SUB-GEV DARK MATTER IN SUPERFLUID HE-4: AN EFFECTIVE THEORY APPROACH

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<u>Talk mostly based on:</u>

Acanfora, AE, Polosa — EPJC (2019); arXiv:1902.02361

Caputo, AE, Polosa — arXiv:1907.10635

Caputo, AE, Geoffray, Polosa, Sun — to appear

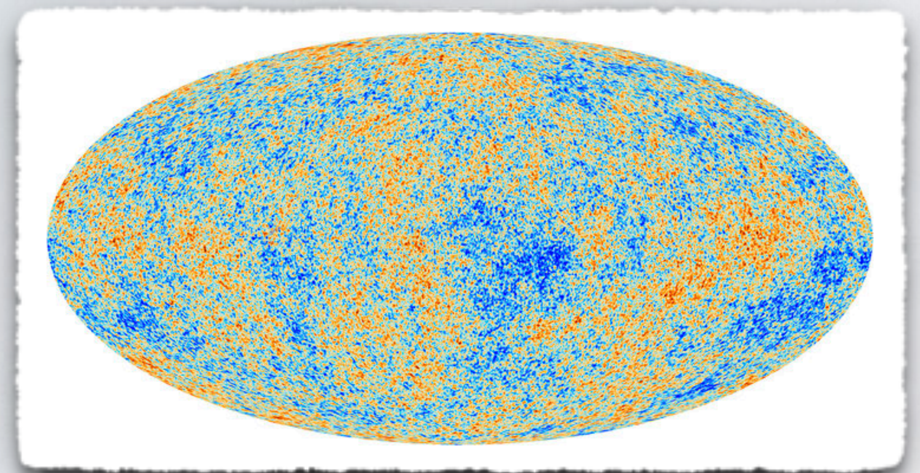
OUTLINE

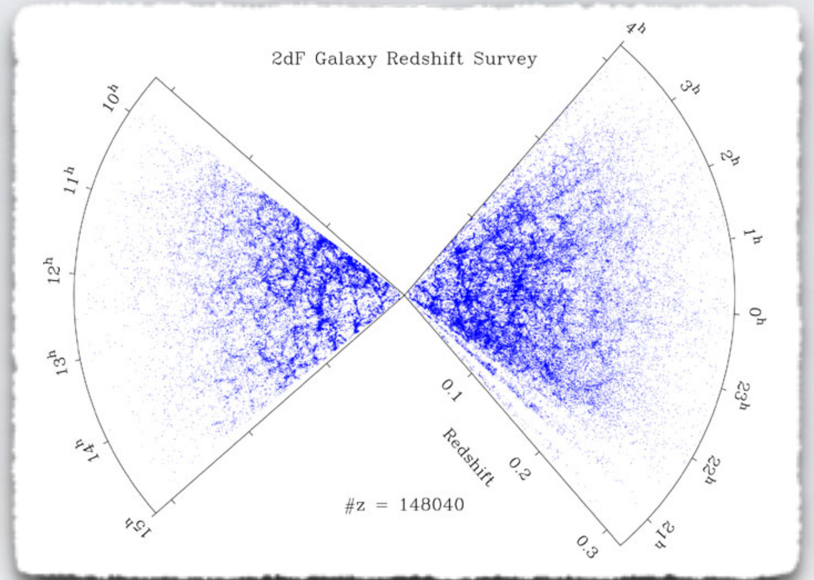
- Introduction and motivation
- Brief intro to the relativistic EFT for superfluids
- Dark matter with a scalar mediator
- Dark matter with vector mediator
- Conclusions and future plans

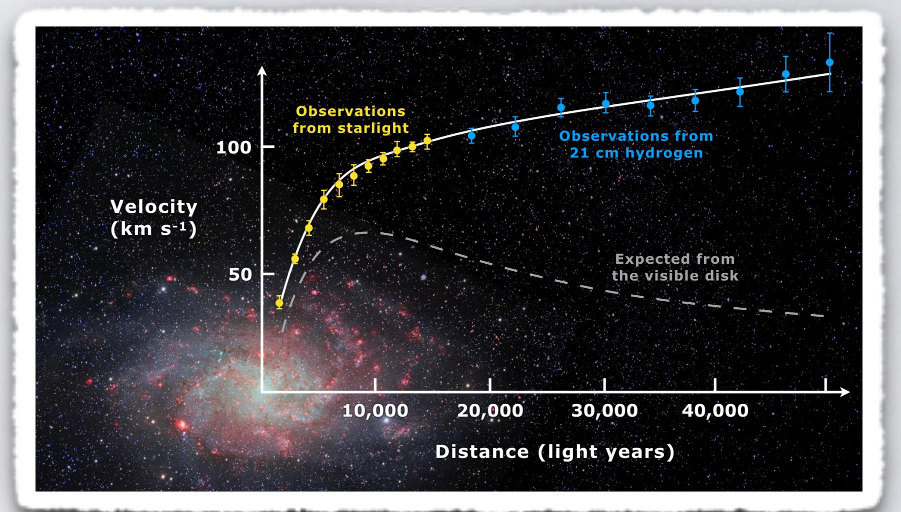
INTRO

Dark matter

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







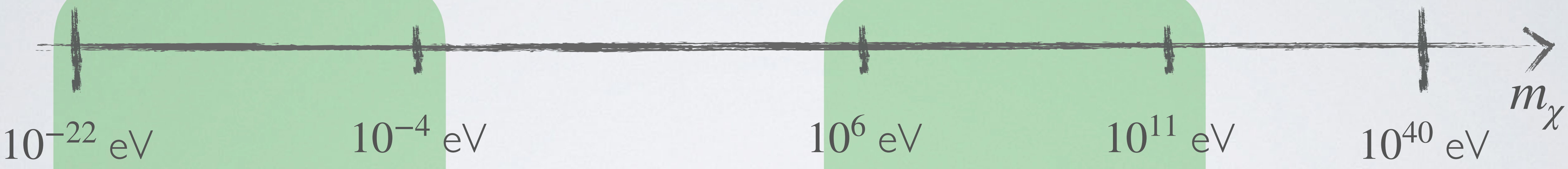
- If interpreted as a new kind of particle, the presence of dark matter might be one of the strongest evidences for physics beyond the Standard Model
- Earth-based experiments have to deal with a huge possible mass range
- Detection techniques vary widely depending on the dark matter mass

INTRO

Dark matter

too light to explain halo structure

less than 1 dark matter per year through Earth



Dark matter is light enough to be treated as a classical field

ADMX, CASPEr, atomic clocks, LIGO, EDMs, …

What about this region?

Dark matter can deposit energy via scattering off nuclei and electrons

XENON, LUX, PANDAX, CDMS, DarkSide, …

- In the sub-MeV region things are more complicated $\longrightarrow$ the dark matter is too light to deposit energy via recoil but too heavy to take advantage of resonant phenomena

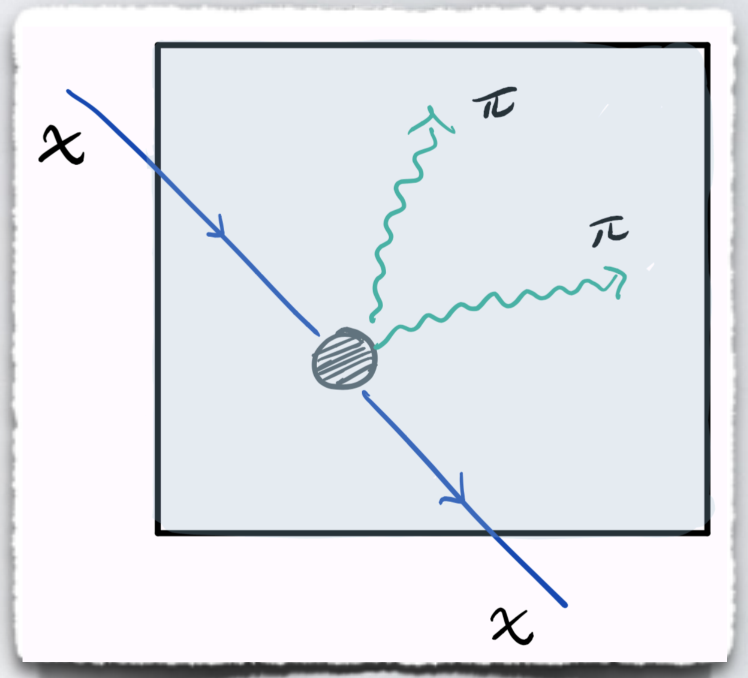
INTRO

Why helium-4?

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

[see e.g. Hochberg, Zhao, Zurek — PRL 2016, 1504.07237; 1712.06598; Bunting, Gratta, Melia, Rajendran — PRD 2017, 1701.06566; Cavoto, Luchetta, Polosa — PLB 2018, 1706.02487]

- A promising proposal is to of employ **superfluid He-4**:
  1. Light nucleus ⟶ large energy released to the material
  2. Collective excitations are gapless
  3. Cheap and pure against radioactive decay



- The emission of collective excitations by the dark matter might release enough energy to be detected!

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

INTRO

A different approach

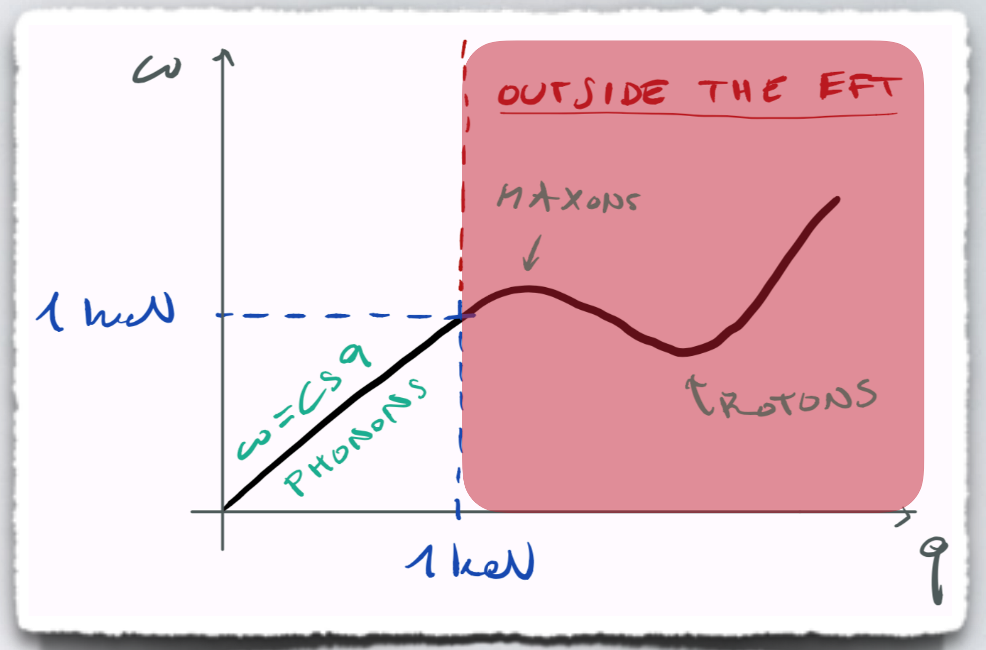
- Standard approach is complicated ⟶ He-4 is strongly coupled ⟶ to describe its interaction with dark matter is hard

- Alternative way: **relativistic EFT for superfluids**

- Advantages for the problem at hand:
  1. It formulates the problem in a QFT language ⟶ easier to deal with in a particle physics context + amenable to compute angular distributions
  2. All couplings are determined from the equation of state ⟶ no free parameters + no need for model or approximations
  3. Extendible to other models of dark matter

EFT FOR SUPERFLUIDS

A quick introduction



- The superfluid phonon is the Goldstone boson for the spontaneous breaking of spacetime and internal symmetries

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

- Other excitations cannot be described by the EFT

- Every state of matter breaks spontaneously at least part of the Poincaré group of fundamental interactions

- A superfluid is a system that:
  1. Has a $U(1)$ symmetry (conserved particle number), whose charge Q is at finite density
  2. Spontaneously breaks boosts, times translations and the $U(1)$
  3. Preserves a combination of the last two: $\bar{H} = H - \mu Q$

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

THE DM - PHONON INTERACTION

The effective action

- The symmetry breaking pattern of He-4 completely determines the phonon self-interactions and its interaction with dark matter
- Our example: scalar dark matter **interacts with He-4 density** via a term given by $\mathcal{L}_{int} = G_\chi m_\chi |\chi|^2 n(x)$
- This uniquely fixes the dark matter - phonon action:

speed of sound

$$S_{eff} = \int d^4x \left[\frac{1}{2}\dot{\pi}^2 - \frac{c_s^2}{2}(\vec{\nabla}\pi)^2 - |\partial\chi|^2 - m_\chi^2|\chi|^2 + \lambda_3\sqrt{\frac{m_{He}}{\bar{n}}}\boxed{c_s}\,\dot{\pi}(\vec{\nabla}\pi)^2 + \lambda_3'\sqrt{\frac{m_{He}}{\boxed{\bar{n}}}}c_s\,\dot{\pi}^3 \right.$$
$$\left. - \left(g_1\sqrt{\frac{m_{He}}{\bar{n}}}c_s\,\dot{\pi} - \frac{g_1}{2}\frac{c_s^2}{\bar{n}}(\vec{\nabla}\pi)^2 + \frac{g_2}{2}\frac{m_{He}c_s^2}{\bar{n}}\dot{\pi}^2 \right)|\chi|^2 \right]$$

number density

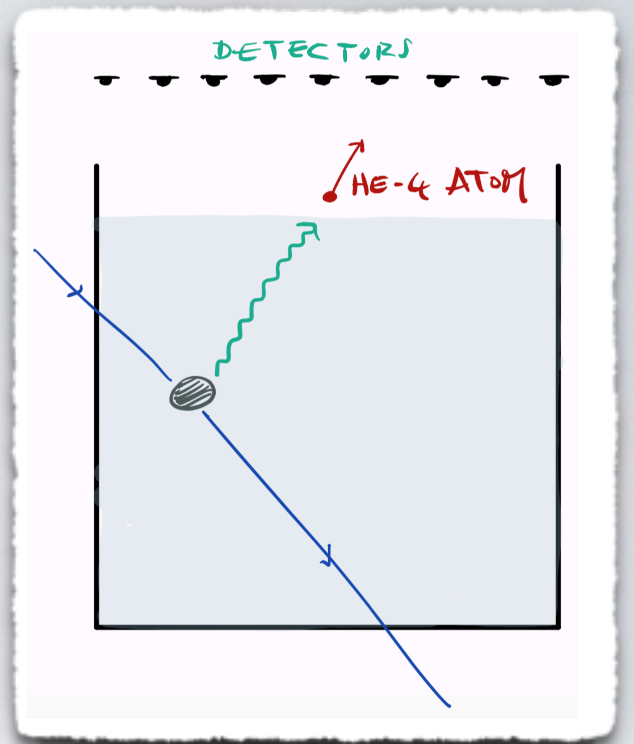
- All couplings are determined by the He-4 equation of state $\longrightarrow$ no free parameters

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

$$\lambda_3 = -\frac{1}{2m_{He}}; \quad \lambda_3' = \frac{1}{6m_{He}c_s^2} - \frac{\bar{n}}{3c_s}\frac{dc_s}{dP}; \quad g_1 = -G_\chi m_\chi \frac{\bar{n}}{m_{He}c_s^2}; \quad g_2 = -G_\chi m_\chi \frac{\bar{n}}{m_{He}c_s^2}\left(\frac{1}{m_{He}c_s^2} - \frac{2\bar{n}}{c_s}\frac{dc_s}{dP}\right)$$

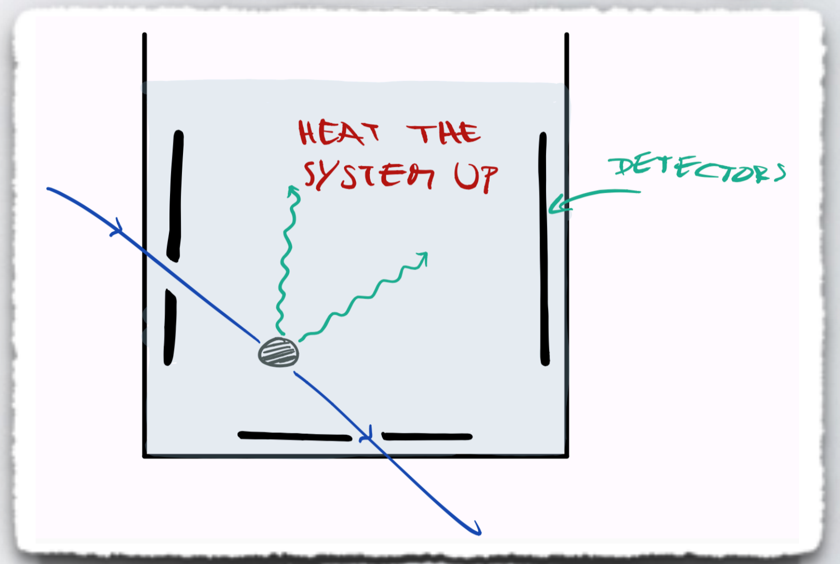
PHONON(S) EMISSION

How do we see phonons?



- **Quantum evaporation:**

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



- **Energy released:**

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

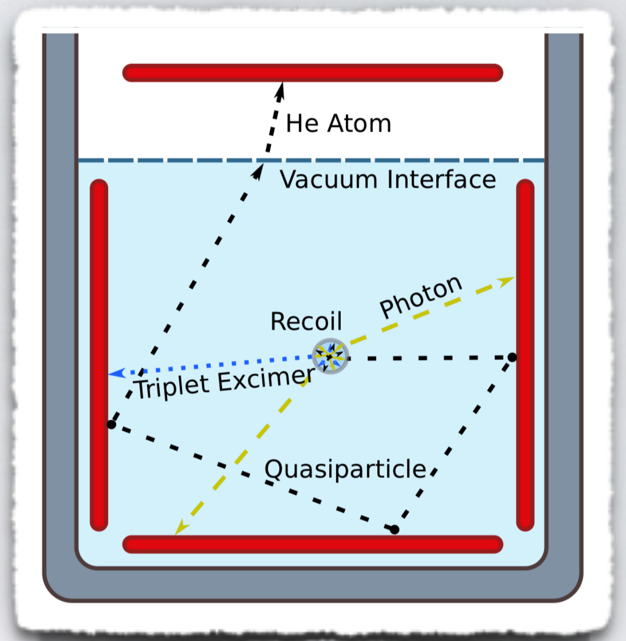
[see e.g. Hertel, Biekert, Lin, Velan, McKinsey — 1810.06283; Maris, Seidel, Stein — PRL 2017, 1706.00117]

PHONON(S) EMISSION

How do we see phonons?

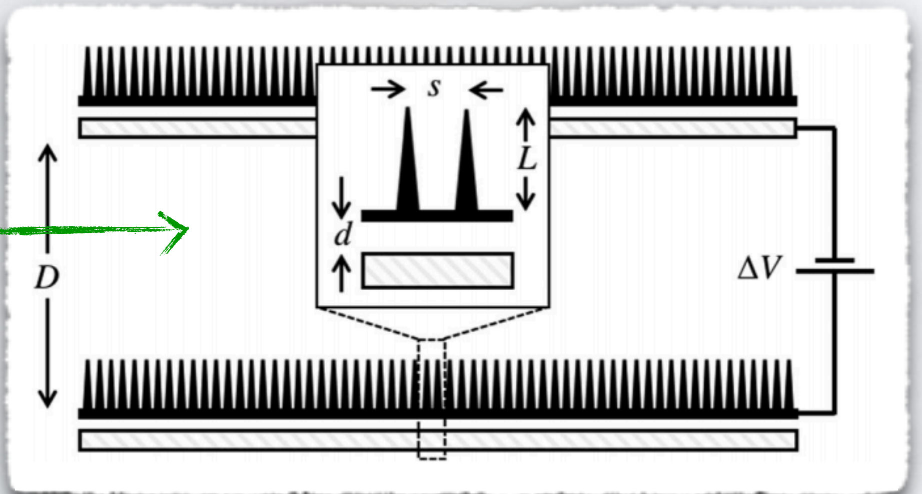
- The are several R&D efforts going on
  1. He-4 has several different signals that can be used to distinguish different events

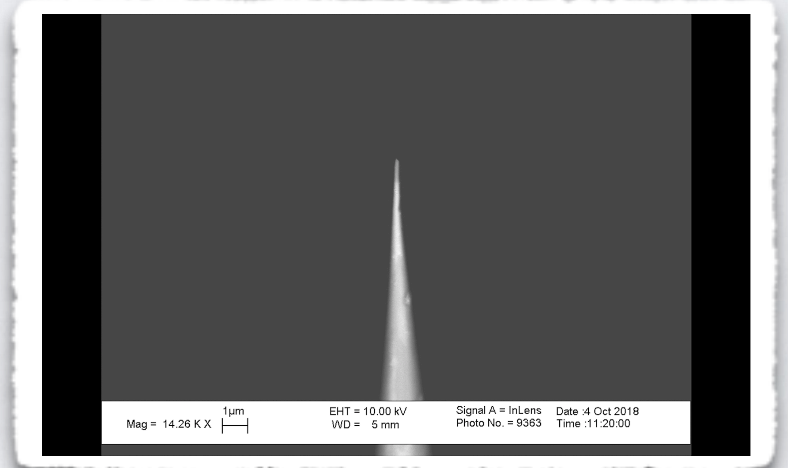
     [Hertel, Biekert, Lin, Velan, McKinsey — 1810.06283]



  2. Single evaporated atoms could be detected using strong field ionization obtained with an array of very small tips [Maris, Seidel, Stein — PRL 2017, 1706.00117]

Evaporated He atom





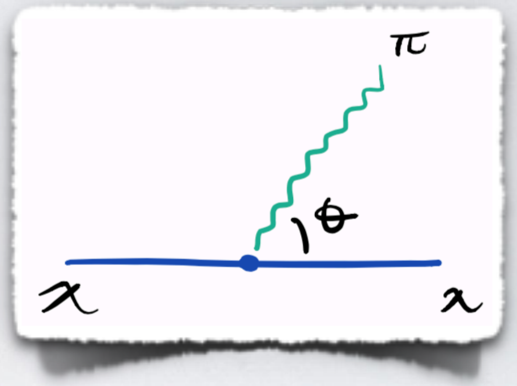
[courtesy of David Osterman, Brown U.]

PHONON(S) EMISSION

One-phonon

- The simplest process one can consider is the **emission of a single phonon**
- When allowed it is dominant and directional ⟶ emission angle is fixed by kinematics (Cherenkov)

$$v_\chi \gg c_s \quad \Longrightarrow \quad \cos\theta = \frac{c_s}{v_\chi} + \frac{q}{2m_\chi v_\chi} \simeq 60^\circ - 70^\circ$$

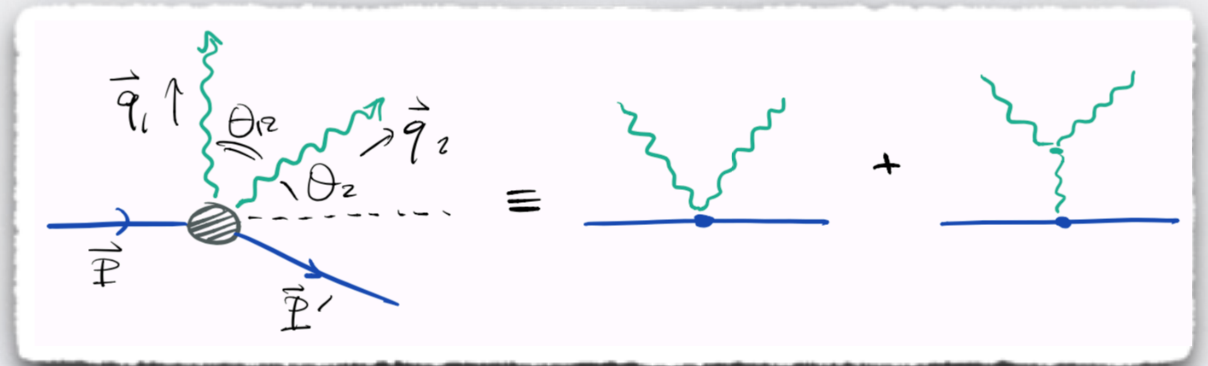


- Phonons can only be detected if they have energy $\omega \geq 0.62$ meV ⟶ this process is only effective for $m_\chi \gtrsim 1$ MeV
- Phonons have at most $\omega \leq 1$ meV ⟶ can only be detected via quantum evaporation

PHONON(S) EMISSION

Two-phonons

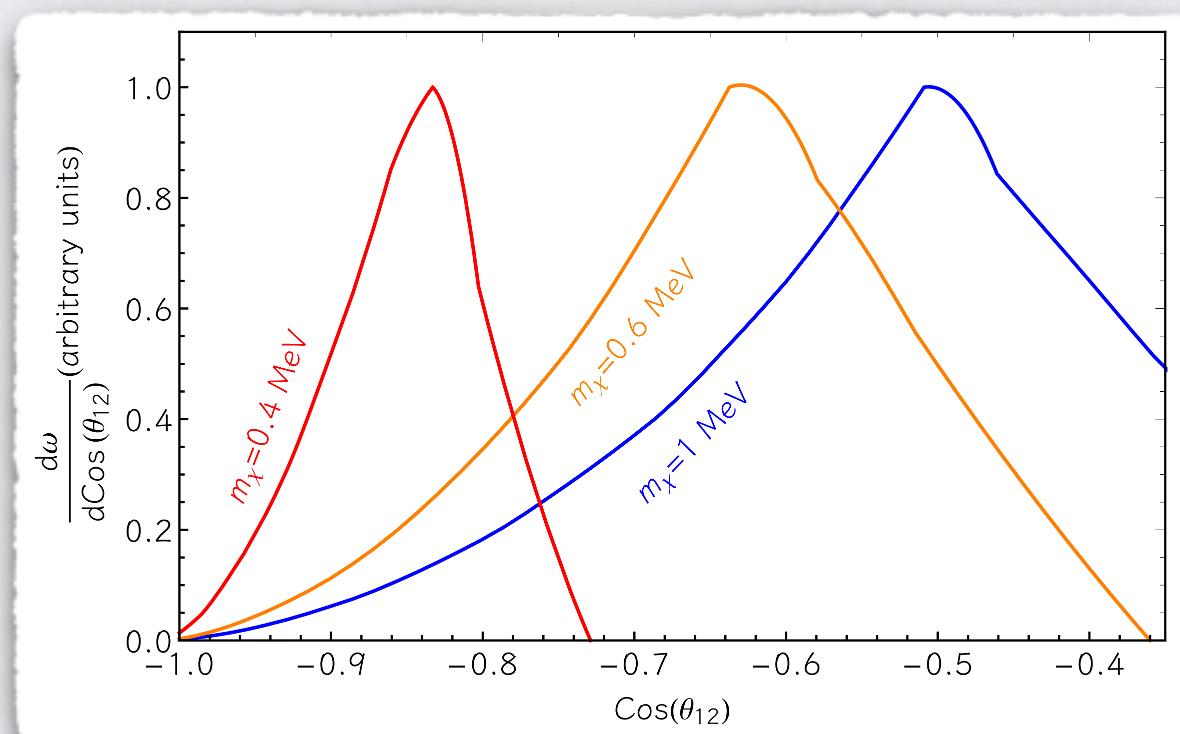
- Another interesting observable is the **emission of two phonons**
- This process is suppressed with respect to the one phonon emission but:
  1. It is effective also for dark matter as light as 1 keV
  2. It should be detectable via both quantum evaporation and energy deposit
- The amplitude gets a contribution from two diagrams of the EFT



PHONON(S) EMISSION

Two-phonons

- The maximum energy released to the system is when the two phonons are almost back-to-back ($\mathbf{q}_1 \simeq -\mathbf{q}_2$)
- Lighter dark matter $\longrightarrow$ the relative angle between phonons gets closer to $180°$
- The angular distribution is strongly dependent on the dark matter mass:



[Caputo, AE, Polosa — arXiv:1907.10635]

PHONON(S) EMISSION

Projected bounds

- Our results match those obtained by Shutz & Zurek and Knapen, Lin & Zurek

↓

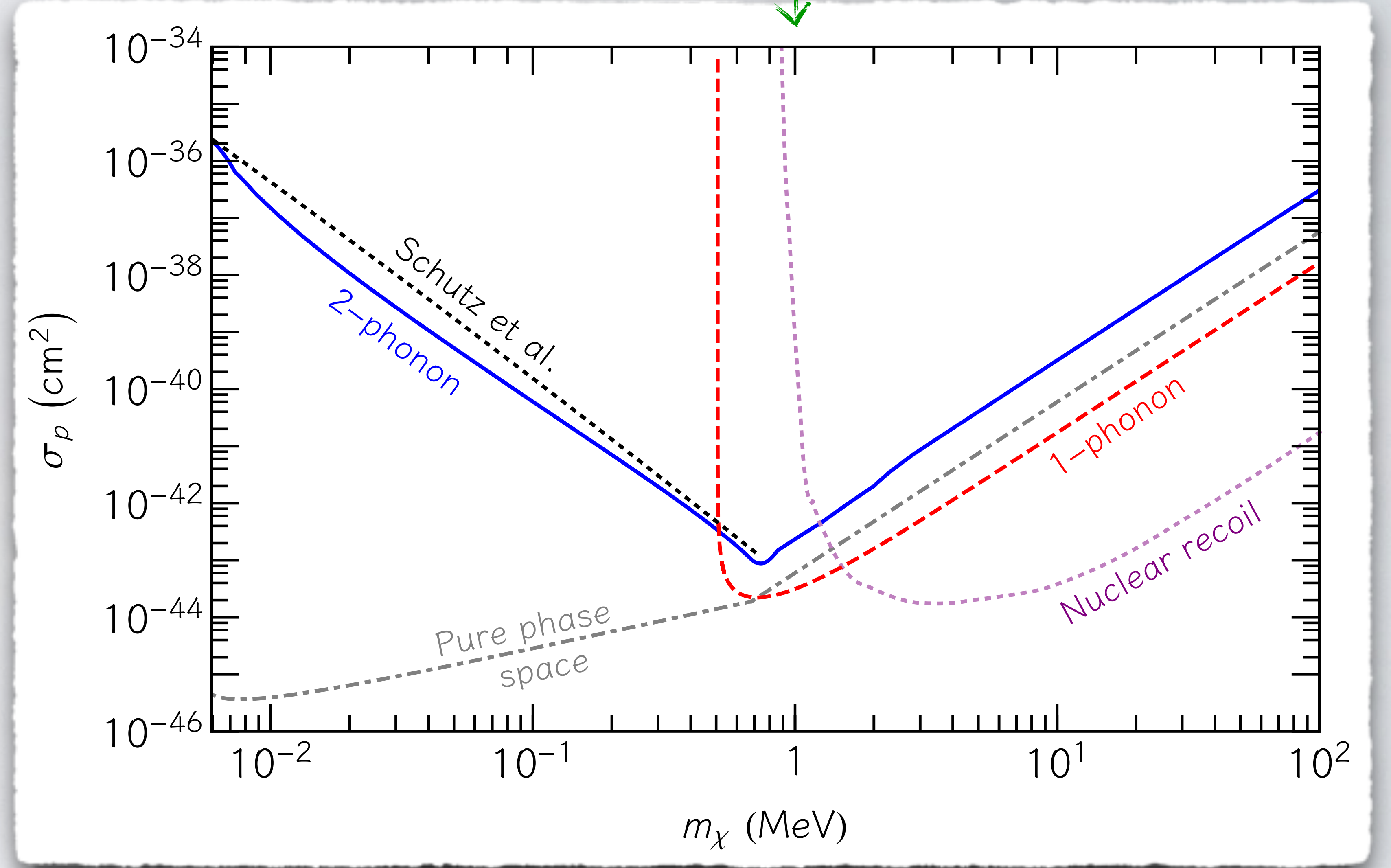
The EFT correctly reproduces the results obtained from neutron scattering on He-4!

+

Most of the rate is due to phonons

Truly unexplored region

Other experiments might be competitive here (see e.g. Essig et al. 1108.5383, 1608.02940, 1907.07682, DarkSide, …)



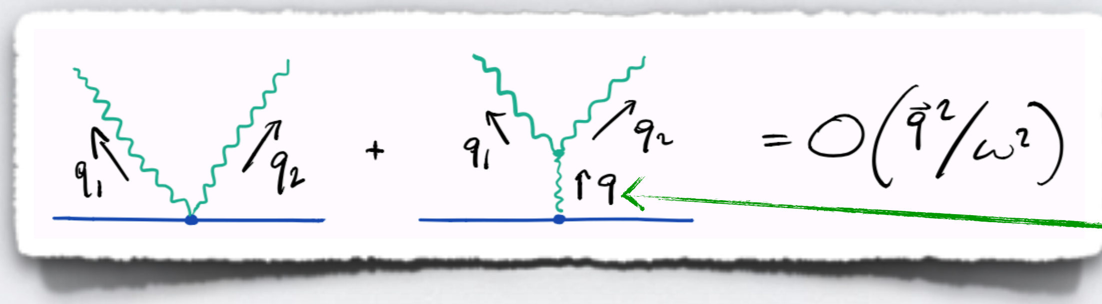
[Caputo, AE, Polosa – arXiv:1907.10635]

- However: huge suppression with respect to pure phase space! Why?

PHONON(S) EMISSION

Small q suppression

- Thanks to the EFT it is easy to understand the reason for the suppression
- For very light masses the dominant configuration is back-to-back $\longrightarrow$ in this limit the two diagrams contributing to the process cancel exactly



Highly off-shell

- At a deeper level, this is a consequence of current conservation for the $U(1)$ symmetry

$$J^\mu(x) = (n(x), \mathbf{j}(x))$$

$$\partial_\mu^{(x)} \langle \mu | T\big(J^\mu(x)\pi(x_1)\pi(x_2)\big) | \mu \rangle = -i\delta^{(4)}(x-x_1)\langle \mu | \pi(x_2) | \mu \rangle - i\delta^{(4)}(x-x_2)\langle \mu | \pi(x_1) | \mu \rangle$$

$$q_\mu \langle \pi(q_1)\pi(q_2) | J^\mu(q) | \mu \rangle = 0 \quad \xrightarrow{\mathbf{q}=0} \quad \boxed{\langle \pi(\omega_1, \mathbf{q}_1)\pi(\omega_1, -\mathbf{q}_1) | n(\omega, \mathbf{q}=0) | \mu \rangle = 0}$$

[similar effect for a phonon in crystals. Any relation? See Cox, Melia, Rajendran — arXiv:1905.05575]

DM - PHONON INTERACTION WITH VECTOR MEDIATOR

The effective action

- Consider a model of fermionic dark matter interacts with the Standard Model via a new massive gauge boson which mixes kinetically with the photon (dark photon)

- Write down the low-energy action for the photon-phonon interaction ⟶ since He-4 is neutral the interaction happens via higher multipoles

- The effective action reads

$$S = -\int d^4x \left[\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{4} V_{\mu\nu}V^{\mu\nu} \underbrace{- \frac{\epsilon}{2} F_{\mu\nu}V^{\mu\nu}}_{\text{Kinetic mixing}} + \frac{m_V^2}{2} V_\mu V^\mu + \underbrace{\bar\chi(i\gamma^\mu\partial_\mu - g\gamma^\mu V_\mu - m_\chi)\chi}_{\text{Dark matter - dark photon coupling}} \right.$$
$$\left. \underbrace{- \frac{a(X)}{2} F_{\mu\nu}F^{\mu\nu} - \frac{b(X)}{2} F^{\mu\sigma}F^\nu{}_\sigma \partial_\mu\psi\partial_\nu\psi}_{\text{Photon - phonon coupling}} \right]$$

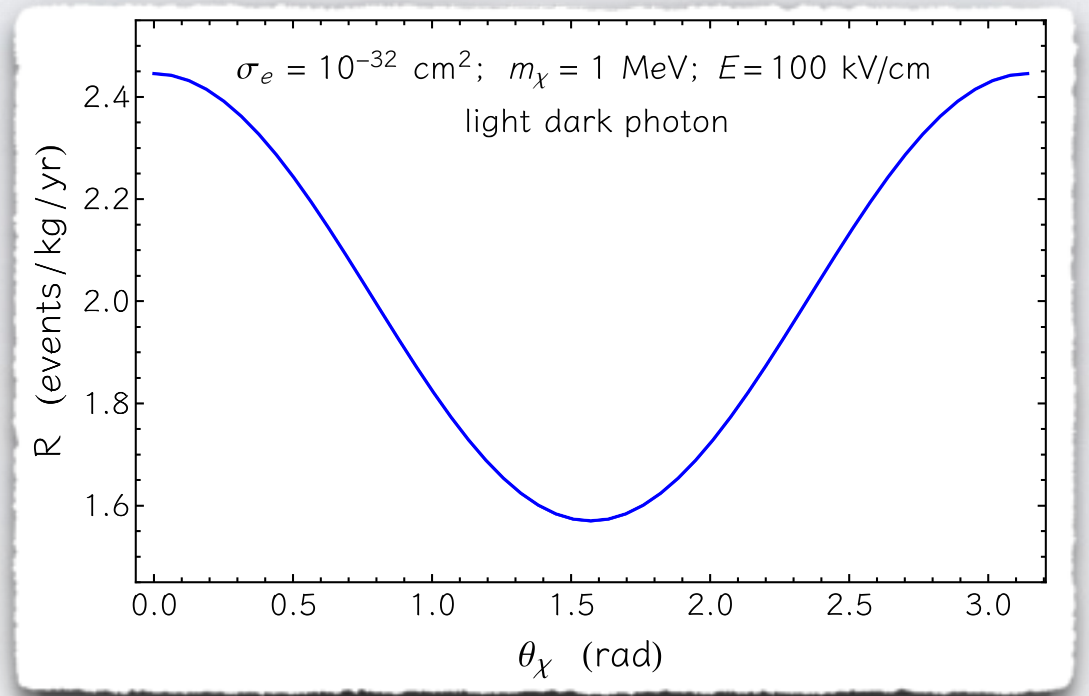
- The effective couplings a and b are uniquely determined by the He-4 electric polarizability

$$a \simeq 0\,; \qquad b \simeq \bar n \alpha_E$$

DM - PHONON INTERACTION WITH VECTOR MEDIATOR

Background rejection

- We focus on the **emission of a single phonon**
- The photon - phonon coupling can be enhanced with an external electric field
- The total rate now depends on the relative angle between the incoming dark matter and the external field



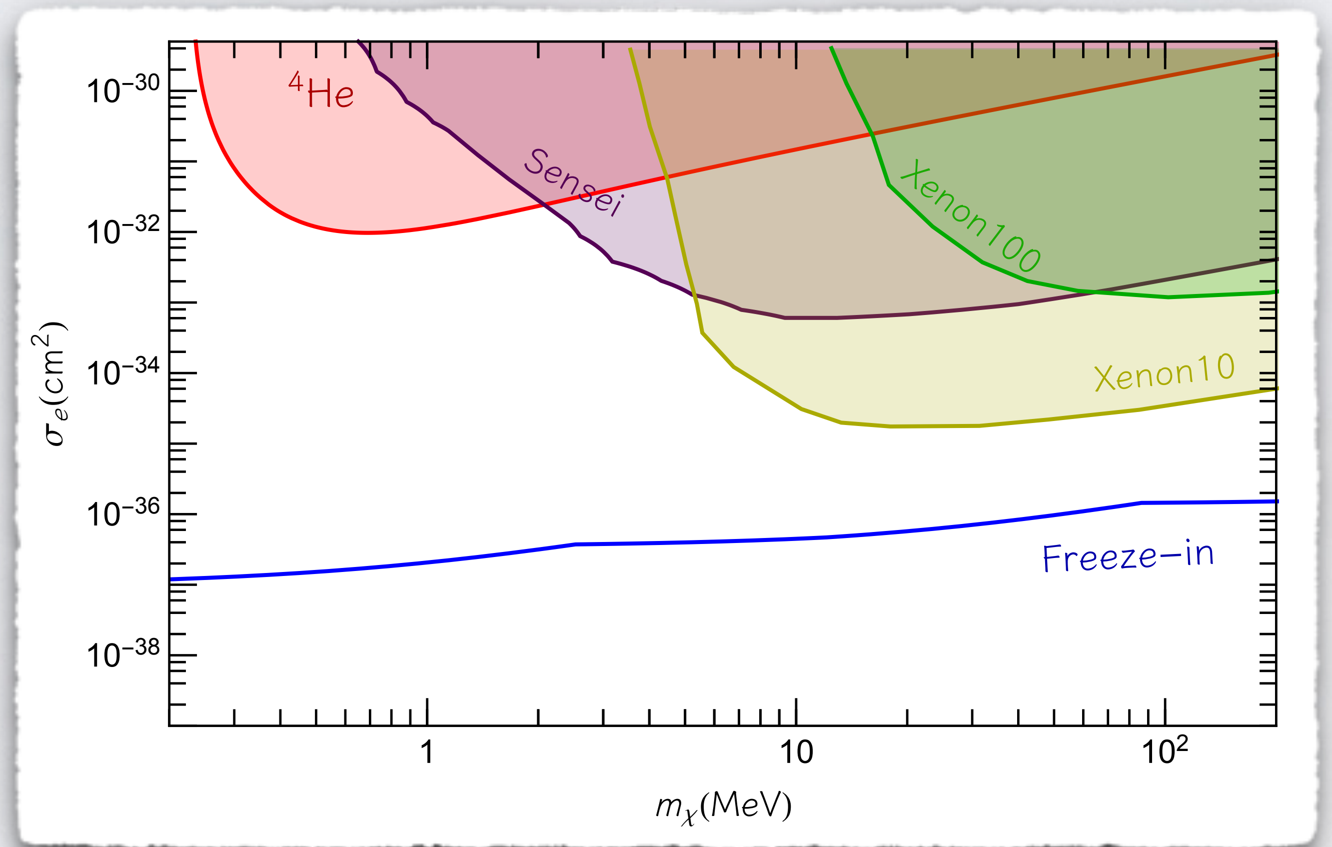
[Caputo, AE, Geoffray, Polosa, Sun — to appear]

- By suitably rotating the electric field with time this can give a good background rejection

DM - PHONON INTERACTION WITH VECTOR MEDIATOR

Sensitivity

- A He-4 experiment can be competitive with other existing bounds only for ultra-light dark photon ($m_V \lesssim 10^{-13}$ eV)
- Emission rate for a single phonon with external electric field $\left.\frac{d\Gamma}{d\omega}\right|_{m_V \ll q} \simeq \frac{\mathbf{E}^2}{12\pi} g^2 \epsilon^2 \frac{\bar{n}\alpha_E^2}{c_s^2 m_{He} v_\chi}$



[Caputo, AE, Geoffray, Polosa, Sun — to appear]

CONCLUSION AND FUTURE PLANS

- A He-4 experiment for sub-MeV dark matter is a promising direction $\longrightarrow$ a lot of R&D to do!
- The EFT for superfluids is simple and suitable for the problem at hand $\longrightarrow$ provides a key tool for future investigations
- Future plans:

1. Other materials? E.g. emission of optical phonons in polar materials (w/ Melia), crystals with high natural electric fields.
2. Other devices involving He-4? E.g. exploit phase transition and viscosity and/or production of vortices

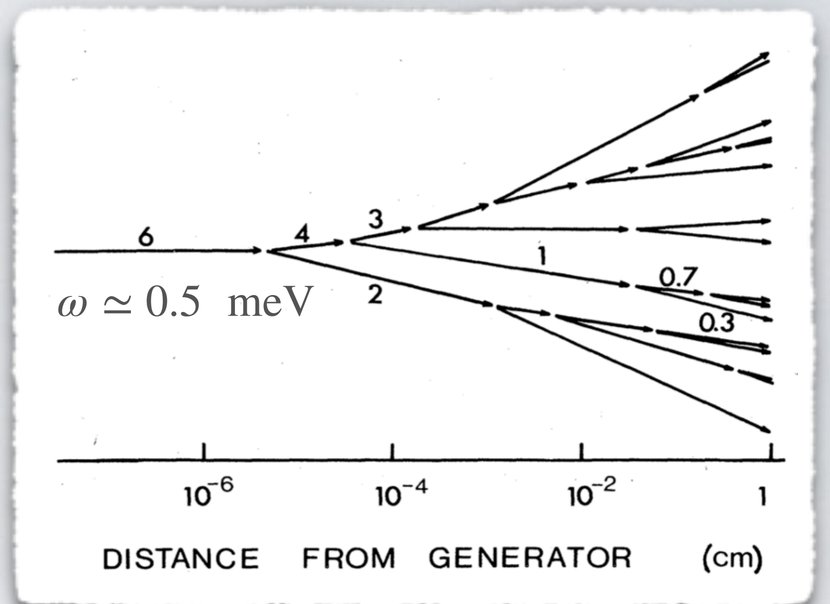
THANK YOU!

BACK UP

PHONON STABILITY

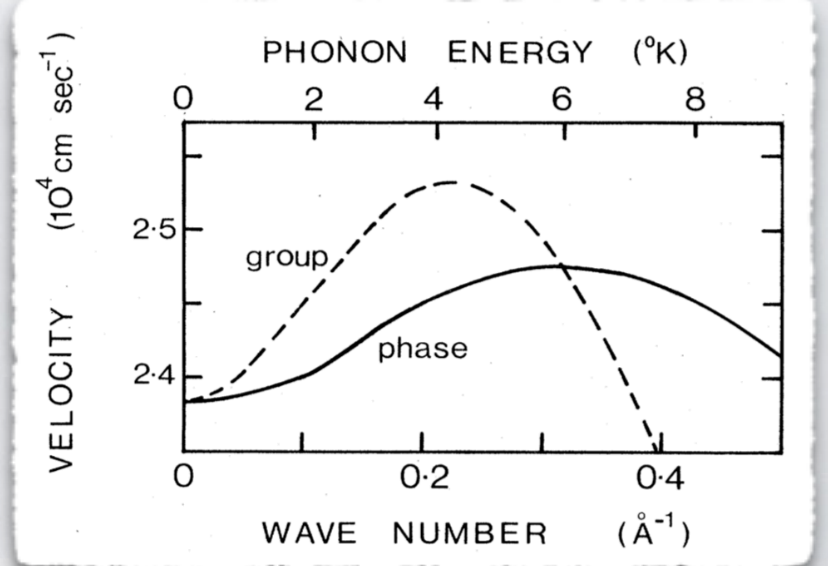
Phonon branching

- Phonons at finite momentum are not eigenstates of the Hamiltonian $\longrightarrow$ they can decay into other phonons and degrade their energy



- It is well know that most phonons can produce a "shower"
- After ~micrometer the phonon decays into softer phonons which are impossible to detect!
- However, if the sound speed of the two final phonons is larger than that of the initial phonon the decay is kinematically forbidden
- The phonon's speed is not exactly linear
- Phonons with $\omega > 0.68$ meV are stable against decay into two other phonons

[Maris — Rev. Mod. Phys. (1977)]



THE EFT FOR HE-4 AND DARK MATTER

- A superfluid is a system with a $U(1)$ symmetry (number of particles) with generator Q that is at finite density
- It breaks boosts, time translations and the $U(1)$ but preserves the modified Hamiltonian $\bar{H} = H - \mu Q$ (standard for finite density systems)
- This symmetry breaking pattern can be realized with a single real scalar, $\psi(x)$, that shifts under the $U(1)$, $\psi \to \psi + \alpha$, and acquires a vev proportional to time, $\langle \psi(x) \rangle = \mu t$
- Fluctuation around equilibrium correspond to the superfluid phonon: $\psi(x) = \mu t + \pi(x)$
- Since the breaking is spontaneous the action must be invariant under Poincaré and the $U(1)$. At lowest order in derivatives (low energy) the only option is

$$S = \int d^4x \, P(X)\,; \qquad X = \sqrt{-\partial_\mu \psi \partial^\mu \psi} = \mu + \dot{\pi} - \frac{(\vec{\nabla}\pi)^2}{2\mu} + \dots$$

THE EFT FOR HE-4 AND DARK MATTER

- As for the interaction with the dark matter we consider a model where it interacts with He-4 via its number density: $\mathscr{L}_{int} = G_\chi m_\chi |\chi|^2 n(X)$
- This can arise, for example, from a coupling to gluons in the UV

$$\mathscr{L}_{\mathsf{UV}} = |\partial\chi|^2 - m_\chi^2|\chi|^2 + \frac{1}{2}(\partial\phi)^2 - \frac{m_\phi^2}{2}\phi^2 - g_\chi m_\chi \phi|\chi|^2 - \frac{g_{\mathsf{SM}}}{\Lambda}\phi\, G^a_{\mu\nu}G^{a\,\mu\nu}$$

- Expanding everything in small fluctuations one finds the action for the interaction of the phonon with itself and with the dark matter:

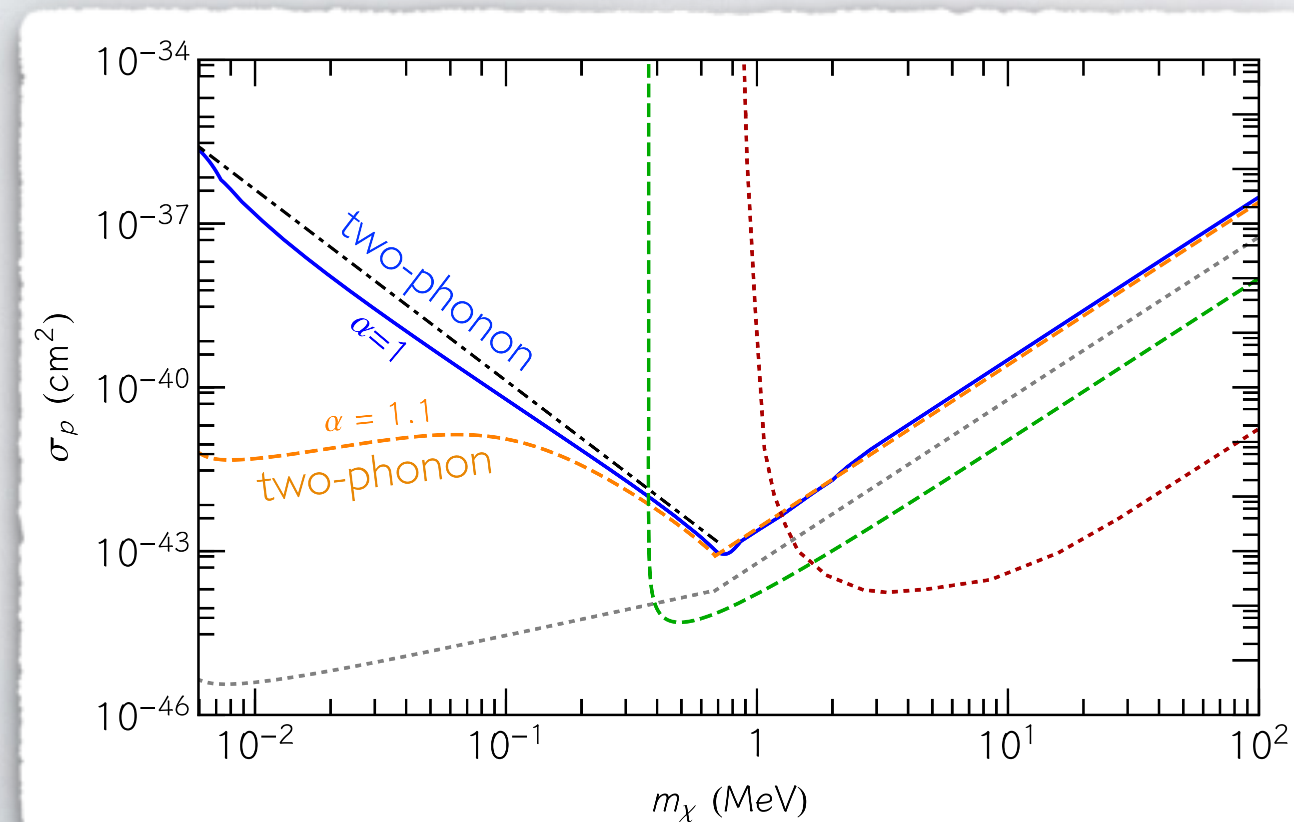
$$S_{eff} = \int d^4x \Bigg[\frac{1}{2}\dot\pi^2 - \frac{c_s^2}{2}\left(\vec\nabla\pi\right)^2 - |\partial\chi|^2 - m_\chi^2|\chi|^2 + \lambda_3\sqrt{\frac{m_{He}}{\bar n}}c_s\,\dot\pi\left(\vec\nabla\pi\right)^2 + \lambda_3'\sqrt{\frac{m_{He}}{\bar n}}c_s\,\dot\pi^3$$
$$-\left(g_1\sqrt{\frac{m_{He}}{\bar n}}c_s\,\dot\pi - \frac{g_1}{2}\frac{c_s^2}{\bar n}\left(\vec\nabla\pi\right)^2 + \frac{g_2}{2}\frac{m_{He}c_s^2}{\bar n}\dot\pi^2\right)|\chi|^2\Bigg]$$

$$\lambda_3 = -\frac{1}{2m_{He}}; \quad \lambda_3' = \frac{1}{6m_{He}c_s^2} - \frac{\bar n}{3c_s}\frac{dc_s}{dP}; \quad g_1 = -G_\chi m_\chi\frac{\bar n}{m_{He}c_s^2}; \quad g_2 = -G_\chi m_\chi\frac{\bar n}{m_{He}c_s^2}\left(\frac{1}{m_{He}c_s^2} - \frac{2\bar n}{c_s}\frac{dc_s}{dP}\right)$$

A SUBTLE CANCELLATION

Consequences

- The cancellation only happens if the dark matter couples exactly to the He-4 number density
- If this coupling is modified things change drastically!
- A toy model: $$\mathscr{L}_{int} = G_\chi m_\chi |\chi|^2 n^\alpha(x)\, \bar{n}^{1-\alpha}$$



How general is a coupling to the number density?

In presence of different couplings a He-4 experiment is much more promising than expected!