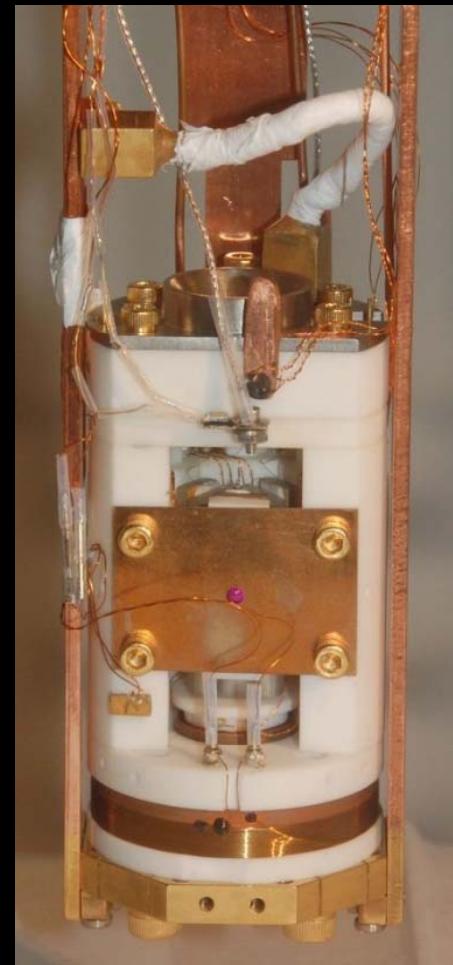
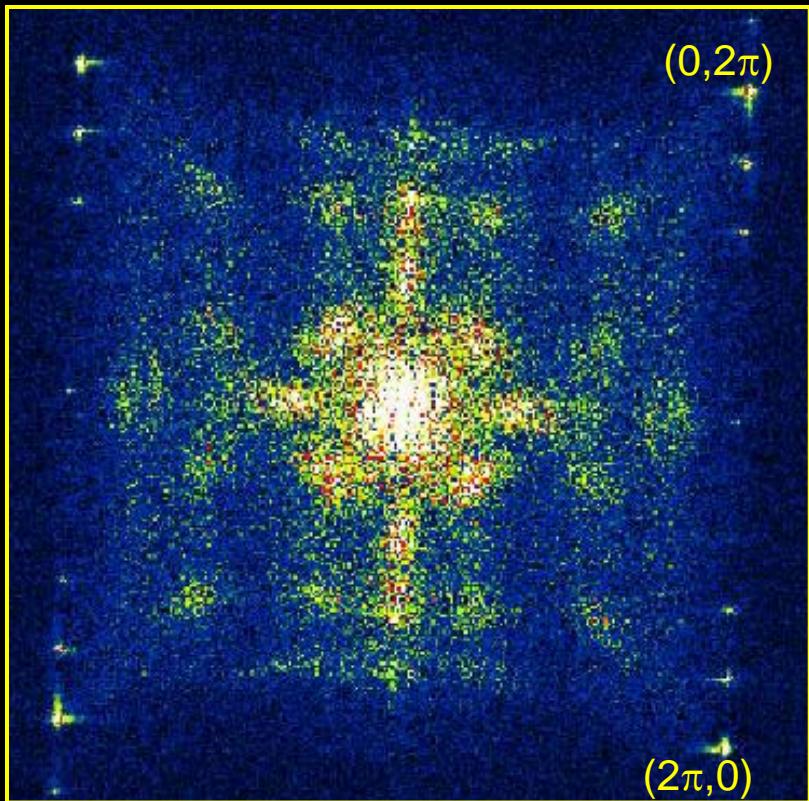


# STM as a Probe of Real and Momentum Spaces in Correlated Electron Systems, Part II



Jenny Hoffman

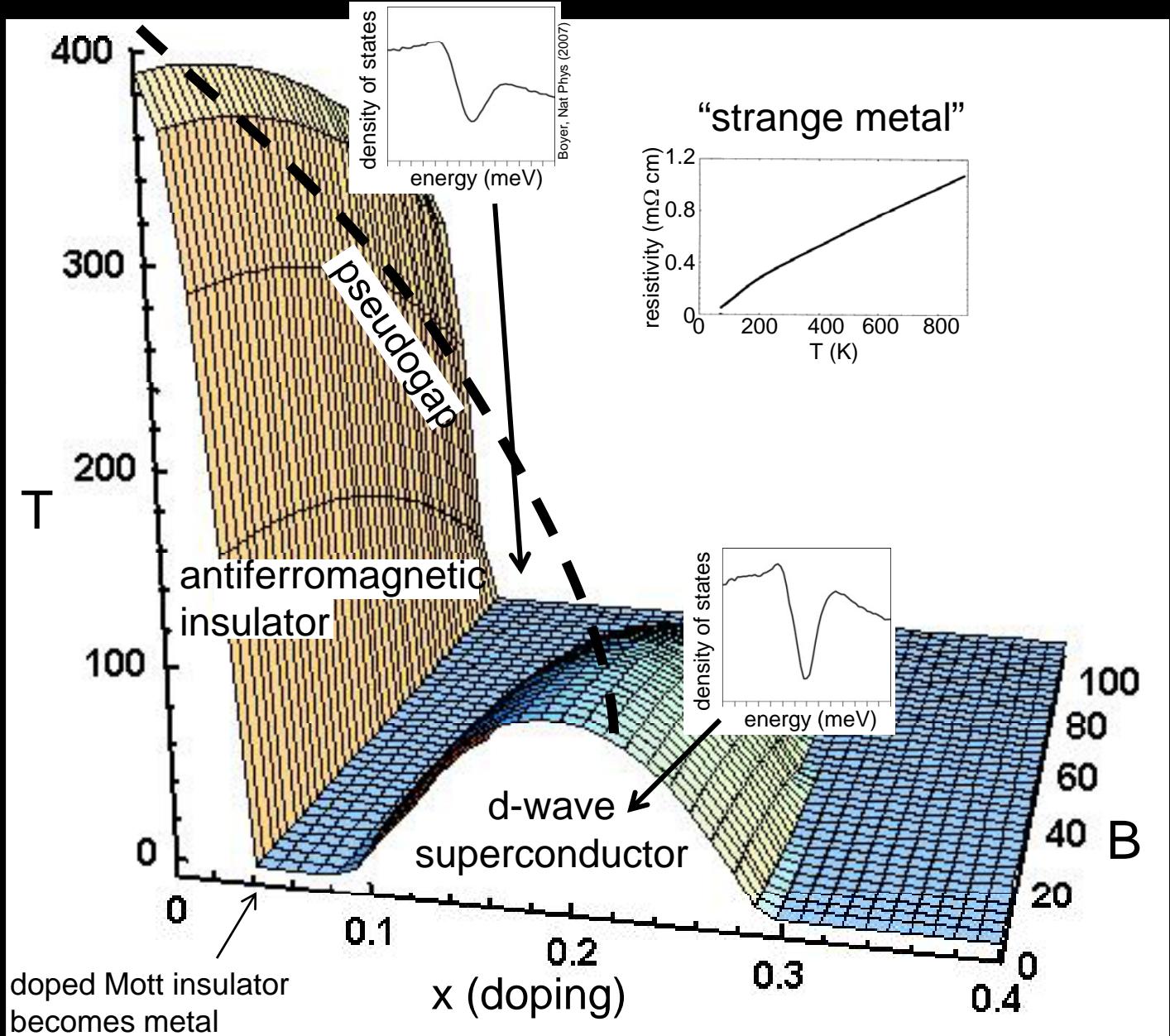


# Outline

- Review of the last 8 years of QPI imaging in cuprate superconductors
  - Controversies in the cuprates:
    - Static vs. dispersing order
    - Pseudogap: competing phase vs. superconducting fluctuations
- Conclusions: we've made progress, but still not sure
  - Need to track QPI and checkerboards through  $T^*$
  - Need to understand spatial phases of patterns
  - Need to fully understand the artifacts of STM setup conditions
- QPI in magnetic field
- STM on pnictide superconductors
  - surfaces, gap-mapping, and vortices
  - demonstrate  $s\pm$  order parameter in  $\text{FeSe}_{1-x}\text{Te}_x$
  - nematic precursor in  $\text{Ca}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$

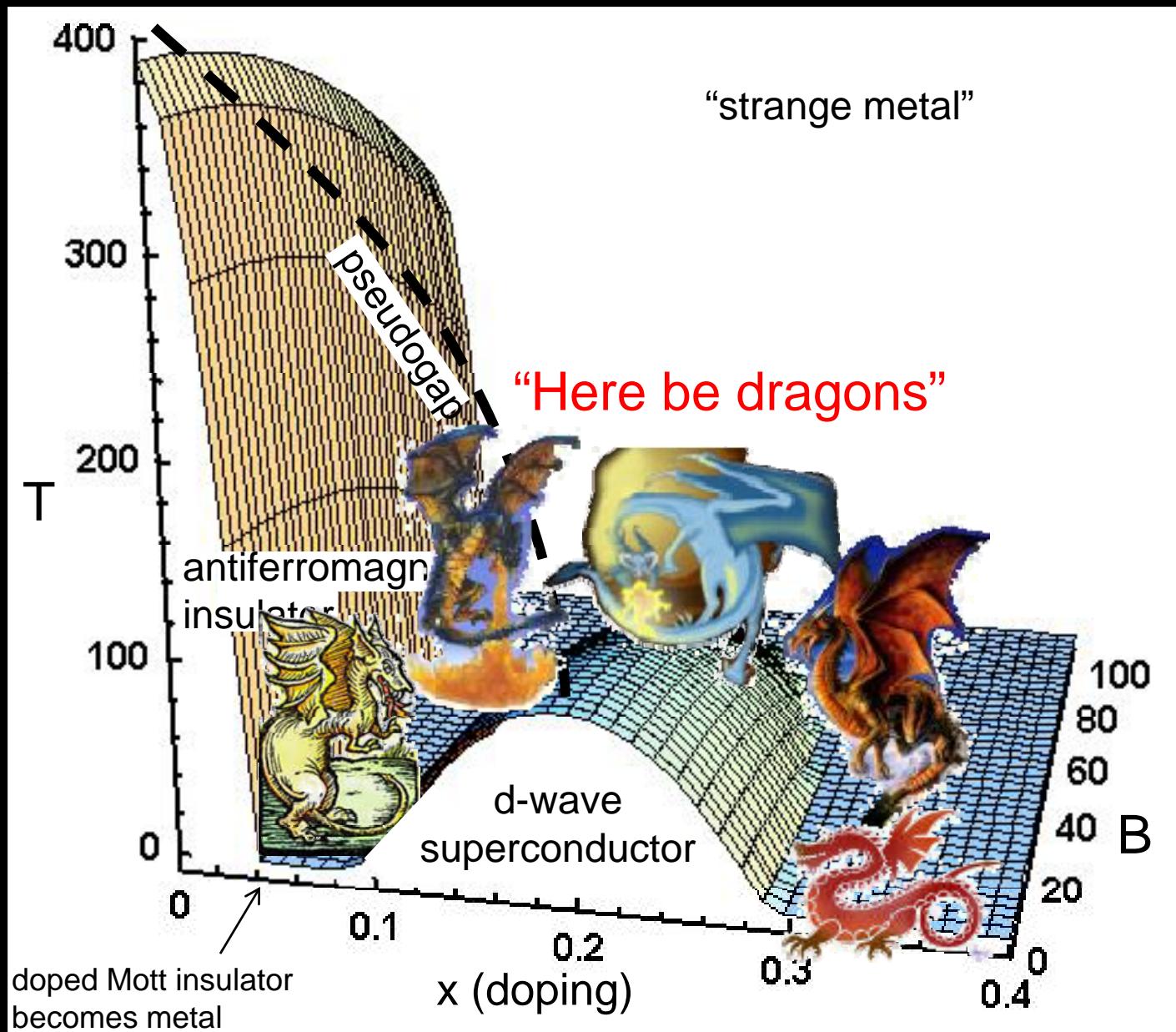


# Cuprate Phase Diagram





# Cuprate Phase Diagram

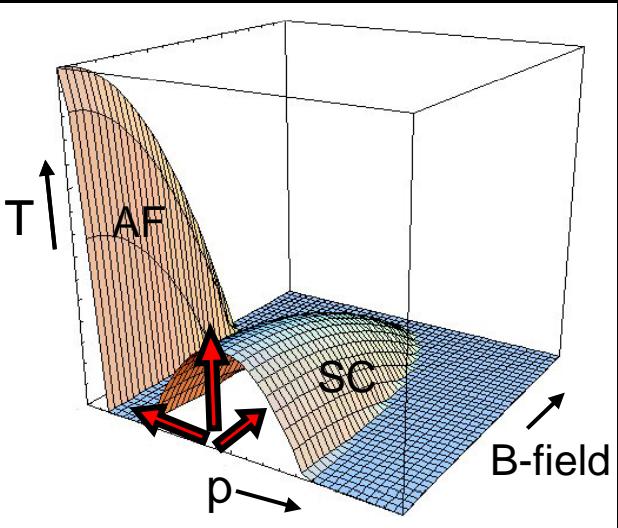


# Controversies in Cuprates



- (1) Static vs. Dispersing order ?
- (2) Pseudogap: competing order vs. preformed pairs ?

# Destroy Superconductivity → Static Order



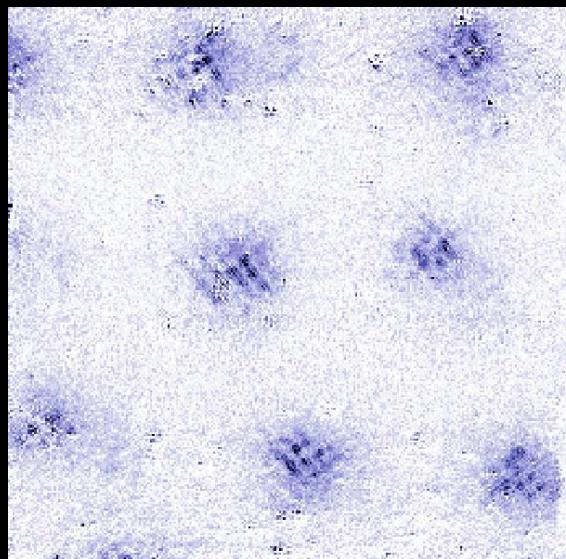
Suppression of Superconductivity in optimal BSCCO:

→ Pseudogap Spectra

→ “checkerboard” LDOS Modulations

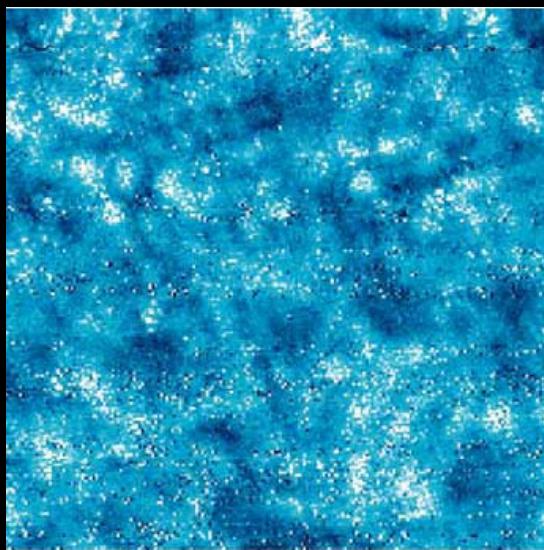
→ Incommensurate:  $4.3a_0$ ,  $4.5a_0$ ,  $4.6a_0$

$B = 5T$



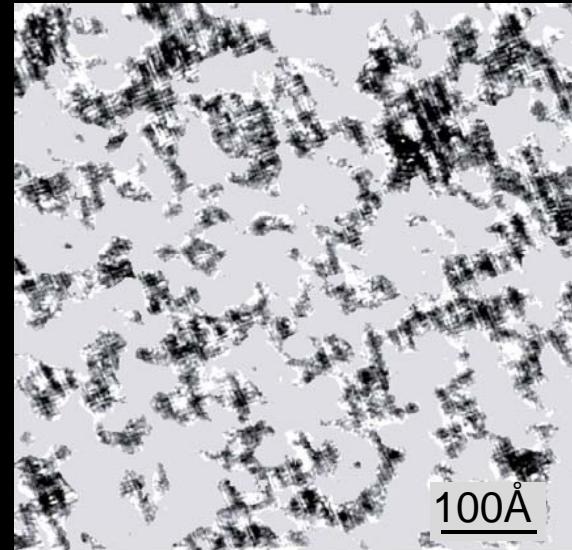
( $E = 7 \text{ meV}$ )

$T = 100\text{K}$



( $E < \Delta$ )

$\Delta > 65 \text{ meV}$  ( $E > 65 \text{ meV}$ )

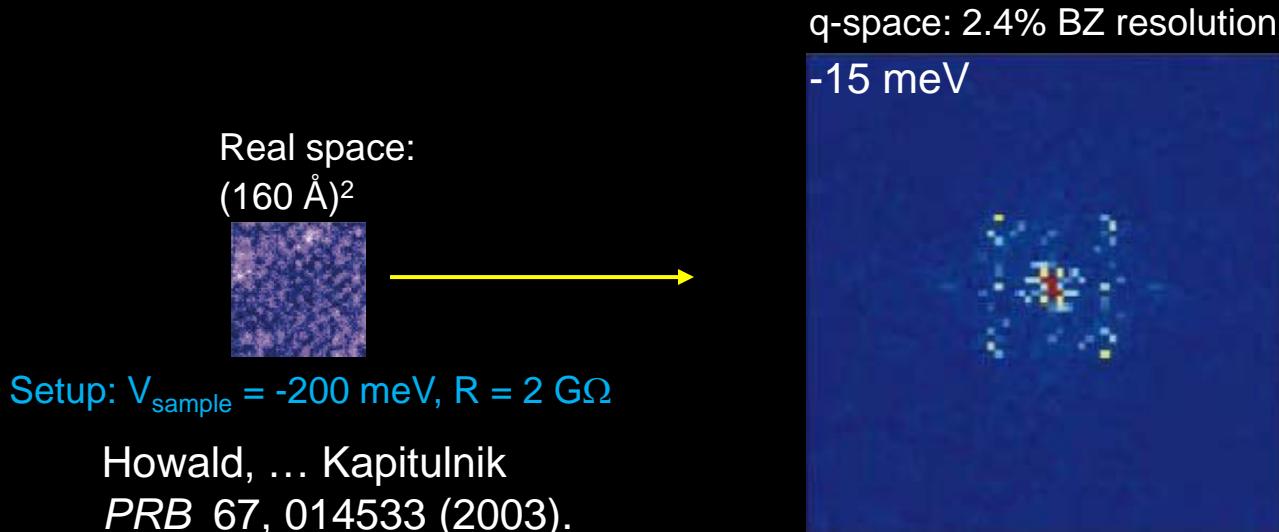


J. Hoffman, ... J.C. Davis  
*Science* 295, 466 (2002)

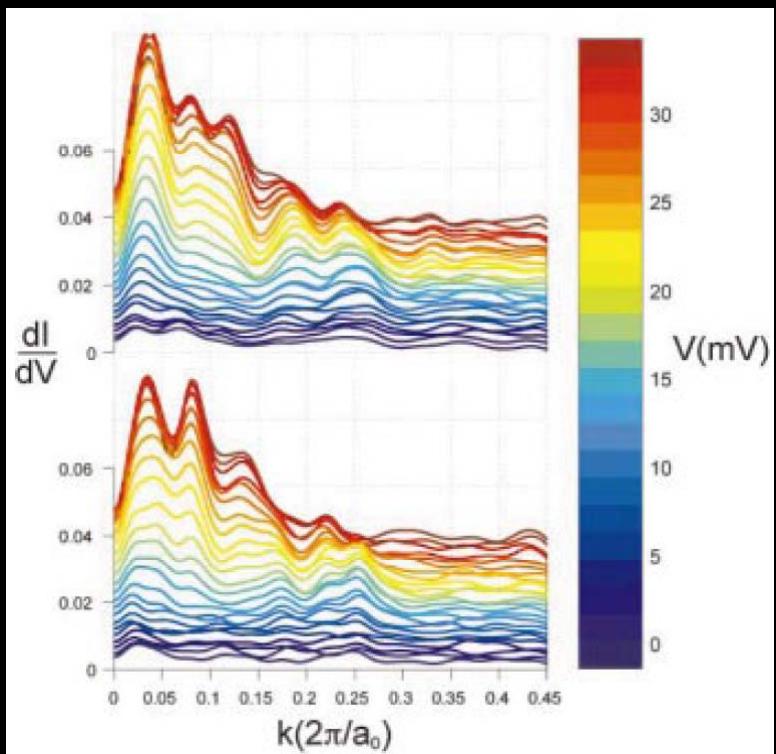
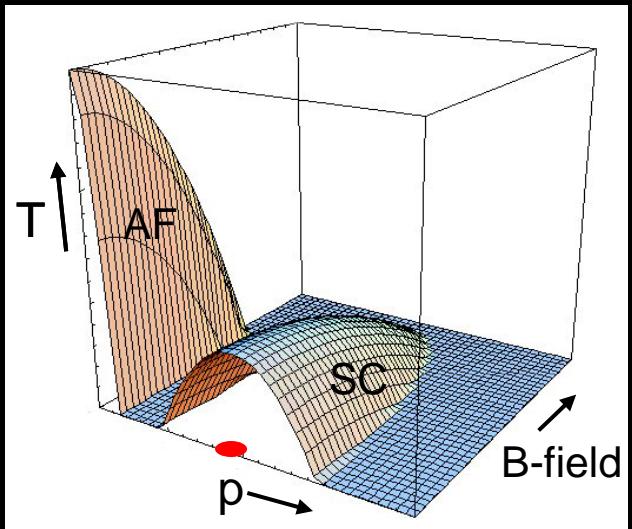
M. Vershinin, ... A. Yazdani  
*Science* 303, 1995 (2004)

K. McElroy, ... J.C. Davis  
*PRL* 94, 197005 (2005)

# Superconducting State: Dispersing vs. Static?



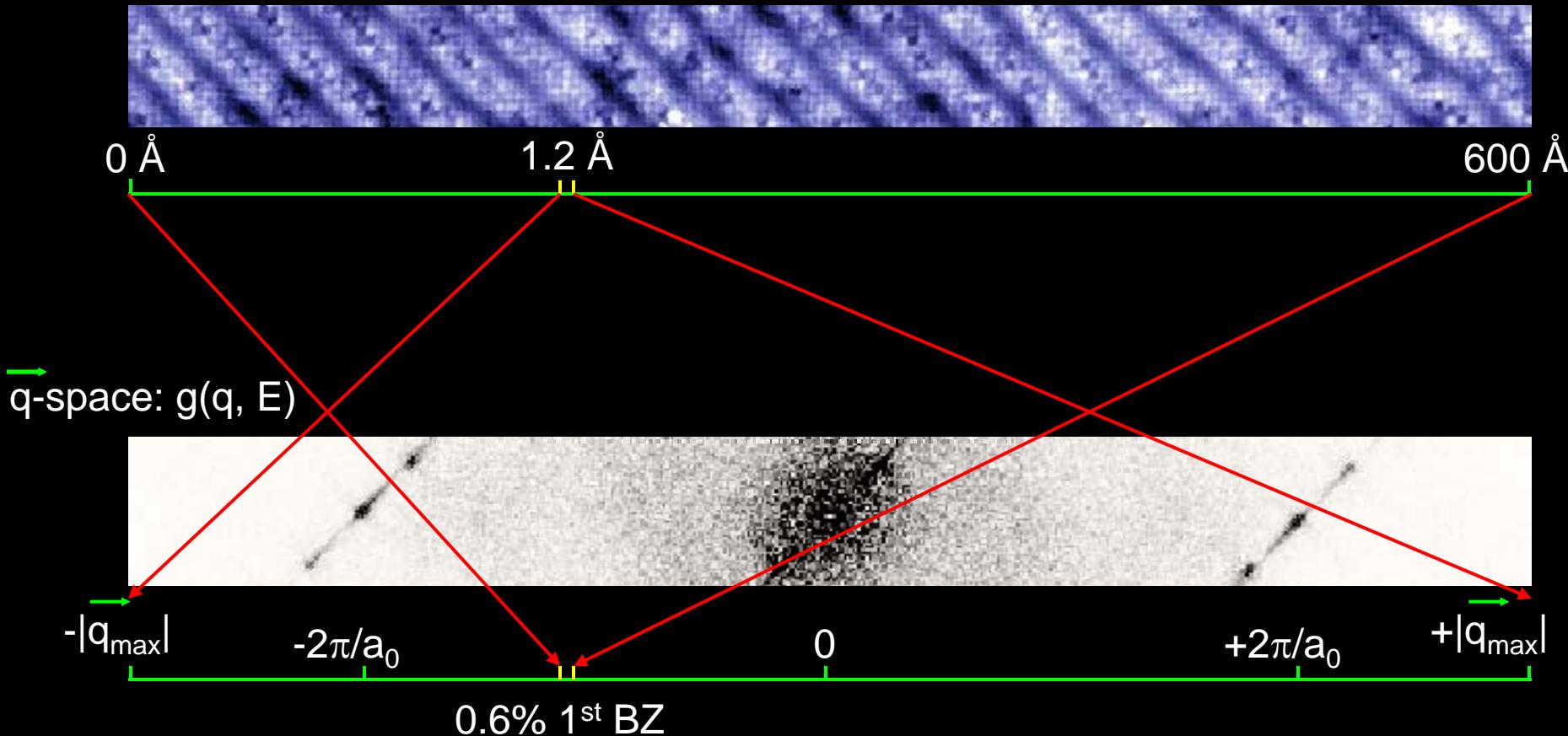
Claim: static order in low-energy (sub-gap) DOS in the superconducting state.



# Superconducting State: Dispersing vs. Static?

How to get high q-space resolution?

Real space:  $g(r, E)$



- real-space resolution  $dx \rightarrow$  q-space extent  $\rightarrow$  need  $dx < 1.3 \text{ \AA}$
- real-space extent  $L \rightarrow$  q-space resolution  $\rightarrow$  need  $L > 450 \text{ \AA}$

# Dispersing vs. Static = Low vs. High Energy

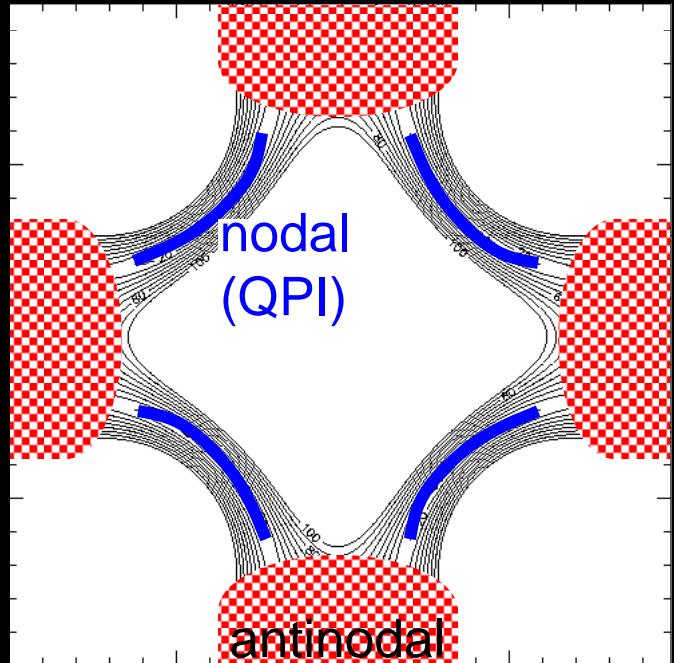
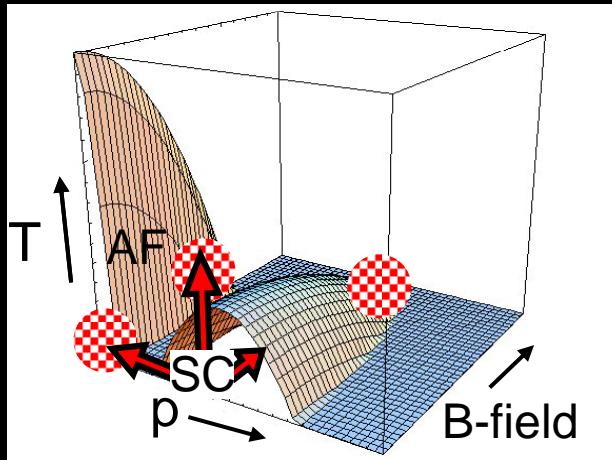


(1) Static vs. Dispersing order ?

→ now we mostly agree that both exist

(but we argue whether they are “CDW” or “ECG”)

Old view:



(1) Where are the checkers in phase space?

- Outside the SC dome: checkers in 3 directions

(2) Where are the checkers in momentum space?

- Associated with the pseudogap, at high energies near BZ edge

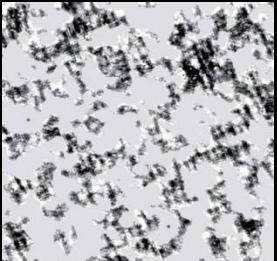
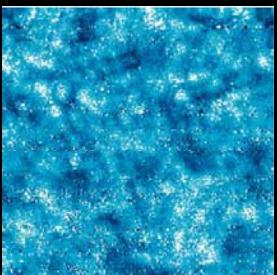
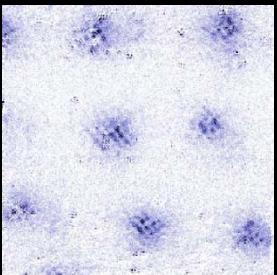
# Another Cuprate for STM: $\text{Na}_x\text{Ca}_{2-x}\text{CuO}_2\text{Cl}_2$



Motivation: previous reports of static checkerboards occurred in small areas (vortices, underdoped areas) & in very disordered BSCCO. Need cleaner, lower  $T_c$  sample.

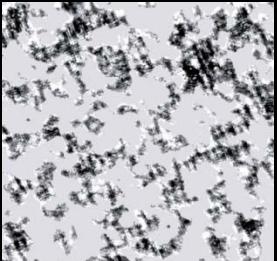
vortices:

- small area



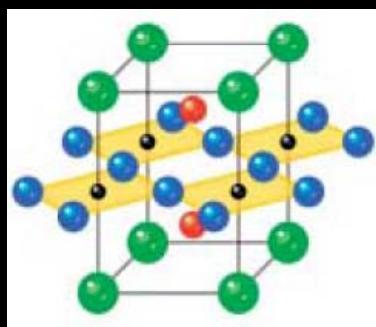
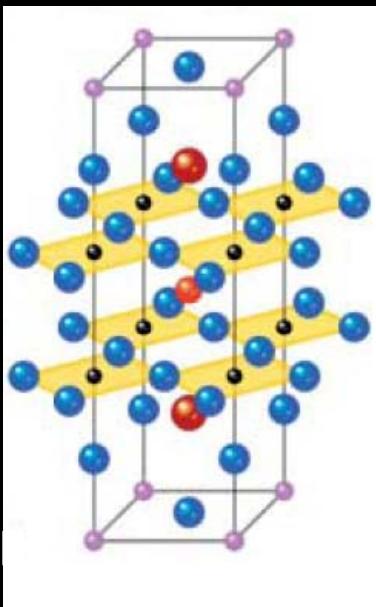
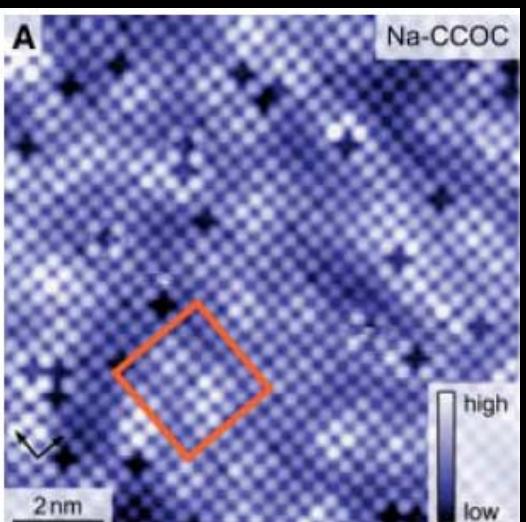
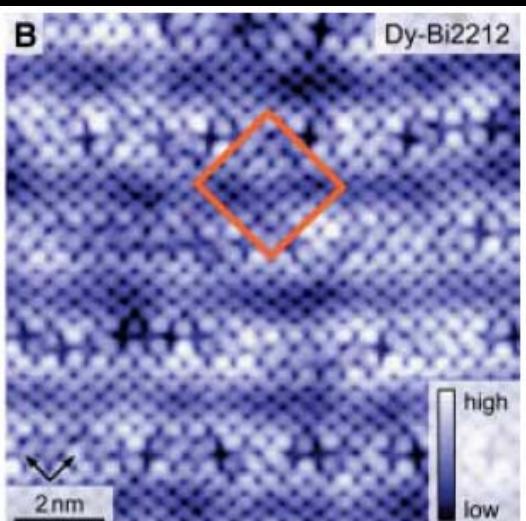
$> T_c$ :

- low E resolution
- large spatial disorder

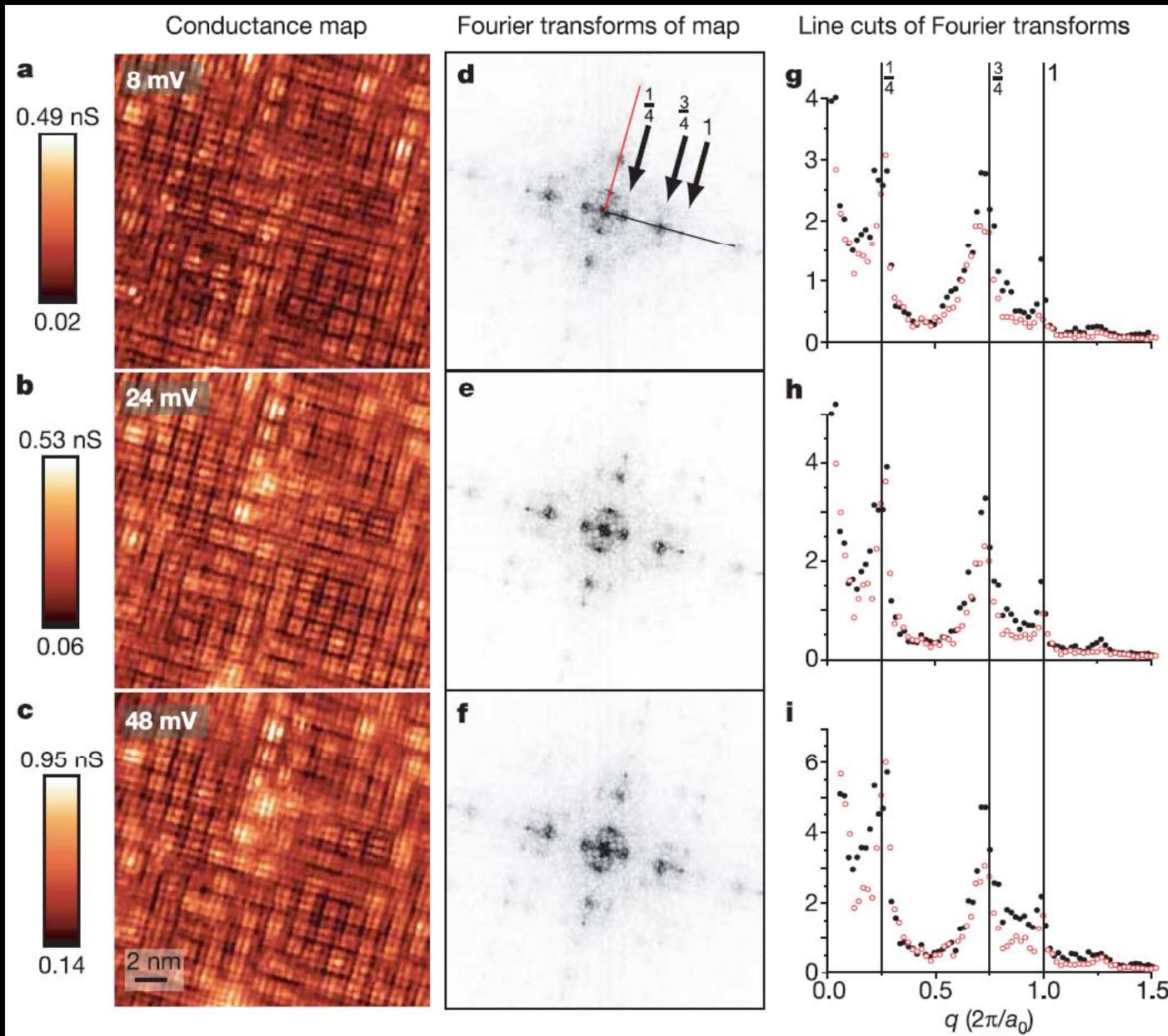


low  $p$ :

- small area
- spatial disorder



# $\text{Na}_x\text{Ca}_{2-x}\text{CuO}_2\text{Cl}_2$ checkerboard does not disperse



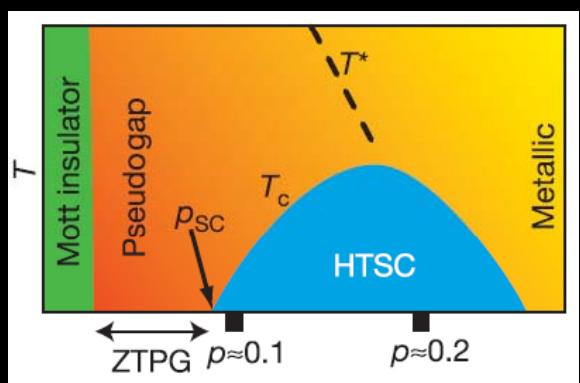
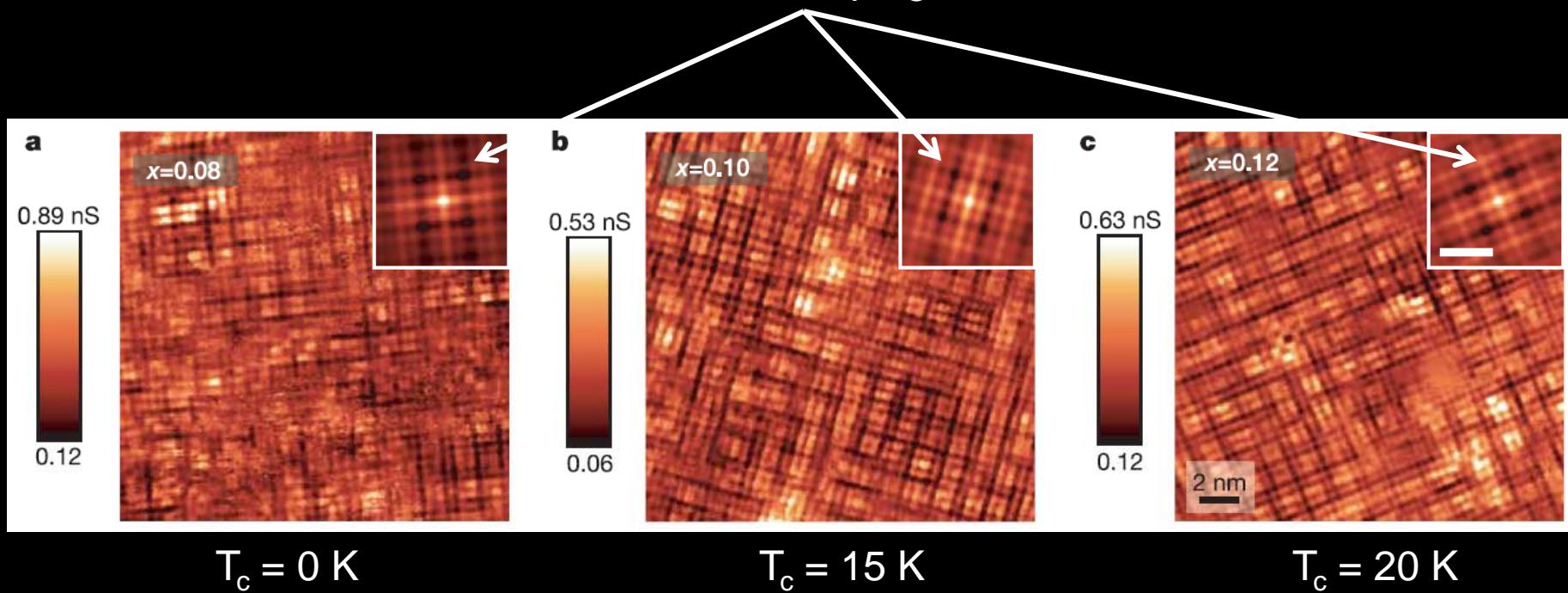
$x = 0.12$   
 $T_c = 20 \text{ K}$

Experiment:  
 $T=100\text{mK}$

# $\text{Na}_x\text{Ca}_{2-x}\text{CuO}_2\text{Cl}_2$ checkerboard does not depend on doping



autocorrelation shows 4-unit-cell plaquette,  
with 3 internal maxima,  
for all 3 dopings



Setup:  $V_{\text{sample}} = +200 \text{ meV}$ ,  $R = 2 \text{ G}\Omega$

# Look for QPI in Na-CCOC



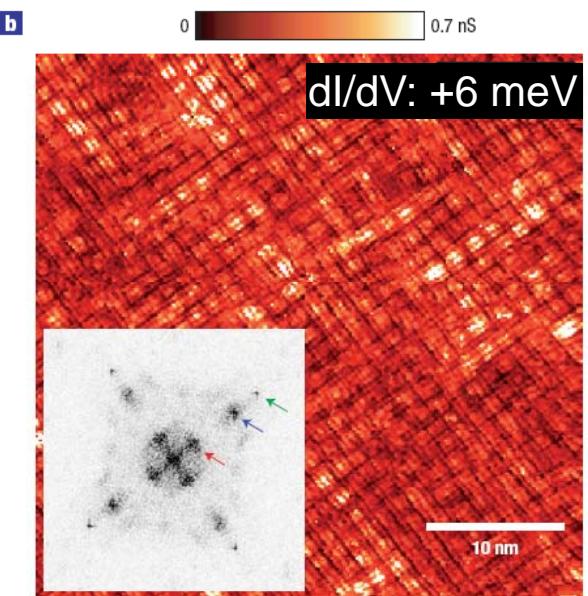
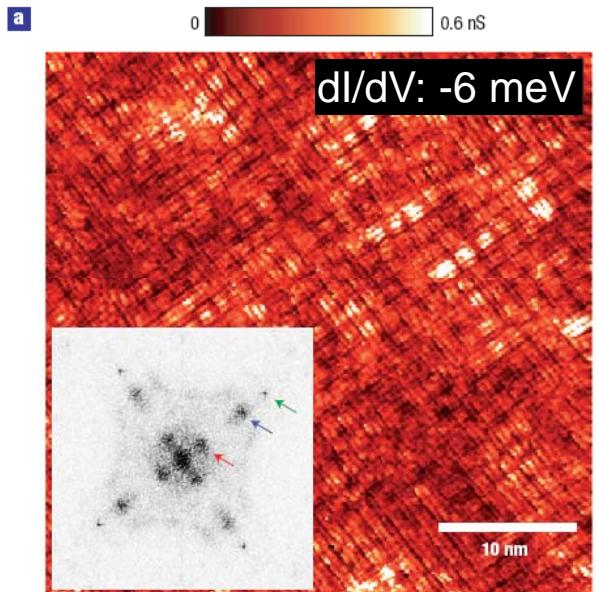
## Motivation:

Superconducting gap in cuprates is often confused w/ pseudogap but we can get unambiguous info on SC gap from QPI.

## Experiment:

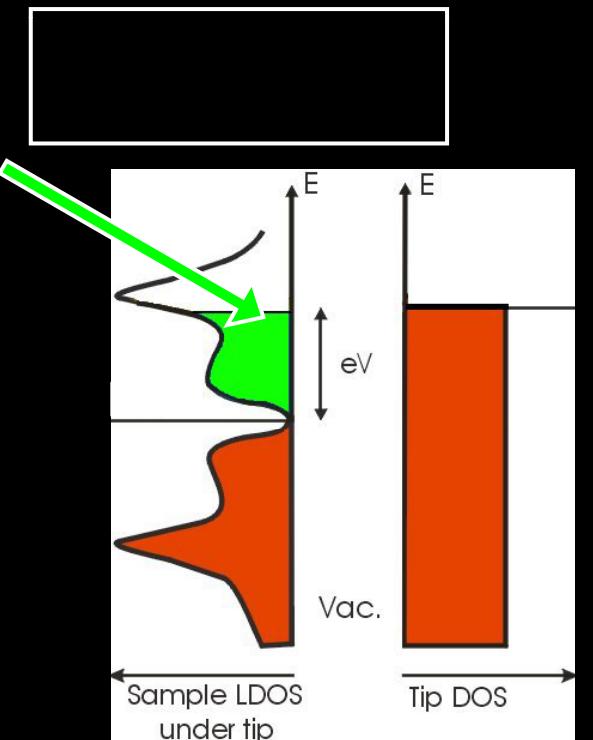
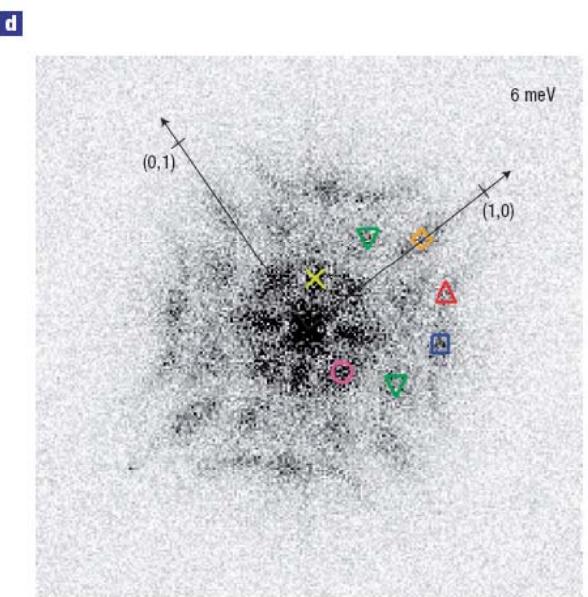
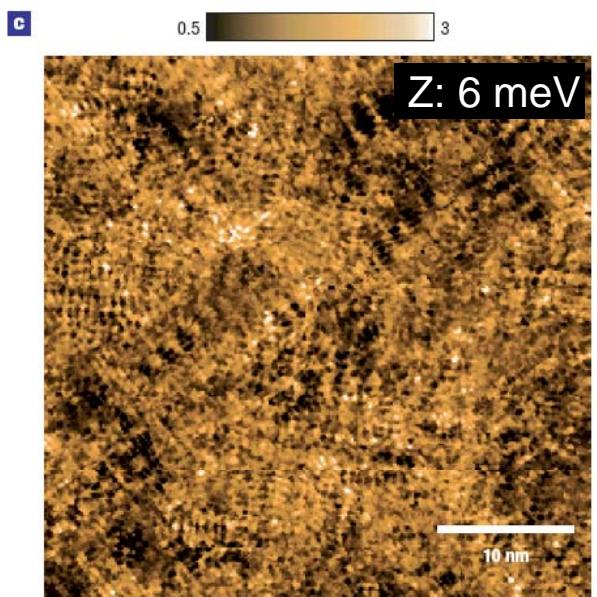
- study QPI in Na-CCOC and compare/contrast w/ BSCCO
- nearly optimally doped  $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$  (Na-CCOC) with  $T_c=25\text{--}28 \text{ K}$

# $\text{Na}_x\text{Ca}_{2-x}\text{CuO}_2\text{Cl}_2$ has QPI too! But hard to find!



Divide +6 and -6 meV maps  
→ “Z map”  
Cancels in-phase checkers  
Enhances out-of-phase QPI

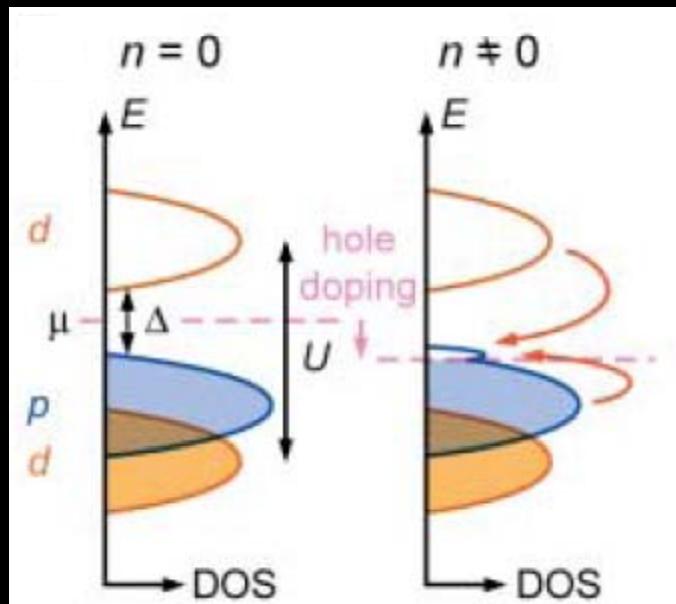
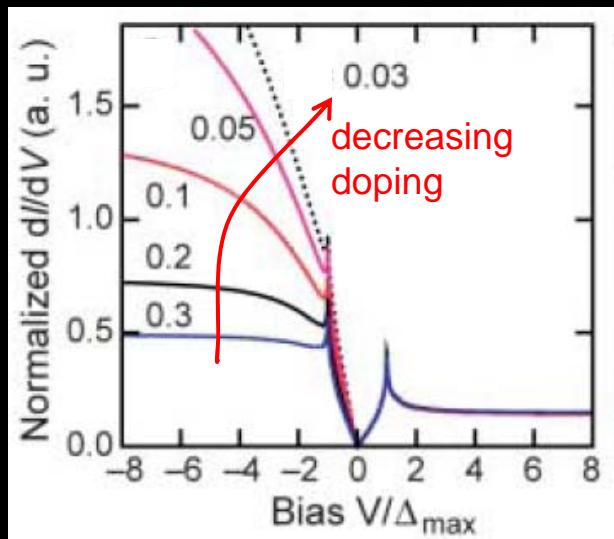
Bonus: cancels position-dependent matrix element!



# Z-maps

Theory:

$$Z(V) \equiv \frac{\overline{N}(E = +eV)}{\overline{N}(E = -eV)} \approx \frac{2n}{1+n}$$



P. W. Anderson, N. P. Ong, *J. Phys. Chem. Solids* **67**, 1 (2006).

Experiment:

$$Z(\vec{r}, V) \equiv \frac{\frac{dI}{dV}(\vec{r}, z, +V)}{\frac{dI}{dV}(\vec{r}, z, -V)}$$



# R-maps

Theory:

$$R(\vec{r}) \equiv \frac{\int_0^{\Omega_c} N(\vec{r}, E) dE}{\int_{-\infty}^0 N(\vec{r}, E) dE} = \frac{2n(\vec{r})}{1 - n(\vec{r})} + O\left(\frac{nt}{U}\right)$$

(  $\Omega_c \sim 1 \text{ eV}$  ) 10%

Randeria, *PRL* **95**, 137001 (2005).

Experiment:

$$R(\vec{r}, V) \equiv \frac{I(\vec{r}, z, +V)}{I(\vec{r}, z, -V)}$$

(  $V = 150 \text{ mV}$  )

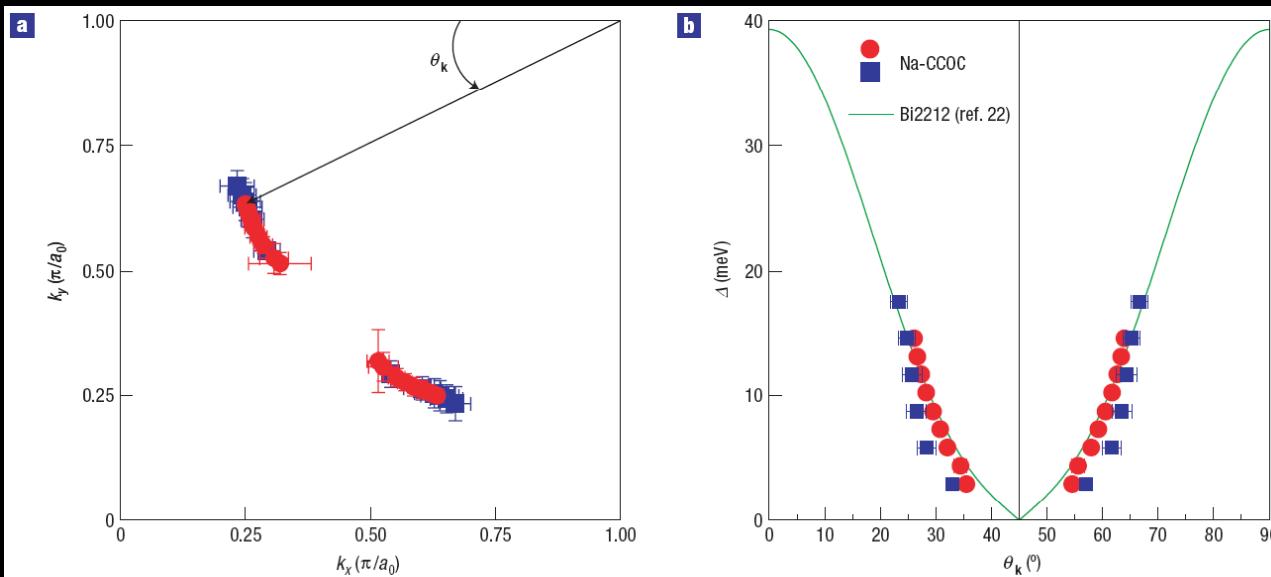


# Z vs. R maps

	Z	R
Theory:	$\frac{\bar{N}(E = +eV)}{\bar{N}(E = -eV)} \approx \frac{2n}{1+n}$ <p style="text-align: center;">Anderson, <i>JPCM</i> (2006)</p>	$\frac{\int_0^{\Omega_c} N(\vec{r}, E) dE}{\int_{-\infty}^0 N(\vec{r}, E) dE} = \frac{2n(\vec{r})}{1 - n(\vec{r})}$ <p style="text-align: center;">Randeria, <i>PRL</i> (2005)</p>
Experiment:	$Z(\vec{r}, V) \equiv \frac{\frac{dI}{dV}(\vec{r}, z, +V)}{\frac{dI}{dV}(\vec{r}, z, -V)}$	$\frac{I(\vec{r}, z, +V)}{I(\vec{r}, z, -V)}$
Advantages:	<u>Divides out the setup condition artifact!</u> Maintain energy resolution	
Disadvantages:	<u>Assumes particle-hole symmetry of the signal of interest!</u> Lose energy resolution. What cutoff to use? Theory: $\Omega_c \sim 1$ eV; Expt: $V = 150$ mV	
In practice:	QPI	static checkerboards

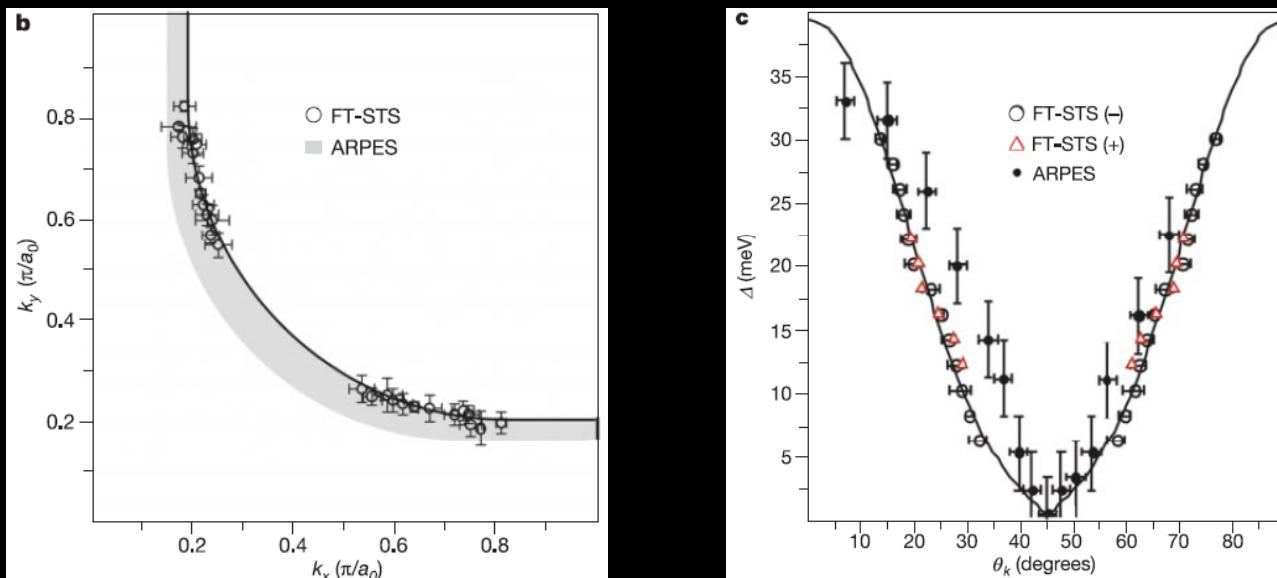
# QPI comparison: Na-CCOC vs. BSCCO

Na-CCOC  
( $x=0.14$ ,  
 $T_c = 28\text{K}$ )



Hanaguri, ... Davis, *Nature Physics* 3, 865 (2007)

BSCCO  
(optimal,  
 $T_c = 86\text{ K}$ )



McElroy, ... Davis, *Nature* 422, 592 (2003)

# Summary: QPI in Na-CCOC



## Motivation:

Superconducting gap in cuprates is often confused w/ pseudogap but we can get unambiguous info on SC gap from QPI.

## Experiment:

- study QPI in Na-CCOC and compare/contrast w/ BSCCO
- nearly optimally doped  $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$ (Na-CCOC) with  $T_c=25\text{--}28\text{ K}$

## Observation:

- QPI near gap node is same as BSCCO despite BSCCO having 3x higher  $T_c$
- QPI in Na-CCOC is confined to much narrower range in energy & momentum than in BSCCO

## Conclusion:

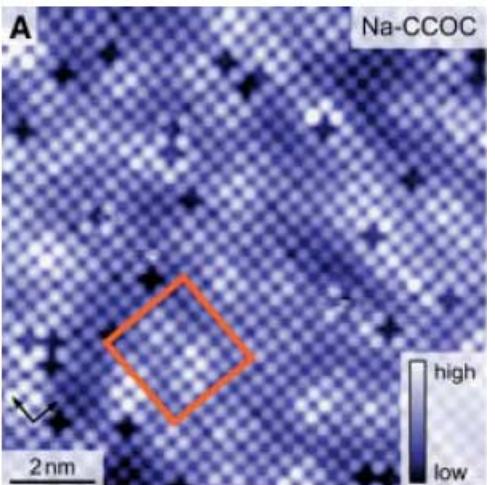
Therefore, we hypothesize that the energy scale which determines the  $T_c$  of optimally doped cuprates is not set by the superconducting gap dispersion alone but by the energy and momentum-space location where this gap terminates on the Fermi arc.

# Checkerboard comparison: Na-CCOC vs. BSCCO

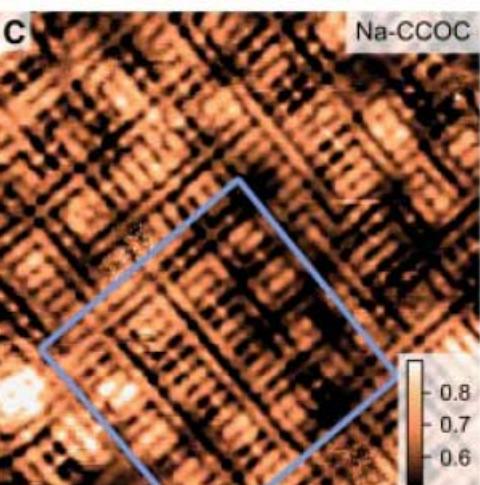


Na-CCOC  
 $x = 0.12$   
 $T_c = 21$  K

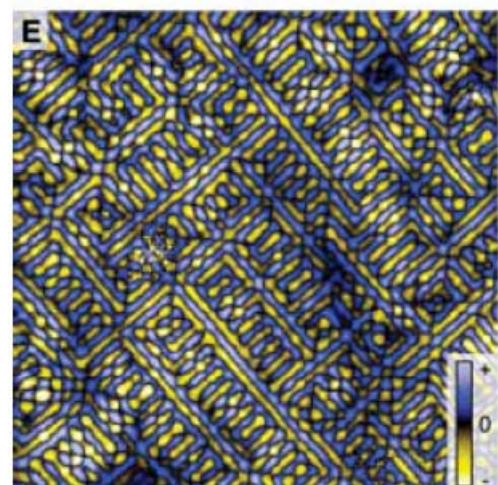
Topography



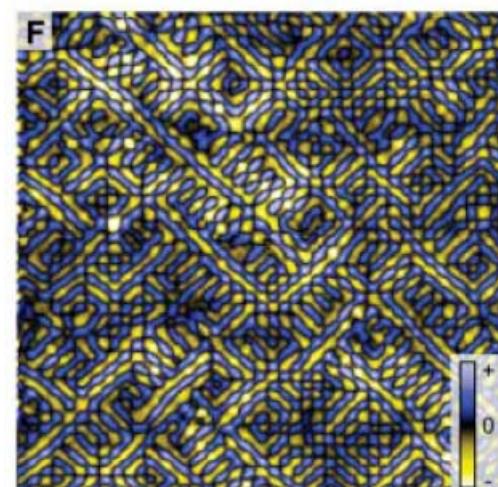
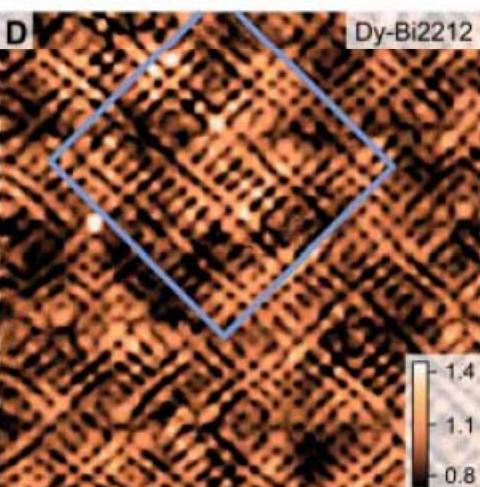
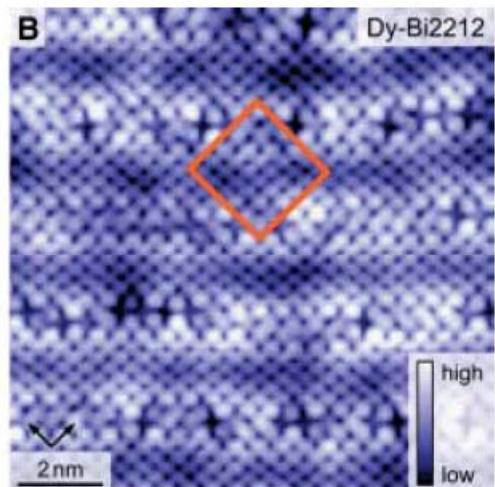
R-map (150 meV)



Laplacian:  $\nabla^2(R)$



Dy-BSCCO  
 $p \sim 0.08$   
 $T_c = 45$  K

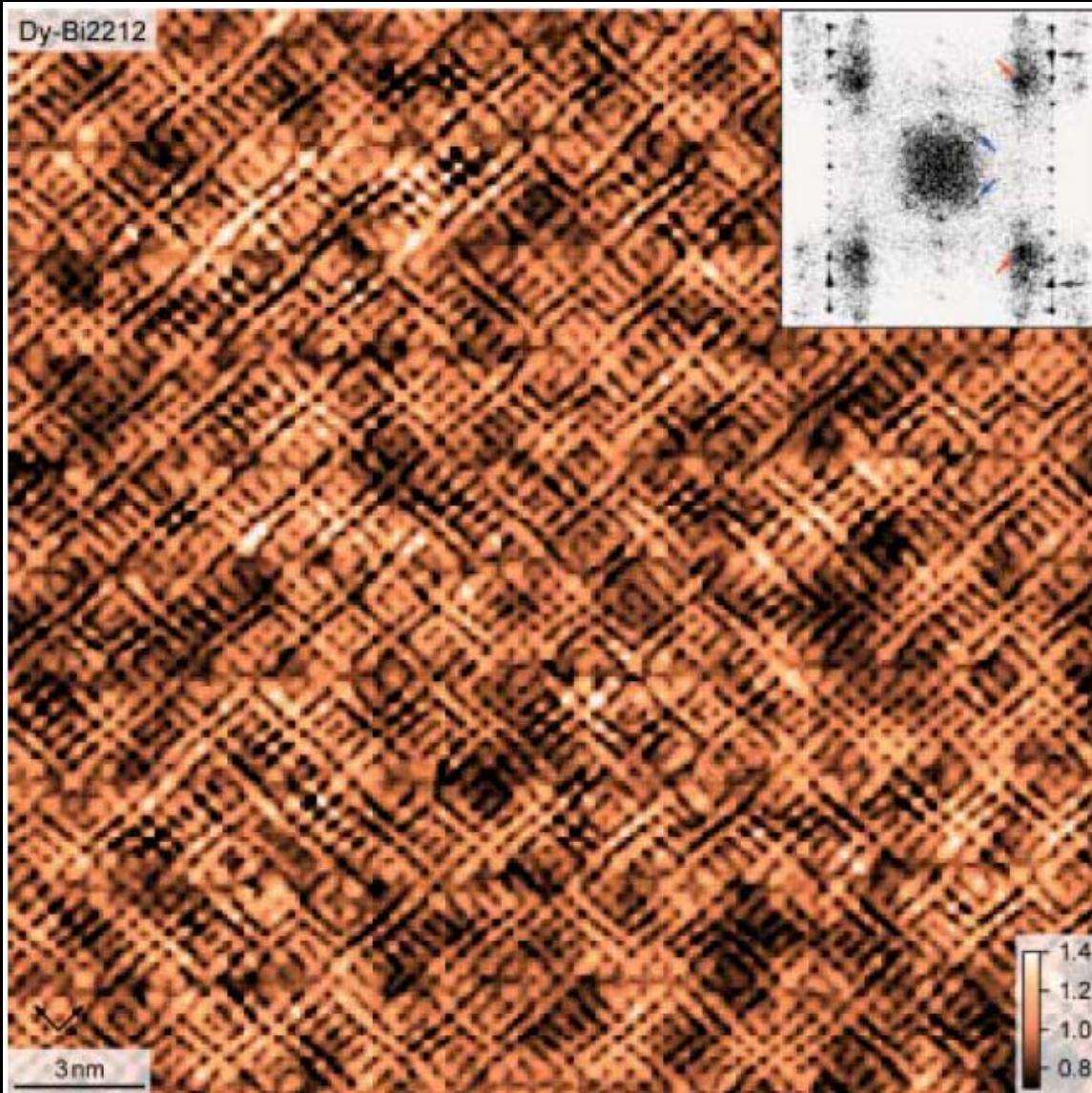


# Claim: static $\frac{3}{4}$ point dominates the FT of the R-map

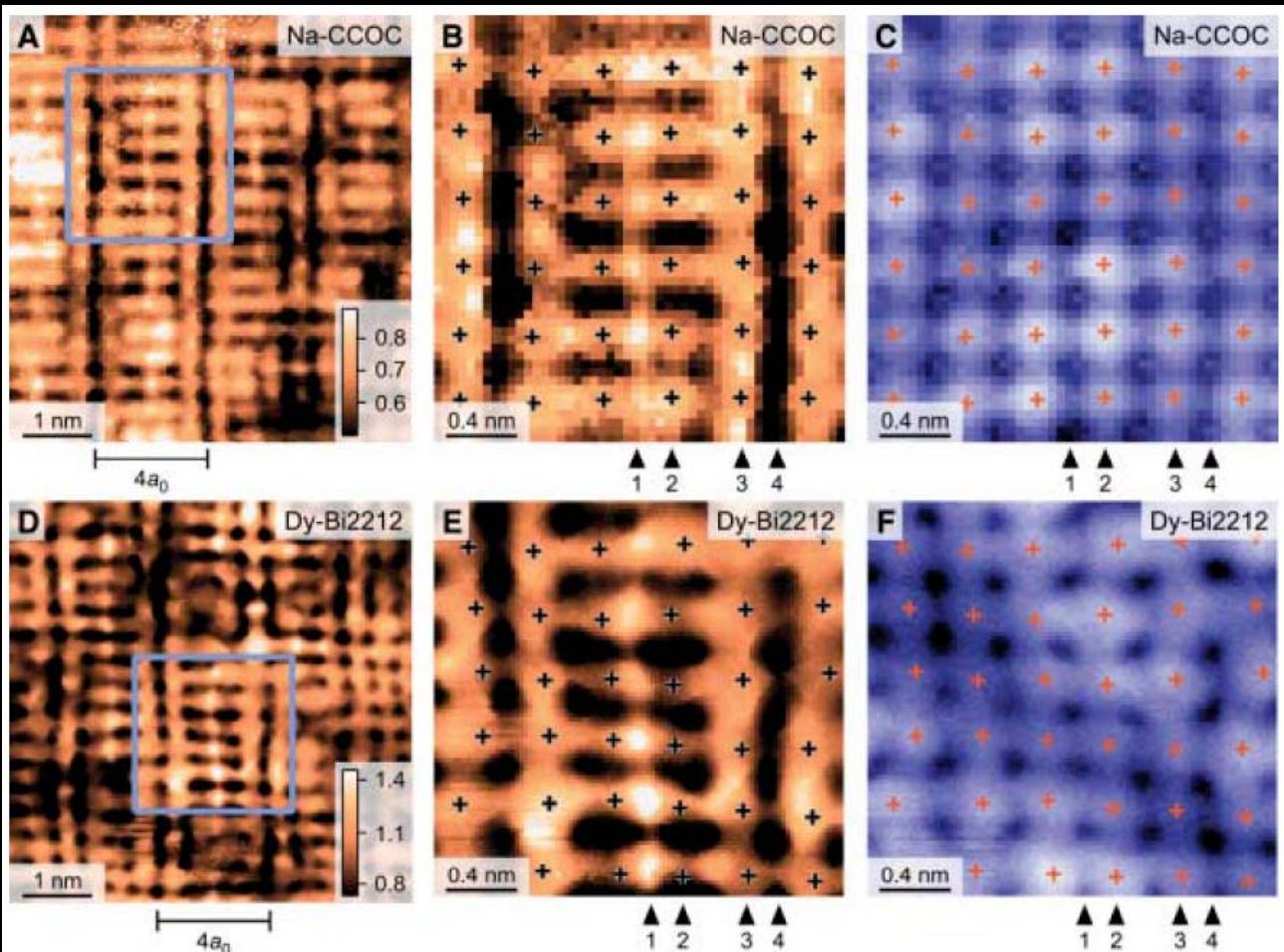
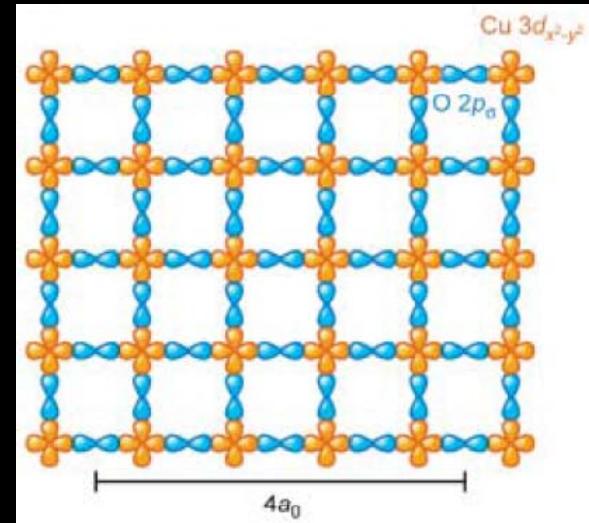


Dy-BSCCO  
 $T_c = 45$  K

R-map  
 $V = 150$  mV



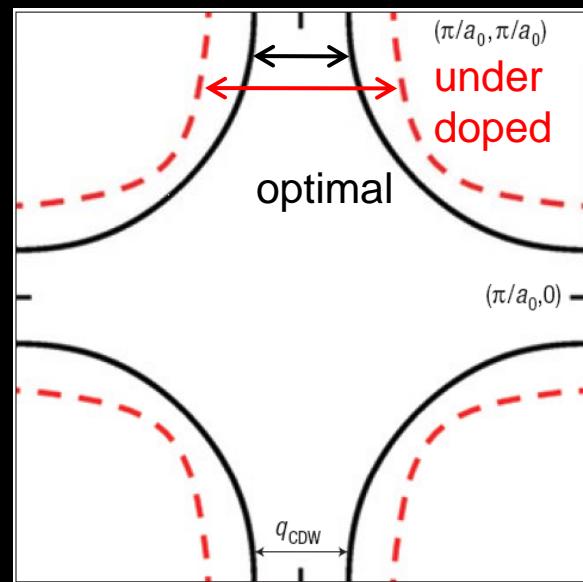
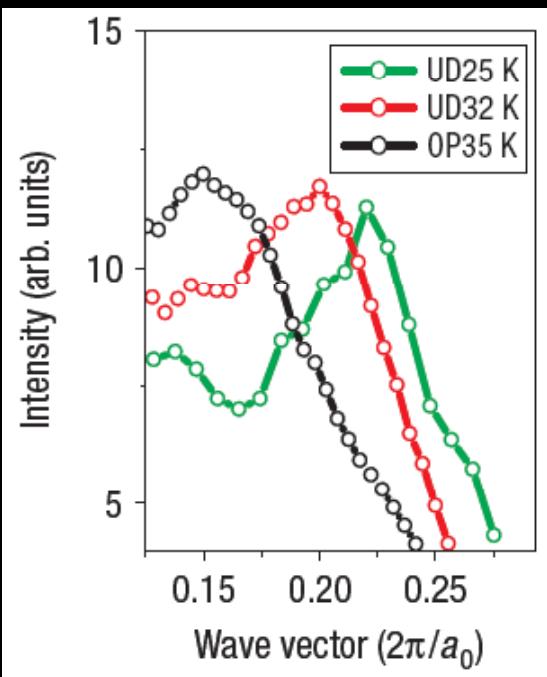
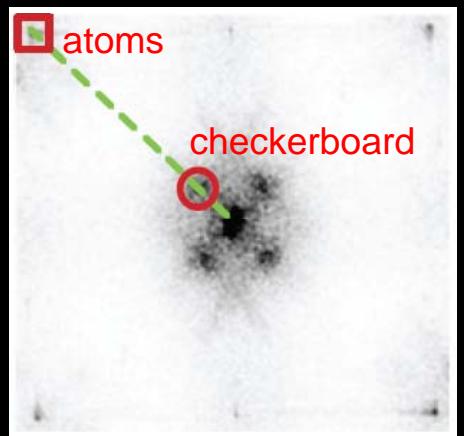
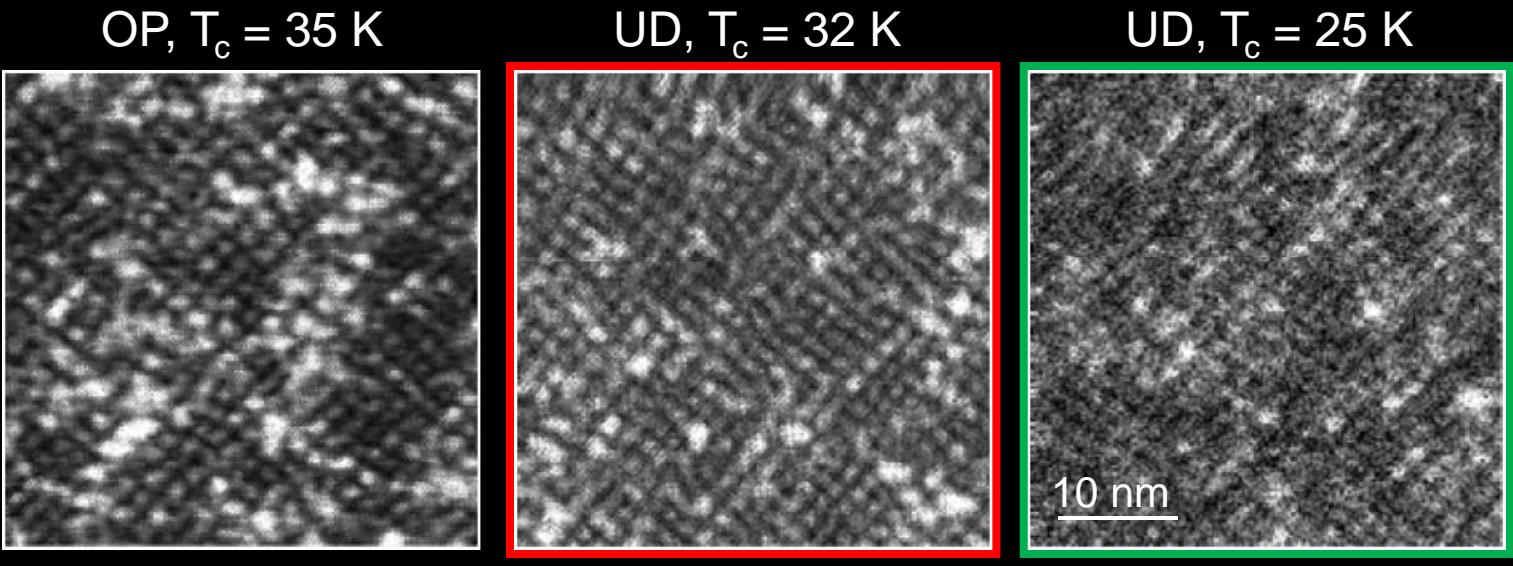
# A look inside the $4a_0$ plaquette (R-maps)



Conclusions:

- the ordering is bond-centered
- it's a  $C_4 \rightarrow C_2$  symmetry-breaking
- electrons choose which O 2p bond to live on
- ECG = “electronic cluster glass”

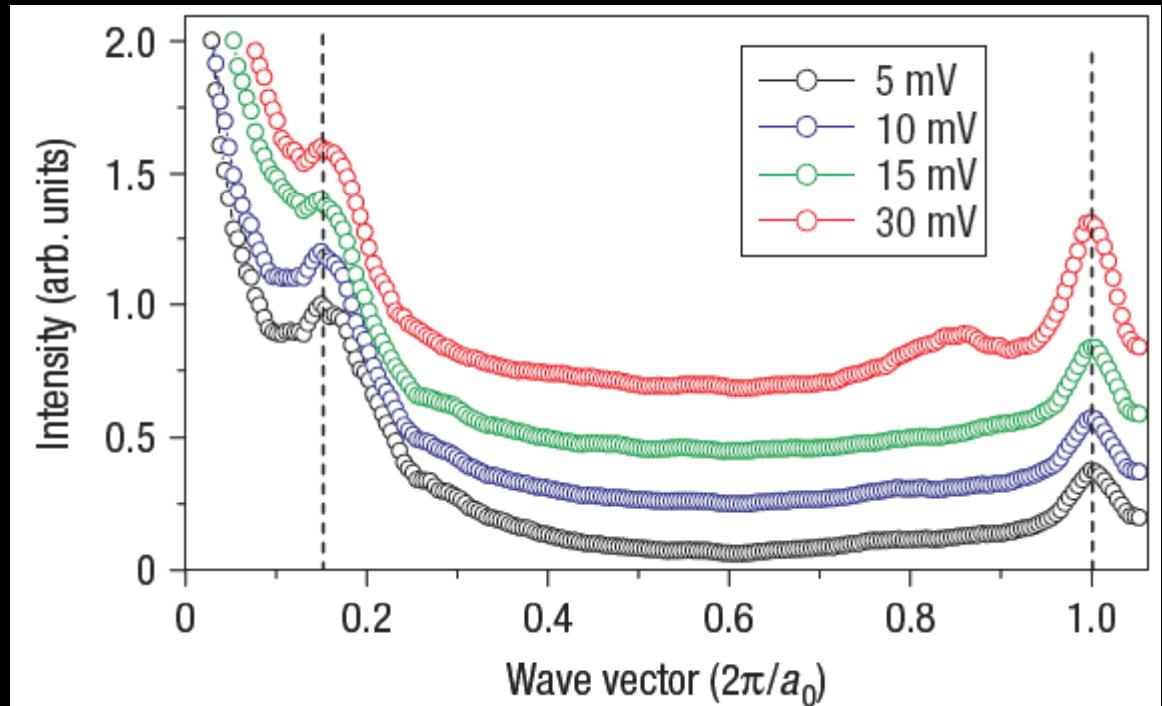
# Bi-2201: Relating checkerboards to pseudogap



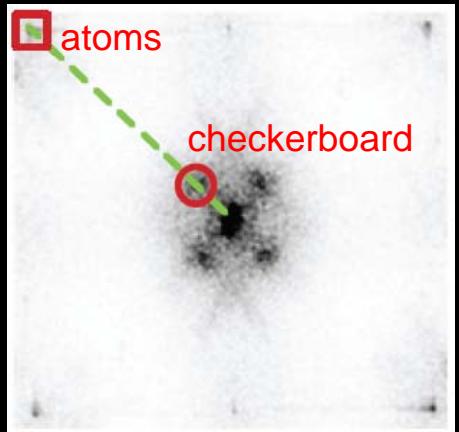
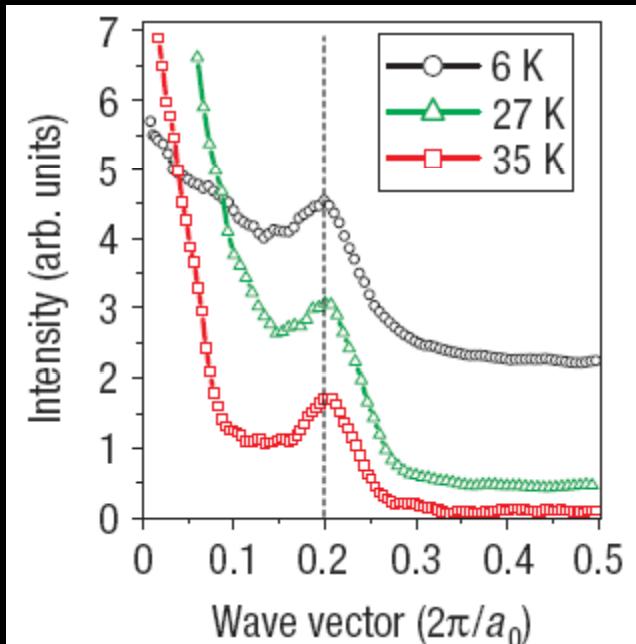
# Conclusion: Pseudogap = Charge Density Wave



Static: doesn't disperse with energy



Persists above  $T_c = 32$  K

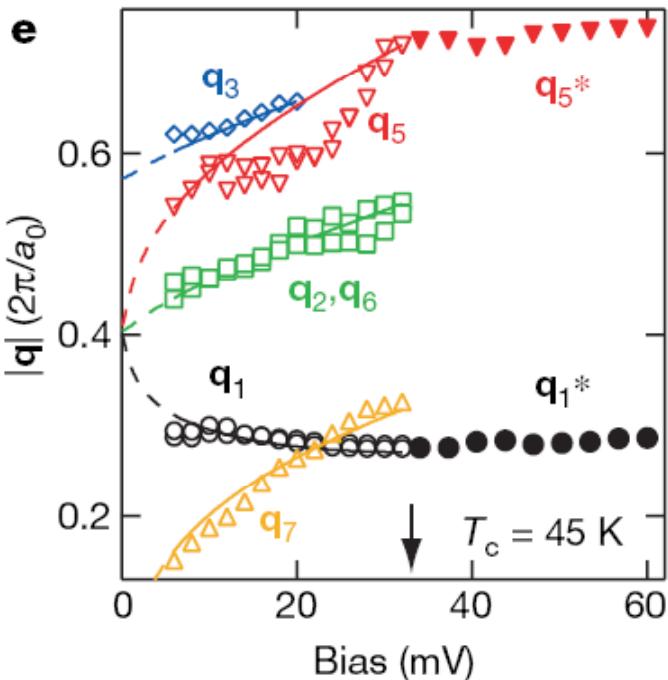
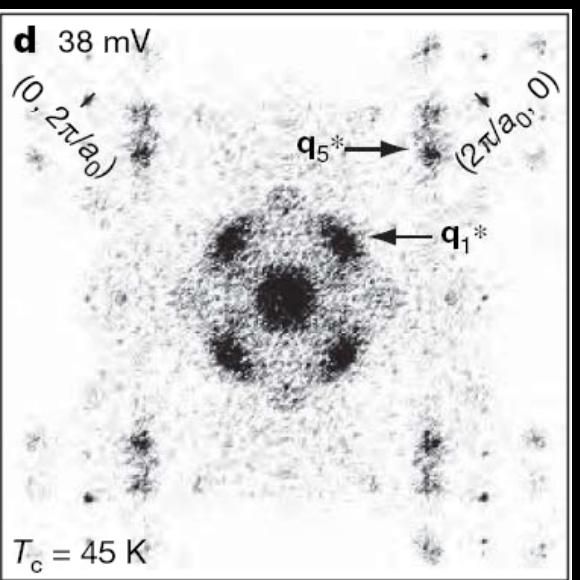
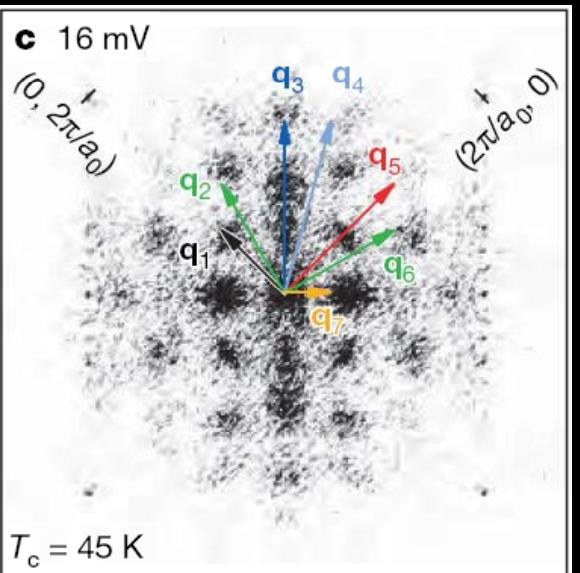
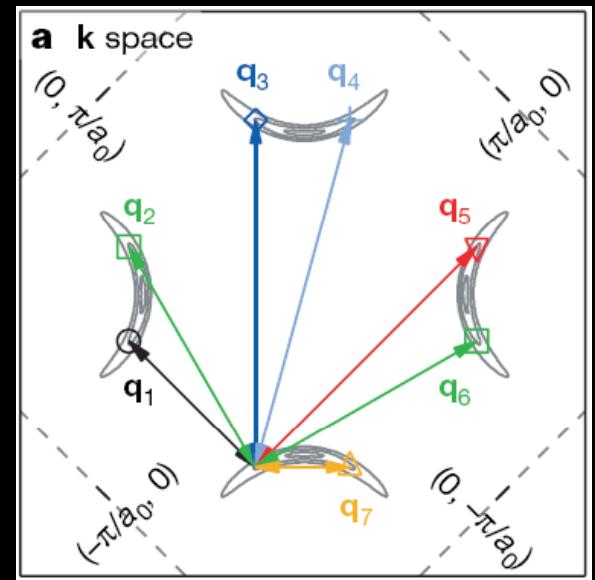


p-h symmetry:

“pseudogap is rarely symmetric about the Fermi energy, with gap-edge peaks at -88 meV and +66 meV”

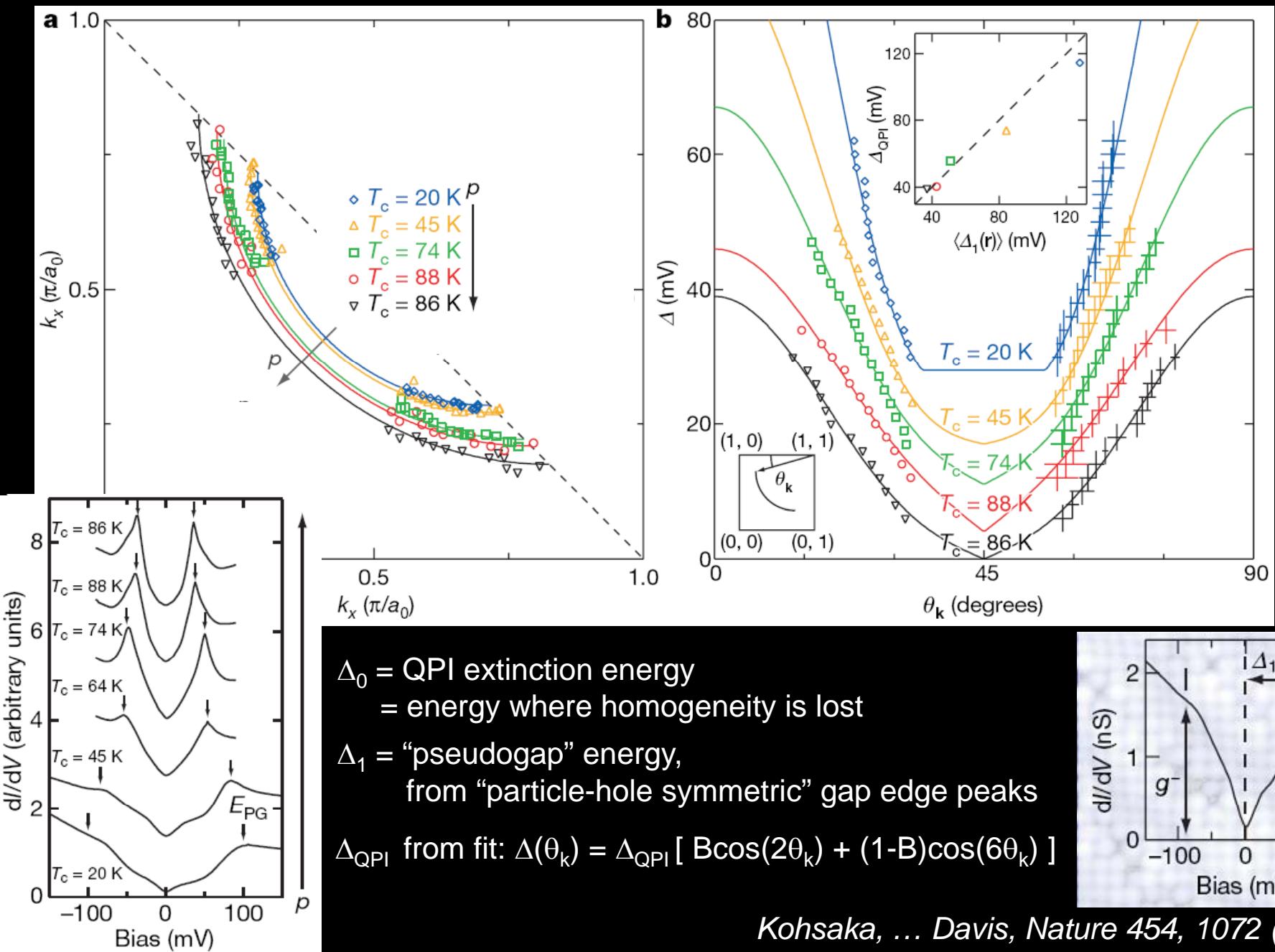
Note: checkerboard appears in topographies with setpoint as low as 5 meV!

# Bi-2212: Energy crossover: dispersing → static

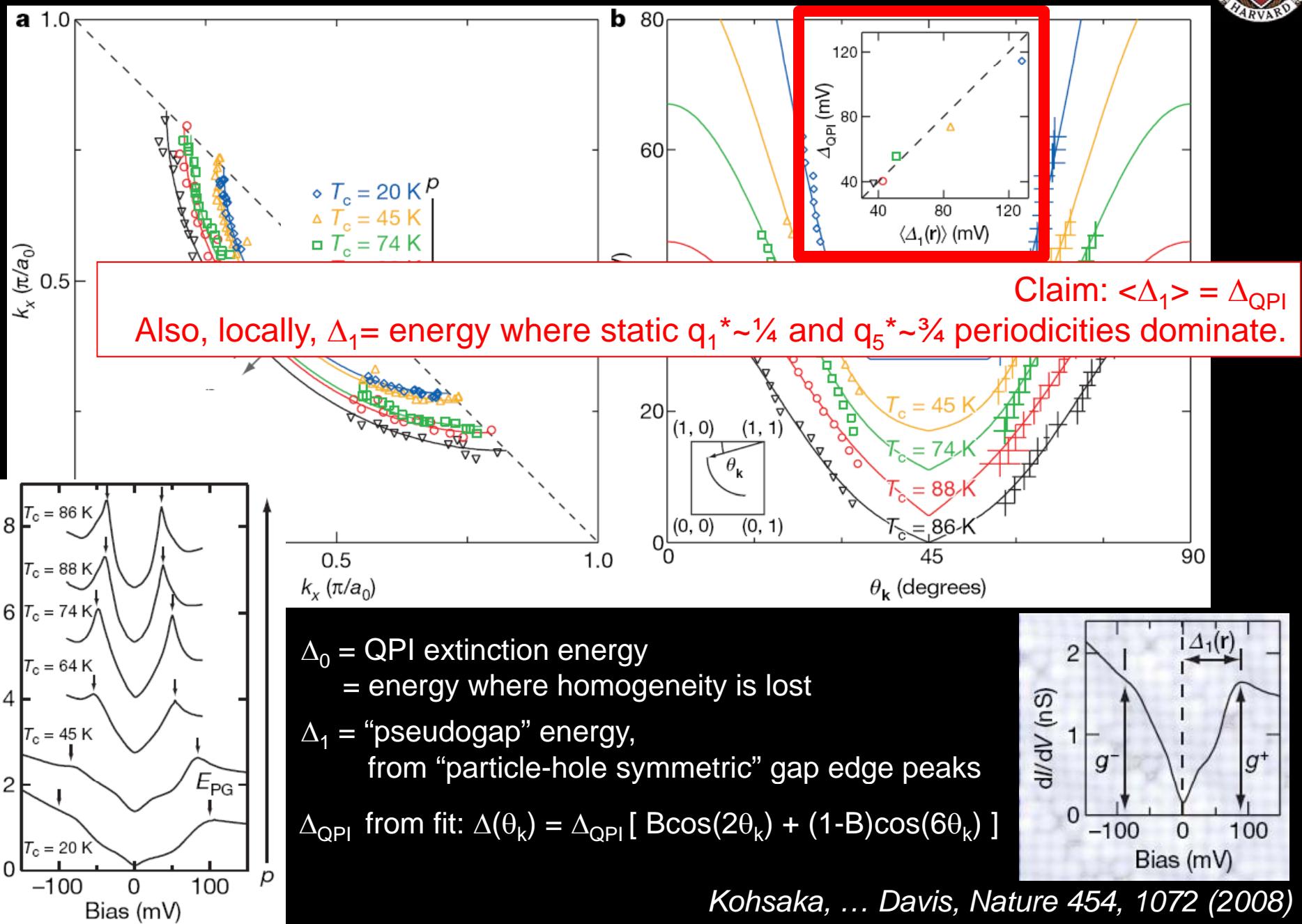


$\mathbf{q}_{1*}, \mathbf{q}_{5*}$  are static at high E  
but Davis group claims no CDW

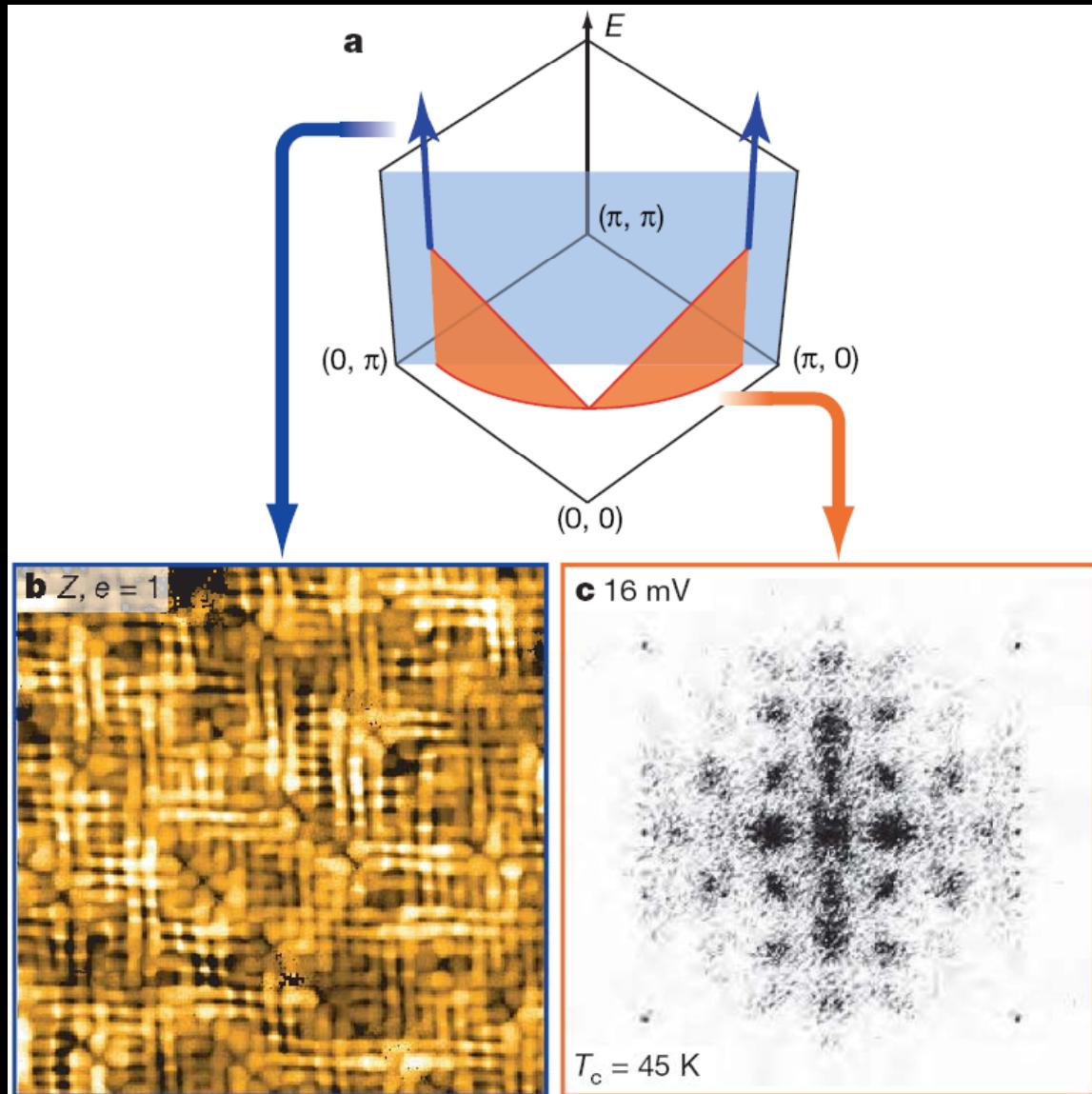
# Bi-2212: k-space crossover: dispersing $\rightarrow$ static



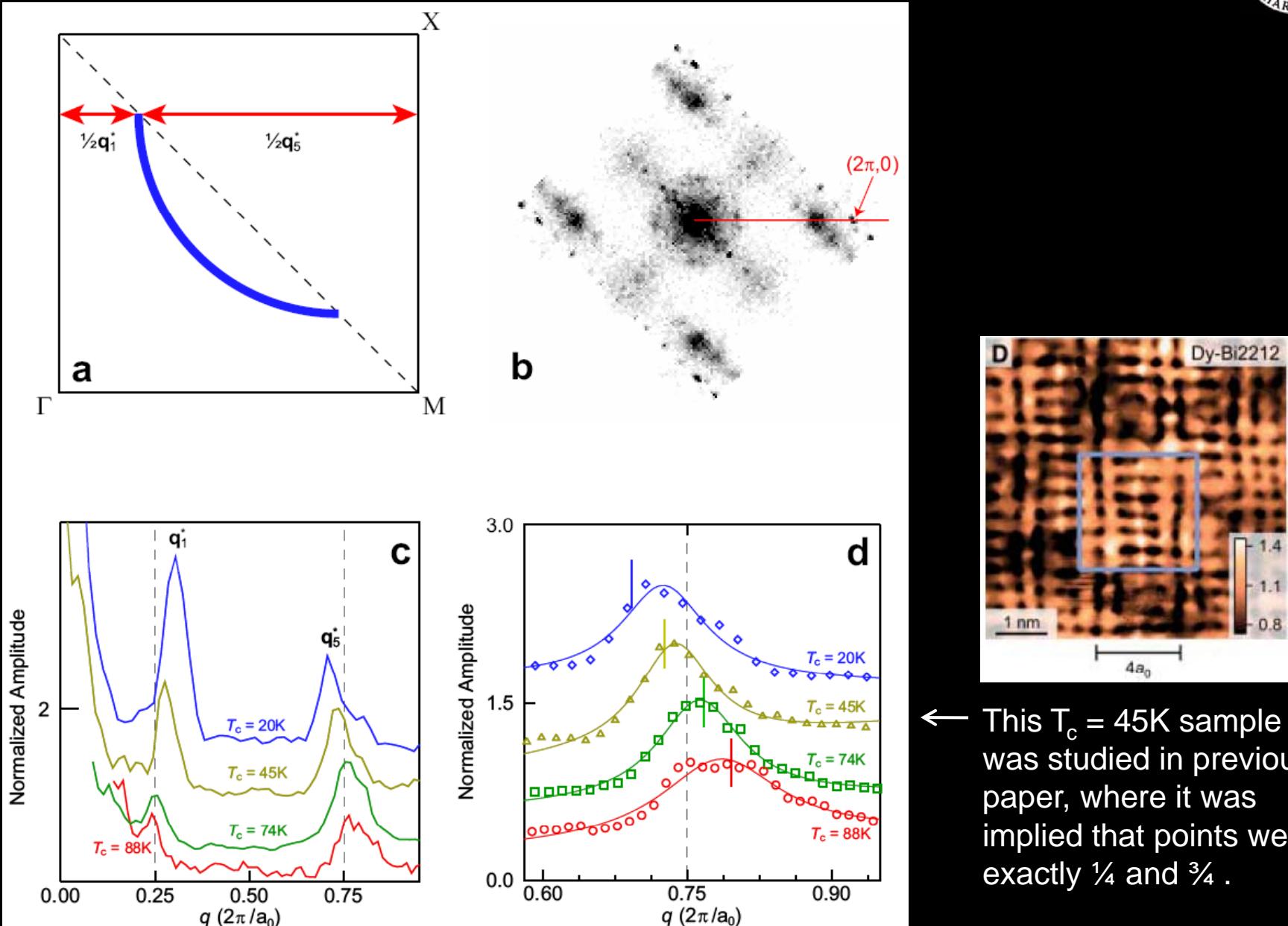
# Bi-2212: k-space crossover: dispersing $\rightarrow$ static



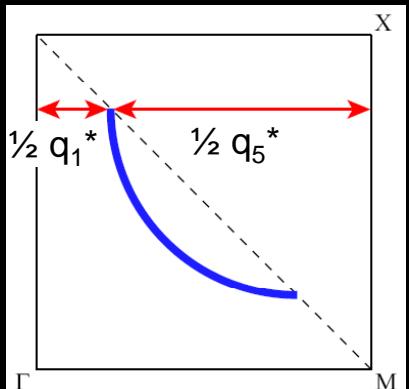
# 2 energy scales



# Checkerboard: $q_1^*$ and $q_5^*$ wavelengths

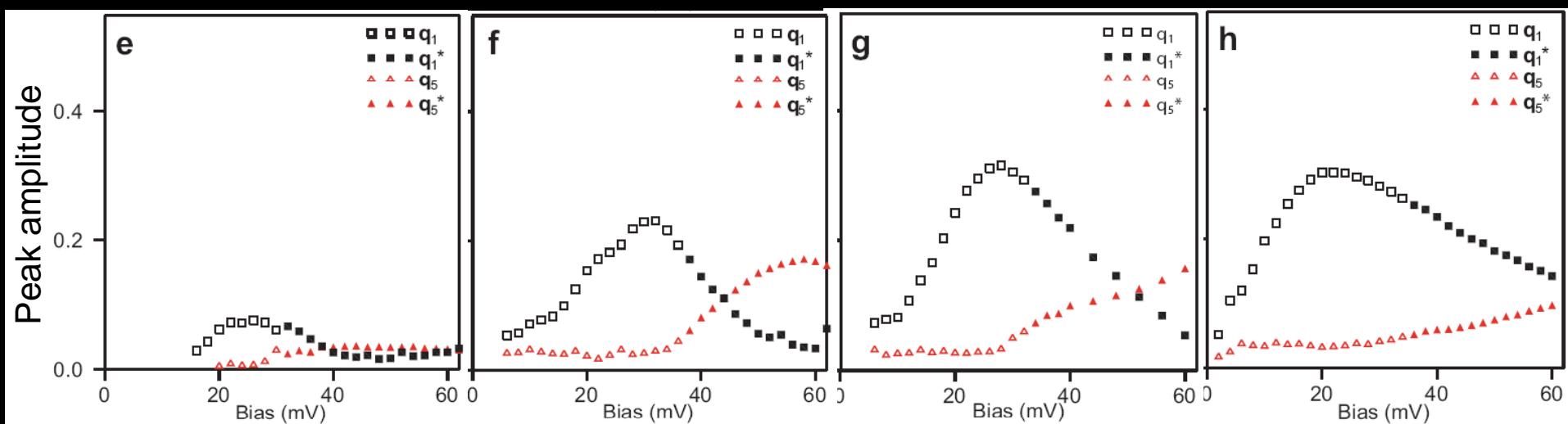


# Checkerboard: $q_1^*$ and $q_5^*$ amplitudes



$q_1^*$  and  $q_5^*$  are computed from:

$$Z(\vec{r}, V) \equiv \frac{\frac{dI}{dV}(\vec{r}, z, +V)}{\frac{dI}{dV}(\vec{r}, z, -V)}$$



Claim: “ $\frac{1}{4}$  point” is cancelled when forming R map but “ $\frac{3}{4}$  point” is not.  
 But how could this be?  $q_1^*$  and  $q_5^*$  seem inextricably linked  
 How could their phases and/or amplitudes vary so differently vs. E?

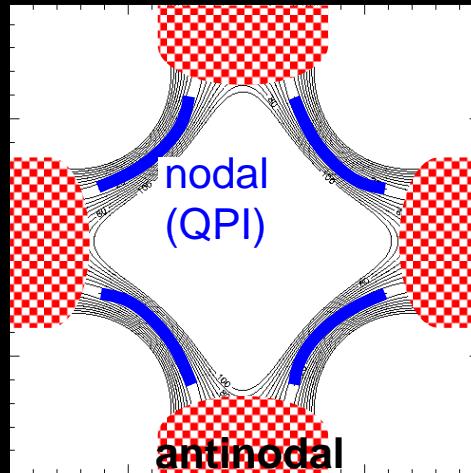
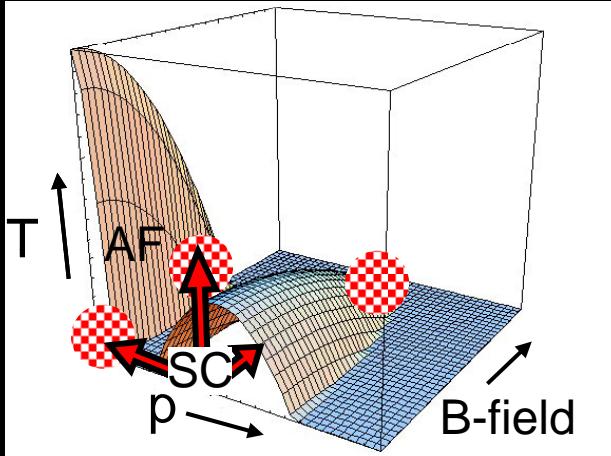
Question: is  $E_F$  the wrong symmetry point?

# Controversies in Cuprates

(1) Static vs. Dispersing order ?

→ now we mostly agree that both exist

(but we argue whether they are “CDW” or “ECG”)



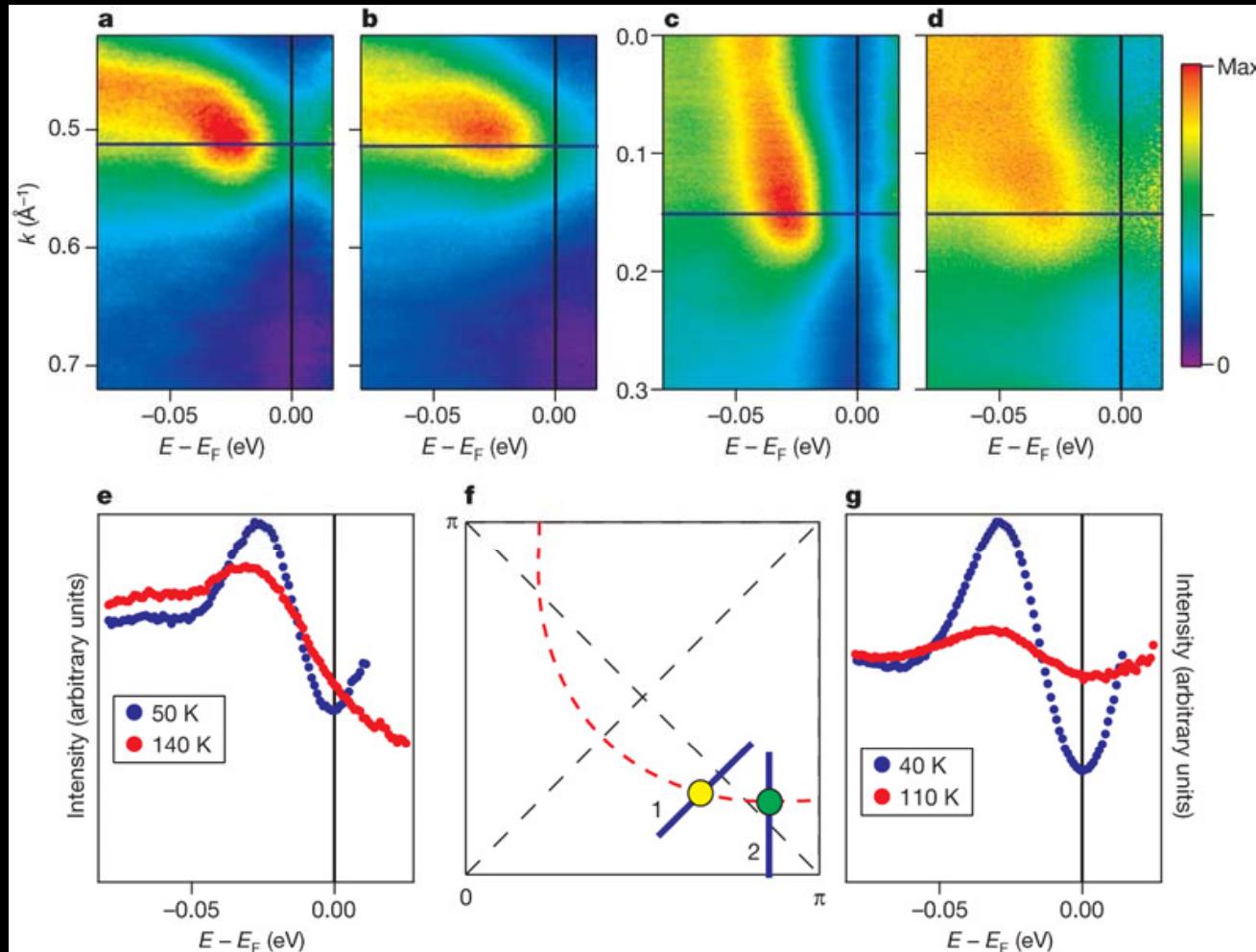
(2) Pseudogap: competing order vs. preformed pairs ?

→ debate ongoing!

# particle-hole symmetry ?

ARPES measures filled states only.

At  $T > 0$ , deconvolute resolution function & divide by Fermi function.



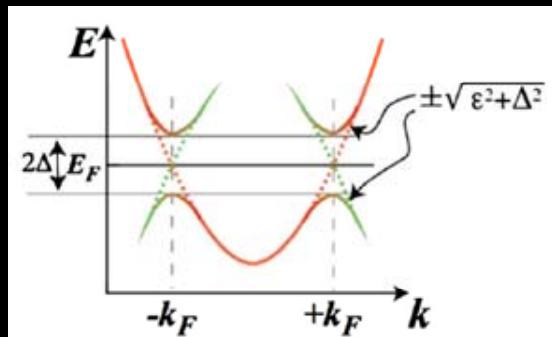
● and ● are both p-h symmetric below  $T_c$ .

But above  $T_c$ , ● is p-h symmetric while ● is not!

# particle-hole symmetry ?

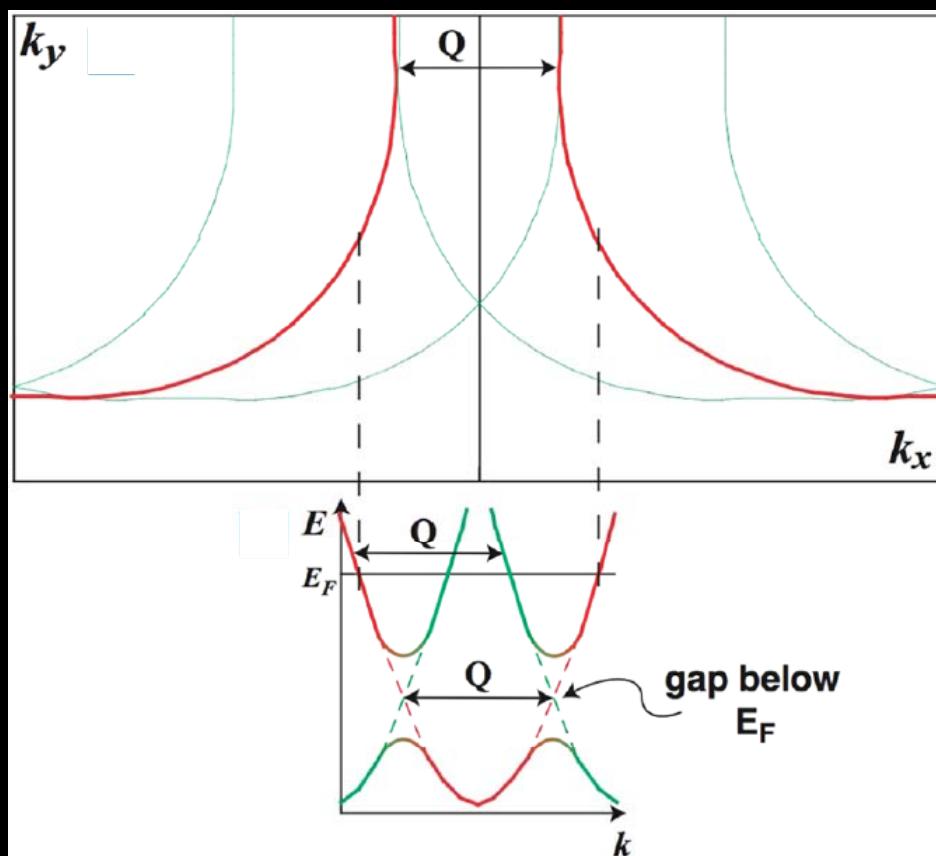
superconductivity:

- p-h symmetric
- back-bending at  $k_F$



other order:

- not p-h symmetric
- back-bending at ordering wavevector  $Q$

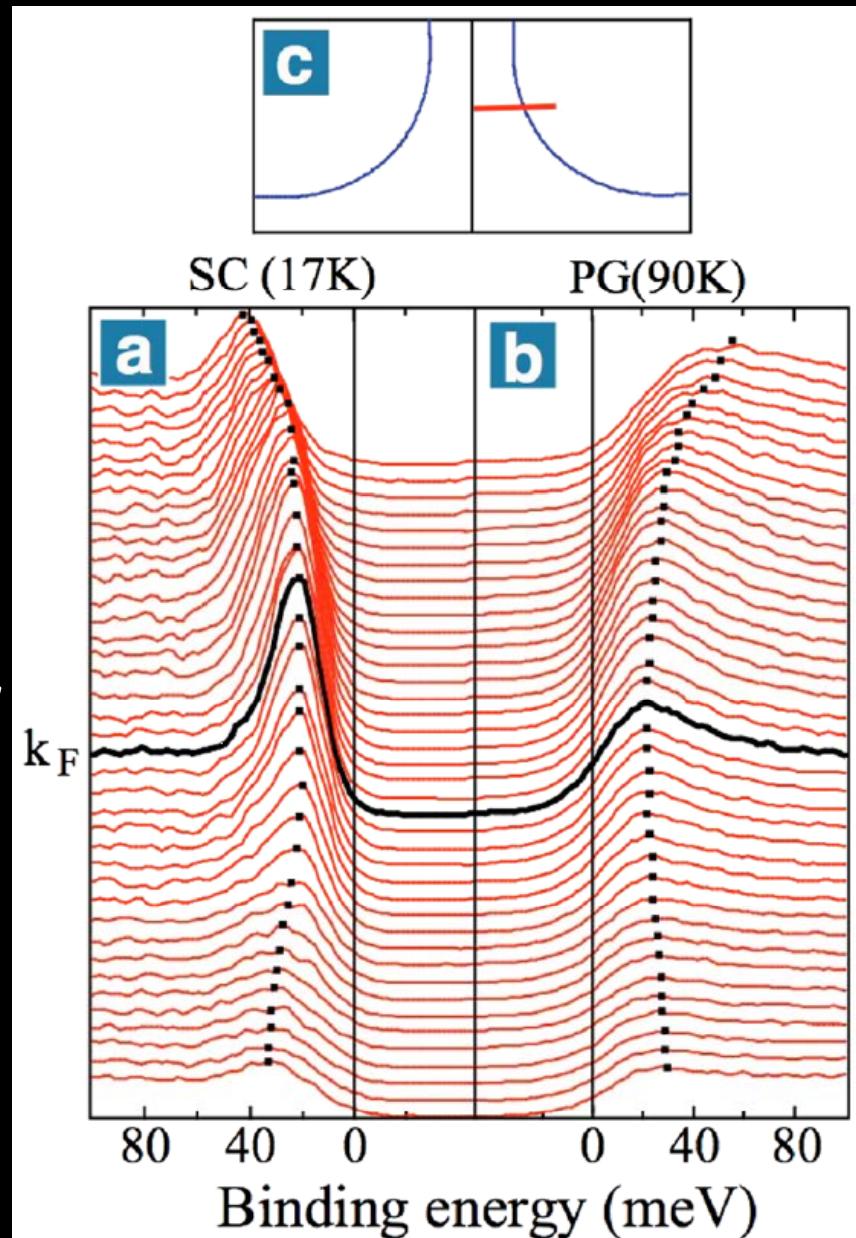


# particle-hole symmetry ?

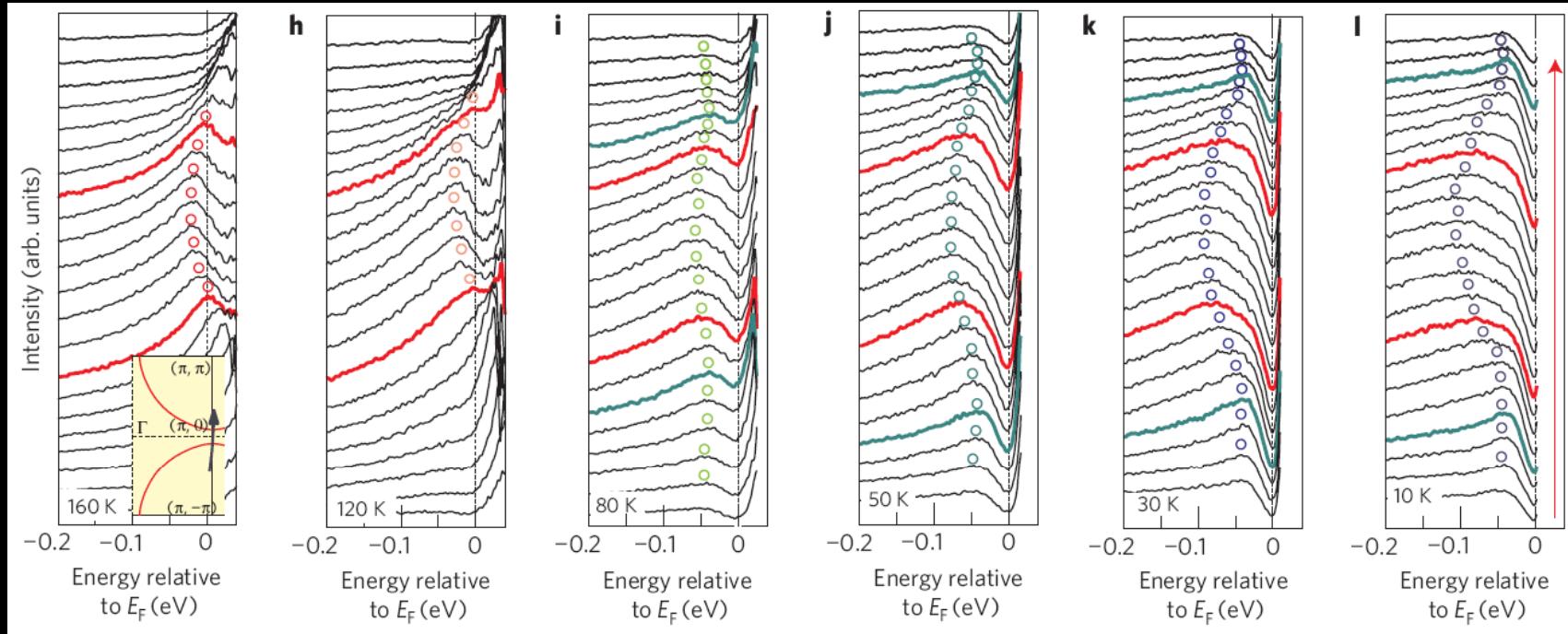
Claim that this is  $k_F$  because there is backbending here in the superconducting state.

But PG effects could persist into the SC state, altering the backbending  $k$  even below  $T_c$ .

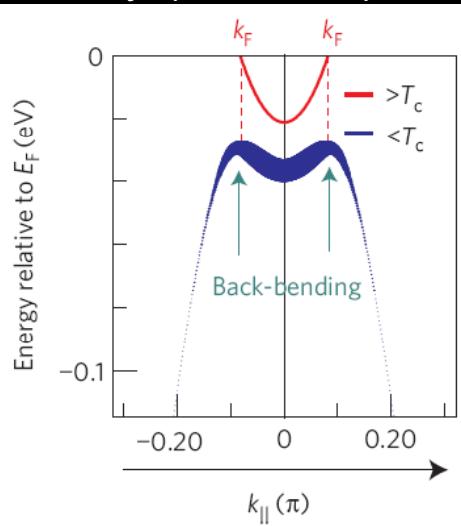
Need to go above  $T^* \sim 125\text{K}$  for reliable reference for  $k_F$ .



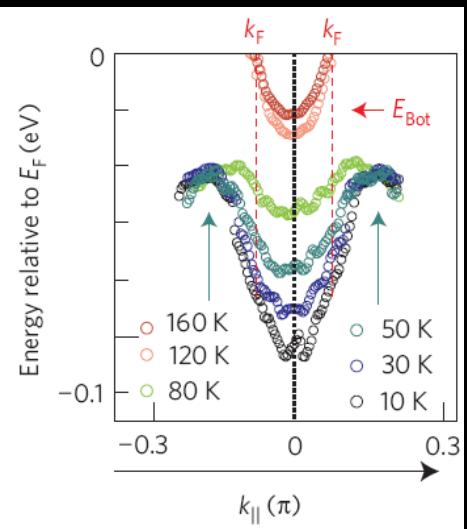
# particle-hole symmetry ?



Theory (SC state):



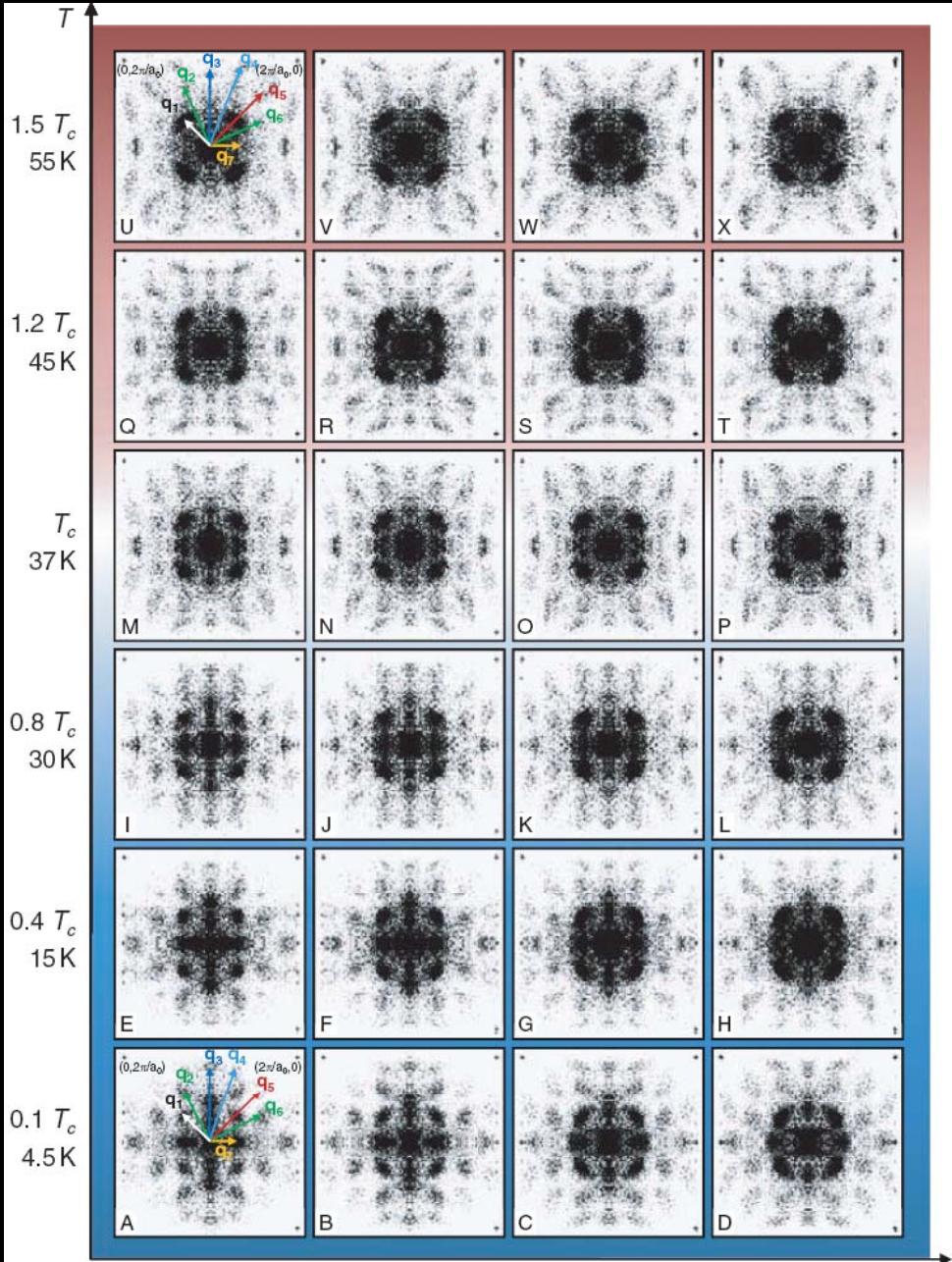
Data:



- locate  $k_F$  at  $T = 160K$ , above  $T^* = 125 K$
- below  $T^*$ , backbending not at  $k_F$

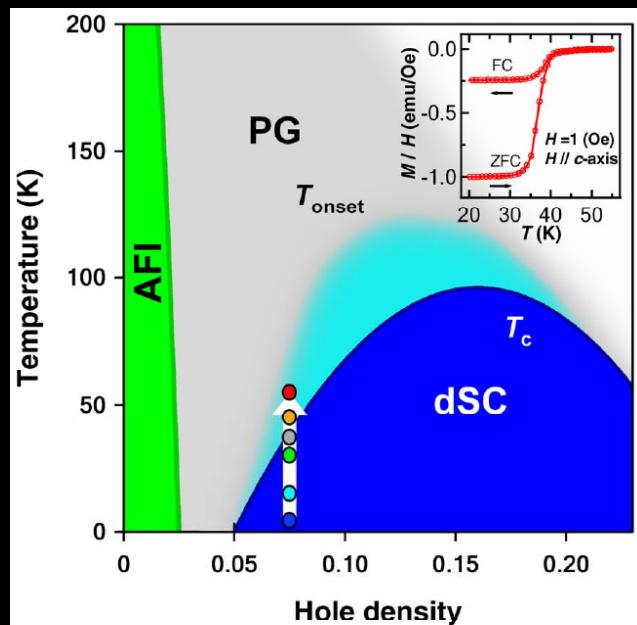
→ p-h symmetry broken in PG state  
at the antinode

# QPI persists to $> 1.5^*T_c$



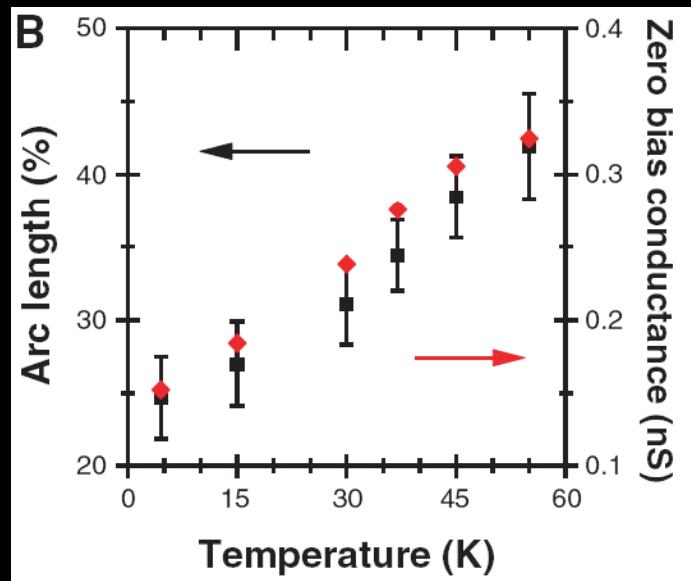
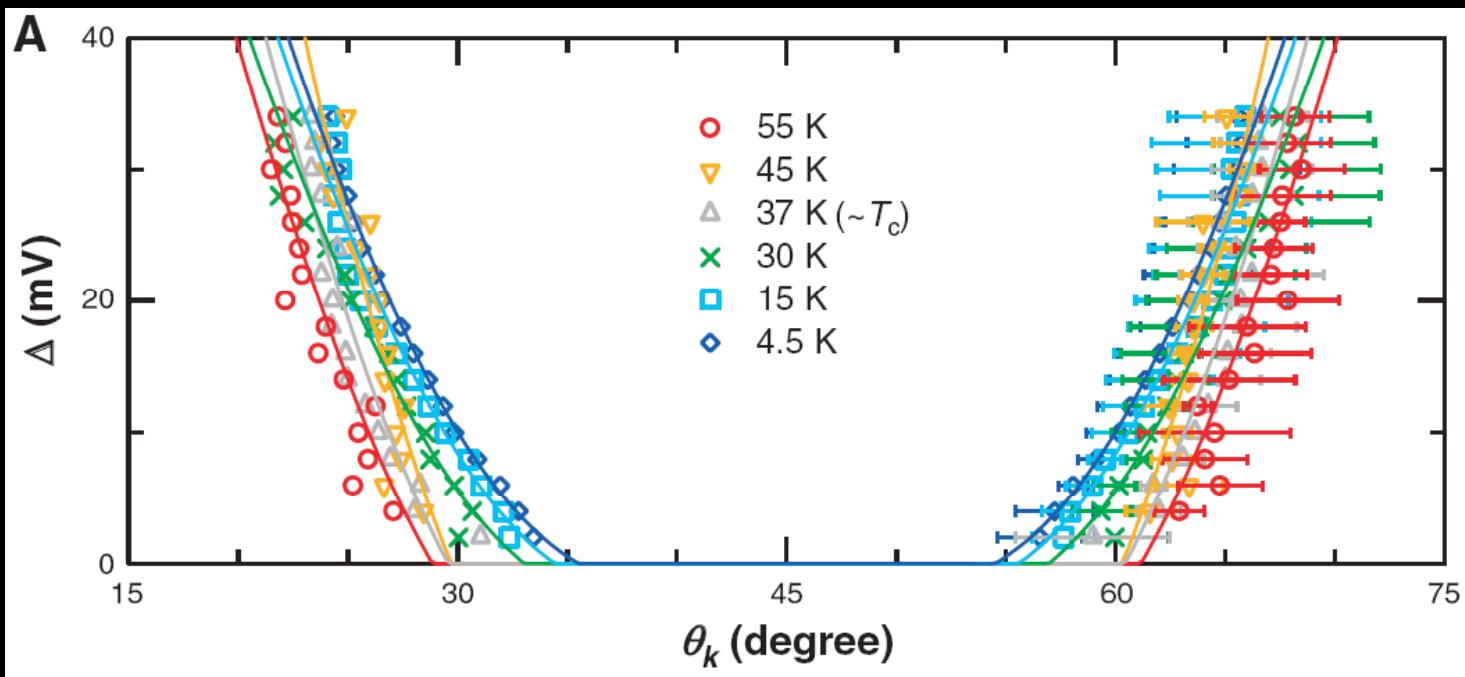
Motivation: QPI is p-h symmetric.  
 Claim: no state other than superconductivity is p-h symmetric.  
 Therefore, QPI is marker for SC.

Dy-BSCCO  
 $T_c \sim 37$  K

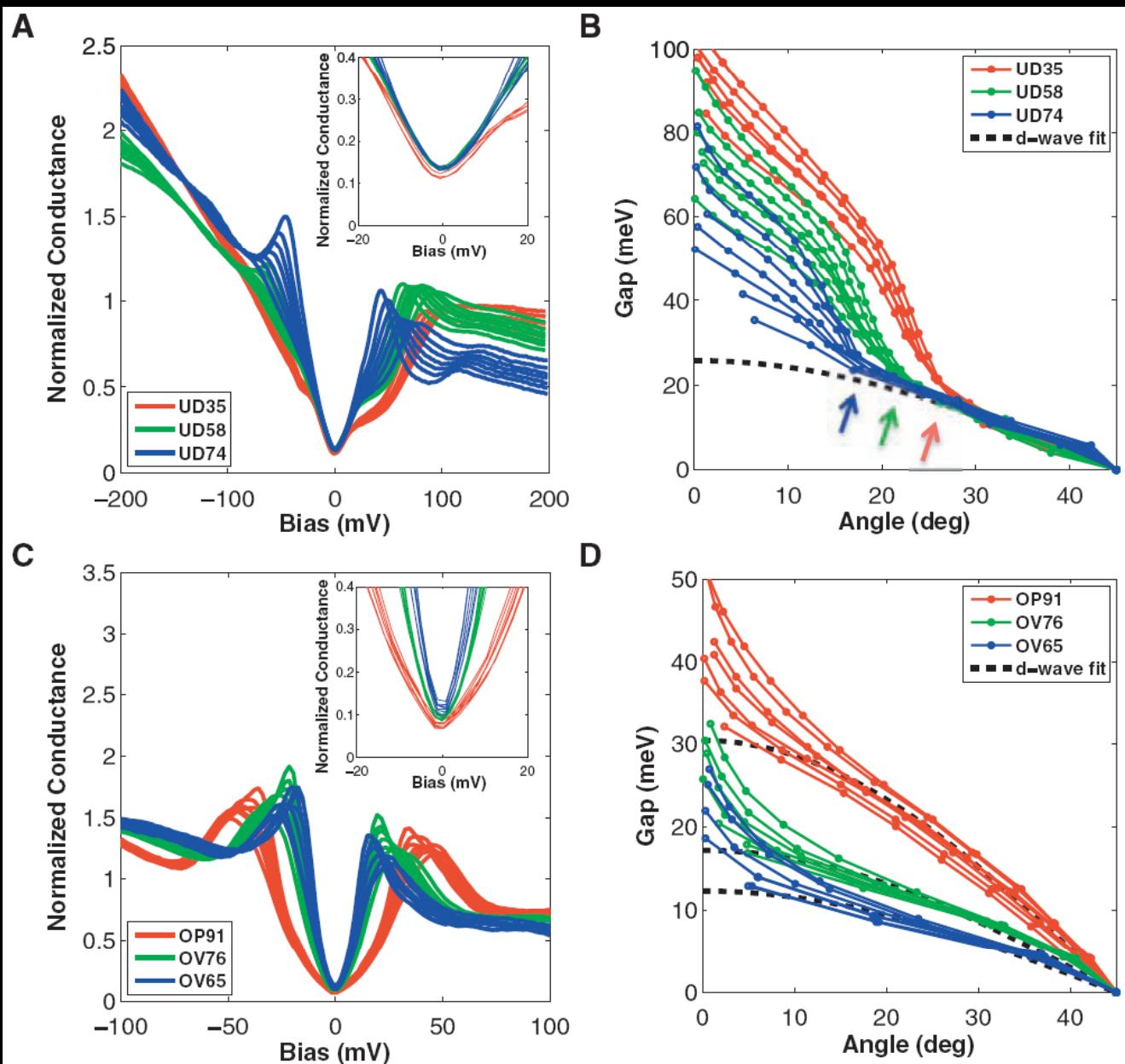


Caveat: these are Z maps  
 → they assume p-h symmetry

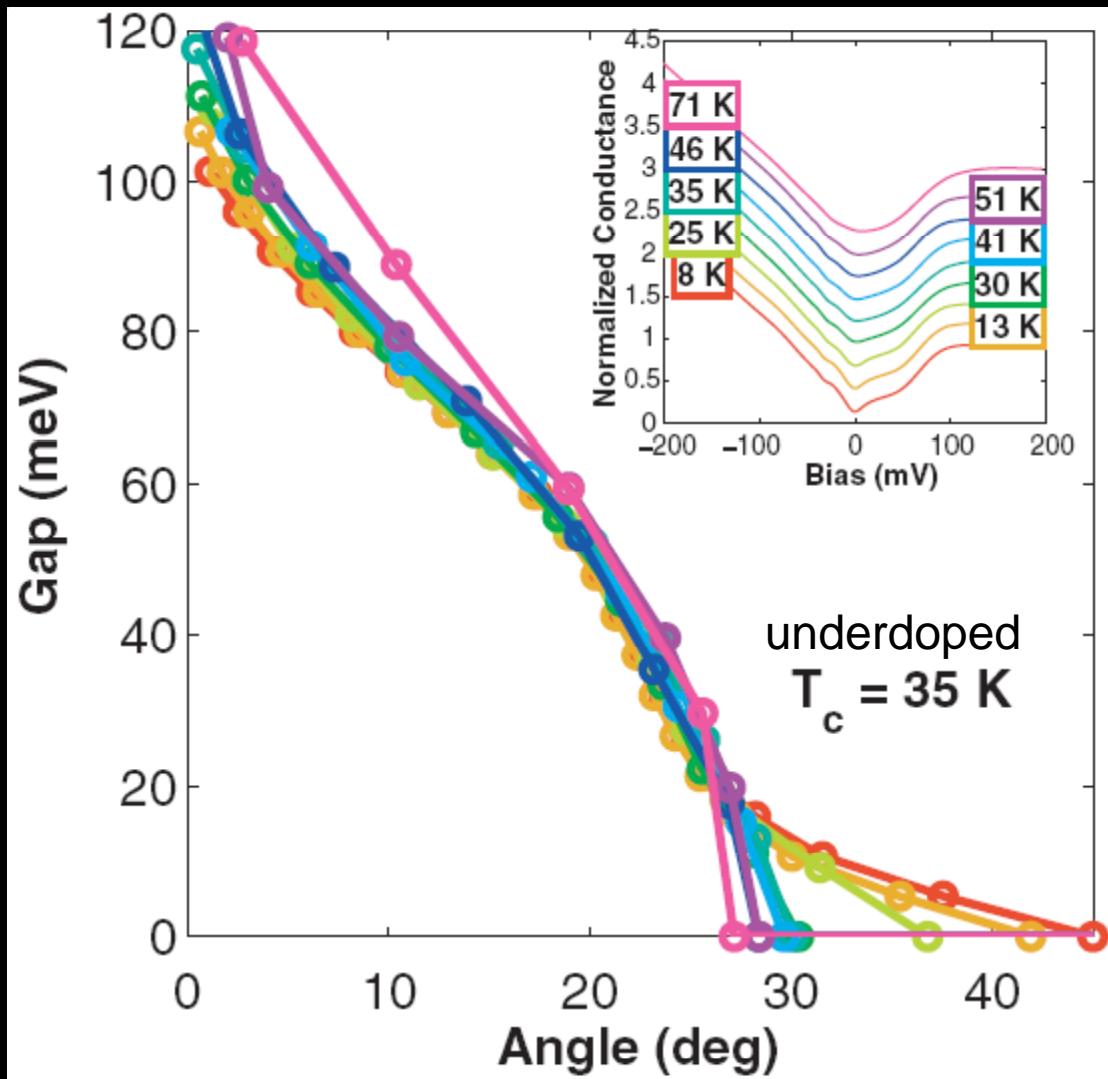
# Gapless arc grows with increasing T



# k-space info, a different way



# Confirms the gapless arc





# Outline

- Review of the last 8 years of QPI imaging in cuprate superconductors
  - Controversies in the cuprates:
    - Static vs. dispersing order
    - Pseudogap: competing phase vs. superconducting fluctuations
- Conclusions: we've made progress, but still not sure
  - Need to track QPI and checkerboards through  $T^*$
  - Need to understand spatial phases of patterns
  - Need to fully understand the artifacts of STM setup conditions
- QPI in magnetic field
- STM on pnictide superconductors
  - surfaces, gap-mapping, and vortices
  - demonstrate  $s\pm$  order parameter in  $\text{FeSe}_{1-x}\text{Te}_x$
  - nematic precursor in  $\text{Ca}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$

# Superconducting Coherence Factors

Normal metal:

$$w(i \rightarrow f) \propto \frac{2\pi}{\hbar} |V(\vec{q})|^2 n_i(E_i, \vec{k}_i) n_f(E_f, \vec{k}_f)$$

Superconductor:

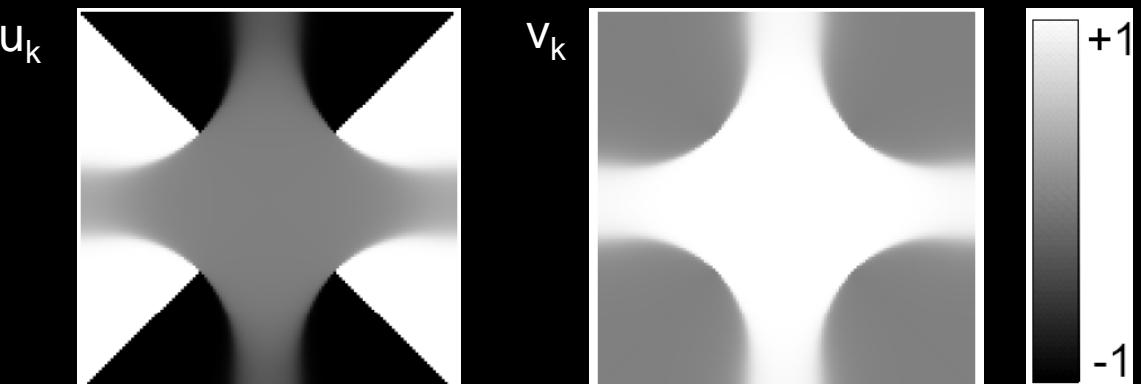
$$w(i \rightarrow f) \propto \frac{2\pi}{\hbar} (u_{k_i} u_{k_f} \pm v_{k_i} v_{k_f}) |V(\vec{q})|^2 n_i(E_i, \vec{k}_i) n_f(E_f, \vec{k}_f)$$

- + for magnetic scatterers
- for non-magnetic scatterers

Coherence factors:

$$v_k^2 = \frac{1}{2} \left[ 1 - \frac{\varepsilon_{\mathbf{k}}}{\sqrt{\Delta_k^2 + \varepsilon_k^2}} \right]; \quad u_k^2 = 1 - v_k^2$$

Coherence factors  
in 1<sup>st</sup> Brillouin zone,  
d-wave superconductor:



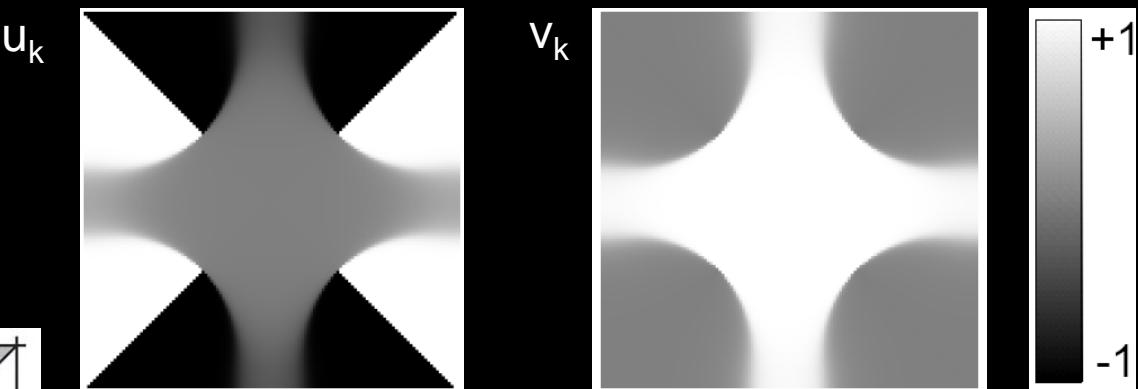
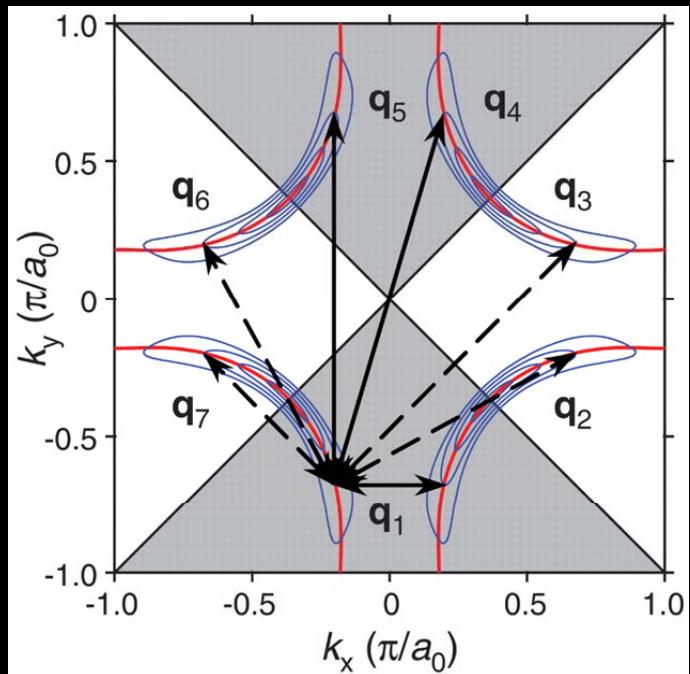
# Superconducting Coherence Factors



Superconductor:  $w(i \rightarrow f) \propto \frac{2\pi}{\hbar} (u_{k_i} u_{k_f} \pm v_{k_i} v_{k_f}) |V(\vec{q})|^2 n_i(E_i, \vec{k}_i) n_f(E_f, \vec{k}_f)$

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- for non-magnetic scatterers

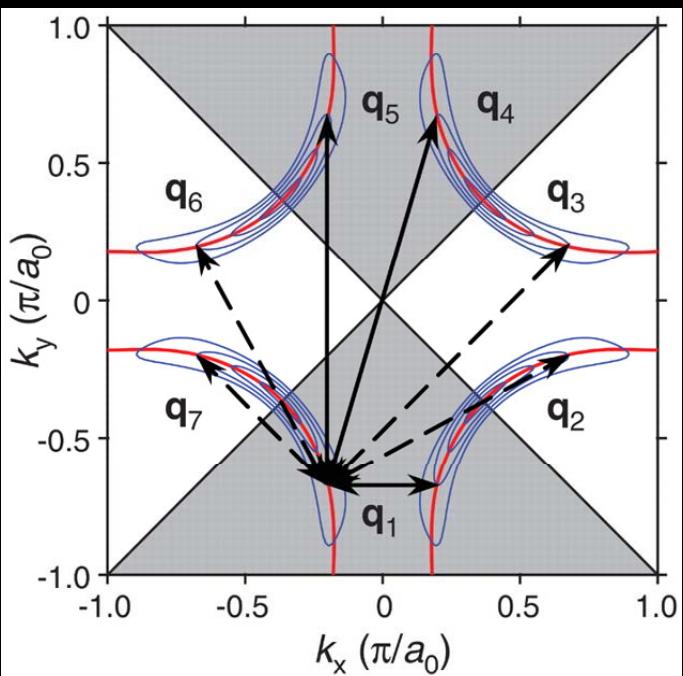
Coherence factors  
in 1<sup>st</sup> Brillouin zone,  
d-wave superconductor:



$\mathbf{q}_1, \mathbf{q}_4, \mathbf{q}_5$ :  
magnetic:  $(u_{ki}u_{kf} + v_{ki}v_{kf}) \rightarrow 2$   
non-magnetic:  $(u_{ki}u_{kf} - v_{ki}v_{kf}) \rightarrow 0$

$\mathbf{q}_2, \mathbf{q}_3, \mathbf{q}_6, \mathbf{q}_7$ :  
magnetic:  $(u_{ki}u_{kf} + v_{ki}v_{kf}) \rightarrow 0$   
non-magnetic:  $(u_{ki}u_{kf} - v_{ki}v_{kf}) \rightarrow -2$

# Superconducting Coherence Factors



$q_1, q_4, q_5$ :

$$\text{magnetic: } (u_{ki}u_{kf} + v_{ki}v_{kf}) \rightarrow 2$$

$$\text{non-magnetic: } (u_{ki}u_{kf} - v_{ki}v_{kf}) \rightarrow 0$$

$q_2, q_3, q_6, q_7$ :

$$\text{magnetic: } (u_{ki}u_{kf} + v_{ki}v_{kf}) \rightarrow 0$$

$$\text{non-magnetic: } (u_{ki}u_{kf} - v_{ki}v_{kf}) \rightarrow -2$$

Challenge: how to ensure dominant scatterers of known magnetic or non-magnetic character?

Idea: use scattering from magnetic vortices!

Expect: as  $B$  ramped up, more magnetic scatterers  
 $\rightarrow q_2, q_3, q_6, q_7$  will be suppressed

# What does an s-wave vortex look like to STM?

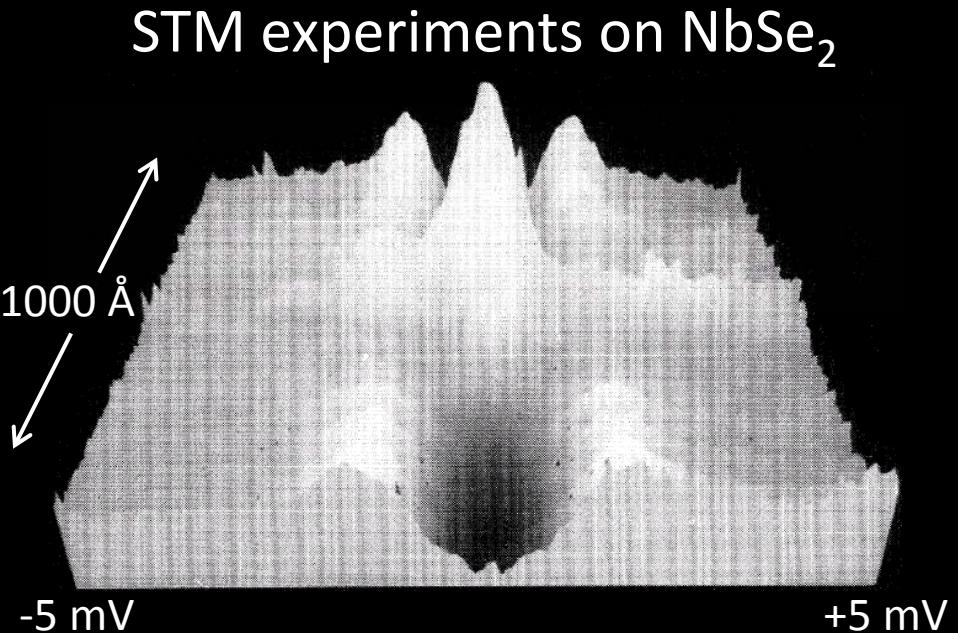


Theory:

Vortex core states  
= particle in a box

$$E = \frac{1}{2} \Delta^2 / \epsilon_F$$

Caroli, deGennes, Matricon,  
PRL 9, 307 (1964)



Hess, PRL 62, 214 (1989)

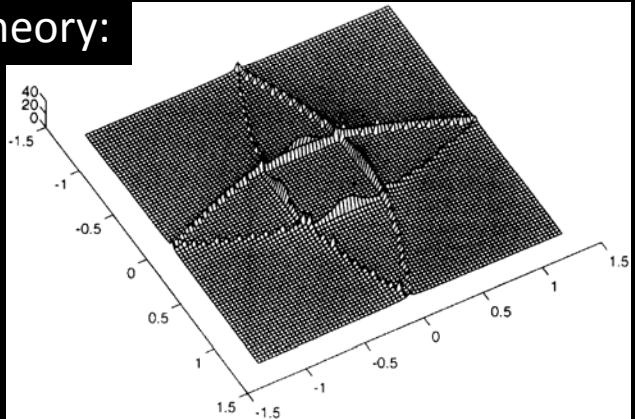
T<sub>c</sub> = 7.2 K; measurement T = 1.45 K

$$\rightarrow T \sim T_c/5$$

$$dV = 0.1 \text{ meV} \sim k_B T$$

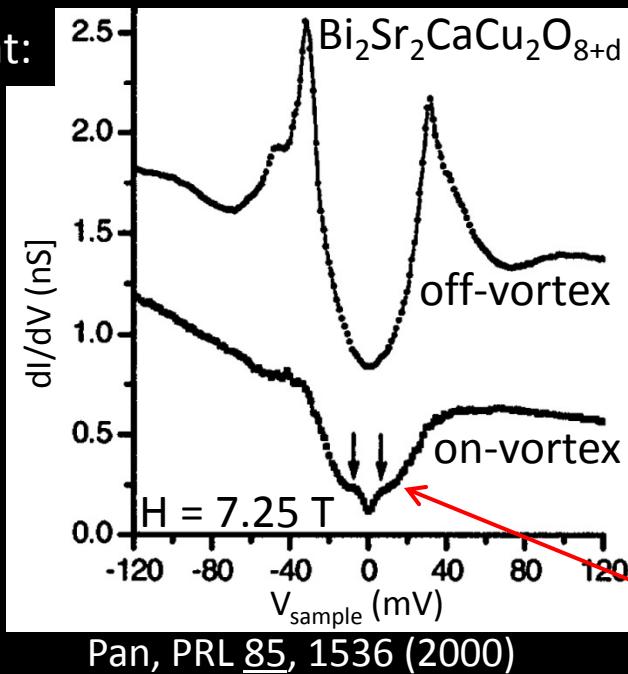
# What does a d-wave vortex look like to STM?

Theory:

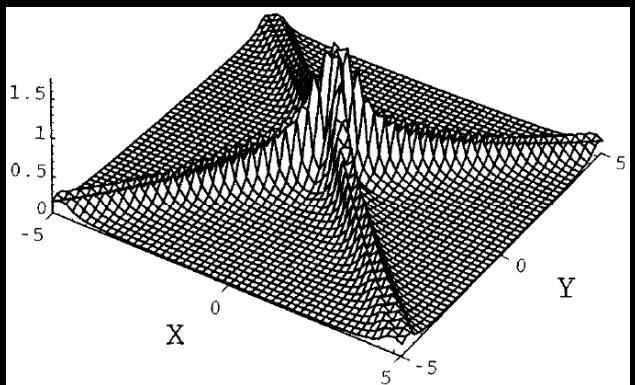


Maki, *Physica B* 204, 214 (1995)

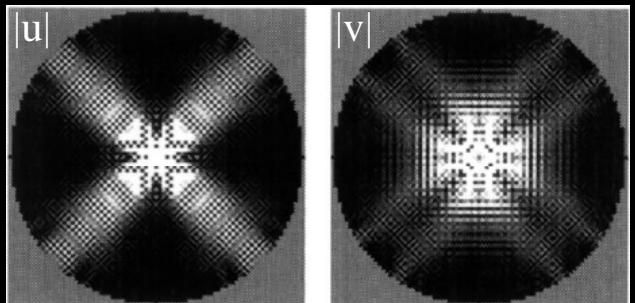
Experiment:



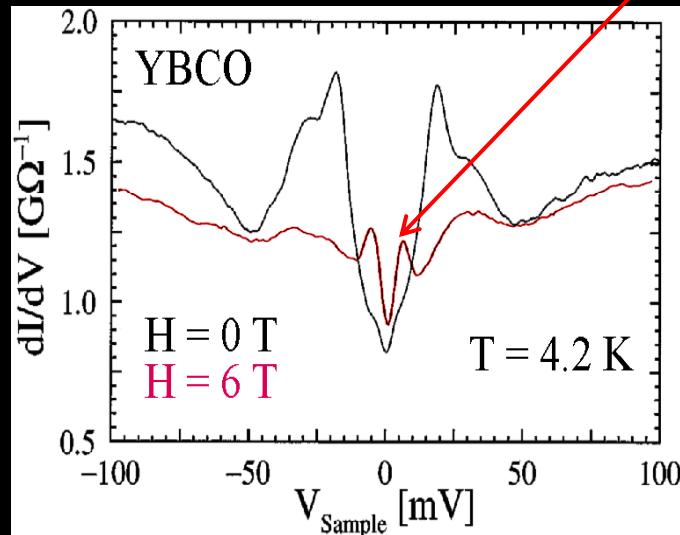
$$E \sim \Delta/4$$



Ichioka, *PRB* 53, 15316 (1996)

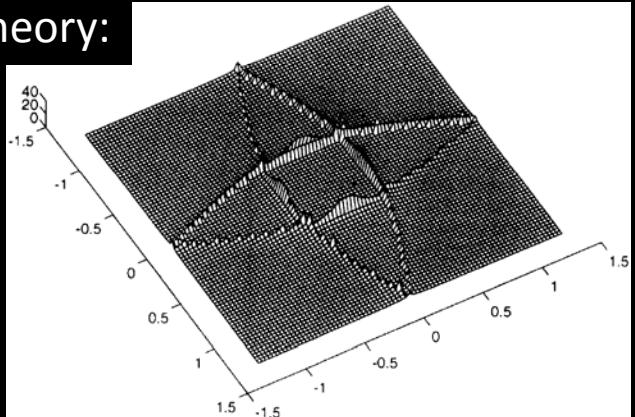


Franz & Tesanovic, *PRB* 53, 15316 (1996)



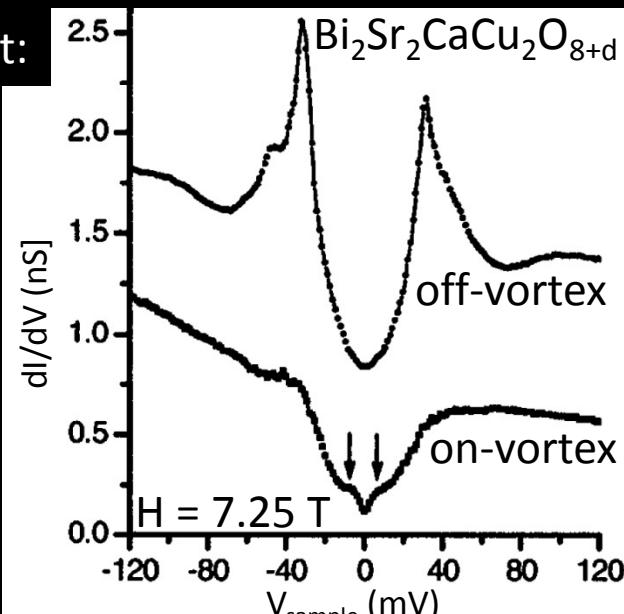
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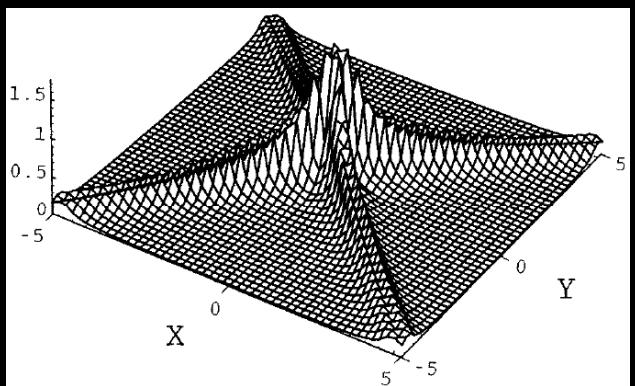


Maki, *Physica B* 204, 214 (1995)

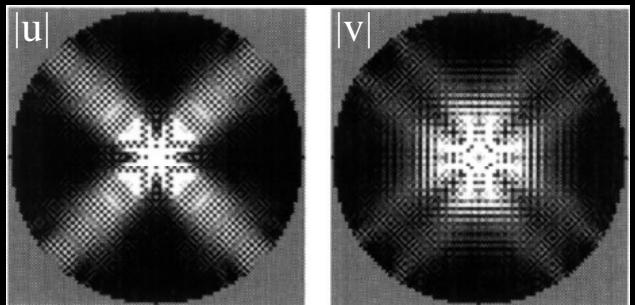
Experiment:



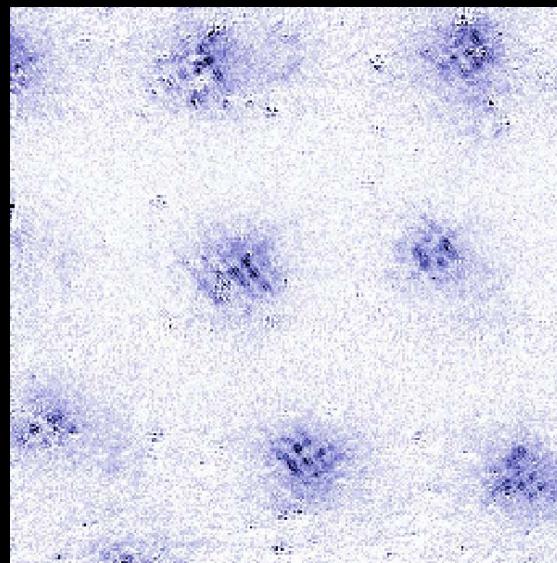
Pan, *PRL* 85, 1536 (2000)



Ichioka, *PRB* 53, 15316 (1996)

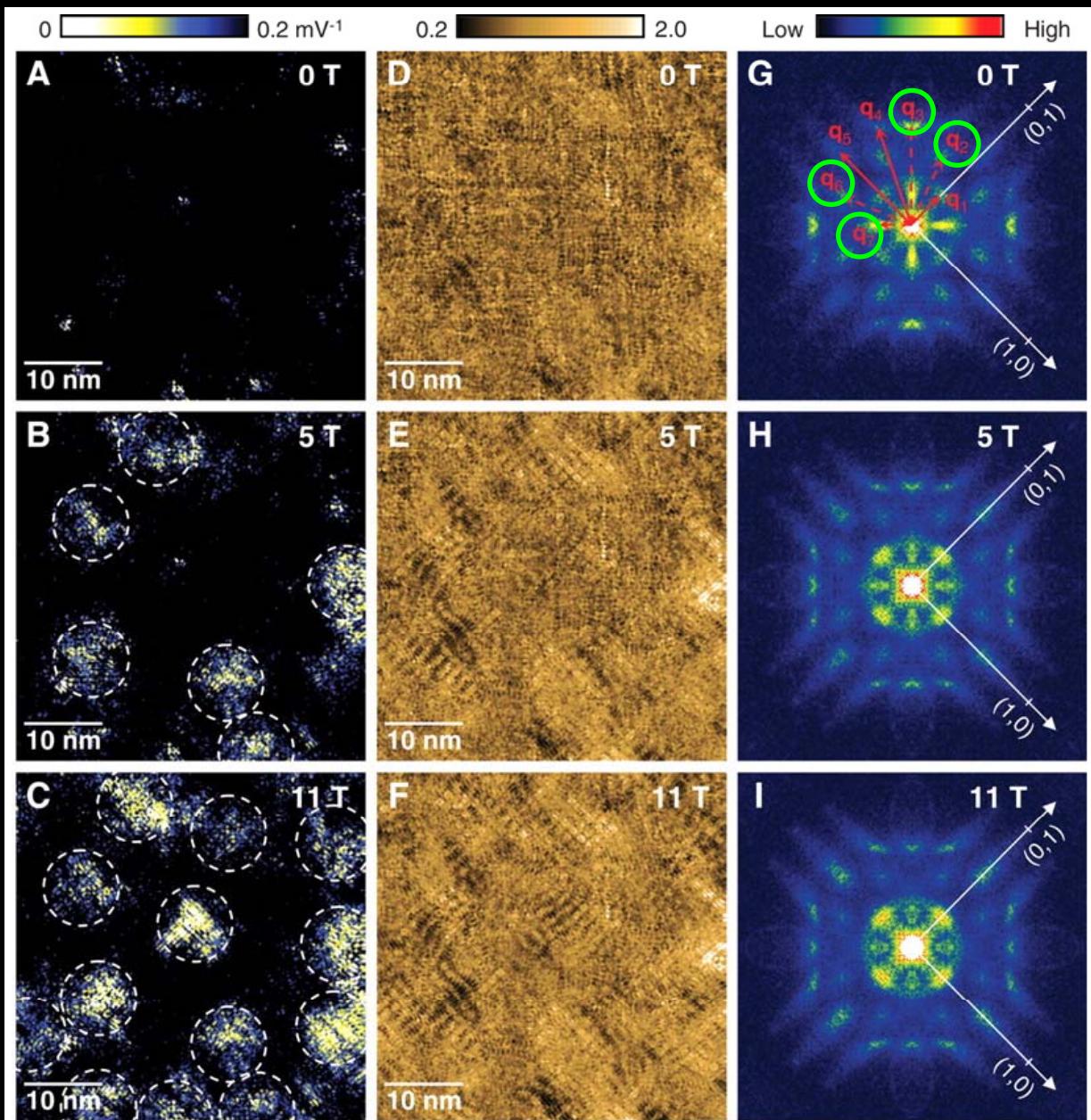


Franz & Tesanovic, *PRB* 53, 15316 (1996)



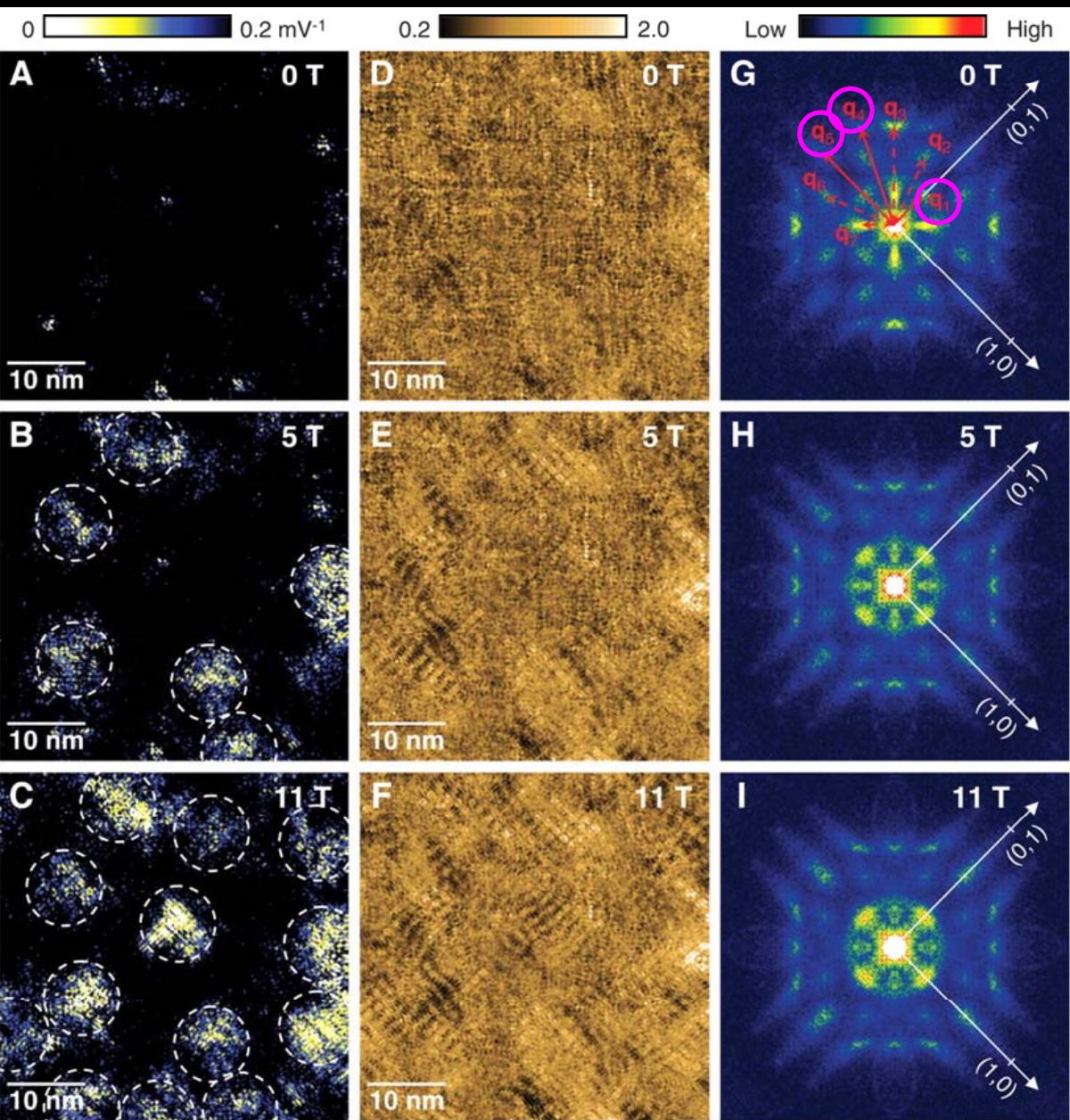
Hoffman, ... Davis, *Science* 295, 466 (2002)

# Vortices as Scatterers in Na-CCOC



○ expect  $q_2, q_3, q_6, q_7$  will be suppressed as  $B$  is ramped up

# Vortices as Scatterers in Na-CCOC



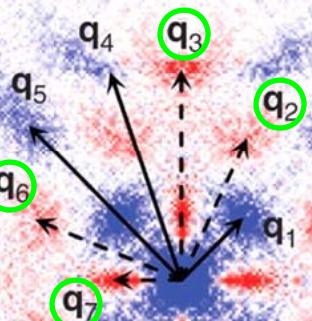
○ expect  $q_1, q_4, q_5$  will be enhanced as  $B$  is ramped up

# Mask Vortex Region & Non-Vortex Region



A

Dec. Inc.



C

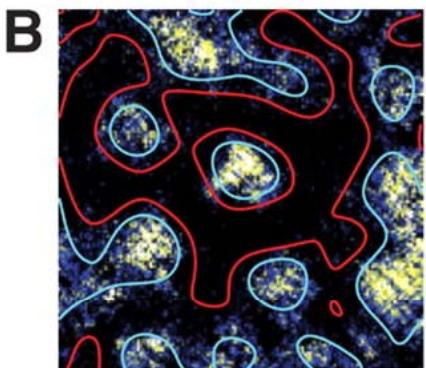
Vortex region

Expect  $q_2, q_3, q_6, q_7$  will be suppressed in vortex region.

D

Matrix region

$E = 4.4 \text{ meV}$   
 $B = 11 \text{ T}$

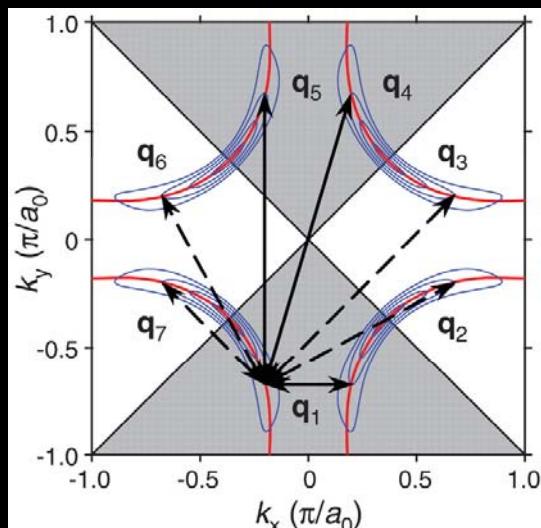


Conclusion:  
phase-sensitive  
verification of d-wave  
gap in Na-CCOC!

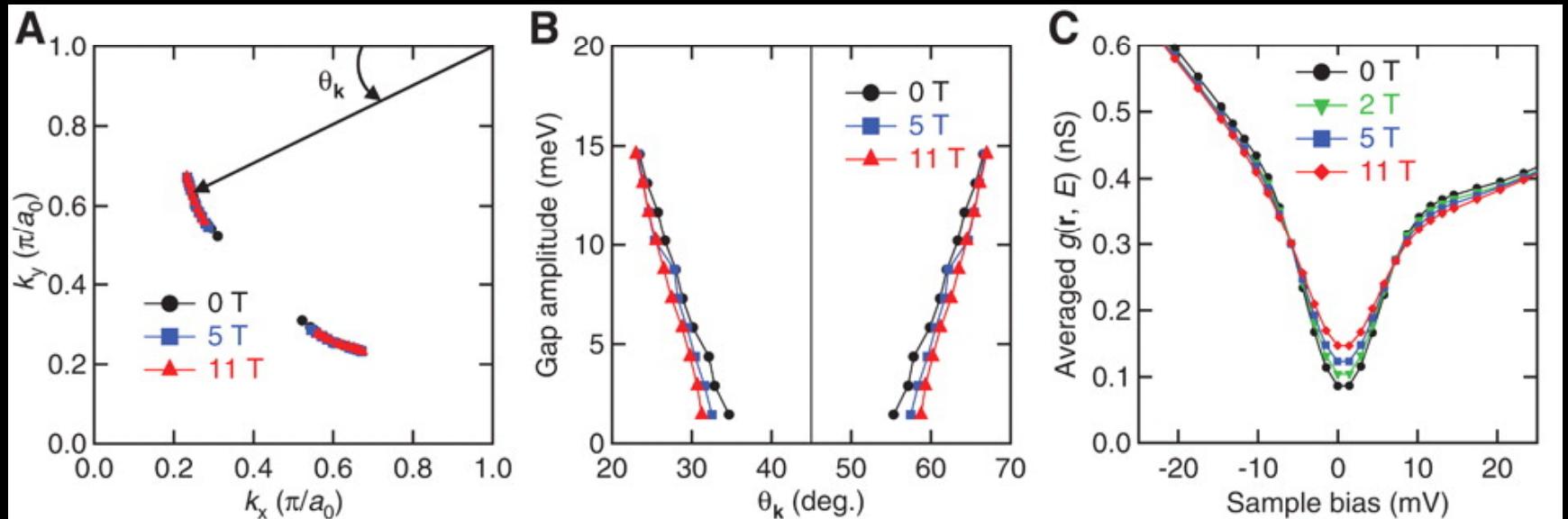
# What about other scatterers?



Scatterer	Coherence factor	Enhanced $\mathbf{q}_i$
Weak scalar	$(u_{\mathbf{k}_i} u_{\mathbf{k}_f} - v_{\mathbf{k}_i} v_{\mathbf{k}_f})^2$	2, 3, 6, 7
Magnetic, phase-gradient	$(u_{\mathbf{k}_i} u_{\mathbf{k}_f} + v_{\mathbf{k}_i} v_{\mathbf{k}_f})^2$	1, 4, 5
Gap amplitude	$(u_{\mathbf{k}_i} v_{\mathbf{k}_f} + v_{\mathbf{k}_i} u_{\mathbf{k}_f})(u_{\mathbf{k}_i} u_{\mathbf{k}_f} + v_{\mathbf{k}_i} v_{\mathbf{k}_f})$	1, 4, 5



# Fermi Surface vs. B-field



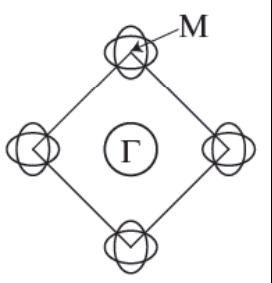
- A) FS location doesn't depend on field
- B) Gapless arc grows as B increases
- C) Zero-bias conductance grows as B increases



# Outline

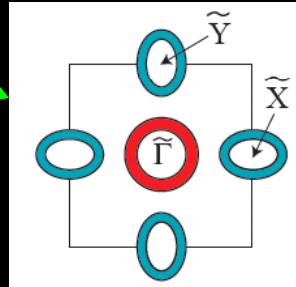
- Review of the last 8 years of QPI imaging in cuprate superconductors
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- Conclusions: we've made progress, but still not sure
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  - demonstrate  $s\pm$  order parameter in  $\text{FeSe}_{1-x}\text{Te}_x$
  - nematic precursor in  $\text{Ca}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$

# Fe-based SC's: What is the pairing symmetry?



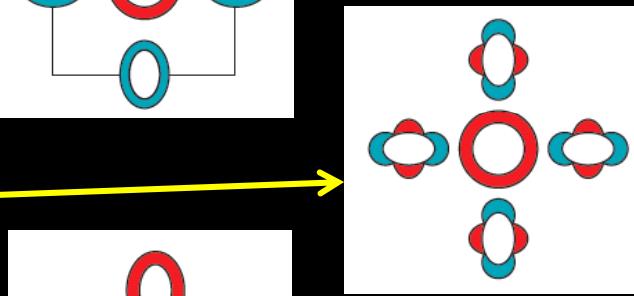
## (1) nodeless extended s-wave ( $s\pm$ )

- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)



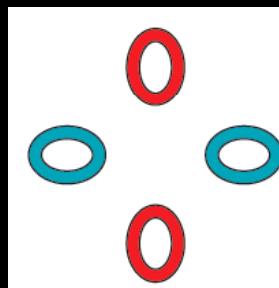
## (2) nodal s-wave

- Kuroki, PRL 101, 087004 (2008)



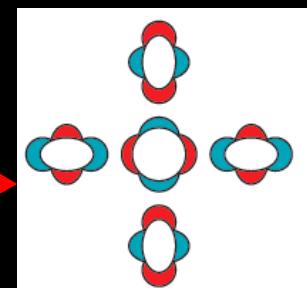
## (3) nodeless d

- Kuroki, PRL 101, 087004 (2008)



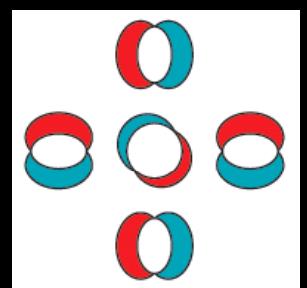
## (4) $d_{x^2-y^2}$ order

- Yao, Li & Wang, New J. Phys. 11, 025009 (2009)



## (5) nodal intraband p order

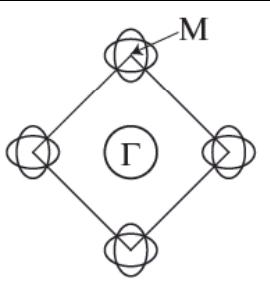
- Lee & Wen, PRB 78, 144517 (2008)



## (6) interband p order

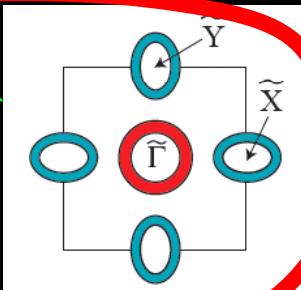
- Dai, PRL 101, 057008 (2008)

# Converging on $s\pm$ symmetry?



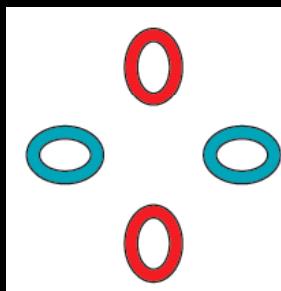
## (1) nodeless extended s-wave ( $s\pm$ )

- Mazin, PRL 101, 057003 (2008)
- Wang, PRL 102, 047005 (2009)
- Cvetkovic & Tesanovic, EPL 85, 37002 (2009)



## (2) nodal s-wave

- Kuroki, PRL 101, 087004 (2008)



## (3) nodeless d

- Kuroki, PRL 101, 087004 (2008)



## (4) $d_{x^2-y^2}$ order

- Yao, Li & Wang, New J. Phys. 11, 025009 (2009)



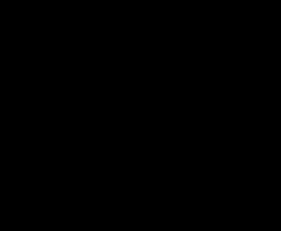
## (5) nodal intraband p order

- Lee & Wen, PRB 78, 144517 (2008)



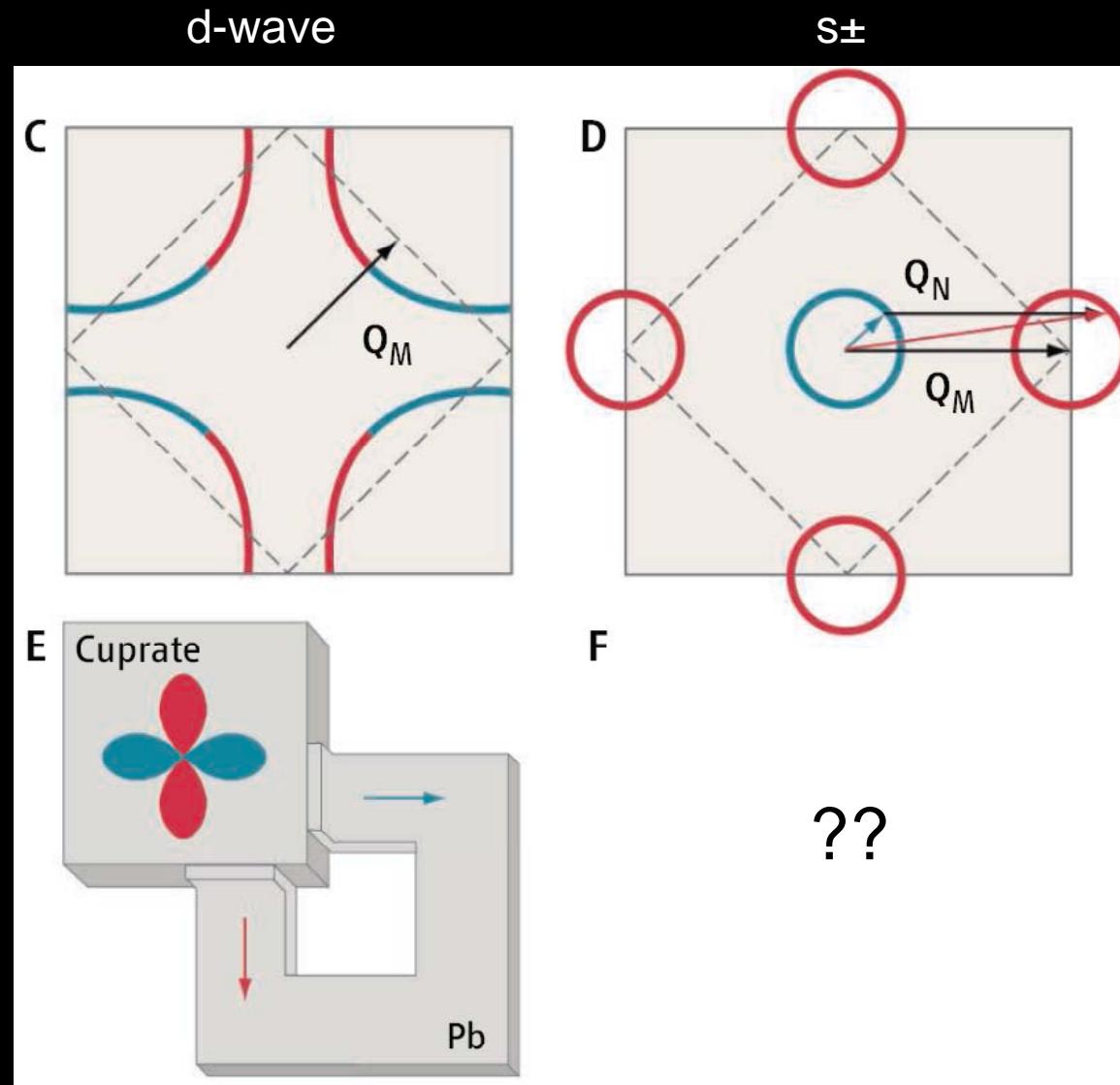
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- Dai, PRL 101, 057008 (2008)



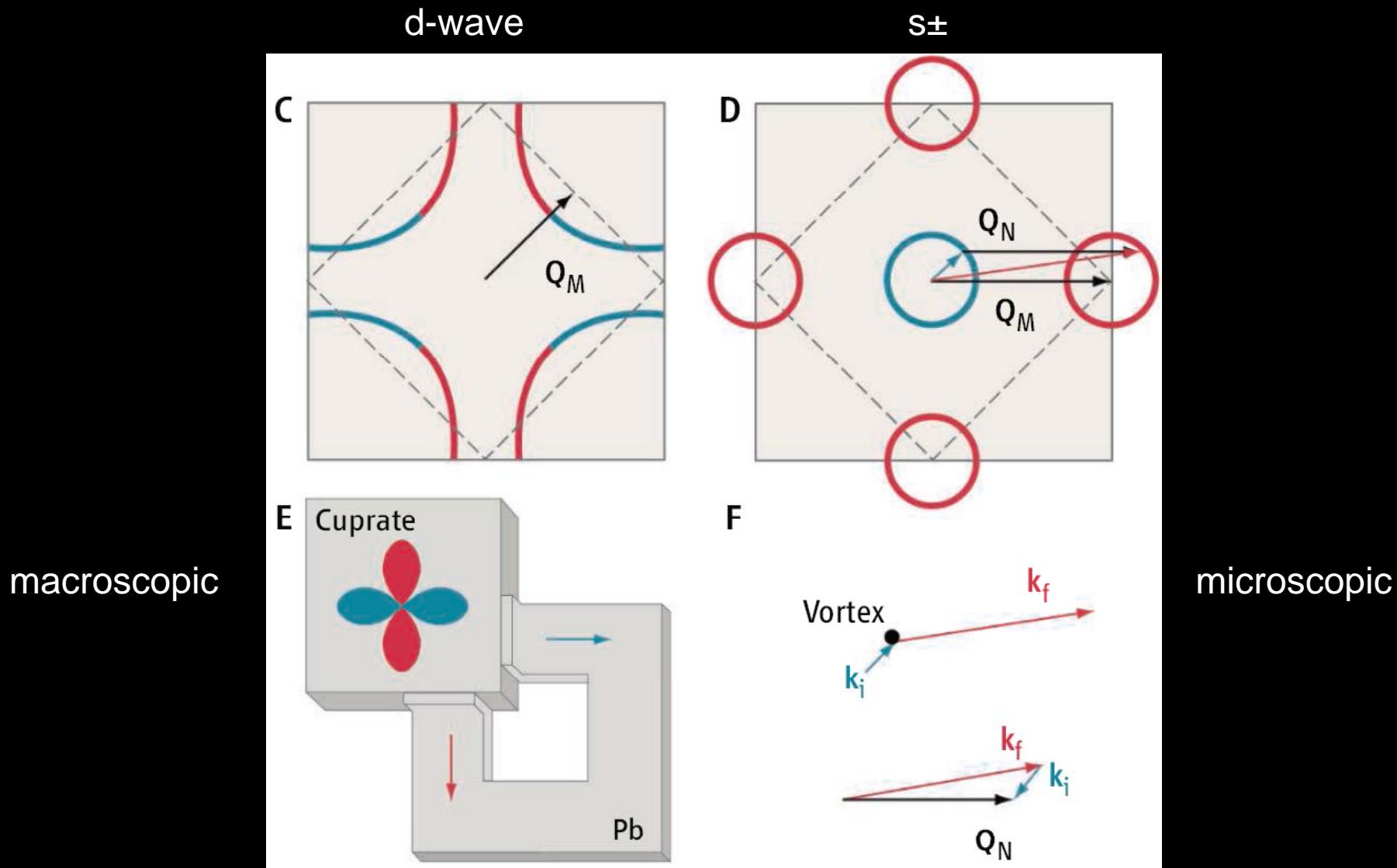
But most experiments just test for low-energy quasiparticles, not phase-sensitive!

# Geometry for phase-sensitive tests



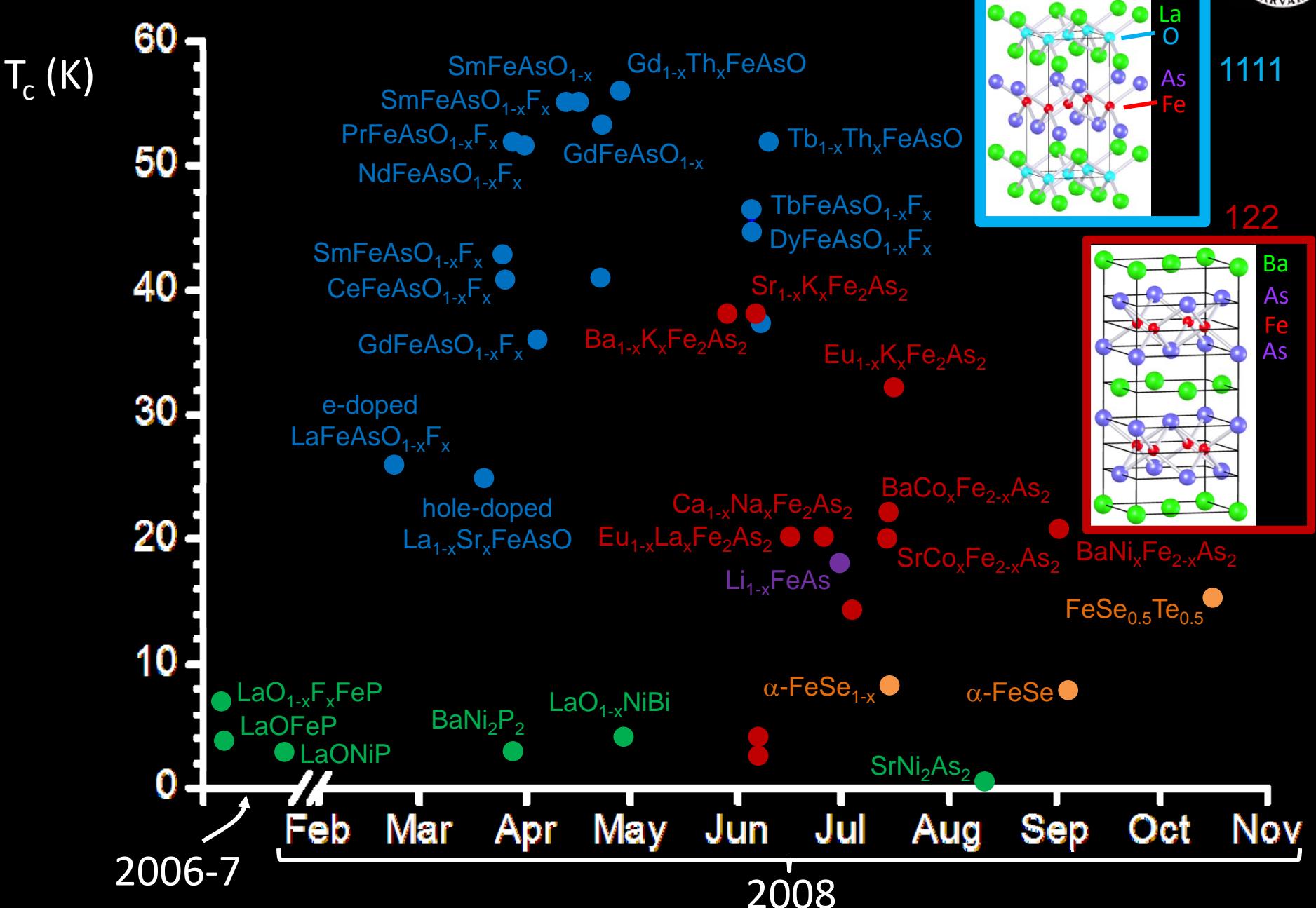
Wollman, Van Harlingen, Lee, Ginsberg,  
Leggett, PRL 71, 2134 (1993)

# Geometry for phase-sensitive tests

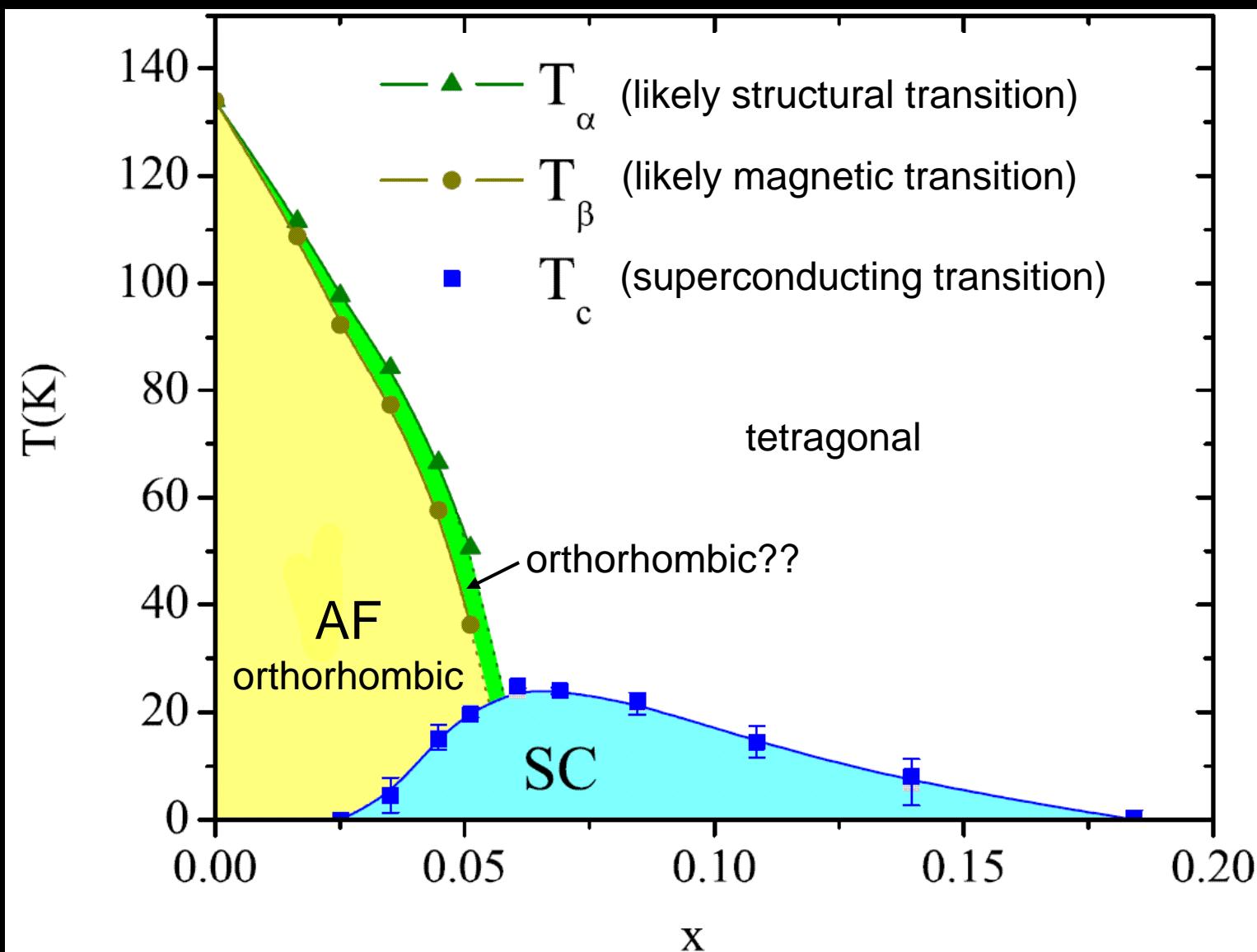


*Wollman, Van Harlingen, Lee, Ginsberg,  
Leggett, PRL 71, 2134 (1993)*

# A Short History of Iron-Pnictide Superconductivity

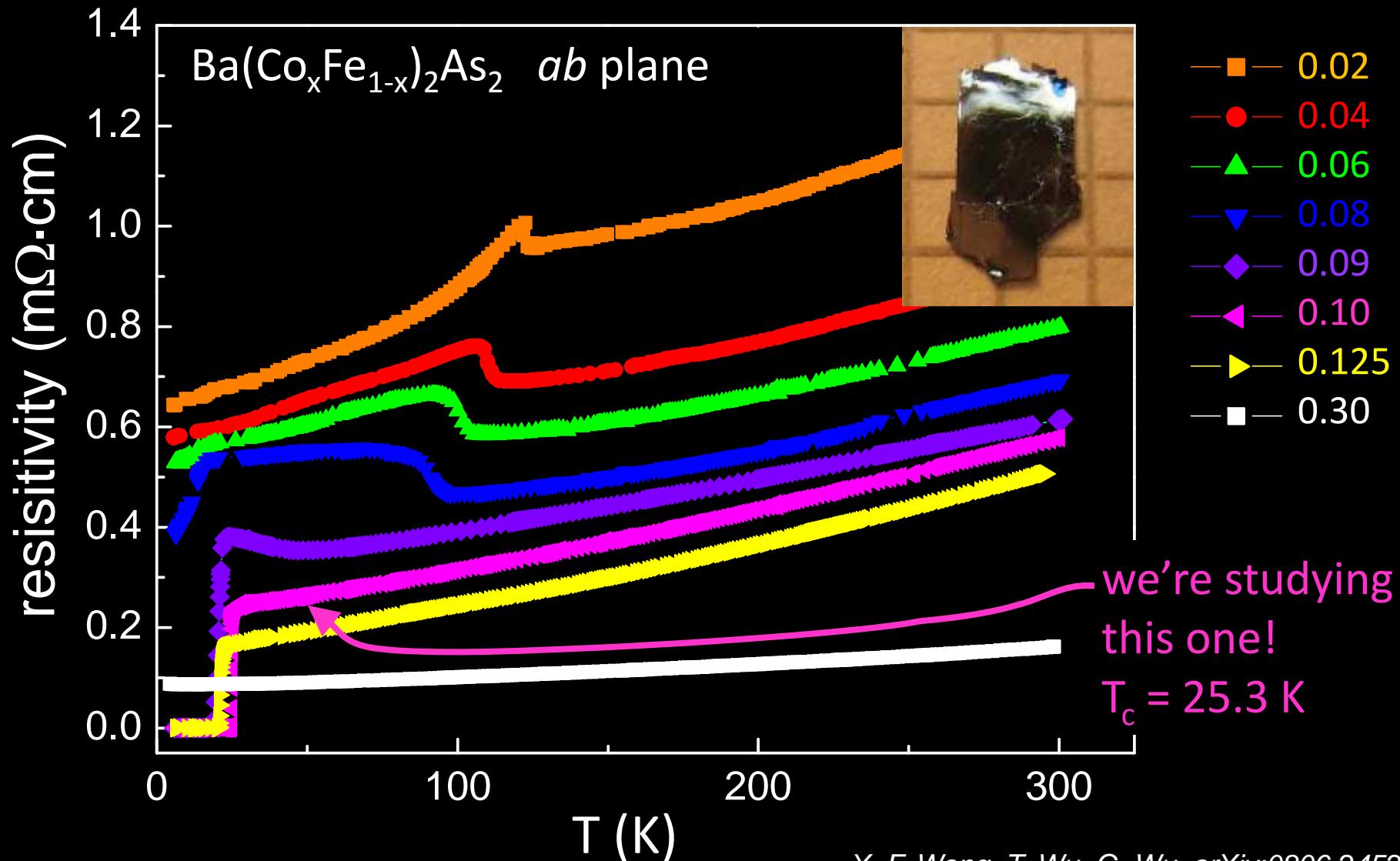


# $\text{Ba}(\text{Co}_x\text{Fe}_{1-x})_2\text{As}_2$ Phase Diagram

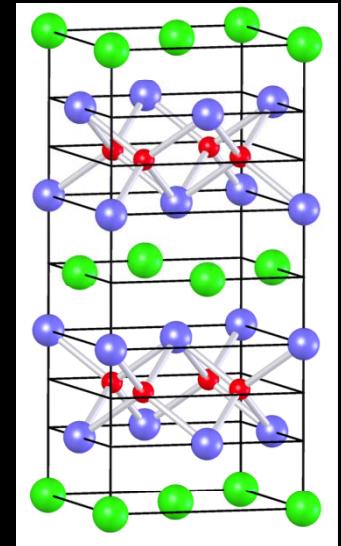


# Resistivity of our $\text{Ba}(\text{Co}_x\text{Fe}_{1-x})_2\text{As}_2$

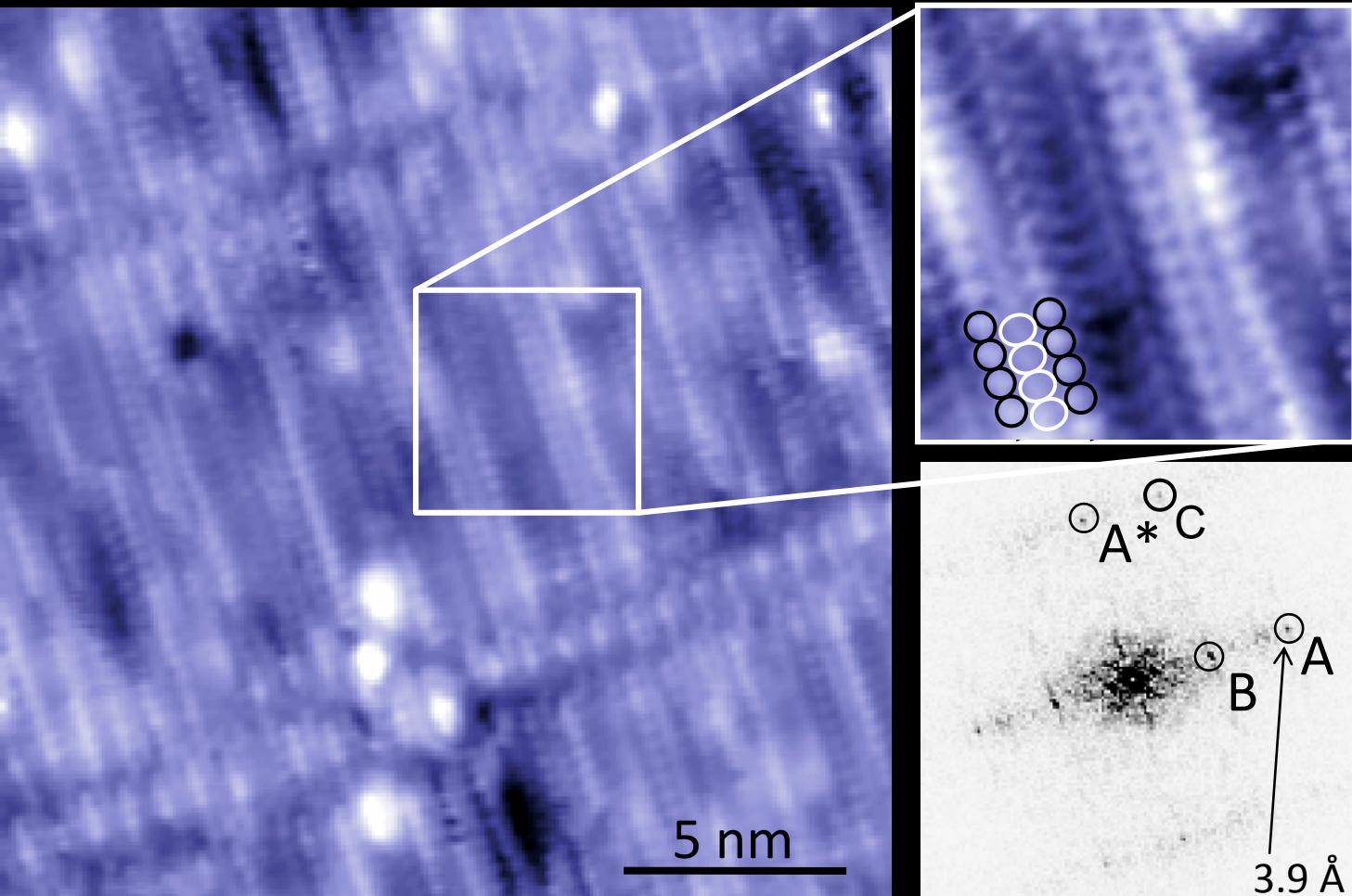
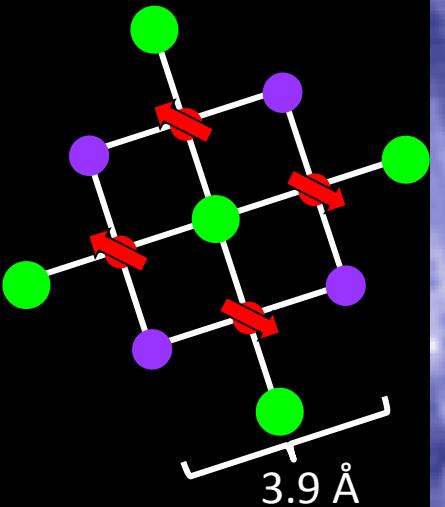
single crystals grown by Prof. XianHui Chen



# Atomic Resolution Topography



$\text{Ba}(\text{Co}_x\text{Fe}_{1-x})_2\text{As}_2$   
( $x=0.1$  nominal,  $T_c=25.3\text{K}$ )

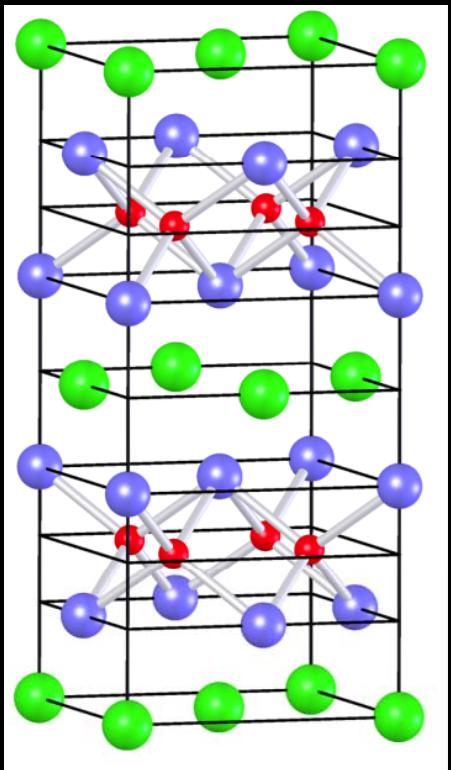


# $\text{Ba}(\text{Co}_x\text{Fe}_{1-x})_2\text{As}_2$ cleavage plane?

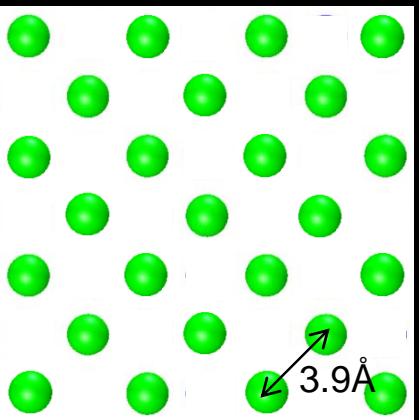
● Ba (2+)

○ As ] (1-)

● Fe

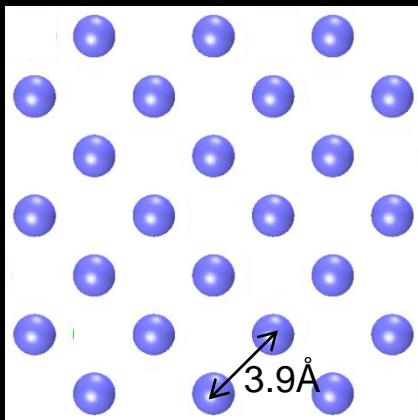


all Ba remain?



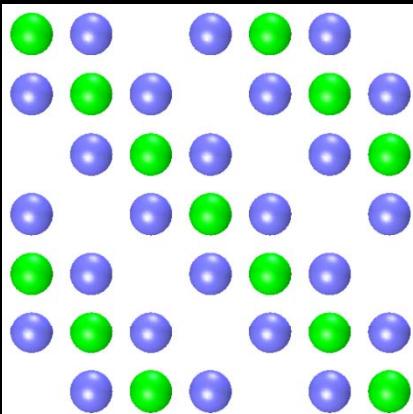
→ top Ba layer has charge 1+

all Ba removed?



→ top As layer has charge 1-

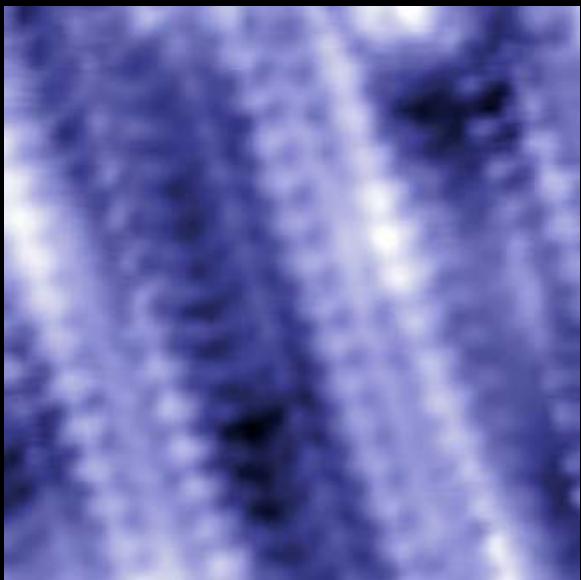
½ Ba removed, ½ Ba remain?



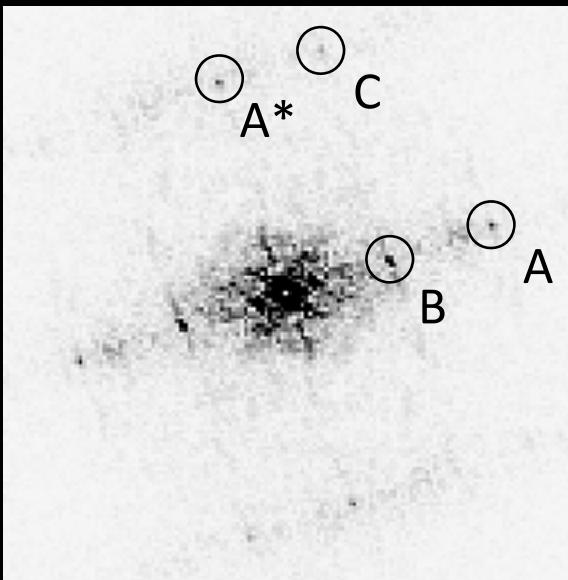
→ top layer is charge neutral

# Fourier Transform Analysis

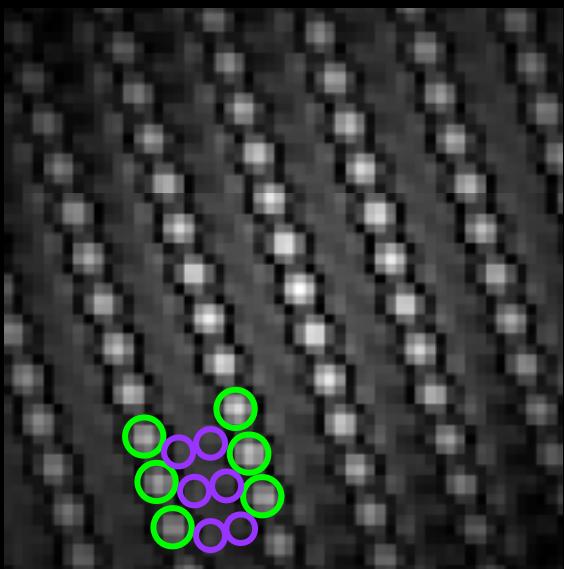
Raw data:



Fourier  
transform



↓ filter



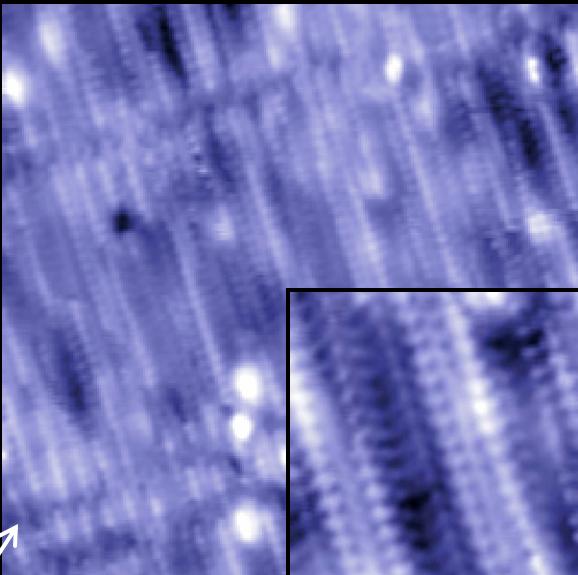
inverse  
Fourier  
transform

←



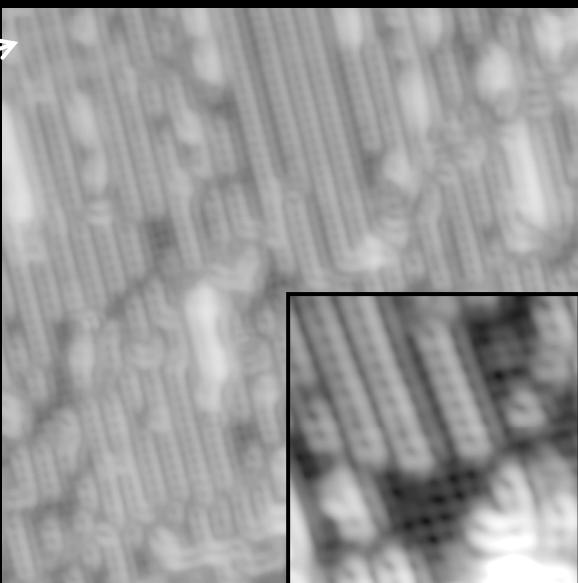
# Topography Comparison

5 nm

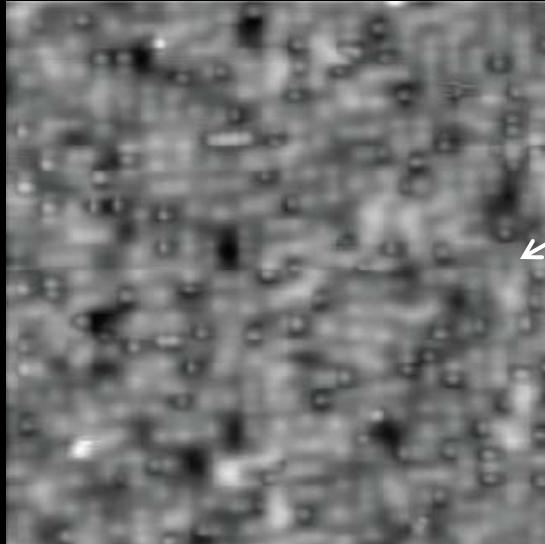


Yin *et al*, THIS WORK  
PRL 102, 097002 (2009)

low-T  
cleave  
(~ 30K)

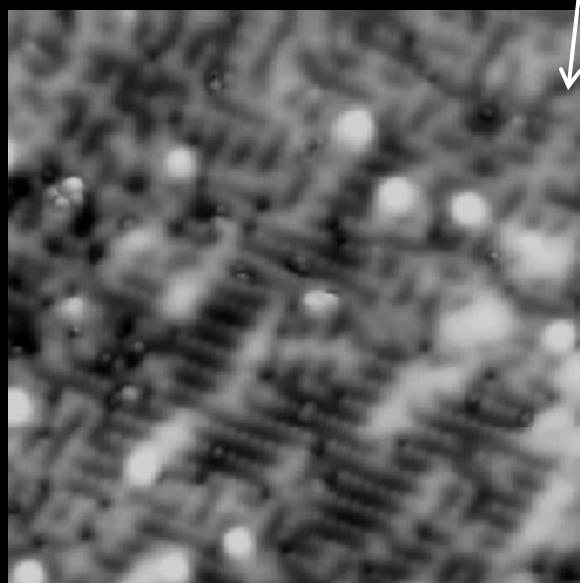


Boyer *et al*, arXiv:0806.4400



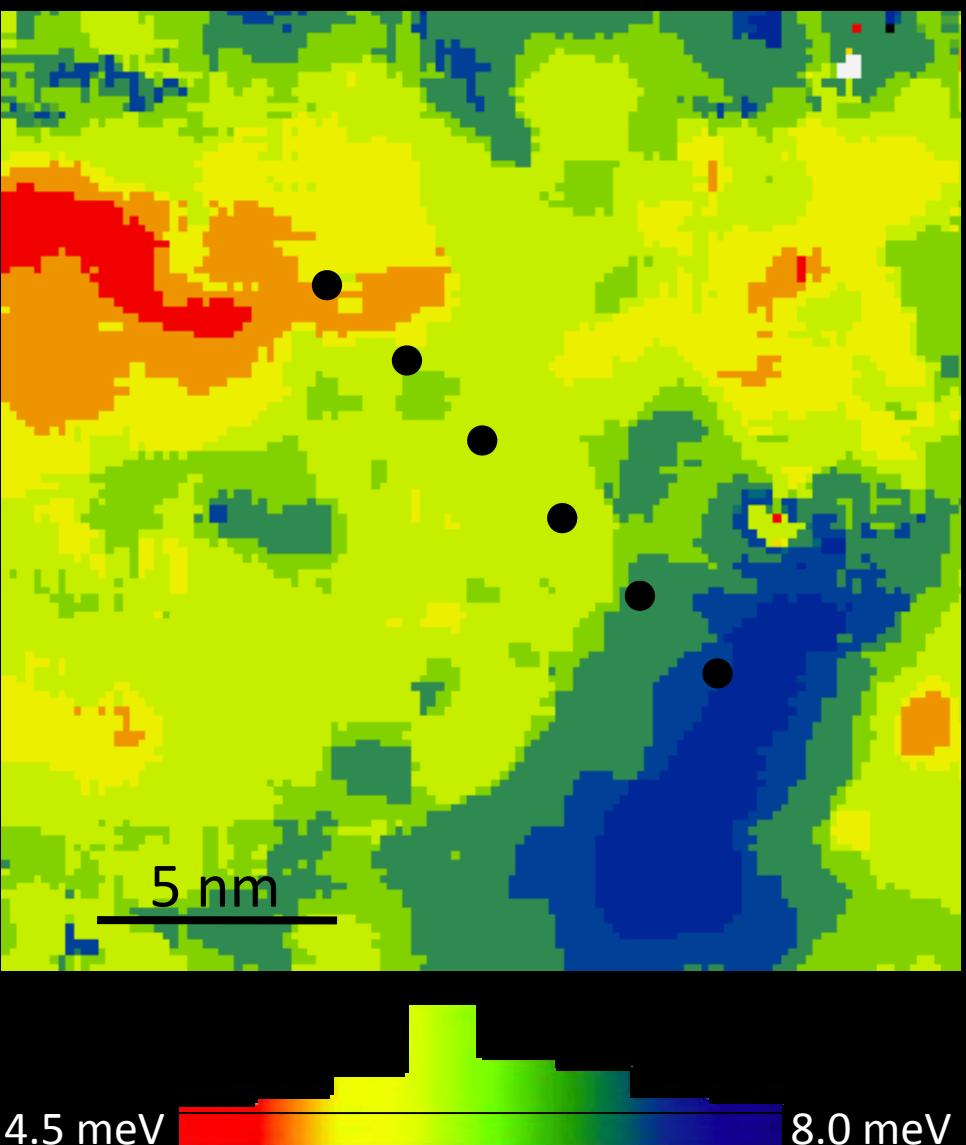
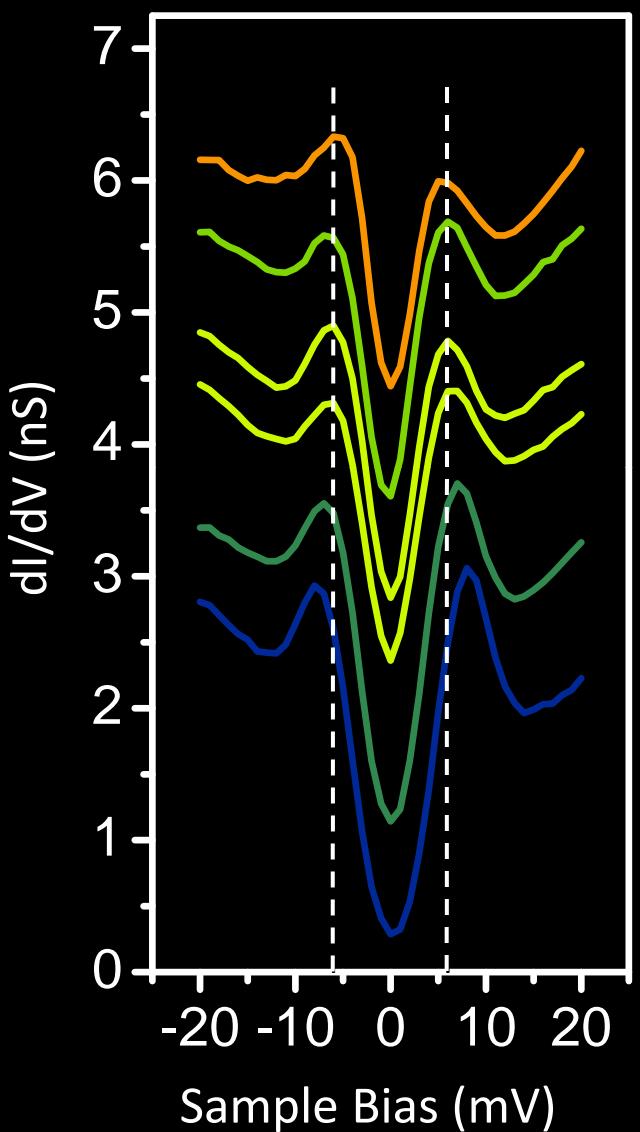
Hsieh *et al*, arXiv:0812.2289

300K cleave



Masse *et al*, arXiv:0812.4539

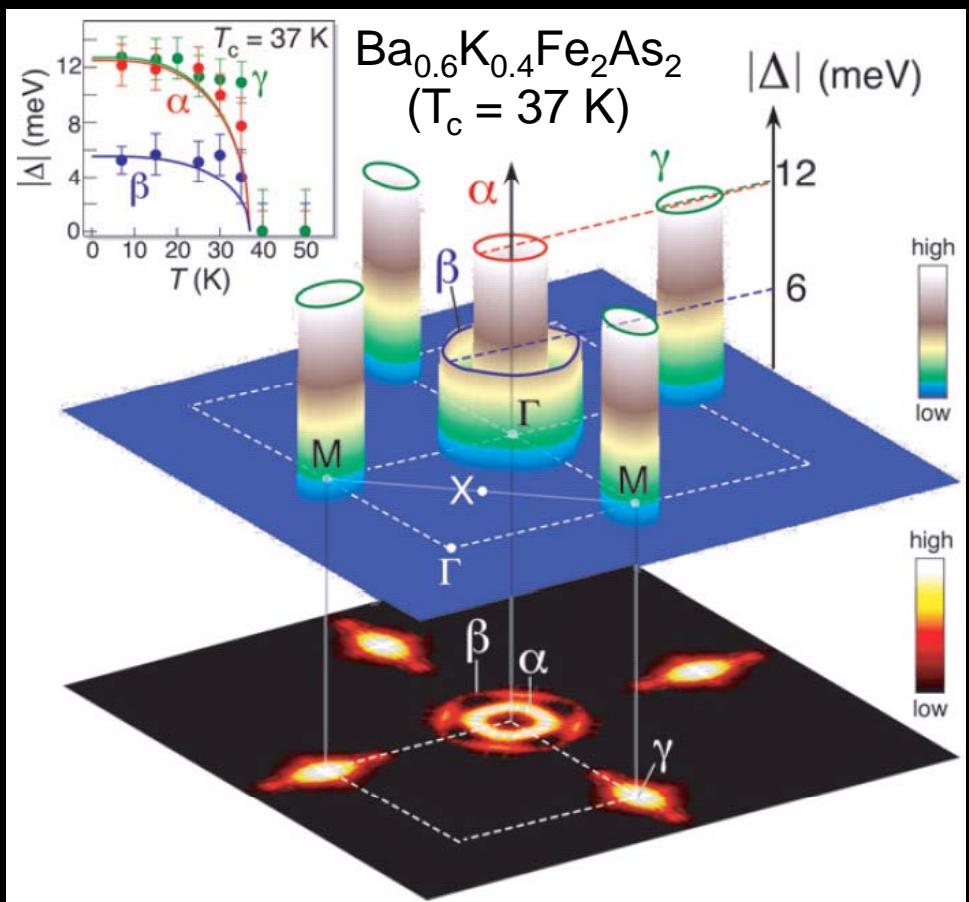
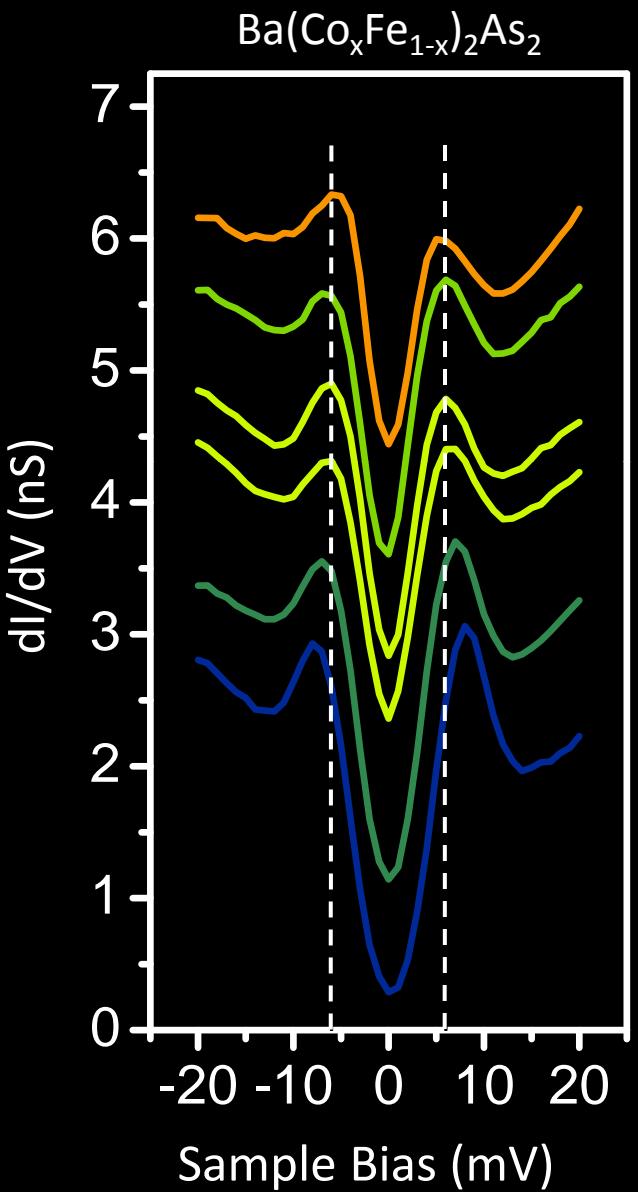
# Gap Mapping



measurements at  $T=6K$ ;  $k_B T = 0.5$  meV  
 $dV$  modulation = 1.5 meV

$$\bar{\Delta} = 6.25 \pm 0.73 \text{ meV (12\% variation)}$$

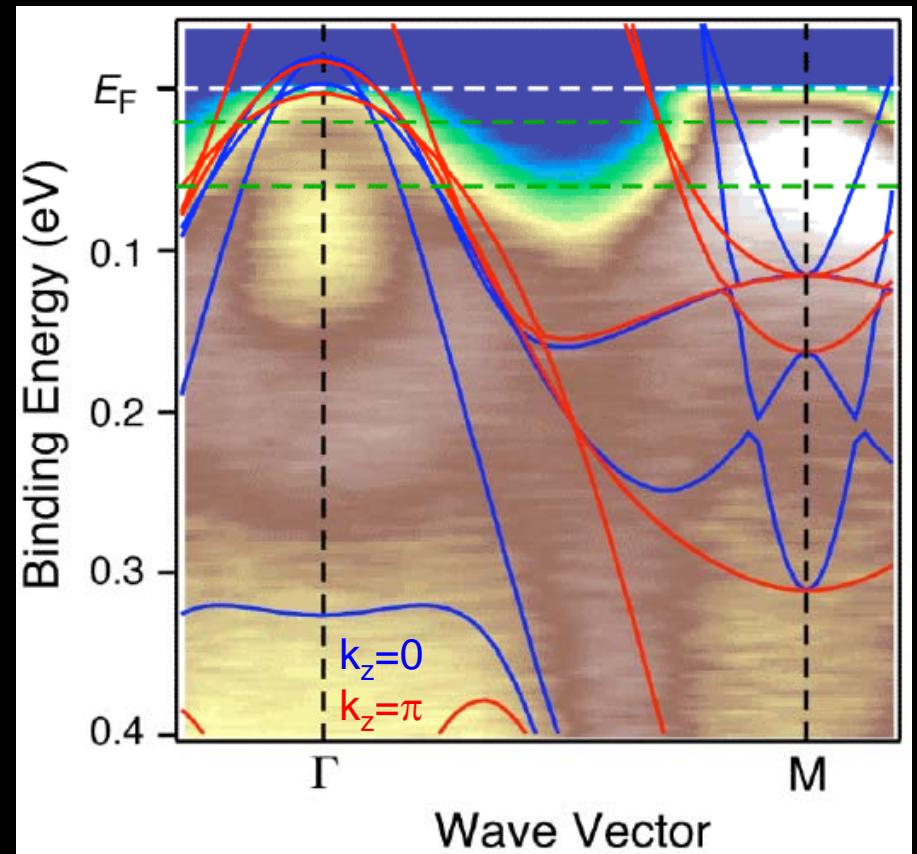
# Comparison to ARPES?



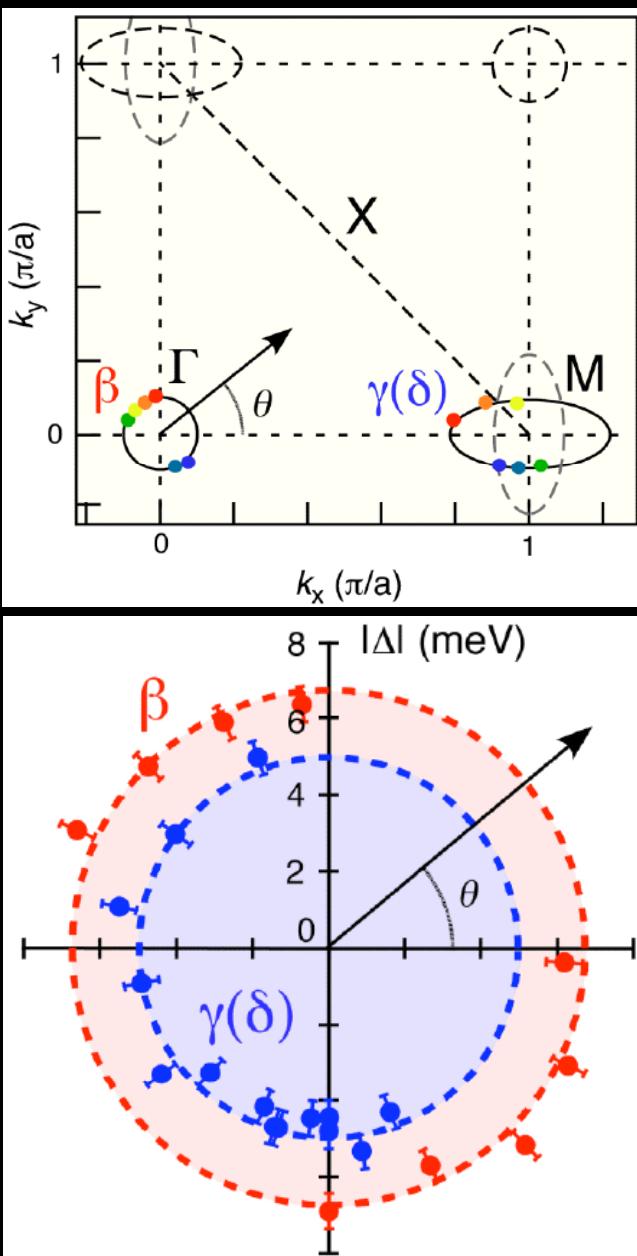
Ding, EPL 83, 47001 (2008)

# Comparison to ARPES

Rigid band model substantiated by  
 C. Liu *et al*, PRL 101, 177005 (2008)

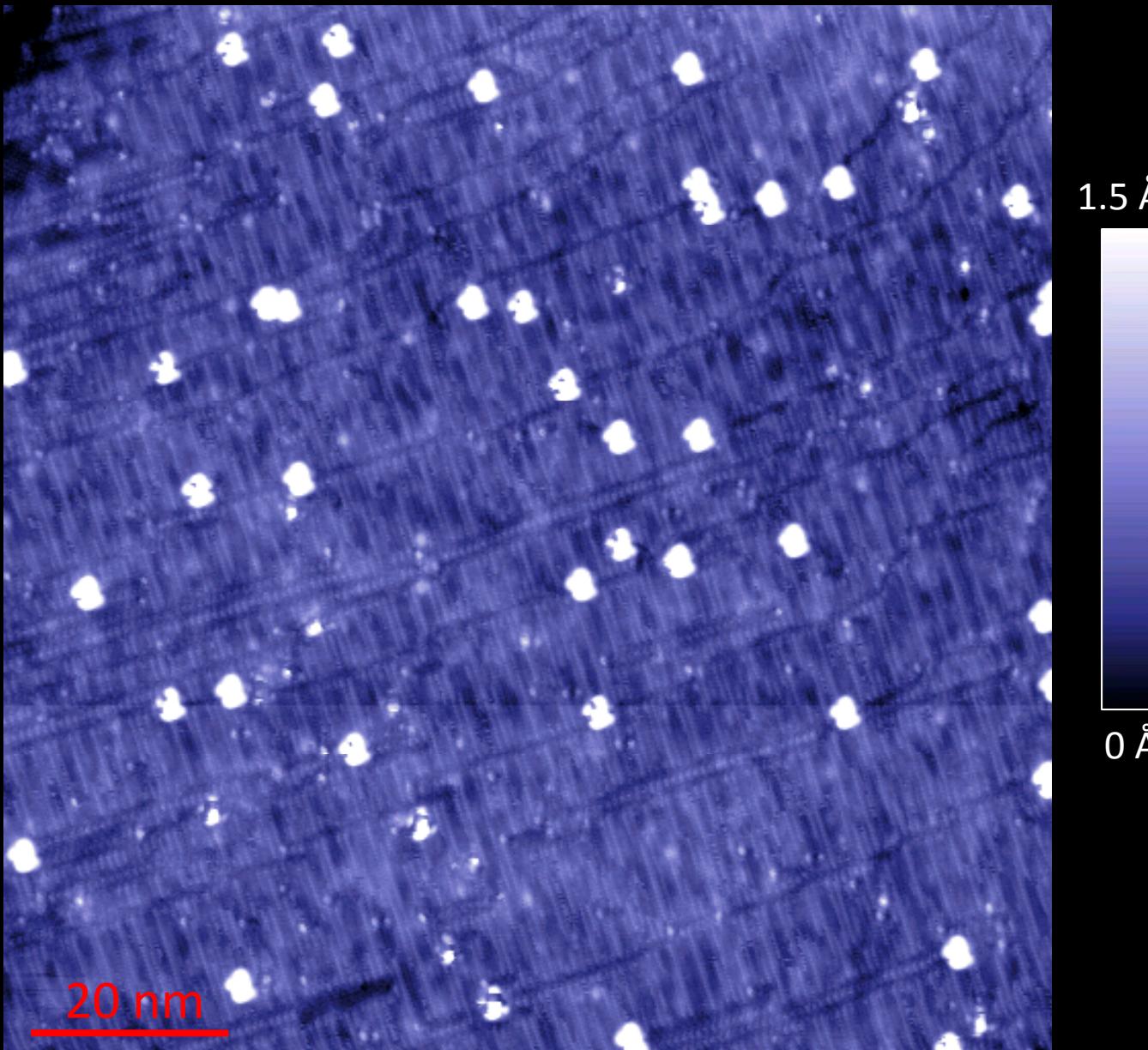


Fermi surfaces:  
 $\text{BaCo}_{0.15}\text{Fe}_{1.85}\text{As}_2$   
 $\text{BaFe}_2\text{As}_2$   
 $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$



Terashima *et al*, arXiv:0812.3704

# Topography

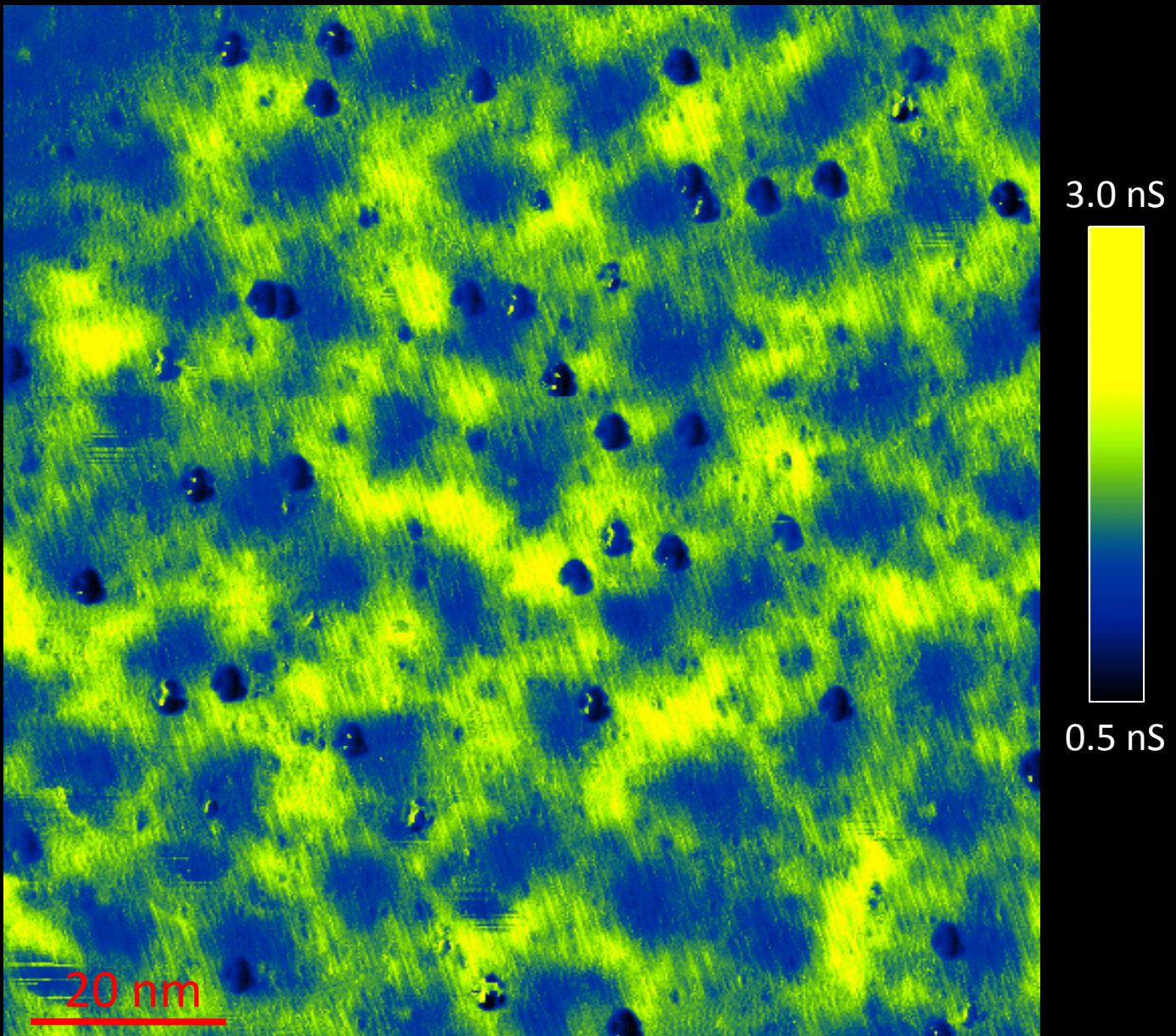




# Vortices at 9T

$dI/dV$  at 5 mV

(approximate  
coherence  
peak energy)

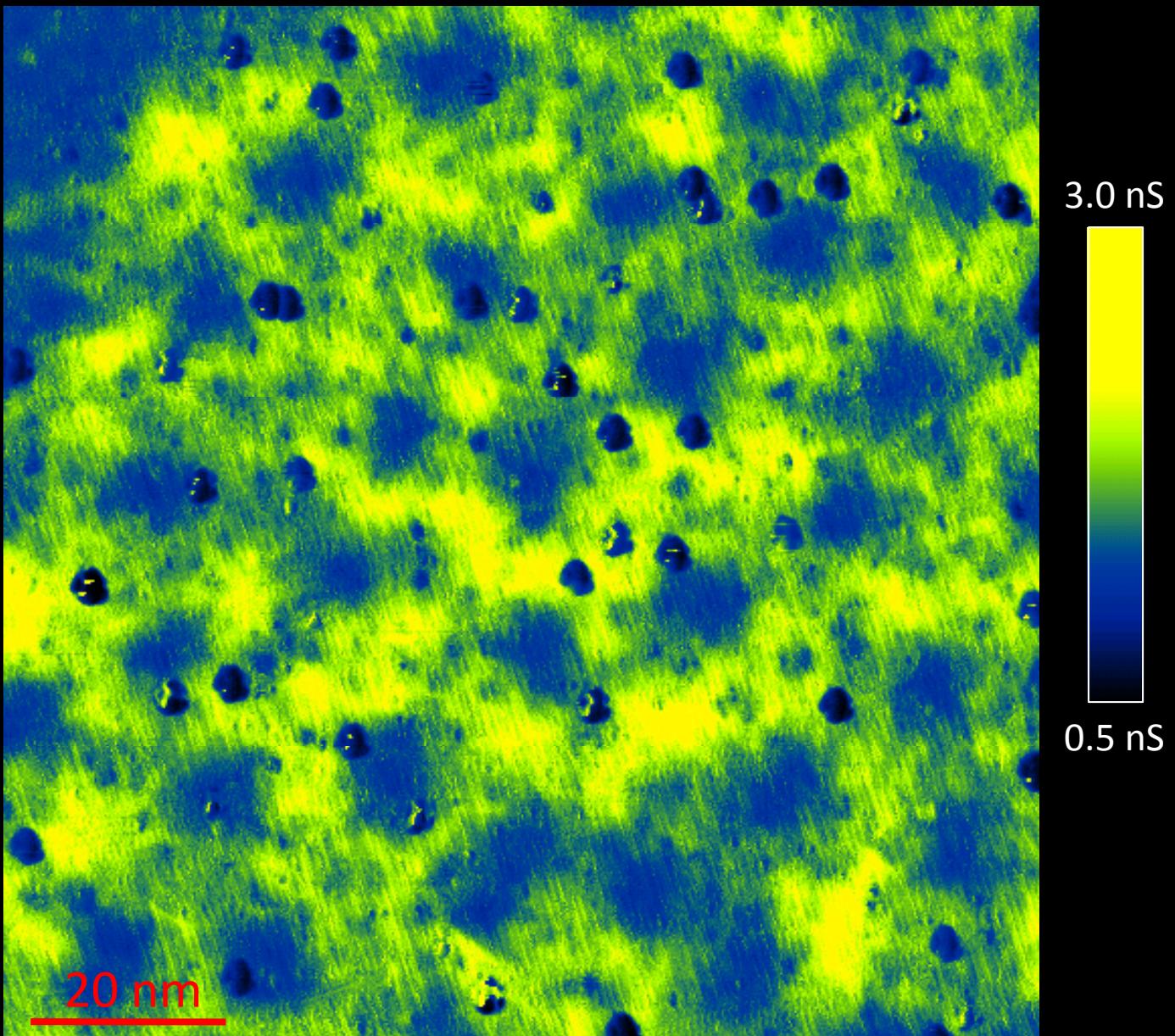




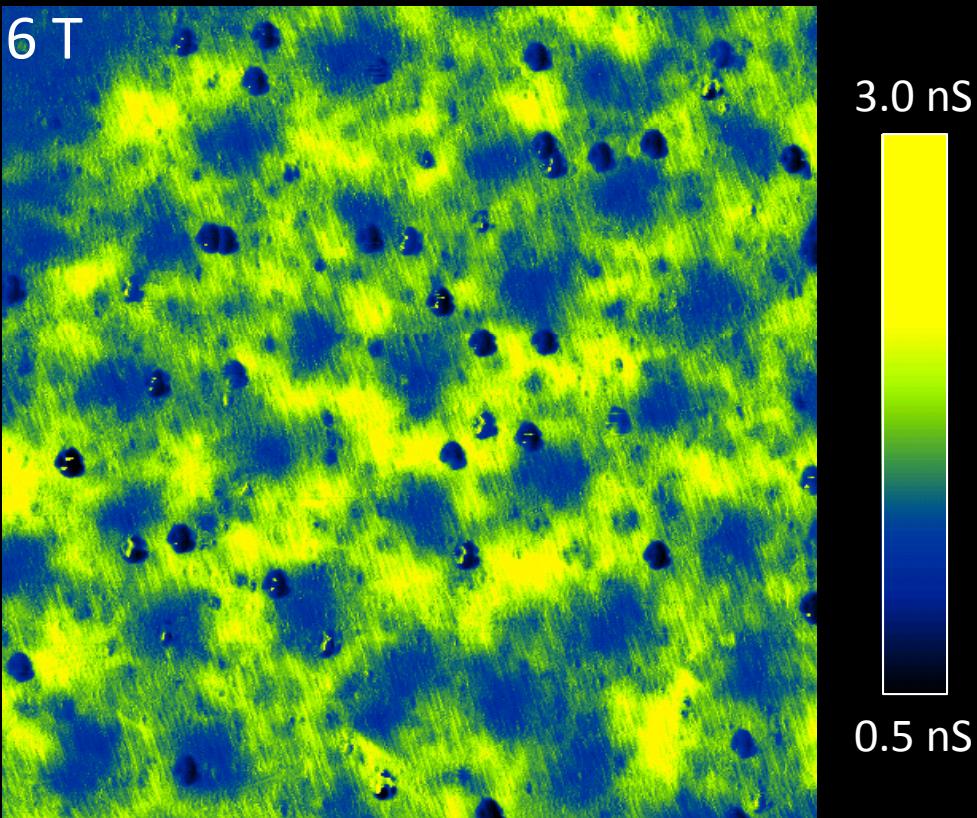
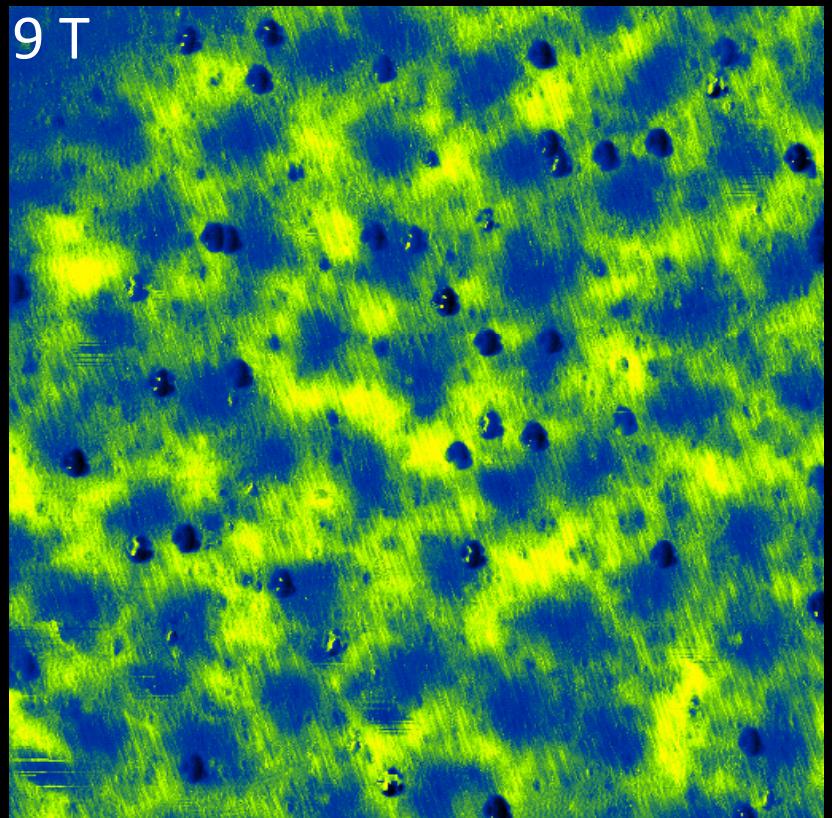
# Vortices at 6T

$dI/dV$  at 5 mV

(approximate  
coherence  
peak energy)



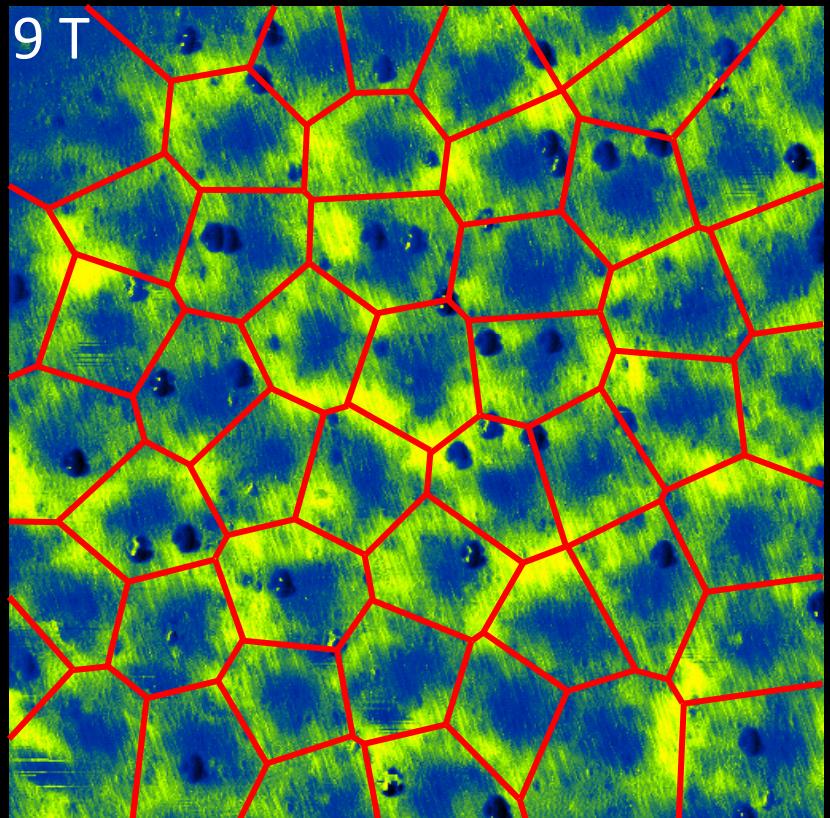
# Flux Measurement



3.0 nS

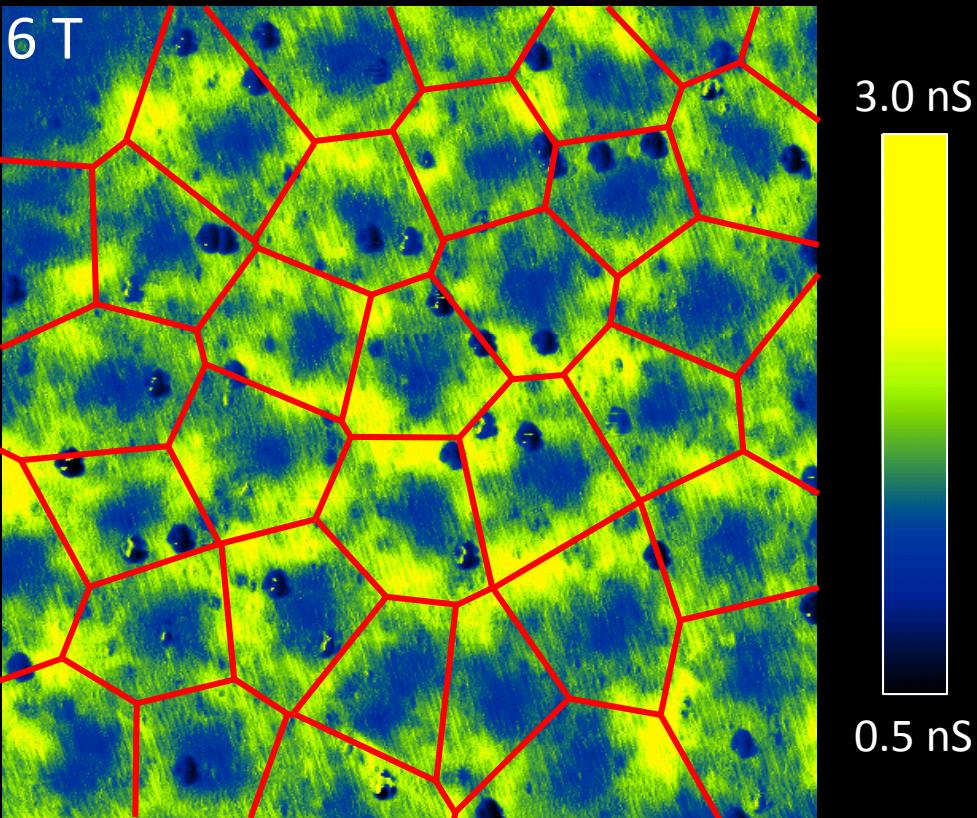
0.5 nS

# Flux Measurement



average vortex area =  $228 \text{ nm}^2$

$$\rightarrow \phi(9T) = 2.05 \times 10^{-15} \text{ T}\cdot\text{m}^2$$



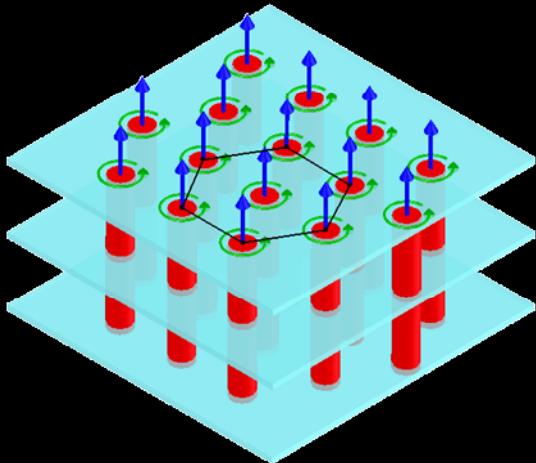
average vortex area =  $362 \text{ nm}^2$

$$\rightarrow \phi(6T) = 2.17 \times 10^{-15} \text{ T}\cdot\text{m}^2$$

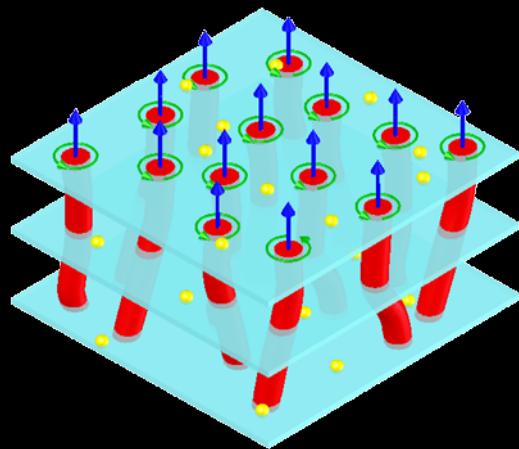
Single magnetic flux quantum:  $\Phi_0 = 2.07 \times 10^{-15} \text{ T}\cdot\text{m}^2$

# Vortex pinning possibilities

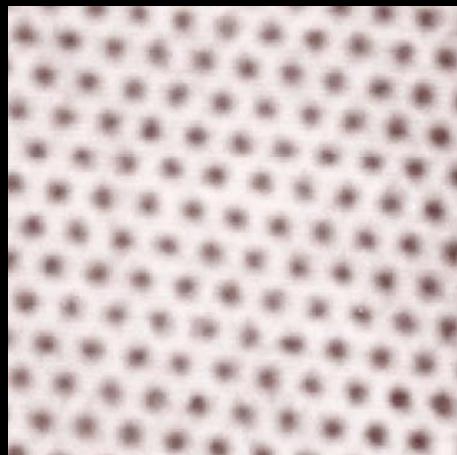
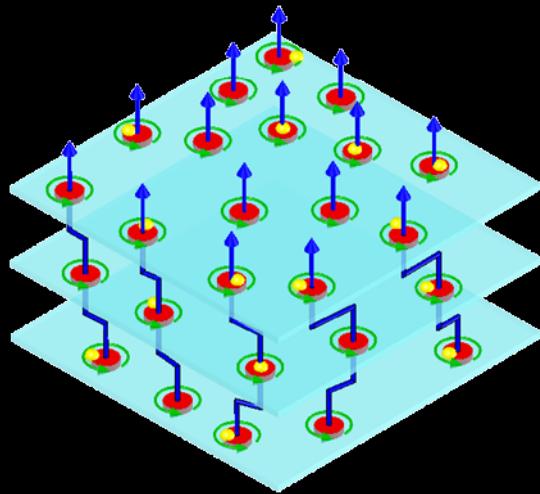
(1) no strong pinners  
inter-vortex forces dominate  
→ lattice formation



(2) strong pinners exist  
low anisotropy  
→ vortices bend slightly  
to accommodate pinners

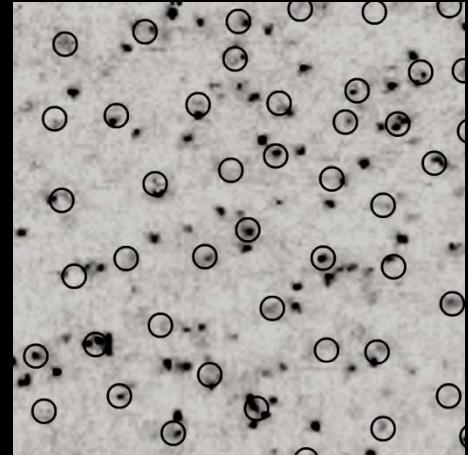


(3) strong pinners exist  
high anisotropy  
→ vortices pancake  
each pancake pins independently



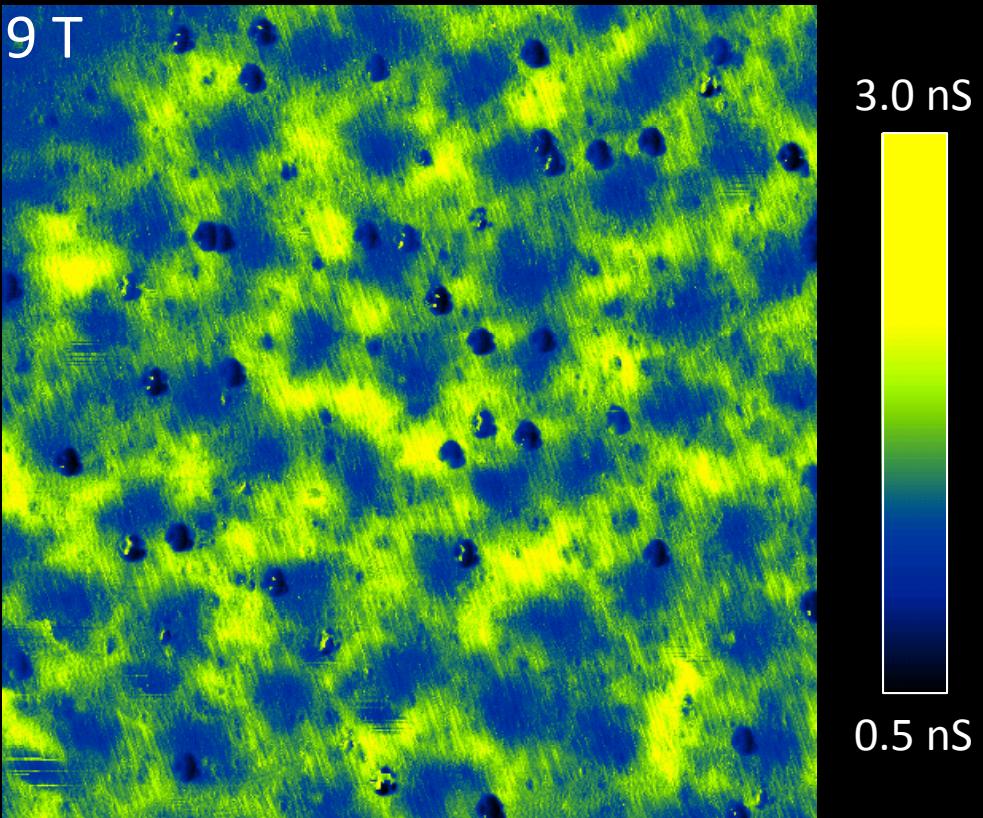
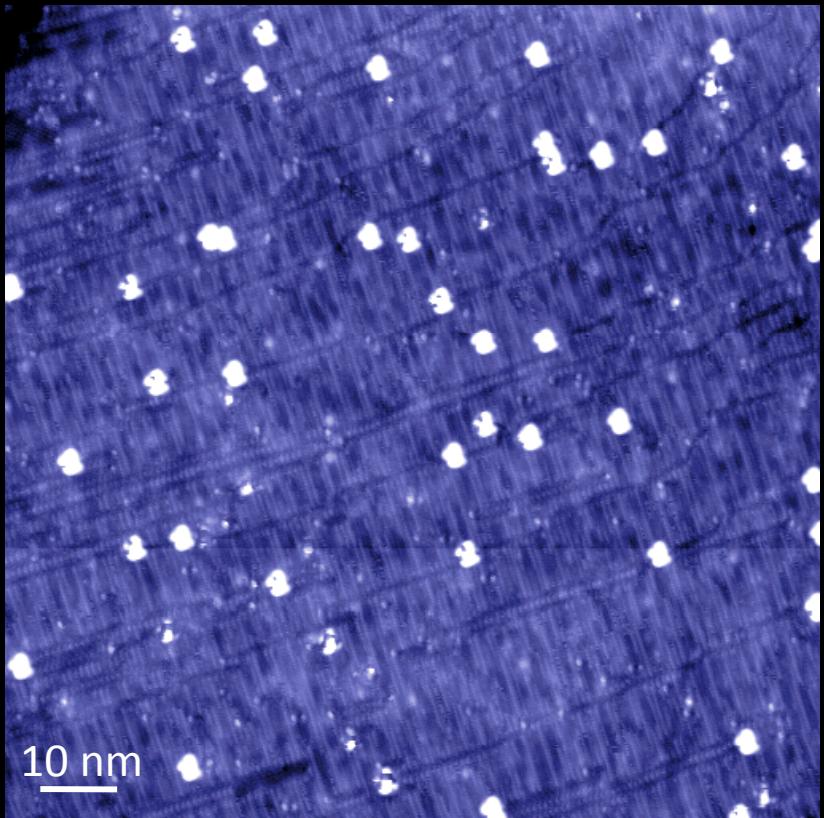
NbSe<sub>2</sub>

ideal case  
for applications



Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>8</sub>

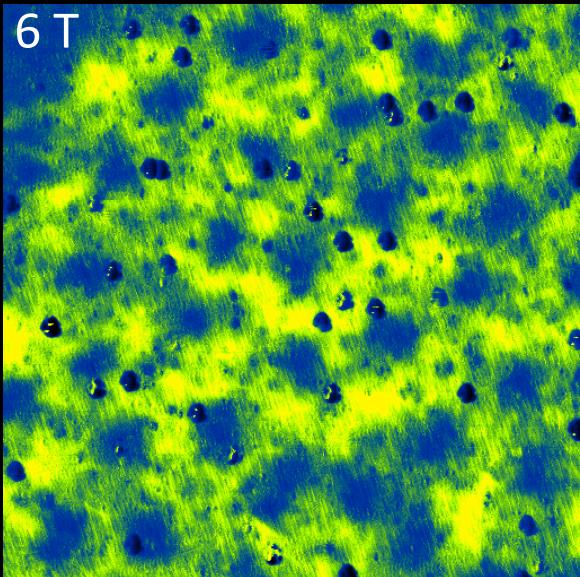
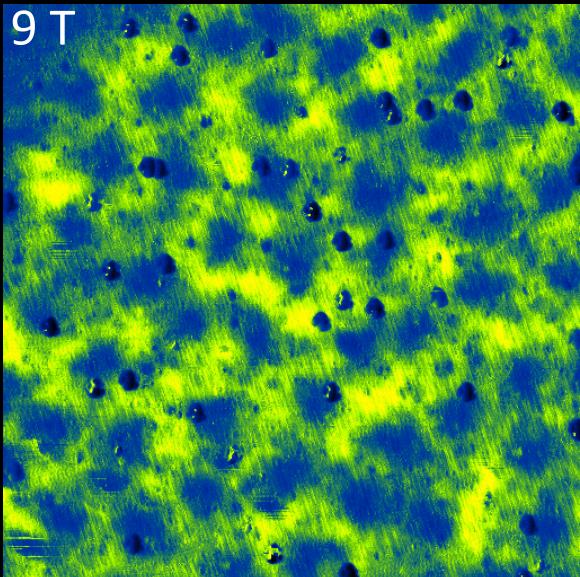
# Are Vortices Pinned to Surface Impurities?



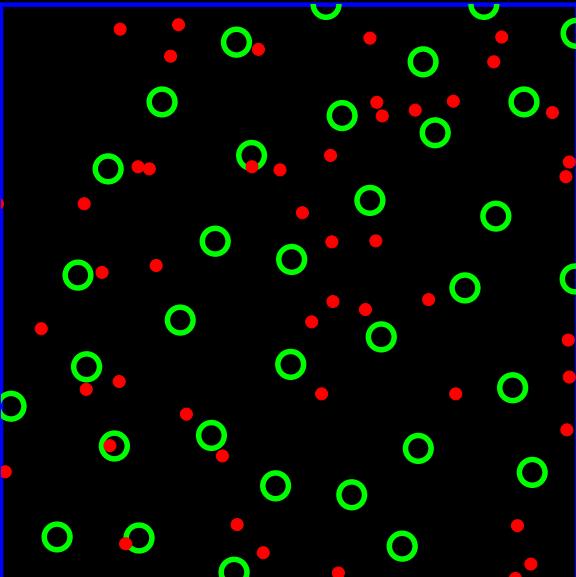
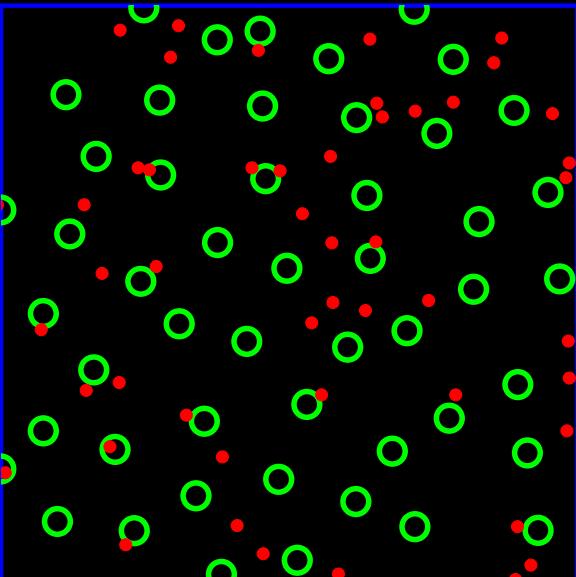
# Are Vortices Pinned to Surface Impurities?



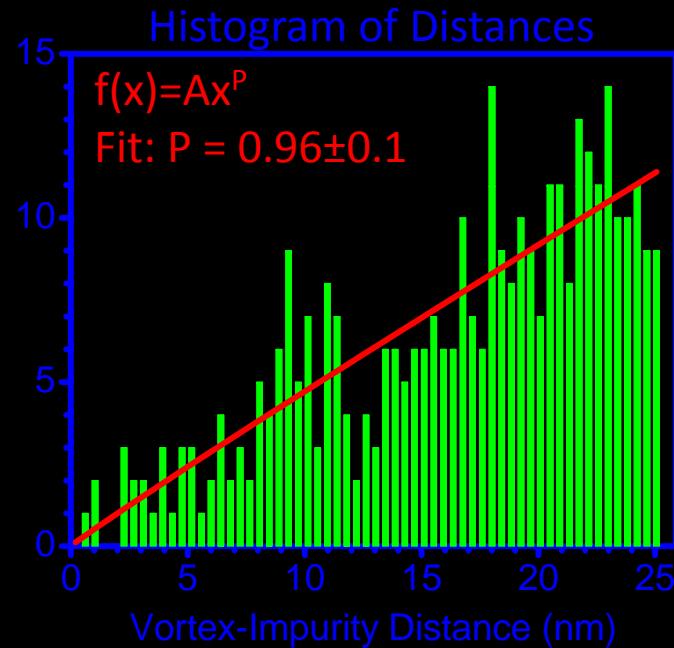
Raw Data



Idealized Data



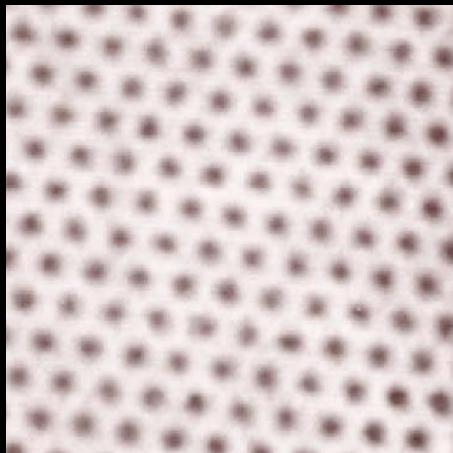
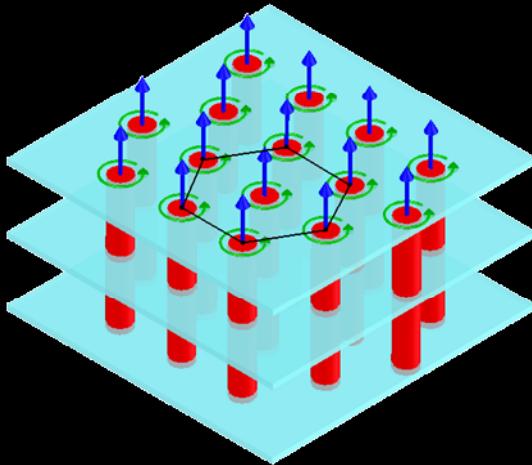
○ vortex, radius  $\xi_0 = 2.76 \text{ nm}$   
● impurity



Linear fit!  
→ Vortices are not pinned  
to visible surface impurities

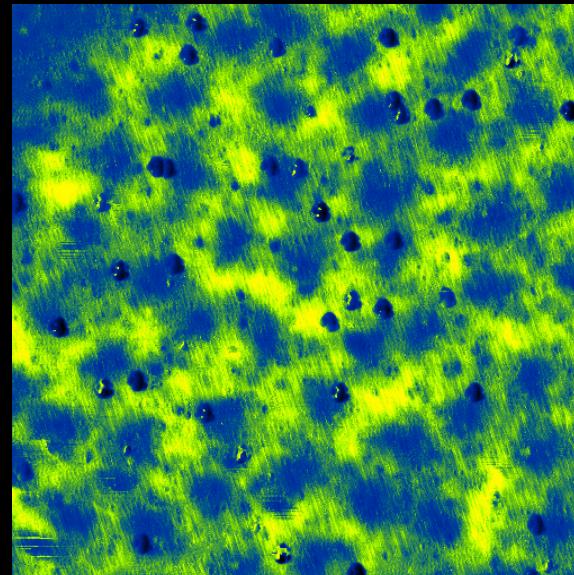
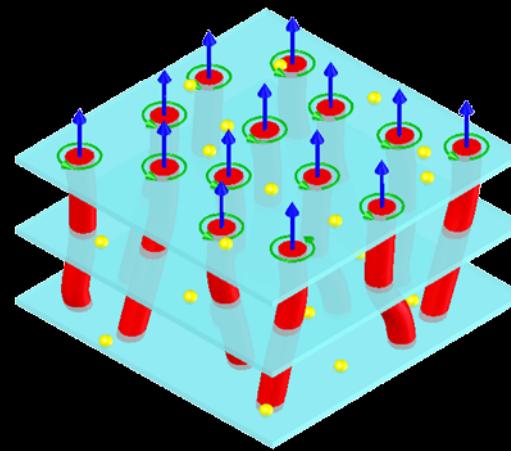
# Vortex pinning possibilities

(1) no strong pinners  
inter-vortex forces dominate  
→ lattice formation



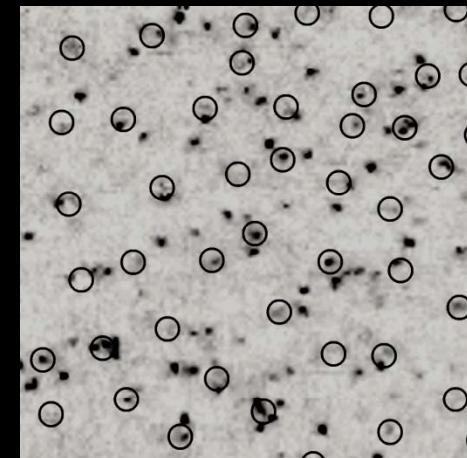
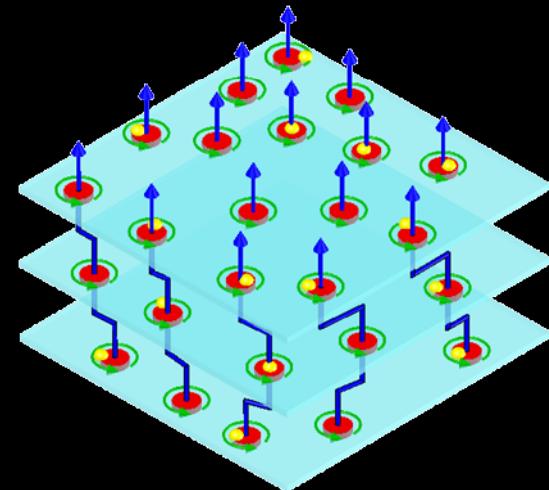
$\text{NbSe}_2$

(2) strong pinners exist  
low anisotropy  
→ vortices bend slightly  
to accommodate pinners



$\text{Ba}(\text{Co}_x\text{Fe}_{1-x})_2\text{As}_2$

(3) strong pinners exist  
high anisotropy  
→ vortices pancake  
each pancake pins independently

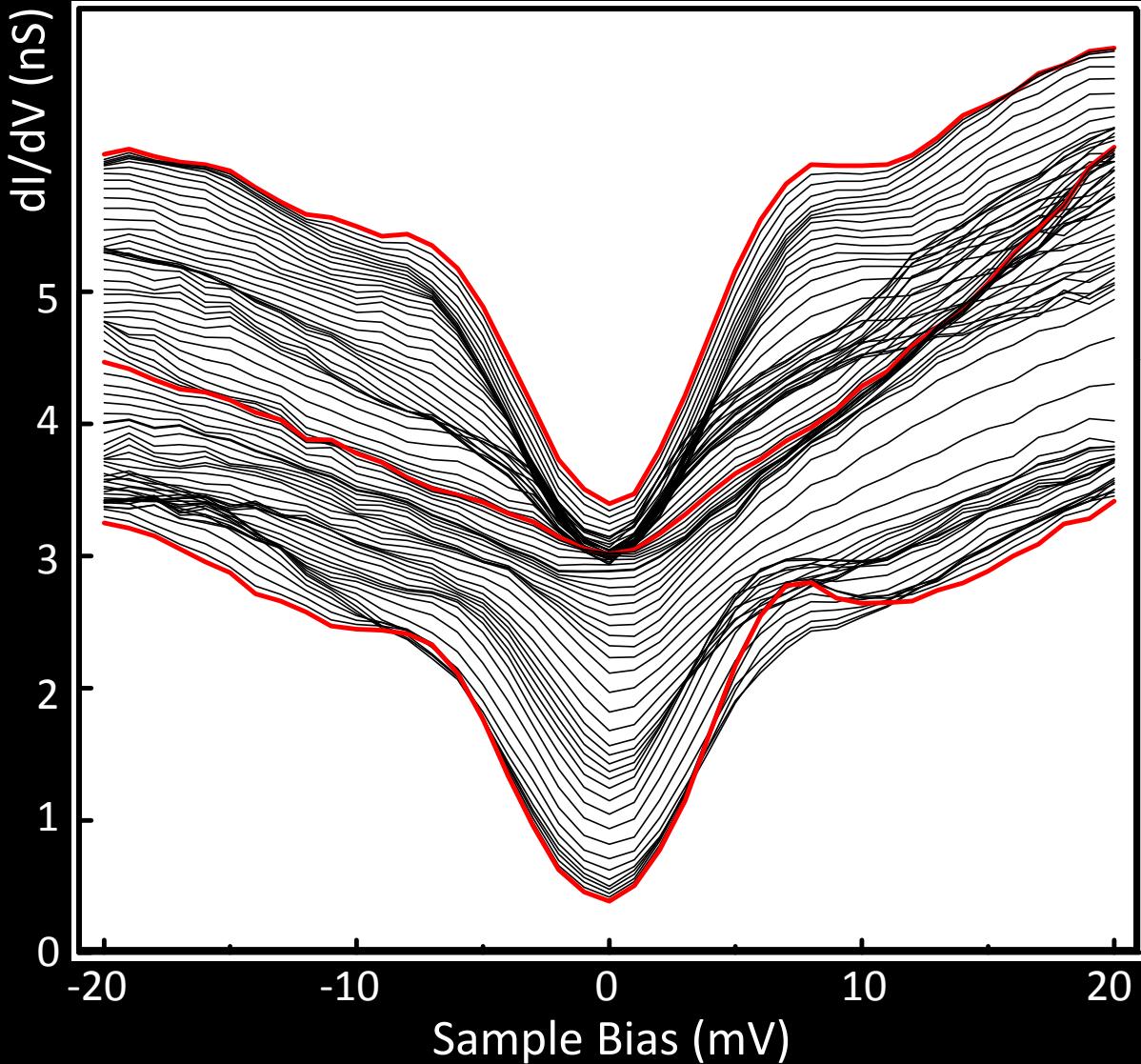
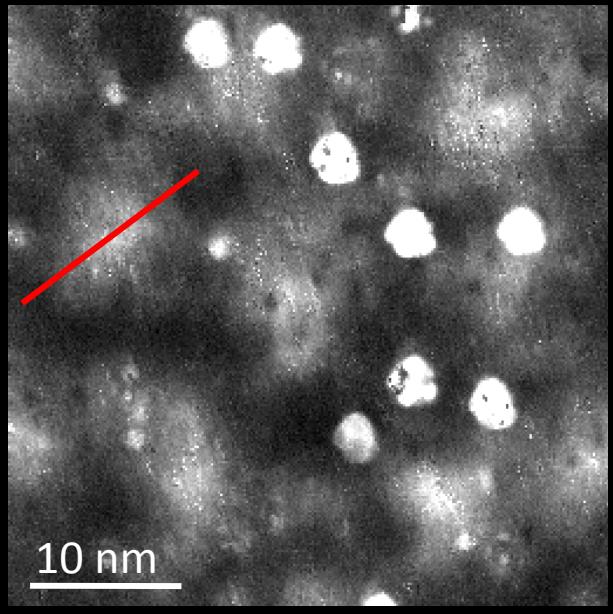


$\text{Bi}_2\text{Sr}_2\text{Ca}\text{Cu}_2\text{O}_8$

# Vortex Spectroscopy

dI/dV map at 0 mV

(Fermi level)

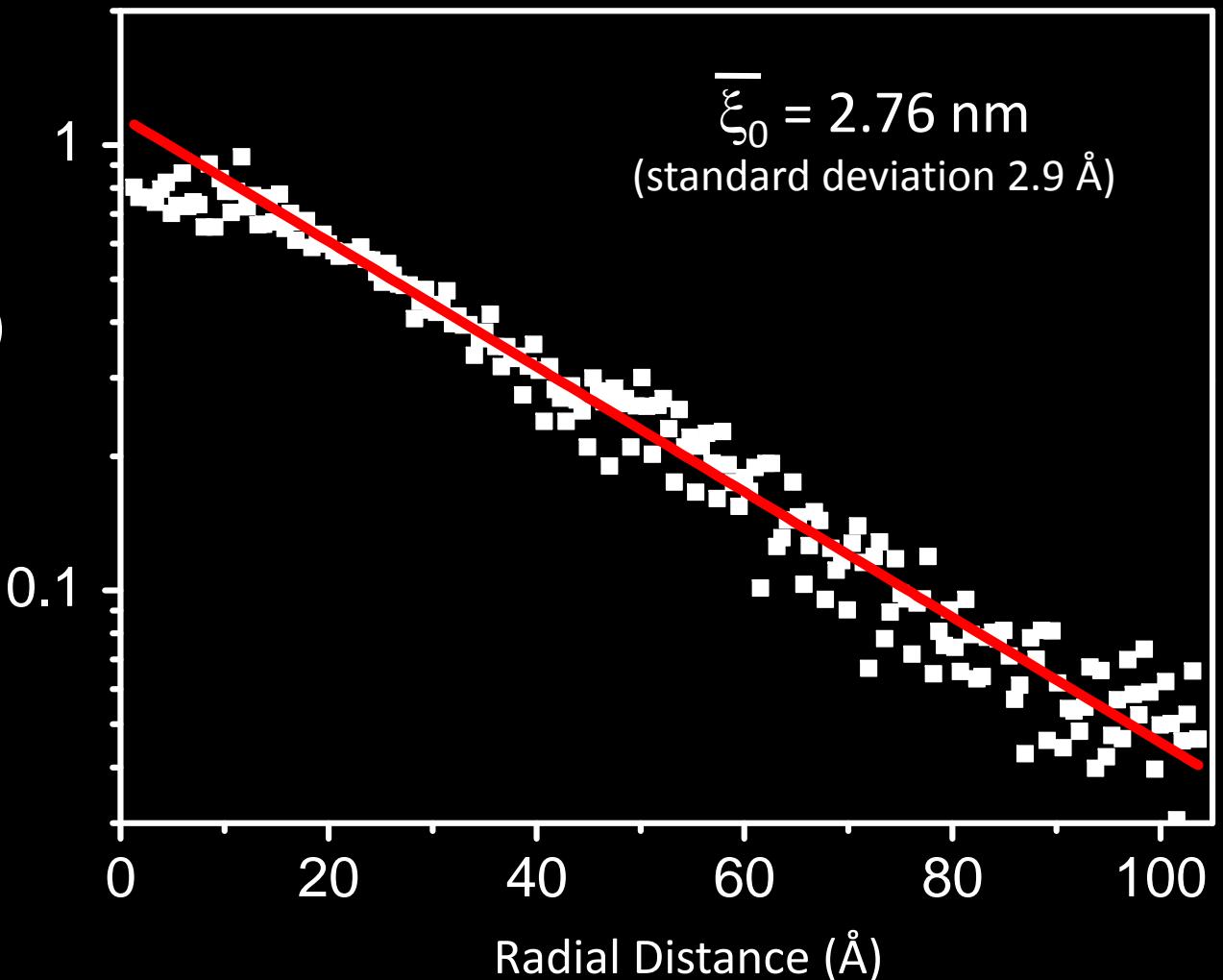


measurements at  $T=6\text{K}$ ;  $k_B T = 0.5 \text{ meV}$   
 $dV$  modulation = 1.5 meV



# Coherence Length

Radially Averaged  
Zero Bias  $dI/dV$  (nS)

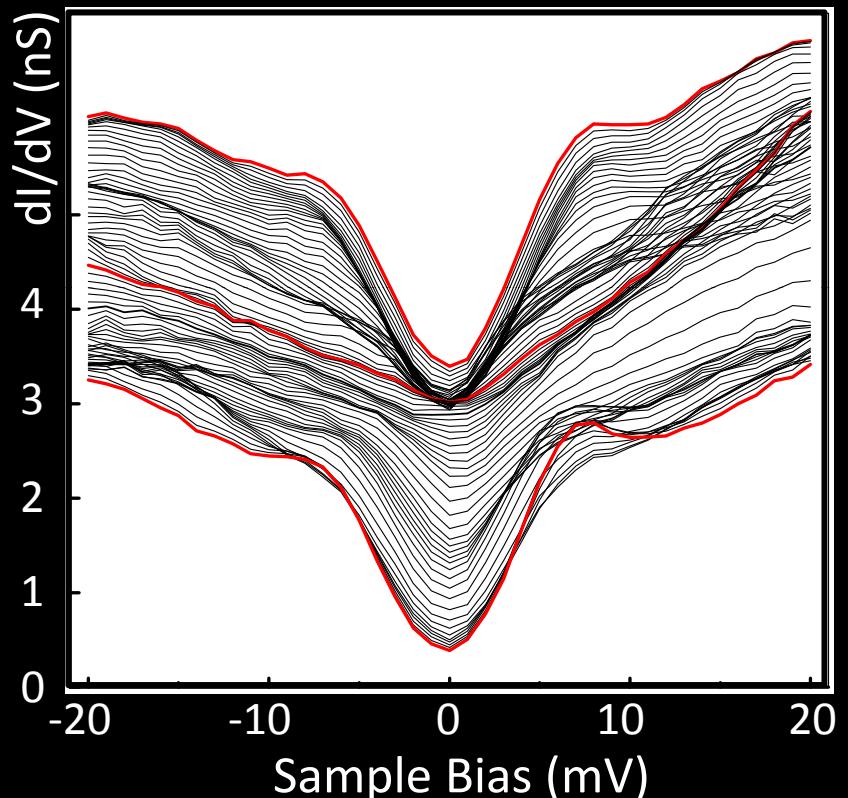


Note: this  $\xi_0$  translates to  $H_{c2} = 43\text{T}$   
[close to 50T extrapolated, Yamamoto, APL 94, 062511 (2009)]

# Compare to Conventional *s*-wave Vortices



$\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$

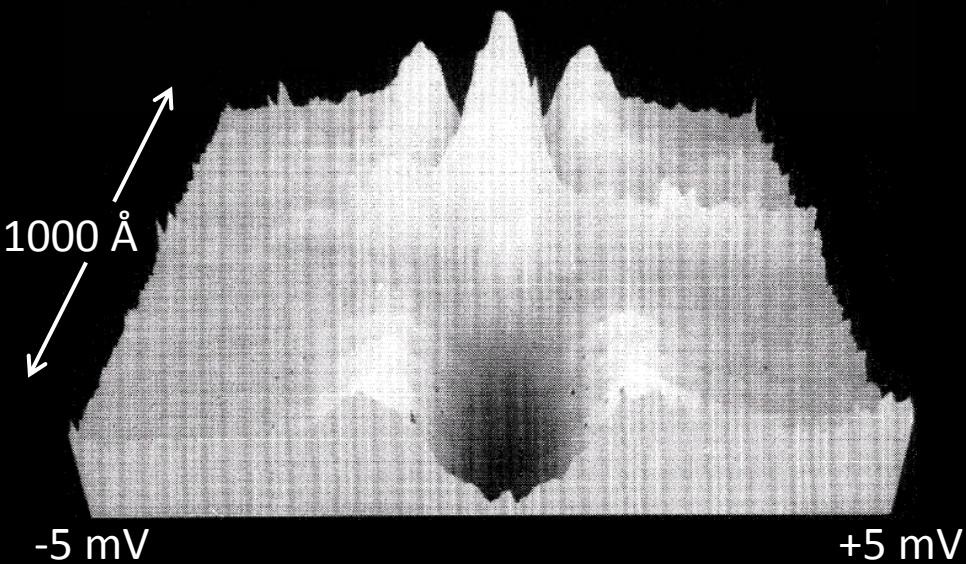


$T_c = 25 \text{ K}$ ; measurement  $T = 6 \text{ K}$   
 $\rightarrow T \sim T_c/4$

$$\text{Theory: } E = \frac{1}{2} \Delta^2 / \epsilon_F$$

Caroli, deGennes, Matricon, PRL 9, 307 (1964)

STM experiments on  $\text{NbSe}_2$



Hess, PRL 62, 214 (1989)

$T_c = 7.2 \text{ K}$ ; measurement  $T = 1.45 \text{ K}$   
 $\rightarrow T \sim T_c/5$



# Clean Limit

Residual resistivity:  $\rho_0 = 0.23 \text{ m}\Omega\cdot\text{cm}$   
Hall coefficient:  $R_H = 11 \times 10^{-9} \text{ m}^3/\text{C}$

bulk values,  
measured by Xianhui Chen

→ electronic mean free path:

$$\ell = \hbar (3\pi^2)^{1/3} / (e^2 n^{2/3} \rho_0) \sim 81 \text{ \AA}$$

Compare to coherence length:  $\xi_0 = 27.6 \text{ \AA}$

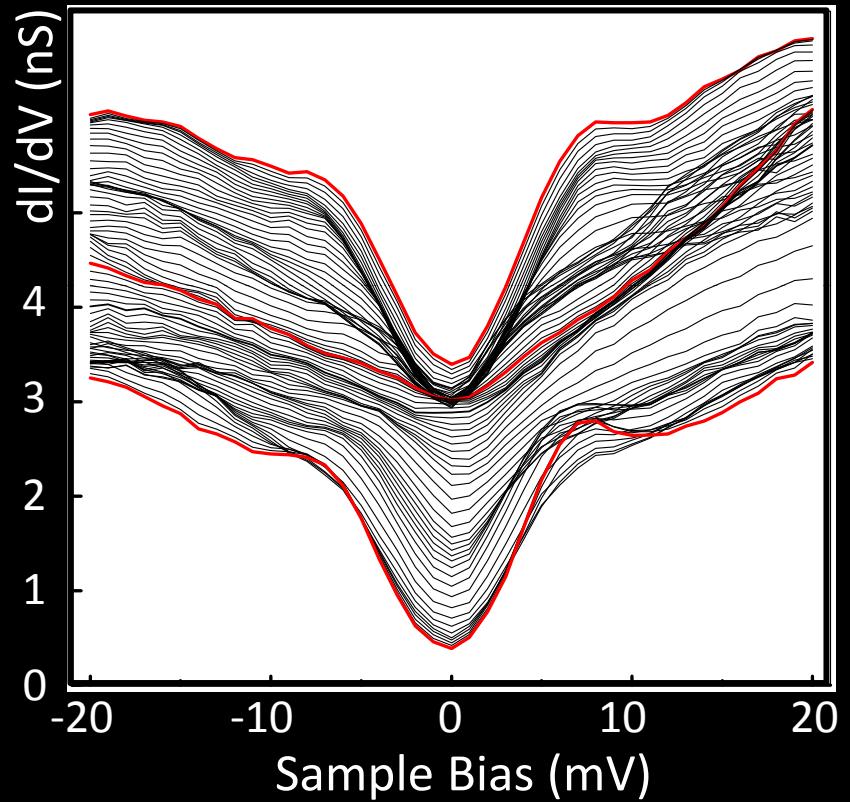
→ Clean limit

→ Wouldn't expect suppression of *s*-wave vortex core states

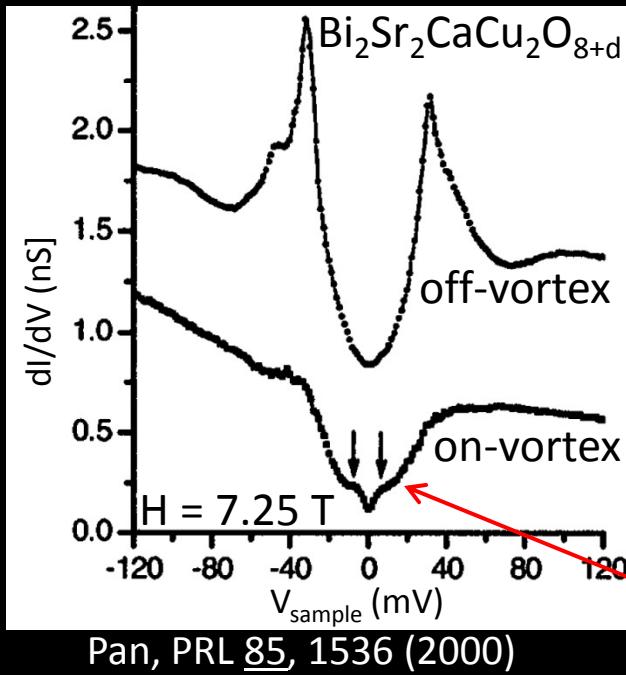
# Compare to $d$ -wave Vortex Spectroscopy



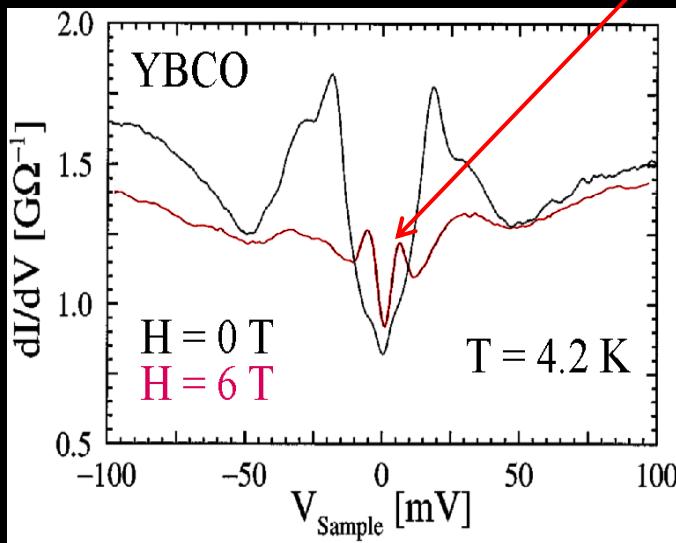
$\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$



measurements at  $T=6\text{K}$ ;  $k_B T = 0.5 \text{ meV}$   
 $dV$  modulation =  $1.5 \text{ meV}$



$$E \sim \Delta/4$$

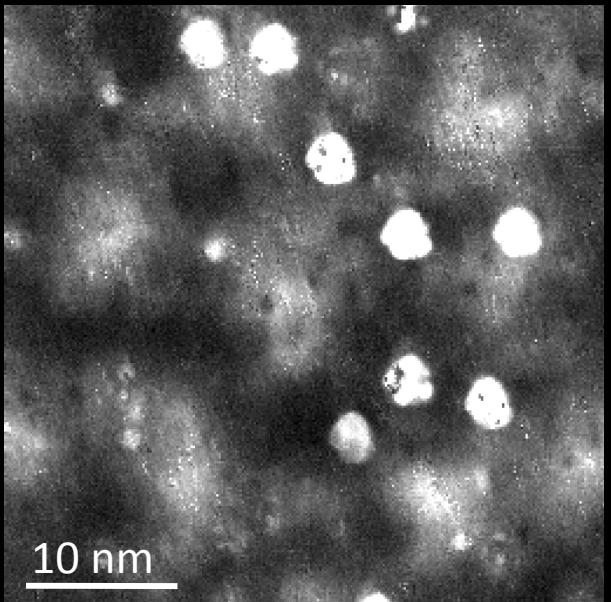


Maggio-Aprile, PRL 75, 2754 (1995)

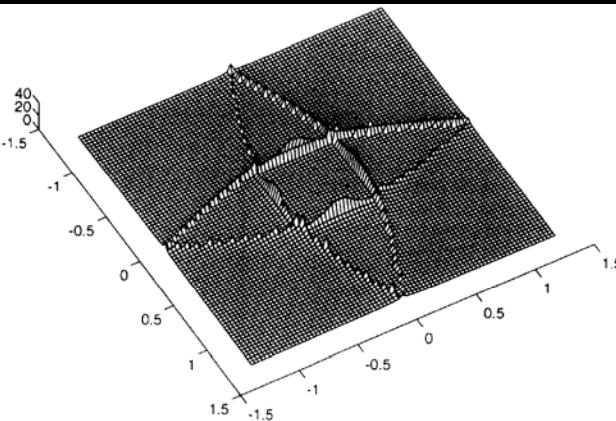
# Compare to Theoretical $d$ -wave Vortex Shape



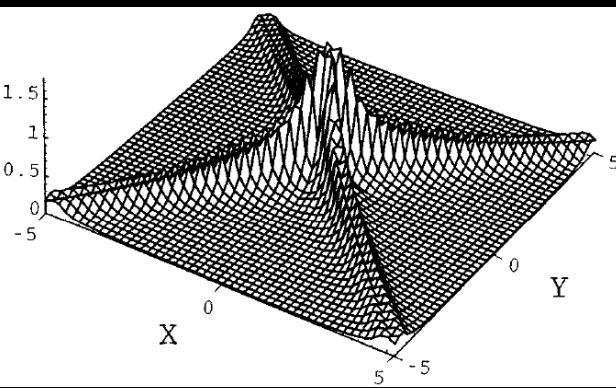
$\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$



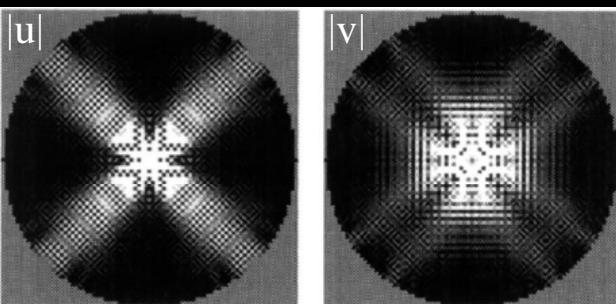
0 nS 1.5 nS



Maki, *Physica B* 204, 214 (1995)



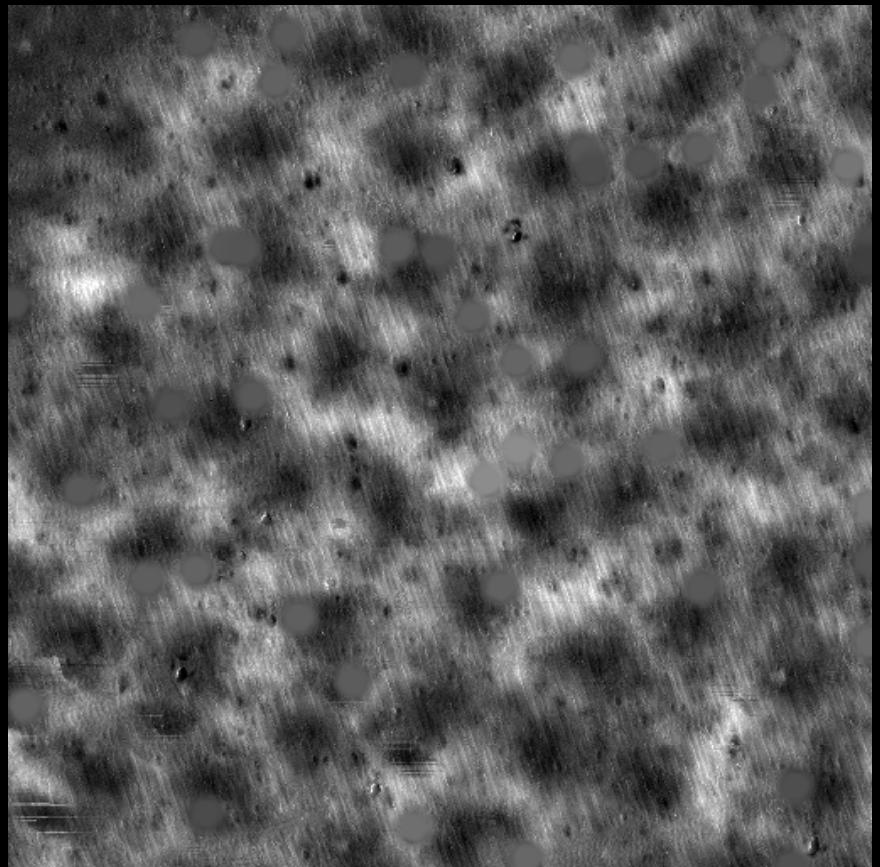
Ichioka, *PRB* 53, 15316 (1996)



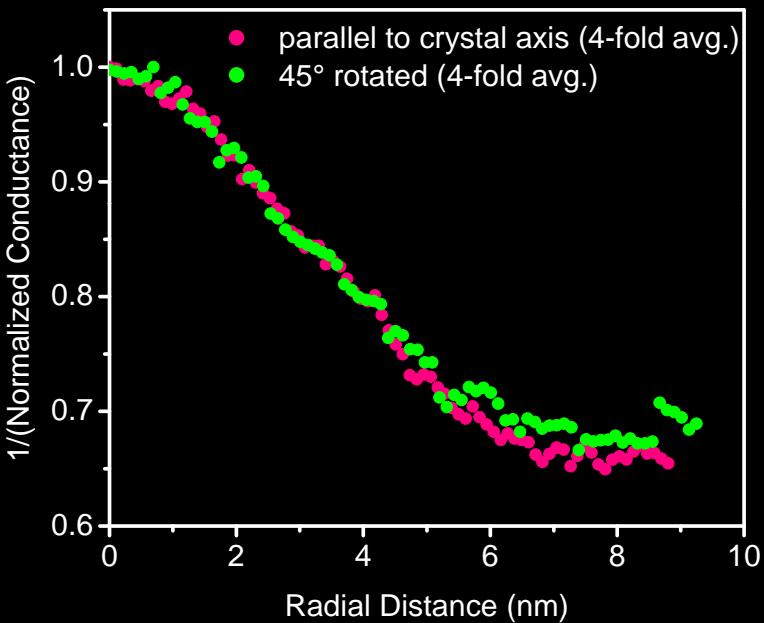
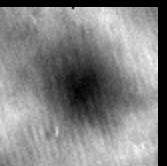
Franz & Tesanovic, *PRB* 53, 15316 (1996)

# Are Vortices Isotropic?

Filter impurities



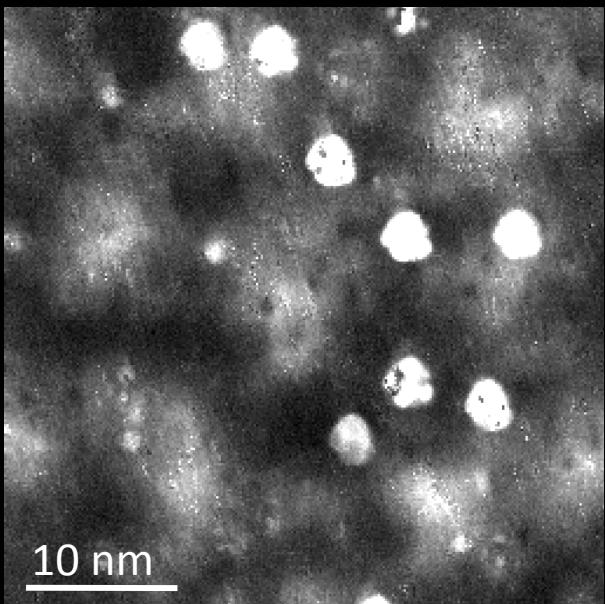
Average vortices



# Compare to Experimental *d*-wave Vortex Shape



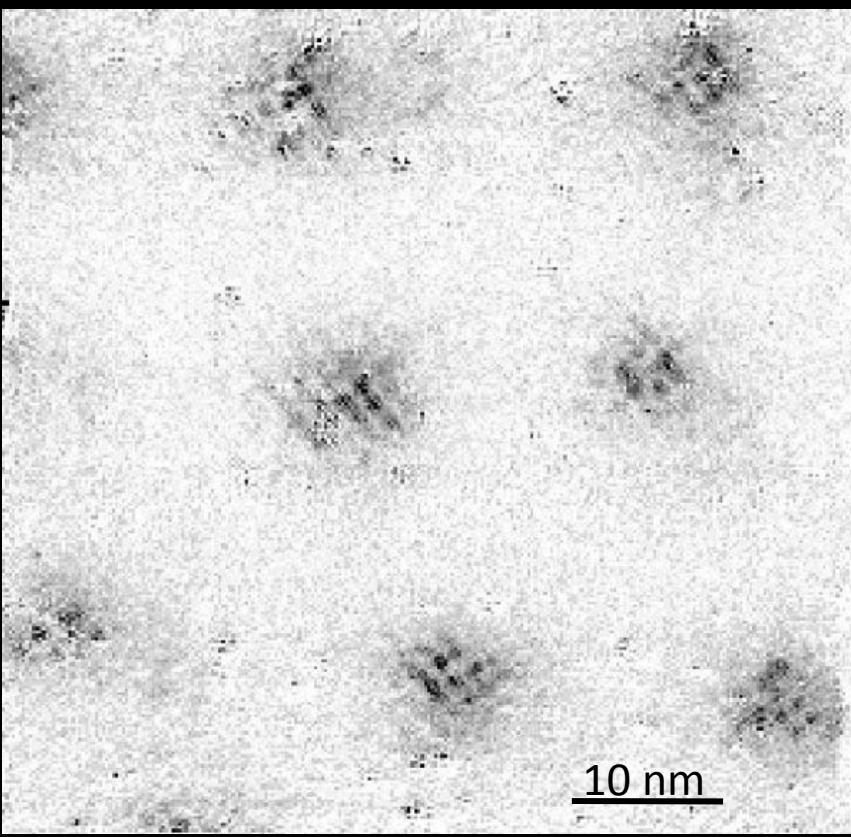
$\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$



10 nm

0 nS 1.5 nS

$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

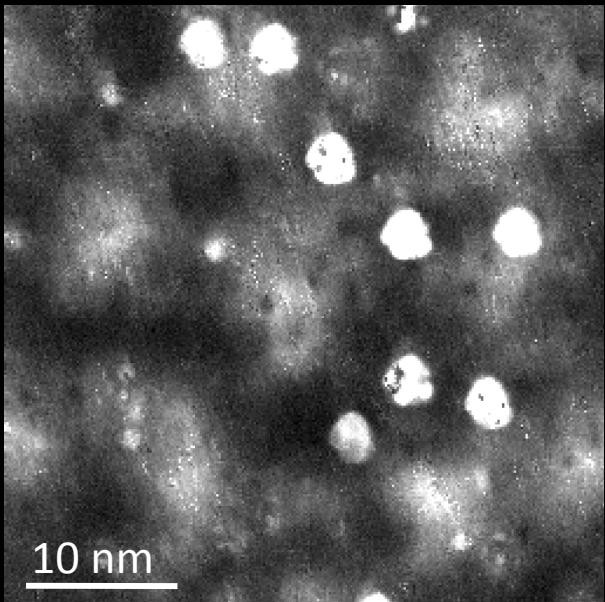


10 nm

(integrated  $dI/dV$  from 0 meV to 12 meV)

0 pA 2 pA

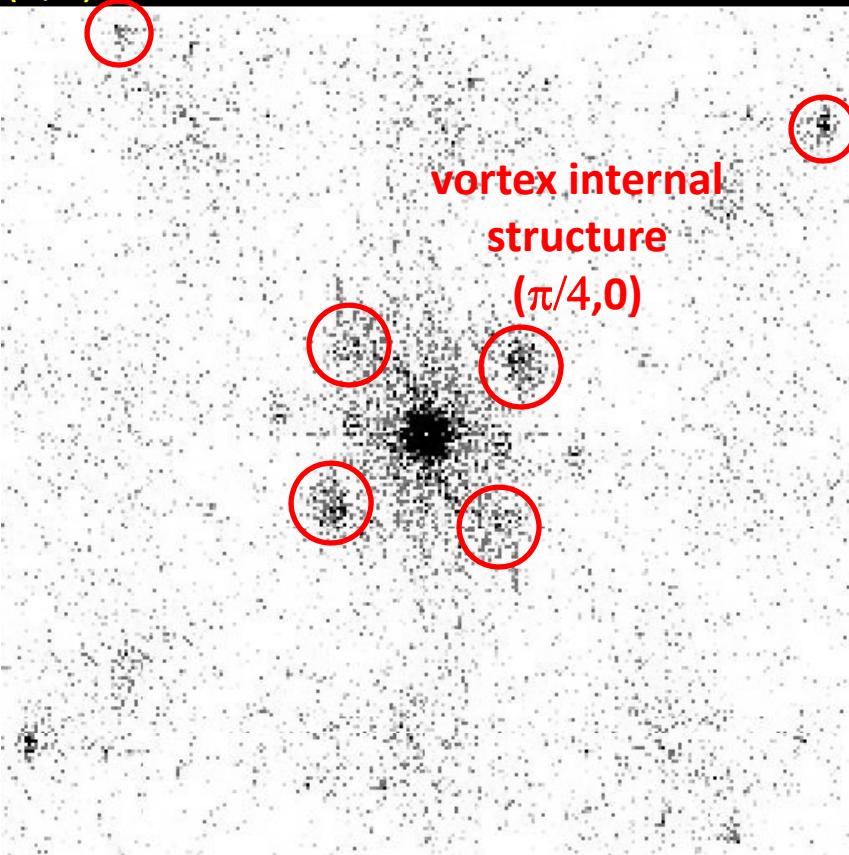
# Compare to Experimental *d*-wave Vortex Shape



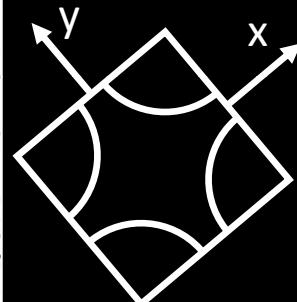
10 nm

0 nS 1.5 nS

atoms  
 $(0,\pi)$



atoms  
 $(\pi,0)$



Fourier Transform

Hoffman, Science 266, 455 (2002)

# Internal structure in $\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$ Vortices?



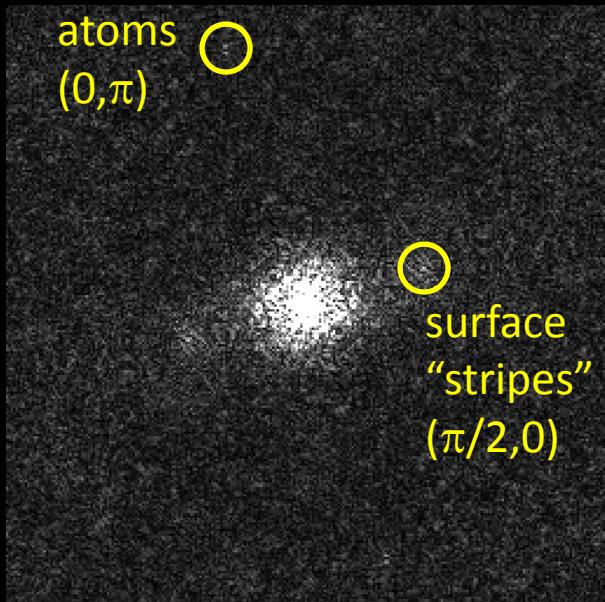
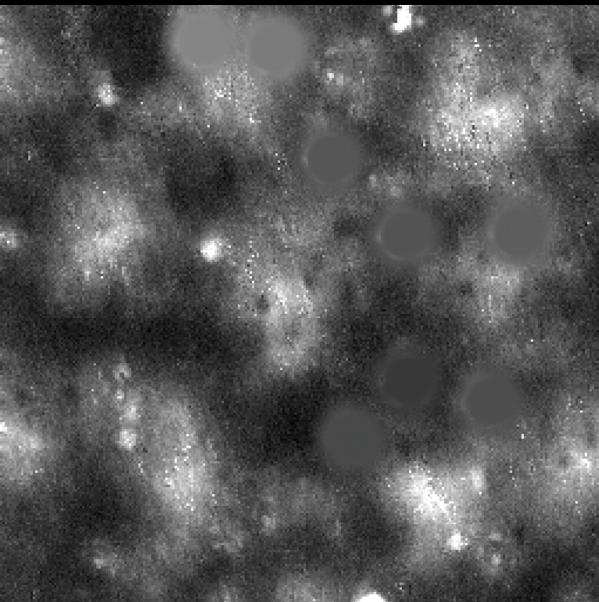
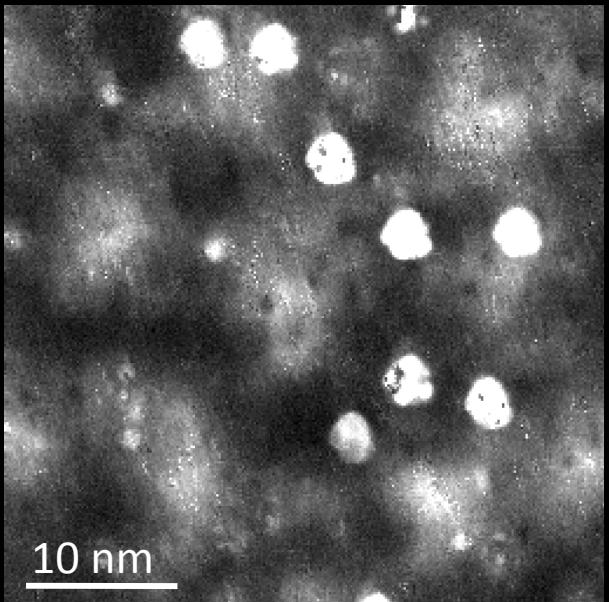
$\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$

→ filter impurities

→ Fourier transform

atoms  
 $(0,\pi)$

surface  
"stripes"  
 $(\pi/2,0)$



0 nS 1.5 nS

→ No internal structure observed.

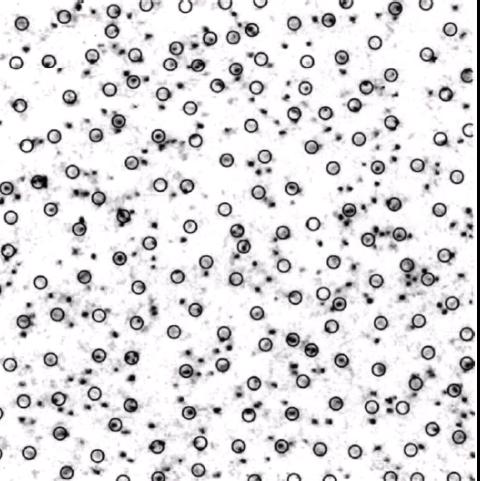
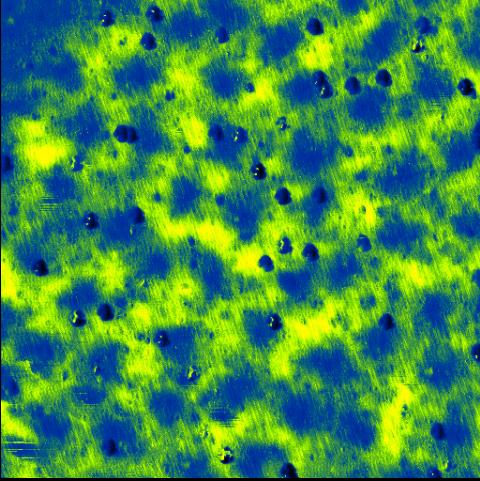
# Cuprate-Pnictide Comparison



	Cuprate: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$	Pnictide: $\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$
phase diagram	<p>Temperature</p> <p>Carrier concentration</p>	<p>Temperature (K)</p> <p><math>x_{\text{WDS}}</math></p> <p>Magnetic &amp; structural order</p> <p>SC</p>
		Ni, Canfield, <i>et al</i> , arXiv:0811.1767
ground state	antiferromagnetic Mott insulator	itinerant antiferromagnet semimetal
gap symmetry	$d$ -wave	$s \pm ??$
anisotropy, $\gamma$	$\sim 50$	$\sim 1-3$
optimal $T_c$	91 K	25.3 K

# Cuprate-Pnictide Comparison

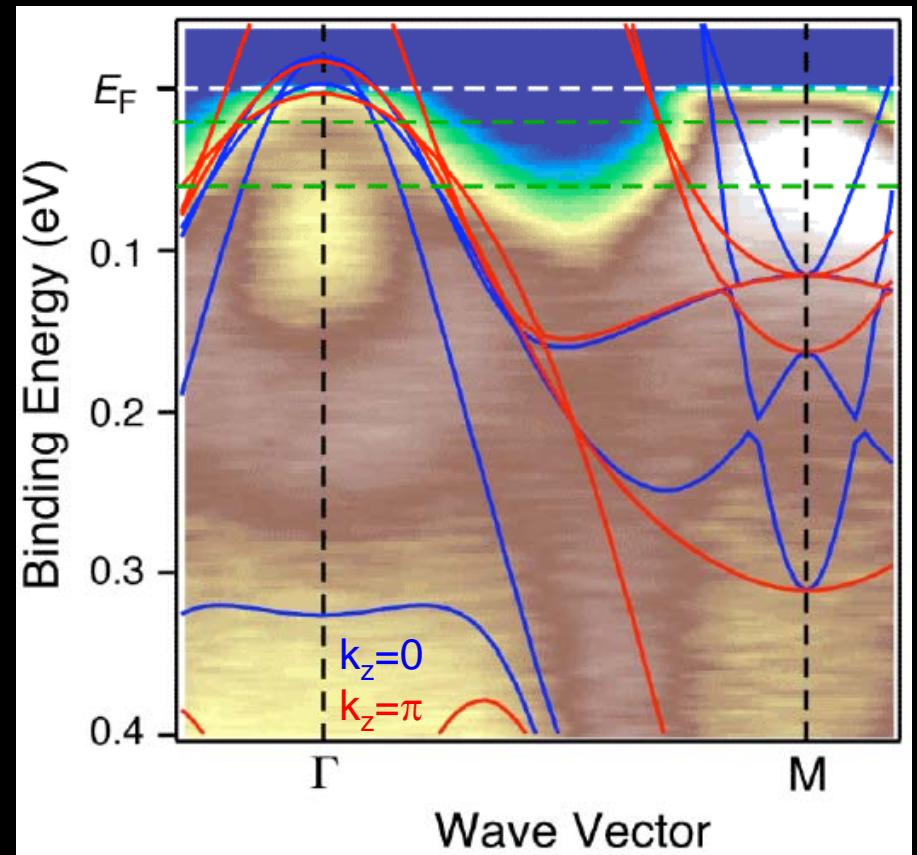


	Cuprate: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+d}$	Pnictide: $\text{BaCo}_x\text{Fe}_{2-x}\text{As}_2$
superconducting gap, $\Delta$	$\Delta \sim 33 \text{ meV}$ $2\Delta/k_B T_c \sim 6-10$	$\Delta = 6.25 \text{ meV}$ $2\Delta/k_B T_c = 5.73$
gap inhomogeneity	$\sigma \sim 7 \text{ meV}$ $\sigma/\Delta \sim 21\%$	$\sigma = 0.73 \text{ meV}$ $\sigma/\Delta = 12\%$
coherence length, $\xi_0$	2.2 nm	2.7 nm
vortex pinning	 <p>vortices pinned to surface impurities</p>	 <p>vortices <b>NOT</b> pinned to surface impurities</p>

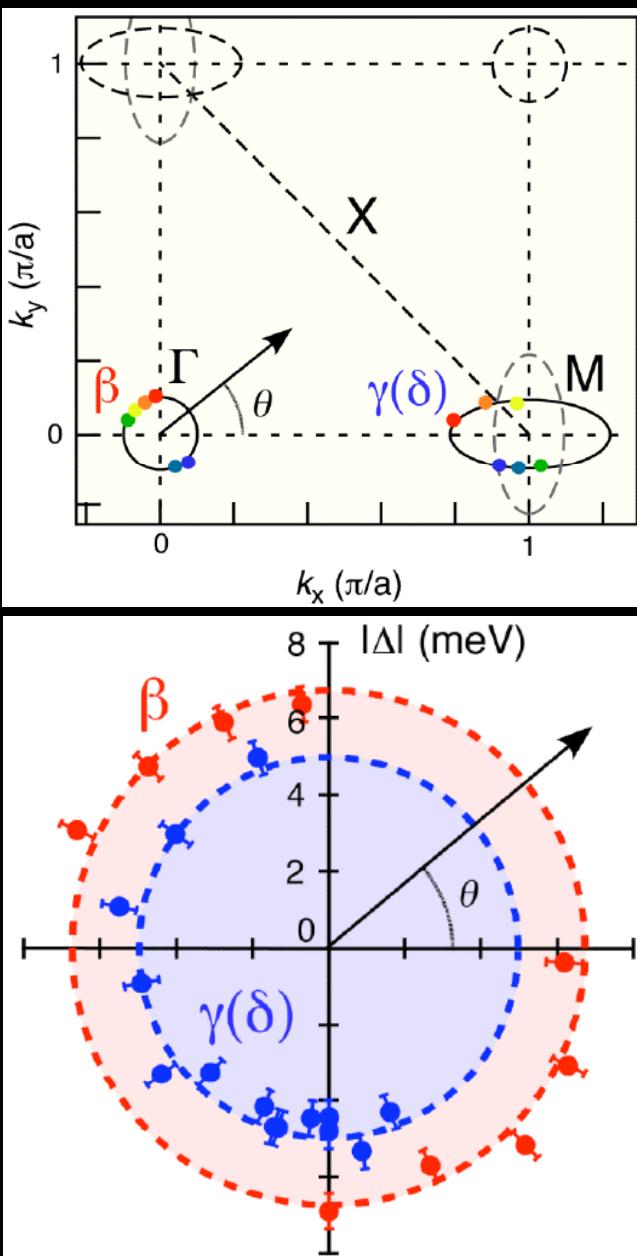
# Compare to hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$



Rigid band model substantiated by  
C. Liu *et al*, PRL 101, 177005 (2008)



Fermi surfaces:  
 $\text{BaCo}_{0.15}\text{Fe}_{1.85}\text{As}_2$   
 $\text{BaFe}_2\text{As}_2$   
 $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$

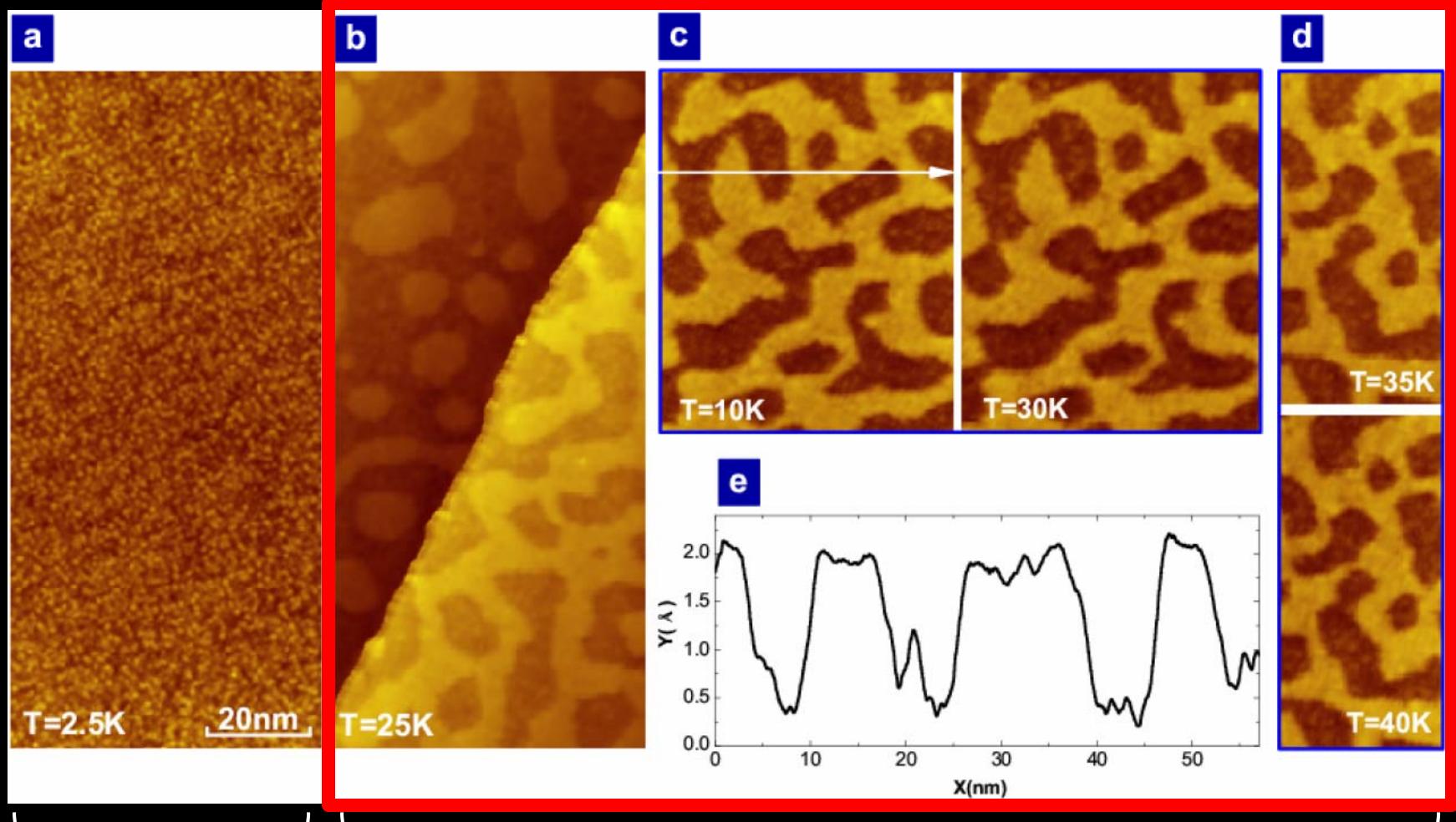


Terashima *et al*, arXiv:0812.3704

# Surface of hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$



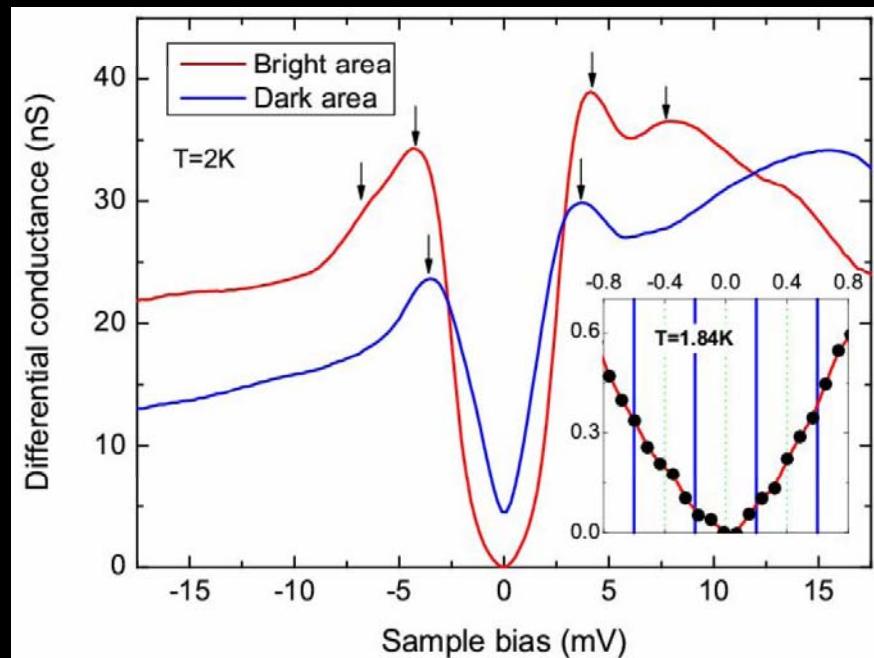
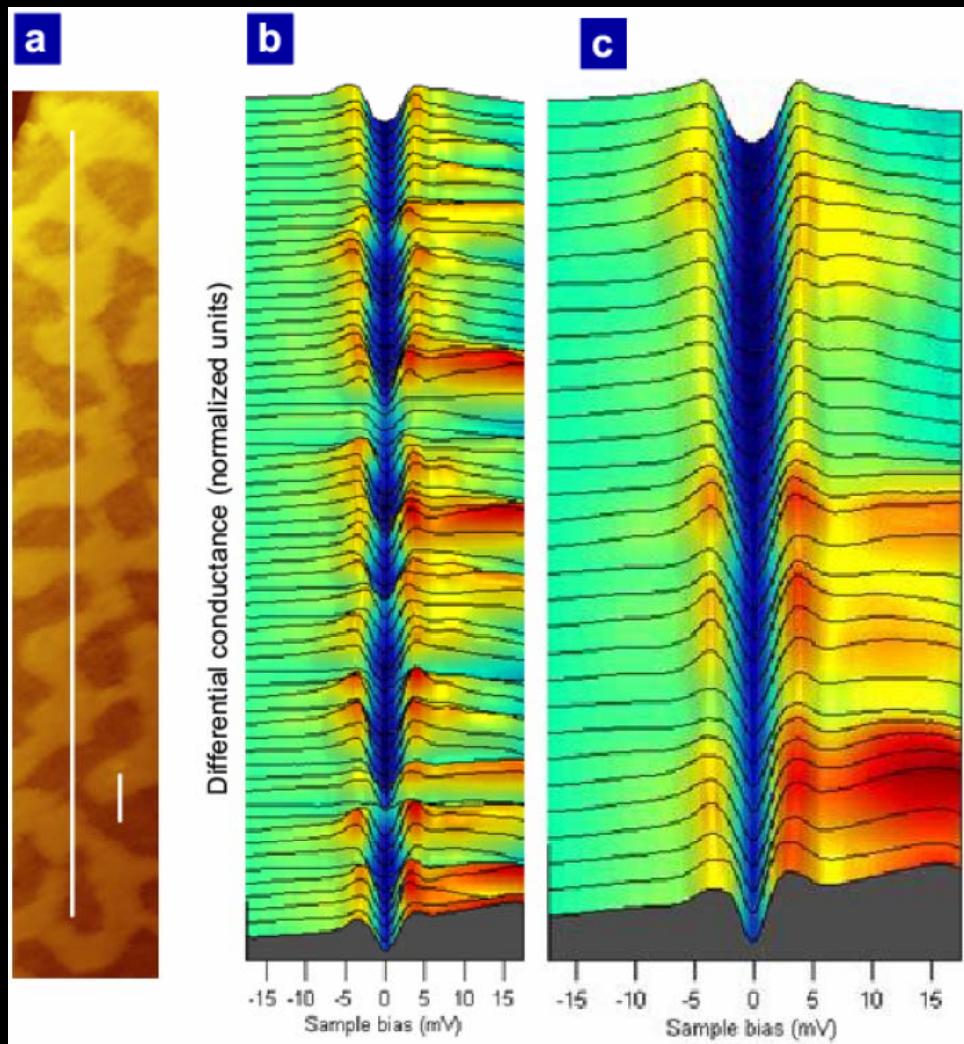
2 types of cleaves:



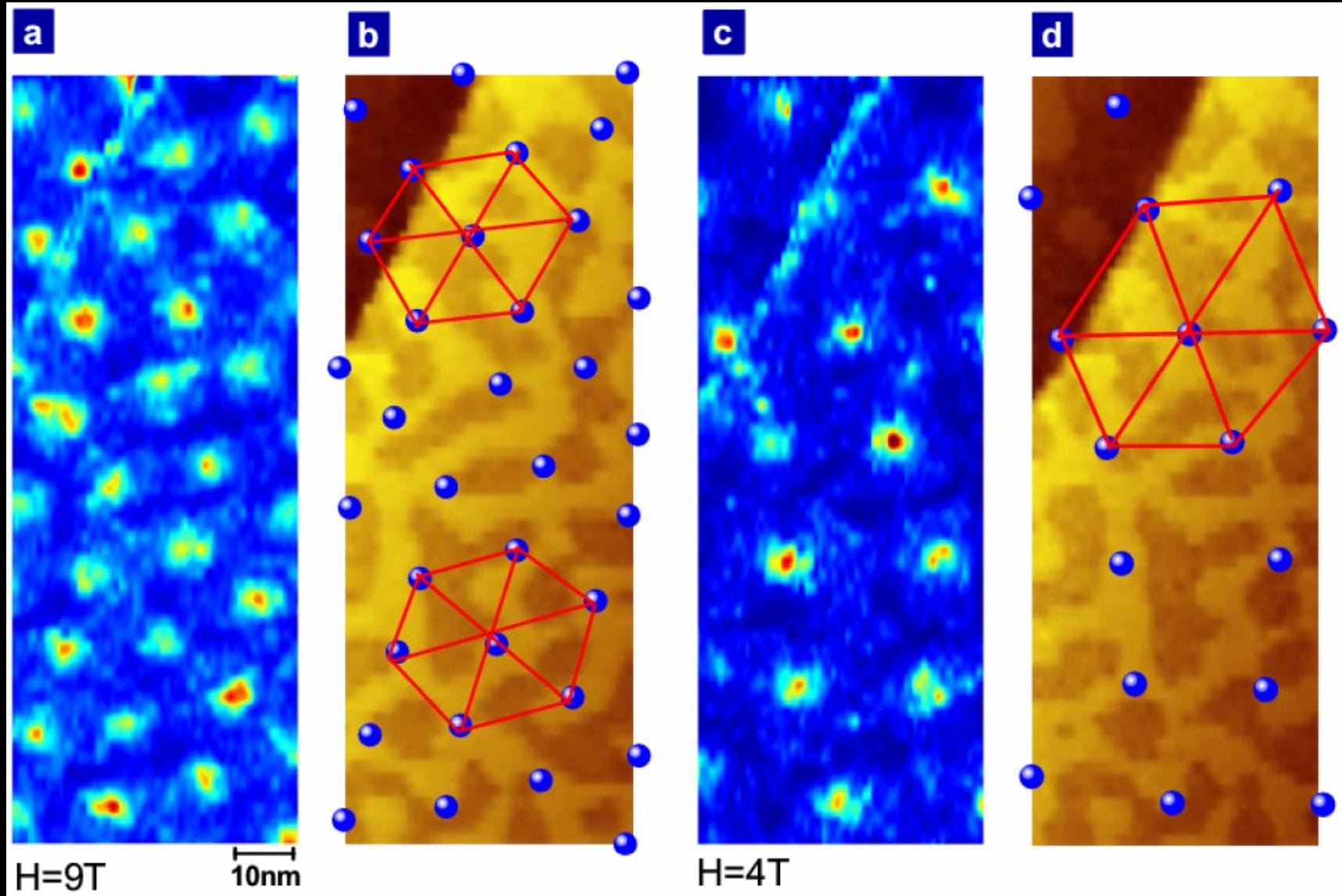
unstable, no  
reproducible data

stable & reproducible, but no atomic resolution  
& we're not sure why it looks like a giraffe...

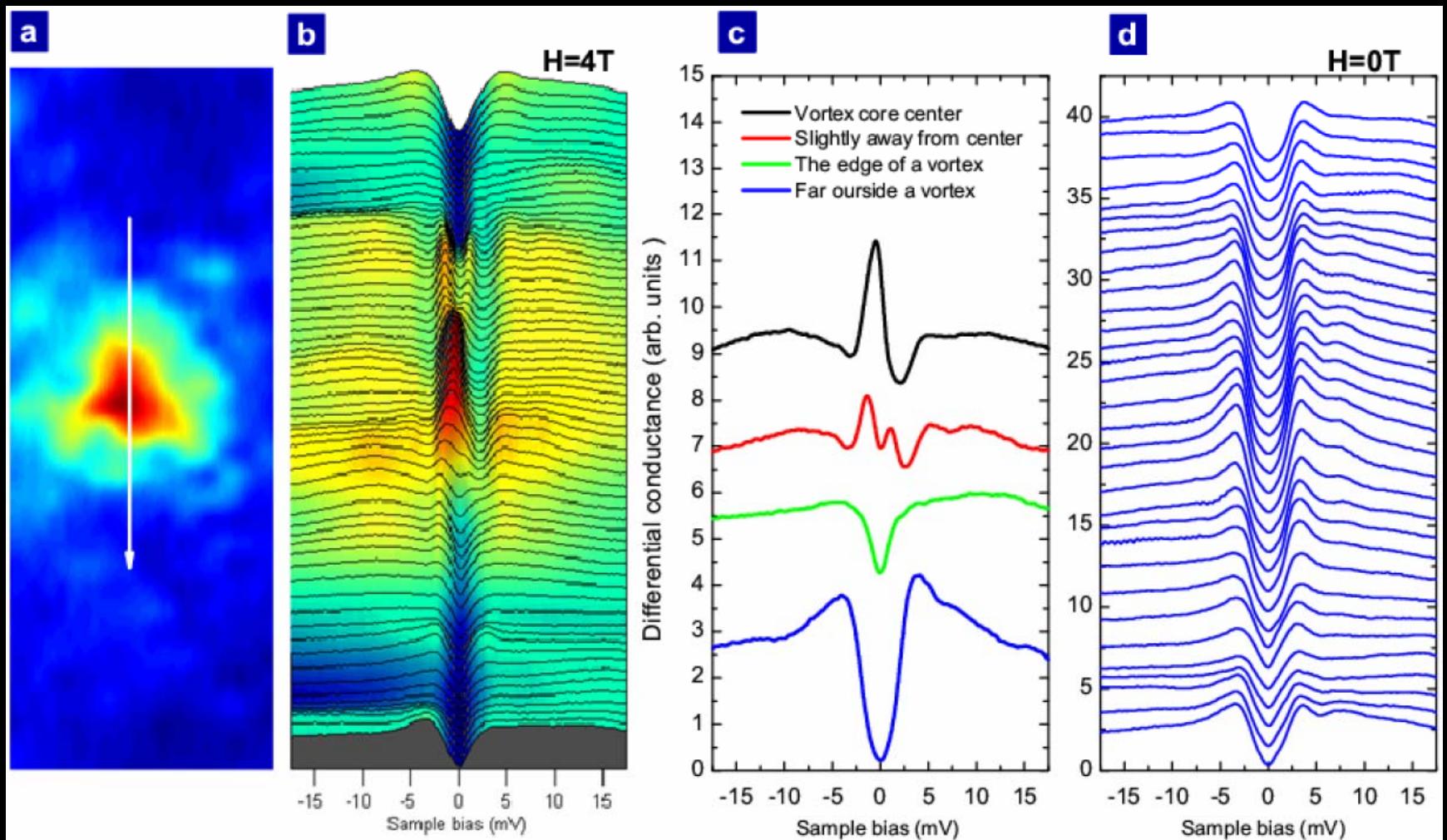
# Spectroscopy on hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$



# Vortex lattice in hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$



# Vortex spectroscopy in hole-doped $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$





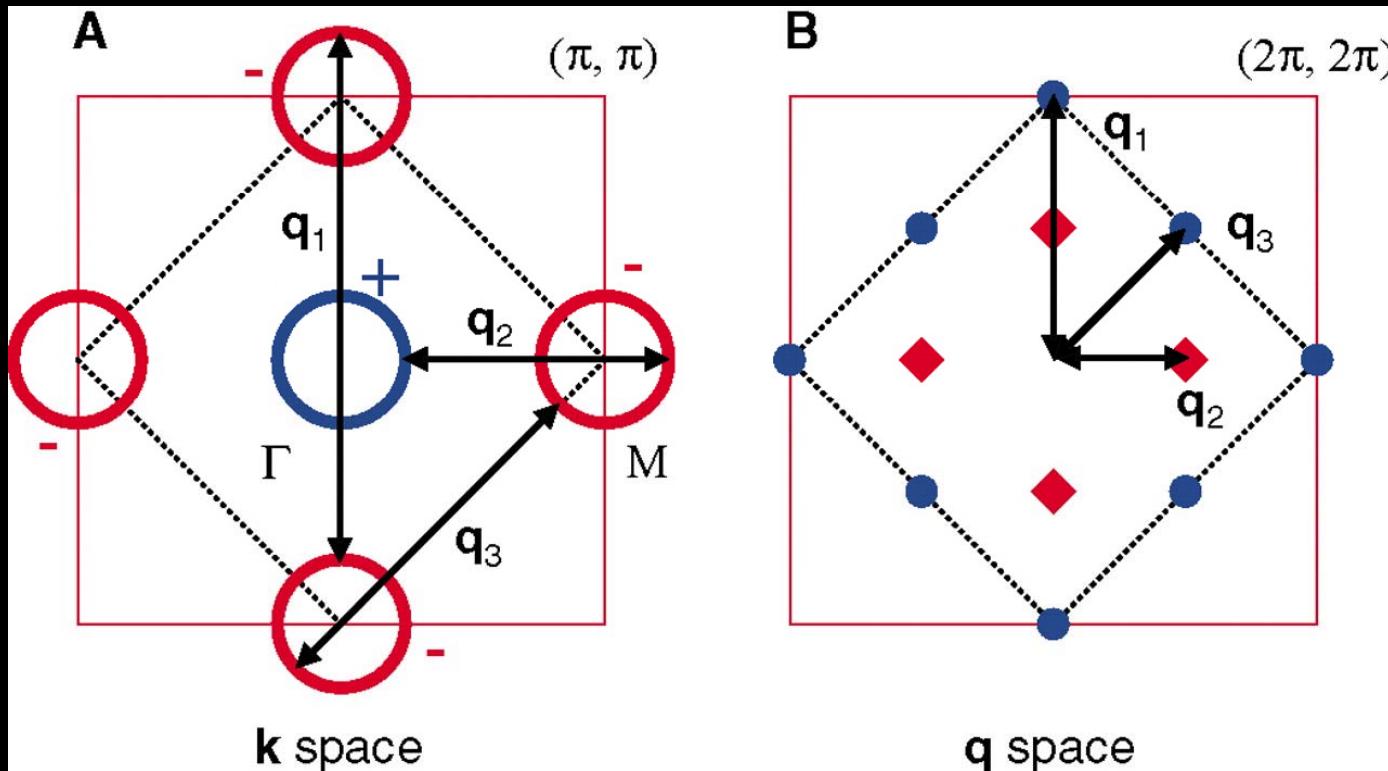
# Outline

- Review of the last 8 years of QPI imaging in cuprate superconductors
  - Controversies in the cuprates:
    - Static vs. dispersing order
    - Pseudogap: competing phase vs. superconducting fluctuations
- Conclusions: we've made progress, but still not sure
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- QPI in magnetic field
- STM on pnictide superconductors
  - surfaces, gap-mapping, and vortices
  - demonstrate  $s\pm$  order parameter in  $\text{FeSe}_{1-x}\text{Te}_x$
  - nematic precursor in  $\text{Ca}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$

# Apply phase-sensitive QPI to $\text{FeSe}_x\text{Te}_{1-x}$



Presumed  $s\pm$  order parameter:

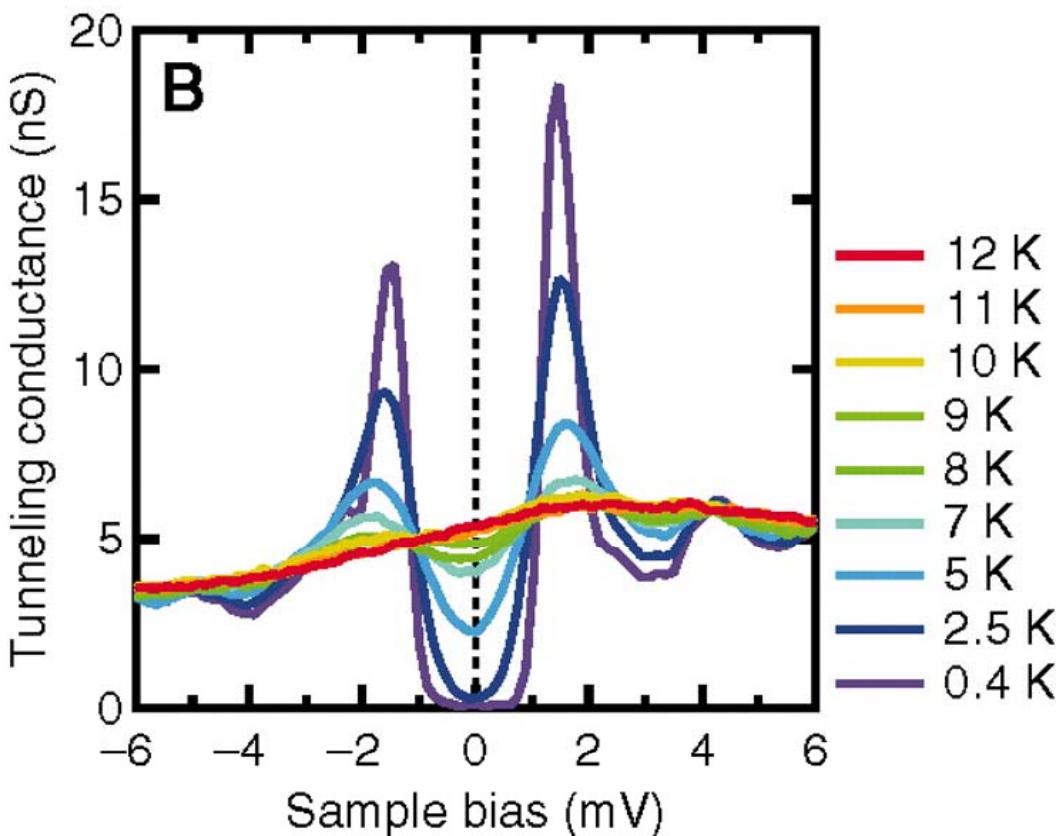
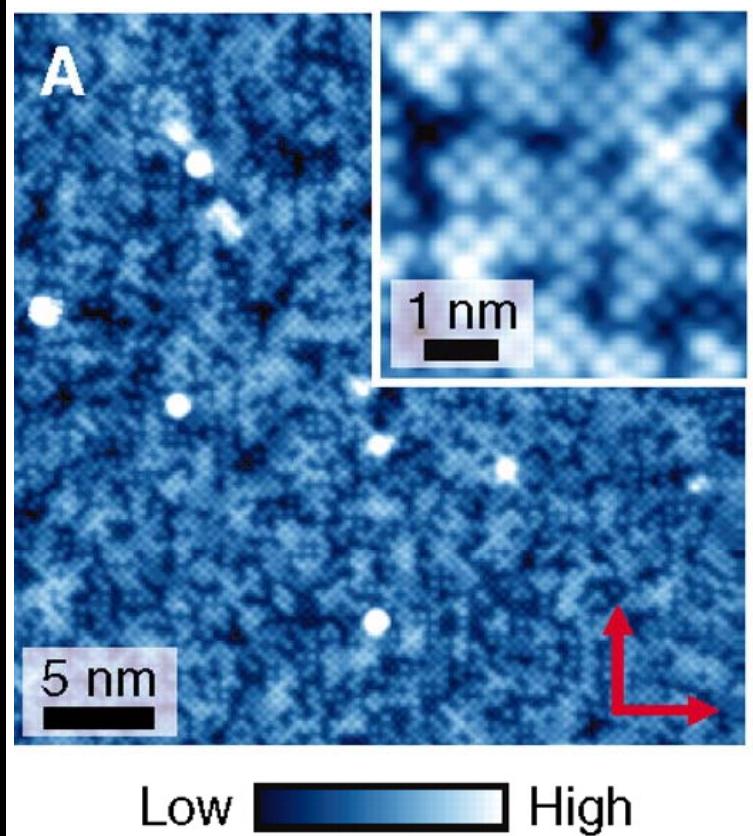


- sign-preserving,  
expect magnetic-field enhancement
- ◆ sign-altering,  
expect magnetic-field suppression

# Topography & Spectroscopy on $\text{FeSe}_x\text{Te}_{1-x}$



nominal  $\text{FeSe}_{0.5}\text{Te}_{0.5}$ ;  $T_c = 13\text{K}$

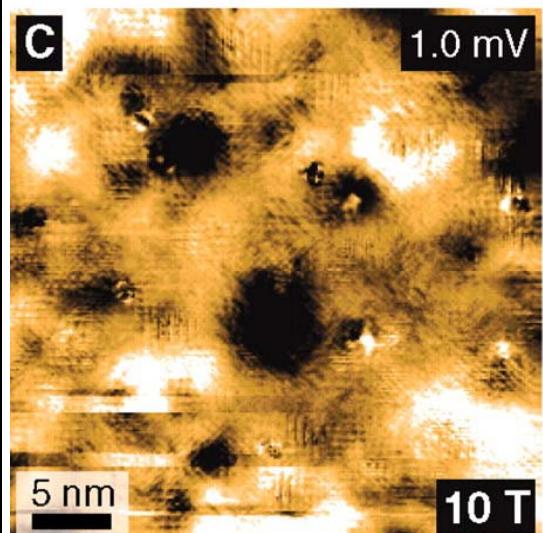
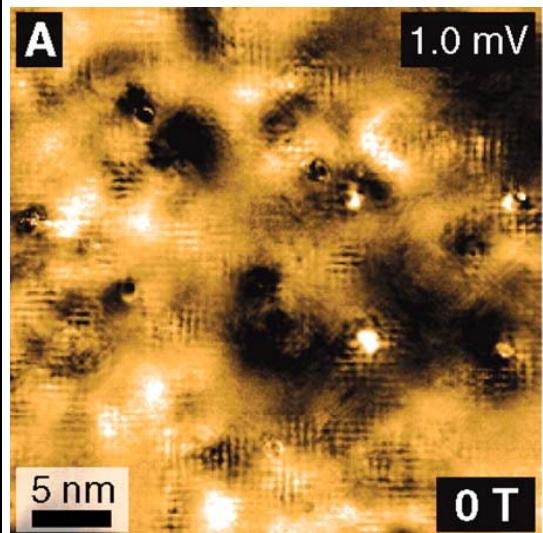


clean, atomic resolution ( $T=1.5\text{K}$ )

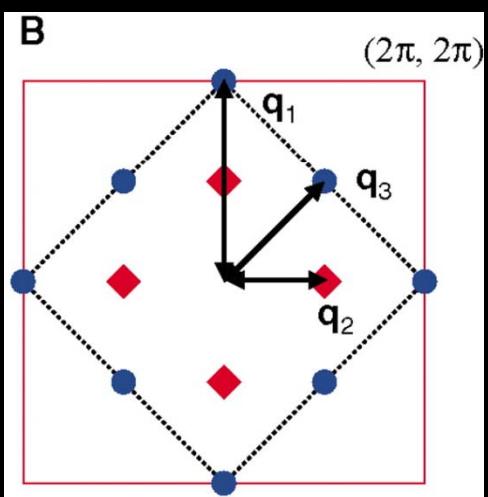
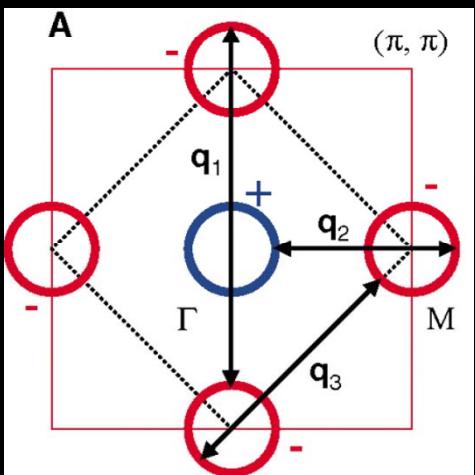
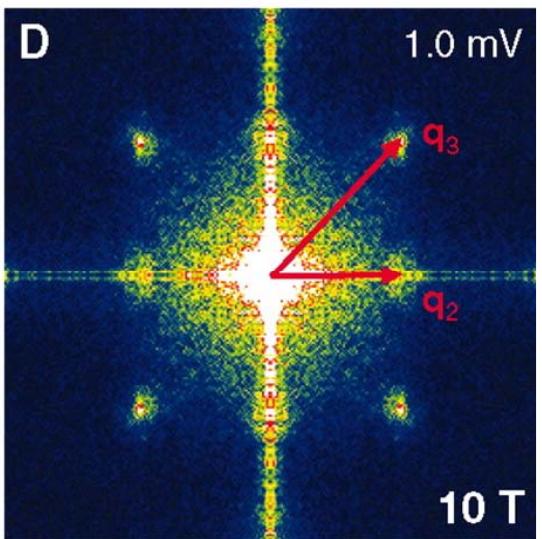
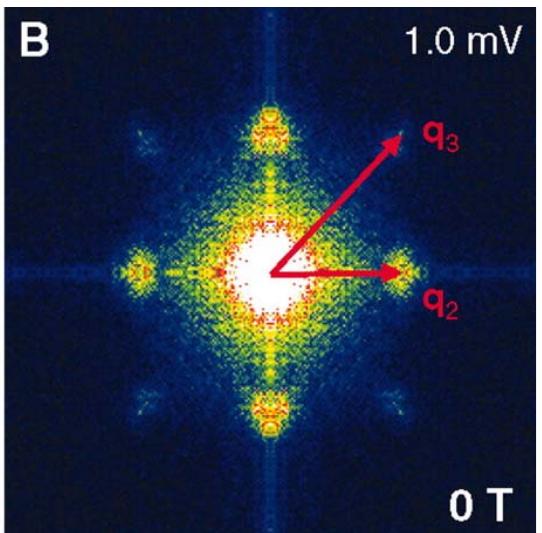
spectroscopy shows full gap (no nodes);  
but spectroscopy alone is not phase-sensitive

# QPI Imaging at 0T and 10T

Z maps:



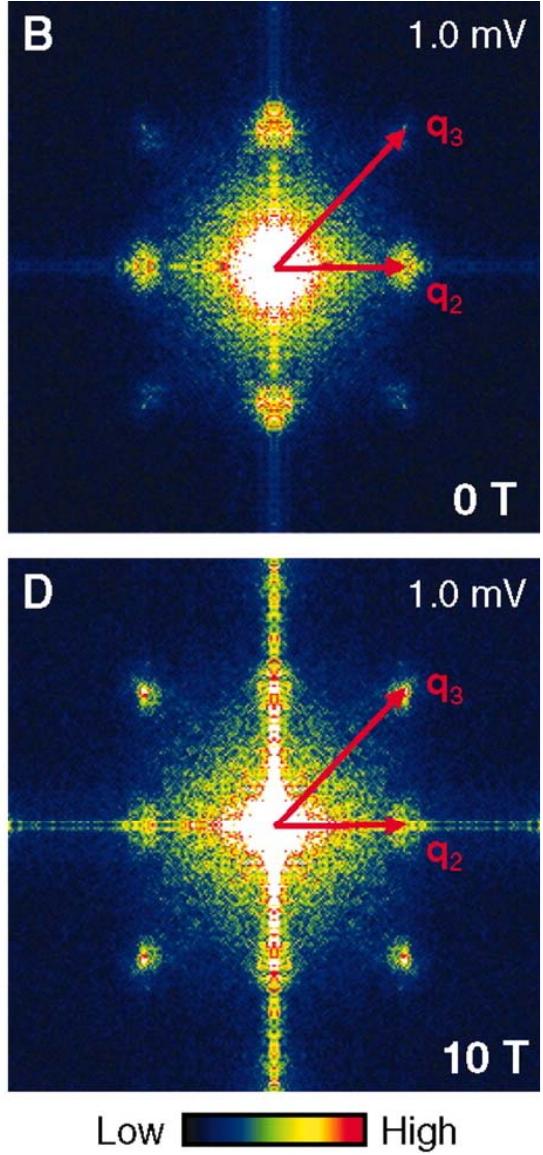
symmetrized FT's:



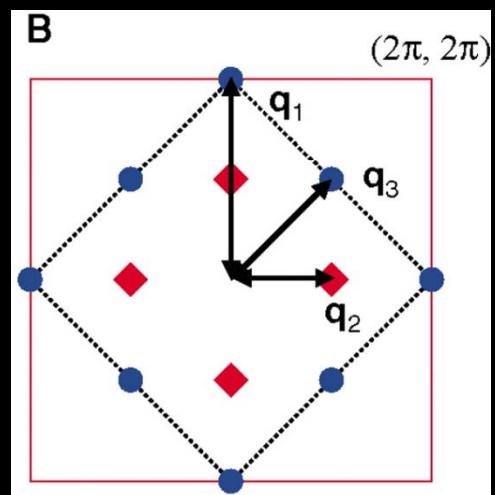
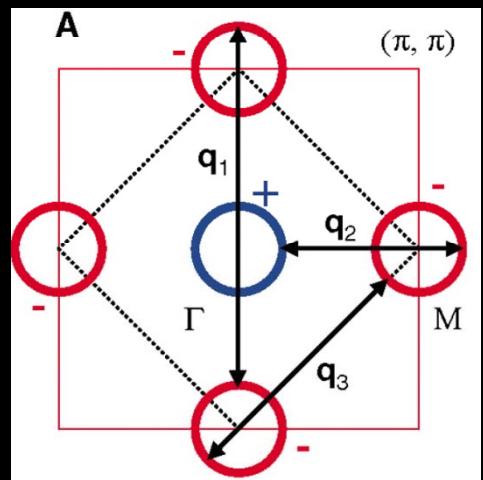
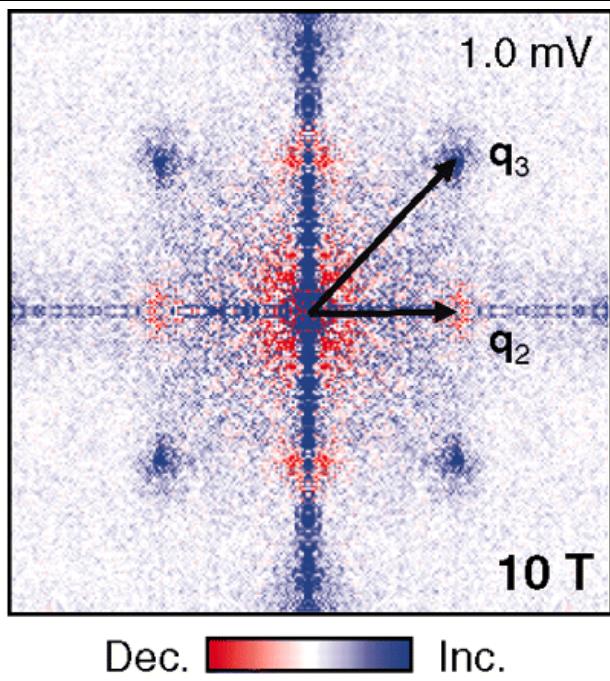
- expect magnetic-field enhancement
- ◆ expect magnetic-field suppression

# QPI Imaging at 0T and 10T

symmetrized FT's:



(10T map) – (0T map)



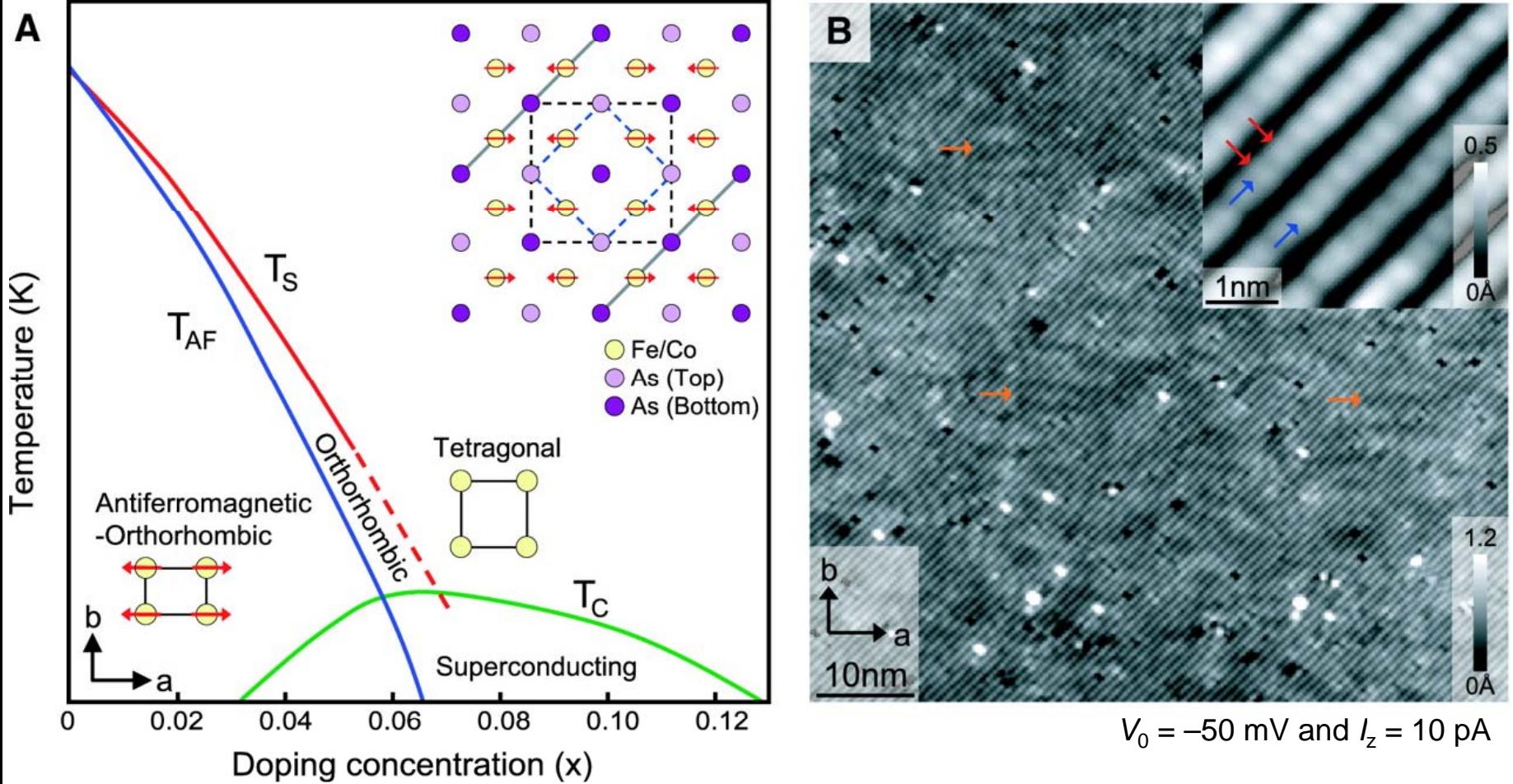
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# Parent state of $\text{Ca}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$



Low-T cleave:  
As-terminated layer, w/ unknown  
distribution of Ca,  
and surface reconstruction.

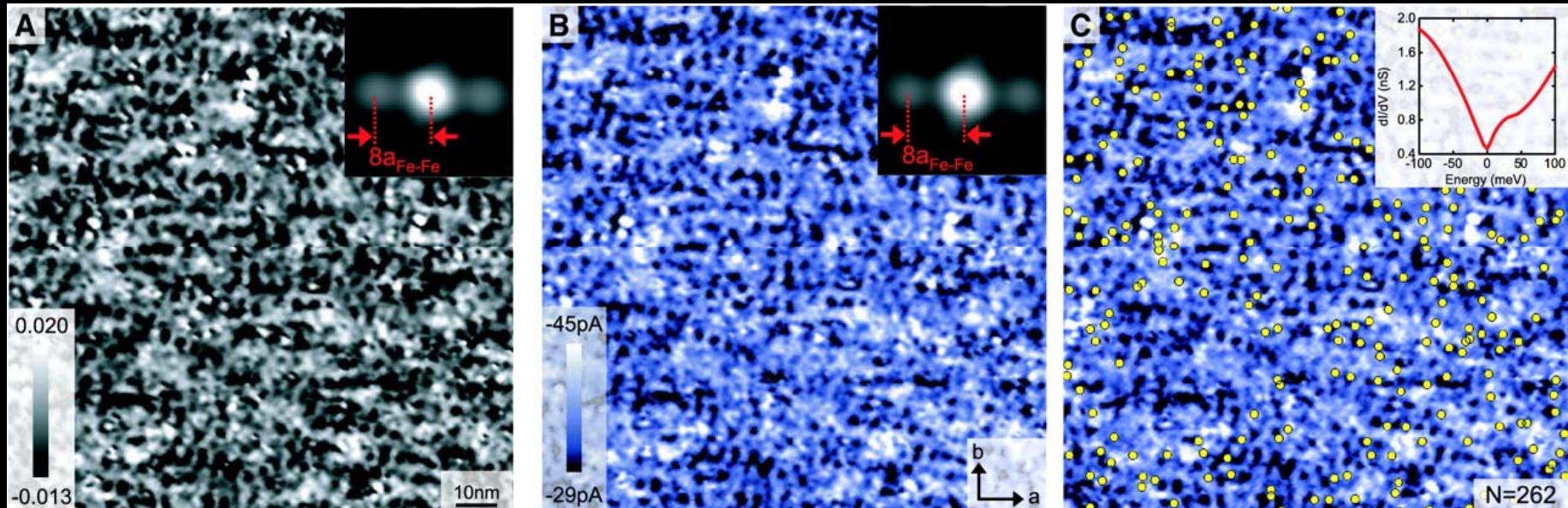
- atoms of  $1 \times 2$  configuration
- first indications of unidirectional  $a$  axis-oriented electronic nanostructures

# Autocorrelation shows $\sim 8a_0$ feature

Subtracted topography  
with +50mV and -50mV  
setup conditions ( $I=10\text{pA}$ )

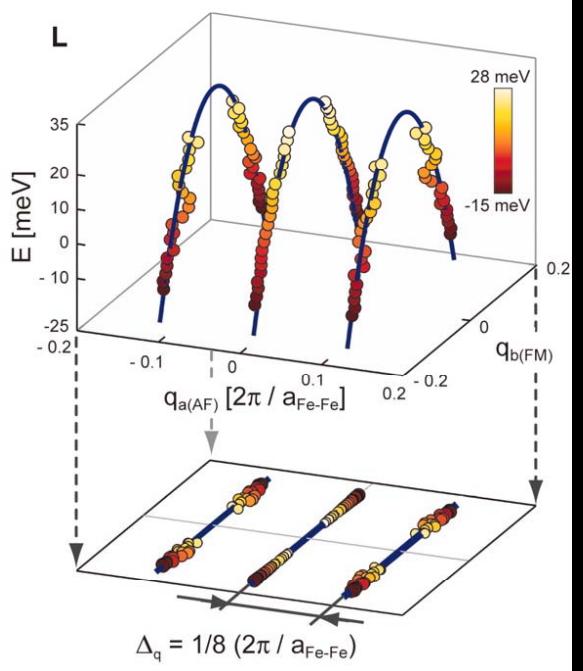
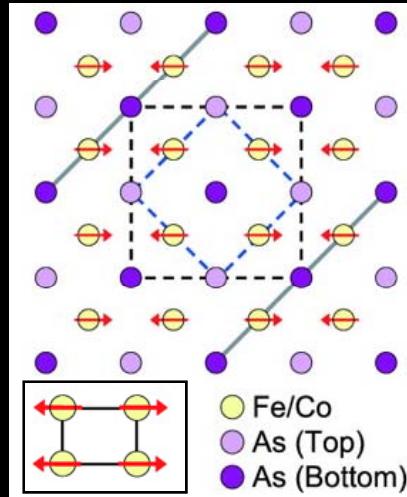
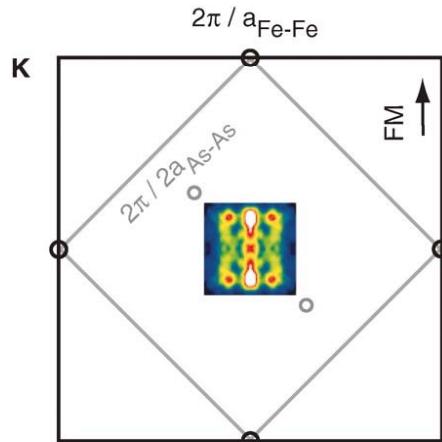
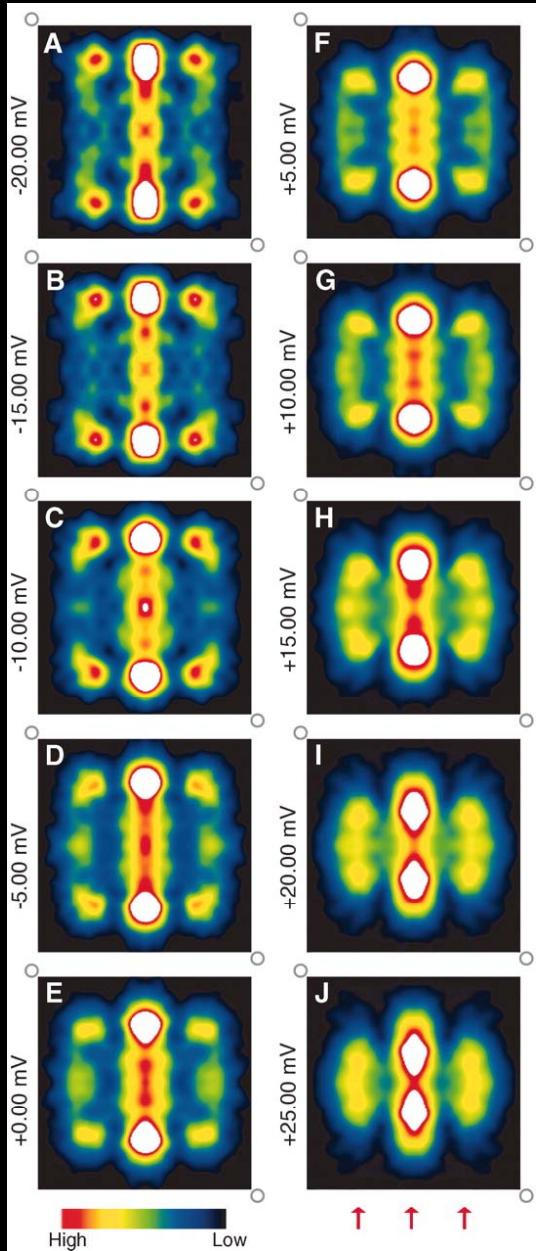
$g(r, 50\text{meV})$

- Co atoms,  
found at +150 meV  
(only 15% of expected #)

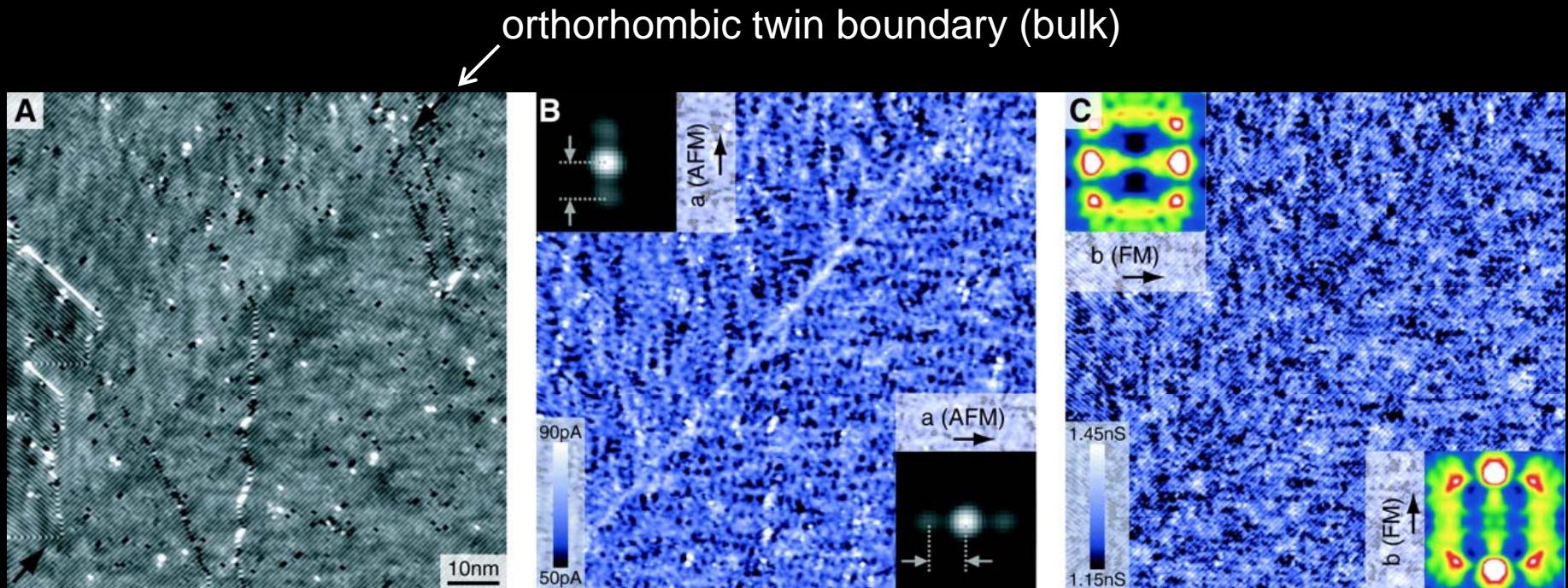


Spectrum: “mixed metallic  
and pseudogap-like shape”

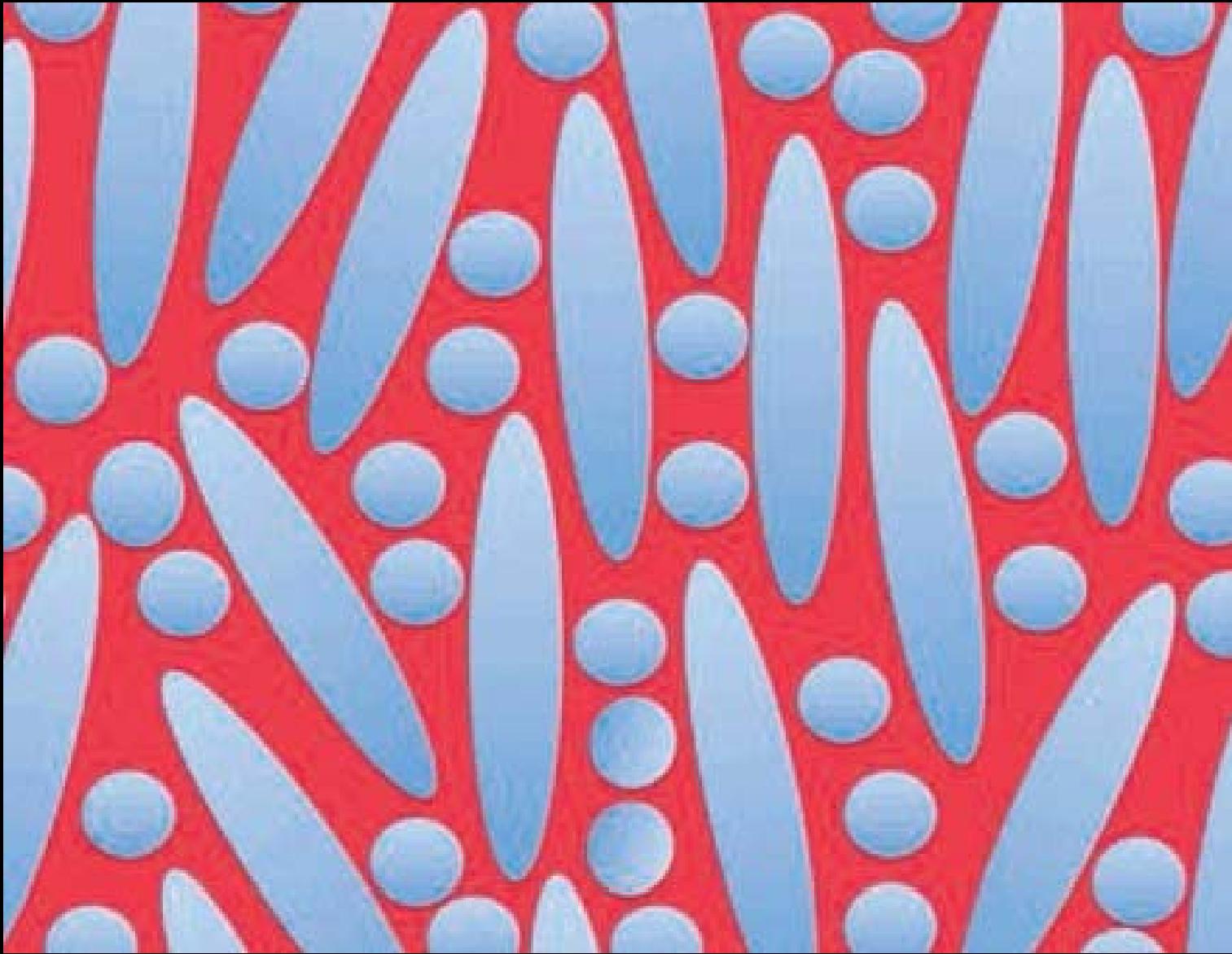
# QPI in $\text{Ca}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$



# Bulk twin boundaries vs. surface reconstruction



# Conclusion: Stripy folks are happy...



Perspective by Eduardo Fradkin and Steven A. Kivelson