LIGHT DARK MATTER DETECTION IN THE LAB

NEW IDEAS AND NEW TOOLS

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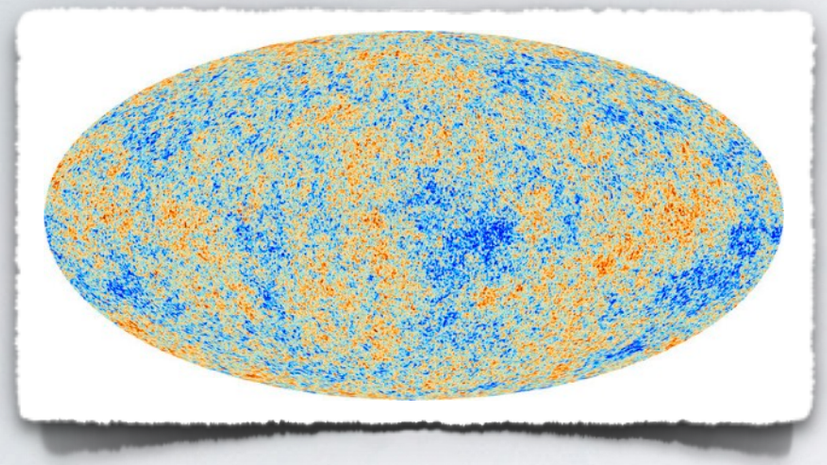
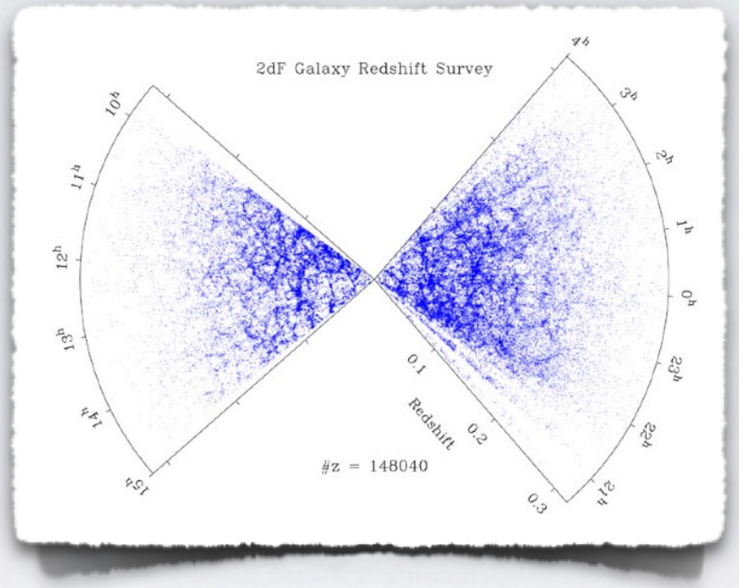
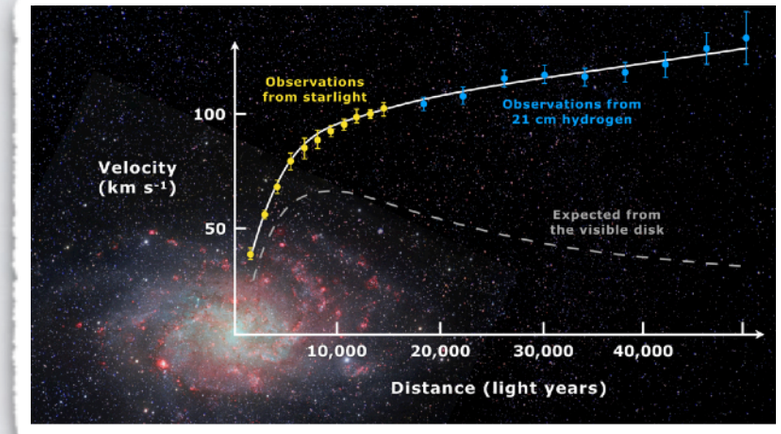
- Most of the matter ($\sim 80\,\%$) that interacts gravitationally is dark







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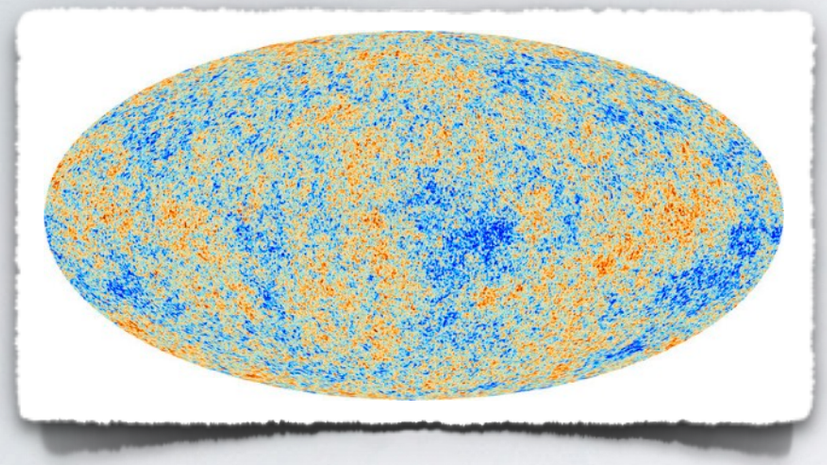

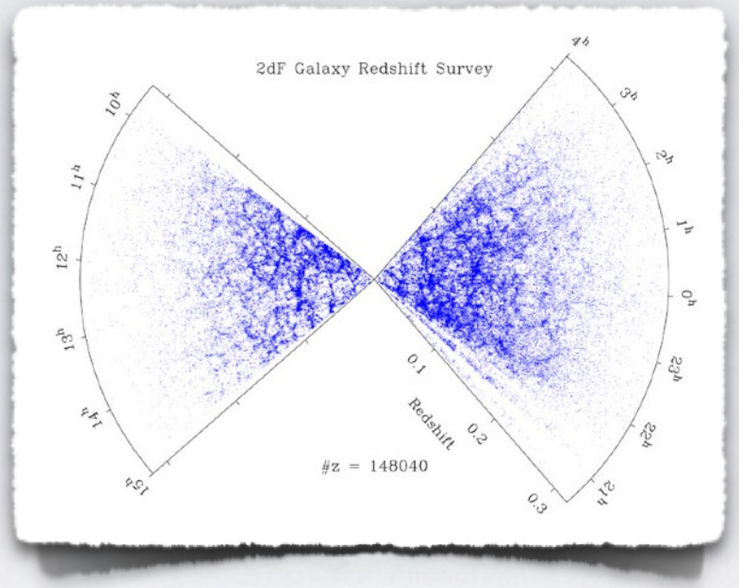

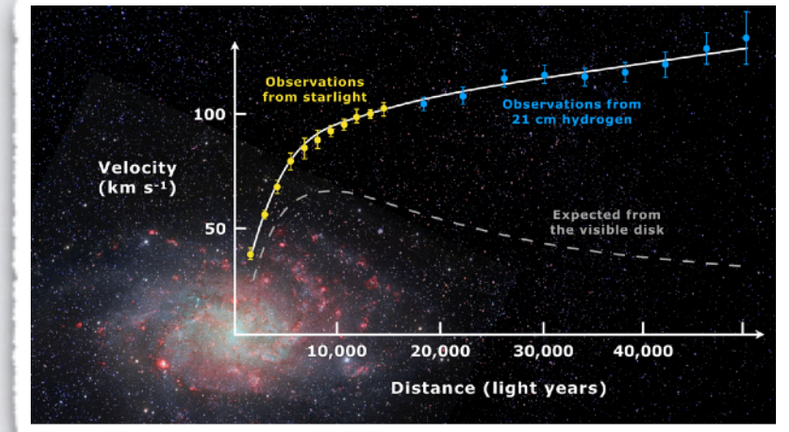

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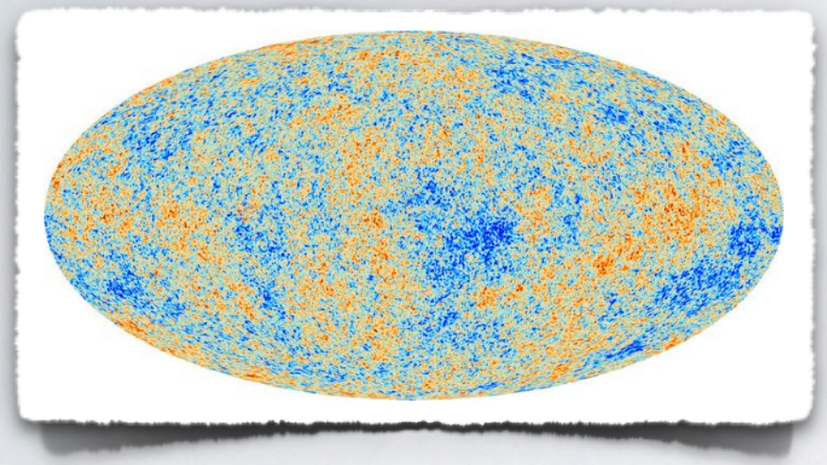

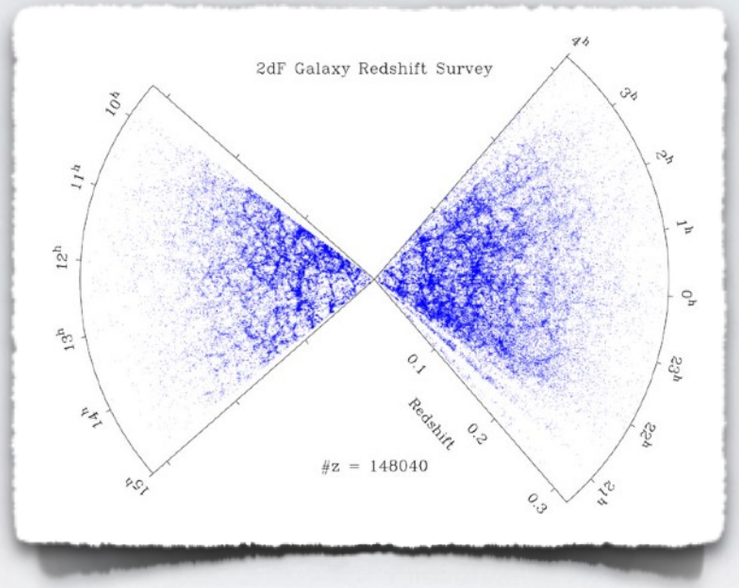

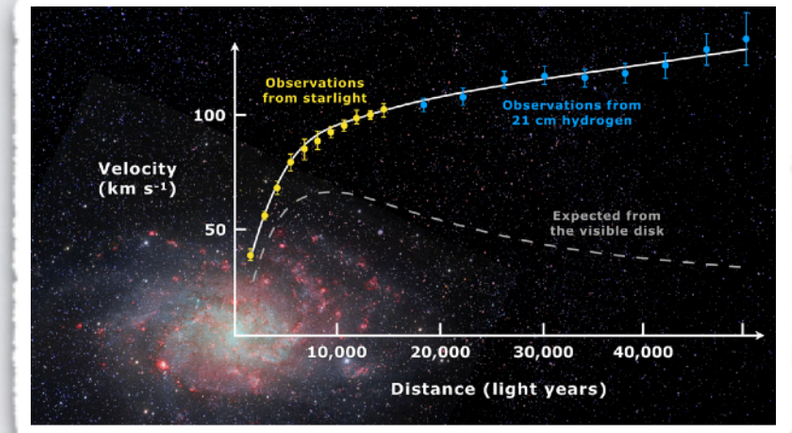

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- However… huge possible mass range → detection techniques vary widely depending on the dark matter mass

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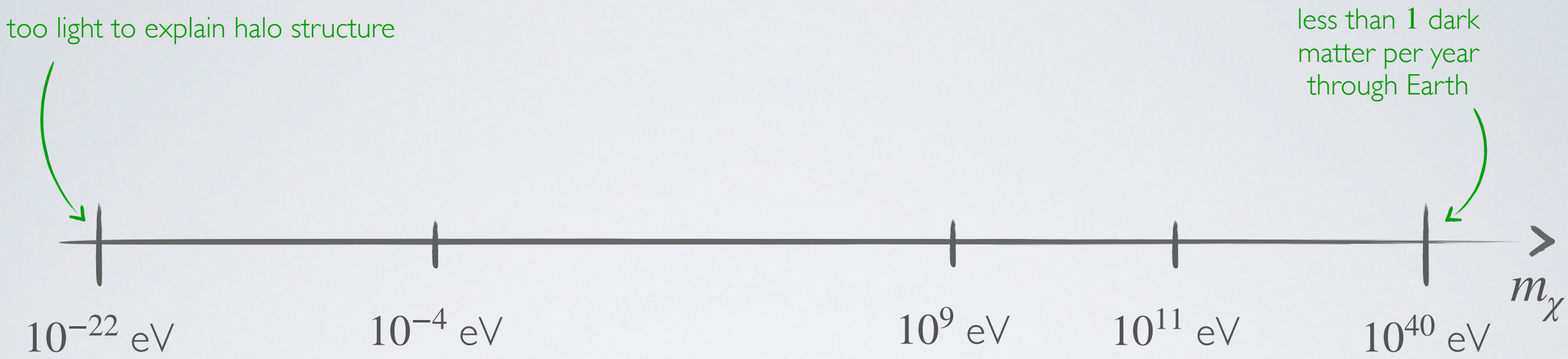

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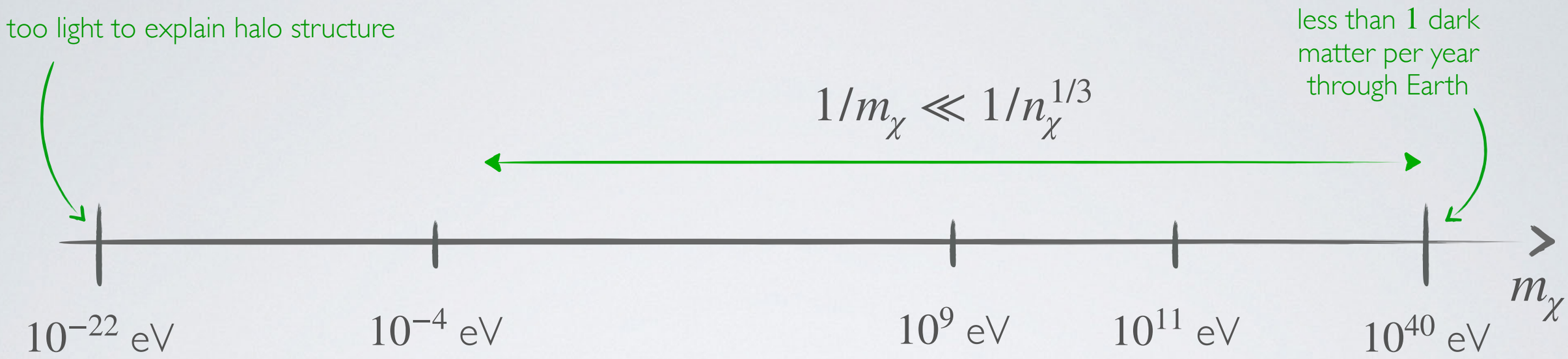

SUB-GEV DARK MATTER

too light to explain halo structure

less than 1 dark matter per year through Earth

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

10^{-22} eV

10^{-4} eV

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10^{11} eV

10^{40} eV

m_χ

Dark matter can deposit energy via scattering off nuclei

XENON, LUX, …

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What about this region?

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- Dark matter is a particle but too light for 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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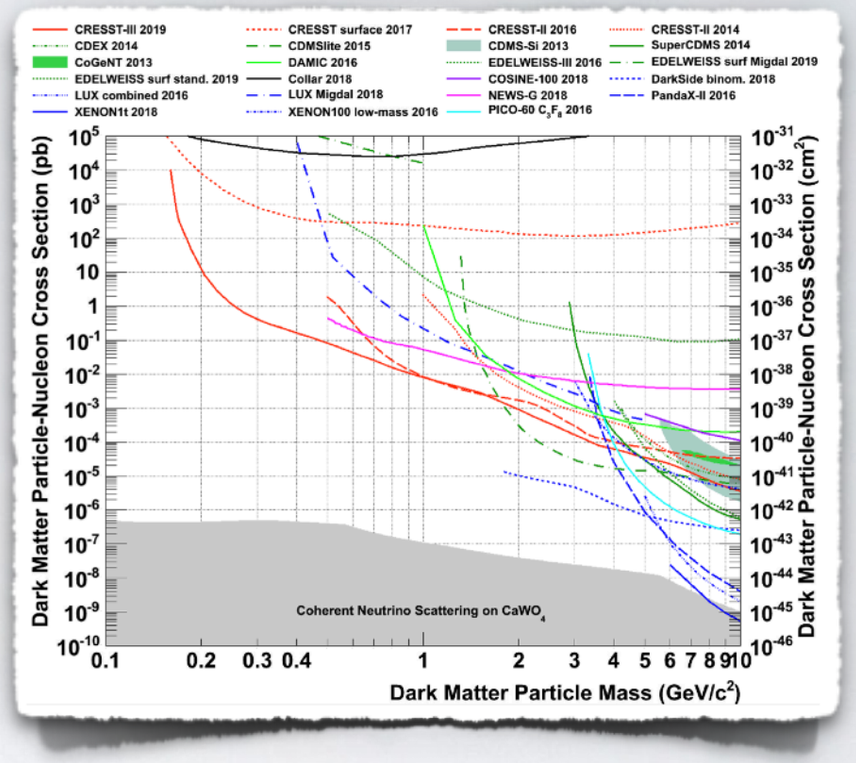

[CRESST – PRD 2019, 1904.00498]

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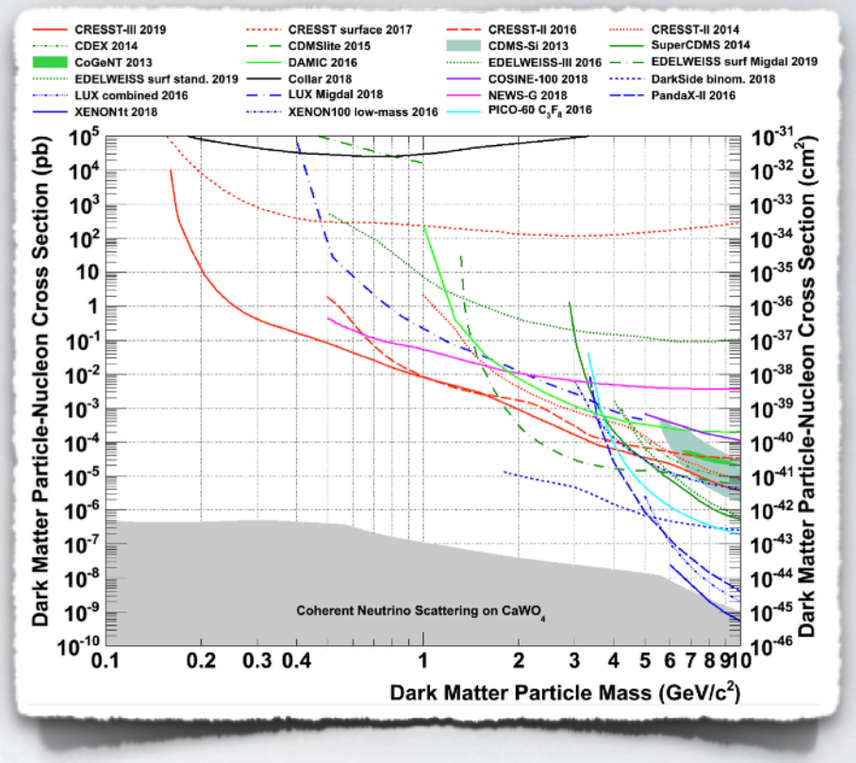

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- Two possibilities:
  1. Look into lighter scattering targets
  2. Look into inelastic processes

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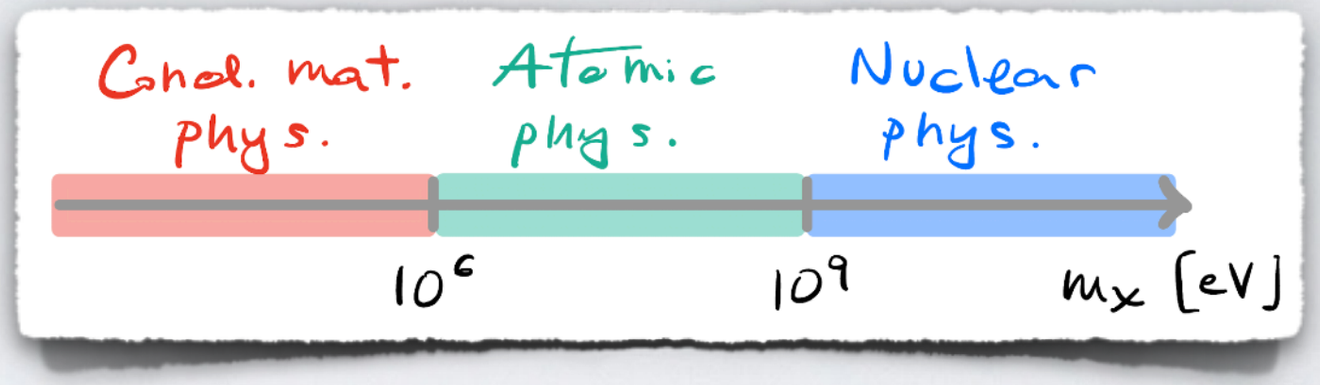

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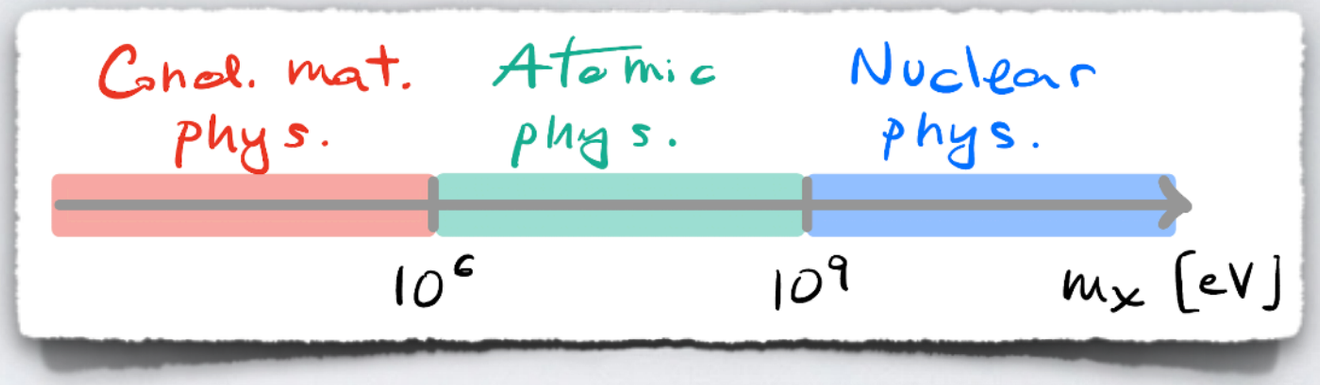
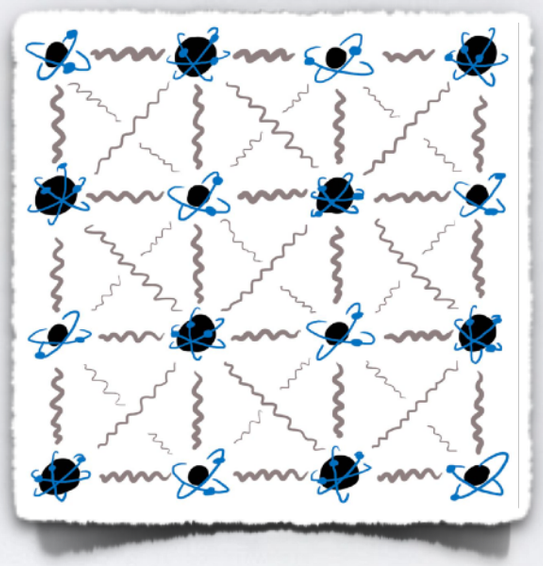


- Need to account for the complicated many-body physics (correlations, strong coupling, …)



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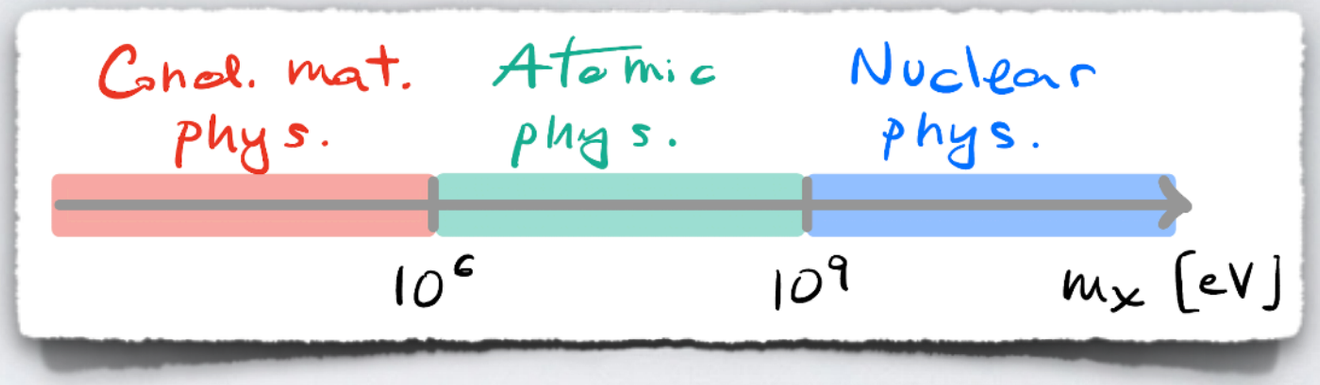

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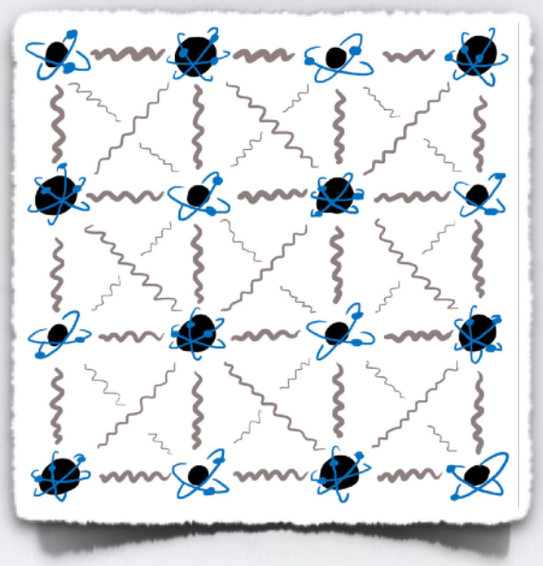
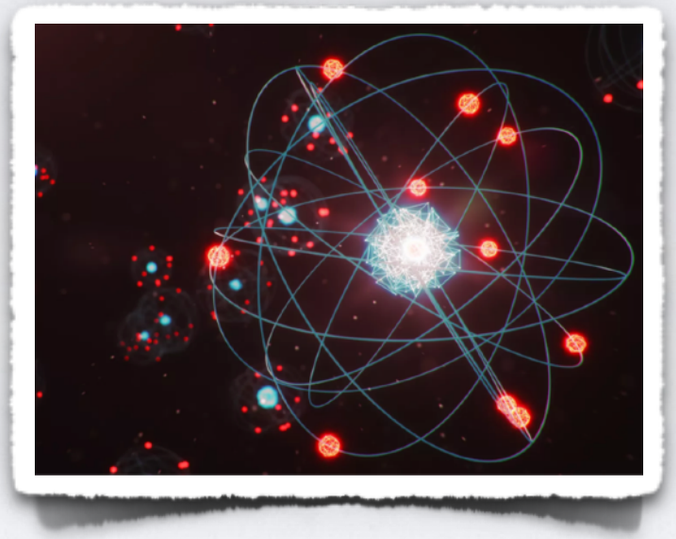


- Need to find theoretical tools that allow to solve or bypass these problems (measured correlation functions, EFTs, …)

Down to the MeV
Migdal effect in semiconductors



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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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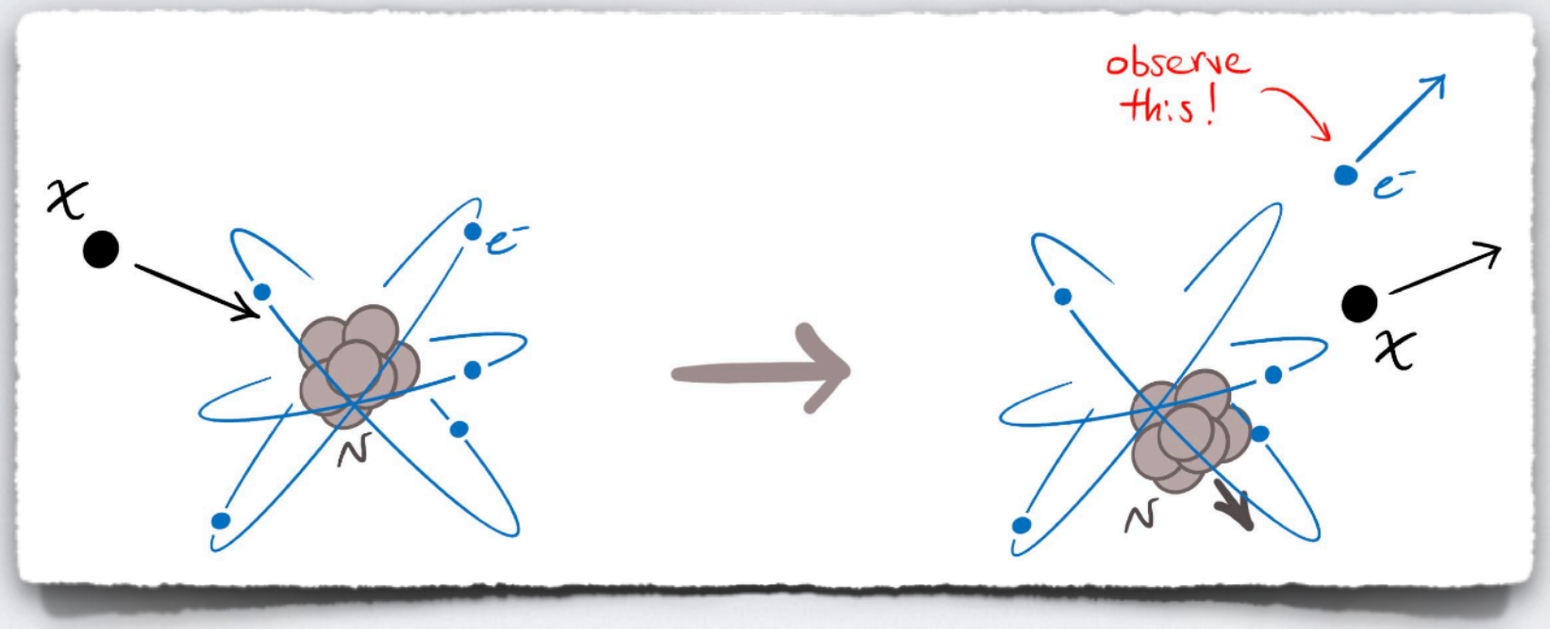

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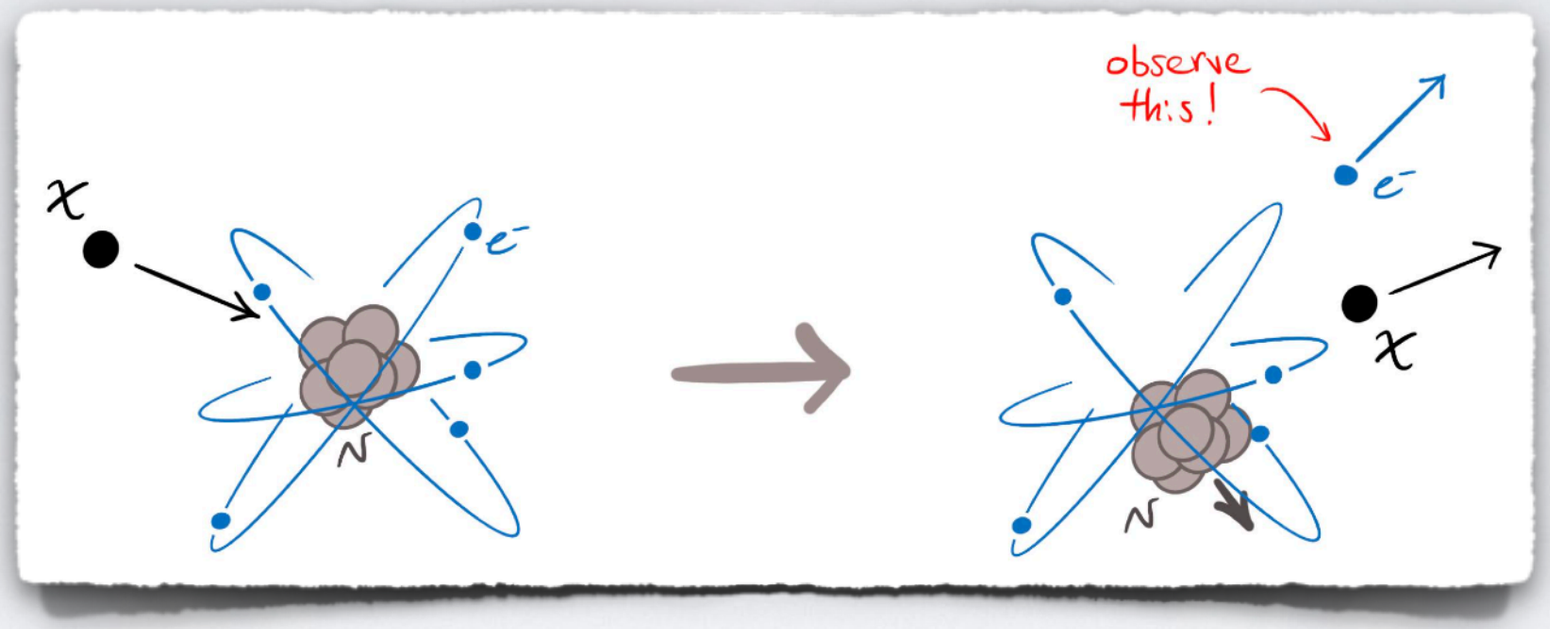

- Less likely… but lower threshold! → sensitivity down to $\mathcal{O}(100\ \text{MeV})$ masses

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

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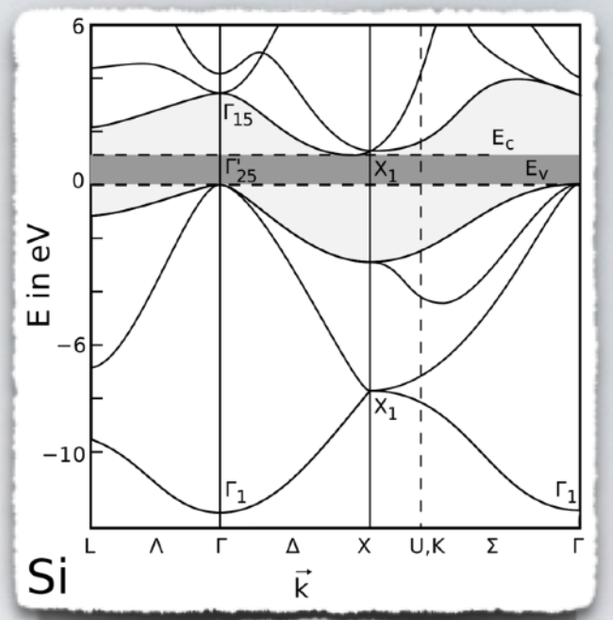
- Semiconductors (Si, Ge, …) have small $\mathcal{O}$(eV) bandgaps → Migdal effect should allow to probe down to $\mathcal{O}$(MeV) masses



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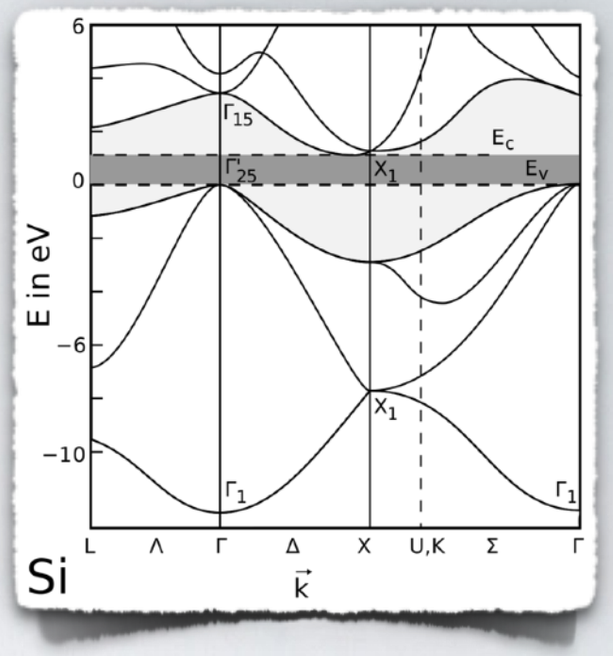

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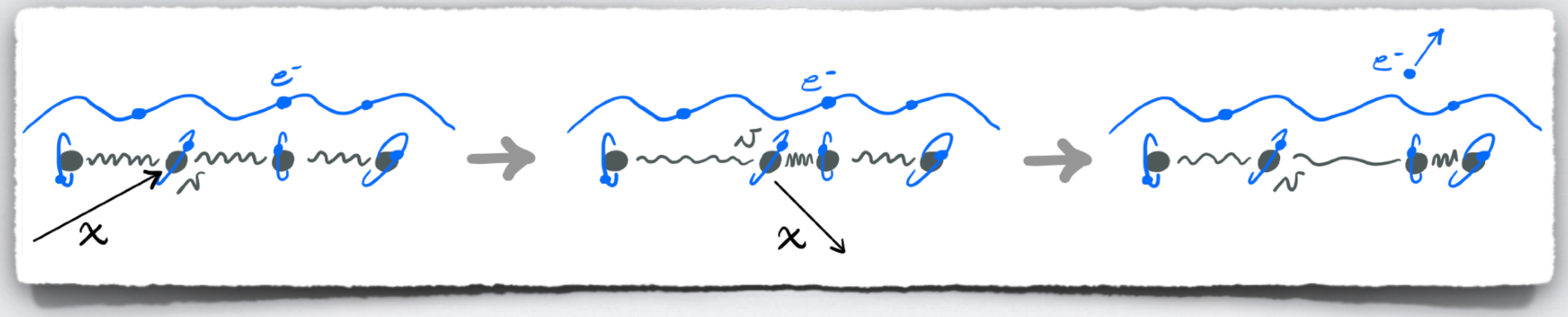

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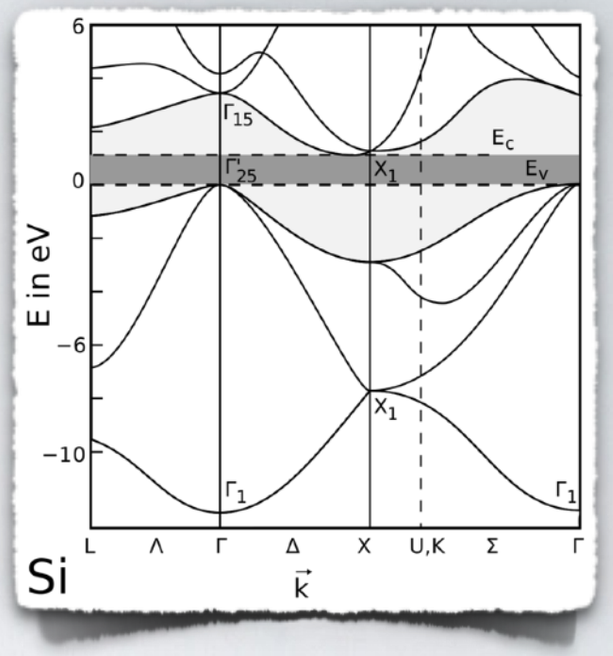

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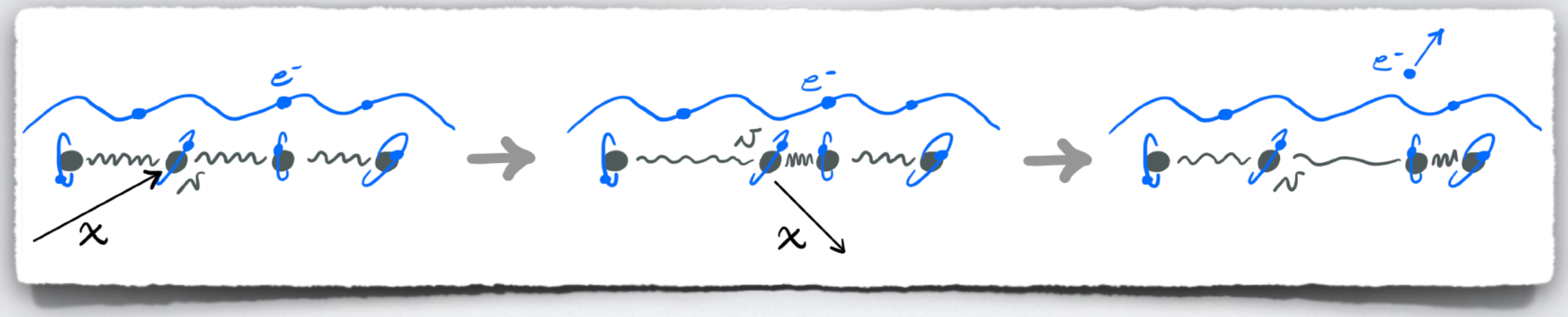

- How to describe nucleus-nucleus and nucleus-electron interactions in a strongly correlated system?

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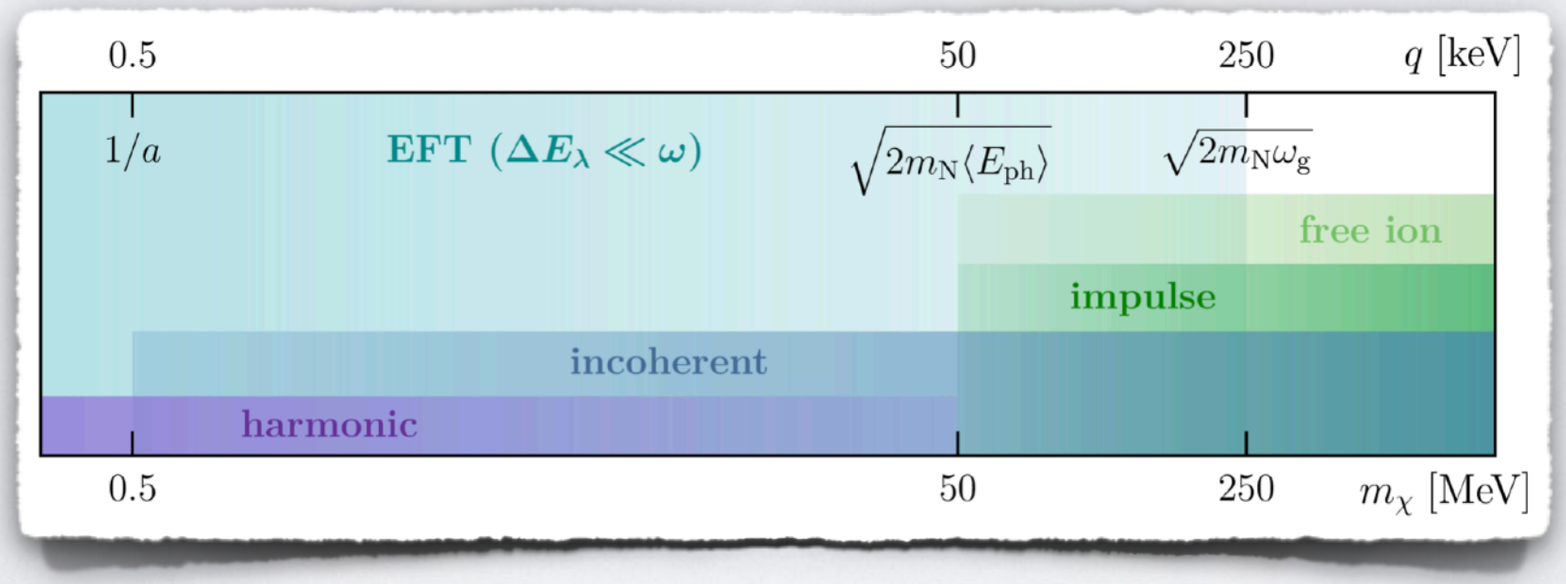

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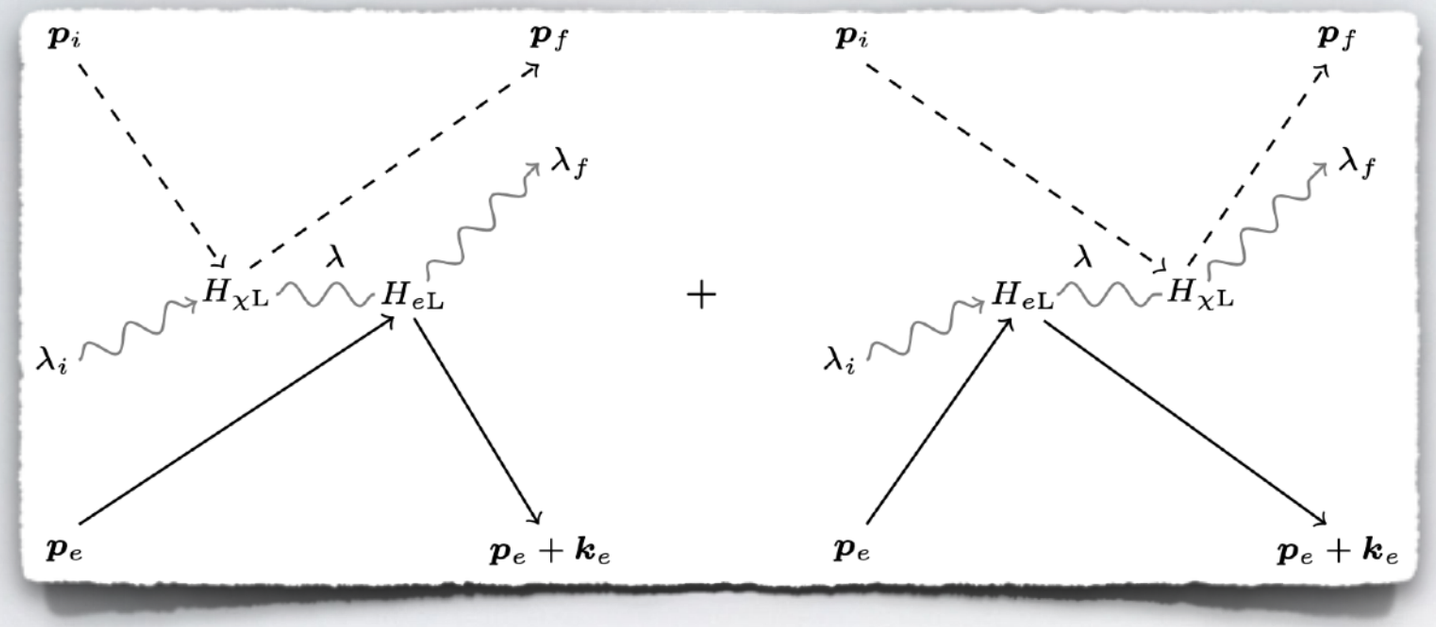

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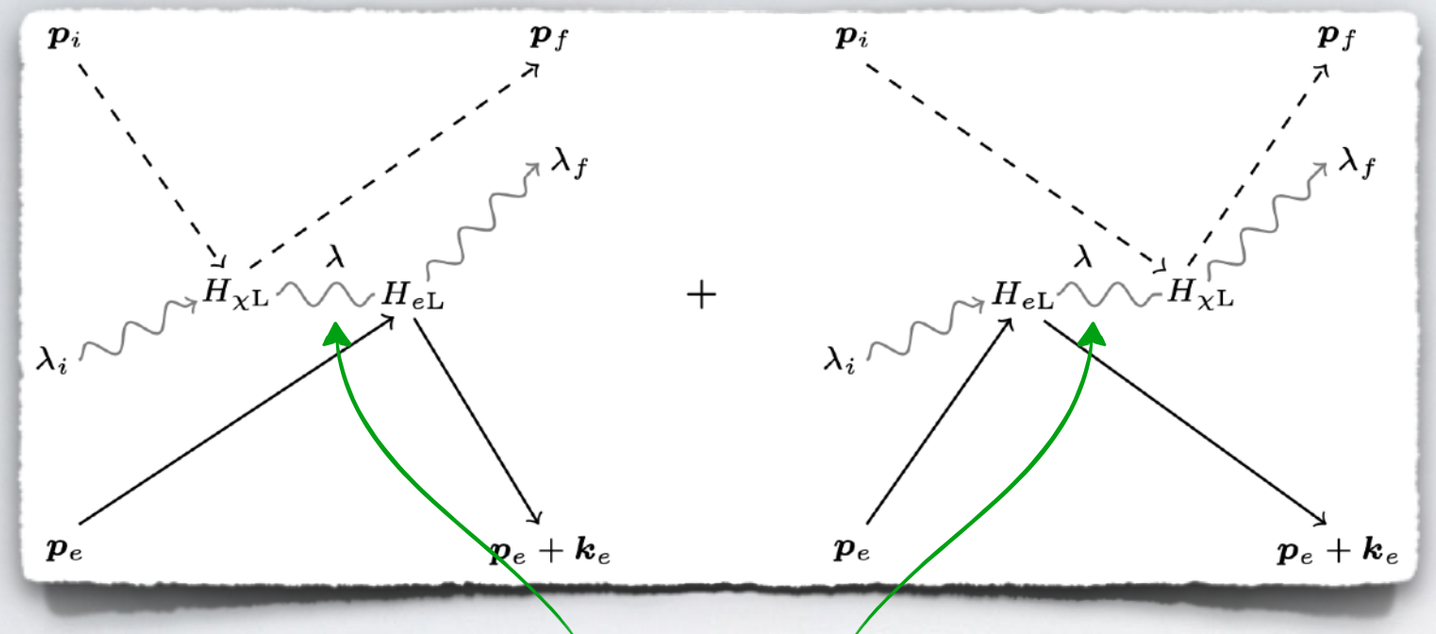

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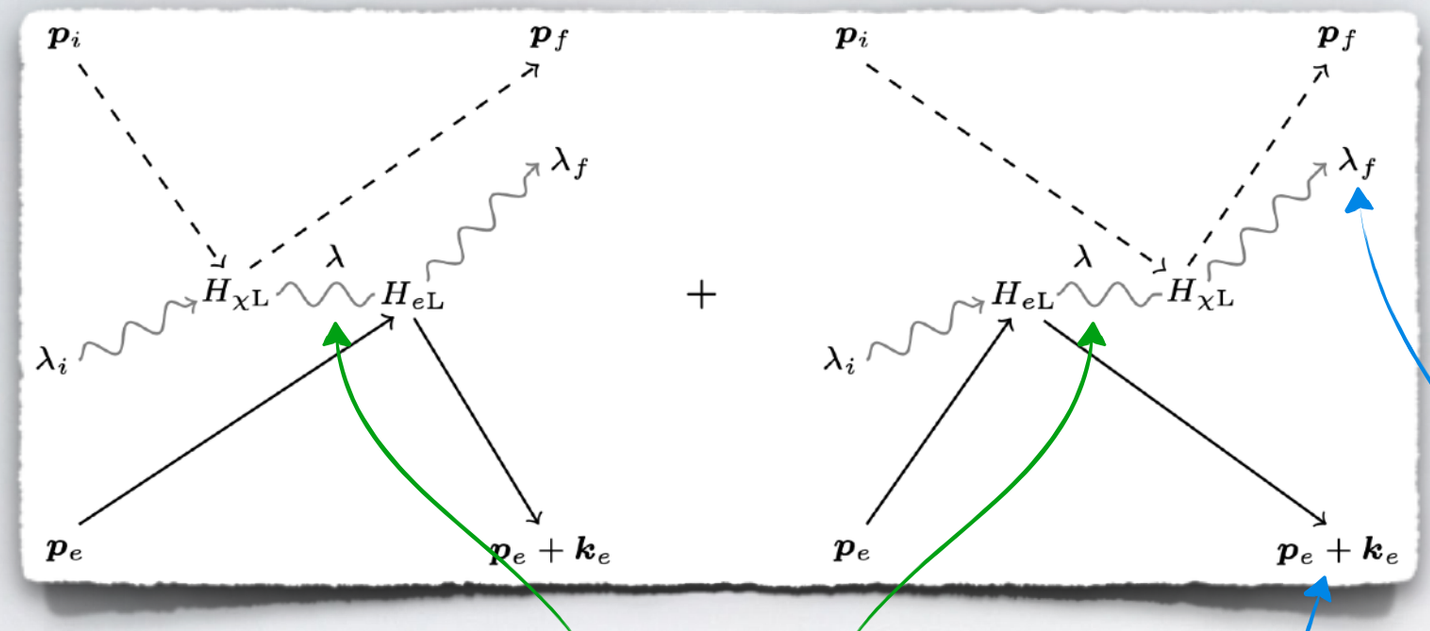

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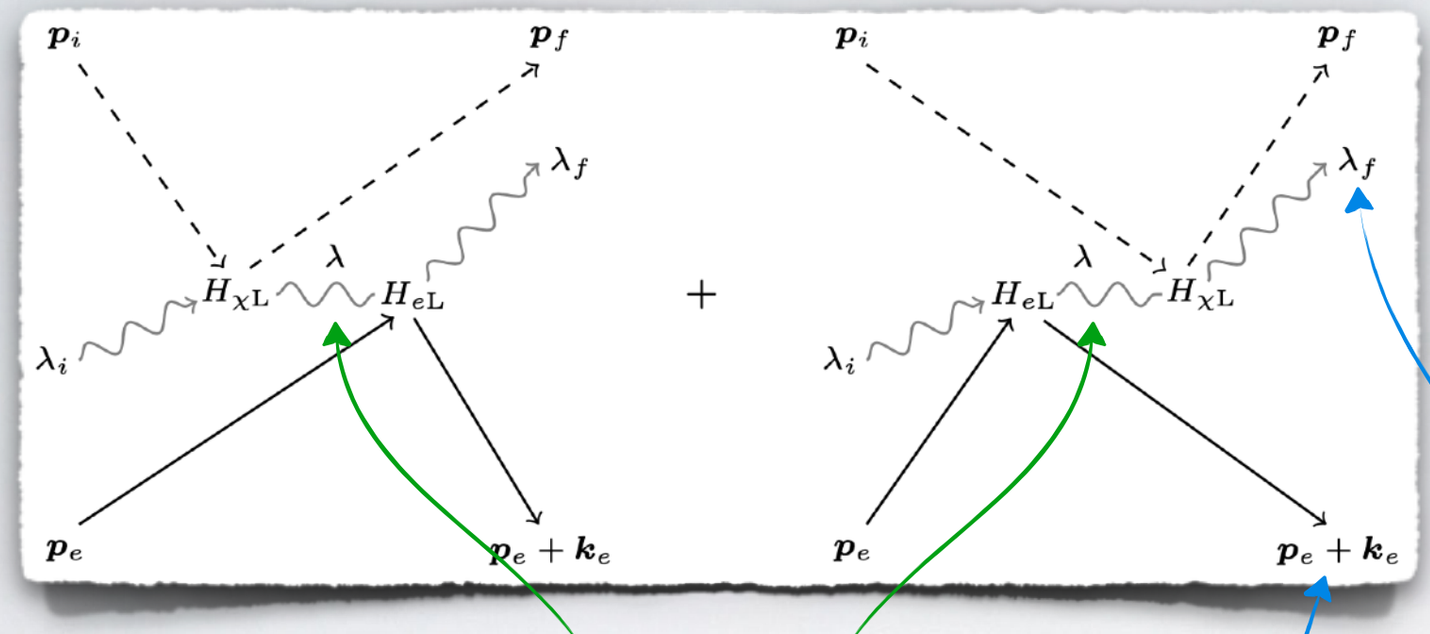

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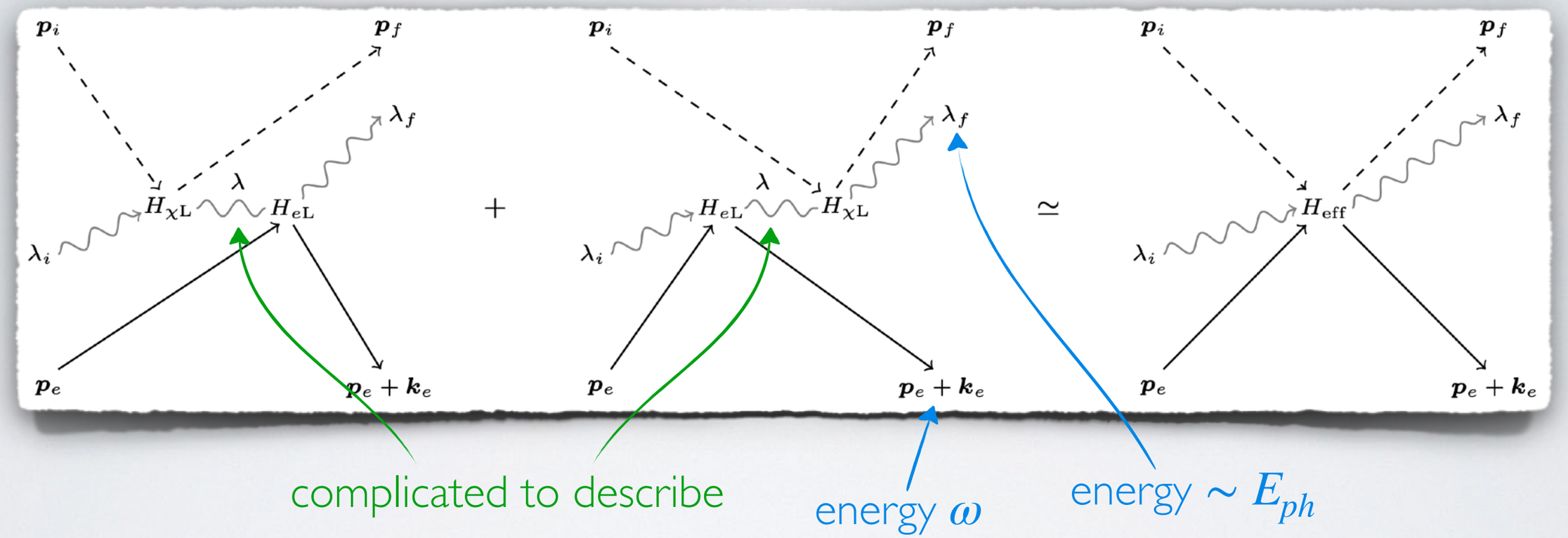

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$$H_{eff} = \frac{1}{m_N \omega^2} \vec{\nabla} H_{\chi L} \cdot \vec{\nabla} H_{eL} + \mathcal{O}\left(\frac{1}{\omega^3}\right)$$

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

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

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- Energy loss function 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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[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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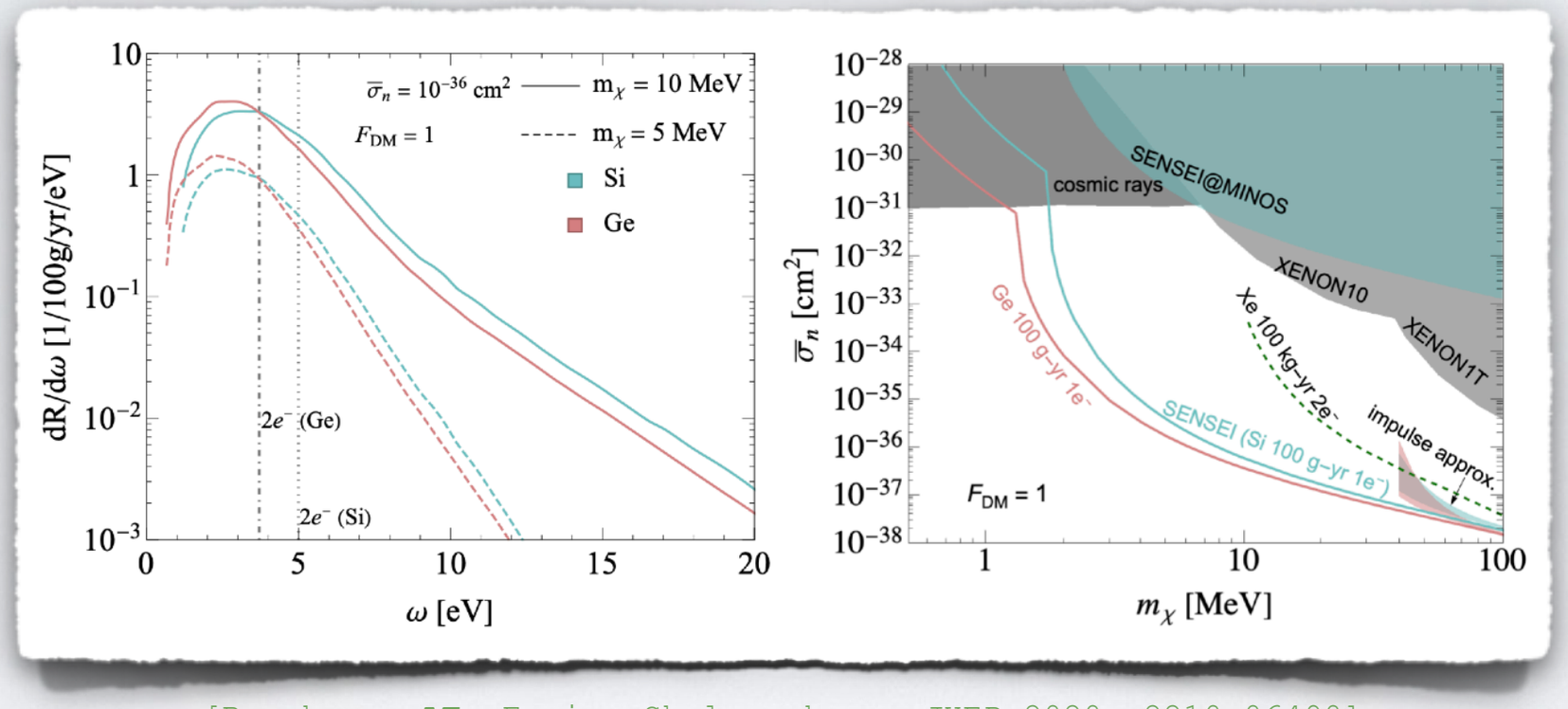

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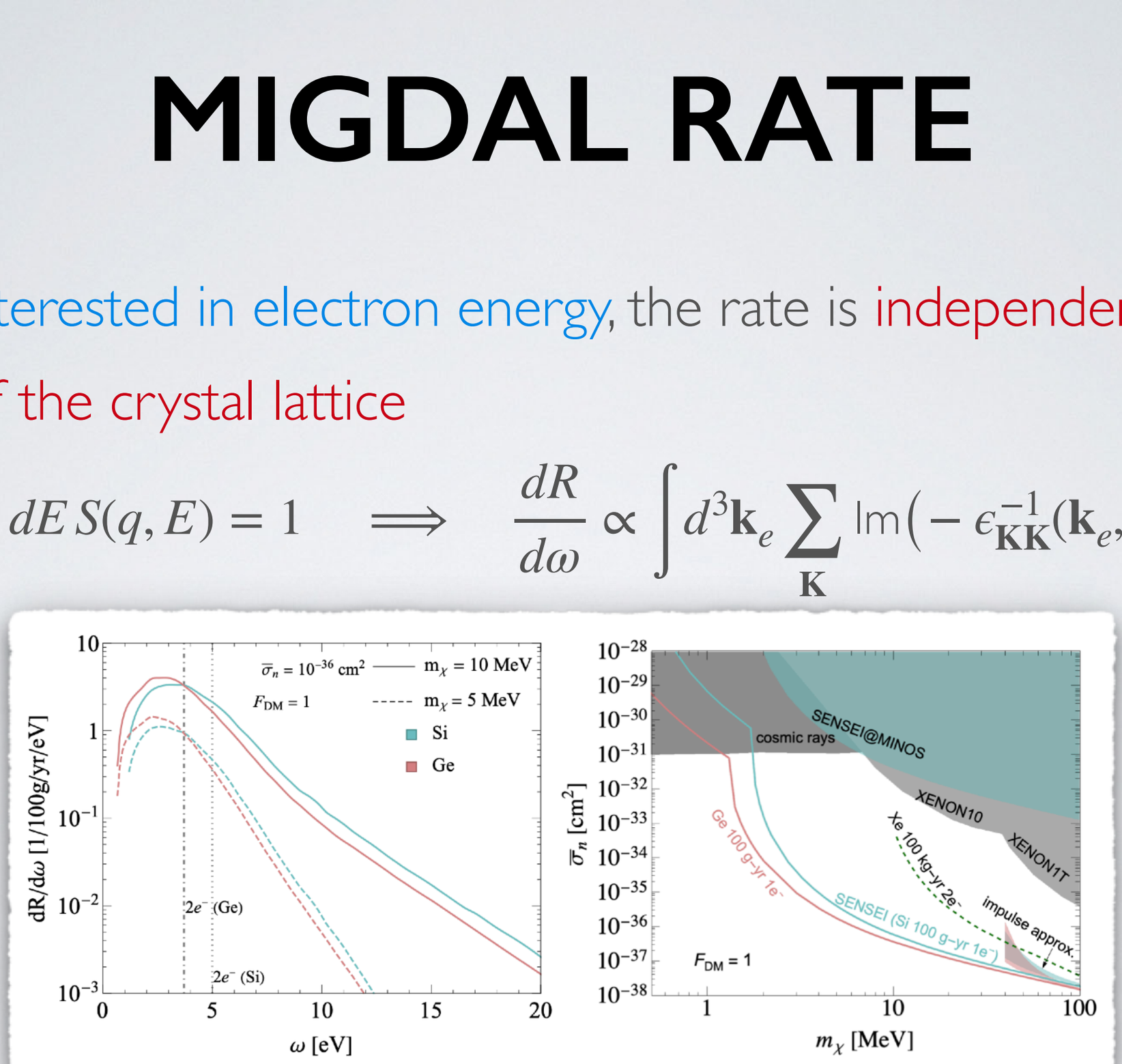

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- Description of Migdal effect in semiconductor extended to all masses

Down to the keV
collective excitations

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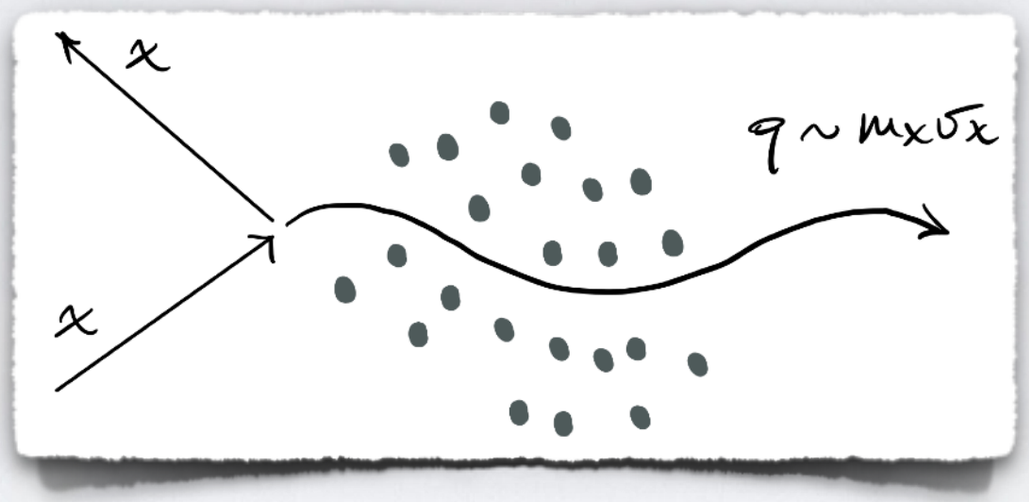

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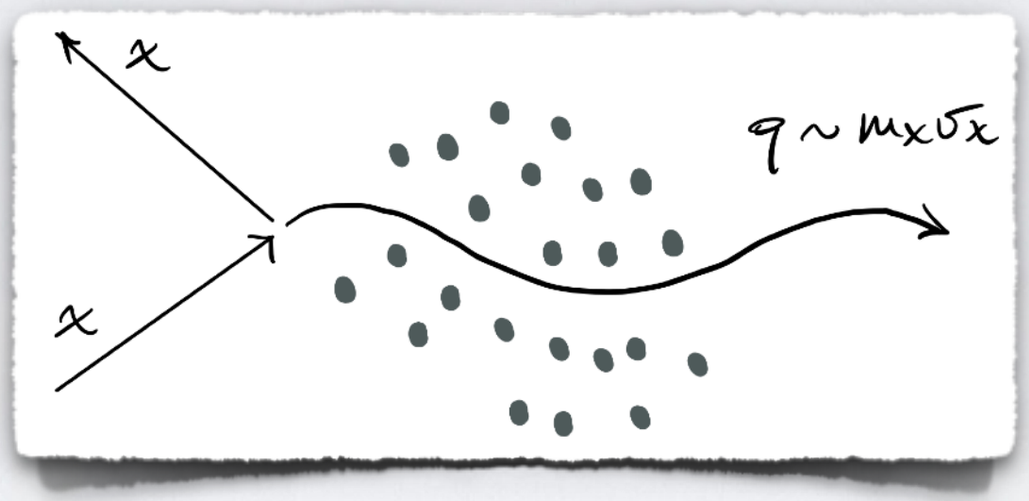

- Typically, no more single particle final states → signatures involve collective excitation [see e.g., Trickle et al. – JHEP 2020, 1910.08092; Griffin et al. – PRD 2020, 1910.10716; Coskuner et al. – PRD 2022, 2102.09567]

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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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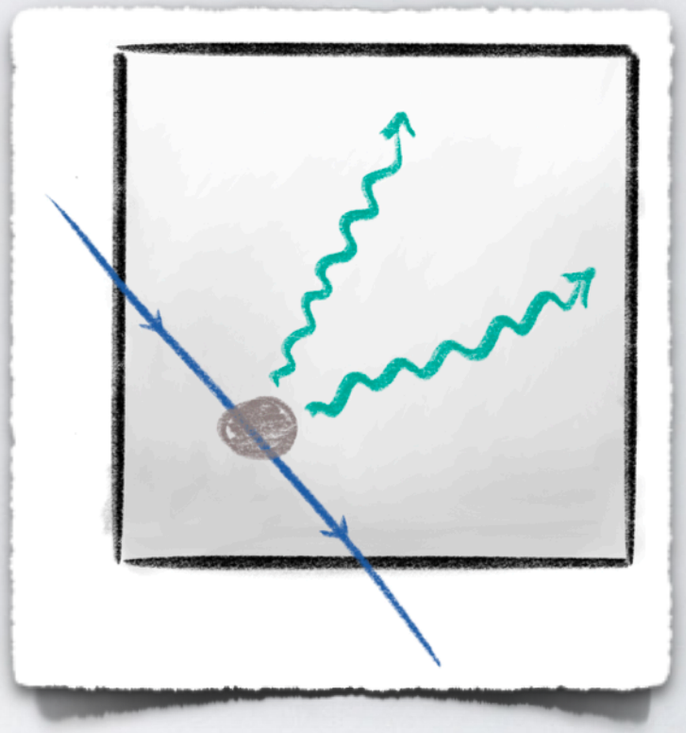

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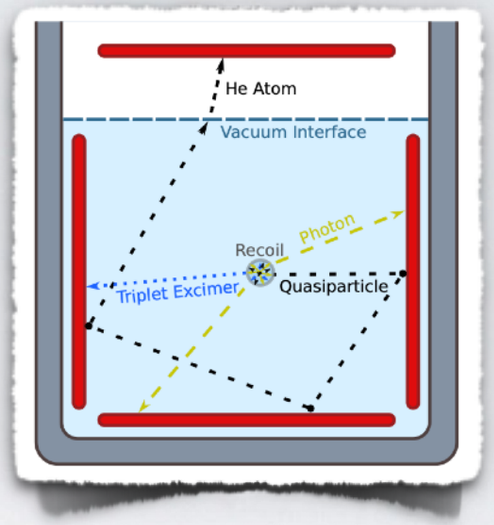

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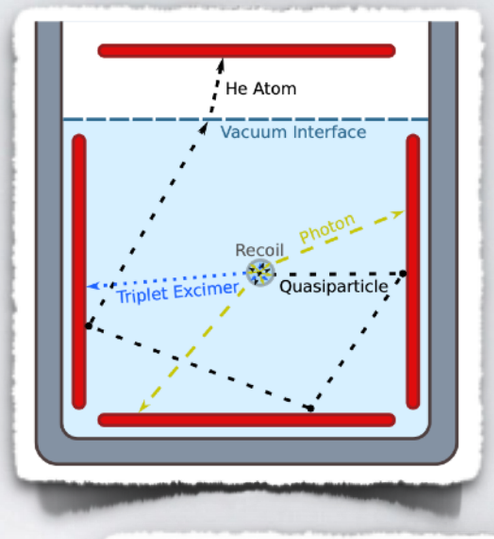

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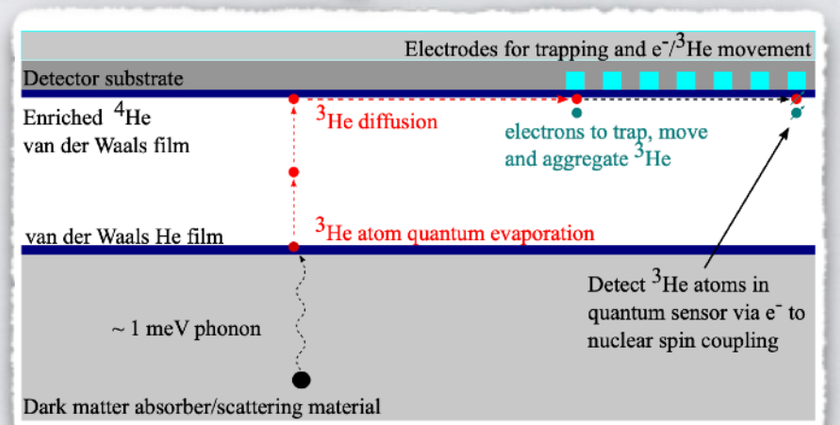
[Maris, Seidel, Stein – PRL 2017, 1706.00117; Lyon et al. – 2201.00738]



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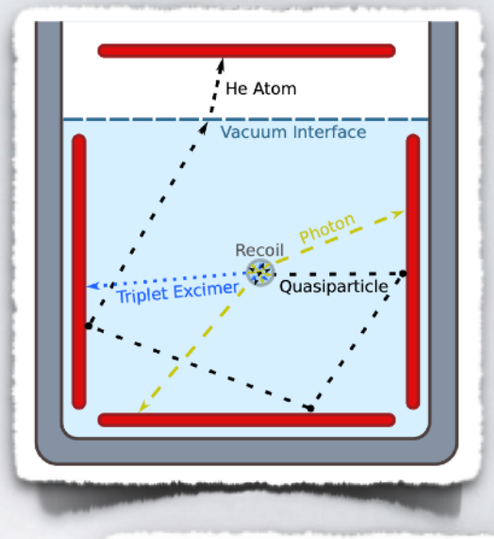

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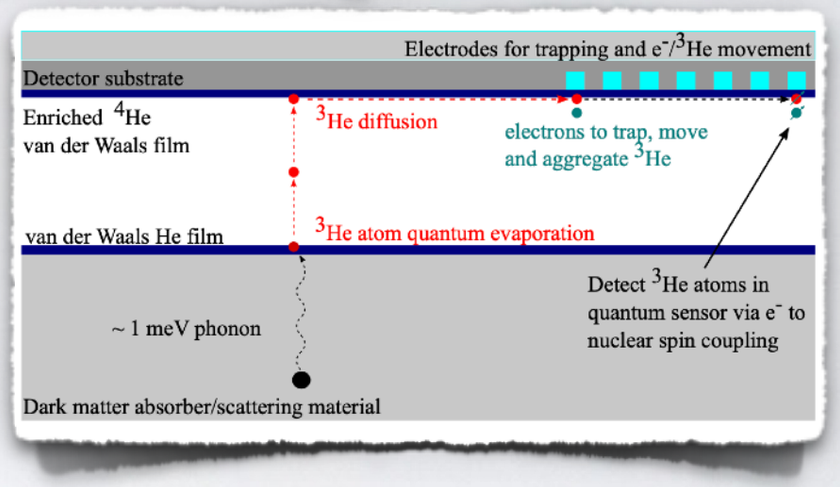
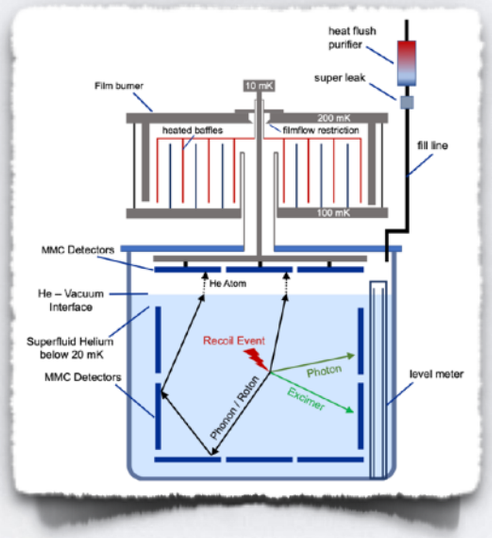


3. DELight

[Krosigk et al. – 2209.10950]



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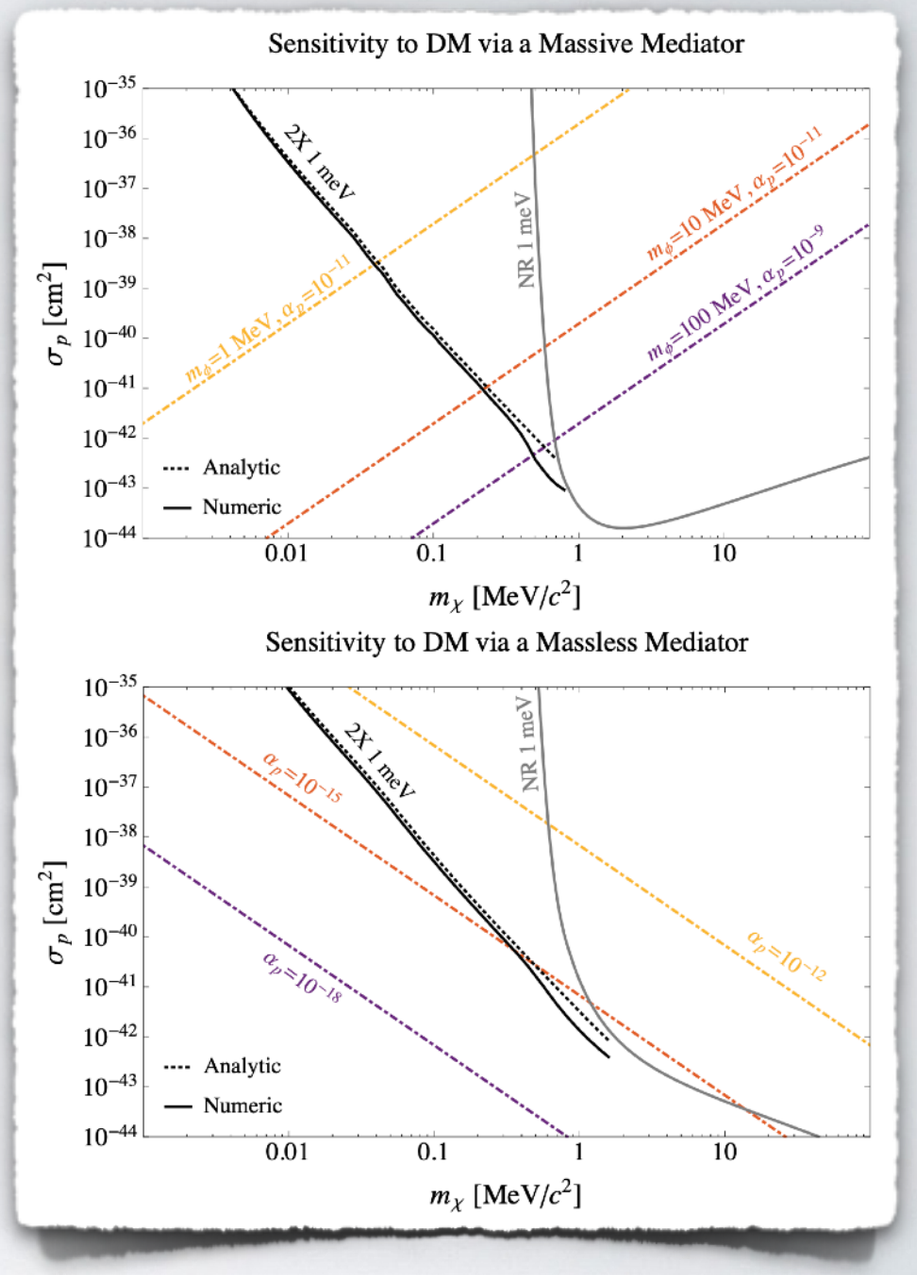

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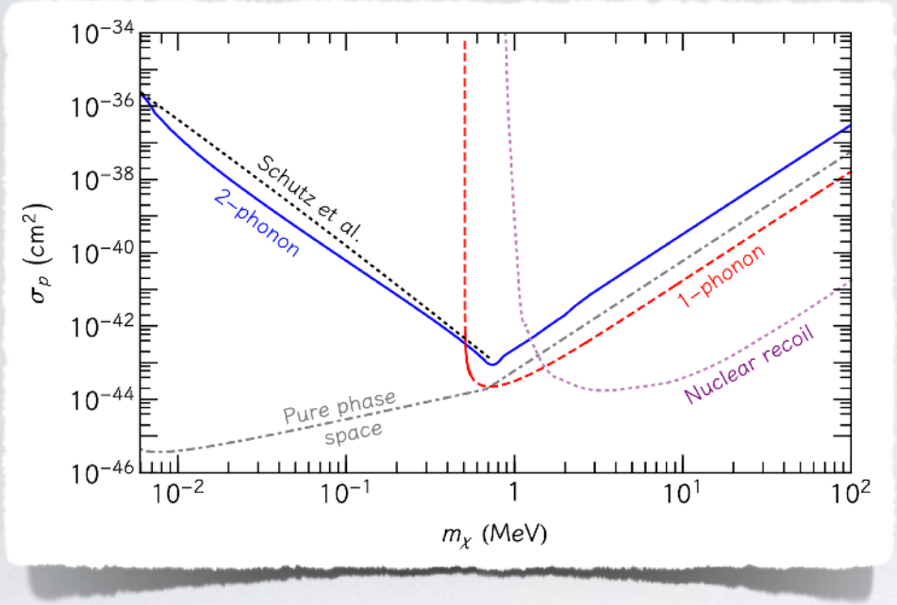

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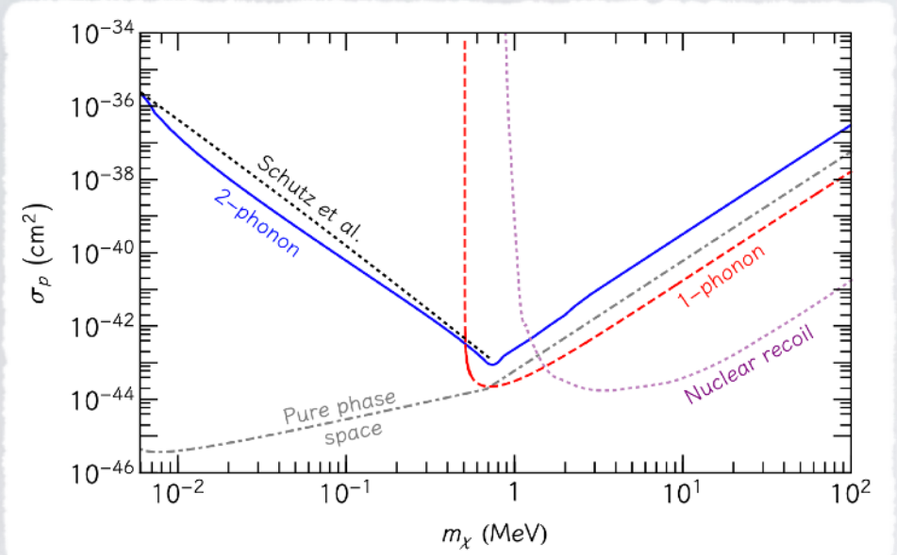

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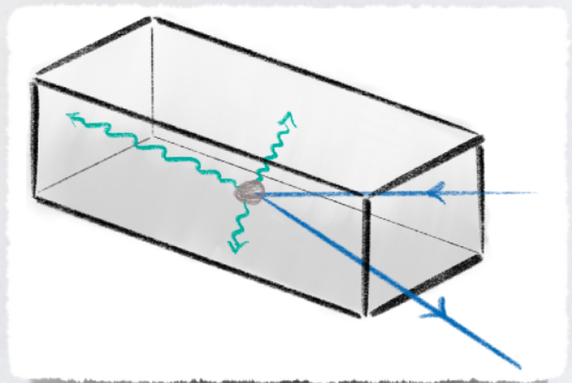

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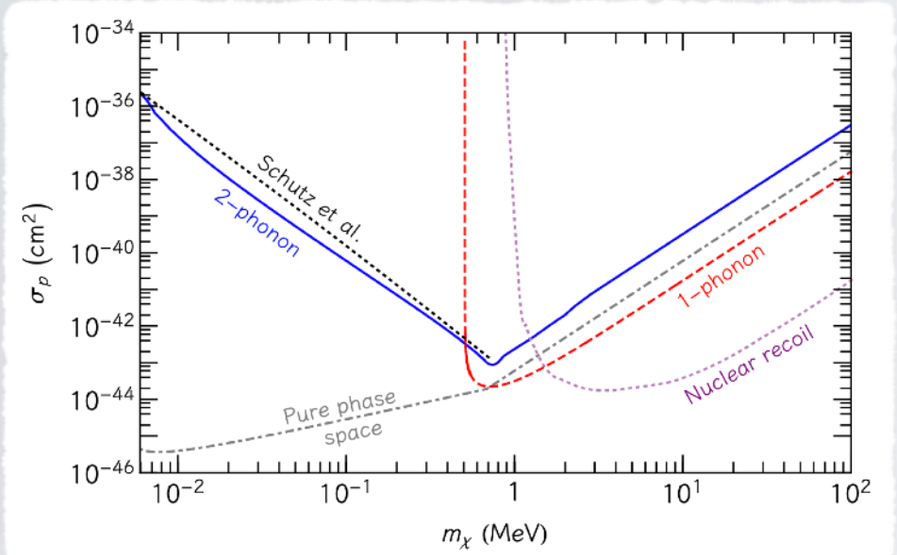

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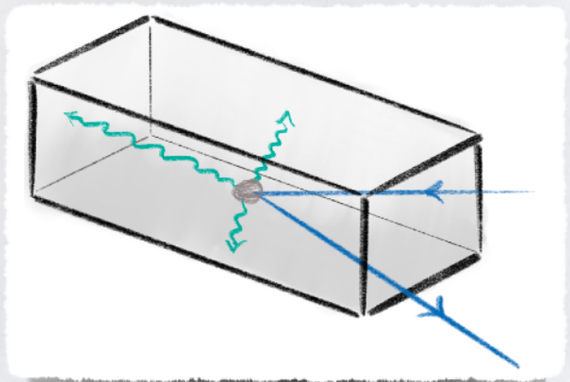

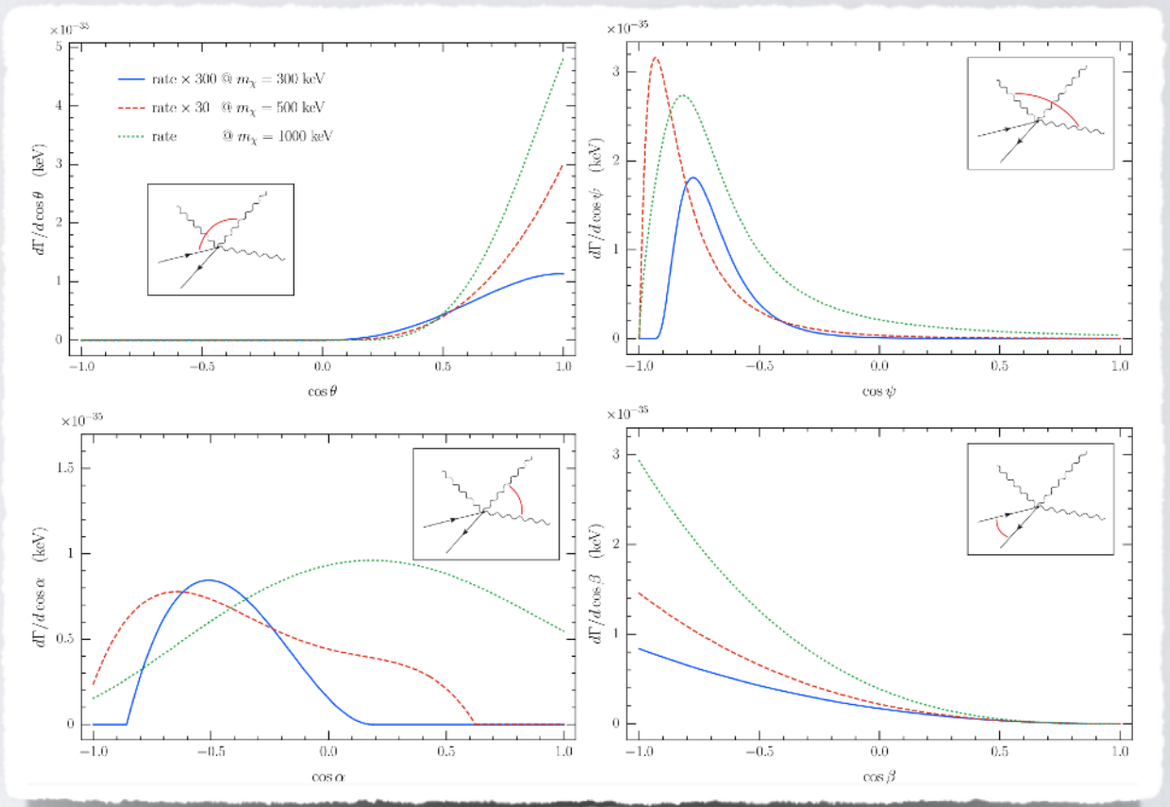

[Caputo, **AE**, Piccini, Polosa, Rossi – PRD 2021, 2012.01432]

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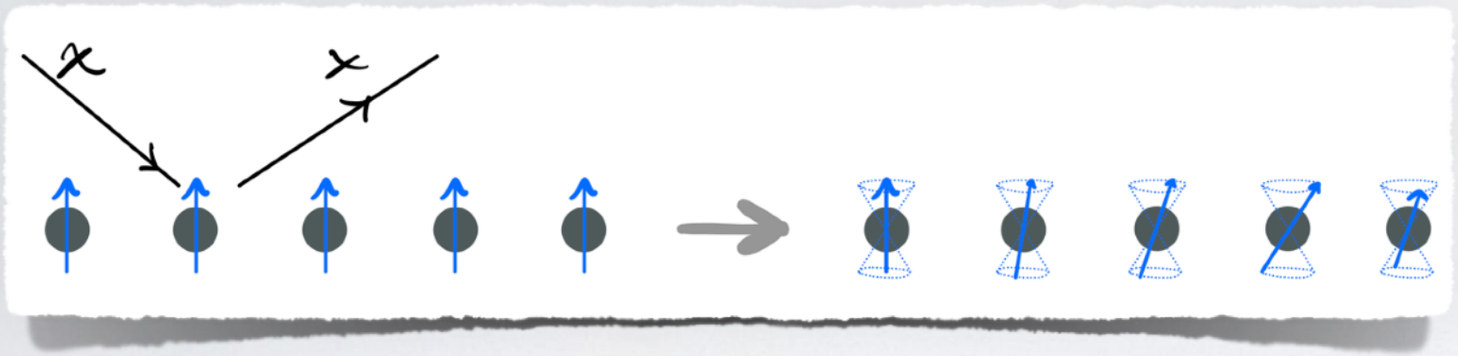

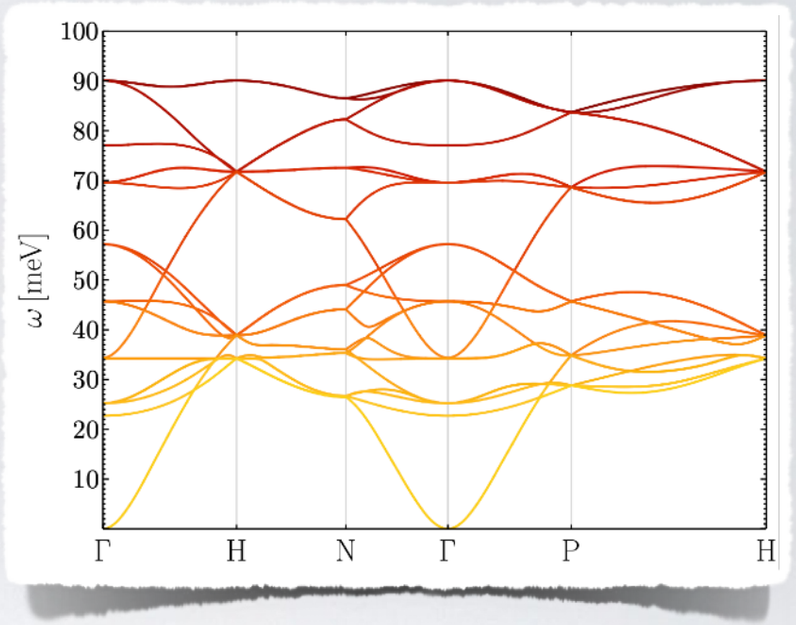

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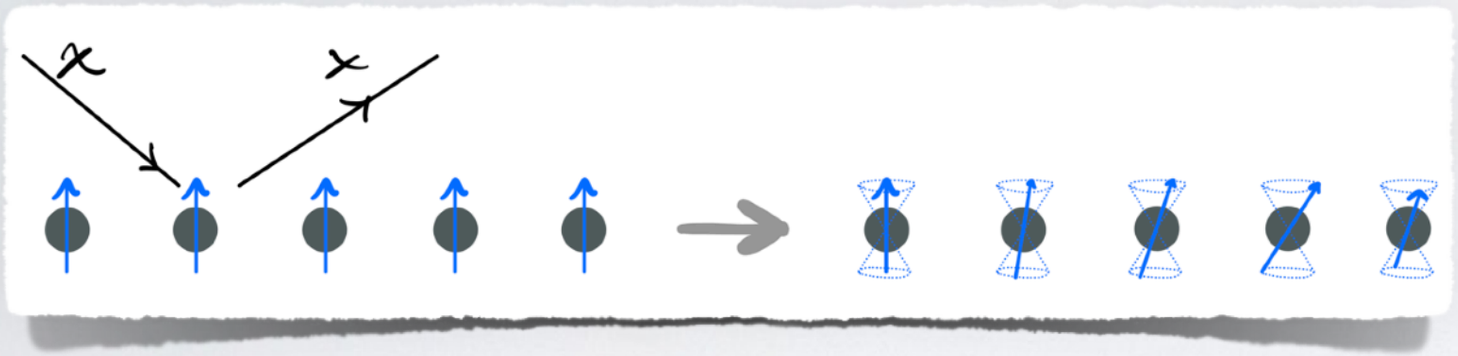

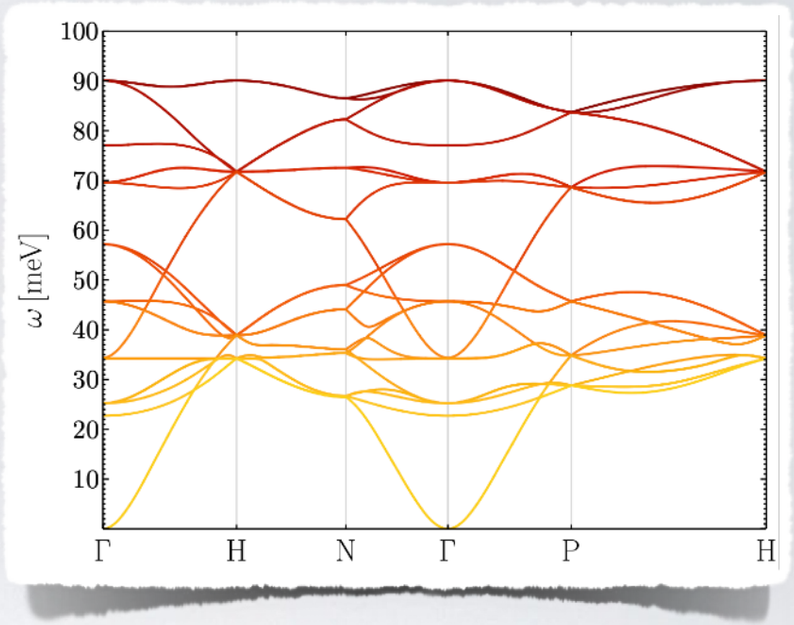

- Ways to detect few magnons have been proposed and under work (TES, MKID, quantum sensors)

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

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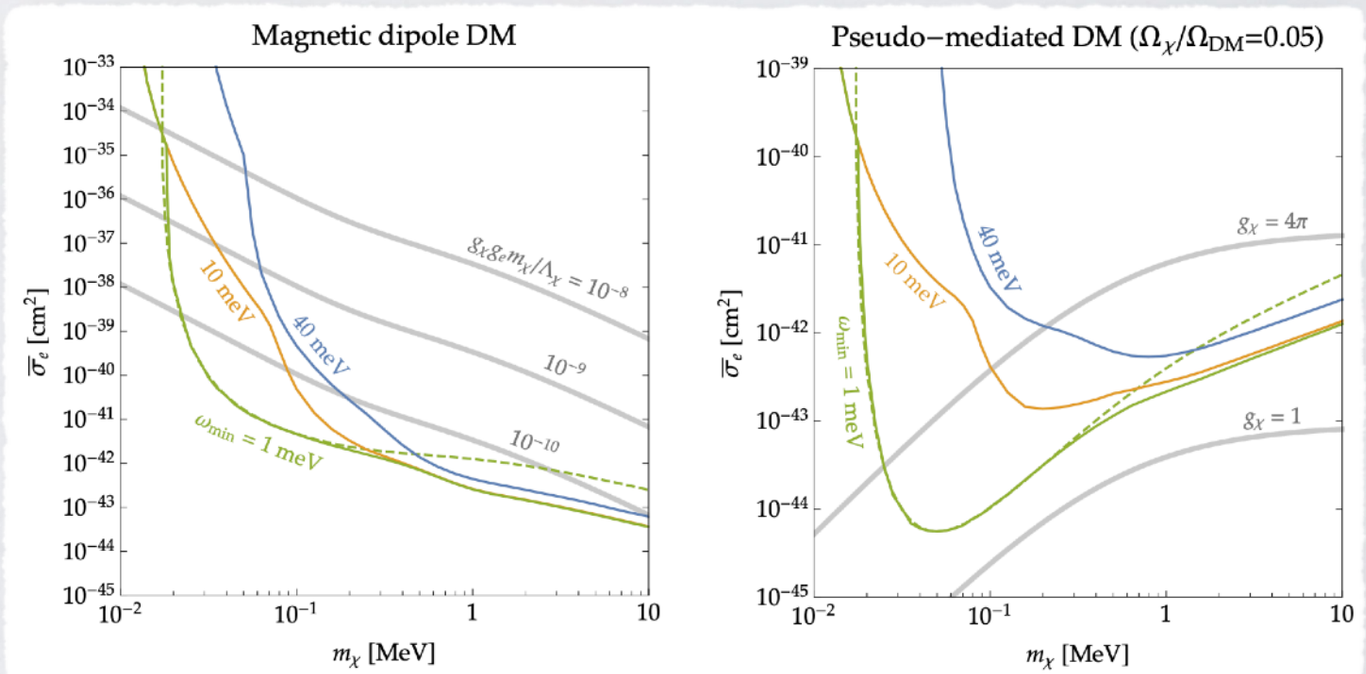
- For small masses only single-magnon emission → probes

$$m_\chi \gtrsim \mathcal{O}(10\ \text{keV})$$

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



ANTI-FERROMAGNETS

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- A better class of materials turns out to be anti-ferromagnets
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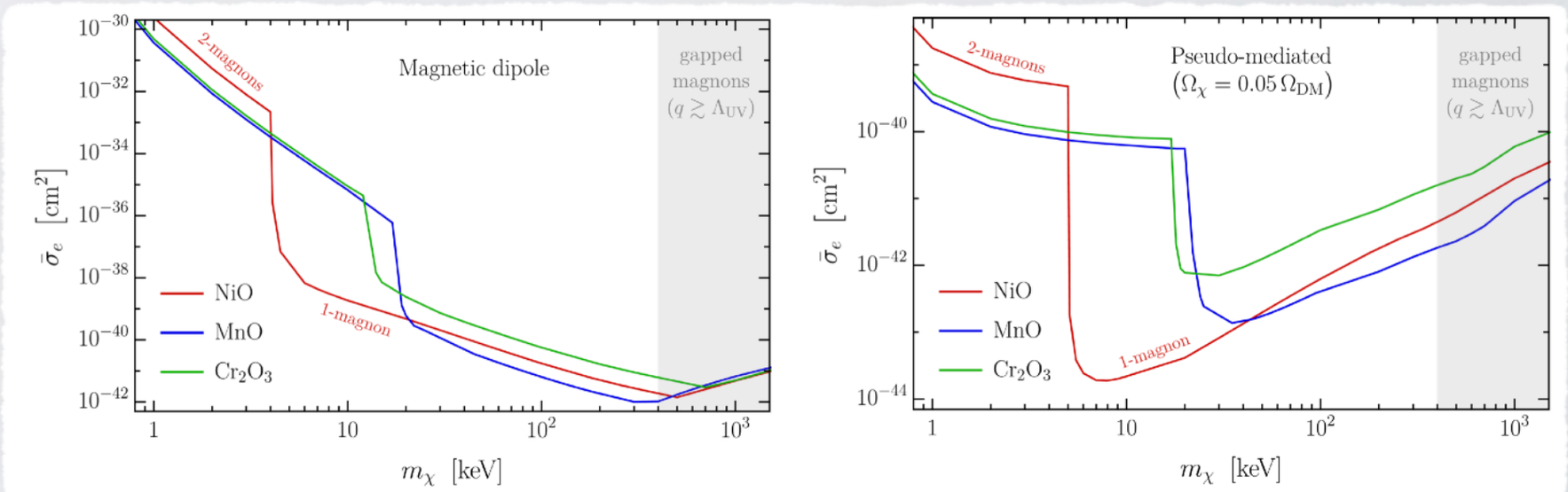
[**AE**, Pavaskar – 2210.13516]



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Thank you for the attention!