SUB-GEV DARK MATTER IN THE LAB

NEW IDEAS AND NEW TOOLS

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Light Dark World 2023, September 2023

OUTLINE

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- Searching for keV-GeV dark matter

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- Down to the MeV: Migdal effect

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- Down to the keV: collective excitations
- Outlook

SUB-GEV DARK MATTER

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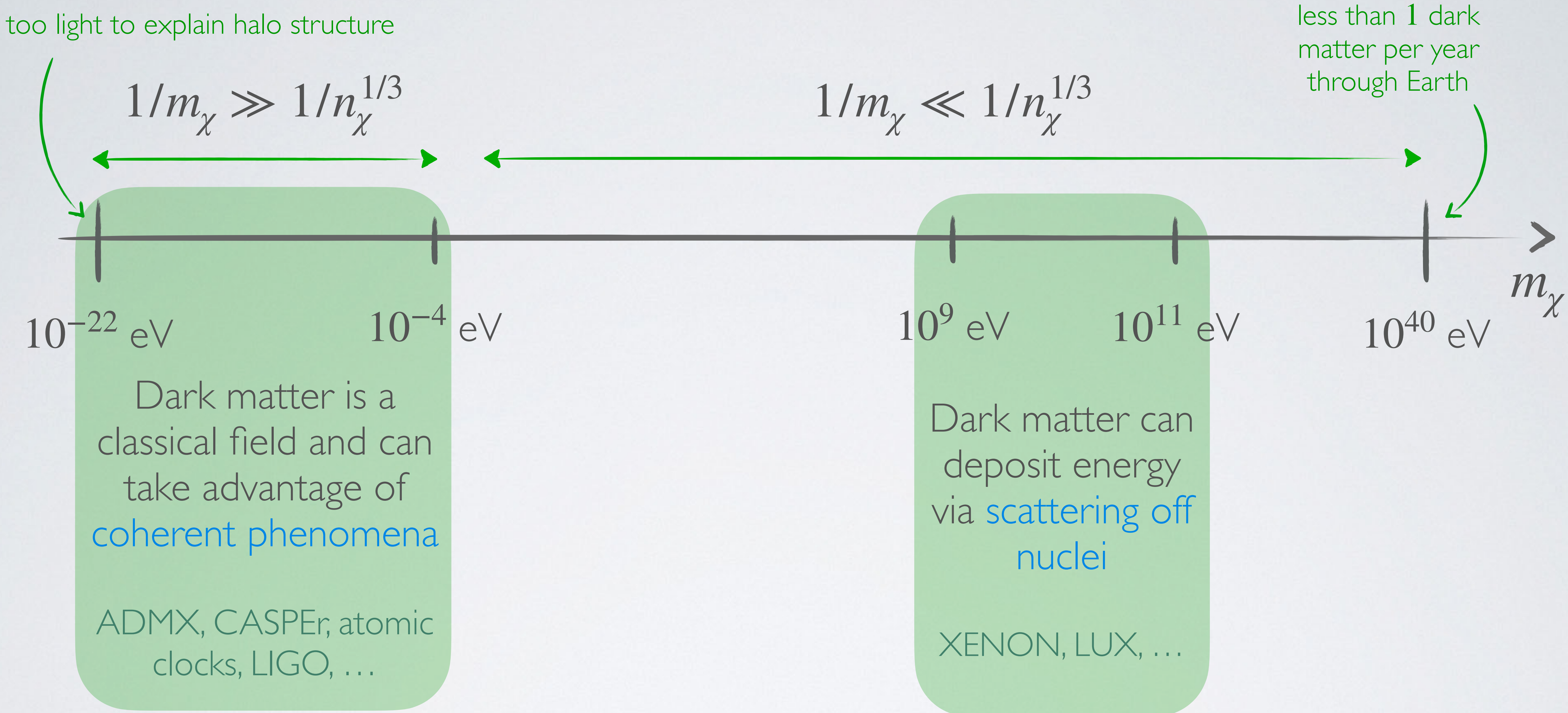

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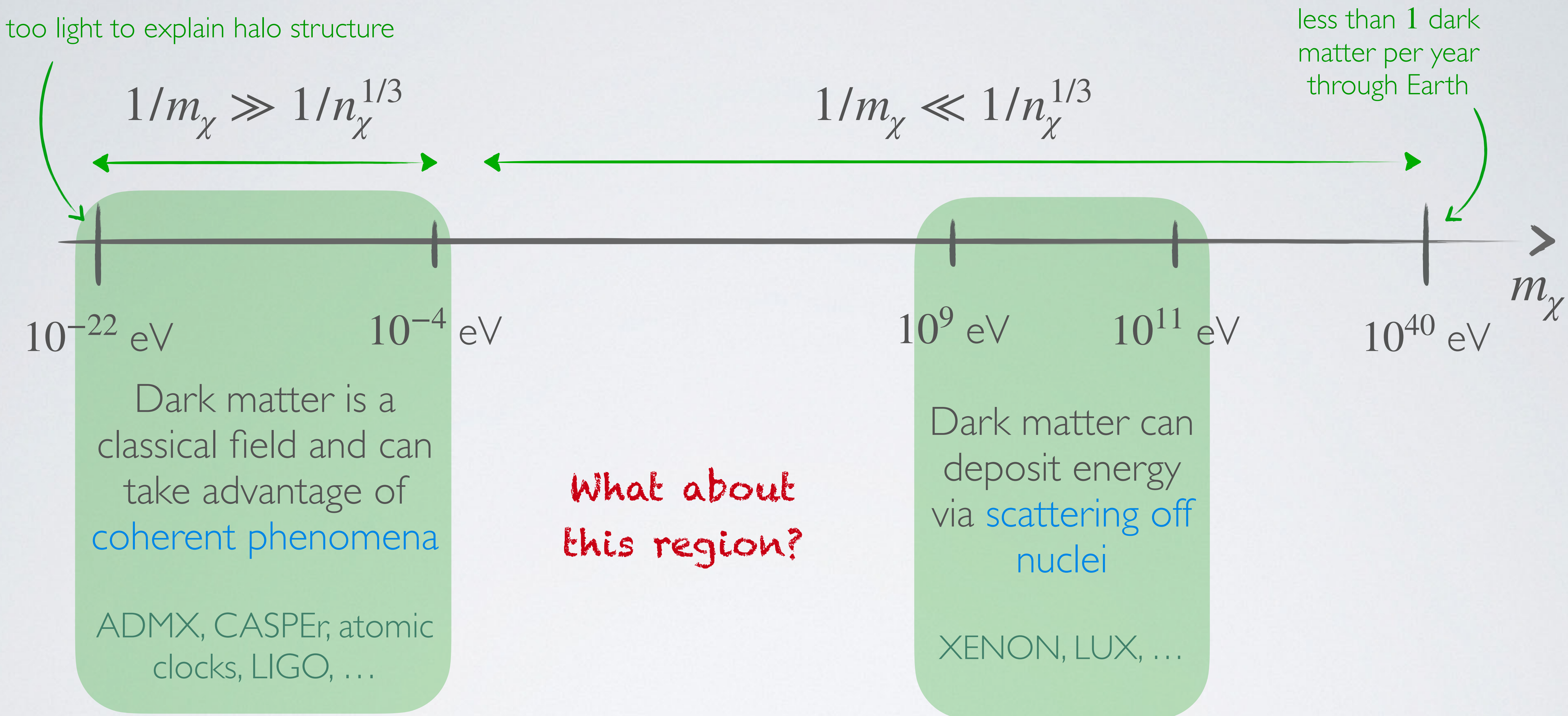

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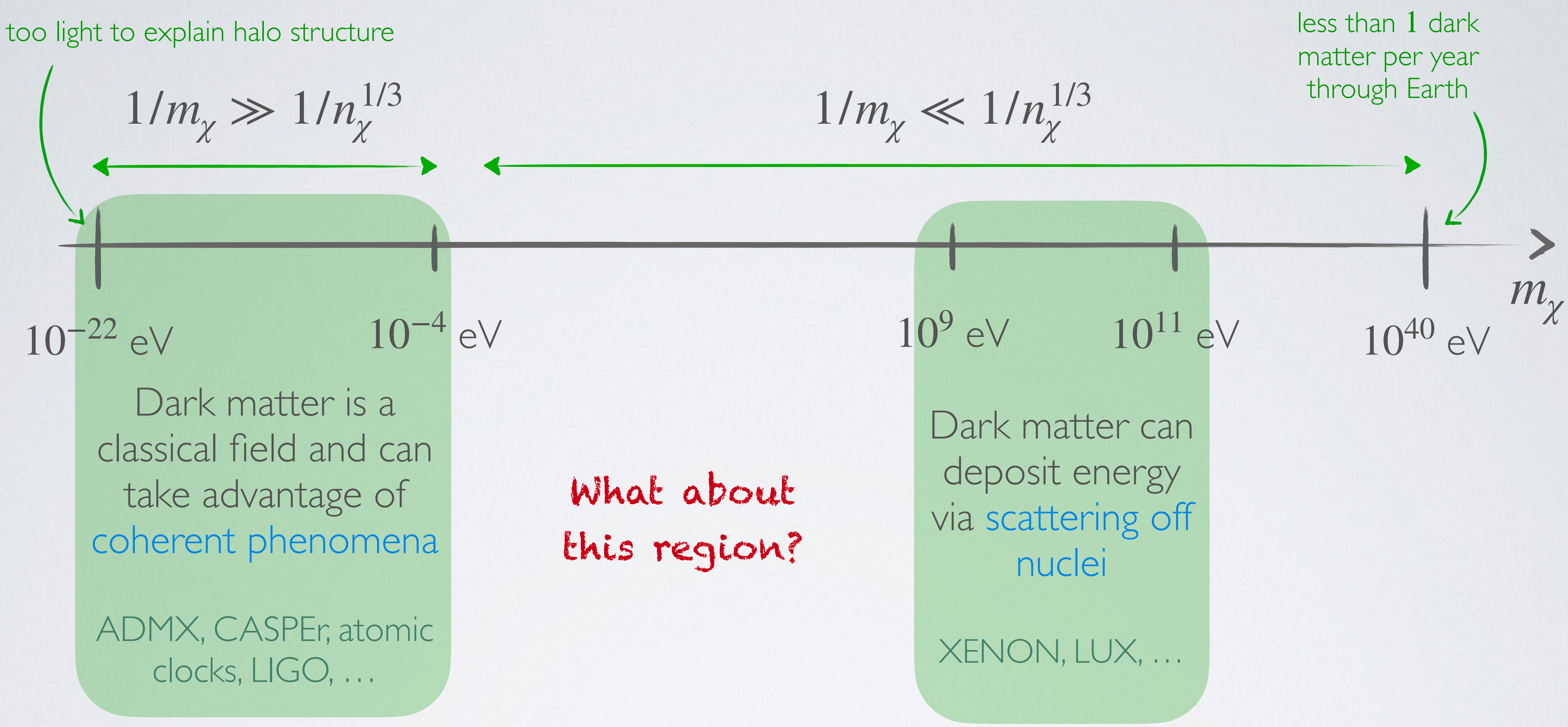

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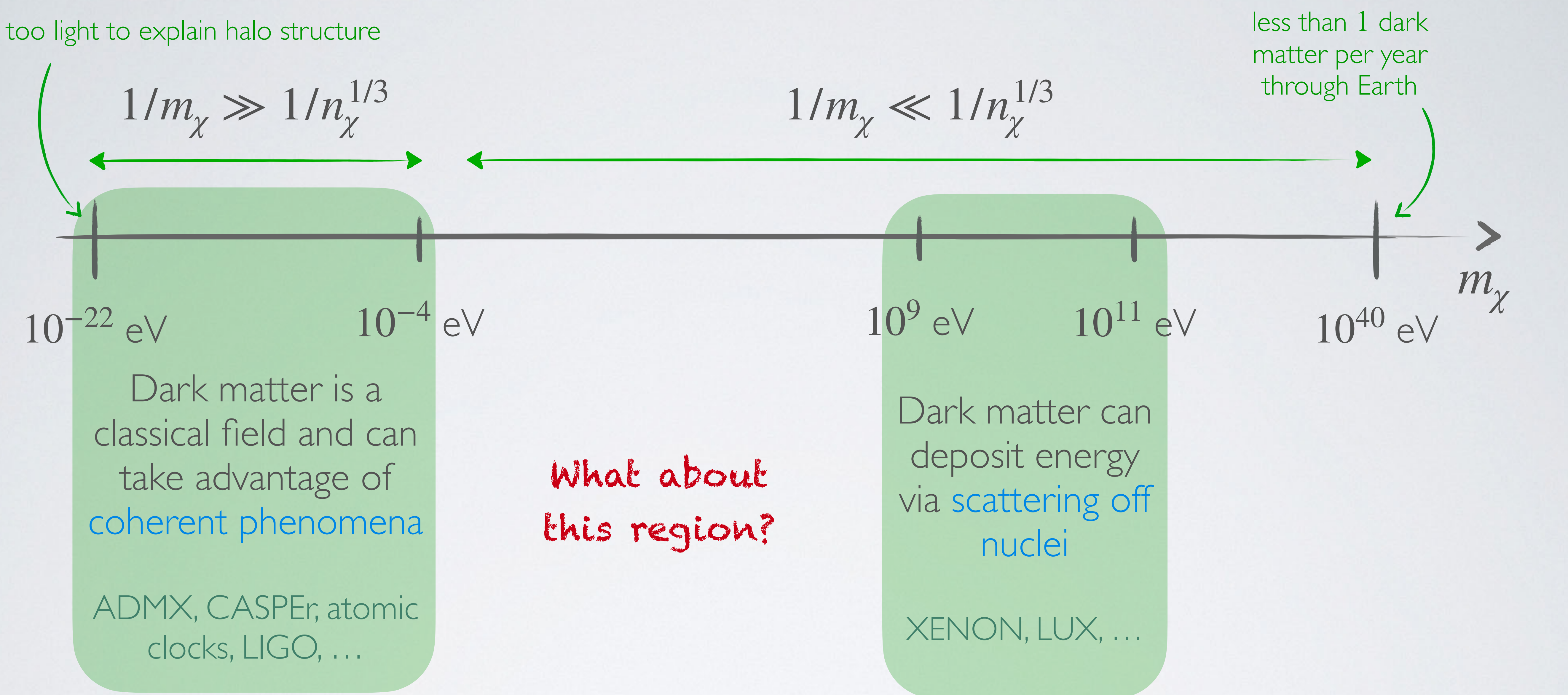

- Dark matter is a particle but too light for elastic nuclear recoil
- Need new materials and/or observables

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

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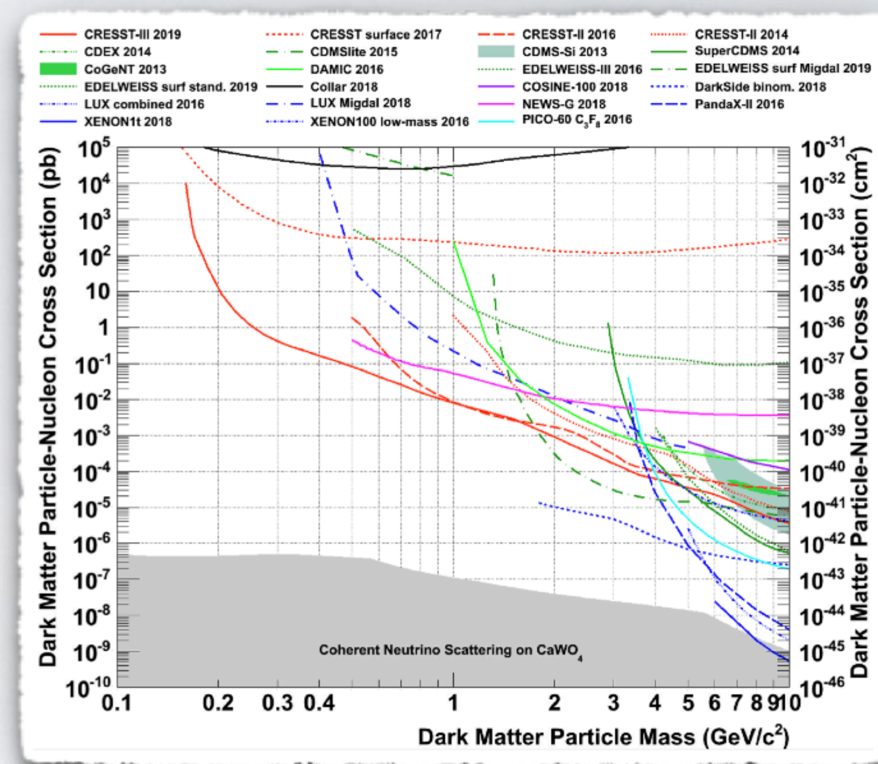

[CRESST — PRD 2019, 1904.00498]

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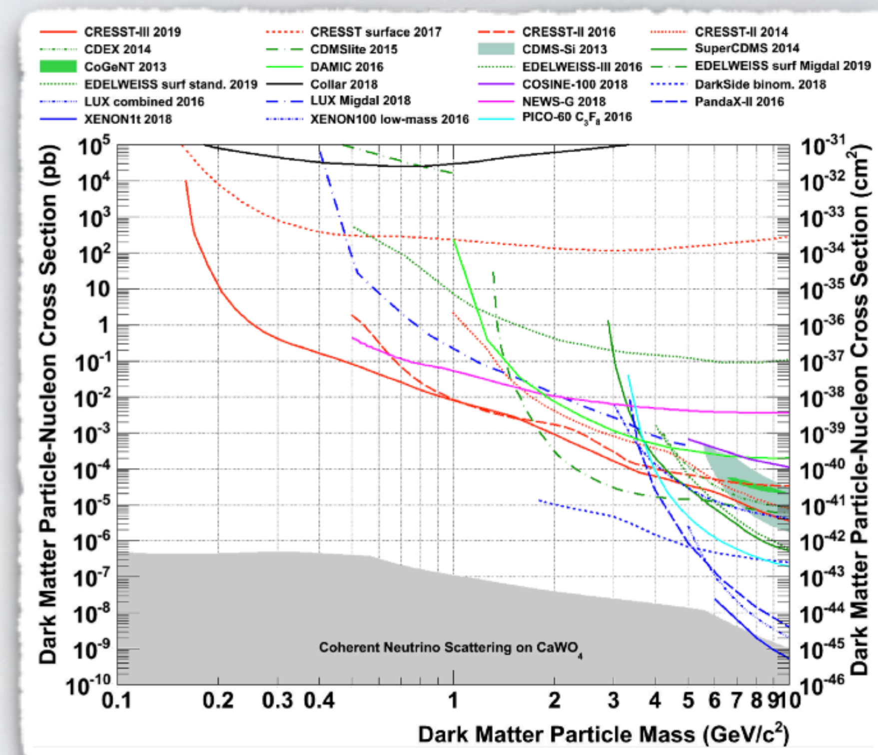

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- Two possibilities:
  1. Look into lighter scattering targets
  2. Look into inelastic processes

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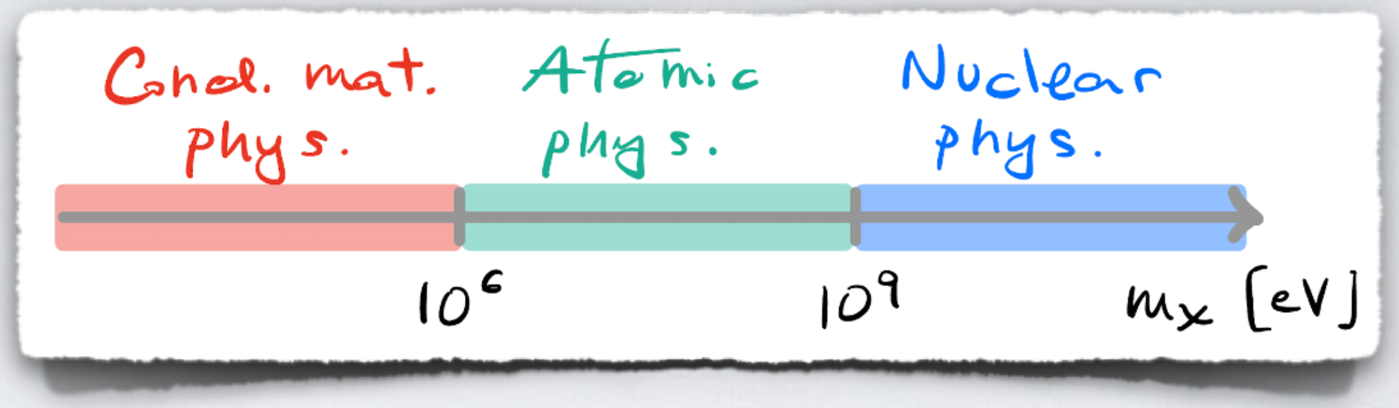

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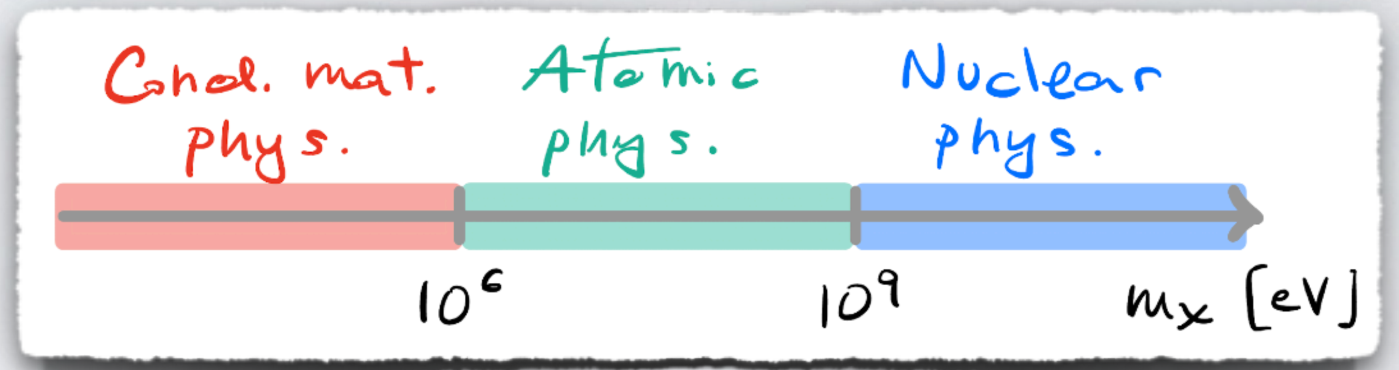

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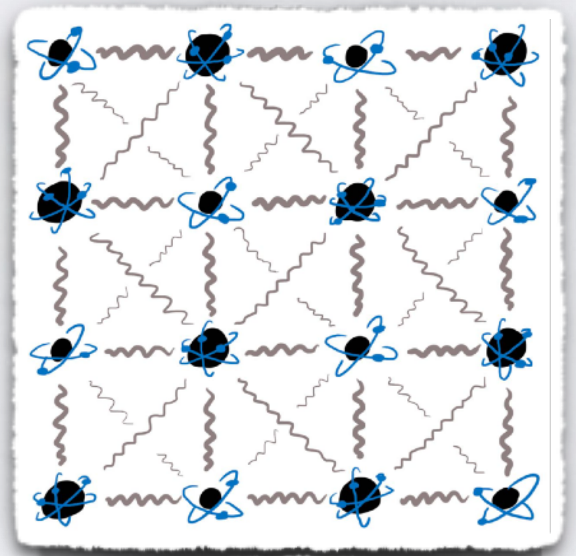

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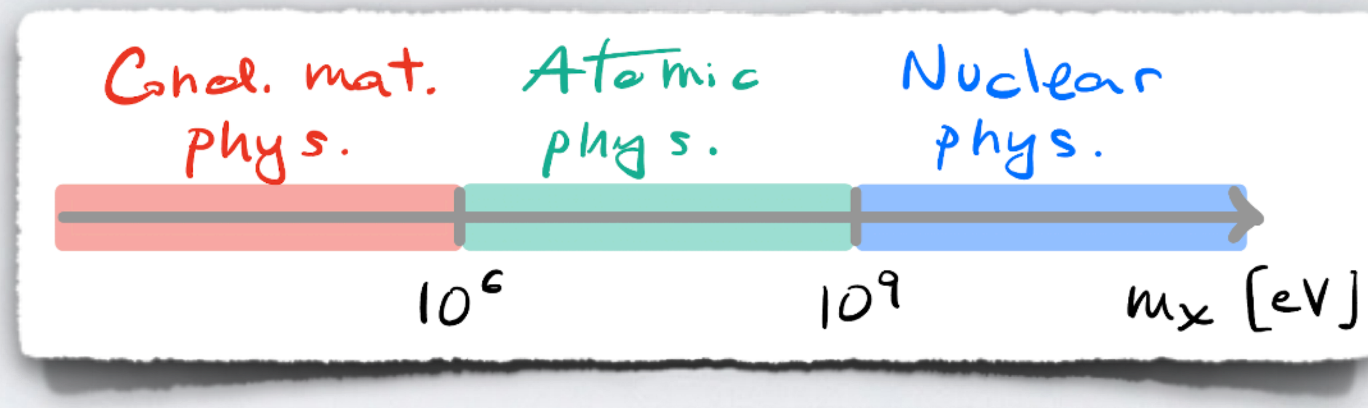

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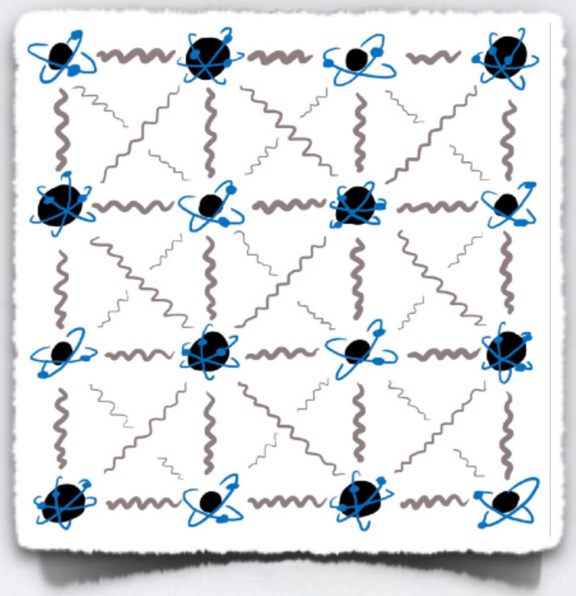
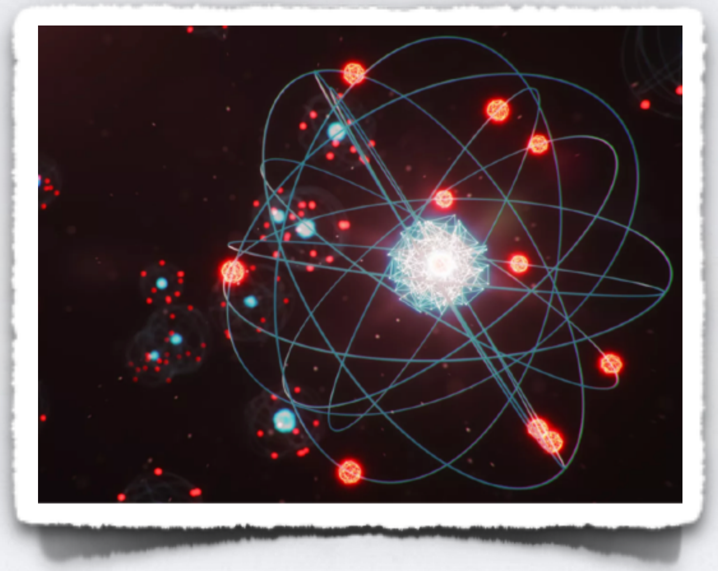


- Need to find theoretical tools that allow to solve or bypass these problems (measured correlation functions, EFTs, …)

Down to the MeV
Migdal effect in semiconductors



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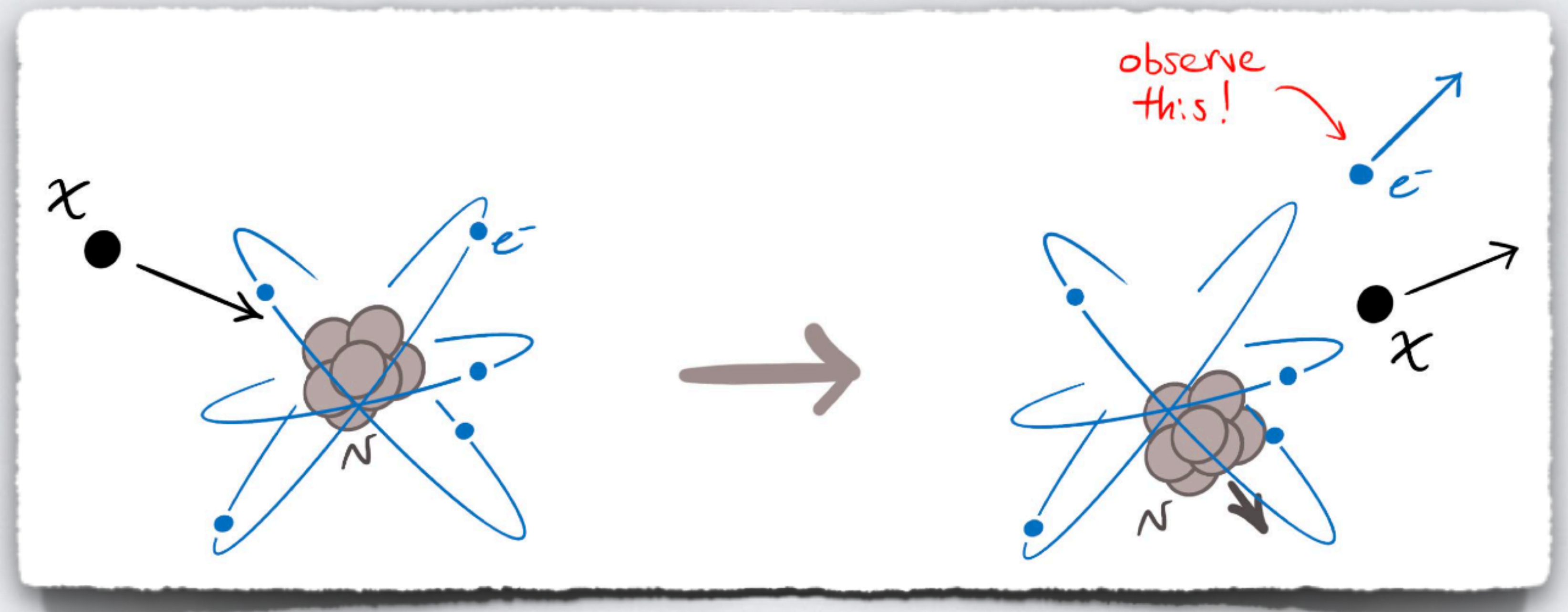

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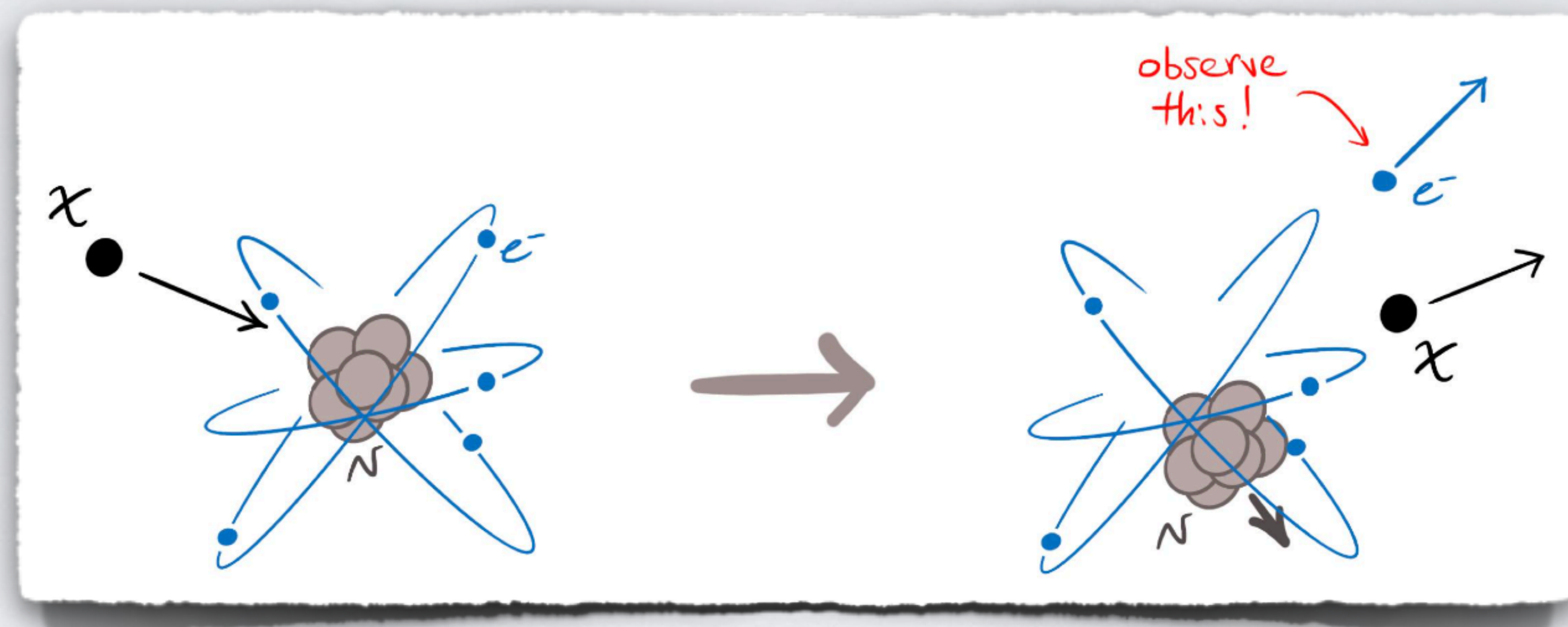

- Less likely… but lower threshold! → sensitivity down to $\mathcal{O}(100\ \text{MeV})$ masses

  [e.g., Ibe, Nakano, Shoji, Suzuki — JHEP 2018, 1707.07258; DarkSide — 2207.11967]

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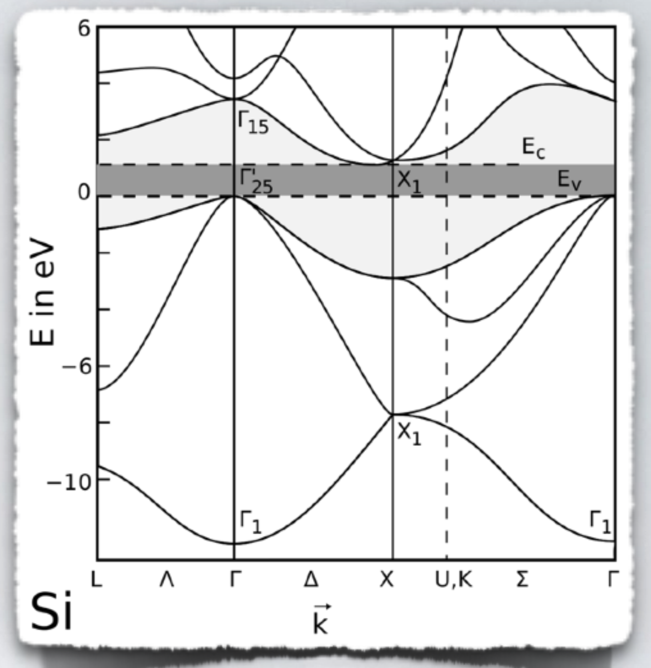

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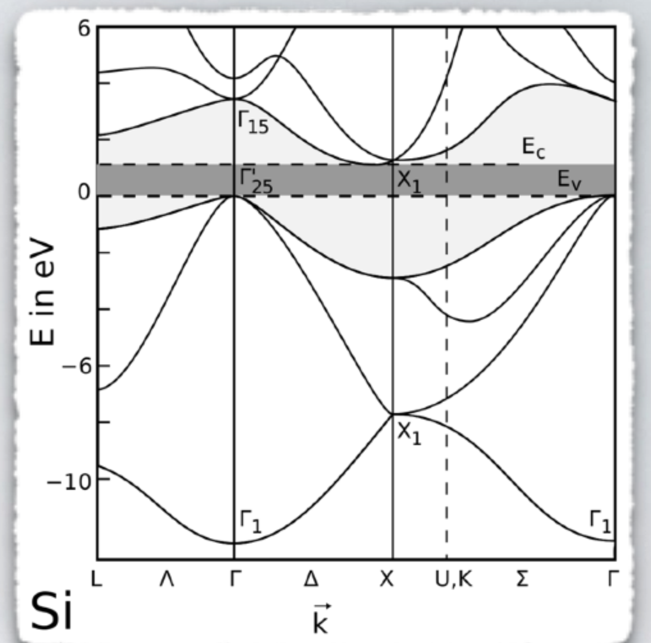

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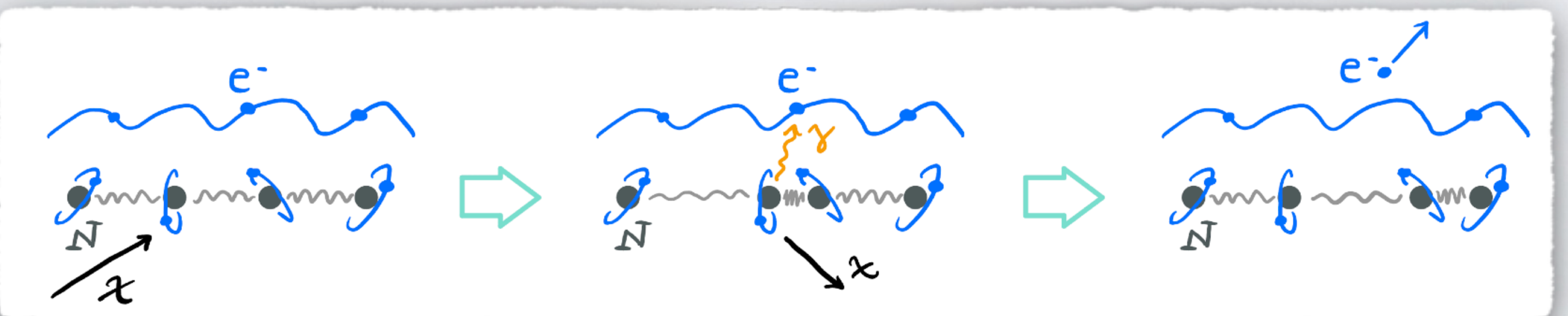

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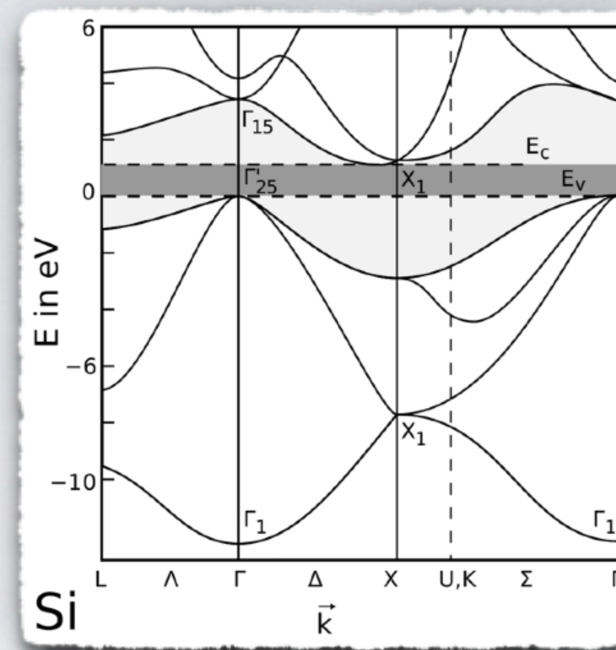

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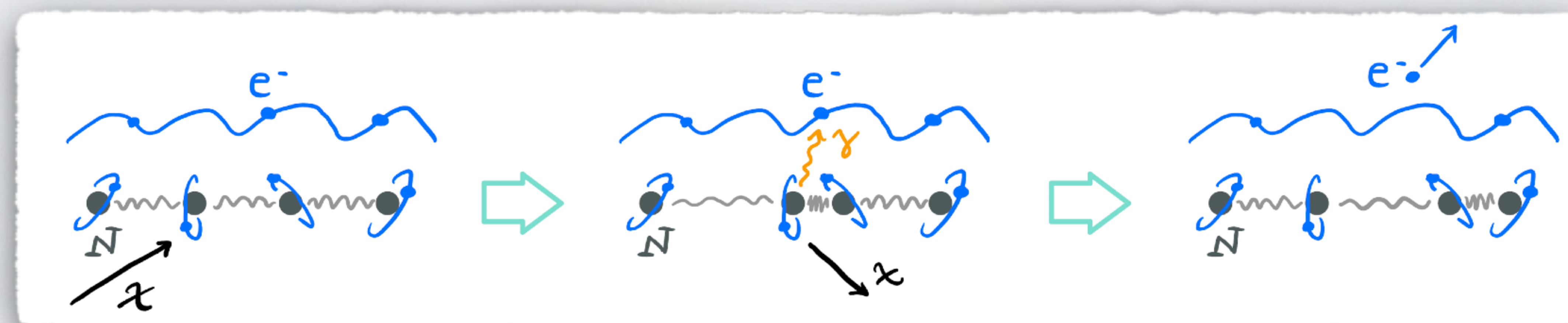

- How to describe nucleus-nucleus and nucleus-electron interactions in a strongly correlated system?

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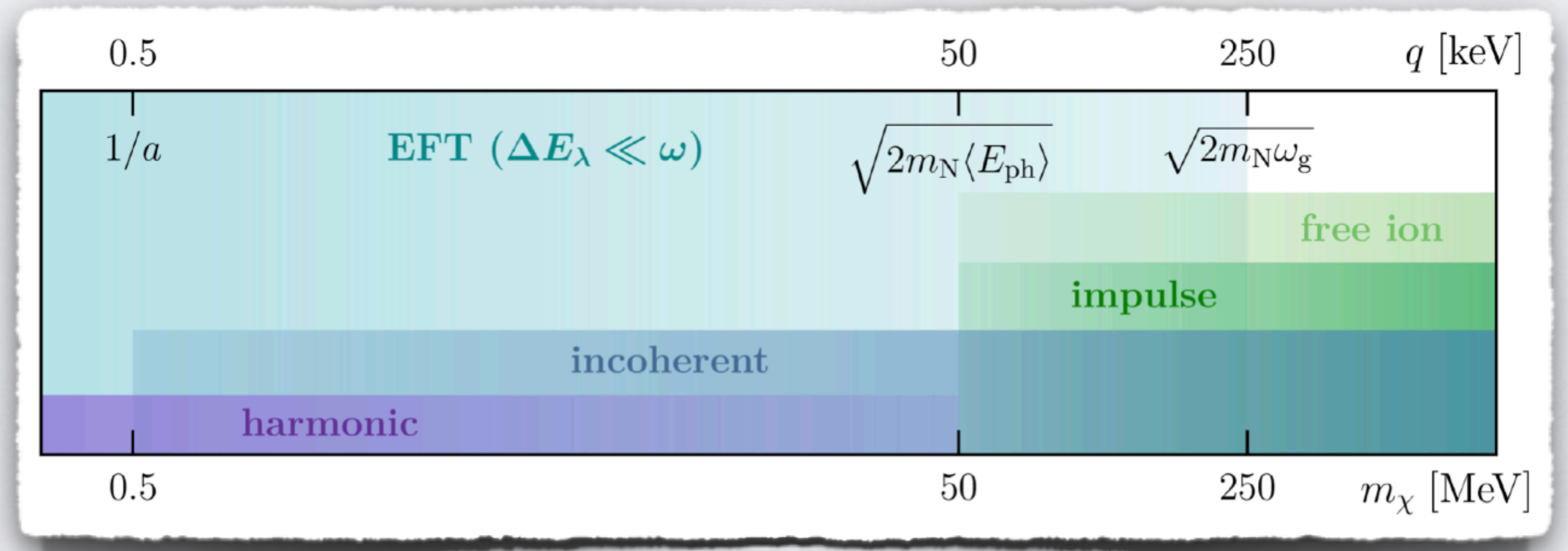

EFT

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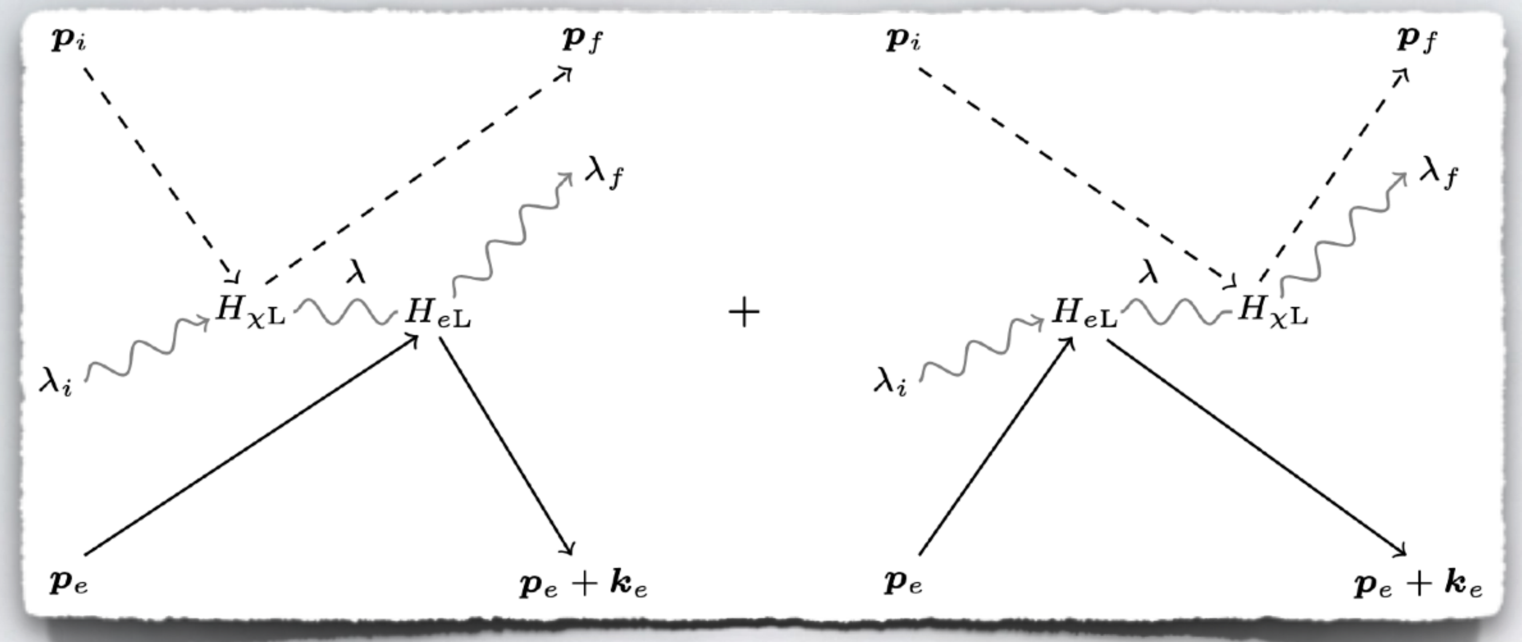

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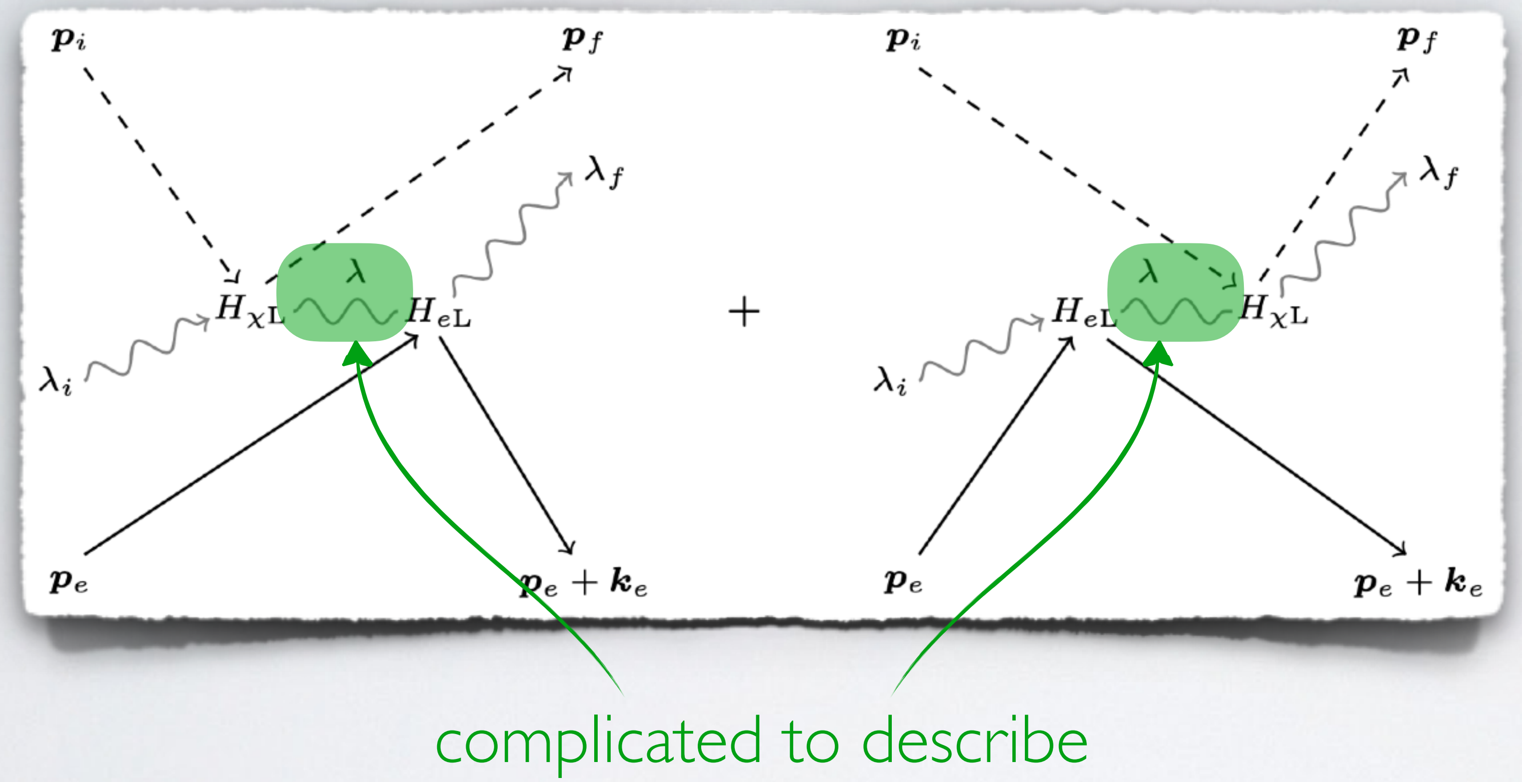

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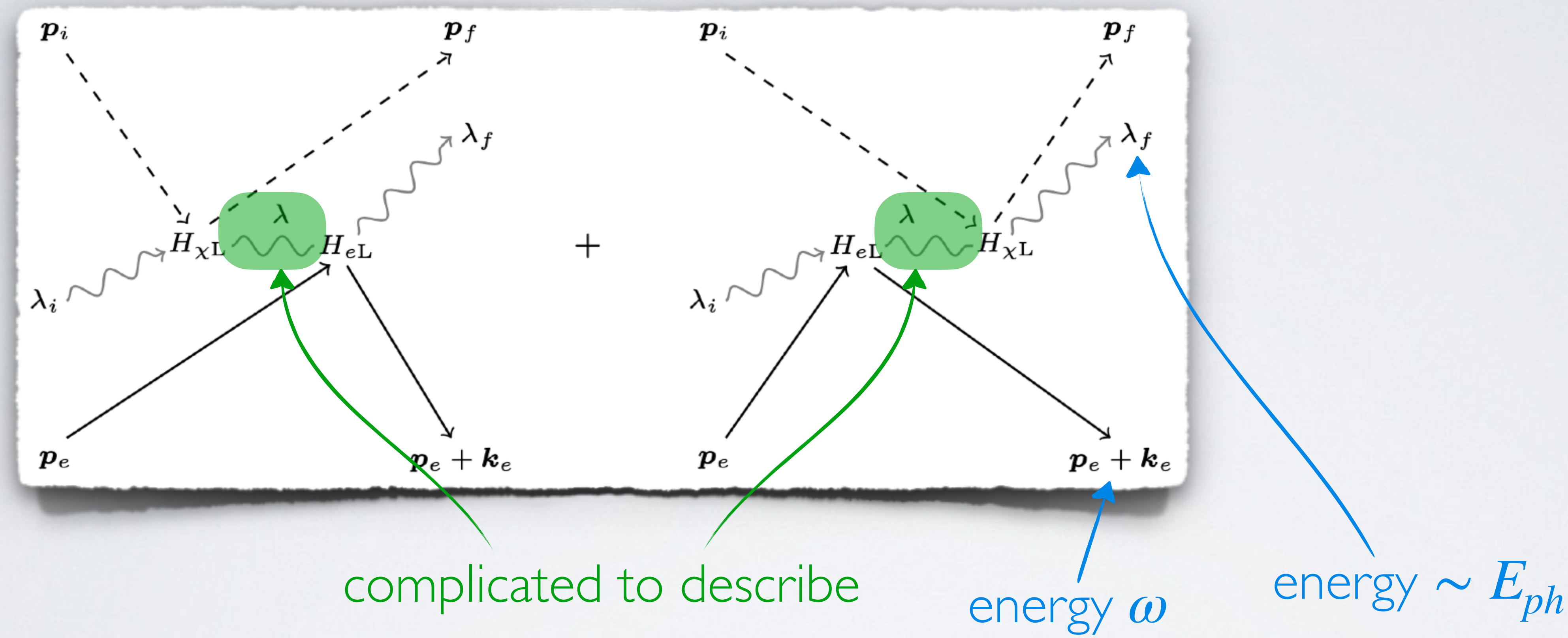

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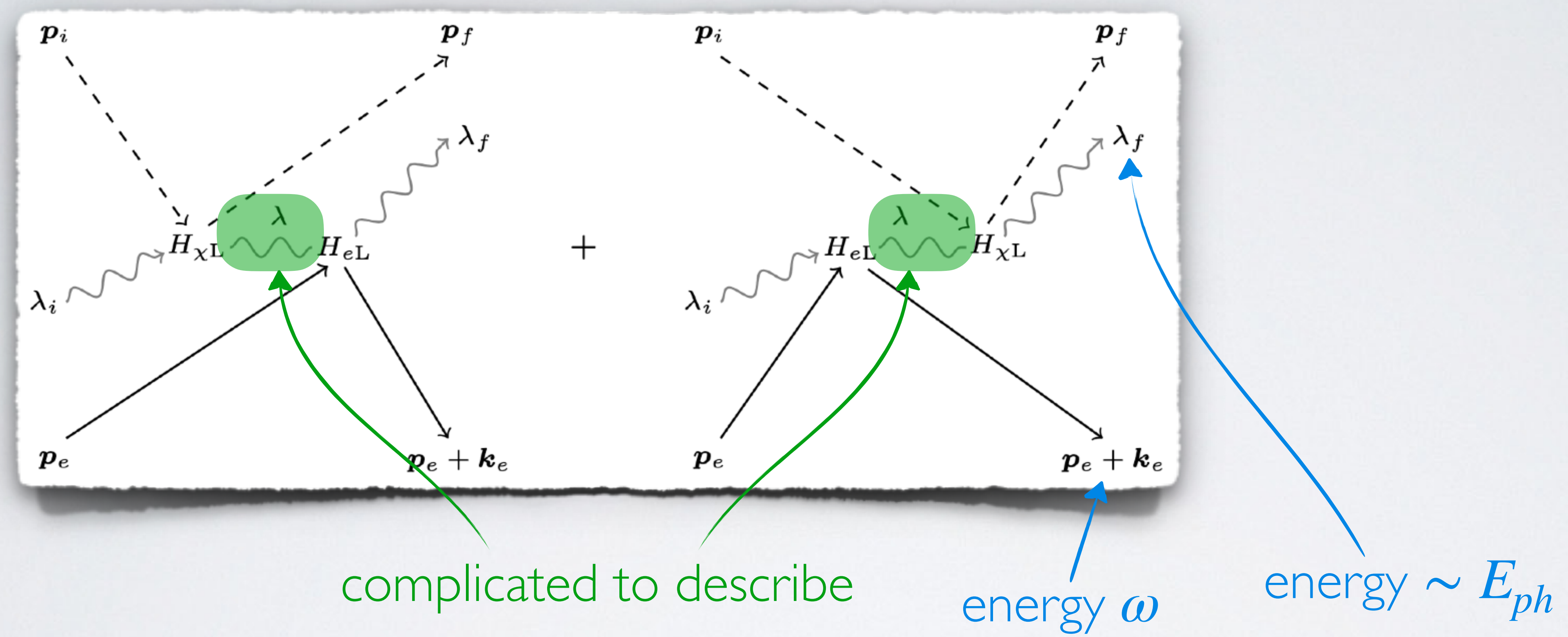

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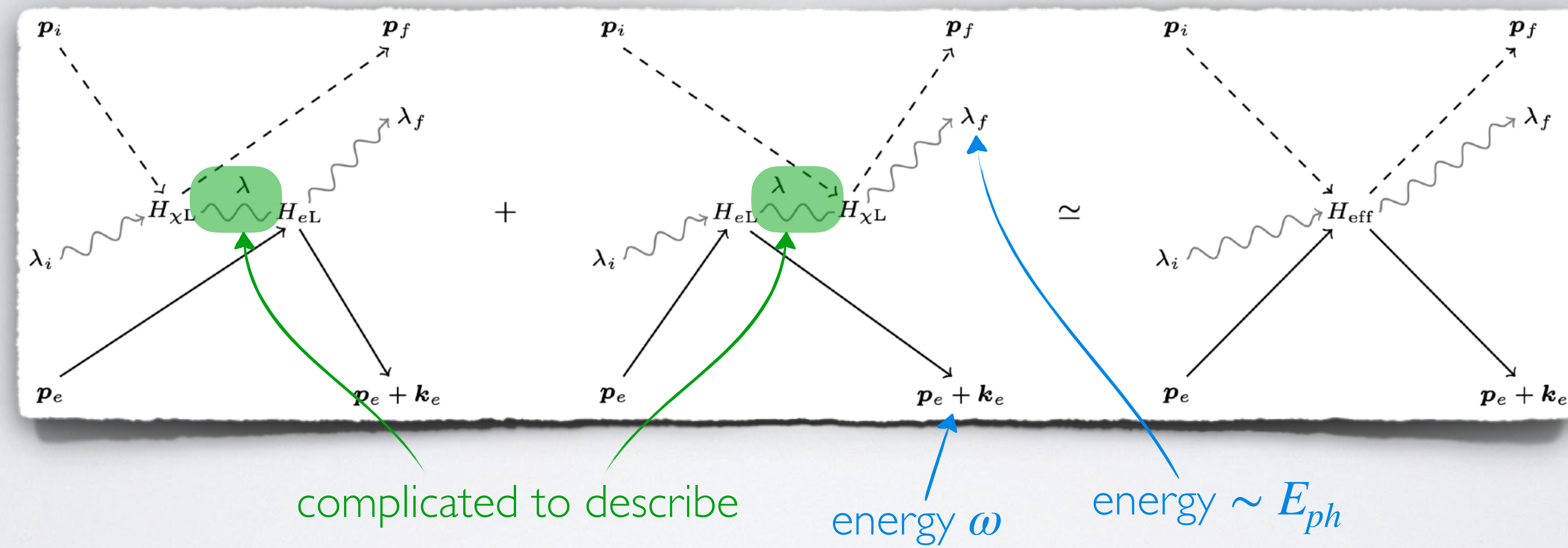

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$$H_{eff} = \frac{1}{m_N \omega^2} \vec{\nabla} H_{\chi L} \cdot \vec{\nabla} H_{eL} + \mathcal{O}\left(\frac{1}{\omega^3}\right)$$

[Berghaus, **AE**, Essig, Sholapurkar – JHEP 2020, 2210.06490]

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- Now simple to determine the rate for Migdal emission

$$\frac{d^2\Gamma}{d\omega dE_{ph}} \propto \sum_{\mathbf{k}} \sum_{\mathbf{K},\mathbf{Q}} \frac{\mathbf{q}\cdot(\mathbf{k}+\mathbf{K})\,\mathbf{q}\cdot(\mathbf{k}+\mathbf{K})}{|\mathbf{k}+\mathbf{K}||\mathbf{k}+\mathbf{Q}|} \mathrm{Im}\big(-\epsilon^{-1}_{\mathbf{KQ}}(\mathbf{k},\omega)\big) S\big(\mathbf{q}-\mathbf{k}-\mathbf{K}, E_{ph}\big)$$

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[e.g., Knapen, Kozaczuk, Lin — PRD 2021, 2101.08275; Hochberg et al. — PRL 2021, 2101.08263; Knapen, Kozaczuk, Lin — PRD 2022, 2104.12786]

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- No data yet in the range of interest ($q \simeq 10$ keV – 100 keV)

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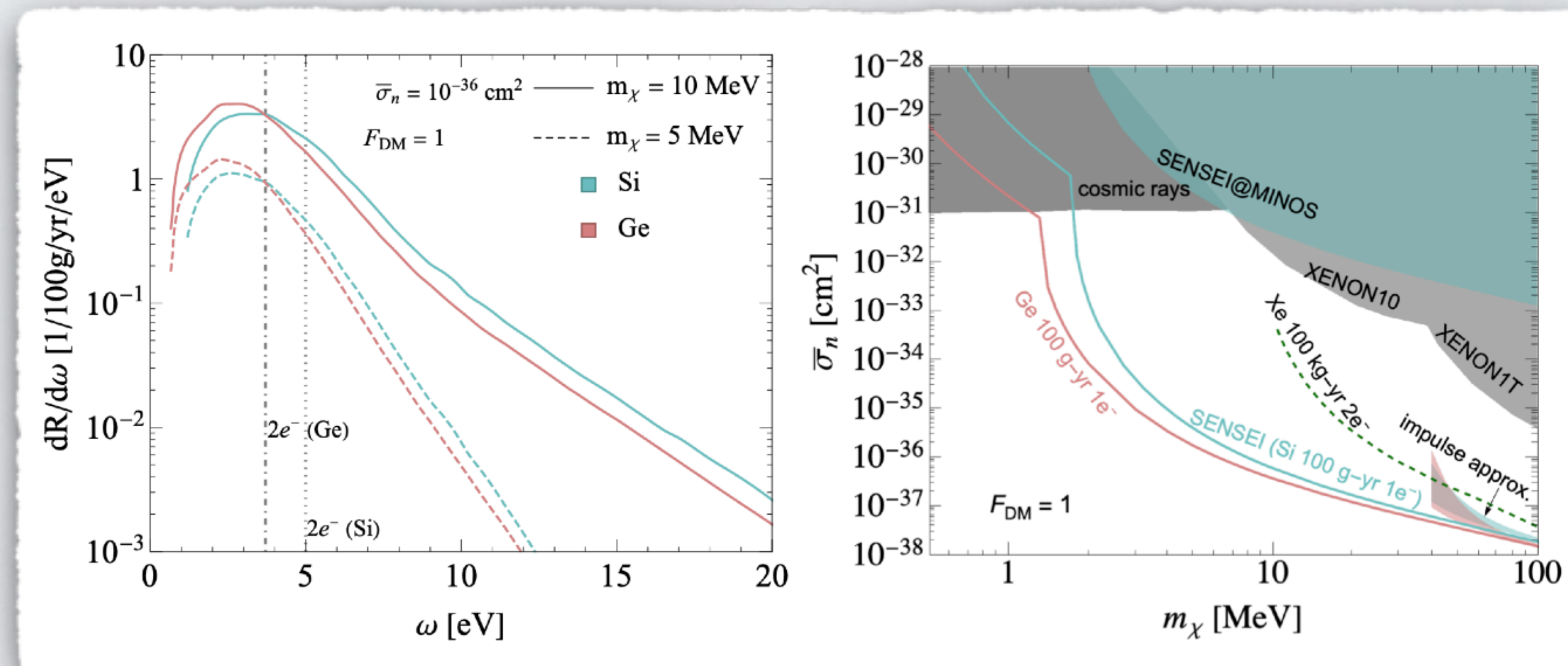

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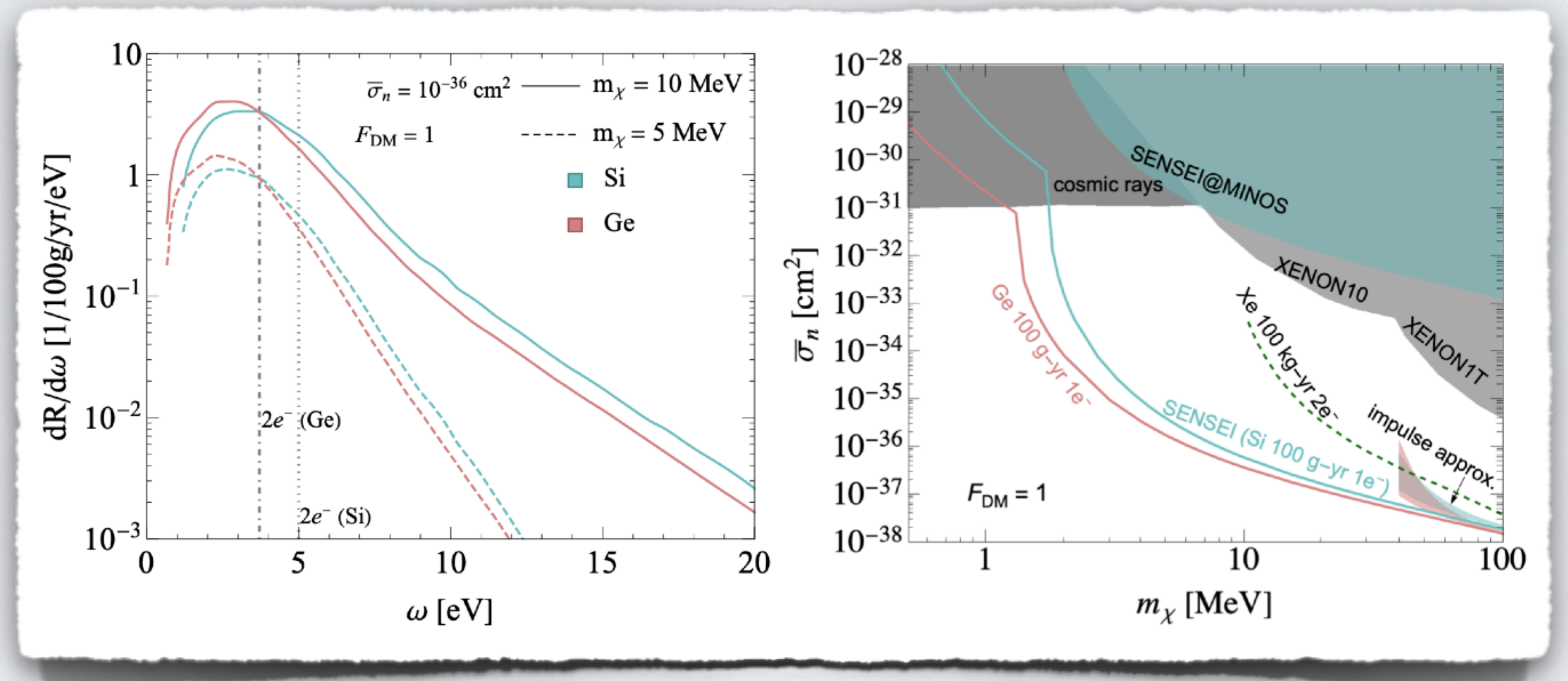

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- Description of Migdal effect in semiconductor extended to all masses

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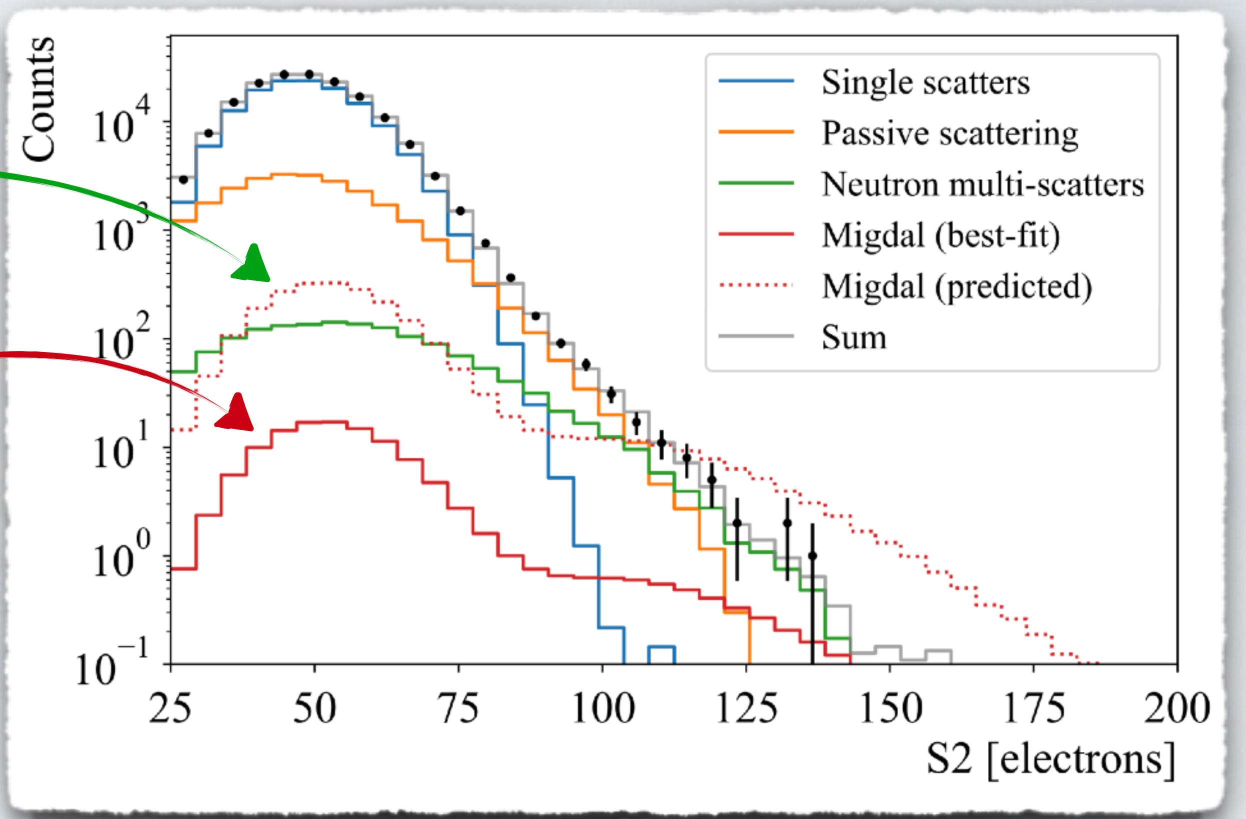
theory

experiment



[Xu et al. — 2307.12952]

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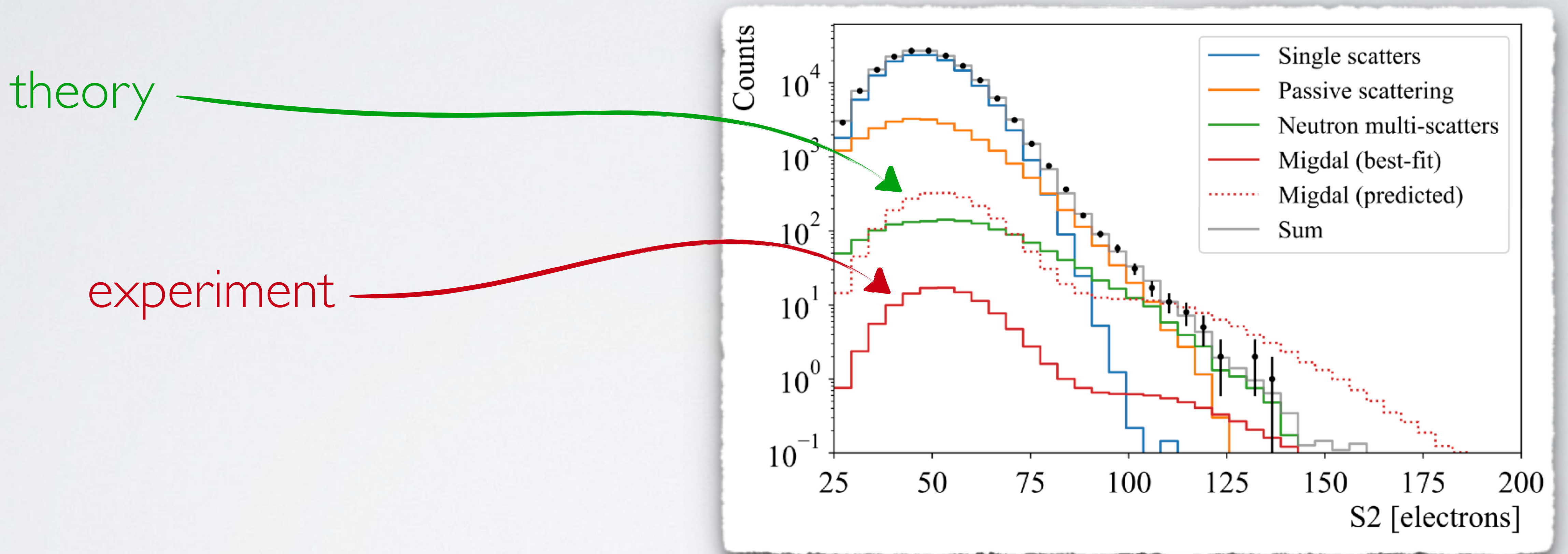
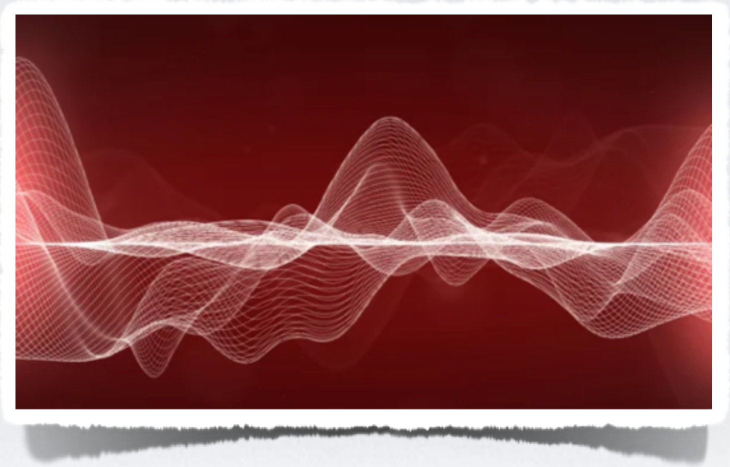


[Xu et al. — 2307.12952]

- Theory assumes free atoms → could the difference be explained by condensed matter effects? [work in progress w/ Grilli di Cortona]

Down to the keV
collective excitations



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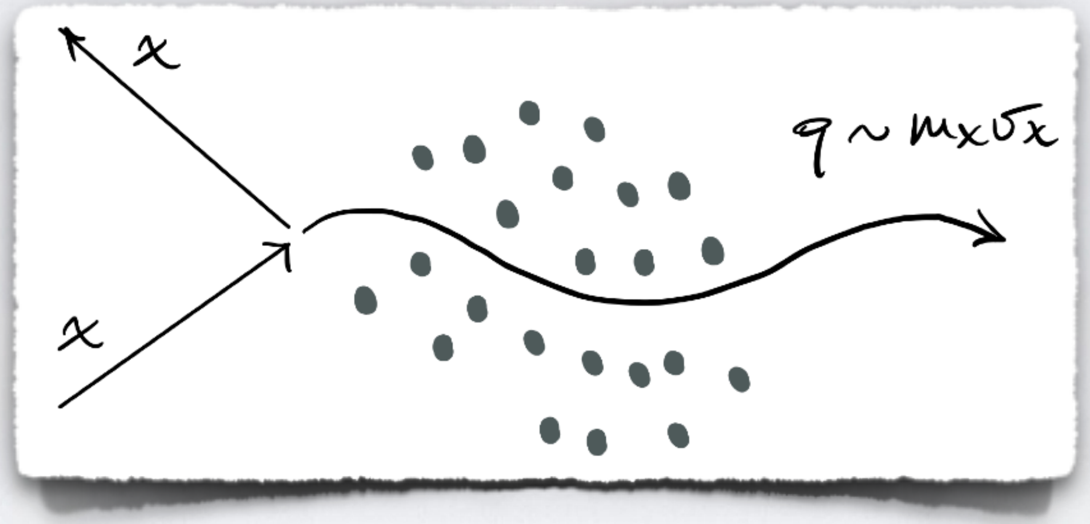

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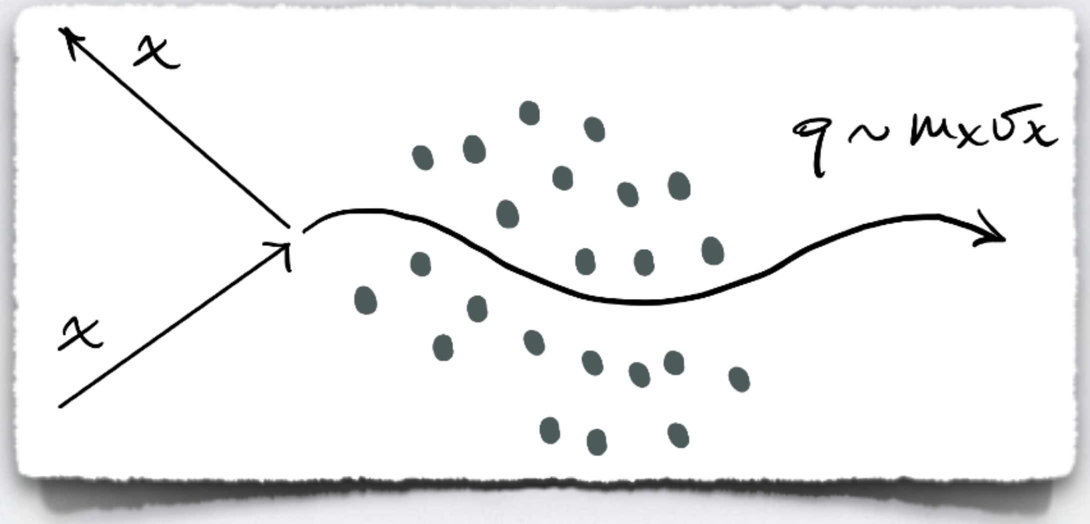

- Typically, no more single particle final states → signatures involve collective excitation [see e.g., Trickle et al. — JHEP 2020, 1910.08092; Griffin et al. — PRD 2020, 1910.10716; Coskuner et al. — PRD 2022, 2102.09567]

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1. Solid crystals (GaAs, SiO, …) → multi-phonon

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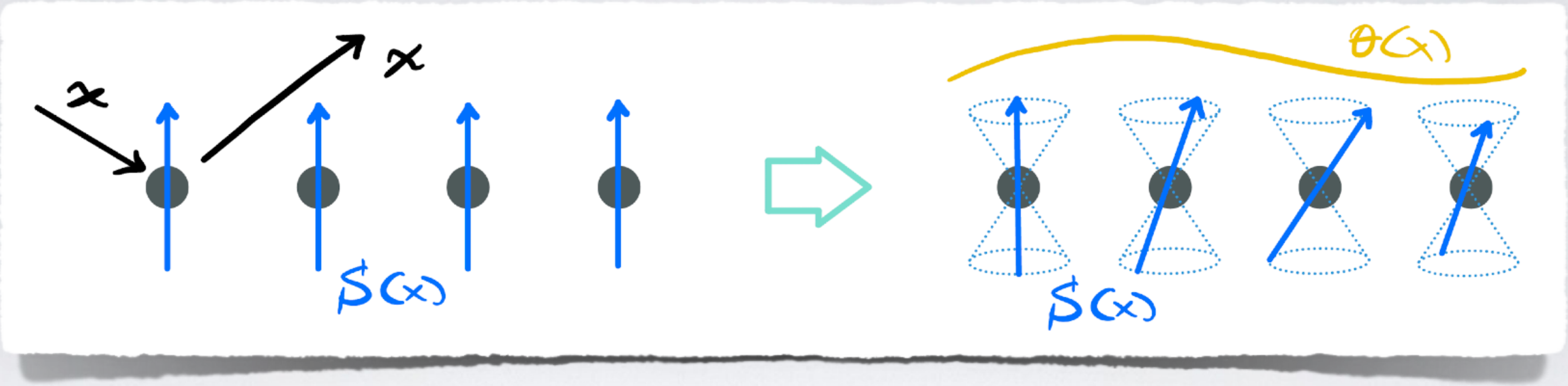

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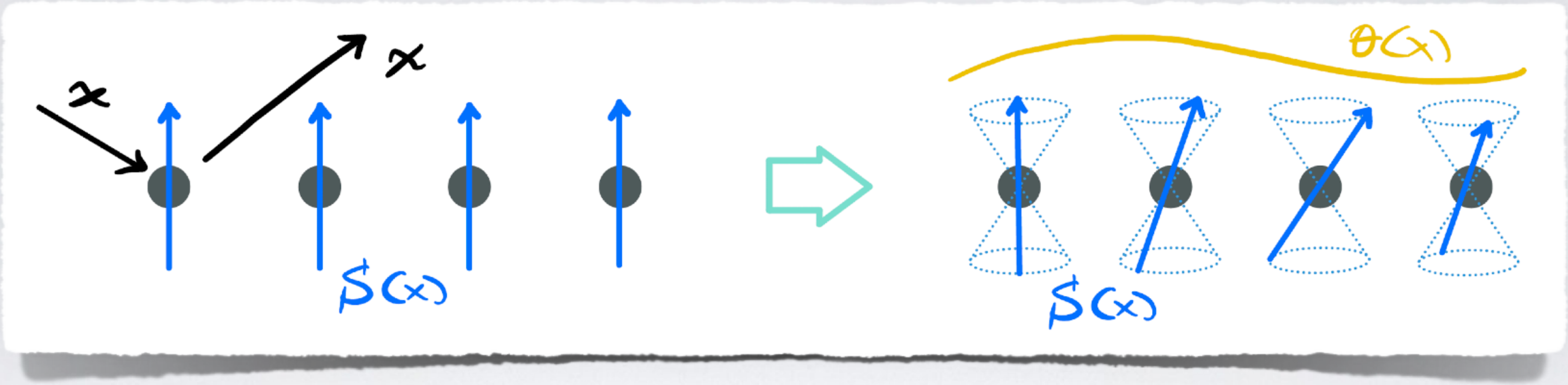

- Ways to detect few magnons have been proposed and under work (TES, MKID, quantum sensors)

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

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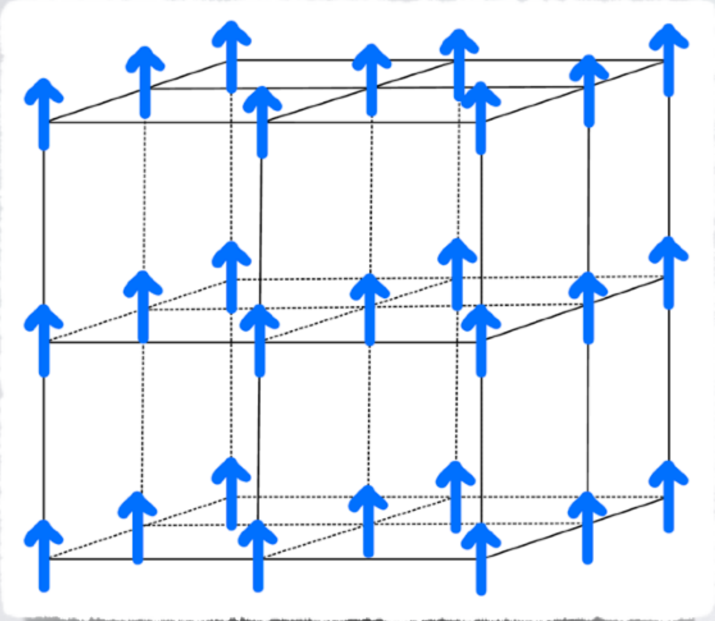

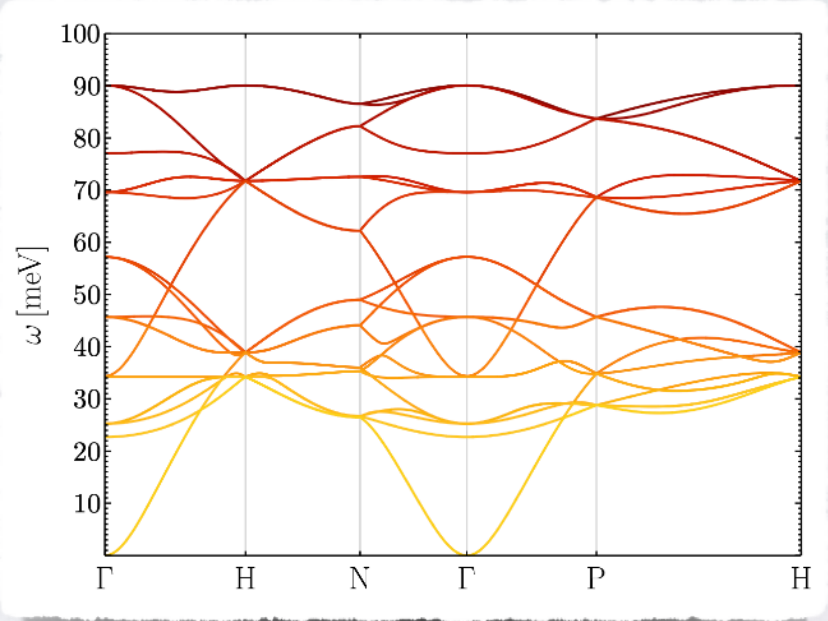

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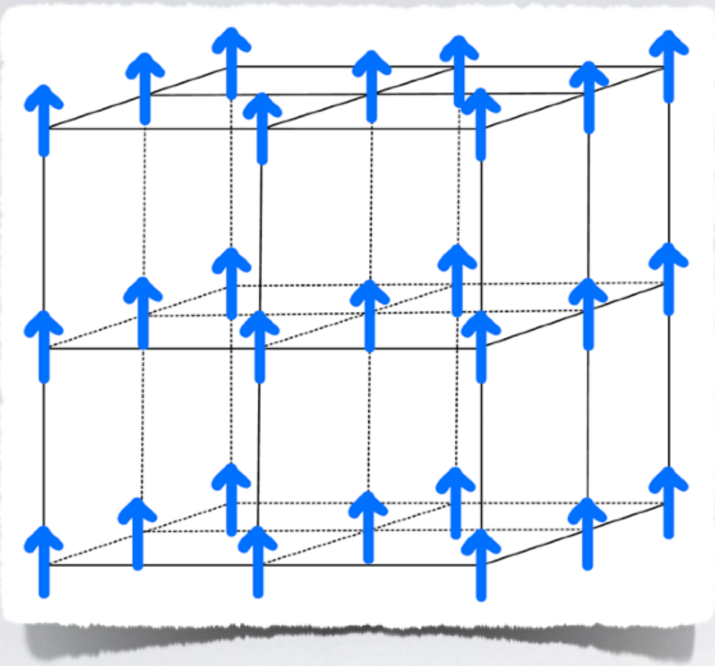

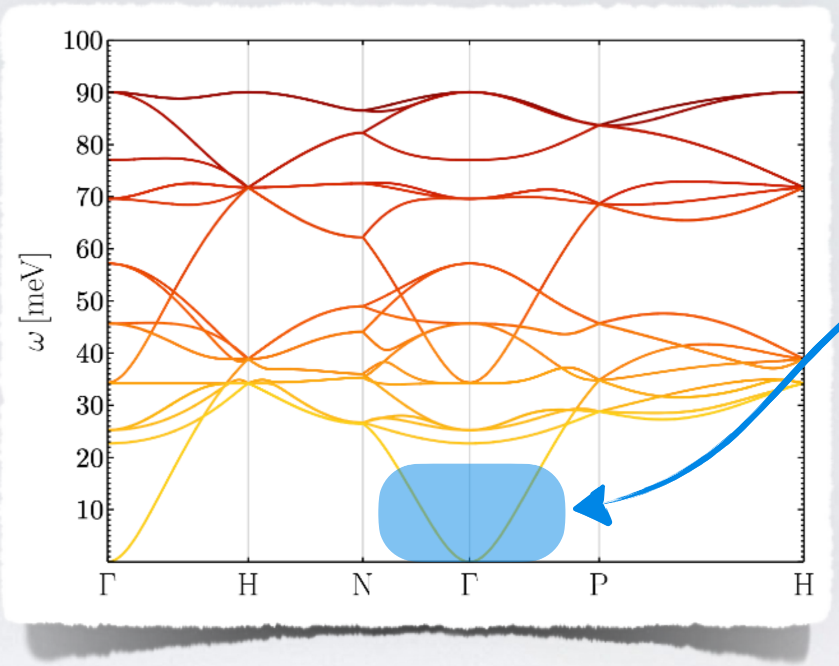

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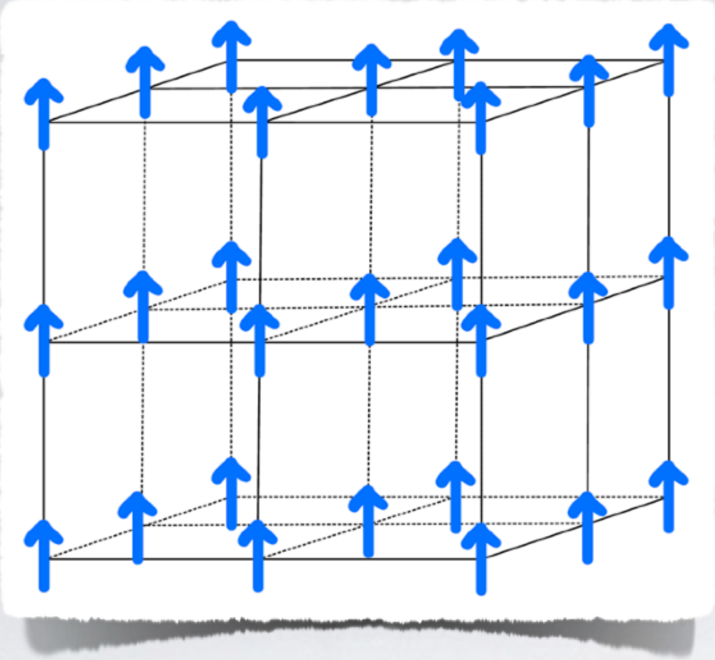

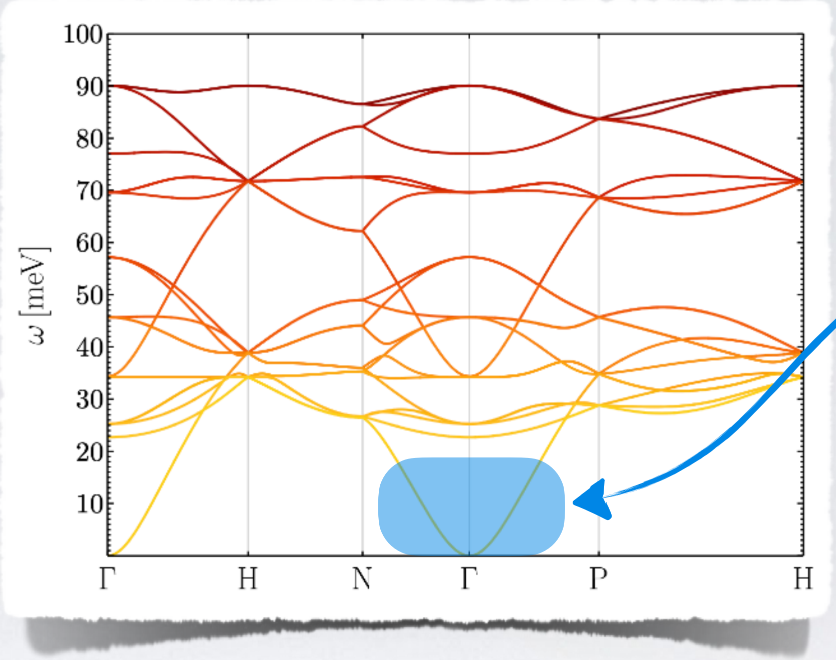

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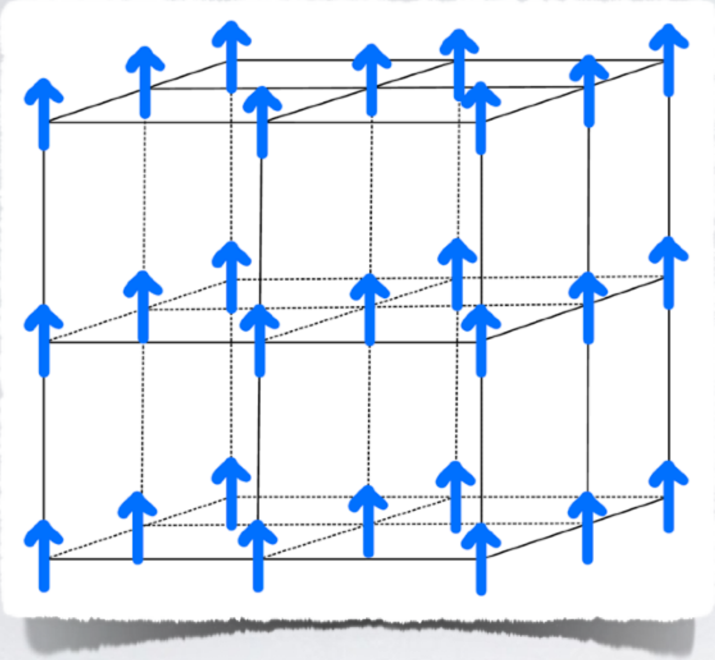

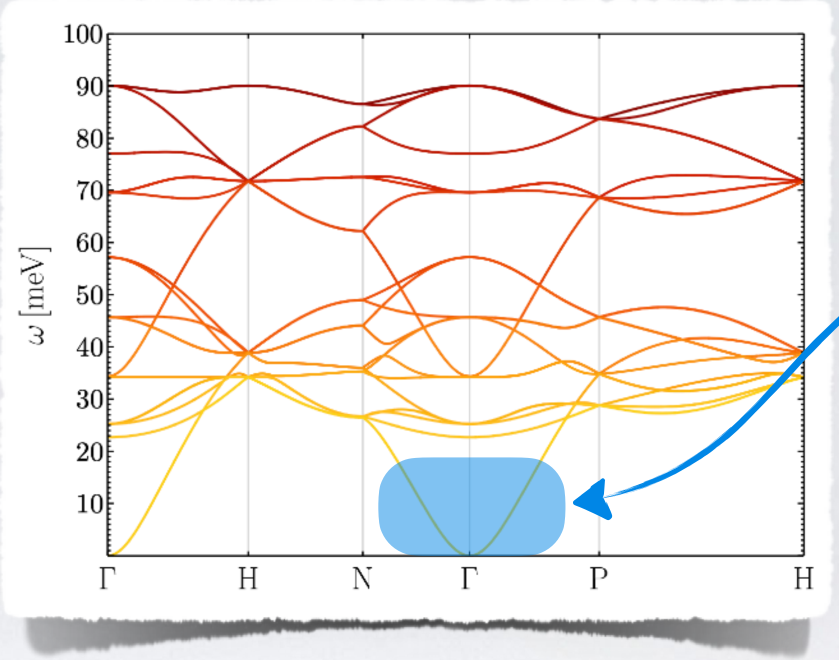

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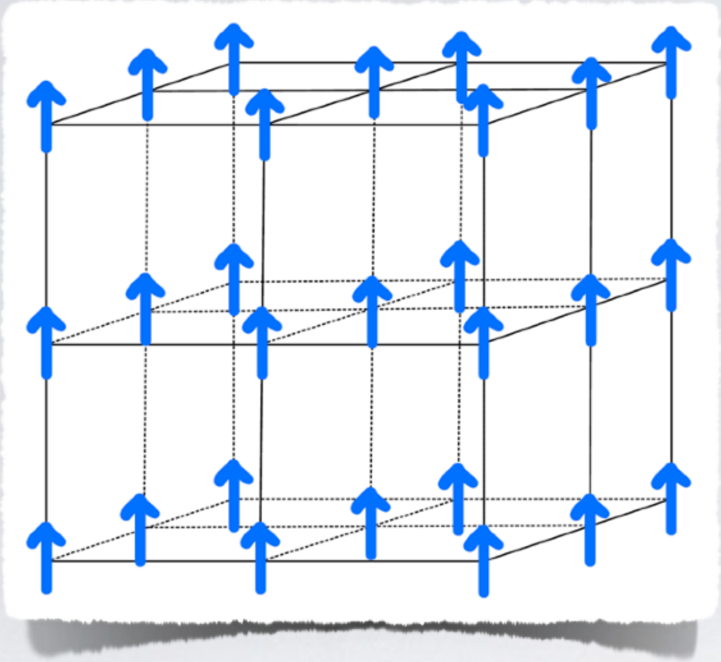

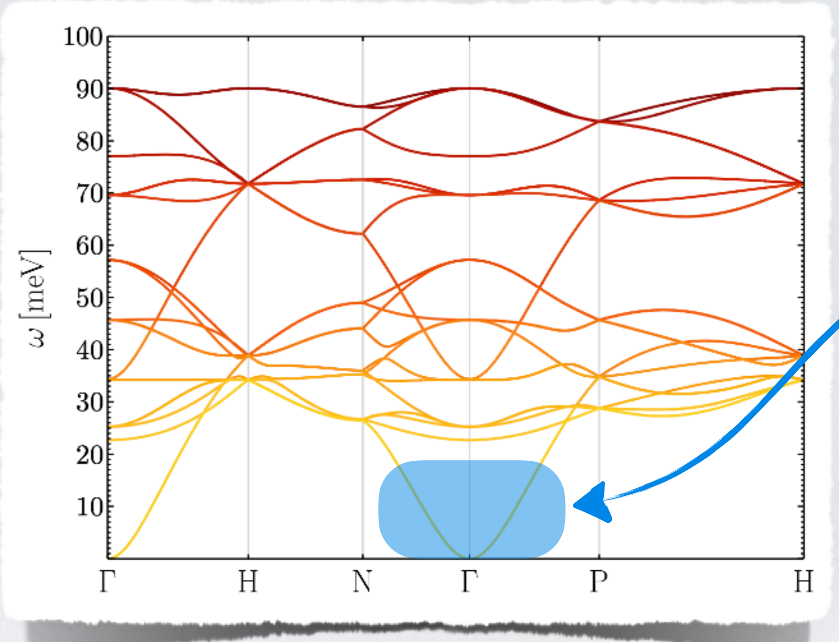

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$$\omega_{max} = E_\chi \frac{4\, m_\theta/m_\chi}{(1 + m_\theta/m_\chi)^2}$$ with $m_\theta \sim 1$ MeV → inefficient for $m_\chi \lesssim 1$ MeV

FERROMAGNETS

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- Traditional approach: quantize the Heisenberg model

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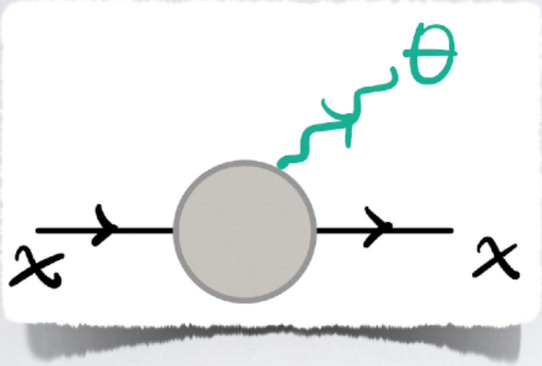

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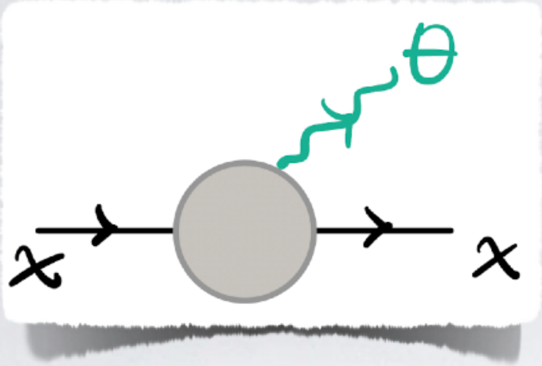

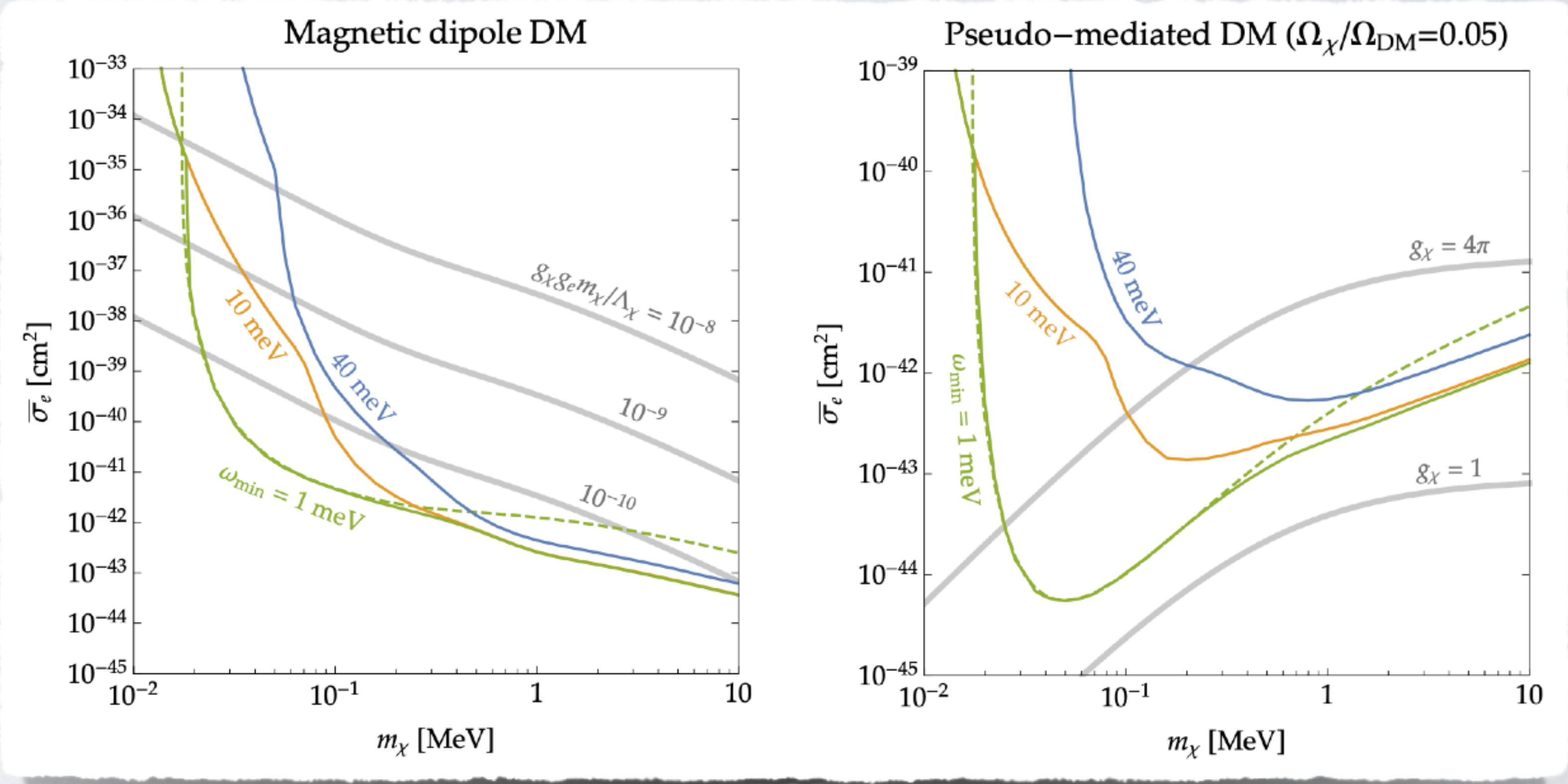

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ANTI-FERROMAGNETS

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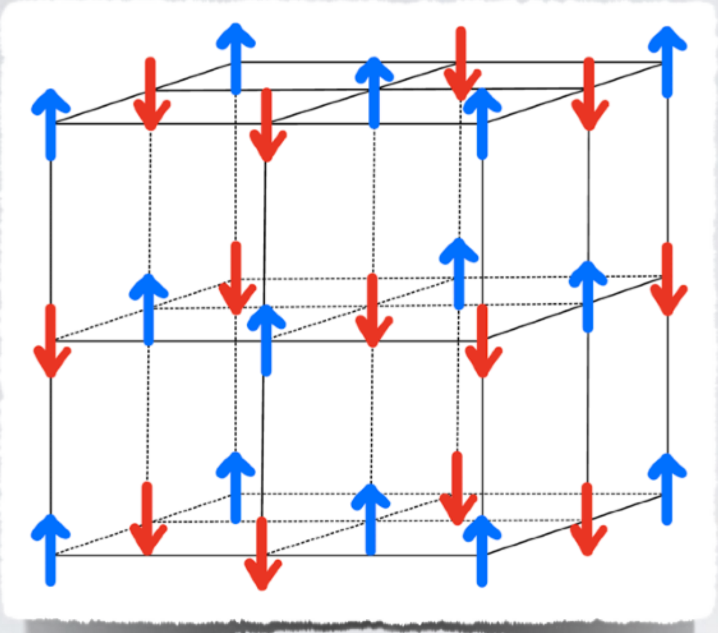

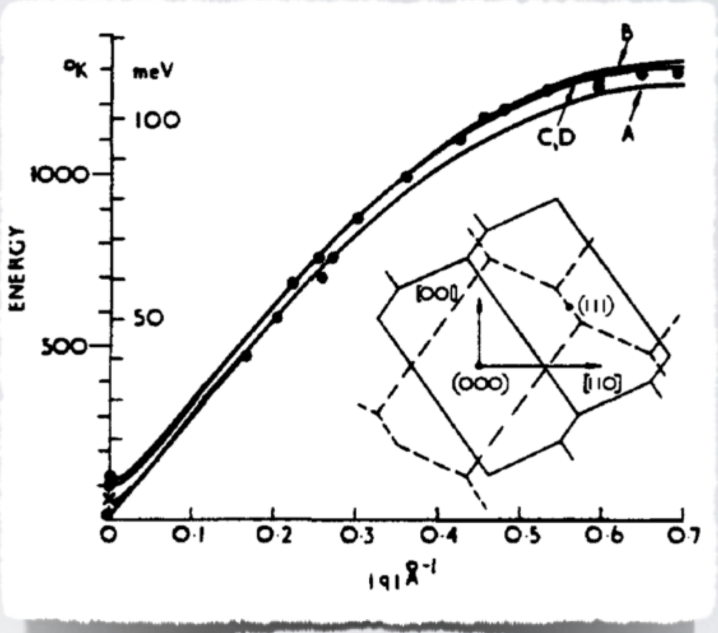

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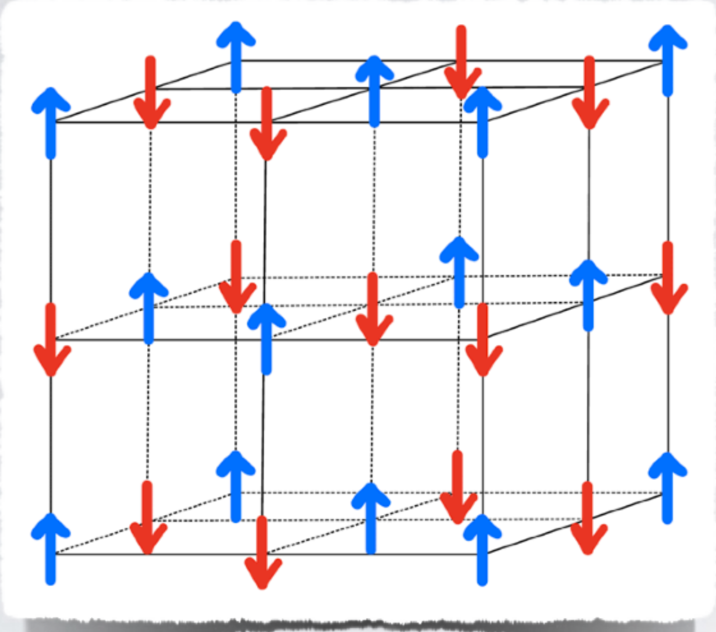

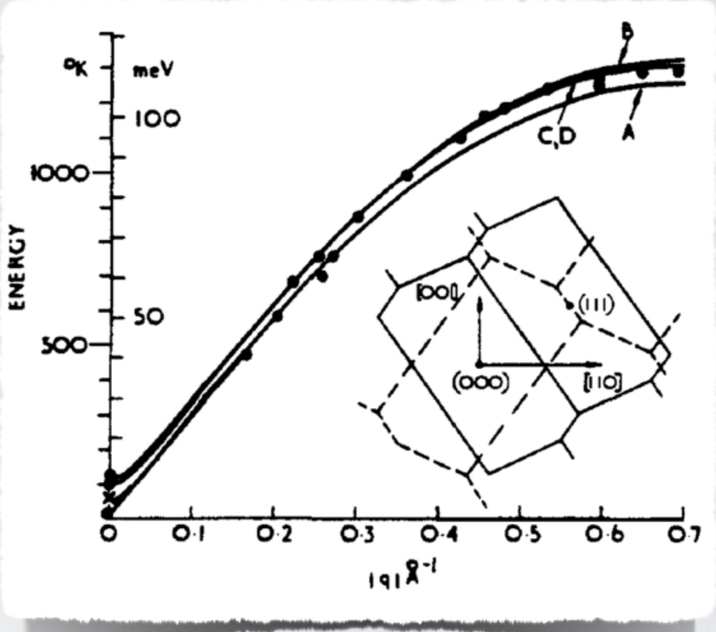

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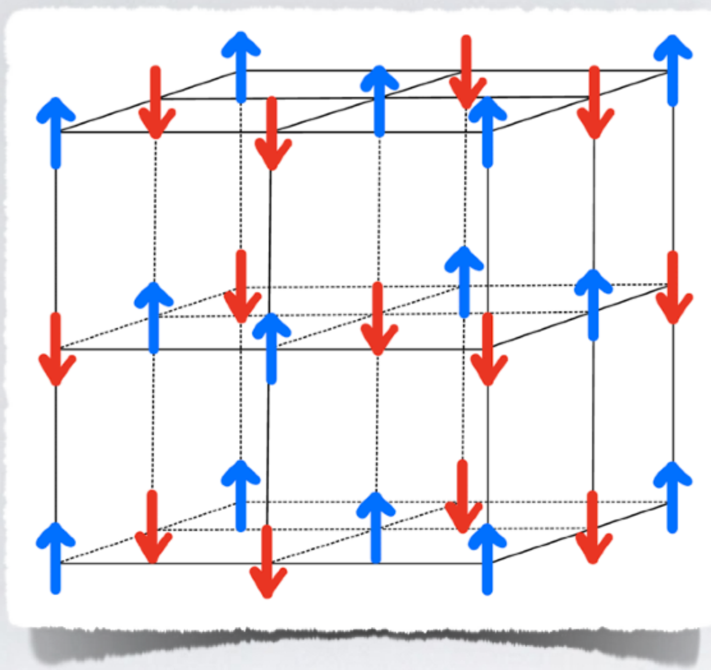

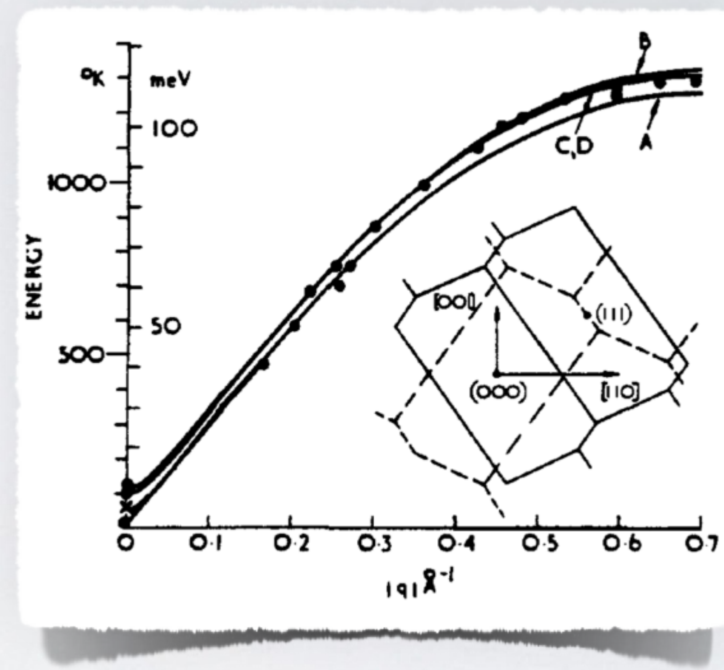

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- Nickel-oxide has $v_\theta \simeq v_\chi$ → very efficient at absorbing dark matter energy [**AE**, Pavaskar — PRD (2023), 2210.13516]

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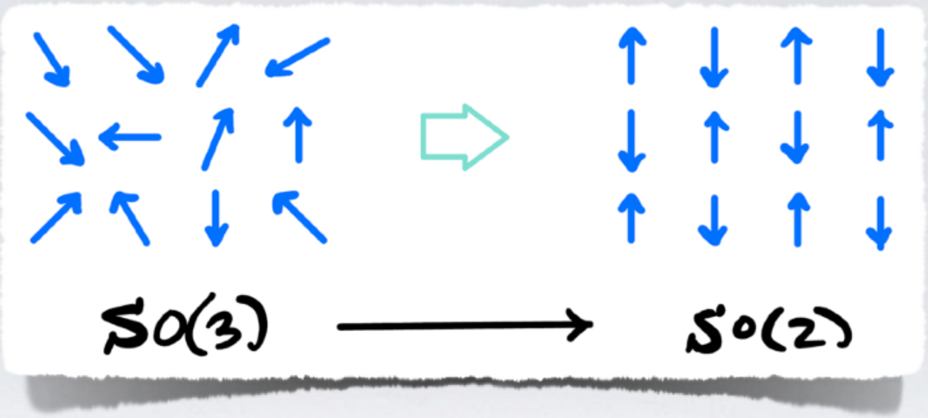
- Anti-ferromagnet spontaneously break internal spin symmetry



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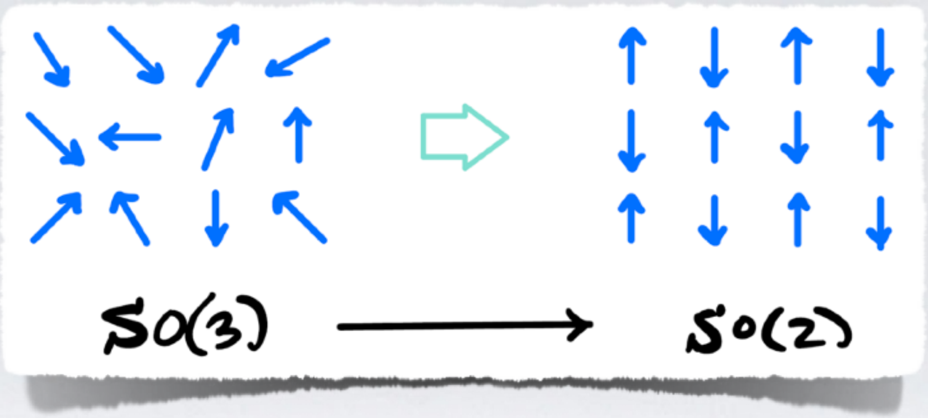

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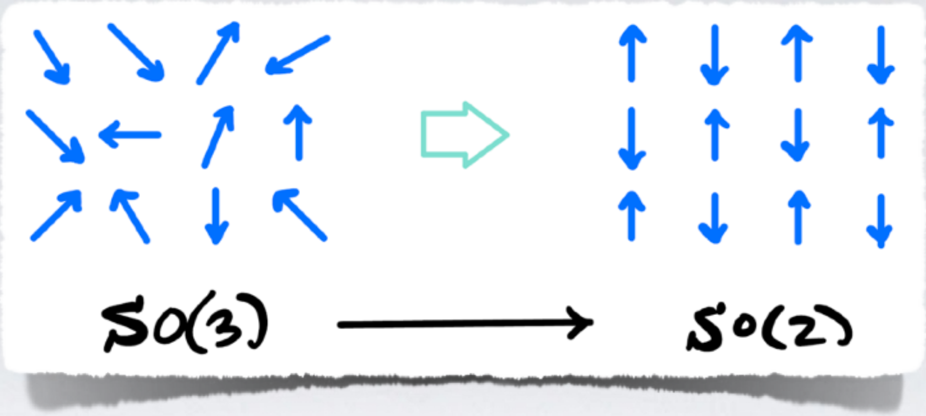

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[Burgess – Phys.Rept. 2000, hep-th/9808176; **AE**, Pavaskar – PRD (2023), 2210.13516]

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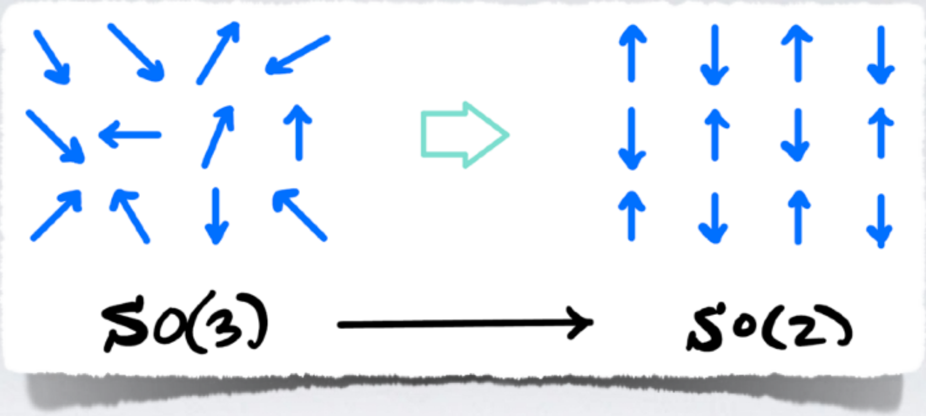

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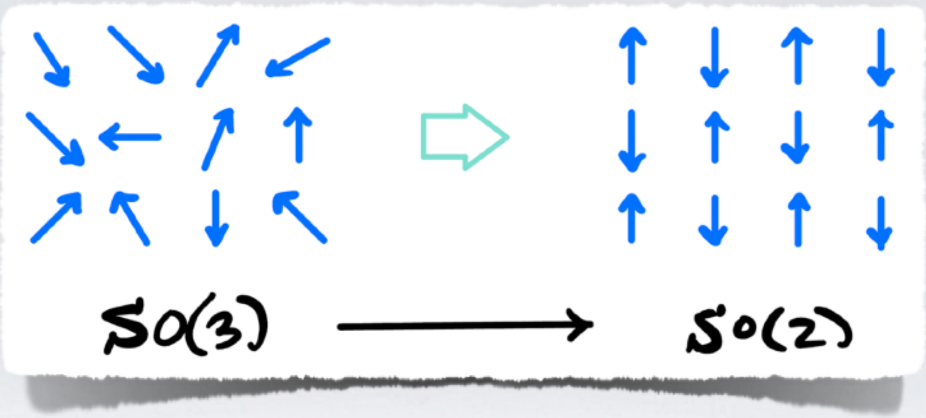

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Bypass standard difficulties in computing multi-magnon processes

[Dyson — Phys. Rev. 1956]

ANTI-FERROMAGNETS

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- With an EFT at hand → use standard QFT methods to compute event rates [**AE**, Pavaskar — PRD (2023), 2210.13516]

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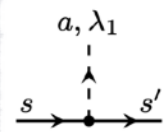
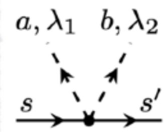


$$= -\frac{g_\chi g_e \sqrt{c_1}}{m_e}\omega \times \begin{cases} \frac{4}{\Lambda_\chi} P_{ia}(\boldsymbol{q})\sigma^i & \text{m.d.} \\ q^a/q^2 & \text{p.m.} \end{cases},$$



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

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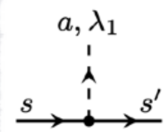

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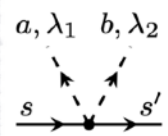

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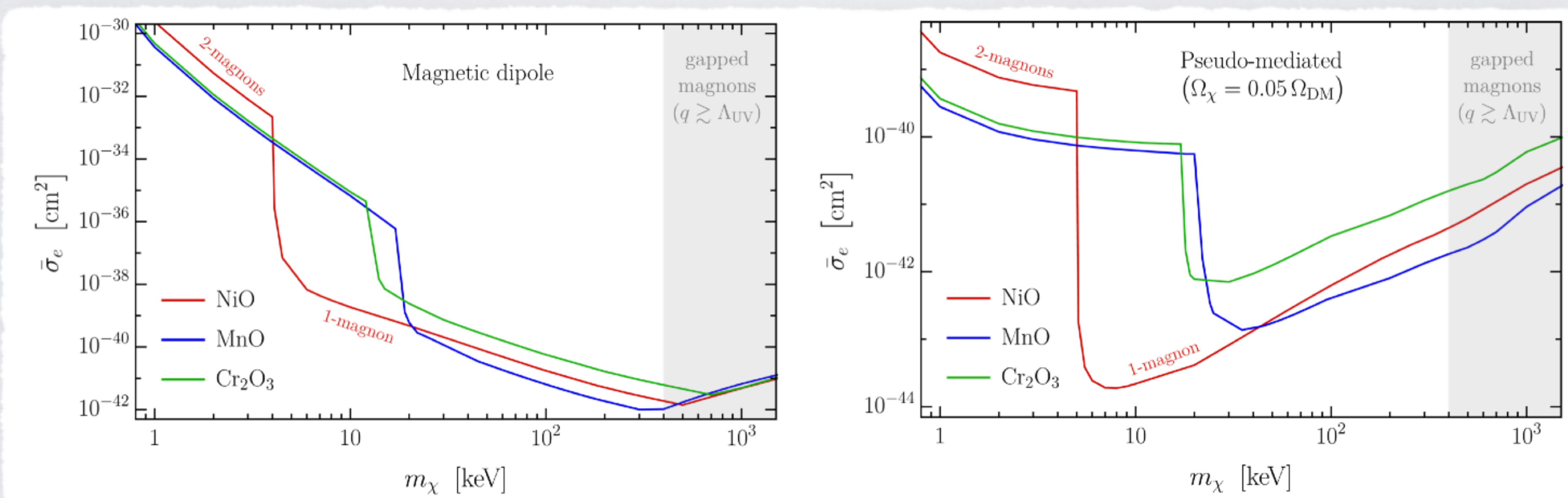

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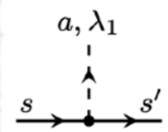

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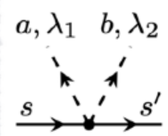

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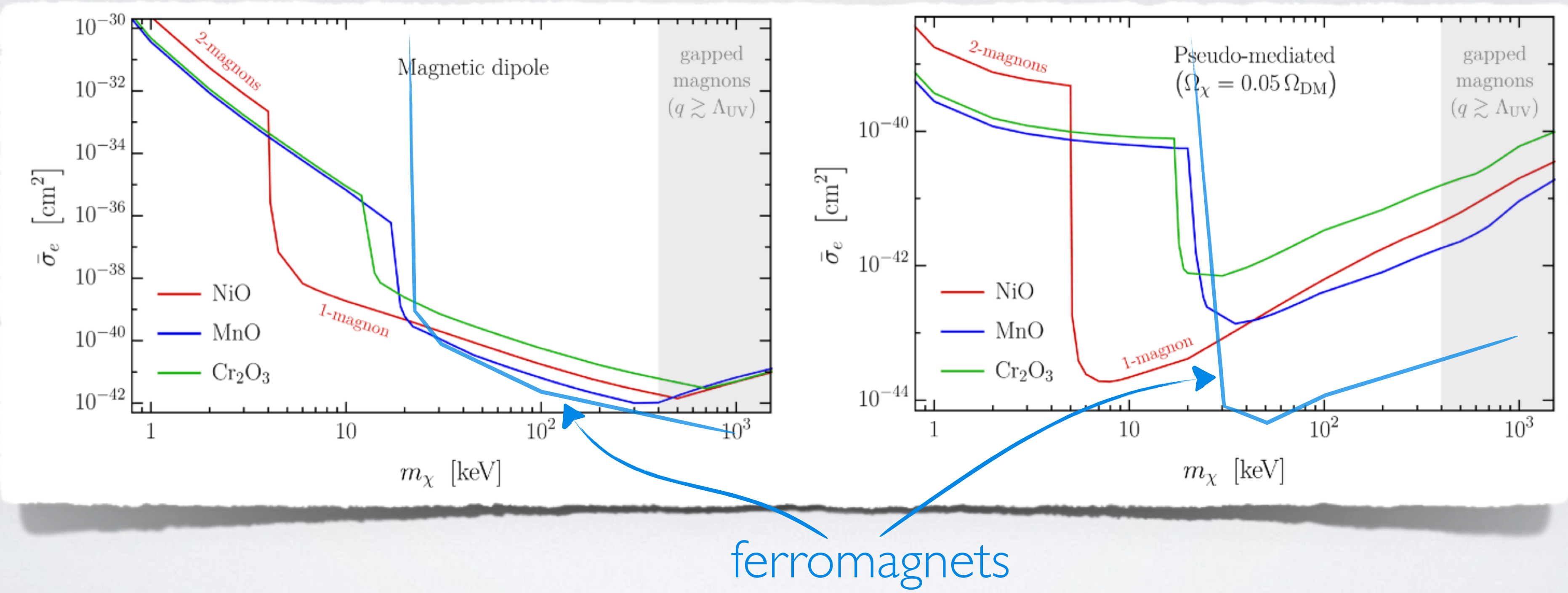
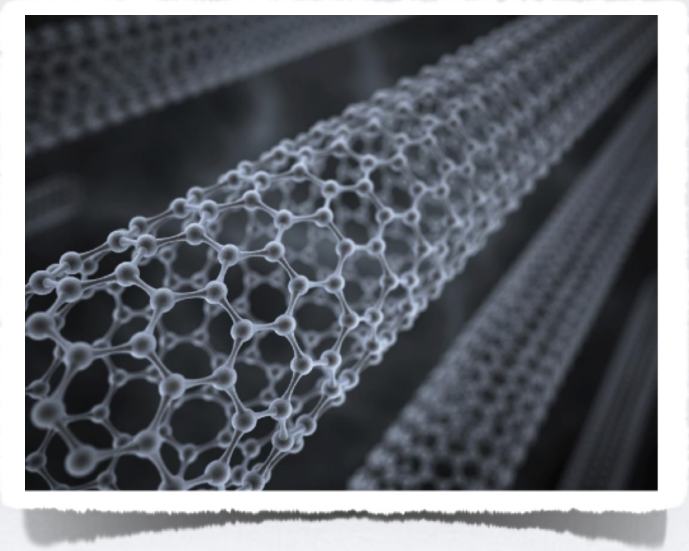


<u>Honorable mention:</u> carbon nanotubes



CARBON NANOTUBES

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- Another promising proposal for sub-GeV dark matter searches are carbon nanotubes

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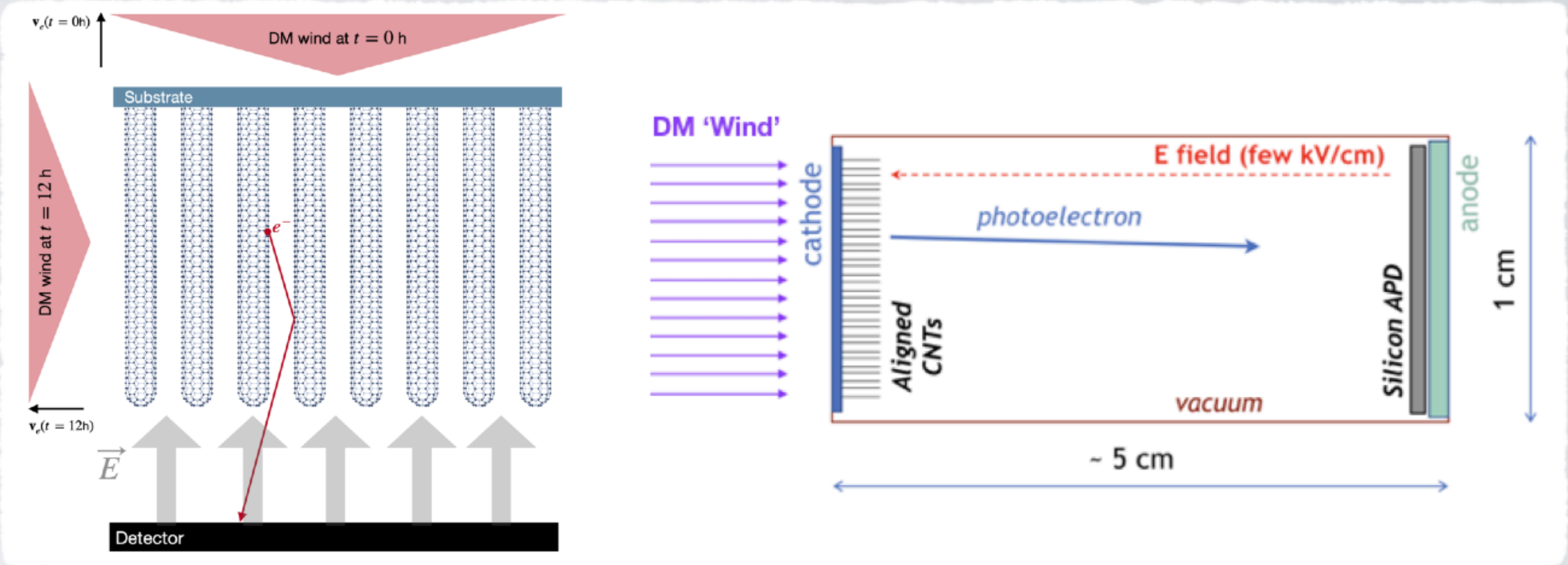

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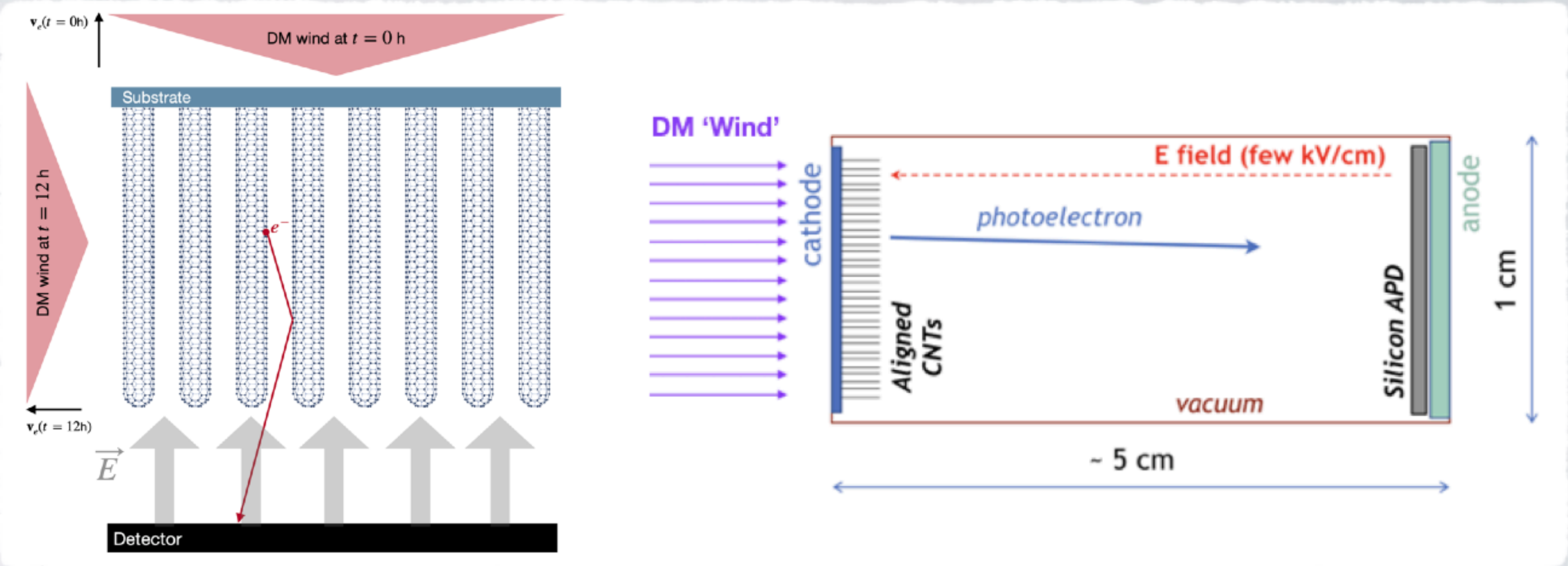

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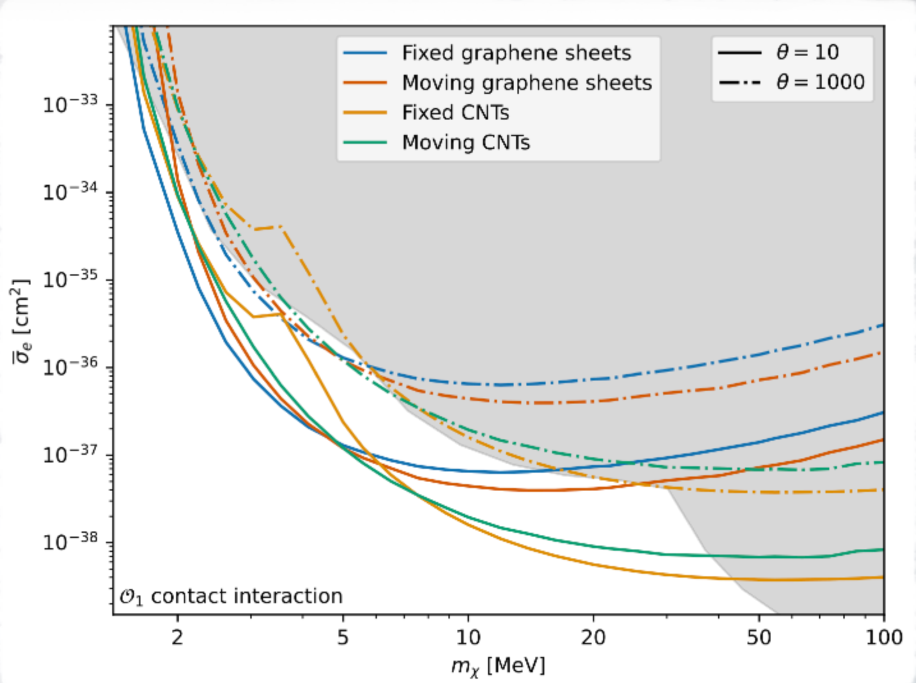

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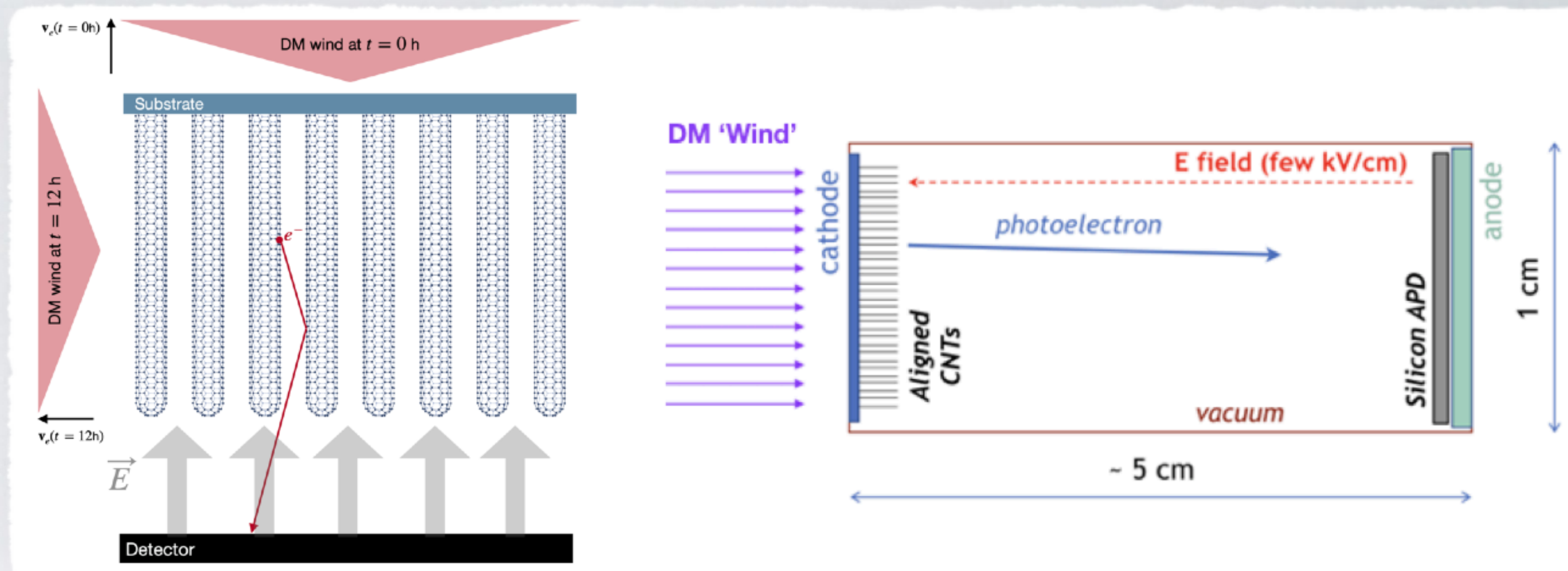

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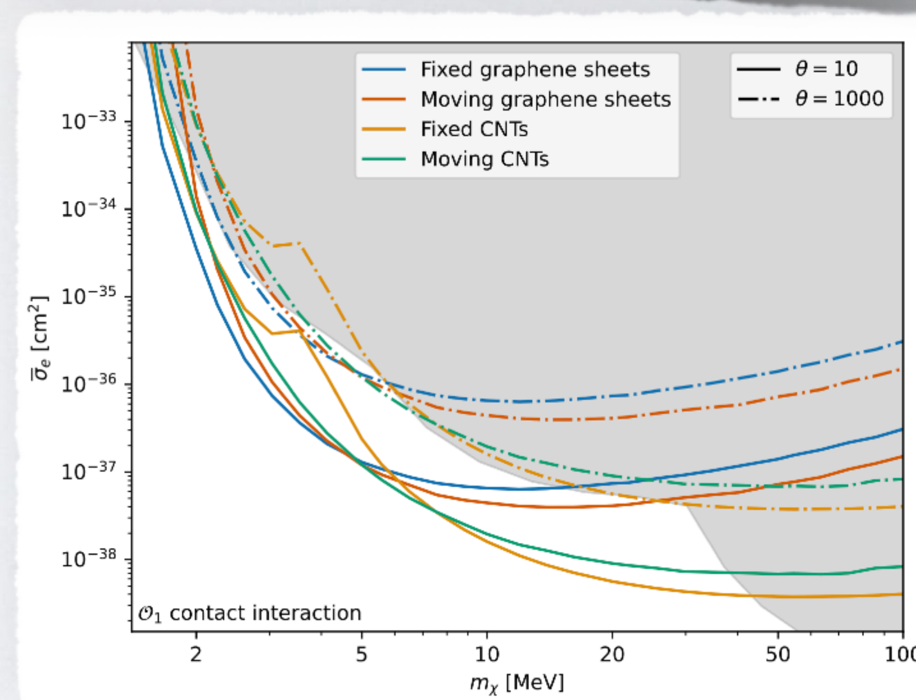
- Might be a good probe for DM-nucleon interactions as well

[Cavoto, **AE**, Pandolfi, Papiri, Polosa, Tarquini — work in progress]



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Thank you for the attention!