Study of the dynamics in superfluid ^{4}He by inelastic neutron scattering

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ILL Supervisors

Björn Fåk (ToF group)

Jacques Ollivier (ToF group)

CNRS Supervisor

Henri Godfrin (ULT group)

Ingredients

Neutron source

ILL reactor

Very-low temperature

Dilution refrigerator

Sample

Superfluid ^{4}He

Outline

I. Liquid ^{4}He

- Properties
- Motivation
- Dispersion relation in superfluid ^{4}He

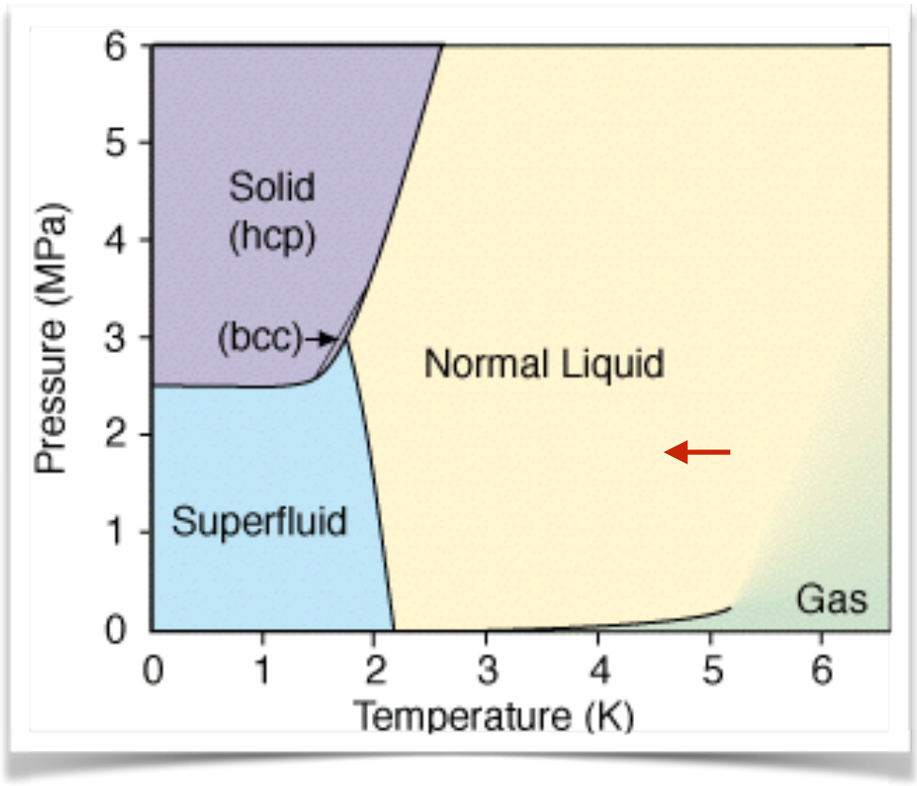
II. Experimental results about the dynamics in superfluid ^{4}He

- Inelastic neutron scattering
- Comparison of the experimental data with the theoretical data
- The experimental multiple scattering issue

Liquid

Properties

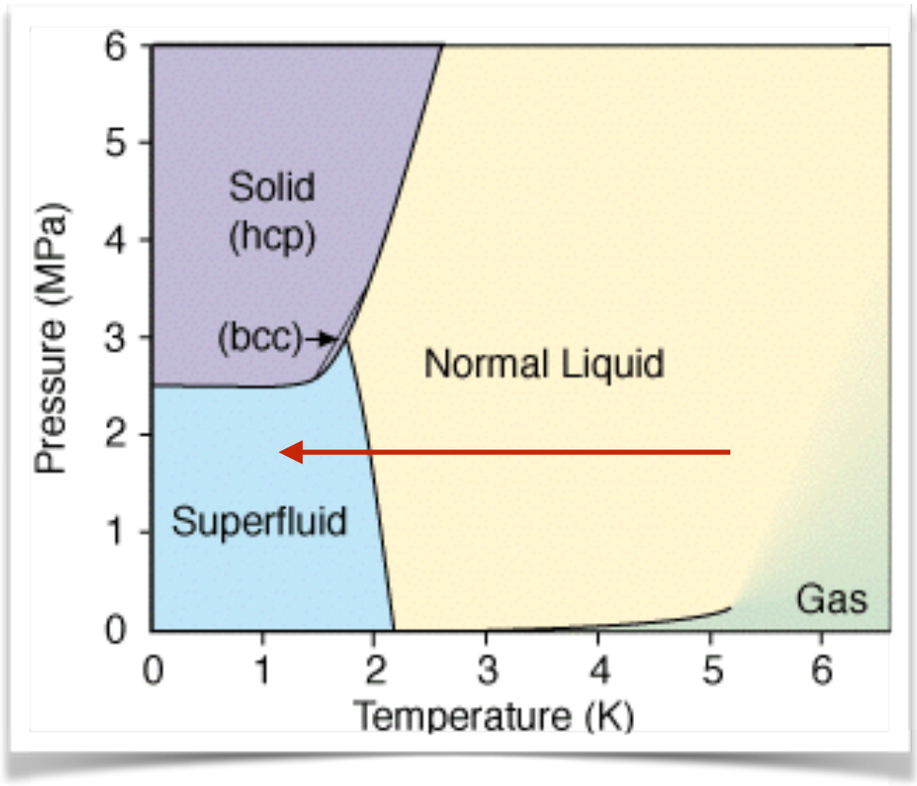
<u>^{4}He phase diagram</u>



Liquid

Properties

<u>^{4}He phase diagram</u>



Liquid until T = 0 K

Very pure liquid

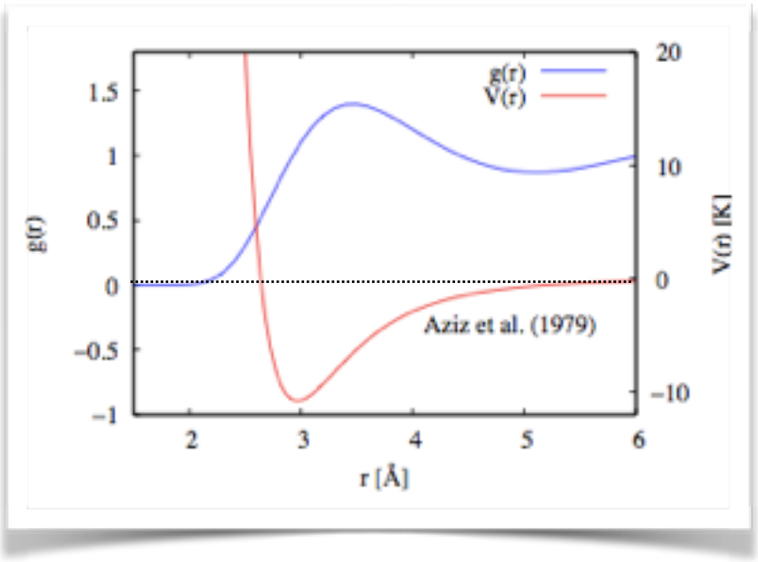
Superfluid below T = 2.17 K

Quantum fluid

- de Broglie wavelength $\lambda_T = \sqrt{\frac{2\pi\hbar^2}{mk_BT}}$ → order of magnitude of the interatomic distances at low T

Motivation

Why is it interesting to study liquid helium ?



Model system
to study interacting particles
in condensed matter physics

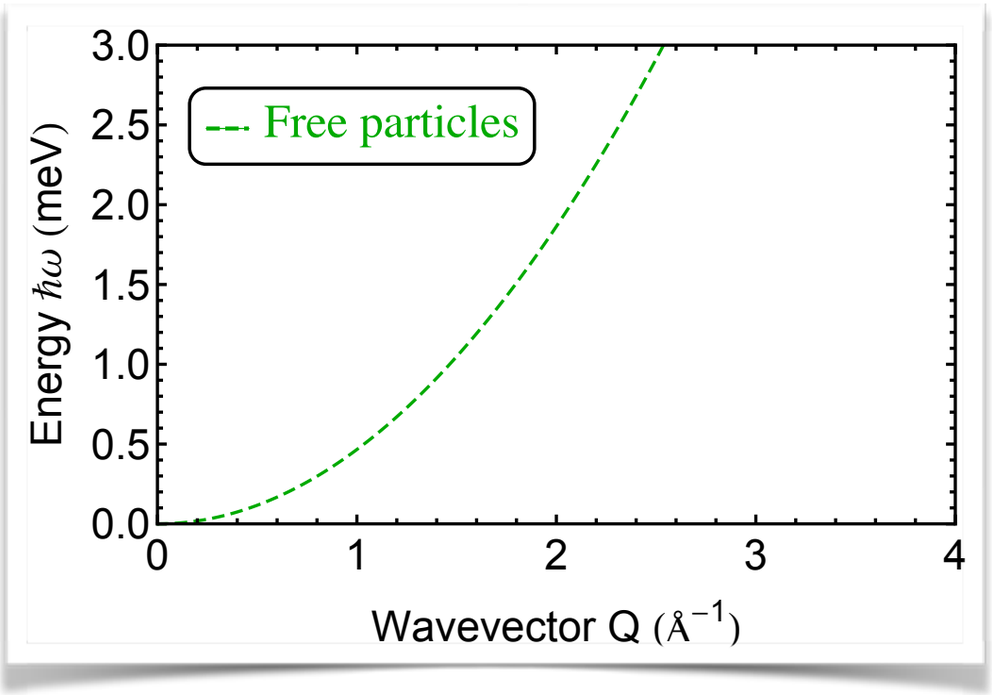
How to study the interaction in liquid helium ?

<u>Fundamental description</u>

- Ground state
- Dynamic response to a perturbation

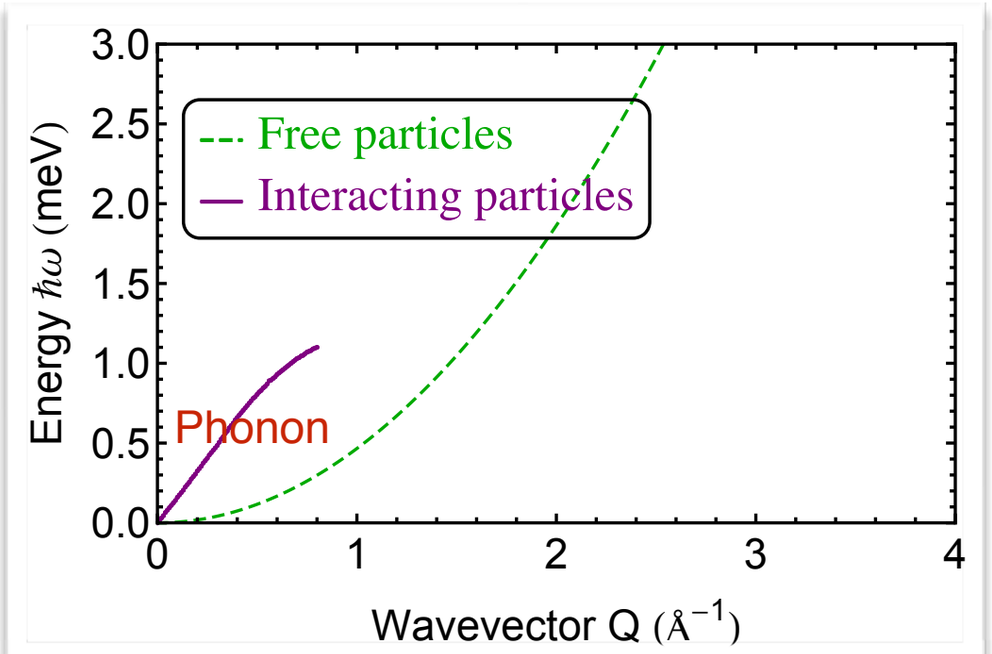
Dynamics in superfluid ^{4}He

Free ^{4}He atom excitations



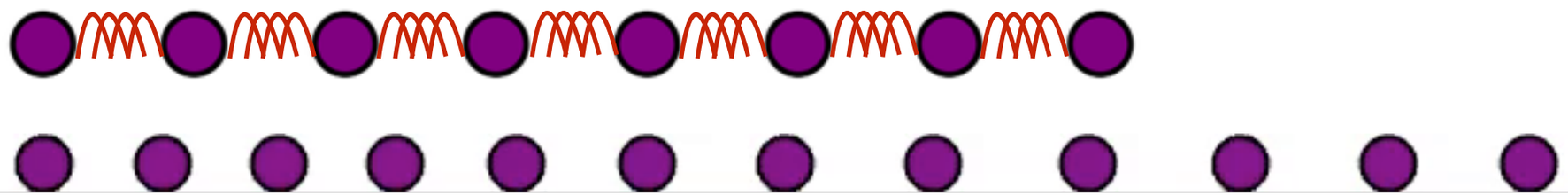
Dynamics in superfluid ^{4}He

Single collective excitations in superfluid ^{4}He



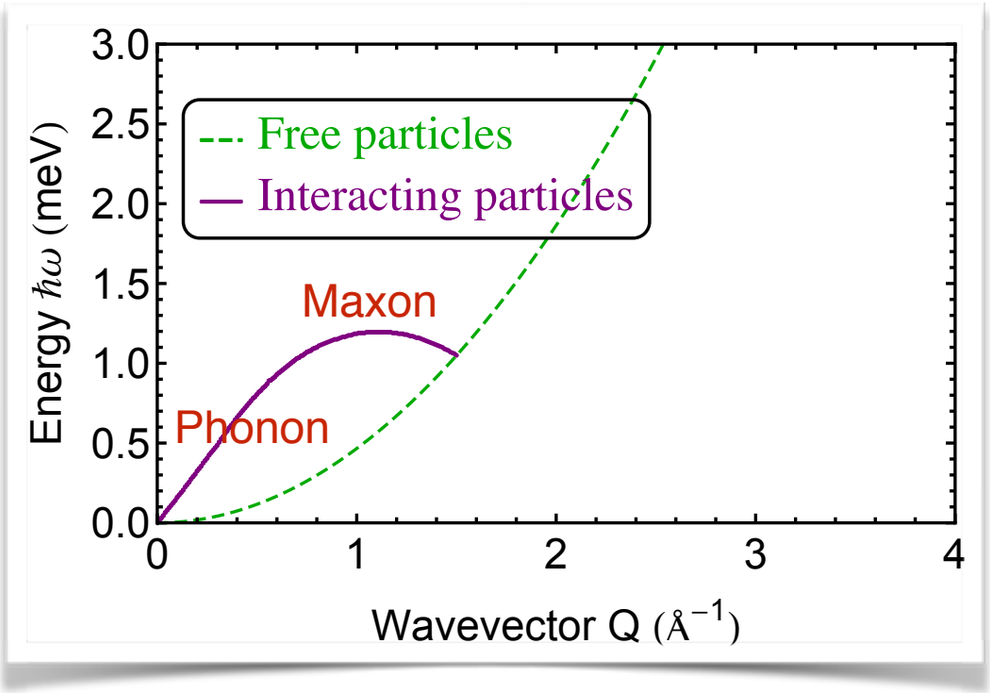
- Phonon
  Density collective mode

- View of a phonon in a crystal:



Dynamics in superfluid ^{4}He

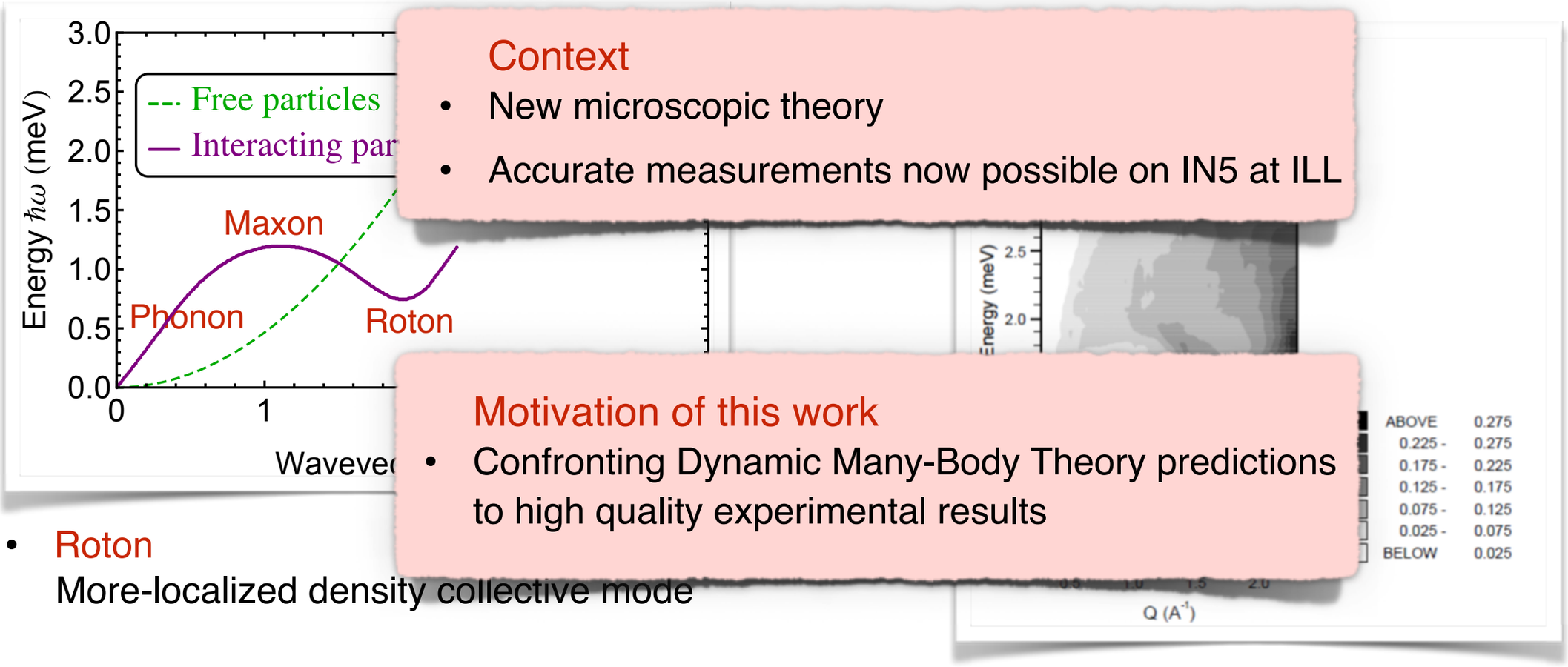
Single collective excitations in superfluid ^{4}He



Dynamics in superfluid ^{4}He

Single collective excitations in superfluid ^{4}He

Is there life elsewhere ?



Context

- New microscopic theory
- Accurate measurements now possible on IN5 at ILL

Motivation of this work

- Confronting Dynamic Many-Body Theory predictions to high quality experimental results

- Roton
  More-localized density collective mode

Contour map of the multi phonon excitations at T = 500 mK, P = 20 bar

K.H. Andersen et al. *J. Phys. Condens. Matter* **6**, 821 (1994)
M. R. Gibbs et al. *J. Phys. Condens. Matter* **11**, 603 (1999)

Neutrons

How Atoms are correlated in Space and Time with each other (Coherent)

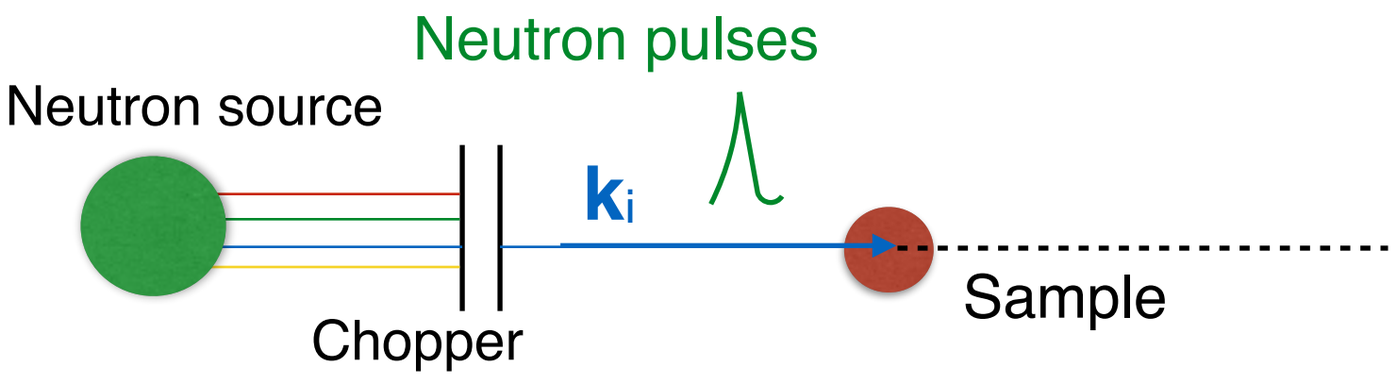
Inelastic Neutron Scattering

Energy range of ours collective excitations ≃ meV

Time of Flight Spectrometer

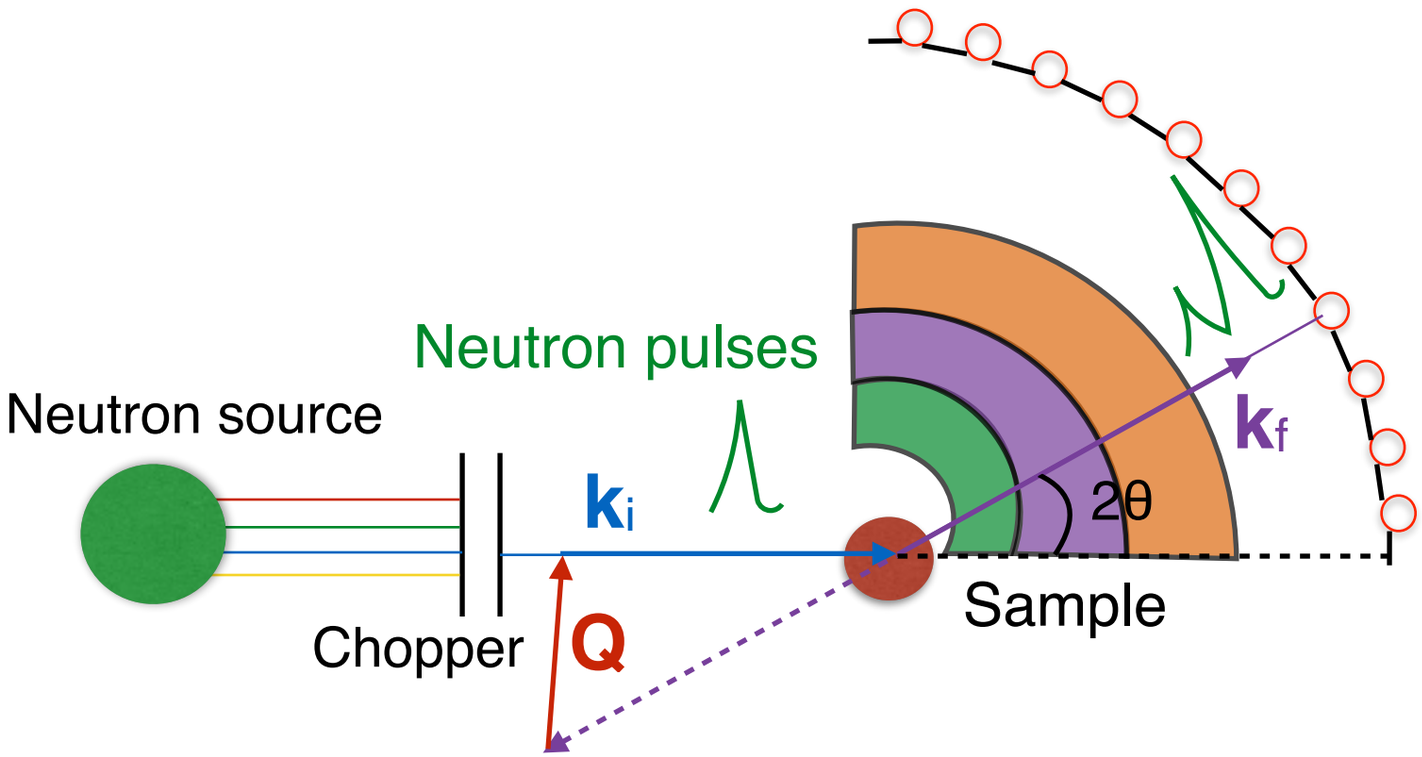
Inelastic neutron scattering

IN5: A high precision Time of Flight spectrometer



Inelastic neutron scattering

IN5: A high precision Time of Flight spectrometer



Conservation laws

- Momentum conservation

$k_i - k_f = Q$

$Q^2 = k_i^2 + k_f^2 - 2k_ik_f\cos(2\theta)$

- Energy conservation

$\hbar\omega = E_i - E_f = \frac{\hbar^2 k_i^2}{2m_n} - \frac{\hbar^2 k_f^2}{2m_n}$

Inelastic neutron scattering

IN5: A high precision Time of Flight spectrometer

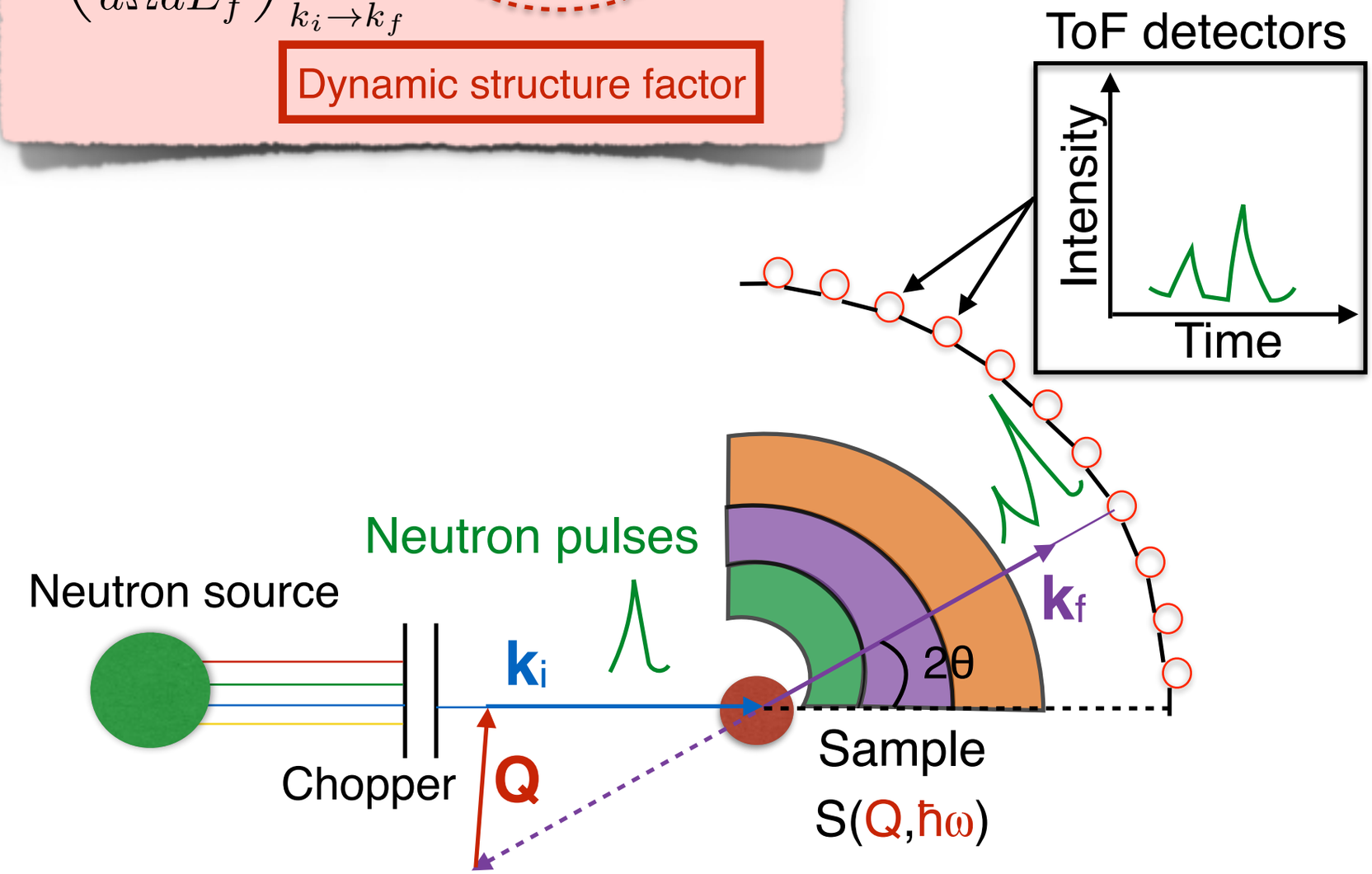
Differential scattering cross section

$$\left(\frac{d^2\sigma}{d\Omega dE_f}\right)_{k_i \to k_f} = k_f/k_i\, S(Q,\hbar\omega)$$

Dynamic structure factor

Time of flight → Energy transfer ħω

Scattering angle 2θ → Wavevector transfer Q



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Inelastic neutron scattering

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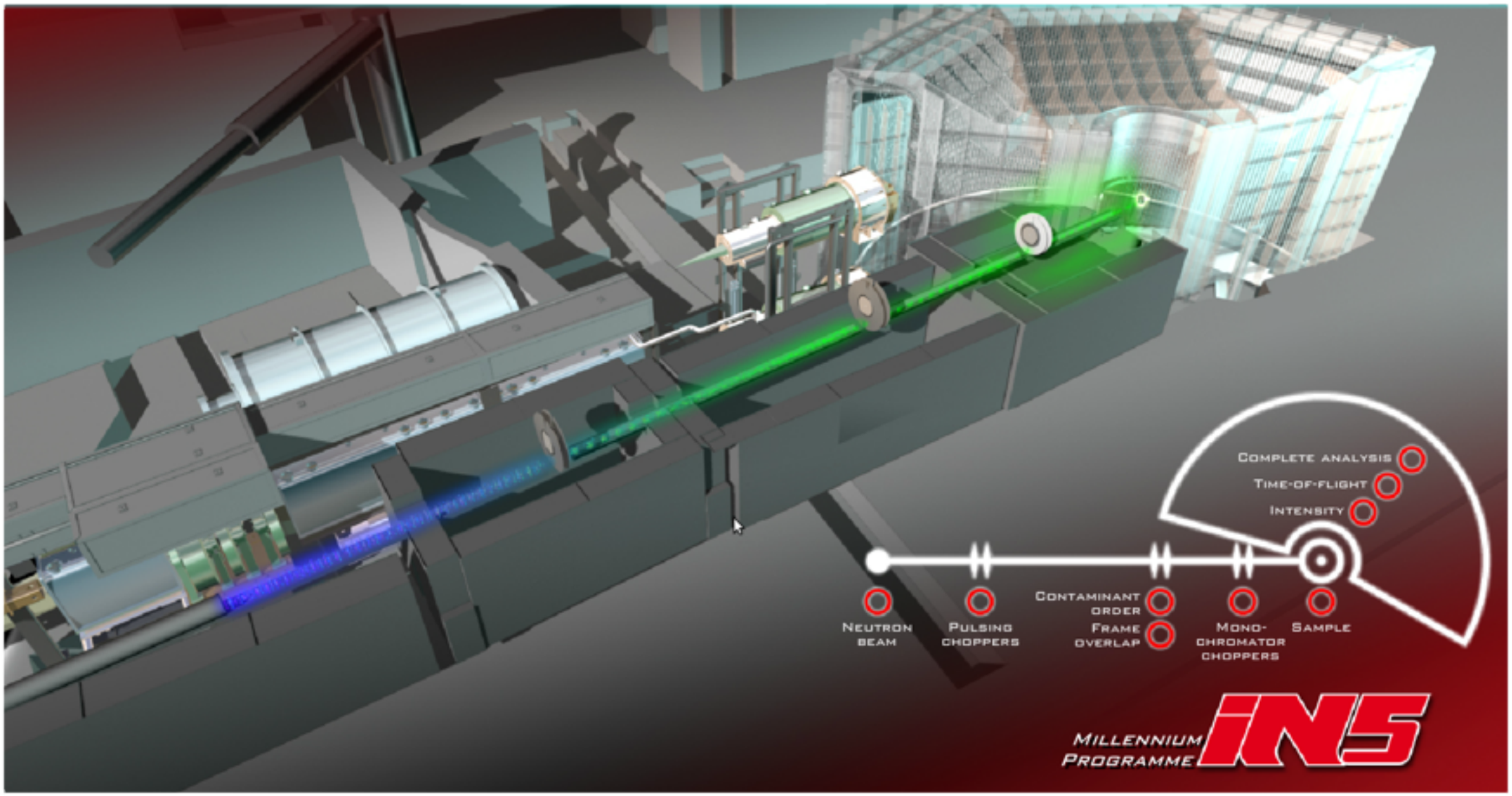
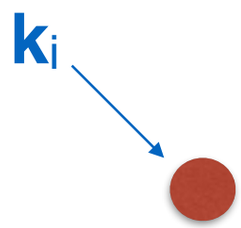


Inelastic neutron scattering

Single and multi-excitation parts of the dynamic structure factor

$$S(Q,\omega) = S_1(Q,\omega) + S_M(Q,\omega)$$

Single excitation



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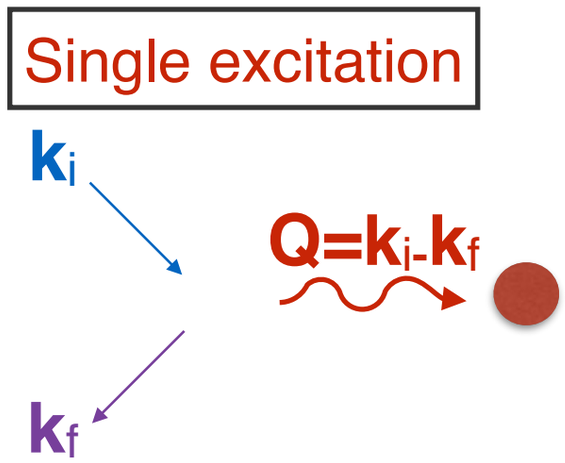

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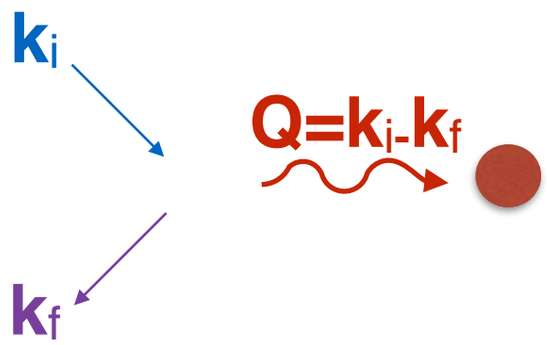
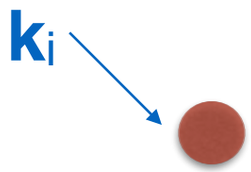


Multi-excitation



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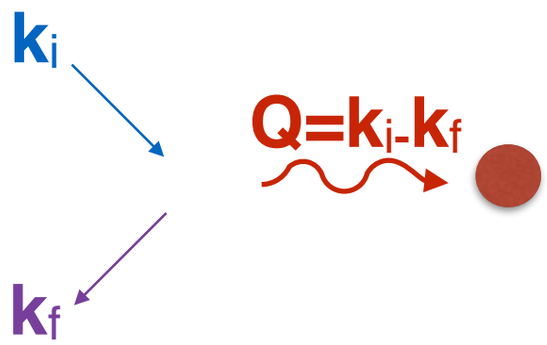
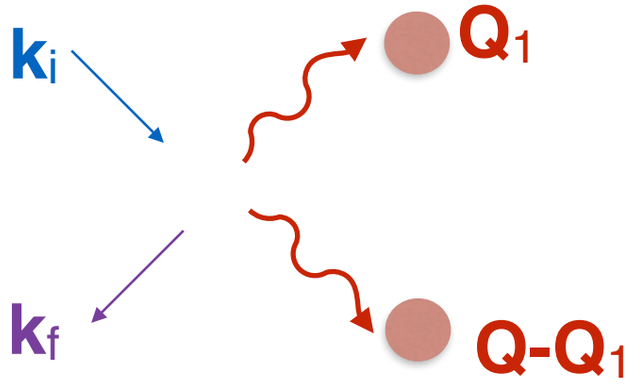


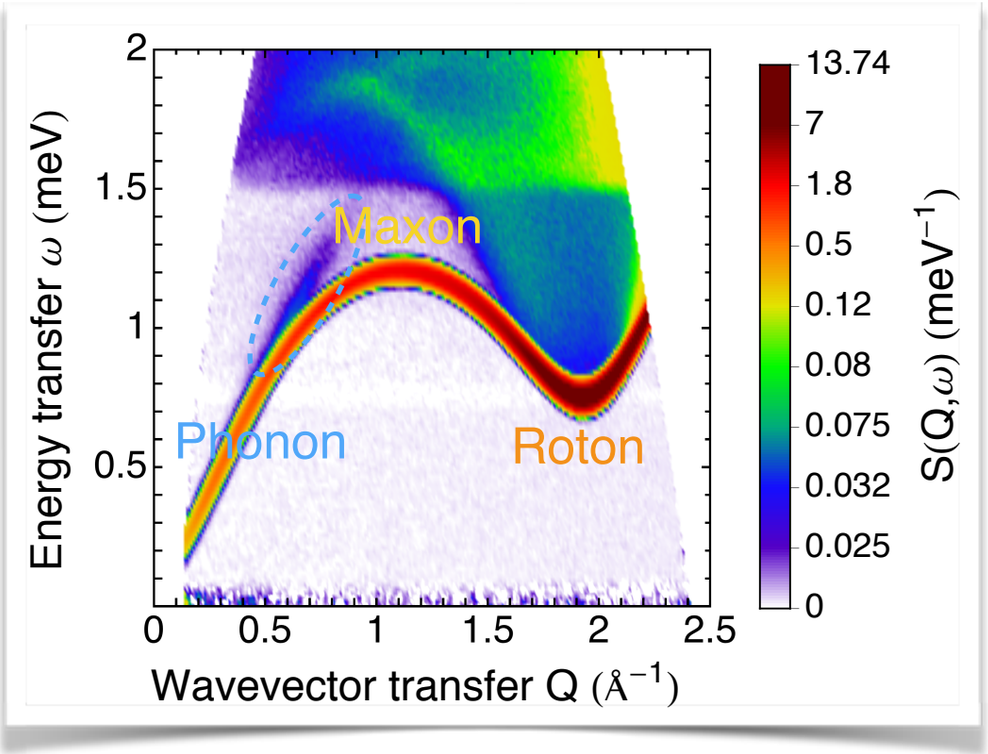
Multi-excitation



Dynamics in superfluid ^{4}He

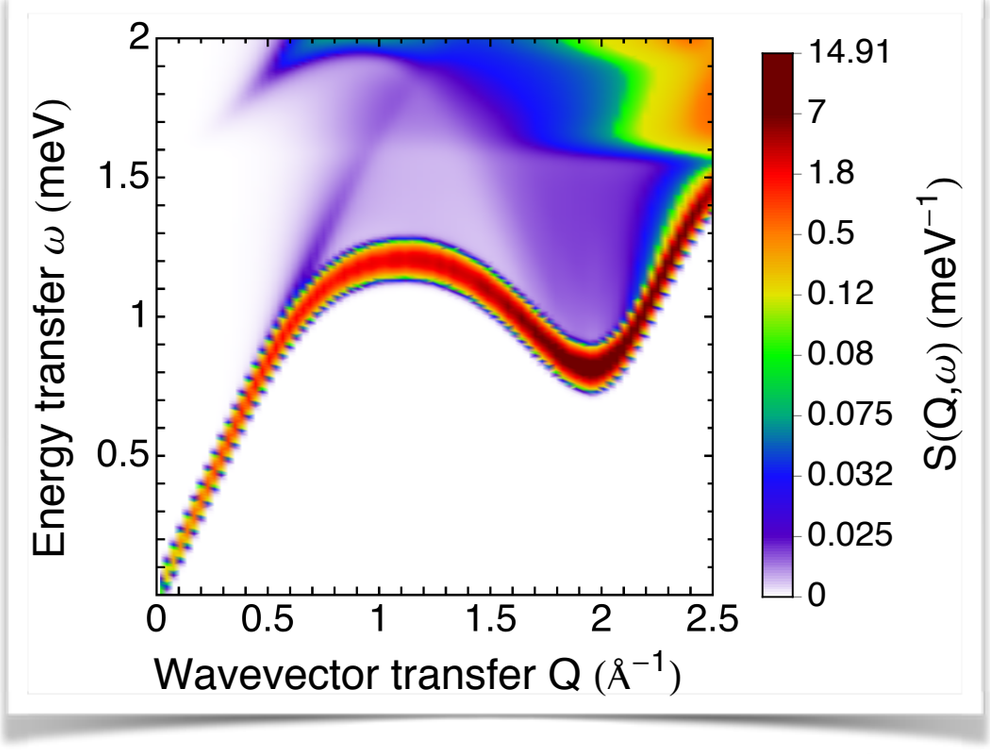
Results: What is happening beyond the phonon-roton curve

Inelastic neutron scattering experiment



IN5-ILL (ToF spectrometer): 100 mK, SVP, 4.8 Å

Dynamic Many Body Theory (DMBT)



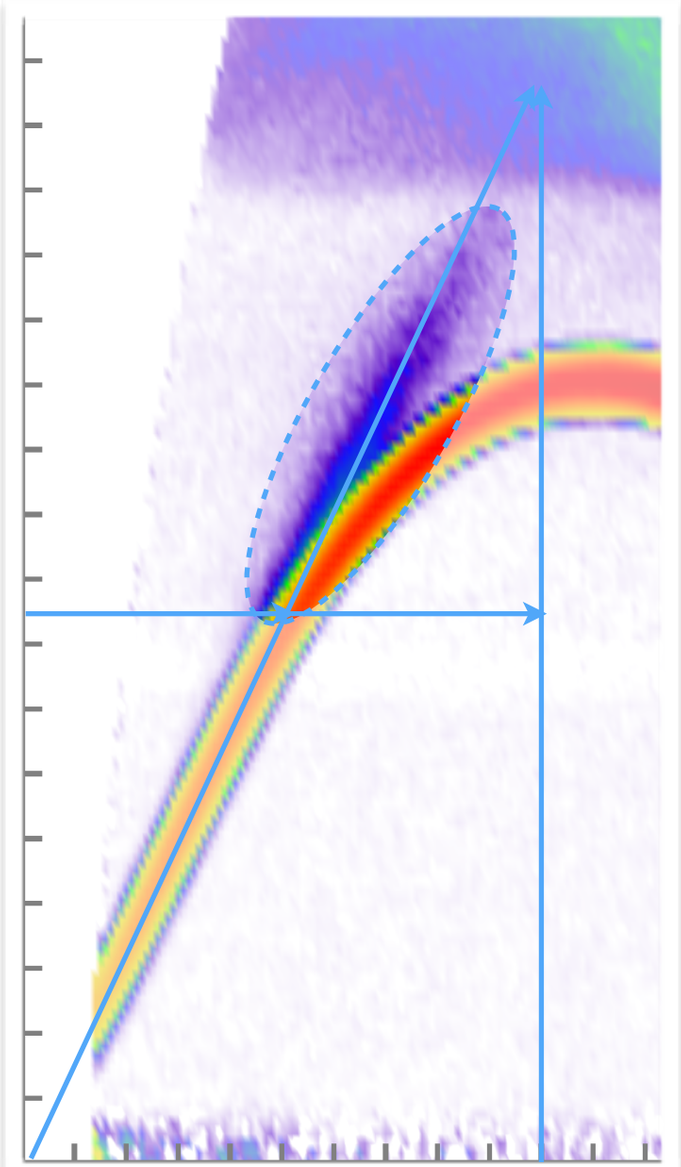
- Takes into account dynamic correlations

C. E. Campbell, E. Krotscheck, T. Lichtenegger
Phys. Rev. B. **91**, 184510 (2015)

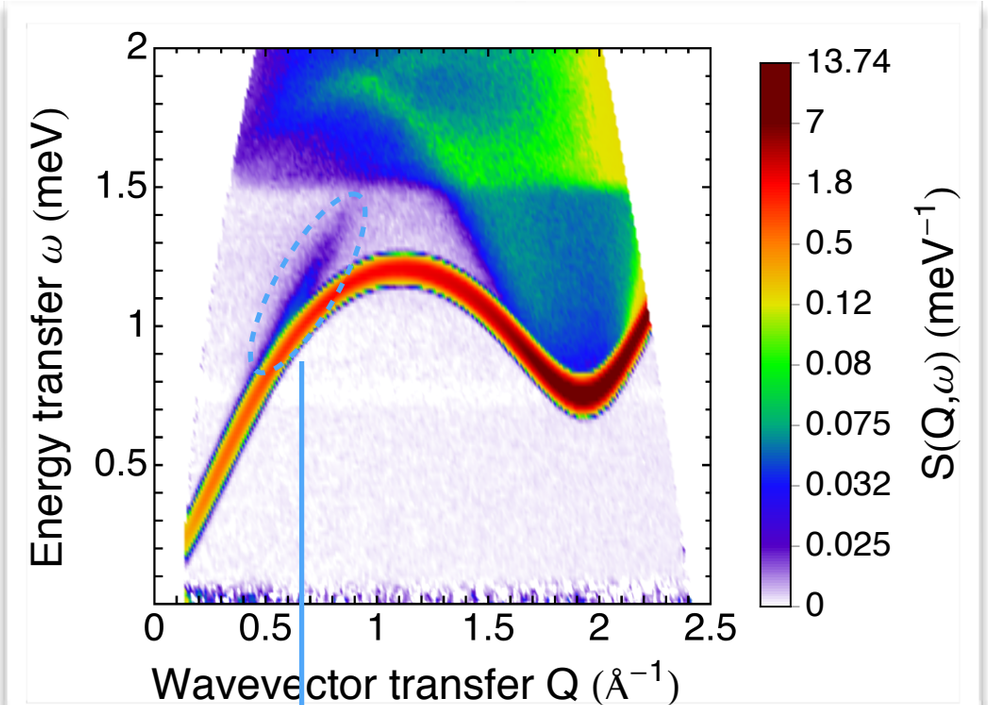
K. Beauvois, C. E. Campbell, B. Fåk, H. Godfrin, E. Krotscheck, H. J. Lauter, T. Lichtenegger, J. Ollivier, A. Sultan.
Superfluid 4He dynamics beyond quasiparticle excitations. *In preparation*.

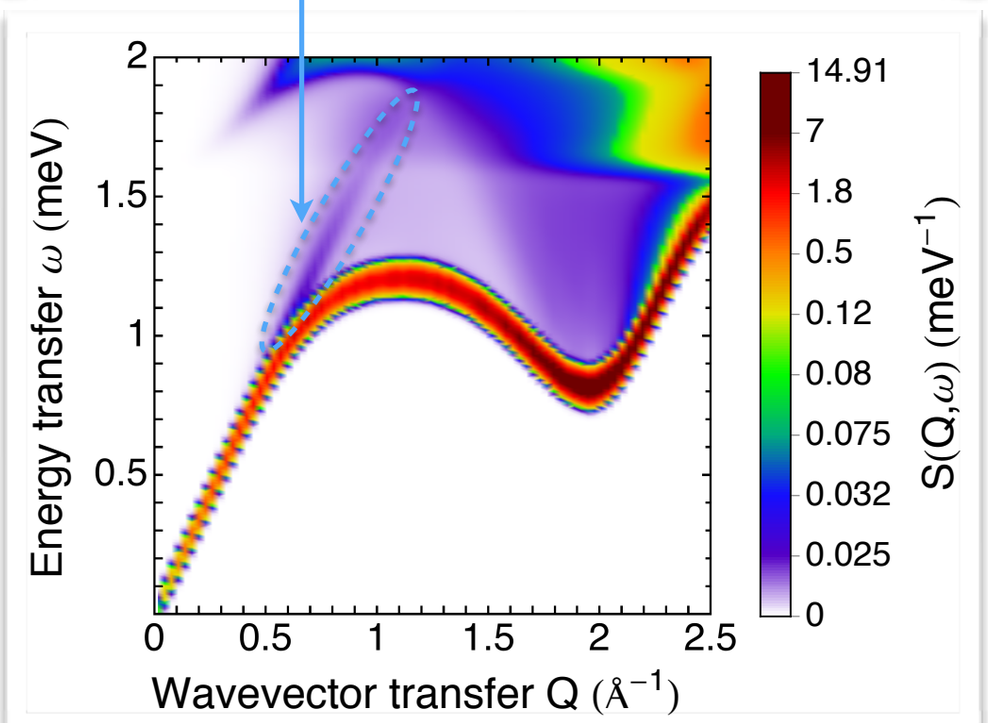
Dynamics in superfluid ^{4}He

Mode-mode coupling



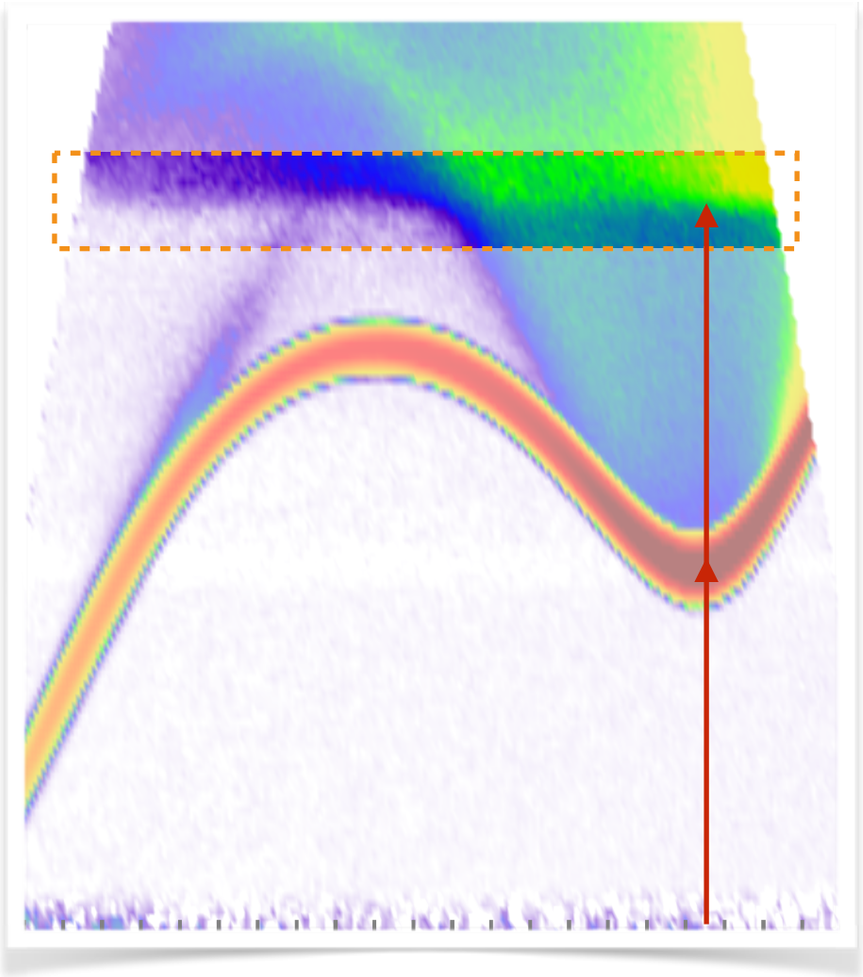
- Ghost Phonon
  Phonon-Phonon coupling



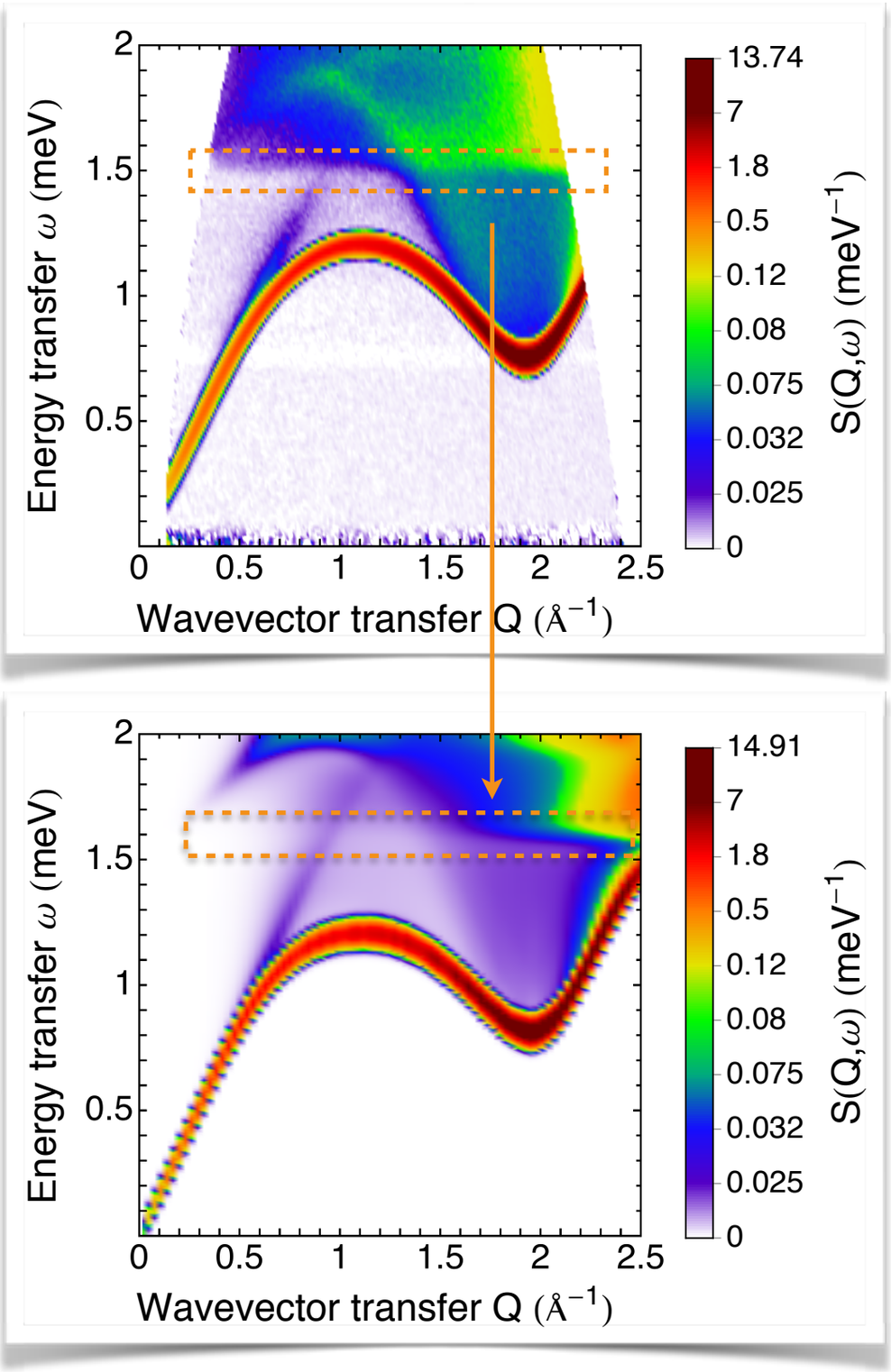


Dynamics in superfluid ^{4}He

Mode-mode coupling

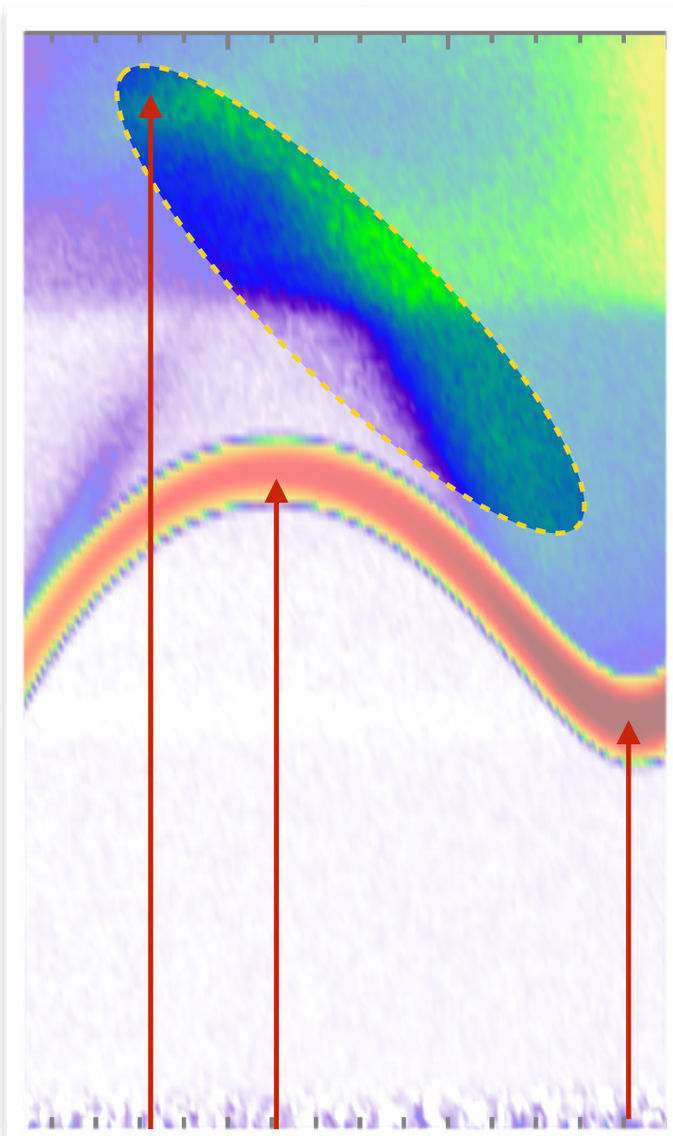


- Roton-Roton coupling

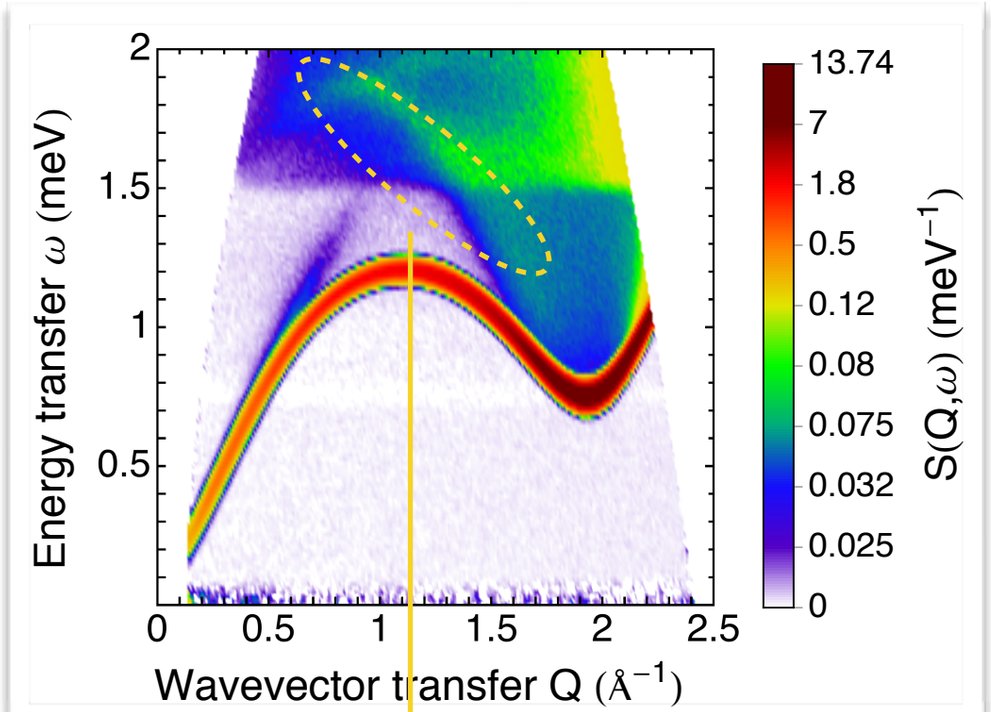


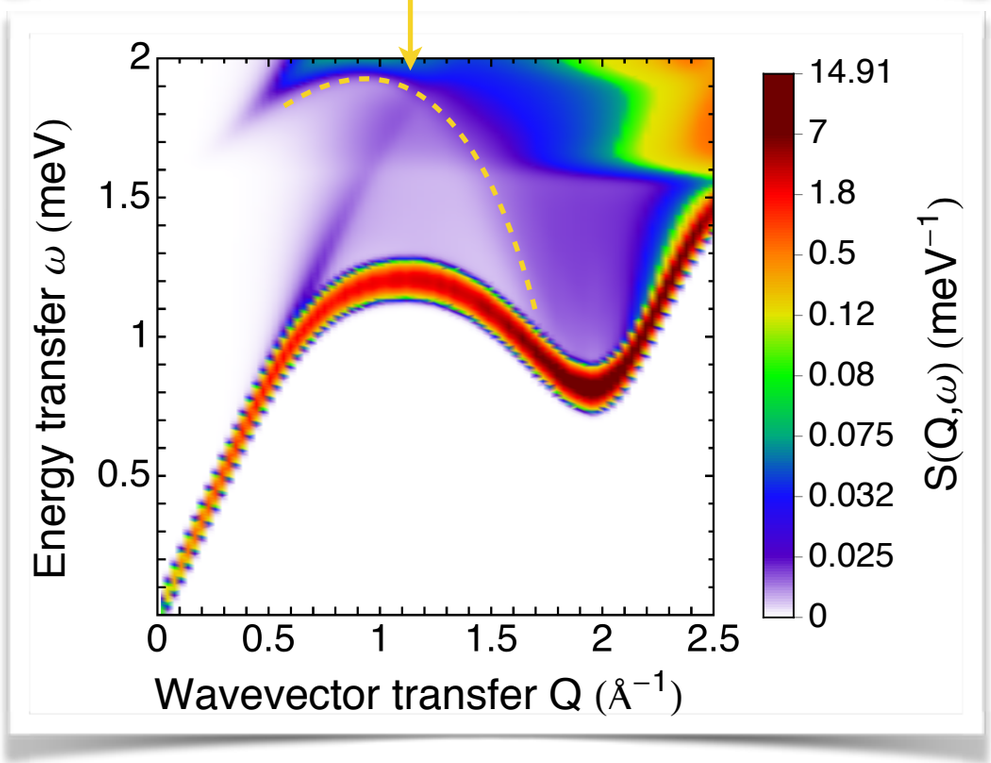
Dynamics in superfluid ^{4}He

Mode-mode coupling



- Maxon-Roton coupling





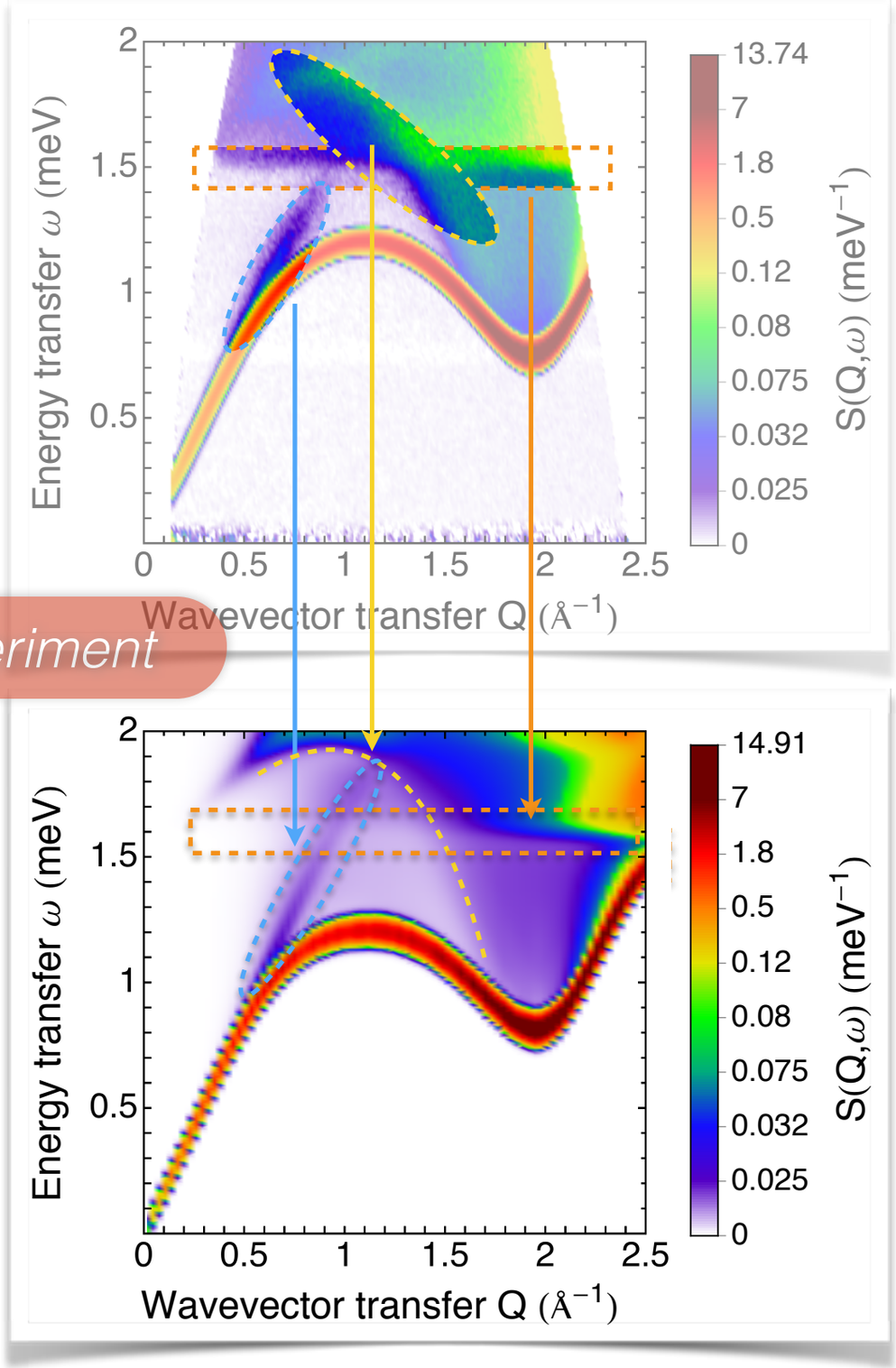
Dynamics in superfluid ^{4}He

Well-defined multi-excitations

Arise from dynamic correlations

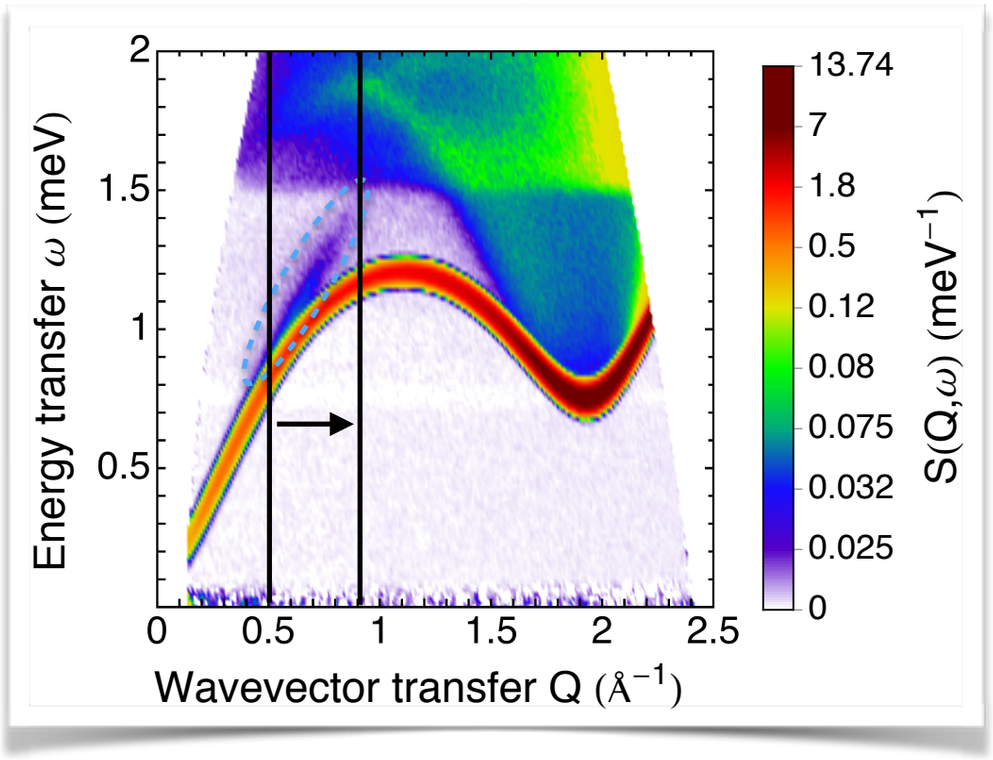
Good agreement between theory and experiment

- Phonon-Phonon coupling
- Roton-Roton coupling
- Maxon-Roton coupling

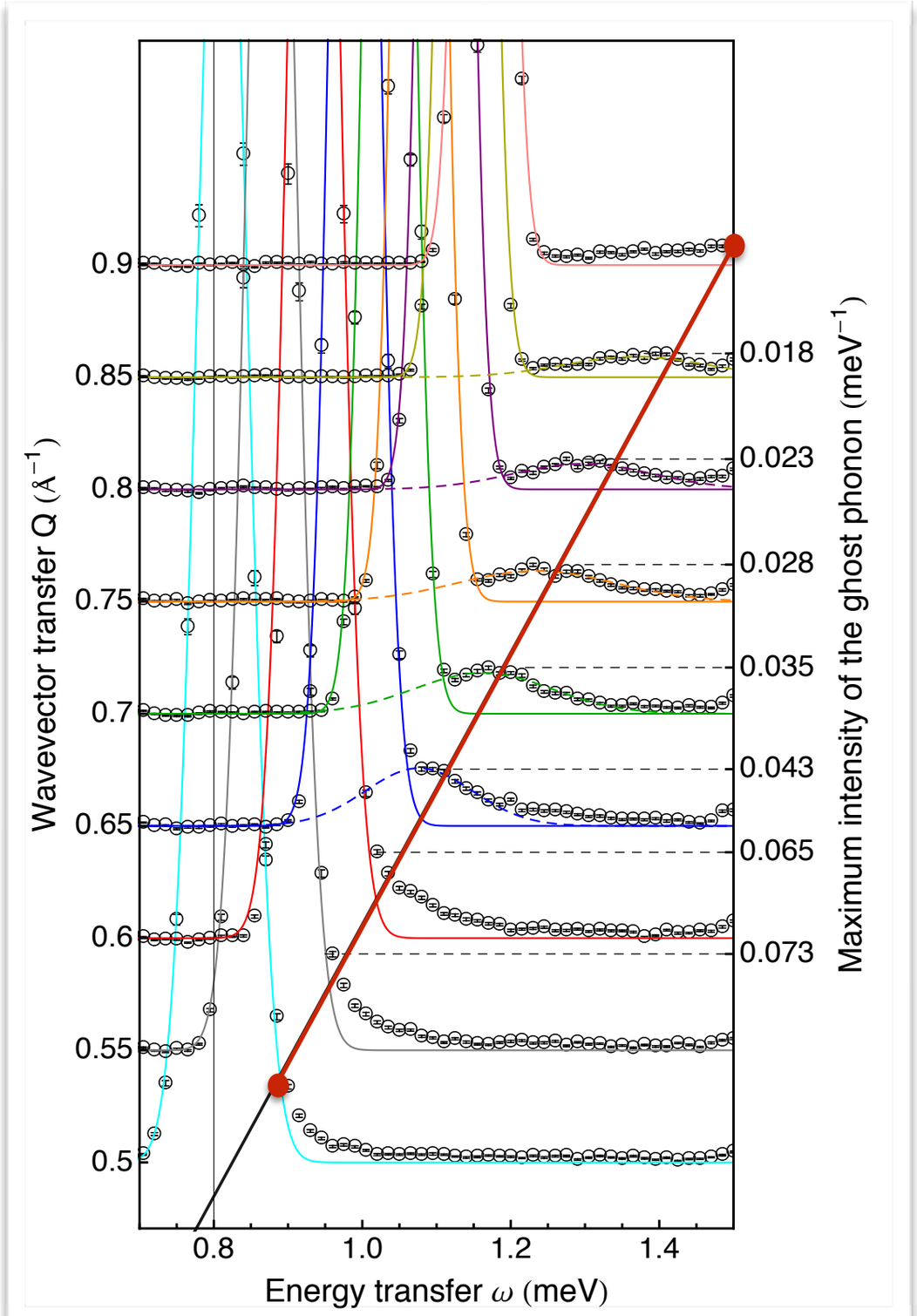


Dynamics in superfluid ^{4}He

S(Q,ω) at selected constant Q

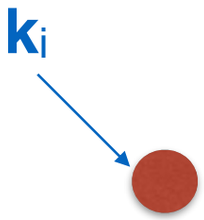


- Ghost phonon



Inelastic neutron scattering

Multiple scattering



Inelastic neutron scattering

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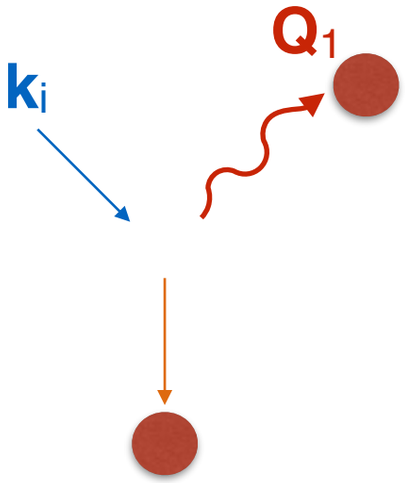
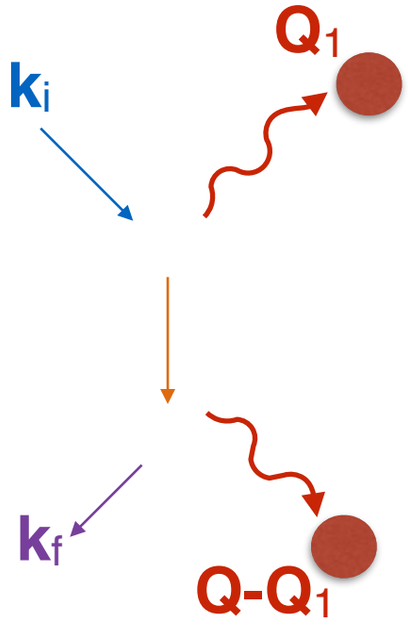


Inelastic neutron scattering

Multiple scattering

Monte Carlo simulations Method

- McStas Instrument - Template TOF (E.Farhi)
  Sample - Component Isotropic_Sqw (E.Farhi)
- MScat (J. R. D. Copley (1974 and 1986))



Input

- $S(Q,\omega)$
- σ_{coh} = 1.34 b
- σ_{inc} = 0
- $\sigma_{abs} \simeq 0$
- Number density = 2.18×10^{22} Atoms/cm^3
- λ_i = 4.8 Å (E_i=3.55)
- T = 2.7 K (only Stokes scattering)
- Dimensions of the cell
- Parameters for the source and the detectors

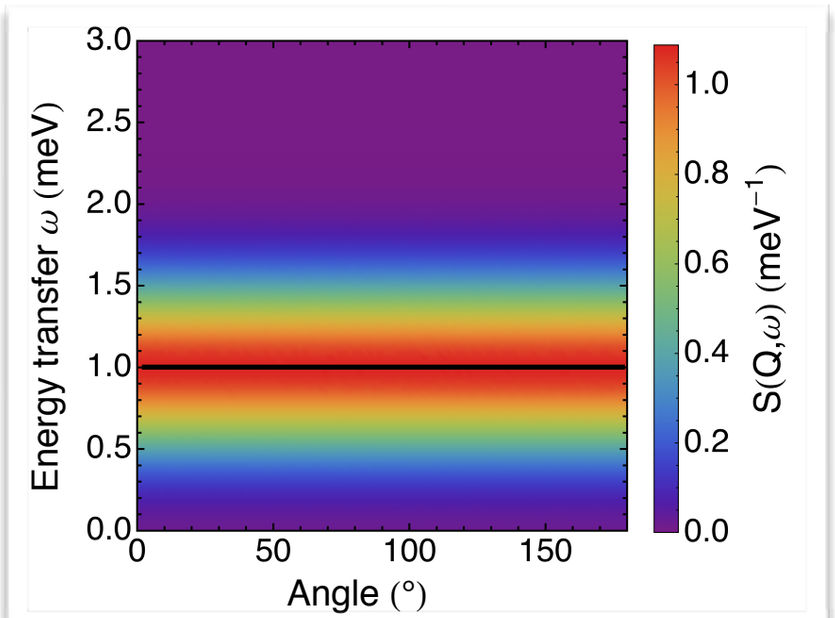
Multi-excitations are only 1 % of the total intensity

Multiple scatterings

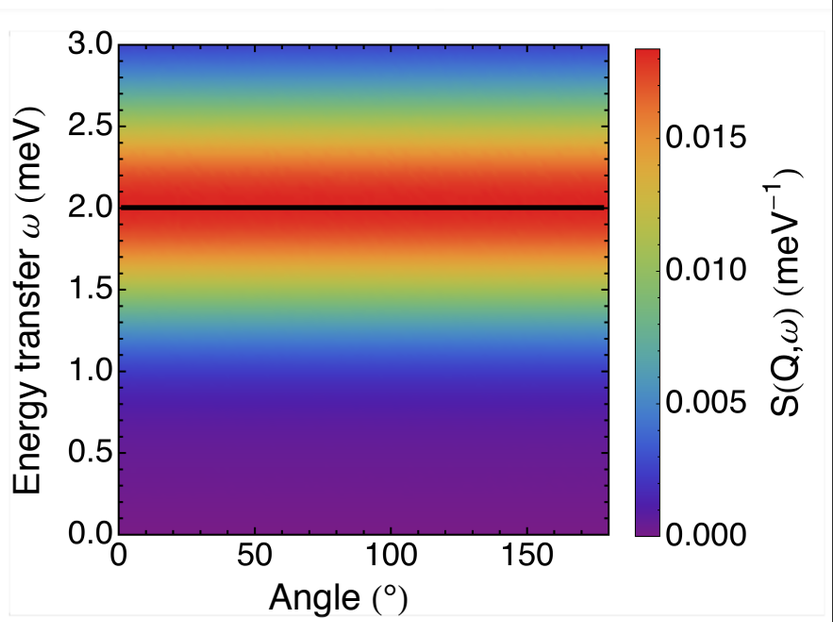
Flat incoherent Sample

MScat
- 3D cell (1×0.75 cm)
- Intensity - ħω = 1 meV

Single scattering



Multiple Scattering



Remark

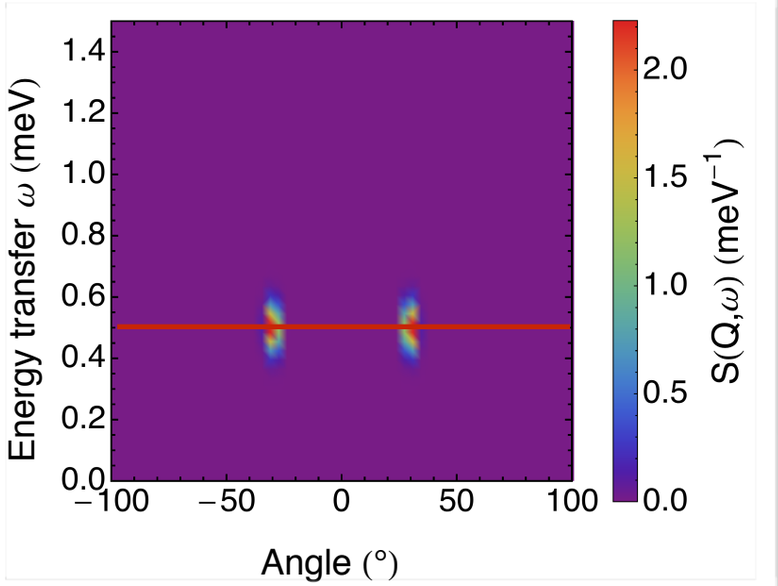
Ratio multiple scattering intensity / total intensity - 2.45 % for a 3D cell

- 0.13 % for a 2D cell (0.01×0.75 cm)

Multiple scattering

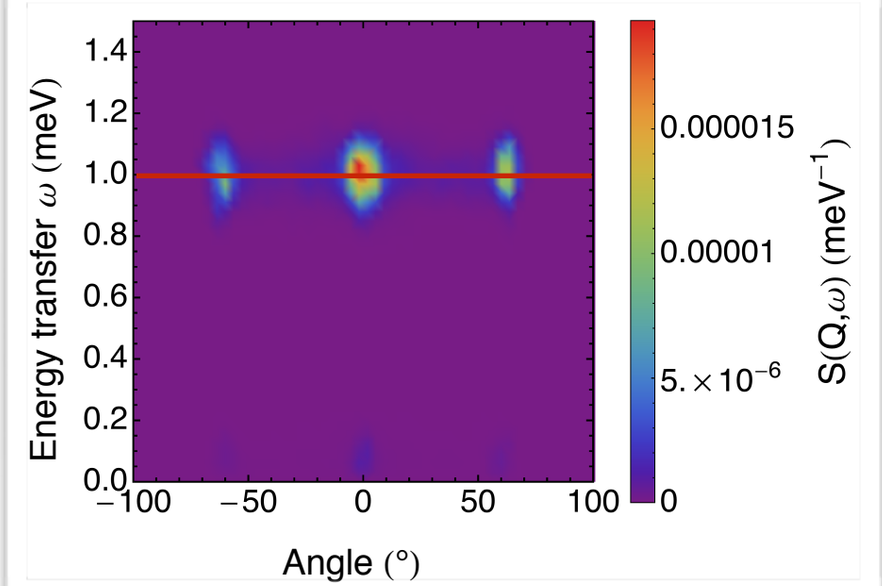
Point Sample

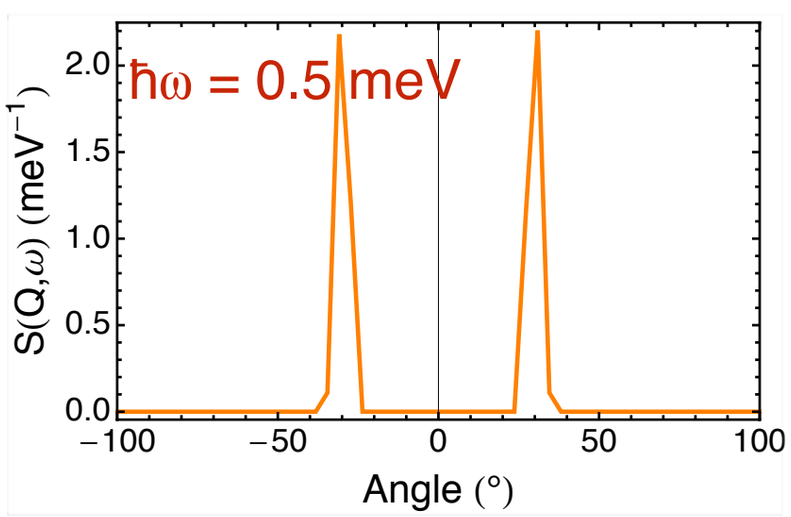
Single scattering

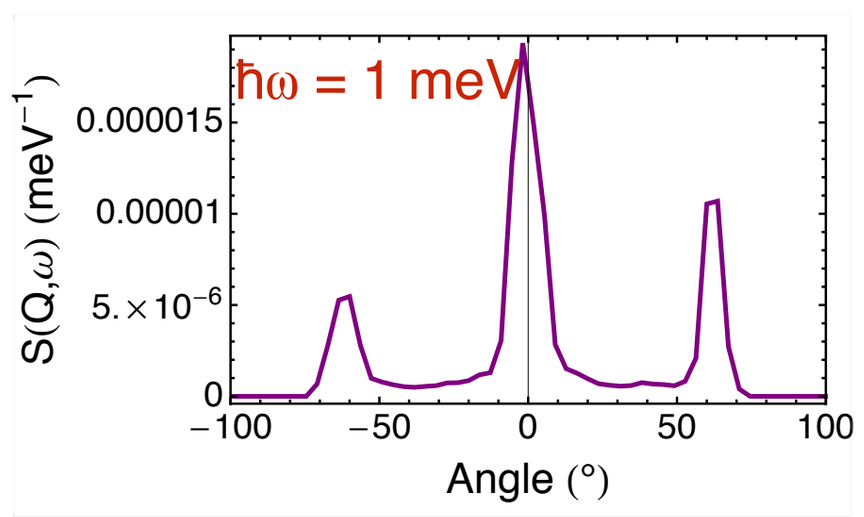


MScat
- 2D cell (0.01×0.75 cm)
- Intensity - ħω = 0.5 meV
  - Q= 0.7 Å^{-1}

Multiple Scattering







Multiple scattering

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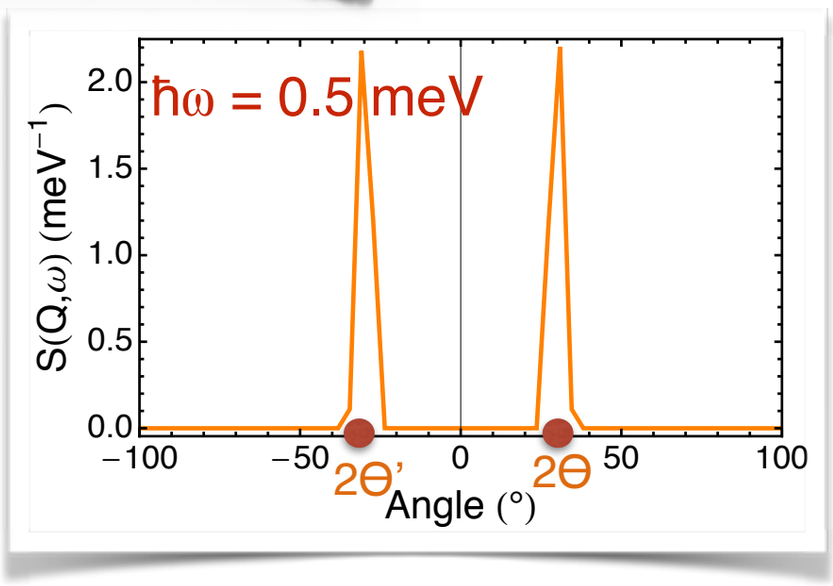
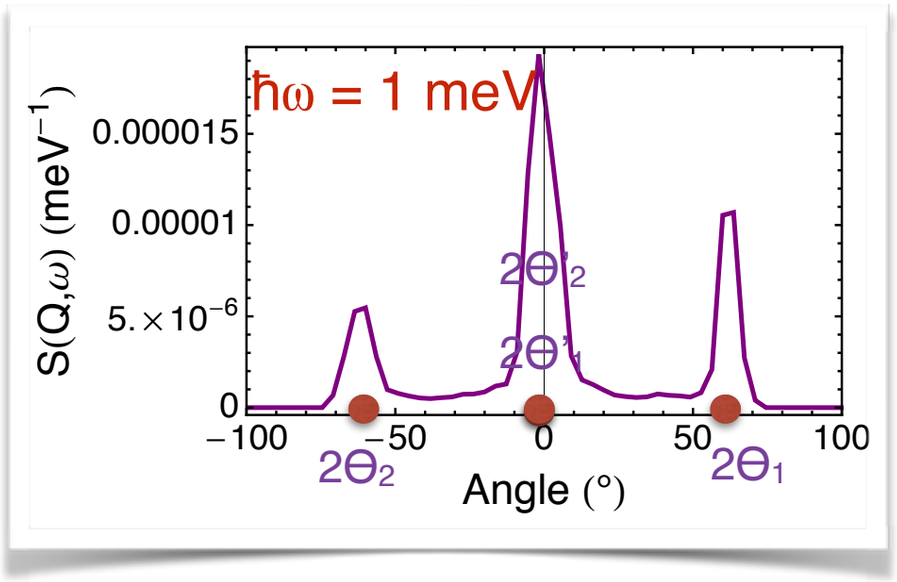
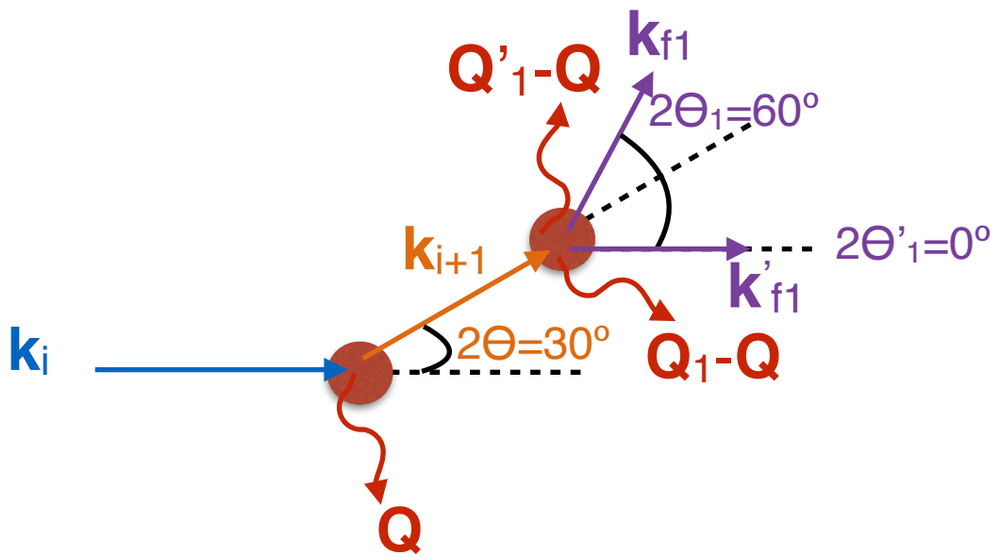
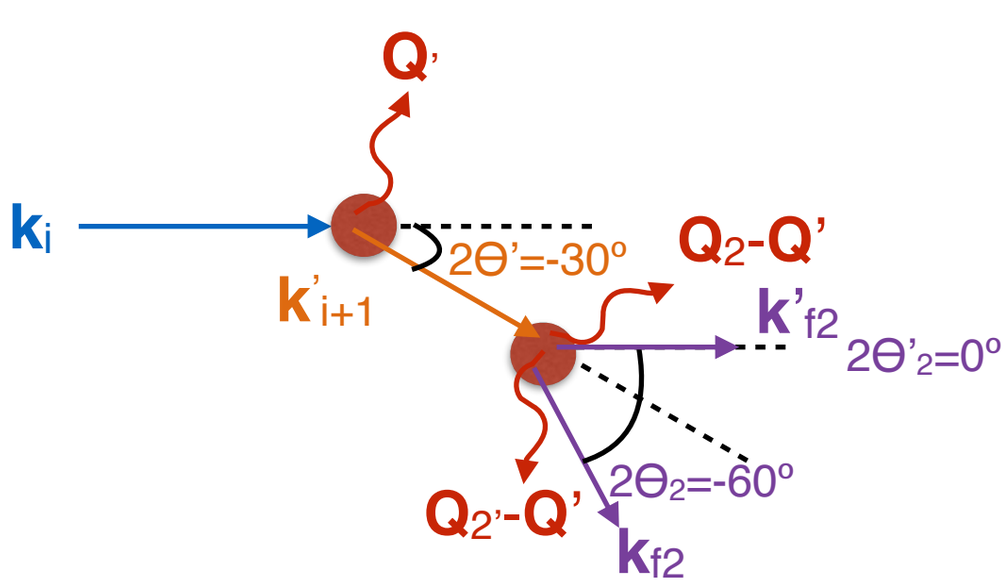




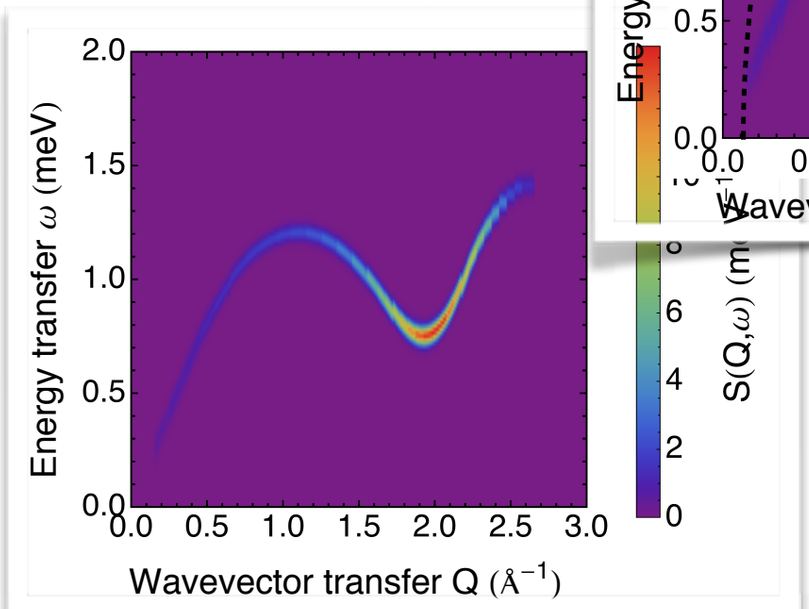




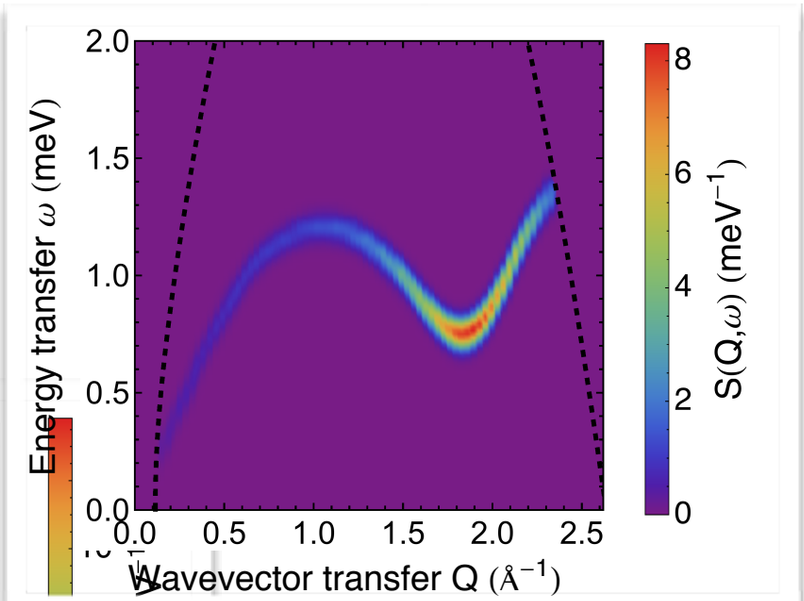
Multiple scattering

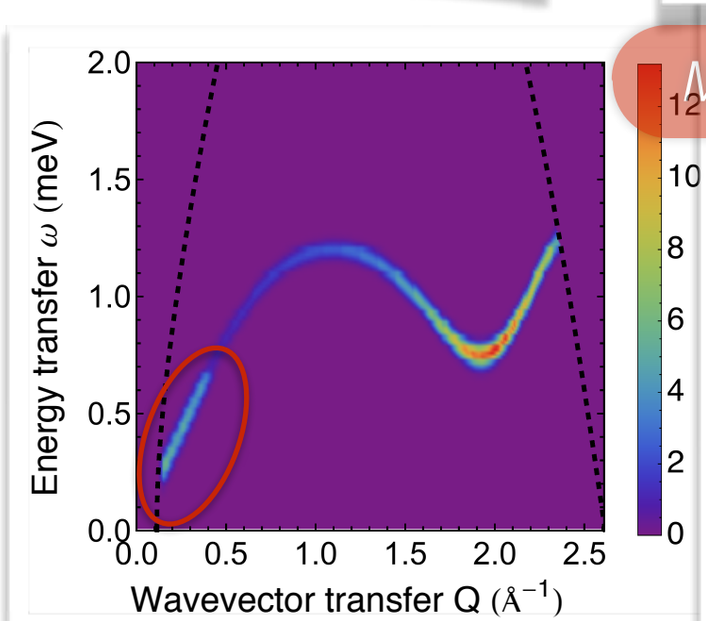
Helium Sample

MScat / McStas
- 3D cell (1*0.75cm)
- Cadmium spacers



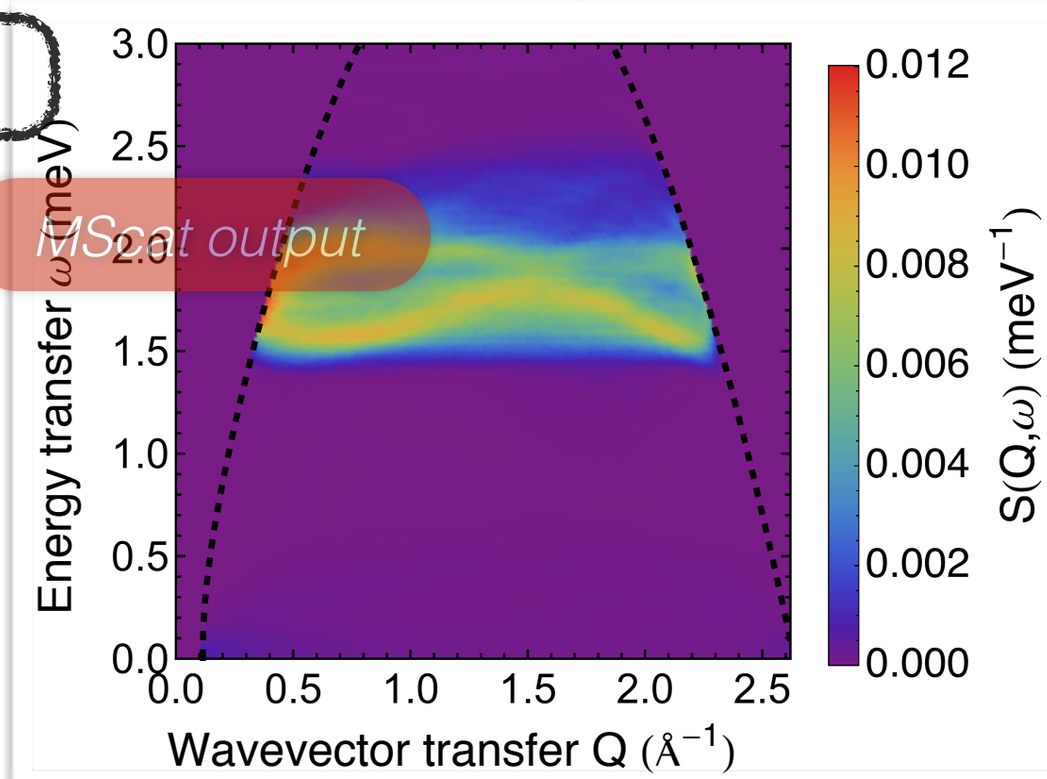
Phonon-Maxon-Roton



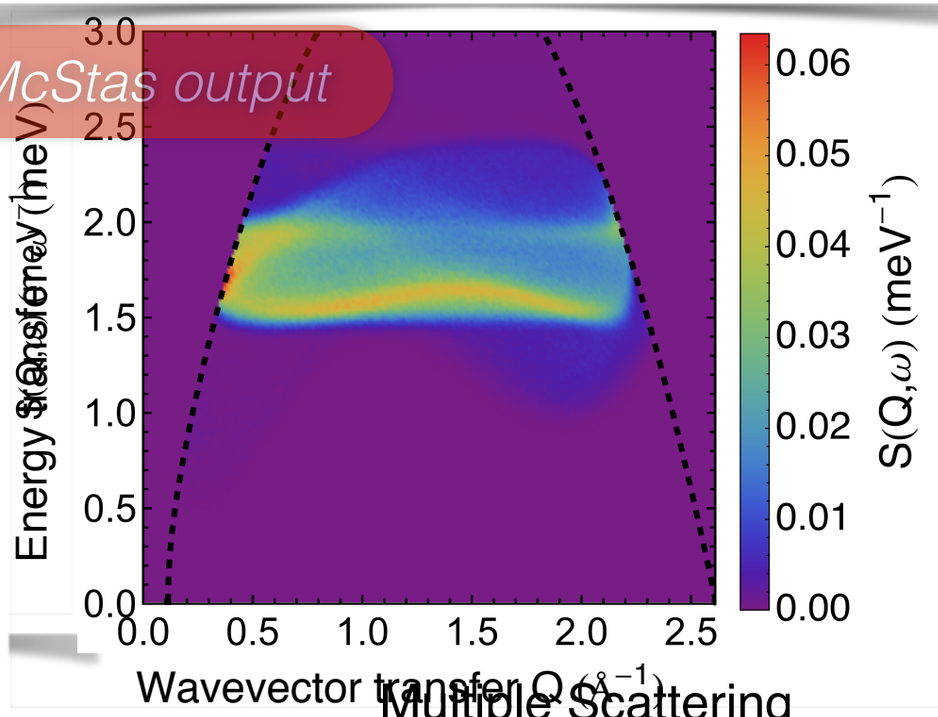


Single Scattering

MScat output



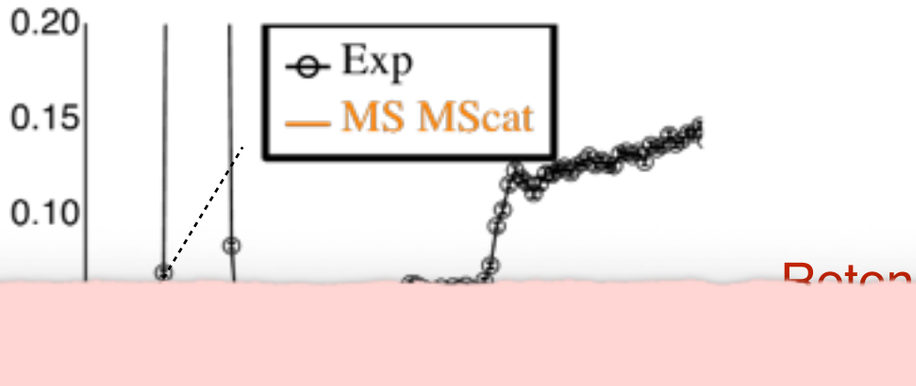
McStas output



Multiple Scattering

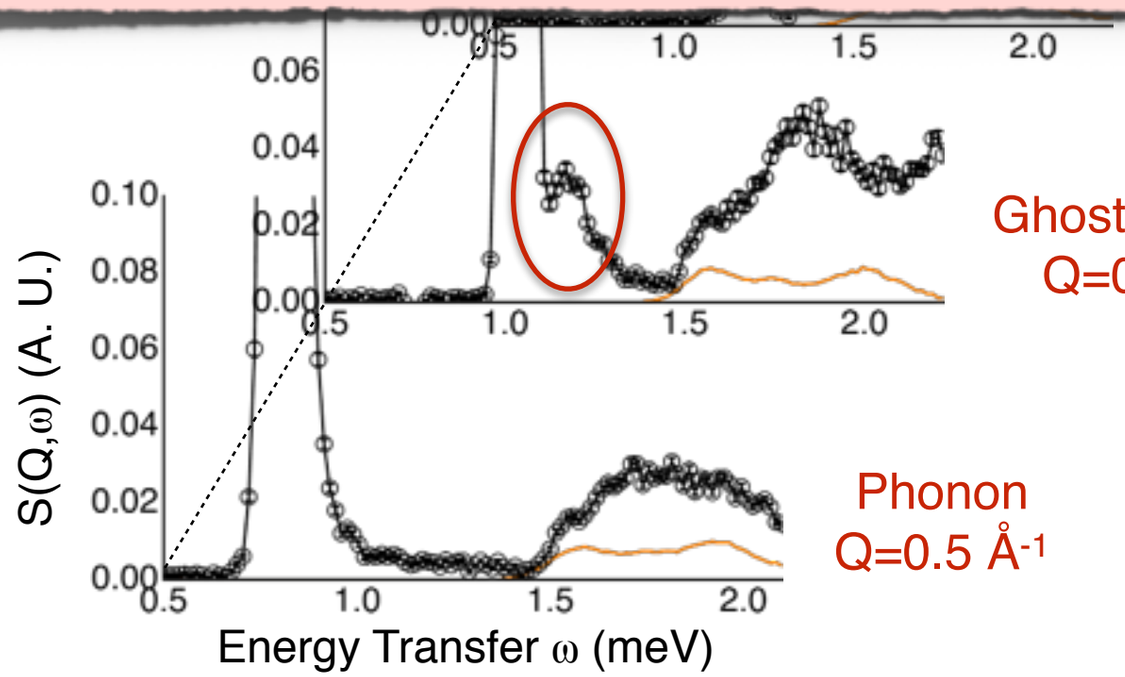
Multiple scattering

Helium Sample - S(Q,ω) at selected constant Q



Results

- Multiple scattering non negligible at low Q
- No multiple scattering in the ghost phonon region
- McStas problem at low Q but similar multiple scattering shapes with McStas and Mscat.
- Ratio multiple scattering intensity / total intensity = 1 % (in agreement with a Sears's type calculation 1.5 %)



Ghost phonon
Q=0.7 Å^{-1}

Phonon
Q=0.5 Å^{-1}

Conclusion

Well-defined multi-excitations

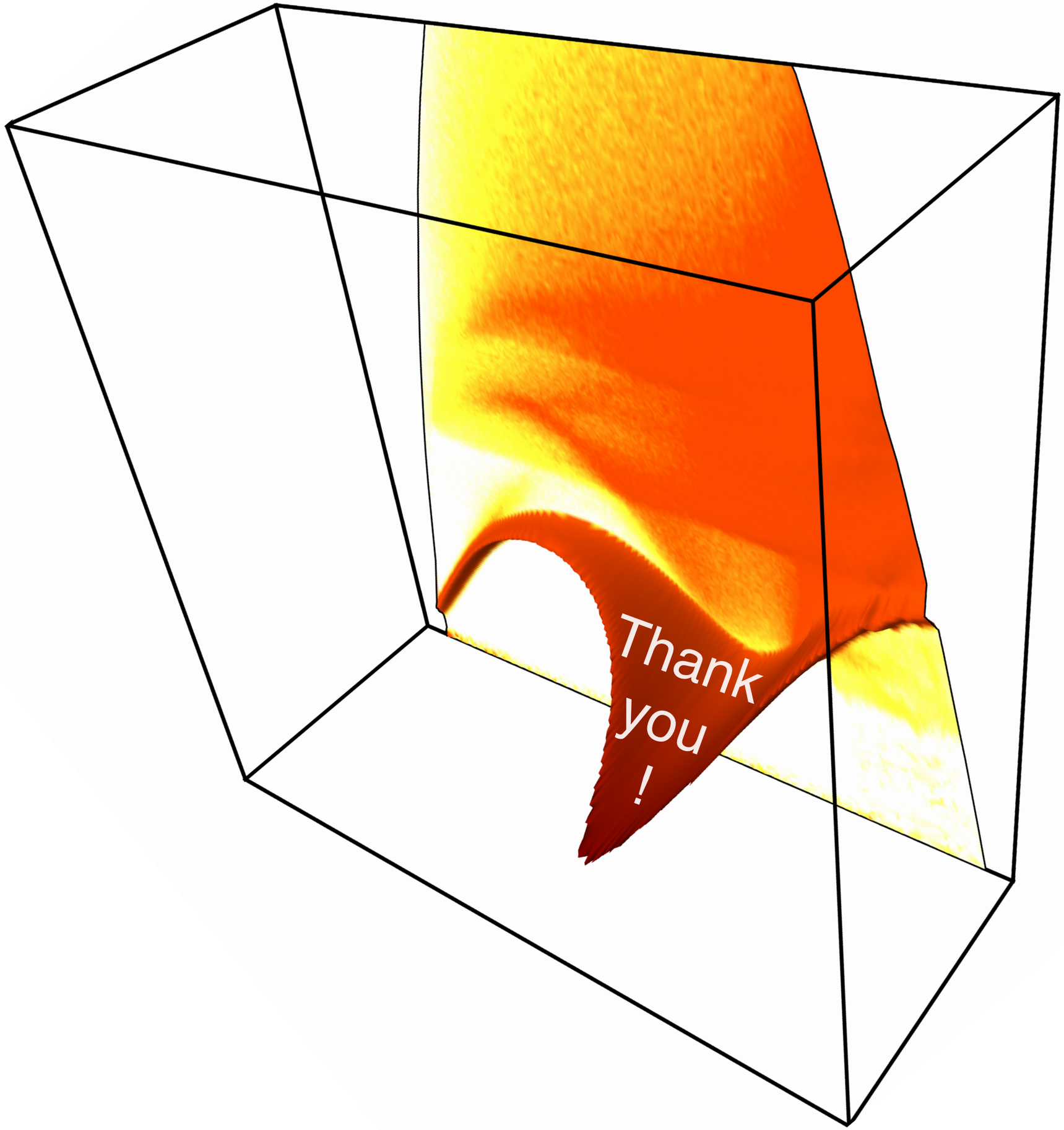
Good agreement between _____

Multi-excitations are an essential part of the dynamic response of the interacting liquid helium

This study could be extended to other interacting systems

Multiple scattering calculation necessary and performed

Ketty Beauvois, "*All you need is neutrons"* seminar, November 10th 2015


Thank
you
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