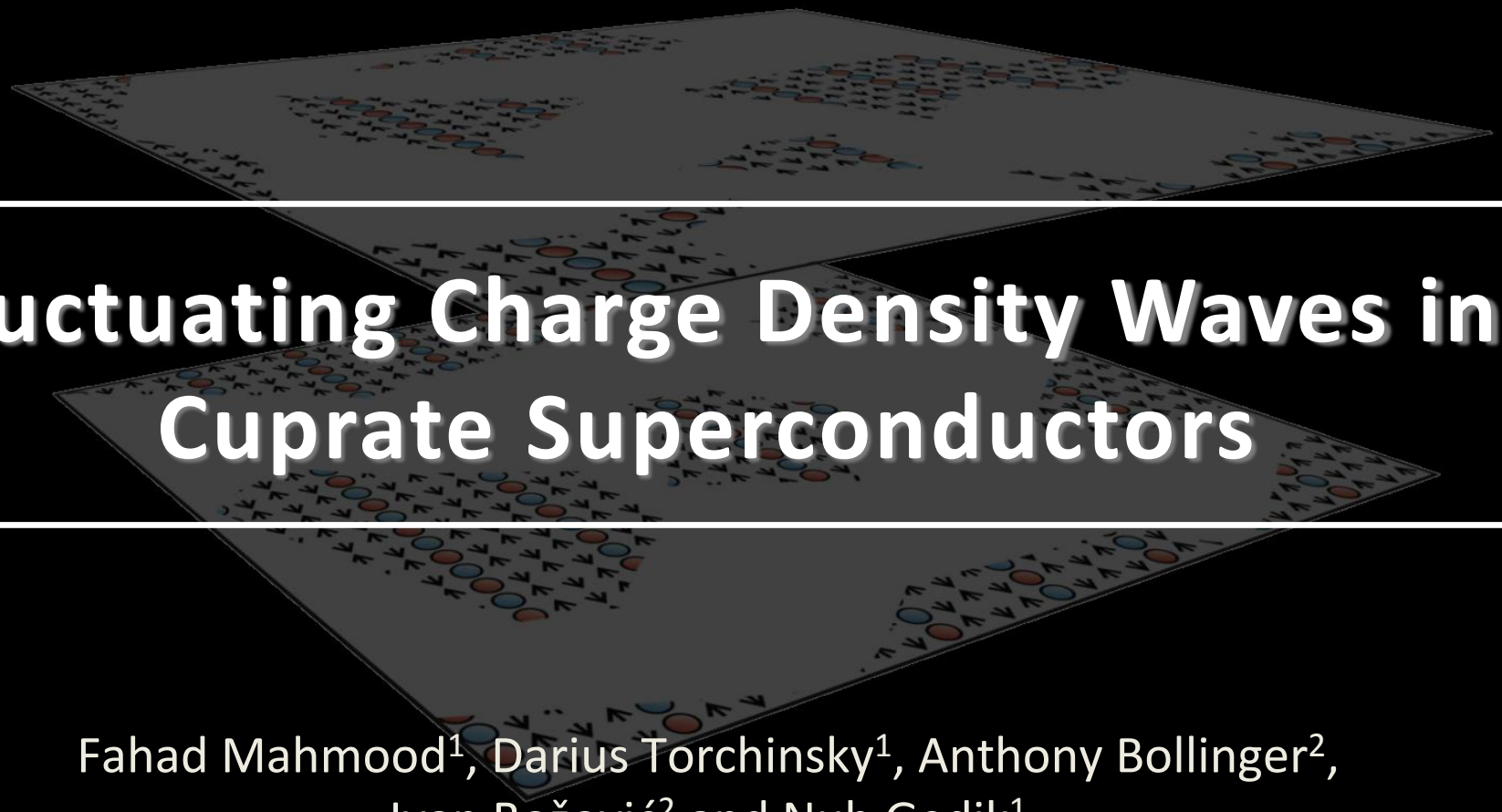

Fluctuating Charge Density Waves in Cuprate Superconductors

Fahad Mahmood[1], Darius Torchinsky[1], Anthony Bollinger[2],
Ivan Božović[2] and Nuh Gedik[1]
[1]Department of Physics, MIT, [2]Brookhaven National Laboratory

International Workshop on Higgs Modes in Condensed Matter & Quantum Gases 2014

Outline

→ Background: Possible CDW order in the cuprates

→ Ultrafast measurement of CDW collective excitations

→ CDW excitations in LSCO thin films

→ Lifetime of CDW fluctuations

→ Related work in YBCO

→ Conclusion

Outline

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

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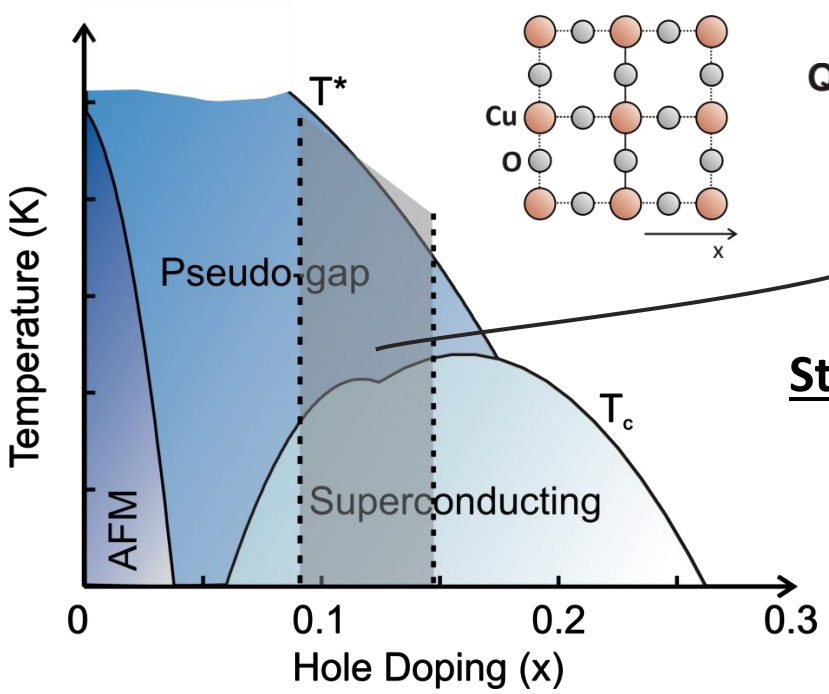
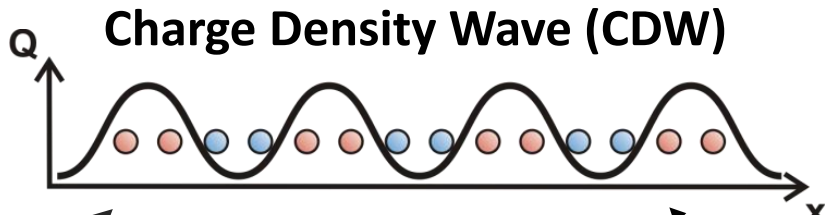
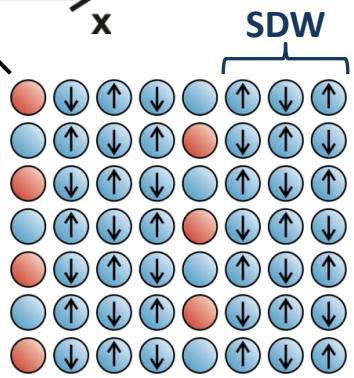
→ Conclusion

Cuprates – Possible CDW order



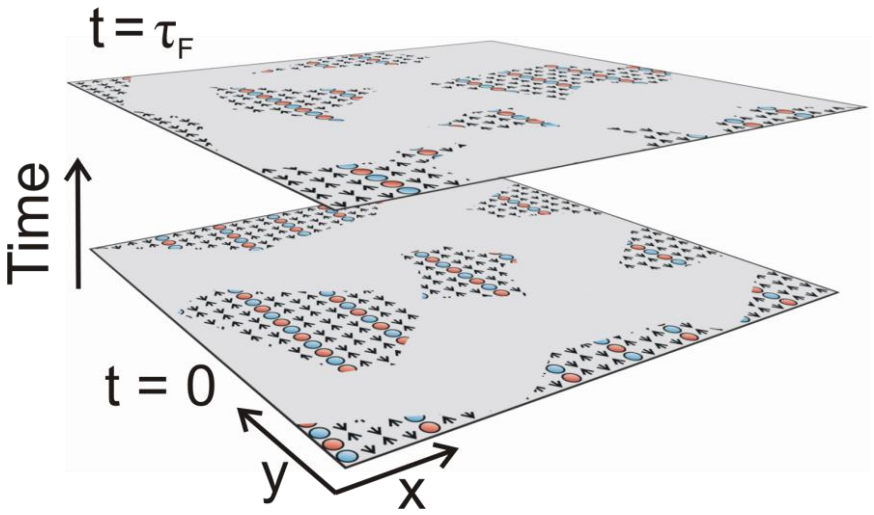




Static "stripe" order in LBCO….

depression in Tc at 1/8 doping

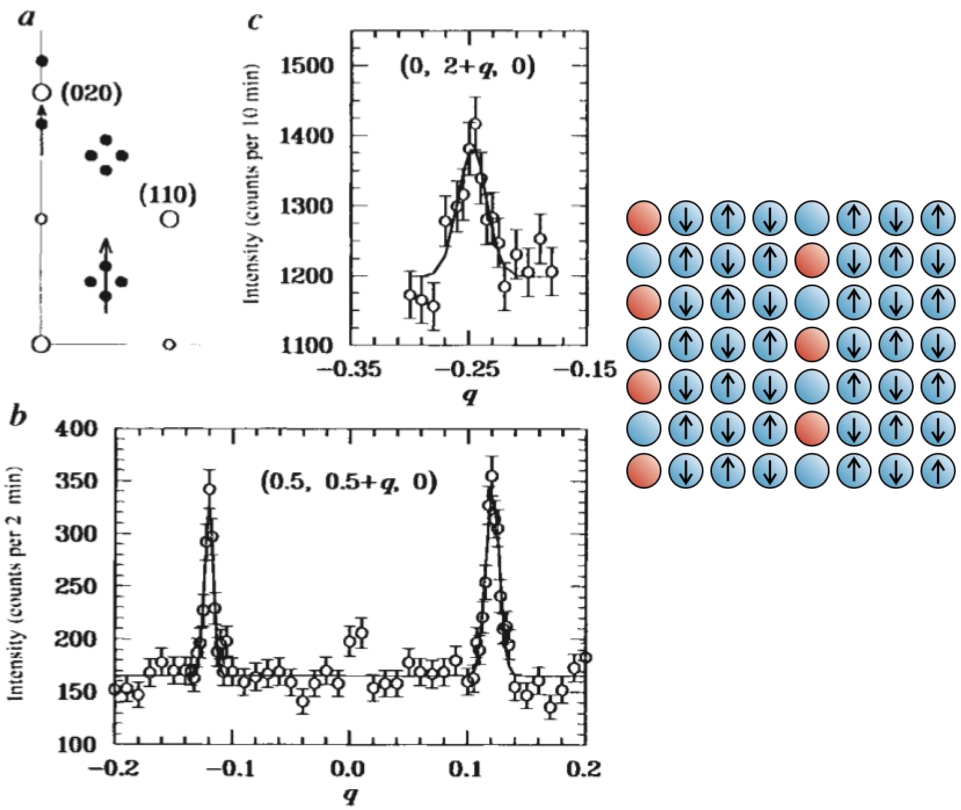
Fluctuating Order in LSCO



- **Specific or general behavior?**
- **Relationship b/w CDW & High-Tc ?**
- **Time scale for fluctuations?**
- **How to observe?**

CDW fluctuations in LSCO

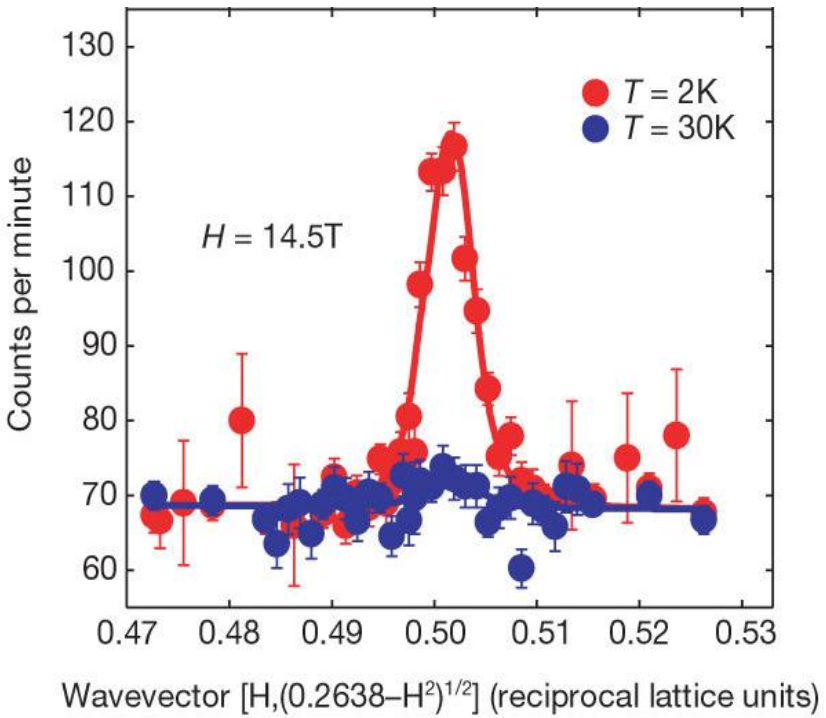
Stabilizing CDW with specific dopants (Nd or Eu)



Neutron and X-ray diffraction

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

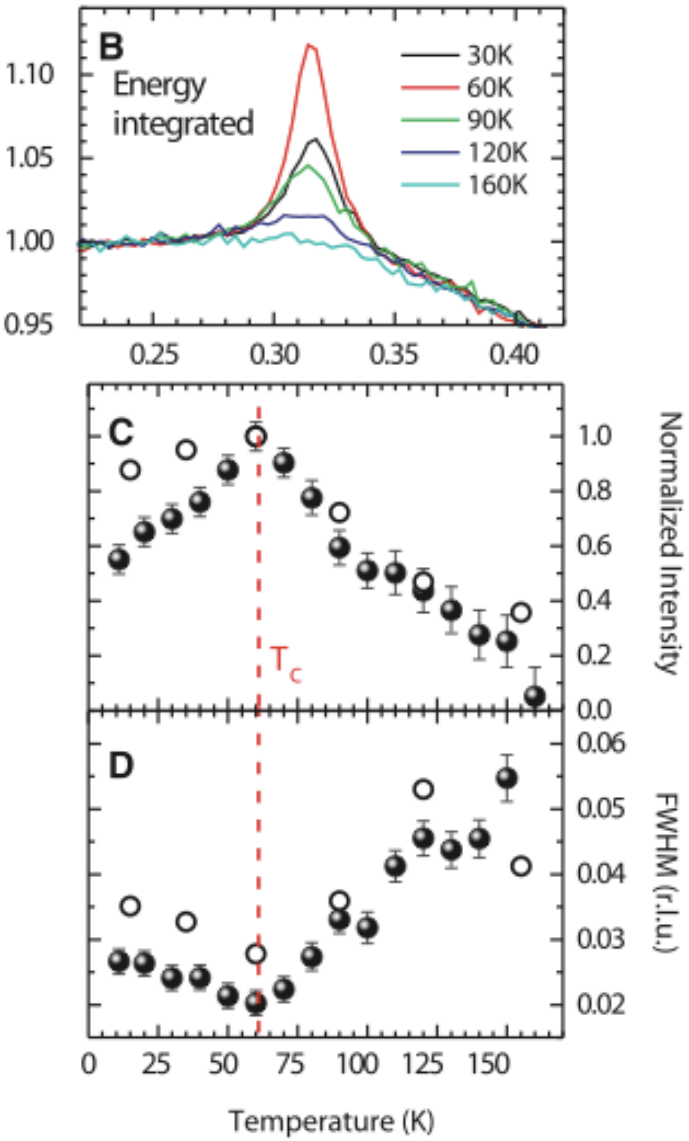
Stabilizing CDW with Magnetic Field in $La_{2-x}Sr_xCuO_4$



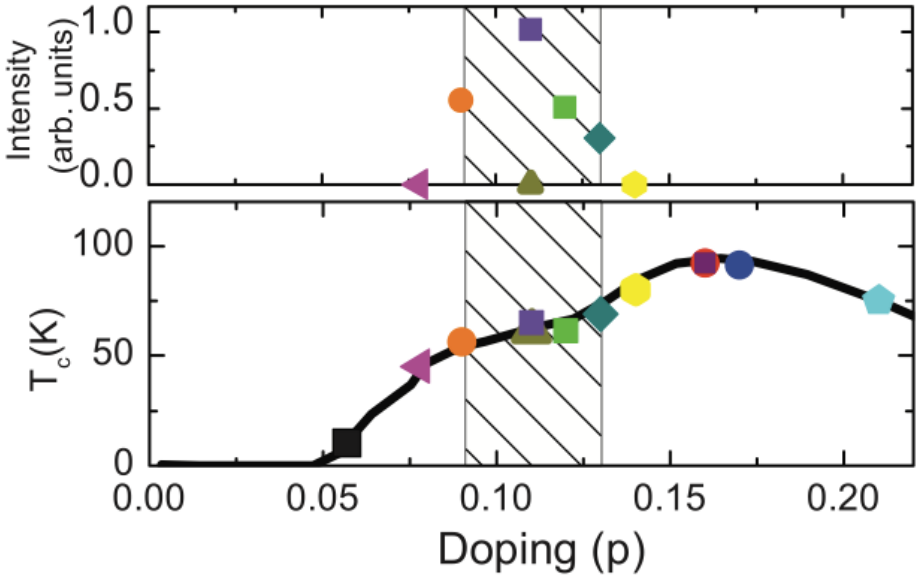
B. Lake et. al. Nature 415, 299–302 (2002)

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

CDW fluctuations in YBCO and NdBCO



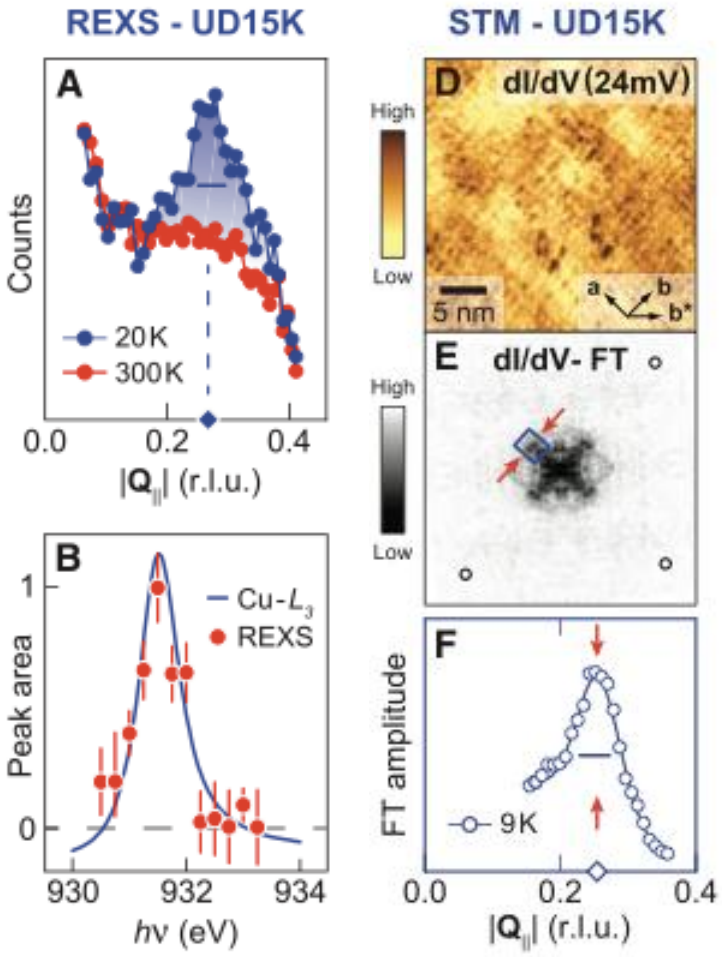
Resonant Elastic X-ray Scattering (REXS)



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

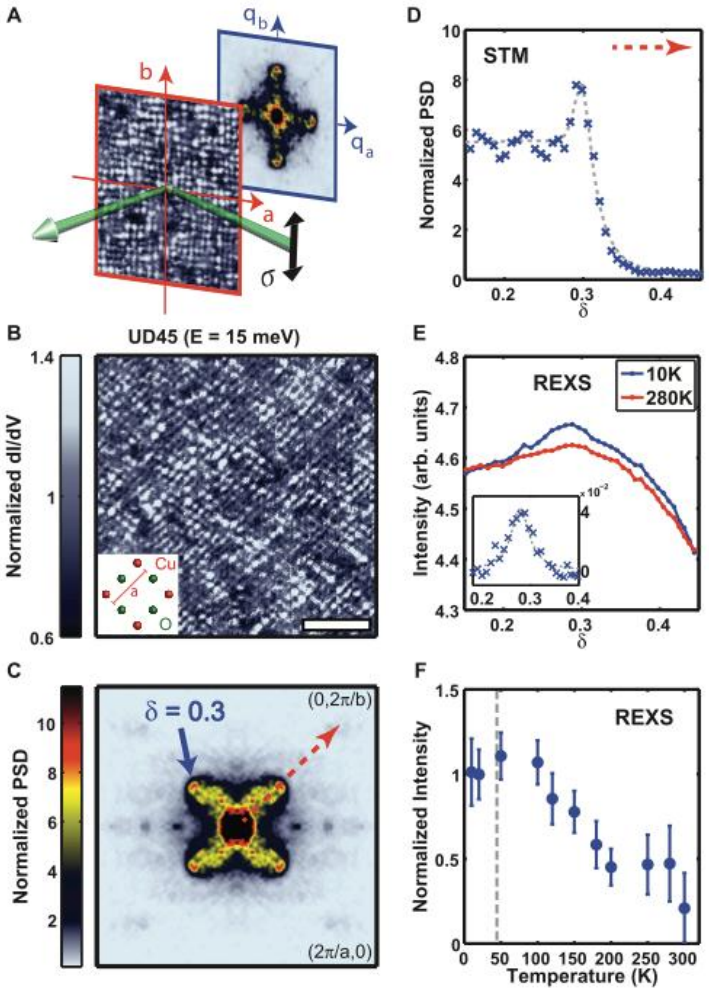
CDW fluctuations in BSCCO

Bi2201



Comin et. al. Science 343, 390 (2014)

Bi2212



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

Outline

→ Background: Possible CDW order in the cuprates

→ **Ultrafast measurement of CDW collective excitations**

→ CDW excitations in LSCO thin films

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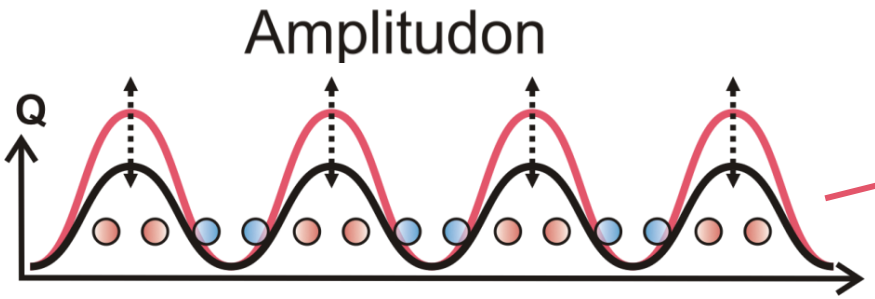
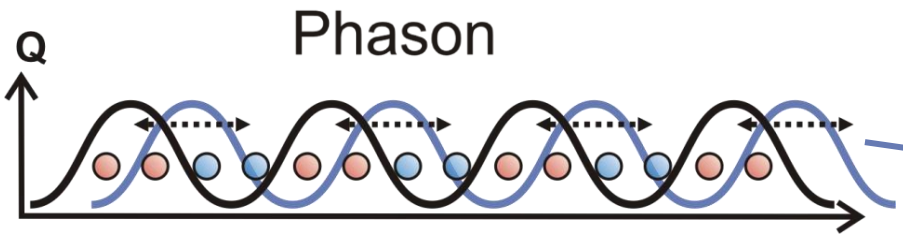
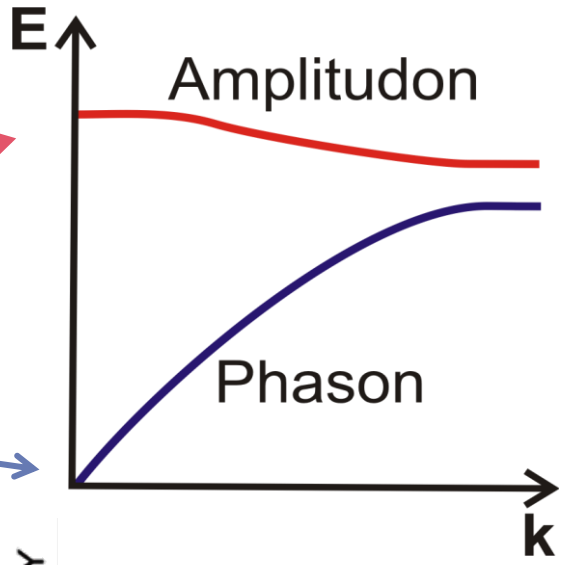
→ Conclusion

CDW Excitations







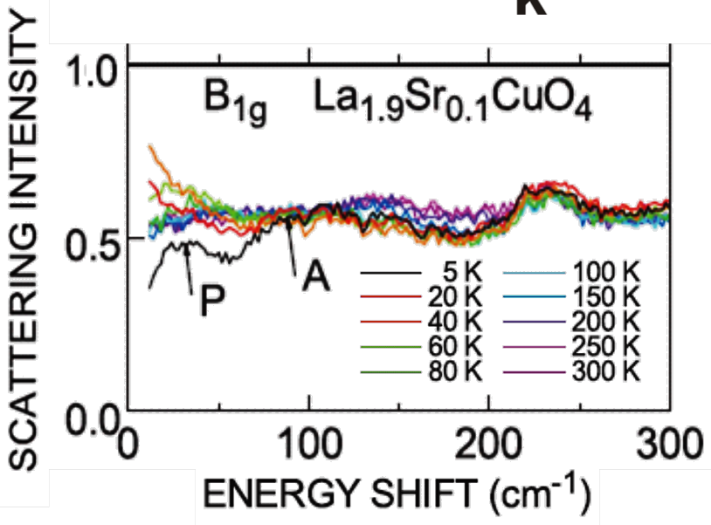
Selectively probe dynamics of each excitation in LSCO thin films

↓

Phason damped by CDW fluctuations

↓

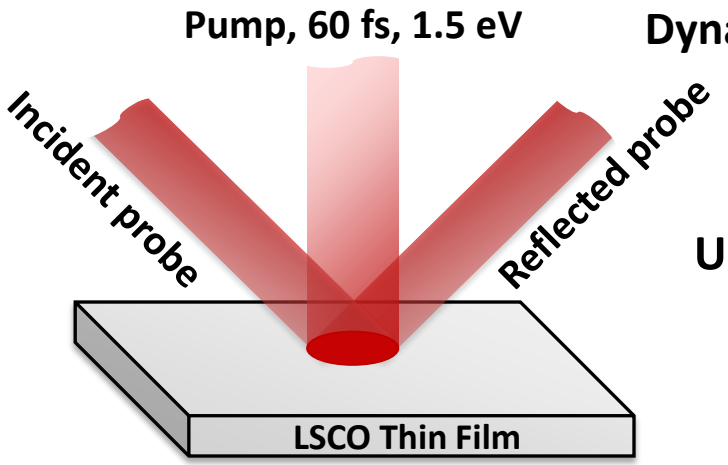
<u>Determine CDW fluctuation lifetime</u>



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

CDW Excitations - Ultrafast Measurements

Amplitudon – Pump-probe (PP) Spectroscopy



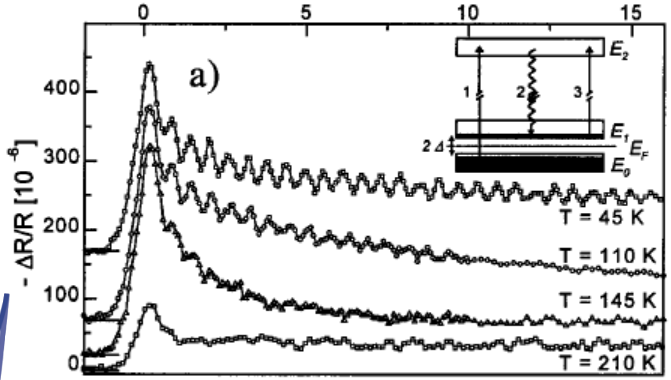
Dynamic change in reflectivity

Track single particle excitations & collective modes

Uniform excitation

$\vec{k}$ = 0 modes

Amplitudons in $K_{0.3}MoO_3$



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

DECP Mechanism

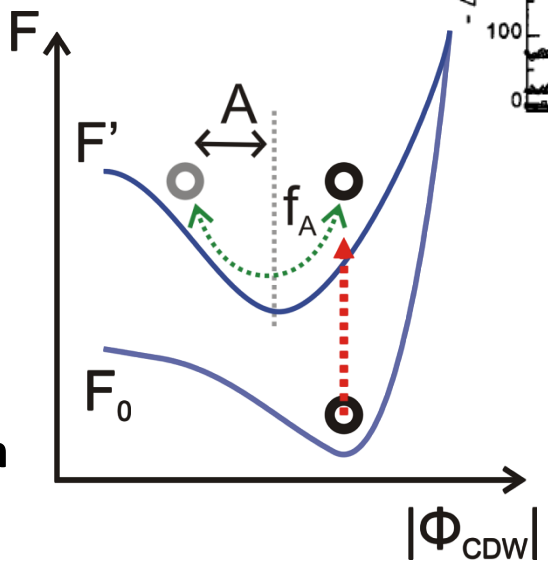
Single-particle excitations

↓

Change in local free energy

↓

Oscillation about new equilibrium

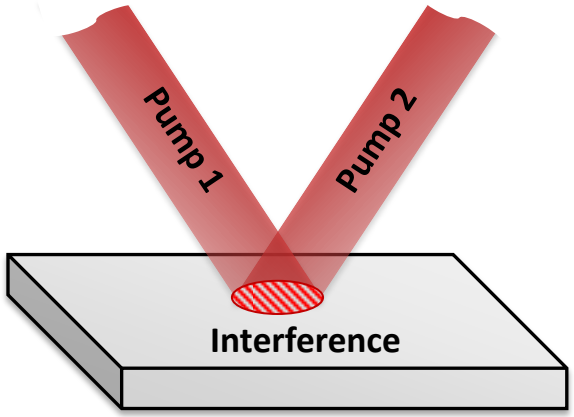


What about phason?
Need to depin…

CDW Excitations - Ultrafast Measurements

Phason – Transient Grating (TG) Spectroscopy

Generation



Single-particle excitations

↓

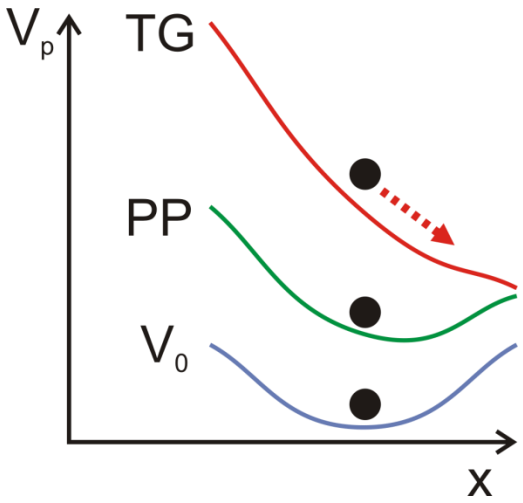
Sinusoidal change in V

↓

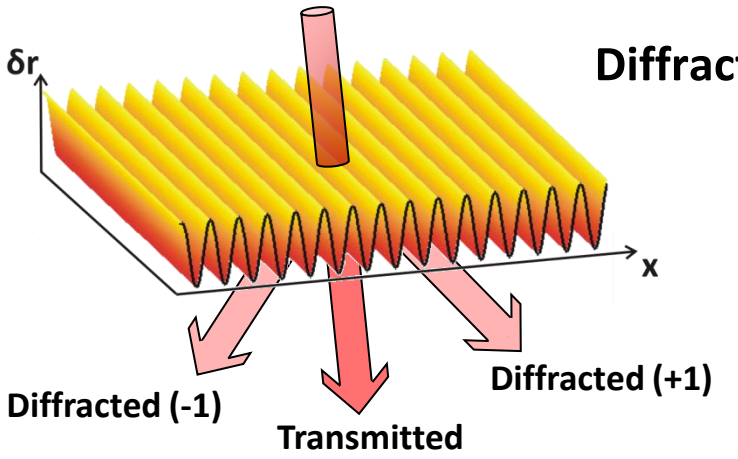
Stronger E-field

↓

Depinning of phason

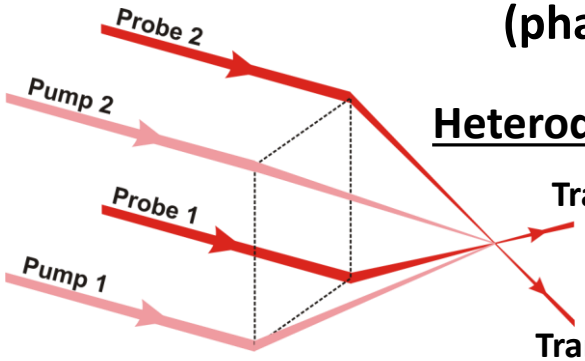


Detection



Transmitted beam --> $\vec{k}$ = 0 excitations (PP signal)

Diffracted beam --> $\vec{k}$ = 0 & finite $\vec{k}$ excitations (TG signal) (phason)



Heterodyne detection

Transmitted P1 + Diffracted P2

Transmitted P2 + Diffracted P1

Outline

→ Background: Possible CDW order in the cuprates

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→ **CDW excitations in LSCO thin films**

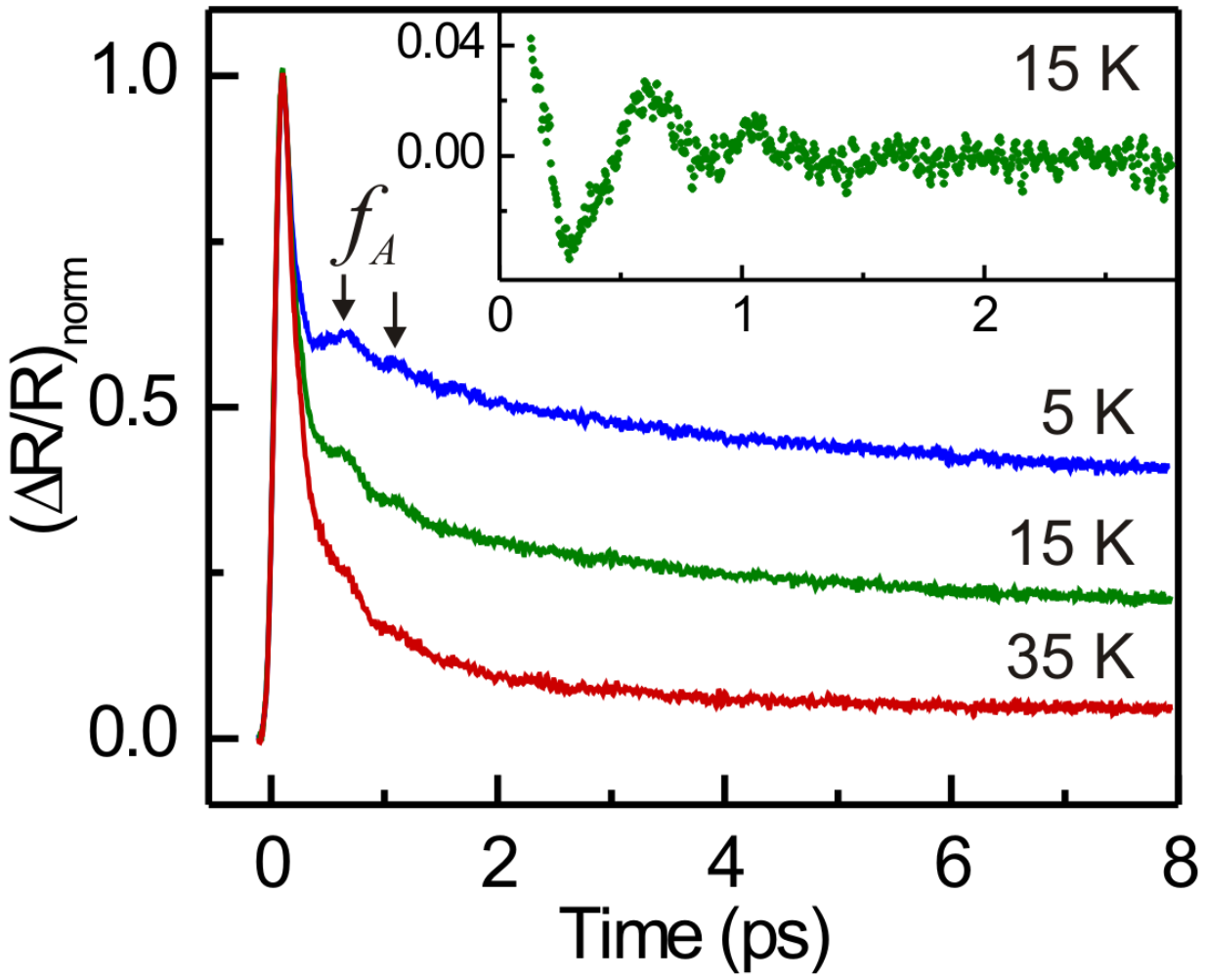
→ Lifetime of CDW fluctuations

→ Related work in YBCO

→ Conclusion

Amplitudon Dynamics

Oscillations in the PP reflectivity transients



Underdoped LSCO

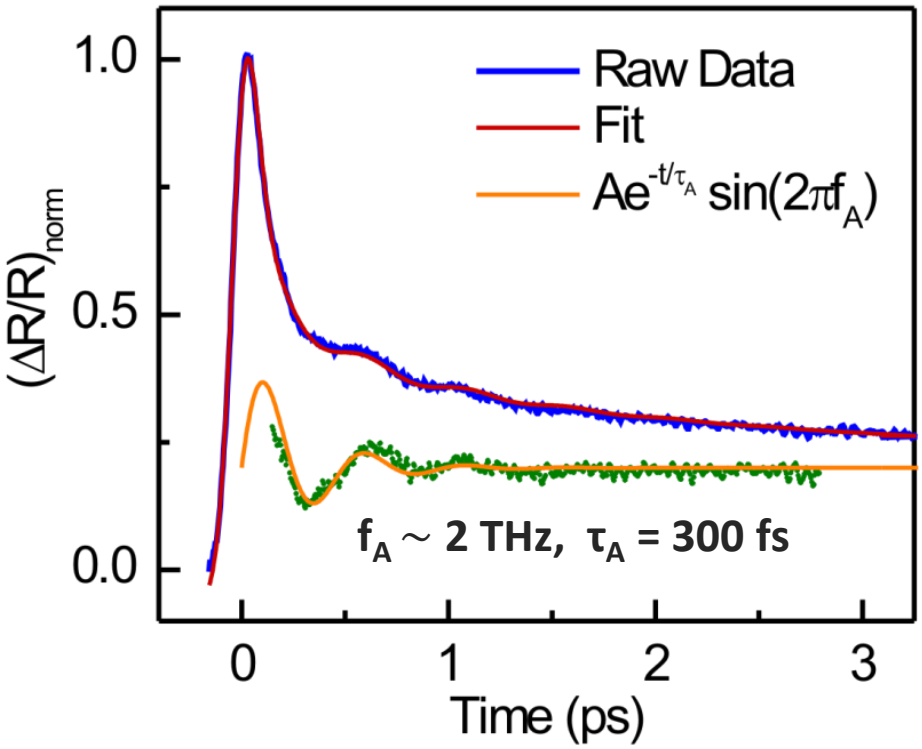
p = 0.10

T_c = 26 K

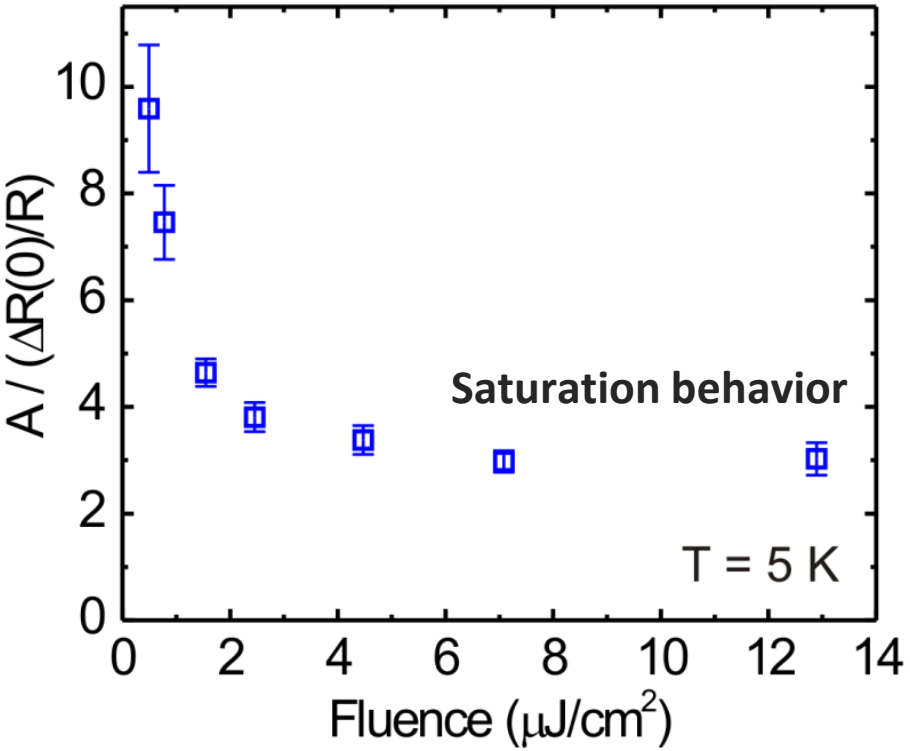
- **Seen both above & below T_c**
- **Persist up to 100 K**

Amplitudon Dynamics

Extracting dynamic parameters



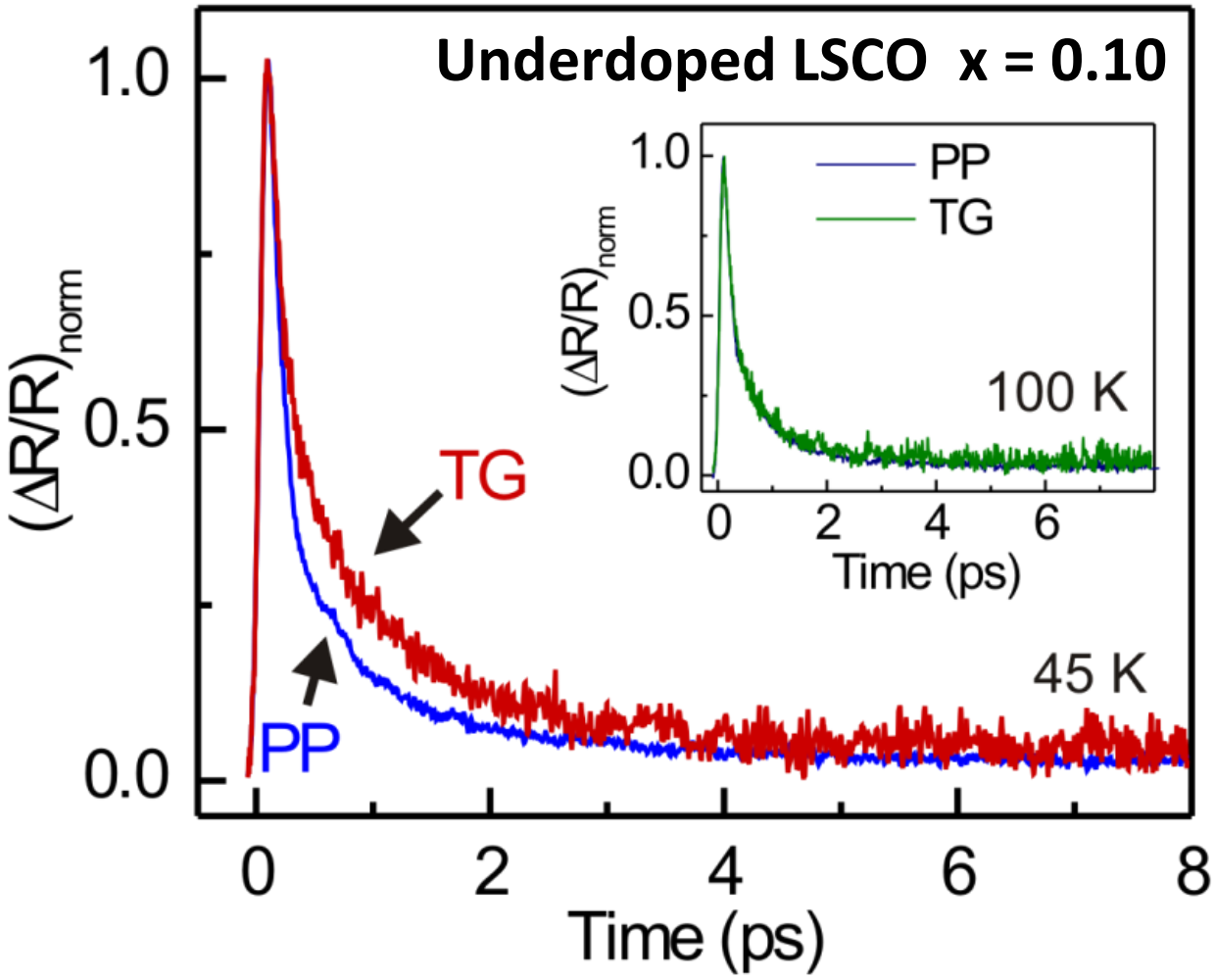
Agreement with Raman results

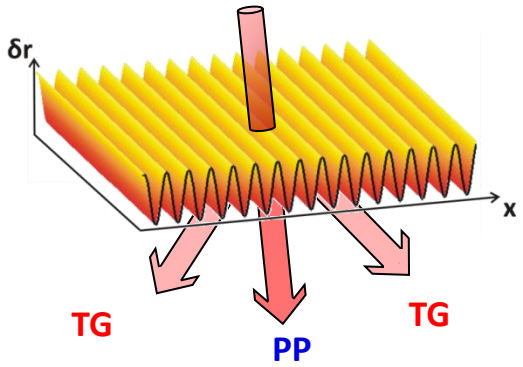


Confirms this is amplitudon

Phason Dynamics

Additional component in the TG response



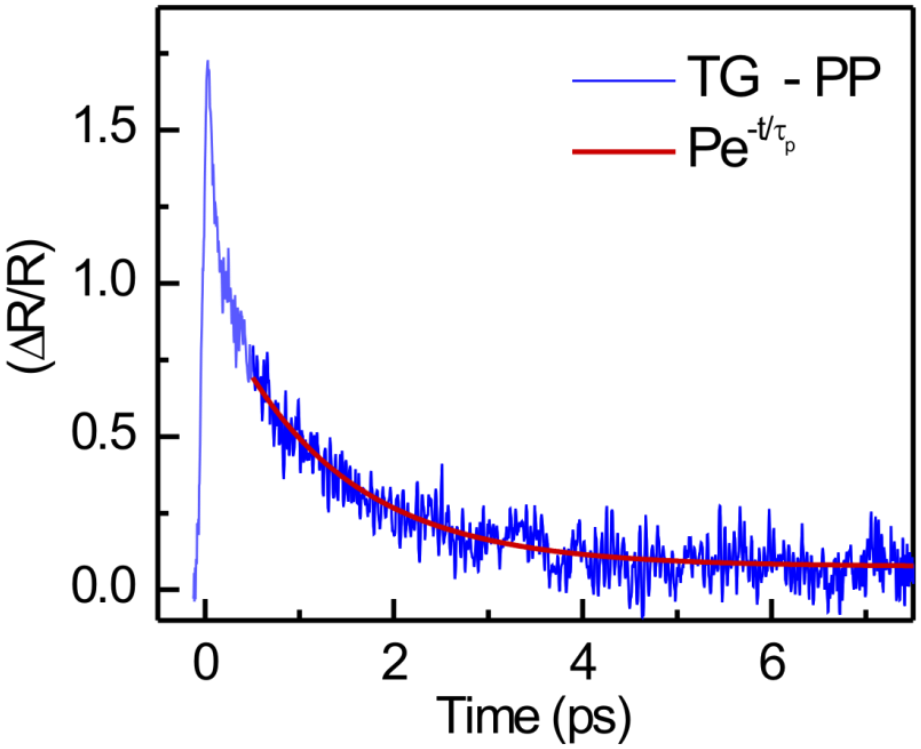


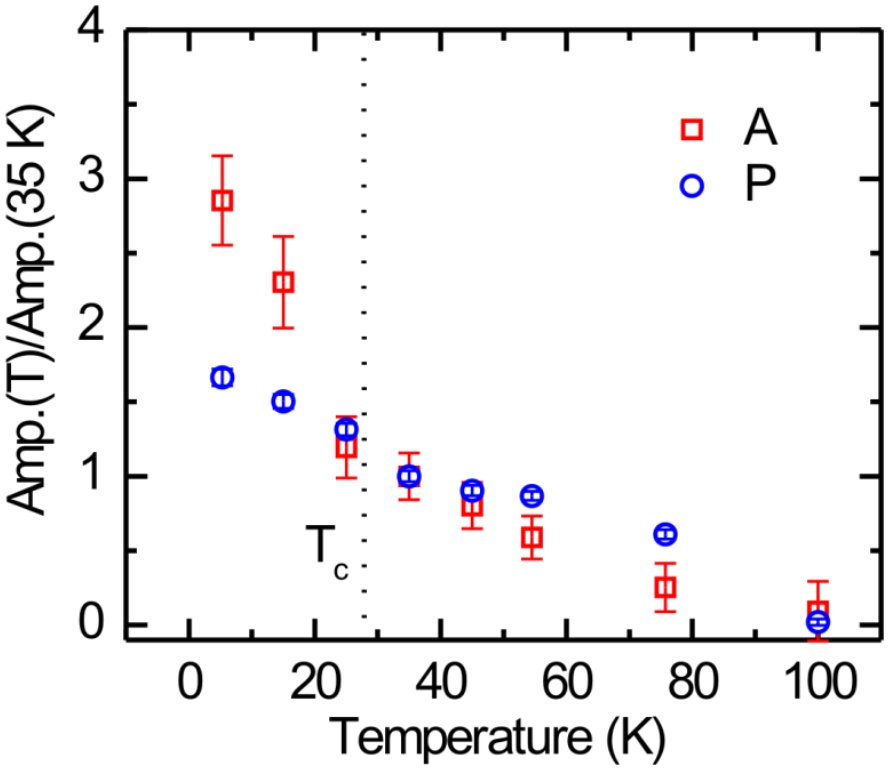
Could be due to:

- ~~Acoustic phonons~~
- ~~Optical phonons~~
- ~~Thermal diffusion~~
- ~~Carrier diffusion~~
- **CDW phason?**

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

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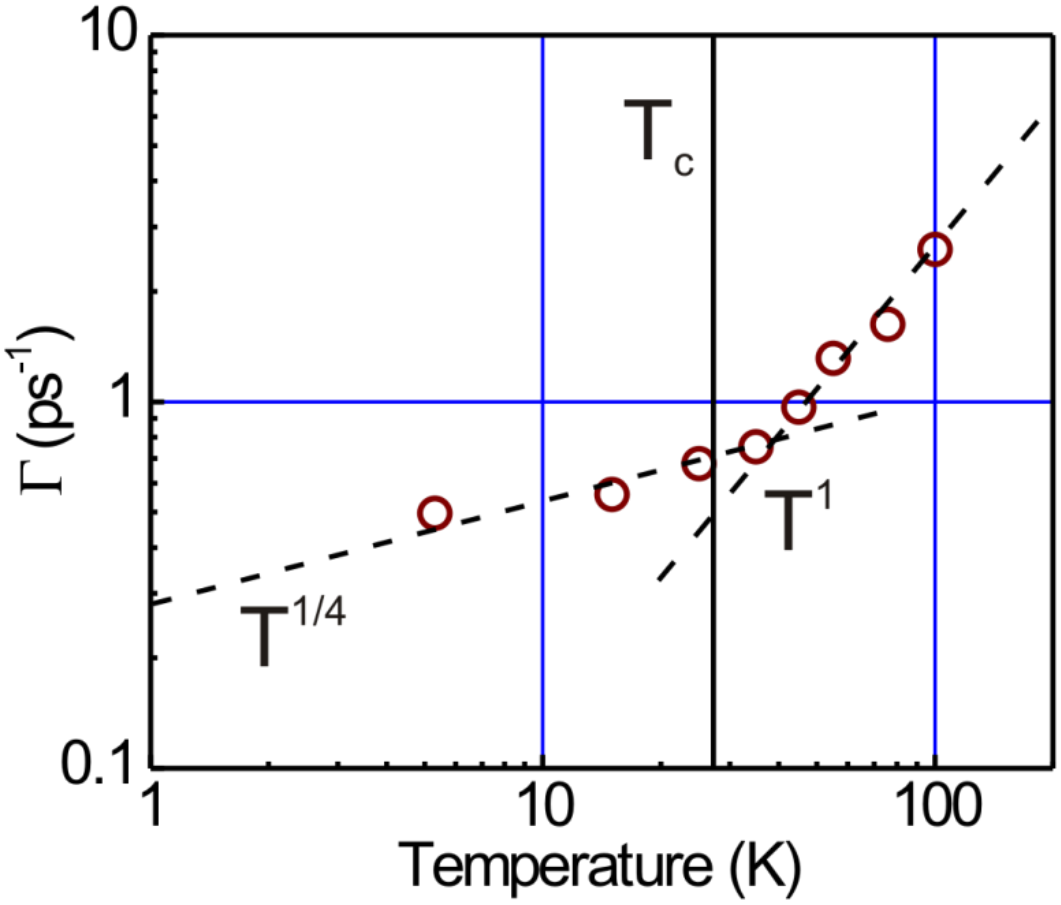
Phason Dynamics

Phason damping --> CDW fluctuations



Source of damping?

- **If intrinsic damping then $\Gamma \sim T^2$ or $\Gamma \sim T^5$**
- **CDW fluctuations**

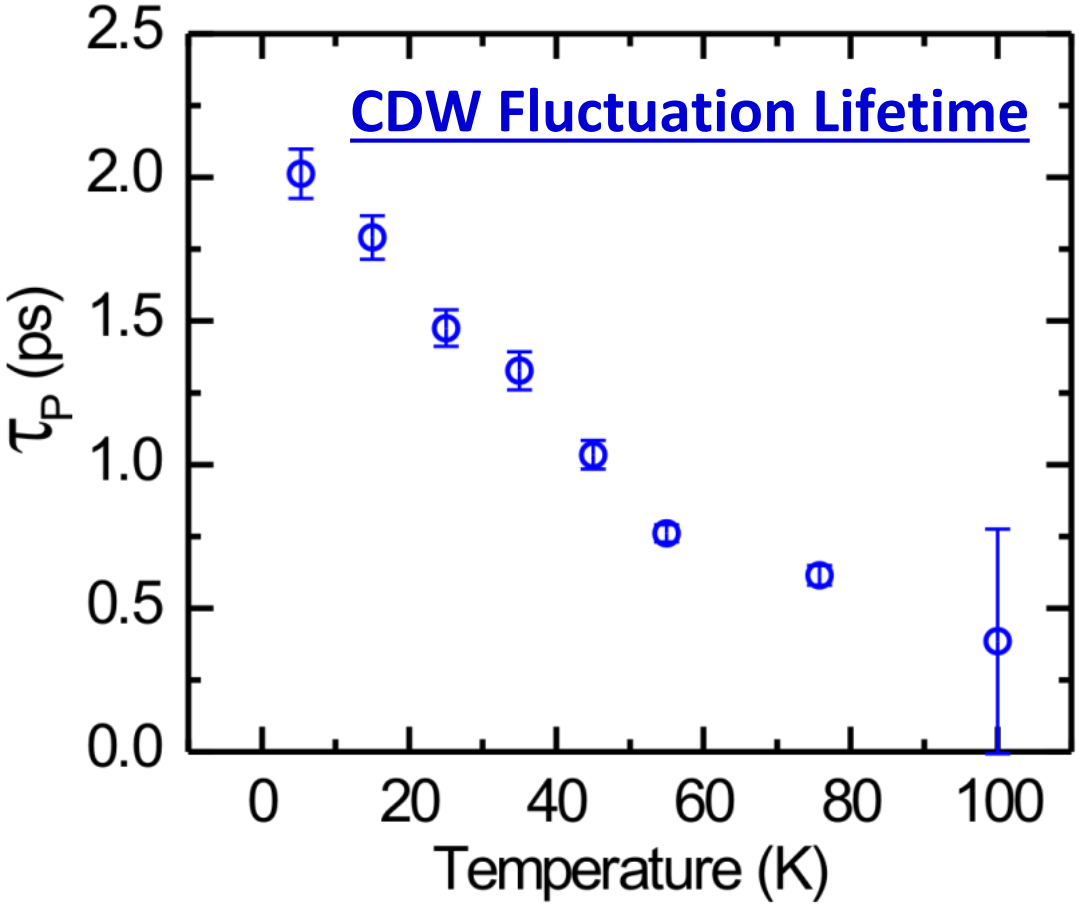
Phason lifetime

↓

Measure of CDW lifetime

Phason Dynamics

Phason damping --> CDW fluctuations



Source of damping?

- **If intrinsic damping then $\Gamma \sim T^2$ or $\Gamma \sim T^5$**
- **CDW fluctuations**

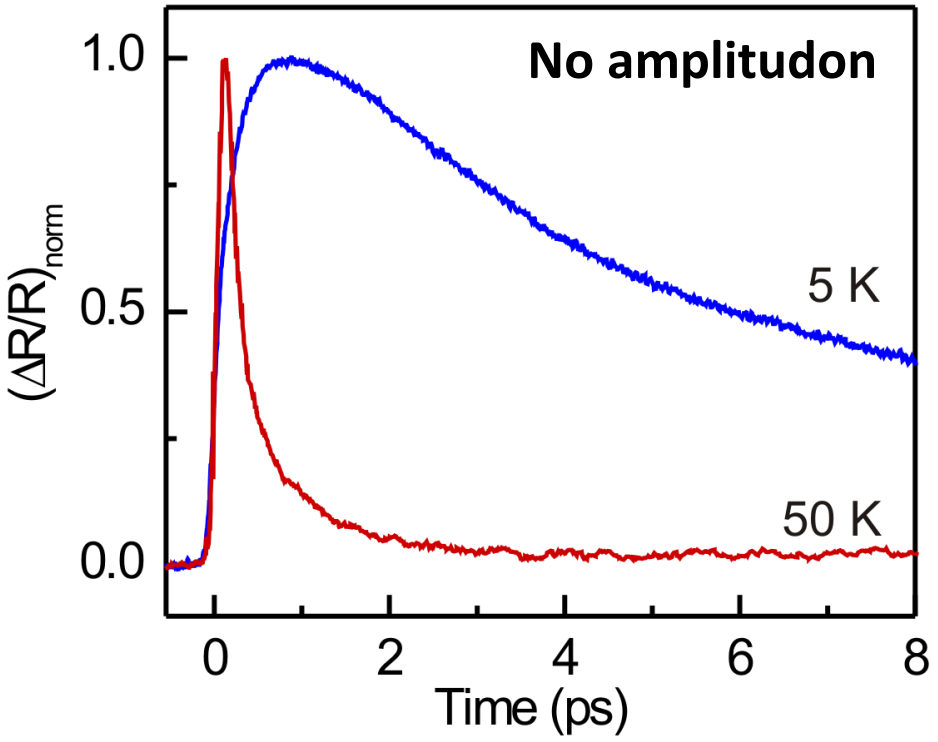
Phason lifetime

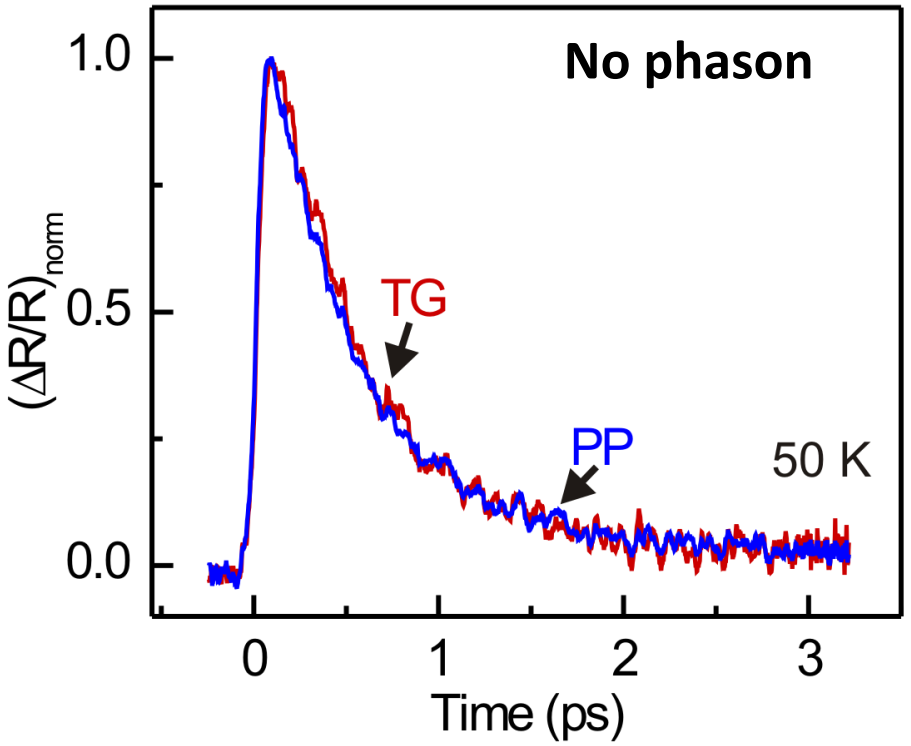
↓

Measure of CDW lifetime

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

Outline

→ Background: Possible CDW order in the cuprates

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→ CDW excitations in LSCO thin films

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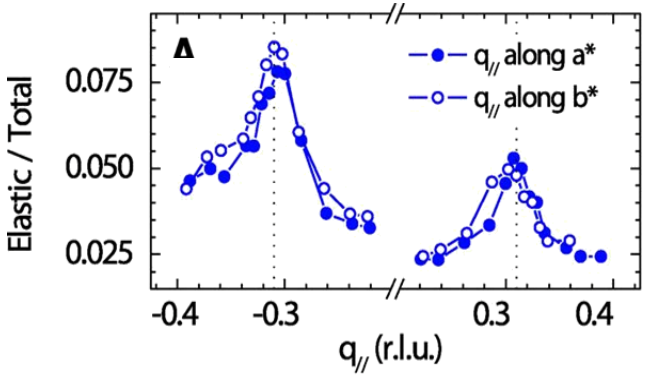
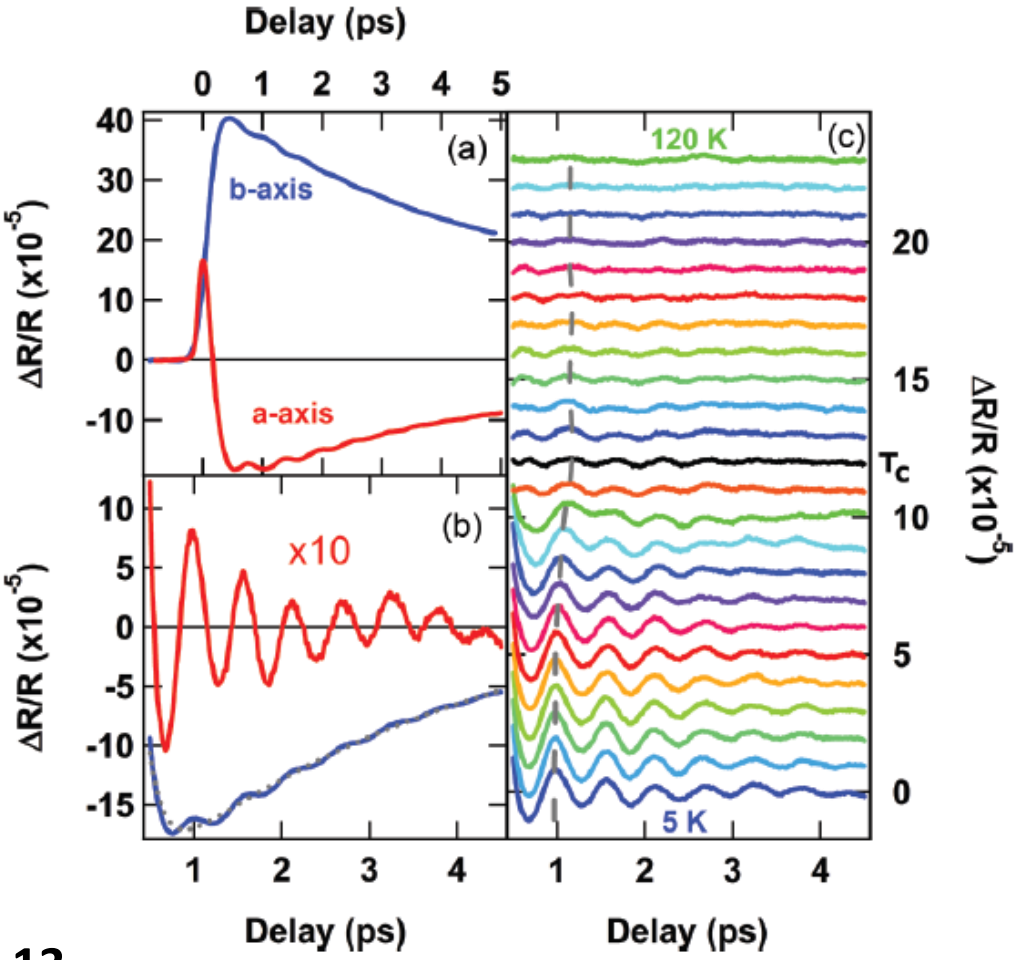
CDW amplitudon in YBCO

Detected by PP spectroscopy



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

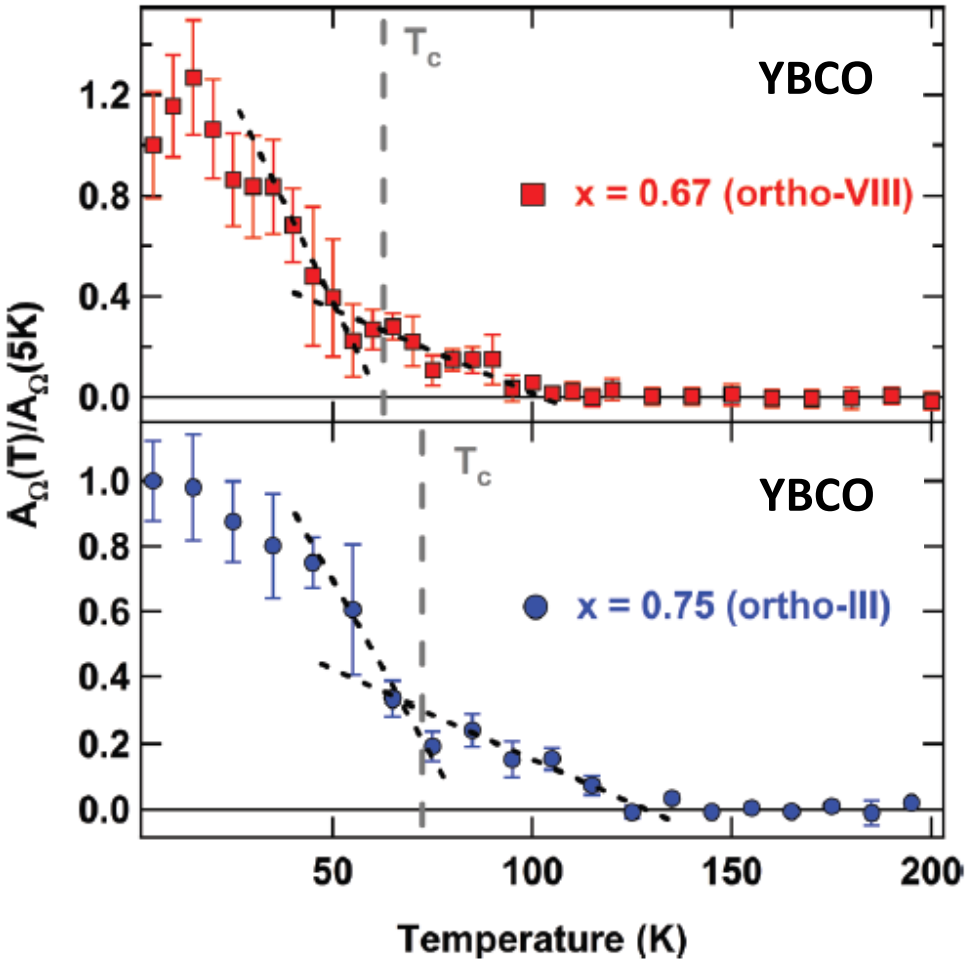
- **CDW in YBCO using RXS**
- **Amplitude mode using PP from T = 5 K to T_{CDW} = 105 K**
- **$f \sim$ 1.8 THz**
- **Similar results for p = 0.12 & p = 0.13**



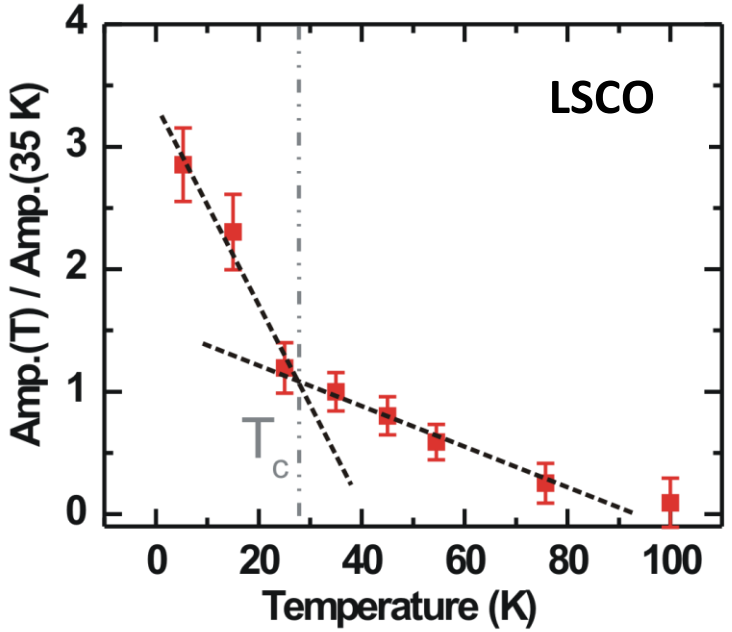
Hinton et. al. PRB 88, 060508 (2013)

CDW amplitudon in YBCO & LSCO

Behavior with temperature



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



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

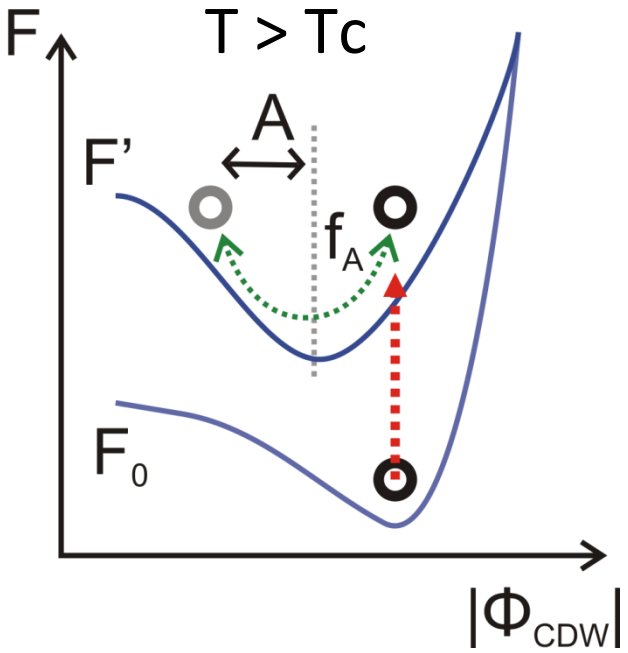
- **Enhancement of amplitudon across superconducting Tc**
- **Consistent with X-ray studies? --> show decrease in CDW amplitude**

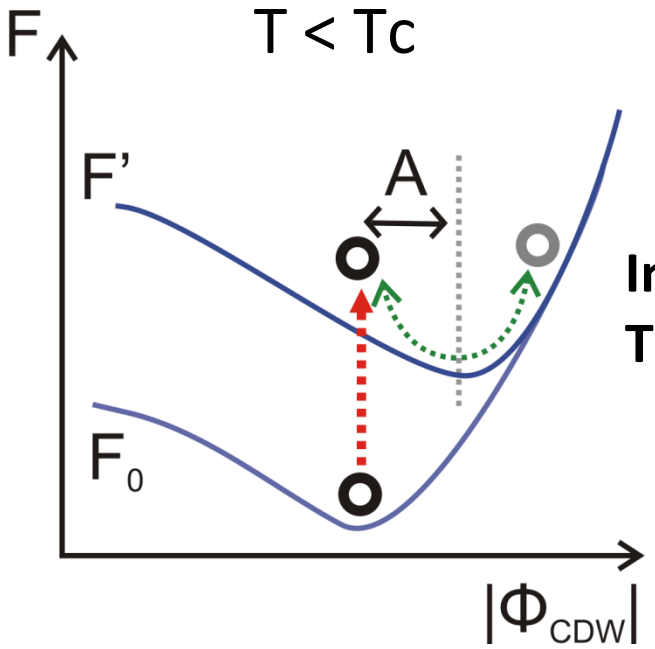
Detailed calculations by Sachdev group: arXiv:1402.0875

CDW amplitudon in YBCO & LSCO

Coupling between SC & CDW

$$F(\Phi,\Psi) = -a|\Phi|^2 + \frac{b}{2}|\Phi|^4 - \alpha|\Psi|^2 + \frac{\beta}{2}|\Psi|^4 + \lambda|\Phi|^2|\Psi|^2$$





Increase in 'A' across Tc due to SC order

Photoexcitation --> decrease $|\Phi_{eq}|$

Photoexcitation --> suppress SC --> increase $|\Phi_{eq}|$

Detailed calculations by Sachdev group: arXiv:1402.0875

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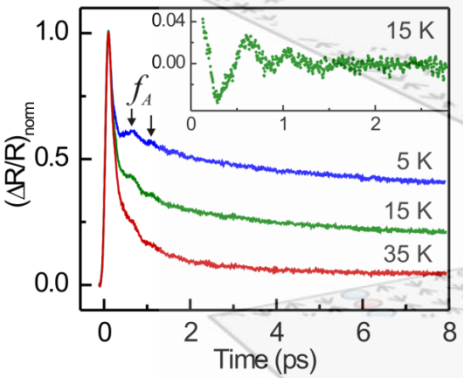
Conclusion

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

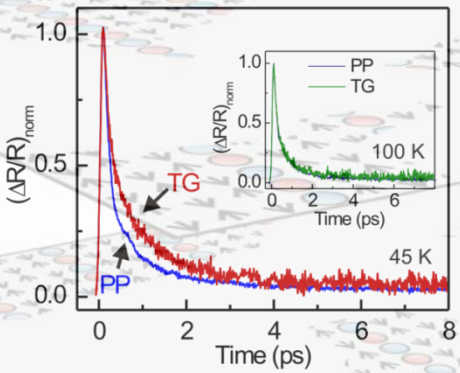
Amplitudon



Frequency ~ 2 THz

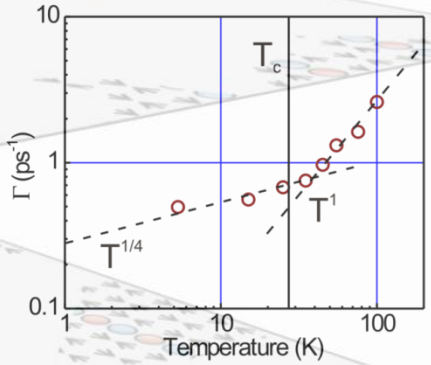
T_{CDW} ~ 100 K

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**
- **Indicates a competition scenario between SC & CDW order**
- **Amplitudon also observed in YBCO --> repuslive interaction b/w SC & CDW orders**

Acknowledgements

Prof. Nuh Gedik

Dr. Darius Torchinsky

Dr. Ivan Božović

Dr. Anthony Bollinger

Nature Materials 12, 387-391 (2013)