Higgs or Amplitude Modes in Condensed Matter Physics

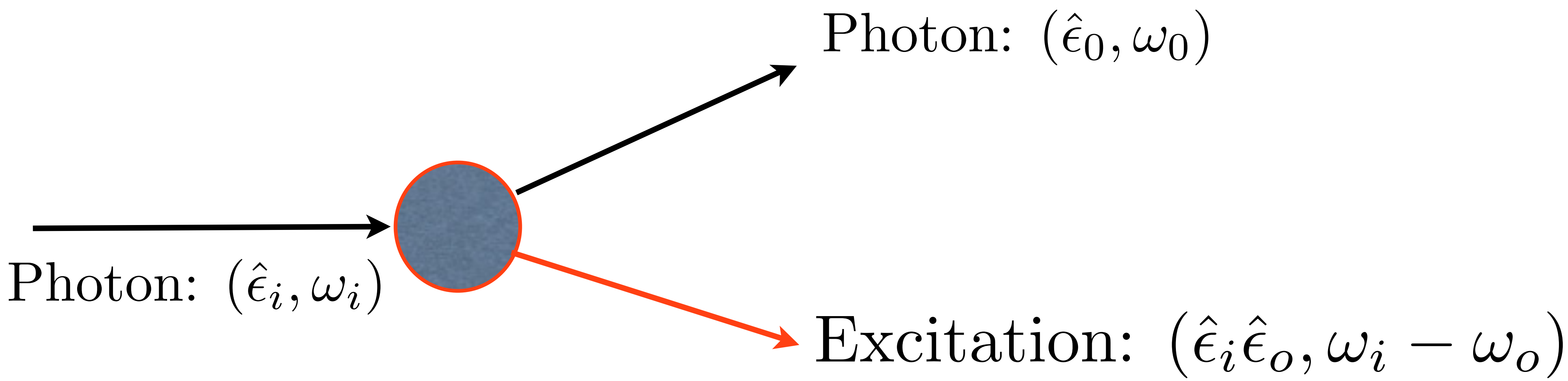
Based On
Littlewood and CMV (1981,1982)
CMV (2001)
Barlas and CMV (2012) ; and Unpublished
Raman Experiments on NbSe2:
Klein et al. (1980's).

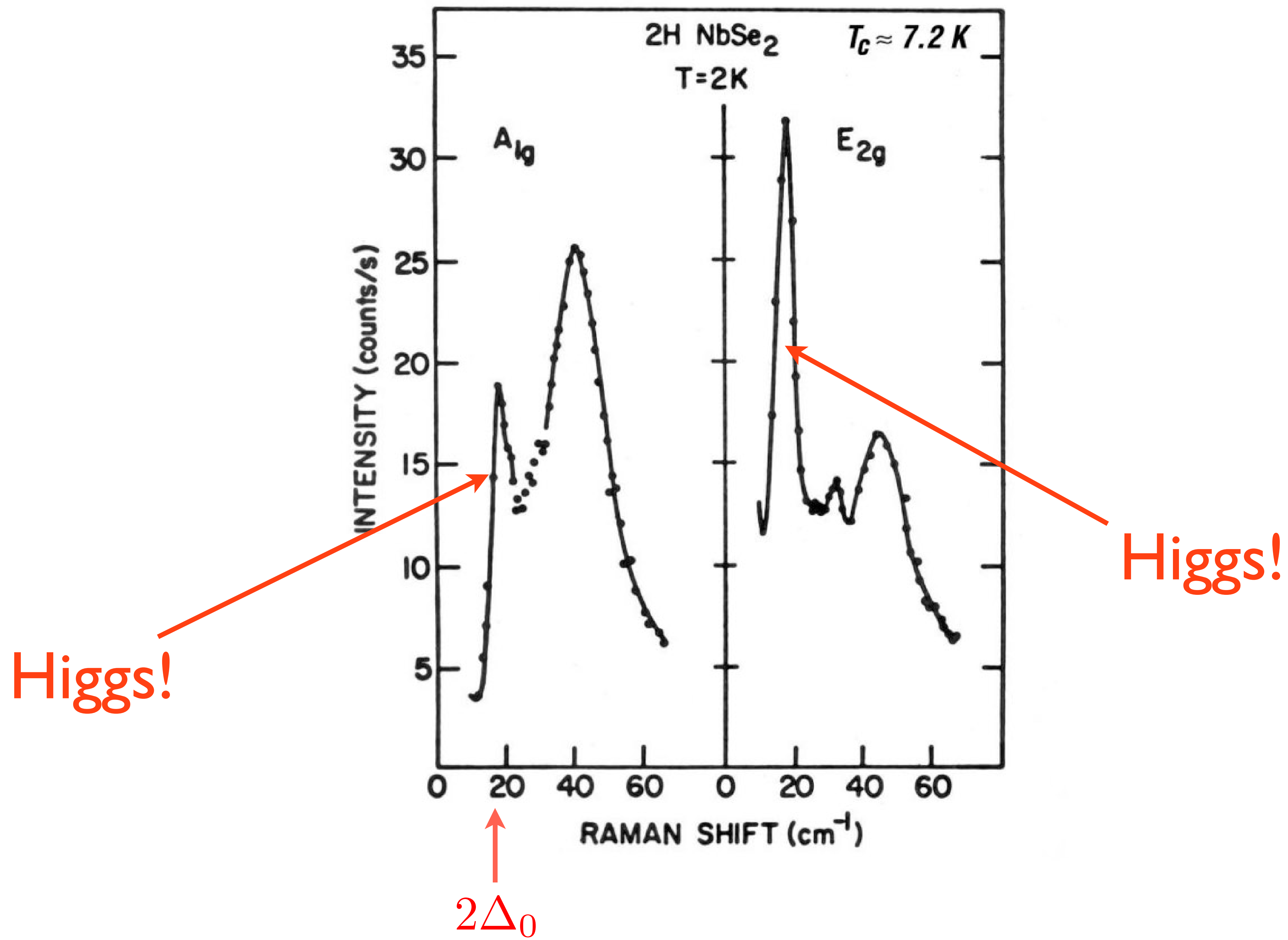
Recent Review article : Pekker and Varma, arXiv

Recent Experiments:
Raman: M-A. Mèasson, A. Sacuto et al. (2012)
Terahertz Pulse excitation: Matsunaga et al. (2013)
With some Nomenclatural reservations:
Cold Atom superfluids : I. Bloch et al. (2012).
Neutron Scatt. on AFM's C. Ruegg et al. (2008)

Urbana Raman Scattering group (1979-80)

Unusual Modes detected in NbSe(2) in Raman Scattering on entering the superconducting phase.





2H NbSe$_2$
T=2K
$T_c \approx 7.2$ K
A$_{1g}$
E$_{2g}$
INTENSITY (counts/s)
RAMAN SHIFT (cm^{-1})
Higgs!
Higgs!
$2\Delta_0$

Organization of this lecture:

1. Basic Phenomenology of Superconductors.
   Phase and Amplitude co-ordinates.

2. Derivation of Higgs using Nambu identities.

3. How to couple to Higgs? Necessity of breaking number conservation. Necessity of particle-hole symmetry.

4. New Experimental Results.

5. Higgs in cold atoms.

Contrasting theory of superconductivity with electro-weak gauge theory : Can CMP say anything helpful?

Phenomenological understanding of Superconductivity:

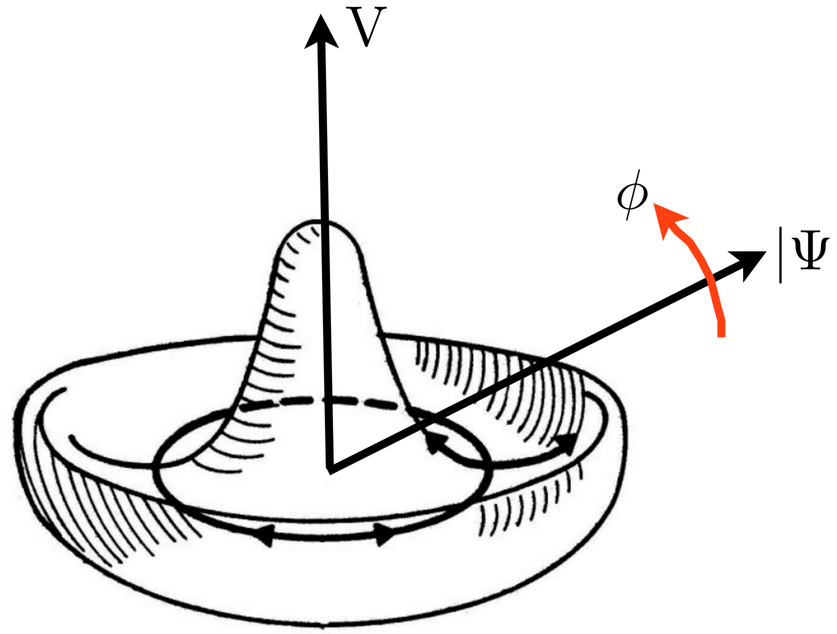
London(s) (1935), Ginzburg-Landau (1950).

Following the Meissner-Ochsenfeld Effect.

Superconductivity is
a MACROSCOPIC COHERENT QUANTUM STATE in which the metallic electrons develop a STIFFNESS.

$$H = \int d^d(r)\left(\frac{1}{2m}|(\nabla - e^*/c\mathbf{A})\Psi|^2 + r|\Psi|^2 + u|\Psi|^4\right)$$

$$\Psi = |\Psi|e^{i\phi}$$

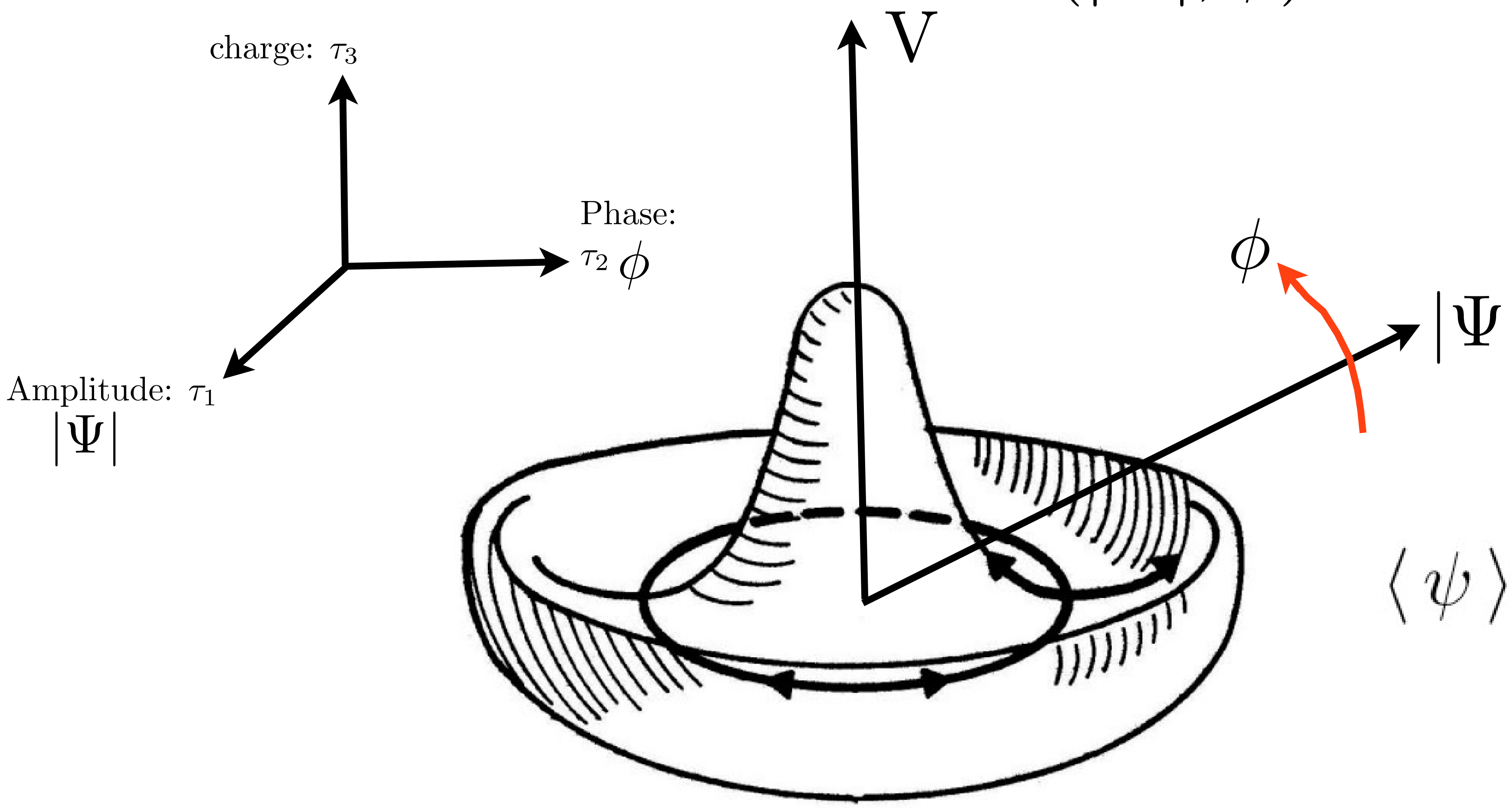


The Ginzburg Landau Model was used to calculate various properties of superconductors.

It did not give Higgs particle to condensed matter theorists.

But it did to Higgs (1964).
And
There is also no Higgs in Superfluid Helium(4).

Effective Potential $V(|\Psi|, \phi)$ for $r < 0$



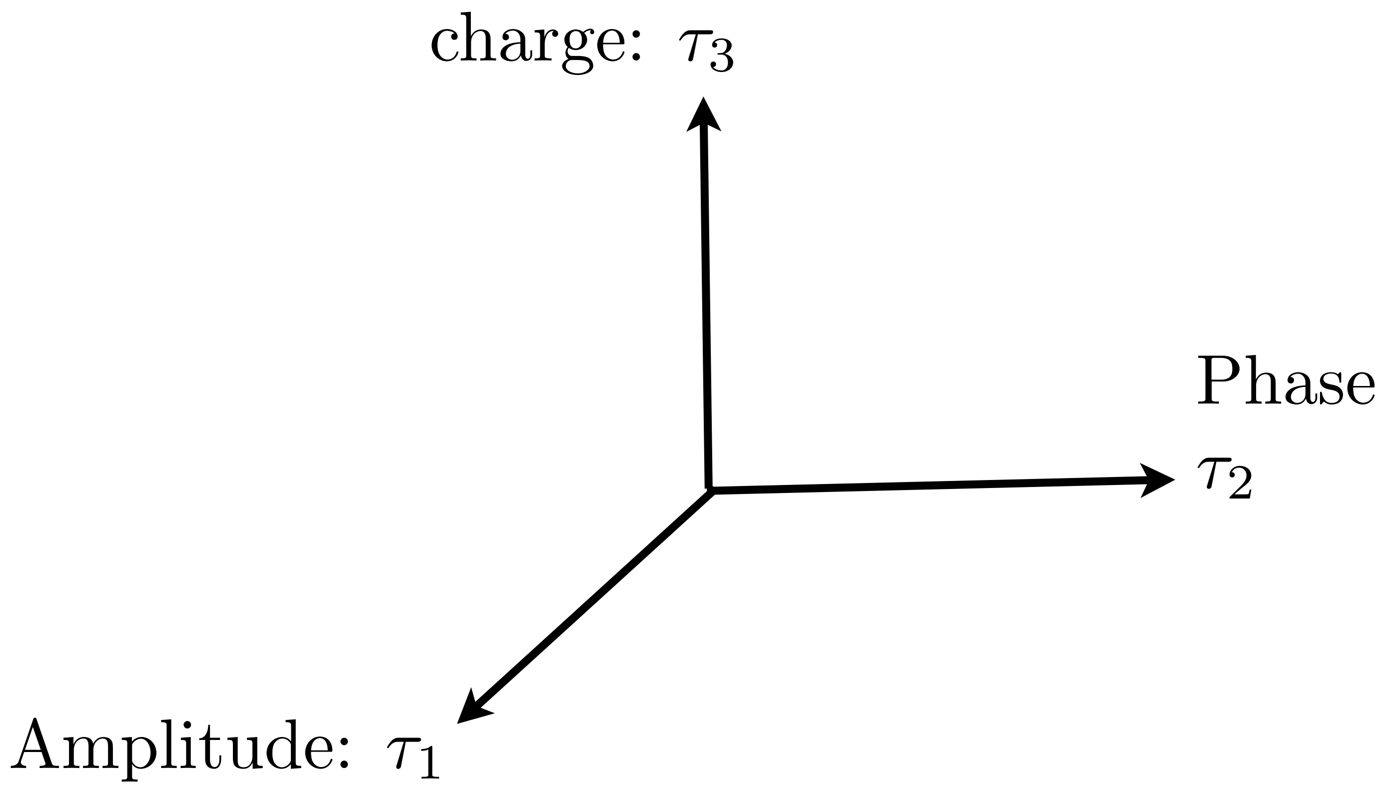
$$\langle \psi \rangle = [-r/2u]^{1/2} \equiv \rho_0^{1/2}$$

In Equilibrium all values of ϕ must have the same energy

Therefore there must exist a collective mode of zero energy at long wavelengths

This is the content of the so-called Goldstone Theorem.

BCS: $\Psi_{\mathbf{k}} = \begin{pmatrix} c_{\mathbf{k}\uparrow} \\ c^{\dagger}_{-\mathbf{k}\downarrow} \end{pmatrix} \qquad \Psi^{\dagger}_{\mathbf{k}} = \left(c^{\dagger}_{\mathbf{k}\uparrow} \; c_{-\mathbf{k}\downarrow} \right)$




Y. Nambu

$$\mathcal{H} = \sum_{\mathbf{k}} \Psi^{\dagger}_{\mathbf{k}} \tau_3 \epsilon_{\mathbf{k}} \Psi_{\mathbf{k}} + \sum_{\mathbf{k},\mathbf{k}',\mathbf{q}} V(\mathbf{k},\mathbf{k}',\mathbf{q}) \Psi^{\dagger}_{\mathbf{k}+\mathbf{q}} \tau_3 \Psi_{\mathbf{k}} \Psi^{\dagger}_{\mathbf{k}'-\mathbf{q}} \tau_3 \Psi_{\mathbf{k}'}$$

$$\begin{aligned} \mathcal{H} &= \mathcal{H}_{BCS} + \mathcal{H}_1, \\ \mathcal{H}_{BCS} &= \sum_{\mathbf{k}} \Psi^{\dagger}_{\mathbf{k}} \left(\epsilon_{\mathbf{k}} \tau_3 + \Delta_{\mathbf{k}} \tau_1 \right) \Psi_{\mathbf{k}}. \end{aligned}$$

Note: BCS Hamiltonian bears a one to one Correspondence with Dirac Hamiltonian. Y. Nambu's important observation (1960)

Local Gauge Invariance:

$$\Psi \to \exp(i\alpha(\mathbf{r},t)\tau_3)\psi$$

➡ Continuity Equation

$$\frac{\partial}{\partial t}(\psi^\dagger \tau_3 \psi) + \nabla \cdot \Psi^\dagger \frac{\mathbf{P}}{m}\Psi = 0.$$

BCS Theory does not satisfy this, yet they got right answers for things they calculated !

Need to do one loop calculations (RPA) using

$\mathcal{H} - \mathcal{H}_{BCS}$

Gorkov (1959): From BCS theory to Ginzburg-Landau

Anderson (1959), and some others did such a calculation:
Obtained the "Goldstone mode" for oscillations of phase:

$$\tau_2 \text{ oscillation} : \omega \propto k$$

But this couples to Longitudinal fluctuations of EM field:
Showed that the oscillation is at the plasmon frequency as in the normal metallic state:

$$\omega = \omega_P = \sqrt{\frac{4\pi n e^2}{m}} - O(\Delta^2/\omega_P)$$

"Anderson mechanism".

ω_P^{-1} sets also the scale for the London penetration depth.

Or of the mass of W or the range of weak interactions.

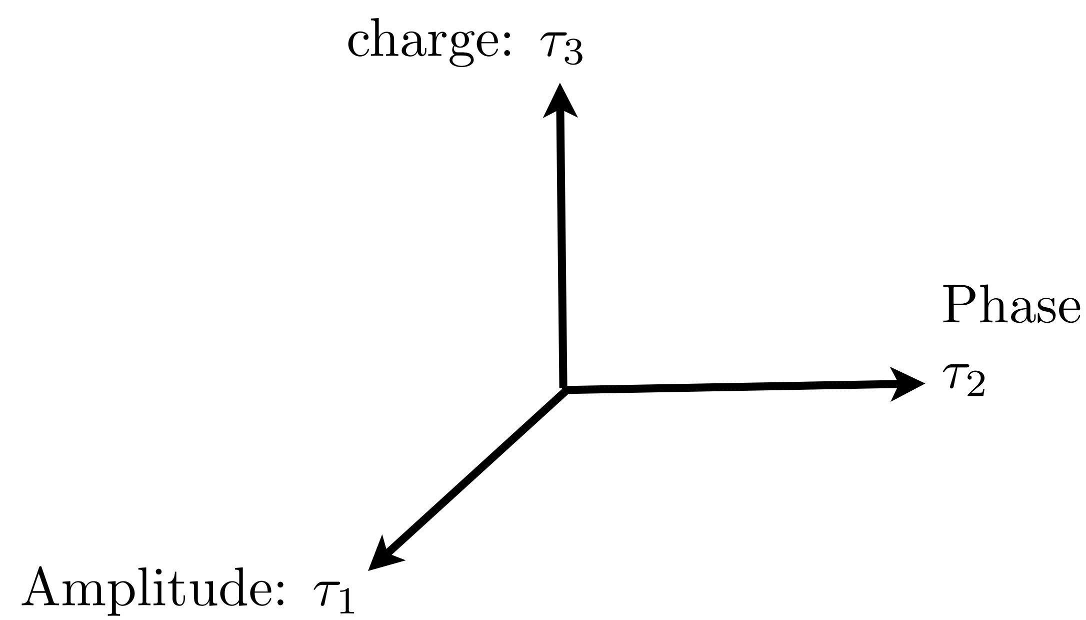
Amplitude Mode: in τ_1 sector: Chargeless, Spin-less

No coupling to electromagnetic field !

$\mathcal{H}$, unlike $\mathcal{H}_{BCS}$ is also invariant to

Y. Nambu (1960):

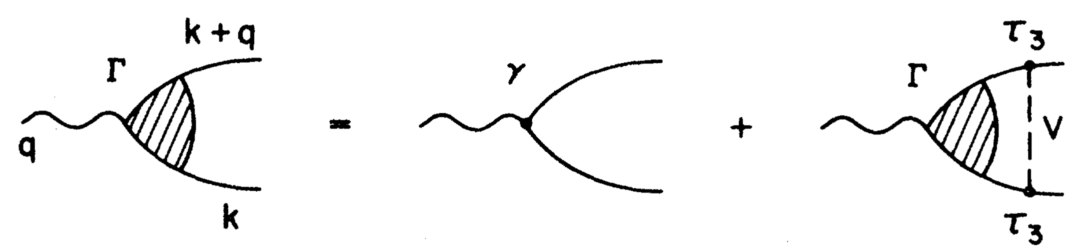
$$\begin{aligned} \Psi &\rightarrow \exp(\alpha(\mathbf{r},t)\tau_1)\Psi \\ \nabla &\rightarrow \nabla + \alpha(\mathbf{r},t)\tau_1, \end{aligned}$$



leading to a "continuity" equation:

$$i\Psi^\dagger\tau_1\left(\frac{\overleftarrow{\partial}}{\partial t} - \frac{\vec{\partial}}{\partial t}\right)\Psi + \nabla\cdot\Psi^\dagger\tau_2\left(\frac{\overleftarrow{P}}{m} + \frac{\vec{P}}{m}\right)\Psi = 0.$$

To satisfy this, solve



with $\gamma \propto \tau_1$.

Note: No renormalization due to Coulomb interaction.

Littlewood, CMV (1981): Calculation consistent with this invariance yields an excitations in the

τ_1 or amplitude sector with

$$\nu_q^2 \approx 4\Delta^2 + \frac{1}{3} v_F^2 q^2 + i\frac{\pi^2}{12}\Delta v_F q.$$

At q=0, the integral Eqn. solved is the same as the gap Eqn. for supercond. All superconds. have this mode. Also, no other scale in the problem.

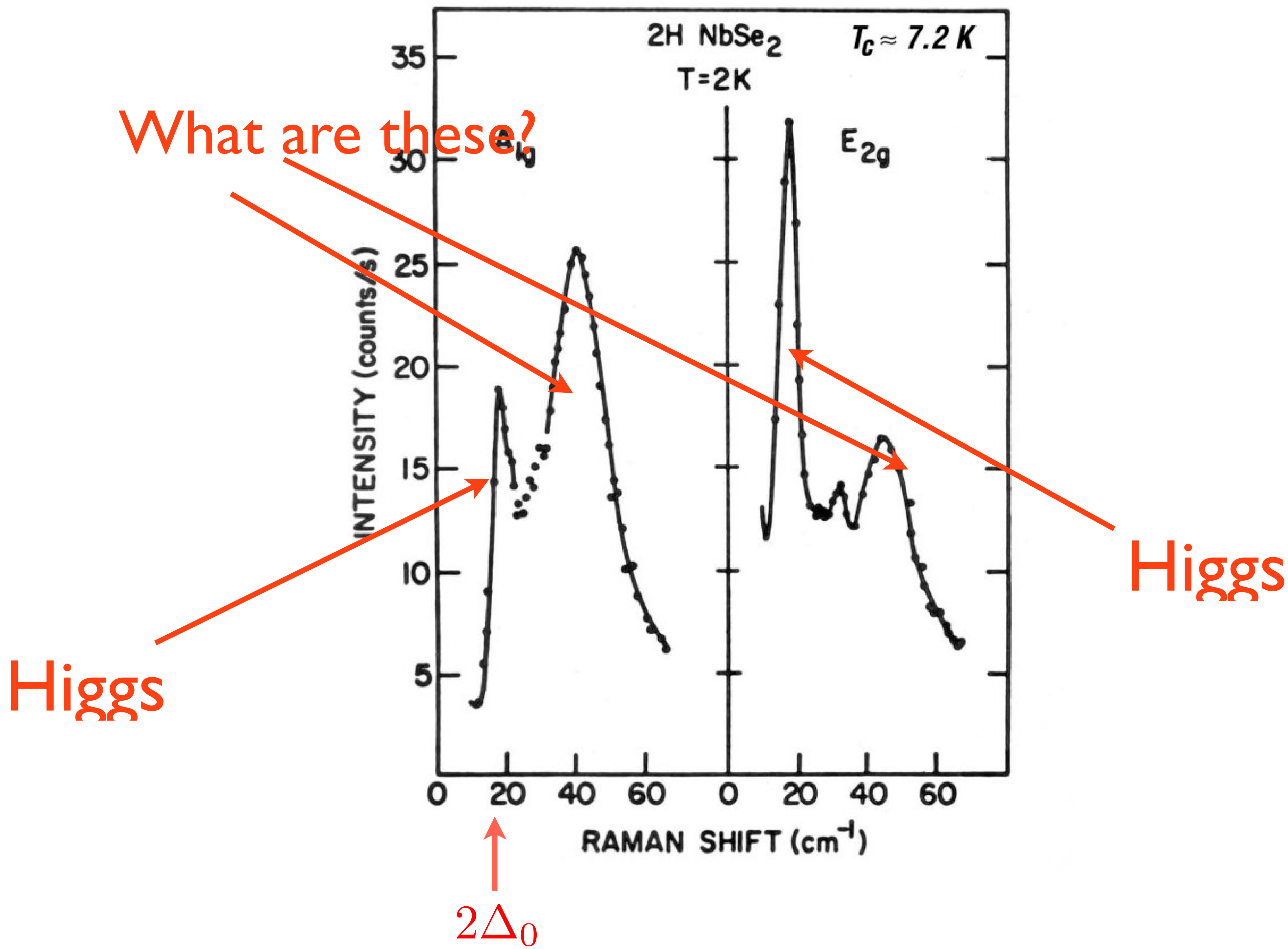
This does not help at all with the observed sharp mode

How would one couple to it anyway?

It has no charge, no dipole moment, no magnetic moment, etc. to which we couple excitations with external probes.

It is a SCALAR

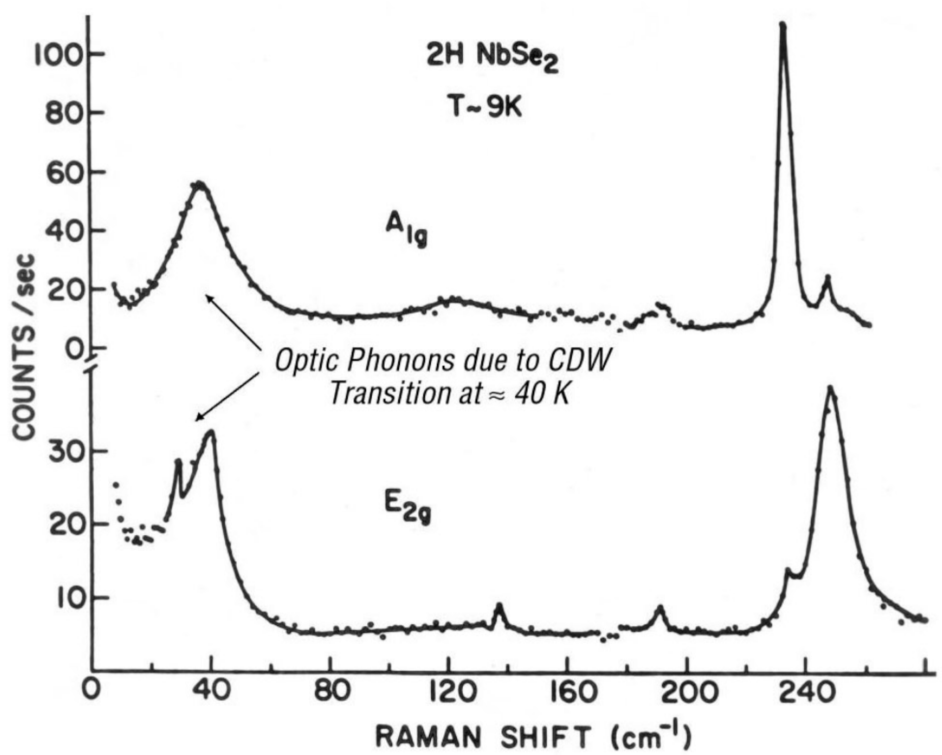
To excite this mode, one must shake the condensate!

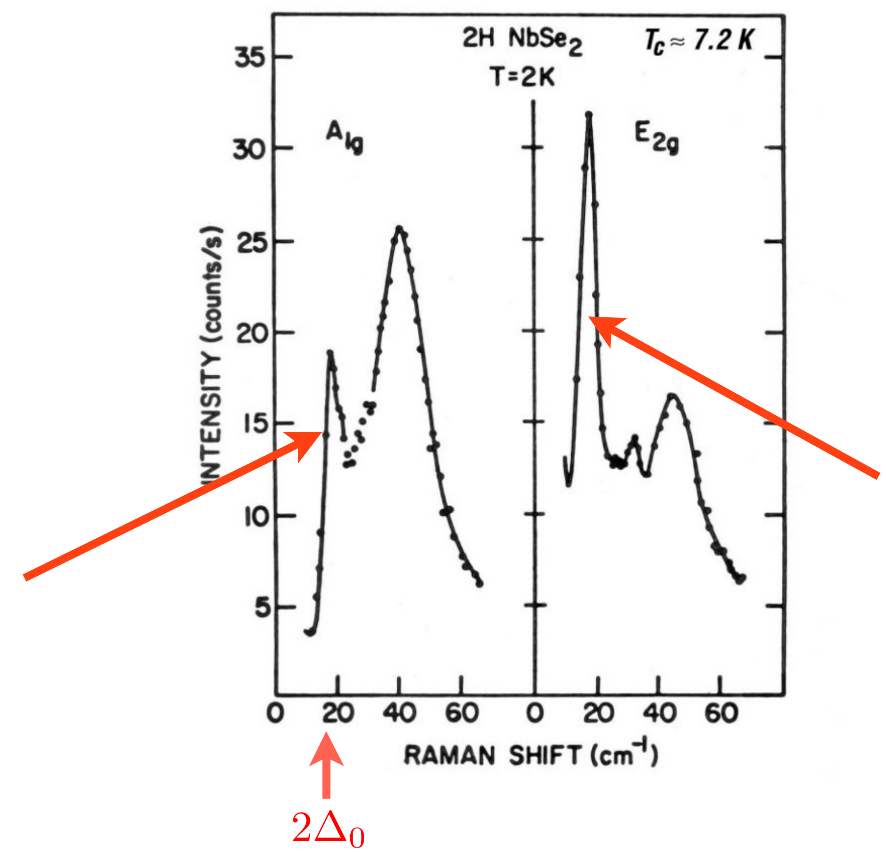


What are these?
Higgs
Higgs
$2\Delta_0$
2H NbSe2
T=2K
Tc ≈ 7.2 K
E1g
E2g
INTENSITY (counts/s)
RAMAN SHIFT (cm-1)

$NbSe_2$ has a charge density wave transition at 33 K.

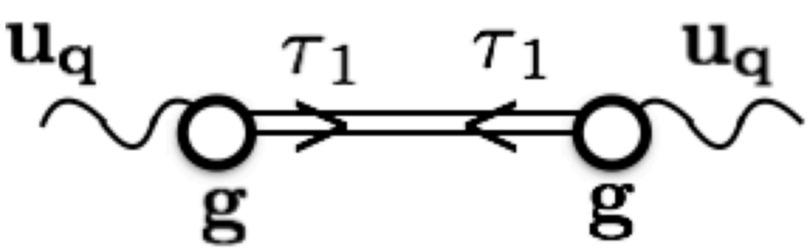
This is a structural transition which gaps part of the Fermi-surface.
In the low T phase, altered periodicity gives new optical phonons at relatively low energies.





Looking at the data suggested to us that the weight in the new peak plus that in what remains of the old peak is the same as the weight of the peak above Tc.

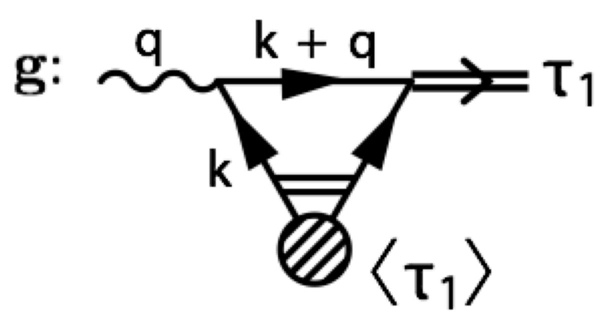
This conservation of weight implies a linear coupling between the excitation above Tc and the daughter peak below Tc.



$$H' = \sum_{\lambda,\mathbf{q}} g_\lambda \, u_{\lambda,\mathbf{q}} \, (\Psi^\dagger \tau_1 \Psi)(-\mathbf{q}) + H.C.$$

But this violates conservation laws!

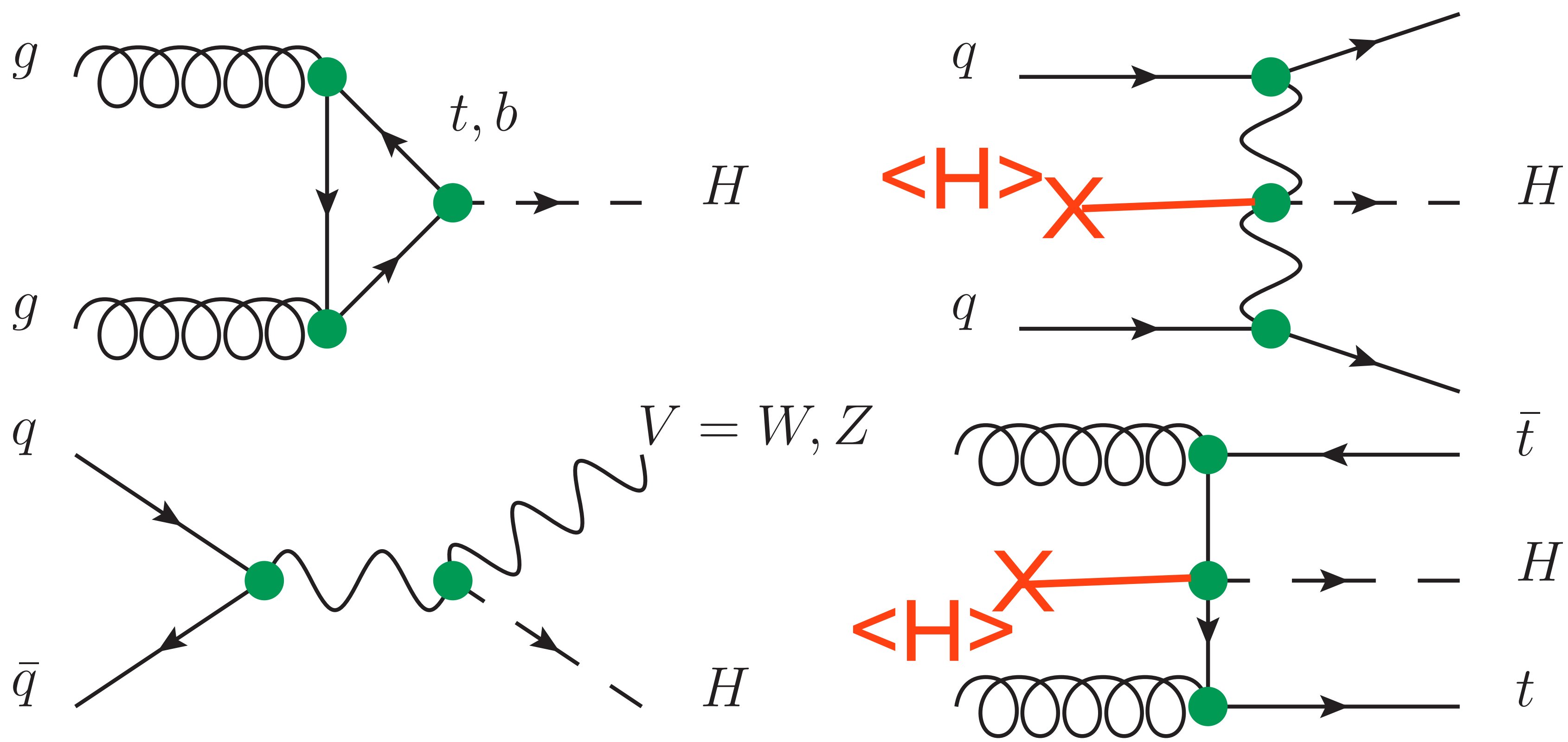
To understand how this is permitted, look closer at g.



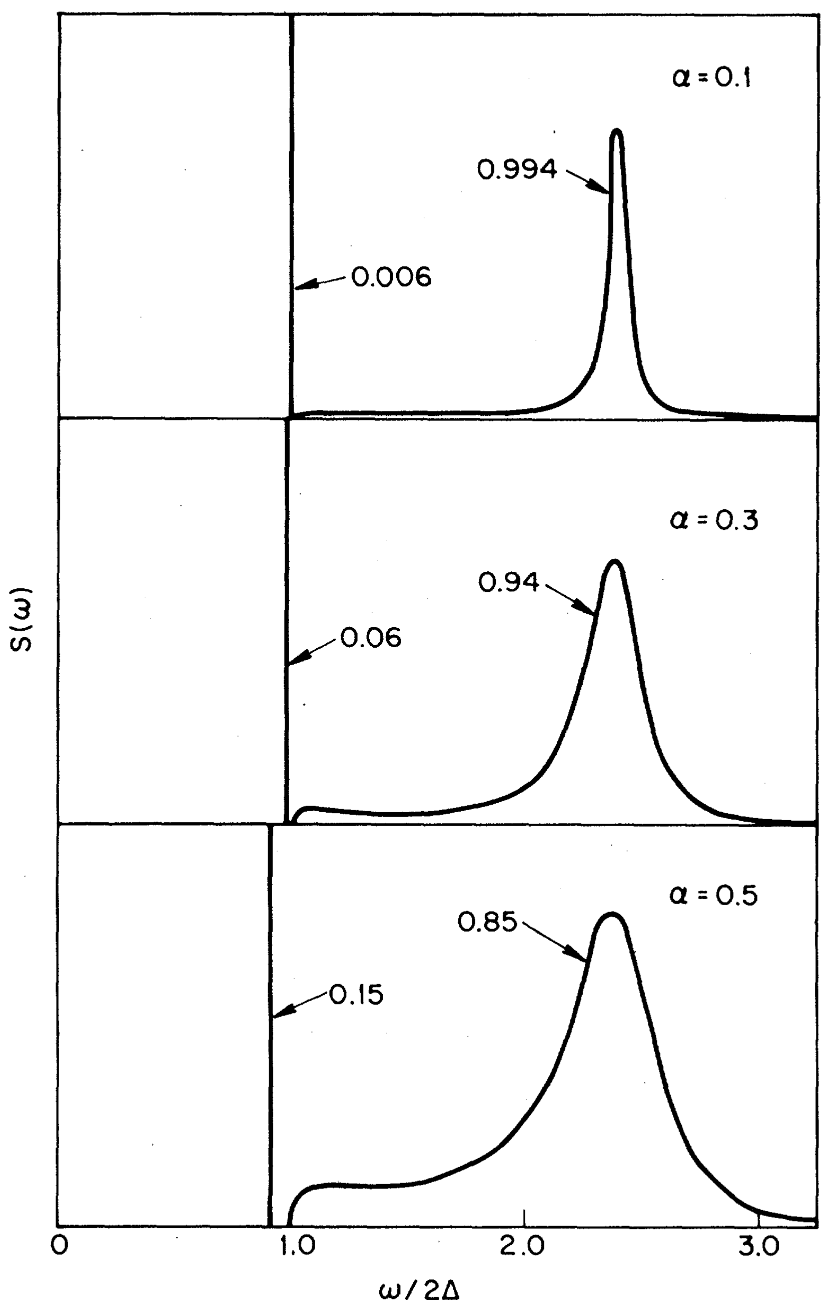
Existence of a condensate allows the detection of the Higgs particle.

The same is true of some of the processes by which Higgs is detected at LHC.

How is Higgs being discovered at LHC?
(From J. Baglio, Thesis (2011), Orsay)



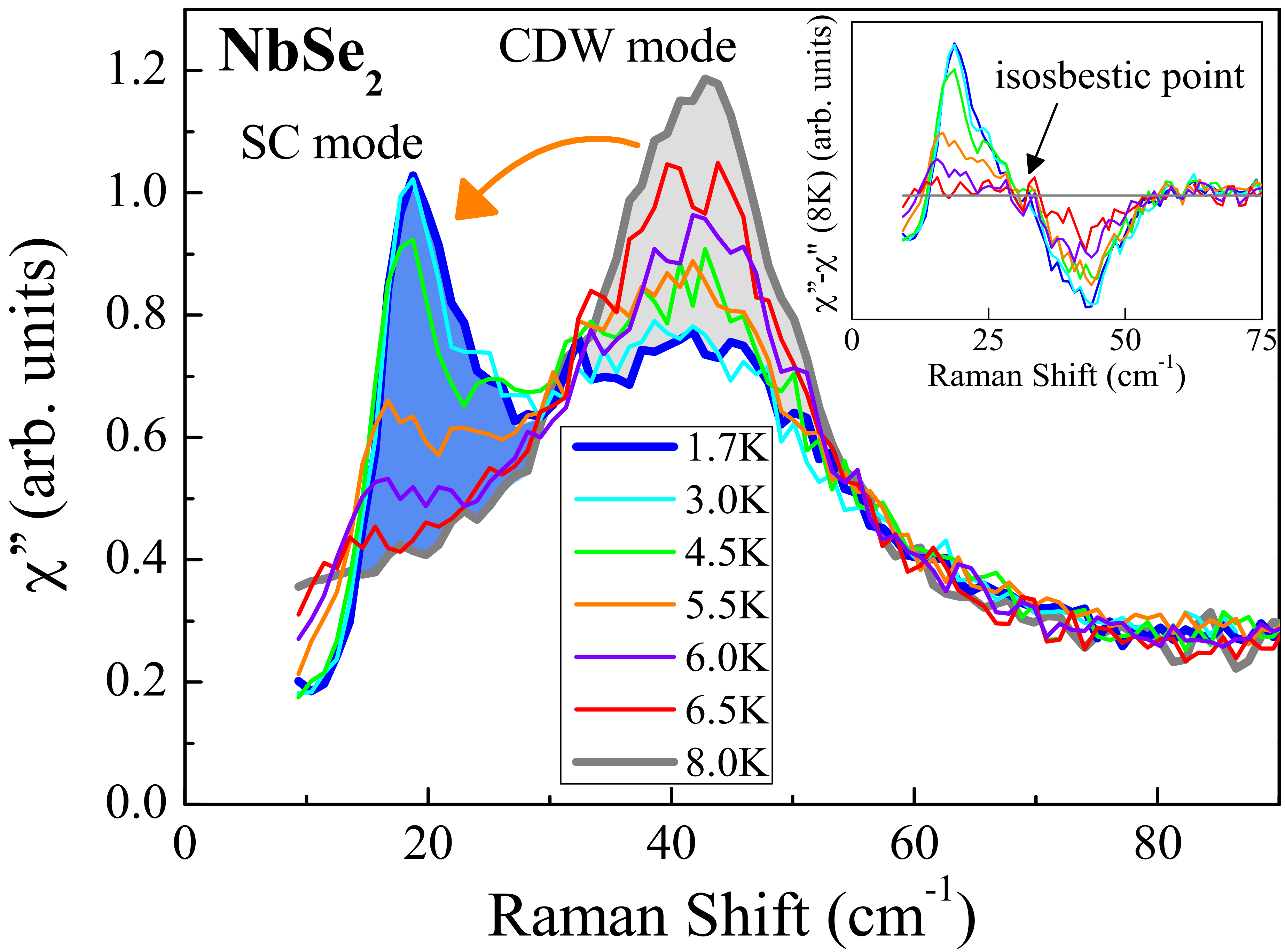
Calculations: (Littlewood, cmv 81)



True test of theory: Conservation of Weight.

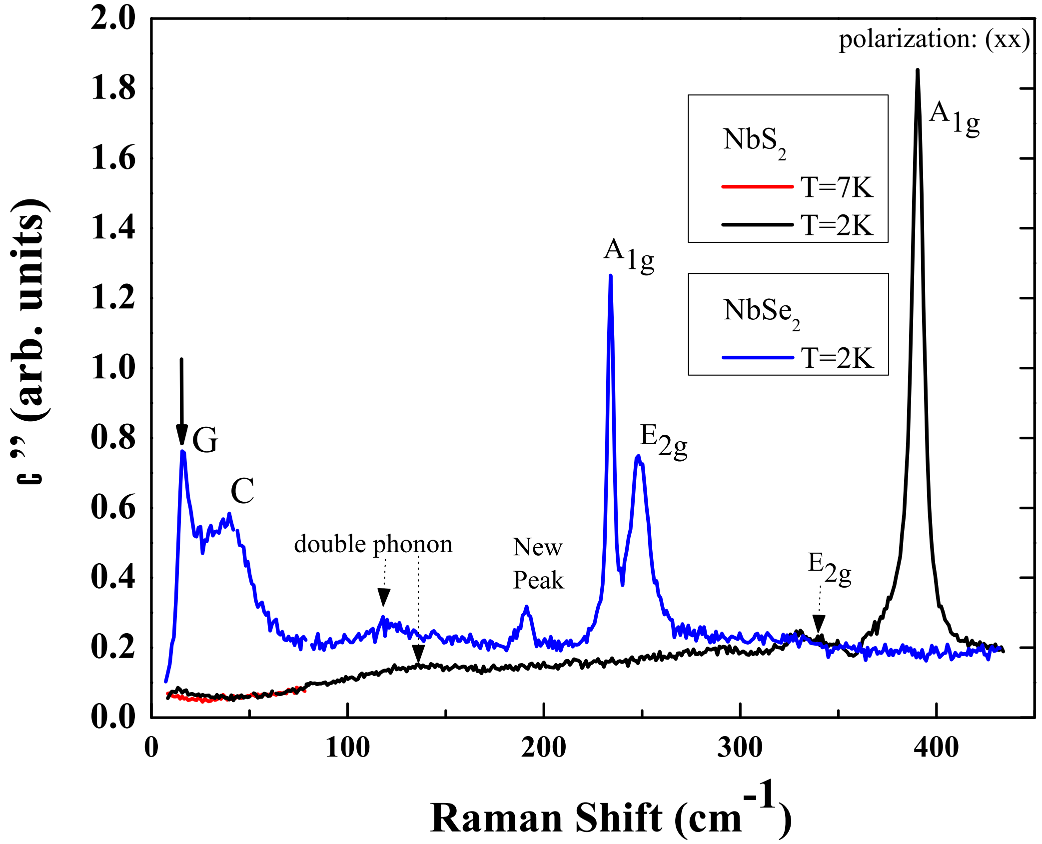
New Experiments: (M-A. Méasson, A. Sacuto, Paris)

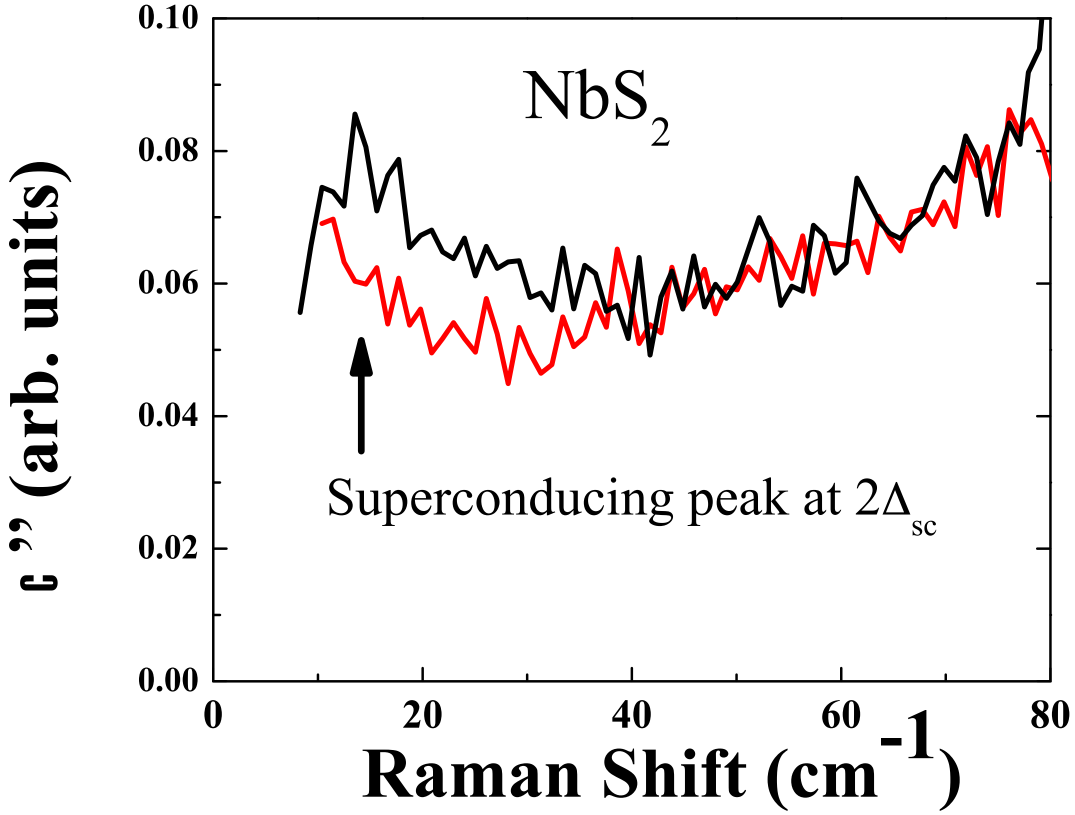
Phys. Rev. B 2013 (and preprint)



Just as interesting

NbS_2 - Same structure, similar T_c, no CDW.

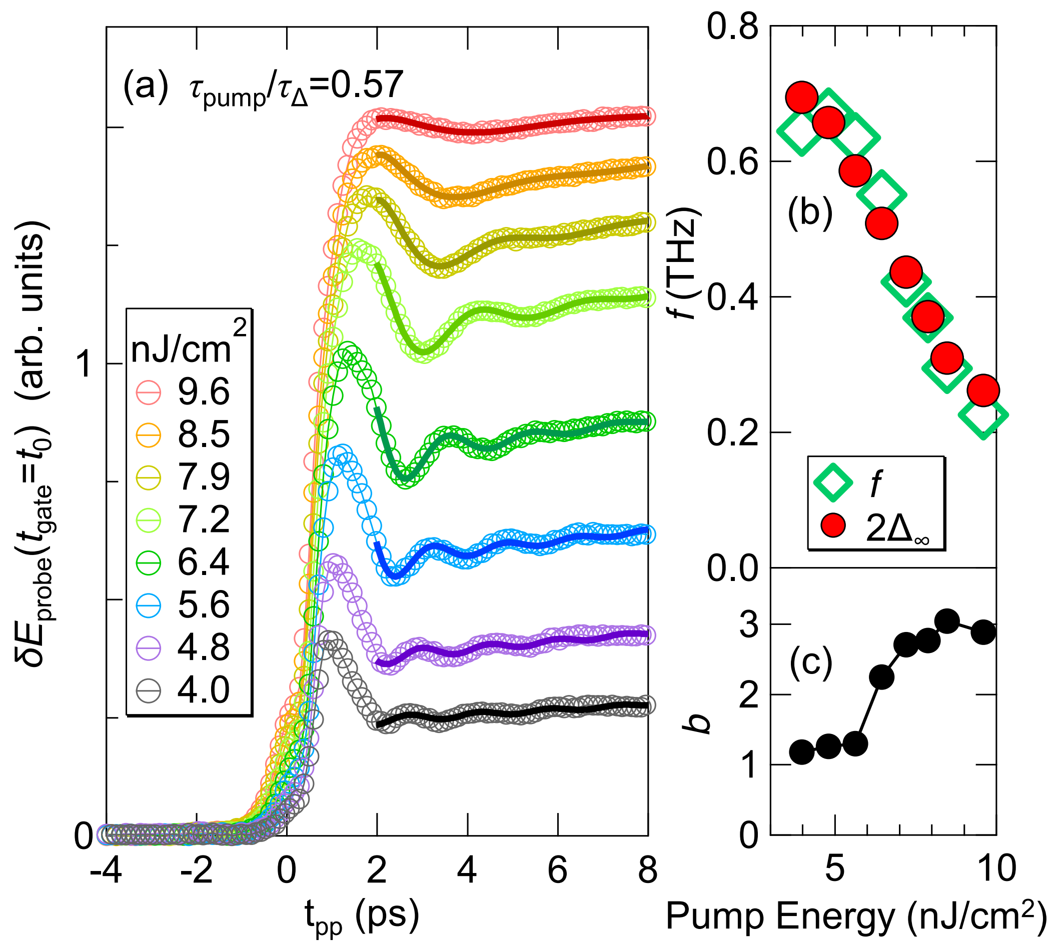




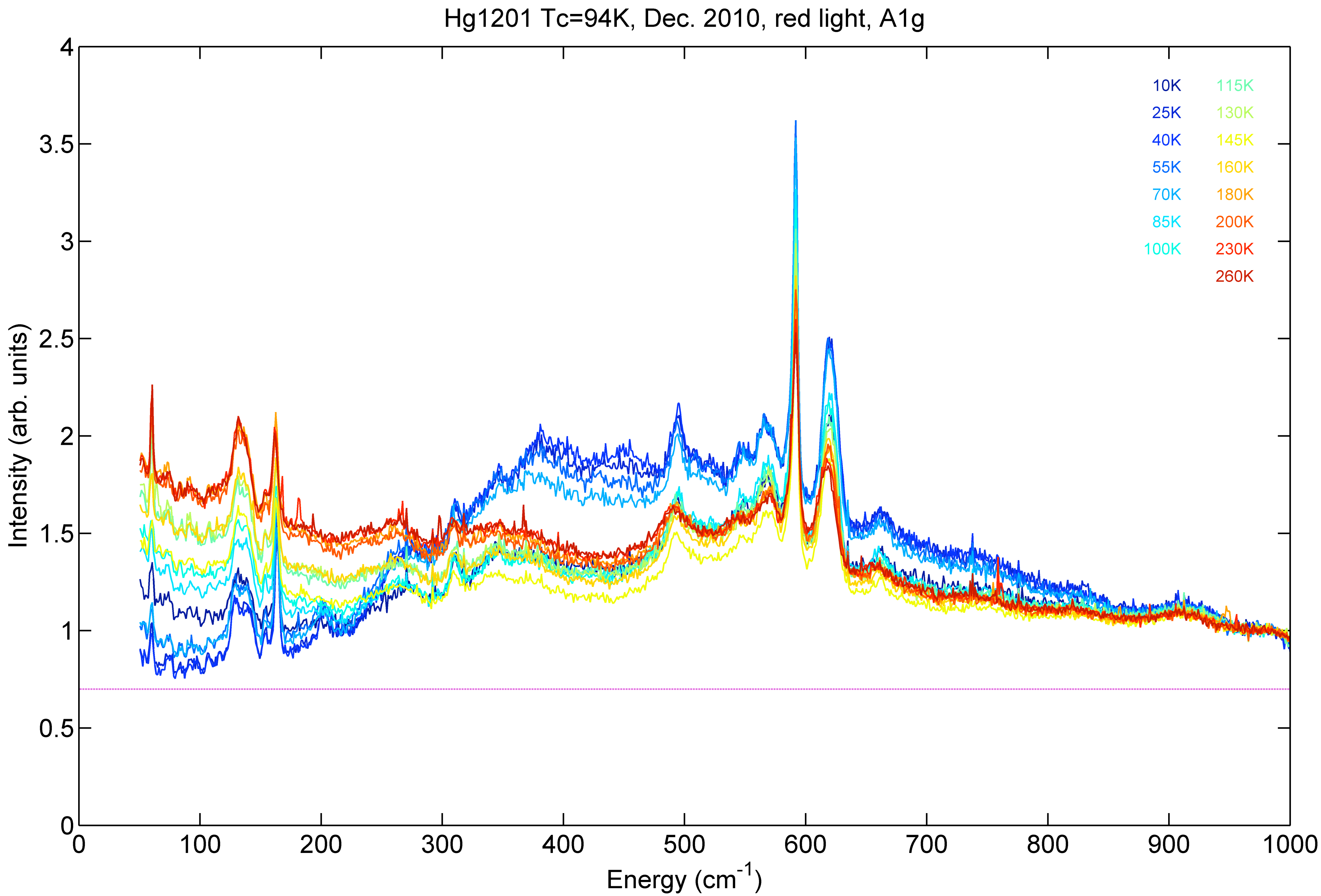
Higgs Amplitude Mode in BCS Superconductors Nb1-*x*Ti*x*N induced by Terahertz Pulse Excitation

Ryusuke Matsunaga et al. (2013)

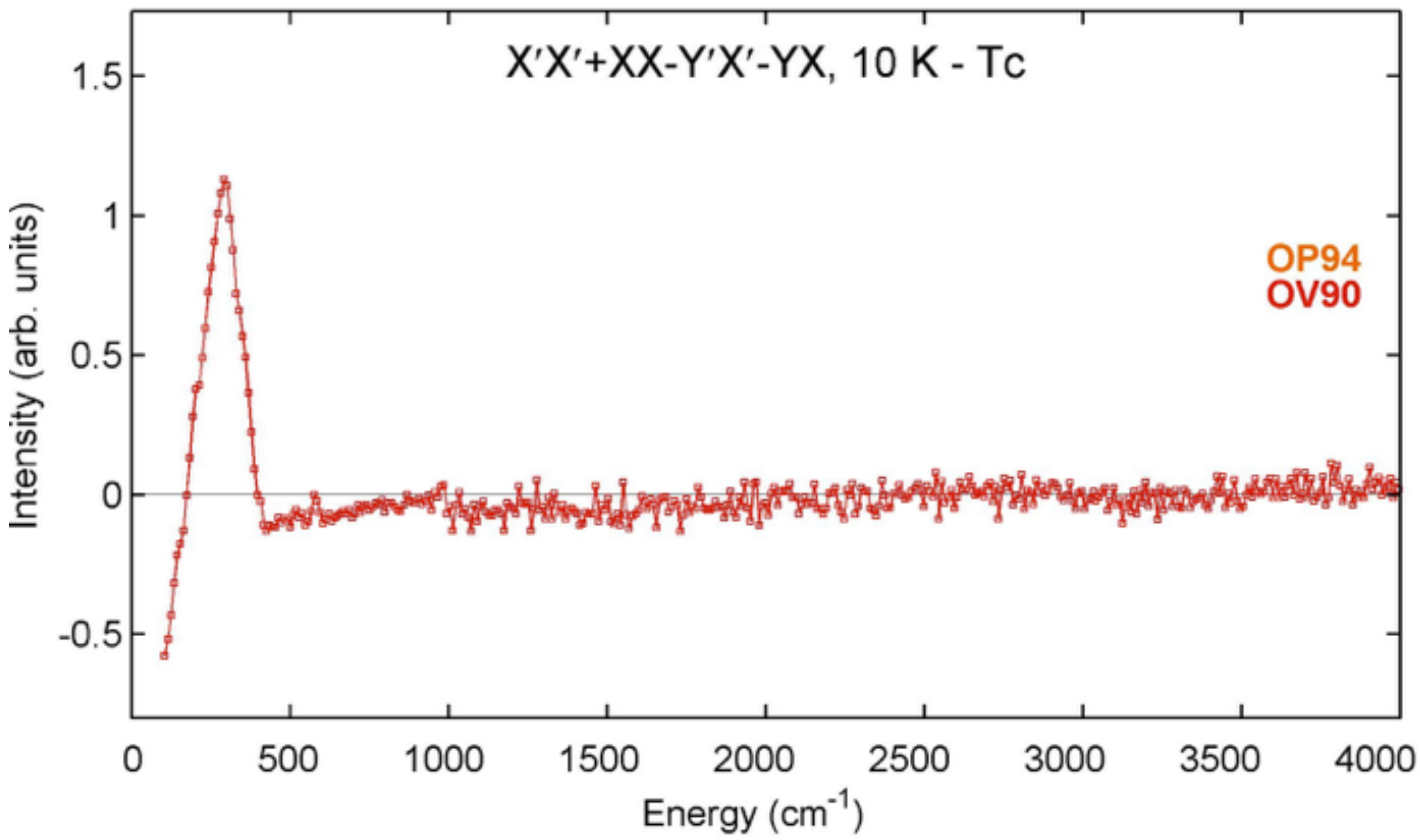
Other ways of Shaking:
Hit the supercond. with femotsec. pulse
of Terahz. radiation and probe
the recovery of the gap by another optical pulse.
Watch oscillations as function of time at the Higgs freq.



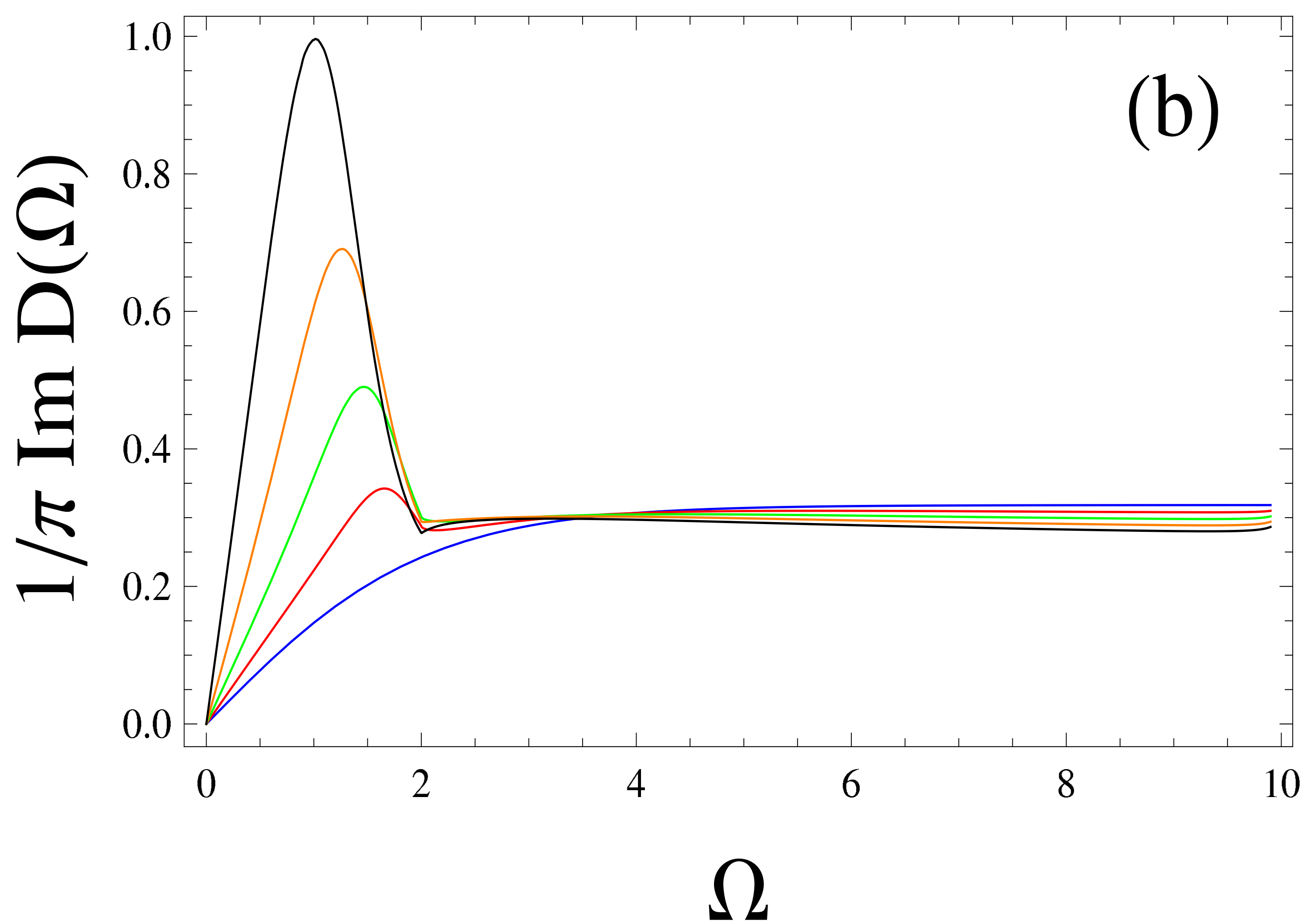
Possible Higgs in a Cuprate Superconductor.



Data at 10K - at Tc after correcting for phonon shifts.



Barlas-cmv (unpublished)
Breathing Higgs in a d-wave superconductor.

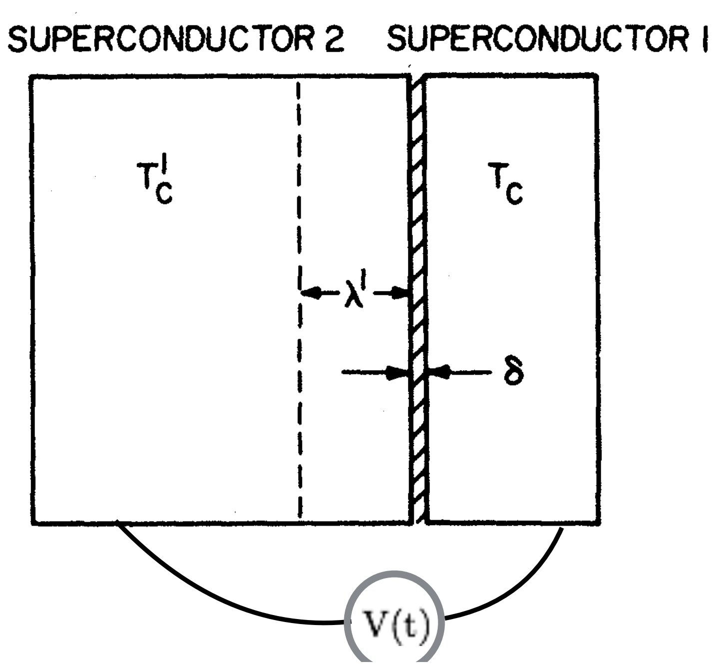


Josephson type coupling to Higgs:

Not quite true that one cannot couple to the Higgs.

One can couple through a Field conjugate to the supercondutin[g]
amplitude. Such a field is provided by proximity to another
superconductor.

Some peculiar unexplained results in such
Experiments by Goldman et al. (1975-1980)



Coupling: $J\ \Psi_1^*\Psi_2 + H.C.$

Why was Higgs missed in CMP over the years?

Suppose we try Ginzburg-Landau Lagrangian:

$$H = \int d\mathbf{r} \left(|\nabla\psi|^2 + r|\psi|^2 + u|\psi|^4 \right).$$

$$\langle \psi \rangle = [-r/2u]^{1/2} \equiv \rho_0^{1/2}$$

$$\psi(\mathbf{r},t) = [\rho_0 + \delta\rho(\mathbf{r},t)]^{1/2} \exp(i\phi(\mathbf{r},t))$$

Suppose now one calculates dynamics by linear in time term in the Lagrangian : $\gamma \frac{\partial \Psi}{\partial t}$ or $i \frac{\partial \Psi}{\partial t}$

$$\begin{aligned} \partial\phi/\partial t &= (\nabla^2\delta\rho + V\delta\rho)/2\rho_0 \\ (1/2\rho_0)\,\partial\delta\rho/\partial t &= \nabla^2\phi \end{aligned}$$

$$\frac{\partial^2(\phi, \delta\rho/\rho_0)}{\partial t^2} = \nabla^2(\phi, \delta\rho/\rho_0) + \nabla^4(\phi, \rho/\rho_0),$$

$\omega^2 = k^2 + k^4$ No Higgs! as in superfluid ^4He.

Try 'Lorentz-invariant' theory:

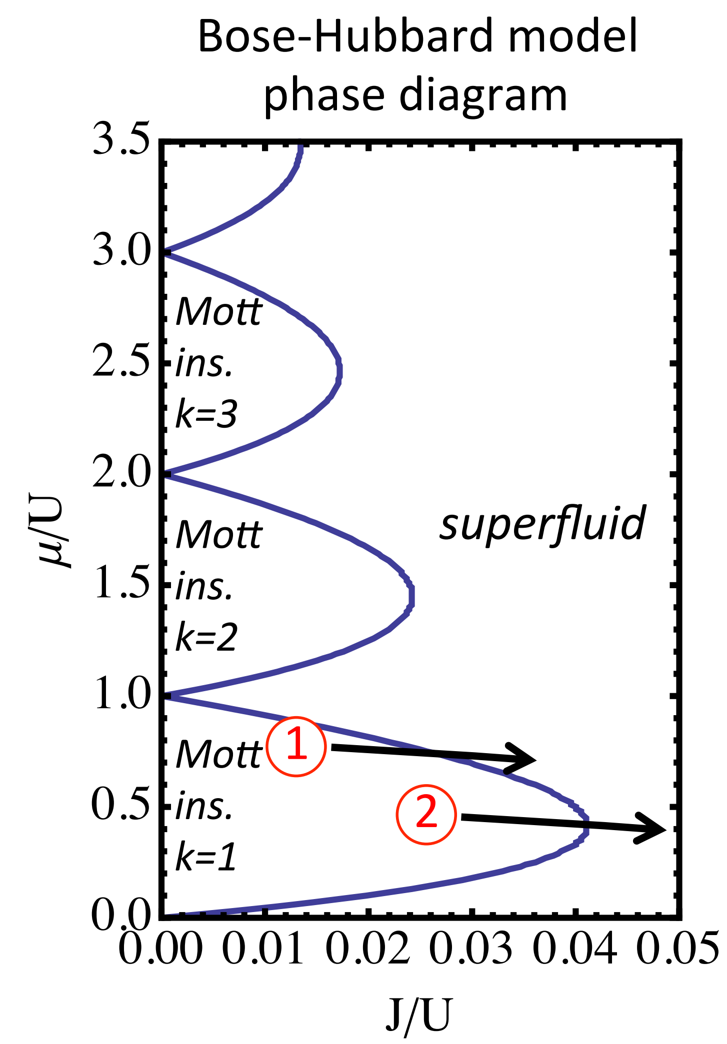
$$\mathcal{L} = |\partial_\mu \psi|^2 + r|\psi|^2 + u|\psi|^4 \;; \quad \mu = (it, \mathbf{r})$$

$$\text{Higgs Immediately} : \Omega_{Higgs} = \sqrt{-2r/u}$$

(Results with both first and second time-derivatives in Pekker-cmv)

Essential Physical Point (CMV -2001)
Weak-coupling equations for superconductivity are mathermatically identical to the Dirac equation, i.e. thery are particle-hole symmetric, although the normal metallic state (and the state just below T_c) is not. Then first order time-derivatives are zero. This point is being displayed in the "Higgs" observations in the cold-atom experiments (Bloch-et al. 2012).

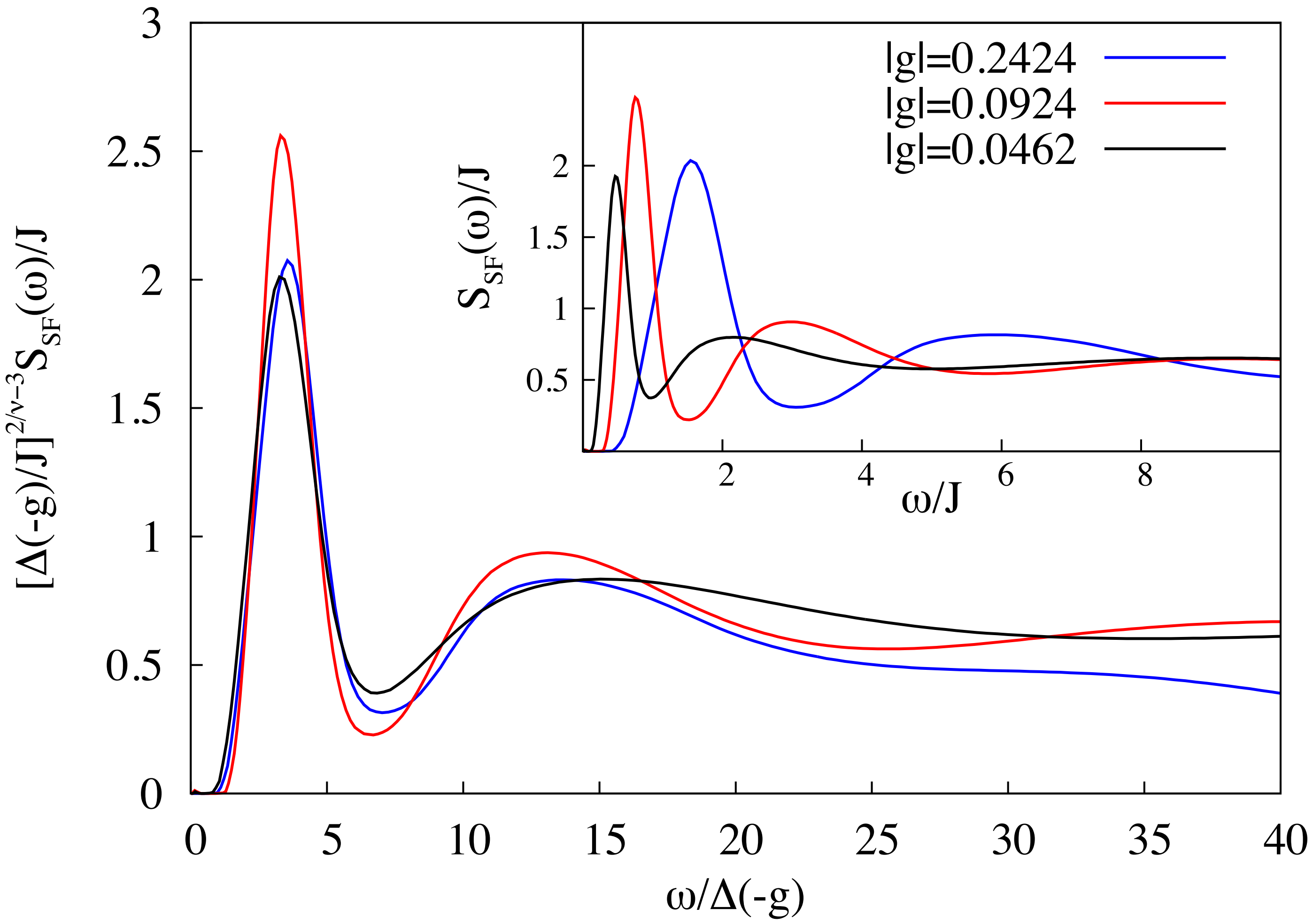
Cold Bosons in a Lattice: (I. Bloch et al., 2012)
Approximate particle-hole symm. at near some fillings



Similarly, also amplitude (and phase) modes
in incomm. CDW's and AFM's (Ruegg et al. 2008).

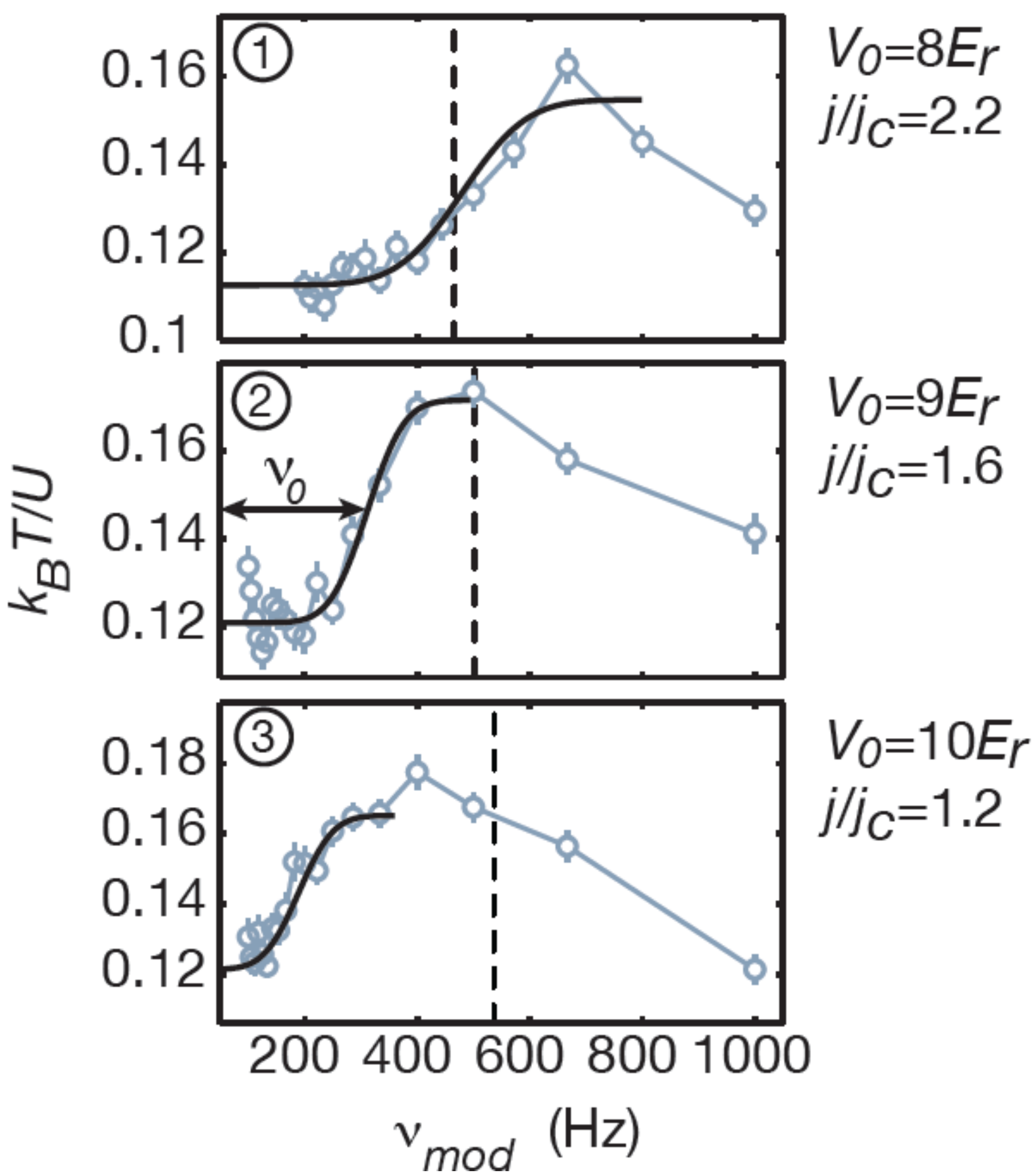
Experiments are done by shaking the lattice which modulates the kinetic energy and by somewhat complicated processes, measuring the Long wave-length correlations of Kinetic energy as a function of time.

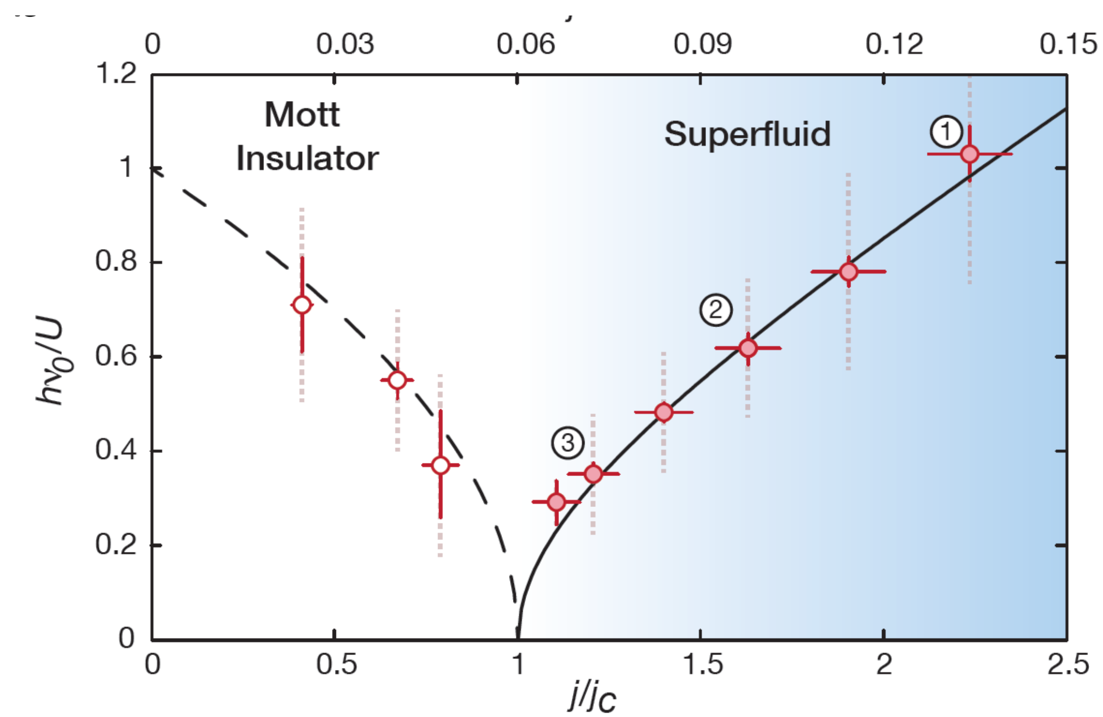
From Monte-Carlo calculations of KE-KE correlations



K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev, Phys. Rev. Lett. **112**, 030402 (2014).

M. Endres, T. Fukuhara, D. Pekker, M. Cheneau, P. Schauss, C. Gross, E. Demler, S. Kuhr, and I. Bloch, Nature **487**, 454 (2012).

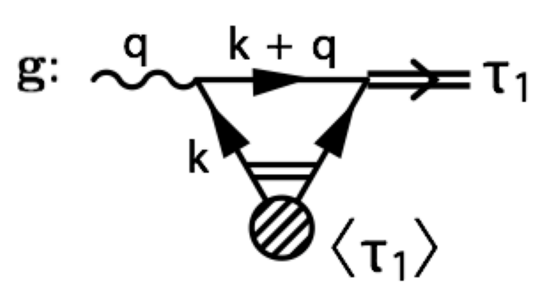


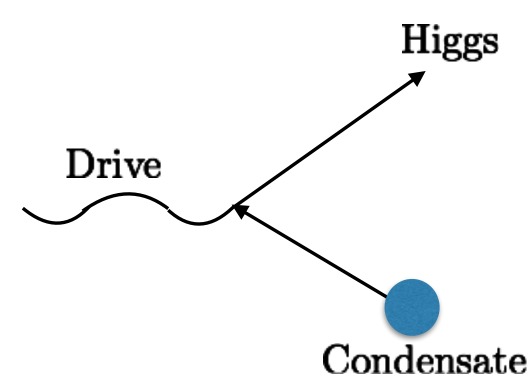


Difficulty with the technique.

By shaking the lattice to modulate KE,
one sees all kinds of multiple-particle-hole excitations besides the Higgs.

There ought to be ways of gently exciting the Higgs in cold-bosons in a lattice which is the analog of what is done in superconductors:





Summary:

1. All superconductors are (almost) p-h symmetric.
So Amplitude mode or Higgs exists in all superconductors
Theorists: use second order time-derivatives in a p-h symmetric problem.

2. It can be detected in several ways in CMP.
So far, they involve shaking the condensate, to be "free" from conservation laws.
They are a proof of the existence of a condensate.

3. Josephson Effect ways of Detecting the Condensate?
Any HEP expts. similar to Josephson Effect?