Higgs mode in Condensed Matter

Marie-Aude Méasson

What is Higgs mode for condensed matter physicist?

Higgs mode are amplitude oscillations of a quantum field. Effective Lorentz symmetry is necessary.

Collective excitations in a quantum many-body systems
Consequence of a spontaneous breaking of a continuous symmetry.

Review in Advance first posted online on January 12, 2015. (Changes may still occur before final publication online and in print.)

Amplitude/Higgs Modes in Condensed Matter Physics

David Pekker[1] and C.M. Varma[2]

Which identified systems?

- *Superconductors (locally gauge invariant)*
- Some antiferromagnet (locally anisotropic)
- Lattice of ultracold boson (globally gauge invariant)
- Charge density wave (not Lorentzian)

Some requirements to be Lorentzian symmetric

A textbook model

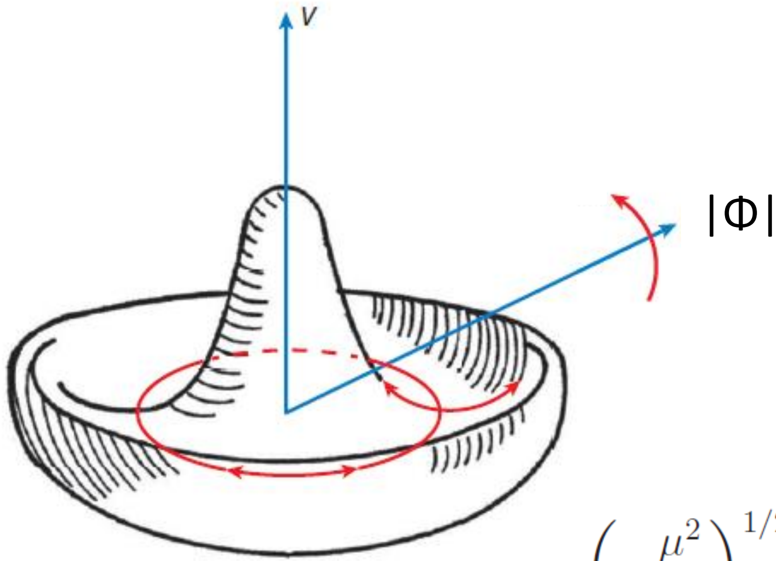
Textbook « Standard model »:

- Local symmetry
- Abelian U(1) model
- Complex scalar field (2 degrees of freedom) coupled to an electromagnetic field (2 degrees of freedom)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + D_\mu\phi^* D^\mu\phi - V(\phi)$$

$$V(\phi) = \mu^2\phi^*\phi + \lambda\,(\phi^*\phi)^2$$

$$D_\mu = \partial_\mu - ieA_\mu$$



Minimum (vev) $\left(-\frac{\mu^2}{2\lambda}\right)^{1/2}$

Expansion around the vacuum state v (U(1) gauge symmetry is broken):

$$\phi(x) = \frac{1}{\sqrt{2}}[v + \phi_1(x) + i\phi_2(x)]$$

1 massive amplitude mode (Higgs mode)
1 Goldstone mode (phase mode)

→

1 massive amplitude mode (Higgs mode)
The photon absorbs the Goldstone mode and becomes massive (BEH mechanism)
Longitudinal polarization of the EM field

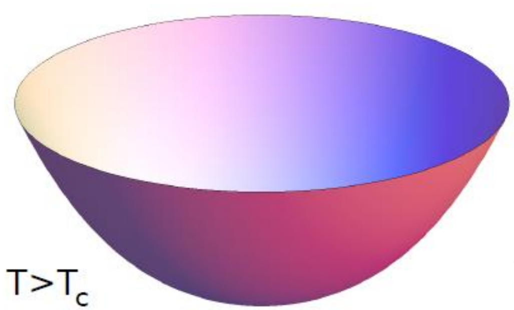
A model for Superconductivity

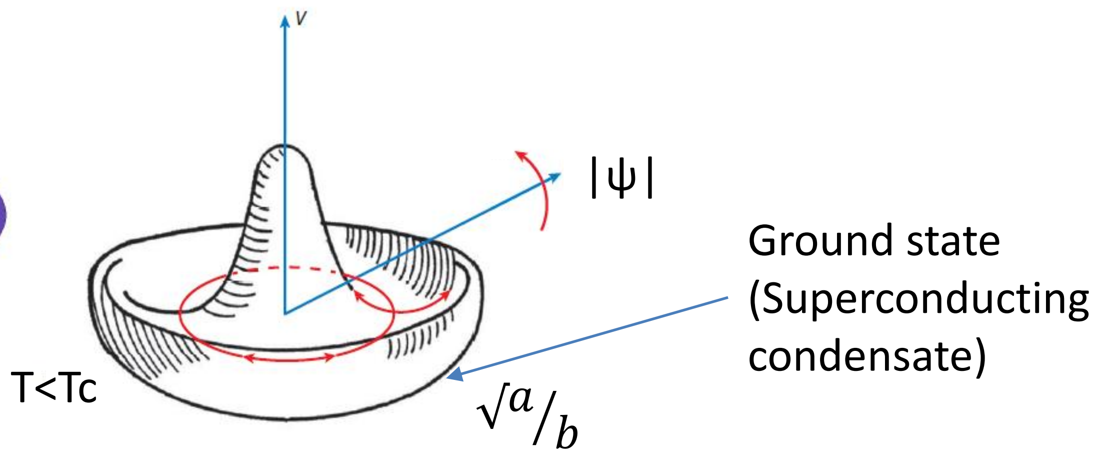
Ginzburg-Landau phenomenological model for Superconductors:

- Local symmetry
- Abelian U(1) model
- Complex matter scalar field (2 degrees of freedom) coupled to an electromagnetic field (2 degrees of freedom)

Ginzburg and Landau postulate the existence of complexe order parameter ψ (macroscopic wave function). Free energy f :

$$f_s(T) = f_n(T) + a(T)|\psi|^2 + \frac{1}{2}b(T)|\psi|^4 \quad \text{with} \quad a(T) = cte \cdot (T - T_c)$$





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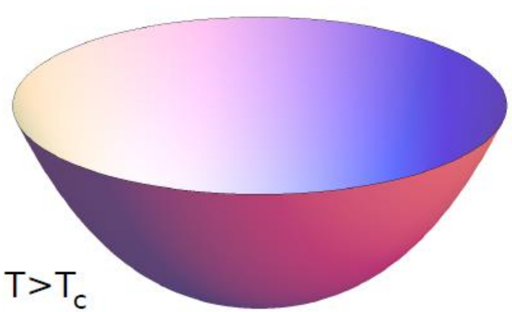
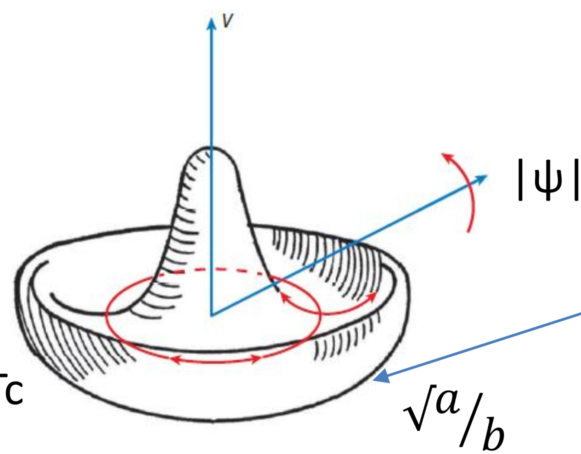


$T>T_c$

T<Tc



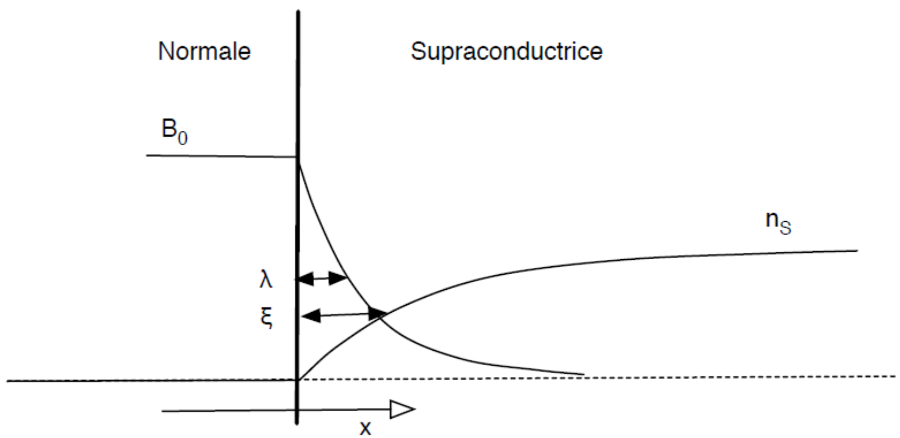
2 modes: Nambu-Goldstone phase mode and amplitude-Higgs mode

A model for Superconductivity: Anderson-Higgs mechanism

Ginzburg and Landau model in inhomogeneous systems under magnetic field

$$F_s(T) = F_n(T) + \int \left(\frac{\hbar^2}{2m^*} \underbrace{|(\frac{\hbar}{i}\nabla + 2e\mathbf{A})\psi|^2}_{\text{gradient terms}} + \underbrace{a|\psi|^2 + \frac{b}{2}|\psi|^4}_{\text{Uniform terms}} \right) d^3r + \underbrace{\frac{1}{2\mu_0}\int B(\mathbf{r})^2 d^3r}_{\text{Field energy}}$$

Normal/Superconductor interface:



Magnetic field
Penetration depth λ

$$\mathbf{j}_s = -\frac{(2e)^2}{2m^*}|\psi|^2\mathbf{A}$$ + Maxwell equations:

$$B = B_0 e^{-x/\lambda}$$

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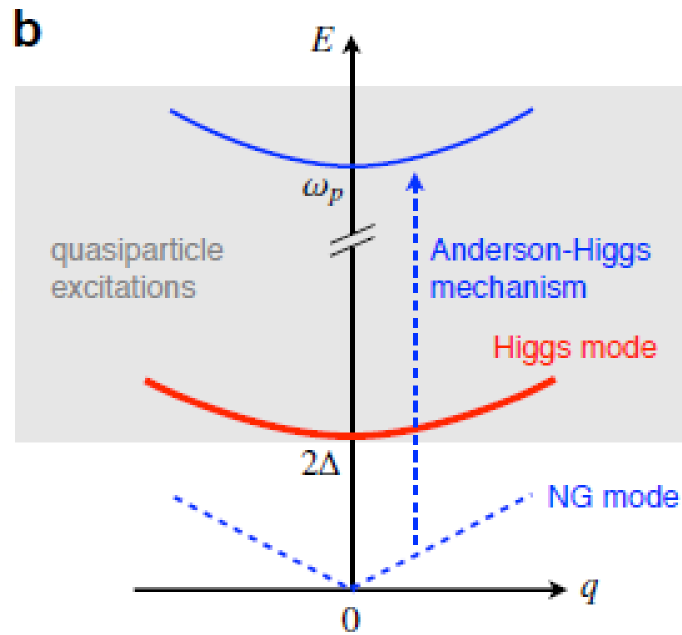


Meissner effect = Anderson-Higgs mechanism

The photon becomes massive in a superconductor, by absorbing the Nambu-Golstone mode. Mass of photon= plasmon frequency.

Lorentz symmetry

Dynamical terms in the action density:

$$S_{dynamic} = iK_1 \Psi^*(\mathbf{r},t) \frac{\partial}{\partial t} \Psi(\mathbf{r},t) - K_2 \left(\frac{\partial}{\partial t} \Psi^*(\mathbf{r},t) \right) \left(\frac{\partial}{\partial t} \Psi(\mathbf{r},t) \right)$$

Lorentz invariant equation for K_1=0.
For superconductivity, this is reached thanks to particle-hole symmetry which is generally true near the Fermi level.
True for cold boson in optical lattice along lines in the parameters space.

Allow: No coupling between the Anderson-Higgs and Nambu-Goldstone modes.

Existence of microscopic theories

Existence of microscopic theories and Higgs mass

Superconductivity is a new phase of matter with 2 fluids and unconserved particle number.
The electrons form a bound state.
BCS theory: they form a condensate of bosons. Superconductivity is a "superfluid" of these boson.

boson: two electrons, composite boson

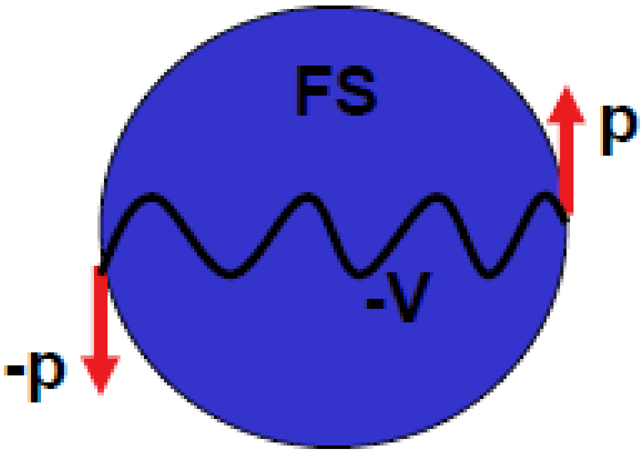
$$|\psi|^2 = n_s$$

L. N. Cooper, Phys. Rev. ***104***, *1189 (1956).*

The Fermi sea is filled. Add two electron above E_F and plug the attractive interaction V :
The two electrons form a bound state with net momentum zero and opposite spin.

$$E = 2E_F - \Delta < 2E_F$$

The Femi liquid is unstable to pairing.



The building block of superconductivity is the Cooper pair.

$\Psi(r_1, r_2)$: two-electron wavefunction: zero momentum and spin singlet state

the SC amplitude 'Higgs' modes correspond to coherent oscillatory pairings and depairings of the Cooper pairs of electrons.
Mass = 2Δ (1 meV – 50 meV). NB: at the threshold of the elementary p-h excitation

Existence of microscopic theories: coupling mechanism

Abrikosov (1928-2017), Fundamentals of theory of Metals

General scheme of the interaction of electrons via the transmitting system A:

$$\mathbf{e}_1 + \mathbf{A} \longrightarrow \mathbf{e}_1' + \mathbf{A}^*, \quad \mathbf{e}_2 + \mathbf{A}^* \longrightarrow \mathbf{e}_2' + \mathbf{A}$$

e_i: electron of momentum p_i: electrons are scattered from each other

A : ground state of the transmitting system

A* : excited state of the transmitting system

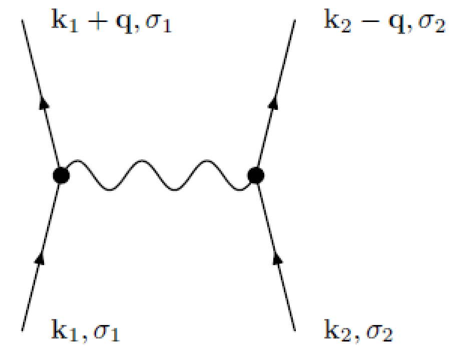
Such an interaction is necessarily an attraction and:

$$T_c \propto \Delta E \cdot e^{\frac{-1}{\lambda}}$$

ΔE: energy difference between A and A*

And λ : interaction of electrons with system A

Exchange of virtual bosons



Phonon attraction belongs to this scheme : Exchange of virtual phonons.
Variants:

- A= system of spin : exchange of paramagnons (fluctuation of magnetic phase). Cuprates, Heavy Fermions, Fe-based Scors…?
- A= system of electrons with fluctuating valence. ex: CeCu2Si2
- A= system of quadrupoles: fluctuations of the quadrupolar phase. Ex: PrTi2Al20
- …

Detection of Higgs mode in Condensed Matter

Higgs mode in condensed matter is a scalar. No charge, no spin, … or other quantum number… It is a dark mode!
Observability question?

- No direct linear coupling to experimental probes
- Need to avoid avenues for rapid decay into other excitations. Avoid over-damping.

Few situations of observability: “Shaking of the condensate”
- Coupling with another electronic states (Temperature, Pressure, magnetic field phase diagram)
- Time resolved measurements (non-equilibrium state)
- Non linear optical coupling
- Proximity of quantum critical point (T=0K 2^{nd} order transition)

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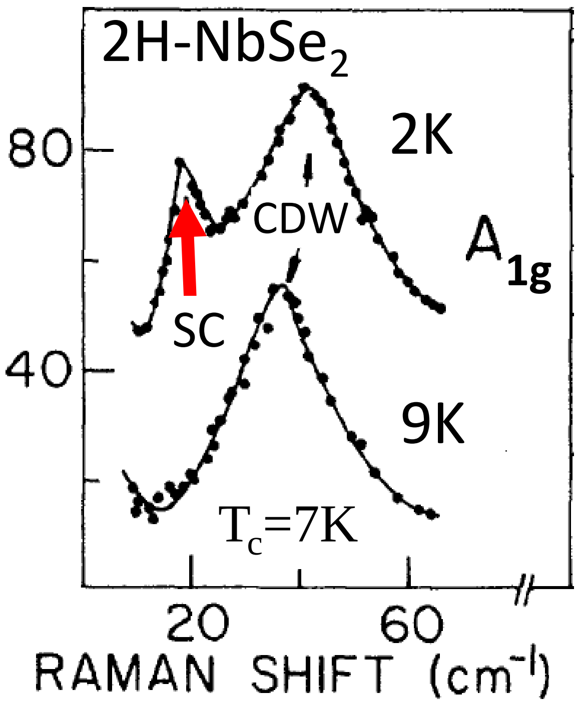
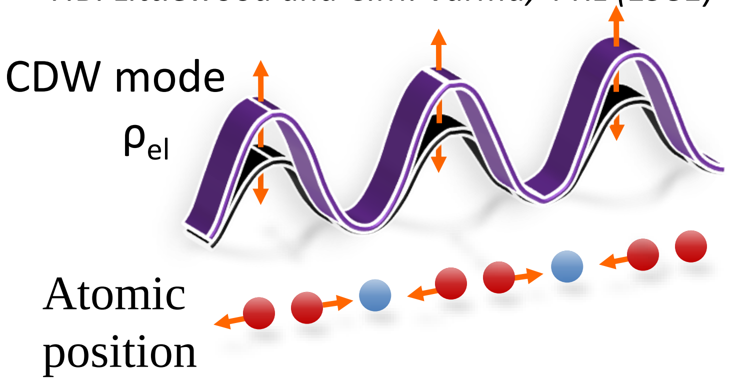
A Mechanism of Observability



Sooryakumar and Klein PRL (1980), PRB (1981)
P.B. Littlewood and C.M. Varma, PRL (1981)



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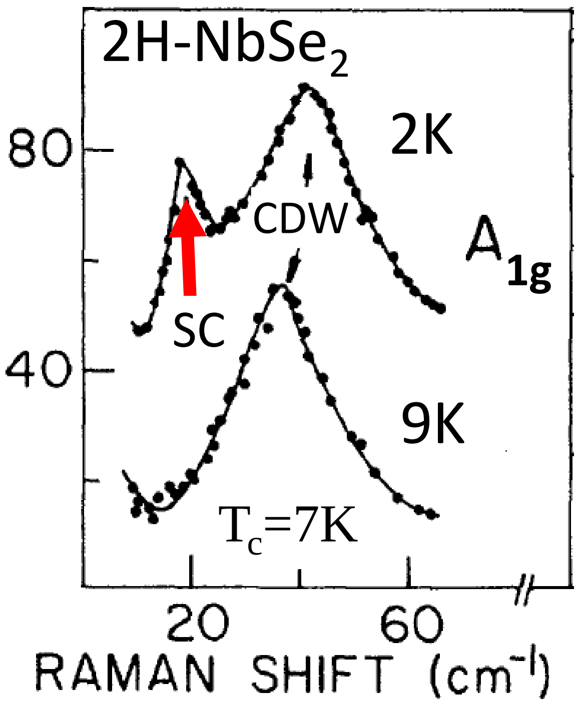

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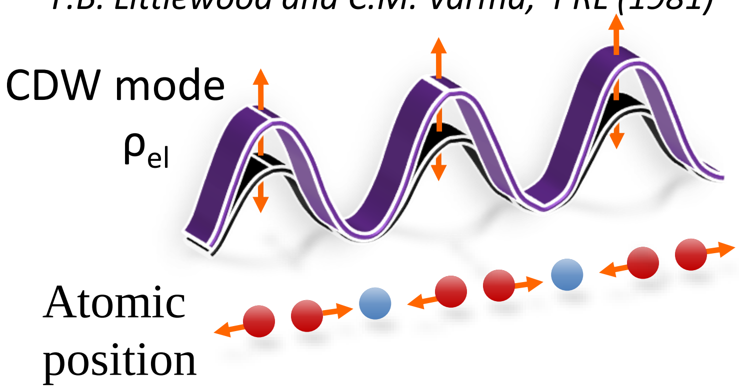
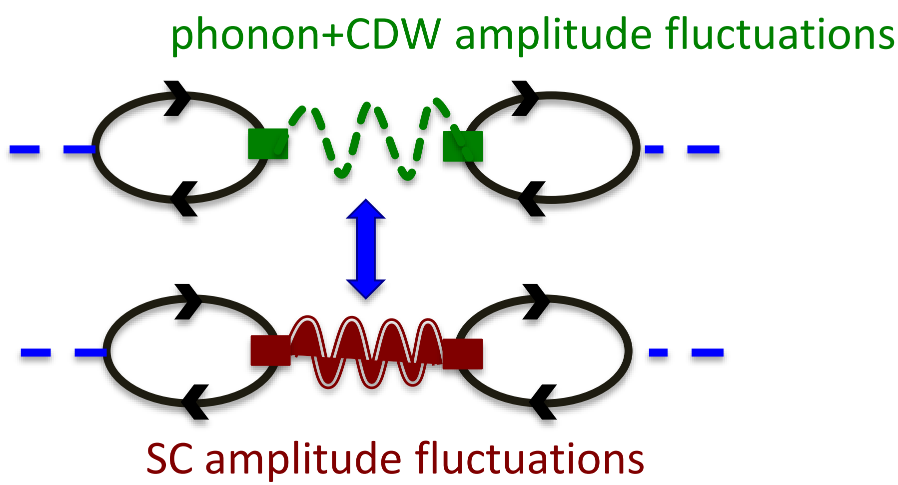


P. Littlewood and C. Varma (1982),
Browne and Levin (1983)
T. Cea and L. Benfatto (2014)

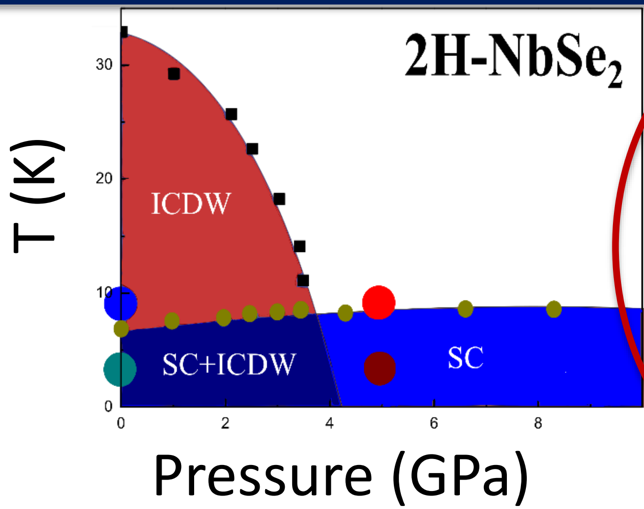
The Higgs become visible via an intermediate electron-phonon coupled mode.

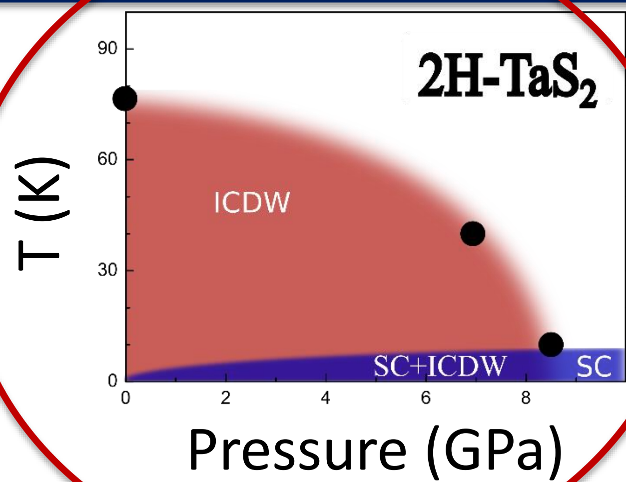
⟶ New pole in the CDW mode propagator.

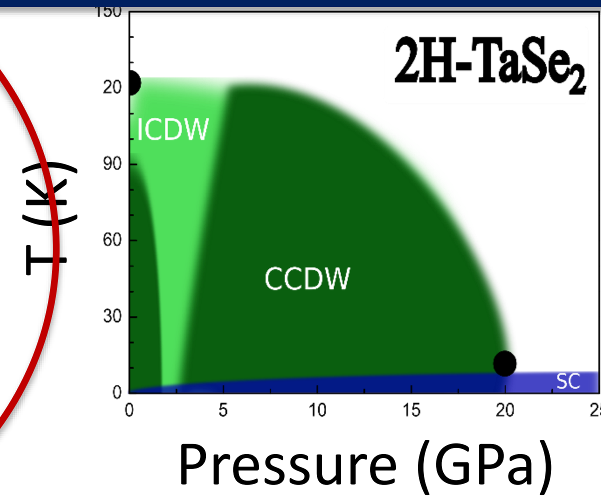
The Higgs mode signature is pushed below $2\Delta_{SC}$



High pressure phase diagram of Charge Density Wave superconductors







Jérome et al., JPC 37 (1976)
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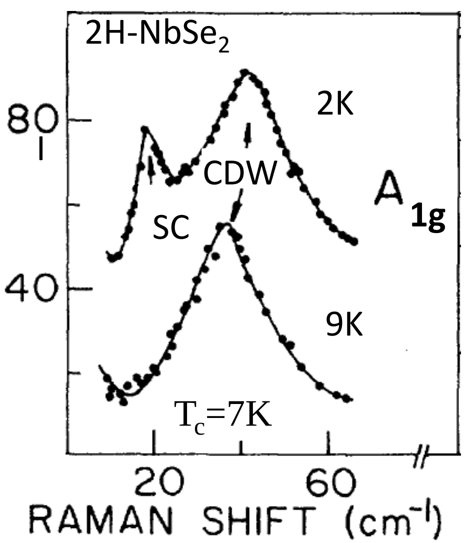
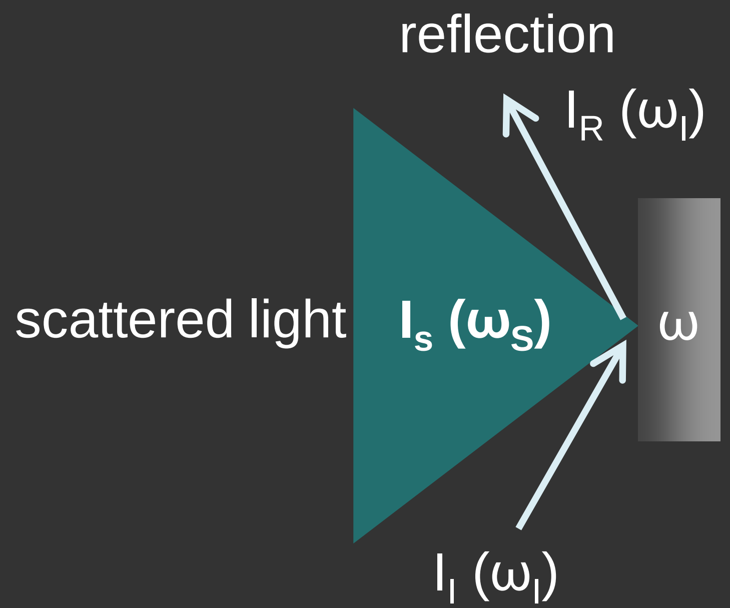
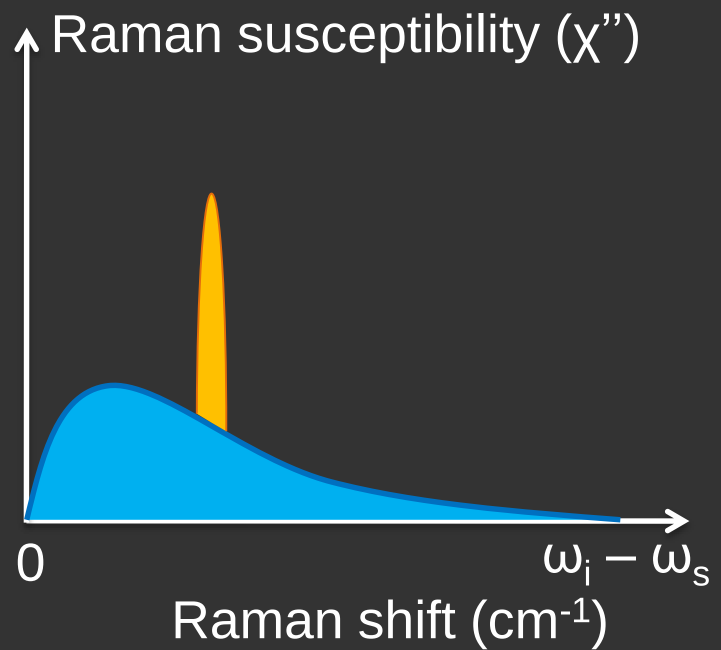


Raman Spectroscopy Under extreme conditions





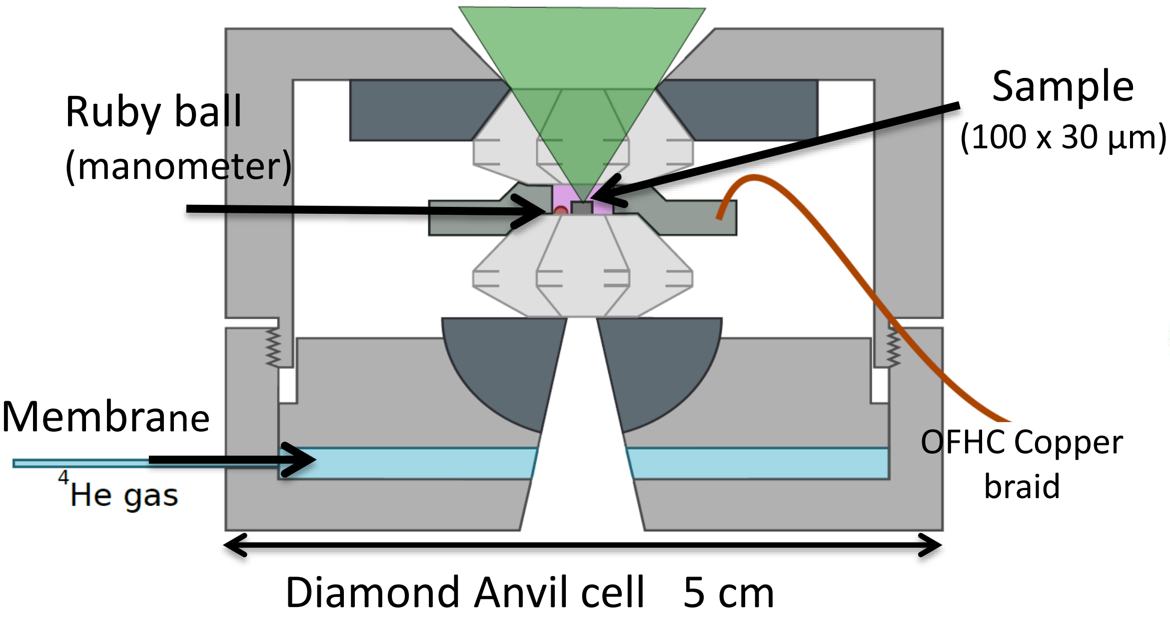
Conservation laws : **q ~ 0**

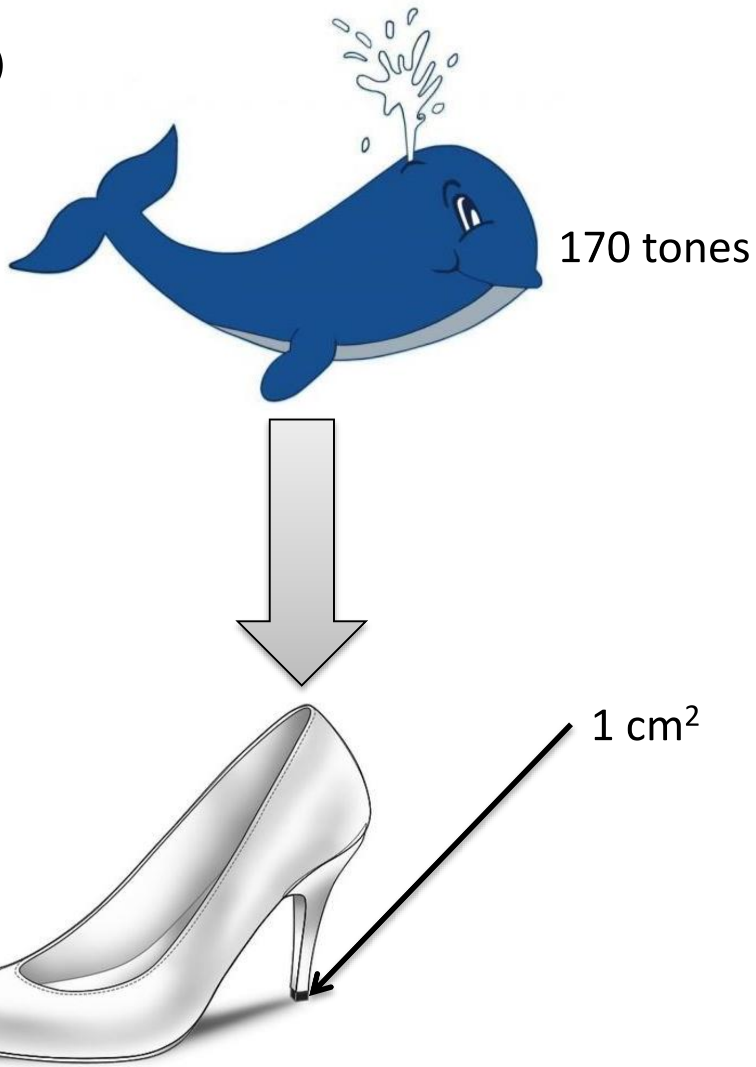
Raman scattering probes excitations with **a total wavevector close to zero**

Raman selection rules (group theory): **symmetry of the excitations**

Raman spectroscopy under High pressure

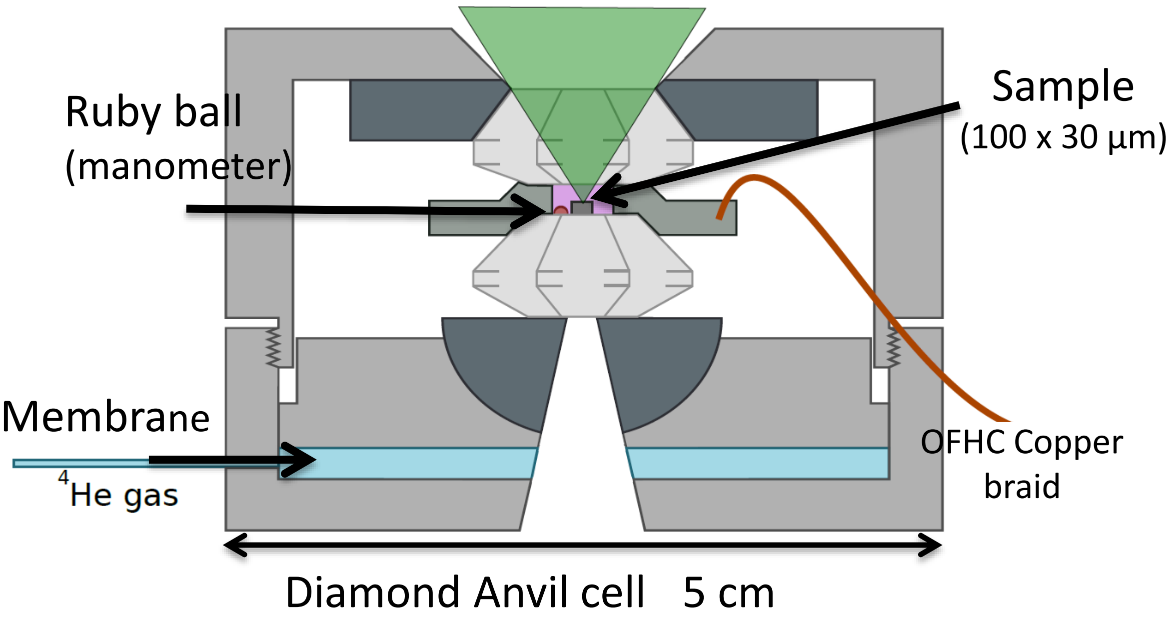
P = 17 GPa

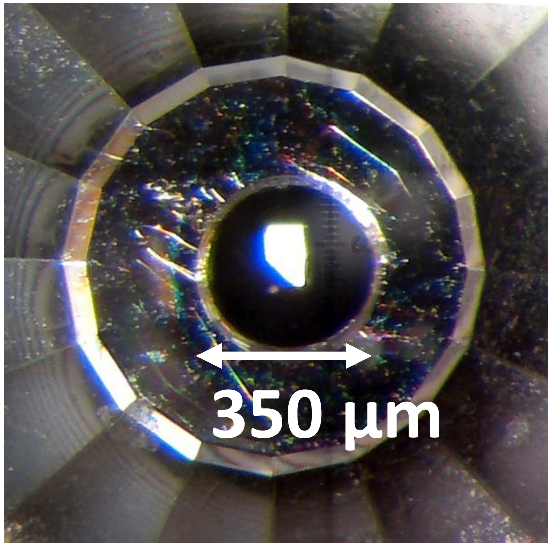


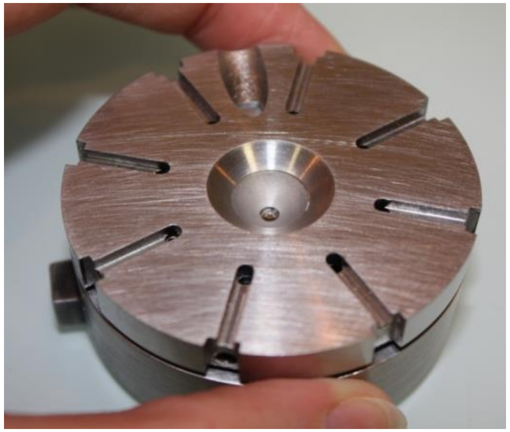


- Shape and nature of the diamonds
- Large numerical aperture 85°

Raman spectroscopy under High pressure







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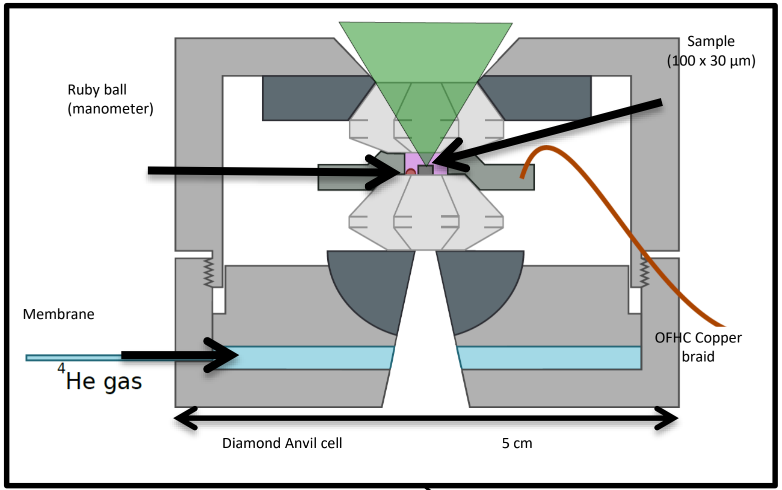
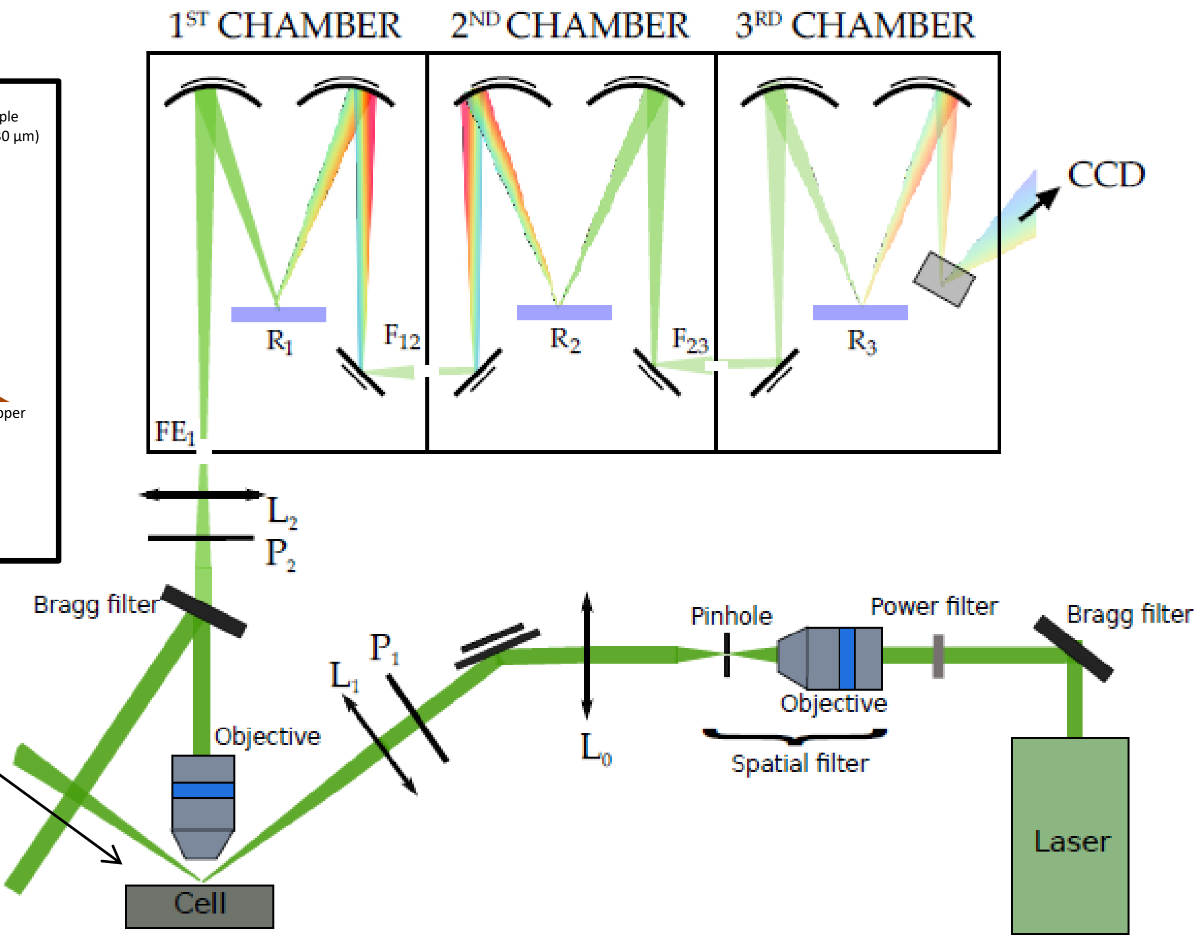
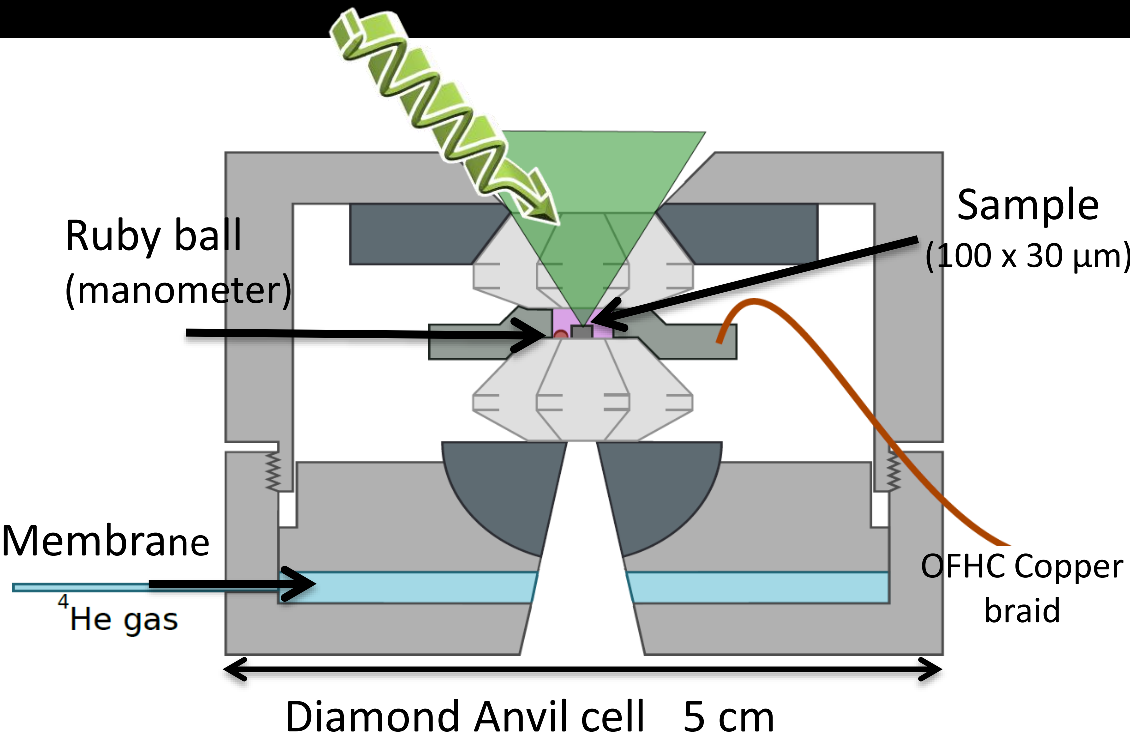
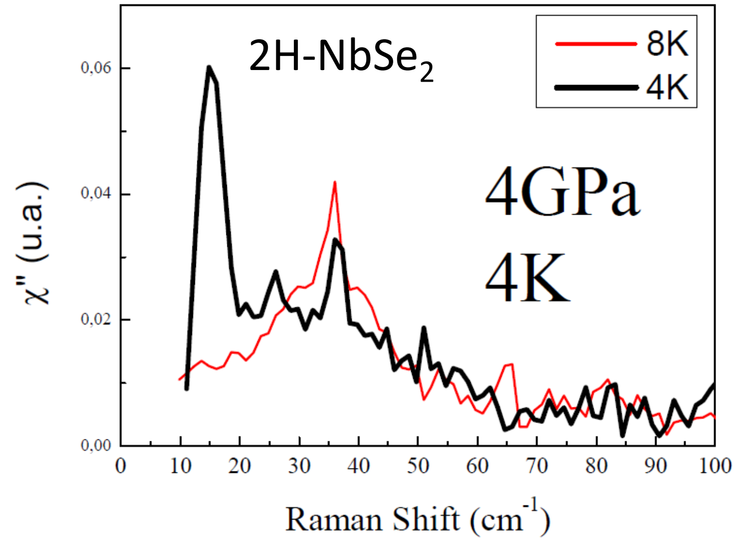




- Shape and nature of the diamonds
- Large numerical aperture 85°
- (Not too) small laser spot (~20µm)
- Angular geometry of incident light

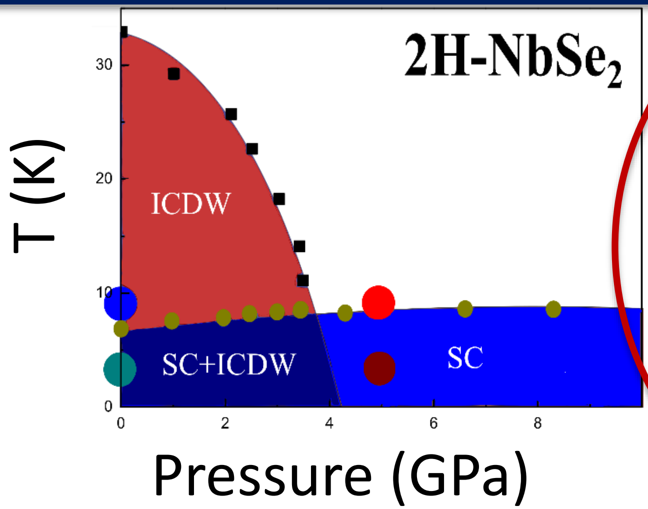
Raman spectroscopy under High pressure

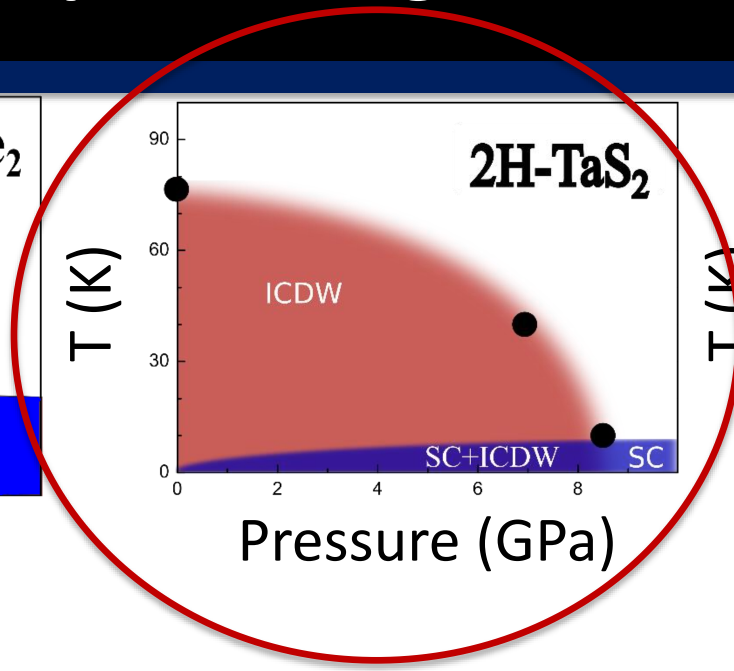


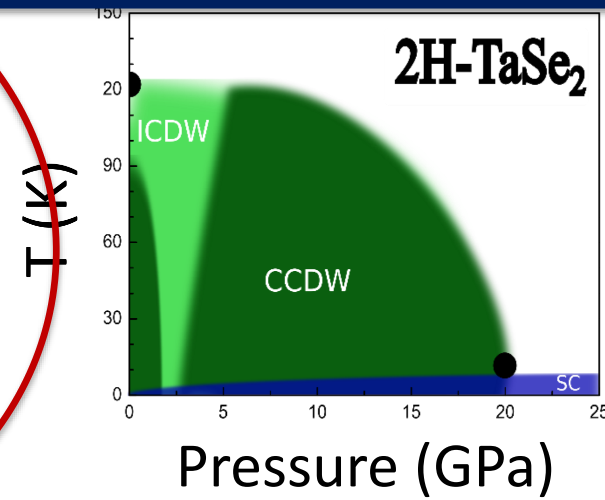


Set-up for Raman spectroscopy to probe low energy excitations (down to 5 cm^{-1} ~ 0.6 meV) under pressure (40 GPa) and at low temperature (3 K)

High pressure phase diagram of CDW TMDCs







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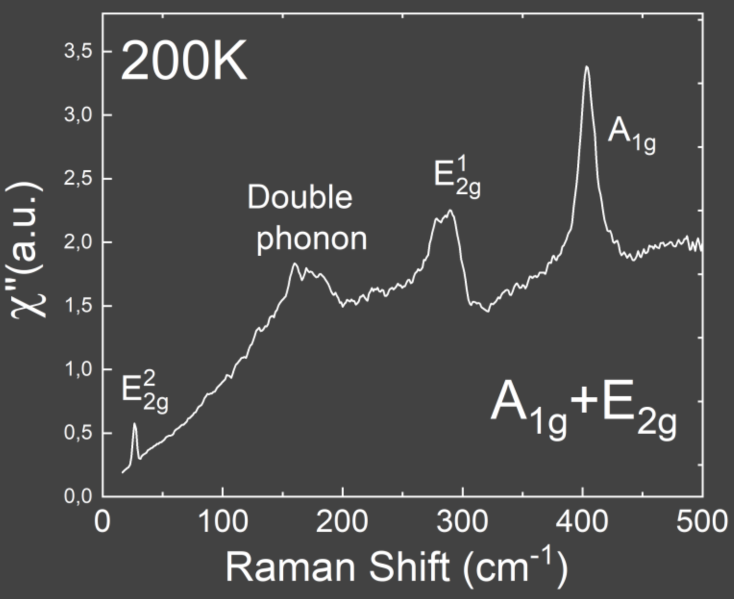
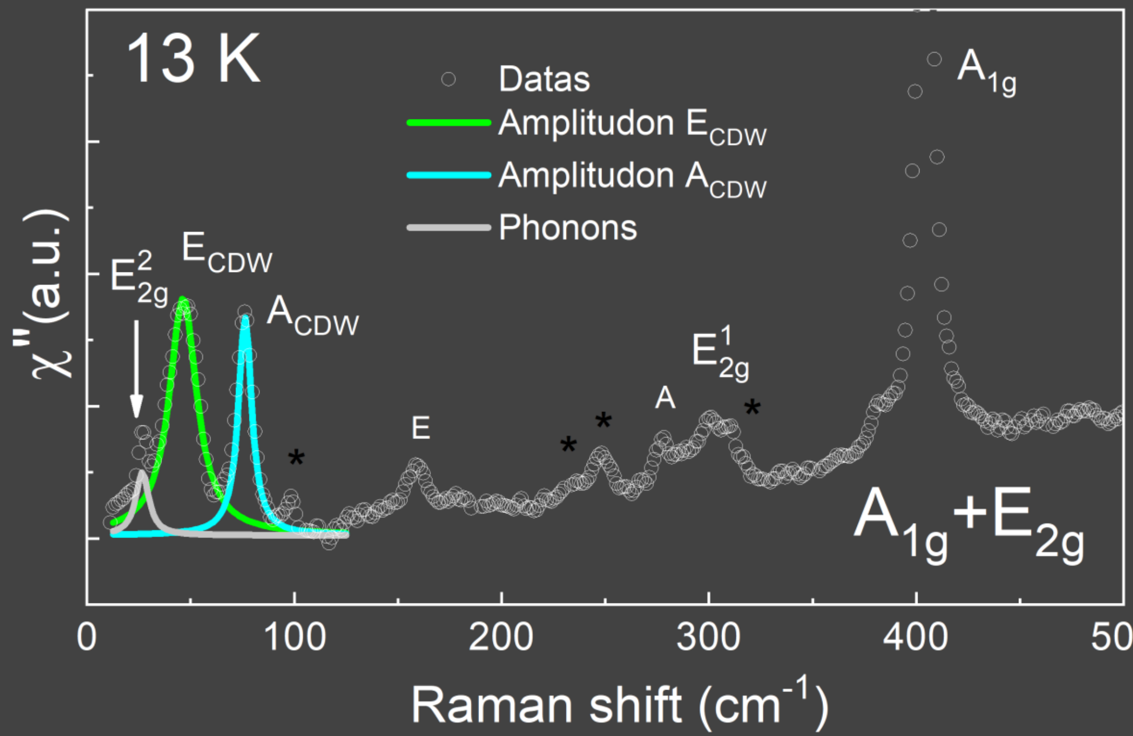
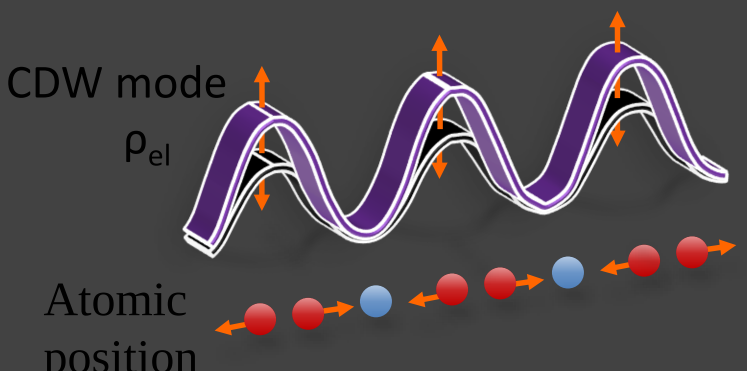
Raman Spectroscopy of 2H-TaS_2



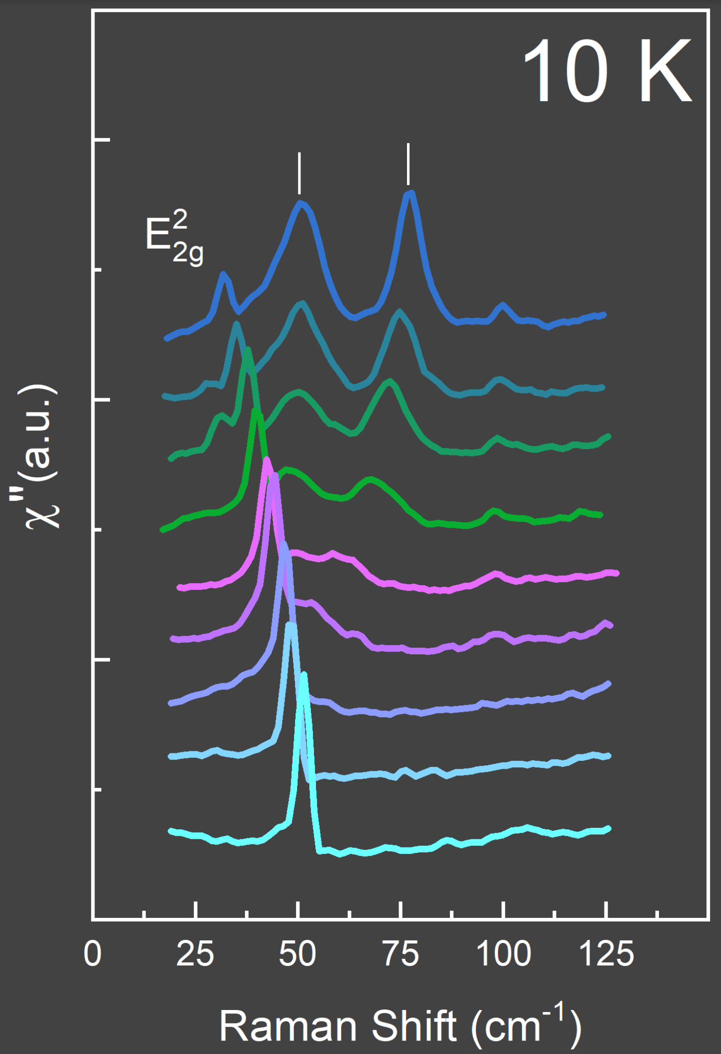


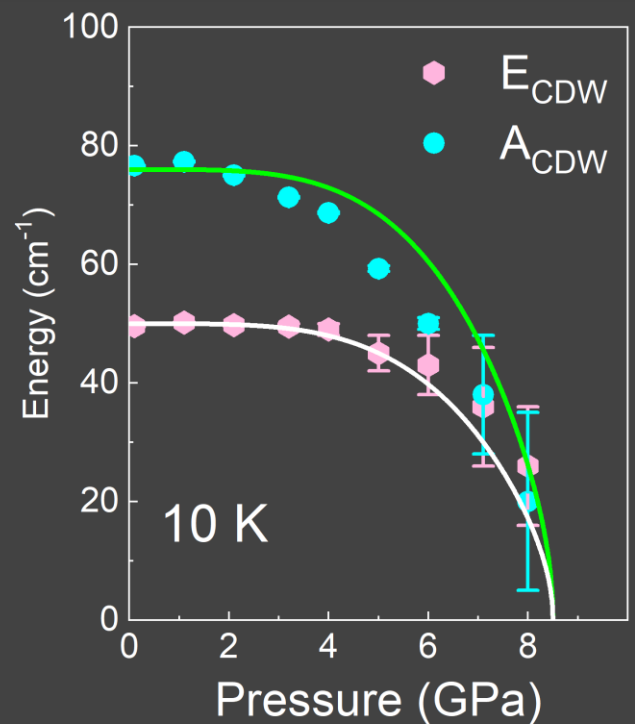
Two CDW amplitudons



Sugai et al., SSC (1981)
R. Grasset, PRL (2019)

Raman Spectroscopy of 2H-TaS_2 under pressure

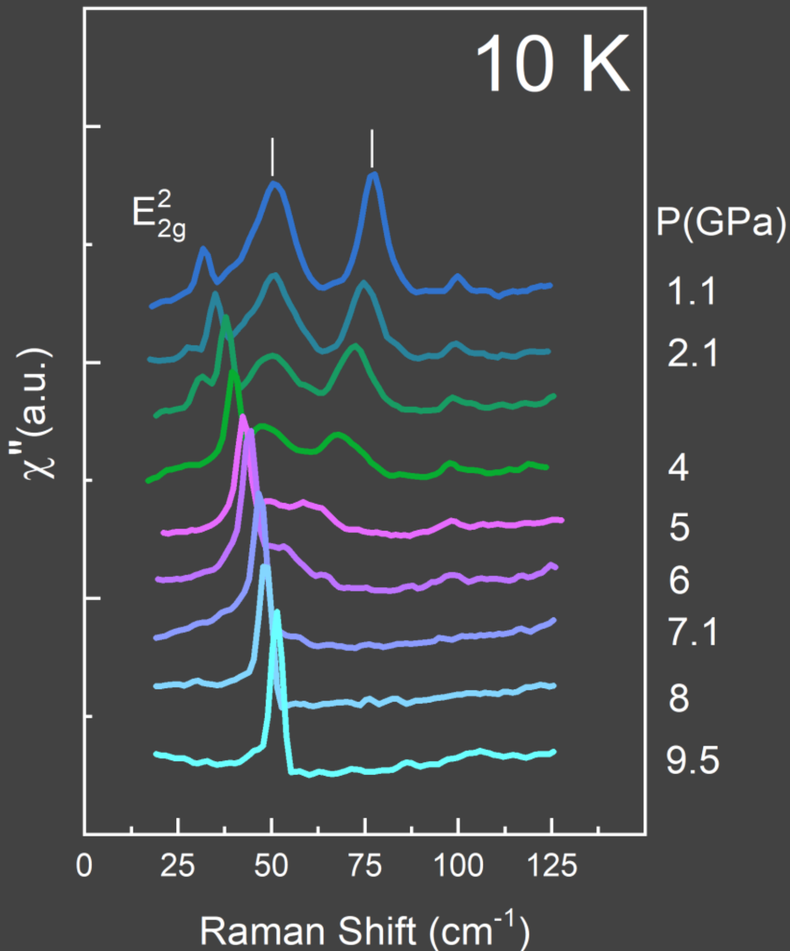


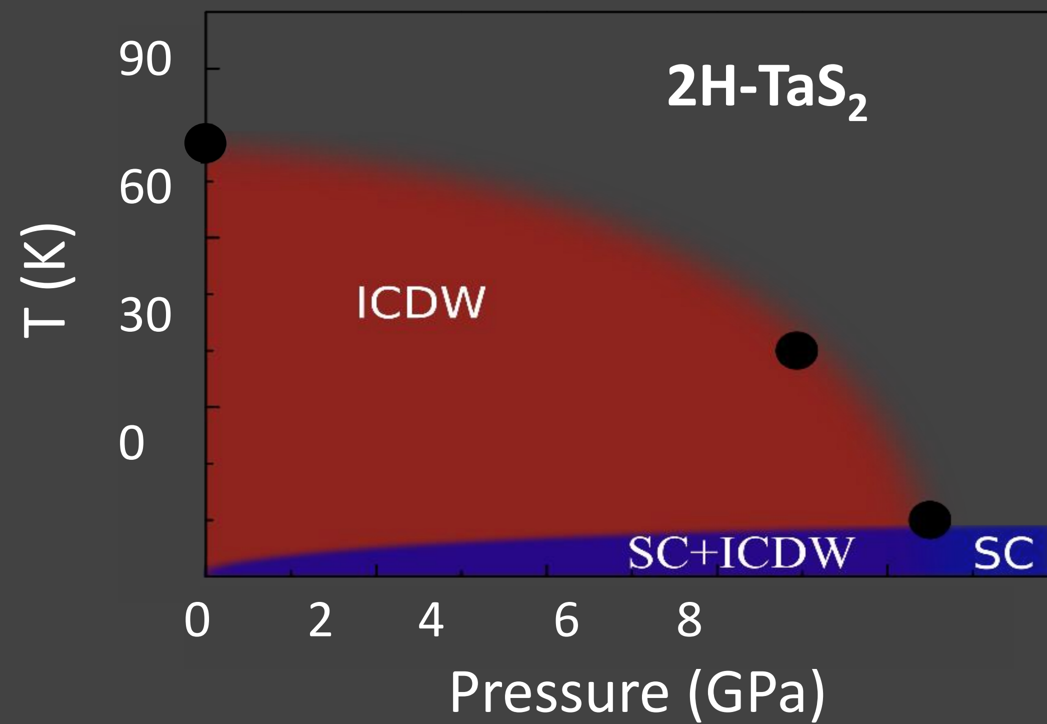


Softening of the two CDW amplitudons

R. Grasset et al., PRL (2019)

Raman Spectroscopy of $2H\text{-}TaS_2$ under pressure

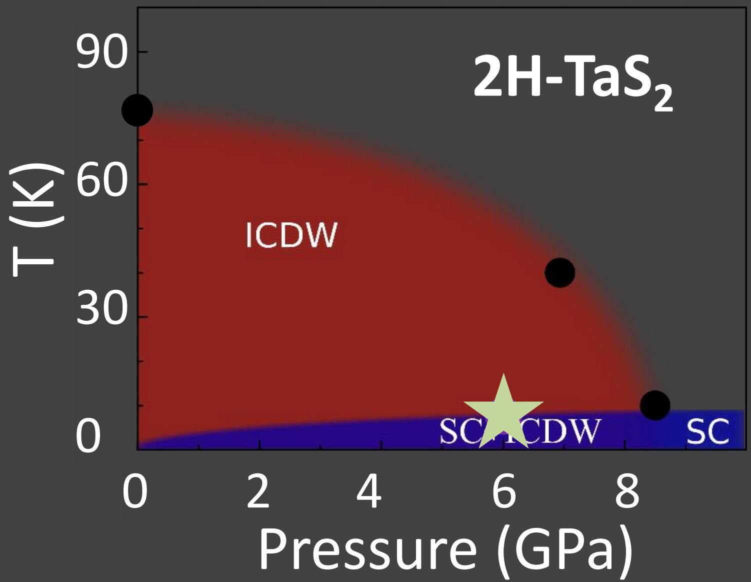


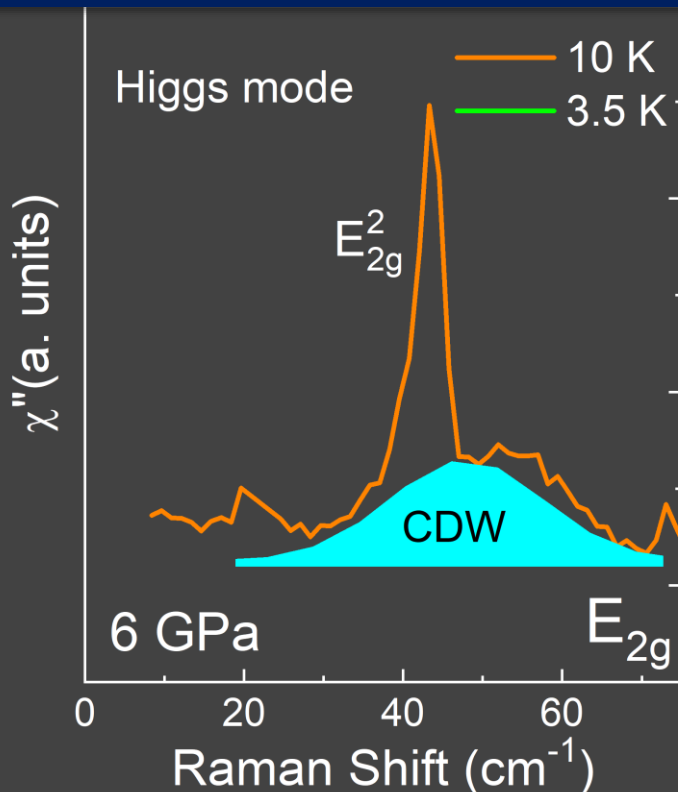


Collapse of the CDW at P_c ~ 8GPa

R. Grasset et al., PRL (2019)

Quest for a new Higgs mode in $2H\text{-}TaS_2$





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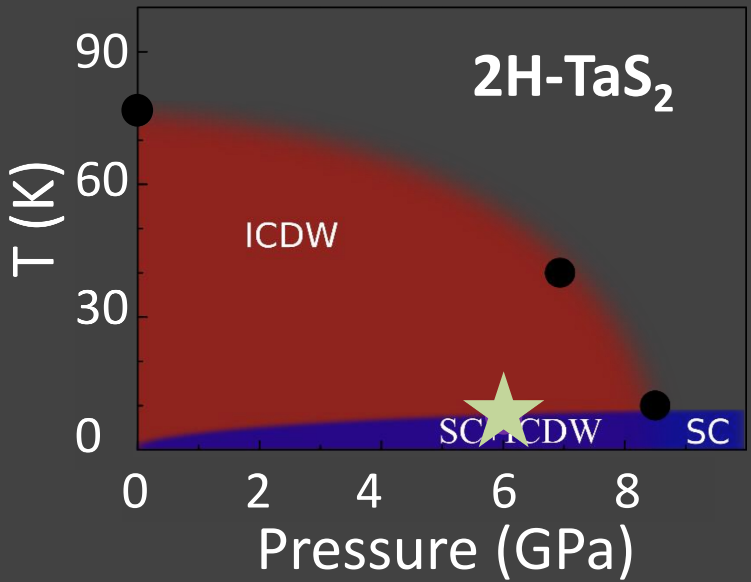
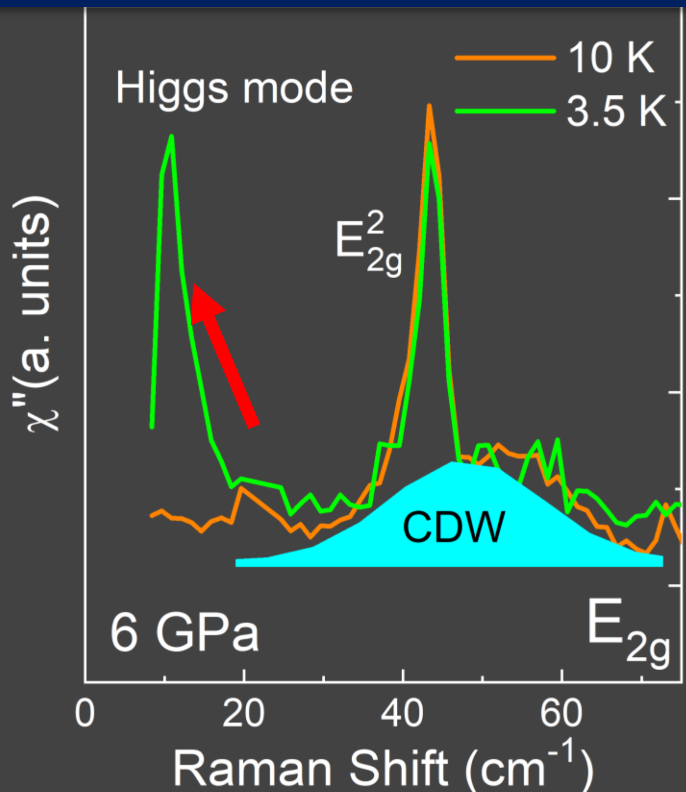
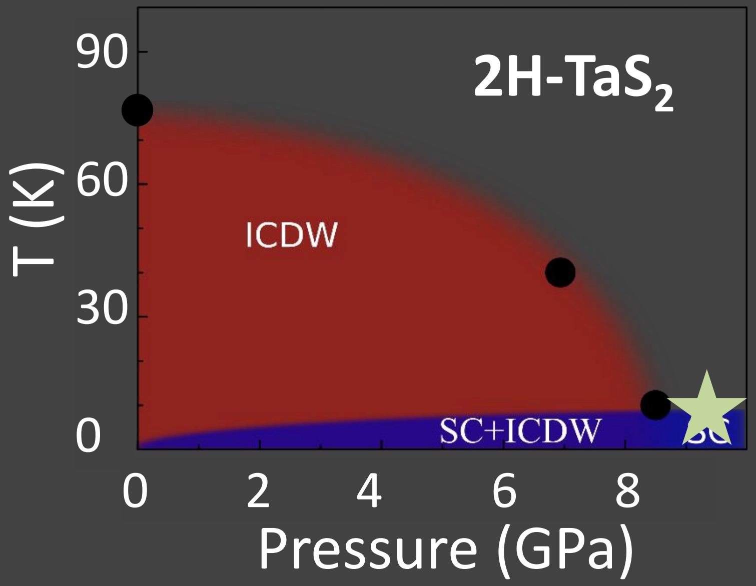


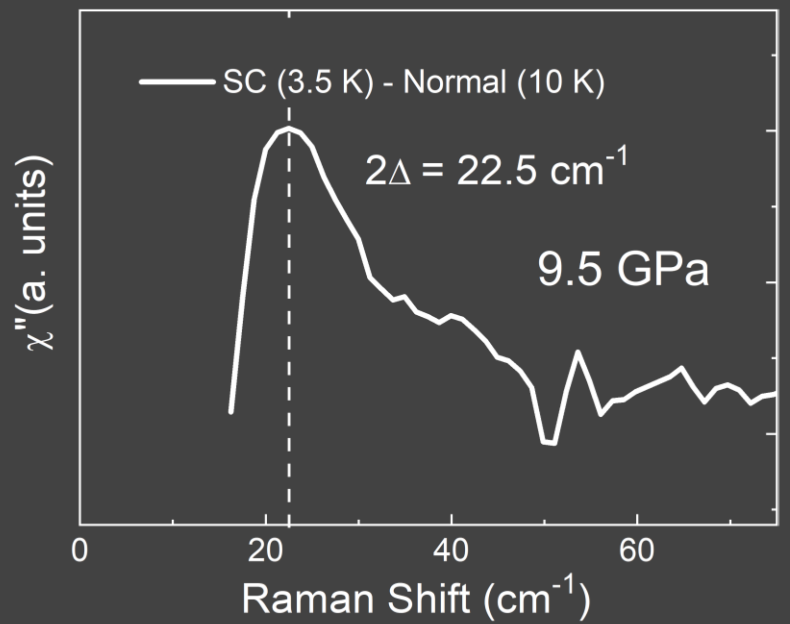


New high-pressure induced in-gap mode in $2H\text{-}TaS_2$

R. Grasset et al., PRL (2019)

Quest for a new Higgs mode in 2H-TaS_2





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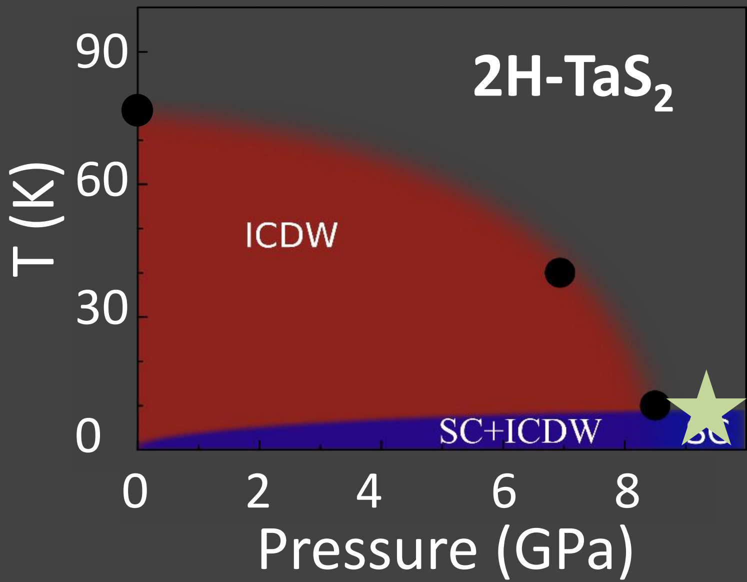
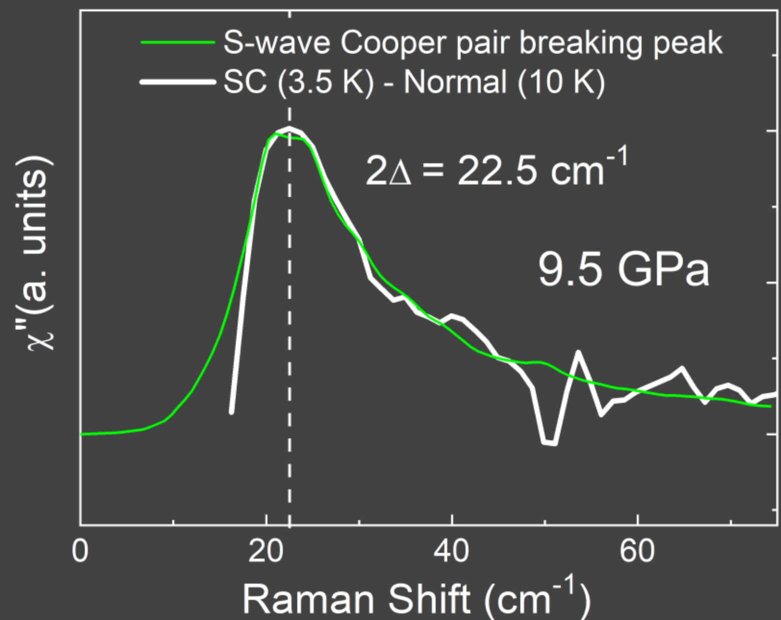
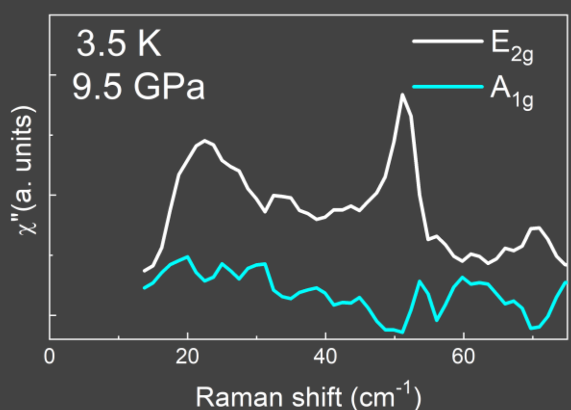




T_c^{BCS}=8.85K T_c^{meas}=8.5K

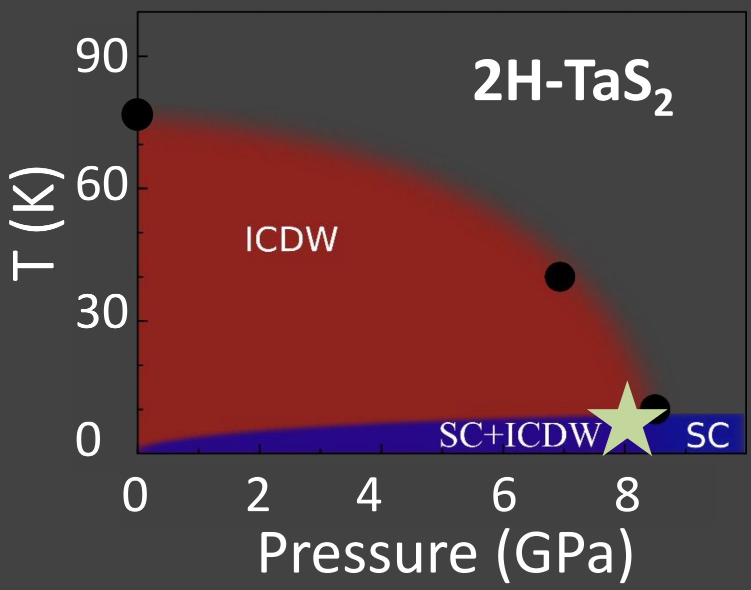


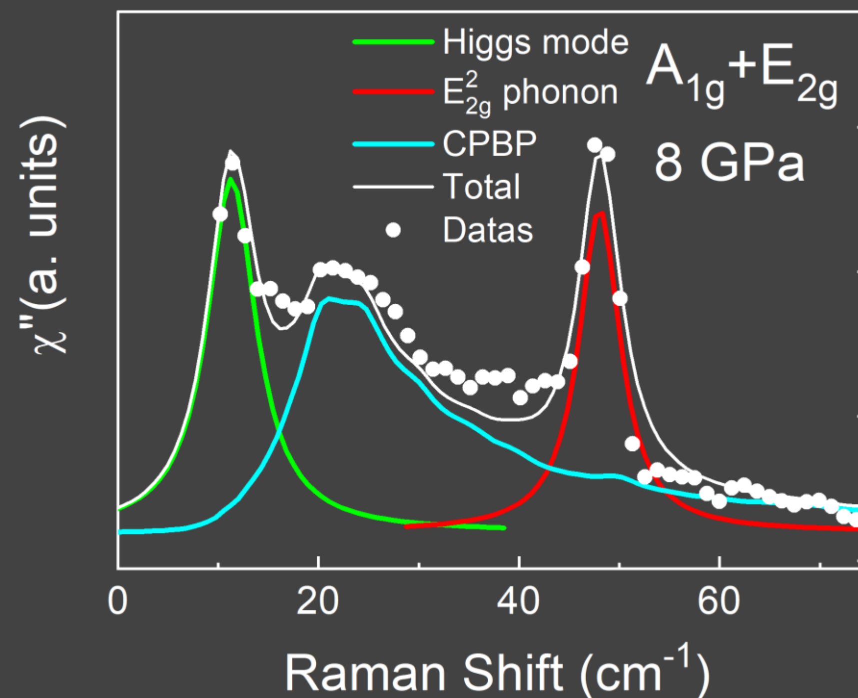
Cooper-pair-breaking peak in the pure superconducting state

The in-gap Higgs mode disappears

R. Grasset et al., PRL (2019)

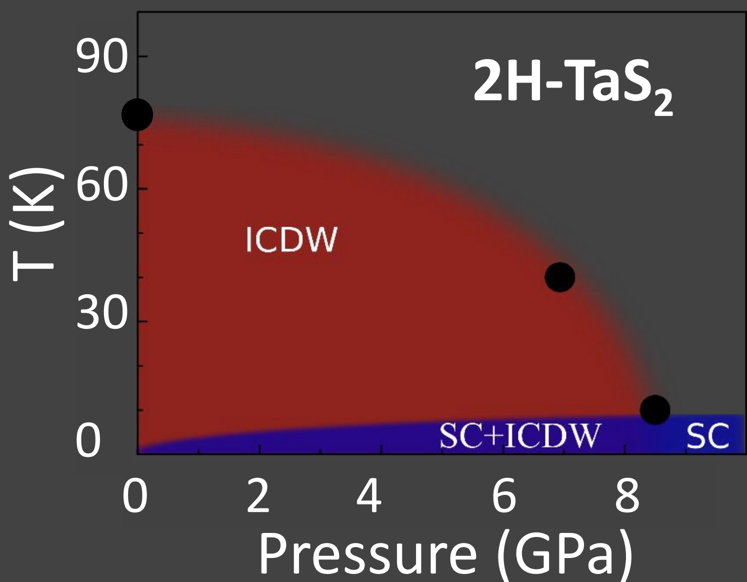
Quest for a new Higgs mode in $2H\text{-}TaS_2$





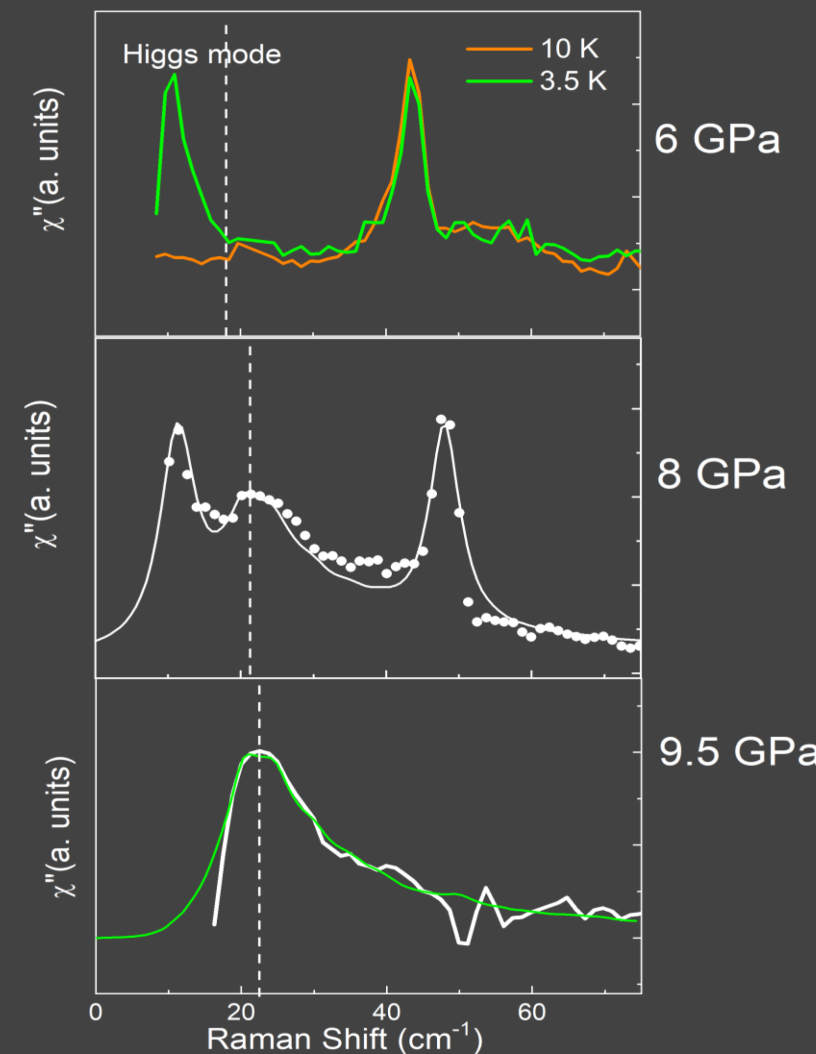
Coexisting Higgs mode and Cooper-pair-breaking peak

Quest for a new Higgs mode in $2H\text{-}TaS_2$

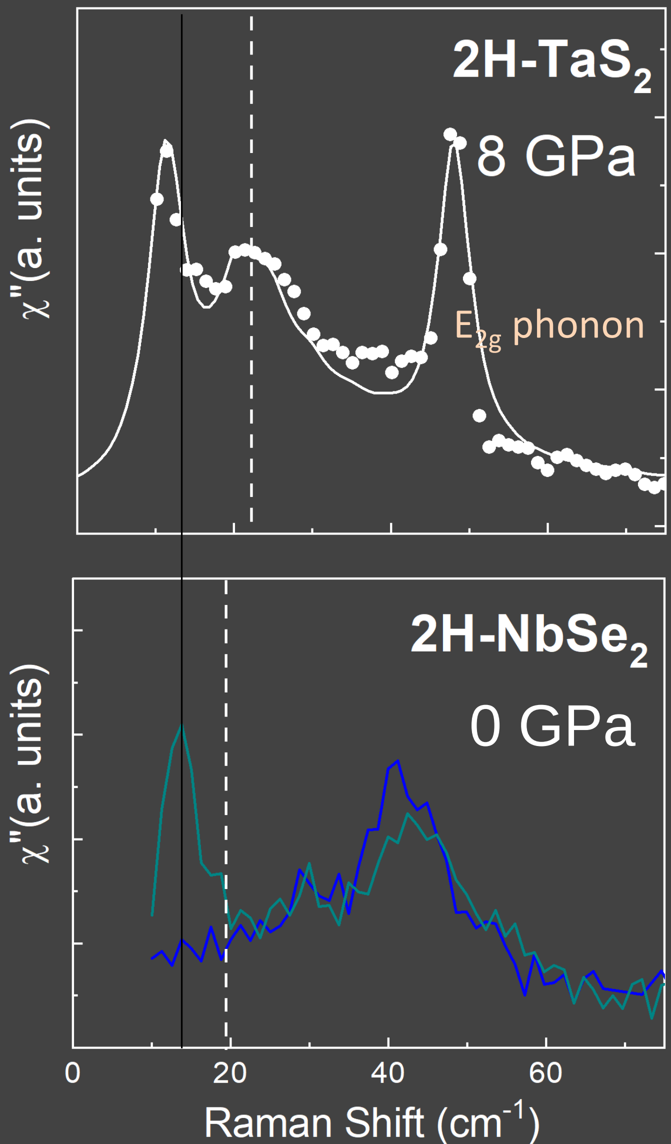


Coexisting Higgs mode and Cooper-pair-breaking peak

We are able to distinguish both SC modes



Higgs mode in 2H-TaS_2 and 2H-$NbSe_2$



Same mechanism of observability is at play in 2H-$NbSe_2$ and 2H-TaS_2

→ overlap of CDW and SC gaps.

Higgs mode is pushed further at low energy as compared to 2Δ.

Consistent with the observation of the CDW gap : Larger overlap of CDW and SC gaps

Higgs mode in Antiferromagnets

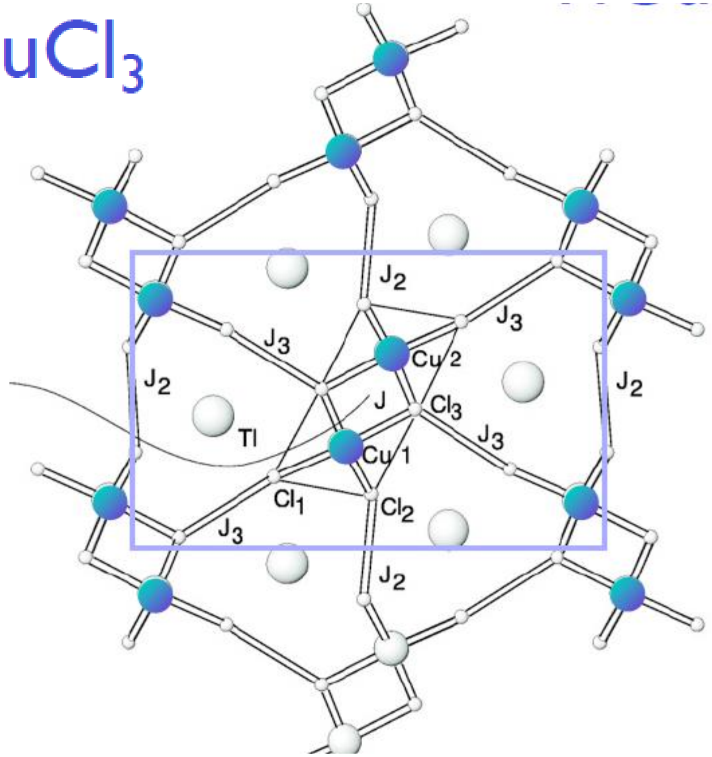
Higgs mode in Antiferromagnets

PRL 100, 205701 (2008) PHYSICAL REVIEW LETTERS week ending 23 MAY 2008

Quantum Magnets under Pressure: Controlling Elementary Excitations in $TlCuCl_3$

Ch. Rüegg,[1] B. Normand,[2,3] M. Matsumoto,[4] A. Furrer,[5] D. F. McMorrow,[1] K. W. Krämer,[6] H. -U. Güdel,[6]
S. N. Gvasaliya,[5] H. Mutka,[7] and M. Boehm[7]

$TlCuCl_3$



$$H = J\sum_{a} S_{l,a}\cdot S_{r,a} - J_{xx}\sum_{a} S^{x}_{l,a}S^{x}_{r,a} + J_2\sum_{\langle a,b\rangle} S_{l,a}\cdot S_{r,b},$$

S: spin operator on Cu site
J: intradimer
Jxx, J2: interdimer
J dominates: nonmagnetic order

Jxx: change the symmetry
broken from SU(2) to U(1)

Higgs mode in Antiferromagnets

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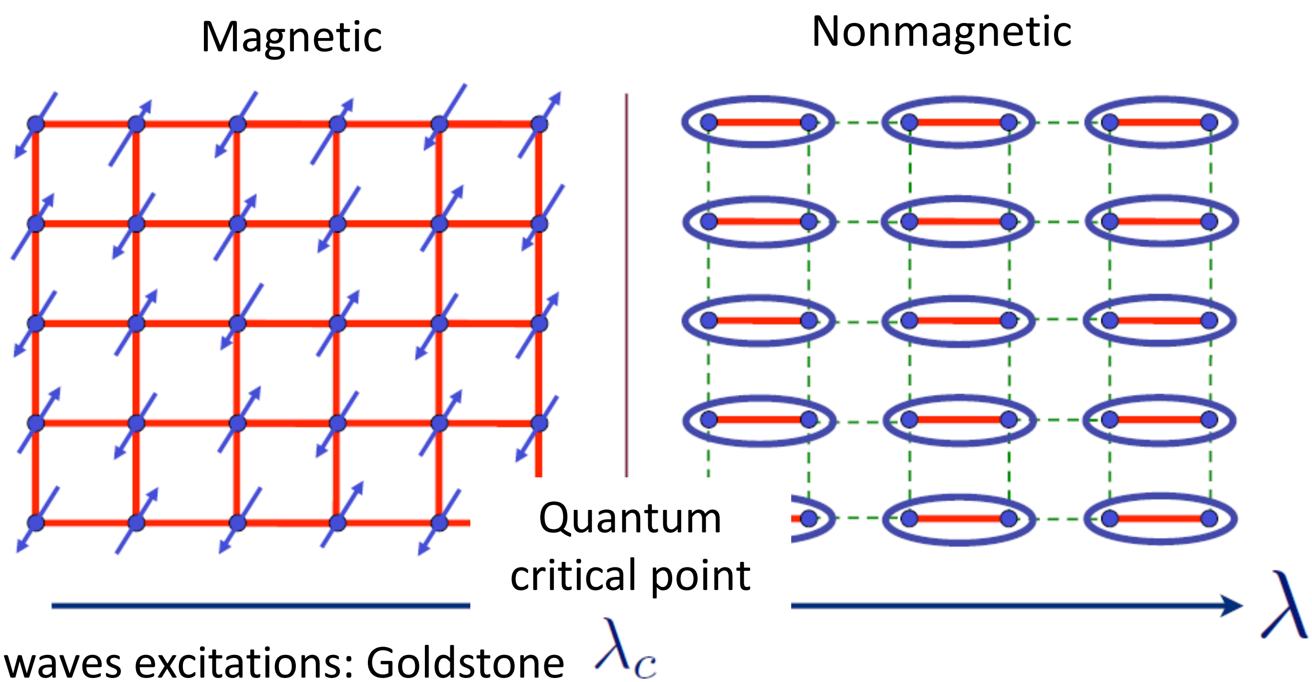

Spin waves excitations: Goldstone mode
A Longitudinal mode : Higgs mode

Spin 1 excitations:
3 triplets modes

Higgs mode in Antiferromagnets

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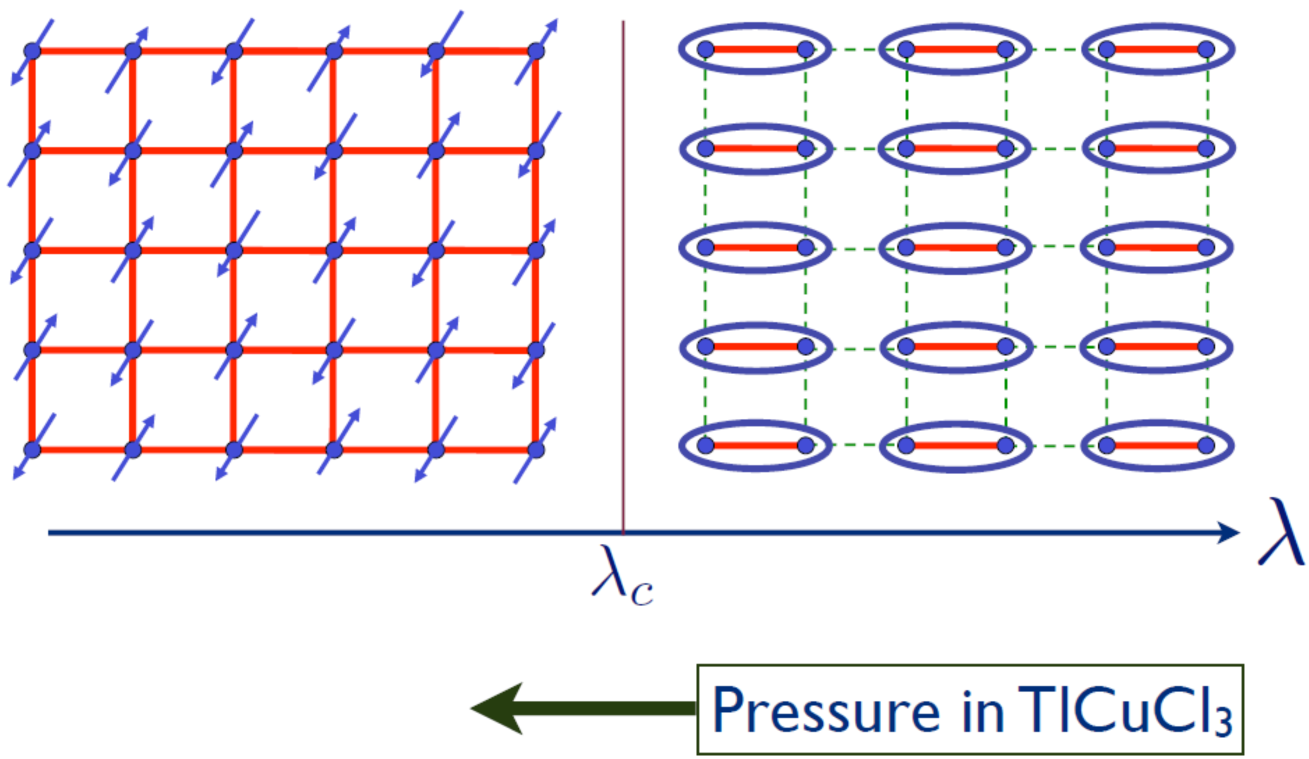

Higgs mode in Antiferromagnets

PRL 100, 205701 (2008) PHYSICAL REVIEW LETTERS week ending 23 MAY 2008

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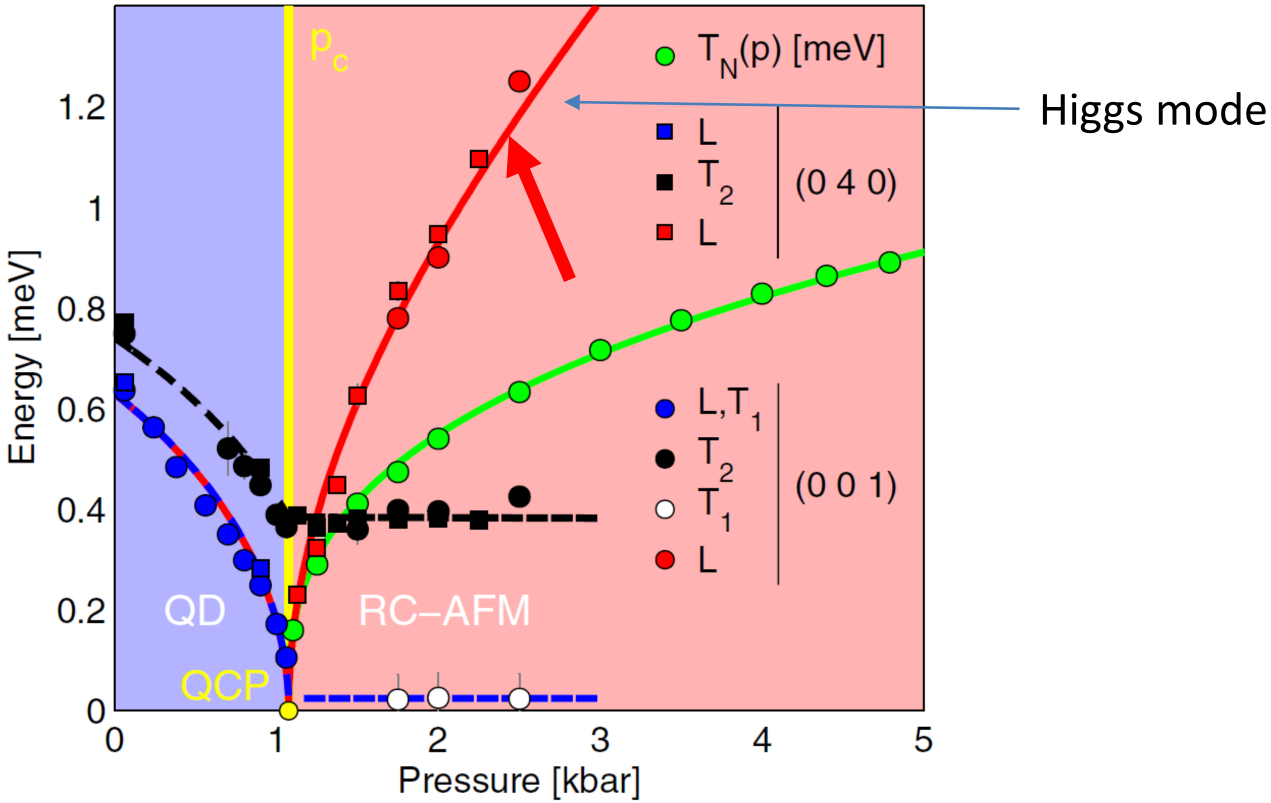
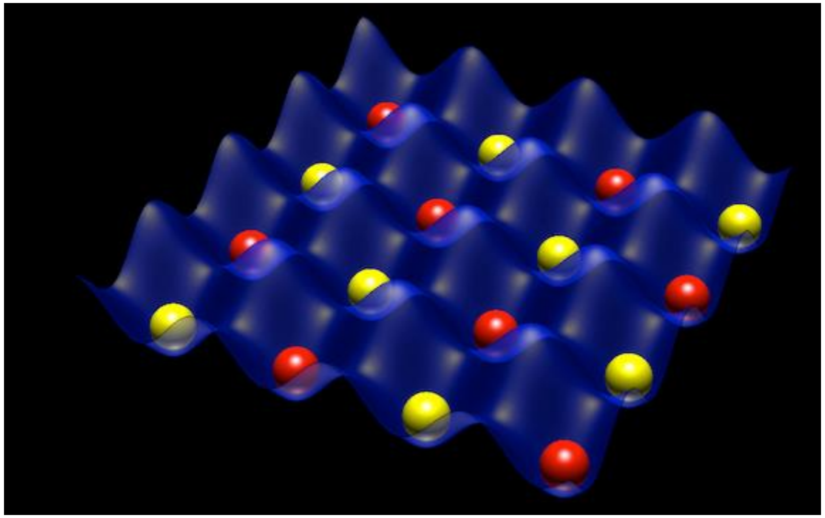


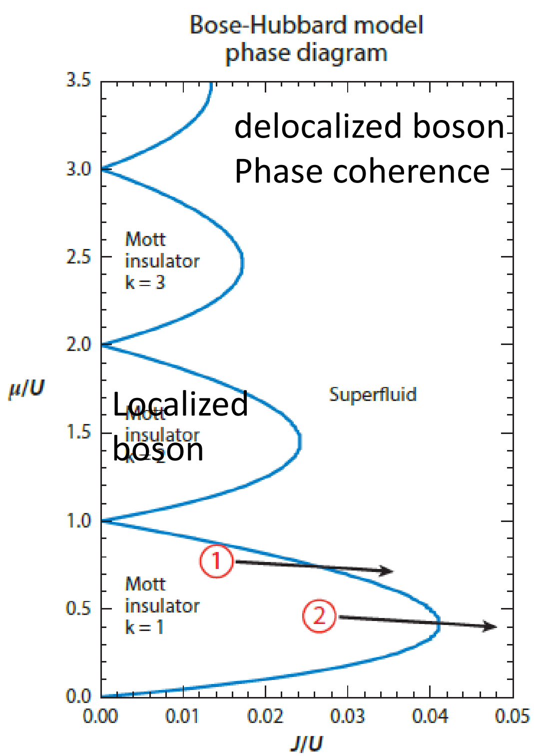
Higgs mode in ultracold bosons lattice



Higgs mode in ultracold bosons lattice

The 'Higgs' amplitude mode at the two-dimensional superfluid / Mott insulator transition

Manuel Endres[1], Takeshi Fukuhara[1], David Pekker[2], Marc Cheneau[1], Peter Schauß[1], Christian Gross[1], Eugene Demler[3], Stefan Kuhr[1,4] & Immanuel Bloch[1,5]



Bose-Hubbard model

$$H_{\mathrm{BH}} = -J\sum_{\langle ij\rangle} b_i^\dagger b_j + \frac{1}{2}U\sum_i n_i(n_i-1) - \mu\sum_i n_i.$$

Dimension = 2

Condensate made from atoms/bosons

Particle-hole symmetric line
Effective Lorentz-invariant near Quantum Criticality Point.

Higgs mode in ultracold bosons lattice

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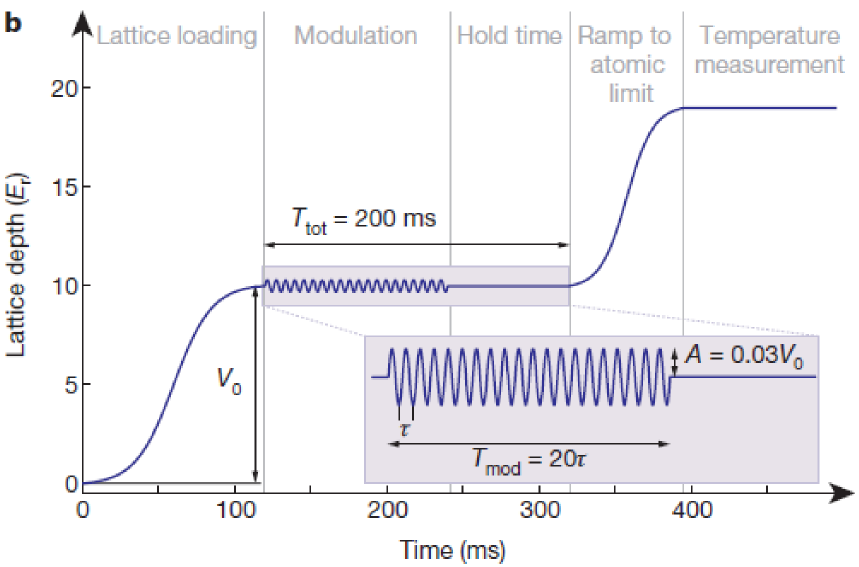
Lattice depth modulation → Periodic modulation of j



$$j = {}^{J}/_{U}$$

Bose-Hubbard model

$$H_{\mathrm{BH}} = -J\sum_{\langle ij\rangle} b_i^{\dagger} b_j + \frac{1}{2}U\sum_i n_i(n_i - 1) - \mu\sum_i n_i.$$

Higgs mode in ultracold bosons lattice

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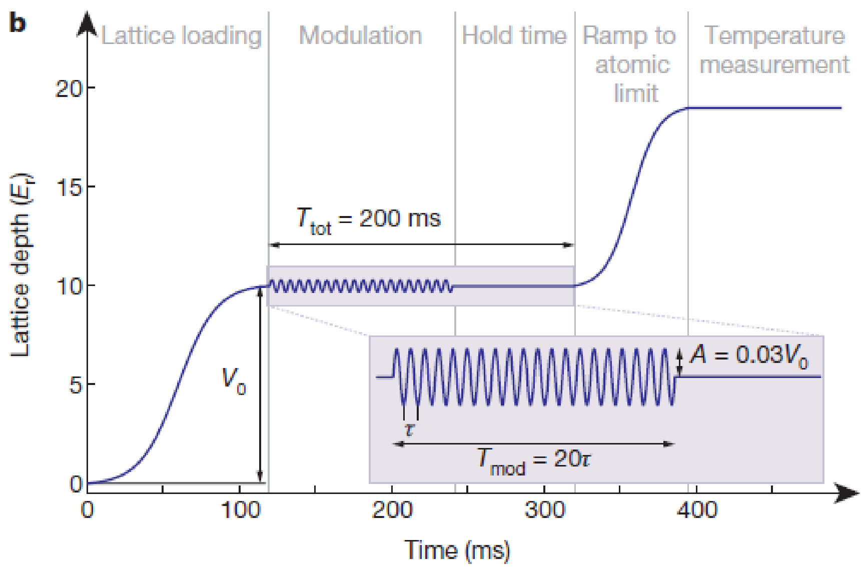
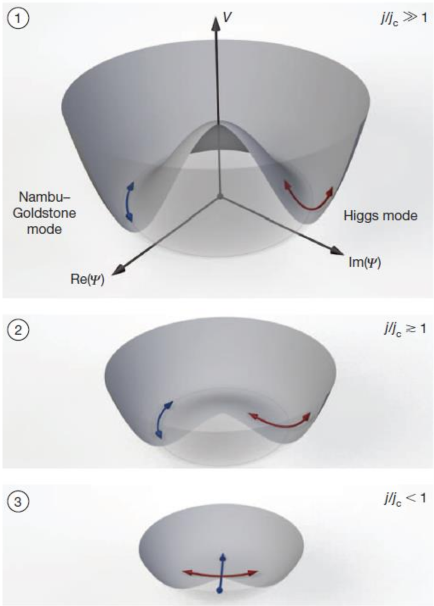
Lattice depth modulation → Shake of the potential



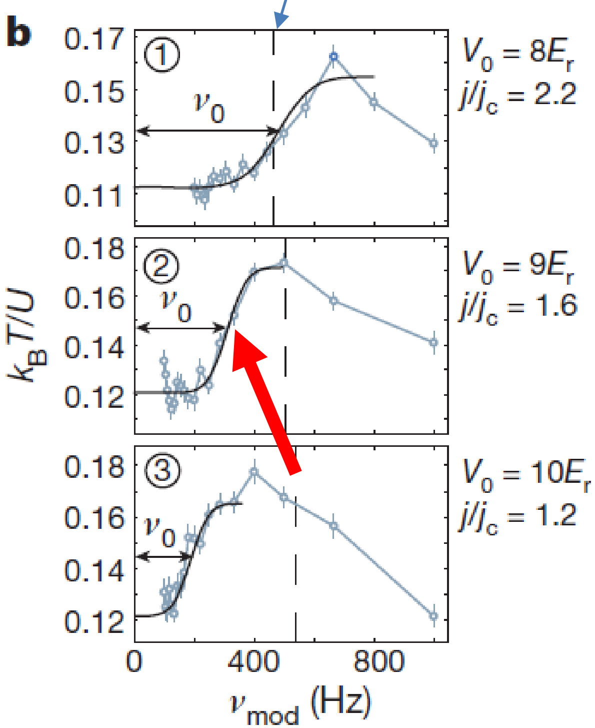


Higgs mode in cold bosons lattice

The ‘Higgs’ amplitude mode at the two-dimensional superfluid / Mott insulator transition

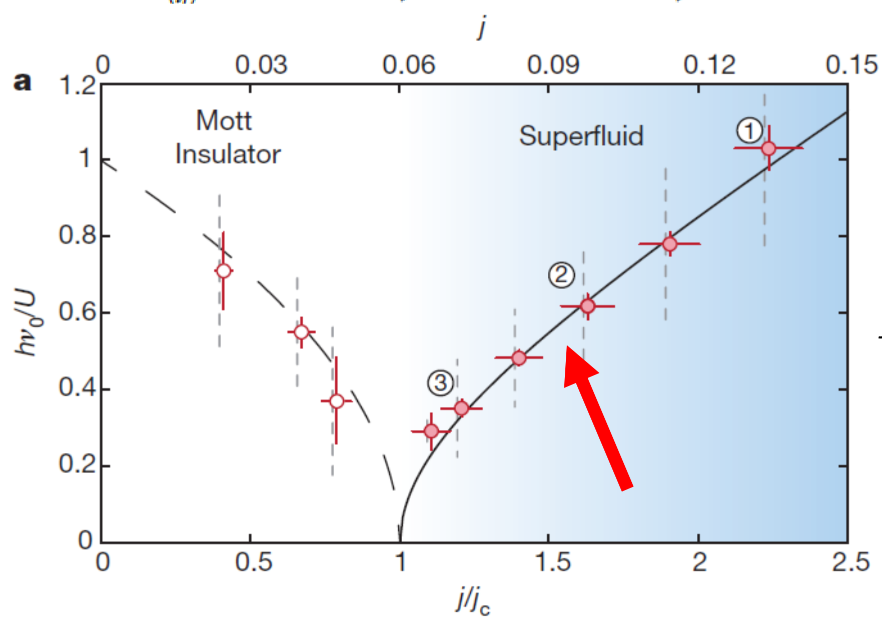
Manuel Endres[1], Takeshi Fukuhara[1], David Pekker[2], Marc Cheneau[1], Peter Schauß[1], Christian Gross[1], Eugene Demler[3], Stefan Kuhr[1,4] & Immanuel Bloch[1,5]

Energy of the lowest p-h excitation



Bose-Hubbard model

$$H_{BH} = -J\sum_{\langle ij\rangle} b_i^\dagger b_j + \frac{1}{2}U\sum_i n_i(n_i - 1) - \mu\sum_i n_i.$$



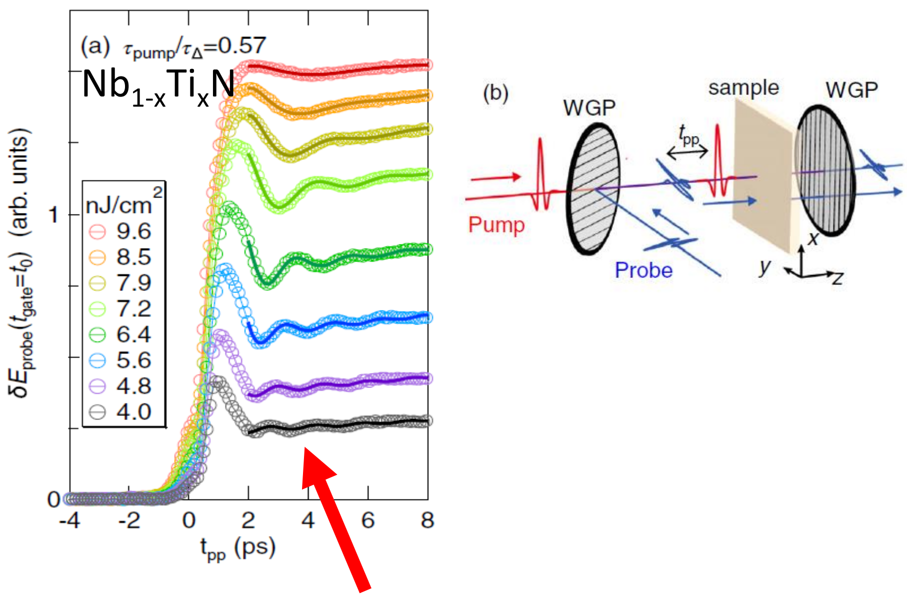
$$j = J/U$$

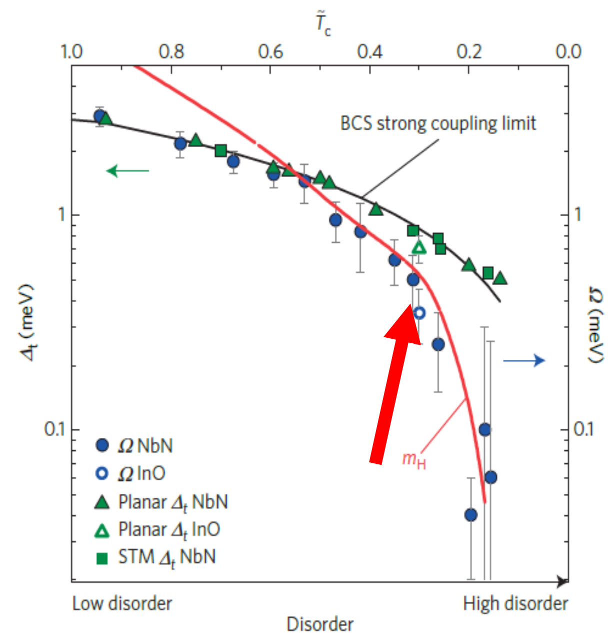
Particle-like & hole-like modes (degenerate)

Goldstone mode & Higgs mode

Other Detection of Higgs mode in Superconductors

Few situations of observability:





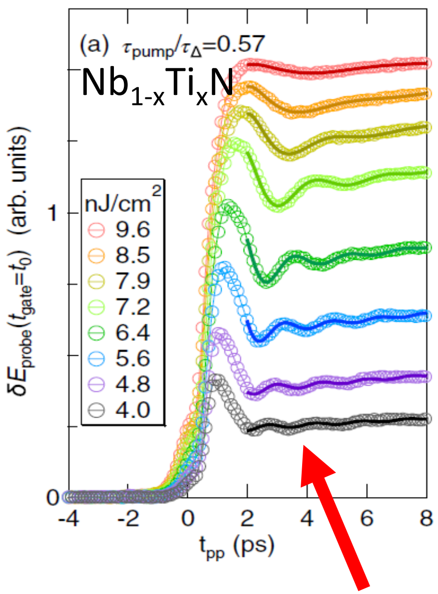
Higgs Amplitude Mode in the BCS Superconductors $Nb_{1-x}Ti_xN$ induced by Terahertz Pulse Excitation
R. Matsunaga, et al., Phys. Rev. Lett. 111, 057002 (2013)

The Higgs mode in disordered superconductors close to a quantum phase transition
Daniel Sherman et al., Nature Physics (2015)

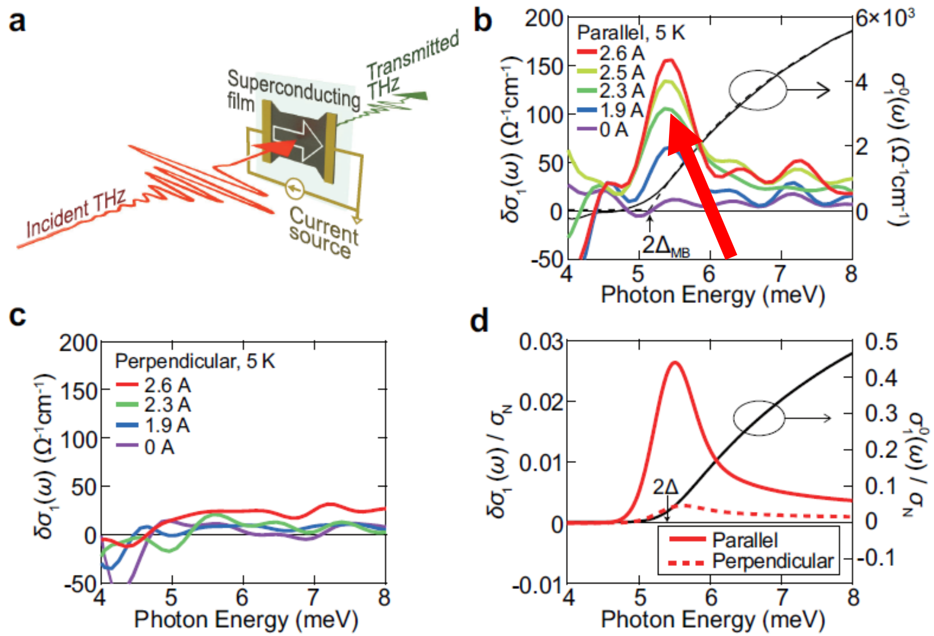
nonlinear coupling term $A^2 H$

Other Detection of Higgs mode in Superconductors

Few situations of observability:



Higgs mode in presence of supercurrent



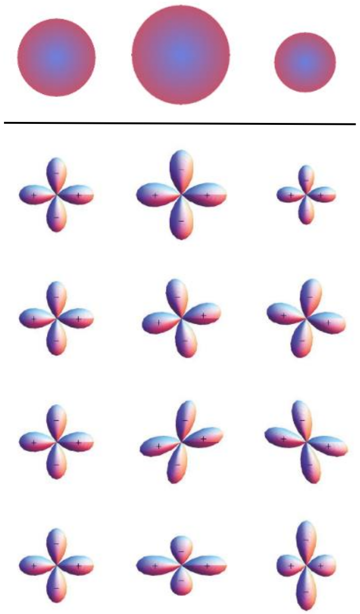
Higgs Amplitude Mode in the BCS Superconductors $Nb_{1-x}Ti_xN$ induced by Terahertz Pulse Excitation

R. Matsunaga, et al., Phys. Rev. Lett. 111, 057002 (2013)

nonlinear coupling term A^2H

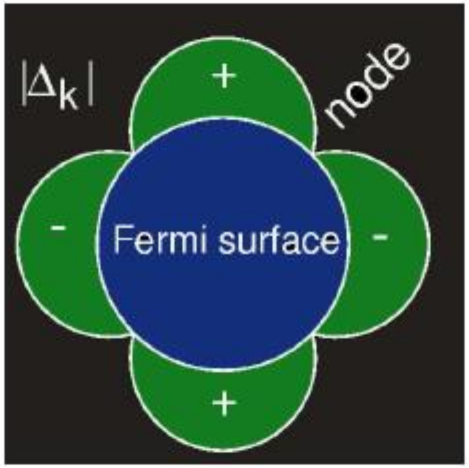
Richness of Superconducting Higgs mode

Non s-wave Order Parameter
Multiple Higgs mode



A single Higgs mode

Multiple and symmetry dependent Higgs modes

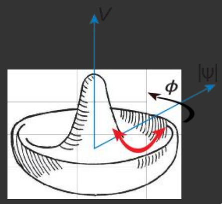


$d_{x^2-y^2}$ gap symmetry

NB: Complex Superconducting state: existence of vortex, pre-formed Cooper pairs above Tc, variety of mechanisms, importance of quantum critical fluctuations, weak to strong correlations, triplet spin state of Cooper pairs ….

« Higgs Spectroscopy »

Higgs mode



Systems properties

Fingerprint

Observability

Number

Symmetry

Parameters' dependence (P, H, density…)

Higgs Spectroscopy
Symmetry of the OP

Coexisting orders

Nematicity

Strong coupling

PDW SCors

Multi-gap SCors

2D QCP SCors

Fauseweh et al. (2018)
Barlas et Varma (2013)

Cea et Benfatto (2014)
Littlewood et Varma (1982)
Browne et Levin (1983)

Uematsu et al. (2019)

Murakami et al. (2016)

Soto-Garrido et al., (2017)

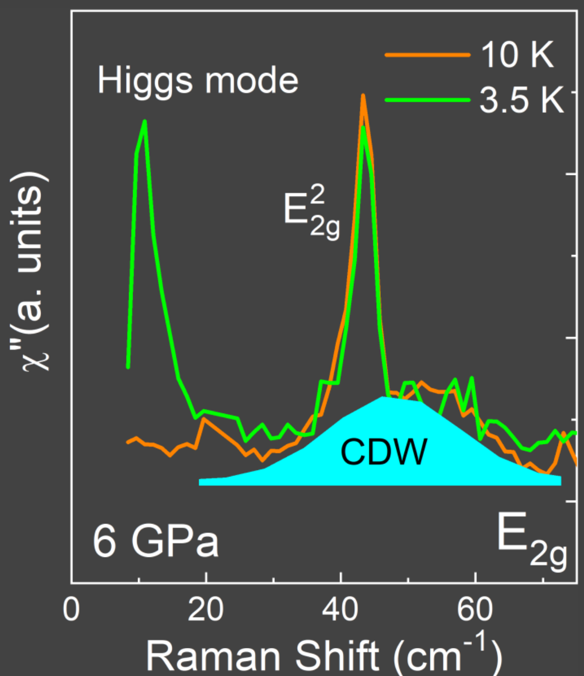
Murotani et al. (2017),

Krull et al. (2016)

Podolsky et al. (2011)

Summary

2H-TaS_2



- Analogous of the Higgs boson exist in Condensed Matter Systems
- Detection is a challenge: requires demanding experiments. Very active field of research.
- Richness of Higgs mode in condensed matter: multiple Higgs mode with various symmetries, microscopic mechanisms for the formation of condensate is generally known and we can play with parameters of the systems.

- Fruitful Exchange of concepts

Collaborators … and Thanks!

Raman Spectroscopy
R. Grasset
J. Buhot
Y. Gallais
M. Cazayous
A. Sacuto

Theory
L. Benfatto
T. Cea
C. Varma

Crystals synthesis
L. Cario
Samuel Mañas-Valero
Eugenio Coronado

High Pressure
A. Polian
P. Parisiadis

Analogy

	Standard Model **Elementary particules**	**Quantum physics** **Superconductivity**
Energy	125GeV	2Δ ~2-50meV
Detection	Detection of products of disintegration	"Shaking of the condensate" •Coupling with another electronic states •Time resolved measurements (non-equilibrium state) •Non linear optical excitation •Proximity of QCP
Give mass to gauge bosons	Z, W particles	photon
Field	Higgs field	|ψ|
condensate	Higgs condensate	Cooper pairs condensate
Transition temperature	Huge	1K-250K
Scalar Boson	Higgs boson	Fundamental excitation of the condensate
		A lot of subtleties (unconventionality, parameters phase space…)
	No experiment with universe/ Clean	Many experiments/ Not clean systems

Reported or discussed interpretations

Type of mode	Main authors	Citations	Main doubts
Renormalized Phonon/ New pole in the phonon propagator	Balseiro and Falicov	C.A. Balseiro and L.M. Falicov, Phy. Rev. Lett (1980) X.L. Lei, C.S. Ting, J.L. Birman, Pyhs. Rev. B (1984) M. V. Klein aud S.B.Dierker, Phys. Rev. B (1984). (check)	Coulomb interaction cancel out this effect (in A1g channel) The E2g mode should follow 2Δ It exists inelastic neutron scattering measurements in the SC state: a small shoulder in the phonon soft mode appears. It is at 2Δ. Need a tail of the phonon mode below 2Δ
Higgs mode (gauge invariant)	Littlewood and Varma Browne and Levin Benfatto	P.B. Littlewood and C.M. Varma, Phys. Rev. B (1982). P.B. Littlewood and C.M. Varma, Phys. Rev. (1981). C. Varma, J. Of Low Temp. Phys. 126 (2002) D. Pekker and C. Varma, Ann. Rev. of Cond. Matt. Phys. 6 (2015). D. A. Browne and K. Levin, Phys. Rev. B (1983). T. Cea and L. Benfatto, PRB (2014)	Most reasonnable interpretation No explanation for different symmetry behavior but Klein explained why 2 amplitudons appears and Varma explained how the s-wave condensate can couple to the E2g ampltidon so it is fine qualitatively.
Effective density mode	I. Tutto and A. Zawadowski	I. Tutto et al., Phys. Rev. B (1992).	Cf. suppl Pekker and Varma. Like BS
Phason		G. Zwicknagel, …	
Cooper pairebreaking peak/Intertwinned pairs breaking peak	Blumberg	G. Blumberg (Aleksej Mialitsin, PhD)	Interpret the amplitudon as the CDW gap (not the case Cf measure CDW gap by STM and our measurement in TaS2 and TaSe2)
Folded plasmon mode			the plasmon does not manifests itself as a peak in the Raman response, both in the presence and in the absence of Coulomb interactions. One could expect to see it in the symmetric A1g channel, but not in the E2g one.
Leggett mode			Need electron and hole pockets The Fermi Surface topology has to change at Pc
Bardasis Schrieffer			Should not appear in the s-wave symmetry (A1g) Require change of SC properties at Pc