Dark Matter interaction with He-4: an EFT approach

Andrea Caputo

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Worked based on:

Acanfora, Esposito, Polosa *Eur.Phys.J.C* 79 (2019) 7, 549
AC, Esposito, Polosa *Phys.Rev.D* 100 (2019) 11, 116007
AC, Esposito, Geoffray, Polosa, Sun *Phys.Lett.B* 802 (2020) 135258
AC, Cavoto, Esposito, Rossi, Polosa and Sun arXiv2007.????

IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

Outline

- EFT ideology
- EFT of He-4 and dark matter interactions
- Detection prospects and results
- Conclusion and future plans

EFT approach

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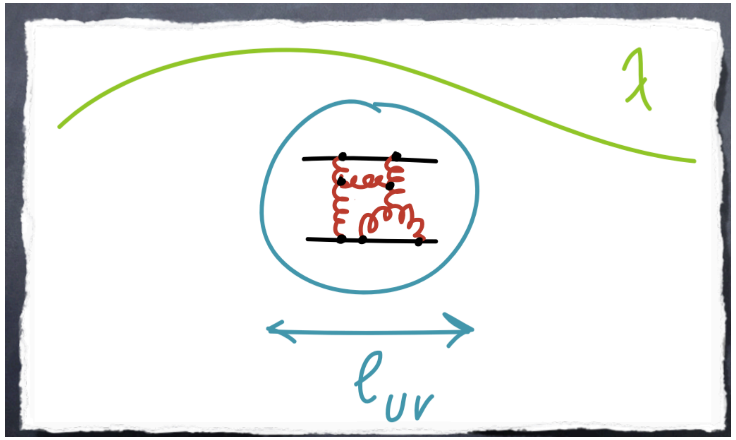
The ideology of EFT is bases on some simple pillars:

- Being agnostic about microscopic dynamics
- Focus on low-energy/long distance degrees of freedom and symmetries
- Organize theory as a derivative expansion



More technically, when we deal with condensed matter systems..

Condensed matter systems generically arise as Poincare symmetry-violating states of a symmetric theory. In particular each condensed matter system spontaneously breaks at least boosts.

Goldstone theorem then tells us that for a spontaneous broken symmetry there will be soft degrees of freedom known as Goldstone bosons

1) Identify Goldstones $\rightarrow$ 2) Identify the transformation under the symmetry group

$\rightarrow$ 3) write down the most general invariant Lagrangian in derivative expansion

EFT for superfluid He-4

From an EFT point of view, a superfluid is a system that

- Has a conserved U(1) symmetry
- Break boosts (as any condensed matter system), the extra U(1) and time translation
- Preserve the combined Hamiltonian $\mathrm{H}' = \mathrm{H} - \mu Q$, where Q is the generator of the U(1) and μ is the relativistic chemical potential. H' generates the unbroken time translations

Son arXiv 0204199
Nicolis arXiv 1108.2513
Nicolis, Piazza — JHEP (2012), 1112.5174

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Simplest implementation via a scalar field

- $Under\ the\ U(1) symmetry$ ψ(x) → ψ(x)+ c
- $< \psi(x) >= \mu t$ (VEV preserves H')
- $\psi(x) = \mu t + \pi(x)$ Goldstone field! The ***phonon***

Son arXiv 0204199
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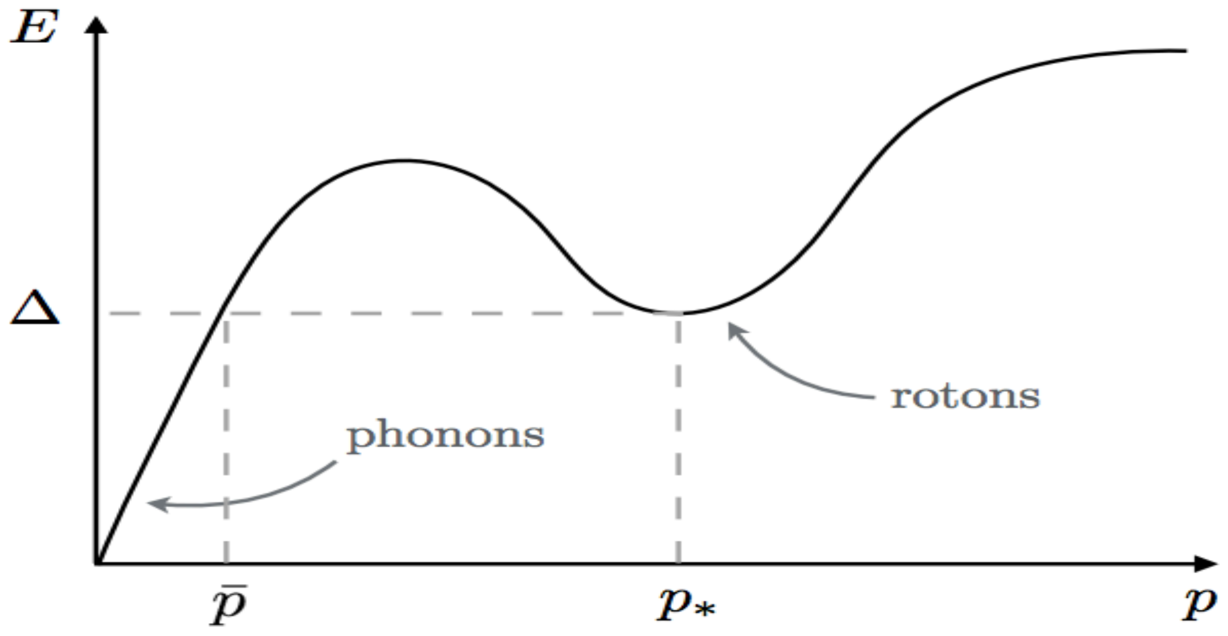
The superfluid U(1) is spontaneously broken by the VEV μt and phonons arise as fluctuations of the field ψ(x) around its VEV.



Nicolis, Penco Phys. Rev. B 97, 134516 (2018)

WE WILL DEAL WITH **PHONONS ONLY**

$$E_{\text{phonon}} \simeq c_s p \;, \qquad E_{\text{roton}} \simeq \Delta + \frac{(p-p_*)^2}{2m_*} \,.$$

$$c_s \sim \frac{1}{ma}, \qquad \Delta \sim \frac{1}{ma^2}, \qquad p_* \sim \frac{1}{a}, \qquad m_* \sim m \,.$$

$$\bar{p} \approx 1keV \; (EFT \;\; cutoff)$$
$$c_s \approx 10^{-6}$$

The EFT Lagrangian of He-4

Now we need to write down the Lagrangian for the superfluid, which needs to be invariant under the entire broken group

$$S_{\text{bulk}} = \int d^4x \, P(X) \quad \text{with} \quad X = \sqrt{-\partial_\mu \psi \partial^\mu \psi}$$

X is the local value of the chemical potential which, in the presence of a nontrivial fluctuations, differs from the equilibrium value μ. P(X) can be in principle a generic function of the invariant X; it turns out to corresponds to the pressure of the superfluid

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Then now one needs to expand the Lagrangian in small fluctuations (the phonon field)

$$S_{\mathrm{bulk}} \supset \frac{\bar{n}}{\mu c_s^2} \int d^4x \left[\frac{1}{2}\dot{\pi}^2 - \frac{c_s^2}{2}(\boldsymbol{\nabla}\pi)^2 + \lambda_3 \dot{\pi}(\boldsymbol{\nabla}\pi)^2 + \lambda_3' \dot{\pi}^3 \right]$$

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

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

Effective parameters for the superfluid action

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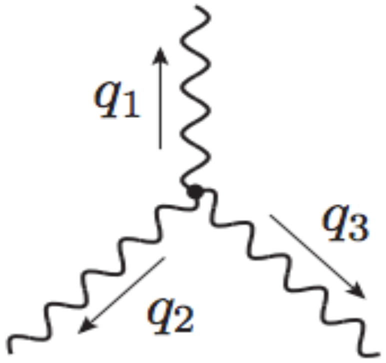

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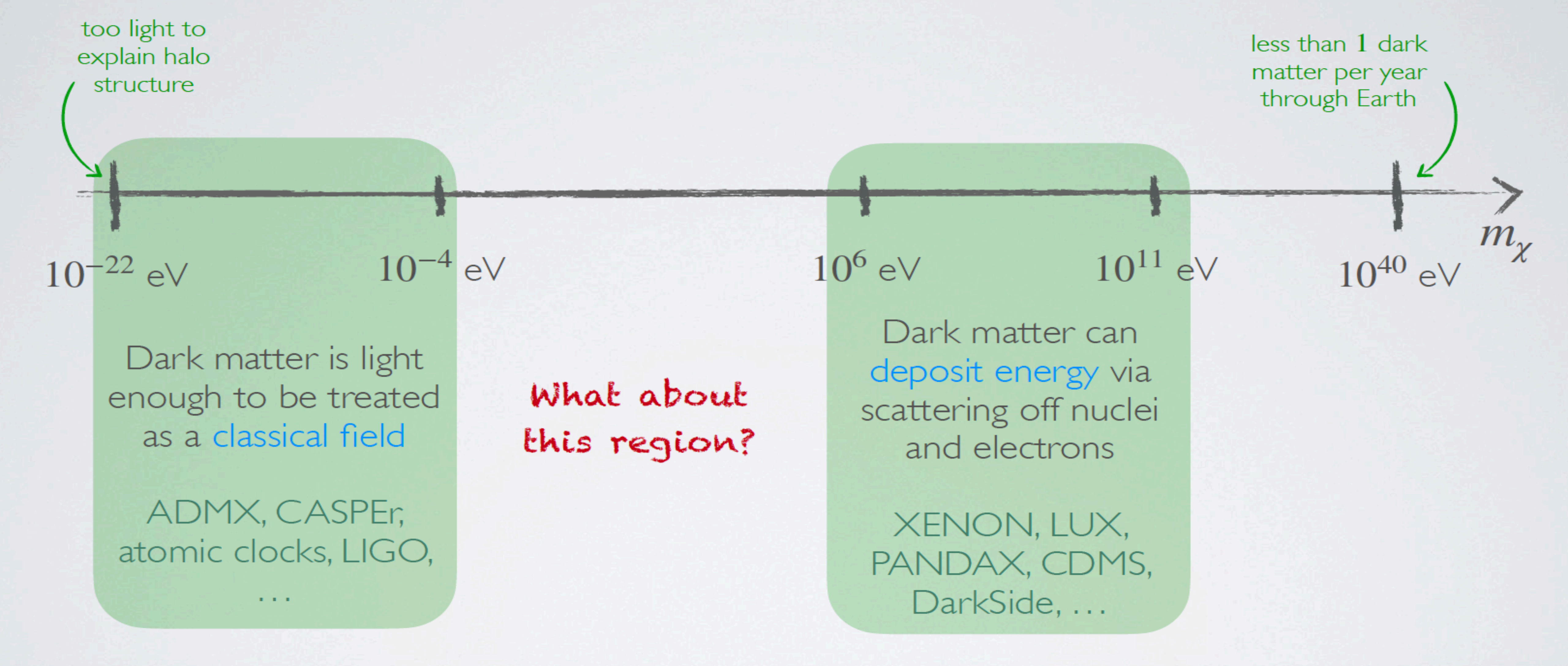
Effective parameters for the superfluid action

We have a description of the bulk of the superfluid, now let's add dark matter!



Light (sub-MeV) dark matter is difficult to see with usual DM experiments base on energy recoil.
He-4 has some advantages: 1) light nucleus 2) gapless excitations!

Guo, McKinsey — PRD (2013), 1302.0534;
Schutz, Zurek — PRL (2016), 1604.08206;
Knapen, Lin, Zurek — PRD (2017), 1611.06228

We can consider the generic interaction

$$\mathcal{L}_{int} = -G_\chi m_\chi |\chi|^2 n(X)$$

Superfluid number density, it depends on the invariant X

χ *is the dark matter*

G_χ *the unknown coupling to determine*

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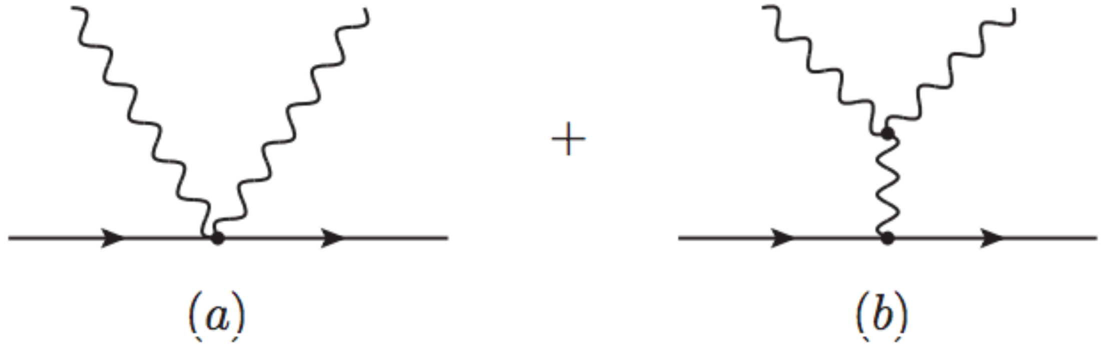
$$\boxed{S_{int} = \int d^3x dt\, G_\chi m_\chi |\chi|^2 \left[\frac{\bar{n}}{\mu c_s^4}\dot{\pi} + \frac{\bar{n}}{2\mu^2 c_s^2}(1 - c_s^2)(\nabla\pi)^2 + \frac{1}{2}\frac{d^2\bar{n}}{d\mu^2}\dot{\pi}^2 \right]}$$



Leading diagrams contributing to the two-phonon emission process

$$\mathcal{M}_a = \frac{c_s^2}{\bar{n}}\left(m_{\mathrm{He}} g_2 \omega_1 \omega_2 - g_1 \boldsymbol{q}_1 \cdot \boldsymbol{q}_2\right) ,$$

$$\mathcal{M}_b = -2 g_1 \frac{m_{\mathrm{He}} c_s^2}{\bar{n}} \frac{\omega}{\omega^2 - c_s^2 \boldsymbol{q}^2} \times \left[\lambda_3(\omega_1 \boldsymbol{q}_2 \cdot \boldsymbol{q} + \omega_2 \boldsymbol{q}_1 \cdot \boldsymbol{q} + \omega \boldsymbol{q}_1 \cdot \boldsymbol{q}_2) + 3\lambda_3' \omega_1 \omega_2 \omega\right]$$

The amplitudes and the cross sections for dark matter scattering are easily calculated from the Lagrangian.

Standard QFT computations!

What about detection?

Two kinds of techniques:

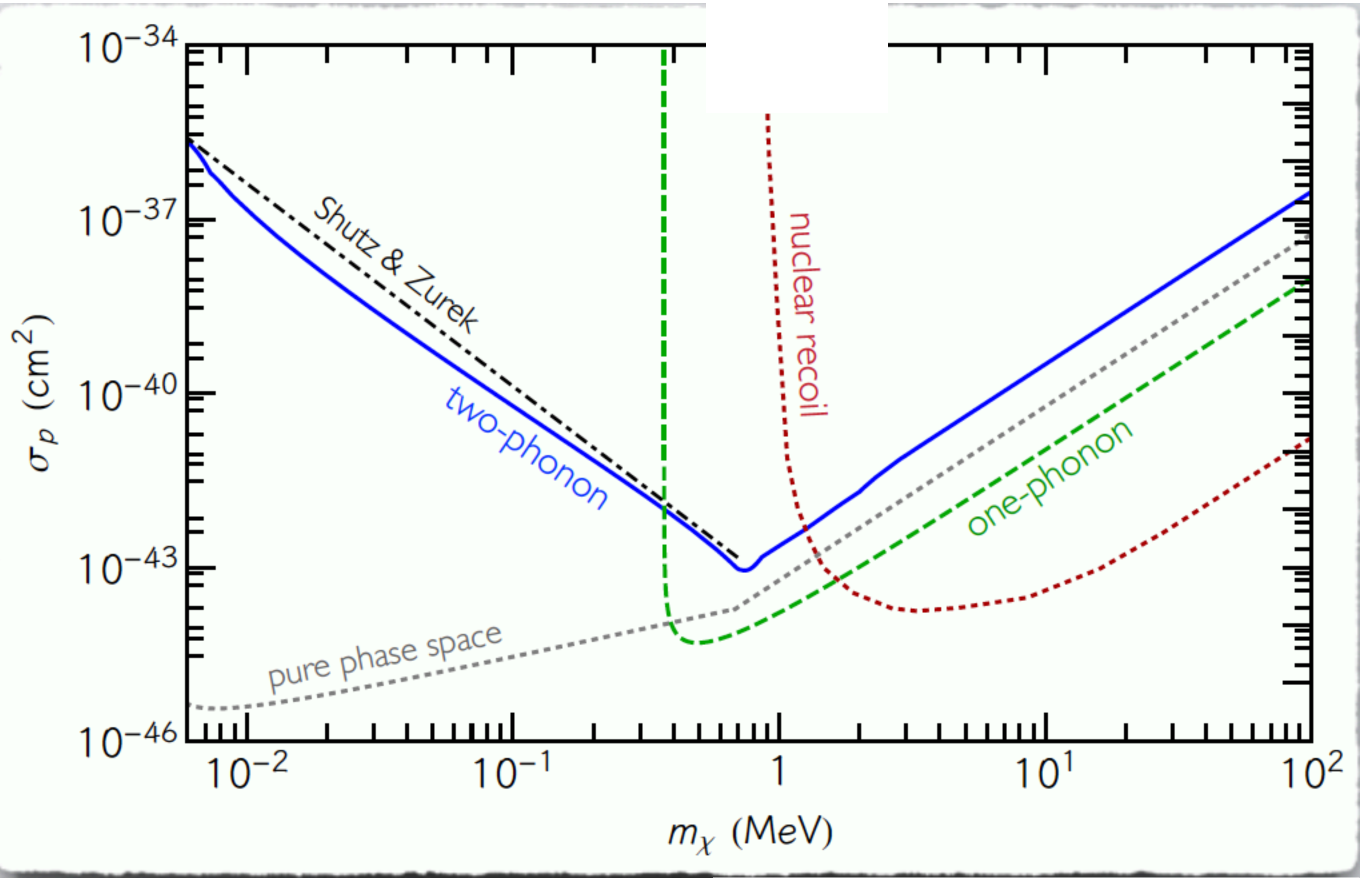
- **Quantum evaporation**: phonons travel up to the surface of He-4 and if energetic enough they can extract an atom ($\omega > 0.62\, meV$)

- **Energy release**: phonons deposit energy which can be detected with calorimetric techniques ($\omega_{tot} > 1\, meV$)

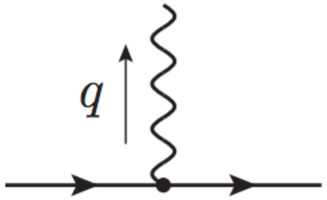
Hertel et al. — PRD (2019), 1810.06283; Maris, Seidel, Stein — PRL (2017), 1706.00117

Some results

AC, Esposito, Polosa — PRD (2019), 1907.10635



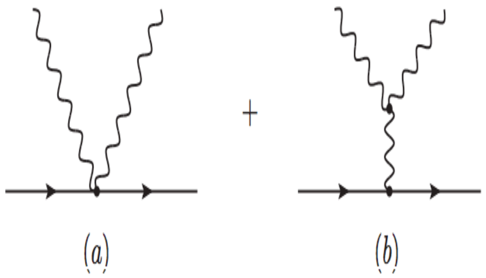
- **One phonon**



Its energy is not enough to be detected with calorimetry, one needs to use quantum evaporation.

$$\omega_{max} = c_s 2 m_\chi v_\chi > 0.62\, meV \ \rightarrow m_\chi > 1 MeV$$

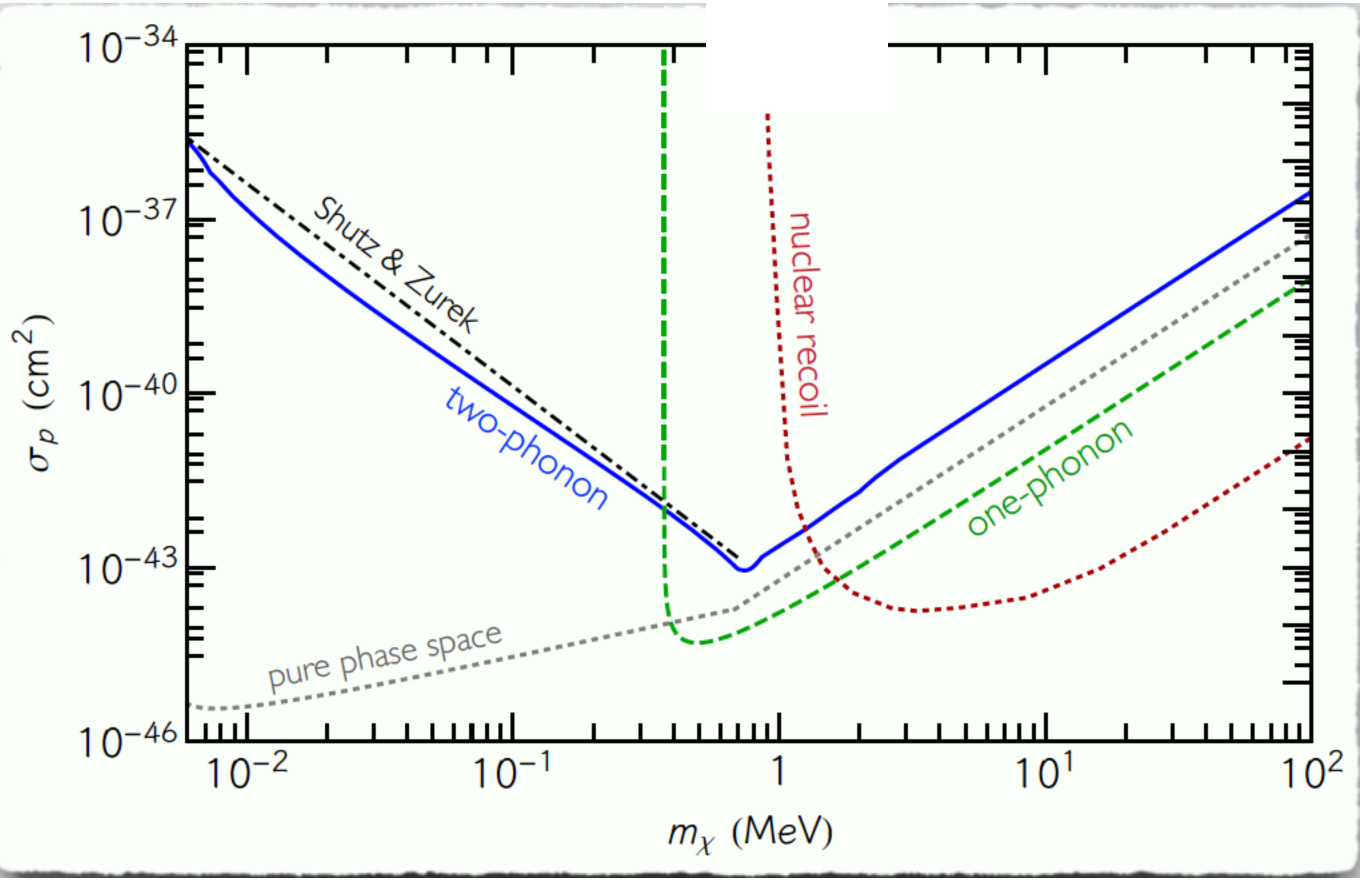
- **Two phonons**



This is effective also at masses lighter than 1 MeV and detectable via both quantum evaporation and energy deposit.
The kinematic is of course more complicated then the single phonon process, and the momentum transfer can go virtual.

Some results

AC, Esposito, Polosa — PRD (2019), 1907.10635



Some remarks:

- Our results match those obtained by Shutz & Zurek and Knapen, Lin & Zurek;
- Our theory does not include rotons, this means that the main contribution is coming from phonons; higher excitations are not relevant;
- For the two phonons case, huge suppression compared to phase space only! Why is that?

Some results

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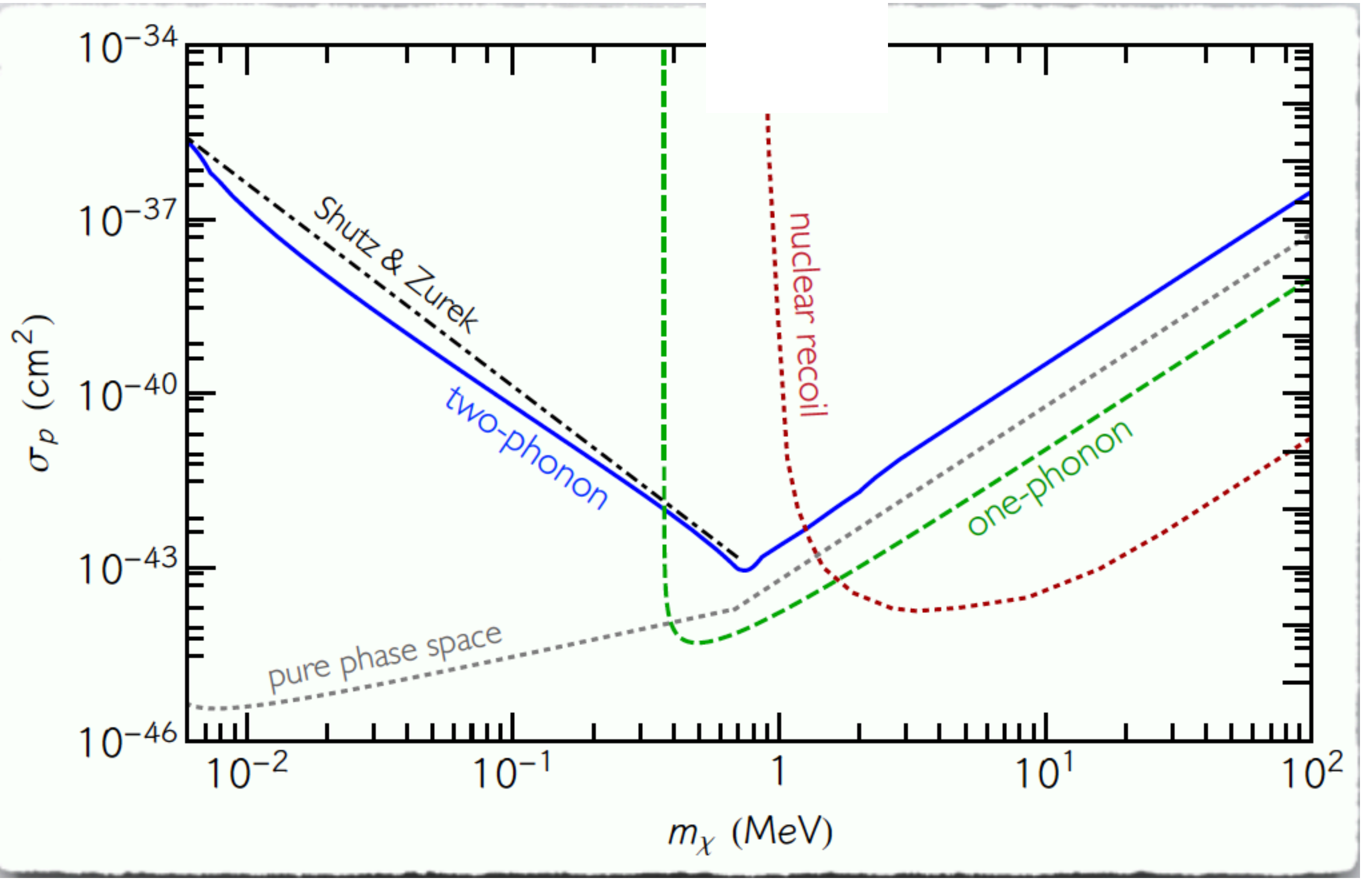

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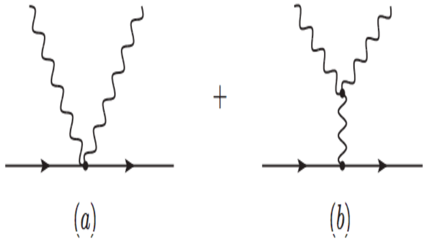
The energy released to the system is maximized when the two phonons are almost back-to-back. In this limit there is an exact cancellation between the two relevant diagrams

$$\mathcal{M}_a + \mathcal{M}_b = O(q^2/\omega^2)$$



- This is a consequence of current conservation for the symmetry $U(1)$ (Ward Identity)

$$\langle \pi(q_1)\pi(q_2)|J^\mu(x)|\mu\rangle = i^2 \int d^4x_1 d^4x_2 e^{-iq_1\cdot x_1 - iq_2\cdot x_2}\left(\partial^2_{t_1} - c_s^2\boldsymbol{\nabla}^2_{x_1}\right)\left(\partial^2_{t_2} - c_s^2\boldsymbol{\nabla}^2_{x_2}\right)\times$$
$$\times\, \langle \mu|T\left(\pi(x_1)\pi(x_2)J^\mu(x)\right)|\mu\rangle\,.$$

Consider then the LSZ formula for the matrix element of the current with two outgoing phonons; use conservation of current and notice that in the limit of zero momentum transfer the matrix element for the emission of two phonons vanished

PECULIAR OF THE COUPLING TO DENSITY!

AC, Esposito, Polosa — *J.Phys.Conf.Ser.* 1468 (2020) 1, 012060

With the EFT approach is very easy to explore different models. Just build your theory, compute your diagrams and get your results!

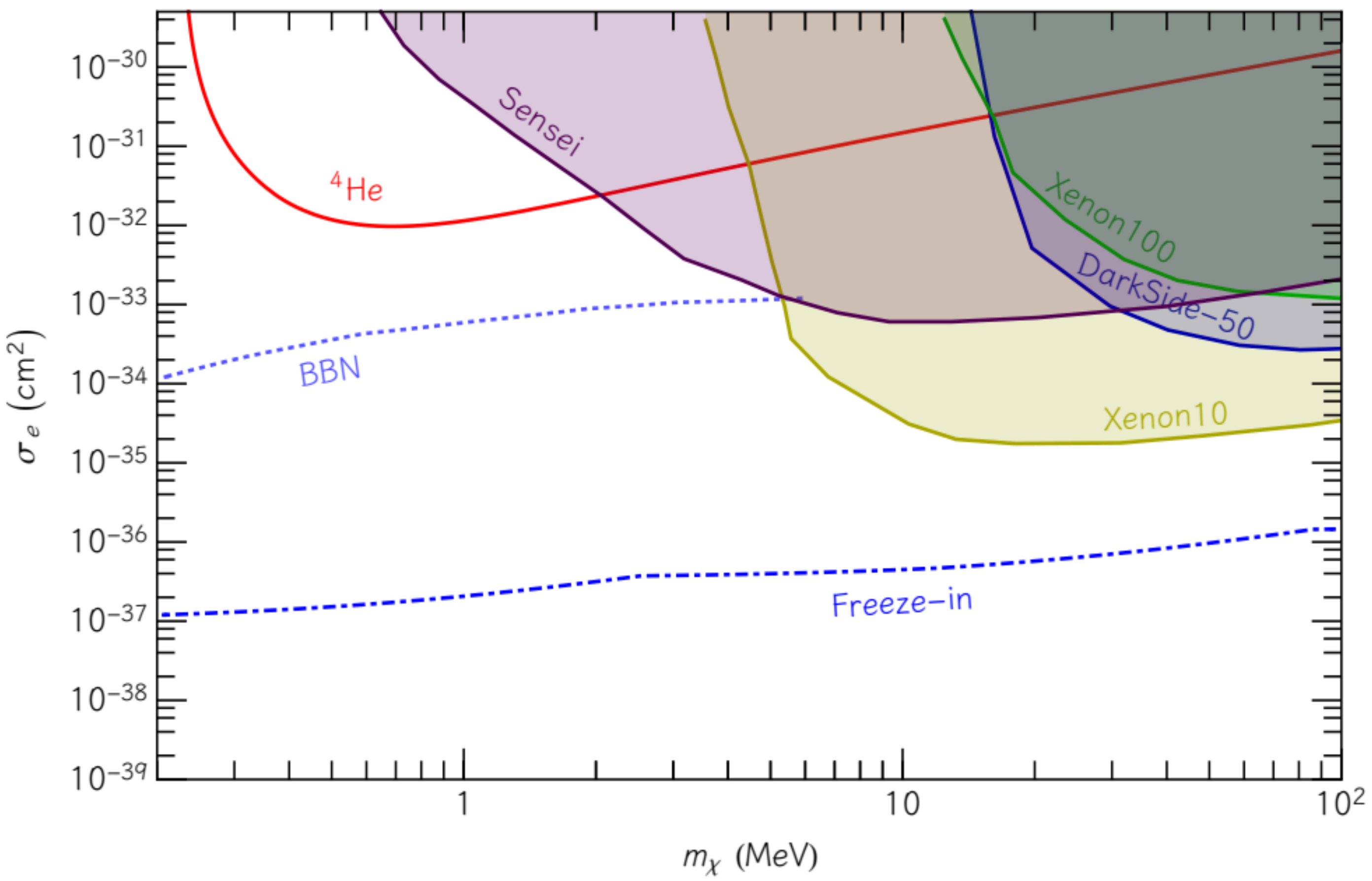
For example you can apply the same idea to a model where dark matter is mediated by a dark photon

$$S_{\rm eff} = -\int d^4x \Big[\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{4} V_{\mu\nu} V^{\mu\nu} - \frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu} + \frac{m_V^2}{2} V_\mu V^\mu - \bar{\chi}\big(i\gamma^\mu D_\mu - m_\chi\big)\chi - \frac{1}{2} a(X) F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} b(X) F^{\mu\rho} F^{\nu}{}_{\rho} \partial_\mu \psi \partial_\nu \psi \Big]$$

Here there are new effective coefficients, a(X) and b(X), that are obtained from the electric and magnetic susceptibilites of He-4

AC, Esposito, Geoffray, Polosa, Sun — PLB 2019, 1911.04511

We find it to be promising just for the single phonon process and with the introduction of a strong external electric field (max 100 kV/cm)



AC, Esposito, Geoffray, Polosa, Sun — PLB 2019, 1911.04511

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

Conclusions

- Superfluid He-4 is a very nice possibility, but there are a lot of experimental details to work out
- For this, having a theoretical control of the signal is crucial; an EFT approach allows to ’’easily’’ do theoretical calculations
- The EFT approach speaks high energy physicist’s language
- Future directions: three-phonon emission, inclusion of phonon’s nonlinearities, study of other systems such as superconductors, crystals, etc.

Thanks for attention