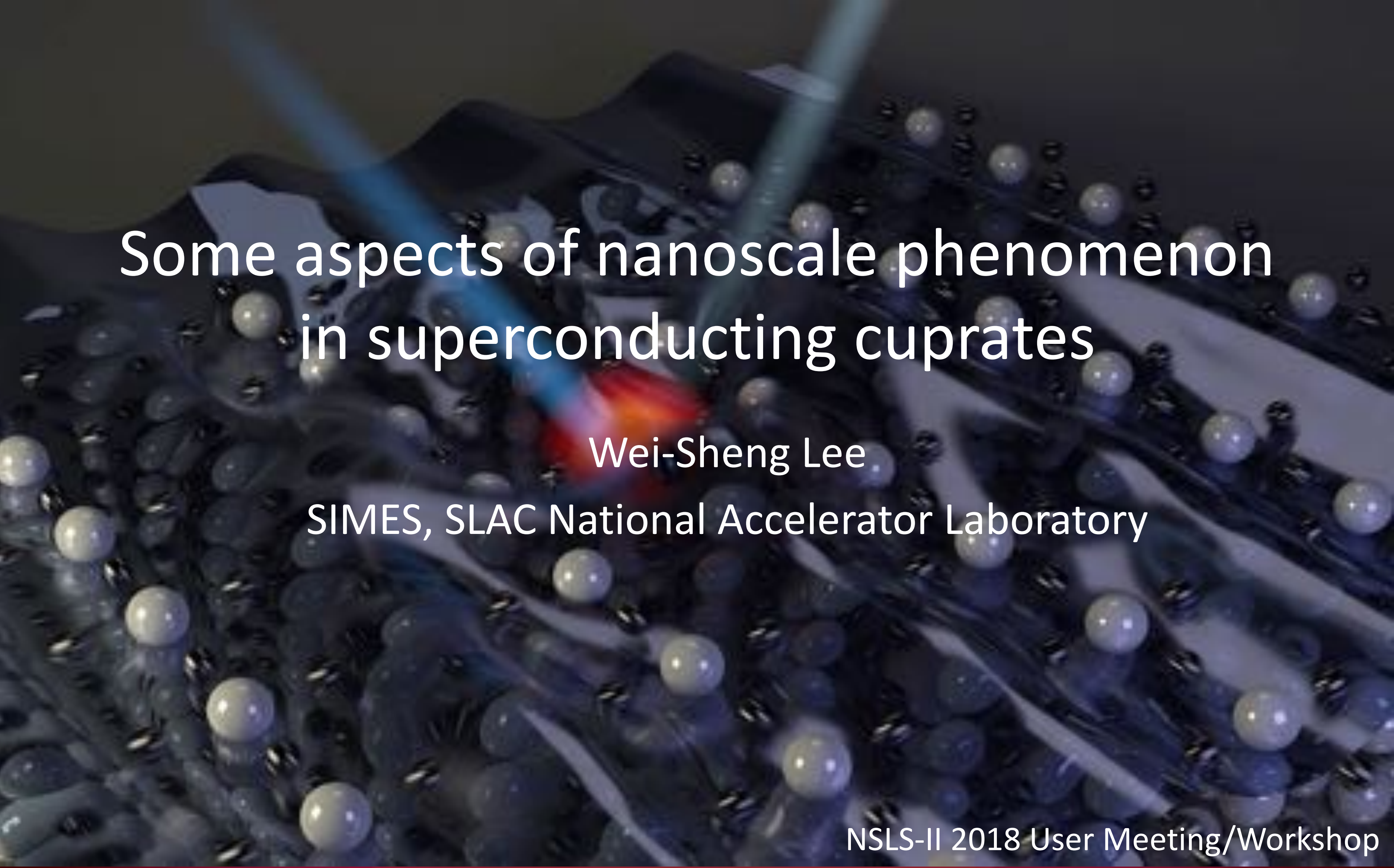


Some aspects of nanoscale phenomenon in superconducting cuprates

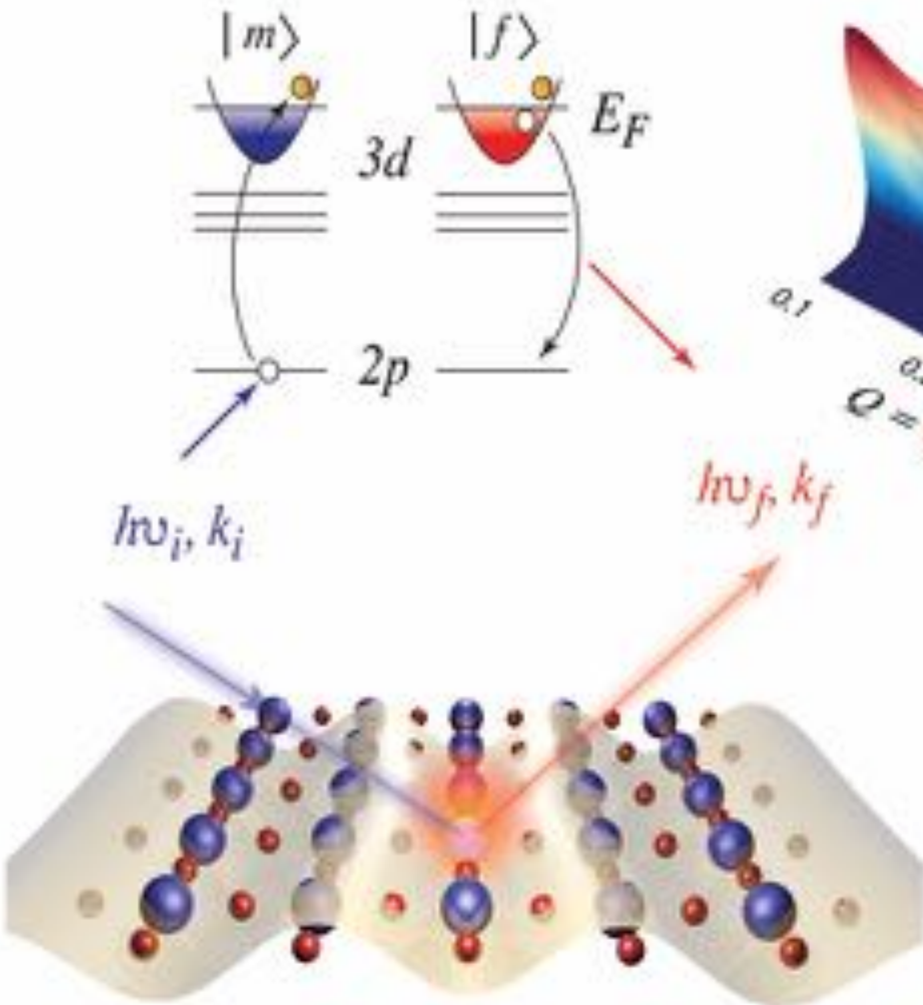
Wei-Sheng Lee
SIMES, SLAC National Accelerator Laboratory

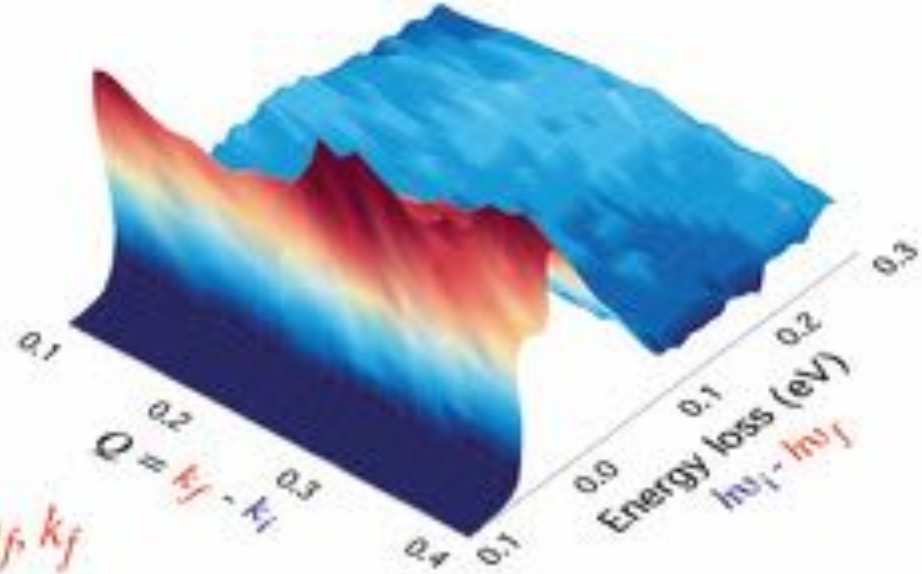
NSLS-II 2018 User Meeting/Workshop

SIMES STANFORD INSTITUTE FOR MATERIALS & ENERGY SCIENCES
THE DIVISION OF MATERIALS SCIENCE AT SLAC

A joint institute of SLAC and Stanford University

Resonant Inelastic X-ray Scattering (RIXS)



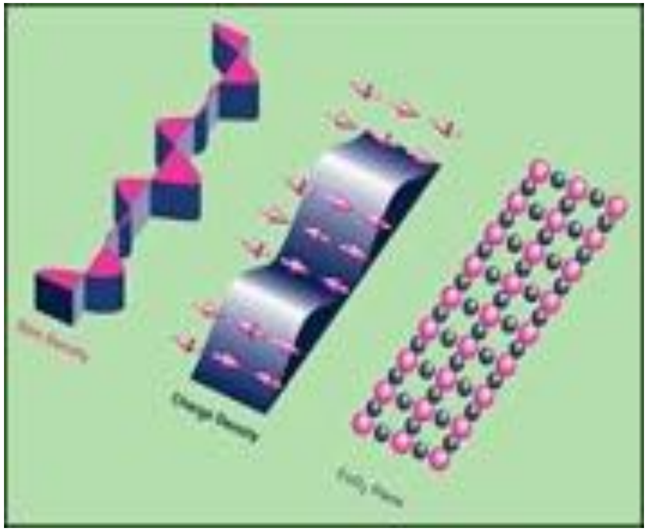


- Element Specific.
- Excited Final States:
  Elementary excitations!
- Momentum-conserved

$$\sum_n \frac{\langle f|\mathcal{D}'^\dagger|n\rangle\langle n|\mathcal{D}|g\rangle}{E_g + \hbar\omega_{\mathbf{k}} - E_n + i\Gamma_n},$$

Outline

- Collective Charge excitations
- Signature of dispersive CDW excitations
- CDW ground and implication of spatial inhomogeneity
- Summary

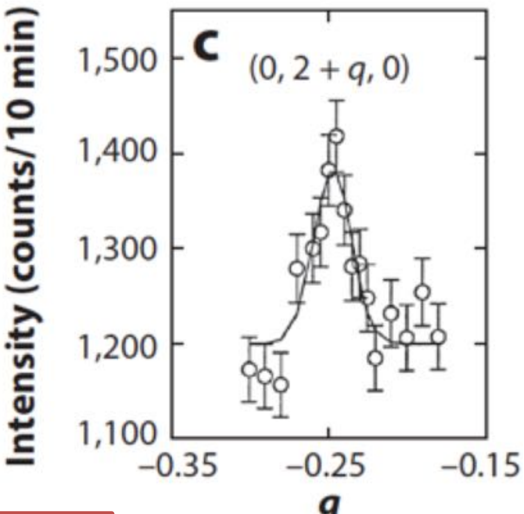


Dr. L. Chaix

CDW in cuprates

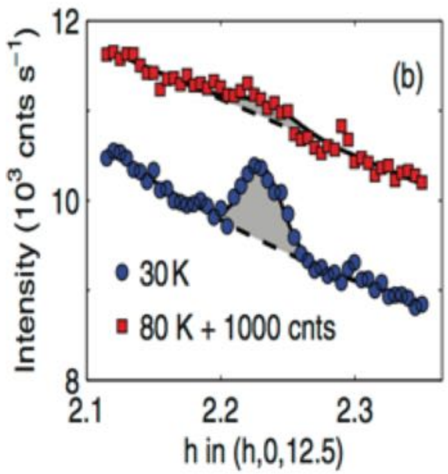
INS

Tranquada *et al.* Nature **375**:561 (1995)



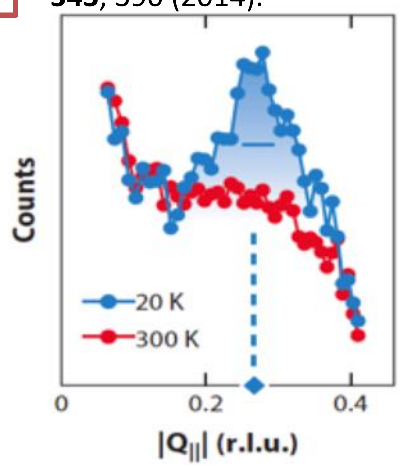
XRD

Croft *et al.*, *PRB* **89**, 224513 (2014).



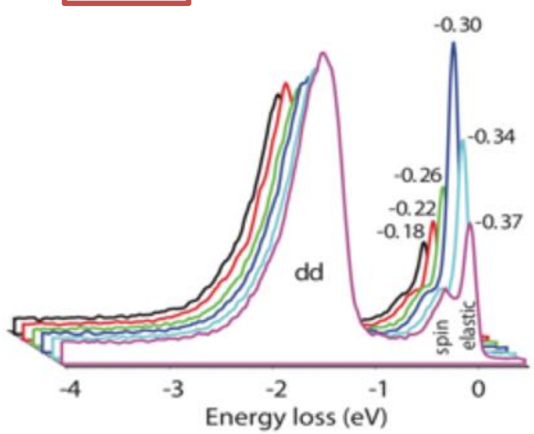
RXS

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



RIXS

Ghiringhelli *et al.*, Science **337**, 821 (2012)



La-based

- $La_{2-x}Sr_xNd_yCu_{1-y}O_4$ (Nd-LSCO)
- $La_{2-x}Ba_xCuO_4$ (LBCO)
- $La_{2-x}Sr_xCuO_4$ (LSCO)

Bi-based

- $Bi_2Sr_2CuO_{6+d}$ (Bi-2201)
- $Bi_2Sr_2CaCu_2O_{8+d}$(Bi-2212)

Y-based

$YBa_2Cu_3O_{6+x}$ (YBCO).

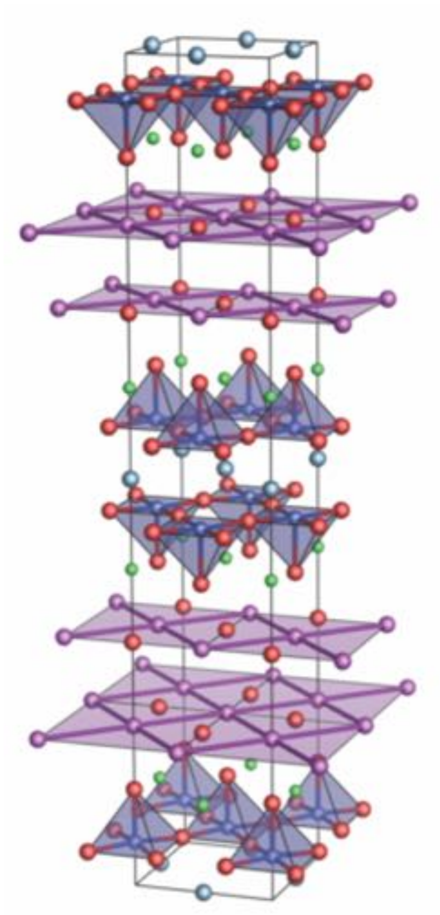
Hg- based

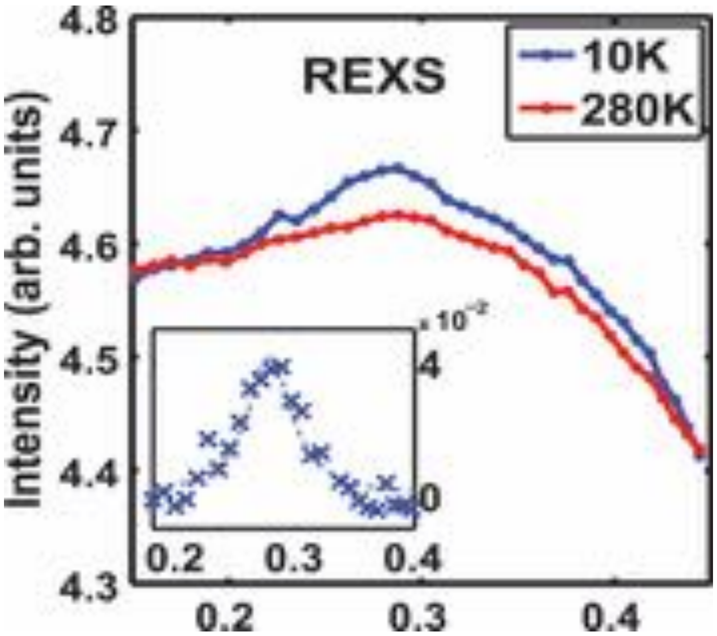
$HgBa_2CuO_4$ (Hg1201)

CDW in Bi2212

SLAC

Underdoped Bi2212 (Tc 40K)



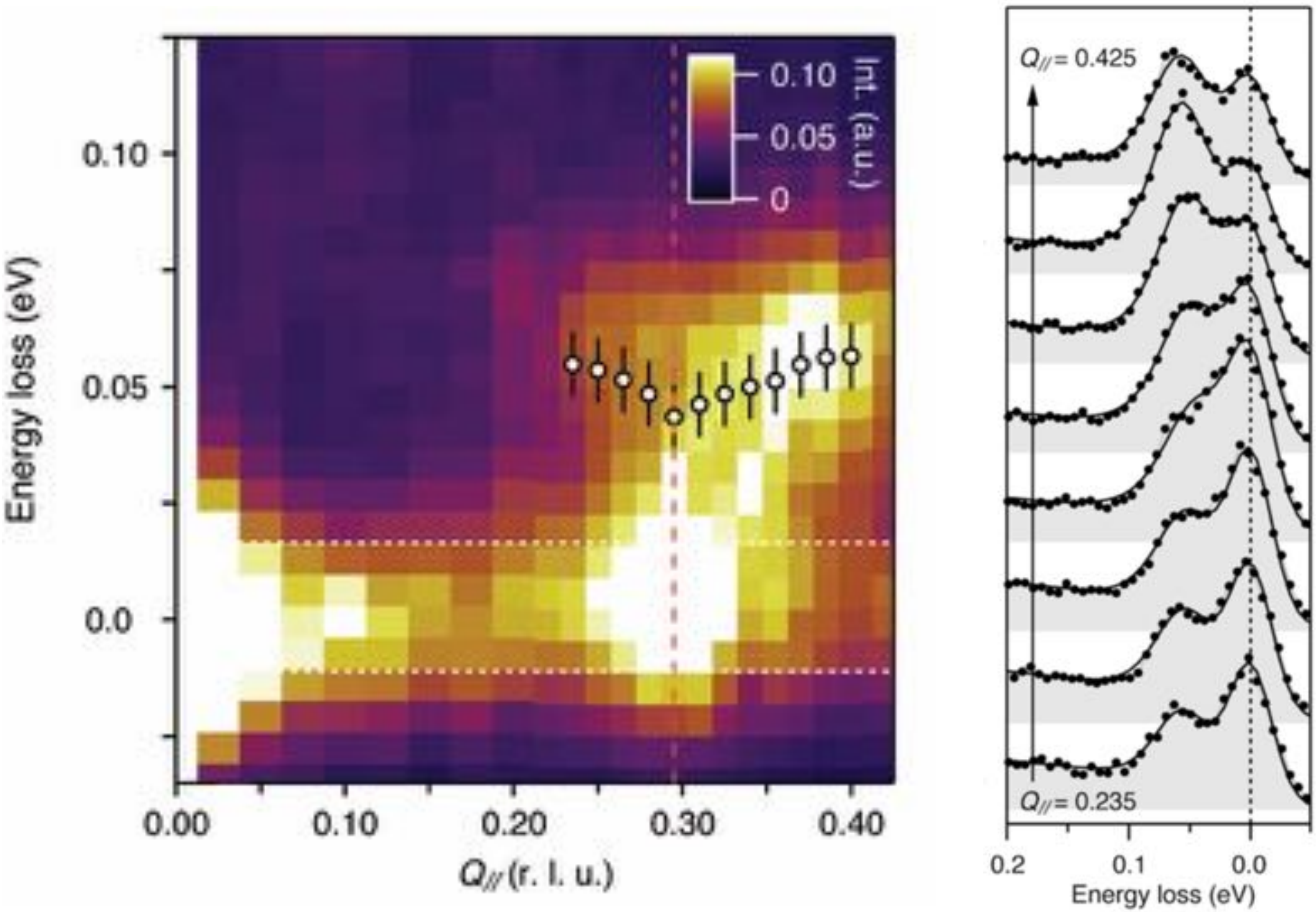


da Silva Neto *et al. Science* ***343****, 393 (2014).*

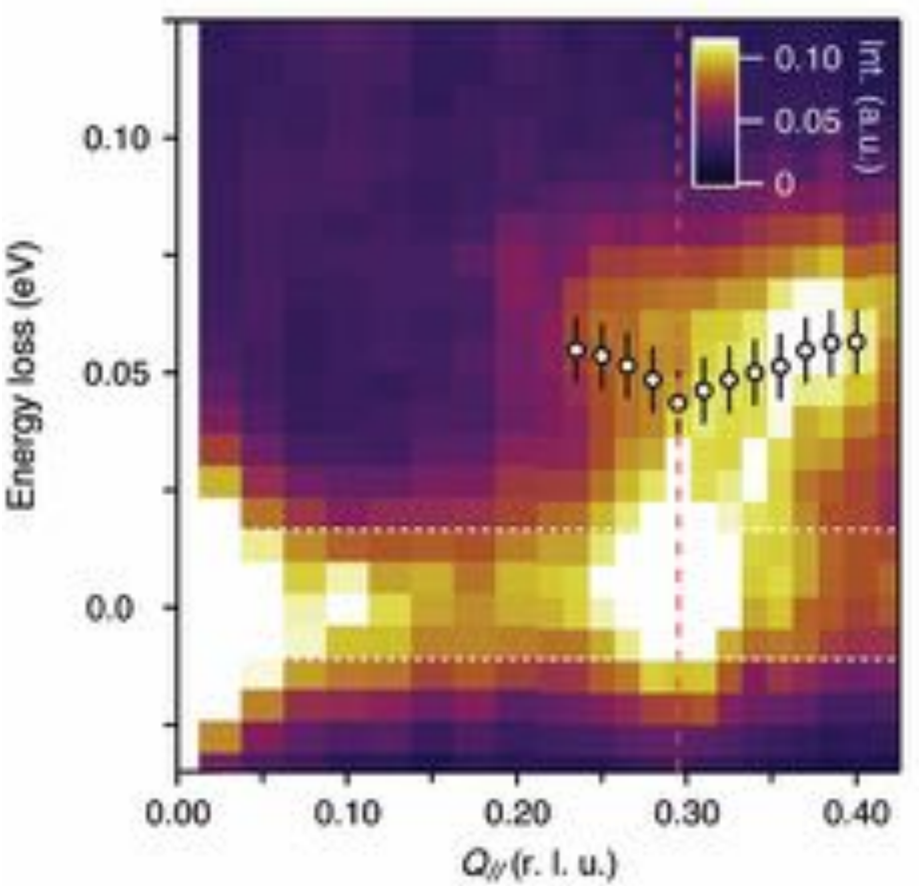
- High fidelity CDW measurement is needed.
- Interaction with other degrees of freedom.
- CDW excitations

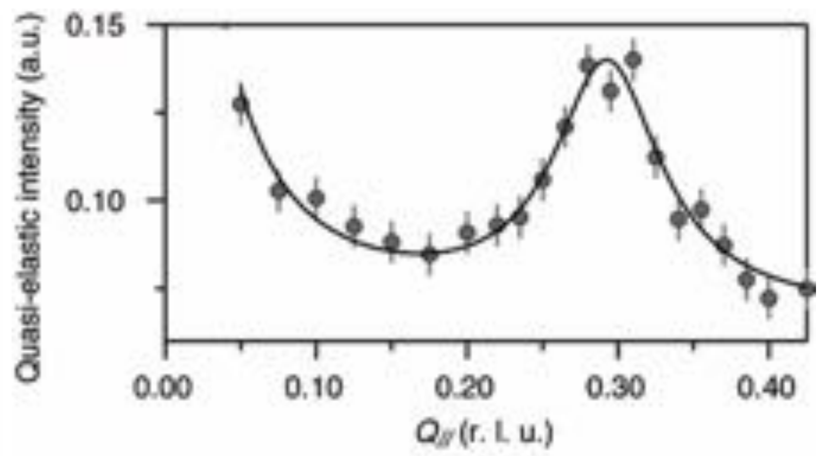
RIXS spectrum on under-doped Bi2212

Bi-2212 Tc = 45 K



CDW scattering in quasi-elastic region

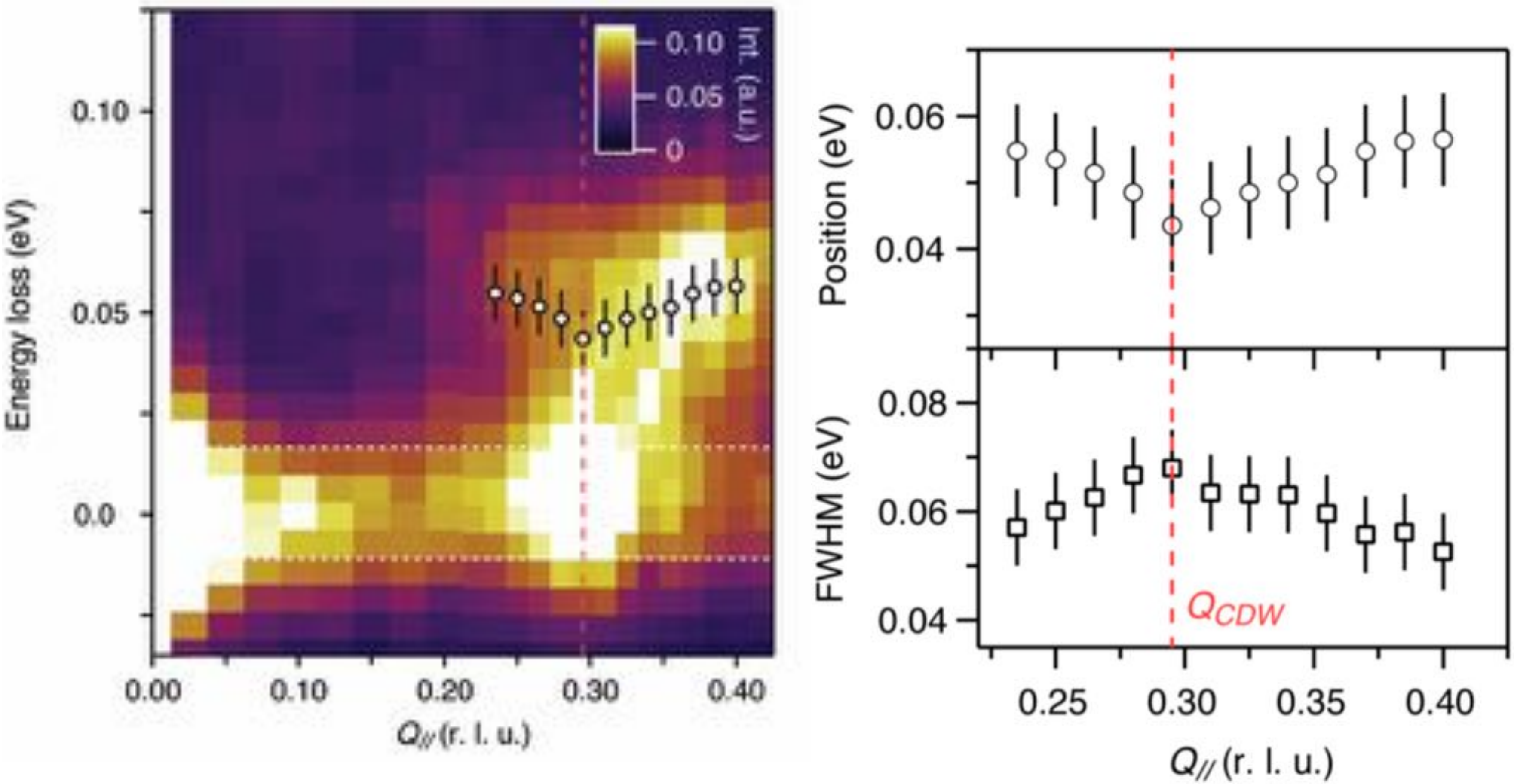




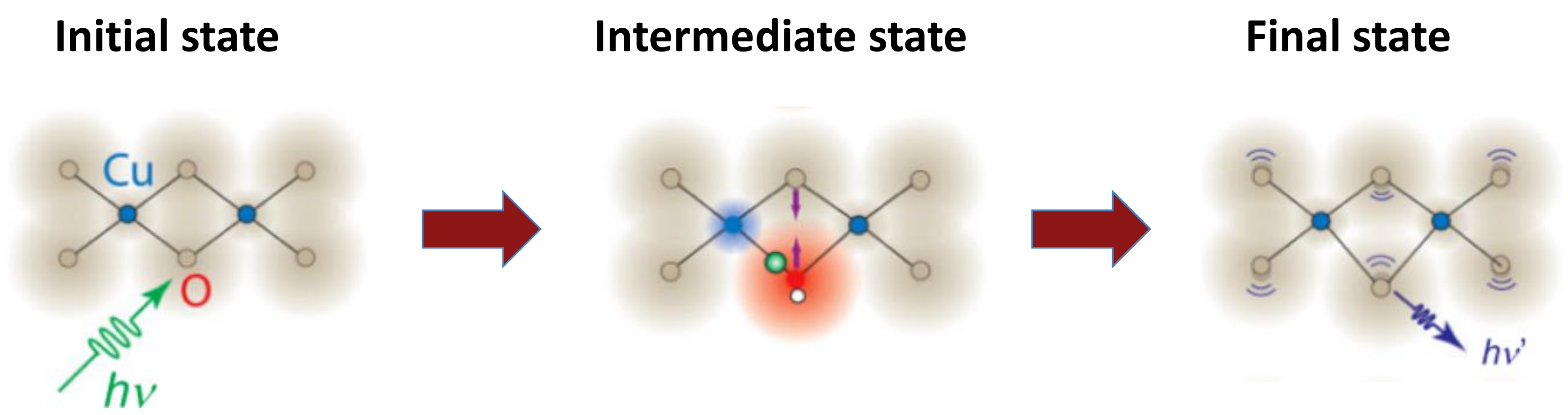
Q_{CDW} = 0.3 r.l.u.

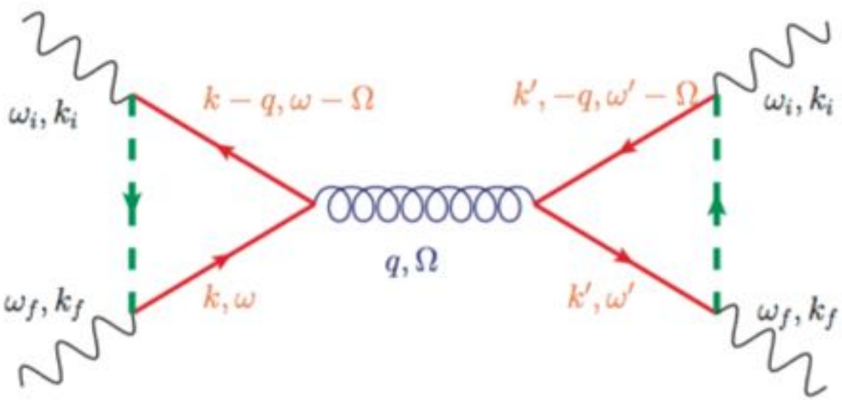
Correlation length ~ 15 Å

Phonon softening at Q_{CDW}



E-ph coupling via RIXS

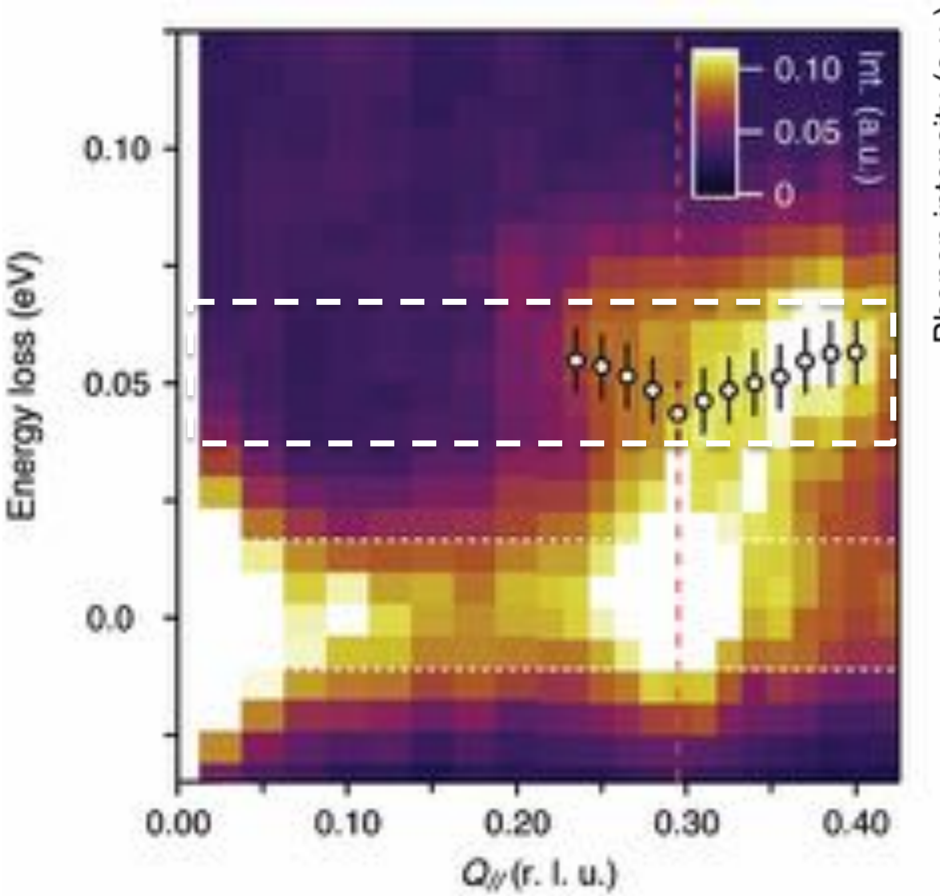


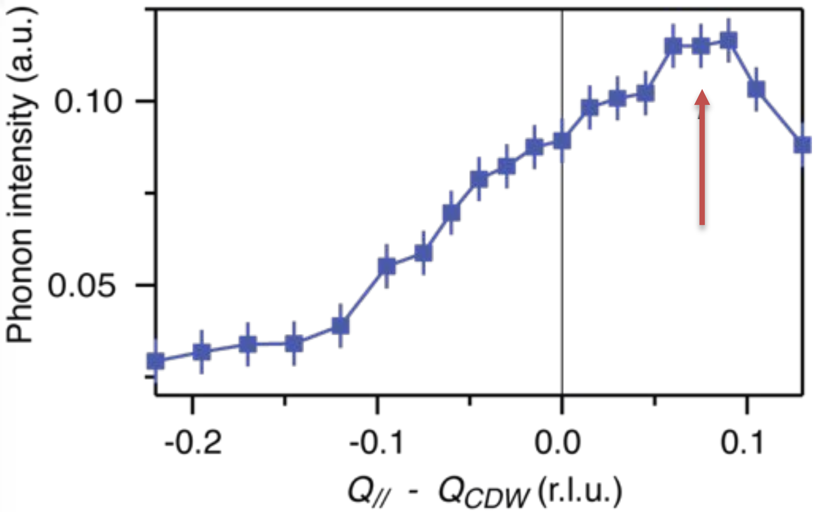


RIXS phonon cross section directly reflects the e-ph strength.

L. J. P. Ament *et al.*, EPL **95**, 27008 (2011).
T.P. Devereaux et al., PRX **6,** 041019 (2016).

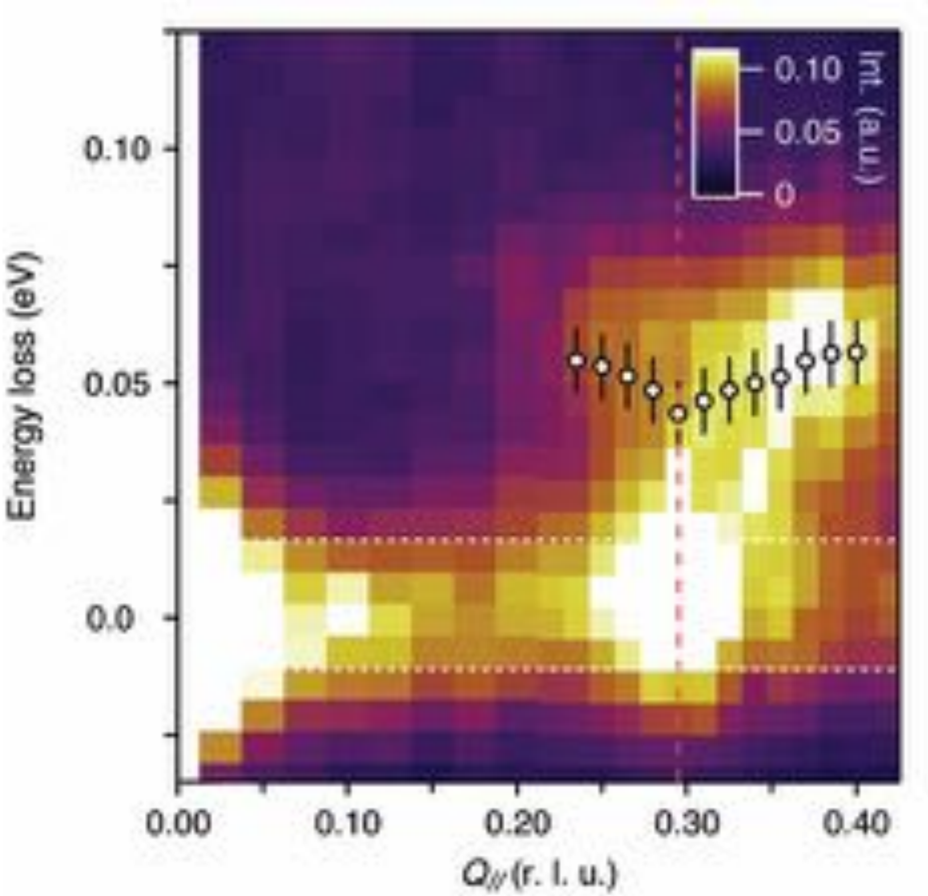
Influence of CDW



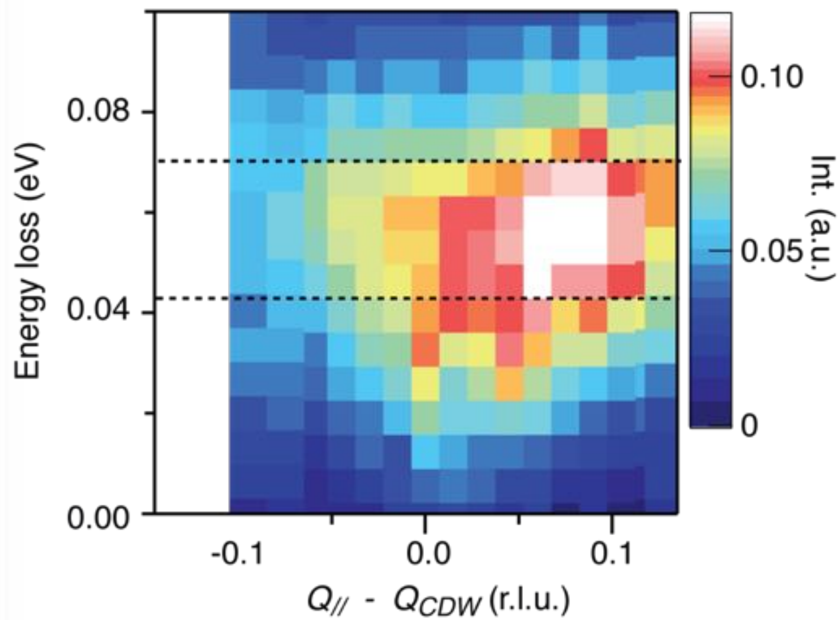


- Phonon slightly soften at Q_{CDW}
- Hot-spot anomaly at Q_a.

Influence of CDW

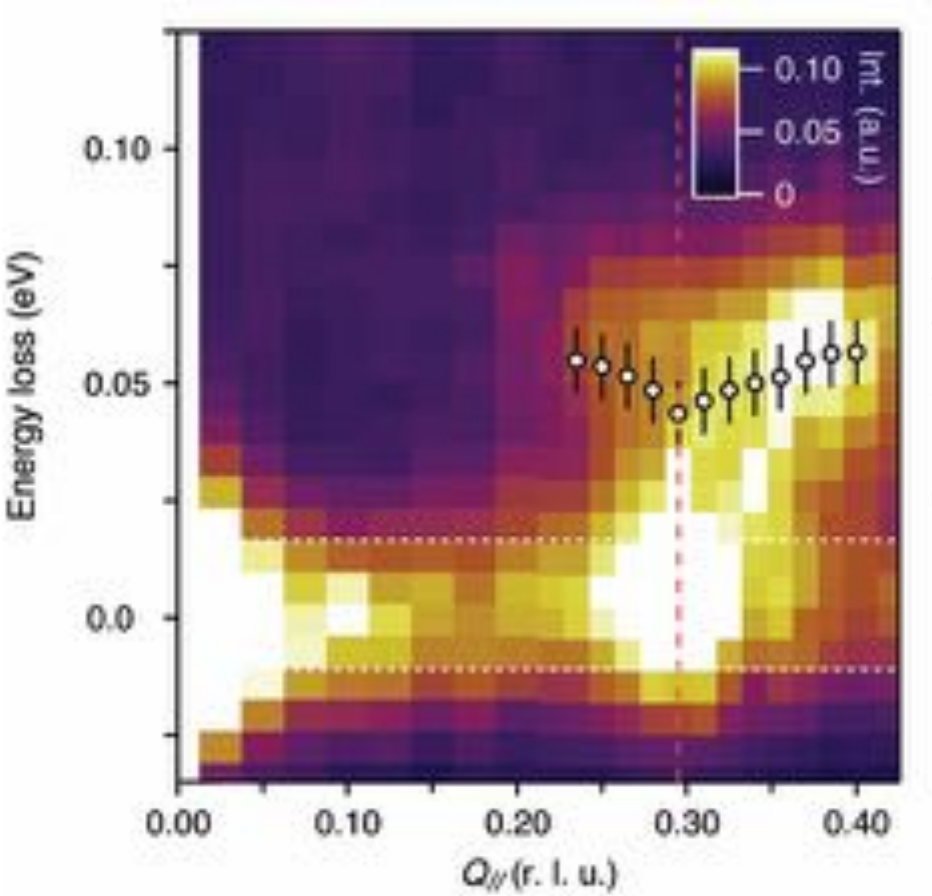


Elastic peak subtracted.

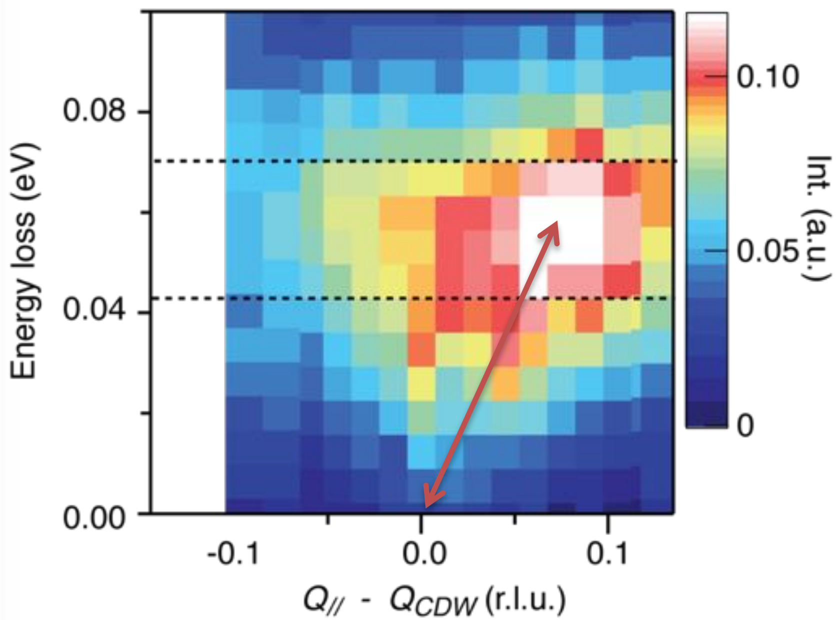


- Funnel-shape excitations emanate from Q_{CDW} and cause hot-spot phonon anomaly.

Influence of CDW



Elastic peak subtracted.

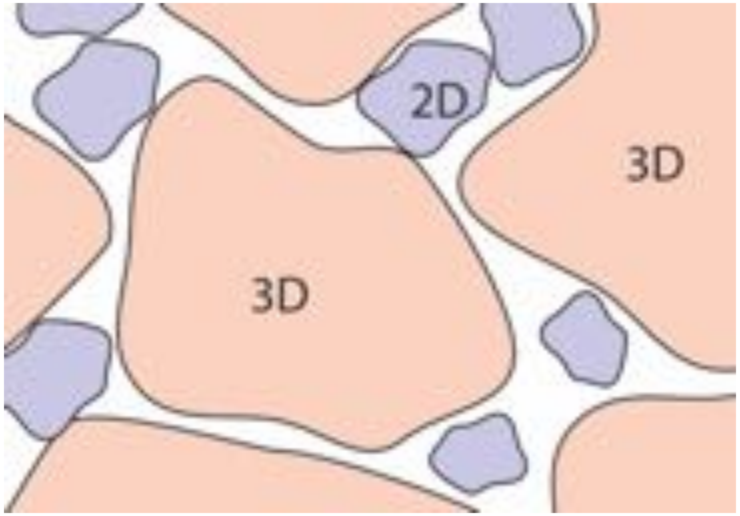


- V_{CDW} ~ 0.6 eV Å

- **Dispersive CDW excitation in cuprate.**

Outline

- Collective Charge excitations
- Signature of dispersive CDW excitations
- CDW ground state and implication of spatial inhomogeneity
- Summary



Dr. H. Jang

Dr. S. Gerber

S. Gerber *et al.* Science 350, 949 (2015)

H. Jang *et al*. PNAS 113, 14645 (2016).

Quasi-2D CDW with Short Correlation length

SLAC

	Bi2201[1]	Bi2212[2]	LSCO[3]	Hg1201[4]	YBCO[4]
ξ_a (a_o)	~ 7	~ 4	~ 8	~ 5	~ 16
ξ_c (c_o)	< 1	< 1	< 1	< 1	< 1
V (u.c.)	~ 50	~ 20	~ 64	~ 25	~ 256

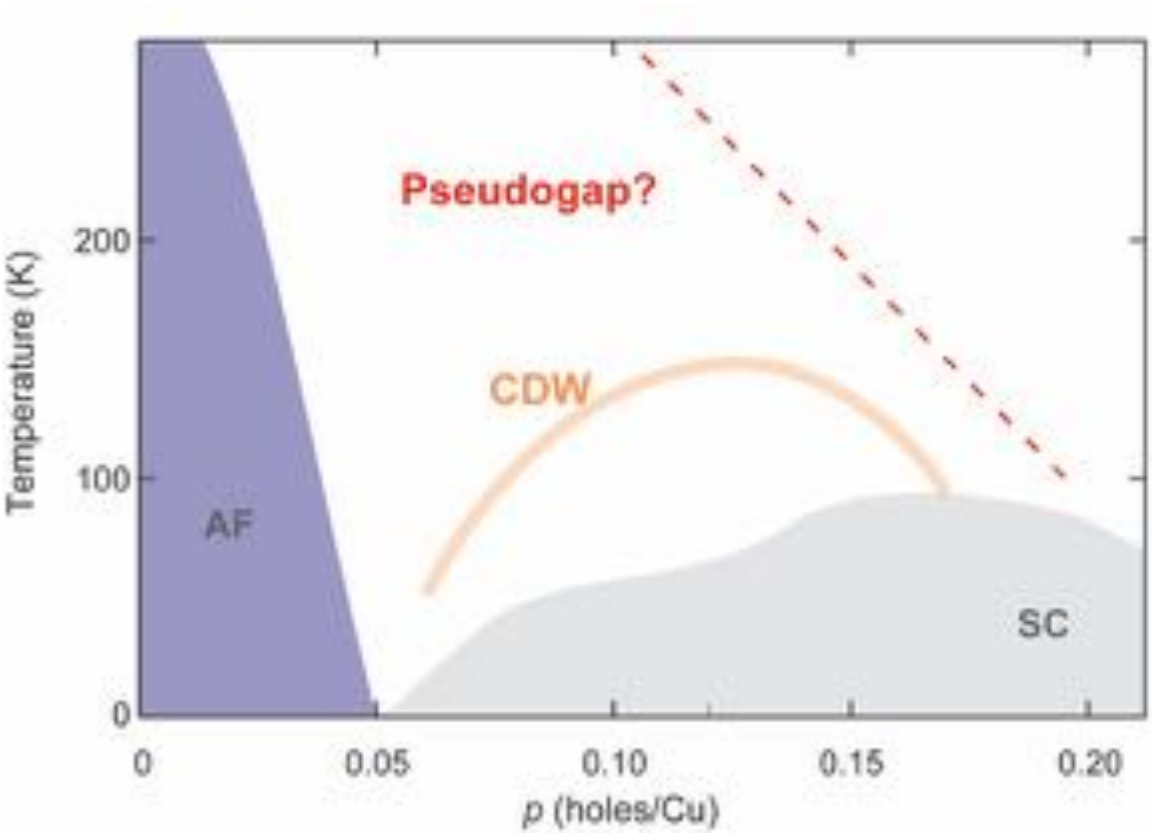
- Very small correlation volume.

Possibly strongly limited by disorders!

What is the ground state CDW ?

1. R. Comin *et al.*, *Science* **343**, 390–392 (2014).
2. da Silva Neto *et al.*,*Science* **343**, 393–396 (2014).
3. T. Croft *et al.*, *Phys. Rev. B* **89**, 224513 (2014).
4. W. Tabis *et al*. *Nature Comm.* **5**, 5875 (2014).
5. G. Ghiringhelli *et al.*, *Science* **337**, 821–825 (2012).
6. J. Change *et al.*, Nature Physics **8**, 871 (2012).

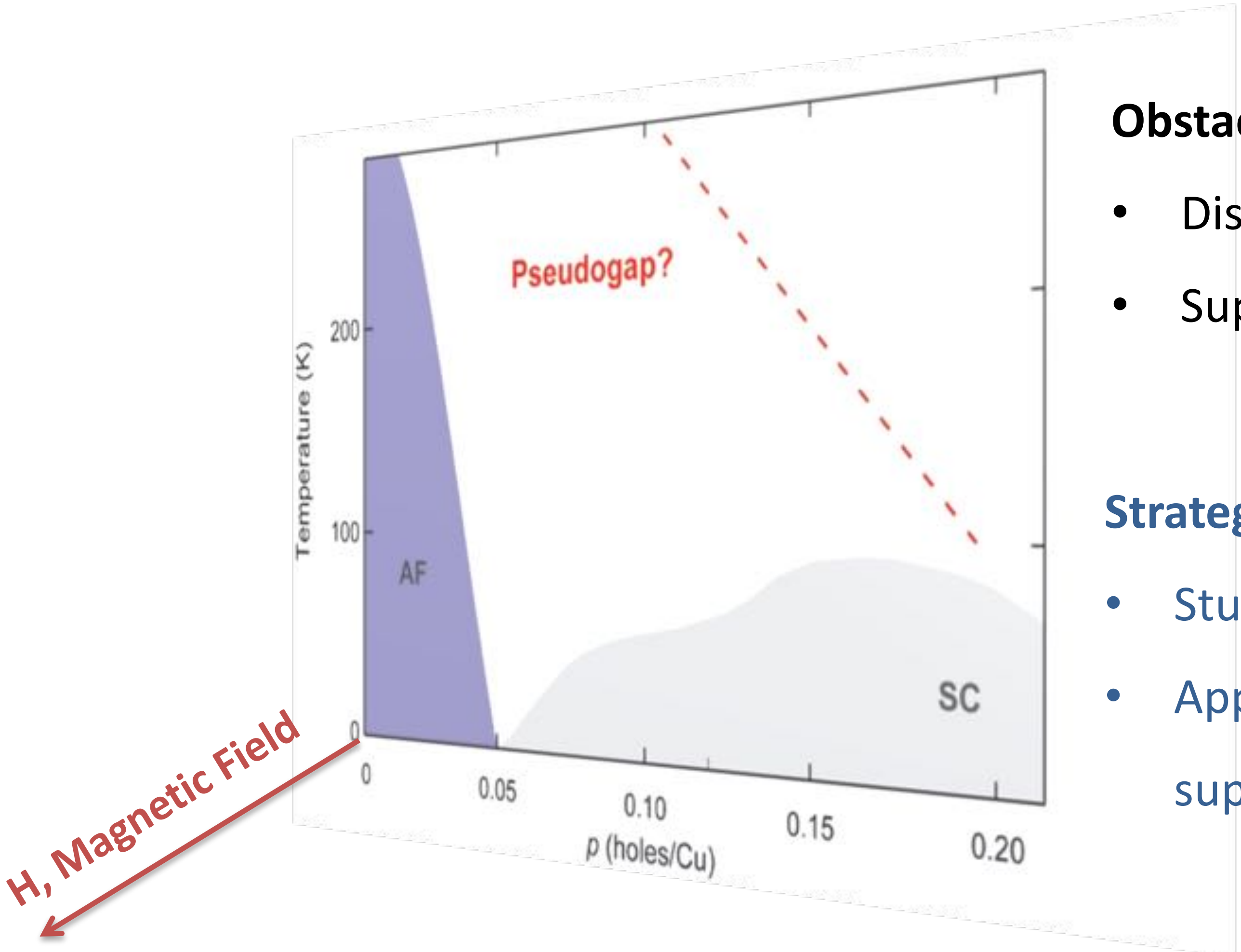
Access to the ground state CDW



Obstacles:

- Disorders
- Superconductivity

Magnetic field as a tuning parameter



Obstacles:

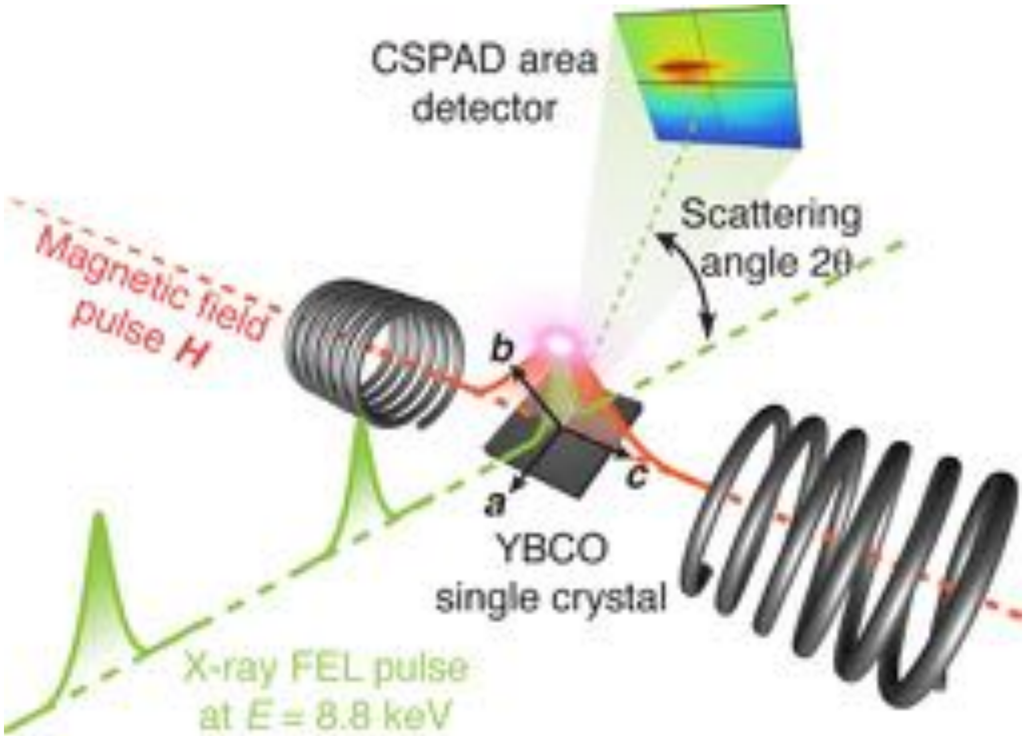
- Disorders
- Superconductivity

Strategies:

- Study cleanest crystal
- Apply high magnetic field to suppress SC.

Linac Coherent Light Source (LCLS)

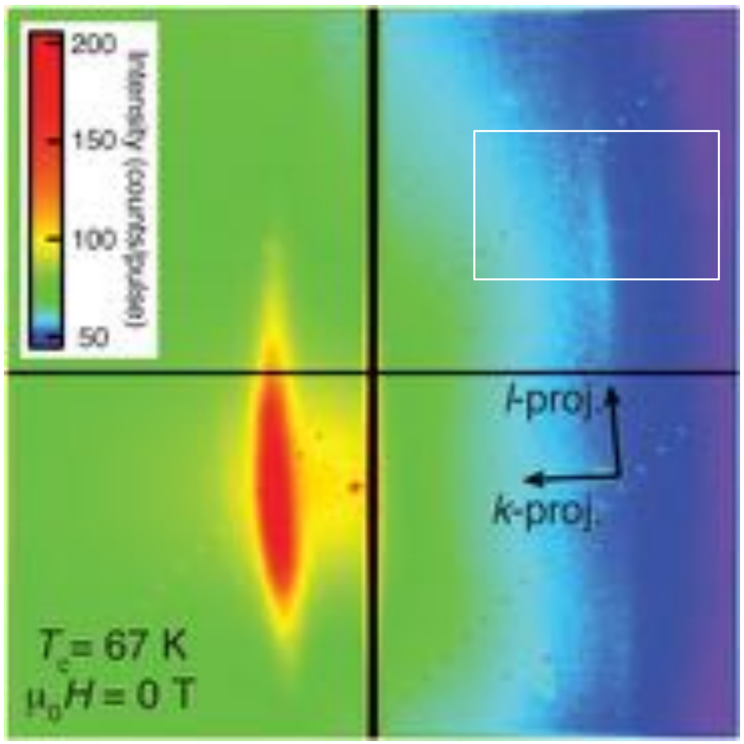
SLAC

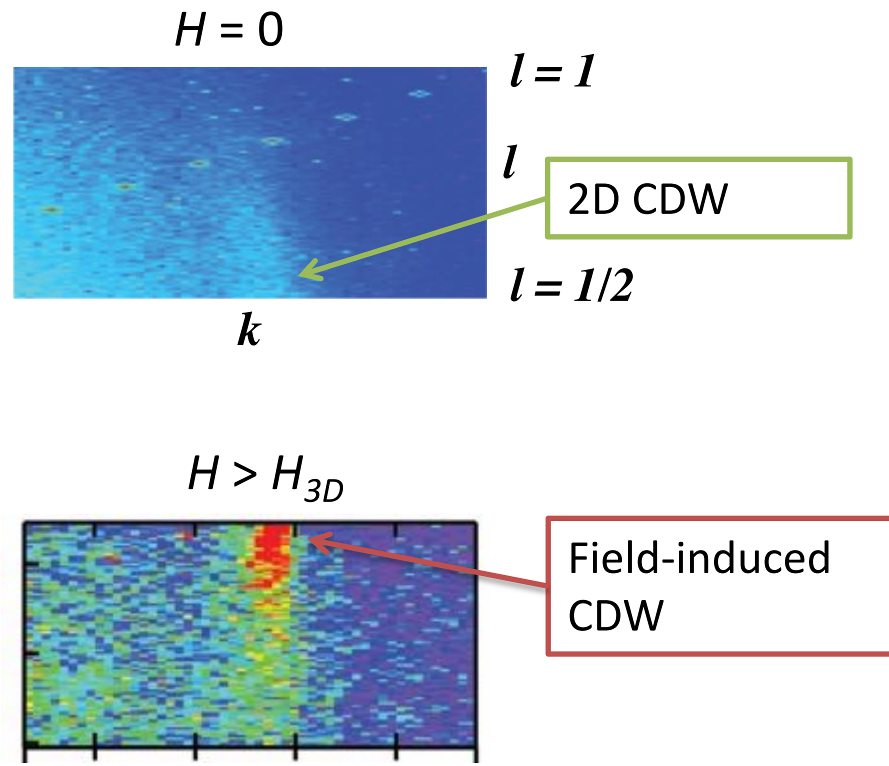


- *H* // c-axis of YBCO
- Shot-by-shot detection of diffraction pattern at fields up to 30 Tesla

Gerber, Jang *et al.*, Science **350**, 949 (2015)

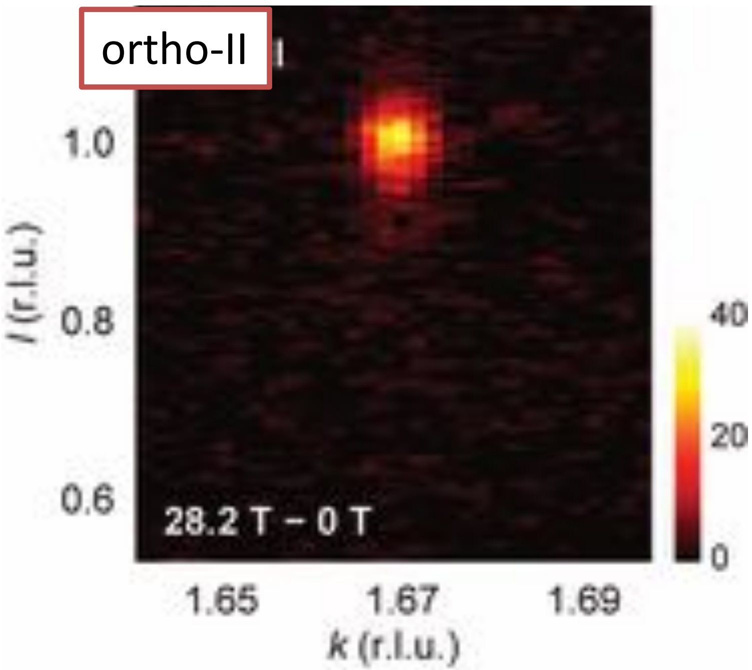
Field-induced CDW in ortho-VIII



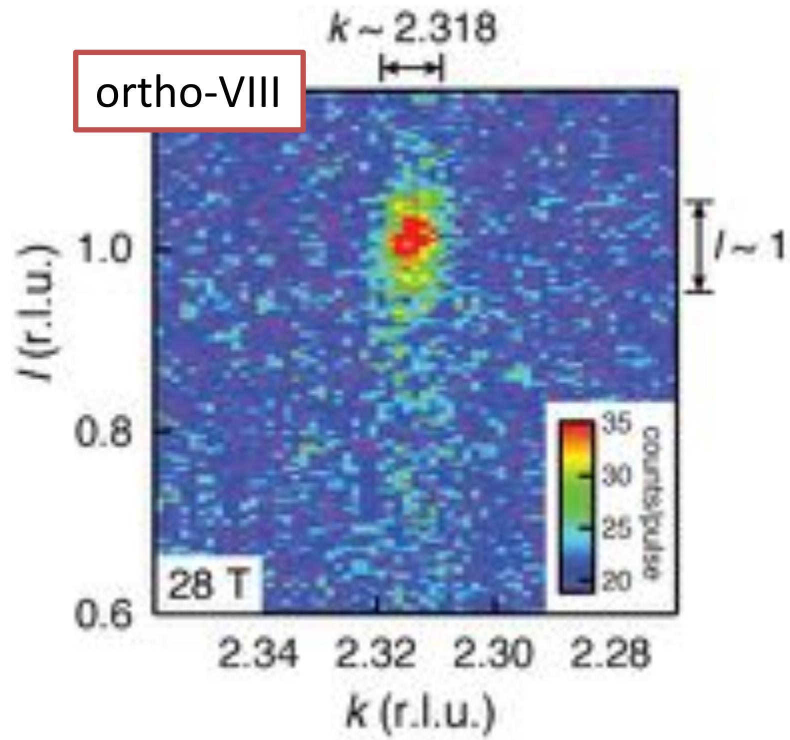


Gerber, Jang *et al.*, Science **350**, 949 (2015)

Three-dimensionally ordered CDW

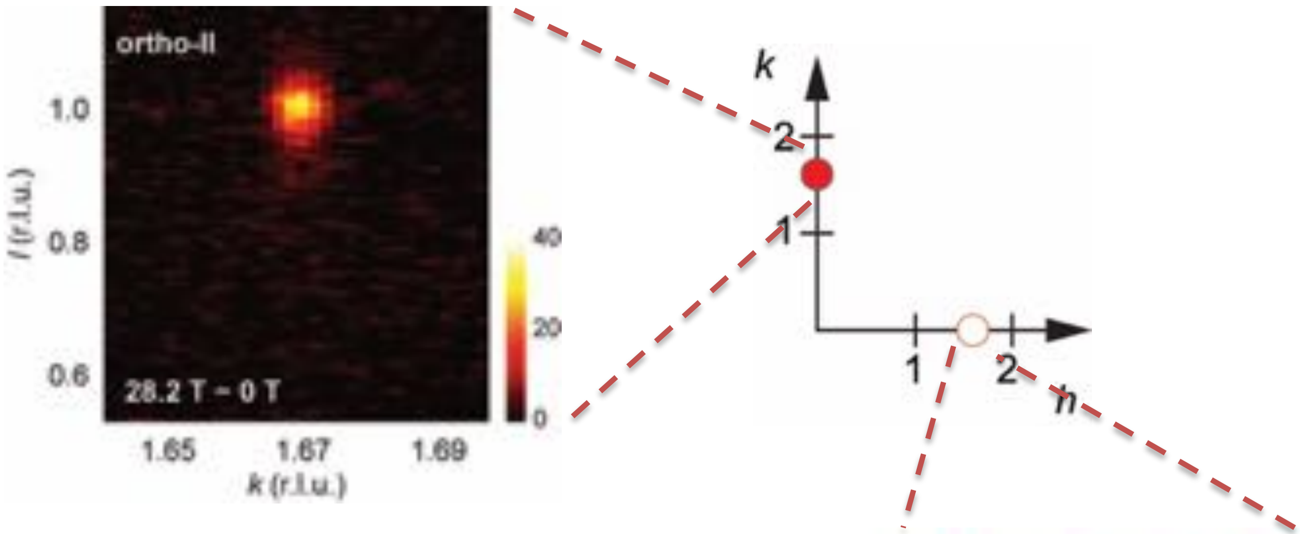


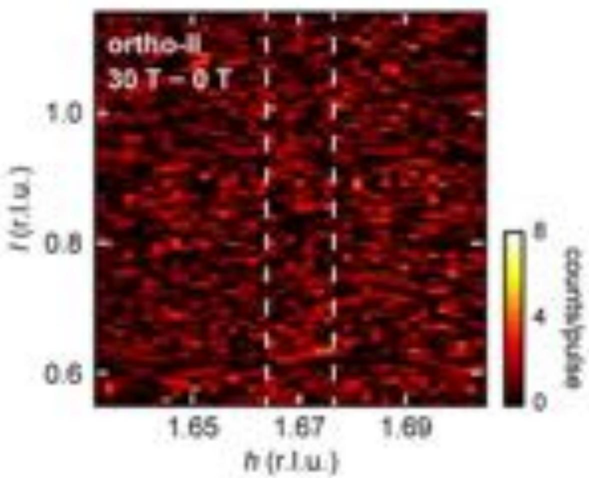
- ξ_b > 280 Å, ξ_c ~ 60 Å
- q= 0.33 r.l.u.
- H_{3D} ~ 18.7 T
- T_{3D} ~ 45 K



- ξ_b > 280 Å, ξ_c ~ 70 Å
- q= 0.318 r.l.u.
- H_{3D} ~ 15 T
- T_{3D} ~ 50 K

Unidirectional 3D CDW

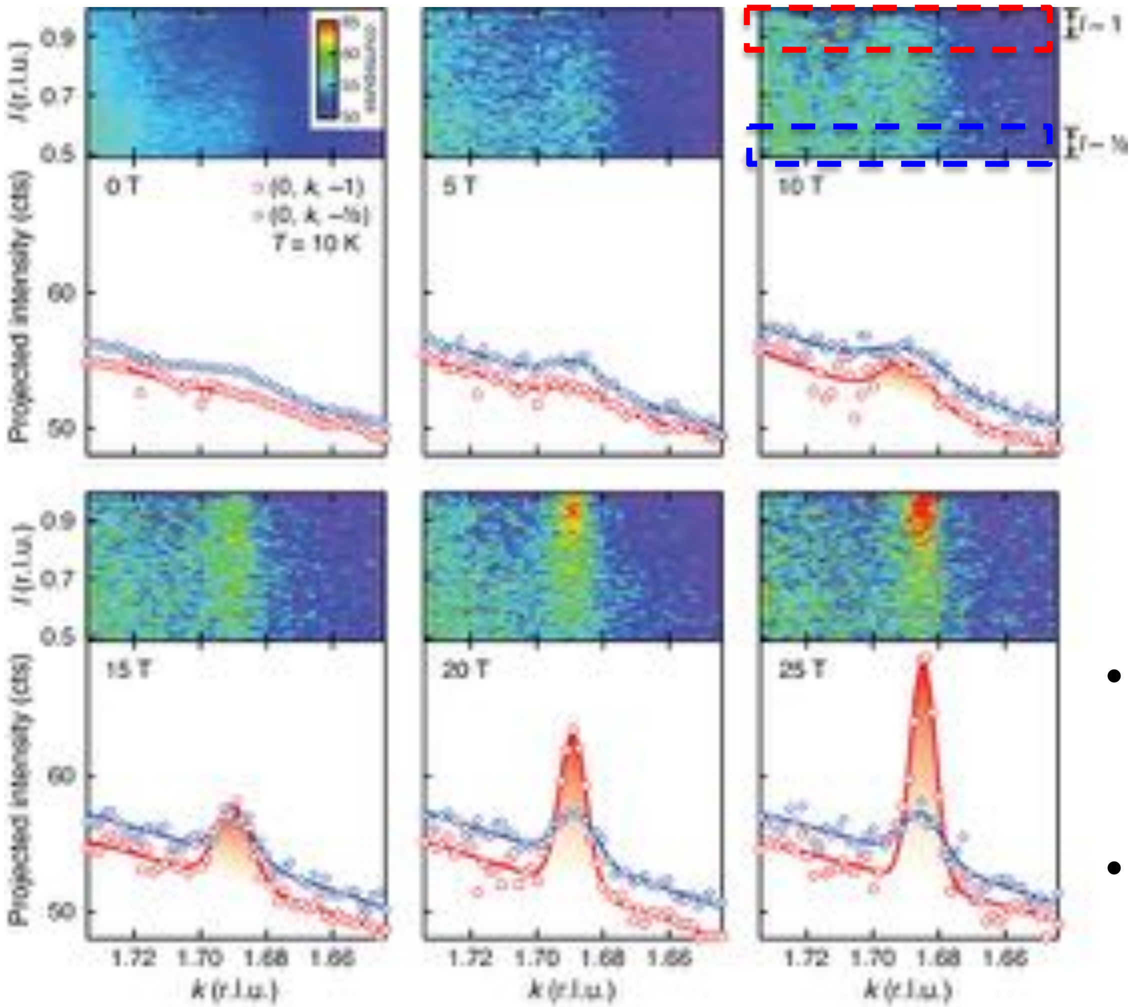


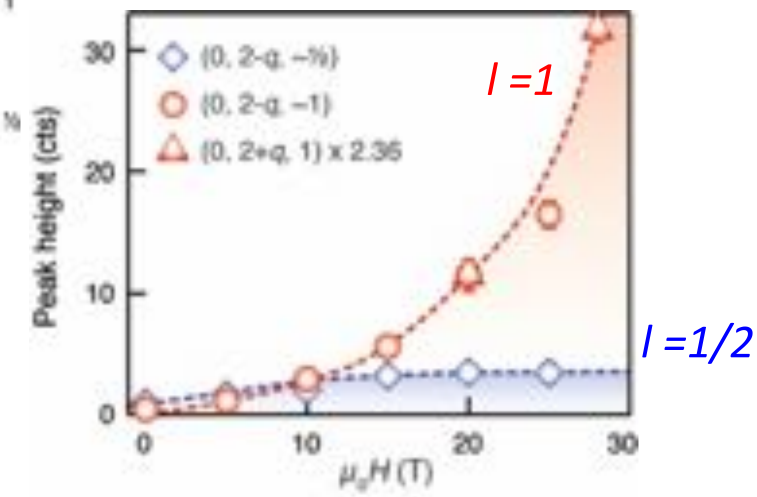


CDW ground state in YBCO:

long-range 3D ordered incommensurate stripes.

Coexisting 2D and 3D CDW



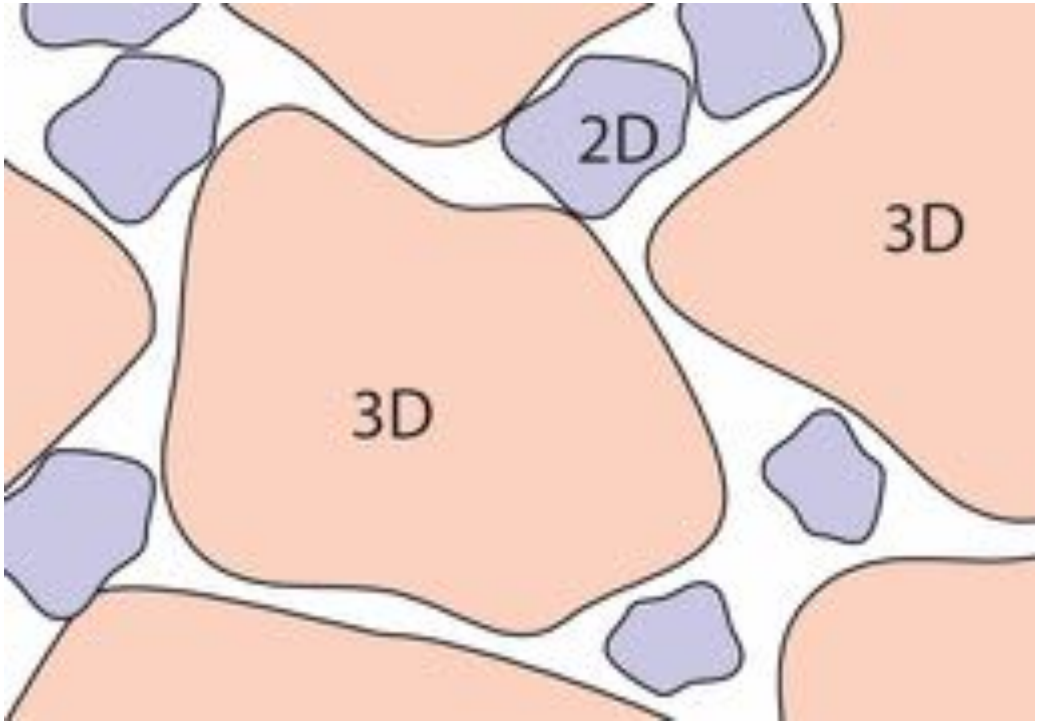


- The CDW at $l = 1$ onset at 10-15 Tesla
- The CDW at $l = ½$ saturates.

Proposal: Coexisting distinct 3D and 2D CDW domains

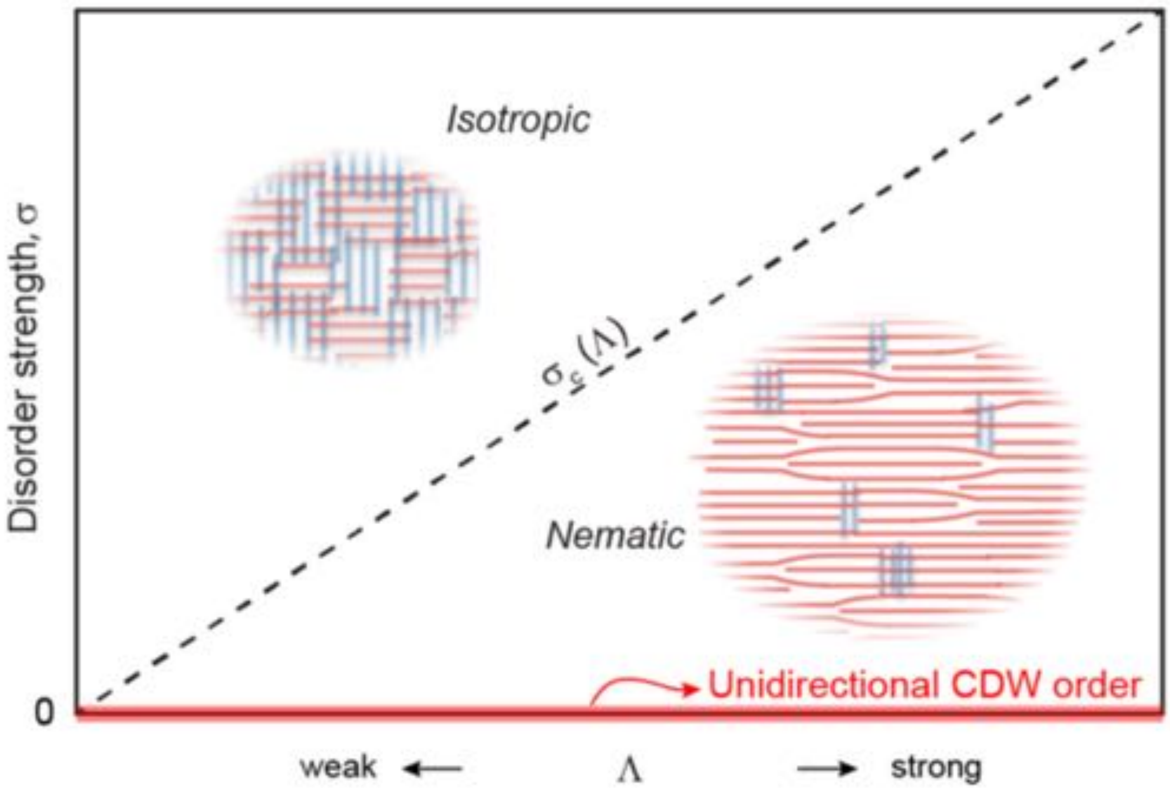
SLAC

***H* > *H*$_{3D}$**



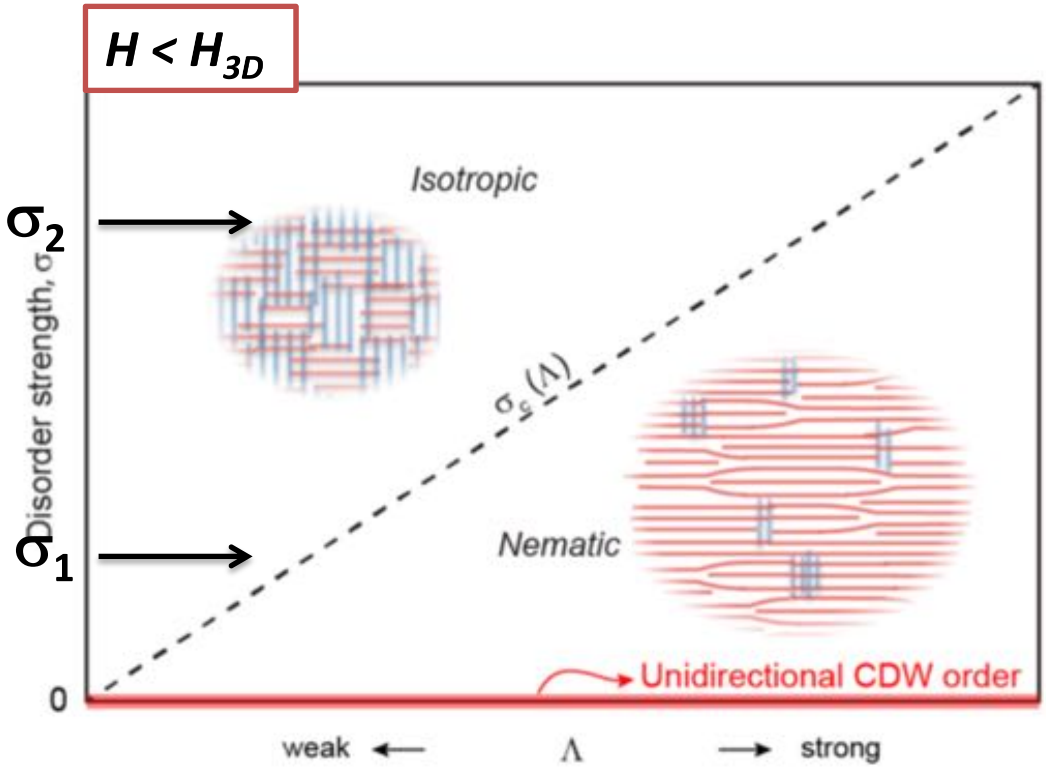
H. Jang *et al*. PNAS **113**, 14645 (2016).

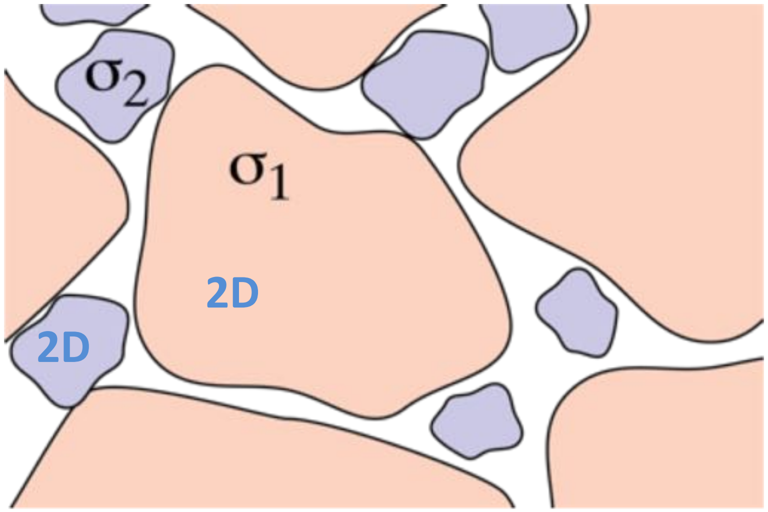
The relation of 2D and 3D CDW order?



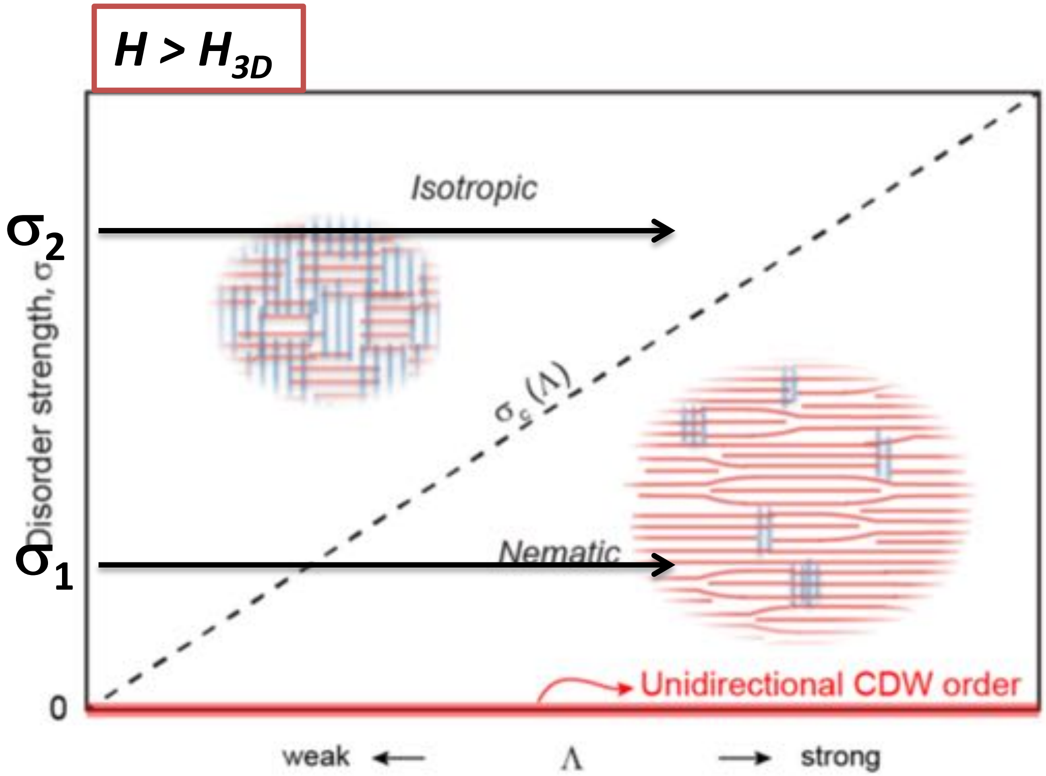
Nie *et al. PNAS* **111**, 7980–7985 (2014).
H. Jang *et al., PNAS* **113**, 14645 (2016).

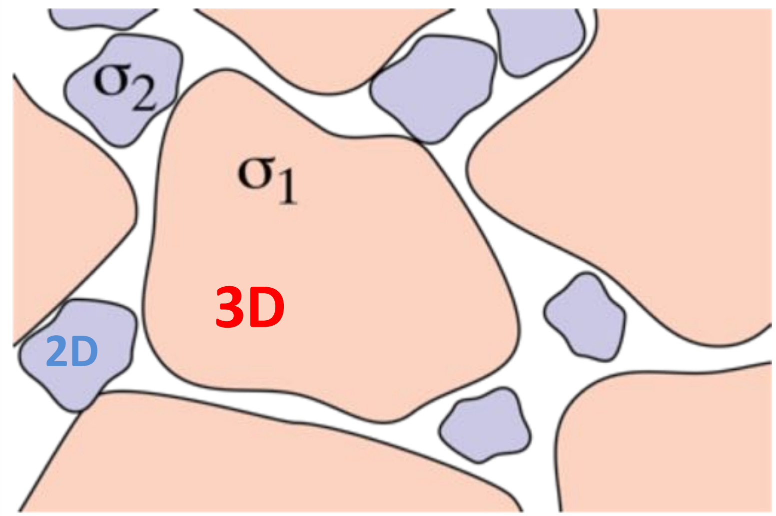
Proposal: Coexisting distinct 3D and 2D CDW domains





Proposal: Coexisting distinct 3D and 2D CDW domains

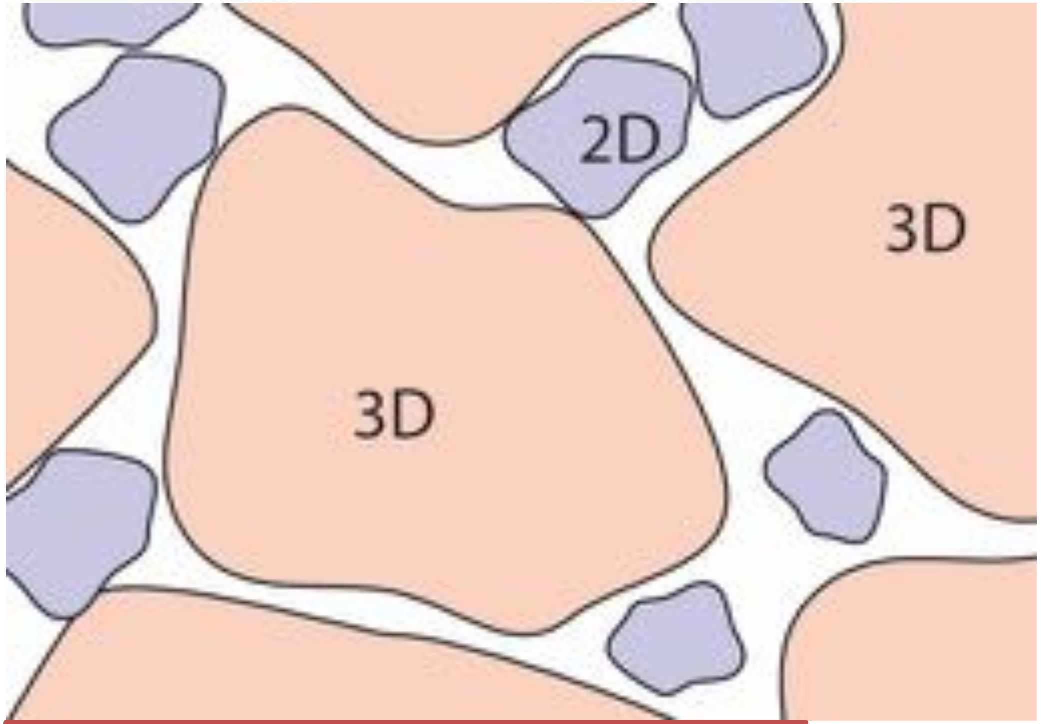




Universal tendency toward unidirectional incommensurate CDW order and a nonuniform distribution of the disorder strengths.

Proposal: Coexisting distinct 3D and 2D CDW domains

***H* > *H*$_{3D}$**



H. Jang *et al*. PNAS **113**, 14645 (2016).

If true, what is the volume fraction between the 2D and 3D region?

Summary

- Evidence of dispersive CDW excitation and coupling to lattice degrees of freedom in Bi2212.
- Coexistence of 3D and 2D CDW may imply an spatially inhomogeneous evolution between CDW and SC under magnetic field.

Acknowledgement

SLAC & Stanford University
M. Hashimoto, Y. He, S. Chen, Z. X. Shen

S. A. Kivelson, T. P. Devereaux, B. Moritz

J. S. Lee, D. Zhu, L. Nie, A. V. Maharaj, C.-C. Kao

Pulsed Magnetic Project

Tohoku University
H. Nojiri, S. Matsuzawa, H. Yasumura

University of British Columbia
D. A. Bonn, R. Liang, W. N. Hardy

Max Planck Institute, Stuttgart
B. Keimer, , J. Porras, M. Mino

Argonne National Laboratory
Z. Islam

RIXS Project

Politecnico di Milano, Italy
Y. Y. Peng, L. Braicovich, G. Ghiringhelli

AIST, Japan
S. Ishida, Y. Yoshida, H. Eisaki

U. Maryland
R. L. Greene, T. Sarkar

ESRF
N. B. Brookes