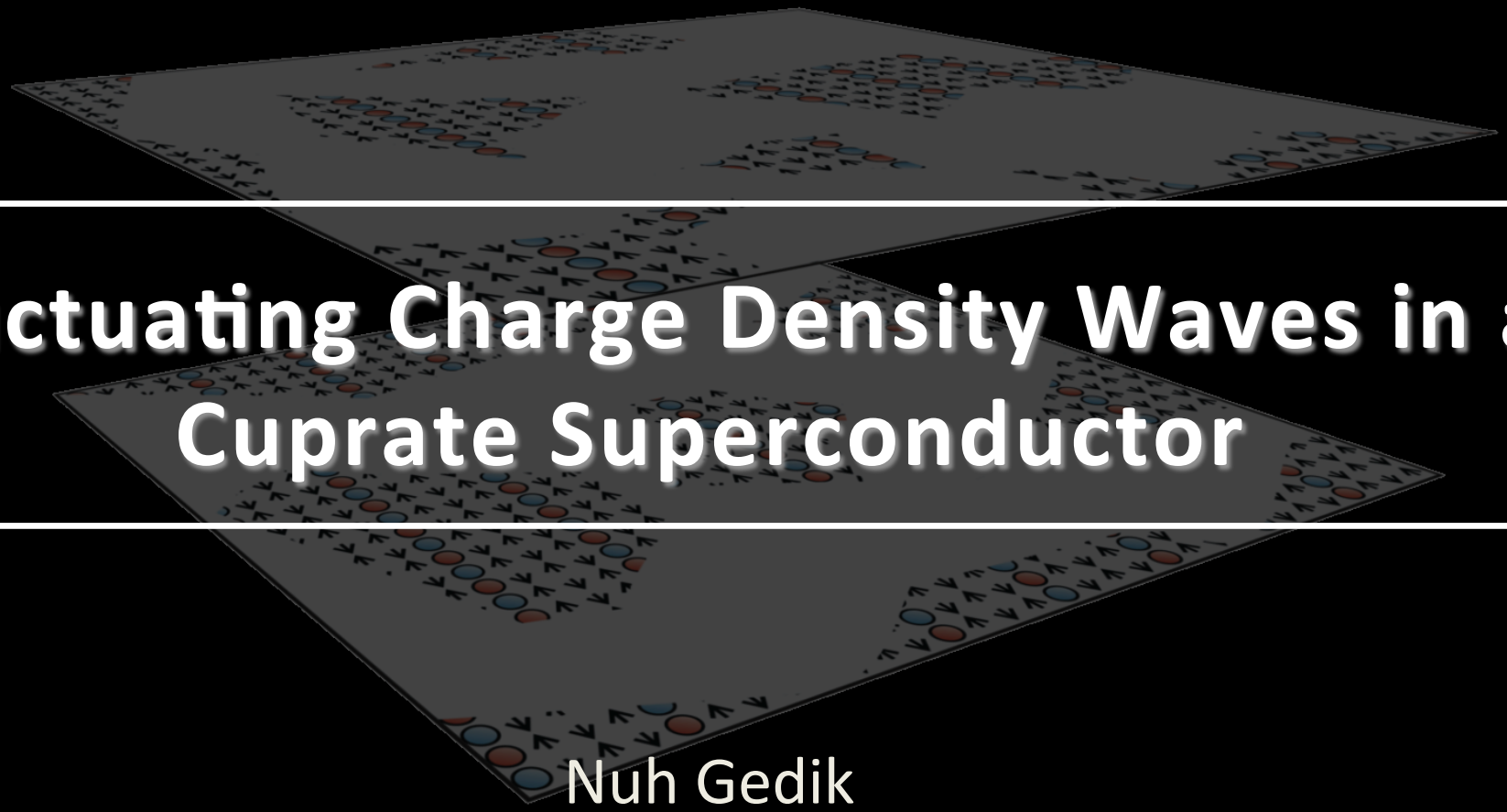


Fluctuating Charge Density Waves in a Cuprate Superconductor

Nuh Gedik

Acknowledgements

Darius Torchinsky

Fahad Mahmood

Ivan Božović

Anthony Bollinger

Nature Materials 12, 387-391 (2013)

Outline

→ Background: Possible CDW order in the cuprates

→ Ultrafast measurement of CDW excitations

→ Detection of CDW excitations in underdoped LSCO

→ Estimate of CDW fluctuation lifetime

→ Summary + Future work

Outline

→ **Background: Possible CDW order in the cuprates**

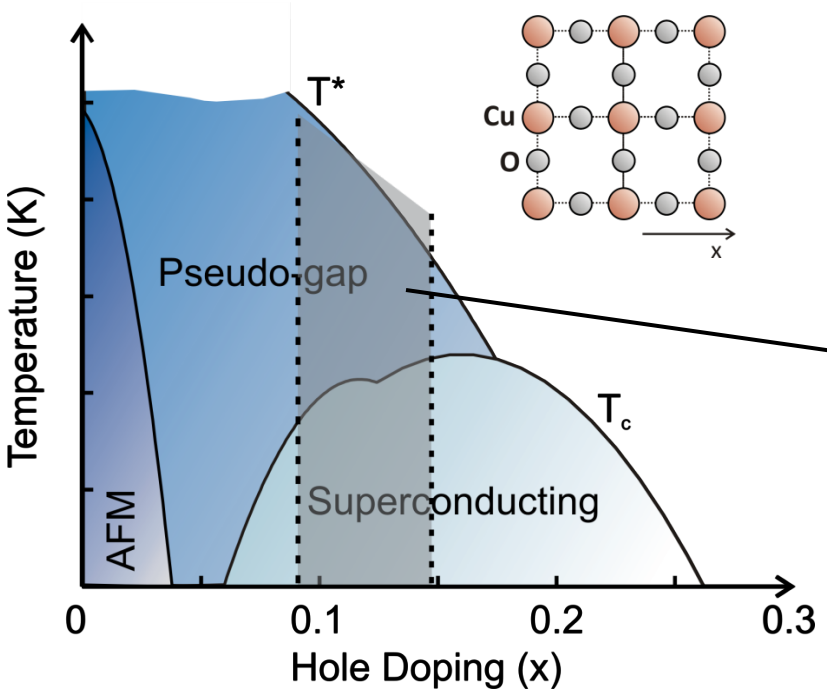
→ Ultrafast measurement of CDW excitations

→ Detection of CDW excitations in underdoped LSCO

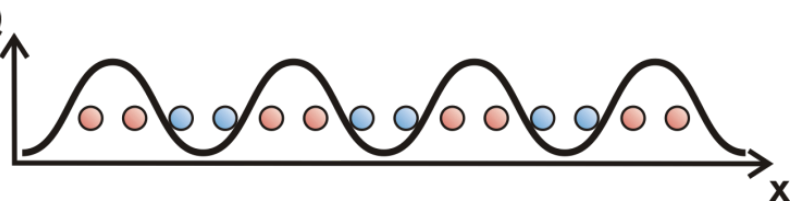
→ Estimate of CDW fluctuation lifetime

→ Summary + Future work

Cuprates – Possible CDW order



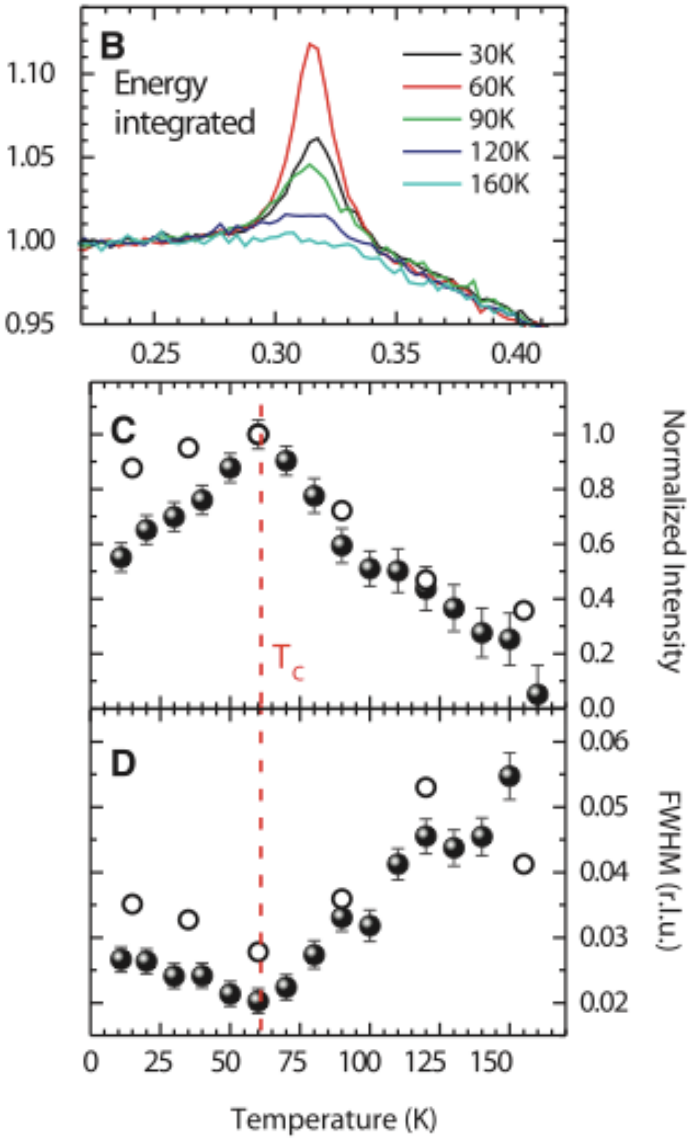
Charge Density Wave (CDW)



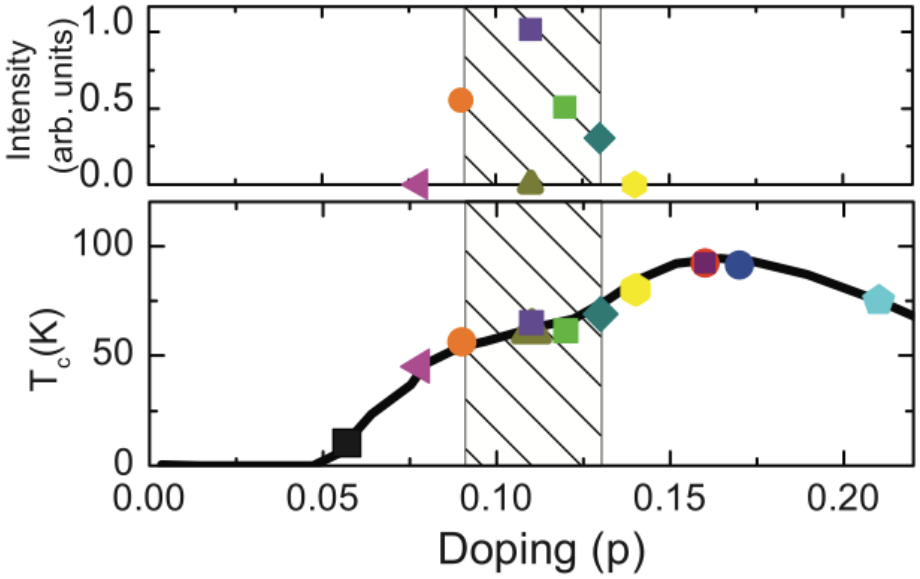
depression in Tc at 1/8 doping

- **Specific or general behavior?**
- **Relationship b/w CDW & High-Tc ?**

CDW fluctuations in YBCO and NdBCO



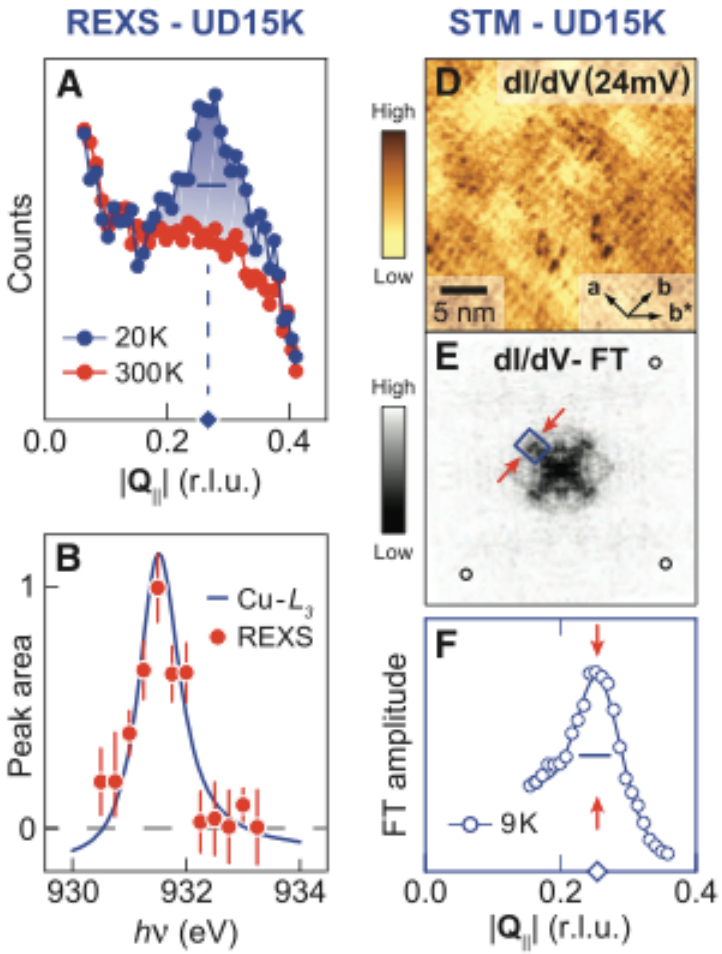
Resonant Elastic X-ray Scattering (REXS)



Ghirenghelli et. al..Science 337, 821–825 (2012)

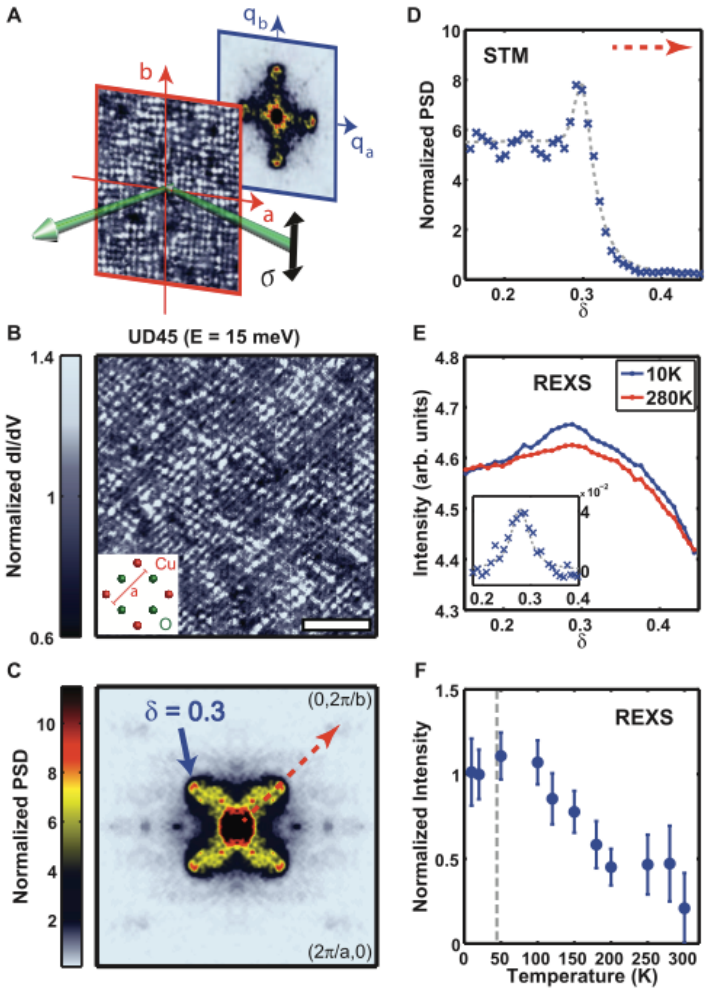
CDW fluctuations in BSCCO

Bi2201



Comin et. al… Science 343, 390 (2014)

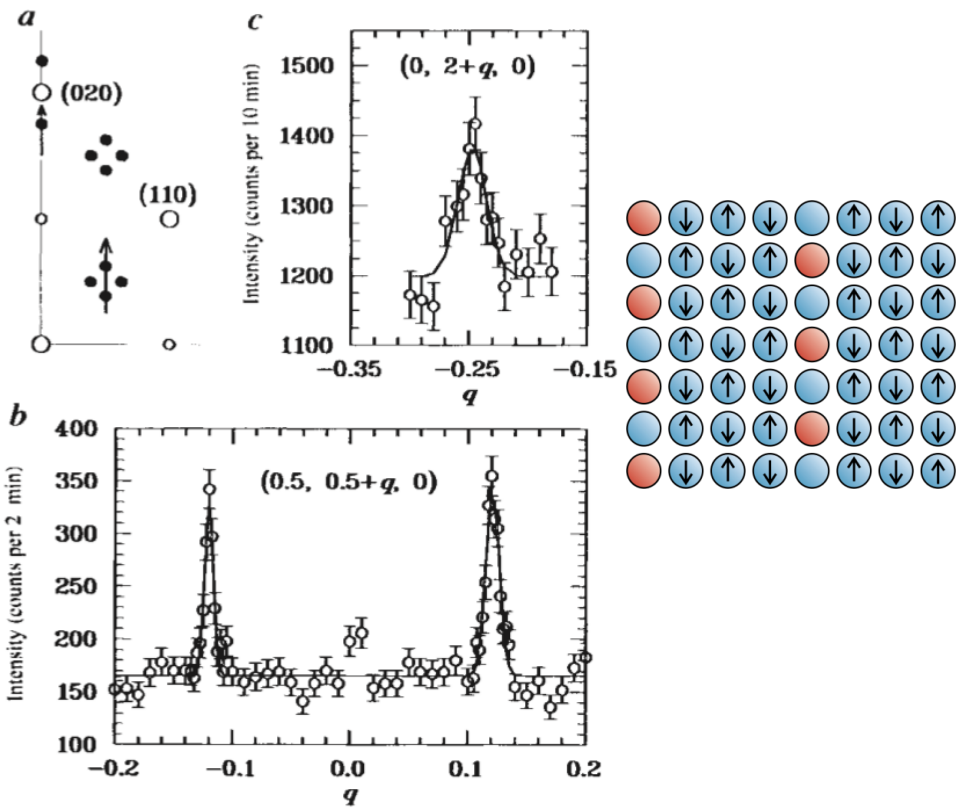
Bi2212



Eduardo H. da Silva Neto et al. Science 343, 393 (2014)

CDW fluctuations in LSCO

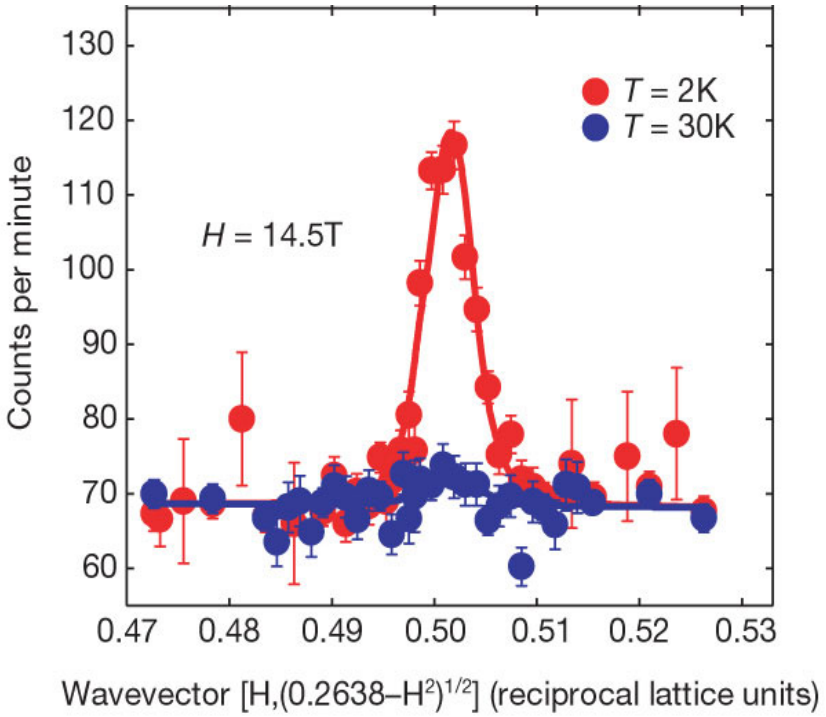
Stabilizing CDW with specific dopants (Nd or Eu)



Neutron and X-ray diffraction

Tranquada et. al. Nature 375, 561–563 (1995)

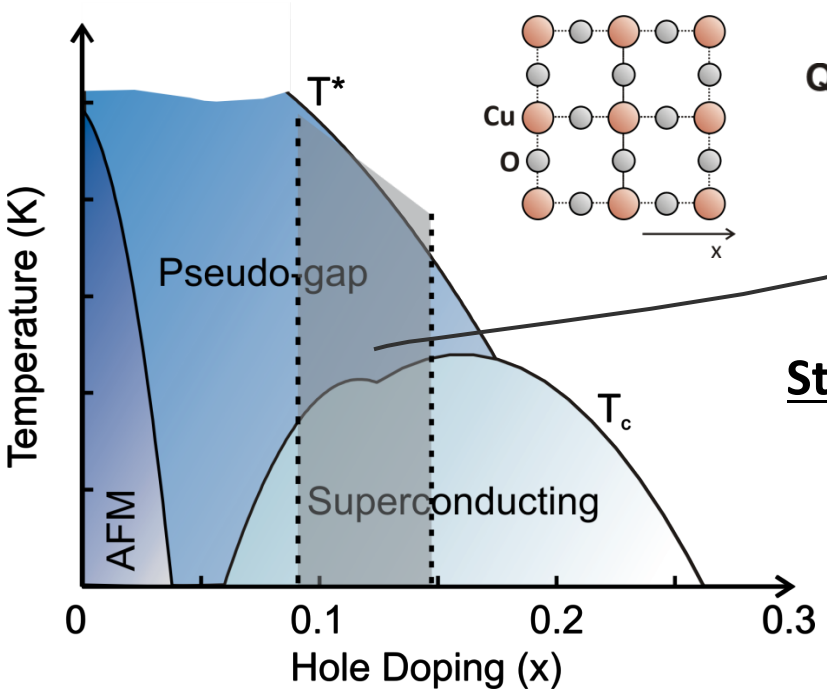
Stabilizing CDW with Magnetic Field in $La_{2-x}Sr_xCuO_4$

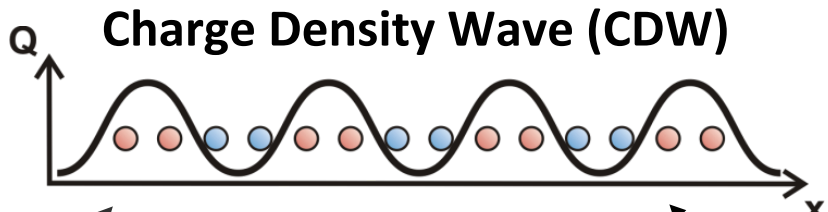


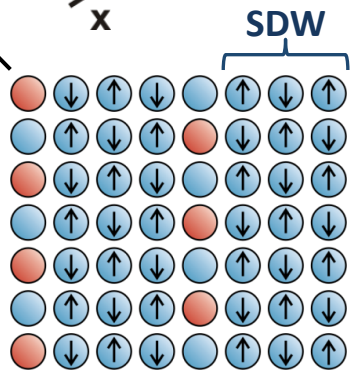
B. Lake et. al. Nature 415, 299–302 (2002)

T. Wu et. al. Nature 477, 191–194 (2011)

Cuprates – Possible CDW order



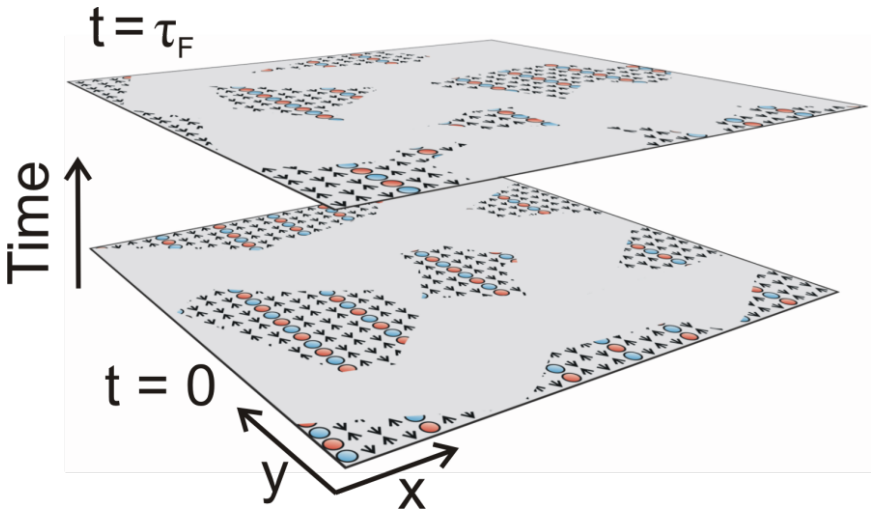




Static "stripe" order in LBCO….

depression in Tc at 1/8 doping

Fluctuating Order in LSCO



- **Relationship b/w CDW & High-Tc ?**
- **Time scale for fluctuations?**
- **How to observe with optics?**

Outline

→ Background: Possible CDW order in the cuprates

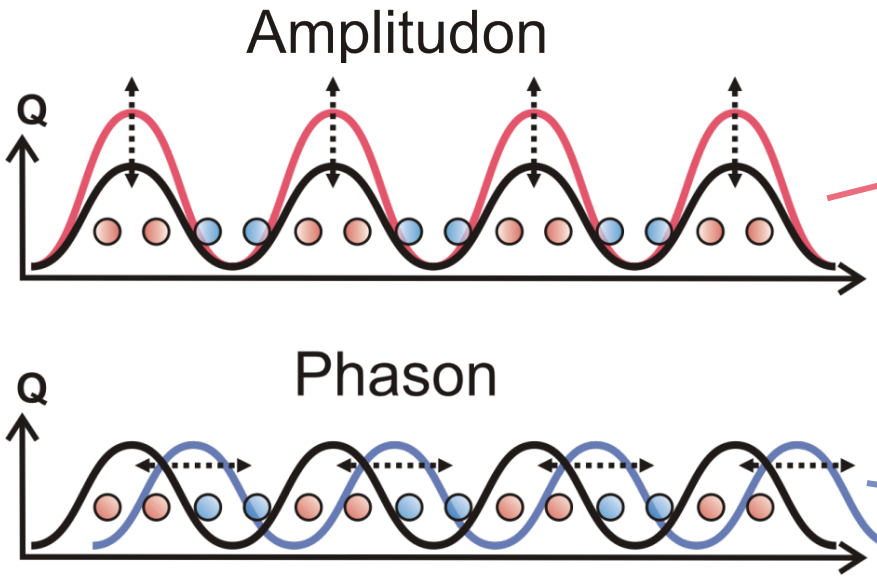
→ **Ultrafast measurement of CDW excitations**

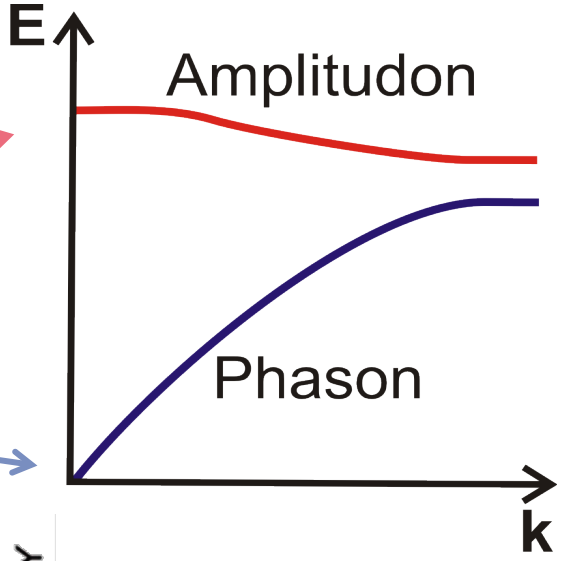
→ Detection of CDW excitations in underdoped LSCO

→ Estimate of CDW fluctuation lifetime

→ Summary + Future work

CDW Excitations





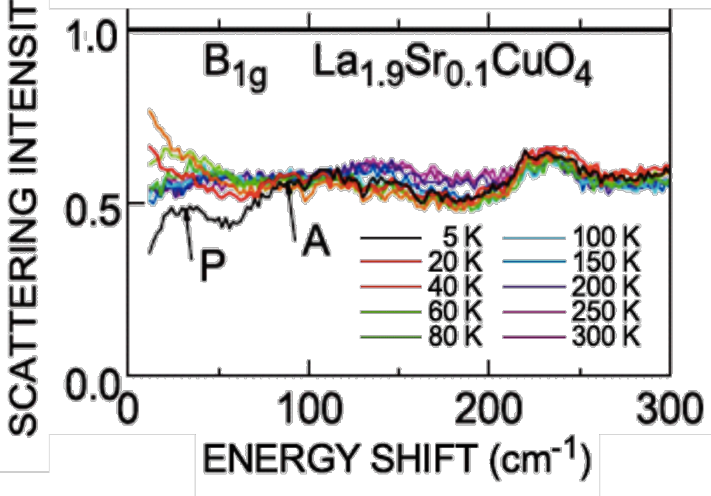
Can we see these collective modes with time resolved optics?

↓

Measure the damping rates

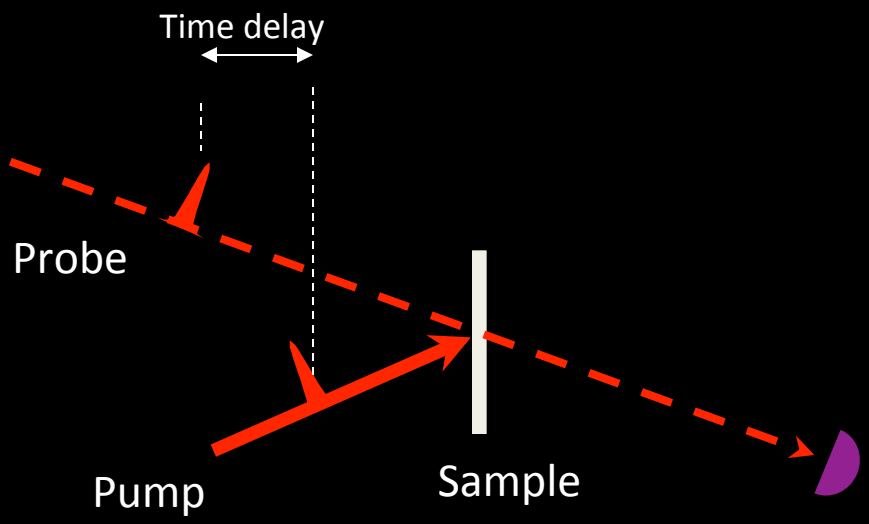
↓

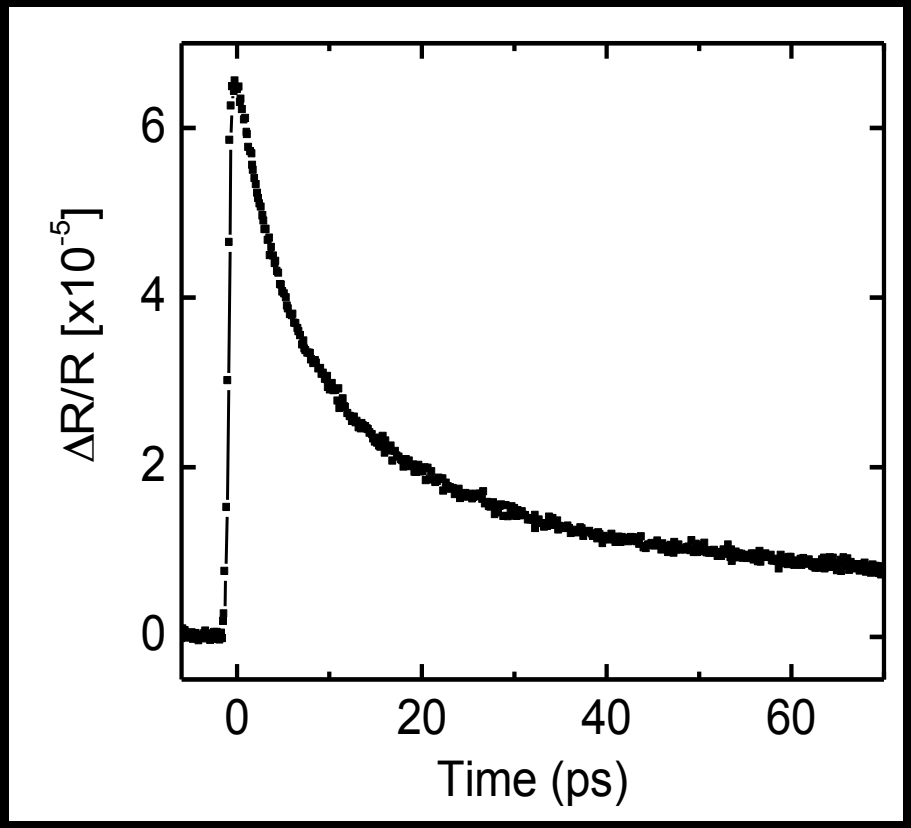
<u>Determine CDW fluctuation lifetime</u>



S. Sugai et. al. PRL 96, 137003 (2006)

Pump probe spectroscopy



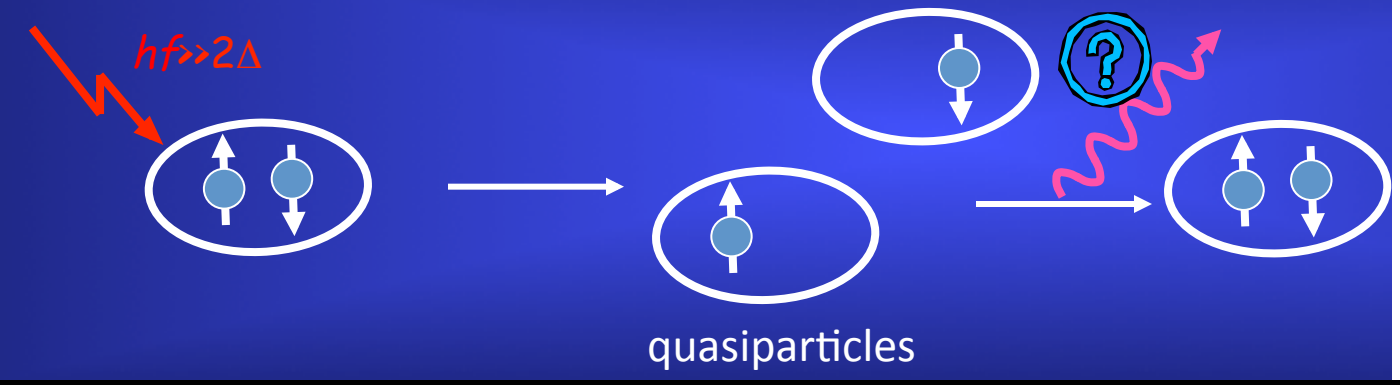


$\Delta n(t) \sim \Delta R(t)$

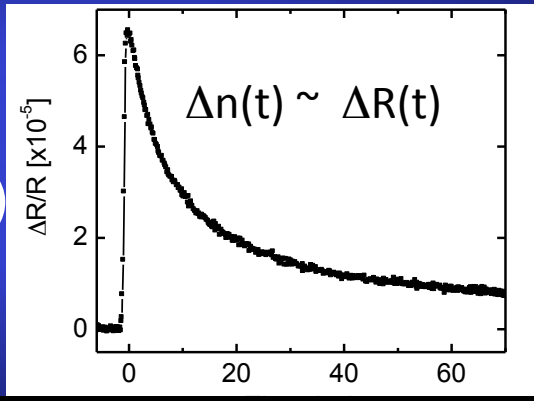
What can we learn from optical pump-probe spectroscopy?

What do we learn from Pump-probe spectroscopy?

Method: Break pairs, watch them in real time as they repair…



Reflectivity change

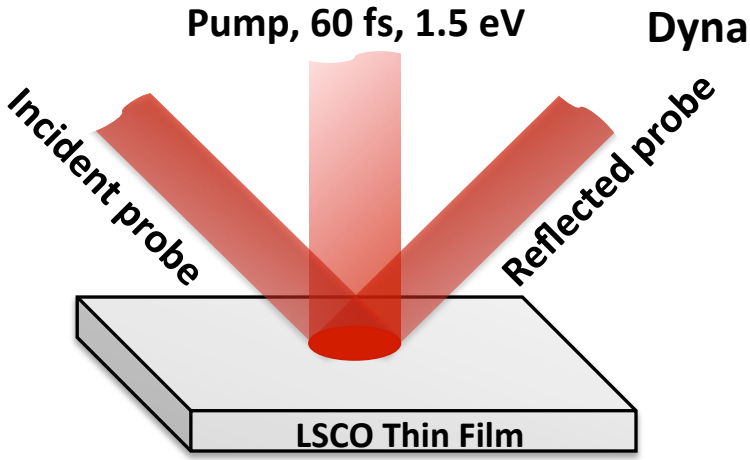


Pump probe spectroscopy -> Relaxation of electronic excitations

Can we use this technique to probe collective excitations?

CDW Excitations - Ultrafast Measurements

Amplitudon – Pump-probe (PP) Spectroscopy

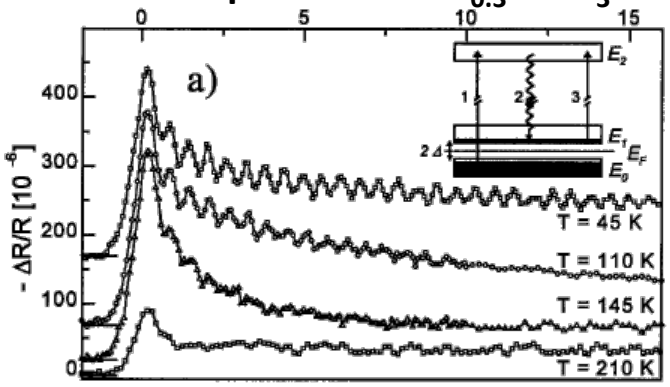


Dynamic change in reflectivity

Track single particle excitations & collective modes

Uniform excitation
$k = 0$ **modes**

Amplitudons in $K_{0.3}MoO_3$



J. Demsar et. al. PRL 83, 800-803 (1999)

DECP Mechanism

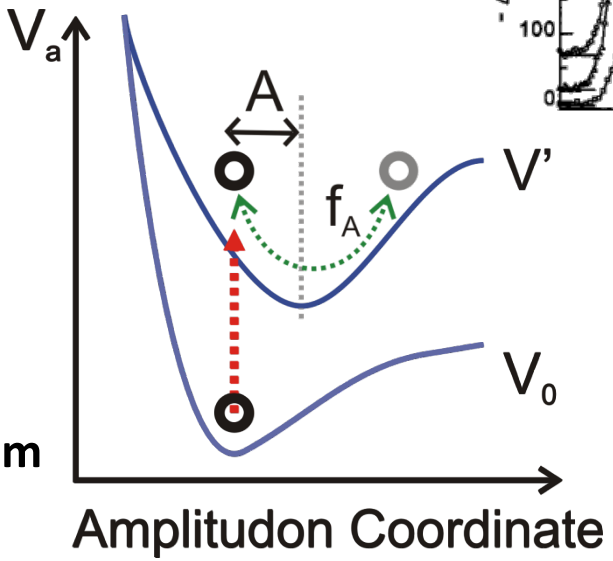
Single-particle excitations

↓

Change in local V

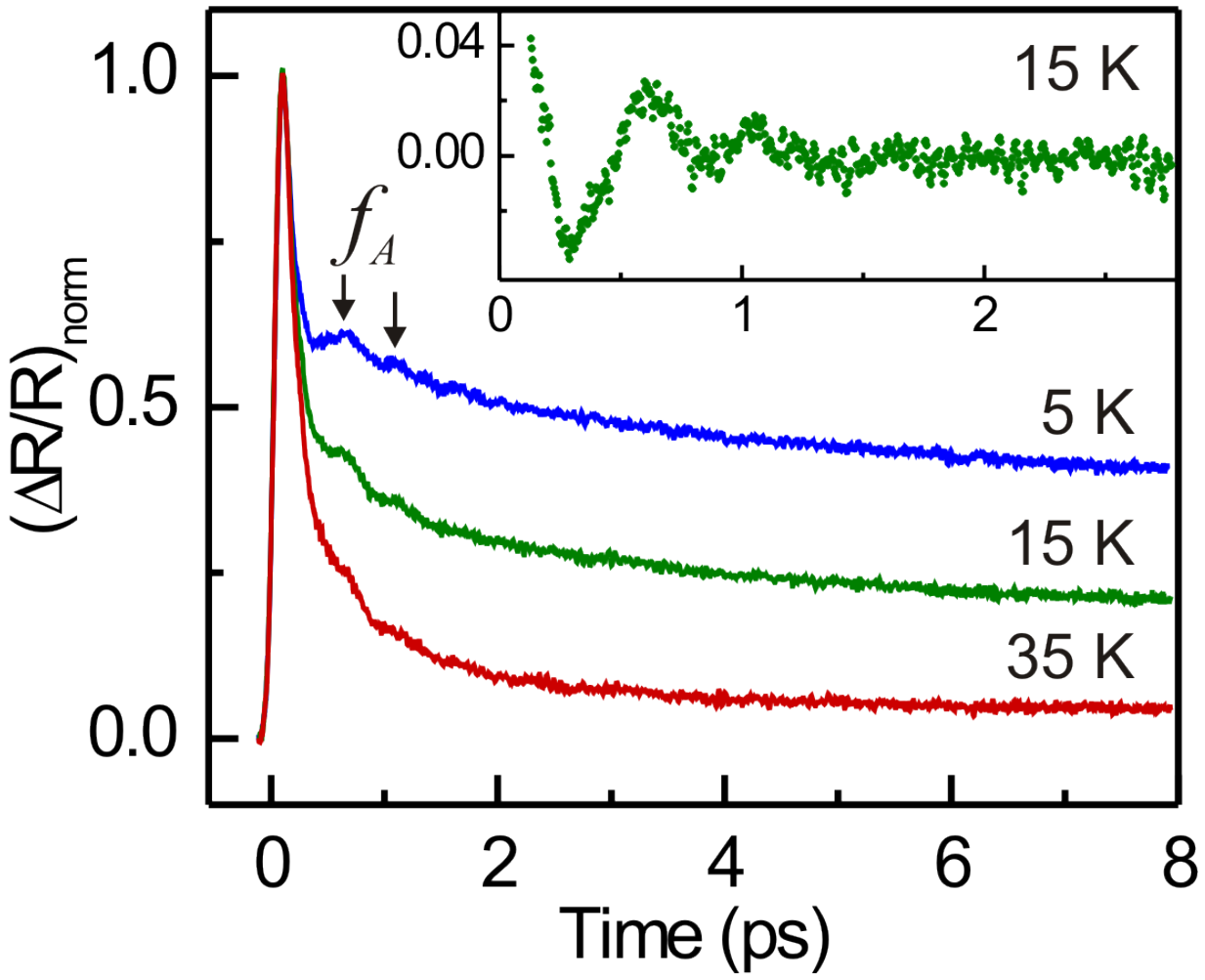
↓

Oscillation about new equilibrium



Amplitudon Dynamics

Oscillations in the PP reflectivity transients



Underdoped LSCO

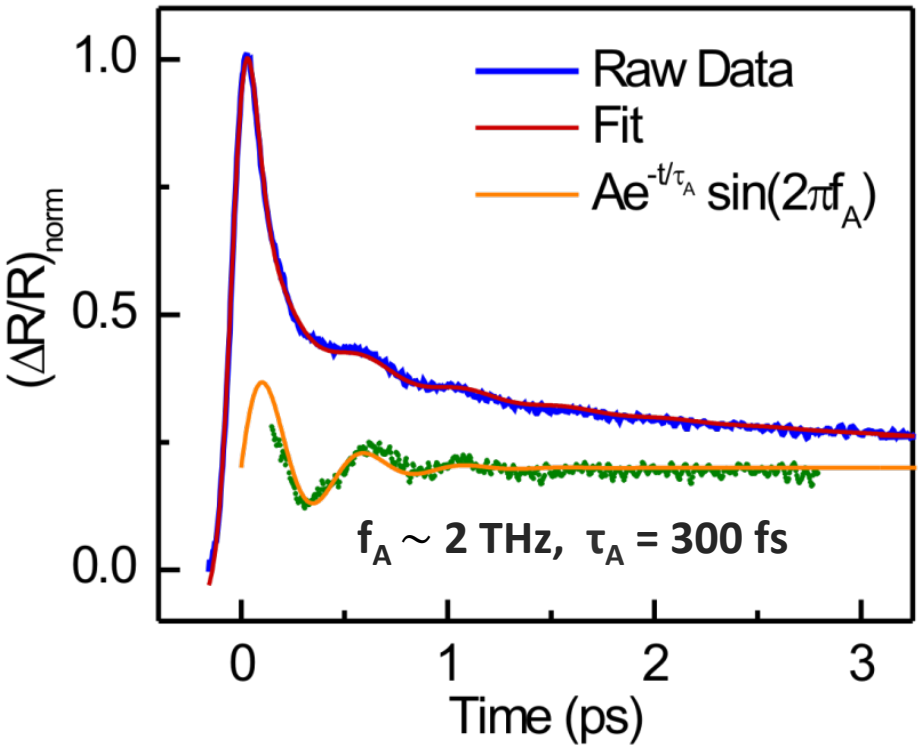
x = 0.10

T_c = 26 K

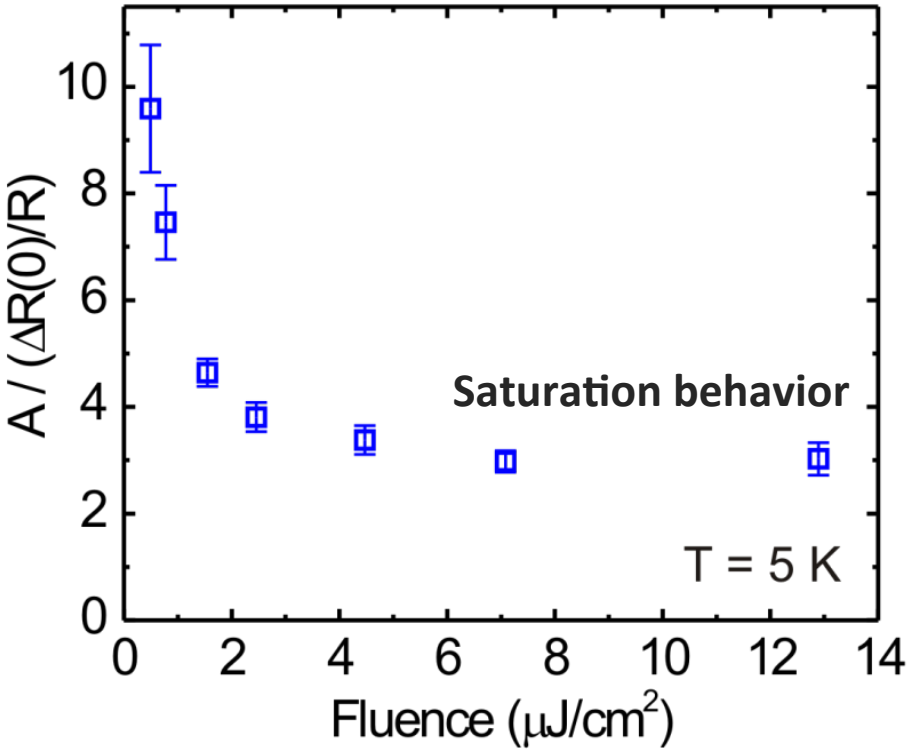
- **Seen both above & below T_c**
- **Persist up to 100 K**

Amplitudon Dynamics

Extracting dynamic parameters



Agreement with Raman results



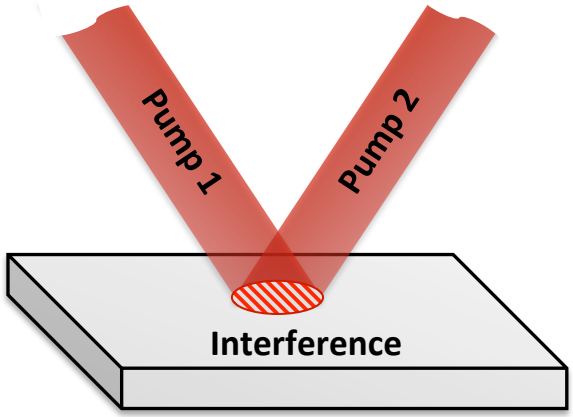
Confirms this is amplitudon

What about phason? Need to depin…

CDW Excitations - Ultrafast Measurements

Phason – Transient Grating (TG) Spectroscopy

Generation



Single-particle excitations

↓

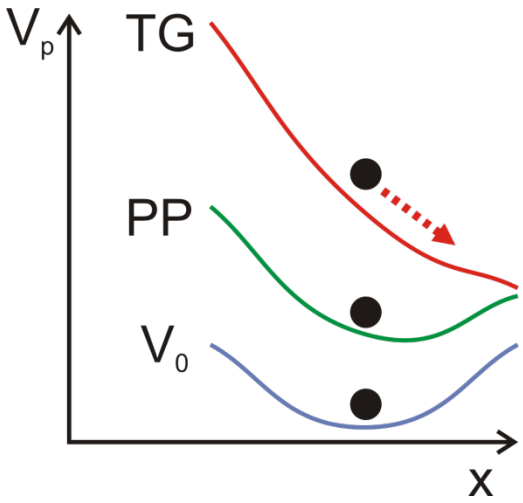
Sinusoidal change in V

↓

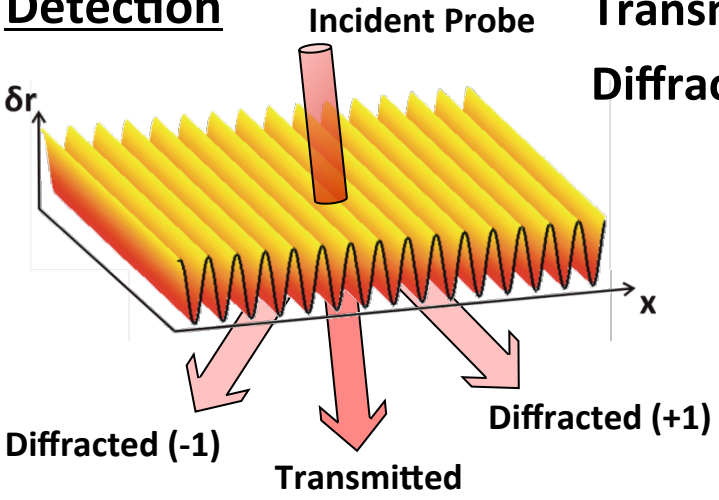
Stronger E-field

↓

Depinning of phason

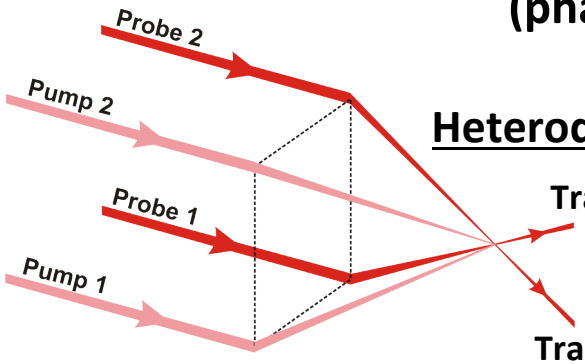


Detection



Transmitted beam --> k = 0 excitations (PP signal)

Diffracted beam --> k = 0 & finite k excitations (TG signal) (phason)



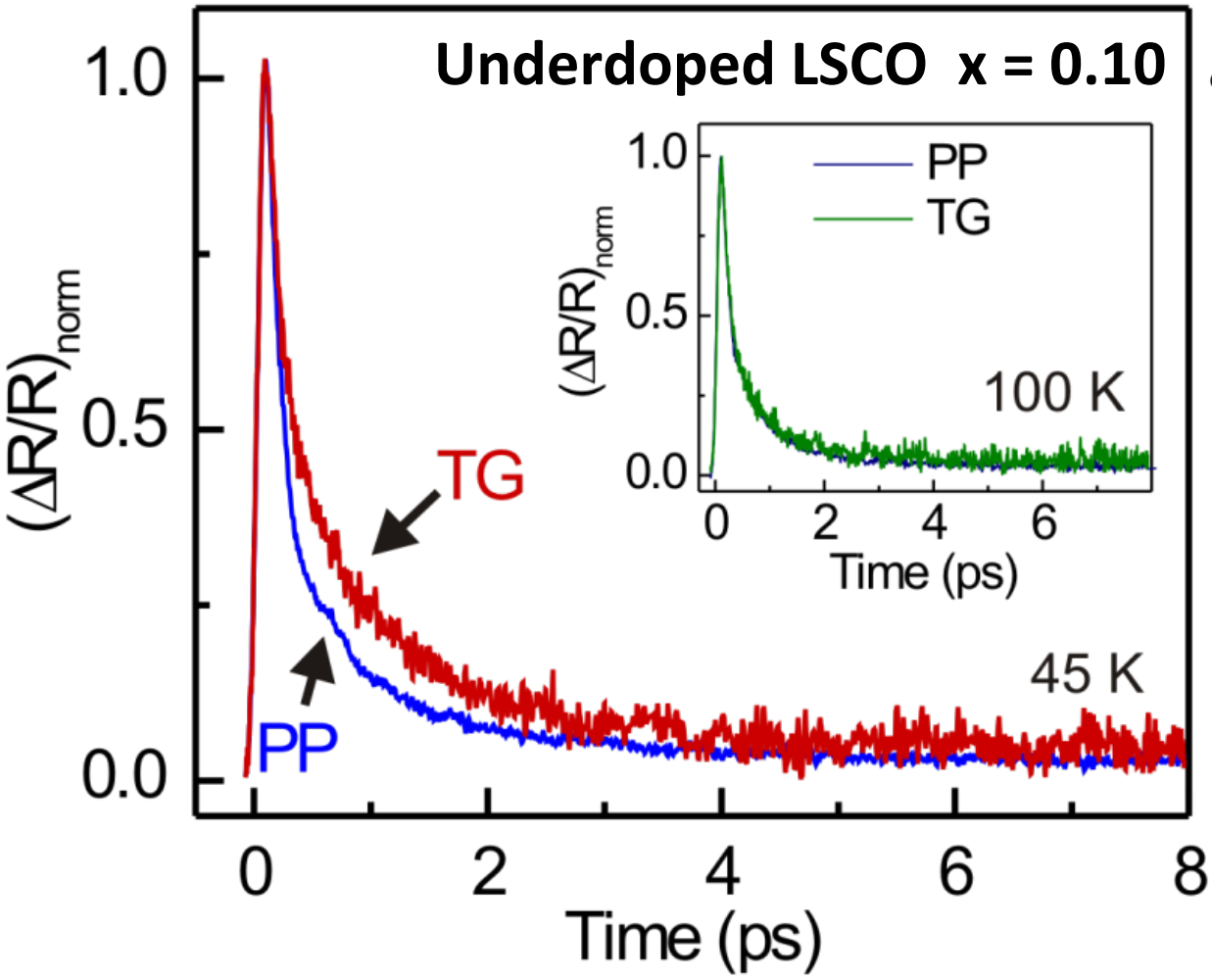
Heterodyne detection

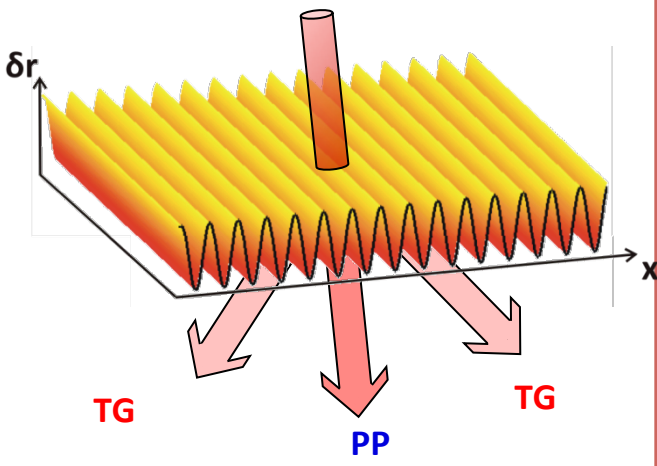
Transmitted P1 + Diffracted P2

Transmitted P2 + Diffracted P1

Phason Dynamics

Additional component in the TG response





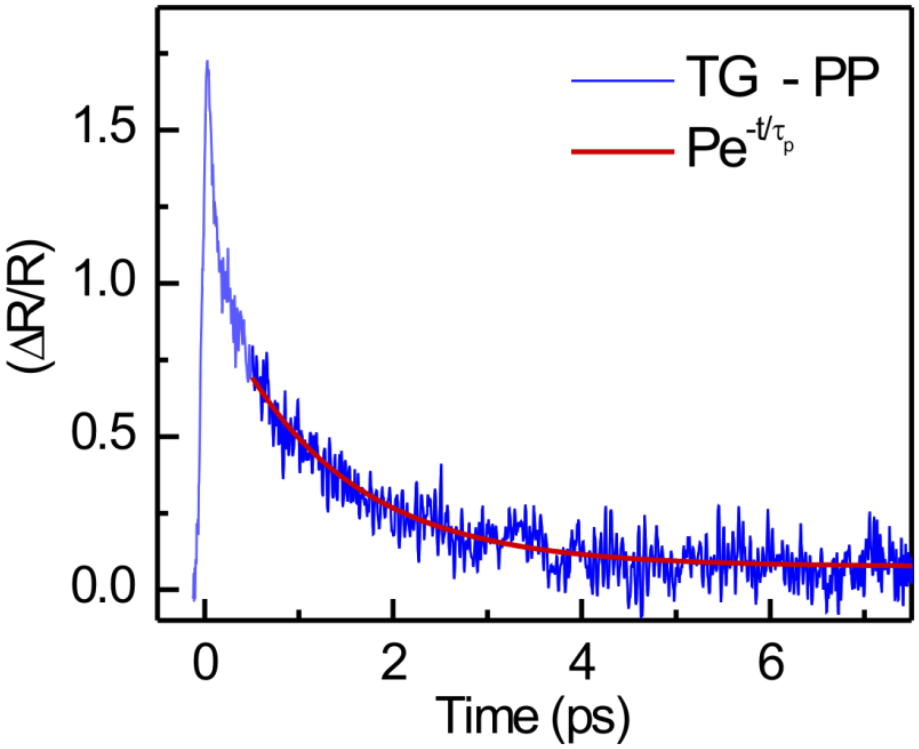
Can not be due to:

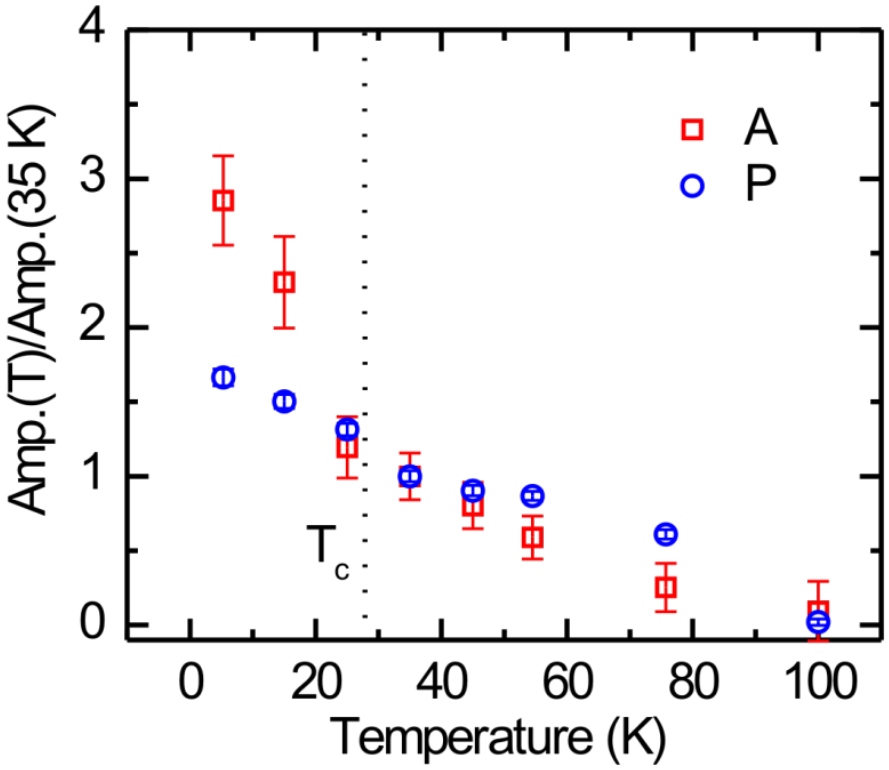
- **Thermal diffusion**
- **Carrier diffusion**

<u>CDW Phason?</u>

Phason Dynamics

Confirm detection of phason





Similar behavior of 'A' and 'P' --> suggests presence of phason

Extract phason lifetime --> study damping with temperature

Outline

→ Background: Possible CDW order in the cuprates

→ Ultrafast measurement of CDW excitations

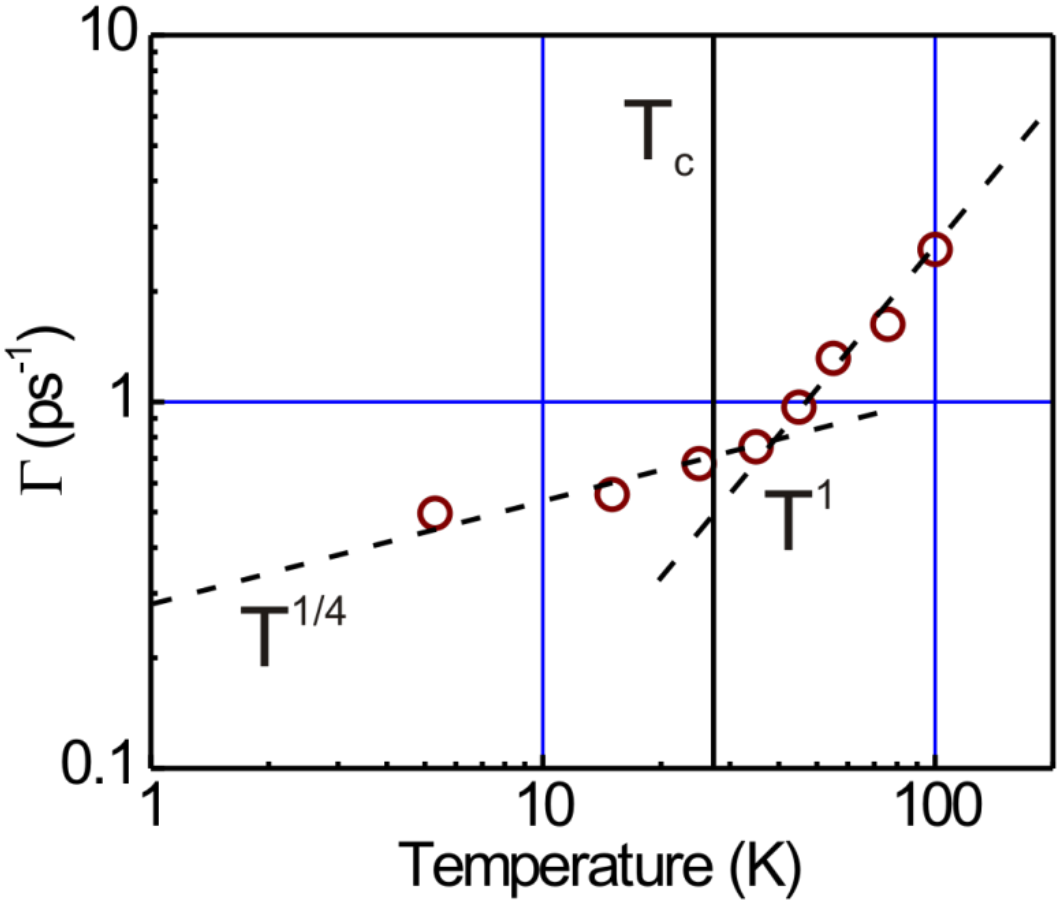
→ Detection of CDW excitations in underdoped LSCO

→ **Estimate of CDW fluctuation lifetime**

→ Summary + Future work

Phason Dynamics

Phason damping



Source of damping?

If intrinsic damping then:

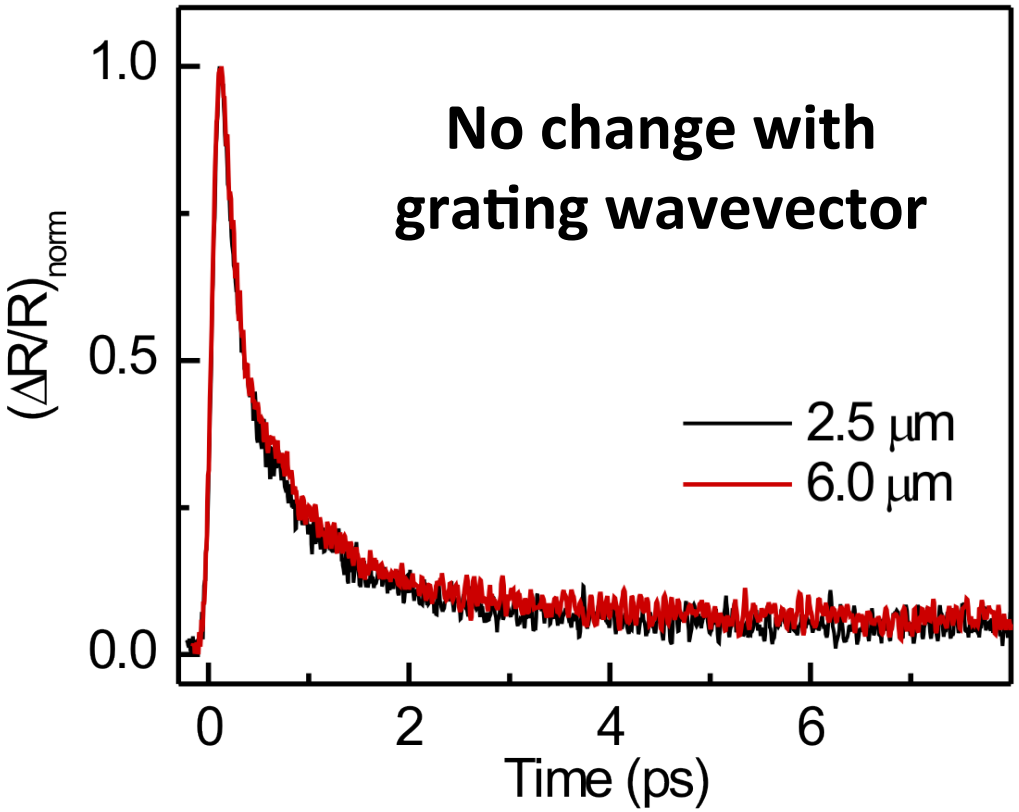
- $\Gamma \sim T^5$ or T^2

- $\Gamma(q)$

Phys. Rev. B **32**, 4639 (1985)

Phason Dynamics

Phason damping



Source of damping?

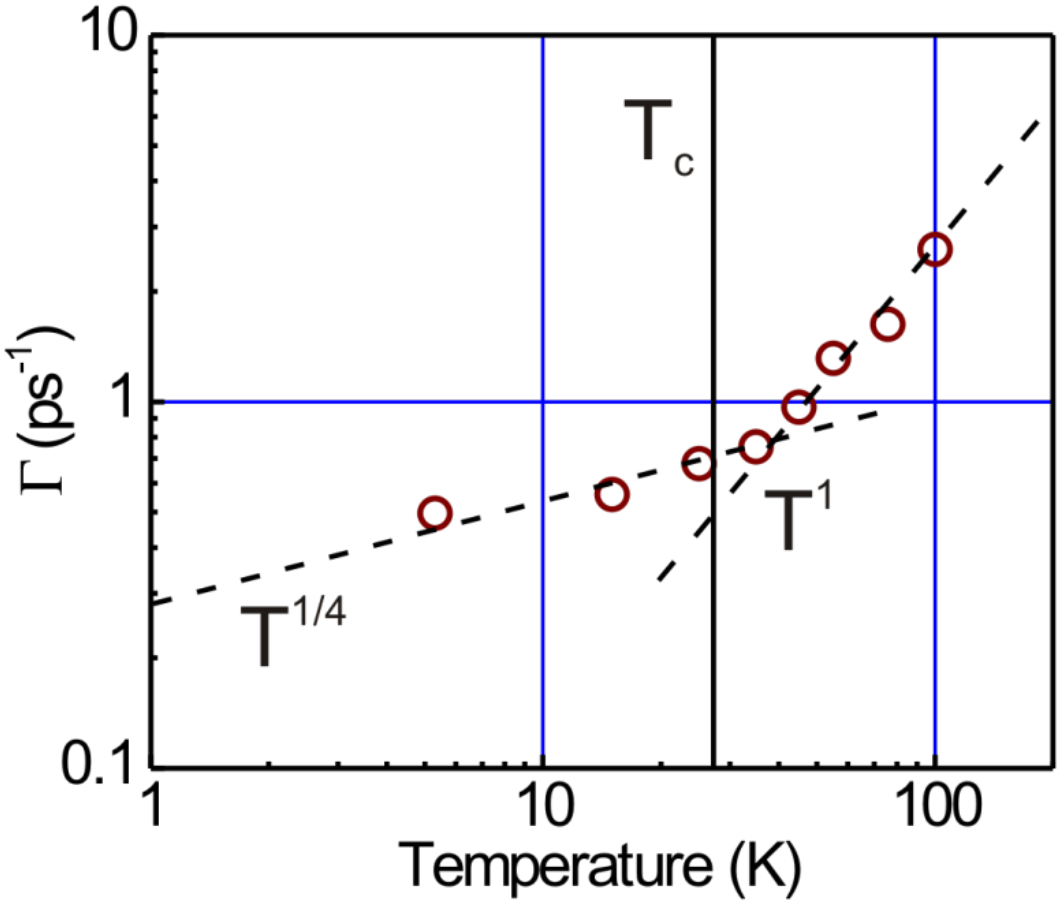
If intrinsic damping then:

- $\Gamma \sim T^5$ or T^2
- $\Gamma(q)$

Phys. Rev. B **32**, 4639 (1985)

Phason Dynamics

Phason damping --> CDW fluctuations



Source of damping?

- **Not intrinsic**
- **CDW fluctuations**

Phason lifetime

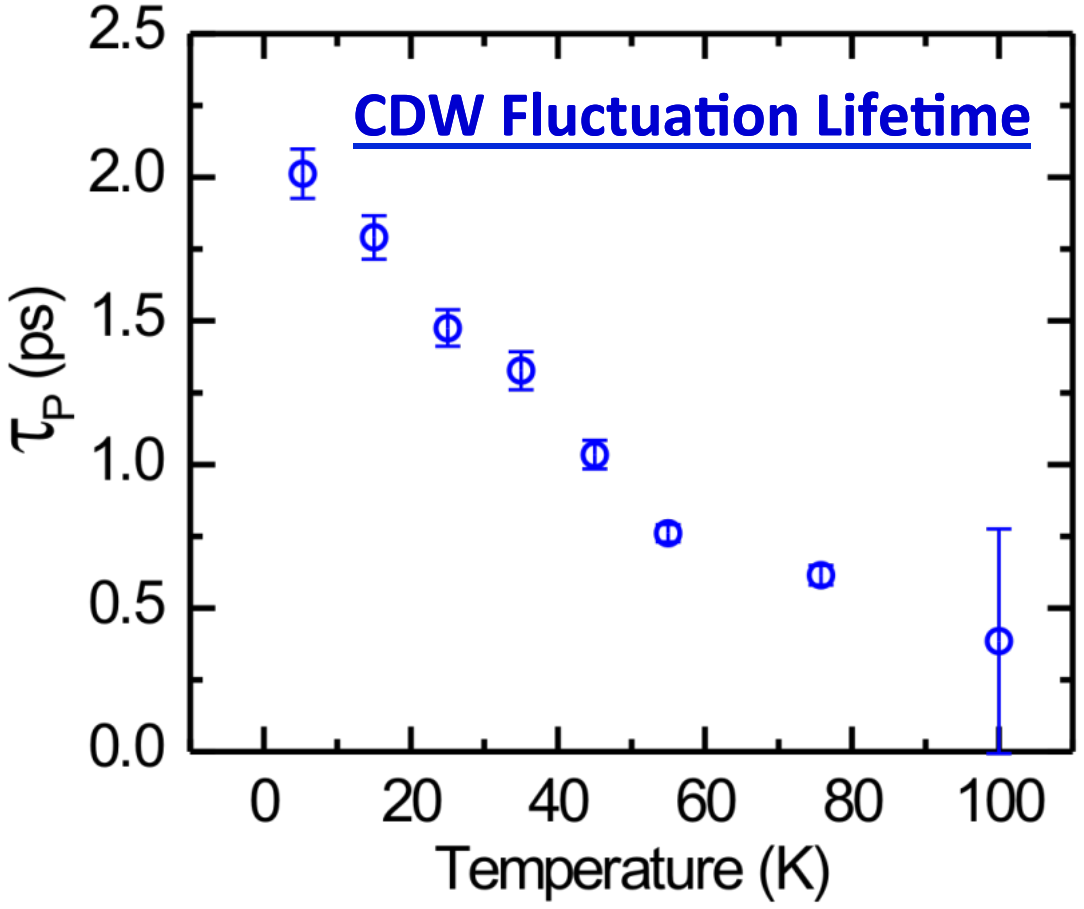
↓

Measure of CDW lifetime

Phys. Rev. B **32**, 4639 (1985)

Phason Dynamics

Phason damping --> CDW fluctuations



Source of damping?

- **Not intrinsic**
- **CDW fluctuations**

Phason lifetime

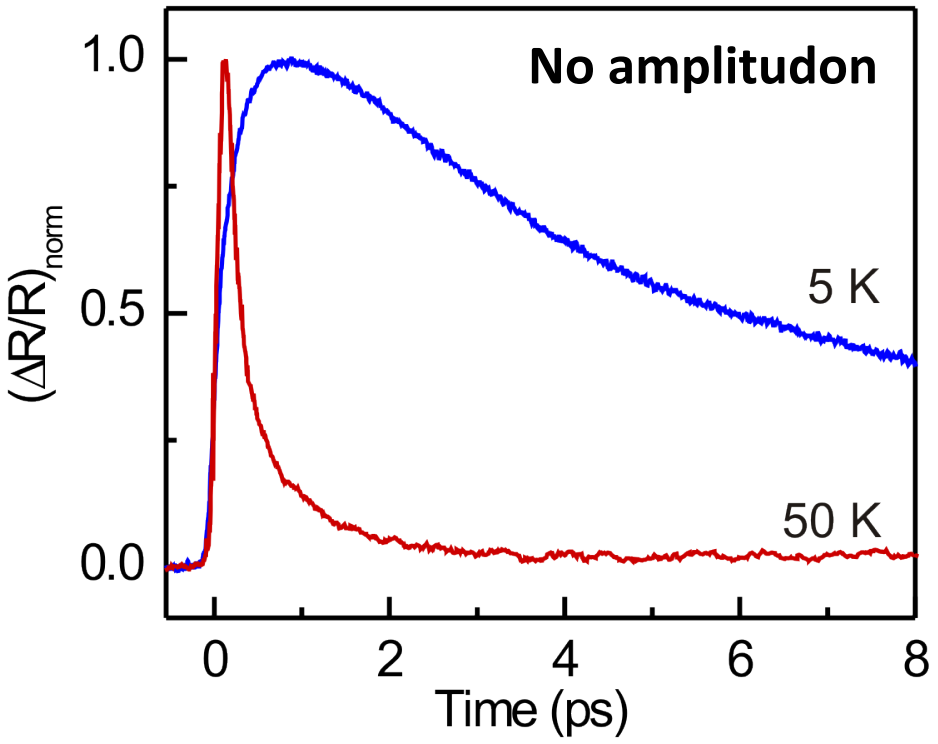
↓

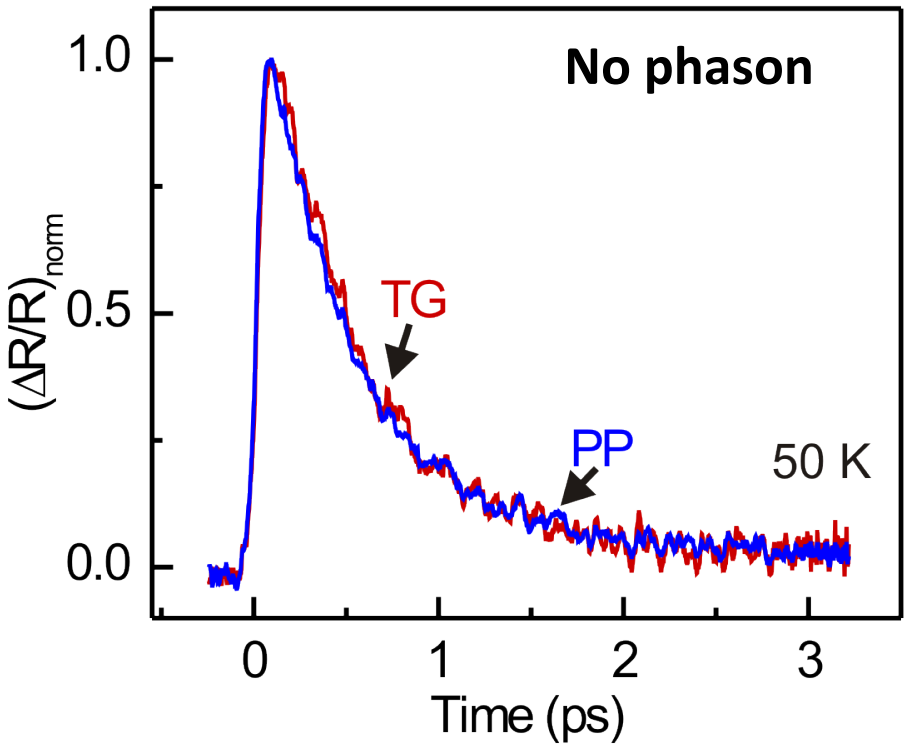
Measure of CDW lifetime

Phys. Rev. B **32**, 4639 (1985)

Relationship with High-Tc?

Optimally Doped (x = 0.16) Sample



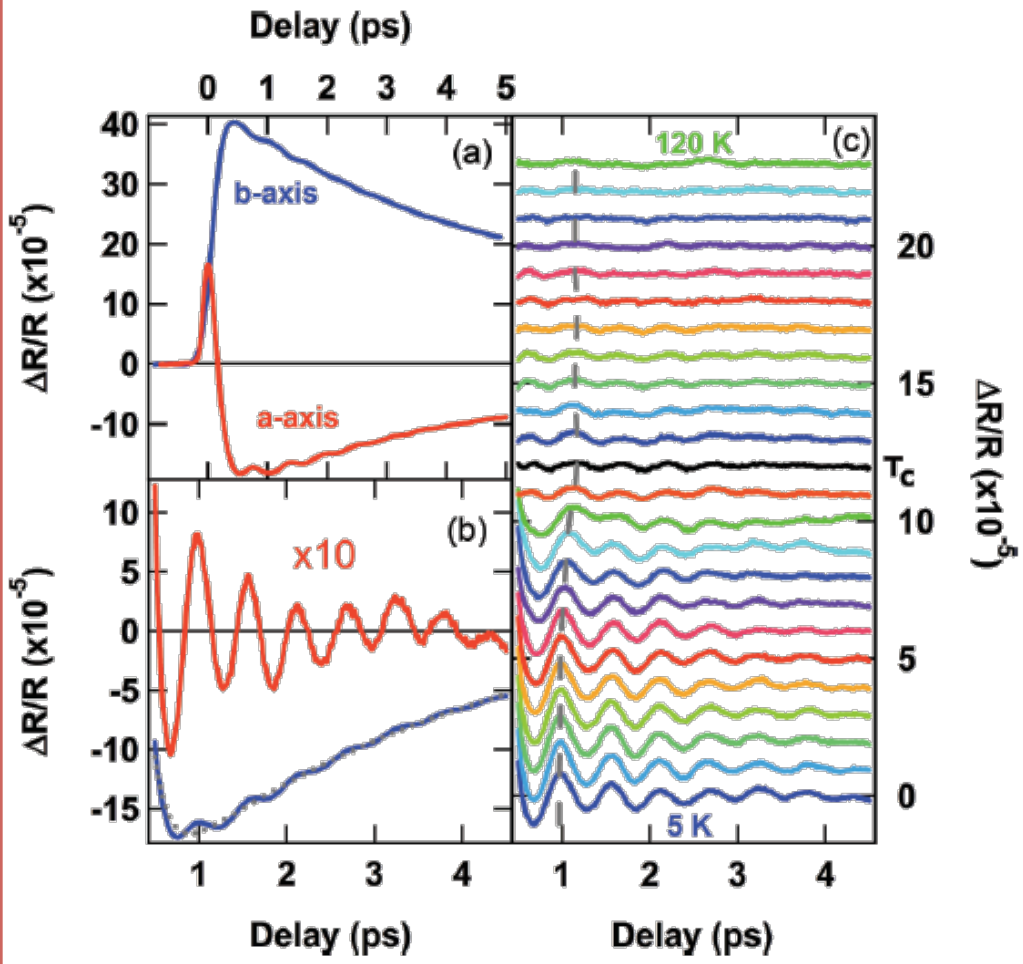


Fluctuating CDW seems to compete with superconductivity

Similar results for overdoped (x = 0.33) sample

CDW amplitudon in YBCO

Detected by PP spectroscopy

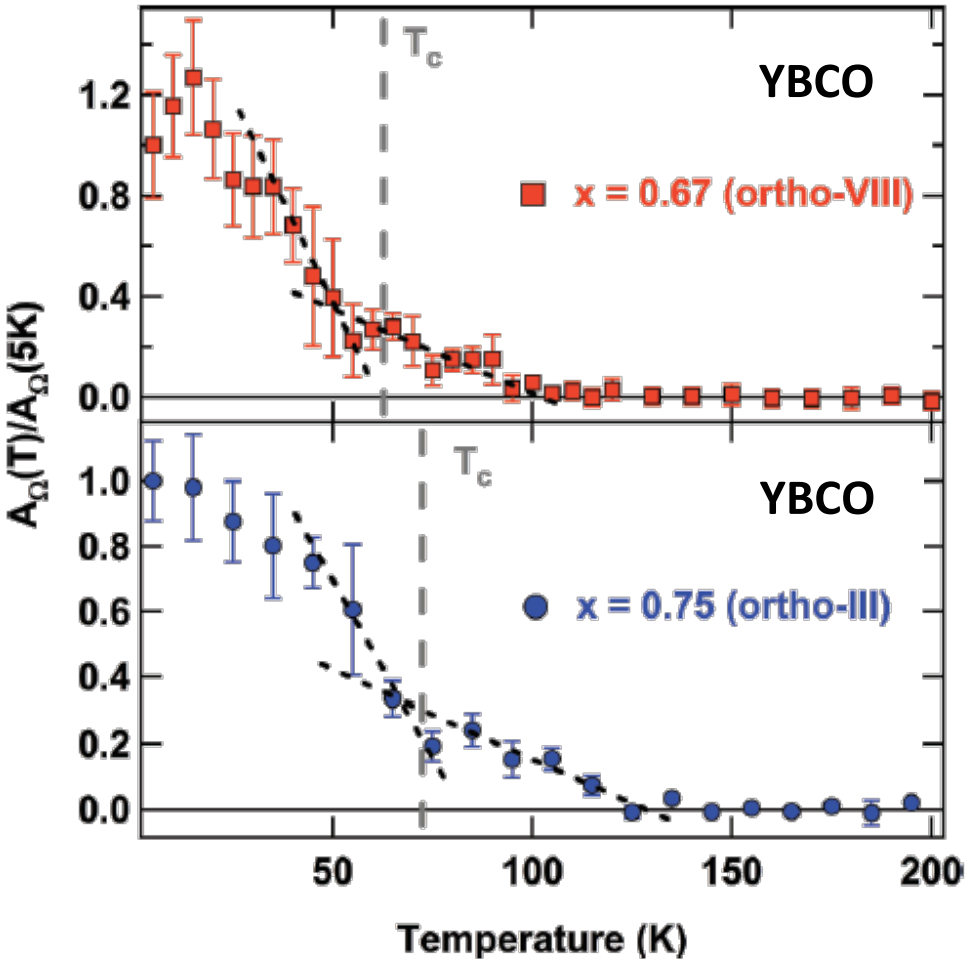


- Similar Results in YBCO
- Amplitude mode from 5-105 K
- Frequency: 1.8 THz

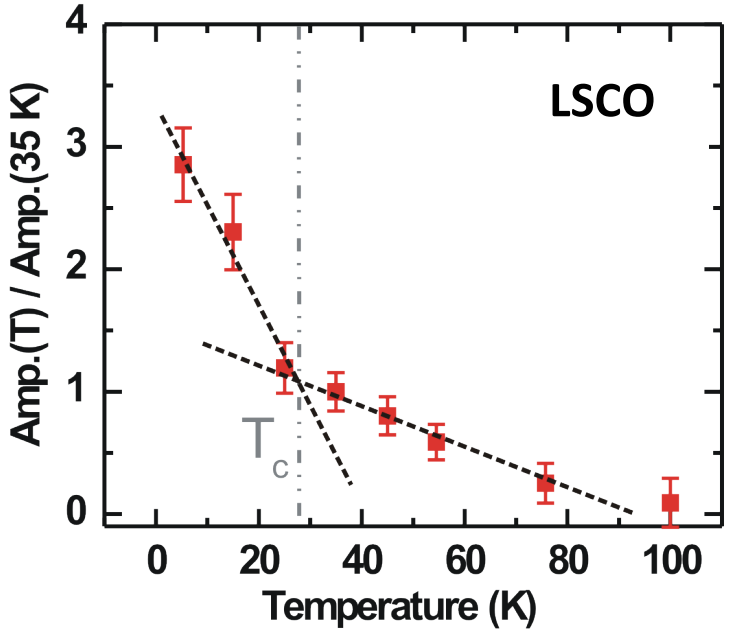
Hinton et. al. PRB 88, 060508 (2013)

CDW amplitudon in YBCO & LSCO

Behavior with temperature



Hinton et. al. PRB 88, 060508 (2013)



Nat. Mat. 12, 387-391 (2013)

- **Enhancement of amplitudon across superconducting Tc**
- **Consistent with X-ray studies? --> show decrease in CDW amplitude**

Outline

→ Background: Possible CDW order in the cuprates

→ Ultrafast measurement of CDW excitations

→ Detection of CDW excitations in underdoped LSCO

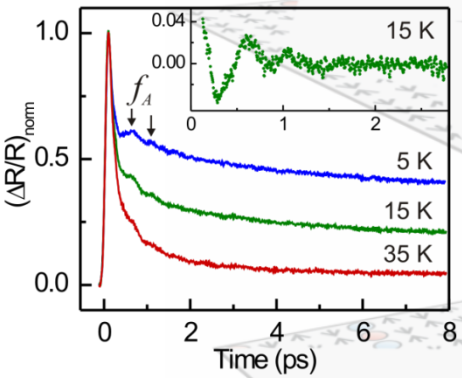
→ Estimate of CDW fluctuation lifetime

→ **Summary + Future work**

Summary & Future work

Selective probing of amplitudon & phason --> Measure Fluctuating CDW lifetime

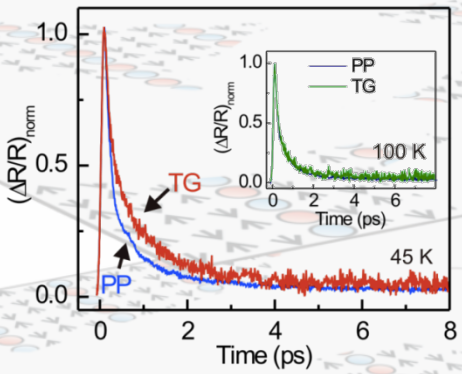
Amplitudon



Frequency ~ 2 THz

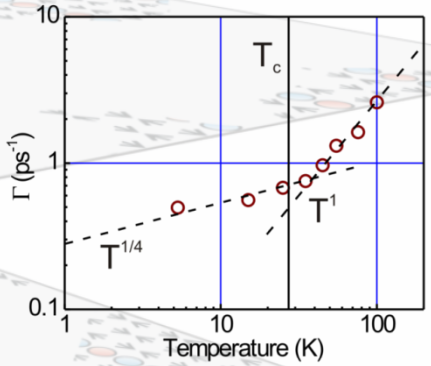
T_{CDW} ~ 100 K

Phason



Similar T-dependence as amplitudon

CDW fluctuations --> Phason damping



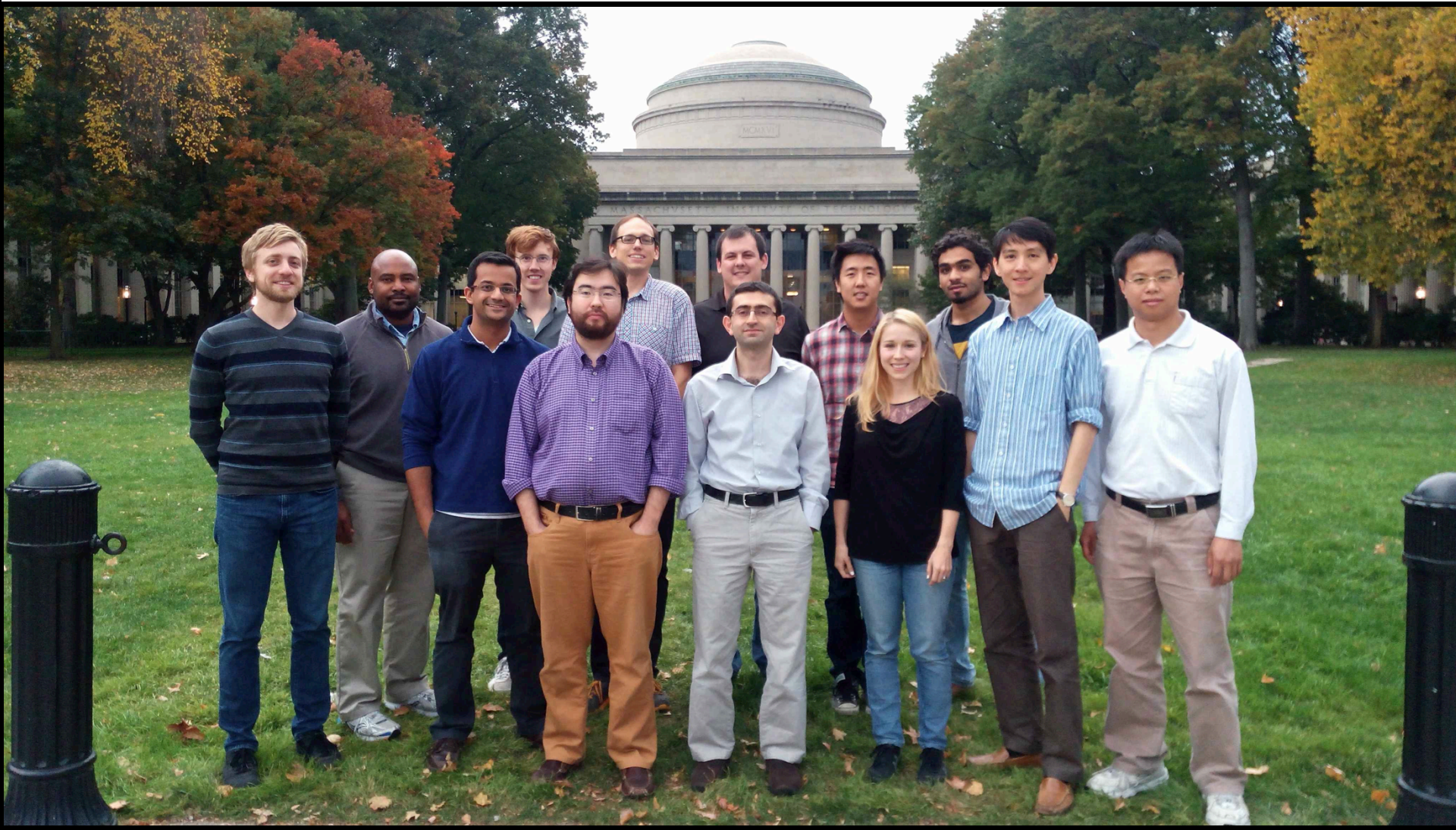
Phason lifetime:

CDW fluctuation lifetime

2 ps @ 5 K to 500 fs @ 100 K

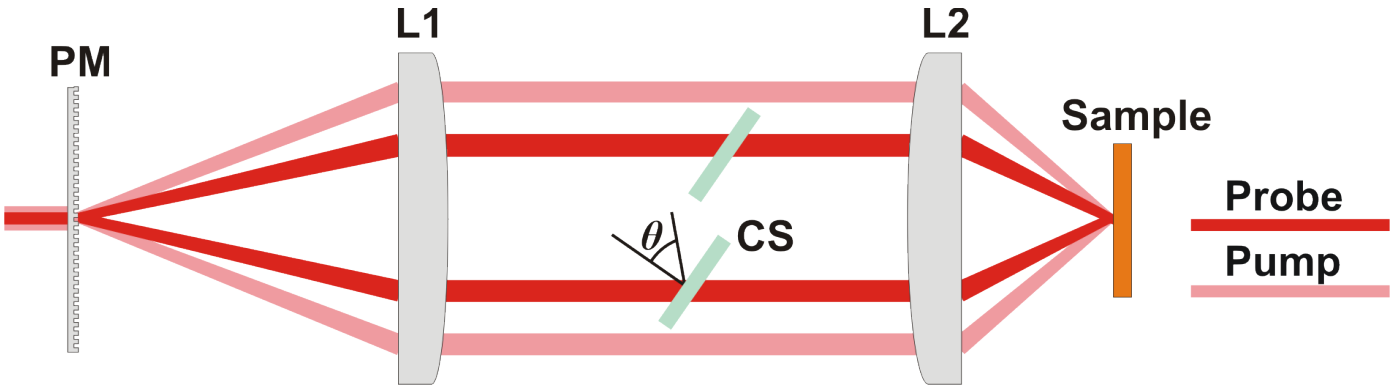
- **Absence of CDW excitations in optimally & over doped sample**
- **Future work:**
  - **Doping dependent study in the vicinity of 1/8 doping**
  - **Effect of magnetic field on fluctuation lifetime**

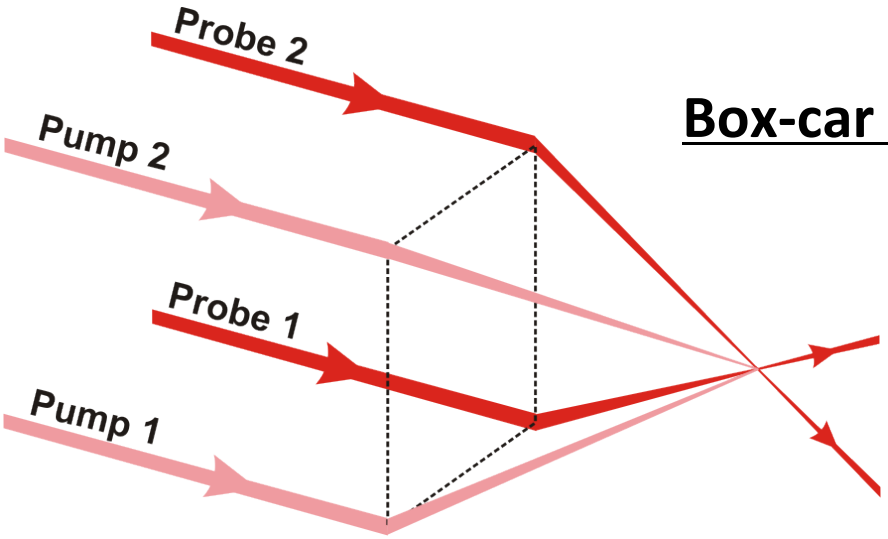
Current Group Members



Transient Grating Spectroscopy

How do we implement it?





Box-car geometry & heterodyne detection

Transmitted P1 + Diffracted P2

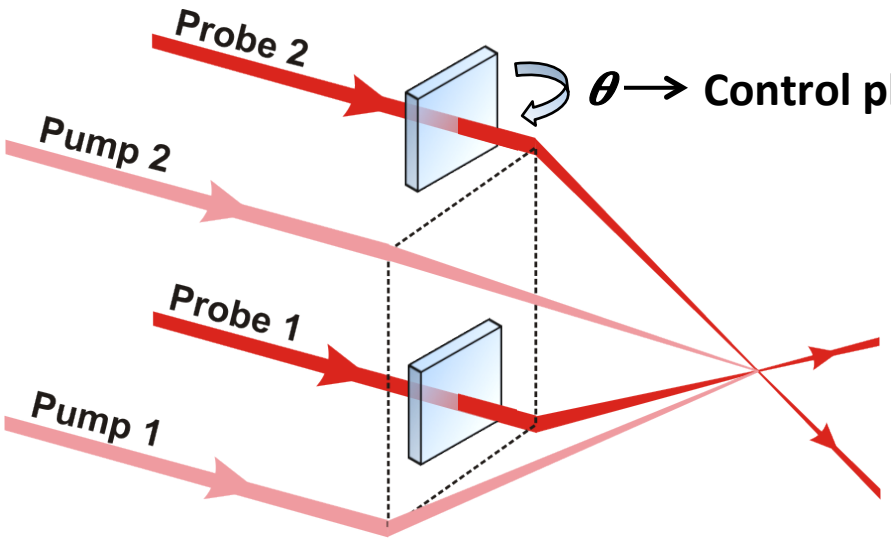
$$E\downarrow P1\ (r\downarrow o+\delta\downarrow r\,(t))+E\downarrow P2\ (\delta\downarrow r\,(t)\epsilon(t))$$

Transmitted P2 + Diffracted P1

$$E\downarrow P1\ (r\downarrow o+\delta\downarrow r\,(t))+E\downarrow P2\ (\delta\downarrow r\,(t)\ \epsilon\uparrow *\,(t))$$

Transient Grating Spectroscopy

What are we actually measuring?



$\theta \rightarrow$ Control phase difference between probe beams

Intensity at detector

$$|r_o|^2 + |\delta_r|\cos(\varphi_s) + |\epsilon|\cos(\psi + \varphi_s)$$

$$|r_o|^2 + |\delta_r|\cos(\varphi_s) + |\epsilon|\cos(\psi - \varphi_s)$$

$|r_o|^2 \rightarrow$ Get rid off by lock-in (modulate pump @ 100 kHz)

$|\delta_r|\cos(\varphi_s) \rightarrow$ Standard pump probe measurement (what we call **PP!**)

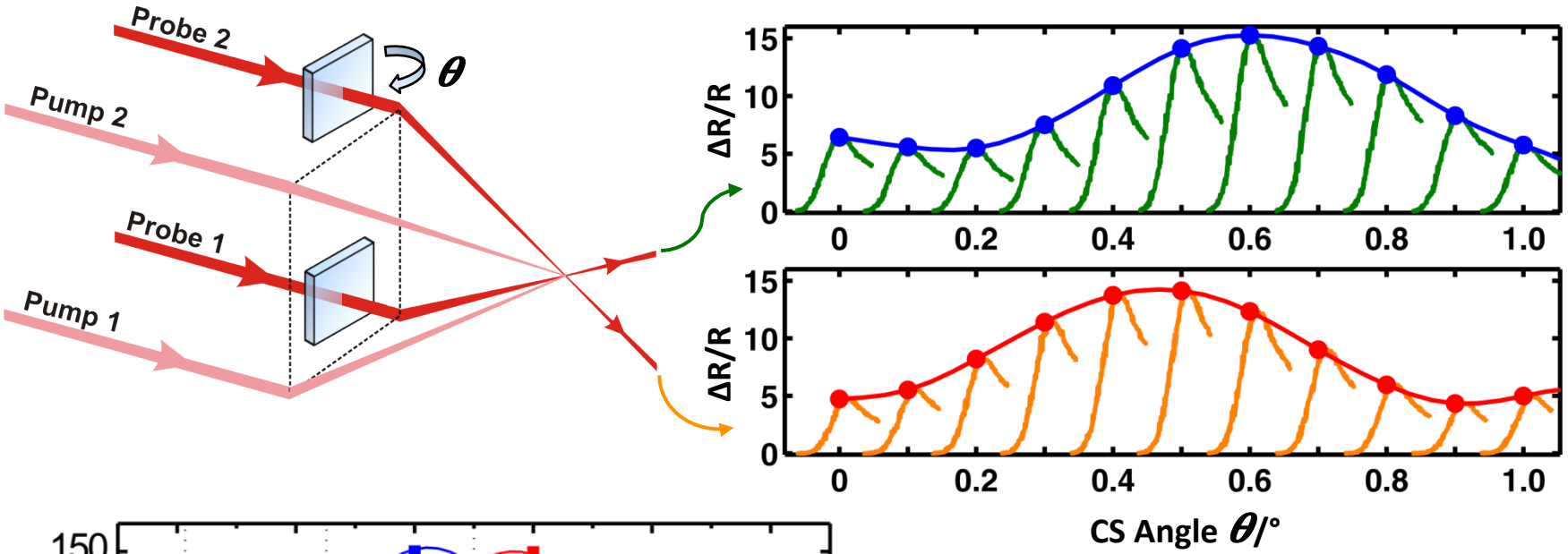
$\varphi_s \rightarrow$ Phase of δ_r w.r.t. r_o, independent of grating

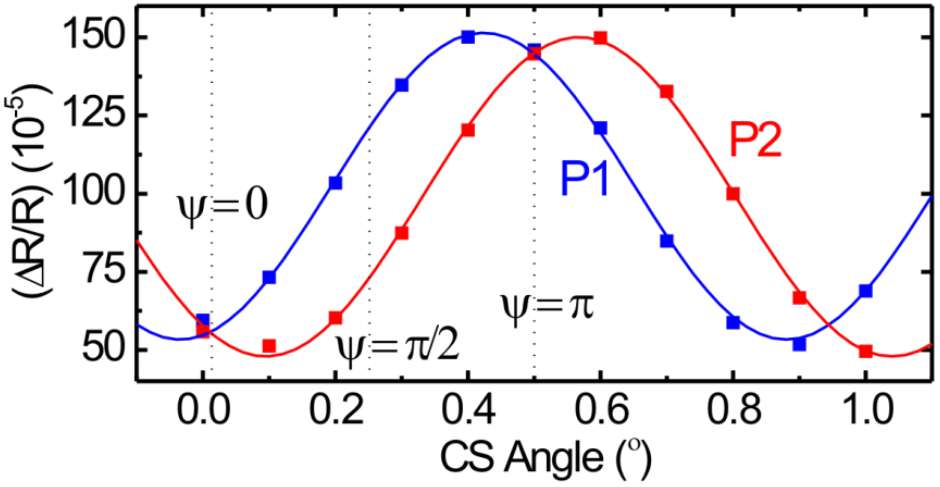
$|\epsilon| \rightarrow$ Finite q response with time (what we call **TG!**)

$\psi \rightarrow \theta + \vartheta_{gr}$

Transient Grating Spectroscopy

Calibration





3-point scheme

$$|\delta\downarrow r|\cos(\varphi\downarrow s)+|\epsilon|\cos(\varphi\downarrow s)$$

$$|\delta\downarrow r|\cos(\varphi\downarrow s)+|\epsilon|\sin(\varphi\downarrow s)$$

$$|\delta\downarrow r|\cos(\varphi\downarrow s)-|\epsilon|\cos(\varphi\downarrow s)$$

Solve!