
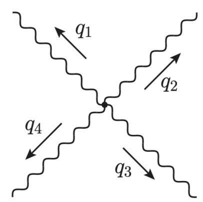
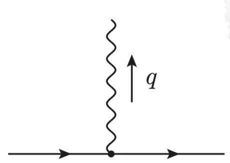


$$= g_1\left(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\right) + g_2\,\omega_1\,\omega_2\,\omega_3\,,$$



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



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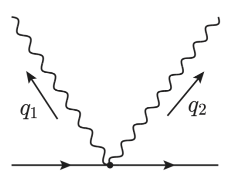
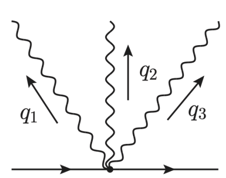
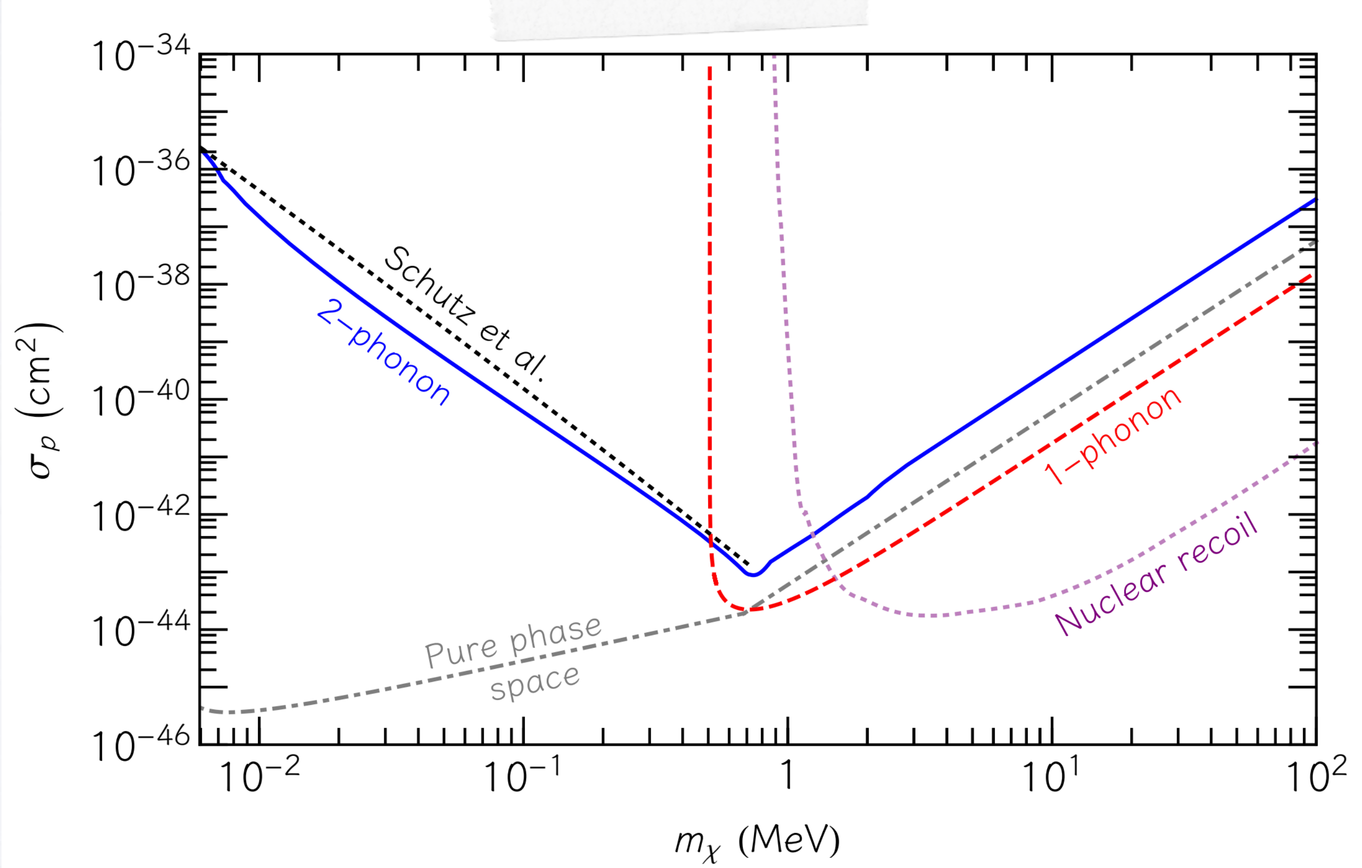


$$= iG_\chi m_\chi\left(\beta_1 \boldsymbol{q}_1\cdot\boldsymbol{q}_2 + \beta_2\omega_1\,\omega_2\right)\,,$$



$$= G_\chi m_\chi\left[\gamma_1\left(\omega_1\,\boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\,\boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\,\boldsymbol{q}_1\cdot\boldsymbol{q}_2\right) + \gamma_2\,\omega_1\,\omega_2\,\omega_3\right].$$



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

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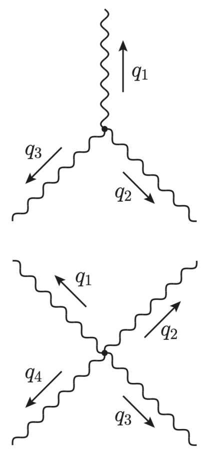
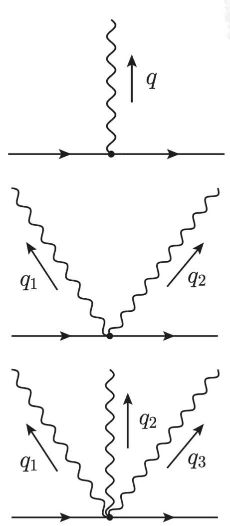


$$= g_1\big(\omega_1\, \boldsymbol{q}_2\cdot\boldsymbol{q}_3 + \omega_2\, \boldsymbol{q}_1\cdot\boldsymbol{q}_3 + \omega_3\, \boldsymbol{q}_1\cdot\boldsymbol{q}_2\big) + g_2\,\omega_1\,\omega_2\,\omega_3\,,$$

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

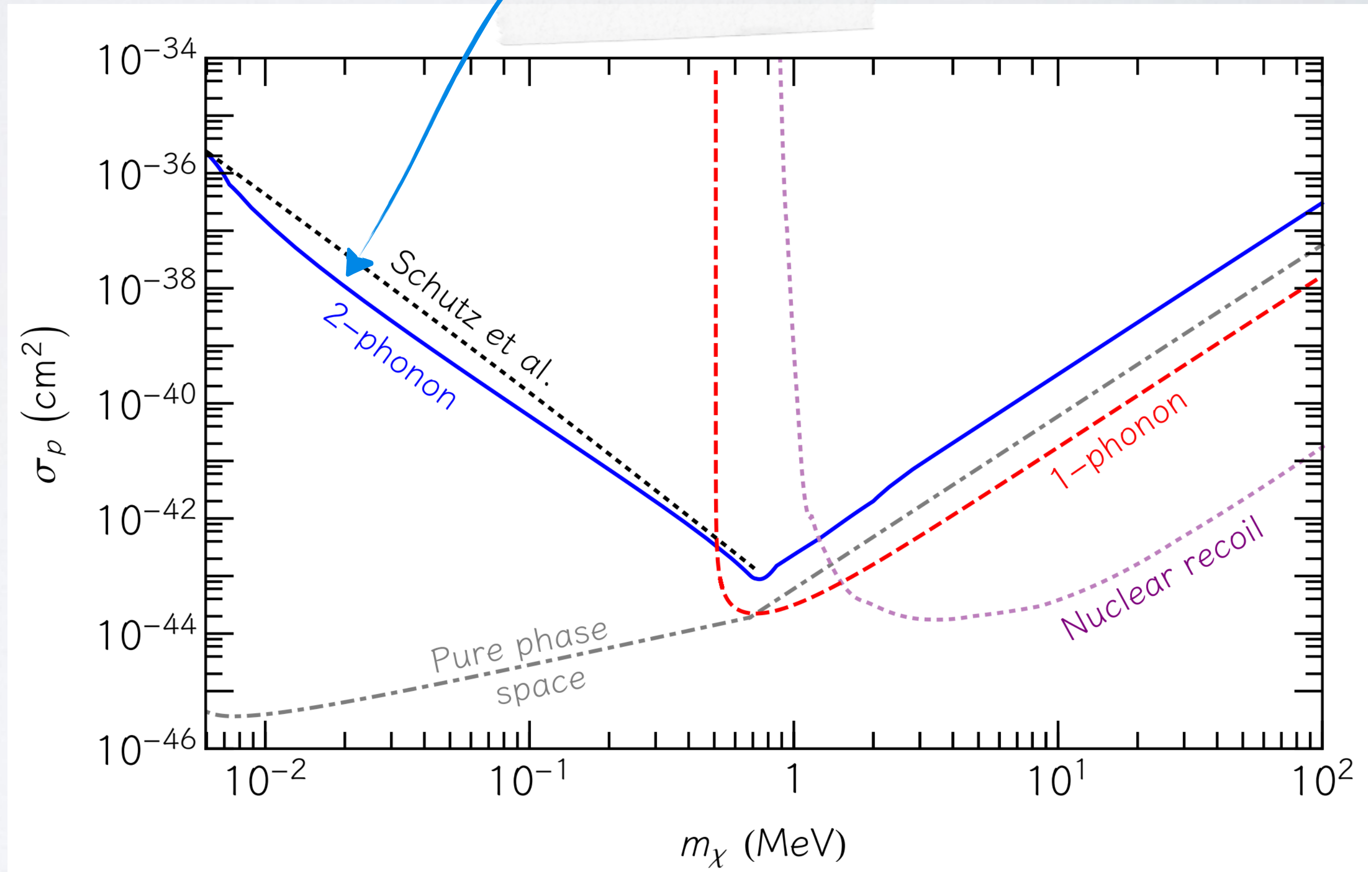


$$= G_\chi m_\chi \alpha\,\omega\,,$$

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

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

revise results obtained with traditional methods



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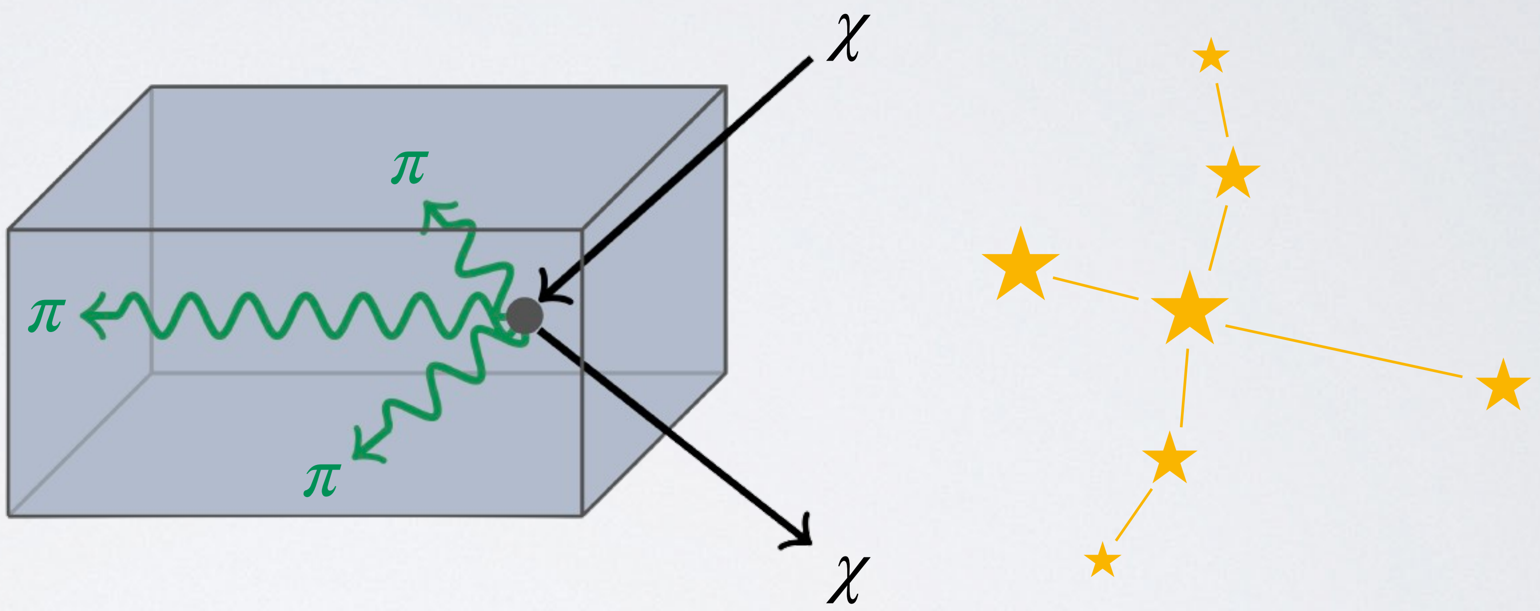

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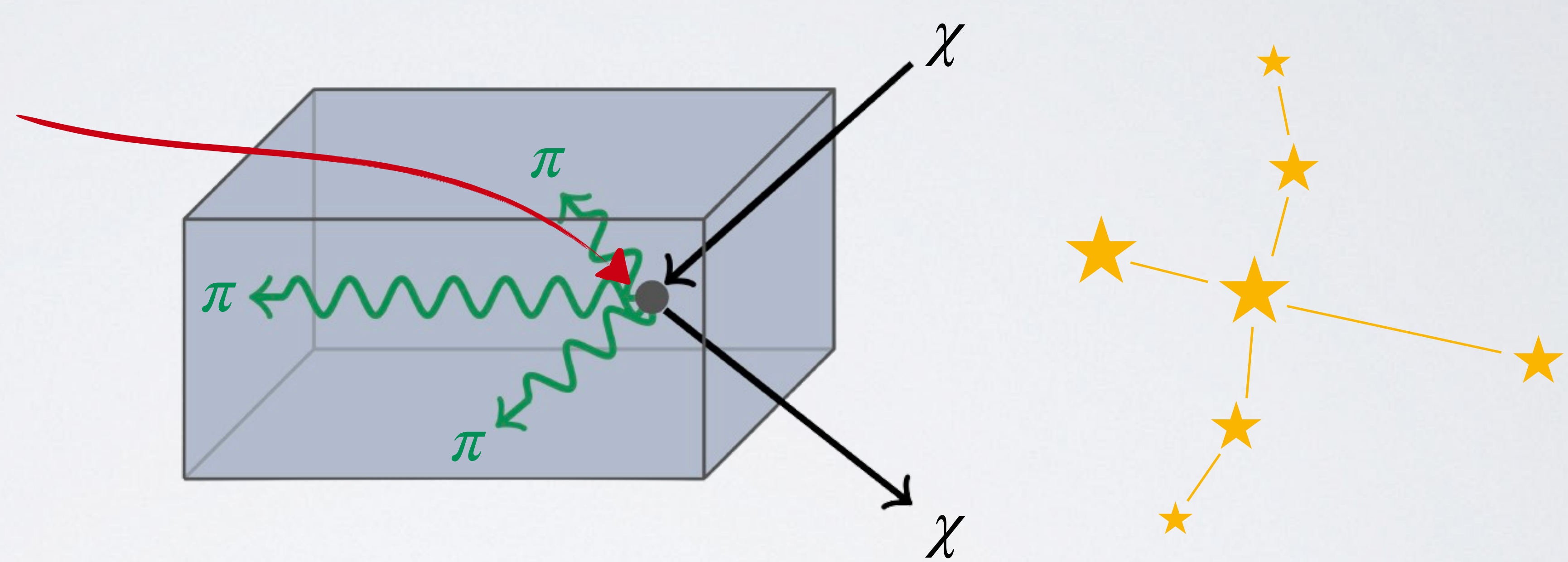

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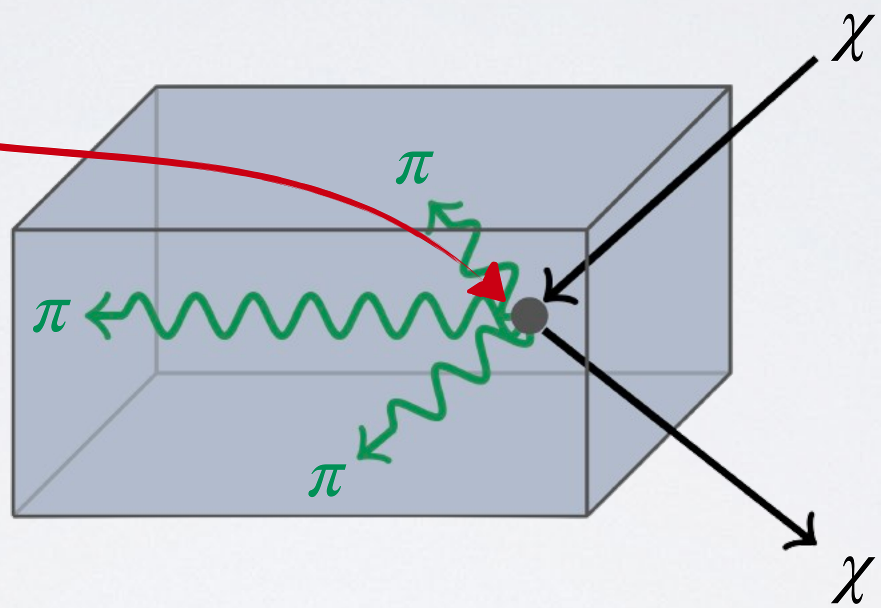

- If not completely suppressed, this configuration would provide a coincident, directional signal → optimal for background rejection

DIRECTIONALITY

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- We compute the 4-body, non-Lorentz invariant phase space using Monte Carlo techniques again borrowed from particle physics

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$$d\Phi_4 \sim d^3p_f \prod_{i=1}^{3} d^3q_i \, \delta\left(\frac{p_i^2}{2m_\chi} - \frac{p_f^2}{2m_\chi} - c_s q_1 - c_s q_2 - c_s q_3\right) \delta^{(3)}\left(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_1 - \mathbf{q}_2 - \mathbf{q}_3\right)$$

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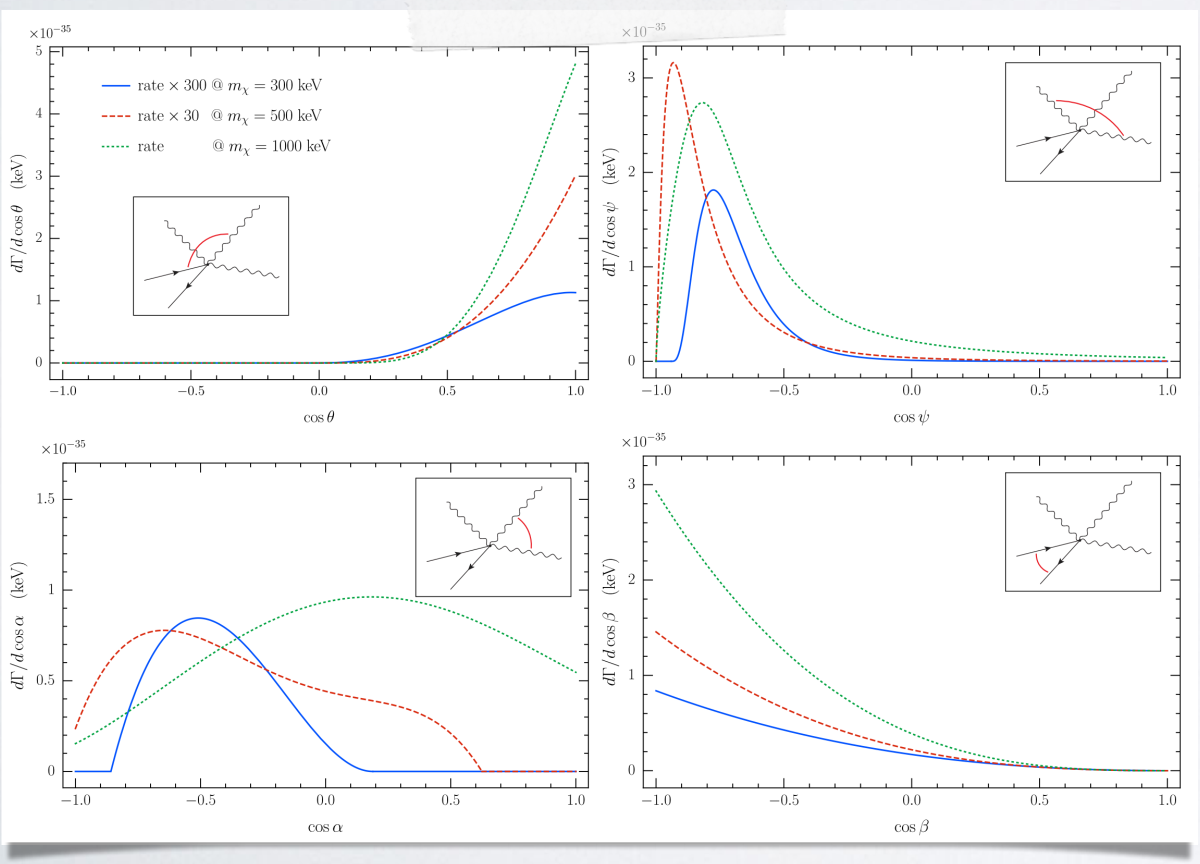

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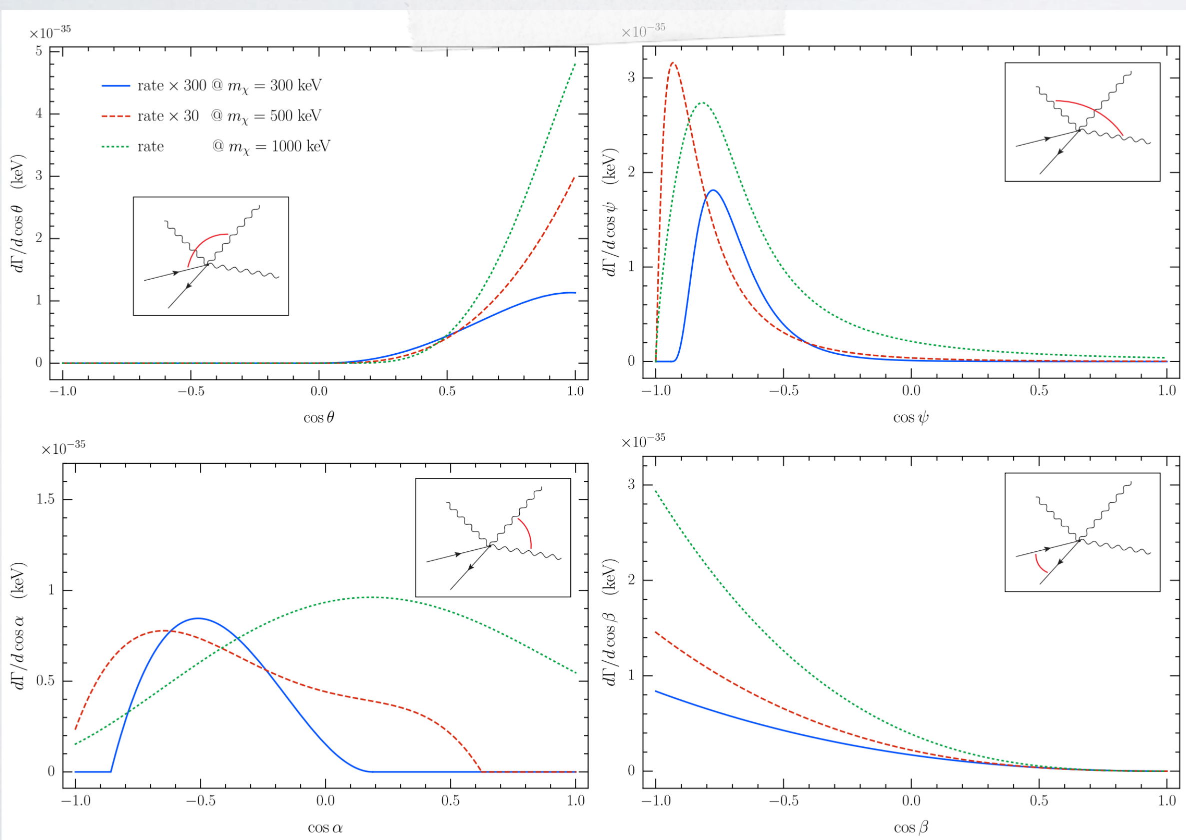
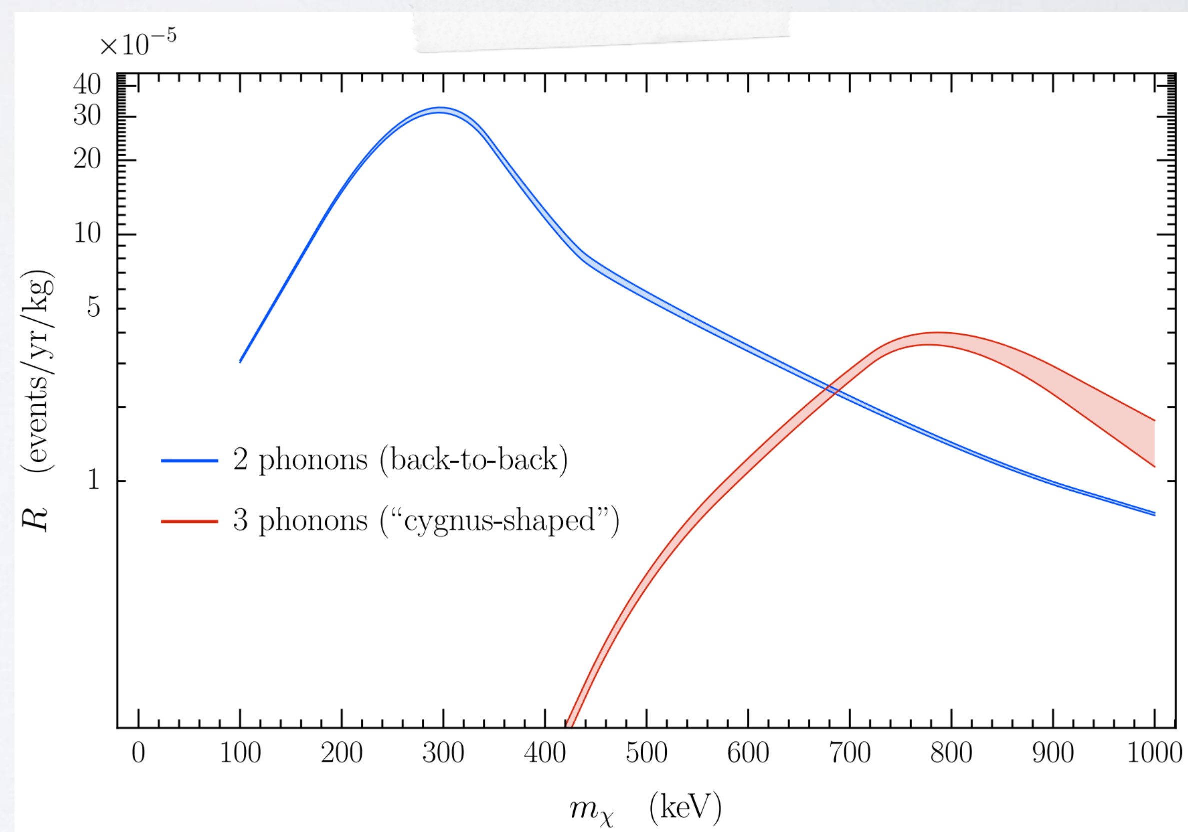
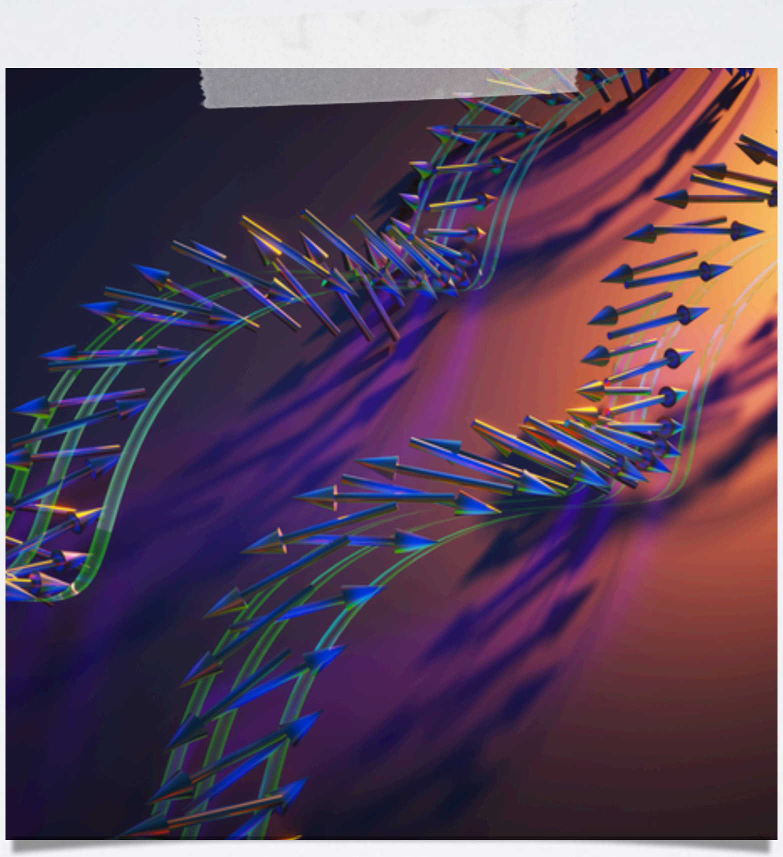




[Caputo, **AE**, Piccini, Polosa, Rossi - PRD 2021, 2012.01432]

Spin-dependent interactions: anti-ferromagnets



[w/ Catinari, Pavaskar]

(ANTI-)FERROMAGNETS

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- How about dark matter with spin-*dependent* interactions?

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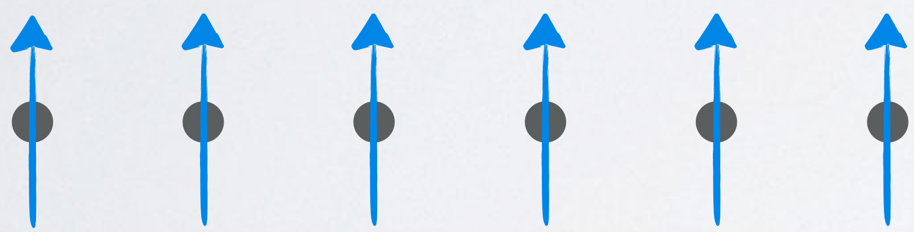

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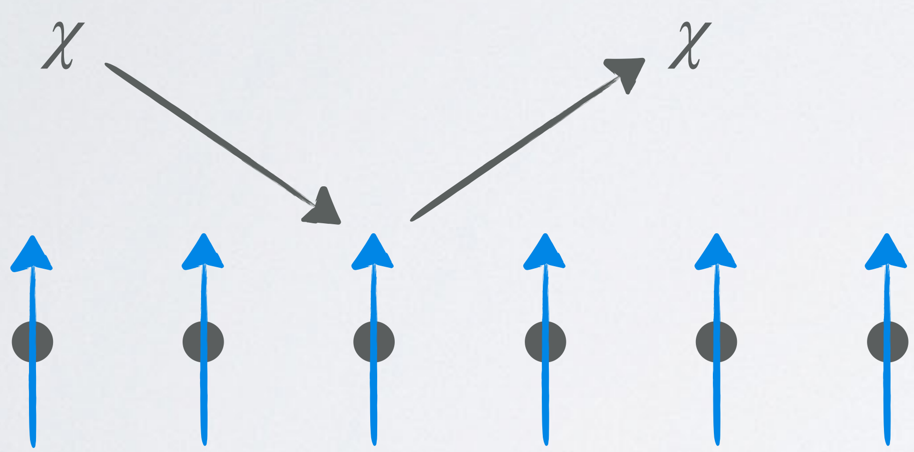

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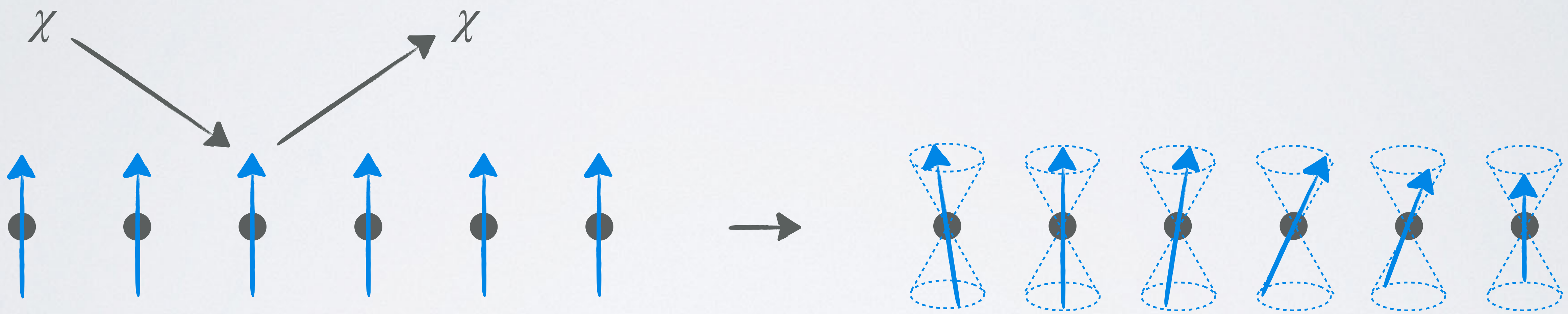

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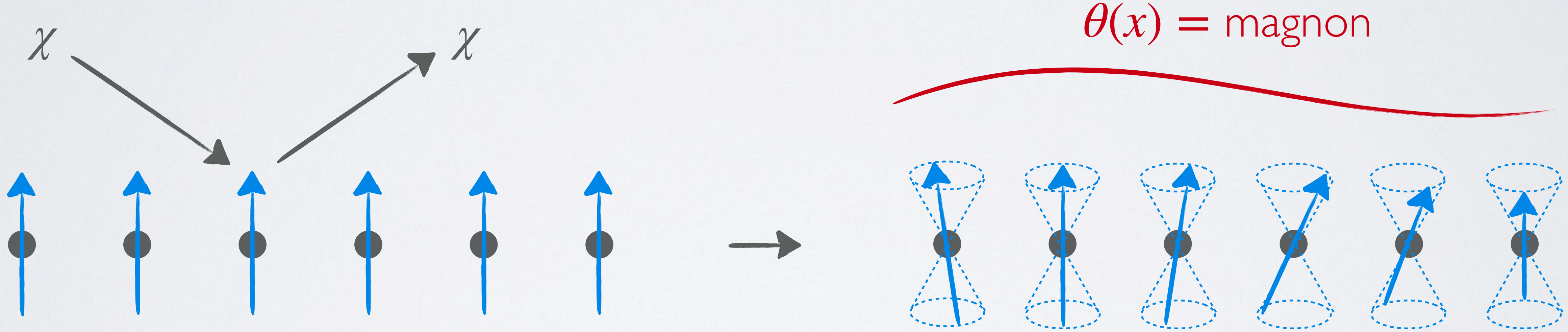

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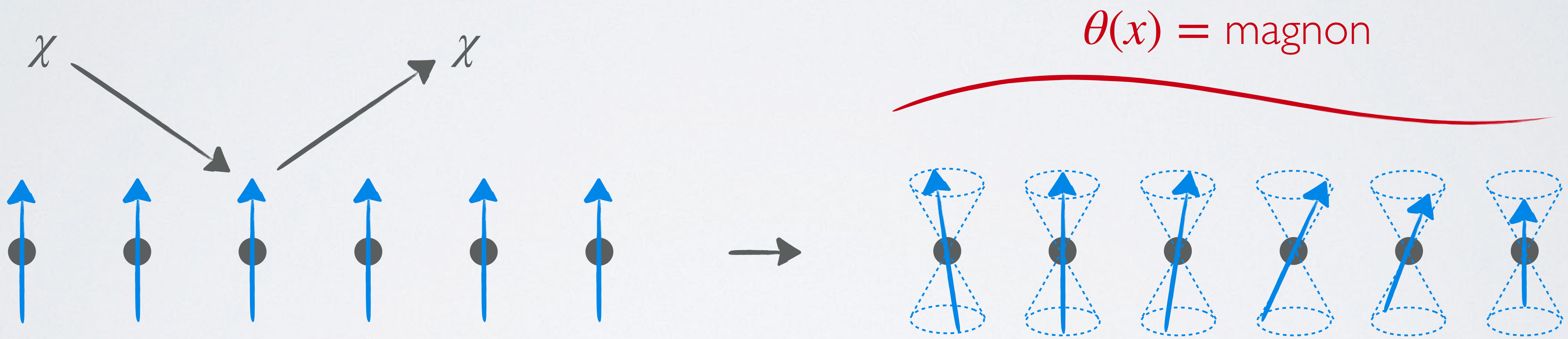

- Ways to detect few magnons have been proposed (TES? SQUIDs? quantum sensors? cavities?)

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

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

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

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

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

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- For a non-relativistic system, at low energies:

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

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spin density

FERROMAGNETS

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- 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]

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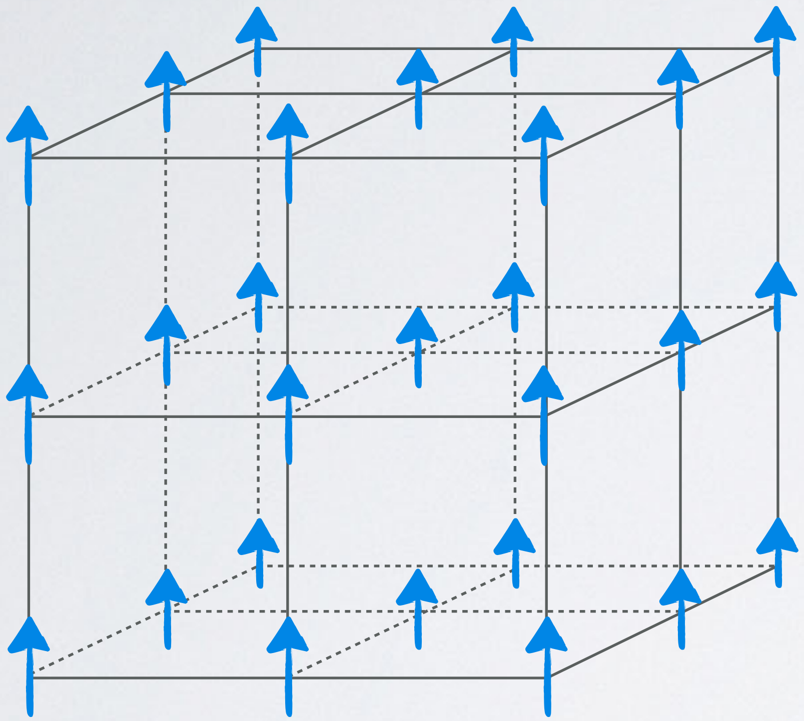

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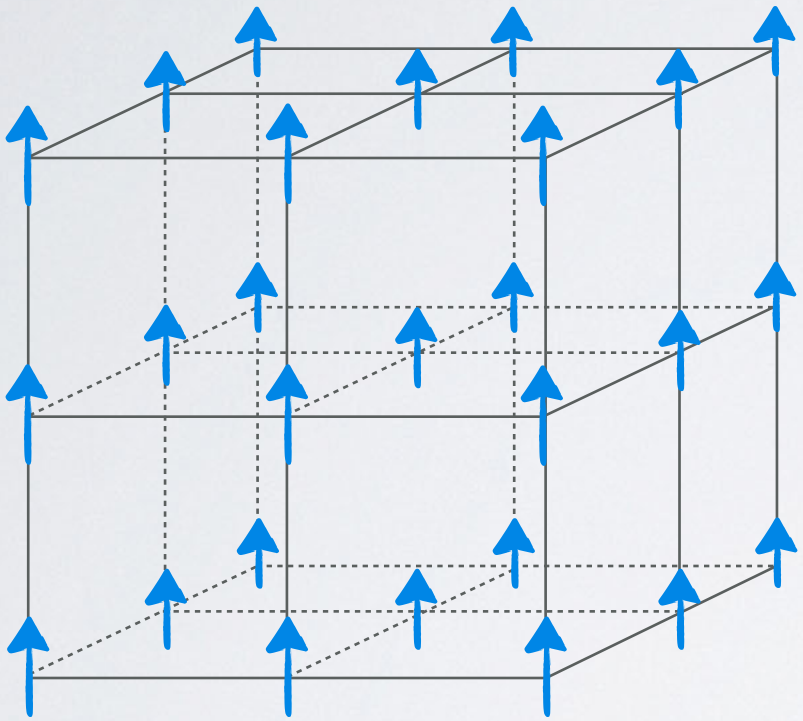

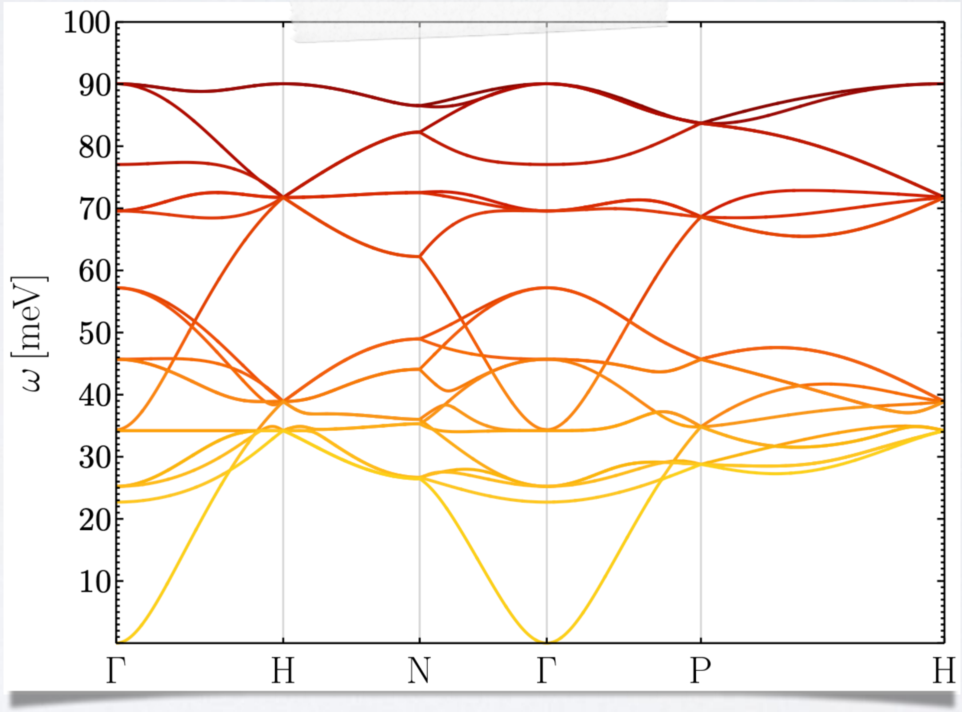

FERROMAGNETS

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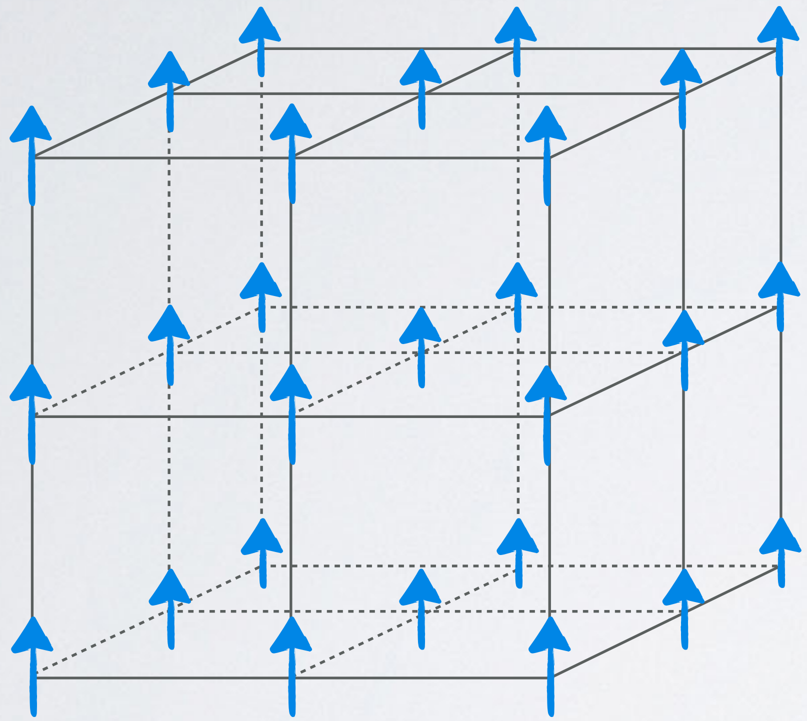
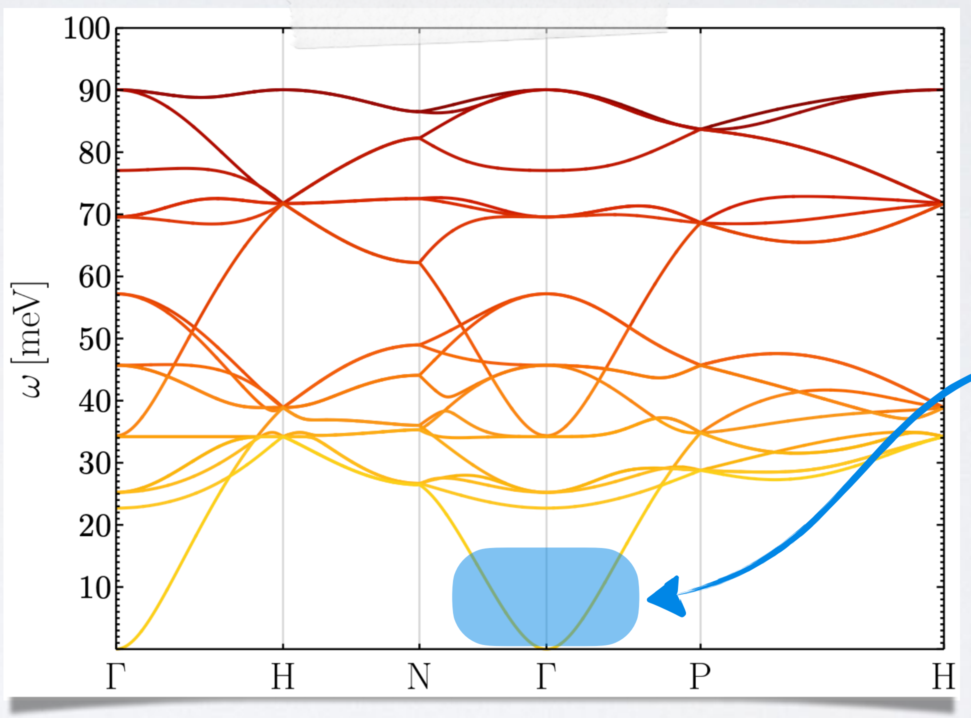
[Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate et al. — PRD 2020, 2005.10256; Chigus, Moroi, Nakayama — PRD 2020, 2001.10666; Trickle, Zhang, Zurek — PRD 2022, 2009.13534]





for $m_\chi \lesssim 10$ MeV only

gapless magnons

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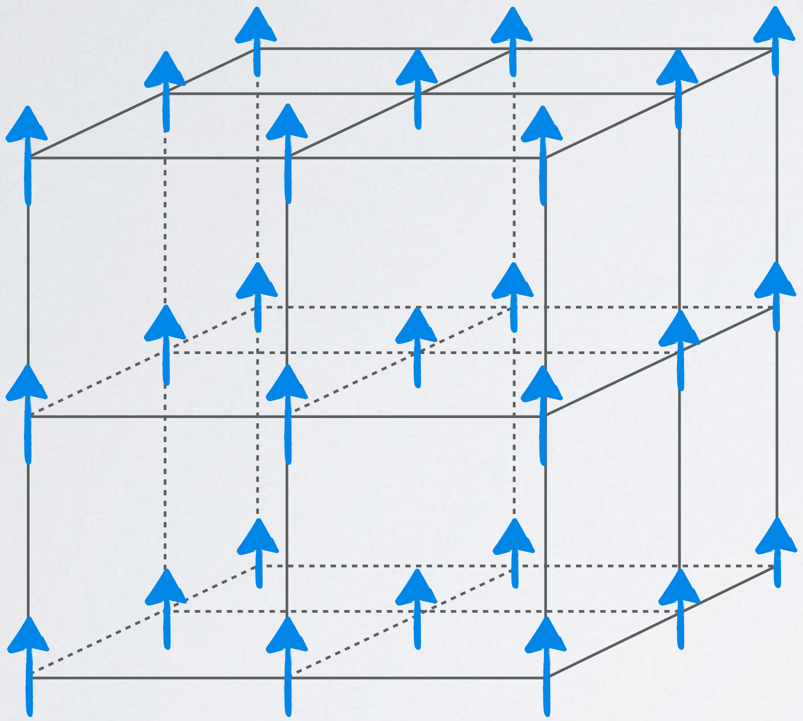

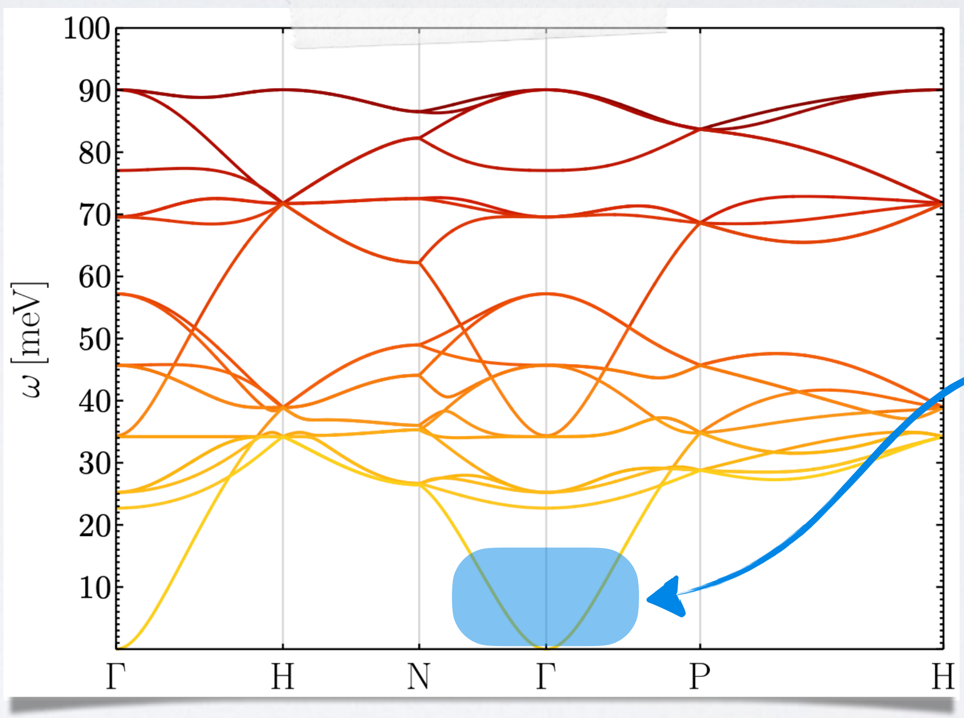

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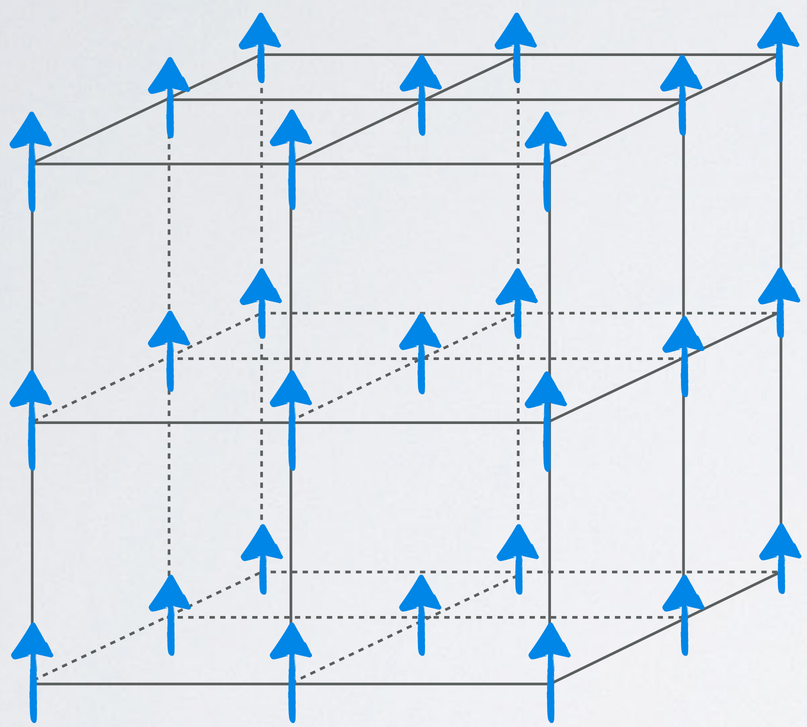

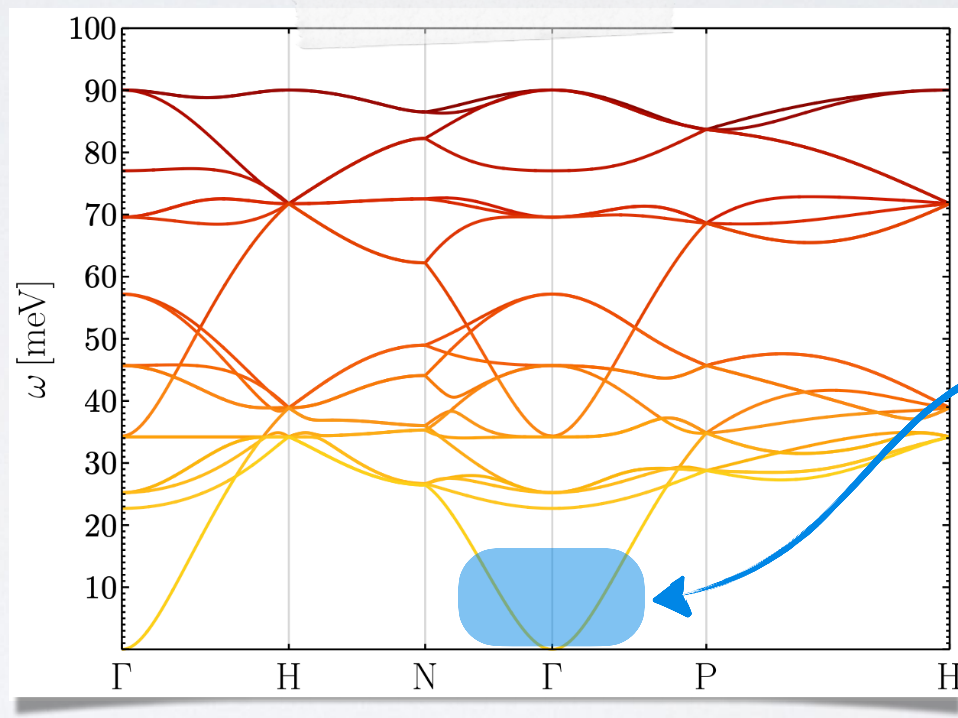

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$$\omega_{\max} \simeq 4\,\frac{m_\theta}{m_\chi}\,E_\chi \quad \text{with} \quad m_\theta \sim 1\ \text{MeV}$$ → inefficient for $m_\chi \lesssim 1$ MeV

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- Traditional approach: quantize the Heisenberg model

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

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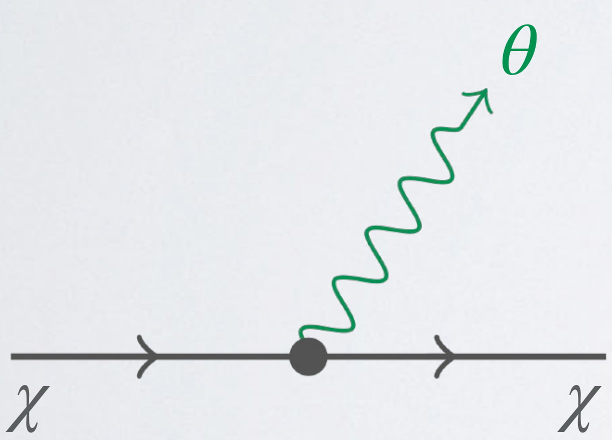

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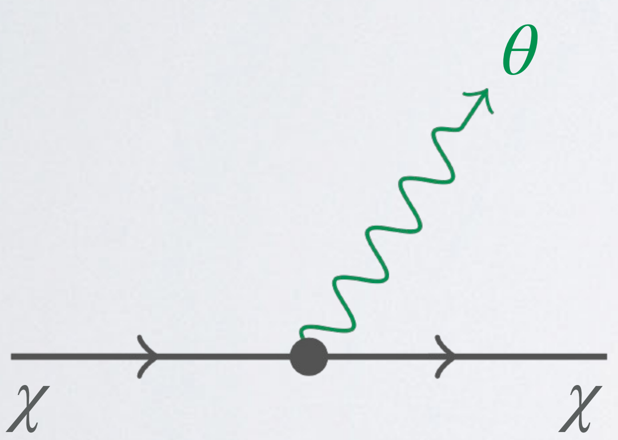

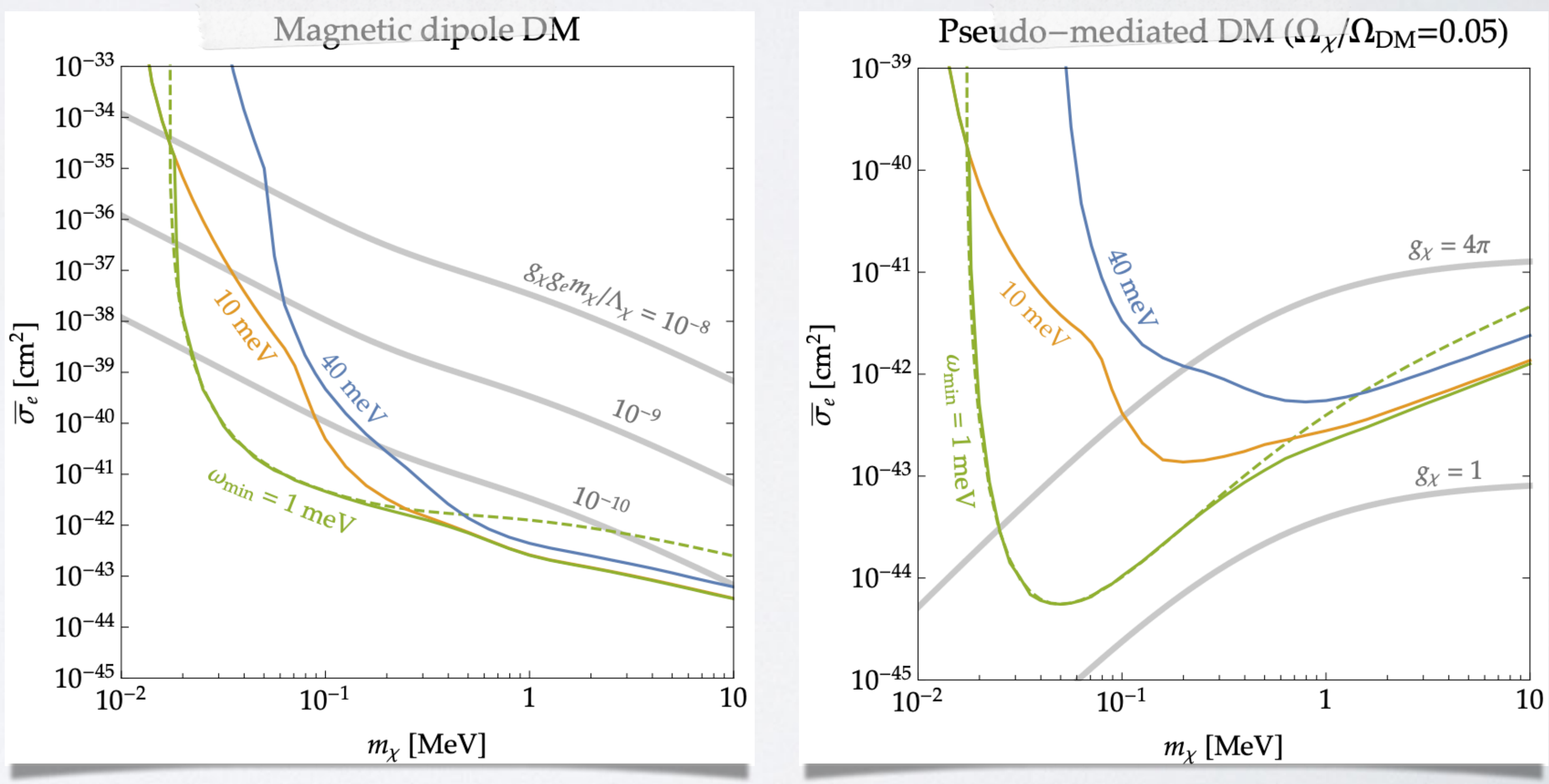

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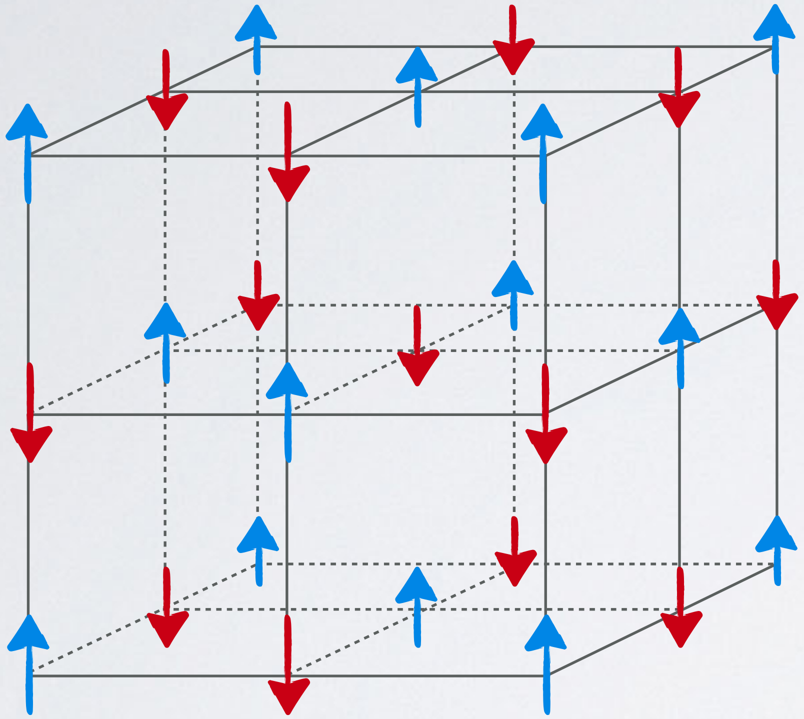

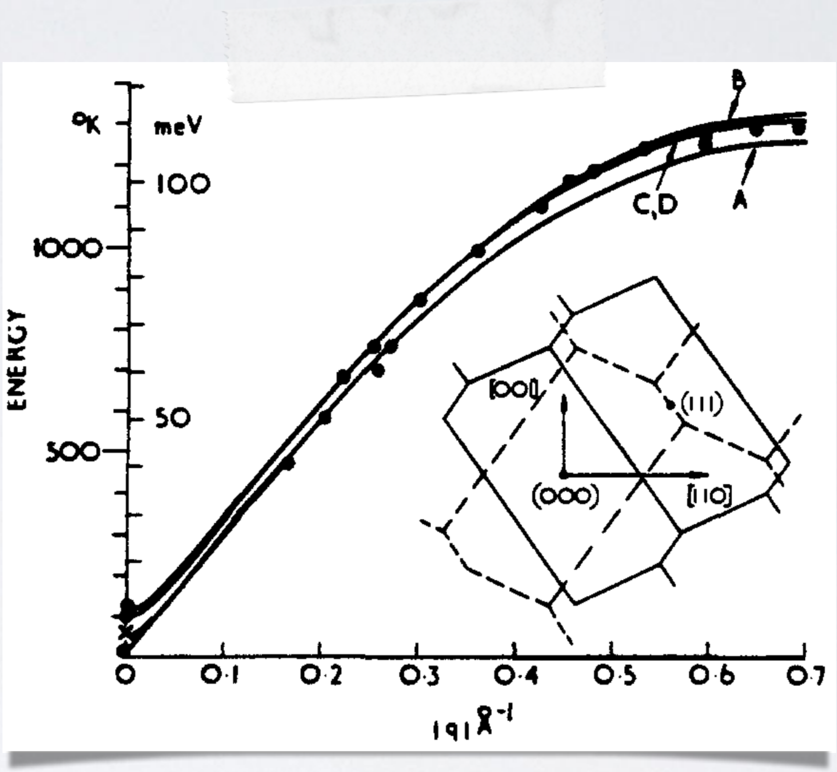

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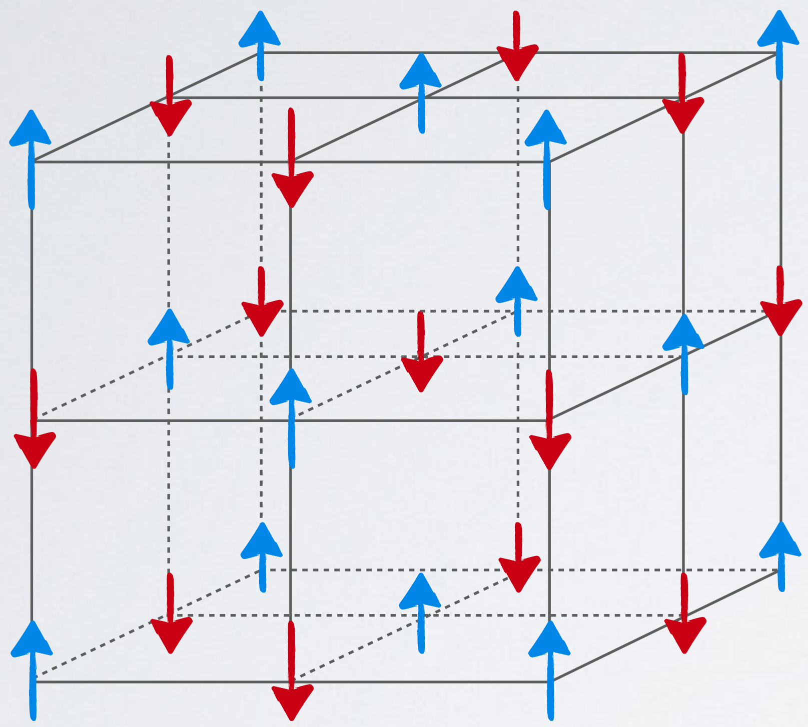

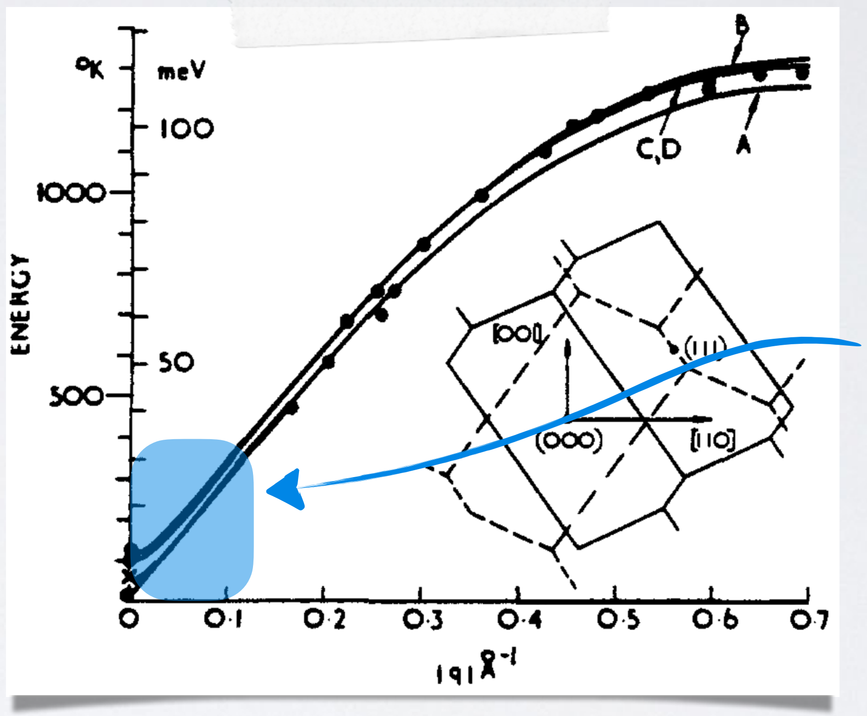

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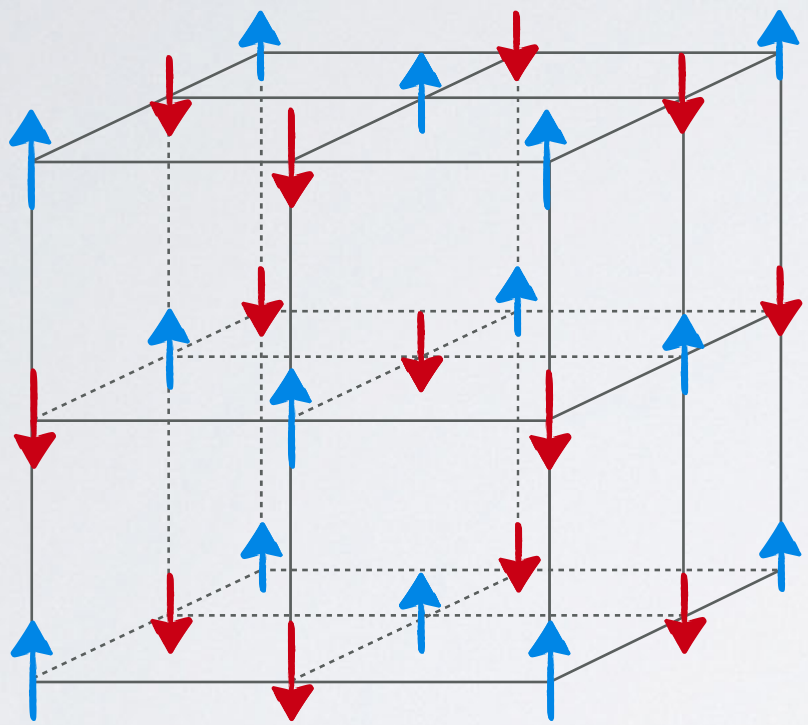

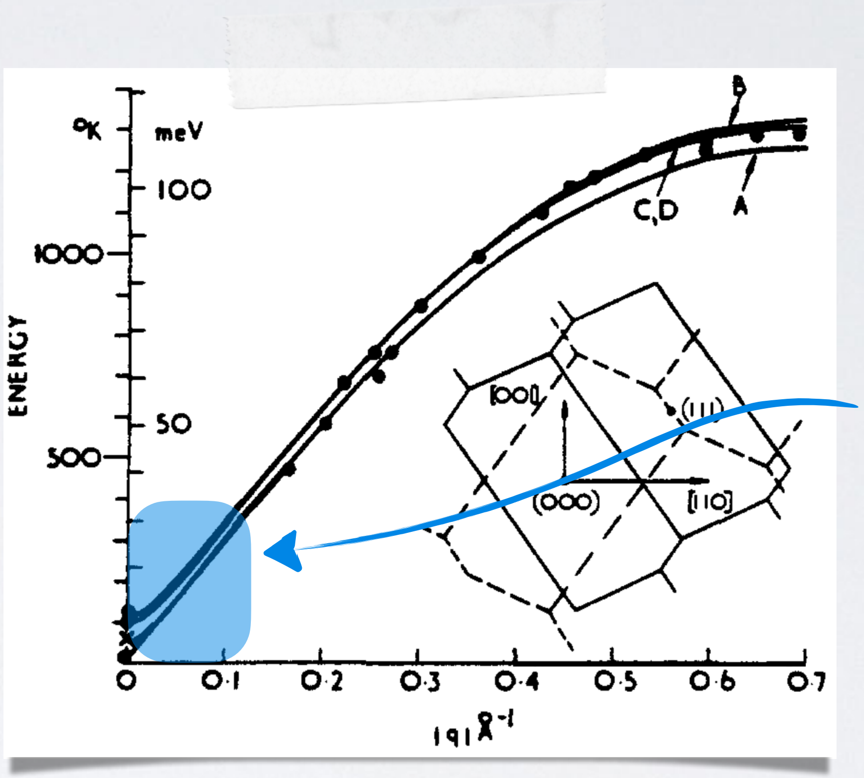

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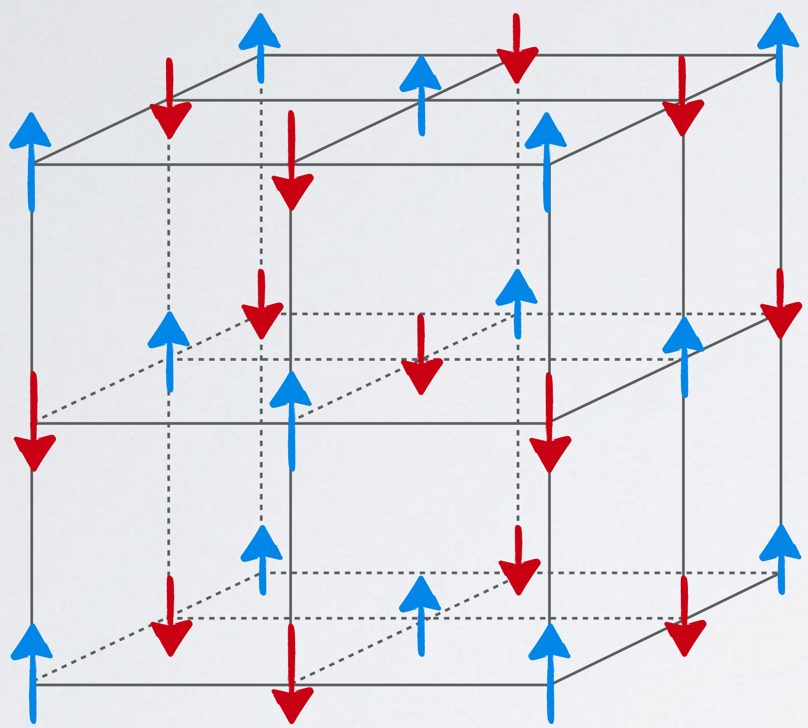

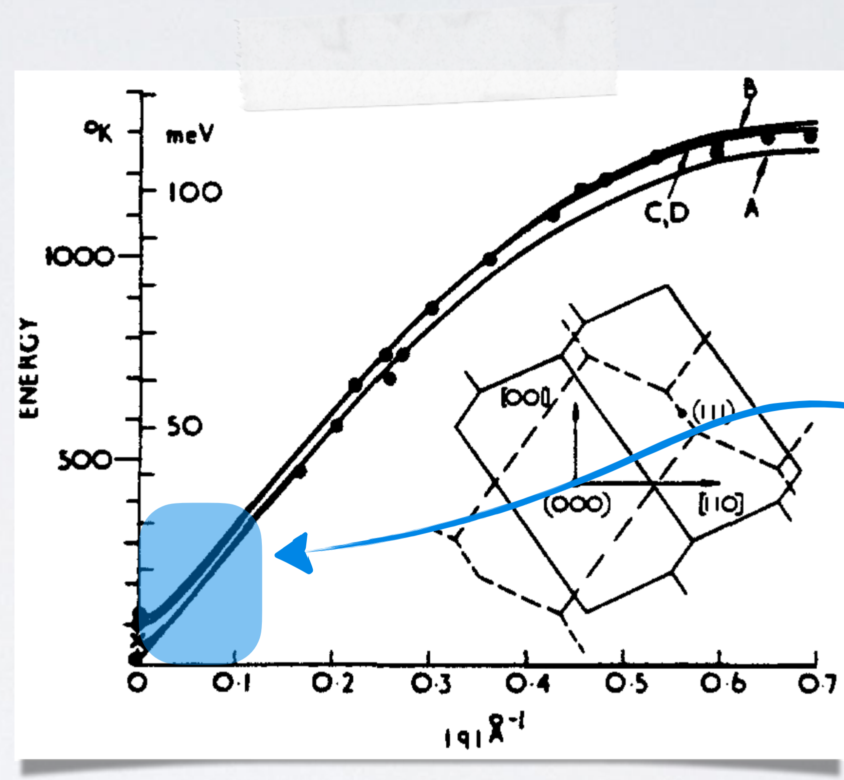

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- Nickel-oxide has $v_\theta \sim 0.1\, v_\chi$ $\rightarrow$ very efficient at absorbing dark matter energy [**AE**, Pavaskar — PRD (2023), 2210.13516]

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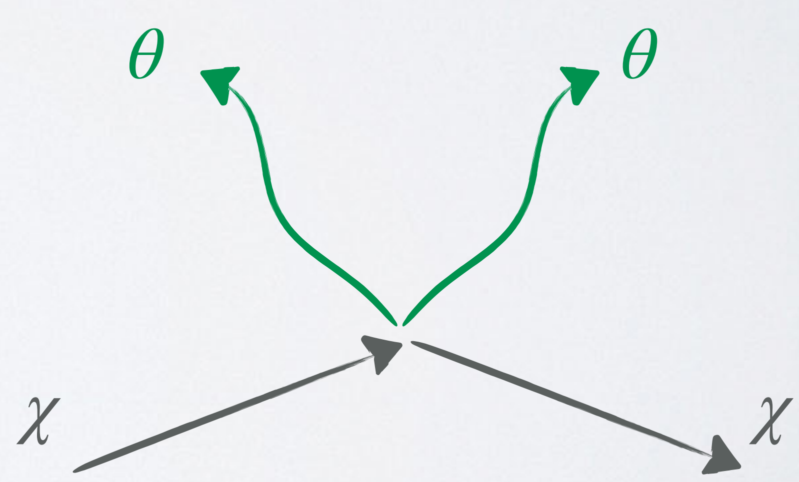

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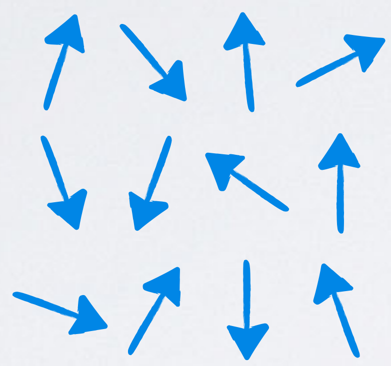

$SO(3)$

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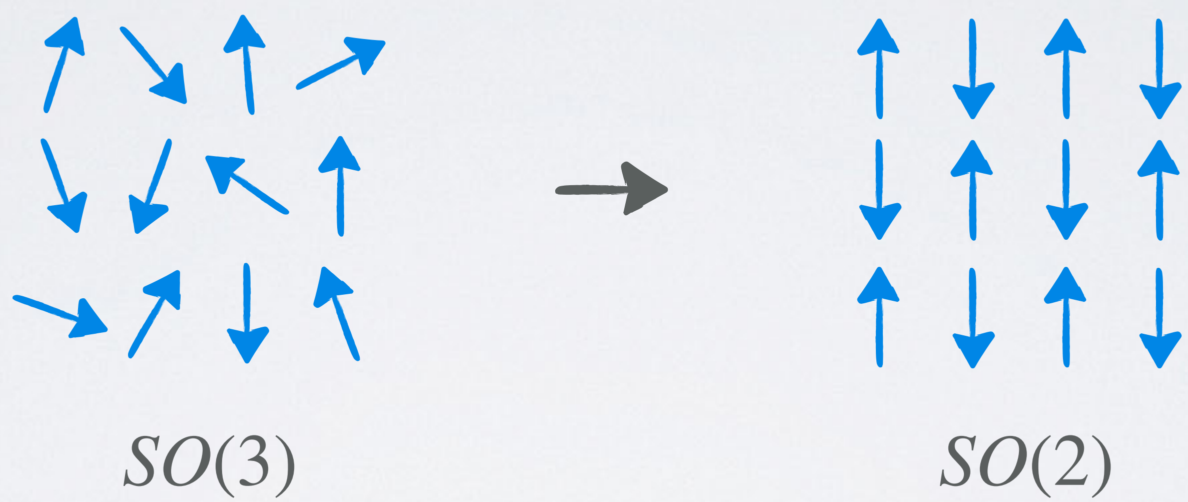

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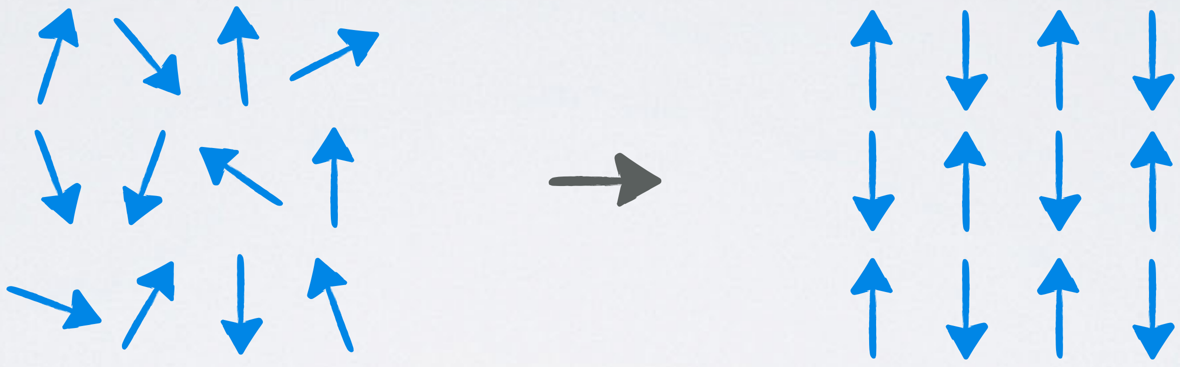

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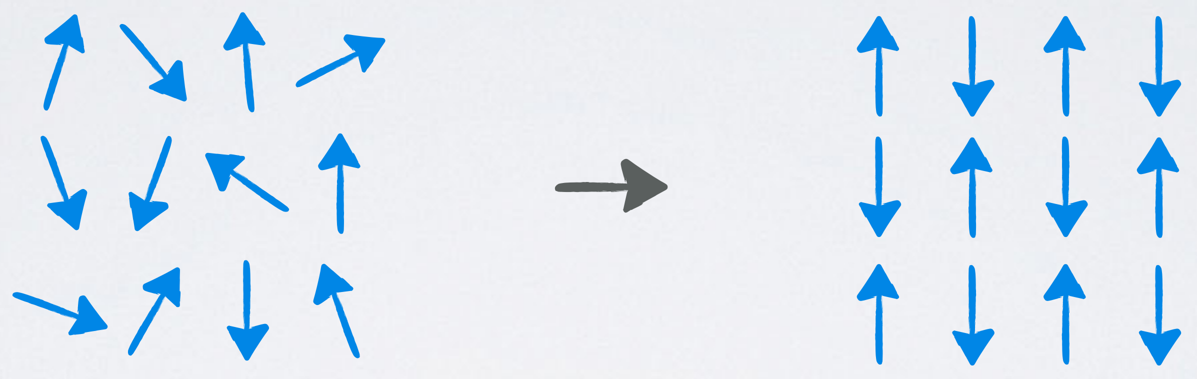

$SO(3)$ $\quad\quad$ $SO(2)$

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- At low energies/momenta magnons can be described by an EFT, invariant under the full symmetry group

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can be extracted from dispersion relation + neutron scattering data

$v_\theta = c_2/c_1$

$\sigma_n \propto c_1$

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

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one-magnon emission

two-magnons emission

- Structure completely dictated by symmetry $\longrightarrow$ just need c_1

- This allows to bypass difficulties in the standard treatment (failure of the Holsten-Primakoff approach) [Dyson — Phys. Rev. 1956]

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

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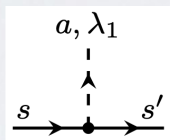

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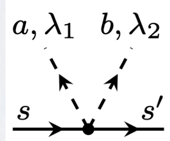

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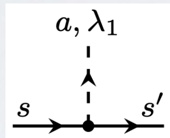

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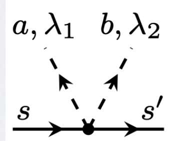

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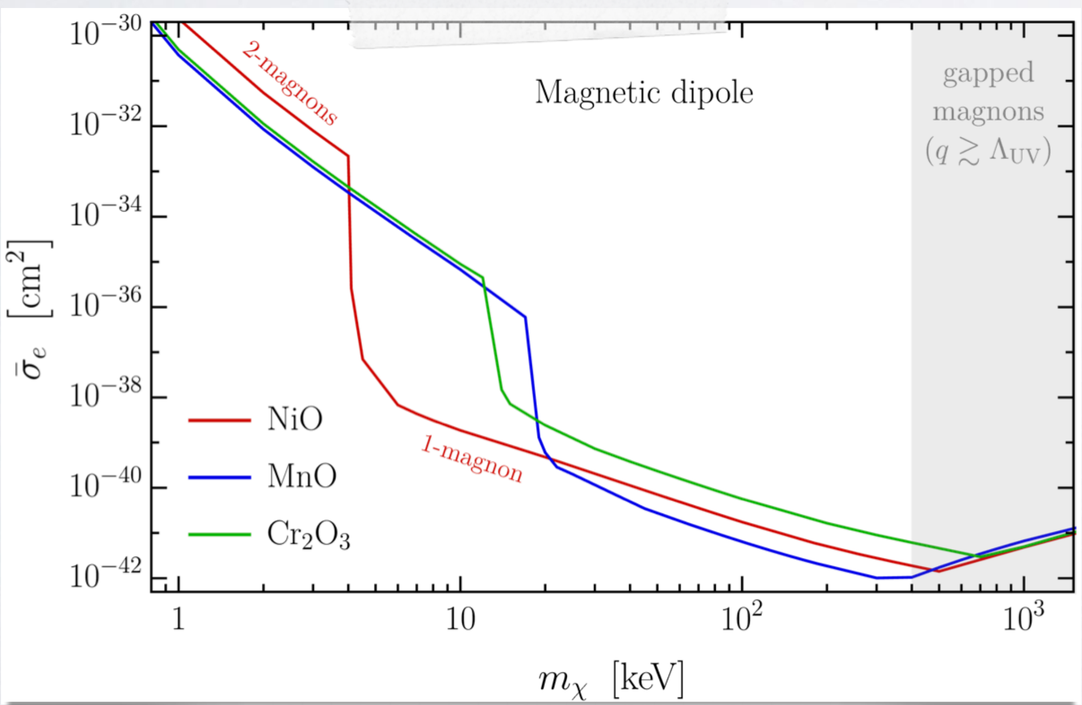

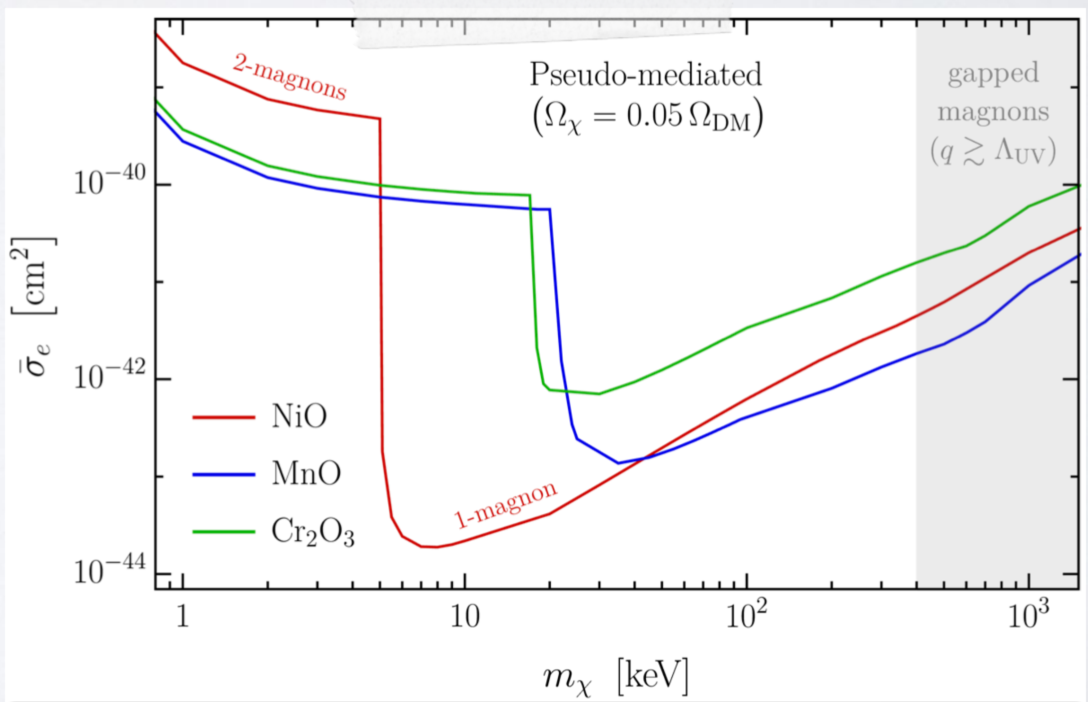

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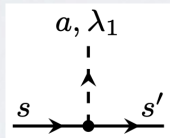

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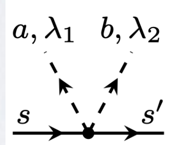

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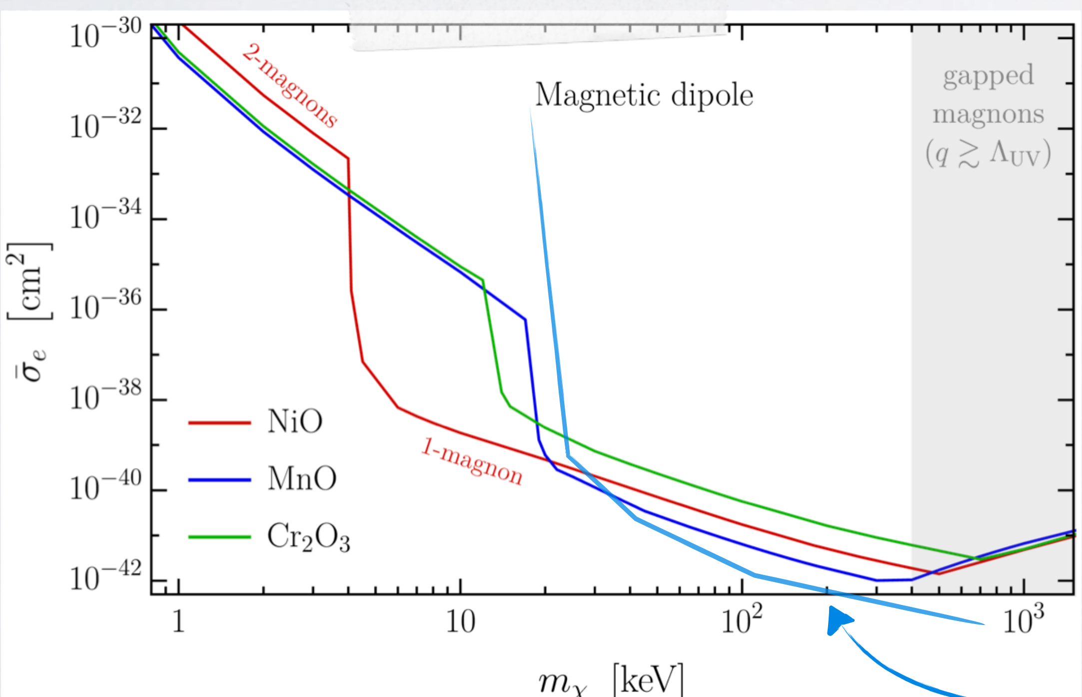

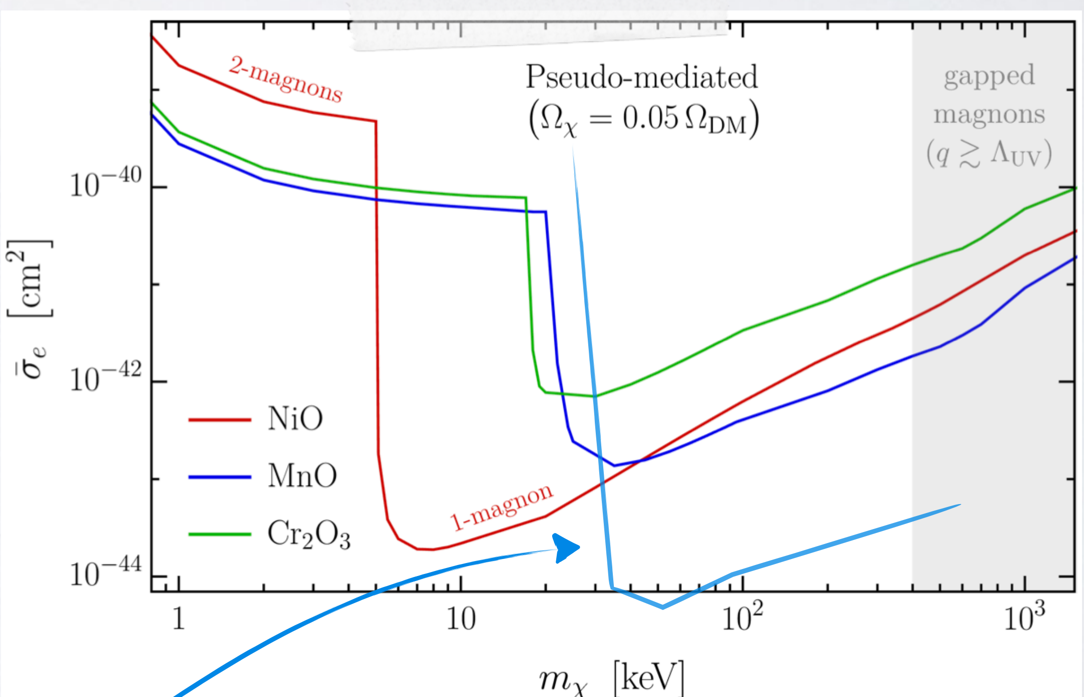

ferromagnets

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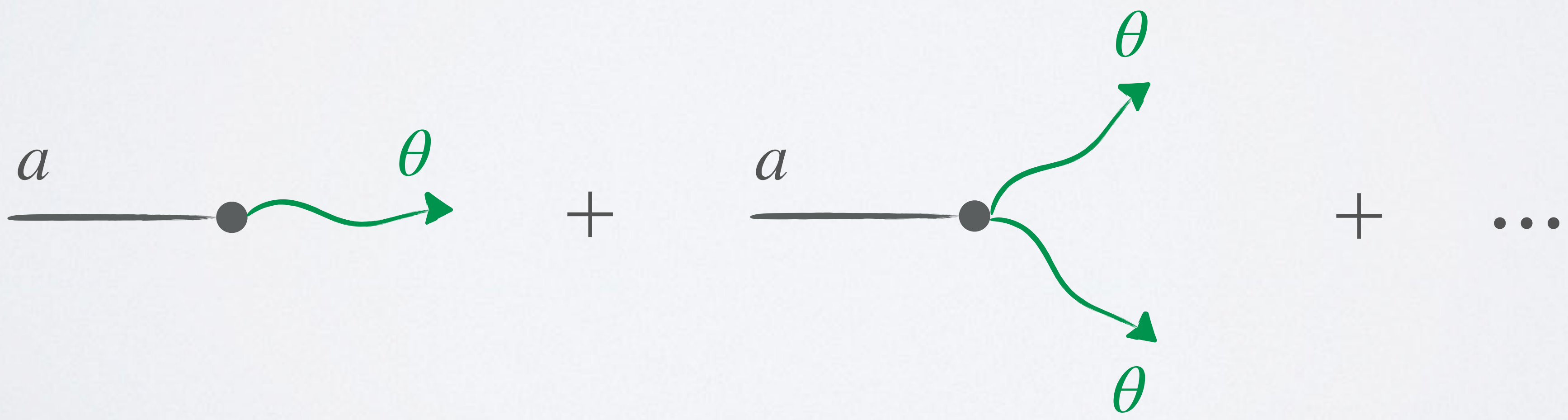

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$$\mathscr{L} = c_1 \left[\left(\dot{\mathbf{n}} + \mu \mathbf{B} \times \mathbf{n} \right)^2 - v_\theta^2 \left(\nabla_i \mathbf{n} \right)^2 + \lambda_z n_z^2 - \lambda_x n_x^2 \right]$$

[Catinari, **AE**, Pavaskar — 2411.09761]

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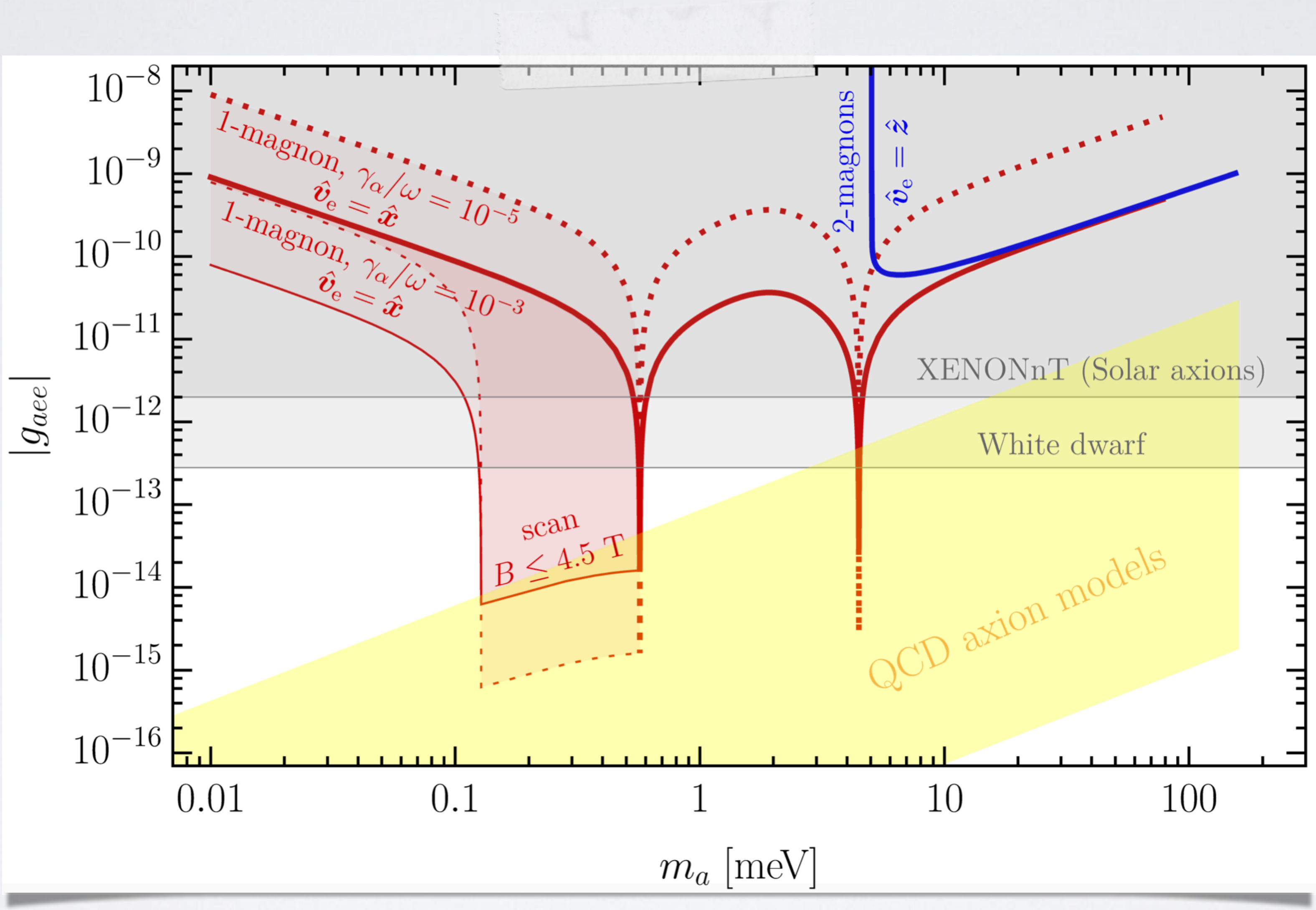

[Catinari, **AE**, Pavaskar — 2411.09761]

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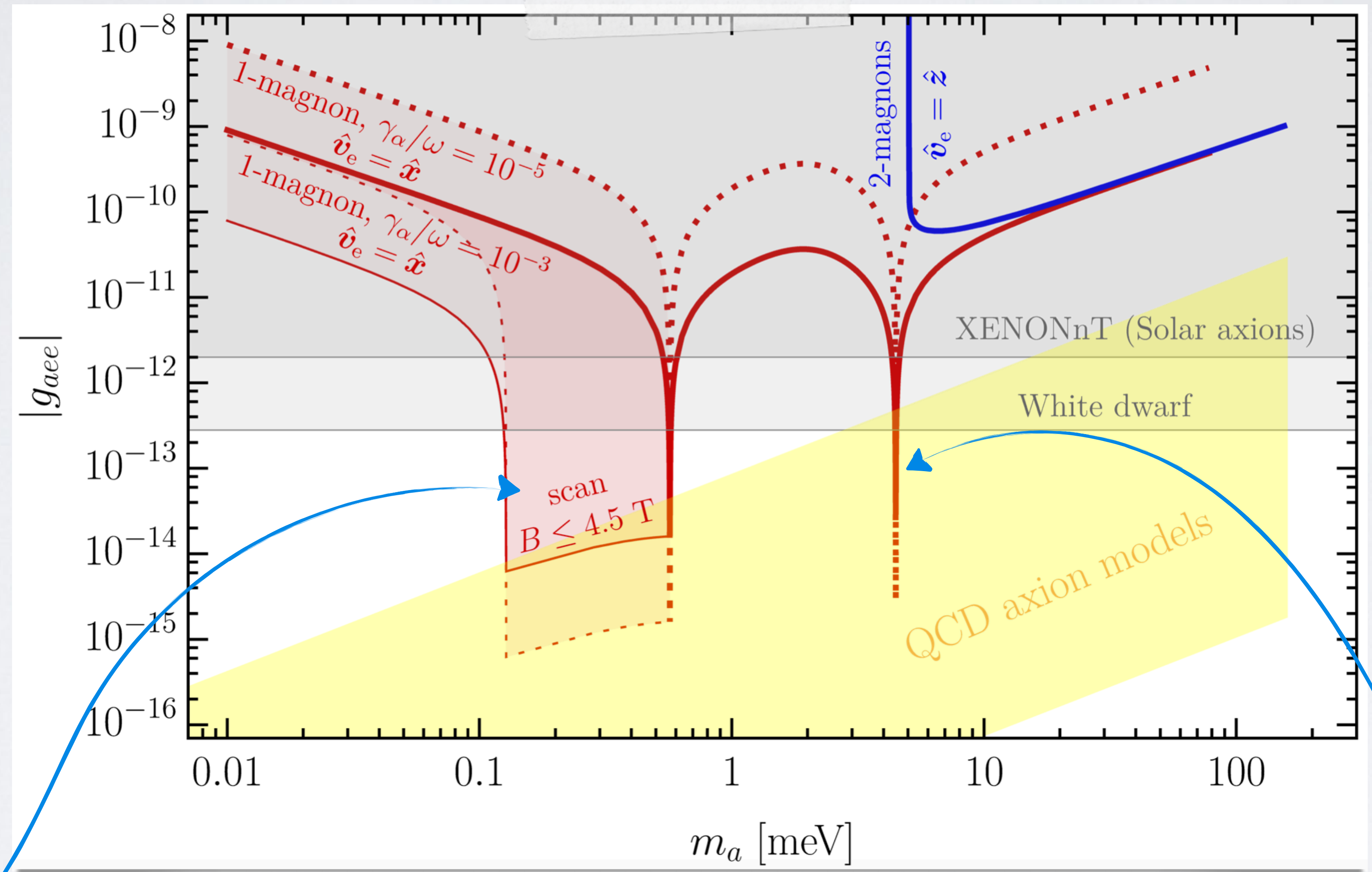

[Catinari, **AE**, Pavaskar — 2411.09761]

B-field scan

higher magnon branch

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- For anti-ferromagnets there is a plethora of open questions:
  - is any other good material out there? [Marocco, Wheater — 2501.18120]
  - what is the actual observable? How do we see magnons? (SQUIDs? cavities?)

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Thank you for the attention!