SUB-GEV DARK MATTER IN THE LAB

NEW IDEAS AND NEW TOOLS

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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

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- Down to the MeV: Migdal effect
- Down to the keV: collective excitations
- Outlook

SUB-GEV DARK MATTER

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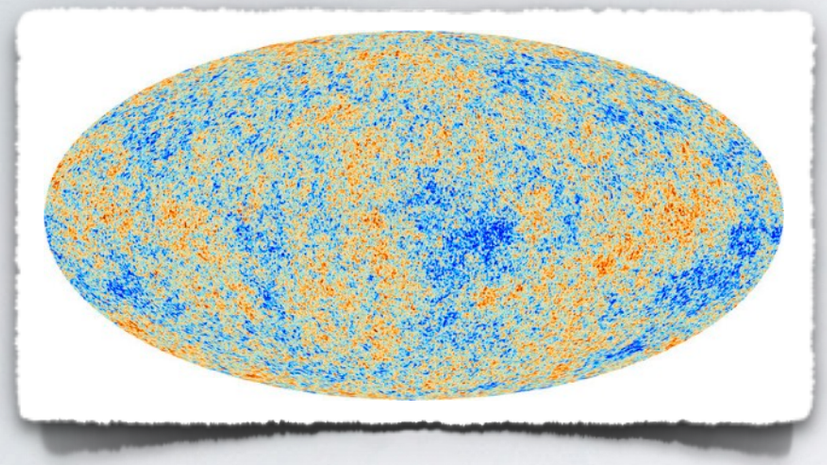
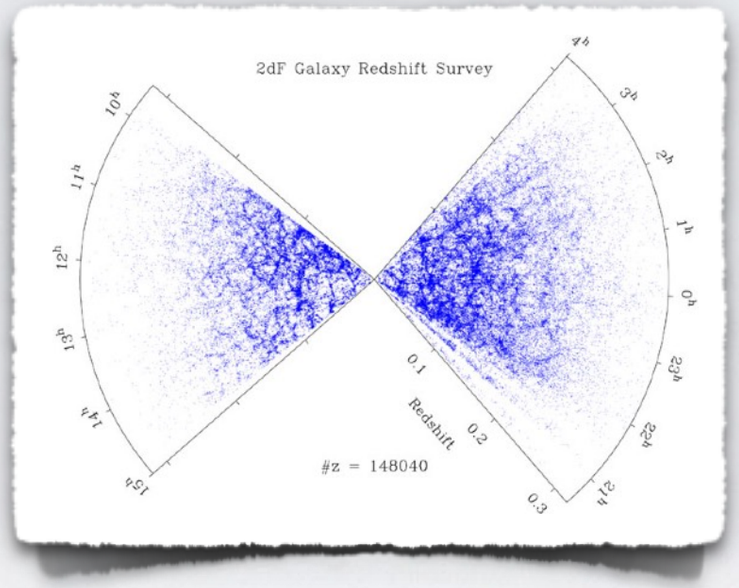
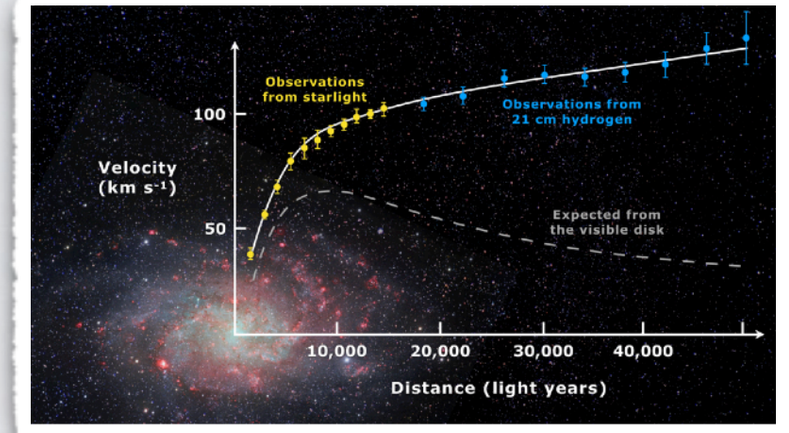
- Most of the matter ($\sim 80\,\%$) that interacts gravitationally is dark







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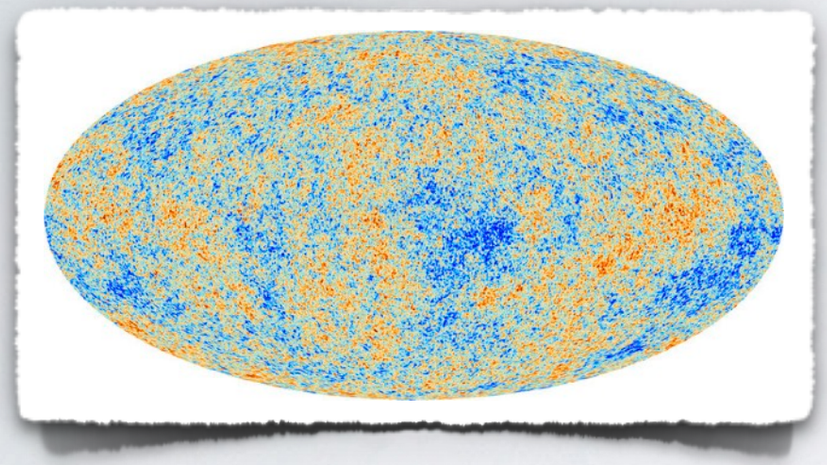

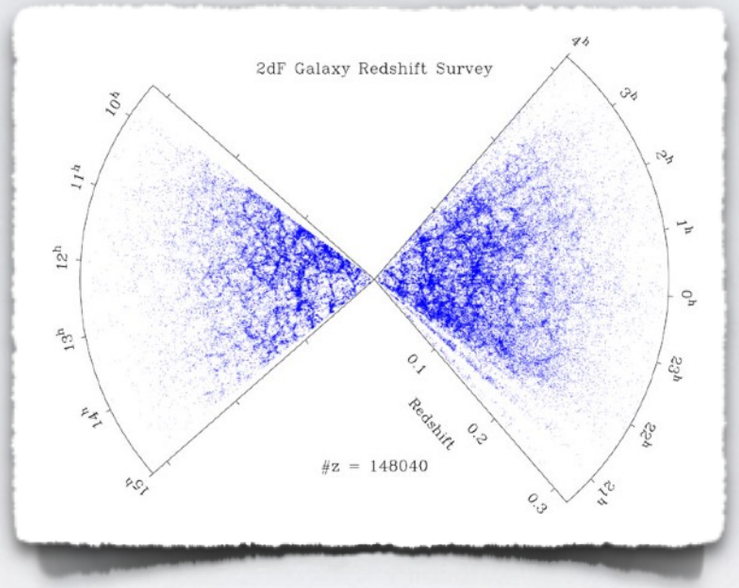

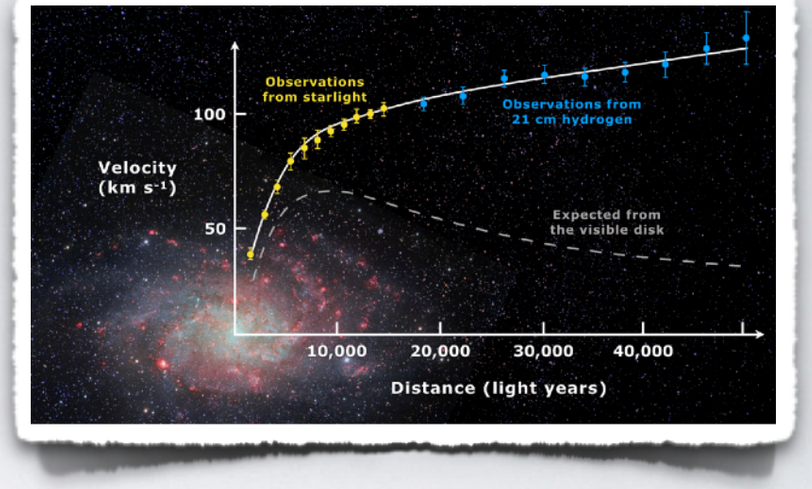

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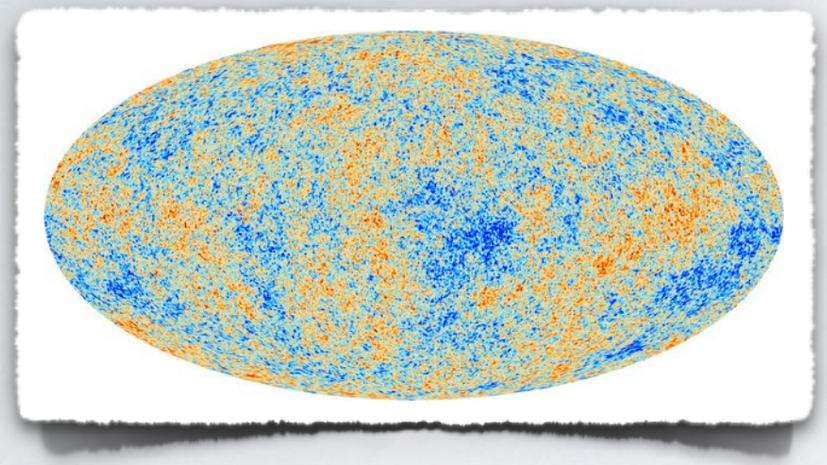

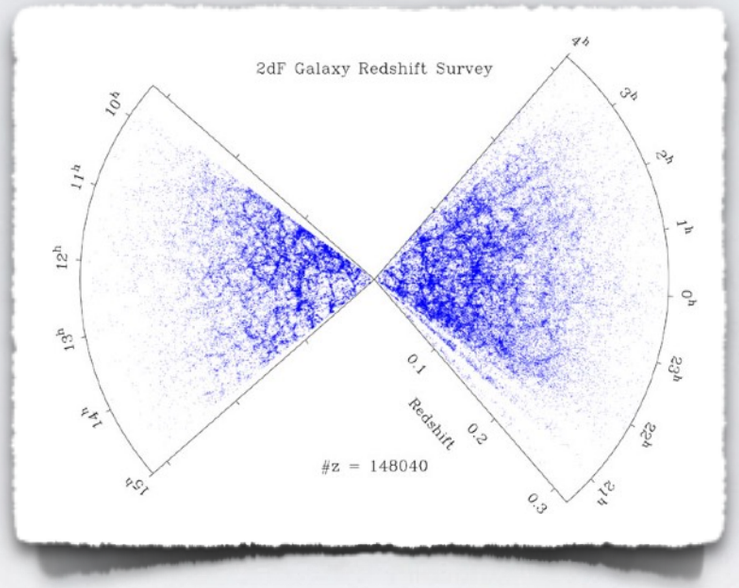

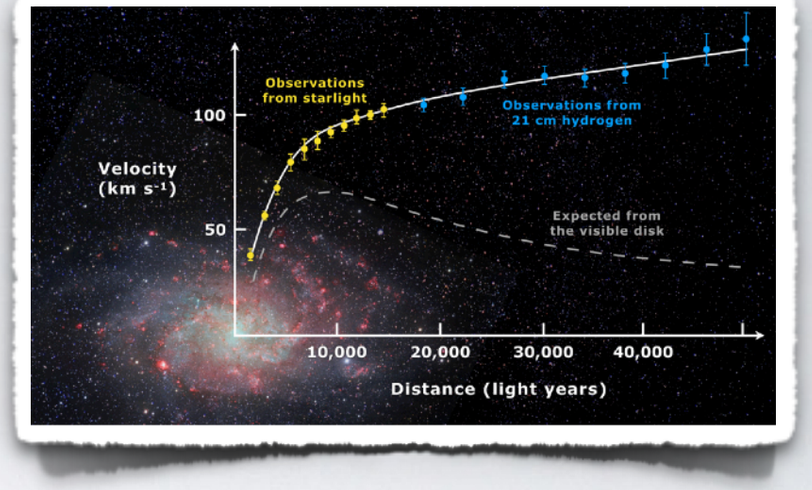

- One of the strongest evidences for physics beyond the Standard Model

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

SUB-GEV DARK MATTER

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too light to explain halo structure

$1/m_\chi \gg 1/n_\chi^{1/3}$

$1/m_\chi \ll 1/n_\chi^{1/3}$

less than 1 dark matter per year through Earth

10^{-22} eV

10^{-4} eV

10^{9} eV

10^{11} eV

10^{40} eV

m_χ

Dark matter is a classical field and can take advantage of coherent phenomena

ADMX, CASPEr, atomic clocks, LIGO, …

Dark matter can deposit energy via scattering off nuclei

XENON, LUX, …

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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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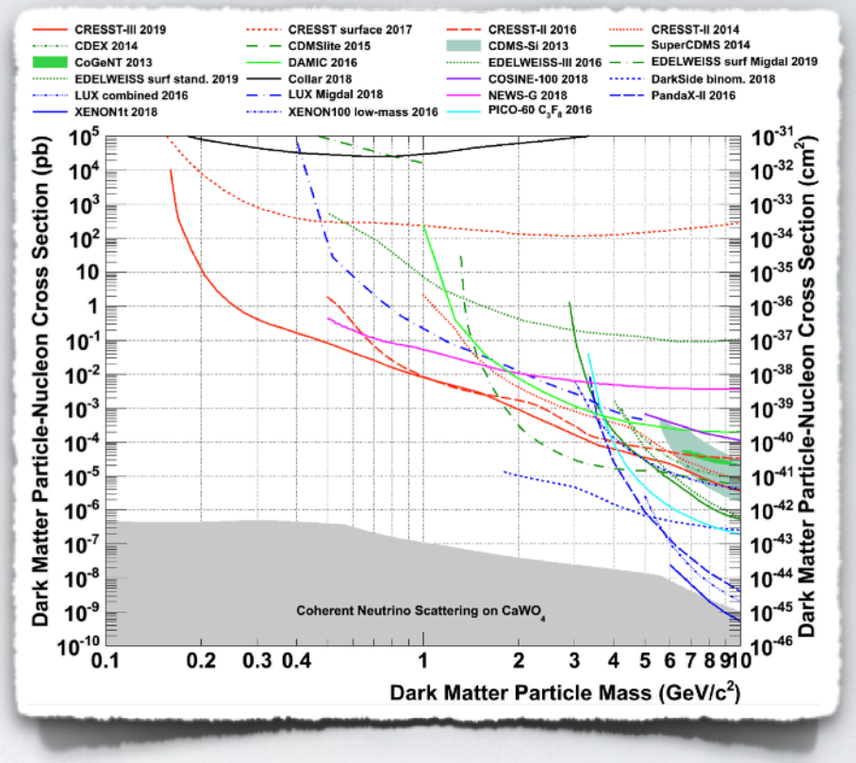

[CRESST – PRD 2019, 1904.00498]

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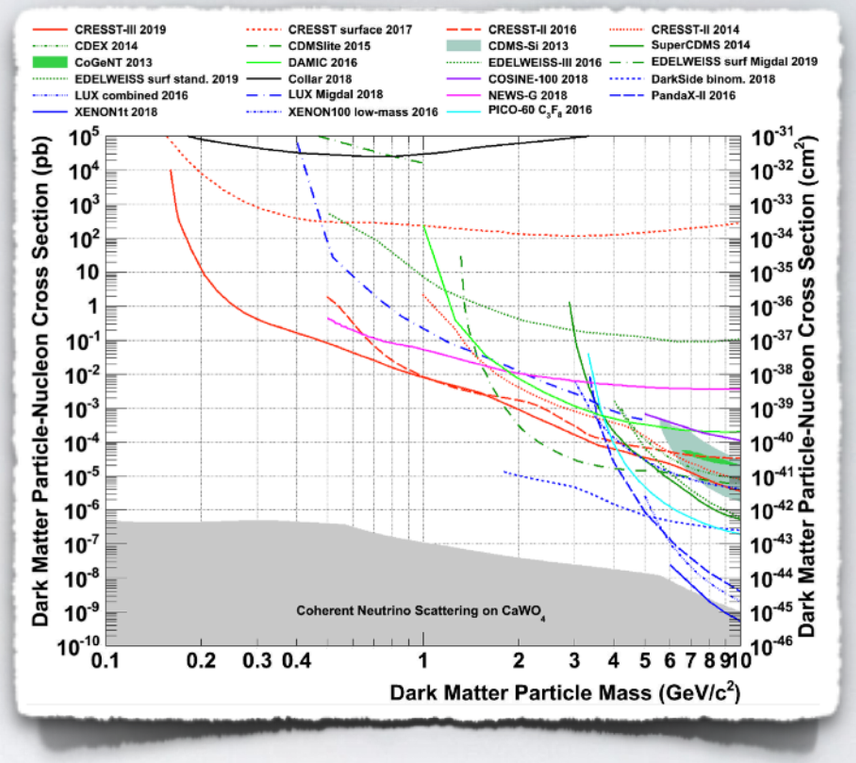

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- Two possibilities:
  1. Look into lighter scattering targets
  2. Look into inelastic processes

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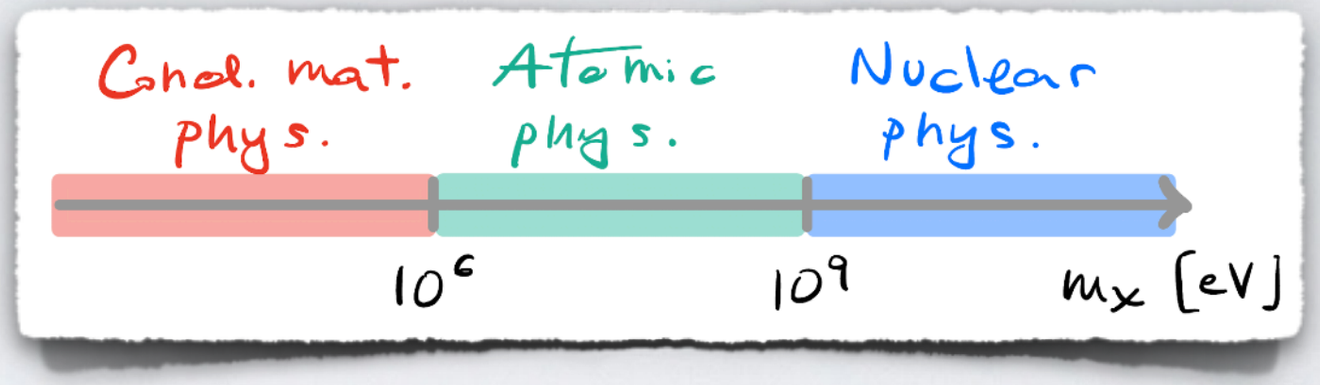

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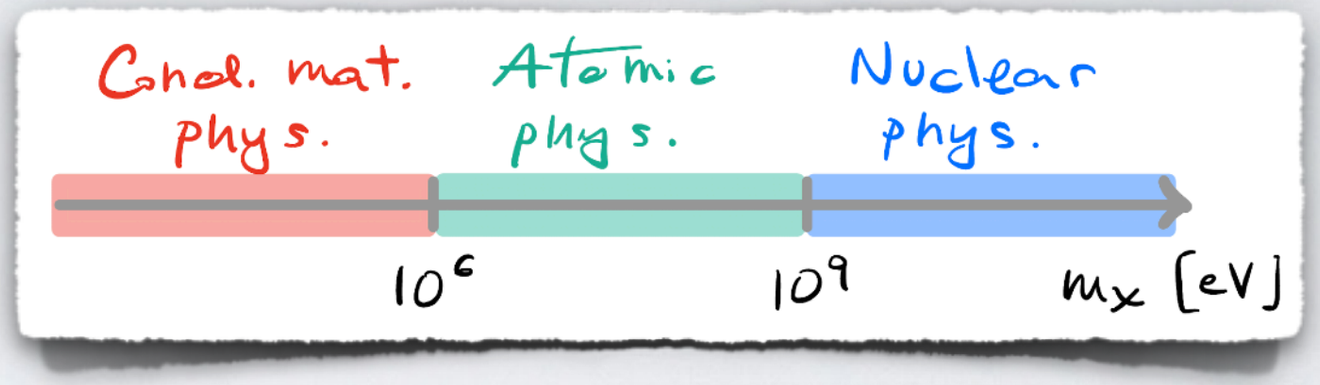

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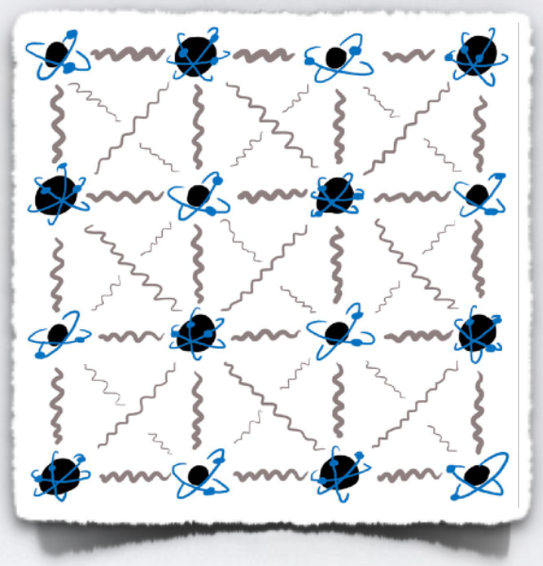

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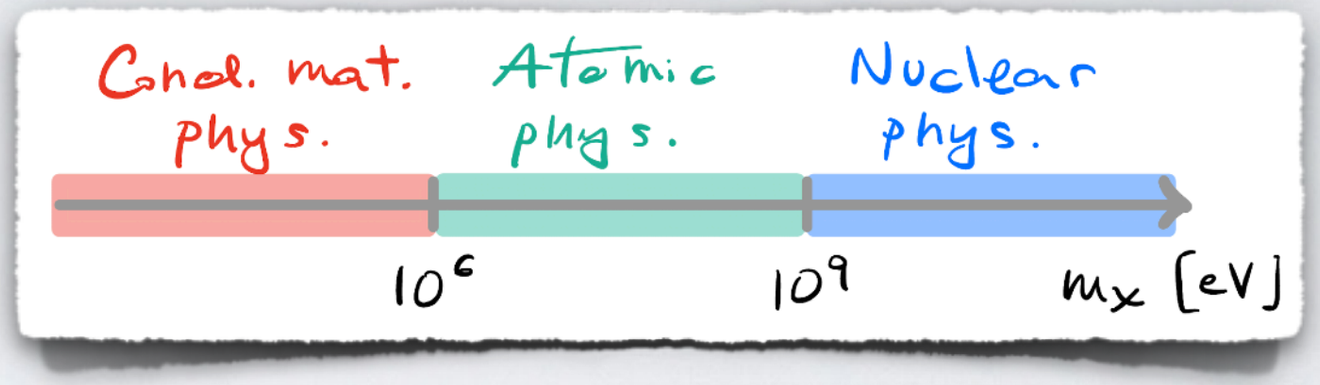

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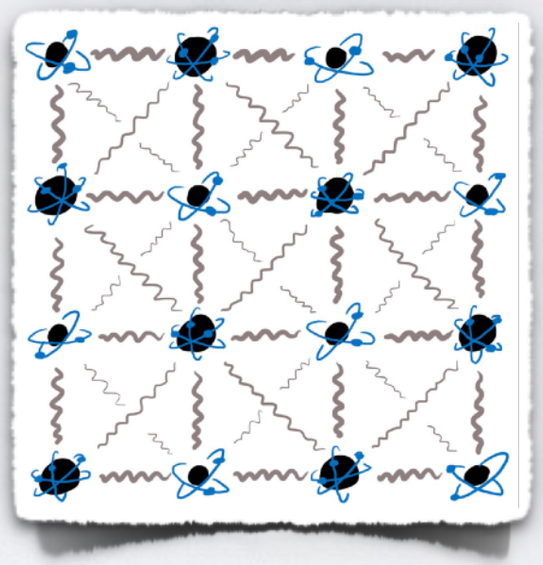
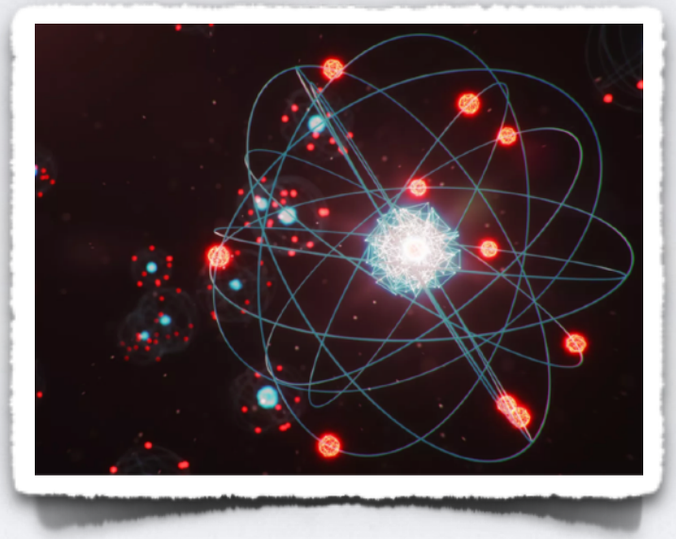


- Need to find theoretical tools that allow to solve or bypass these problems (measured correlation functions, EFTs, …)

Down to the MeV

Migdal effect in semiconductors



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- For sub-GeV dark matter nuclear recoil signals become challenging

  → sensitivity can be lowered by looking for inelastic processes

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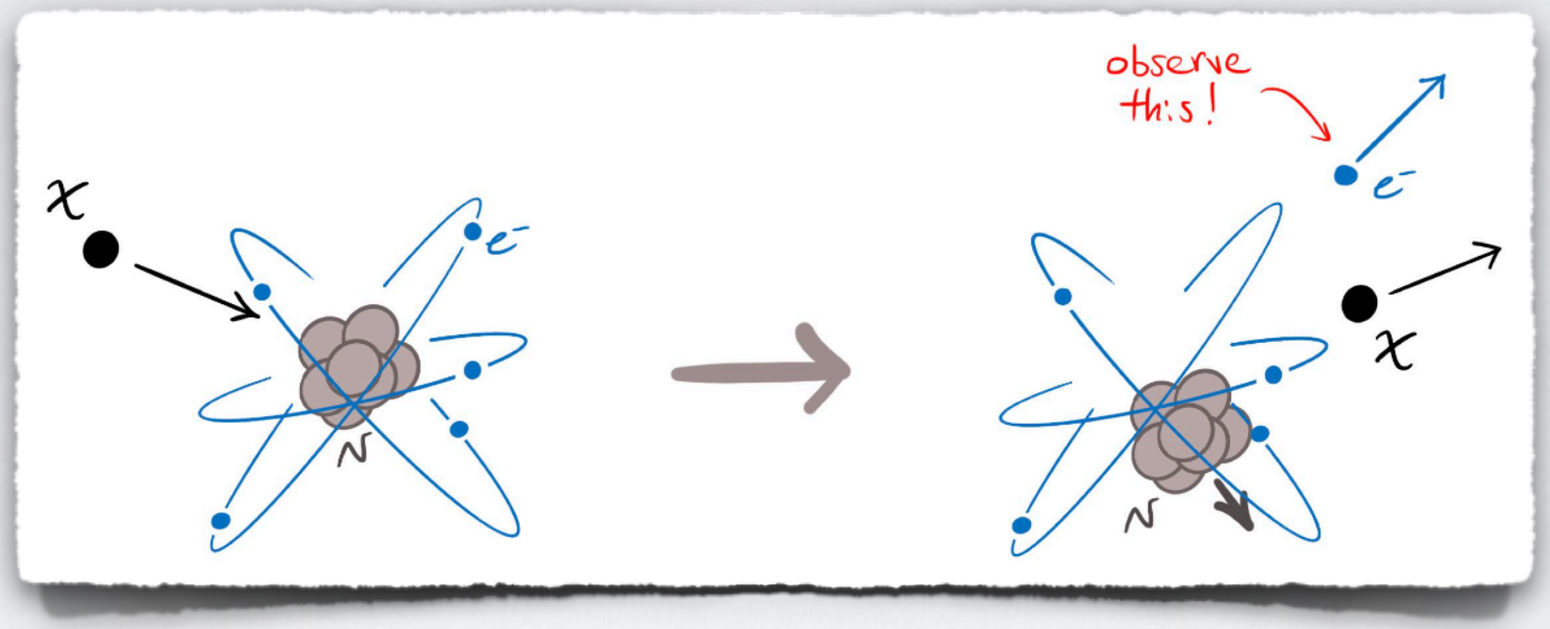
- Hadrophilic dark matter on free atoms → Migdal effect



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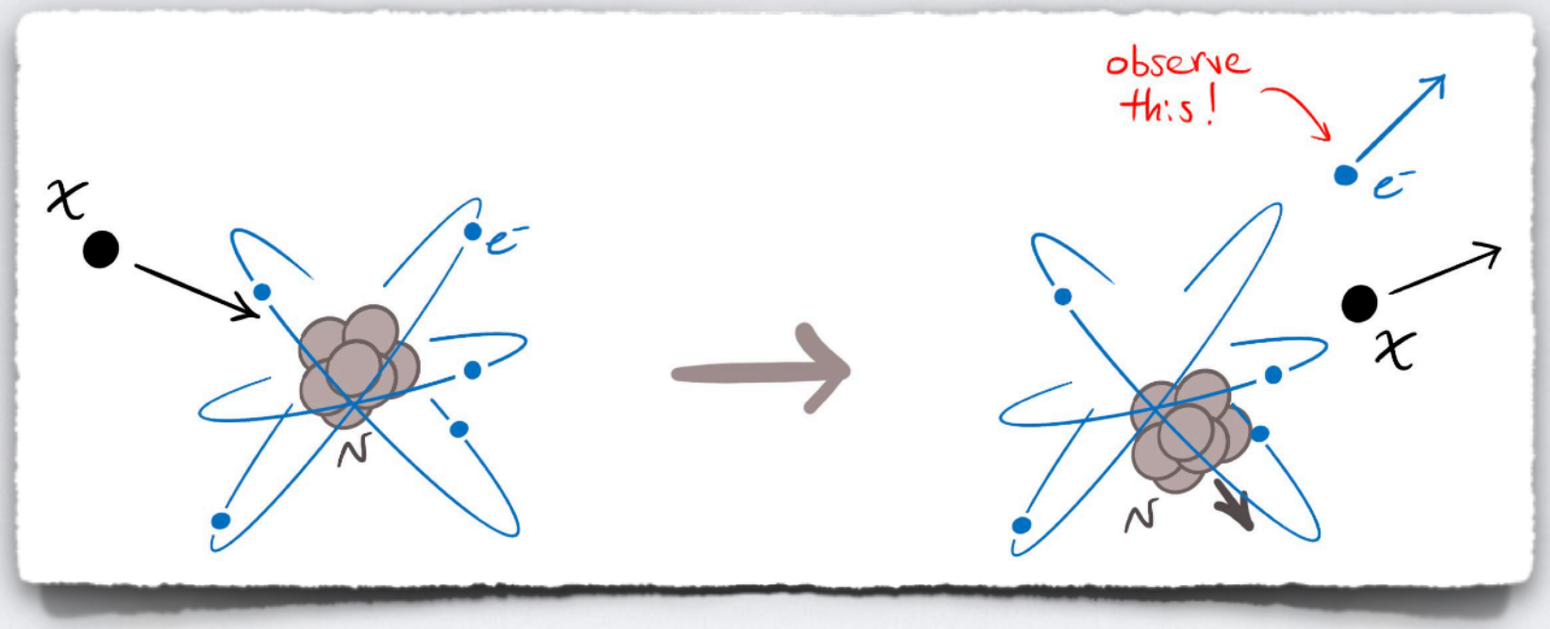

- Less likely… but lower threshold! → sensitivity down to $\mathcal{O}(100\ \text{MeV})$ masses

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

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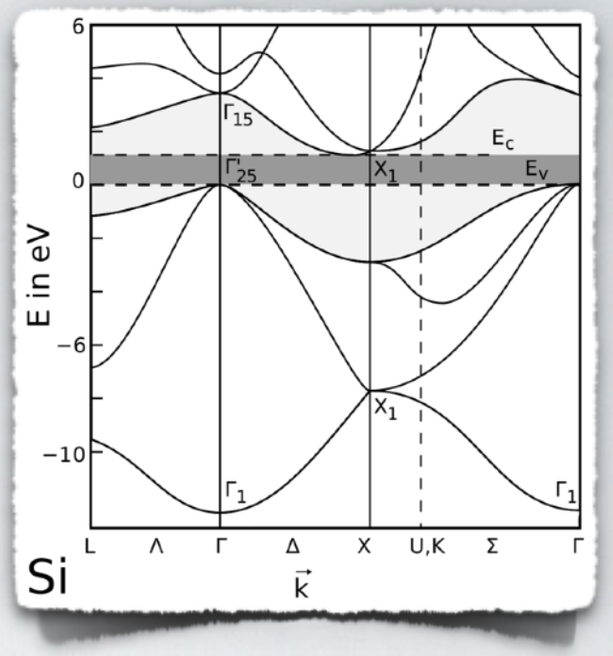
- Semiconductors (Si, Ge, …) have small $\mathcal{O}$(eV) bandgaps → Migdal effect should allow to probe down to $\mathcal{O}$(MeV) masses



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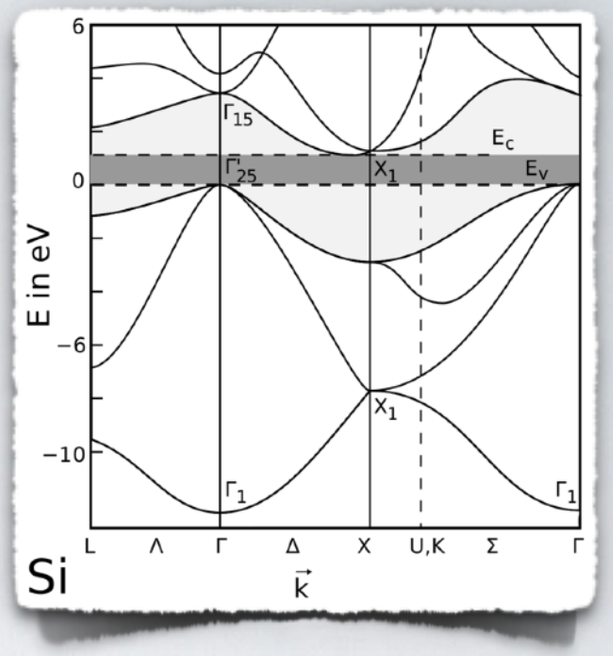

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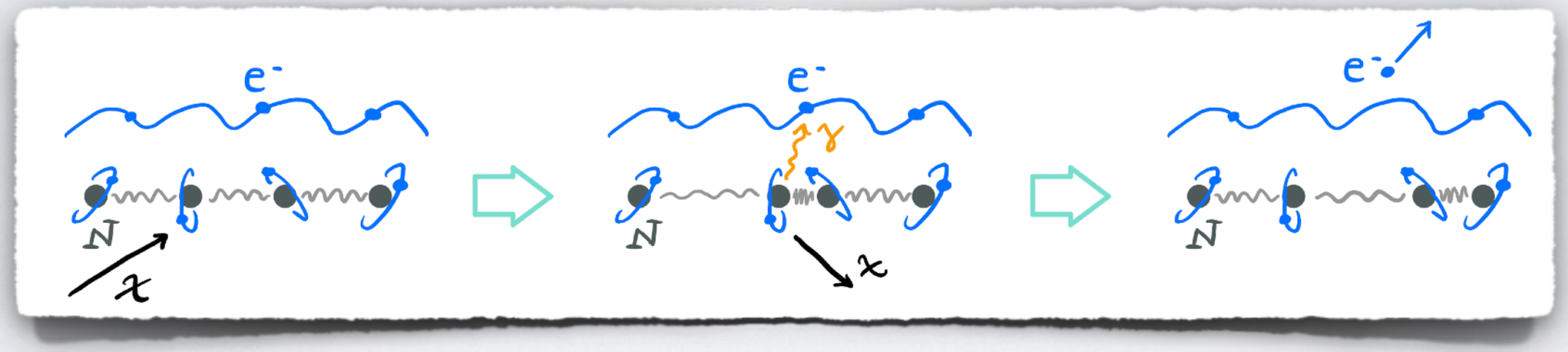

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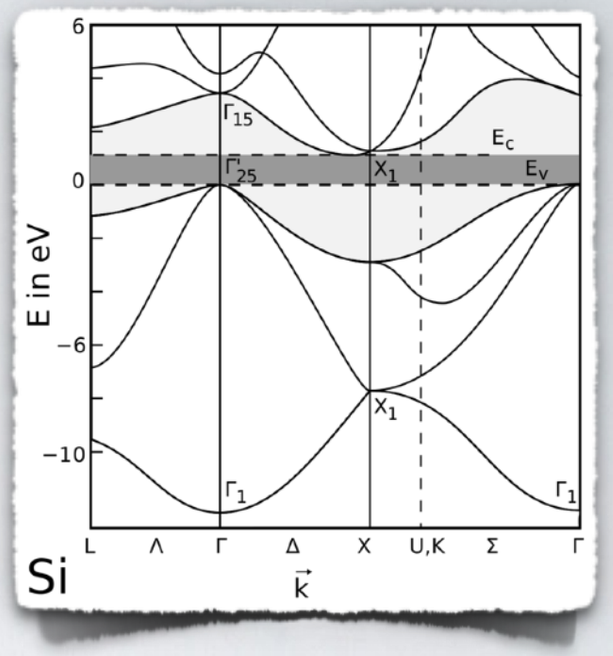

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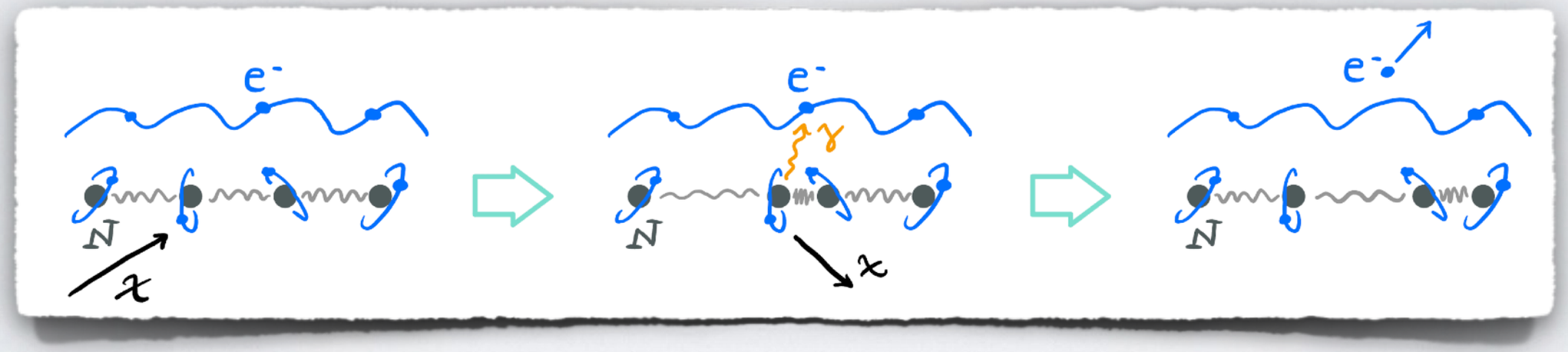

- How to describe nucleus-nucleus and nucleus-electron interactions in a strongly correlated system?

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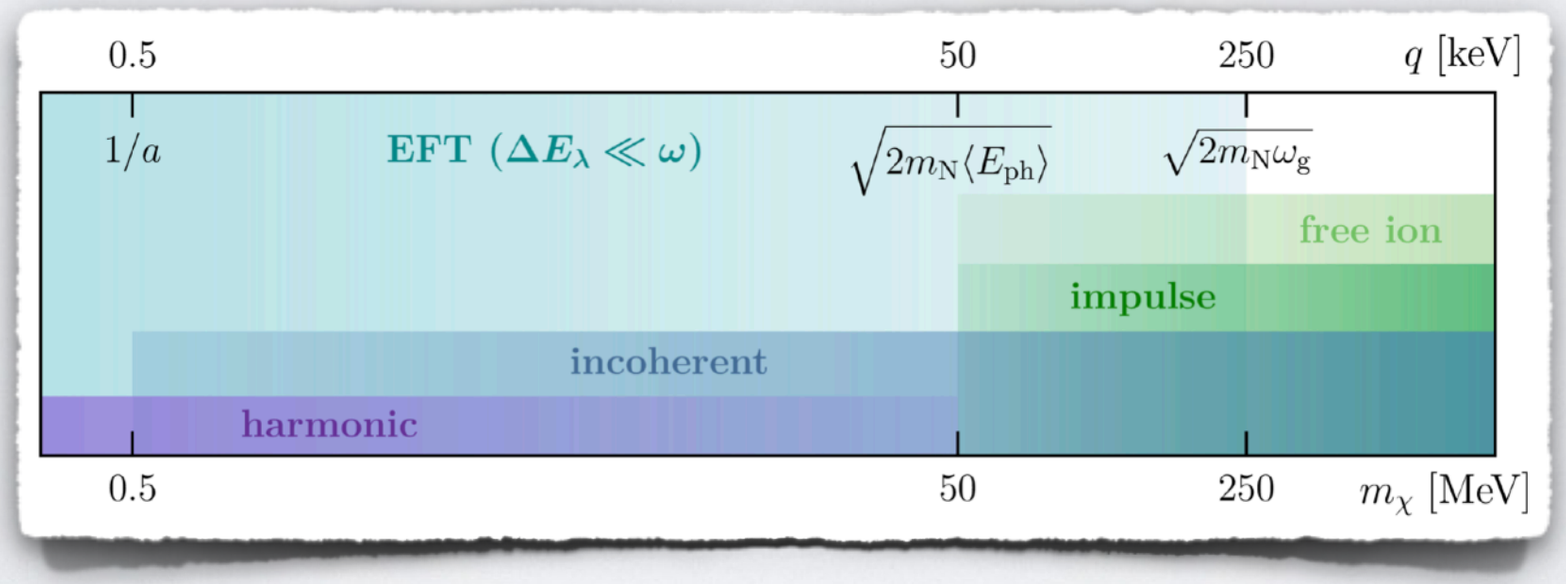

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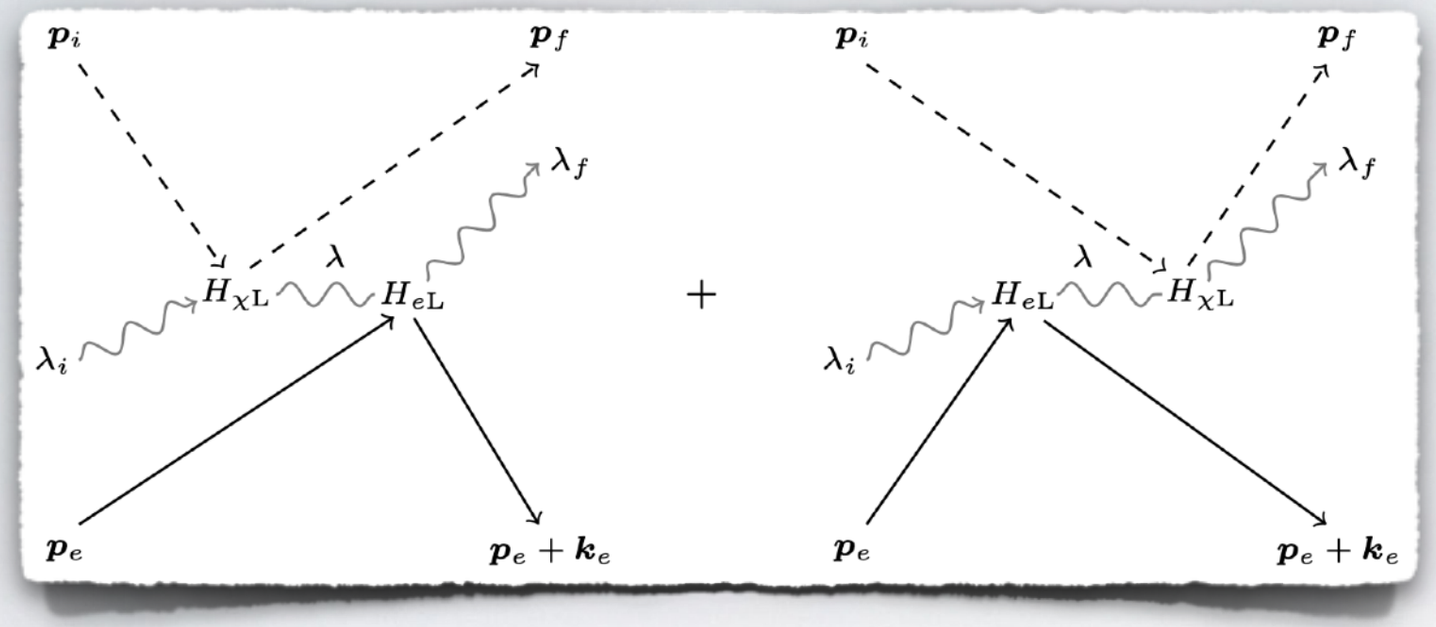

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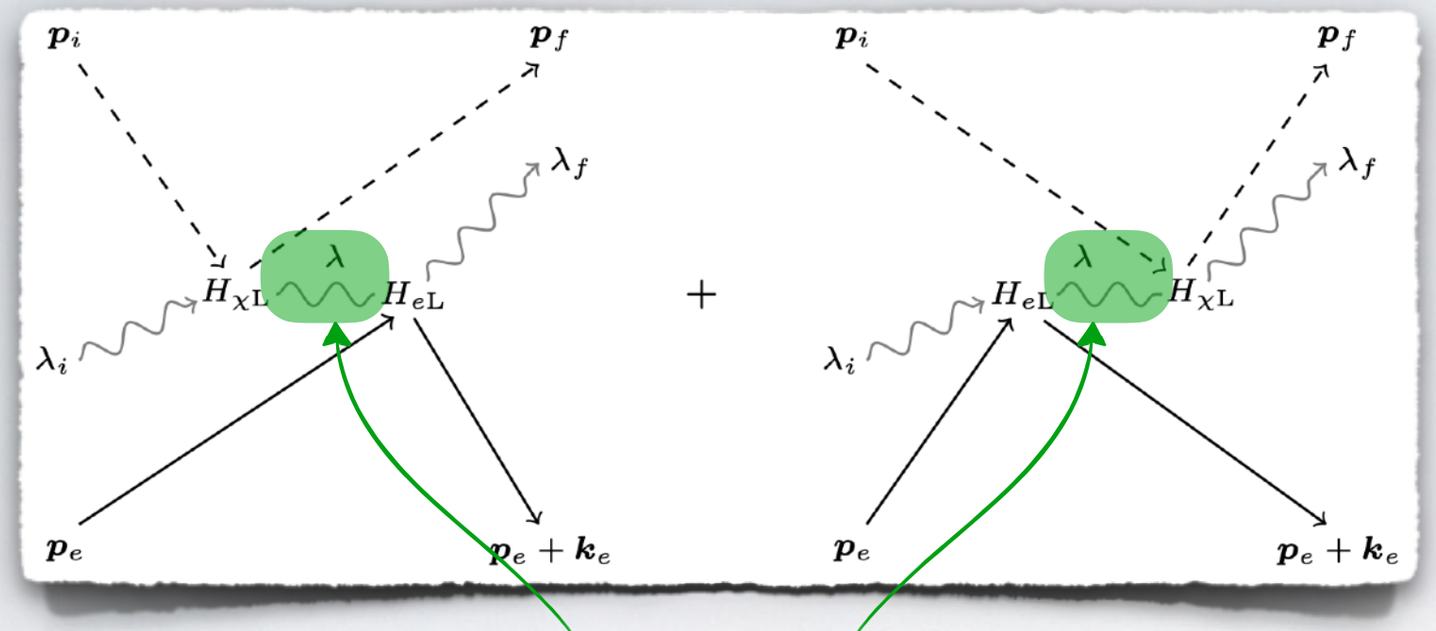

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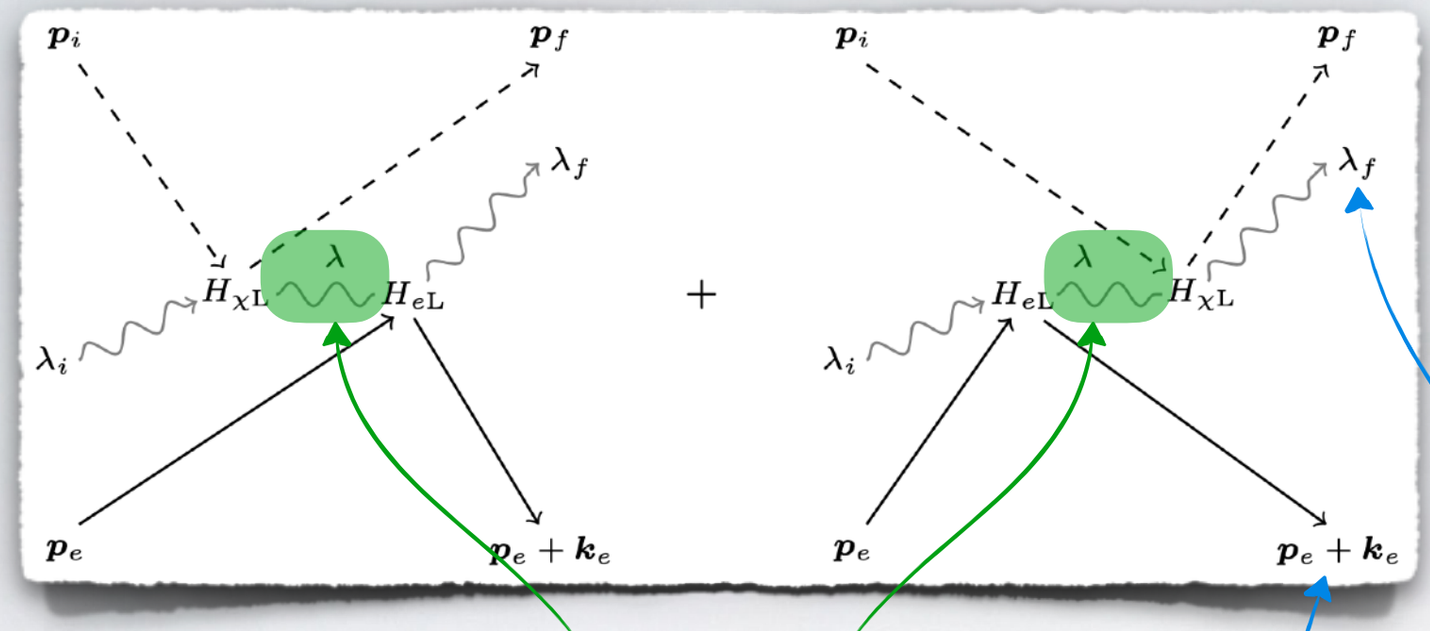

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energy ω

energy $\sim E_{ph}$

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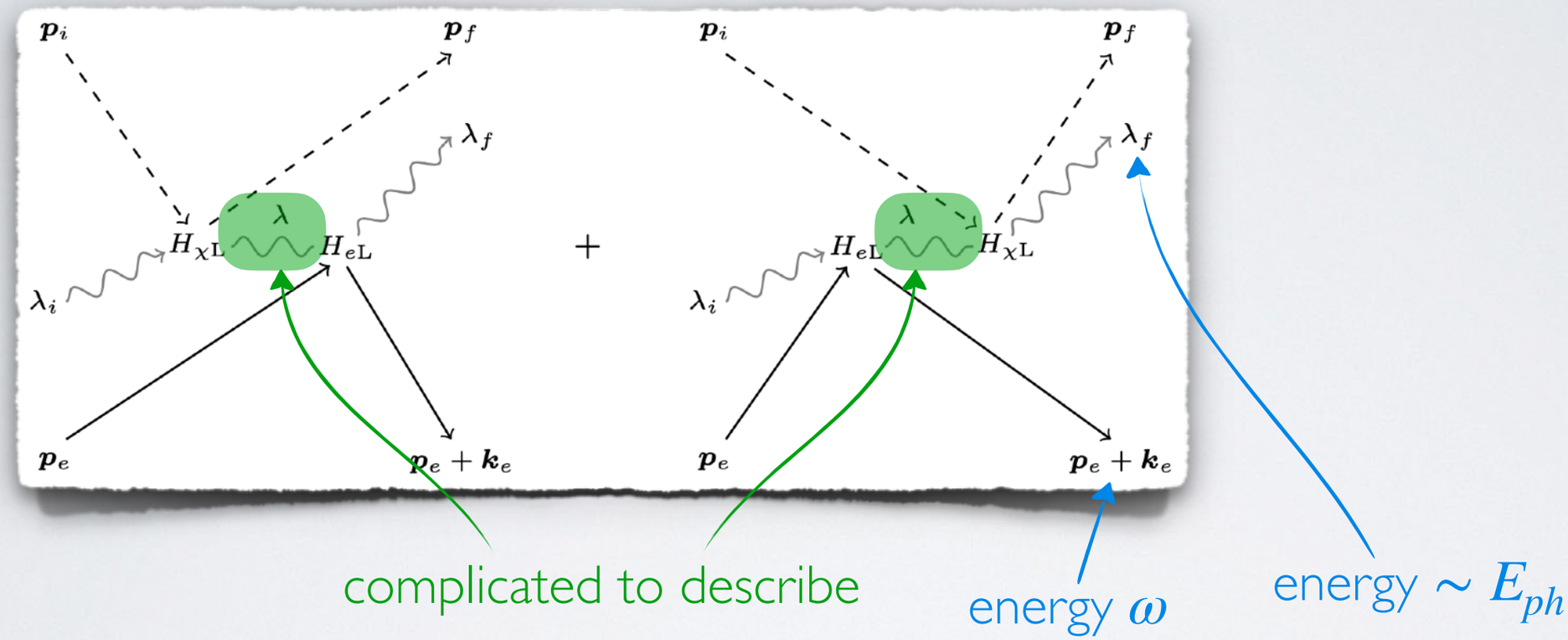

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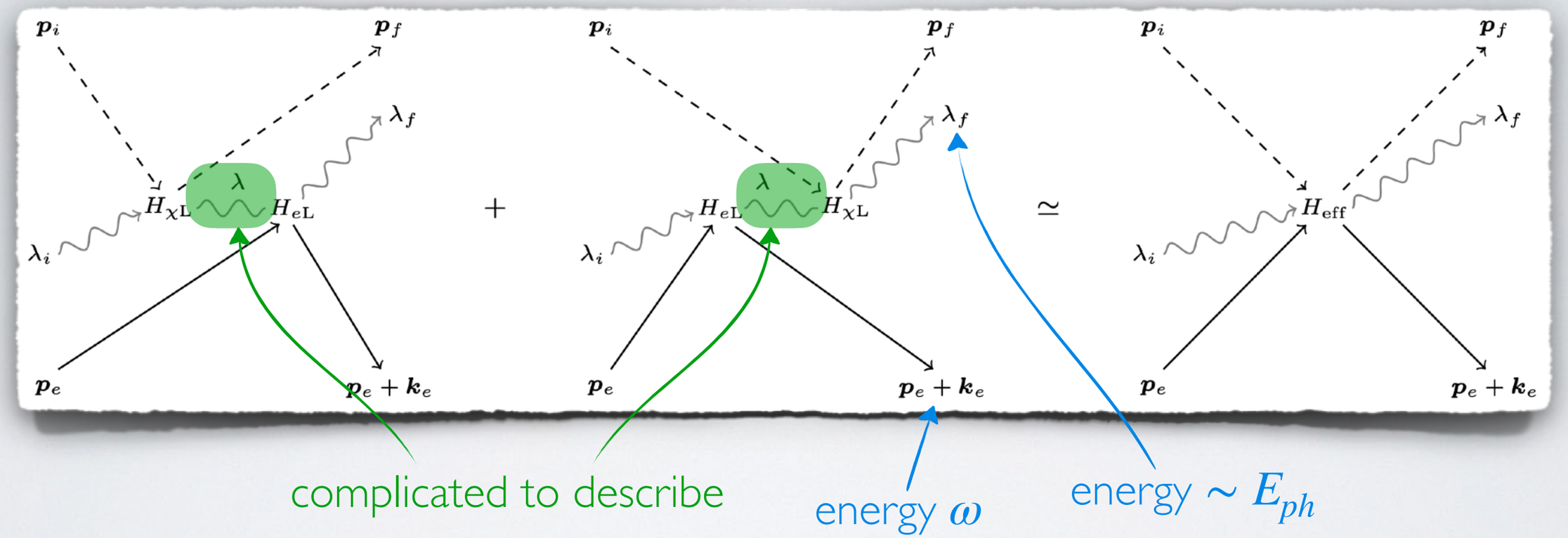

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$$H_{eff} = \frac{1}{m_N \omega^2} \vec{\nabla} H_{\chi L} \cdot \vec{\nabla} H_{eL} + \mathcal{O}\left(\frac{1}{\omega^3}\right)$$

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

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- Now simple to determine the rate for Migdal emission

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

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energy loss function (ELF) — electronic dynamics

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- Energy loss function is already well studied

[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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- Structure factor should be measured from neutron scattering data

$$\frac{d^2\sigma_n}{d\Omega dE} = \frac{\sigma_n}{4\pi}\frac{k_f}{k_i} S(q,E)$$

MIGDAL RATE

- Now simple to determine the rate for Migdal emission

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

energy loss function (ELF) — electronic dynamics

structure factor — crystal response

- Energy loss function is already well studied

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

- Structure factor should be measured from neutron scattering data

$$\frac{d^2\sigma_n}{d\Omega dE} = \frac{\sigma_n}{4\pi}\frac{k_f}{k_i} S(q,E)$$

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

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- If only interested in electron energy, the rate is independent on the details of the crystal lattice

$$\int_0^\infty dE\, S(q,E) = 1 \quad \Longrightarrow \quad \frac{dR}{d\omega} \propto \int d^3\mathbf{k}_e \sum_{\mathbf{K}} \mathrm{Im}\left(-\epsilon^{-1}_{\mathbf{K}\mathbf{K}}(\mathbf{k}_e,\omega)\right)$$

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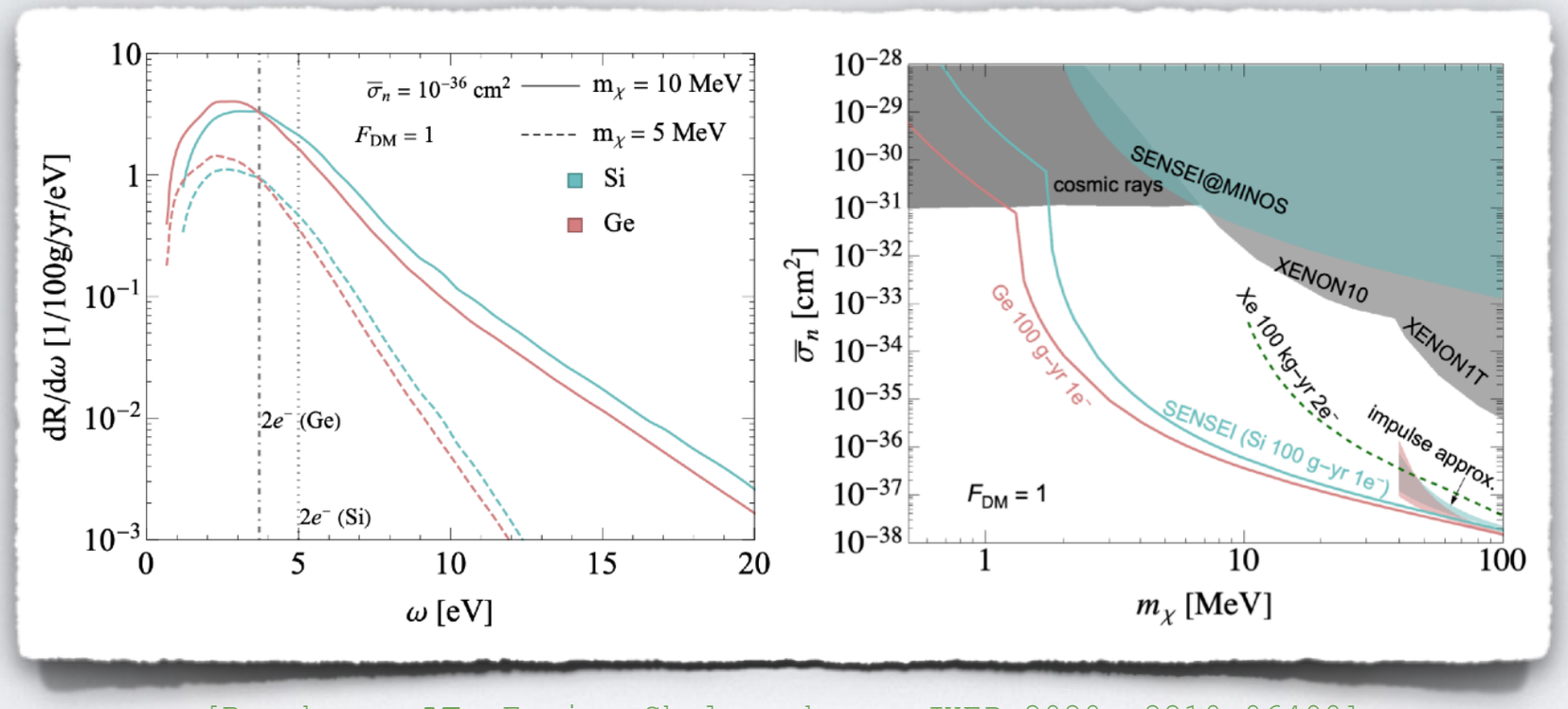

[Berghaus, **AE**, Essig, Sholapurkar — JHEP 2020, 2210.06490]

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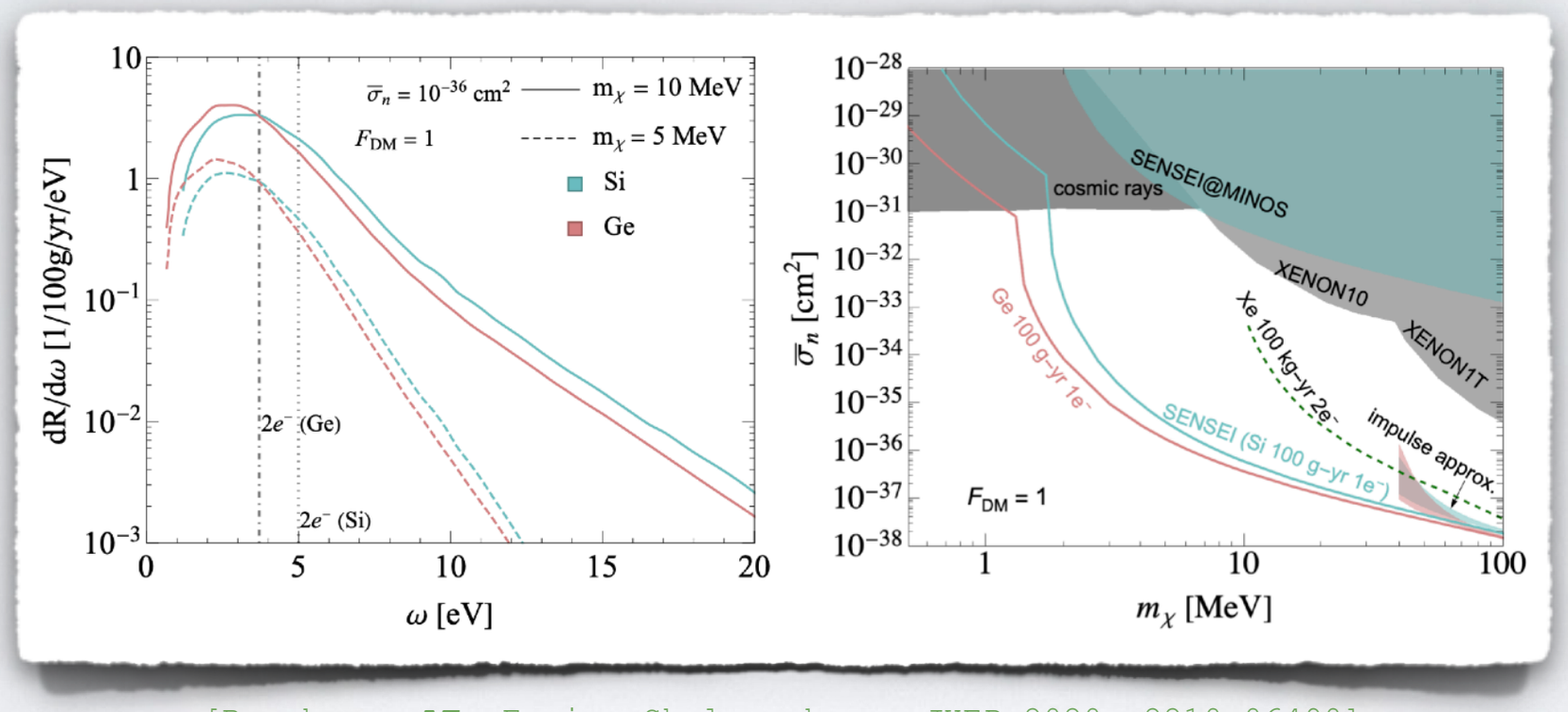

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- Description of Migdal effect in semiconductor extended to all masses

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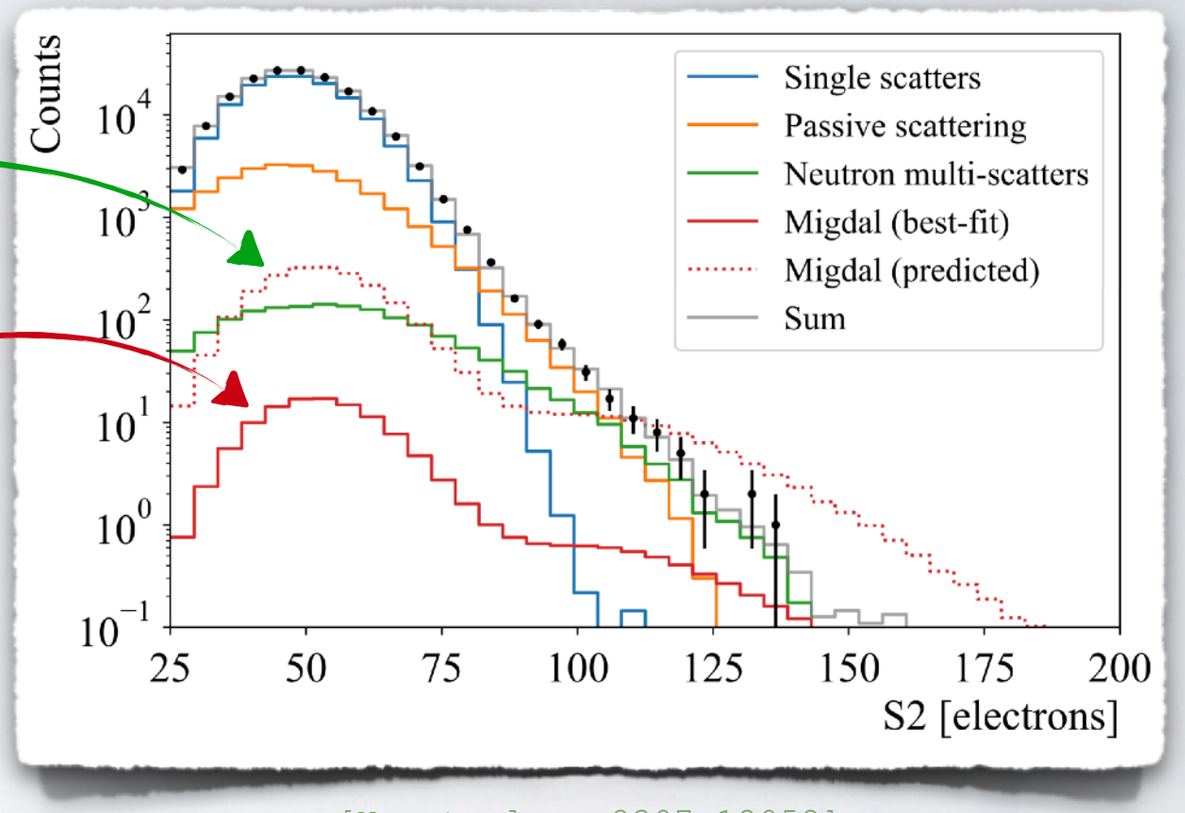

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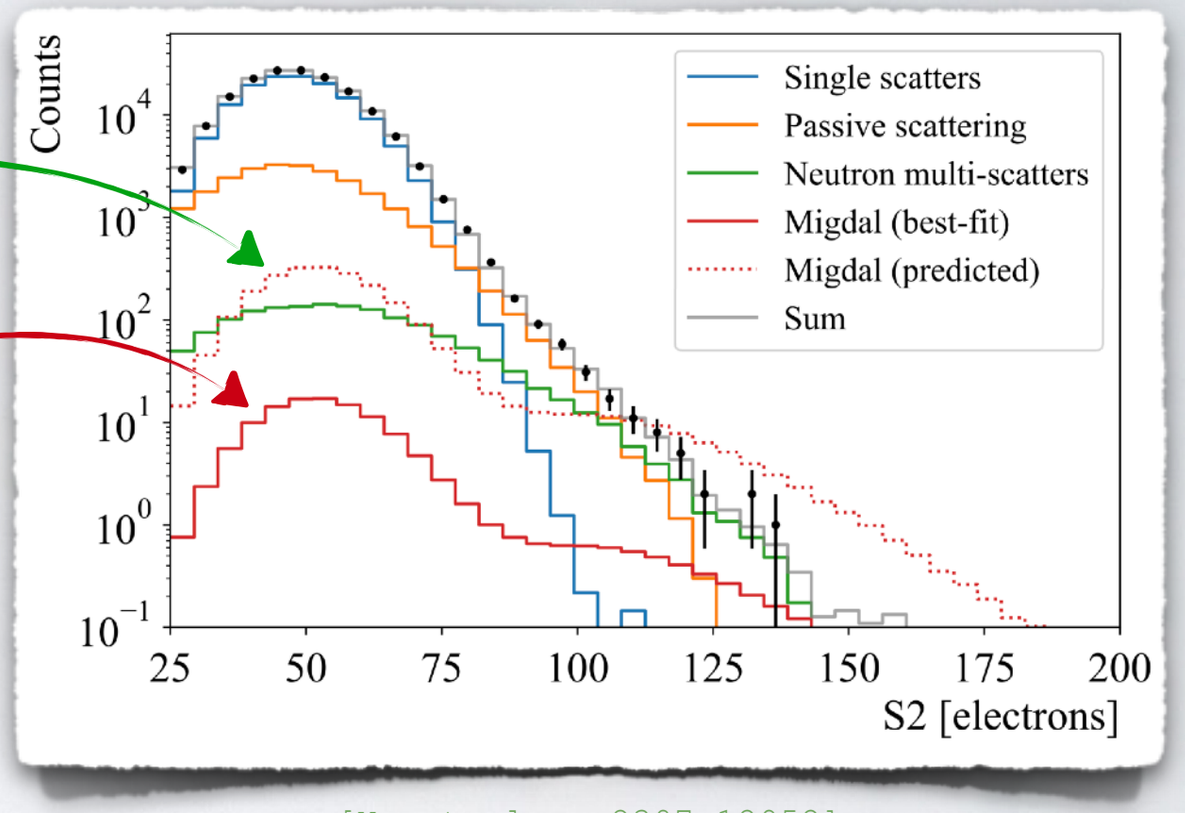

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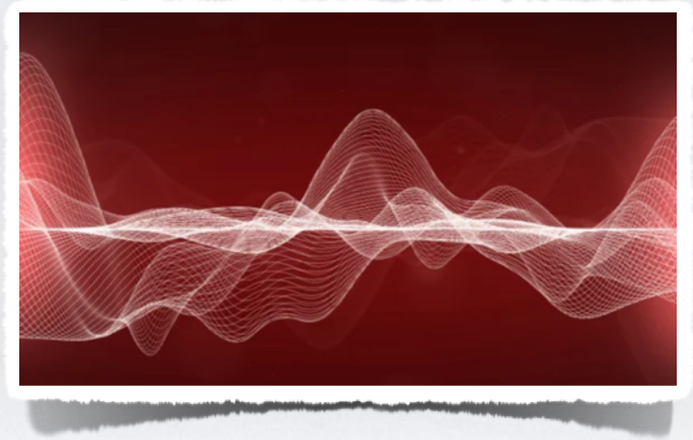
- Theory assumes free atoms → could the difference be explained by condensed matter effects? [work in progress w/ G. Grilli di Cortona]

Down to the keV
collective excitations



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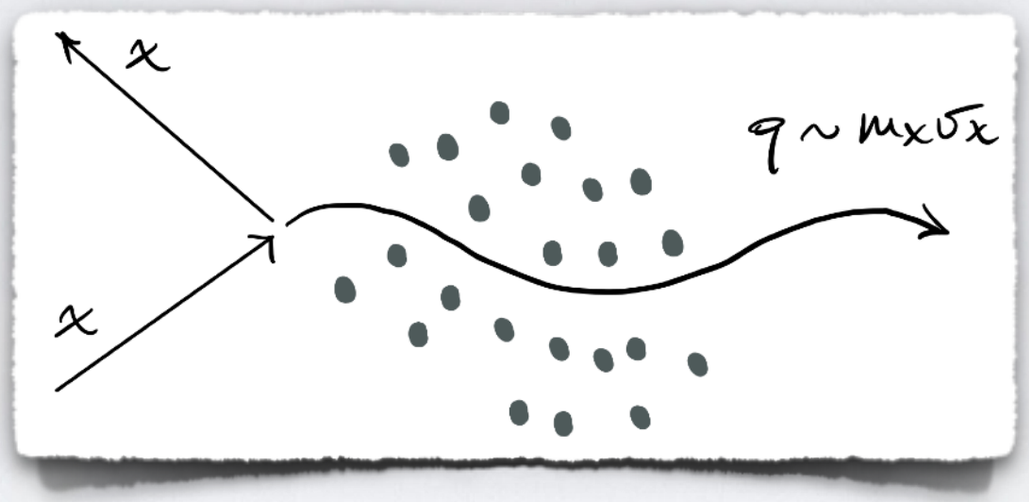

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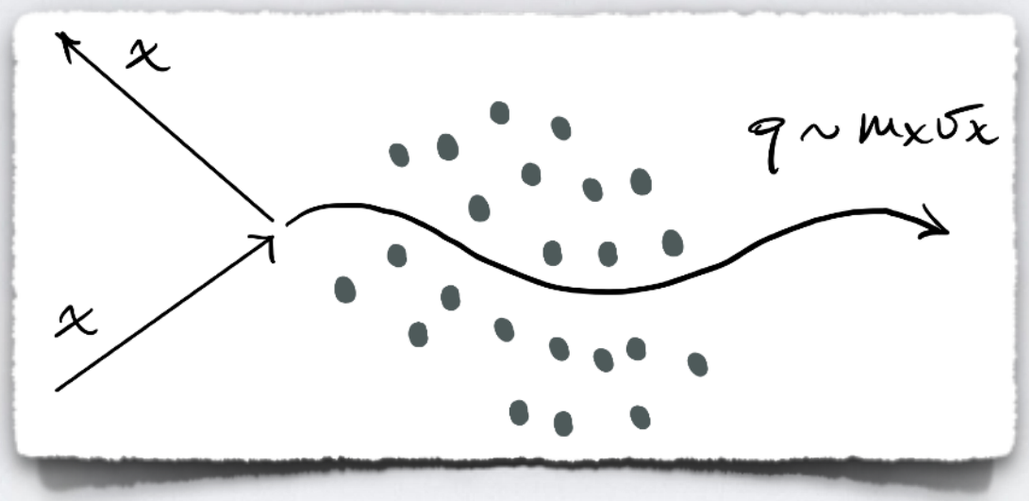

- Typically, no more single particle final states → signatures involve collective excitation [see e.g., Trickle et al. – JHEP 2020, 1910.08092; Griffin et al. – PRD 2020, 1910.10716; Coskuner et al. – PRD 2022, 2102.09567]

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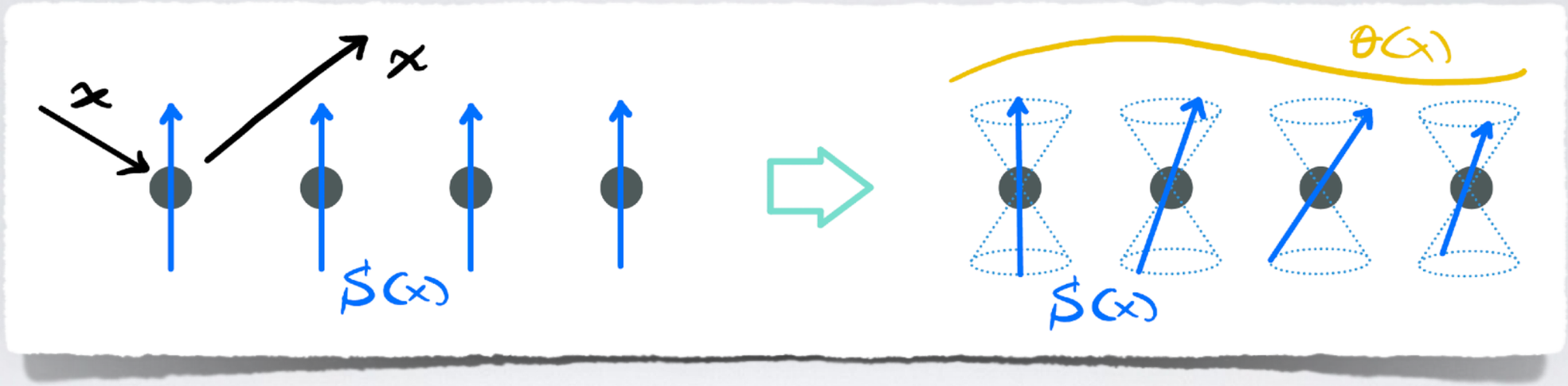

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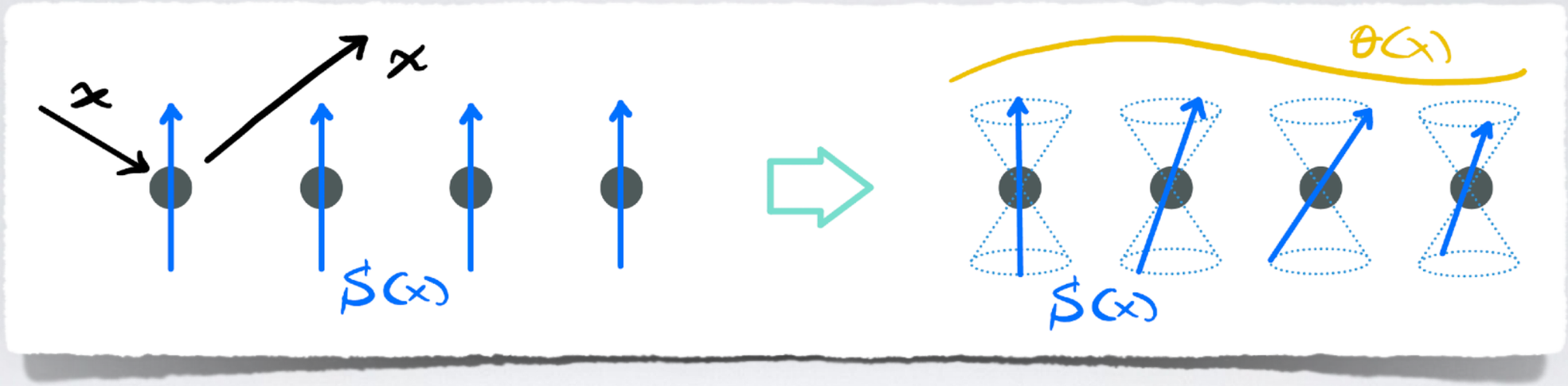

- Ways to detect few magnons have been proposed and under work (TES, MKID, quantum sensors)

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

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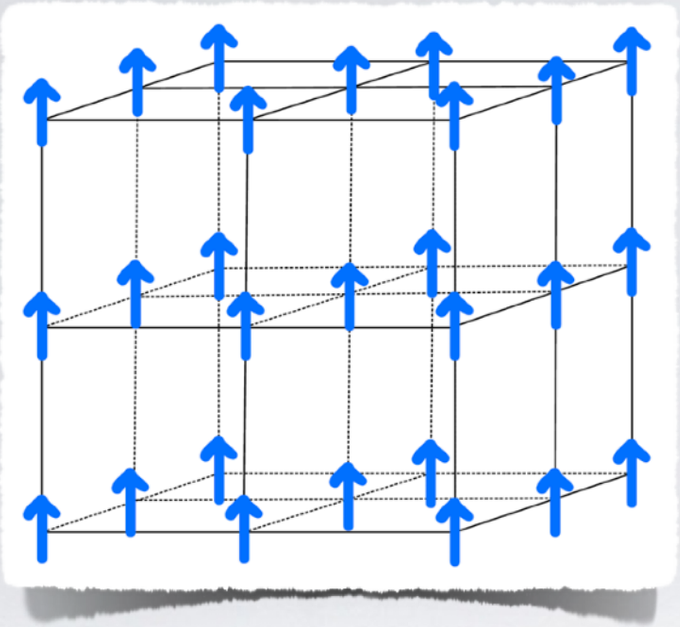

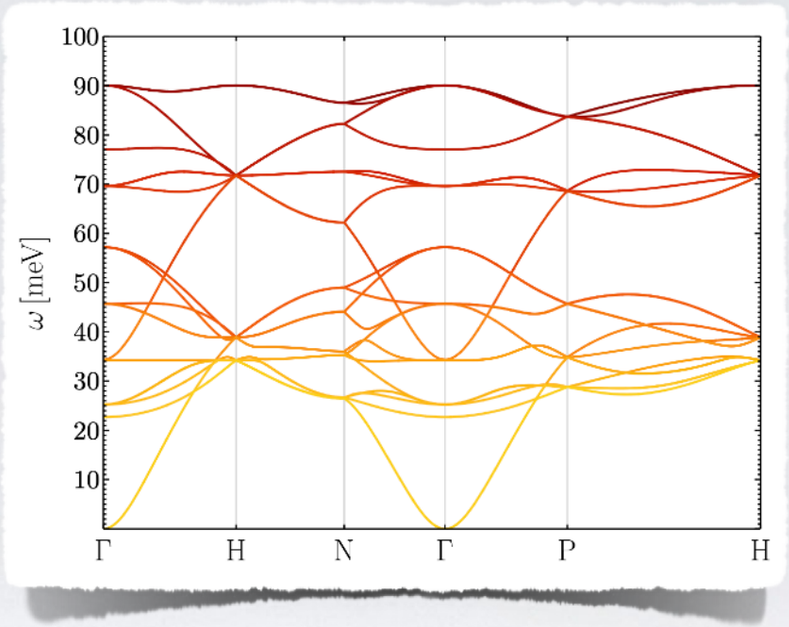

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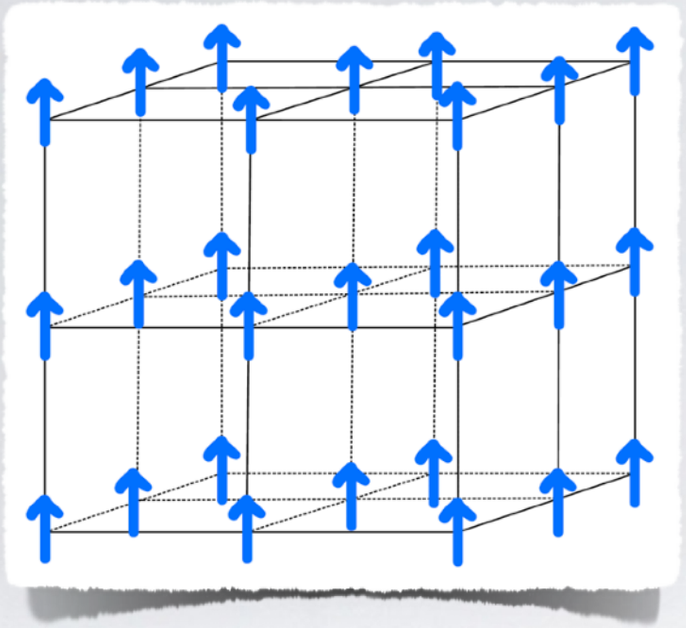

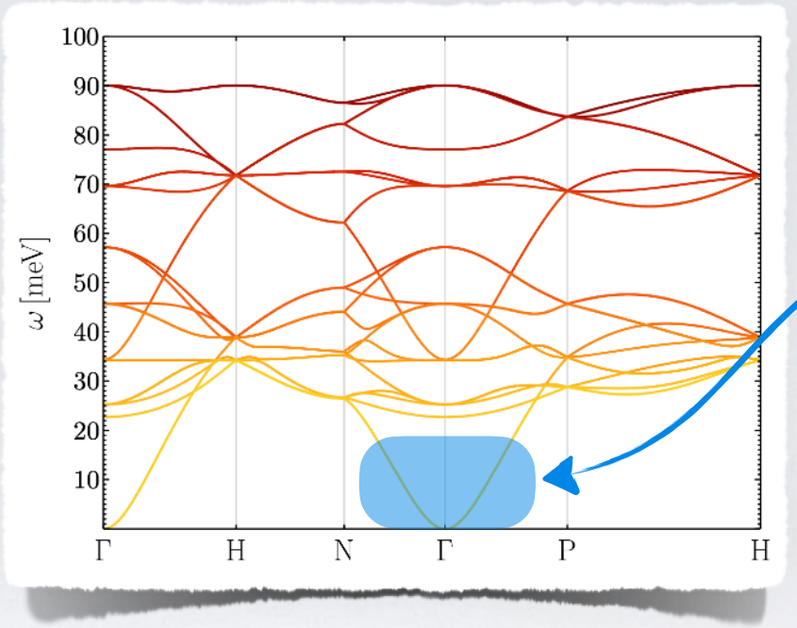

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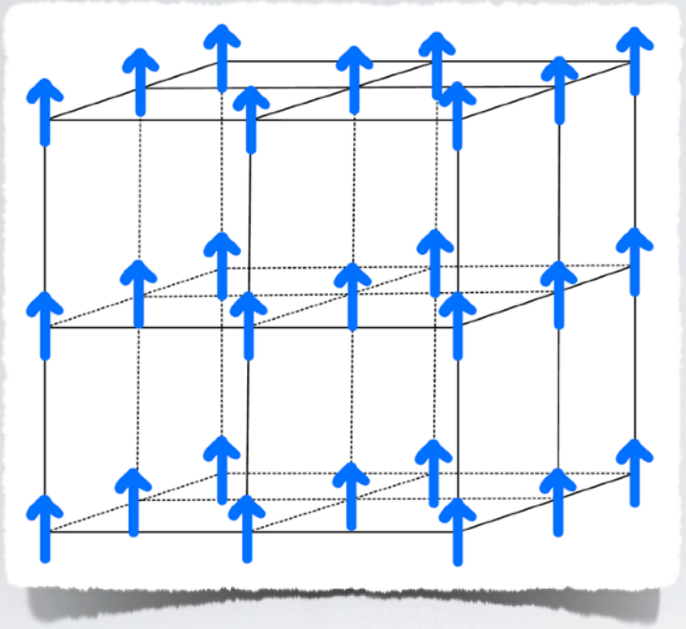

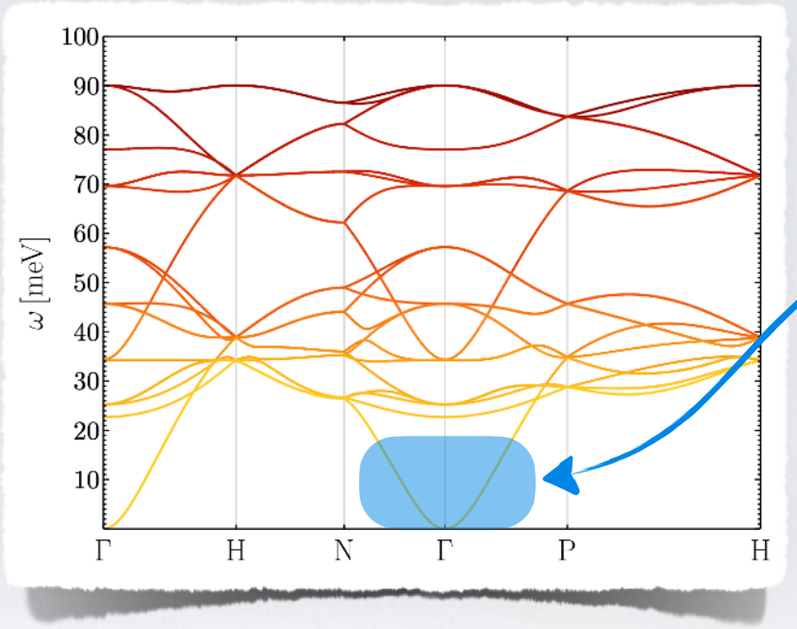

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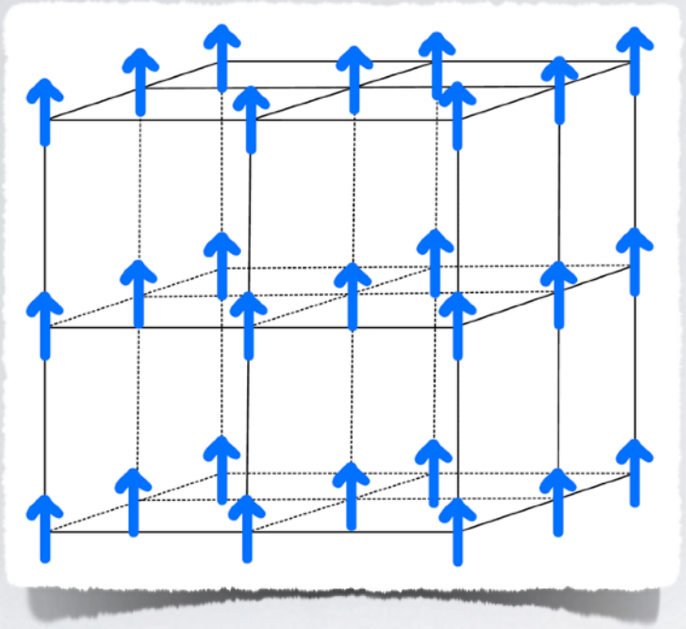

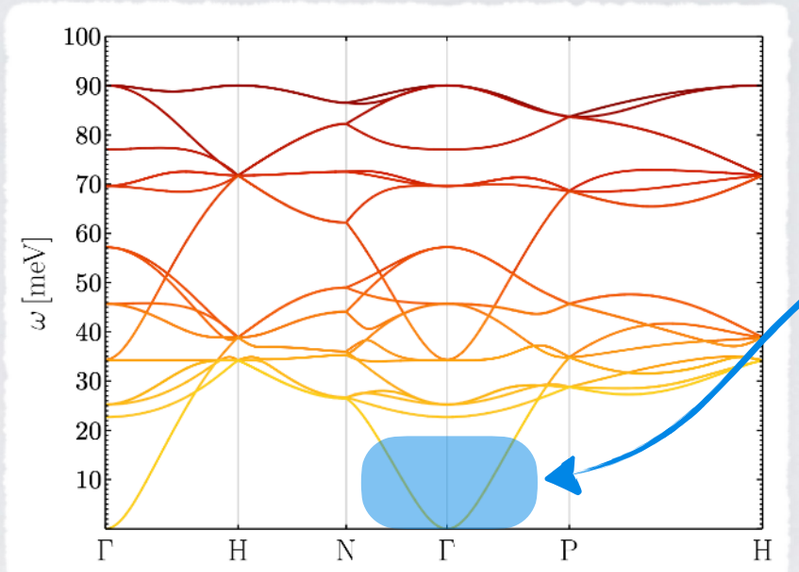

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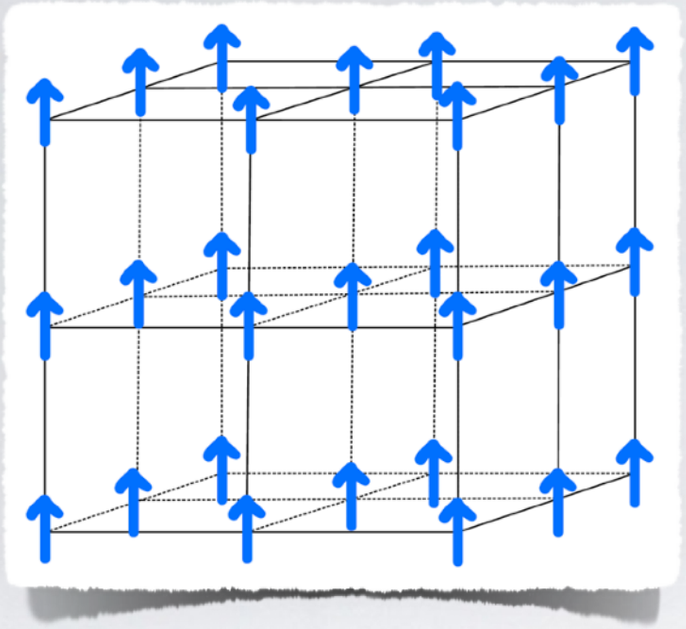

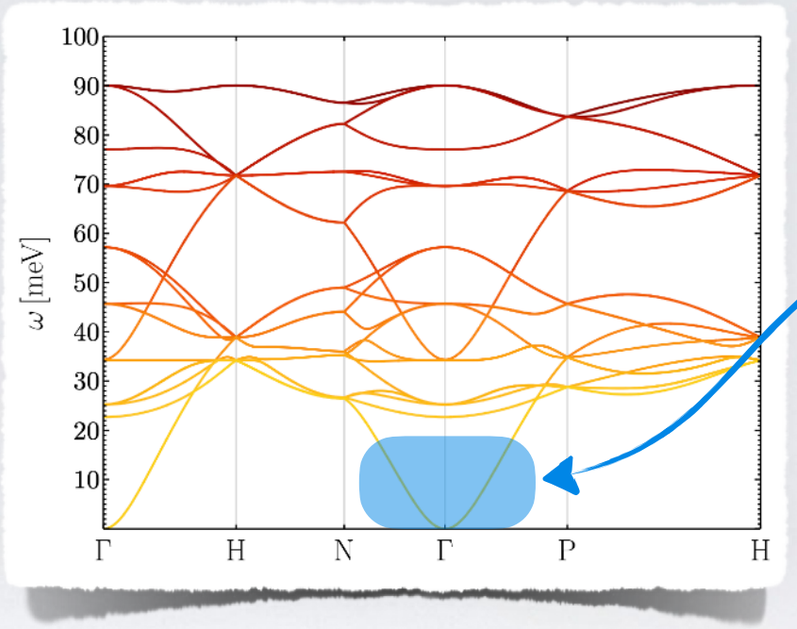

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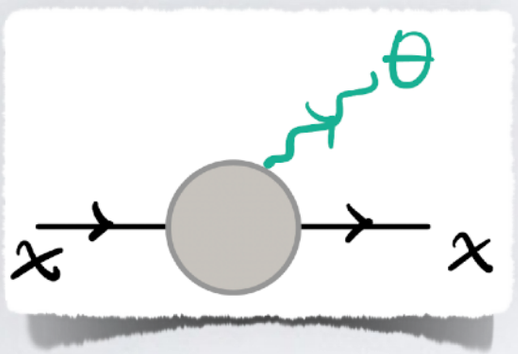

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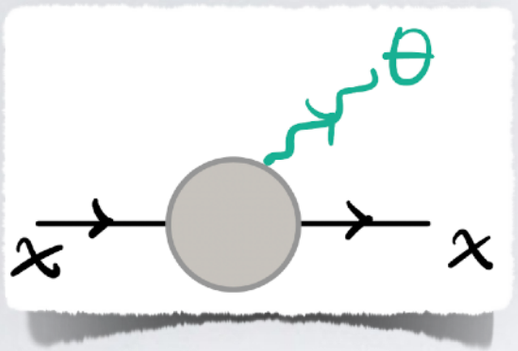

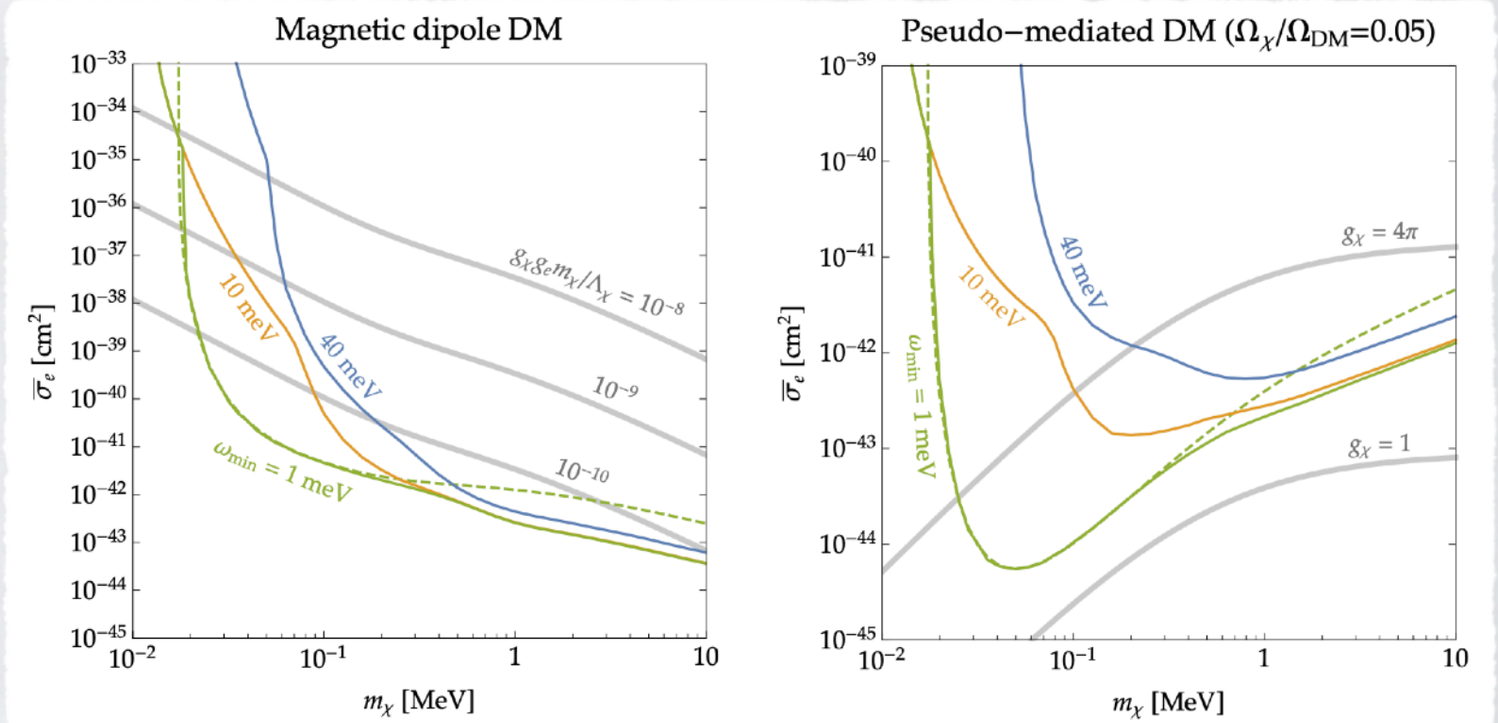

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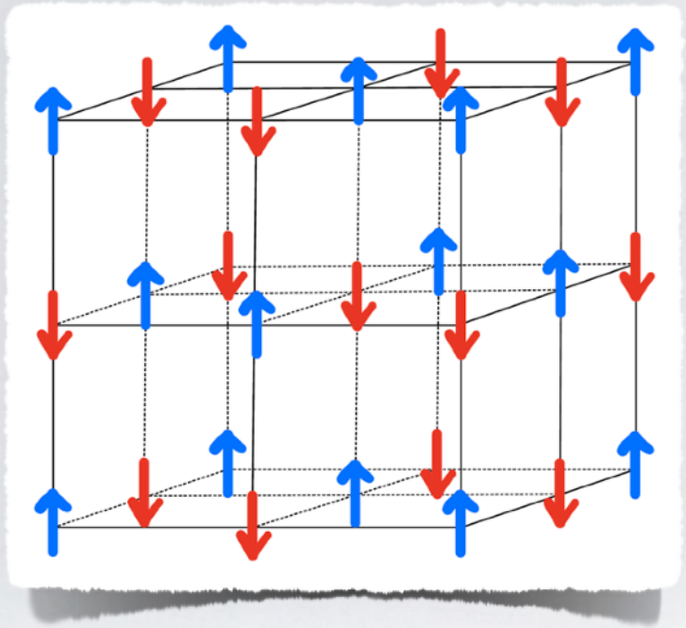

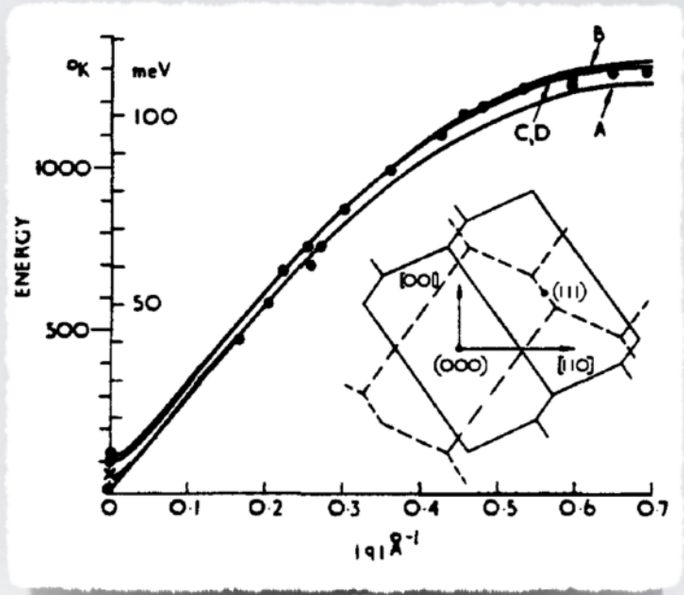

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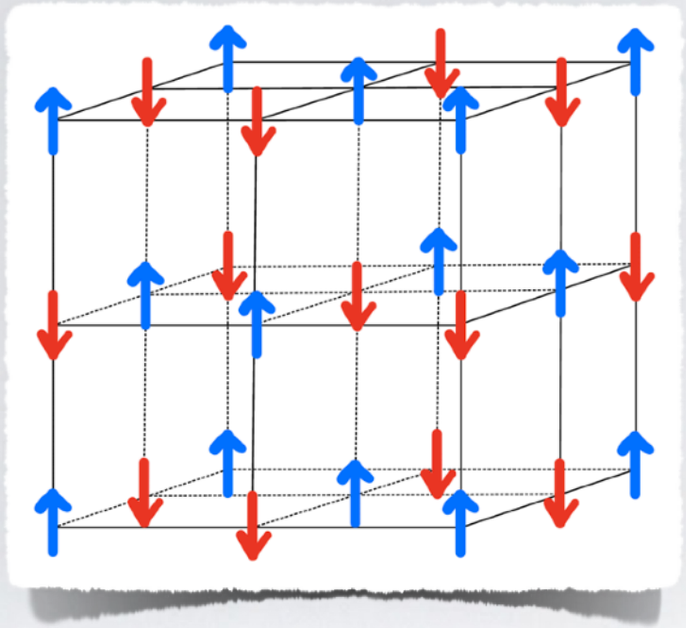

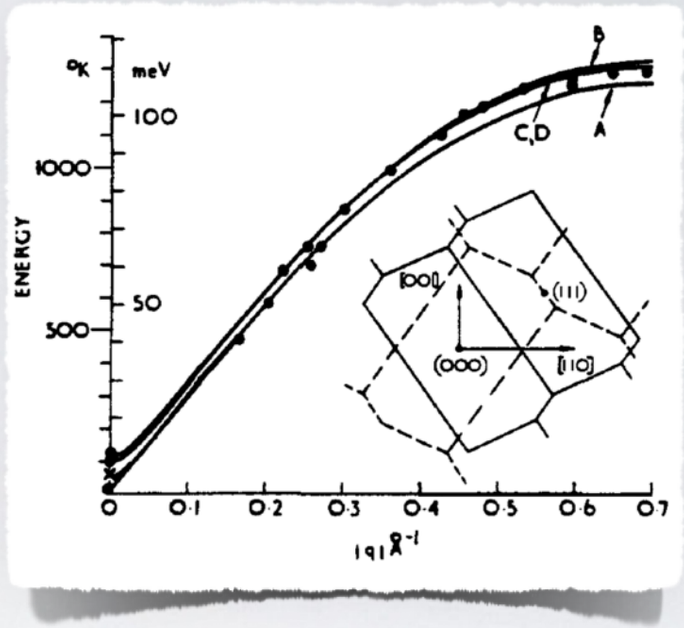

- Can always emit more than one magnon → multi-magnon emission allow to probe down to $m_\chi \sim 1$ keV

ANTI-FERROMAGNETS

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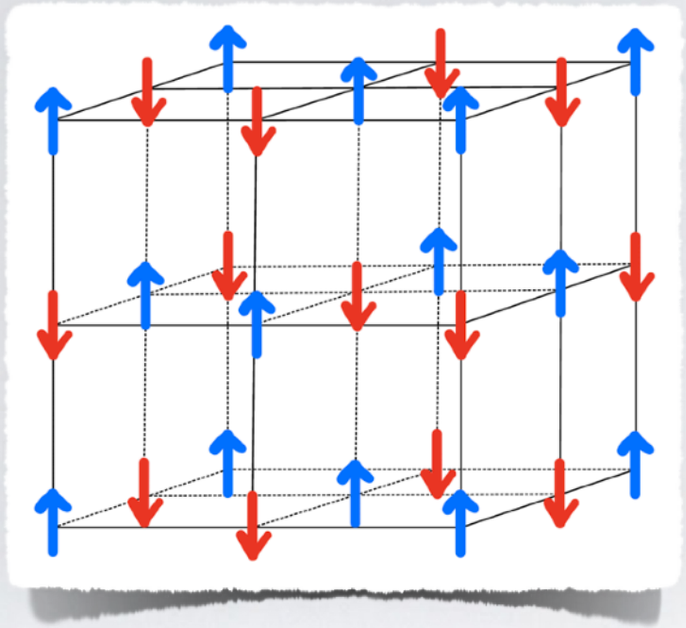

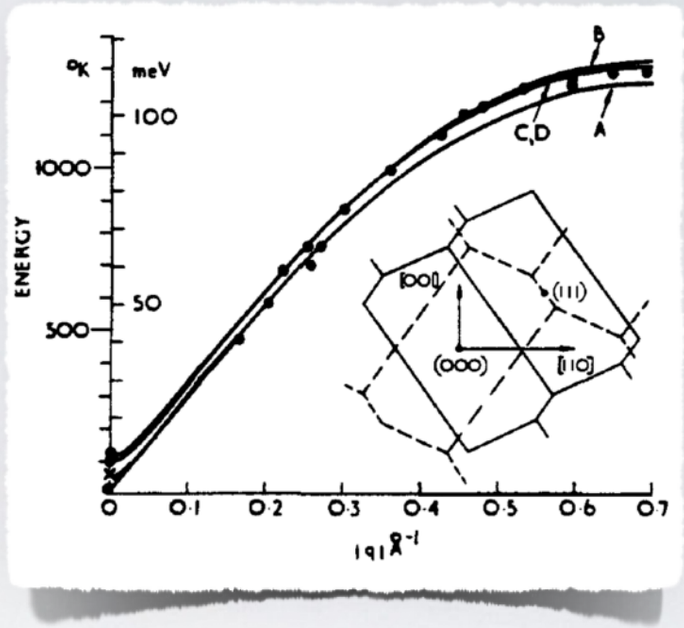

- Can always emit more than one magnon → multi-magnon emission allow to probe down to $m_\chi \sim 1$ keV

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

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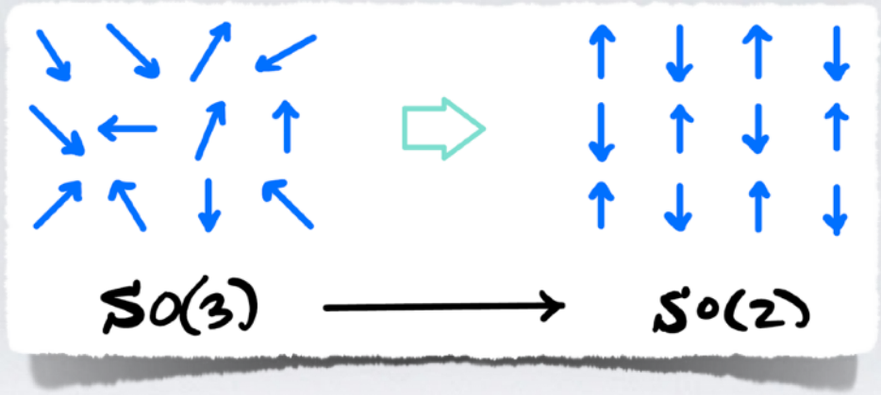
- Anti-ferromagnet spontaneously break internal spin symmetry



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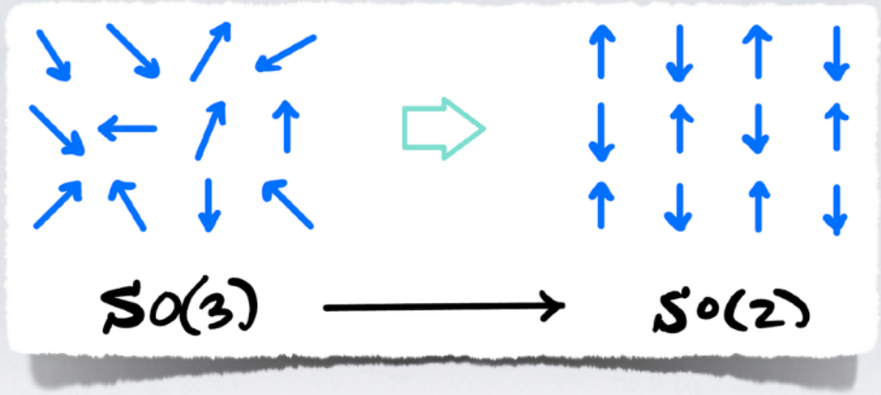

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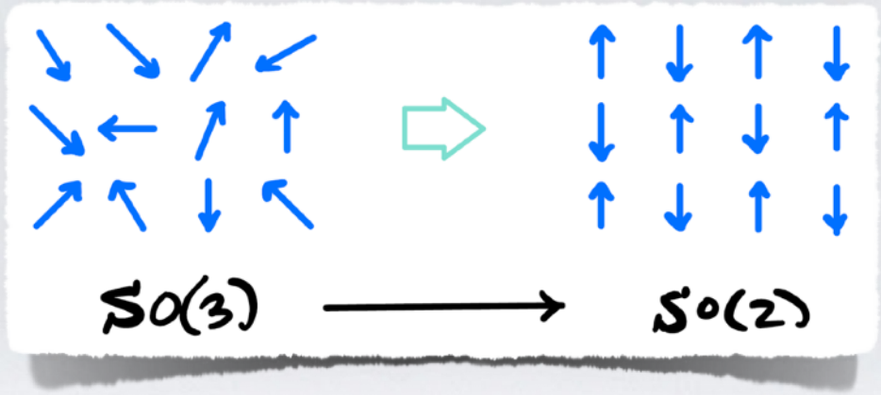

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⇩

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]

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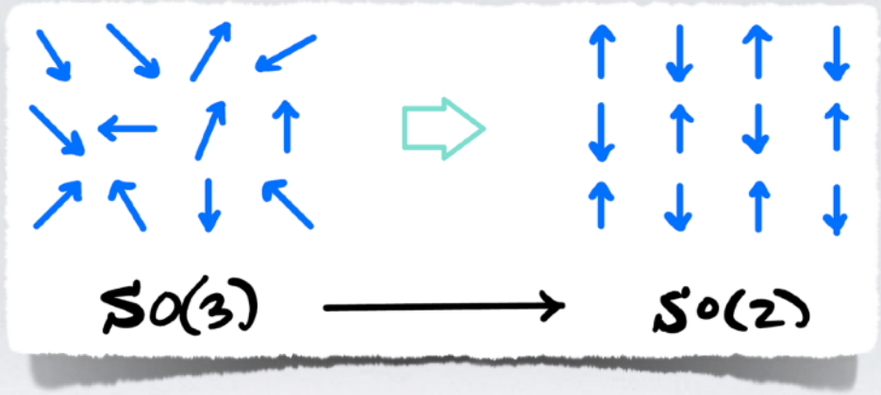

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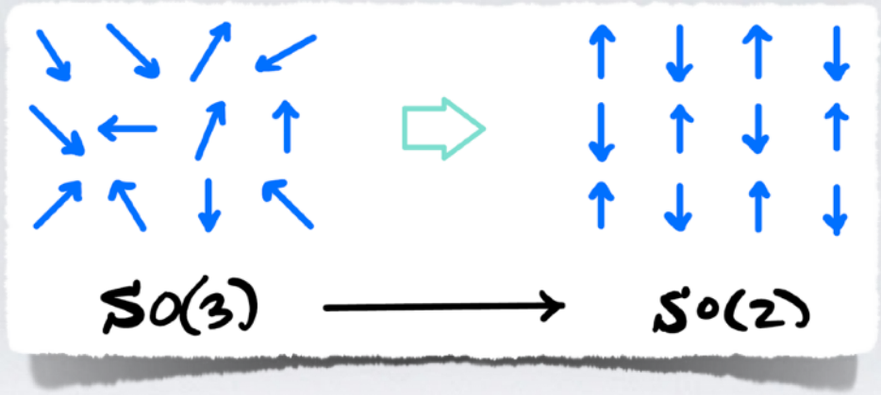

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Bypass standard difficulties in computing multi-magnon processes

[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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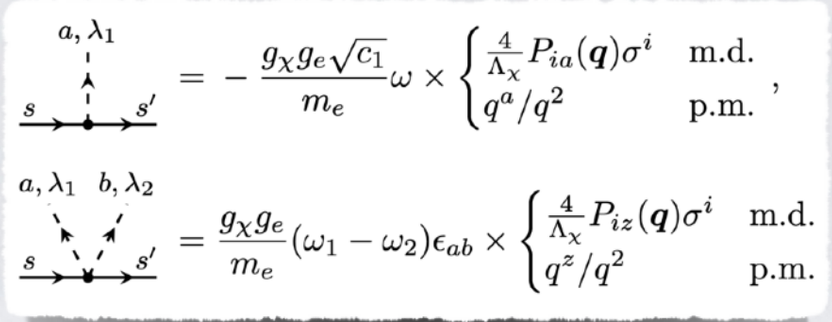

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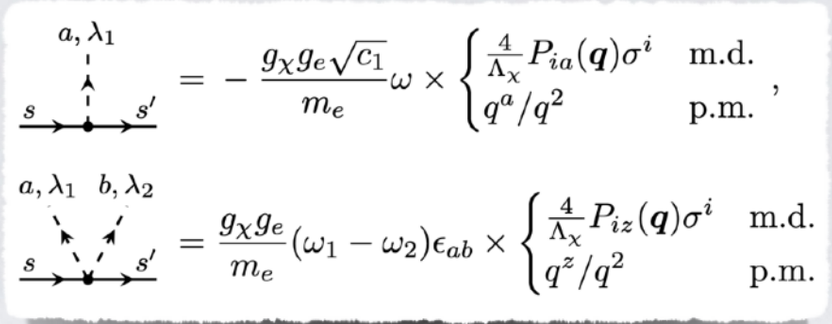

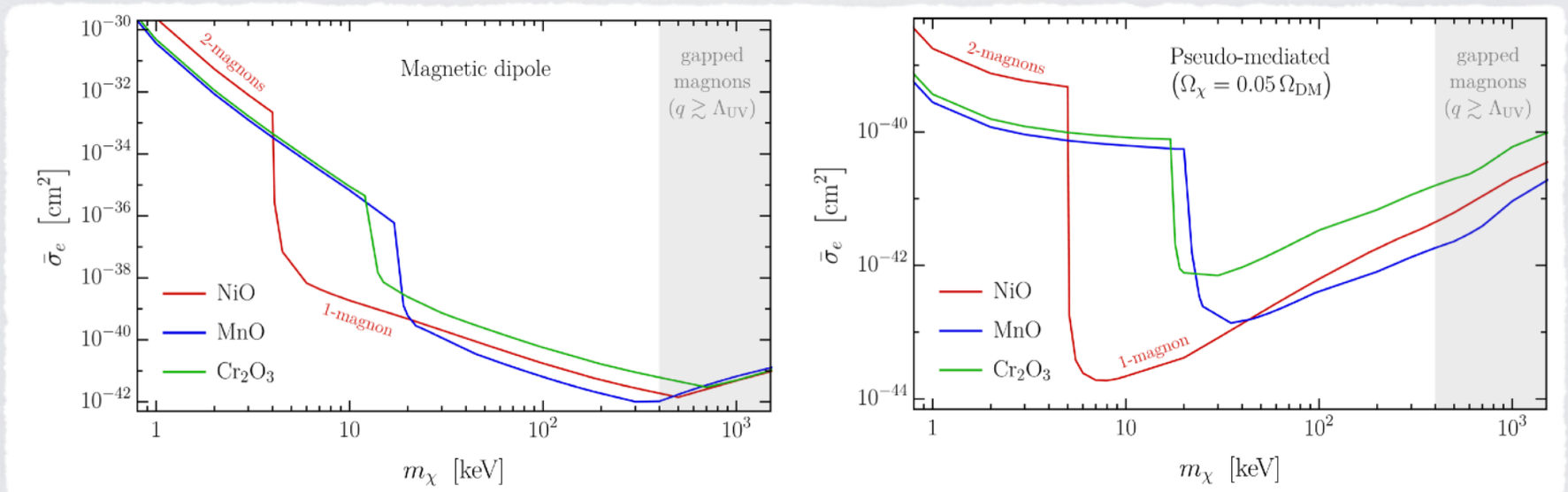

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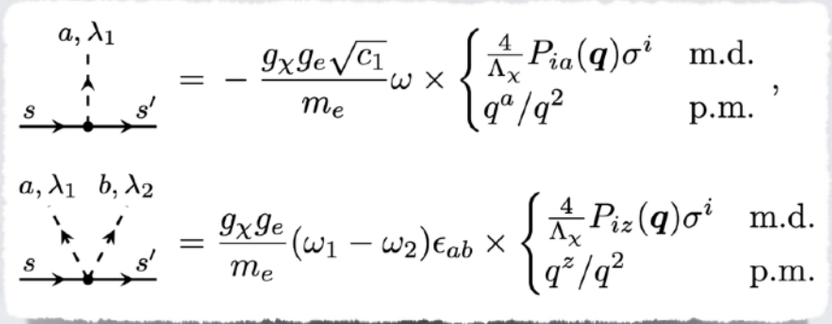
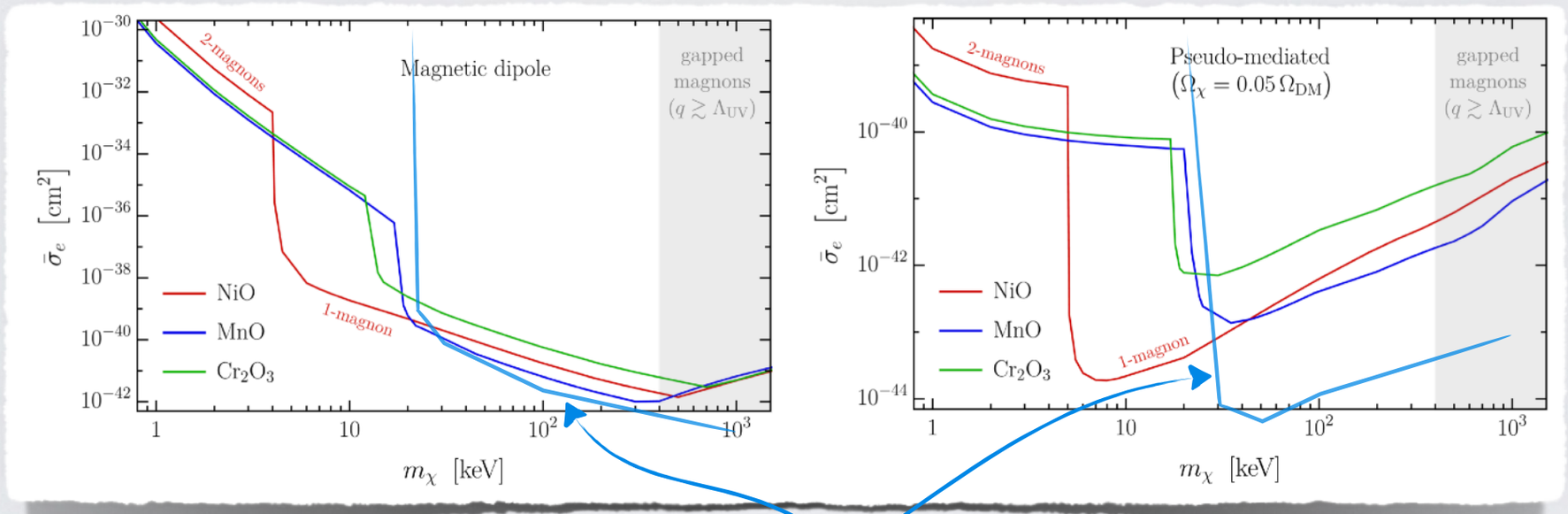
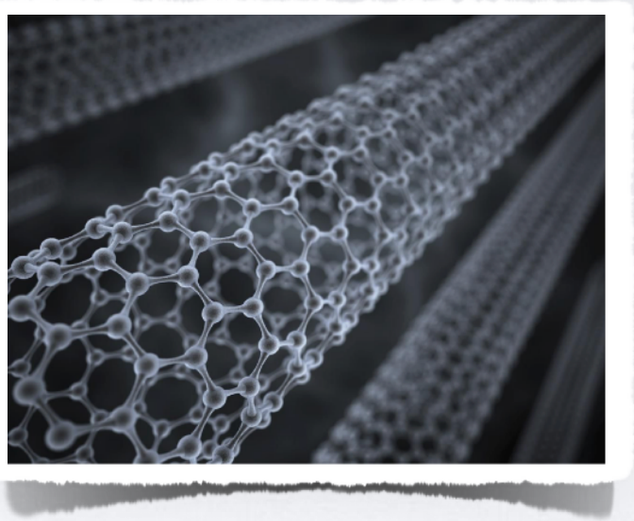




ferromagnets

<u>Honorable mention:</u>

carbon nanotubes



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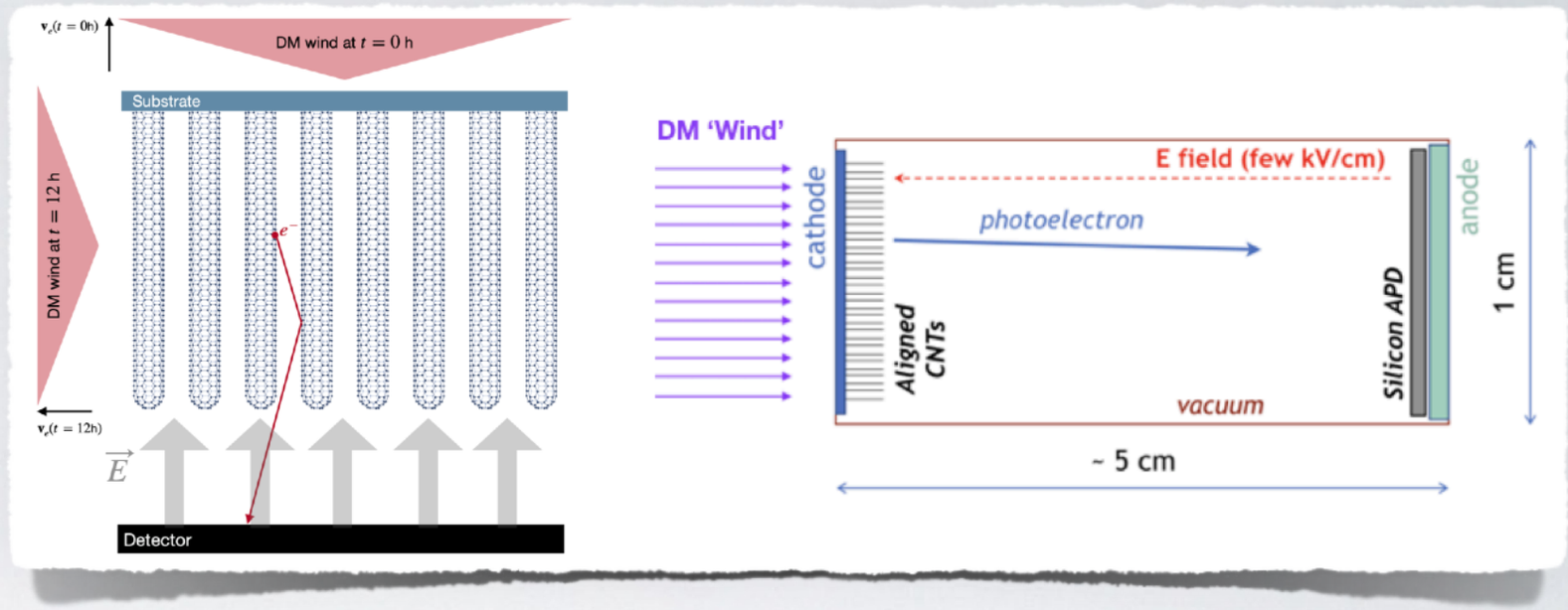
[Capparelli, Cavoto, Mazzilli, Polosa – Phys. Dark. Univ. 2015, 1412.8213; Cavoto, Cirillo, Cocina, Ferretti, Polosa – EPJC 2016, 1602.03216; Hochberg, Kahn, Lisanti, Tully, Zurek – PLB 2017, 1606.08849; Cavoto, Lucchetta, Polosa – PLB 2018, 1706.02487; Catena, Emken, Matas, Spaldin, Urdshals – 2303.15509]



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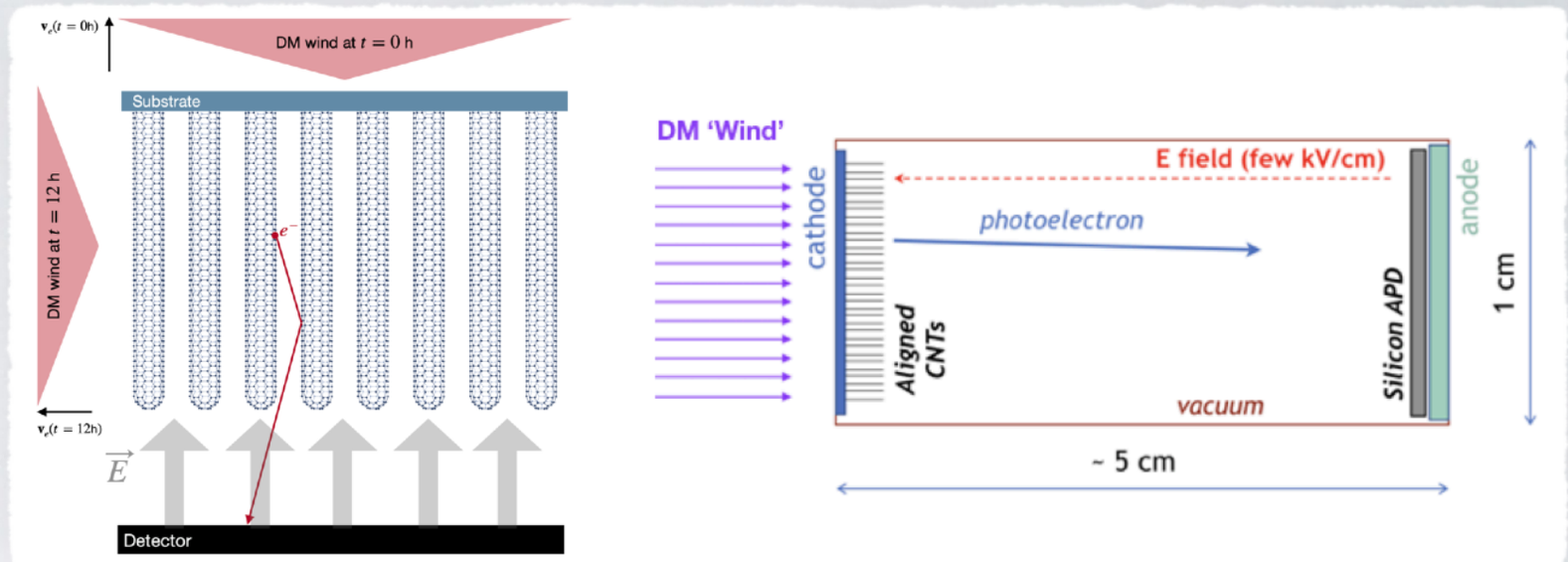

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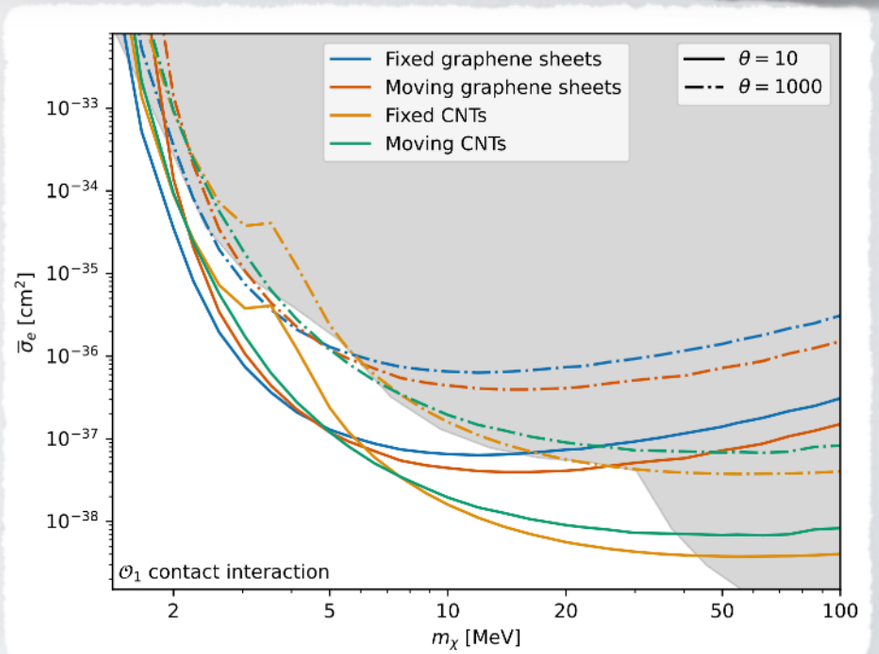

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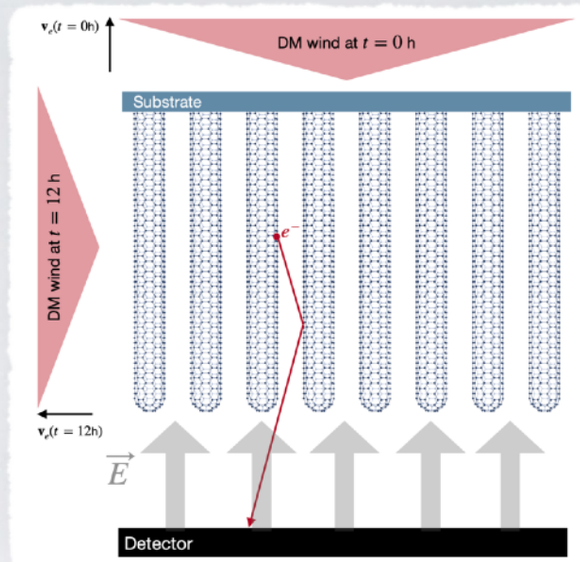

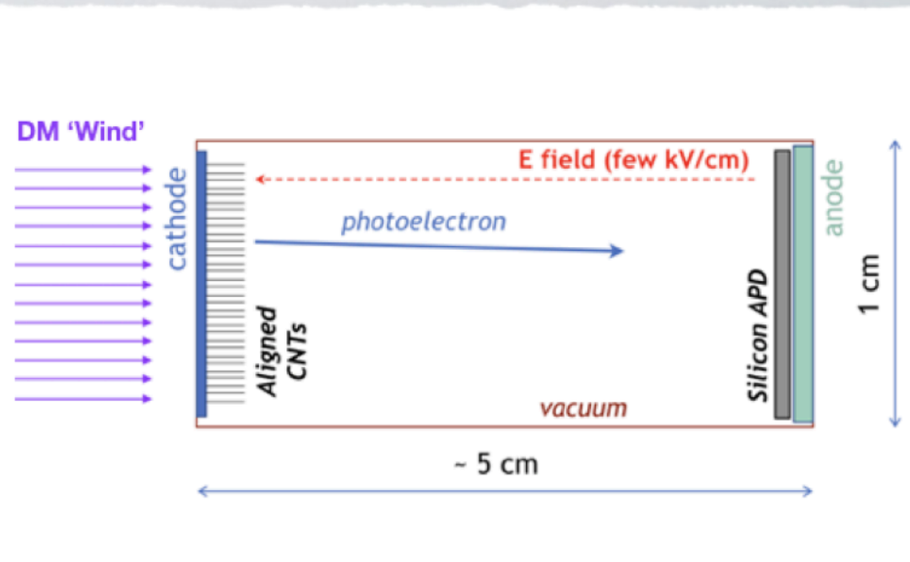

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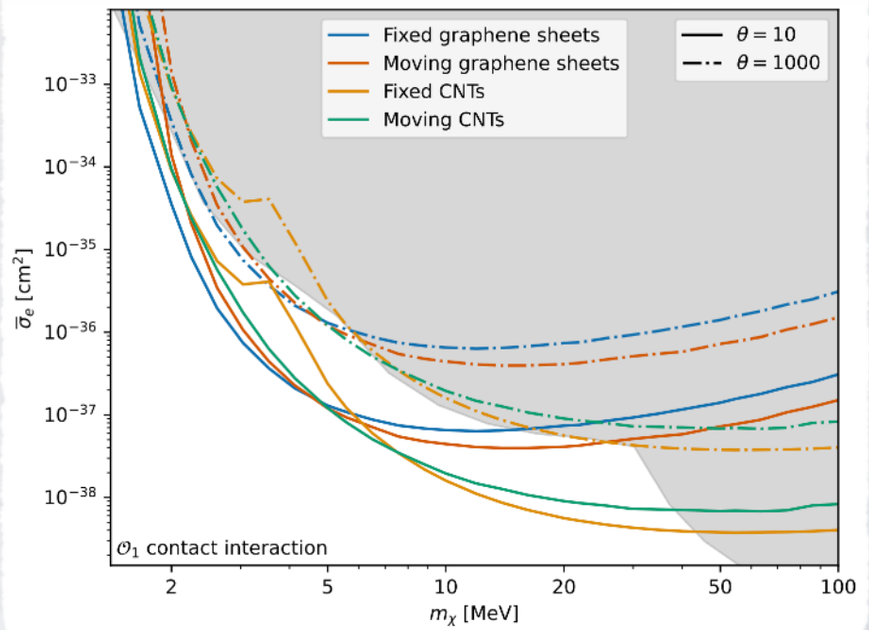
- Might be a good probe for DM-nucleon interactions as well

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



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Thank you for the attention!