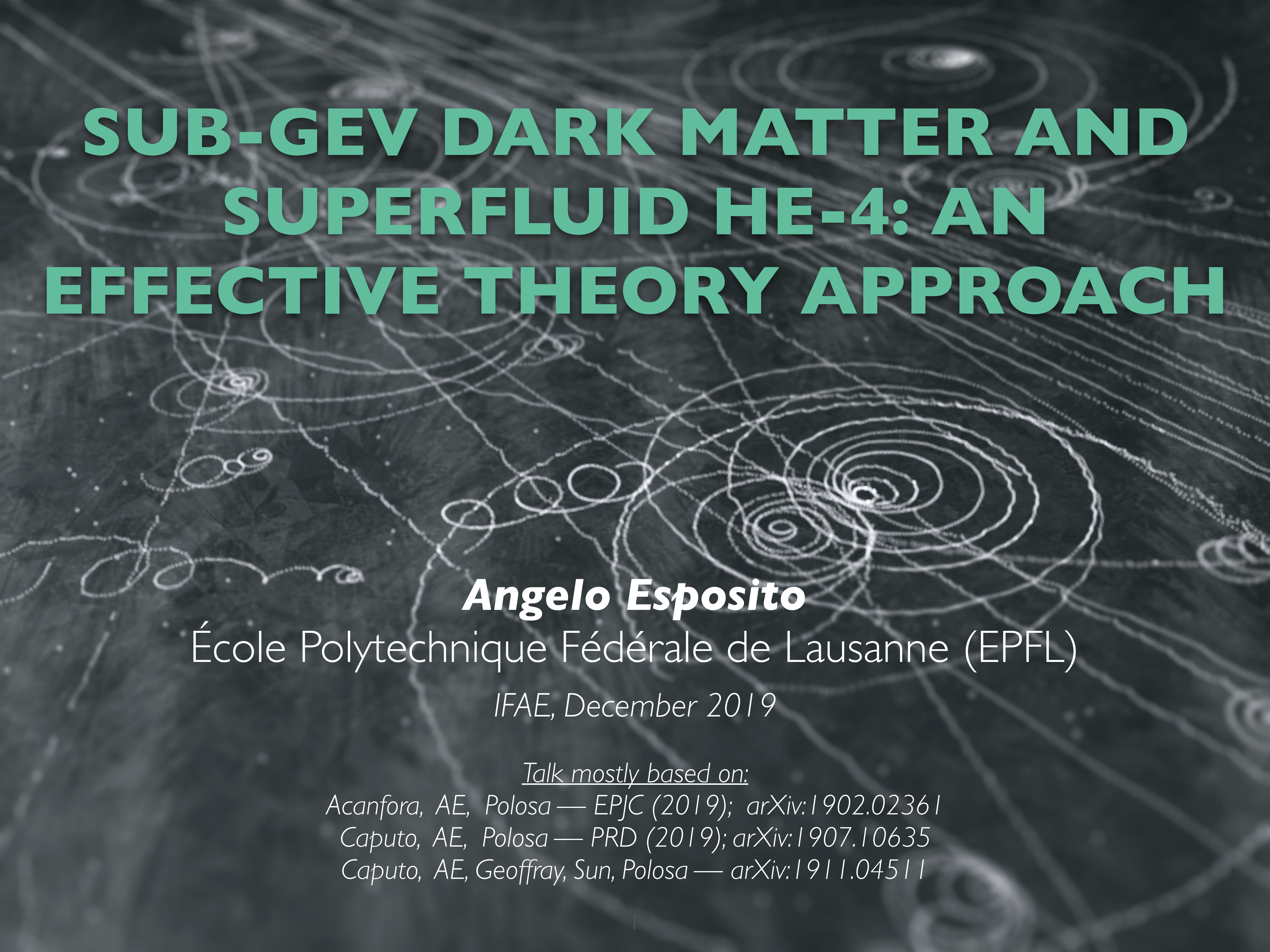

SUB-GEV DARK MATTER AND SUPERFLUID HE-4: AN EFFECTIVE THEORY APPROACH

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IFAE, December 2019

Talk mostly based on:
Acanfora, AE, Polosa — EPJC (2019); arXiv:1902.02361
Caputo, AE, Polosa — PRD (2019); arXiv:1907.10635
Caputo, AE, Geoffray, Sun, Polosa — arXiv:1911.04511

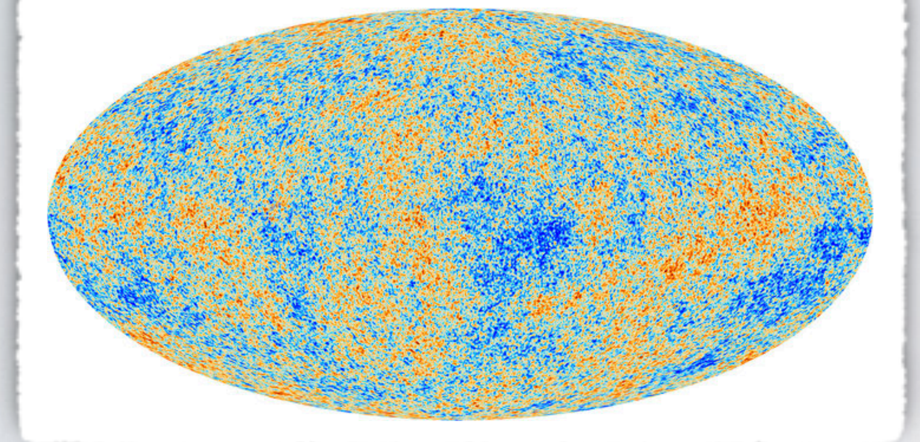
OUTLINE

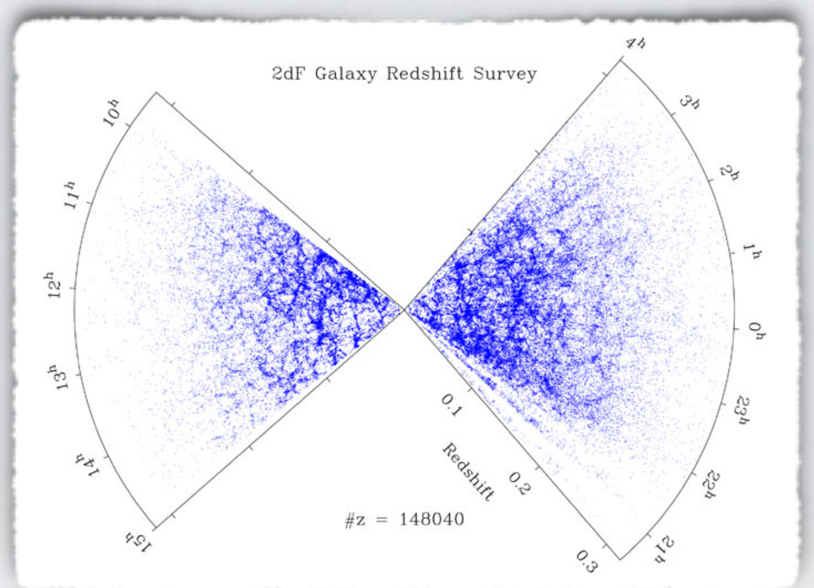
- Introduction and motivation
- Intro to the relativistic EFT for superfluids
    1. Phonon as Goldstone boson
    2. Phonon's self interactions
- Dark matter with a scalar mediator
    1. Dark matter - phonon interaction
    2. Emission of one and two phonons
    3. A subtle cancellation
- Dark matter with vector mediator
    1. Dark matter - phonon interaction
    2. Emission of one phonon
- Conclusions and future plans

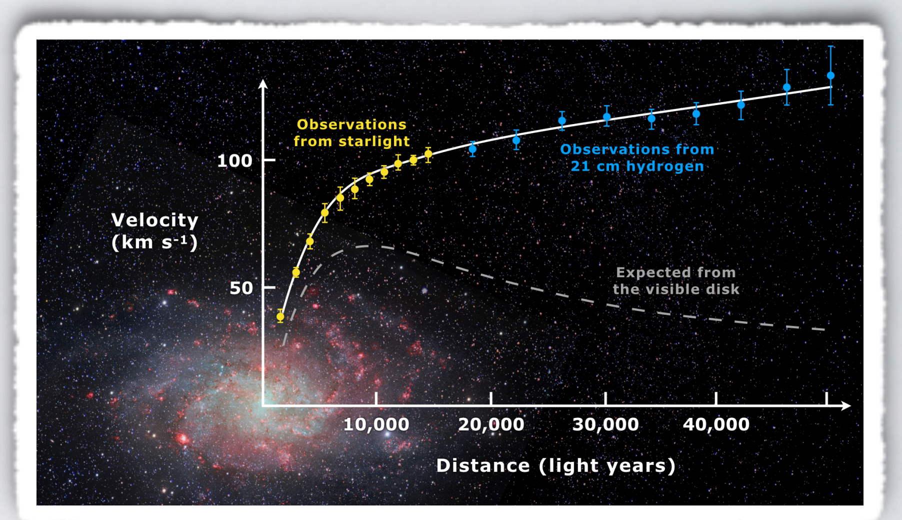
INTRO

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 is one of the strongest evidences for physics beyond the Standard Model

- Earth-based experiments have to deal with a huge possible mass range

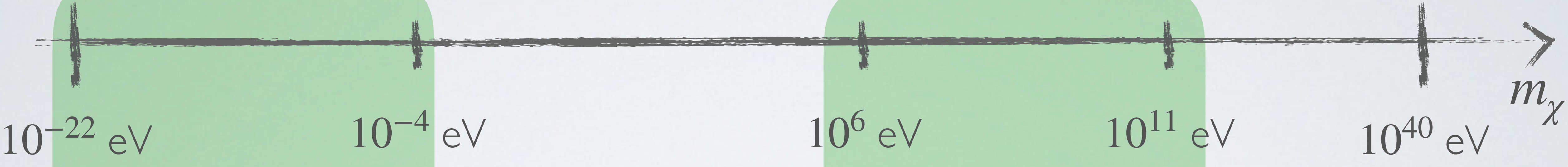
- Detection techniques vary widely depending on the dark matter mass

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, …

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 ⟶ the dark matter is too light to deposit energy via recoil but too heavy to take advantage of resonant phenomena

INTRO

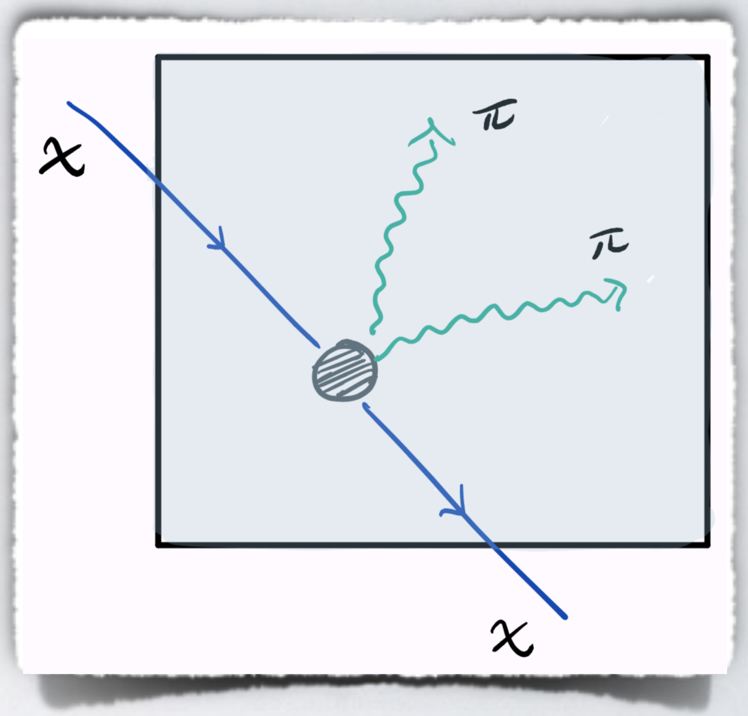
Why helium-4?

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

  [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, and many others]

- 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
  4. Allows to go down to masses of ~keV



- The emission of two 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 interactions 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 CONDENSED MATTER

General idea

- The fundamental laws of Nature are Poincaré invariant but different states of matter (solids, superfluids, etc.) are not
- Condensed matter systems must arise as symmetry-violating states of an underlying invariant theory ⟶ the Poincarè symmetry is spontaneously broken
- All condensed matter systems select a particular reference frame ⟶ boosts are always broken
- Other spacetime symmetries and/or internal symmetries might be broken too ⟶ different systems are characterized by different symmetry breaking patterns

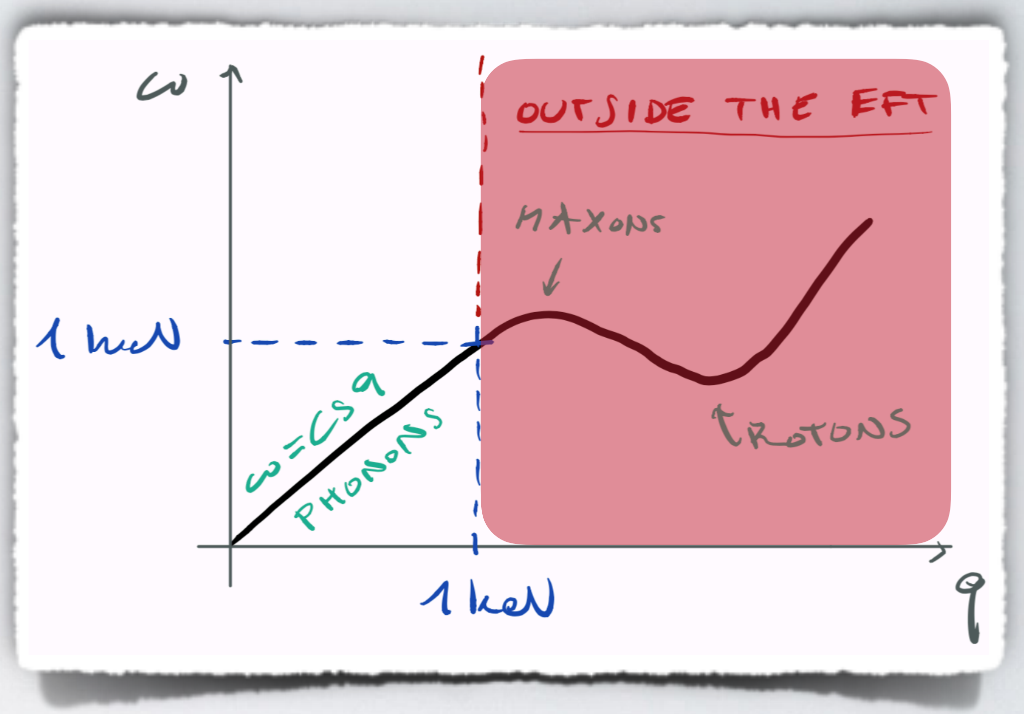
[Nicolis, Penco, Piazza, Rattazzi – JHEP 2015, 1501.03845]

EFT FOR SUPERFLUIDS

Symmetry breaking pattern

- 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

- A superfluid is a system that:
  1. Is at finite density for a conserved charge Q of a $U(1)$ group (particle number)
  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]

EFT FOR SUPERFLUIDS

Phonon's self-interaction

- Symmetry breaking pattern can be realized with a real scalar field such that

$$\psi \xrightarrow{U(1)} \psi + a\,; \qquad \langle \psi(x) \rangle = \mu t \qquad \psi(x) = \mu t + \pi(x)$$

Goldstone = phonon

- Most general action at low energies:

pressure as a function of chemical potential

speed of sound

$$S = \int d^4x\, P(X) \qquad \text{with:} \quad X = \sqrt{-\partial_\mu \psi \partial^\mu \psi} = \mu + \dot{\pi} - \frac{(\nabla \pi)^2}{2 m_{He}} + \dots$$

$$\to \left[\frac{1}{2}\dot{\pi}^2 - \frac{c_s^2}{2}\left(\vec{\nabla}\pi\right)^2 + \lambda_3 \sqrt{\frac{m_{He}}{\bar{n}}}\, c_s \dot{\pi} \left(\vec{\nabla}\pi\right)^2 + \lambda_3' \sqrt{\frac{m_{He}}{\bar{n}}}\, c_s \dot{\pi}^3 + \dots \right]$$

equilibrium number density

$$\lambda_3 = -\frac{1}{2 m_{He}}\,; \qquad \lambda_3' = \frac{1}{6 m_{He} c_s^2} - \frac{\bar{n}}{3 c_s} \frac{d c_s}{dP}$$

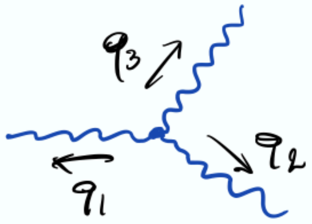
- All couplings are determined by the He-4 equation of states ⟶ no free parameters

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

EFT FOR SUPERFLUIDS

A validity check

- An interesting check of the validity of the EFT can be obtained by computing the $\pi \to \pi\pi$ decay
- Feynman rule:



$$= 2\sqrt{\frac{m_{He}}{n}}\, c_s \left\{ \lambda_3 \left(\omega_1 \vec{q}_2 \cdot \vec{q}_3 + \omega_2 \vec{q}_1 \cdot \vec{q}_3 + \omega_3 \vec{q}_1 \cdot \vec{q}_2 \right) + 3\lambda_3' \omega_1 \omega_2 \omega_3 \right\}$$

- Corresponding total rate:

$$\Gamma = \frac{1}{240\pi \rho_{He} c_s^5} \left(1 + \rho_{He} c_s \frac{dc_s}{dP} \right)^2 \omega_1^5$$

- This is in perfect agreement with what already known about He-4

`[see e.g. Maris — Rev. Mod. Phys. 1977]`

DM - PHONON INTERACTION WITH SCALAR MEDIATOR

The effective action

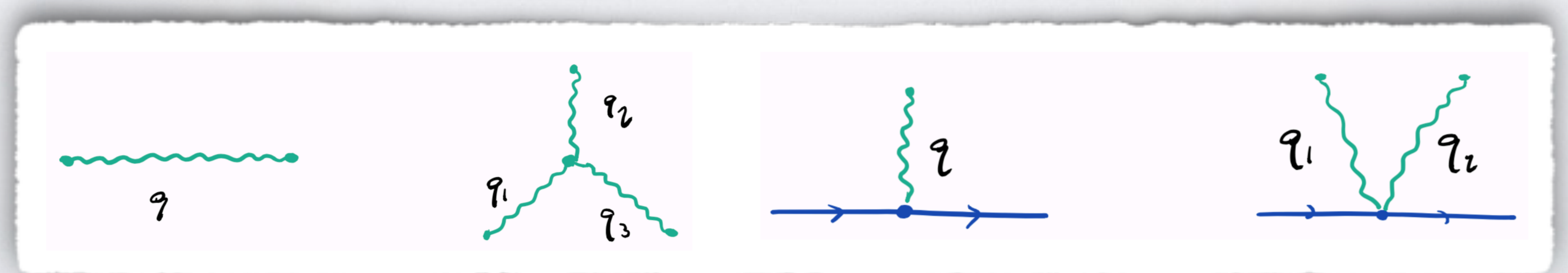
- Let us consider a coupling between dark matter and phonon that happens via the ***He-4 number density***: $\mathscr{L}_{\text{int}} = -G_\chi m_\chi |\chi|^2 n(X)$

- This coupling could be generated, for example, by a coupling to gluons via a scalar mediator in the nonrelativistic limit:

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

- This produces the following dark matter - phonon coupling:

$$S = \int d^4x \left[|\partial\chi|^2 - m_\chi^2|\chi|^2 + G_\chi m_\chi \left(\frac{d\bar n}{d\mu}\sqrt{\frac{m_{He}}{\bar n}}\, c_s \dot\pi - \frac{1}{2}\frac{d\bar n}{d\mu}\frac{c_s^2}{\bar n}(\nabla\pi)^2 + \frac{1}{2}\frac{d^2\bar n}{d\mu^2}\frac{m_{He}c_s^2}{\bar n}\dot\pi^2 \right)|\chi|^2 \right]$$



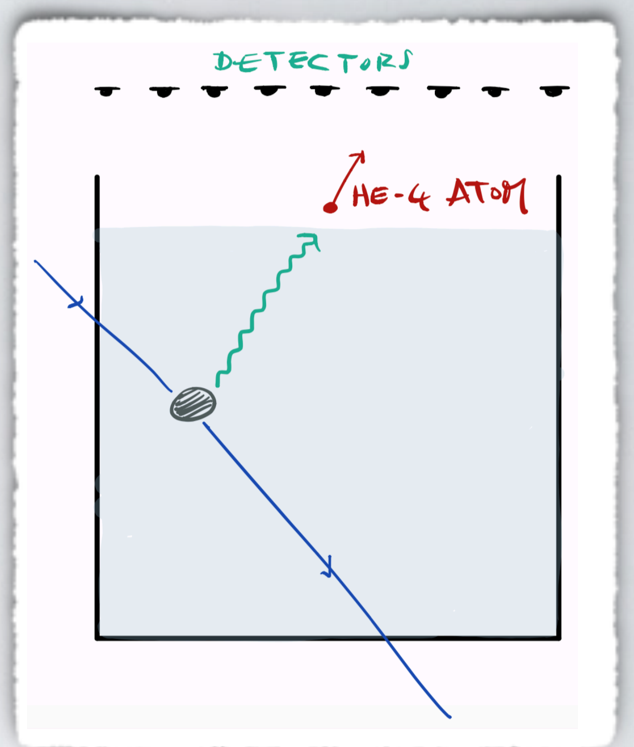
PHONON(S) EMISSION

How do we see phonons?

- How would one detect phonons experimentally?

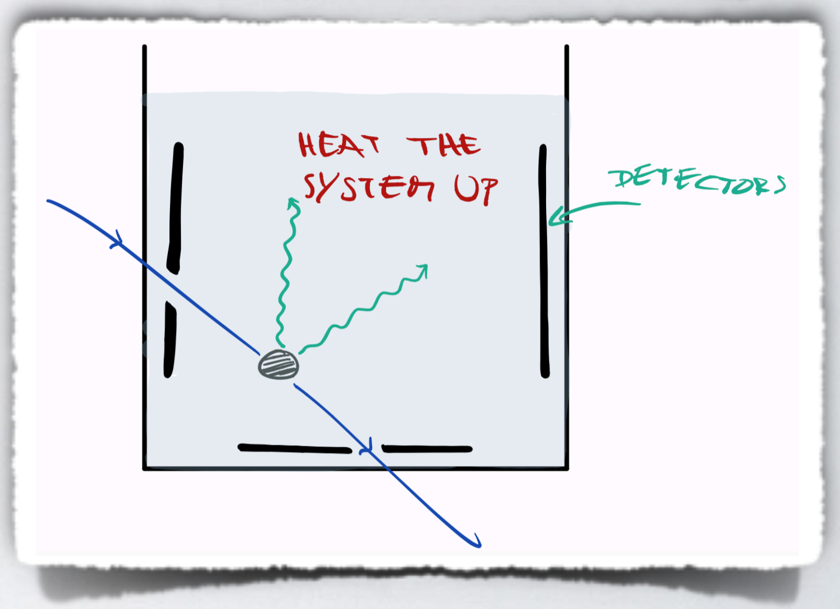
- **Quantum evaporation:**

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



- **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)



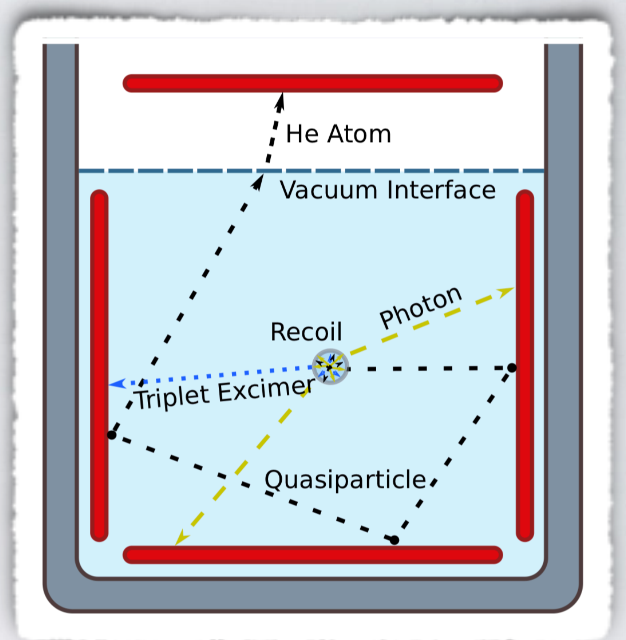
[see e.g. Hertel, Biekert, Lin, Velan, McKinsey — 1810.06283; Maris, Seidel, Stein — PRL 2017, 1706.00117]

PHONON(S) EMISSION

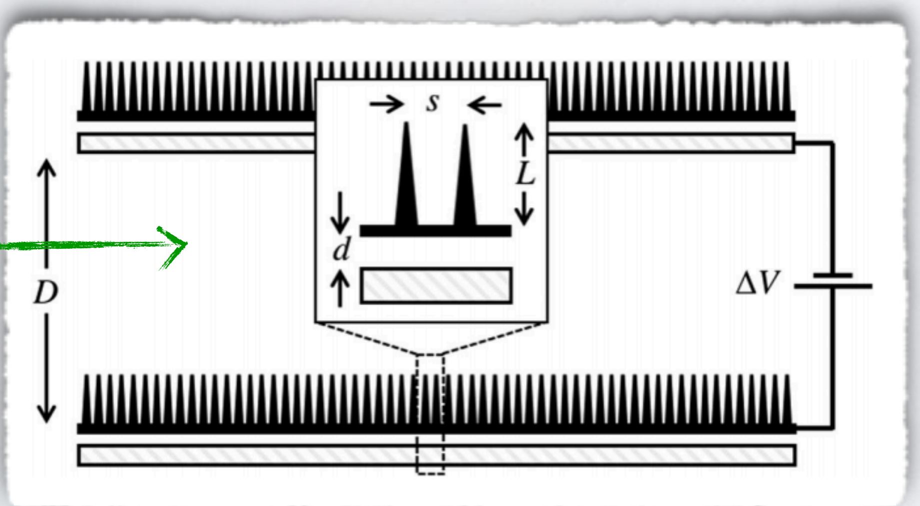
How do we see phonons?

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

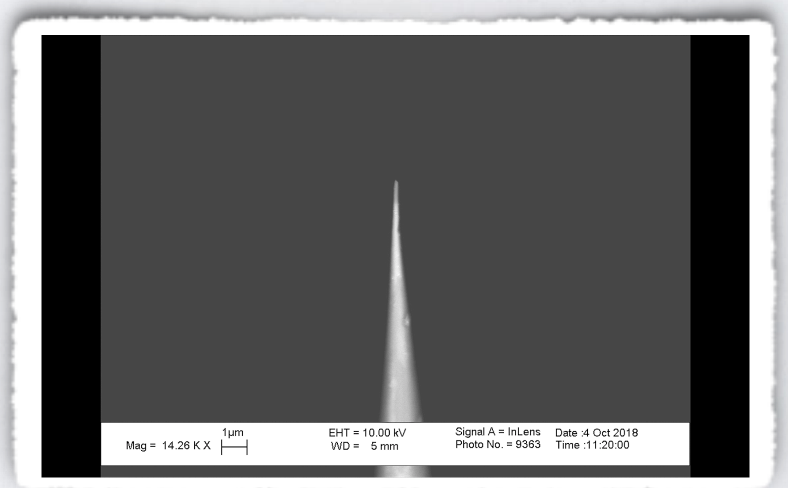
     [Hertel, Biekert, Lin, Velan, McKinsey — 1810.06283]



  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

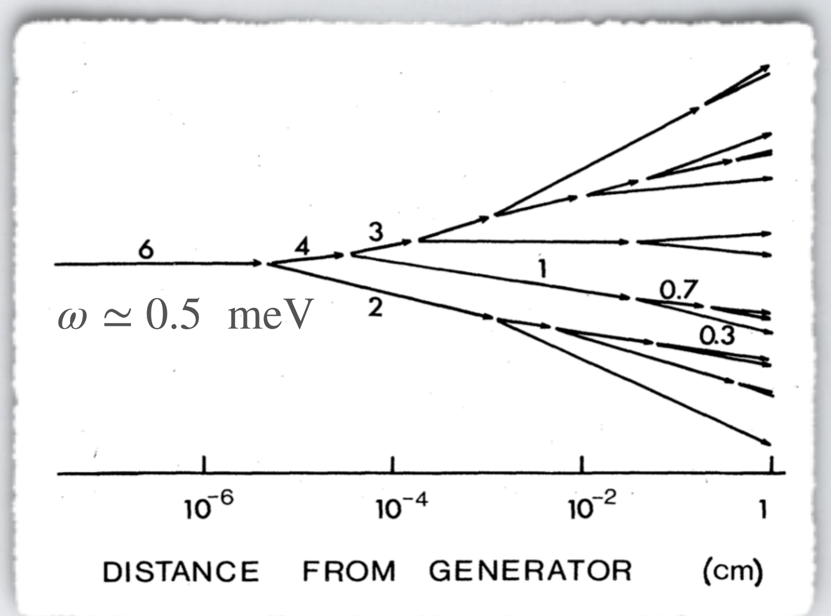


[courtesy of David Osterman, Brown U.]

PHONON STABILITY

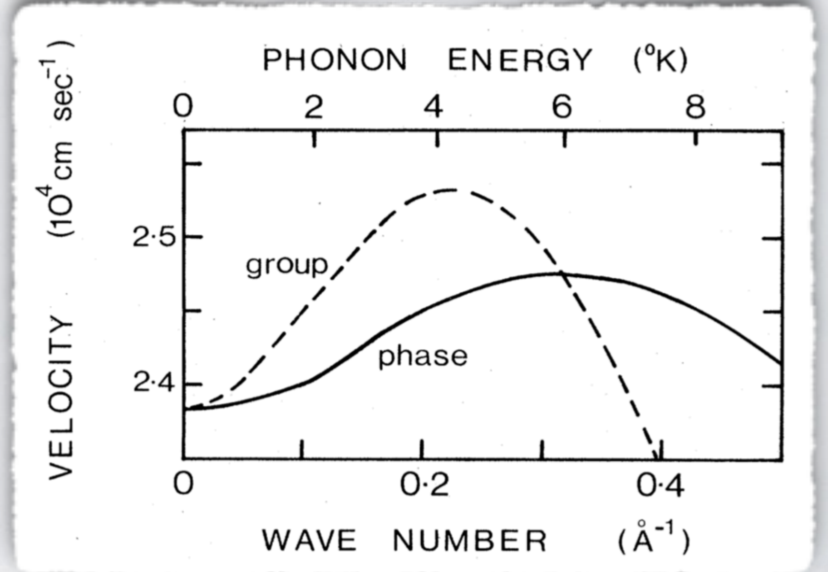
Phonon branching

- Phonons at finite momentum are not eigenstates of the Hamiltonian ⟶ 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)]`

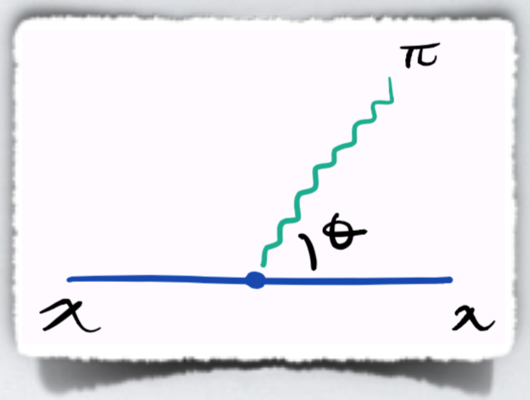


PHONON(S) EMISSION

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)

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



- Max phonon's energy is $\omega_{\rm max} = 2c_s m_\chi v_\chi \simeq 10^{-9} m_\chi$ ⟶ 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
- Total rate:

$$\frac{d\Gamma}{d\omega} = \frac{G_\chi^2}{16\pi} \frac{\bar{n}}{m_{He} c_s^4 v_\chi} \omega^2$$

PHONON(S) EMISSION

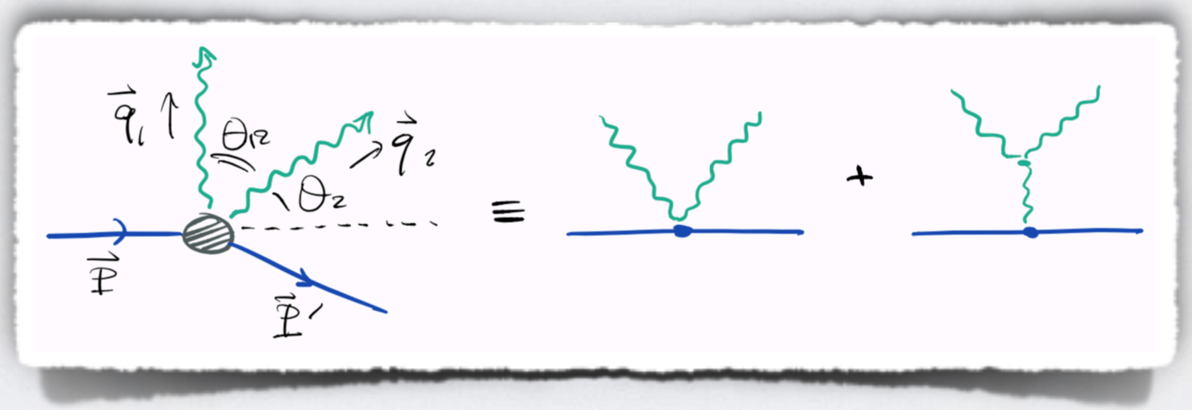
Two-phonons

- Another interesting observable is the **emission of two phonons**

- This process is suppressed with respect to the one-phonon emission but:

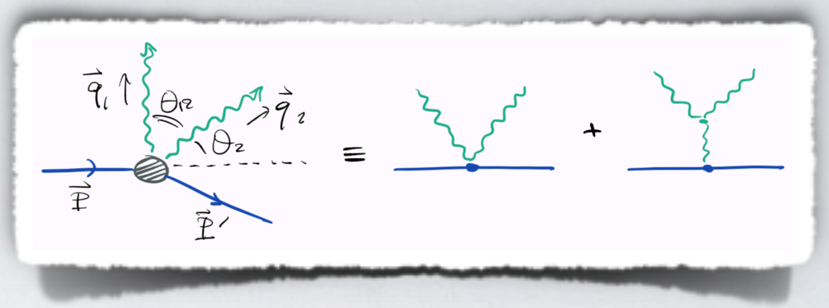
1. It is effective also for [dark matter as light as 1 keV]
2. It should be detectable via both quantum evaporation and energy deposit

- The amplitude gets a contribution from two diagrams of the EFT → crucial (see later)!



PHONON(S) EMISSION

Two-phonons



- Matrix elements:

$$\mathcal{M}_a = iG_\chi \frac{c_s^2}{\bar{n}} \left(m_{He} \frac{d^2\bar{n}}{d\mu^2} \omega_1 \omega_2 - \frac{d\bar{n}}{d\mu} \mathbf{q}_1 \cdot \mathbf{q}_2 \right)$$

$$\mathcal{M}_b = 2i \frac{m_{He} c_s^2}{\bar{n}} \frac{\omega}{\omega^2 - c_s^2 q^2} \left[\lambda_3 \left(\omega_1 \mathbf{q}_2 \cdot \mathbf{q} + \omega_2 \mathbf{q}_1 \cdot \mathbf{q} + \omega \mathbf{q}_1 \cdot \mathbf{q}_2 \right) + 3\lambda_3' \omega_1 \omega_2 \omega \right]$$

- One difficulty: Lorentz boosts are broken ⟶ cannot go to the reference frame of the incoming dark matter ⟶ the calculation must be performed in the lab frame with Monte Carlo techniques

$$\Gamma = \frac{1}{8(2\pi)^4 c_s^5 m_\chi} \int_{\boxed{\mathcal{R}}} d\theta_{12} d\theta_2 d\omega_1 d\omega_2 \frac{\omega_2}{P} \frac{|\mathcal{M}_a + \mathcal{M}_b|^2}{\sqrt{1 - \mathcal{A}(\theta_{12}, \theta_2, \omega_1, \omega_2)^2}}$$

1) energy-momentum conservation;
2) experimental cuts;
3) applicability of EFT

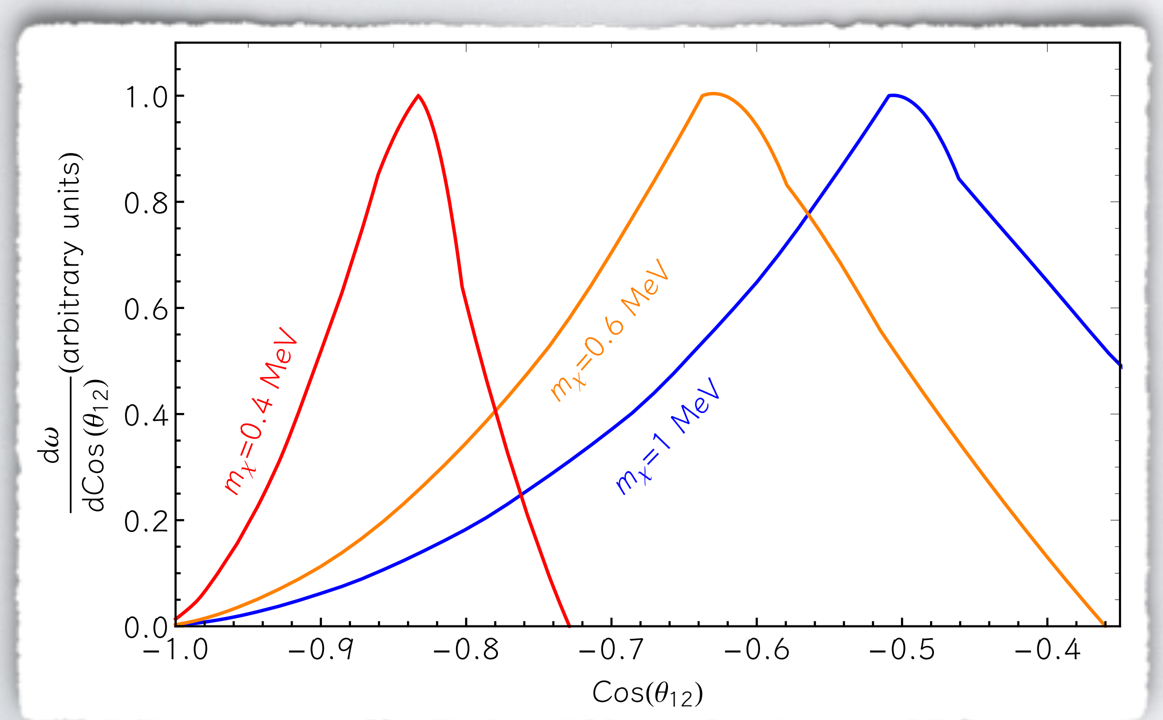
$$\mathcal{A}(\theta_{12}, \theta_2, \omega_1, \omega_2) = \frac{1}{\sin\theta_{12} \sin\theta_2} \left(\cos\theta_{12} \cos\theta_2 + \frac{\omega_2}{\omega_1} \cos\theta_2 - \frac{\omega_2}{c_s P} \cos\theta_{12} - \frac{\omega_1^2 + \omega_2^2}{2\omega_1 c_s P} \right)$$

$$-1 \leq \mathcal{A}(\theta_{12}, \theta_2, \omega_1, \omega_2) \leq 1$$

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 ⟶ 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]

- A hopeful idea: the distribution of the relative angle between the phonons could be used to measure the mass of the dark matter

PHONON(S) EMISSION

Projected bounds

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

↓

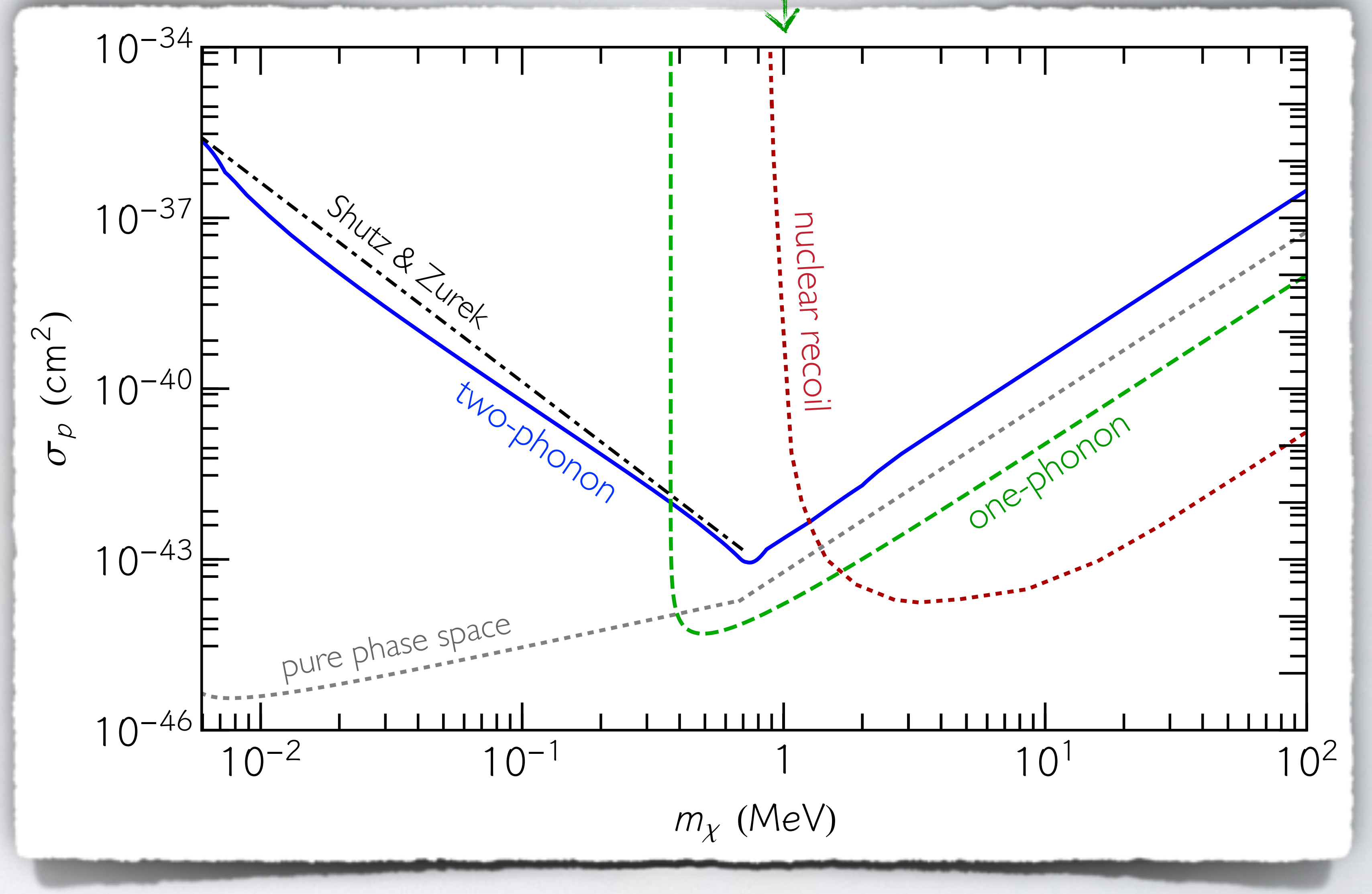
The EFT correctly reproduces the results obtained from neutron scattering on He-4!

+

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, …)



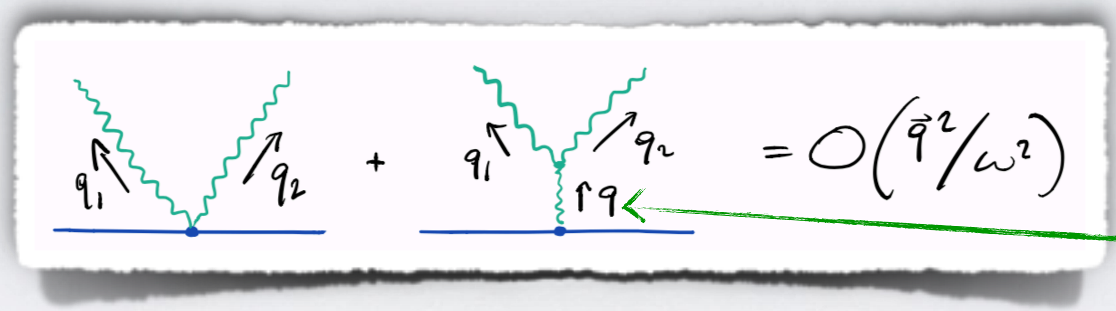
[Caputo, AE, Polosa — arXiv:1907.10635]

- 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 ⟶ 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

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

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

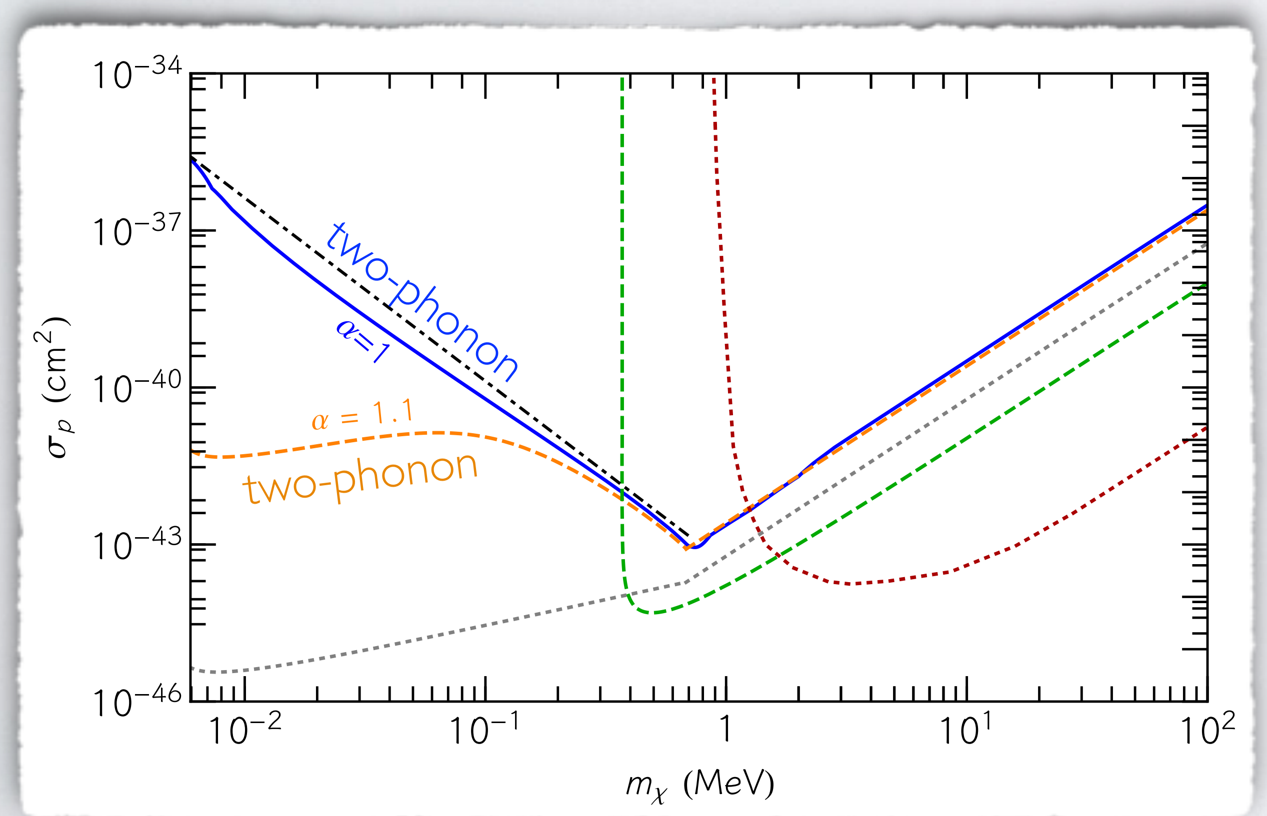
$$q_\mu\langle\pi(q_1)\pi(q_2)|J^\mu(q)|\mu\rangle = 0 \xrightarrow{\mathbf{q}=0} \boxed{\langle\pi(\omega_1,\mathbf{q}_1)\pi(\omega_1,-\mathbf{q}_1)|n(\omega,\mathbf{q}=0)|\mu\rangle = 0}$$

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

PHONON(S) EMISSION

Small q suppression

- The previous 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: $\mathscr{L}_{int} = G_\chi m_\chi |\chi|^2 n^\alpha(x)\, \bar{n}^{1-\alpha}$



[Caputo, AE, Polosa — arXiv:1907.10635]

How general is a coupling to the number density?

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

SUMMARY SO FAR

- To summarize the main points so far:

1. The EFT for superfluids allows to describe the phonon's interactions with itself and with the dark matter in a QFT language (actions, Feynman diagrams, etc.)
2. A combination of one- and two-phonon emission allows to cover a range of masses from the GeV down to the keV (if phonons are detectable!)
3. We reproduce the results obtained with standard techniques $\longrightarrow$ first proof that the EFT reproduces neutron scattering data
4. This points to the fact that most of the rate is due to phonons with little contribution from rotons
5. The total rate is suppressed due to an exact cancellation in the $q = 0$ limit $\longrightarrow$ can we bypass this?

DM - PHONON INTERACTION WITH VECTOR MEDIATOR

The effective action

- Consider a model where the 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 (at least two photon fields)

- The effective action reads (recall: $\psi = \mu t + \pi\,, \quad X = \sqrt{-\partial_\mu\psi\partial^\mu\psi}$)

Kinetic mixing

Dark matter - dark photon coupling

$$S = -\int d^4x \left[\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}(1-\epsilon)V_\mu V^\mu + |\partial_\mu\chi + igV_\mu\chi|^2 + m_\chi^2|\chi|^2 \right.$$
$$\left. - \frac{a(X)}{2}F_{\mu\nu}F^{\mu\nu} - \frac{b(X)}{2}F^{\mu\sigma}F^{\nu}{}_{\sigma}\partial_\mu\psi\partial_\nu\psi \right]$$

Photon - phonon coupling

- What are the functions a and b?

DM - PHONON INTERACTION WITH VECTOR MEDIATOR

Estimate the effective couplings

- The effective couplings a and b can be related to static properties of He-4
- Consider the equilibrium configuration, $\langle \psi \rangle = \mu t$ and $\langle X \rangle = \mu$. The Lagrangian and Hamiltonian read

$$\mathscr{L} \supset -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{a(\mu)}{2} F_{\mu\nu} F^{\mu\nu} + \frac{\mu^2 b(\mu)}{2} F_{0\mu} F_0{}^{\mu} \quad \to \quad H = \int d^3x \frac{1}{2} \Big[\big(1 - 2a + \mu^2 b\big) \, \mathbf{E}^2 + (1 - 2a) \mathbf{B}^2 \Big]$$

- From standard electromagnetism we then deduce that

$$1 - 2a + \mu^2 b = 1 + \bar{n} \alpha_E \, , \quad \text{and} \quad \frac{1}{1 - 2a} = 1 + \bar{n} \alpha_M$$

- Since $\bar{n} \alpha_M \ll \bar{n} \alpha_E$ we find the effective couplings as function of the chemical potential

$$a(\mu) \simeq 0 \, , \qquad \mu^2 b(\mu) \simeq \bar{n}(\mu) \alpha_E \sim 10^{-2}$$

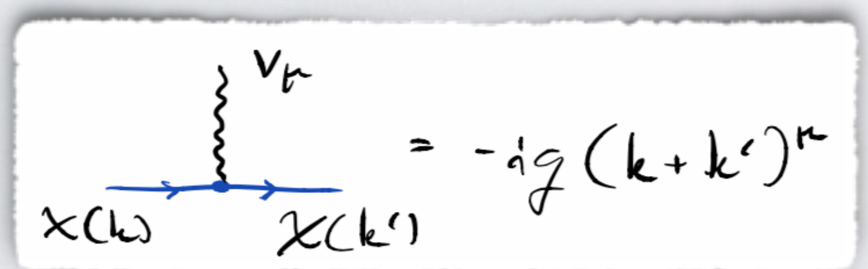
`[see e.g. Fetter – Journal of Low Temperature Physics (1972)]`

DM - PHONON INTERACTION WITH VECTOR MEDIATOR

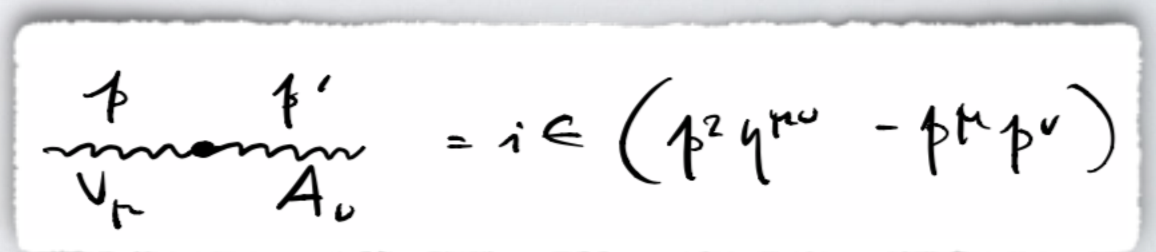
Help from an external field

$$S=-\int d^4x\Big[\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{1}{4}V_{\mu\nu}V^{\mu\nu}-\frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu}+\frac{m_V^2}{2}(1-\epsilon)V_\mu V^\mu+|\partial_\mu\chi+igV_\mu\chi|^2+m_\chi^2|\chi|^2$$
$$-\frac{a(X)}{2}F_{\mu\nu}F^{\mu\nu}-\frac{b(X)}{2}F^{\mu\sigma}F^{\nu}{}_{\sigma}\partial_\mu\psi\partial_\nu\psi\Big]$$

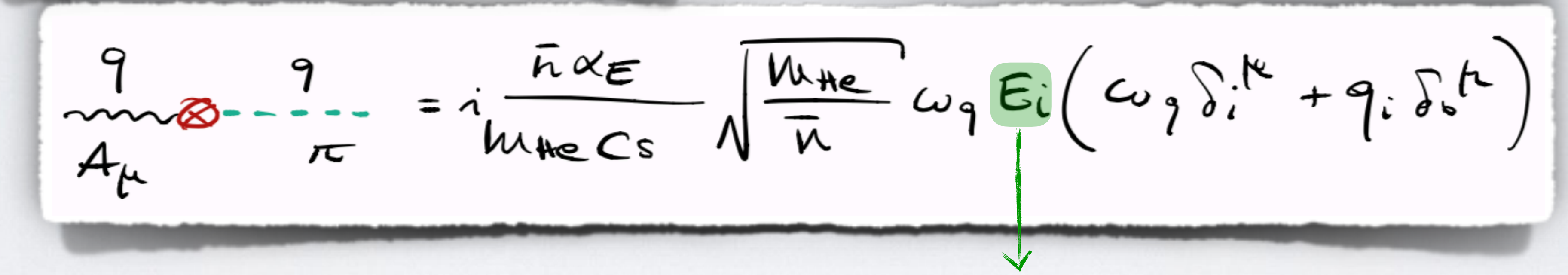
- The relevant Feynman rules obtained from the previous action are:



$$=-ig(k+k')^\mu$$



$$=i\epsilon(p^2\eta^{\mu\nu}-p^\mu p^\nu)$$



$$=i\frac{\bar n\alpha_E}{m_{He}c_s}\sqrt{\frac{m_{He}}{\bar n}}\,\omega_q E_i\left(\omega_q\delta_i^\mu+q_i\delta_0^\mu\right)$$

External electric field

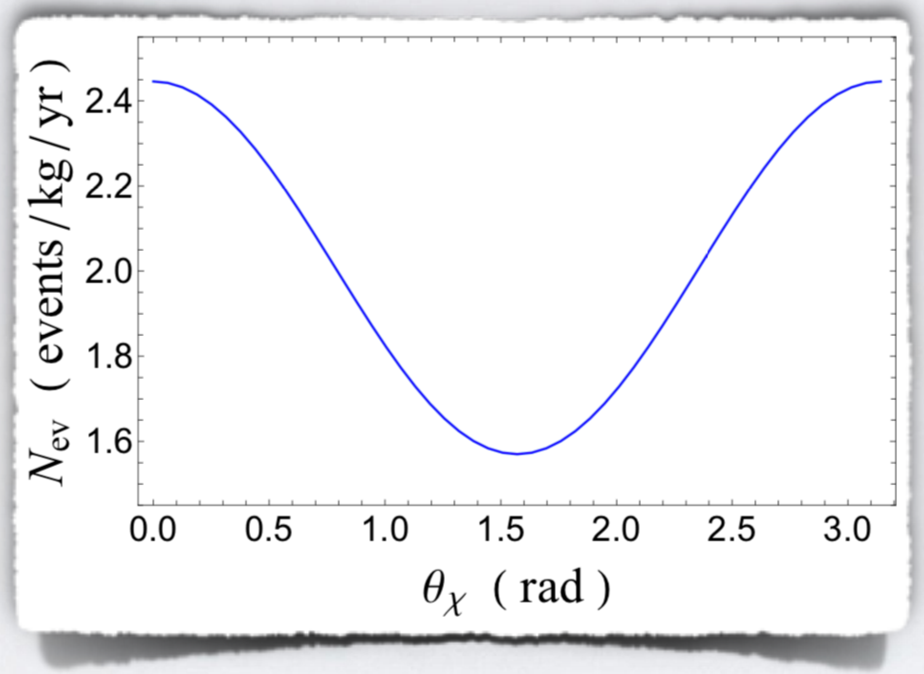
- Phonon-photon coupling is small but it can be enhanced introducing an external field

ONE-PHONON EMISSION

Background rejection

- The smallness of the coupling makes the rate pretty small ⟶ the only promising process is the **emission of a single phonon**
- The strongest electric field one can produce in lab is ~ 100 kV/cm

  [Ito et al. — Rev. Sci. Instrum. 2016, 1510.06068]
- The total rate now depends on the relative angle between the incoming dark matter and the external field



Obtained for $m_\chi = 1$ MeV, $\epsilon\, g = 10^{-9}$ and $E = 100$ kV/cm

[Caputo, AE, Geoffray, Polosa, Sun — arXiv:1911.04511]

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

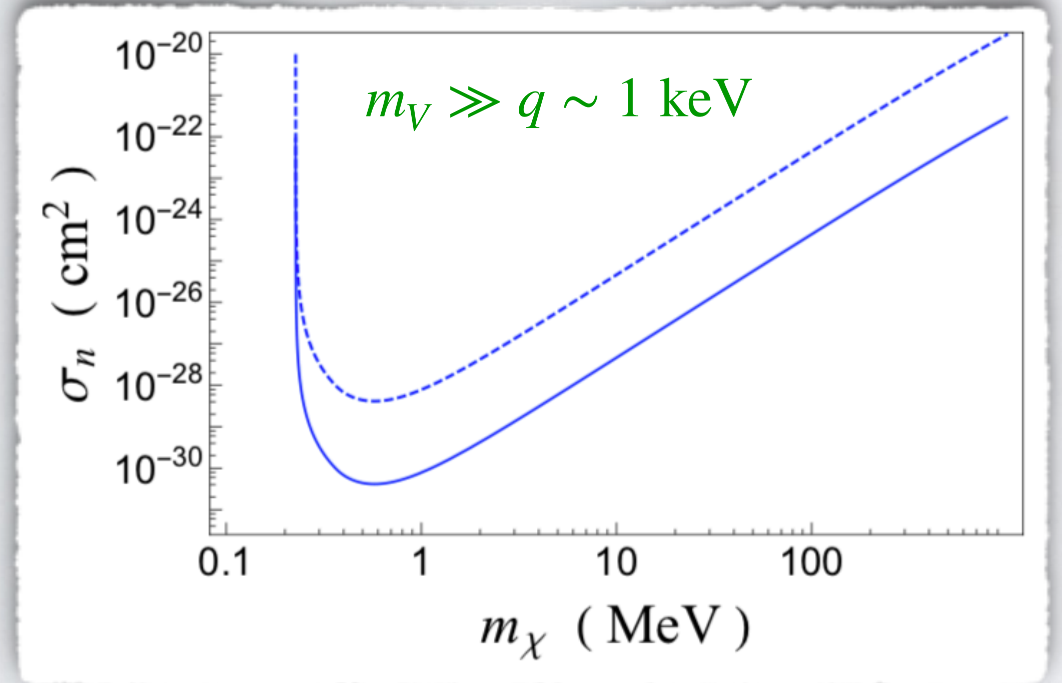
ONE-PHONON EMISSION

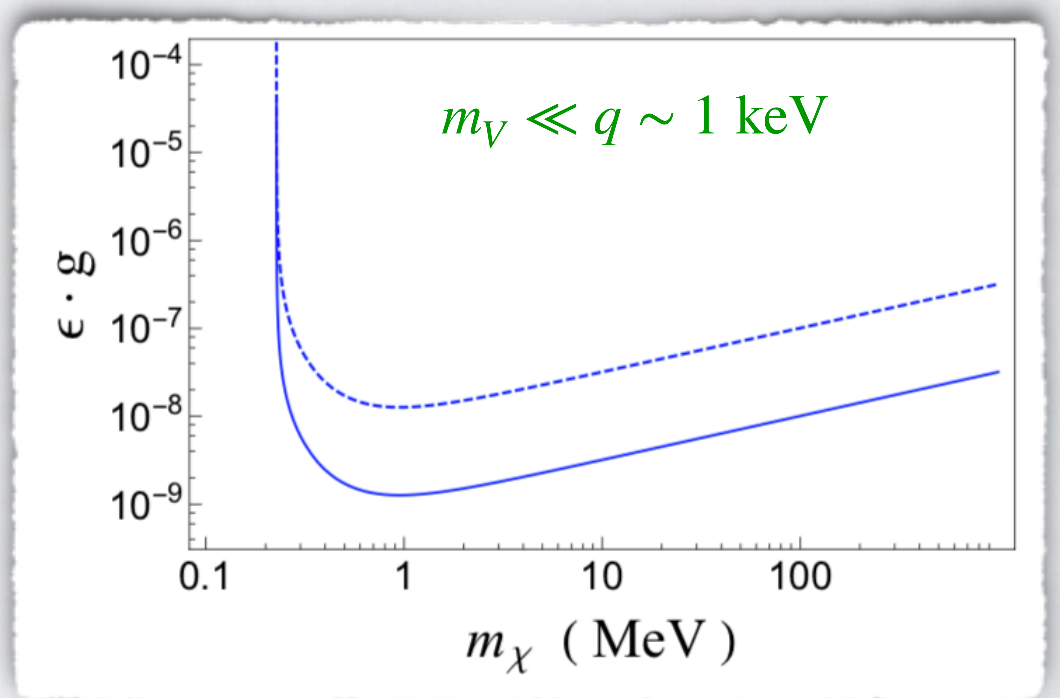
Total rates

- The emission rates for the case of a heavy and a light dark photon are

$$\left.\frac{d\Gamma}{d\omega}\right|_{m_V\gg q} \simeq \frac{\mathbf{E}^2}{12\pi}\frac{g^2\epsilon^2}{m_V^4}\frac{\bar{n}\alpha_E^2}{c_s^6 m_{He} v_\chi}\omega^4 \, ; \qquad \left.\frac{d\Gamma}{d\omega}\right|_{m_V\ll q} \simeq \frac{\mathbf{E}^2}{12\pi}g^2\epsilon^2\frac{\bar{n}\alpha_E^2}{c_s^2 m_{He} v_\chi}$$

- The projected excluded regions are then





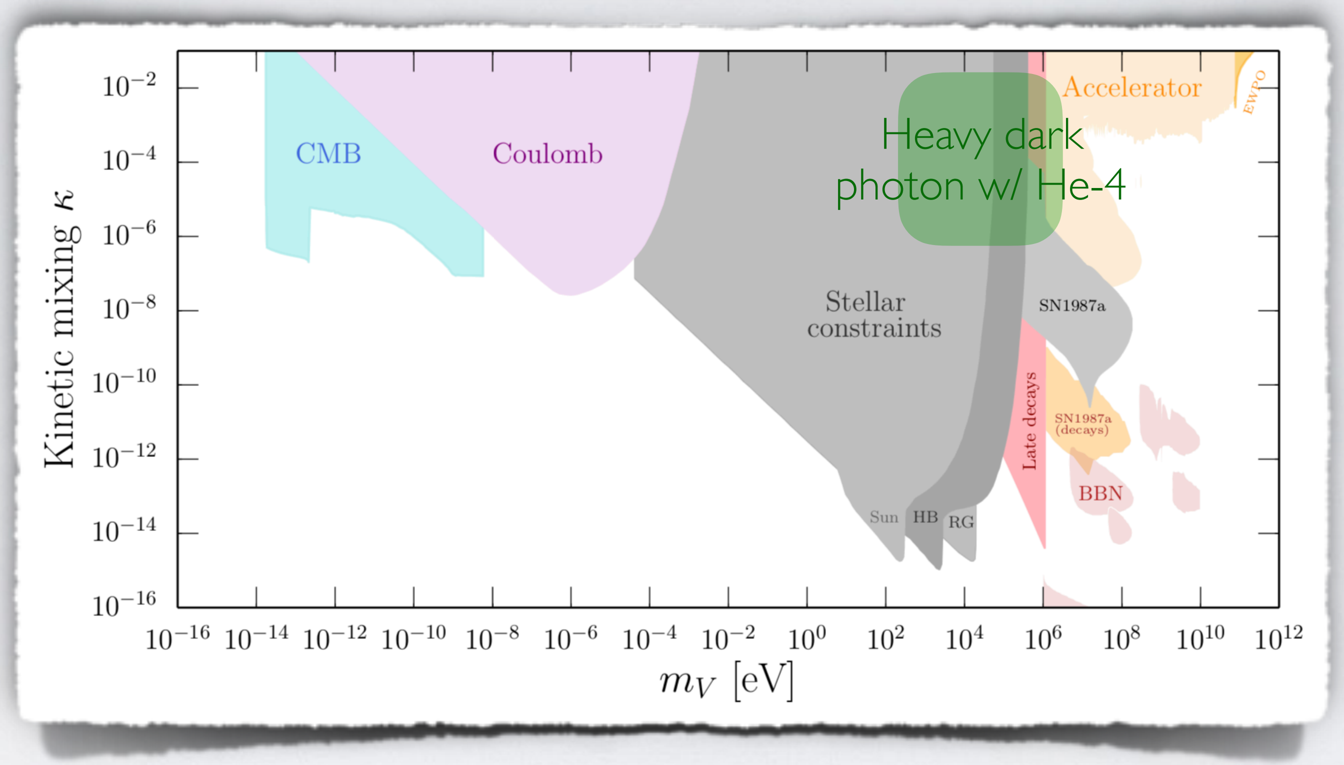
[Caputo, AE, Geoffray, Polosa, Sun — arXiv:1911.04511]

- How competitive are these?

ONE-PHONON EMISSION

Exclusion region — heavy dark photon

- The current existing constraints are



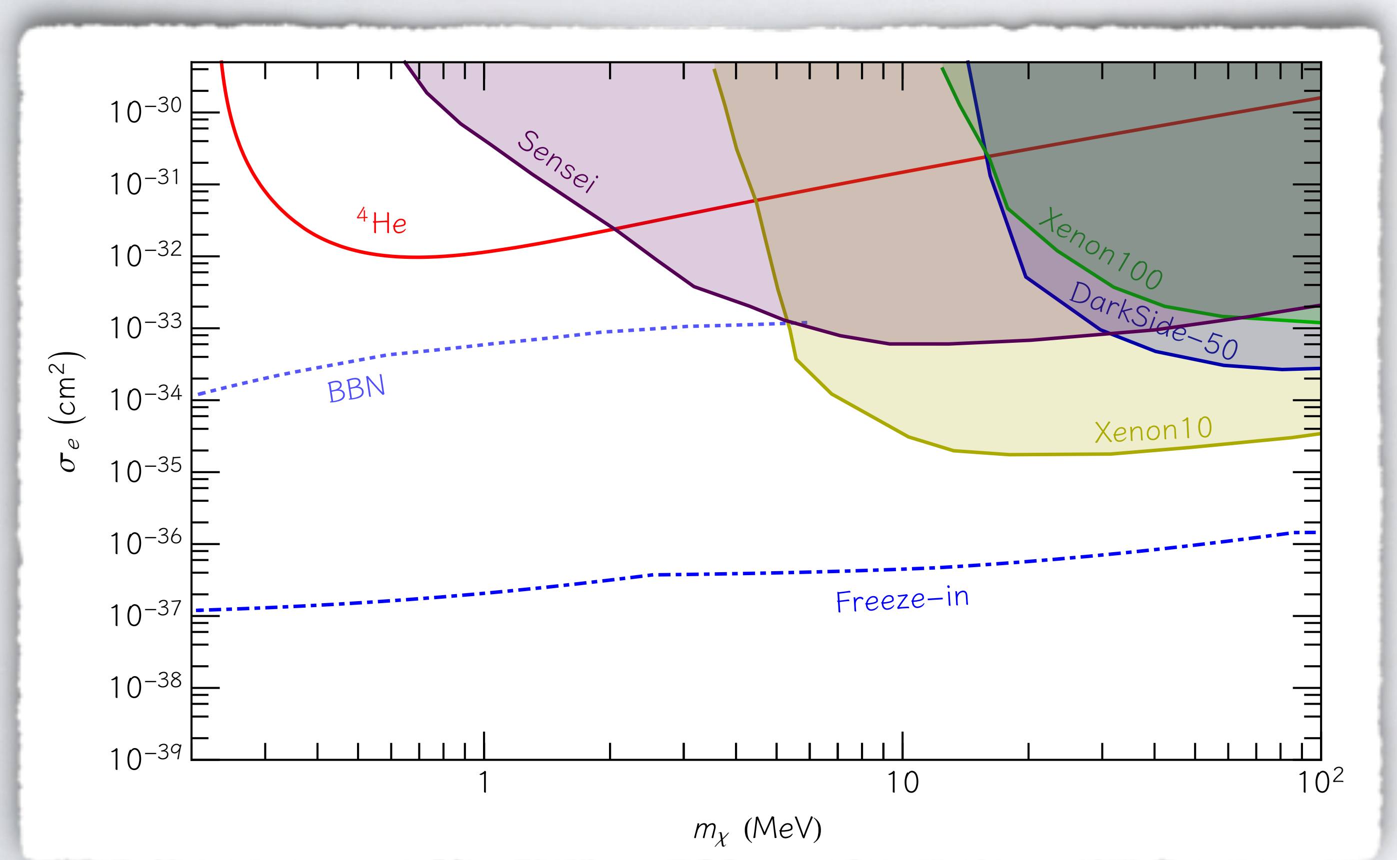
`[T. Lin — arXiv:1904.07915]`

- The heavy dark photon bounds from He-4 fall right in the middle of the stellar and accelerator constraints $\longrightarrow$ not competitive

ONE-PHONON EMISSION

Exclusion region — light dark photon

- A He-4 experiment can be competitive with other existing bounds only for ultra-light dark photon ($m_V \lesssim 10^{-13}$ eV)
- Excluded region for a single phonon with external electric field



[Caputo, AE, Geoffray, Polosa, Sun — arXiv:1911.04511]

However, in the region where He-4 performs best there are existing BBN bounds which are competitive

CONCLUSIONS

- A He-4 experiment for sub-MeV dark matter is a promising direction → a lot of R&D to do!
- The EFT for superfluids reproduces the standard results on He-4 dynamics → provides a key tool for future investigations
- In particular:

  a. Rotons play only a marginal role for the observable we are interested in

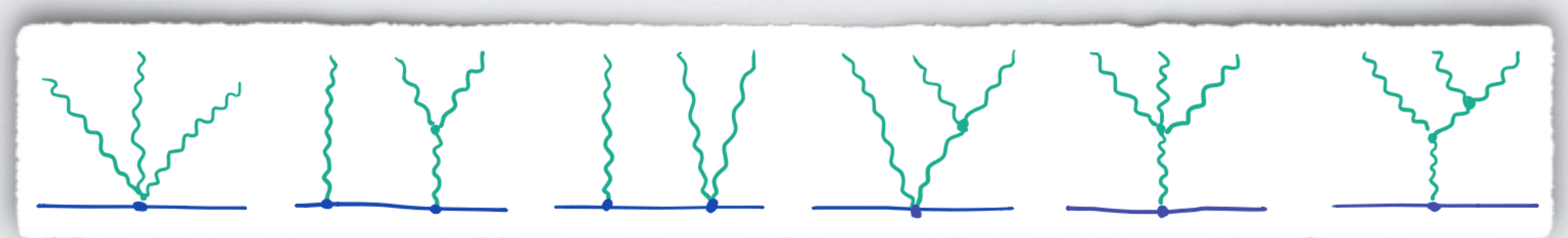
  b. We can compute easily angular distributions → key for detector design

  c. We understood why the keV-MeV mass region is strongly influenced by a cancellation between matrix elements

- More generally, the EFTs for condensed matter are mature enough to be successfully applied to relevant phenomenological problems

FUTURE PLANS

- Very important check: what about the 2 + (1-soft) phonon? Can this modify the projected exclusion region in a significant way?



- Possible other materials? E.g. emission of optical phonons in polar materials (w/ T. Melia), Crystals with high natural electric fields.

- Other devices involving He-4? E.g. exploit phase transition and viscosity and/or production of vortices

THANK YOU!

BACK UP

PHONON'S STABILITY

- Conservation of energy and momentum for a phonon decaying into two other phonons give

$$c_1 q_1 = c_2 q_2 + c_3 q_3 \,, \qquad q_1 = \sqrt{q_2^2 + q_3^2 + 2 q_2 q_3 \cos\theta_{23}} \leq q_2 + q_3$$

- The first equation implies

$$q_1 = q_2 + q_3 + \frac{c_2 - c_1}{c_1} q_2 + \frac{c_3 - c_1}{c_1} q_3$$

- If both $c_2, c_3 > c_1$ then the last equation gives $q_1 \geq q_2 + q_3$, which is in contradiction with the first equation and hence the decay is forbidden