Superfluid effective field theory

for sub-GeV dark matter direct detection

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1. Direct detection set-up

\[ m_{DM} = \text{MeV} \sim \text{GeV} \]

Superfluid He-4
2. Quasi-particles in Superfluid He-4

“Collective excitation”

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 $\text{MeV} < m_{DM} < \text{GeV}$

DM scatters helium atom

Helium cascade

Helium atoms emit quasi-particles

Quasi-particles decay/self interaction
4. Phonon as Goldstone boson

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

Number conservation U(1) symmetry -- $\Phi e^{-i\alpha}$
Symmetry breaking produce Goldstone boson -- $\pi + \alpha$

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

Son, D. T. 2002
5. Roton $\varphi^4$ from power counting

Phase space similar to Fermi surface

$\Lambda_p \times \Lambda_l$

Power counting shows $\varphi^4$ is a marginal operator
6. Phonon interact with hard quasi-particles

![Graph showing energy vs. wave-vector with labeled points: $\Delta_M$, $\Delta_R$, and $2\Delta_R$. The graph indicates the presence of Phonon, Roton, and Hard quasi-particle.]
6. Hard quasi-particle as an impurity

\[ \vec{P} \]

Static fluid

\[ \vec{P} \]

Moving fluid \( \vec{u} \)

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)

Calculable/Measurable form factor $S(q, \omega)$
7. Helium-phonon coupling

\[ D_\mu \Phi = (\partial_\mu + i\partial_\mu \pi)\Phi \]

Scalar + Vector coupling between Helium \( \Phi \) and phonon \( \pi \) currents

\[ \downarrow \]

Reproduce form factor \( S(q, \omega) \) of phonon
7. “Form factor”

Scalar + Vector coupling between Helium $\Phi$ and phonon $\pi$  
\[ \downarrow \]
Scalar + Vector coupling between Helium $\Phi$ and any quasi-particles  
\[ \downarrow \]
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!