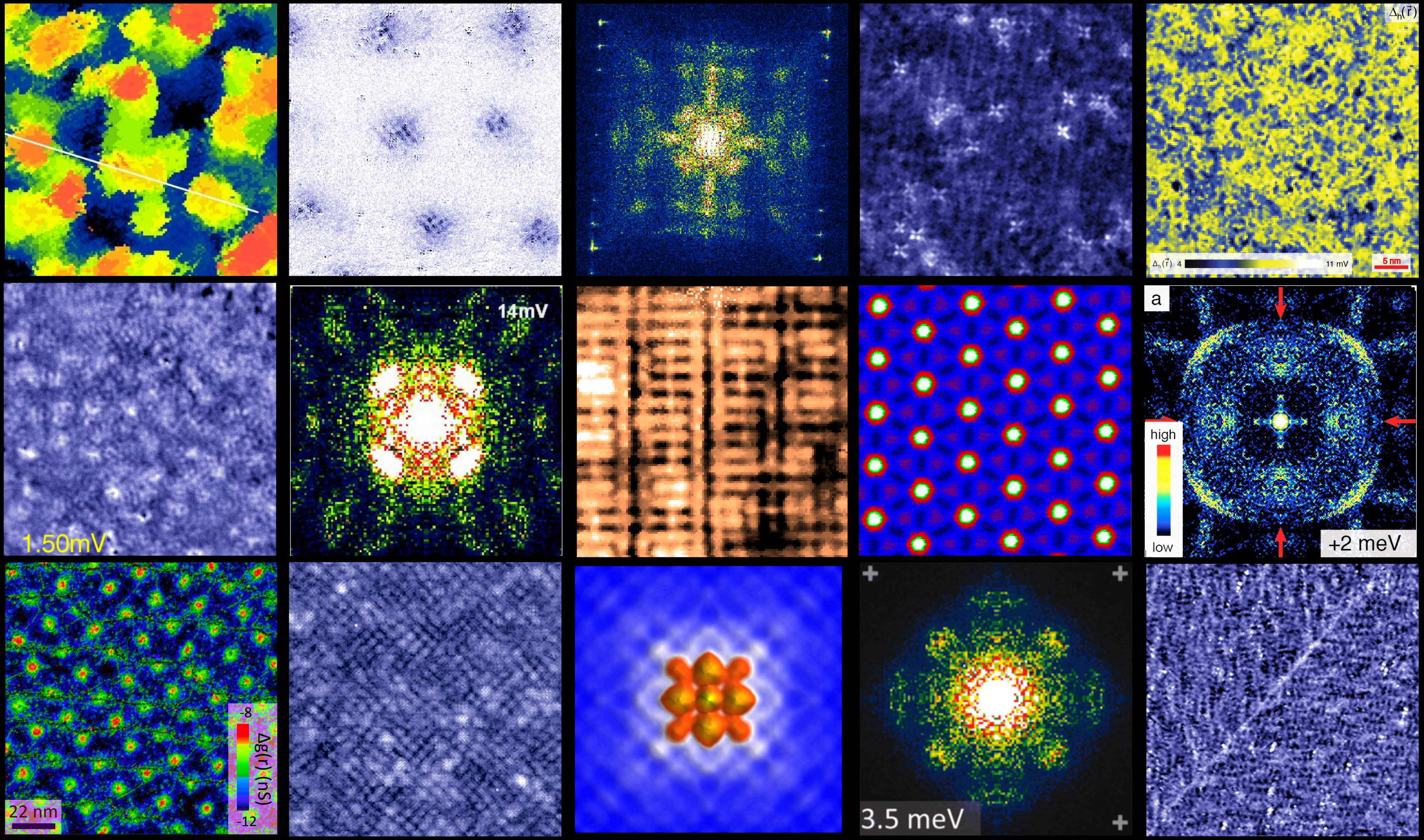
VISUALIZING THE QUANTUM WORLD



Cornell University

BROOKHAVEN
NATIONAL LABORATORY

St. Andrews

STOP ME & ASK QUESTIONS!

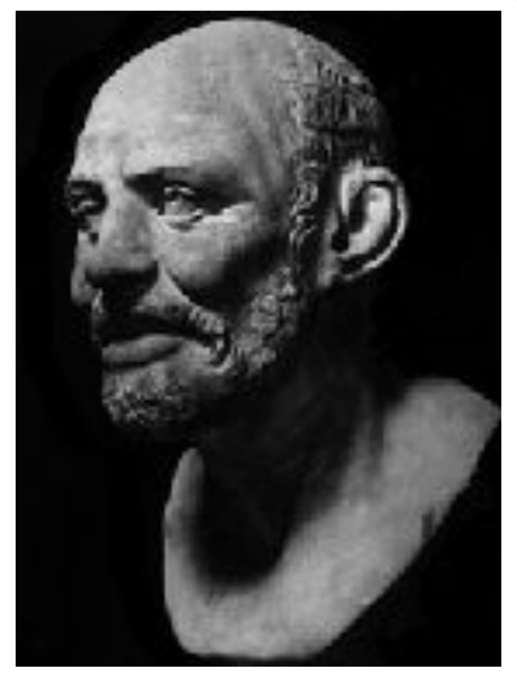
Cornell University

BROOKHAVEN
NATIONAL LABORATORY

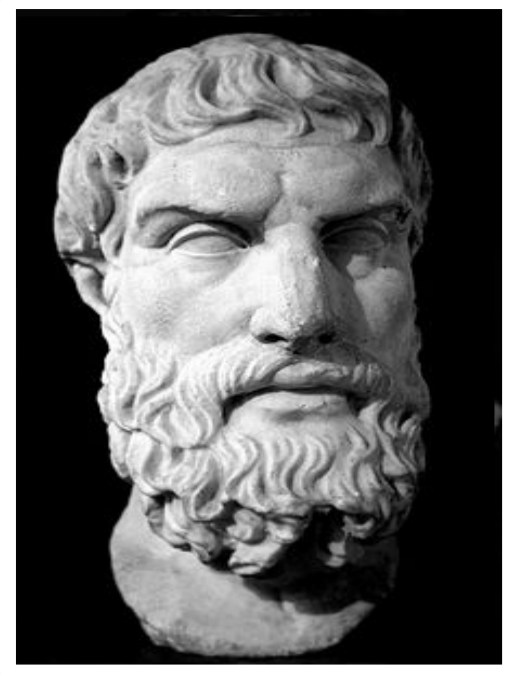
St. Andrews

ELEMENTARY CONSTITUENTS OF MATTER ?

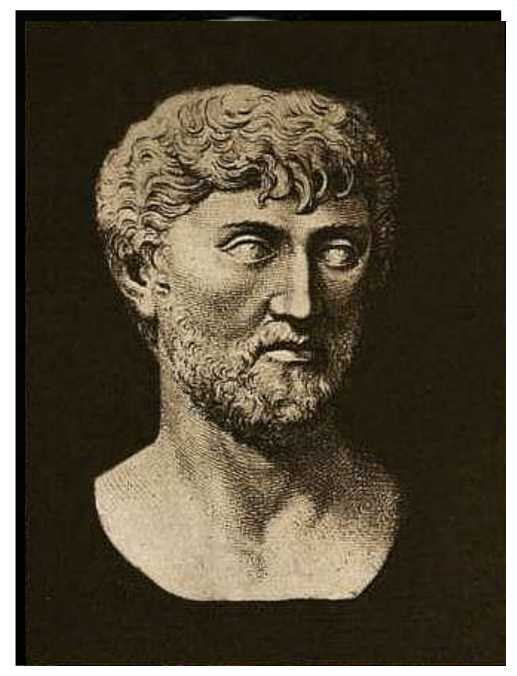
Atomos: Indivisible



Democritus of Abdera
460-370 BCE

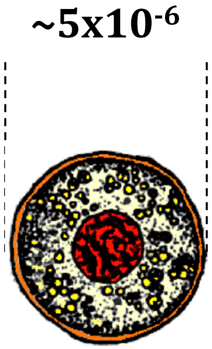


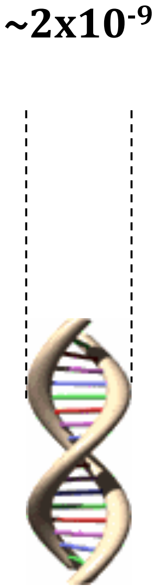
Epicurus of Samos
342-270 BCE

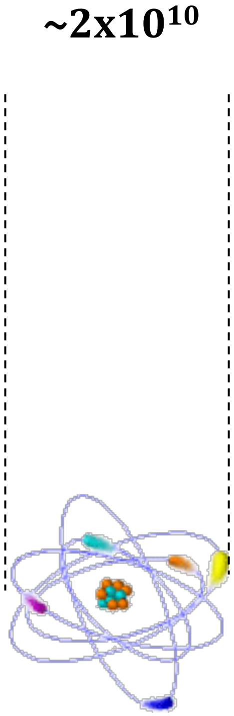


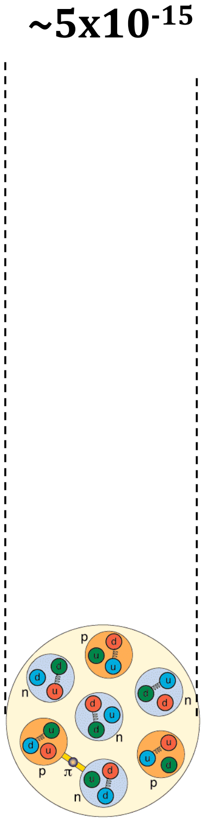
Titus Lucretius
99-55 BCE

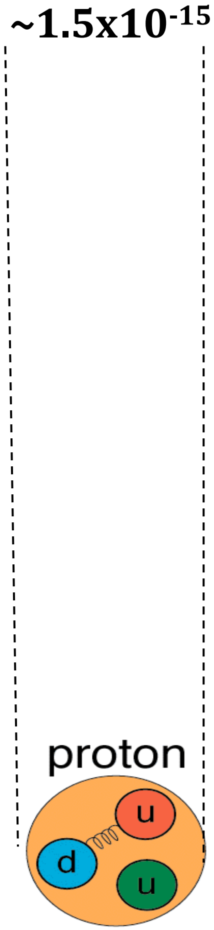
ELEMENTARY CONSTITUENTS OF MATTER











Quarks and electrons are the most elementary stable constituents of matter that we know about today. They are no larger than 10^{-18} m. All matter in our world made of ONLY these two particles.

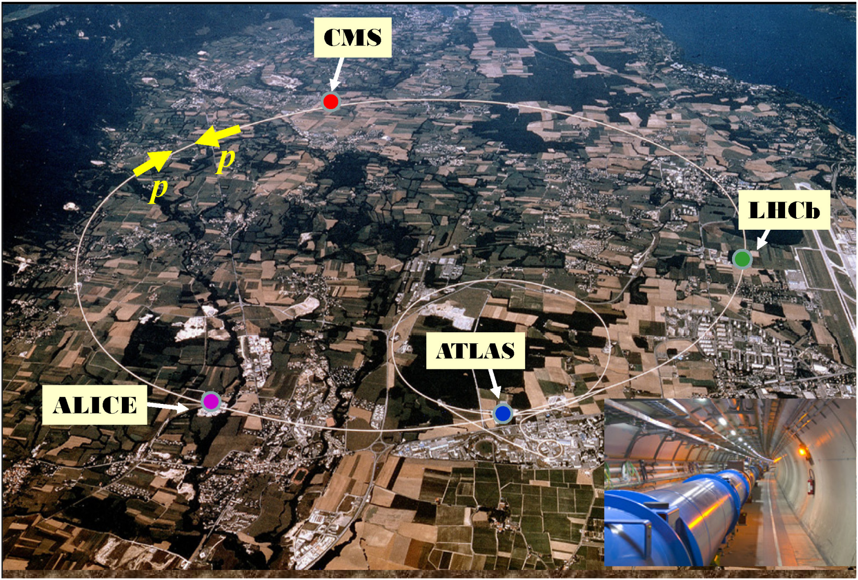
EXPLORING QUANTUM MATTER


Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

COSMOS

CONDENSED



COLLIDER

QUANTUM MECHANICS

FREE ELECTRONS – MATTER WAVES

Schrödinger matter waves

$$\Psi(\vec{r},t)$$

predict probability of events

$$P = |\Psi(\vec{r},t)|^2$$

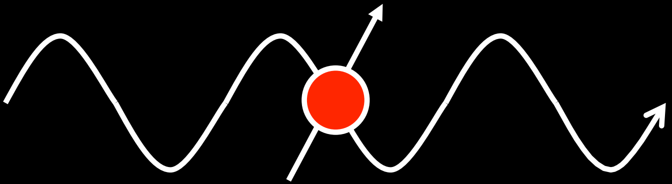
MASS: $m = 10^{-30}$ Kg

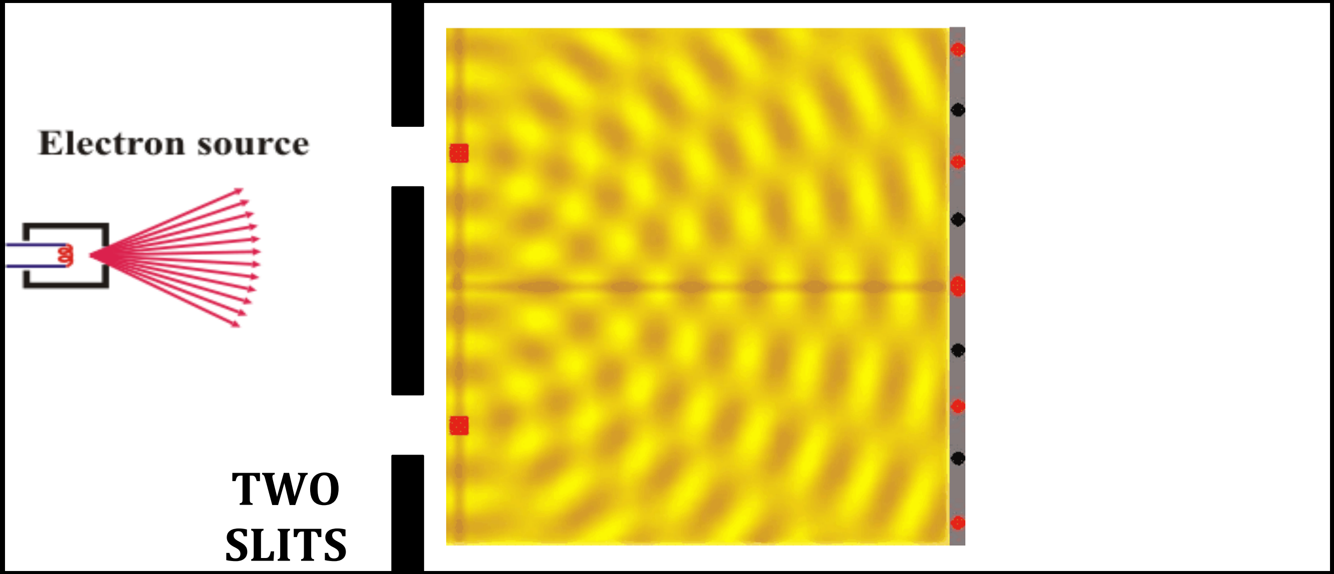
CHARGE: $q = 1.6\text{x}10^{-19}$ C

Moment: $\mu = 5\text{x}10^{-24}\ \text{Am}^2$

Wavelength: $\lambda = h/\sqrt{2mE}$

FREE ELECTRON = TRAVELING WAVE





Erwin Schrödinger

Werner Heisenberg

Scan ©American Institute of Physics

Max Born

FREE ELECTRONS – MATTER WAVES

Schrödinger matter waves

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predict probability of events

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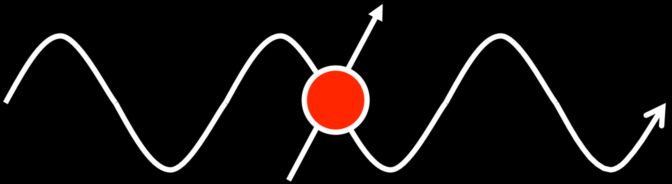
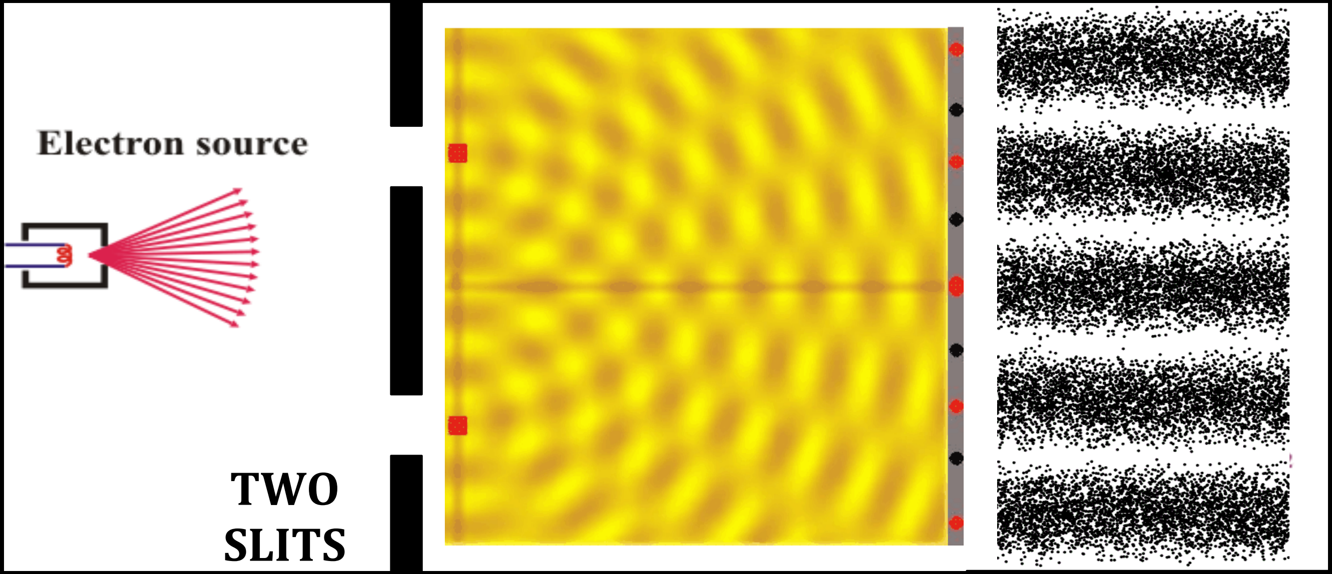




Erwin Schrödinger

Werner Heisenberg

Scan ©American Institute of Physics

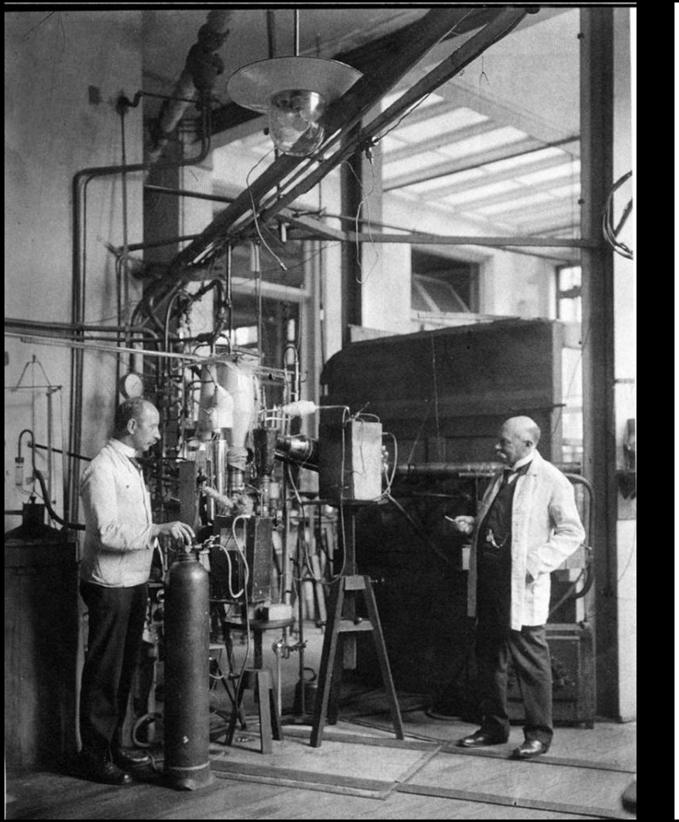
Max Born

PAIRED ELECTRONS – SUPERCONDUCTIVITY

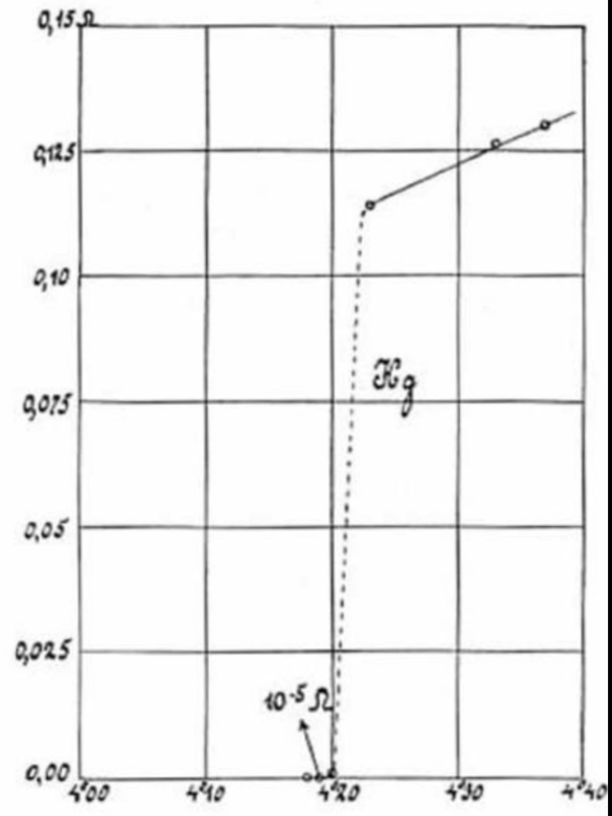
Heike Kamerlingh Onnes

Verslagen van de Afdeeling
Natuur-kunde der Kon. Acad. van
Wetenschappen te Amsterdam,
pp. 1479, 28 April 1911.

Liquefied Helium 4K = -269°C



Superconductivity 1911



.

Superconductivity: Perfectly dissipationless electrical/electronics.

PAIRED ELECTRONS – SUPERCONDUCTIVITY

Schrödinger matter waves

$$\Psi(\vec{r},t)$$

predict probability of events

$$P = |\Psi(\vec{r},t)|^2$$

MASS: $m_e = 10^{-30}$ Kg

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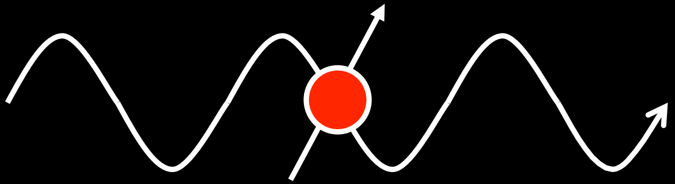
FREE ELECTRON = TRAVELING WAVE

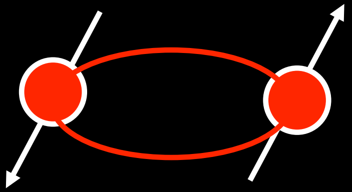


MASS: $m = 2m_e$

CHARGE: $Q = 2q_e$

Moment: $\mu = 0$

BOUND PAIR OF OPPOSITE SPIN ELECTRONS

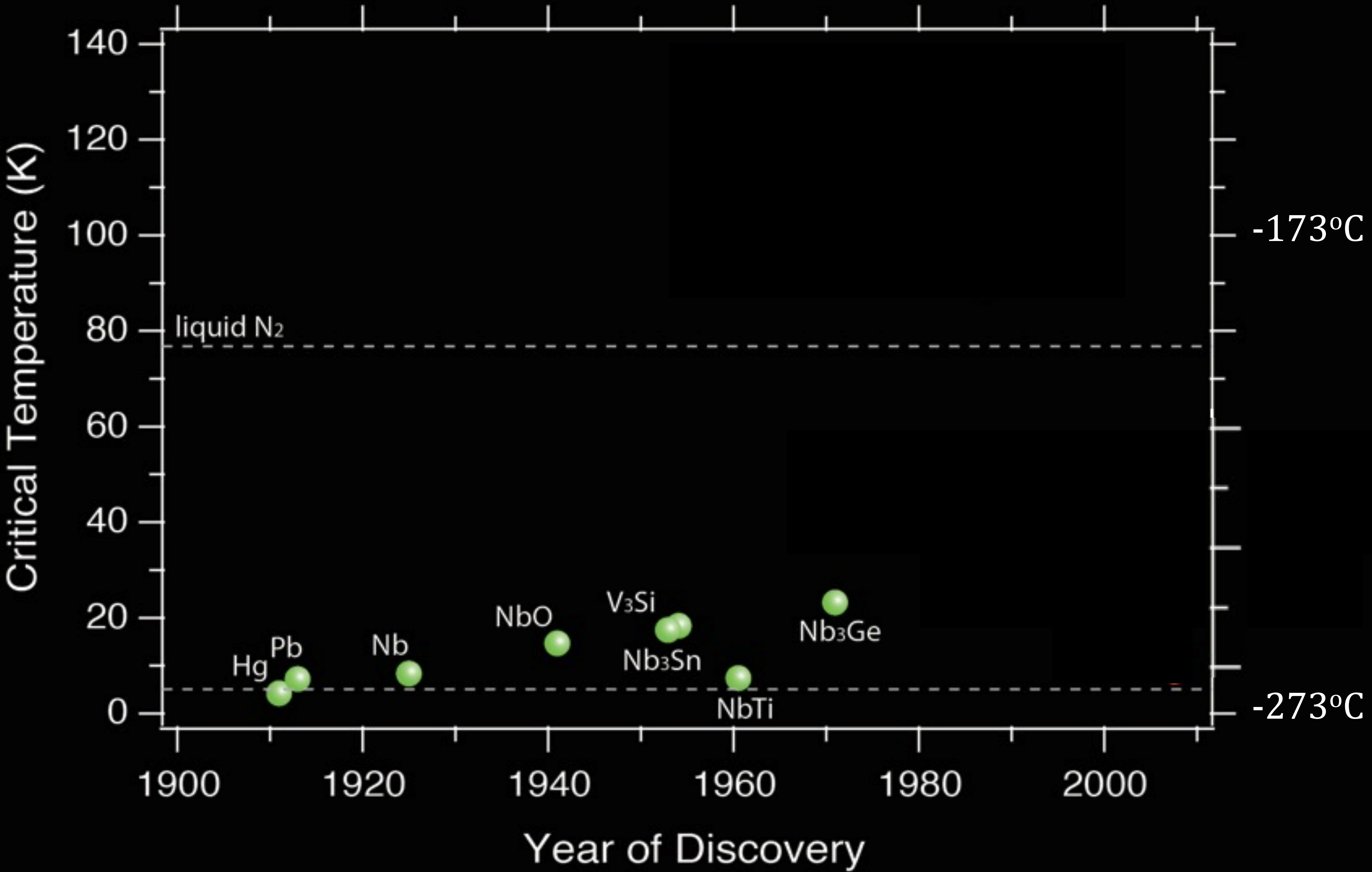


Leon Cooper

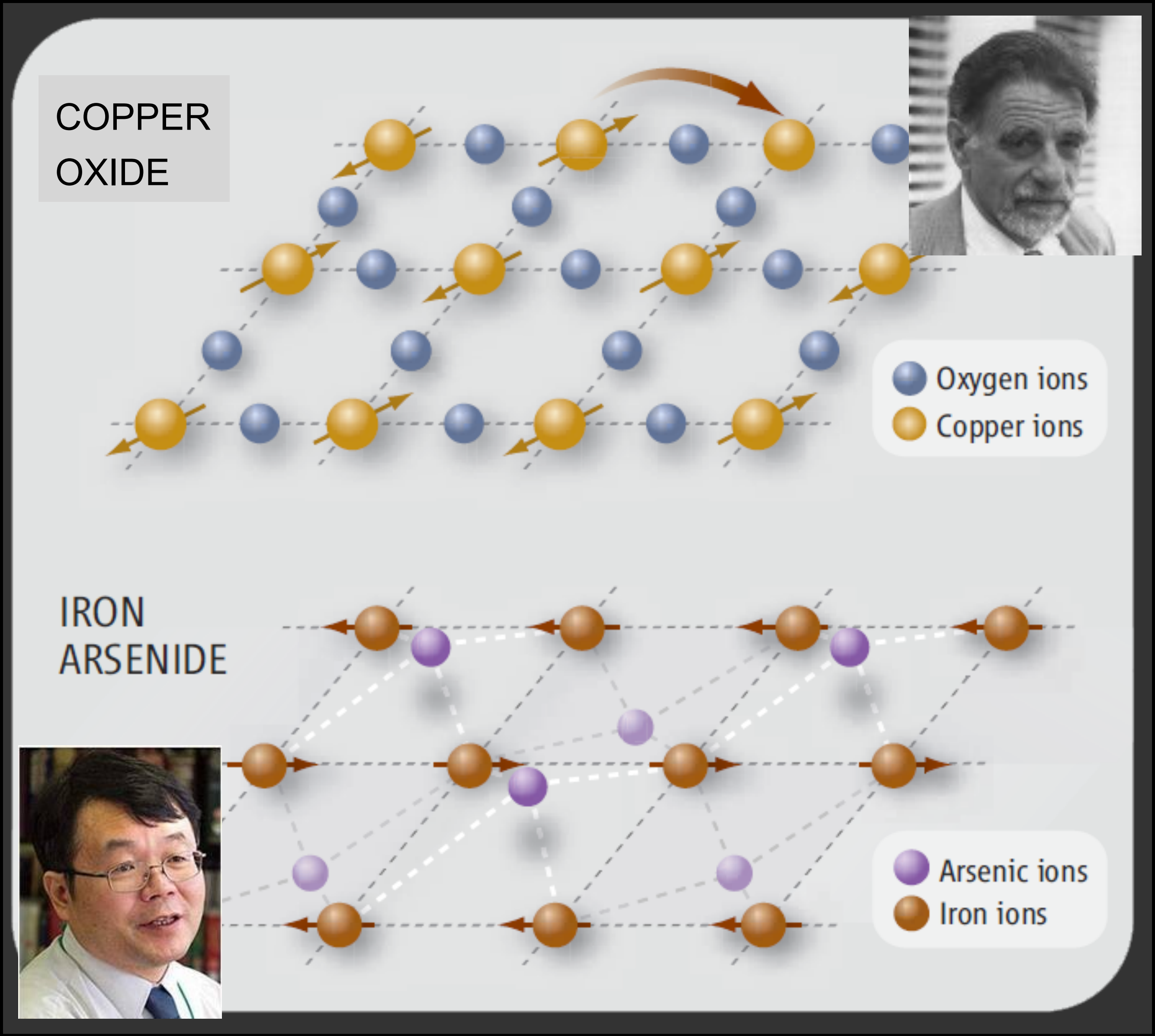
Bob Schrieffer

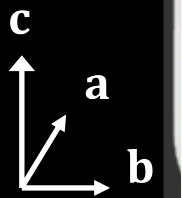
John Bardeen

CONVENTIONAL SUPERCONDUCTIVITY

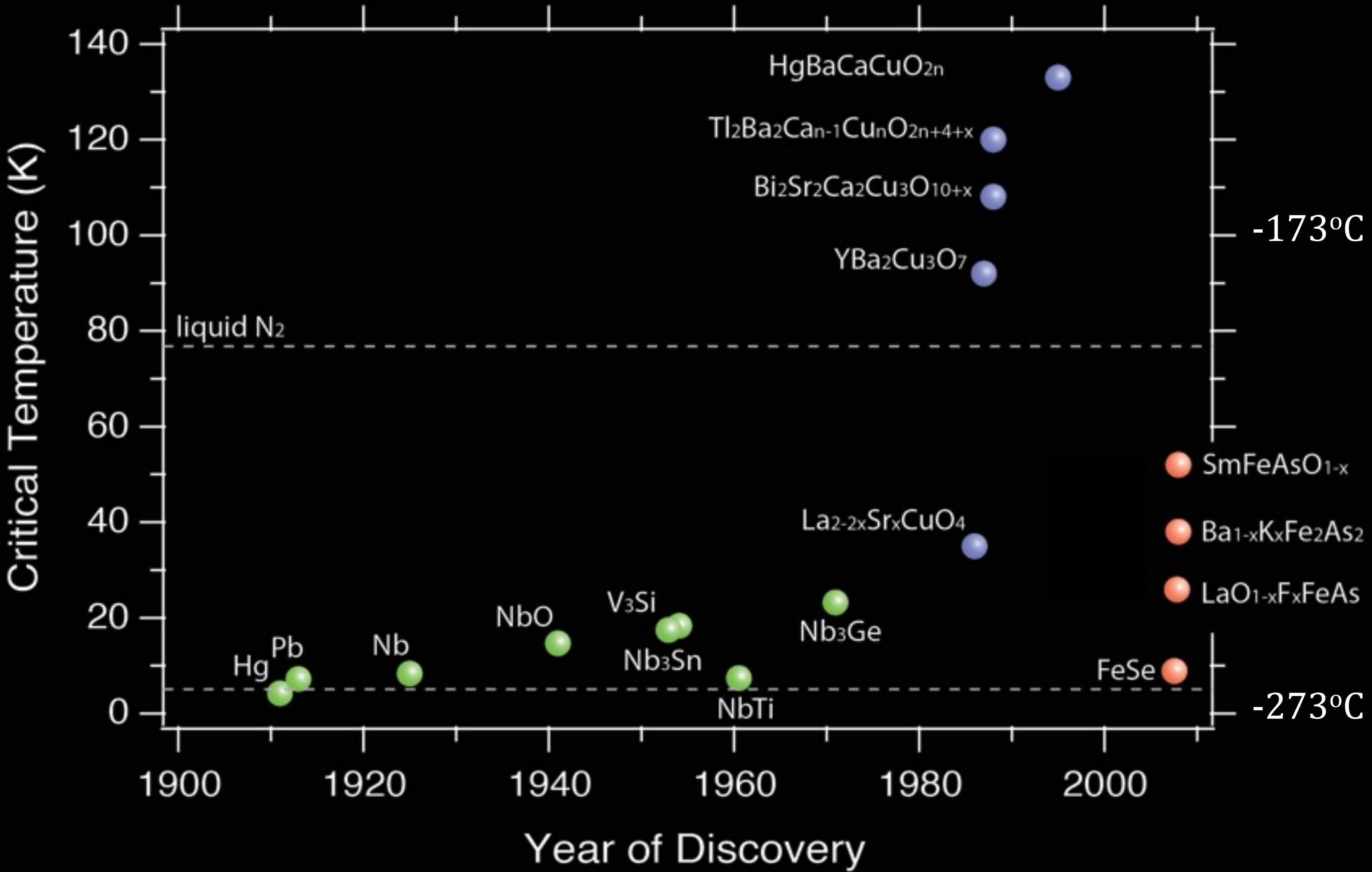


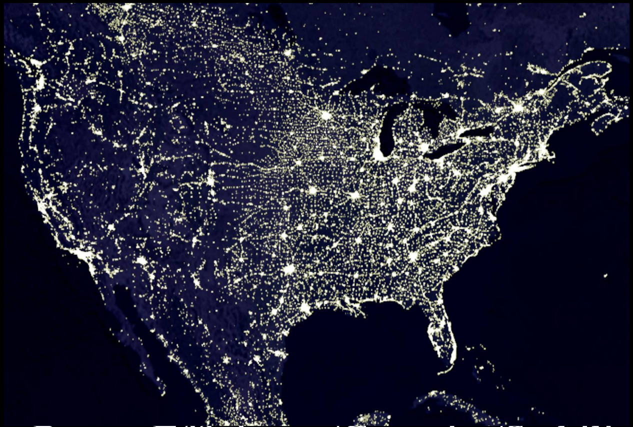
HIGH TEMPERATURE SUPERCONDUCTIVITY





HIGH TEMPERATURE SUPERCONDUCTIVITY



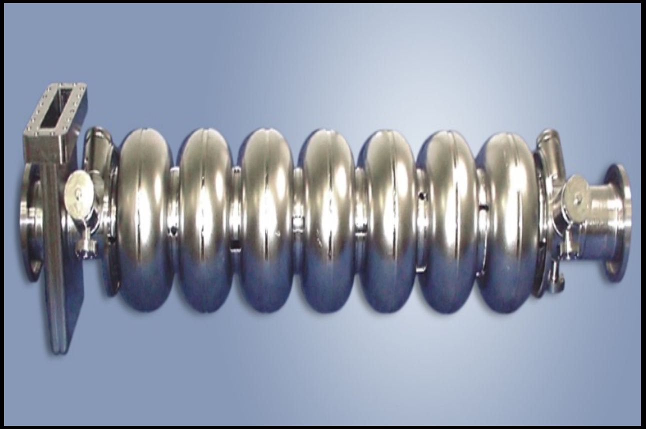

Power Efficiency/Capacity/Stability

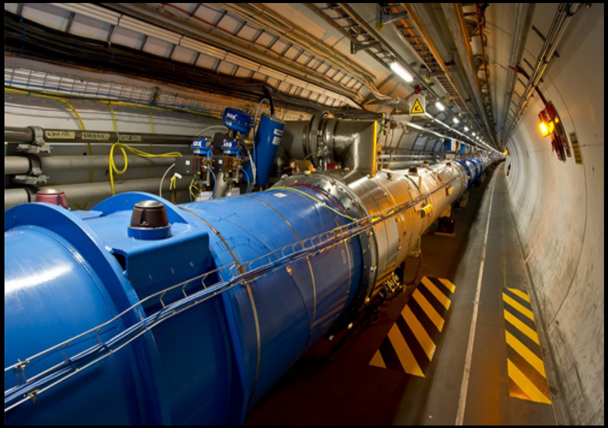

Power Bottlenecks


Accommodate Renewable Power


Efficient Rotating Machines


Information Technology


Next Generation HEP

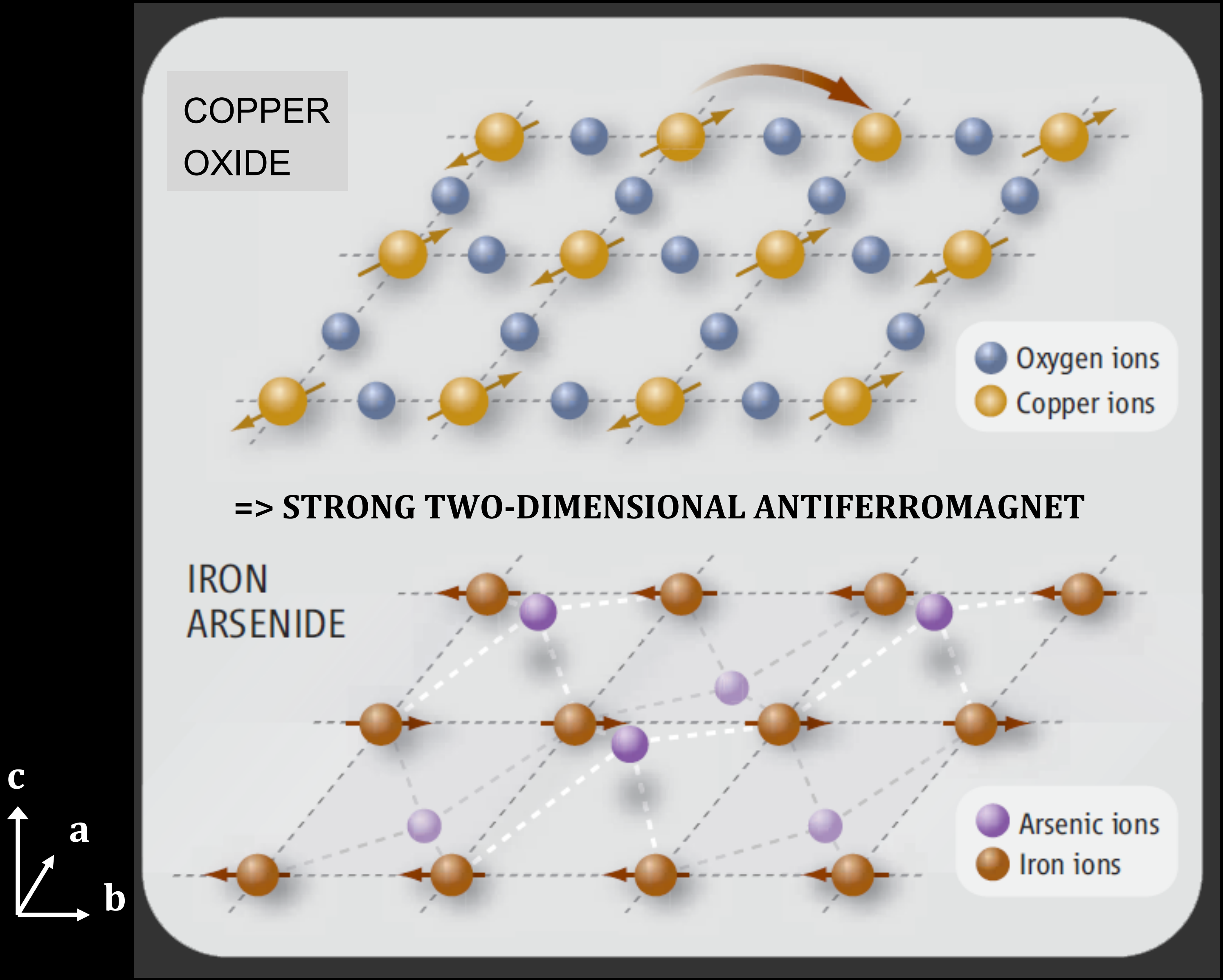

Ultra-High Magnetic Fields


Medical


Transport

CHALLENGES TO UNDERSTAND HIGH TEMPERATURE SUPERCONDUCTIVITY

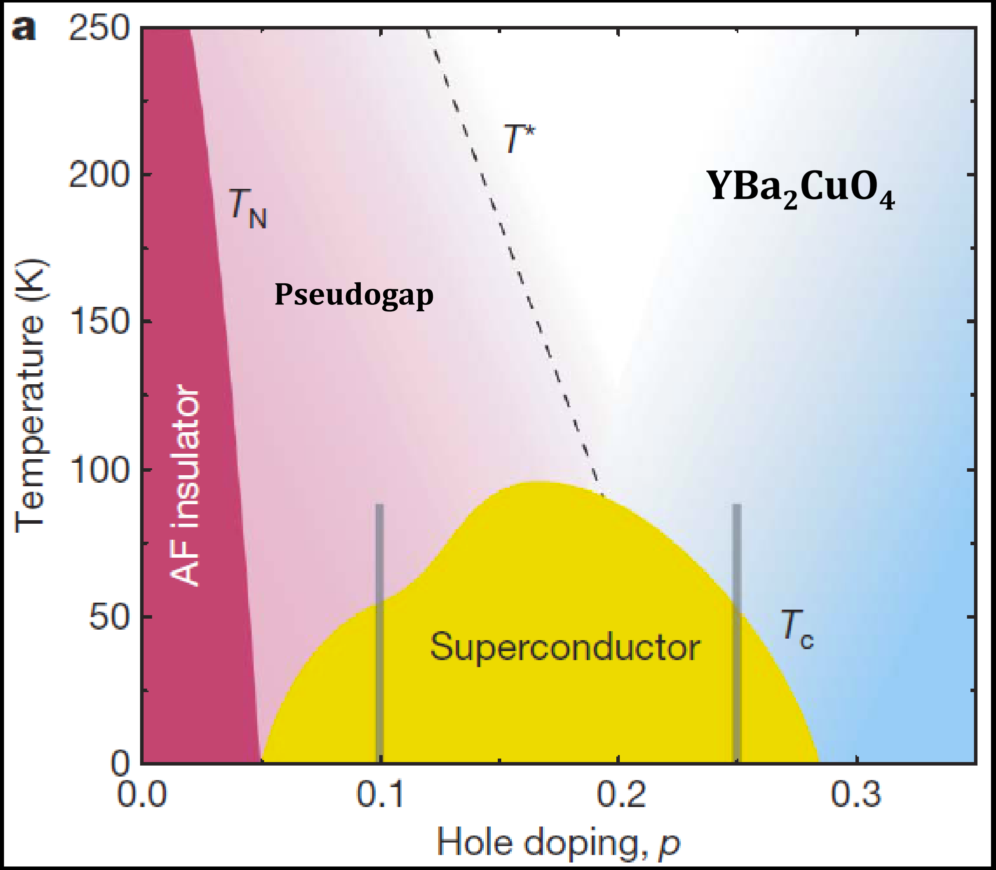
Extremely Strong Electron-Electron Interactions



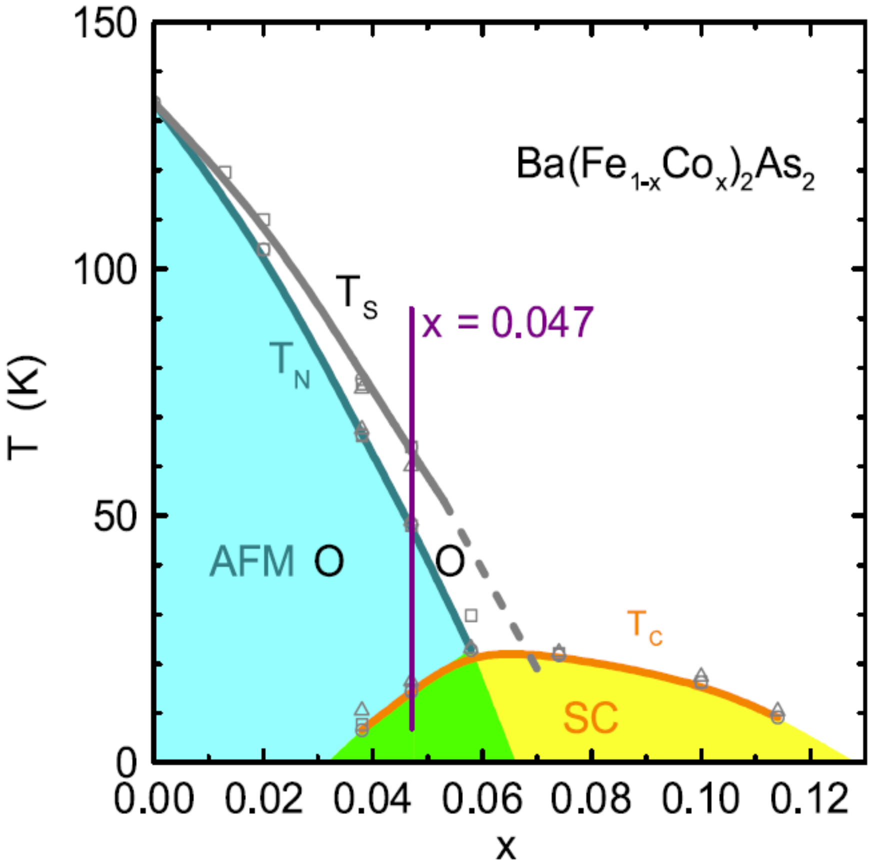
=> STRONG TWO-DIMENSIONAL ANTIFERROMAGNET

PHASE DIAGRAMS

Copper-based



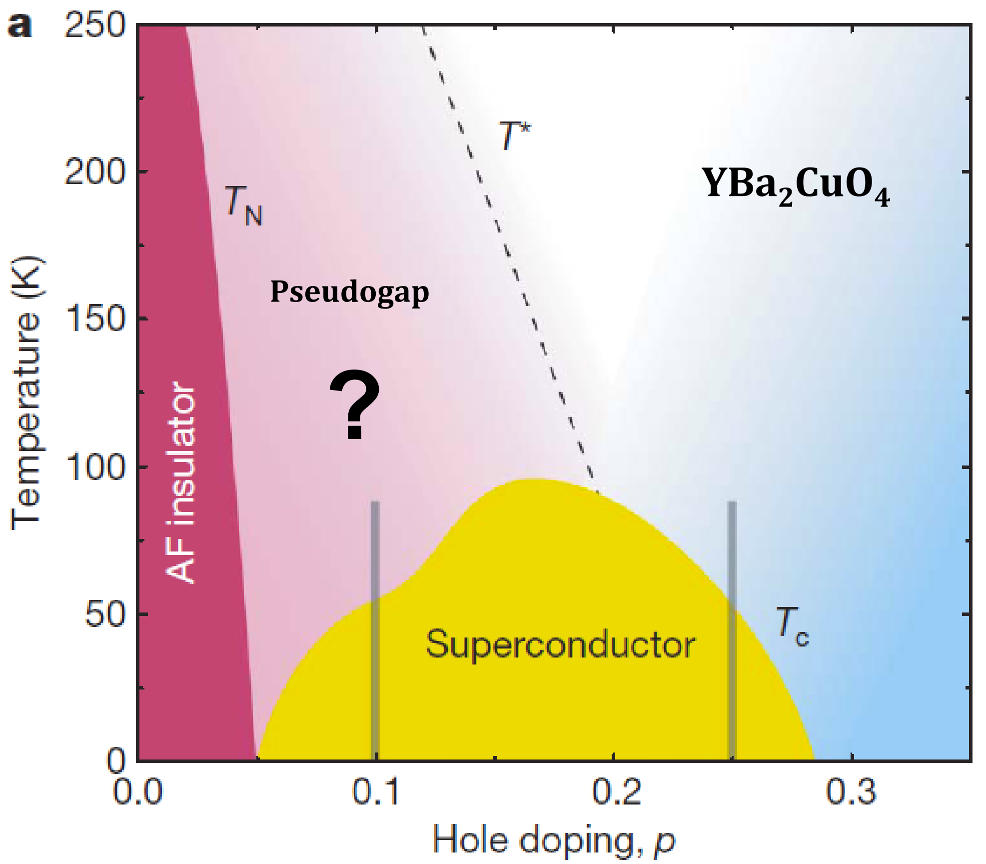
Iron-based



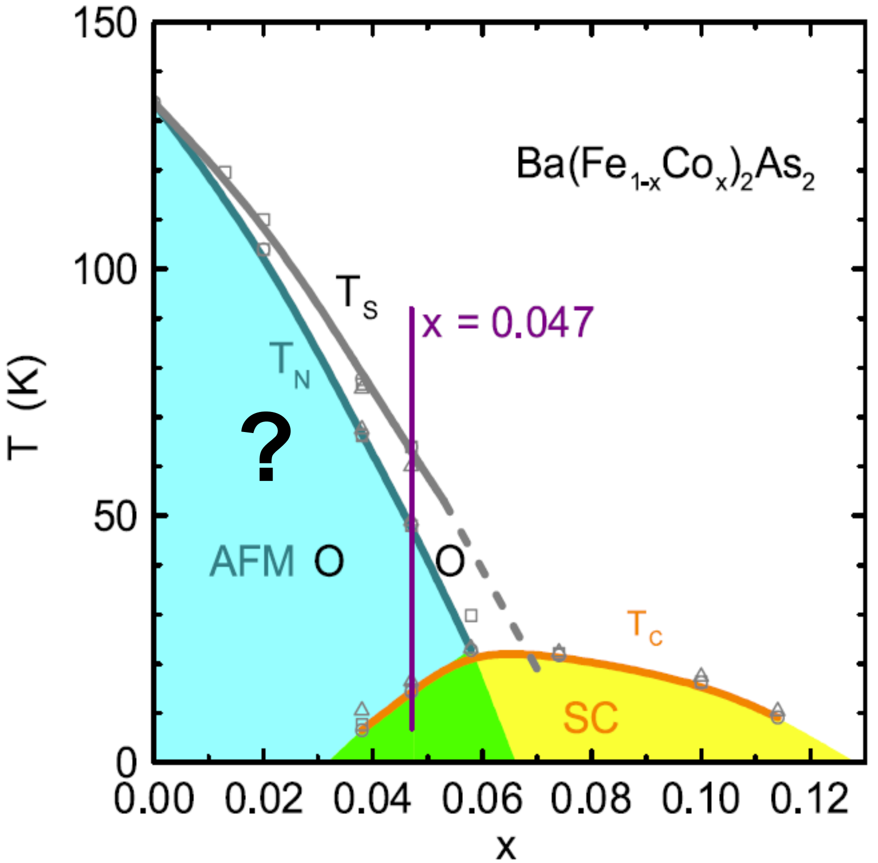
Many similarities as a function of electron density.

EXOTIC NEW STATES of ELECTRONIC MATTER

Copper-based

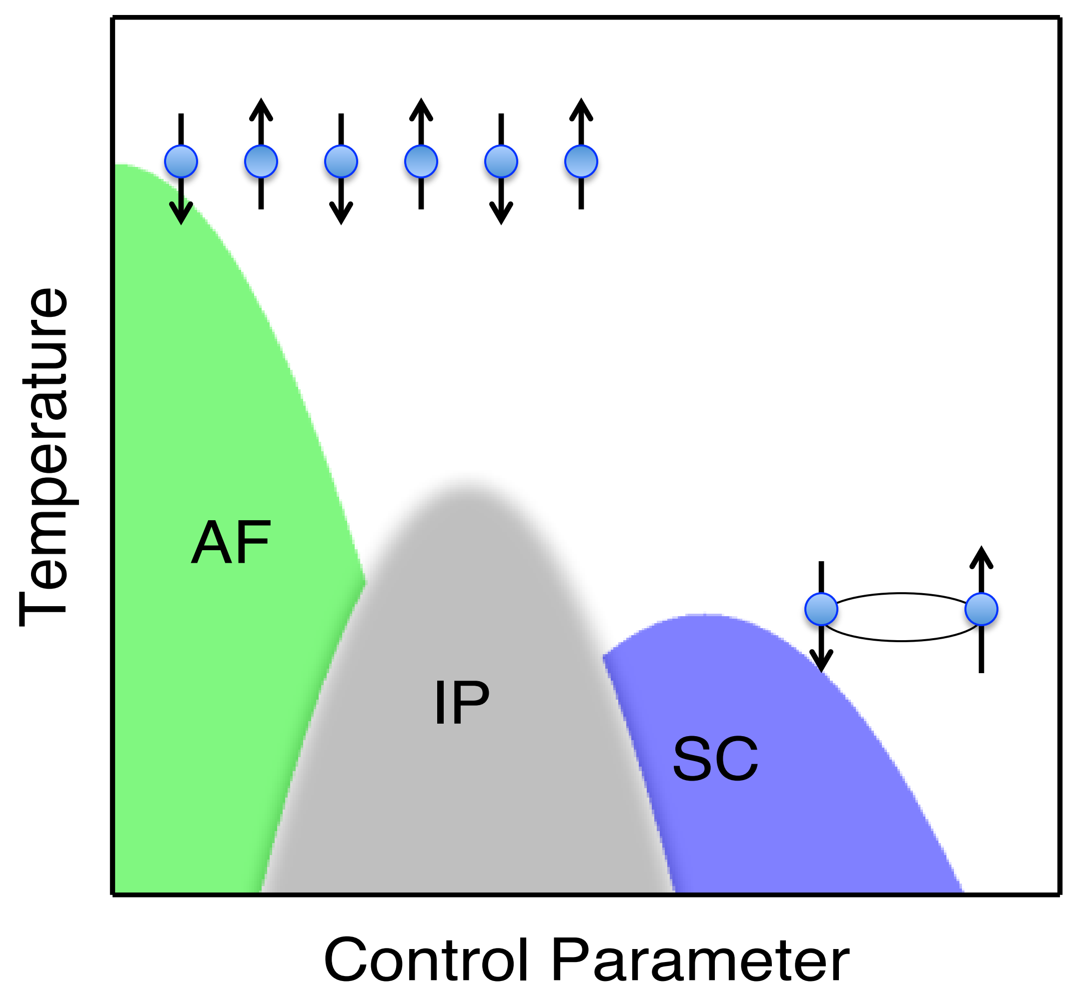


Iron-based

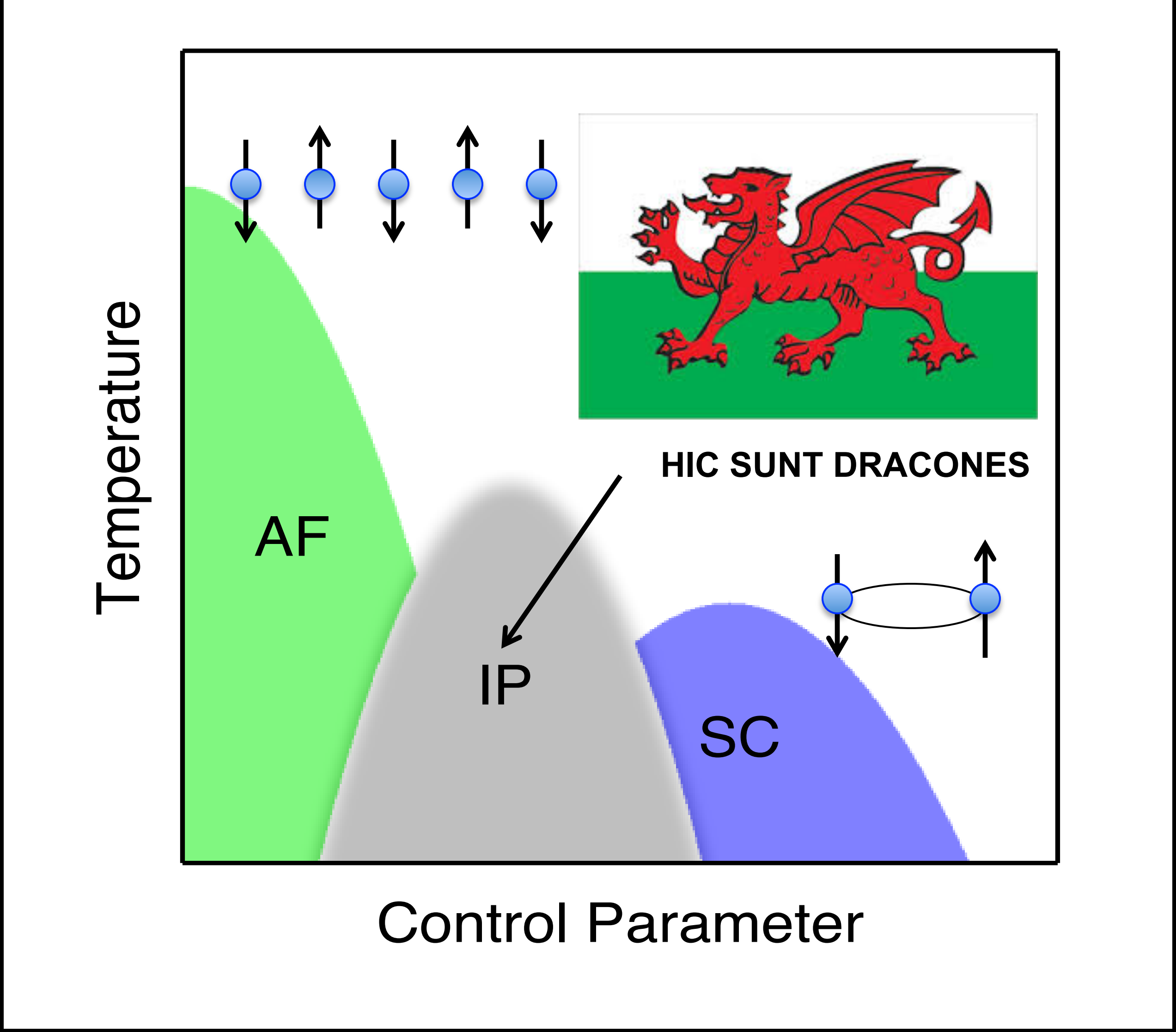


Very challenging to understand!

EXOTIC NEW STATES OF MATTER?

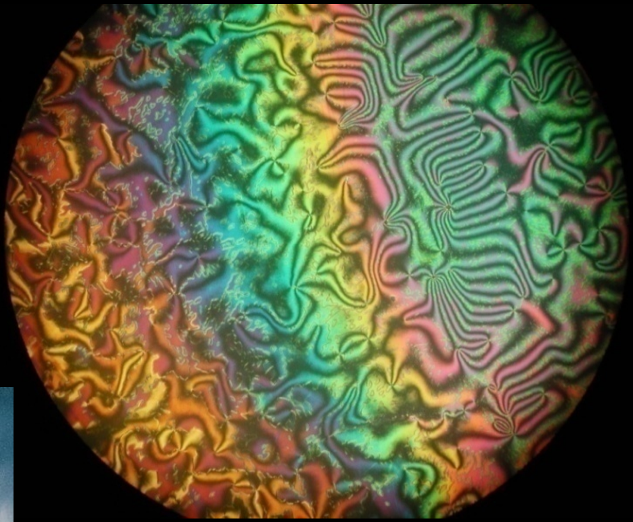


EXOTIC NEW STATES OF MATTER?



Gas → Fluid → Liquid Crystal

Increasing
interactions
& complexity

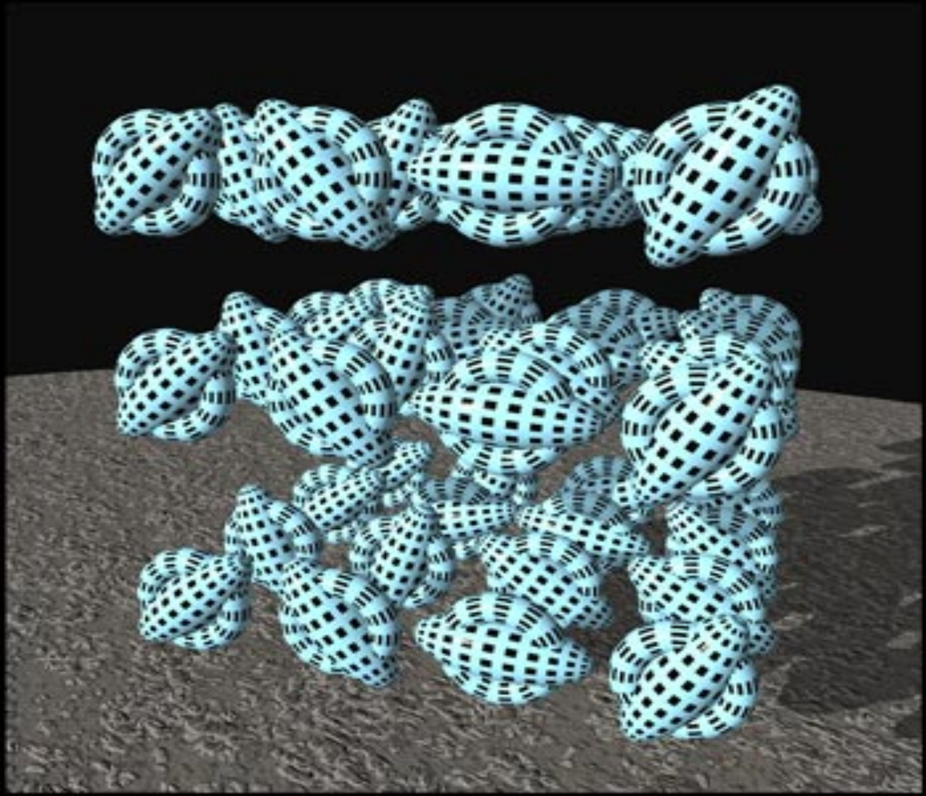


Liquid Crystal

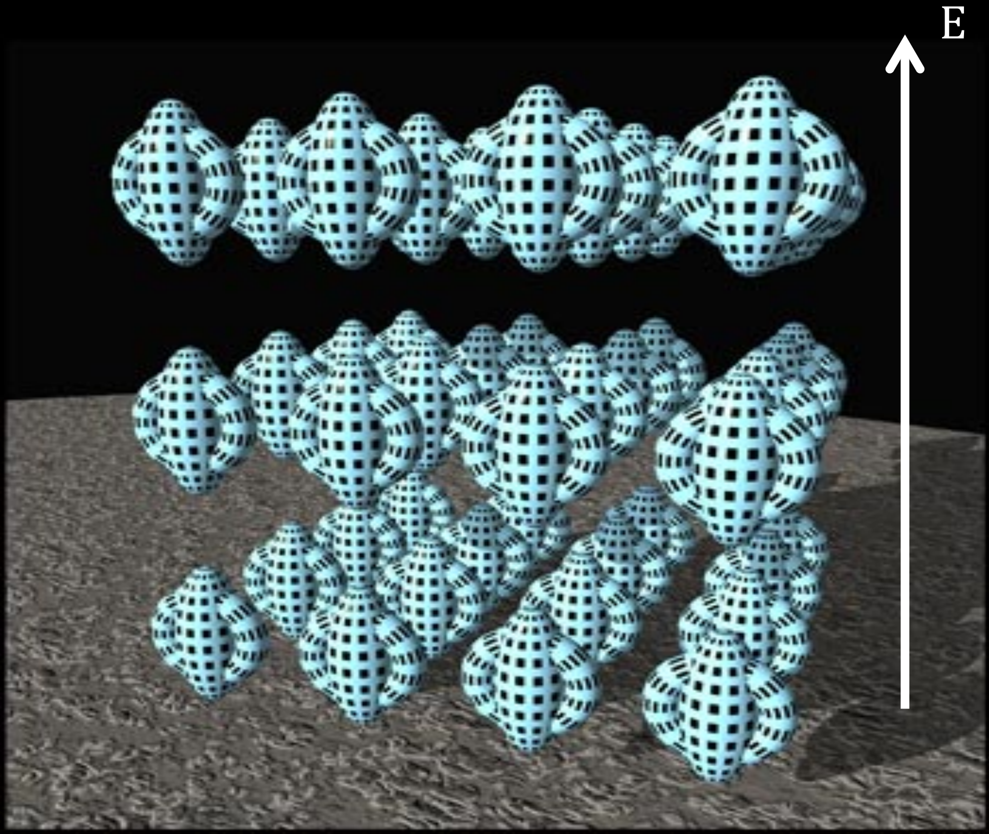
Liquid

Vapour

Controllable Liquid Crystal States

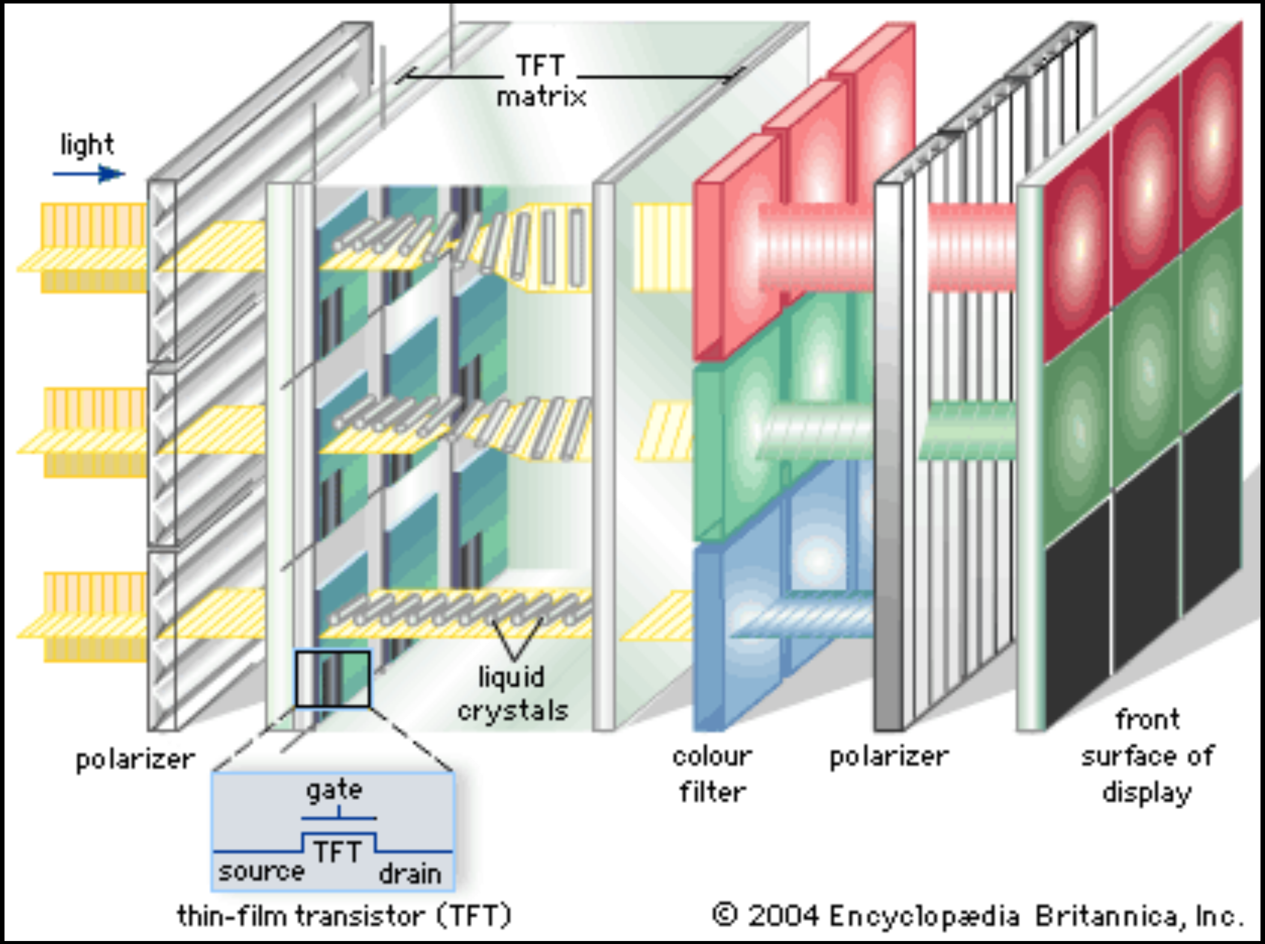


Random molecular orientation



Molecules aligned by electric field

Controllable Liquid Crystal States



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Controllable Liquid Crystal States

$10^{1}\$$ Industry

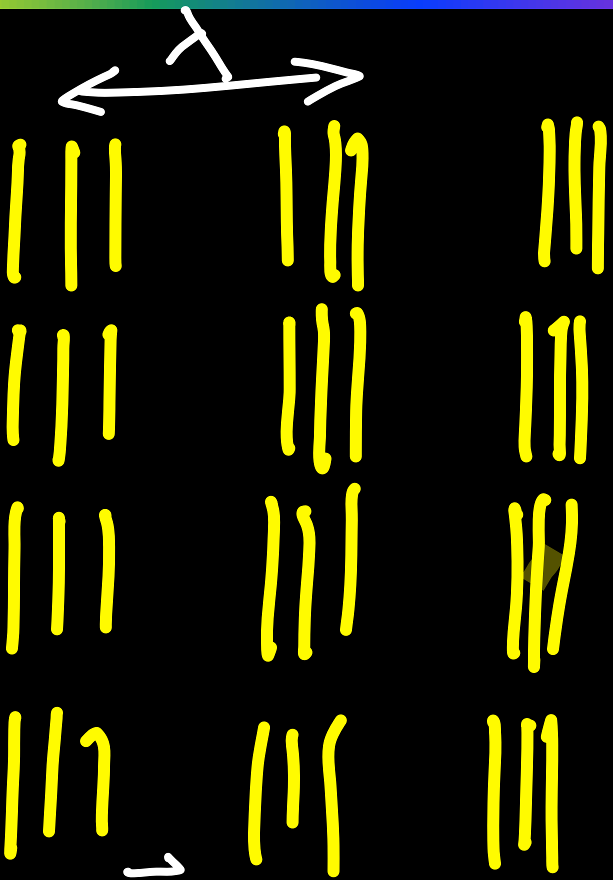
- Monitors
- LCD Displays
- LCD TVs
- ‘Smart’ Windows
- Much more…..

Two Key Types of Liquid Crystal States

$\vec{Q} = 0$

Nematic LC

breaks rotational symmetry only

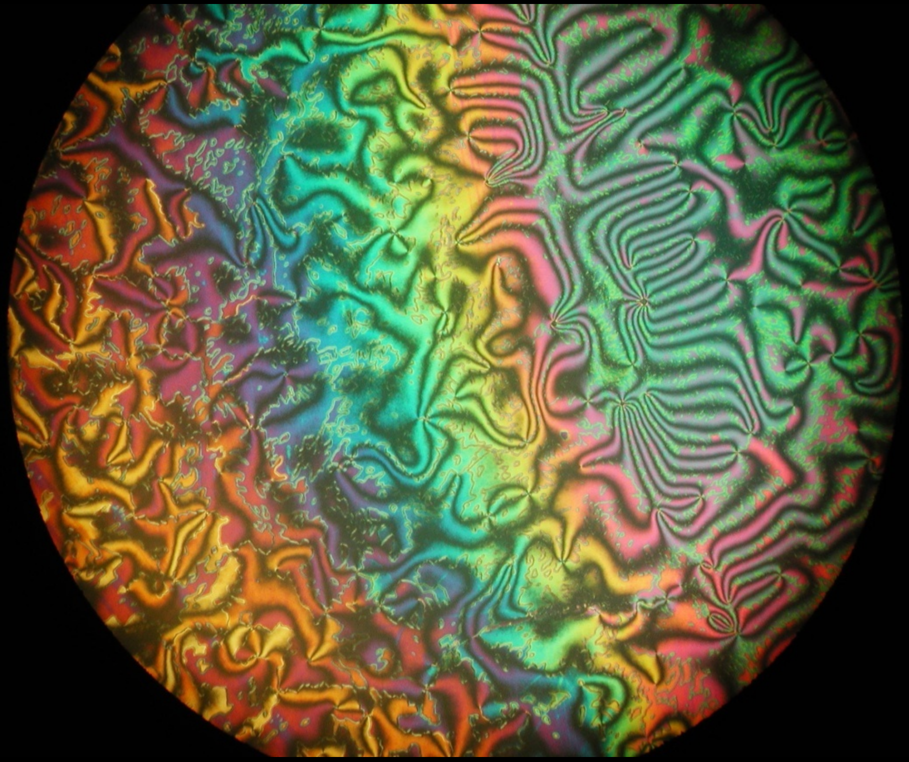


$\vec{S} = 2\pi/\lambda$

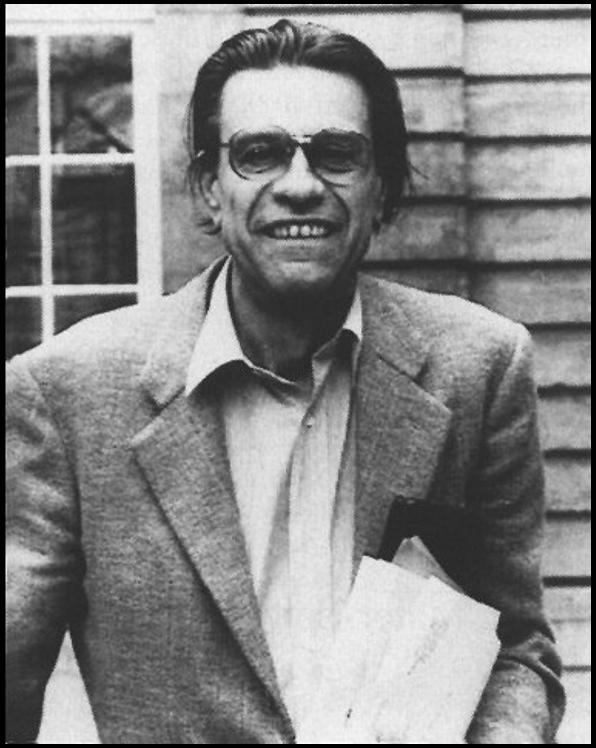
Smectic LC

breaks rotational & translational symmetry

Understanding Liquid Crystals Required <u>Visualization</u>



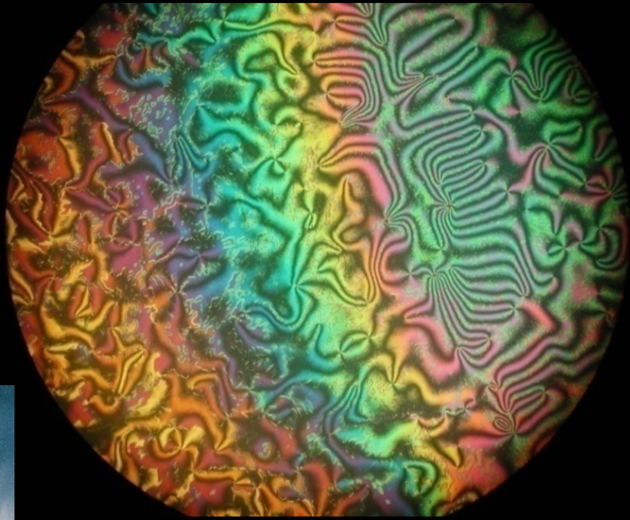
P.-G. de Gennes



Visualization ↔ Understanding

Gas → Fluid → Liquid Crystal

Increasing
interactions
& complexity



Liquid Crystal

Liquid

Vapour

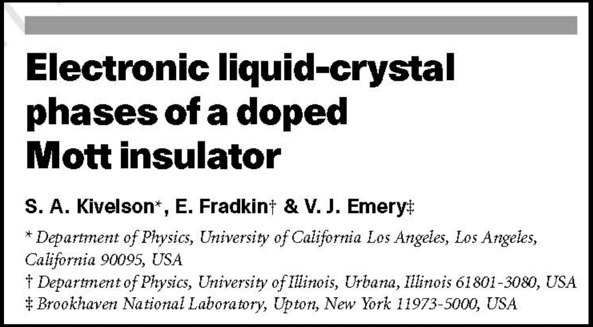
Electron Gas → Electronic Fluid → Electronic Liquid Crystal

Increasing
interactions
& complexity

?

Electronic Liquid Crystal

Heavy Electron Fluid



Electronic liquid-crystal phases of a doped Mott insulator

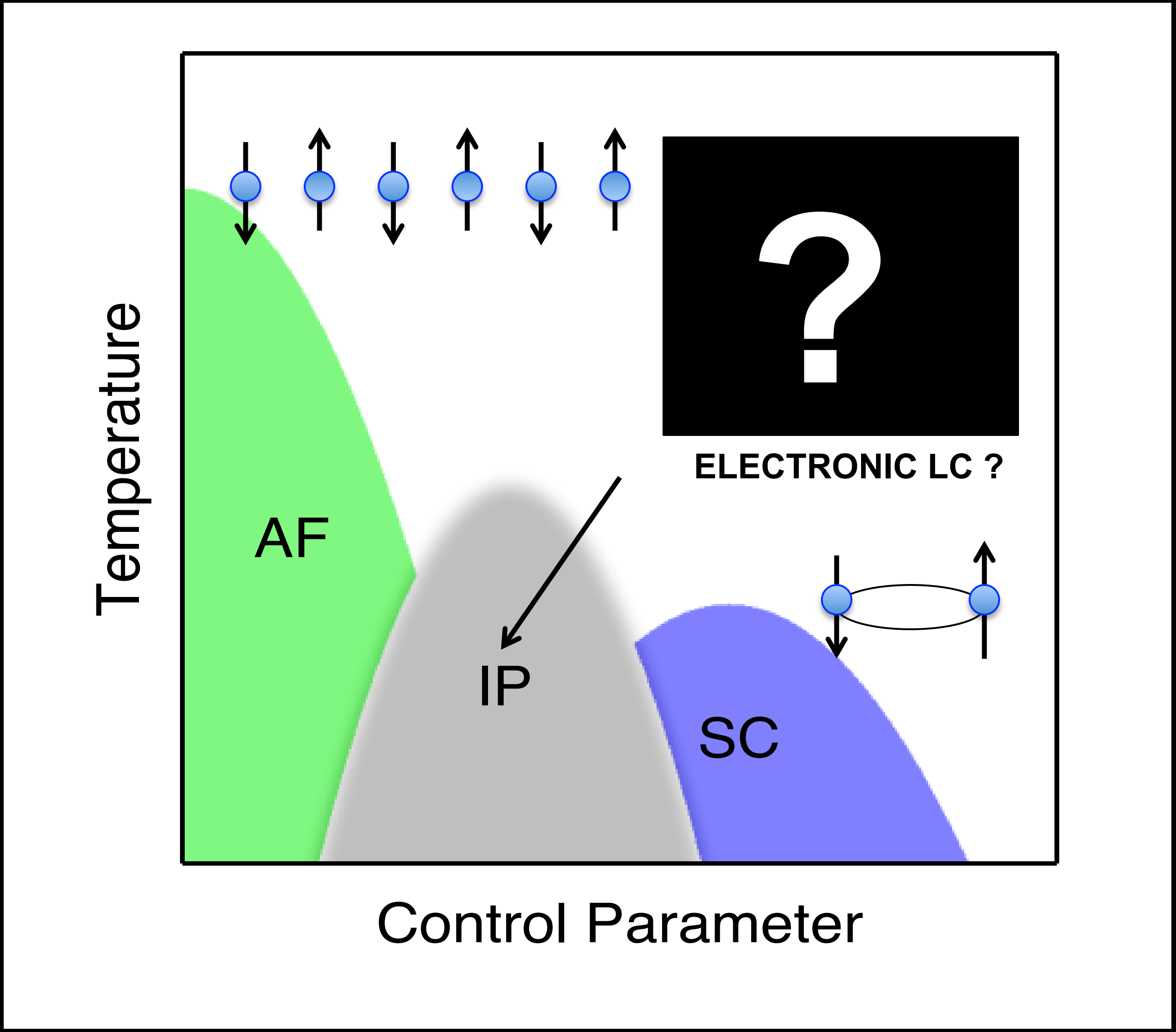
S. A. Kivelson*, E. Fradkin† & V. J. Emery‡

* *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*

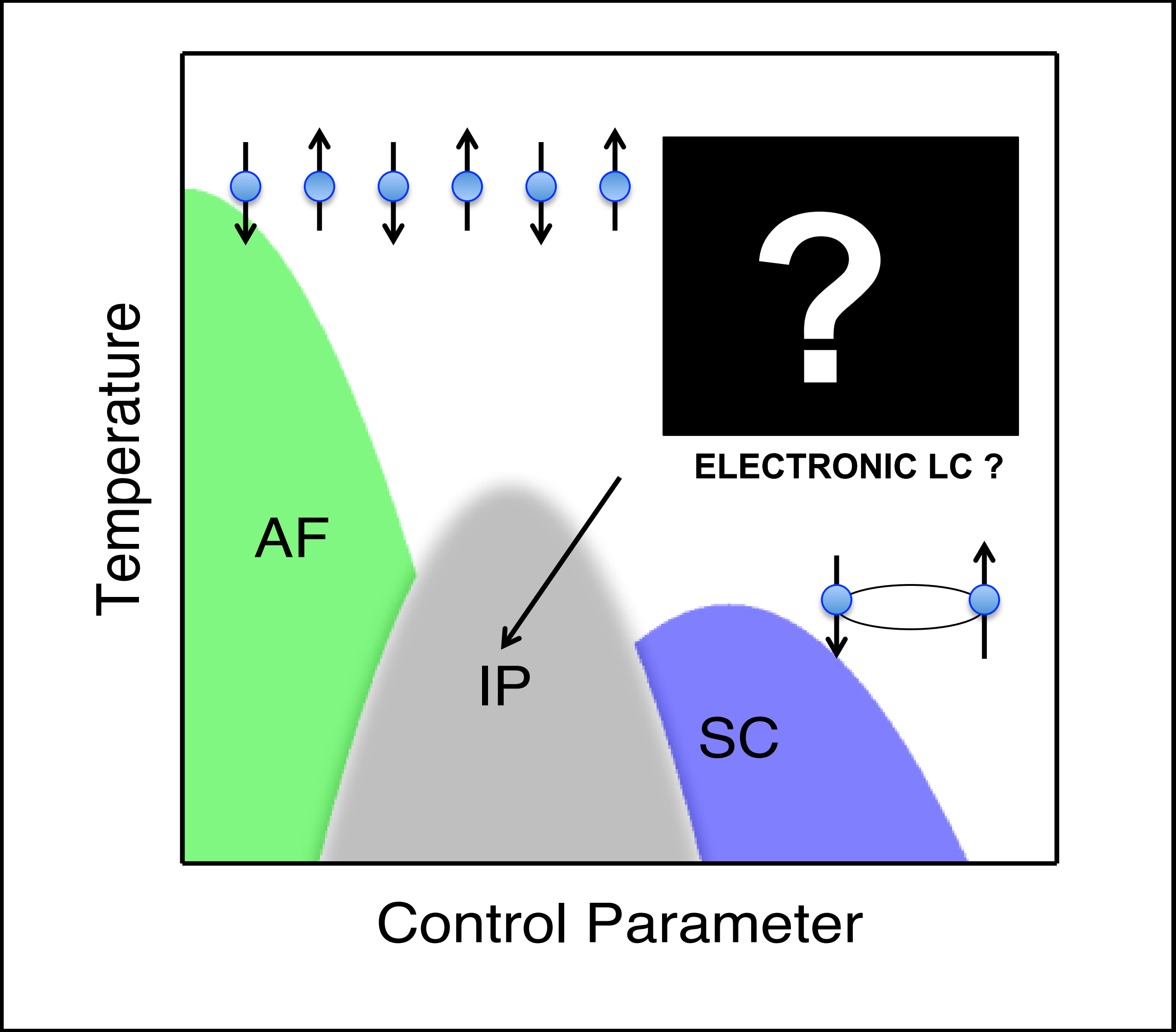
Nature 393, 550 (1998).

Electron Gas

ELECTRONIC LIQUID CRYSTALS ?

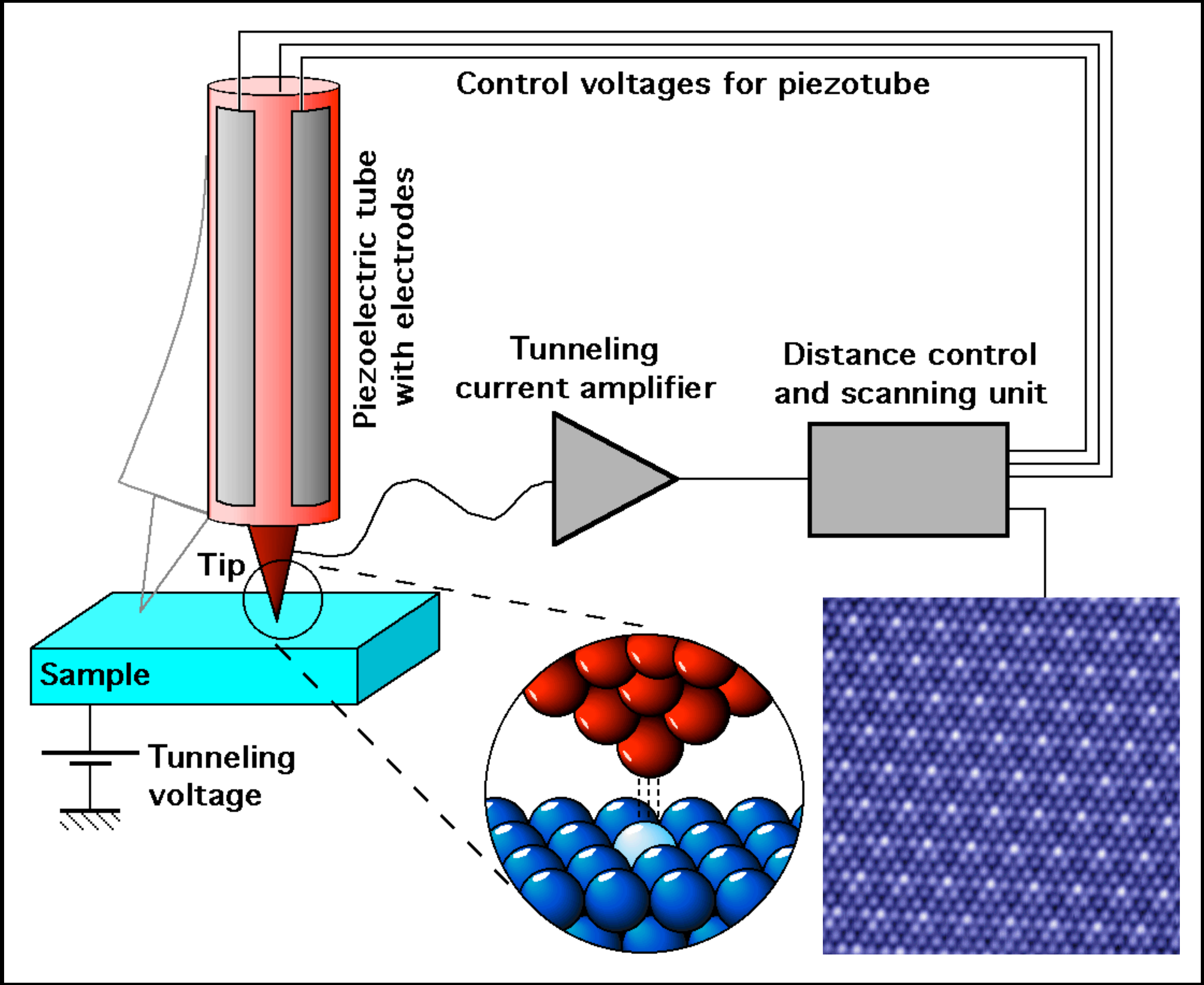


VISUALIZE ELECTRONIC MATTER DIRECTLY !



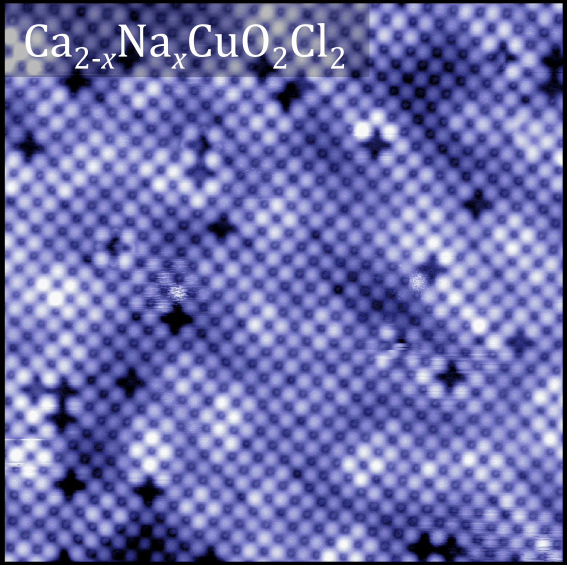
VISUALIZING ELECTRONIC QUANTUM MATTER

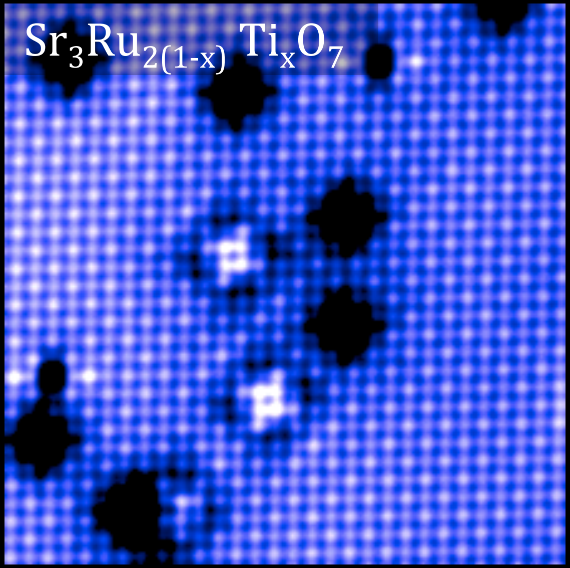
Scanning Tunneling Microscopy (STM)

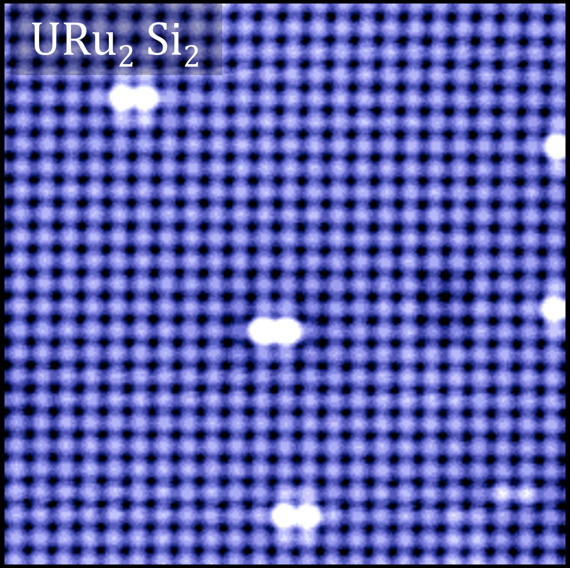


Images atomic locations – not electronic wavefunctions


$Bi_2Sr_2CaCu_2O_{8+d}$


$Ca_{2-x}Na_xCuO_2Cl_2$

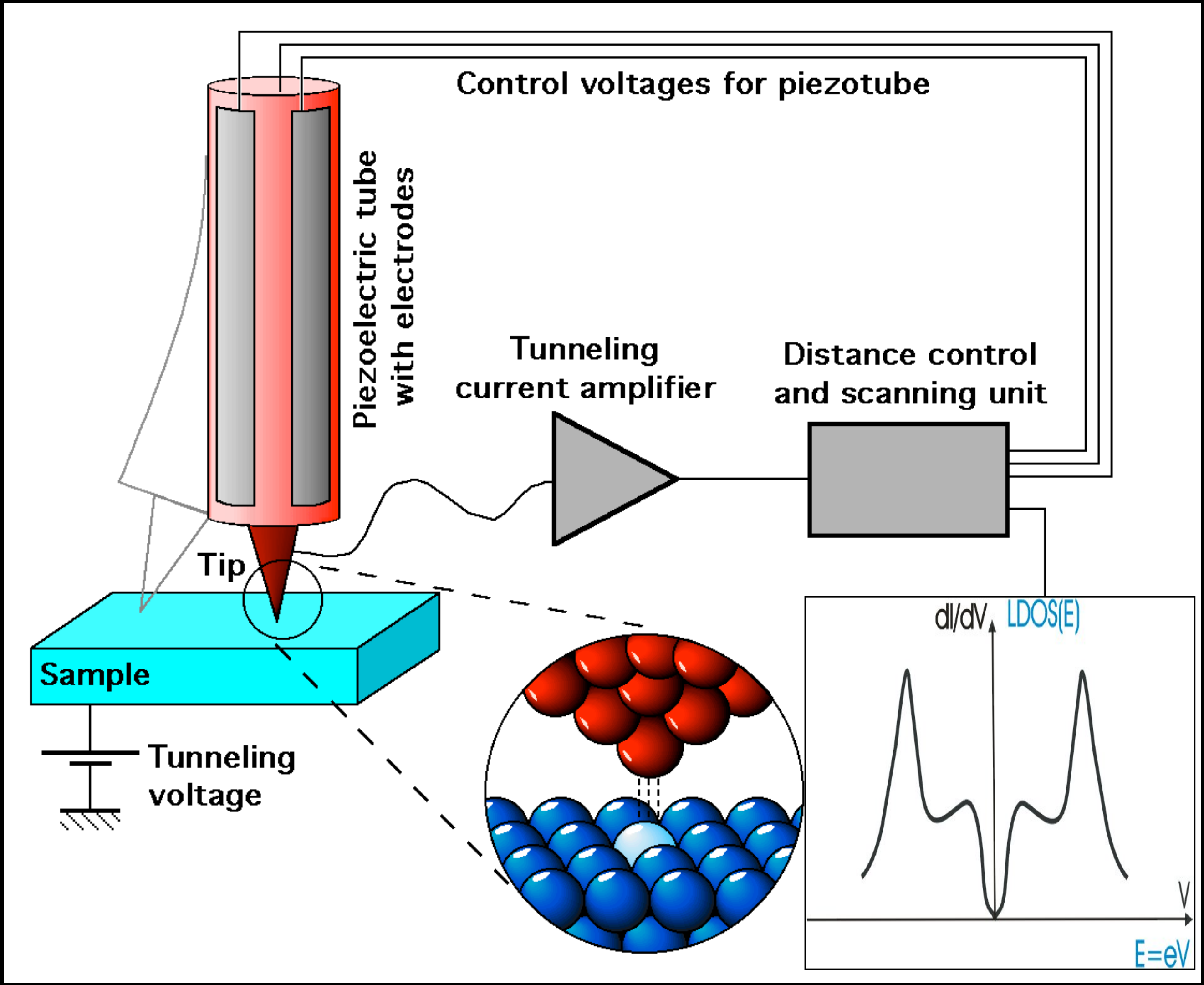

$Sr_3Ru_{2(1-x)}Ti_xO_7$


URu_2Si_2

← ~100 Å →

← ~100 Å →

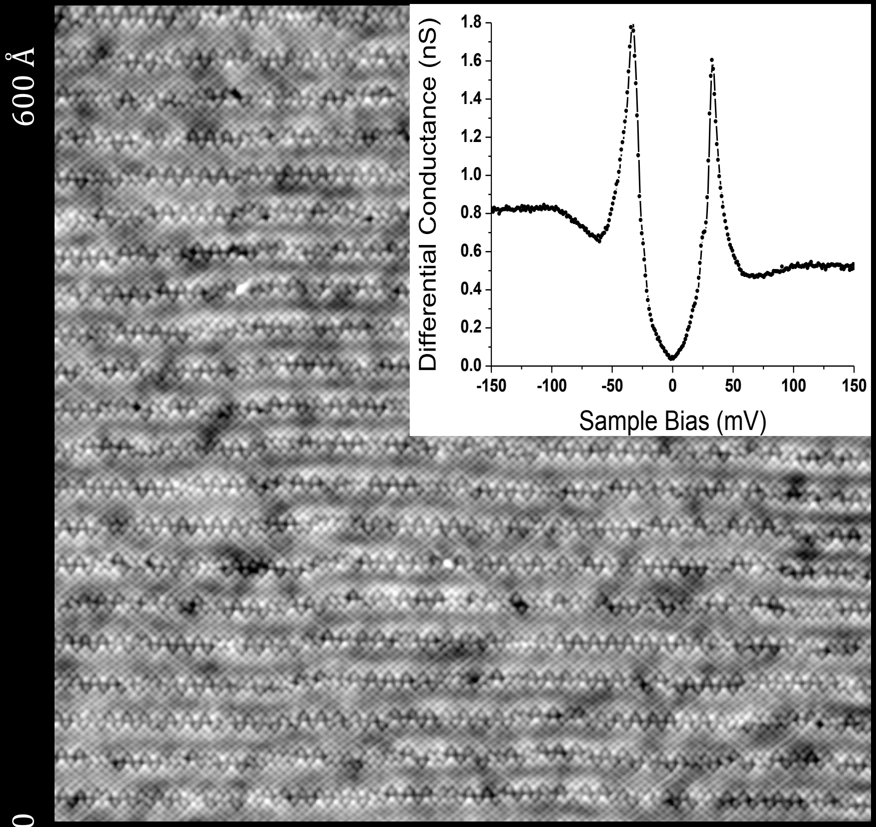
Differential Conductance Spectrum



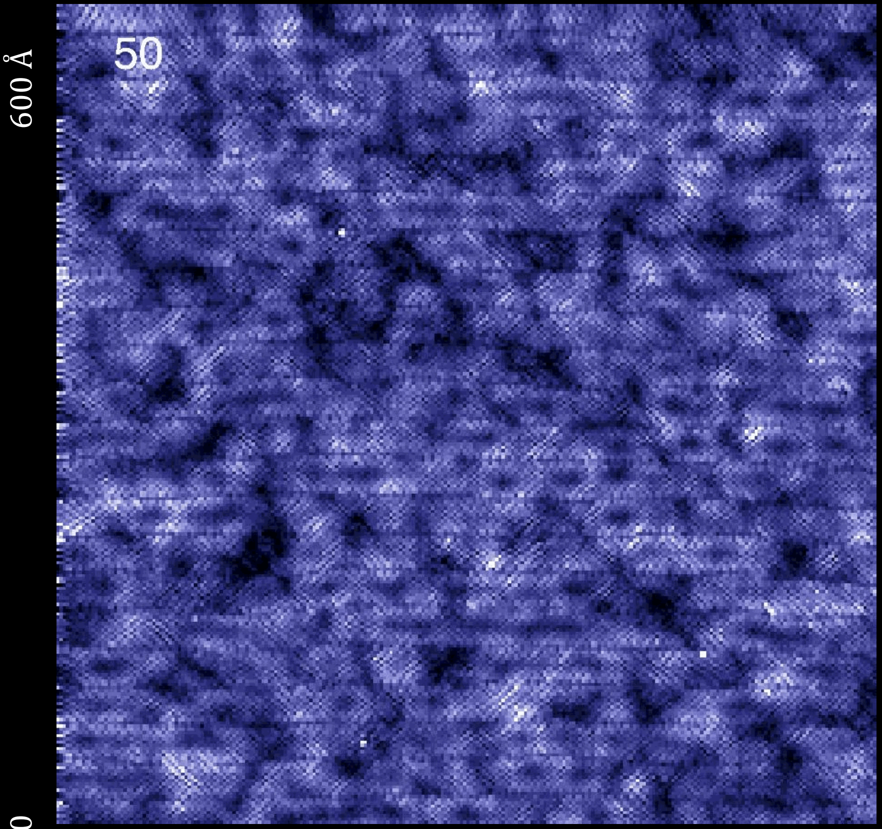
Differential conductance $[dI/dV]_{E=eV}$ proportional to $|\Psi(E)|^2$

Spectroscopic Imaging STM (SI-STM)

dI/dV spectrum at every atom →



Topography

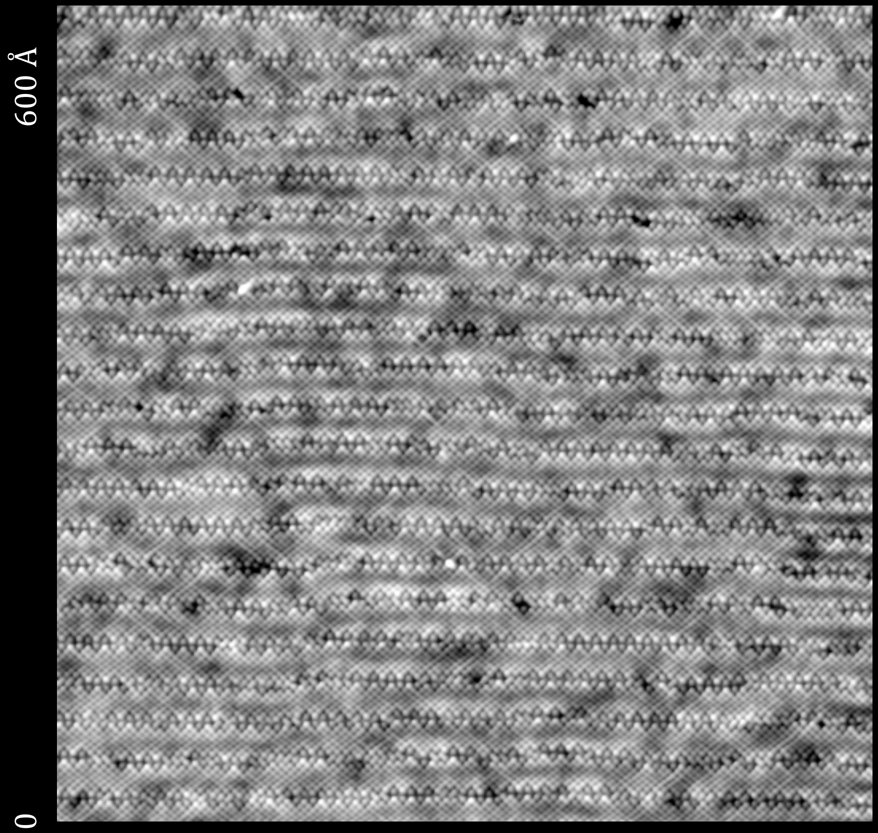


SI-STM

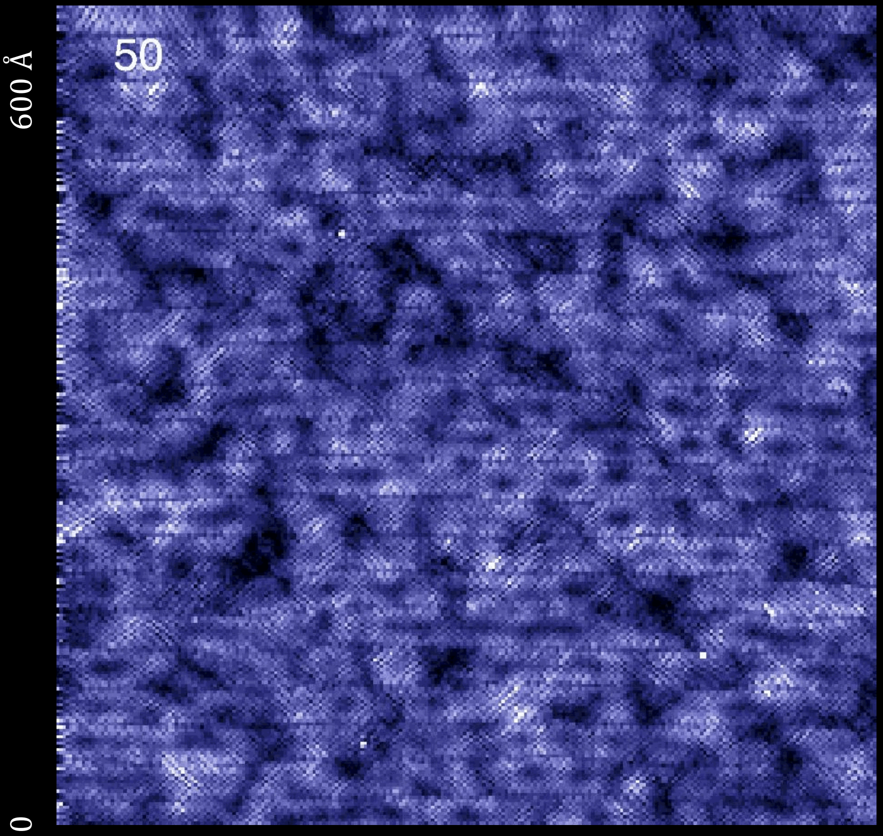
Rev. Sci. Inst. **70**, 1459 (1999).

Atomic-scale Wavefunction Imaging

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



Topography

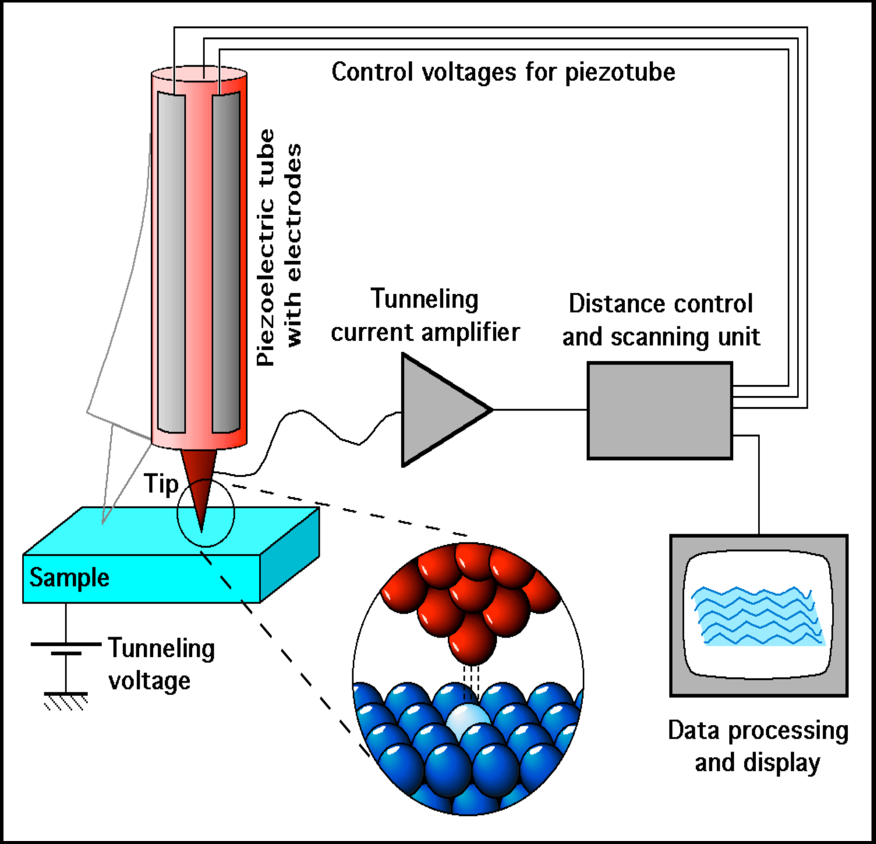


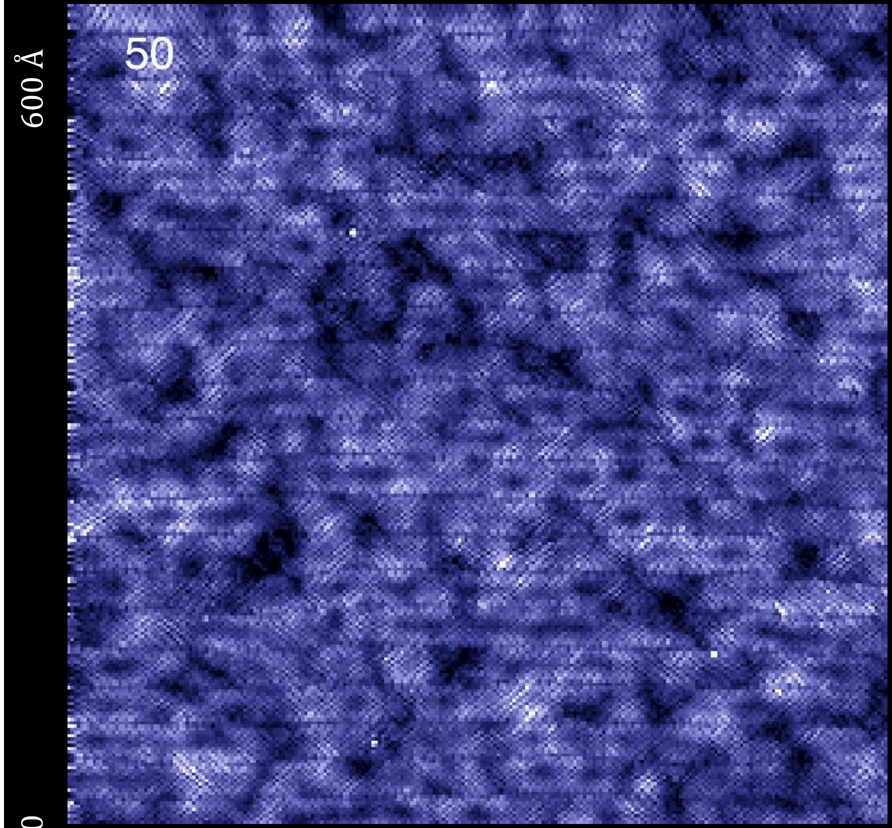
SI-STM

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

Technically Challenging !

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





SI-STM

Passively stabilize tip position ~ 10^{-15} m RMS motion.

Technically Challenging !

STM tip = Matterhorn

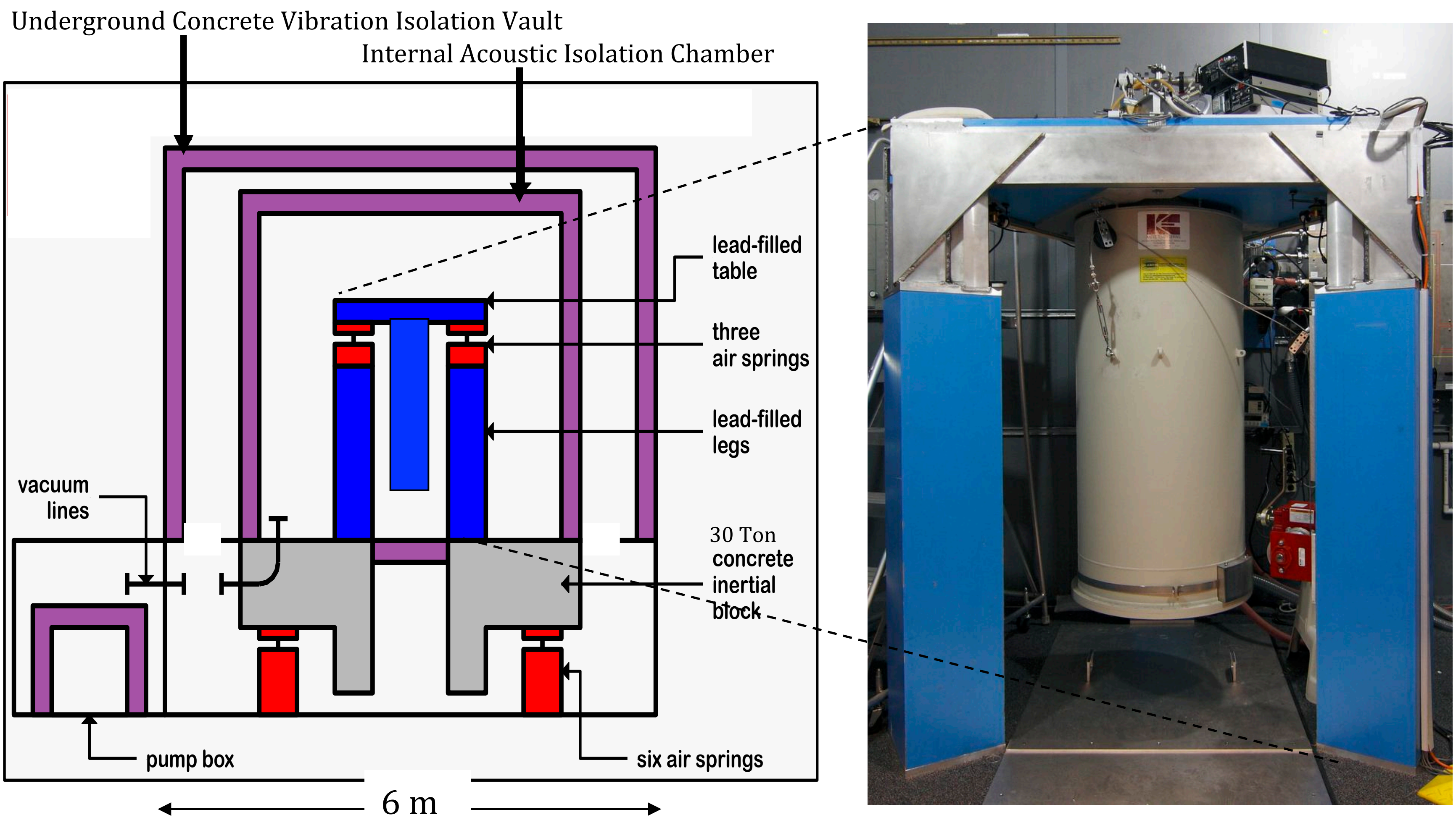
⇒ vibrations ~ 1% hair

Passively stabilize tip position ~ 10^{-15} m RMS motion.

Ultra Low Vibration Laboratory

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

Ultra Low Vibration Laboratory

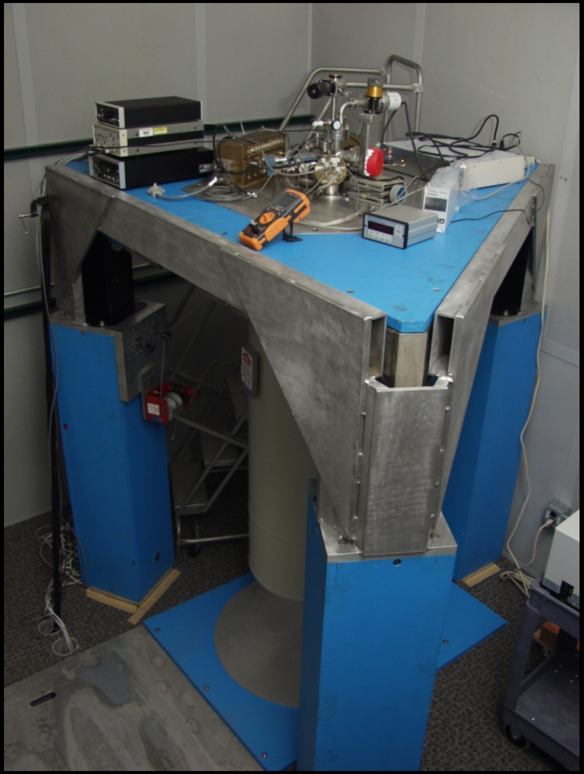

ULTRA LOW VIBRATION LAB

ULTRA LOW VIBRATION CRYOSTAT

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

OUR SISTM SYSTEMS

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



BNL STM1 (4K->100K
Copper-based HTS

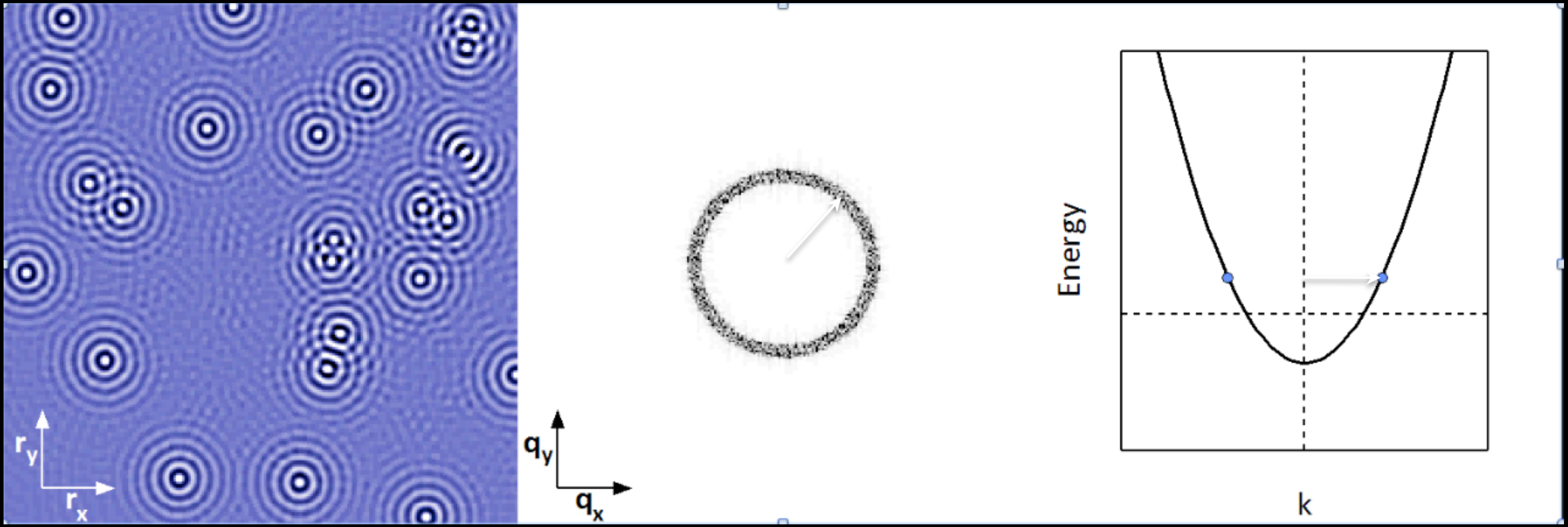
STM2(9T/10mK)
Heavy Fermion SC

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

Imaging Quantum Matter Waves

Imaging Quantum Matter Waves

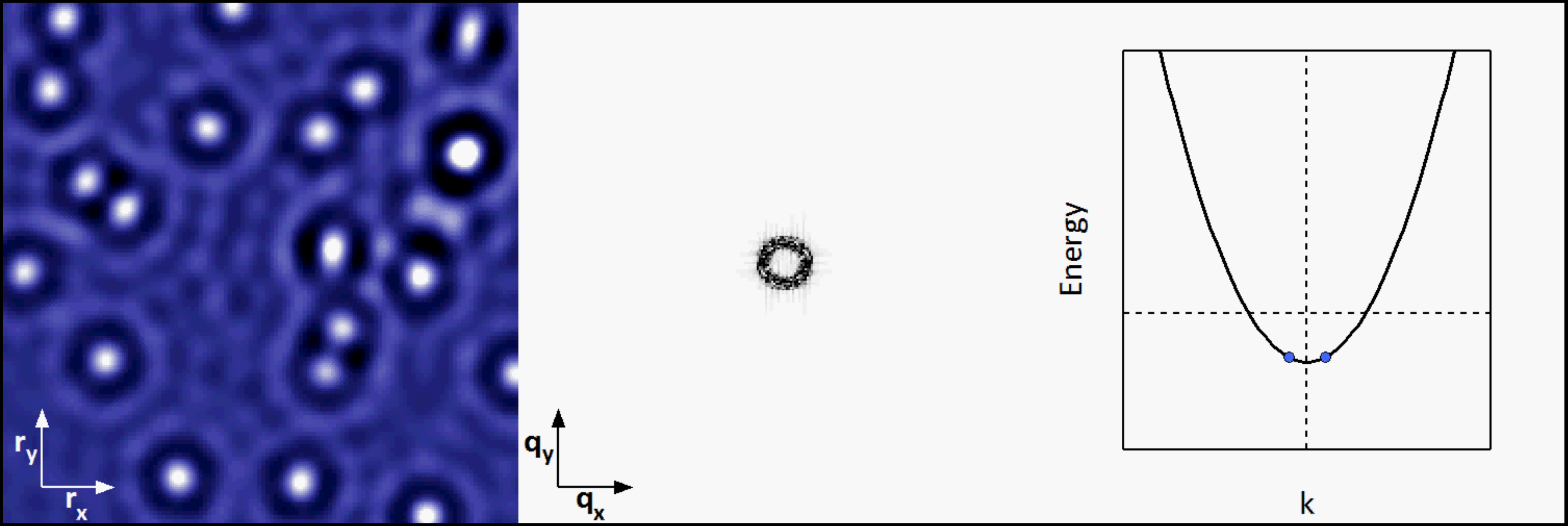
Interference Pattern = Electron Wavelength => $k = 2\pi\, p/h$
$= 2\pi/\lambda(\mathrm{E})$



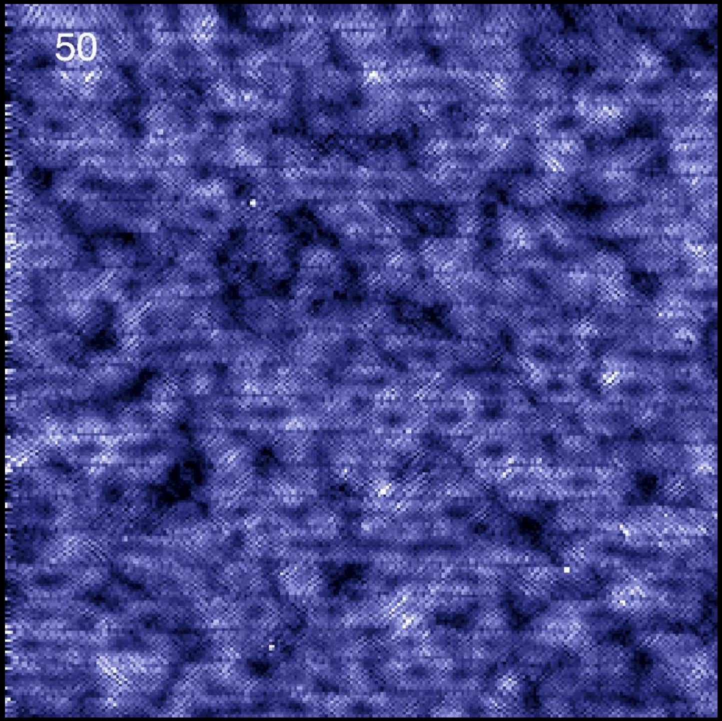
Imaging Quantum Matter Waves

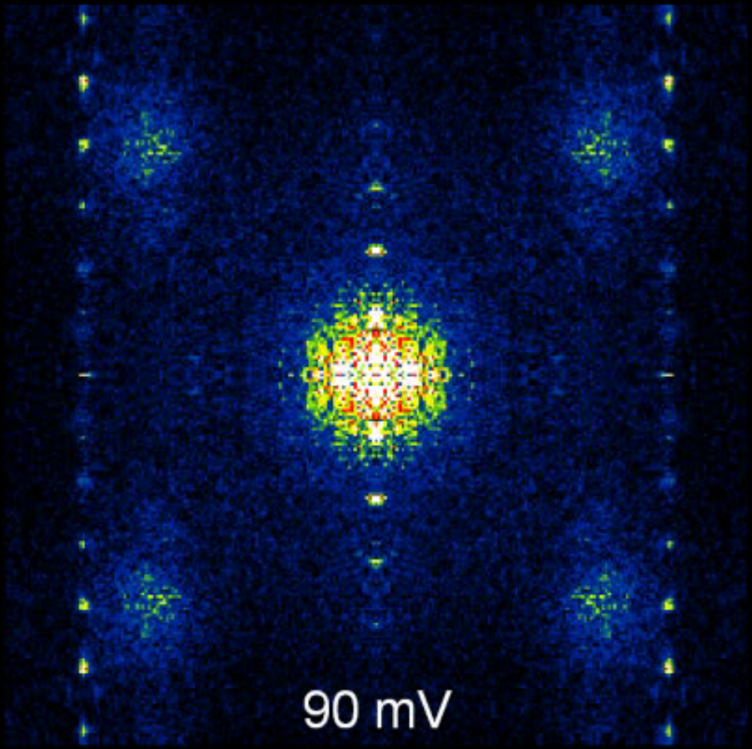
Interference Pattern = Electron Wavelength => $k = 2\pi\, p/h$

$= 2\pi/\lambda(\mathrm{E})$



Imaging Quantum Matter Waves: Cu-based HTS





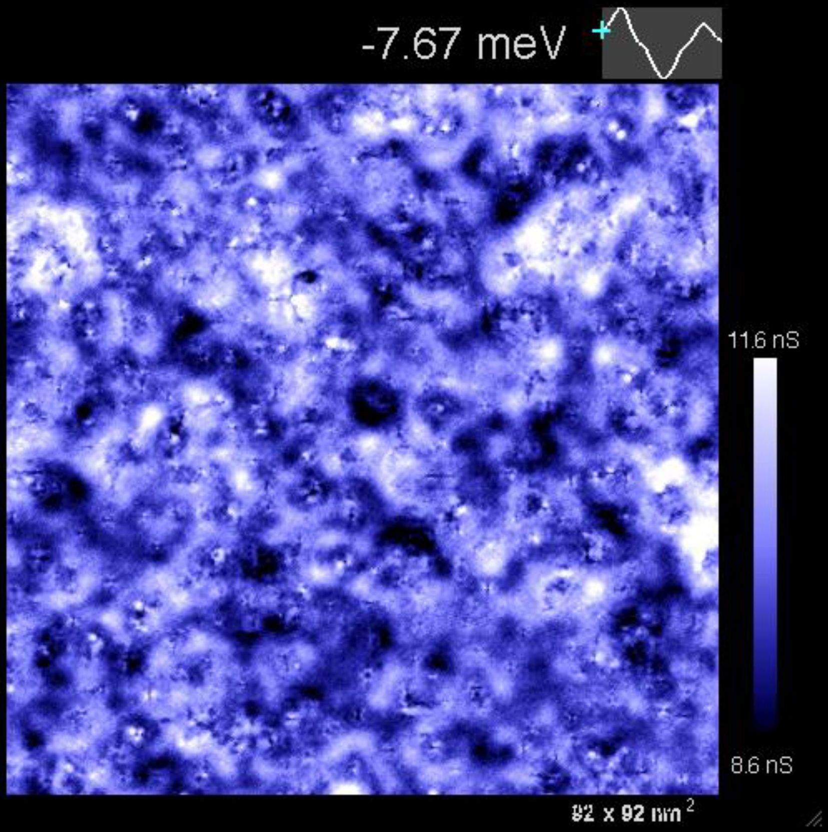
$g(r,\omega)$

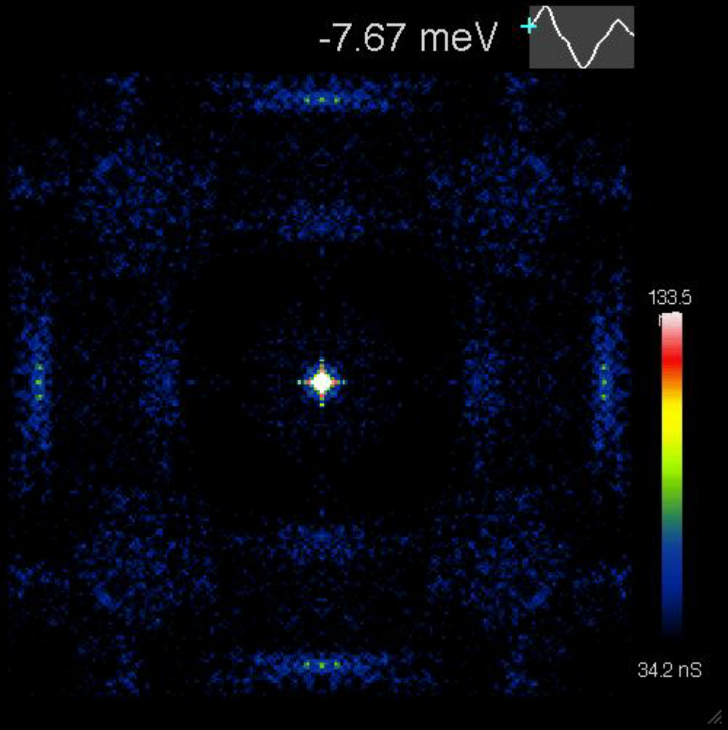
$g(q,\omega)$

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

Imaging Quantum Matter Waves: Fe-based HTS

***g*(E,r)**



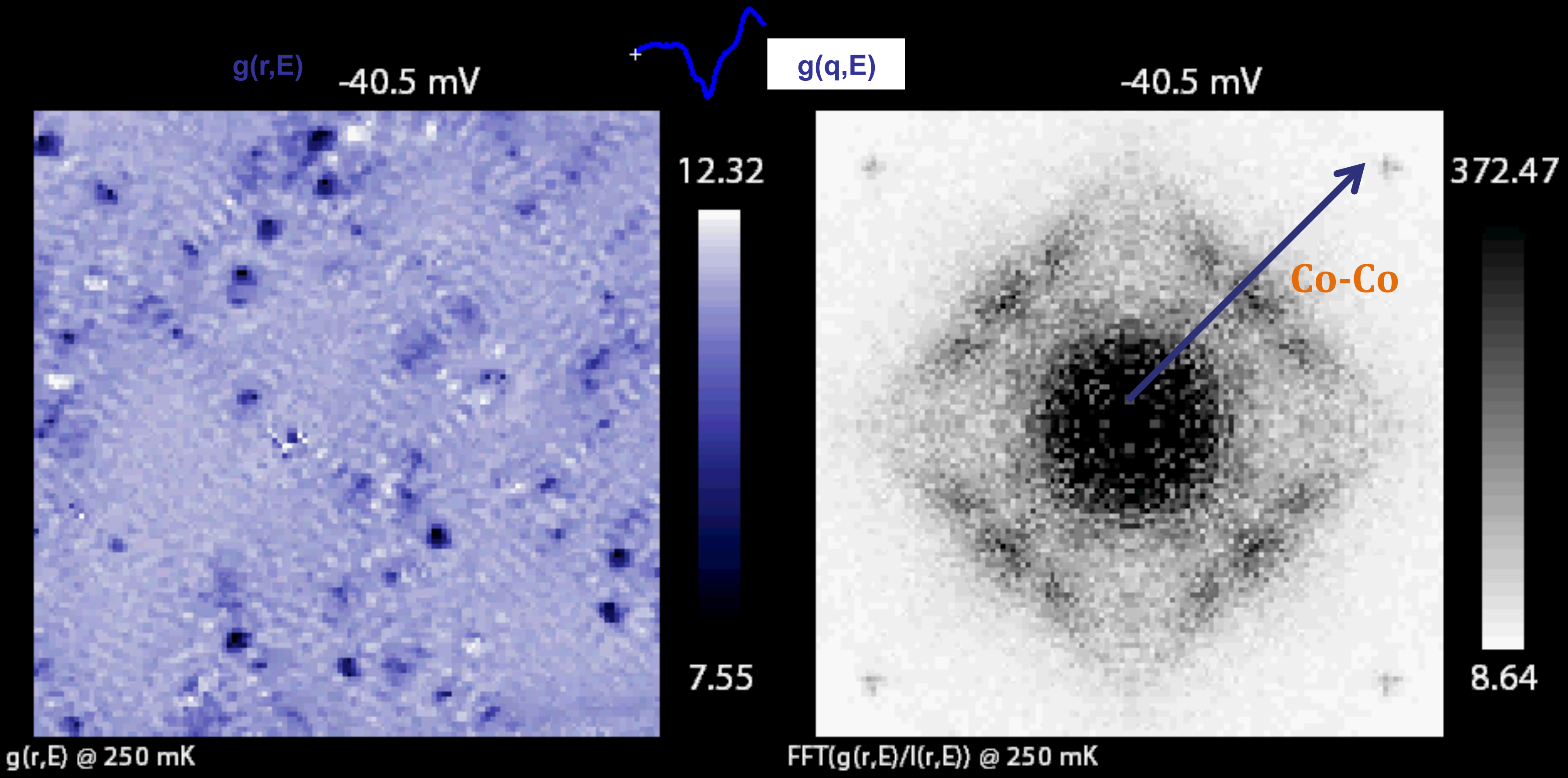


$g(\boldsymbol{r},\omega)$

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

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

Imaging Quantum Matter Waves: HF-based HTS

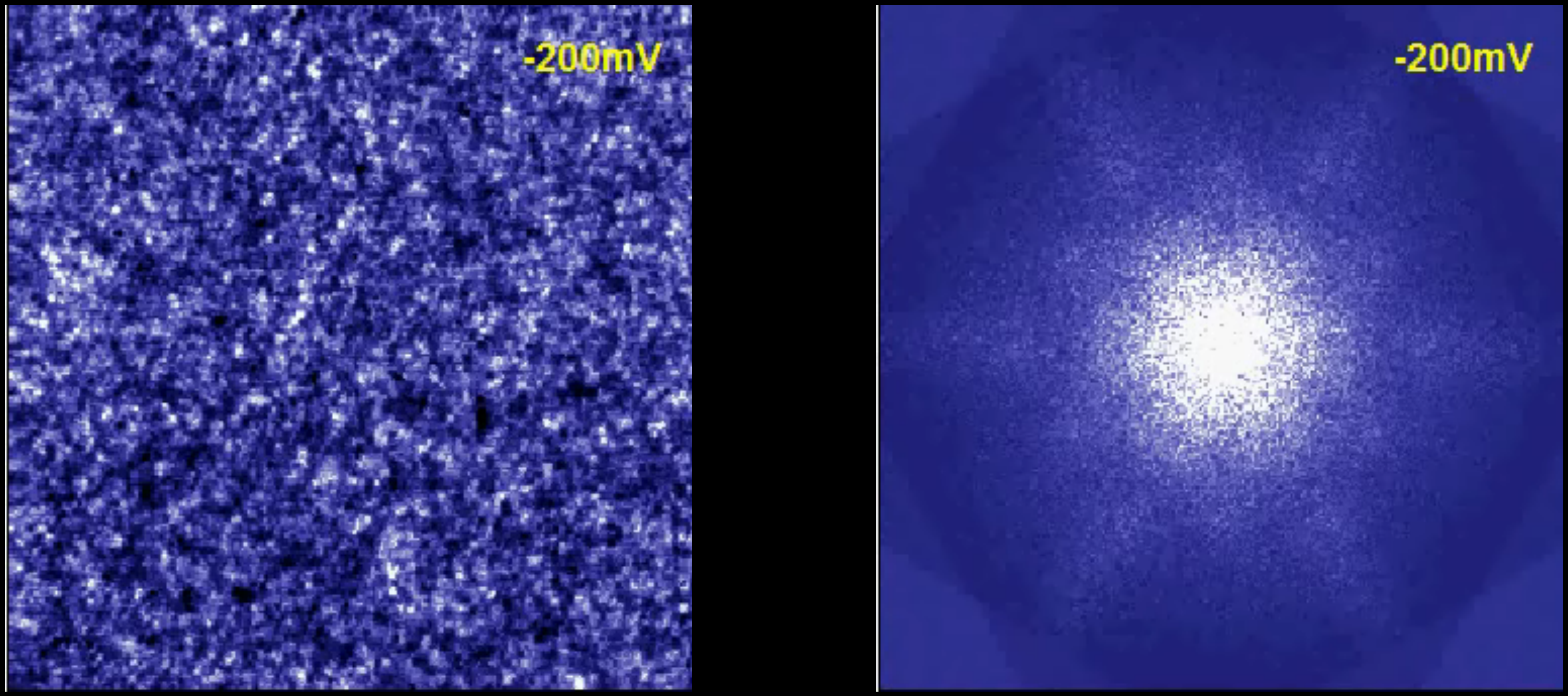


$g(\boldsymbol{r},\omega)$

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

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

Imaging Quantum Matter Waves: Topological Insulator



g($\boldsymbol{r}$,ω)

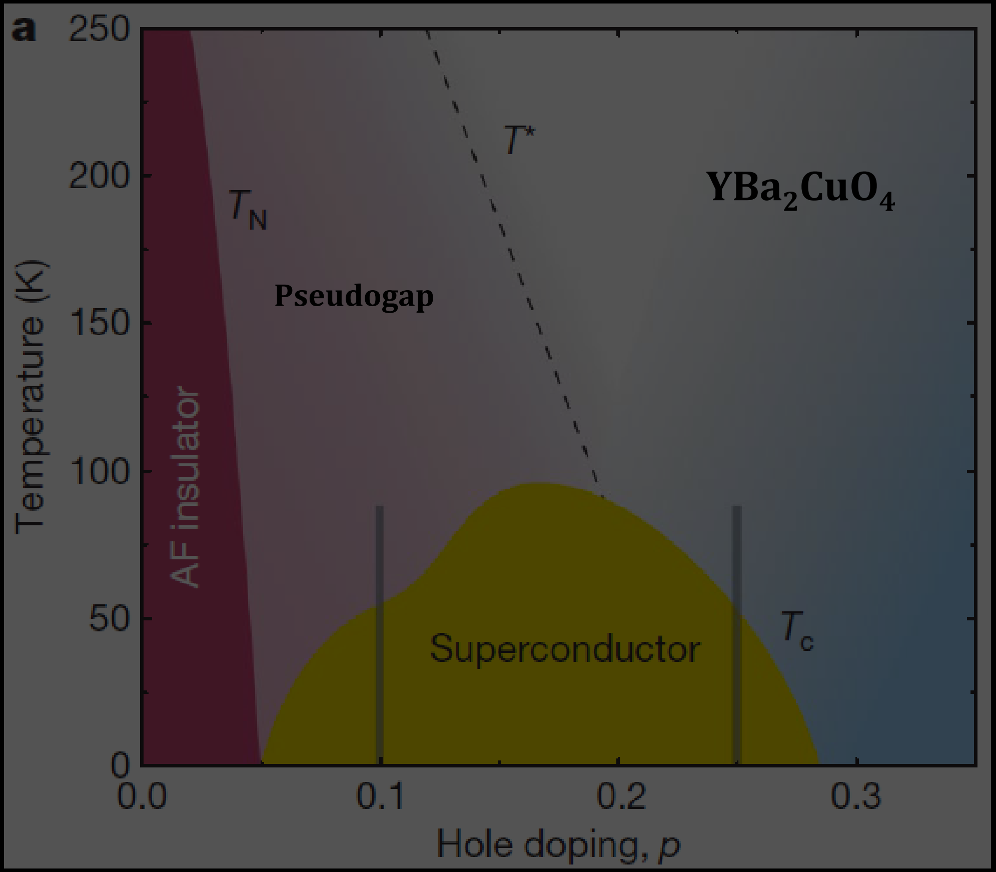
g($\boldsymbol{q}$,ω)

Science (2014)

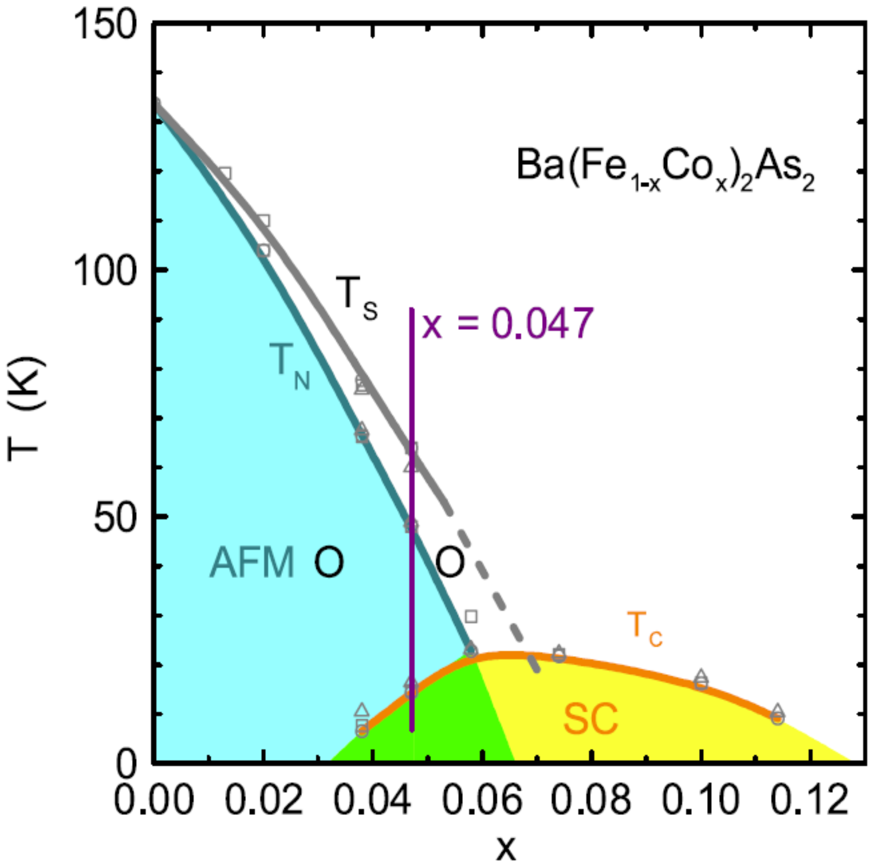
IRON-BASED HIGH-T_c SUPERCONDUCTIVITY

Fe-based HTS

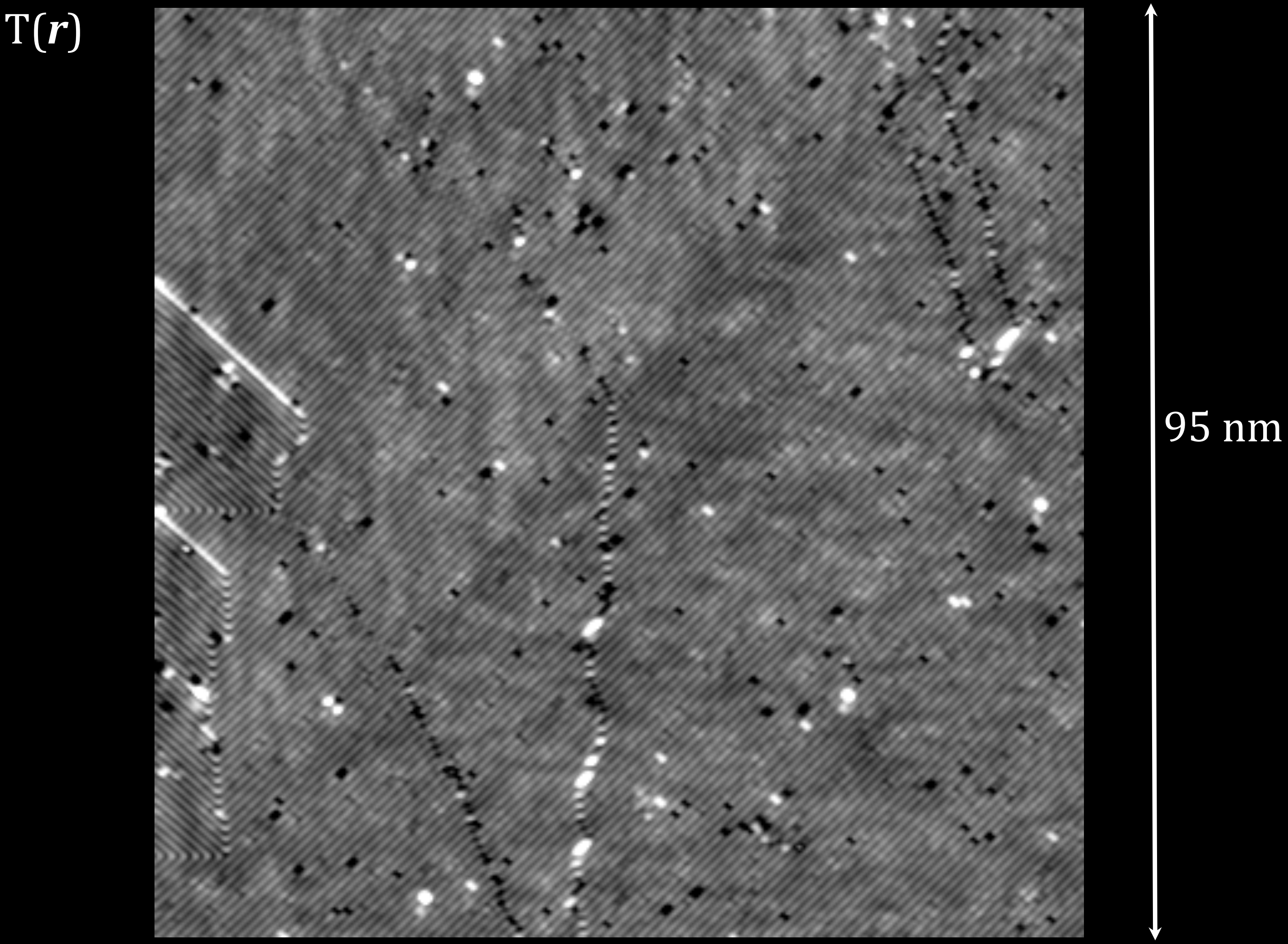
Copper-based



Iron-based

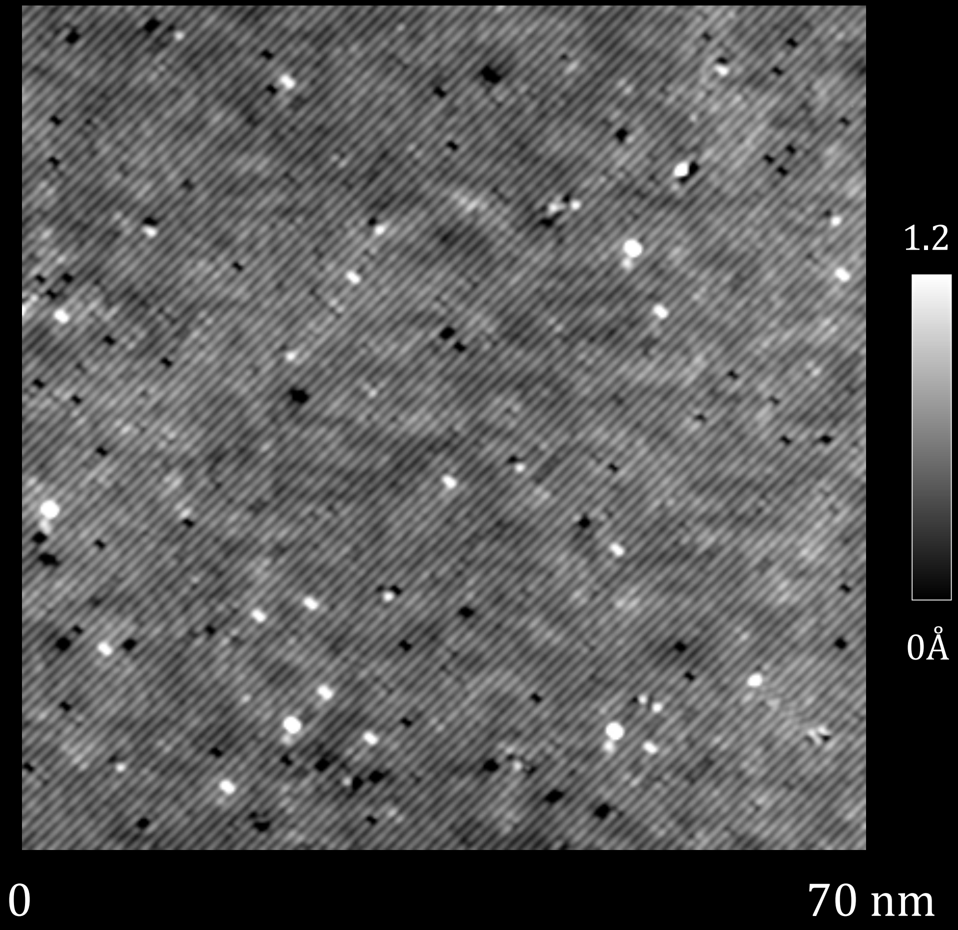


Fe-based HTS Crystal Surface

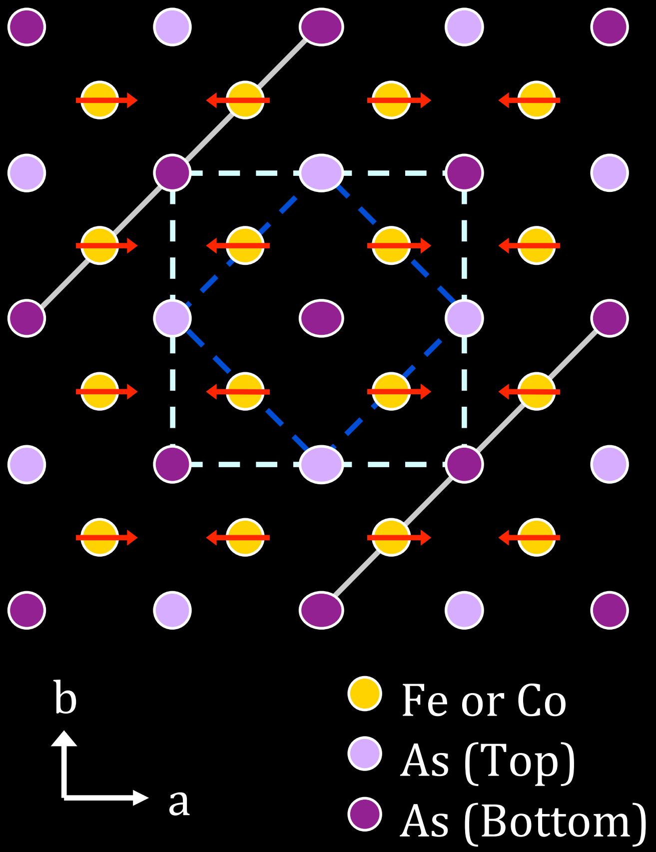


$Ca(Fe_{1-x}Co_x)_2As_2$ -- Excellent cryo-cleave surface

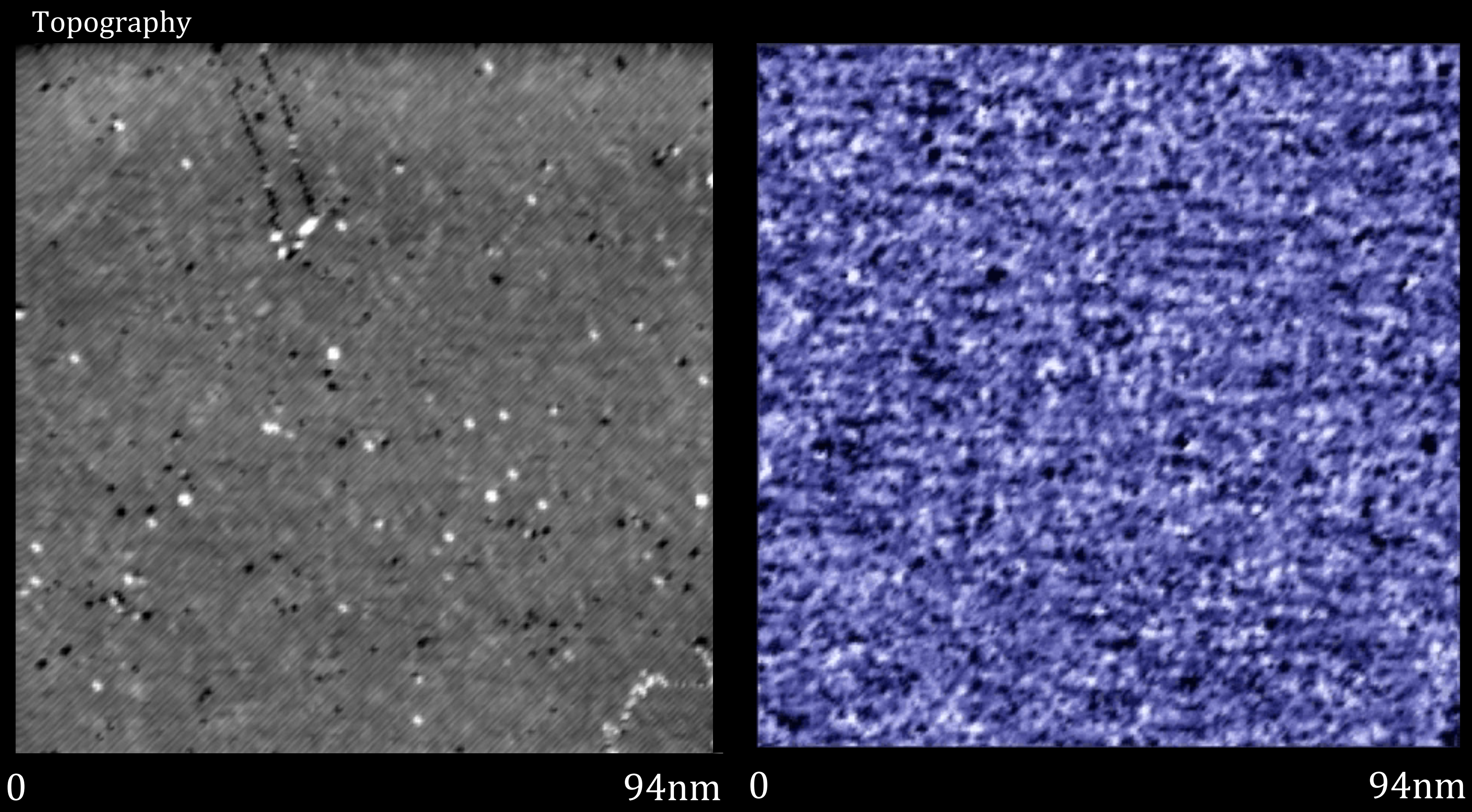
Topography



FeAs-layer Reconstruction

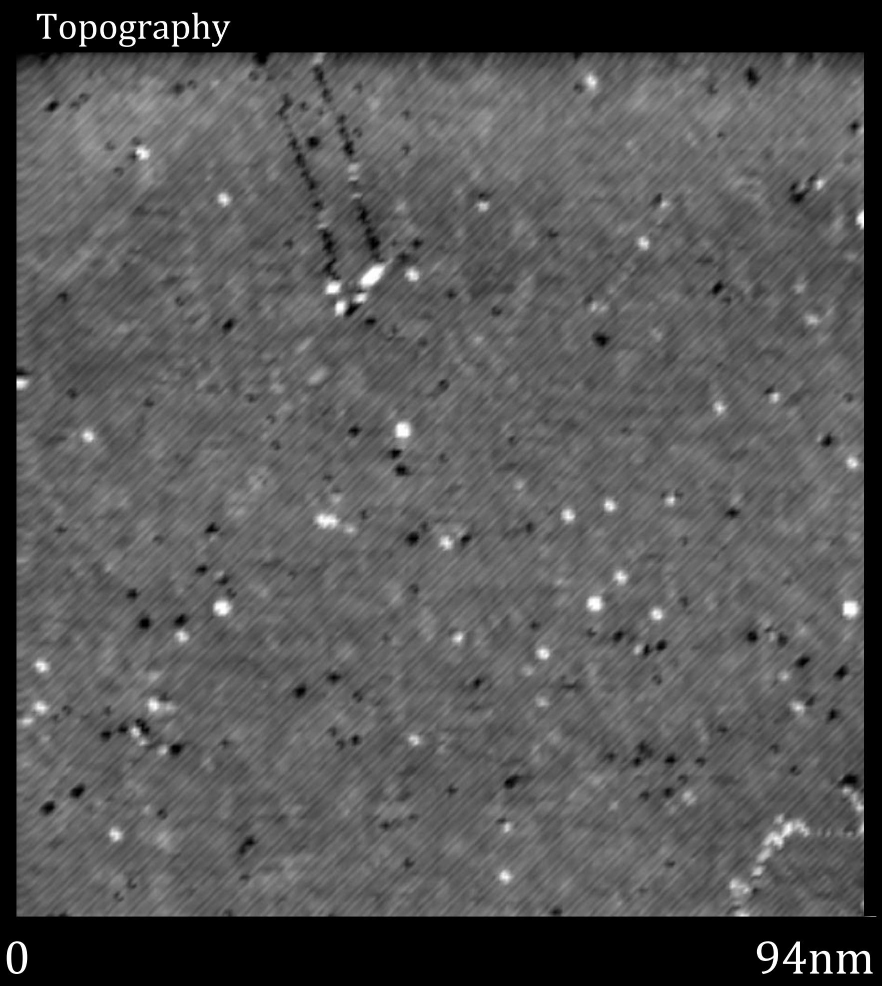


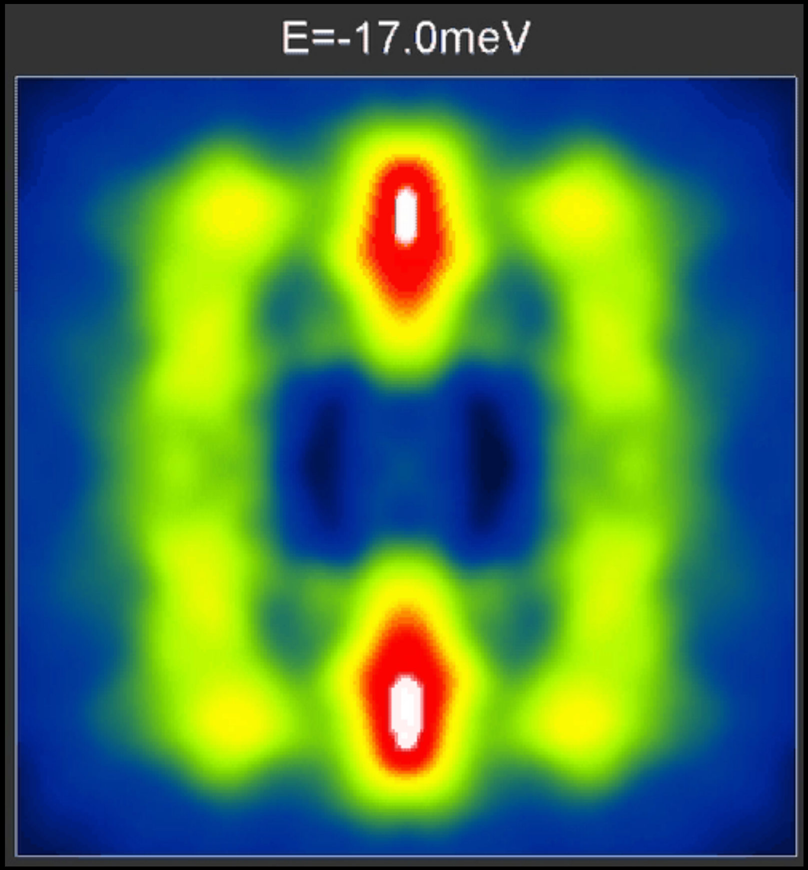
Electronic Matter Waves in $CaFe_2As_2$



Science **327**, 181 (2010)

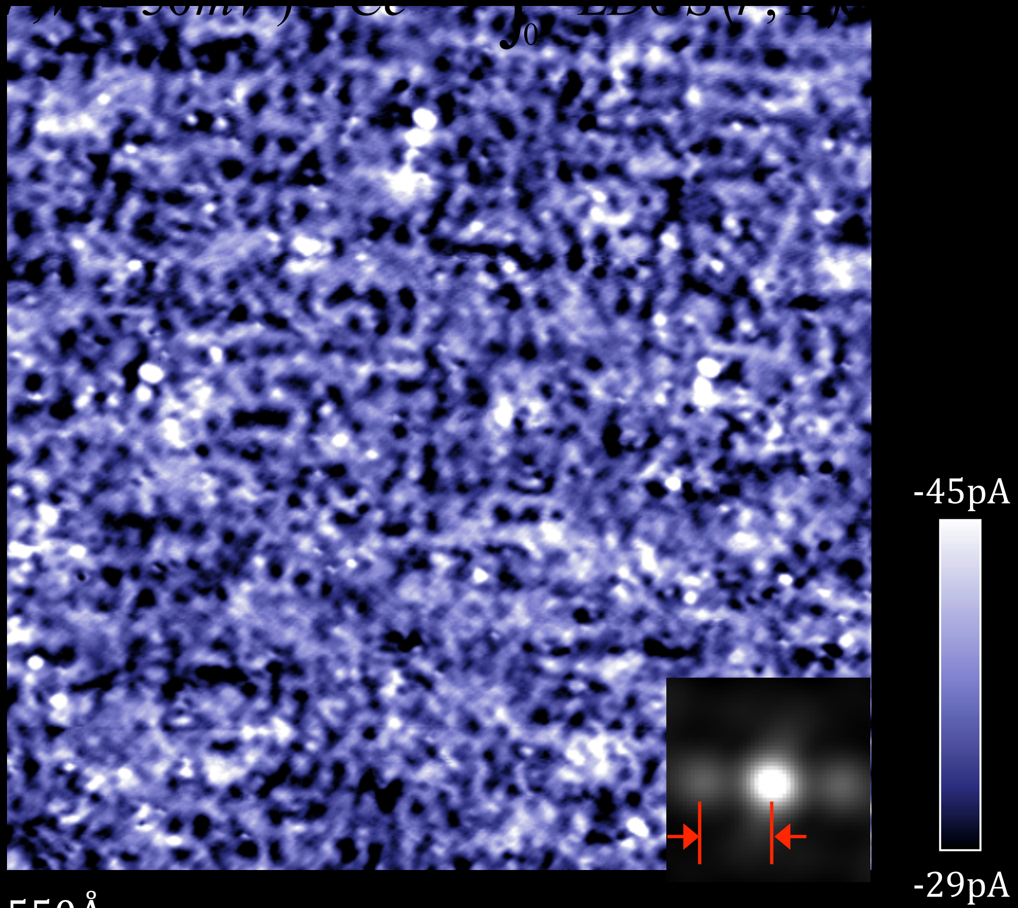
Electronic Matter Waves in $CaFe_2As_2$





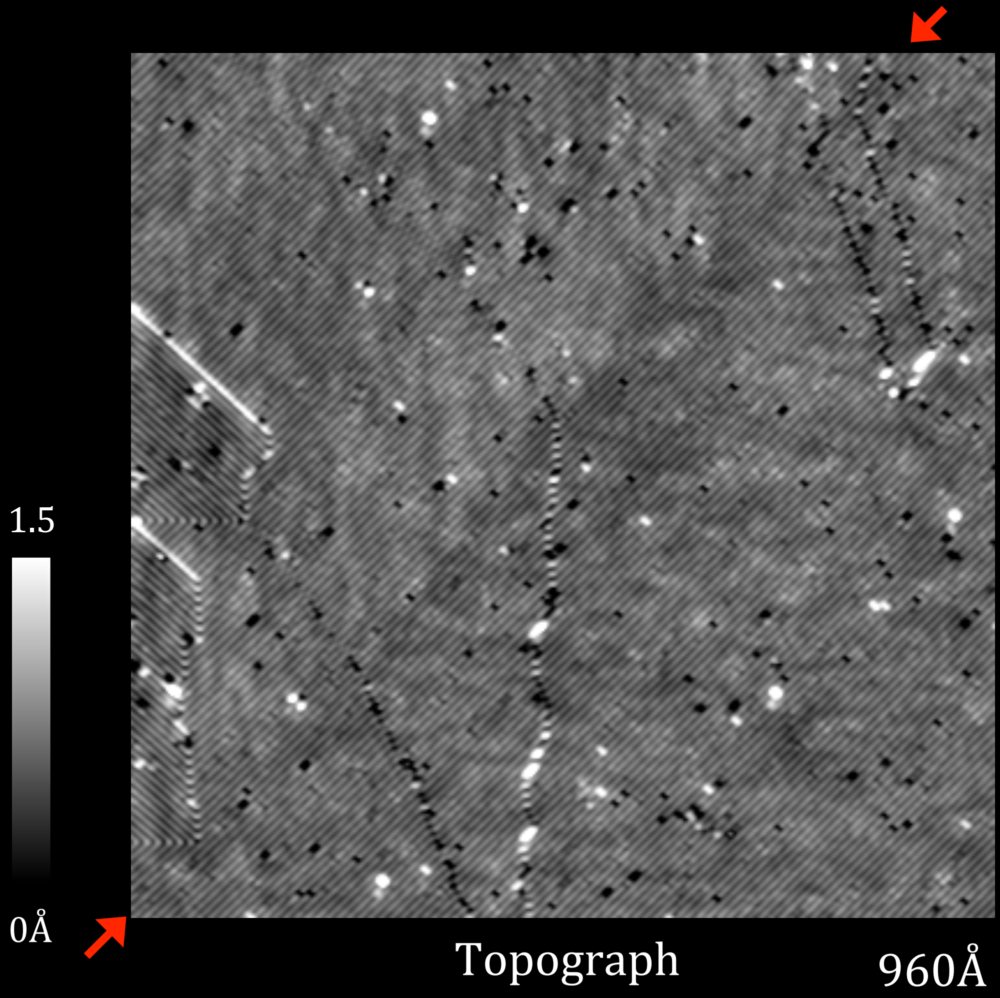
Science **327**, 181 (2010)

Electronic nanostructures ~$8a_{FeFe}$ aligned



Science **327**, 181 (2010)

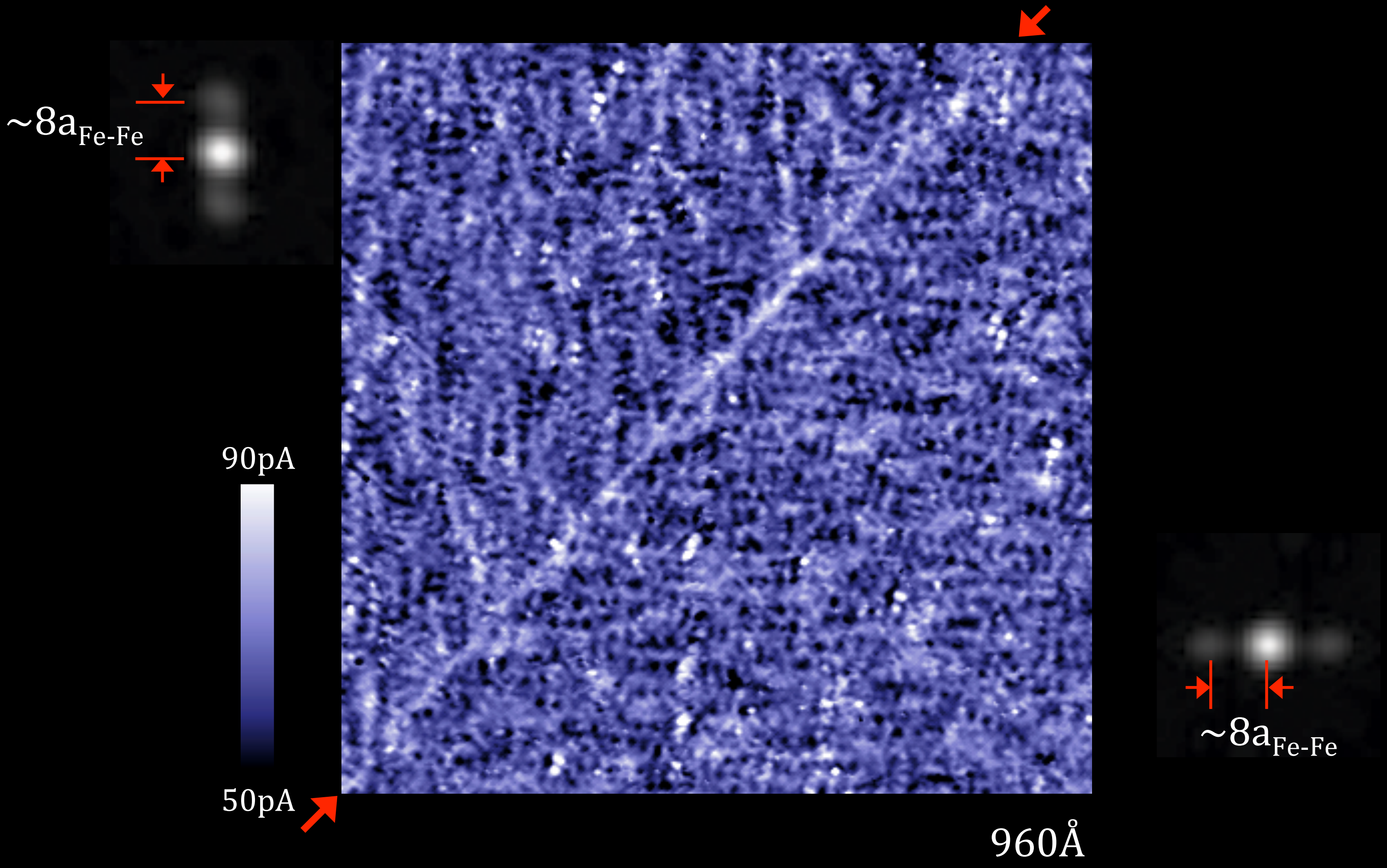
Effect of Crystal Boundary



Topograph

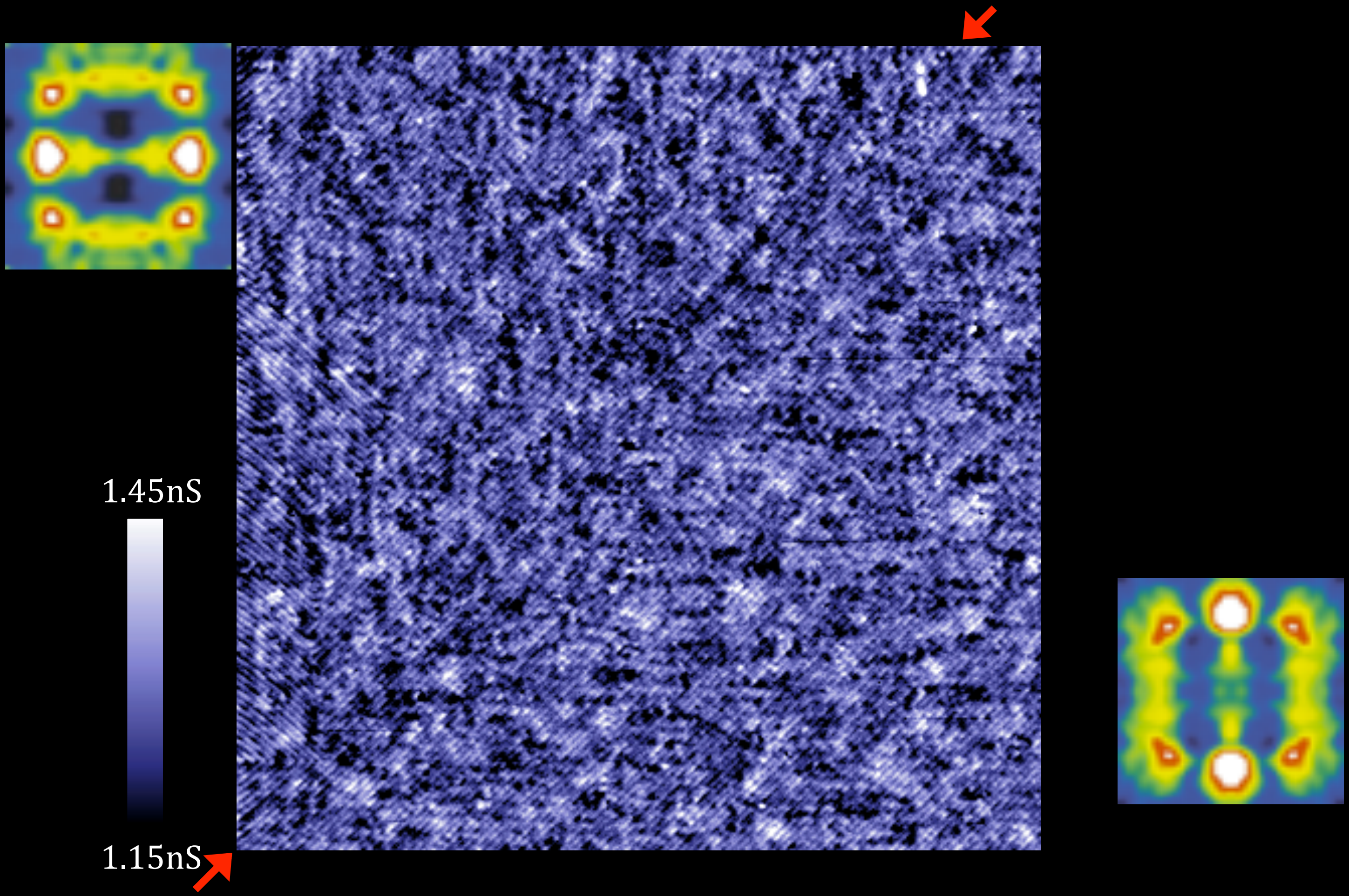
Science **327**, 181 (2010)

Electronic nanostructures rotate by 90 degrees



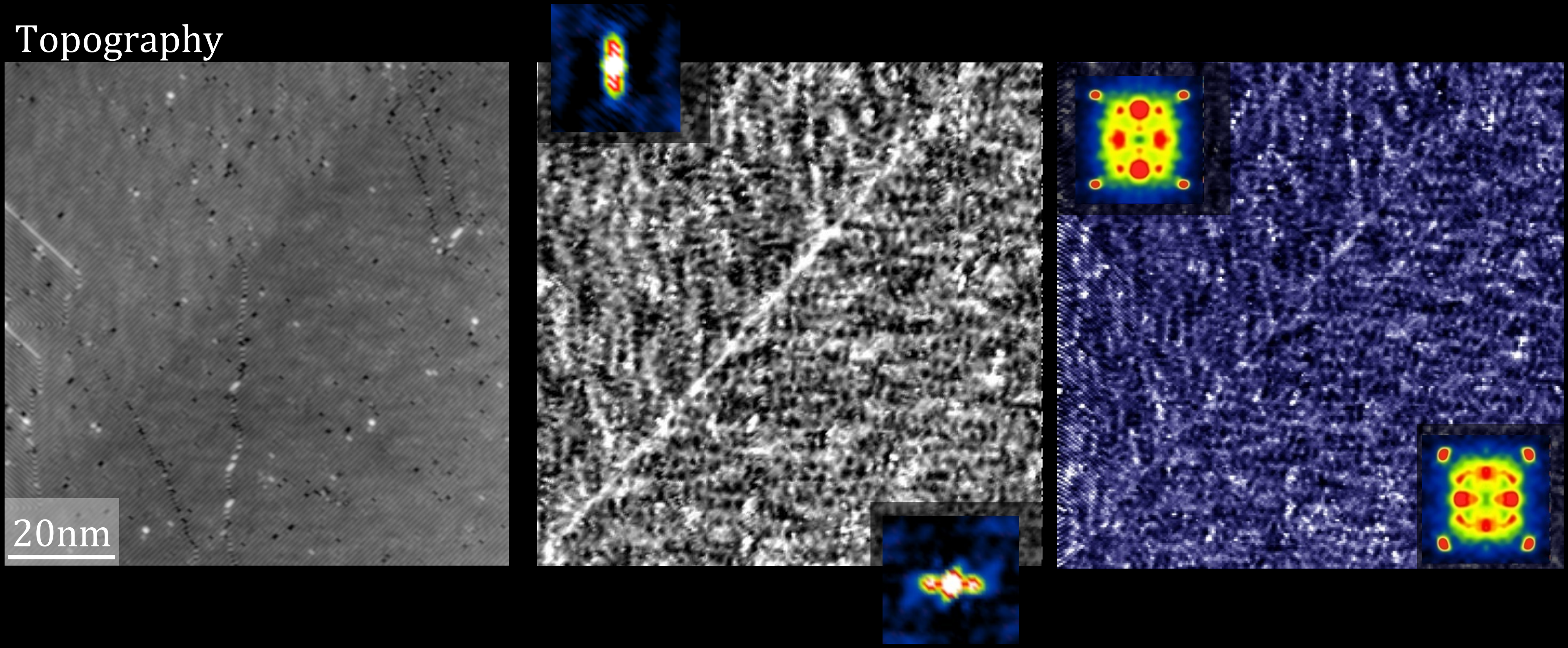
Science **327**, 181 (2010)

Electron wavefunctions rotate by 90 degrees



Science **327**, 181 (2010)

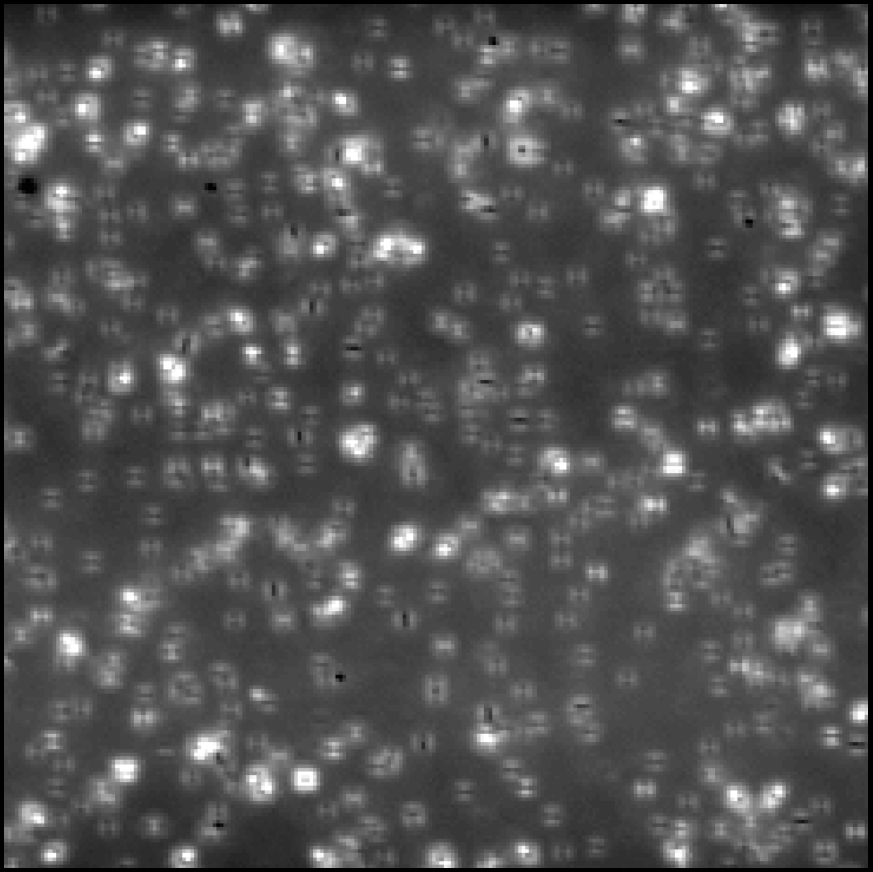
Discovery of Electronic Nematic Phase in Iron-Pnictides

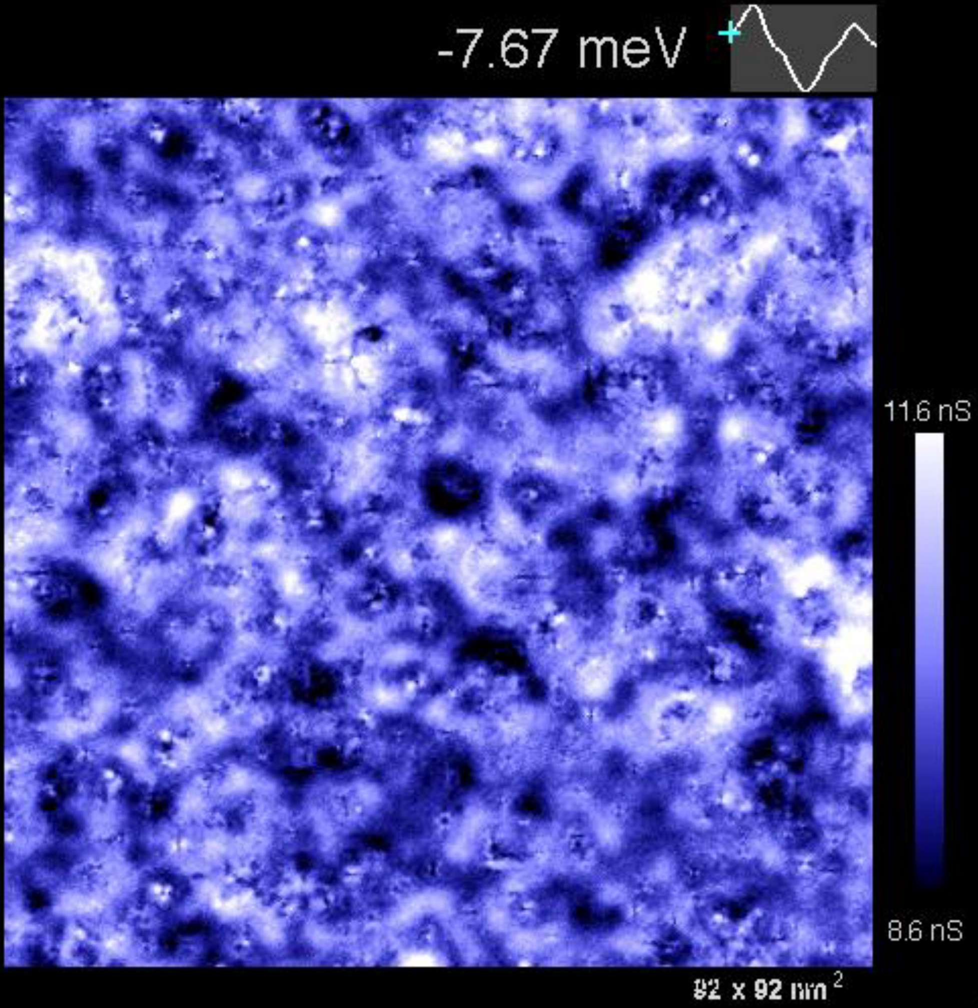


Topography

Science **327**, 181 (2010)

SUPERCONDUCTING WAVEFUNCTIONS

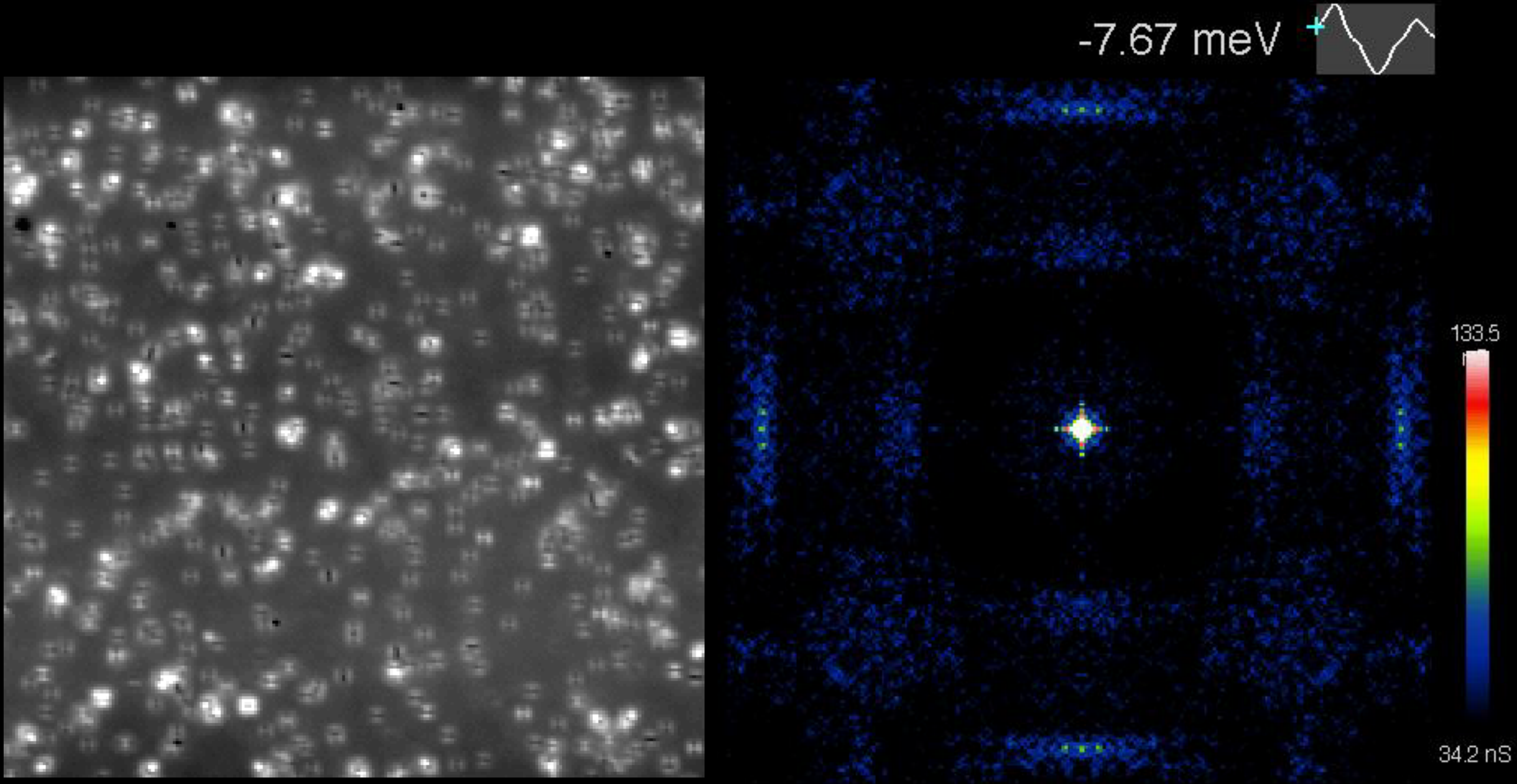




AsAs - direction

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

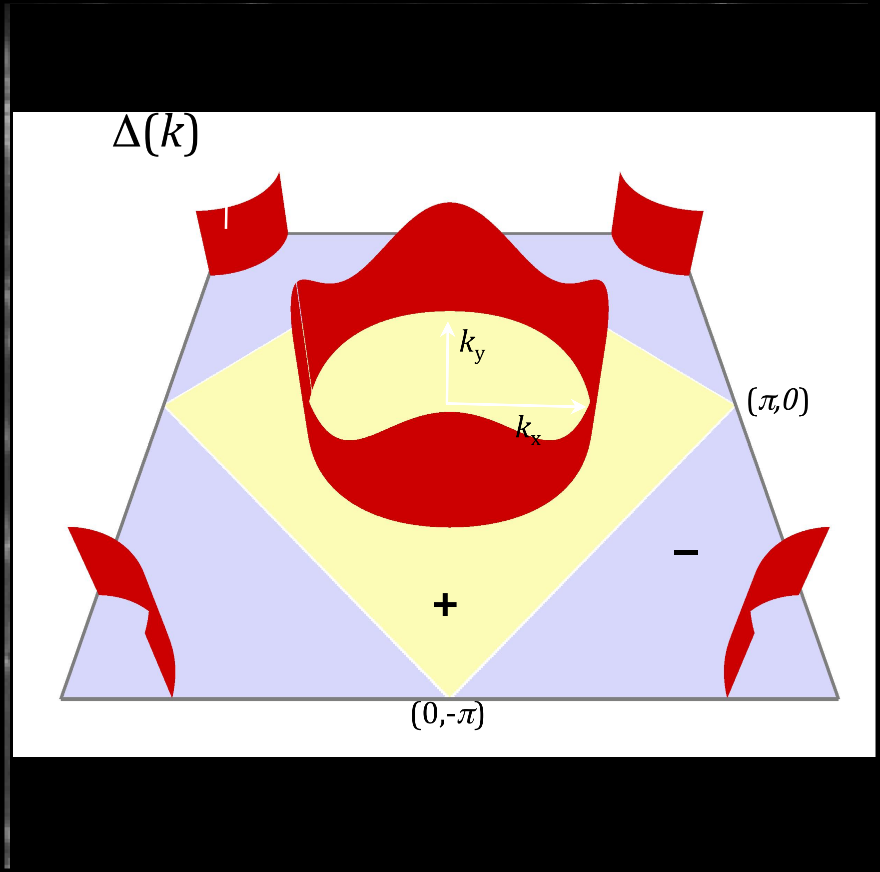
SUPERCONDUCTING WAVEFUNCTIONS

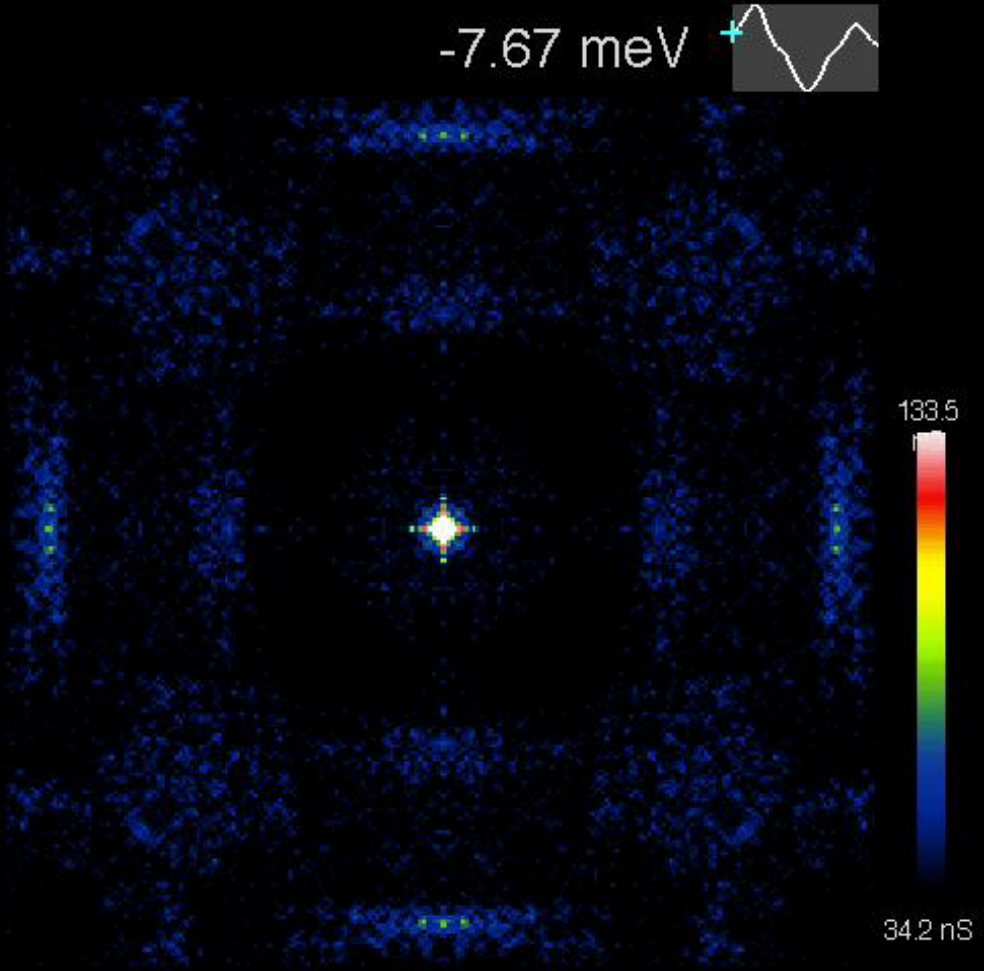


AsAs -
direction

Science 336, 563, (2012)

SUPERCONDUCTING WAVEFUNCTIONS



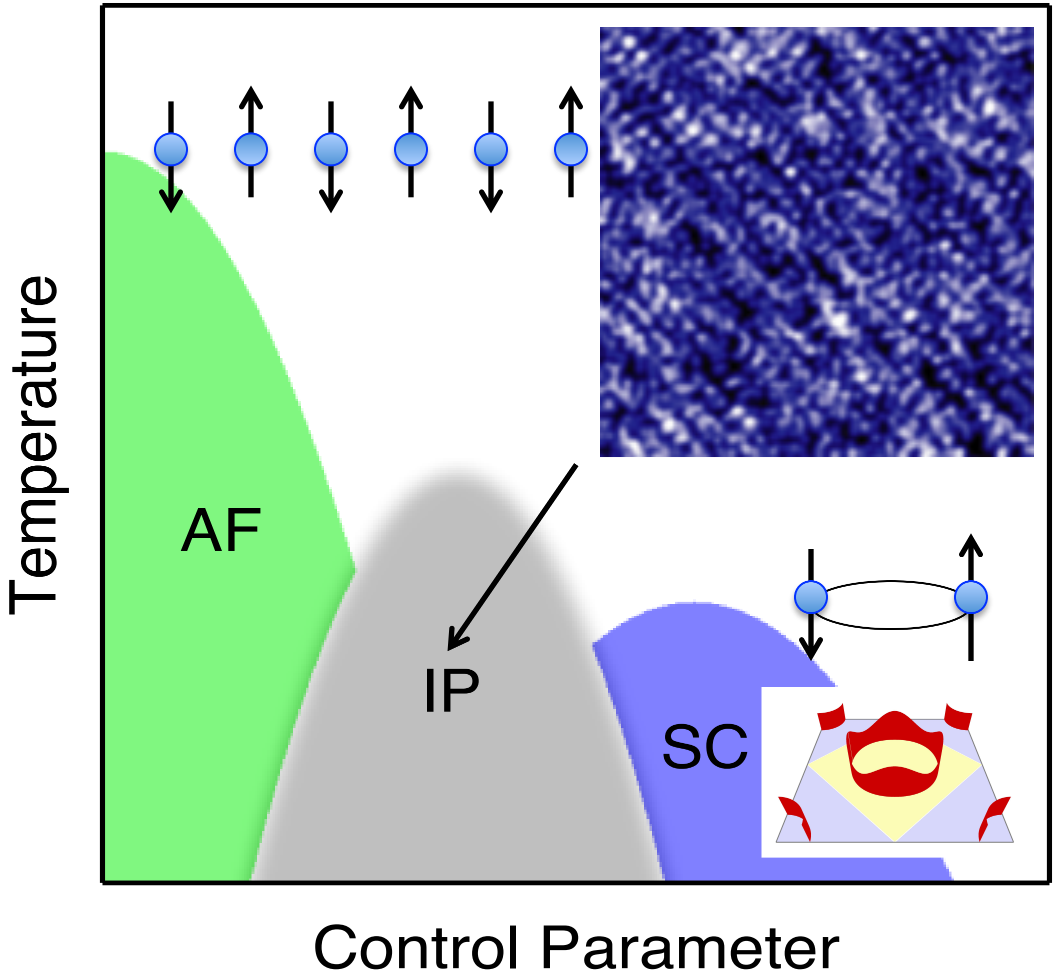


AsAs - direction

Δ(K)

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

ELECTRONIC NEMATIC PHASE / IRON-BASED HTS



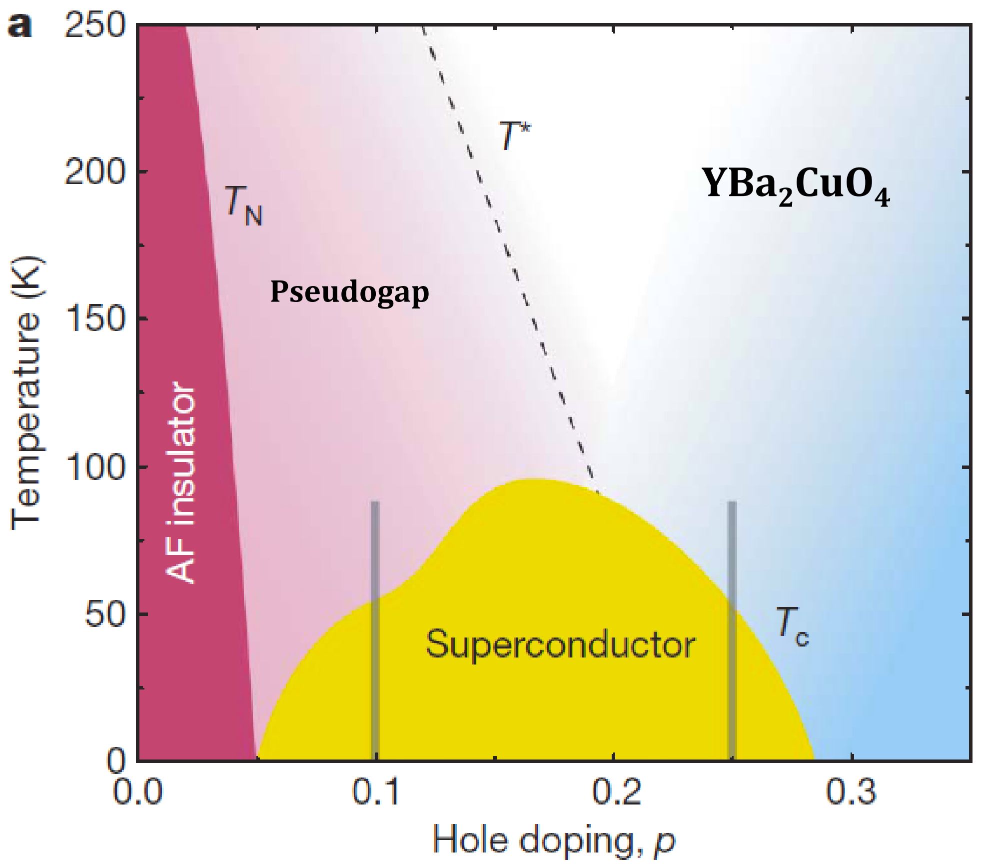
Science 336, 563, (2012)

Science 327, 181 (2010)

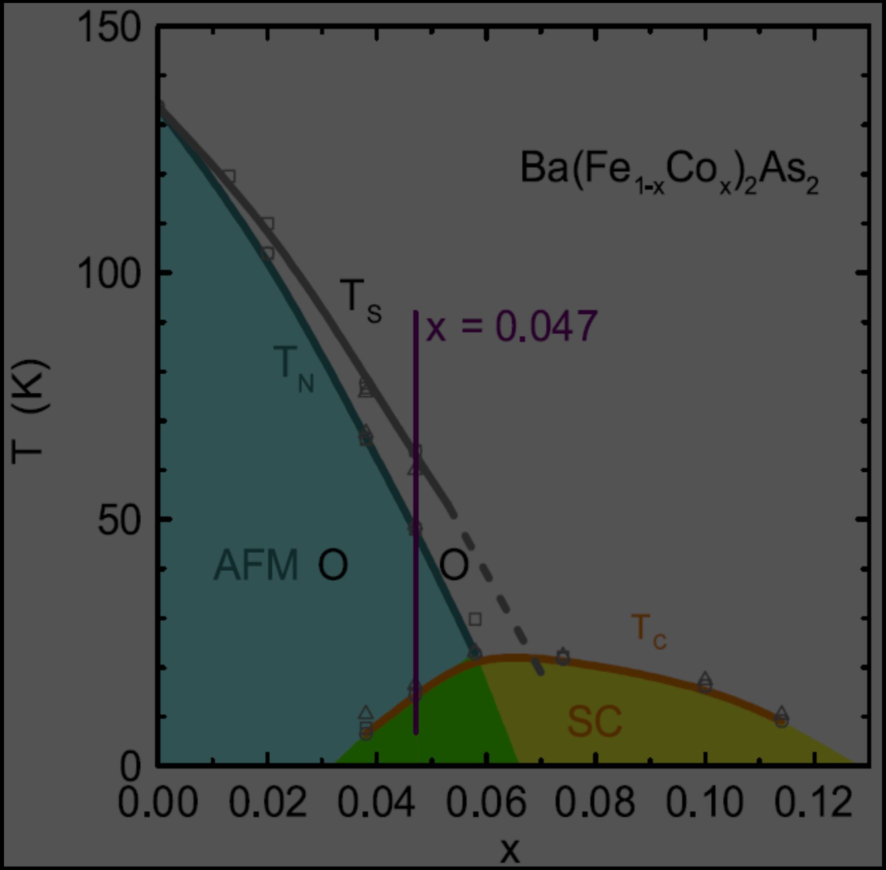
COPPER BASED HIGH-T_c SUPERCONDUCTIVITY

Cu-based HTS

Copper-based

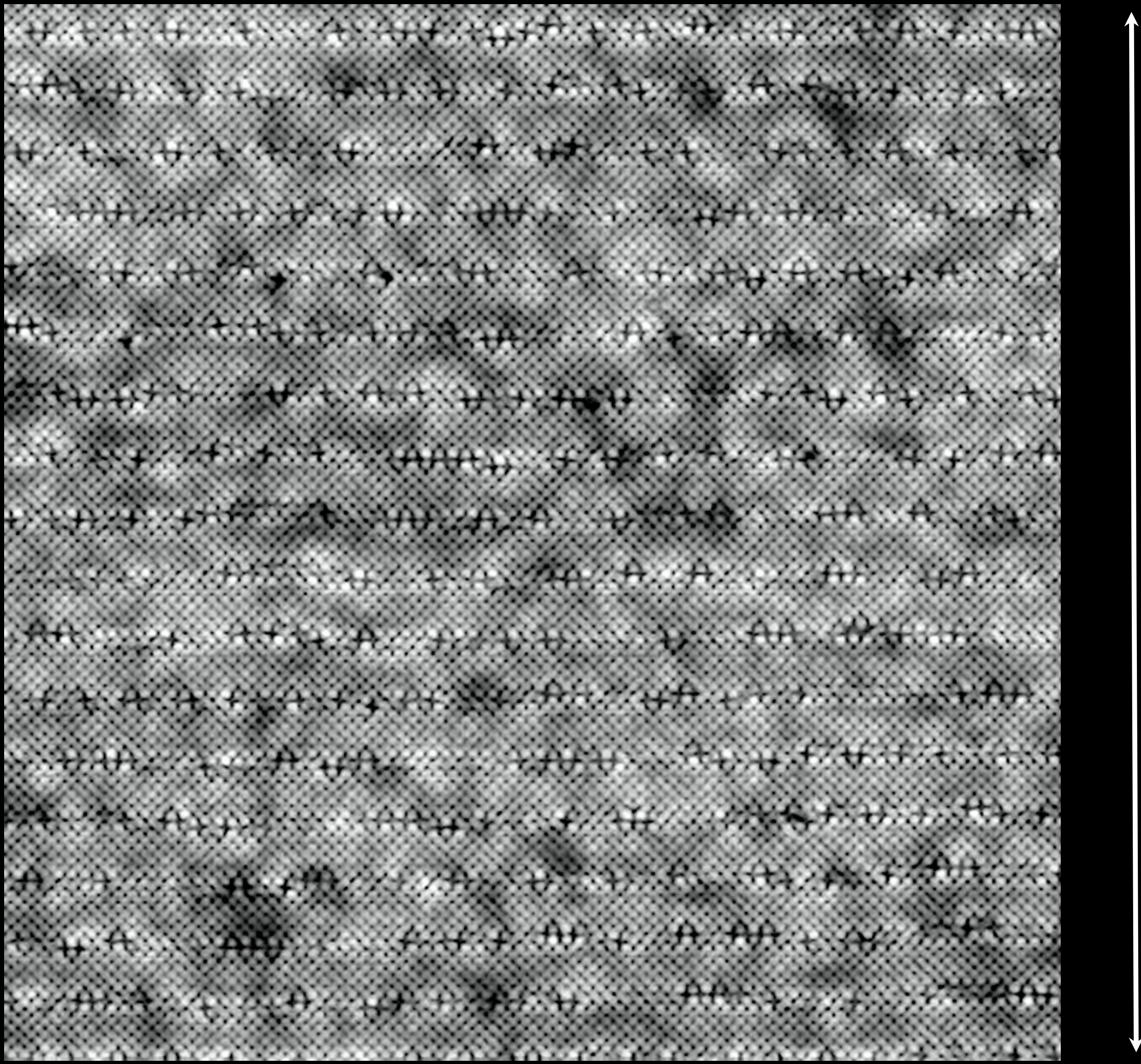


Iron-based



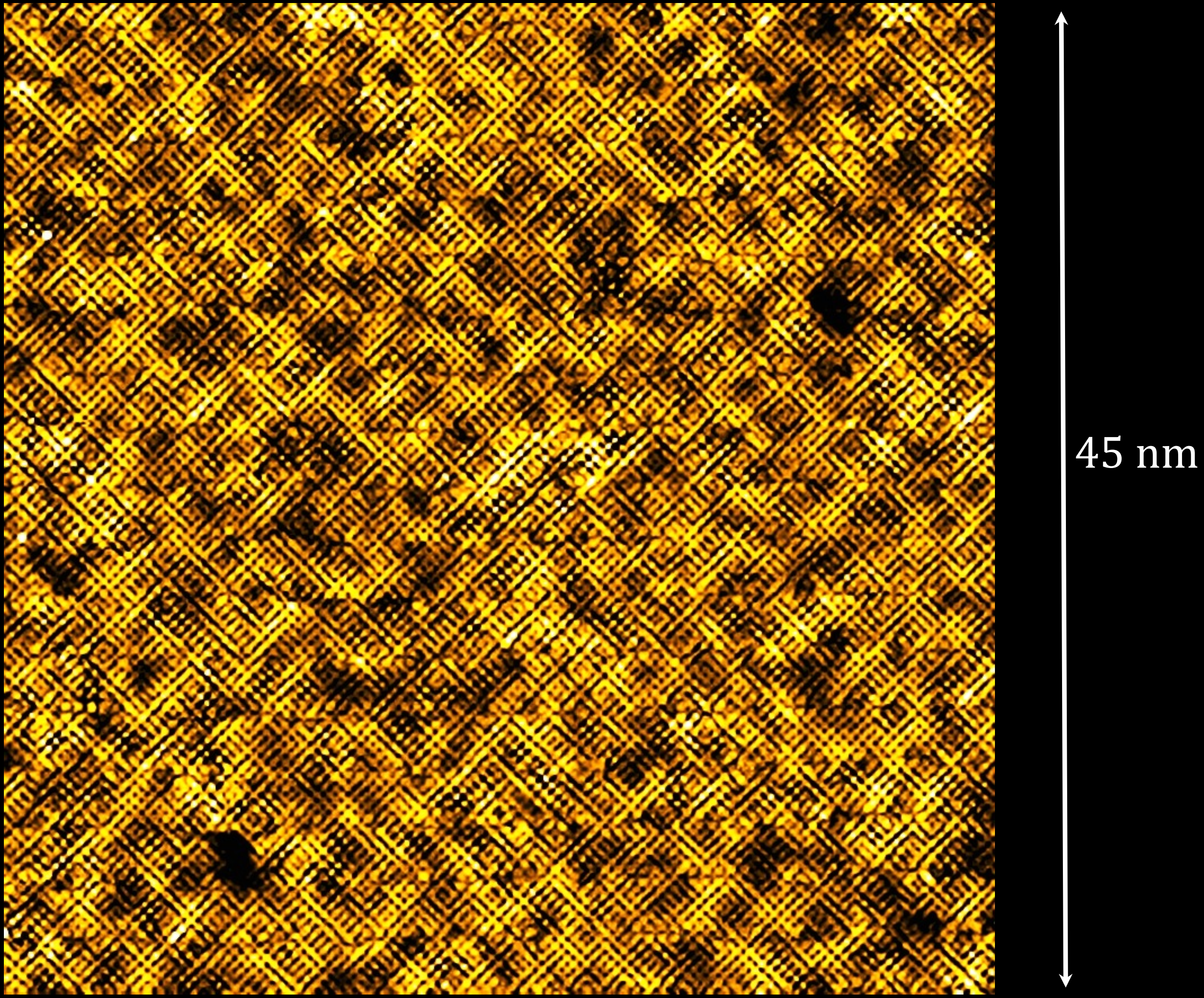
Cu-based HTS Crystal Surface

T($\boldsymbol{r}$)



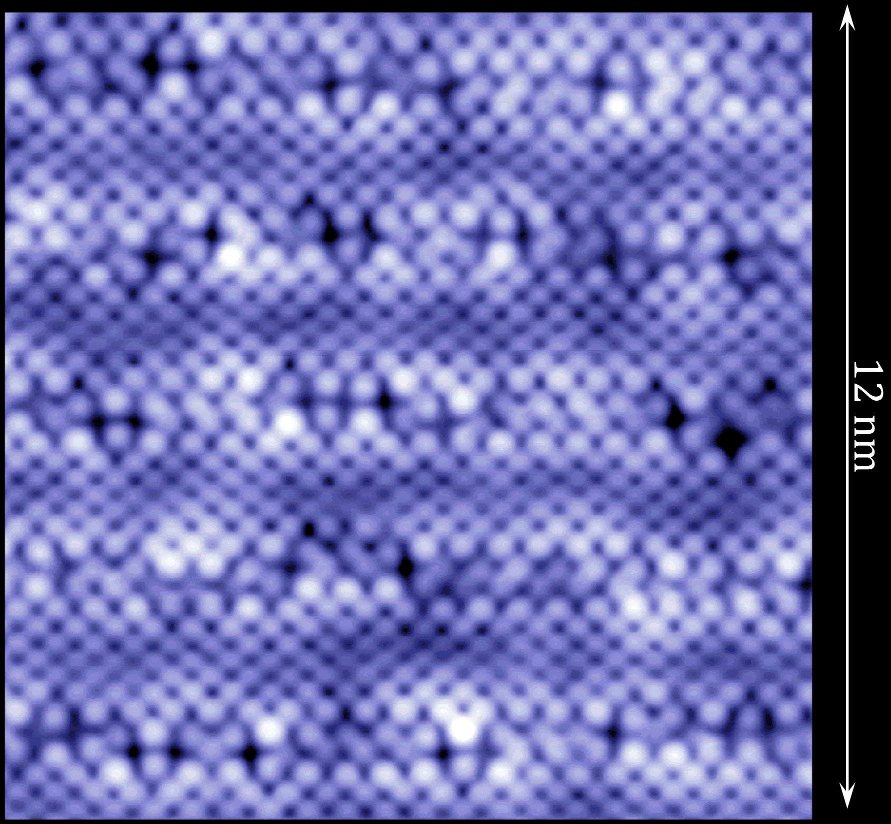
Nature **466,** 374 (2010) ***Science 333***, 4526 (2011) ***Science 344, 612*** (2014)

Cu-based HTS Electronic Matter



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

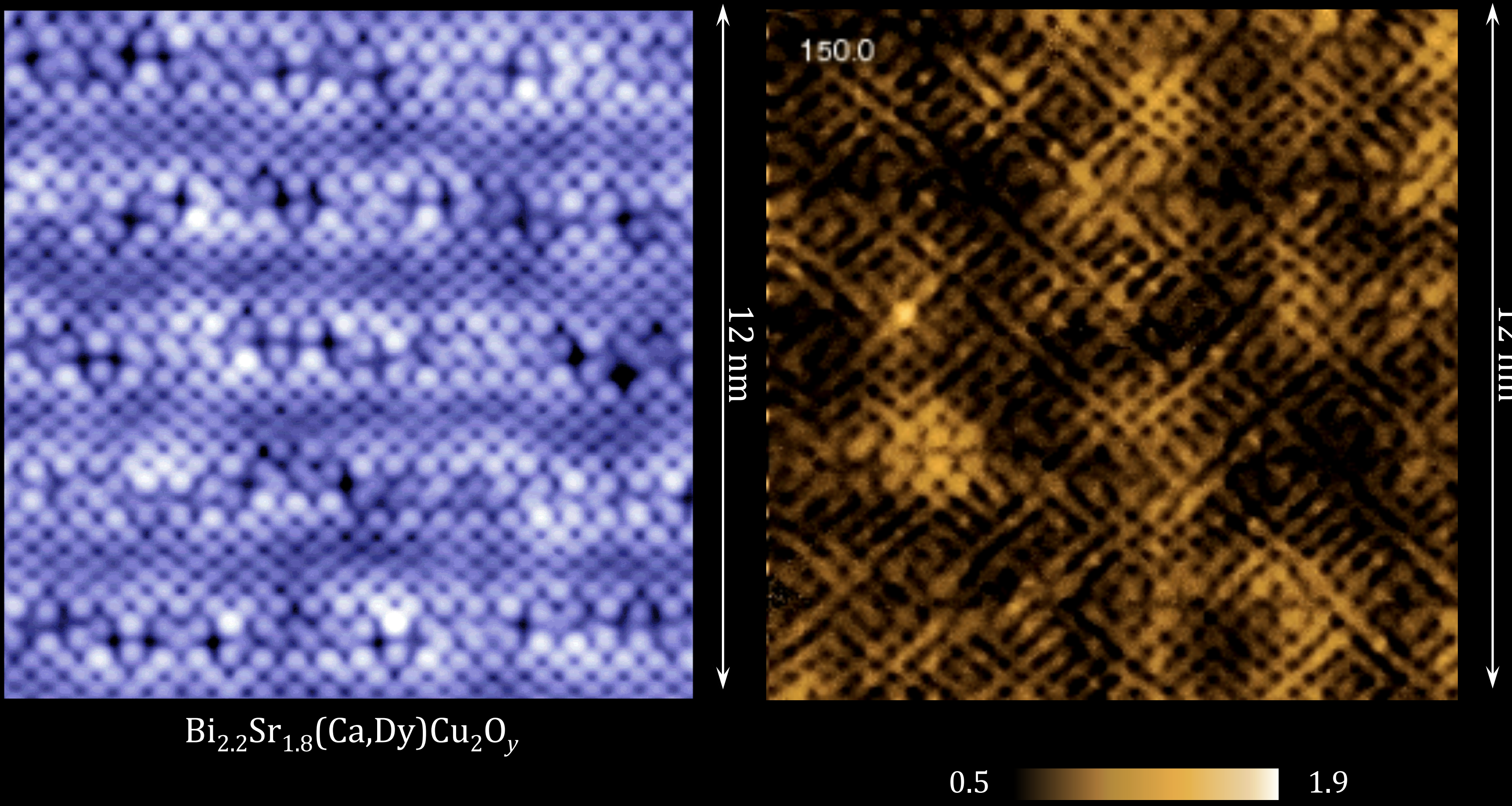
High-resolution Electronic Matter Imaging



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

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

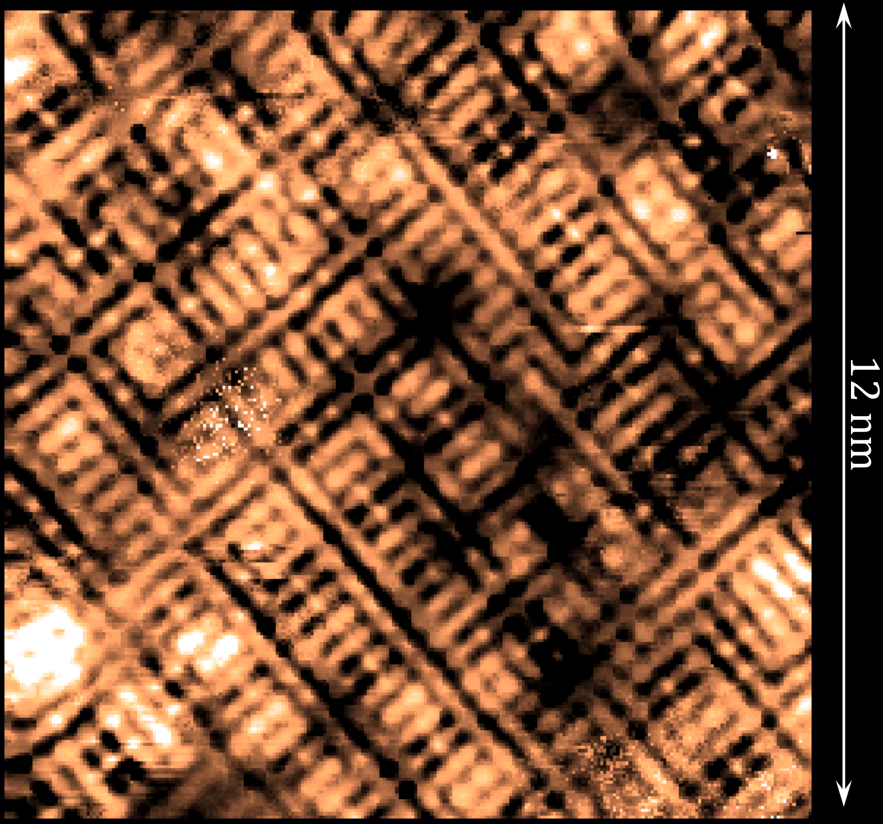
High-resolution Electronic Matter Imaging



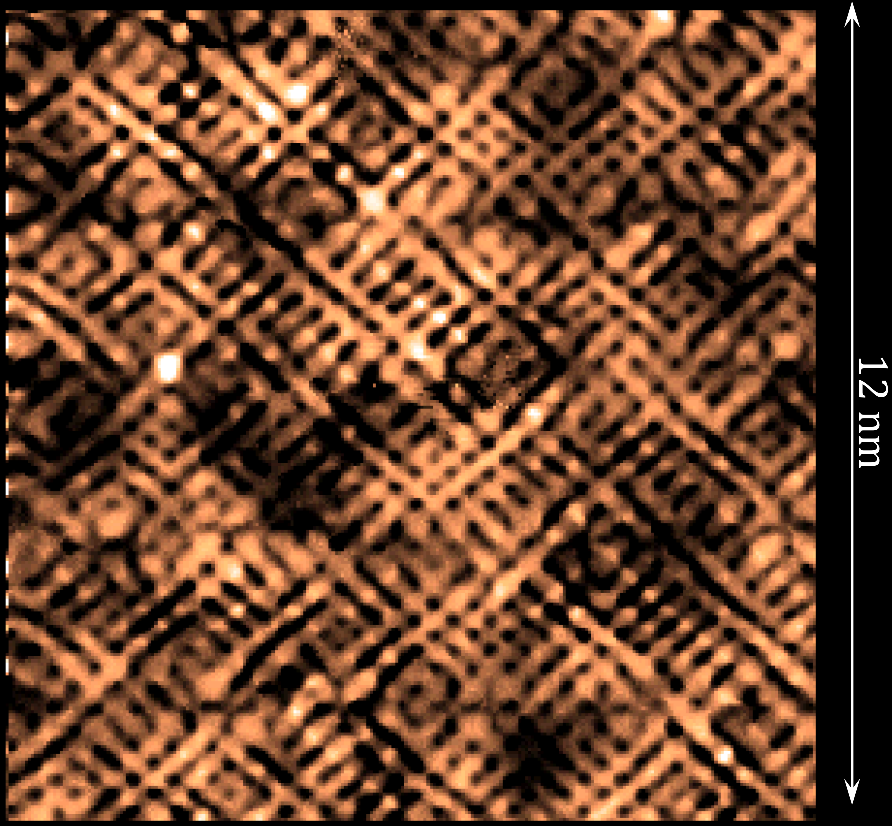
$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$

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

High-resolution Electronic Matter Imaging



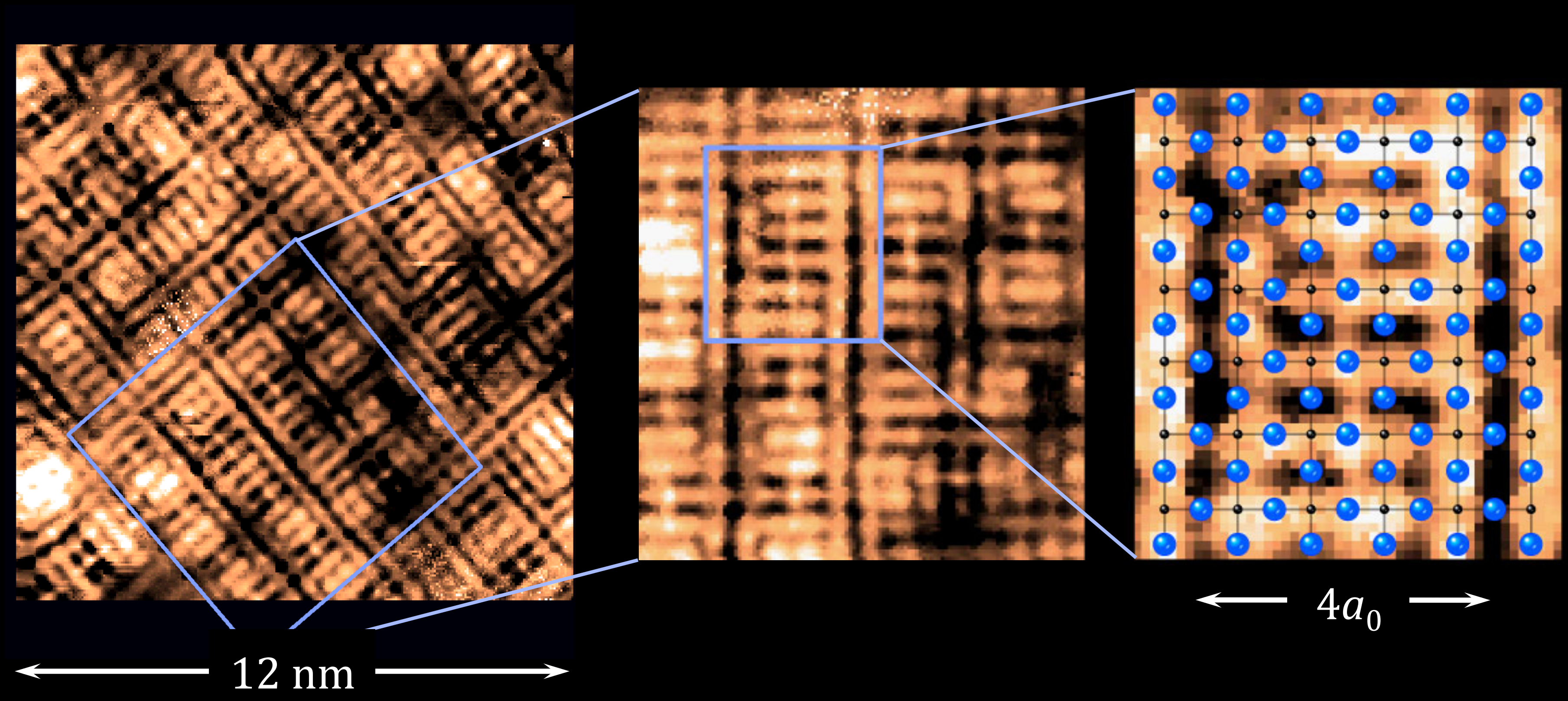
$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



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

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

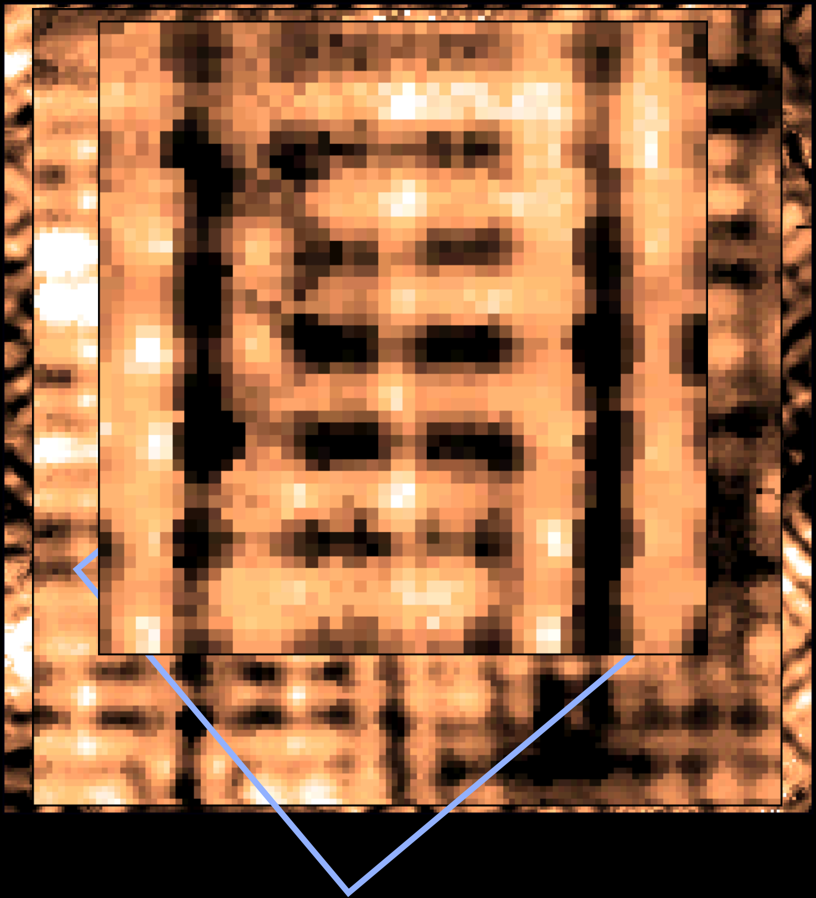
Electronically Inequivalent Oxygen-sites within CuO_2 Unit Cell



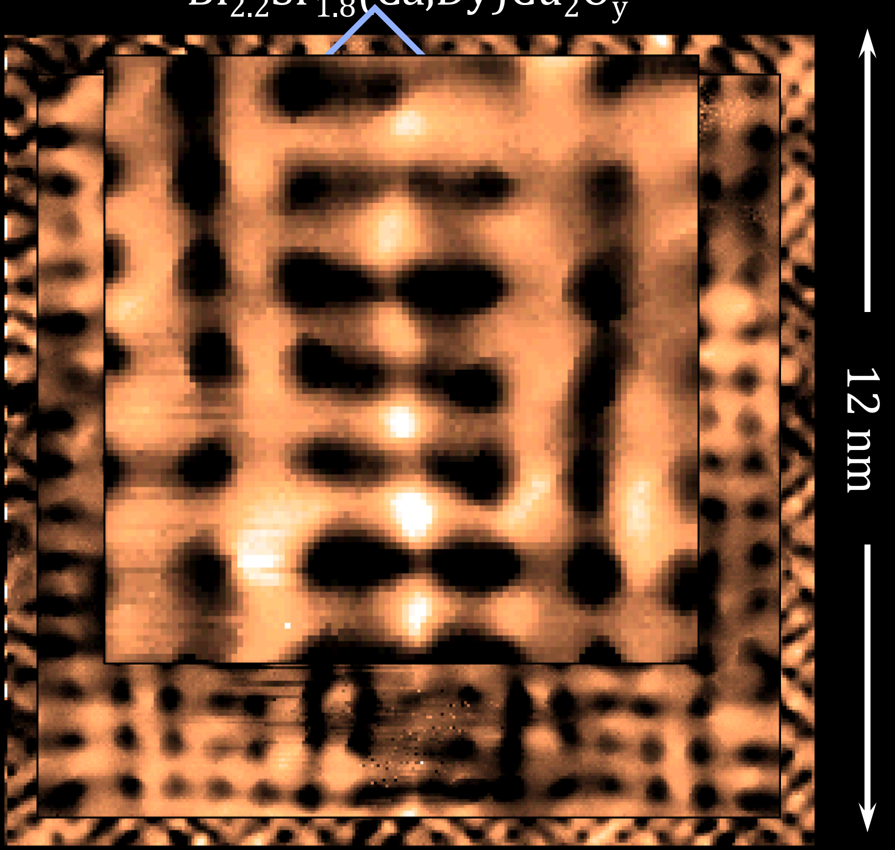
***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) ***J. Phys. Soc. Jpn* 82**, 011005 (2011)

Complex / Repeatable Patterns

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$



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



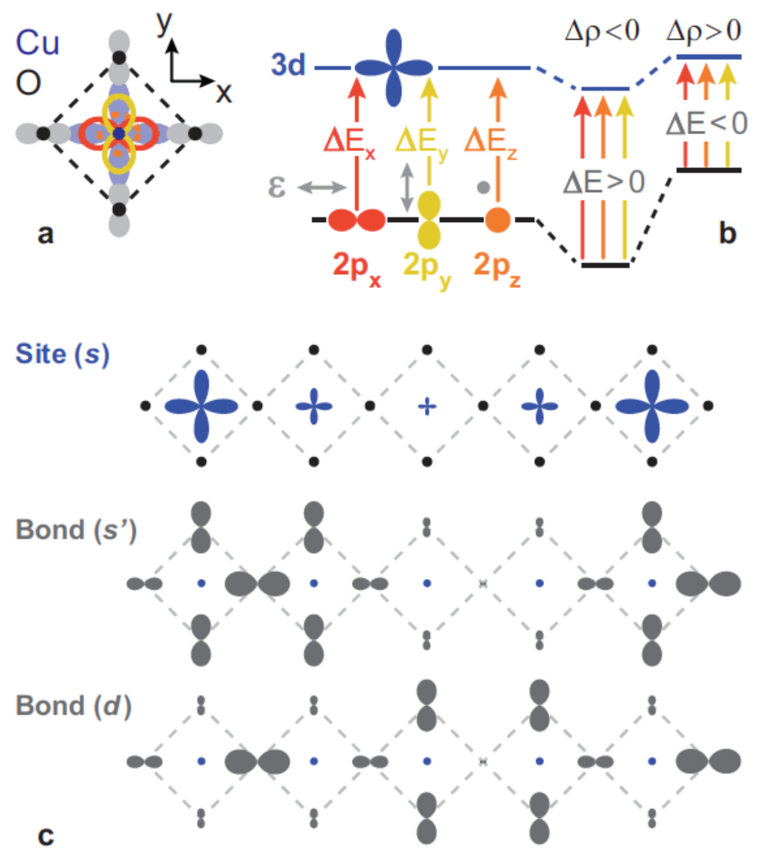
150 mV, 4.2 K

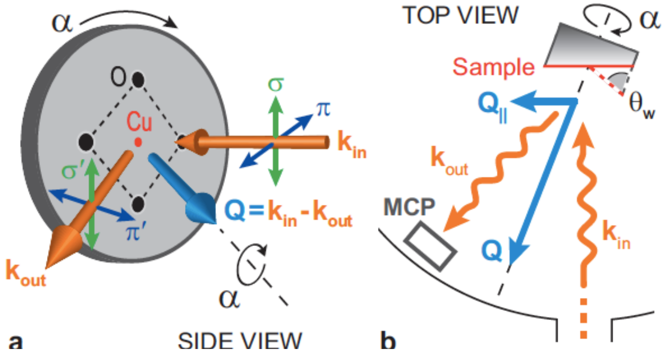
***Science* 315,** 1380 (2007)

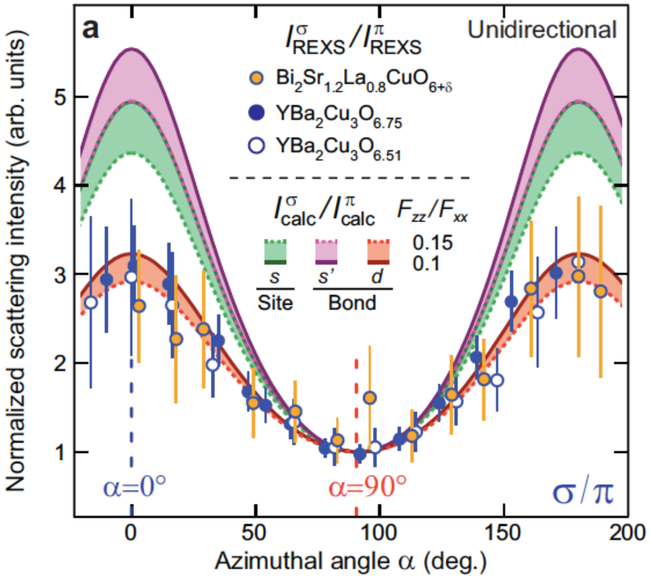
Nature **466,** 374 (2010)

***J. Phys. Soc. Jpn* 82,** 011005 (2011)

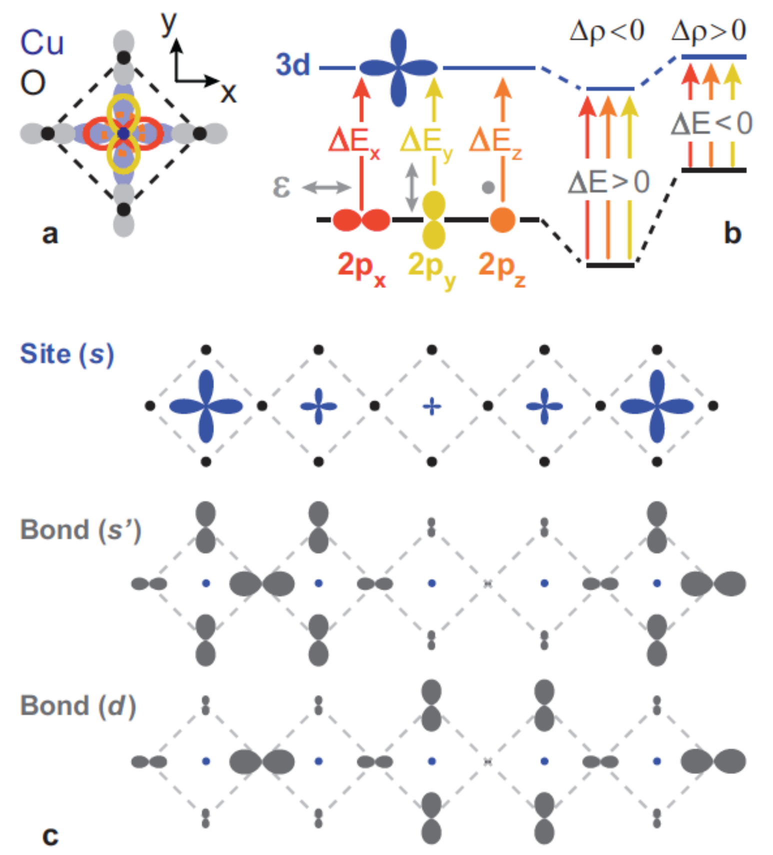
UBC Breakthrough: Comin *et al arXiv* 1402.5415

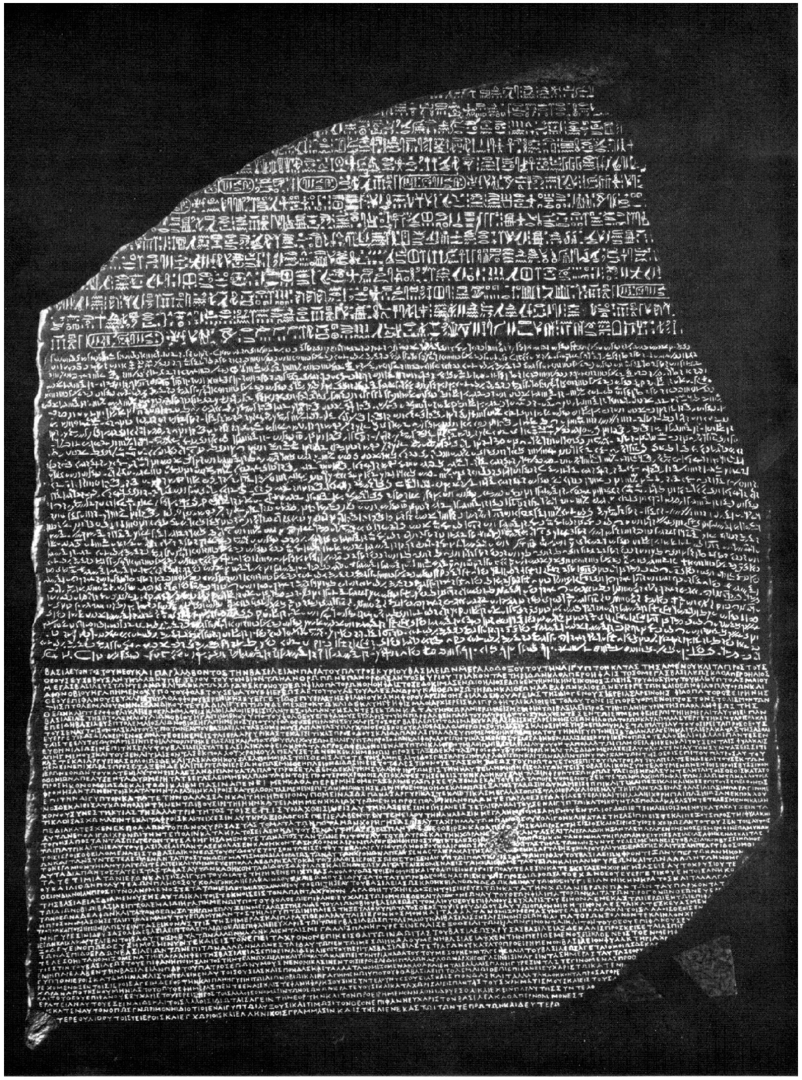






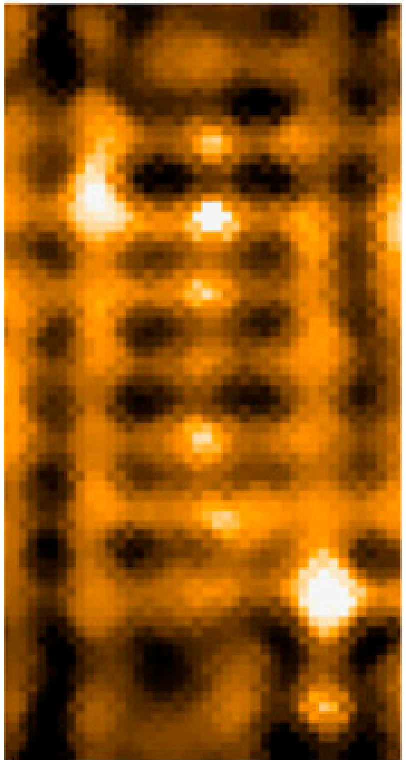
UBC Breakthrough: Comin *et al* *arXiv* 1402.5415



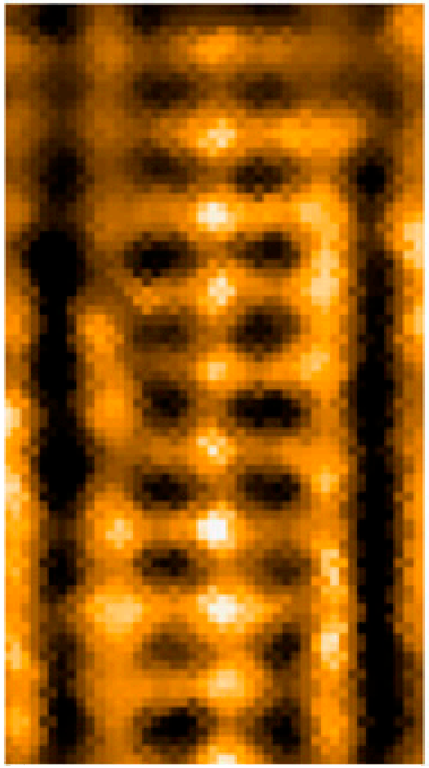


Unidirectional *d*-Form Factor DW

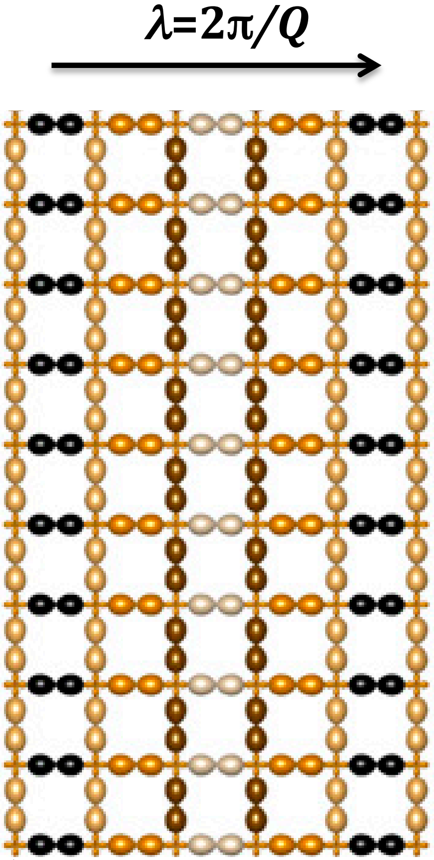
***Science* 315,** **1380 (2007)**



$Bi_2Sr_2CaCu_2O_{8+\delta}$



$Ca_{2-x}Na_xCuO_2Cl_2$

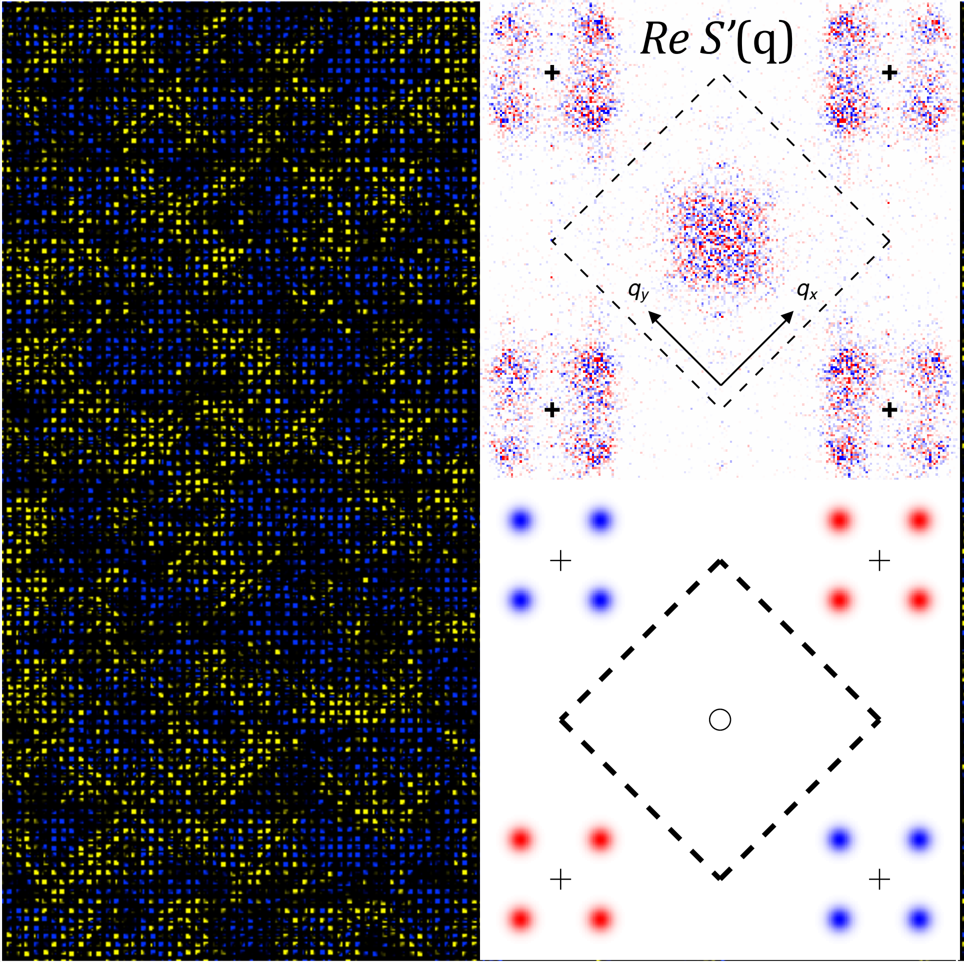


***D*-FF DW**

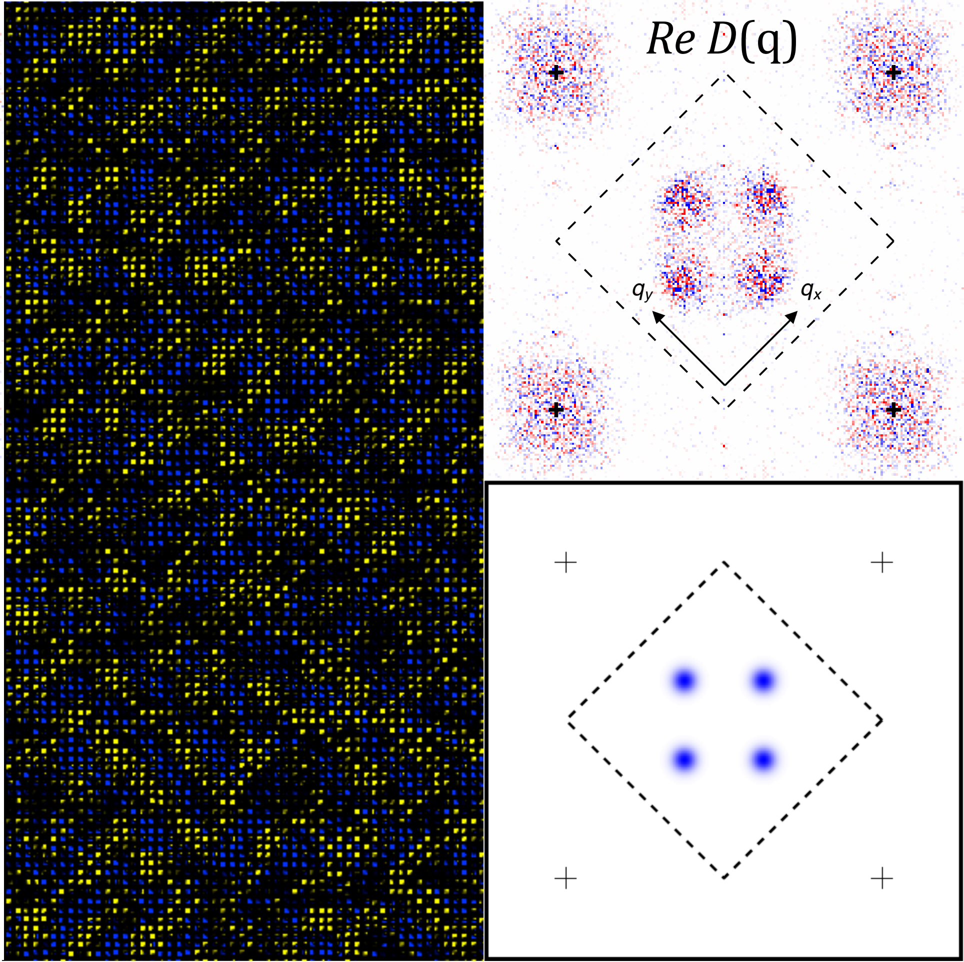
***PNAS* 111, E3026 (2014)**

Sublattice Phase-resolved *d*-Symmetry Form Factor

S' : $(O_x(r)+O_y(r))/2$



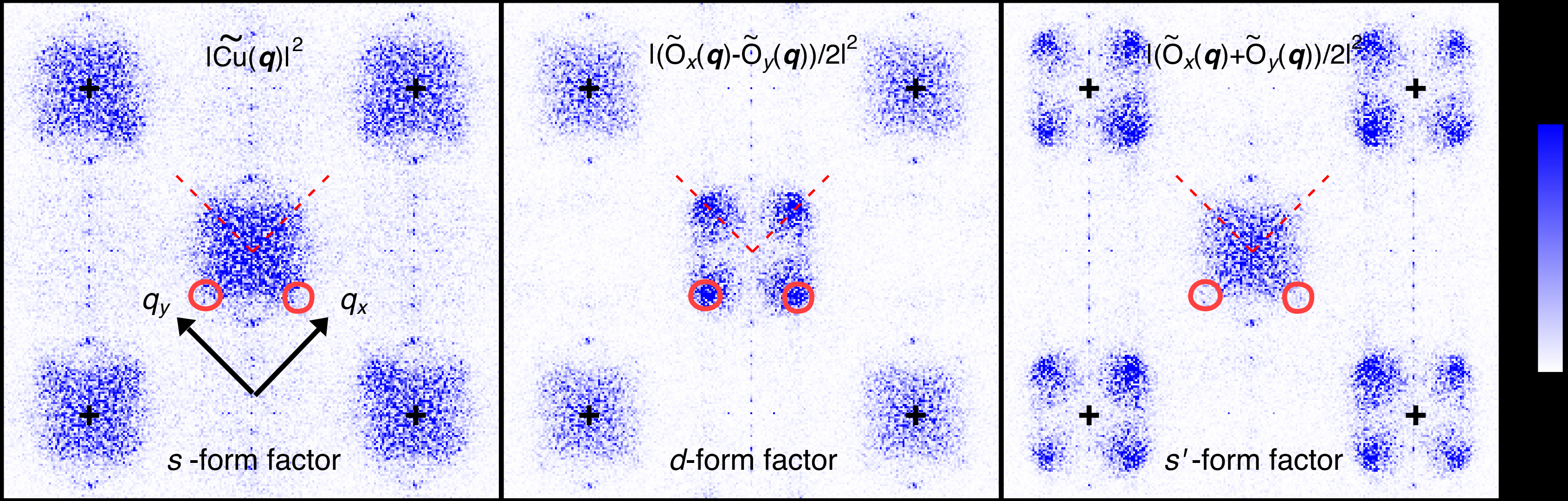
D : $(O_x(r)-O_y(r))/2$

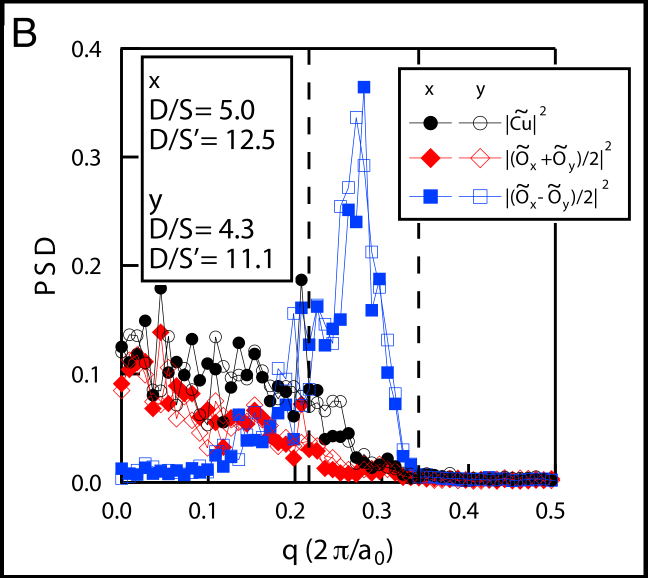


PNAS **111, E3026 (2014)**

$$Cu(\mathbf{r}) \equiv R(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}_{Cu})$$
$$O_x(\mathbf{r}) \equiv R(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}_{O_x})$$
$$O_y(\mathbf{r}) \equiv R(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}_{O_y})$$

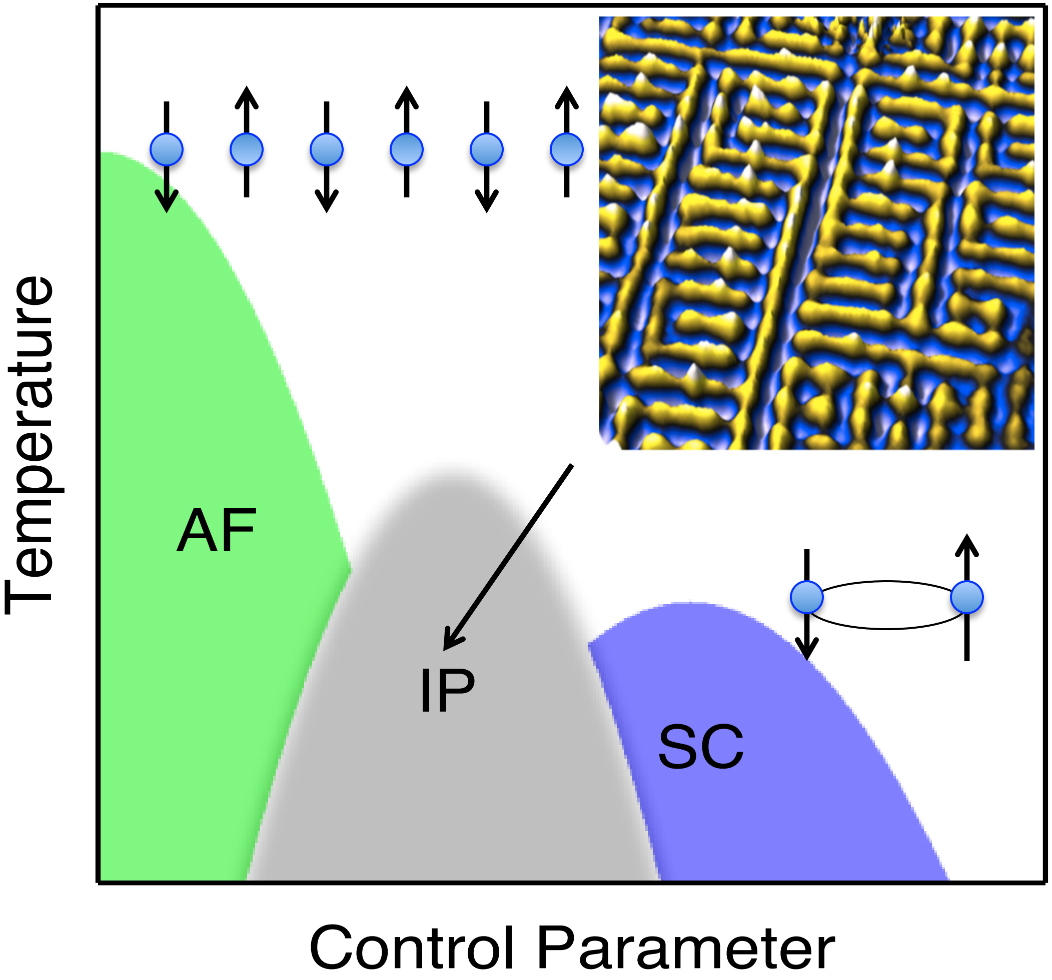
Predominant *d*-Symmetry Form Factor





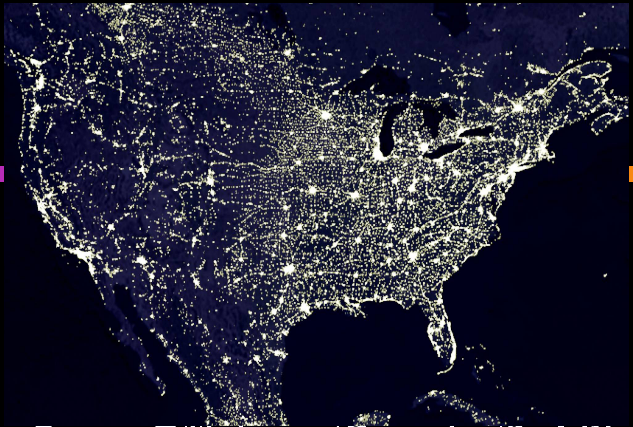
***PNAS* 111, E3026 (2014)**

d-SYMMETRY ELECTRONIC CRYSTAL / Cu-BASED HTS



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

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



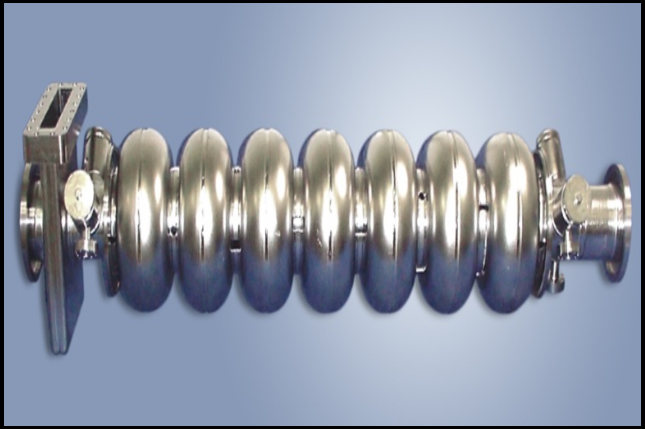
Power Efficiency/Capacity/Stability

Power Bottlenecks

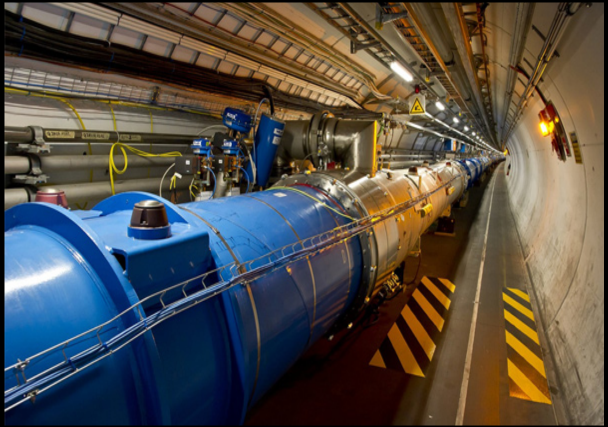
Accommodate Renewable Power

Efficient Rotating Machines

Information Technology



Next Generation HEP



Ultra-High Magnetic Fields

Medical

Transport