# NATURE AND RAMAN SIGNATURE OF THE HIGGS AMPLITUDE MODE IN THE COEXISTING SUPERCONDUCTING AND CHARGE-DENSITY-WAVE STATE

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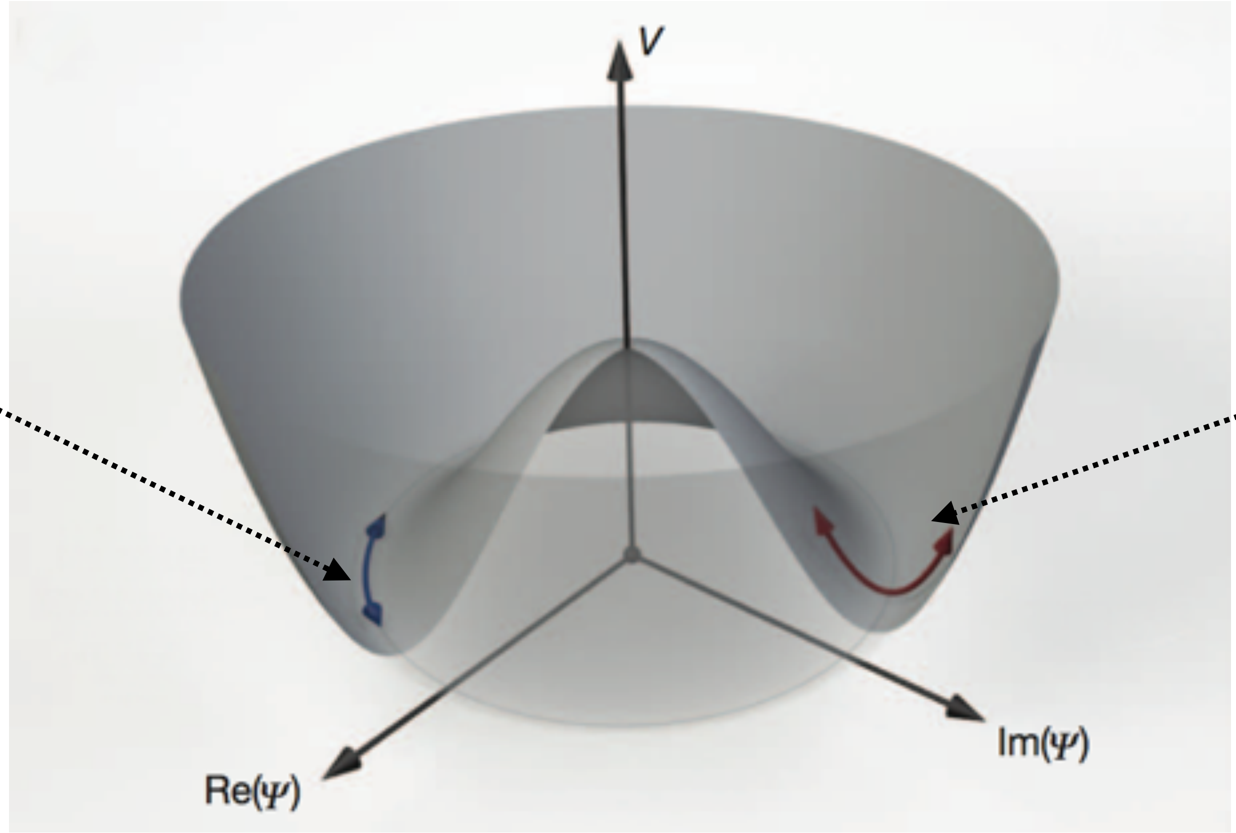
# HIGGS (AMPLITUDE) MODE IN SUPERCONDUCTORS AND ITS VISIBILITY

In a superconductor the breaking of the continuous U(1) symmetry comes along with the emergence of two kinds of collective modes

The phase (Nambu-Goldstone) modes: massless




The amplitude (Higgs) modes: massive

In a conventional BCS superconductor it is very difficult to detect the Higgs mode in the experiments:

1) Over damping by quasi-particle continuum

2) Weak coupling to any external probe

# DYNAMICS OF THE SC AMPLITUDE MODE

The Ginzburg-Landau model well describes the STATIC properties of a BCS superconductor

$$\mathcal{F} = a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + c|\nabla\Psi|^2$$

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**Problem: how to introduce the DYNAMICS?**

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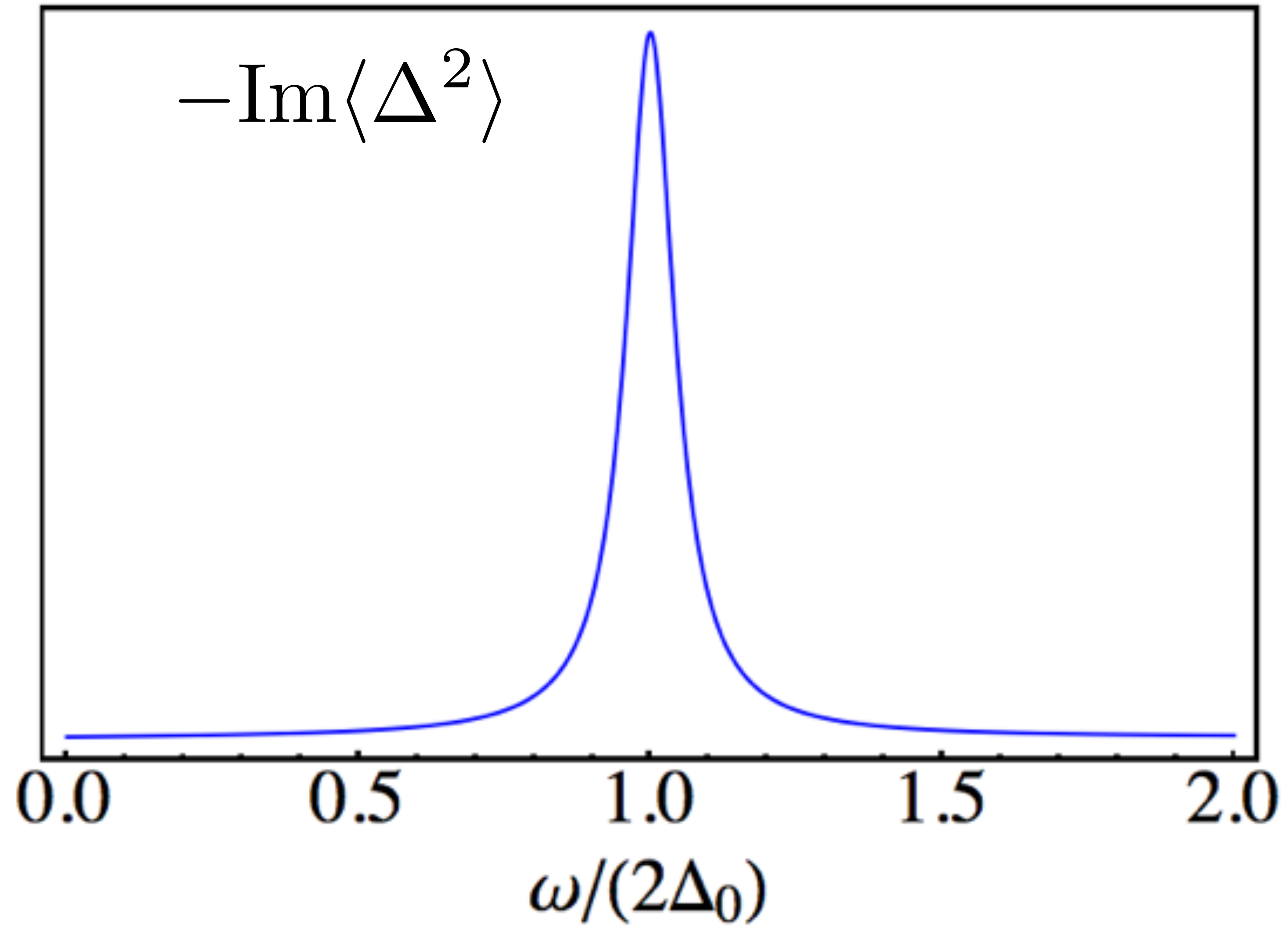
Then a well defined power-law singularity would arise in the amplitude propagator at twice the SC gap

$$\langle\Delta^2\rangle^{-1} \propto \omega^2 - (2\Delta_0)^2$$



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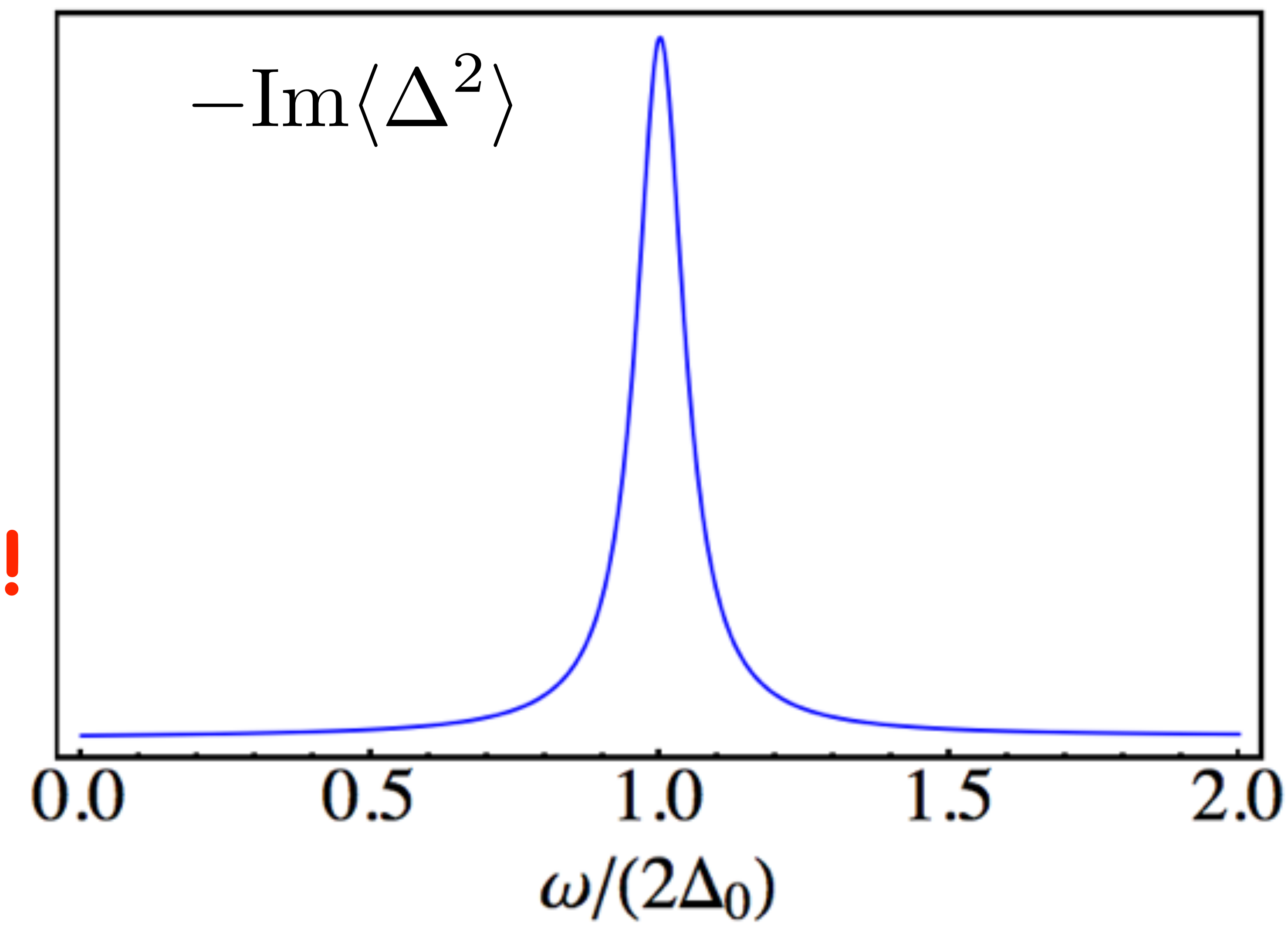


**BUT THIS IS WRONG !!**

(See also T. Cea et al. arXiv:1503.07733, to appear on PRL )

# DYNAMICS OF THE SC AMPLITUDE MODE

The correct way to describe the dynamic properties of a superconductor is to use a microscopic model, taking into account the fermionic degrees of freedom

$$\mathcal{L} = \sum_{\sigma} c^{\dagger}_{\sigma} \left( i\partial_t + \frac{\nabla^2}{2m} \right) c_{\sigma} + \lambda c^{\dagger}_{\uparrow} c^{\dagger}_{\downarrow} c_{\downarrow} c_{\uparrow}$$

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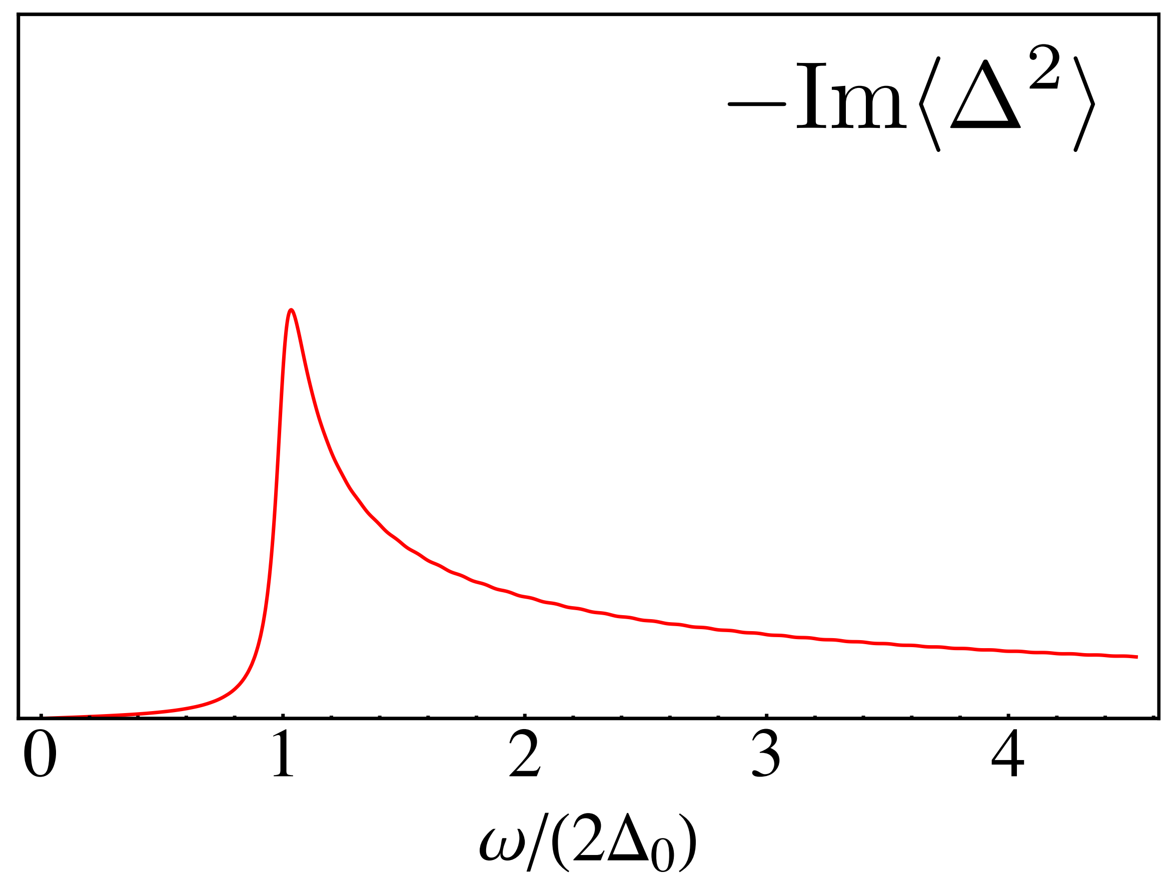

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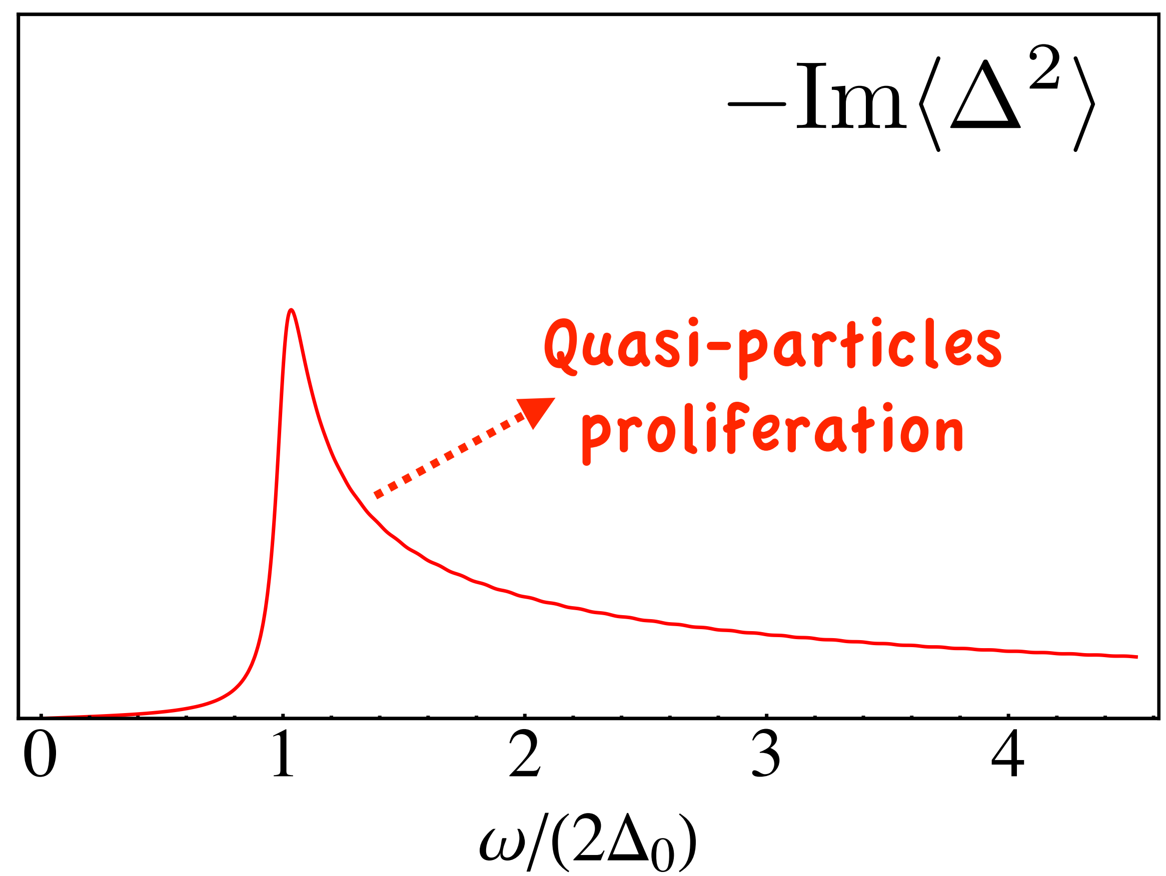

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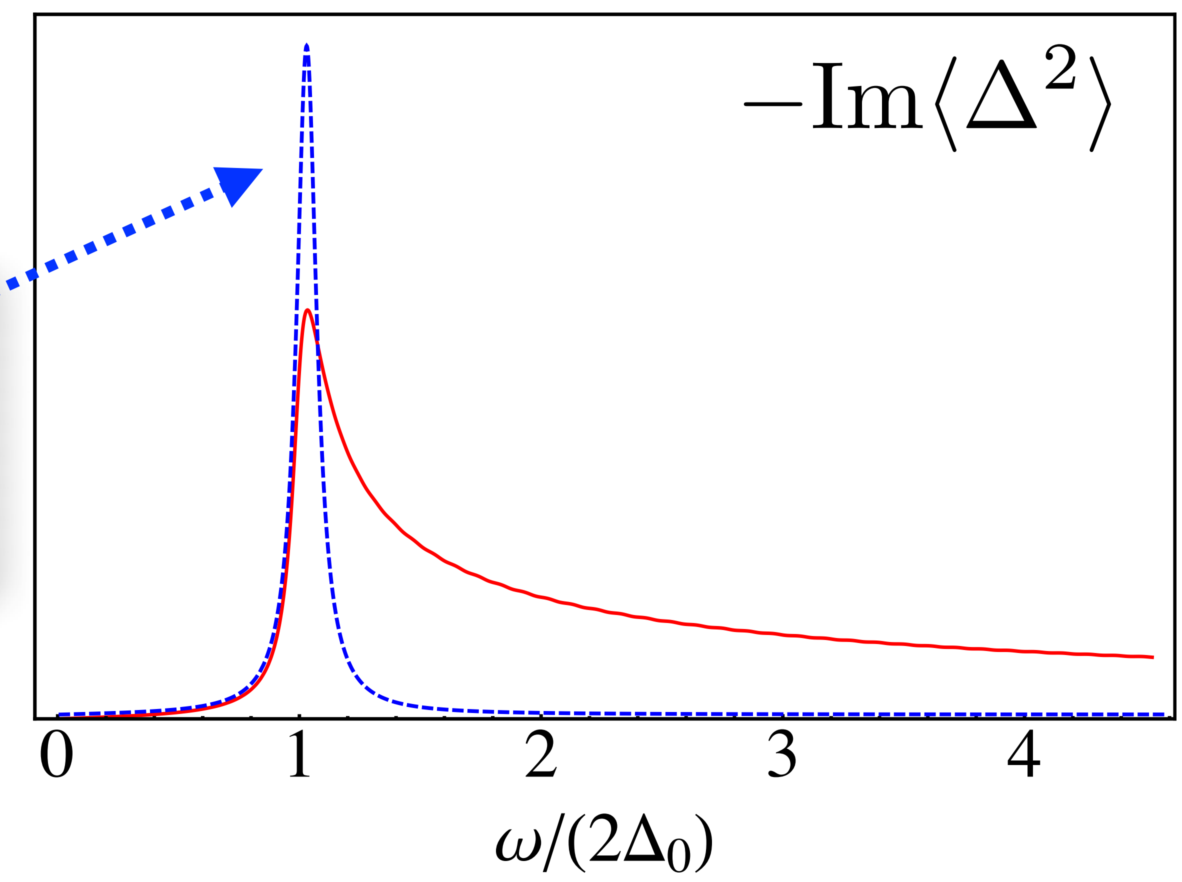
Very different picture as compared to the ''relativistic'' one



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SC+CDW state: $$F_{QP}(\omega) = \sum_{\mathbf{k}} \frac{E_{\mathbf{k}}^{-1}}{(\omega + i\delta)^2 - 4(\Delta_0^2 + D_0^2 + \xi_{\mathbf{k}}^2)}$$

$E_{gap} = 2(\Delta_0^2 + D_0^2)^{1/2}$, so the Higgs remains undamped

$D_0$ is the CDW gap

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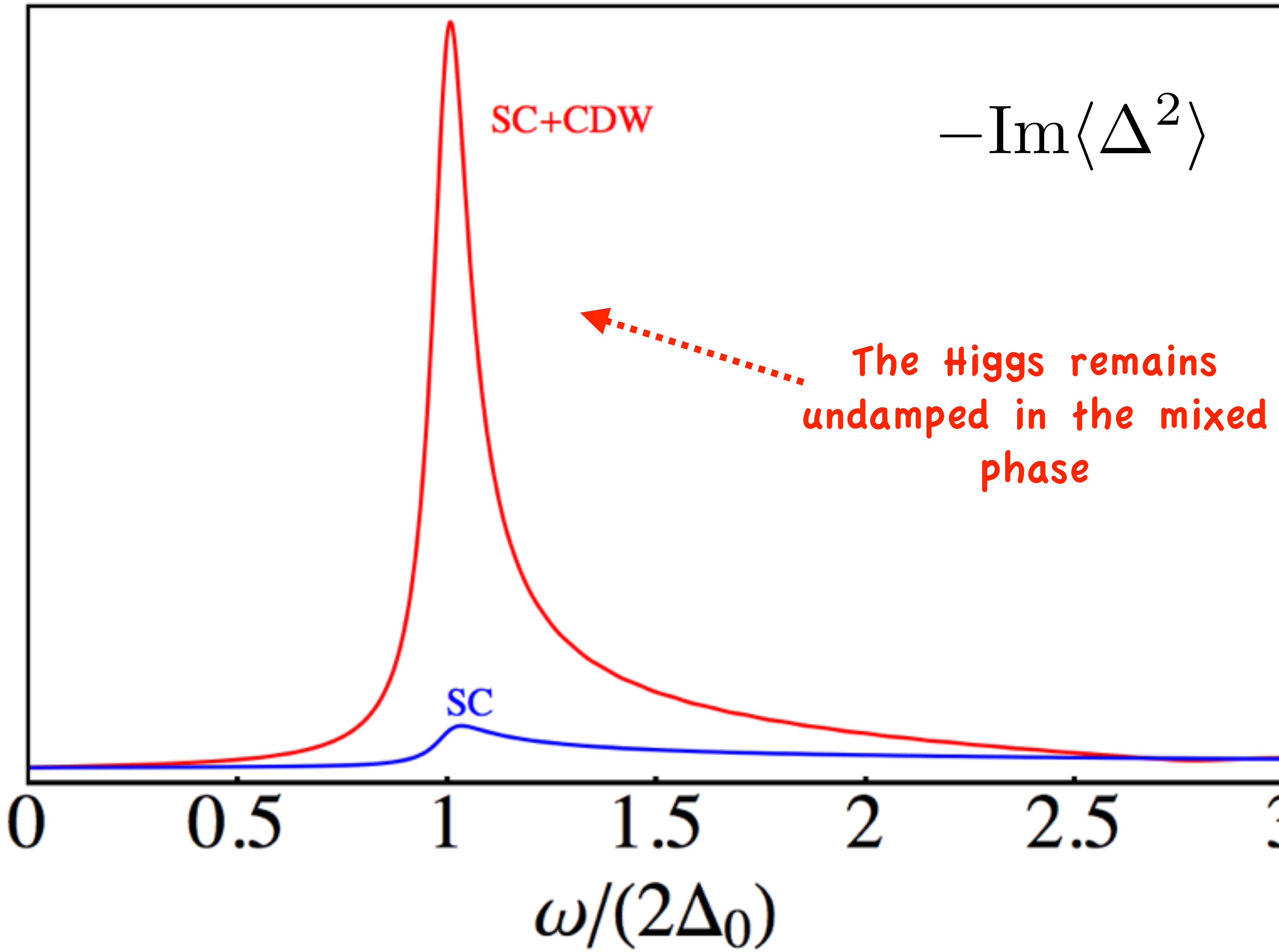



The Higgs remains undamped in the mixed phase

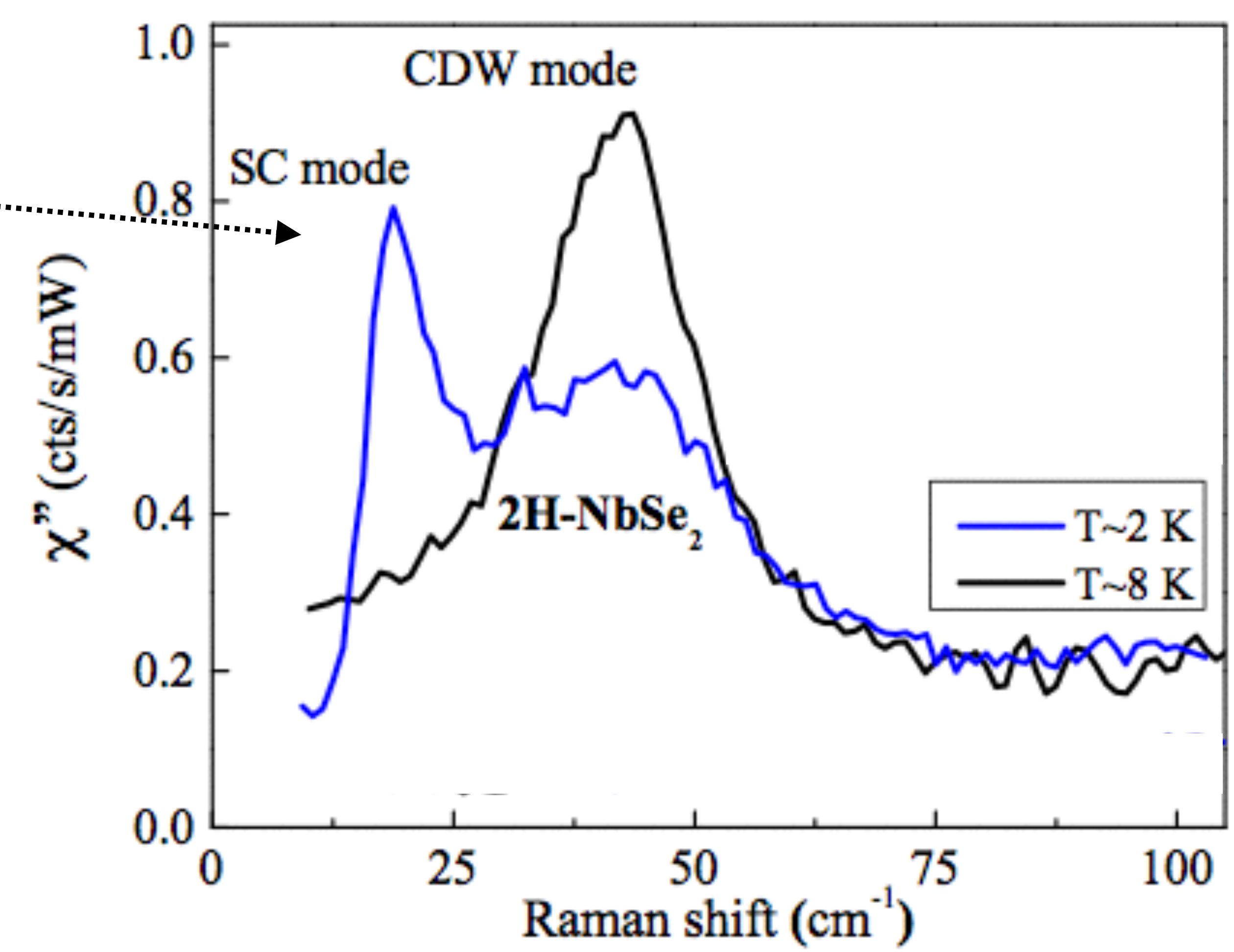
T. Cea and L. Benfatto PRB 90, 224515 (2014)

# THE PECULIAR CASE OF $NbSe_2$

$NbSe_2$ presents the coexistence of SC with CDW:
$T_C$=7K and $T_{CDW}$=33K

The Higgs mode becomes visible via Raman spectroscopy

At $T<T_C$ a strong peak in the Raman response appears at the typical scale of the Higgs mass $\omega_{Higgs}=2\Delta_0$




A. Sacuto et al. PRB (2014)

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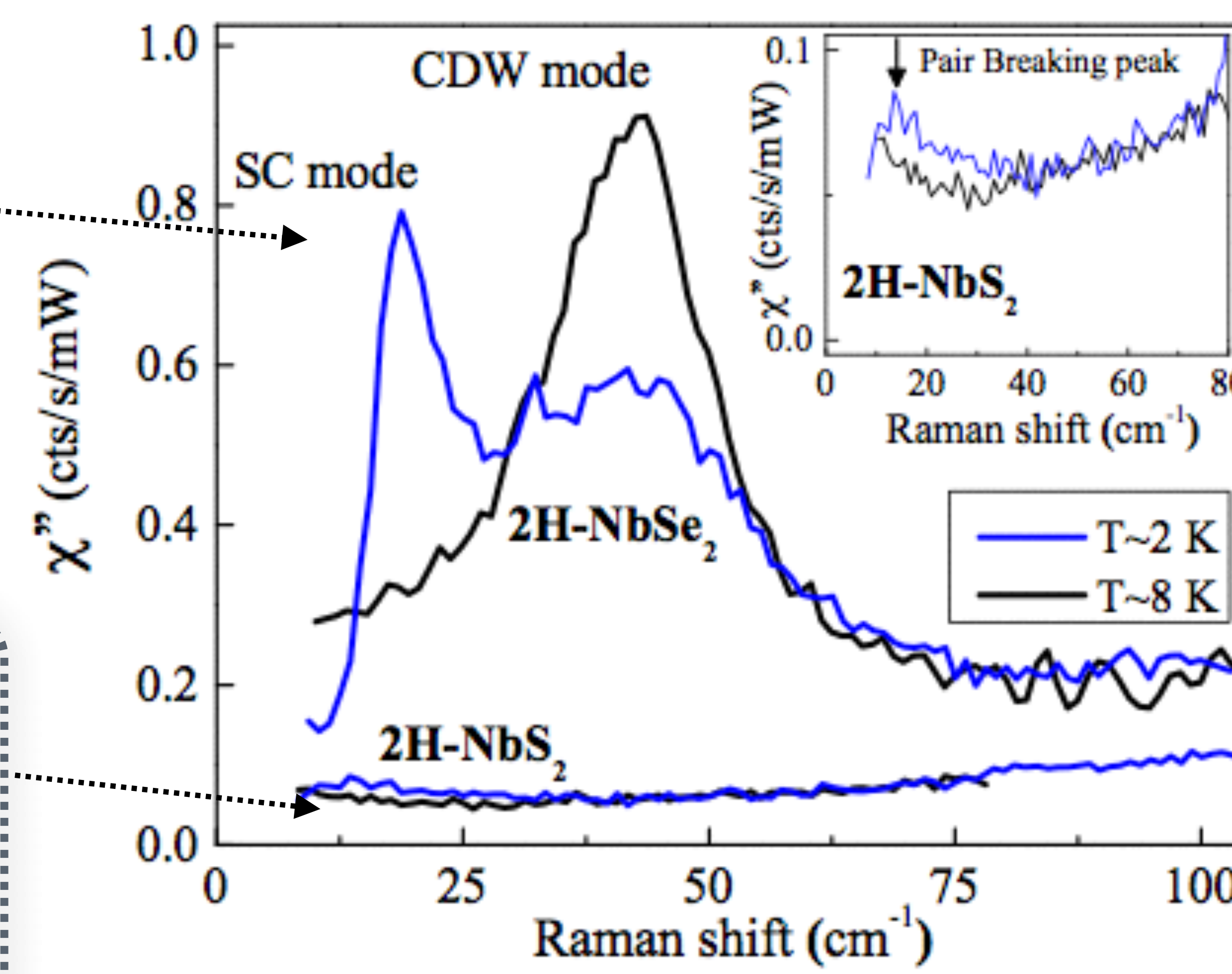
The direct comparison with the isostructural superconductor $NbS_2$ displays only a weak pair breaking signal

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# THE ROLE OF THE CDW PHONON

CDW order → lattice instability

**CDW induced by the coupling of a phonon to the electronic density**

$$H_{CDW} \to H_{ph} + H_{e-ph}$$

$$H_{ph} = \omega_0 a^\dagger_{\mathbf{Q}} a_{\mathbf{Q}}$$

$$H_{e-ph} = \frac{g}{\sqrt{N}} \left( a_{\mathbf{Q}} + a^\dagger_{-\mathbf{Q}} \right) \sum_{\mathbf{k}\sigma} \gamma_{\mathbf{k}} c^\dagger_{\mathbf{k}+\mathbf{Q}\sigma} c_{\mathbf{k}\sigma}$$

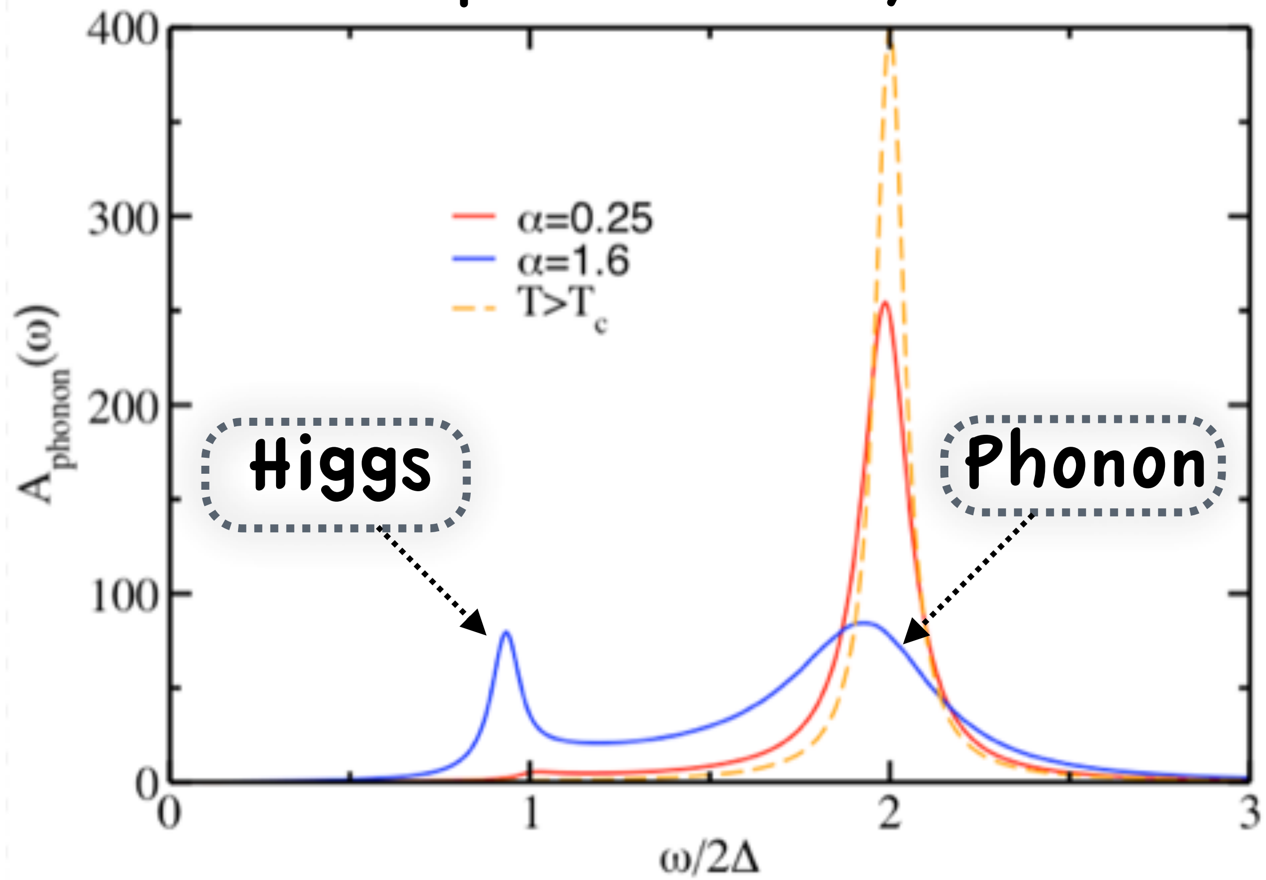
**The phonon acts as an additive collective mode which couples to both the Higgs mode and the Raman probe**

# PREVIOUS THEORETICAL INTERPRETATION

## Finite coupling of the Higgs to the CDW phonon

P. B. Littlewood and C. M. Varma PRB (1982)
D. A. Browne and K. Levine PRB (1983)

Effective phonon density of states

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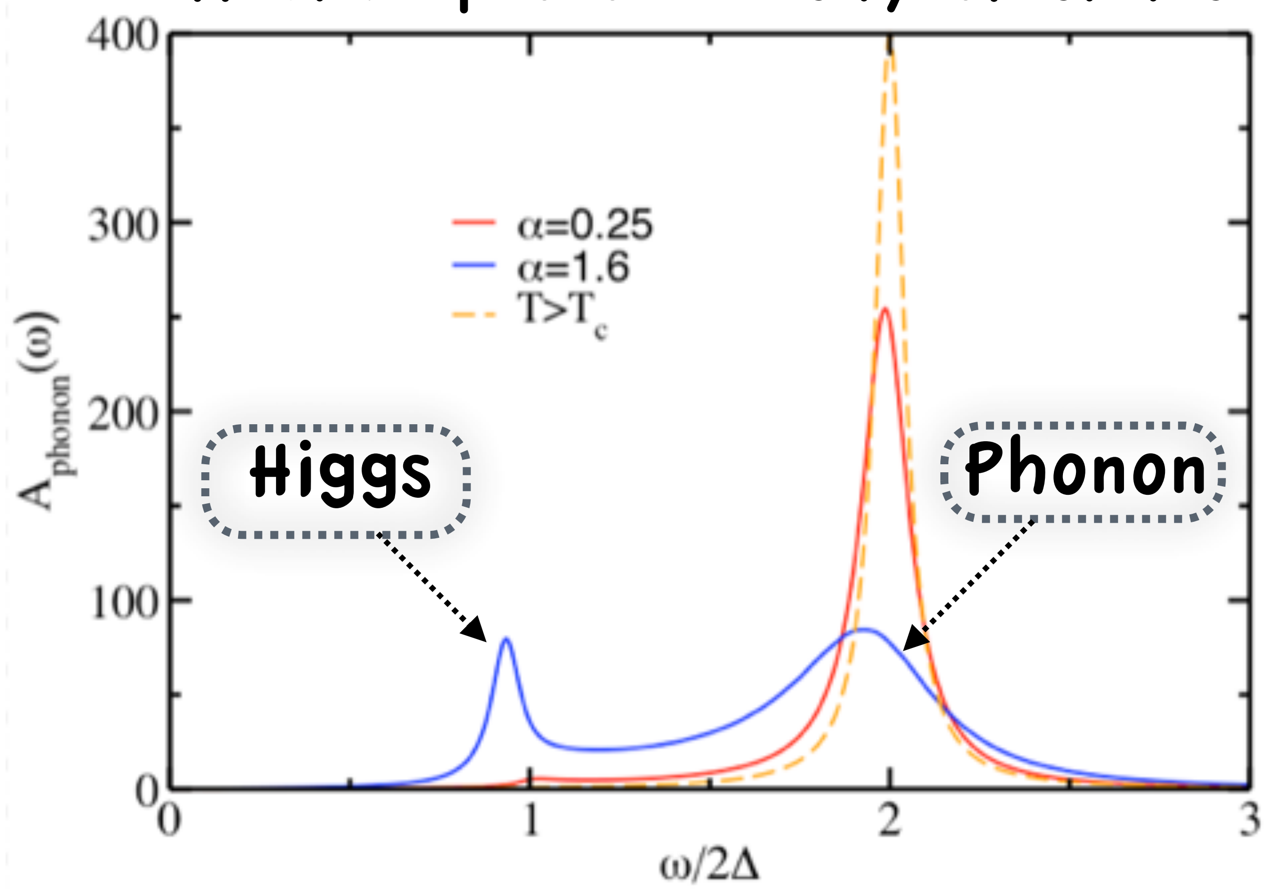


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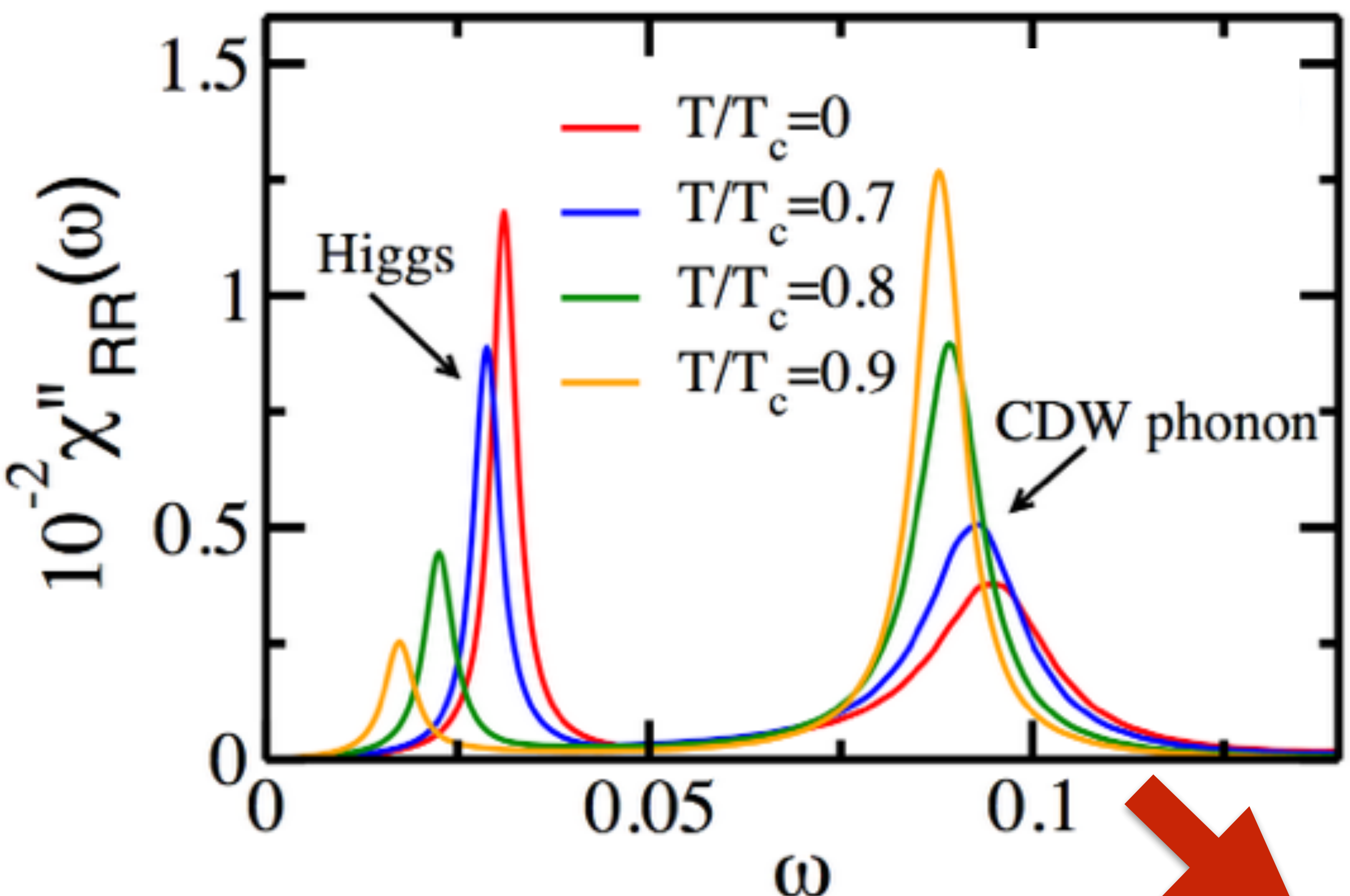
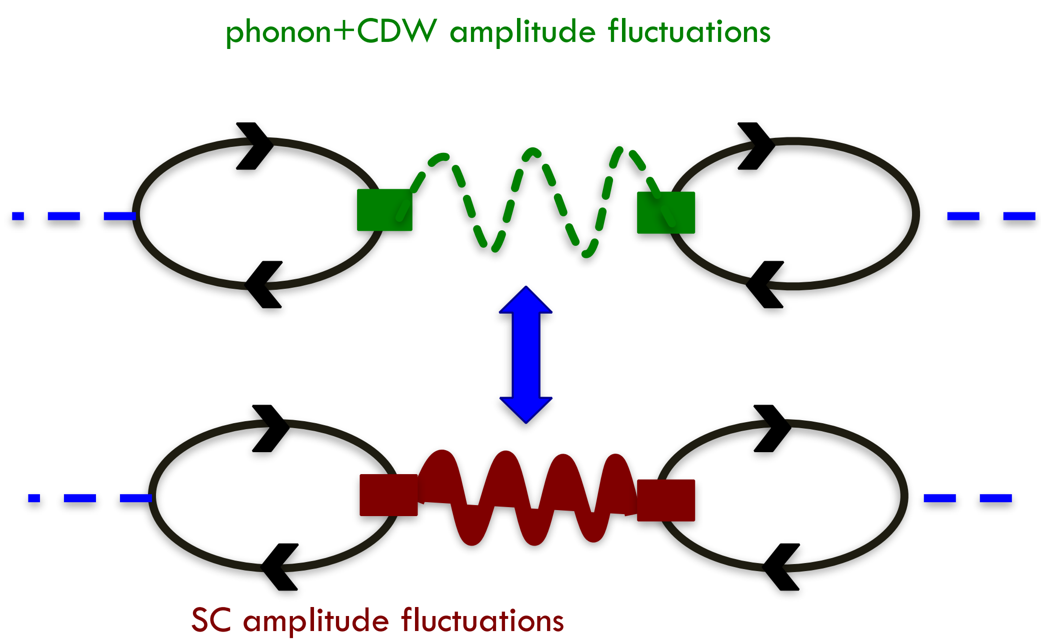
This is not enough to explain the experiments: the true nature of the Higgs and the computation of the full Raman response are needed

# THE RAMAN RESPONSE

We compute the RPA Raman response function by including the contributions of both the (undamped) Higgs and the CDW phonon

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Two peaks appears below Tc

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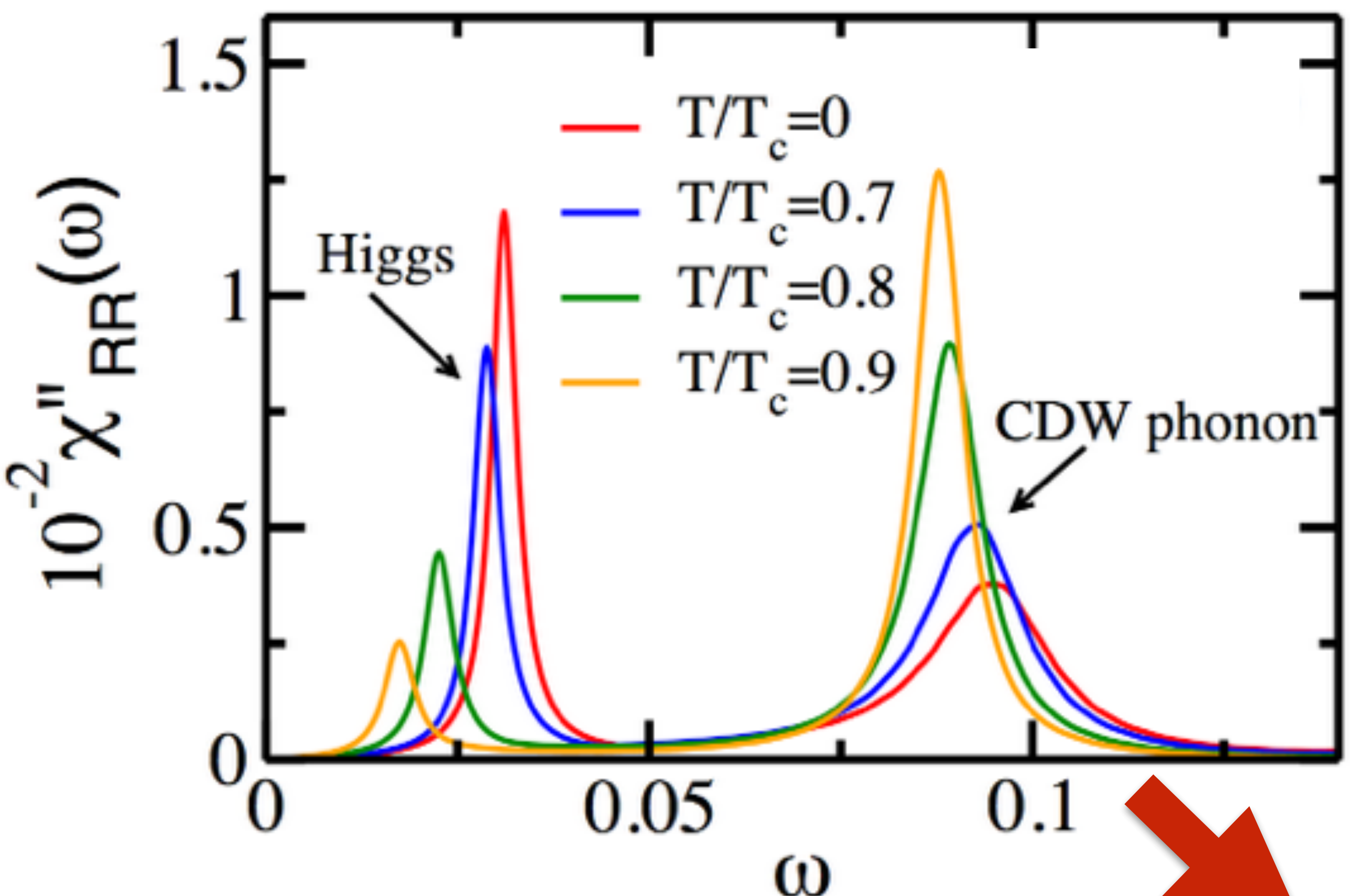


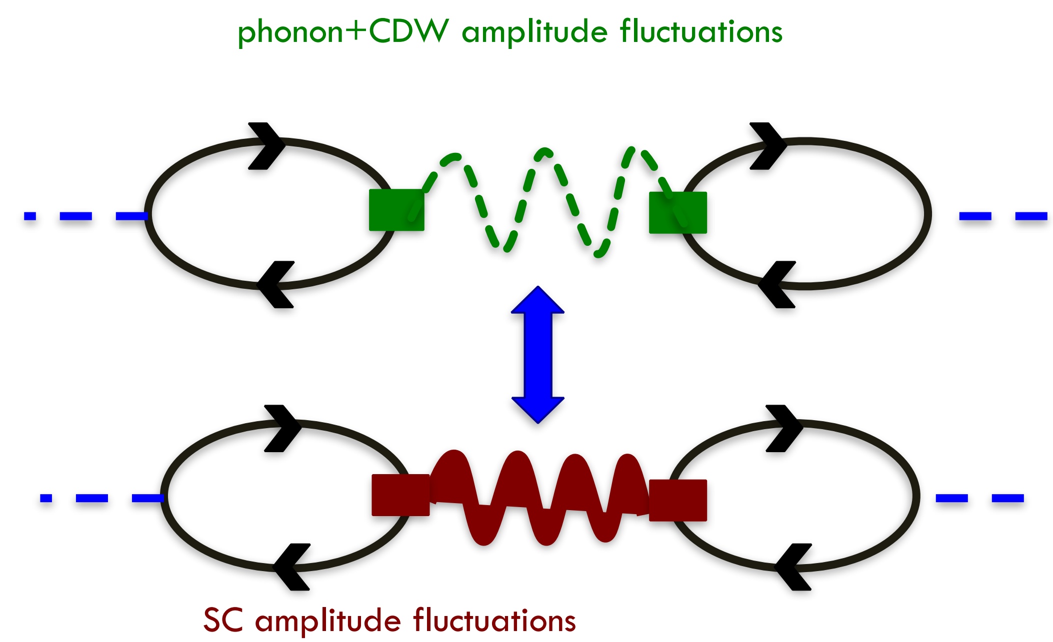


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The Higgs mode seems to acquire spectral weight from the CDW phonon by entering in the SC phase

# CONCLUSIONS AND PERSPECTIVES

- New nature of the amplitude fluctuations in the SC+CDW state (power-law singularity)
- The Higgs manifests itself as a sharp resonance in the Raman response
- What about the dynamics of the Higgs?

↓

Pump-probe tests...
Matsunaga et al. PRL (2013), Science (2014)

T. Cea and L. Benfatto PRB 90, 224515 (2014)

T. Cea, G. Seibold, L. Benfatto and C. Castellani arXiv:1503.07733, to appear on PRL