非従来型超伝導体のヒッグスモード
Higgs mode in unconventional superconductors

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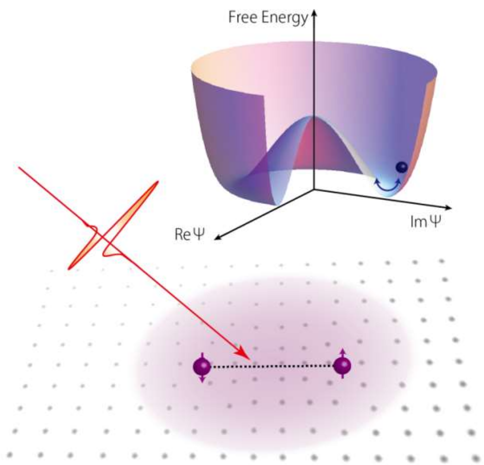

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Outline

(1) Introduction to Higgs mode and
Higgs mode in isotropic pairing(s-wave)
superconductor (NbN)

(2) Higgs mode in anisotropic pairing (d-wave)
High-Tc superconductor ($Bi_2Sr_2CaCu_2O_x$)

(3) Higgs mode in multiband superconductor ($FeSe_{0.5}Te_{0.5}$)

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Particle Physics and BCS theory

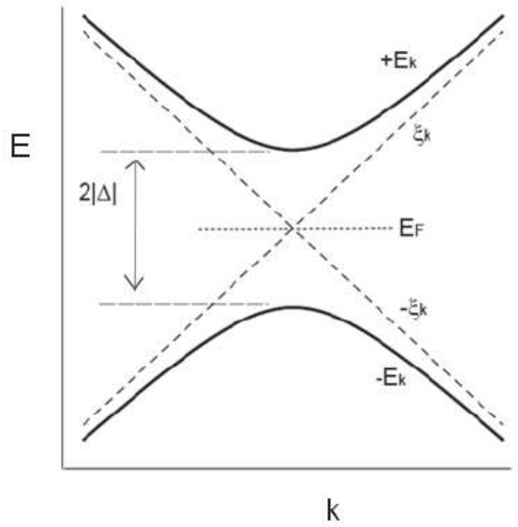
1957 BCS theory(Bardeen, Cooper & Schrieffer)
1960 Nambu's theory of SSB
1960-61 Nambu-Goldstone theorem
1963-66 Anderson-Higgs theory(Anderson, Higgs)
1967 Unified theory of electroweak interaction (Winberg& Salam)
2012 Discovery of Higgs boson(CERN LHC)

BCS theory

$$\Delta(\boldsymbol{k}) = -\sum_{\boldsymbol{k}'} V(\boldsymbol{k},\boldsymbol{k}')\langle c_{k'\uparrow} c_{-k'\downarrow}\rangle \neq 0$$

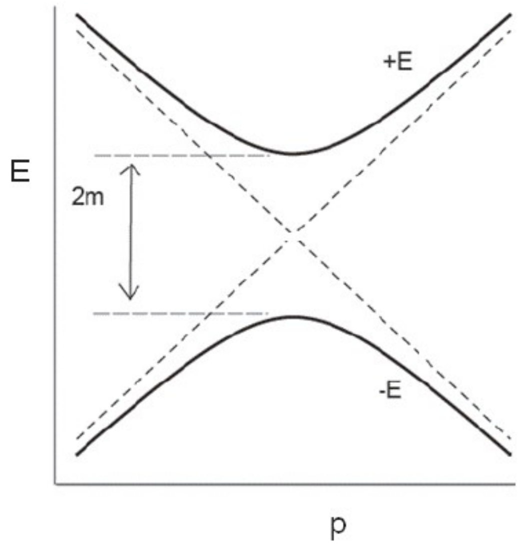
SSB of U(1) gauge symmetry

Energy dispersion of Quasiparticles in BCS



$$E(\boldsymbol{k}) = \sqrt{\xi(\boldsymbol{k})^2 + |\Delta(\boldsymbol{k})|^2}$$

Energy dispersion of particle and antiparticle

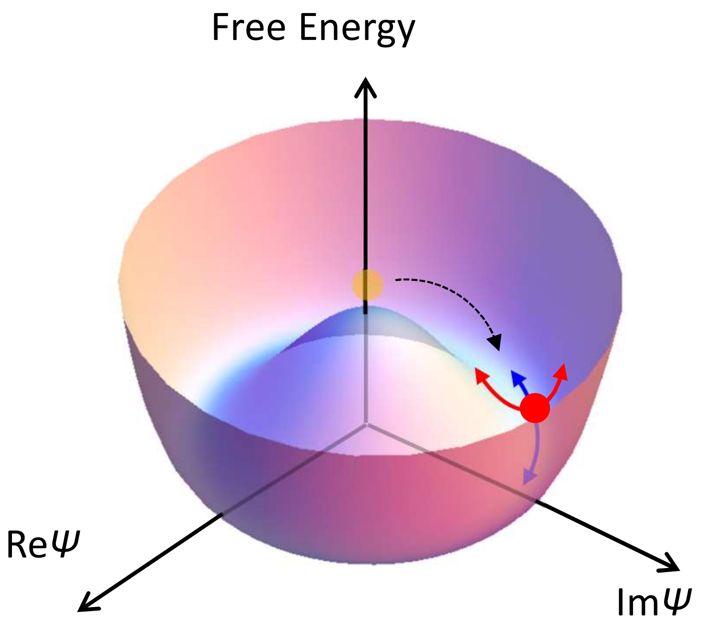


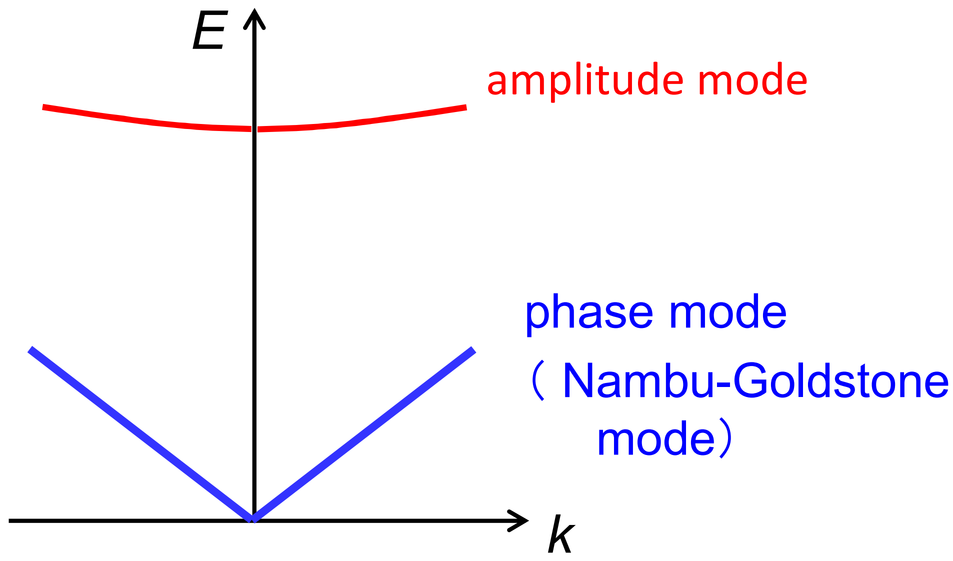
$$E(\boldsymbol{k}) = \pm\sqrt{k^2 + m^2}$$

青木秀夫: "南部理論と物性物理学" [日本物理学会誌、**64**, 80 (2009)]より

Spontaneous Symmetry breaking and collective modes

When spontaneous symmetry breaking occurs, massless and massive collective modes with respect to the order parameter appear.



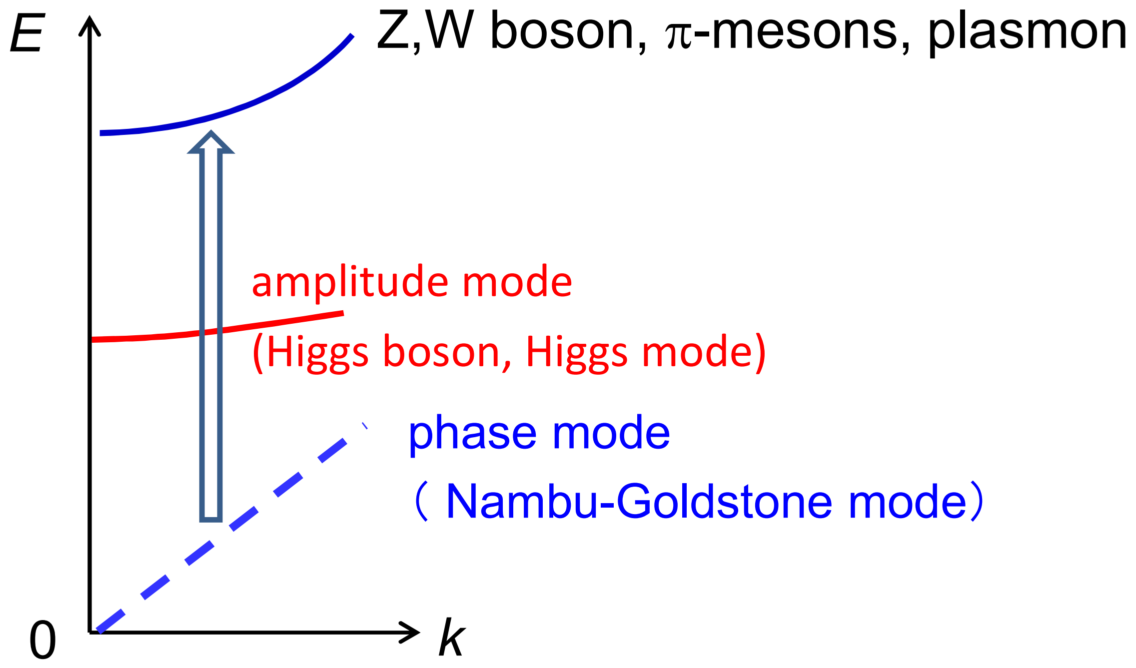


Anderson-Higgs mechanism

"Anderson-Higgs mechanism" or " Brout-Englert-Higgs mechanism"

"ABEGHHK'tH mechanism "

[for Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and 't Hooft]



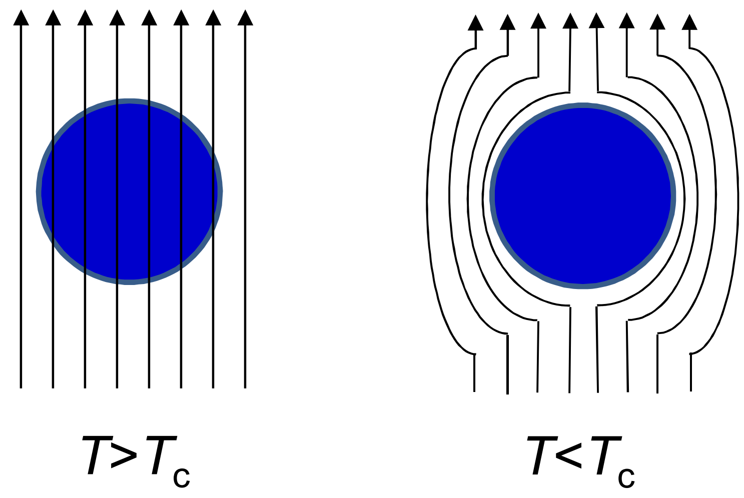
Massive gauge boson(photon) in superconductors

P. W. Anderson "Plasmons, Gauge Invariance, and Mass"
Phys. Rev. 130, 439 (1963)

Longitudinal mode of photon couples with collective mode of electrons and shifts to the plasma frequency.

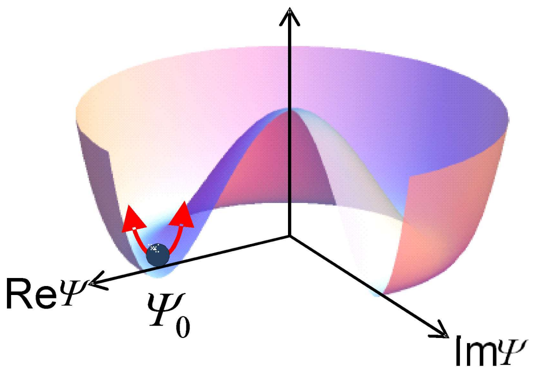
Meissner-Ochsenfeld effect 1933

$$\nabla^2 B = \frac{B}{\lambda^2}$$



Transverse mode of gauge boson (photon) is also massive in superconductors.

Scalar field theory of the Anderson-Higgs mechanism



$$f[\Psi] = f_0 + a|\Psi(\boldsymbol{r})|^2 + \frac{b}{2}|\Psi(\boldsymbol{r})|^4 + \frac{1}{2m^*}|(-i\nabla - e^*\boldsymbol{A})\Psi(\boldsymbol{r})|^2$$

$$a < 0 \qquad \Psi(\mathrm{r}) = [\Psi_0 + \mathrm{H}(\mathrm{r})]e^{i\theta(\mathrm{r})}$$

$$f = -2aH^2 + \frac{1}{2m^*}(\nabla H)^2 + \frac{e^{*2}}{2m^*}\left(\boldsymbol{A} - \frac{1}{e^*}\nabla\theta\right)^{\mathbf{2}}(\Psi_0 + H)^2 + \cdots$$

Local gauge transformation $\quad \boldsymbol{A}' = \boldsymbol{A} - \nabla\theta/e^* \quad \boldsymbol{A}' \to \boldsymbol{A}$

$$f = -2aH^2 + \frac{1}{2m^*}(\nabla H)^2 + \frac{e^{*2}\Psi_0^2}{2m^*}\boldsymbol{A}^{\mathbf{2}} + \frac{e^{*2}\Psi_0}{m^*}\boldsymbol{A}^{\mathbf{2}}H + \cdots$$

massive amplitude mode massive gauge boson

Note that the phase degree of freedom is gone. "Gauge boson has eaten the N-G boson."

Quantum quench problem

Quenching the interaction U(t) much faster than

$\tau_\Delta \sim \hbar/\Delta$ （Δ:order parameter）

⇨ Emergence of order parameter oscillation (Higgs mode)

Theoretical studies for

dynamics of nonequilibrium BCS state after *nonadiabatic* excitation

Volkov *et al*., Sov. Phys. JETP 38, 1018 (1974).

Barankov *et al*., PRL 94, 160401 (2004).

Yuzbashyan *et al*., PRL 96, 230404 (2006).

Gurarie *et al*., PRL 103, 075301 (2009).

Podolsky, PRB84, 174522 (2011).

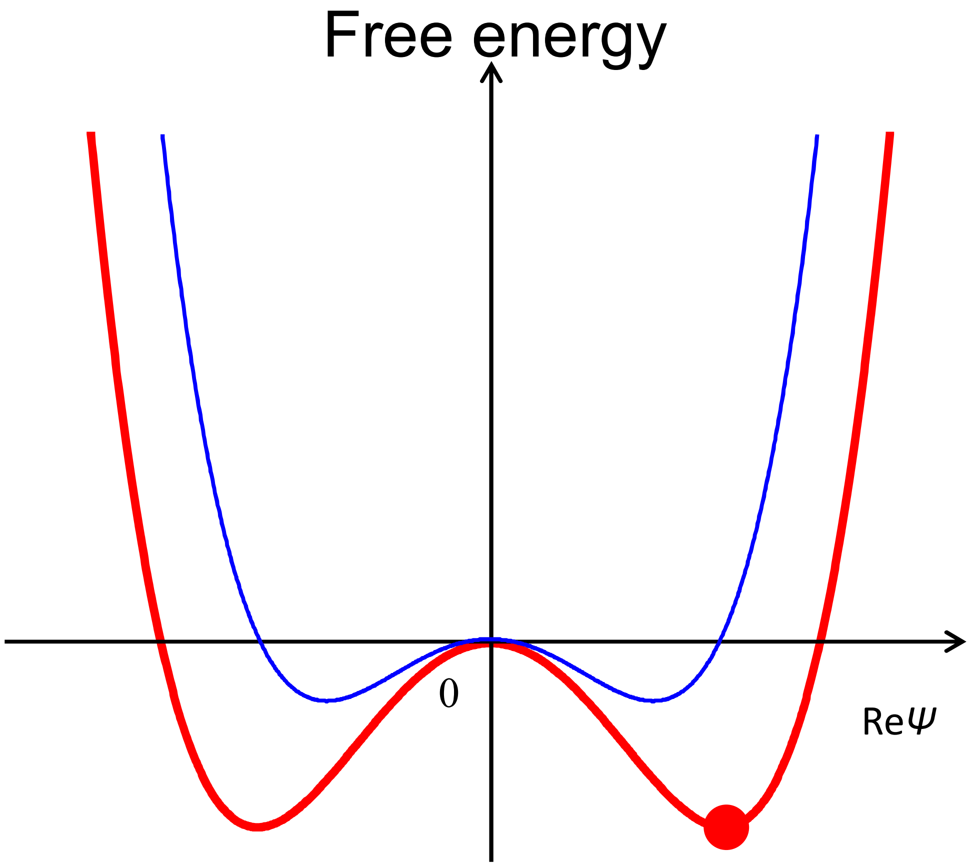
A. P. Schnyder et al., PRB84, 214513 (2011)

N. Tsuji et al., PRB 88,165115 (2013).

N. Tsuji *et al*., PRL 110, 136404 (2013).

⋮

$$\frac{\Delta(t)}{\Delta_\infty} = 1 + a\frac{\cos(2\Delta_\infty t + \pi/4)}{\sqrt{\Delta_\infty t}}$$



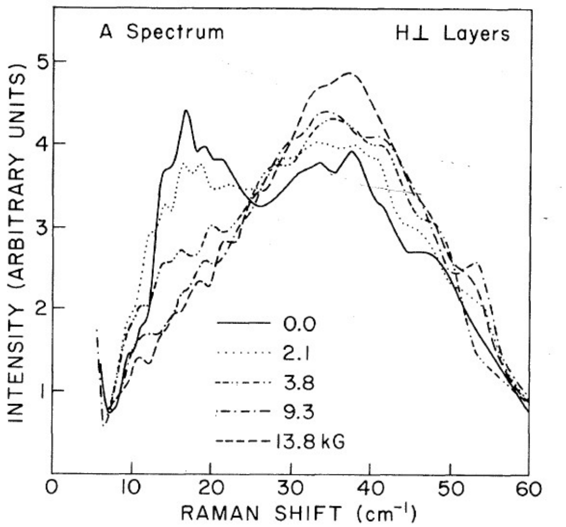
Higgs mode in superconductors

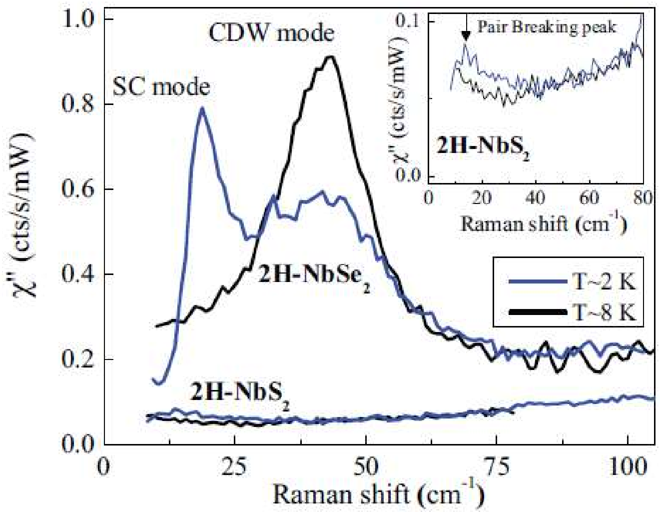
BCS-CDW coexistent compound $NbSe_2$

R. Sooryakumar and M. V. Klein, PRL 45, 660 (1980).

P.B. Littlewood and C. M. Varma, PRL 47, 811 (1982).

C. M. Varma, J. Low Temp. Phys.126, 901 (2002)





M.-A. Measson, et al., PRB 89, 060503 (2014).

Cf.) *p*-wave superfluid ^{3}He (not Higgs, but amplitude mode as there is no Higgs mechanism)

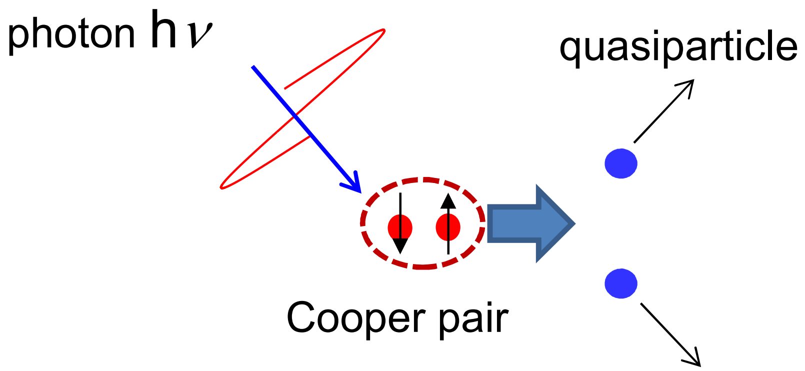
For a review, e.g., Lee, J. Phys. Chem. Sol. 59, 1682 (1998).

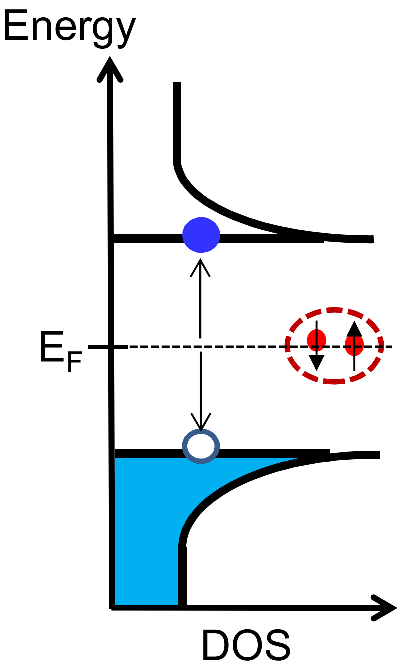
G. E. Volovik, and M. A. Zubkov, J. Low Temp. Phys.175, 486 (2014)

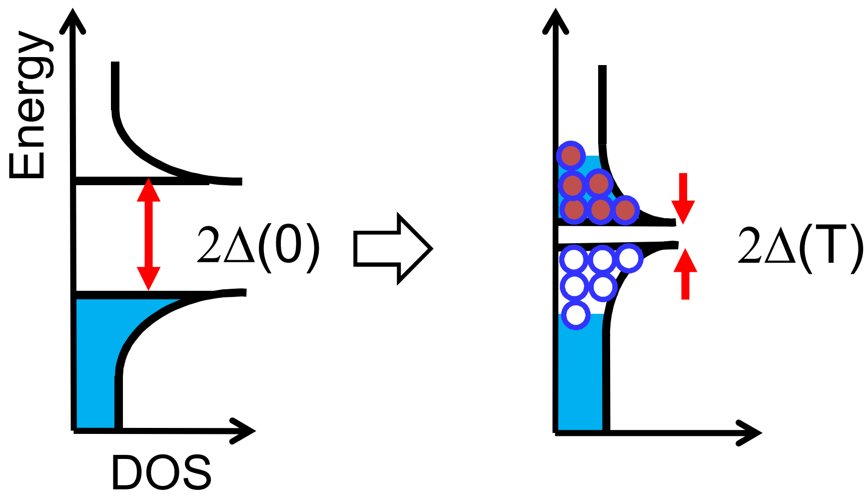
For a recent review: David Pekker and C. M. Varma, Ann. Rev. Cond. Matt. Phys.6, 269(2015).

Quench by the injection of quasiparticles

Quasiparticle injection by ultrafast optical pulse



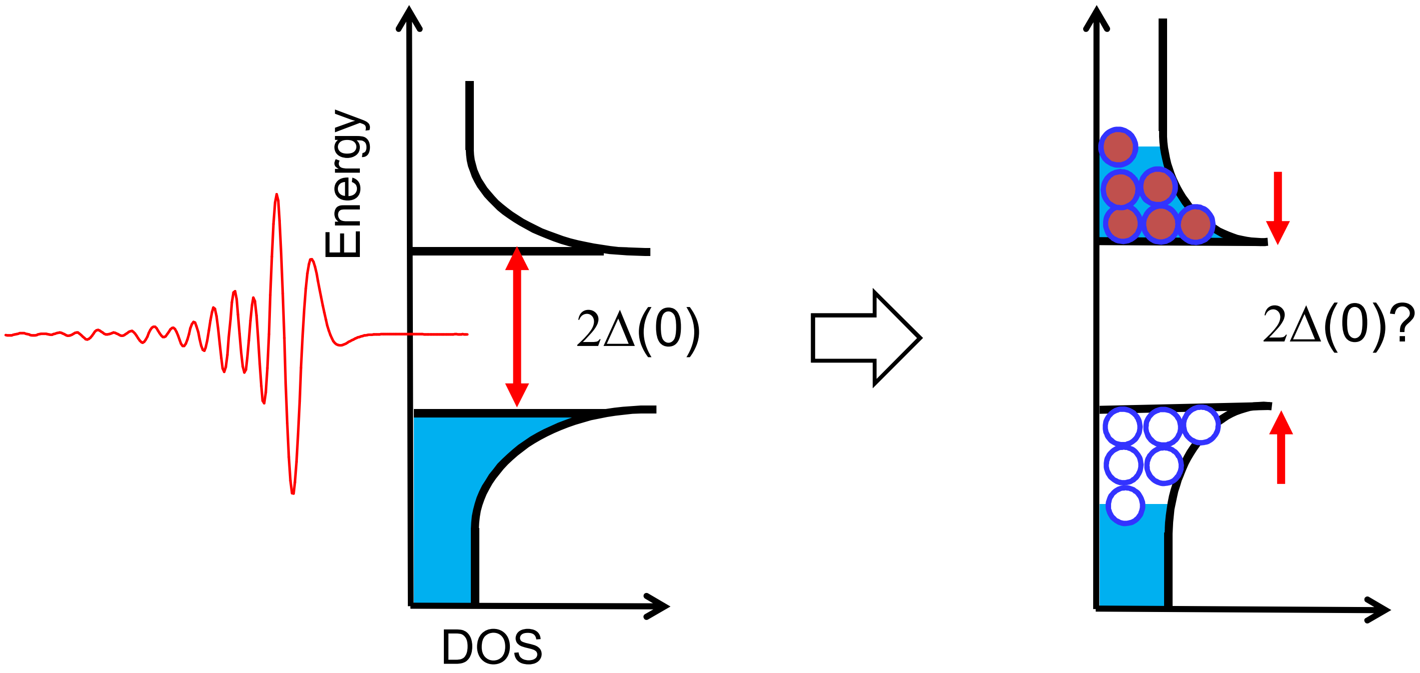




The gap (order parameter) is determined self-consistently with the quasiparticle distribution $f(\varepsilon)$ through the gap equation

$$\Delta = V \int_{\Delta}^{\hbar\omega_D} d\varepsilon \frac{\Delta}{\sqrt{\varepsilon^2 - \Delta^2}} [1 - 2f(\varepsilon)]$$

What happens if one create quasiparticel instantaneously, $\tau < \Delta^{-1}$



THz pump and THz probe experiment in NbN

Sample

$Nb_{0.8}Ti_{0.2}N$ film (12nm)/Quartz

T_C = 8.5 K,

2Δ(T=4 K) = 3.0 meV = 0.72 THz

response time : $\tau_\Delta = \Delta^{-1} \sim 2.8$ ps

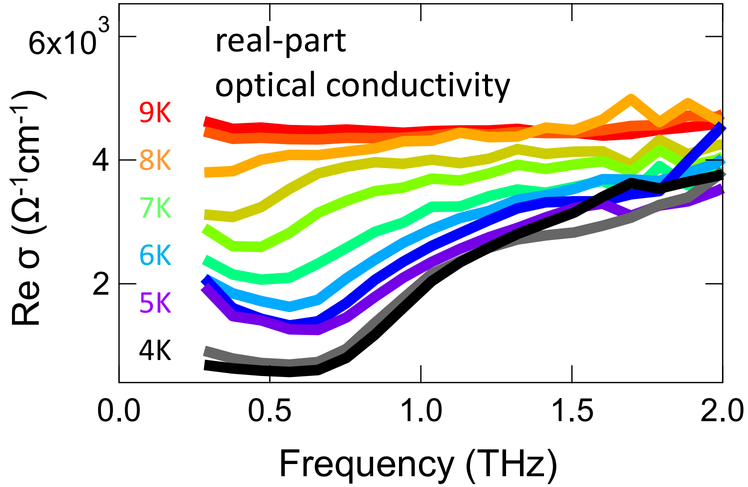
THz pump pulse

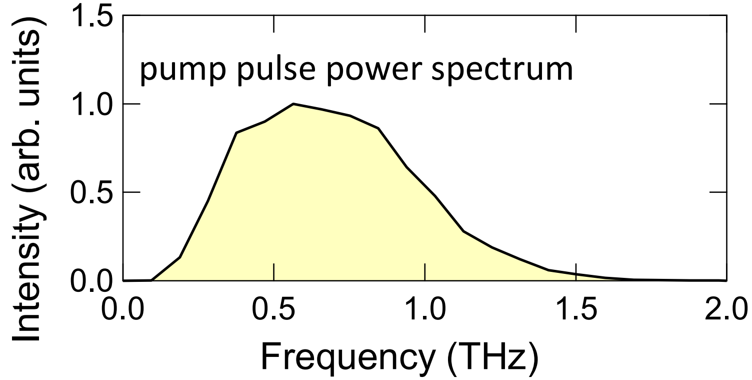
Center frequency 0.7THz∼2Δ

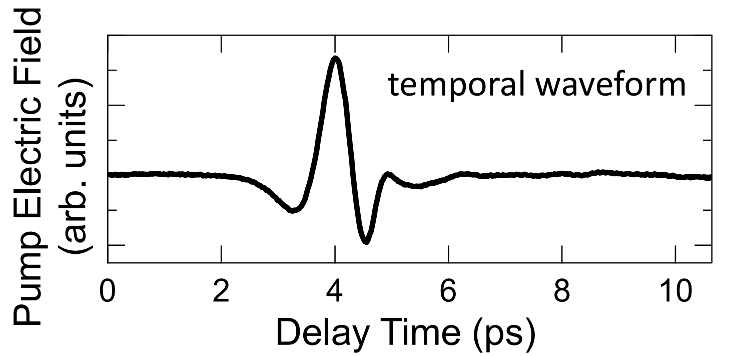
pulse width: $\tau_{pump} \sim 1.5$ ps

τ_{pump}/τ_Δ ∼0.57 < 1

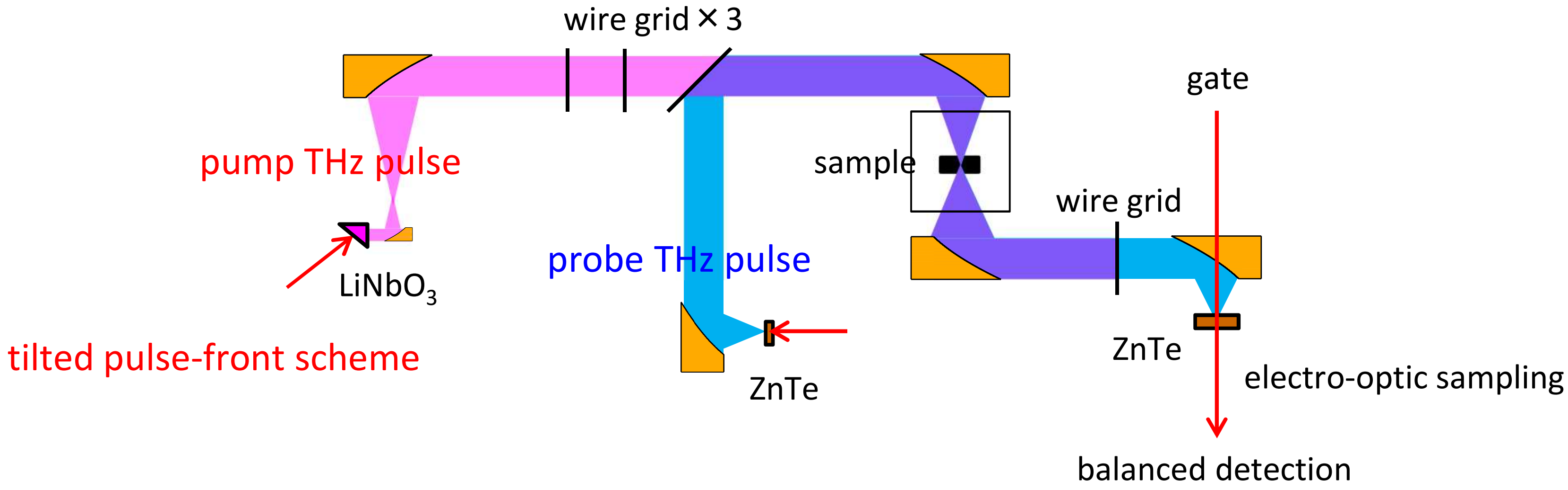
nonadiabatic excitation condition

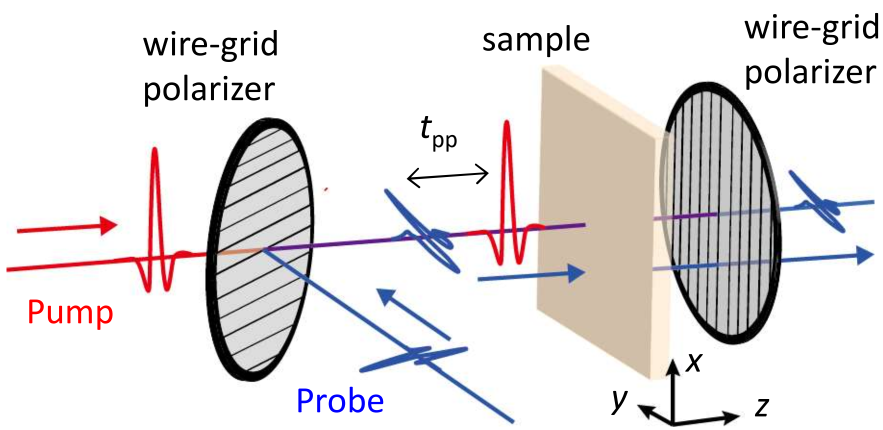






THz pump and THz probe experiment in NbN





Pump : $E_{pump}//x$

Probe : $E_{probe}//y$

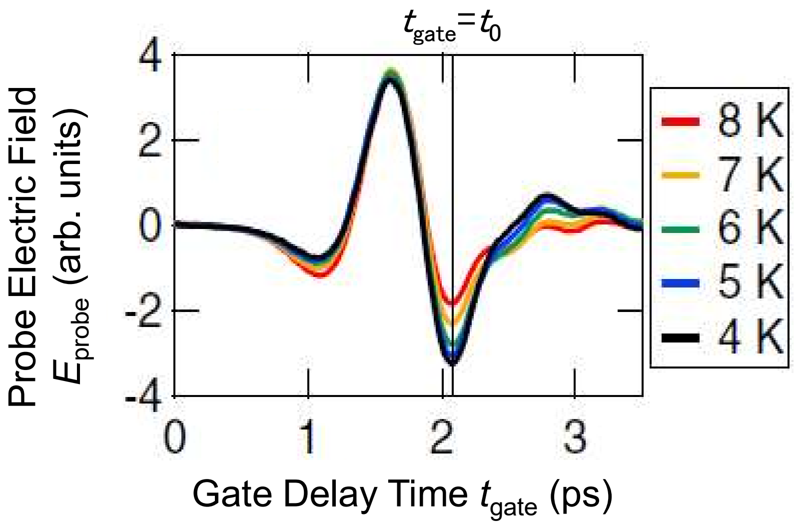
t_{pp}: pump-probe delay

Transmitted probe THz electric field:

Free space EO sampling

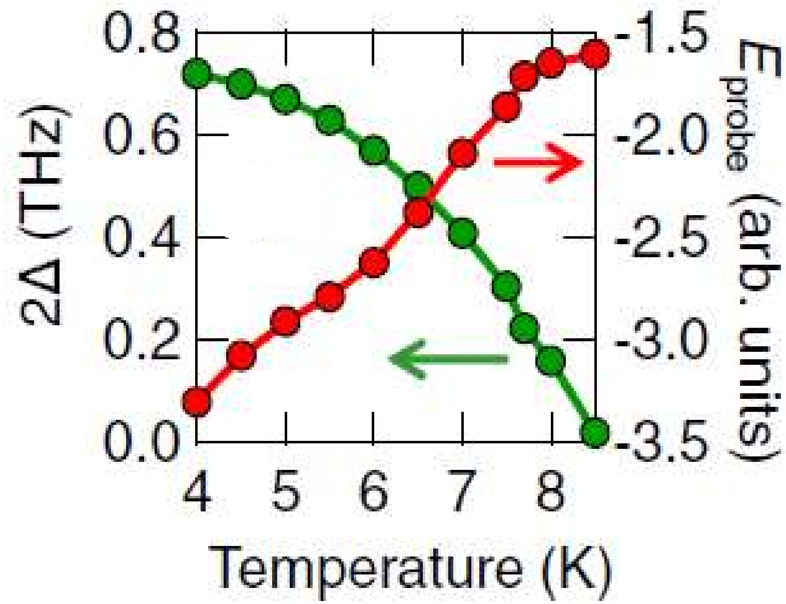
t_{gate}: gate pulse delay

Detection of order parameter dynamics



Temperature dependence of the probe E-field without pump $E_{probe}(t_{gate})$

At $t_{gate}=t_0$, the change in E_{probe} is proportional to the change in the order parameter Δ.

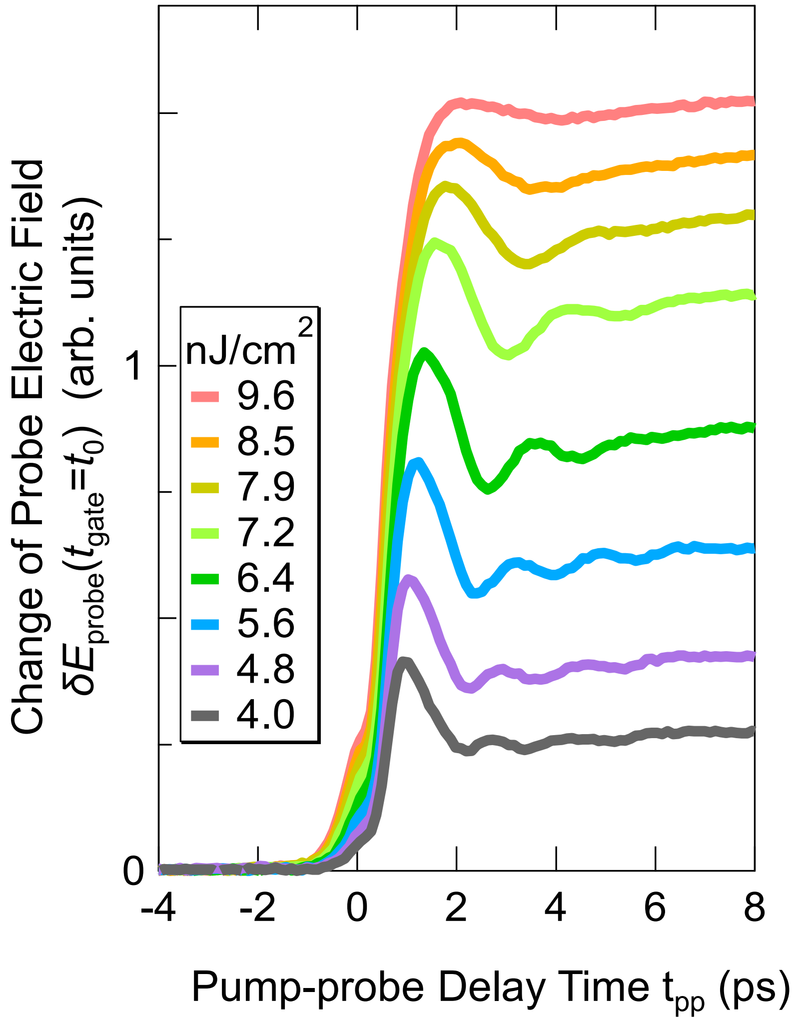


We fixed the gate delay at $t_{gate}=t_0$
and measure the pump-probe delay dependence

Dynamics after the THz pump pulse

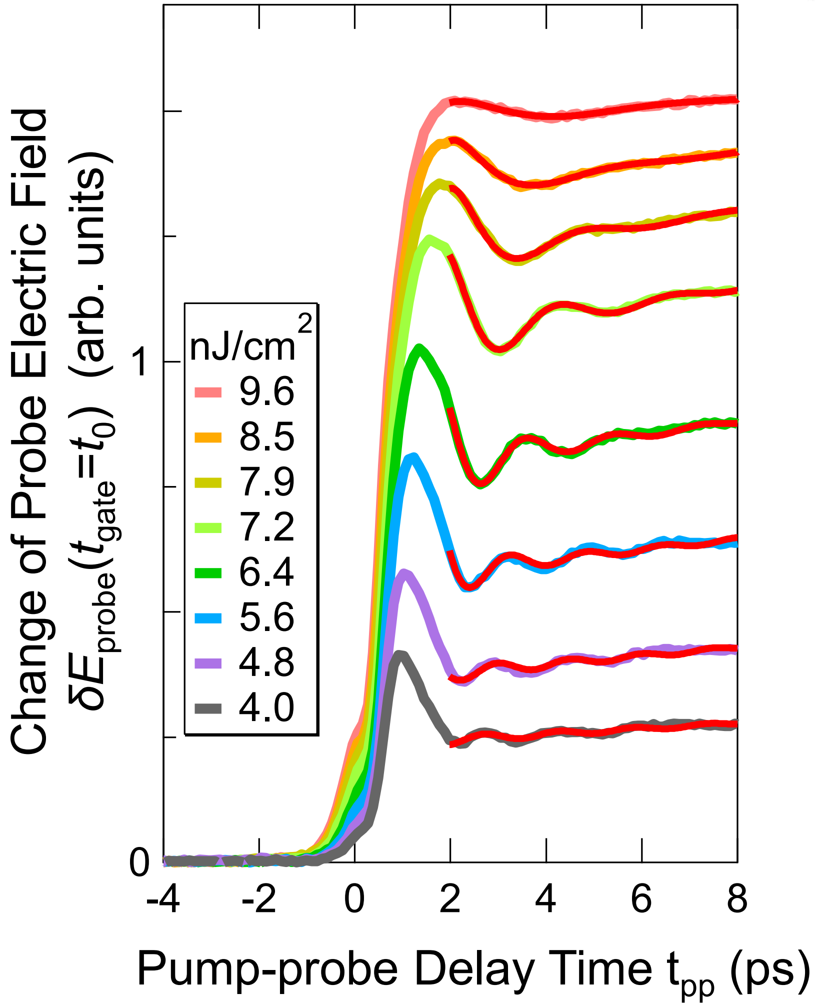
THz pump-induced change in the probe E-field $\delta E_{probe}(t_{gate}=t_0)$

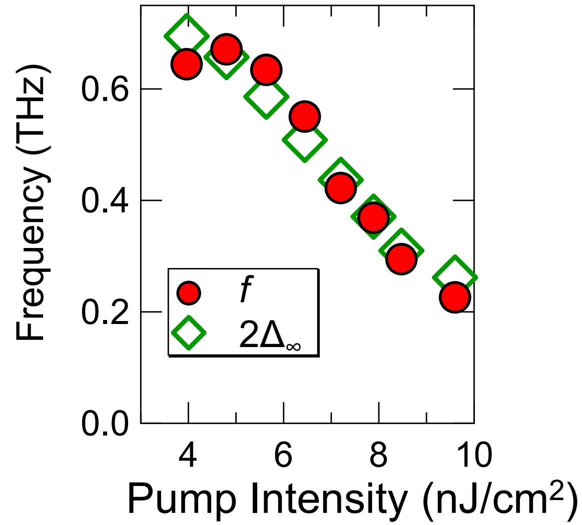
$\tau_{pump}/\tau_{\Delta}=0.57$

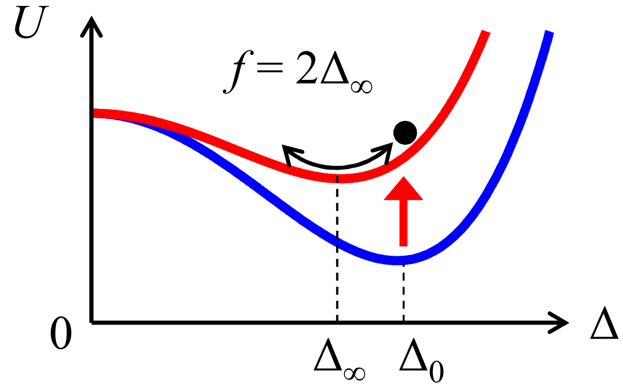


Order parameter dynamics

$$\delta\Delta(t_{pp}) = C_1 + C_2 t_{pp} + \frac{a}{(t_{pp})^b} \cos(2\pi f t_{pp} + \phi)$$

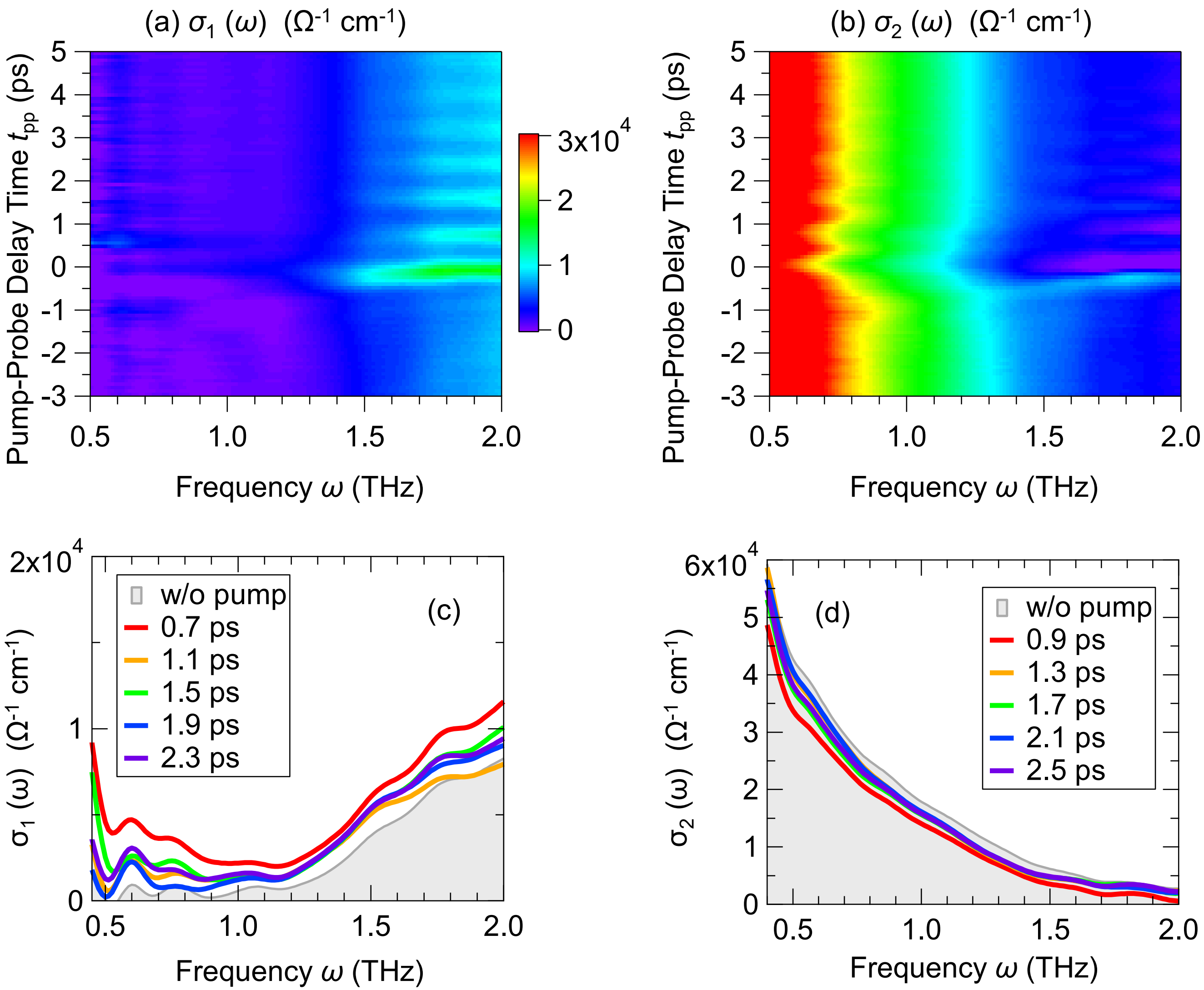




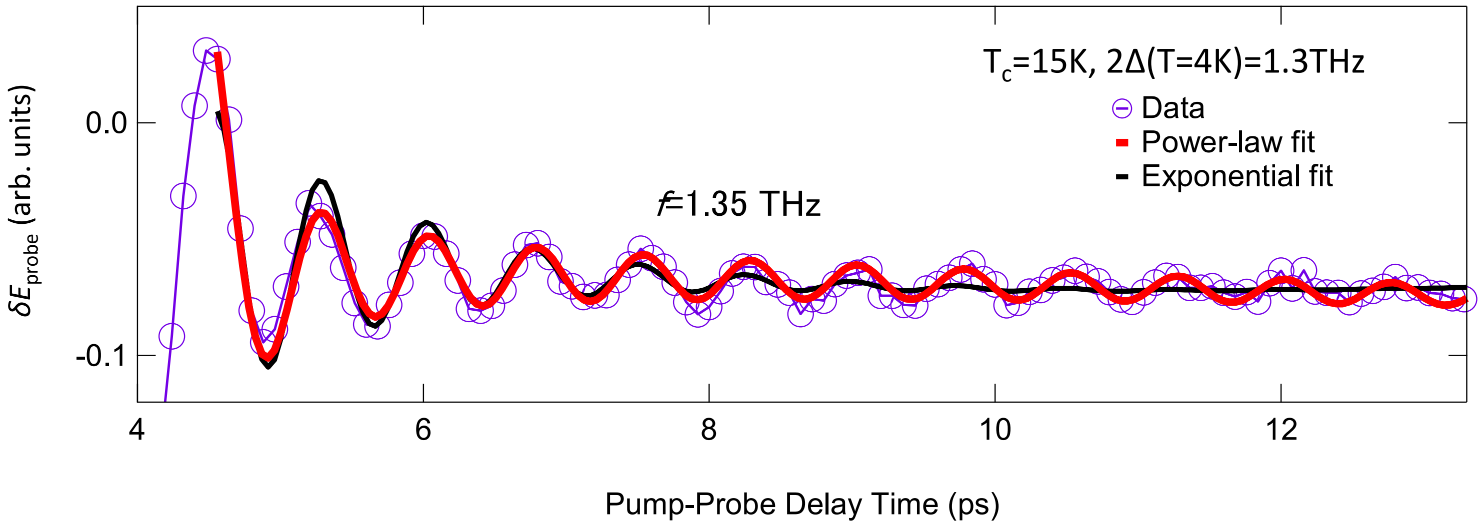


R. Matsunaga et al., PRL111, 057002 (2013)

Time evolution of conductivity spectrum $\sigma_1(\omega; t_{pp})$



Power law decay



Weak coupling case (BCS)

$$\frac{\Delta(t)}{\Delta_\infty} = 1 + a\frac{\cos(2\Delta_\infty t + \pi/4)}{\sqrt{\Delta_\infty t}}$$

Volkov *et al*., Sov. Phys. JETP 38, 1018 (1974).
Yuzbashyan *et al*., PRL 96, 097005 (2006).

exponential decay $$\delta E_{\mathrm{probe}}(t_{\mathrm{pp}}) = C + A\exp\left(-\frac{t}{\tau}\right)\cos(2\pi f t_{\mathrm{pp}} + \phi)$$

τ= 1.3 ps χ^2= 3.6 × 10^{-4}

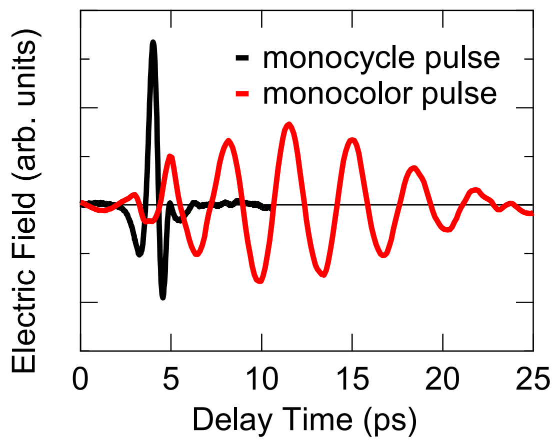
power-law decay $$\delta E_{\mathrm{probe}}(t_{\mathrm{pp}}) = C + \frac{A}{(t_{\mathrm{pp}} - t_0)^b}\cos(2\pi f t_{\mathrm{pp}} + \phi)$$

b = 0.71 χ^2= 2.8 × 10^{-4}

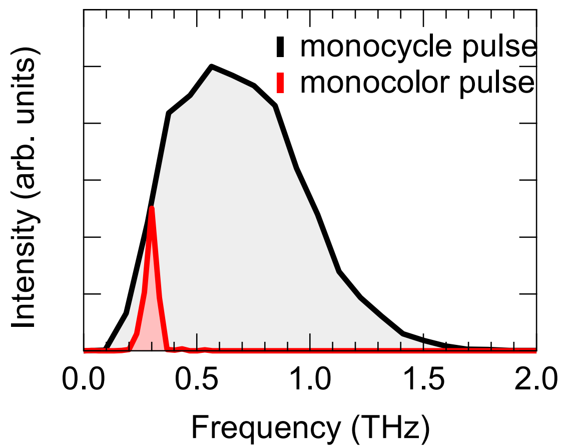
Coherent excitation regime with multicycle THz pulse

Quasi-monochromatic THz pulse（0.3THz, pulsewidth～13ps）

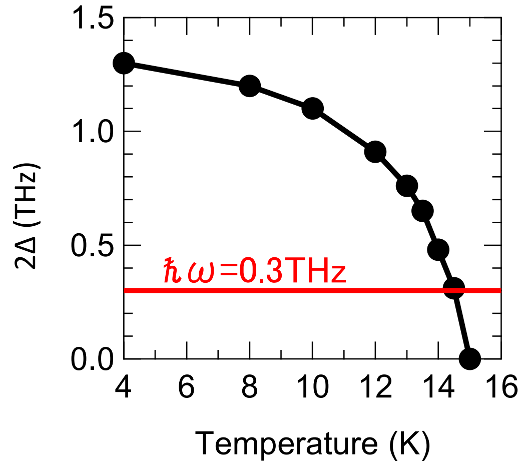
E-field waveform



Power Spectrum



Photon energy vs BCS gap



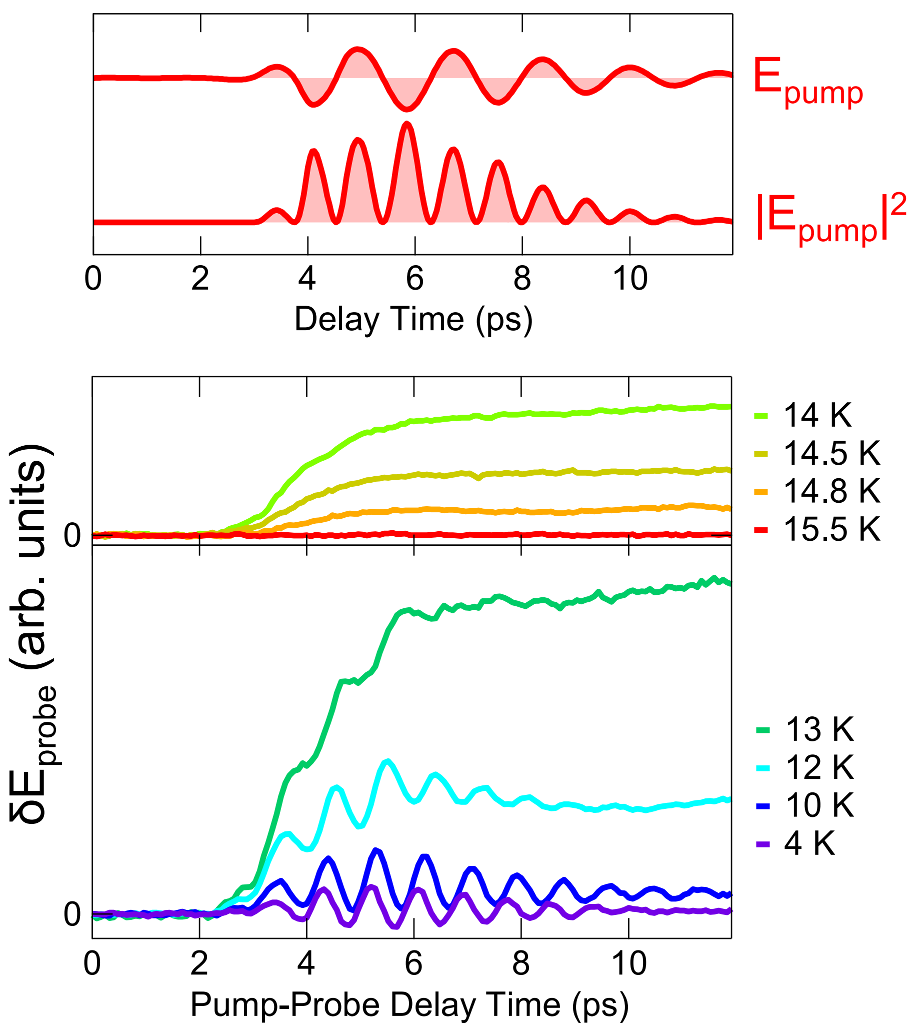
How does the BCS ground state respond to the strong electromagnetic field with $\hbar\omega < 2\Delta$?

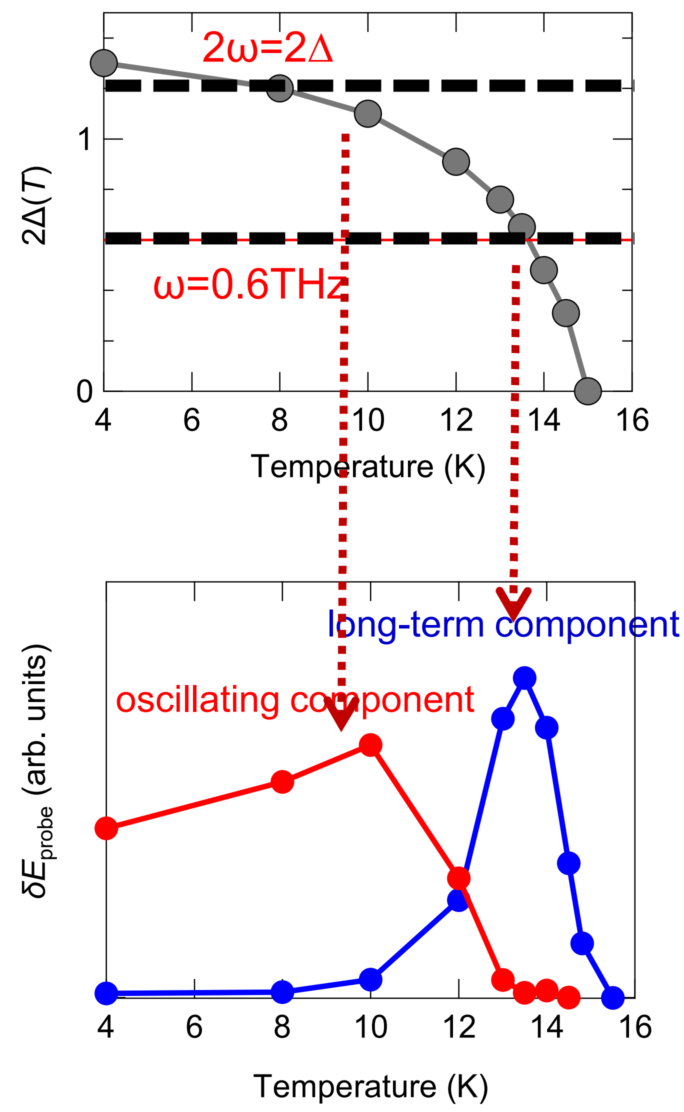
Coherent Excitation Regime Experiments

R. Matsunaga et al., Science 345, 1145 (2014)

ω=0.6THz

E=3.5 kV/cm @ peak





Anderson's pseudospin representation

The BCS Hamiltonian and ground state

P.W. Anderson, PR 112, 1900 (1958)

$$H^{BCS} = 2\sum_{\boldsymbol{k},\sigma} \varepsilon_{\boldsymbol{k}}\, c^{\dagger}_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} - \Delta^* \sum_{\boldsymbol{k}} c^{\dagger}_{-\boldsymbol{k}\downarrow} c^{\dagger}_{\boldsymbol{k}\uparrow} - \Delta \sum_{\boldsymbol{k}} c_{-\boldsymbol{k}\downarrow}\, c_{\boldsymbol{k}\uparrow}$$

$$|\Psi_{\mathrm{BCS}}\rangle = \prod_{\boldsymbol{k}} \left(u_{\boldsymbol{k}} + v_{\boldsymbol{k}} c^{\dagger}_{\boldsymbol{k}\uparrow} c^{\dagger}_{-\boldsymbol{k}\downarrow}\right)|0\rangle$$

Here we introduce the pseudospin:

$$\sigma_{\boldsymbol{k}} = \frac{1}{2}\Psi^{\dagger}_{\boldsymbol{k}} \tau \Psi_{\boldsymbol{k}} = \frac{1}{2}\begin{pmatrix} \Psi^{\dagger}_{\boldsymbol{k}} \tau^x \Psi_{\boldsymbol{k}} \\ \Psi^{\dagger}_{\boldsymbol{k}} \tau^y \Psi_{\boldsymbol{k}} \\ \Psi^{\dagger}_{\boldsymbol{k}} \tau^z \Psi_{\boldsymbol{k}} \end{pmatrix}$$

where $\tau = (\tau^x, \tau^y, \tau^z)$ are the Pauli matrices

and $\Psi_{\boldsymbol{k}} = (c_{k\uparrow}, c^{\dagger}_{-k\downarrow})^t$

is the Nambu spinor.

Then the BCS Hamiltonian can be written in a simple form as

$$H^{BCS} = 2\sum_{\boldsymbol{k}} \boldsymbol{b}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}_{\boldsymbol{k}}$$

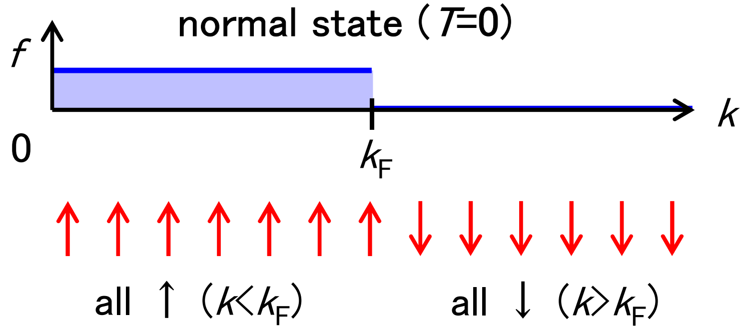
where $\boldsymbol{b}_{\boldsymbol{k}}$ is the pseudo magnetic field

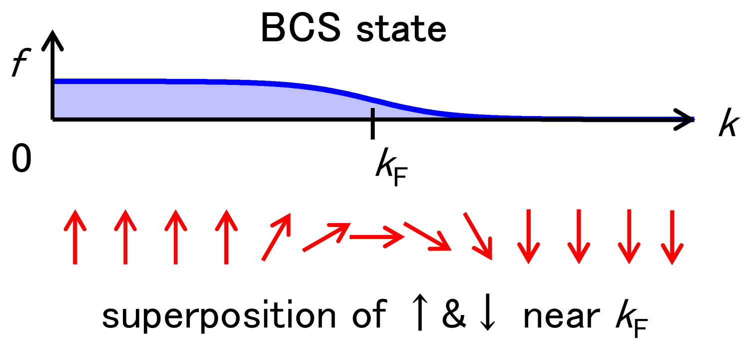
$$\boldsymbol{b}_{\boldsymbol{k}} = (-\Delta', -\Delta'', \varepsilon_{\boldsymbol{k}})$$

$$\Delta = \Delta' + i\Delta'' = V\sum_{\boldsymbol{k}} (\sigma^x_{\boldsymbol{k}} + i\sigma^y_{\boldsymbol{k}})$$

Pseudospin up : (k, $-k$) both occupied

Pseudospin down: (k, $-k$) both empty





The time evolution of the pseudospin is given by the Heisenbergs' equation of motion

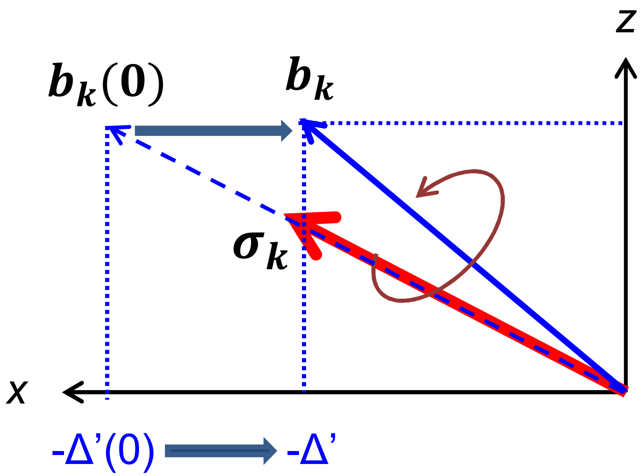
$$\frac{d}{dt}\boldsymbol{\sigma}_{\boldsymbol{k}} = -i[H^{BCS}, \boldsymbol{\sigma}_{\boldsymbol{k}}] = 2\boldsymbol{b}_{\boldsymbol{k}} \times \boldsymbol{\sigma}_{\boldsymbol{k}}$$

$$\Delta(t) = \Delta'(t) + i\Delta''(t) = V\sum_{\boldsymbol{k}}\left(\sigma_{\boldsymbol{k}}^{x}(t) + i\sigma_{\boldsymbol{k}}^{y}(t)\right)$$

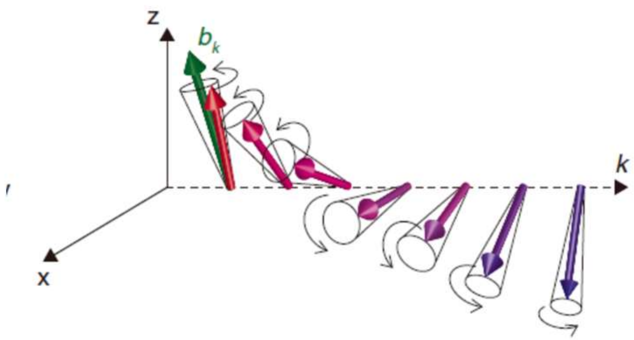
$$\boldsymbol{b}_{\boldsymbol{k}}(\boldsymbol{t}) = (-\Delta'(\boldsymbol{t}), -\Delta''(\boldsymbol{t}), \varepsilon_{\boldsymbol{k}})$$

Time evolution of BCS state is described by the motion of pseudospins under effective magnetic field

Let's consider that Δ' is suddenly quenched at t=0.



Each pseudospin $\boldsymbol{\sigma}_{\boldsymbol{k}}$ starts the precession around the new $\boldsymbol{b}_{\boldsymbol{k}}$.

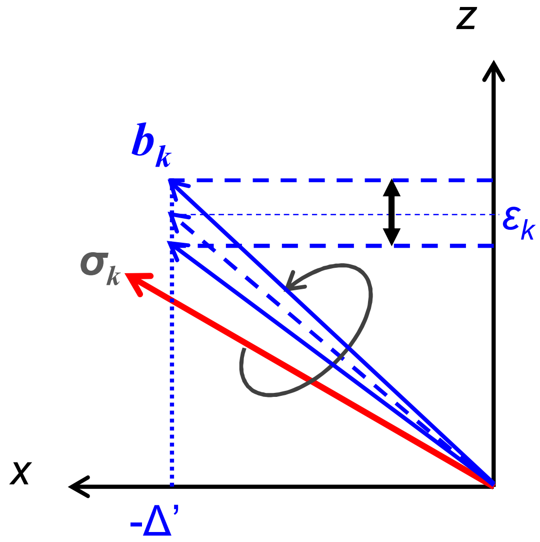


Pseudospin dynamics under the presence of vector potential A(t)

$$\frac{d}{dt}\boldsymbol{\sigma}_k = i\left[\mathcal{H}^{\mathrm{BCS}}, \boldsymbol{\sigma}_k\right] = 2\boldsymbol{b}_k^{\mathrm{eff}} \times \boldsymbol{\sigma}_k$$

$$\Delta = \Delta' + i\,\Delta'' = U\sum_k \left(\sigma_k^x + i\sigma_k^y\right)$$

$$\mathbf{b}_\mathbf{k}^{\mathrm{eff}} = \left(-\Delta', \ -\Delta'', \ \boxed{\varepsilon_\mathbf{k}}\right)$$



In the presence of EM field (vector potential)

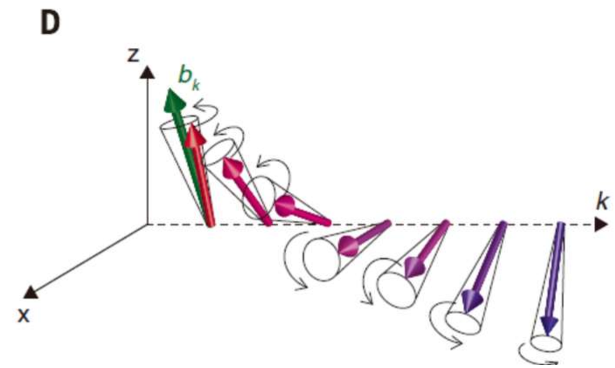
$$\frac{1}{2}\left(\varepsilon_{\mathbf{k}-e\mathbf{A}(t)} + \varepsilon_{-\mathbf{k}-e\mathbf{A}(t)}\right) = \varepsilon_\mathbf{k} + \frac{e^2}{2}\sum_{i,j}\frac{\partial^2 \varepsilon_\mathbf{k}}{\partial k_i \partial k_j} A_i(t)A_j(t) + O(A^4)$$

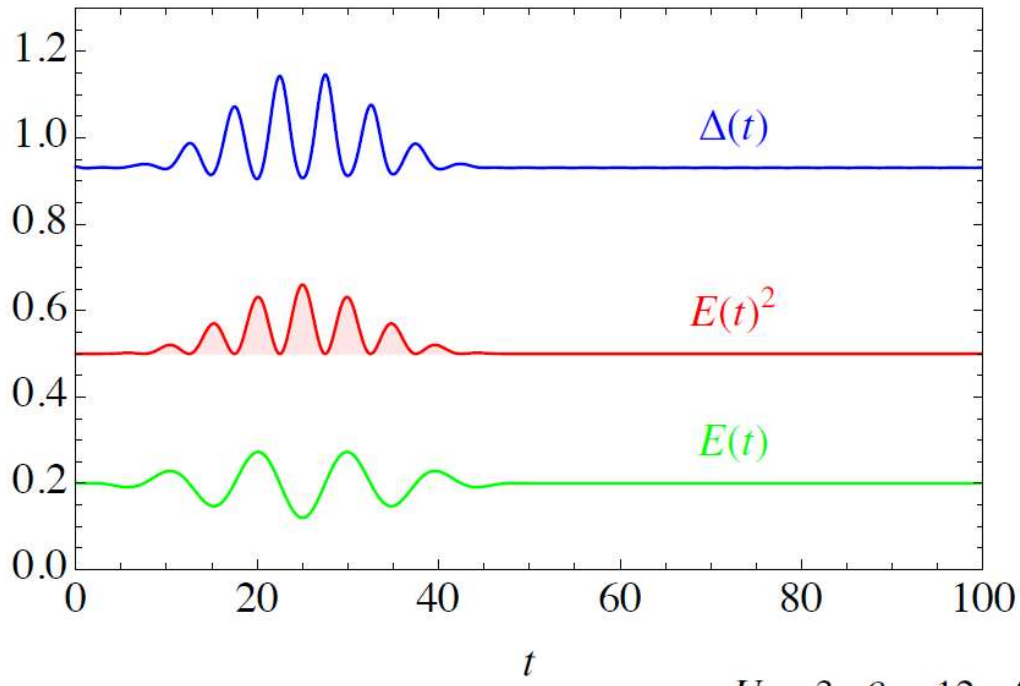
$$= \varepsilon_\mathbf{k} - \underline{\frac{e^2}{2}\sum_{i,j}\frac{\partial^2 \varepsilon_\mathbf{k}}{\partial k_i \partial k_j}\frac{E_i E_j}{\omega^2}\mathrm{e}^{i2\omega t}} + O(A^4).$$

z-component of effective magnetic field oscillates at 2ω

⇒ precession of Anderson's pseudospins

Pseudospin dynamics : simulation with BdG equation

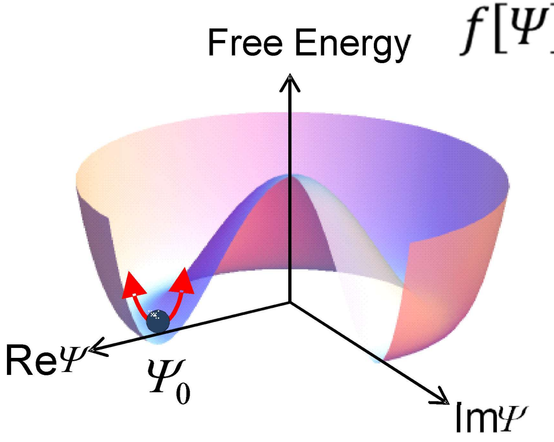




$U = 3,\ \beta = 12,\ A = 0.2,$

$\Omega = 0.628,\ 2\Delta(0) = 1.87$

Ginzburg-Landau picture



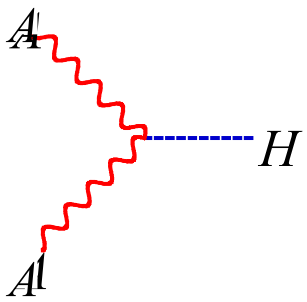
$$f[\Psi] = f_0 + a|\Psi(\boldsymbol{r})|^2 + \frac{b}{2}|\Psi(\boldsymbol{r})|^4 + \frac{1}{2m^*}|(-i\nabla - e^*\boldsymbol{A})\Psi(\boldsymbol{r})|^2$$

$$a < 0 \qquad \Psi(\mathrm{r}) = [\Psi_0 + \mathrm{H}(\mathrm{r})]e^{i\theta(\mathrm{r})}$$

$$f = -2aH^2 + \frac{1}{2m^*}(\nabla H)^2 + \frac{e^{*2}}{2m^*}\left(\boldsymbol{A} - \frac{1}{e^*}\nabla\theta\right)^{\mathbf{2}}(\Psi_0 + H)^2 + \cdots$$

Local gauge transformation $\boldsymbol{A}' = \boldsymbol{A} - \nabla\theta/e^*$ $\quad \boldsymbol{A}' \rightarrow \boldsymbol{A}$

$$f = -2aH^2 + \frac{1}{2m^*}(\nabla H)^2 + \frac{e^{*2}\Psi_0^2}{2m^*}\boldsymbol{A}^{\mathbf{2}} + \boxed{\frac{e^{*2}\Psi_0}{m^*}\boldsymbol{A}^{\mathbf{2}}H} + \cdots$$



THz THG by Higgs mode

Current density

$$\boldsymbol{j}(t) = e\sum_{\boldsymbol{k}} \boldsymbol{v}_{\boldsymbol{k}-\boldsymbol{A}} n_{\boldsymbol{k}} = e\sum_{\boldsymbol{k}} \frac{\partial \varepsilon_{\boldsymbol{k}-e\boldsymbol{A}(t)}}{\partial \boldsymbol{k}} \left(\sigma^z_{\boldsymbol{k}}(t) + \frac{1}{2} \right)$$

$$\sim \boldsymbol{j}_{\mathrm{linear}}(t) - \underline{\frac{e^2\Delta}{U} \boldsymbol{A}(t)\delta\Delta(t)}$$

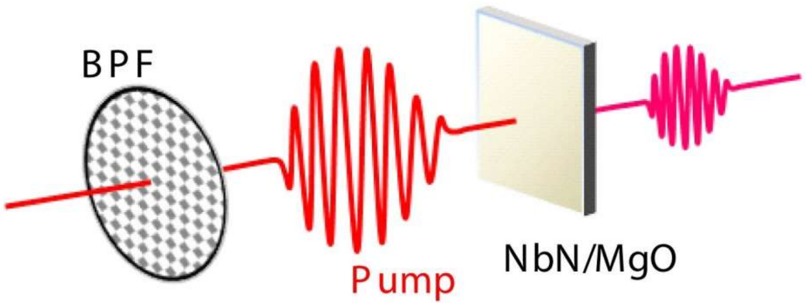
London equation for nonlinear current j_{nl}

$$\delta\Delta(t) \sim e^{i2\omega t}, \quad A(t) \sim e^{i\omega t} \quad \Rightarrow \quad j(t) \sim e^{i3\omega t}$$

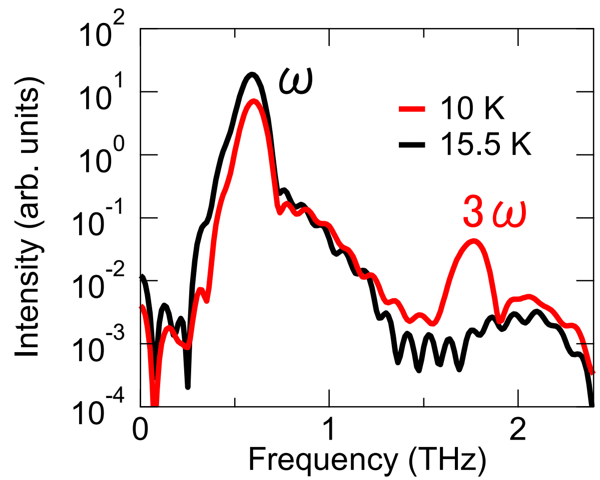
Does superconductor emit THz third harmonics?

Efficient THG from superconductor

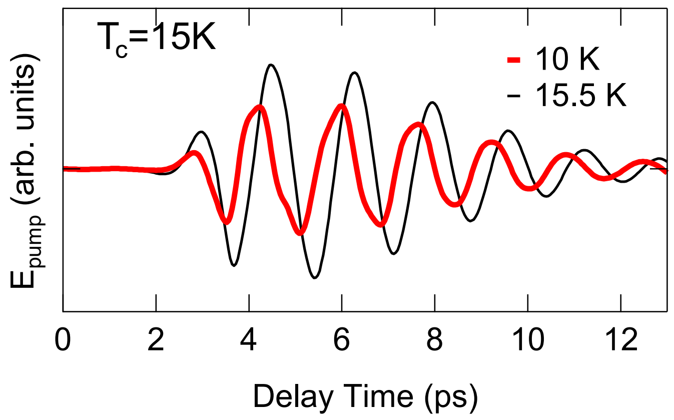
Nonlinear transmission experiment

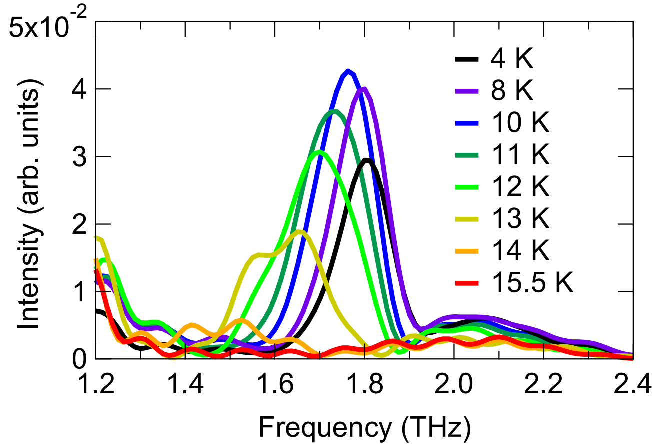


Power spectrum of the transmitted pulse



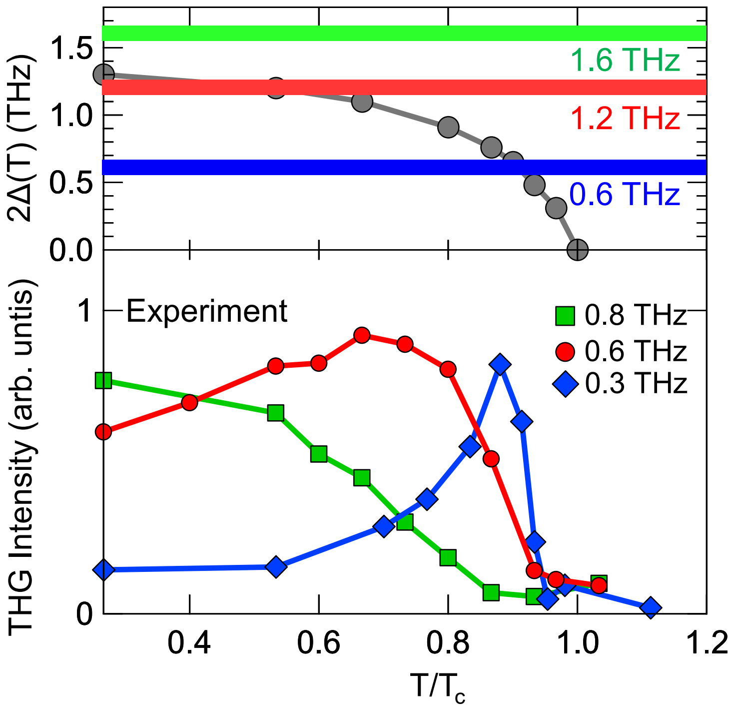
Waveform of the transmitted pulse

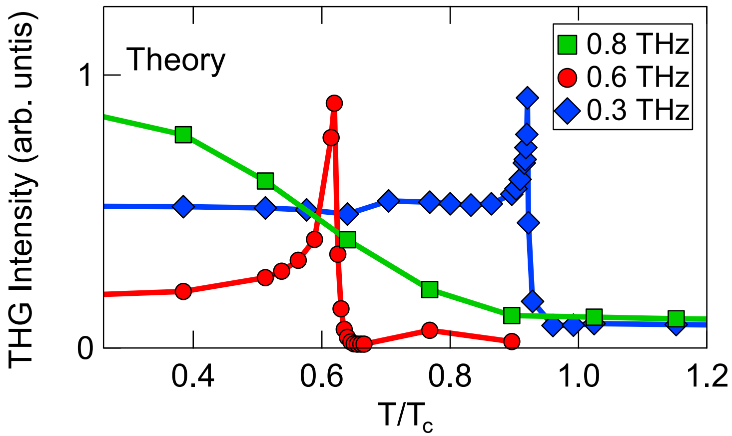




R. Matsunaga, R.Shimano et al., Science 345, 1145 (2014)

Temperature dependence of THG



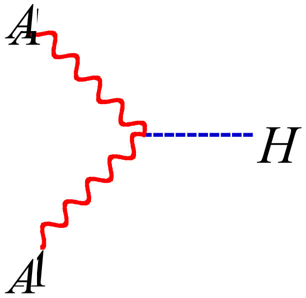


Experiments with different frequencies

ω=0.3, 0.6, 0.8 THz

THG shows a peak at $2\omega=2\Delta(T)$,

but not at $\omega=2\Delta(T)$!



R. Matsunaga et al.,
Science 345, 1145 (2014)

Theory: N. Tsuji and H. Aoki,
Phys. Rev. B 92, 064508(2015)

PHYSICS

Particle physics in a superconductor

Science 345, 1121 (2014)

A superconducting condensate can display analogous behavior to the Higgs field

By **Alexej Pashkin** *and* **Alfred Leitenstorfer**

The recent discovery of the Higgs boson has created a lot of excitement among scientists. Celebrated as one of the most fundamental results in experimental physics (*1*), the observation of this particle confirms the existence of

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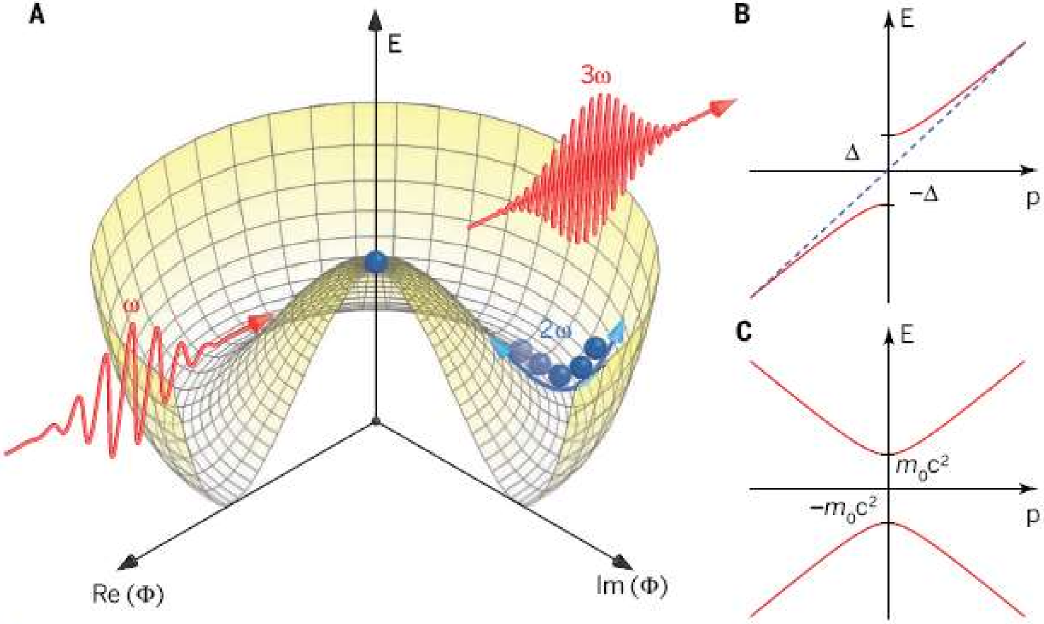

The Higgs amplitude mode. (**A**) Energy of a system as a function of the complex order parameter **Φ** in a state with spontaneously broken symmetry. The Higgs mode corresponds to the amplitude oscillations of **Φ** shown by the blue arrow. The excitation by a light pulse at half the resonance frequency starts a coherent oscillation of the order parameter. The induced superconducting current is nonlinear and leads to emission of the third harmonic of the excitation wave. (**B**) Energy of quasi-particles as a function of their momentum near the Fermi energy of a normal metal (dashed blue line) and a superconductor with energy gap 2Δ (solid red line). (**C**) Energy of a relativistic particle-antiparticle system with rest mass m_0 as a function of its momentum.

Outline

(1) Introduction to Higgs mode and
Higgs mode in isotropic pairing(s-wave)
superconductor (NbN)

(2) Higgs mode in anisotropic pairing (d-wave)
High-Tc superconductor ($Bi_2Sr_2CaCu_2O_x$)

(3) Higgs mode in multiband superconductor ($FeSe_{0.5}Te_{0.5}$)

Higgs in High Tc cuprate

PHYSICAL REVIEW LETTERS **120,** 117001 (2018)

Editors' Suggestion

Higgs Mode in the *d*-Wave Superconductor $Bi_2Sr_2CaCu_2O_{8+x}$ Driven by an Intense Terahertz Pulse

Kota Katsumi,[1] Naoto Tsuji,[2] Yuki I. Hamada,[1] Ryusuke Matsunaga,[1,3] John Schneeloch,[4] Ruidan D. Zhong,[4] Genda D. Gu,[4] Hideo Aoki,[1,5,6] Yann Gallais,[1,7,8] and Ryo Shimano[1,8]

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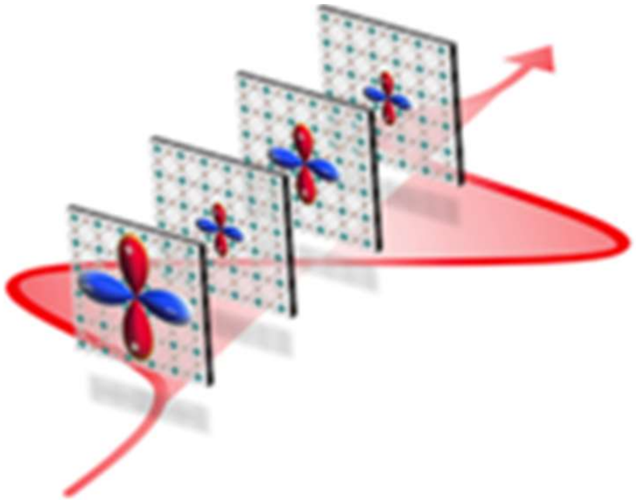
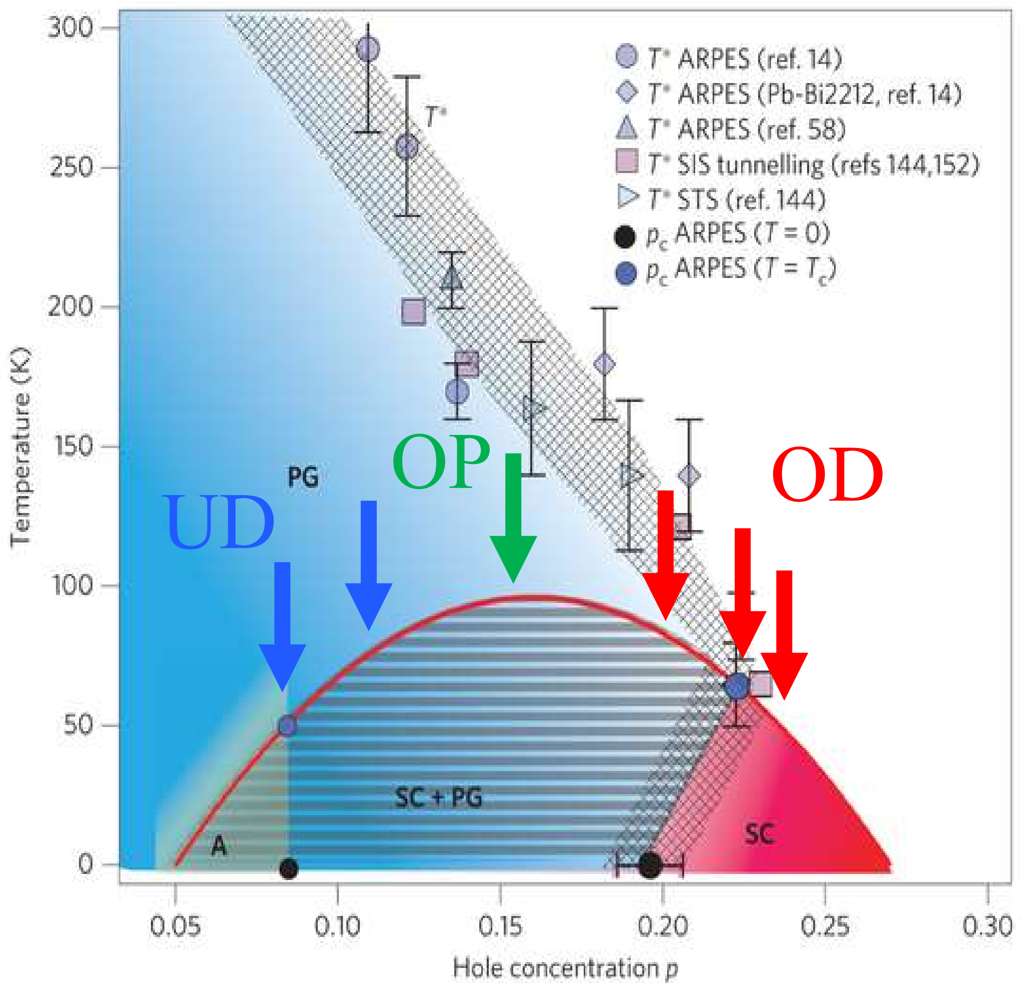


Phase diagram of $Bi_2Sr_2CaCu_2O_x$

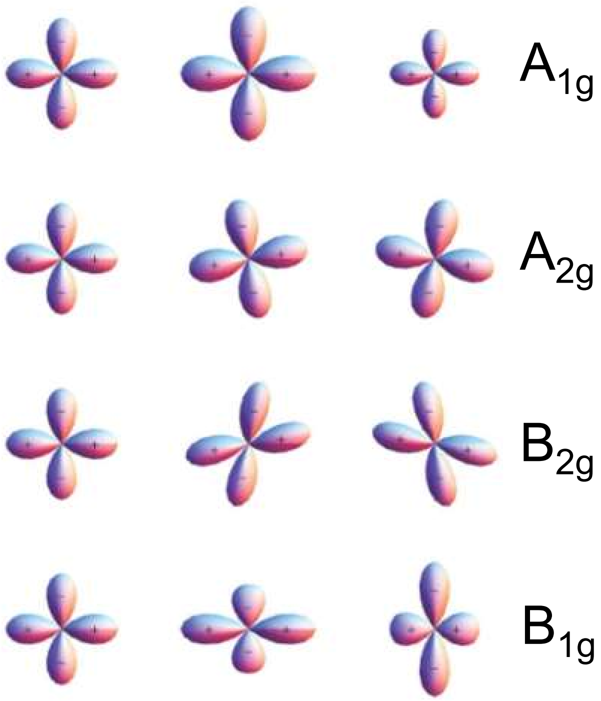


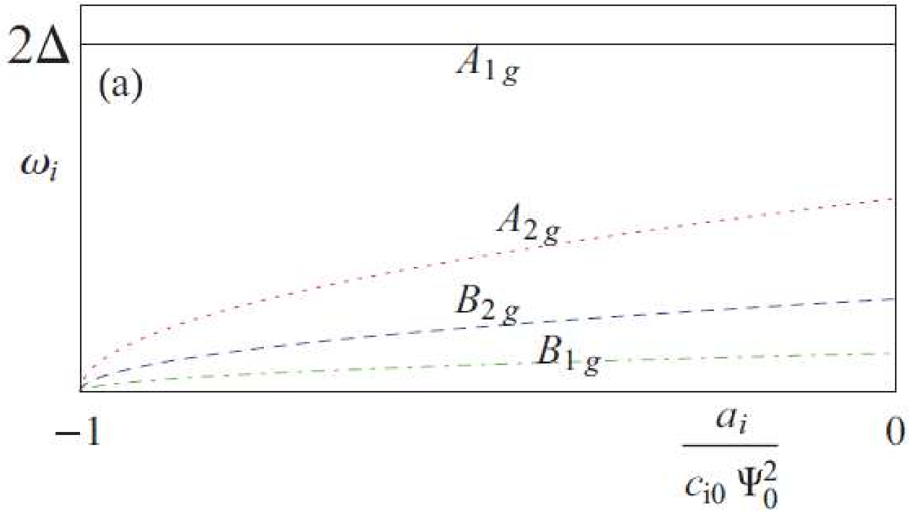
M. Hashimoto et al., Nat. Phys. 10, 483 (2014)

Higgs modes in d-wave SC

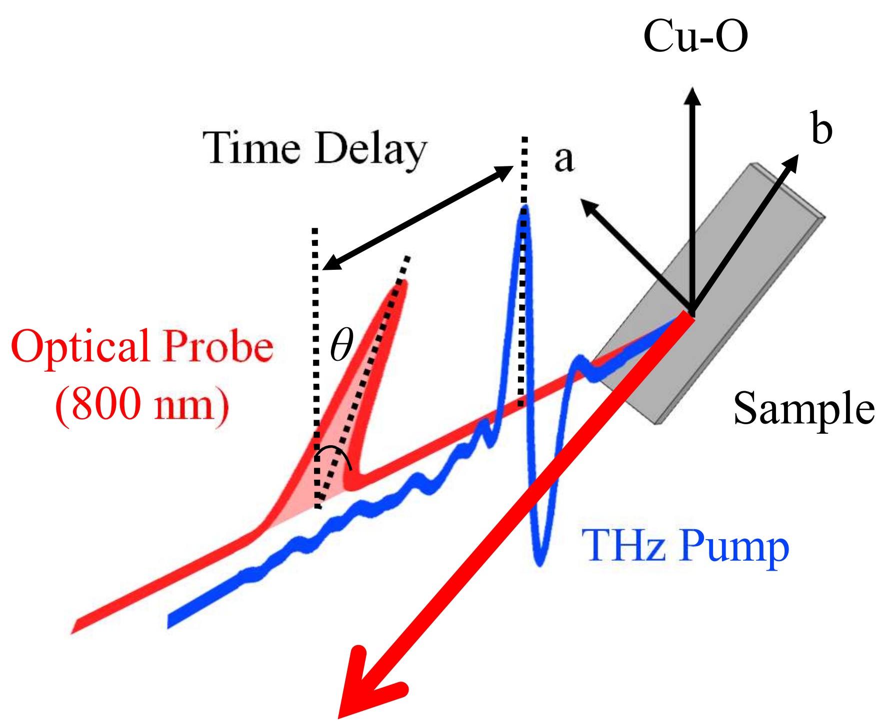
Barlas and Varma,
PRB 87, 054503 (2013)

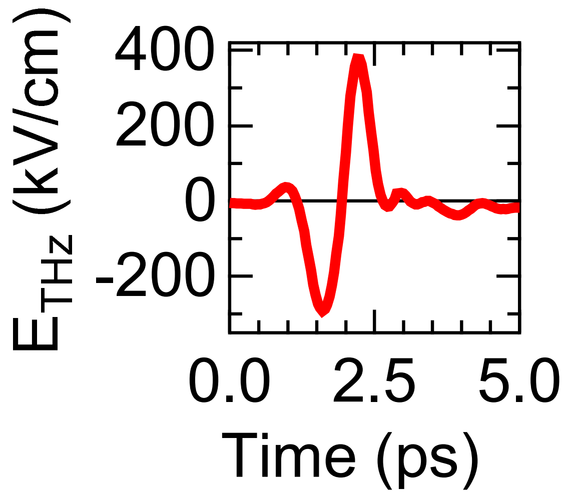
$$\mathcal{L} = \sum_{i=0}^{3} |\partial_t \phi_i|^2 + a_i |\phi_i|^2 - b_i |\phi_i|^4 - \sum_{i<j} \left(c_{ij} |\phi_i|^2 |\phi_j|^2 + \frac{d_{ij}}{2} (\phi_i^\star \phi_j - \phi_j^\star \phi_i)^2 \right)$$

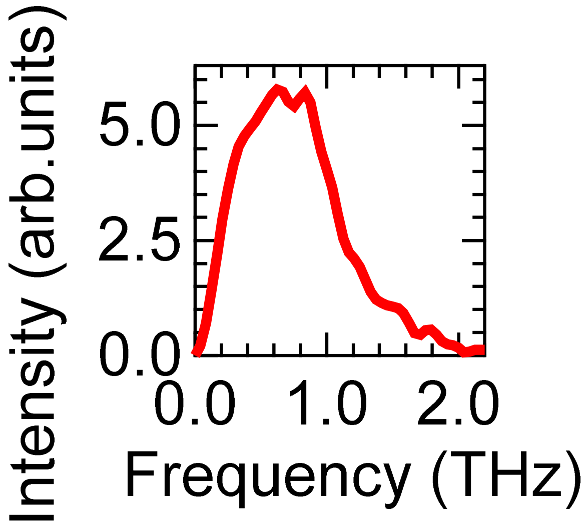




THz pump and optical probe experiments in $Bi_2Sr_2CaCu_2O_x$





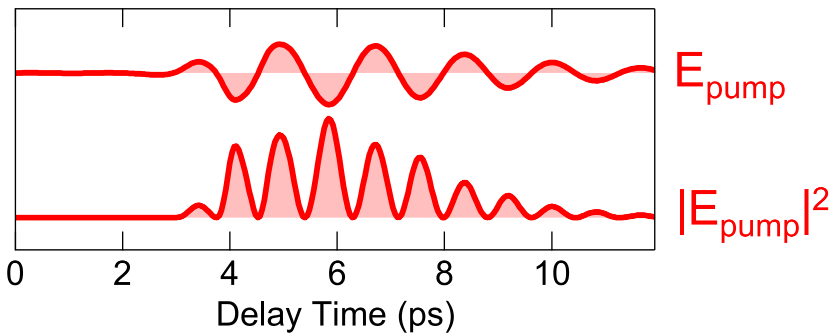


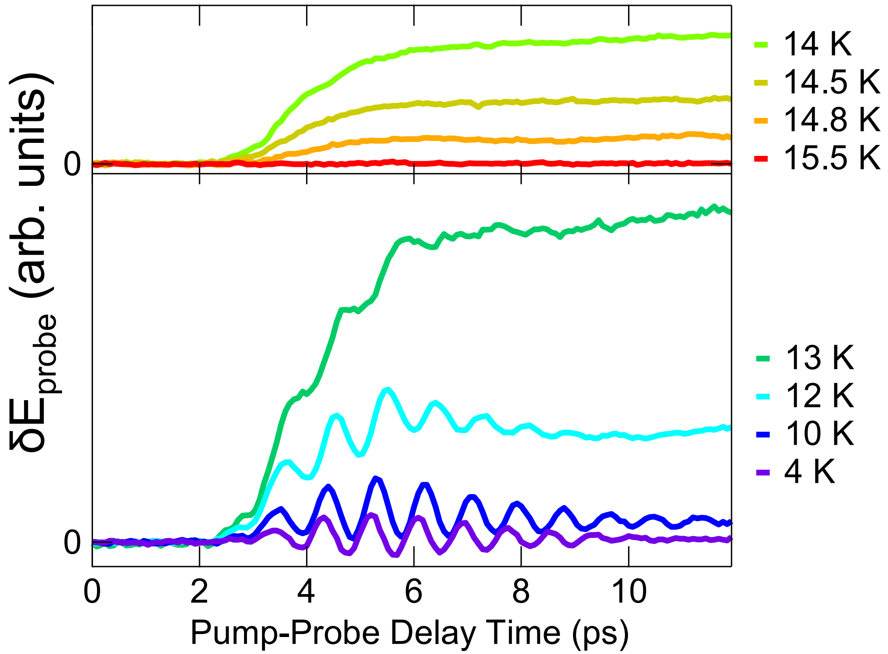
Coherent Excitation Regime Experiments in NbN

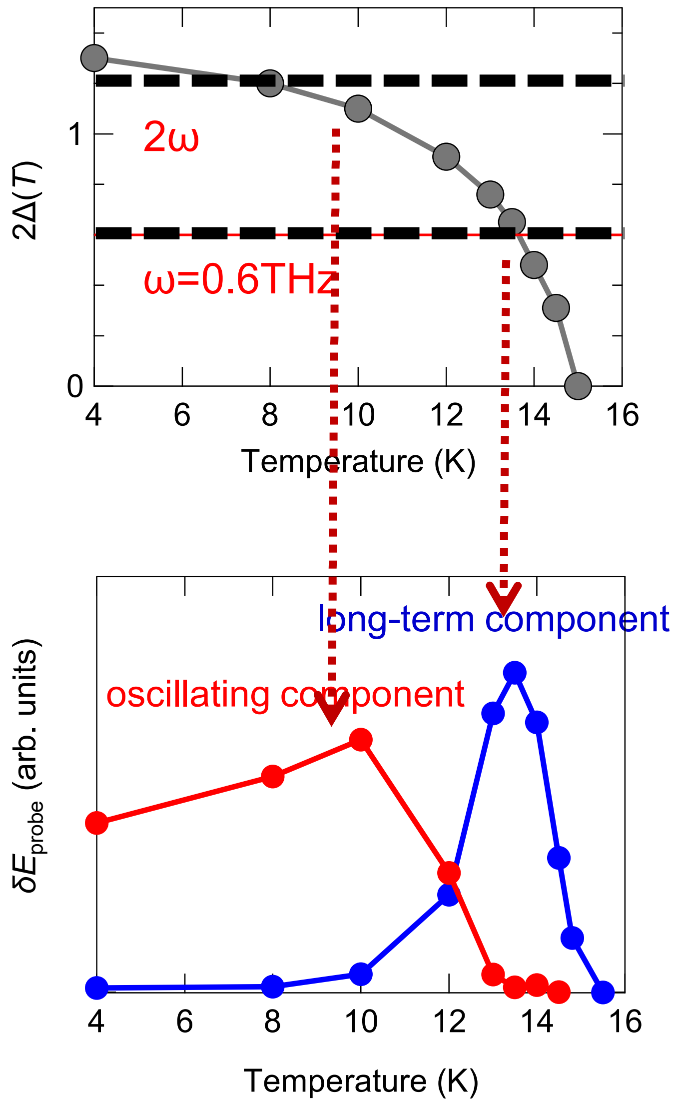
R. Matsunaga et al., Science 345, 1145 (2014)

ω=0.6THz

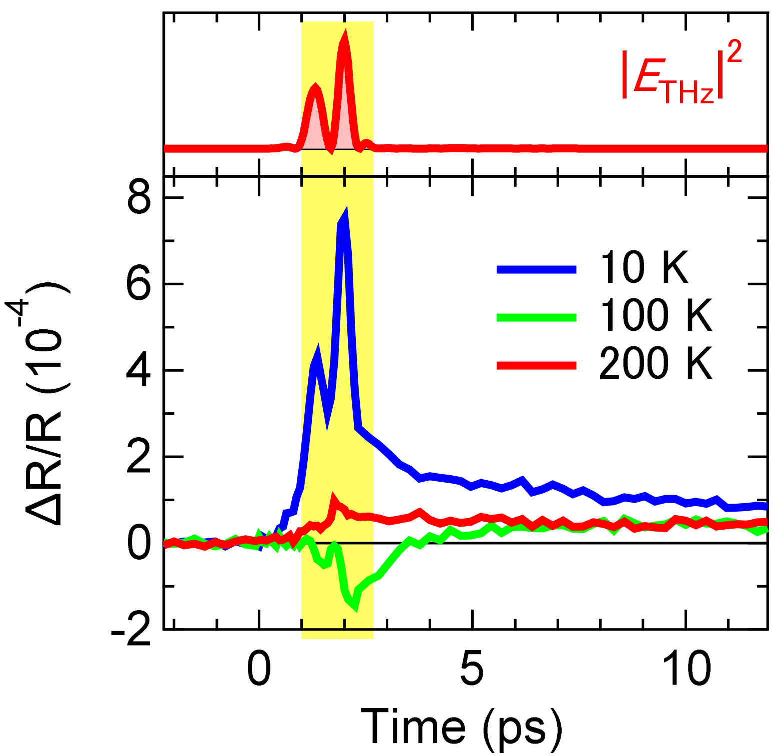
E=3.5 kV/cm @ peak

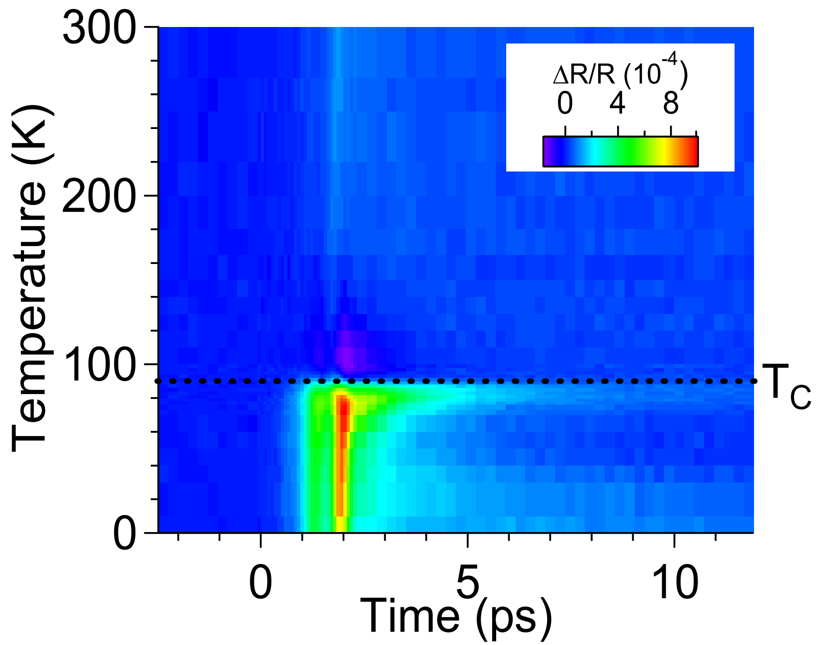


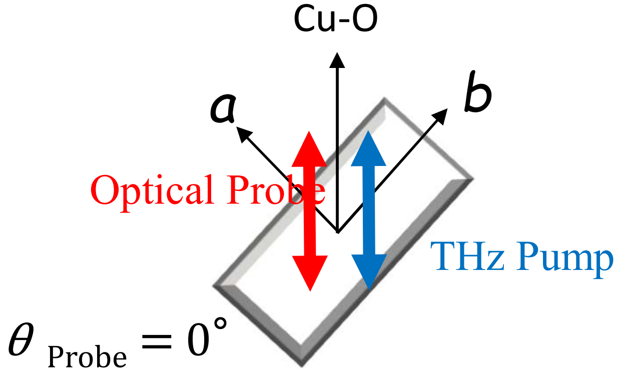




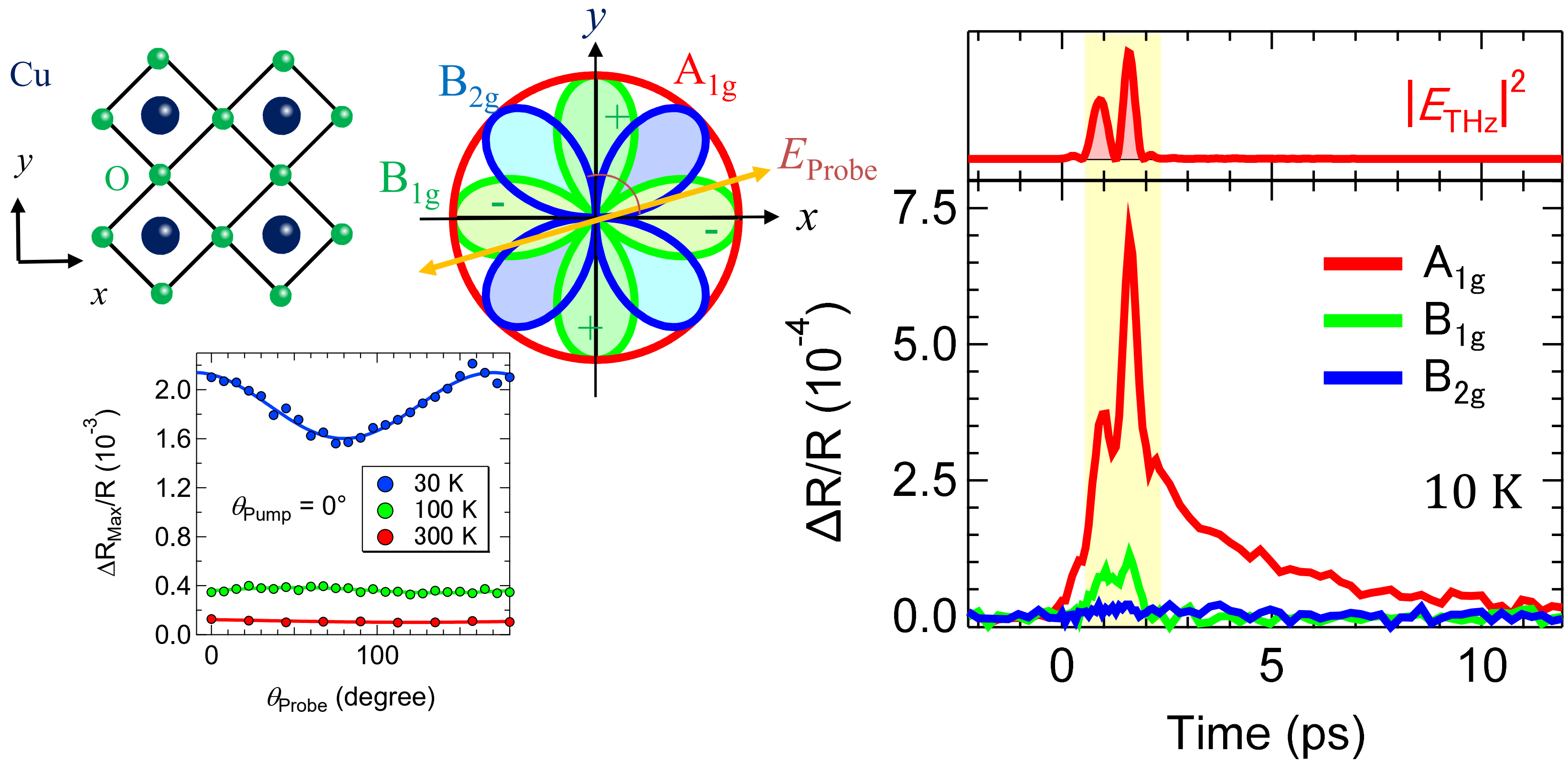
Transient reflectivity change







Symmetry of the signal



$$\frac{\Delta R}{R}(E_i^{probe}, E_j^{probe}) \sim \frac{1}{R}\frac{\partial R}{\partial \varepsilon_1}\varepsilon_0 \operatorname{Re} \chi_{ijkl}^{(3)} E_k^{pump} E_l^{pump}$$

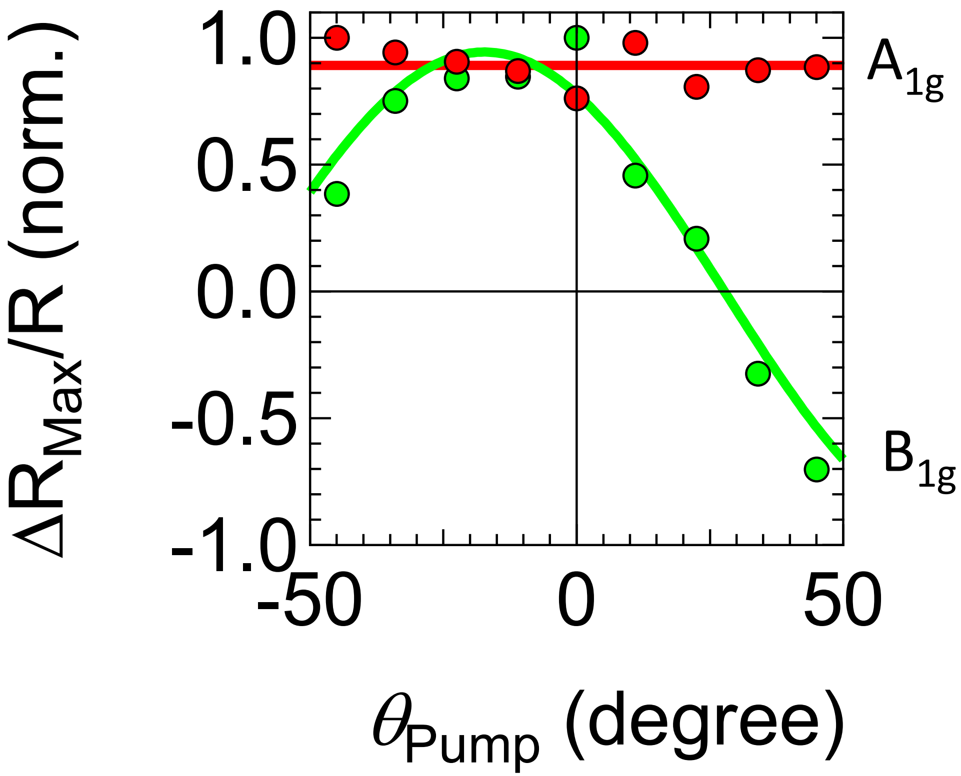
THz-induced Kerr effect

Bi2212: D_{4h} point group

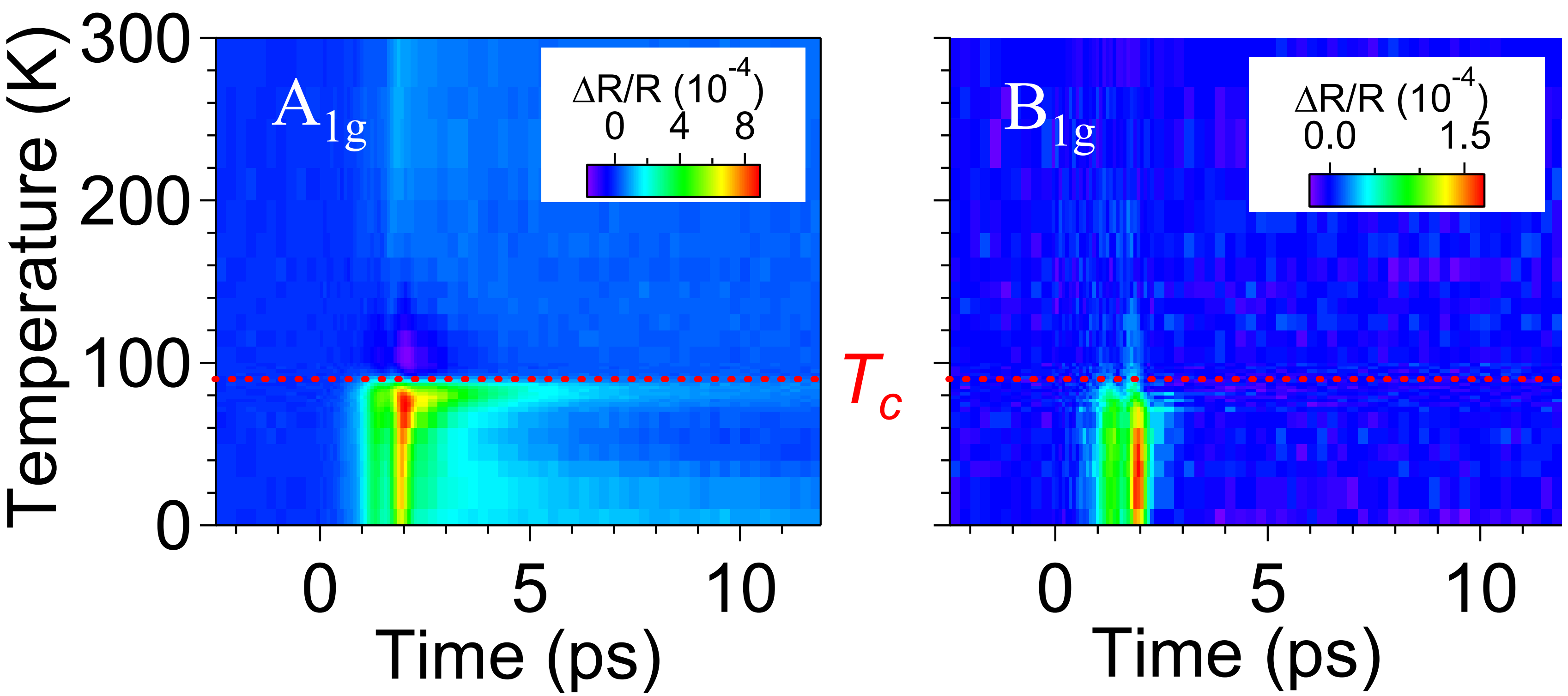
$$\chi^{(3)} = \frac{1}{2}(\chi_{A_{1g}}^{(3)} + \chi_{B_{1g}}^{(3)} \cos 2\theta_{pump} \cos 2\theta_{probe} + \chi_{B_{2g}}^{(3)} \sin 2\theta_{pump} \sin 2\theta_{probe})$$

Pump polarization dependence

$$\chi^{(3)} = \frac{1}{2}\left(\underline{\chi^{(3)}_{A_{1g}}} + \underline{\chi^{(3)}_{B_{1g}} \cos 2\theta_{pump}} \cos 2\theta_{probe} + \chi^{(3)}_{B_{2g}} \sin 2\theta_{pump} \sin 2\theta_{probe}\right)$$



Temperature dependence of A_{1g} and B_{1g}

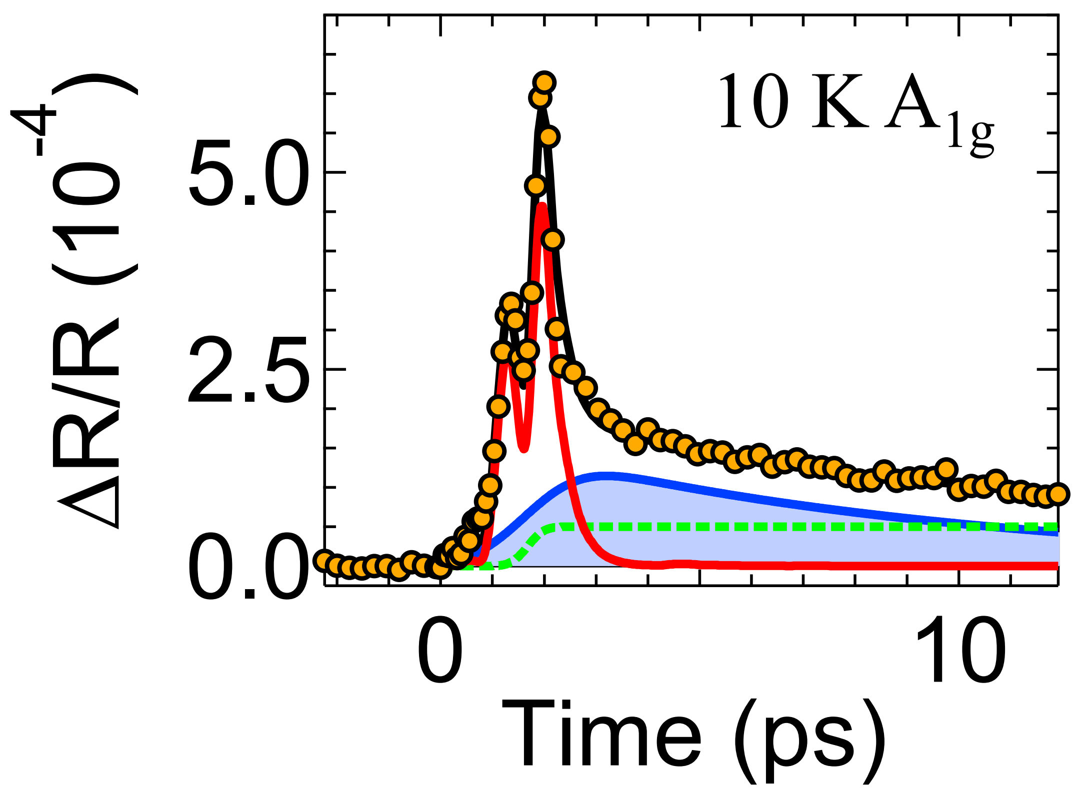


A1g: oscillatory(coherent) component + decay(incoherent) component

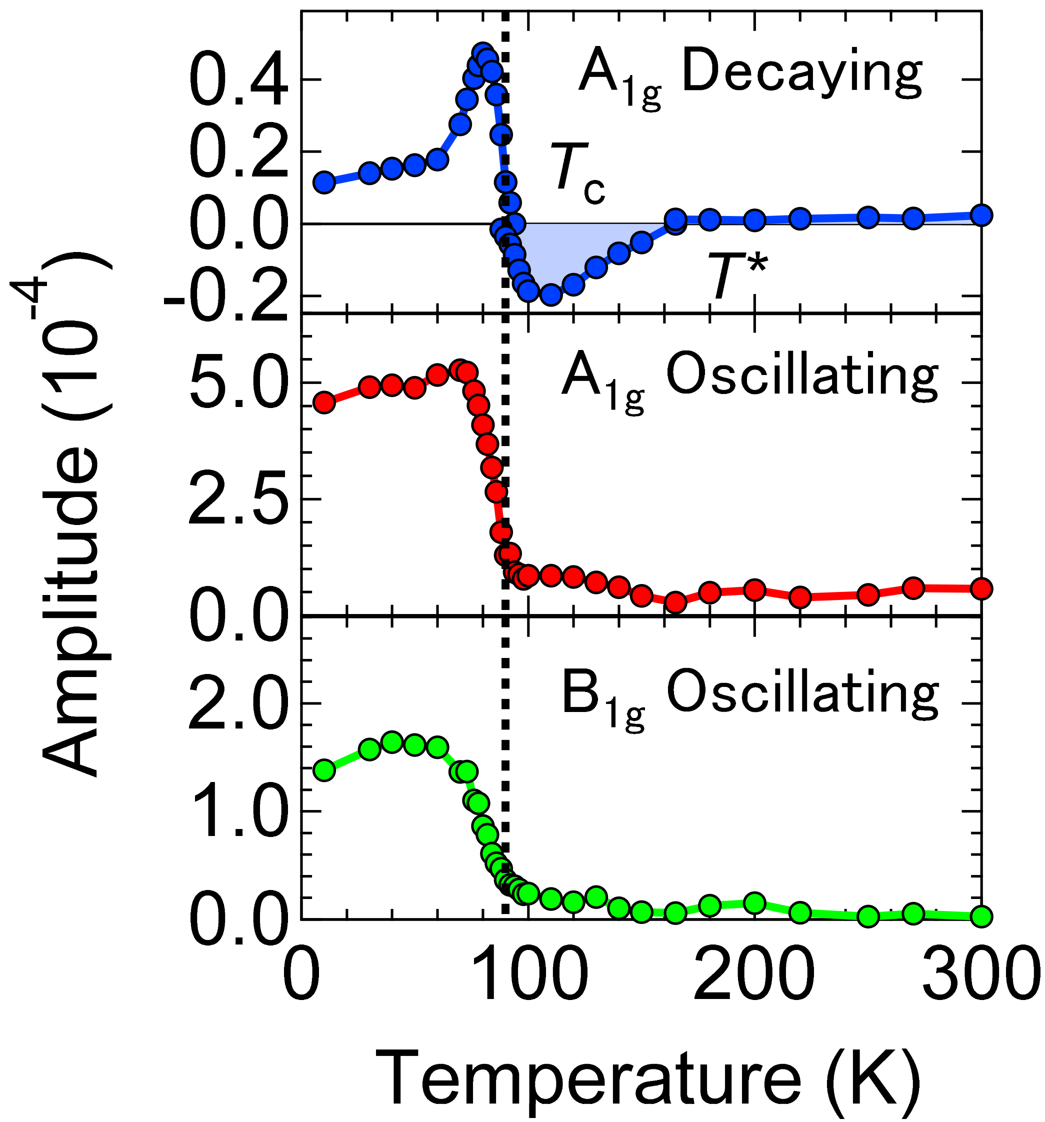
B1g: only oscillatory(coherent) component

Decomposition into coherent and incoherent part

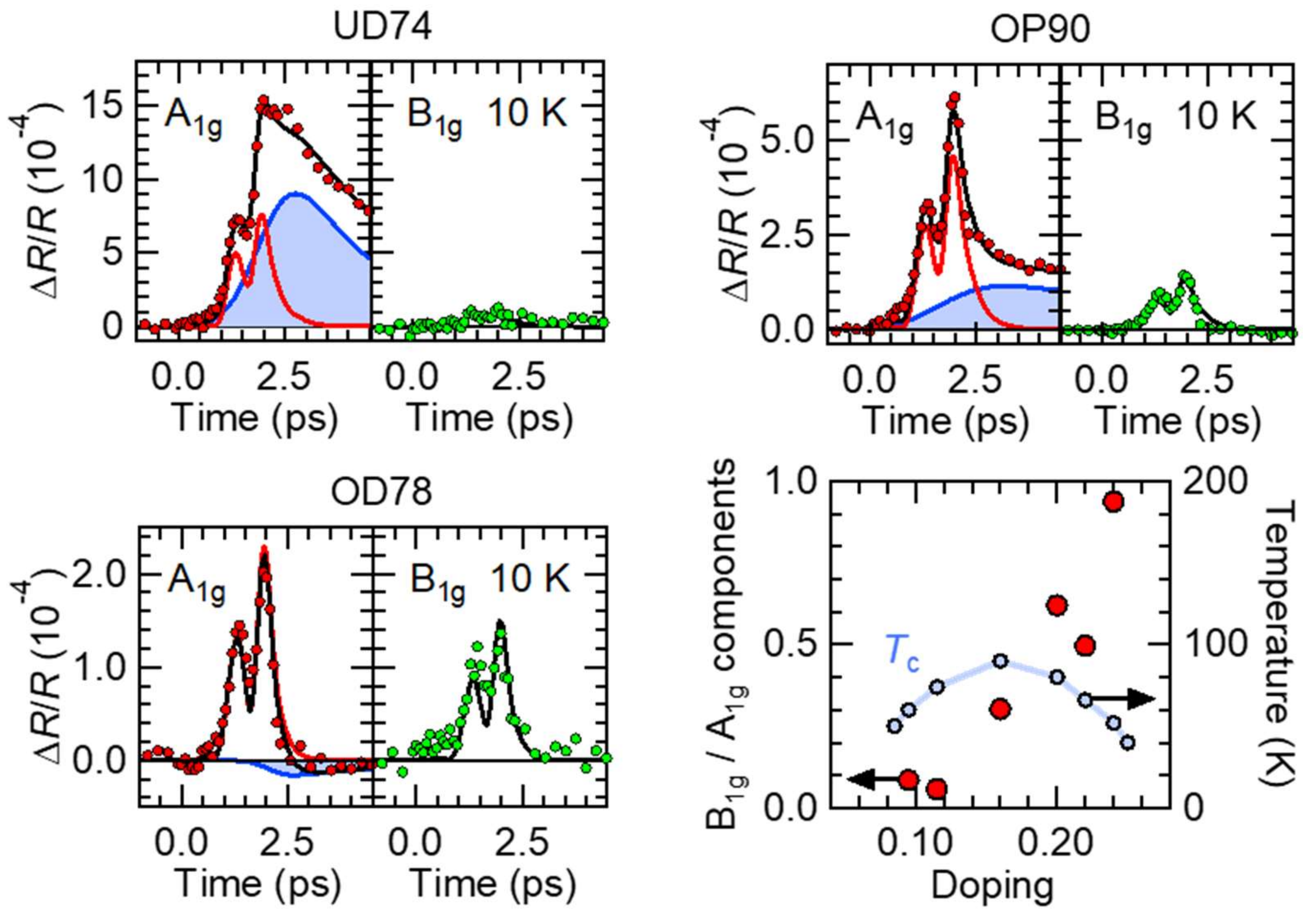
$$\frac{\Delta R}{R}(t) = A\int_{-\infty}^{\infty} \left|E_{\mathrm{Pump}}(t-\tau)\right|^2 e^{-\frac{\tau}{\tau_0}} d\tau + B\int_{-\infty}^{\infty} e^{-\frac{\tau^2}{\tau_p^2}} e^{-\frac{t-\tau}{\tau_I}} d\tau + \text{Offset}$$



Temperature dependence of each component

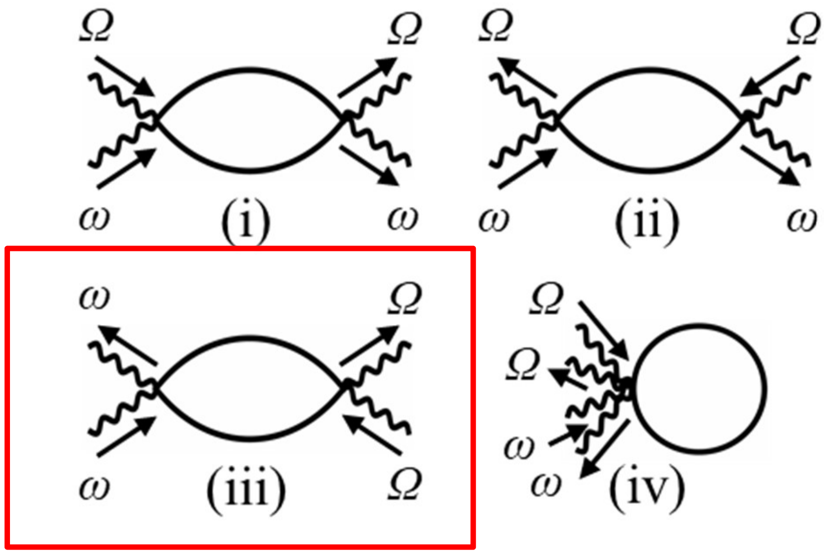


Doping dependence



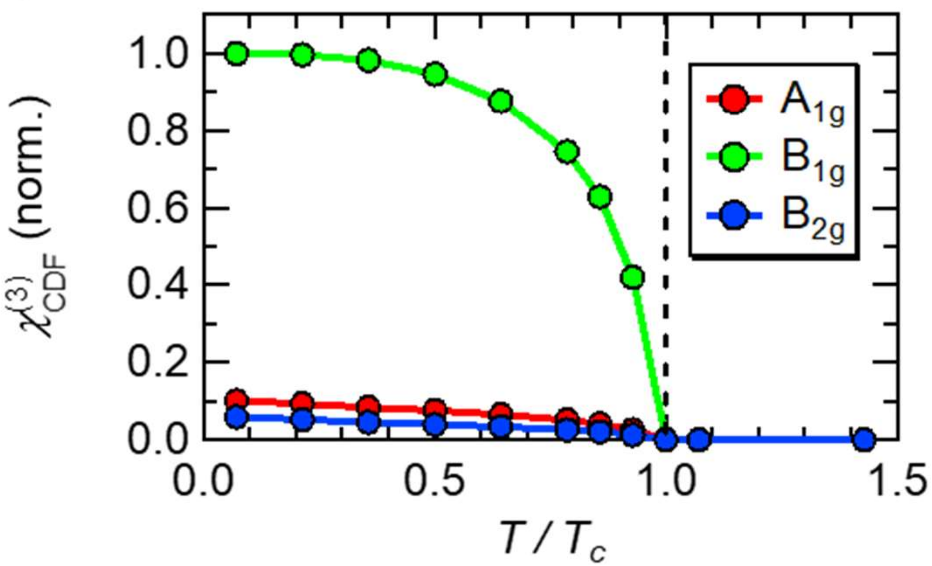
A_{1g} signal is always dominant.

Polarization dependence of CDF
mean field(BCS) theory with d-wave symmetry



THz pump-optical probe

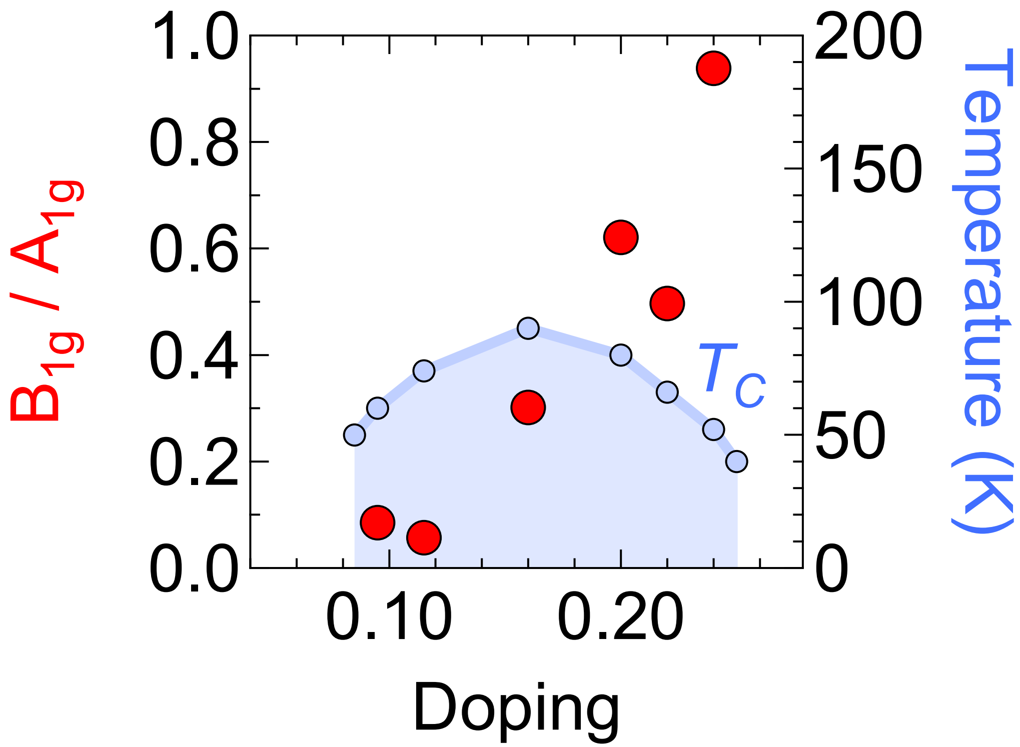
Ω: 4meV ω: 1.5 eV

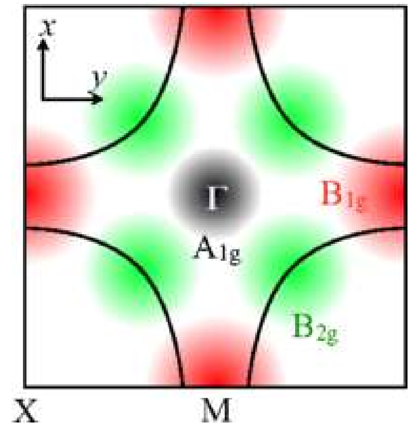


CDF: B_{1g} is dominant

The dominance of A_{1g} signal cannot be explained by CDF.

Doping dependence of the oscillating component





A_{1g} signal is attributed to Higgs.

B_{1g} is most likely CDF.

K. Katsumi et al, Phys. Rev. Lett. **120**, 117001 (2018).

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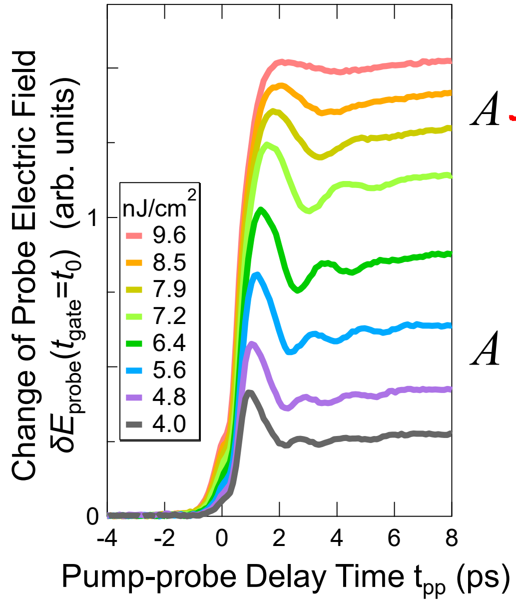
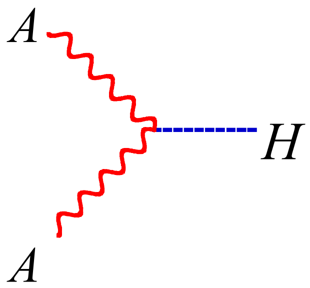
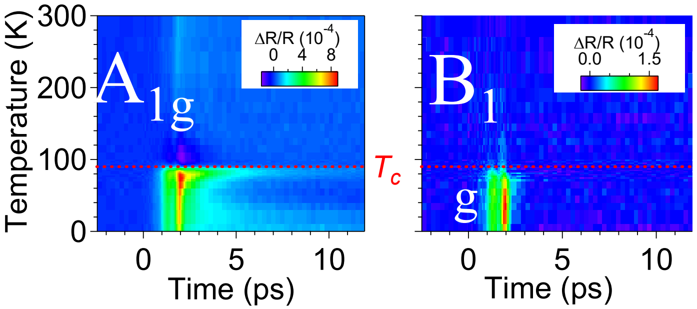
Summary

(1) Higgs mode in s-wave SC (NbN)





(2) Higgs mode in d-wave High-Tc SC ($Bi_2Sr_2CaCu_2O_x$)



(3) Higgs mode in multiband SC ($FeSe_{0.5}Te_{0.5}$)

Outlook: toward the Higgs spectroscopy in "strongly" unconventional SCs, $U(1)\otimes SU(2)\otimes T$