Superfluid effective field theory

for sub-GeV dark matter direct detection

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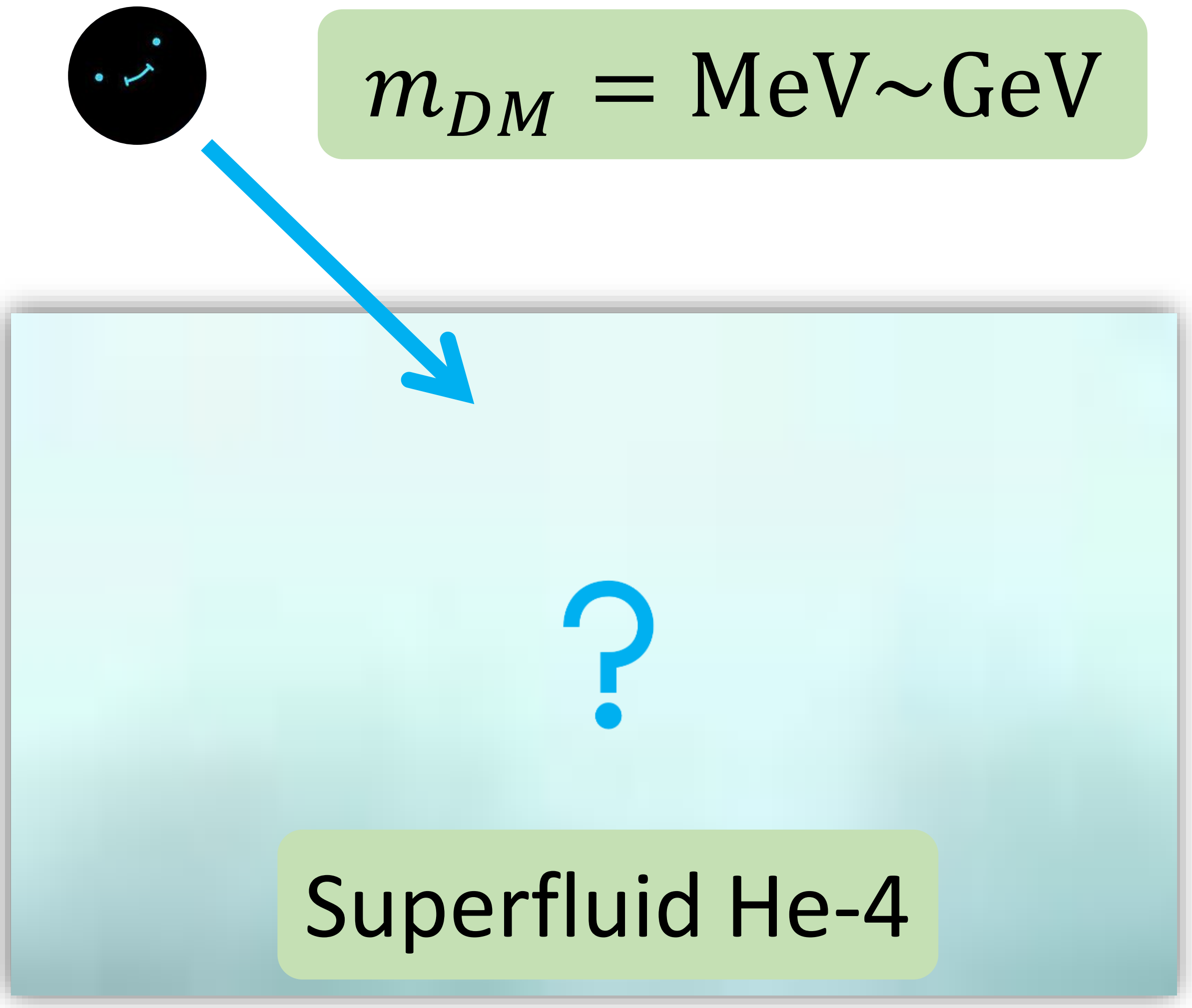
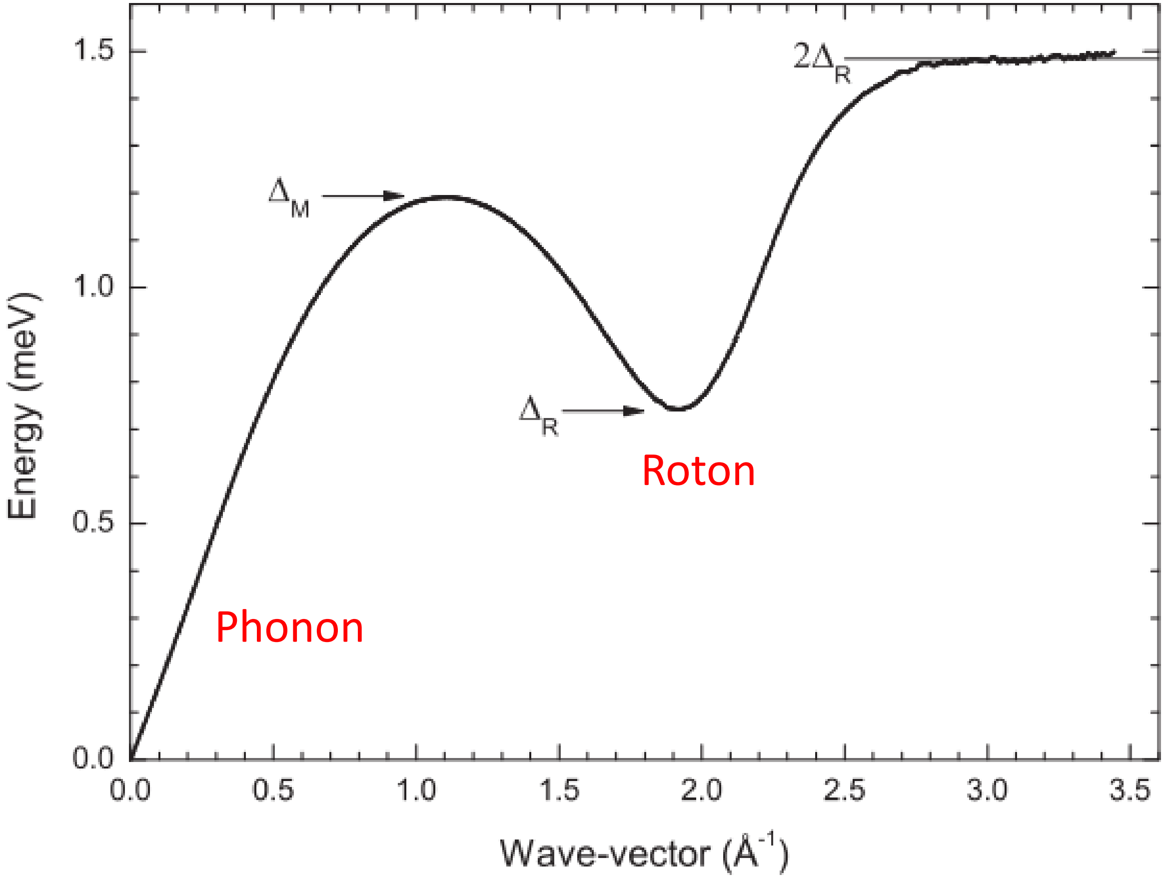
1. Direct detection set-up



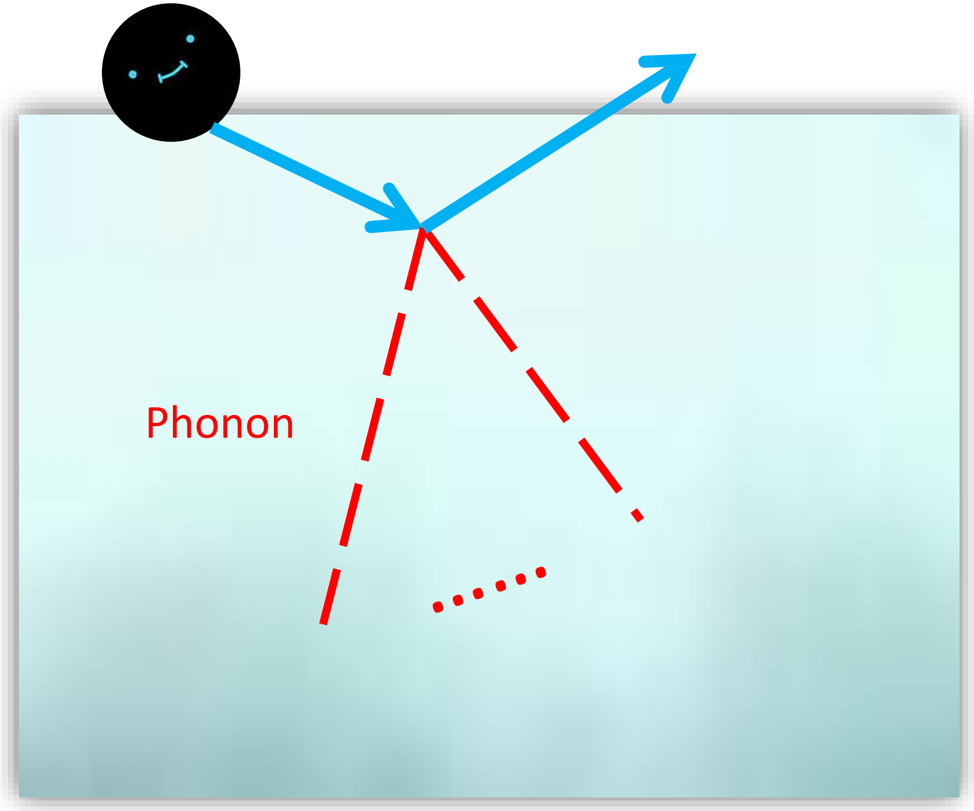
2. Quasi-particles in Superfluid He-4



Godfrin, H., et al. 2021

3. Deliverables

Previous works $m_{DM} < \text{MeV}$



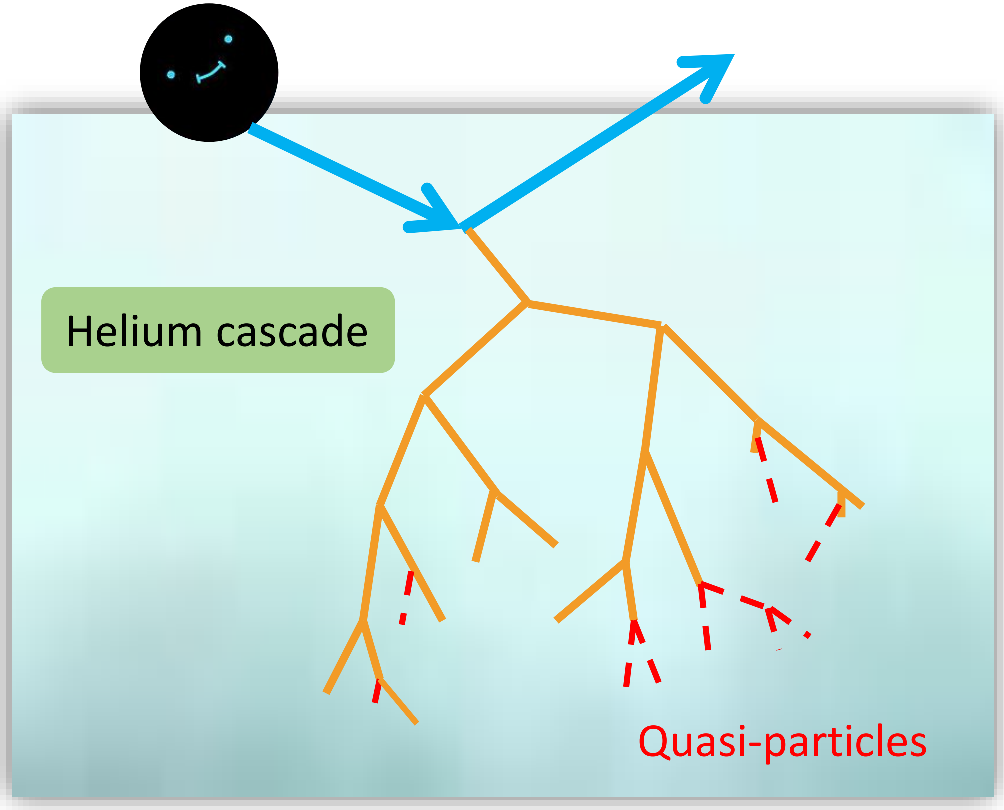
Knapen, S., et al. 2017

Caputo, A., et al. 2019

Baym, G., et al. 2020

3. Deliverables

Our work MeV $< m_{DM} <$ GeV



DM scatters helium atom

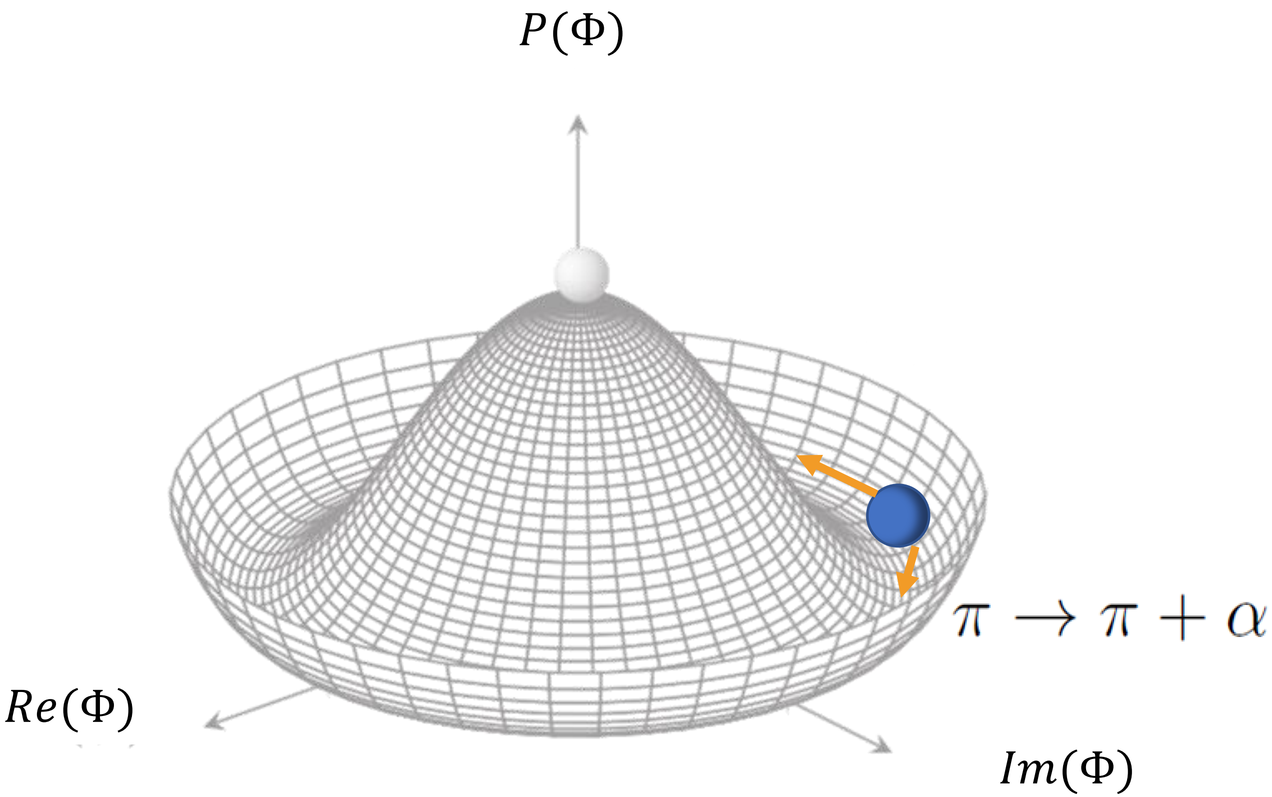
Helium cascade

Helium atoms emit quasi-particles

Quasi-particles decay/self interaction

Son, D. T. 2002

4. Phonon as Goldstone boson



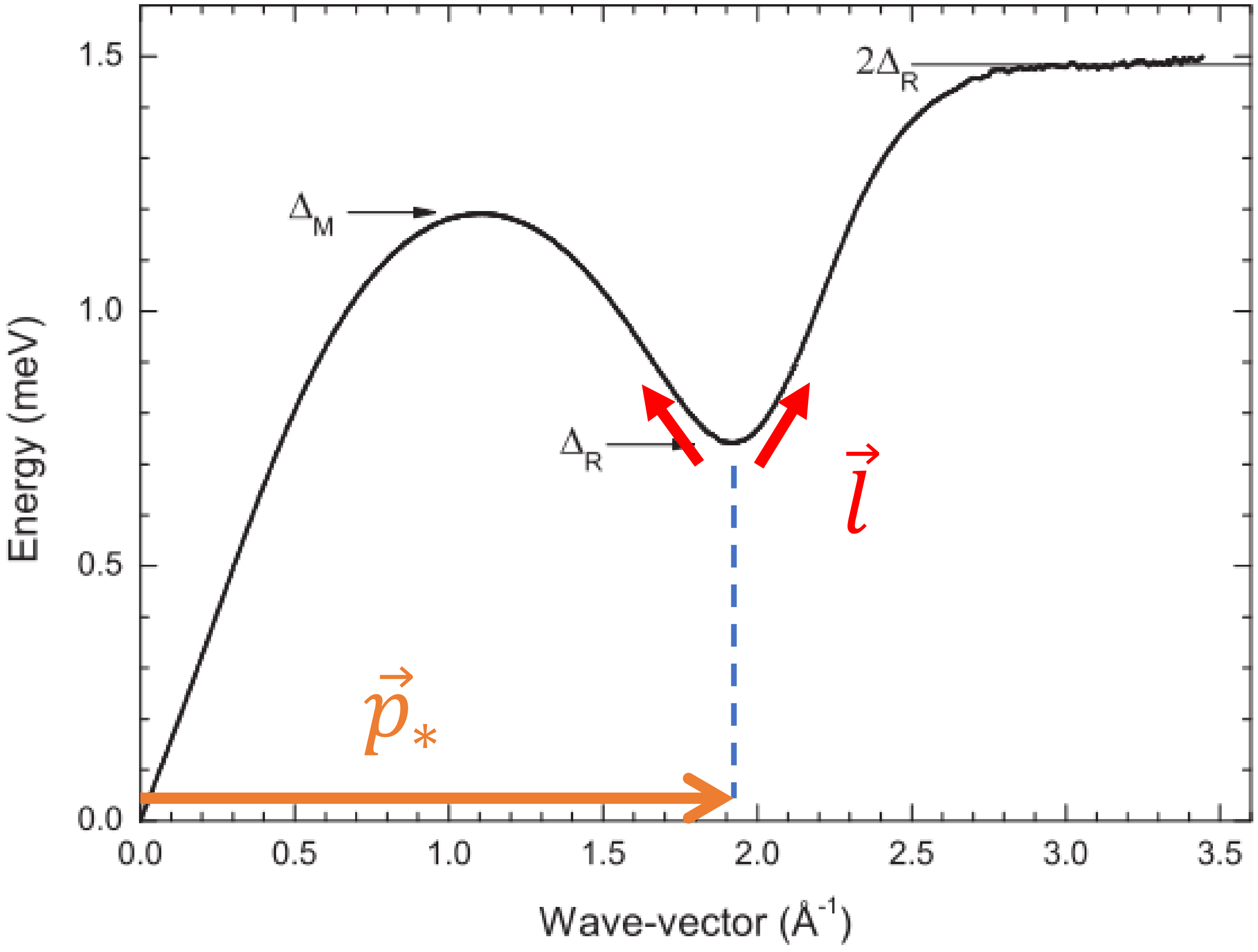
Phonon -- π
Superfluid helium -- $\Phi = \langle vac \rangle e^{-i\pi}$

Number conservation U(1) symmetry -- $\Phi e^{-i\alpha}$

Symmetry breaking produce Goldstone boson -- $\pi + \alpha$

$$\mathcal{L}(\Phi) \to \mathcal{L}(\pi)$$

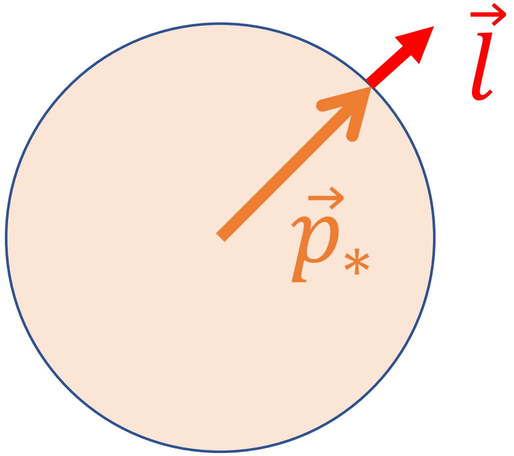
5. Roton φ^4 from power counting



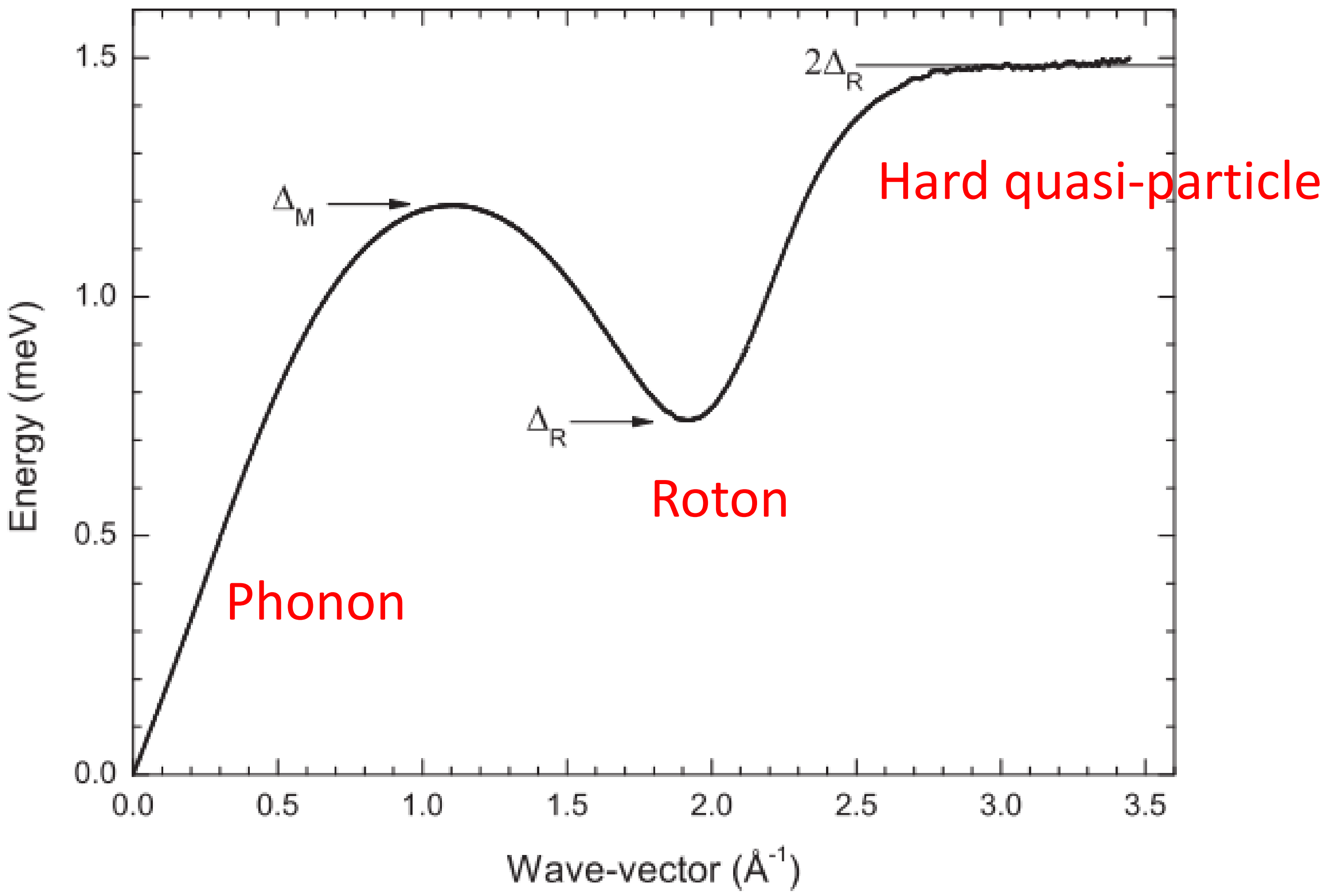
Phase space similar to Fermi surface

↓

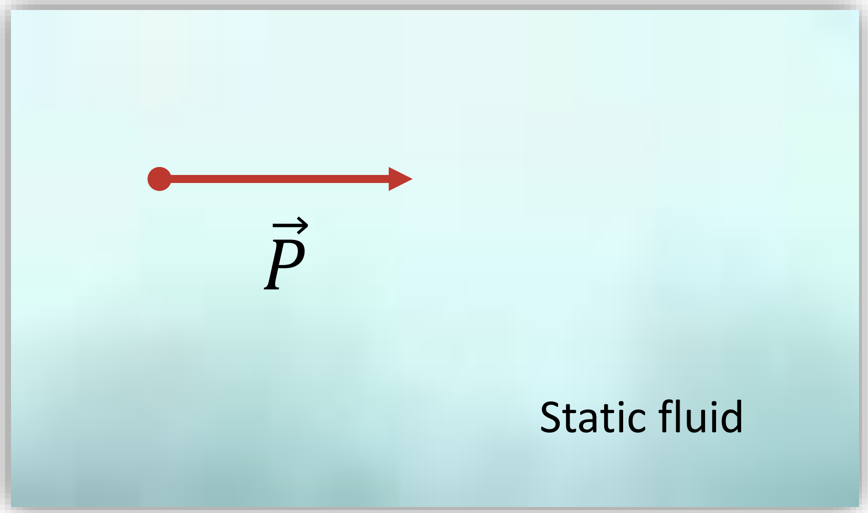
Power counting shows φ^4 is a marginal operator

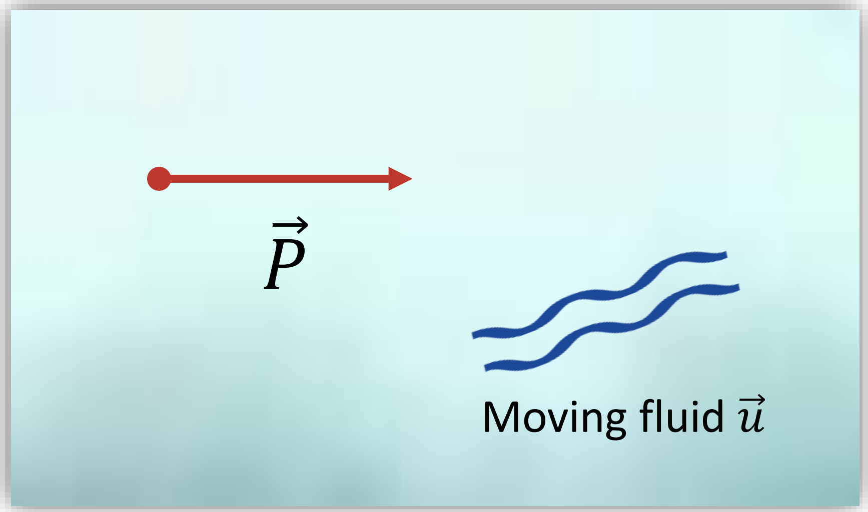


6. Phonon interact with hard quasi-particles



6. Hard quasi-particle as an impurity



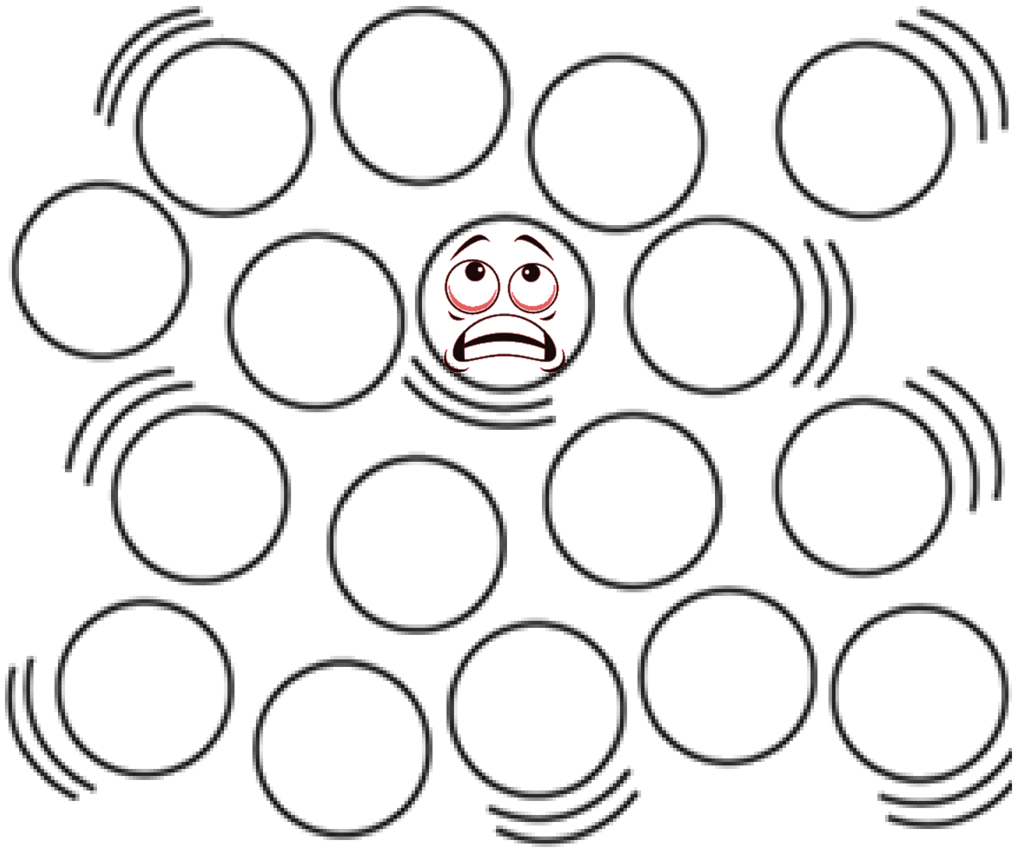


Dispersion in moving fluid – Dispersion in static fluid = Interaction with the moving fluid

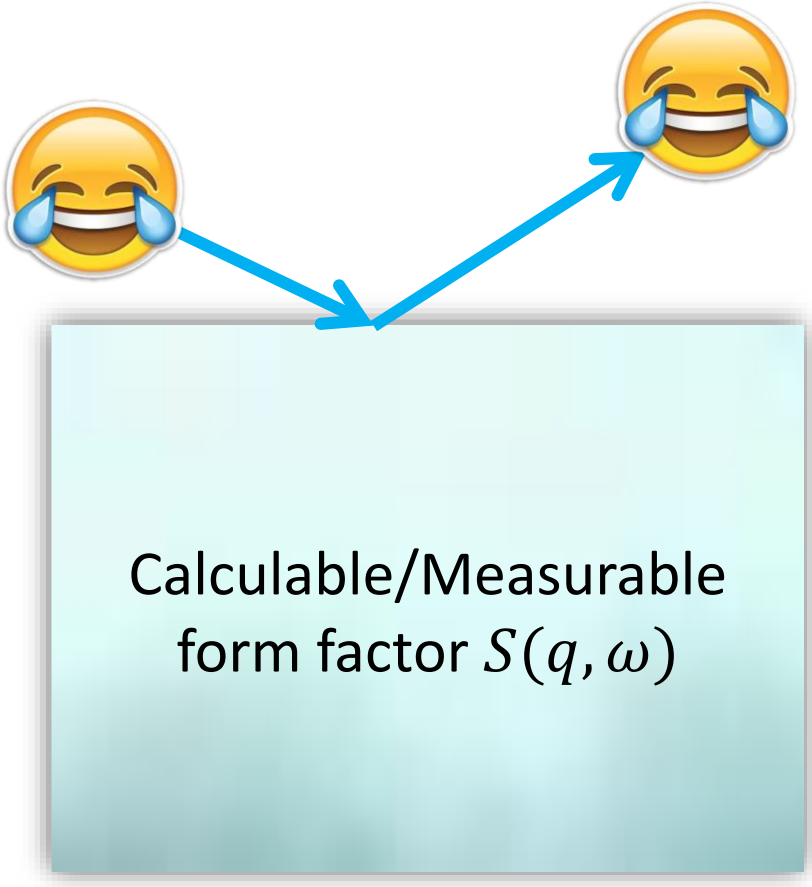
(after quantization) with phonon

Landau, L. D. Statistical physics, part 2

7. Helium emitting quasi-particles

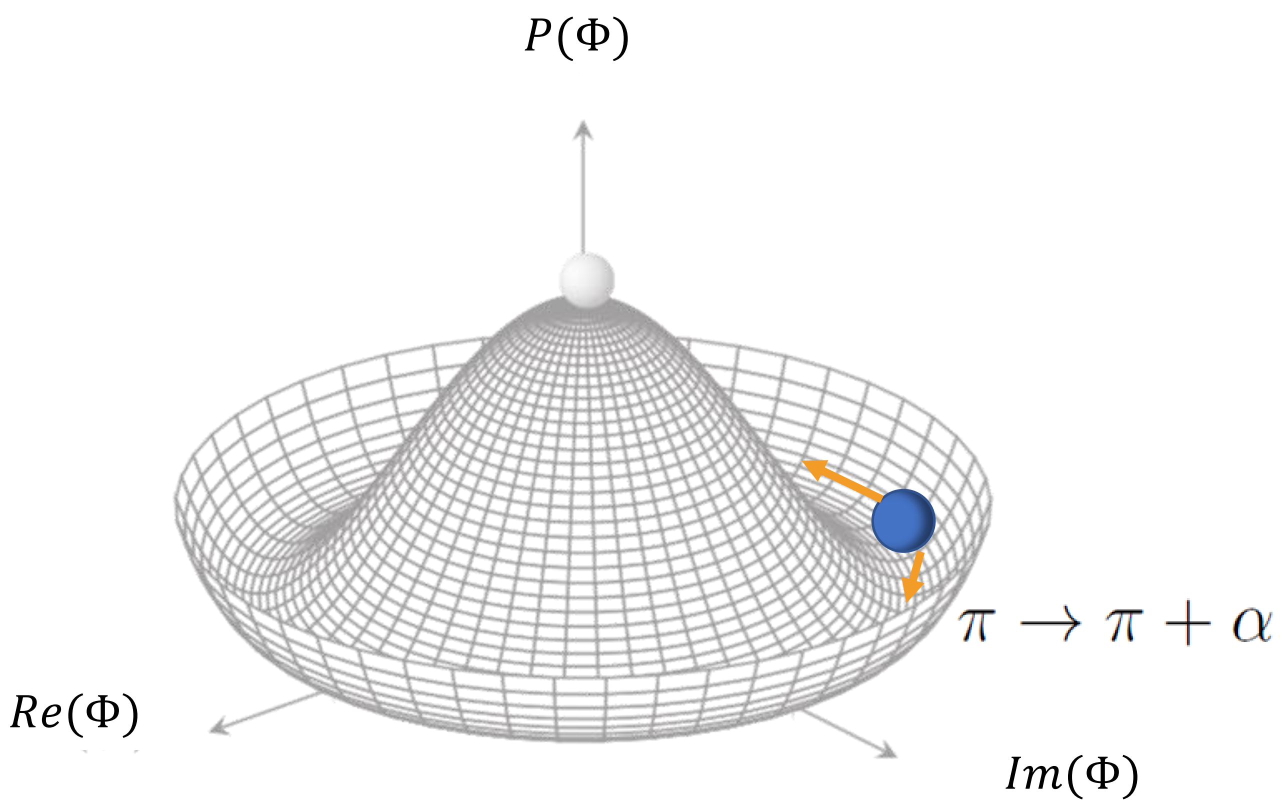


Slow helium (Non-perturbative)



Fast/Weakly interacting particles
(Perturbative)

7. Helium-phonon coupling



$$D_\mu \Phi = (\partial_\mu + i\partial_\mu \pi)\Phi$$

↓

Scalar + Vector coupling between Helium Φ and phonon π currents

↓

Reproduce form factor $S(q,\omega)$ of phonon

7. "Form factor"

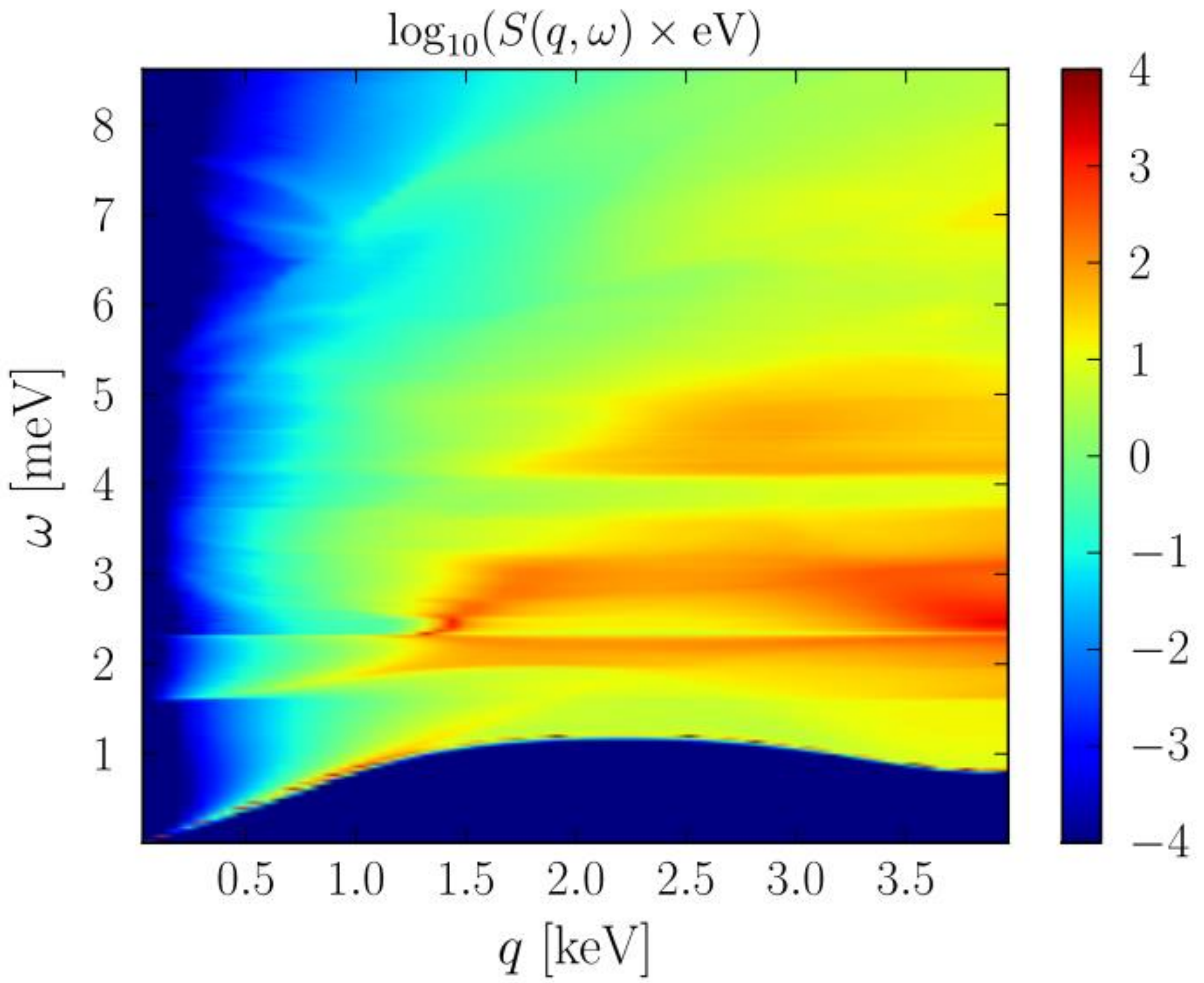
Scalar + Vector coupling between Helium Φ and phonon π

↓

Scalar + Vector coupling between Helium Φ and any quasi-particles

↓

We can calculate the production rate from numerical/experimental value of the form factor



Campbell, C. E., et al. 2015

Summary

- Phonon as Goldstone boson → phonon as spurious gauge boson → Helium-phonon coupling
- Roton with a Fermi type power counting
- Hard quasi-particle interacting with phonon (impurity)
- Helium emitting quasi-particles from Form Factors

Thanks for your attention!