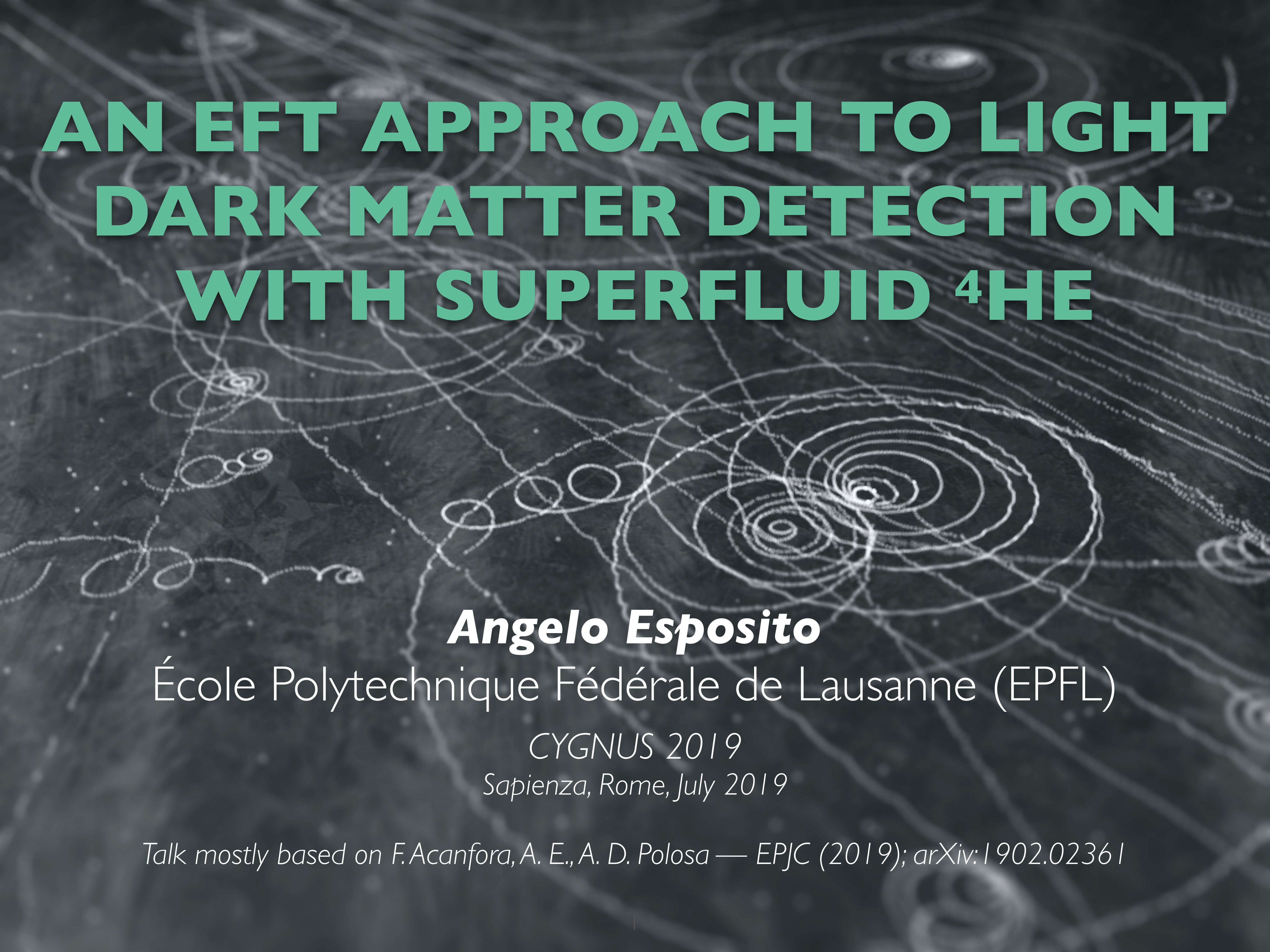

AN EFT APPROACH TO LIGHT DARK MATTER DETECTION WITH SUPERFLUID ^{4}HE

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Talk mostly based on F. Acanfora, A. E., A. D. Polosa — EPJC (2019); arXiv:1902.02361

OUTLINE

- Introduction and motivation
- Relativistic EFT for superfluids
- The dark matter - phonon interaction
- Results
- Conclusions and future plans

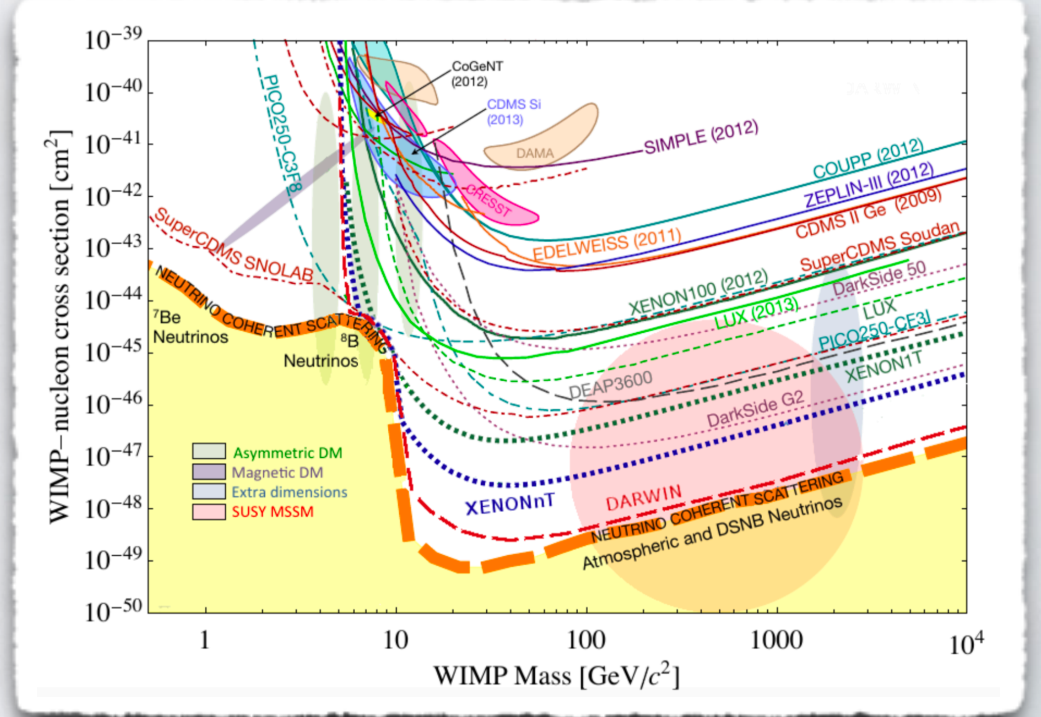
INTRO

Why light dark matter?

- Only a small fraction of the matter in the Universe is visible ⟶ most of the matter that interacts gravitationally is dark
- If interpreted as new invisible particles, this is one of the strongest evidences for physics beyond the Standard Model
- Great experimental effort has been devoted to the search for WIMPS

$$\begin{cases} m_{WIMP} \sim 100\ \text{GeV} \\ \sigma_{WIMP} \sim \text{electroweak} \end{cases}$$

- No positive results so far!
- What about lighter dark matter? ⟶ The mass region below 1 GeV is essentially unexplored



INTRO

Why helium-4?

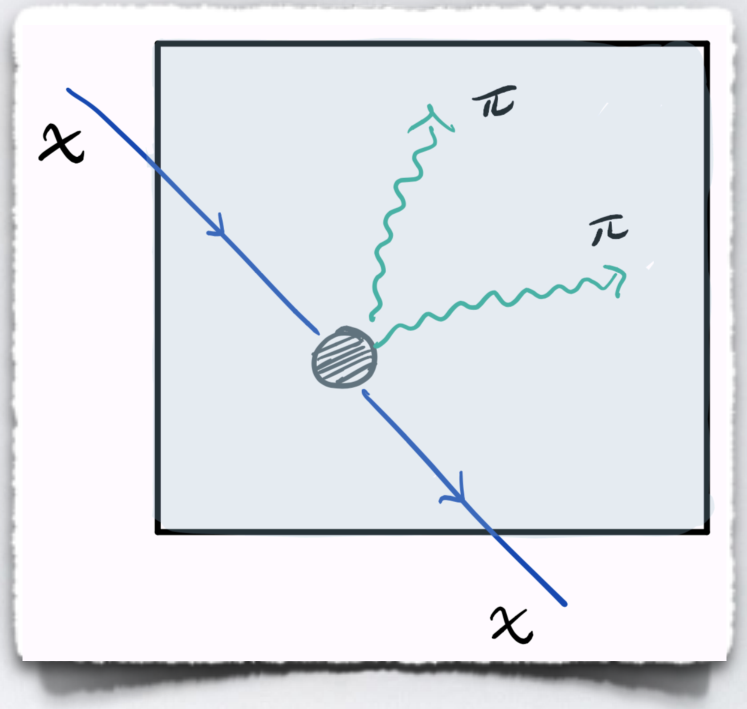
- To look for lighter dark matter requires new materials and detectors ⟶ growing field with lots of ideas (superconductors, carbon nanotube, graphene, …)

  `[for a review see e.g. Dark Sector 2016 – 1608.08632]`

- A promising proposal is that of employing **superfluid helium-4**:

  1. Light nucleus ⟶ large energy released to the material
  2. Collective excitations are gapless
  3. Cheap and pure against radioactive decay
  4. Almost no electronic excitations

- A processes where a dark matter emits two collective excitations might release enough energy to be detected!



`[Schutz, Zurek – PRL 2016, 1604.08206;  Knapen, Lin, Zurek – PRD 2017, 1611.06228]`

INTRO

Plan of action

- The standard approach is complicated ⟶ helium-4 is strongly coupled ⟶ to model its microscopic interactions with dark matter is hard

- The new **relativistic EFT approach** presents some advantages:
  1. Expresses the problem in a quantum field theory language ⟶ more transparent for a particle physics problem + allows to compute angular distributions easily
  2. EFT couplings are taken from data ⟶ no need for models or approximations
  3. Only based on symmetries ⟶ extendible to other models of dark matter

- Our *plan of action*:
  1. Write the most general low-energy action for the phonon and its interaction with the dark matter particle
  2. Determine the effective couplings with a matching procedure
  3. Compute total rates and angular distributions

EFT FOR SUPERFLUIDS

Spontaneous symmetry breaking

- All states of matter break <u>spontaneously</u> at least part of the fundamental Poincaré group

- The associated Goldstones are (often) gapless ⟶ collective excitations of the medium

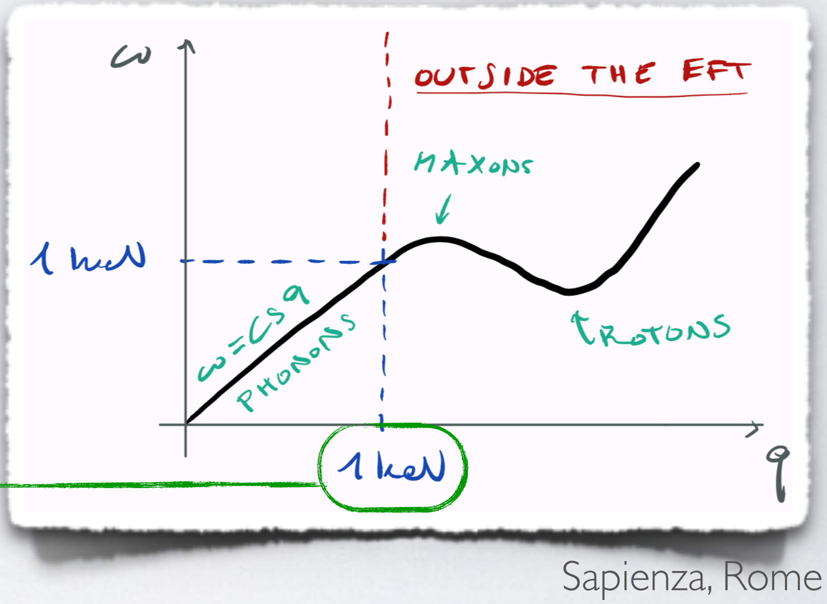
  `[see e.g. Lange – PRL 1965; Leutweyler – HPA 1970, hep-ph/9609466; Nicolis, Penco, Piazza, Rattazzi – JHEP 2015, 1501.03845]`

- In this language, an s-wave superfluid is characterized by

  1. A *U(1)* symmetry (particle number) with charge Q that is at finite density
  2. Spontaneously breaks boost invariance (as any state of matter)
  3. Spontaneously breaks the charge Q and time-translations H but preserves $\bar{H} = H - \underset{\text{chemical potential}}{\boxed{\mu}} Q$

  `[see e.g. Son – hep-ph/0204199;  Nicolis – 1108.2513]`

- This pattern is associated to a single Goldstone boson ⟶ the **superfluid phonon**



cutoff of the EFT!

EFT FOR SUPERFLUIDS

Phonon's effective action

- The simplest way to implement the previous pattern is via a single real scalar field:

$$\psi(x) \to \psi(x) + a \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

shifts under the *U(1)*

breaks boosts, time-transl. and the *U(1)*
but preserves $\bar{H} = H - \mu Q$

fluctuations around equilibrium:
Goldstone = phonon

- The most general low-energy action for the phonon must be invariant under all symmetries

$$S = \int d^4x \, P(X) \qquad \text{with:} \qquad \boxed{X = \sqrt{-\partial_\mu \psi \partial^\mu \psi}}$$

pressure

local chemical potential

- Expanding in small fluctuations

sound speed

effective couplings

$$S = \int d^4x \left[\frac{1}{2}\dot{\pi}^2 - \frac{c_s^2}{2}\left(\vec{\nabla}\pi\right)^2 + \lambda_3 \sqrt{\frac{\mu}{\bar{n}}} c_s \dot{\pi} \left(\vec{\nabla}\pi\right)^2 + \lambda_3' \sqrt{\frac{\mu}{\bar{n}}} c_s \dot{\pi}^3 + \dots \right]$$

equilibrium number density

- All couplings are given only by the superfluid's equation of state

$$c_s^2 = \frac{P'}{\mu P''}\,; \quad \bar{n} = P'\,; \quad \lambda_3 = \frac{c_s^2 - 1}{2\mu}\,; \quad \lambda_3' = \frac{1}{6}\frac{\mu c_s^2}{\bar{n}} P'''$$

DARK MATTER-PHONON INTERACTION

Effective action

- Let us focus on a specific model
- We consider a scalar dark matter, charged under a new $U_d(1)$, and interacting with the Standard Model via a heavy scalar mediator

$$S_{DM} = -\int d^4x \left[\overbrace{\boxed{|\partial\chi|^2 + m_\chi^2 |\chi|^2}}^{\text{dark matter candidate}} + \underbrace{\boxed{\frac{1}{2}(\partial\phi)^2 + \frac{m_\phi^2}{2}\phi^2}}_{\text{heavy mediator}} + \overbrace{\boxed{g_\chi m_\chi \phi |\chi|^2}}^{\text{Yukawa}} + \underbrace{\boxed{g_{He}\phi\, n}}_{\text{Coupling between mediator and helium density}} \right]$$

- Integrating out the mediator at tree level shifts the mass of the dark matter

$$S_{DM} = -\int d^4x \left[|\partial\chi|^2 + m^2(X) |\chi|^2 \right]$$

- The effective in-medium mass is a function of the local density

$$m^2(X) \simeq m_\chi^2 - g_\chi g_{He} \frac{m_\chi}{m_\phi^2} \boxed{n(X)} \longrightarrow \text{contains the phonon field!}$$

DARK MATTER-PHONON INTERACTION

Effective action

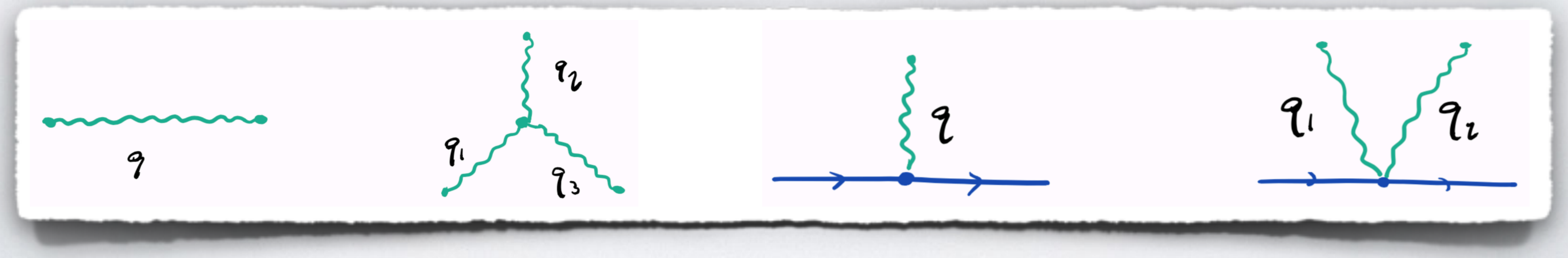
- Expanding again in small fluctuations we get the dark matter-phonon interactions

$$S_{DM} \supset \int d^4x \left[g_\chi g_{He} \frac{m_\chi}{m_\phi^2} \boxed{\frac{d\bar{n}}{d\mu}\sqrt{\frac{\mu}{\bar{n}}} c_s} \dot{\pi} - \frac{1}{2} g_\chi g_{He} \boxed{\frac{d\bar{n}}{d\mu}\frac{c_s^2}{\bar{n}}} \left(\vec{\nabla}\pi\right)^2 + \frac{1}{2} g_\chi g_{He} \boxed{\frac{d^2\bar{n}}{d\mu^2}\frac{\mu c_s^2}{\bar{n}}} \dot{\pi}^2 \right] |\chi|^2$$

- Again the effective couplings only depend on the helium-4 equation of state ⟶ already measured experimentally

[Abraham, Eckstein, Ketterson, Kuchnir, Roach — PRA 1970]

- Putting all together we get the Feynman rules for the following diagrams



RESULTS

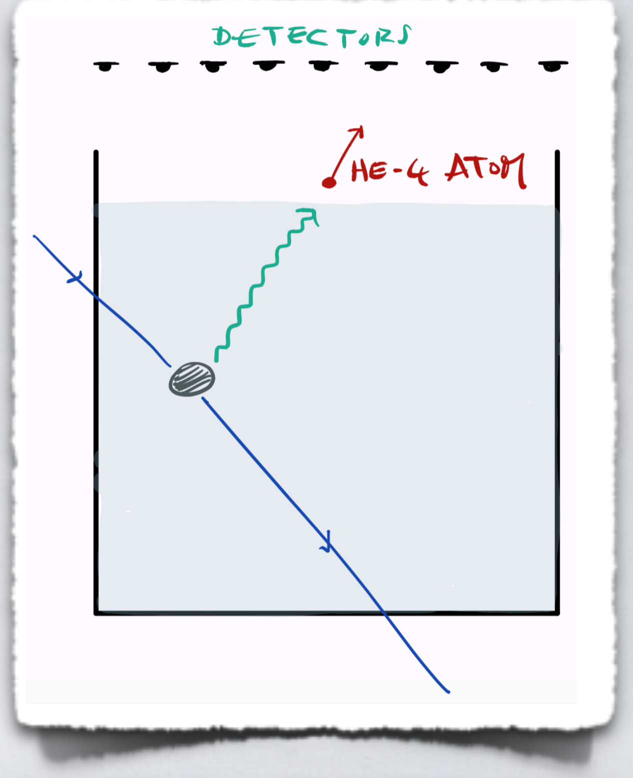
How do we see phonons?

- How would one detect phonons experimentally?

- **Quantum evaporation:**

  Phonon travels up to the surface of helium-4 → if it has enough energy ($\omega \geq 0.62$ meV) it can eject an atom from the surface → the atom can then be detected

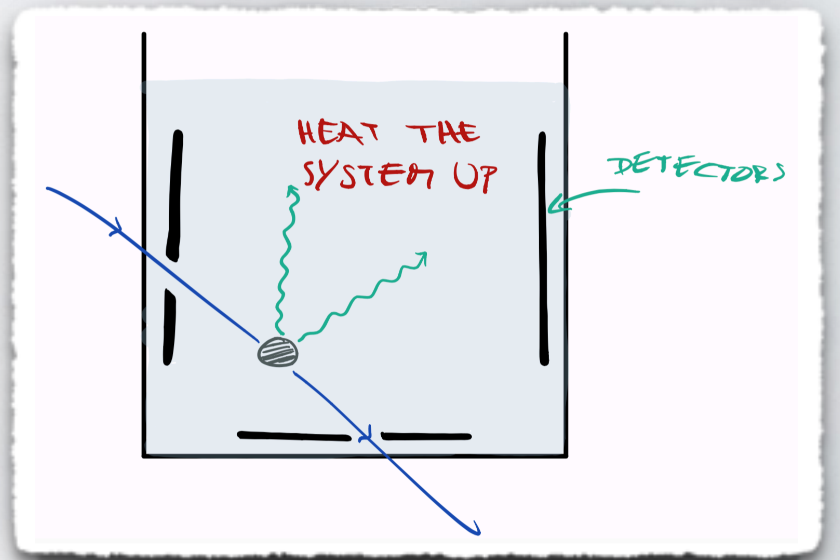
  [Hertel, Biekert, Lin, Velan, McKinsey — 1810.06283; Maris, Seidel, Stein — PRL 2017, 1706.00117]



- **Energy released:**

  Phonons heat the system up → if the energy released is enough ($\omega_{tot} \geq 1$ meV) the change in temperature is appreciable → detect with bolometers (e.g. TES)

  [Hertel, Biekert, Lin, Velan, McKinsey — 1810.06283]



RESULTS

One-phonon

- The simplest process one can consider is the emission of a single phonon
- This process has two important features:

1. Leading order in small phonon's coupling ⟶ dominant when allowed
2. Since $v_\chi \simeq 10^{-3} \gg c_s \simeq 10^{-6}$ the emission angle is fixed (Cherenkov) ⟶ possible directionality!

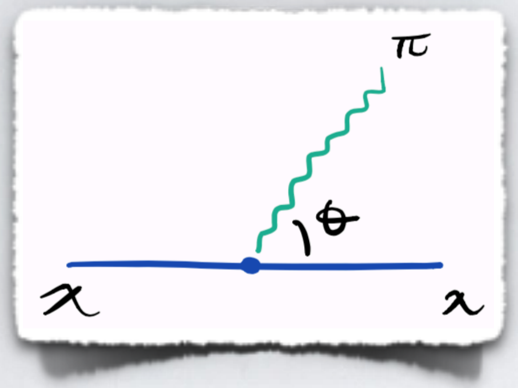
- However, it is relevant only in a limited kinematical regime:

1. Max phonon's energy is $\omega_{max} = 2c_s m_\chi v_\chi \simeq 10^{-9} m_\chi$ ⟶ in order for the phonon to be detected it has to be $\omega \geq 0.62$ meV ⟶ only effective for $m_\chi \gtrsim 1$ MeV
2. Phonons never have energies larger than 1 meV (cutoff) ⟶ can only be detected via quantum evaporation

RESULTS

One-phonon

- Given the Feynman rules the rate is given by



$$\frac{d\Gamma}{d\Omega d\omega} = \frac{g_\chi^2 g_{He}^2}{m_\phi^4}\left(\frac{d\bar{n}}{d\mu}\right)^2 \frac{m_{He}\omega^2}{32\pi^2 v_\chi \bar{n}}\delta\left(\cos\theta - \frac{c_s}{v_\chi} - \frac{q}{2m_\chi v_\chi}\right)$$

- The emission angle is fixed to be

$$\cos\theta = \frac{c_s}{v_\chi} + \frac{q}{2m_\chi v_\chi} \simeq 10^{-3} \quad \Longrightarrow \quad \theta \simeq 90^\circ$$

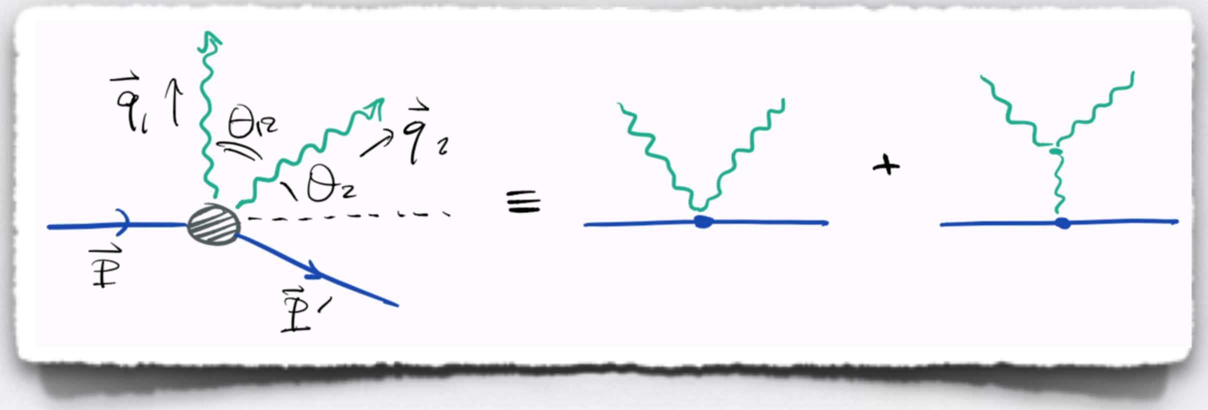
- The total rate can then be found as a function of the dark matter - proton cross section

$$\Gamma = 4\left(\frac{m_{He}+m_\chi}{m_{He}m_\chi}\right)^2 \sigma_p \frac{\bar{n}}{m_{He}c_s^4 v_\chi}\frac{\omega_{max}^3 - \omega_{min}^3}{3}$$

RESULTS

Two-phonons

- Another interesting observable is the **emission of two phonons**
- This process is suppressed with respect to the one phonon emission but:
  1. It is effective also for dark matter as light as 1 keV
  2. It should be detectable via both quantum evaporation and energy deposit
- One technicality: Lorentz symmetry is broken ⟶ cannot perform the calculation in the center of mass



Integration region implementing:
1) energy-momentum conservation;
2) experimental cuts;
3) applicability of EFT

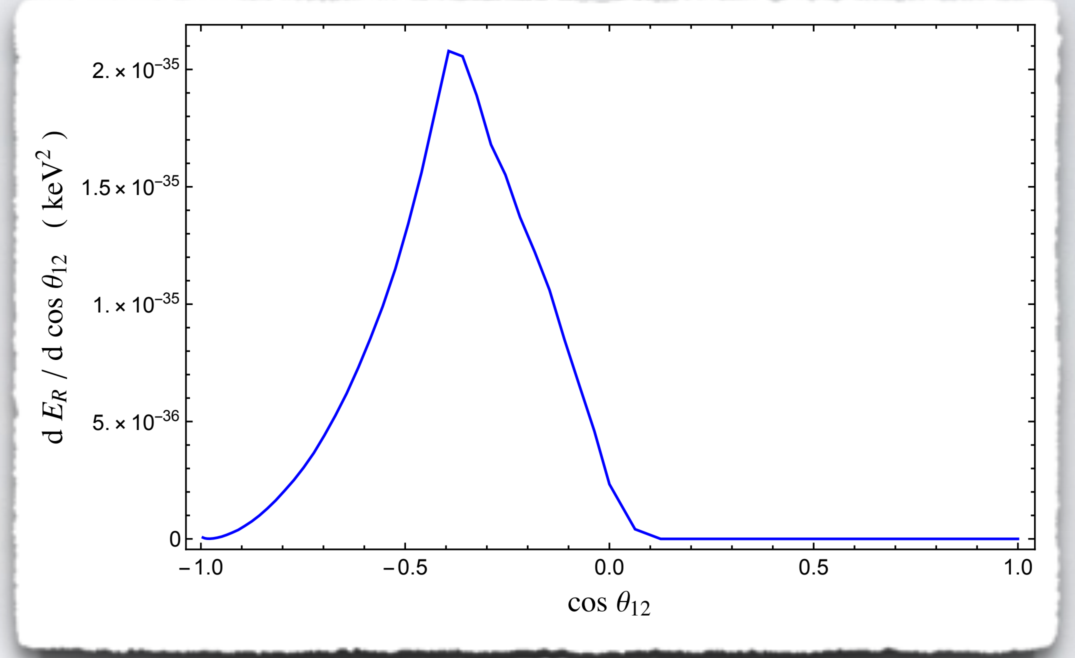
$$\Gamma = \frac{1}{8(2\pi)^4 c_s^5 m_\chi} \int_{\boxed{\mathscr{R}}} d\theta_{12} d\theta_2 d\omega_1 d\omega_2 \frac{\omega_2}{P} \frac{|\mathscr{M}|^2}{\sqrt{1-\boxed{\mathscr{A}(\theta_{12},\theta_2,\omega_1,\omega_2)}^2}} \longrightarrow \mathscr{A} = \cos(\phi_{12}-\phi_2)$$

RESULTS

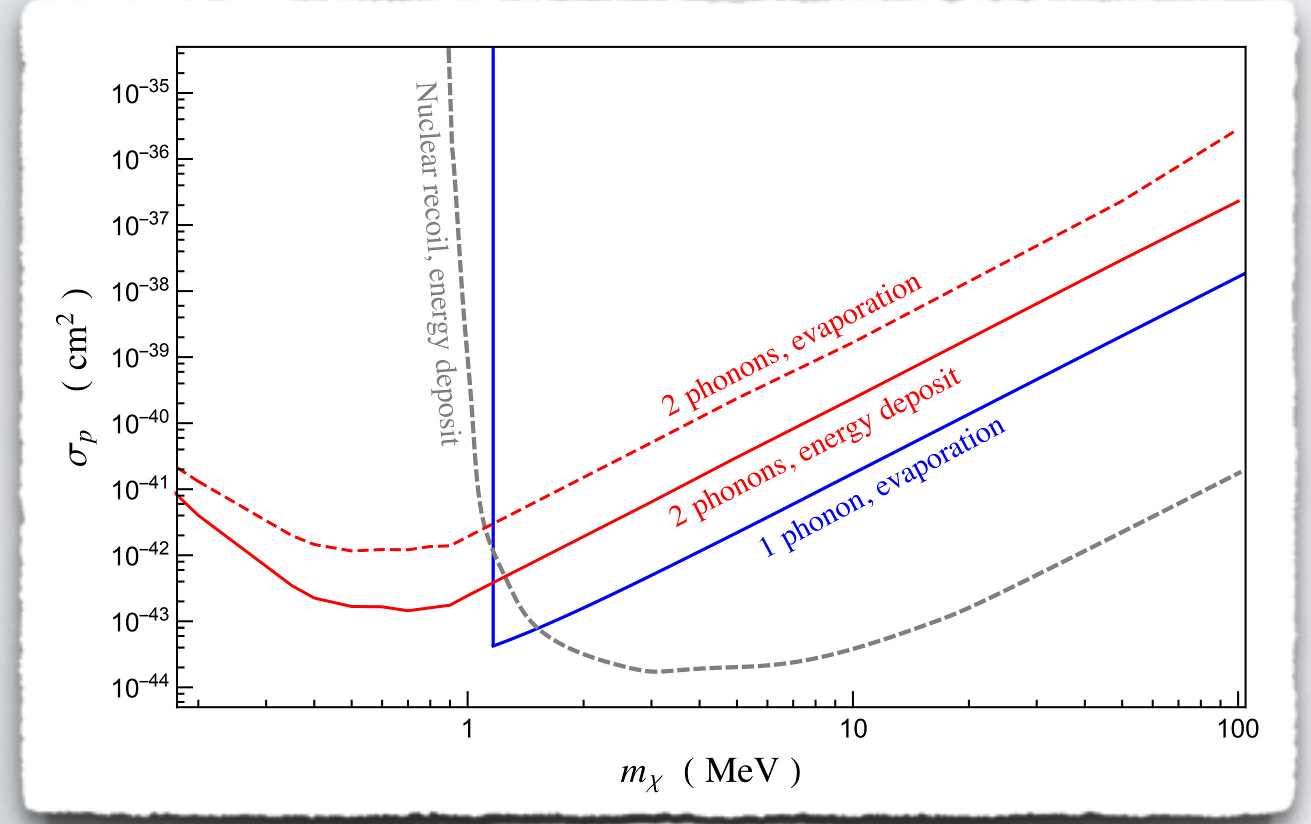
Distributions and projected bounds

- We have all the ingredients to compute angular distributions and exclusion plots

Most of the dark matter energy is released when the two phonons are almost back-to-back



95% C.L. for 1 kg of helium for 1 year exposure



The exclusion region is very promising.

However… disagreement between different theoretical approaches in the small mass region!

CONCLUSION AND FUTURE PLANS

- The EFT approach to the description of the coupling between dark matter and collective excitations can present some advantages over standard techniques
- The possibility of detecting sub-GeV dark matter using superfluid helium-4 seems promising. The projected bounds are promising even for 1 year exposure and 1 kg of material
- Future plans:

1. Compare the EFT with standard approaches. Small mass discrepancy?
2. Try different models of dark matter. E.g. dark photon mediator, work in progress with also Emma Geoffray (EPFL)
3. Possible other materials?
4. Many others…

THANK YOU!