Superfluid effective field theory

for sub-GeV dark matter direct detection

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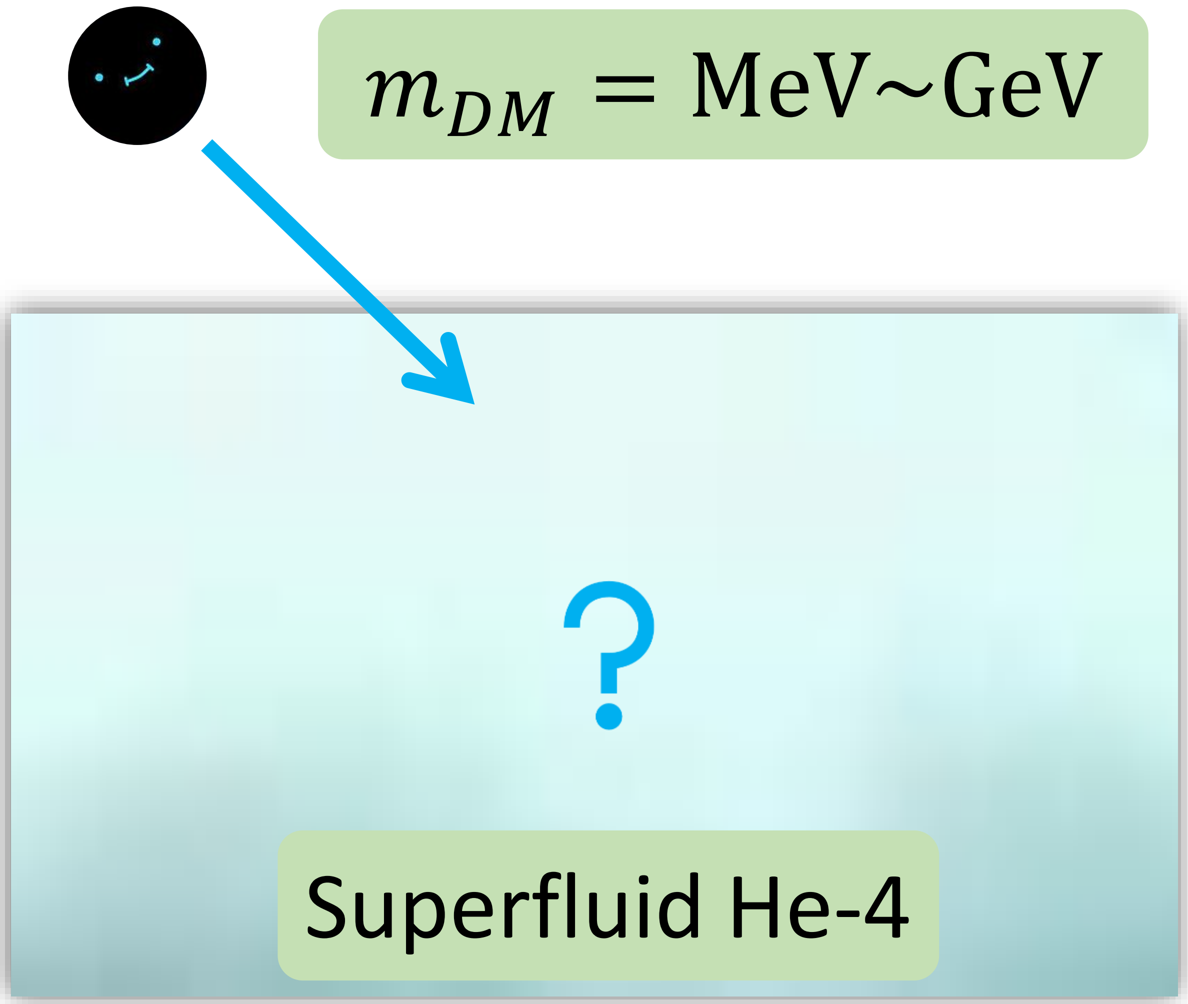
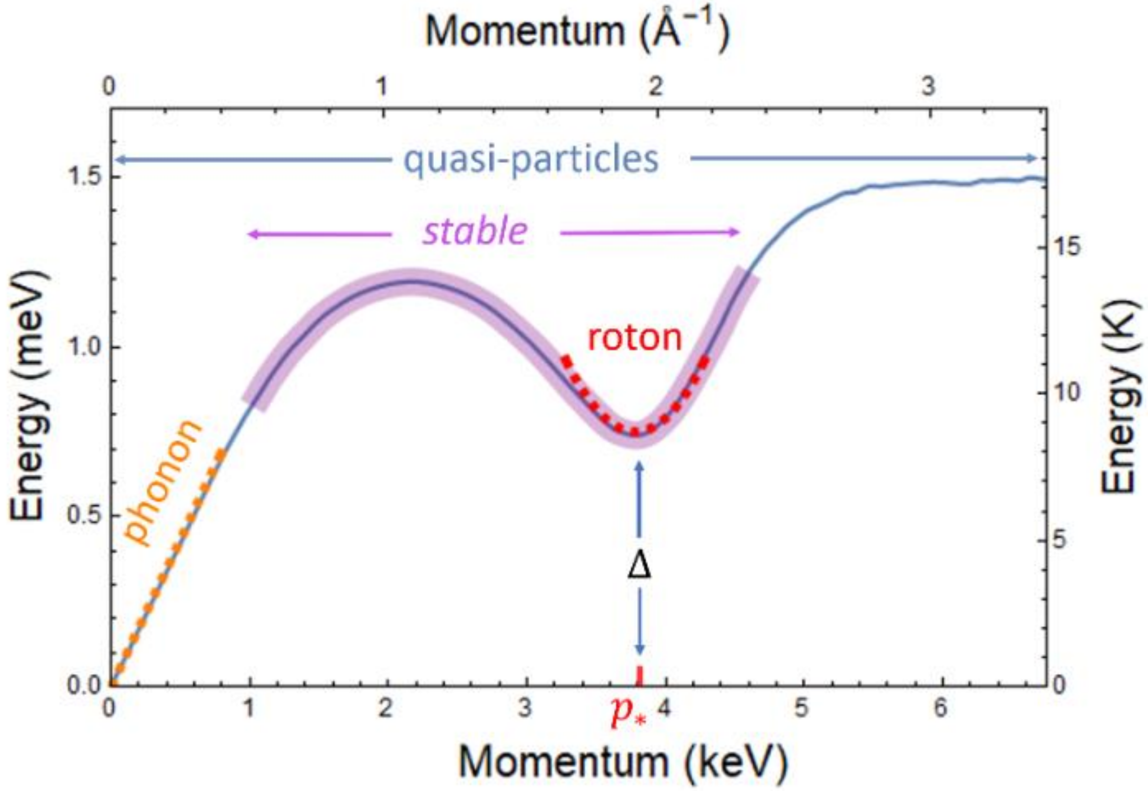
DPF 2021, July 12th

1. Direct detection set-up



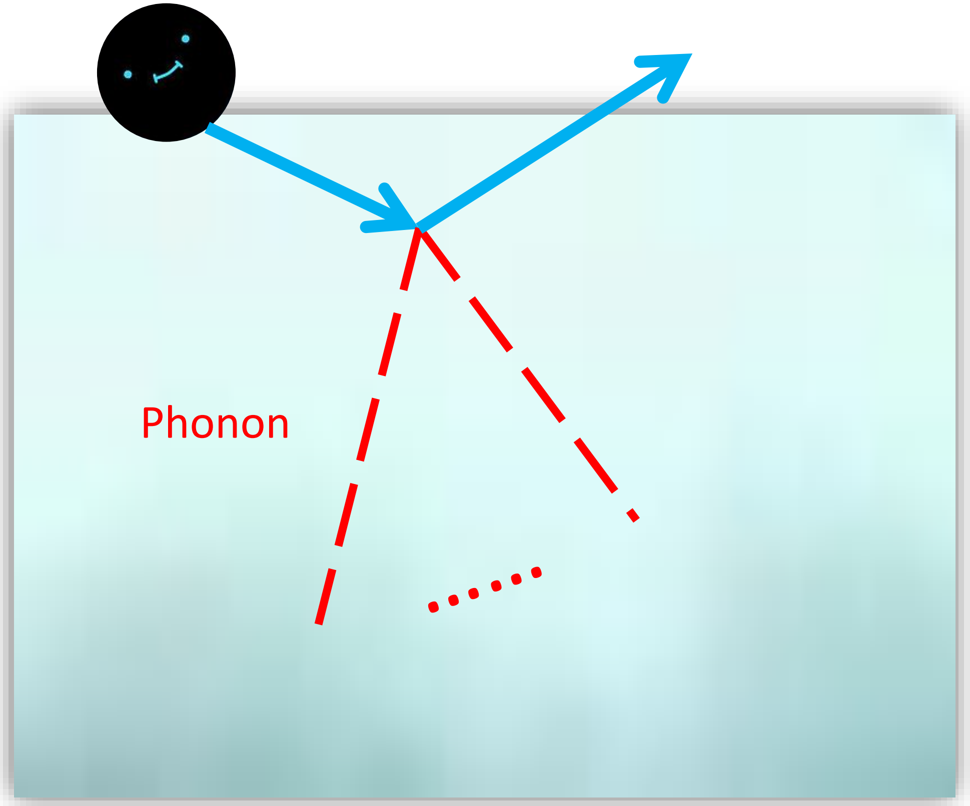
2. Quasi-particles in Superfluid He-4



Godfrin, H., et al. 2021

3. Deliverables

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



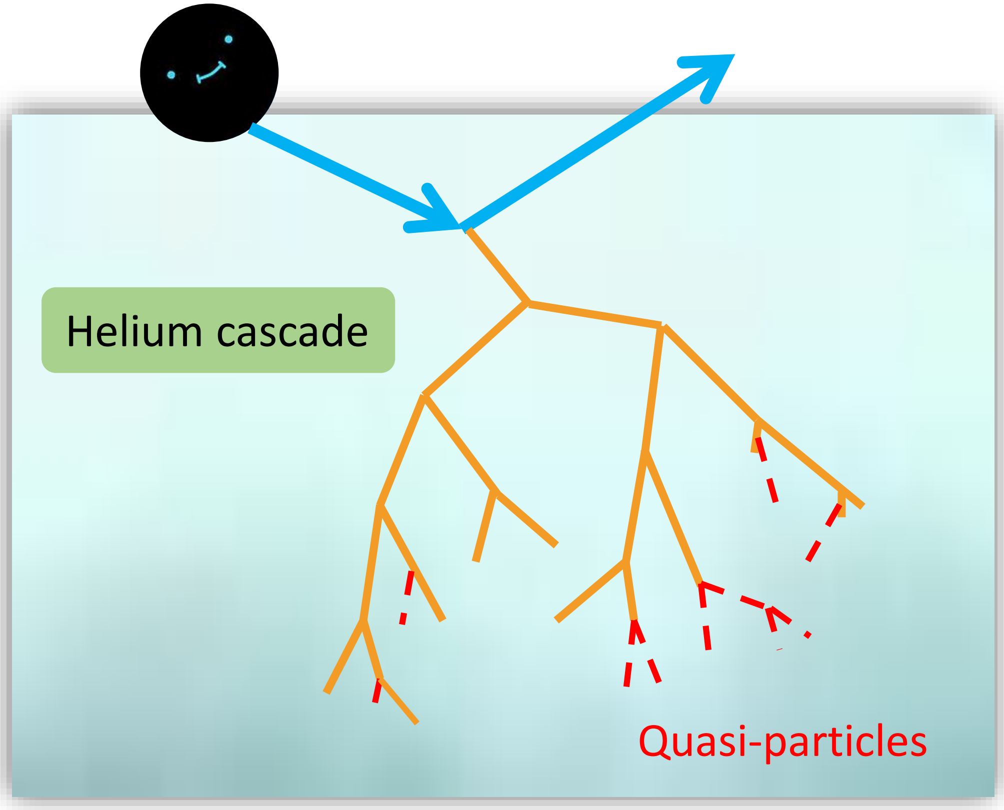
Knapen, S., et al. 2017

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

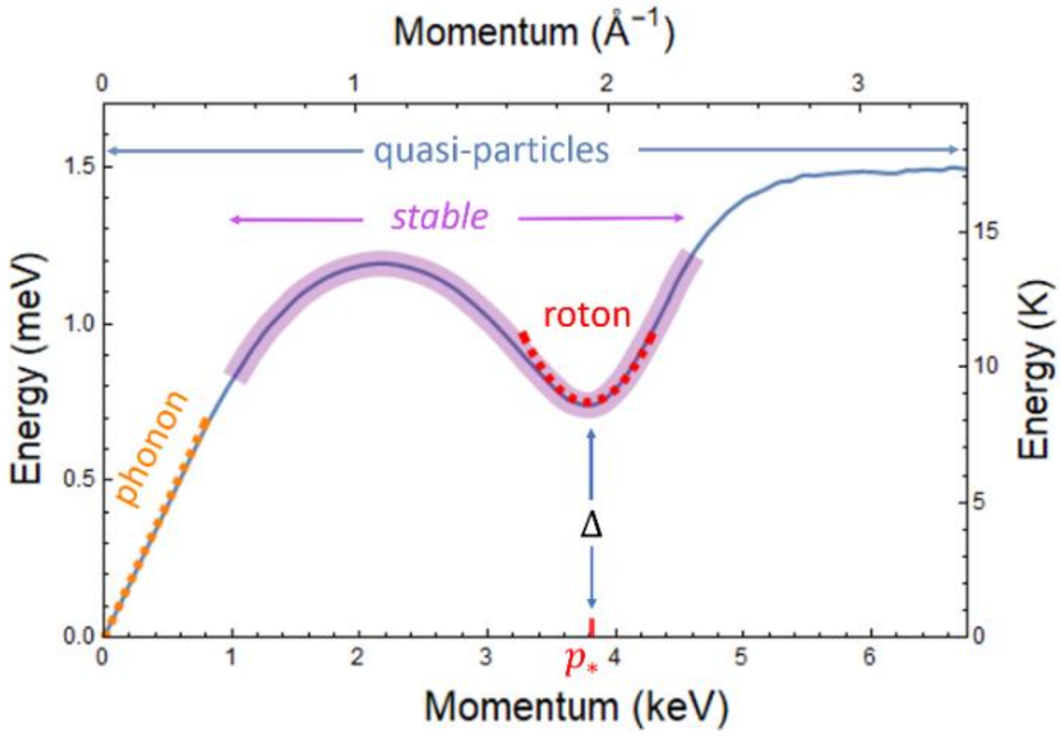
Quasi-particles decay/self interaction

4. New deliverables for DPF21

Power counting:

to determine Wilson coefficients in bottom-up EFT

- Phonon self-interaction
- Roton self-interaction
- Phonon - quasi-particle coupling
- Helium atom - quasi-particle coupling



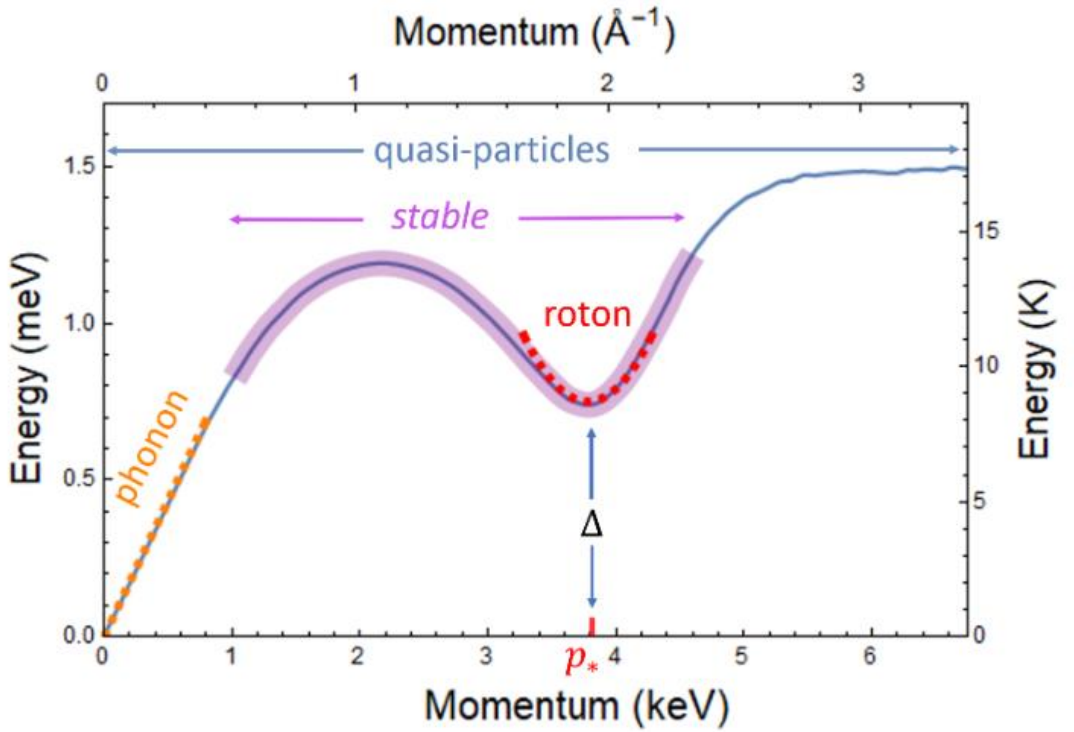
5. Phonon self-interaction

$$E_{\text{phonon}} \simeq c_s \left(p - \frac{\gamma}{\Lambda^2} p^3\right)$$

Low momentum phonon is an exact Goldstone boson

$$p \to 0, E_{\text{phonon}} \to 0$$

Power counting



5. Phonon self-interaction

EFT: C. Burgess, Intro to EFT

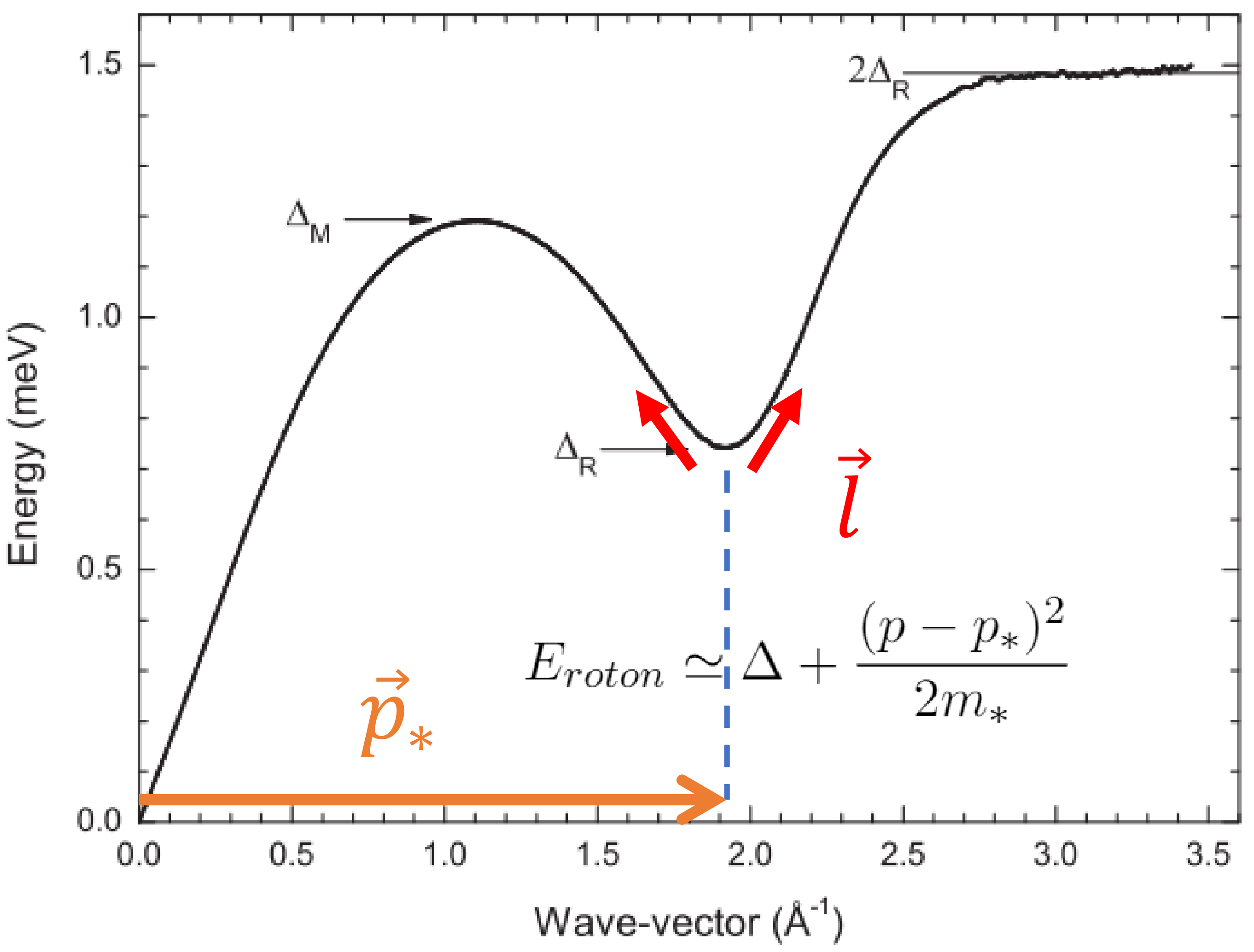
Non-EFT: Landau, Statistical Physics II

$\Lambda \sim p_*$

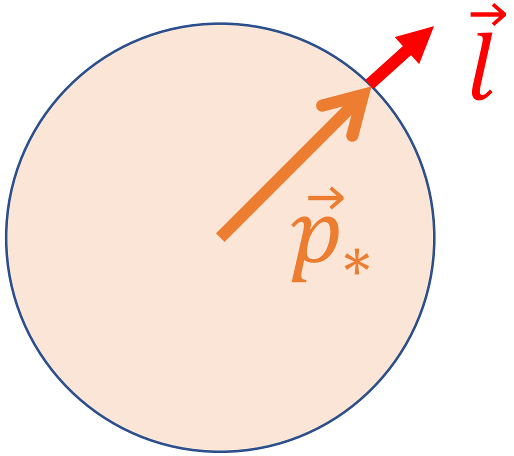
$$[p] = 1\,, \quad [\partial_i] = 1\,, \quad [t] = -1\,, \quad [\partial_t] = 1\,, \quad [x] = -1\,, \quad [\pi] = 1$$

$$\mathcal{L}_{\rm ph} = \frac{1}{2}\left(\dot\pi^2 - c_s^2\,\partial_i\pi\partial_i\pi\right) - \frac{c_s^{3/2}}{2\Lambda^2}\,\dot\pi\,\partial_i\pi\,\partial_i\pi + \frac{g_3\,c_s^{-1/2}}{6\,\Lambda^2}\,\dot\pi^3 + \frac{c_s^3}{8\,\Lambda^4}\left(\partial_i\pi\,\partial_i\pi\right)^2 - \frac{g_3\,c_s}{4\,\Lambda^4}\,\dot\pi^2\,\partial_i\pi\,\partial_i\pi + \frac{g_4\,c_s^{-1}}{24\,\Lambda^4}\,\dot\pi^4 + \cdots$$

6. Roton φ^4 self-interaction



Phase space similar to Fermi surface
↓
Power counting shows φ^4 is a marginal operator

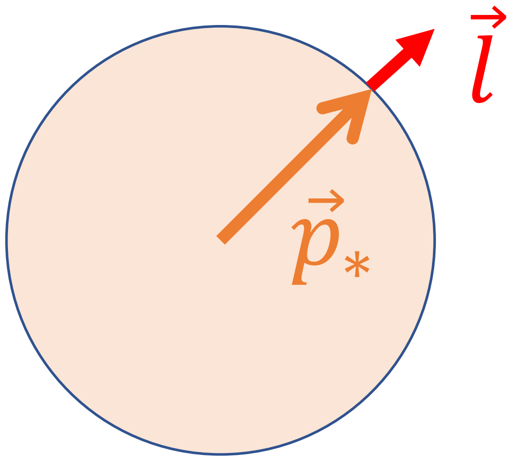


EFT: J. Polchinski 1992

Non-EFT: Landau 1949

6. Roton φ^4 self-interaction

$$[\ell] = 1\,, \quad [p_*] = 0\,, \quad [\mathrm{d}^3 p] = 1\,, \quad [\tilde{\varphi}_r] = -\frac{1}{2}\,, \quad [\mathrm{d}t] = -2\,, \quad [\partial_t] = 2$$



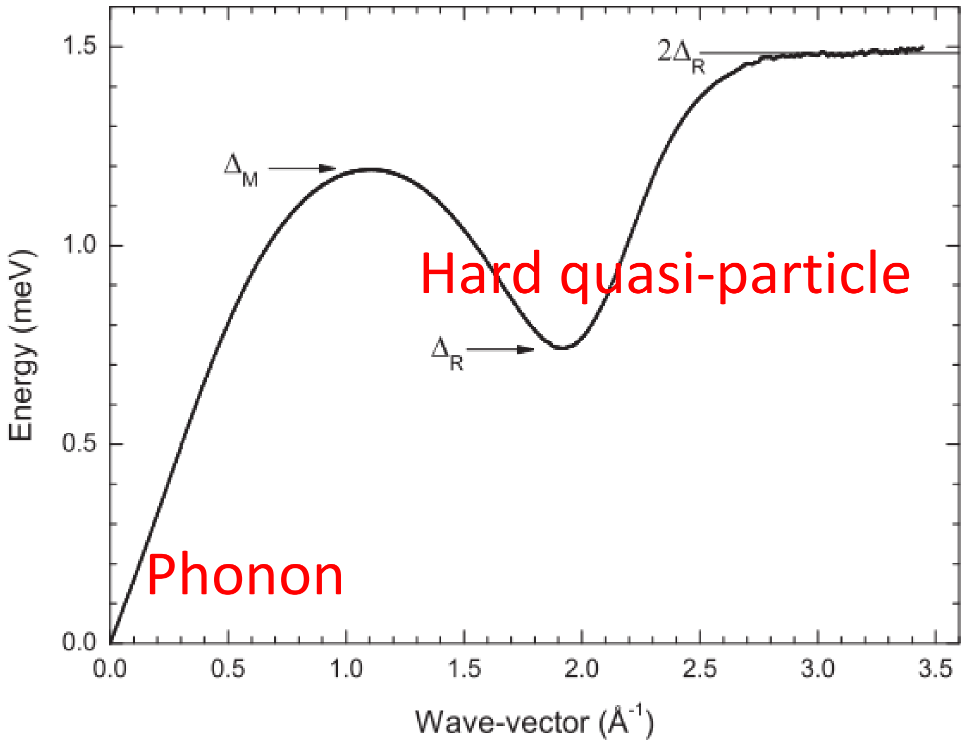
$$S_{\text{int}}[\varphi_r] = \frac{1}{(2\pi)^9}\int \mathrm{d}t(\mathrm{d}^2\mathbf{p}_*)^4 \mathrm{d}\boldsymbol{l}_1 \mathrm{d}\boldsymbol{l}_2 \mathrm{d}\boldsymbol{l}_3 \mathrm{d}\boldsymbol{l}_4\ \delta^3(\boldsymbol{p}_1 + \boldsymbol{p}_2 - \boldsymbol{p}_3 - \boldsymbol{p}_4)$$

$$\frac{\lambda_r(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3, \mathbf{p}_4)}{m_*\, p_*} \tilde{\varphi}_r^*(\mathbf{p}_1)\, \tilde{\varphi}_r(\mathbf{p}_2)\, \tilde{\varphi}_r^*(\mathbf{p}_3)\, \tilde{\varphi}_r(\mathbf{p}_4)$$

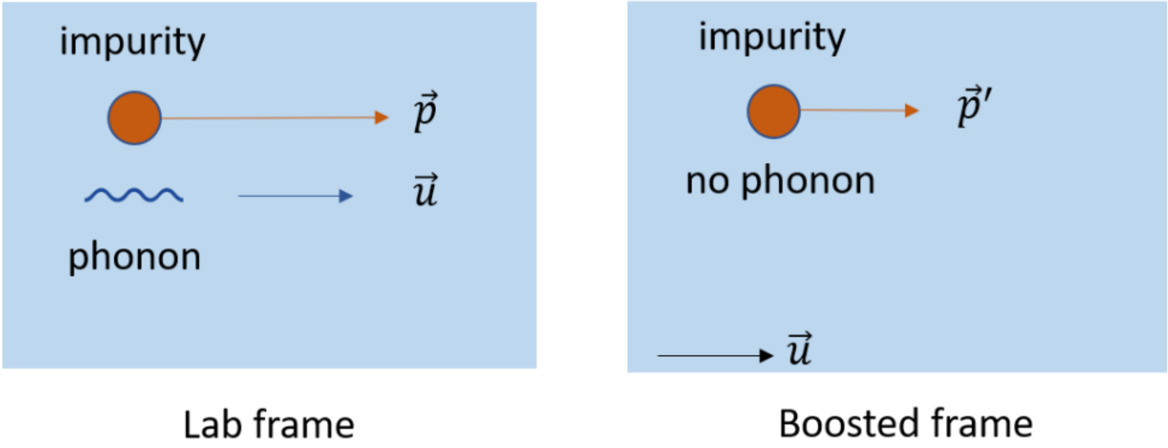
Wilson coefficient has no UV scale

7. Phonon interacts with hard quasi-particles

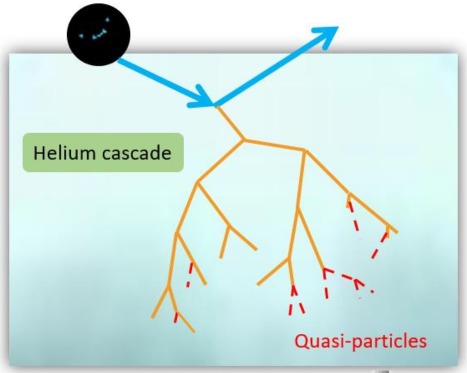
Hard quasi-particle exclusive quantities do not scale with phonon $\vec{p}$, but might contribute Λ

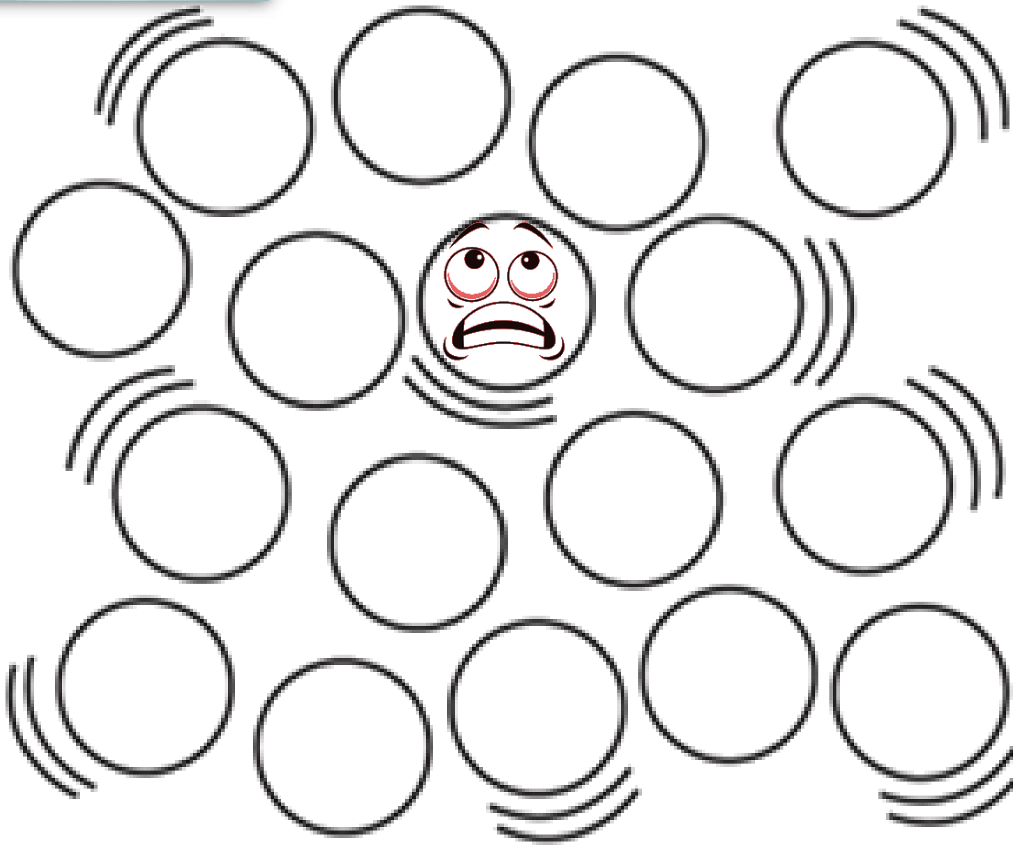


Still, need a non-EFT theory to look for coefficients. Landau: Statistical Physics II, Impurity interaction with phonon

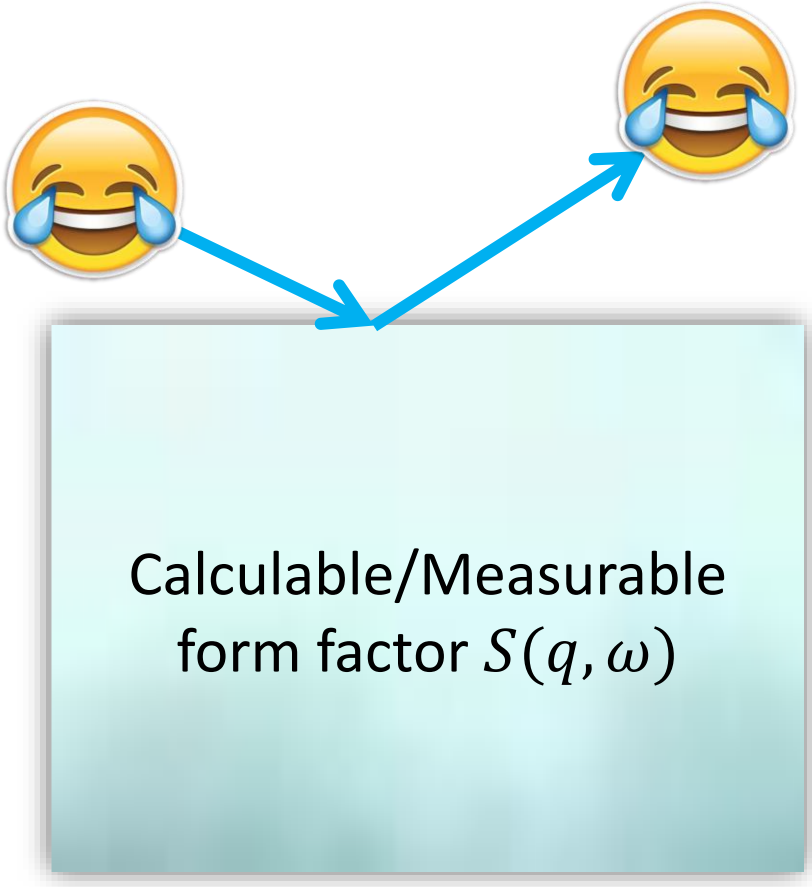


8. Helium emitting quasi-particles





Slow helium (Non-perturbative)



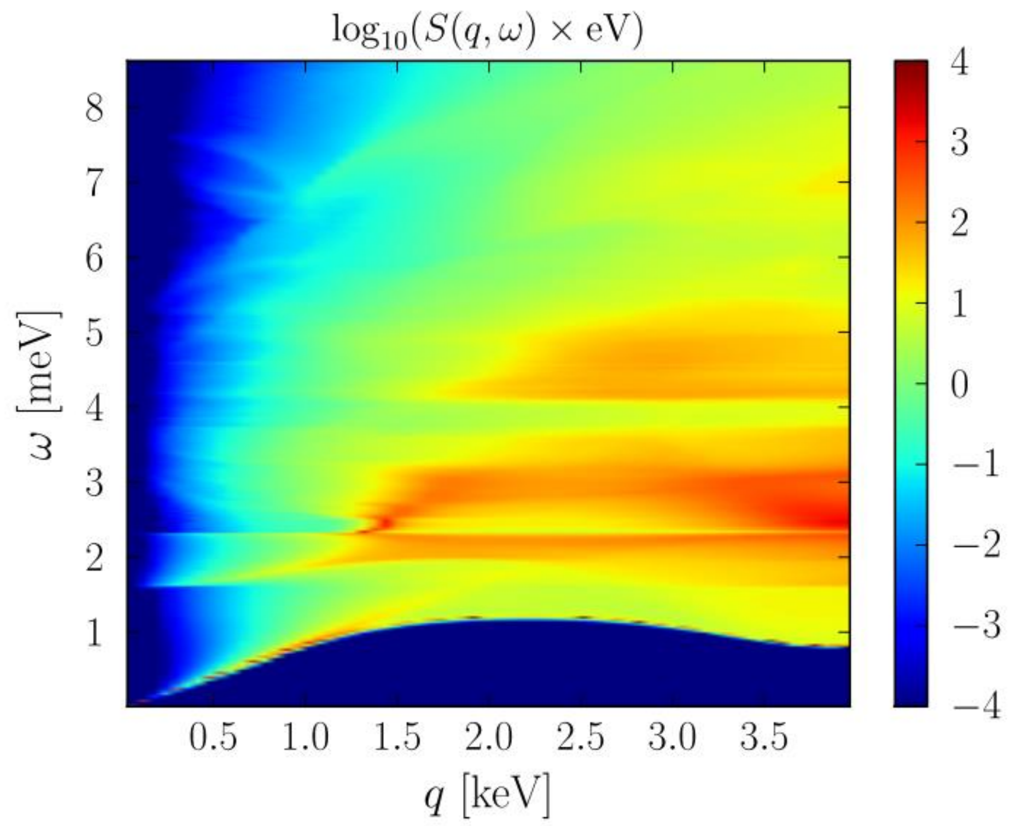
Fast/Weakly interacting particles (Perturbative)

8. Effective current-current coupling with undetermined coupling constants

$$\mathcal{L}_{\text{cl-ph}} = \frac{m_{\text{He}} c_s}{\sqrt{\rho}} \left(\lambda_1 \dot{\pi} \Phi^* \Phi + \lambda_2 \boldsymbol{\nabla} \pi \cdot \frac{i \Phi^* \boldsymbol{\nabla} \Phi + h.c.}{2m} \right)$$

The phonon π side of matrix element is known – the "form factor" $S(q,\omega)$
↓
If we assume formula works for any quasi-particle, we can use the whole spectrum of $S(q,\omega)$

$$\Gamma \simeq \frac{(\lambda_1 + \lambda_2)^2 \Lambda}{2\pi m_{\text{He}}^2 v_{\text{He}}} \int_0^{k_{\max}} k S(k) dk$$



Campbell, C. E., et al. 2015

Summary:

Various EFT power counting in the superfluid Helium-4

Thanks for your attention!