UNIVERSITÀ
DEGLI STUDI DI TRIESTE

T-ReX Research Group

Elettra Sincrotrone Trieste

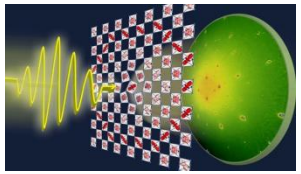
Witnessing quasi-particle dynamics in strongly correlated electron system

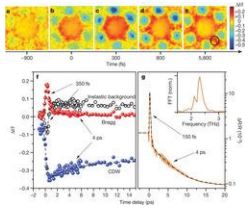
Daniele Fausti,

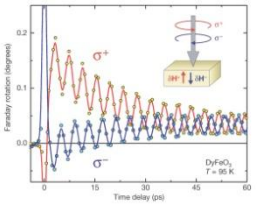
Elettra-Sincrotrone Trieste S. c. p. a. and University of Trieste

Time domain studies of complex materials

-Pump & Probe ⟶ Time resolved spectroscopies







- ✓Time Resolved x-rays and electron diffraction
- ✓TR Kerr, moke and X-MCD, Arpes
- ✓TR Spectroscopy, TRRaman

Phys. Rev. Lett., 106, 217401 (2011), Nature 468, 799–802, Nature 435, 655 (2005)

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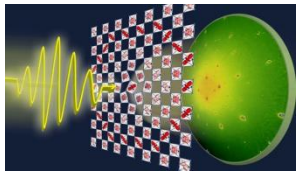

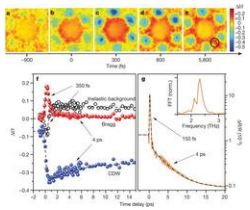

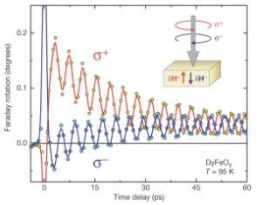

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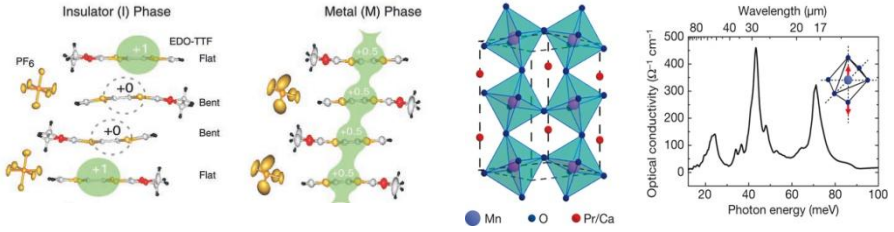
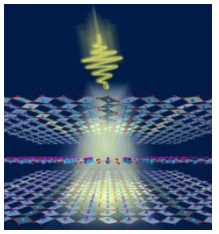
-Pump & Probe ⟹ Optical Control of Material



- ✓Photo-Induced phase transitions
- ✓Coherent control (IR and THz)
- ✓Light control of quantum coherent phases



Science 307, 2005, Nature 449(2007)

Science 331, 2011

Non-equilibrium "Parameters Space"

Pump

Equilibrium physics:

✓Adiabatic Vs. Non-adiabatic heat

Non-equilibrium physics:

✓Photo-induced phase transition

✓Wavelength *selectivity of the excitation processes*

&

Dephasing processes, coherent "artifacts", and **Coherent control**

Probe

Electronic Structure:

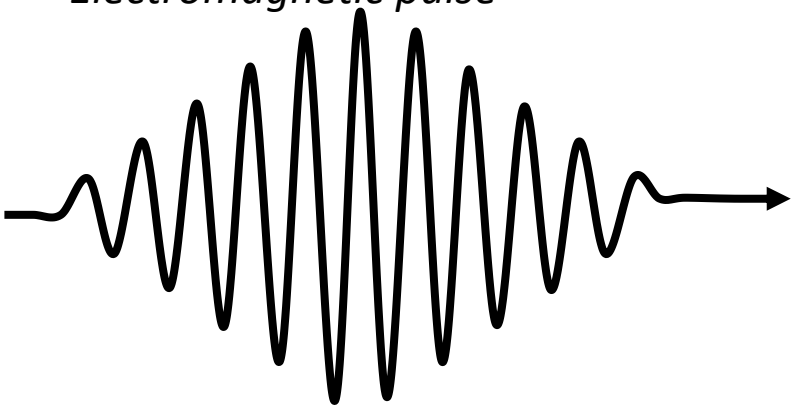
✓*Optical probes:* Refl., Absorption, MOKE, WL Spectroscopy, XAS, XMCD, **Probe quantum state**

✓*Electronic states:* Photoemission

✓*Structural probes*: Electron and x-ray diffraction

Pump & Probe

Electromagnetic pulse



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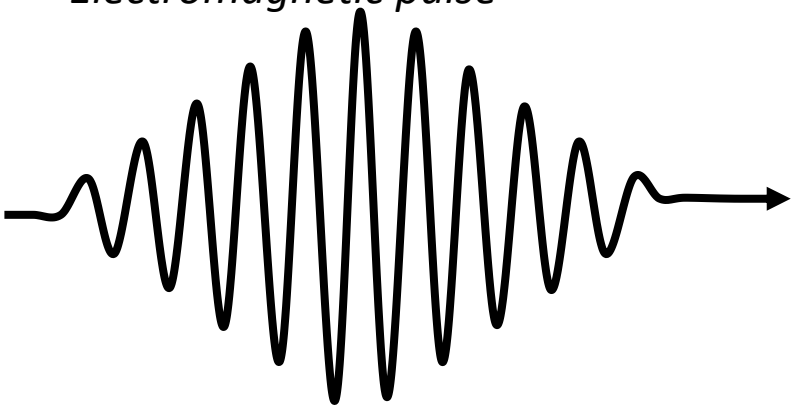
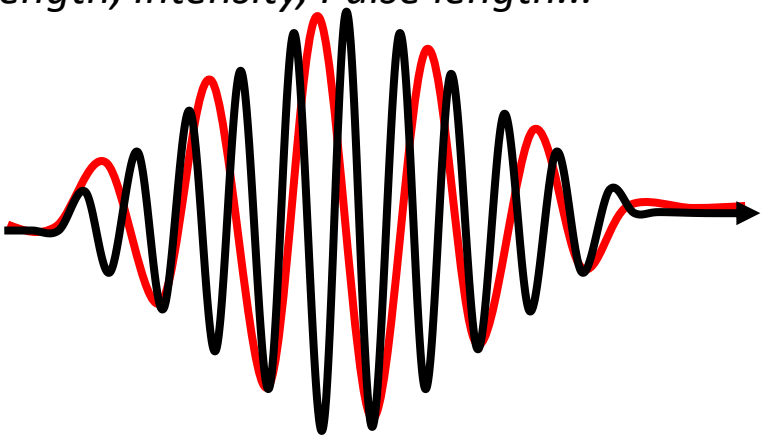


Wavelength, Intensity, Pulse length...



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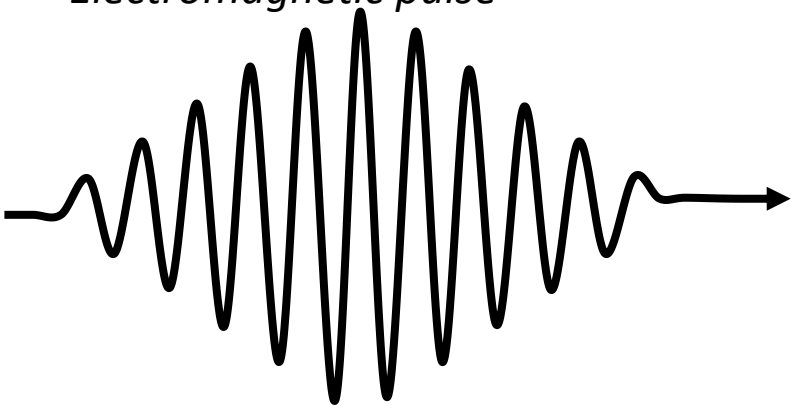
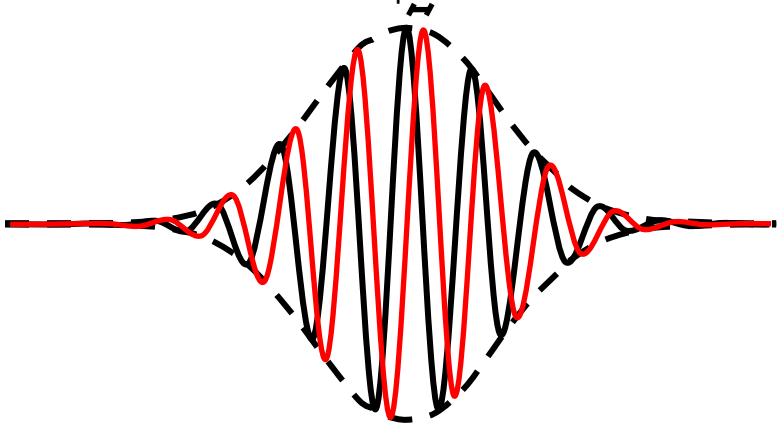


Carrier Envelope Phase

$\Delta\phi=\pi/2$



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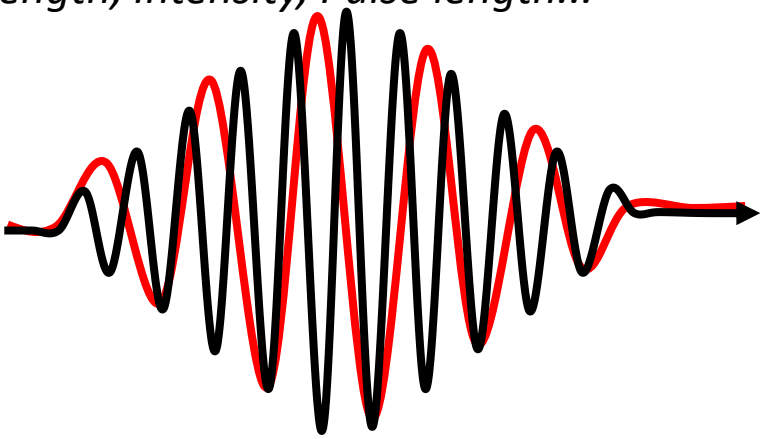
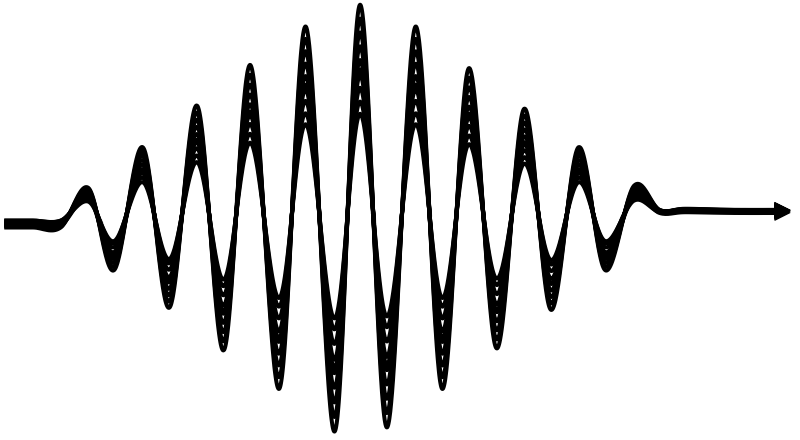


Quantum State of the e.m. Field

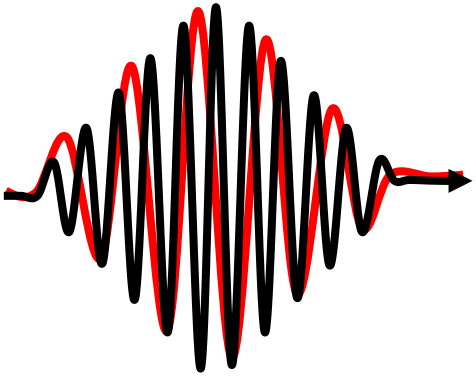


Outline

Witnessing quasi-particles in strongly correlated electron systems

- High Vs. Low-photon energy excitation in CTI La_2CuO_4

Nat. Comm. 5, 5112, 2014

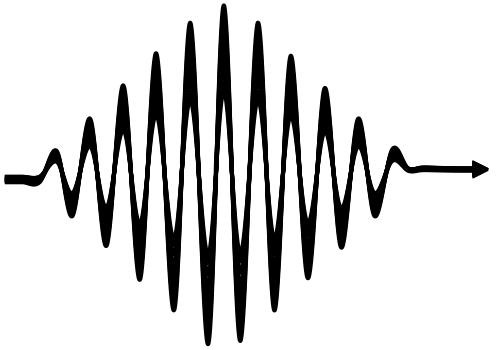


Towards selective excitations of low energy modes

- Phonon pump and dd-transitions probe in CuGeO3

Quantum Optics for studying ultra-fast processes in Condensed Matter

- Balanced Homodyne Detection
- Impulsive phonon excitation: the case of quartz
- Time evolution of the probe quantum state after the interaction with the material



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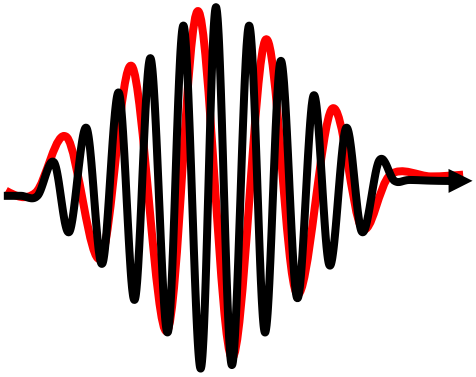

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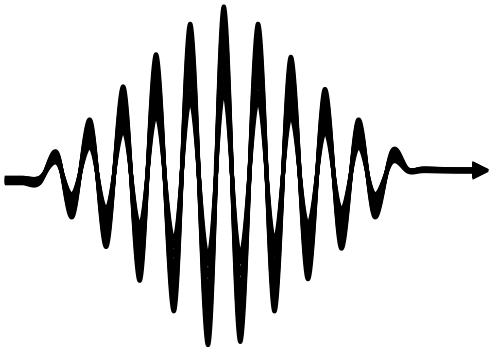
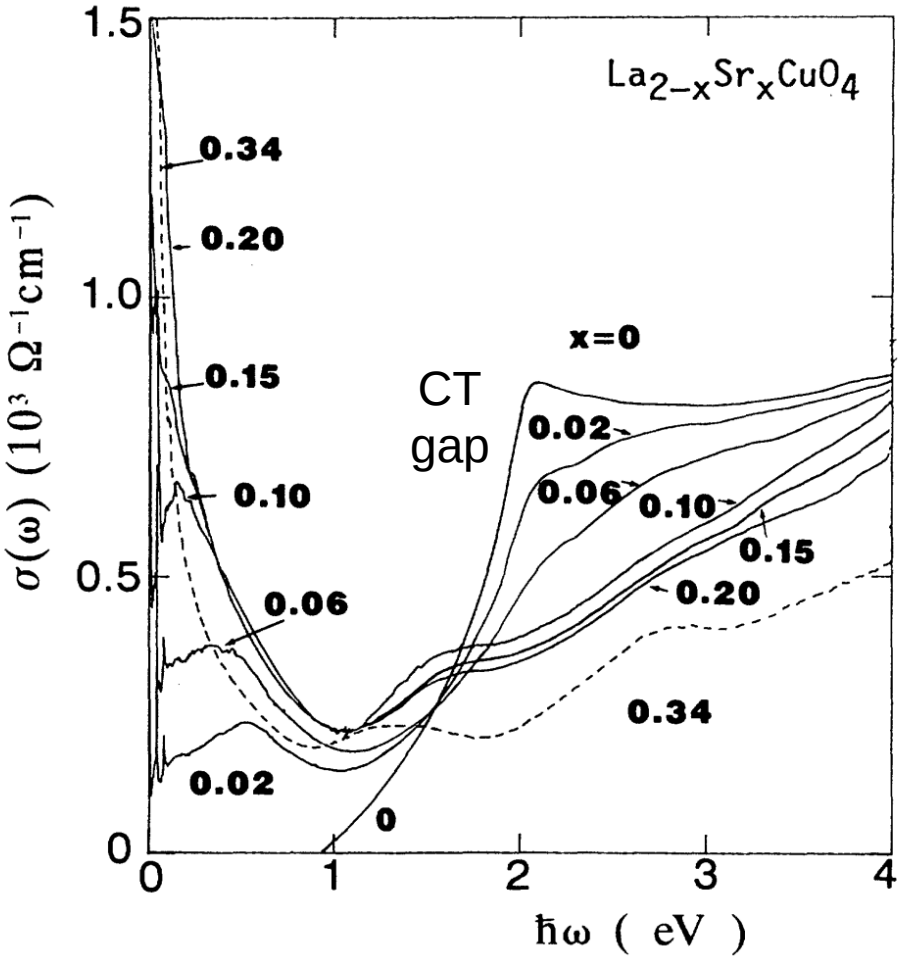


Optical properties of $La_{2-x}Sr_xCuO_4$



PRB 43 7942 1991

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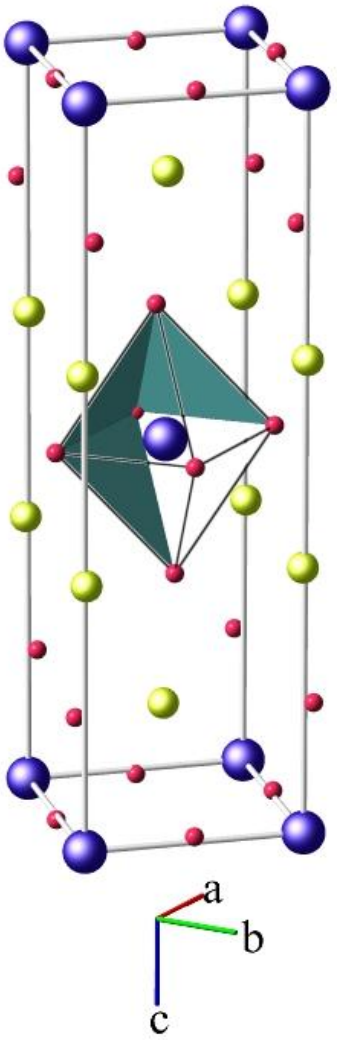
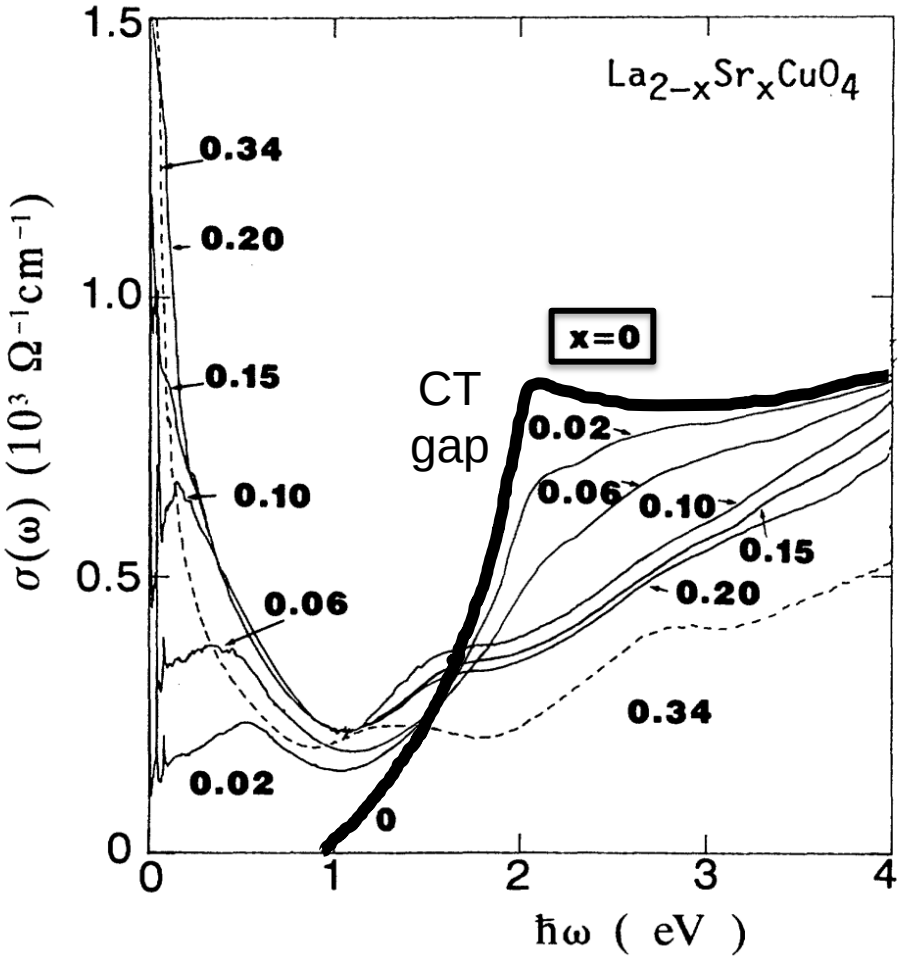
La_2CuO_4





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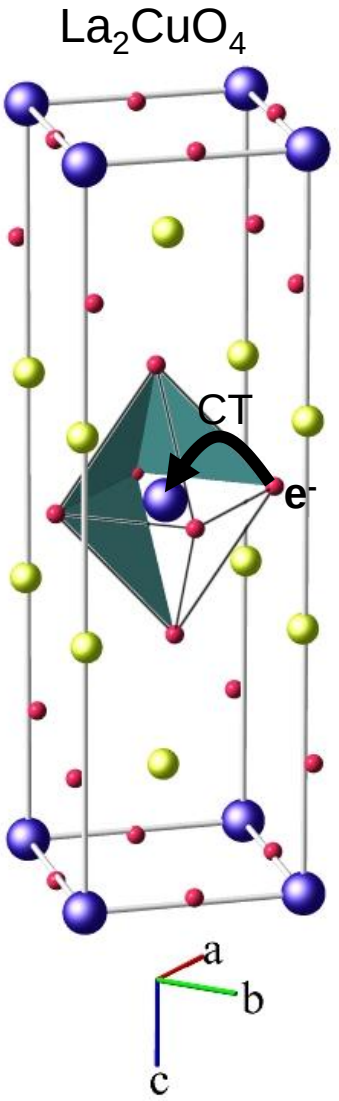

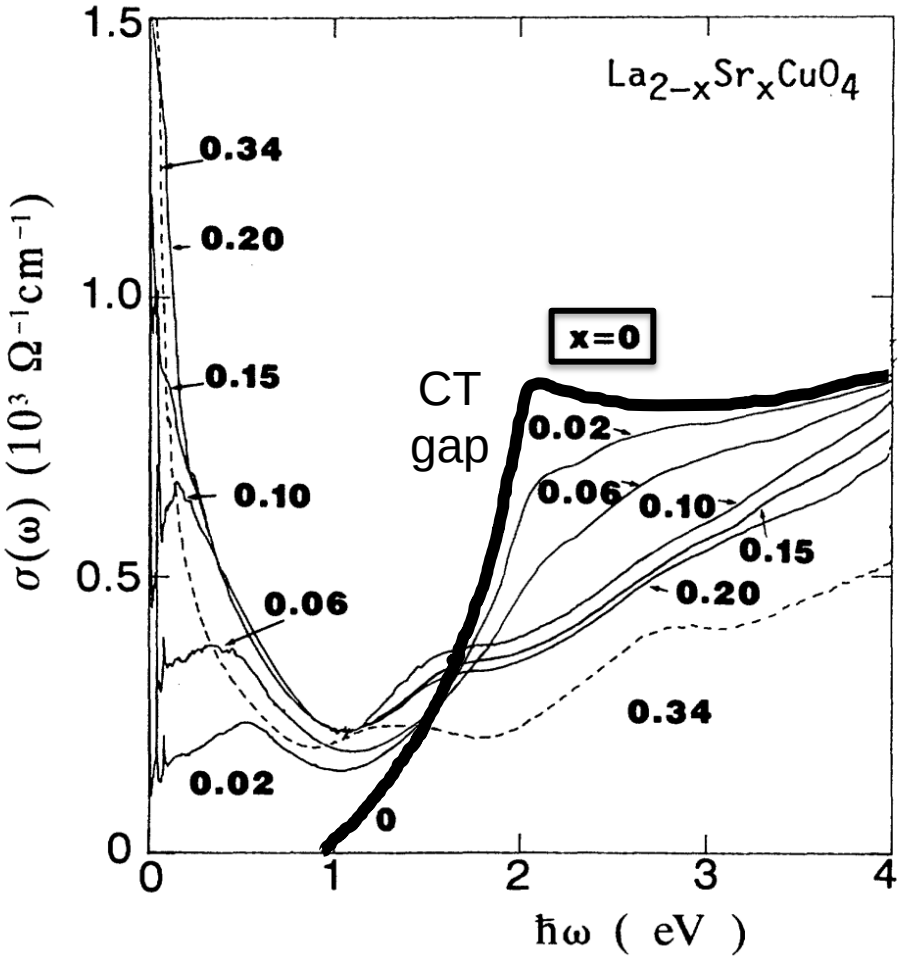

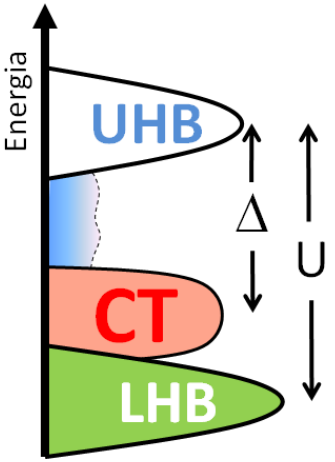

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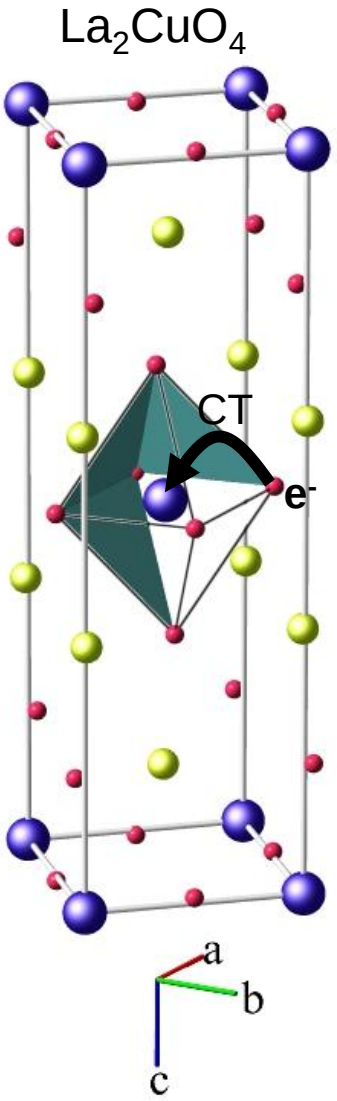

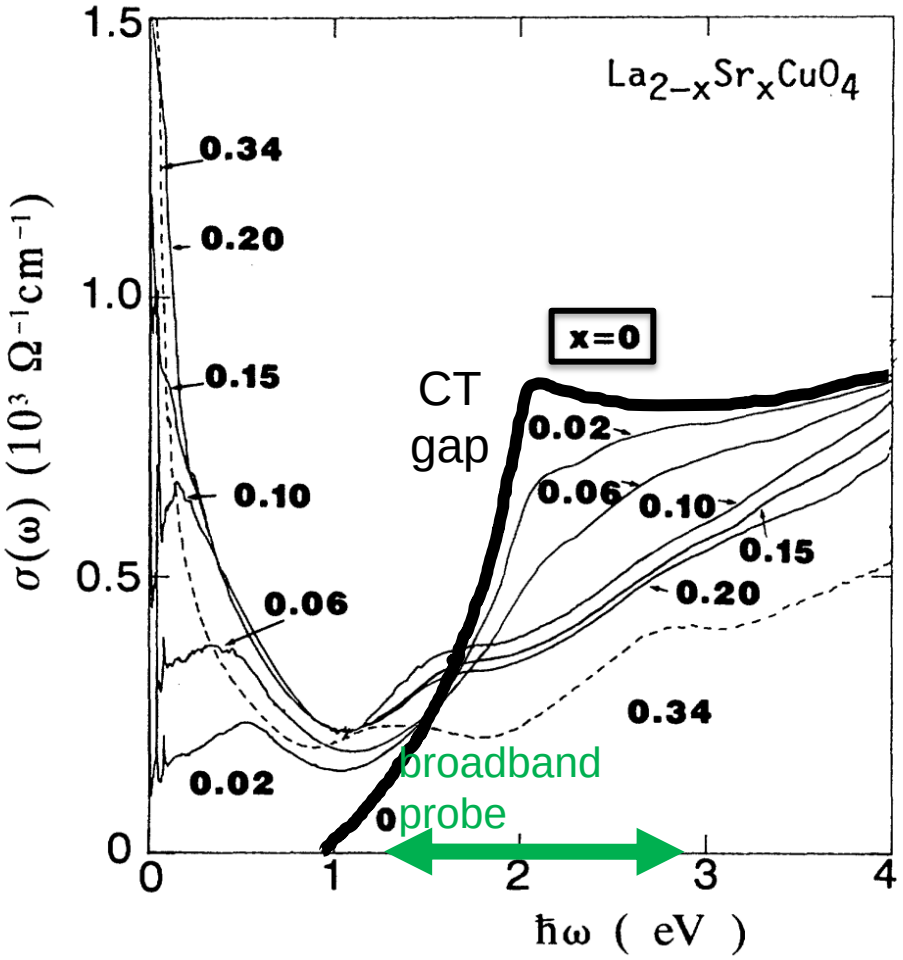

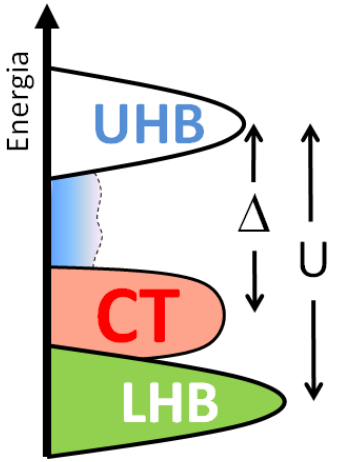

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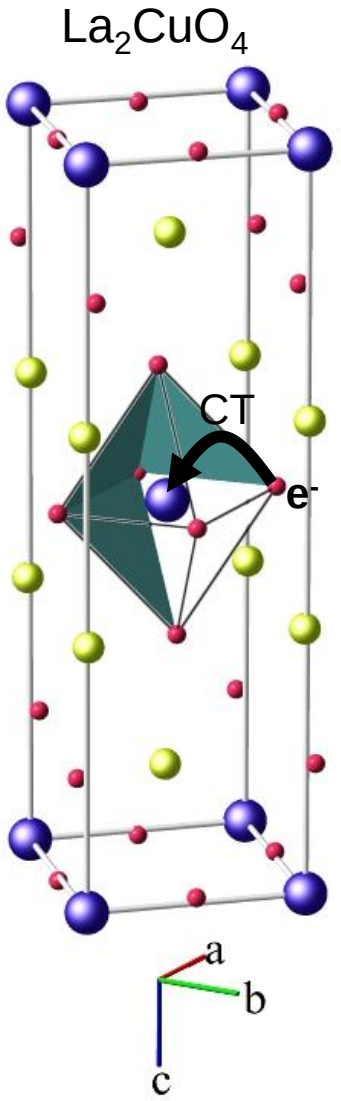

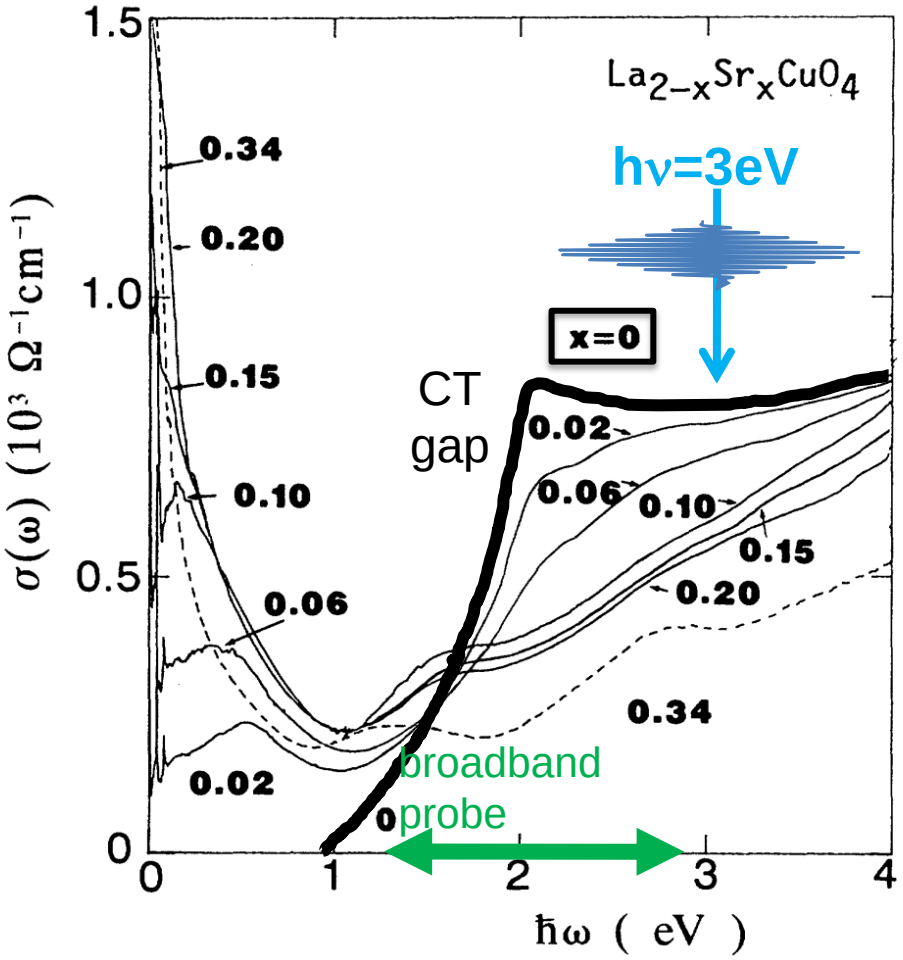

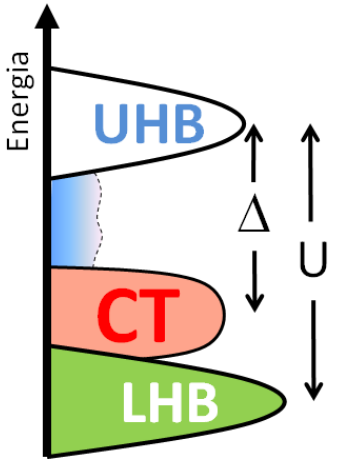

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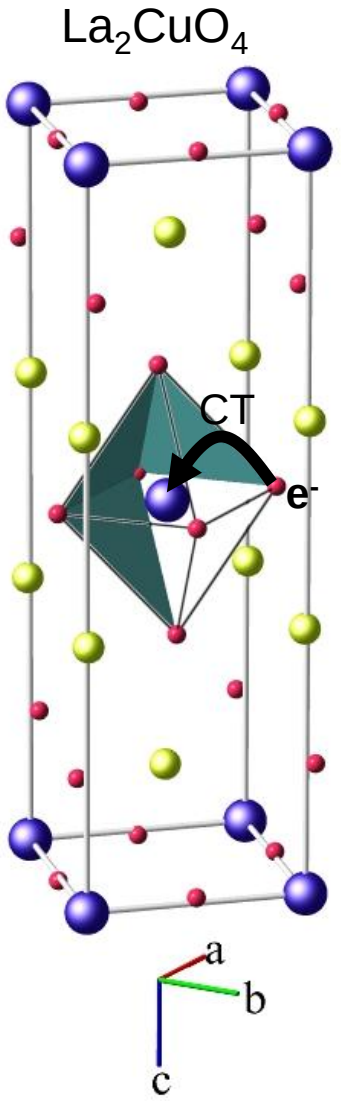

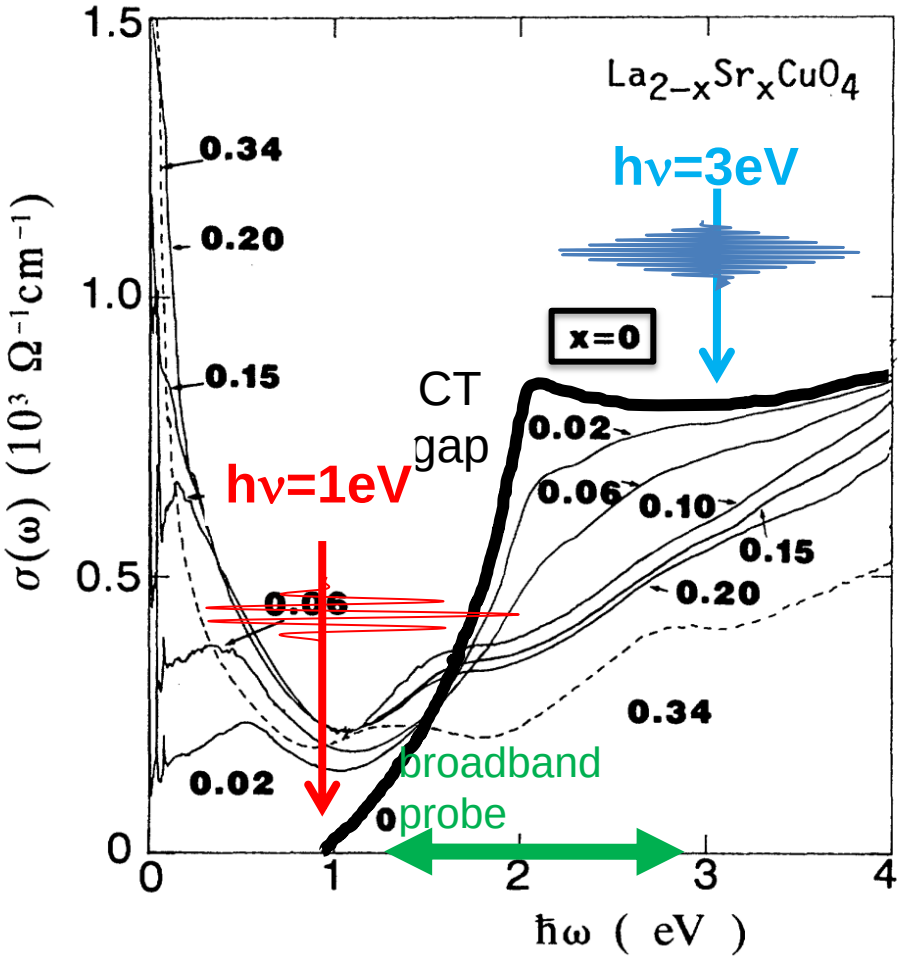

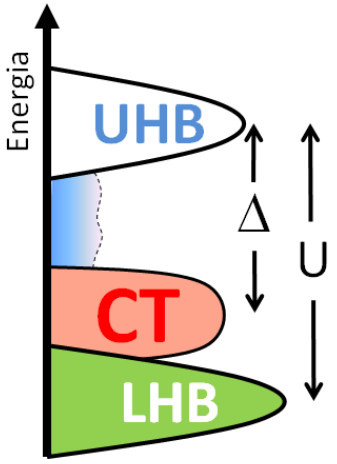

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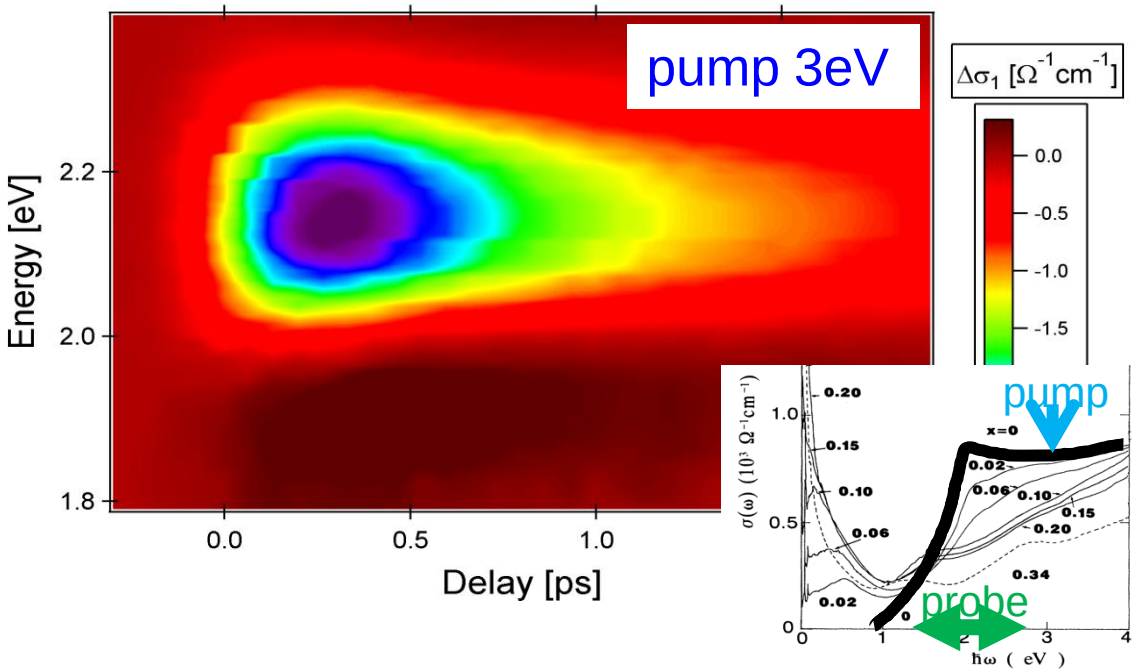
Selectivity of the excitation process



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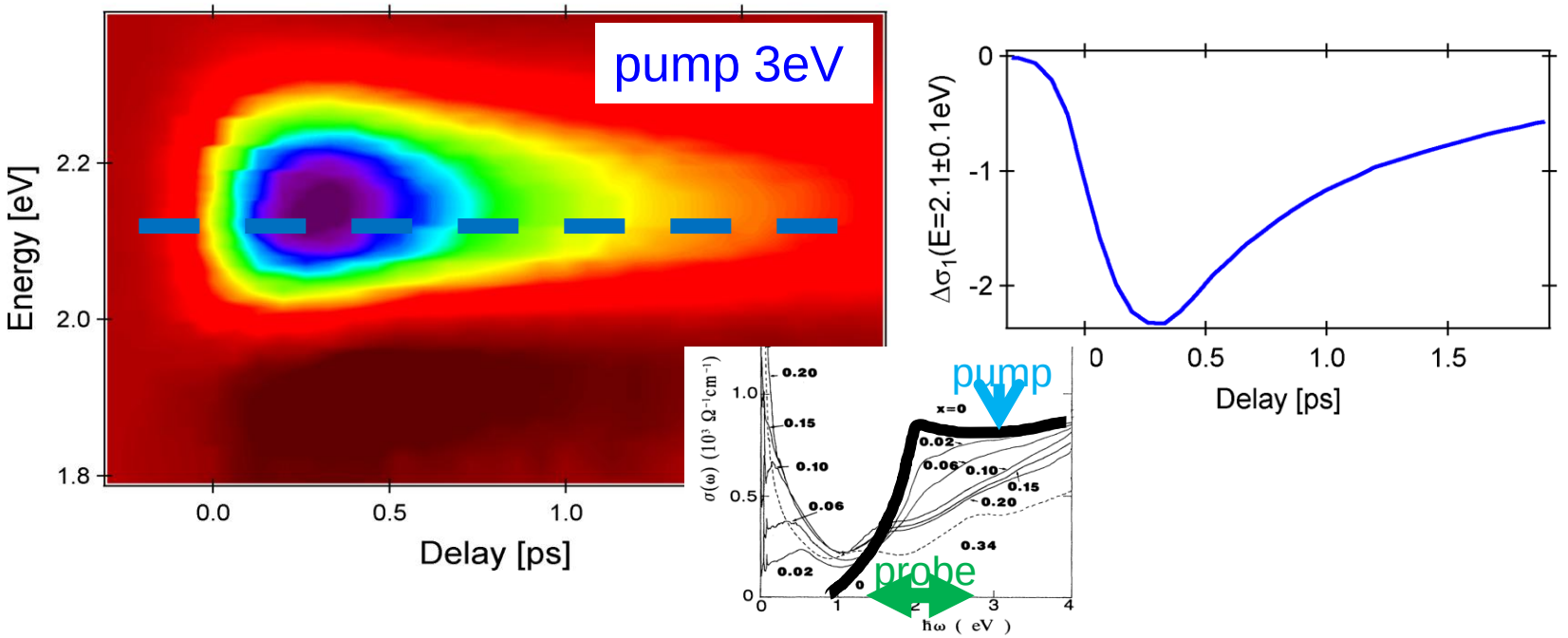

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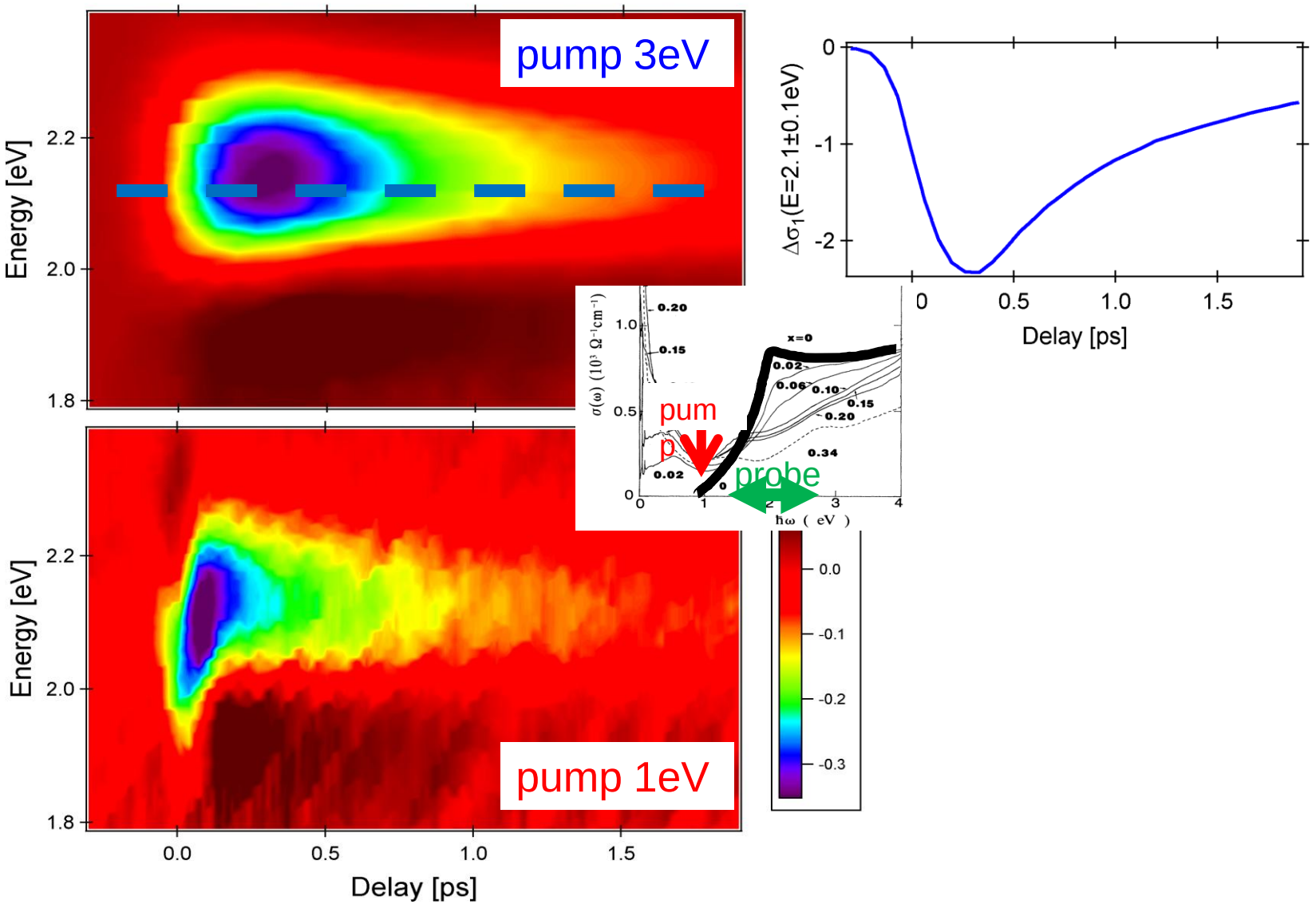

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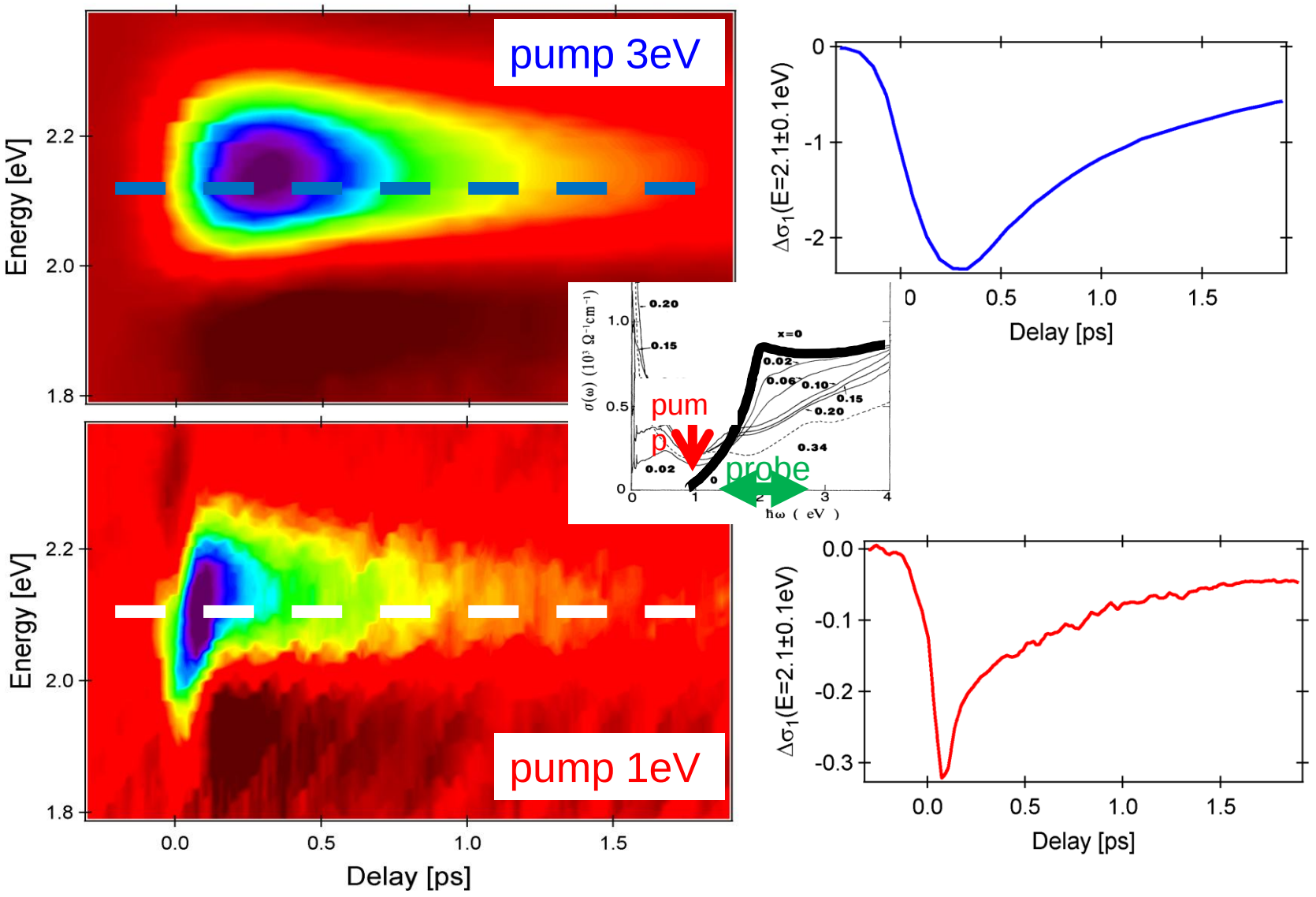

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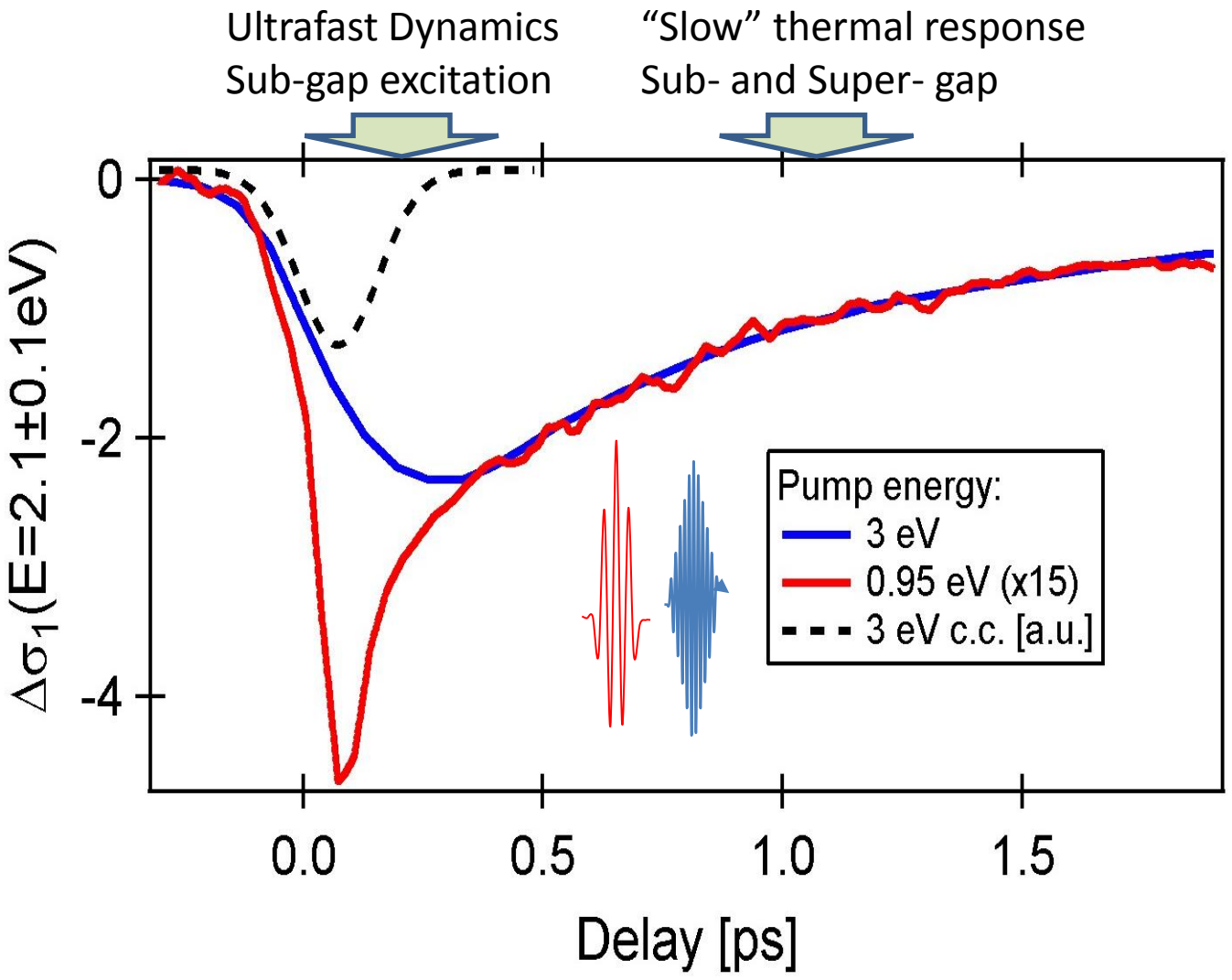

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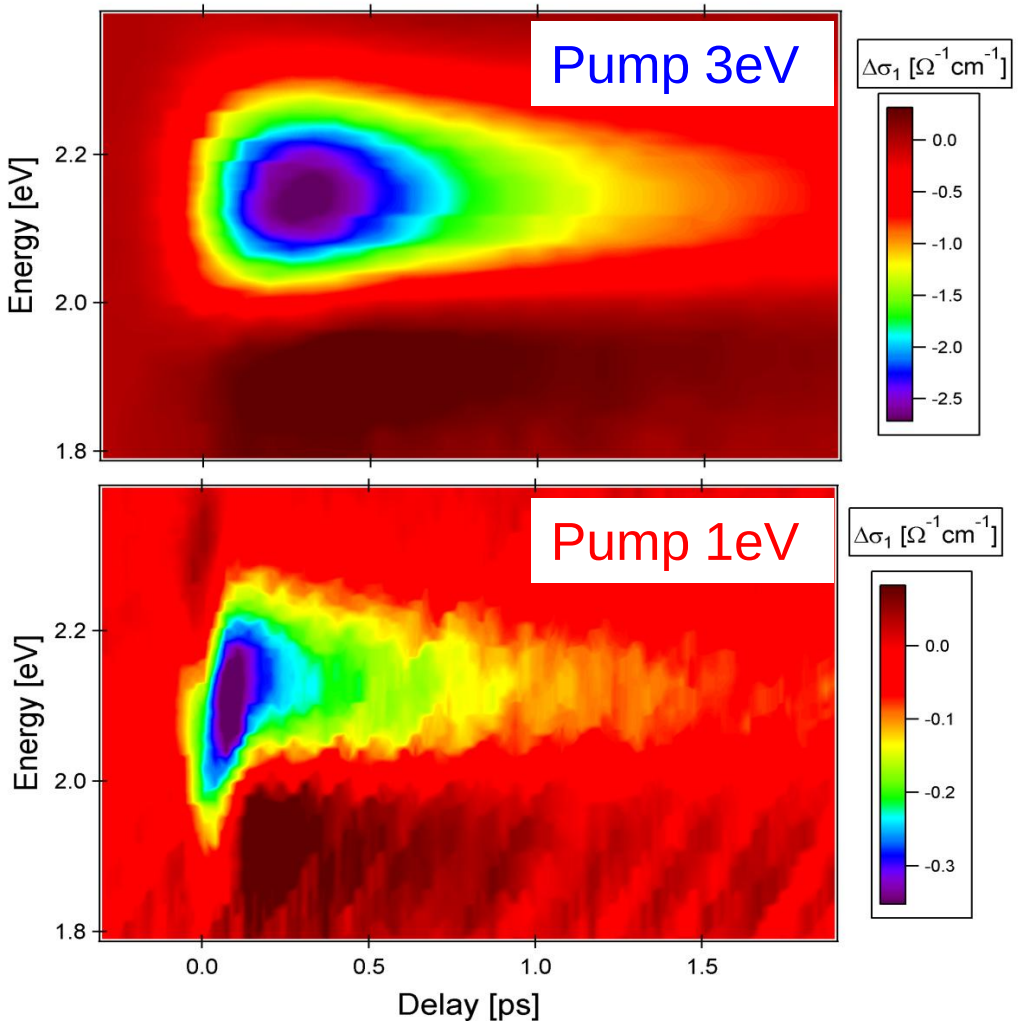

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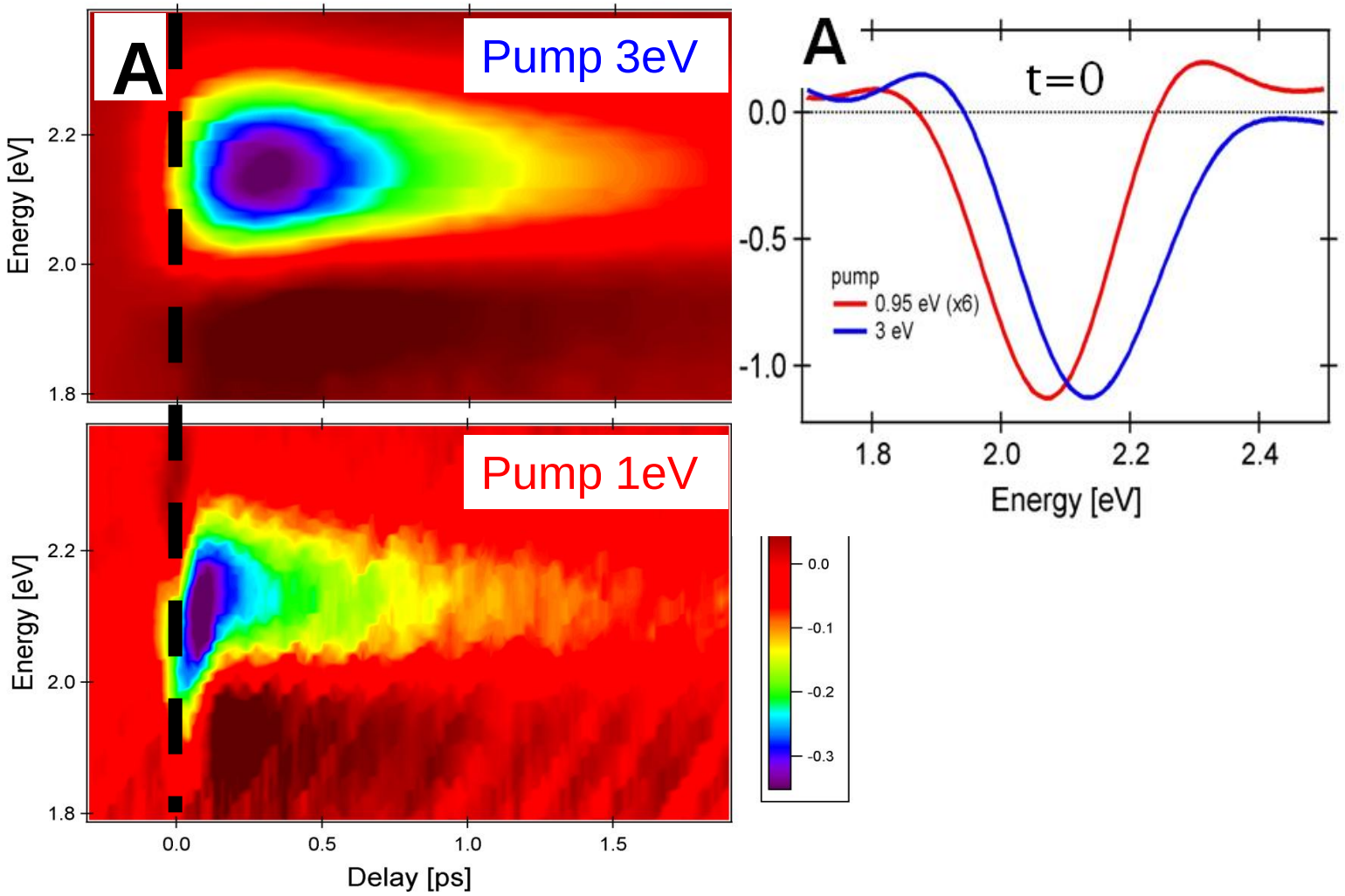

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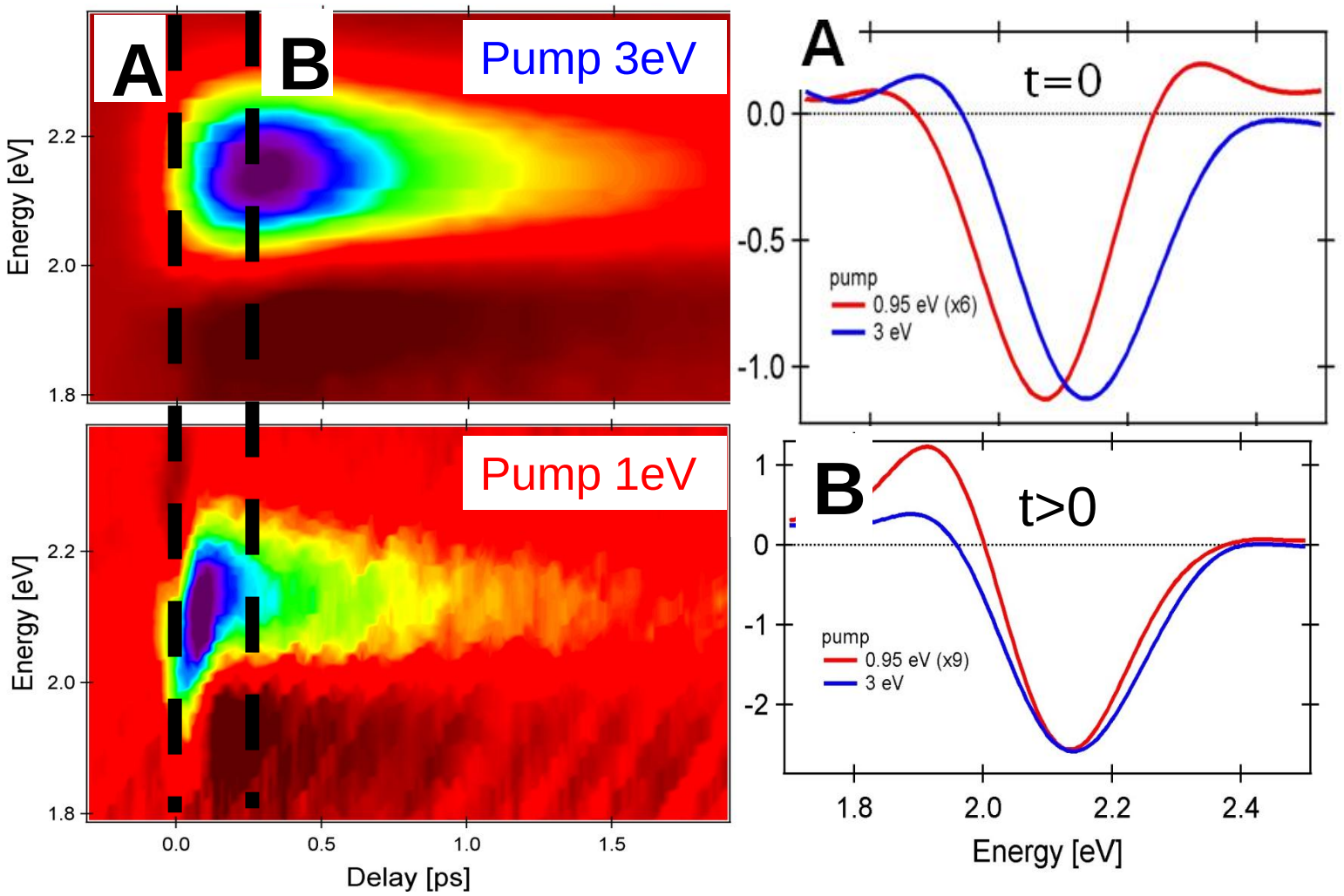

Hubbard Holstein Hamiltonian

$$H = H_t + H_U + H_{EPI}$$

$$H_t = -t \sum_{i,\mu,\sigma} (\quad c^{\dagger}_{i+\mu,\sigma} c_{i,\sigma} + H.c.),$$ ← Hopping

$$H_U = U \sum_i (n_{i,\uparrow} - \frac{1}{2})(n_{i,\downarrow} - \frac{1}{2}),$$ ← e-e repulsion

$$H_{EPI} = \omega_0 \sum_i a_i^{\dagger} a_i + g\omega_0 \sum_i (a_i^{\dagger} + a_i)(1 - n_i).$$ ← Boson coupling

collaboration with N. Nagaosa, A. Mishchenko, G. De Filippis and V. Cataudella

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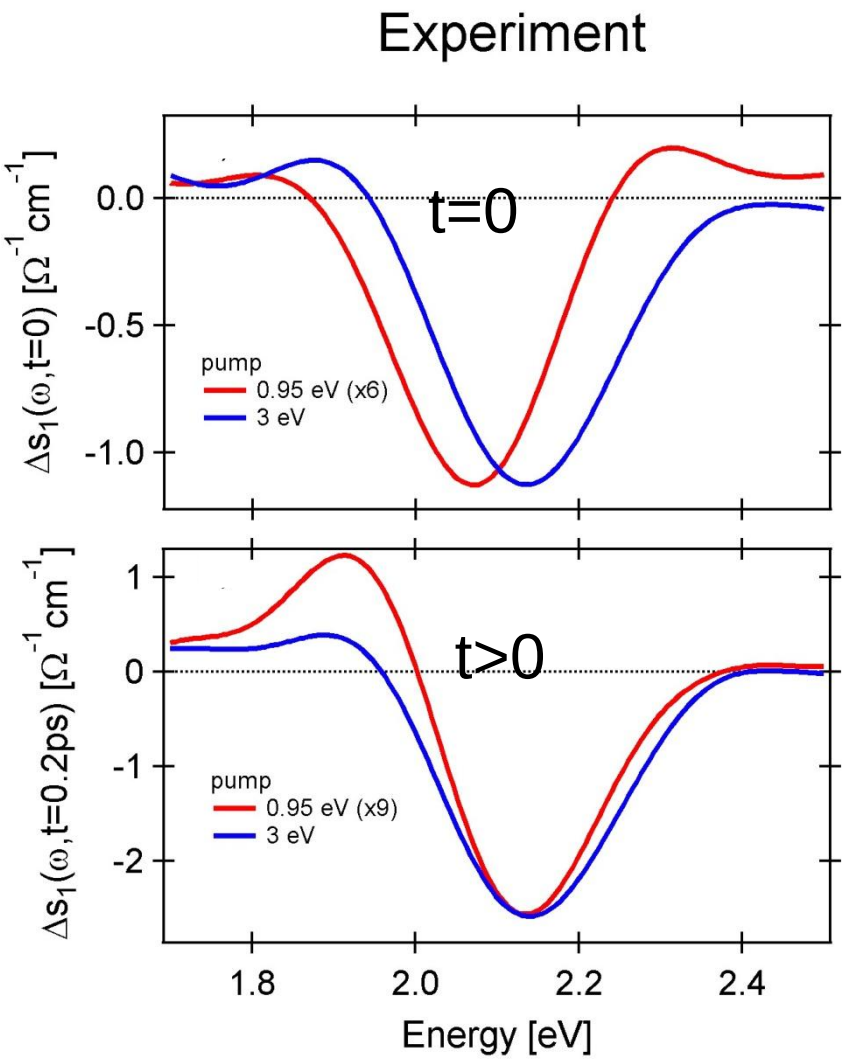
Experiment Vs. Theory



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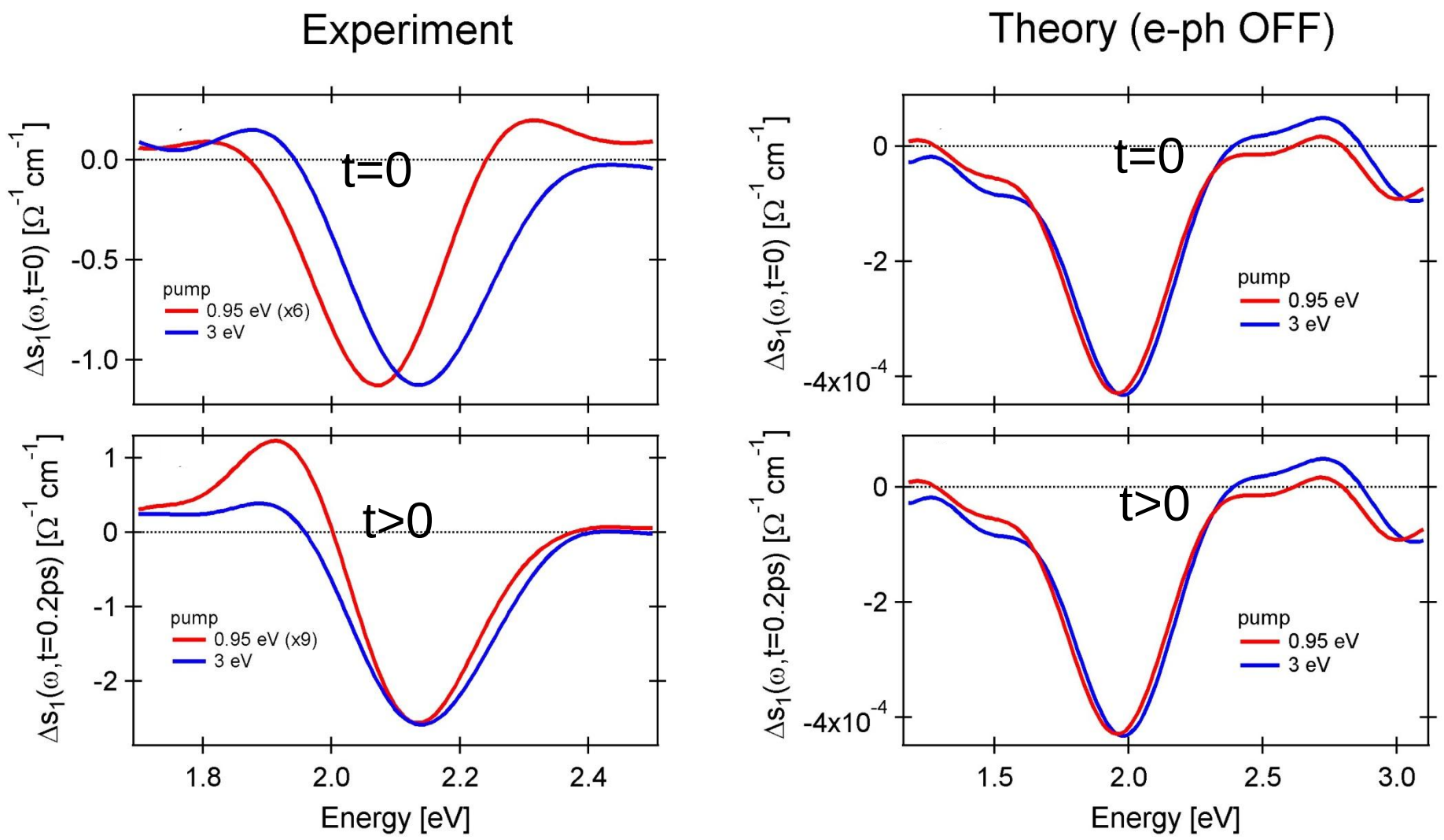

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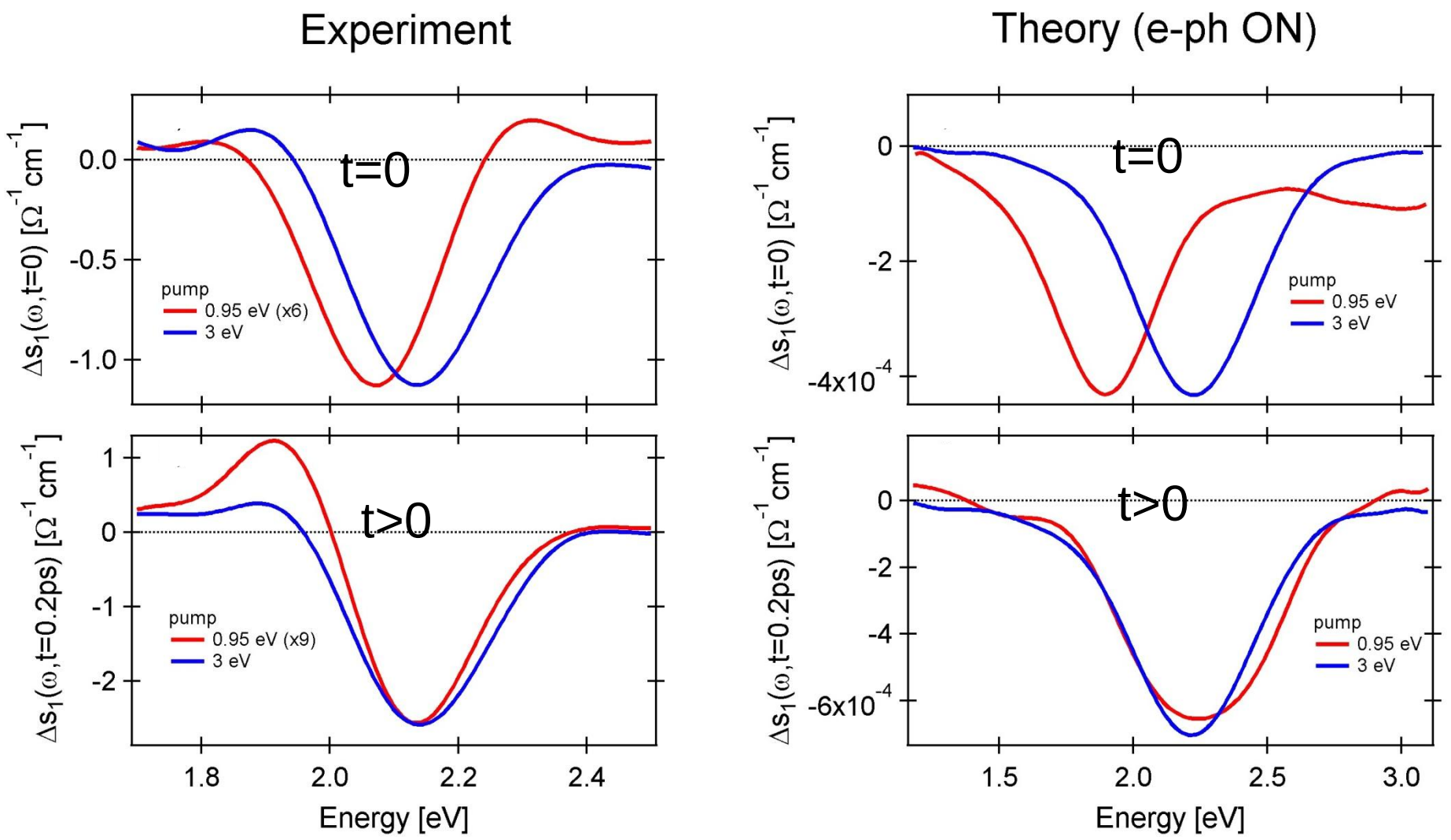
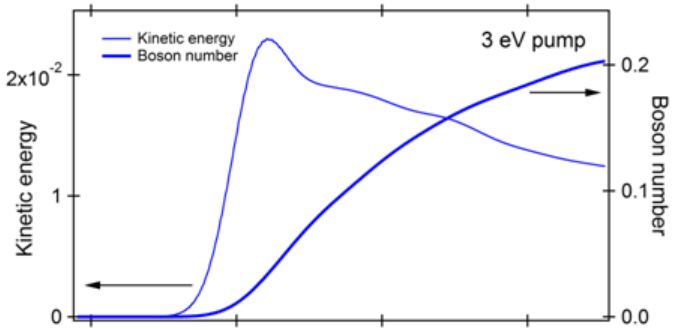
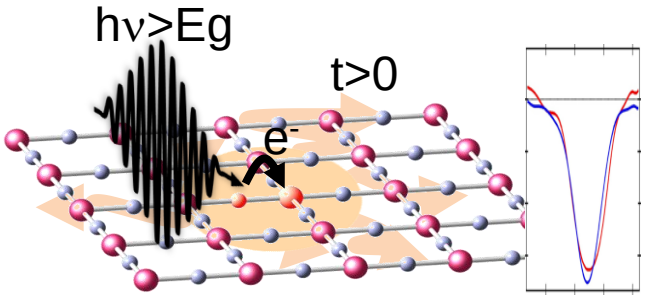


High Vs. Low-photon energy excitation





Incoherent Dressing

Nat. Comm. 5, 5112, 2014

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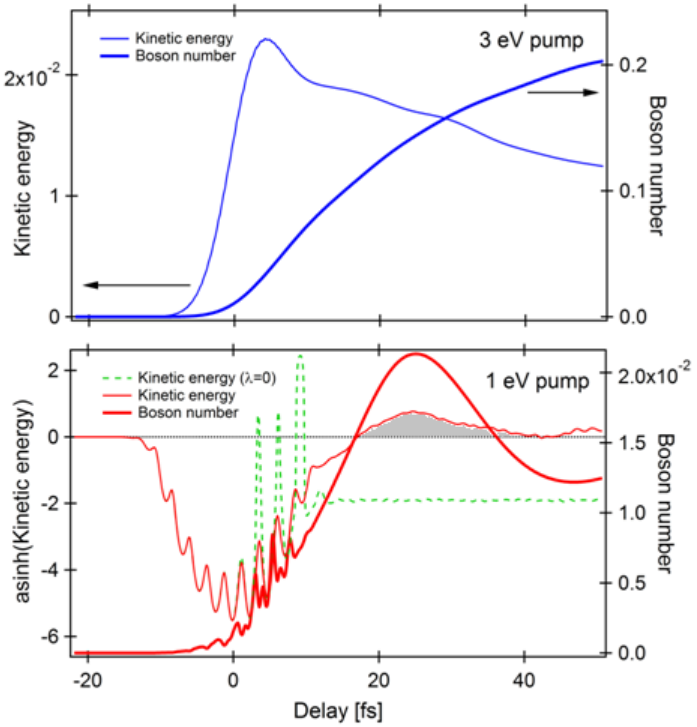

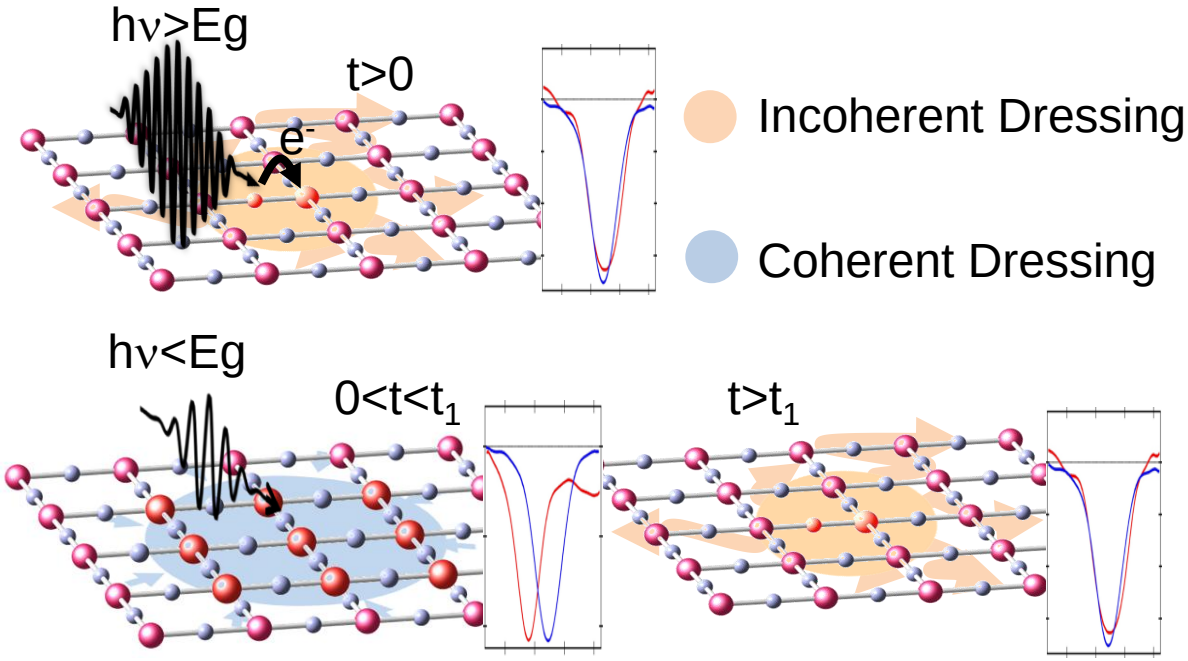

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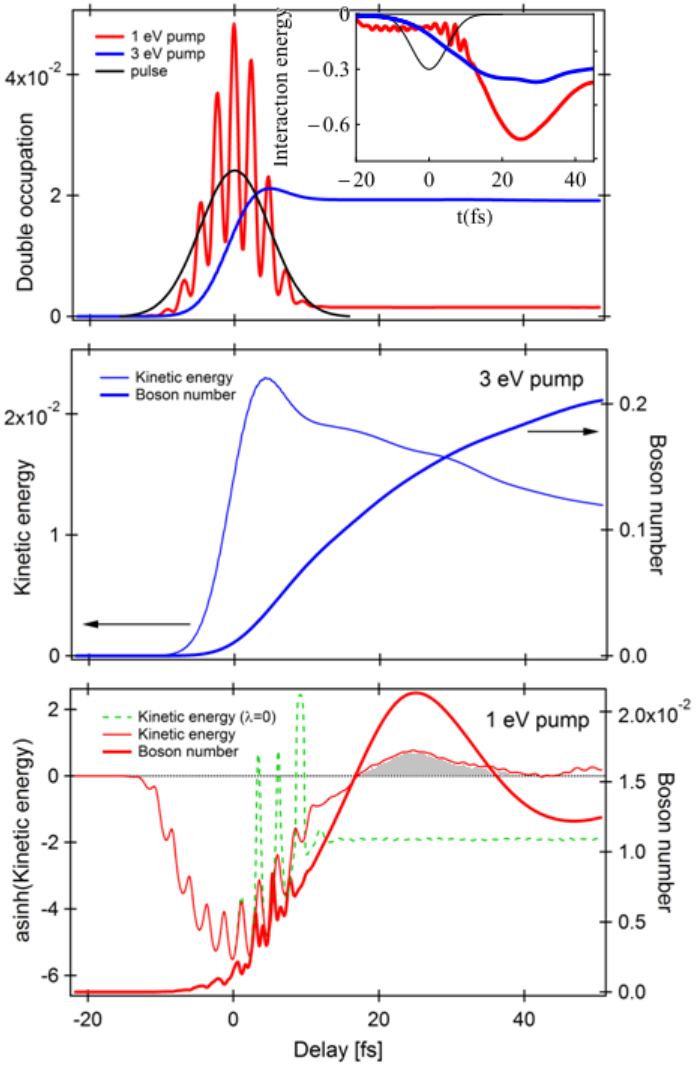

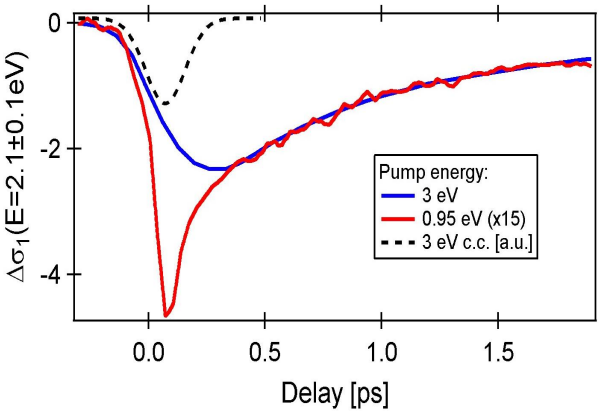

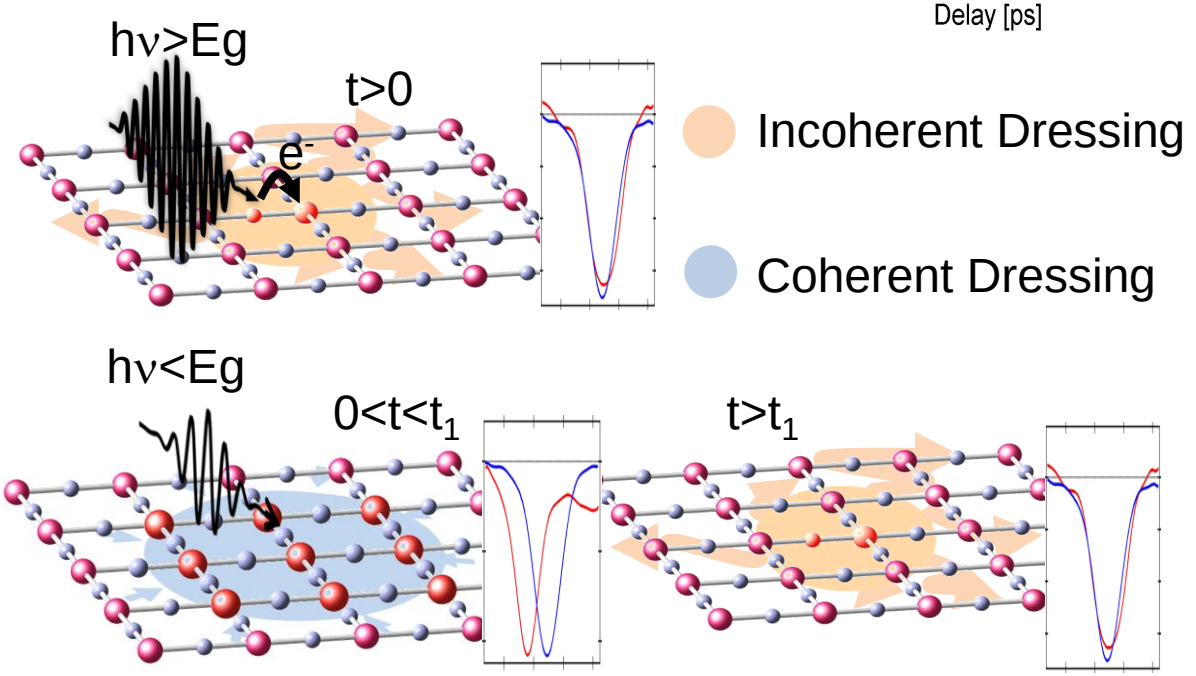

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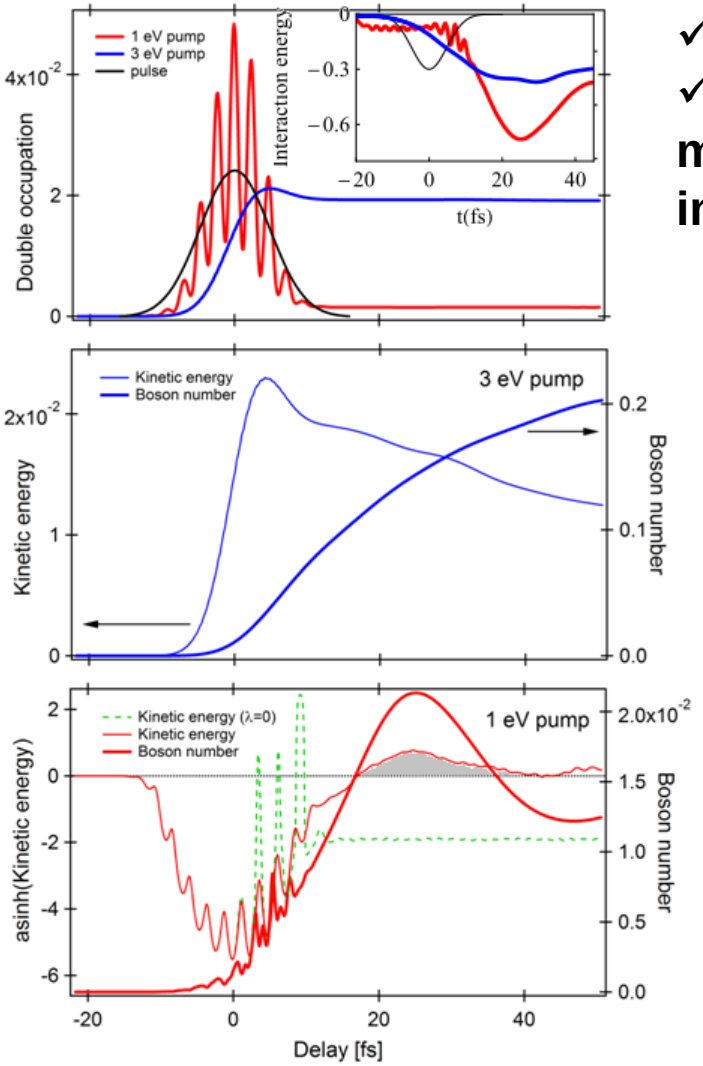
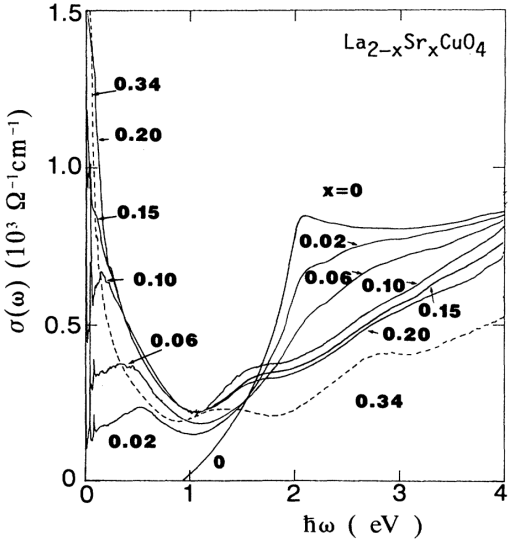
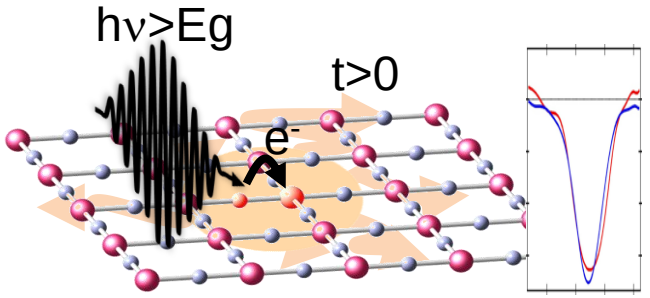
High Vs. Low-photon energy excitation



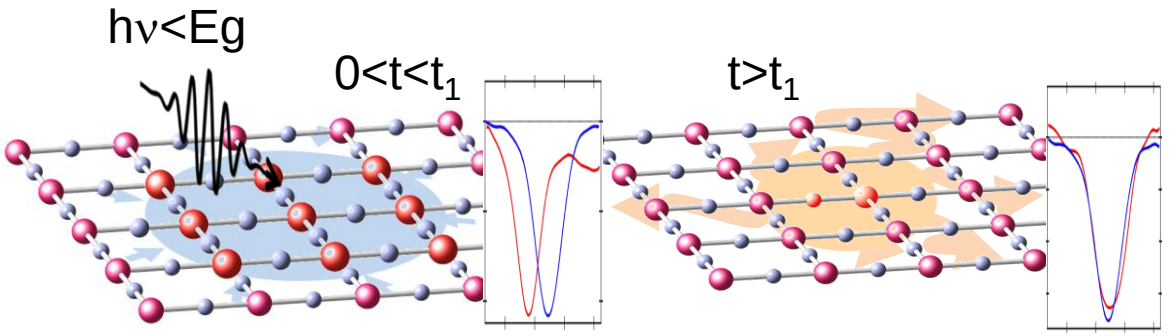
- ✓The boson is necessary
- ✓Will this excitation mechanism influence response in conducting systems?





Incoherent Dressing

Coherent Dressing



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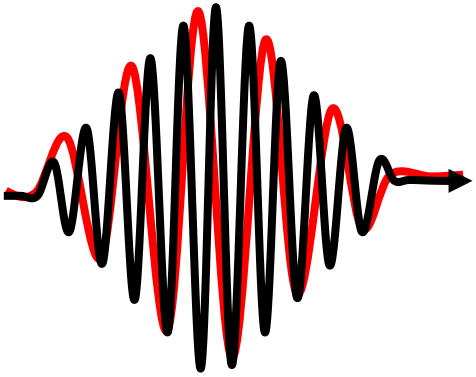
Outline

Witnessing quasi-particles in strongly correlated electron systems

- **High Vs. Low-photon energy excitation in CTI La_2CuO_4**

Towards selective excitations of low energy modes

- **Phonon pump and dd-transitions probe in $CuGeO_3$**



Quantum Optics for studying ultra-fast processes in Condensed Matter

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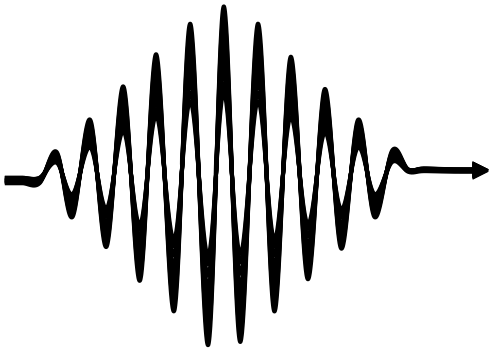
- **Impulsive phonon excitation: the case of quartz**
- **Time evolution of the probe quantum state after the interaction with the material**



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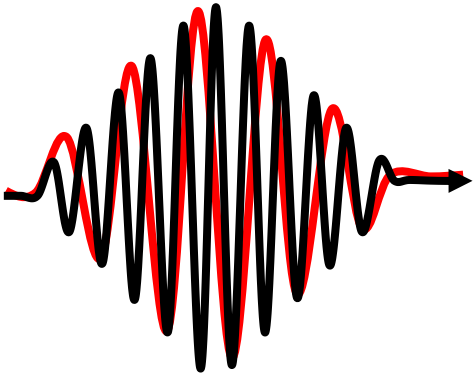

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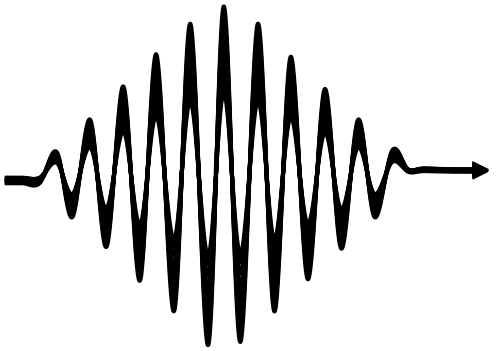

Phonon Pump in CuGeO3

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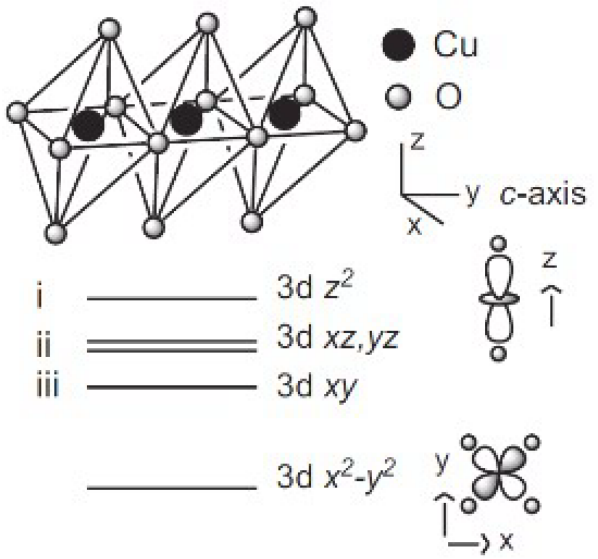

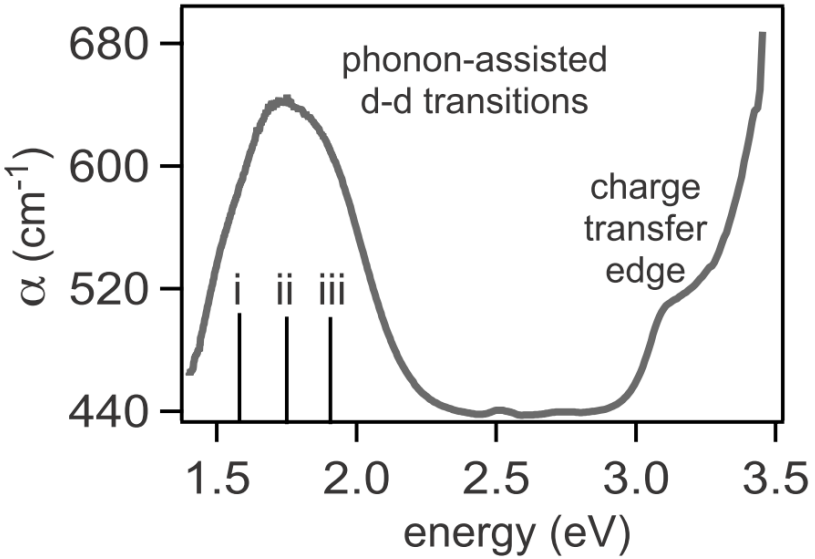

Prb, 80, 235139

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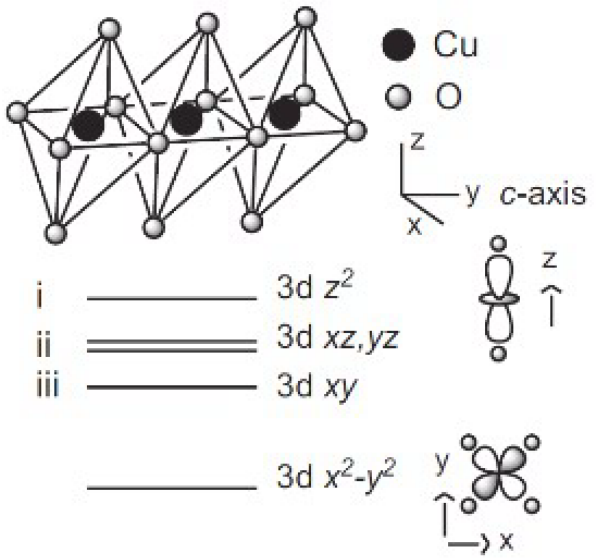

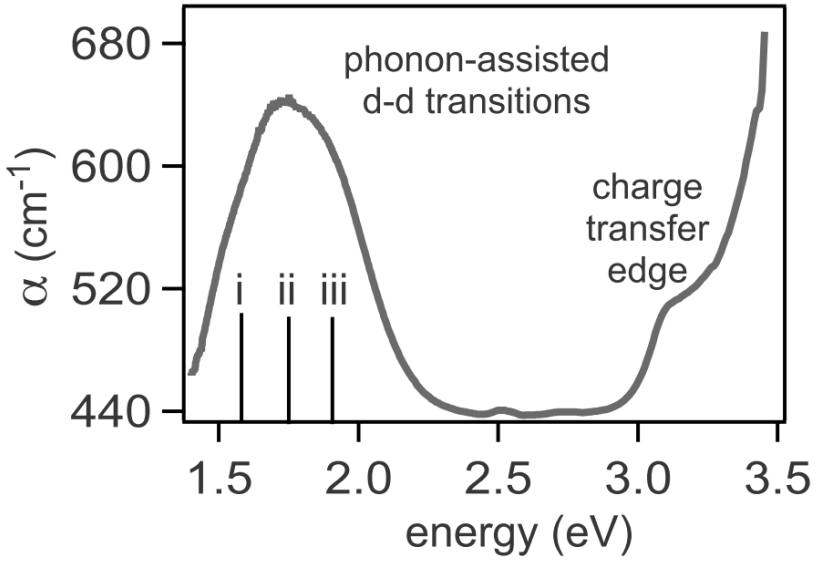

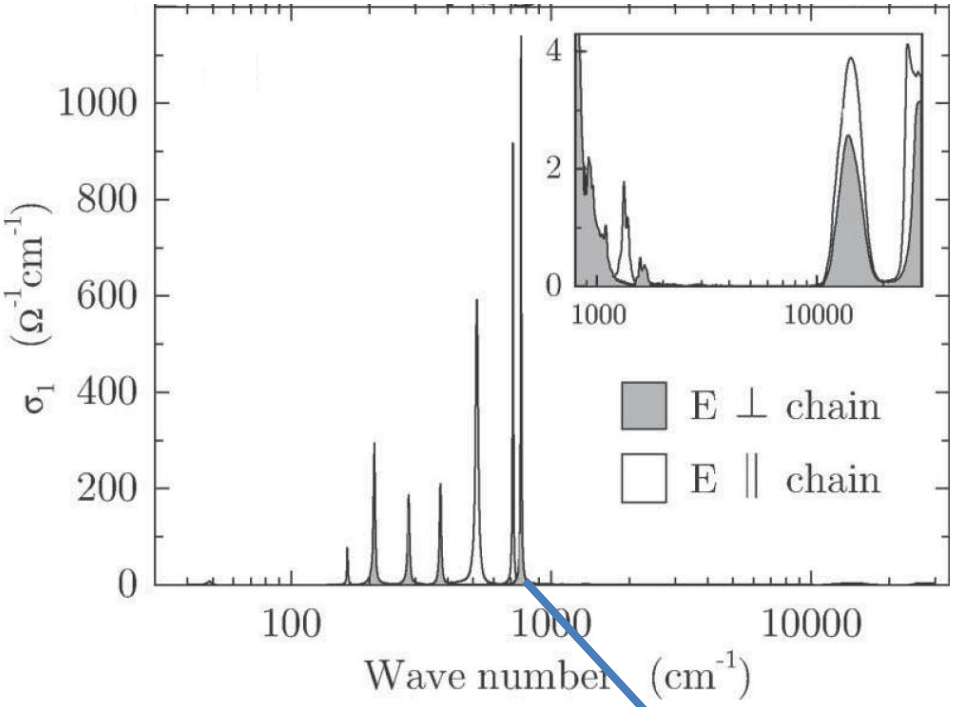

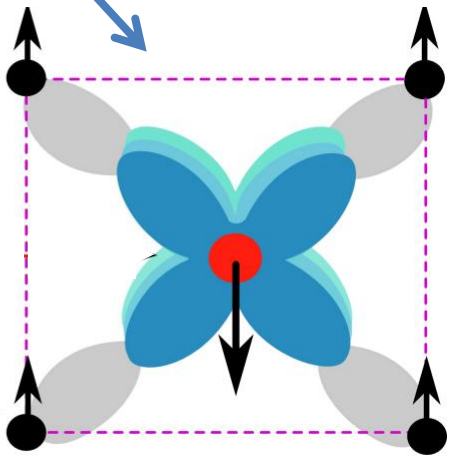

Prb, 80, 235139; Prb, 61, 12063

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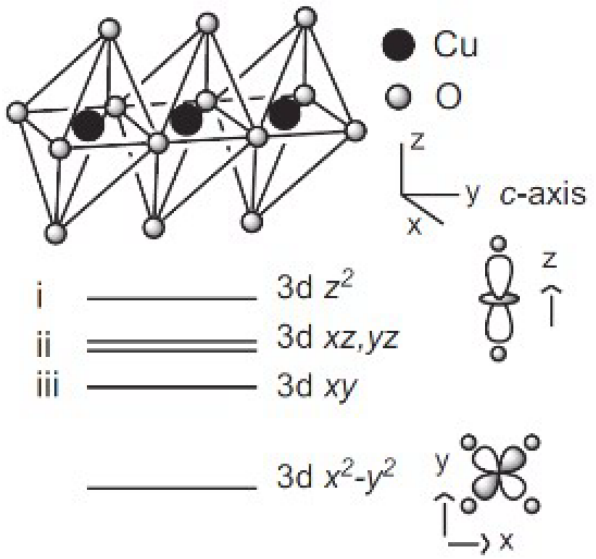

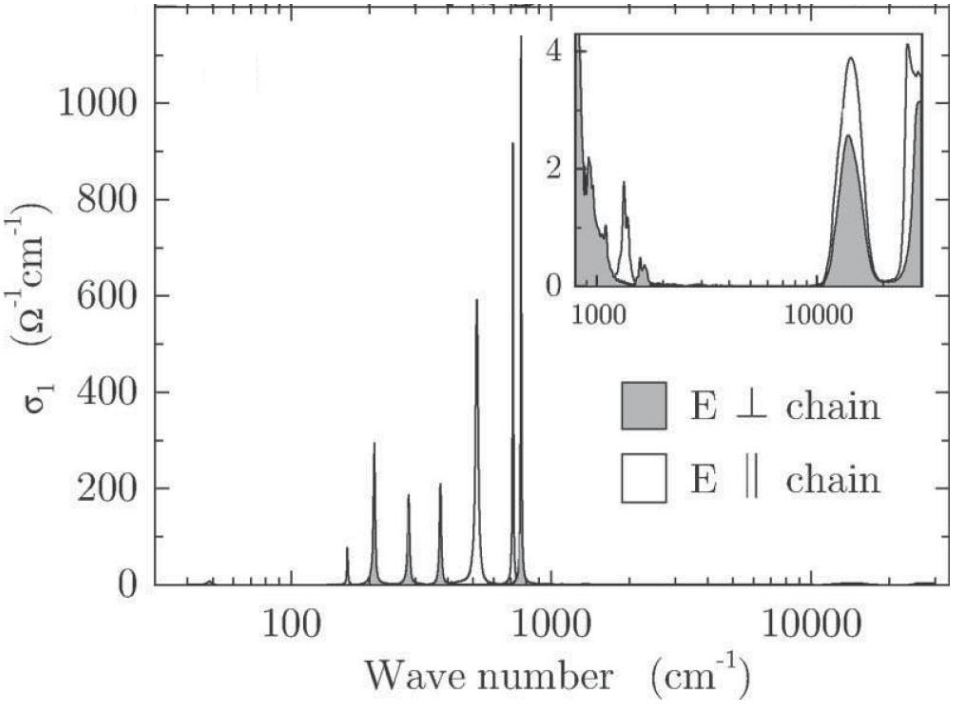

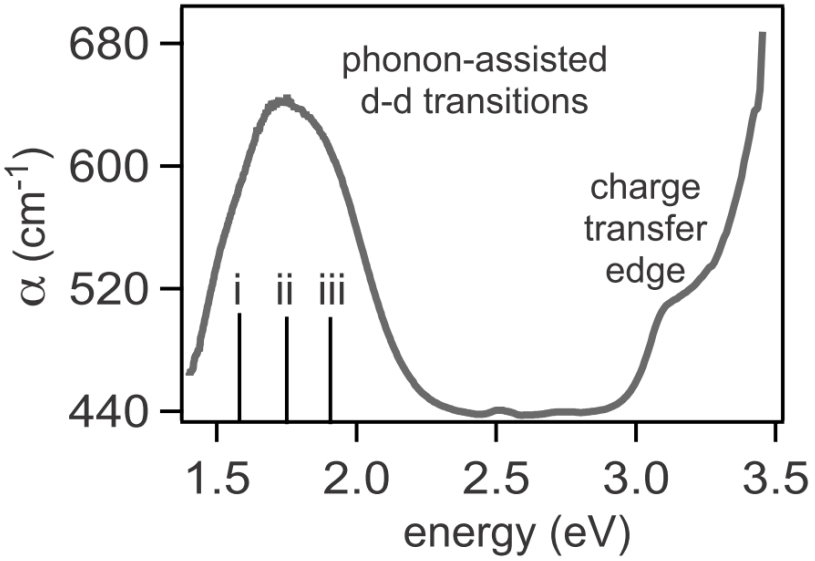

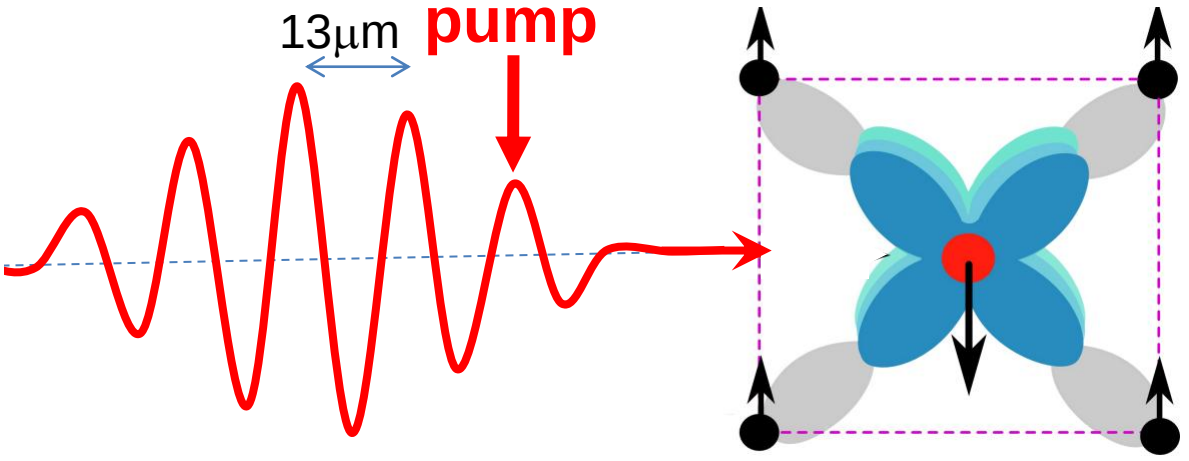

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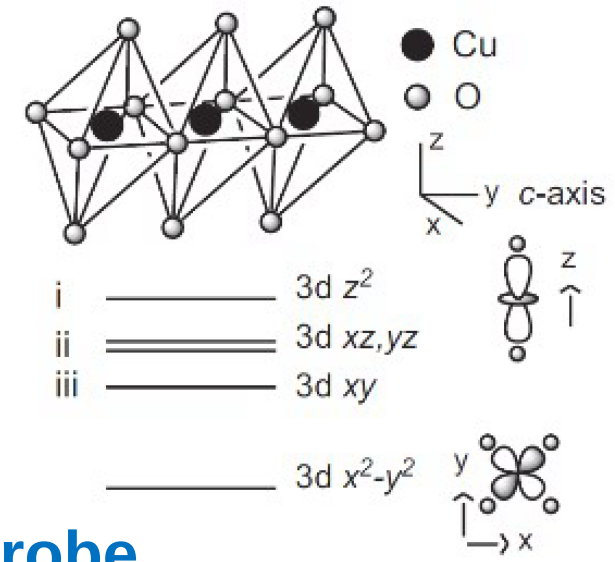

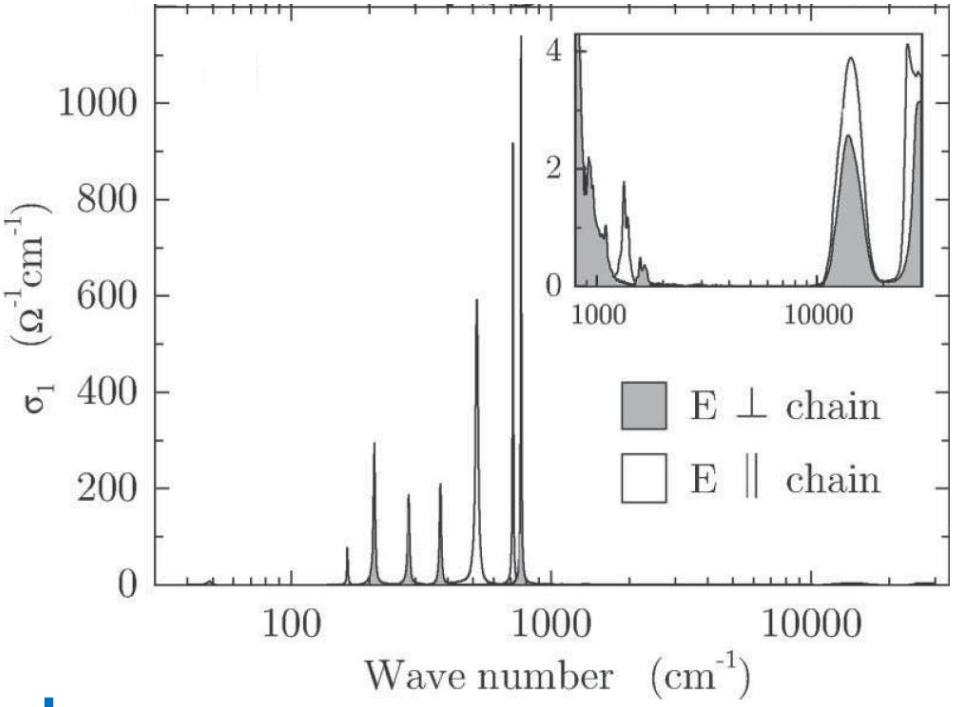

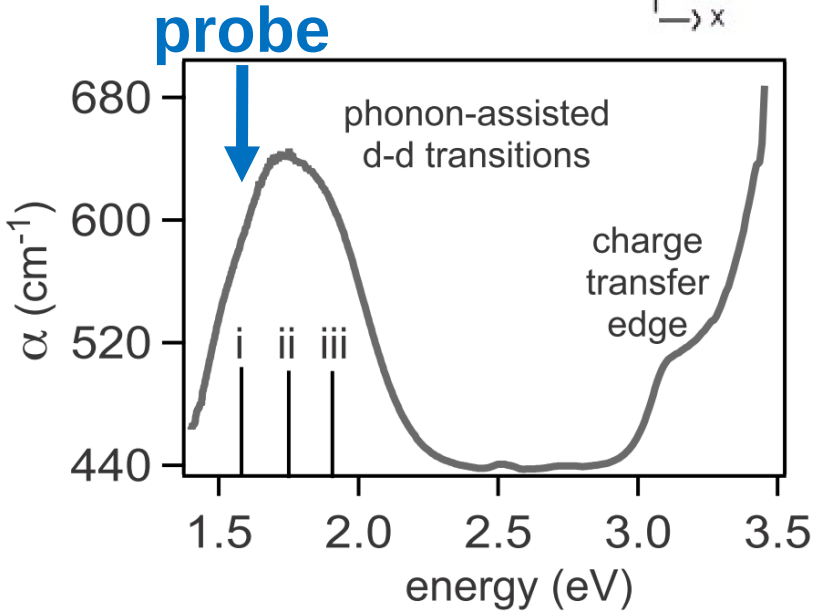

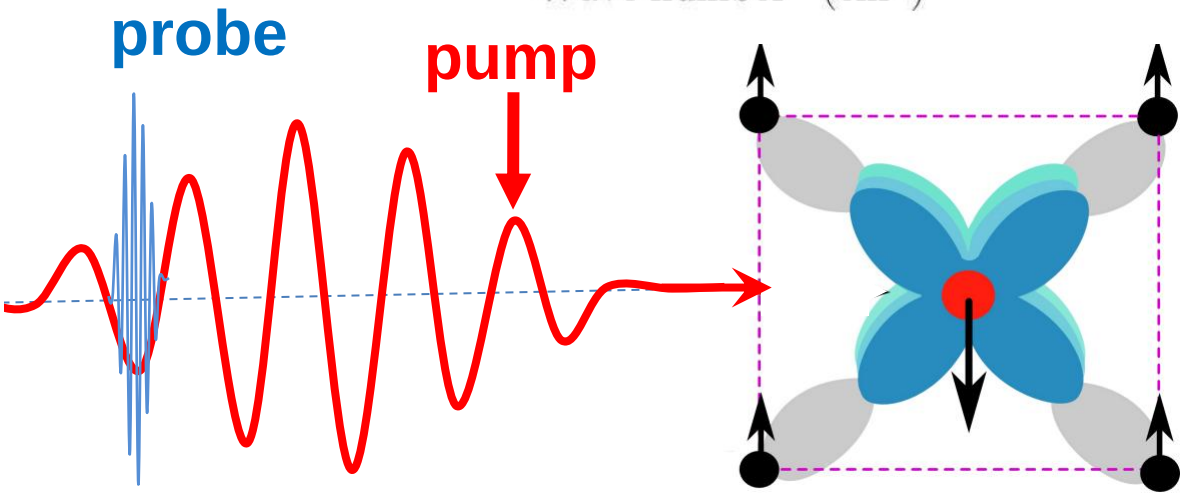

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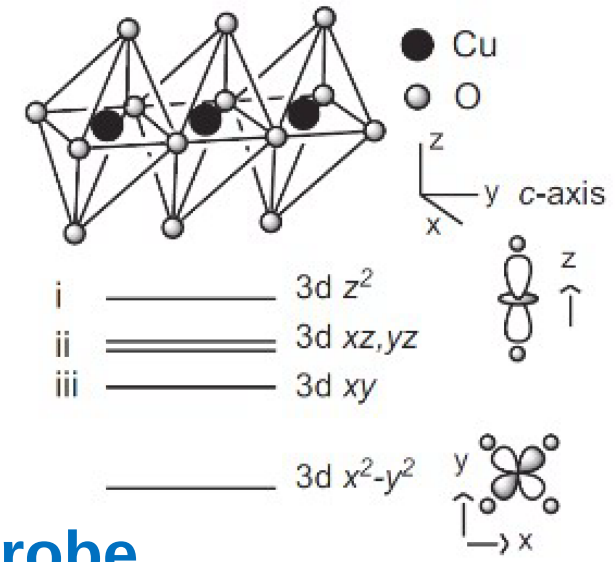

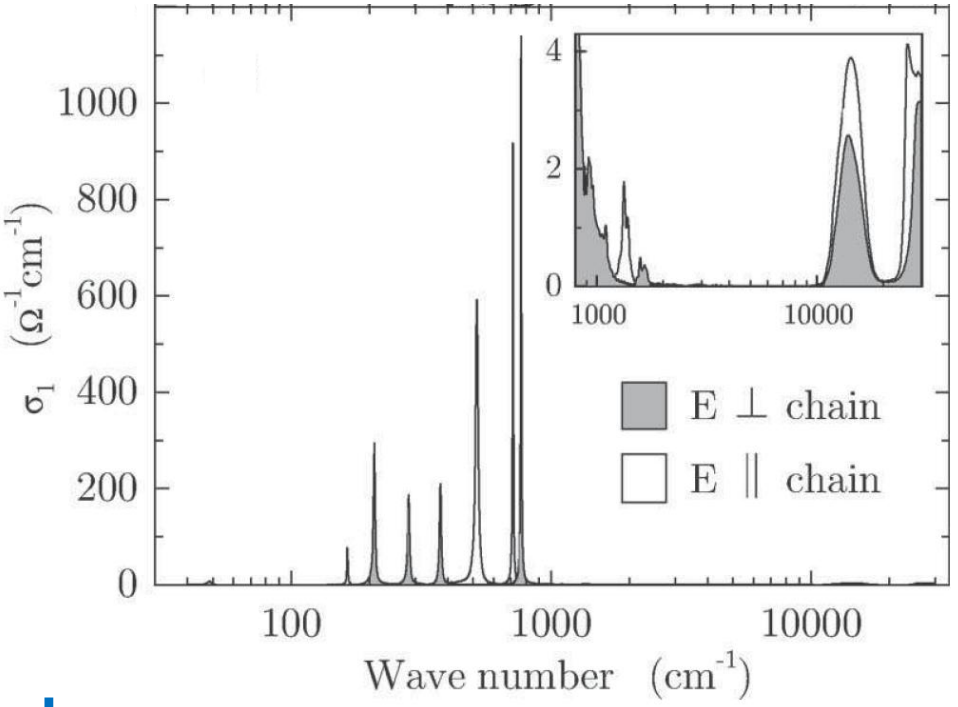

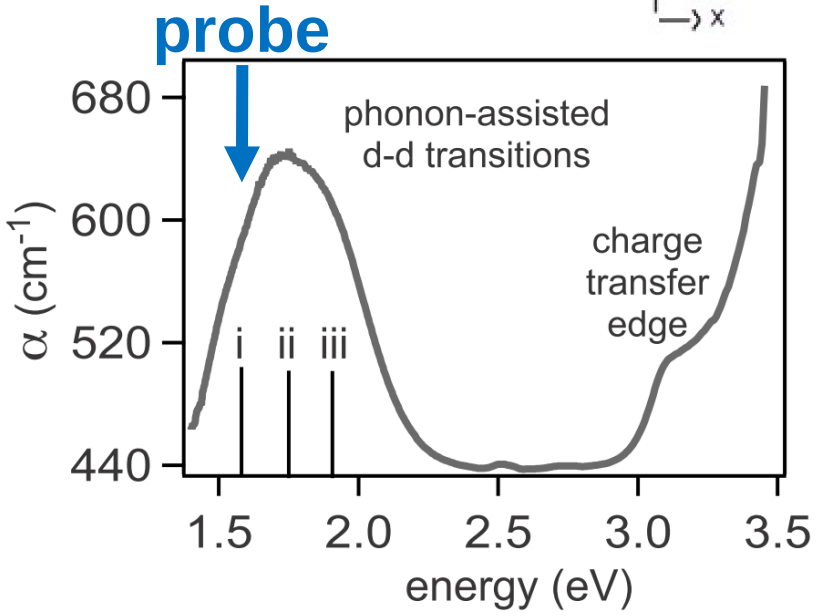

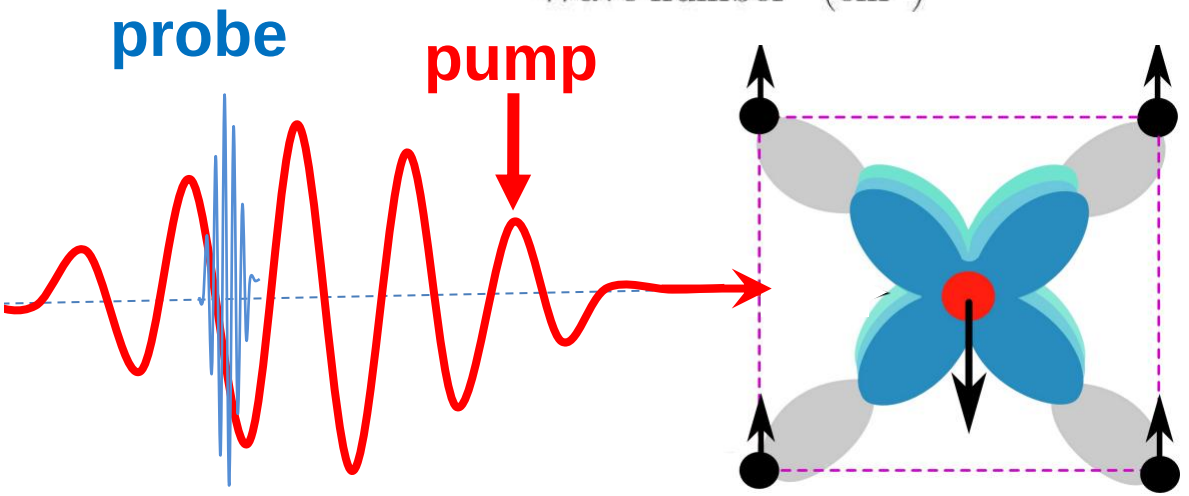

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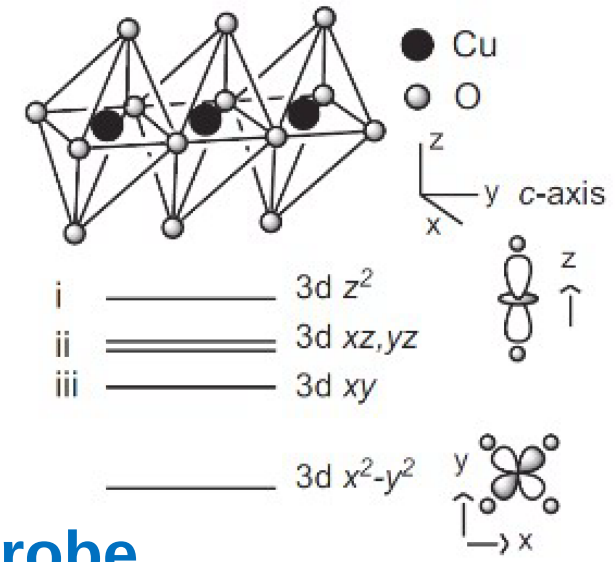

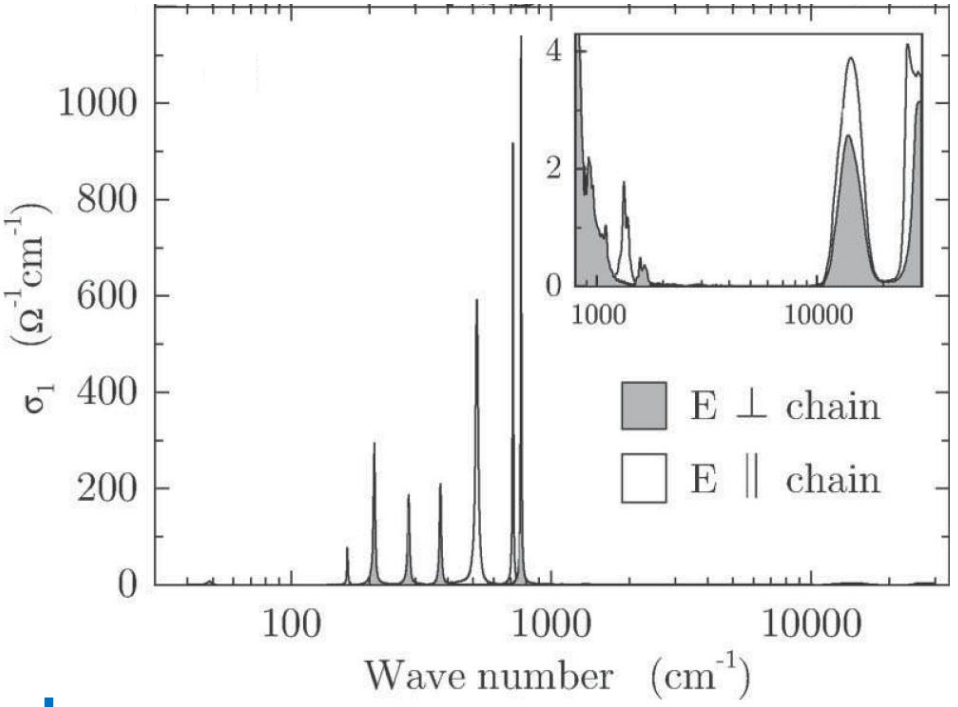

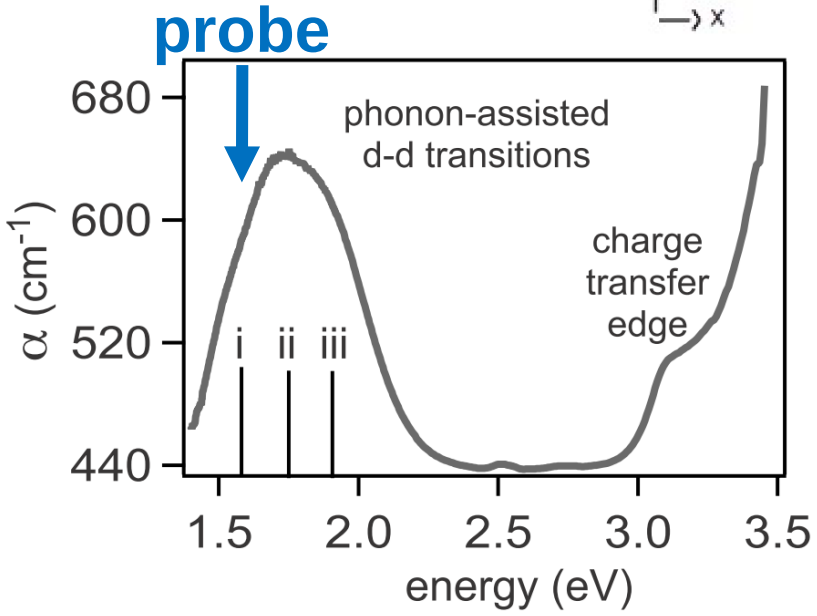

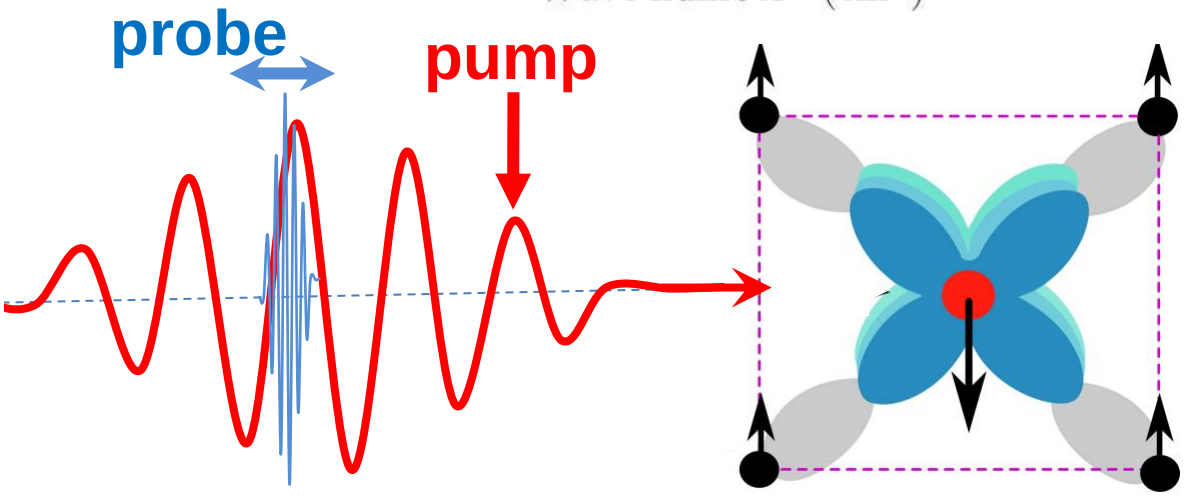

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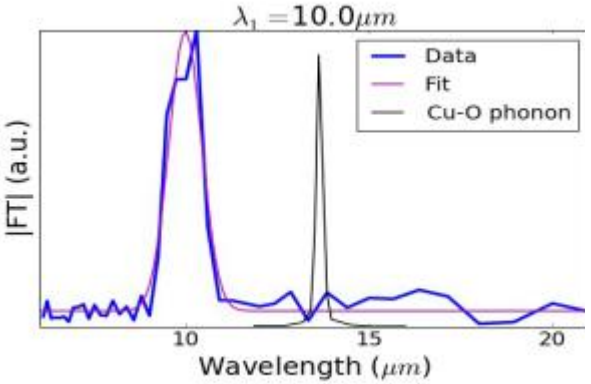

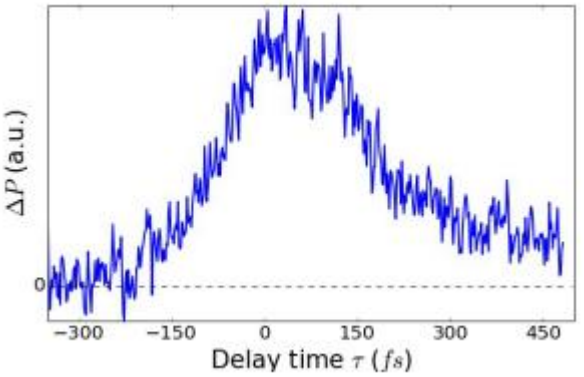

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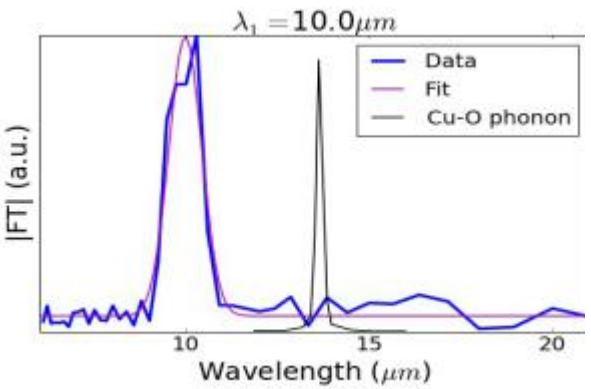

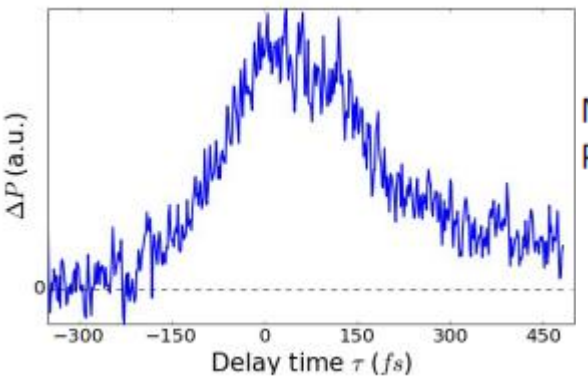

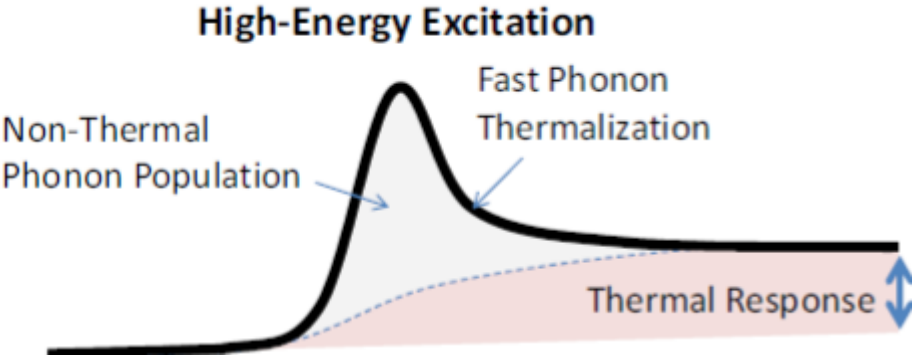

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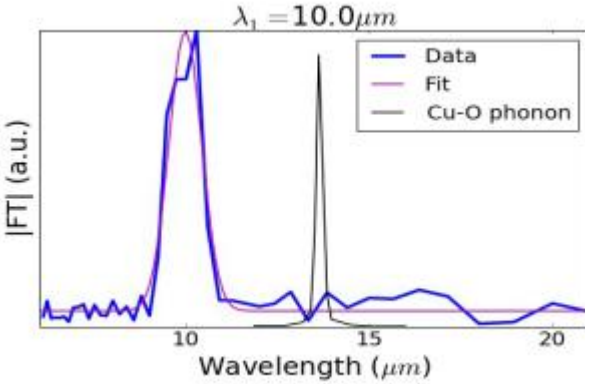

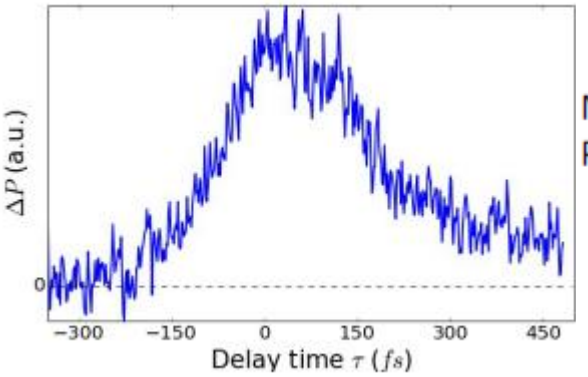

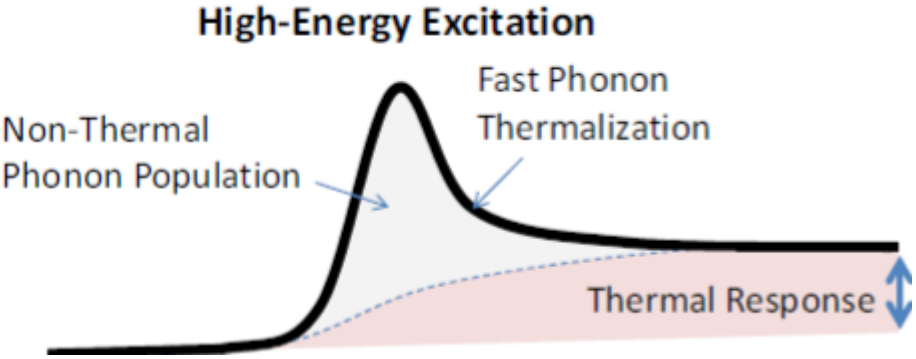

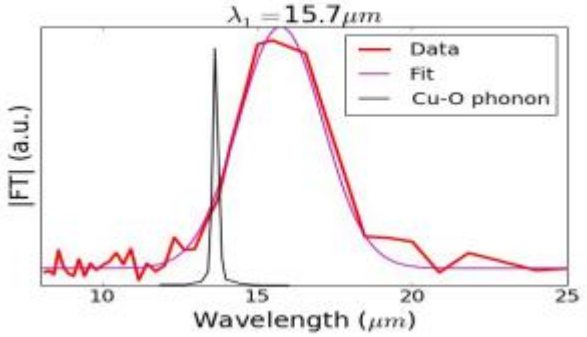

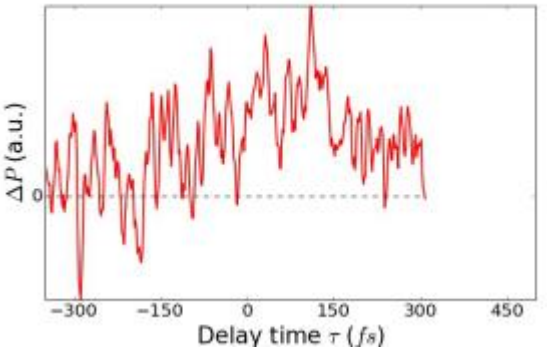

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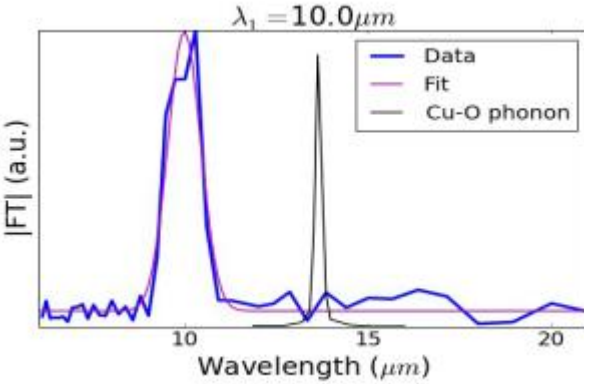

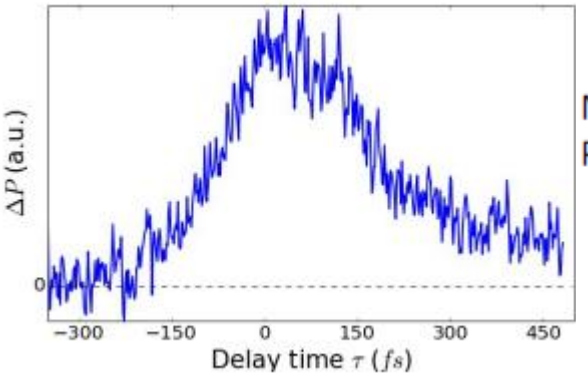

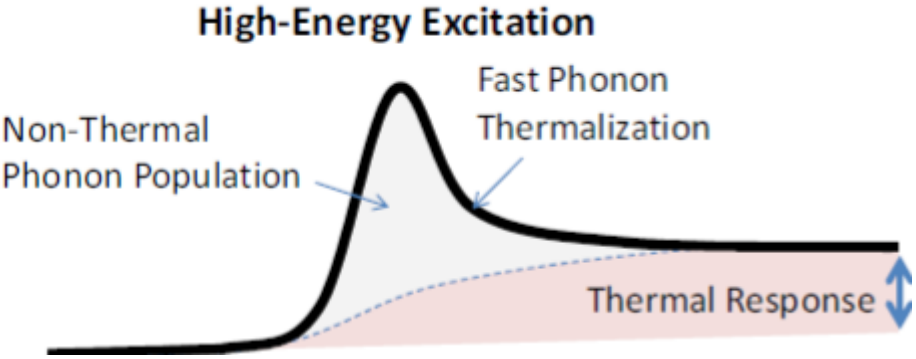

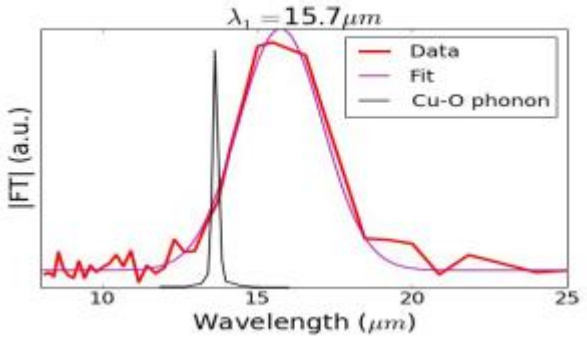

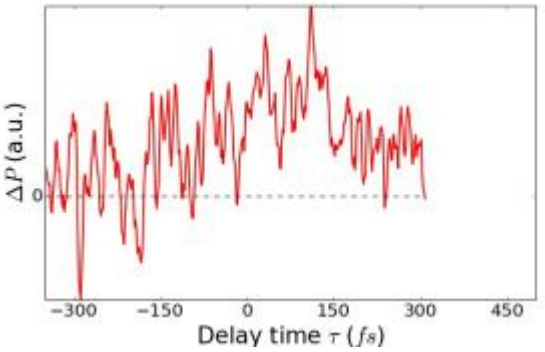

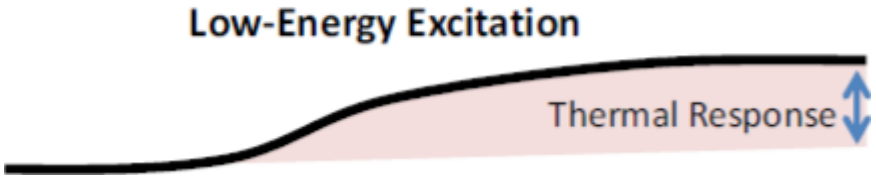

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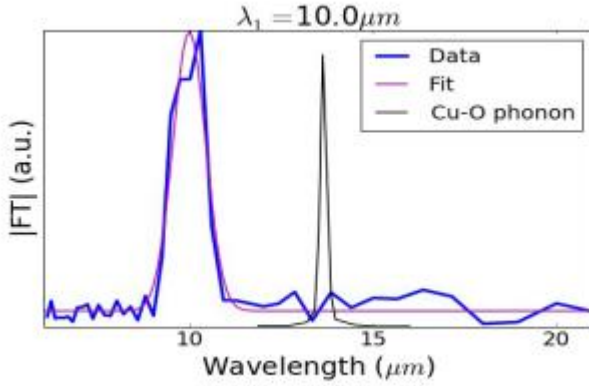
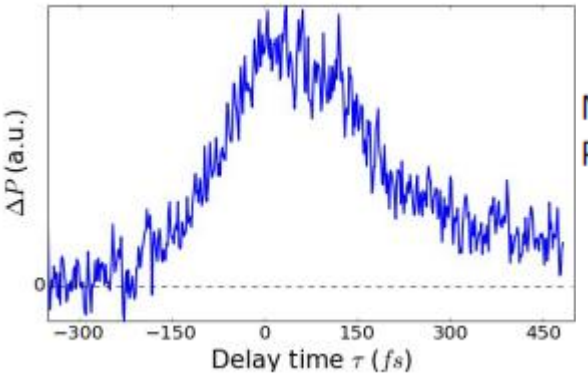
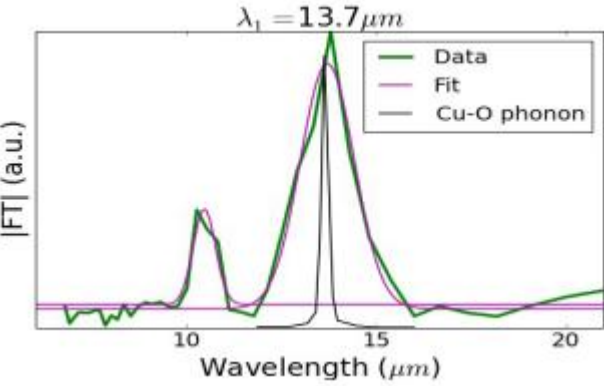
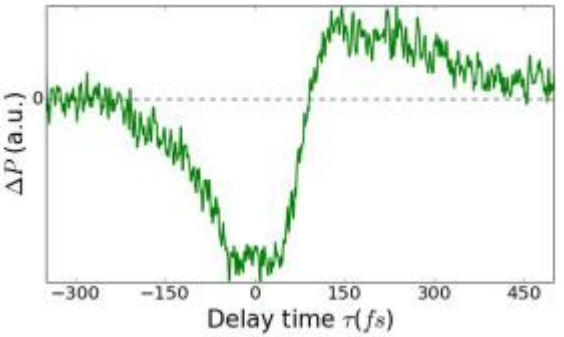
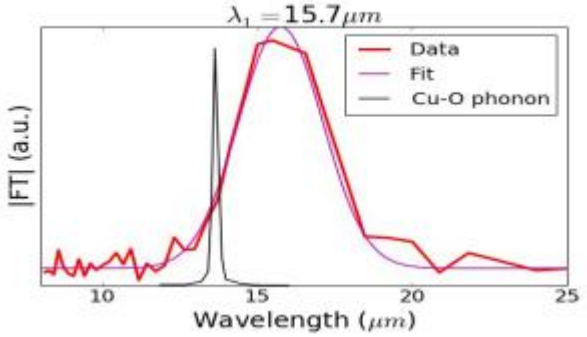
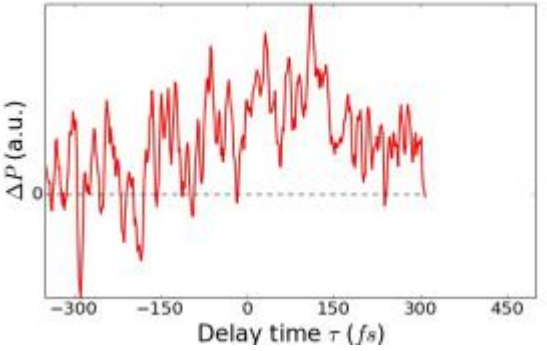


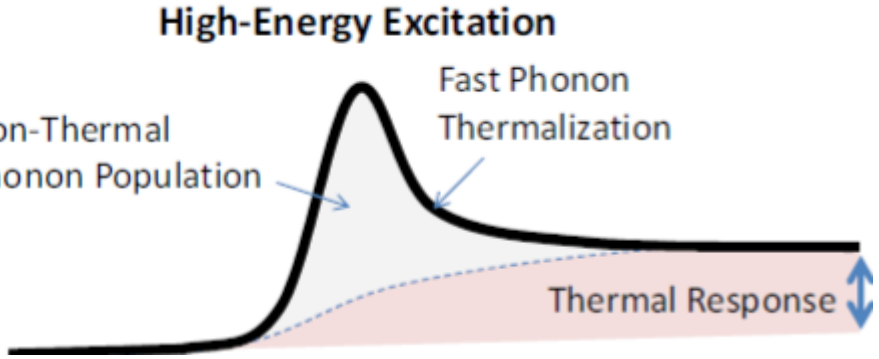


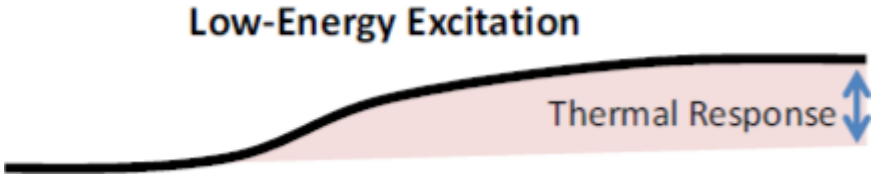




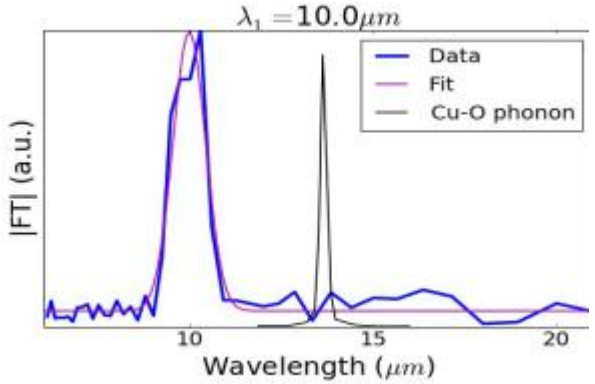


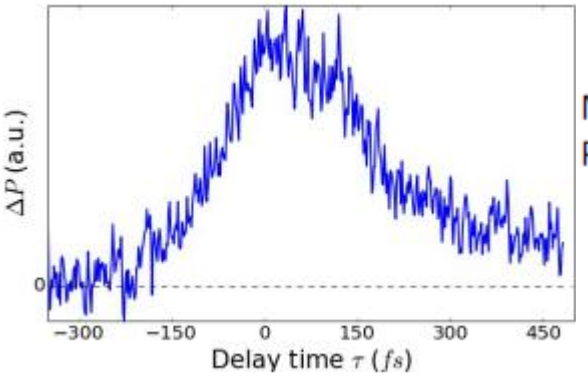


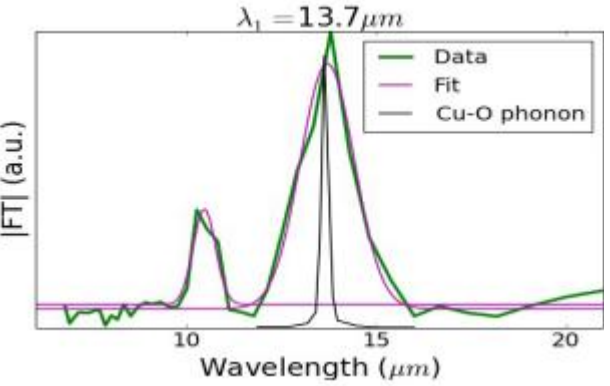


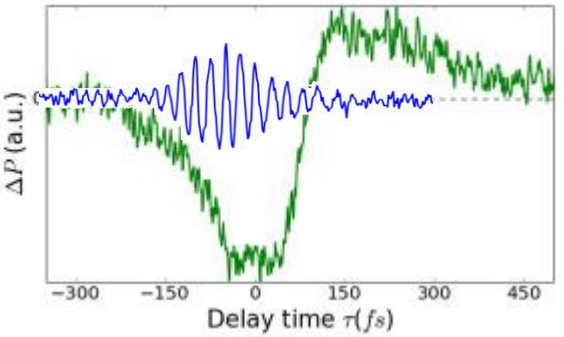


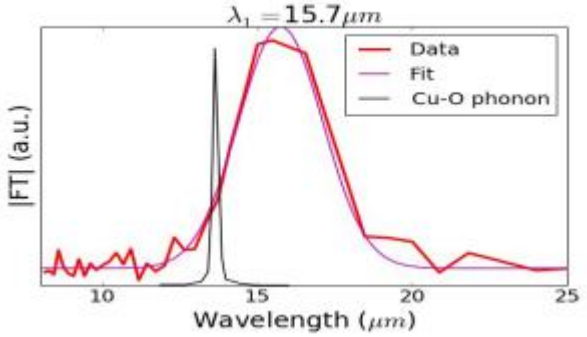
Phonon Pump in CuGeO3

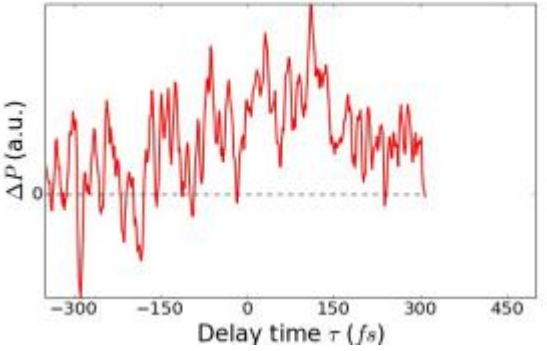


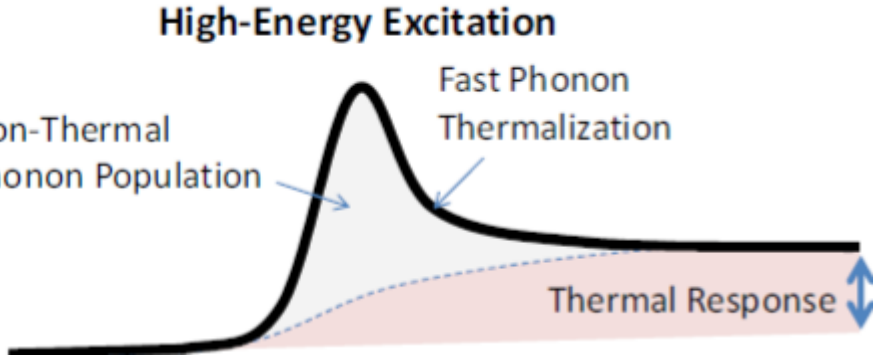


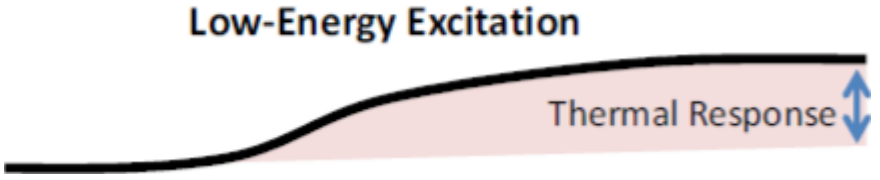












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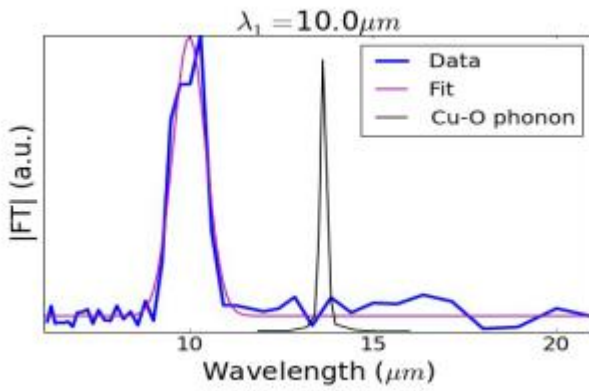
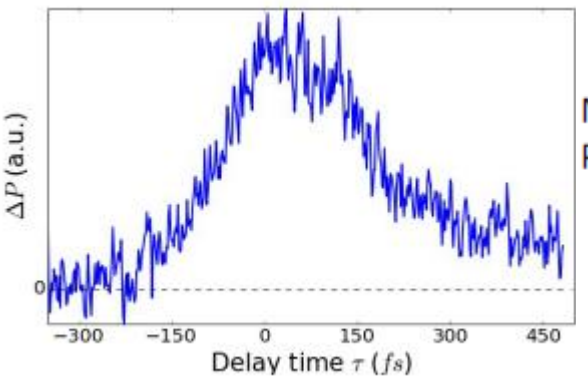
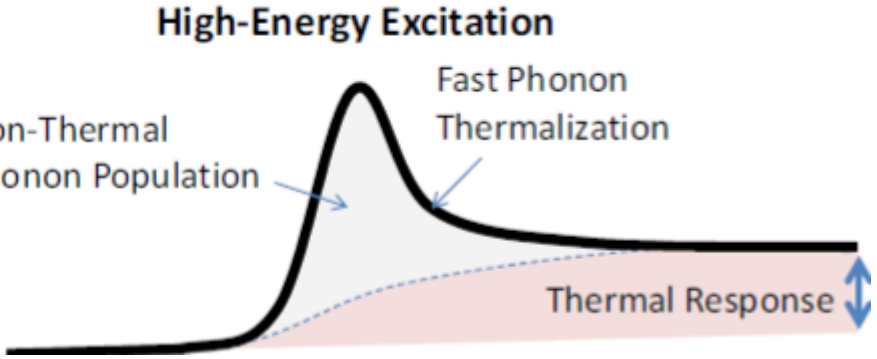
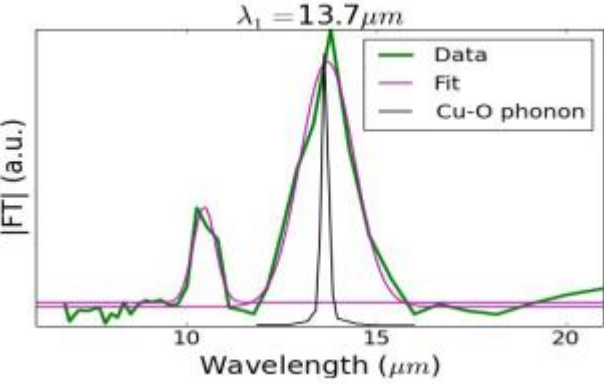
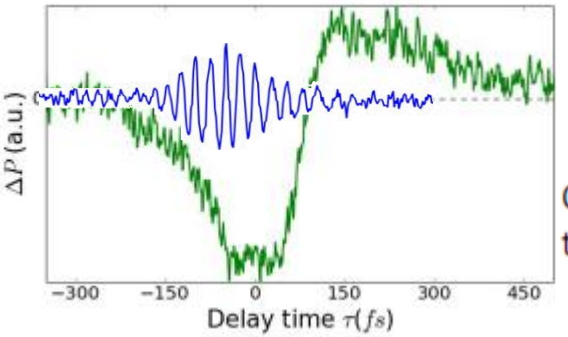
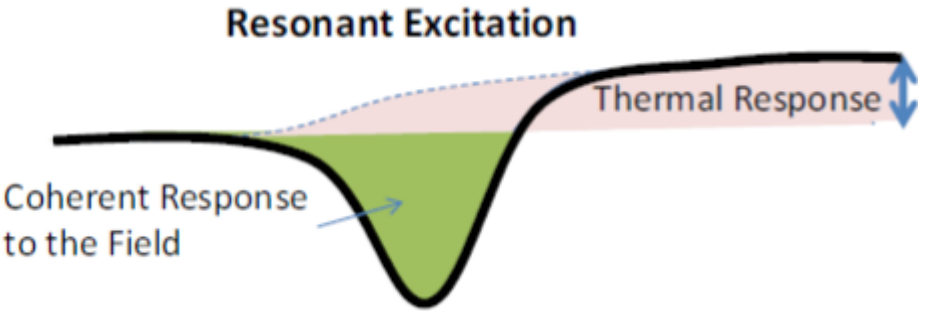


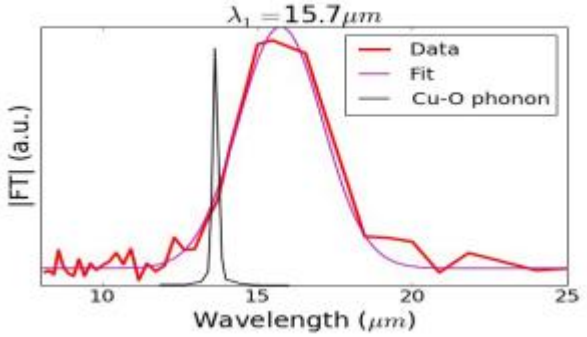


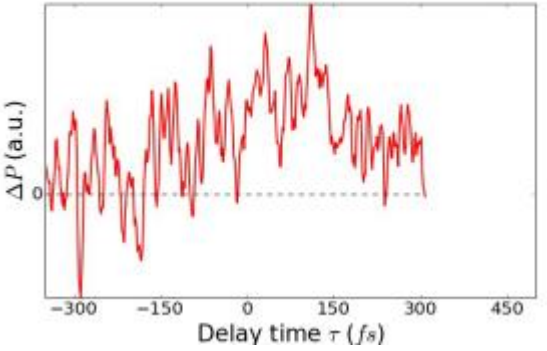


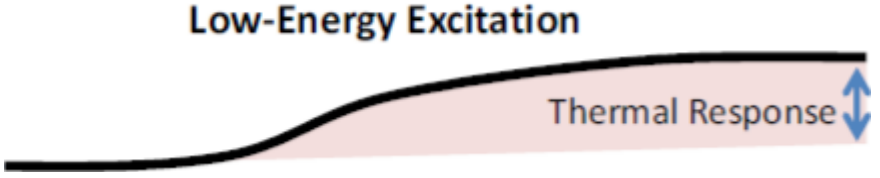












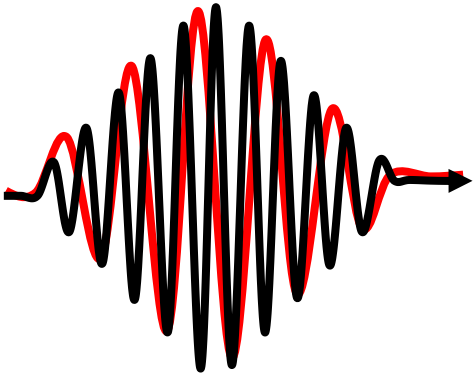
Outline

Witnessing quasi-particles in strongly correlated electron systems

- **High Vs. Low-photon energy excitation in CTI La_2CuO_4**

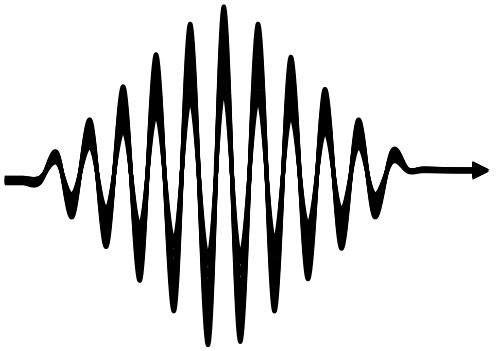
Towards selective excitations of low energy modes

- **Phonon pump and dd-transitions probe in $CuGeO_3$**



Quantum Optics for studying ultra-fast processes in Condensed Matter

- **Balanced Homodyne Detection**
- **Impulsive phonon excitation: the case of quartz**
- **Time evolution of the probe quantum state after the interaction with the material**



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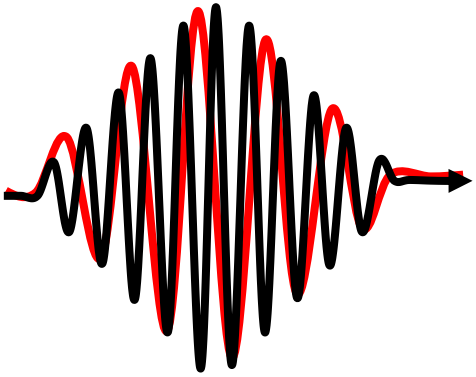

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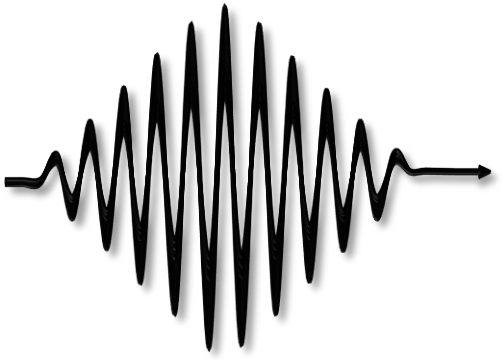
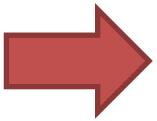
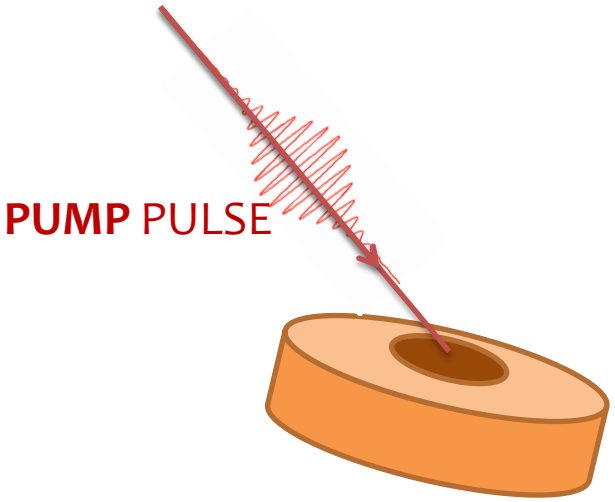


Quantum Optics for studying **Condensed Matter** out of equilibrium

Experimental **Quantum Optics**
Measurements of quantum states of light



Study of out of equilibrium states in
Condensed Matter: Pump&Probe



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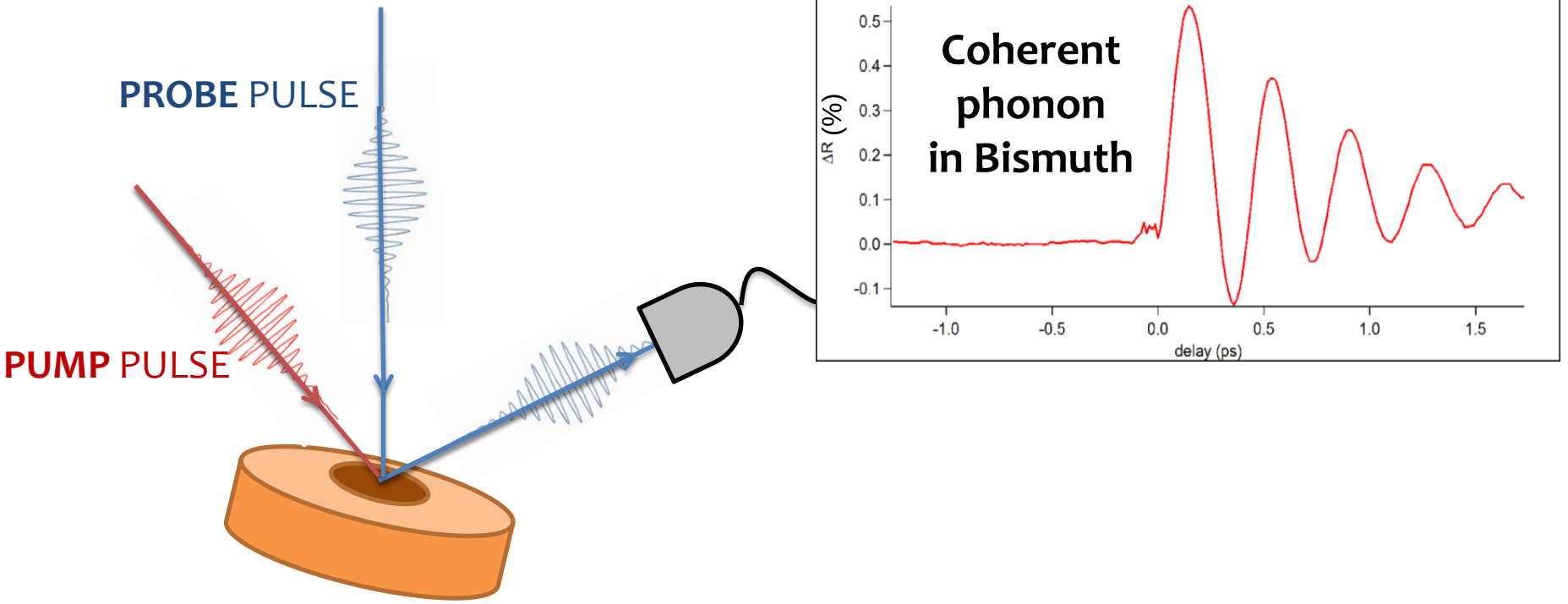

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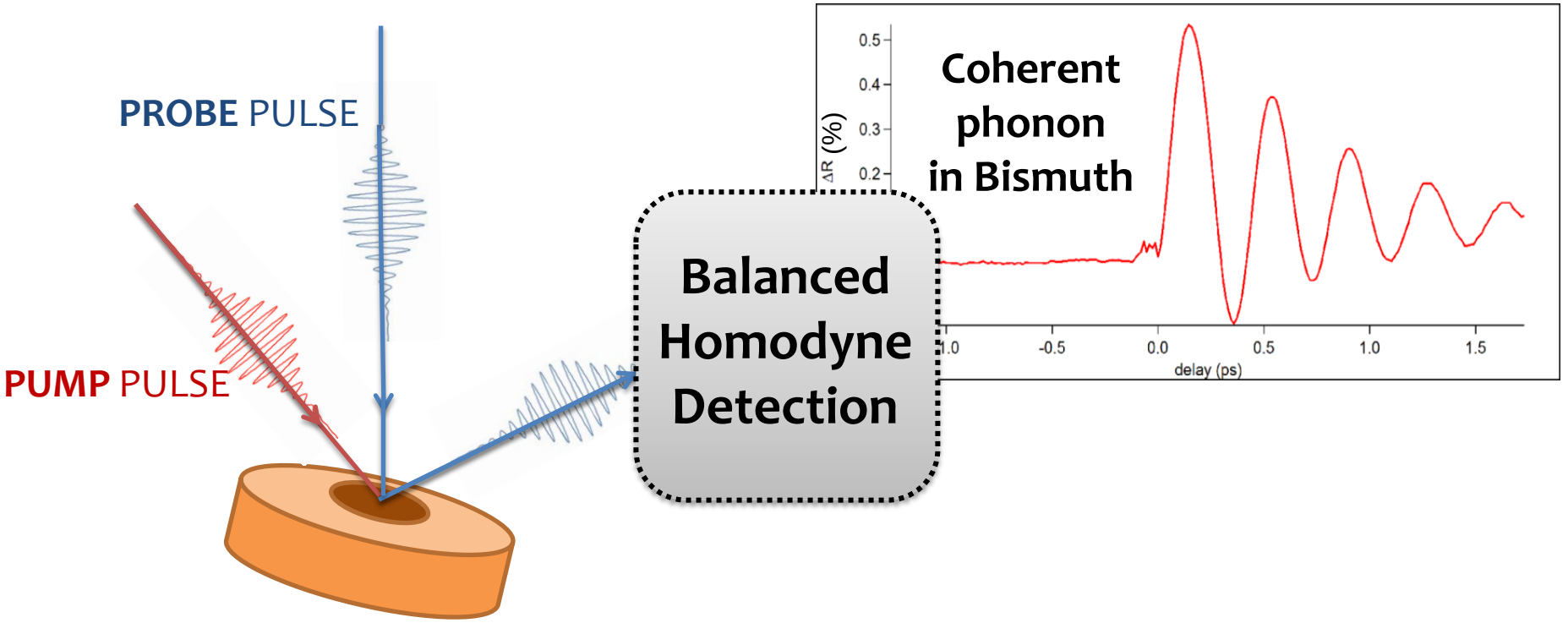
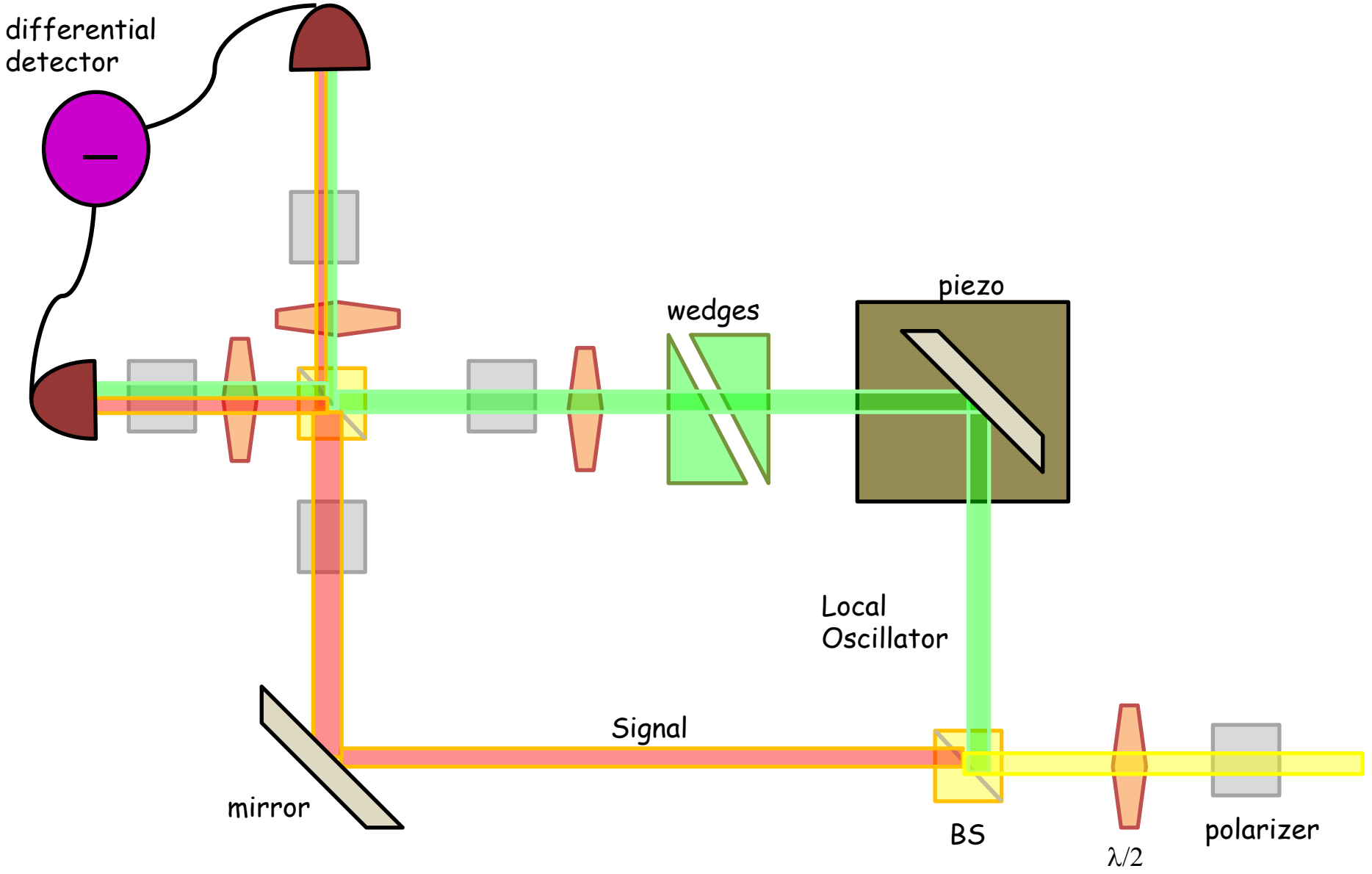


Quantum State Reconstruction



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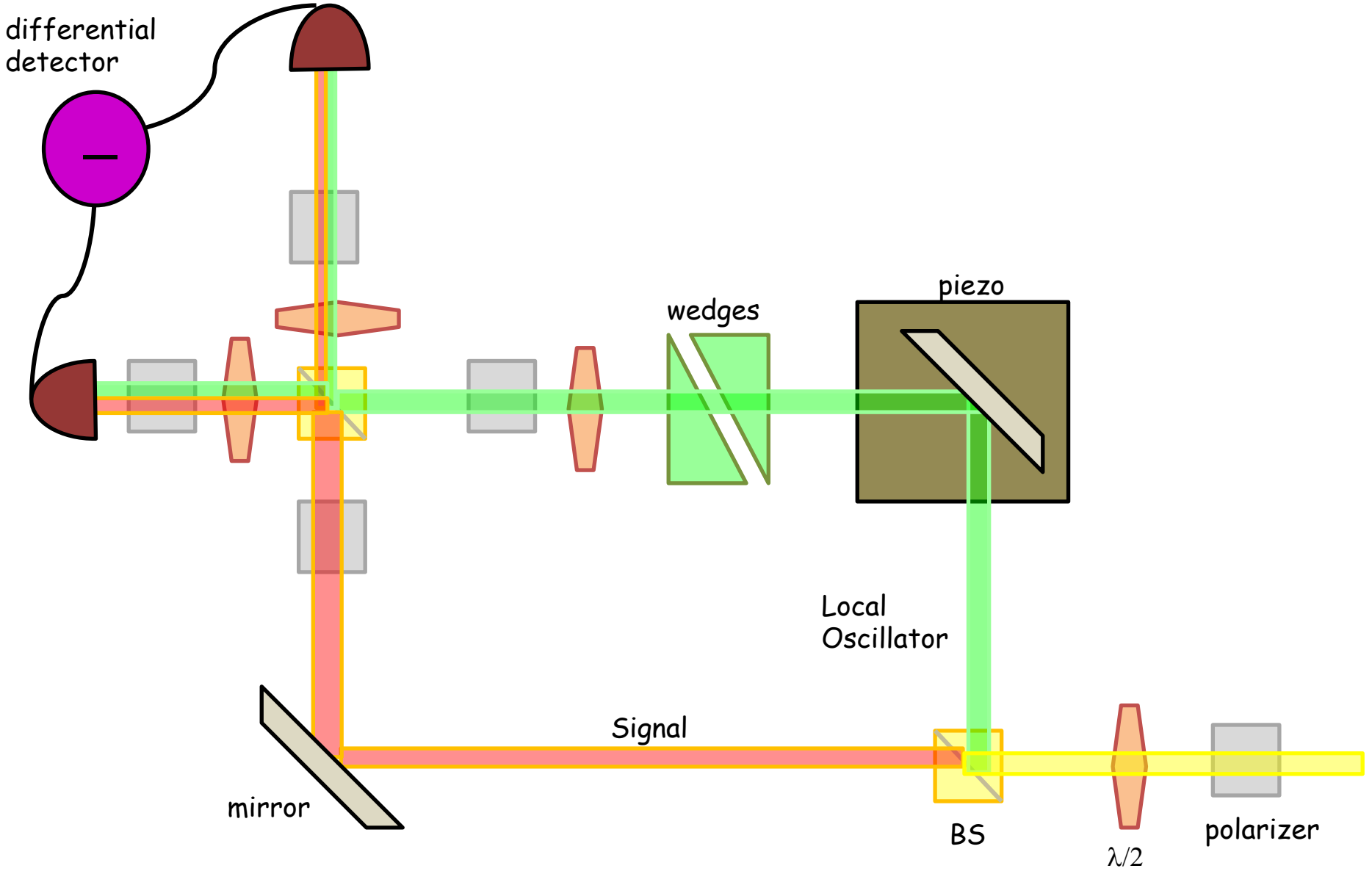

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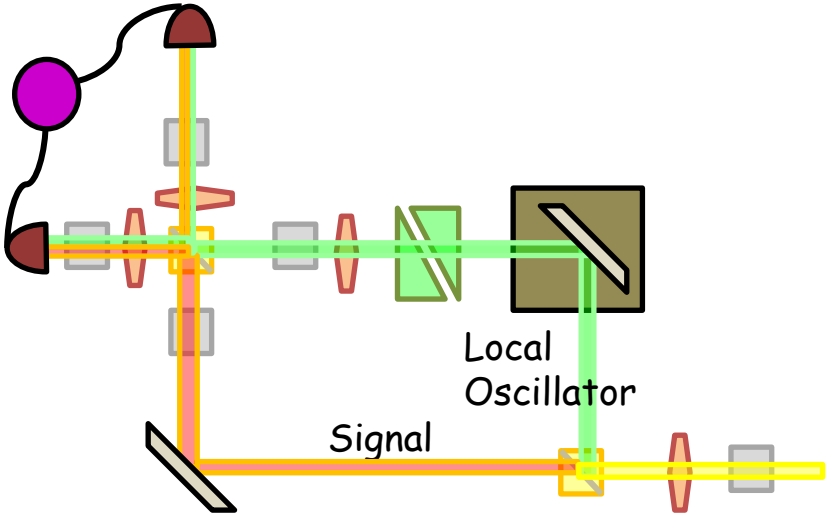

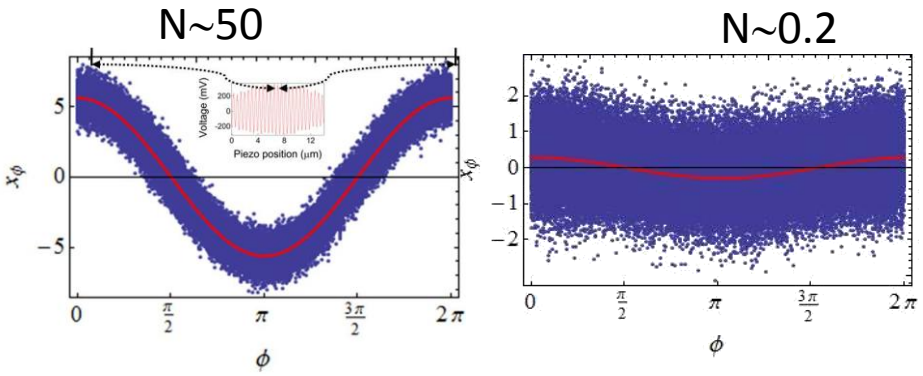

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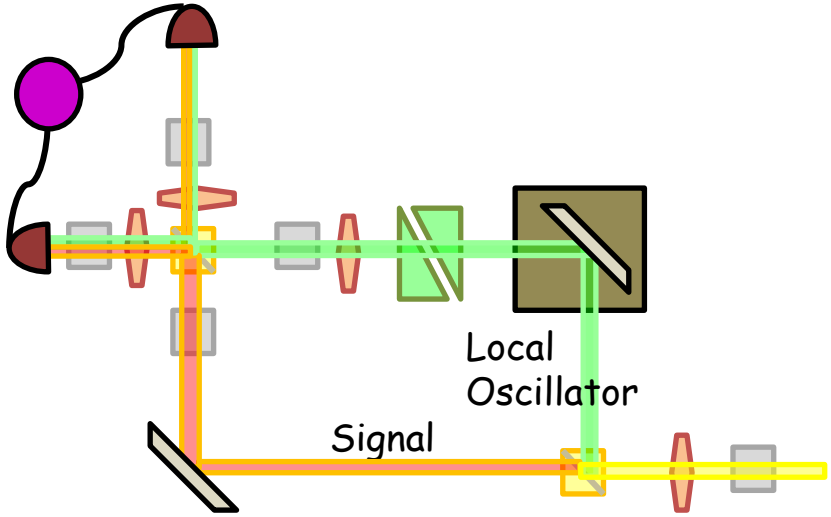
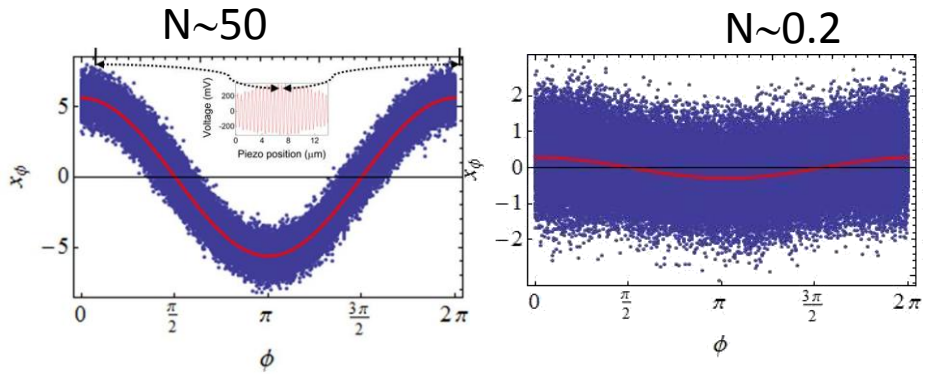
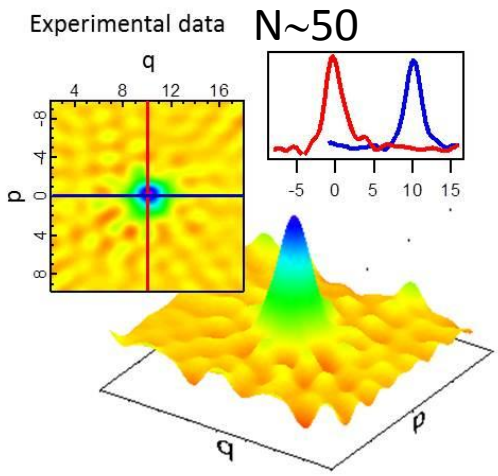
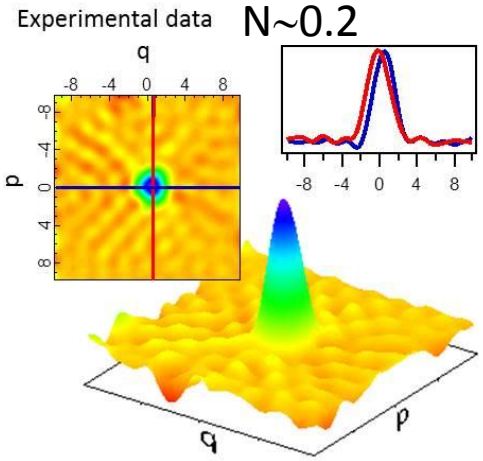




WIGNER FUNCTION RECONSTRUCTION





M. Esposito et al.
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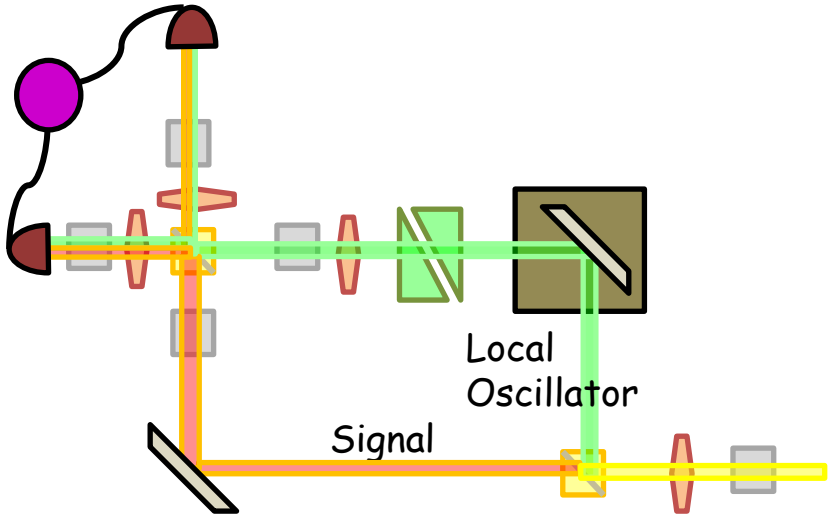
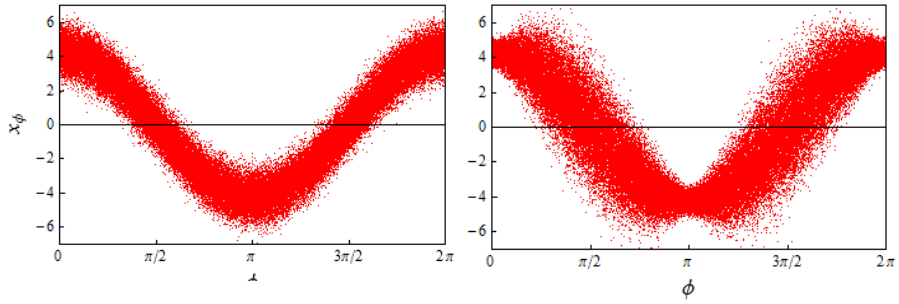
C. Butucea, M. Guta and L. Artiles, *Ann. Stat.* **35**, 465 (2007)

Quantum State Reconstruction

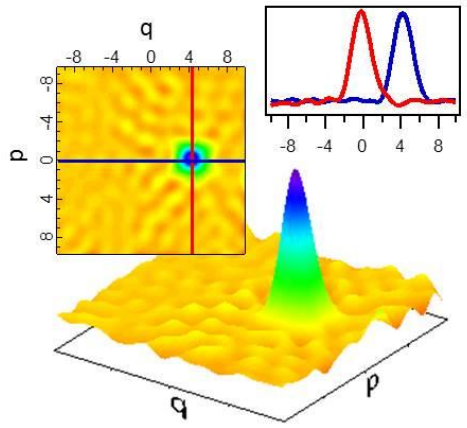


Coherent State N=9 Squeezed State N=9

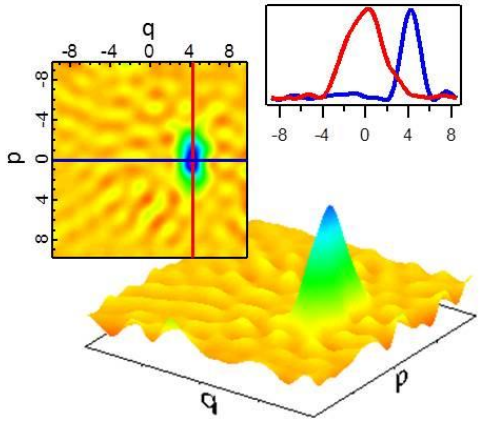


WIGNER FUNCTION RECONSTRUCTION

Coherent state $D(\alpha)|0\rangle$



Coherent-squeezed state $D(\alpha)S(\xi)\,|0\rangle$



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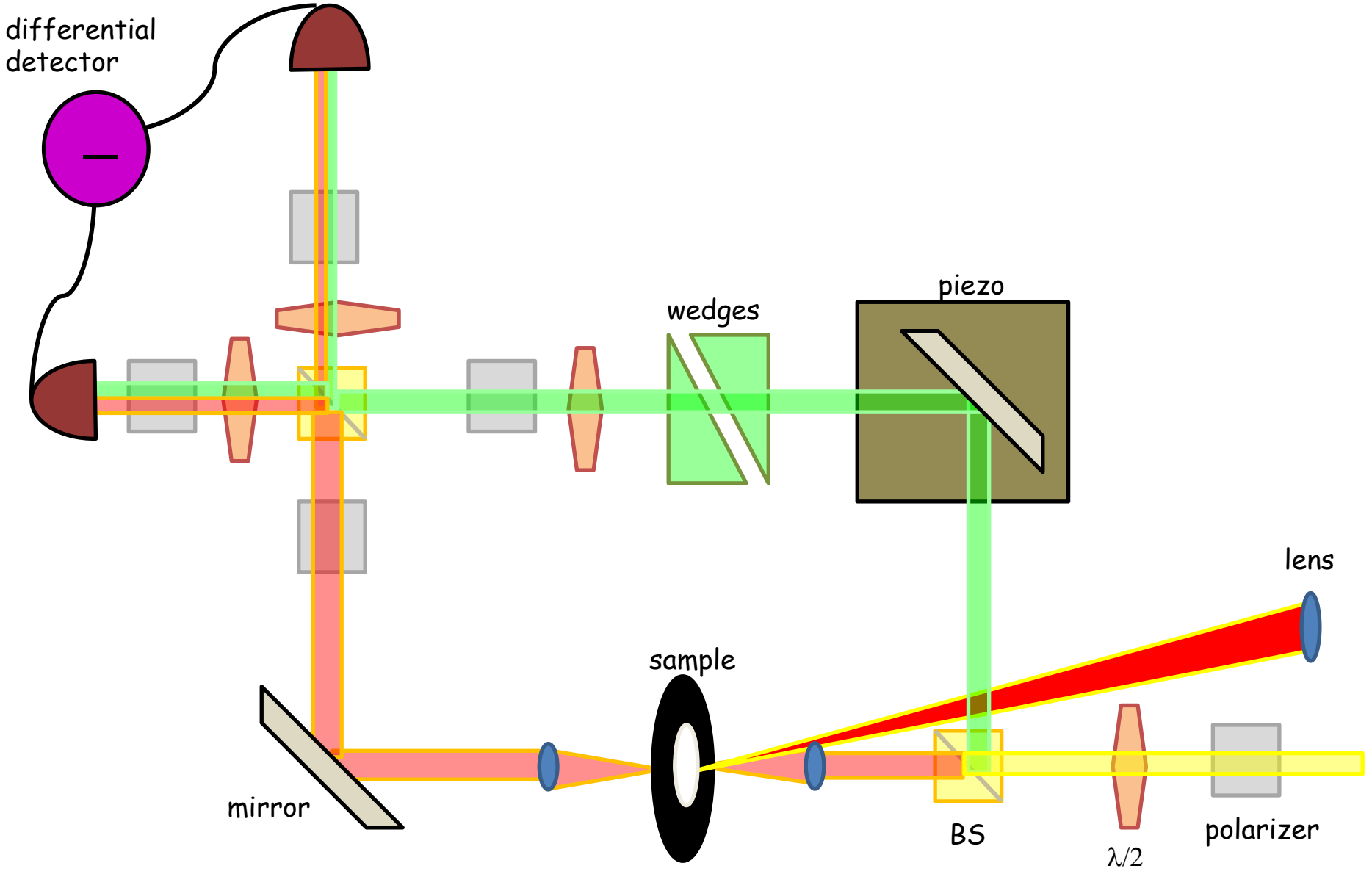
Quantum Optics for studying **Condensed Matter** out of equilibrium



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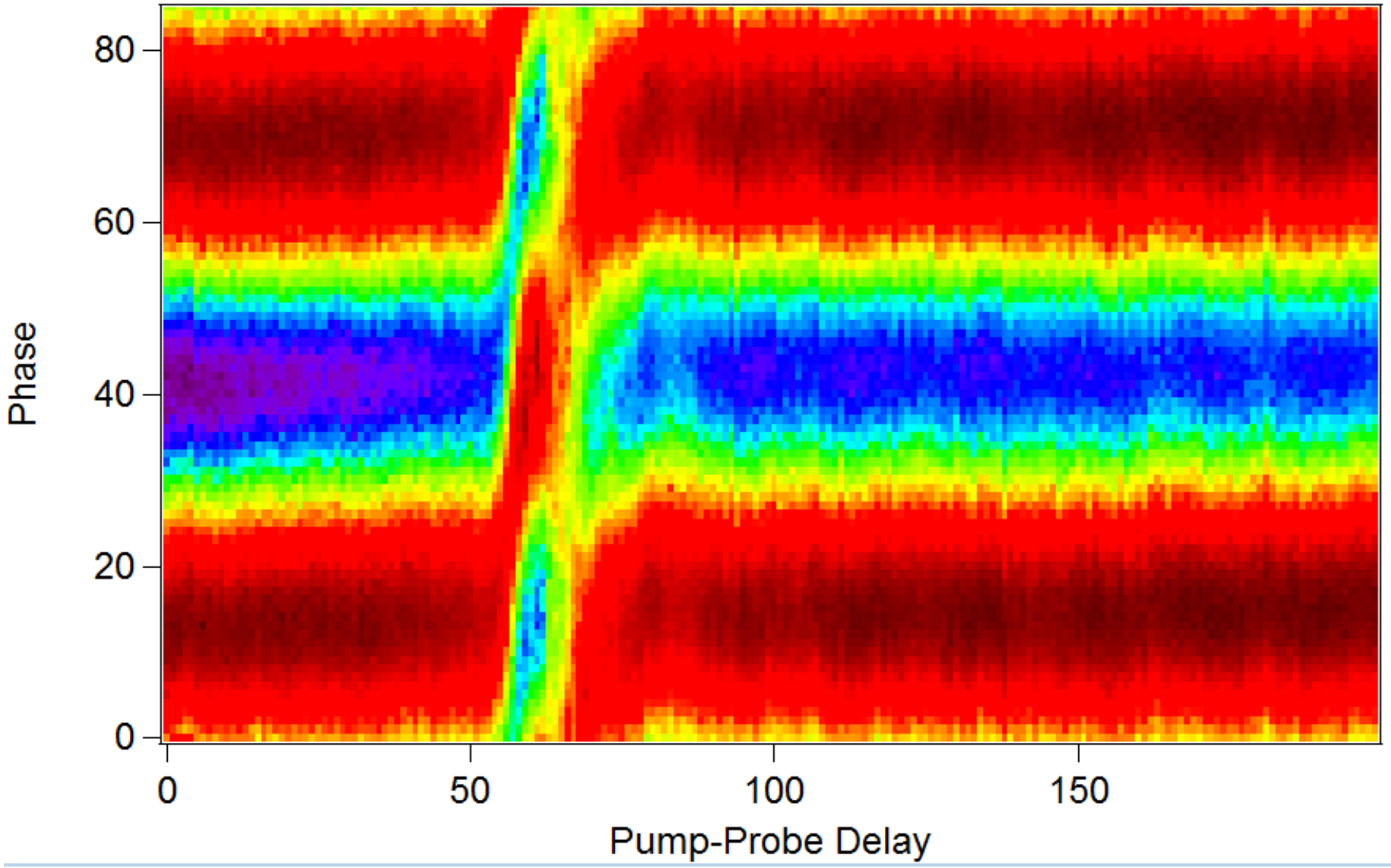

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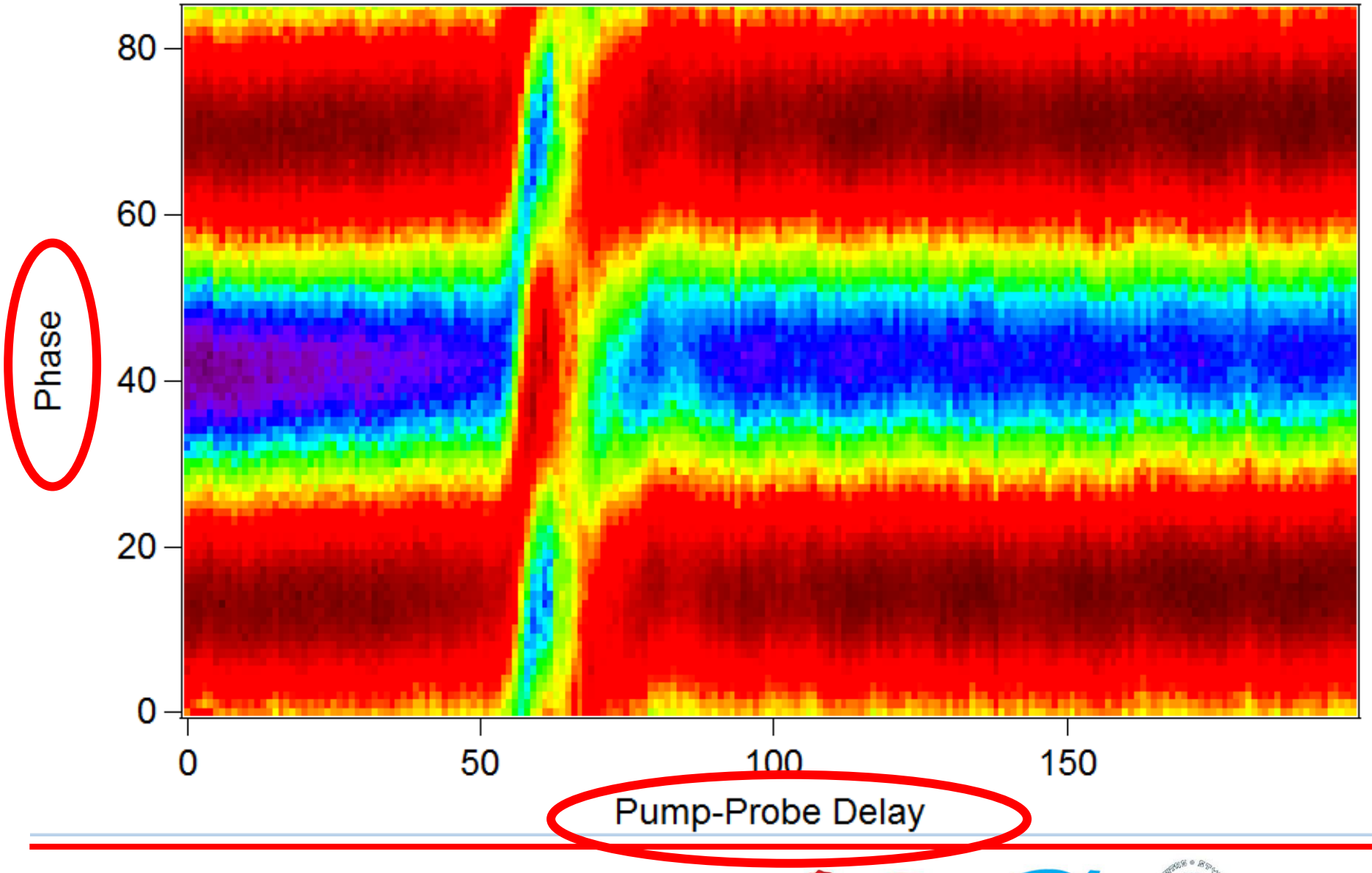

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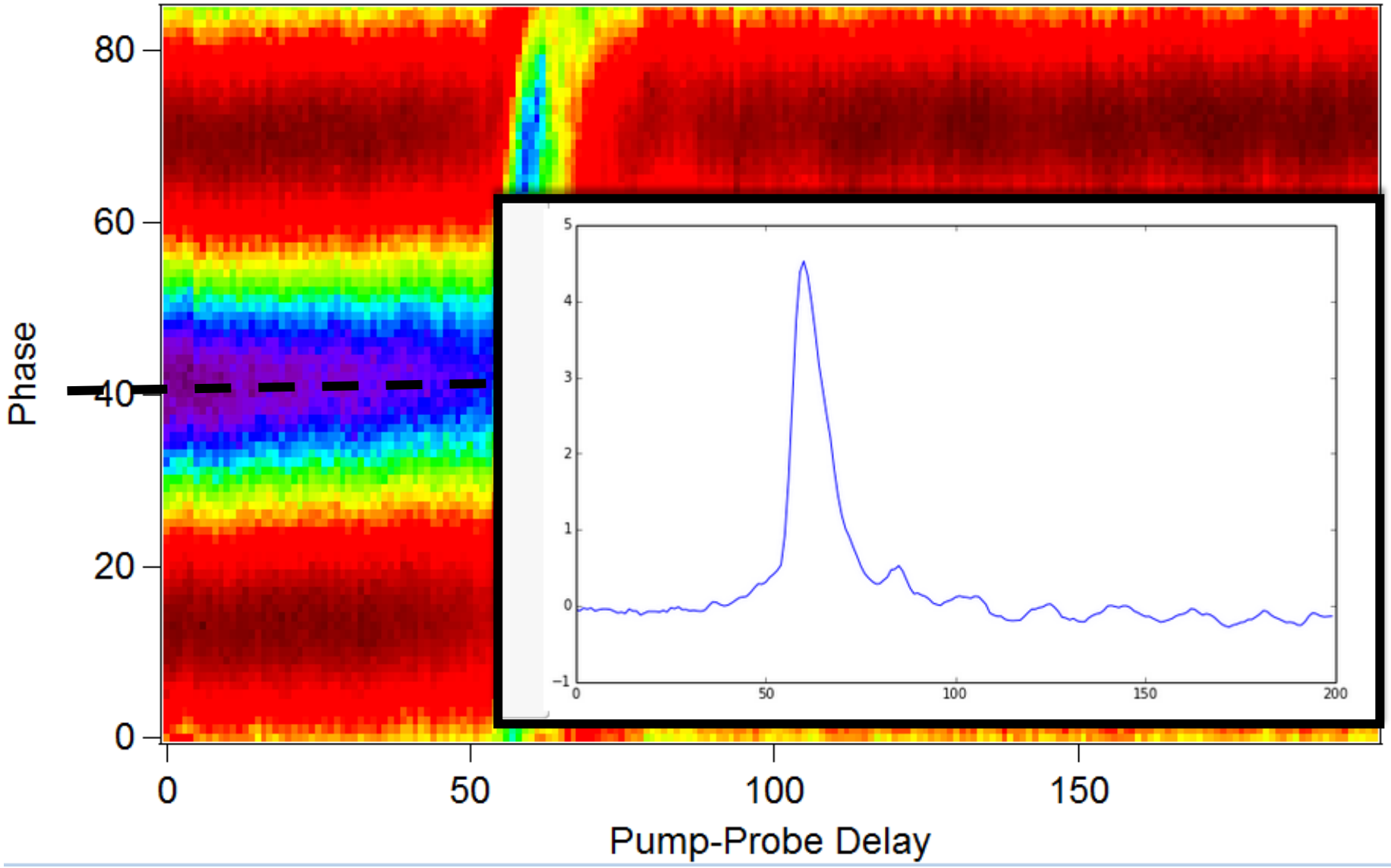

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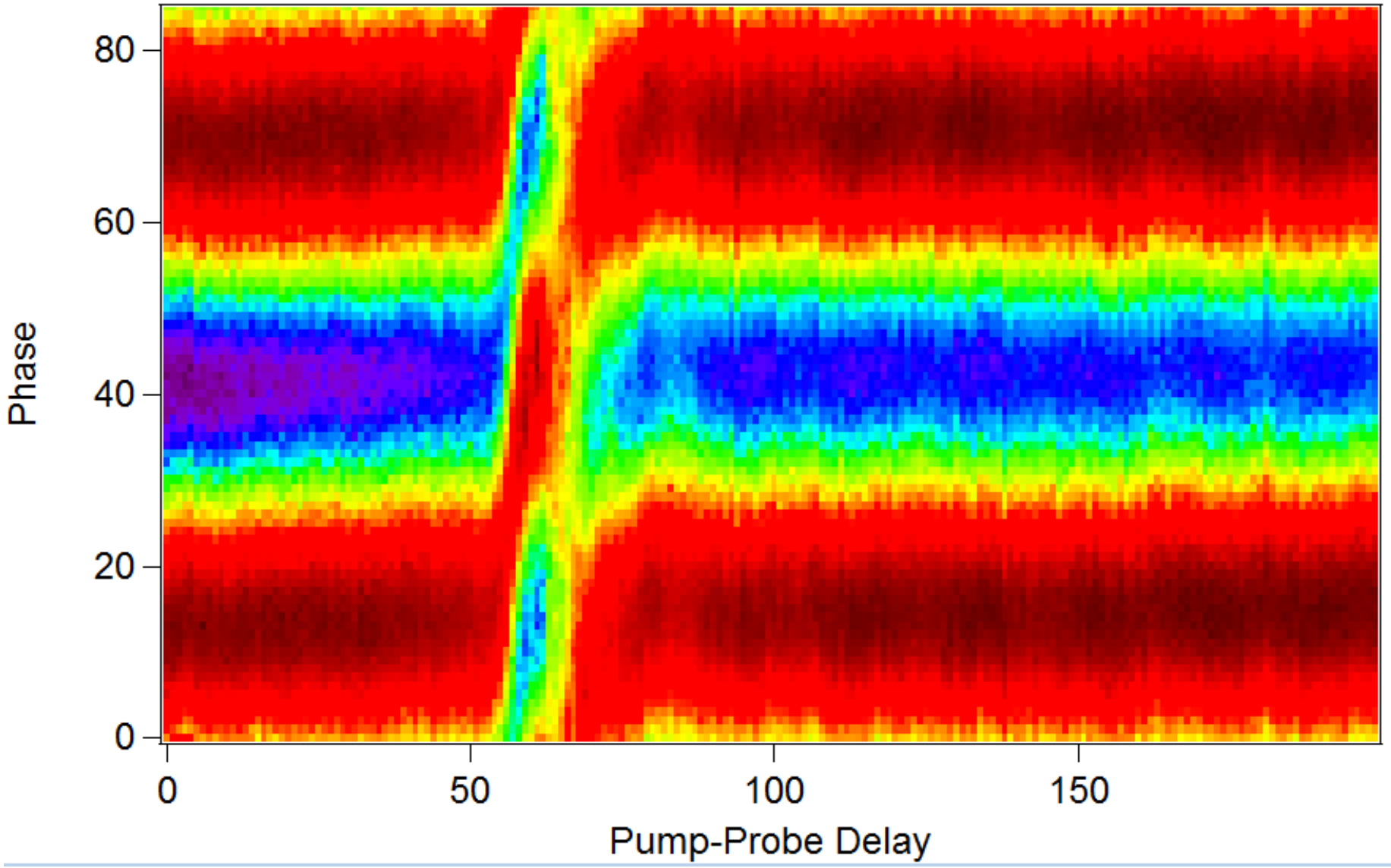

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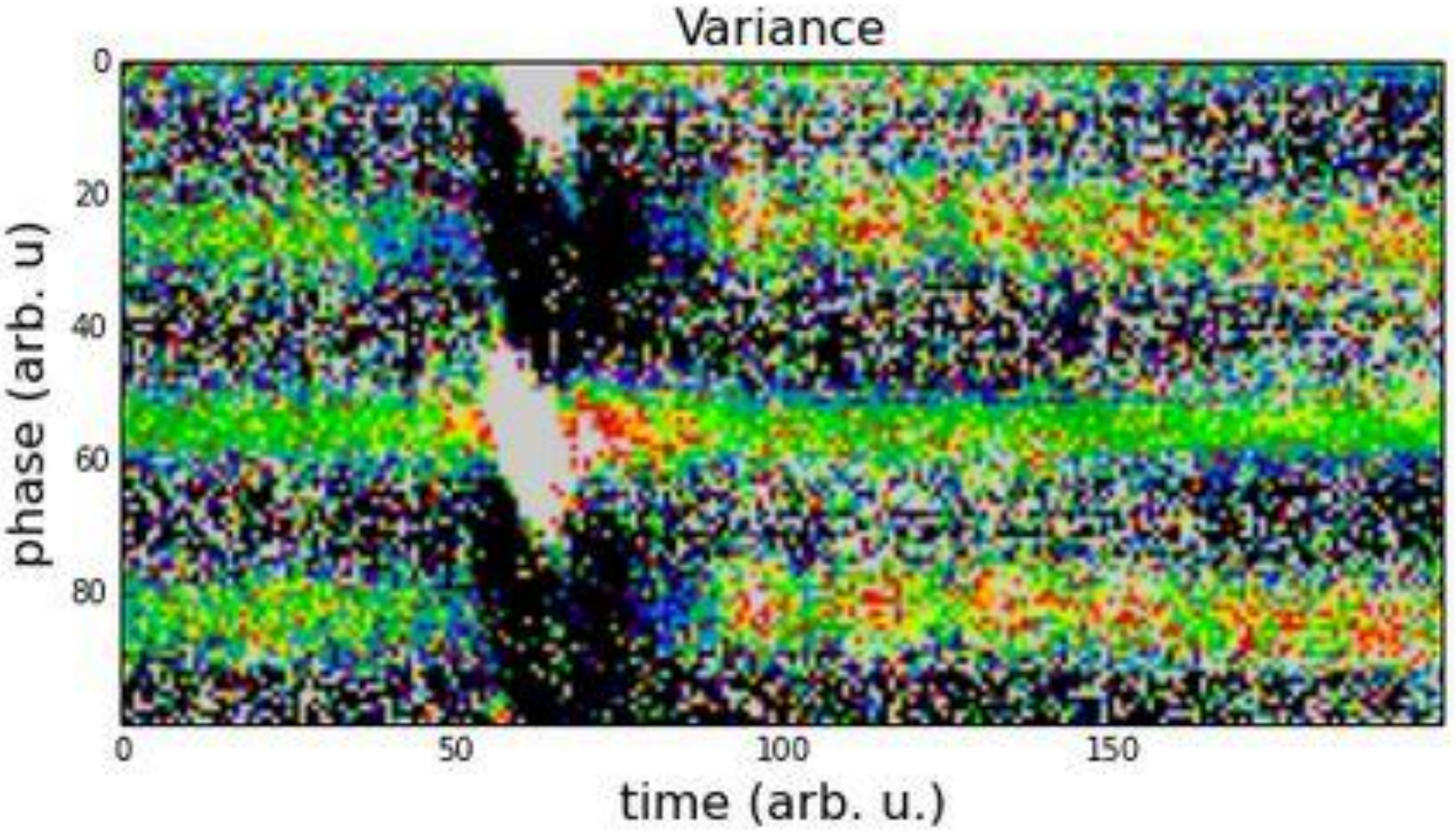

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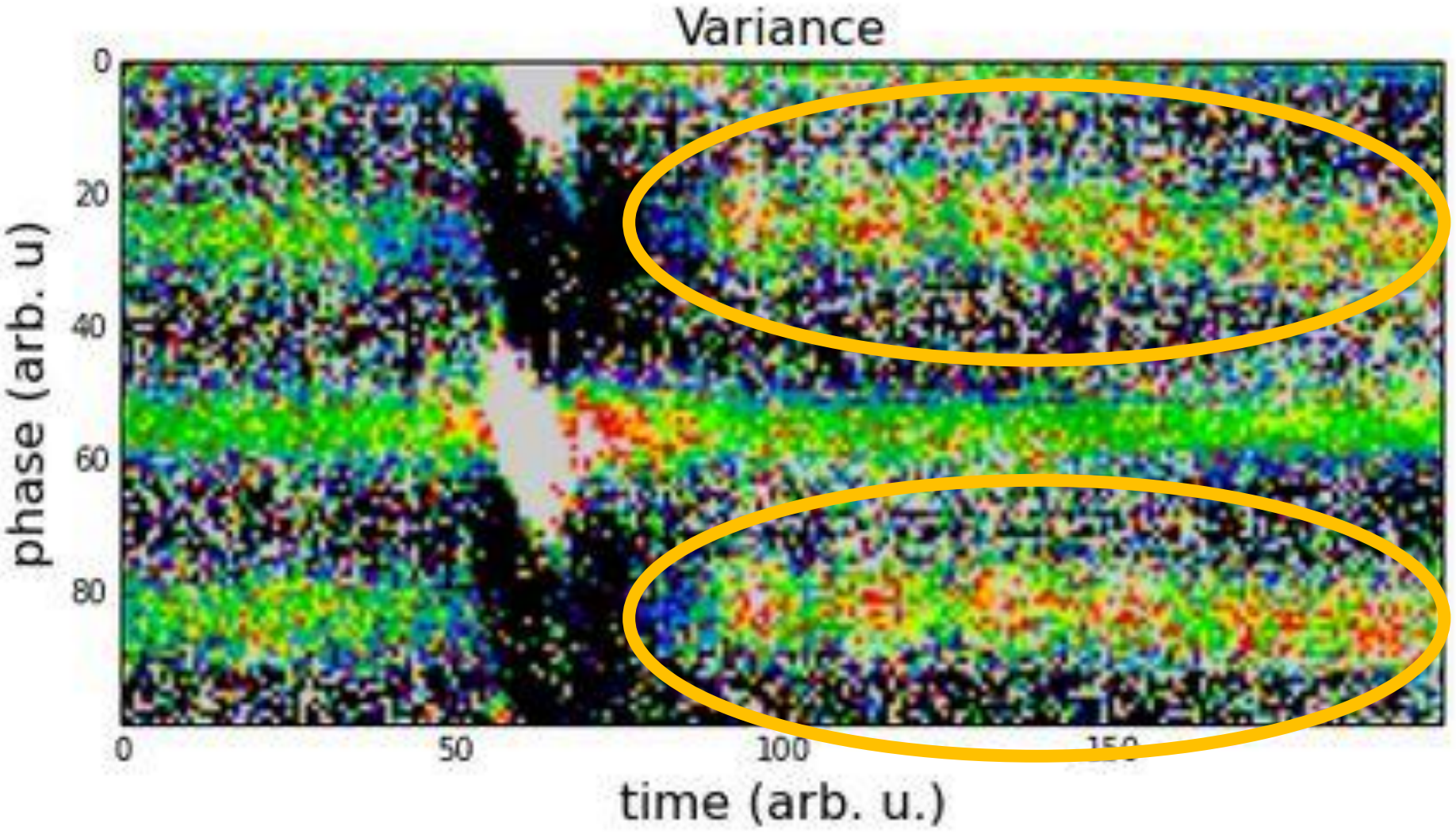

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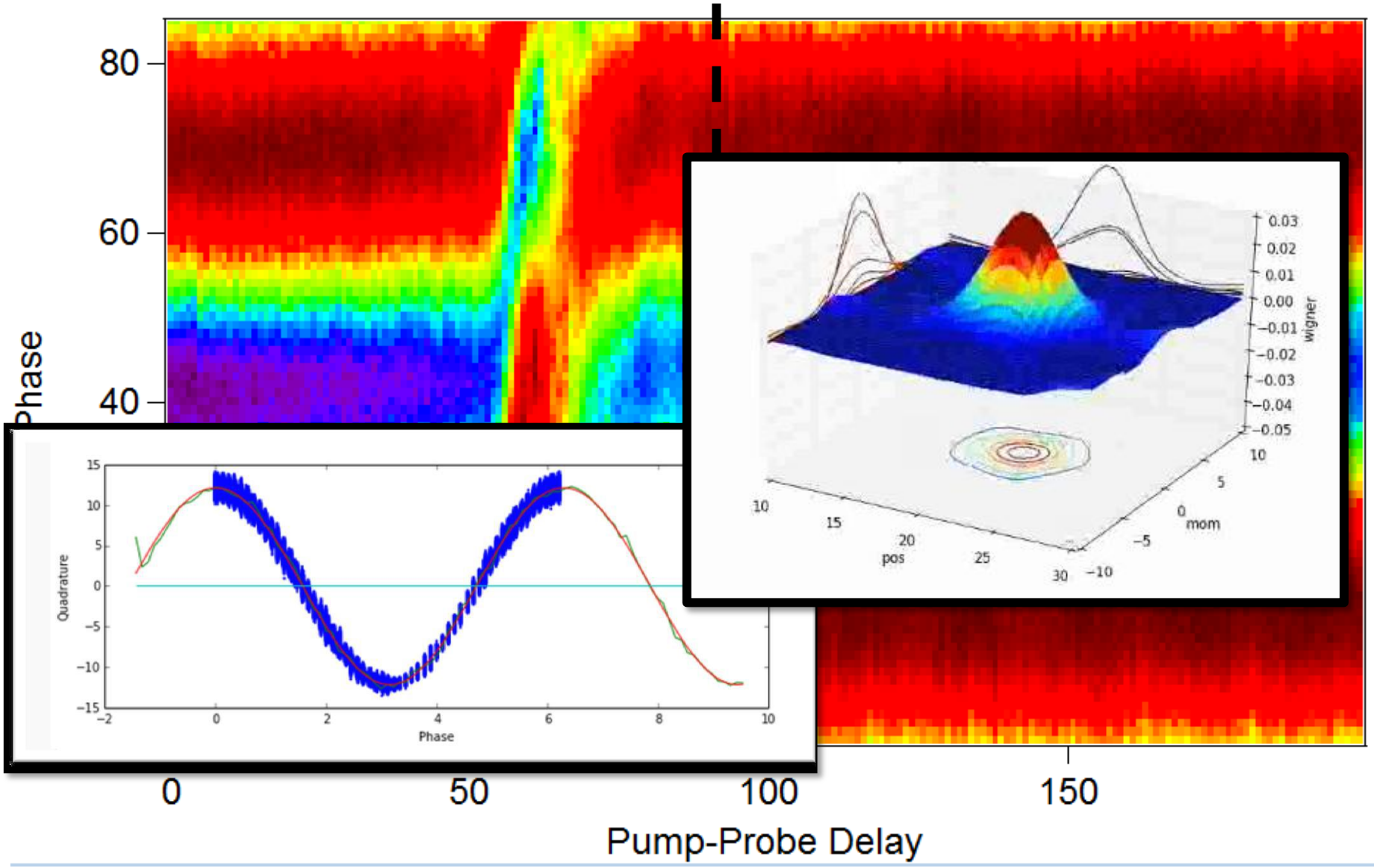

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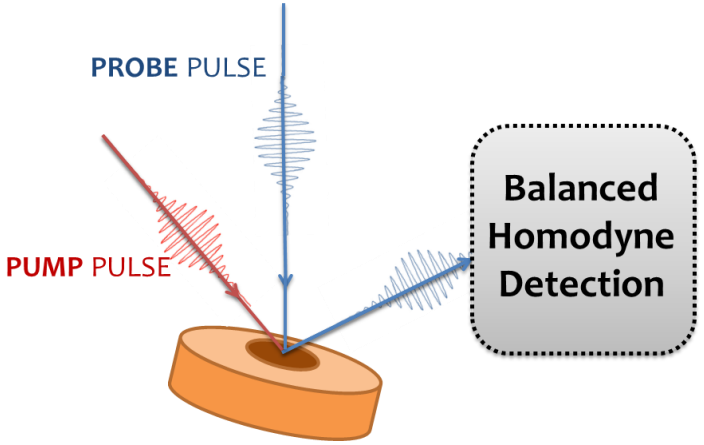

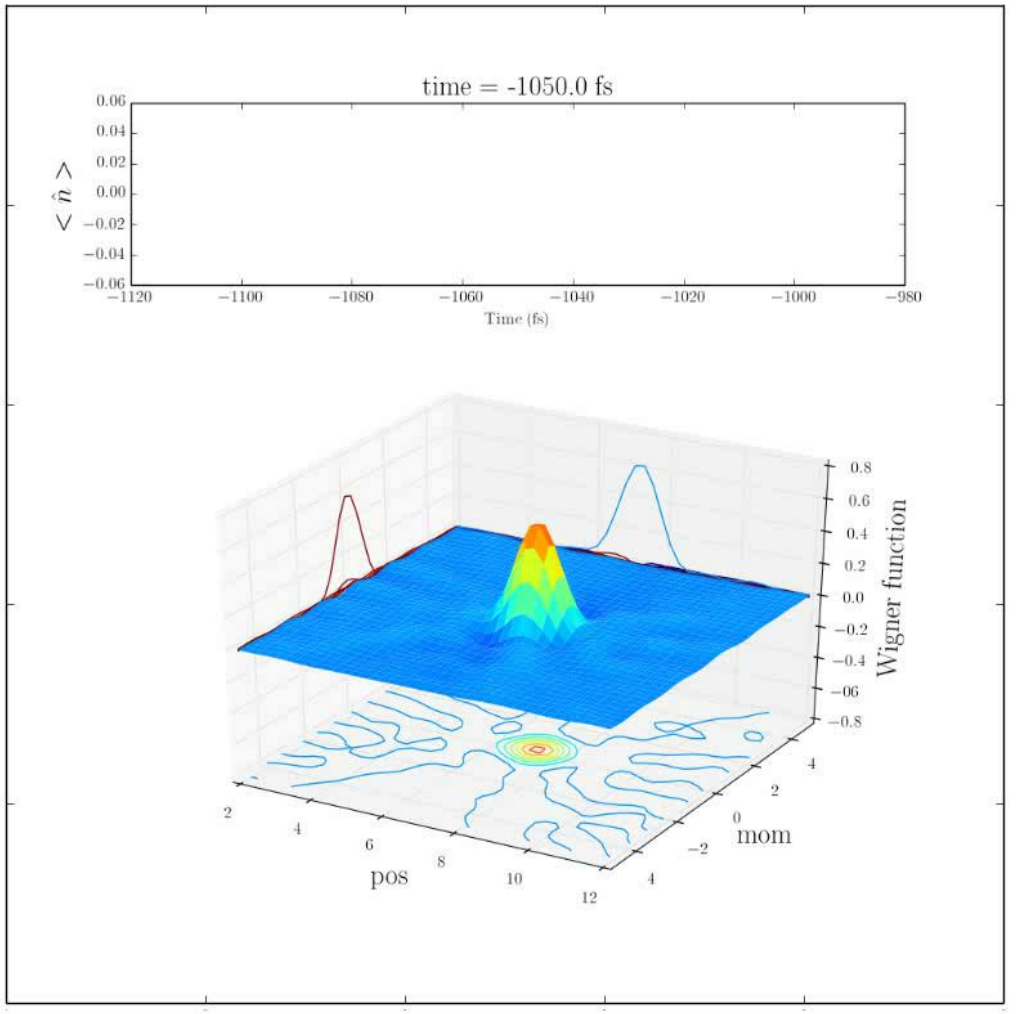

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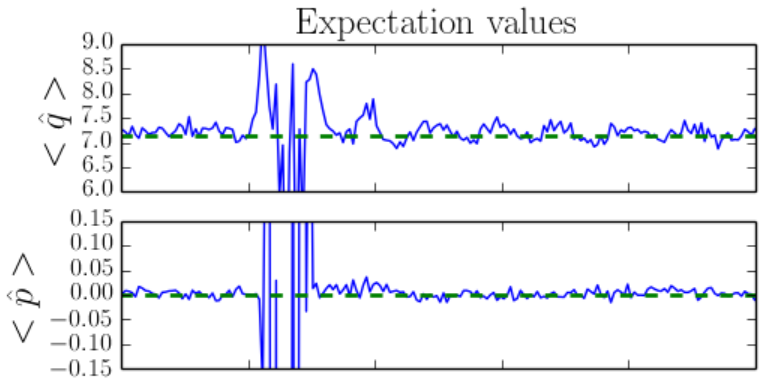

Full quantum state reconstruction of the probe pulses

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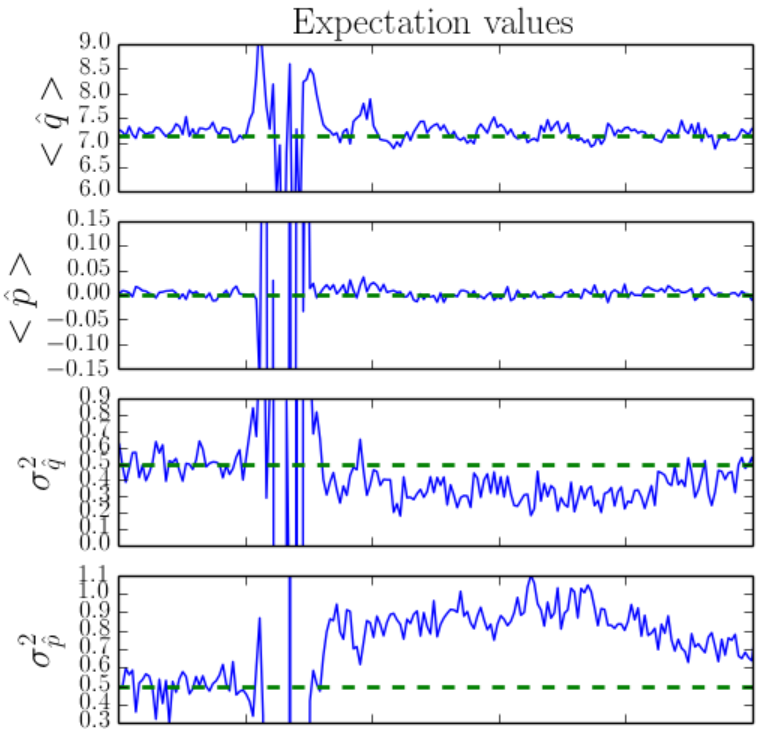

Full quantum state reconstruction of the probe pulses

High Order Momenta!

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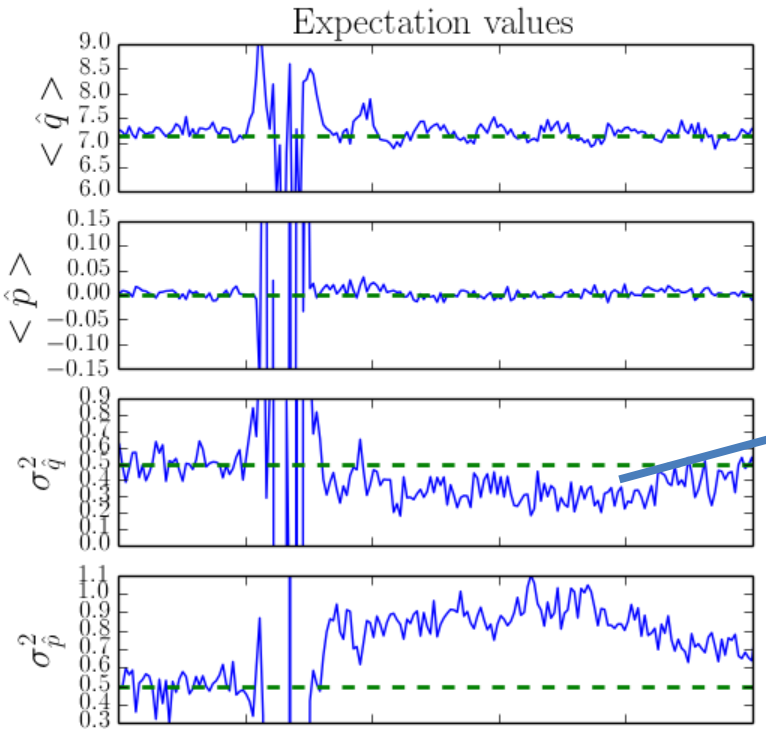

Full quantum state reconstruction of the probe pulses

Squeezing of light!!!

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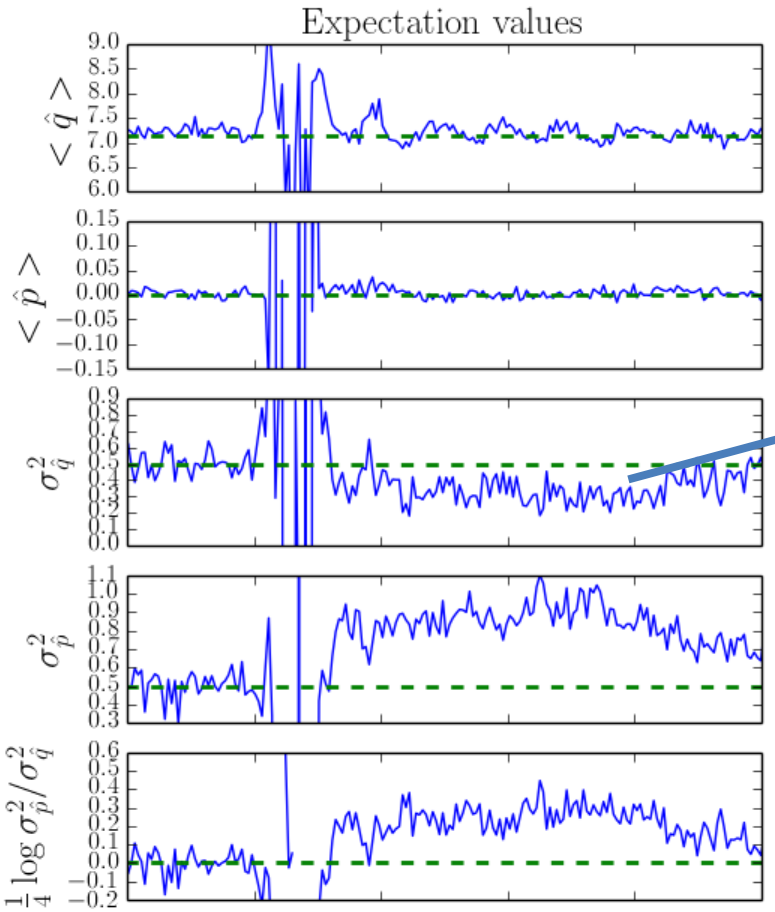

Full quantum state reconstruction of the probe pulses

Squeezing of light!!!

High Order Momenta!

Squeezing Parameter

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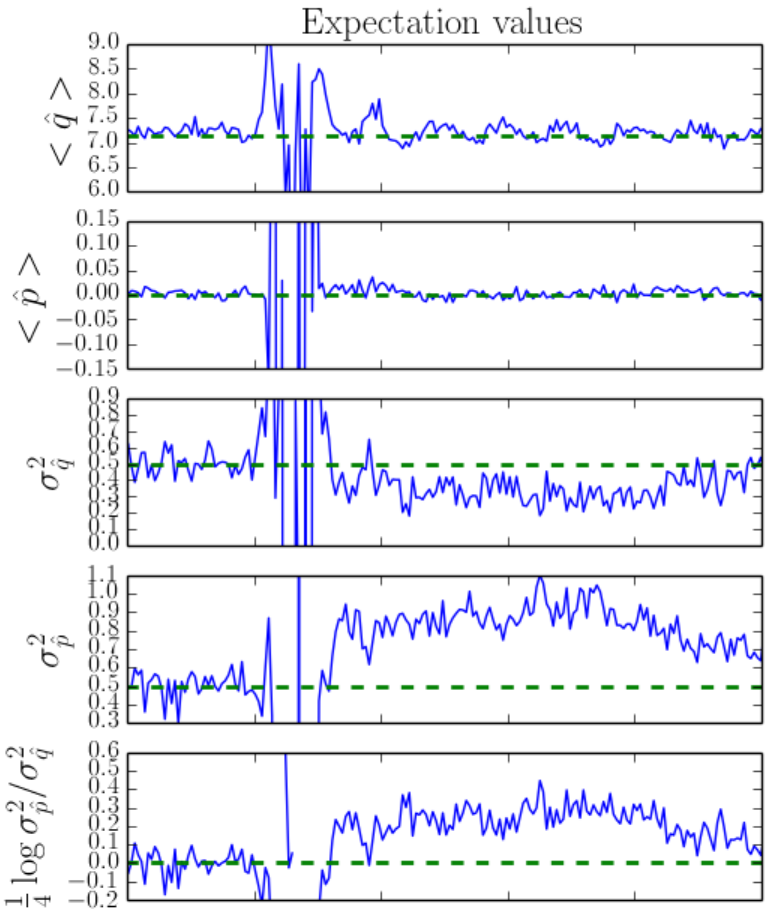

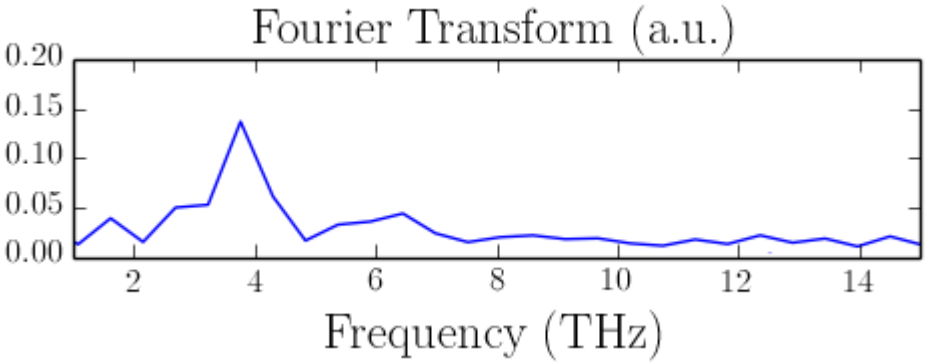

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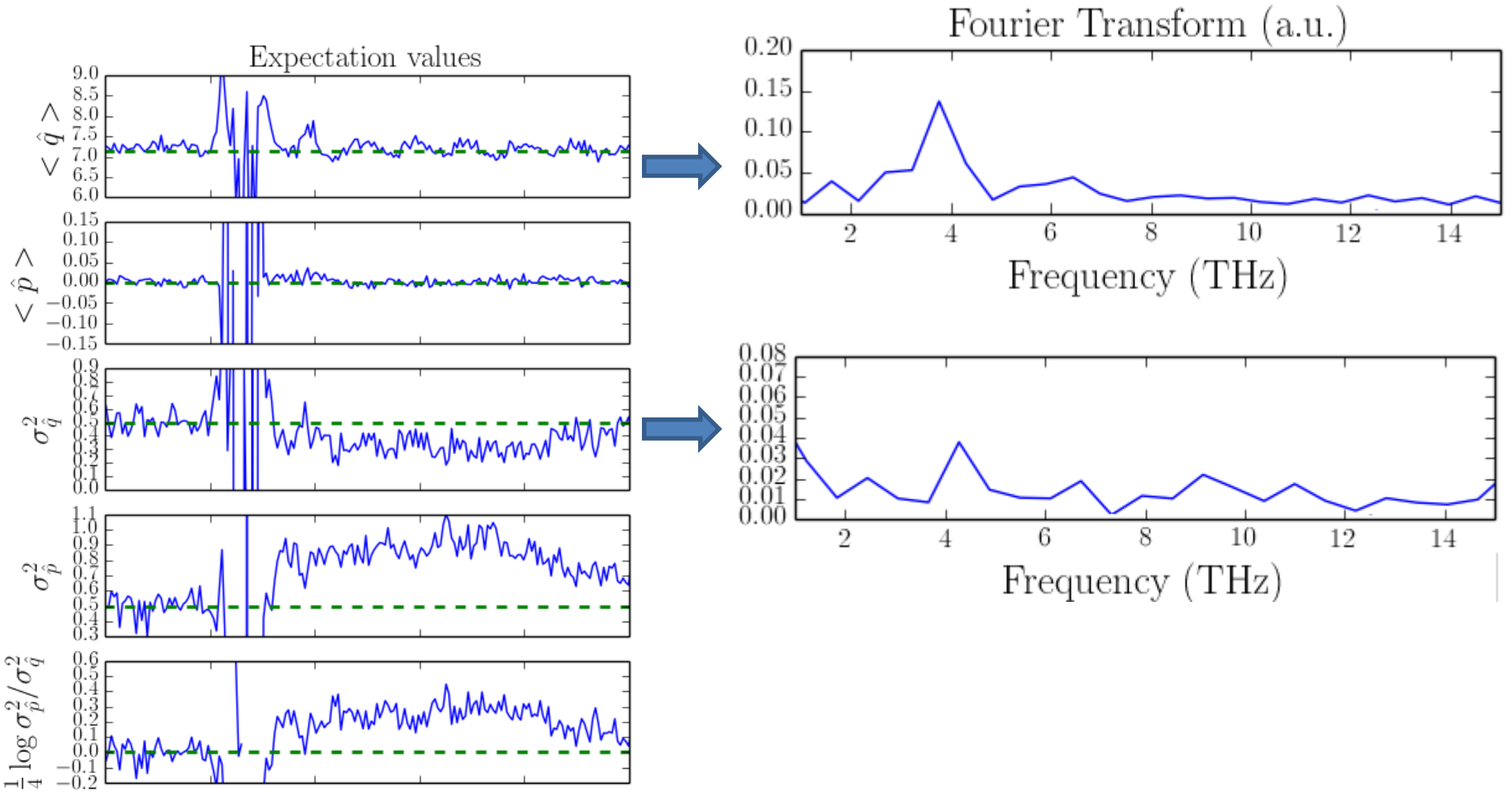

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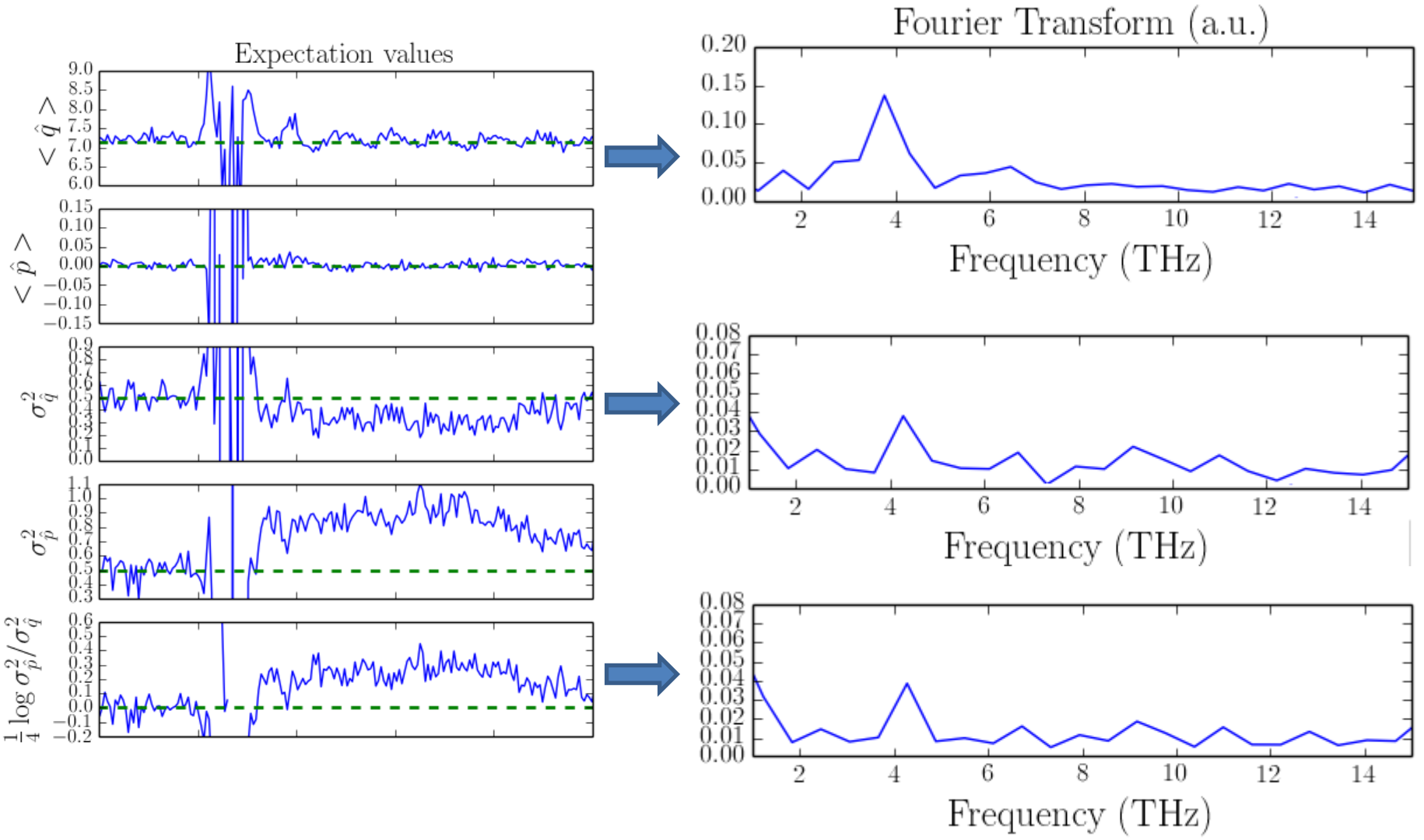
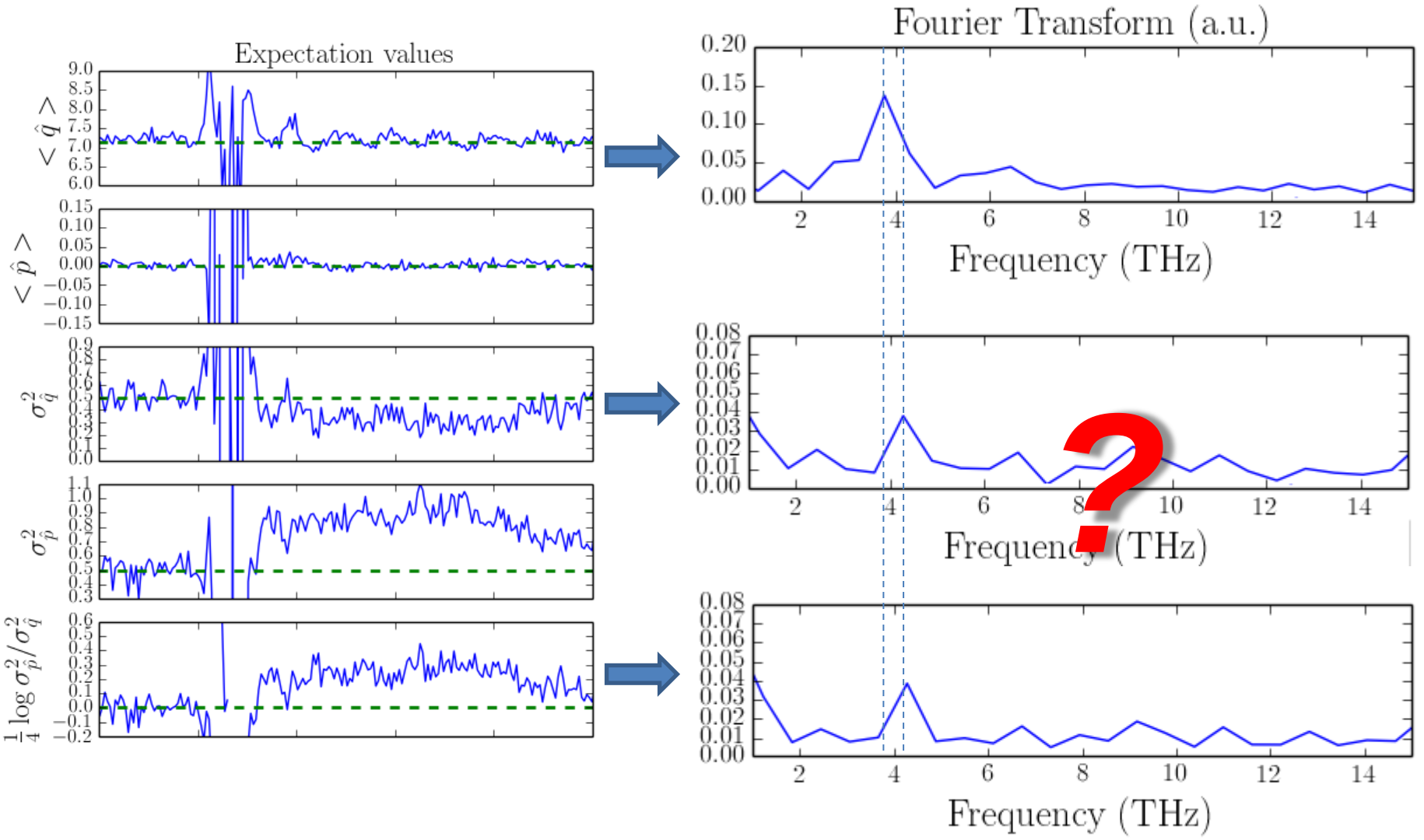


Photon Squeezing by phonon!!

Quantum Optics for studying **Condensed Matter** out of equilibrium



Photon Squeezing by phonon!!

Conclusions

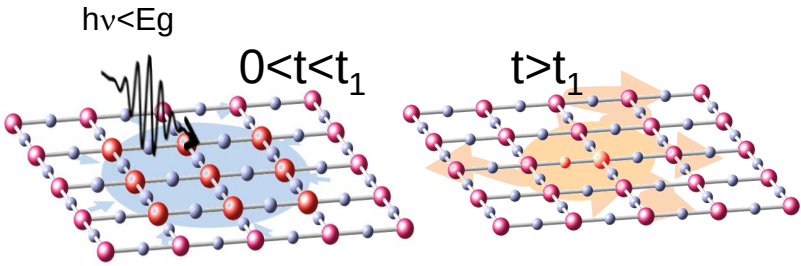
✓The light pulses do not “just” inject energy into the system!

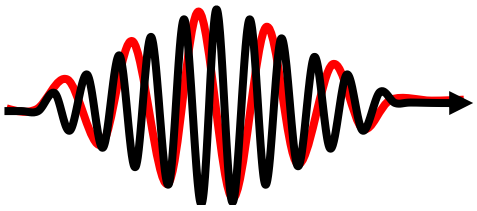
✓Unravel *e-e* and *e-ph* interactions in condensed matter through selective excitations:

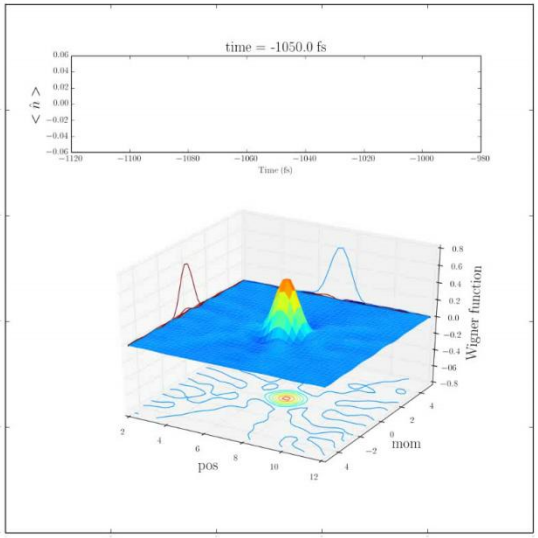
- •Witnessing the boson dressing of electronic excitations
- •Coherent response of low energy degrees of freedom

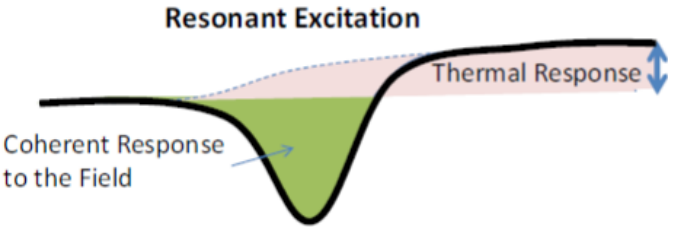
✓Full treatment of light matter interaction is needed beyond effective temperature models

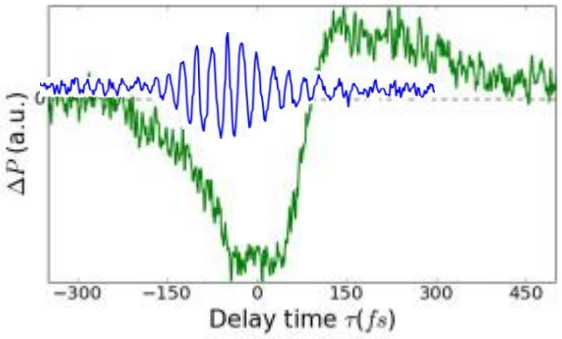
✓Time domain tomographic quantum state reconstruction











Perspectives

✓Higher order measurements of fluctuation spectroscopy in inhomogeneous phases

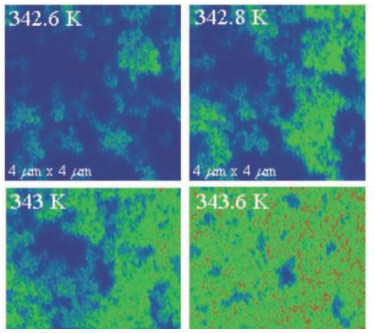
✓Higher order measurements of silent modes AntiFerrimagnet

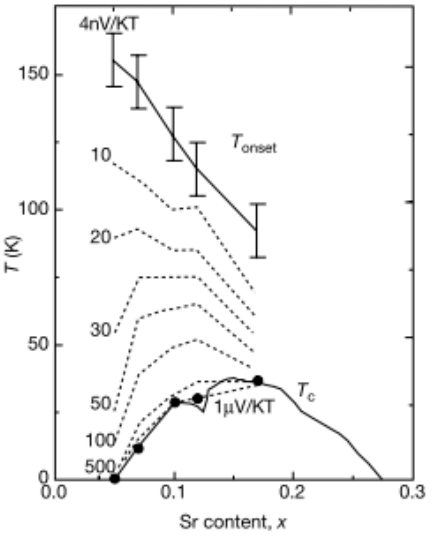
✓Coupling infrared pumps with quantum state reconstruction

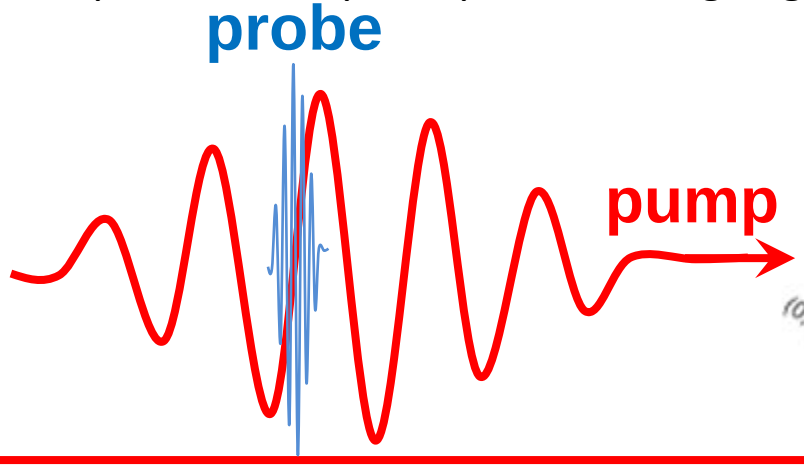
IR "prepare" the low energy mode in a coherent state

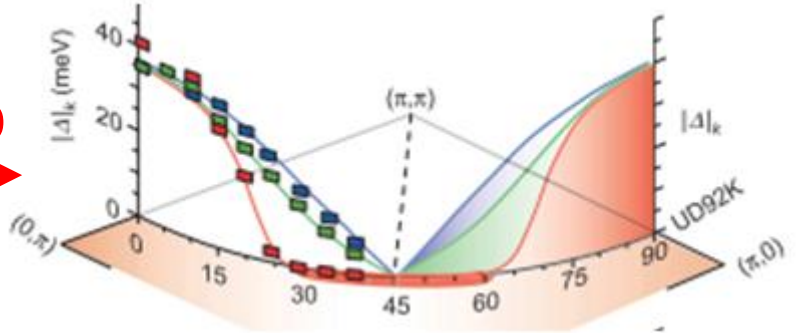
Homodyne reconstruction measure the interaction with electronic excitation

✓Manipulation of optical pulses through light Matter interactions









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