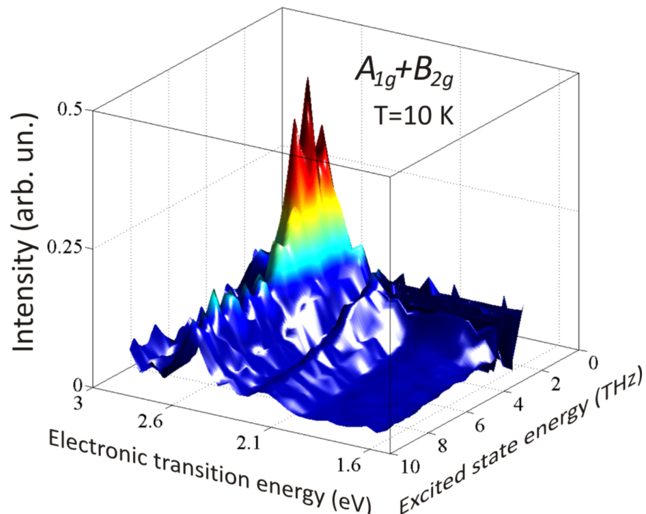
Coupling of a high-energy excitation to superconducting quasiparticles in a high-T_c cuprate from coherent charge fluctuation spectroscopy



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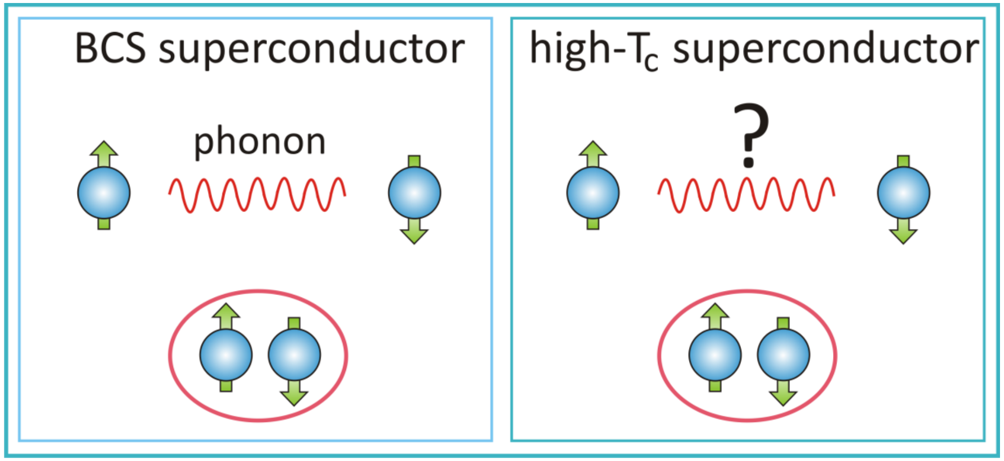
Pairing interactions in high-T_c cuprates



What is the glue (if any) maintaining electrons of Cooper pairs together?

Low-energy theories (Eliashberg formalism)

High-energy theories

Pairing interactions in high-T_c cuprates

Low-energy theories (Eliashberg formalism)

$$H_{BCS} = \sum_{\mathbf{k},\sigma} \xi_k c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} - \frac{V}{2\Omega} \sum_{\mathbf{k},\ \mathbf{k}',\ \mathbf{q},\sigma\sigma'}^{\prime} c^\dagger_{\mathbf{k}+\mathbf{q},\sigma} c_{\mathbf{k},\sigma} c^\dagger_{\mathbf{k}'-\mathbf{q},\sigma'} c_{\mathbf{k}',\sigma'}$$

$$\Psi = \prod_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}} c^\dagger_{\mathbf{k}\uparrow} c^\dagger_{-\mathbf{k}\downarrow}) |0\rangle$$

Electrons bind in Cooper pairs through attractive effective potential V>0

BCS: phonons
Cuprates: spin fluctuations (?)

Energy scale: **meV**
Time-scale: picosecond

RETARDED INTERACTIONS

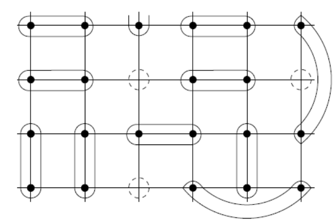
Scalapino et al., PRB 34 (1986)

High-energy theories

$$H_{t-J} = P \sum_{\mathbf{k},\sigma} \xi_k c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} P + J \sum_{i,j} \mathbf{S}_i . \mathbf{S}_j \qquad J \propto t^2/U$$

$$P\Psi = P \prod_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}} c^\dagger_{\mathbf{k}\uparrow} c^\dagger_{-\mathbf{k}\downarrow}) |0\rangle \qquad P = \prod_i (1 - n_{i\uparrow} n_{i\downarrow})$$

Formation of a Resonating-Valence-Bonds liquid of Cooper pairs due to strong electronic correlations



Energy scale: U: **eV**
Time-scale: sub-femtosecond

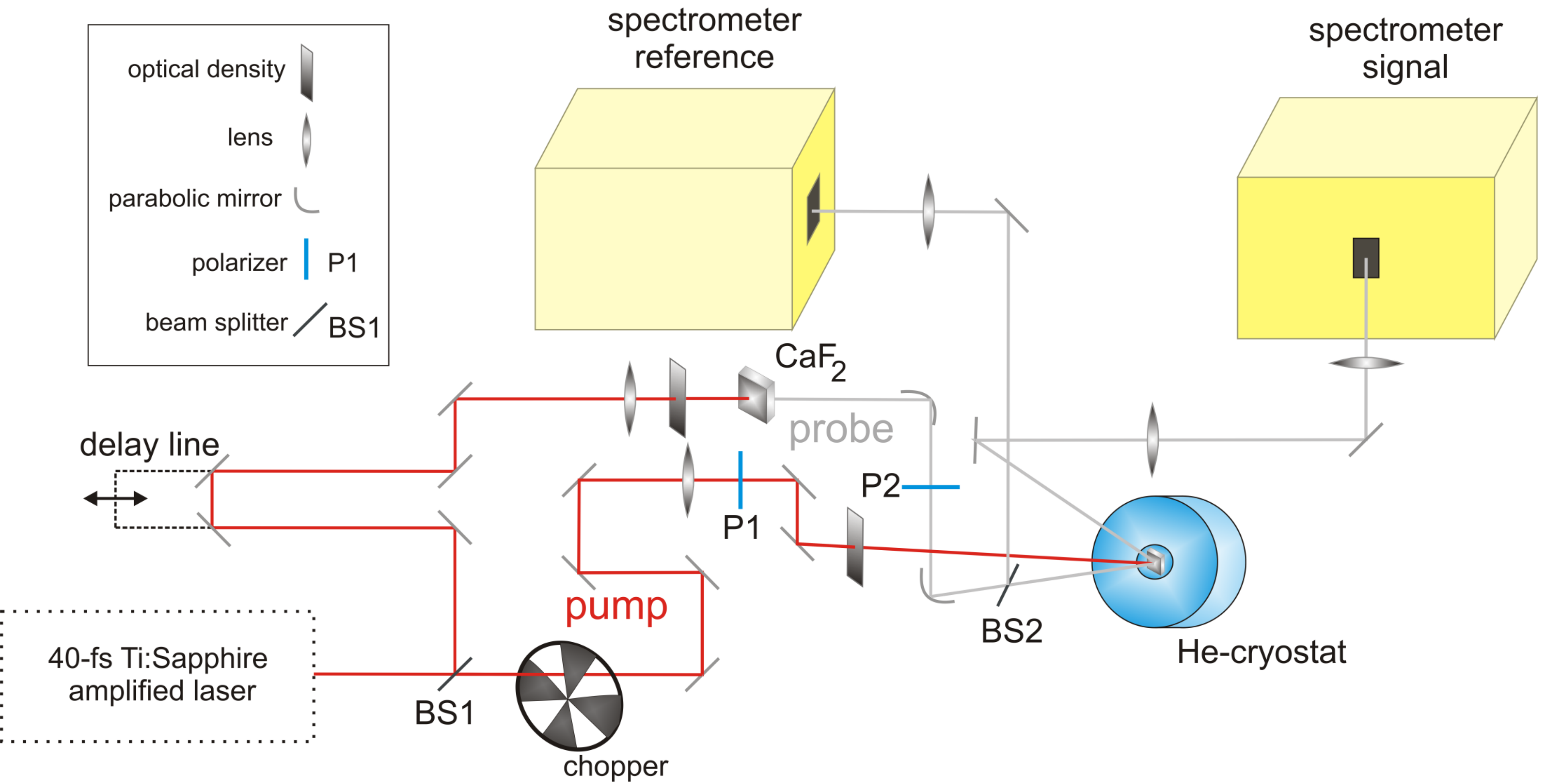
$$\mathrm{r} \bullet\!\!-\!\!\bullet \mathrm{r}' = \frac{|\uparrow_r \downarrow_{r'}\rangle - |\downarrow_r \uparrow_{r'}\rangle}{\sqrt{2}}$$

NON-RETARDED INTERACTIONS

Anderson, Science 235 (1987)

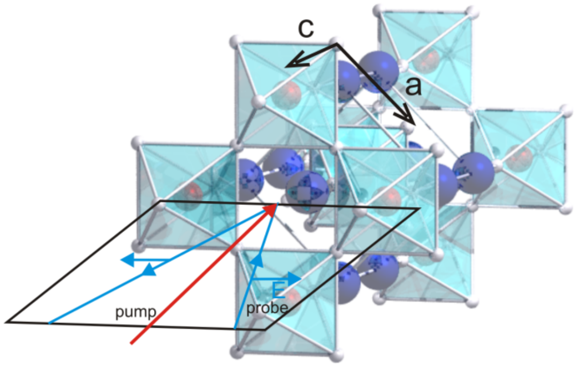
Determination of the pairing mechanism: study of the energy-scale and/or the time-scale of the pairing interactions

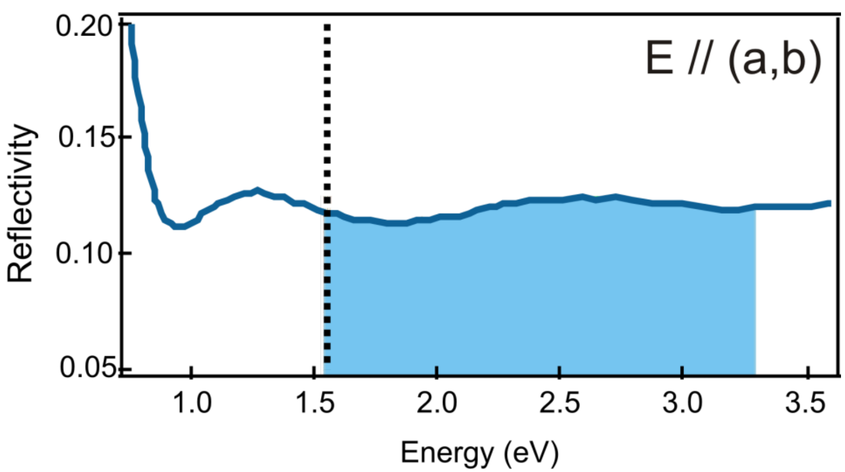
Experimental setup: broadband pump-probe reflectivity

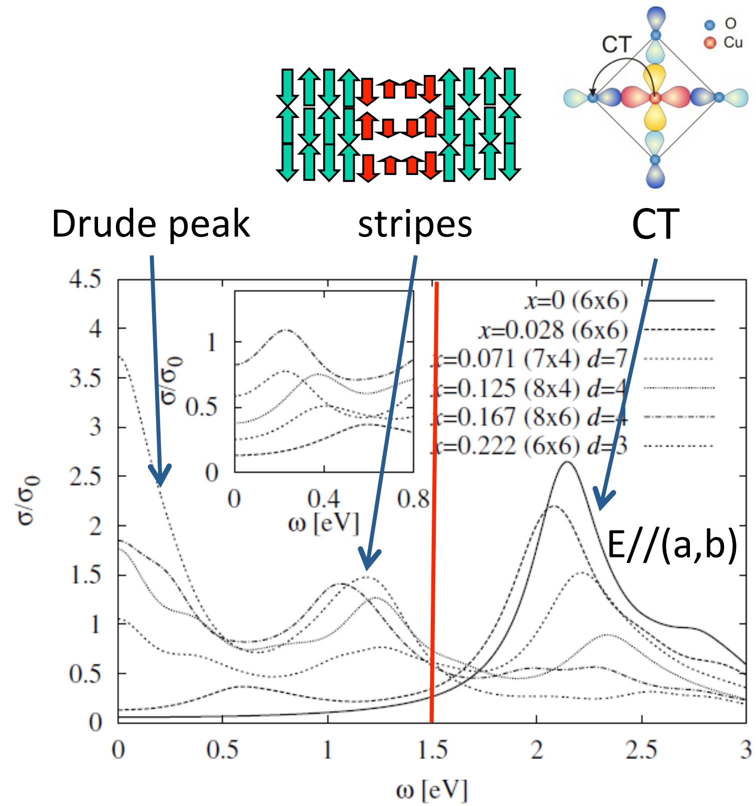


B. Mansart et al, PNAS 109 (2012)

Static optical properties of $La_{2-x}Sr_xCuO_4$, x=0.15



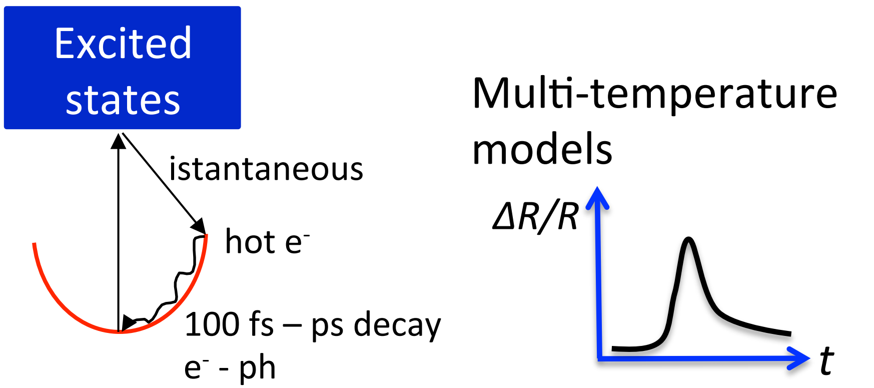




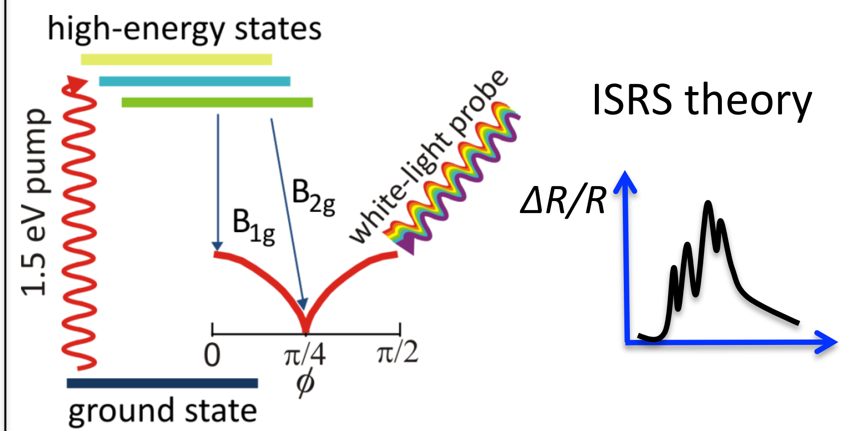
Lorenzana et al., PRL 90 (2003)

- Static optical properties isotropic in (a,b) plane
- Broadband measurements: access to the relation between high-energy excitations and superconducting condensate

Effect of laser excitation



S. Dal Conte et al
Science 335 (6076), 2012



Raman perturbation

Raman term
quadratic in E

H = H_{gs} + H_R

QPs close to Fermi

$$H_R = -\frac{1}{2}\mathbf{E}(t).\boldsymbol{\chi}(\omega).\mathbf{E}(t).$$

Rayleigh

Laser-induced term

$$\boldsymbol{\chi} = \boldsymbol{\chi}_0 + \frac{\partial \boldsymbol{\chi}}{\partial \xi}\xi.$$

$$H_R(t) = -\frac{1}{2}\mathbf{E}(t).\frac{\partial \boldsymbol{\chi}(\omega_L)}{\partial \xi}.\mathbf{E}(t)\hat{\xi} = -F(t)\hat{\xi}$$

Generalization for charge fluctuations

$$H_R = \sum_X v_X(t)\hat{N}_X \qquad v_X(t) = -\frac{1}{2}\mathbf{E}(t).\frac{\partial \boldsymbol{\chi}(\omega_L)}{\partial N_X}.\mathbf{E}(t).$$

Charge fluctuations
and their symmetries

$$X = A_{1g}, B_{1g}, B_{2g}, .$$

$$\hat{N}_X = \sum_{i\sigma} f^X_{\mathbf{k}} c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma},$$

$$f^{B_{1g}}_{\mathbf{k}} = \frac{1}{2}[\cos(k_x a) - \cos(k_y a)],$$

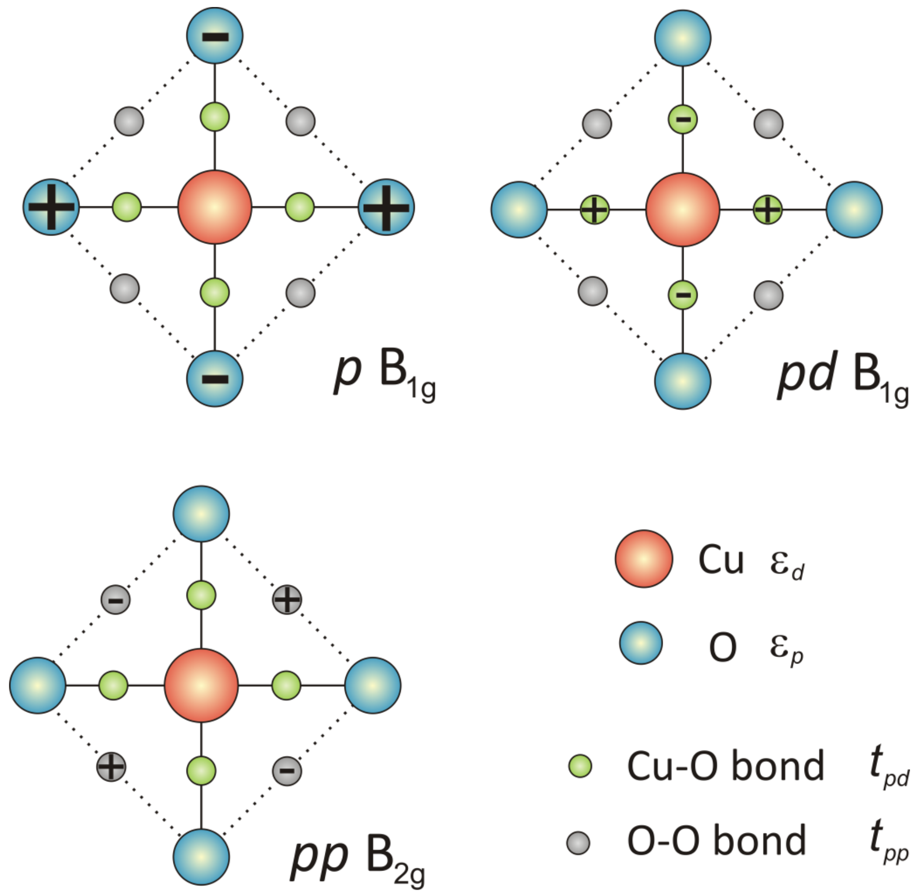
Coherent generation of elementary excitations: charge fluctuations

$$\hat{N}_{yX} = \sum_{i\sigma} f_i^{yX} n_{i\sigma} + \sum_{<ij>} f_{ij}^{yX} (\gamma_{ij\sigma} + h.c.)$$

X=A_{1g}, B_{1g}…
y=p, pd…
f_{ij}=0, 1

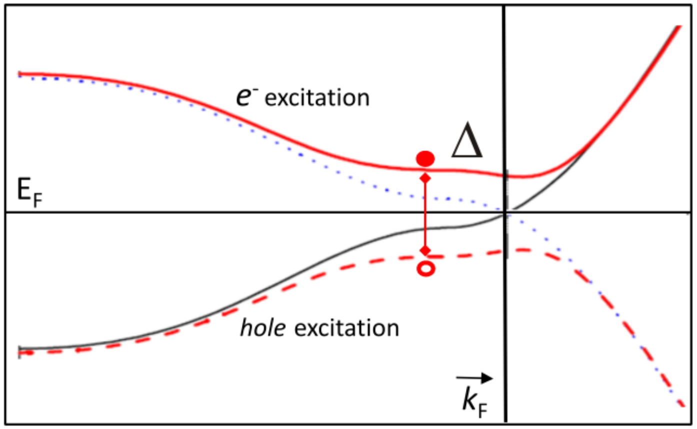
Bond operator:

$$\hat{\gamma}_{ij\sigma} \equiv \eta_{ij} c_{i\sigma}^{\dagger} c_{j\sigma}$$



Effect of laser excitation in a superconductor

$$H = H_{BCS} + H_R$$



Bogoliubon: superposition of an e⁻ - excitation and a hole-excitation in a SC

Excited state wavefunction

$$|\Psi(t)\rangle = |BCS\rangle + \sum_k \epsilon_k e^{-i2E_k t} \gamma^{+}_{k\uparrow} \gamma^{+}_{-k\downarrow} |BCS\rangle$$

$$E_k = \sqrt{(\epsilon_k - \mu)^2 + |\Delta_k|^2}$$

Pump: Prepare the system on a wave function that is the SC GS + a given charge-fluctuation

Describe the GS with PS formalism, the fluctuations induce precession of the PS.

$$H_{BCS} = -2 \underbrace{\sum_k \xi_k \sigma^z_k}_{\text{Ekin}} - \underbrace{\sum_{k,k'} (\sigma^x_k \sigma^x_{k'} + \sigma^y_k \sigma^y_{k'})}_{\text{CP}} + cste$$

$$\begin{cases} \sigma^x_k = \frac{1}{2}(b^\dagger_k + b_k) \\ \sigma^y_k = \frac{1}{2} i (b^\dagger_k - b_k) \\ \sigma^z_k = \frac{1}{2}(1 - 2 b^\dagger_k b_k) \end{cases} \qquad \begin{cases} b_k = c_{-k\downarrow} c_{k\uparrow} \\ b^\dagger_k = c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} \end{cases}$$

Anderson, Phys. Rev. 112 (1958)

BCS Hamiltonian → ferromagnetism problem

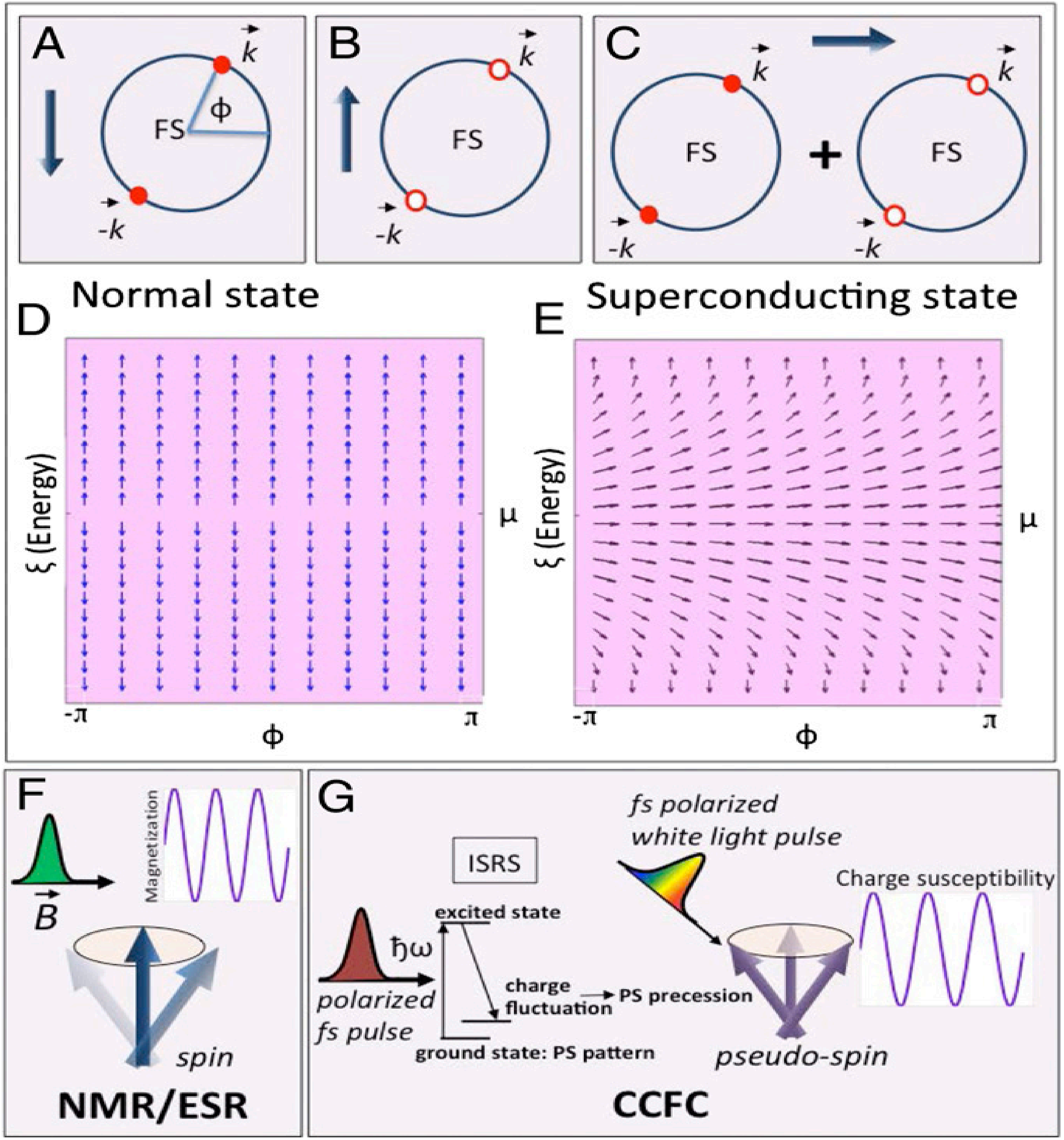
Pump effect → time-dependent impulsive potential

→ fictitious magnetic field δb_k which makes the pseudospins precessing

$$\hbar \frac{\partial \boldsymbol{\sigma}_{\mathbf{k}}}{\partial t} = -2[\mathbf{b}^0_{\mathbf{k}} + \delta \mathbf{b}_{\mathbf{k}}(t)] \times \boldsymbol{\sigma}_{\mathbf{k}}.$$

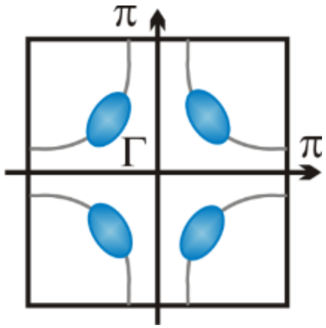
PS motion $2|\mathbf{b}^0_{\mathbf{k}}|/\hbar$, $|\mathbf{b}^0_{\mathbf{k}}| = \sqrt{\xi^2_{\mathbf{k}} + \Delta^2_{\mathbf{k}}}$ Angular freq.

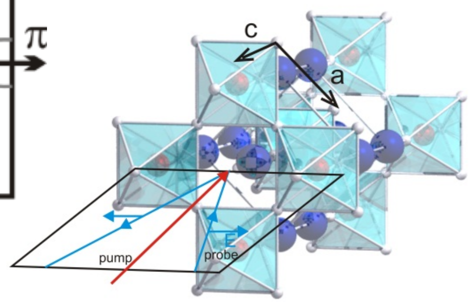
Effect of laser excitation in a superconductor



B. Mansart, et al.
PNAS **110** 4539 (2013).

Transient A_{1g}+B_{2g} response



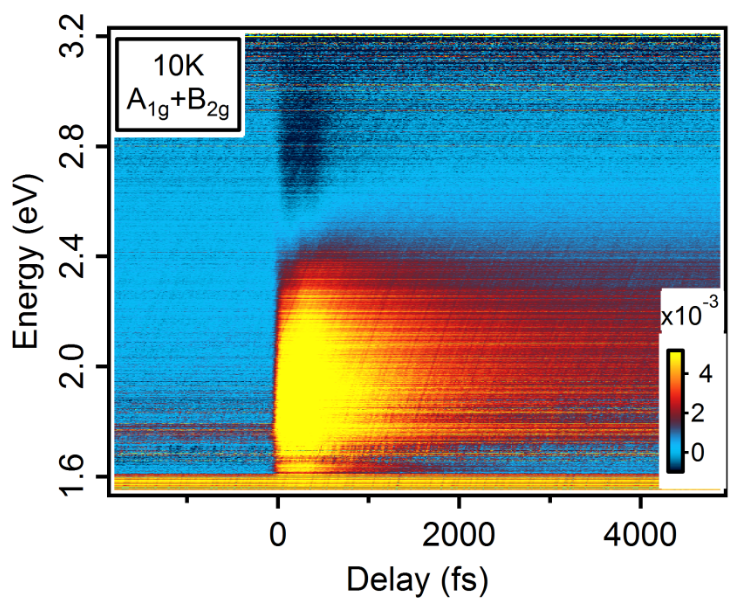


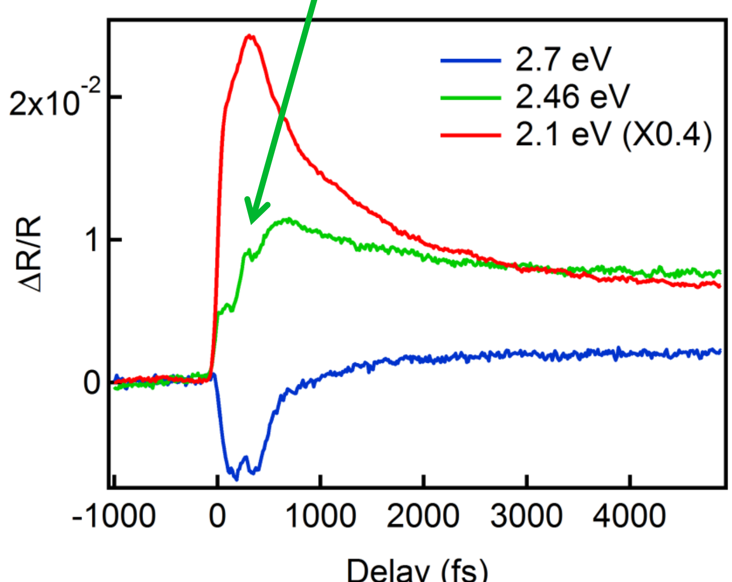
E_{pump}//(110), E_{probe}//(110), k//001
F ~ 300 μJ/cm^2

A_{1g}+B_{2g} Raman excitation

The signal changes sign as a function of wavelength

Observation of coherent oscillations





B. Mansart, et al.
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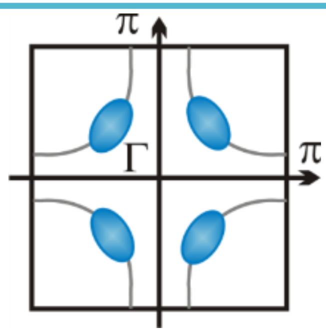
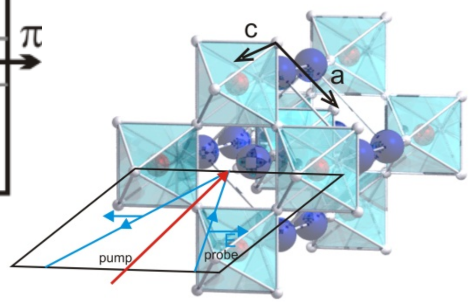
Transient $A_{1g}+B_{2g}$ response



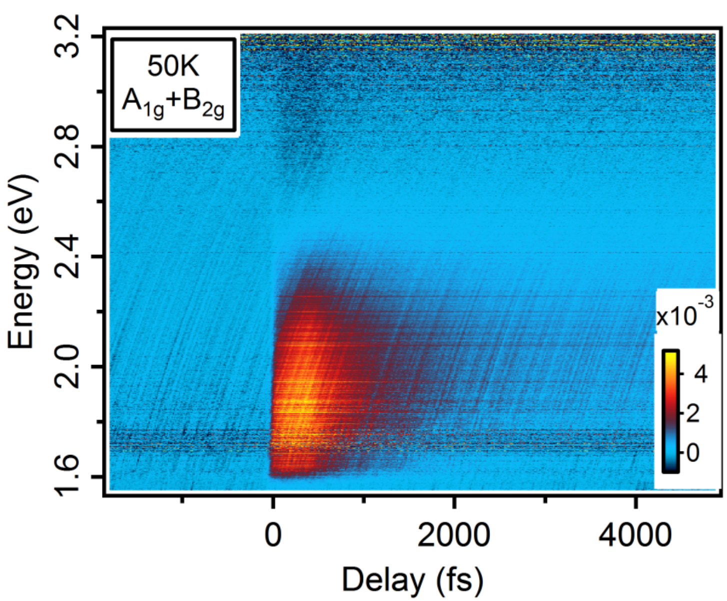


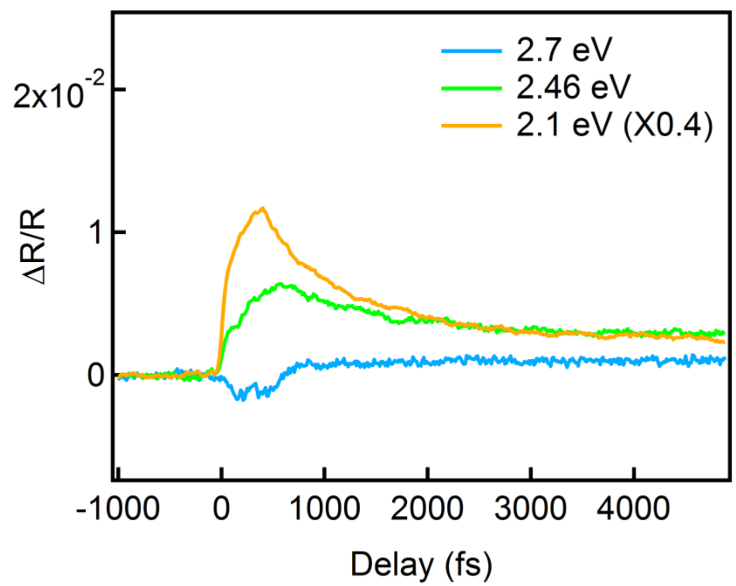
E_{pump}//(110), E_{probe}//(110), k//001
F ~ 300 μJ/cm^2

$A_{1g}+B_{2g}$ Raman excitation

The signal changes sign as a function of wavelength

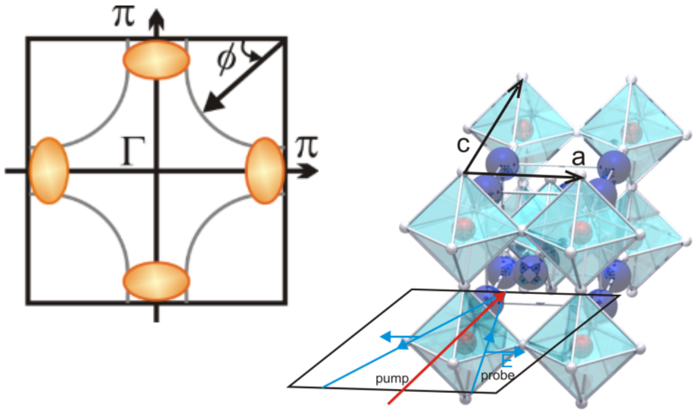
The coherent oscillations vanish above T_c





B. Mansart, et al.
PNAS **110** 4539 (2013).

Transient A_{1g}+B_{1g} response

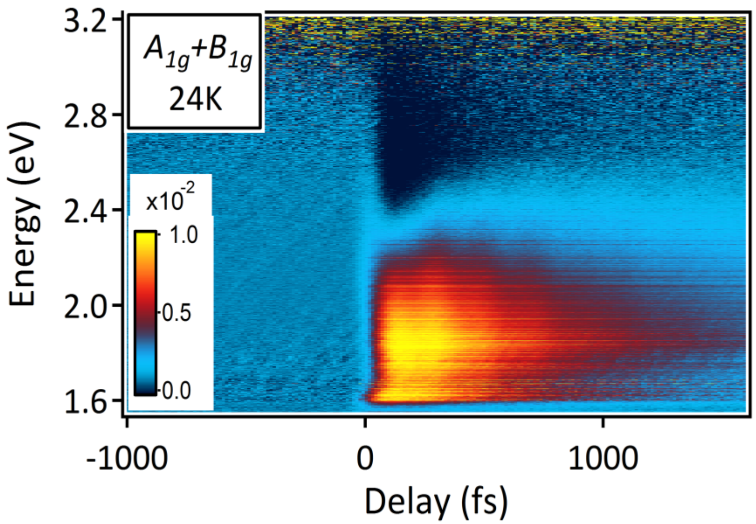


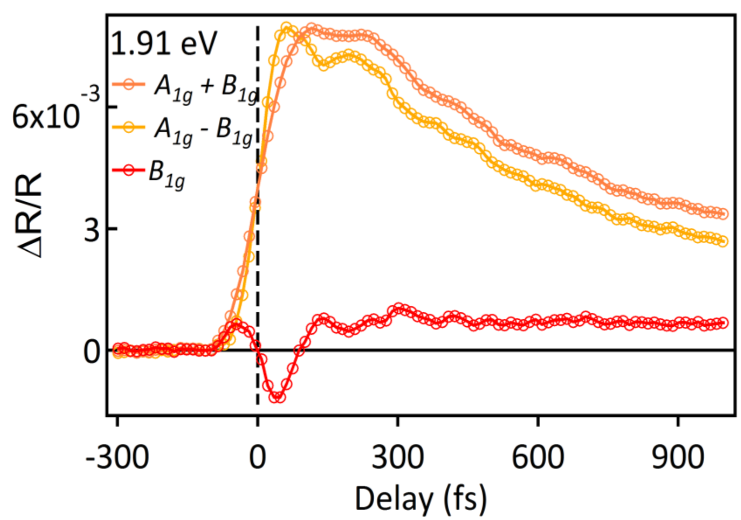
E_{pump}//(100), E_{probe}//(100), k//001
F ~ 300 μJ/cm²

A_{1g}+B_{1g} Raman excitation

The signal changes sign as a function of wavelength

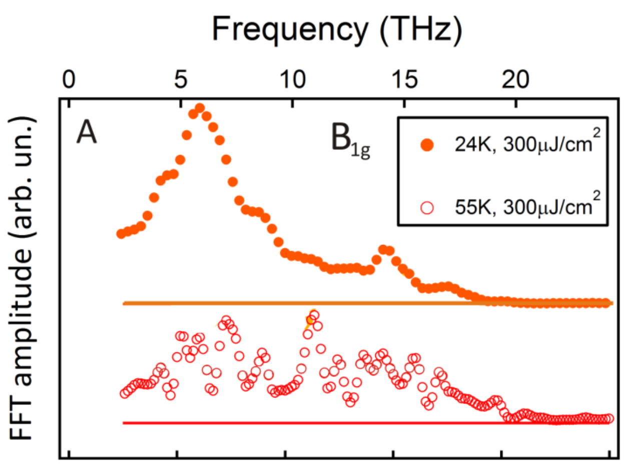
The coherent oscillations vanish above T_c

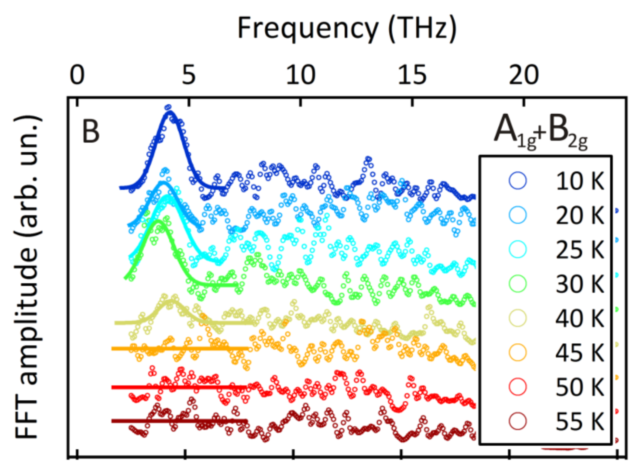




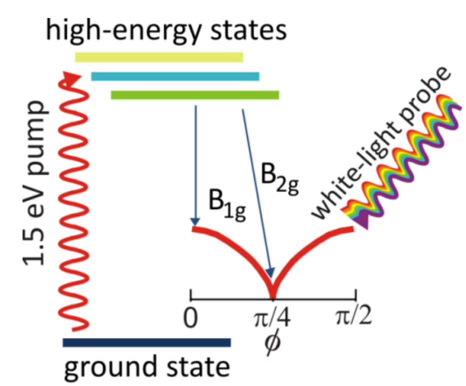
B. Mansart, et al.
PNAS **110** 4539 (2013).

Generating and probing coherent superconducting condensate oscillations





Ultrafast experiments compared to static Raman scattering



B. Mansart, et al.
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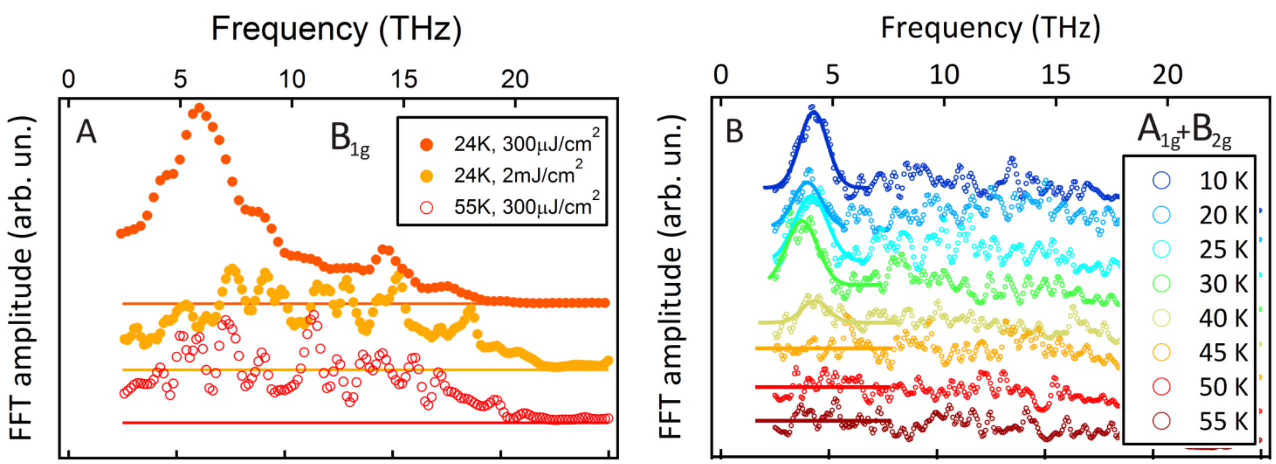
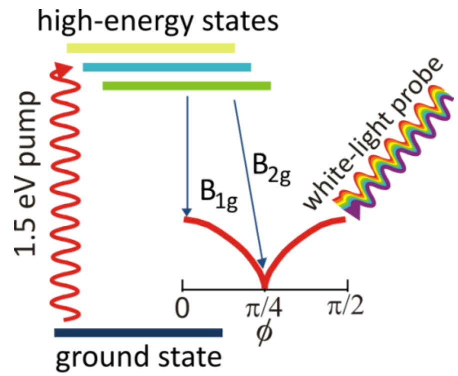
Generating and probing coherent superconducting condensate oscillations



Ultrafast experiments compared to static Raman scattering



B. Mansart, et al.
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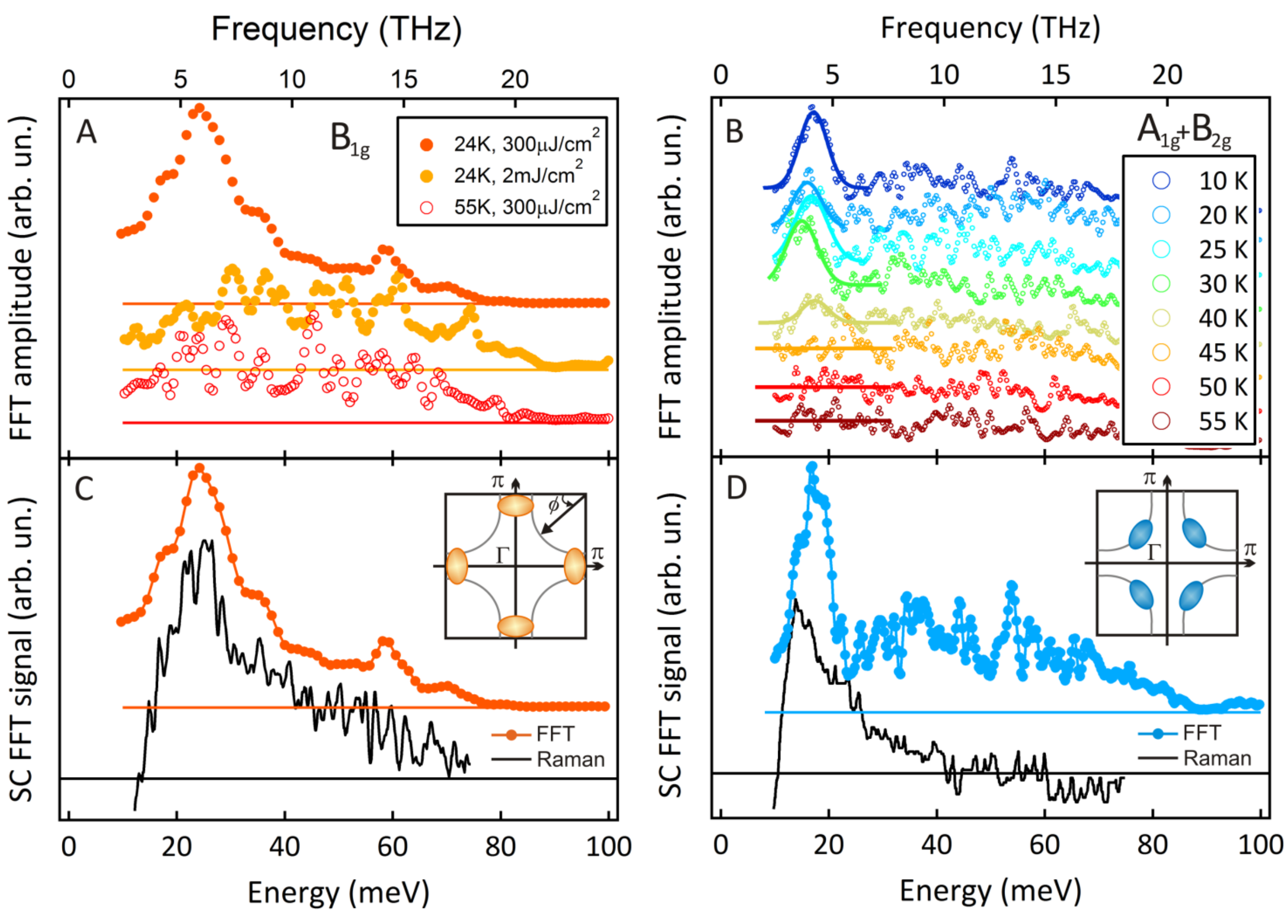
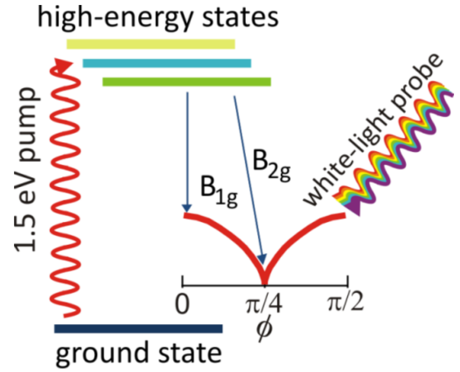
Generating and probing coherent superconducting condensate oscillations



Ultrafast experiments compared to static Raman scattering



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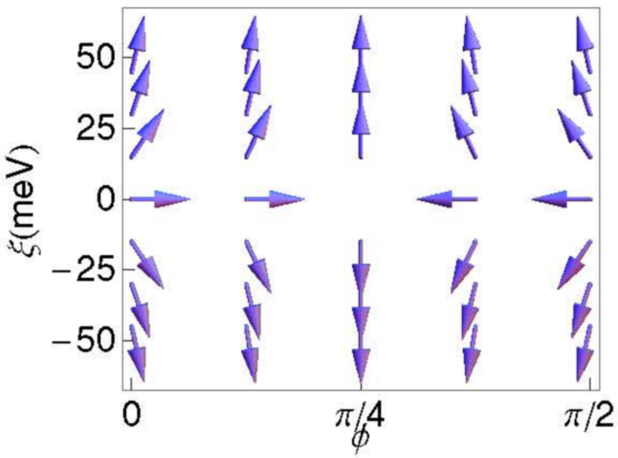
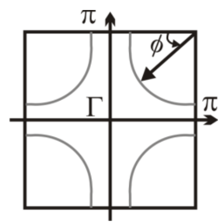
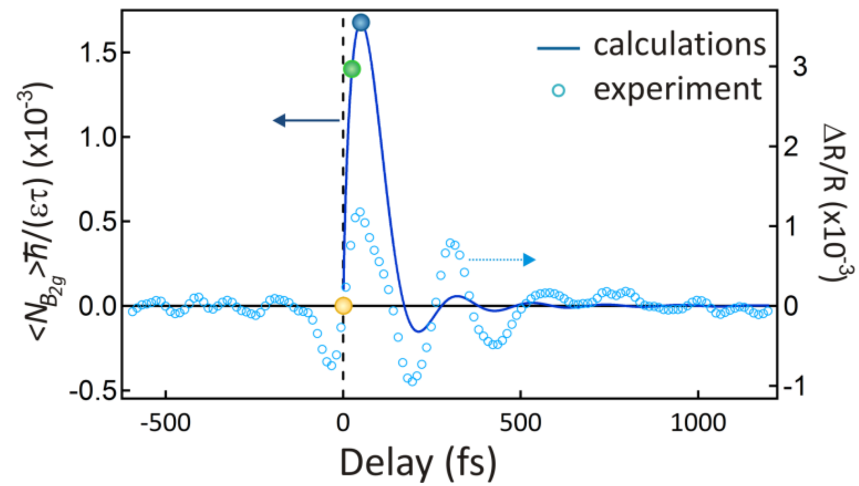
PNAS **110** 4539 (2013).

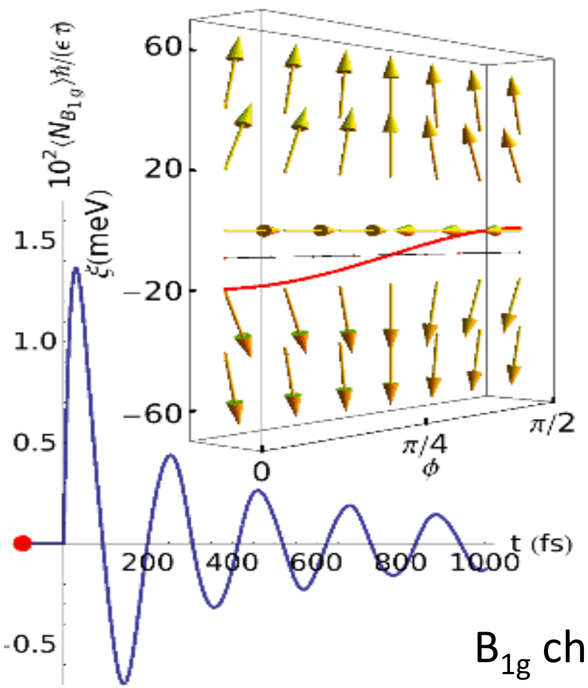
Coherent Charge Fluctuations: pseudospins description



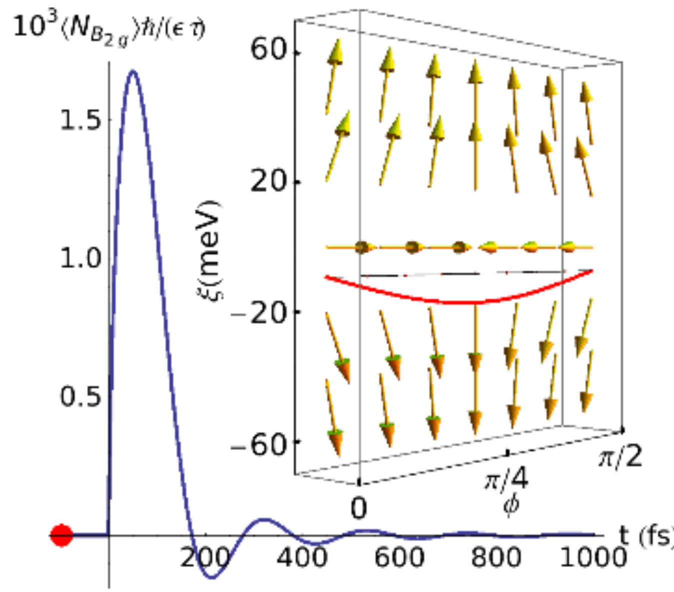


Ground state



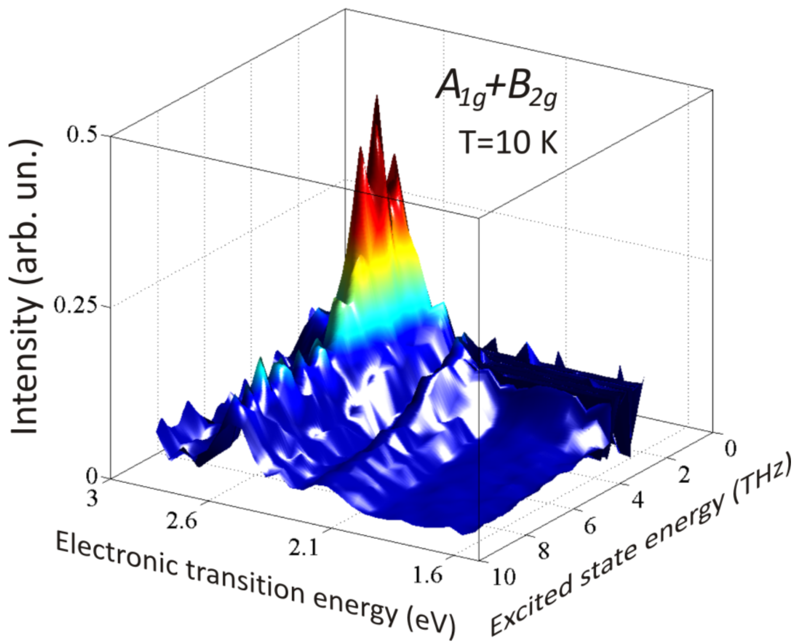


B_{1g} charge fluctuation



B_{2g} charge fluctuation

Superconducting condensate oscillations energy scale



Probe-energy dependence of B_{2g} fluctuation in frequency-domain

Clear resonance at 2.6 eV

↓

Charge-transfer energy of the parent compound

Evidence for non-retarded contribution to the pairing mechanism

B. Mansart, et al.
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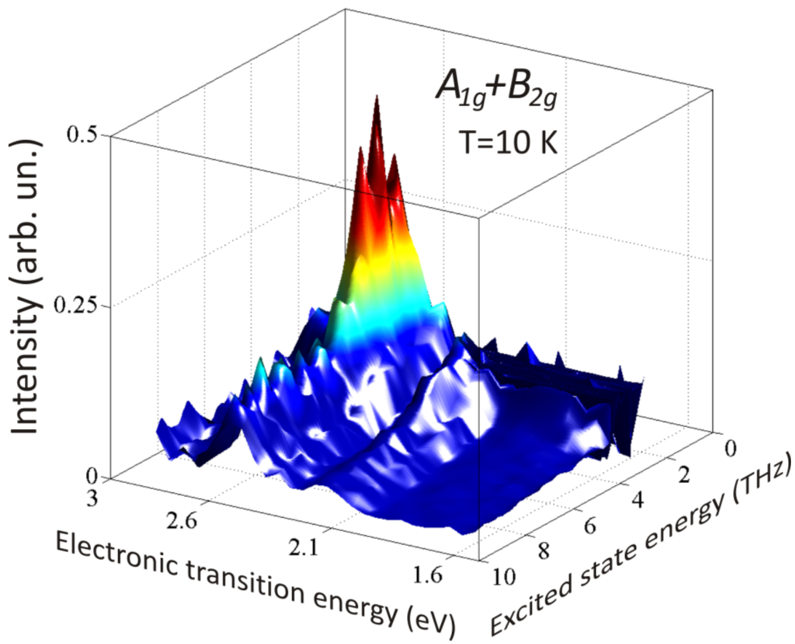
Conclusion



- Evidence for instantaneous pair-breaking by charge-transfer excitation
- New technique, Coherent Charge Fluctuation Spectroscopy, which has a high degree of specificity (similar to the isotope effect for BCS systems)
- Evidence for non-retarded (high energy) contribution to the pairing mechanism (Anderson scenario)
- Polarization, spectroscopy and time resolution are mandatory

B. Mansart, et al.
PNAS **110** 4539 (2013).

Broken symmetry and collective modes

- Below Tc (100K/250GeV) amplitude and phase fluctuations lead to well-defined collective excitations

Phase and amplitude fluctuations are decoupled

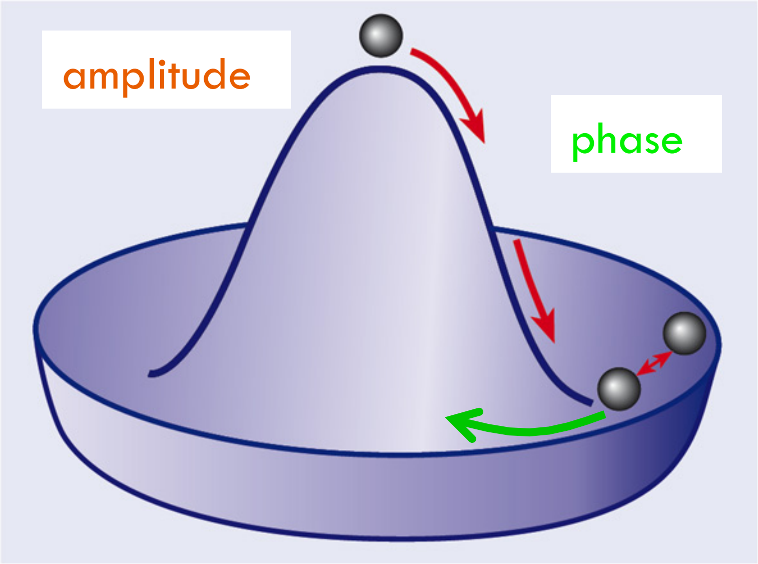
massive: $\omega^2 = m^2 + (v_s q)^2$

Higgs

$$\left(|\bar{\Delta}| + \delta|\bar{\Delta}|(x)\right) e^{i\bar{\vartheta}}$$

$$|\bar{\Delta}|\, e^{i\bar{\vartheta}}$$

$$|\bar{\Delta}|\, e^{i\bar{\vartheta} + i\delta\vartheta(x)}$$



Goldstone

For a neutral superconductor
massless: $\omega = v_s\, q$

Adapted from a slide by **Lara Benfatto**

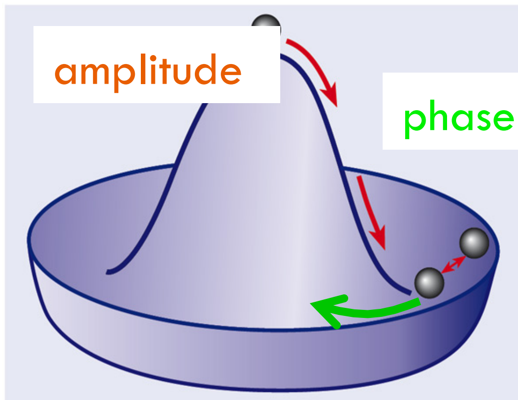
Anderson-Higgs mechanism

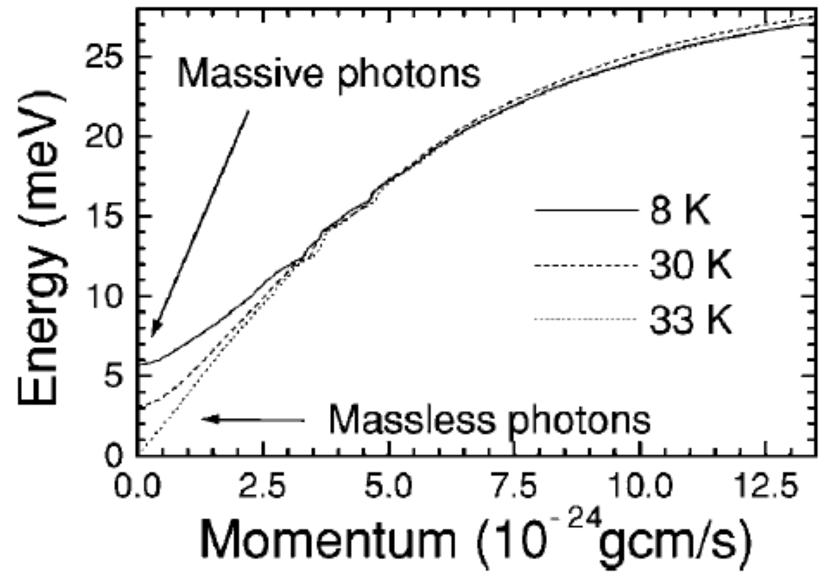
In a superconductor:

D. Van der Marel

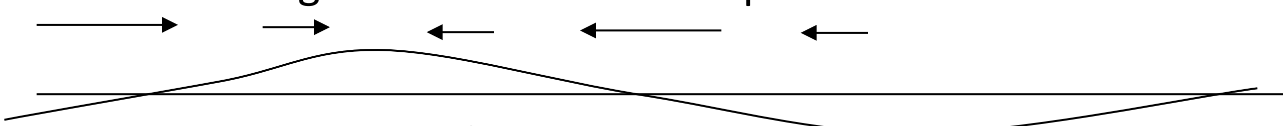
Journal of Superconductivity: Incorporating Novel Magnetism, Vol. 17, No. 5, October 2004 (© 2004)

$$j = \rho \frac{\hbar \nabla \theta}{m}$$





Phase and charge fluctuations are coupled.



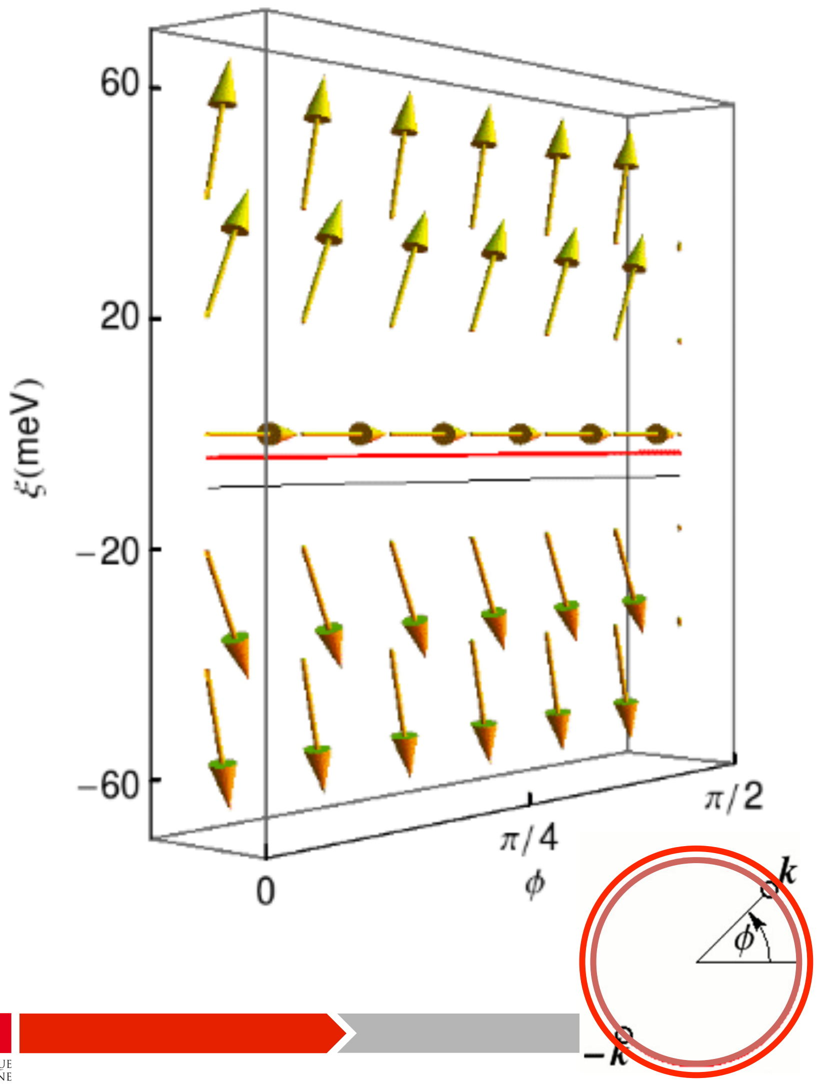
$$\nabla . j + \dot{\rho} = 0$$

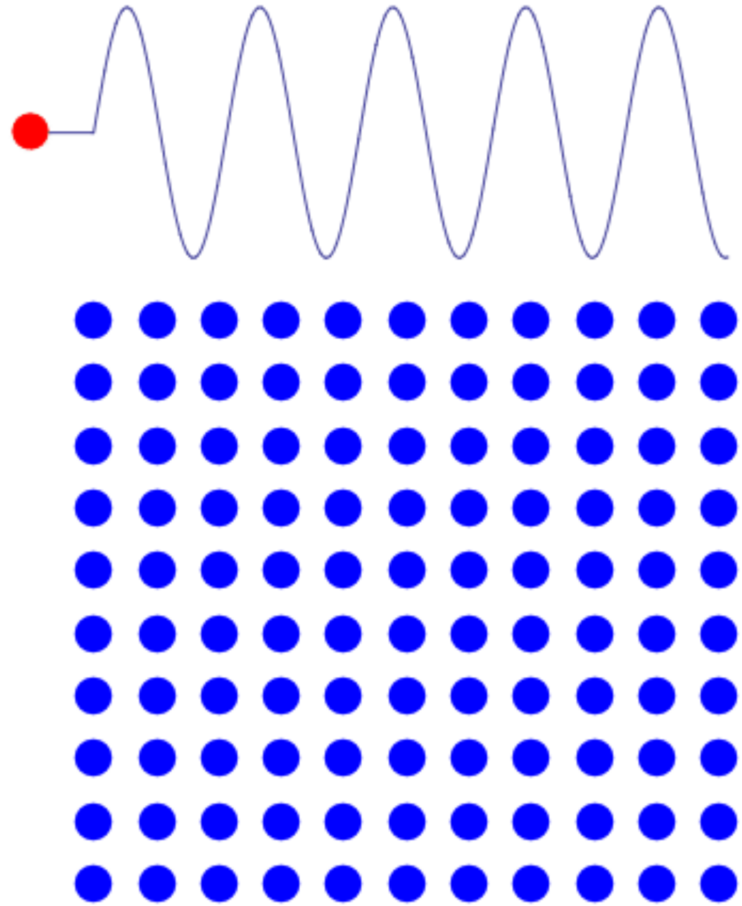
The Goldstone (sound) mode becomes a plasmon

Condensed Matter vs High Energy Physics

Amplitude mode	Higgs Boson	
Bogoliubov mode	Nambu-Goldstone	
Anderson mechanism	Higgs-mechanism (phase and amplitude coupled)	
plasmon	W particle	mediate
Neutral phase oscillations	Z particle	the weak interaction

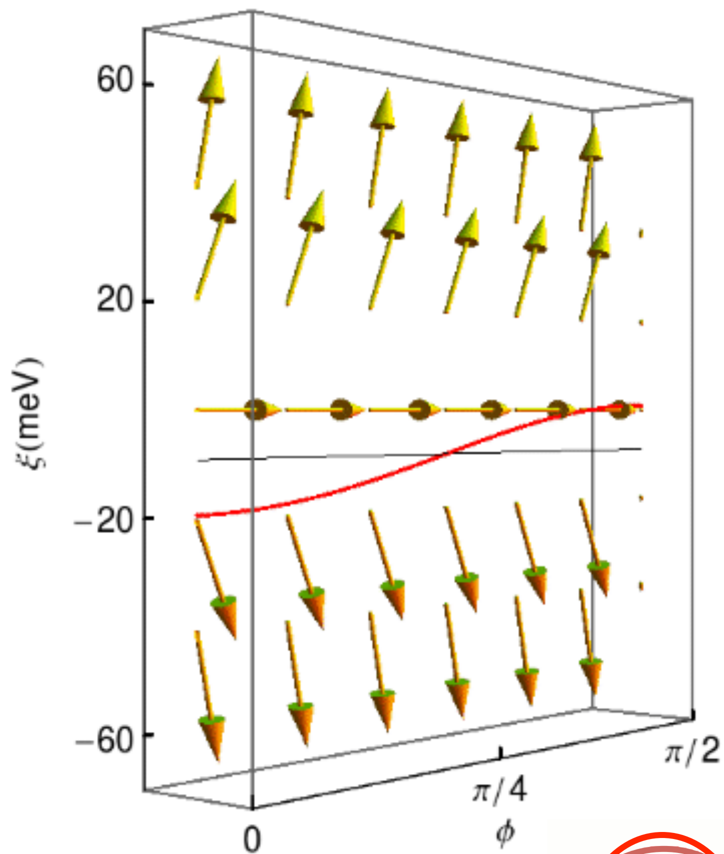
A_{1g} Bogoliubov or Nanbu-Goldstone mode made massive by Anderson-Higgs

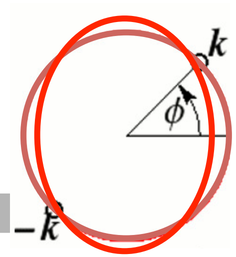


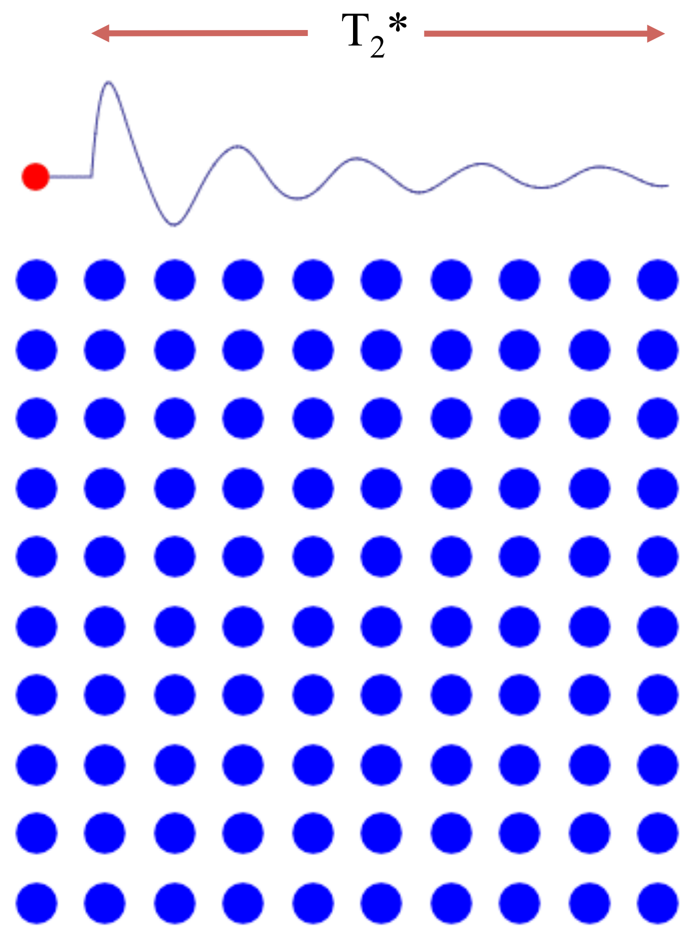


Courtesy of J. Lorenzana

B_{1g} Mode

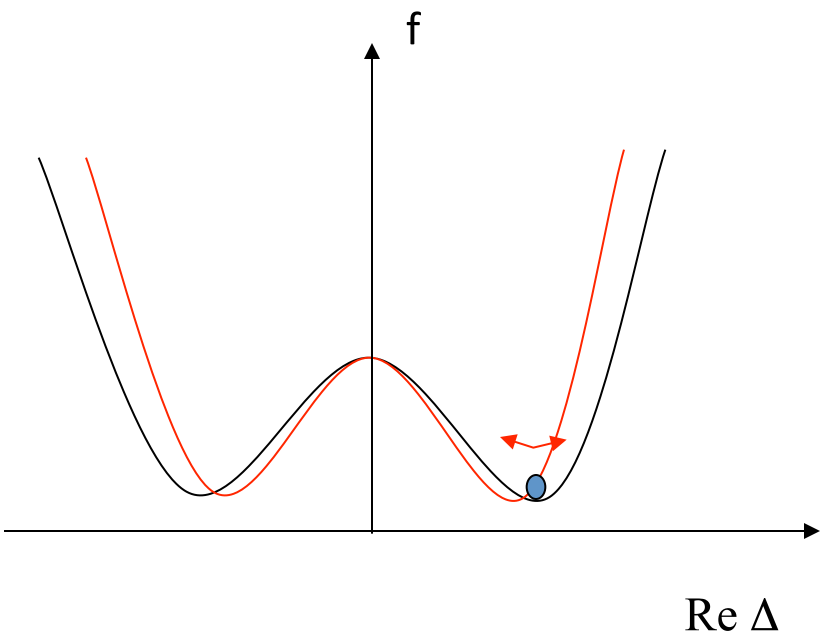


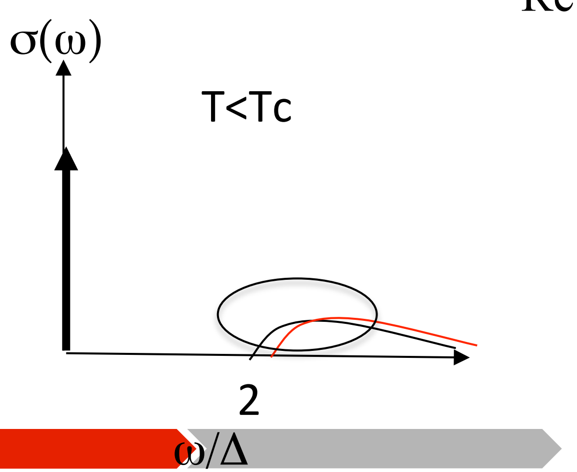




Courtesy of J. Lorenzana

How to excite the Higgs mode?





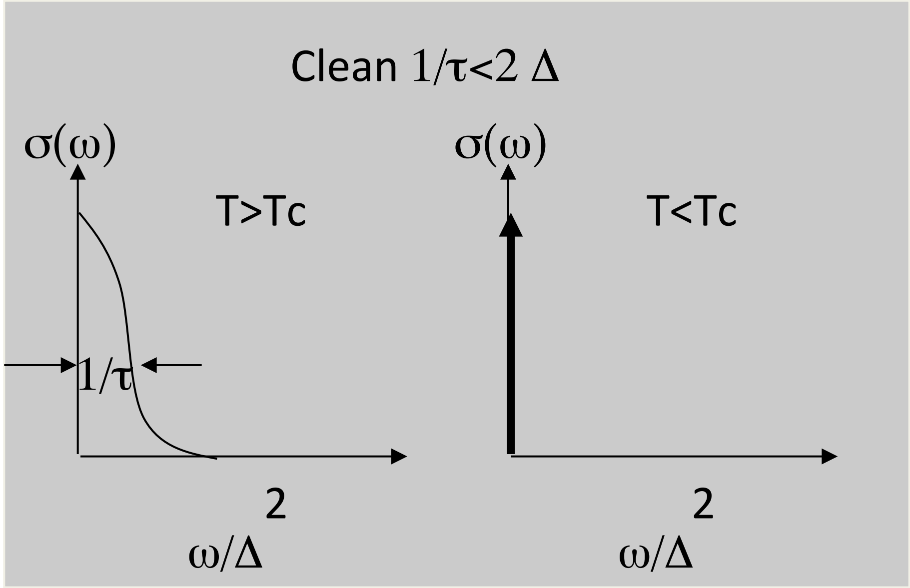
A transient change in the pairing interaction may excite the amplitude mode.

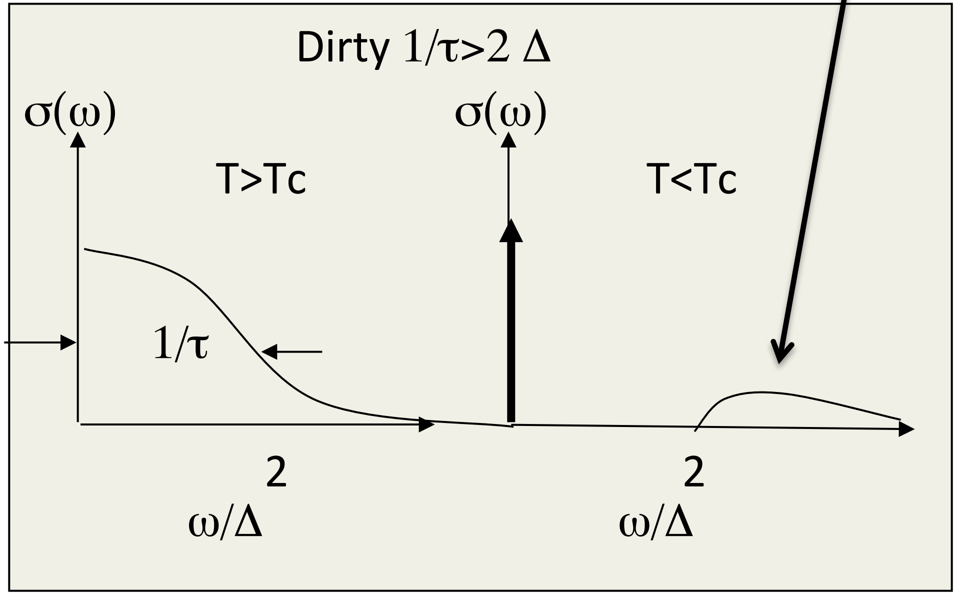
Also pumping in the gap region in a dirty superconductor may excite the Higgs in a similar way to a Raman process.

H= $\chi'(\omega)\, E\, E\, \Delta$

Higgs mechanism and TH spectroscopy

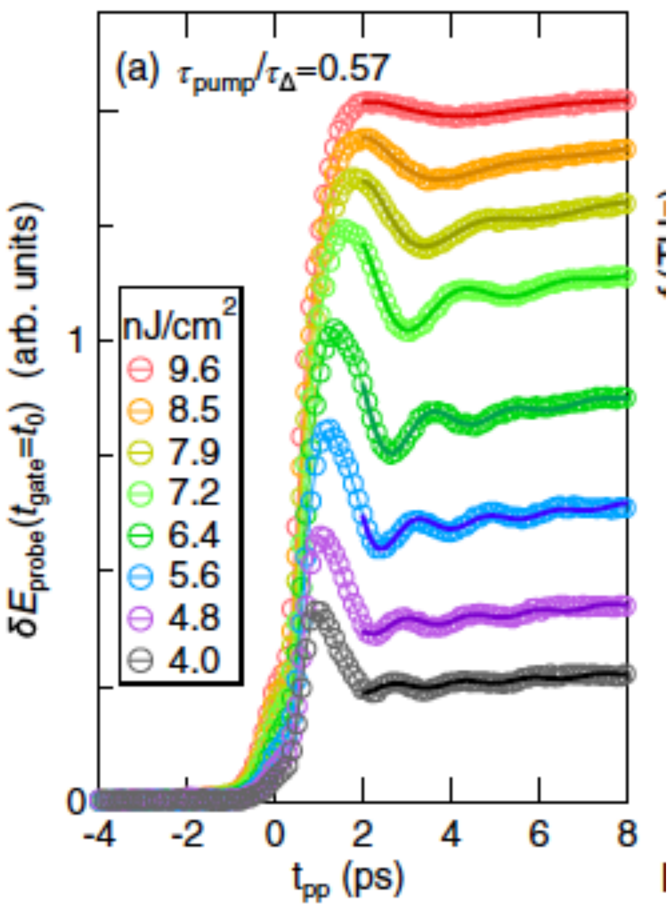
The condensate SW changes have
a direct impact on the spectrum at 2Δ





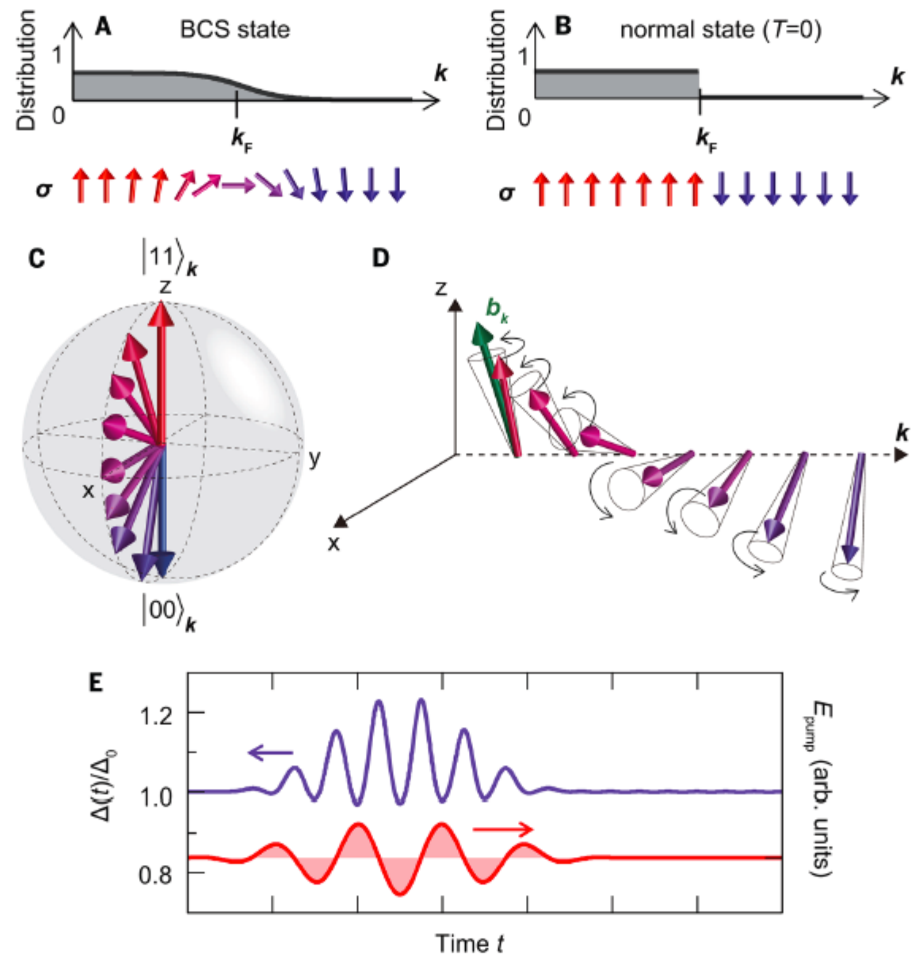
It was such a good idea......

Coherent condensate oscillations in a BCS material at 2Δ



Matsunaga et al. PRL 111, 057002 (2013)

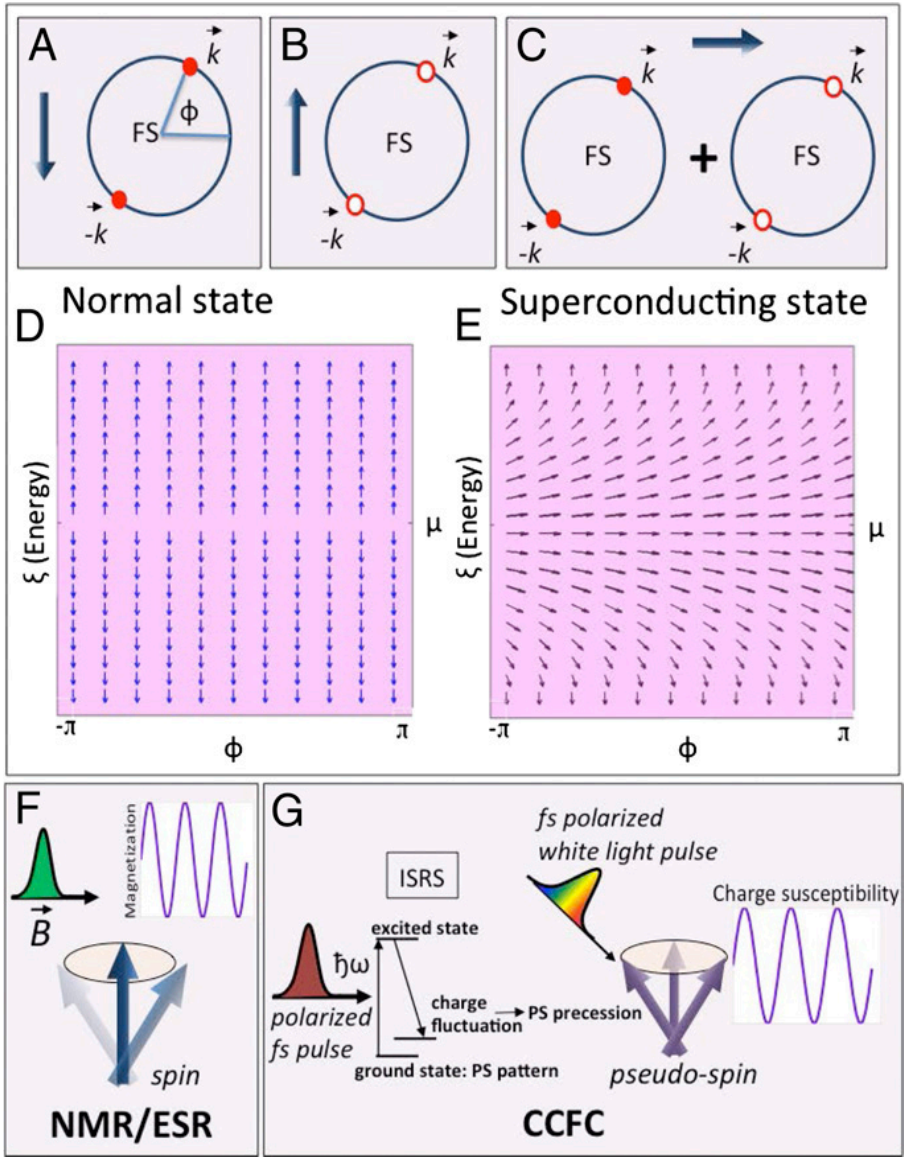
Light-induced collective pseudospin precession resonating with Higgs mode in a superconductor

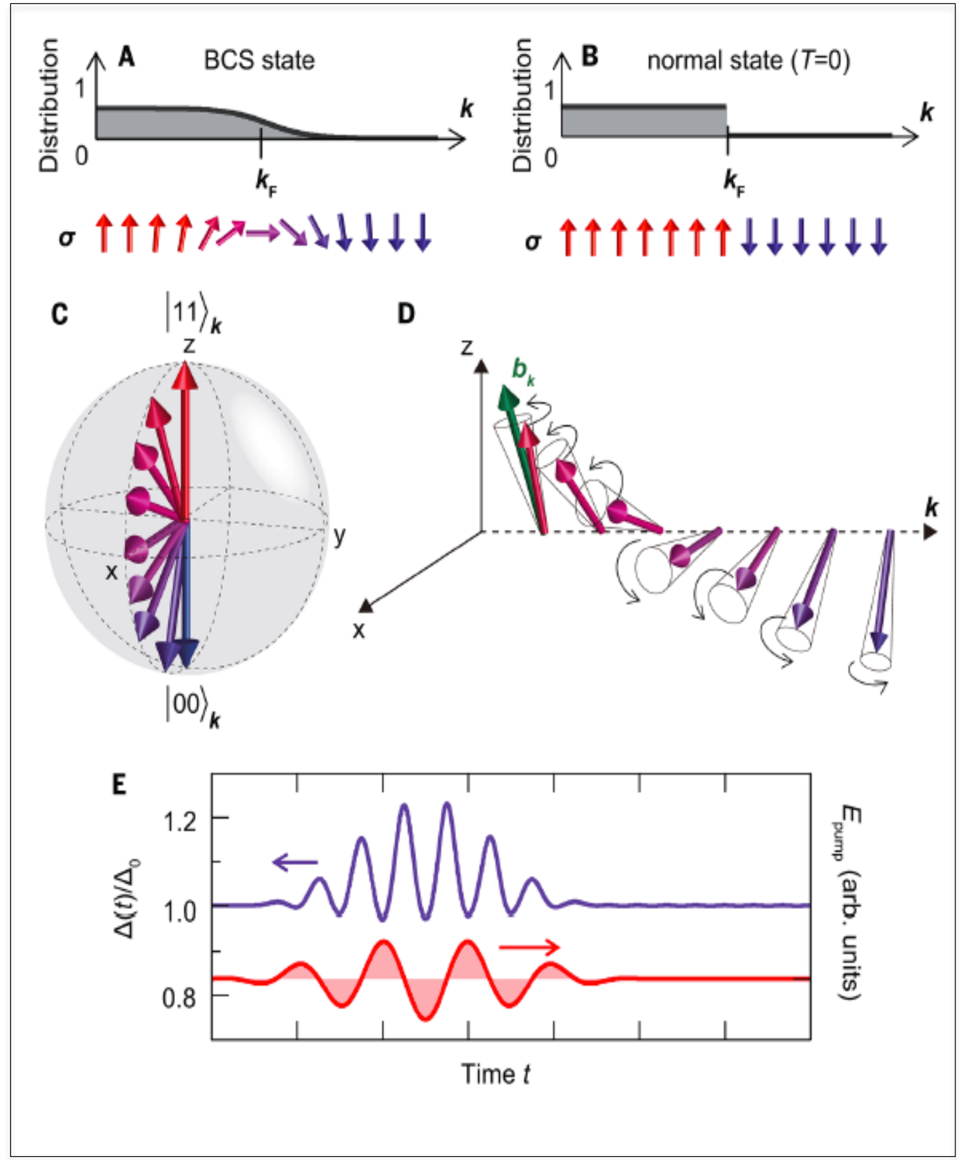


Science, 2014

B. Mansart, et al.
PNAS **110** 4539 (2013).
Arxiv 2011.....

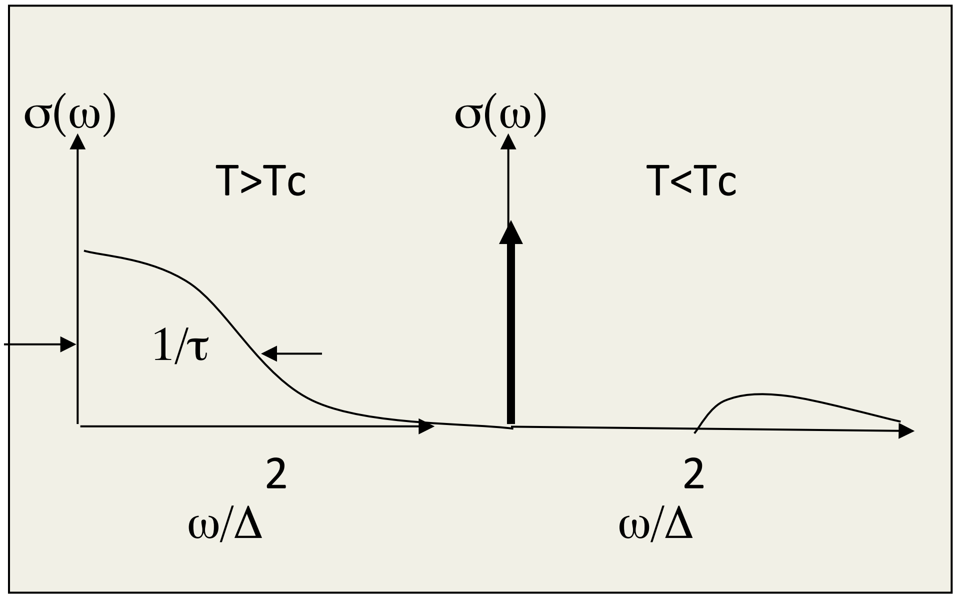
Matsunaga et al.,
Science, 2014



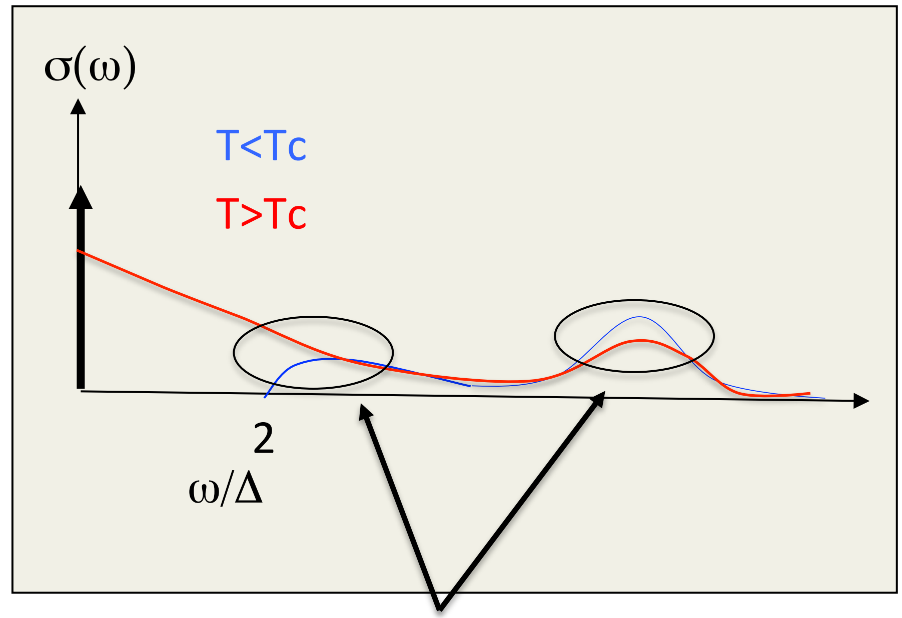


Higgs mechanism and visible light spectroscopy

In BCS dirty limit



In High Tcs



The superconducting condensate changes influence the SW at 2Δ AND at the CT energy

PHYSICAL REVIEW B 74, 024502 (2006)
PHYSICAL REVIEW B 74, 064510 (2006)

Disentangling the origin of the condensate's coherent oscillations is not as straightforward as It seems...........

Take-home messages

- Light excitation can excite coherent oscillations of the Cooper pairs condensate

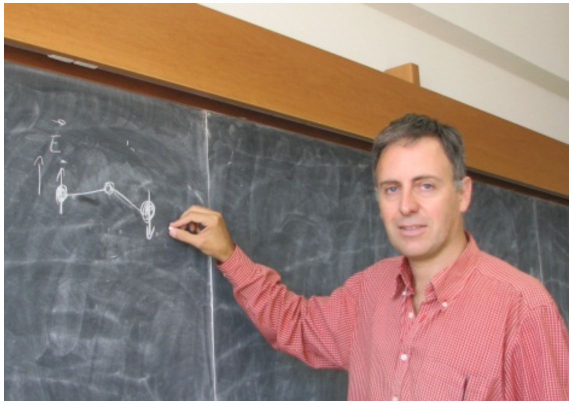
- These oscillations resonate at the CT energy (High-energy scale, suggestive of RVB type of pairing mechanism)

- These oscillations may be driven by Higgs modes (under debate)

Acknowledgments

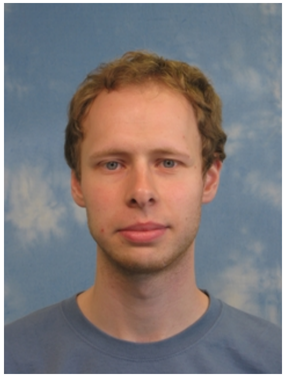
Dr. Barbara Mansart

Pr. Dr. José Lorenzana



Pr. Dr. Majed Chergui

Andreas Mann



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