LIGHT DARK MATTER DETECTION

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SAPIENZA
UNIVERSITÀ DI ROMA

CYGNO Collaboration meeting, December 2022

OUTLINE

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- Searching for keV-MeV dark matter

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- Down to the MeV: Migdal effect

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- Outlook

SUB-GEV DARK MATTER

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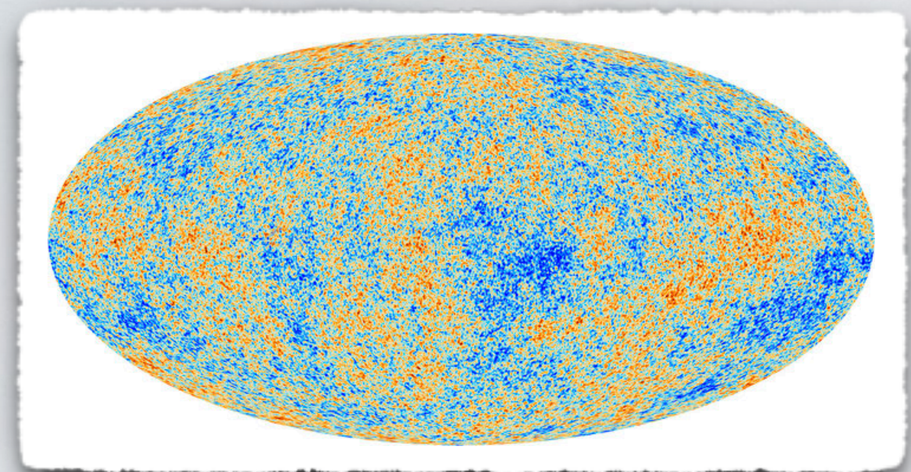
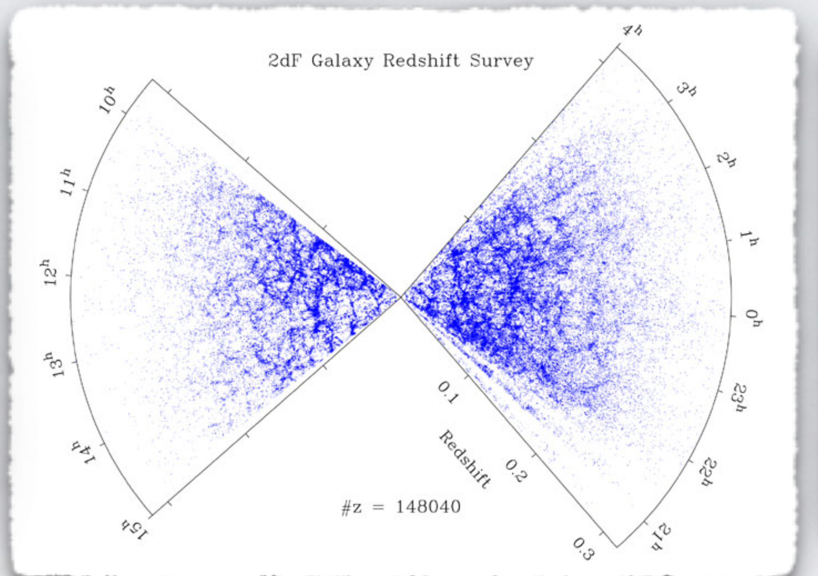
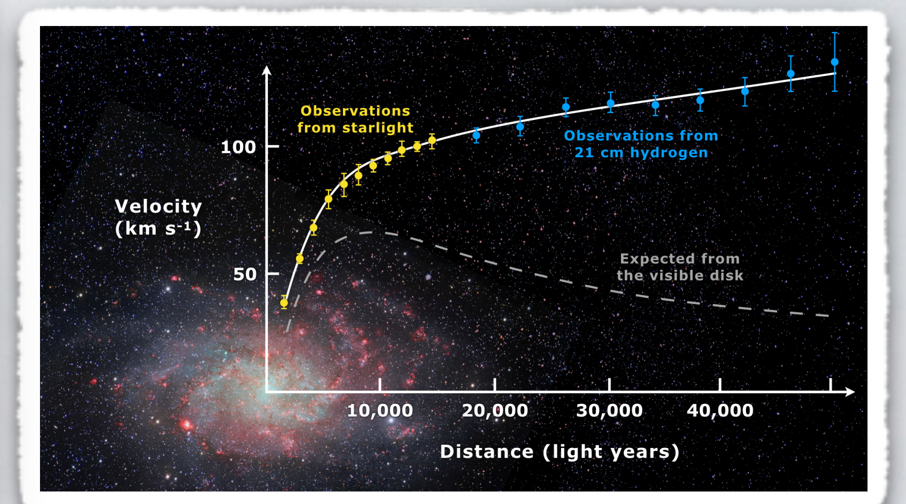
- Most of the matter ($\sim$80 %) that interacts gravitationally is dark







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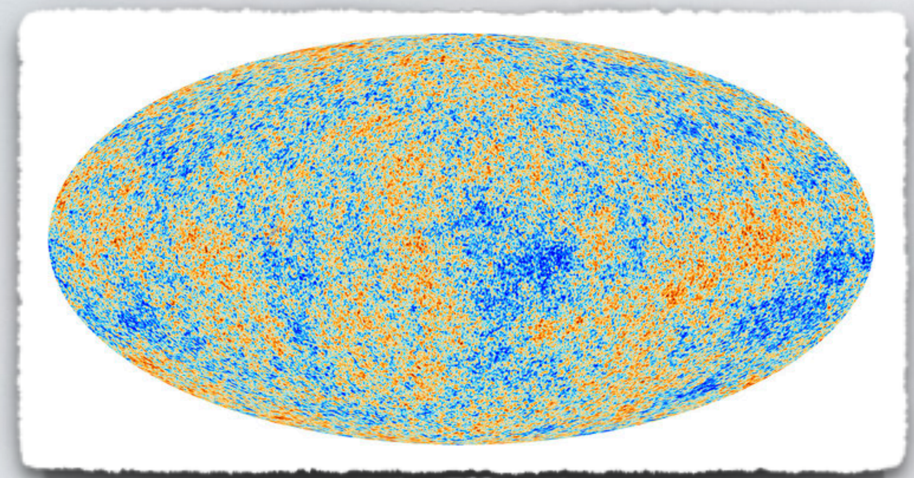

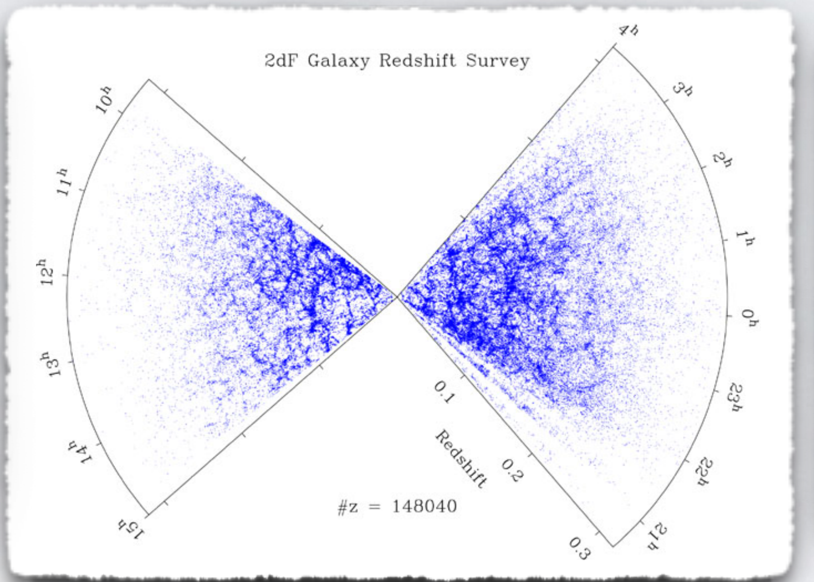

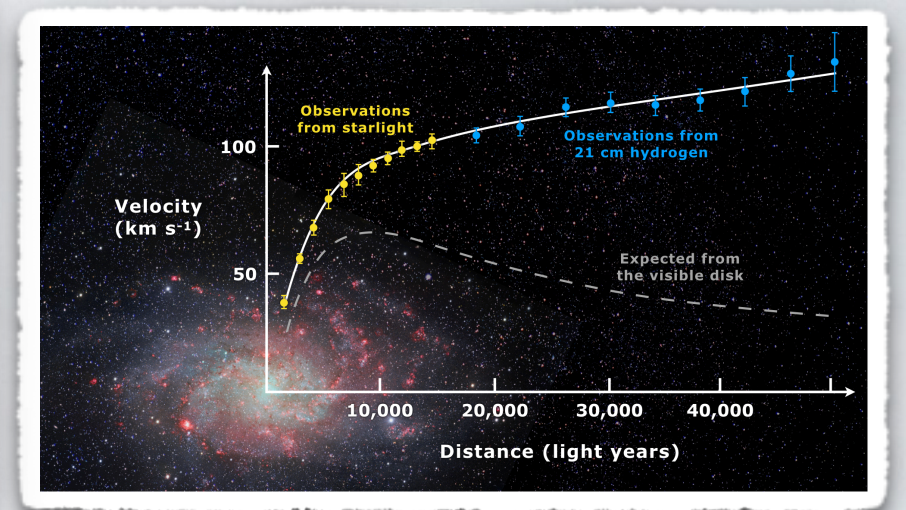

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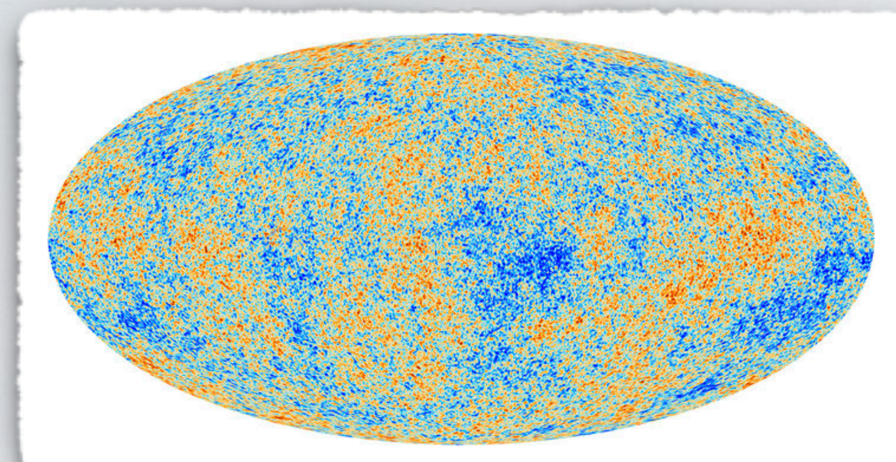

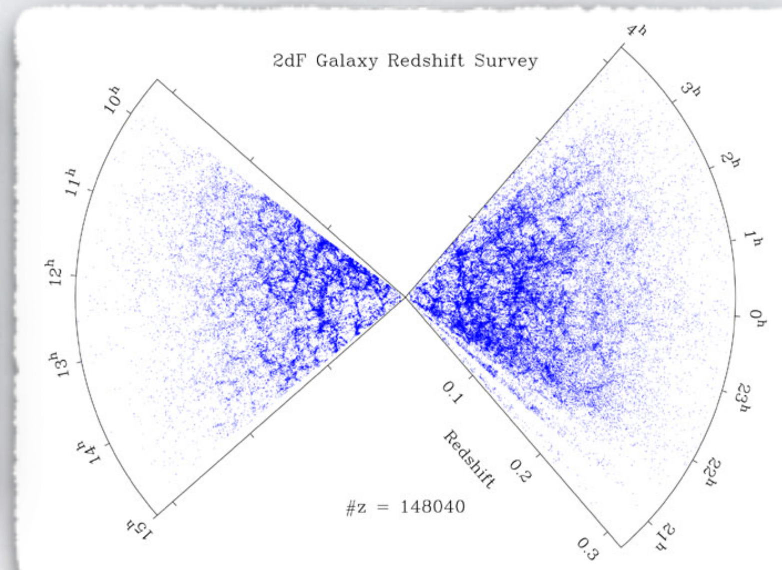

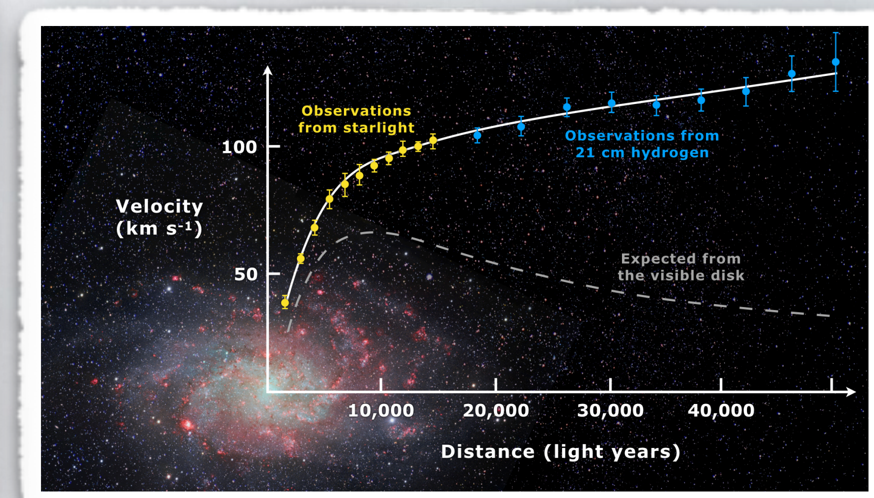

- One of the strongest evidences for physics beyond the Standard Model

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

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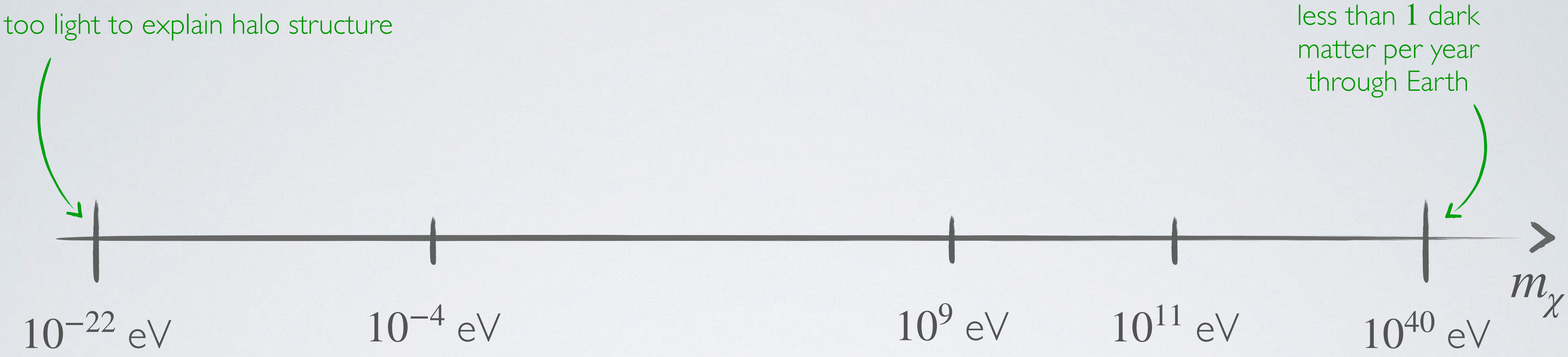

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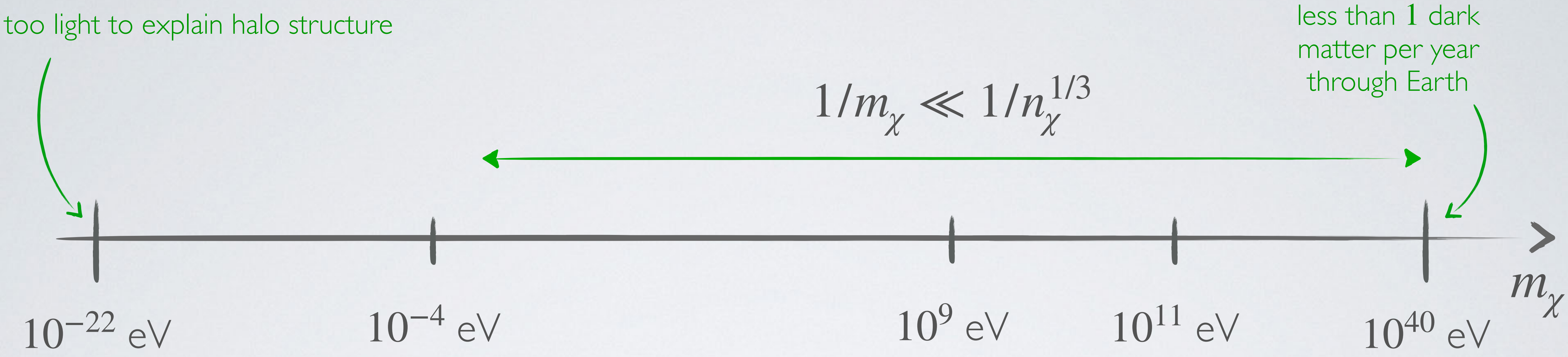

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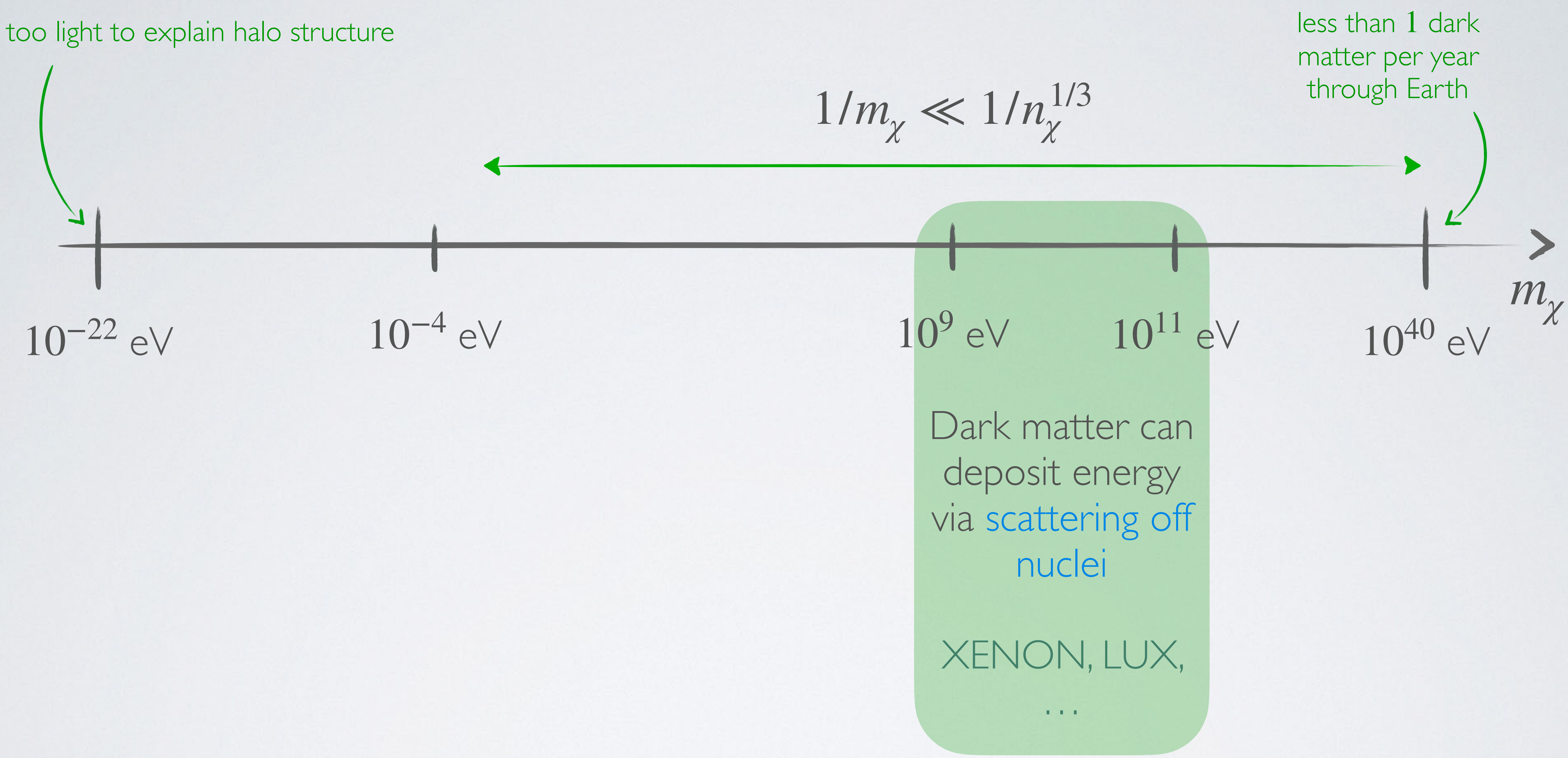

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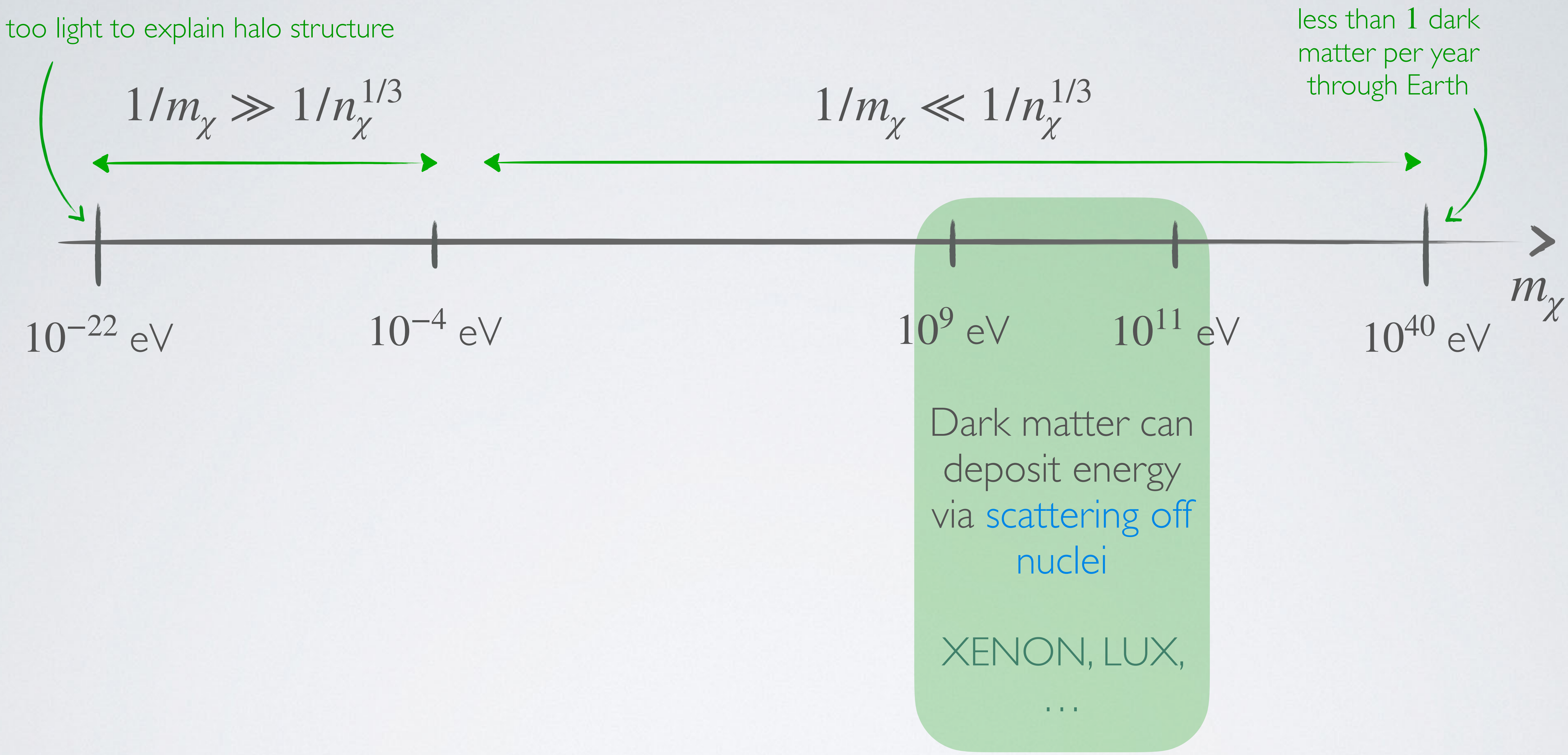

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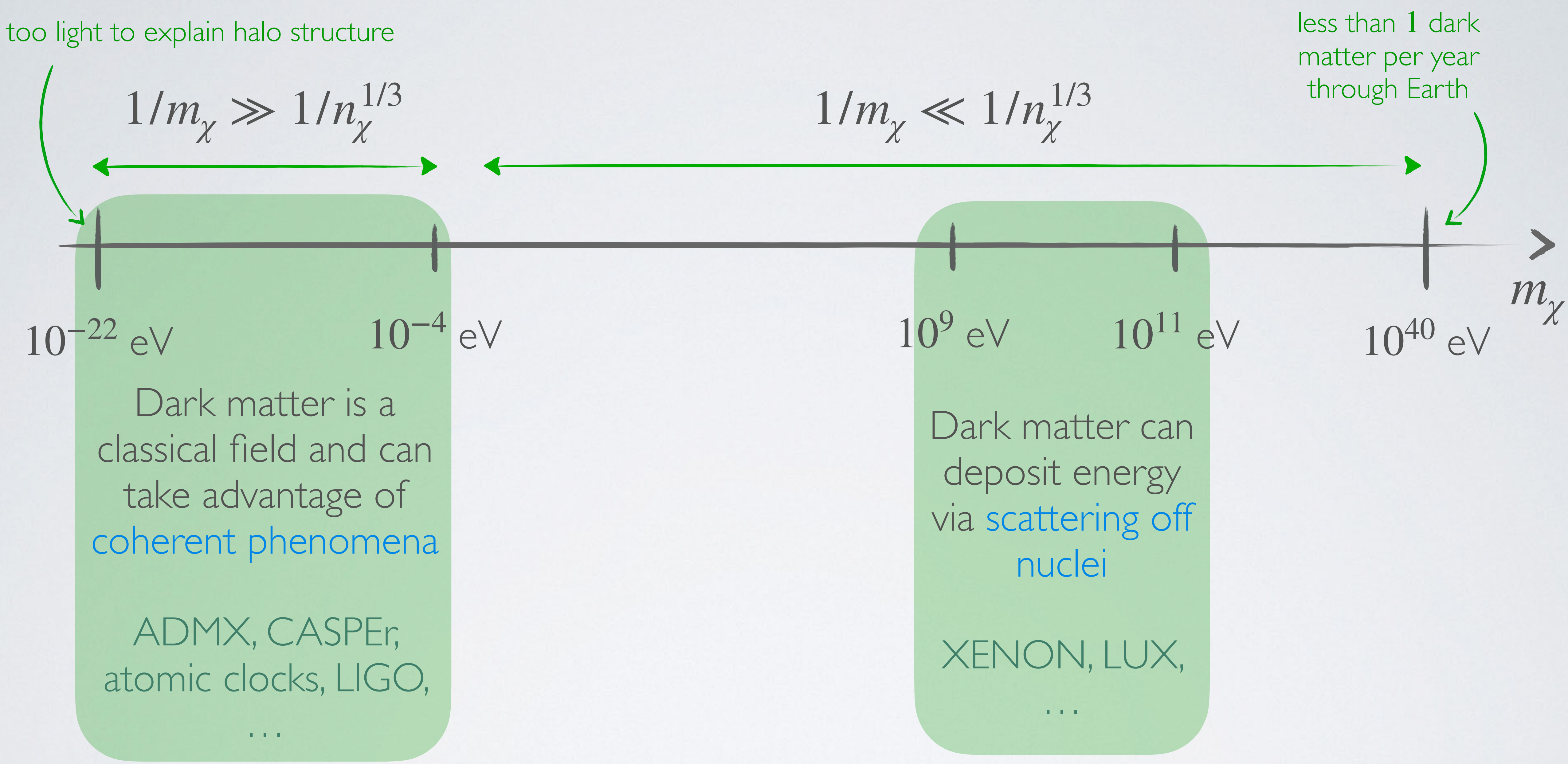

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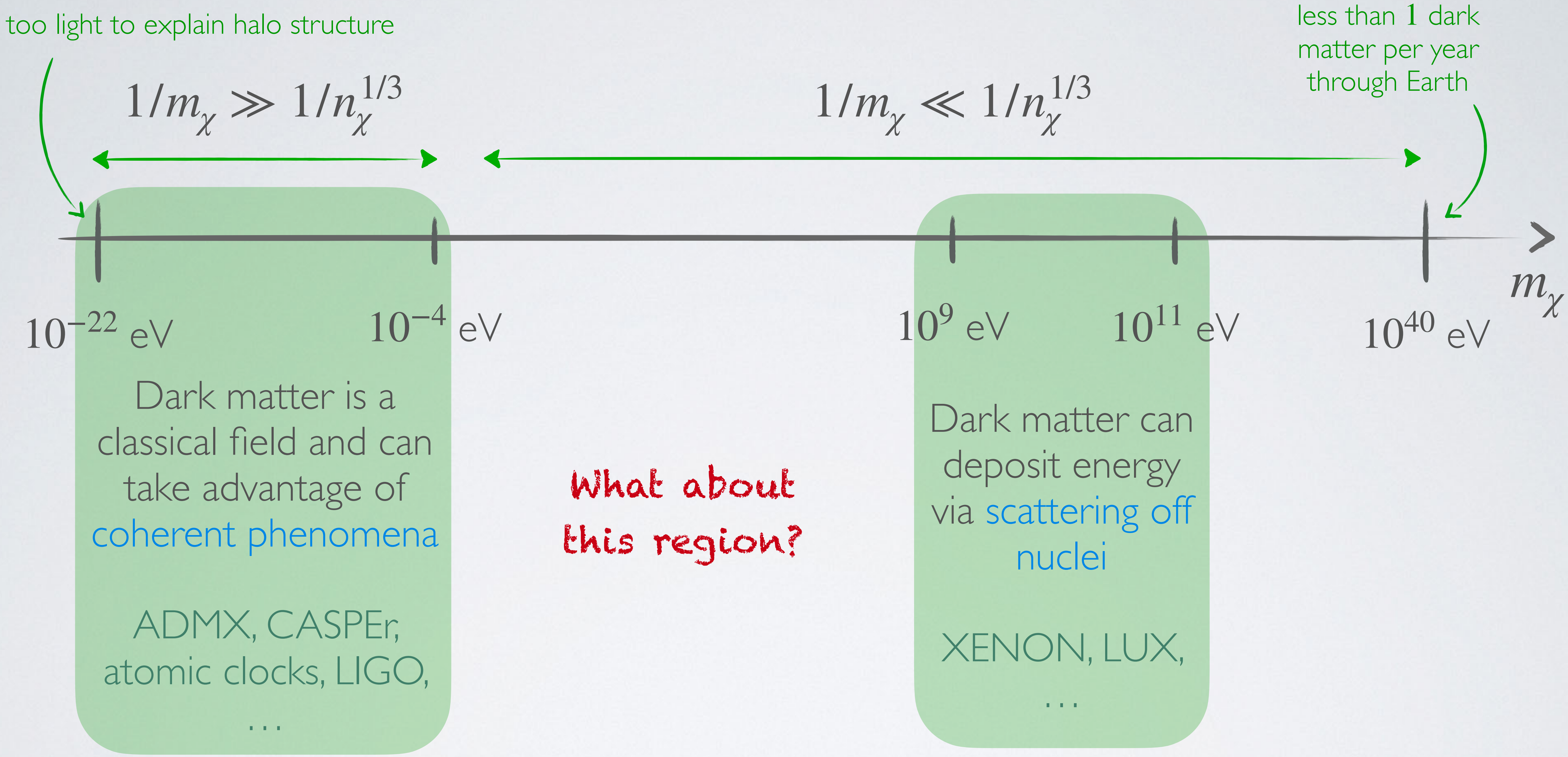

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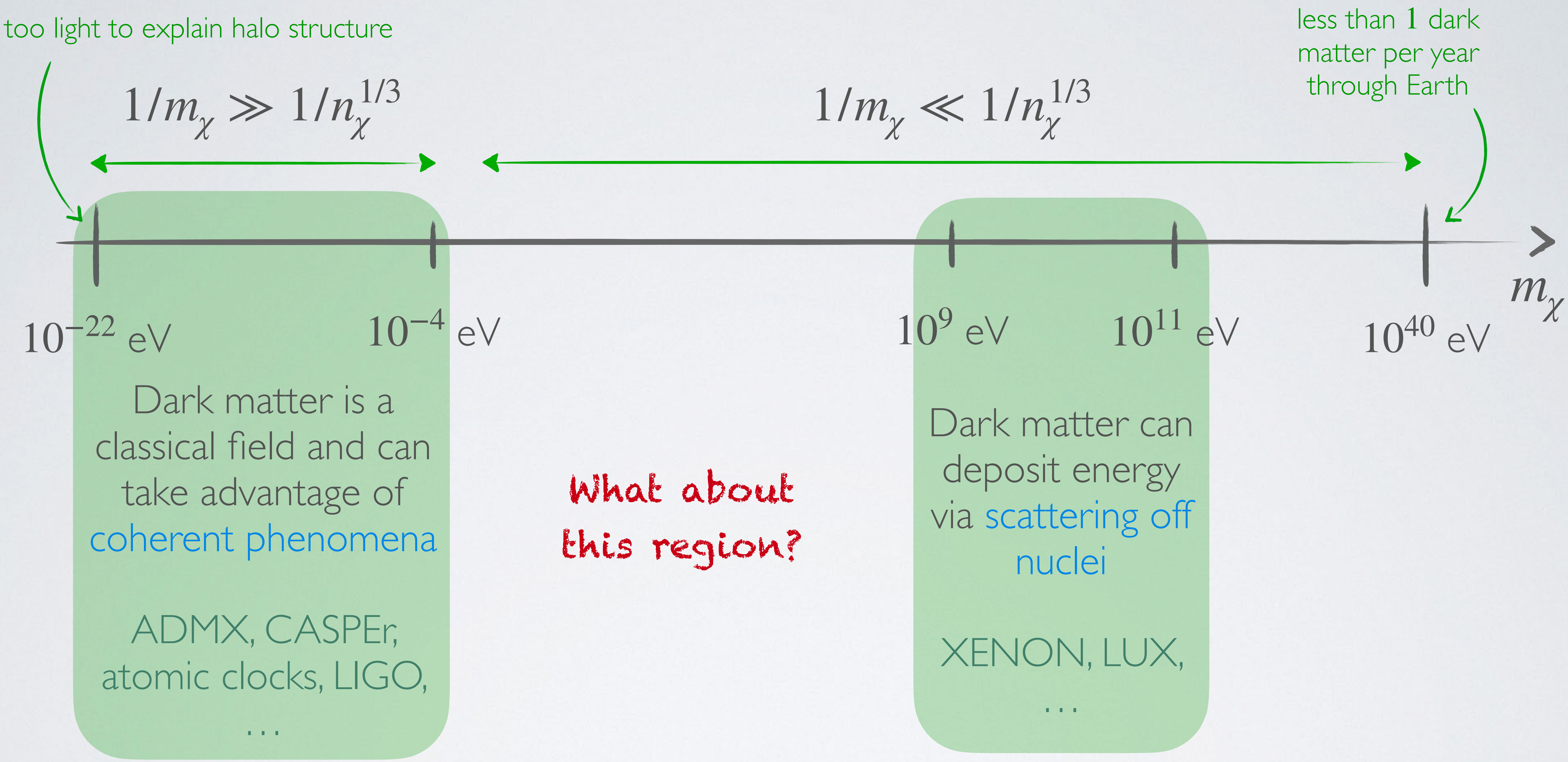

- Dark matter is a particle but too light for nuclear recoil

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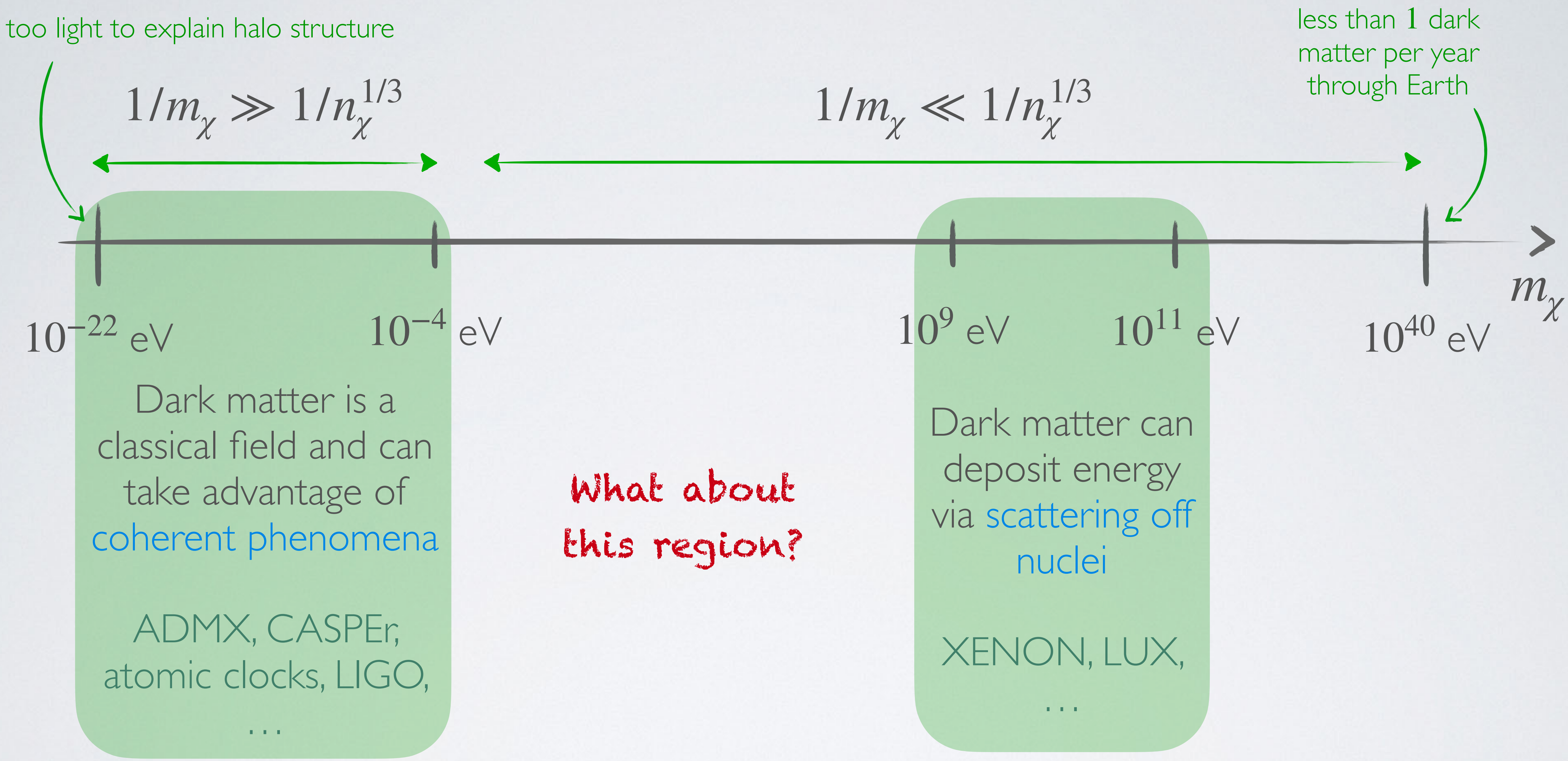

- Dark matter is a particle but too light for nuclear recoil
- Need new materials or observables

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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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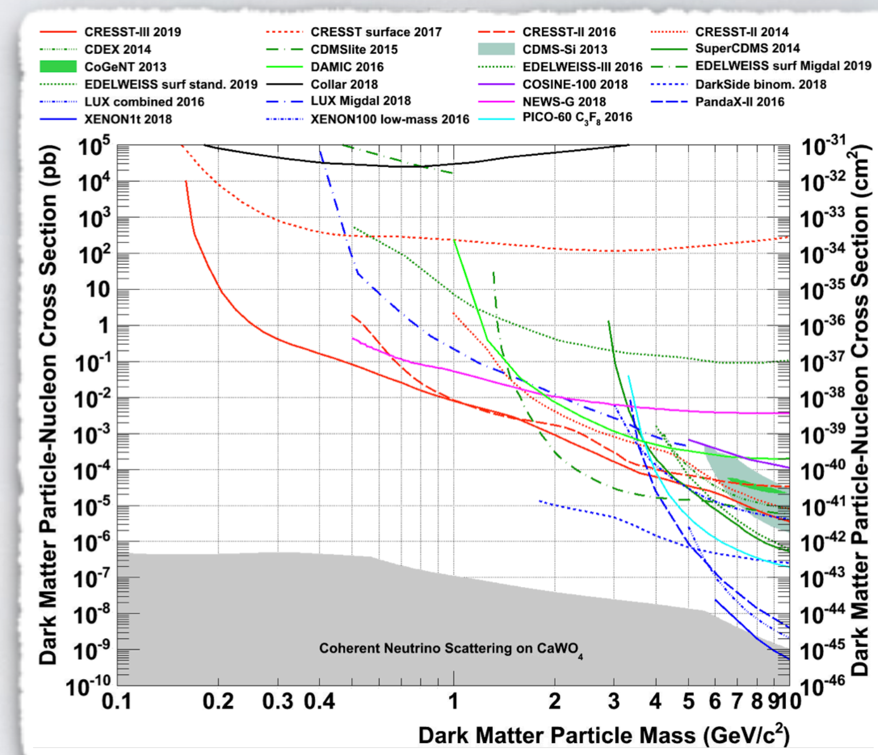

[CRESST — PRD 2019, 1904.00498]

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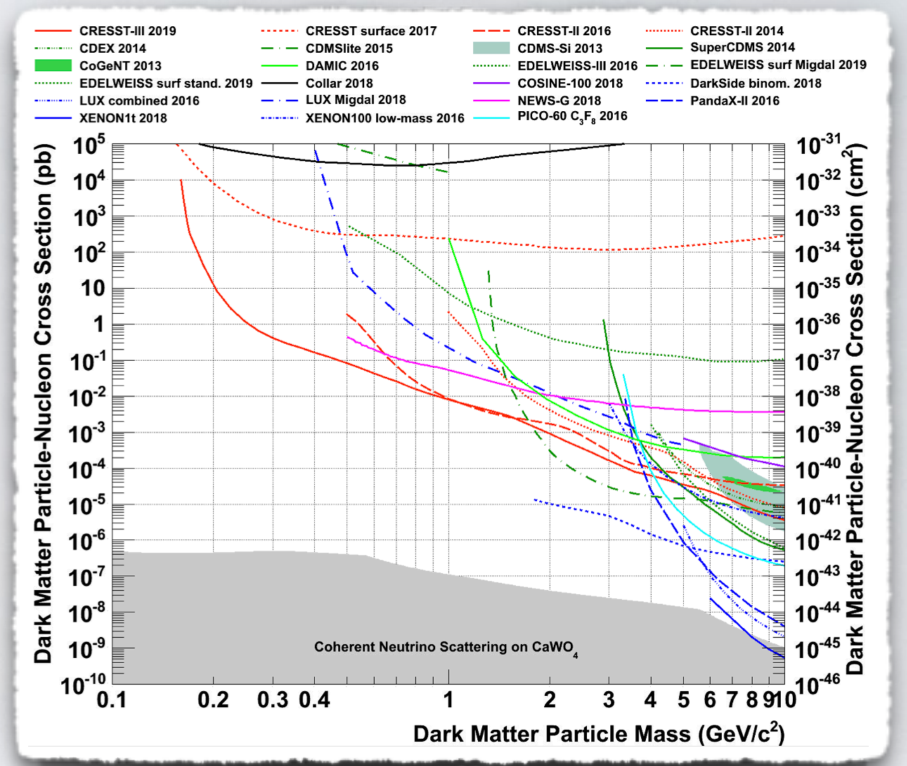
- Two possibilities:
    1. Look into lighter scattering targets
    2. Look into inelastic processes



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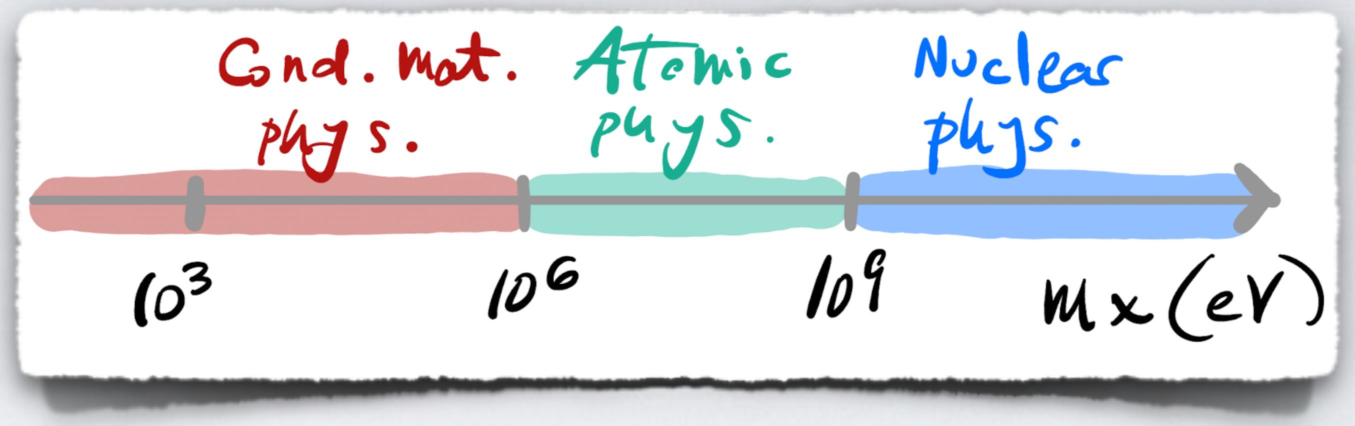
- For sub-GeV dark matter one needs to delve into the condensed matter world



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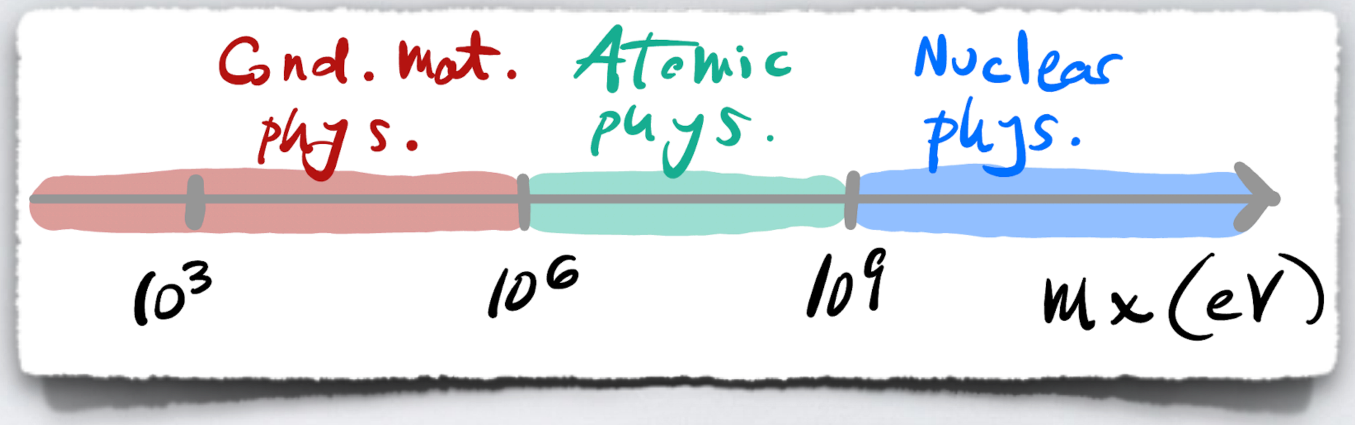
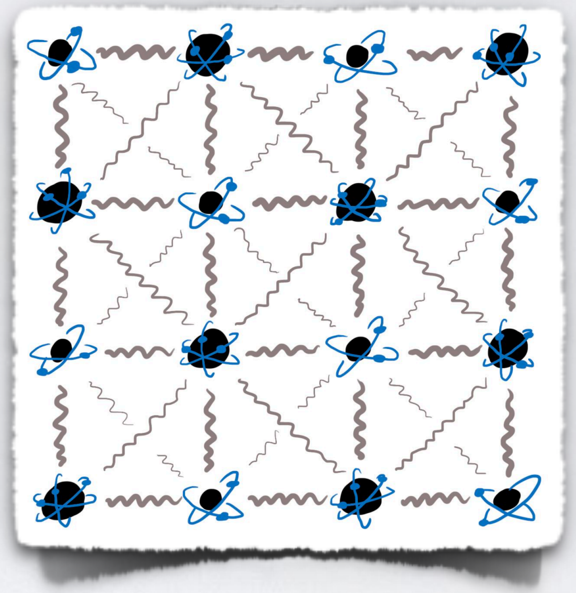


- Need to account for the complicated many-body physics (correlations, strong coupling, …)



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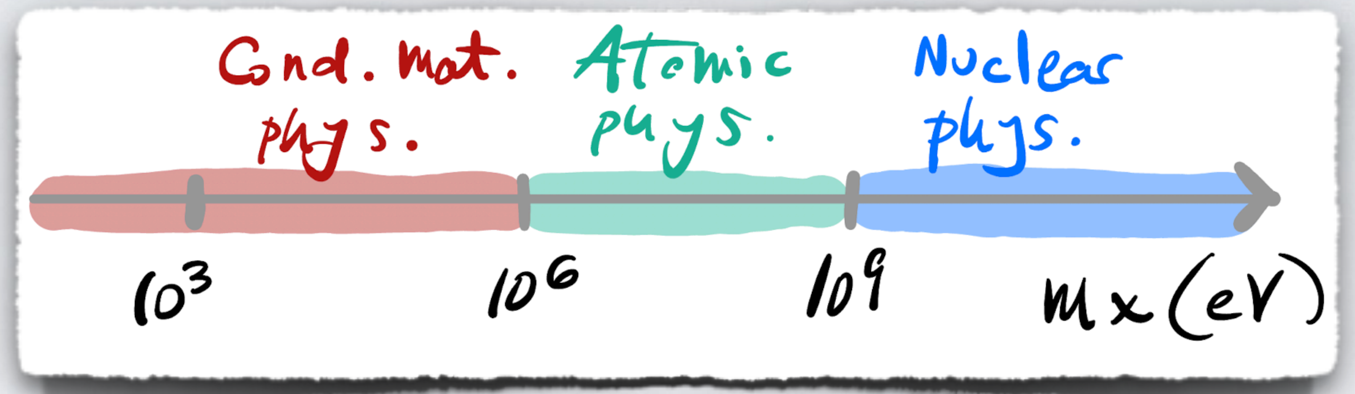

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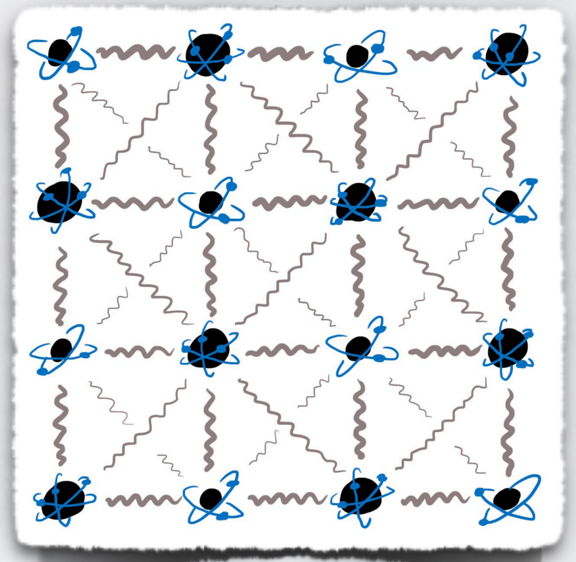
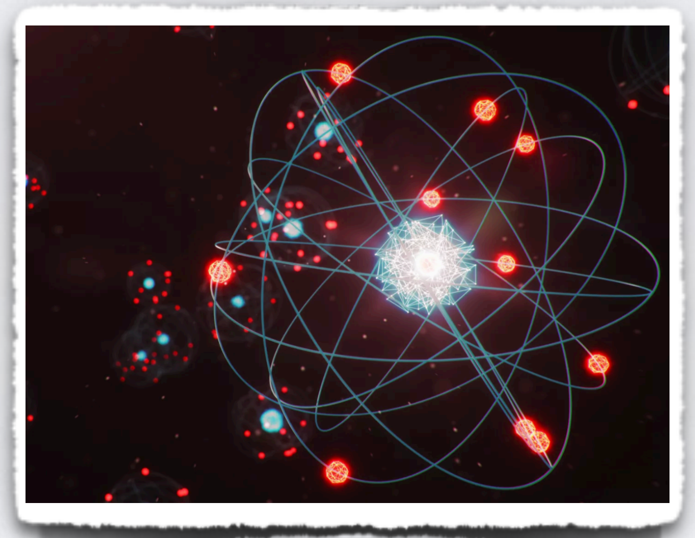


- Need to find theoretical tools that allow to solve or bypass these problems (measured correlation functions, EFTs, …)

Down to the MeV
Migdal effect in semiconductors



MIGDAL EFFECT

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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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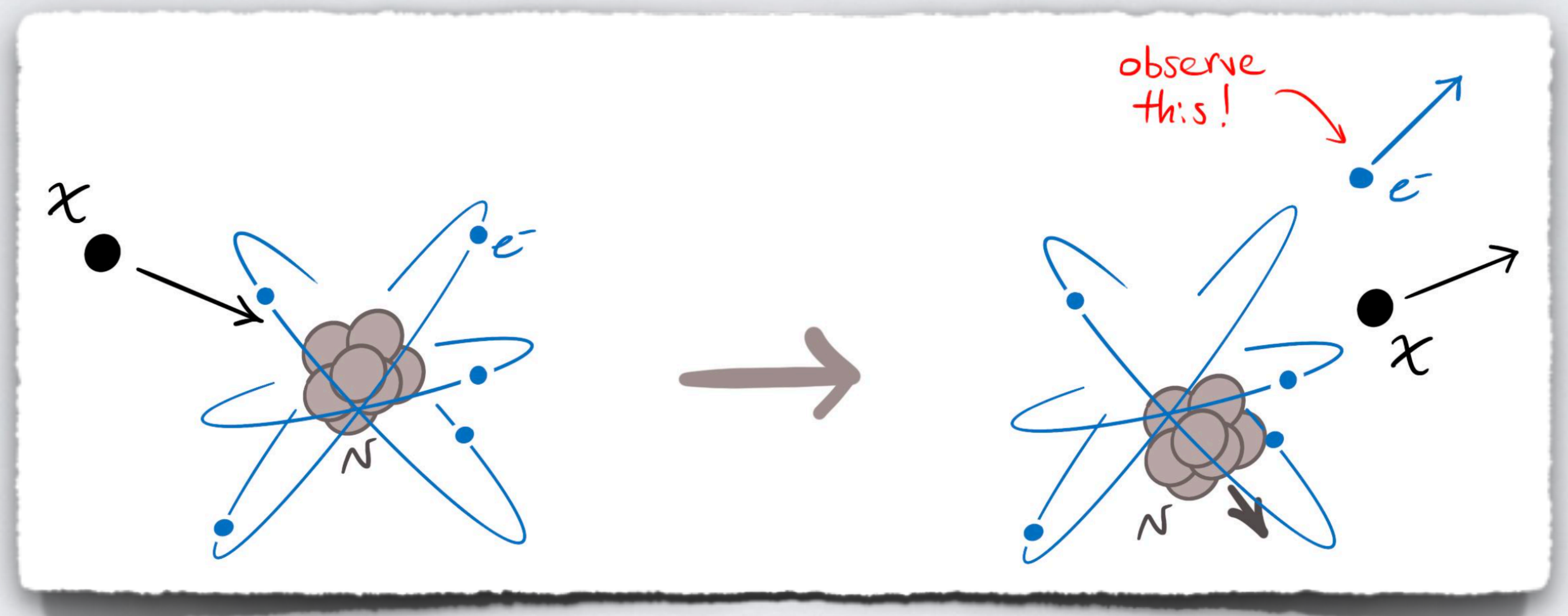

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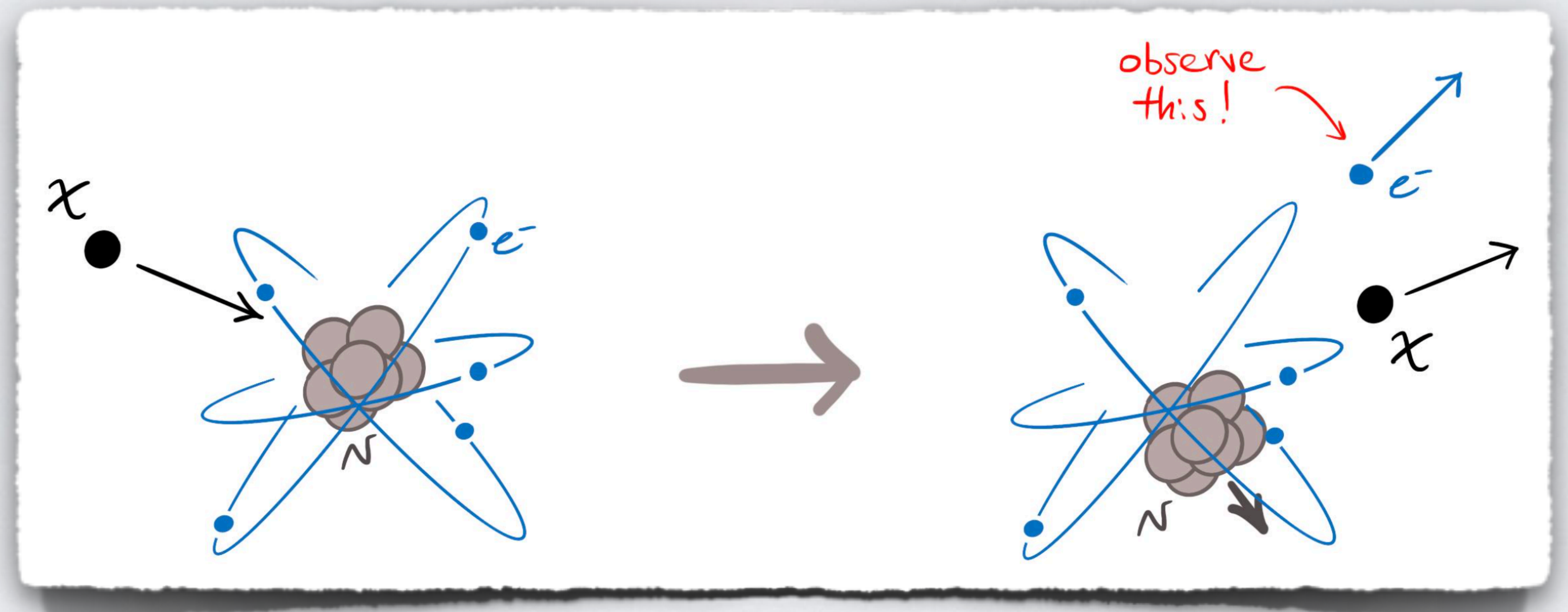

- Less likely… but lower threshold! → sensitivity down to $\mathcal{O}(100$ MeV) masses (see Giovanni's talk)

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

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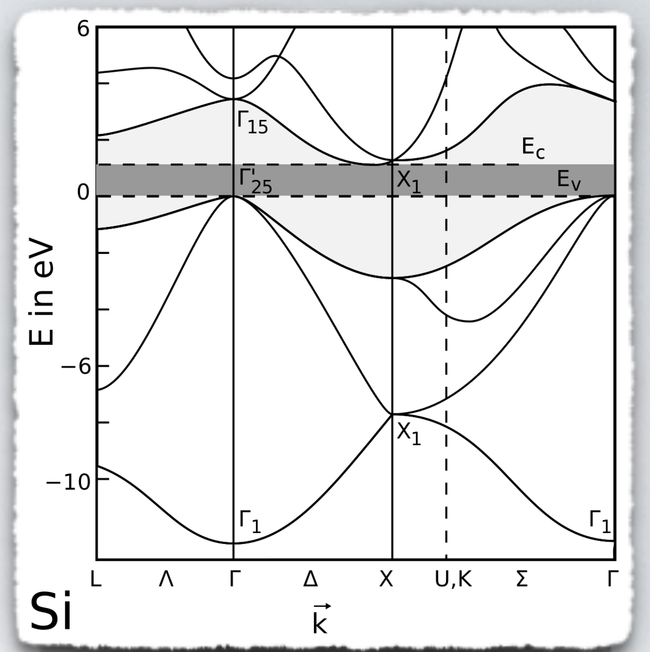
- Semiconductors (Si, Ge, …) have small $\mathcal{O}$(eV) bandgaps ⟶ Migdal effect should allow to probe down to $\mathcal{O}$(MeV) masses



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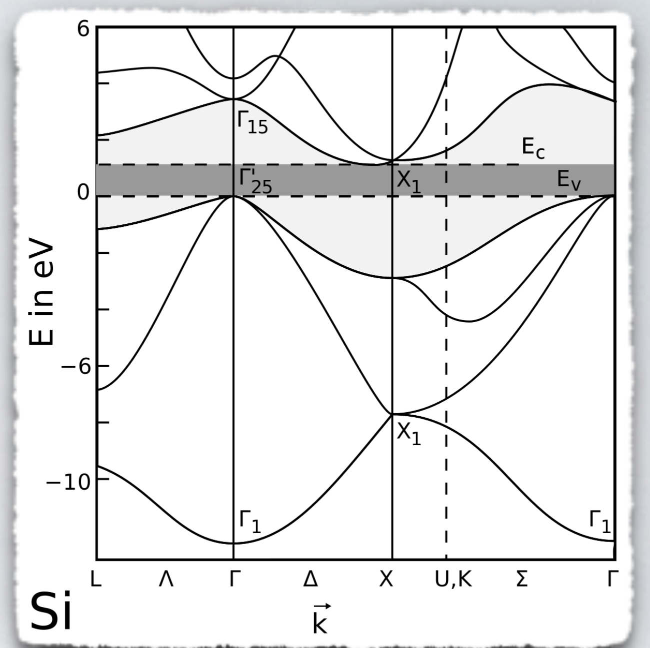

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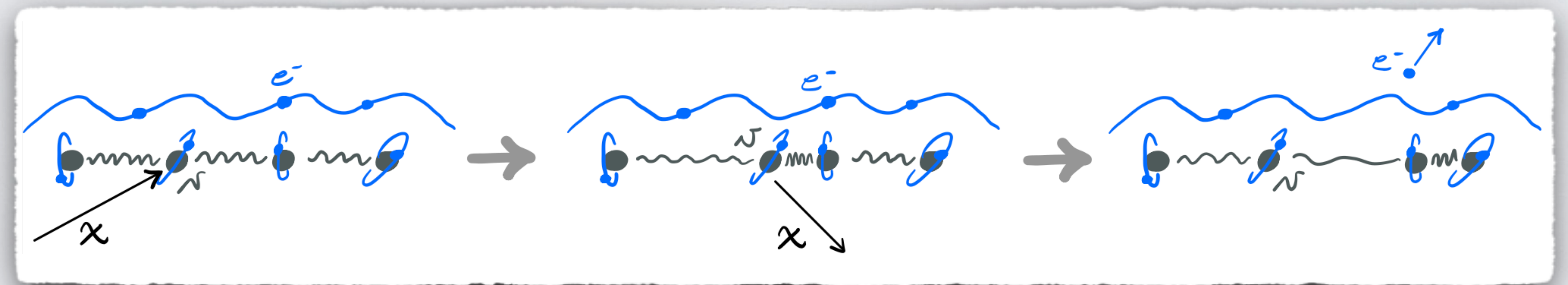

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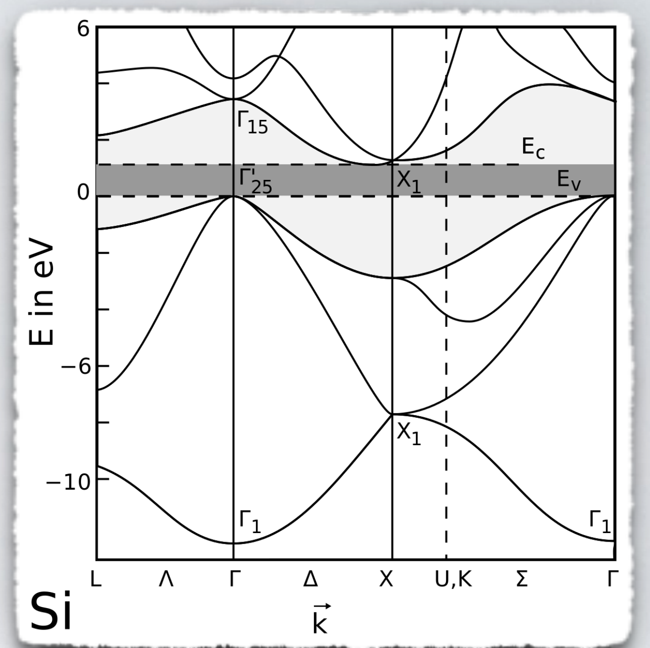

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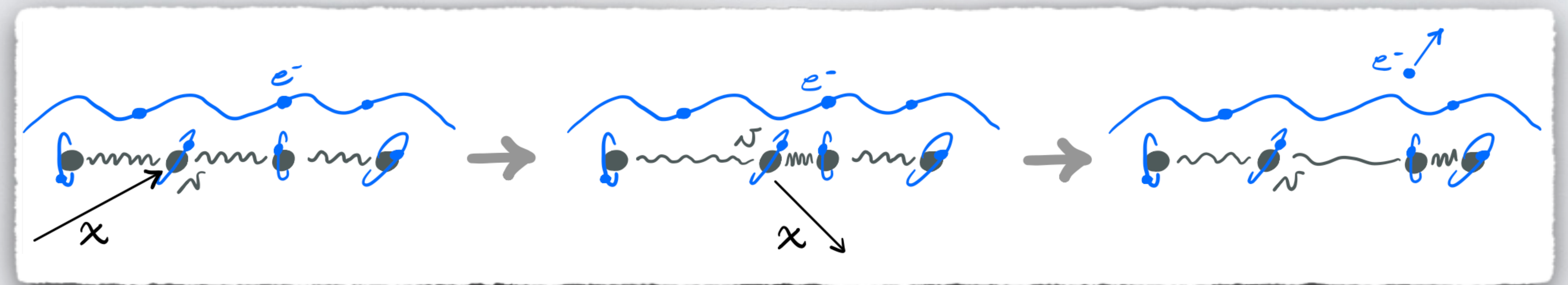

- How to describe nucleus-nucleus and nucleus-electron interactions in a strongly correlated system?

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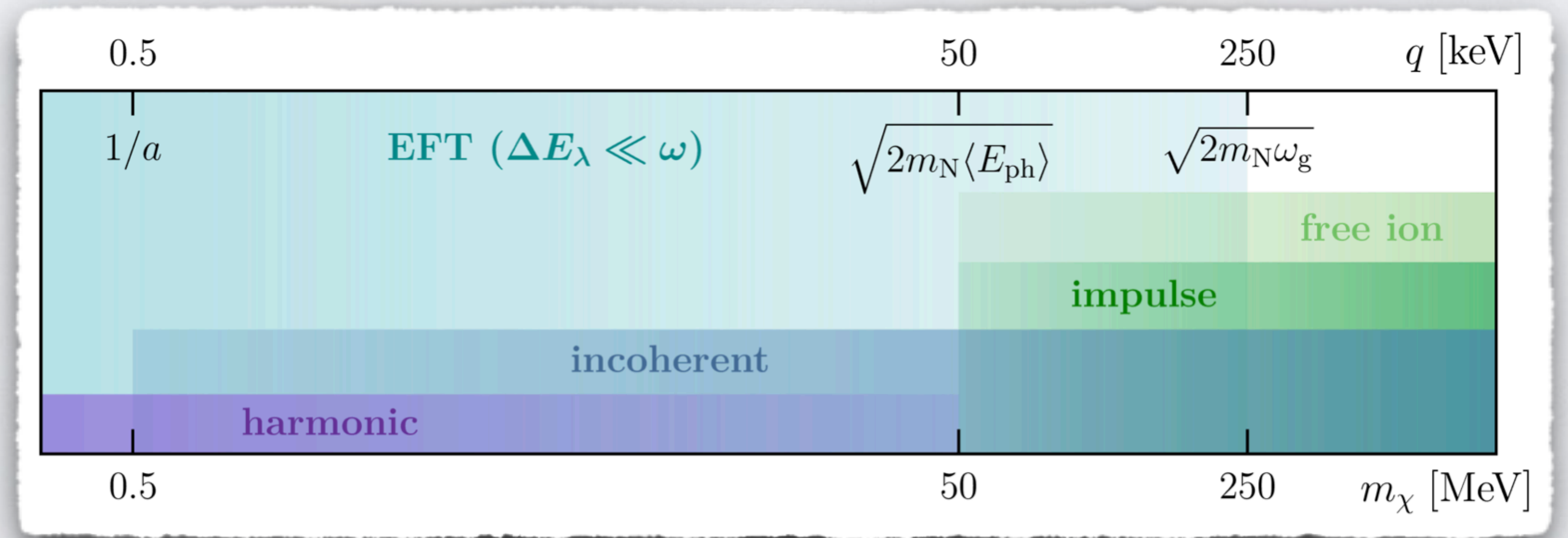

EFT

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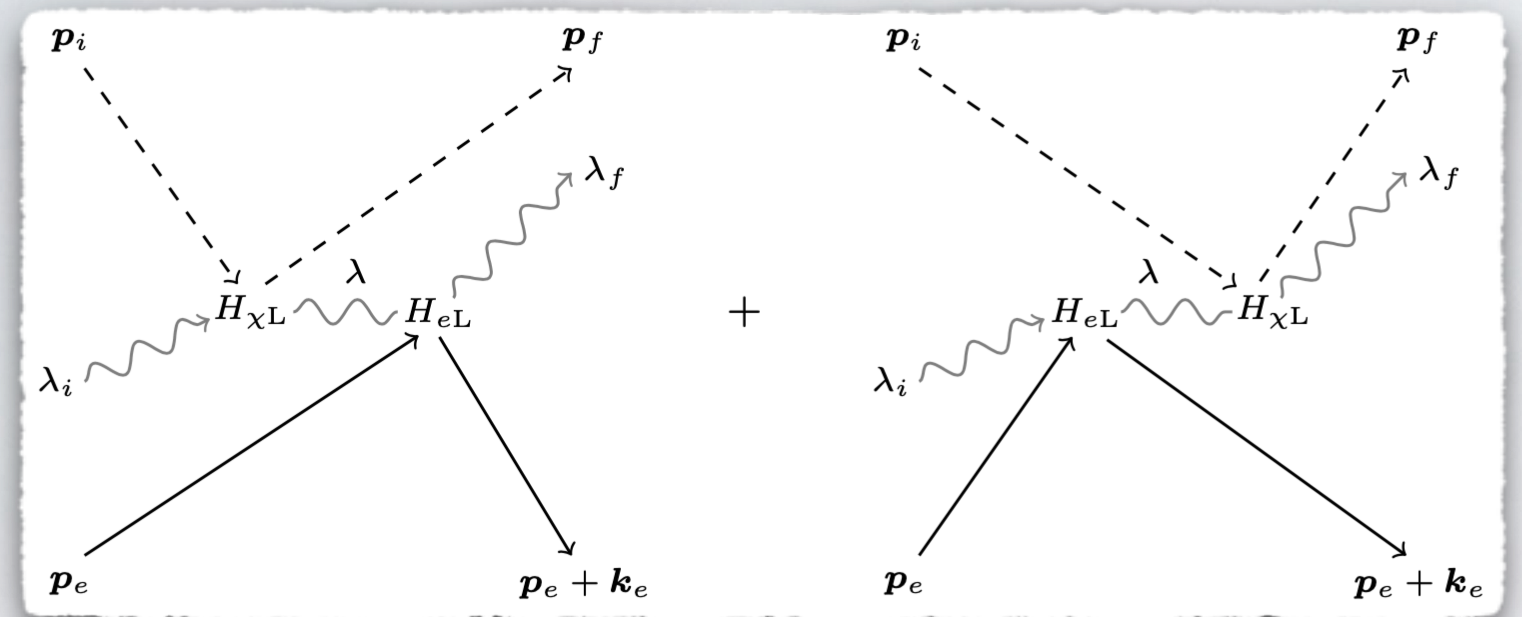

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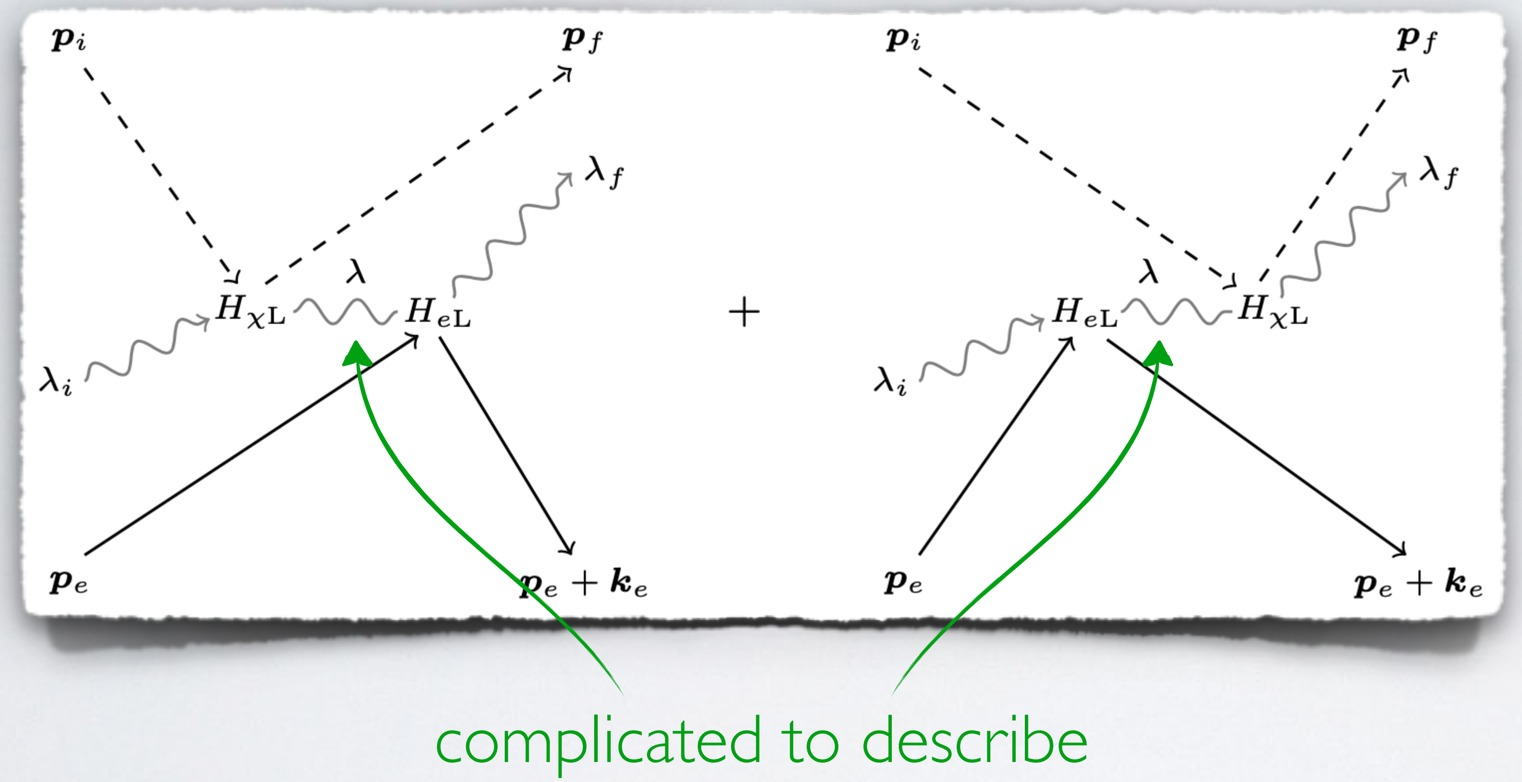

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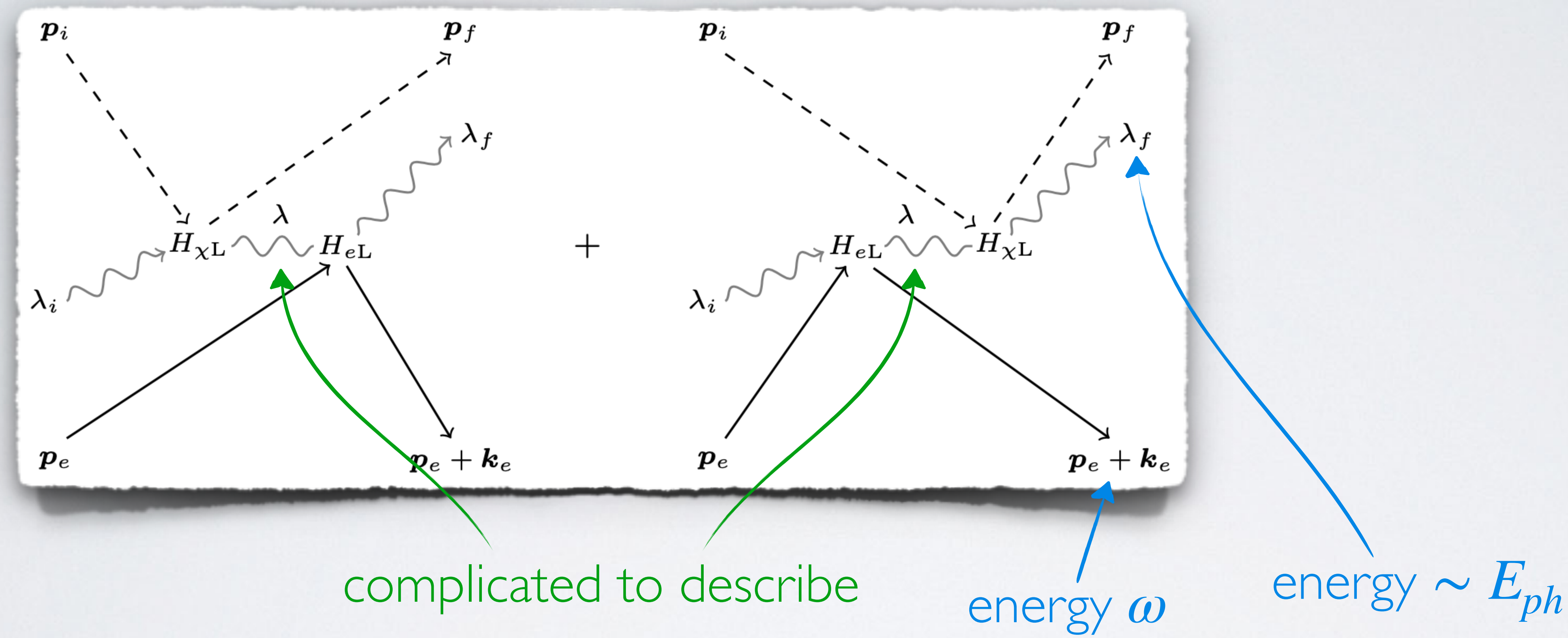

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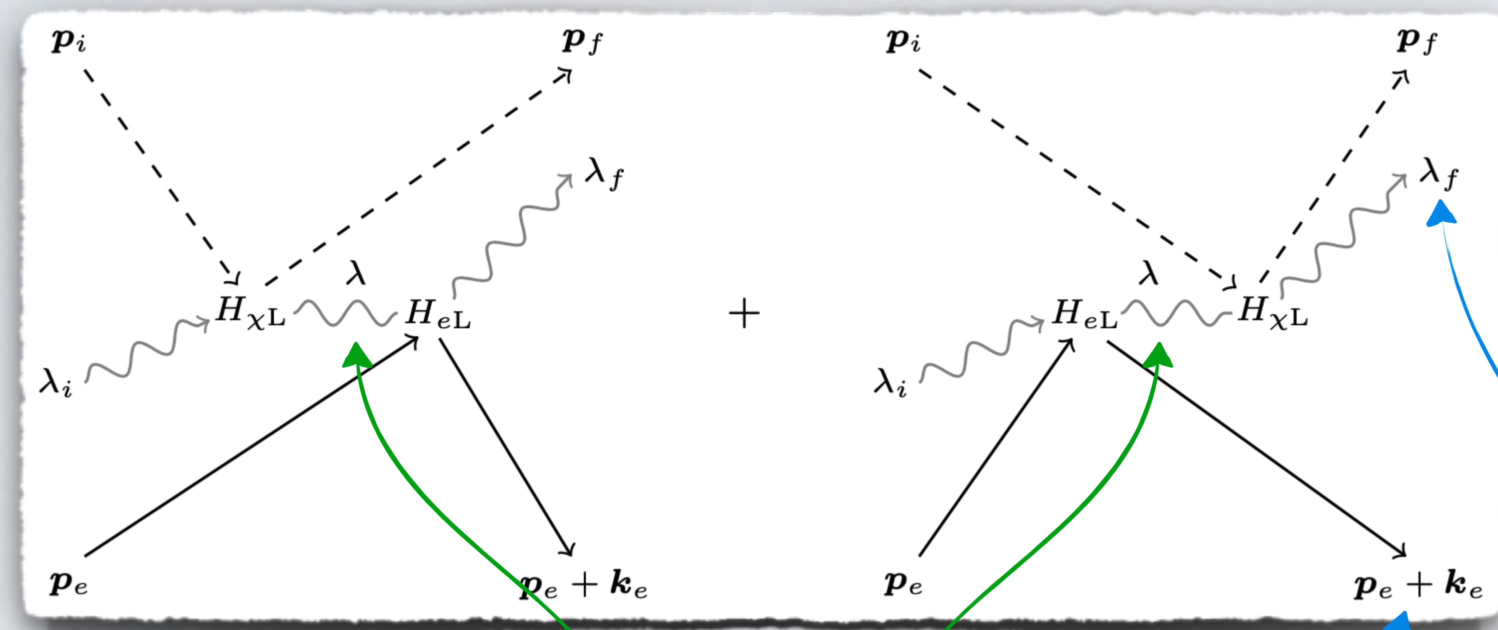

complicated to describe

energy ω

energy $\sim E_{ph}$

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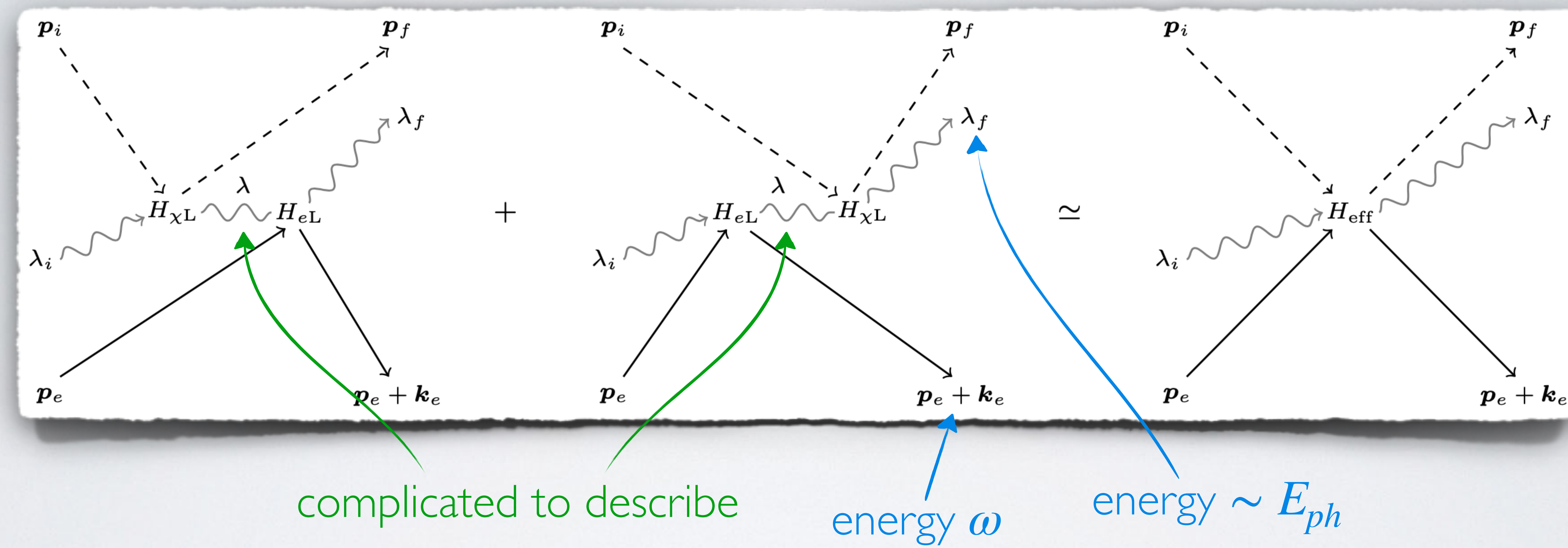

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$$H_{eff} = \frac{1}{m_N \omega^2} \vec{\nabla} H_{\chi L} \cdot \vec{\nabla} H_{eL} + \mathcal{O}\left(\frac{1}{\omega^3}\right)$$

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

MIGDAL RATE

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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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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

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

- 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

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

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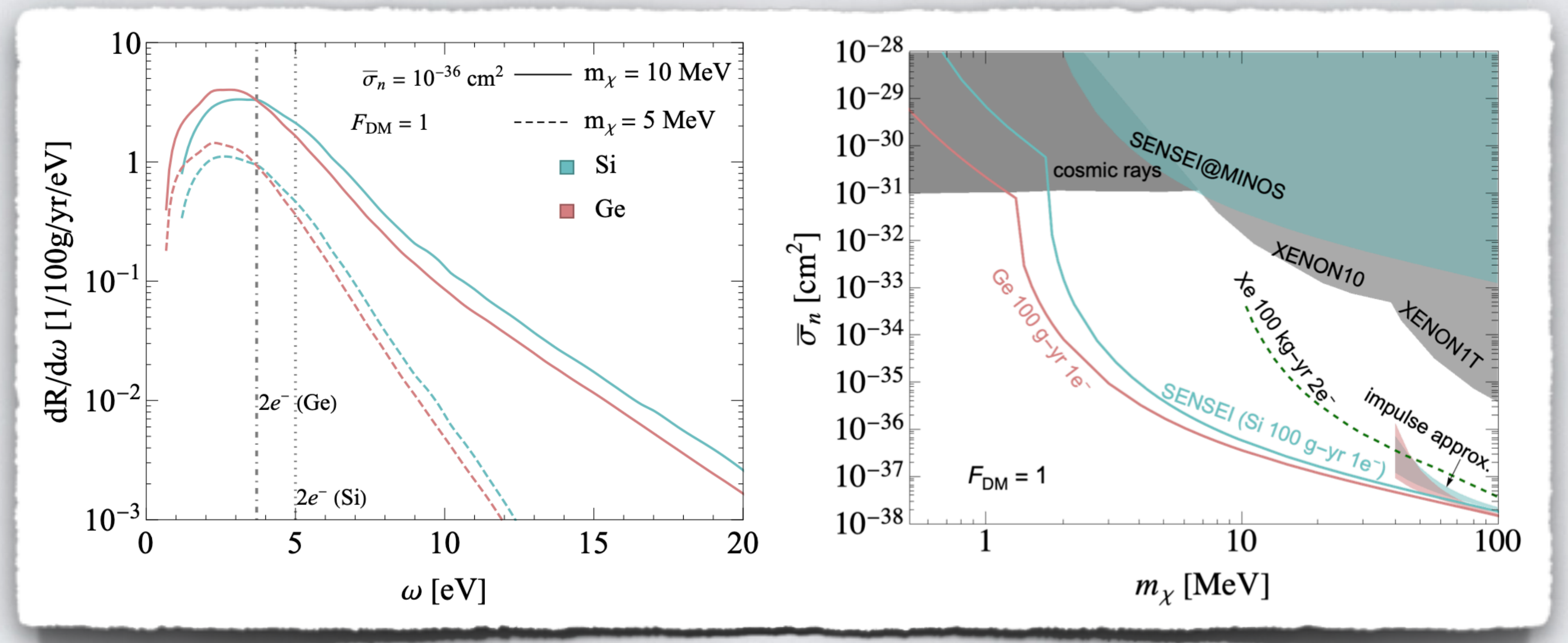

[Berghaus, **AE**, Essig, Sholapurkar — JHEP 2020, 2210.06490]

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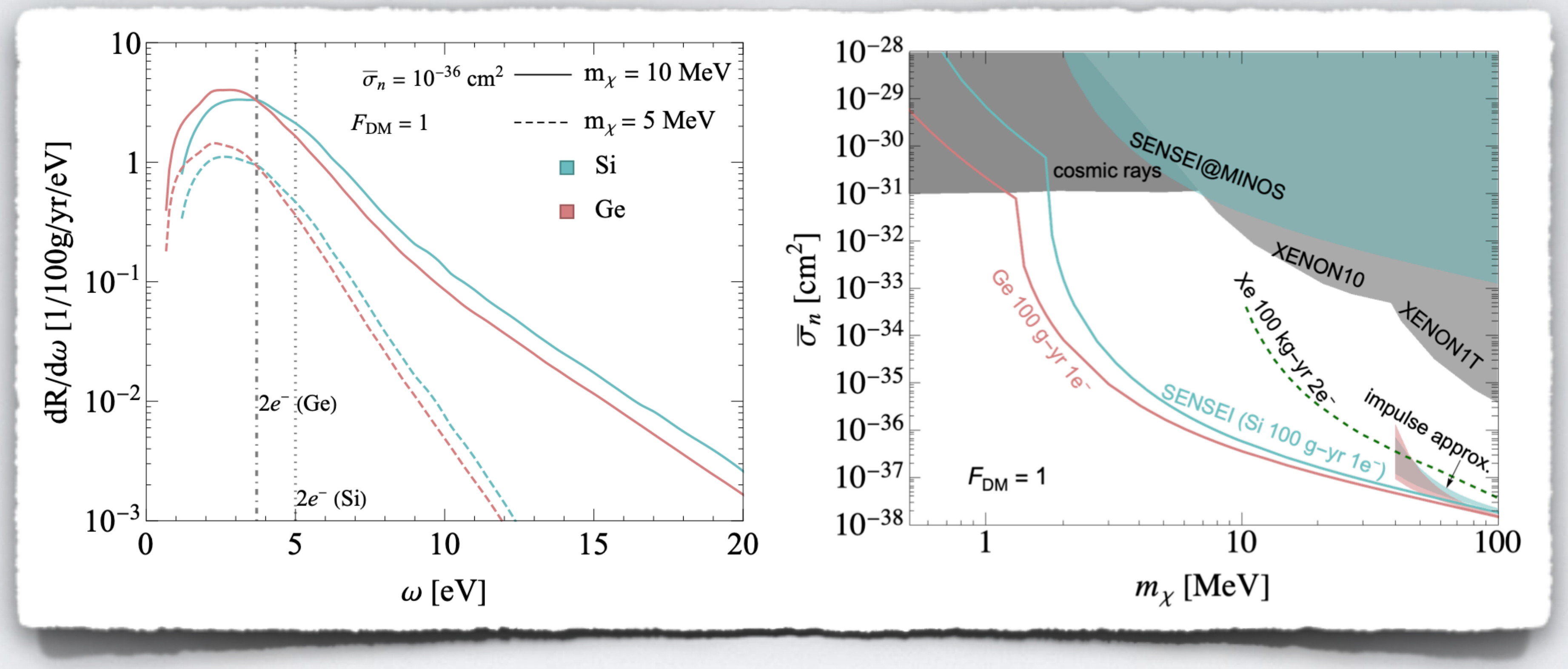

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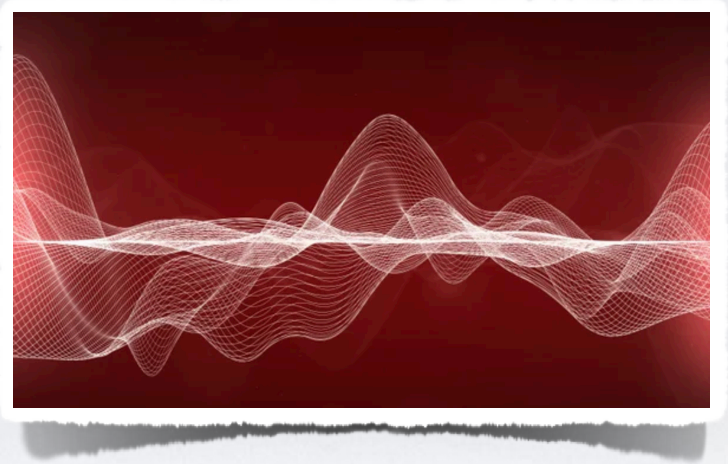
- The description of Migdal effect in semiconductor is now complete

Down to the keV

collective excitations



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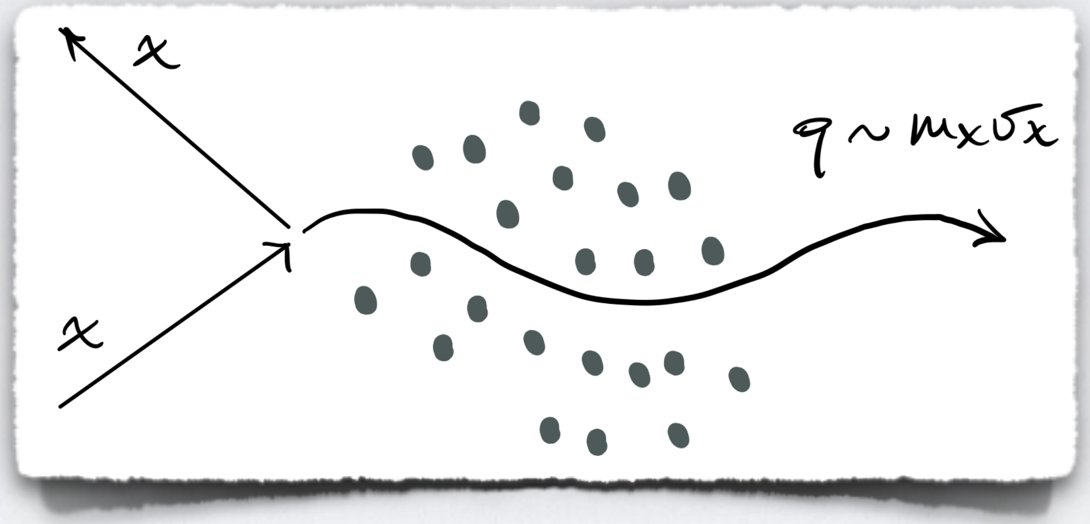

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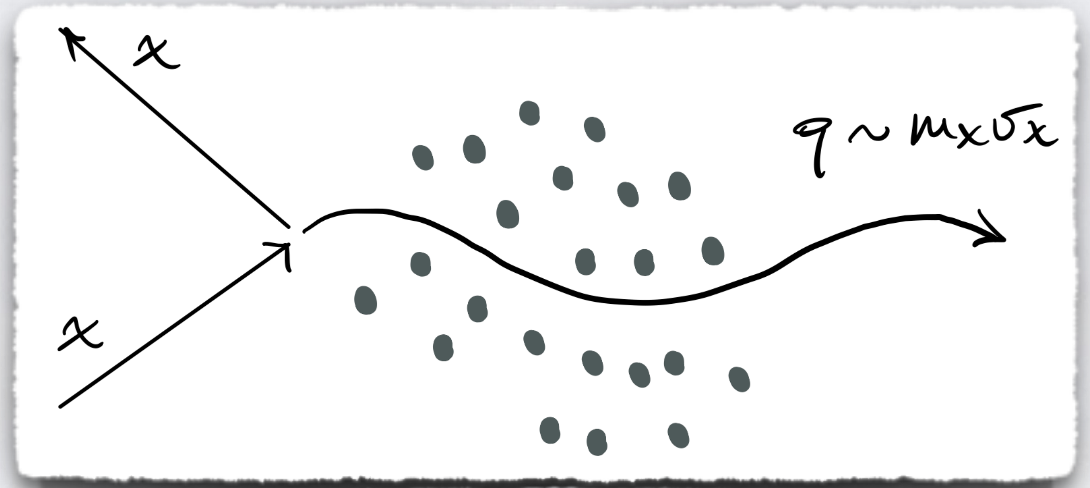

- Typically, no more single particle final states → signatures involve collective excitation [see e.g., Trickle et al. — JHEP 2020, 1910.08092; Griffin et al. — PRD 2020, 1910.10716; Coskuner et al. — PRD 2022, 2102.09567]

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- I will focus on those I know best…

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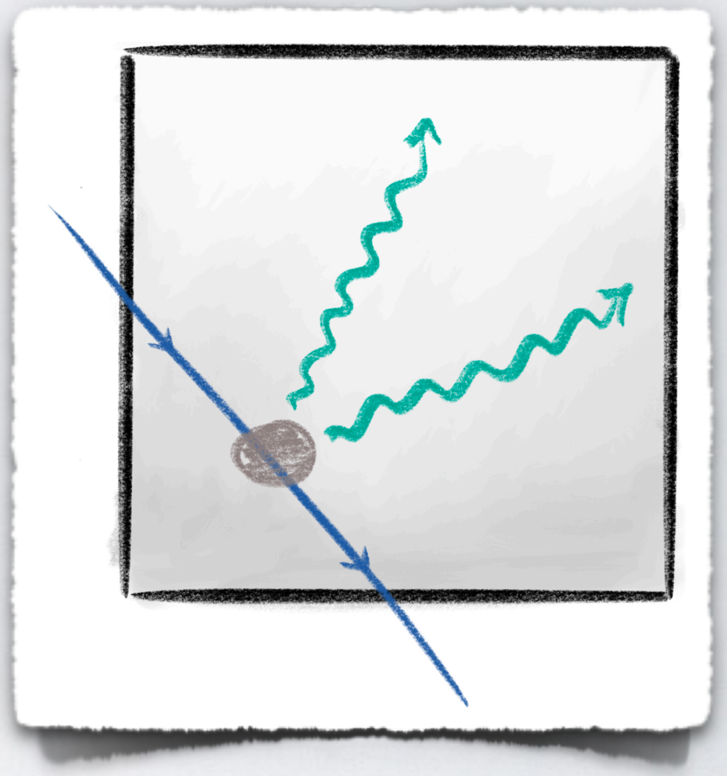
- Idea: look for events where the dark matter produces more than one phonon



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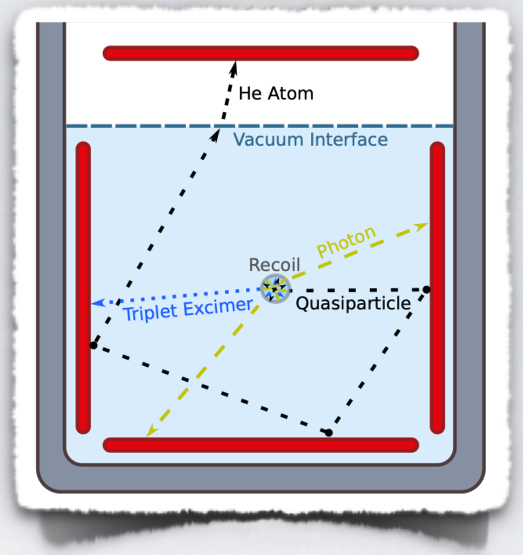

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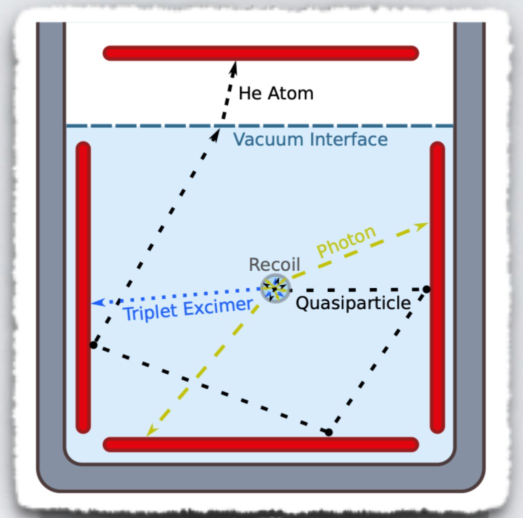

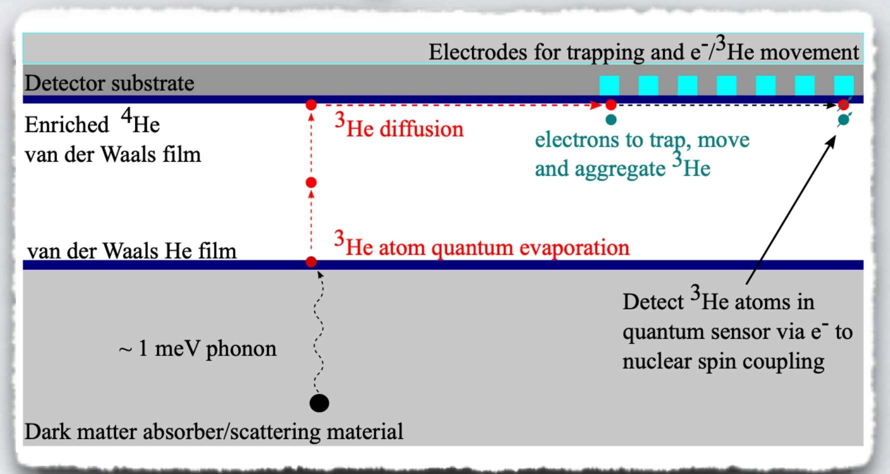

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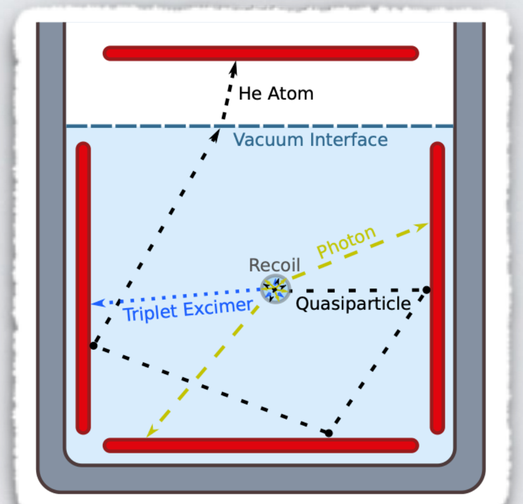

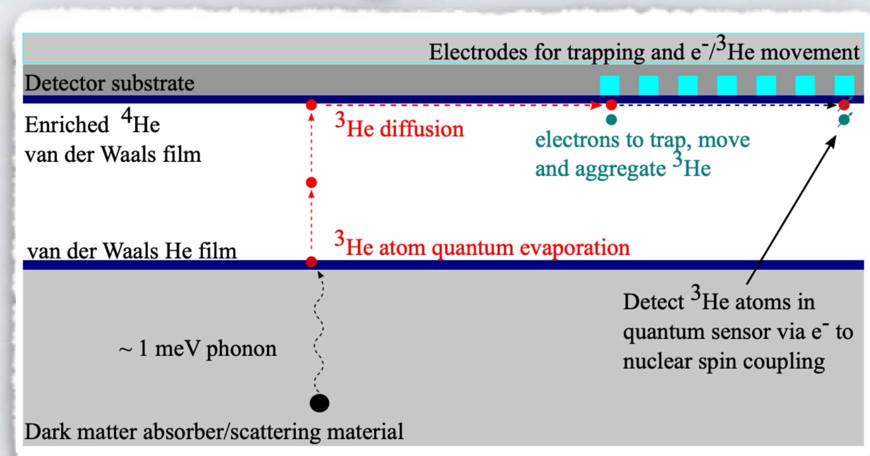

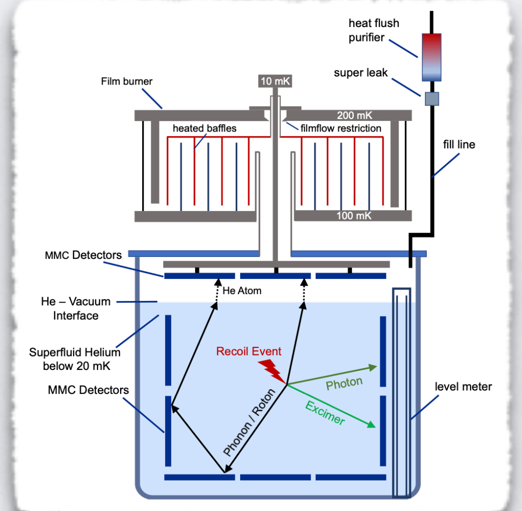

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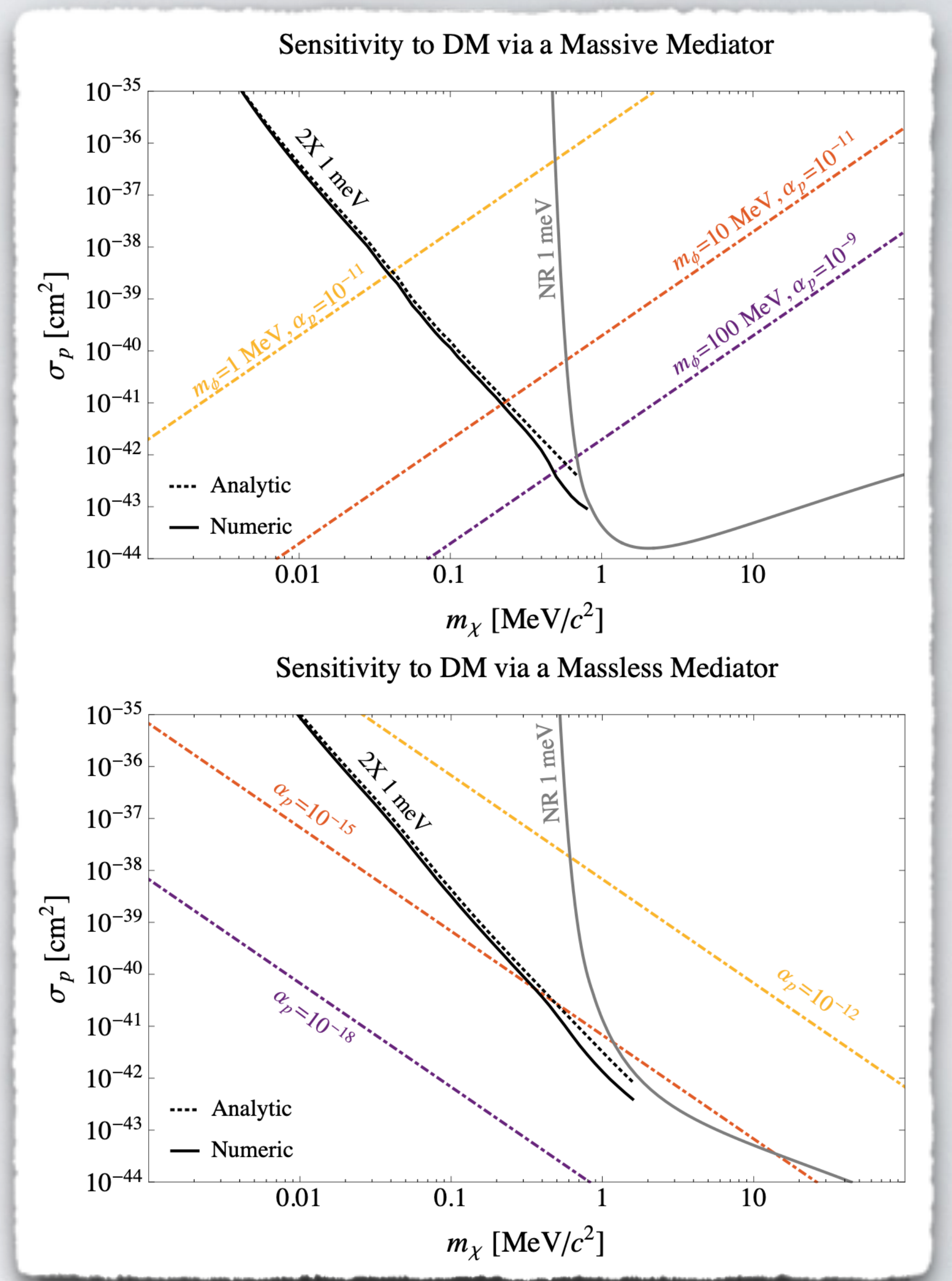

$$\frac{d^2\Gamma}{d\omega dq} = \frac{\rho_{He}\sigma_{\chi n} q}{2 m_\chi m_{He} p_i} S(q,\omega)$$

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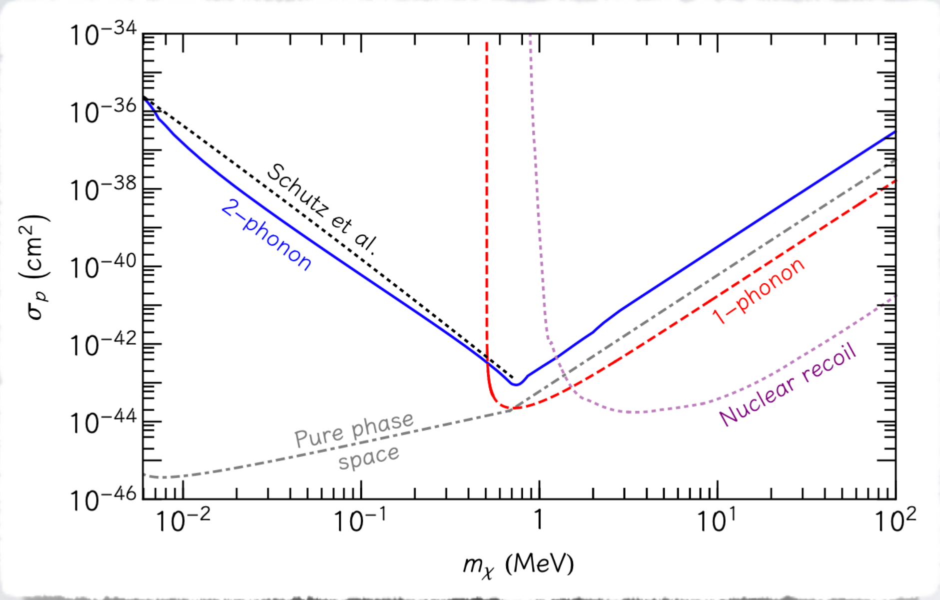

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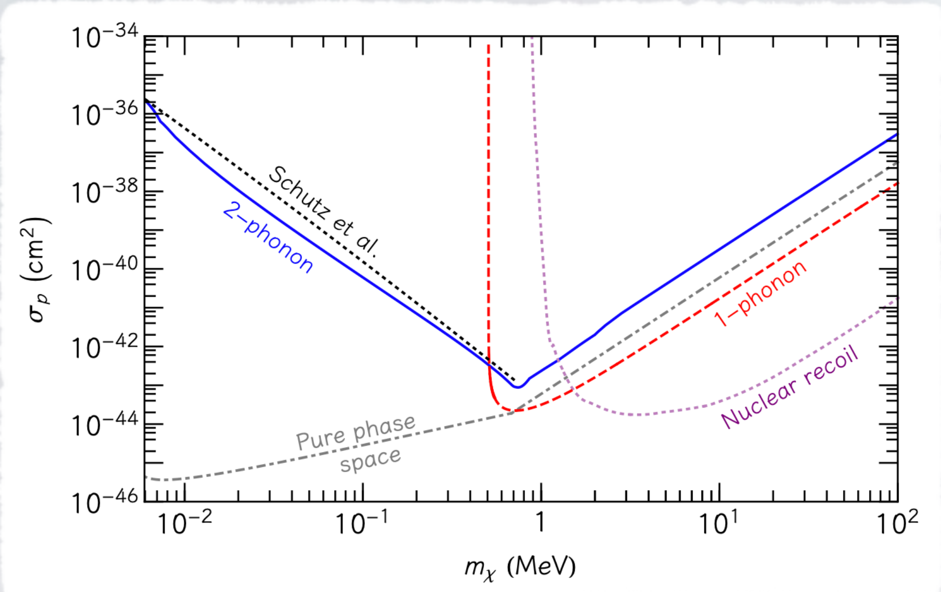

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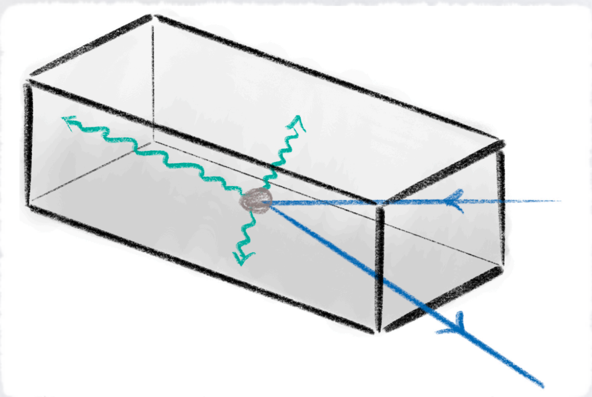

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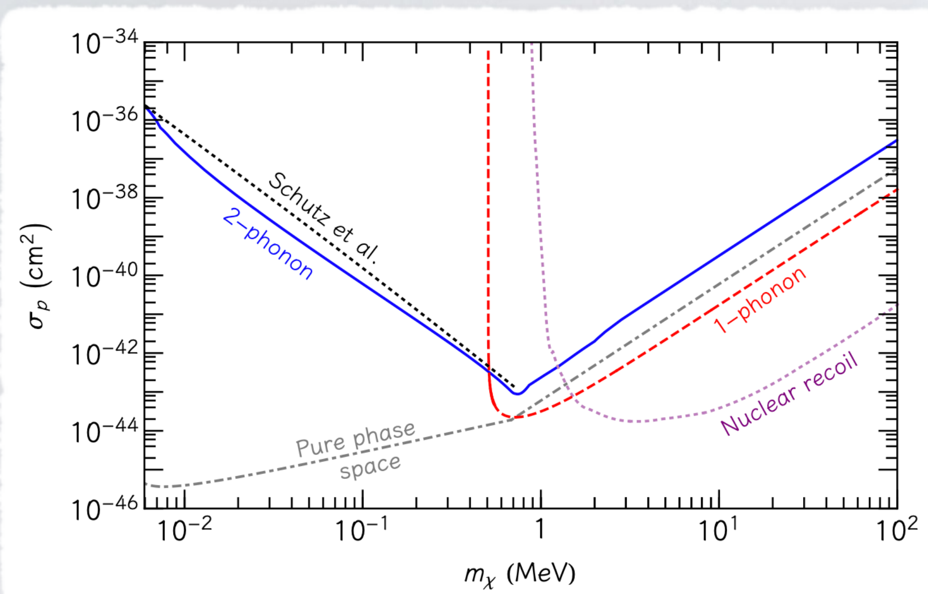

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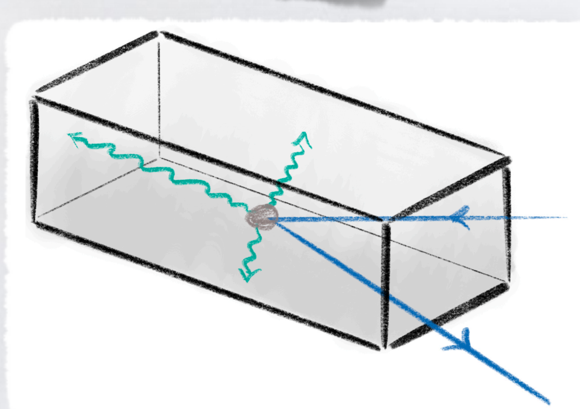

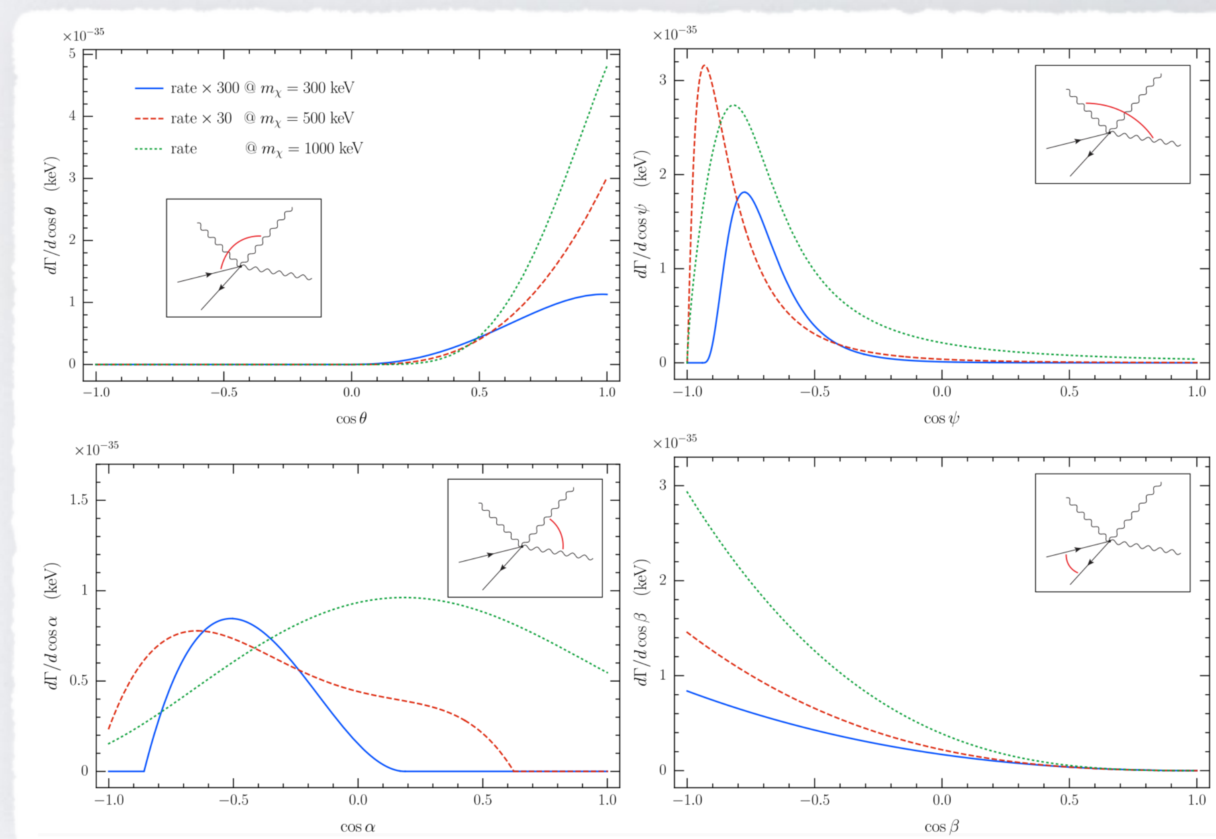

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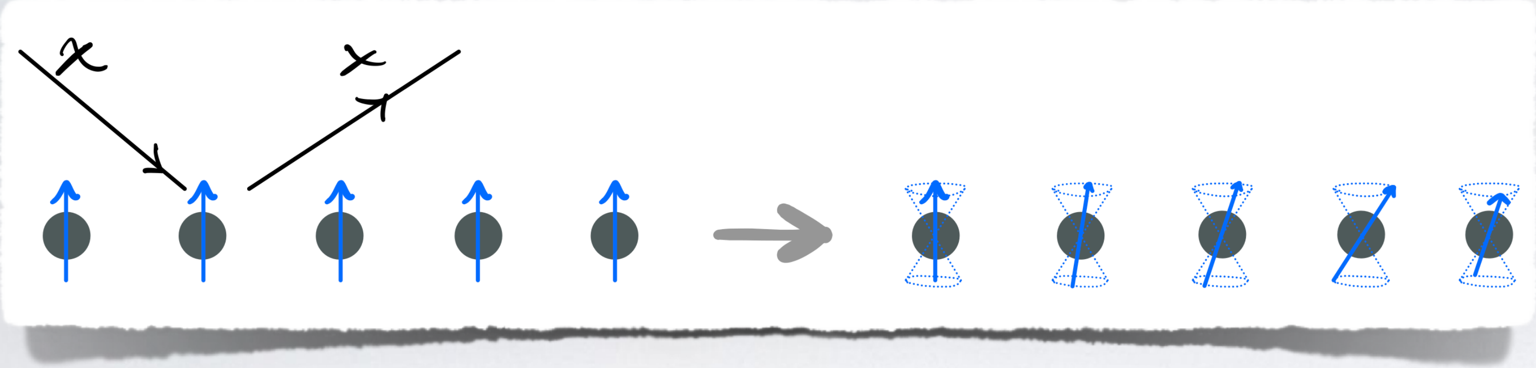

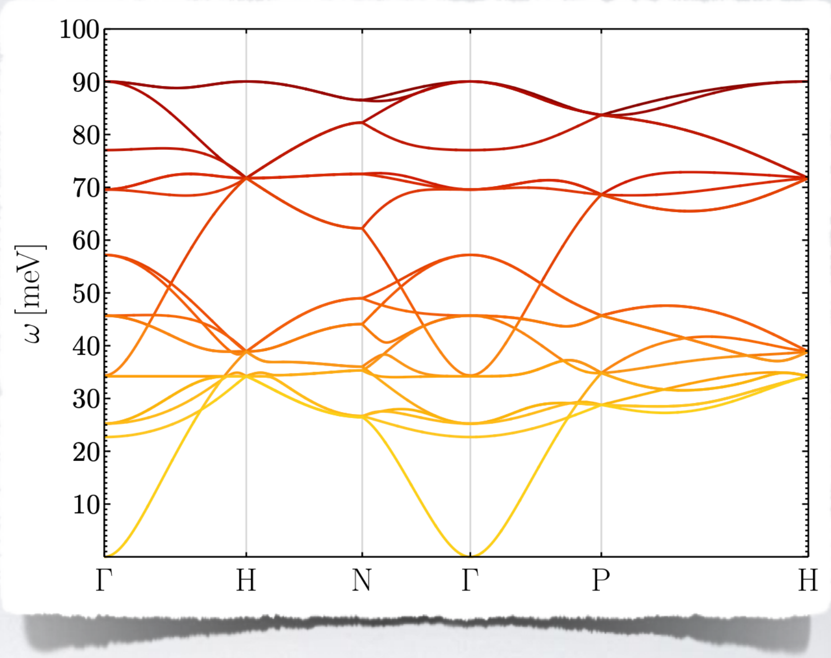

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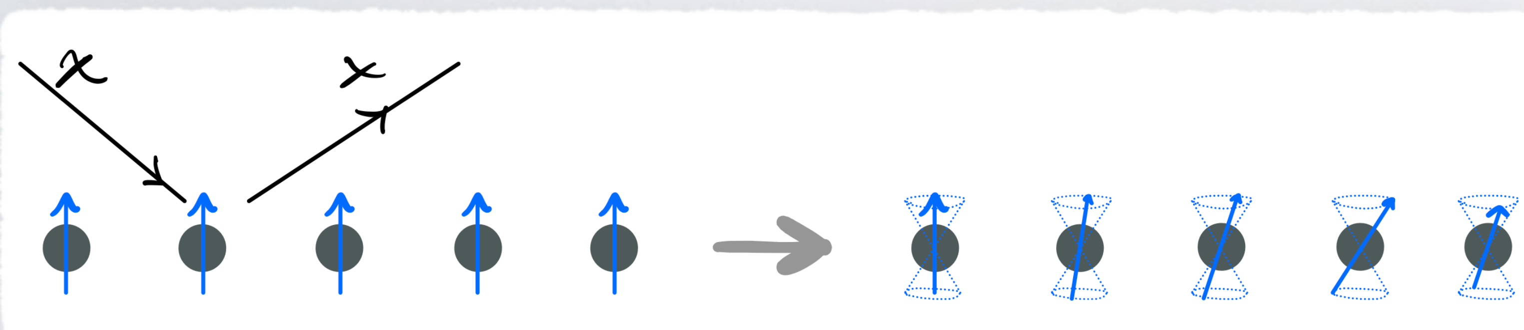

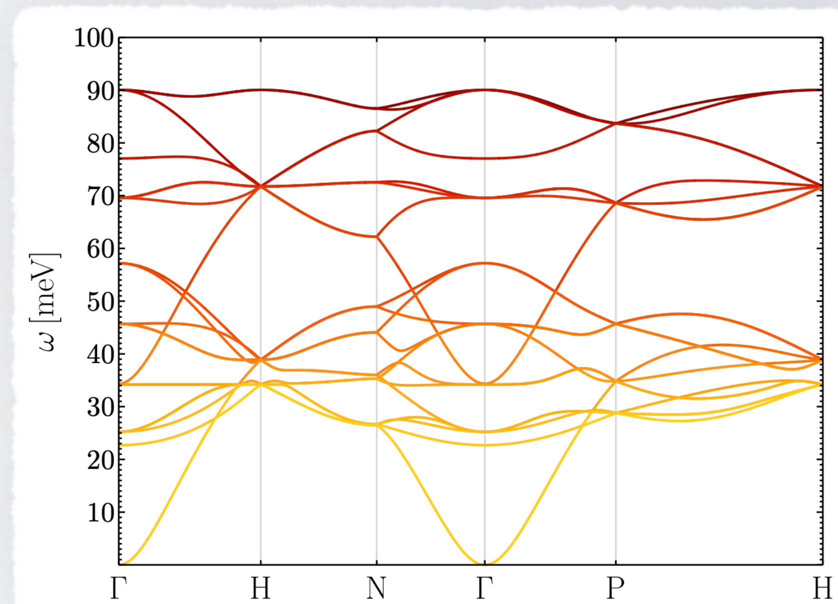

- Ways to detect few magnons have been proposed and under work (TES, MKID, quantum sensors)

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

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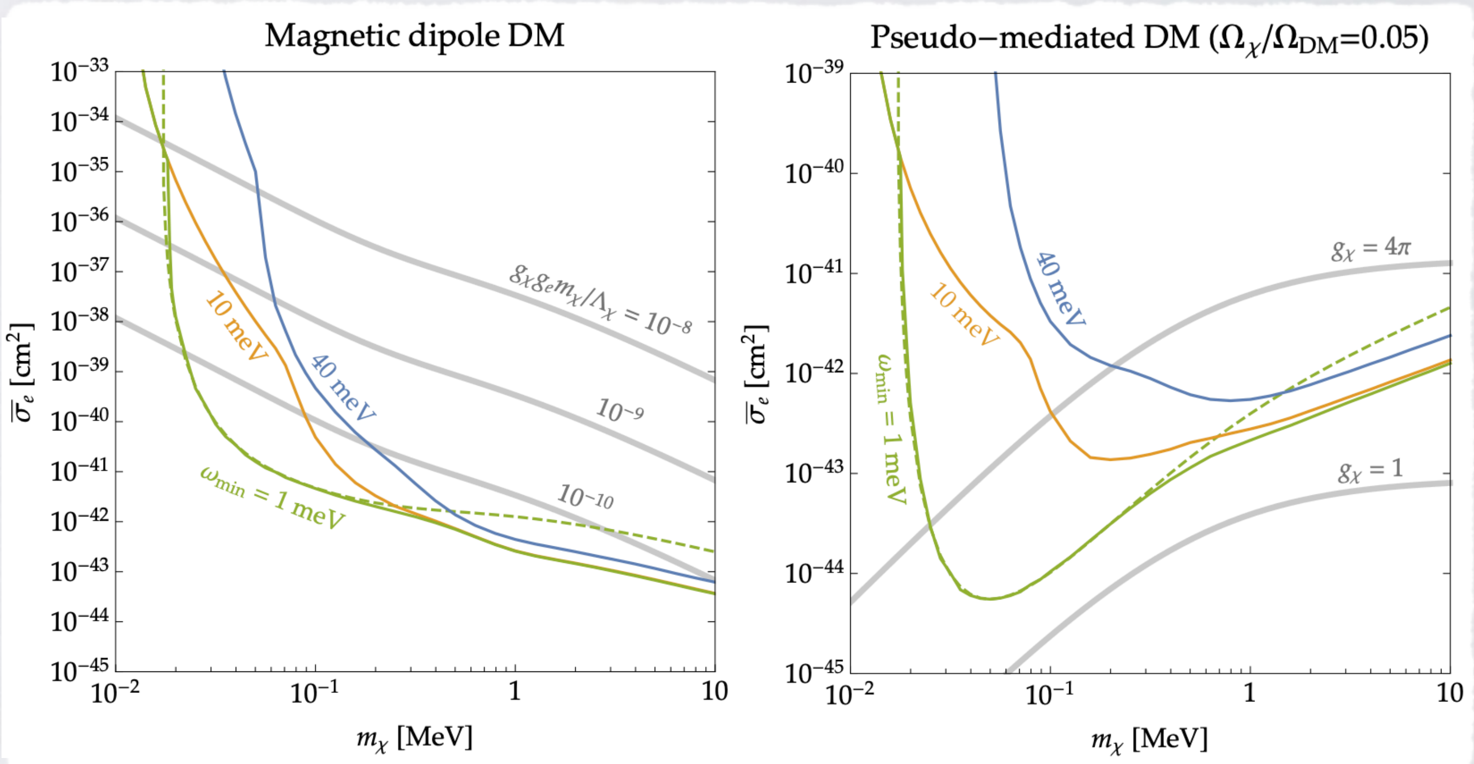

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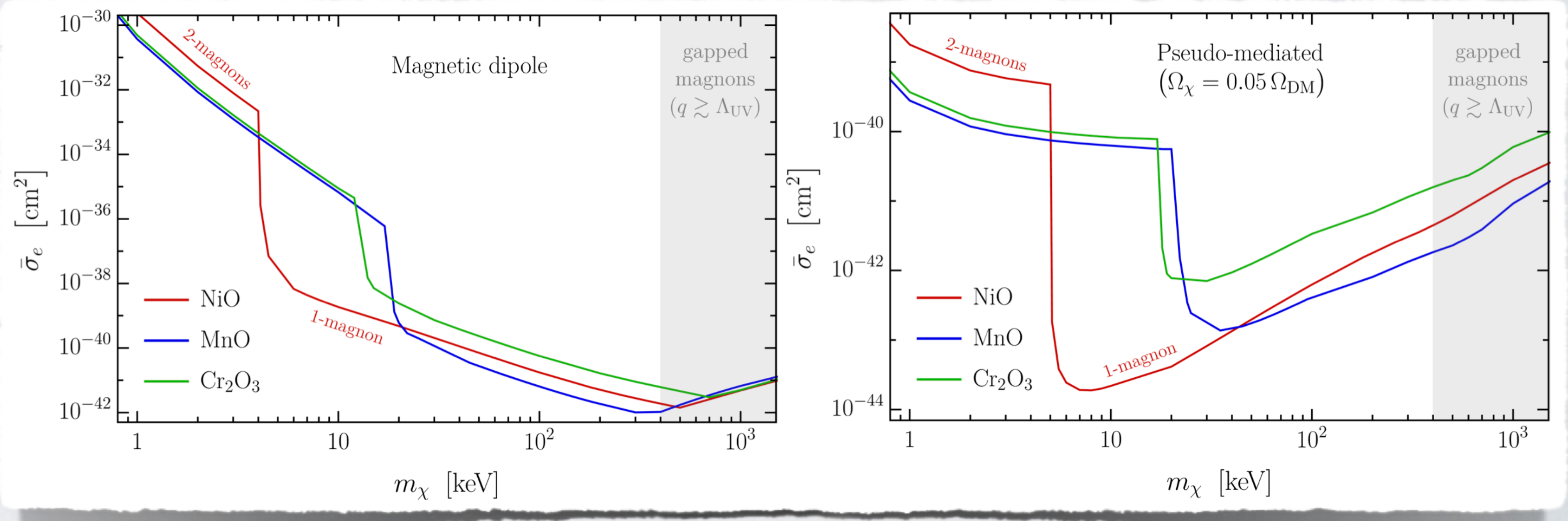
[**AE**, Pavaskar – 2210.13516]



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- The search for keV-MeV dark matter requires new ideas
- One must delve in the condensed matter world
- **Migdal effect**: push the sensitivity of present day experiments to $\mathcal{O}$(MeV) masses
- **Collective excitations**: to probe spin-indep. and spin-dep. interactions down to $\mathcal{O}$(keV) one most likely will have to deal with events with few phonons/magnons

Thanks for your attention!