LIGHT DARK MATTER DETECTION

NEW IDEAS AND NEW TOOLS

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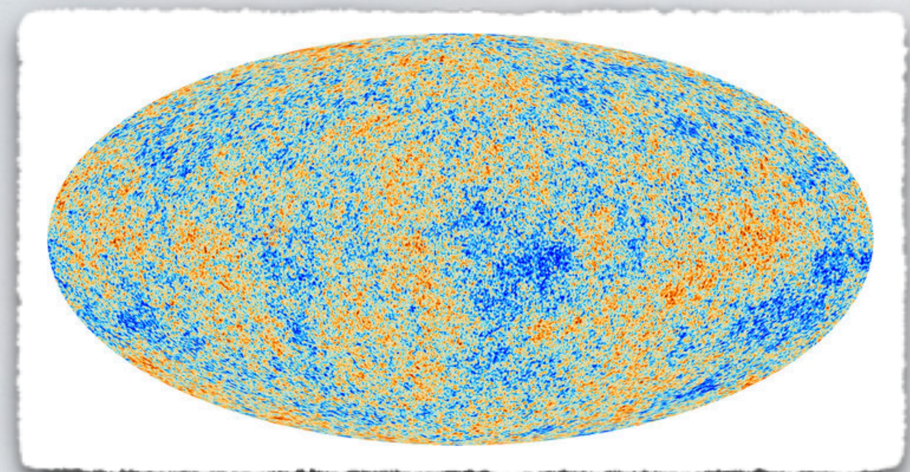
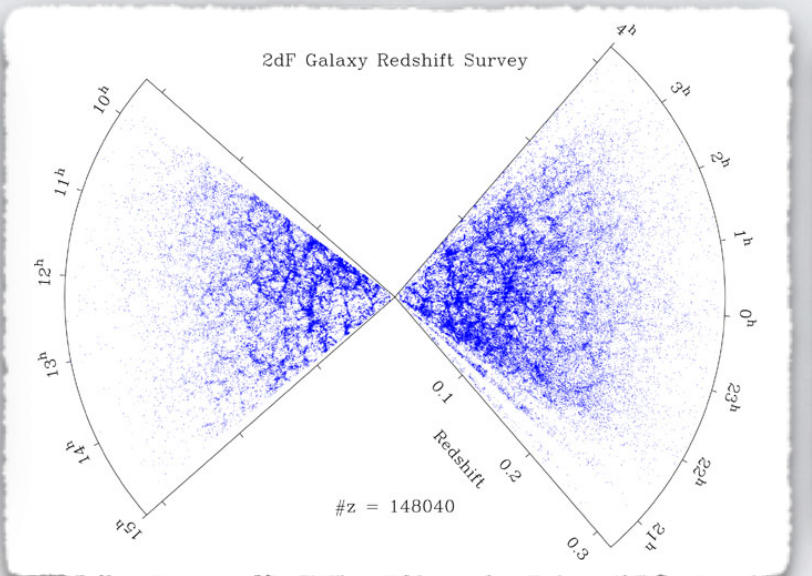
OUTLINE

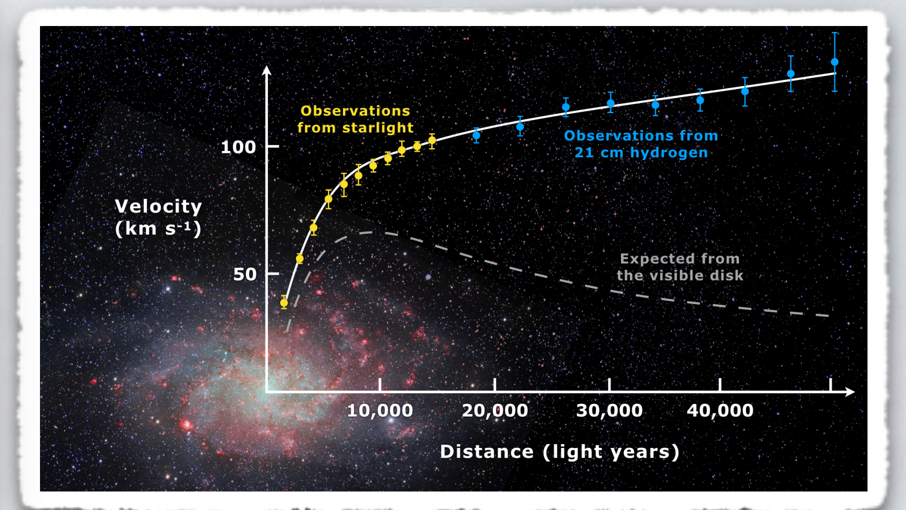
- Searching for sub-GeV dark matter
- The effective theory approach
- MeV to GeV: Migdal effect in semiconductors
- keV to MeV: superfluid ^{4}He and anti-ferromagnets
- Outlook

SUB-GEV DARK MATTER

- Most of the matter (~80%) that interacts gravitationally is dark



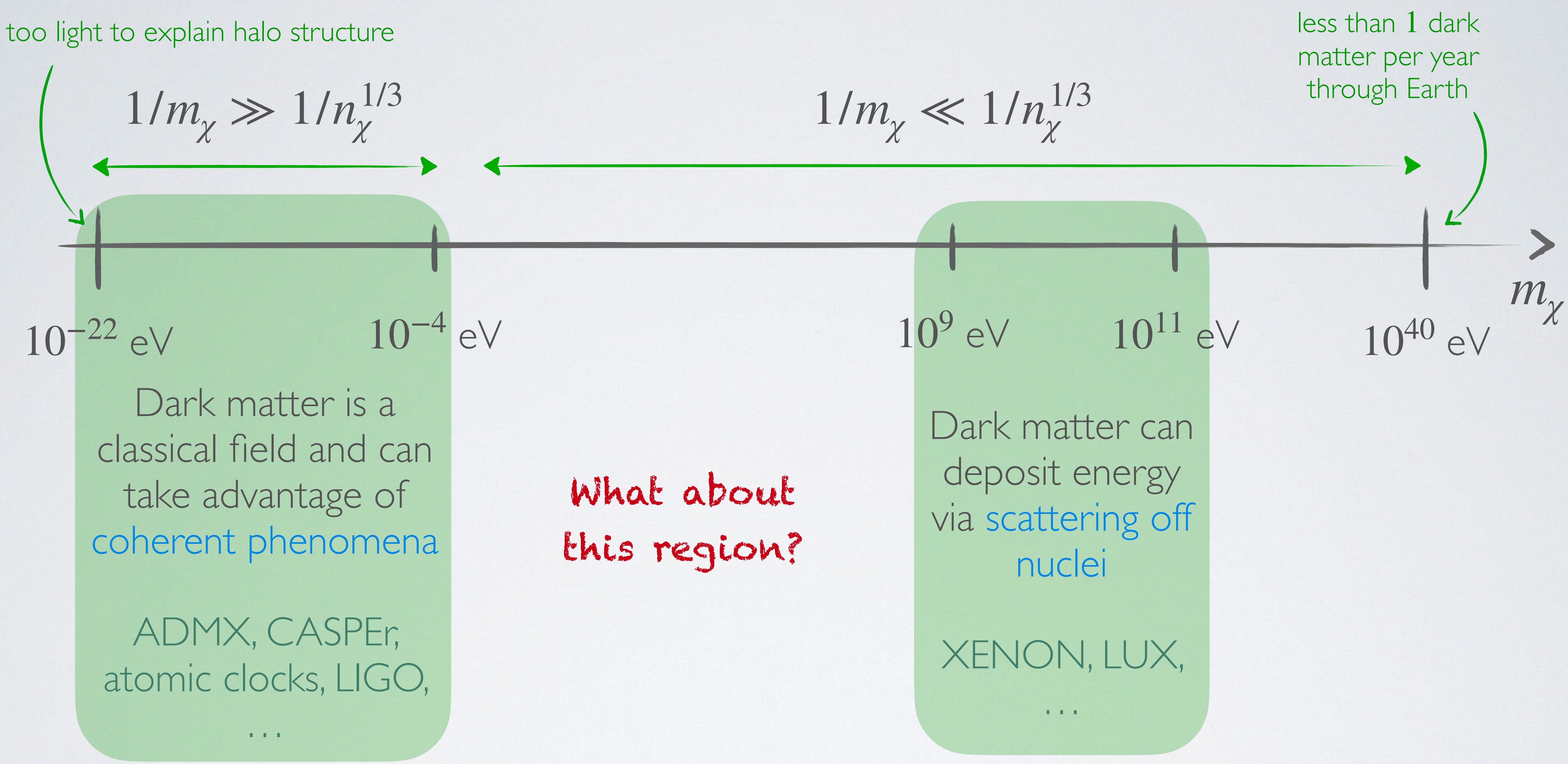




- One of the strongest evidences for physics beyond the Standard Model

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

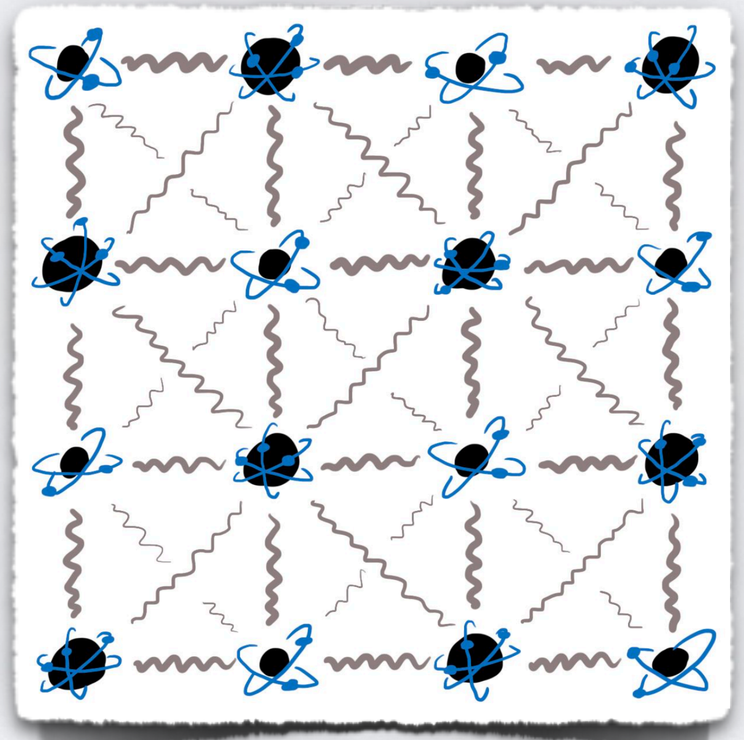
SUB-GEV DARK MATTER



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

EFT APPROACH

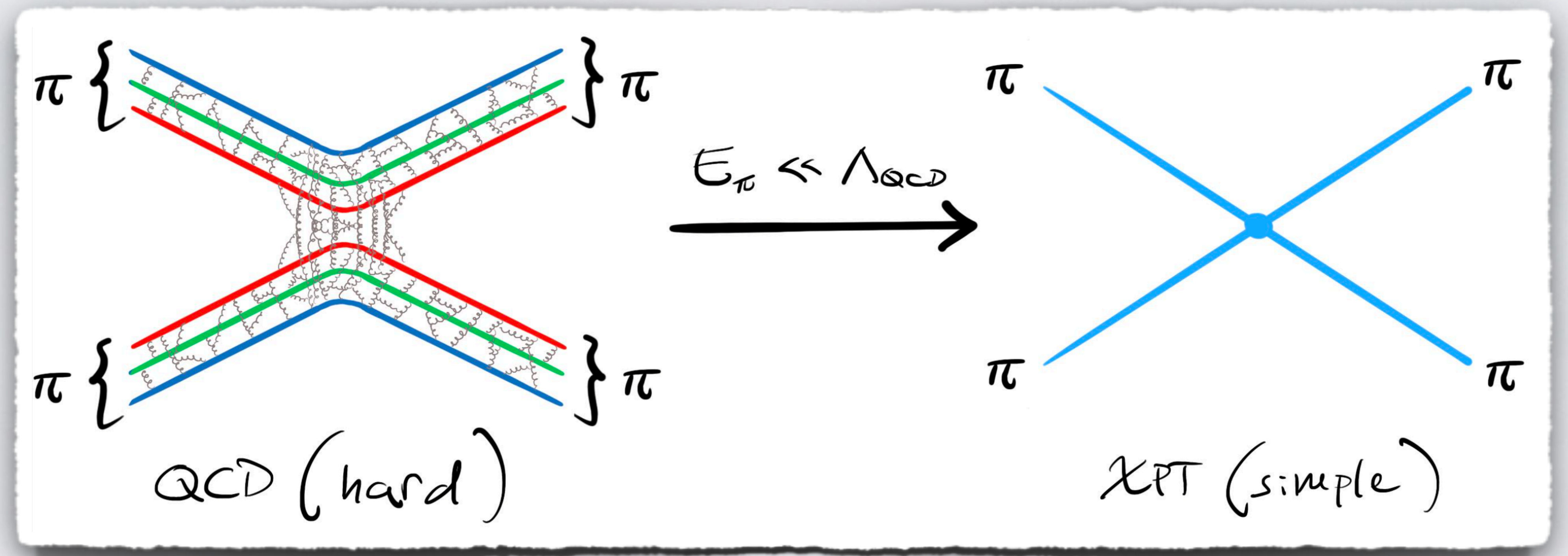
- For sub-GeV dark matter one needs to delve into the condensed matter world
- Need to account for the complicated many-body physics (correlations, strong coupling, …), e.g.:



- It would be ideal to be able to ignore these intricacies

EFT APPROACH

- Hierarchy between scales (energy, time, wavelength, …) → formulate the problem in effective field theory terms
- The EFT is universal → independent on the complicated physics of the far away scale, e.g.



- Apply the same idea to condensed matter!

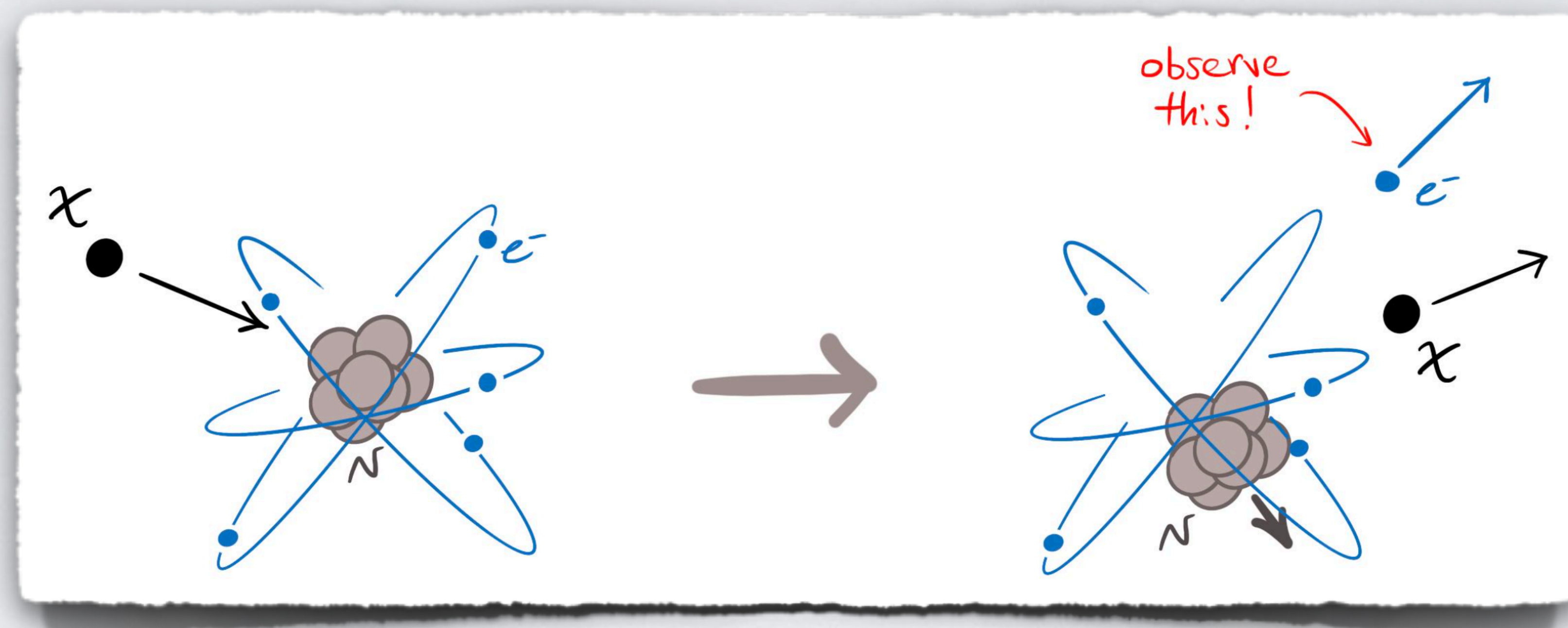
<u>MeV to GeV</u>
Migdal effect in semiconductors

[Berghaus, **AE**, Essig, Sholapurkar — to appear]

MIGDAL EFFECT

- For sub-GeV dark matter nuclear recoil signals become challenging
  → sensitivity can be lowered by looking for inelastic processes
  [e.g., Essig, Mardon, Volansky — PRD 2012, 1108.5383; Kouvaris, Pradler — PRL 2017, 1607.01789]

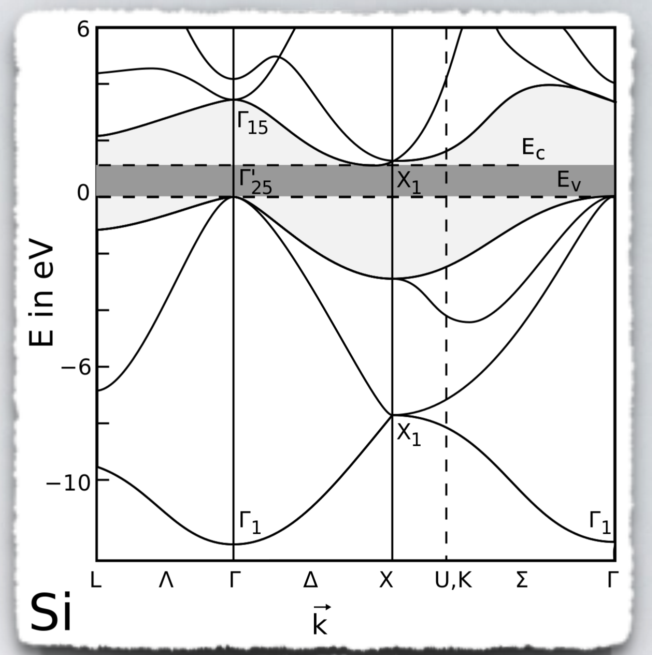
- One such process is the Migdal effect



- Less likely… but lower threshold! → expected to lower the sensitivity to $\mathcal{O}(100\ \mathrm{MeV})$ masses [e.g., Vergados, Ejiri — PLB 2005, hep-ph/0401151; Ibe, Nakano, Shoji, Suzuki — JHEP 2018, 1707.07258]

MIGDAL EFFECT

- Semiconductors have small $\mathcal{O}(\text{eV})$ bandgap
  $\longrightarrow$ Migdal effect should allow to probe down to $\mathcal{O}(\text{MeV})$ masses

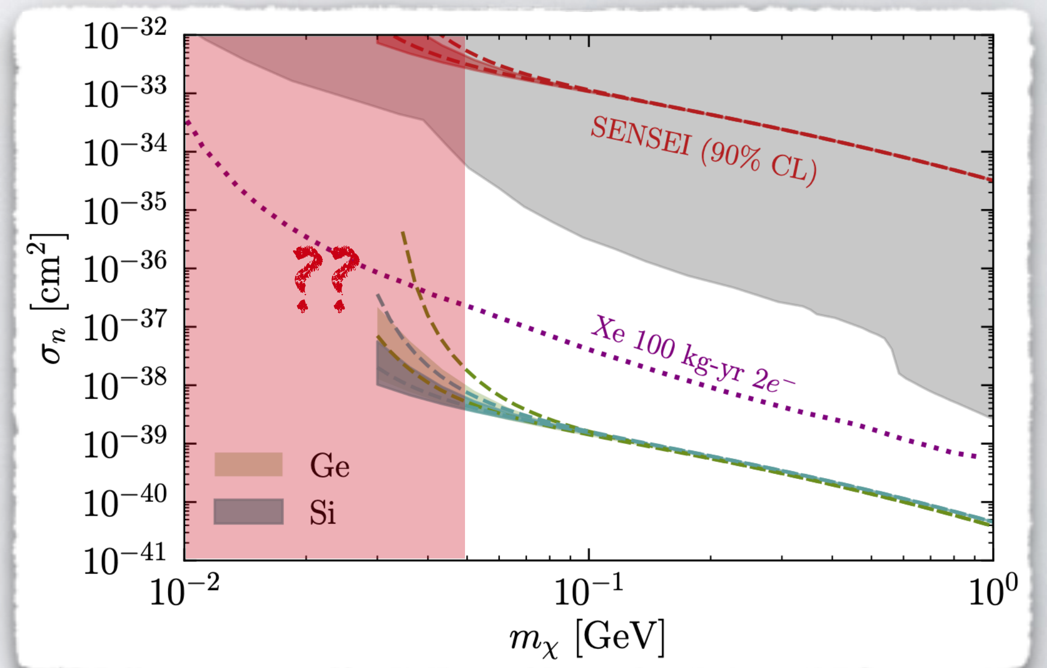


- Migdal rate in a semiconductor is much harder

- So far approached only under some simplifying assumptions

[Liang, Zhang, Zheng, Zhang — PRD 2020, 1912.13484; Liu, Wu, Chi, Chen — PRD 2020, 2007.10965; Knapen, Kozaczuk, Lin — PRL 2021, 2011.09496; Liang, Mo, Zheng, Zhang — PRD 2021, 2011.13352; Liang, Mo, Zheng, Zhang — 2205.03395]

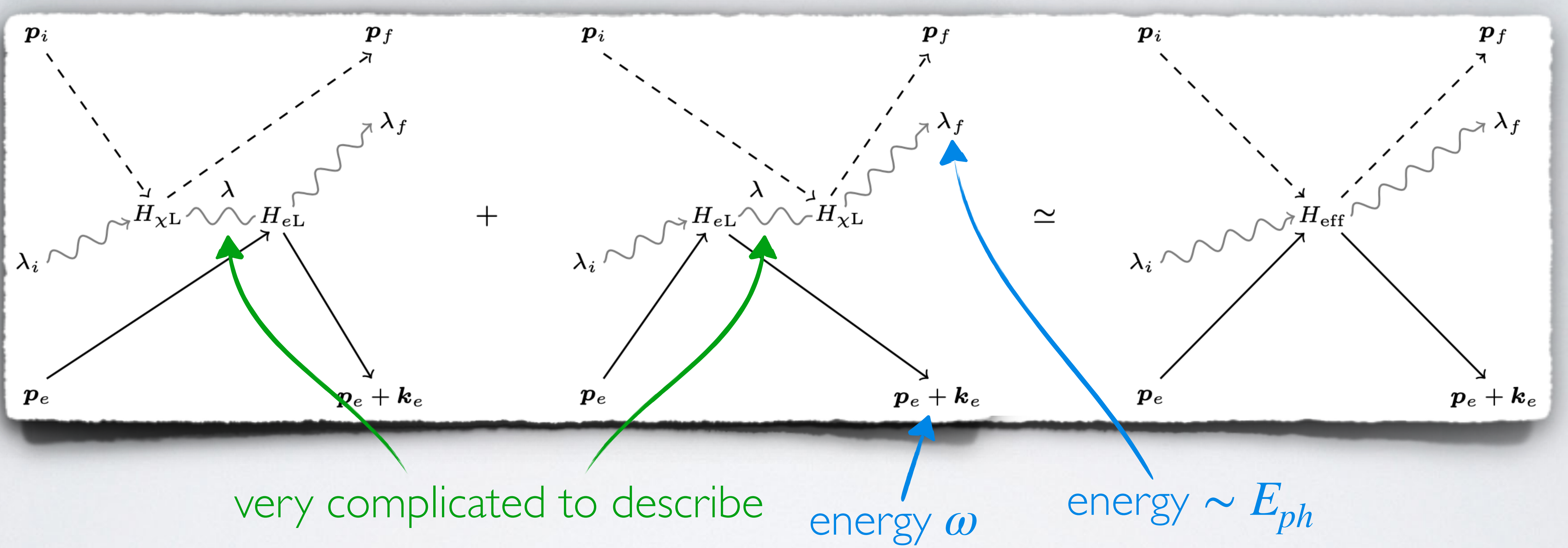
- There is no reliable prediction for $m_\chi \lesssim 50$ MeV



[Knapen, Kozaczuk, Lin — PRL 2021, 2011.09496]

EFT

- Migdal effect in old-fashioned perturbation theory



- Separation of scales ($\omega \sim$ eV $\gg E_{ph} \sim 10$ meV) allows to integrate out the intermediate lattice mode

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

[Berghaus, **AE**, Essig, Sholapurkar – to appear]

MIGDAL RATE

- Now simple to determine the rate for Migdal emission

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

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

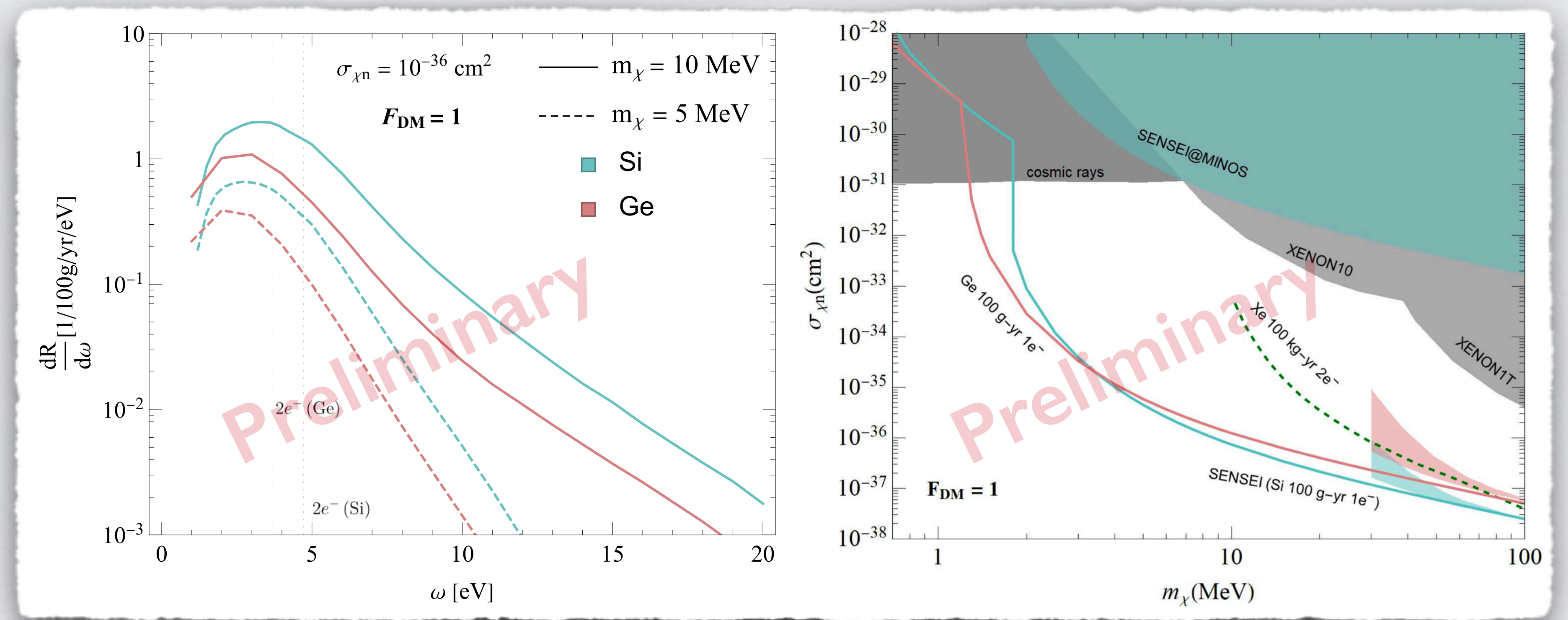
$$\frac{d^2\sigma_n}{d\Omega dE} = \frac{\sigma_n}{4\pi}\frac{k_f}{k_i} S(q,E)$$

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

MIGDAL RATE

- If not interested in phonon energy, the rate is independent on the details of the crystal lattice!

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



[Berghaus, **AE**, Essig, Sholapurkar — to appear]

- The description of Migdal effect in semiconductor is now complete

<u>keV to MeV</u>
superfluid ^{4}He and anti-ferromagnets

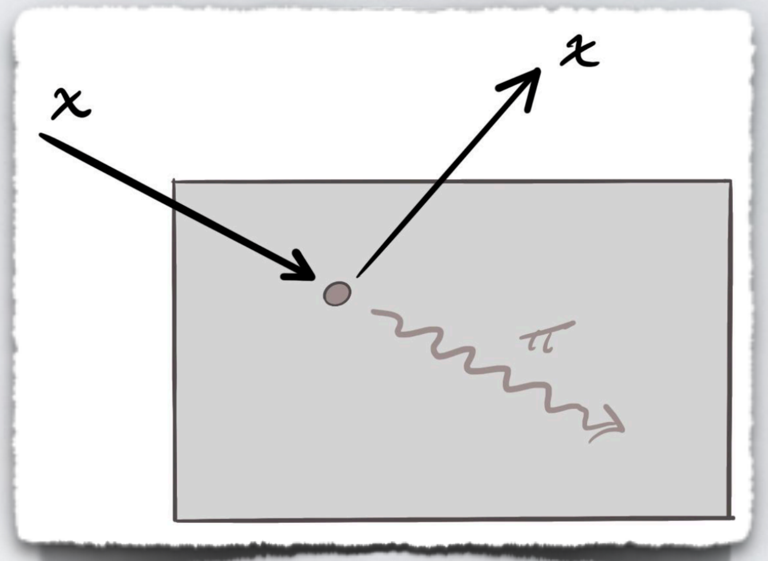
[Acanforda, **AE**, Polosa — EPJC 2019, 1902.02361; Caputo, **AE**, Polosa — PRD 2019, 1907.10635; Caputo, **AE**, Geoffray, Polosa, Sun — PLB 2020, 1911.04511; Caputo, **AE**, Piccinini, Polosa, Rossi — PRD 2021, 2012.01432]

[**AE**, Pavaskar — to appear]

COLLECTIVE EXCITATIONS

- For sub-MeV dark matter nuclear and electronic recoils are not good probes anymore $\longrightarrow$ dark matter excites collective modes

[see e.g., Trickle et al. — JHEP 2020, 1910.08092; Griffin et al. — PRD 2020, 1910.10716; Coskuner et al. — PRD 2022, 2102.09567]



- I will focus on two possibilities:

A. Spin-independent interactions: phonons in superfluid ^{4}He

[see also Guo, McKinsey — PRD 2013, 1302.0534; Schutz, Zurek — PRL 2016, 1604.08206; Kapen, Lin, Zurek — PRD 2017, 1611.06228; Baym et al. — PRD 2020, 2005.08824]

B. Spin-dependent interactions: magnons in anti-ferromagnets

[see also Trickle, Zhang, Zurek — PRL 2020, 1905.13744; Mitridate, Trickle, Zhang, Zurek — PRD 2020, 2005.10256]

COLLECTIVE EXCITATIONS

- Try to detect the collective modes created by the interaction with a dark matter particle

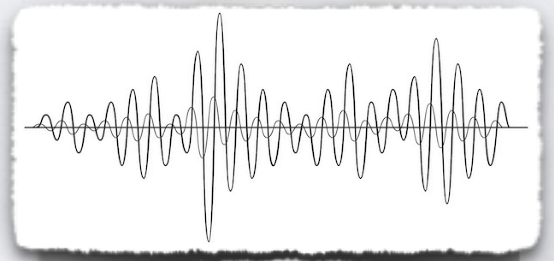
- Simple part: dark matter interaction with material

superfluid ^{4}He	anti-ferromagnets
$\mathscr{L}_{int} \sim \bar{\chi}\chi\,\rho_m(\mathbf{q},\omega)$	$\mathscr{L}_{int} \sim \bar{\chi}\chi\, f(\mathbf{q})\,\rho_s(\mathbf{q},\omega)$

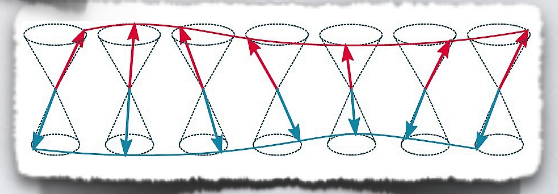
[Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361; **AE**, Pavaskar — to appear]

- Collective modes:

A. superfluid → phonon (sound)



B. anti-ferromagnet → magnon (spin wave)



EFT

- Hard part: description of the dynamics of phonons and magnons
- Superfluids and anti-ferromagnets spontaneously break a set of symmetries $\longrightarrow$ gapless collective excitations are Goldstones
- When $q \ll 1/a$, they can be described by an EFT:

superfluid phonon

$$\mathscr{L}_\pi \sim \dot{\pi}^2 - \boxed{c_s^2}(\nabla\pi)^2 + \boxed{\lambda}\dot{\pi}^3 + \boxed{\lambda'}\dot{\pi}(\nabla\pi)^2$$

$$\rho_m \sim \boxed{g_1}\dot{\pi} + \boxed{g_2}\dot{\pi}^2 + \boxed{g_3}(\nabla\pi)^3 + \cdots$$

from equation of state data

[Acanfora, **AE**, Polosa — EPJC 2019, 1902.02361]

magnon in anti-ferromagnets

$$\mathscr{L}_\mu \sim (\dot{\mu}^a)^2 - \boxed{v_\mu}(\nabla\mu^a)^2 + \ldots$$

$$\rho_s^i \sim \boxed{c_6}\left(\delta^{ia}\dot{\mu}^a + \delta^{i3}\epsilon^{ab}\mu^a\dot{\mu}^b + \ldots\right)$$

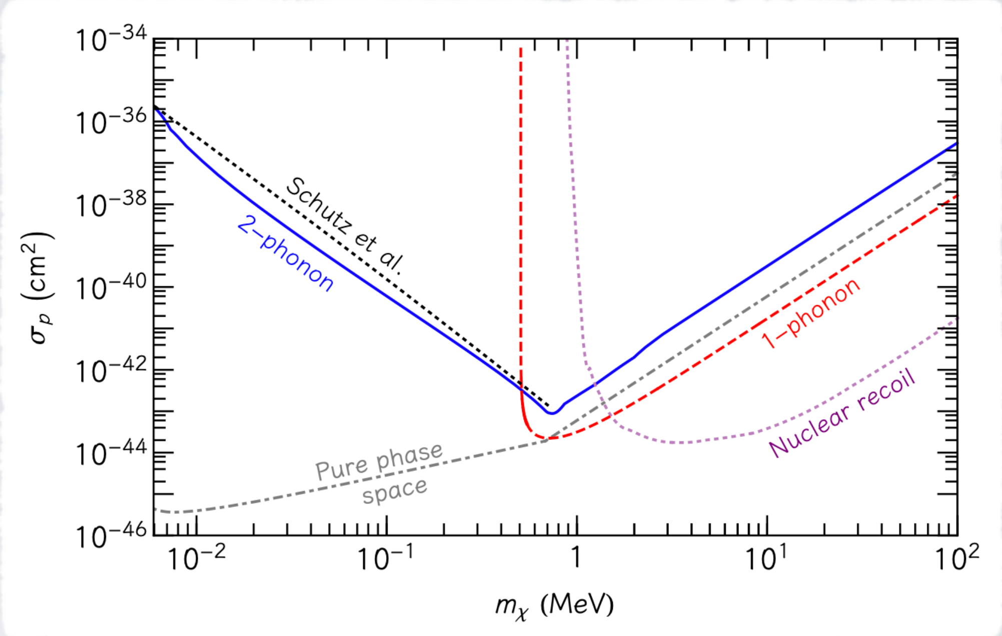
from neutron scattering data

[**AE**, Pavaskar — to appear]

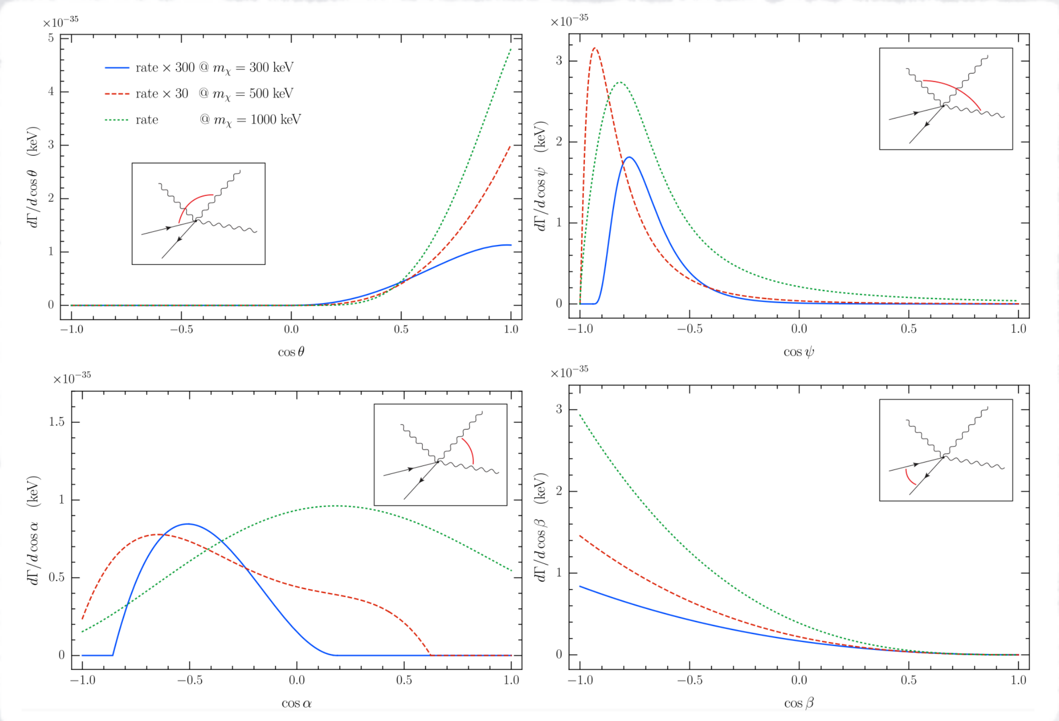
- Use particle physics method to compute condensed matter rates!

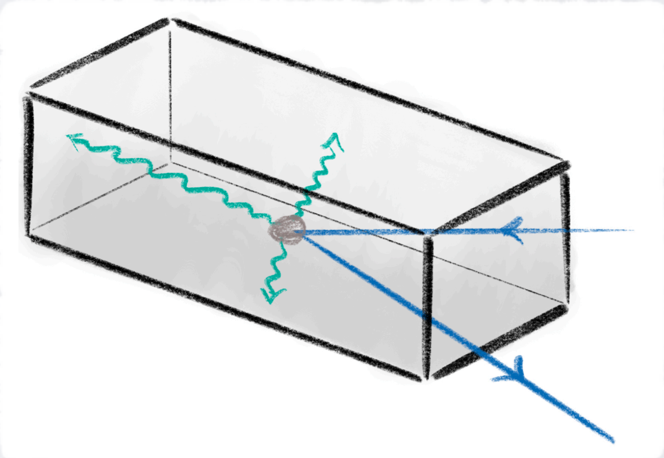
SUPERFLUID ^{4}He

- Calculation of event rates are now easy
- Reproduce (and correct) the result obtained with standard methods
- Extend to 3-phonon emission and discuss intriguing directional signal



[Caputo, **AE**, Polosa — PRD 2019, 1907.10635; Caputo, **AE**, Polosa — J.Phys.Conf.Ser. 2020, 1911.07867]



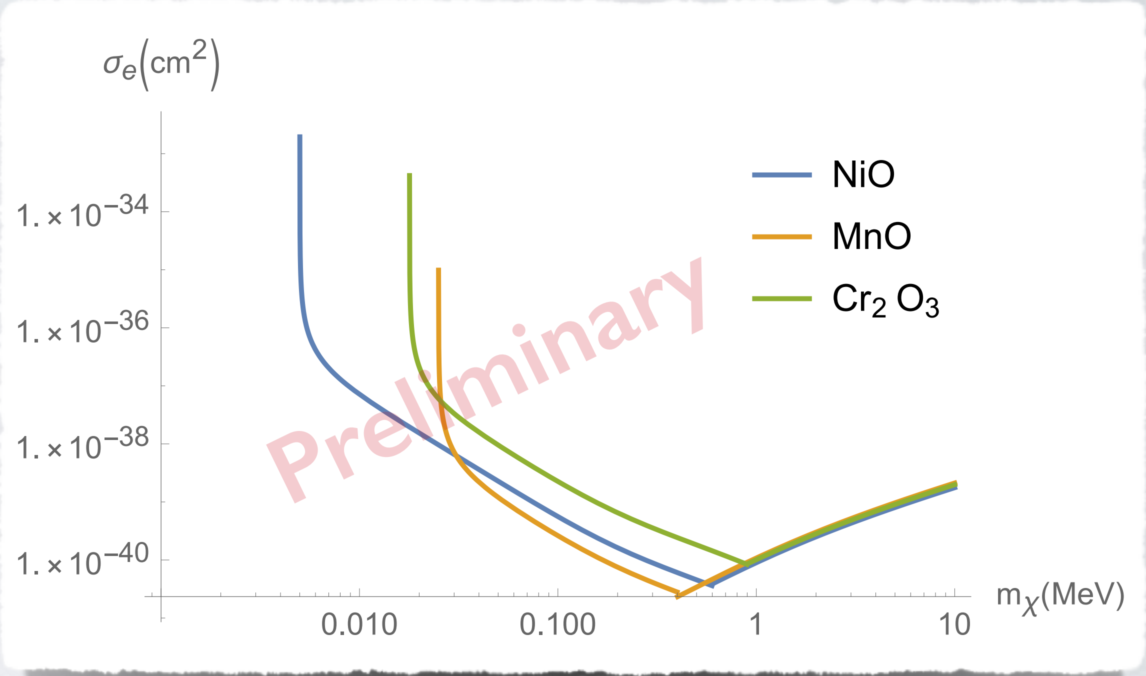


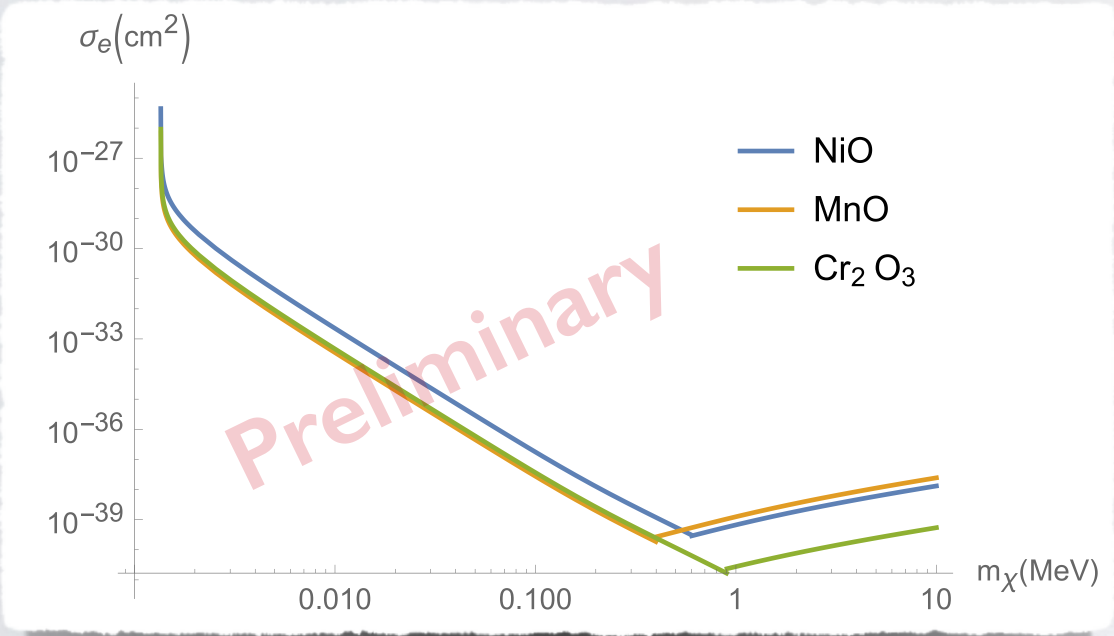
[Caputo, **AE**, Piccinini, Polosa, Rossi — PRD 2021, 2012.01432]

ANTI-FERROMAGNETS

- Identified the optimal candidate → NiO has $v_m \simeq v_\chi$ → can probe down to $\mathcal{O}$(keV) masses with single magnon

- The EFT makes it possible to also compute the 2-magnon rate → push all anti-ferromagnets to $\mathcal{O}$(keV)





[**AE**, Pavaskar — to appear]

OUTLOOK

- The search for sub-GeV dark matter requires new ideas
- For light dark matter one must delve in the condensed matter world
- Many problems can be made simple by the use of EFTs
- **Migdal effect:** push the sensitivity of present day experiments to $\mathcal{O}(\text{MeV})$ masses
- **^{4}He and anti-ferromagnets:** using collective excitations can probe spin-indep. and spin-dep. interactions down to $\mathcal{O}(\text{keV})$

Thanks for your attention!