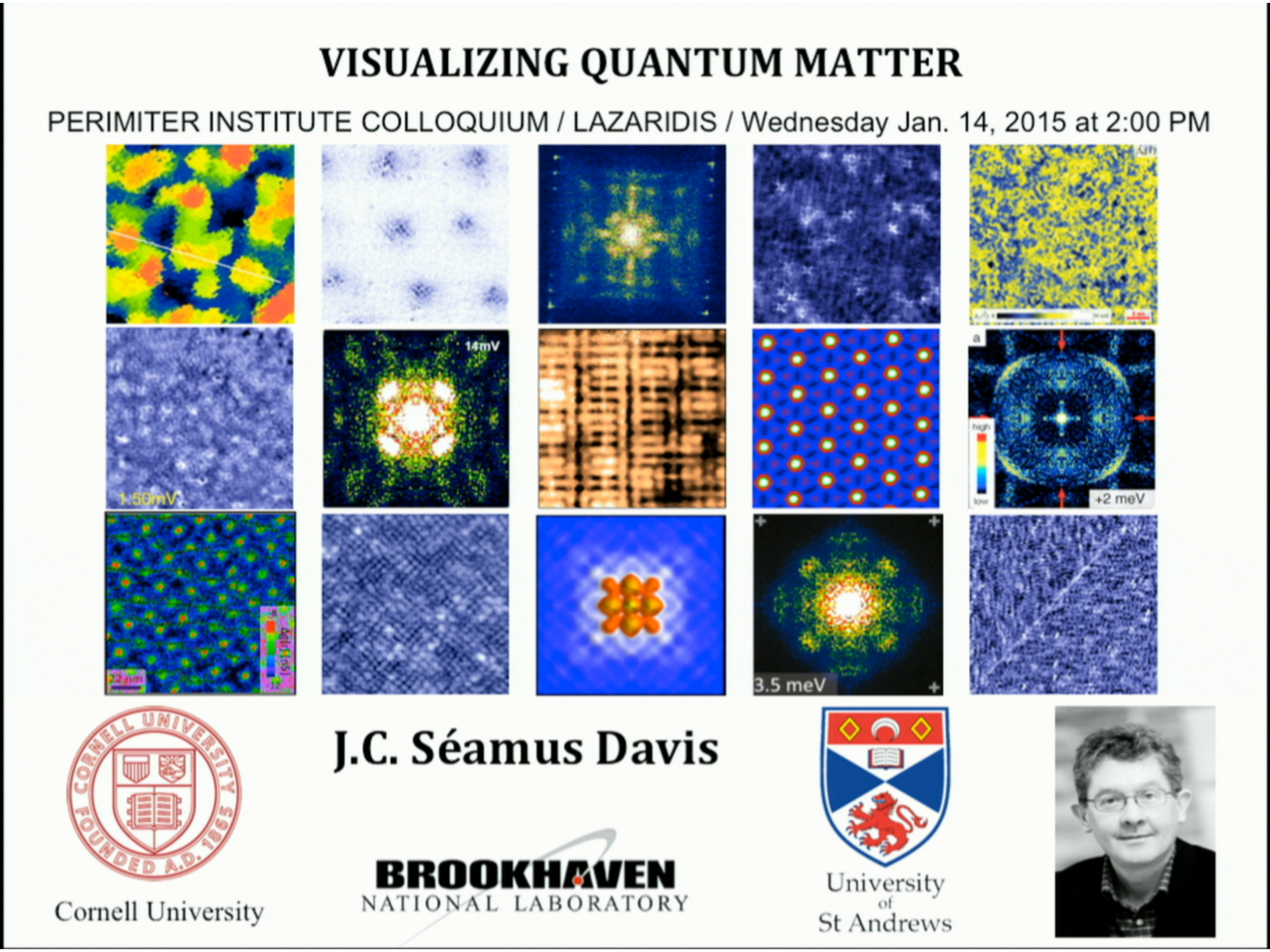
Title: Visualizing Quantum Matter

Date: Jan 14, 2015 02:00 PM

URL: http://pirsa.org/15010080

Abstract: <p>Everything around us, everything each of us has ever experienced, and virtually everything underpinning our technological society and economy is governed by quantum mechanics. Yet this most fundamental physical theory of nature often feels as if it is a set of somewhat eerie and counterintuitive ideas of no direct relevance to our lives. Why is this? One reason is that we cannot perceive the strangeness (and astonishing beauty) of the quantum mechanical phenomena all around us by using our own senses. I will describe the recent development of techniques that allow us to image electronic quantum matter directly at the atomic scale. As examples, we will visually explore the previously unseen and very beautiful forms of quantum matter making up electronic liquid crystals [1,2]; hybridized heavy-fermions [3,4]; topological-insulator surface states [5]; and high temperature superconductors [6,7]. We will discuss the implications for fundamental research, and also for advanced materials and new technologies, arising from the development and application of these novel techniques .</p>



VISUALIZING QUANTUM MATTER

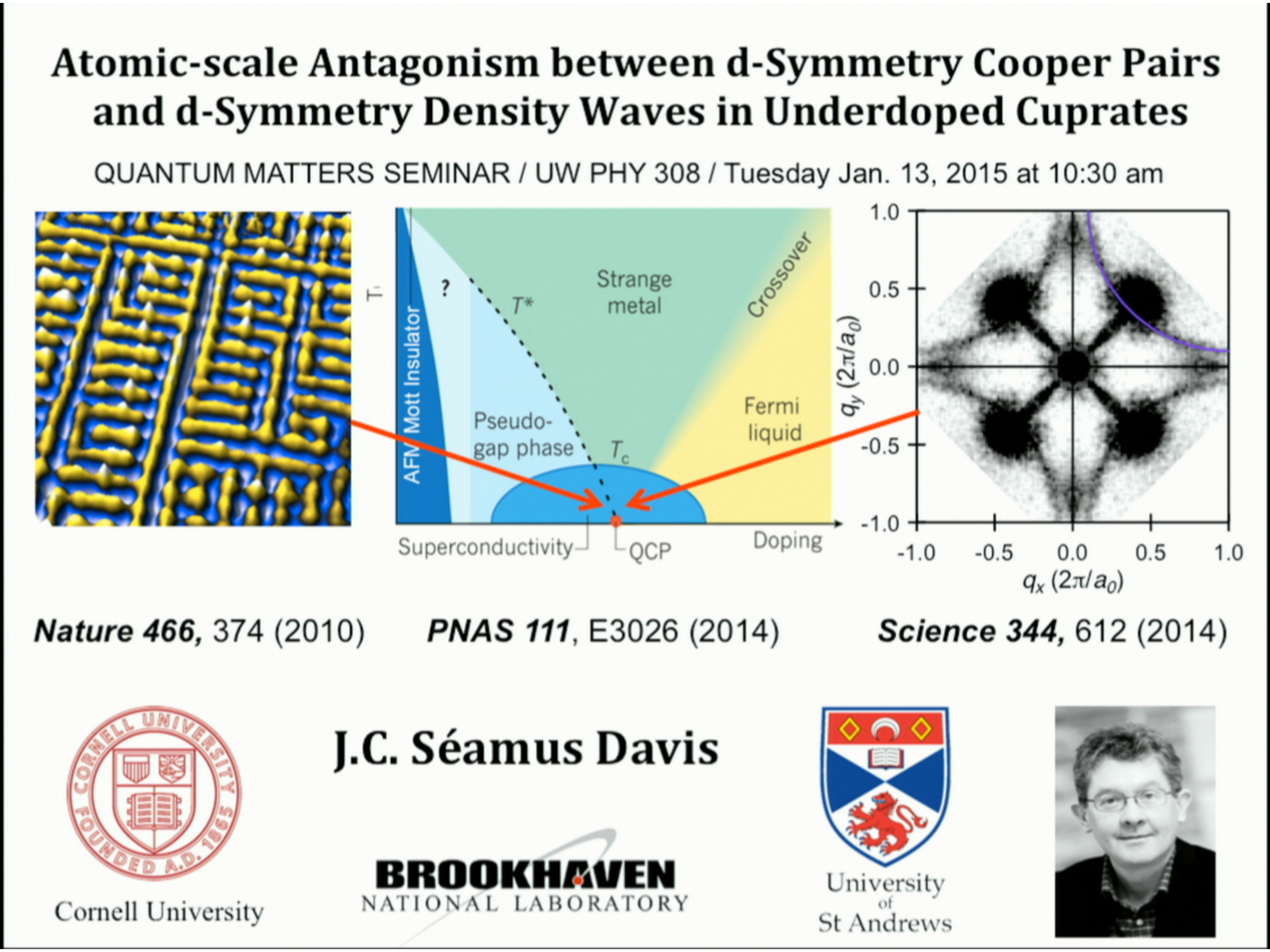
PERIMITER INSTITUTE COLLOQUIUM / LAZARIDIS / Wednesday Jan. 14, 2015 at 2:00 PM

J.C. Séamus Davis

Cornell University

BROOKHAVEN
NATIONAL LABORATORY

University
of
St Andrews



Atomic-scale Antagonism between d-Symmetry Cooper Pairs and d-Symmetry Density Waves in Underdoped Cuprates

QUANTUM MATTERS SEMINAR / UW PHY 308 / Tuesday Jan. 13, 2015 at 10:30 am

***Nature* 466,** 374 (2010)   ***PNAS* 111**, E3026 (2014)   ***Science* 344,** 612 (2014)

J.C. Séamus Davis

Cornell University

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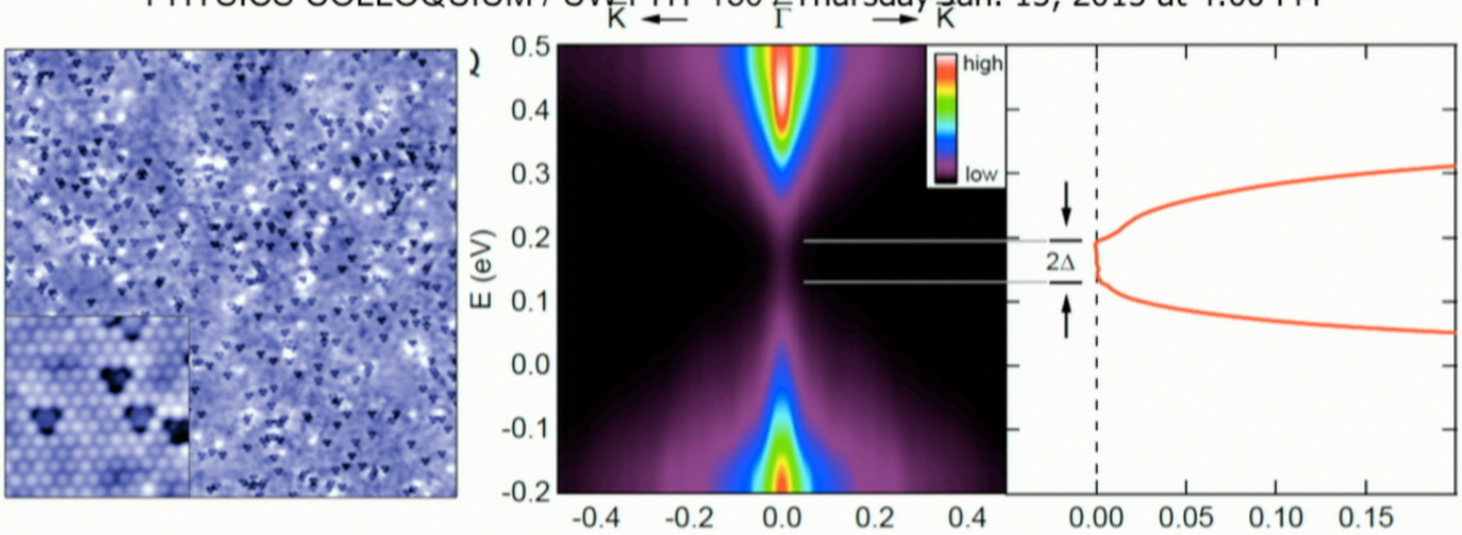
University of St Andrews

Atomic-scale Imaging of Dirac-Mass Configurations in Ferromagnetic Topological Insulators

PHYSICS COLLOQUIUM / UW PHY 150 / Thursday Jan. 15, 2015 at 4:00 PM



arXiv 1412.2718 ; ***PNAS 112*** (2015)

Cornell University

J.C. Séamus Davis

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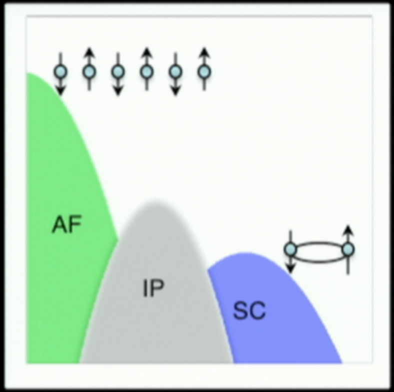
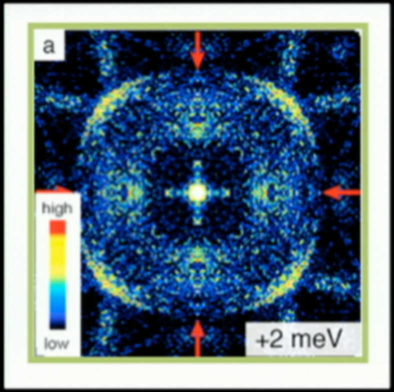
of
St Andrews

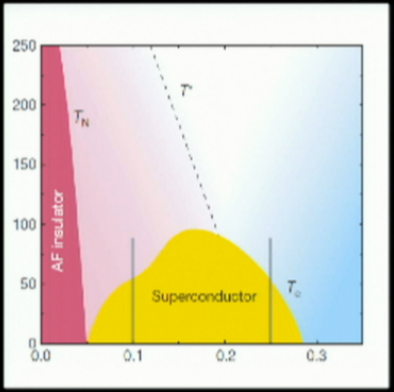
ANTIFERROMAGNETISM
& SUPERCONDUCTIVITY



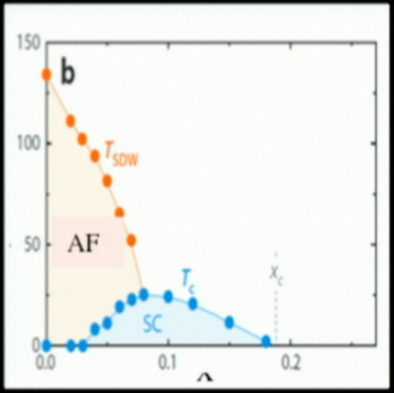
VISUALIZING ELECTRONIC
QUANTUM MATTER



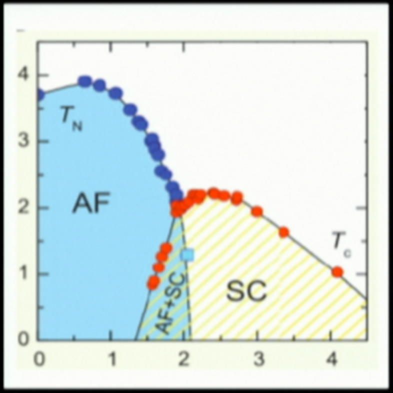
COPPER-BASED
SUPERCONDUCTIVITY
& INTERTWINED PHASES



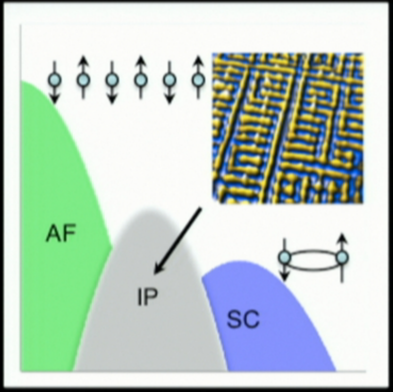
IRON-BASED
SUPERCONDUCTIVITY
& INTERTWINED PHASES



HEAVY-FERMION
SUPERCONDUCTIVITY
& INTERTWINED PHASES



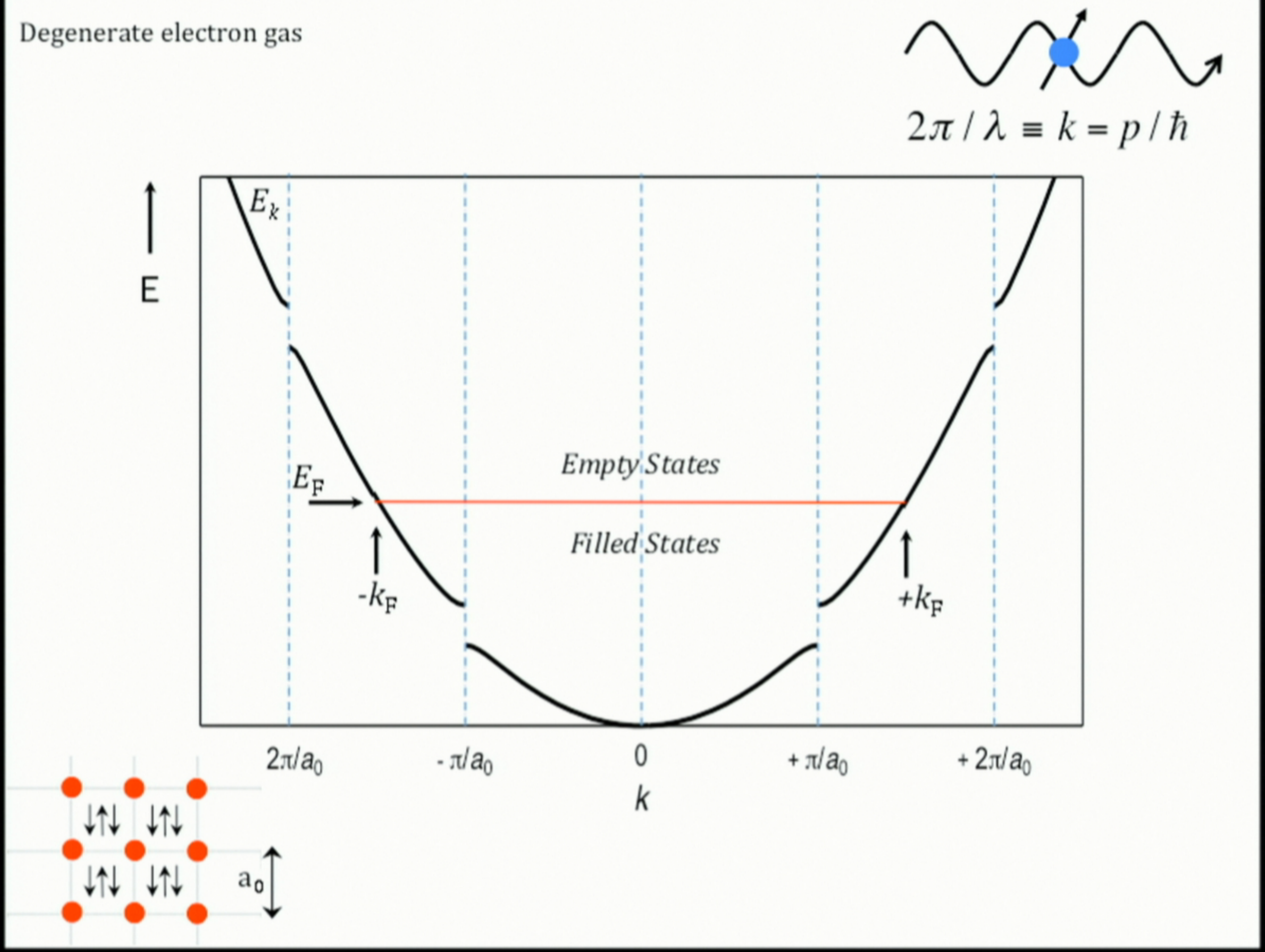
'UNIFIED' MODEL
OF AF INTERACTIONS
INTERTWINED PHASES & HT SC



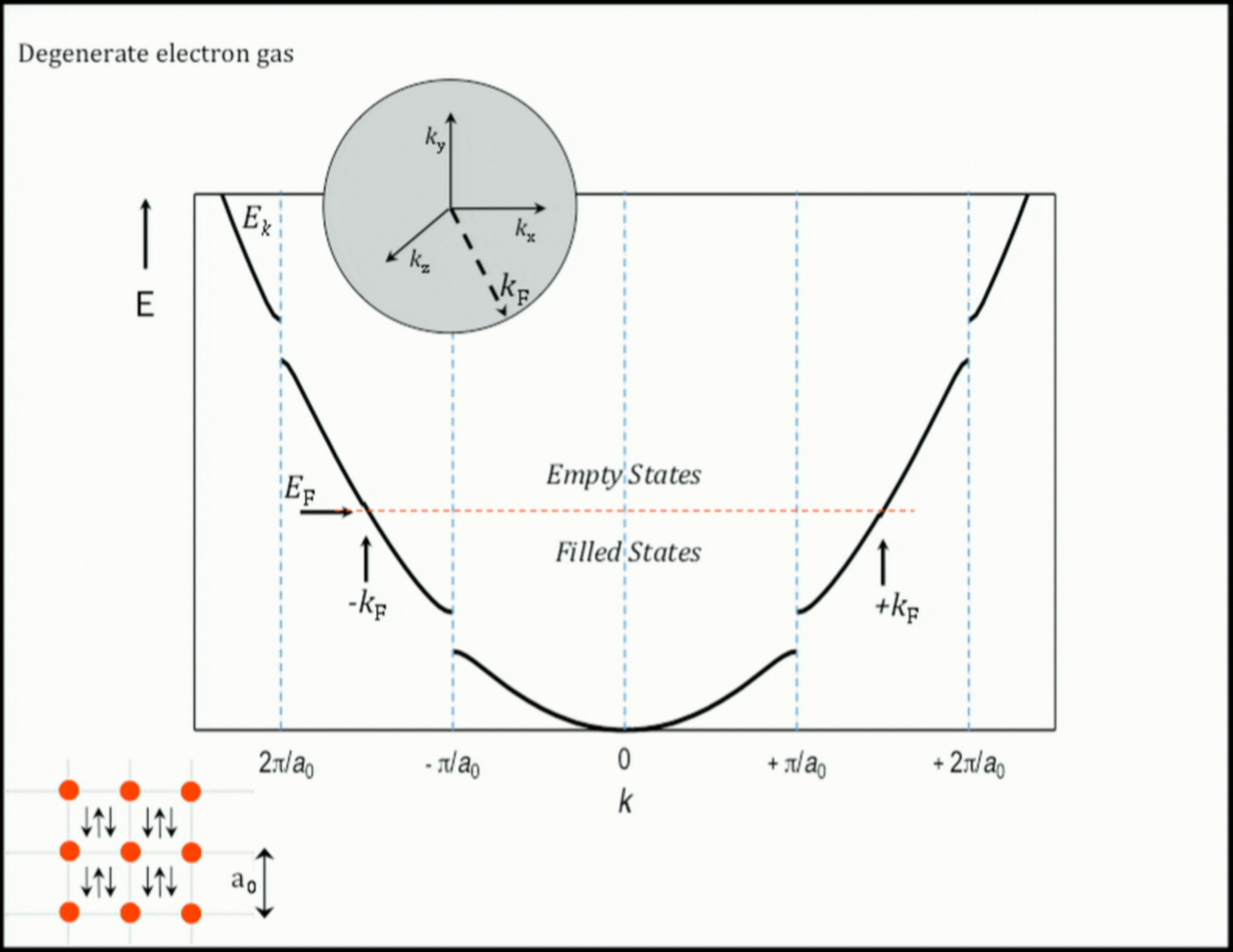
Fermi Energy E_F and Wavevector k_F

Degenerate electron gas

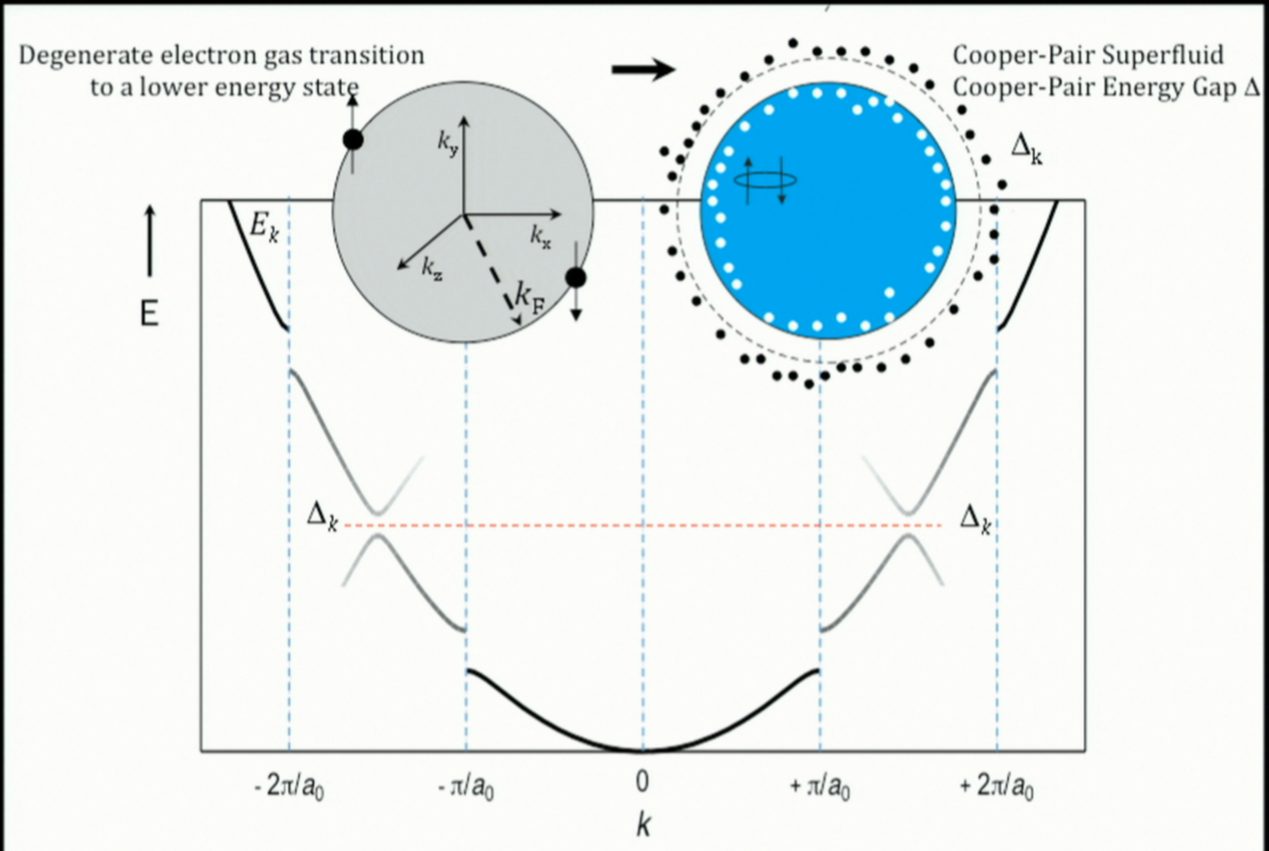
$$2\pi / \lambda \equiv k = p / \hbar$$



Fermi Energy E_F and Wavevector k_F



Bosonic Superfluid of Cooper Pairs

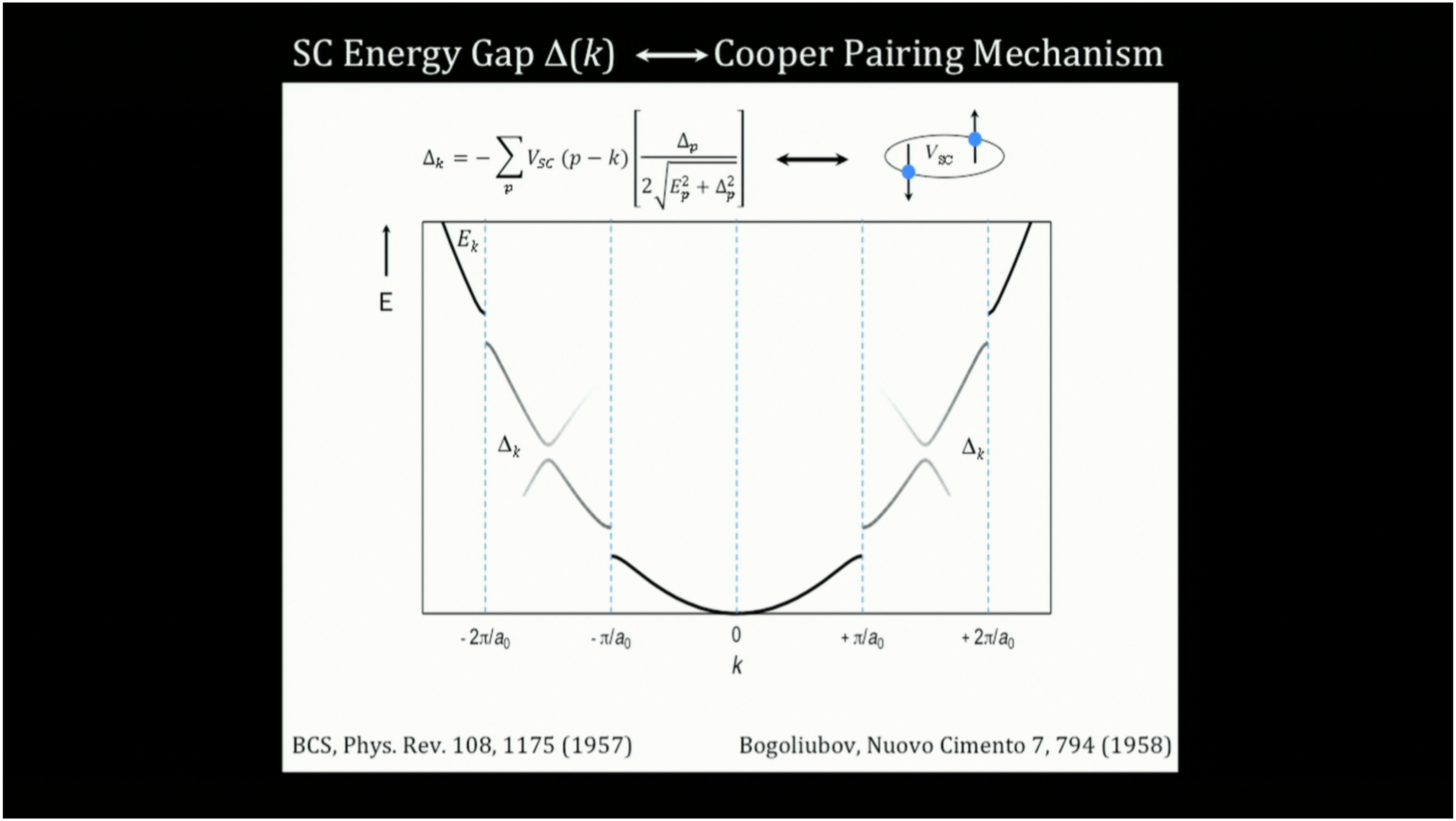


Degenerate electron gas transition
to a lower energy state

Cooper-Pair Superfluid
Cooper-Pair Energy Gap Δ

BCS, Phys. Rev. 108, 1175 (1957)

Bogoliubov, Nuovo Cimento 7, 794 (1958)



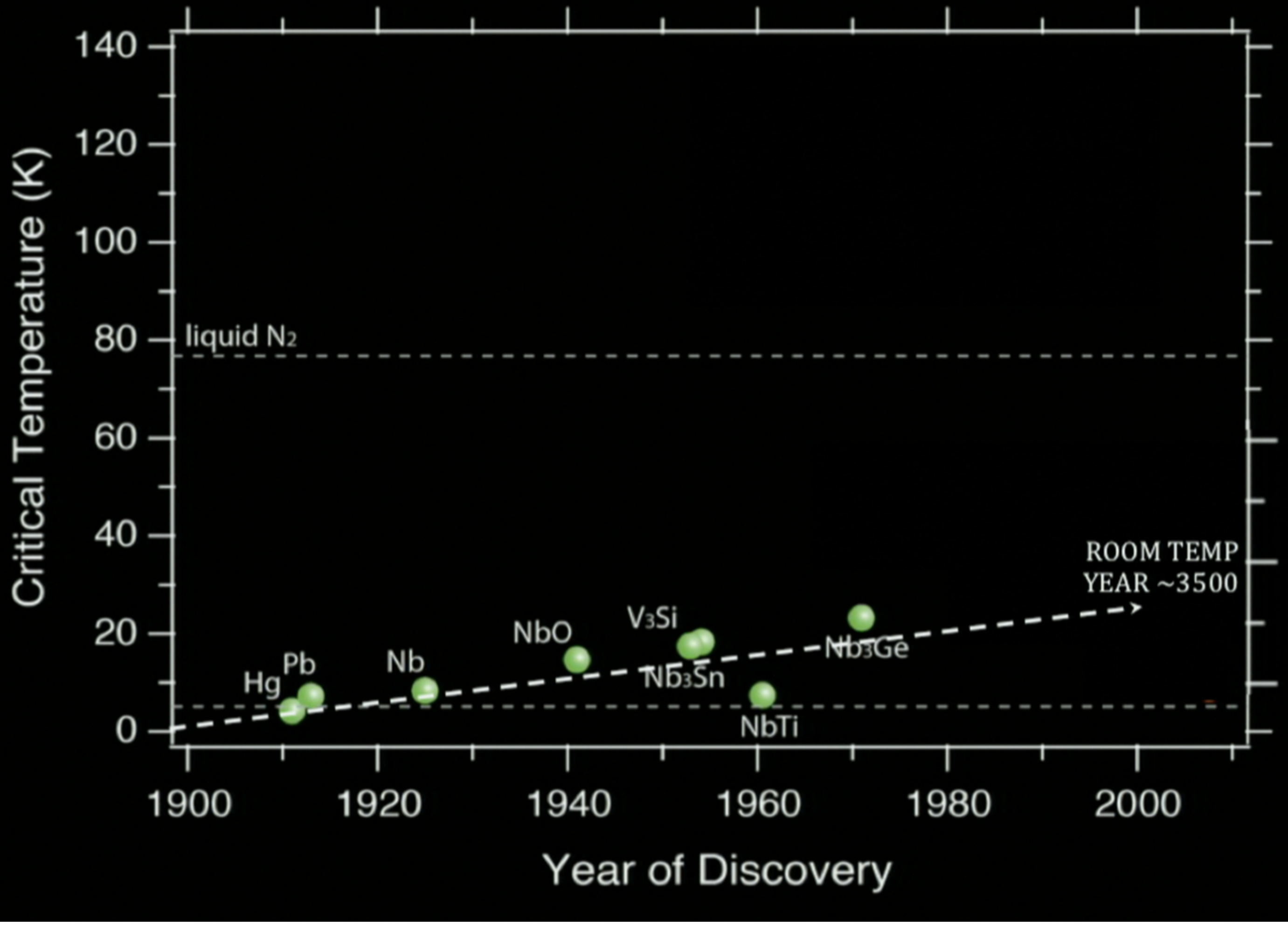
SC Energy Gap $\Delta(k)$ ⟷ Cooper Pairing Mechanism

$$\Delta_k = -\sum_p V_{SC}\,(p-k)\left[\frac{\Delta_p}{2\sqrt{E_p^2+\Delta_p^2}}\right] \longleftrightarrow$$

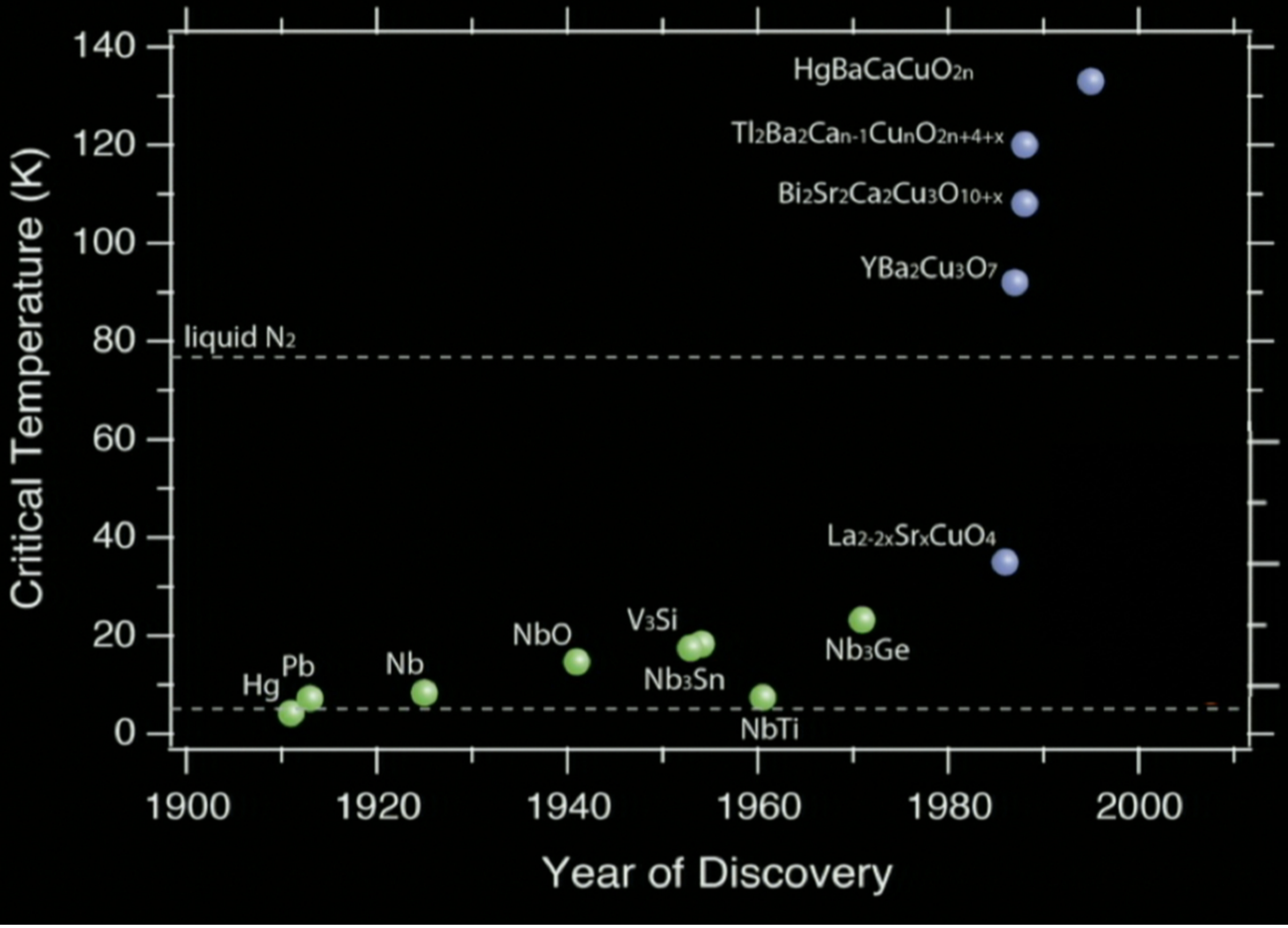
BCS, Phys. Rev. 108, 1175 (1957)

Bogoliubov, Nuovo Cimento 7, 794 (1958)

Conventional Superconductivity



Copper-based High-T_c SC



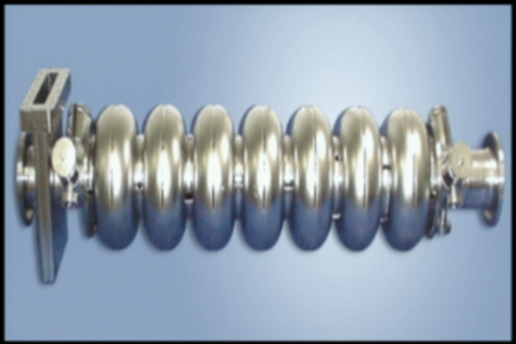
Power Efficiency/Capacity/Stability

Power Bottlenecks

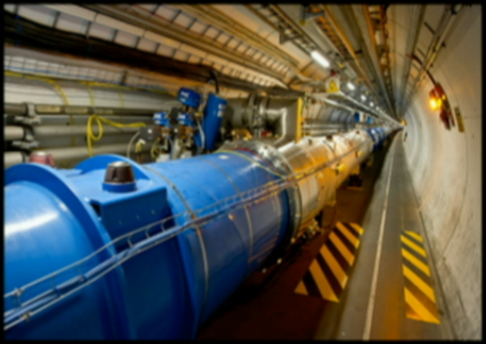
Accommodate Renewable Power

Efficient Rotating Machines

Information Technology



Next Generation HEP



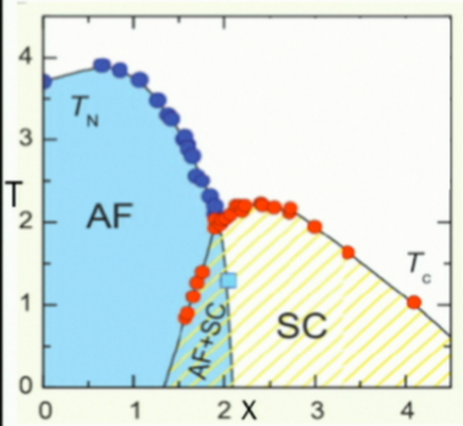
Ultra-High Magnetic Fields

Medical

Transport

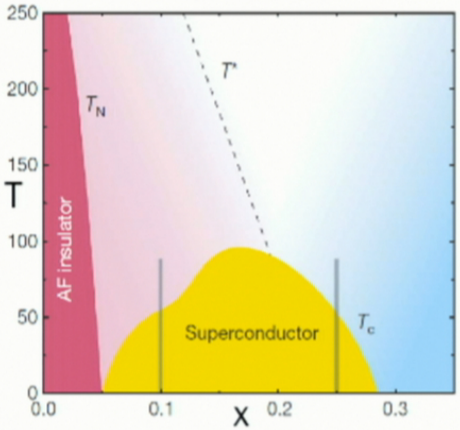
Physics of Unconventional HTS Superconductors

Heavy Fermion
(d-wave)



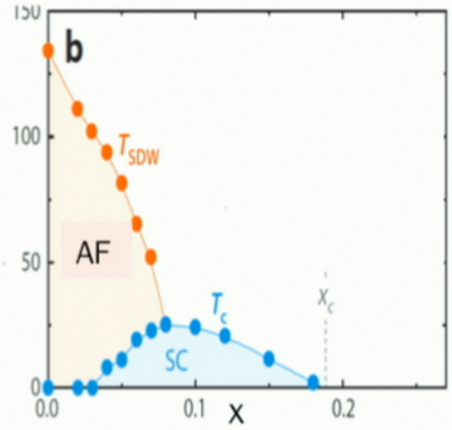
Steglich
PRL **43**, 1892 (1979)

Copper-oxide
(d-wave)



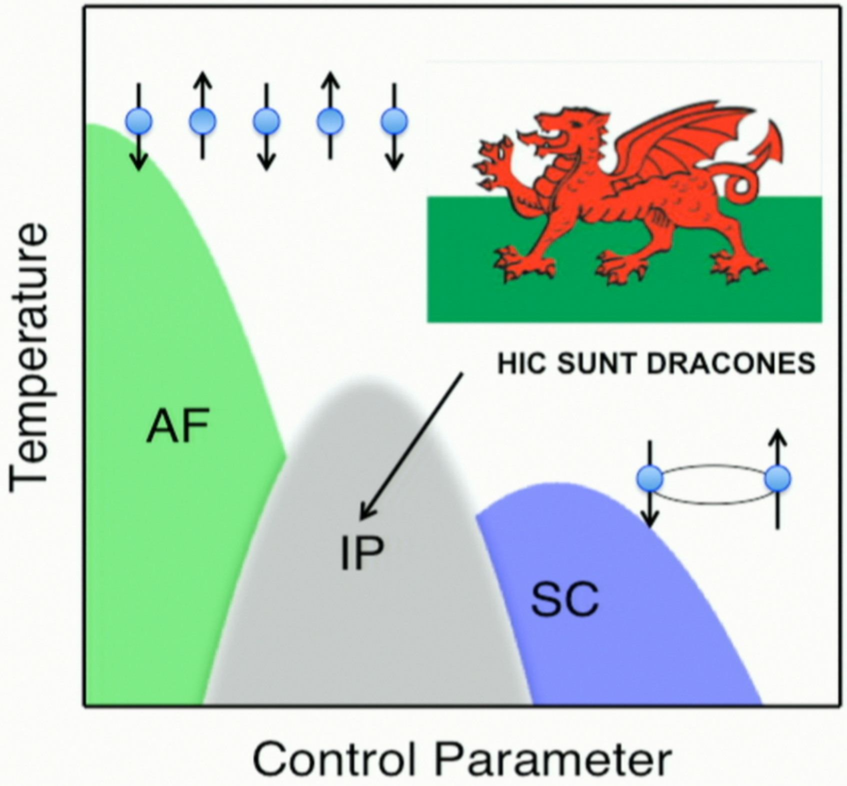
Muller
Z. Physic. **B 64** 189 (1986)

Iron-pnictide
(s±-wave?)



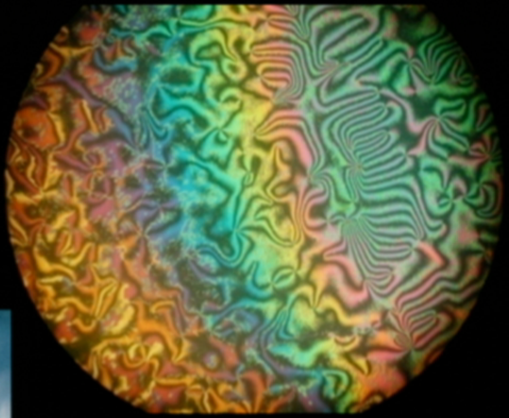
Hosono
JACS. **130**, 3296 (2008)

Novel 'Intertwined' Phases of Electronic Matter ?



Gas → Fluid → Liquid Crystal

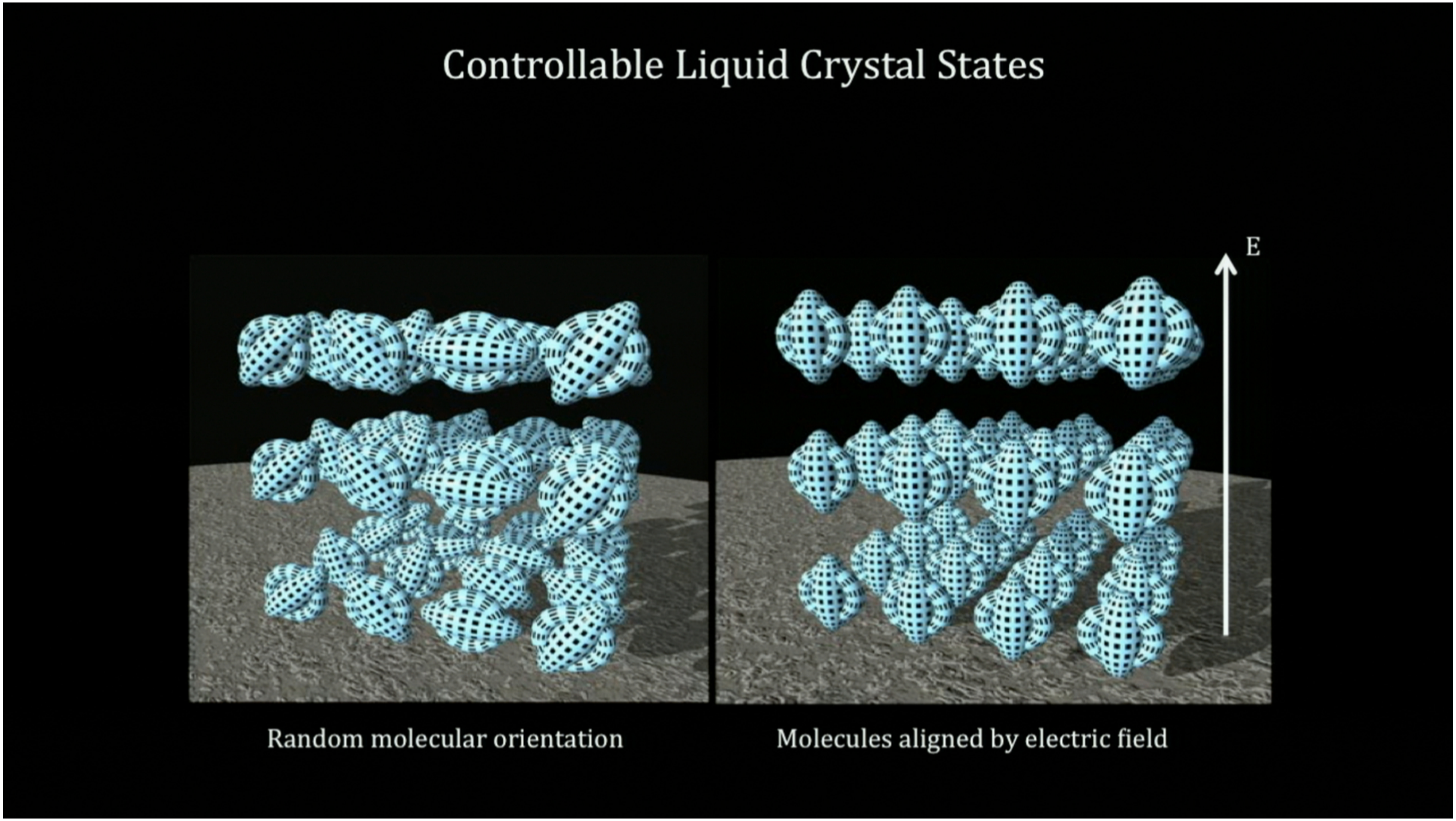
Increasing
interactions
& complexity



Liquid Crystal

Liquid

Vapour



Controllable Liquid Crystal States

Random molecular orientation

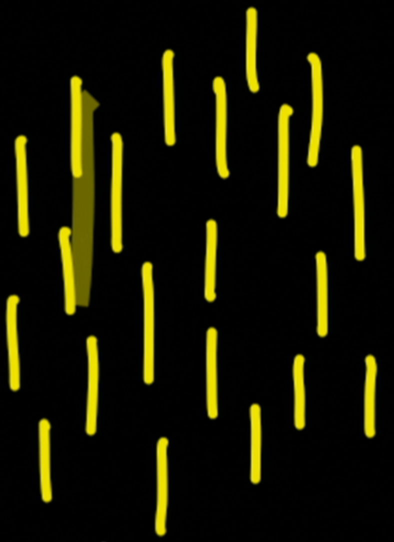
Molecules aligned by electric field

Controllable Liquid Crystal States

$10^{1}\$$ Industry

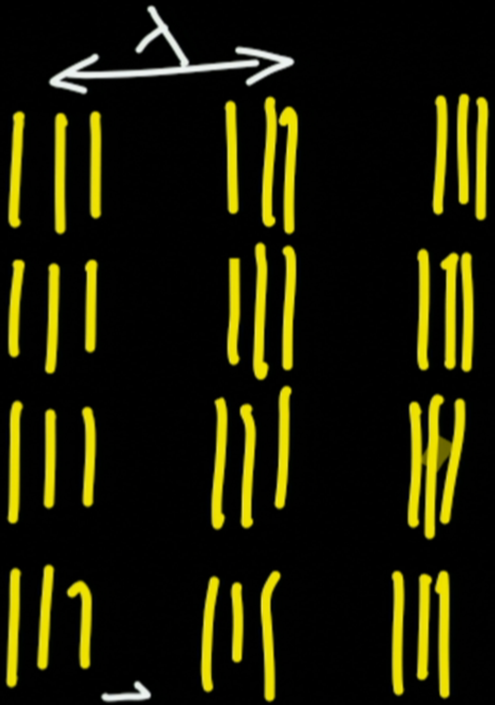
- Monitors
- LCD Displays
- LCD TVs
- ‘Smart’ Windows
- Much more…..

Two Key Types of Liquid Crystal States



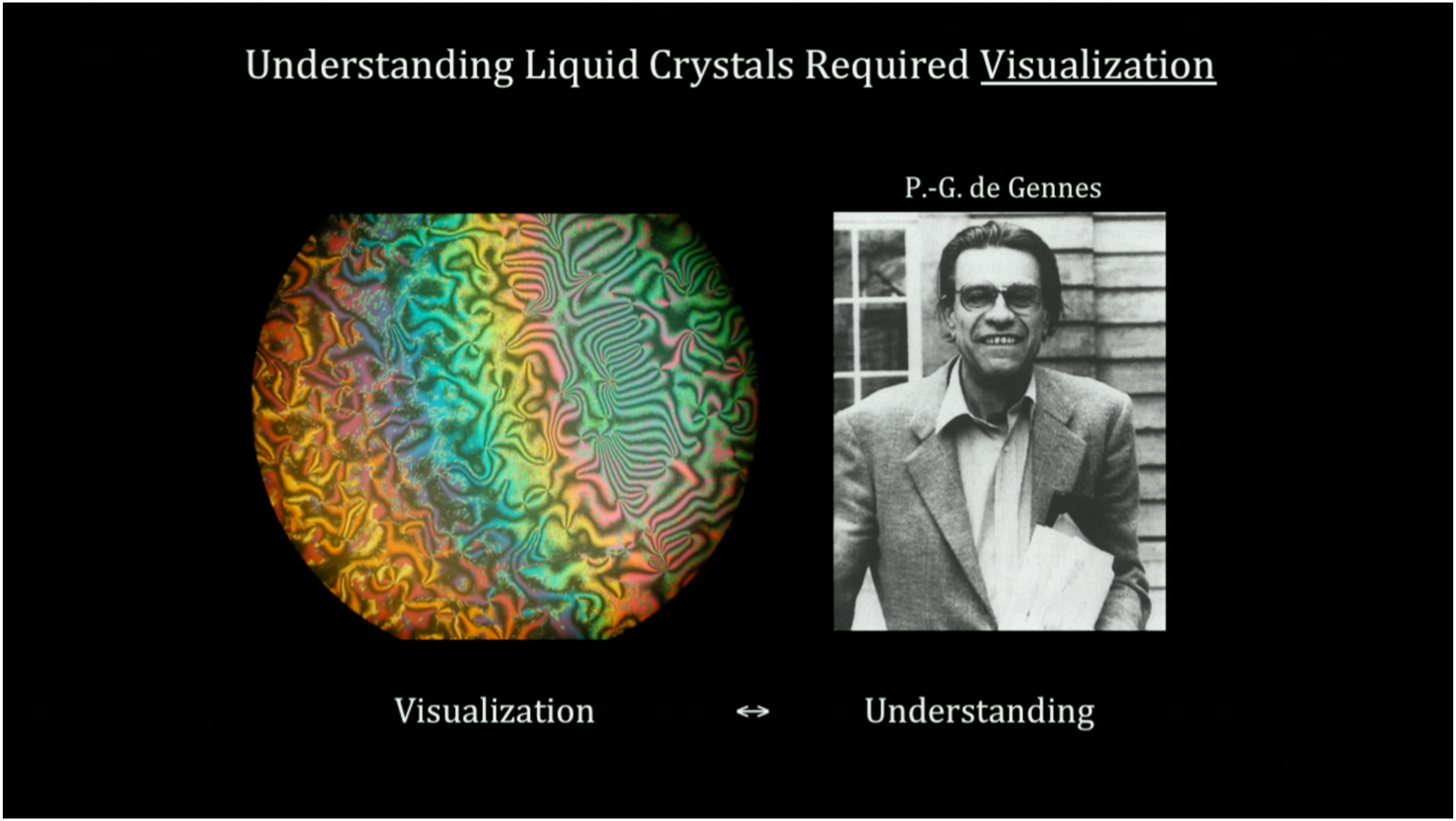
$\vec{Q} = 0$

Nematic LC
breaks rotational
symmetry only



$\vec{S} = 2\pi/\lambda$

Smectic LC
breaks rotational &
translational symmetry



Understanding Liquid Crystals Required Visualization

P.-G. de Gennes

Visualization ↔ Understanding

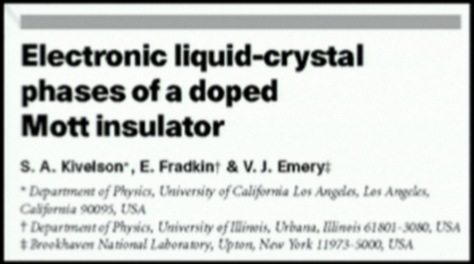
Electron Gas → Electronic Fluid → Electronic Liquid Crystal

Increasing
interactions
& complexity

?

Electronic Liquid Crystal

Heavy Electron Fluid



Electronic liquid-crystal phases of a doped Mott insulator

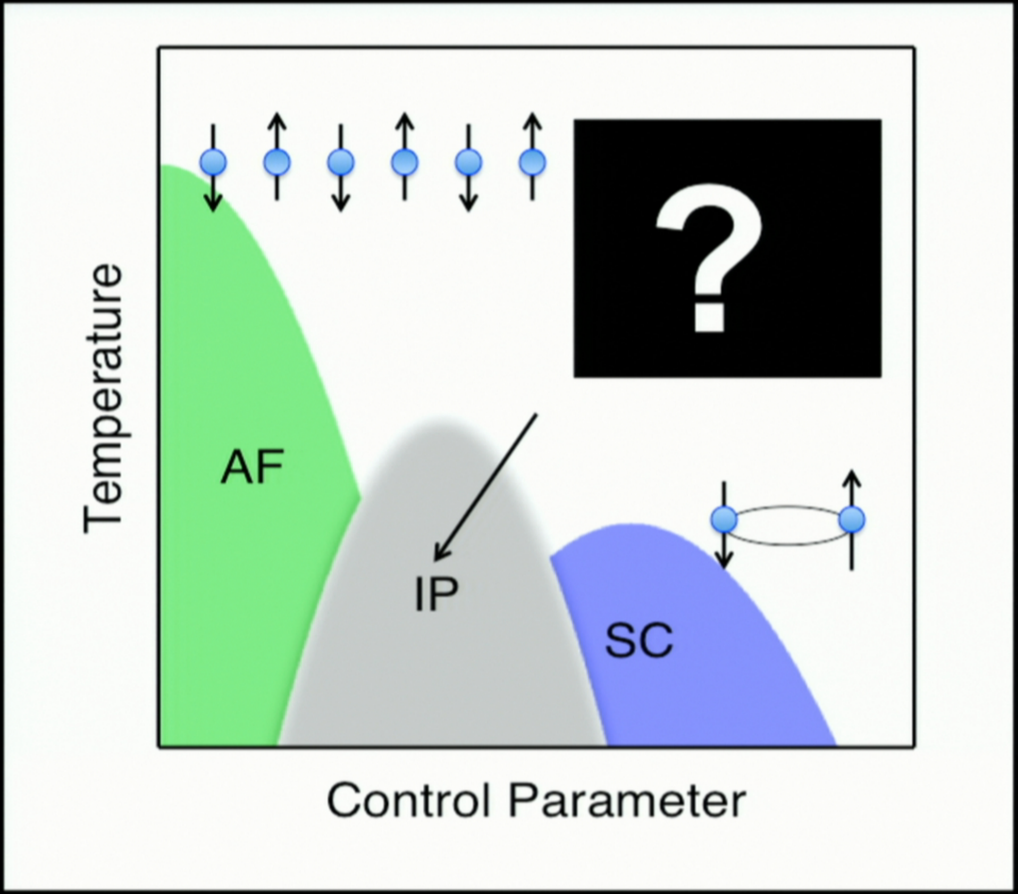
S. A. Kivelson[*], E. Fradkin[†] & V. J. Emery[‡]

[*] Department of Physics, University of California Los Angeles, Los Angeles, California 90095, USA
[†] Department of Physics, University of Illinois, Urbana, Illinois 61801-3080, USA
[‡] Brookhaven National Laboratory, Upton, New York 11973-5000, USA

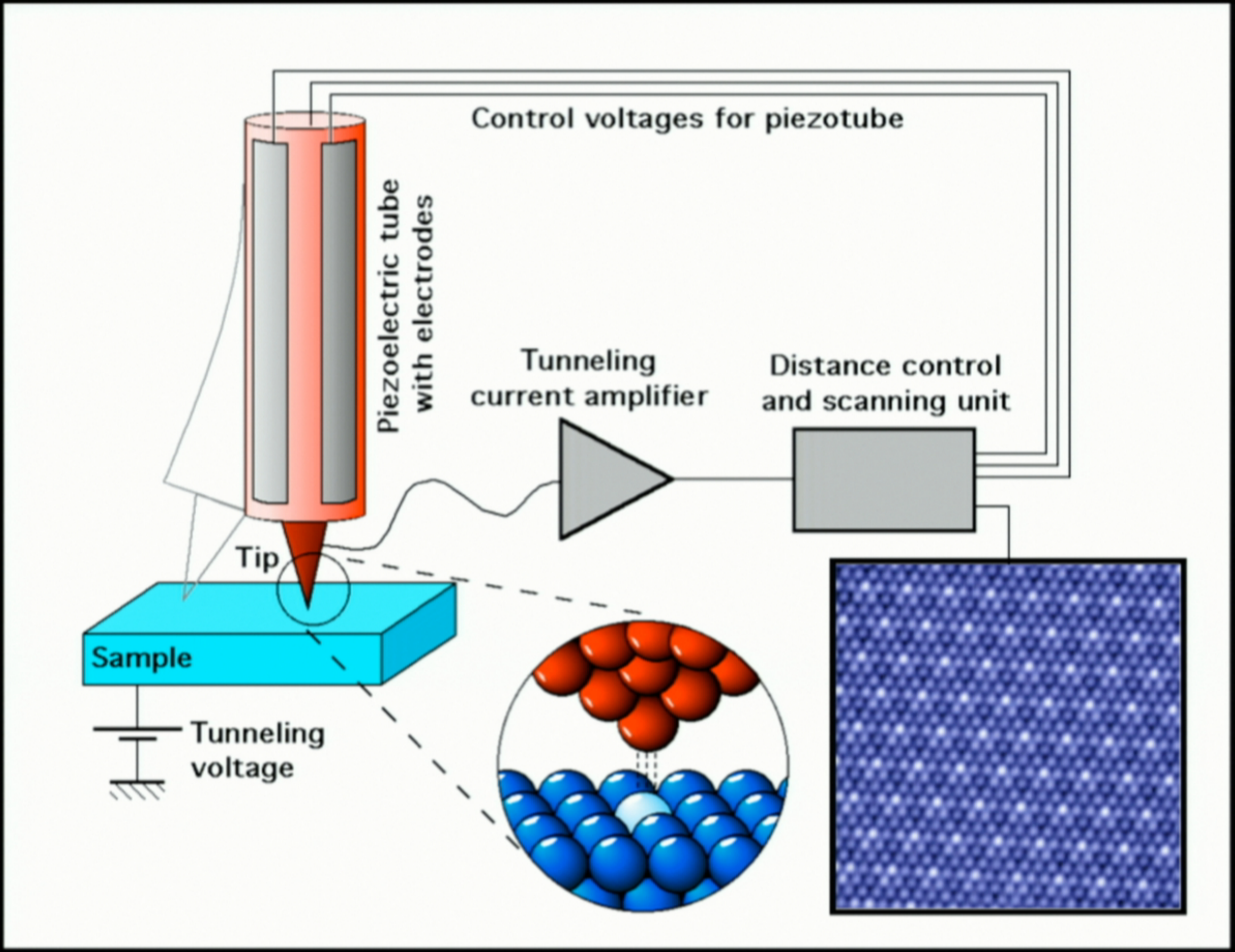
Nature 393, 550 (1998).

Electron Gas

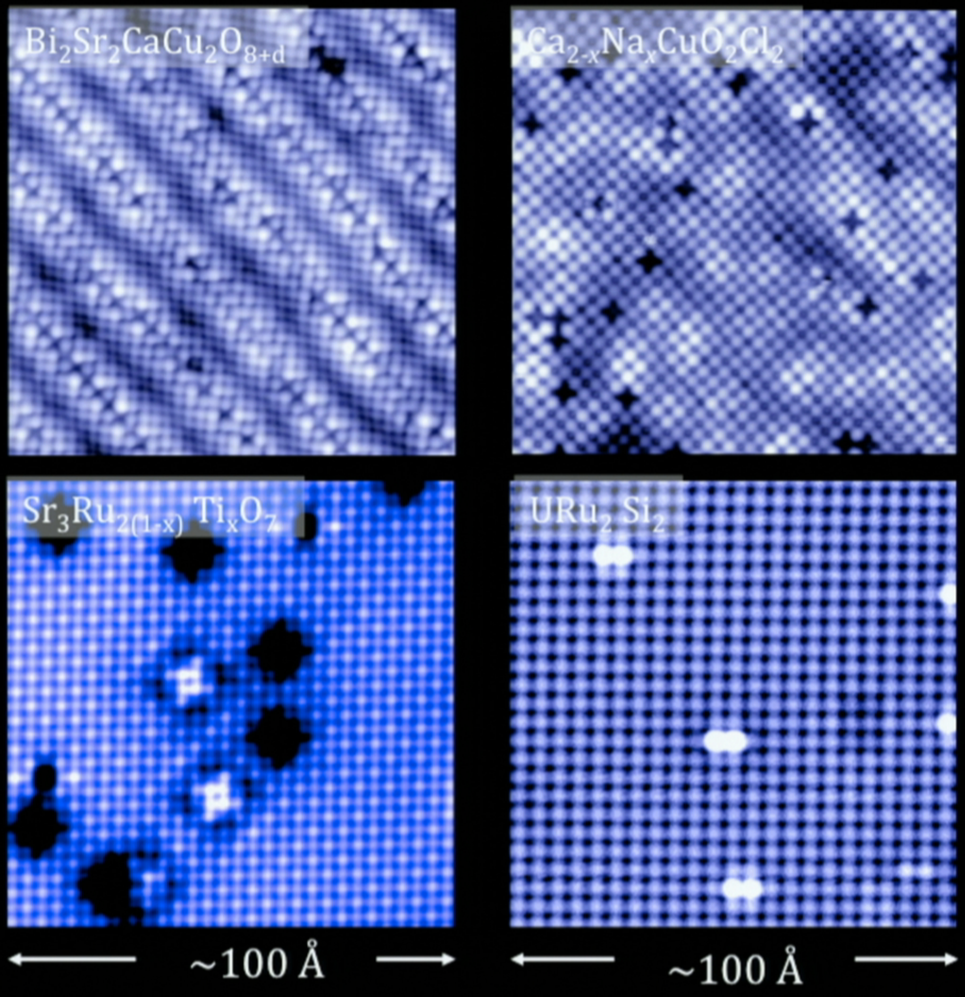
Electronic Liquid Crystals?



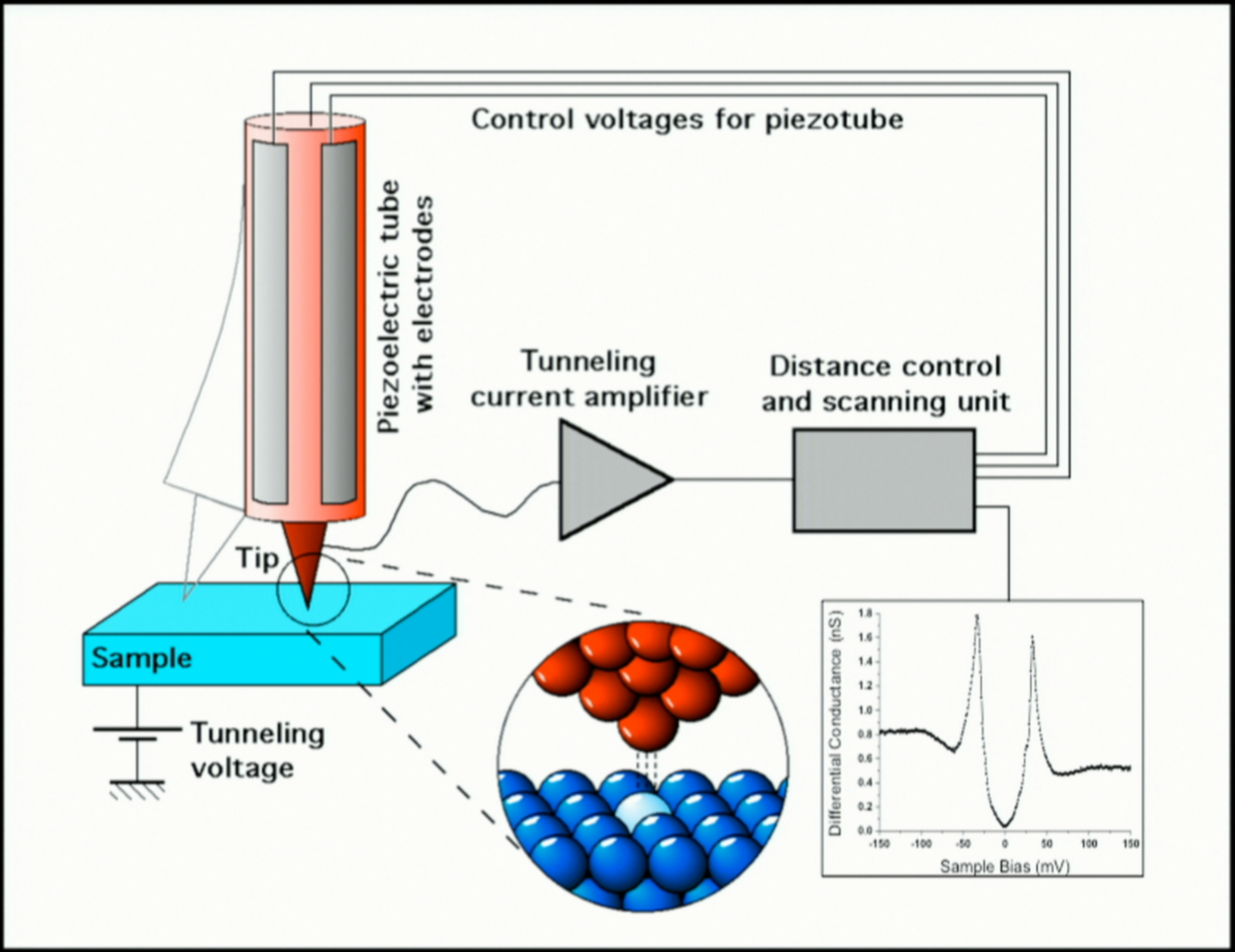
Scanning Electron-Tunneling Microscopy (STM)



Images Atomic Locations Only

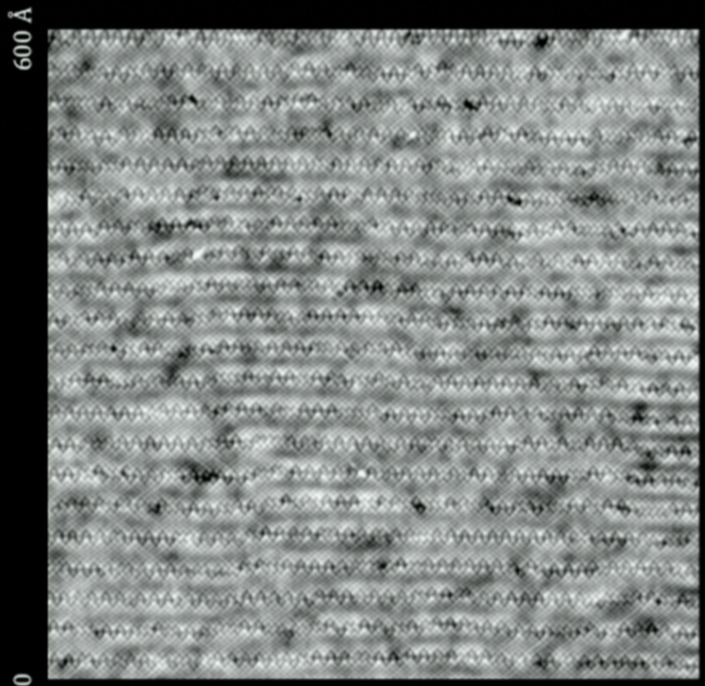


Spectroscopic Imaging STM



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

Spectroscopic Imaging STM

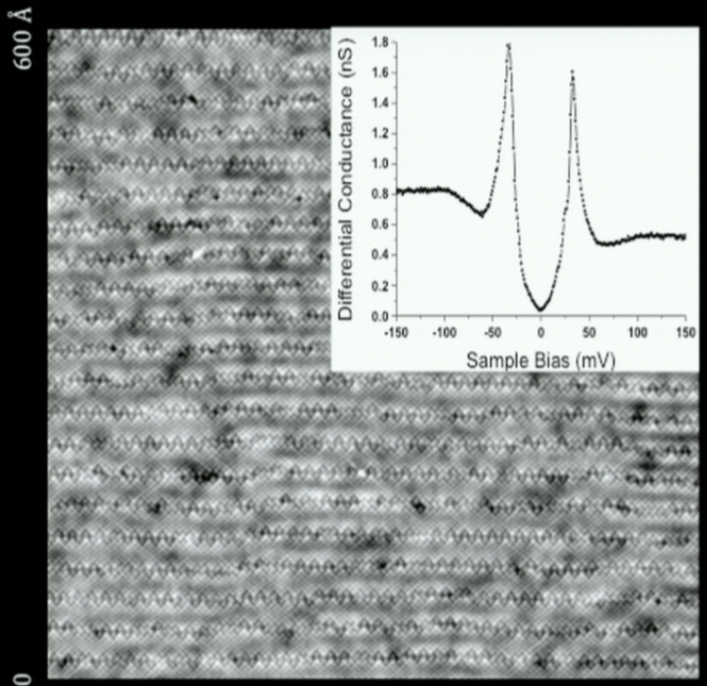


Topography

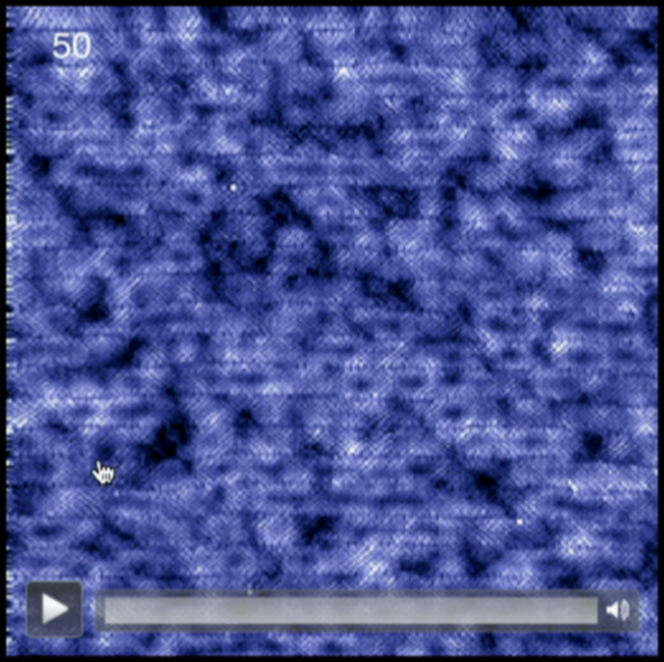
Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom →



Topography

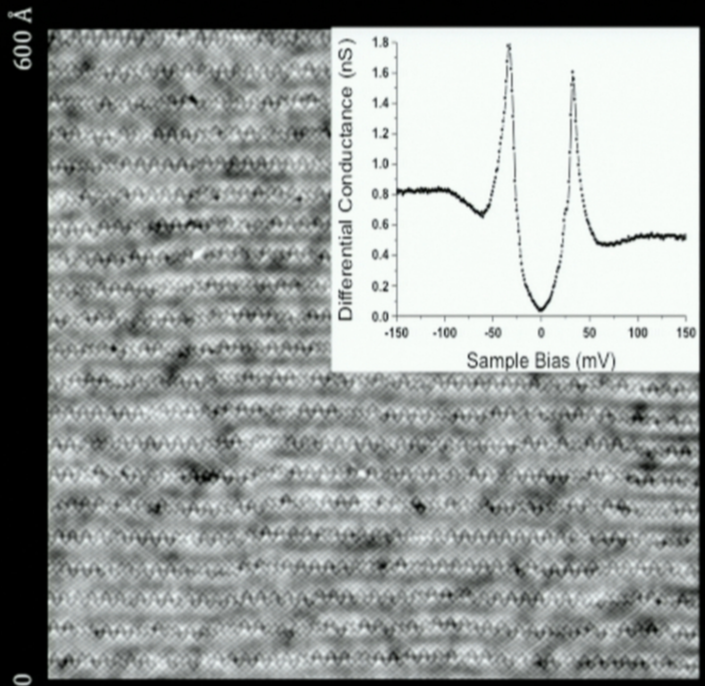


SI-STM

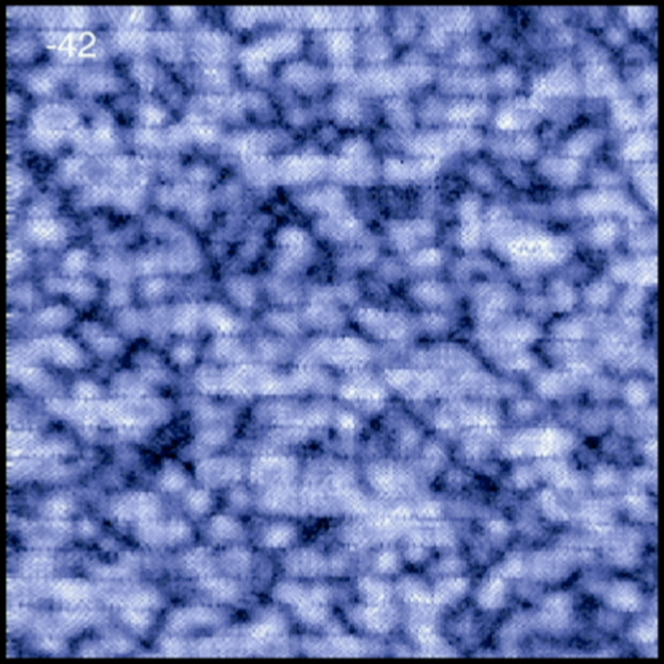
Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom →



Topography

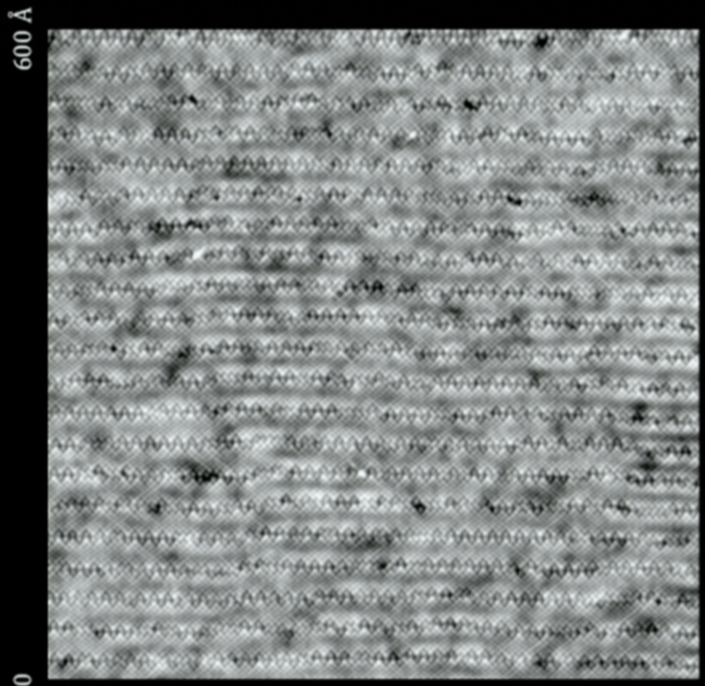


SI-STM

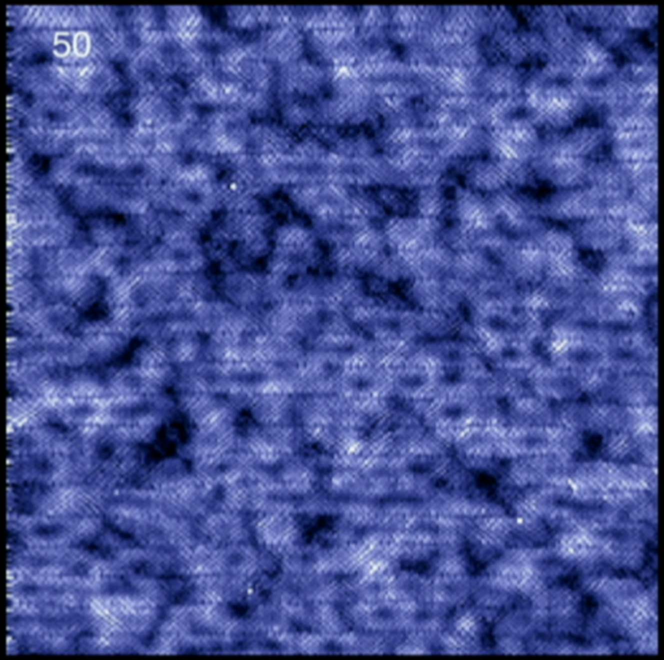
Rev. Sci. Inst. **70**, 1459 (1999).

Spectroscopic Imaging STM

dI/dV spectrum at every atom → Atomic-resolution energy-resolved $N(r,E) \sim |\Psi(r,E)|^2$



Topography

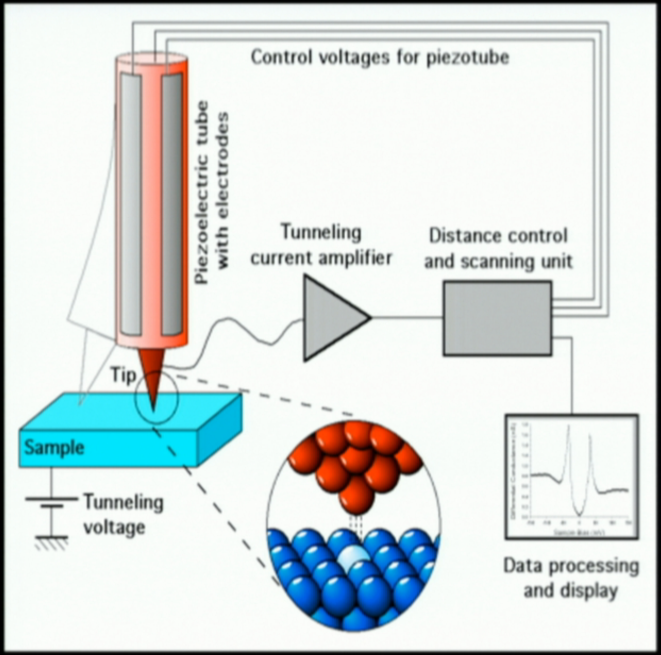


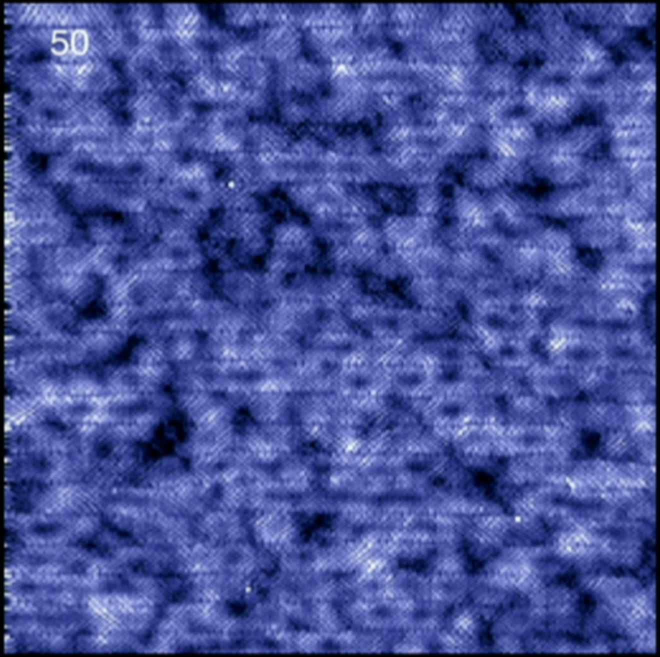
SI-STM

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

Technically Challenging!

dI/dV spectrum at every atom → Atomic-resolution energy-resolved $N(r,E) \sim |\Psi(r,E)|^2$



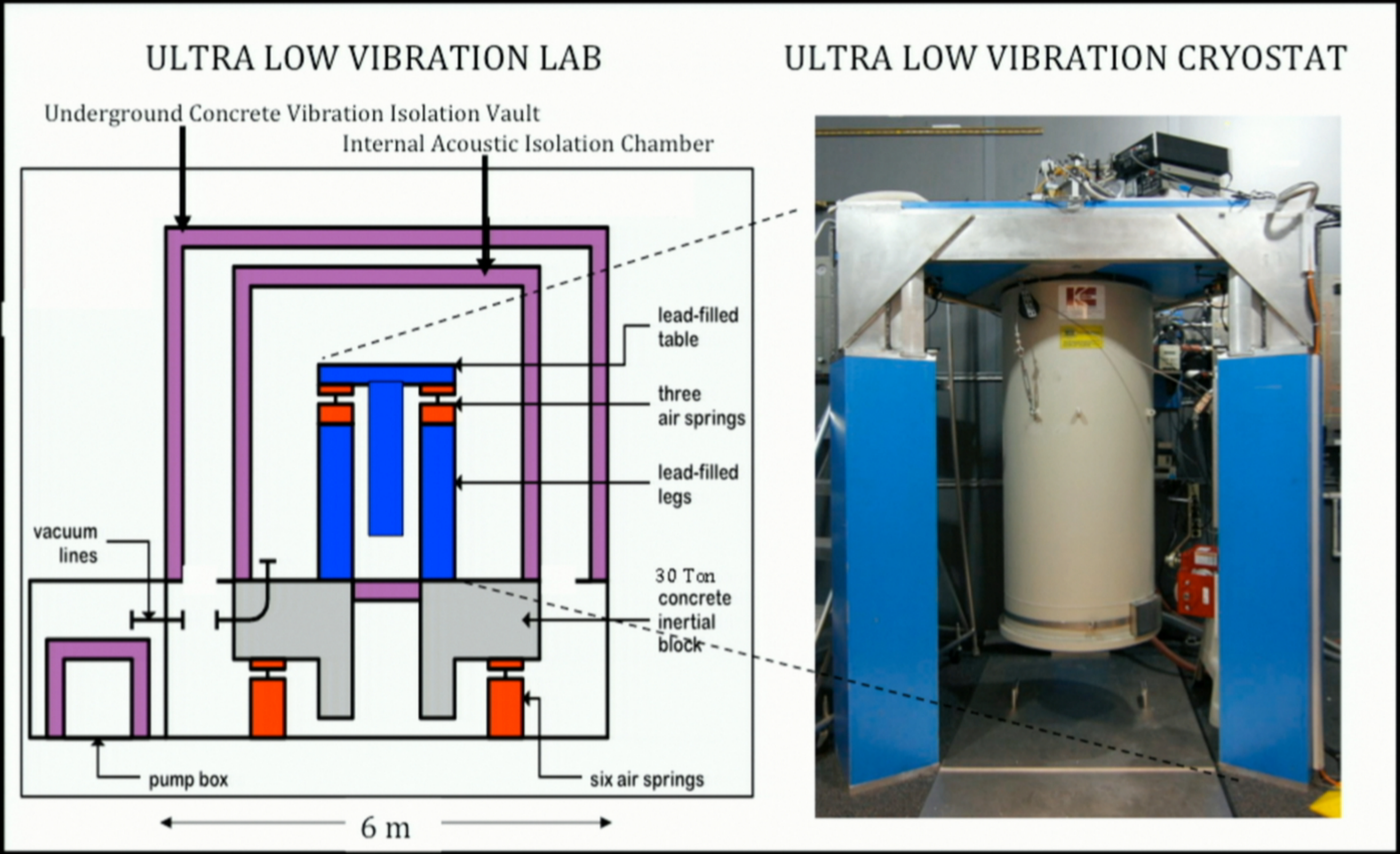


SI-STM

$512 \times 512 \times 200 = 5 \times 10^6$ measurements

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

Ultra Low Vibration Cryostat & Laboratory



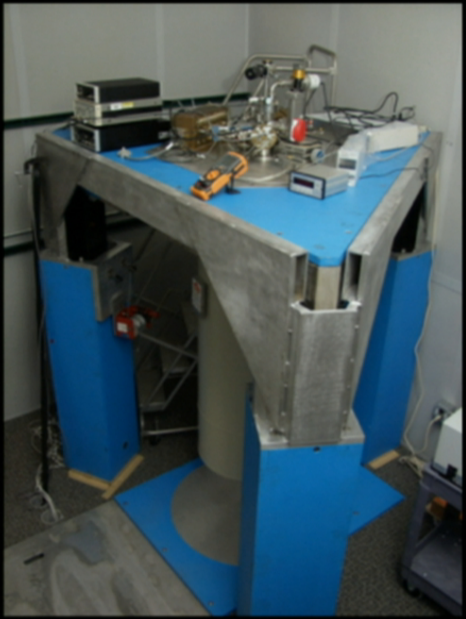
Rev. Sci. Inst. **70**, 1459 (1999).

Ultra Low Vibration Cryostat & Laboratory

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

Davis Group Spectroscopic Imaging STM Systems

STM1 (9T/250mK)
Iron-based HTS



STM3 (1K->100K)
Copper-based HTS

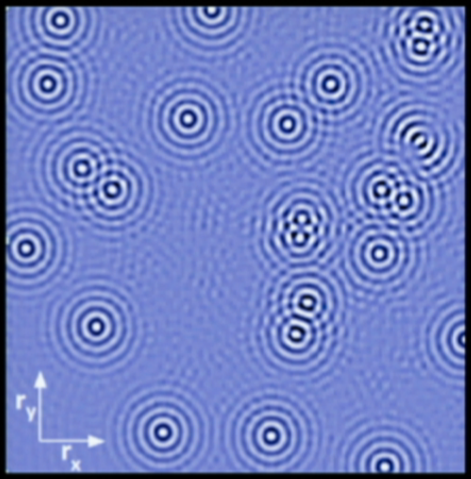
STM2 (9T/10mK)
Heavy Fermion SC

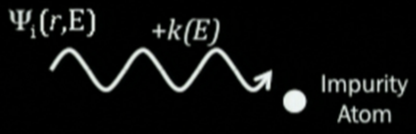
Visiting scientists from UK, Korea, Japan, Taiwan, Canada, Israel, France, Italy, Holland, Portugal, Germany, India, and several US Nat. Labs use our systems.

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

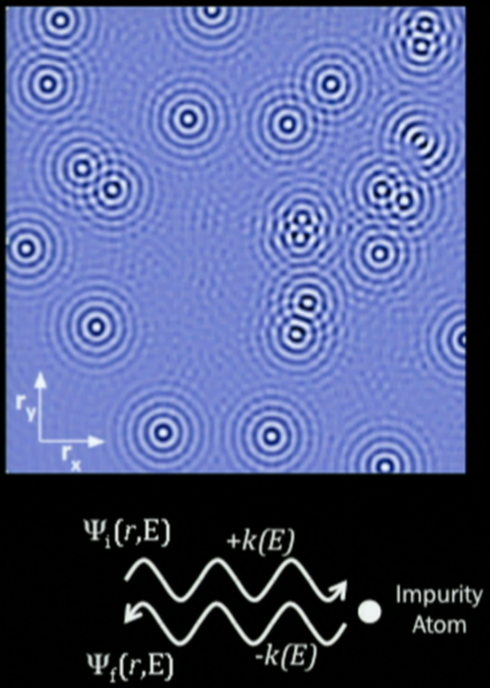
Quasiparticle Scattering Interference (QPI) Imaging

Quasiparticle Scattering Interference (QPI) Imaging



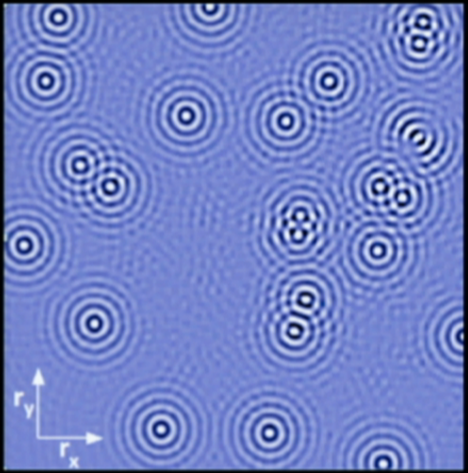


Quasiparticle Scattering Interference (QPI) Imaging



Quasiparticle Scattering Interference (QPI) Imaging

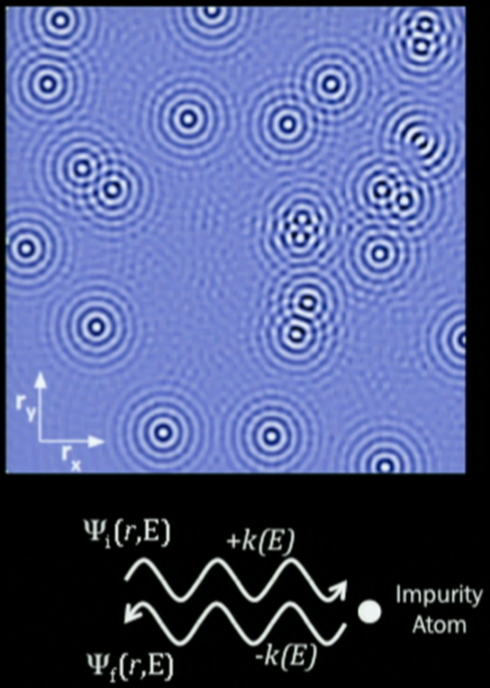
Interference Pattern



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

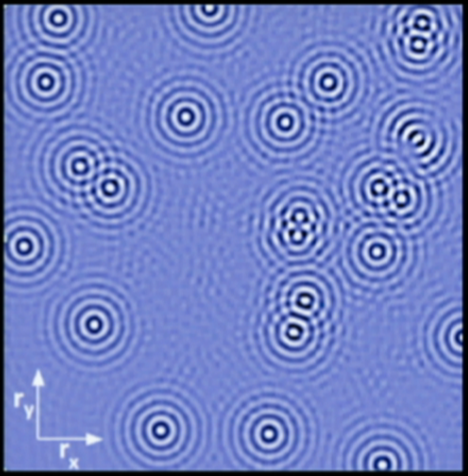
$q(\mathrm{E}) = 2k(E)$

Quasiparticle Scattering Interference (QPI) Imaging



Quasiparticle Scattering Interference (QPI) Imaging

Interference Pattern

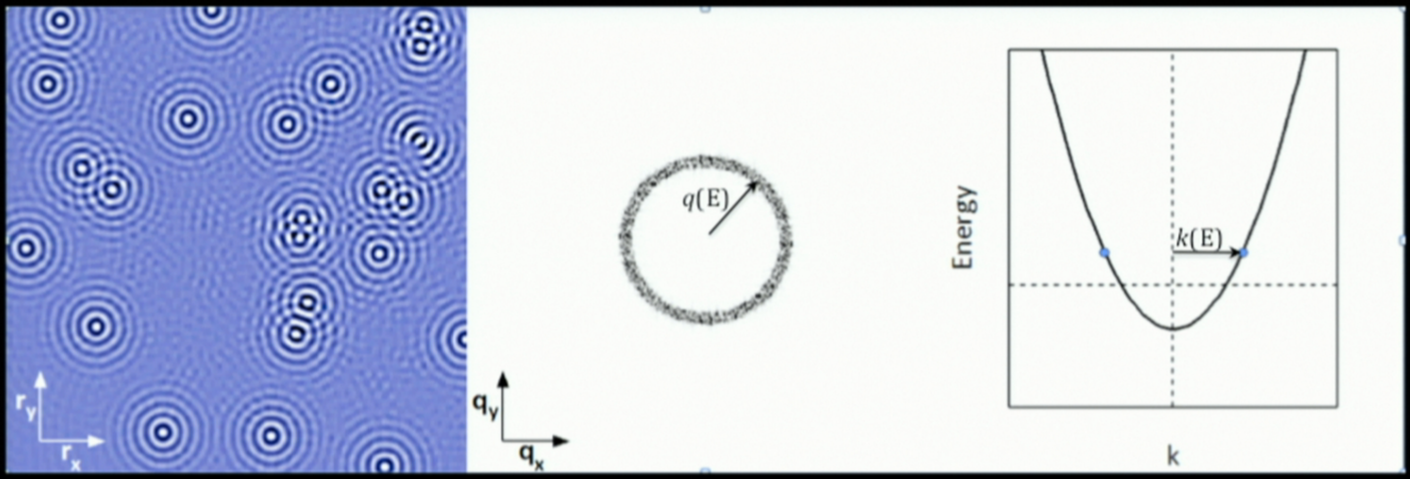


$|\Psi(r,E)|^2$

$q(E) = 2k(E)$

Quasiparticle Scattering Interference (QPI) Imaging

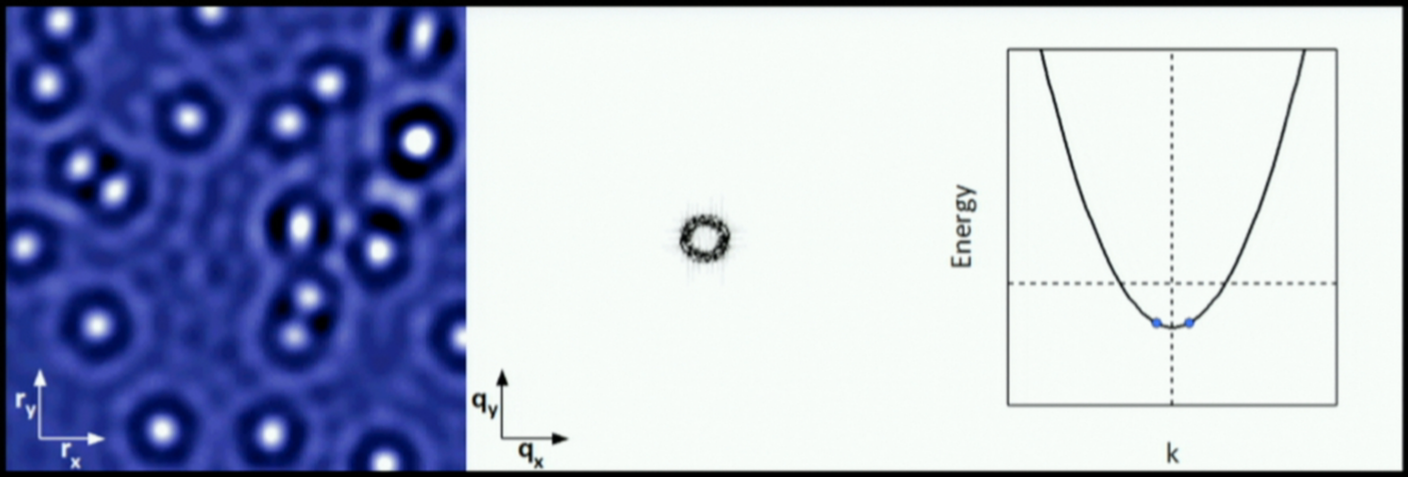
Interference Pattern $q(E)=2k(E)$ => Maxima $N(q,E)$ $q(E)=2k(E)$ => $k(E)=\pm q(E)/2$



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

Quasiparticle Scattering Interference (QPI) Imaging

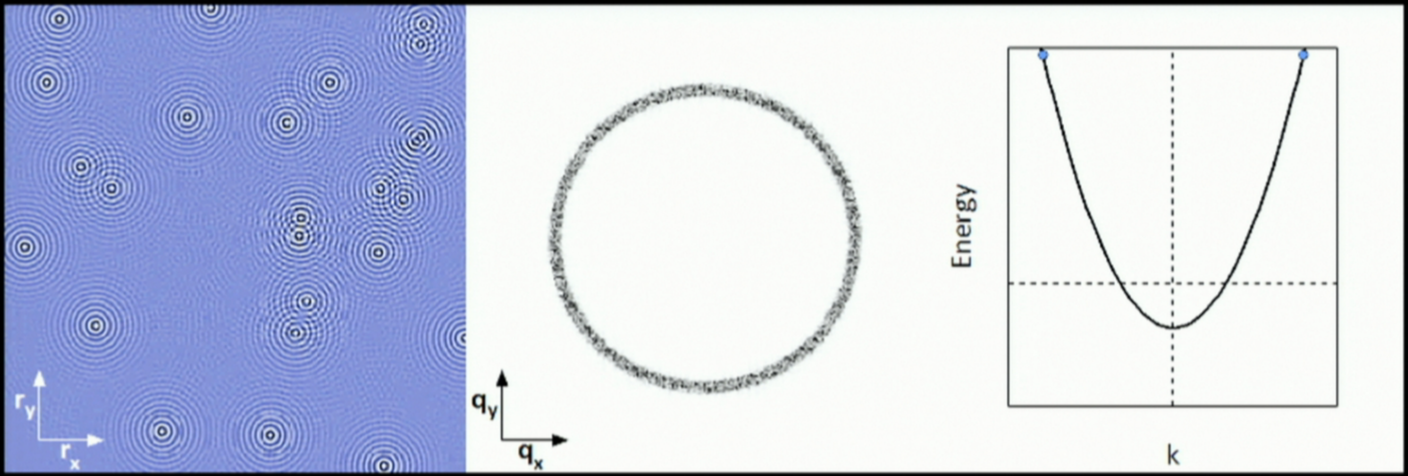
Interference Pattern $q(E)=2k(E)$ => Maxima $N(q,E)$ $q(E)=2k(E)$ => $k(E)=\pm q(E)/2$



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

Quasiparticle Scattering Interference (QPI) Imaging

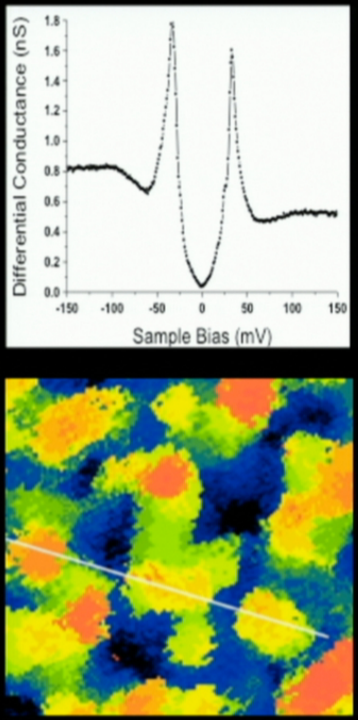
Interference Pattern $q(\mathrm{E})=2k(\mathrm{E})$ => Maxima $\mathrm{N}(q,\mathrm{E})$ $q(\mathrm{E})=2k(\mathrm{E})$ => $k(\mathrm{E})=\pm q(\mathrm{E})/2$



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

Direct Visualization of Electronic Quantum Matter

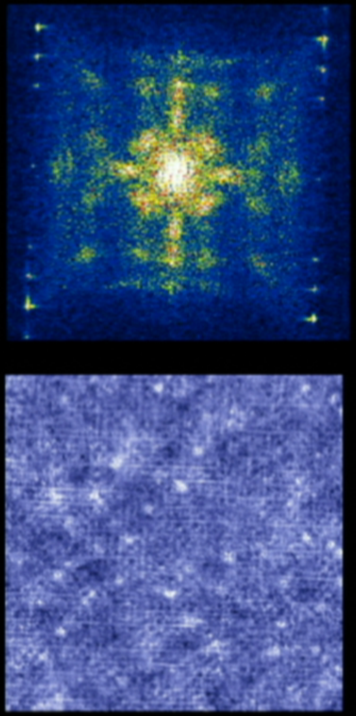
Nanoscale e-disorder



15 nm
Gapmap, B=0

Nature 414 282 (2001)
Nature 415 412 (2002)

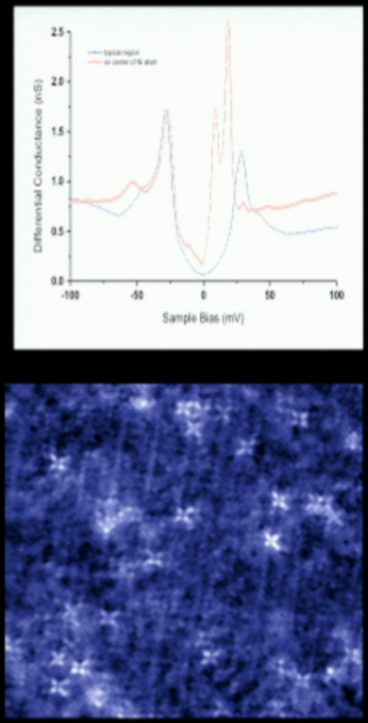
Q. Interference



56 nm
0-12mV LDOS,B=5T

Science 297, 1148 (2002)
Nature 422, 520 (2003)

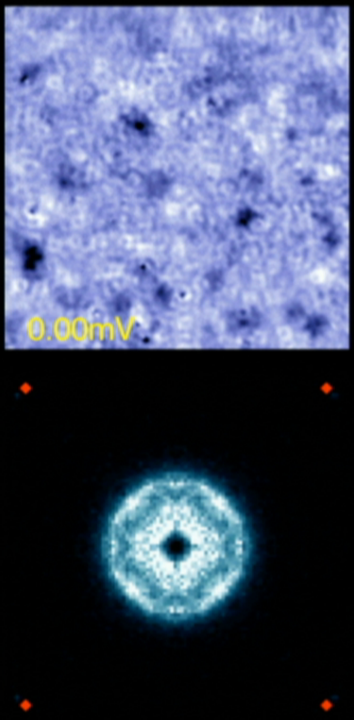
Impurity Atoms



64 nm
12 mV LDOS, B=0

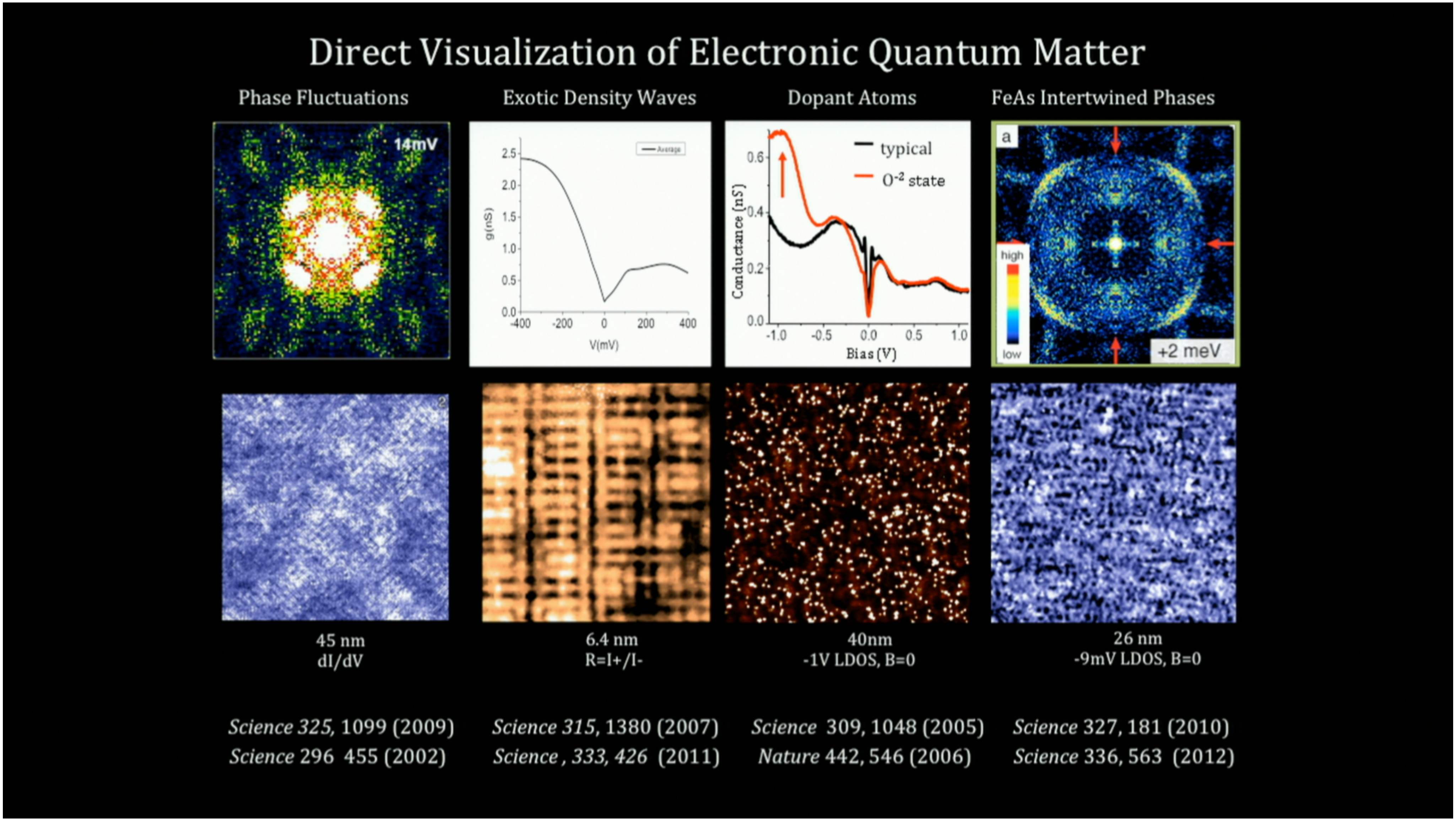
Nature 411, 920 (2001)
Nature 403, 746 (2000)

Heavy Fermion SC



26 nm
250 mV

Nature 465, 570 (2010)
Nat. Phys. 9, 458 (2013)



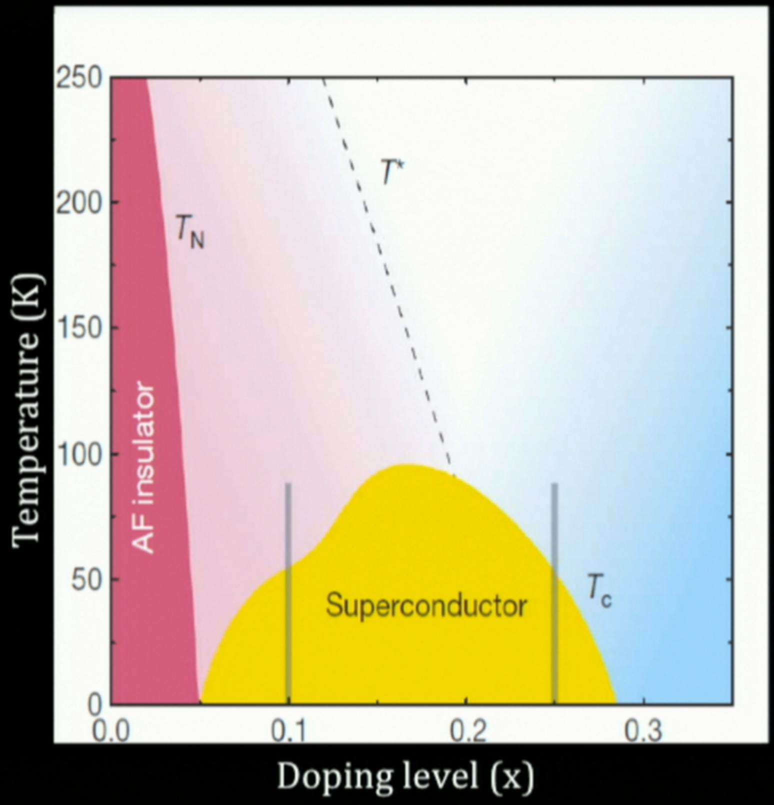
Direct Visualization of Electronic Quantum Matter

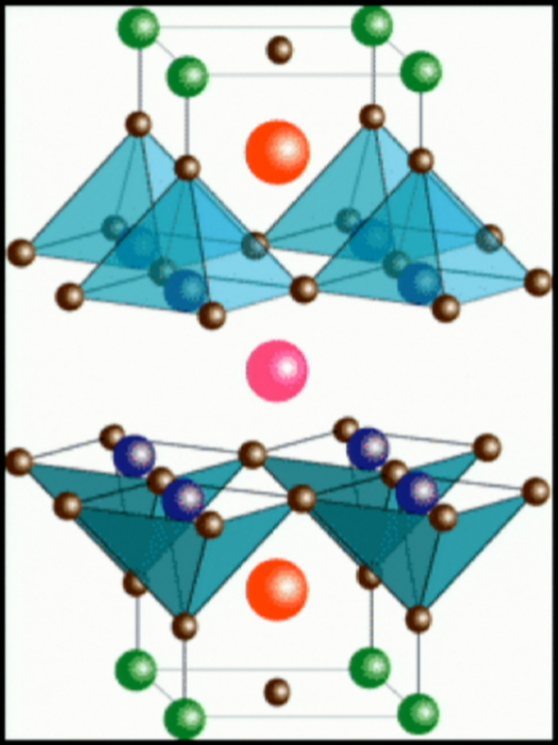
Phase Fluctuations	Exotic Density Waves	Dopant Atoms	FeAs Intertwined Phases
45 nm dI/dV	6.4 nm R=I+/I-	40nm -1V LDOS, B=0	26 nm -9mV LDOS, B=0
Science 325, 1099 (2009) *Science* 296 455 (2002)	*Science 315*, 1380 (2007) *Science , 333, 426* (2011)	*Science* 309, 1048 (2005) *Nature* 442, 546 (2006)	*Science* 327, 181 (2010) *Science* 336, 563 (2012)

Ultra Low Vibration Cryostat & Laboratory

Institute for Quantum Computing , U. of Waterloo (2015)

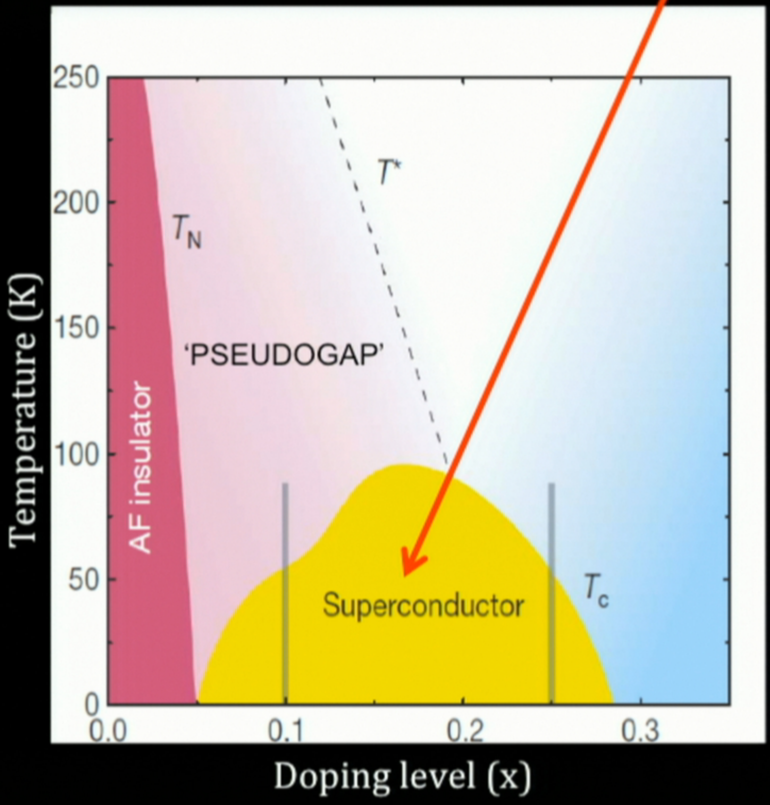
Typical CuO_2 Phase Diagram

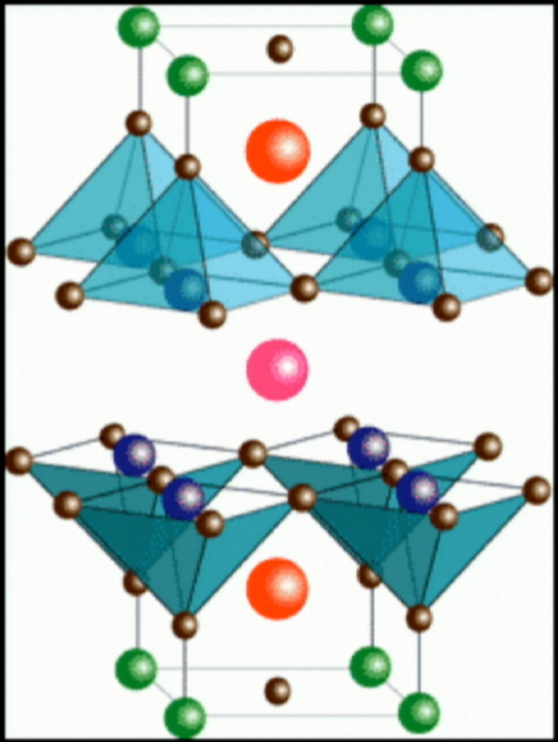




$YBa_2Cu_3O_7$

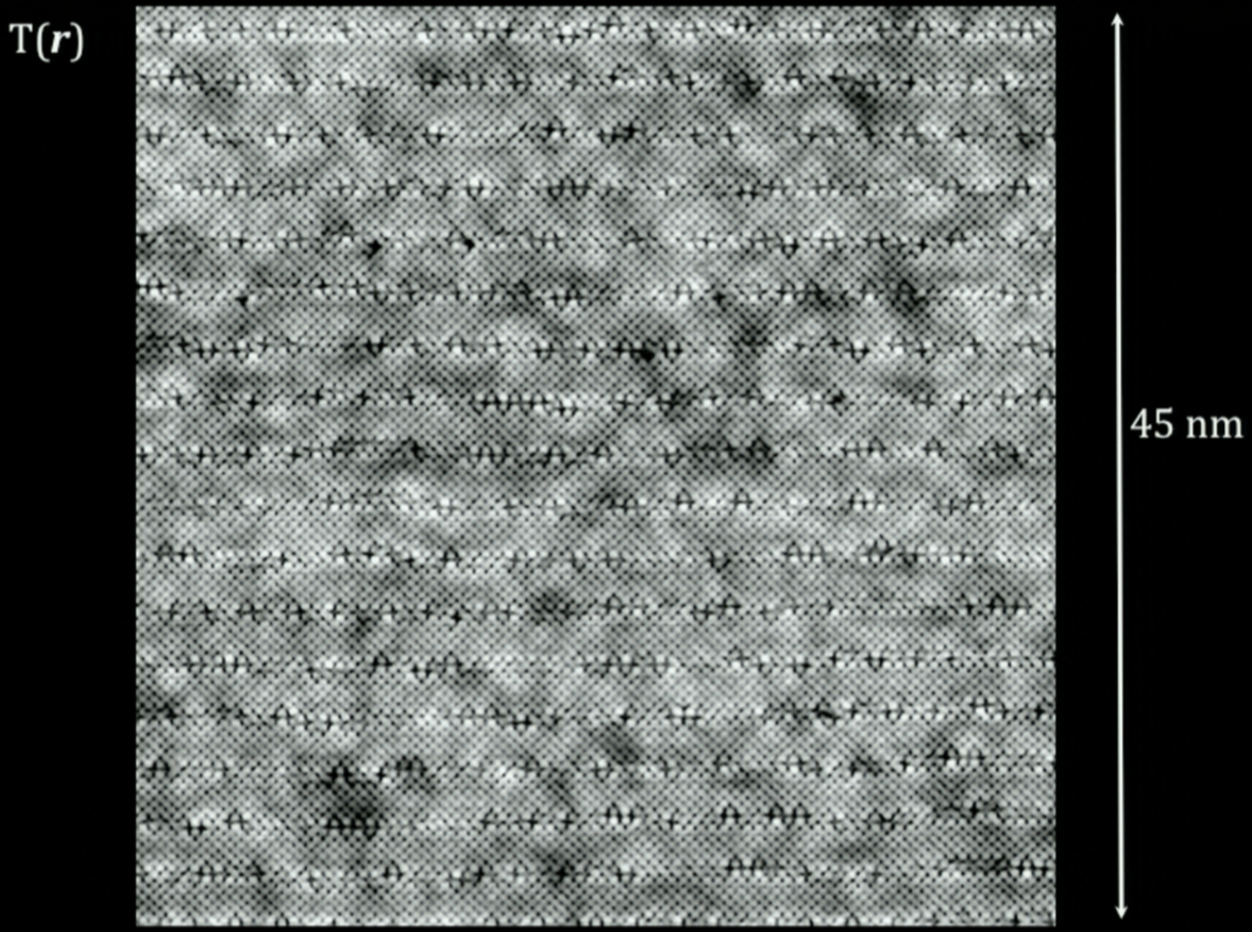
Mechanism of High-Tc Superconductivity?





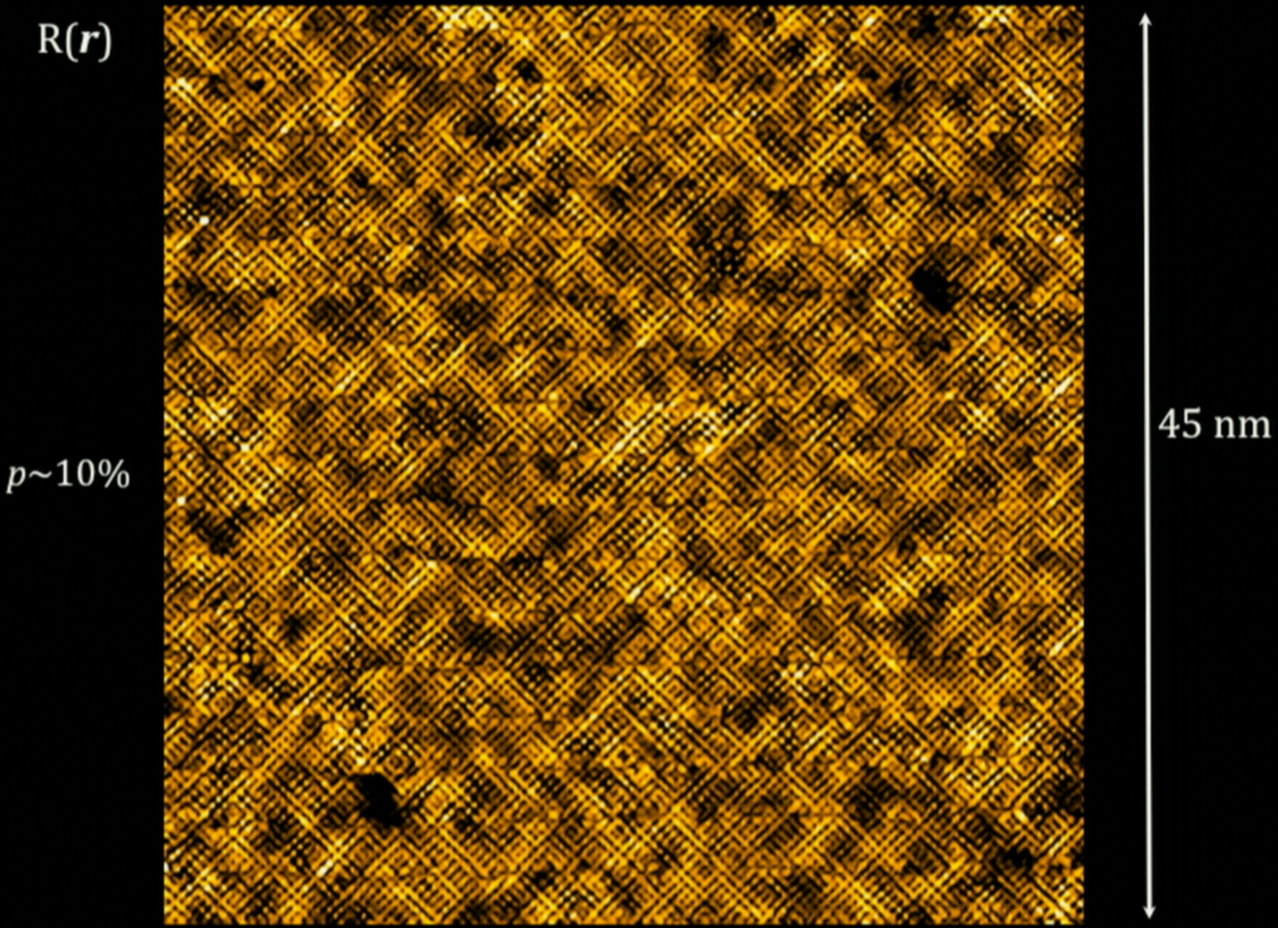
$YBa_2Cu_3O_7$

Topograph



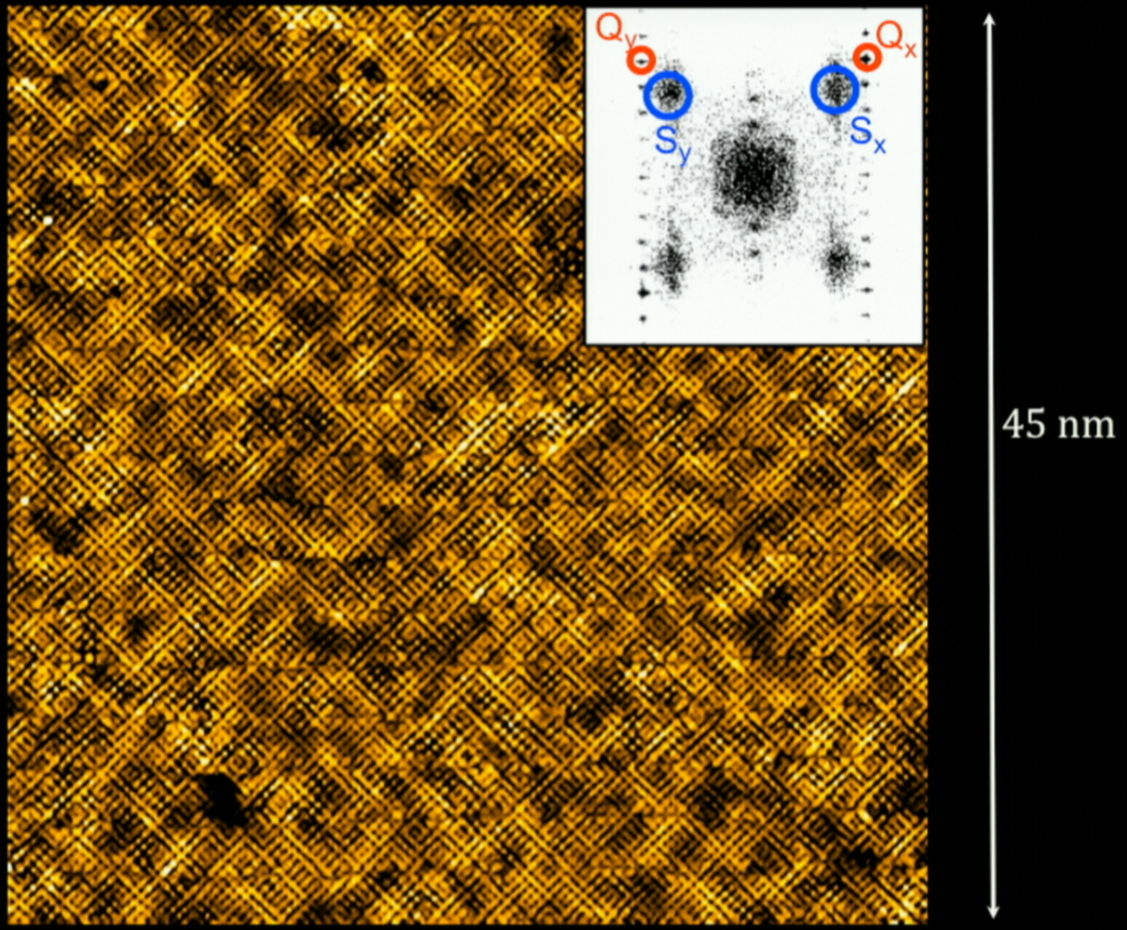
Nature **466,** 374 (2010) ***Science 333***, 4526 (2011) ***Science 344, 612*** (2014)

‘Pseudogap’ Electronic Structure



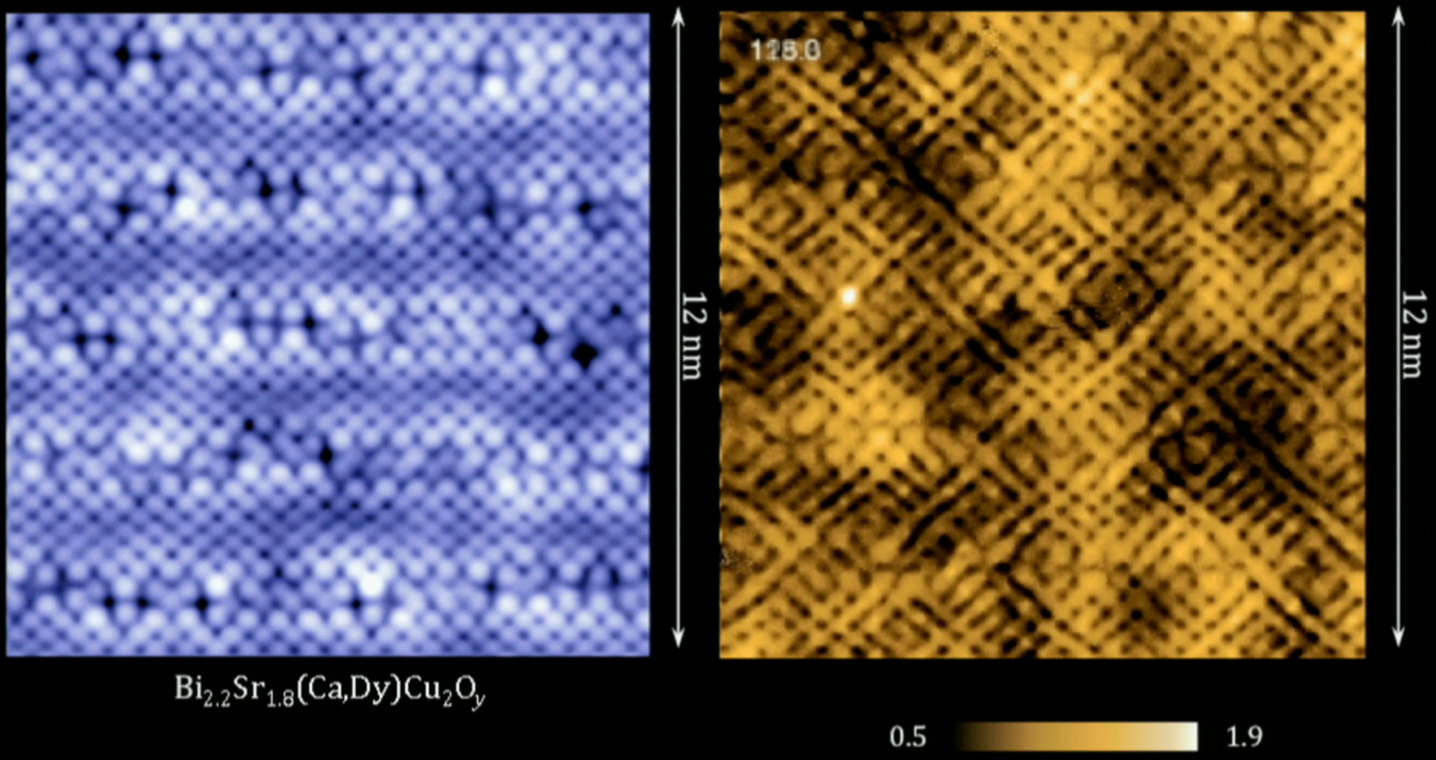
Nature **466,** 374 (2010)   ***Science 333***, 4526 (2011)   ***Science 344, 612*** (2014)

Incommensurate Density Wave



Nature **466,** 374 (2010) ***Science 333***, 4526 (2011) ***Science 344, 612*** (2014)

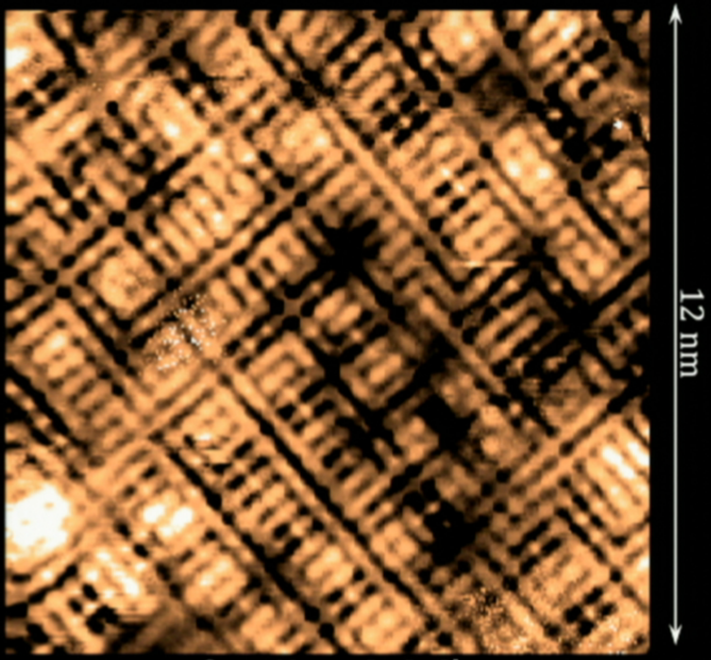
High-resolution Imaging Cuprate Broken-Symmetry States



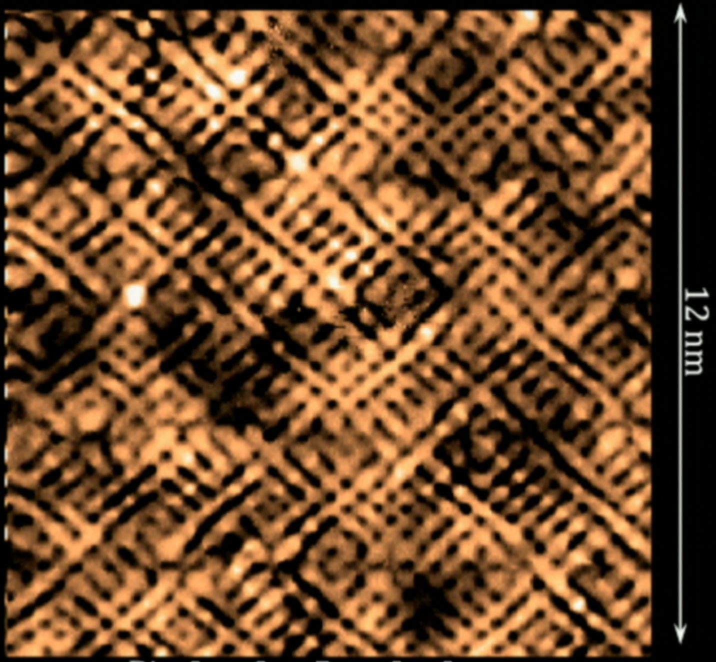
$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$

***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

High-resolution Imaging Cuprate Broken-Symmetry States



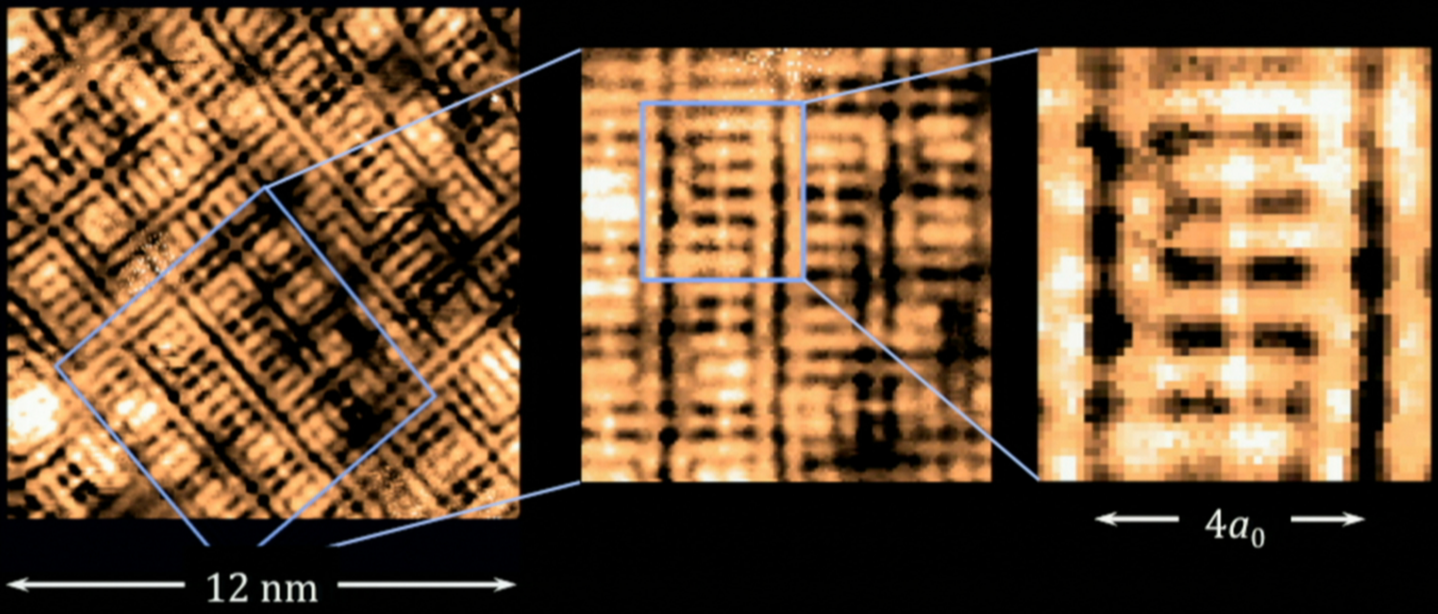
$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



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

***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

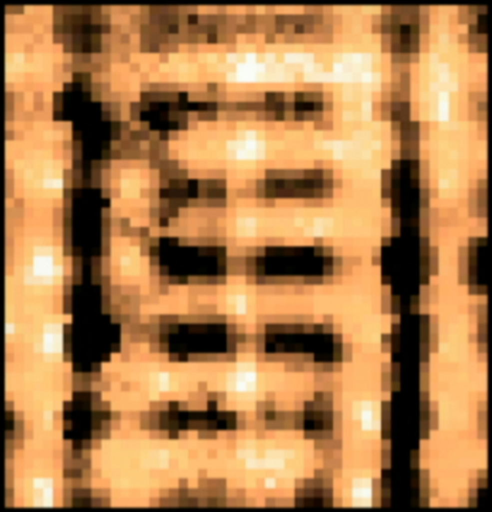
Rotational Symmetry Breaking within CuO_2 Unit Cell



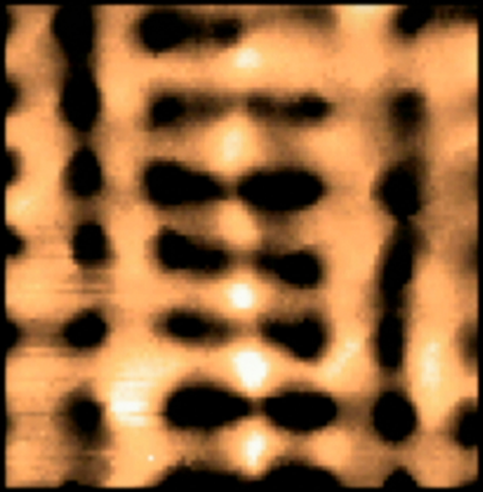
***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

Complex / Repeatable Patterns of IUC C_4 Breaking

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$



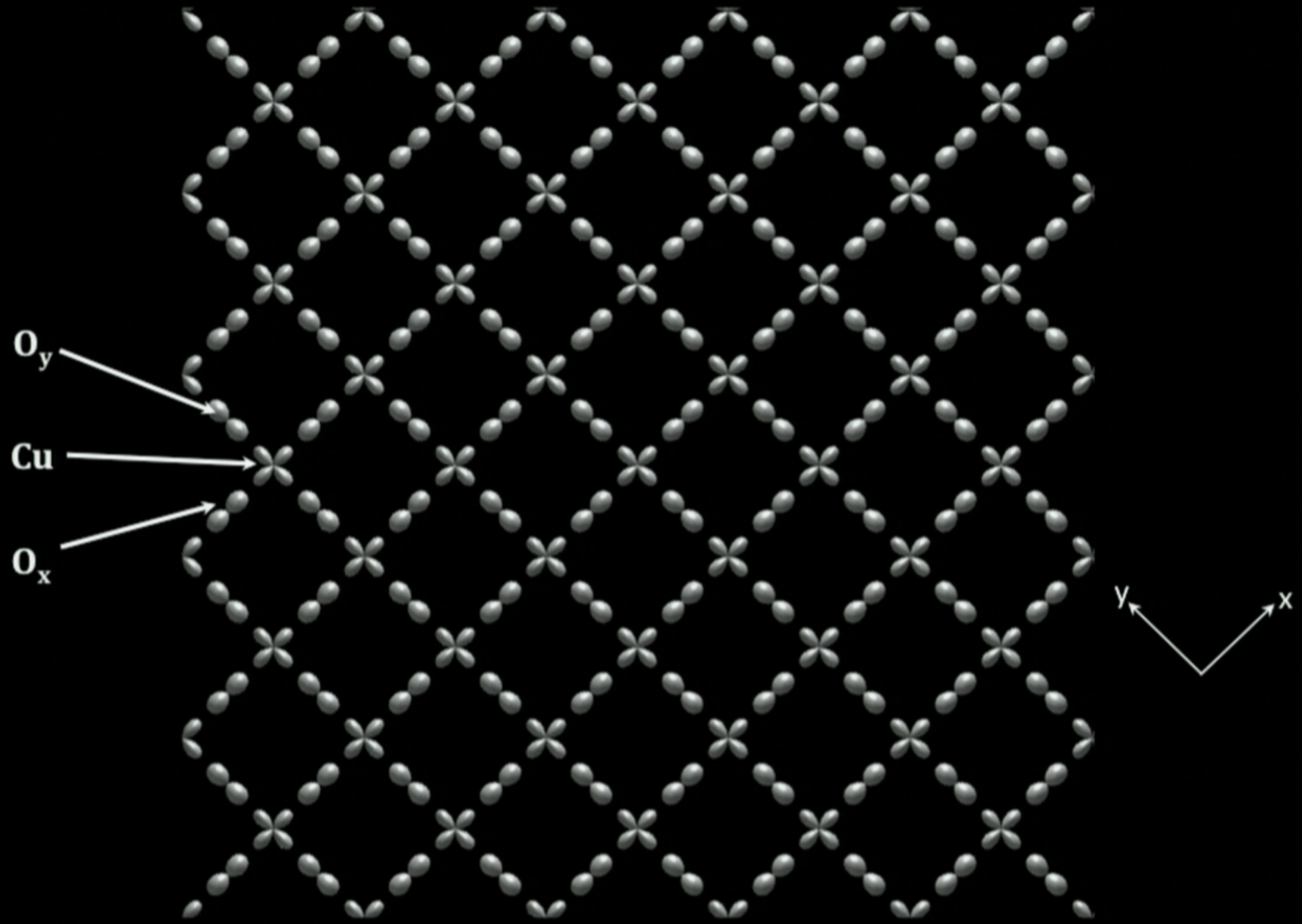
$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$



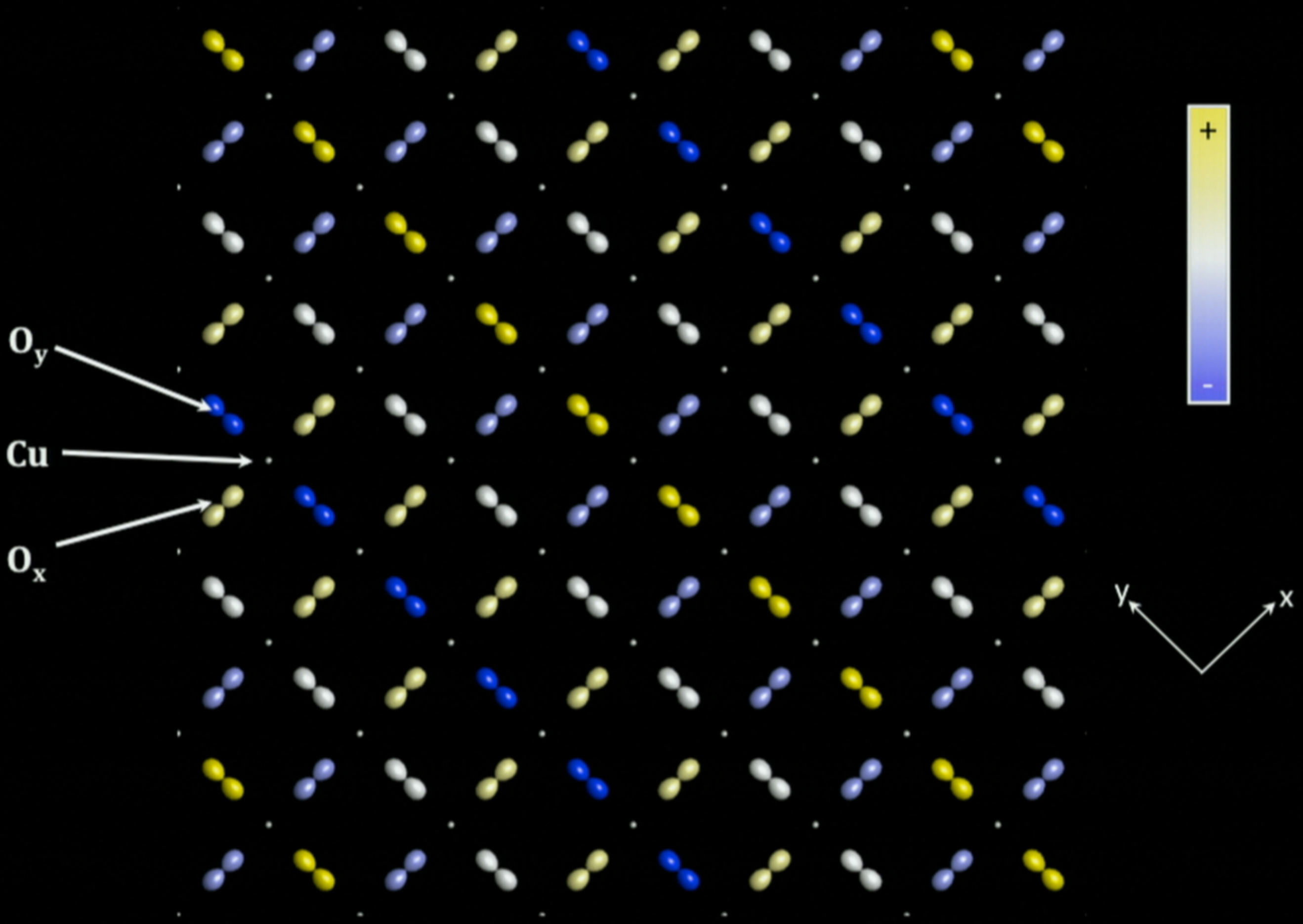
150 mV, 4.2 K

***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

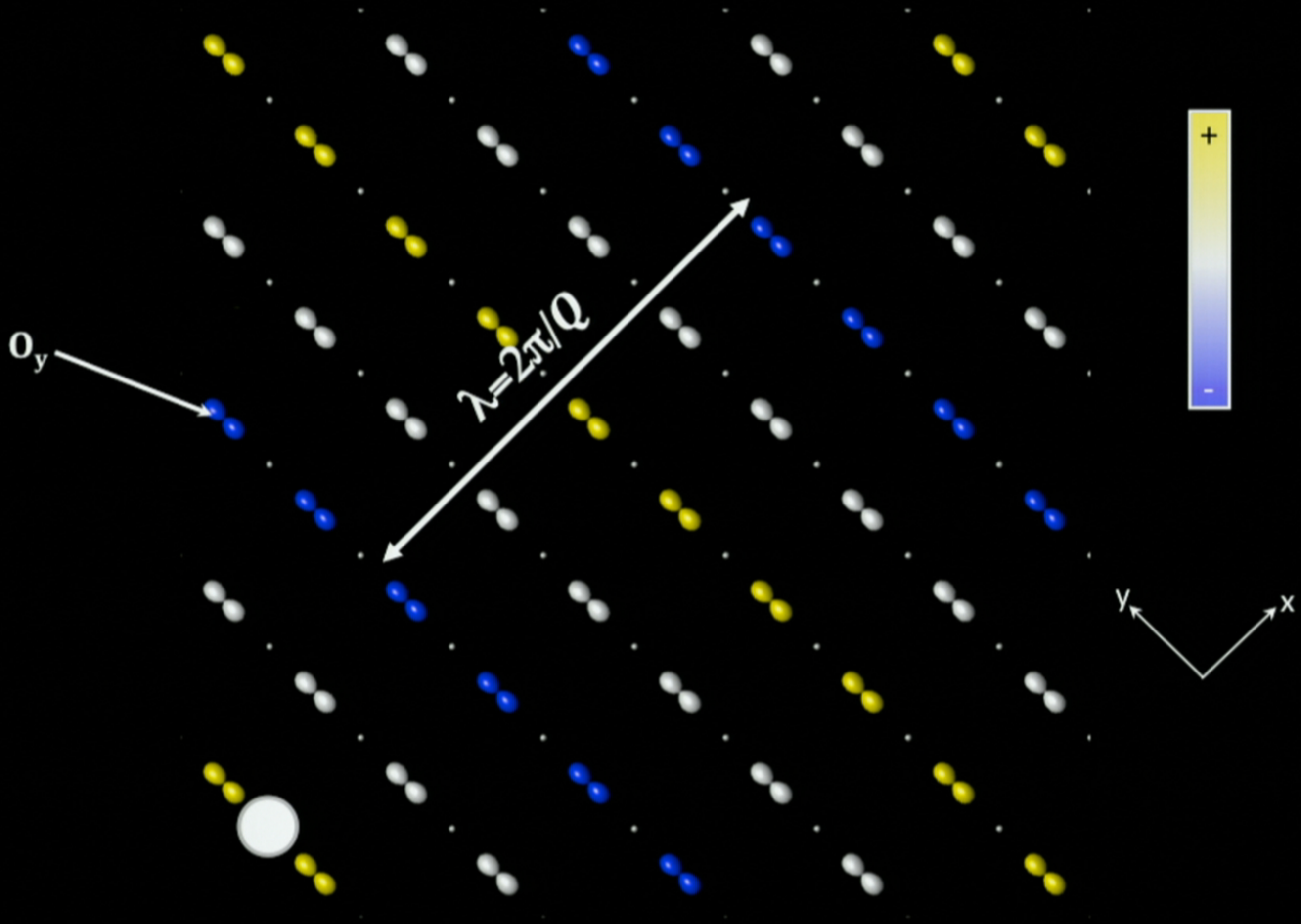
CuO_2 Lattice



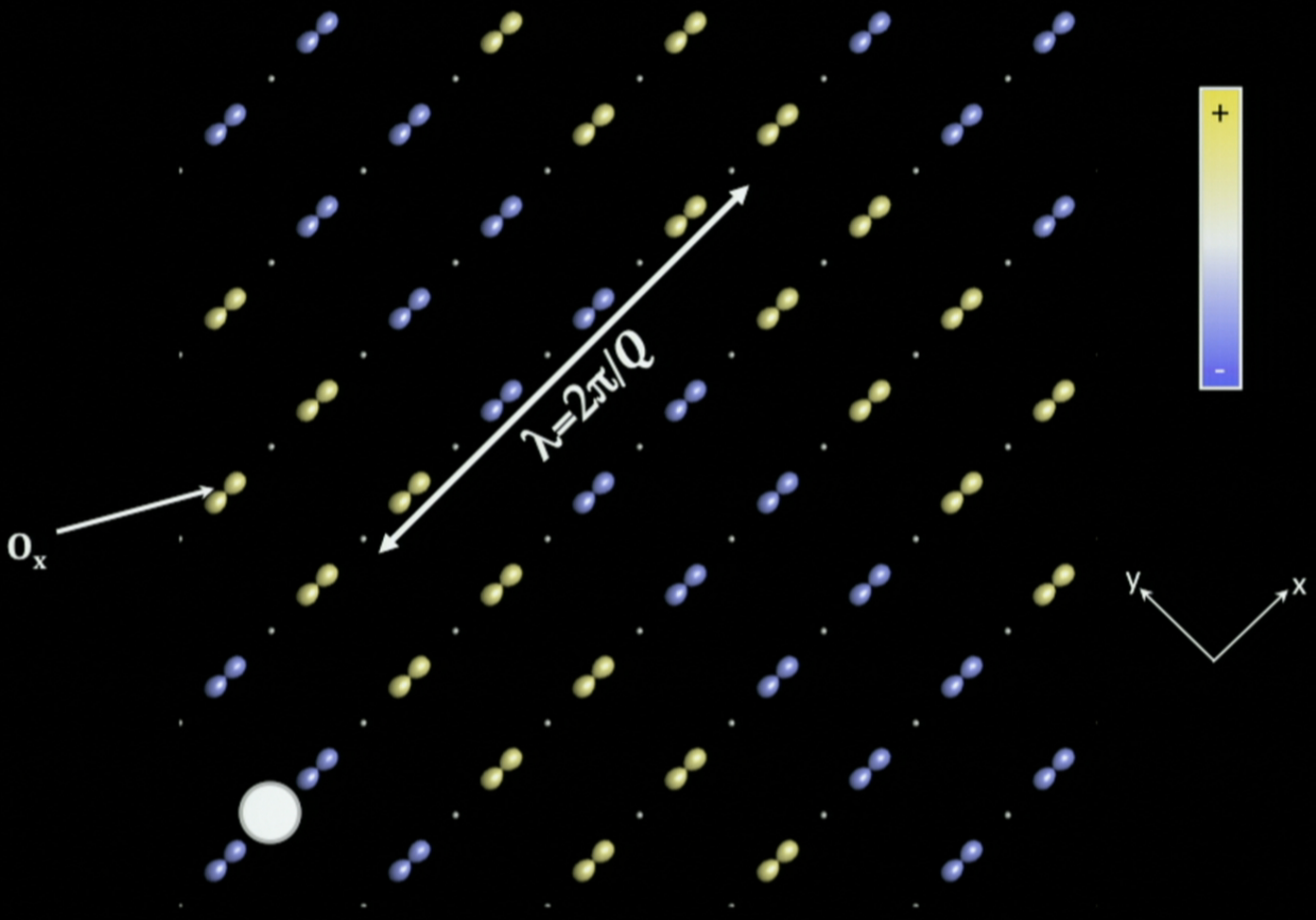
d-Symmetry Form Factor Density Wave



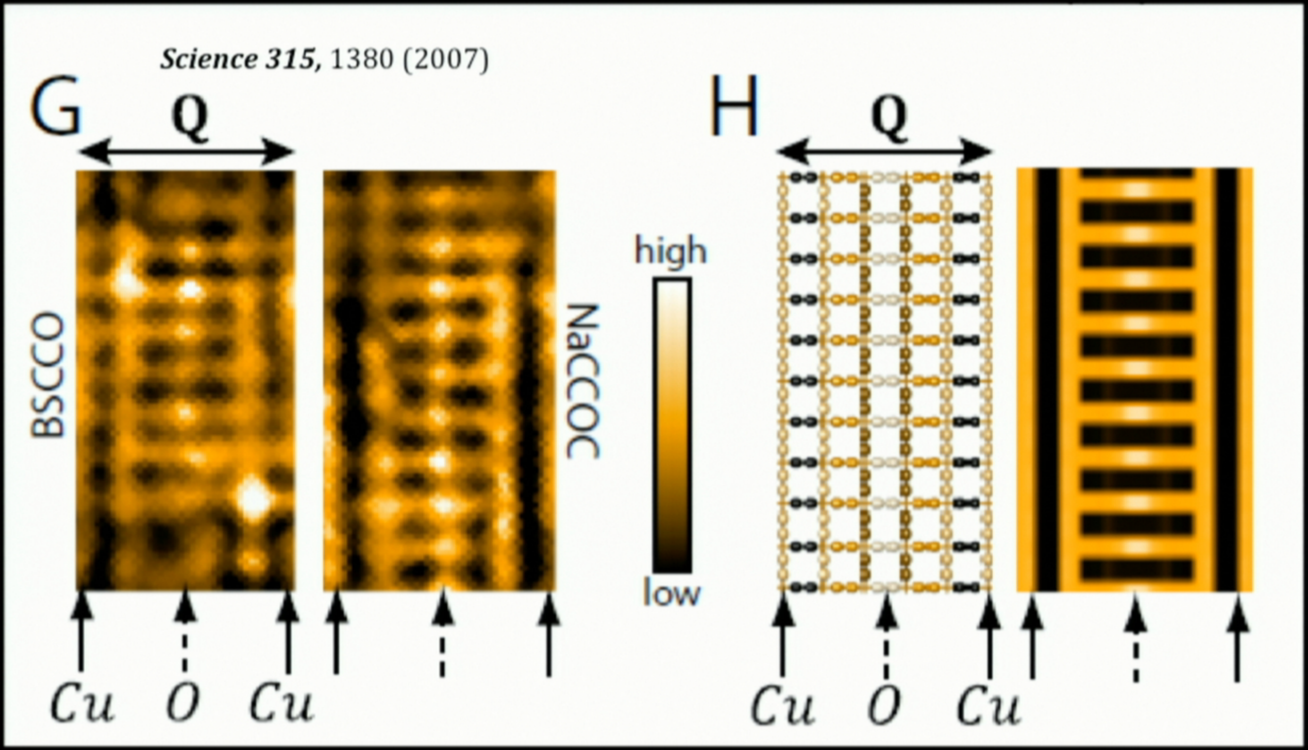
O_y Modulates at $\boldsymbol{Q}_x$



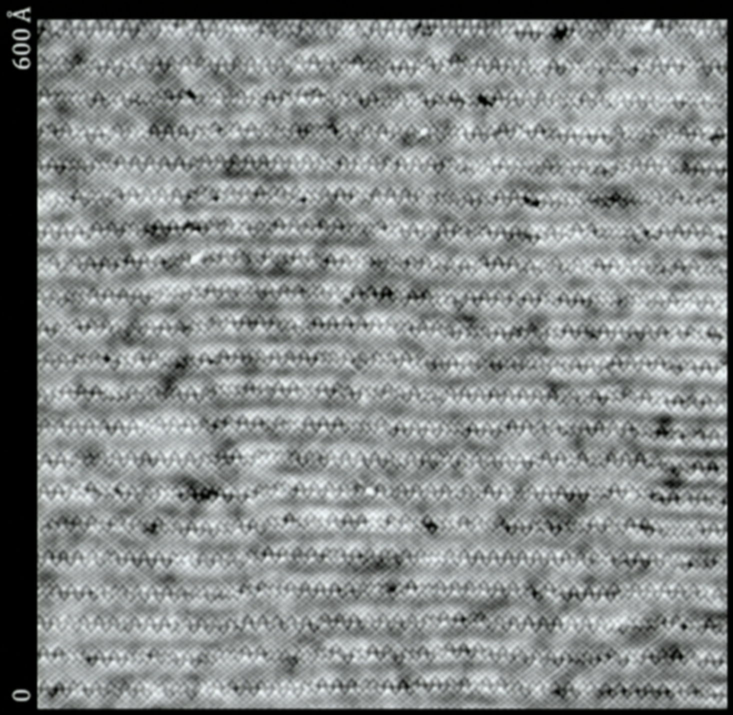
O_x Modulates at $\boldsymbol{Q}_x$



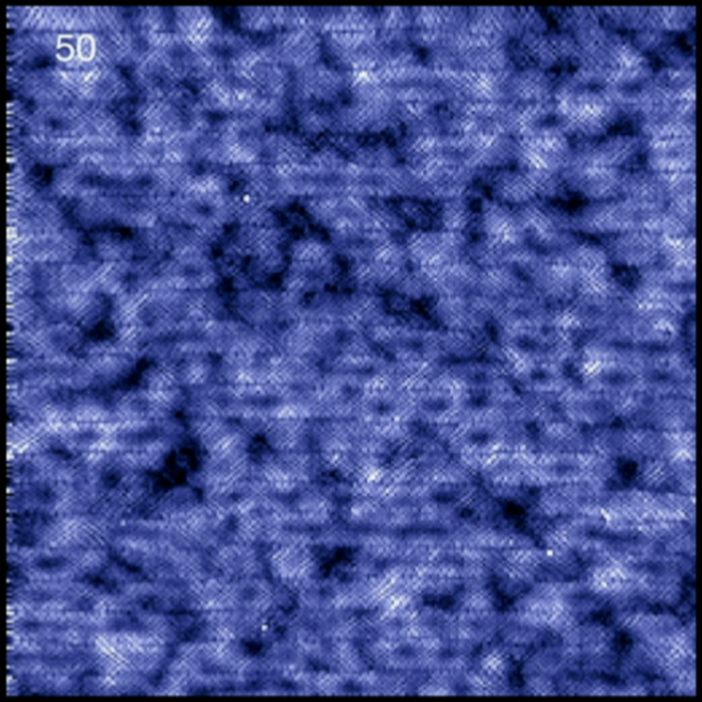
Unidirectional *d*-Symmetry FF Density Wave



Copper-based HTS: Band/Gap Structure from QPI



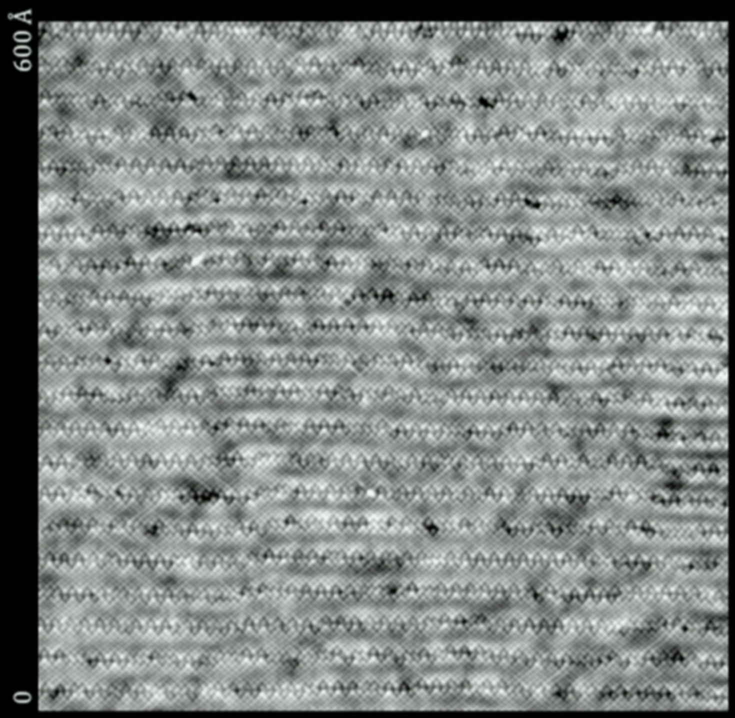
Topograph



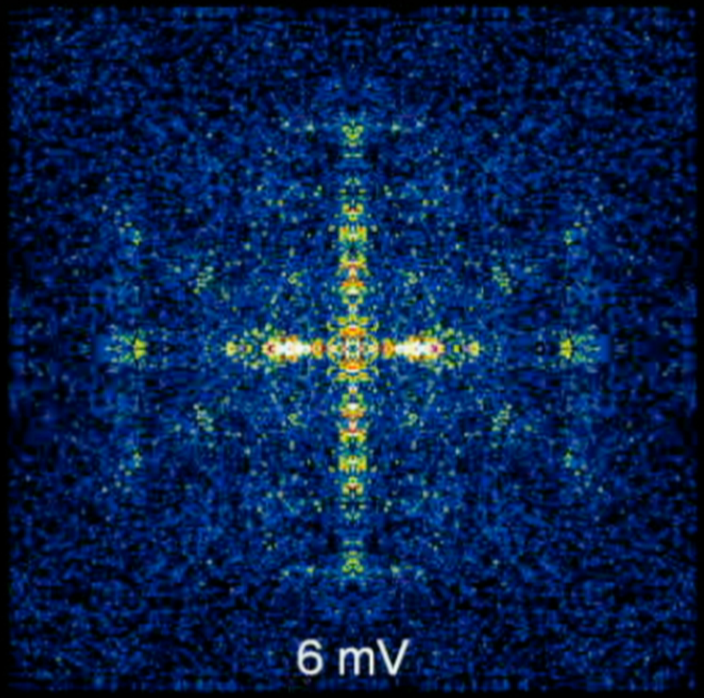
g (r,V)

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

Copper-based HTS: Band/Gap Structure from QPI



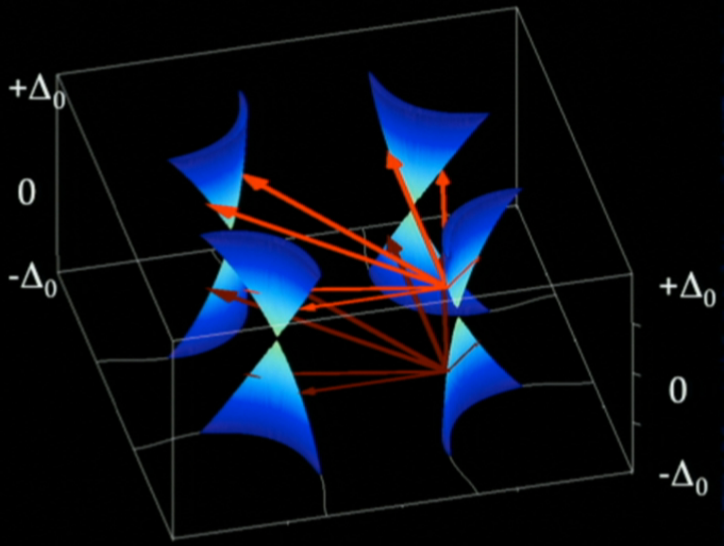
Topograph



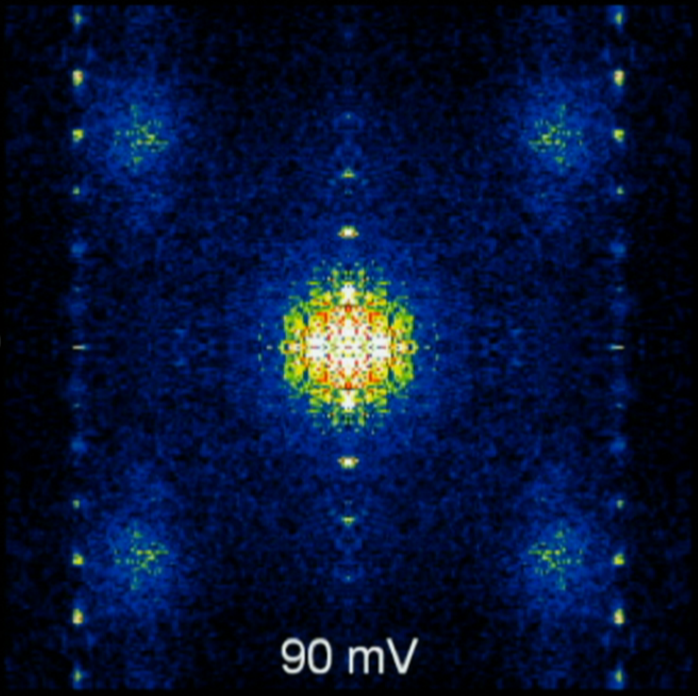
g (q, **E)**

Nature 454, 1072, (2008)

Copper-based HTS: Band/Gap Structure from QPI



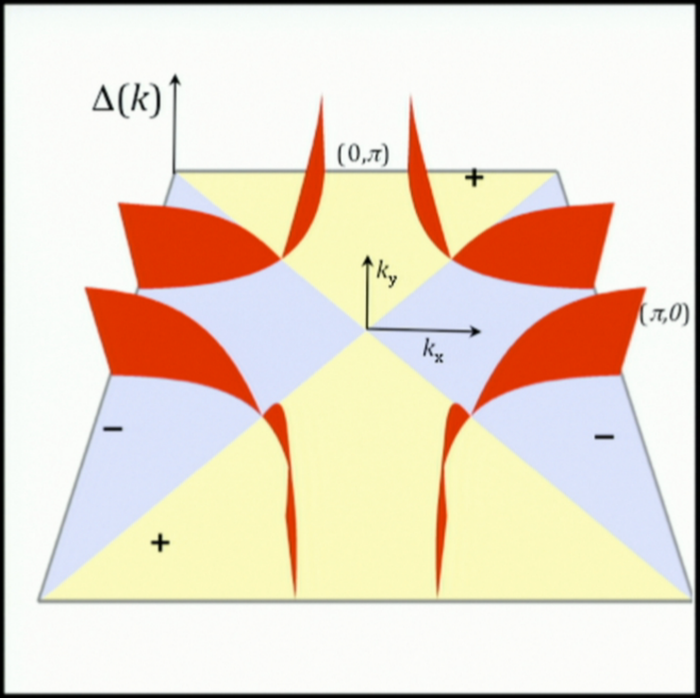
Particle-hole symmetric
i=1,..7 Bogoliubov QPI



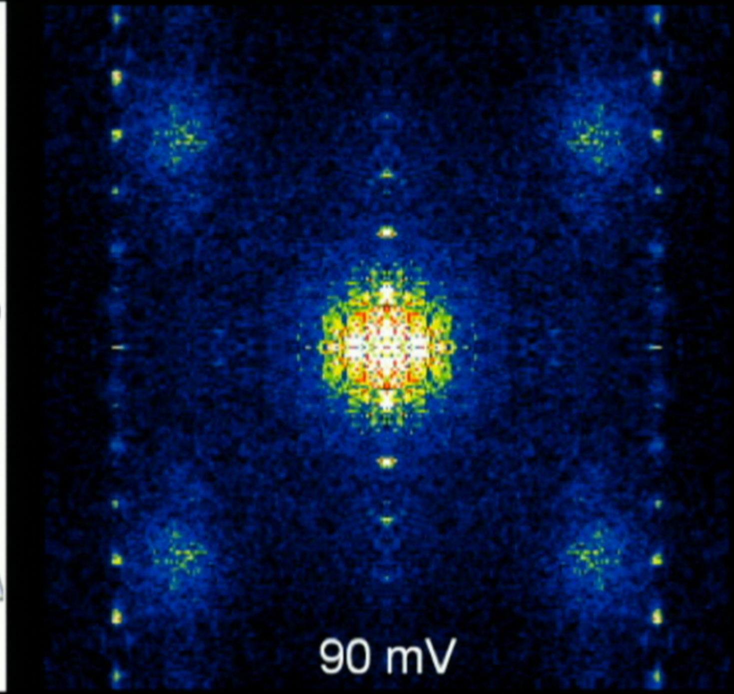
g (q, **E**)

Nature 454, 1072, (2008)

Copper-based HTS: Band/Gap Structure from QPI



Δ(K)

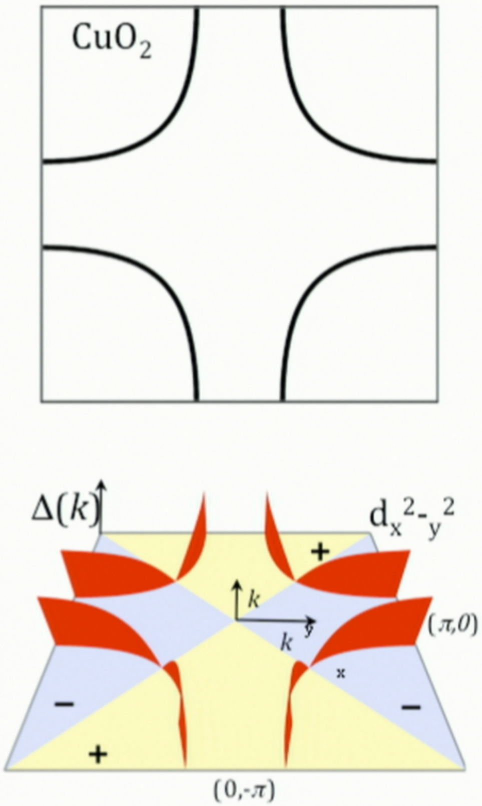


g (q, **E**)

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

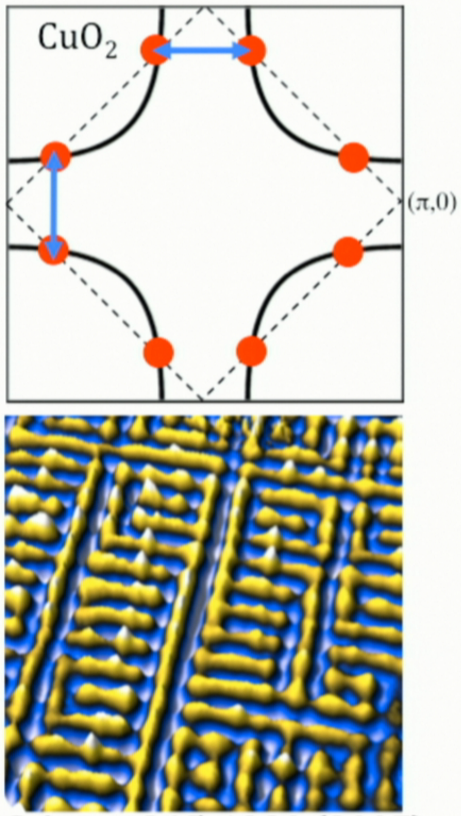
Copper-based SC Energy Gaps Δ_k & Intertwined Phases

Δ_k



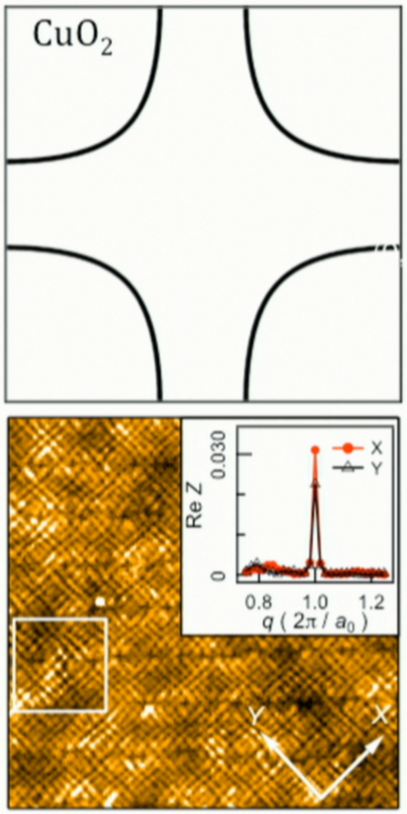
***Nature* 454,** 1072, (2008)

Q≠0



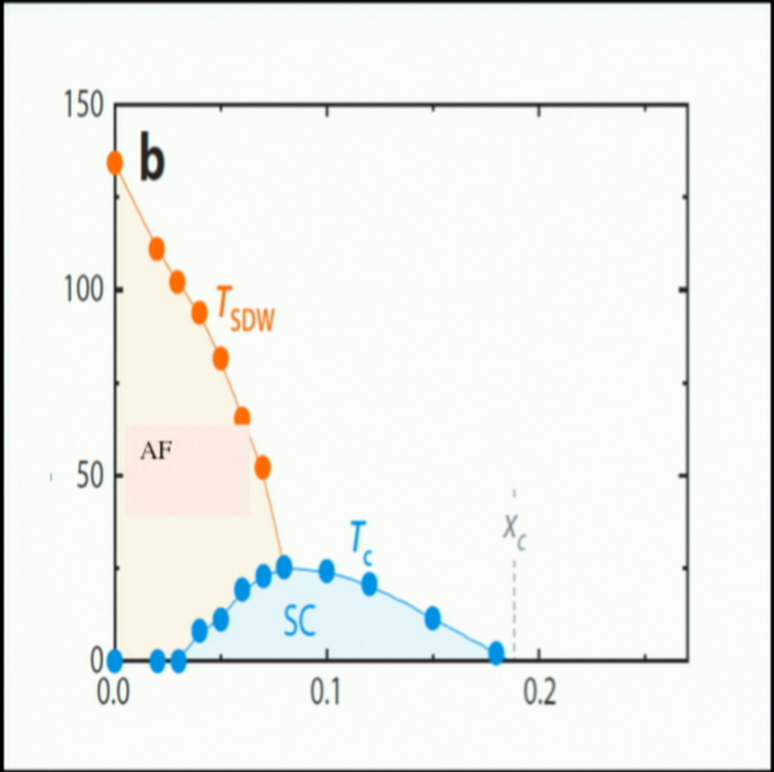
***Science* 315**, 1380 (2007)

Q=0

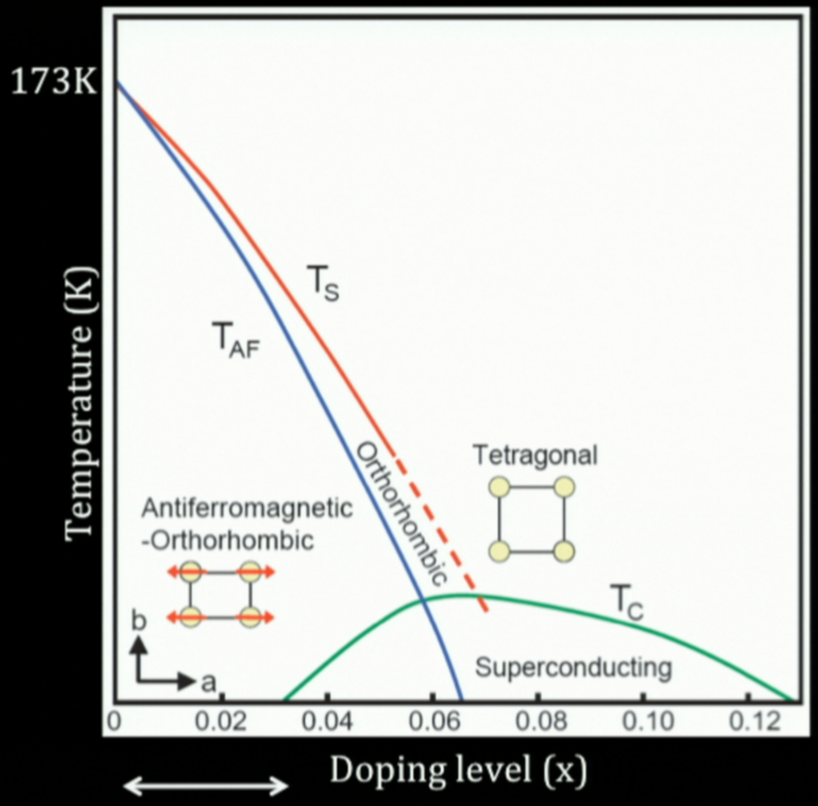


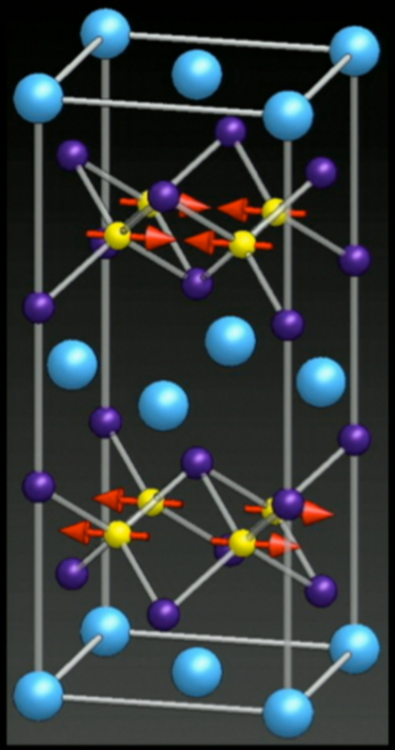
Nature 466, 324 (2010)

IRON-BASED SUPERCONDUCTVITY & INTERTWINED PHASES



Typical FeAs Phase Diagram



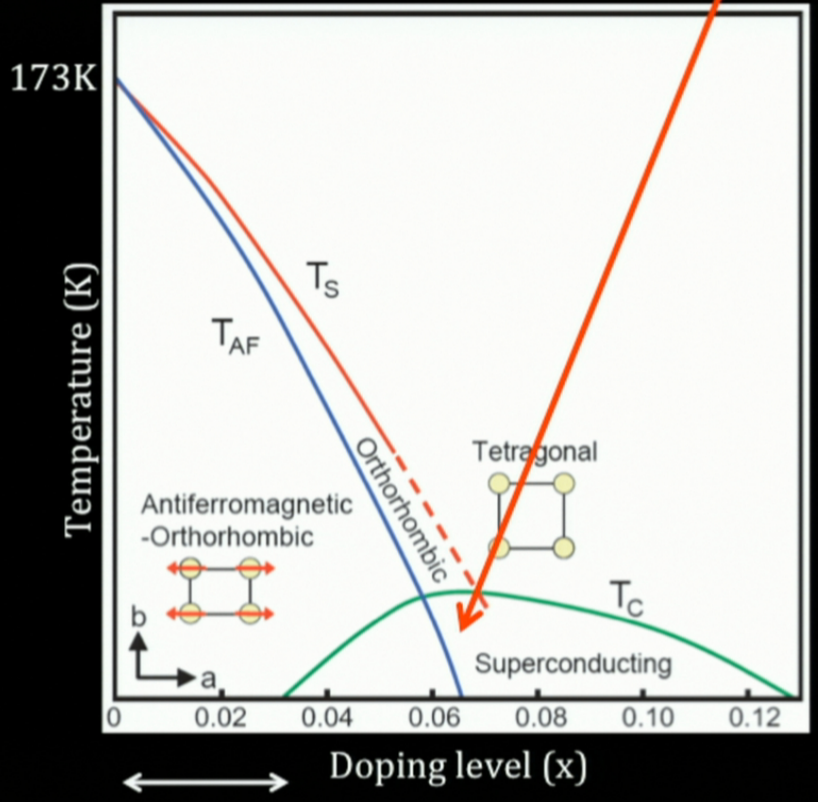


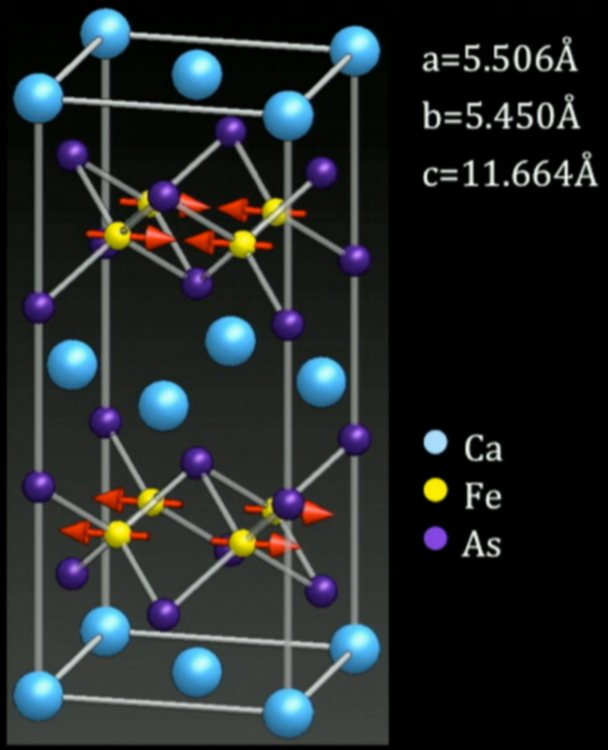
a=5.506Å
b=5.450Å
c=11.664Å

● Ca
● Fe
● As

$Ca(Fe_{1-x}Co_x)_2As_2$

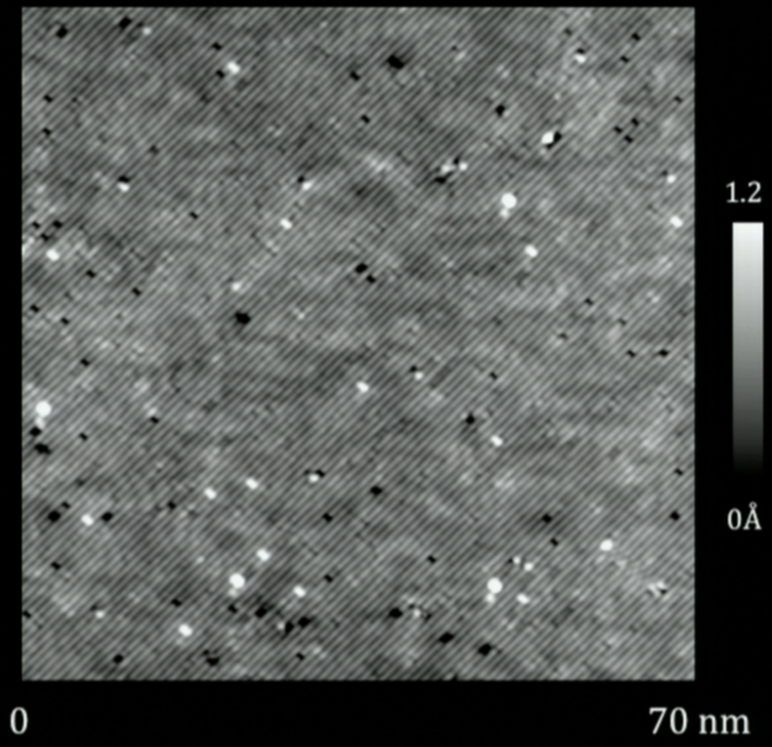
Mechanism of High-Tc Superconductivity?

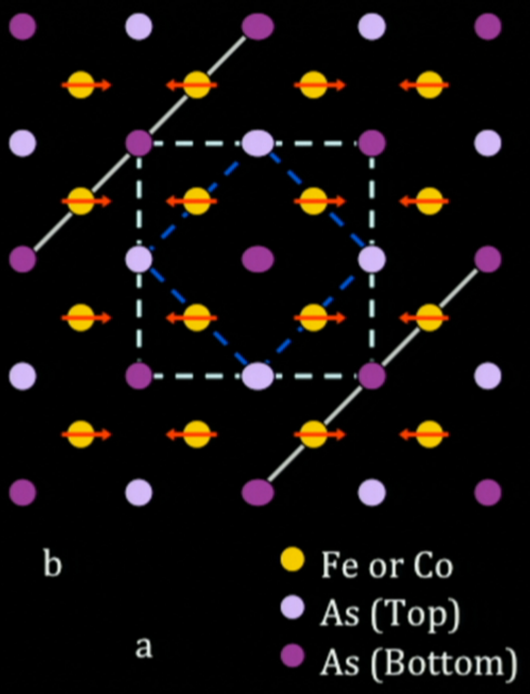




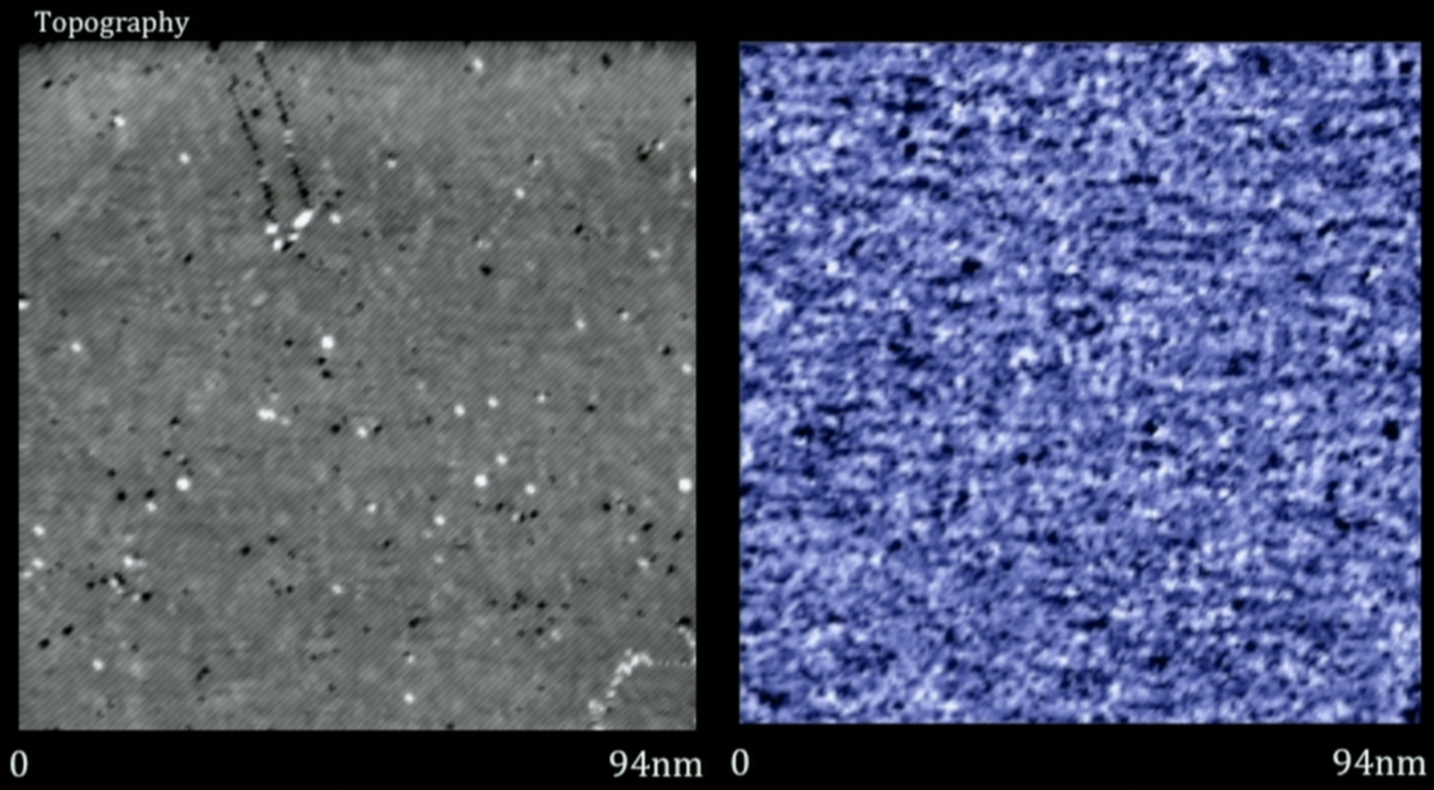
$Ca(Fe_{1-x}Co_x)_2As_2$

$Ca(Fe_{1-x}Co_x)_2As_2$ -- Excellent cryo-cleave surface


Topography

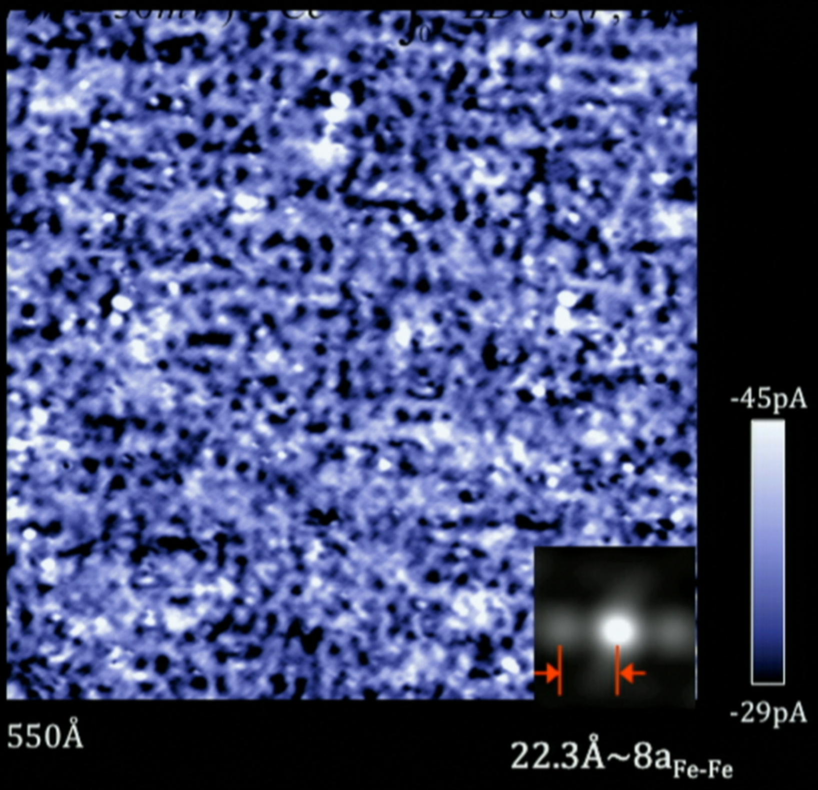

FeAs-layer Reconstruction

Quasiparticle Interference in ‘Parent’ State $CaFe_2As_2$



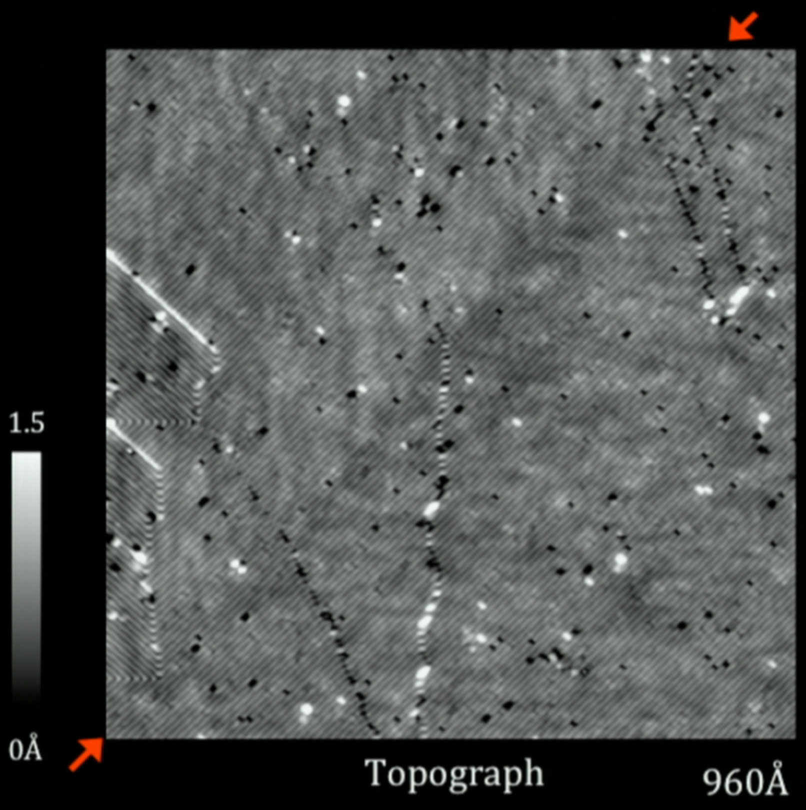
Science **327**, 181 (2010)

Static electronic nanostructures ~8a_{FeFe} along a-axis



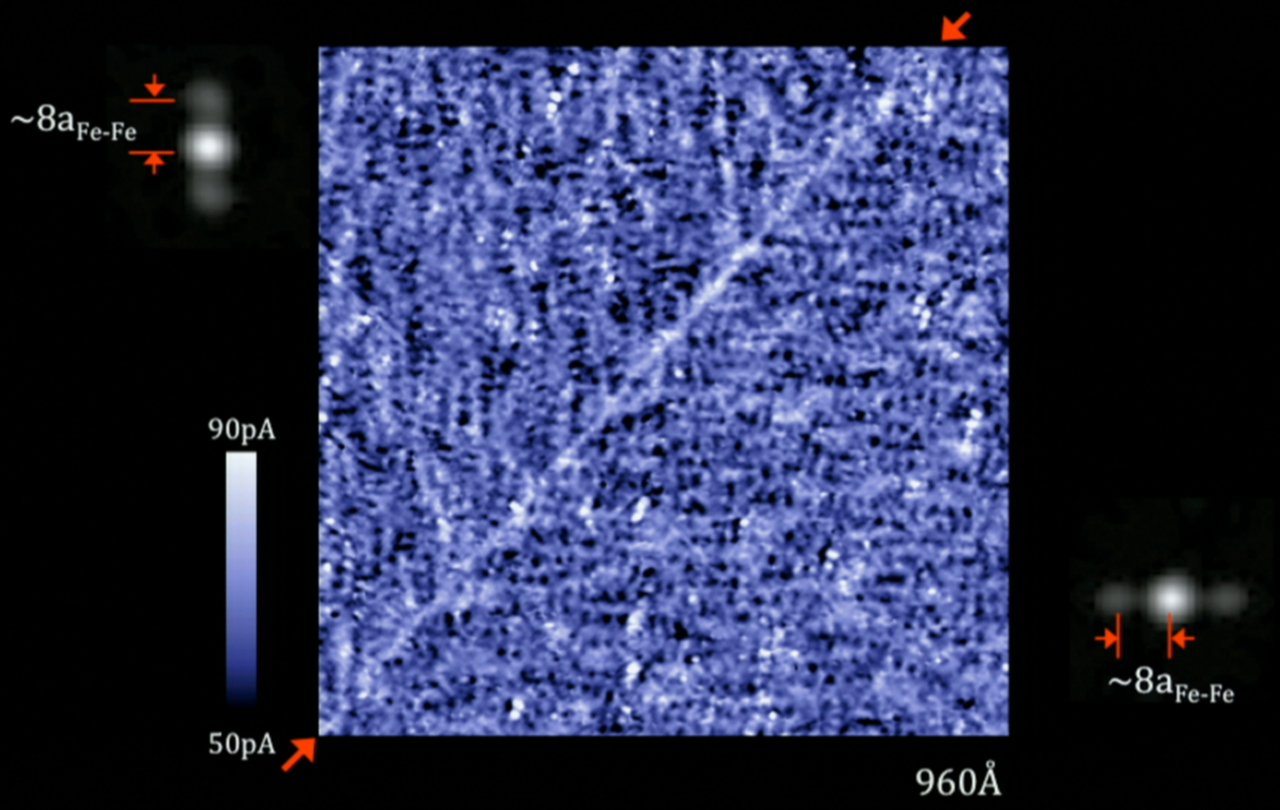
Science **327**, 181 (2010)

Effect of orthorhombic twin boundary



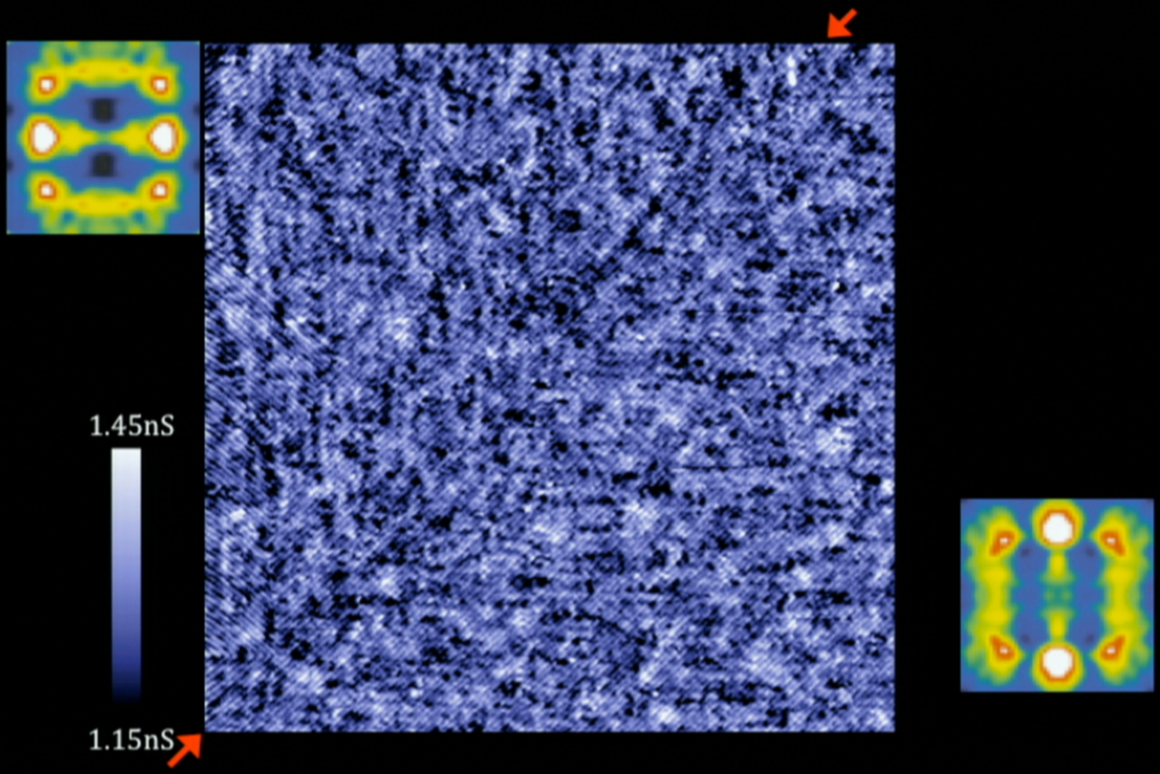
Science **327**, 181 (2010)

Static $8a_0$ electronic nanostructures rotate by 90 degrees



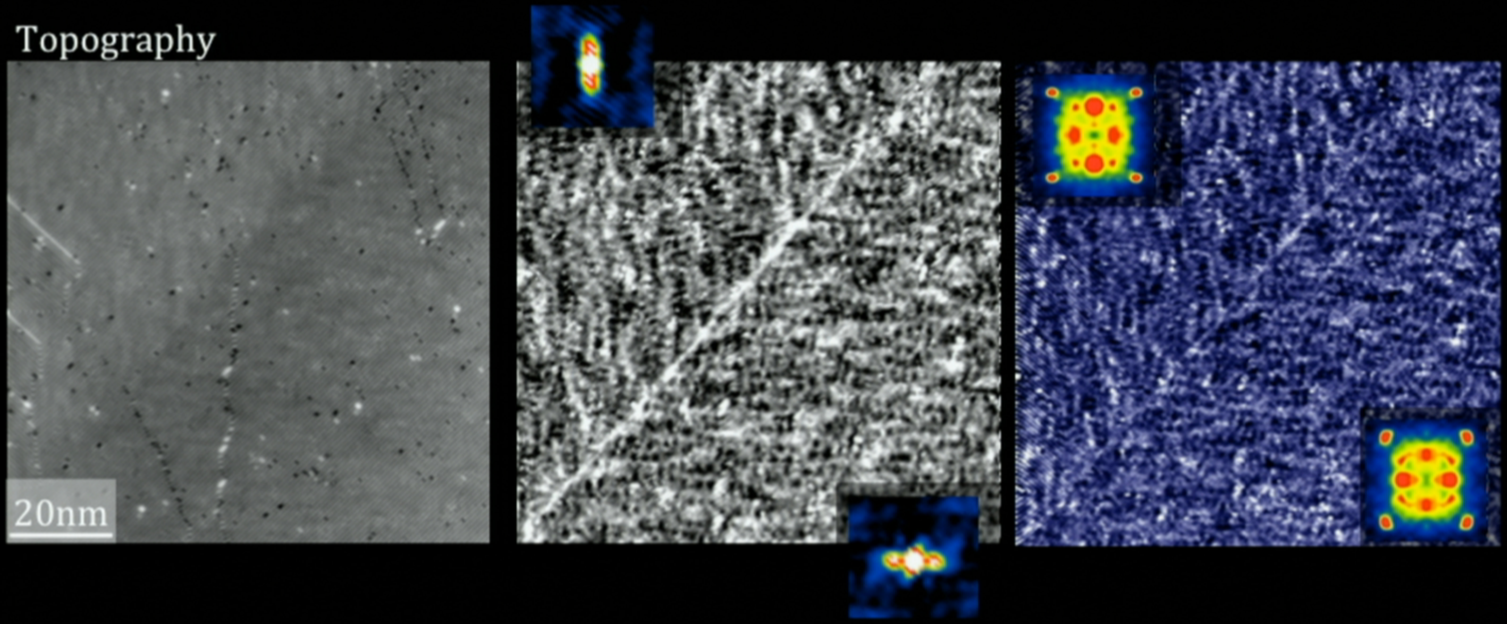
Science **327**, 181 (2010)

QPI modulation wavevectors rotate by 90 degrees



Science **327**, 181 (2010)

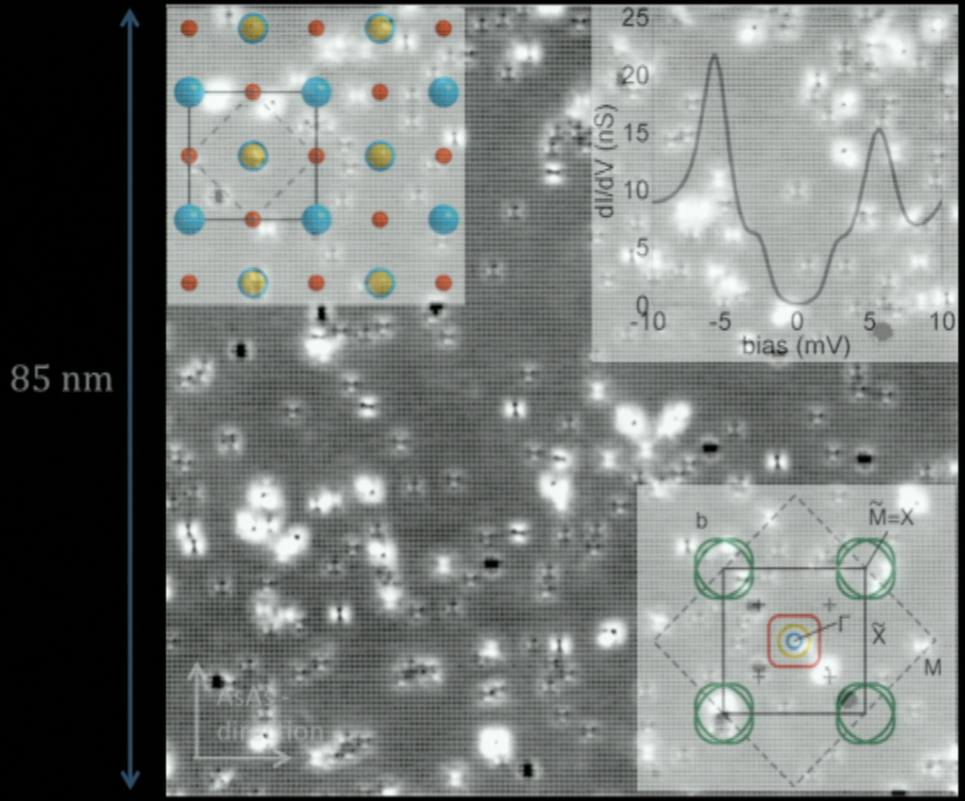
Discovery of Electronic Nematic Phase in Iron-Pnictides



Science **327**, 181 (2010)

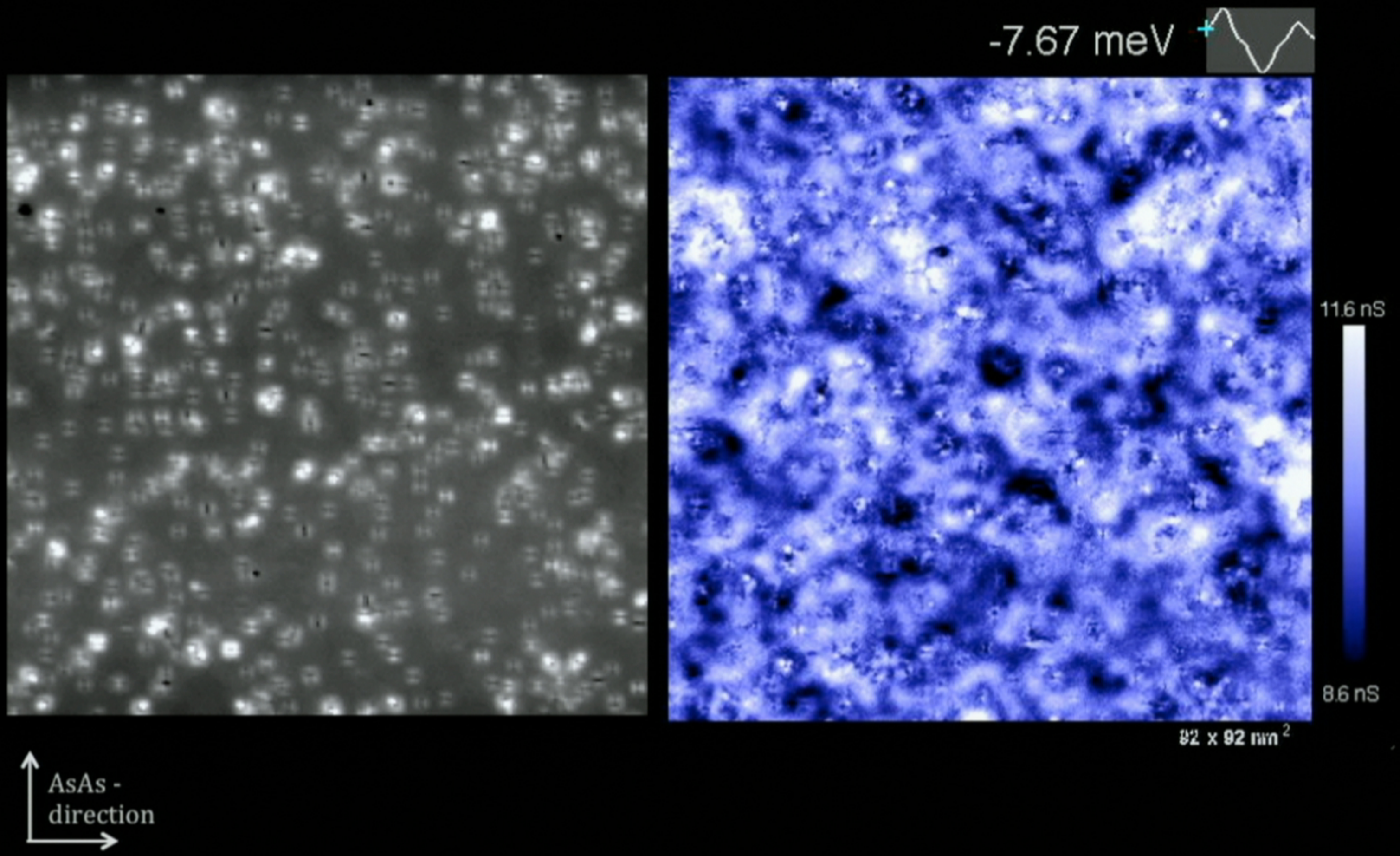
LiFeAs: Cleave Surface & Tunneling

Energy Gap $\Delta_i(k)$ of Iron-based HTS



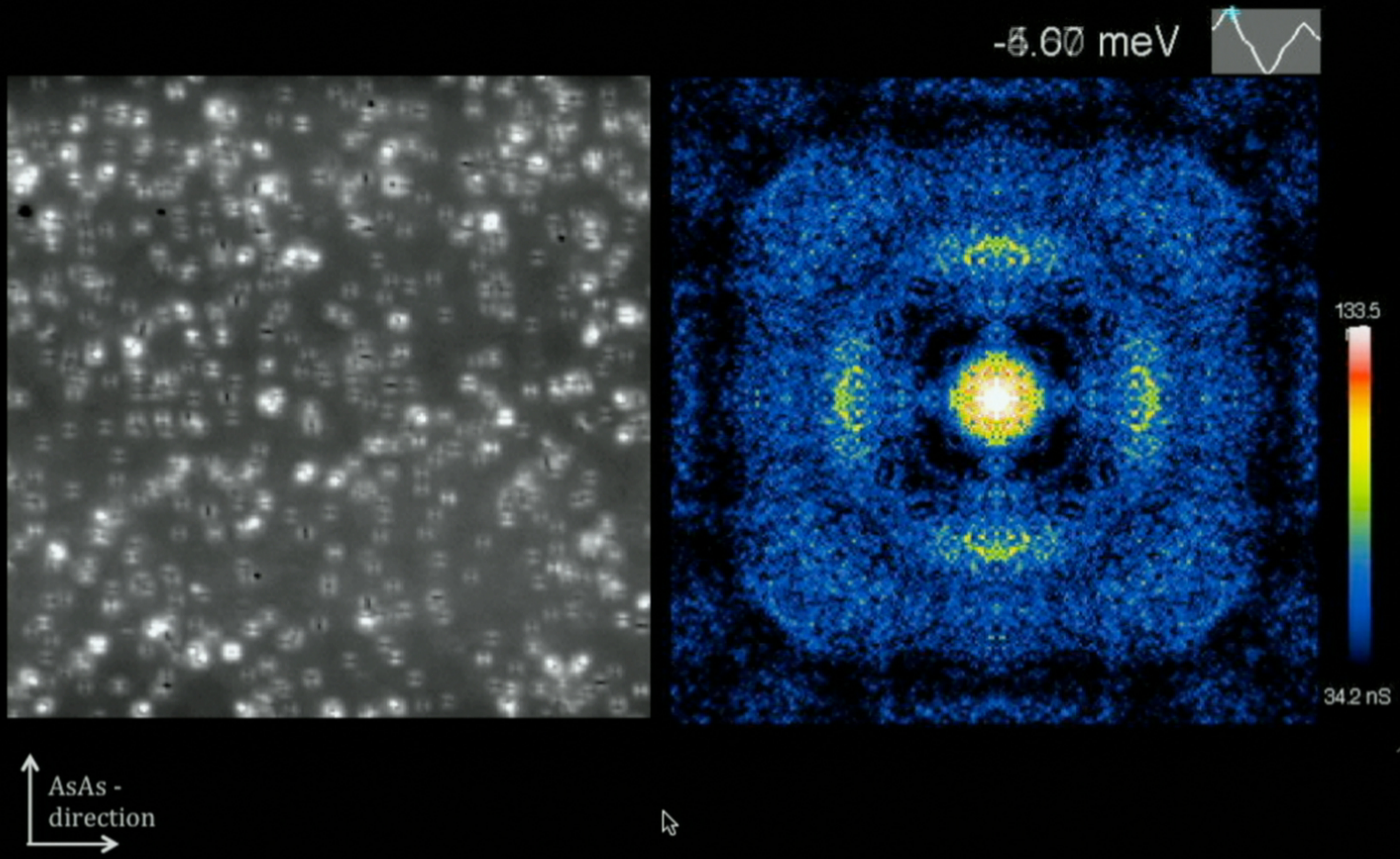
Science 336, 563, (2012)

LiFeAs Bogoliubov QPI $g(\boldsymbol{r},E)$



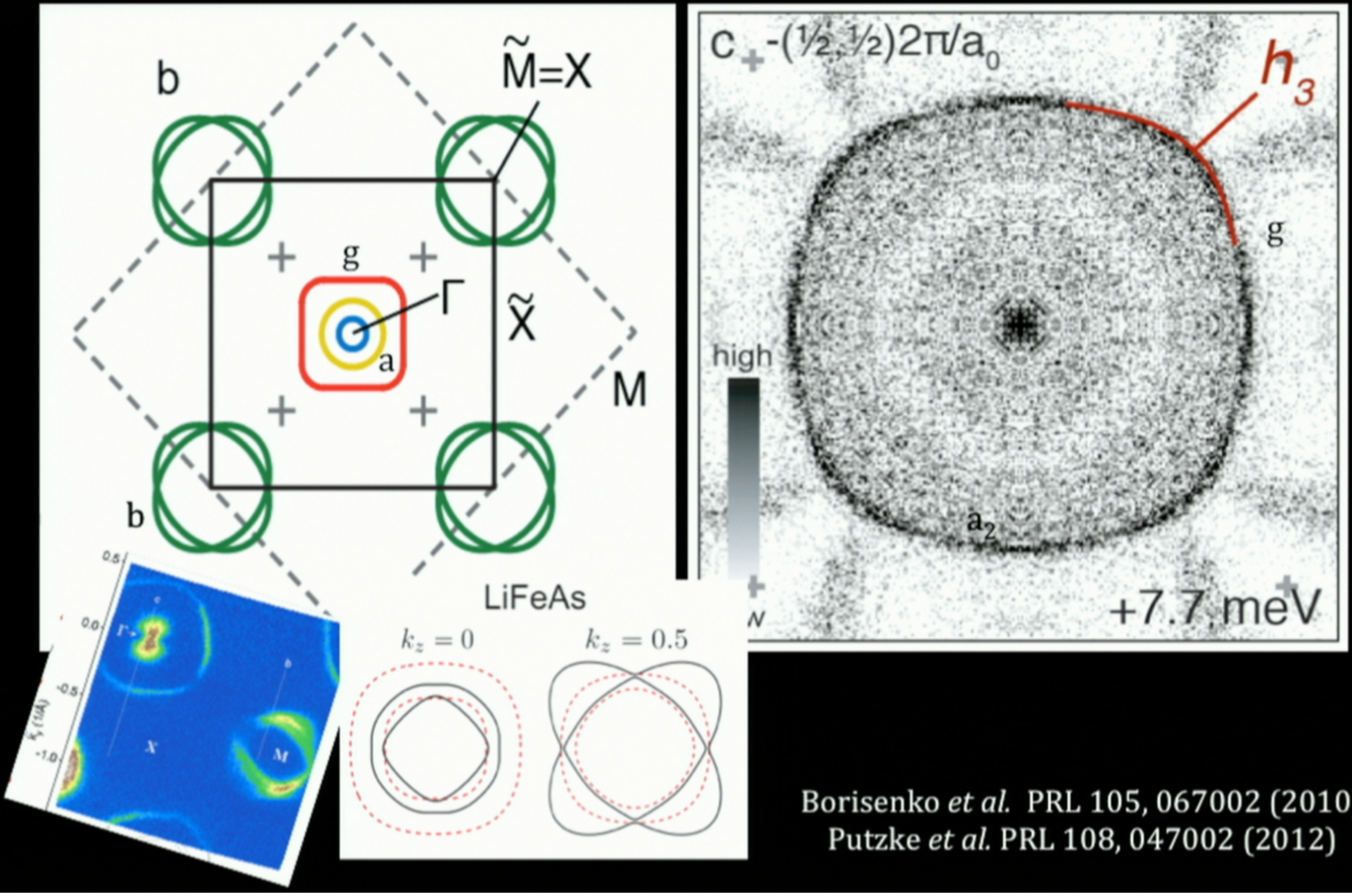
***Science* 336,** 563, (2012)

LiFeAs Bogoliubov QPI g(***q***,E)



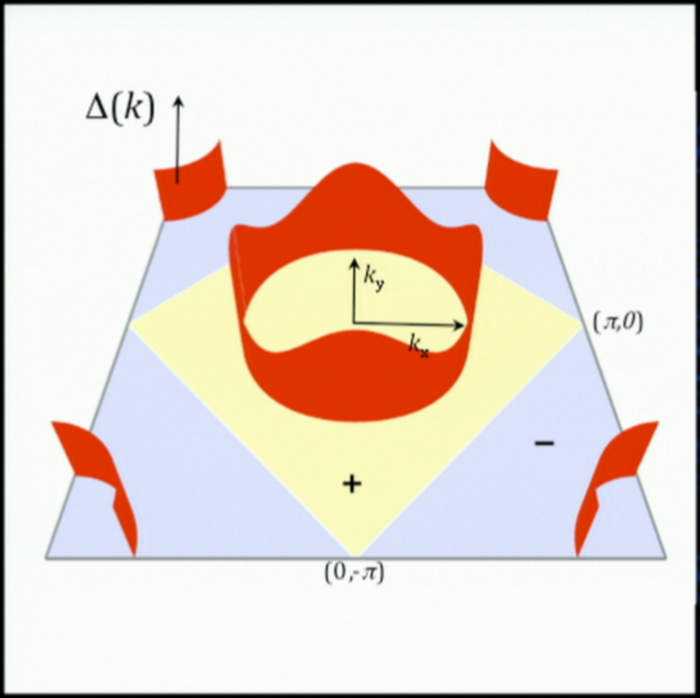
Science 336, 563, (2012)

Band Identification : Correspondence to ARPES and Quantum Oscillations

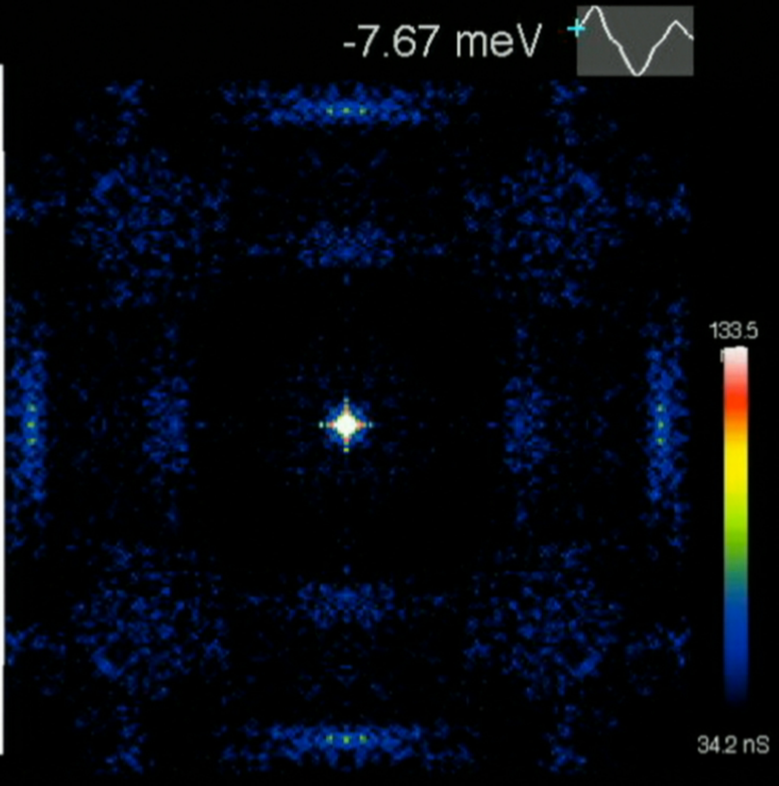


Borisenko *et al.* PRL 105, 067002 (2010)
Putzke *et al.* PRL 108, 047002 (2012)

Iron-based HTS: Band/Gap Structure from QPI

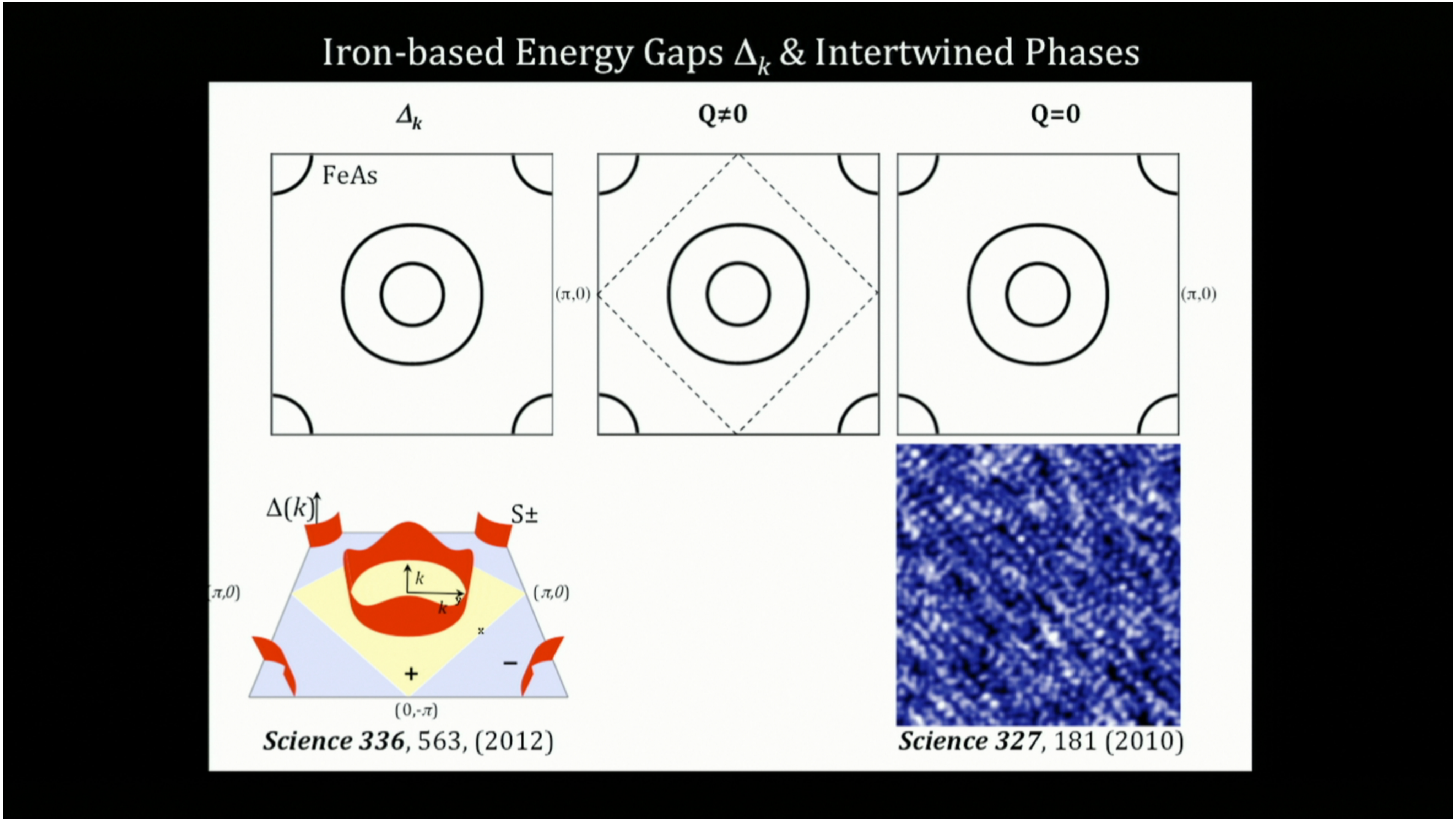


Δ(K)



g (q, **E**)

Science 336, 563, (2012)



Iron-based Energy Gaps Δ_k & Intertwined Phases

Δ_k

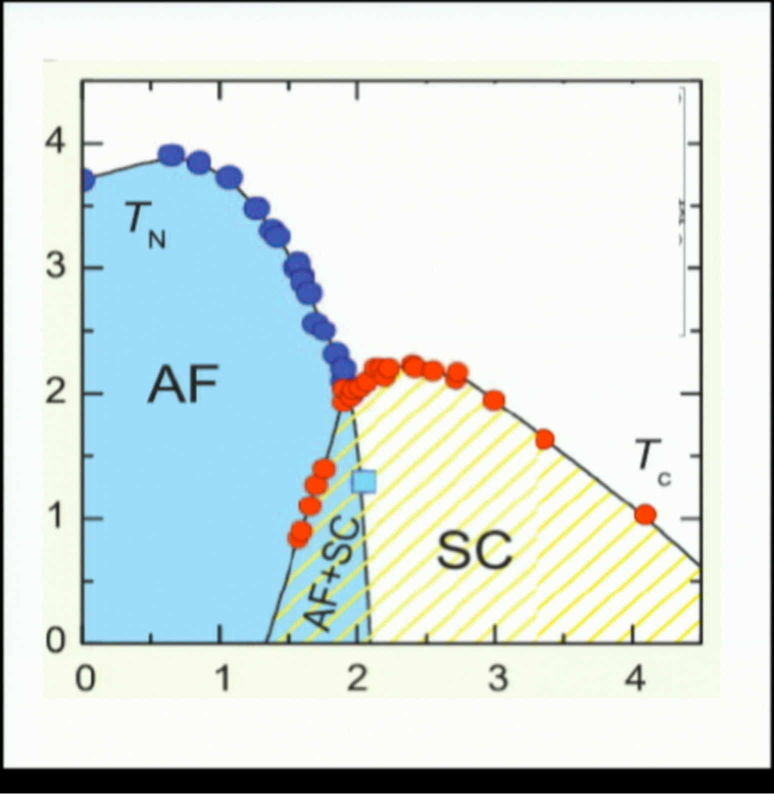
Q≠0

Q=0

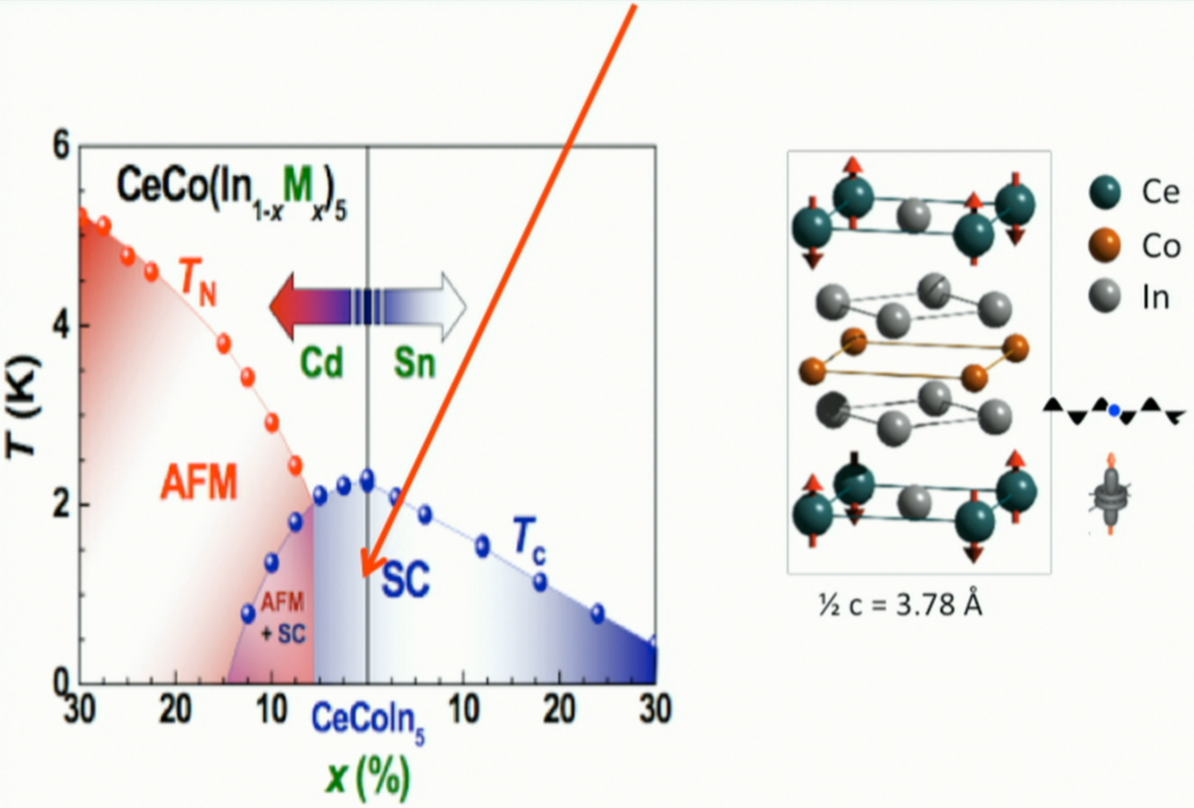
***Science* 336**, 563, (2012)

***Science* 327**, 181 (2010)

HEAVY FERMION SUPERCONDUCTVITY & INTERTWINED PHASES

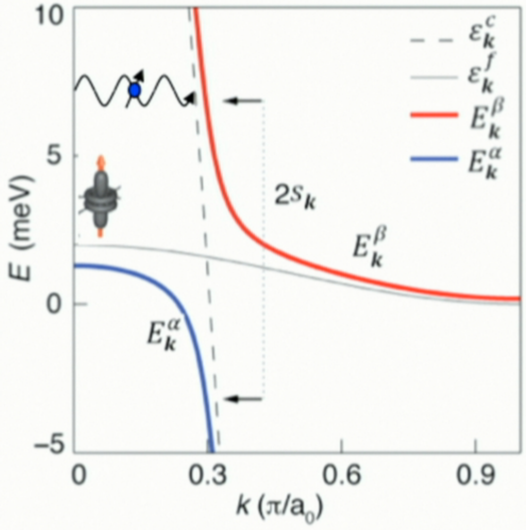


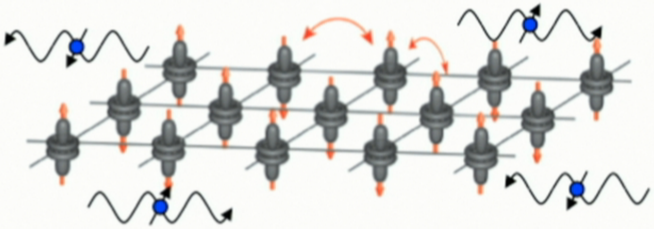
Mechanism of ‘High-Tc’ Superconductivity?



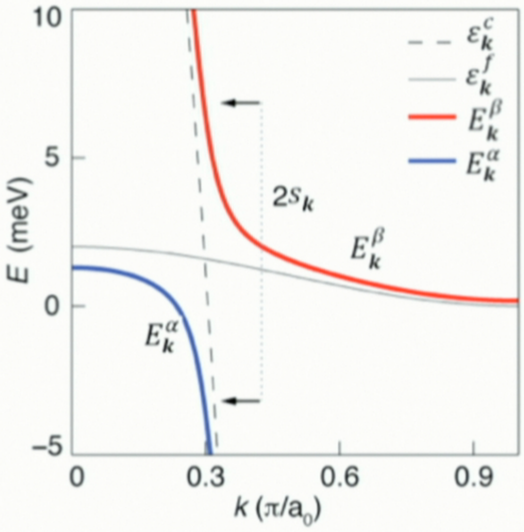
$CeCoIn_5$

Heavy-Fermion Formation (*f*-electron Hybridization)





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



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

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

Diagonalize:

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

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

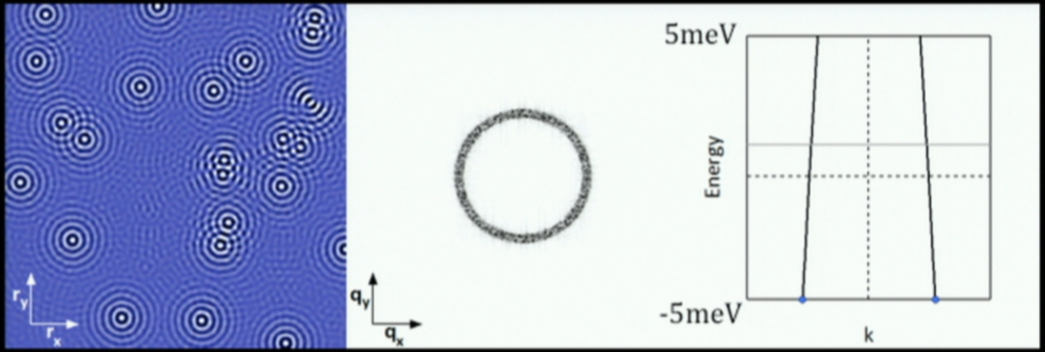
$$\boxed{E_{\mathbf{k}}^{\alpha,\beta} = \frac{\varepsilon_{\mathbf{k}}^c + \varepsilon_{\mathbf{k}}^f}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}}^c - \varepsilon_{\mathbf{k}}^f}{2}\right)^2 + s_{\mathbf{k}}^2}}$$

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

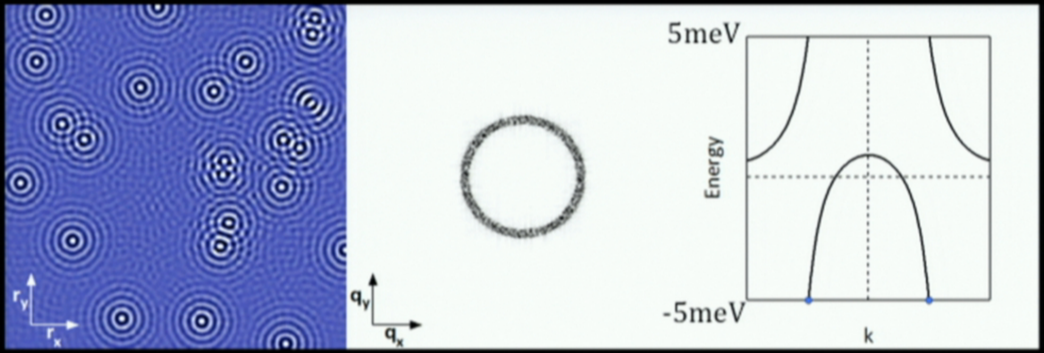
Heavy-Fermion Scattering Interference Imaging with Millikelvin SI-STM

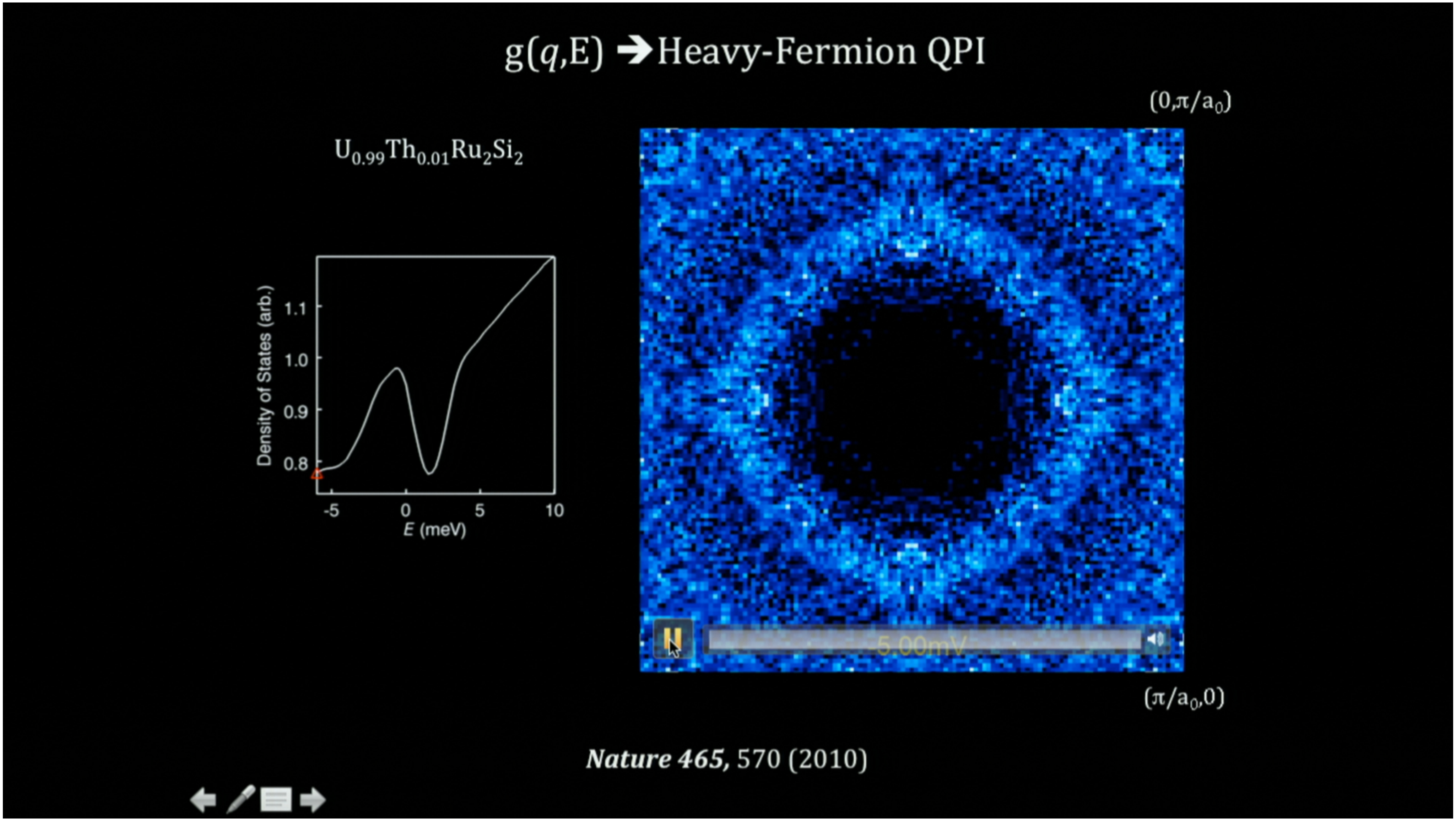
Measure $E_k^{\alpha,\beta}$ for Heavy-Fermion Bands ?

Scattering
interference
within
'light' band



Scattering
interference
within two
'heavy-fermion'
bands



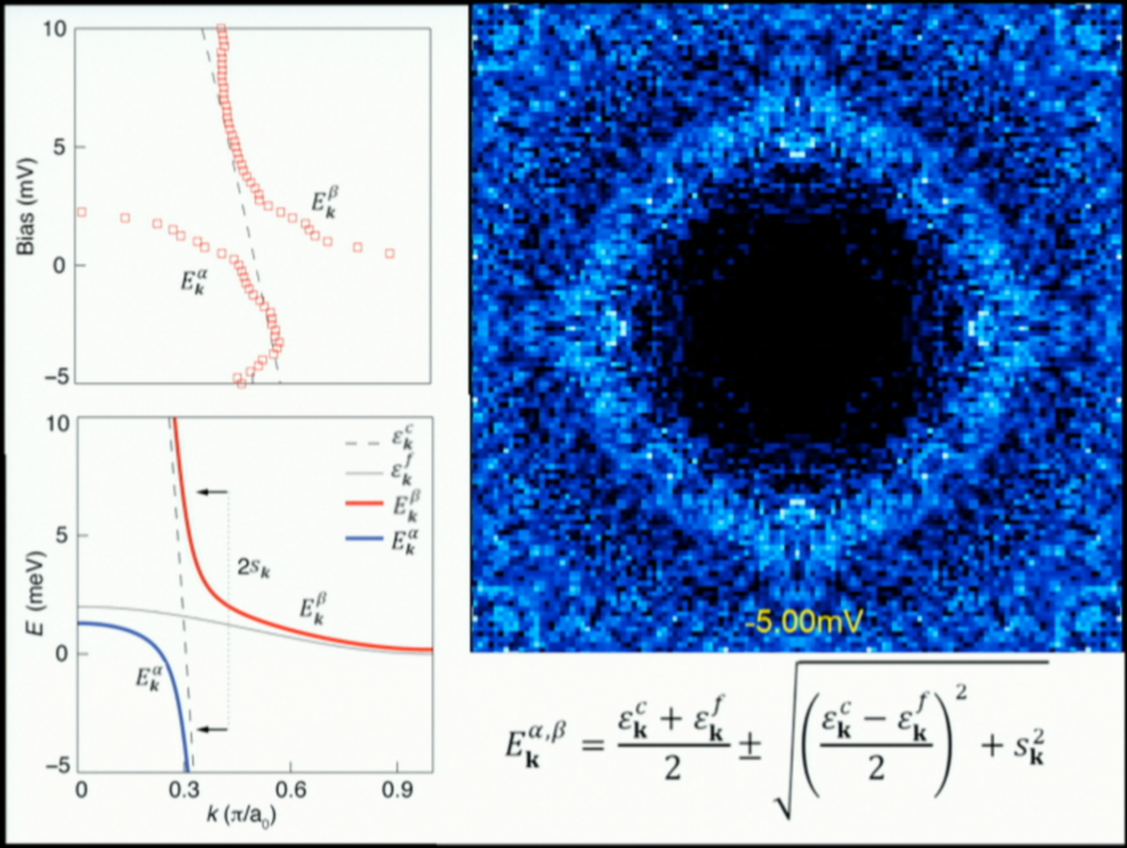


g(q,E) ➔ Heavy-Fermion QPI

$U_{0.99}Th_{0.01}Ru_2Si_2$

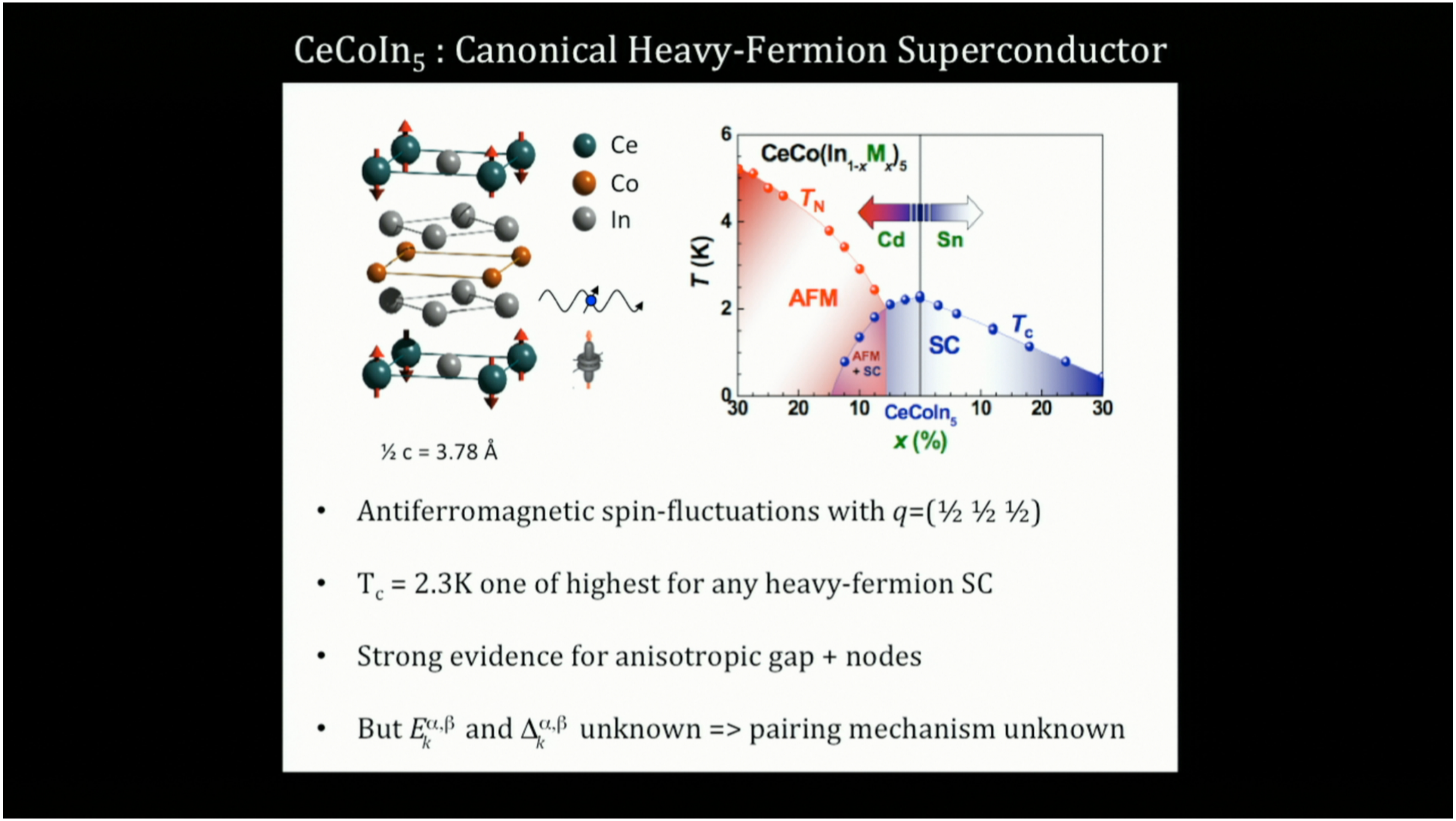
***Nature* 465,** 570 (2010)

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)



CeCoIn$_5$: Canonical Heavy-Fermion Superconductor

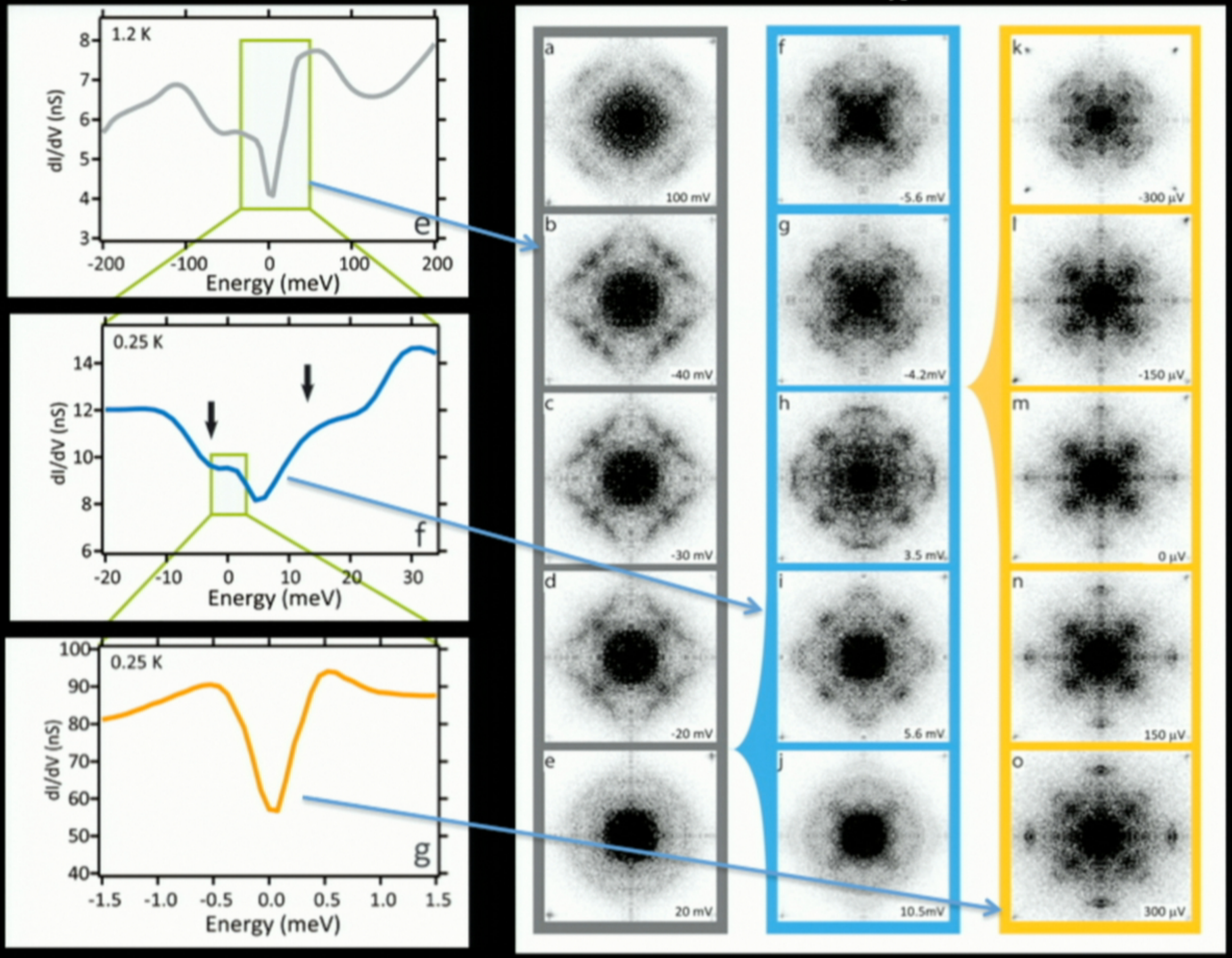
- Antiferromagnetic spin-fluctuations with q=(½ ½ ½)
- T_c = 2.3K one of highest for any heavy-fermion SC
- Strong evidence for anisotropic gap + nodes
- But $E_k^{\alpha,\beta}$ and $\Delta_k^{\alpha,\beta}$ unknown => pairing mechanism unknown

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

Light Band

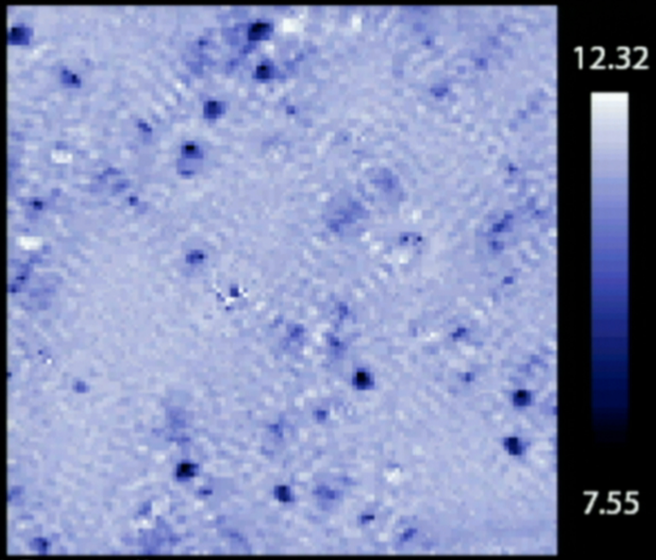
Heavy Bands

SC Gap



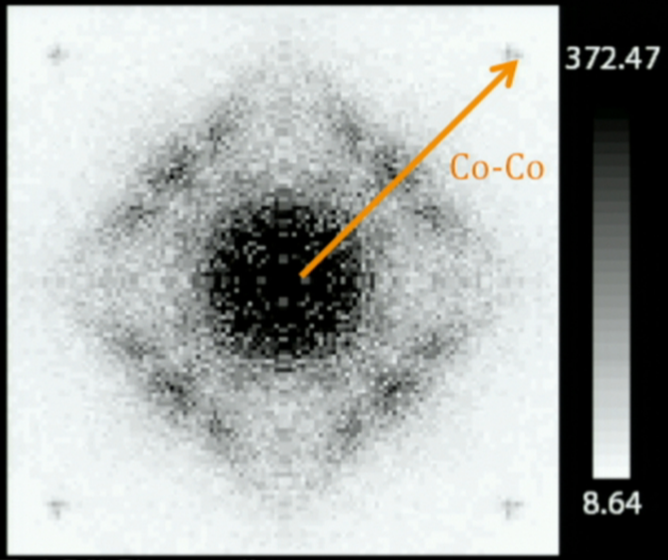
Measure : ε_k^c / $E_k^{\alpha,\beta}$

-40.5 mV



g(r,E) @ 250 mK

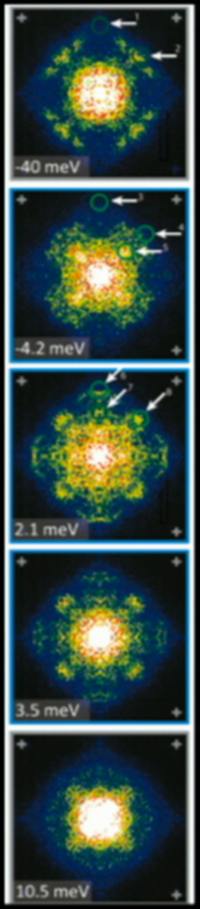
-40.5 mV

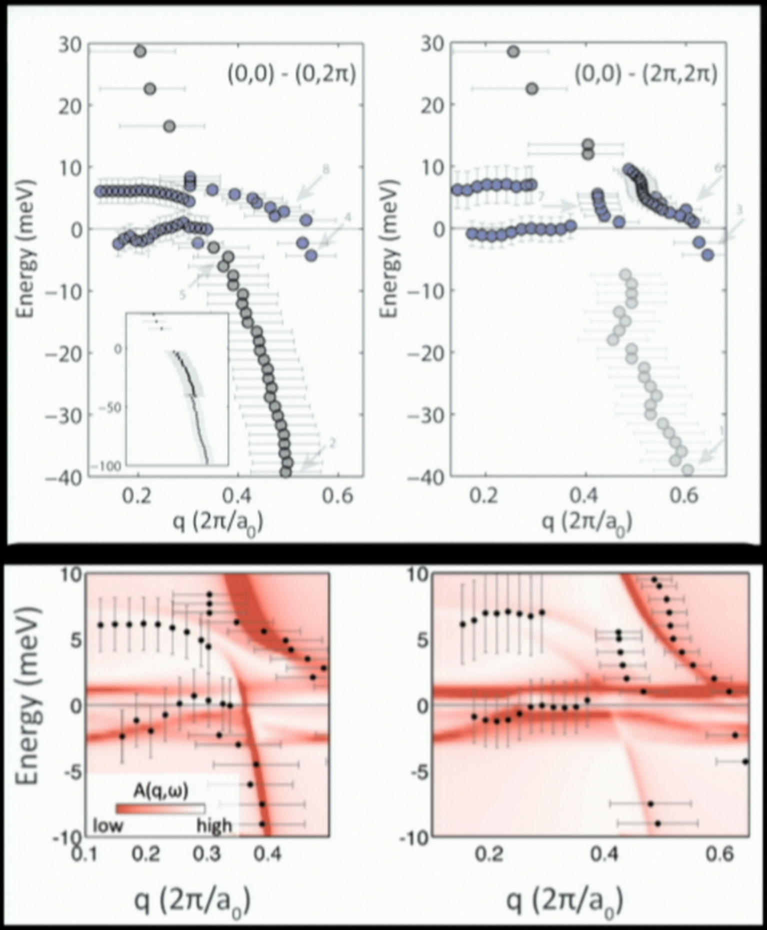


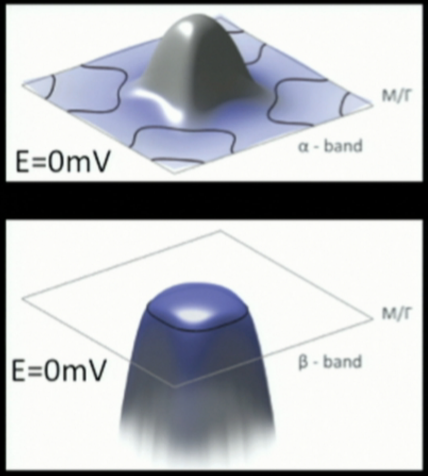
FFT(g(r,E)/I(r,E)) @ 250 mK

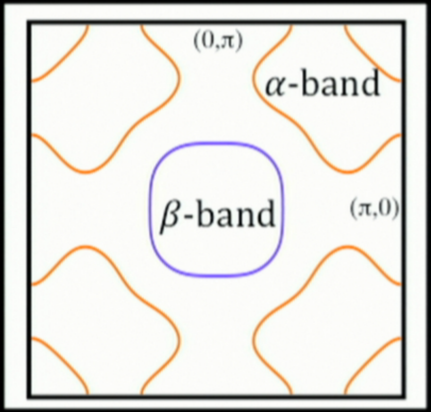
***Nature Physics* 9,** 468 (2013)

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



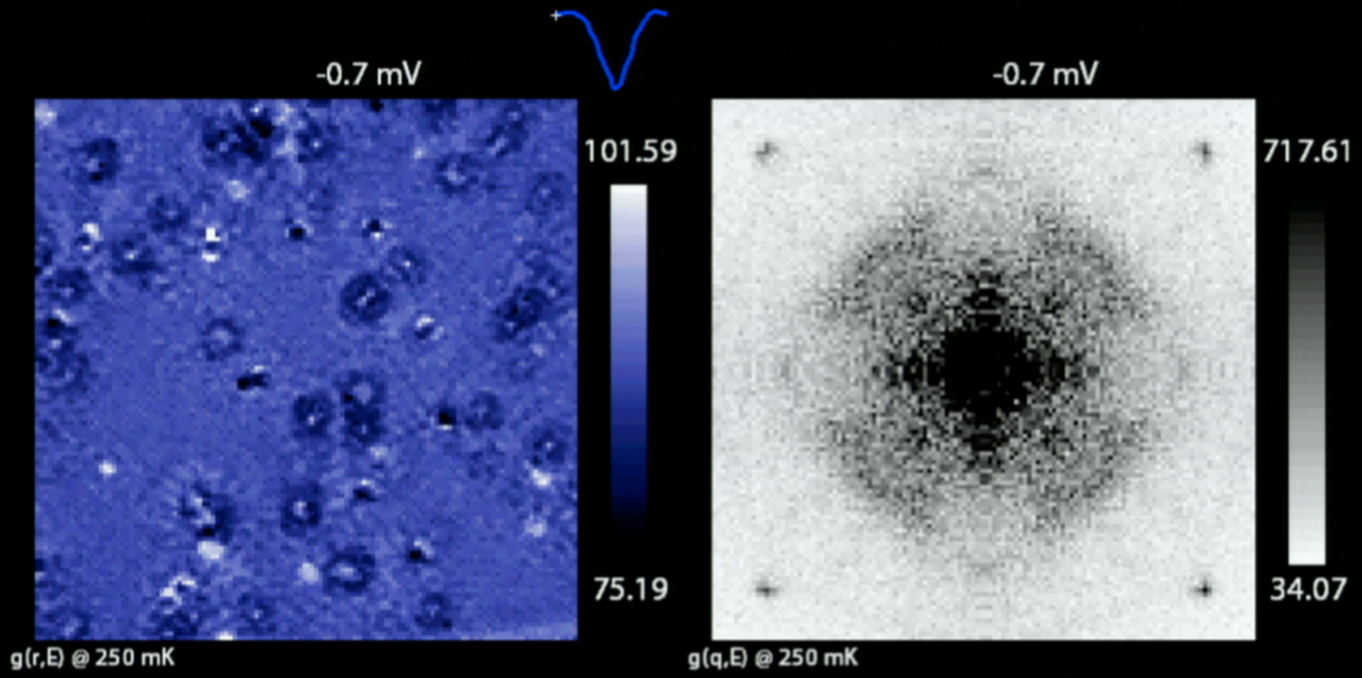






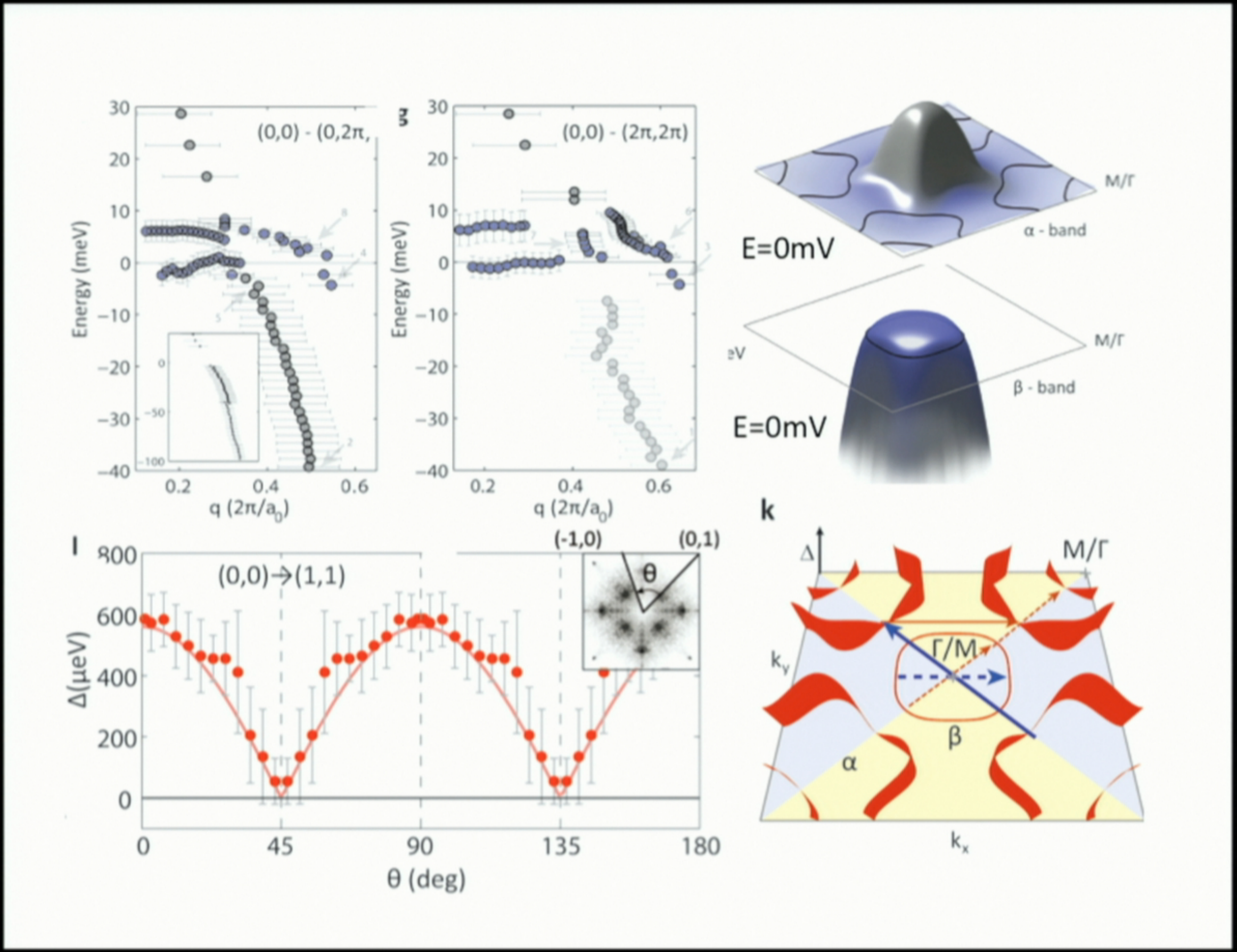
***Nature Physics* 9,** 468 (2013)

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



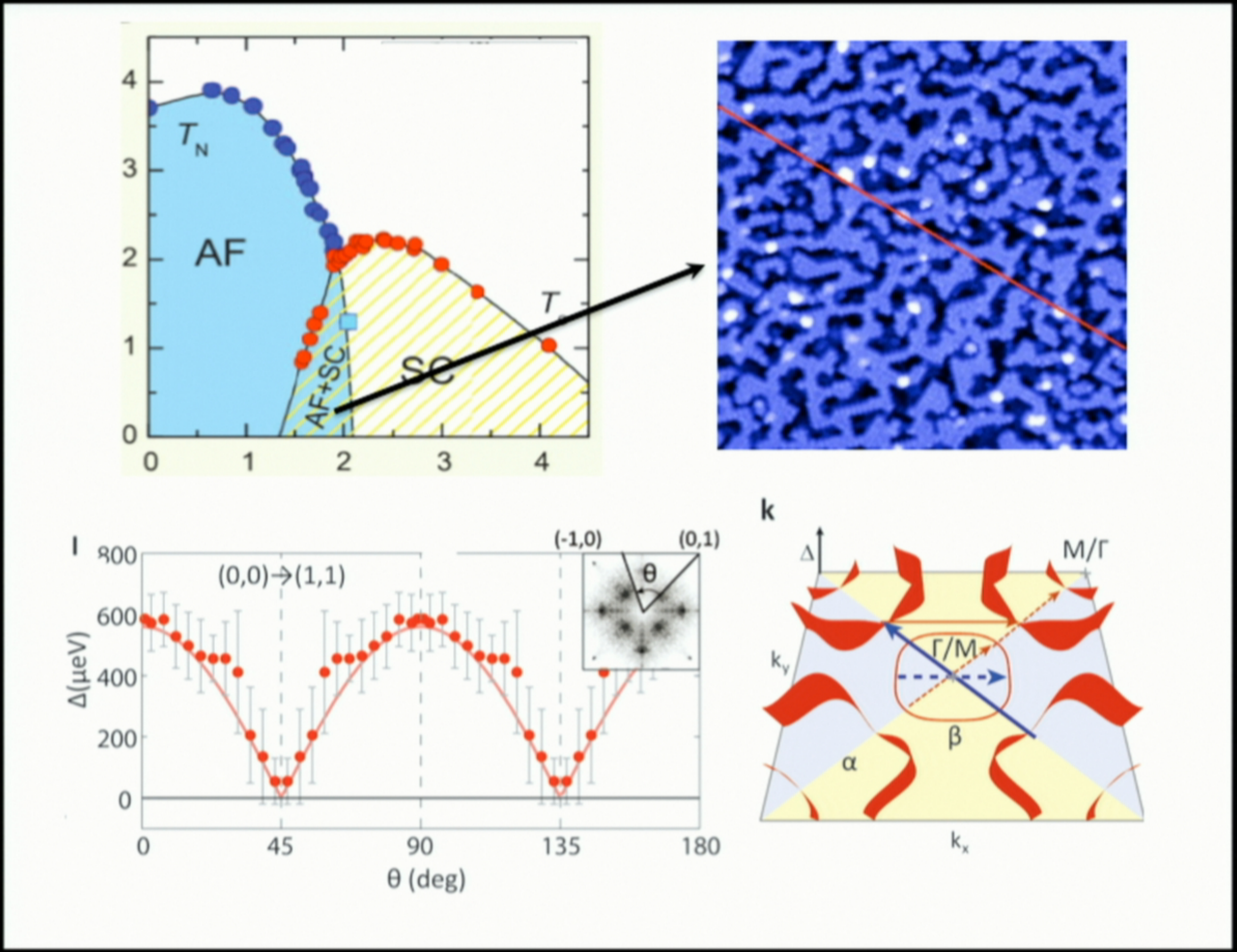
***Nature Physics* 9,** 468 (2013)

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

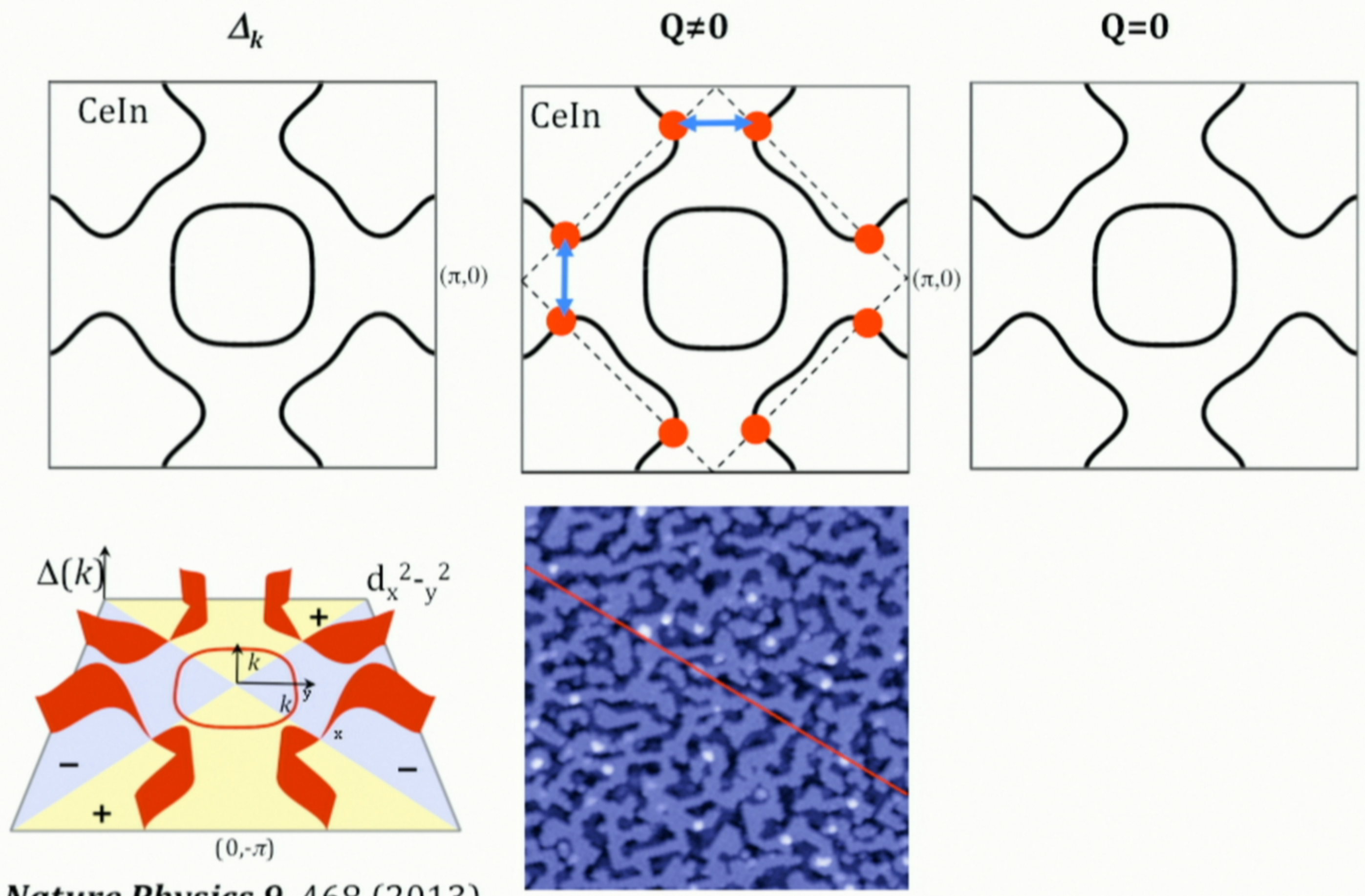


***Nature Physics* 9,** 468 (2013)

Heavy-Fermion Intertwined Electronic Phases ?

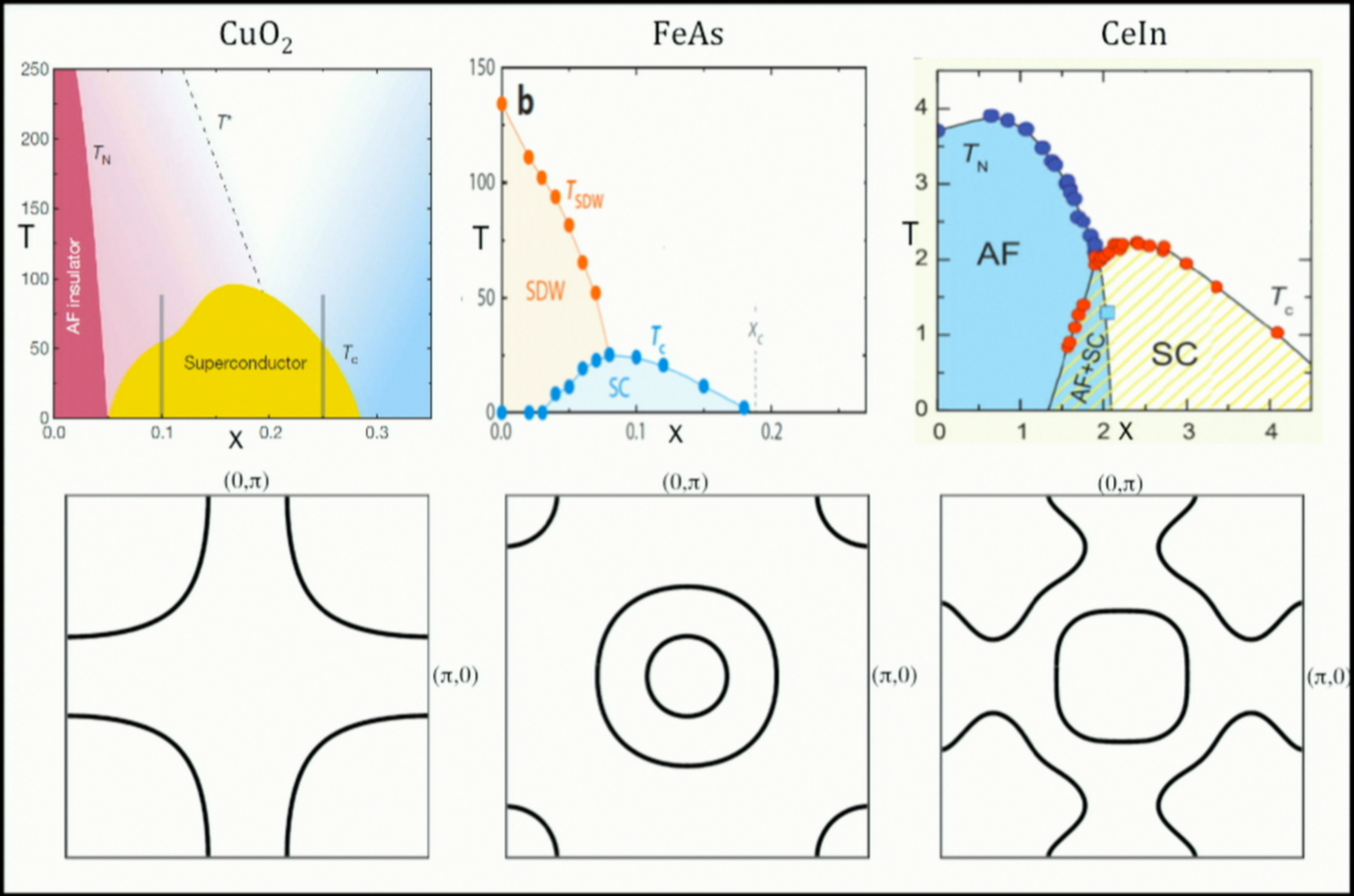


Heavy-fermion Energy Gaps Δ_k & Intertwined Phases

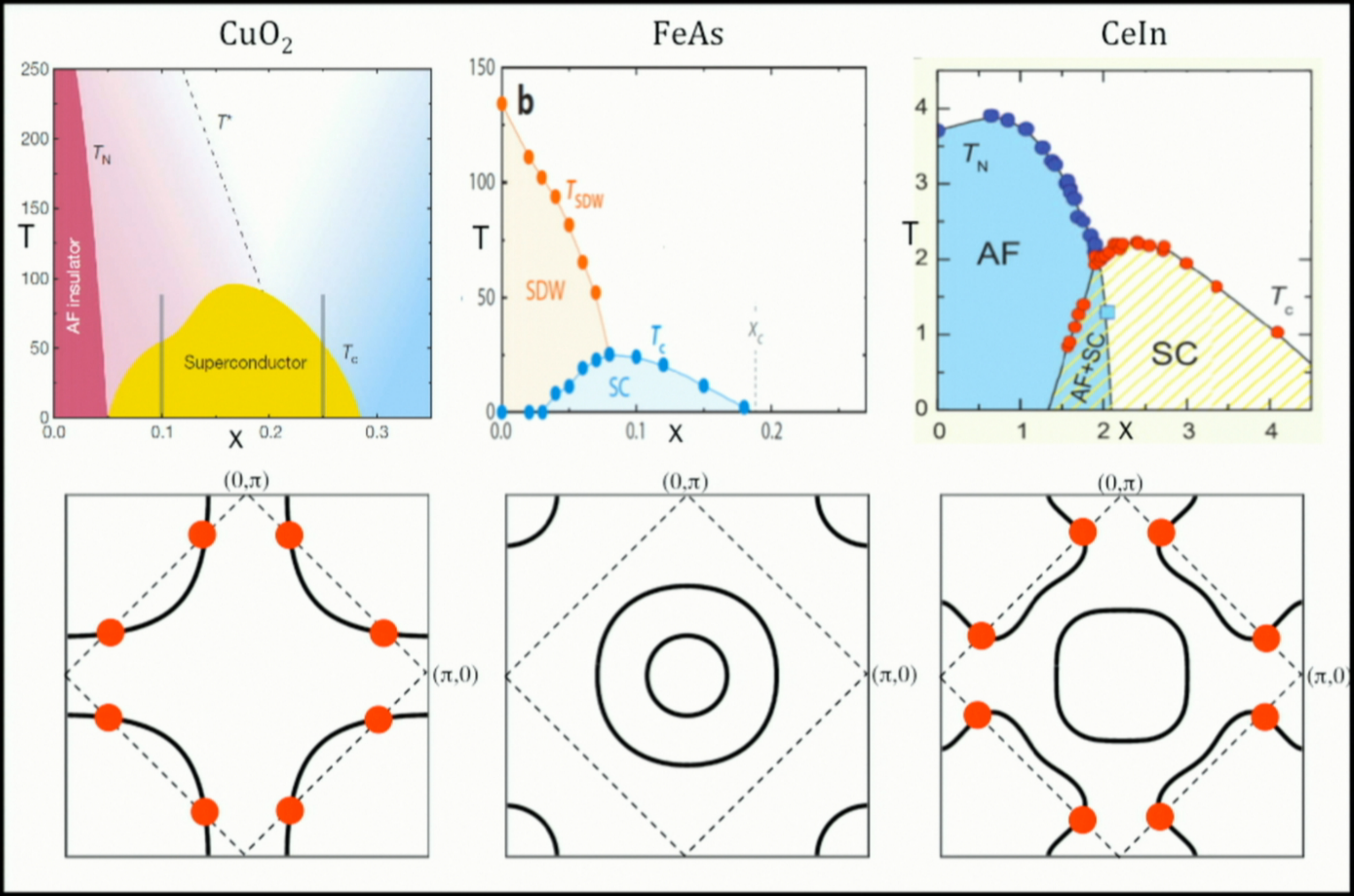


***Nature Physics* 9,** 468 (2013)

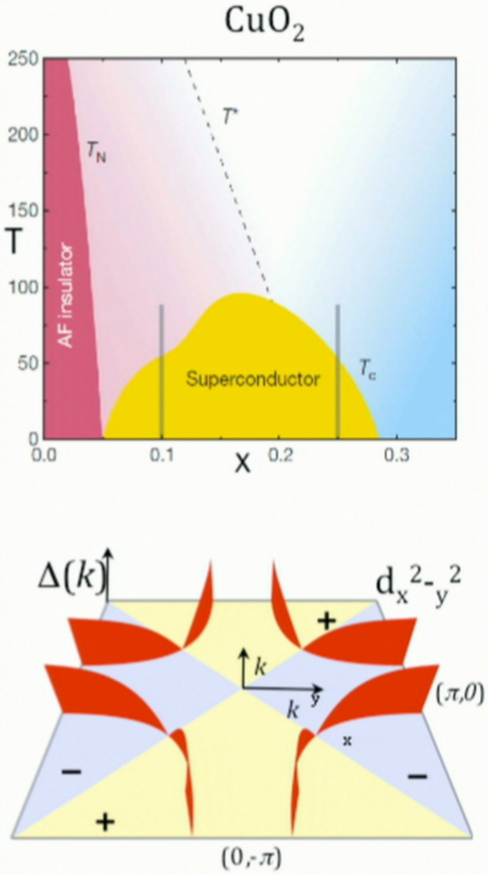
Distinct Fermi Surfaces



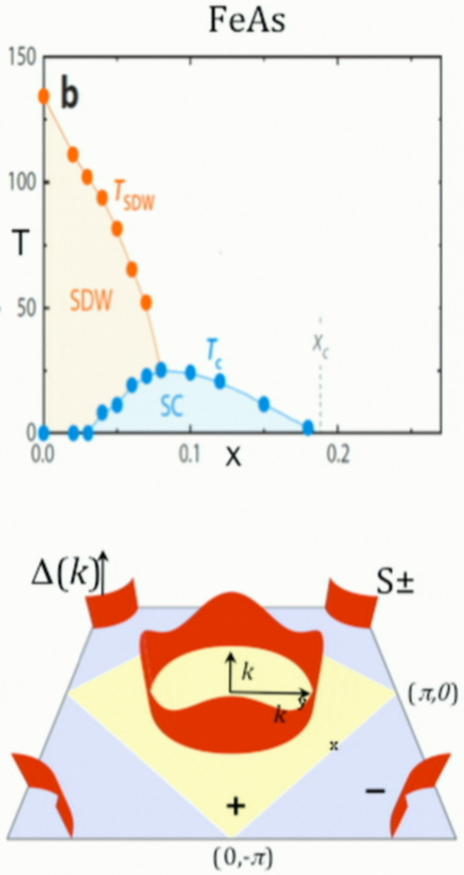
Distinct Antiferromagnetic 'Hot Spots'



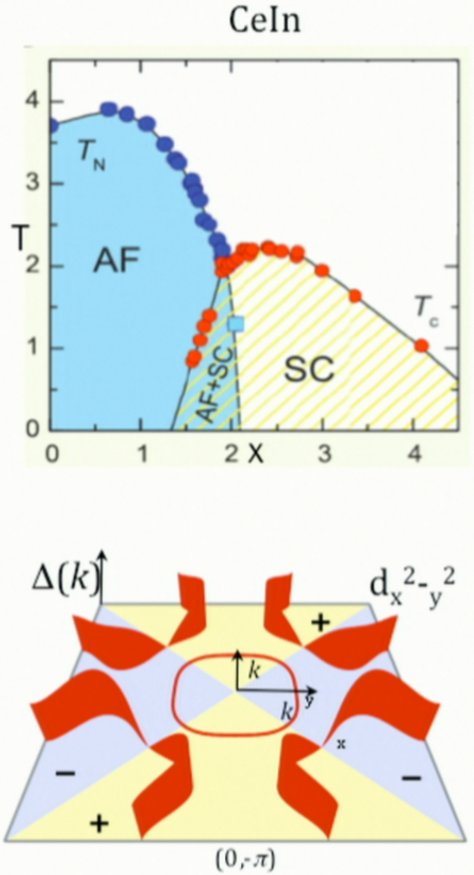
Distinct SC Gap Structure



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

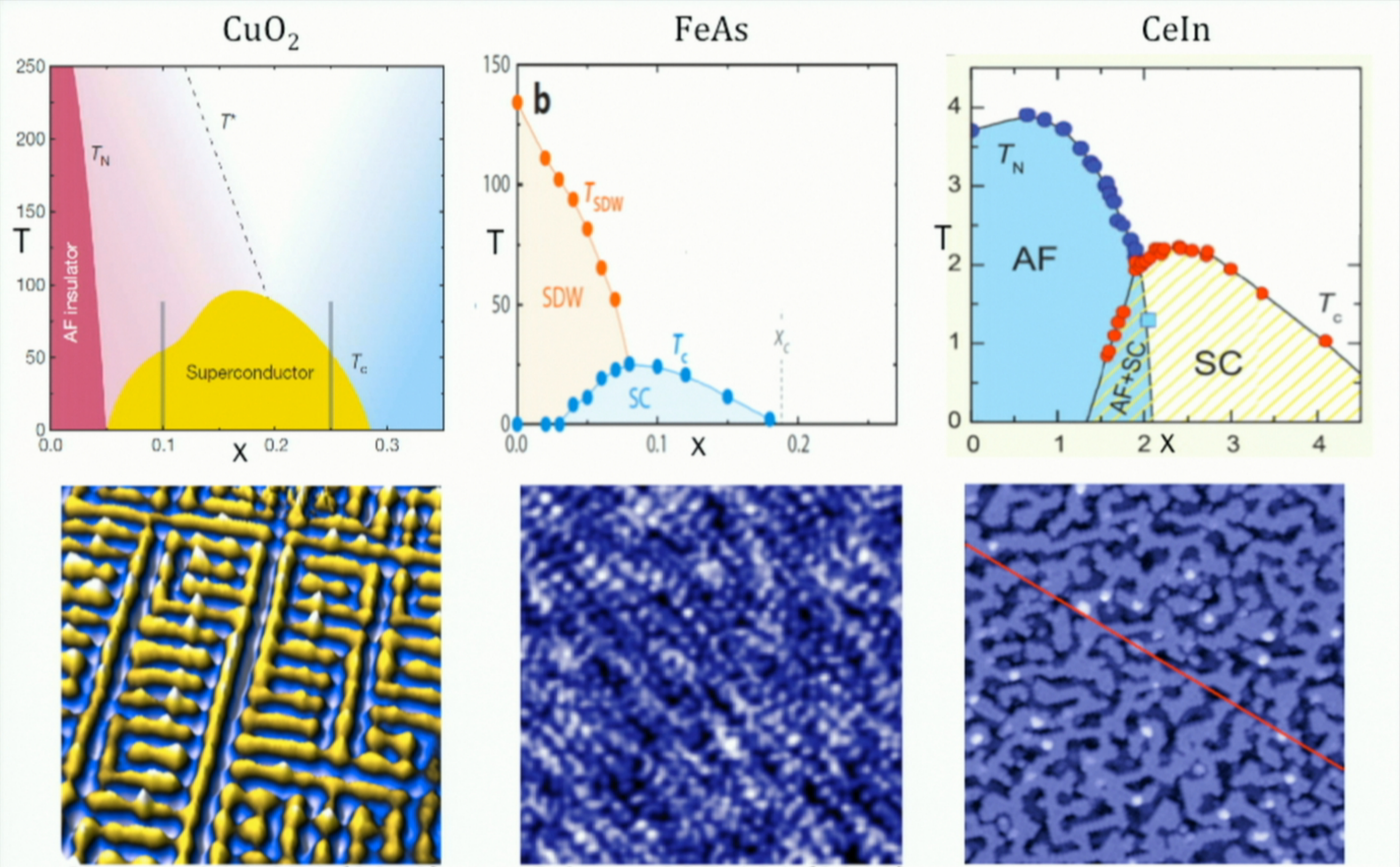


***Science* 336**, 563, (2012)



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

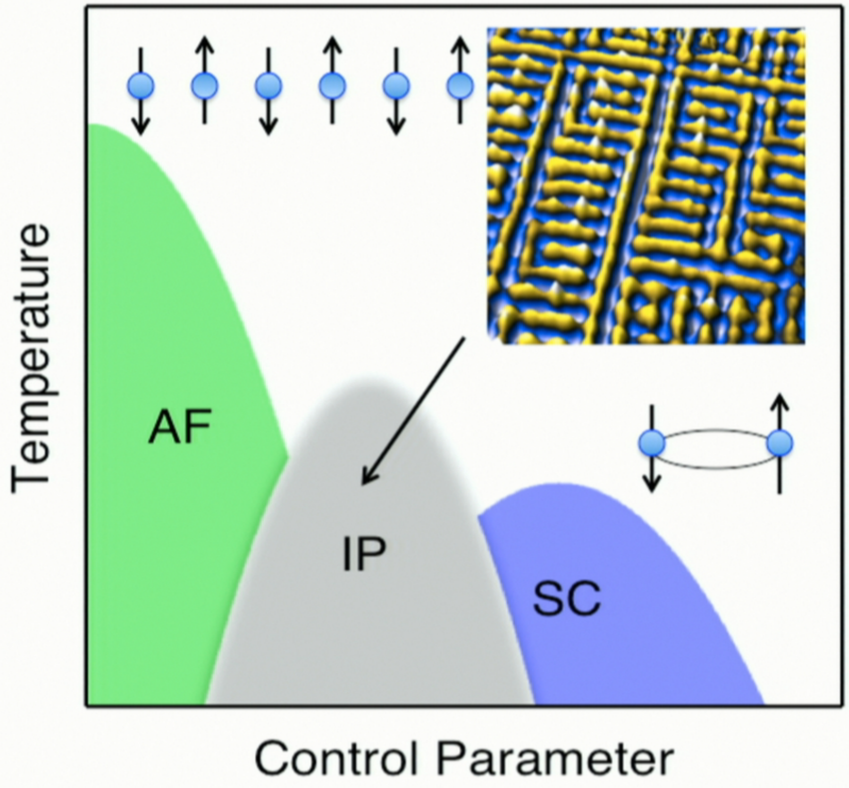
Distinct SC Intertwined Phases



***Nature* 466**, 374 (2010)

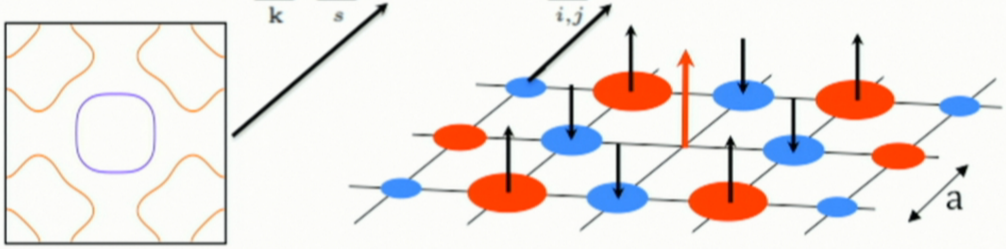
***Science* 327**, 181 (2010)

Single Simple Explanation Possible?



CONCEPTUAL FRAMEWORK LINKING AF, IP and SC

$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j.$$



$$\sum_{i,j} J_{ij}\vec{S}_i \cdot \vec{S}_j = \frac{1}{A}\sum_{\mathbf{k},\mathbf{p},\mathbf{q}} \sum_{s_{1,2,3,4}} V_{\mathbf{q}}(\mathbf{k};\mathbf{p})\psi^{\dagger}_{\mathbf{k}+\mathbf{q},s_1}\vec{\sigma}_{s_1,s_2}\psi_{\mathbf{k},s_2} \cdot \psi^{\dagger}_{\mathbf{p}-\mathbf{q},s_3}\vec{\sigma}_{s_3,s_4}\psi_{\mathbf{p},s_4}; \qquad [3]$$

where

$$V_{\mathbf{q}}(\mathbf{k};\mathbf{p}) = J(\mathbf{q})\{\phi^{*}_{\alpha(\mathbf{k}+\mathbf{q})}(\mathbf{k}+\mathbf{q})\cdot\phi_{\alpha(\mathbf{k})}(\mathbf{k})\} \times\{\phi^{*}_{\alpha(\mathbf{p}-\mathbf{q})}(\mathbf{p}-\mathbf{q})\cdot\phi_{\alpha(\mathbf{p})}(\mathbf{p})\}.$$

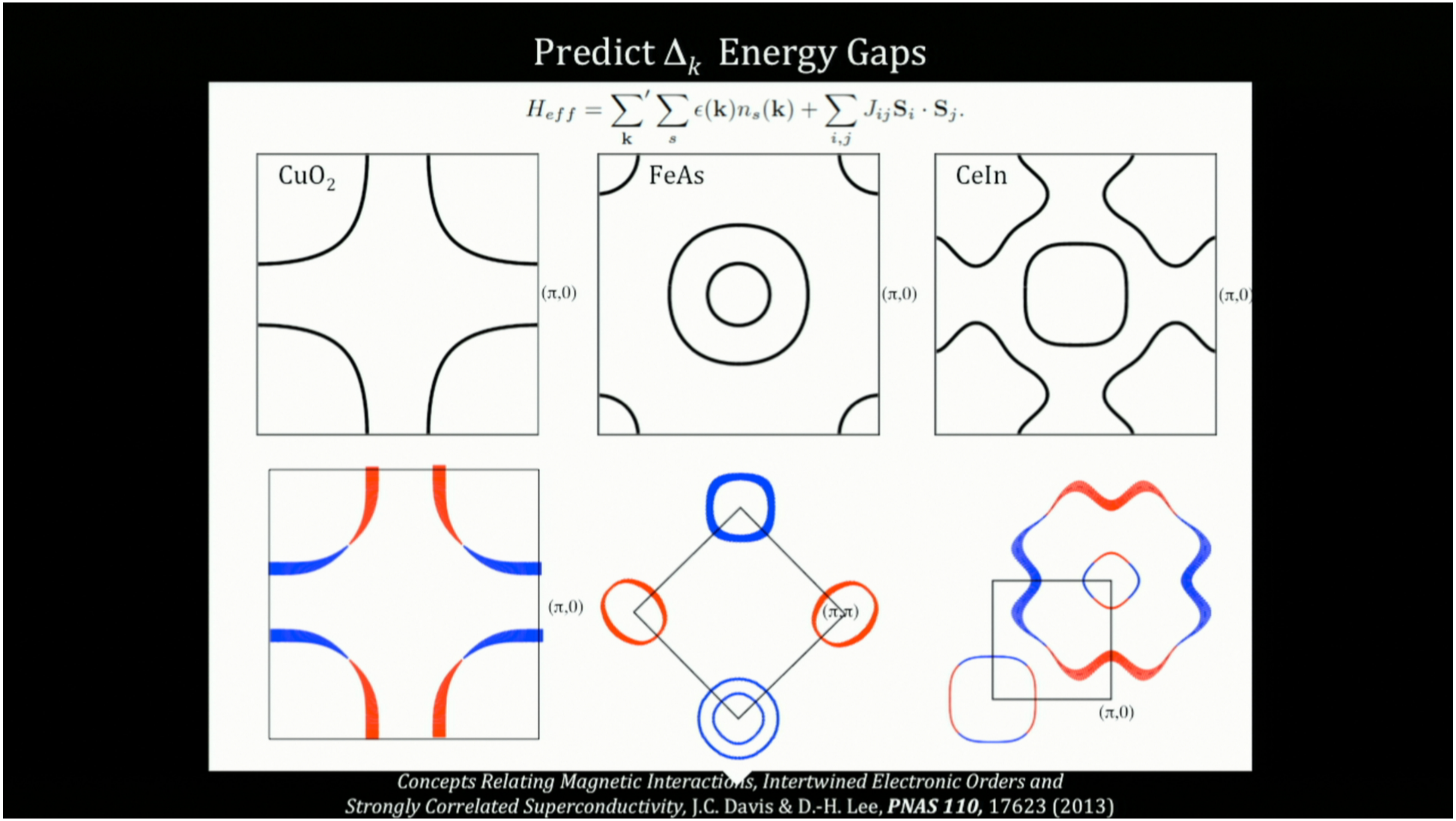
Here A is the total area, ϕ is the band eigen wavefunctions in the orbital basis, and $J(\mathbf{q})$ is the Fourier transform of J_{ij}. For the copper-based, iron-based, and heavy fermion superconductors $J(\mathbf{q})$ is taken to be an over all coupling strength J_{eff} times the following form factors:

$$\begin{aligned}&\cos k_x + \cos k_y(\text{copper}-\text{based})\\ &\cos\theta(\cos k_x + \cos k_y) + \sin\theta(2\cos k_x \cos k_y)(\text{iron}-\text{based})\\ &\cos k_x + \cos k_y(\text{heavy}-\text{fermion}),\end{aligned} \qquad [4]$$

The next step is to decouple Eq. (3) in the particle-particle (for Cooper pairing) and particle-hole (for charge and spin density wave and Pomeranchuk). The "first-instability-mode analysis" described in section I-III allows us to determine the functional form of the order parameter. However it does not fix the overall magnitude. Once the functional form is determined we use the mean-field Hamiltonians described in section I-III to determine the energy gaps, fermi surface distortions,

Determine using a single Hamiltonian
(but different Fermiology)
I SC Order Parameters
II Q=0 IUC Order Parameters
III Q≠0 CDW Order Parameters
IV Q≠0 SDW Order Parameters
for cuprates/pnictides/heavy fermions.

Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS 110,*** 17623 (2013)



Predict Δ_k Energy Gaps

$$H_{eff} = {\sum_{\mathbf{k}}}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j.$$

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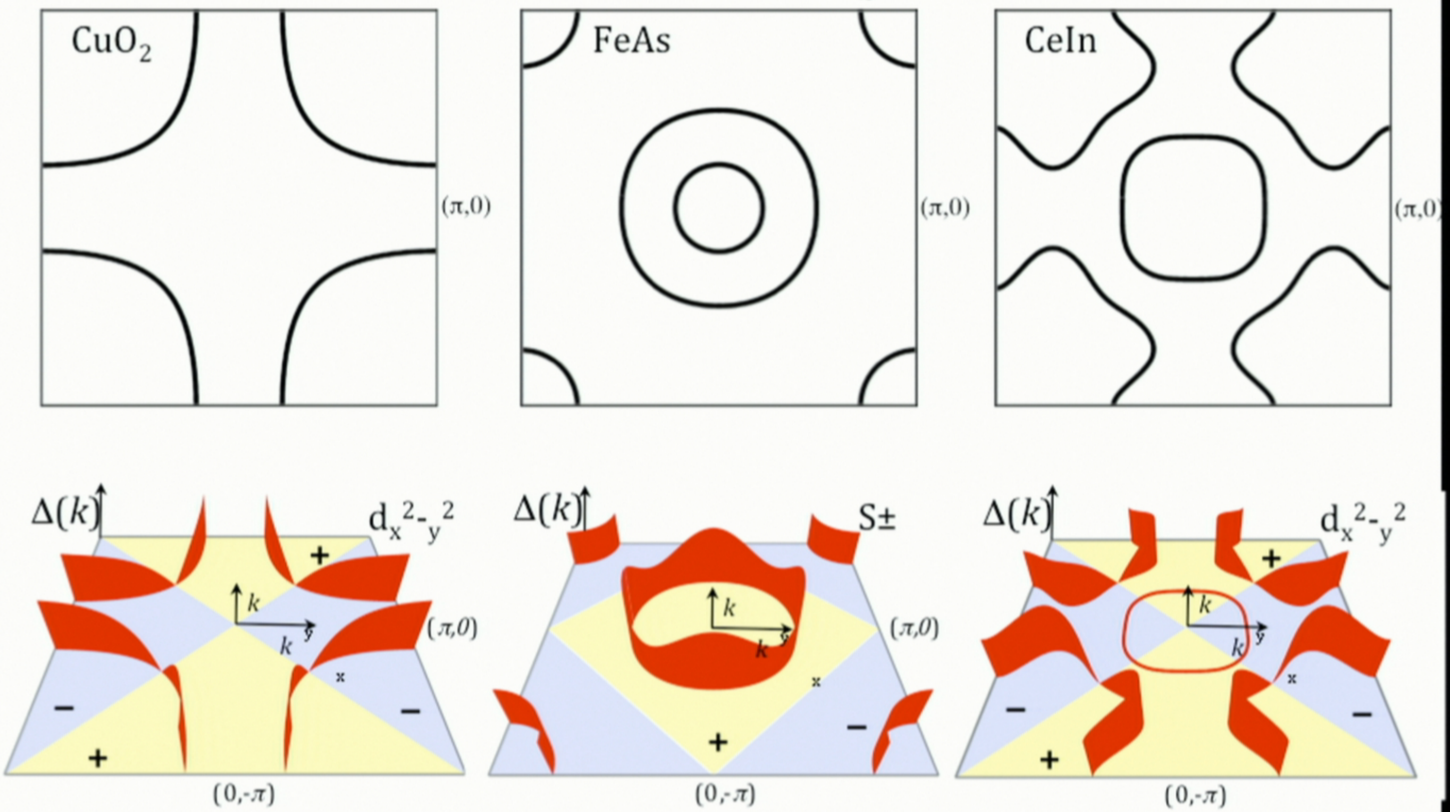
Measured Δ_k Energy Gaps

$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j .$$

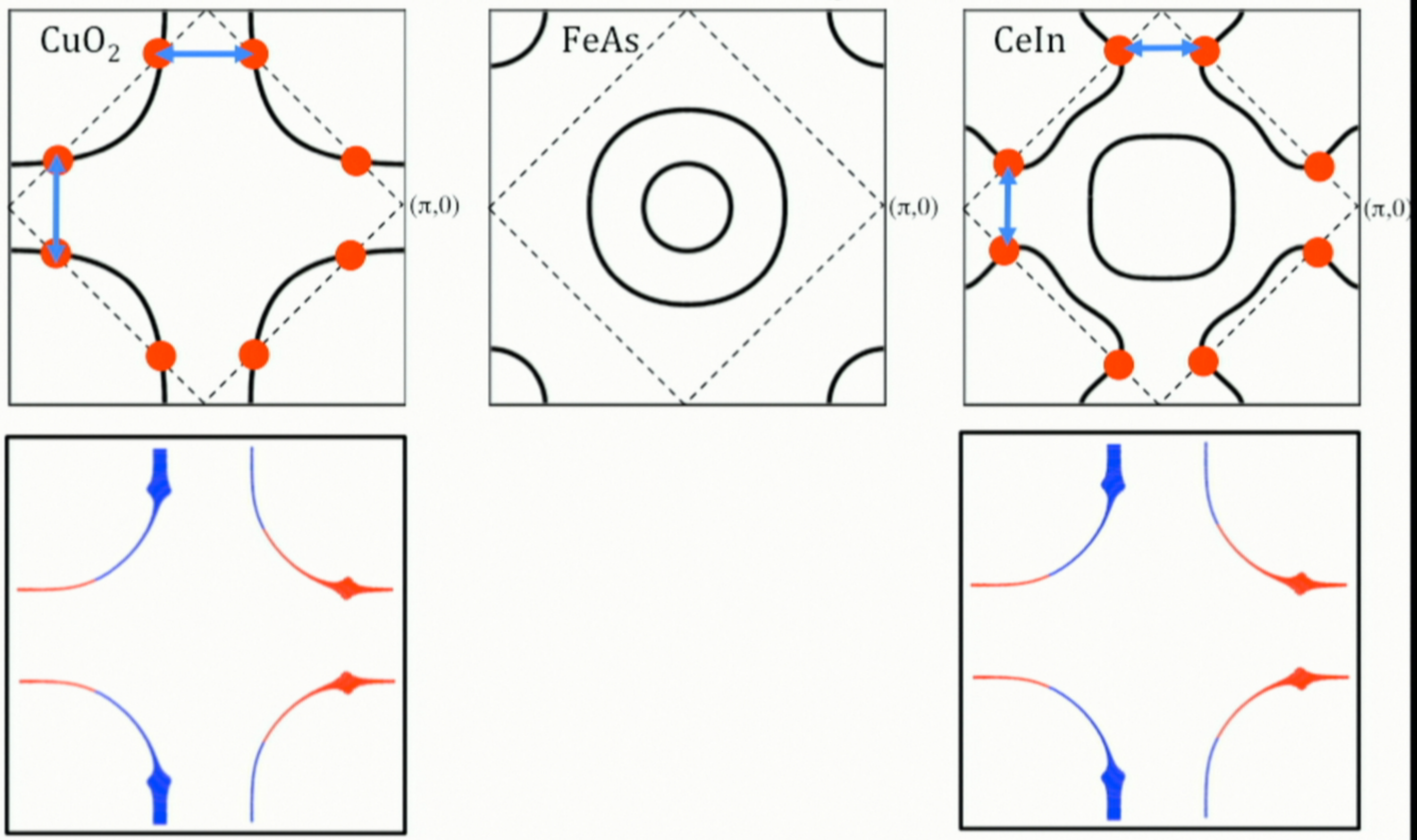


***Nature* 454,** 1072, (2008) ***Science* 336**, 563, (2012) ***Nature Physics* 9,** 468 (2013)

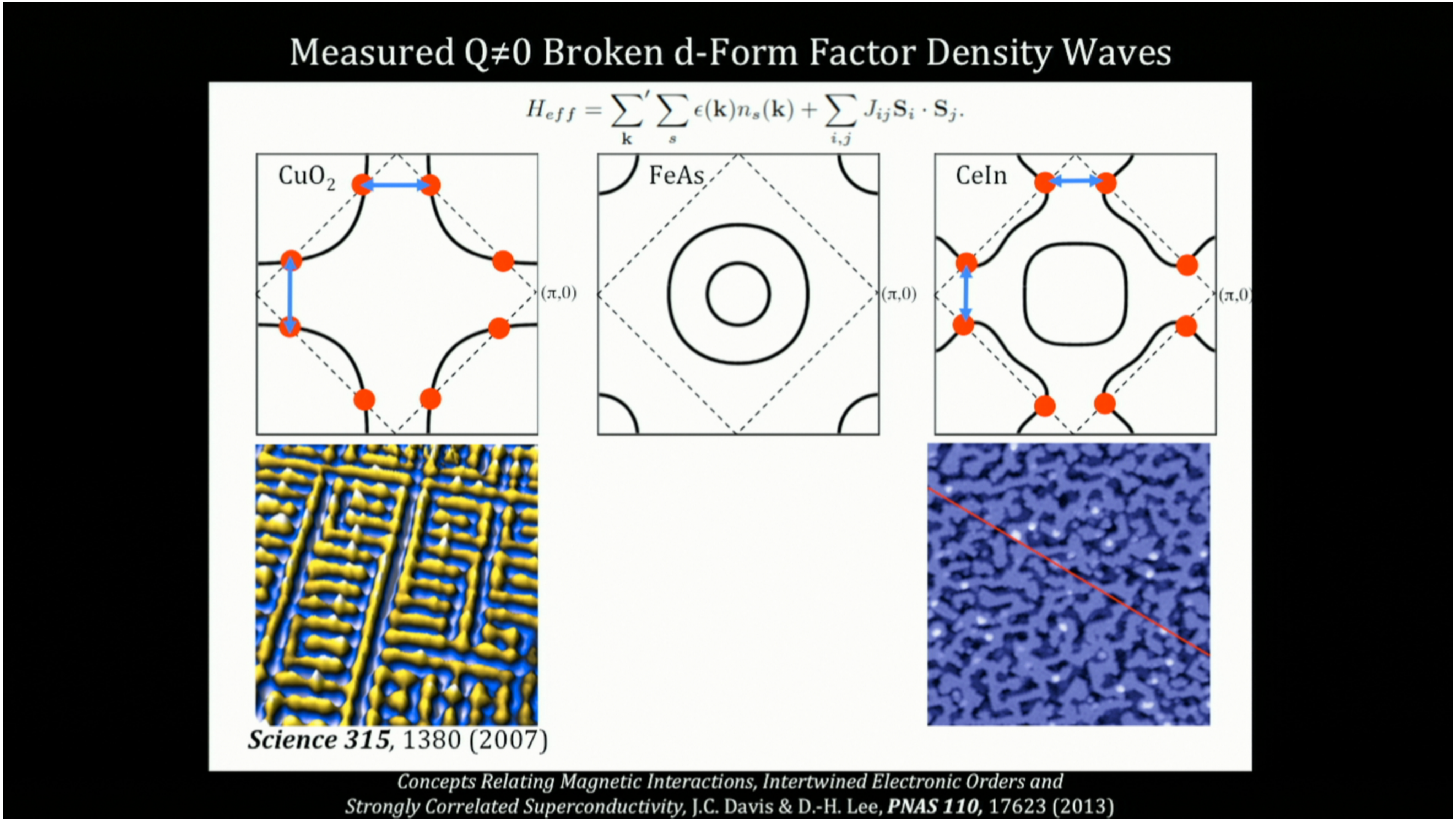
Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS* 110,** 17623 (2013)

Predicted Q≠0 Broken Symmetry (Density Wave) Phases

$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j.$$



Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS 110***, 17623 (2013)



Measured Q≠0 Broken d-Form Factor Density Waves

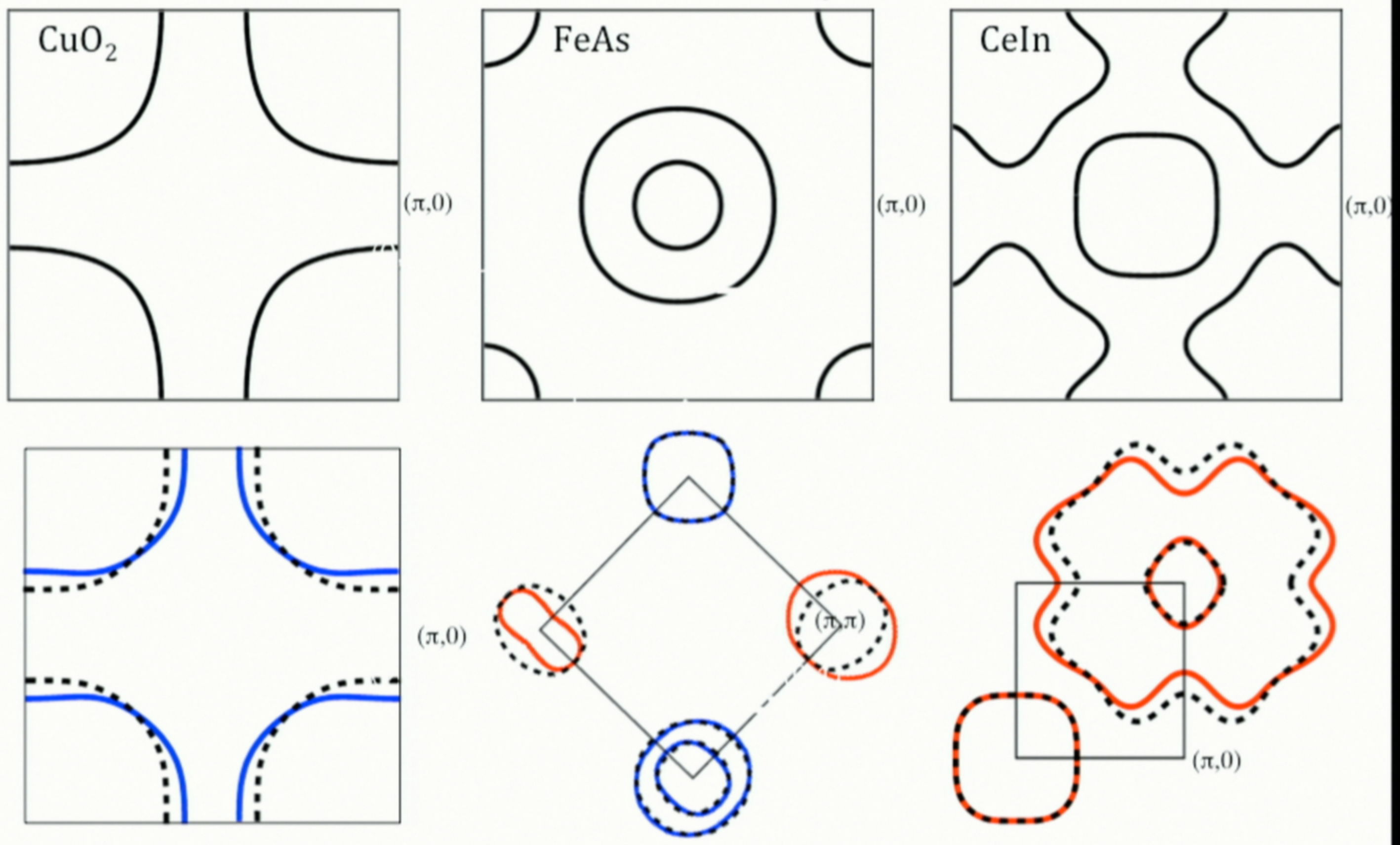
$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j.$$

***Science* 315**, 1380 (2007)

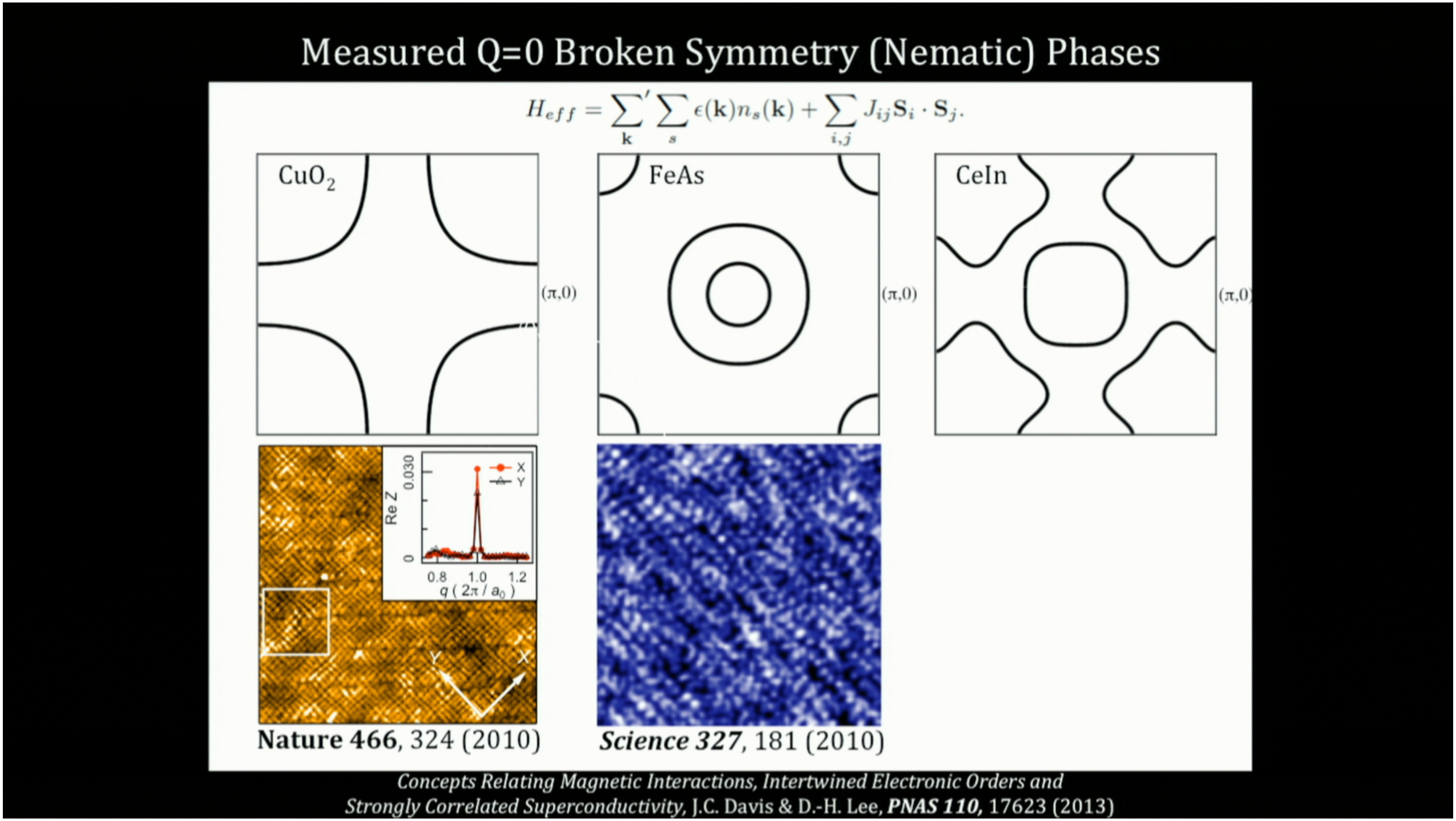
Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS* 110**, 17623 (2013)

Predicted Q=0 Broken Symmetry (Nematic) Phases

$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j.$$



Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS 110,*** 17623 (2013)



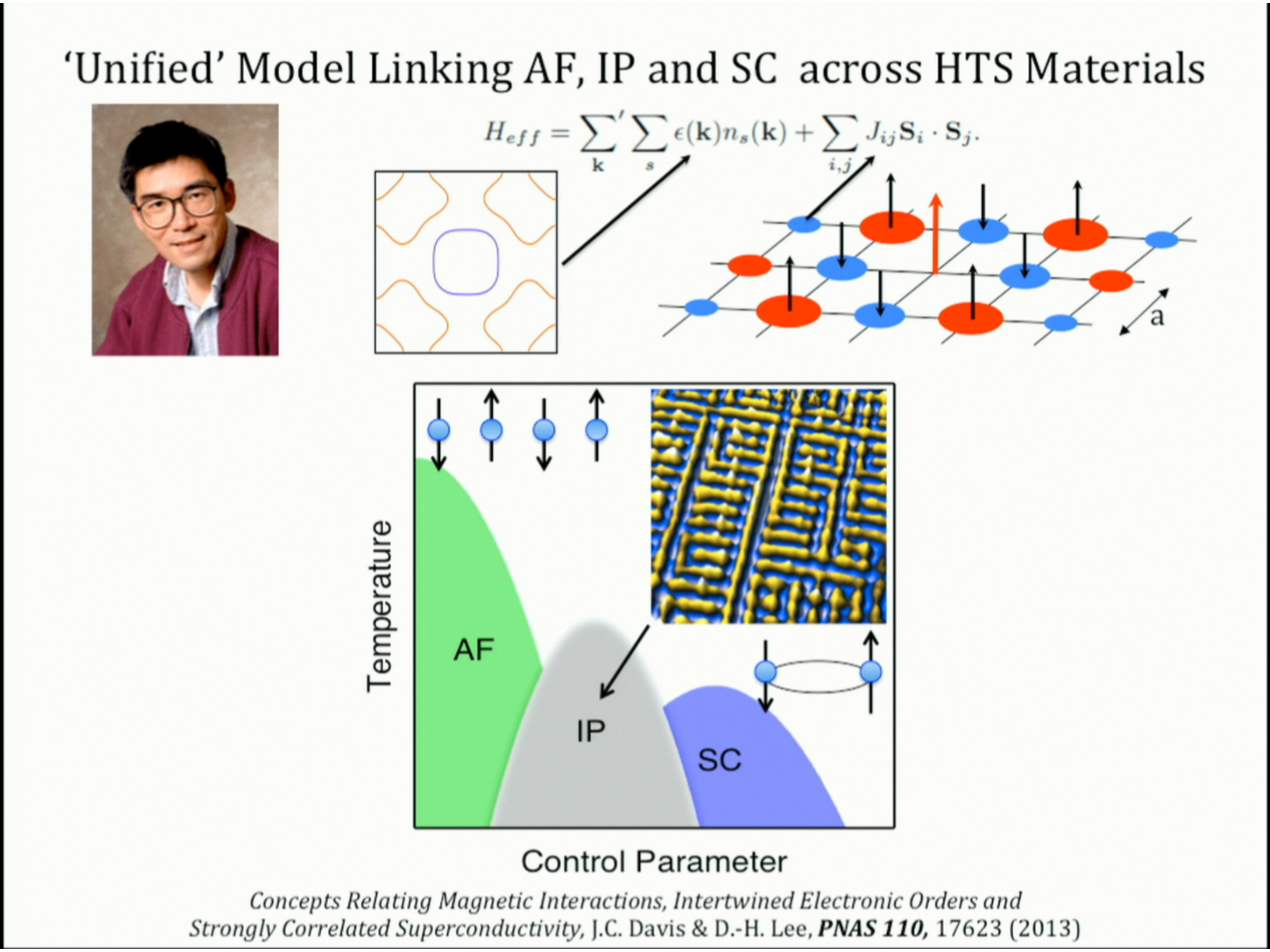
Measured Q=0 Broken Symmetry (Nematic) Phases

$$H_{eff} = {\sum_{\mathbf{k}}}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j.$$

Nature 466, 324 (2010)

Science 327, 181 (2010)

Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS 110***, 17623 (2013)

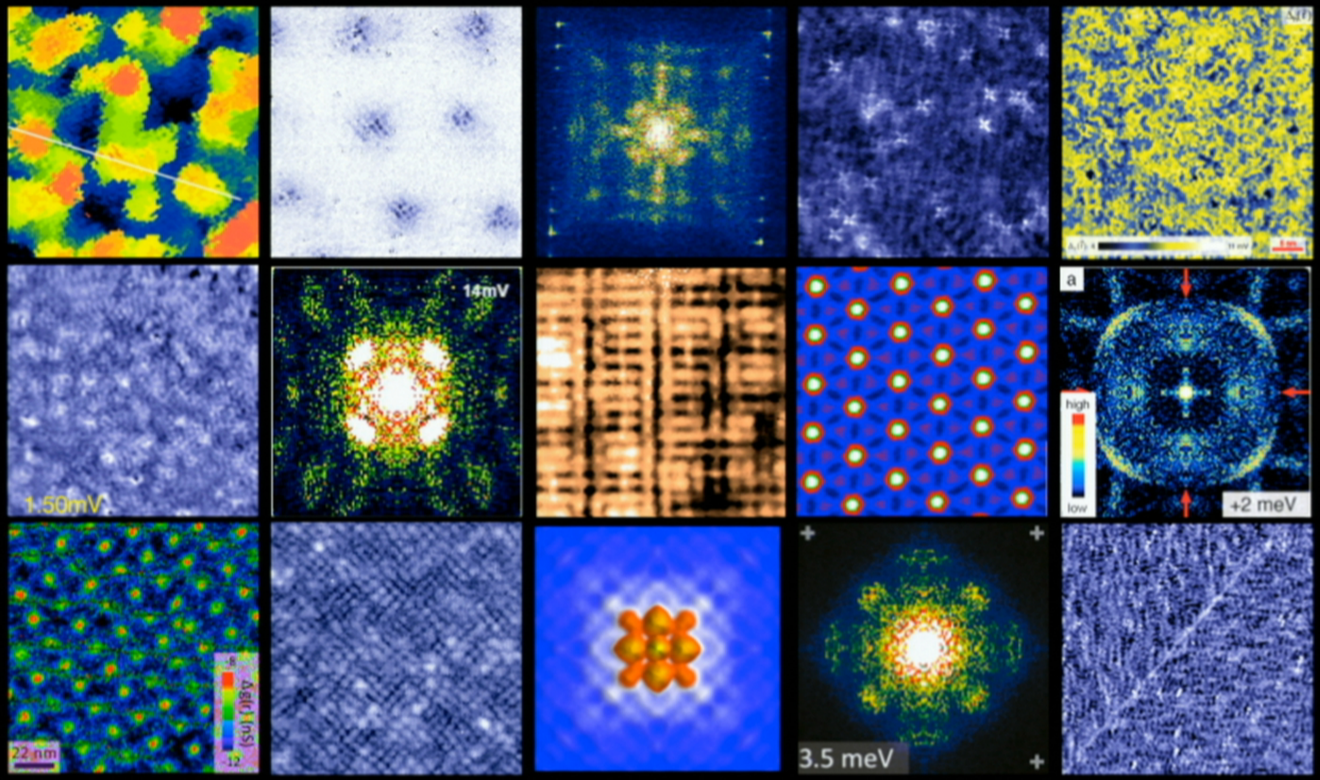


'Unified' Model Linking AF, IP and SC across HTS Materials

$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j.$$

Concepts Relating Magnetic Interactions, Intertwined Electronic Orders and Strongly Correlated Superconductivity, J.C. Davis & D.-H. Lee, ***PNAS 110,*** 17623 (2013)

THANKS!



J.C. Séamus Davis

Cornell University

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