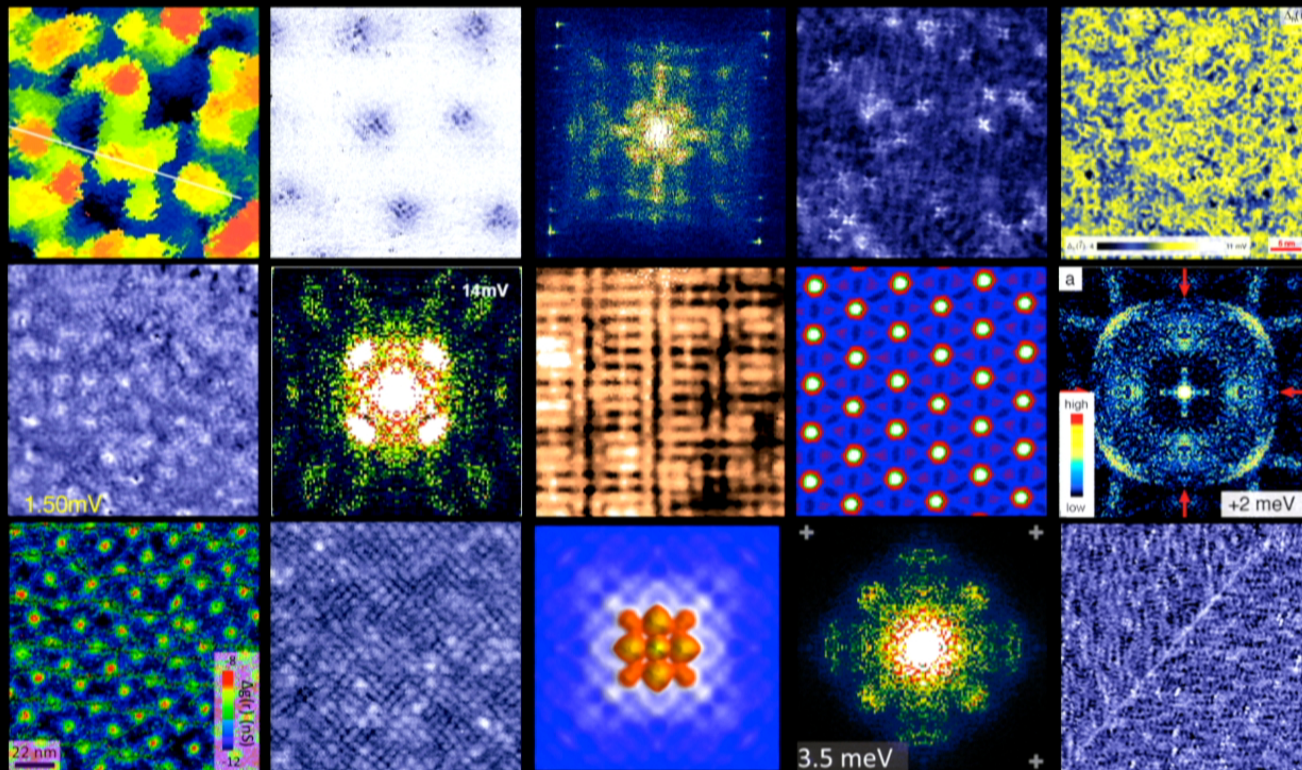
Title: Visualizing Quantum Matter

Date: May 27, 2014 09:00 AM

URL: http://pirsa.org/14050100

Abstract: Recently developed techniques allow imaging of electronic quantum matter directly at the atomic scale. I will introduce the basic principles and describe the set of observables available from these techniques. As examples, I will survey visualization of exotic forms of electronic quantum matter including heavy fermions, quantum critical electrons, topological surface states, electronic liquid crystals, and high temperature superconductors.

VISUALIZING QUANTUM MATTER



J.C. Séamus Davis

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BROOKHAVEN NATIONAL LABORATORY

St. Andrews

Stop Me – Ask Questions!

http://www.physics.cornell.edu/

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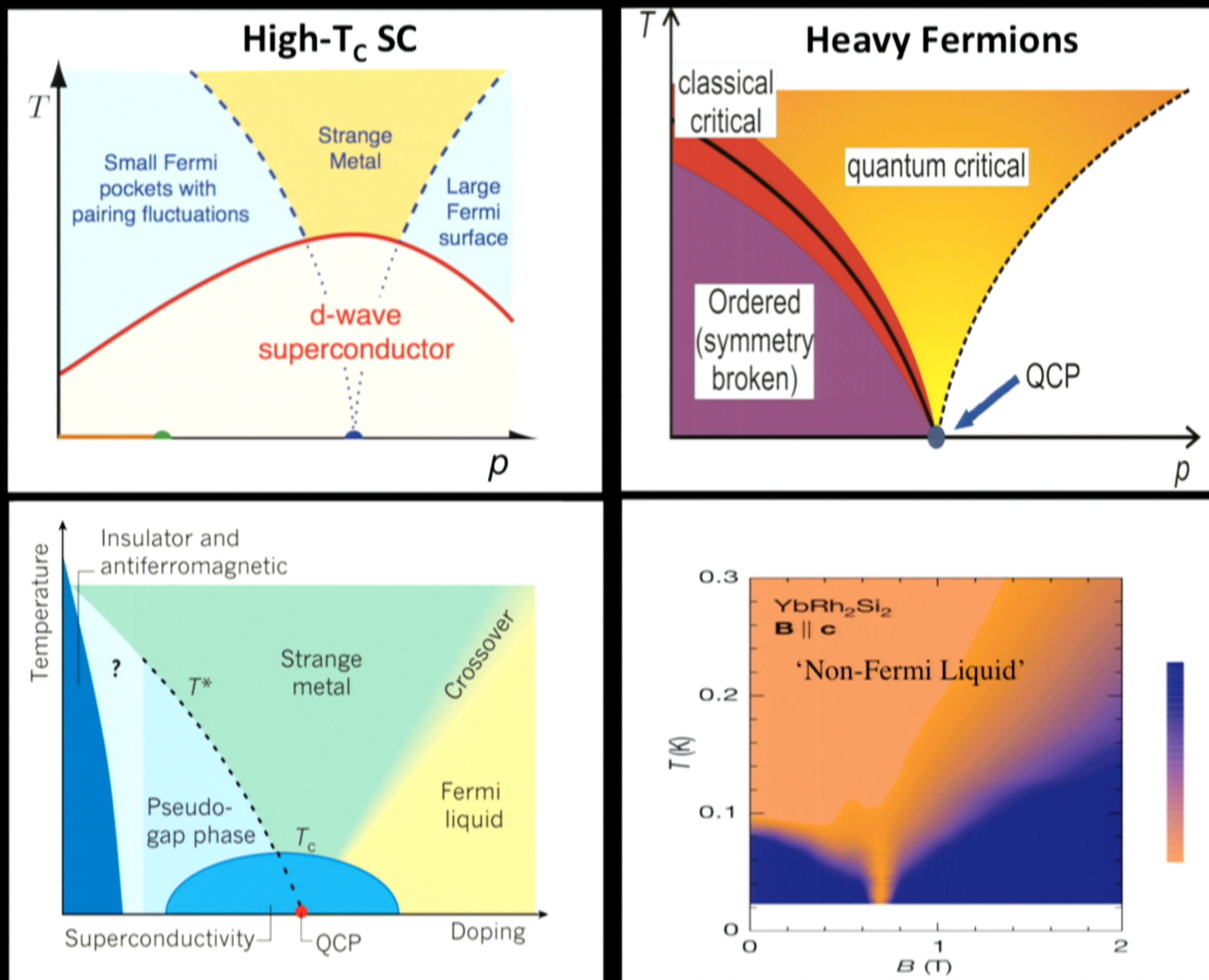
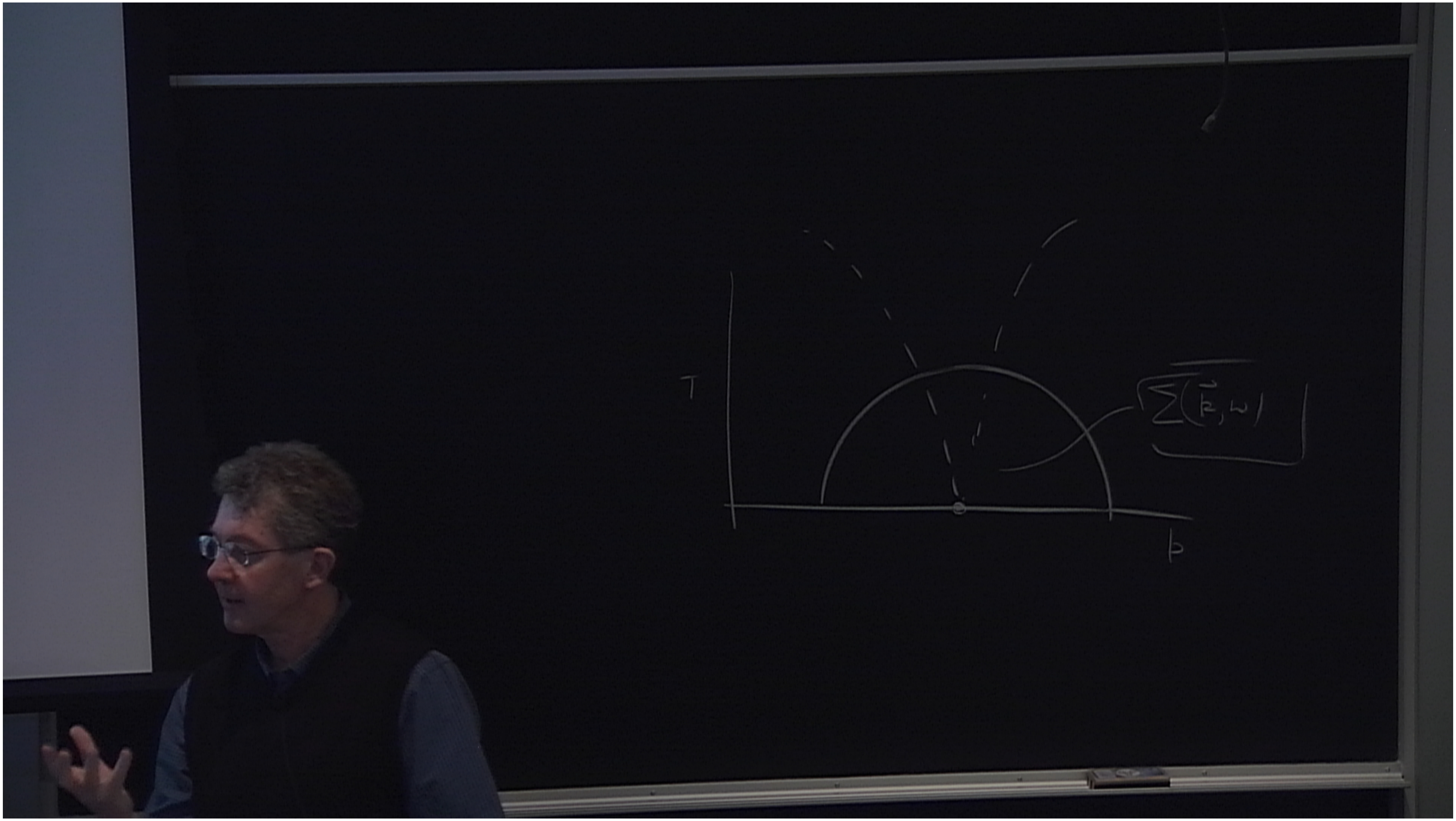
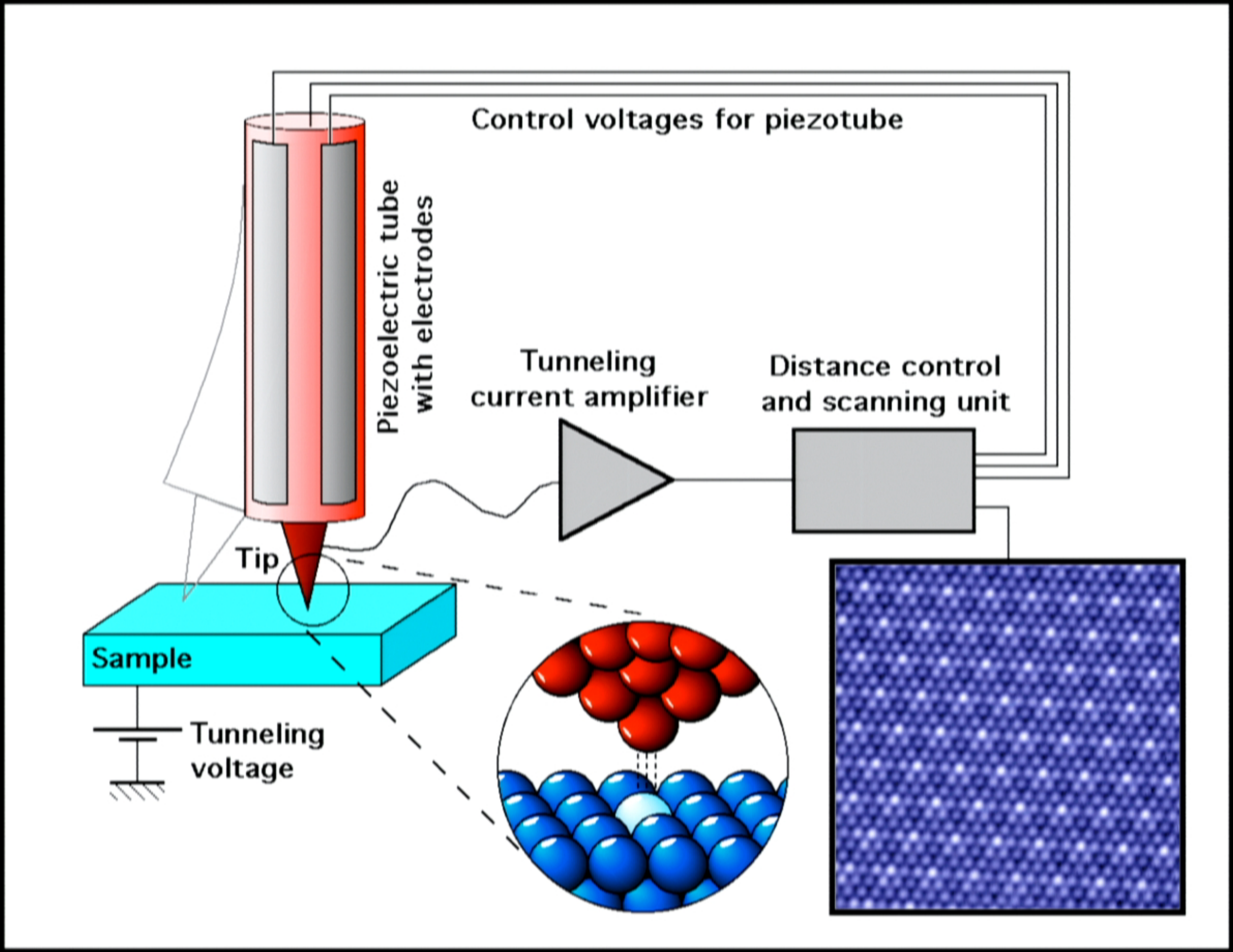
Quantum Critical Electronic Matter

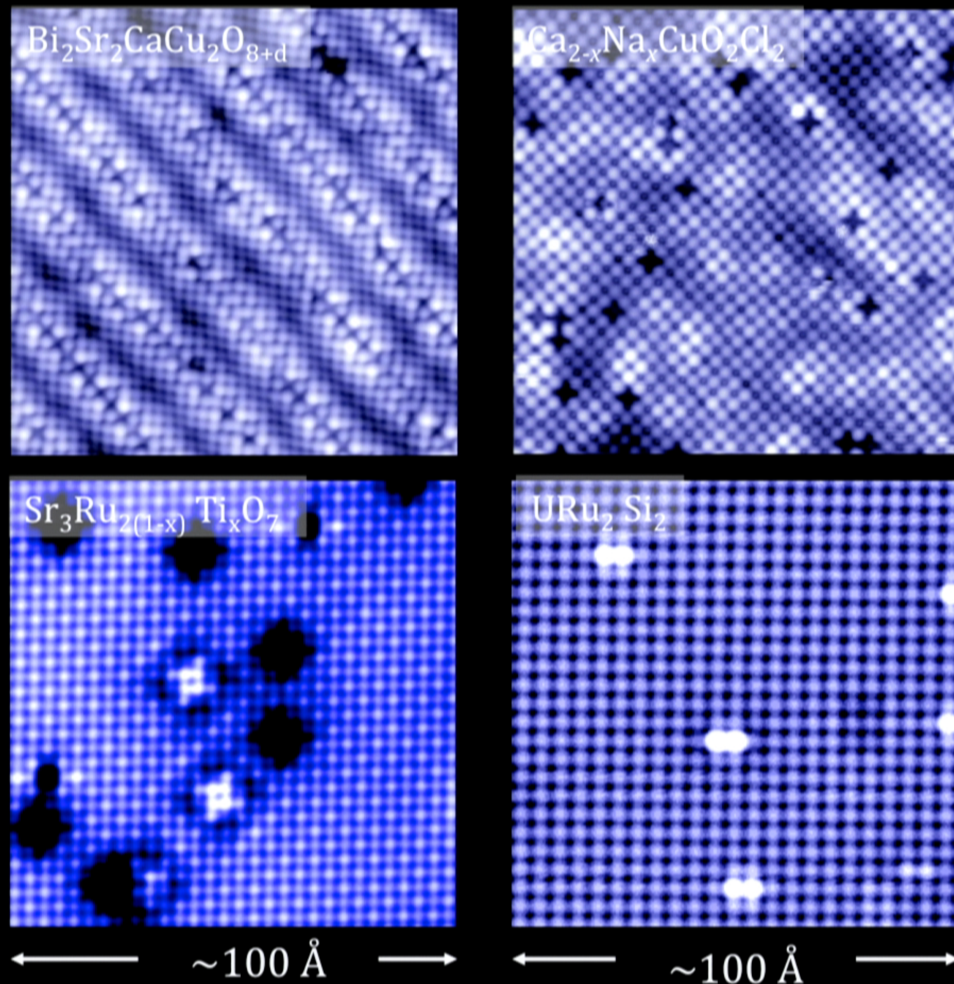



T
p

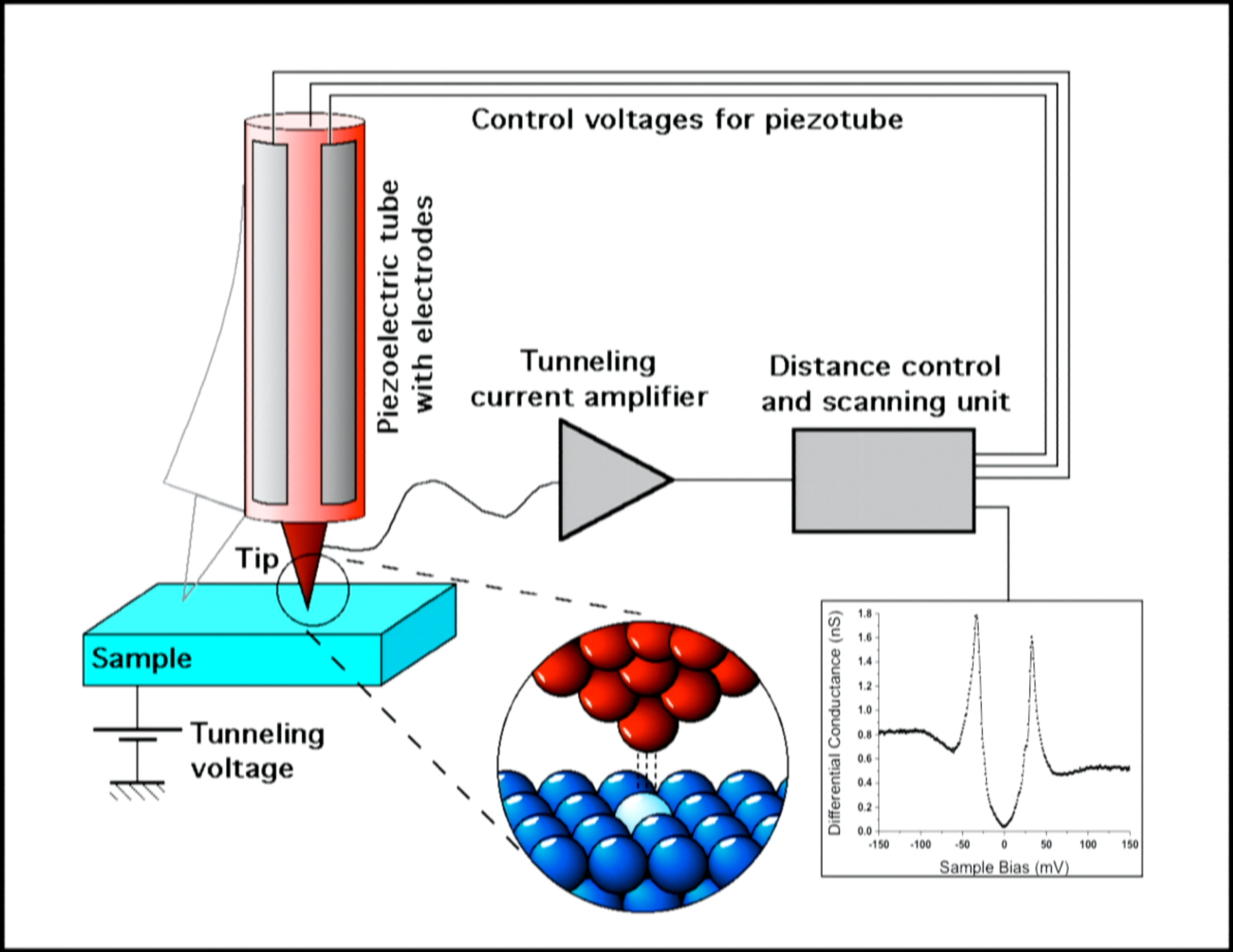
Scanning Electron-Tunneling Microscopy (STM)



Images Atomic Locations Only

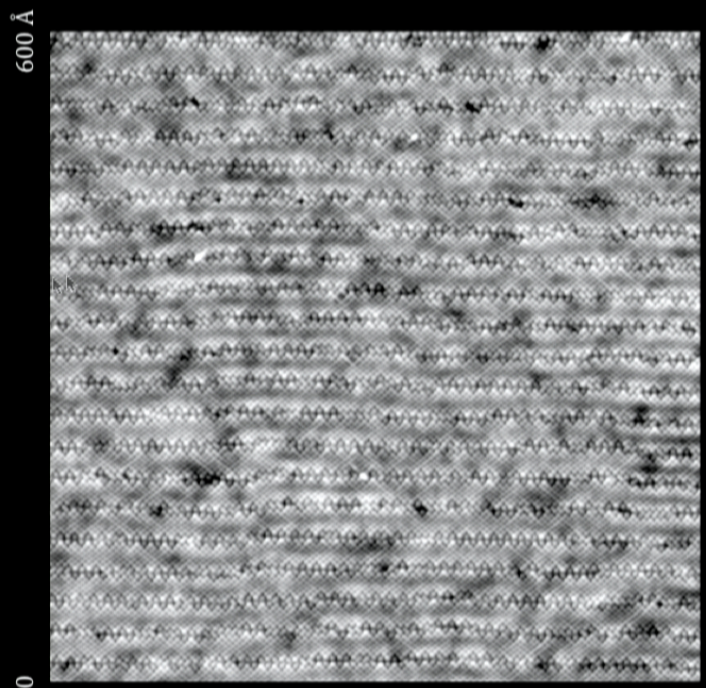


Spectroscopic Imaging STM



Differential conductance dI/dV @ V proportional to N(E=eV)

Spectroscopic Imaging STM

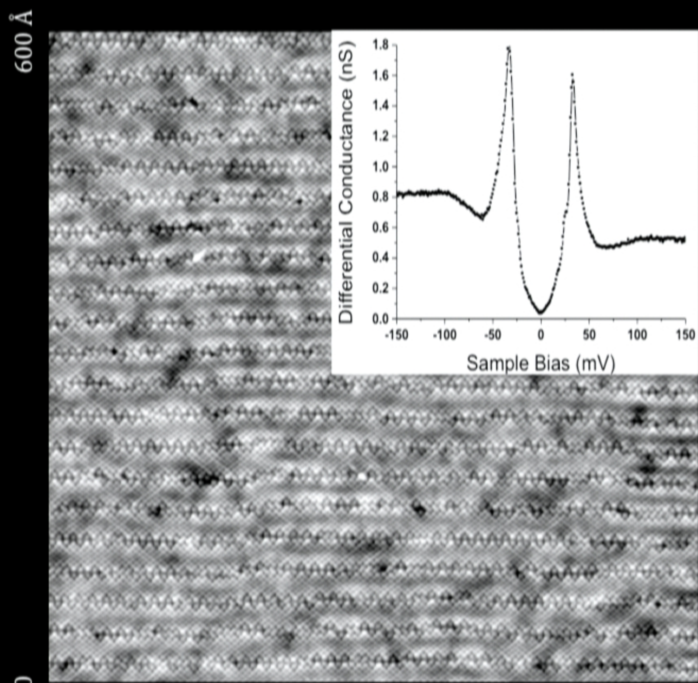


Topography

Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at single atom

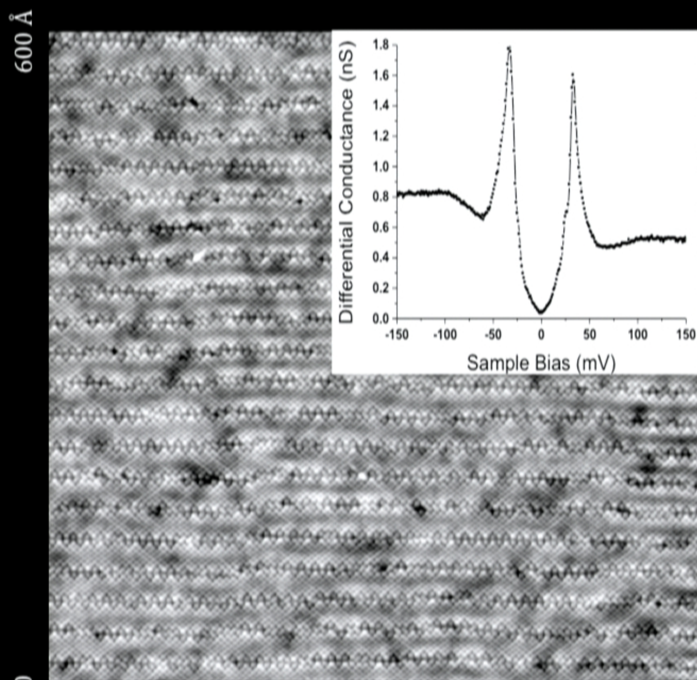


Topography

Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom



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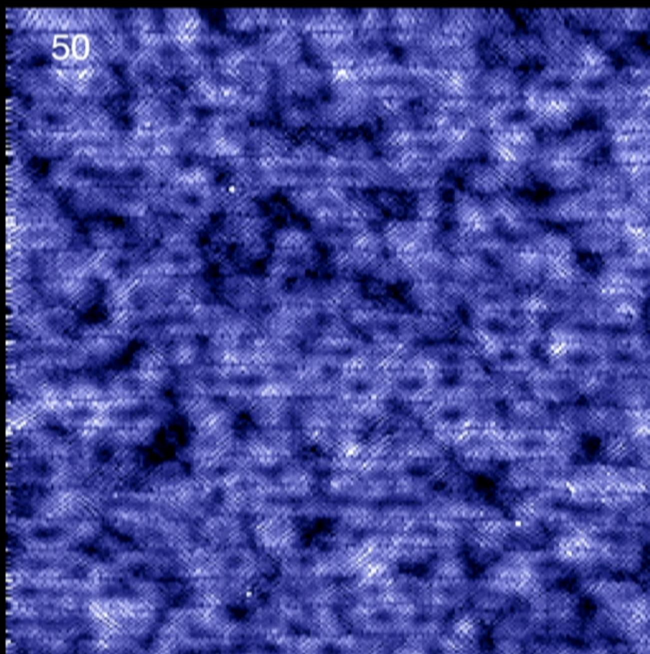
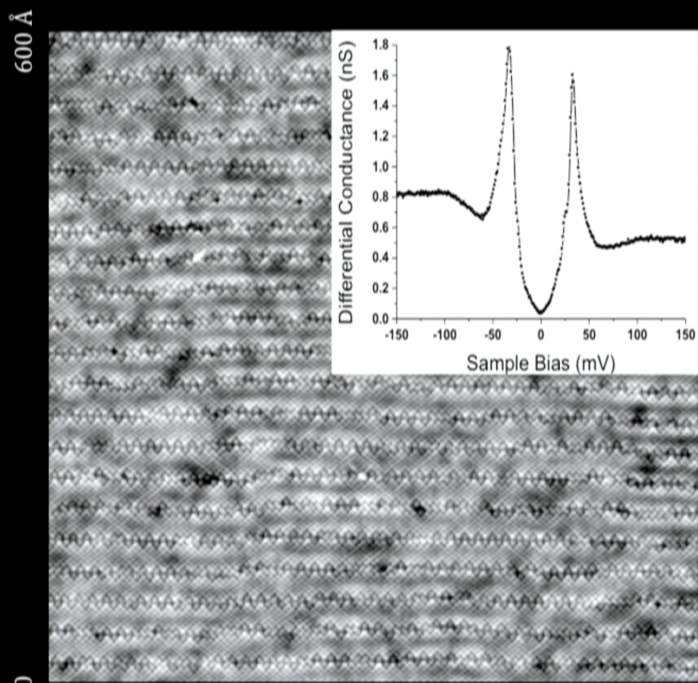


SI-STM

Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom →



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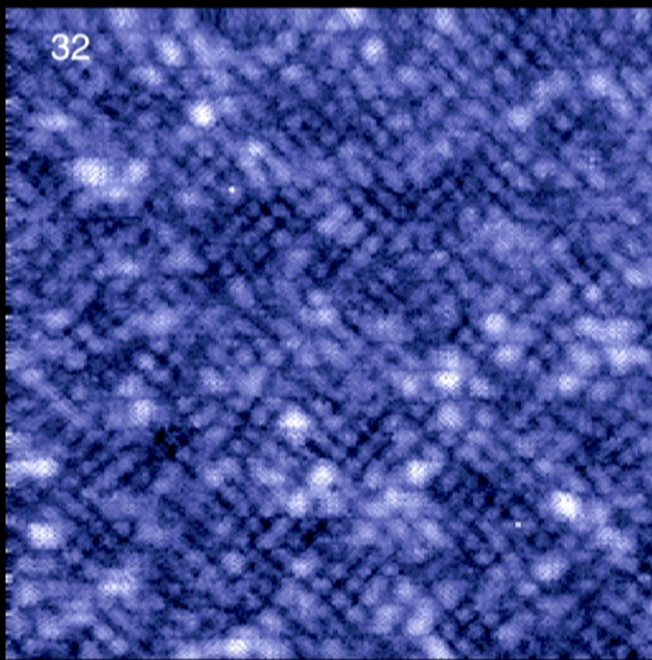
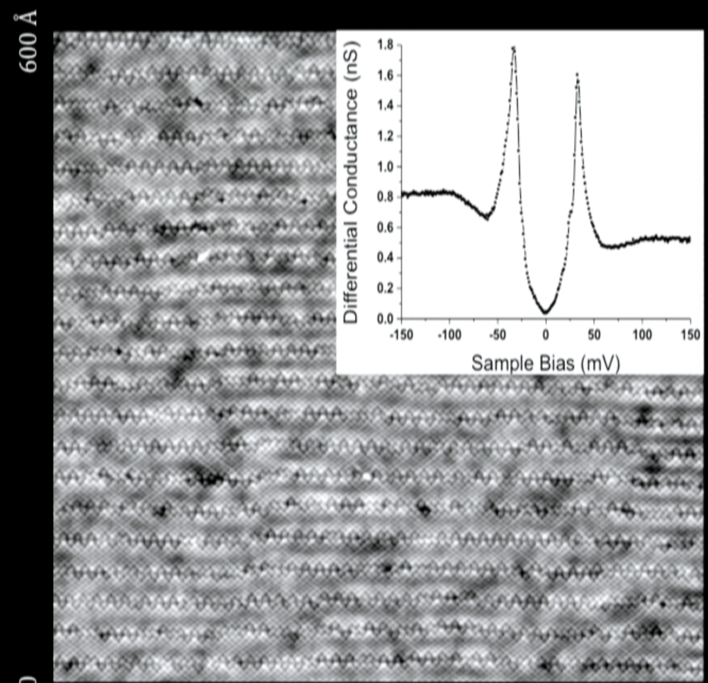


SI-STM

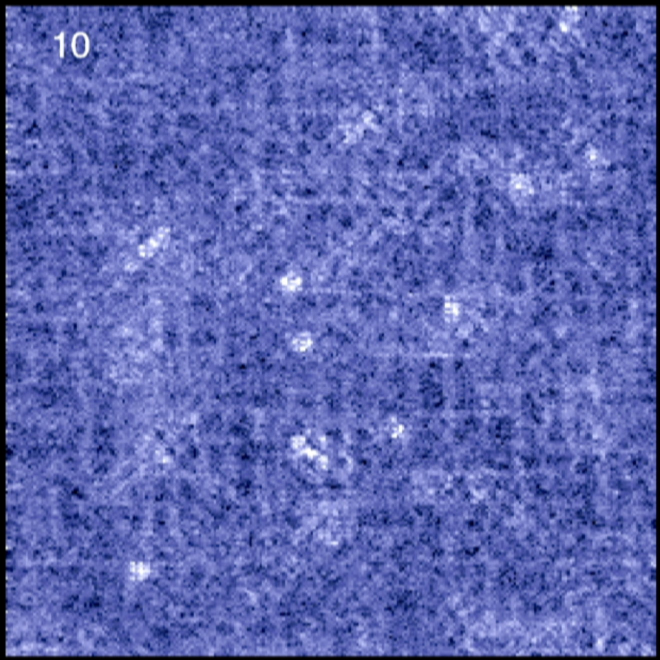
Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom →



Topography

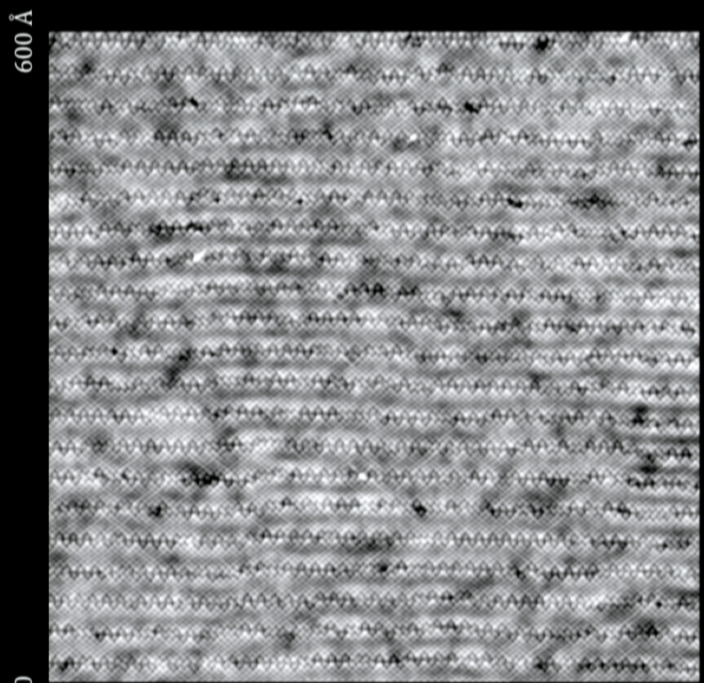


SI-STM

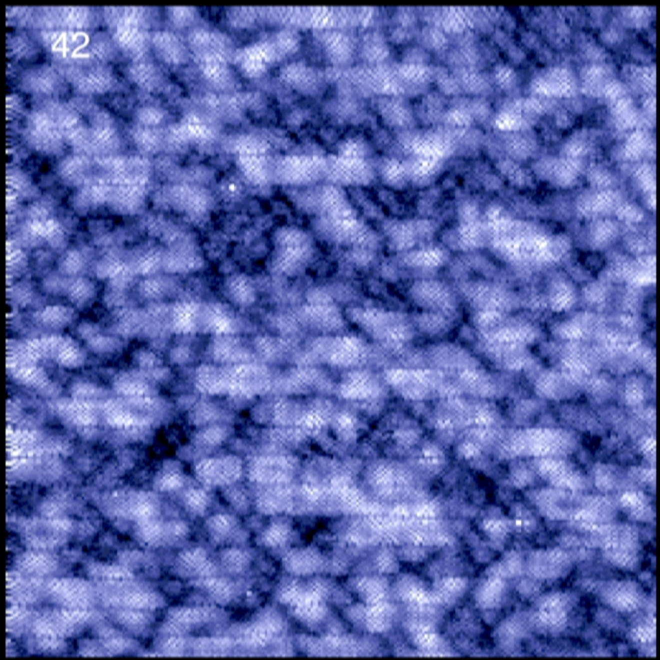
Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom → Atomic-resolution energy-resolved N(r,E)



Topography



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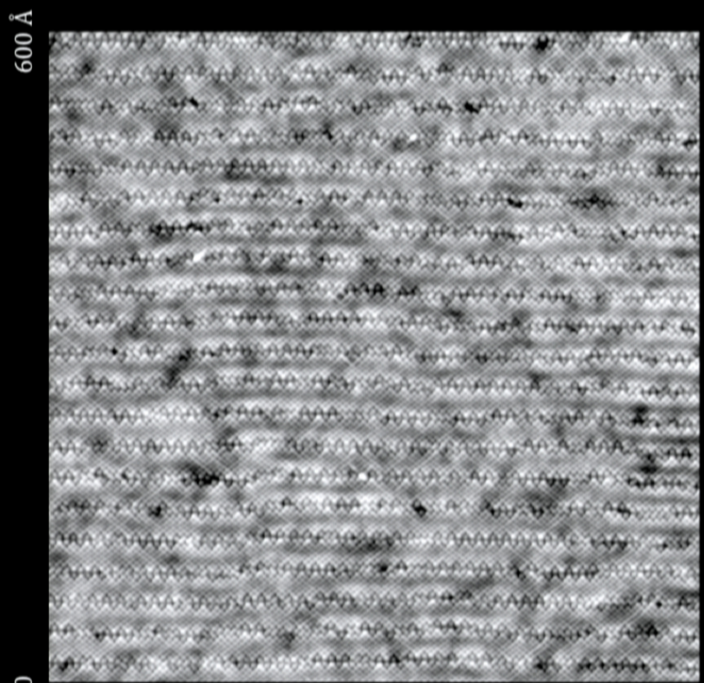
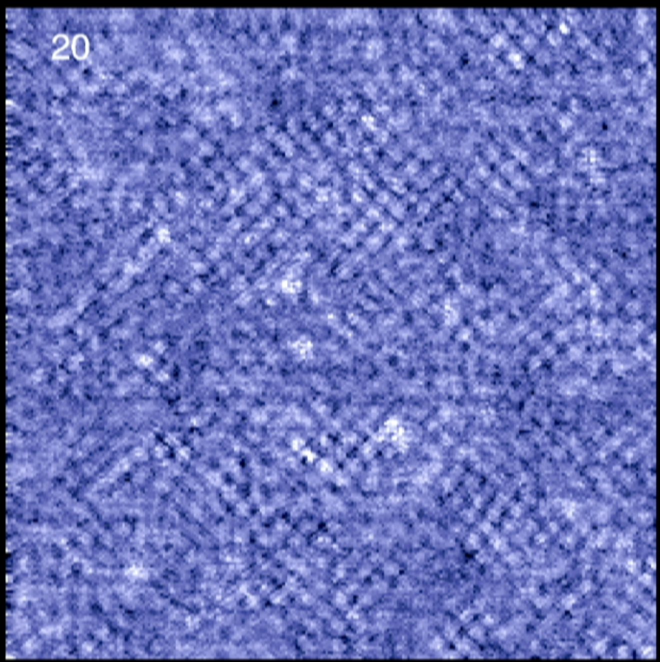


Topography



SI-STM

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Spectroscopic Imaging STM

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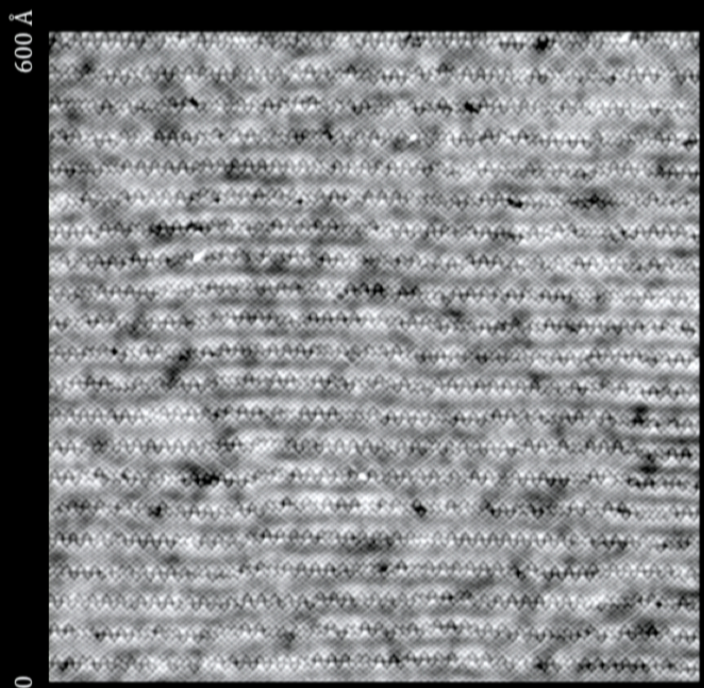
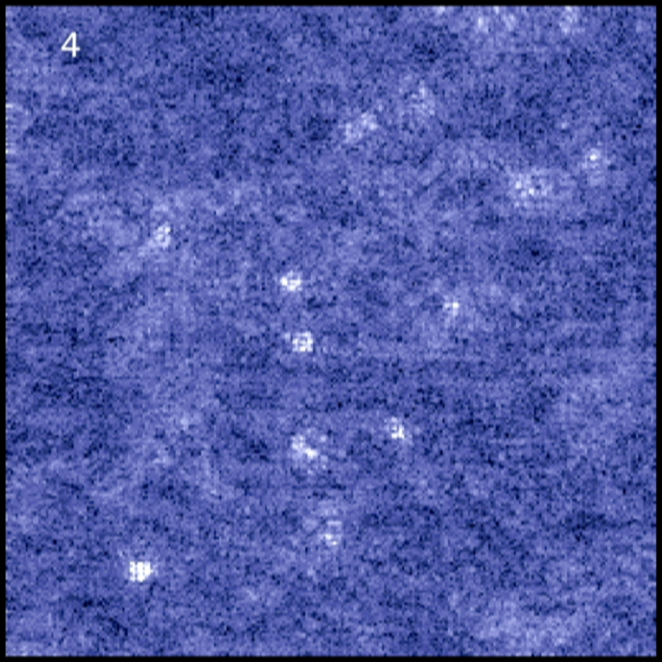


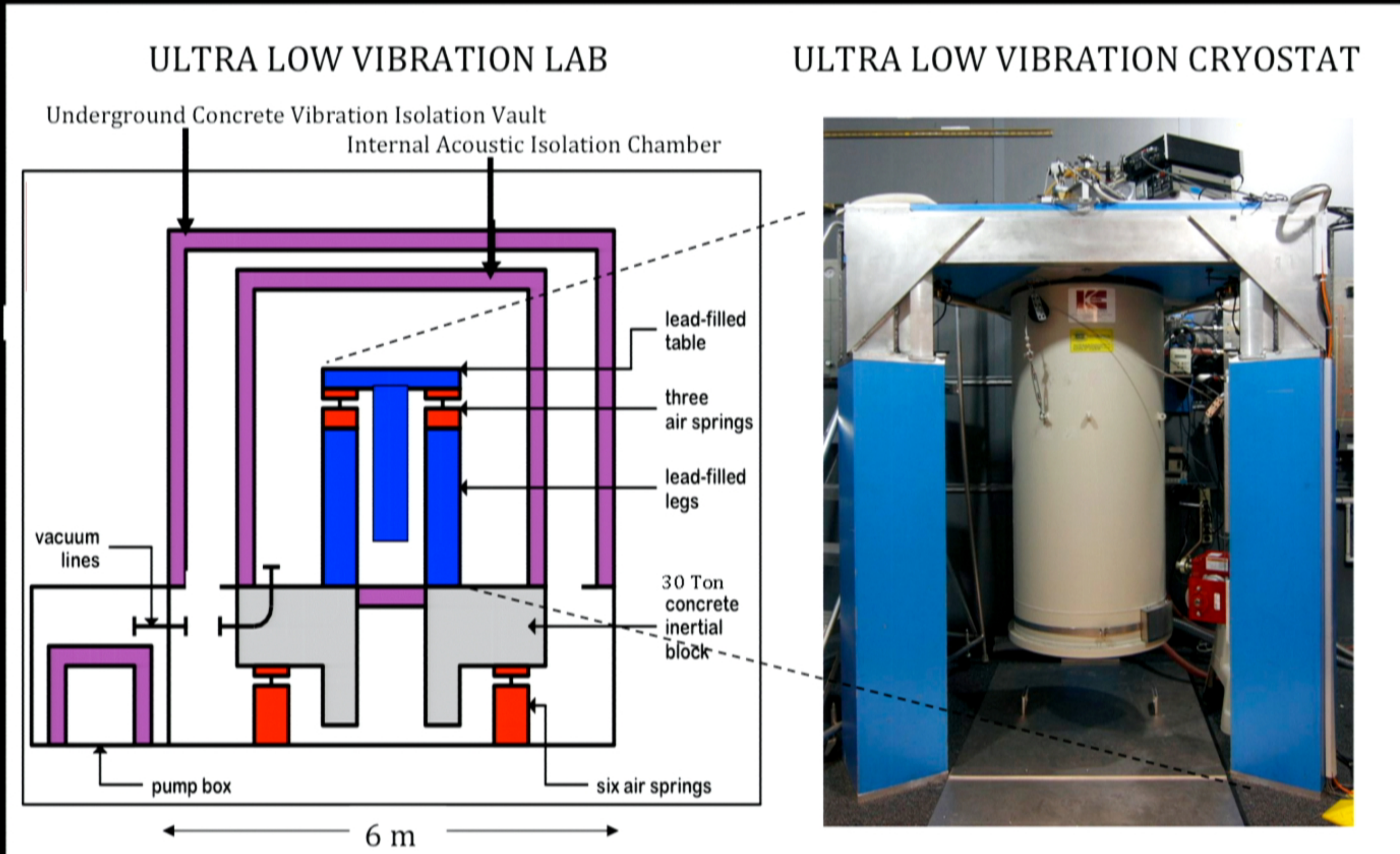
Topography



SI-STM

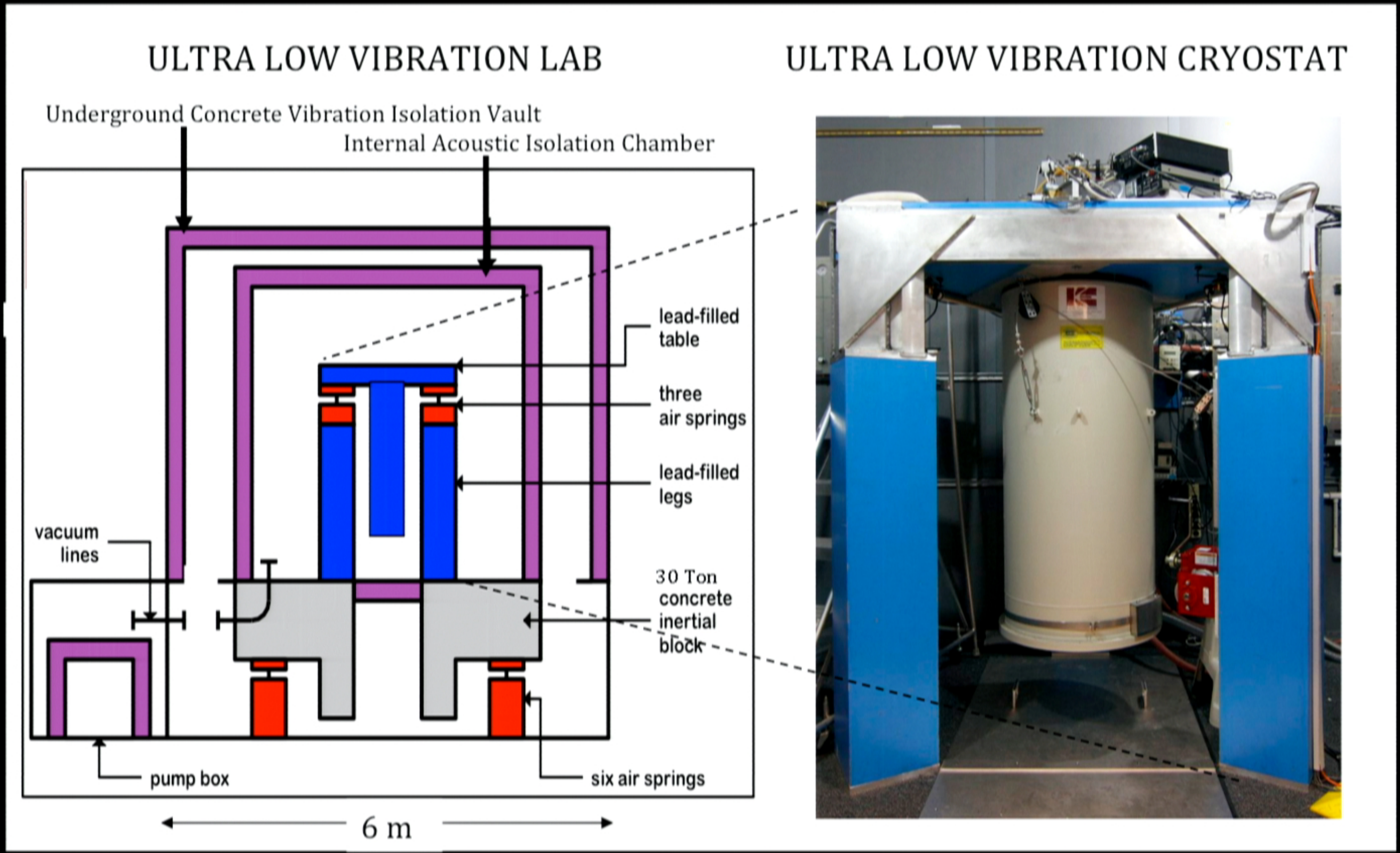
Rev. Sci. Inst. **70**, 1459 (1999).

Ultra Low Vibration Cryostat & Laboratory



Rev. Sci. Inst. **70**, 1459 (1999).

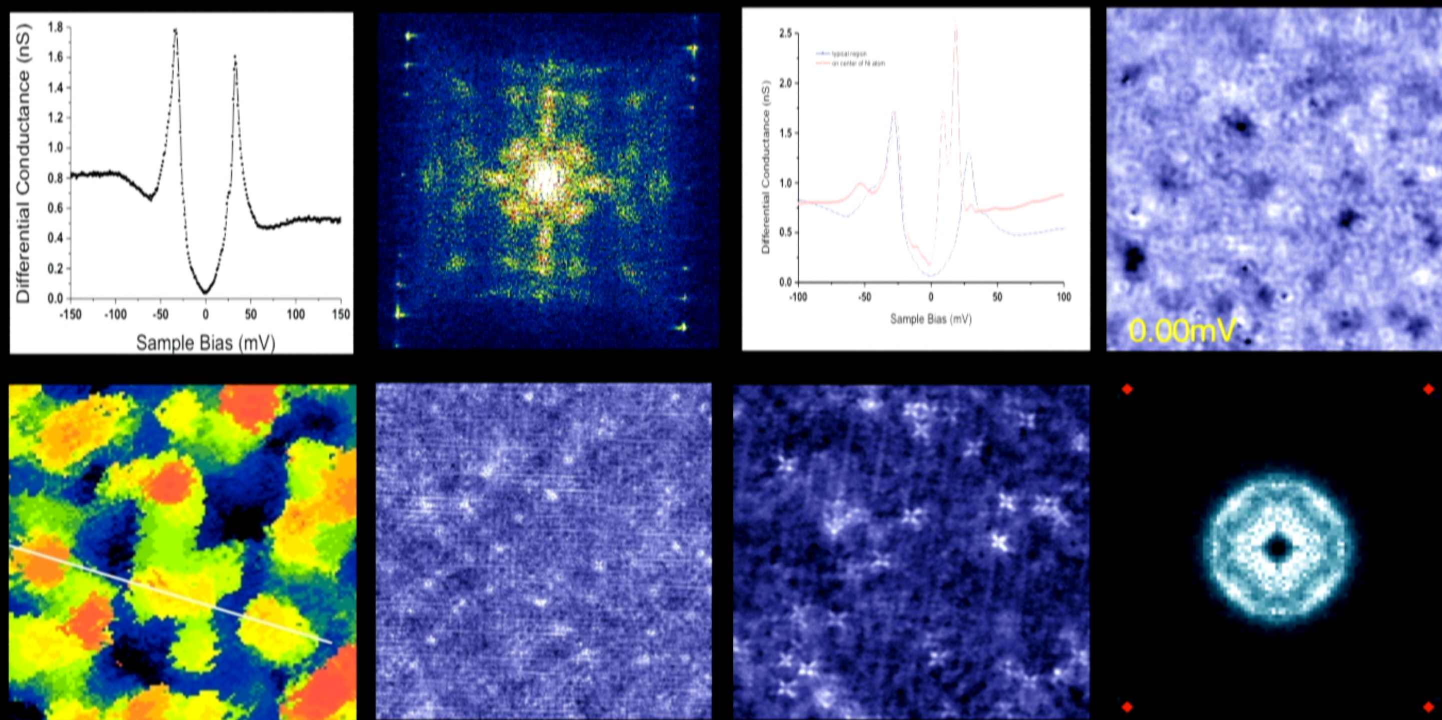
Ultra Low Vibration Cryostat & Laboratory



Rev. Sci. Inst. **70**, 1459 (1999).

Direct Visualization of Electronic Quantum Matter

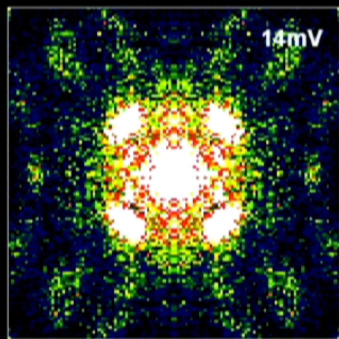
Nanoscale e-disorder	Q. Interference	Impurity Atoms	Heavy Fermion SC

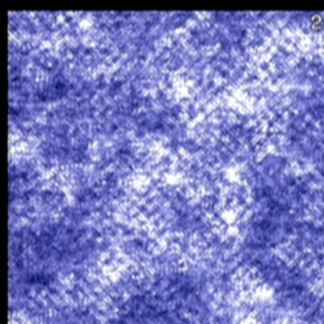


15 nm Gapmap, B=0	56 nm 0-12mV LDOS,B=5T	64 nm 12 mV LDOS, B=0	26 nm 250 mV
Nature 414 282 (2001) *Nature* 415 412 (2002)	*Science* 297, 1148 (2002) *Nature 422,* 520 (2003)	*Nature* 411, 920 (2001) *Nature* 403, 746 (2000)	*Nature* 465, 570 (2010) *Nat. Phys. 9, 458* (2013)

Direct Visualization of Electronic Quantum Matter

Phase Fluctuations

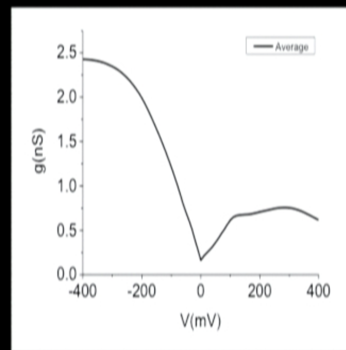


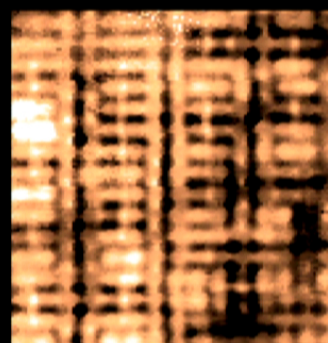


45 nm
dI/dV

Science 325, 1099 (2009)
Science 296 455 (2002)

Exotic Density Waves

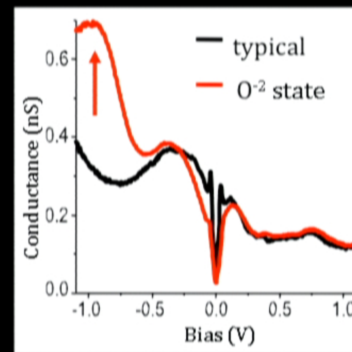


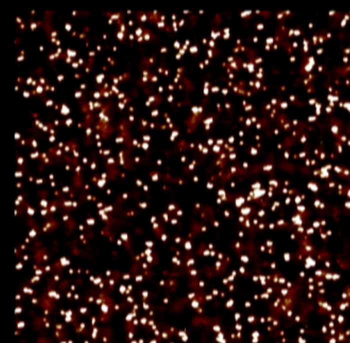


6.4 nm
R=I+/I-

Science 315, 1380 (2007)
Science , 333, 426 (2011)

Dopant Atoms

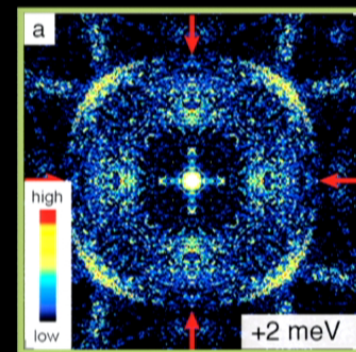


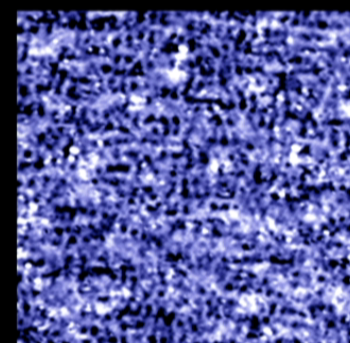


40nm
-1V LDOS, B=0

Science 309, 1048 (2005)
Nature 442, 546 (2006)

FeAs Intertwined Phases



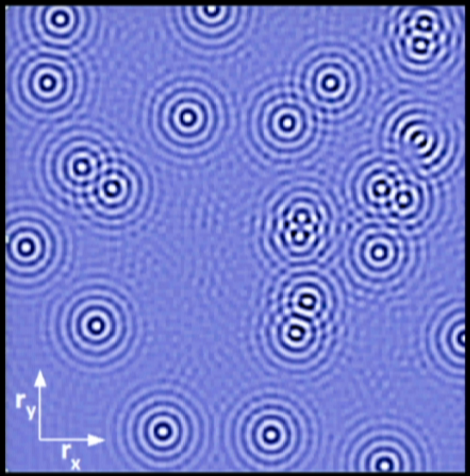


26 nm
-9mV LDOS, B=0

Science 327, 181 (2010)
Science 336, 563 (2012)

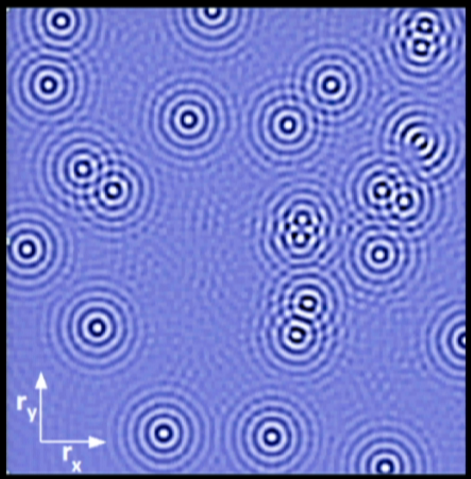
Quasiparticle Scattering Interference (QPI) Imaging

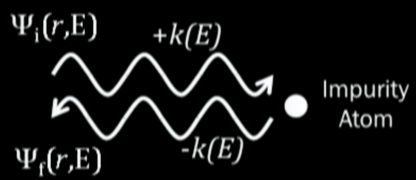
Quasiparticle Scattering Interference (QPI) Imaging



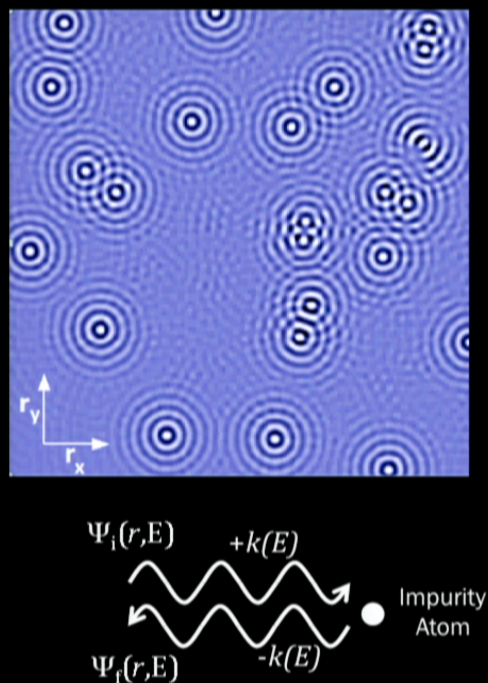
Impurity
Atom

Quasiparticle Scattering Interference (QPI) Imaging



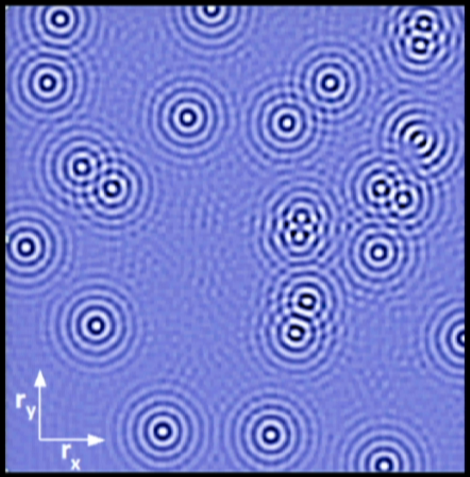


Quasiparticle Scattering Interference (QPI) Imaging



Quasiparticle Scattering Interference (QPI) Imaging

Interference Pattern

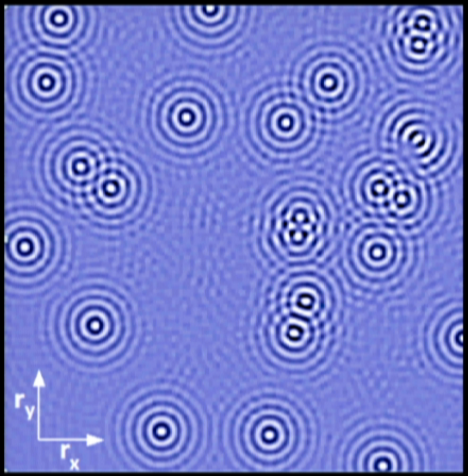


$|\Psi(r,\mathrm{E})|^2$

$q(\mathrm{E}) = 2k(E)$

Quasiparticle Scattering Interference (QPI) Imaging

Interference Pattern
$q(\mathrm{E})=2k(\mathrm{E})$



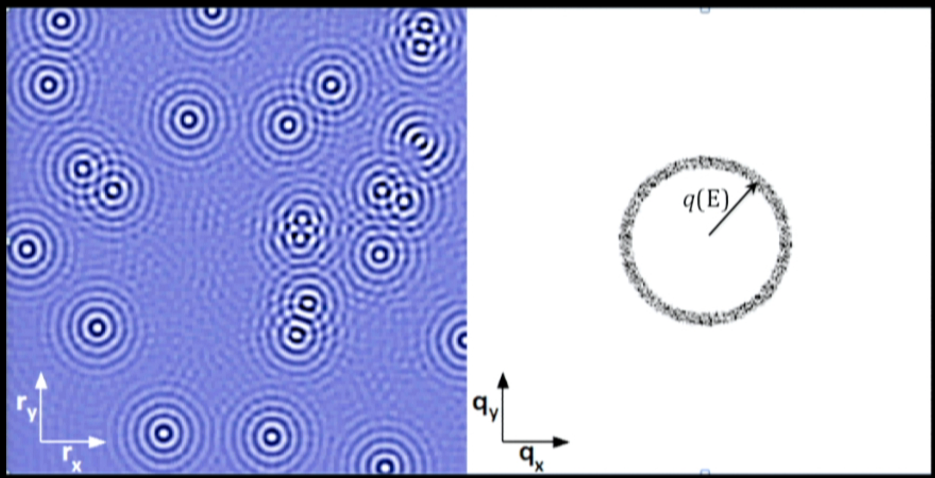
$\mathrm{N}(r,\mathrm{E})$

Quasiparticle Scattering Interference (QPI) Imaging

Interference Pattern
$q(\mathrm{E})=2k(\mathrm{E})$

=>

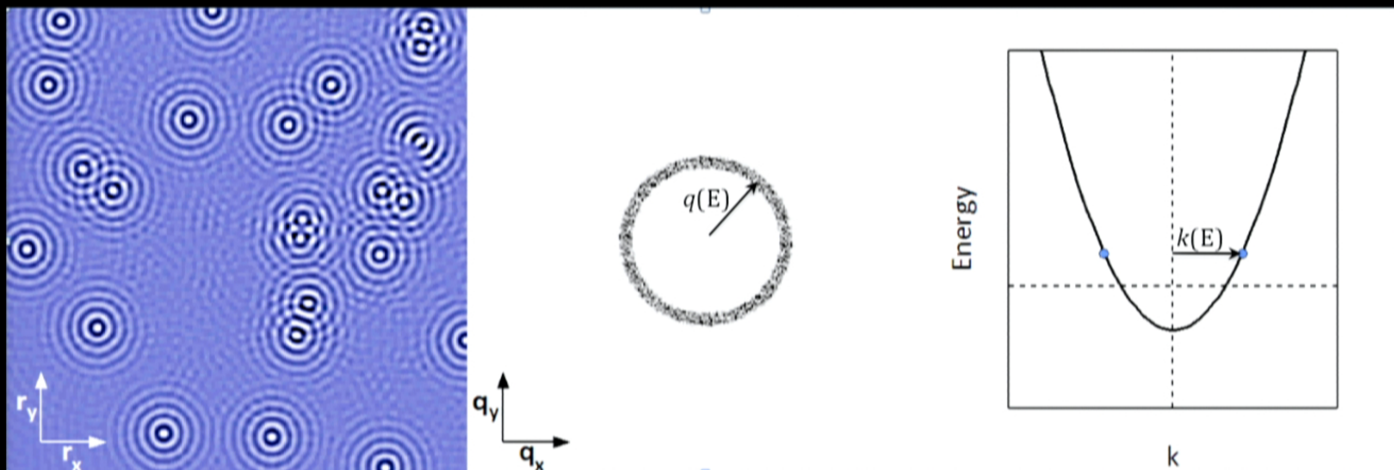
Maxima FT(N(r,E))
$q(\mathrm{E})=2k(\mathrm{E})$



N(r,E) N(q,E)

Quasiparticle Scattering Interference (QPI) Imaging

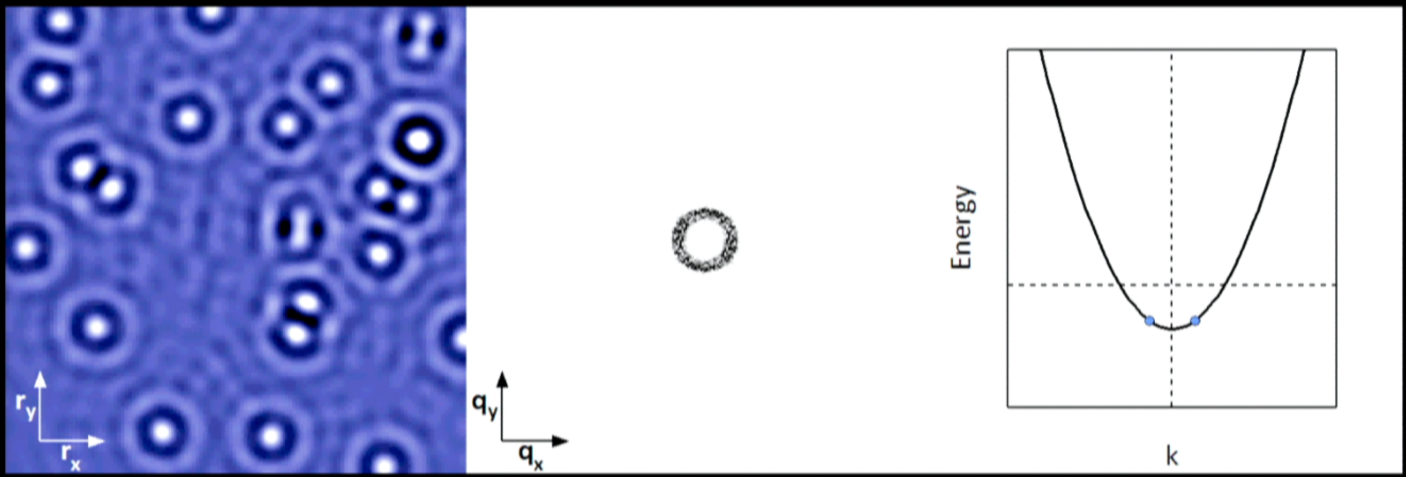
Interference Pattern $q(\mathrm{E})=2k(\mathrm{E})$ => Maxima FT(N(r,E)) $q(\mathrm{E})=2k(\mathrm{E})$ => $k(\mathrm{E})=\pm q(\mathrm{E})/2$



N(r,E) N(q,E) k(E)

Quasiparticle Scattering Interference (QPI) Imaging

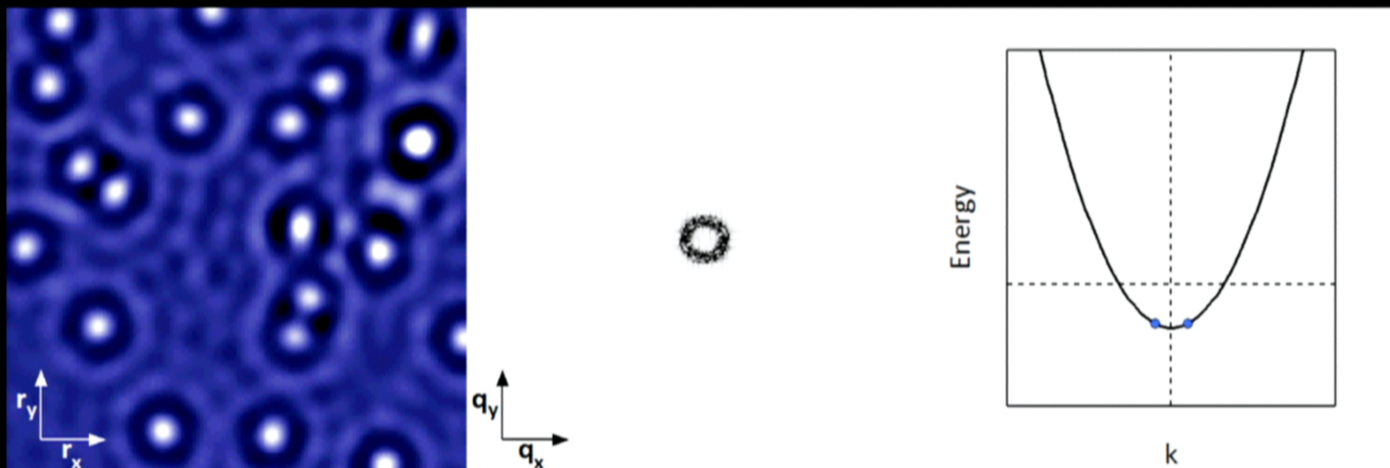
Interference Pattern $q(\mathrm{E})=2k(\mathrm{E})$ => Maxima FT(N(r,E)) $q(\mathrm{E})=2k(\mathrm{E})$ => $k(\mathrm{E})=\pm q(\mathrm{E})/2$



N(r,E) N(q,E) k(E)

Quasiparticle Scattering Interference (QPI) Imaging

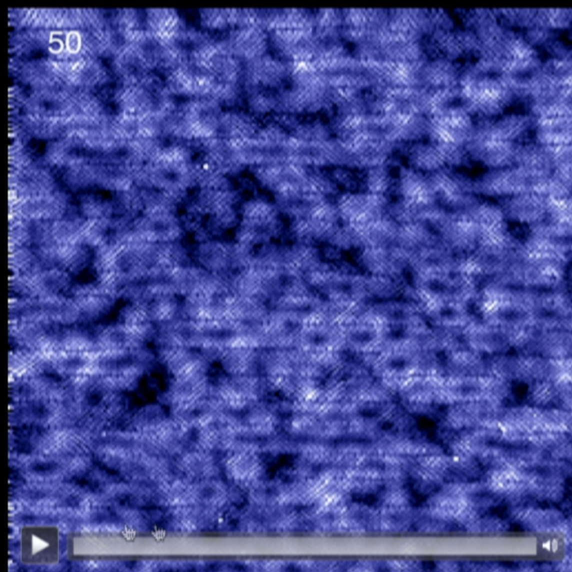
Interference Pattern $q(\mathrm{E})=2k(\mathrm{E})$ => Maxima FT(N(r,E)) $q(\mathrm{E})=2k(\mathrm{E})$ => $k(\mathrm{E})=\pm q(\mathrm{E})/2$



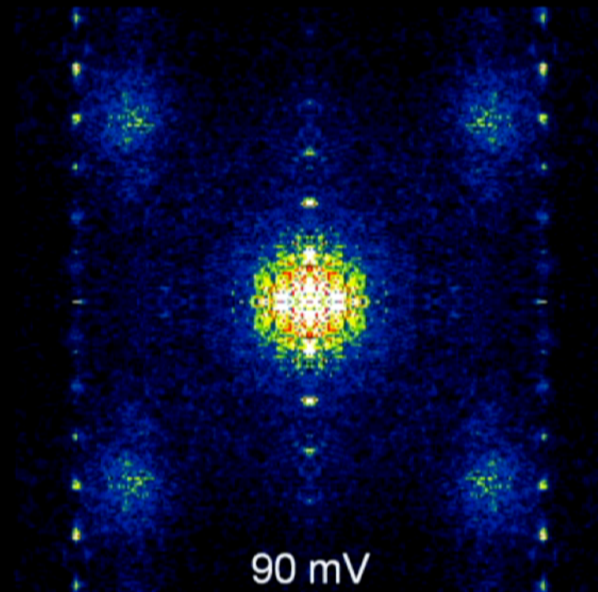
N(r,E) N(q,E) k(E)

Access to empty & filled states, operates to T~10mK (dE~10μV) and in high B fields.

Cu-based HTS: PSD Fourier Transform g(r, ω) = g(q, ω)



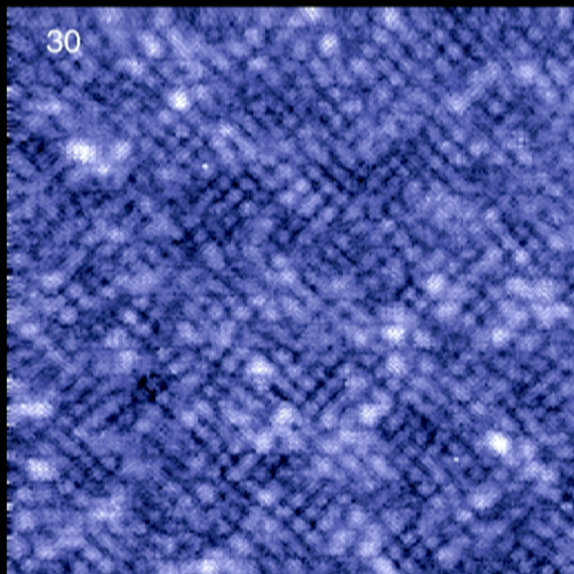
g($\boldsymbol{r}$,ω)



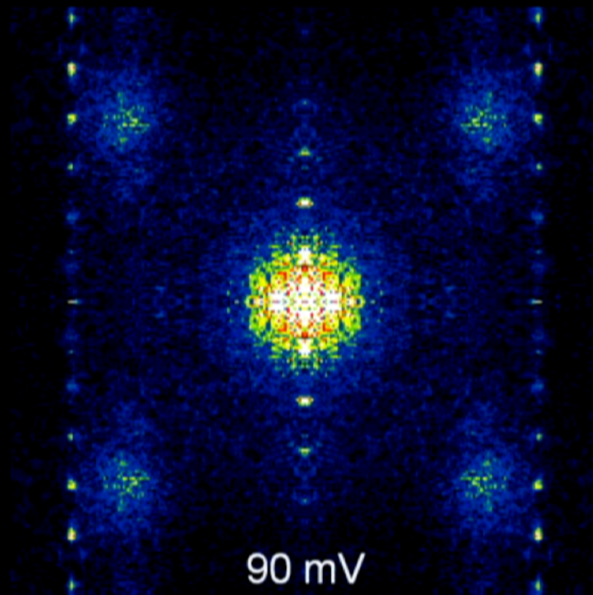
g($\boldsymbol{q}$,ω)

***Nature* 454**, 1072, (2008)

Cu-based HTS: PSD Fourier Transform $g(r, \omega) = g(q, \omega)$



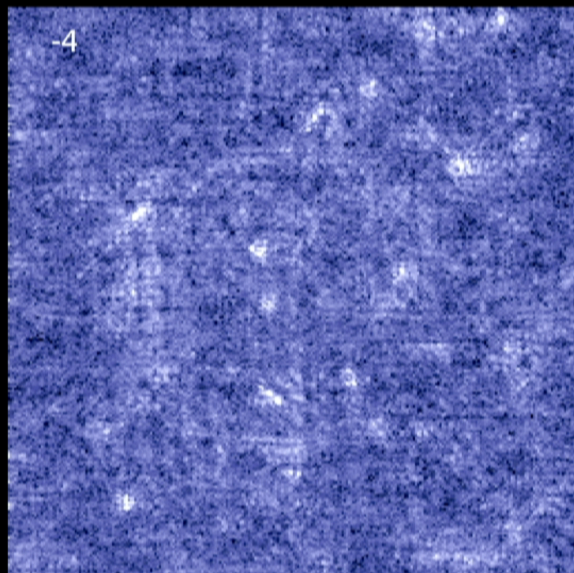
$g(\boldsymbol{r},\omega)$



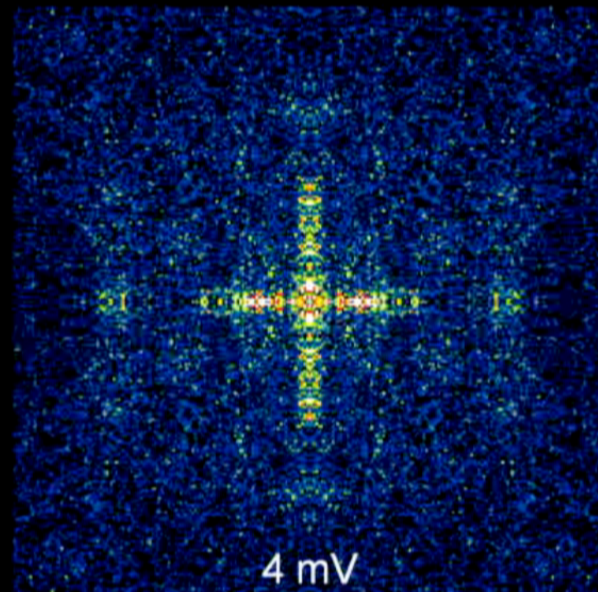
$g(\boldsymbol{q},\omega)$

***Nature* 454**, 1072, (2008)

Cu-based HTS: PSD Fourier Transform $g(r, \omega) = g(q, \omega)$



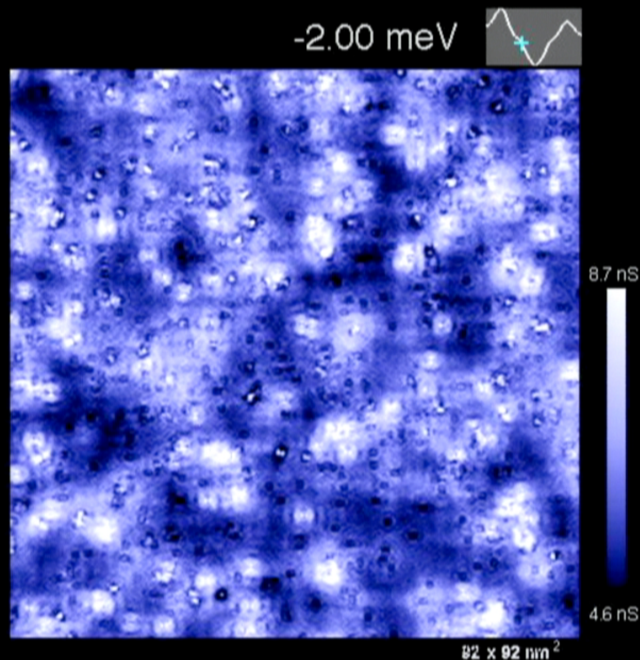
$g(\boldsymbol{r},\omega)$



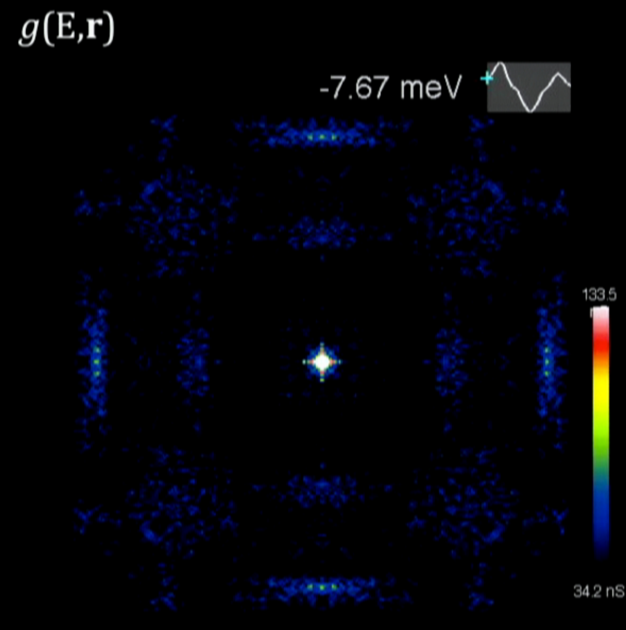
$g(\boldsymbol{q},\omega)$

***Nature* 454**, 1072, (2008)

Fe-based HTS: PSD Fourier Transform $g(r, \omega) = g(q, \omega)$



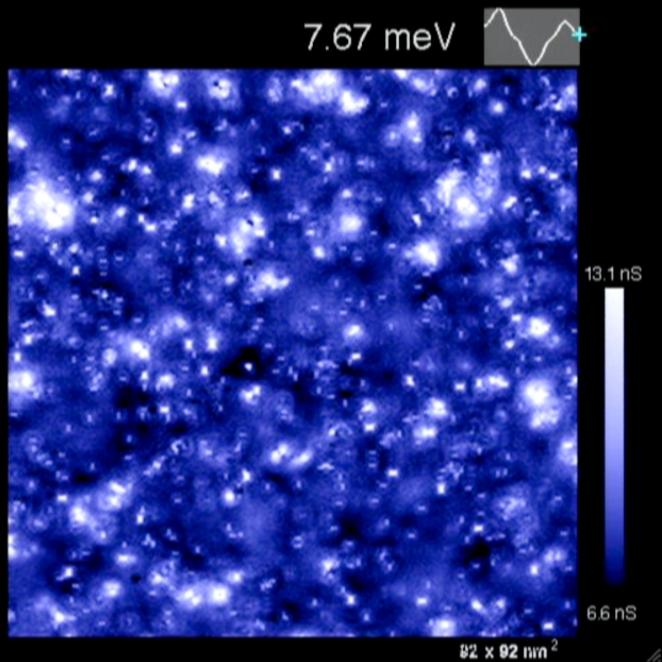
$g(\mathbf{r},\omega)$



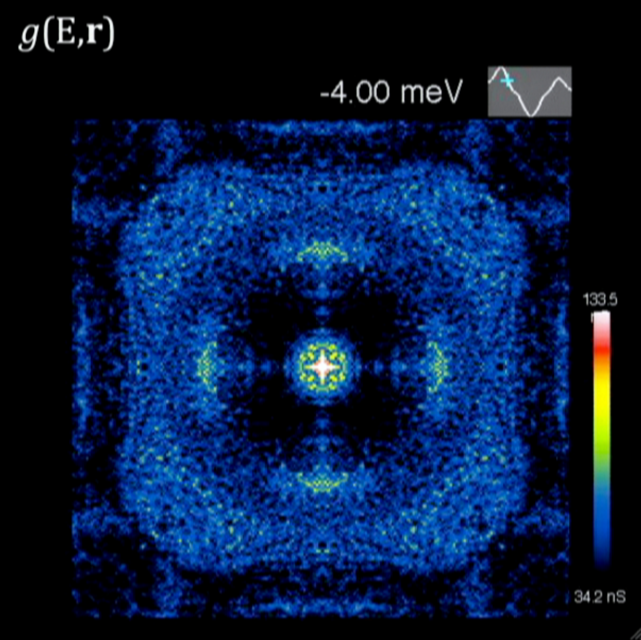
$g(\boldsymbol{q},\omega)$

Science 336, 563, (2012)

Fe-based HTS: PSD Fourier Transform g(*r*, ω) = g(*q*, ω)



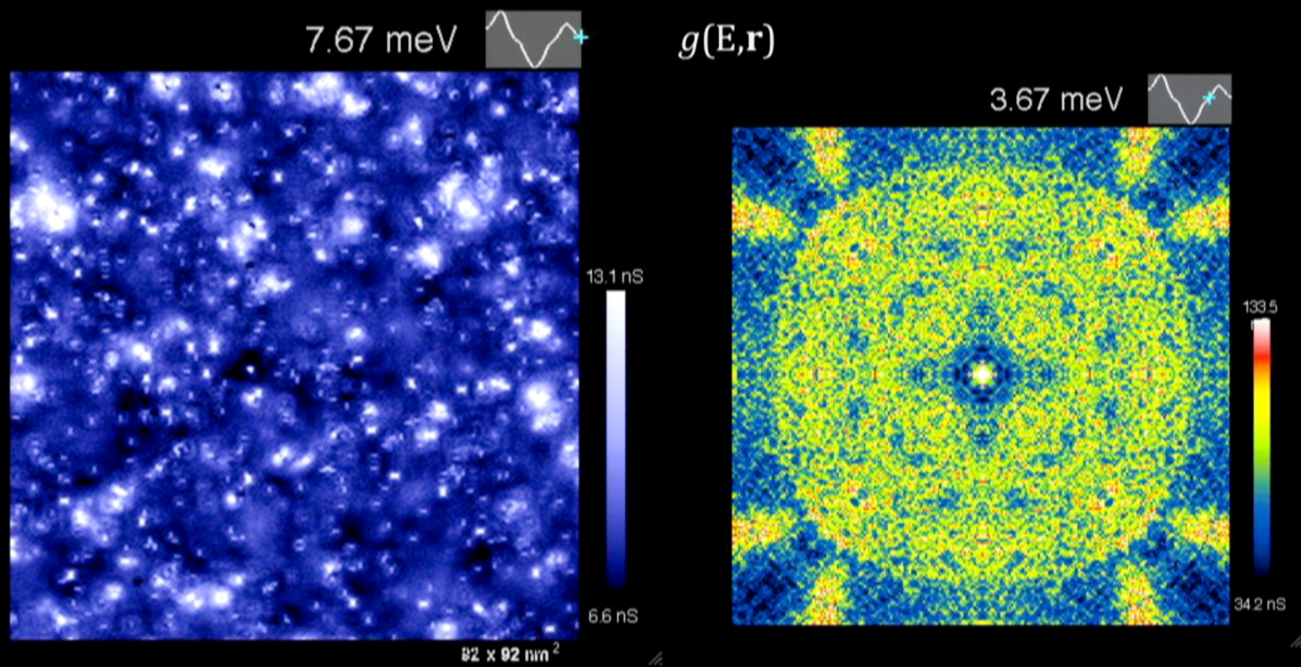
$g(\mathbf{r},\omega)$



$g(\mathbf{q},\omega)$

Science 336, 563, (2012)

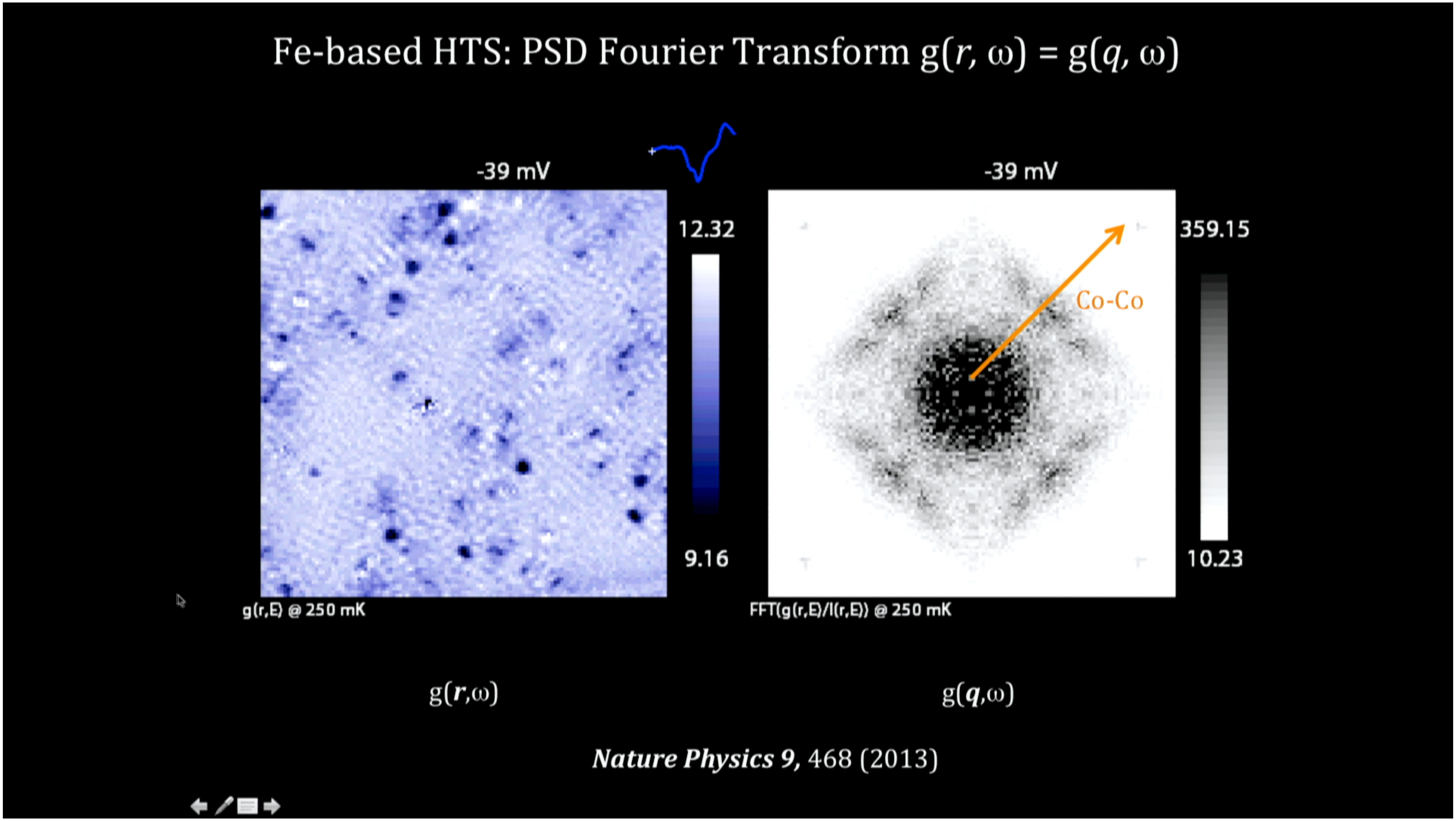
Fe-based HTS: PSD Fourier Transform g(*r*, ω) = g(*q*, ω)



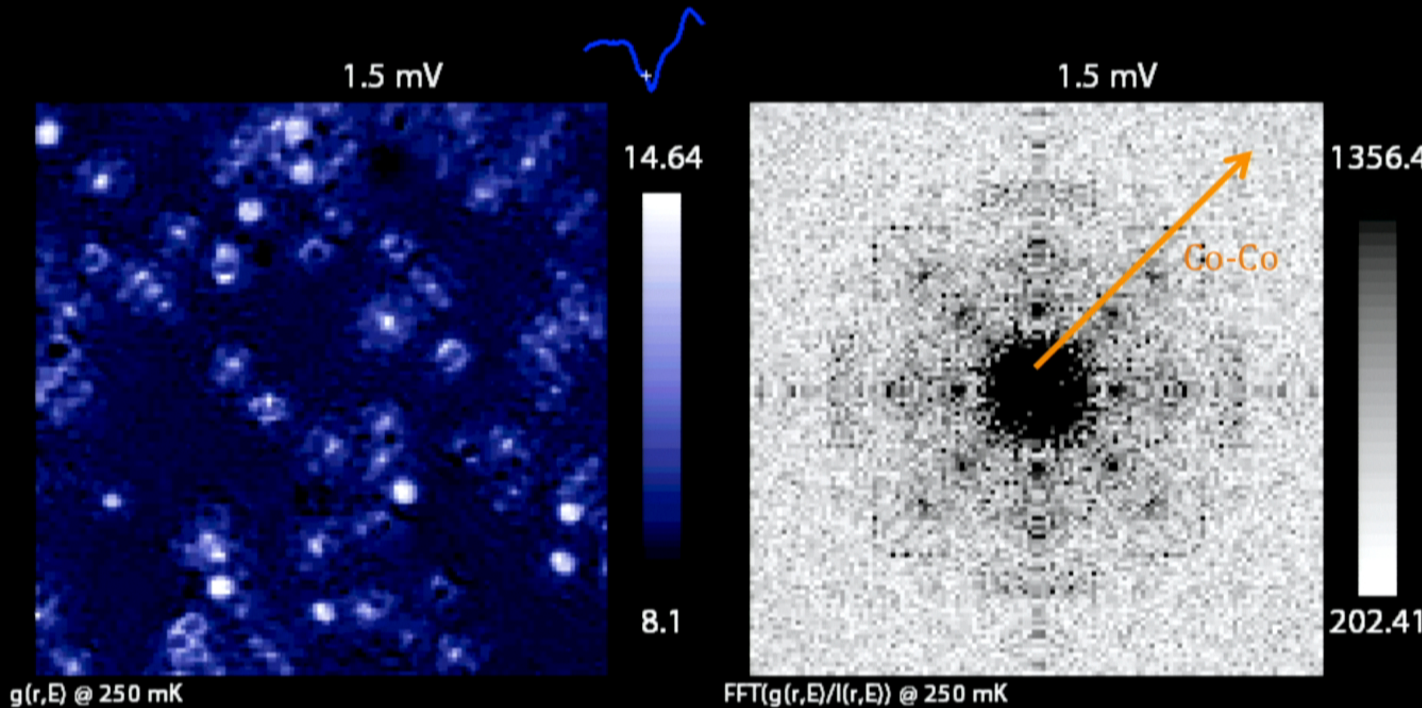
g(***r***,ω)

g(***q***,ω)

Science 336, 563, (2012)


Fe-based HTS: PSD Fourier Transform g(r, ω) = g(q, ω)
-39 mV
12.32
9.16
g(r,E) @ 250 mK
-39 mV
359.15
Co-Co
10.23
FFT(g(r,E)/I(r,E)) @ 250 mK
g(r,ω)
g(q,ω)
Nature Physics 9, 468 (2013)

Fe-based HTS: PSD Fourier Transform $g(r, \omega) = g(q, \omega)$



$g(\boldsymbol{r},\omega)$ $g(\boldsymbol{q},\omega)$

***Nature Physics* 9,** 468 (2013)

Relating N($\boldsymbol{q}$,ω) to Electron Greens Function G($\boldsymbol{r}$,ω)

DOS Perturbation from Impurity Scattering

$$N(\vec{r},\omega) = -\frac{1}{\pi}\mathrm{Im}\int d^2r''G_0(\vec{r}-\vec{r}'',\omega)\delta E(\vec{r}'')G_0(\vec{r}''-r,\omega)$$

$$N(\vec{q},\omega) \quad = \sum_{LXL} e^{-i\vec{q}\bullet\vec{r}} N(\vec{r},\omega)$$

Separable in Born Approx.

$$= -\frac{\delta E(\vec{q})}{\pi}\mathrm{Im}\,\Lambda(\vec{q},\omega)$$

Lambda Integral

$$\Lambda(\vec{q},\omega) = \int d^2r\, e^{-iq.r} G_0(\vec{r},\omega)G_0(-\vec{r},\omega)$$

Power Spectral Density FT STM

$$P(\vec{q},\omega) = \frac{1}{M}\left|\frac{1}{\pi}\mathrm{Im}\,\Lambda(\vec{q},\omega)\right|^2 \left|\delta E(\vec{q})\right|^2$$

2d EG + Born Approx. + Point Scatterers

$$\boxed{P(\vec{q},\omega) \propto \left|\mathrm{Im}\,\Lambda(\vec{q},\omega)\right|^2}$$

PRB **68**, 014508 (2003) & NJP **16** 23003 (2014)

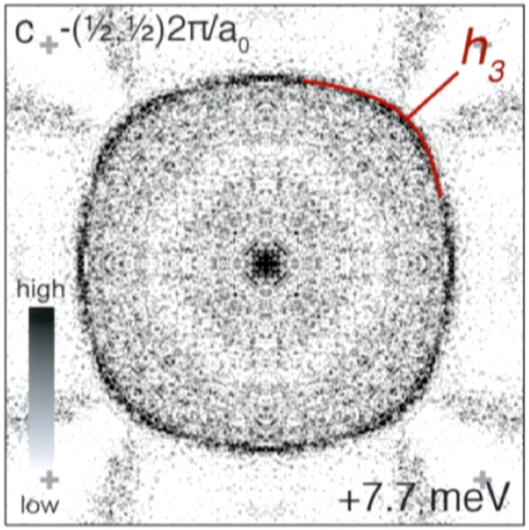
Relation of N($\boldsymbol{q}$,ω) to Self-Energy $\Sigma(\boldsymbol{k},\omega)=\omega\,(1-Z(\boldsymbol{k},\omega))$

$$G(k,\omega)=[\omega-E(k)-\Sigma(k,\omega)]^{-1}=[\omega Z(k,\omega)-E(k)]^{-1}$$

$$\frac{(k_1+ik_2)^2}{2m}-\frac{k_F^2}{2m}=\omega Z(k,\omega)$$

$$\frac{-1}{\pi}\mathrm{Im}\,\Lambda(\vec{q},\omega)=\frac{8N_0^2}{q}\mathrm{Re}\frac{1}{\sqrt{q^2-(2k(\omega))^2}}$$

$$k_1(\omega)=q_m(\omega)/2$$
$$k_2(\omega)=\delta q_m(\omega)/2$$



$$k_1^2(\omega)-k_2^2(\omega)=k_F^2+2m\omega\,\mathrm{Re}\,Z(\omega)$$
$$2k_1(\omega)k_2(\omega)=2m\omega\,\mathrm{Im}\,Z(\omega)$$

PRB **68**, 014508 (2003) & NJP **16** 23003 (2014)

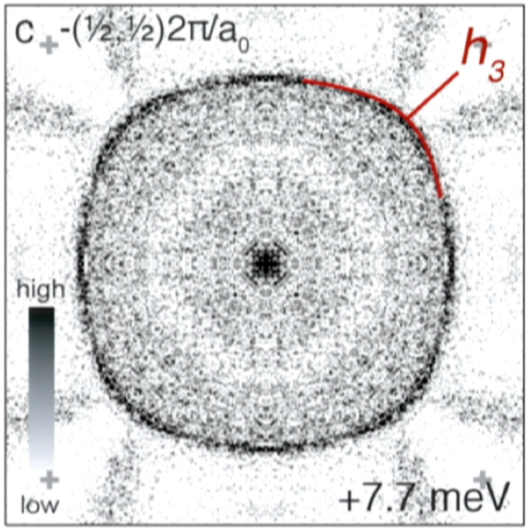
Relation of N(***q***,ω) to Self-Energy Σ(***k***, ω)=ω (1- Z(***k***, ω))

$$G(k,\omega) = [\omega - E(k) - \Sigma(k,\omega)]^{-1} = [\omega Z(k,\omega) - E(k)]^{-1}$$

$$\frac{(k_1 + ik_2)^2}{2m} - \frac{k_F^2}{2m} = \omega Z(k,\omega)$$

$$\frac{-1}{\pi}\mathrm{Im}\,\Lambda(\vec{q},\omega) = \frac{8N_0^2}{q}\mathrm{Re}\frac{1}{\sqrt{q^2 - (2k(\omega))^2}}$$

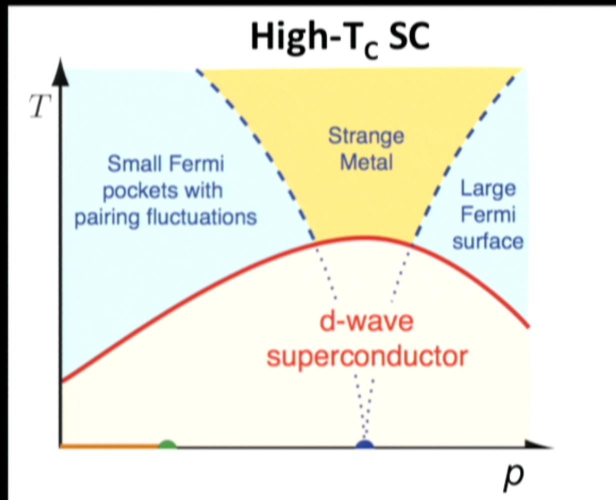
$$\boxed{\begin{aligned} k_1(\omega) &= q_m(\omega)/2 \\ k_2(\omega) &= \delta q_m(\omega)/2 \end{aligned}}$$

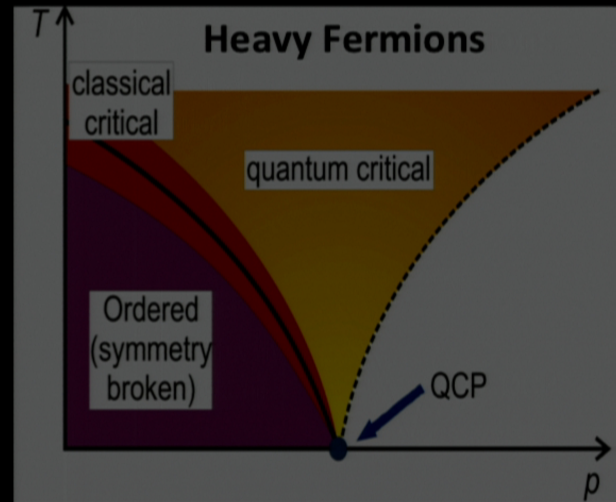


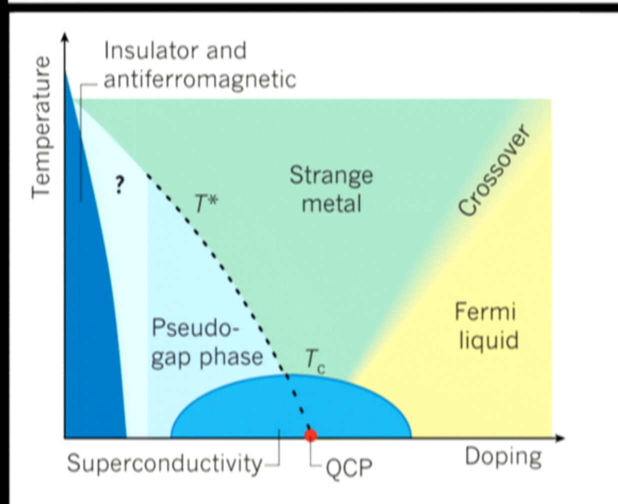
$$\boxed{\begin{aligned} k_1^2(\omega) - k_2^2(\omega) &= k_F^2 + 2m\omega\,\mathrm{Re}\,Z(\omega) \\ 2k_1(\omega)k_2(\omega) &= 2m\omega\,\mathrm{Im}\,Z(\omega) \end{aligned}}$$

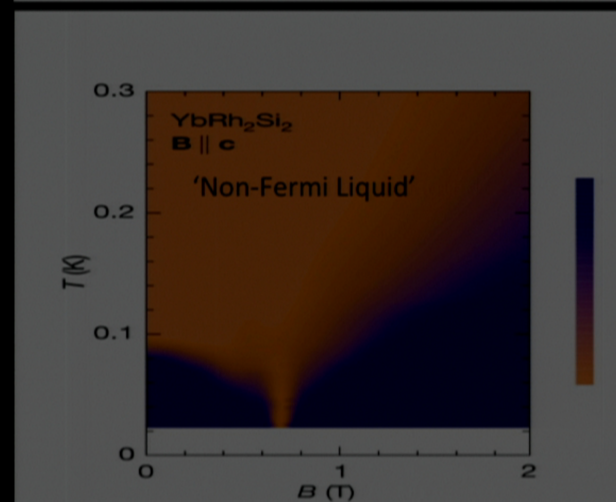
PRB **68**, 014508 (2003) & NJP **16** 23003 (2014)

QUANTUM CRITICAL ELECTRONIC MATTER

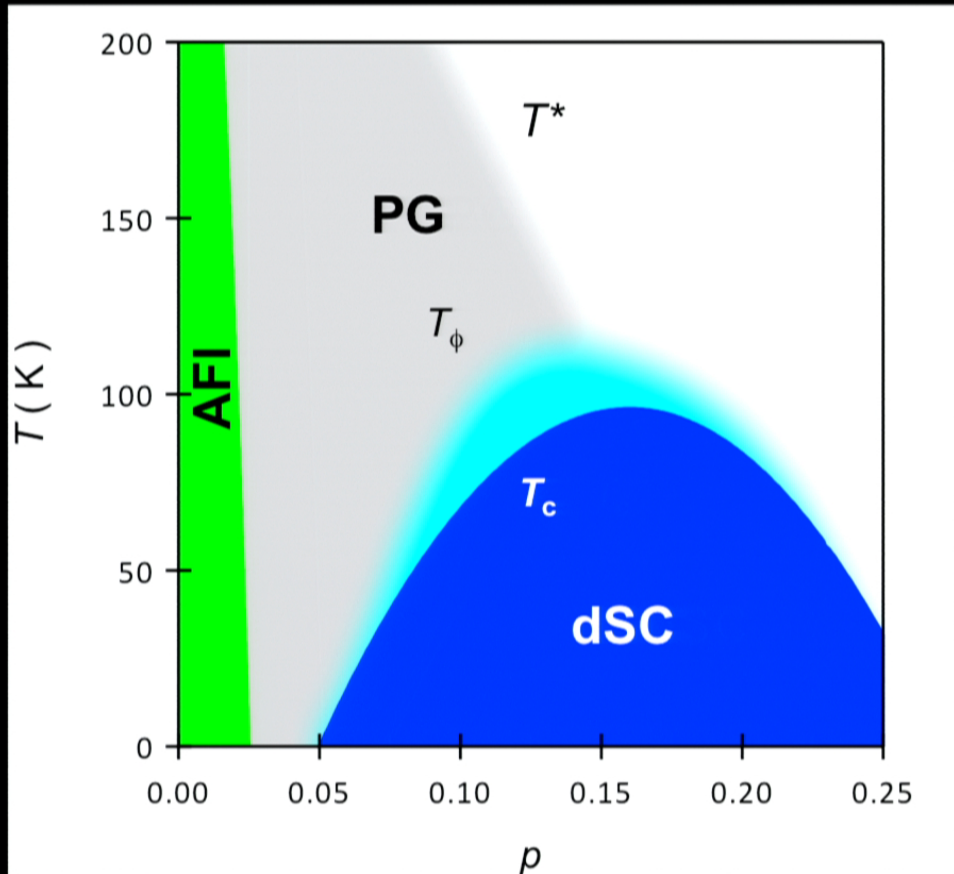




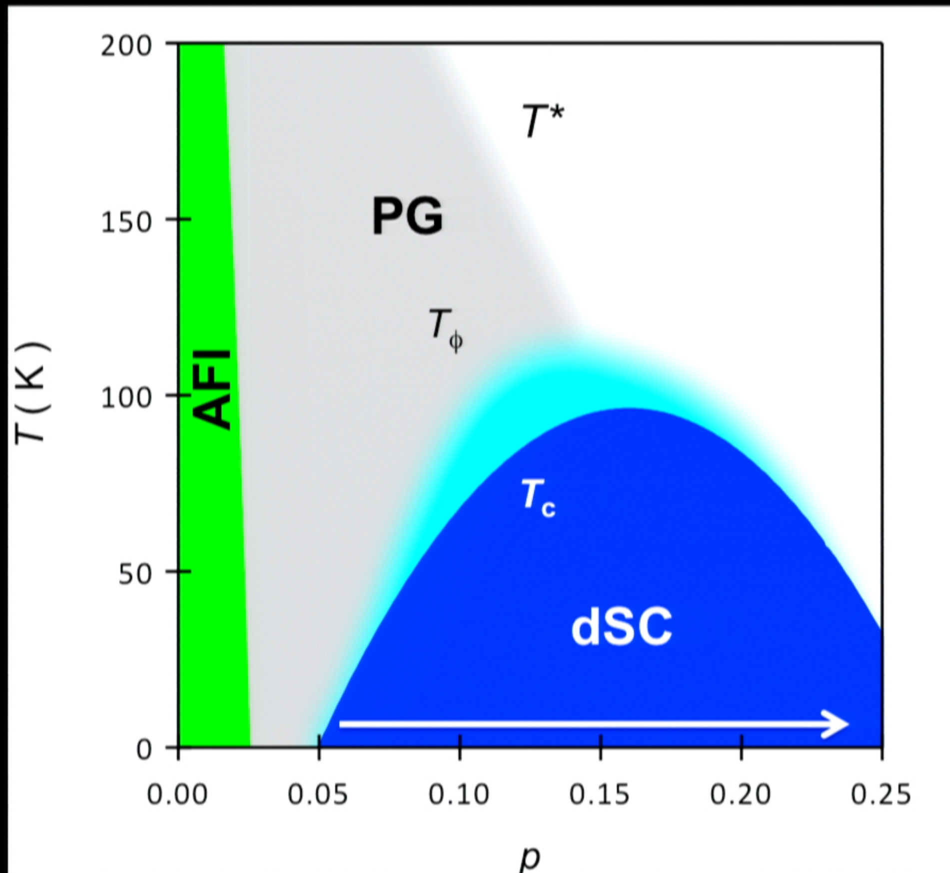




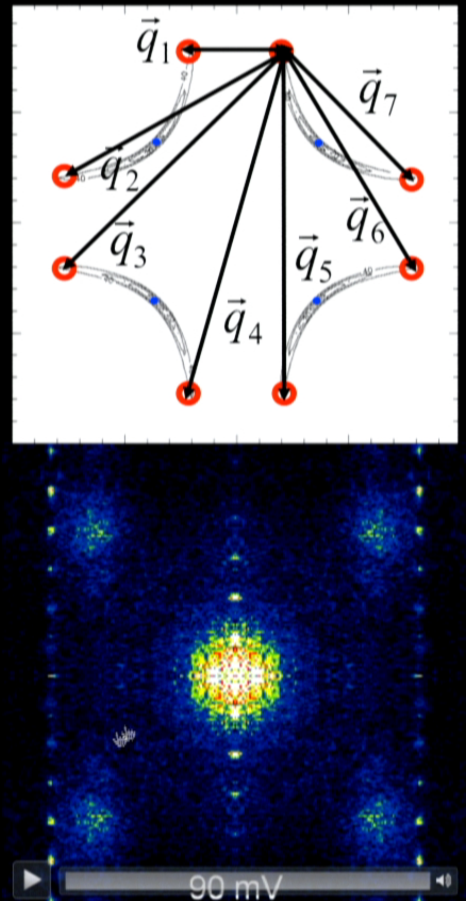
Hole-doped Cuprate Phase Diagram



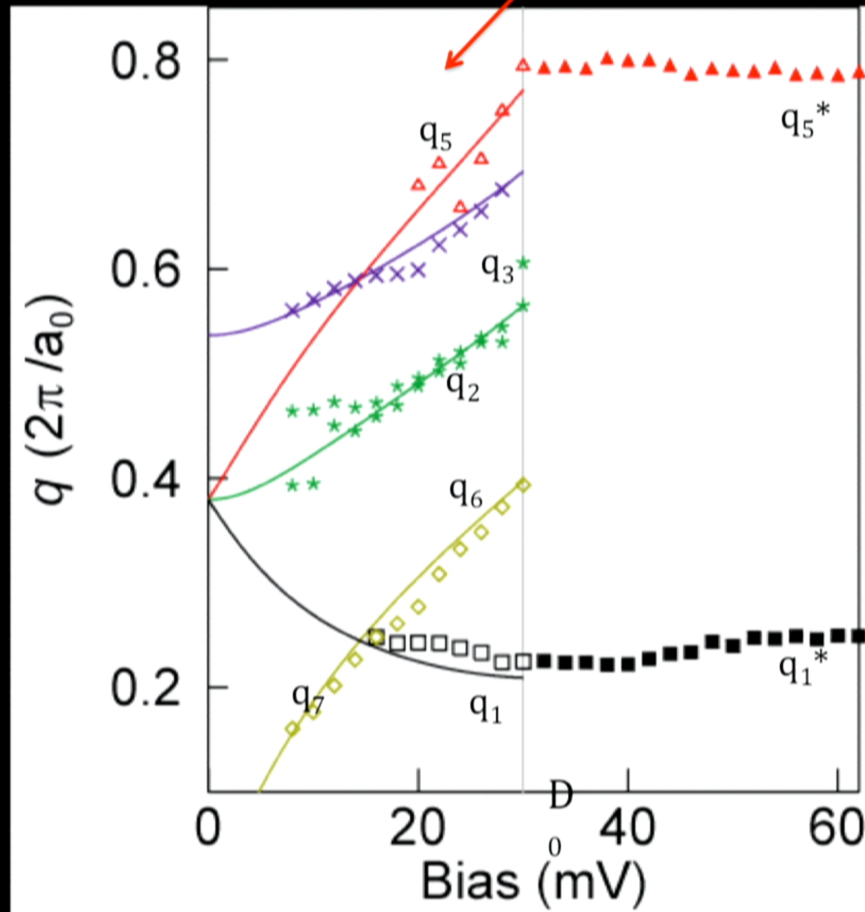
Visualize Broken Symmetries & QPI across Phase Diagram ?



Low Energy: Signature of d-wave Cooper pairing



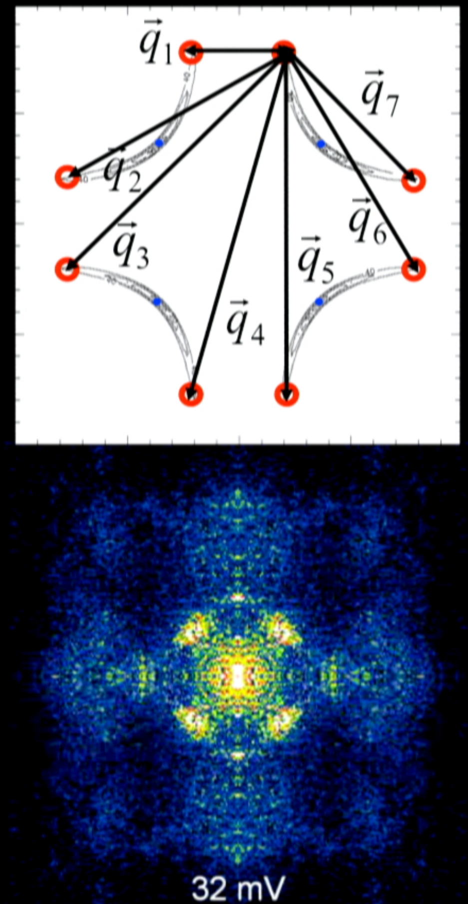
Science ***297***, 1148 (2002)



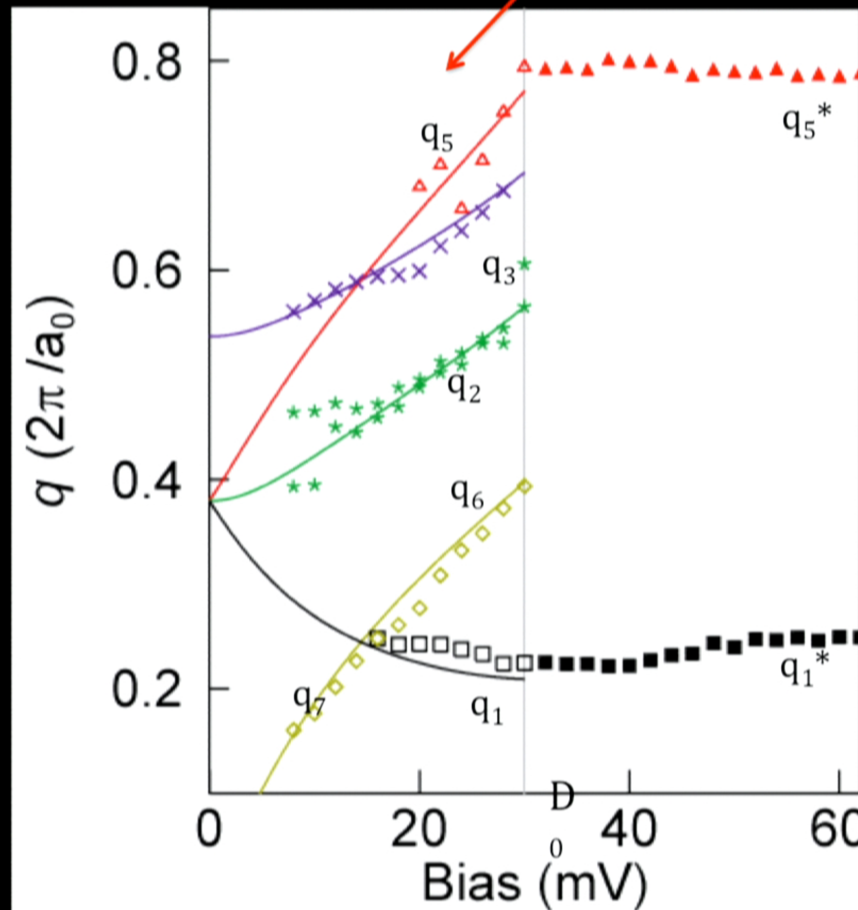
Nature 454, 1072 (2008)

JPSJ 82, 011005 (2011)

Low Energy: Signature of d-wave Cooper pairing



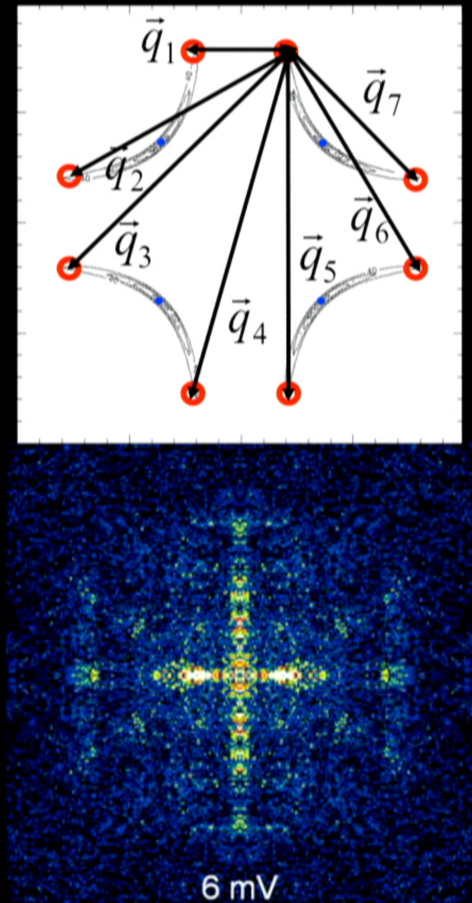
***Science* 297,** 1148 (2002)

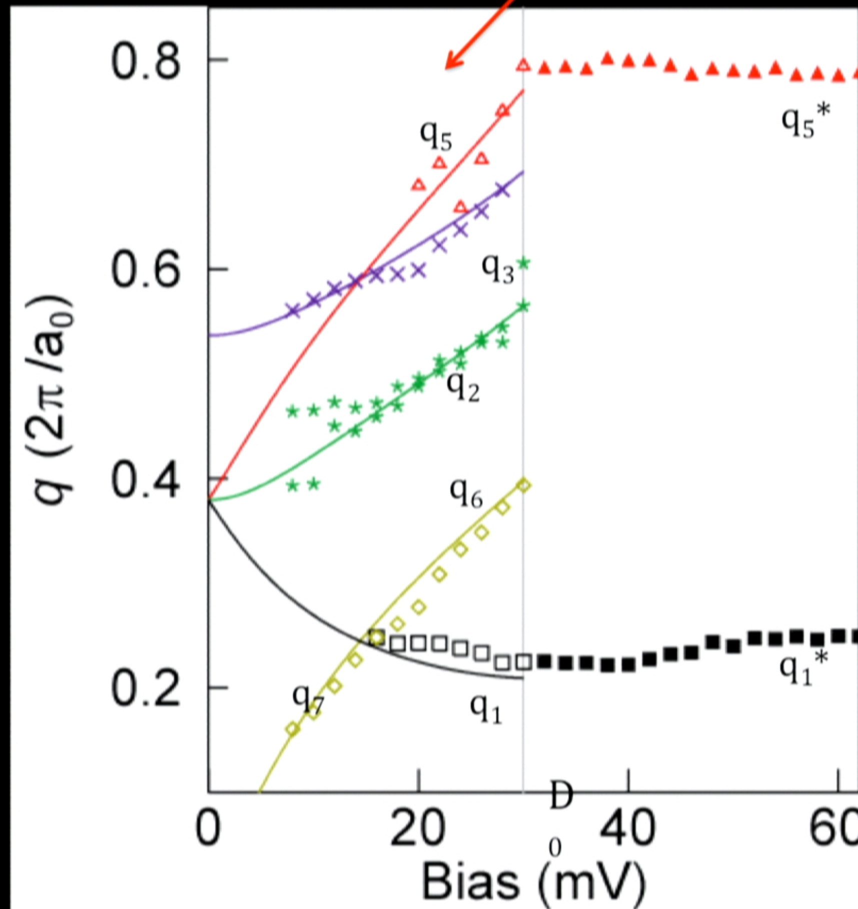


***Nature* 454,** 1072 (2008)

***JPSJ* 82**, 011005 (2011)

Low Energy: Signature of d-wave Cooper pairing



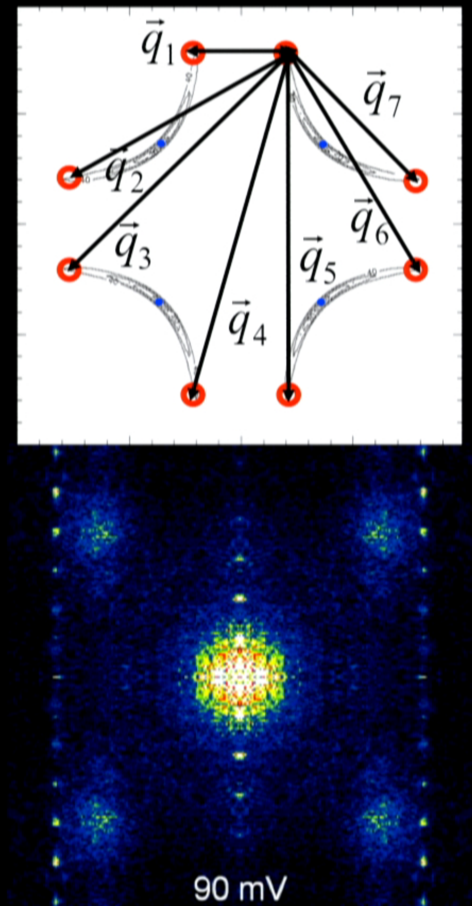


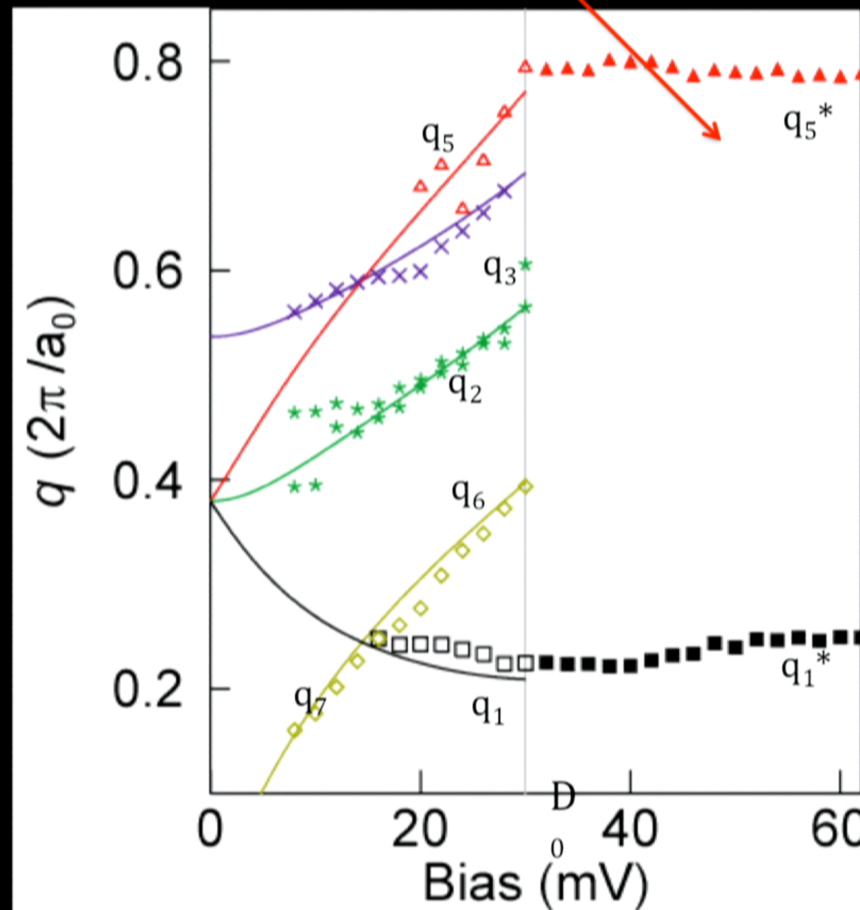
Science 297, 1148 (2002)

Nature 454, 1072 (2008)

JPSJ 82, 011005 (2011)

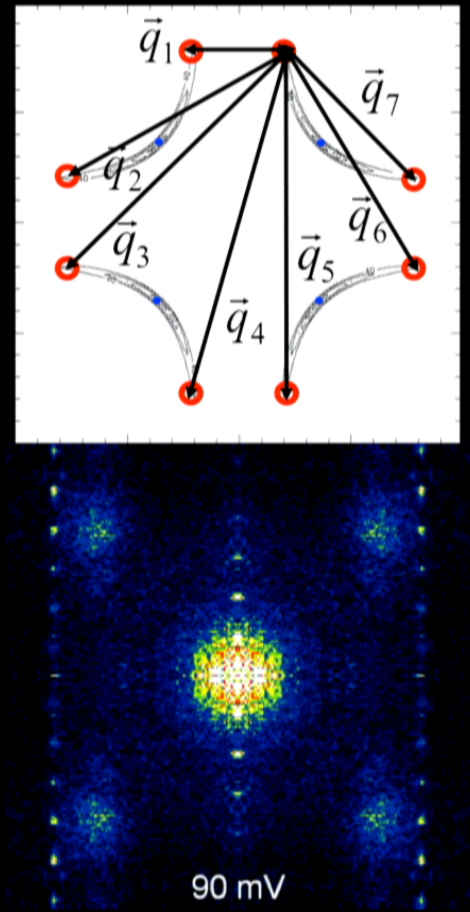
High Energy: Quasi-static Broken Symmetry States



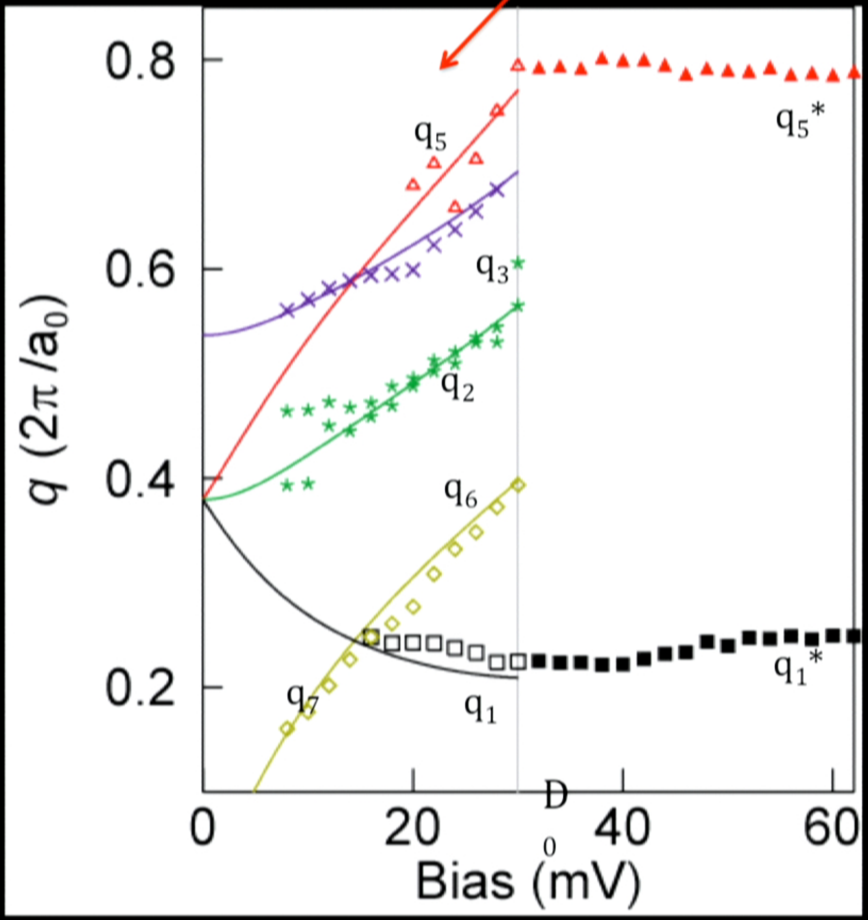


PRL 94, 197005 (2005); ***Science 454,*** 1072 (2007); ***JPSJ 82***, 011005 (2011); ***Science 344,*** 612(2014)

Low Energy: Signature of d-wave Cooper pairing



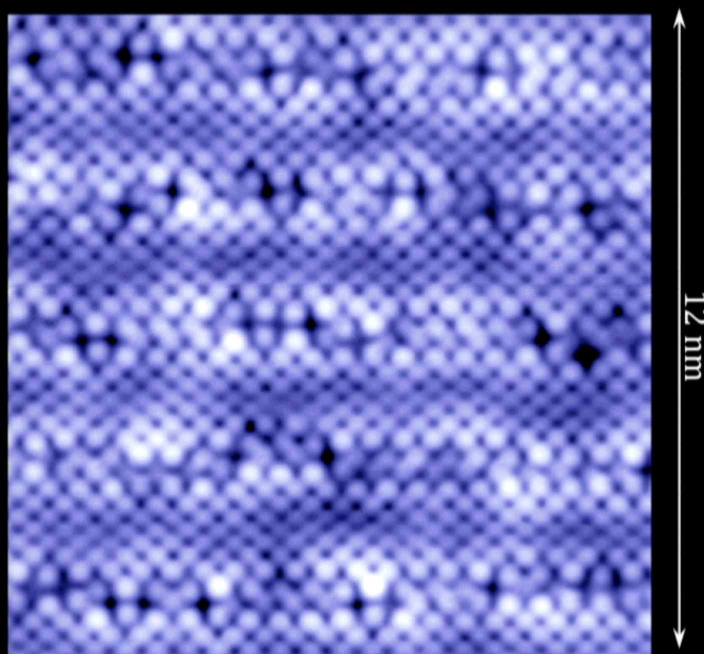
***Science* 297,** 1148 (2002)



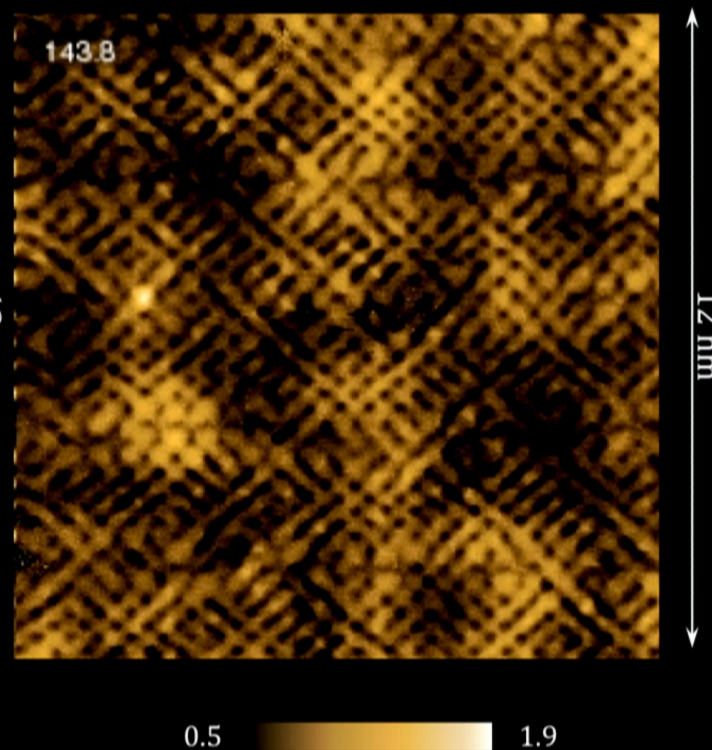
***Nature* 454,** 1072 (2008)

***JPSJ* 82**, 011005 (2011)

Visualize Broken-Symmetry States

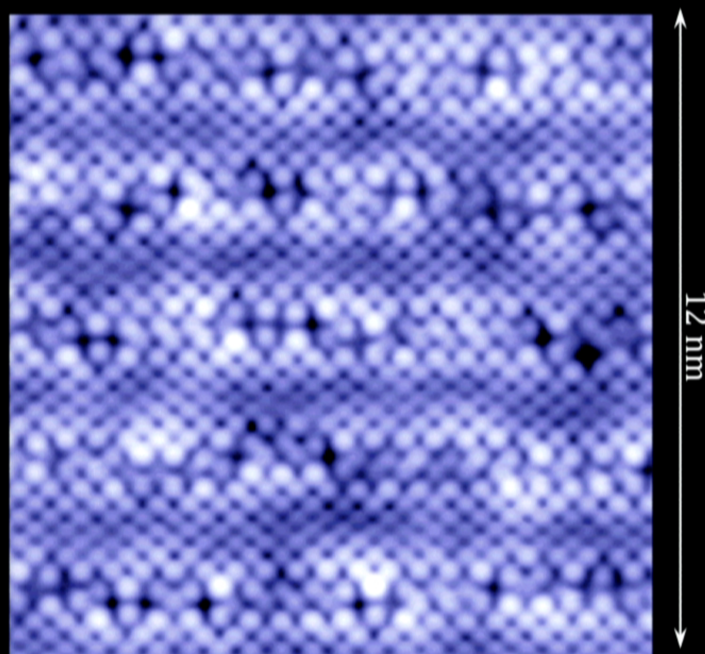


$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$

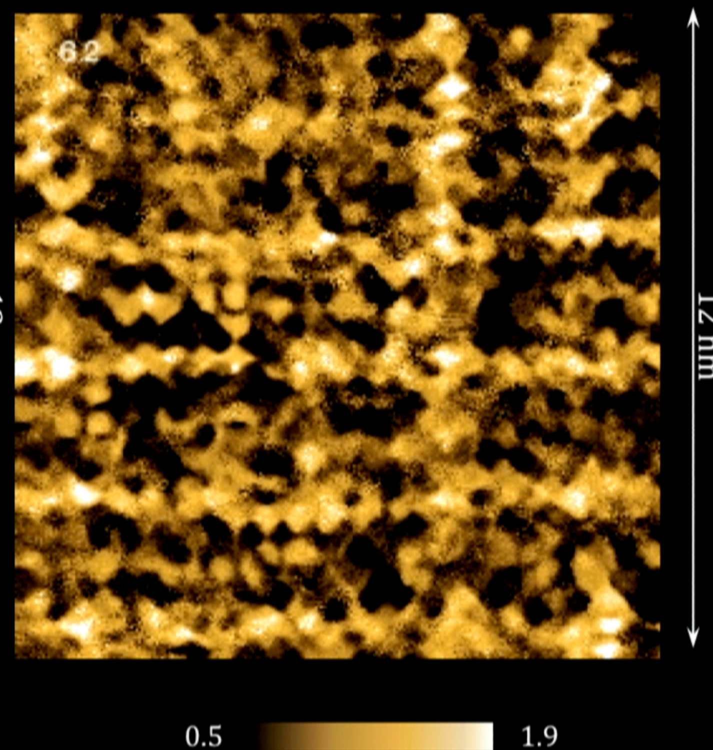


Nature 430, 1001 (2004)   ***Science 315,*** 1380 (2007)   ***J. Phys. Soc. Jpn 82***, 011005 (2011)

Visualize Broken-Symmetry States

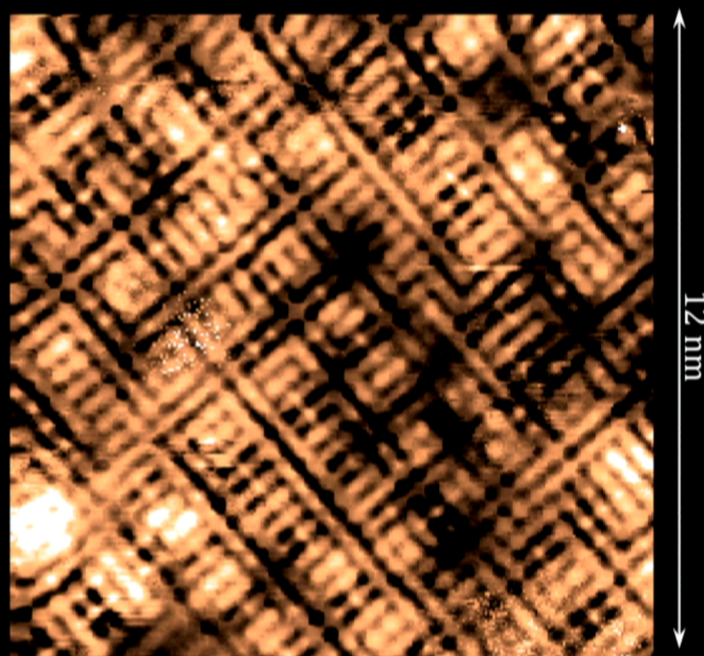


$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$

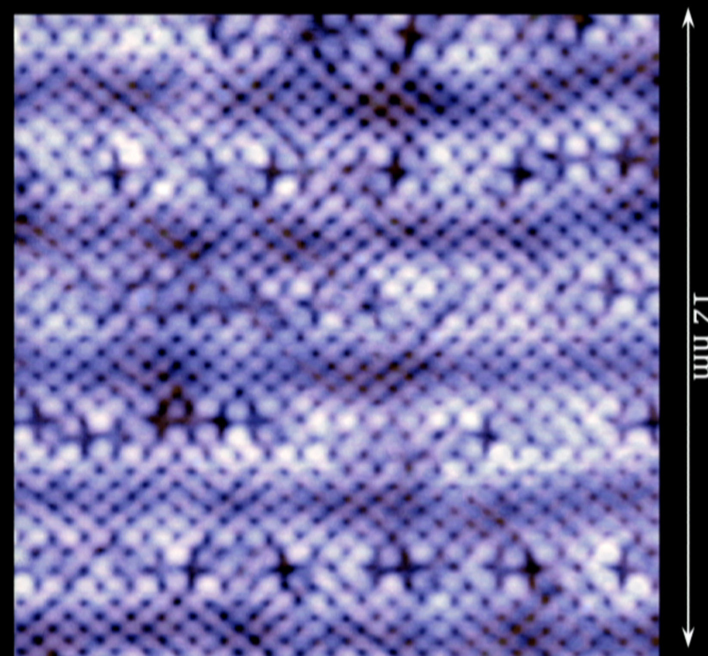


***Nature* 430**, 1001 (2004)　***Science* 315,** 1380 (2007)　***J. Phys. Soc. Jpn* 82**, 011005 (2011)

Q≠0 Trans. & Rot. Symmetry Breaking @ E~Δ_{PG}



$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$

Nature 430, 1001 (2004)　　***Science 315,*** 1380 (2007)　　***J. Phys. Soc. Jpn 82***, 011005 (2011)

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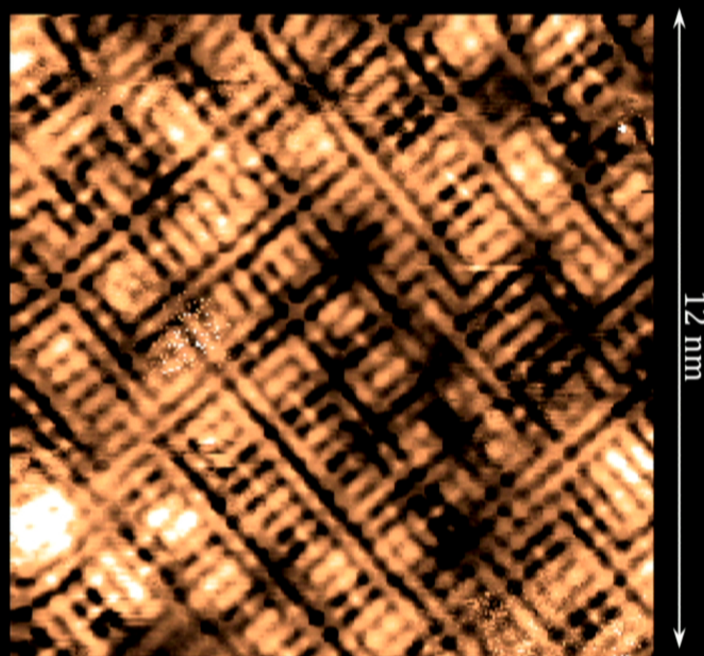

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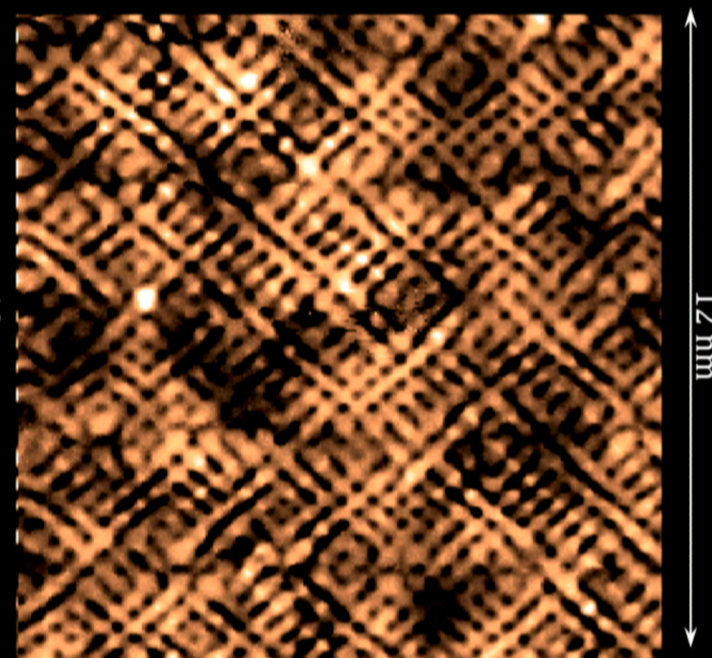

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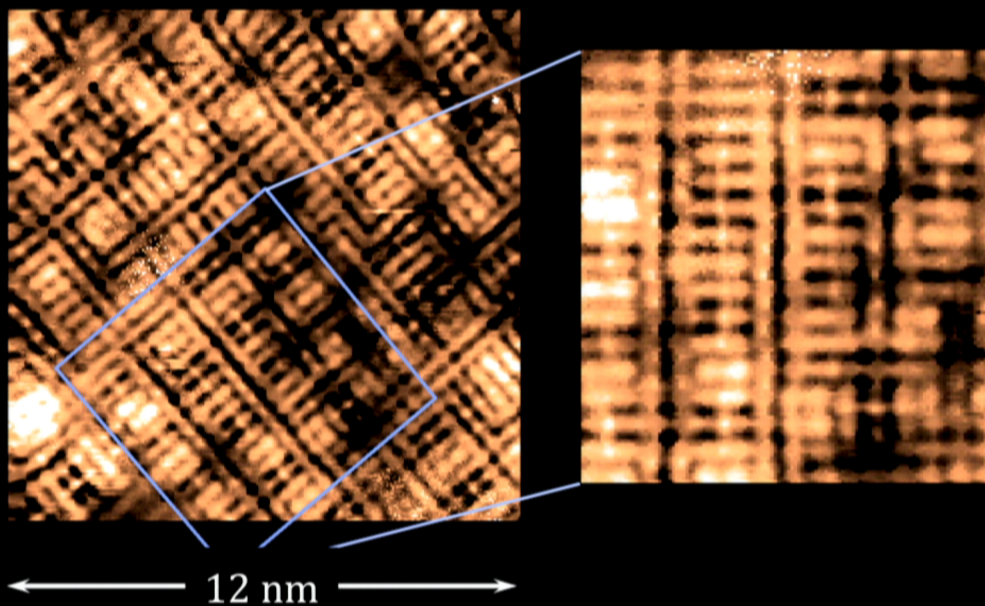
Nature 430, 1001 (2004) ***Science 315,*** 1380 (2007) ***J. Phys. Soc. Jpn 82***, 011005 (2011)

Electronically Inequivalent Oxygen-sites in every CuO_2 Unit Cell



***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) ***J. Phys. Soc. Jpn* 82**, 011005 (2011)

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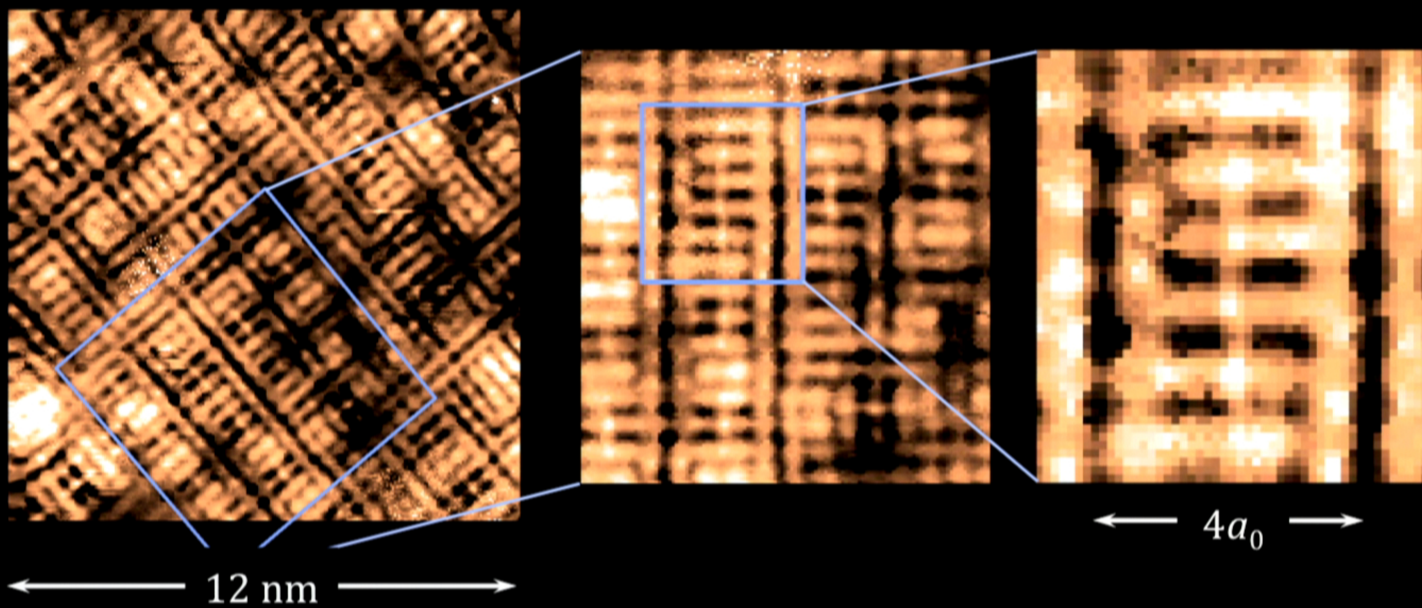
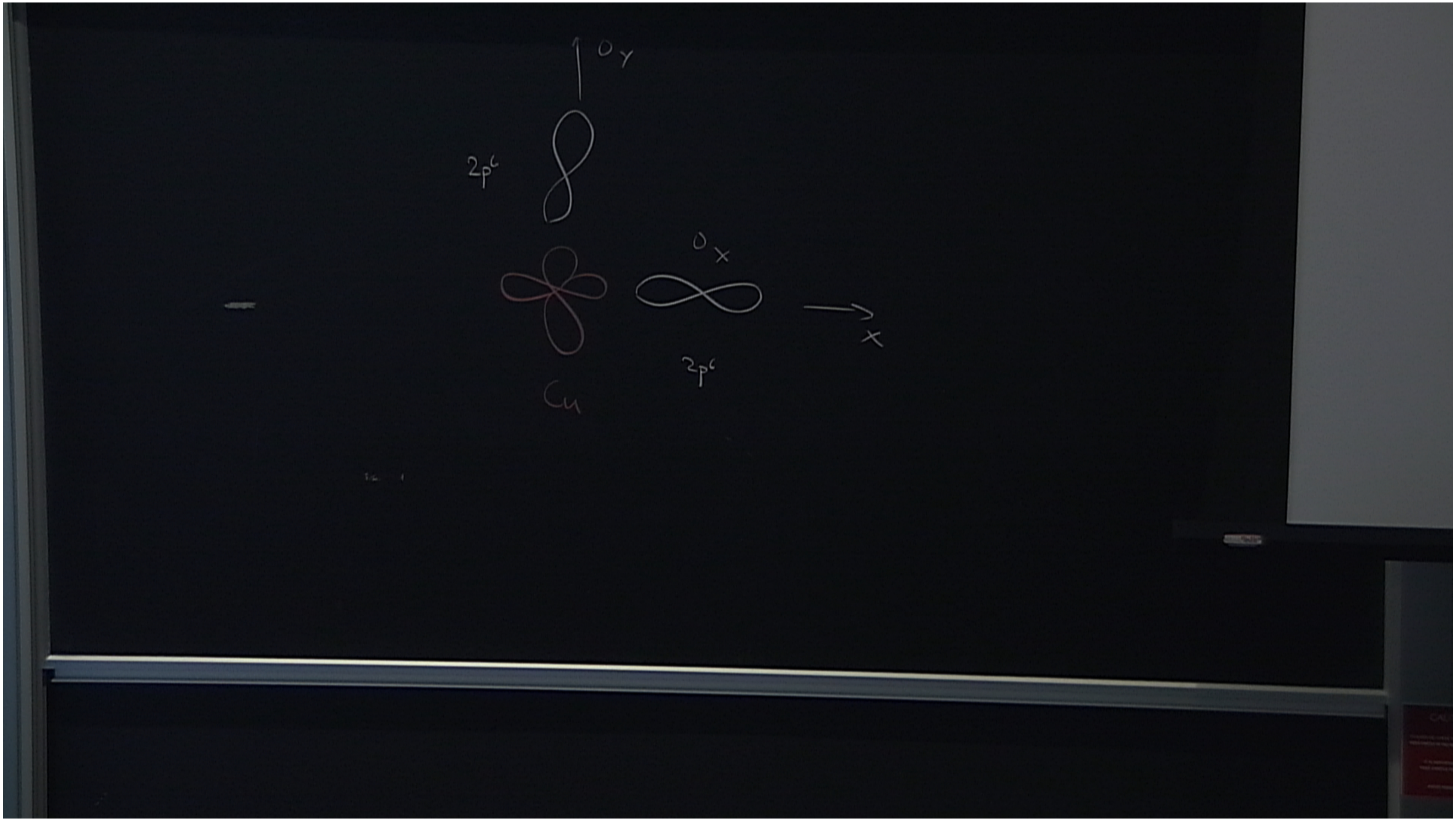
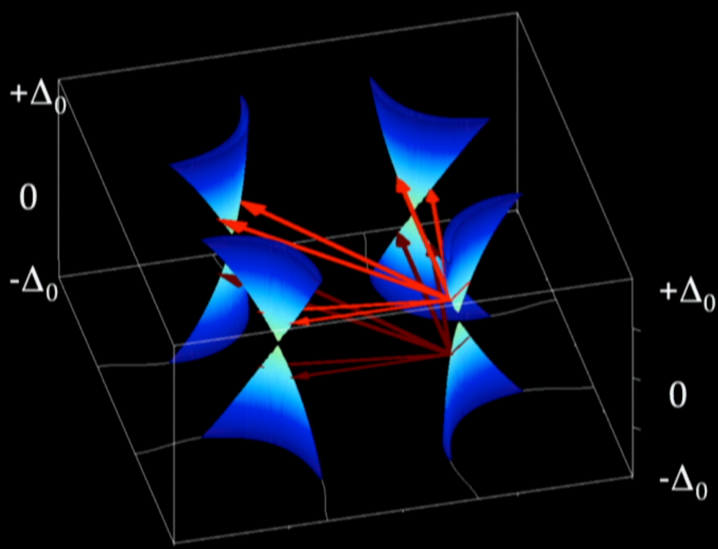


***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) ***J. Phys. Soc. Jpn* 82**, 011005 (2011)

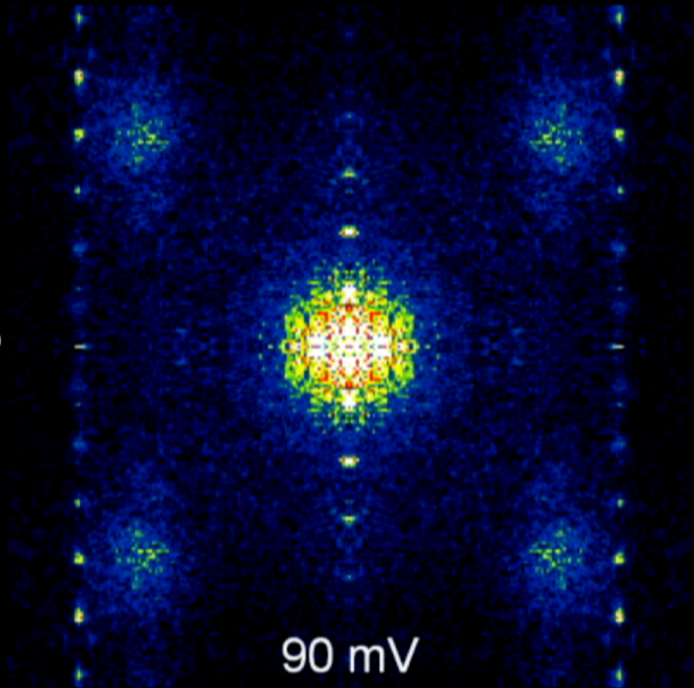


O y
2p6
O x
2p6
x
Cu

$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



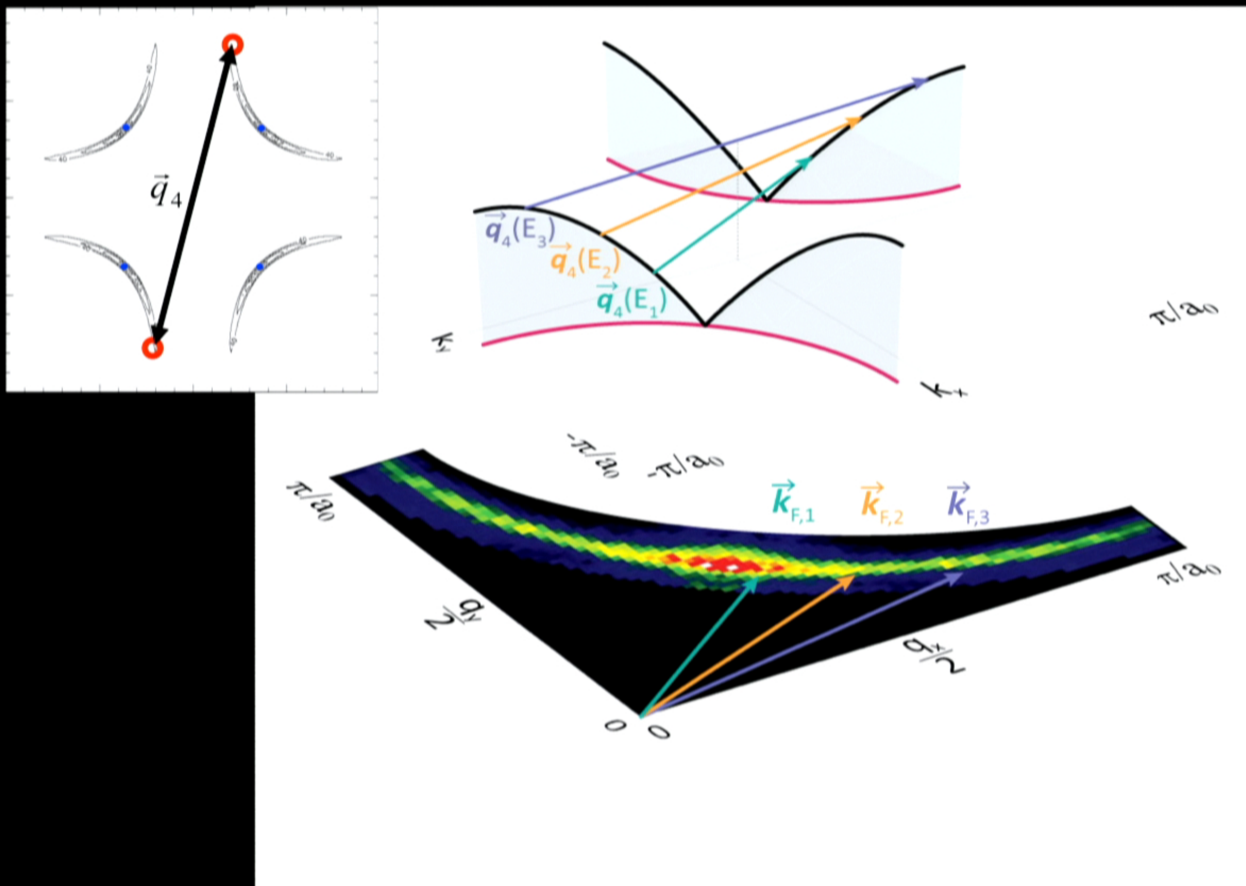
Particle-hole symmetric
i=1,..7 Bogoliubov QPI



g (q, **E**)

Science 344, 612 (2014)

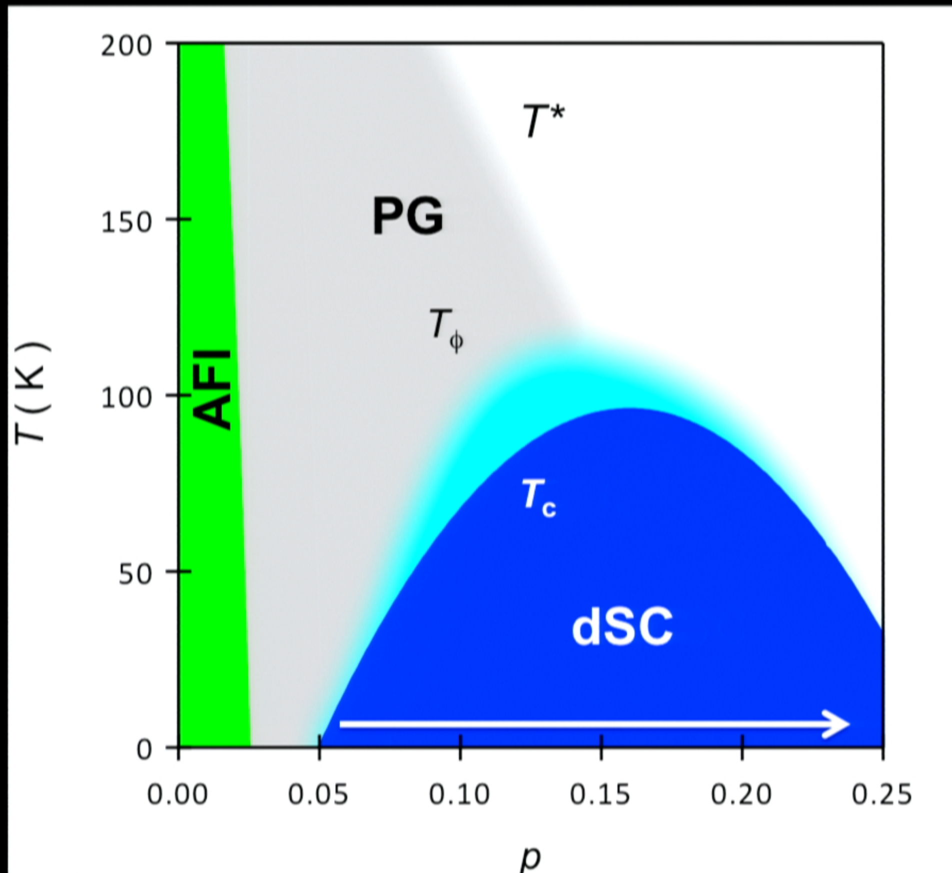
$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



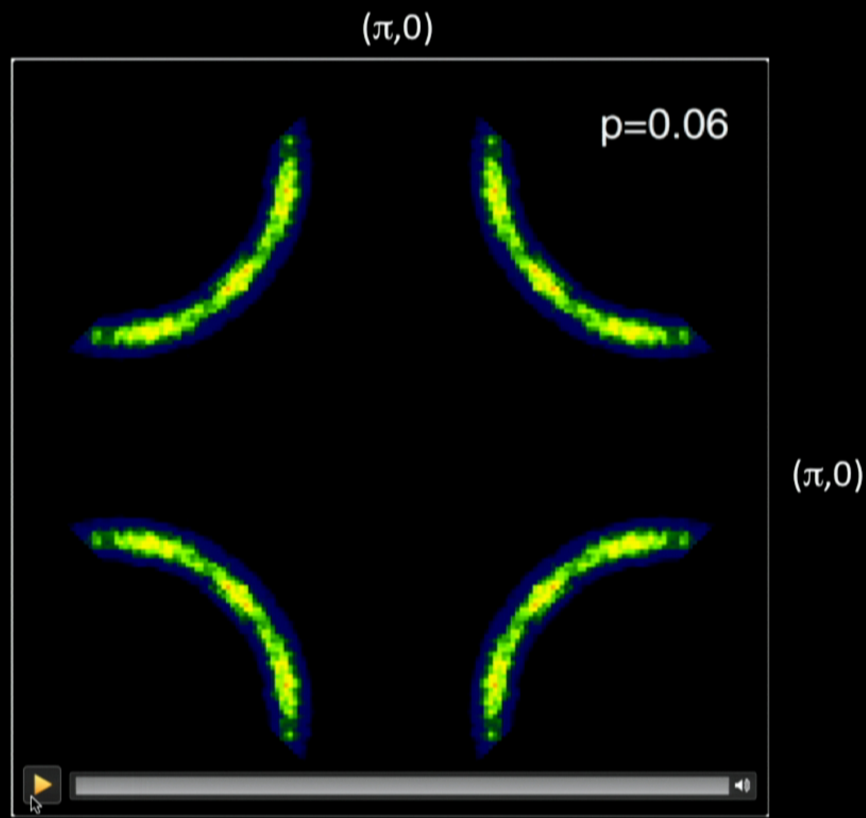
$k_F = q_4/2$

Science 344, 612 (2014)

Visualize Broken Symmetries & QPI across Phase Diagram ?

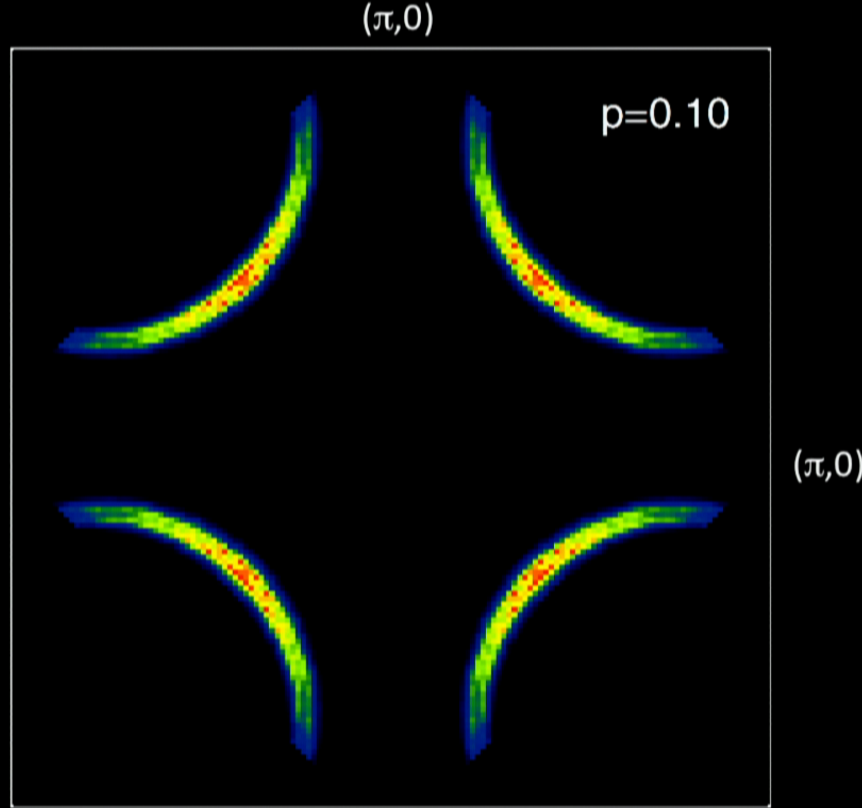


$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



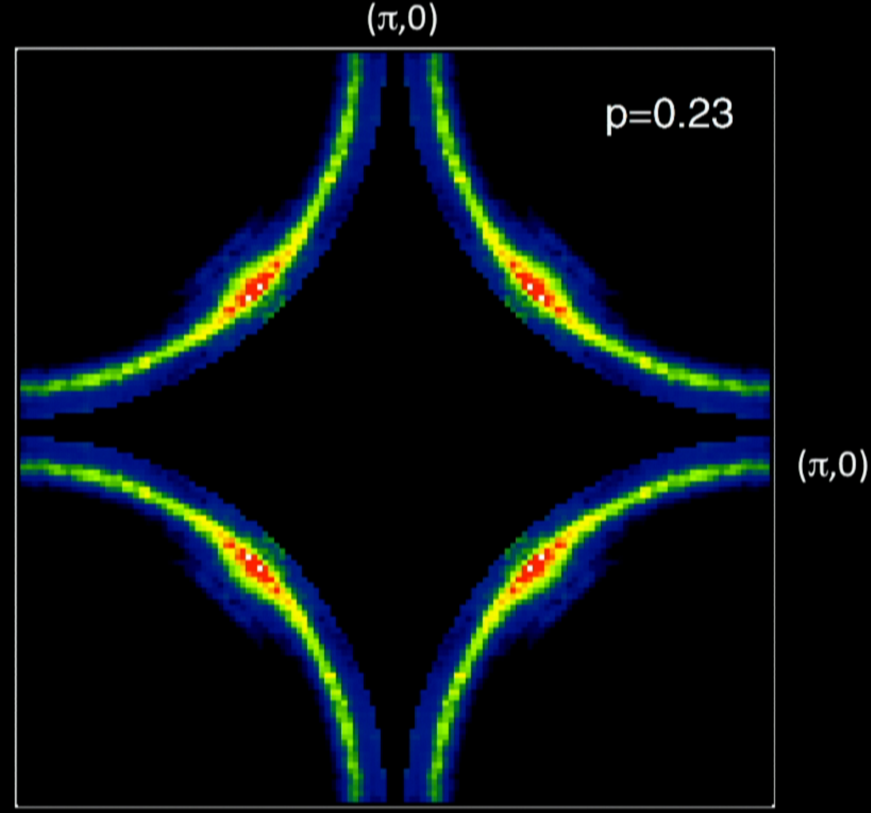
Science 344, 612 (2014)

$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



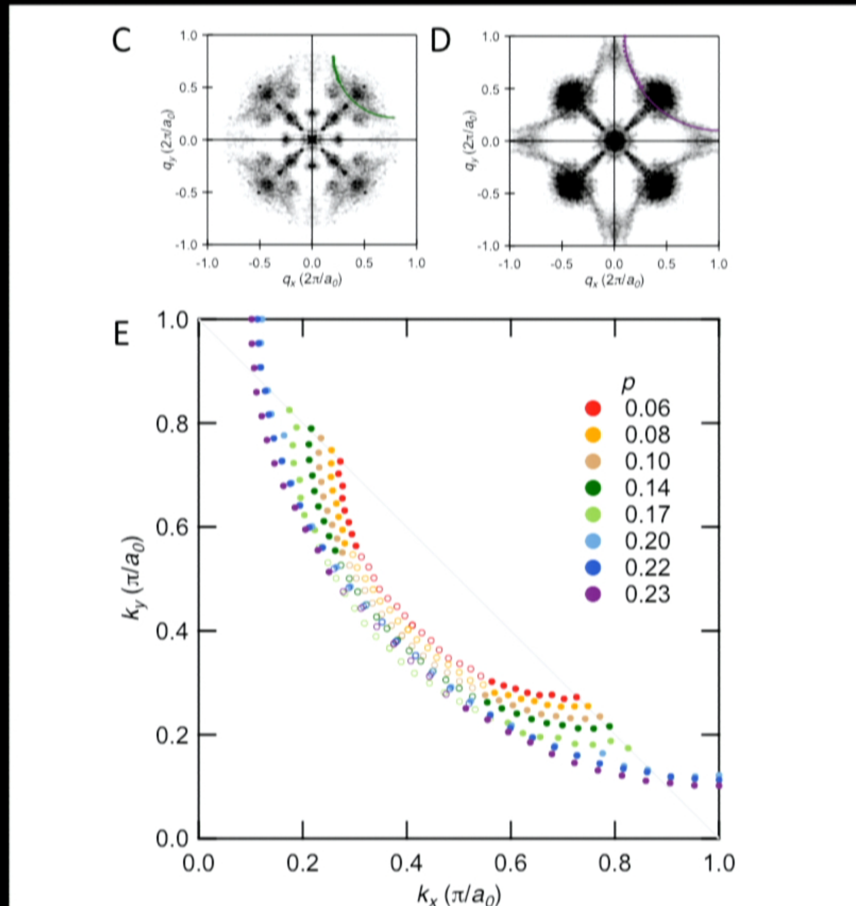
***Science* 344, 612** (2014)

$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



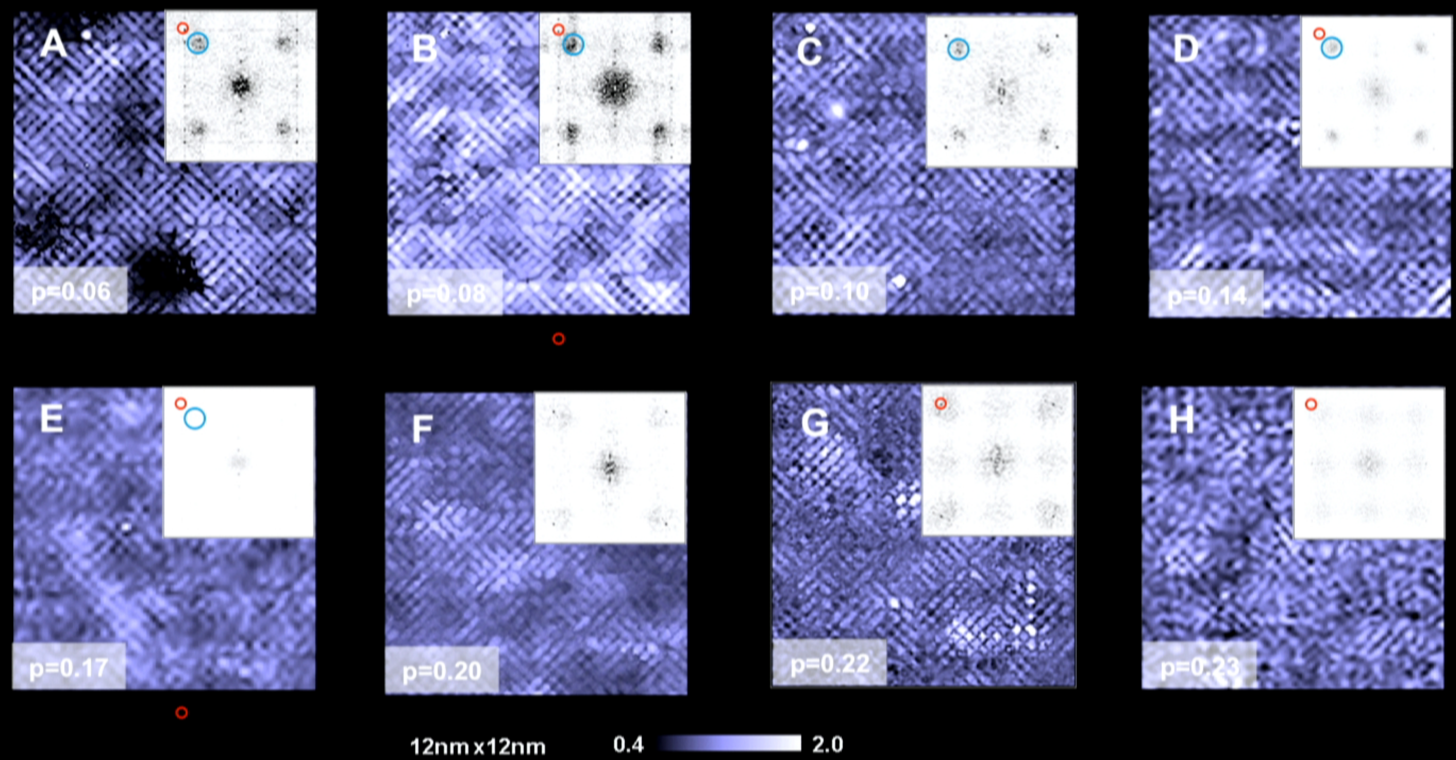
***Science* 344, 612** (2014)

Abrupt Transition in $Bi_2Sr_2CaCu_2O_8$ *k*-space Topology at p=19±1%



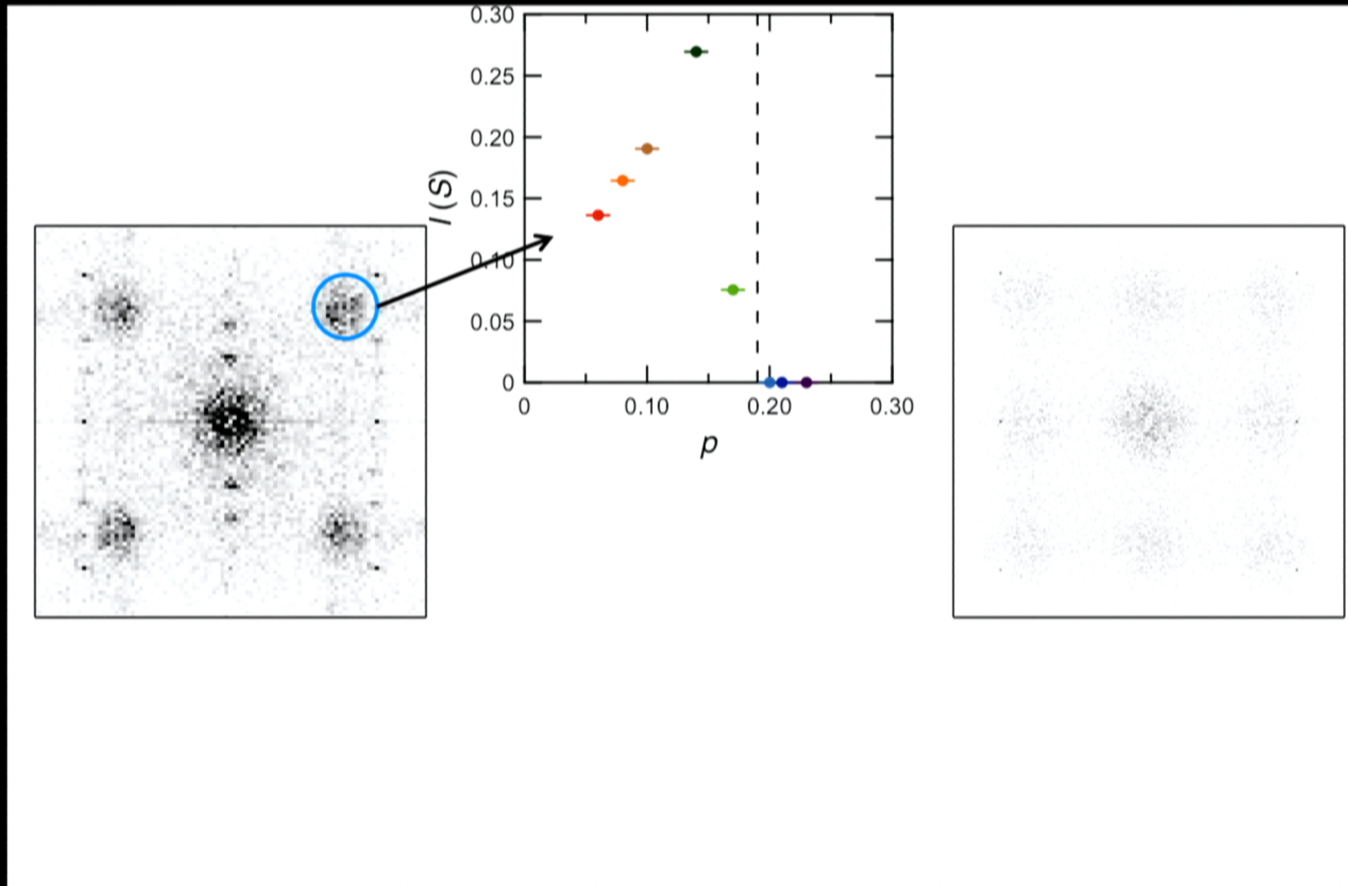
Science 344, 612 (2014)

Doping Dependence of Q≠0 Symmetry Breaking



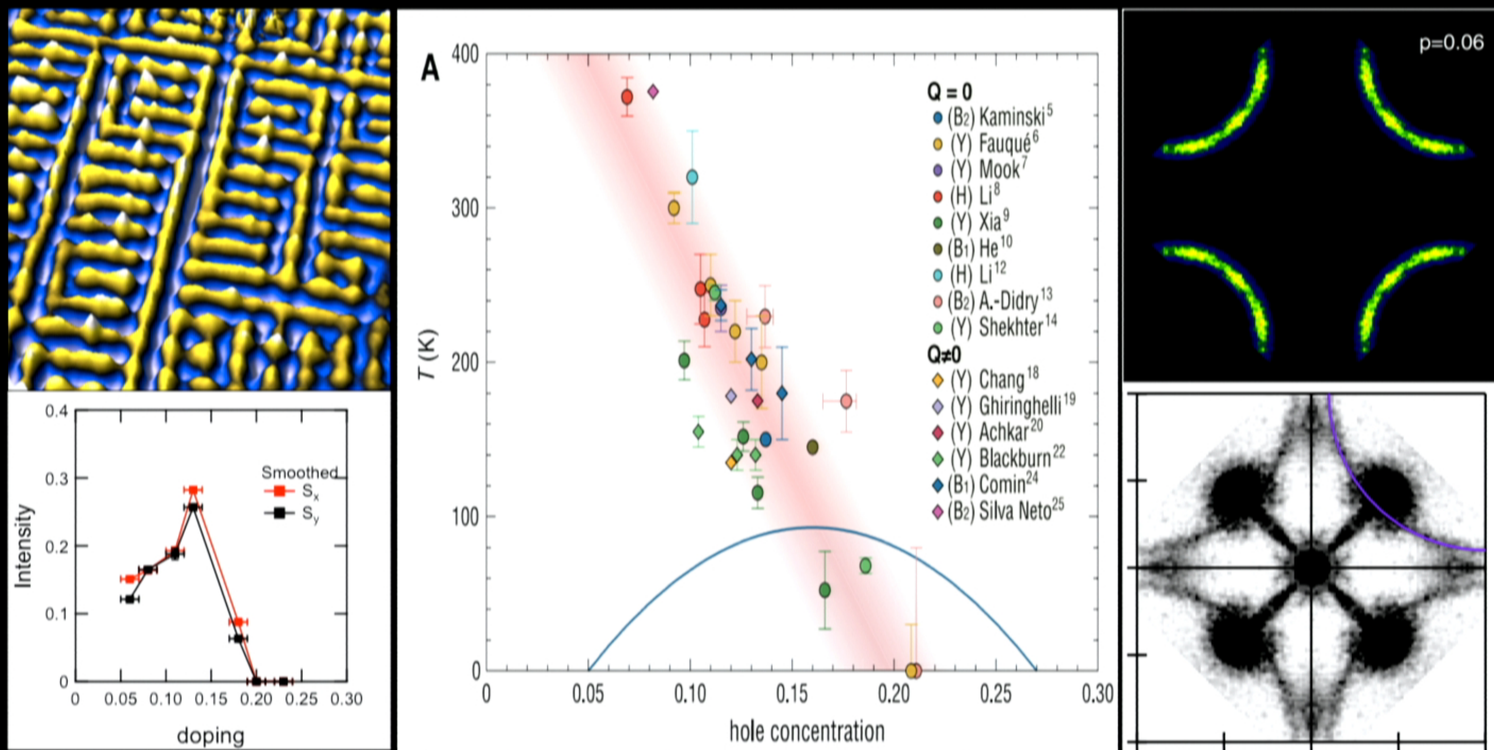
Science 344, 612 (2014)

Doping Dependence of Q≠0 Symmetry Breaking



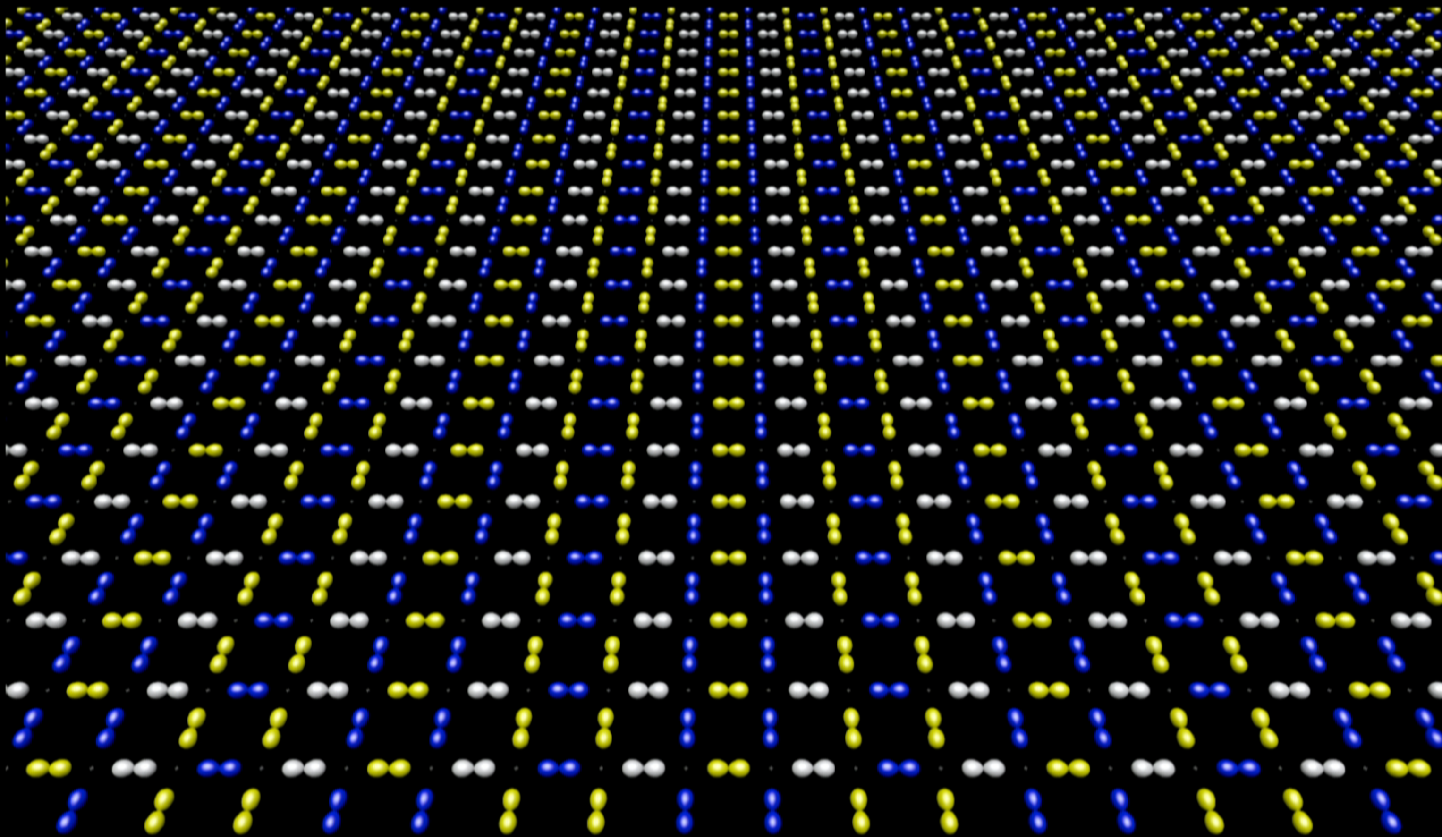
***Science* 344, 612** (2014)

Simultaneous Symmetry & *k*-space Topology Transitions

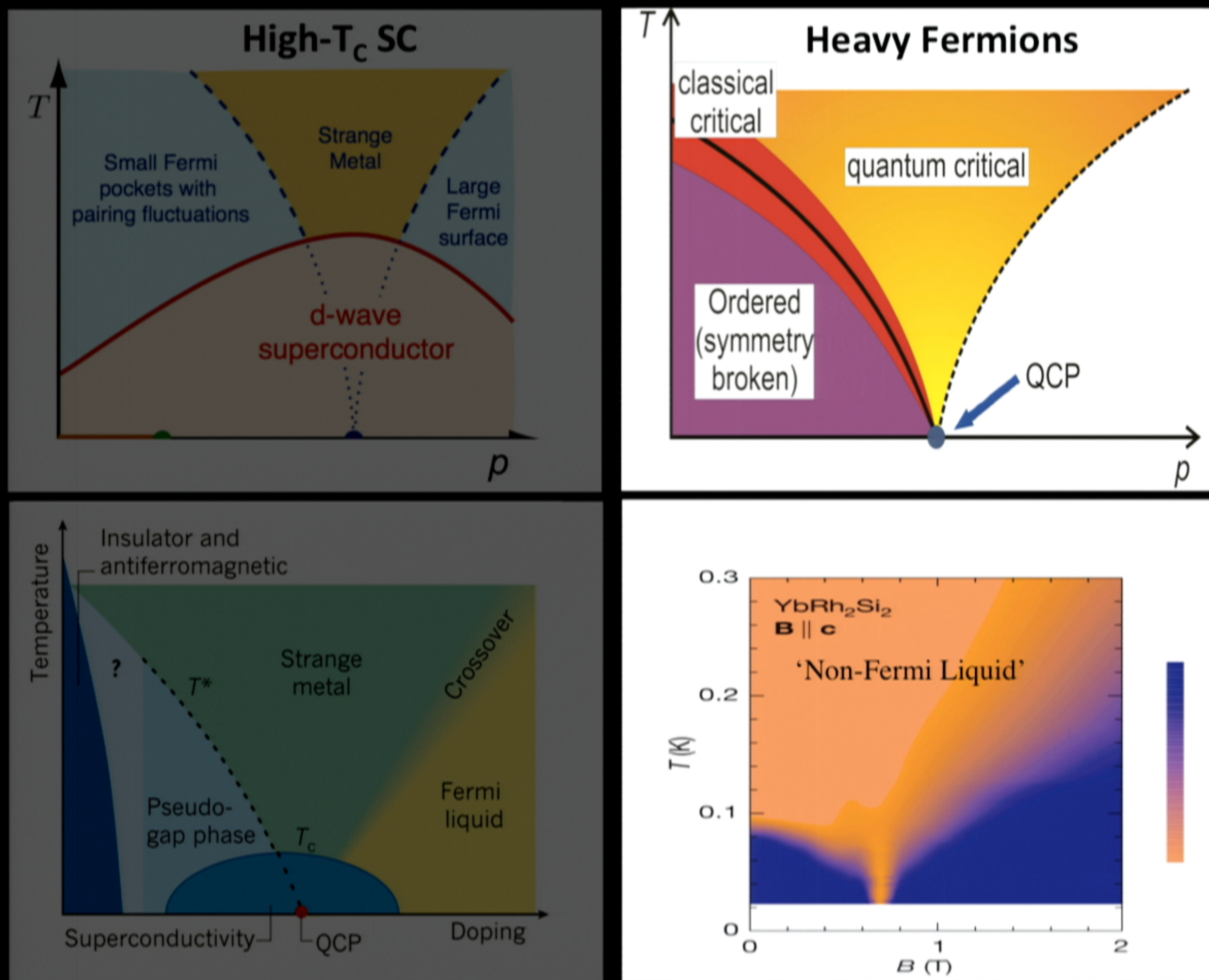


Science 344, 612 (2014)

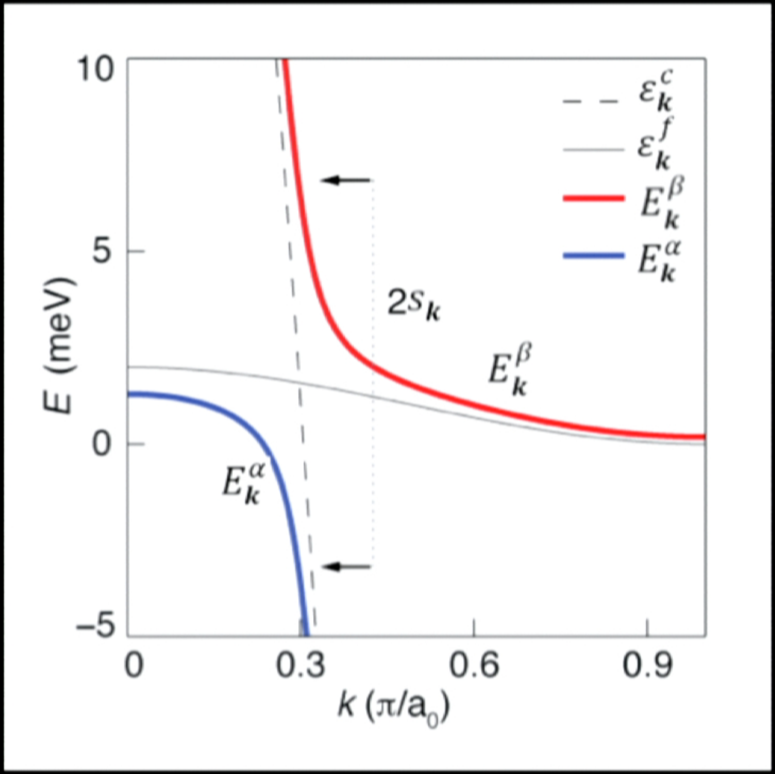
See ‘Phenomenology of Charge Order in the Cuprates’
A. Allais – 3PM



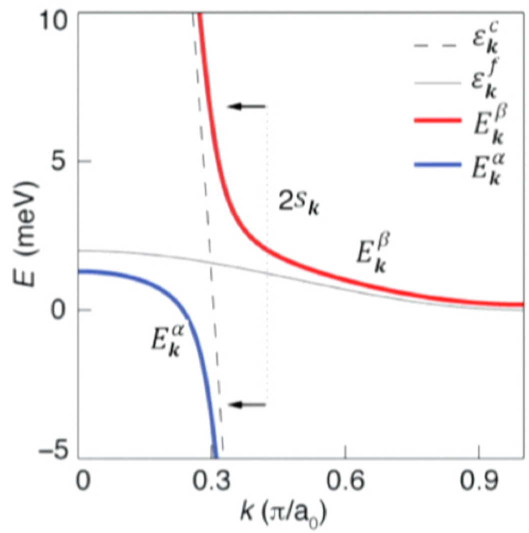
QUANTUM CRITIAL ELECTRONIC MATTER



VISUALIZE HEAVY FERMIONS ?



Heavy-Fermion Band Structure $E^{\alpha,\beta}$



$$H = \sum_{k,\sigma} \varepsilon_k^c c^\dagger_{k,\sigma} c_{k,\sigma} + \varepsilon_k^f f^\dagger_{k,\sigma} f_{k,\sigma} - S_k^* f^\dagger_{k,\sigma} c_{k,\sigma} - S_k c^\dagger_{k,\sigma} f_{k,\sigma}$$

$$H = \sum_{k,\sigma} \begin{pmatrix} c^\dagger_{k,\sigma} & f^\dagger_{k,\sigma} \end{pmatrix} \begin{pmatrix} \varepsilon_k^c & -S_k \\ -S_k^* & \varepsilon_k^f \end{pmatrix} \begin{pmatrix} c_{k,\sigma} \\ f_{k,\sigma} \end{pmatrix}$$

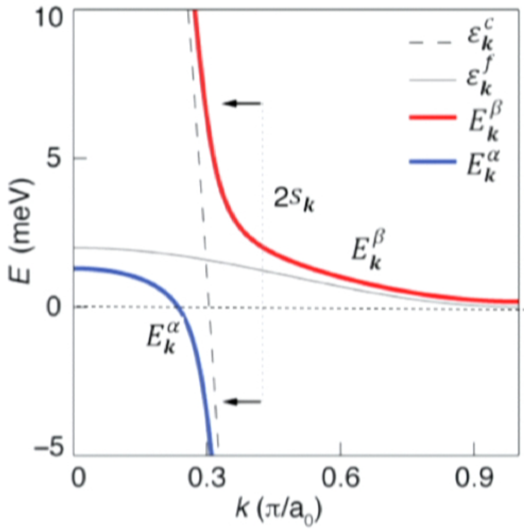
Diagonalize:

$$det \begin{vmatrix} \varepsilon_k^c & -S_k \\ -S_k^* & \varepsilon_k^f \end{vmatrix} = 0$$

$$0 = (\varepsilon_k^c - E)(\varepsilon_k^f - E) - S_k^2 = E^2 - E(\varepsilon_k^c + \varepsilon_k^f) + \varepsilon_k^c \varepsilon_k^f - S_k^2$$

$$\boxed{E_{\mathbf{k}}^{\alpha,\beta} = \frac{\varepsilon_{\mathbf{k}}^c + \varepsilon_{\mathbf{k}}^f}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}}^c - \varepsilon_{\mathbf{k}}^f}{2}\right)^2 + s_{\mathbf{k}}^2}}$$

Measure $E_k^{\alpha,\beta}$ for Heavy-Fermion Bands ?



- Heavy-fermion primary effects often in empty states $E>E_F$ => challenging for ARPES.
- Heavy-fermion bands extremely flat $(dE/dk \rightarrow 0)$ => $\delta E<100\ \mu V$ energy resolution or T< 1K is required.
- No techniques existed with sufficient combined E,*k* resolution.

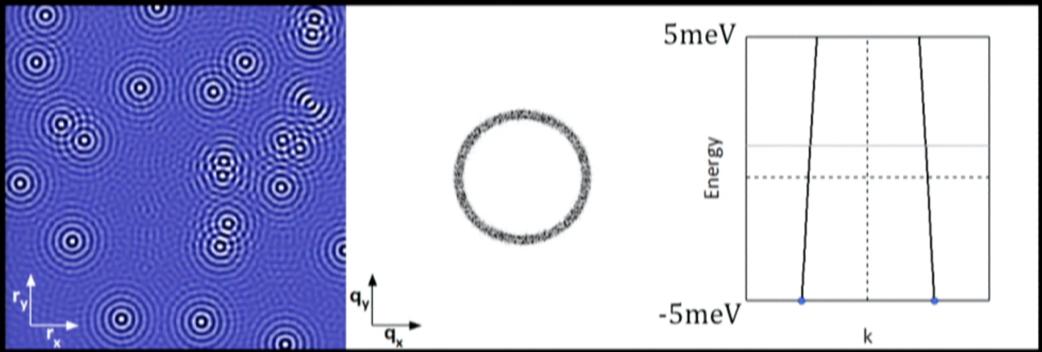
$$E_{\mathbf{k}}^{\alpha,\beta} = \frac{\varepsilon_{\mathbf{k}}^{c} + \varepsilon_{\mathbf{k}}^{f}}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}}^{c} - \varepsilon_{\mathbf{k}}^{f}}{2}\right)^2 + s_{\mathbf{k}}^2}$$

Measure $E_k^{\alpha,\beta}$ for Heavy-Fermion Bands ?

Heavy-Fermion Scattering Interference Imaging with Millikelvin SI-STM

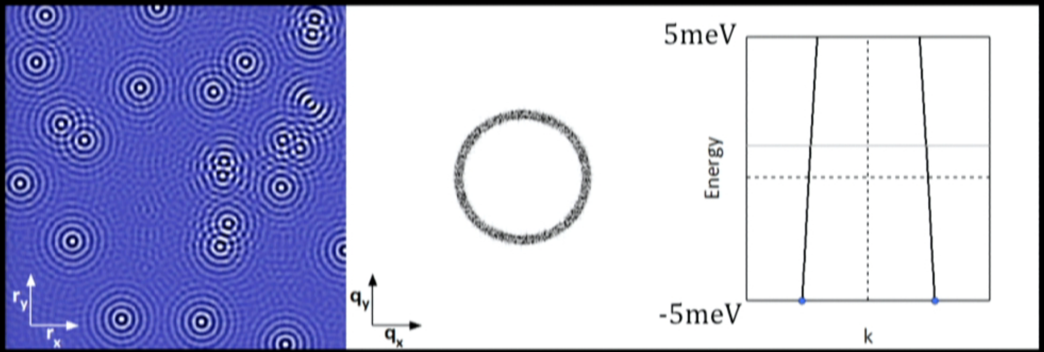
Measure $E_k^{\alpha,\beta}$ for Heavy-Fermion Bands ?

Scattering interference within 'light' band

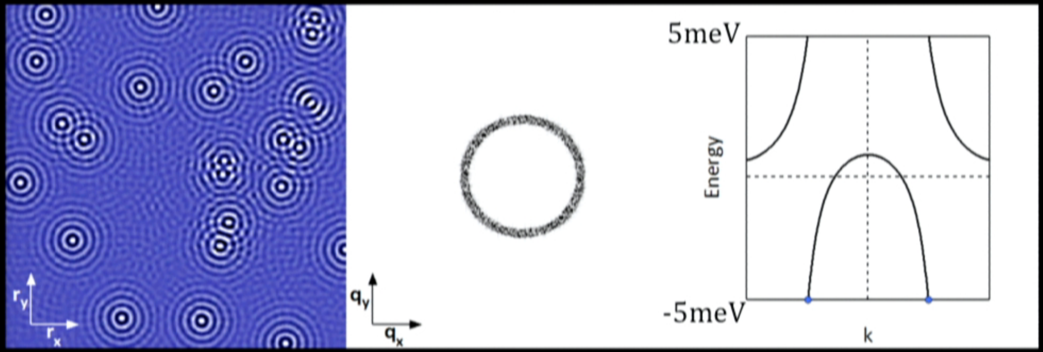


Measure $E_k^{\alpha,\beta}$ for Heavy-Fermion Bands ?

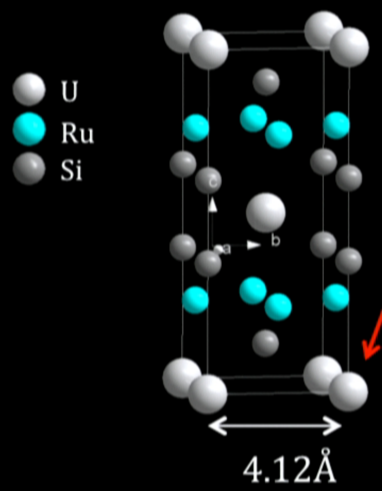
Scattering interference within 'light' band



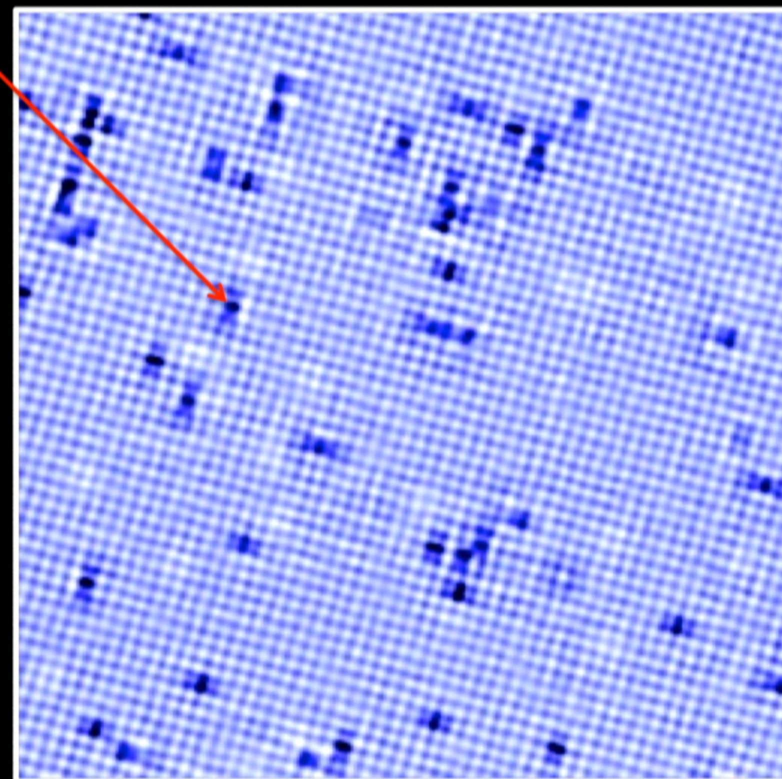
Scattering interference within two 'heavy-fermion' bands



Heavy-Fermion Compound URu_2Si_2



Th



a=4.124Å c=9.582Å

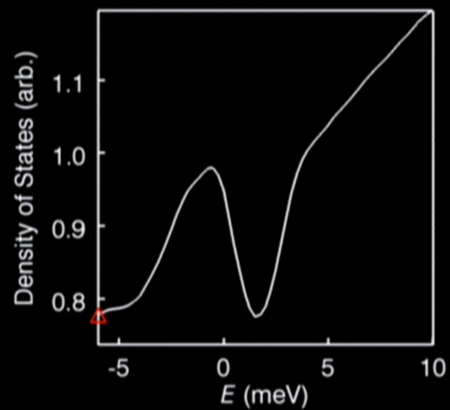
Effective mass $m^* = 25m_e$

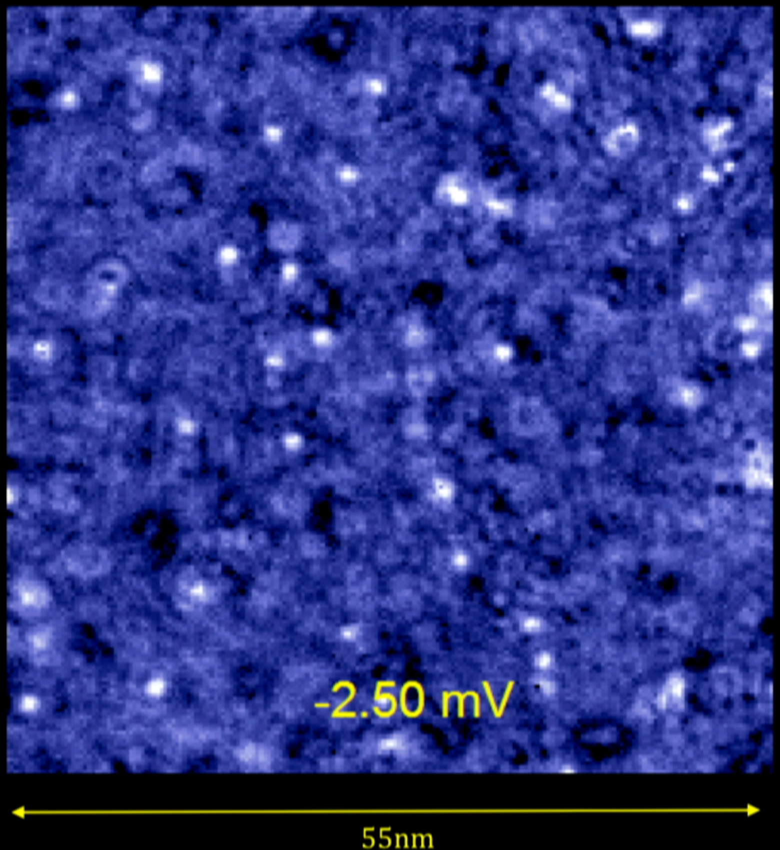
Palstra *et. al.PRL* **55**, 2727 (1985)
Maple *et. al. PRL* **56**, 185 (1986)

Nature 465, 570 (2010)

Spectroscopic Imaging $g(r,E) \sim N(r,E)$

$U_{0.99}Th_{0.01}Ru_2Si_2$

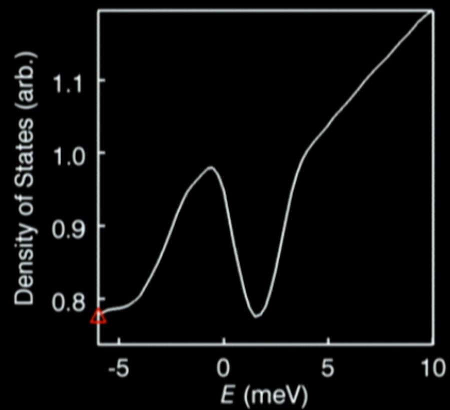




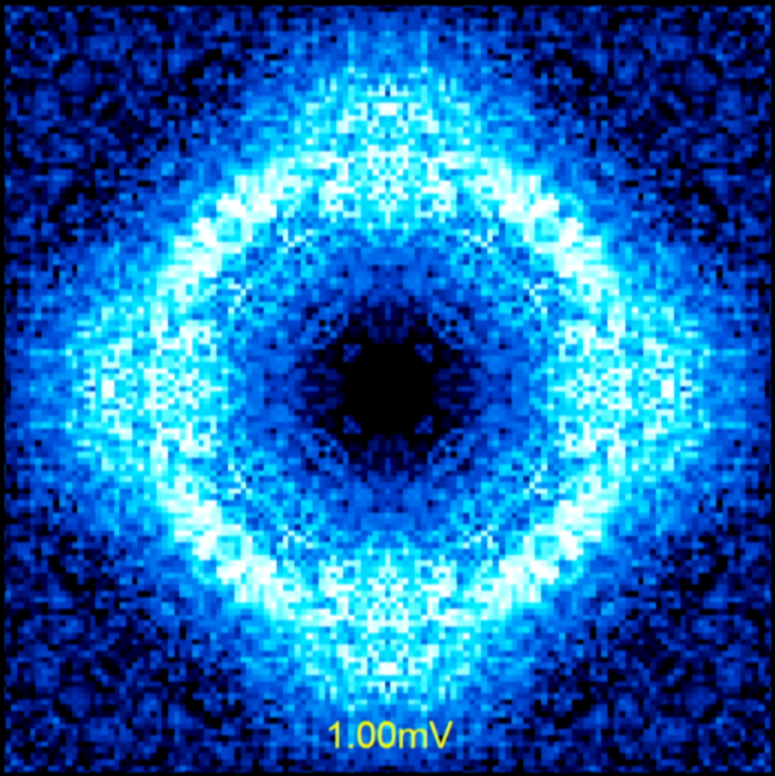
Nature 465, 570 (2010)

g(q,E) ➔Heavy-Fermion QPI

$U_{0.99}Th_{0.01}Ru_2Si_2$



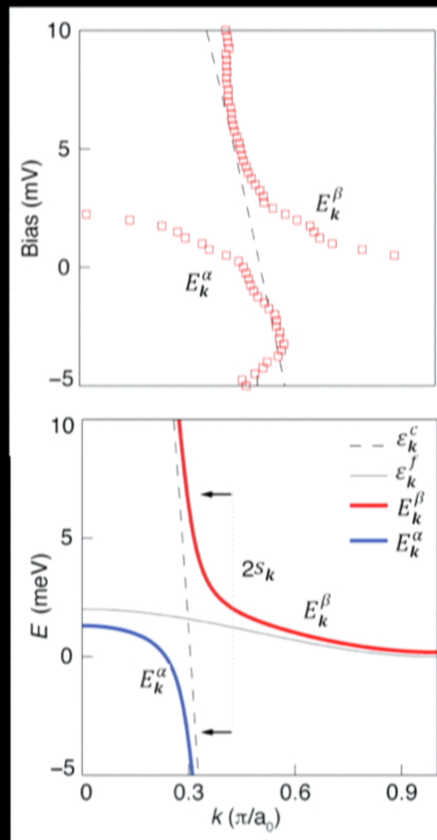
$(0,\pi/a_0)$

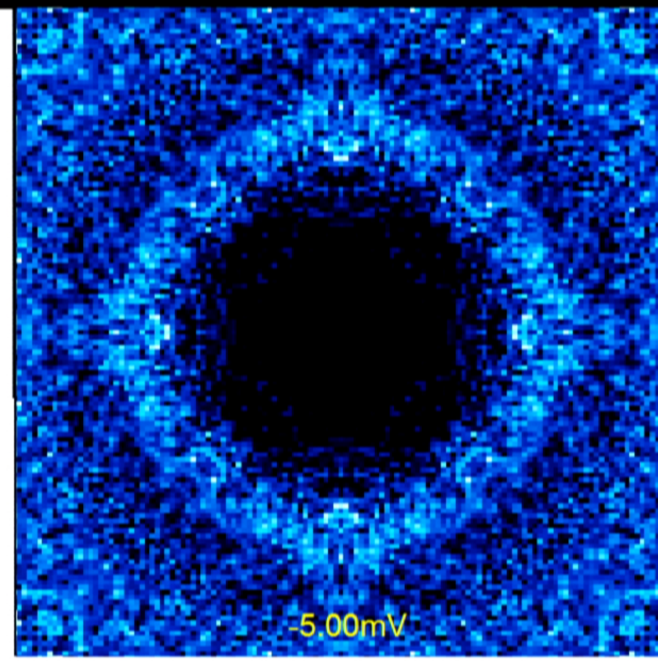


$(\pi/a_0,0)$

***Nature* 465,** 570 (2010)

New technique ➔ Measure Heavy-Fermion $E_k^{\alpha,\beta}$

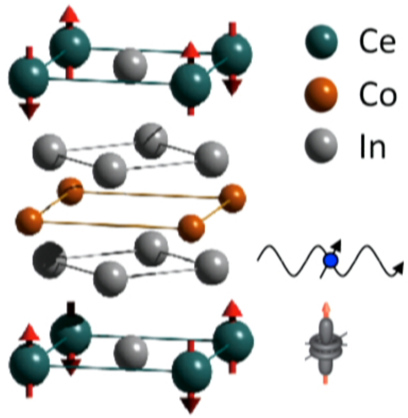


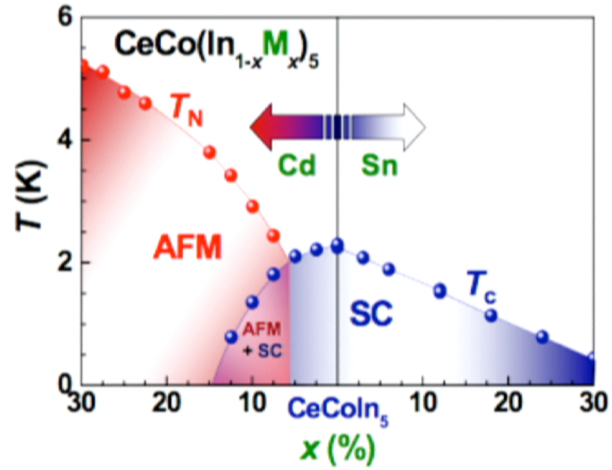


$$E_{\mathbf{k}}^{\alpha,\beta} = \frac{\varepsilon_{\mathbf{k}}^{c} + \varepsilon_{\mathbf{k}}^{f}}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}}^{c} - \varepsilon_{\mathbf{k}}^{f}}{2}\right)^2 + s_{\mathbf{k}}^2}$$

***Nature* 465,** 570 (2010)

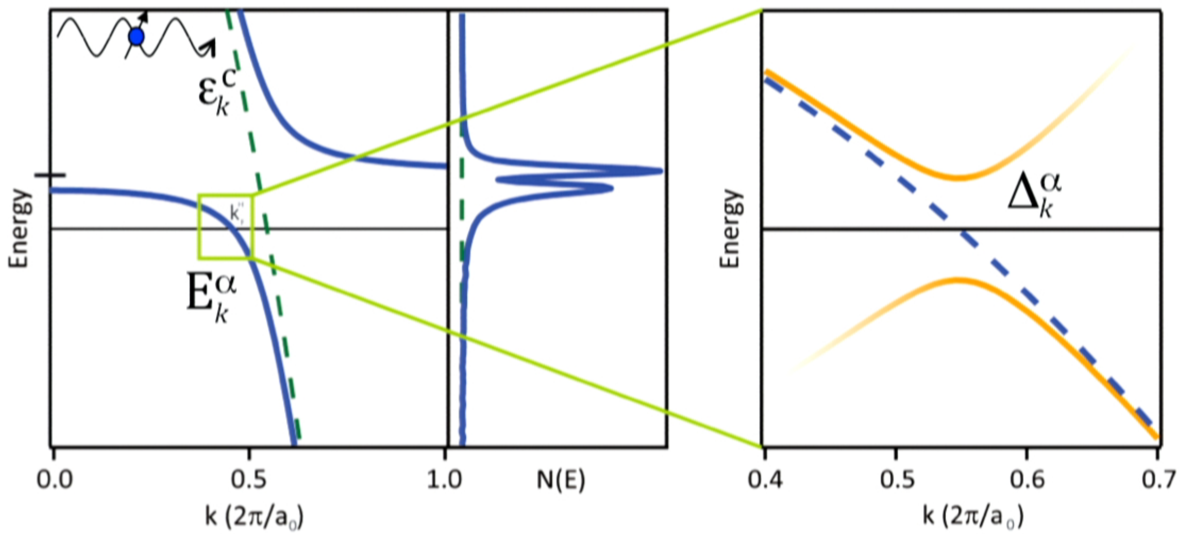
Heavy Fermion Superconductivity $CeCoIn_5$





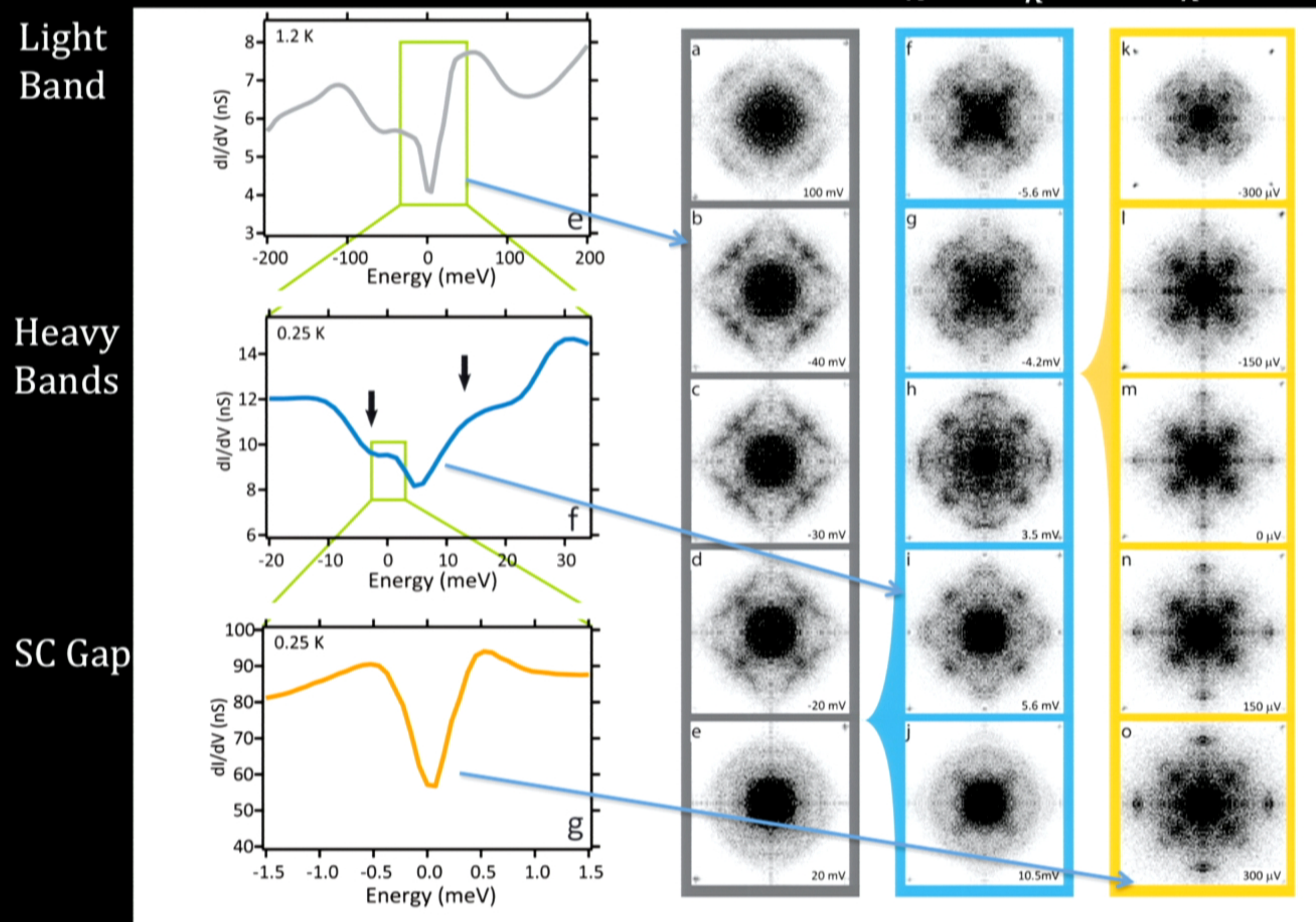
- Antiferromagnetic spin-fluctuations with q=(½ ½ ½)
- T_c = 2.3K ~high for heavy-fermion SC
- Strong evidence for anisotropic gap + nodes
- But $E_k^{\alpha,\beta}$ and $\Delta_k^{\alpha,\beta}$ unknown

HF SC : Three Energy Scales : ε_k^c / $E_k^{\alpha,\beta}$ / $\Delta_k^{\alpha,\beta}$



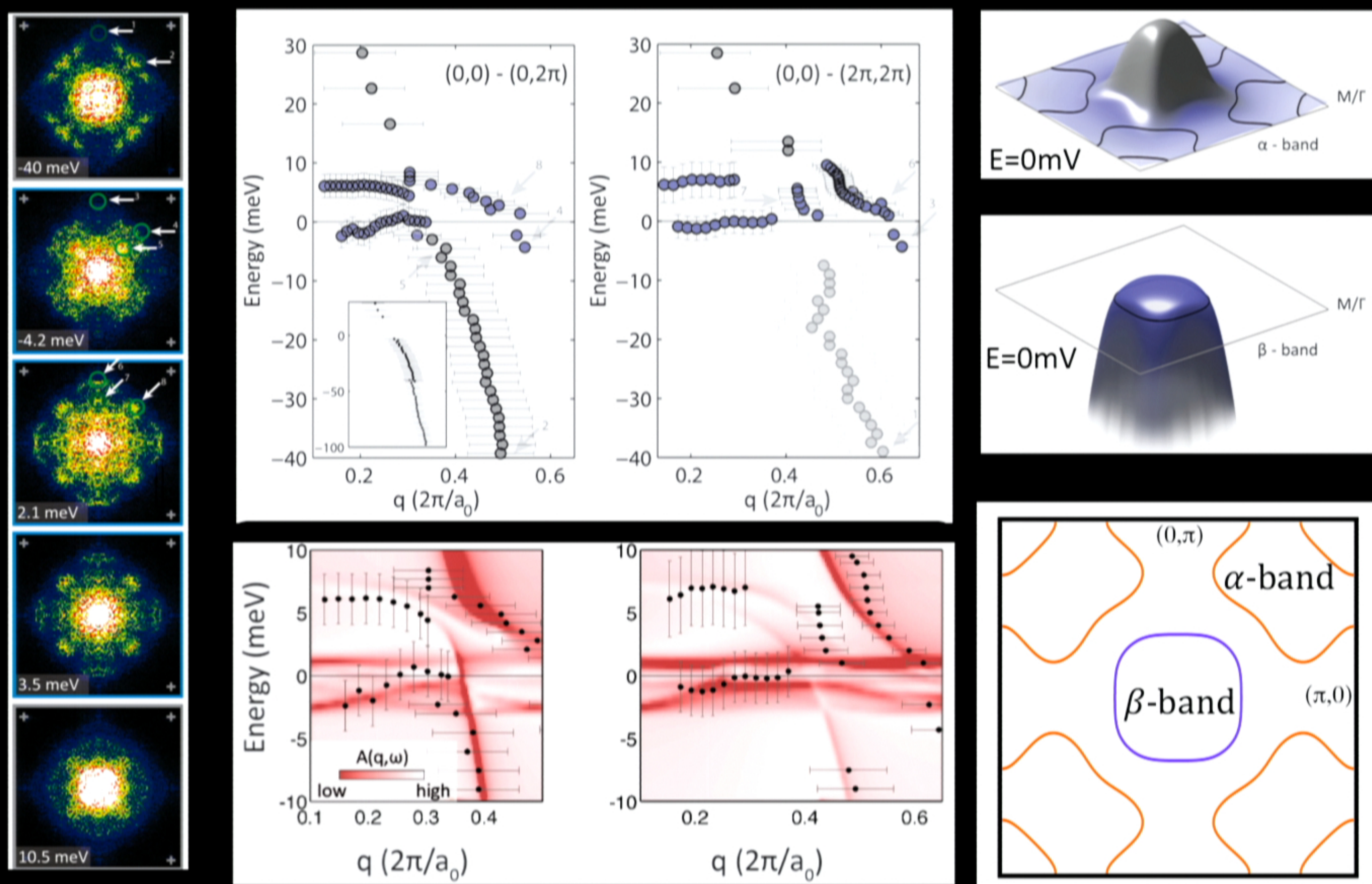
Sub-meV gap magnitudes have prevented direct measurement of Δ_k for any heavy fermion superconductor.

CeCoIn$_5$: Three Energy Scales : ε_k^c / $E_k^{\alpha,\beta}$ / $\Delta_k^{\alpha,\beta}$



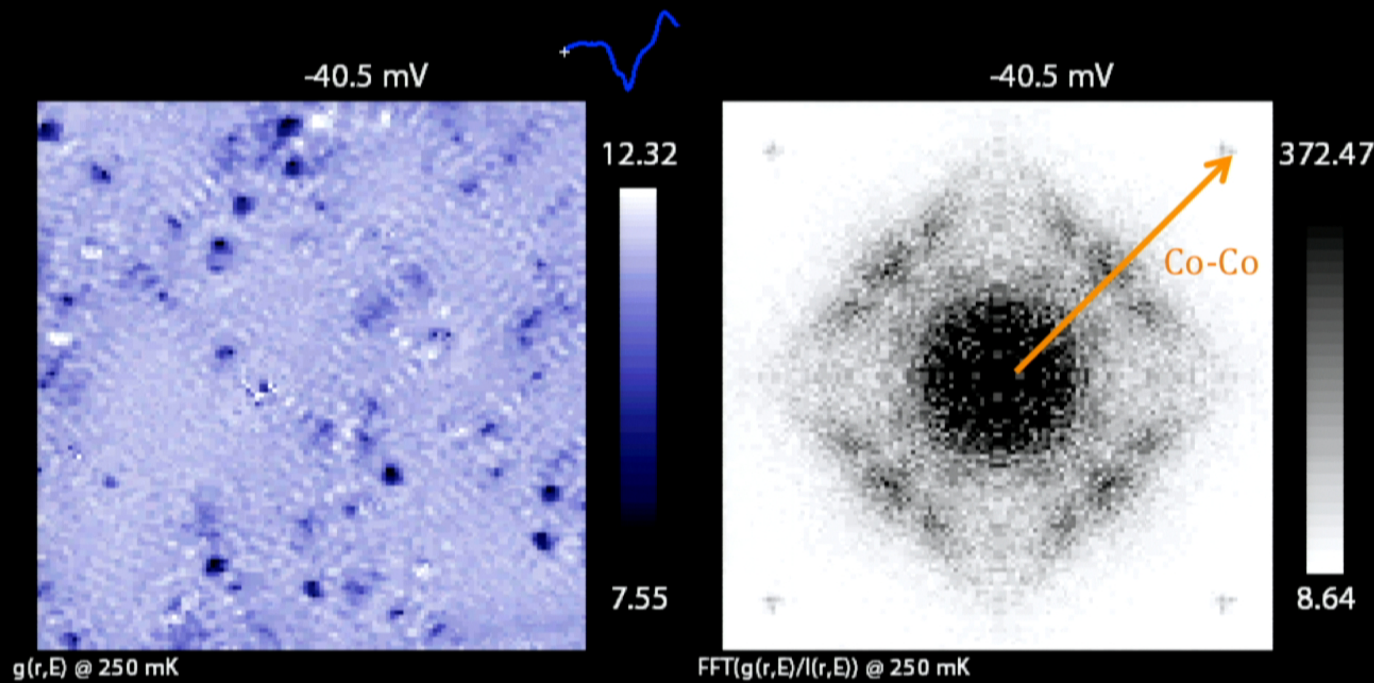
***Nature Physics* 9,** 468 (2013)

Measure : ε_k^c / $E_k^{\alpha,\beta}$



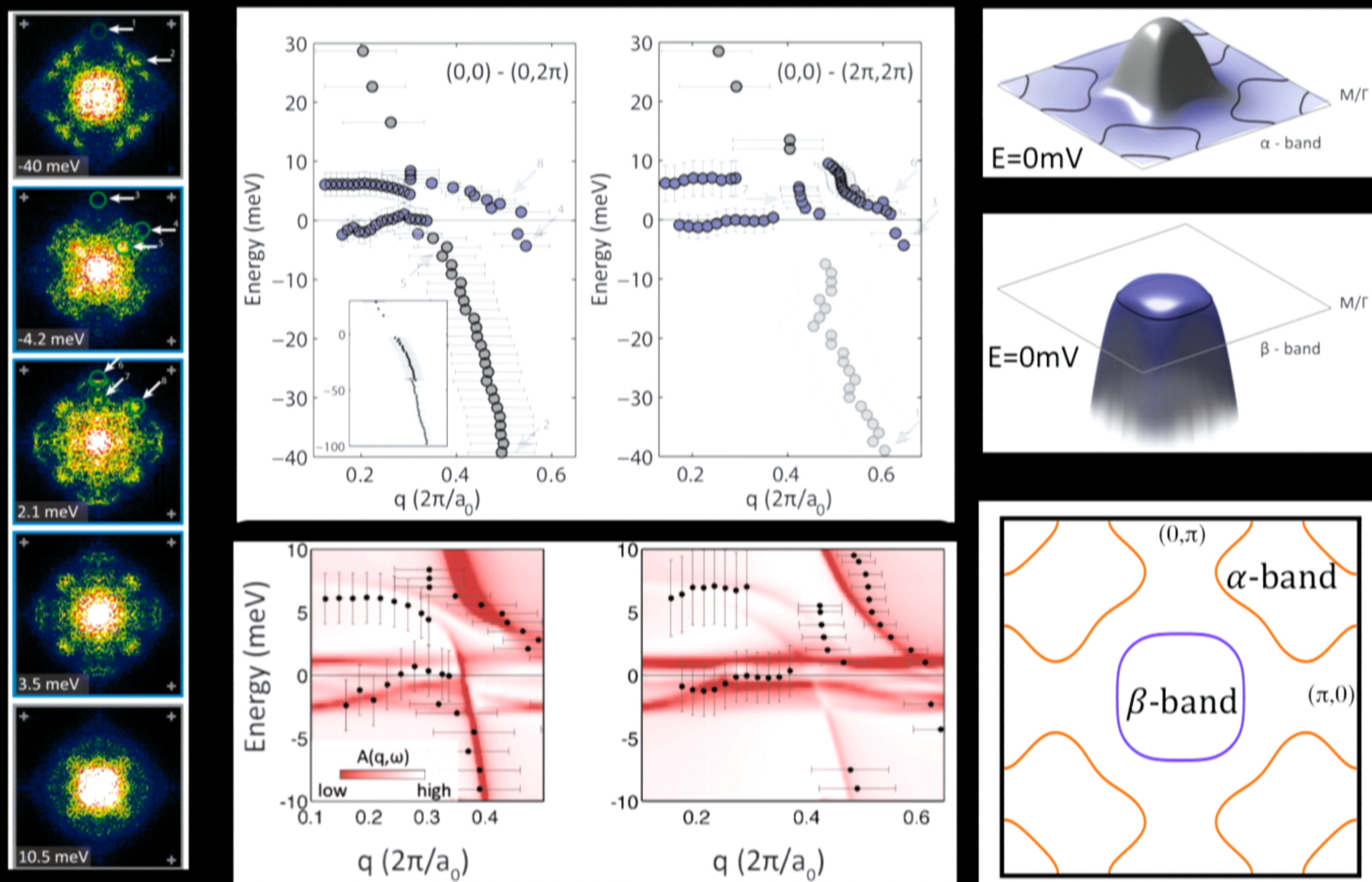
Nature Physics ***9***, 468 (2013)

Measure : ε_k^c / $E_k^{\alpha,\beta}$



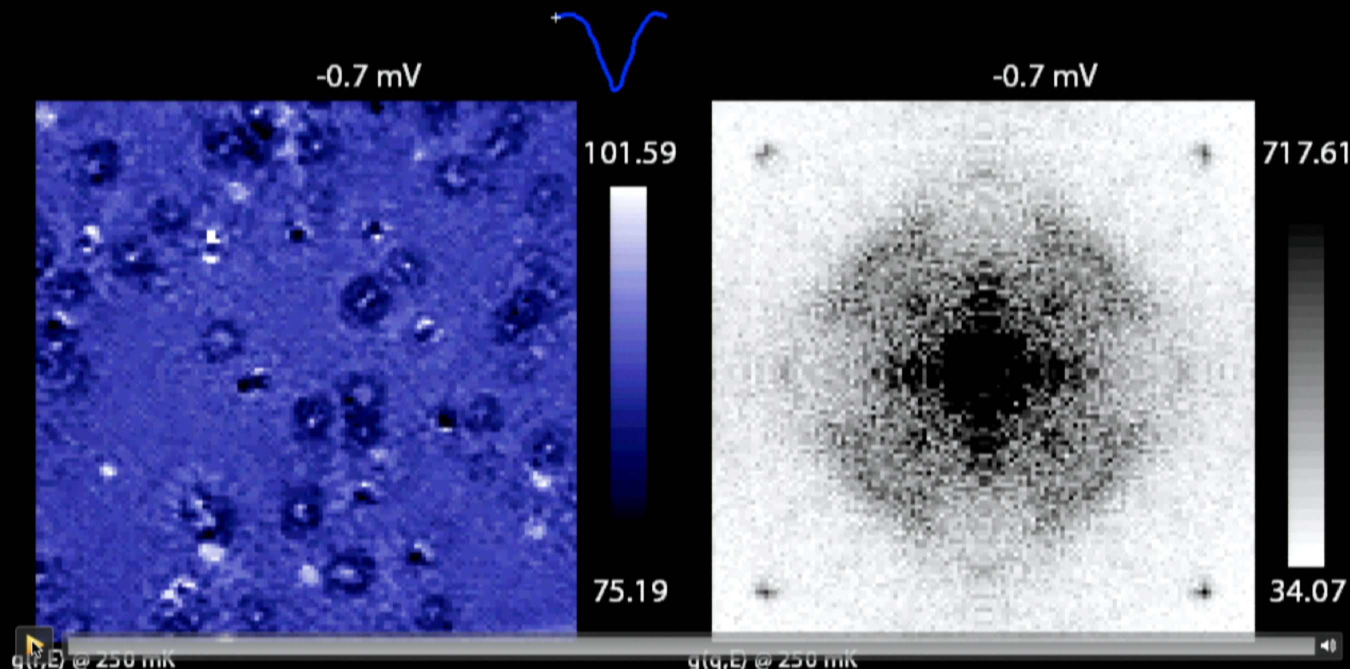
Nature Physics 9, 468 (2013)

Measure : ε_k^c / $E_k^{\alpha,\beta}$



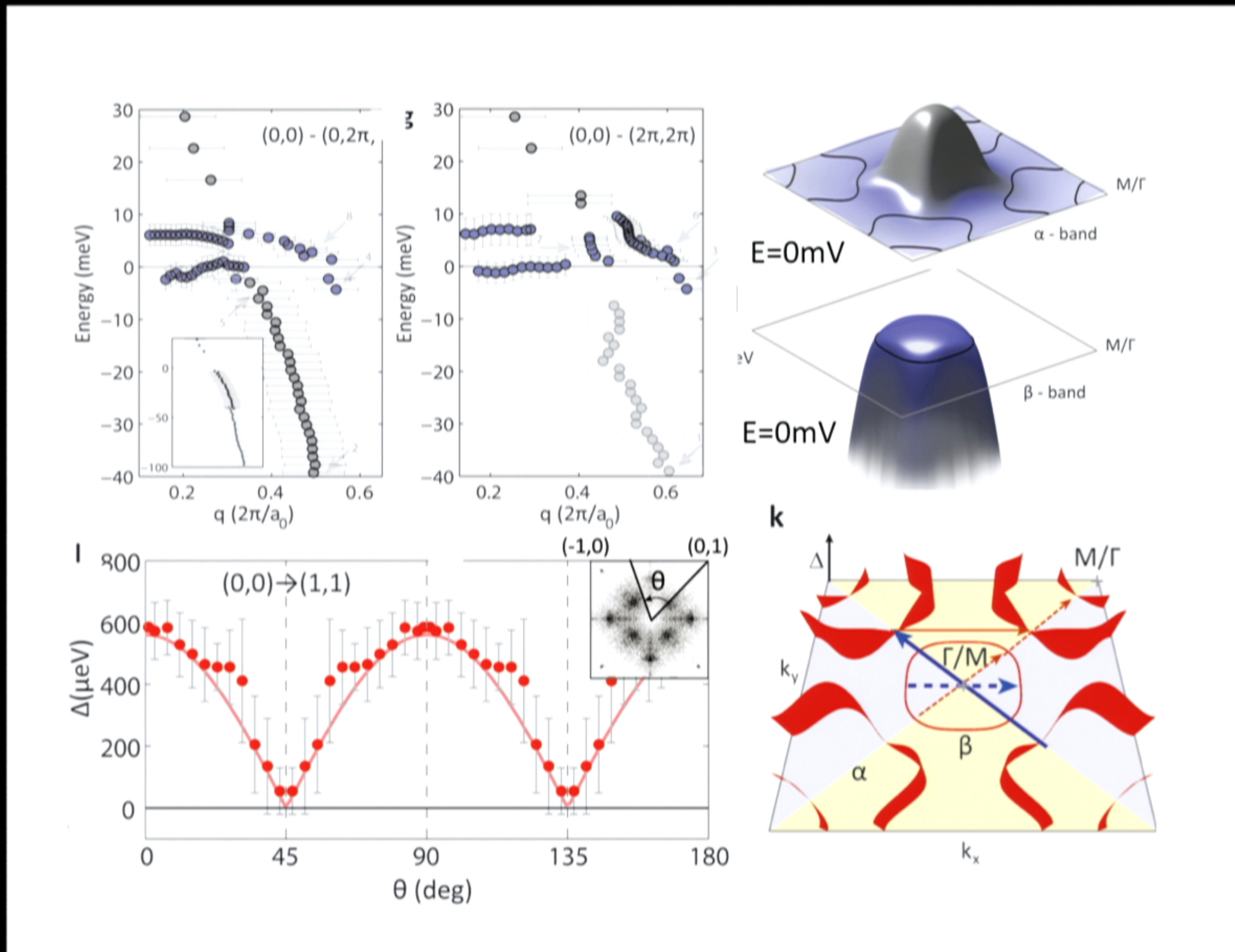
***Nature Physics* 9**, 468 (2013)

Measure : ε_k^c / $E_k^{\alpha,\beta}$ / $\Delta_k^{\alpha,\beta}$



***Nature Physics* 9,** 468 (2013)

Heavy-Fermion Superconductor : ε_k^c / $E_k^{\alpha,\beta}$ / $\Delta_k^{\alpha,\beta}$



Nature Physics **9**, 468 (2013)

Magnetically Mediated d-wave Superconductivity

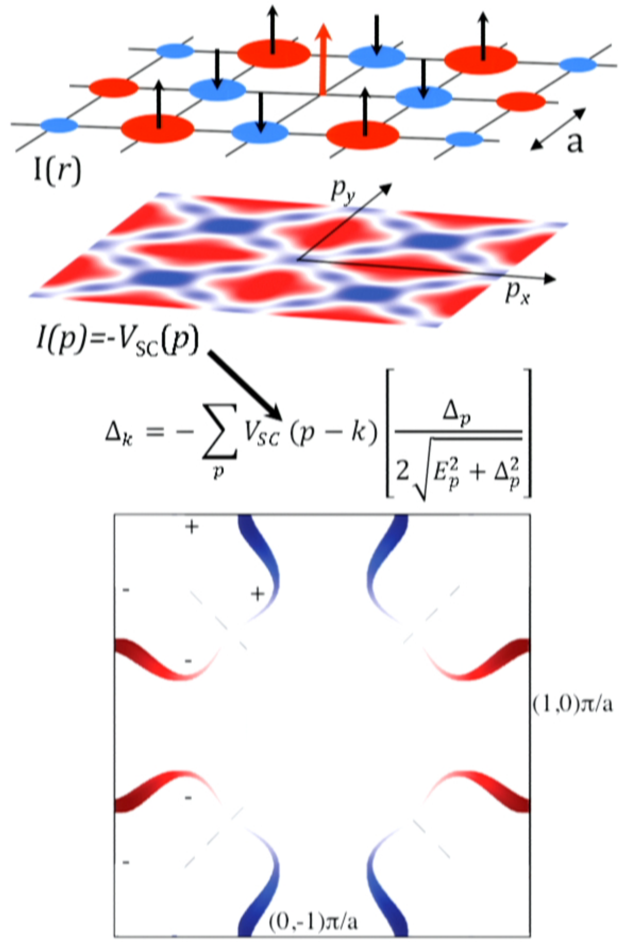
THEORY

K. Miyake *et al*. PRB **34**, 6554 (1986)

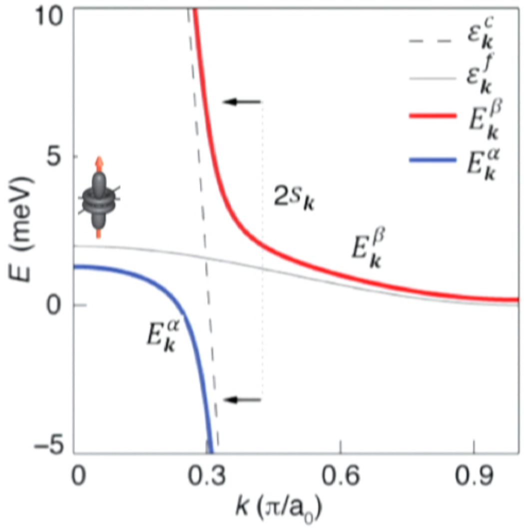
M. Béal-Monod *et al*. PRB **34**, 7716 (1986)

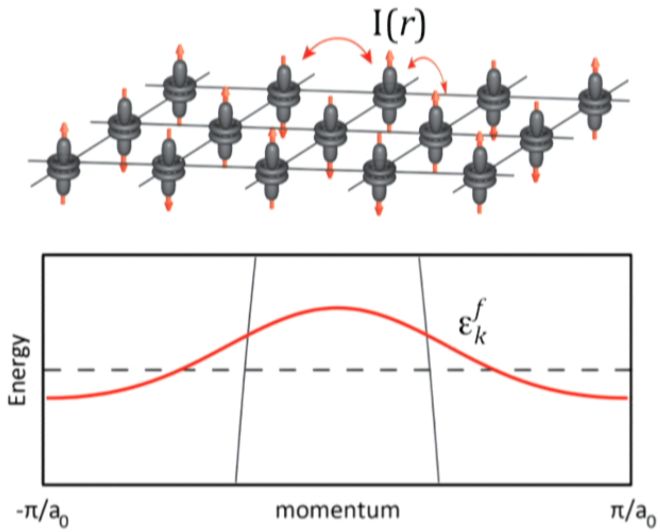
D.J. Scalapino *et al*. PRB **34**, 8190 (1986)

M. Lavagna *et al.* PRL 58, 266 (1987)



Derive f-electron Band Structure ε^f_k from $E_k^{\alpha,\beta}$

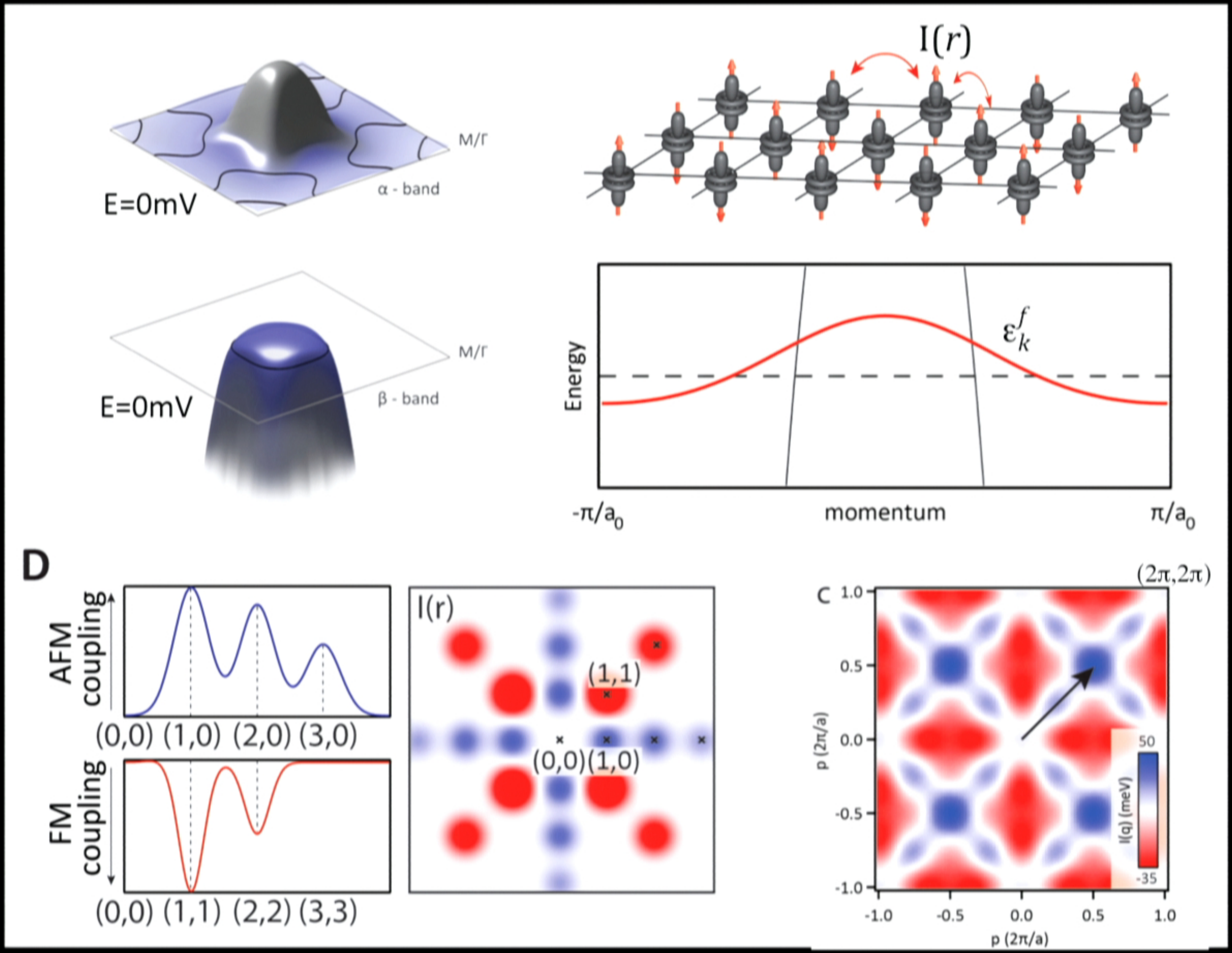




$$E_{\mathbf{k}}^{\alpha,\beta} = \frac{\varepsilon_{\mathbf{k}}^{c} + \varepsilon_{\mathbf{k}}^{f}}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}}^{c} - \varepsilon_{\mathbf{k}}^{f}}{2}\right)^2 + s_{\mathbf{k}}^2}$$

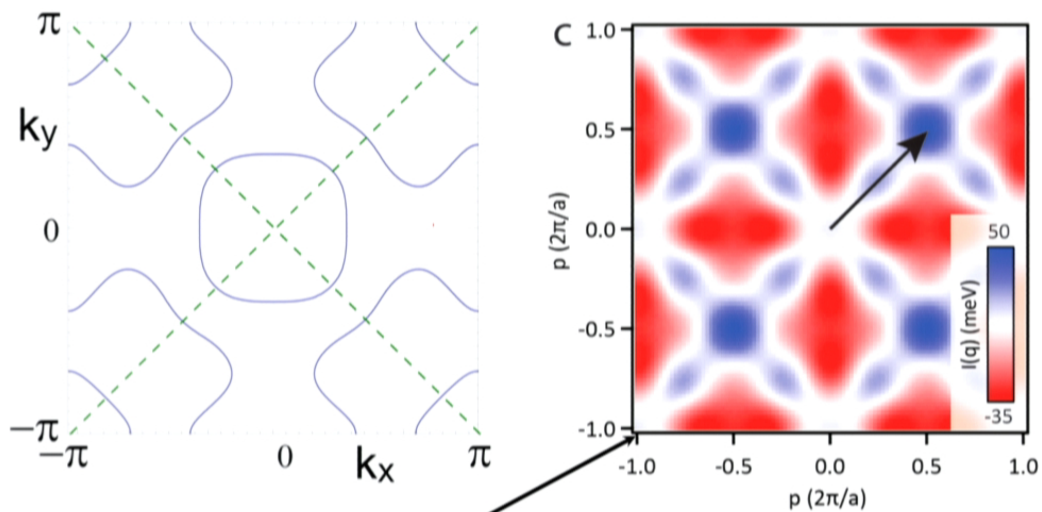
arXiv 1405.5833 / ***PNAS*** (2014)

$CeCoIn_5$: Derive I(r) & I(q) from ε_k^f



arXiv 1405.5833 / ***PNAS*** (2014)

Hypothesize Measured I(q) = - $V_{SC}(q)$ for $CeCoIn_5$



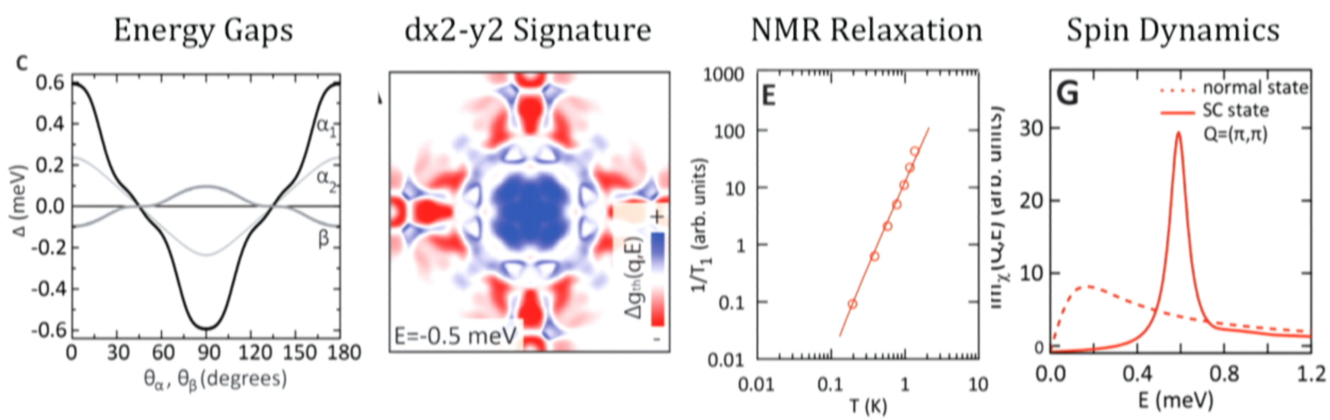
$$\Delta^{\alpha}_{\vec{k}} = -\frac{x^2_{\vec{k}}}{N}\sum_{\vec{p}} V_{SC}\,(\vec{p}-\vec{k})\left[x^2_{\vec{p}}\,\frac{\Delta^{\alpha}_{\vec{p}}}{2\,\Omega^{\alpha}_{\vec{p}}}\tanh\left(\frac{\Omega^{\alpha}_{\vec{p}}}{2k_BT}\right)+w^2_{\vec{p}}\,\frac{\Delta^{\beta}_{\vec{p}}}{2\,\Omega^{\beta}_{\vec{p}}}\tanh\left(\frac{\Omega^{\beta}_{\vec{p}}}{2k_BT}\right)\right]$$

$$\Delta^{\beta}_{\vec{k}} = -\frac{w^2_{\vec{k}}}{N}\sum_{\vec{p}} V_{SC}\,(\vec{p}-\vec{k})\left[x^2_{\vec{p}}\,\frac{\Delta^{\alpha}_{\vec{p}}}{2\,\Omega^{\alpha}_{\vec{p}}}\tanh\left(\frac{\Omega^{\alpha}_{\vec{p}}}{2k_BT}\right)+w^2_{\vec{p}}\,\frac{\Delta^{\beta}_{\vec{p}}}{2\,\Omega^{\beta}_{\vec{p}}}\tanh\left(\frac{\Omega^{\beta}_{\vec{p}}}{2k_BT}\right)\right]$$

$$\Omega^{\alpha,\beta}_{\vec{k}} = \sqrt{\left(E^{\alpha,\beta}_{\vec{k}}\right)^2+\left(\Delta^{\alpha,\beta}_{\vec{k}}\right)^2}$$

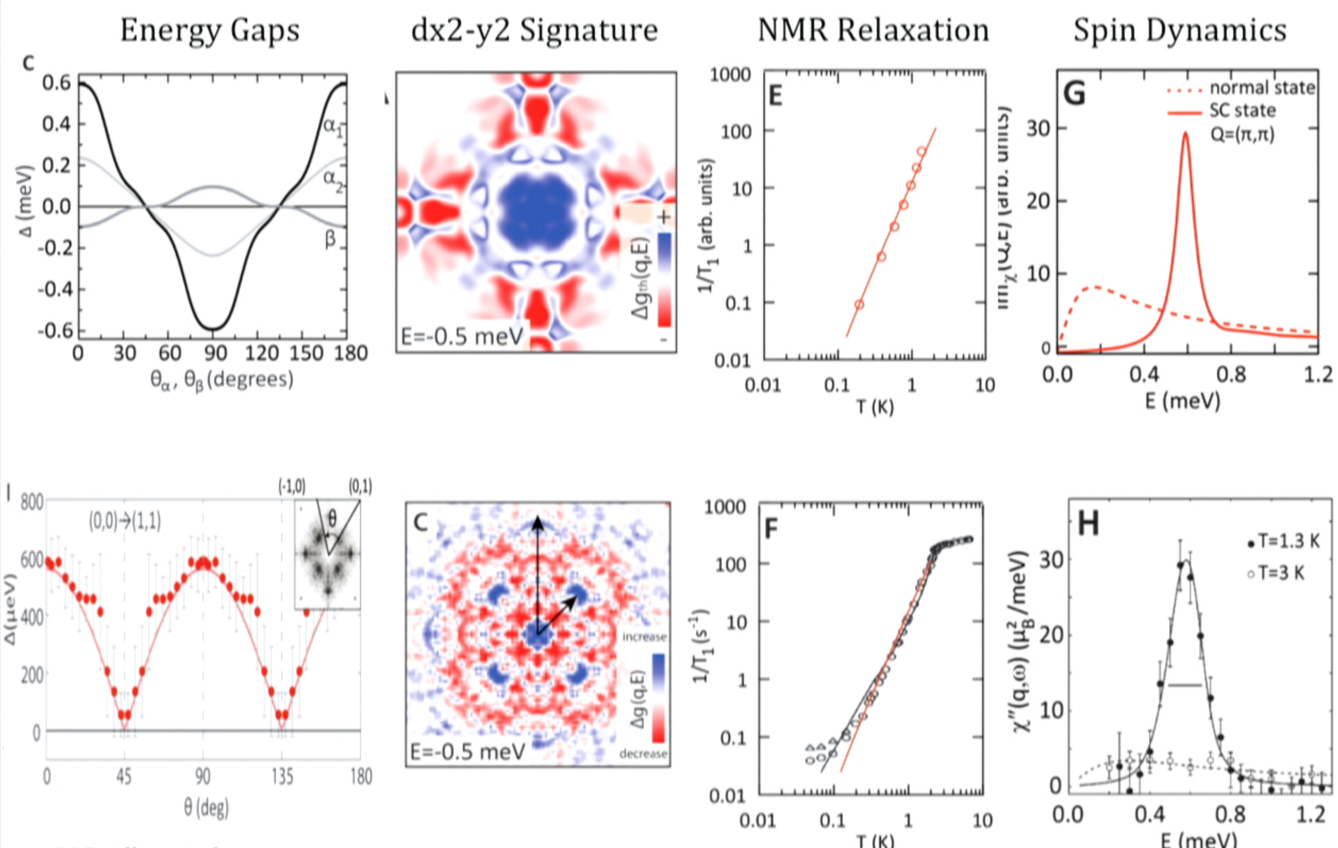
arXiv 1405.5833 / ***PNAS*** (2014)

Predict Superconductive Properties of $CeCoIn_5$



arXiv 1405.5833 / ***PNAS*** (2014)

Agreement of Magnetically Mediated Theory / Variety of Expts.



M.P. Allan *et al.* *Nature Physics* **9**, 468 (2013)

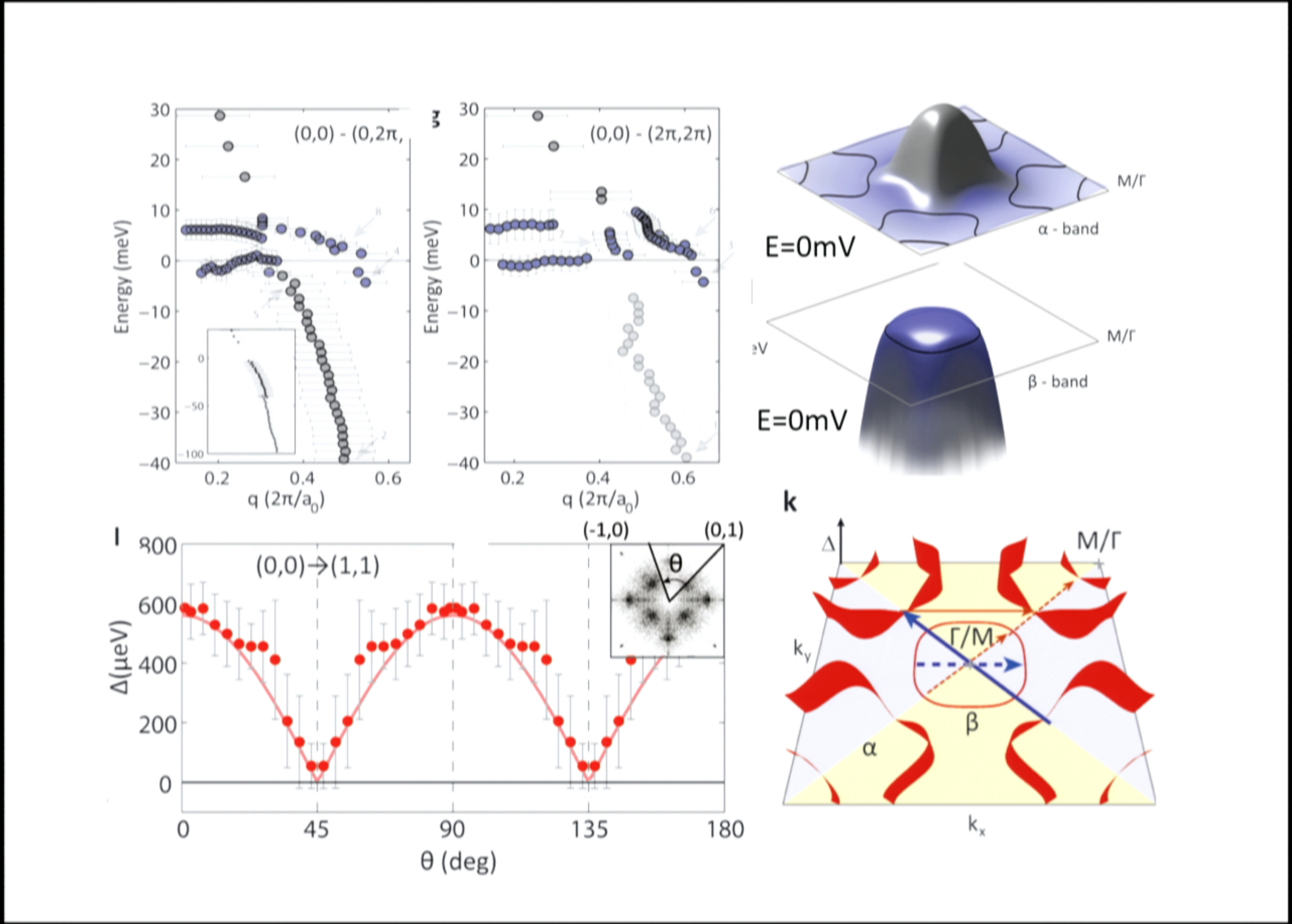
T. Hanaguri et al., *Science* **323**, 923 (2009)

Y. Kohori et al., *PRB* **64**, 134526 (2001)

C. Stock *et al.*, *PRL* **100**, 087001 (2008)

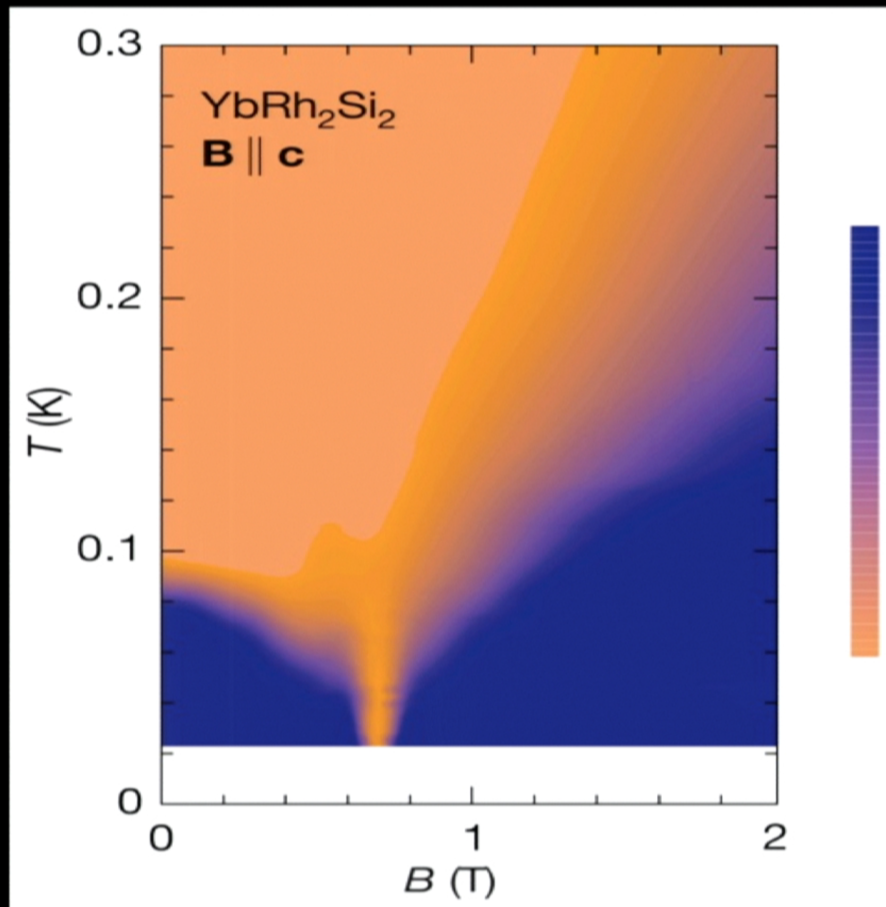
arXiv 1405.5833 / ***PNAS*** (2014)

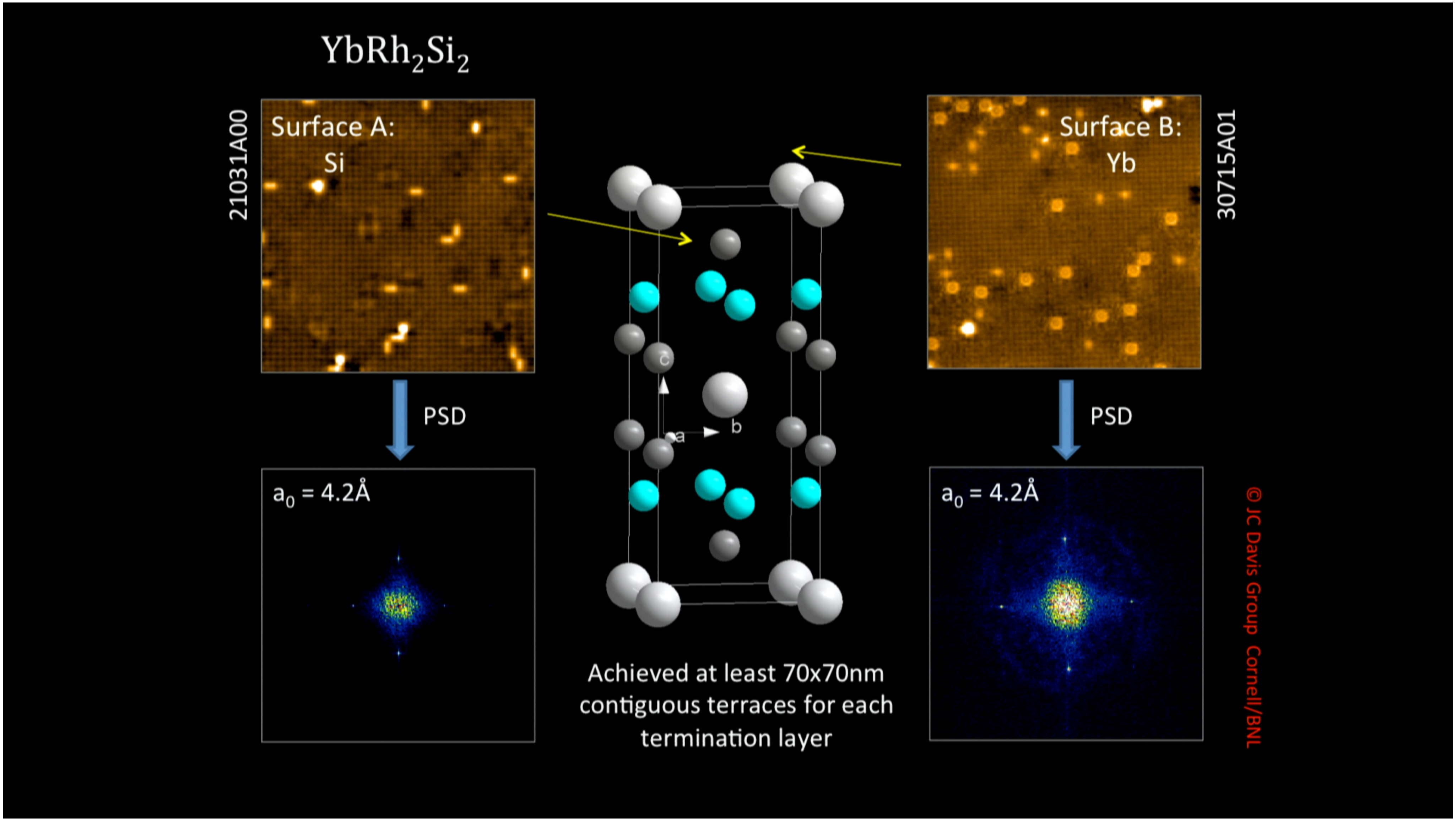
Magnetic f-electron Mediated Pairing in $CeCoIn_5$



Nature Physics* 9,** 468 (2013) & ***arXiv 1405.5833 / ***PNAS*** (2014)

$YbRh_2Si_2$

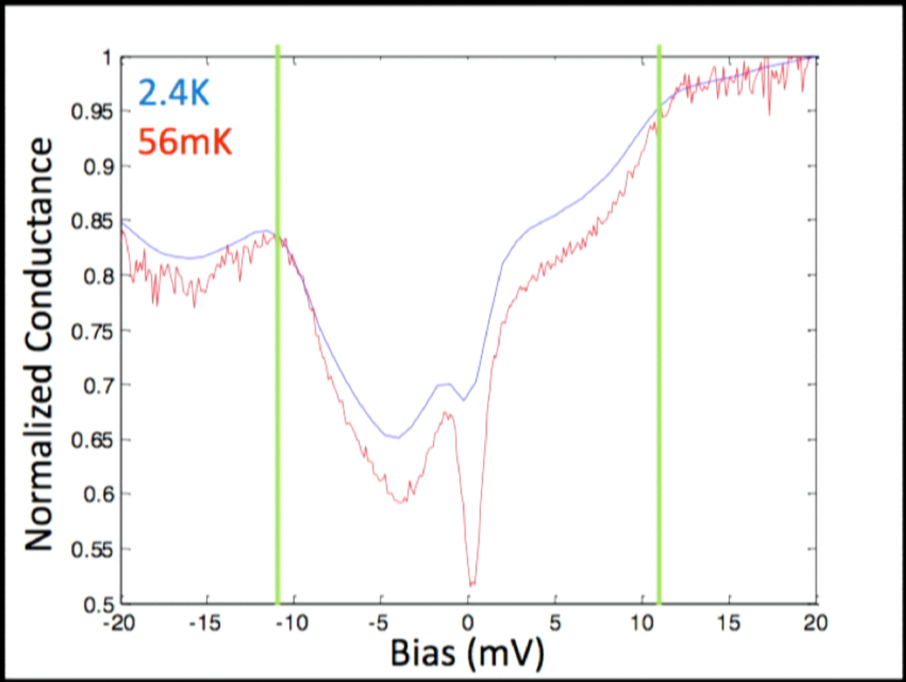




$YbRh_2Si_2$
21031A00
Surface A:
Si
Surface B:
Yb
30715A01
PSD
PSD
c
a
b
a_0 = 4.2Å
a_0 = 4.2Å
Achieved at least 70x70nm contiguous terraces for each termination layer
© JC Davis Group Cornell/BNL

$YbRh_2Si_2$

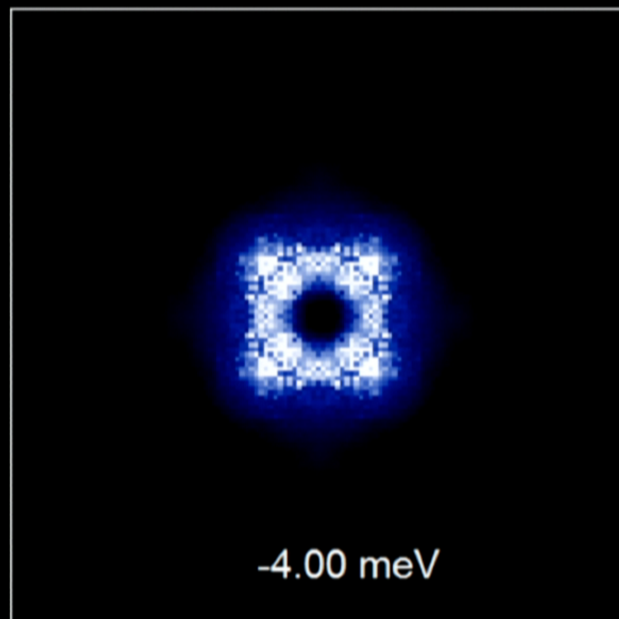
Spectroscopy at 50mK
dE<50μV energy resolution



2.4K data is very close to thermally broadened version of 50mK data

$YbRh_2Si_2$

High Energy Resolution QPI
T = 30mK

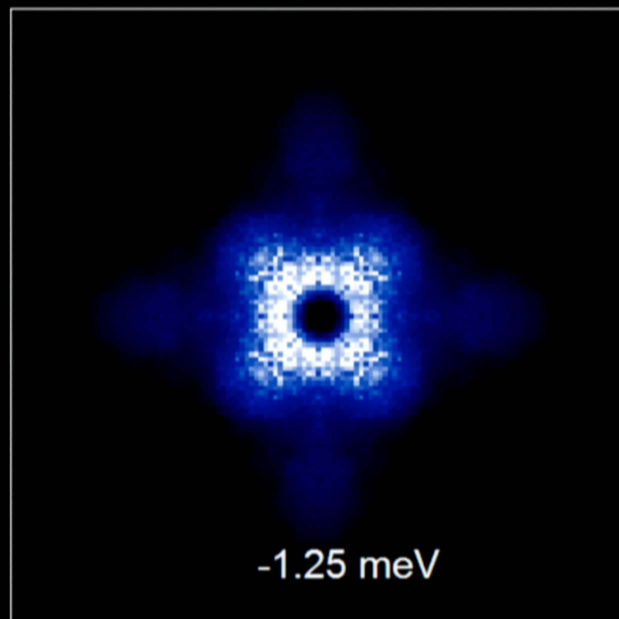


Energy spacing = 125μV
Bias Modulation = 125 μV
Junction: -4mV@400pA (10MΩ)

30525A00

$YbRh_2Si_2$

High Energy Resolution QPI
T = 30mK

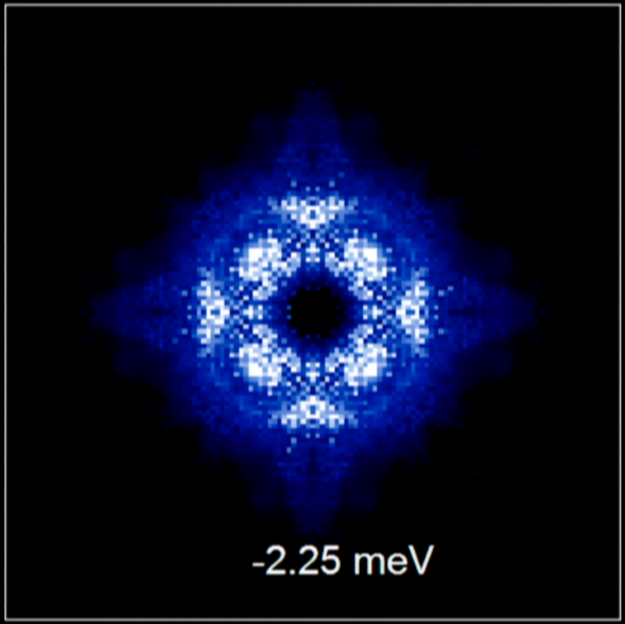


Energy spacing = 125μV
Bias Modulation = 125 μV
Junction: -4mV@400pA (10MΩ)

30525A00

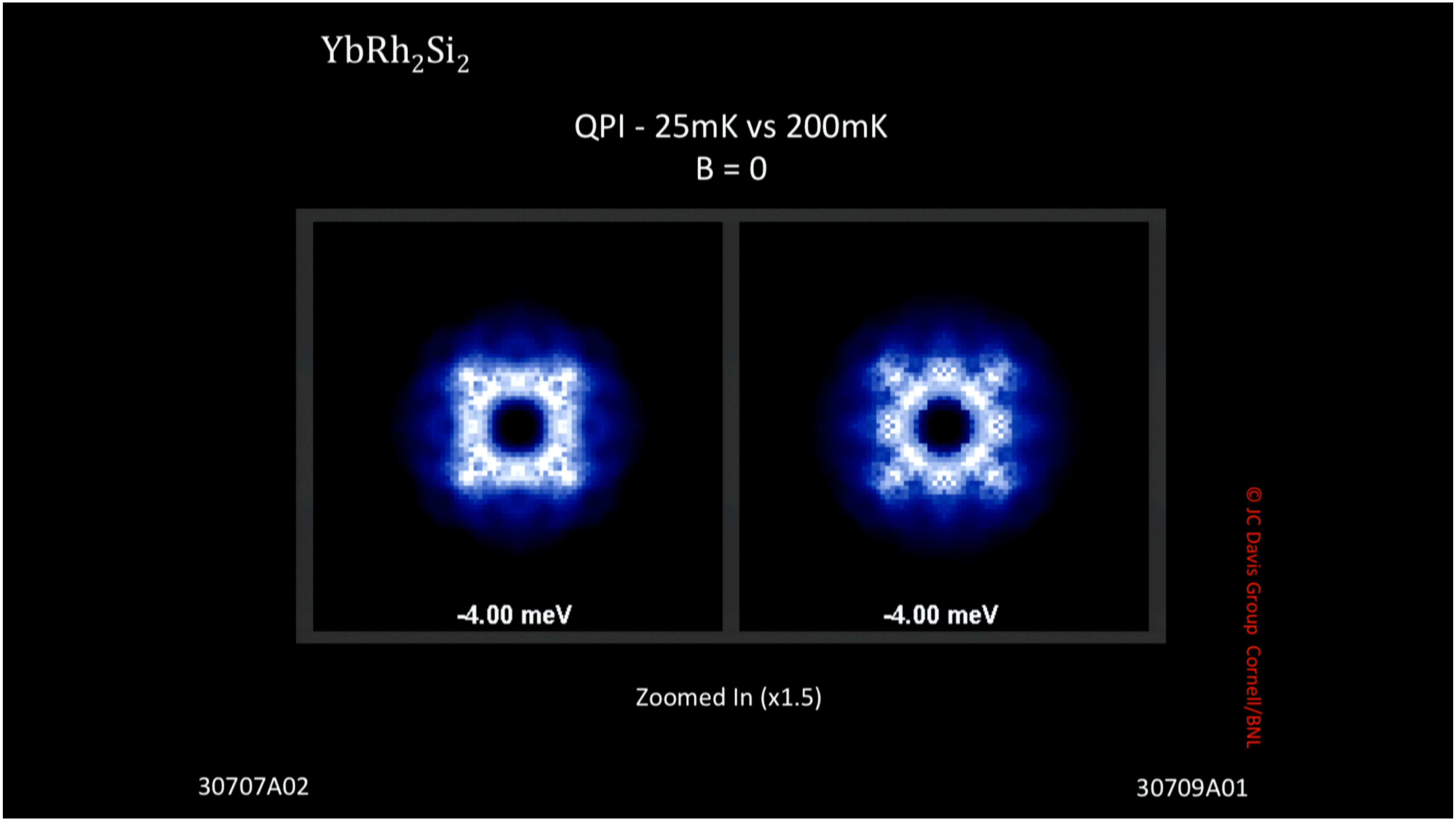
$YbRh_2Si_2$

High Energy Resolution QPI
T = 30mK



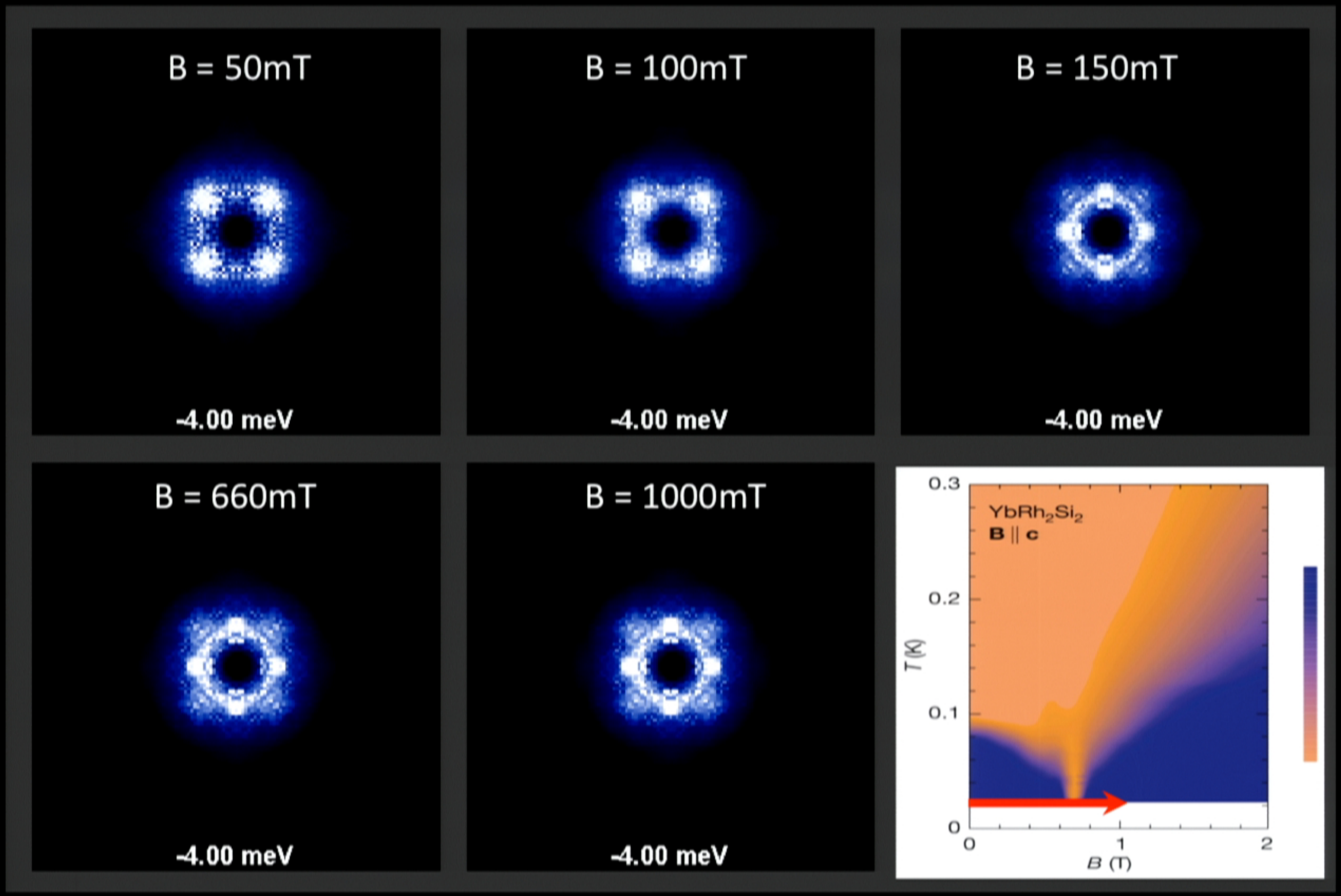
Energy spacing = 125μV
Bias Modulation = 125 μV
Junction: -4mV@400pA (10MΩ)

30525A00



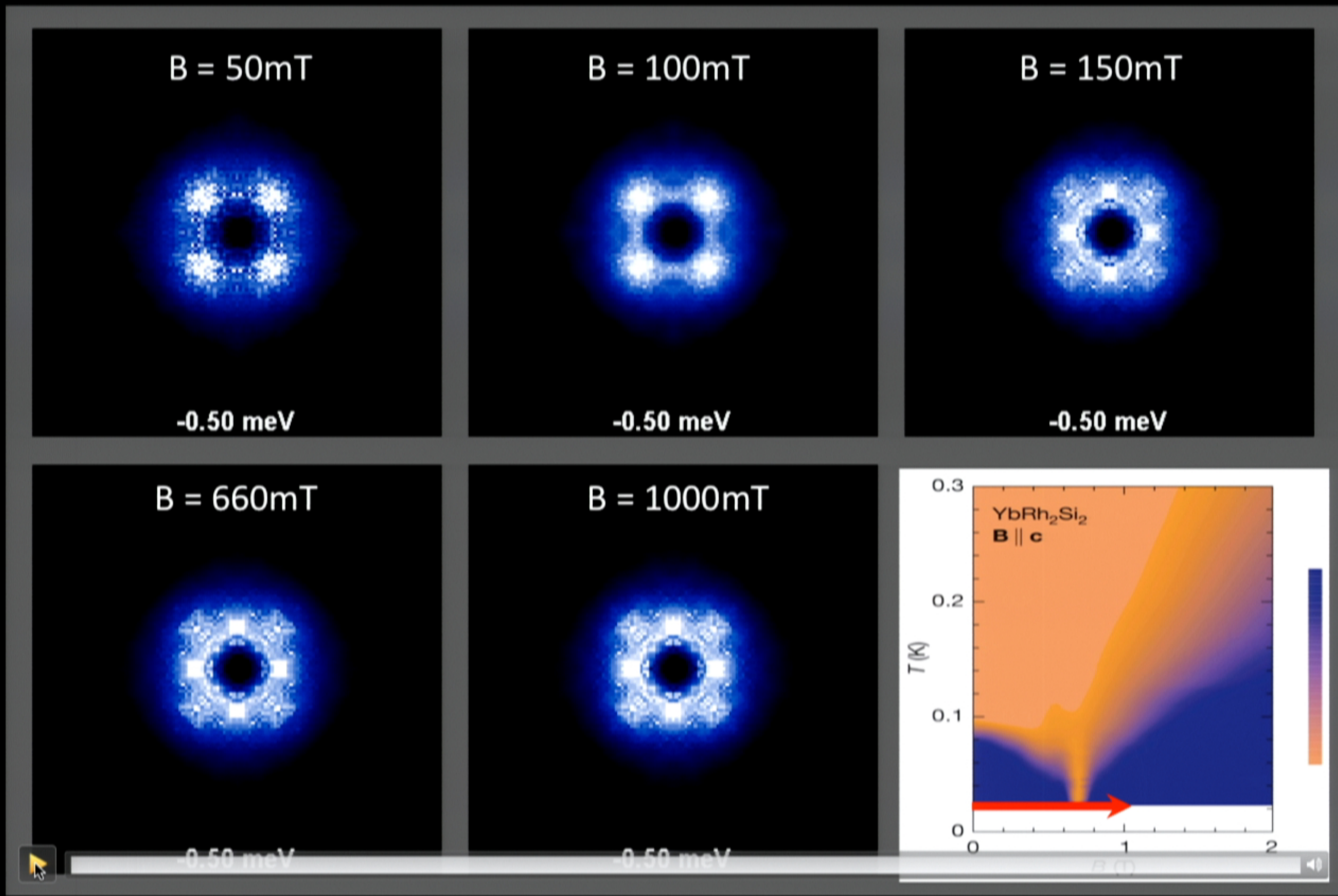
YbRh$_2$Si$_2$
QPI - 25mK vs 200mK
B = 0
-4.00 meV
-4.00 meV
Zoomed In (x1.5)
30707A02
30709A01
© JC Davis Group Cornell/BNL

$YbRh_2Si_2$



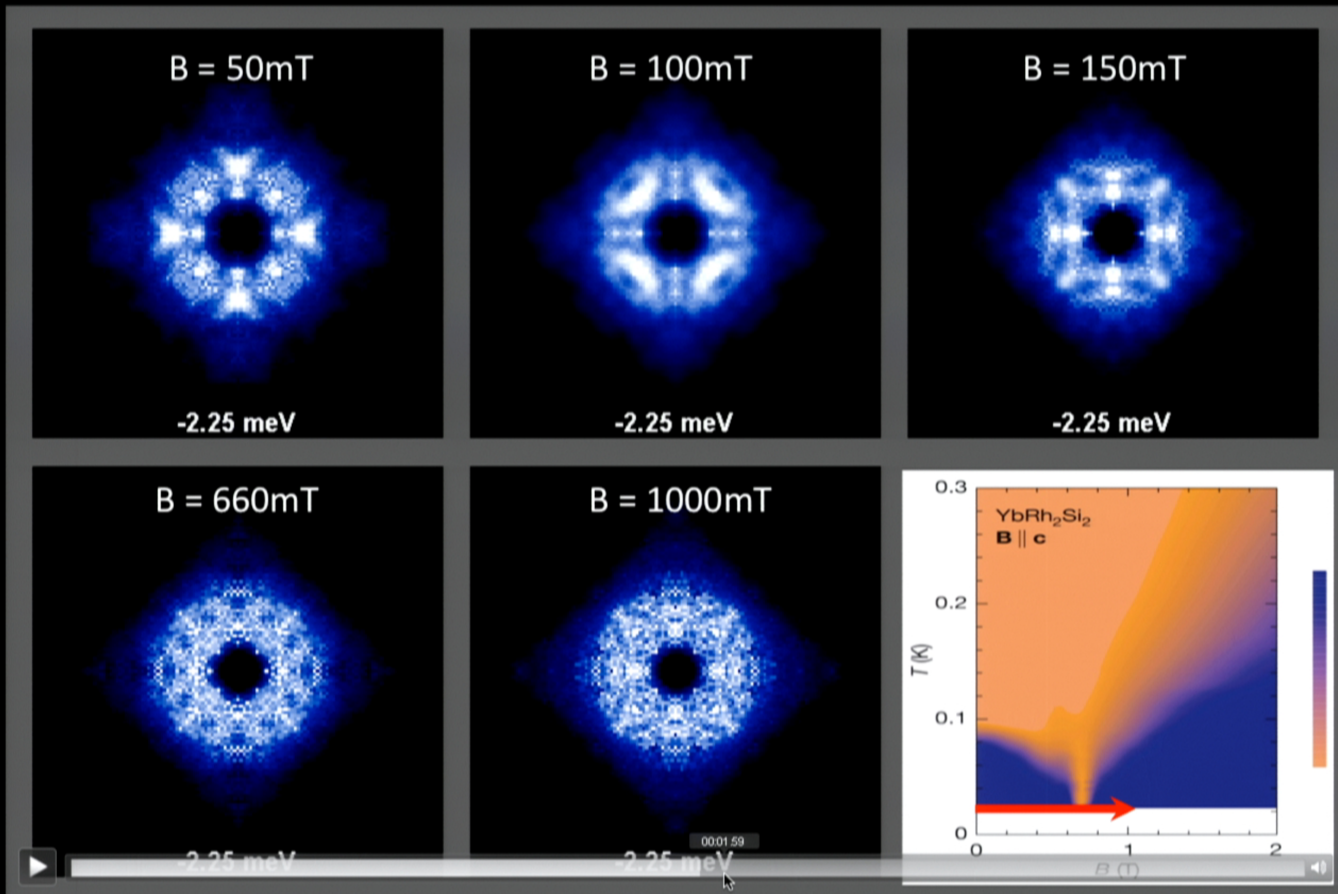
30522A01; 30523A01; 30603A00; 30605A02; 30609A00

$YbRh_2Si_2$



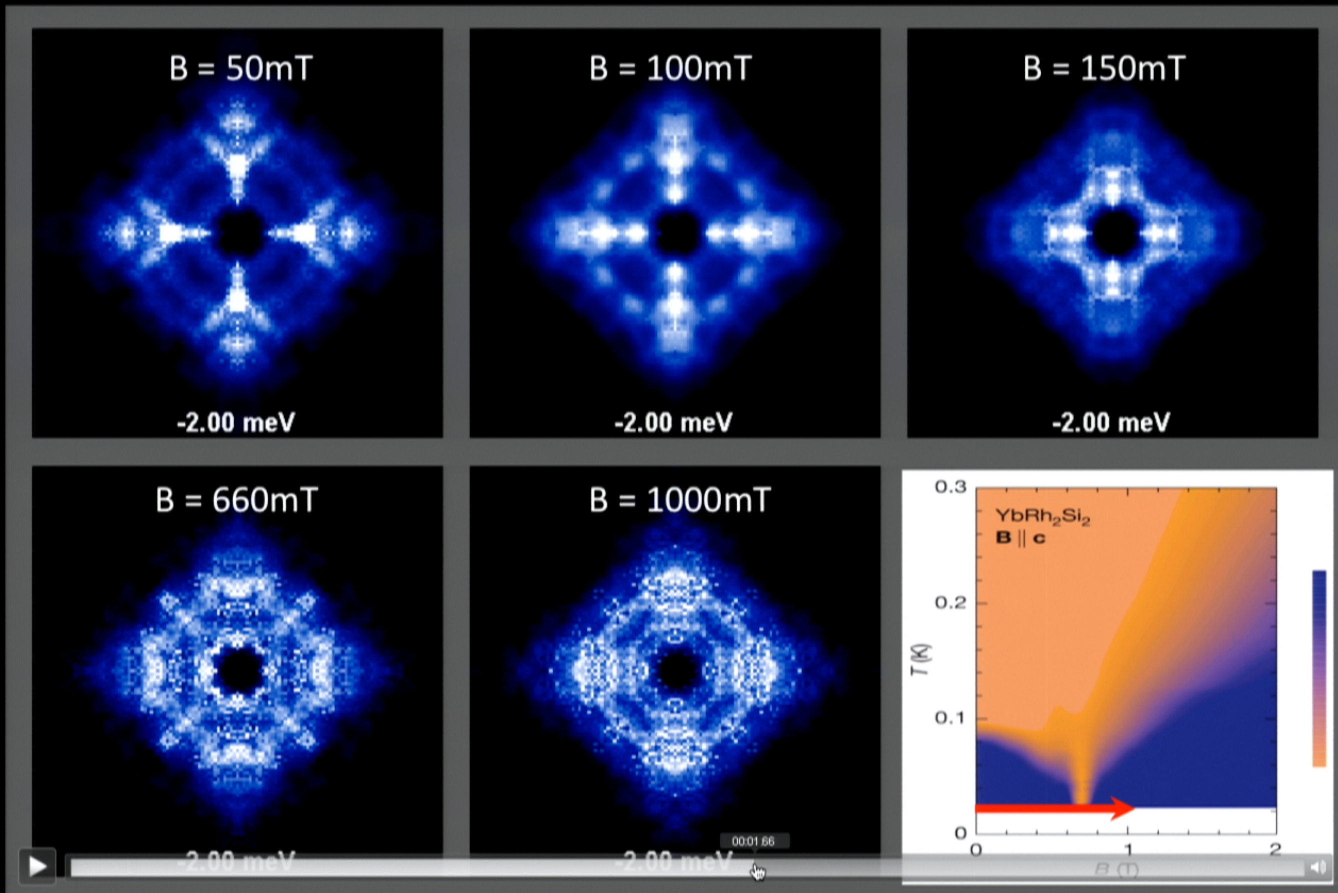
30522A01; 30523A01; 30603A00; 30605A02; 30609A00

$YbRh_2Si_2$



30522A01; 30523A01; 30603A00; 30605A02; 30609A00

YbRh$_2$Si$_2$



30522A01; 30523A01; 30603A00; 30605A02; 30609A00

THANKS!