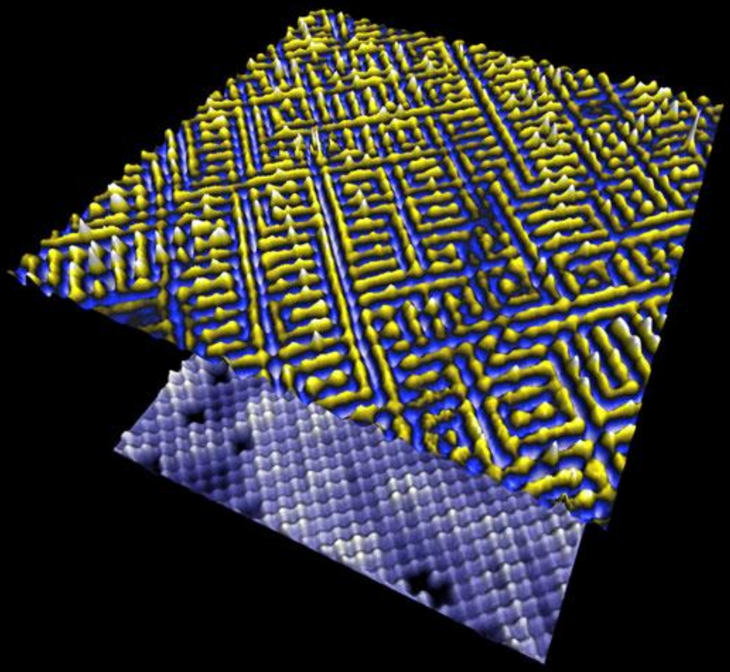
STM Study of Unconventional Superconductivity



Tien-Ming Chuang (莊天明)
Institute of Physics, Academia Sinica

May 11, 2016

Outline

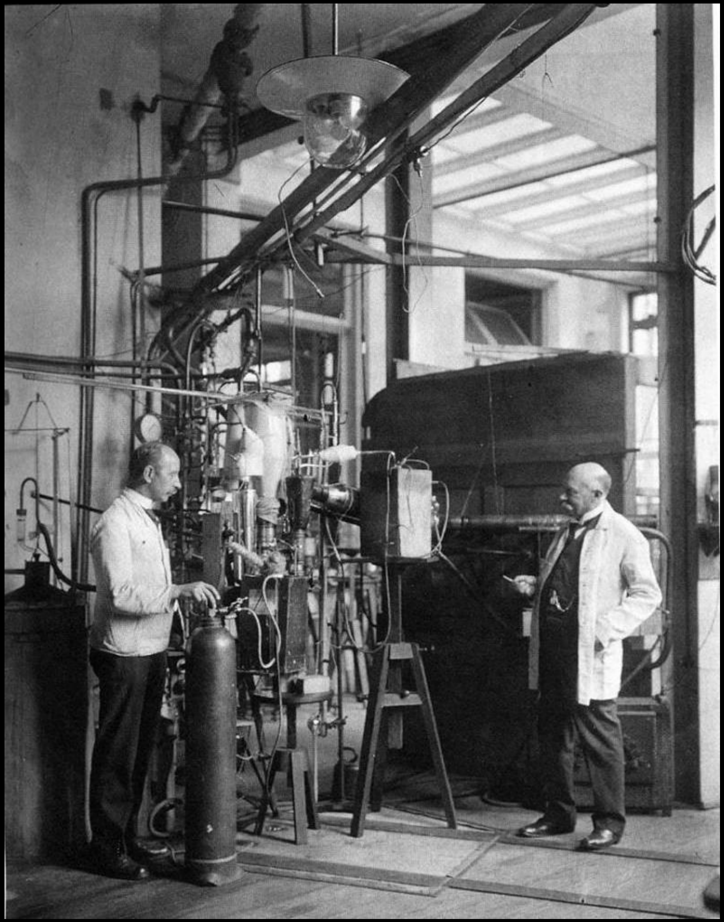
1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

Outline

1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

Helium Liquefaction in 1908

July 10, 1908



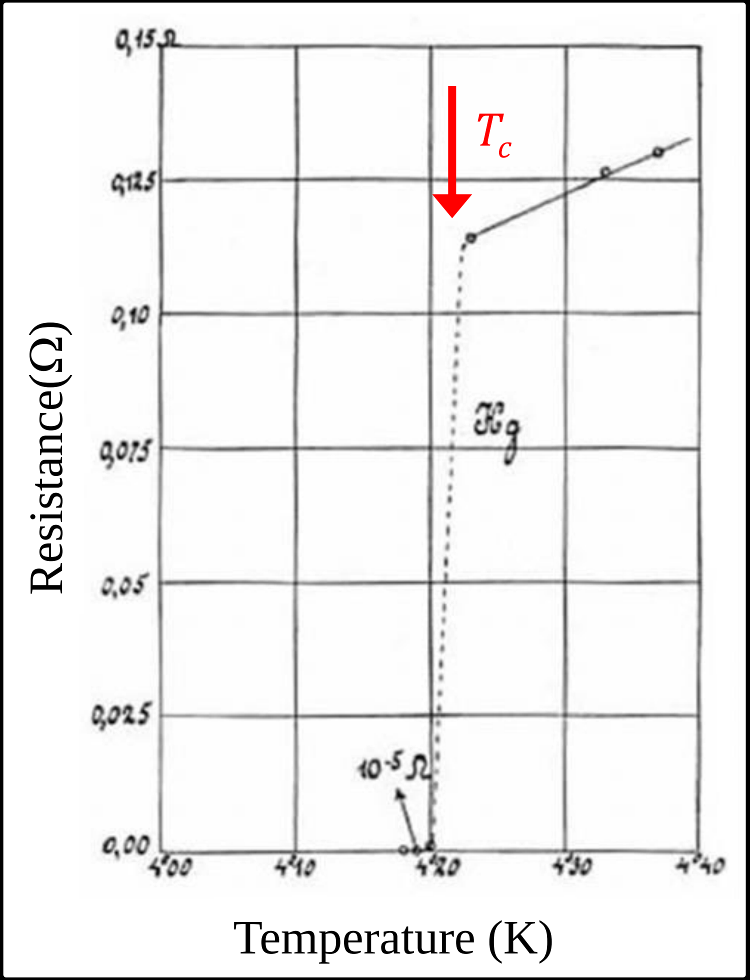
Heike Kamerlingh Onnes

Nobel Prize, 1913

“Door meten tot weten”
(Knowledge through measurement)

Discovery of Superconductivity in 1911

April 8, 1911



Heike Kamerlingh Onnes

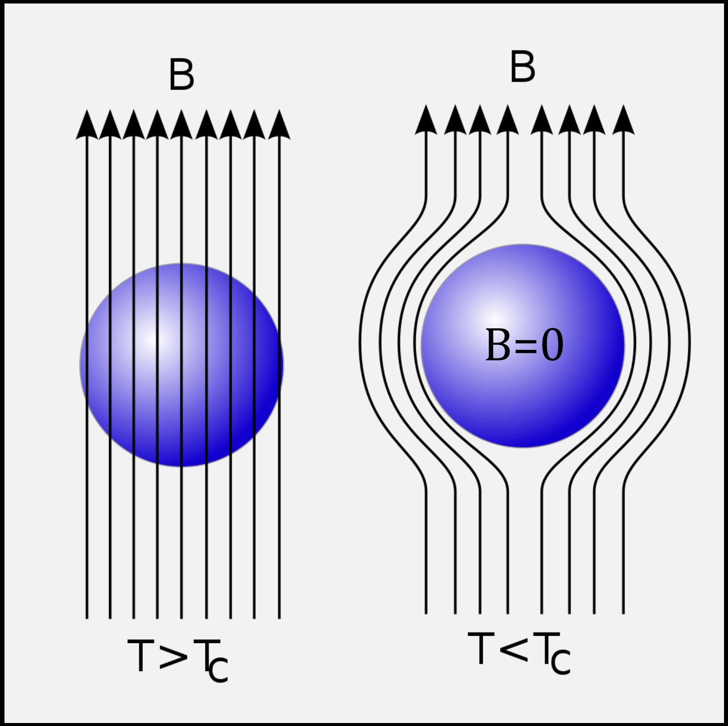
Nobel Prize, 1913

"Door meten tot weten"
(Knowledge through measurement)

H. Kamerlingh Onnes, *Commun. Phys. Lab. Univ. Leiden. Suppl.* **29** (Nov. 1911).

The Meissner Effect in 1933

Perfect diamagnetism



Walther Meißner

Robert Ochsenfeld

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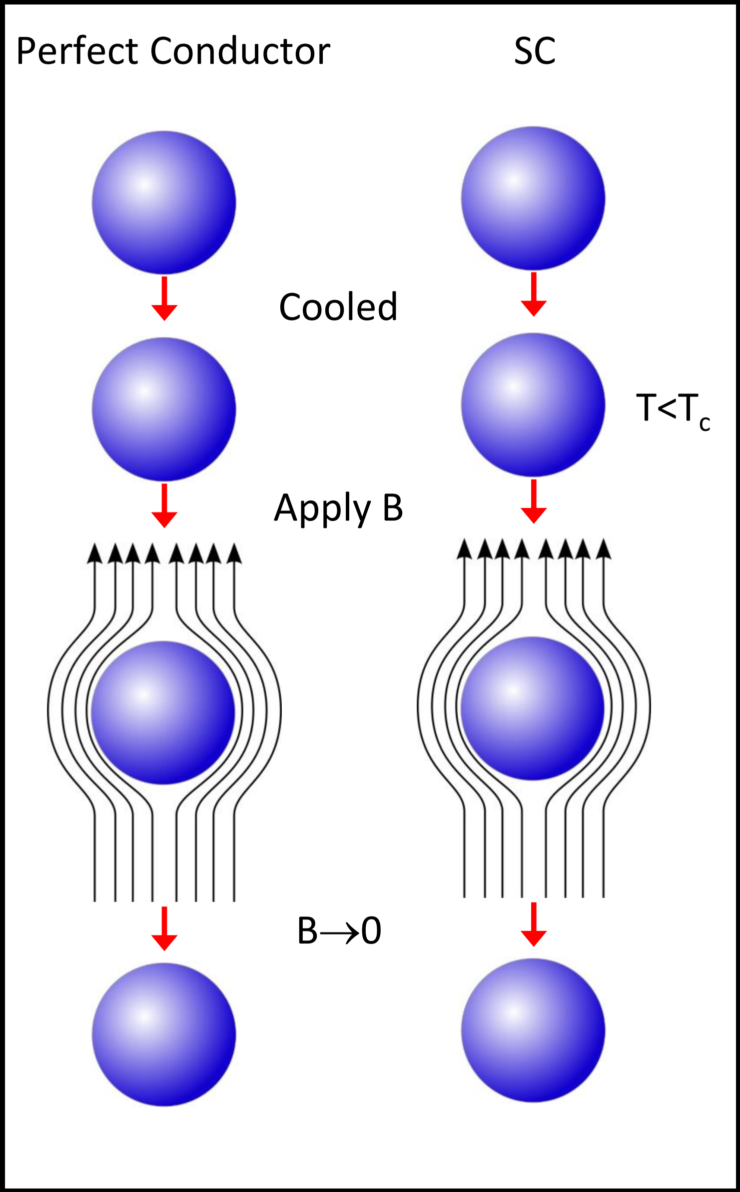
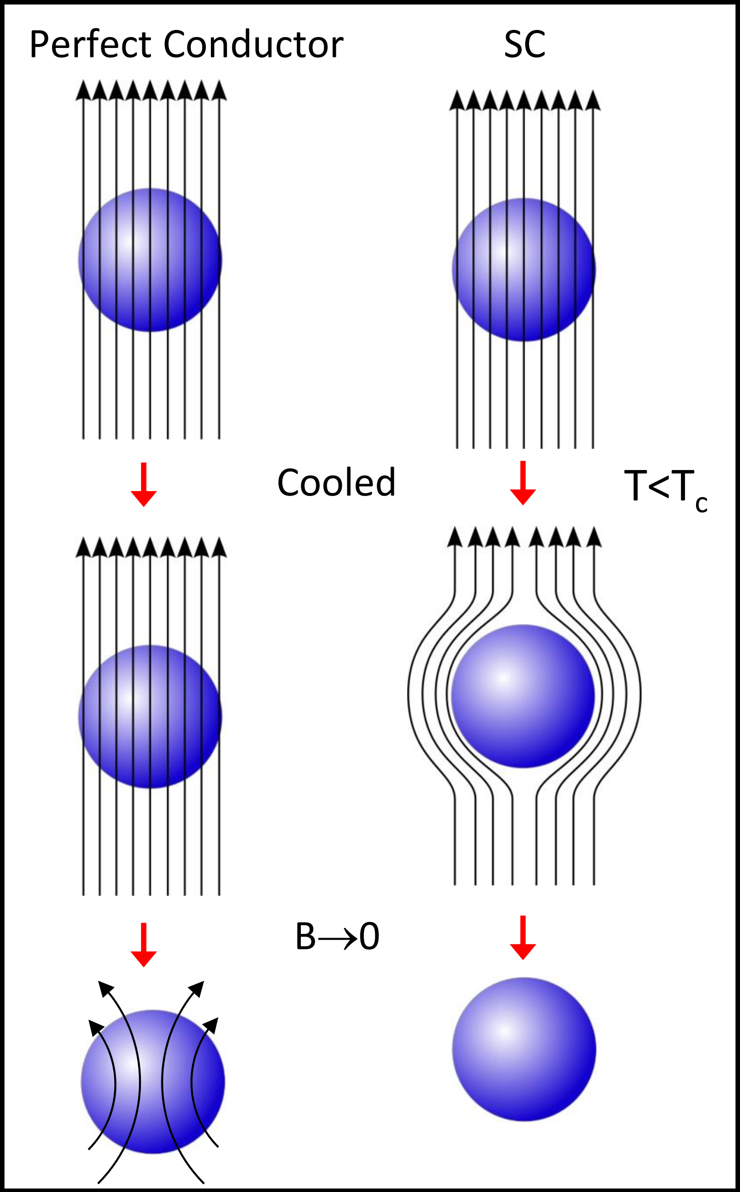
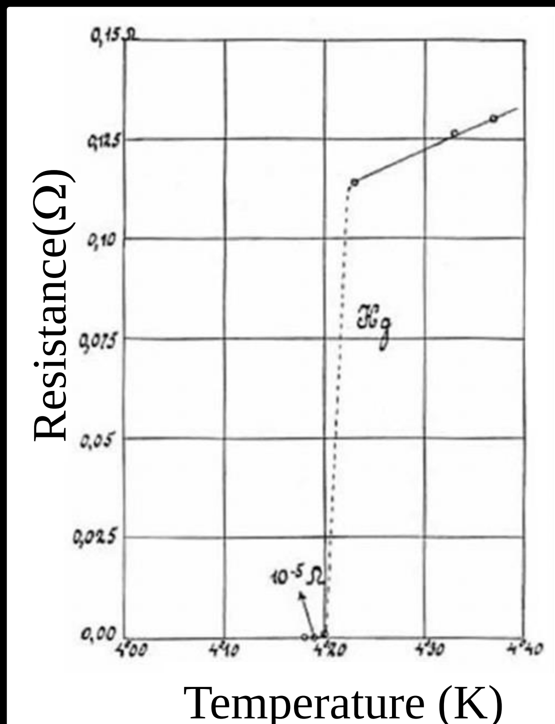
Perfect Conductor vs Superconductor

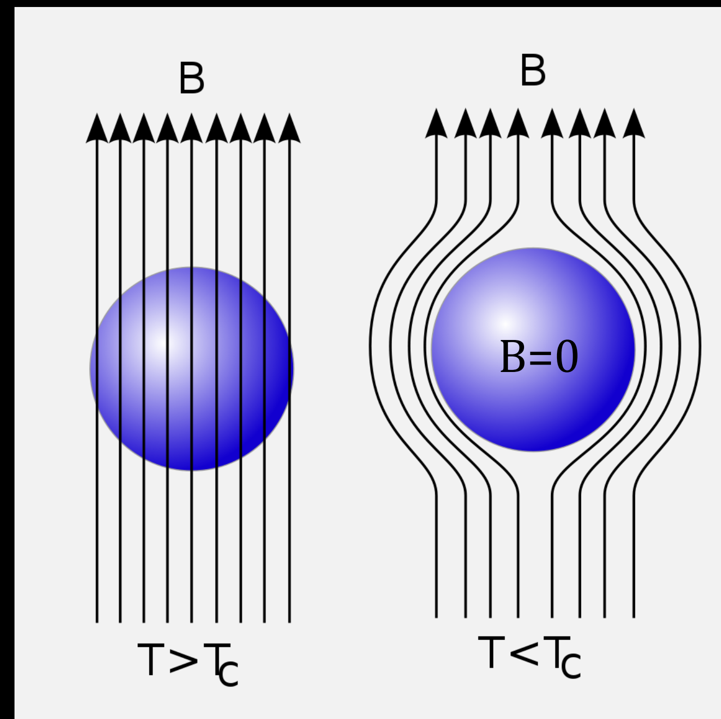




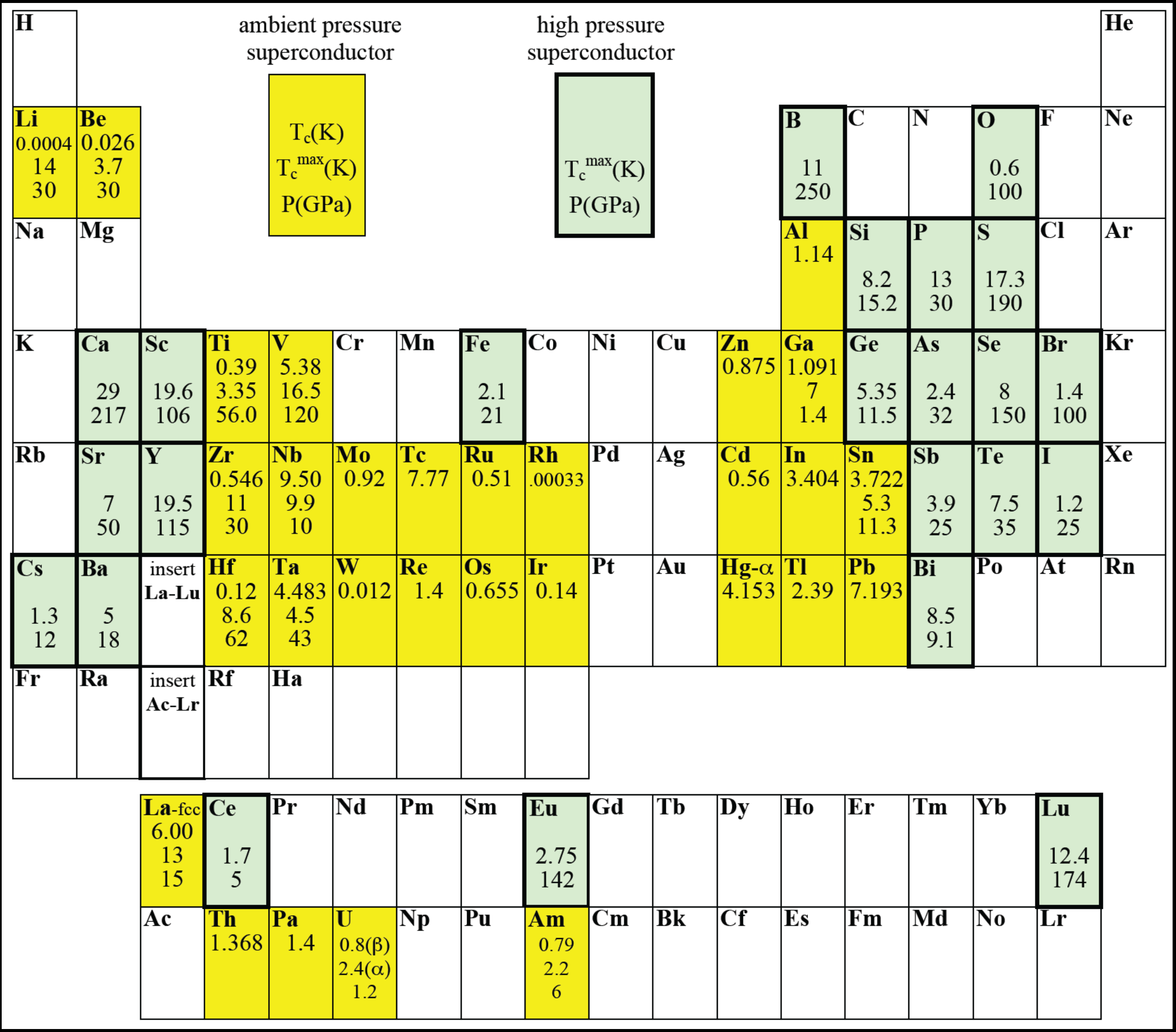
Basic Properties of Superconductors

Zero electrical resistance + Meissner effect





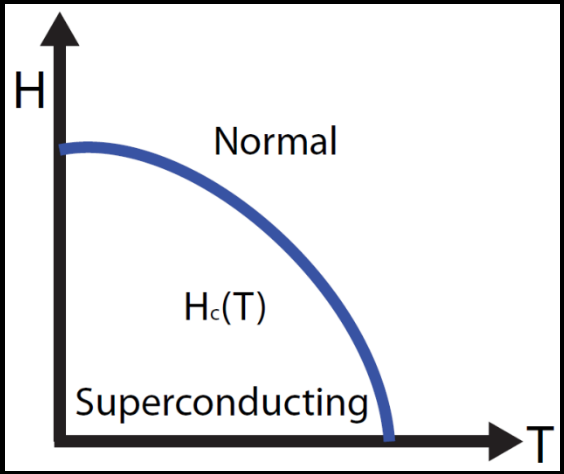
Periodic Table of Superconductivity



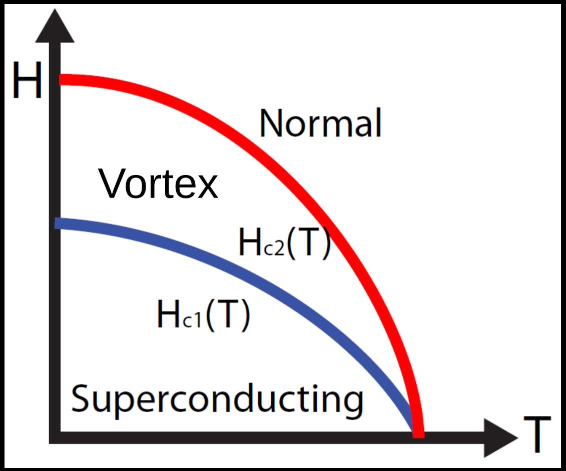
M. Debessai *et al.*, J. Phys.: Conf. Series 215, 012034 (2010).

Type I & II Superconductors

Type I : Al, Pb…



Type II : Nb, NbTi, Nb_3Sn and HTSC



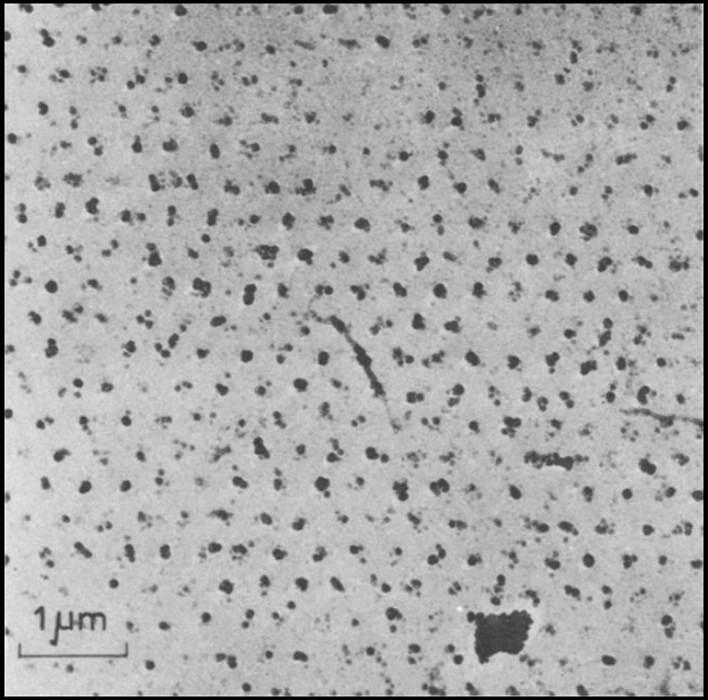
Lev V. Shubnikov

found type-II SC in Pb-Bi alloy in 1935.
Excuted in 1937.

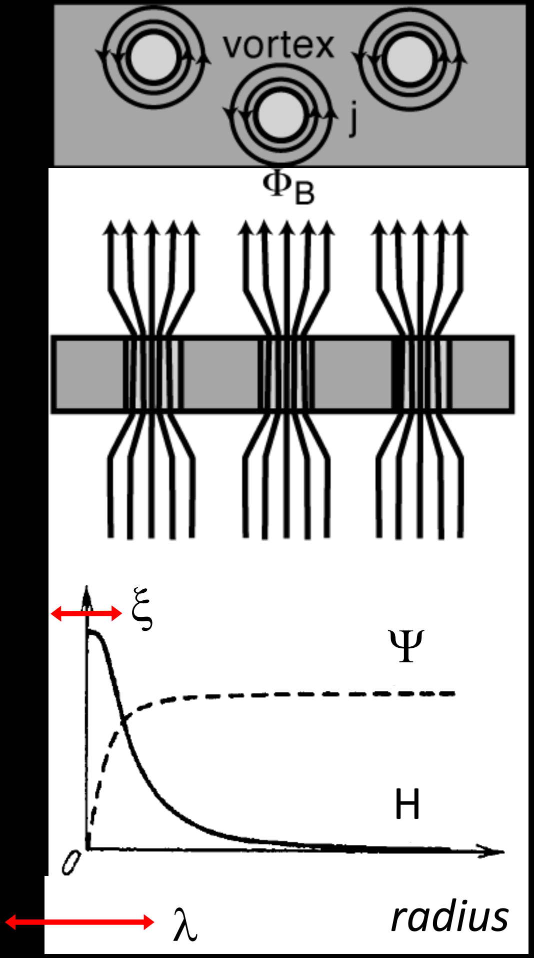
J. N. Rjabinin, L.W. Schubnikow, Physikalische Zeitschrift der Sowjetunion 7, 122 (1935)

Superconducting Vortices

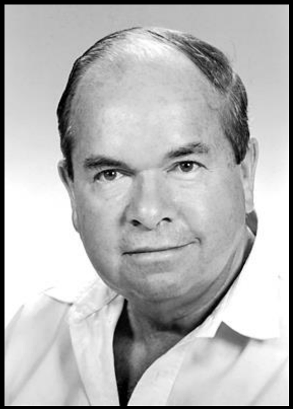
Decoration image of vortex lattice



U. Essmann and H. Trauble, Physics Letters 24A, 526 (1967)



Alexei A. Abrikosov



Nobel Prize 2003

A. A. Abrikosov, Doklady Akademii Nauk SSSR 86, 489 (1952)
A. A. Abrikosov, Sov. Phys. JETP **5**,1174 (1957)

Vortex-Current Interaction

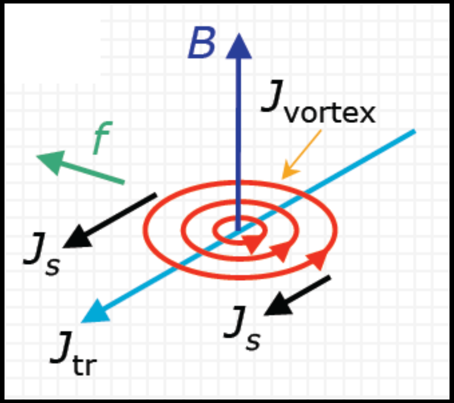
- Lorentz force on J_S due to the interaction between J_S and B.

$$f = \int J_s \times B \, d^2 r = J_{tr} \times \int B \, d^2 r = J_{tr} \times (\phi_0 \hat{B})$$

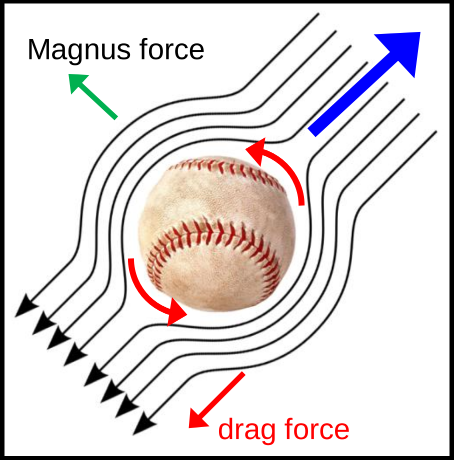
- Vortex motion implies that the vortex is subject to a power input per unit volume of vortex of characteristic radius r_B

$$P = \frac{f v}{\pi r_B^2} = J_{tr} \frac{\phi_0}{\pi r_B^2} v = \underbrace{J_{tr} B}_{\substack{\text{Lorentz force} \\ \text{per unit volume}}} v$$

- Vortex motion leads to dissipation! R≠0 !
- Vortex pinning is crucial for applications.

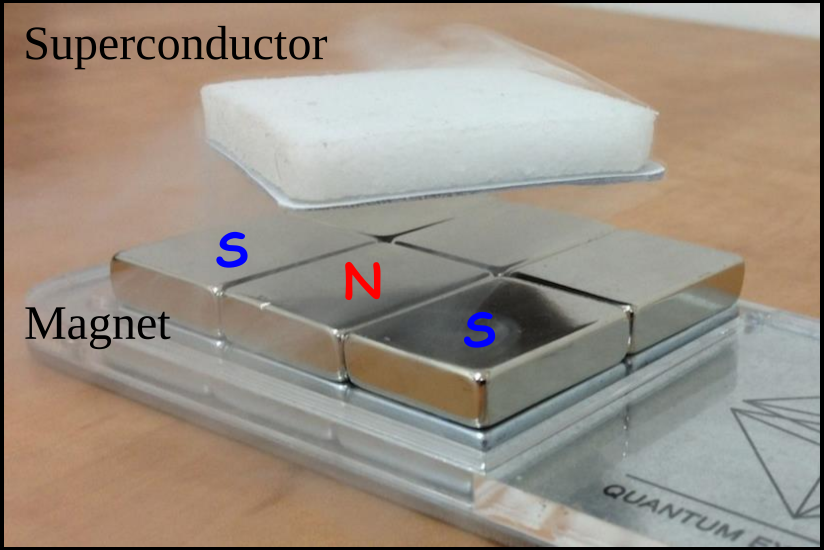


Magnus force

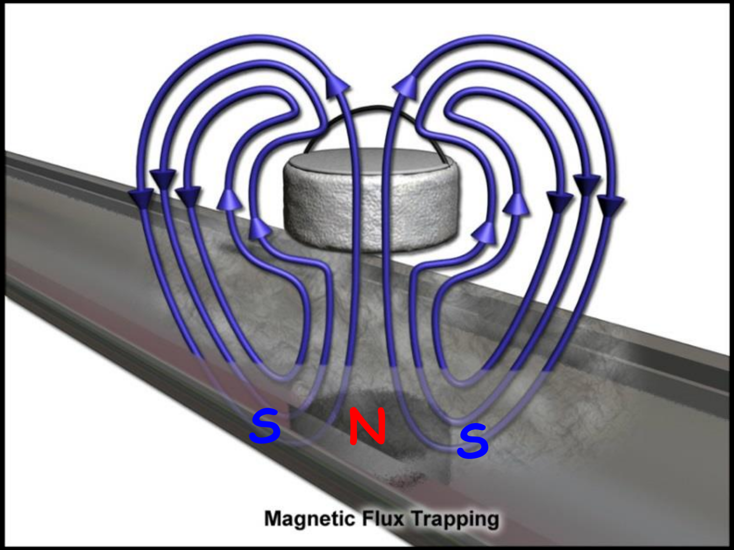


Quantum Levitation

Magnetic flux pinning is key.
Unstable for type I superconductors.



© Quantum Experience ltd.



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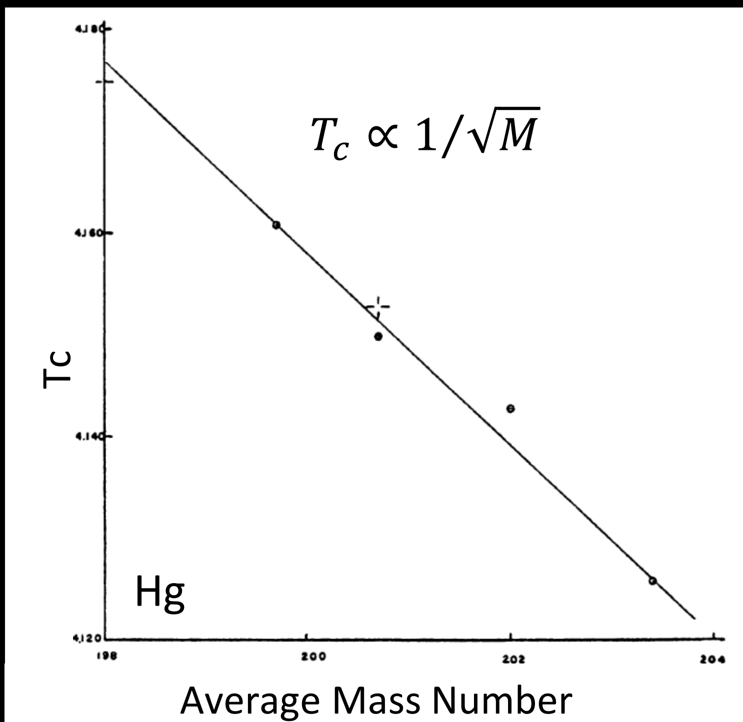
The Origin of Conventional Superconductivity

Isotope Effect in 1950

- Lattice vibration is a part of the SC process.
- A crucial step to a microscopic theory.



Emanuel Maxwell, Phys. Rev. 78, 477 (1950)
C.A. Reynolds et al., Phys. Rev. 78, 487 (1950)

Emanuel Maxwell

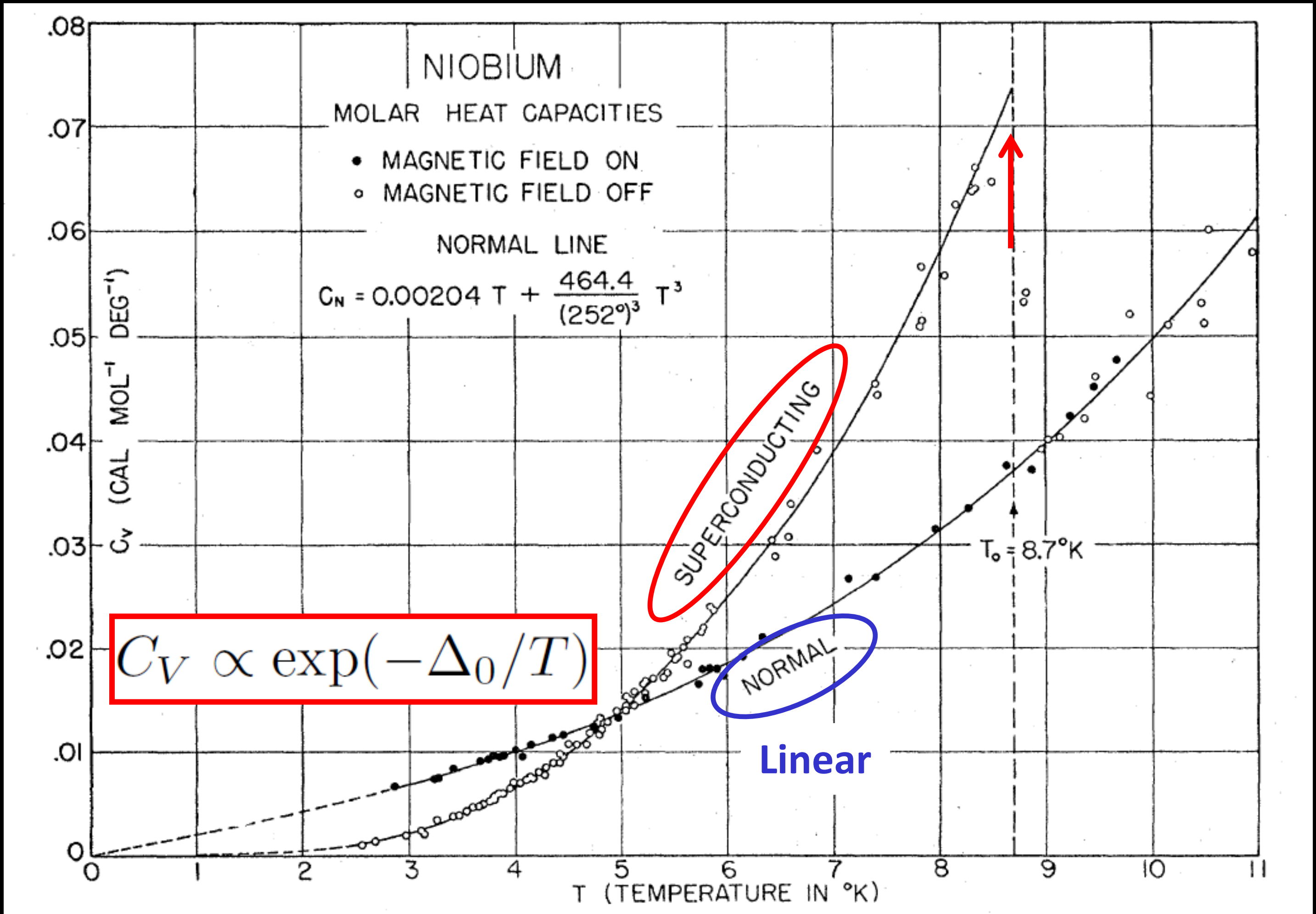
© MIT

Bernard Serin & Charles Reynolds

© Rutgers University

Evidence for Energy Gap in 1953

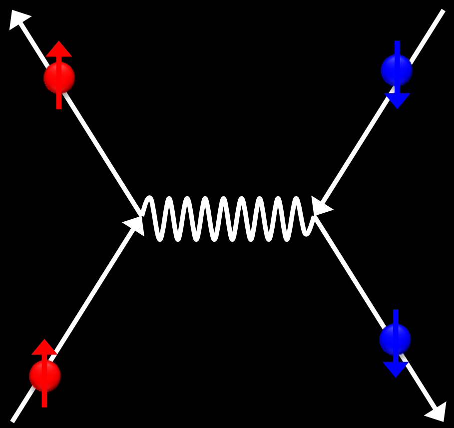
Another motivation for the BCS theory of superconductivity.



A. Brown, M. W. Zemansky, and H. A. Boorse, Phys. Rev. 92, 52 (1953)
B. B. Goodman, Proc. Phys. Soc. (London) **A66**, 217 (1953)

BCS Theory in 1957

Cooper Pairs



Exchange boson:
Lattice Vibration Mode

Microscopic theory for SC

John Bardeen

Leon Cooper

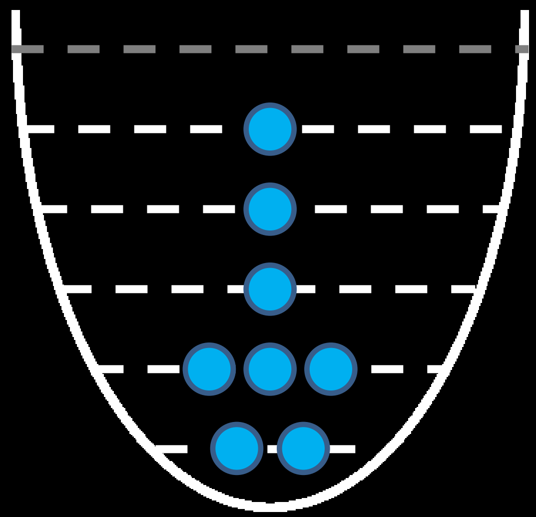
Robert Schrieffer

Nobel Prize 1972

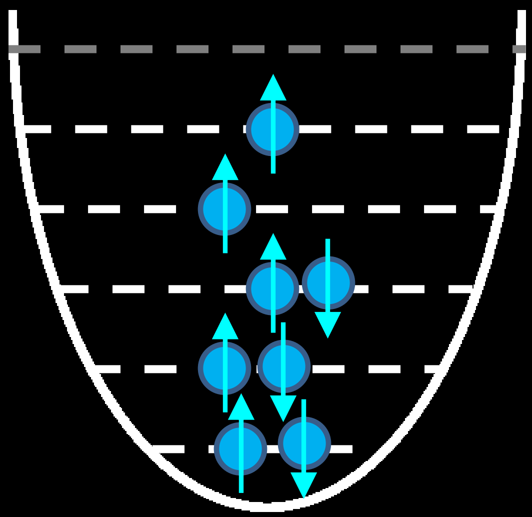
J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957)

Bosons vs Fermions

Bosons



Fermions



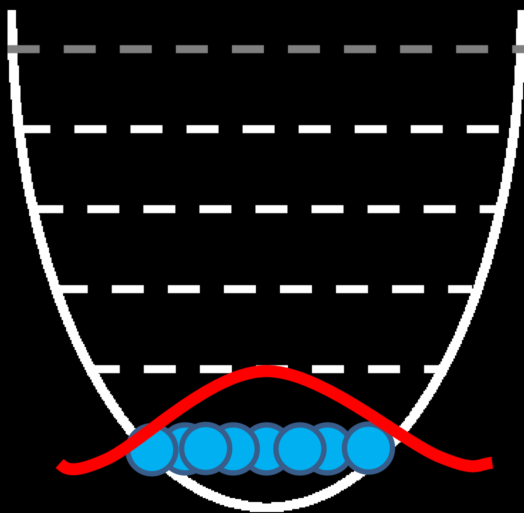
Pauli Exclusion Principle

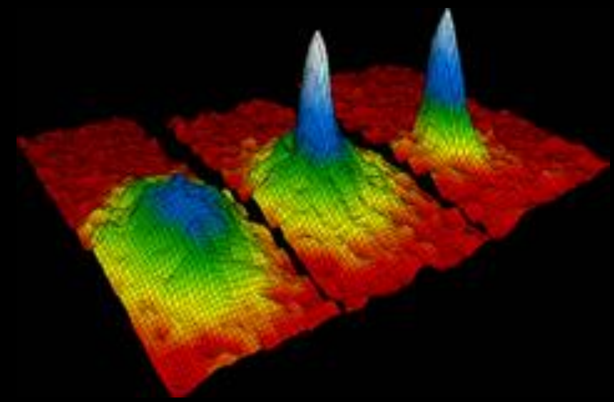
Wolfgang Pauli

Nobel Prize 1945

Bose-Einstein Condensation

T↓ Bosons

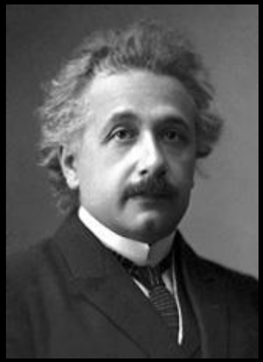




Predicted in 1924

Satyendra Nath Bose

Albert Einstein

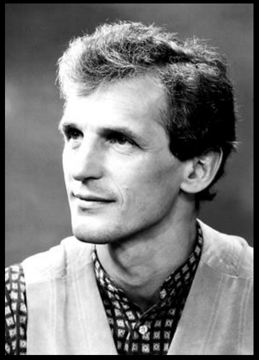


BEC in Rb and Na in 1995

Eric Cornell

Carl Wieman

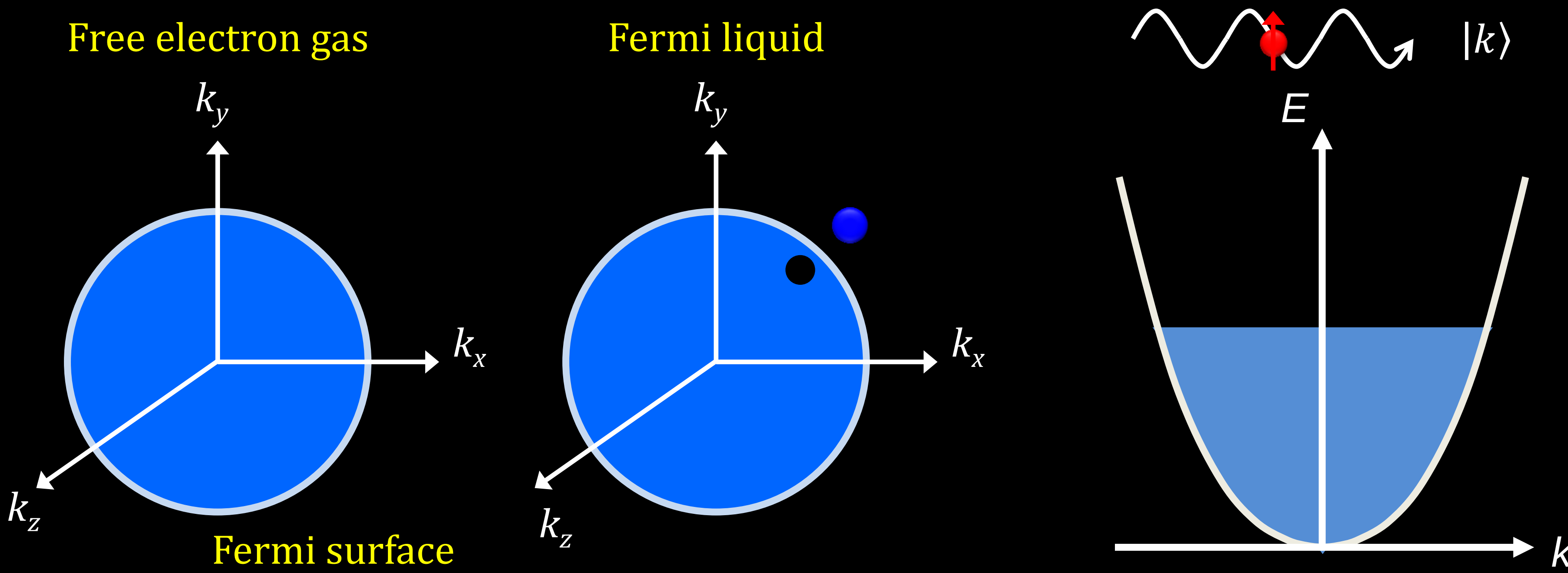
Wolfgang Ketterle



Nobel Prize 2001

Normal Metallic State

Electrons in wave-like states in momentum-space (*k*-space)

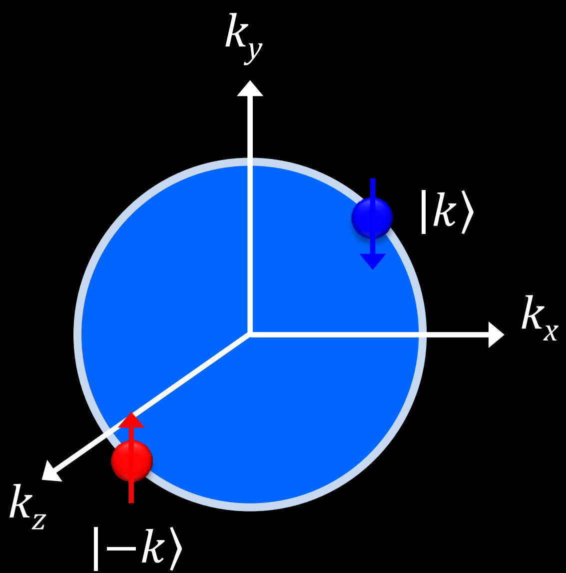


$$p = \hbar k = h/\lambda$$

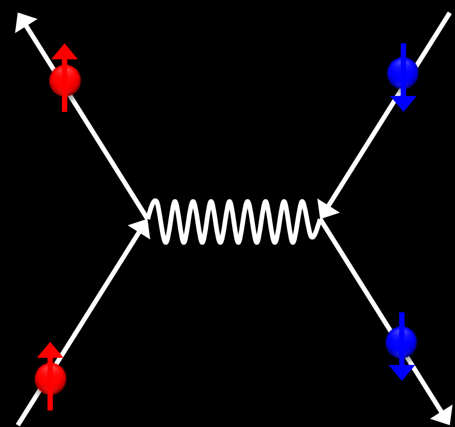
$$E = \frac{\hbar^2 k^2}{2m}$$

Superconducting Ground State

Normal state

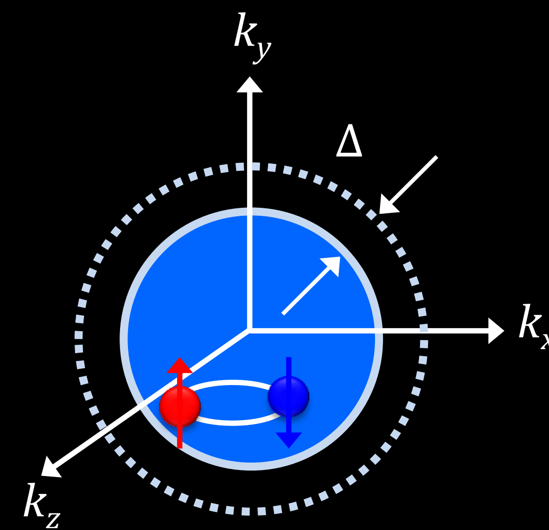


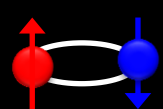
Cooper Pairs



Exchange boson:
Lattice Vibration Mode

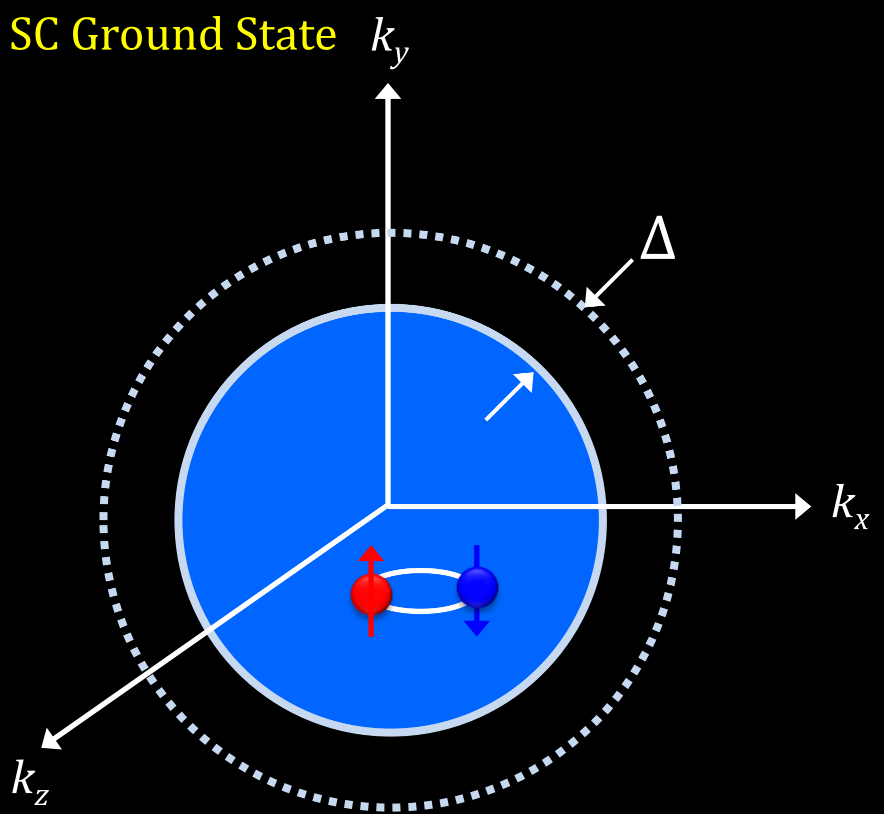
Superconducting ground state





- Spin singlet
- L=0; S=0
- Binding energy: Δ

Superconducting Ground States



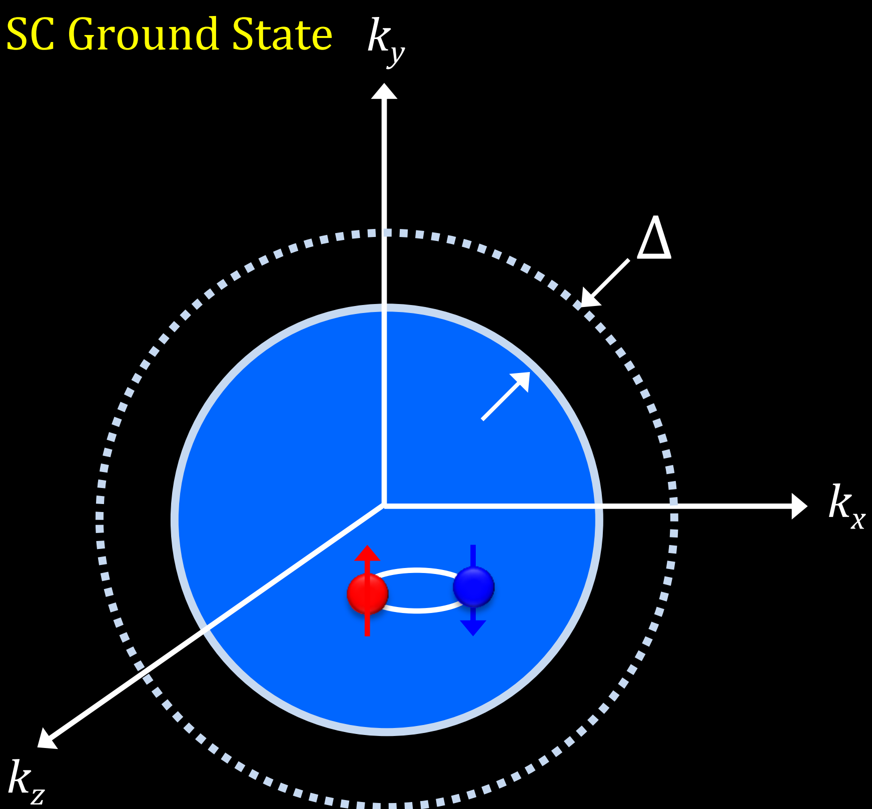
$$\Psi_{BCS} = \prod_k \left(u_k + v_k c^*_{k\uparrow} c^*_{-k\downarrow}\right) | 0 >$$

u_k and v_k : coherence factor

BCS, Phys Rev 108, 1175 (1957)

Superconducting Excited States

SC Ground State

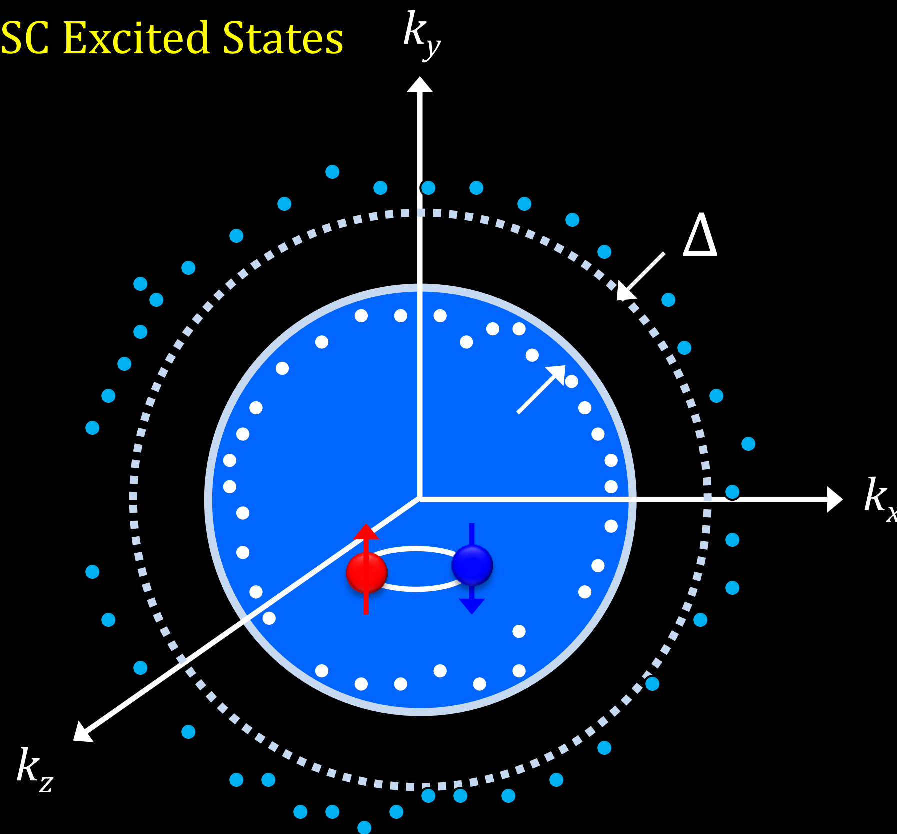


$$\Psi_{BCS} = \prod_k \left(u_k + v_k c^*_{k\uparrow} c^*_{-k\downarrow} \right) | 0 >$$

u_k and v_k : coherence factor

BCS, Phys Rev 108, 1175 (1957)

SC Excited States



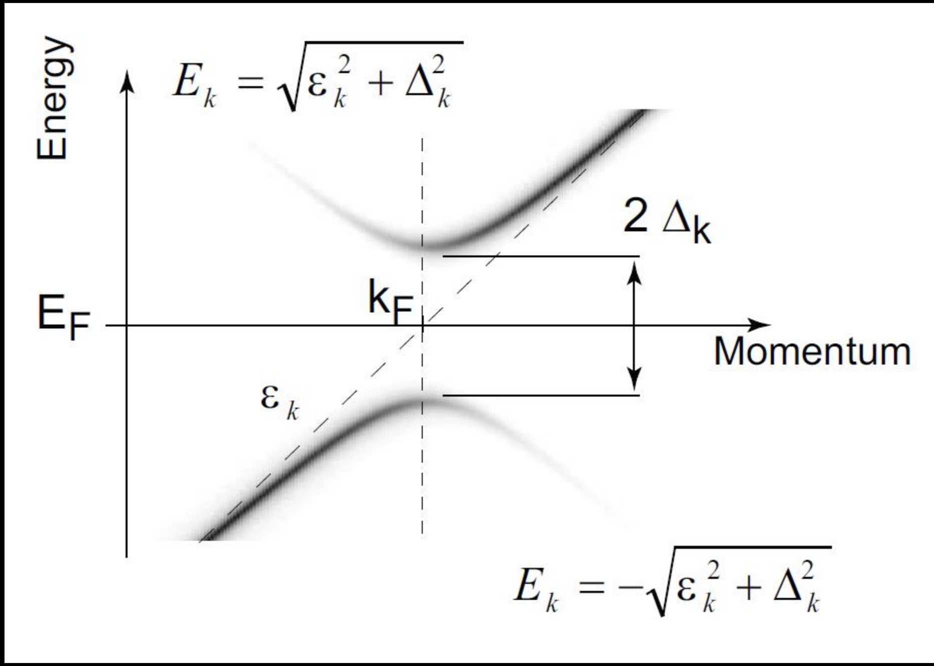
Bogoliubov quasiparticle

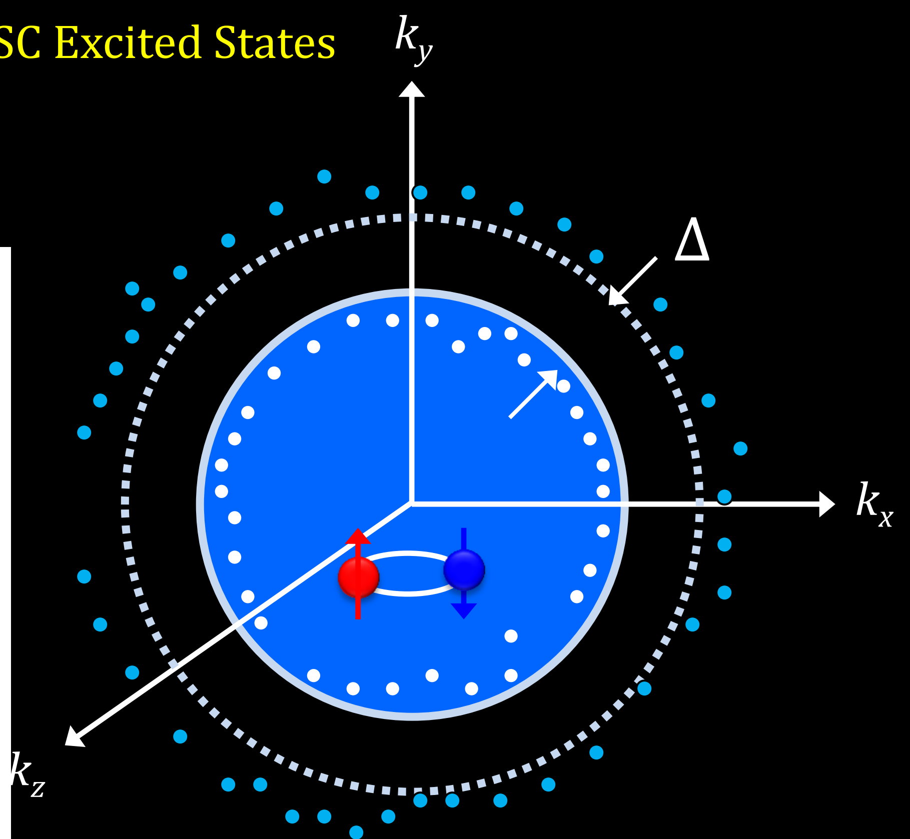
$$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$$

Bogoliubov, Nuovo Cimento 7, 794 (1958)

Superconducting Excited States

$$E_{\pm}(\vec{k}) = \pm\sqrt{\varepsilon(\vec{k})^2 + \Delta(\vec{k})^2}$$





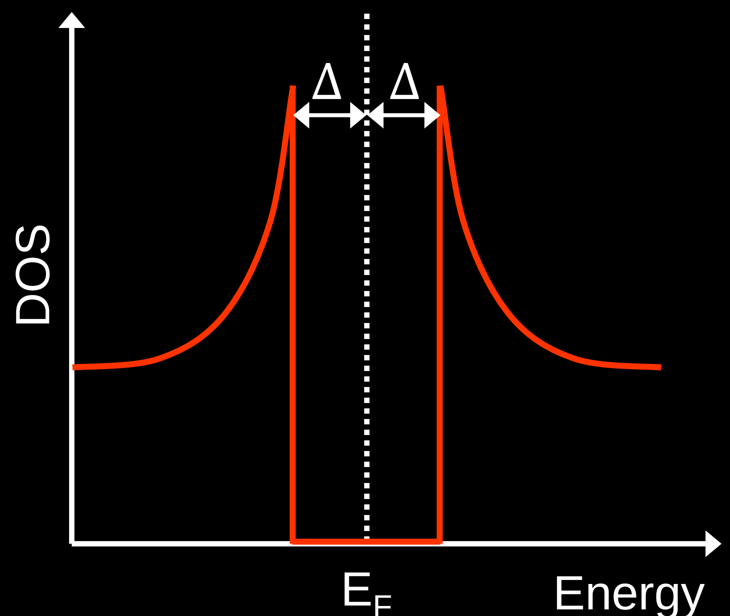
Bogoliubov quasiparticle

$$\gamma^*_{k\uparrow} = u_k c_{k\uparrow} + v_k c^*_{-k\downarrow}$$

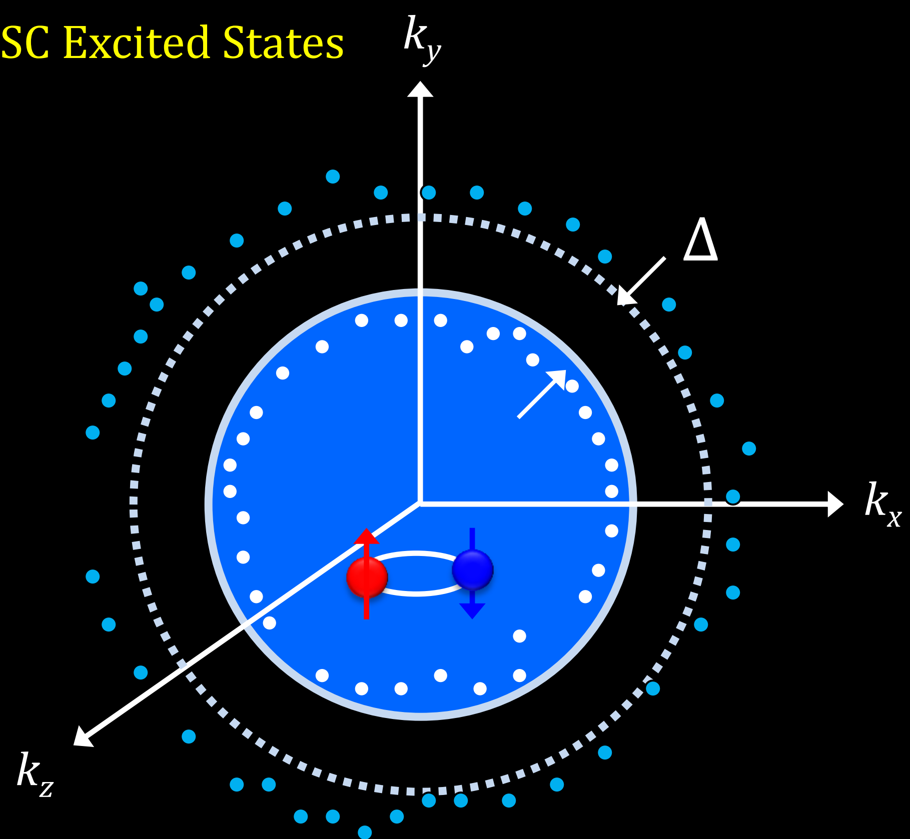
Bogoliubov, Nuovo Cimento 7, 794 (1958)

Superconducting Excited States

Superconducting energy gap=2Δ
(T=0)



SC Excited States



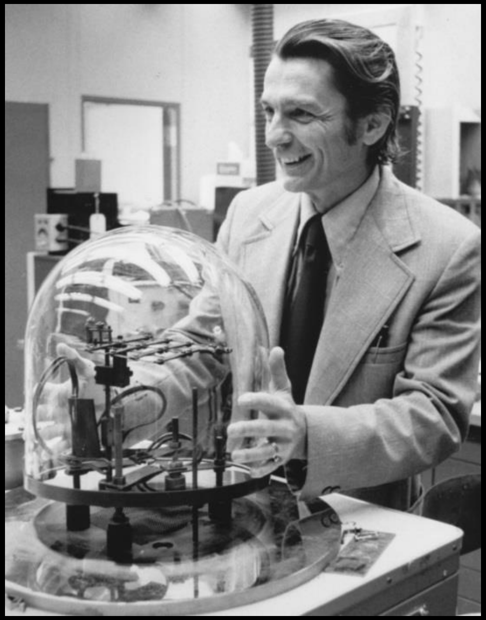
Bogoliubov quasiparticle

$$\gamma^{*}_{k\uparrow} = u_k c_{k\uparrow} + v_k c^{*}_{-k\downarrow}$$

Bogoliubov, Nuovo Cimento 7, 794 (1958)

Superconducting Energy Gap in 1960

Ivar Giaever



Nobel Prize in 1973
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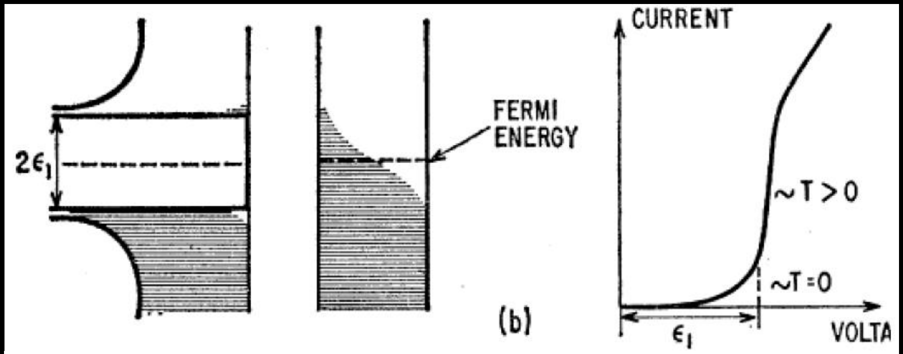
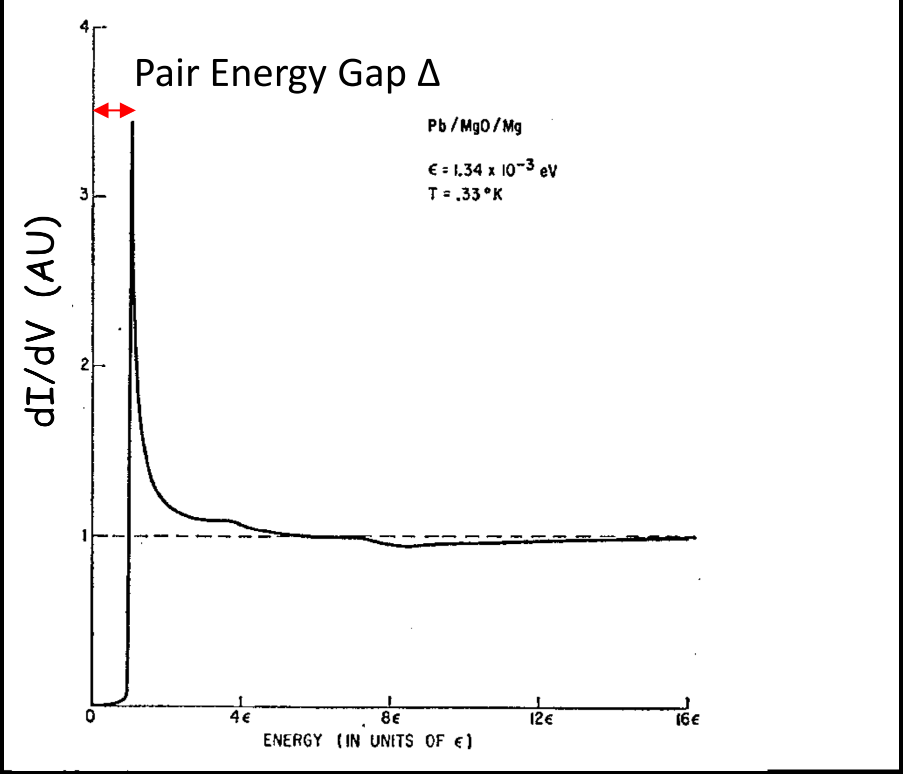
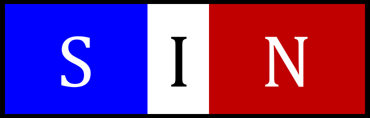




I. Giaever, Phys. Rev. Lett. 5, 147 (1960)
I. Giaever, Phys. Rev. 126, 941 (1962)

Tunneling junction



Superconducting Gap

Pair wave function : $\Psi_{kss'} = \langle \Psi_{BCS} | c_{-ks'} c_{ks} | \Psi_{BCS} \rangle = g(k)\, \chi_{ss'}$

Spin part : $\chi_{ss'}$ $(\uparrow\downarrow - \downarrow\uparrow)$ $S = 0$

$(\uparrow\uparrow, \uparrow\downarrow + \downarrow\uparrow, \downarrow\downarrow)$ $S = 1$

Orbital part : $g(k)$

$$\psi(\mathbf{r}) \propto \sum_{\mathbf{k}} \frac{\Delta(\mathbf{k})}{\sqrt{\epsilon(\mathbf{k})^2 + \Delta(\mathbf{k})^2}} \exp(-i\mathbf{kr})$$

Spin	Orbital
anti-symmetric ($S = 0$)	symmetric (s, d, ...)
symmetric ($S = 1$)	anti-symmetric (p, f, ...)

$l = 0$: s wave (conventional SC)

$l = 1$: p wave (superfluid ^{3}He)

$l = 2$: d wave (cuprate SC)

If $l > 0$, $\psi(0) = 0$

→ { repulsive interaction
$\Delta(k)$ must change its sign }

Gap Equation

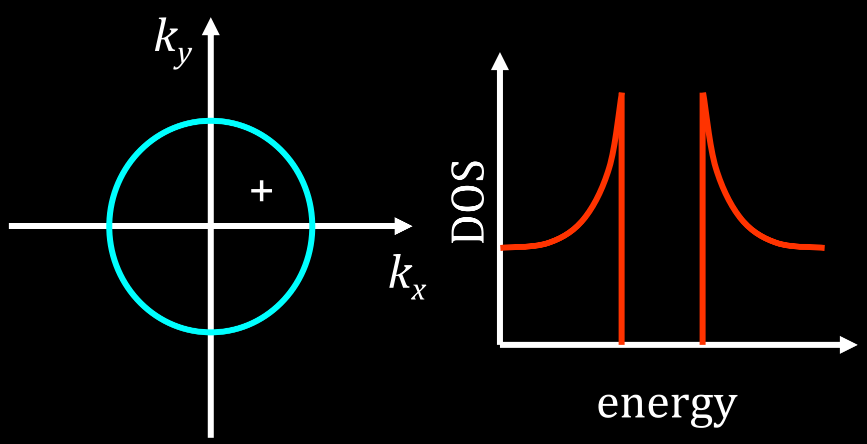
$$\Delta(\mathbf{k}) = -\frac{1}{2}\sum_{\mathbf{q}} V(\mathbf{q}) \frac{\Delta(\mathbf{k})}{\sqrt{\epsilon(\mathbf{k}+\mathbf{q})^2 + \Delta(\mathbf{k}+\mathbf{q})^2}} \tanh \frac{\sqrt{\epsilon(\mathbf{k}+\mathbf{q})^2 + \Delta(\mathbf{k}+\mathbf{q})^2}}{2k_B T}$$

Pairing interaction

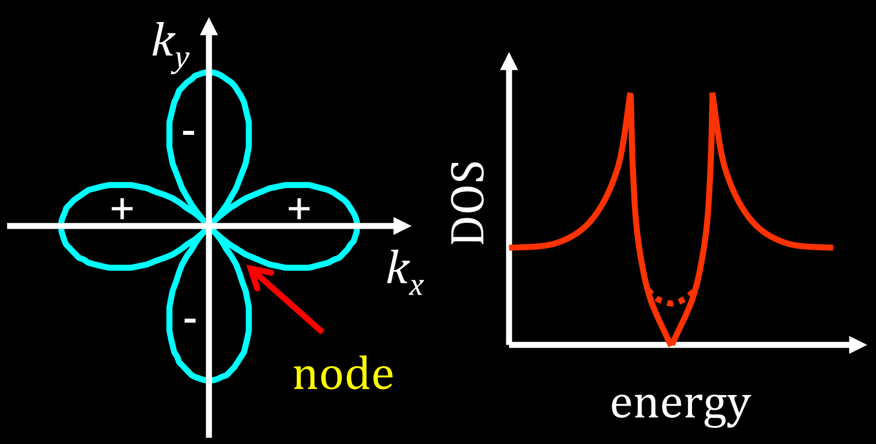
In conventional BCS, $V(\mathbf{q}) = -|V| < 0$: Δ is always positive.

If $V(\mathbf{q} = \mathbf{Q}) > 0$ plays a role, $\Delta(\mathbf{k})$ and $\Delta(\mathbf{k+Q})$ have a different sign.

s wave



d wave



Flux Quantization Theory in 1950

* We note that in order for Ψ to be a single-valued function, as required by quantum mechanics, it is necessary that the moduli of χ fulfill a kind of quantum condition:

$$<\chi> = \oint \bar{\mathrm{p}}_s \cdot \mathrm{ds} = Kh$$

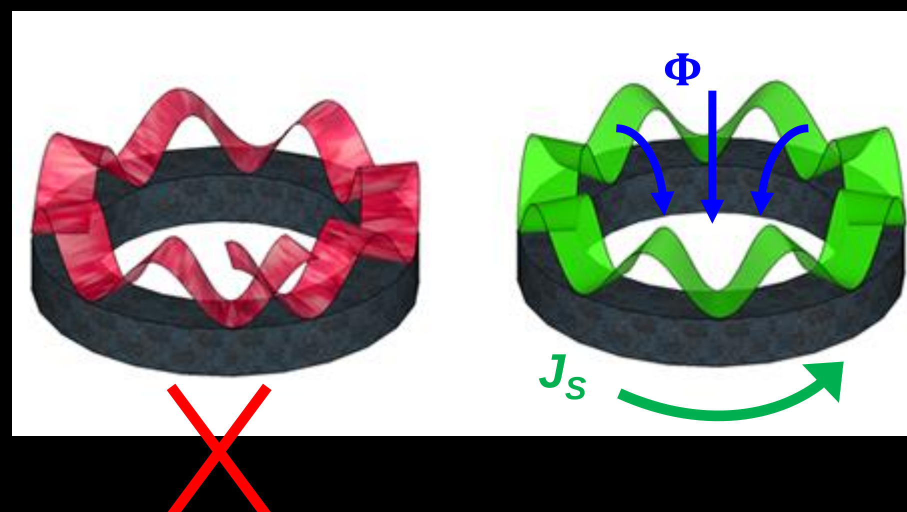
where K must be an integer. This means that there exists a universal unit for the fluxoid:

$$\Phi_1 = hc/e \simeq 4 \cdot 10^{-7}\ \mathrm{gauss} \cdot \mathrm{cm}^2$$

Fritz London

© Duke Univ.

Superconducting ring



Superfluids, Macroscopic Theory of Superconductivity, Structure of Matter Vol. 1 (Wiley, New York, 1950)

Flux Quantization Experiments in 1961

Bascom Deaver

William Fairbank

$|\Phi| = n\,{}^{hc}/_{2e} = n\Phi_0,$

where $\Phi_0 = 2.0 \times 10^{-15} Tesla - m^2$

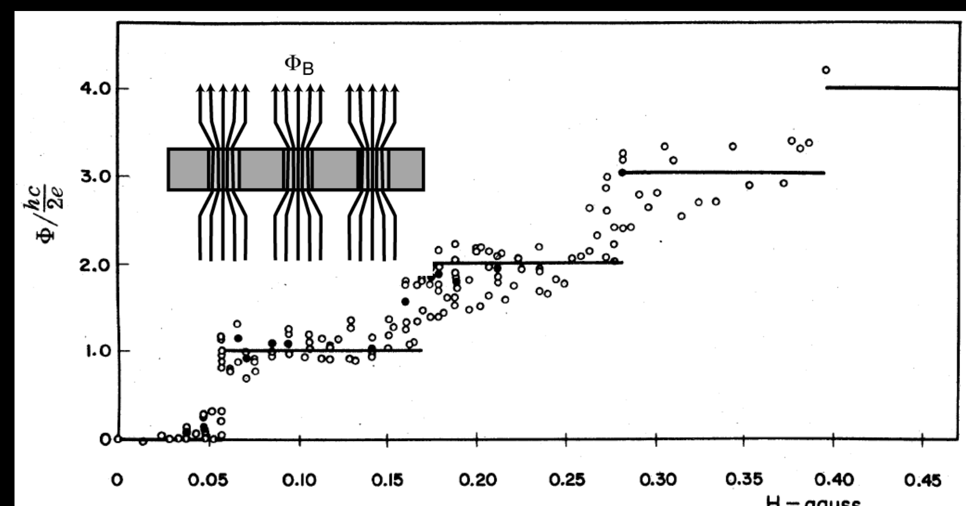
Each vortex carries one flux quanta

SC carriers are 2e!

Confirmation of Cooper pairs!

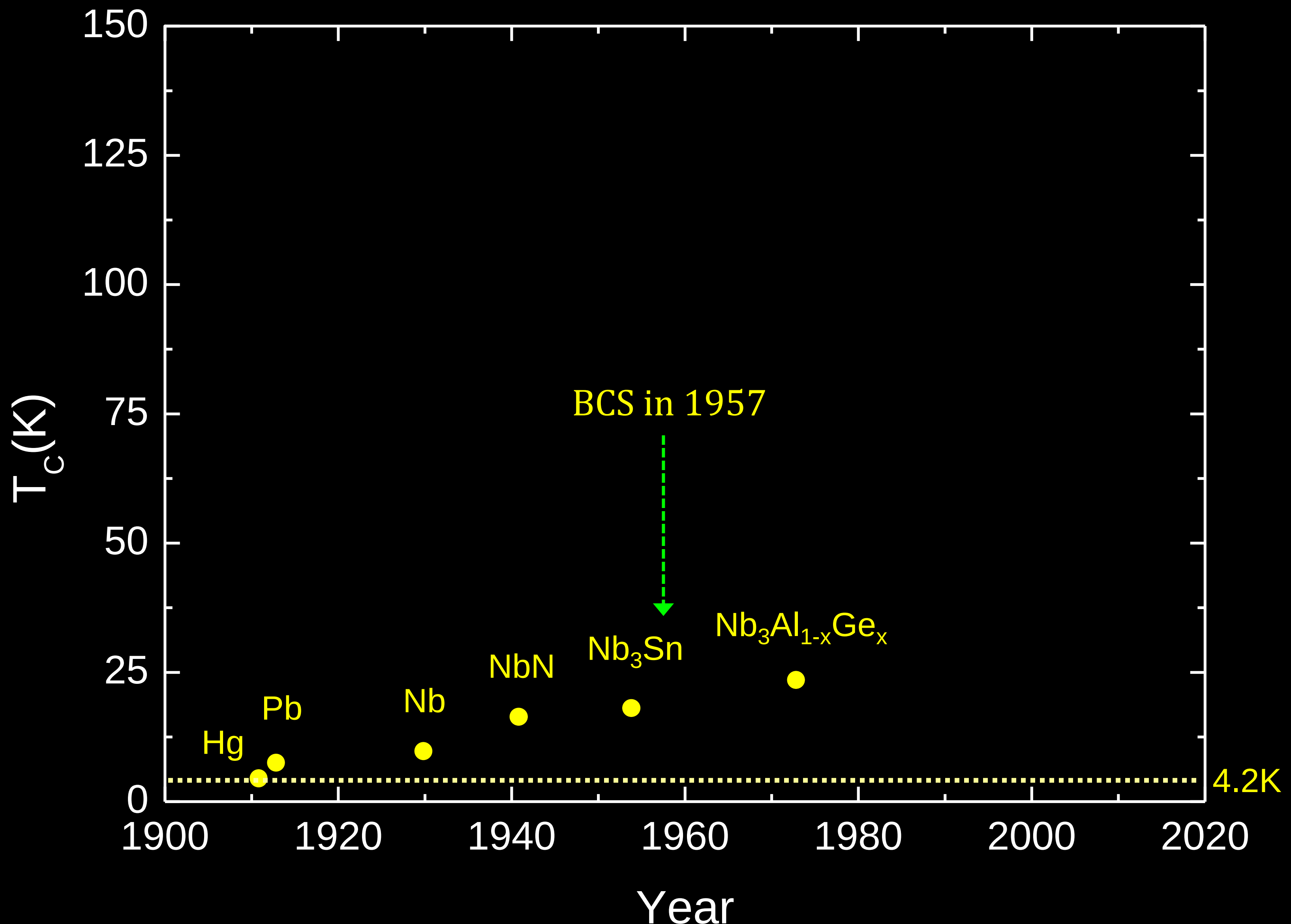
Robert Doll

Martin Näbauer

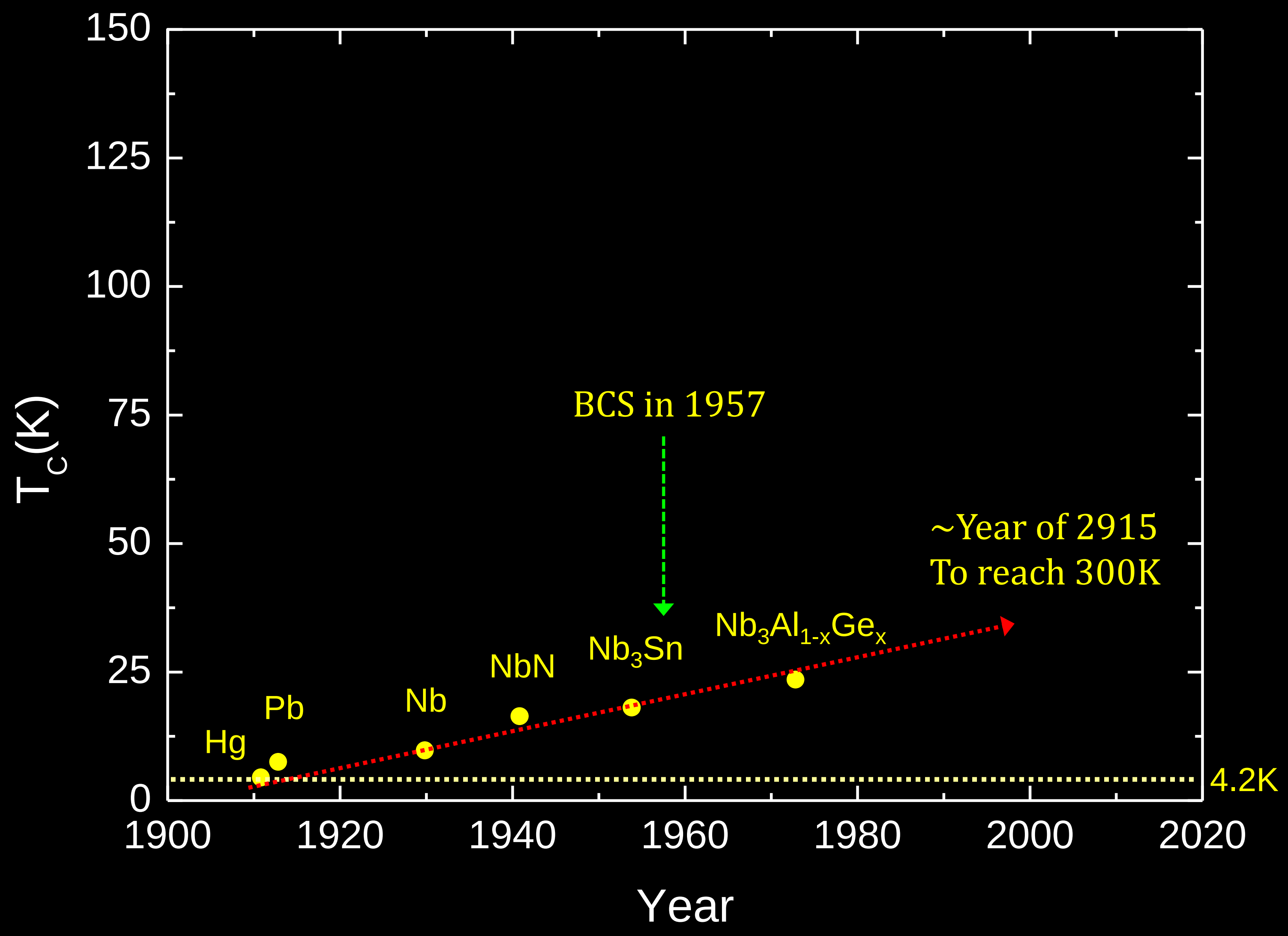


B. D. Deaver and W. M. Fairbank, PRL **7**, 43 (1961)
R. Doll and M. Näbauer, PRL **7**, 51 (1961)

History of Conventional SC



History of Conventional SC



Matthias's Rules for Searching High TC SC

Bernd Matthias

By Joel Broida©

1. Stay away from insulators; transition metals are better.
2. There are favorable electron/atom ratios.
3. High symmetry is good; cubic symmetry is best.
4. Stay away from Oxygen
5. Stay away from magnetism
6. Stay away from theorists.

W. E. Pickett , Physica B **296**, 112 (2001)
I. I. Mazin, Nature **464**, 183 (2010)

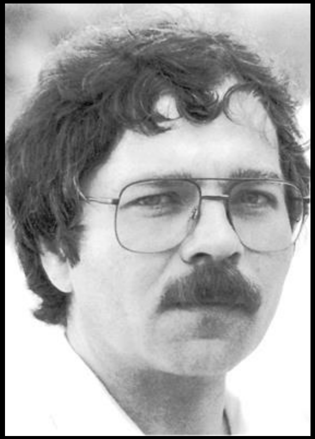
The Woodstock of Physics : Discovery of Cuprates

Possible High T_c Superconductivity in the Ba – La – Cu – O System

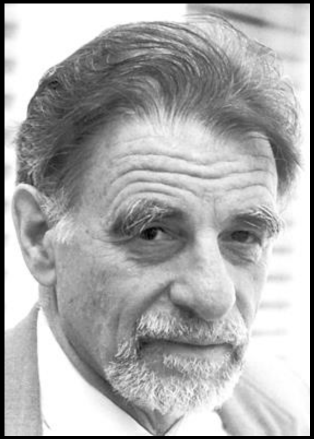
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986
Z. Phys. B – Condensed Matter 64,189 (1986)

J. Georg Bednorz

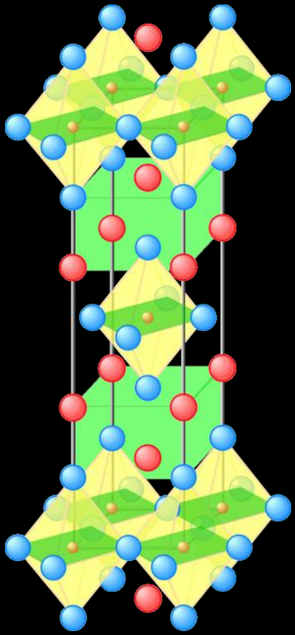


K. Alex Müller



Nobel Prize 1987

$La_{2-x}Ba_xCuO_4$, Tc=30K



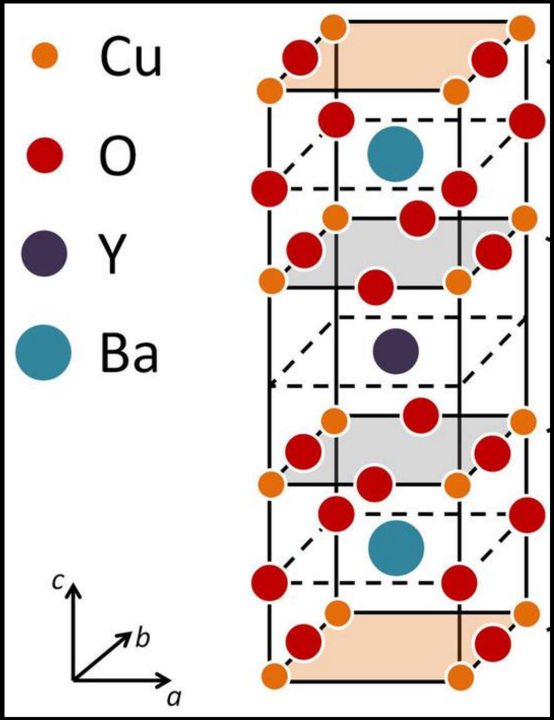
The Woodstock of Physics : Discovery of Cuprates

Tc>77K !

朱經武

吳茂昆

$YBa_2Cu_3O_{7-\delta}$, T_c~93K



CuO chain

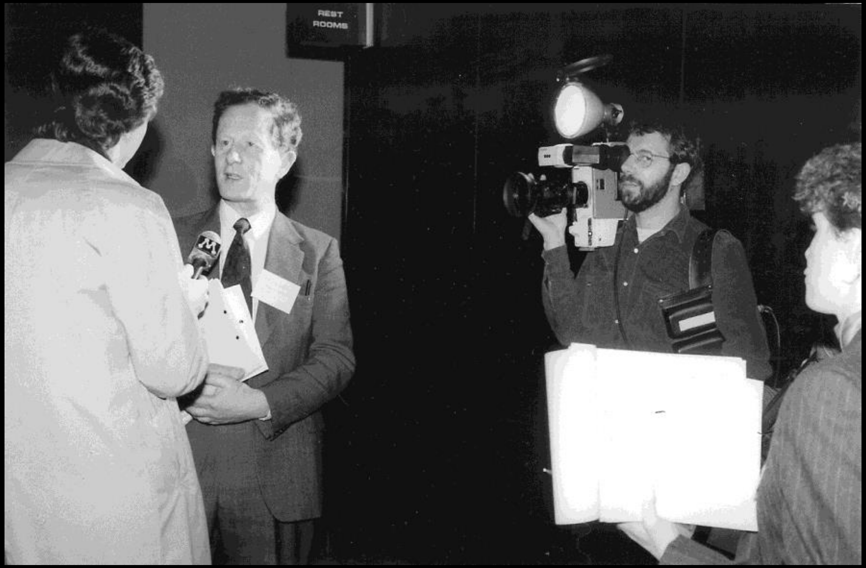
BaO

CuO plane

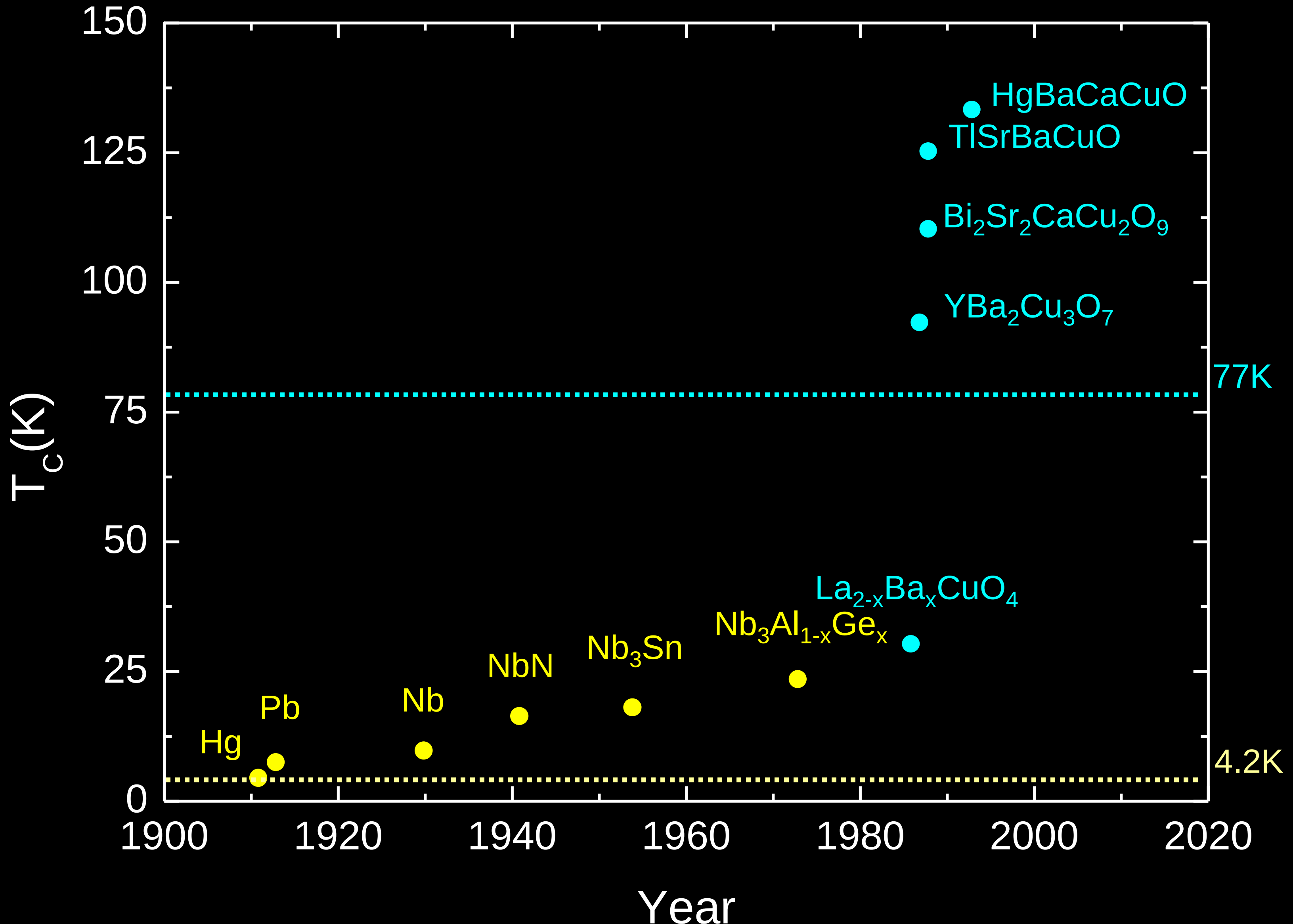
M. K. Wu *et al.*, PRL **58**, 908 (1987)

Woodstock of Physics - March Meeting 1987

“The stores and the bars were all ‘Physicists welcome,’ ” said Paul M. Grant, who headed the superconductivity research at I.B.M.’s Almaden Research Center in San Jose. He recalled a discotheque in Chelsea with a long line of people waiting to get in. “The bouncers took anybody that had a physical society badge on to the front,” Dr. Grant recalled, “and we got in gratis. Can you imagine what a culture shift? We had a hell of a good time.” – NY Times



History of Superconductors



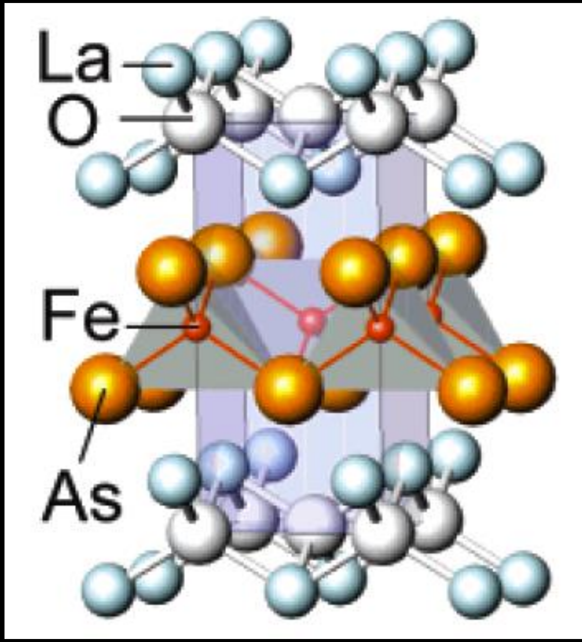
The Discovery of Fe-based Superconductors (FeSC)

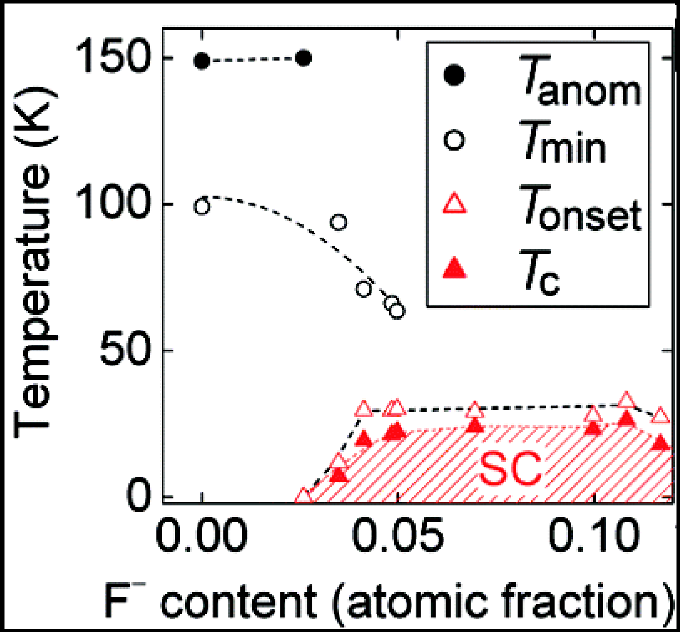
2006 : $LaFeP(O_{1-x}F_x)$, T_C~5K

2007 : LaNiPO, T_C~3K

Feb 23, 2008 : $LaFeAs(O_{1-x}F_x)$, T_C~26K

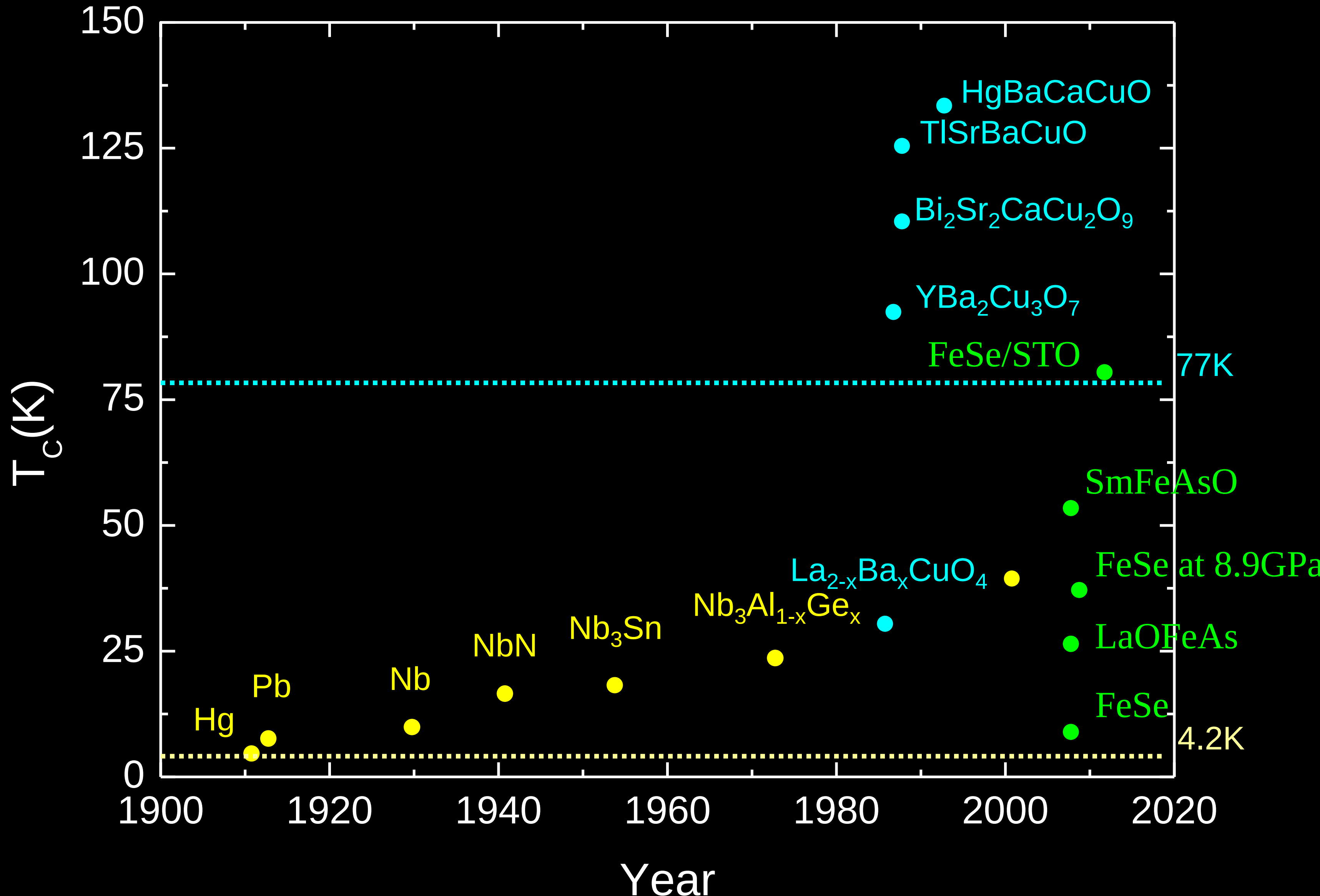
Hideo Hosono





Y. Kamihara *et al.*, JACS. **128**, 10012 (2006)
T. Watanabe *et al.*, JACS. **46**, 7719 (2007)
Y. Kamihara *et al.*, JACS. **130**, 3296 (2008)

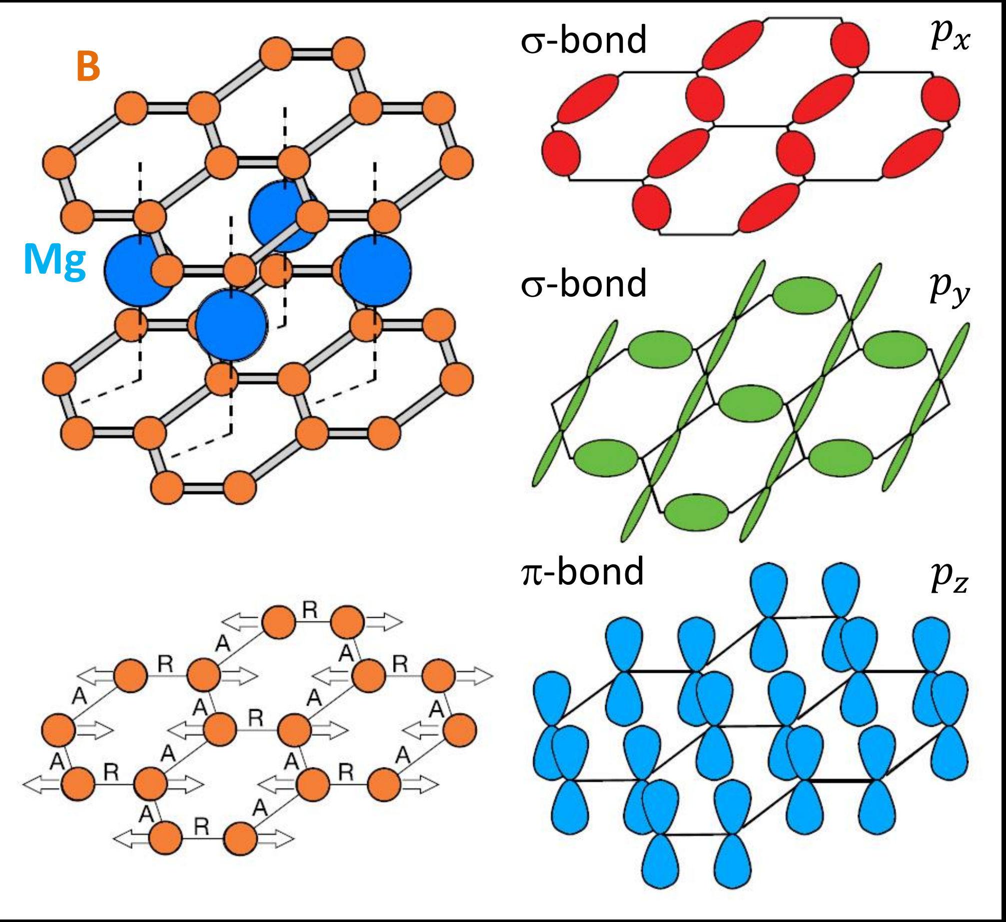
History of Conventional and High T_C Superconductors

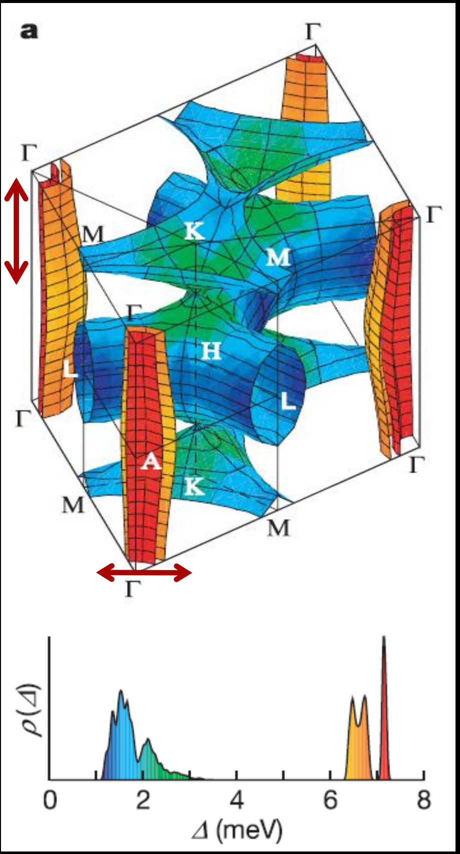


Honorable Mention : MgB_2 in 2001

Tc=39K
Two superconducting gaps
Strong *sp²* bonding and hybridization
E_{2g} phonon and σ bond coupling leads to high Tc

Jun Akimitsu
秋光純



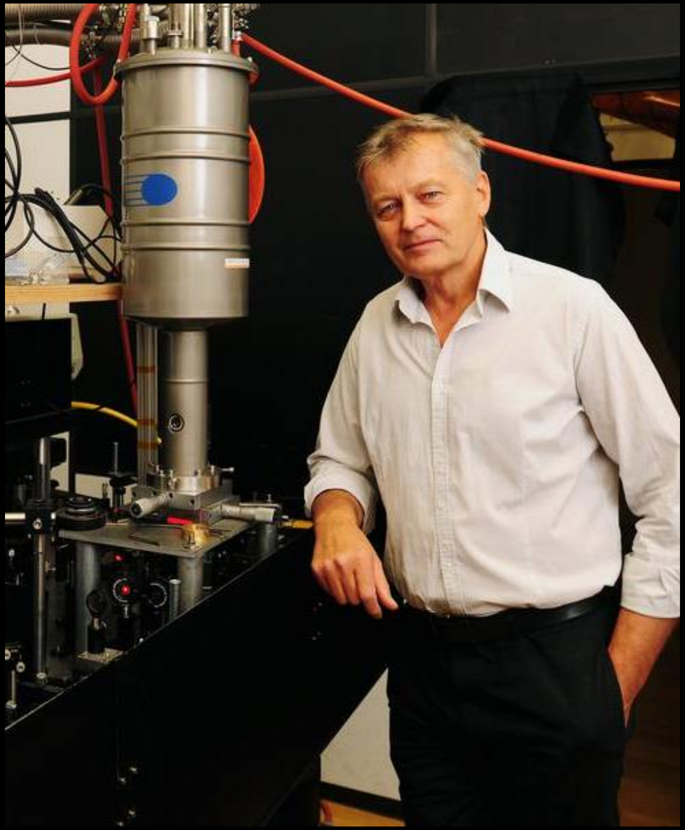


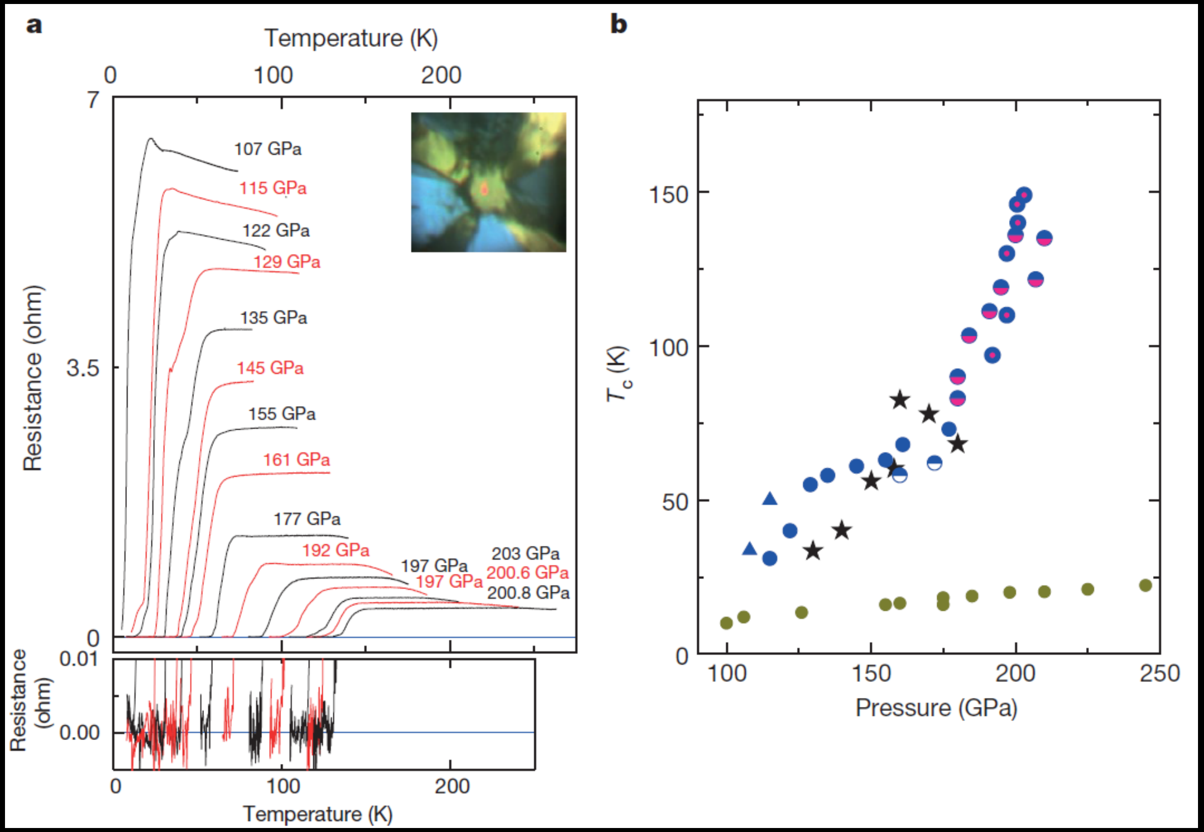
J. Nagamatsu *et al*., Nature 410, 63 (2001)
Amy Liu *et al*., PRL 87, 087005 (2001)
H.J. Choi *et al*., Nature 418, 758 (2002)

Honorable Mention : H_3S in 2015

T_C=203K under High Pressure
Likely H-rich H_3S
Conventional superconductor?

Mikhail Eremets



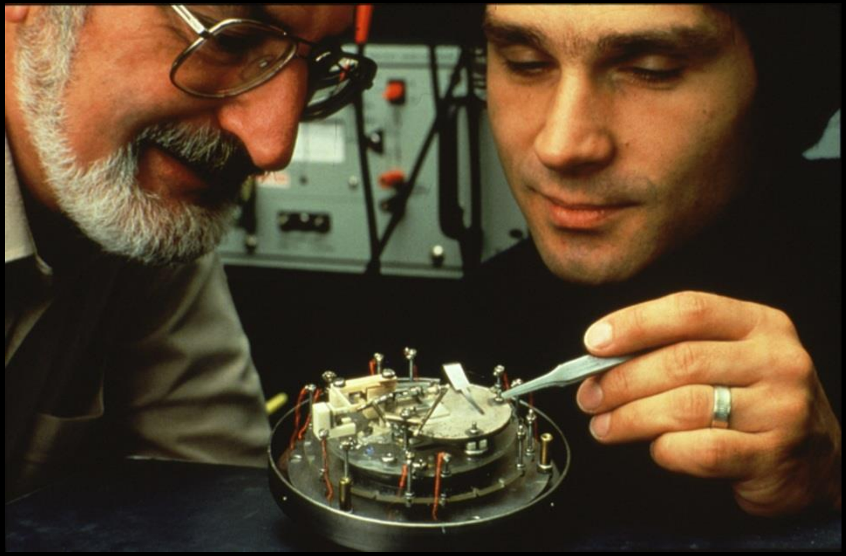


A. P. Drozdov *et al.*, Nature 525, 73 (2015)

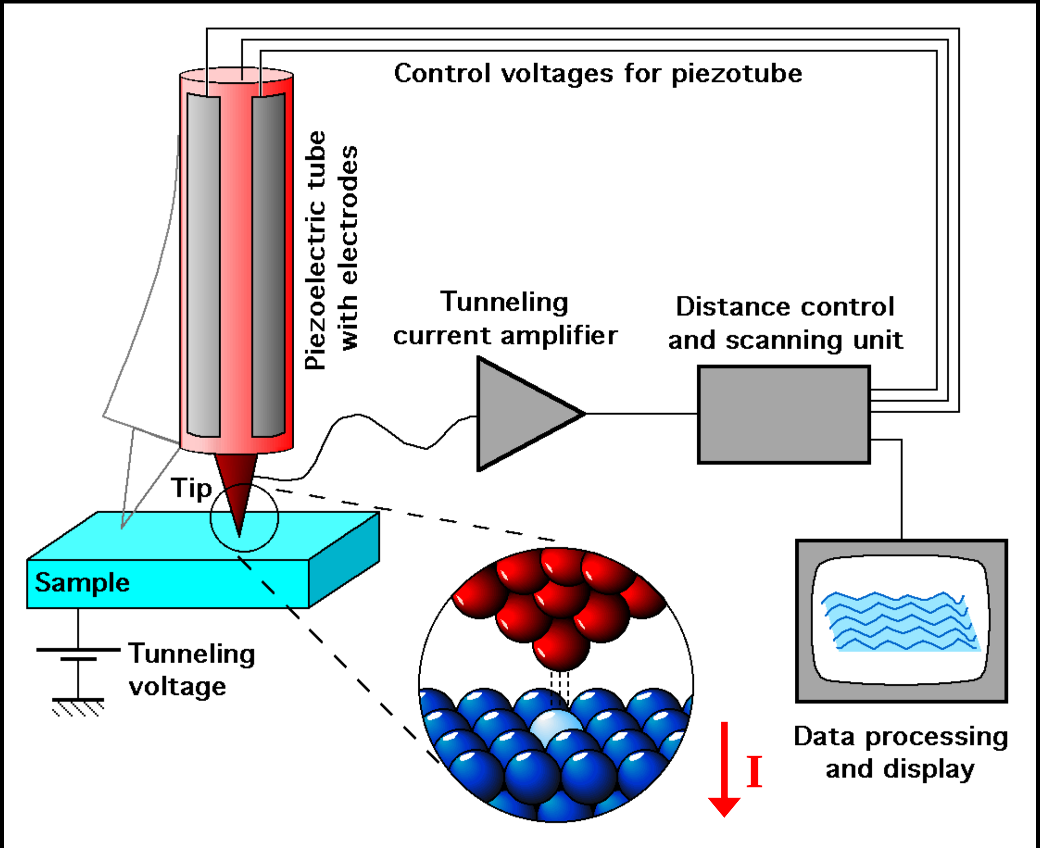
1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

Scanning Tunneling Microscope (STM)

Heinrich Rohrer & Gerd Binnig



Nobel Prize in 1986 © IBM

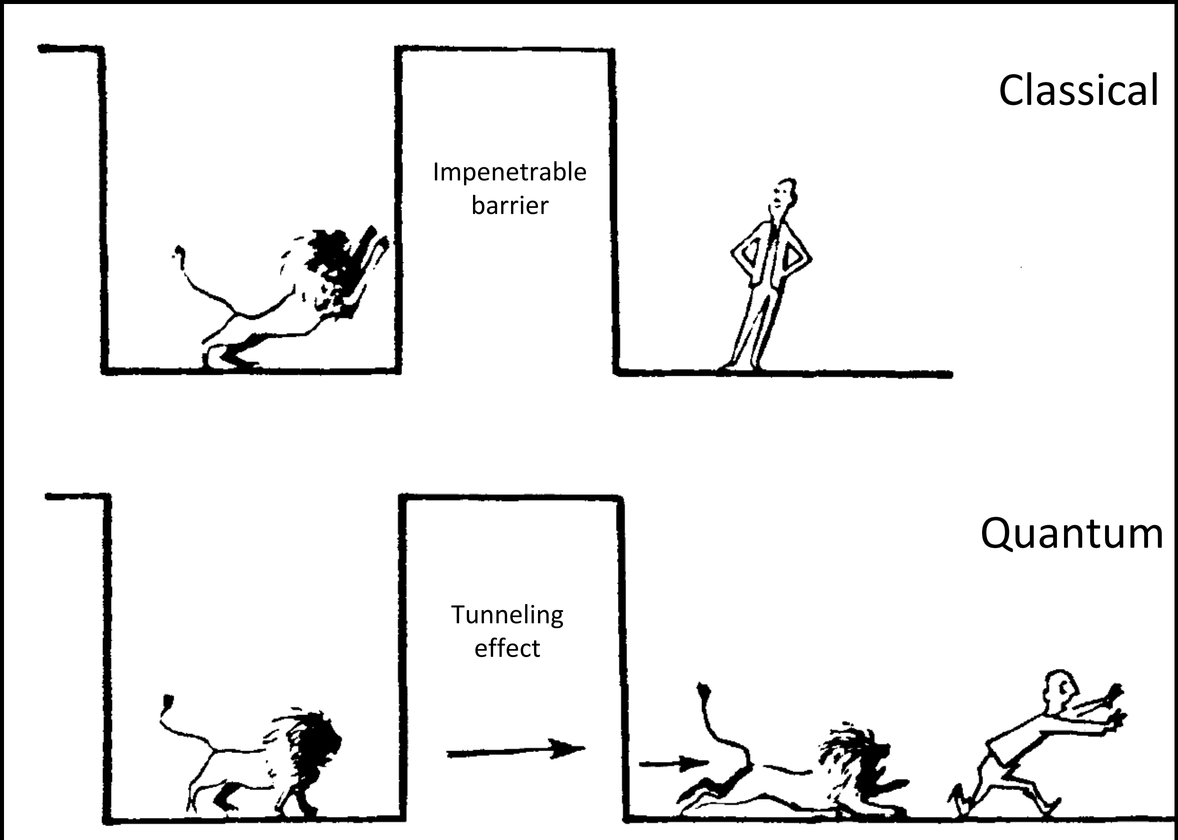


© Wikipedia

Quantum Tunneling

Erwin Schrödinger

Nobel Prize in 1933



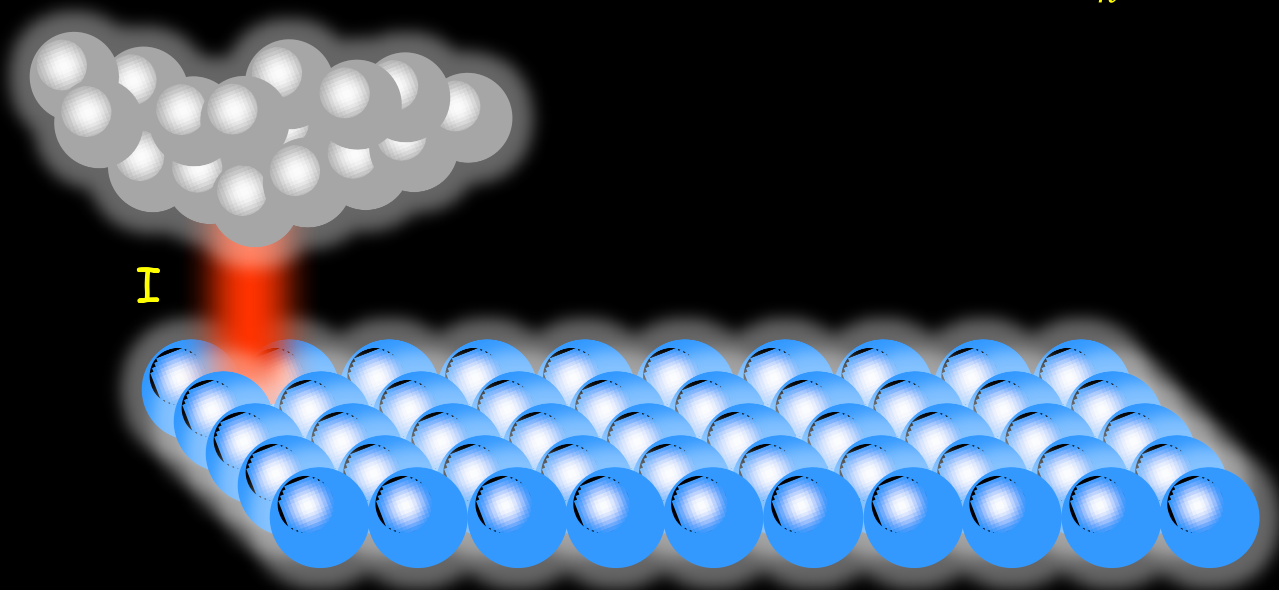
$$-\frac{\hbar^2}{2m}\nabla^2\Psi(\vec{r},t) = i\hbar\frac{\partial}{\partial t}\Psi(\vec{r},t)$$

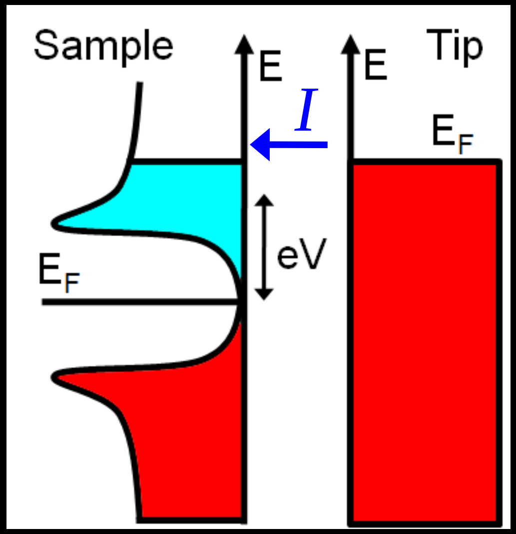
B. Bleaney, Contemp. Phys. 25, 315 (1984)

Tunneling current

$$I(\vec{r},z,V) \propto \exp(-2\kappa(\vec{r})z)\int_0^{E=eV} LDOS_{sample}(\vec{r},E)dE$$

where $\kappa(\vec{r}) = \sqrt{2m\emptyset(\vec{r})}/_{\hbar} \sim 1\text{Å}^{-1}$

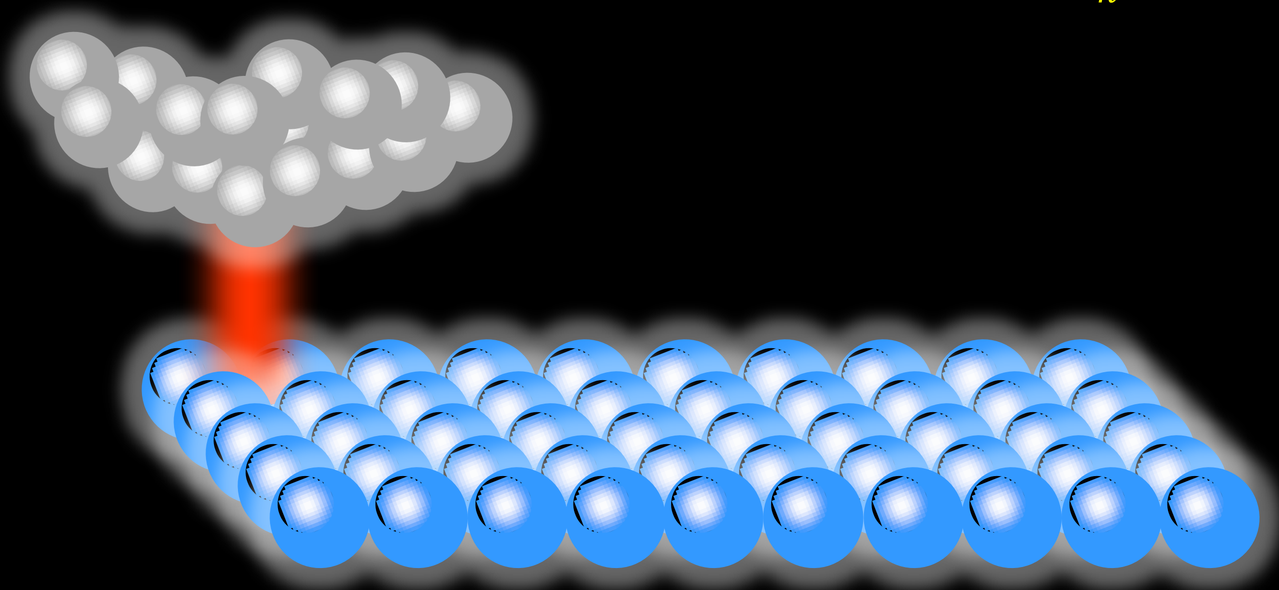


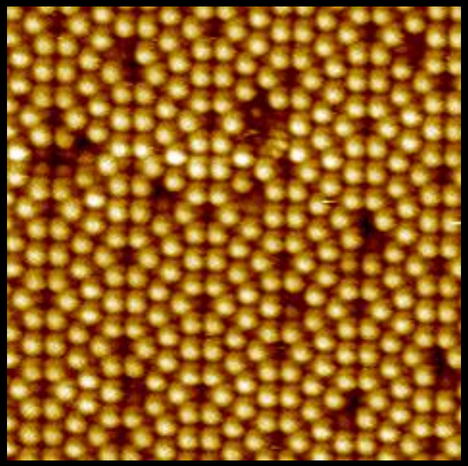


Constant Current Topography

$$I(\vec{r}, z, V) \propto \exp(-2\kappa(\vec{r})z) \int_0^{E=eV} LDOS_{sample}(\vec{r}, E)\,dE$$

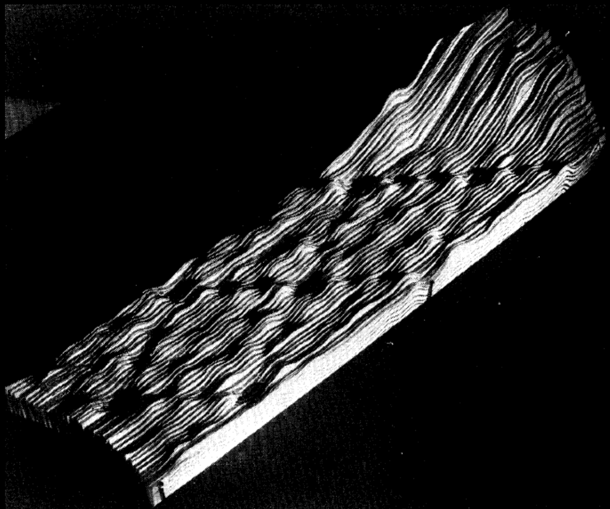
where $\kappa(\vec{r}) = \sqrt{2m\phi(\vec{r})}/\hbar \sim 1\text{Å}^{-1}$



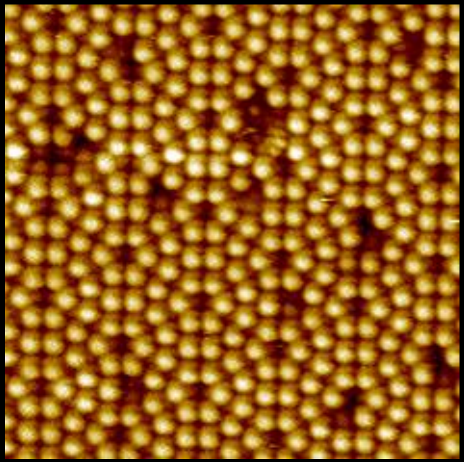


Si(111) 7x7

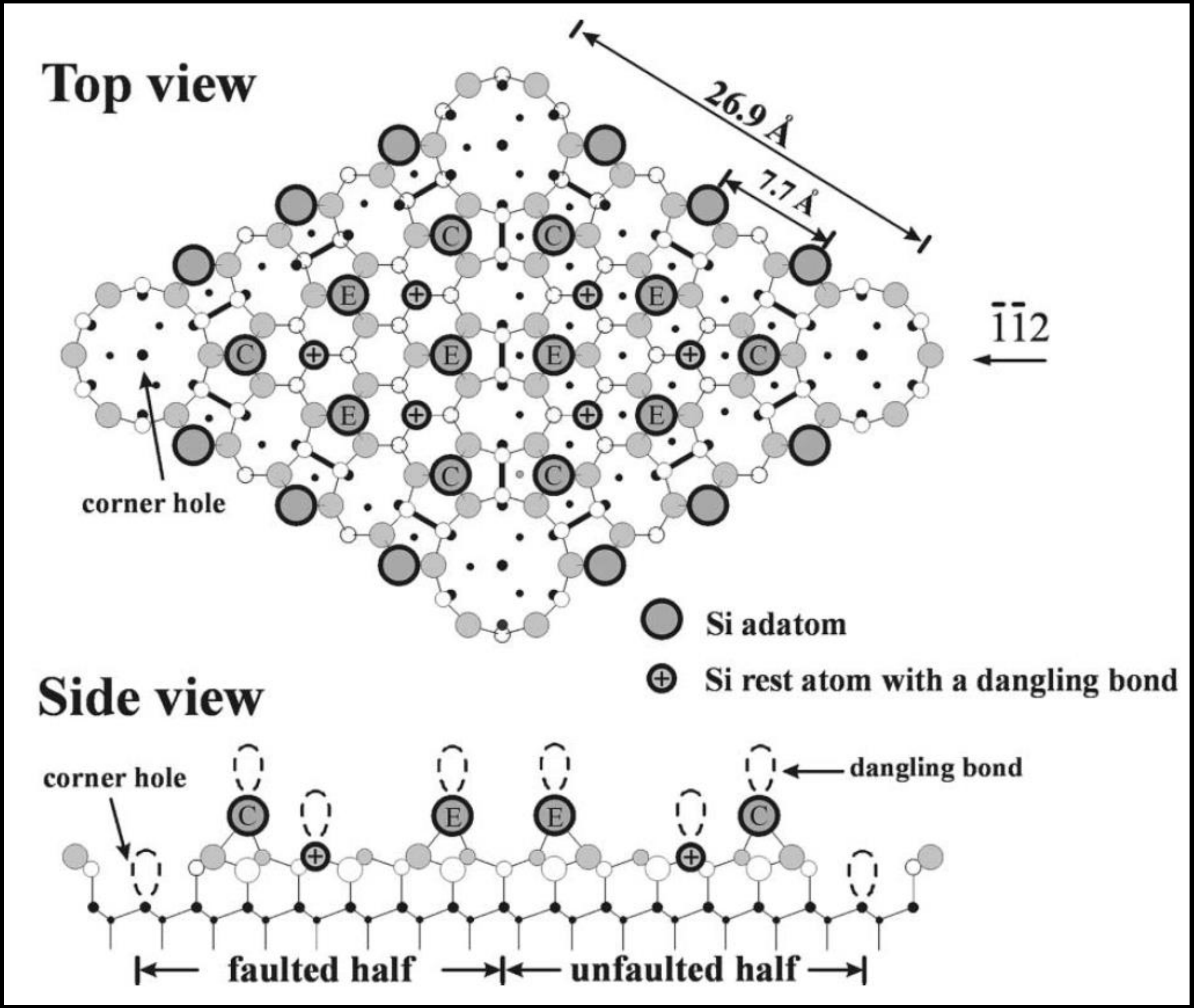
Si(111) 7x7 Structure



G. Binning *et al.*, Phys. Rev. Lett. 50, 120 (1983)



DAS Model



K. Takayanagi *et al.*, Surf. Sci. 164, 367 (1985)

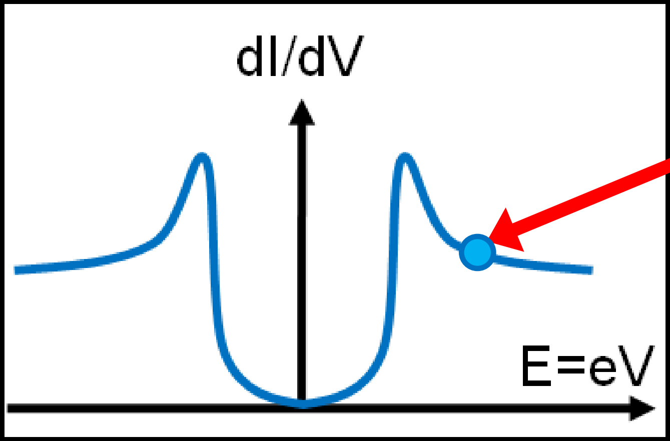
Tunneling Spectroscopy

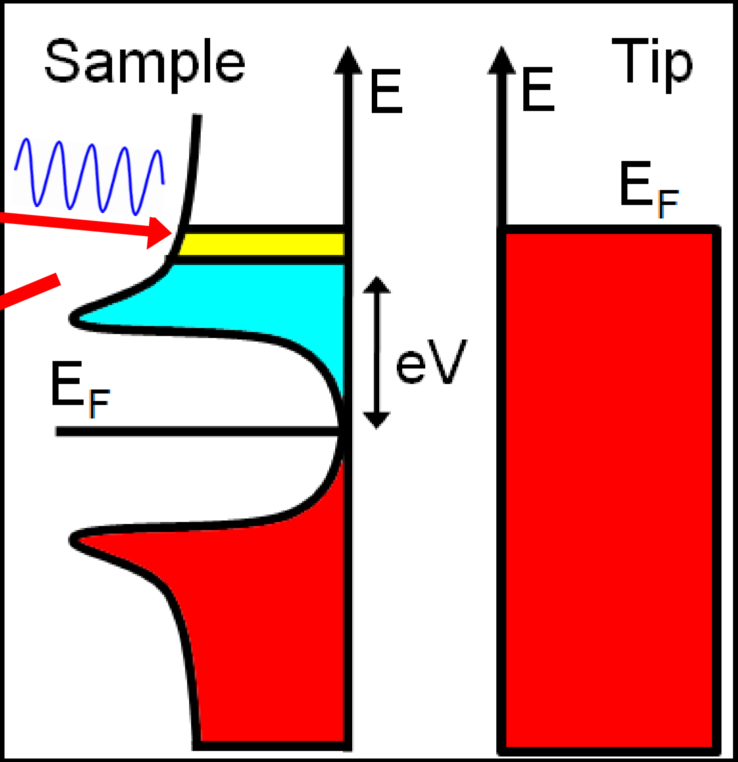
$$\text{Local Density of States}: \frac{dI}{dV}(\vec{r},V) \propto LDOS_{sample}(\vec{r},E=eV)$$

$$I(V+\Delta V\sin\omega t) = I(V) + \frac{dI}{dV}\Delta V\sin\omega t + \ldots$$

Point Spectrum

Modulation, dV





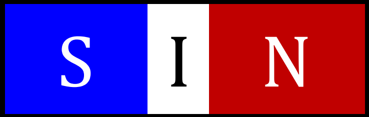
Superconducting Energy Gap in 1960

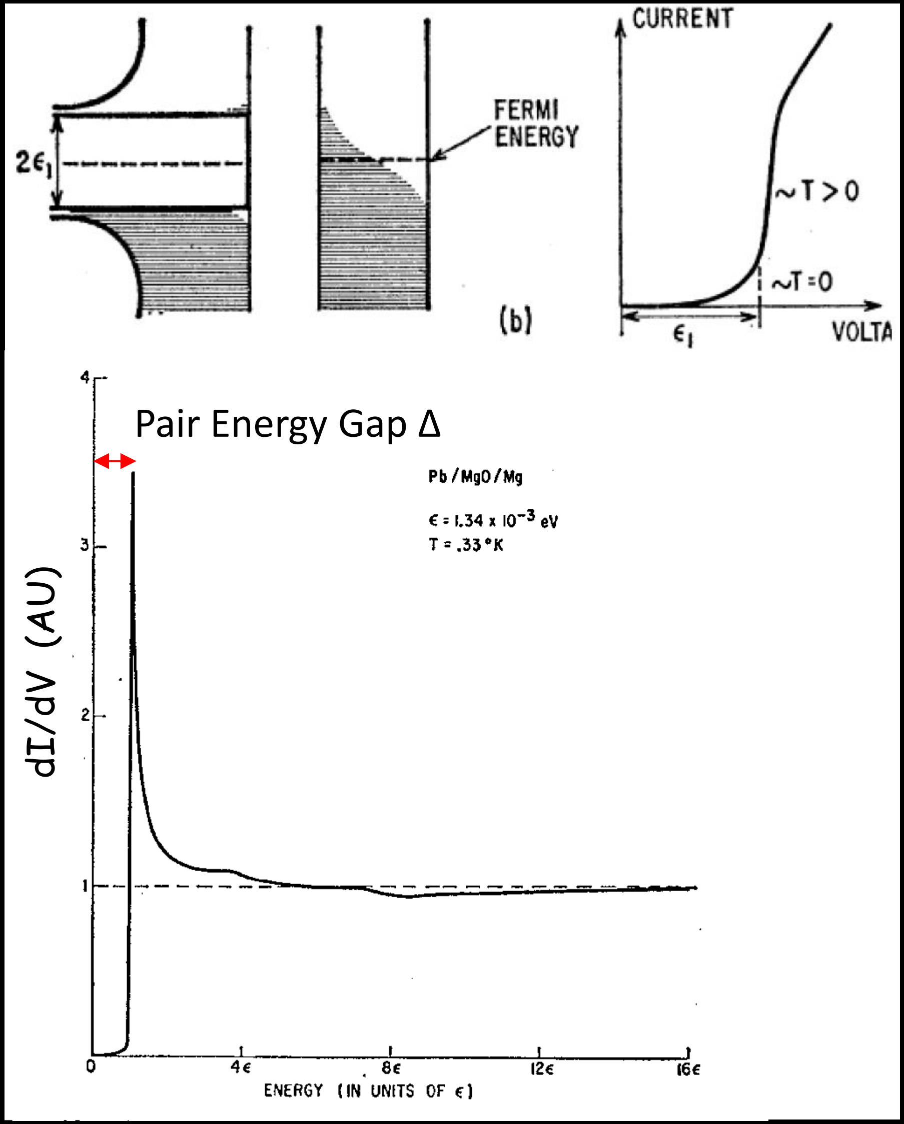
Ivar Giaever

Nobel Prize in 1973

© Schenectady Museum

Tunneling junction





Ivar Giaever, Phys. Rev. Lett. 5, 147 (1960)

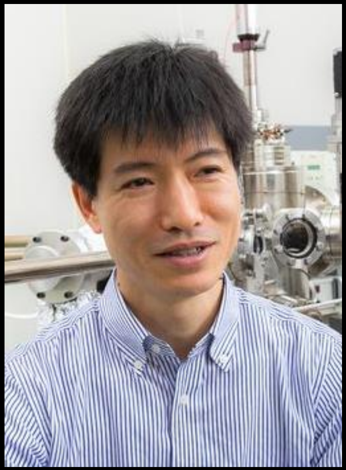
I. Giaever, Phys. Rev. 126, 941 (1962)

Superconducting Energy Gap by STM

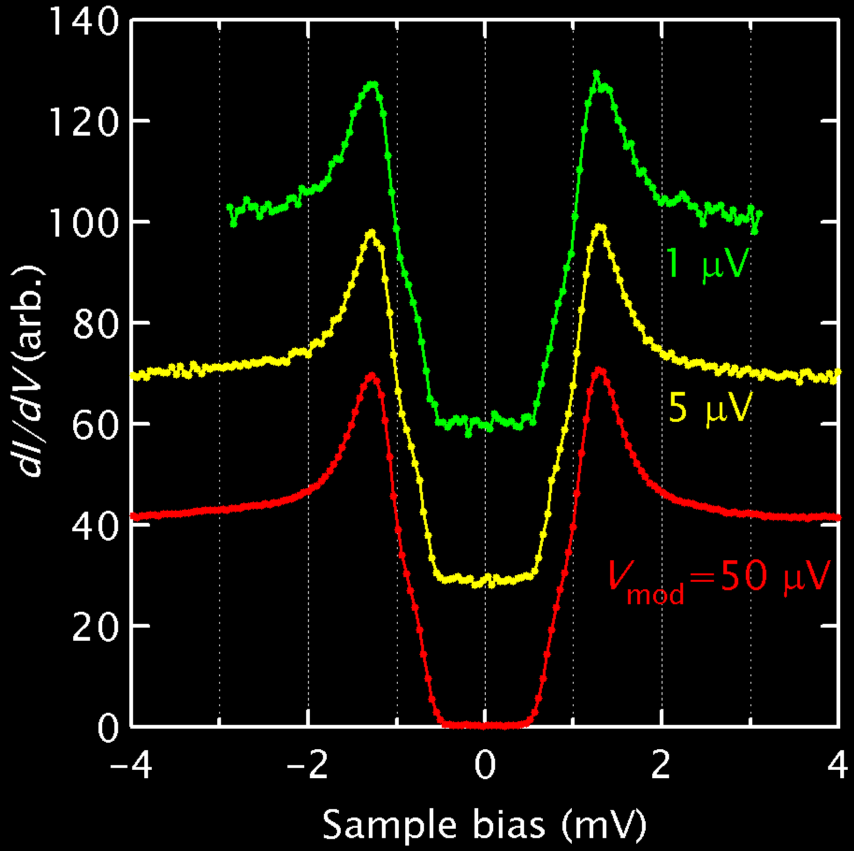
Energy resolution is thermally limited.

2H-$NbSe_2$, T_c = 7.1 K, measured at $T \sim 0.4$K

Tetsuo Hanaguri



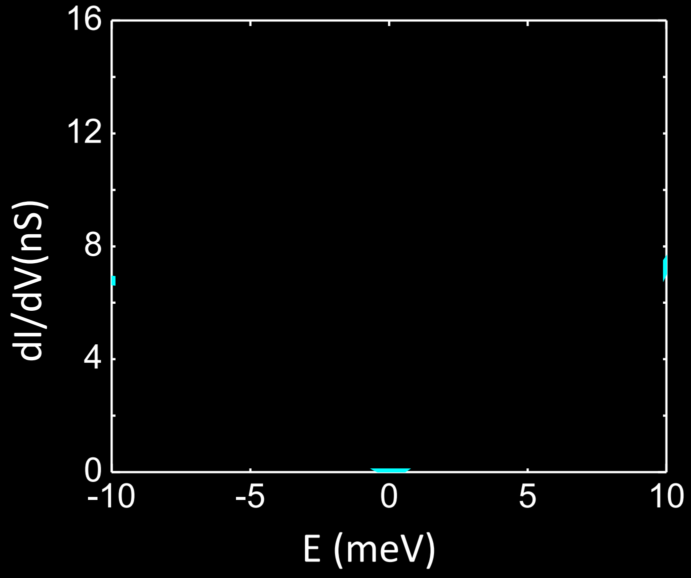
© RIKEN

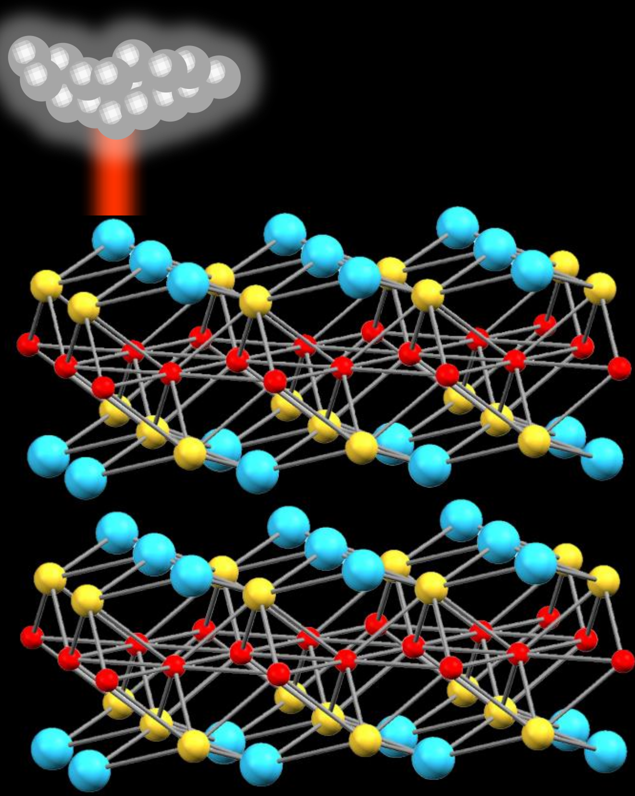


Scanning Tunneling Spectroscopy (STS) Mapping

Atomic resolution energy resolved conductance images, $g(r,E) \propto LDOS(r,E)$

Energy resolution ≤ 0.35meV at T=1.2K

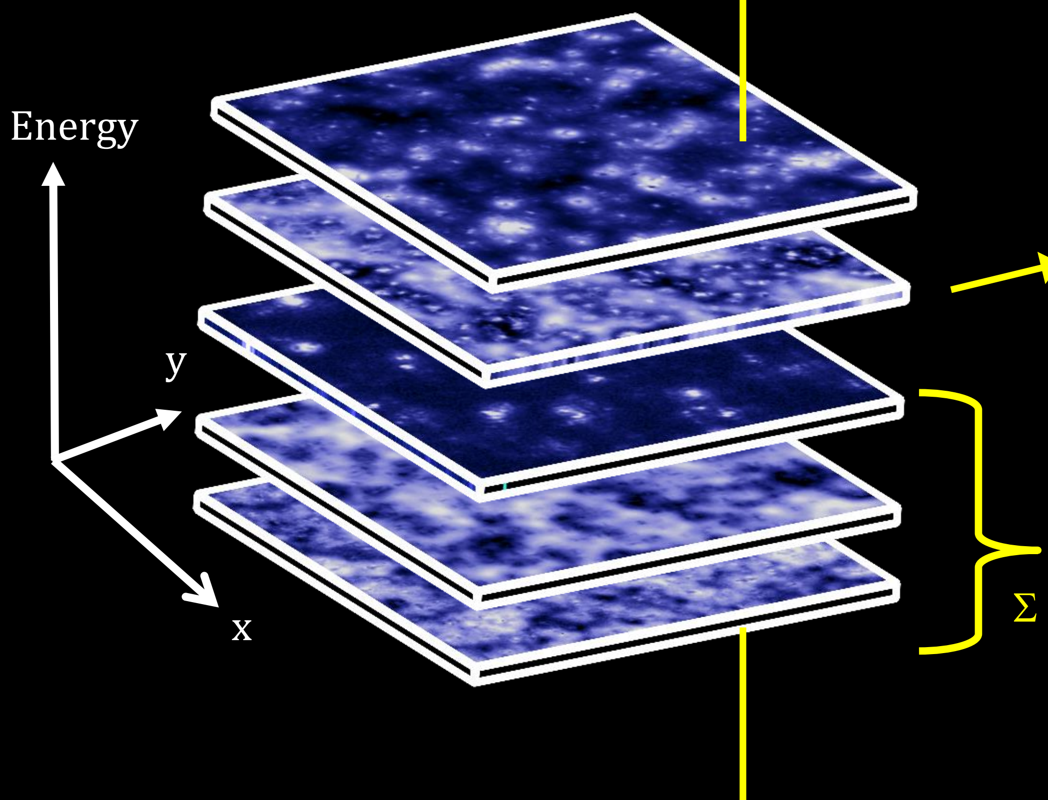


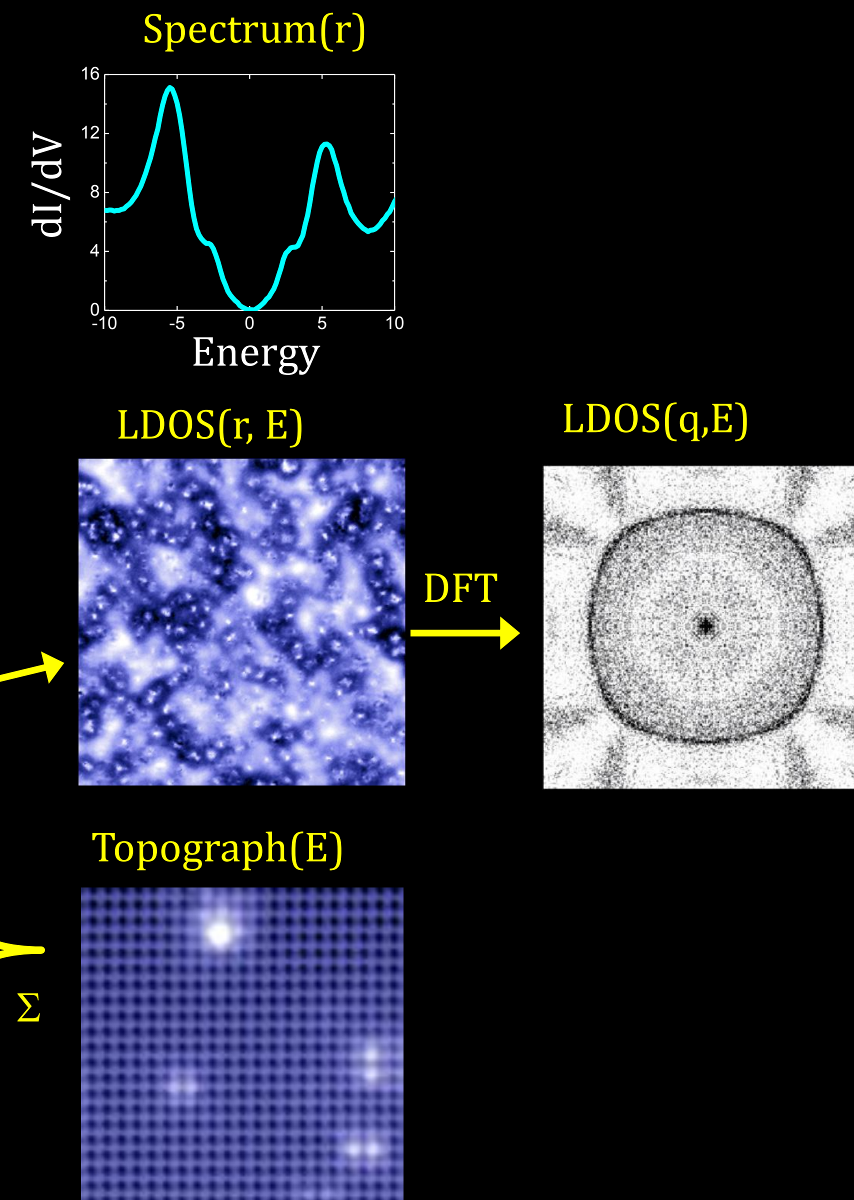


LiFeAs

Atomic Resolution Energy Resolved Images, LDOS(r,E)

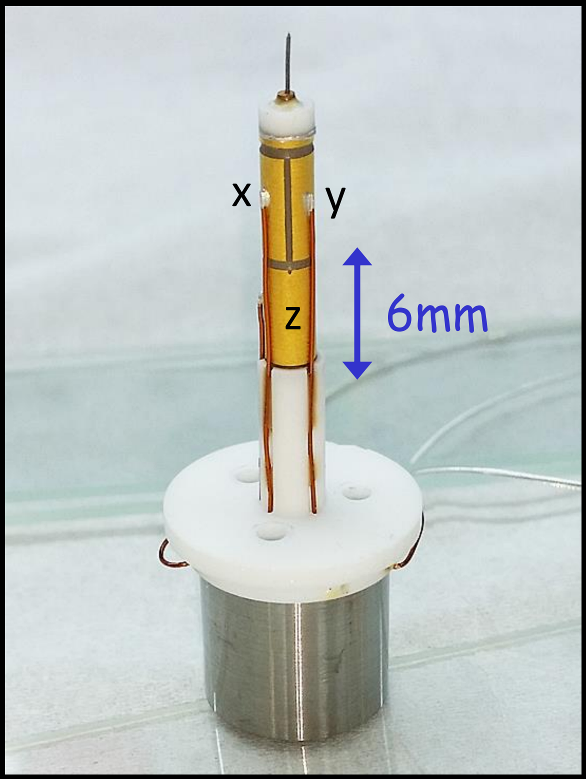
~5M dI/dV(r,E):
>50ms each with S/N~100
Total measurement > 72 hours
Requires < 10^{-15} m STM-tip vibration



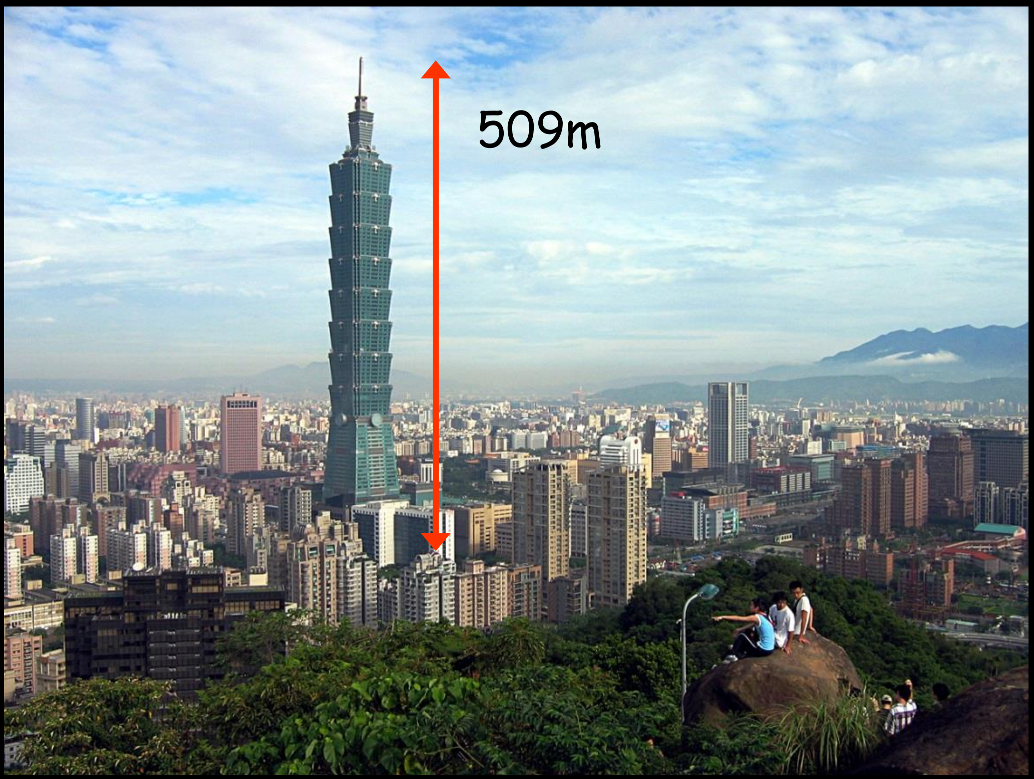


Our Resolution and Stability

STM Tip on Piezo Scanner



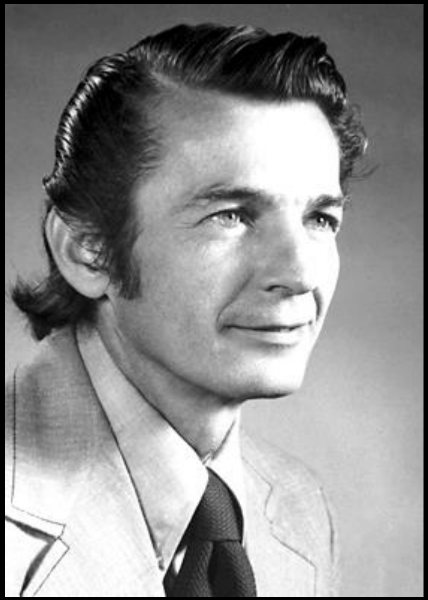
Taipei 101



@Wikipedia

0.5pm/6mm → 42nm/509m!

Ivar Giaever



Nobel Prize 1973

The best way to do science is not to buy a big piece of expensive equipment and use it to do research. There are lots of other people who have the same big expensive equipment. The best way to do science is if you can make your own equipment, make your own thing.

- Ivar Giaever, BCS@50 Conference, 2007

1.6K-9Tesla Cryogenic UHV STM @ Academia Sinica

100% Homemade!

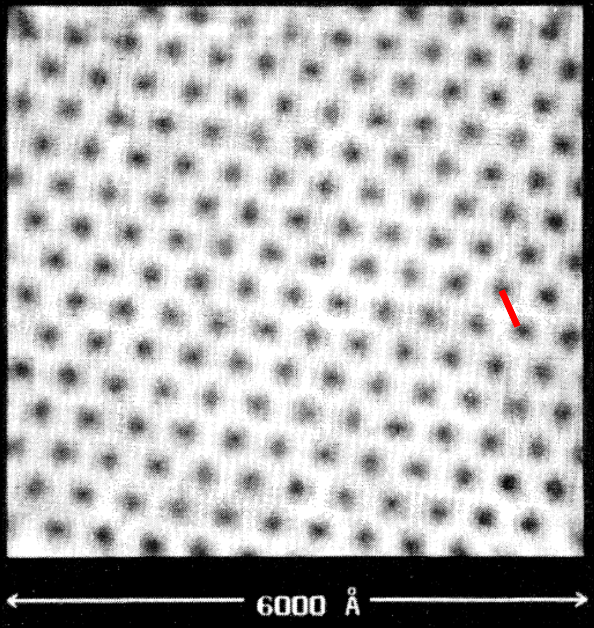
http://www.phys.sinica.edu.tw/~chuangtm/

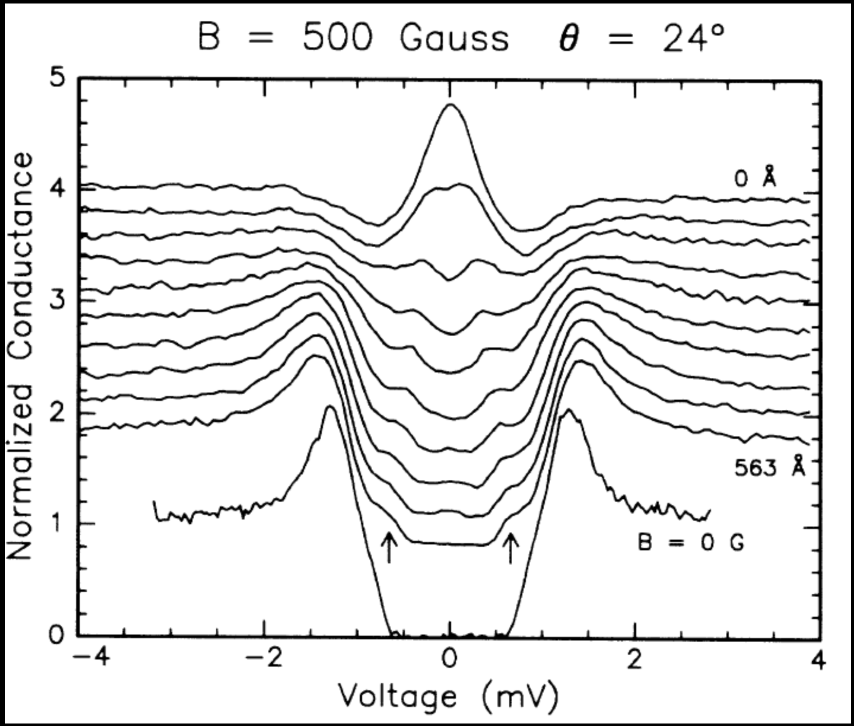
Vortex Imaging of $NbSe_2$ by STM

Harald F. Hess

© www.janelia.org

$2H\text{-}NbSe_2$: $T_c = 7.1$ K, $T_{CDW} = 29$ K





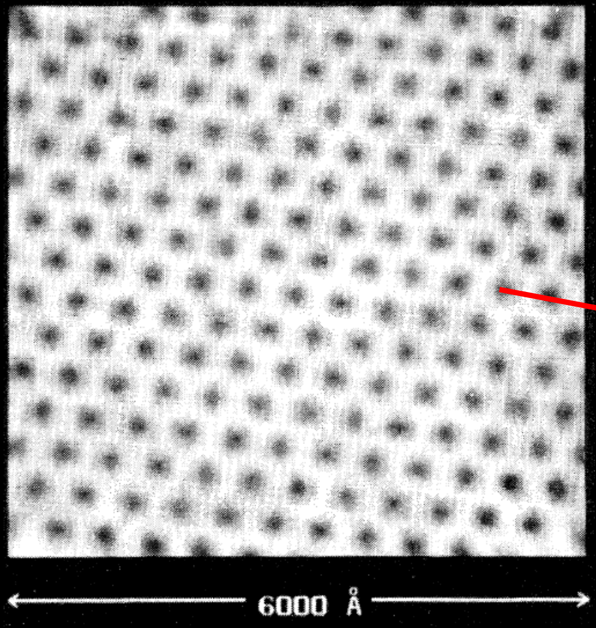
H. F. Hess *et al.*, PRL 62, 214 (1989).
H. F. Hess *et al.*, PRL 64, 2711 (1990).

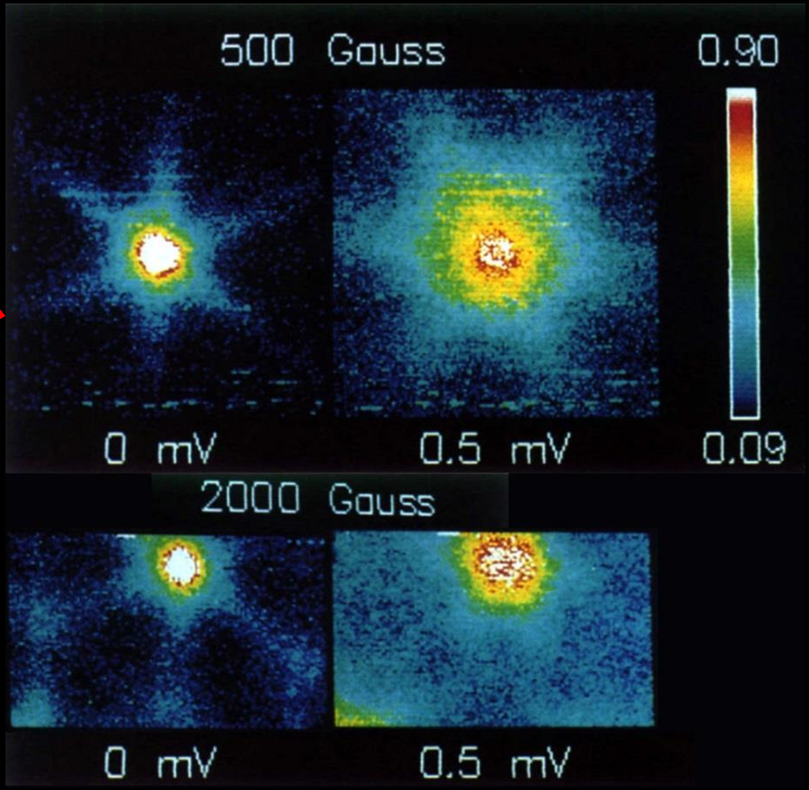
Vortex Imaging of $NbSe_2$ by STM

Harald F. Hess

© www.janelia.org

2H-$NbSe_2$: T_c = 7.1 K, T_{CDW} = 29 K



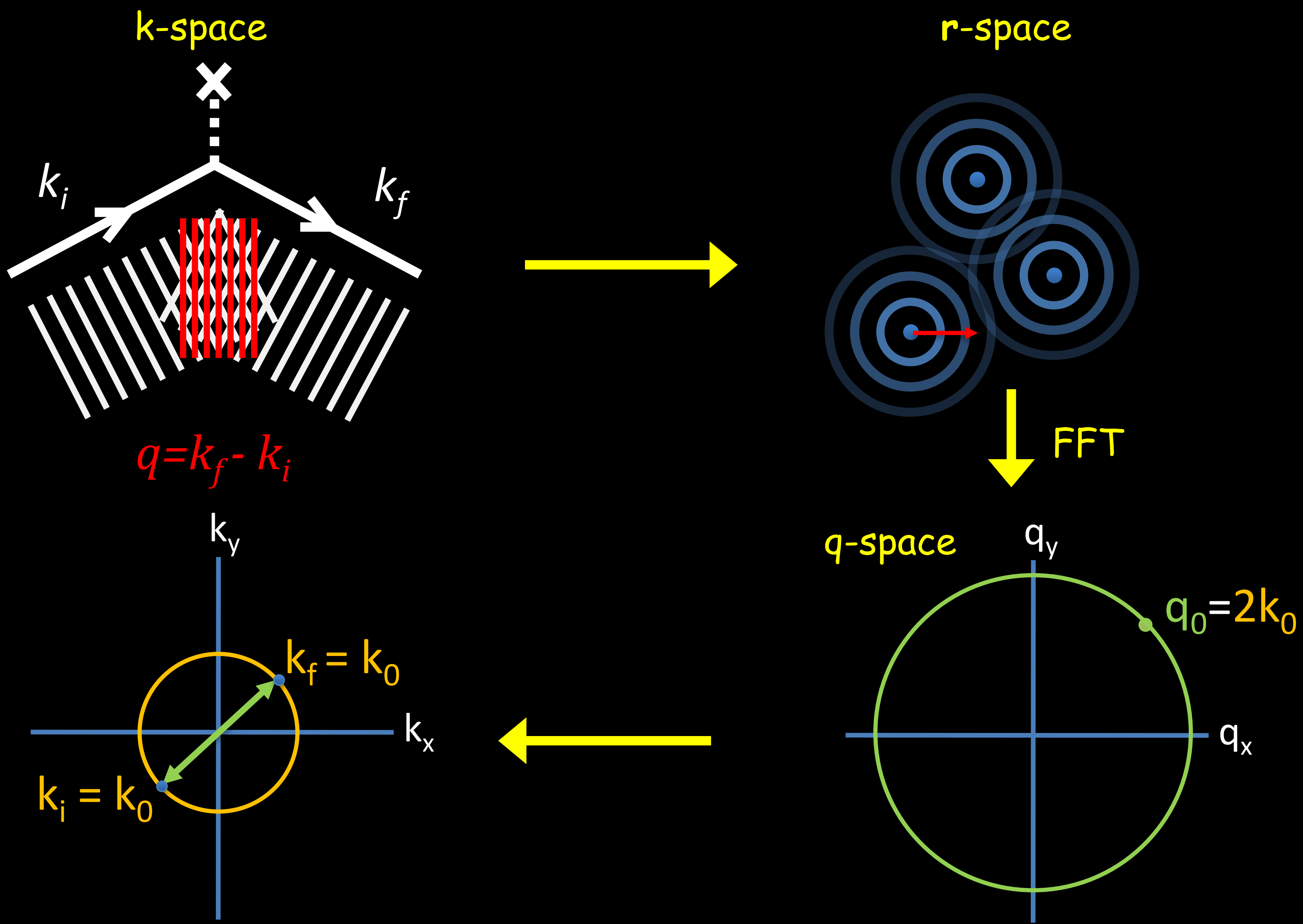


H. F. Hess *et al.*, PRL 62, 214 (1989).
H. F. Hess *et al.*, PRL 64, 2711 (1990).

Quasiparticle Scattering Interference (QPI)

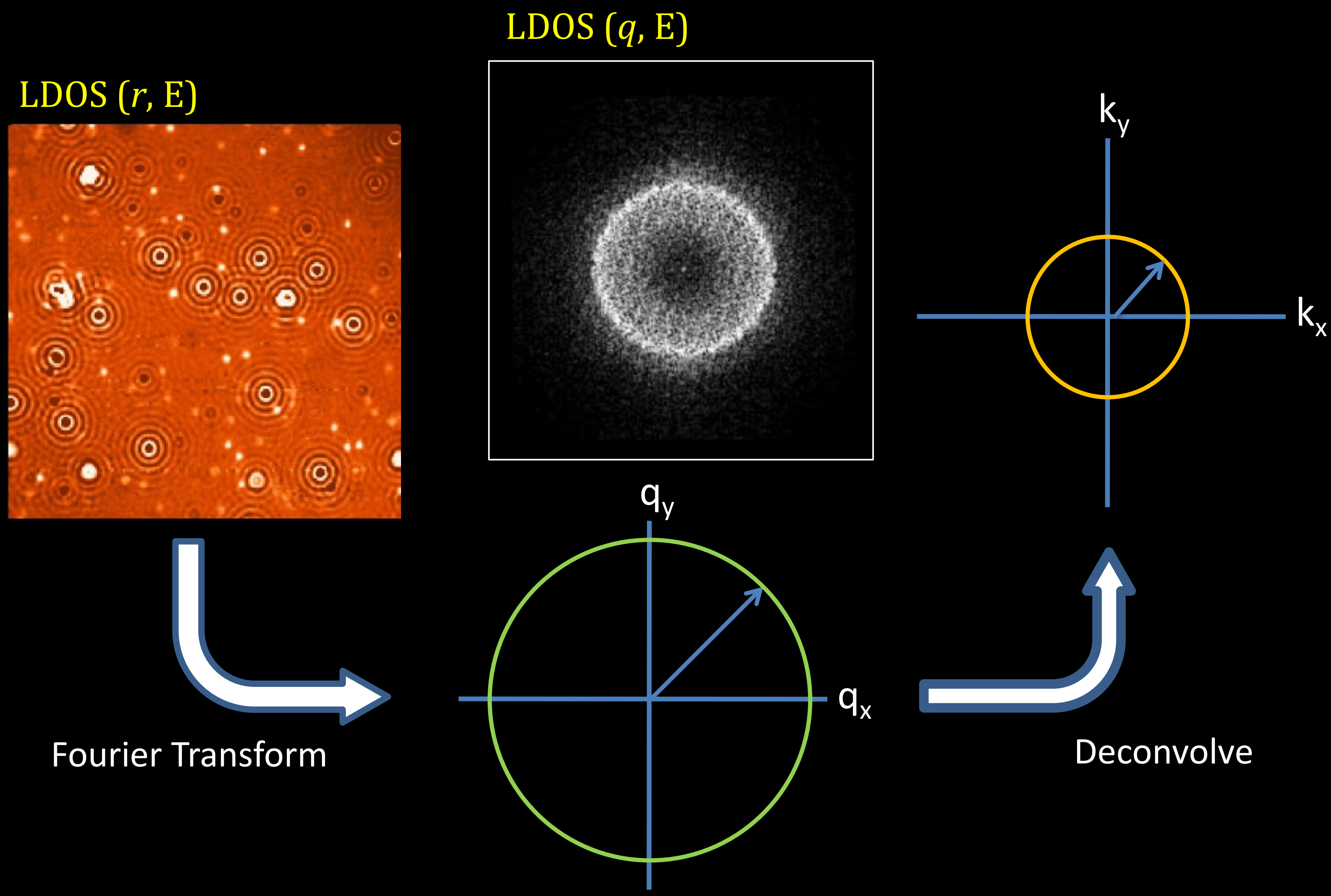
A path to determining momentum space structure by STM

Quasiparticle Scattering Interference (QPI)



Y. Hasegawa and Ph. Avouris, PRL 71, 1071 (1993).
M.F. Crommie *et al.*, Nature **363**, 524 (1993)

Inferring Band Structure from QPI

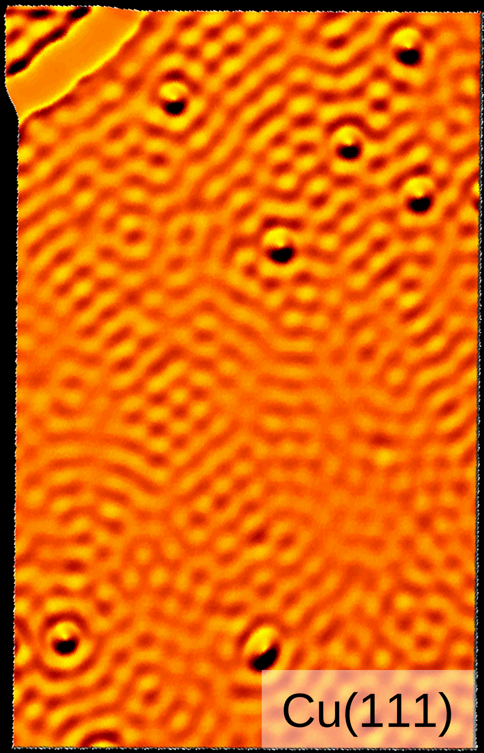


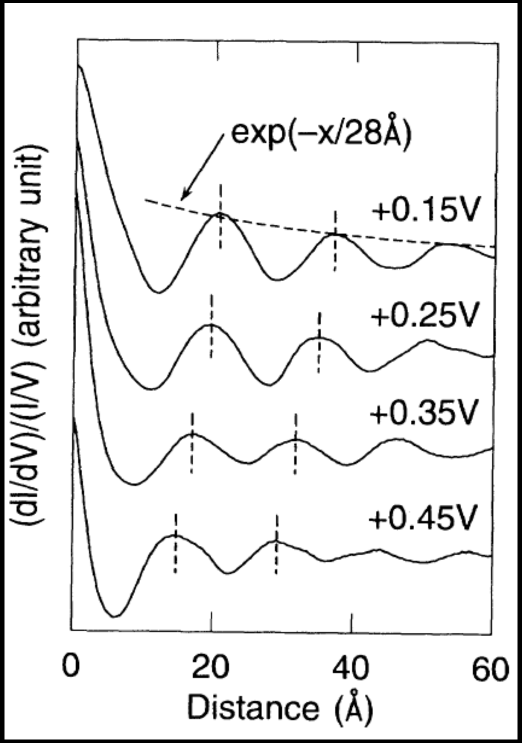
QPI on Simple Metals

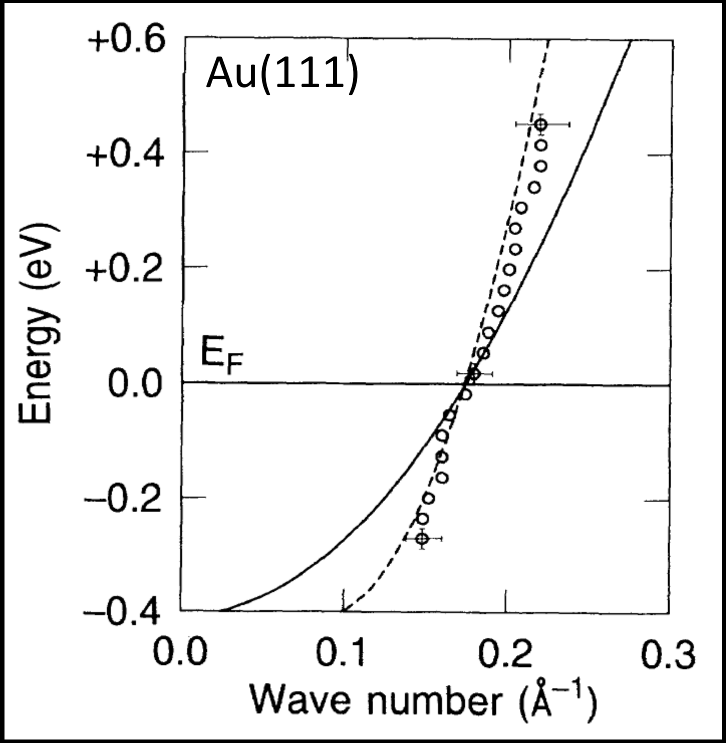
Landau quasiparticle standing waves at the surface of a 2D electron gas system.

Scattering off impurities and edges.

Dispersion relation of Bloch electrons







Y. Hasegawa and Ph. Avouris, PRL 71, 1071 (1993).
M.F. Crommie *et al.*, Nature **363**, 524 (1993)

Atomic Scale Visualization of Novel Materials by STM

Advantages:

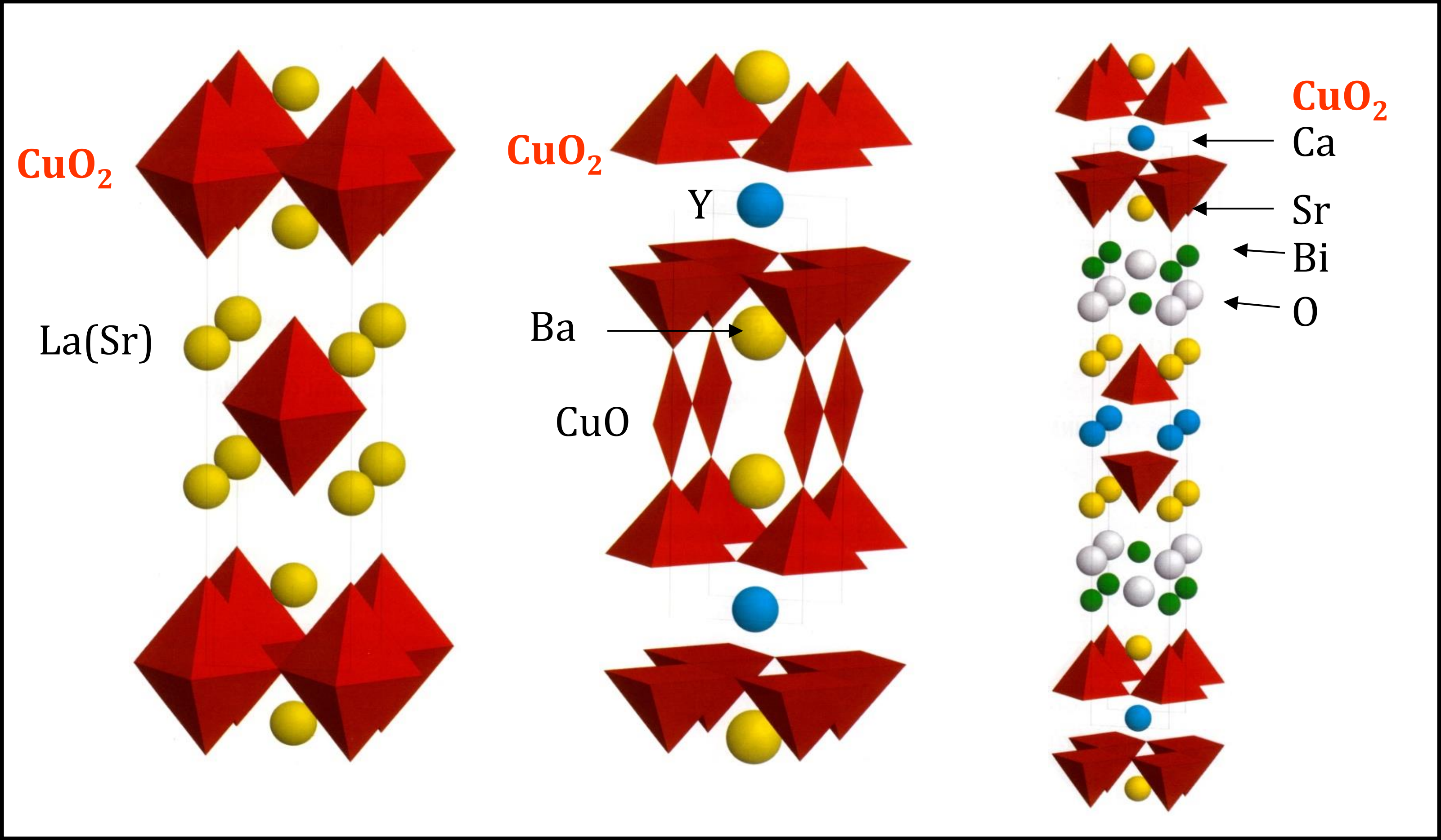
- Both occupied and empty states can be explored.
- Both real and momentum spaces can be explored.
- Magnetic-field compatible.
- Excellent energy resolution at low temperature

Disadvantages:

- Quasi-particle scatterers are necessary.
- Measurement takes VERY long time.

1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

High Tc Cuprate Superconductors (CuSC)



$La_{2-x}Sr_xCuO_4$
(LSCO)

(T_c^{max} ~ 40 K)

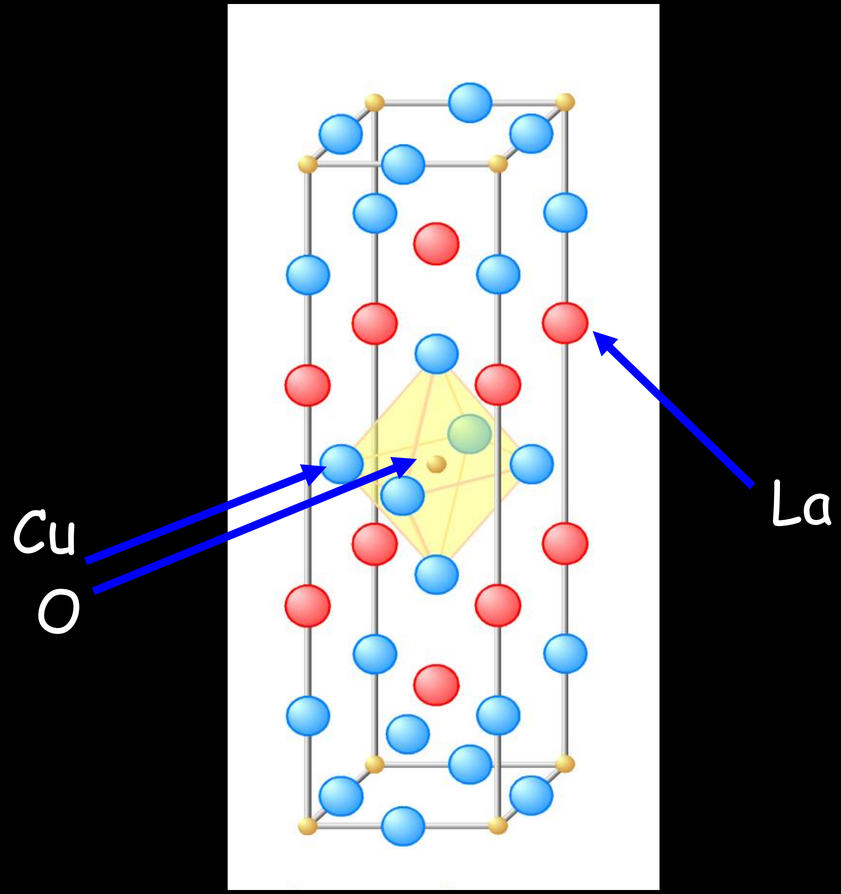
$YBa_2Cu_3O_y$
(YBCO)

(T_c^{max} ~ 93 K)

$Bi_2Sr_2CaCu_2O_y$
(Bi2212 or BSCCO)

(T_c^{max} ~ 95 K)

$La_{2-x}Ba_xCuO_4$

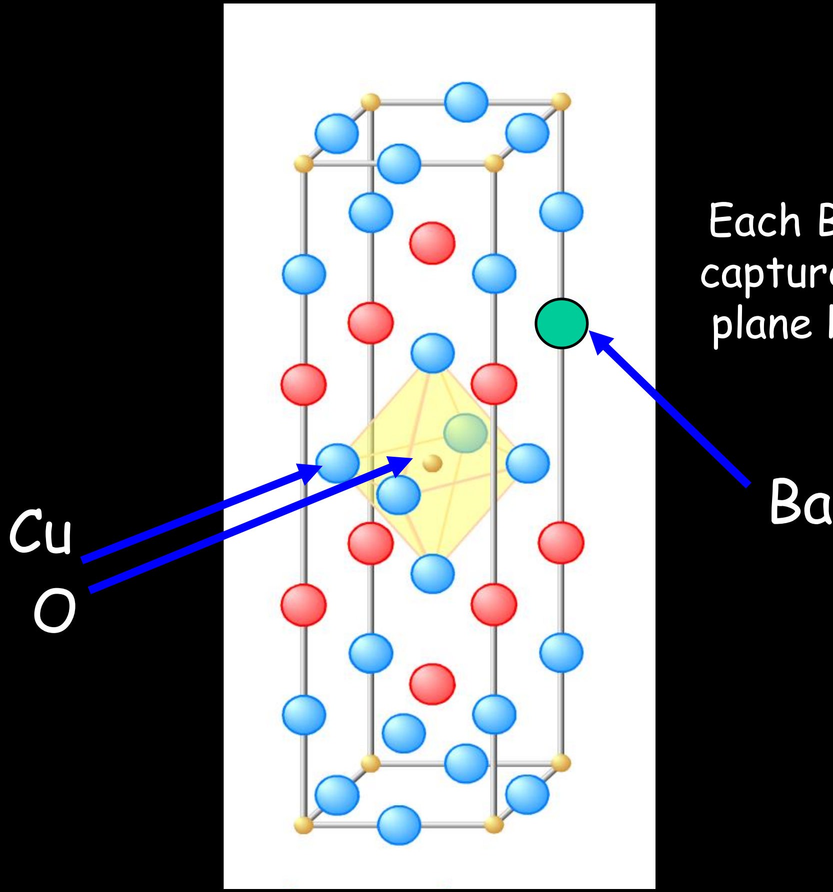


Antiferromagnetic

Mott Insulator

Z. Phys. Rev. **B 64** 189 (1986)

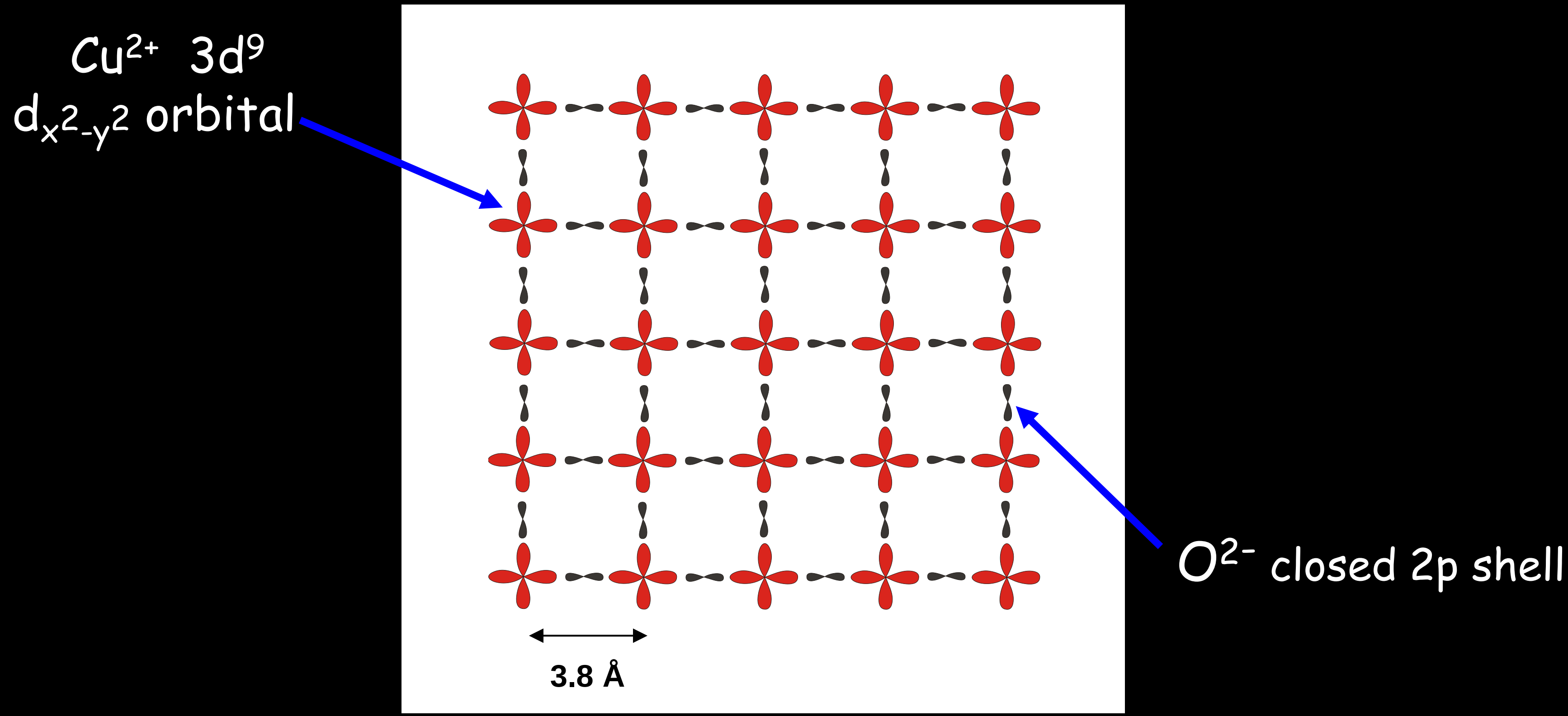
$La_{2-x}Ba_xCuO_4$

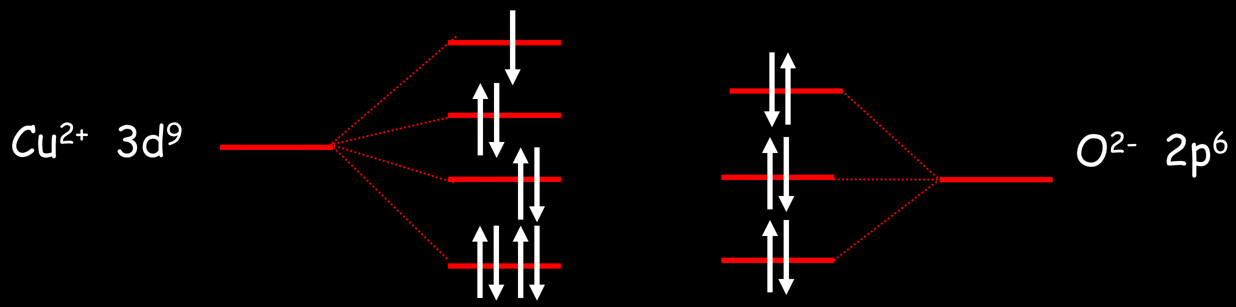


Each Ba atom substituted for Sr captures and electron from CuO_2 plane leaving *p* holes per unit cell

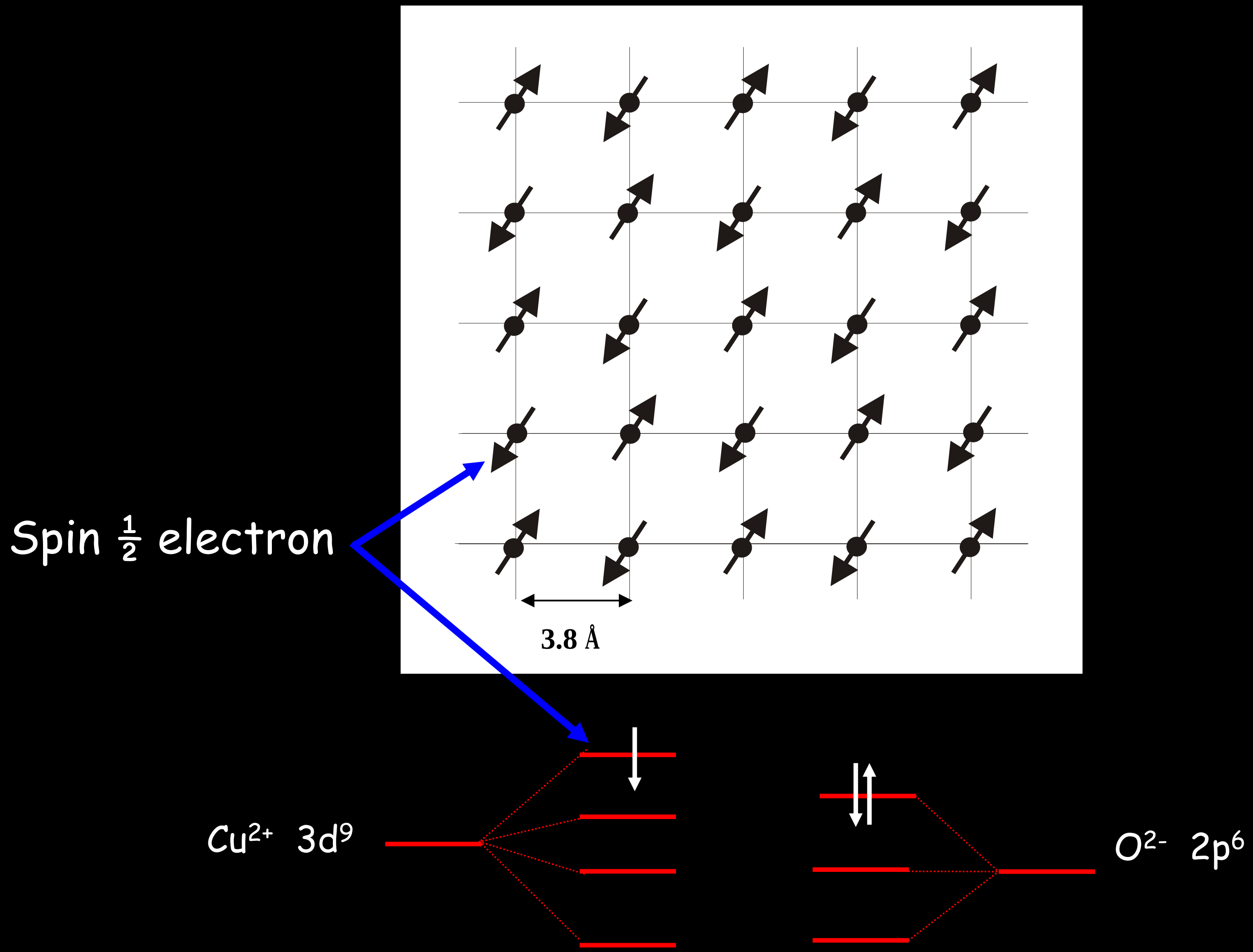
Z. Phys. Rev. **B 64** 189 (1986)

CuO_2: Charge transfer yields a Cu-$3d^9$ $d_{x^2-y^2}$ band

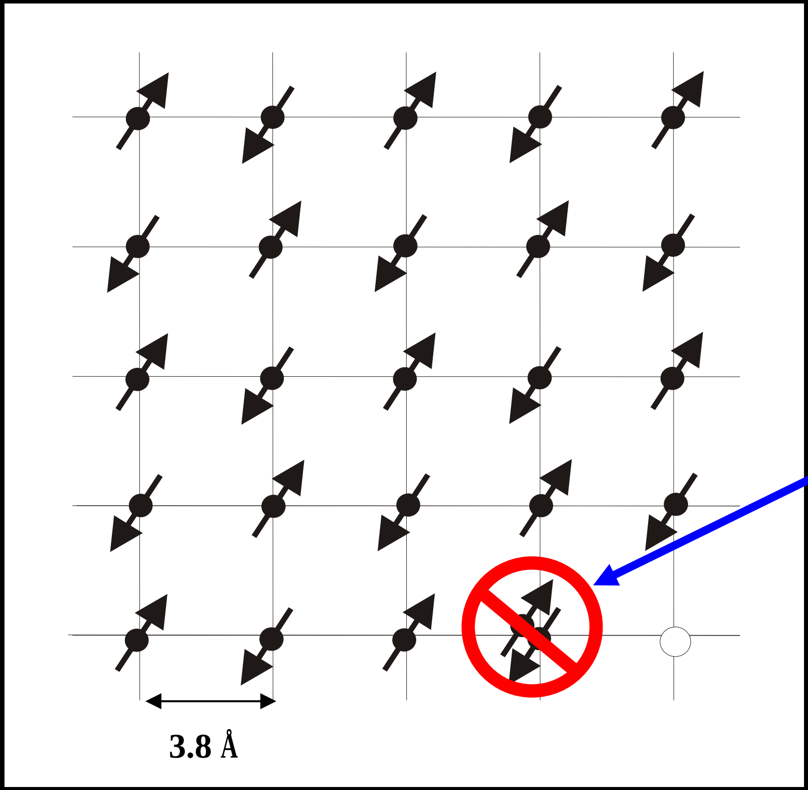




Half filling: Antiferromagnetic Mott Insulator



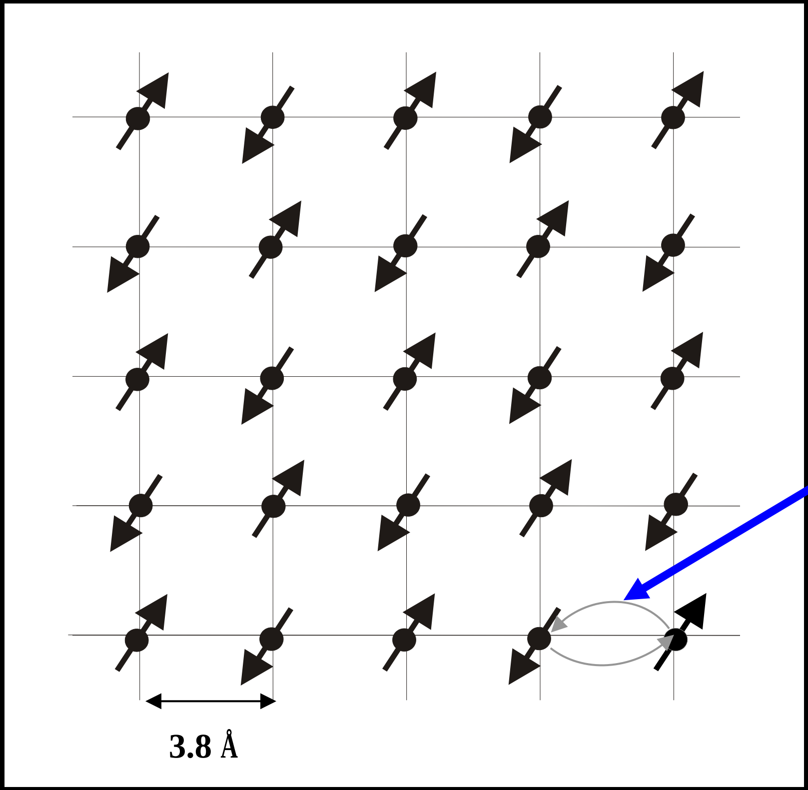
Mott Insulator: Repulsive Coulomb U~3eV



No double occupancy allowed..

N.F. Mott, *Proc. Phys. Soc A62*, 416 (1949)

Antiferromagnetic: Superexchange J~0.14eV

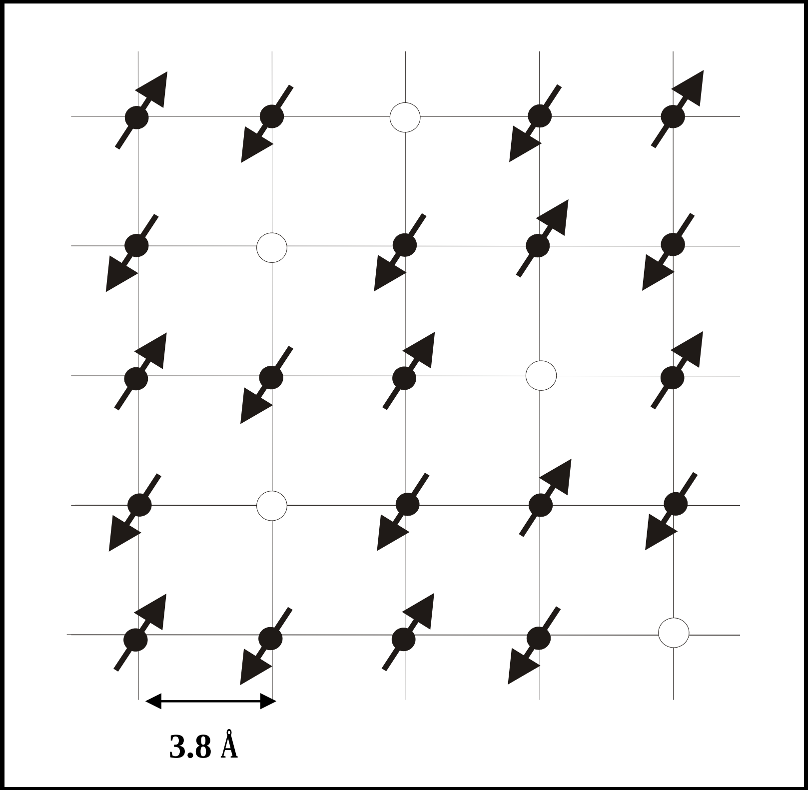


..except as a virtual process.

$$H = \frac{4t^2}{U} \sum_{<i,j>} \vec{S}_i \bullet \vec{S}_j - \frac{1}{4} n_i n_j$$

P. W. Anderson, ***Phys. Rev. 115***, 2 (1959)

Holes introduced $\Longrightarrow$ carriers become mobile

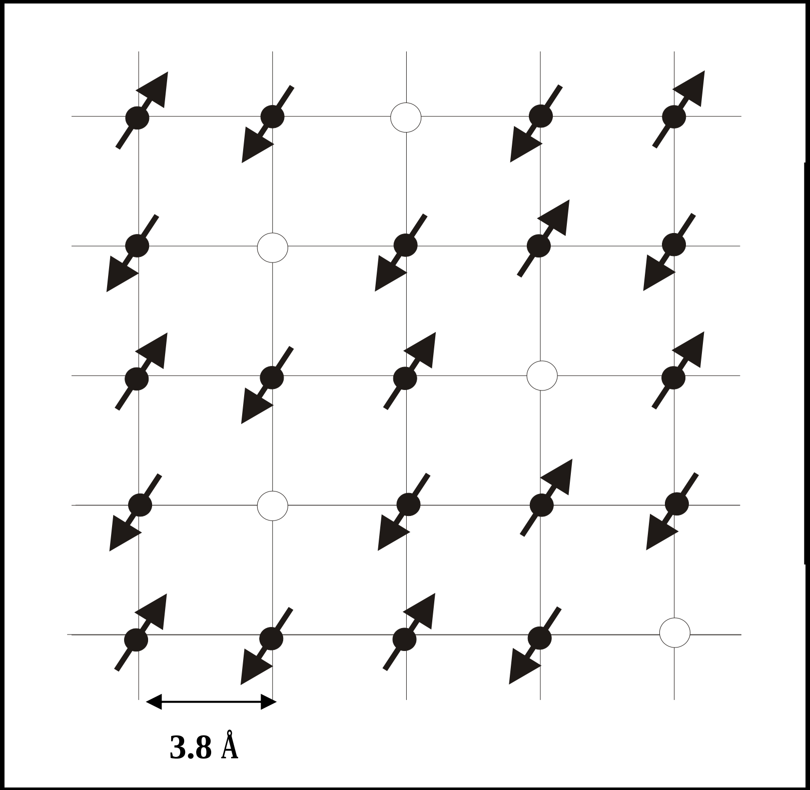


Dopant density p
= number of holes
per CuO_2 plaquette

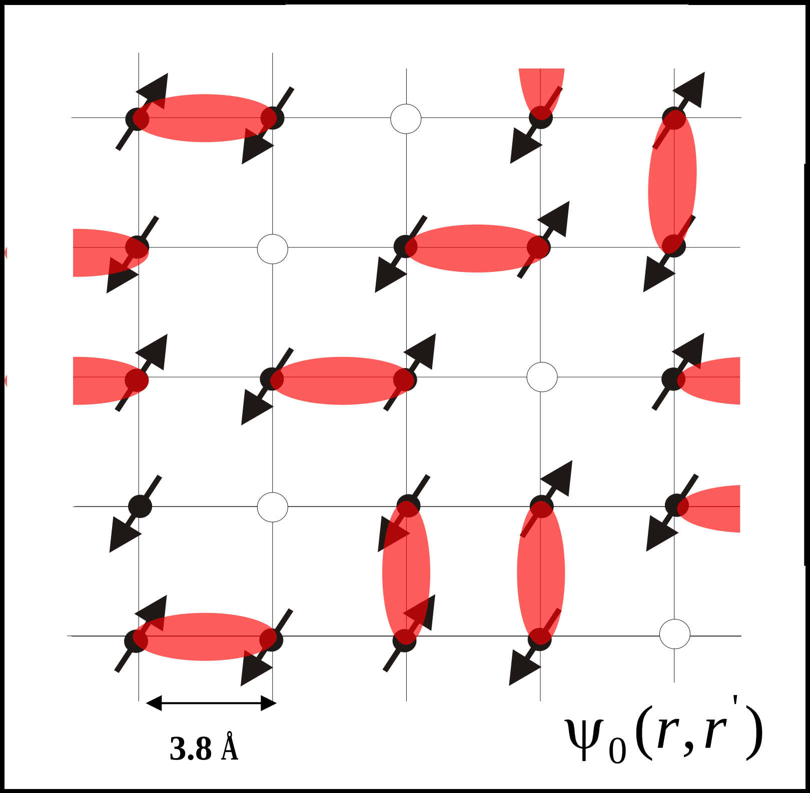
$$H = -t \sum_{<i,j>} (c_{i\sigma}^{\dagger} c_{j\sigma} + h.c.) \quad + \quad U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

J. Hubbard, ***Proc. Roy. Soc A276***, 238 (1963)

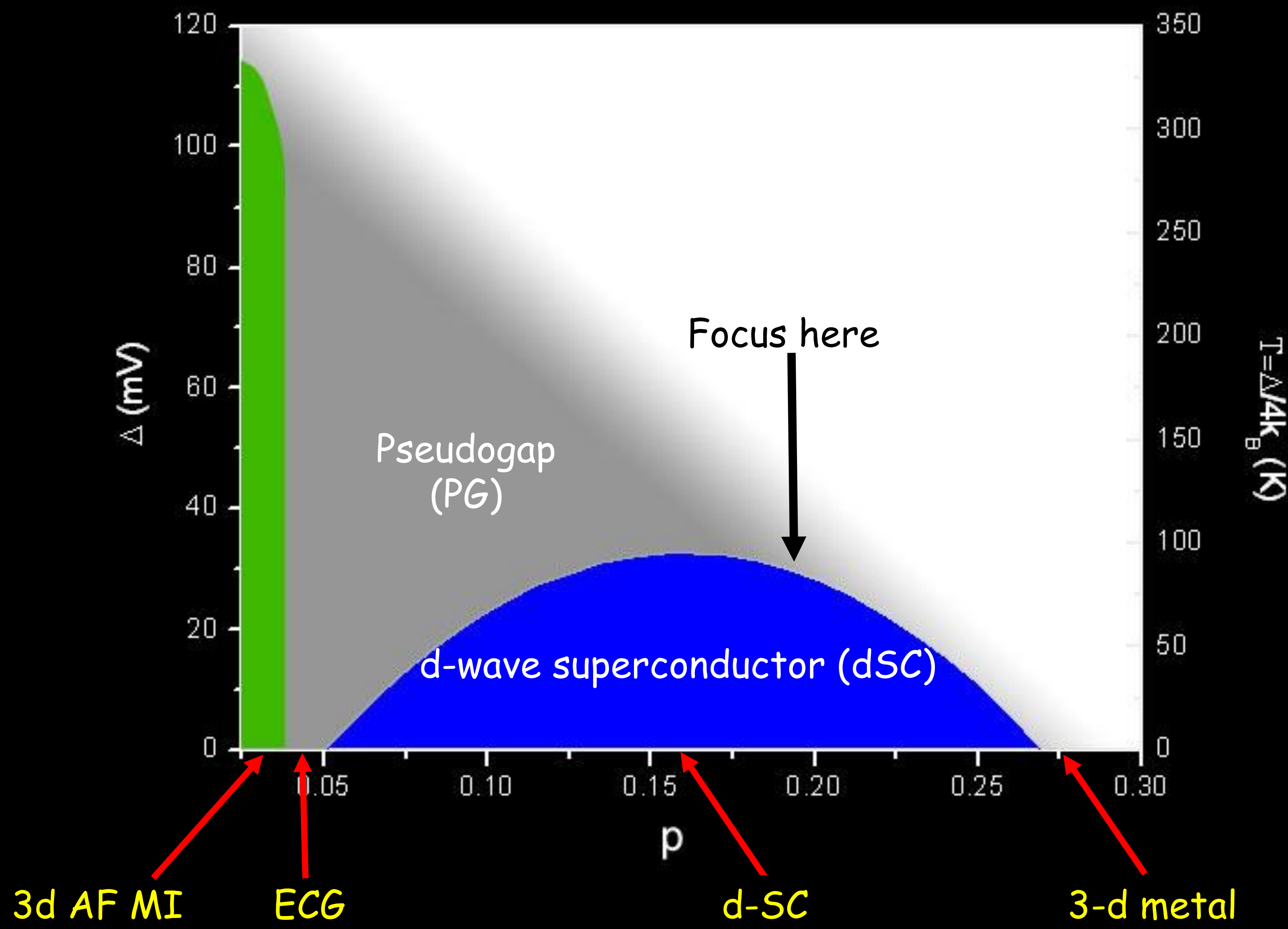
How could this state become superconducting?



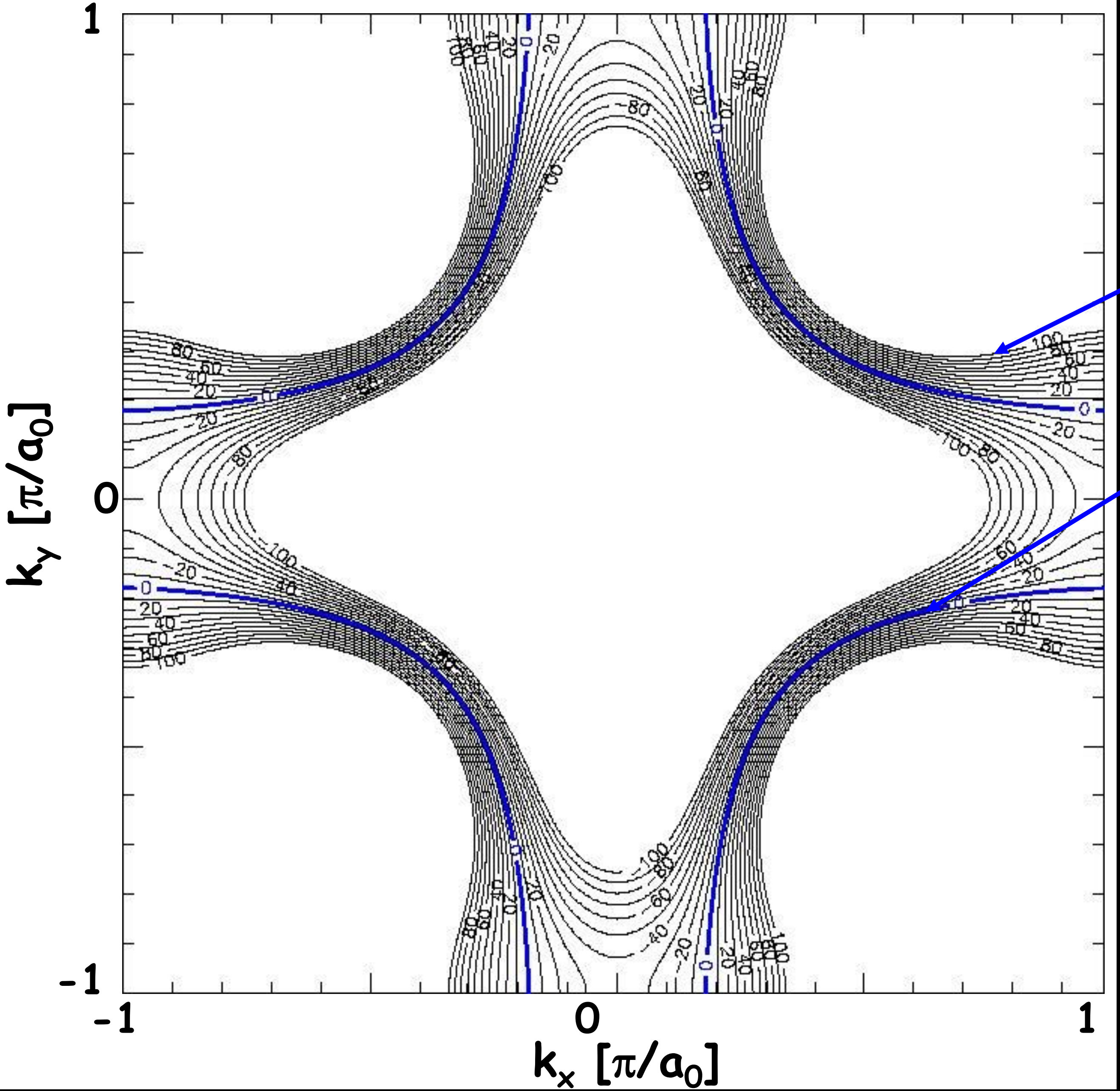
How could this state become superconducting?



Schematic Phase Diagram of Hole-doped Cuprates



Normal State Band Structure

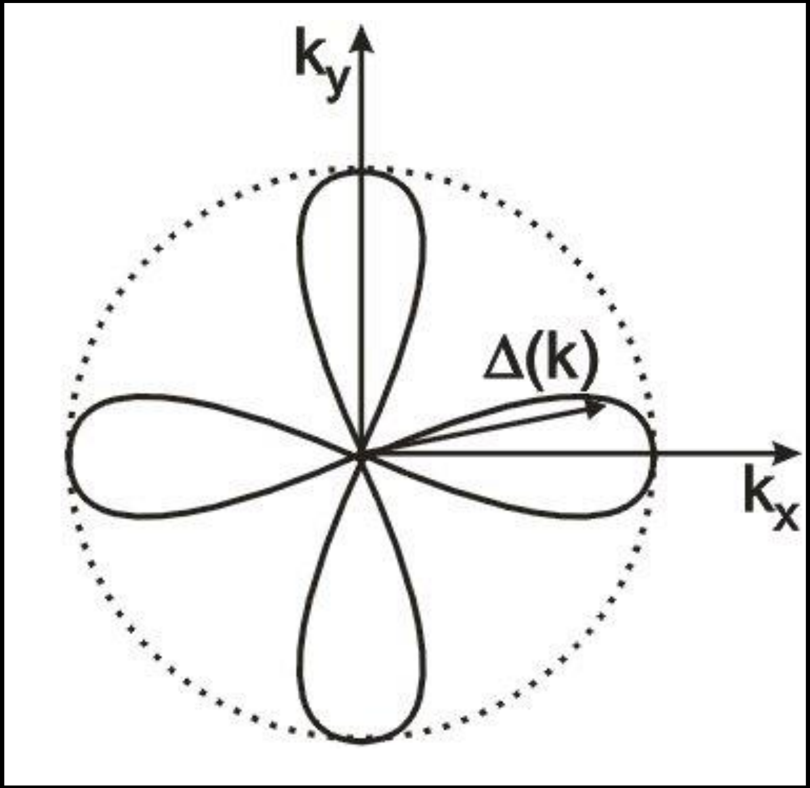


CEC (E): The location in k-space of states with energy E

Fermi Surface CCE(0)

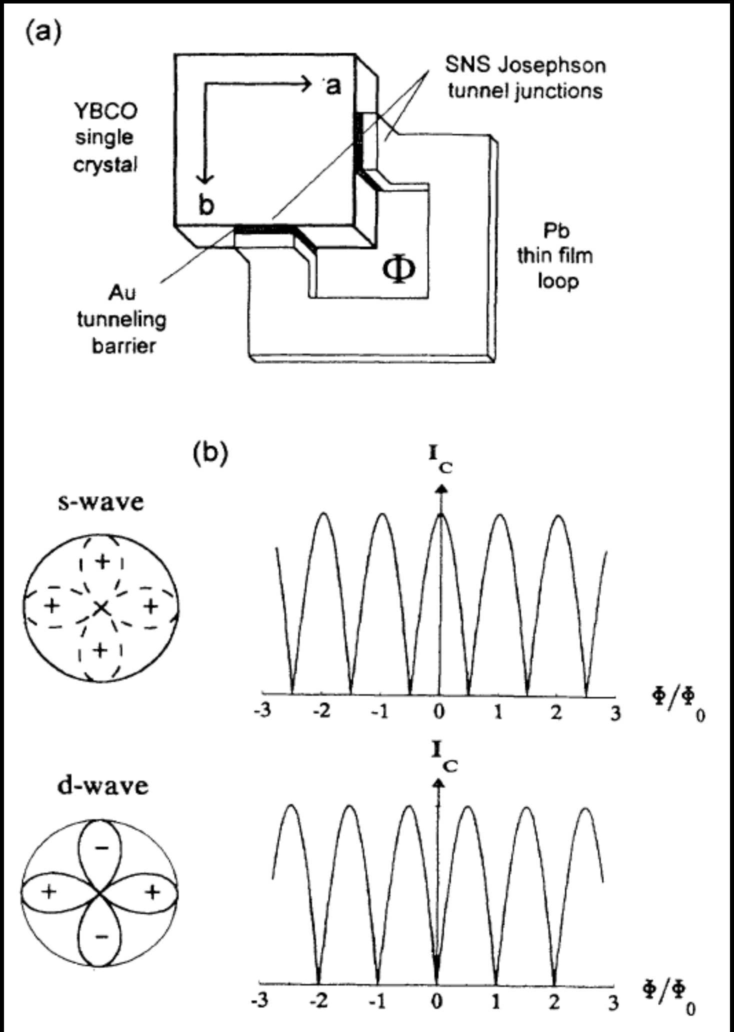
Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

The SC energy gap, $\Delta(\boldsymbol{k})$ has four nodes.

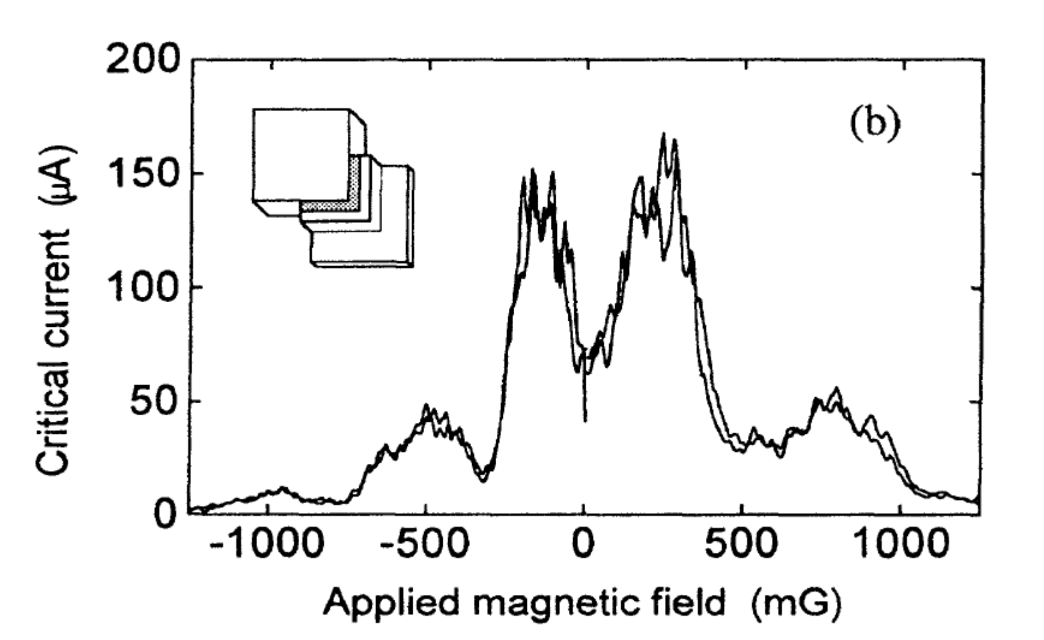


Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

DC SQUID



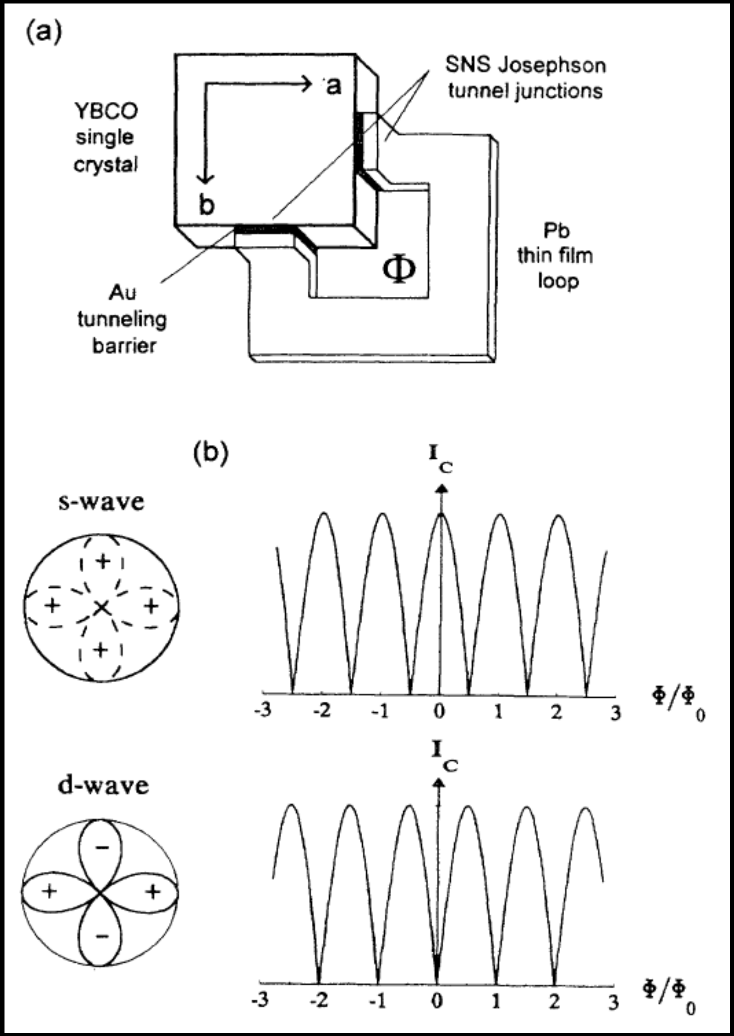
$$I_c(\Phi,\gamma) = J_0 A \left| \frac{\sqrt{\sin^2(\gamma\pi\Phi/\Phi_0) + [\cos(\pi\Phi/\Phi_0) - \cos(\gamma\pi\Phi/\Phi_0)]^2}}{\pi(\Phi/\Phi_0)} \right|$$



D. A. Wollman *et al.*, PRL 71, 2134 (1993)
D. A. Wollman *et al.*, PRL 74, 797 (1995)

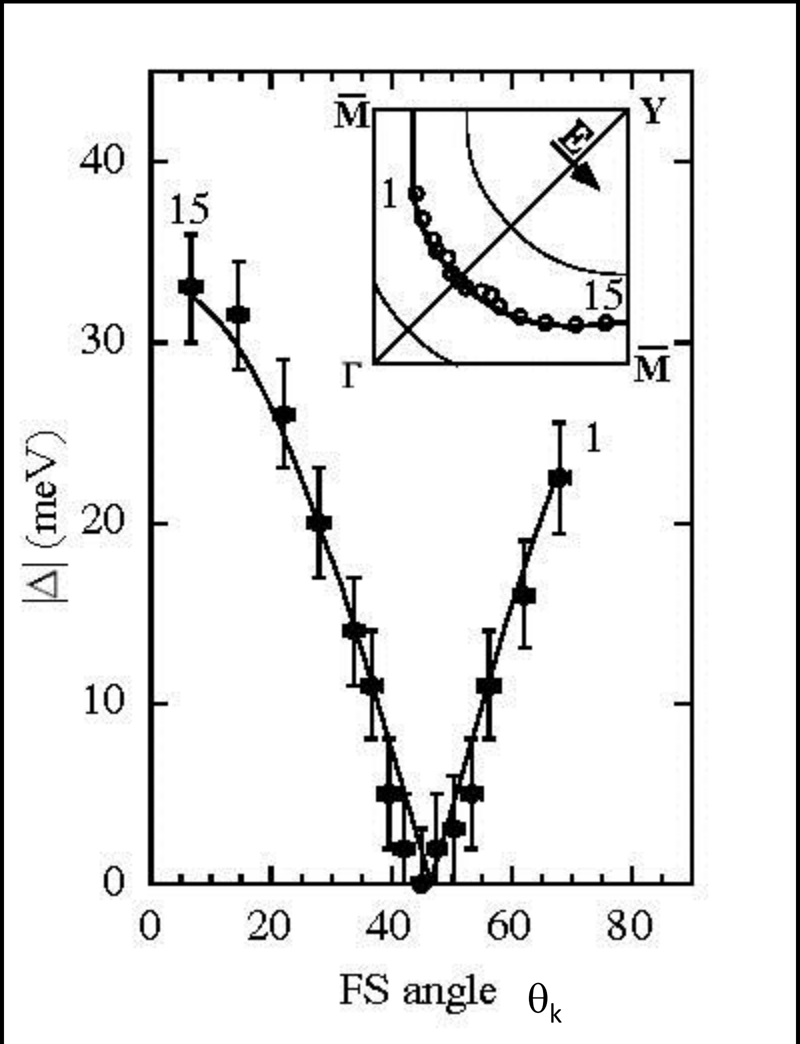
Superconducting State : $d_{x^2-y^2}$ Pairing Symmetry

DC SQUID



D. A. Wollman *et al.*, PRL 71, 2134 (1993)
D. A. Wollman *et al.*, PRL 74, 797 (1995)

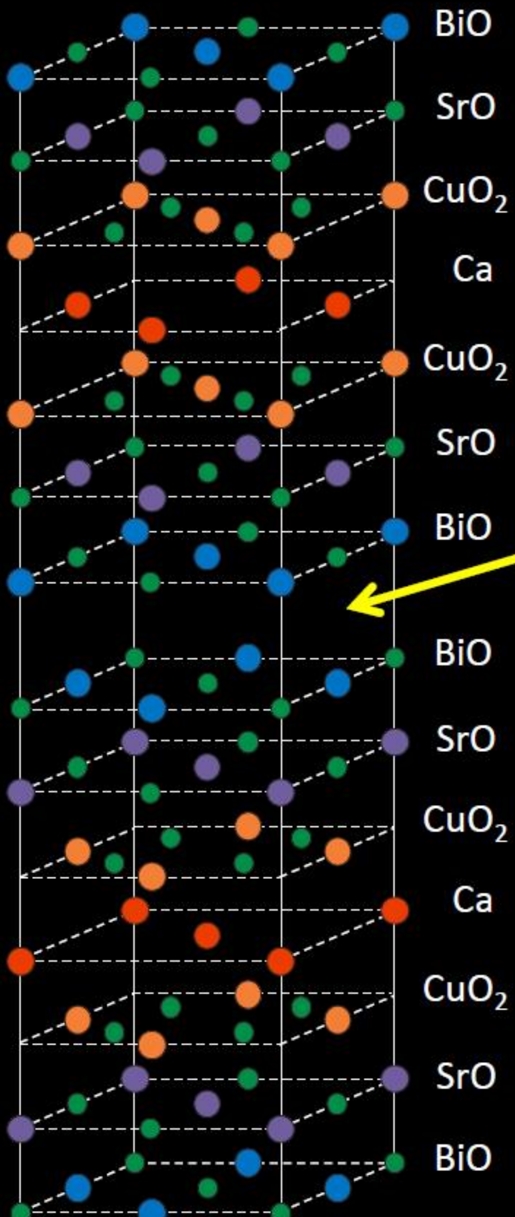
ARPES

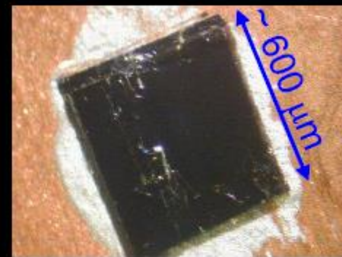


H. Ding *et al.*, PRB 54, 9678 (1996)
J. Mesot *et al.*, PRL 83, 840 (1999)

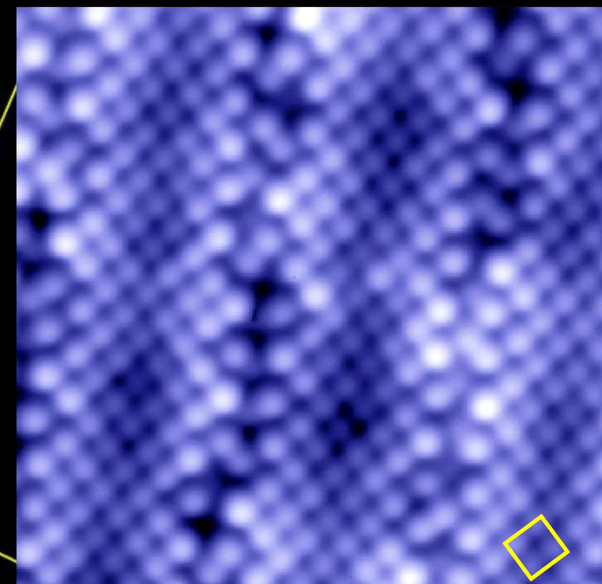
$d_{x^2-y^2}$ Pairing Symmetry by STM

$Bi_2Sr_2CaCu_2O_{8+d}$

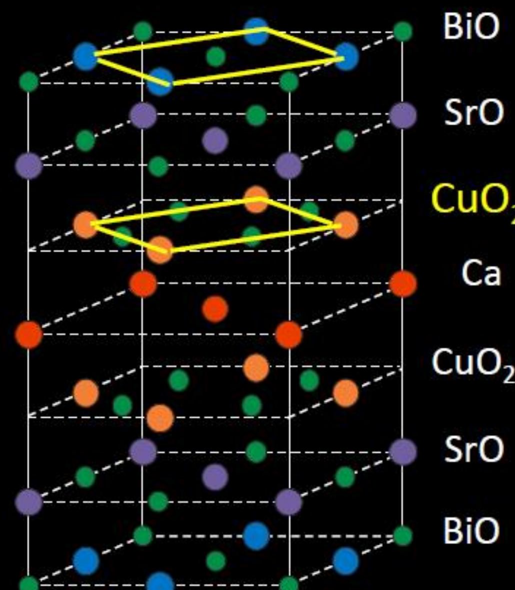




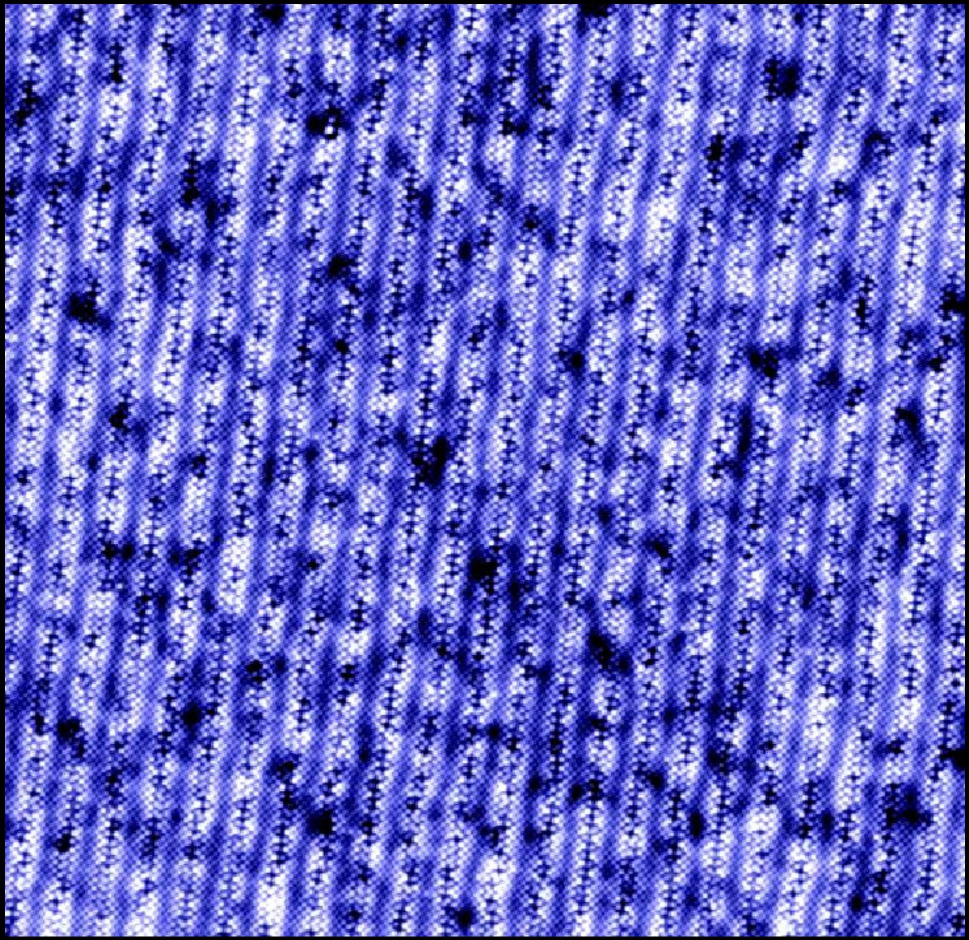
Cleave Here
Reveals
BiO Surface



BiO
plaquette



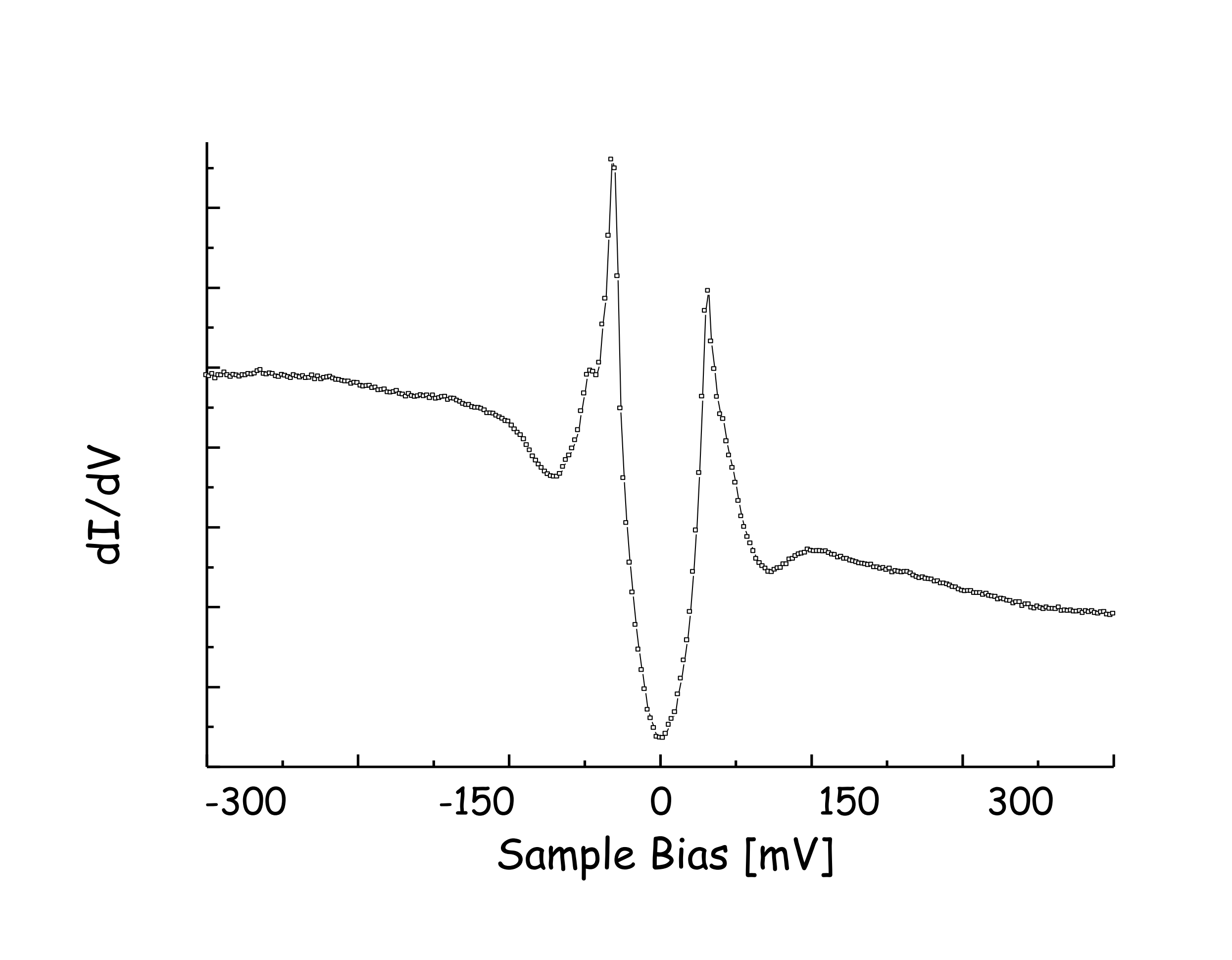
$Bi_2Sr_2CaCu_2O_{8+d}$



56nm

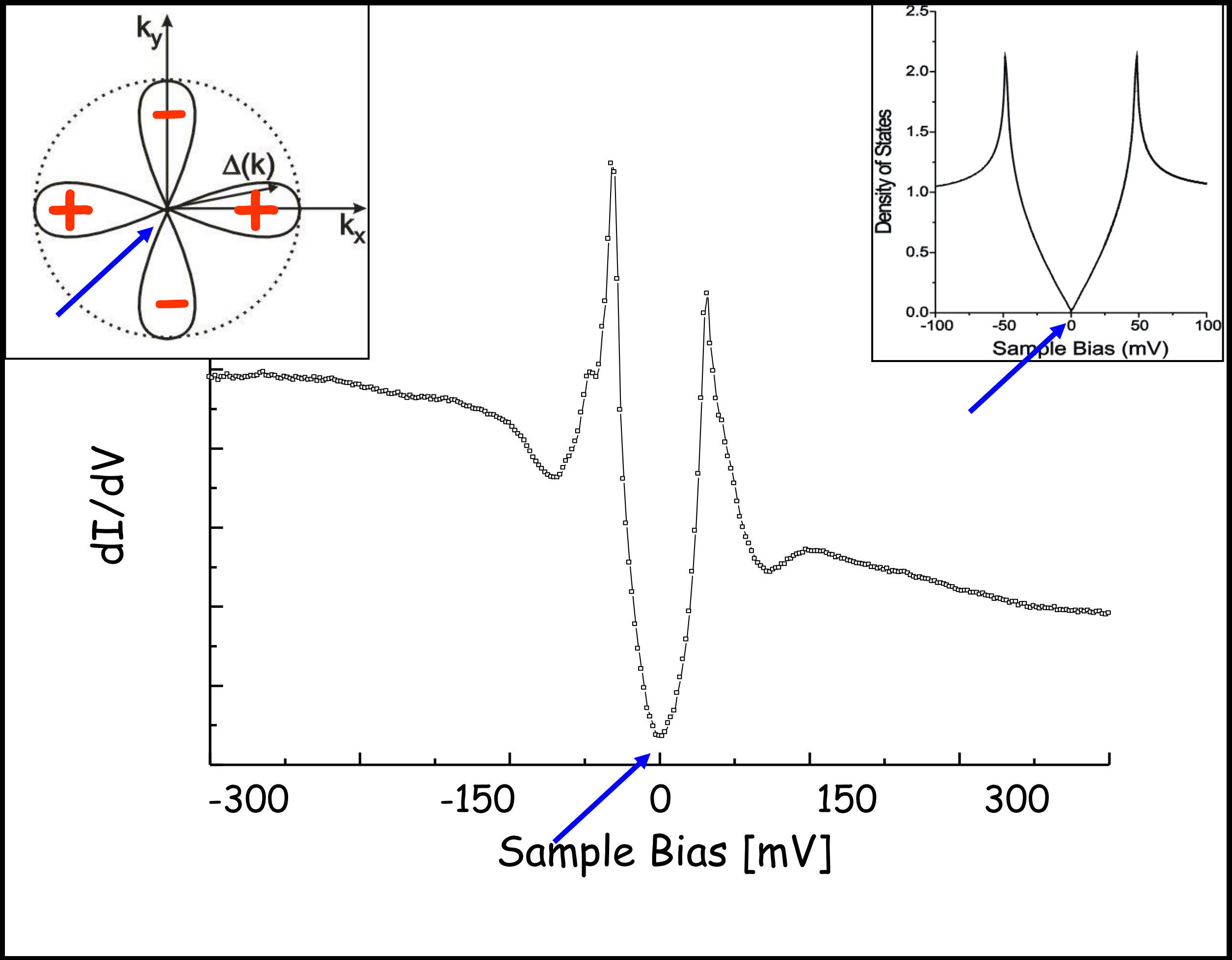
$d_{x^2-y^2}$ Pairing Symmetry by STM

$Bi_2Sr_2CaCu_2O_{8+d}$ dI/dV Spectrum



$d_{x^2-y^2}$ Pairing Symmetry by STM

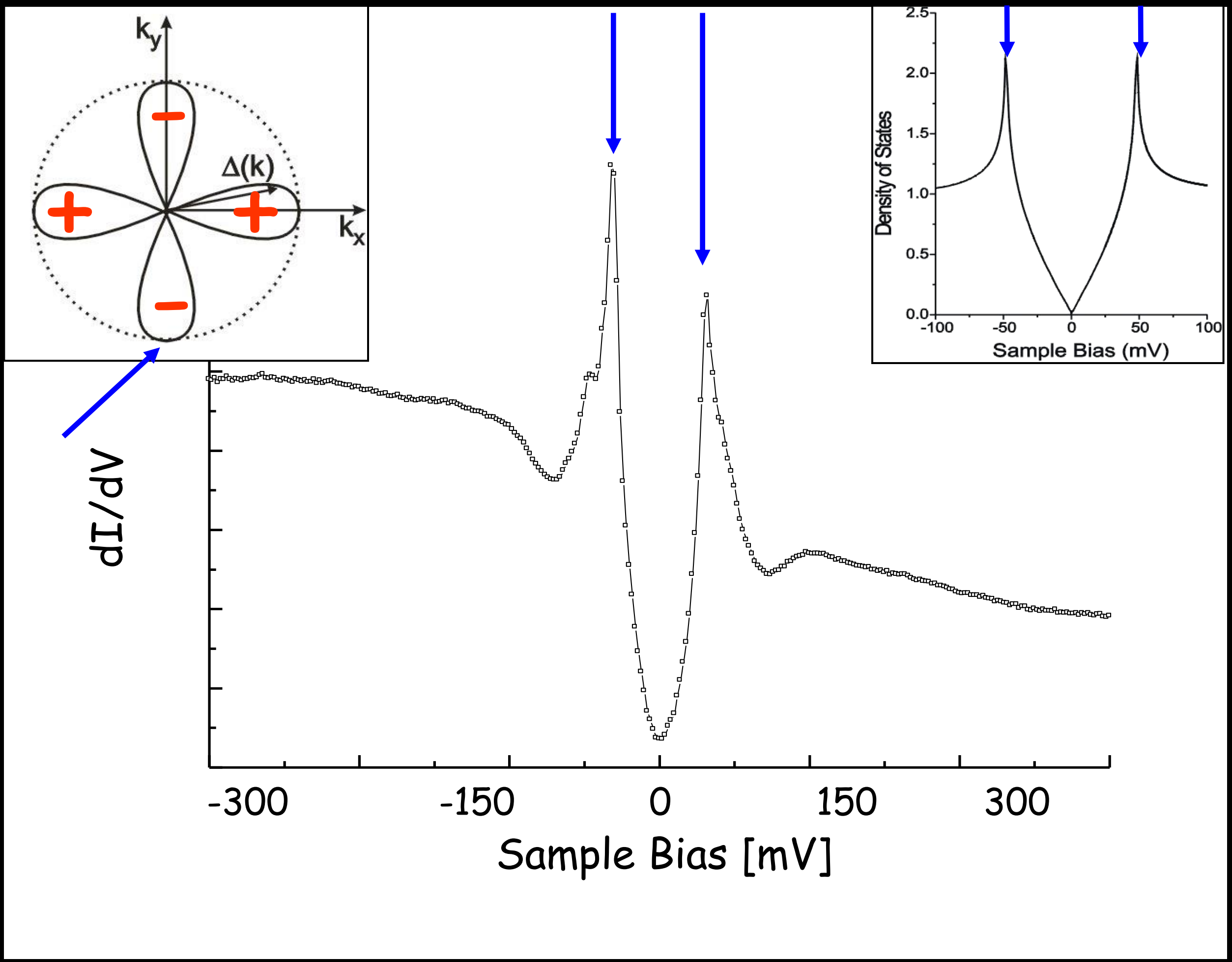
$Bi_2Sr_2CaCu_2O_{8+d}$ dI/dV Spectrum



Node E=0

$d_{x^2-y^2}$ Pairing Symmetry by STM

$Bi_2Sr_2CaCu_2O_{8+d}$ dI/dV Spectrum

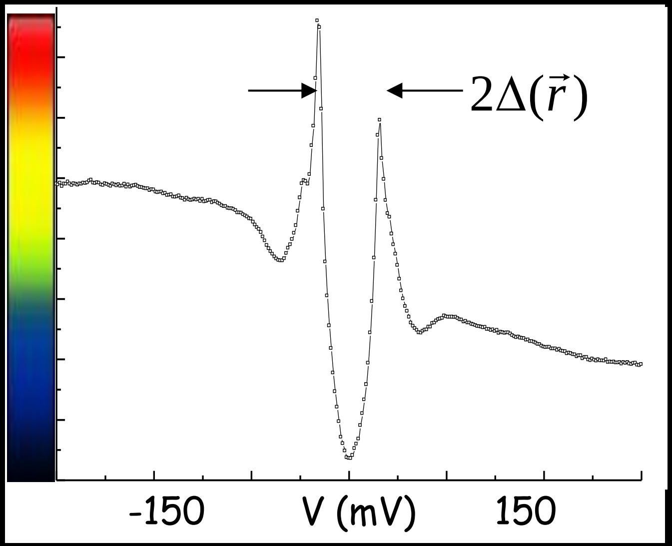


Anti-node E=Δ

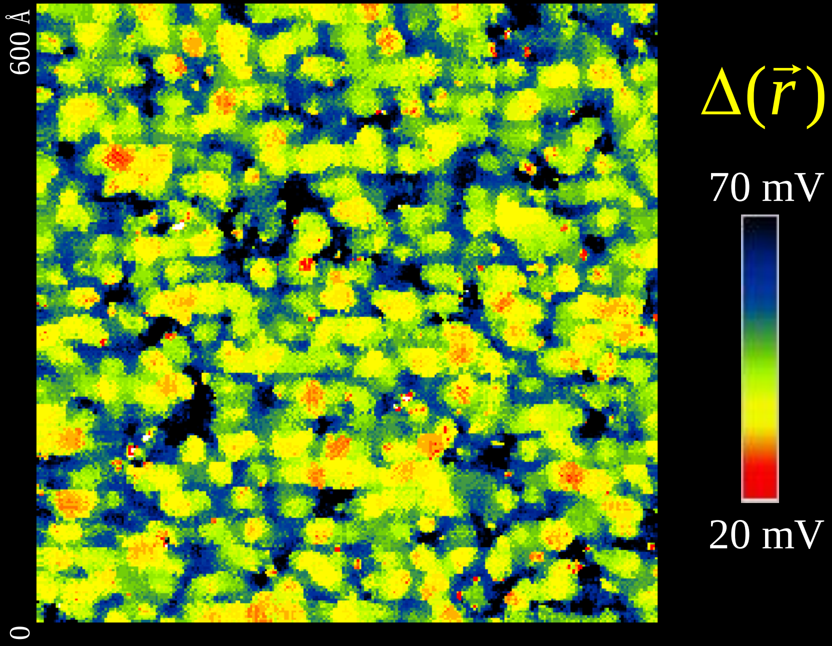
SC Gap Mapping

Intense nanoscale disorder in Δ

$\Delta(\vec{r}\,)$

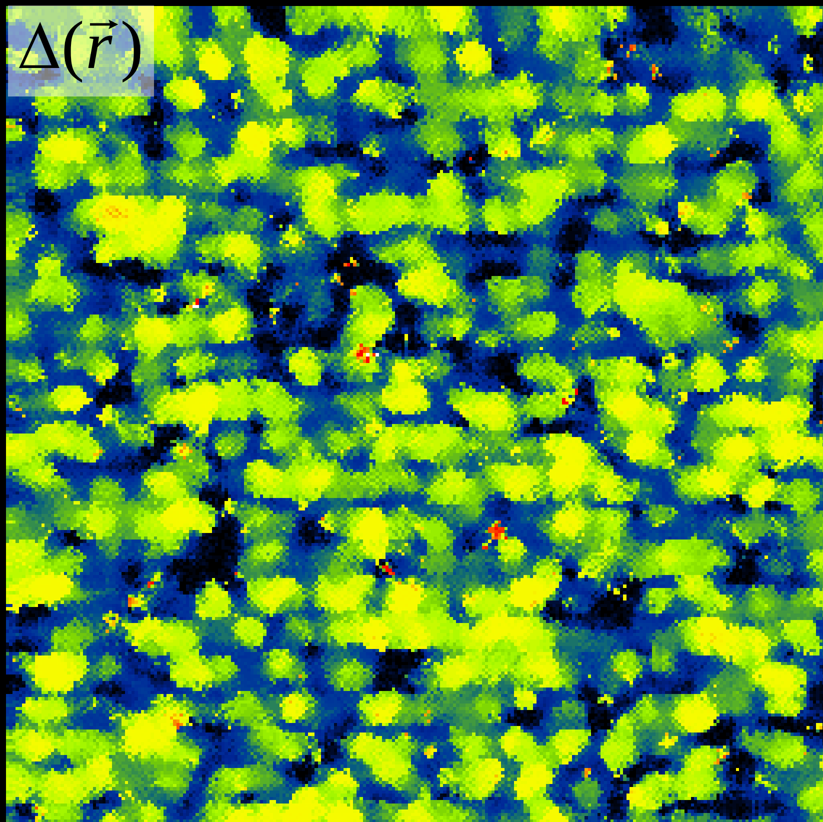


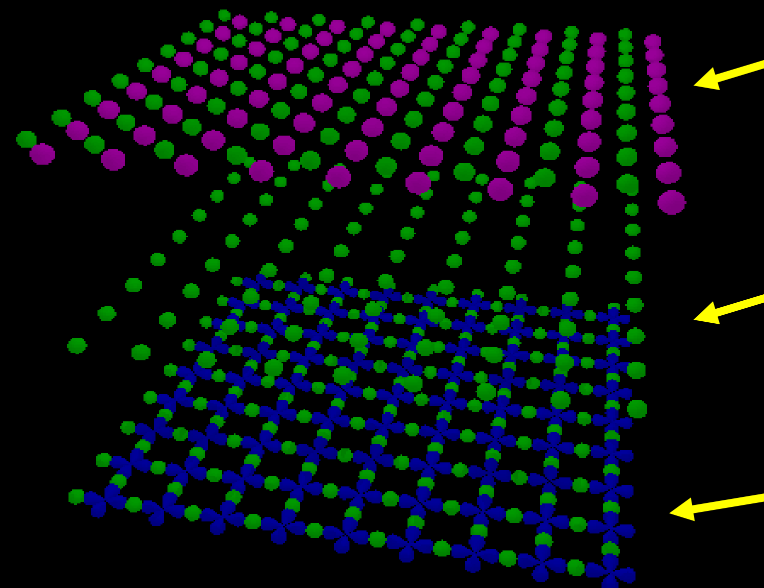
Point dI/dV $\equiv g(\vec{r}, E)$ Spectrum



Nature 413, 282 (2001), Nature 415, 412 (2002)

What 'foreign' atoms always exists in $Bi_2Sr_2CaCu_2O_{8+\delta}$? Dopant Atoms!

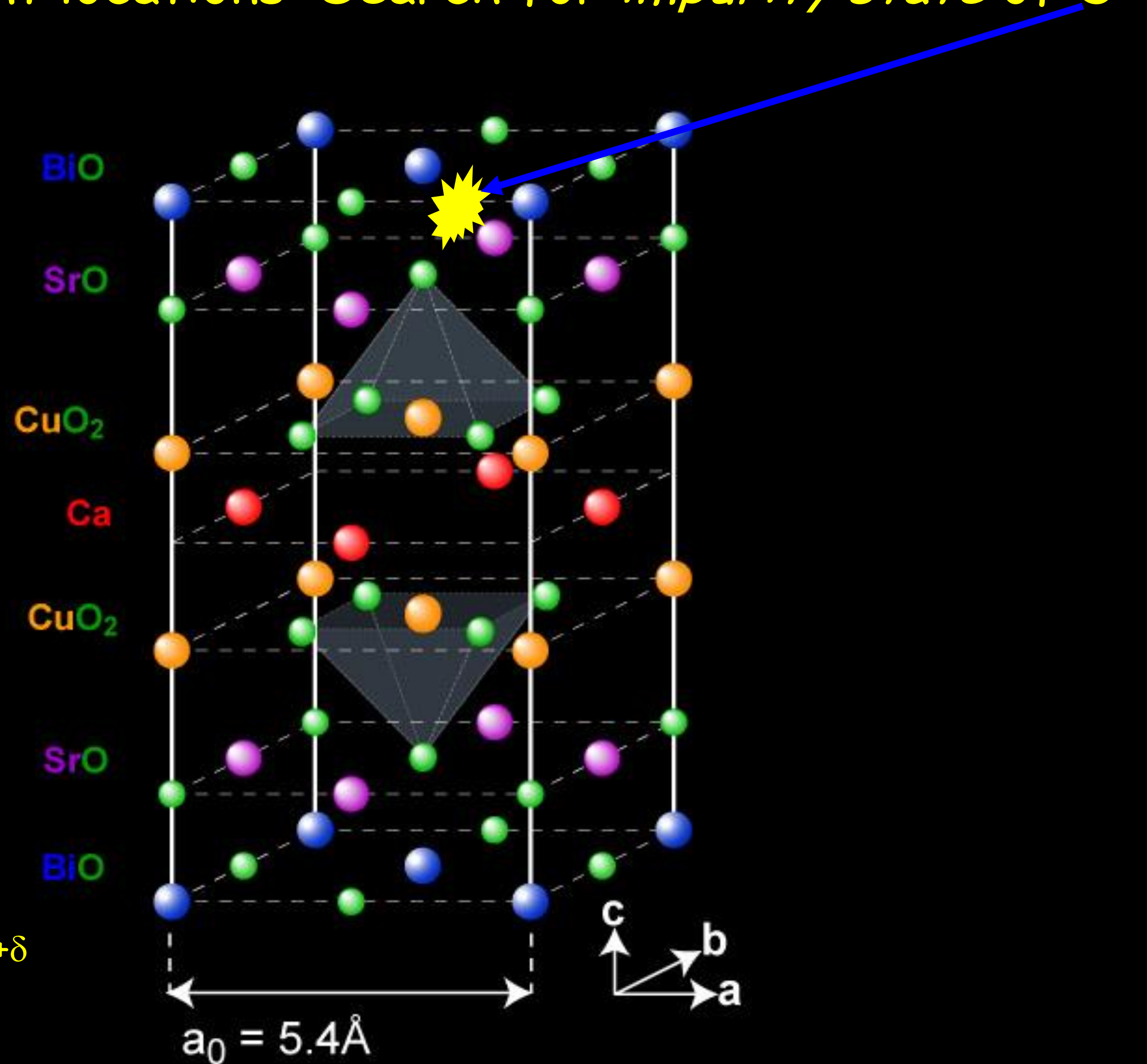




~600 Å

Densities 4% -> 12%.

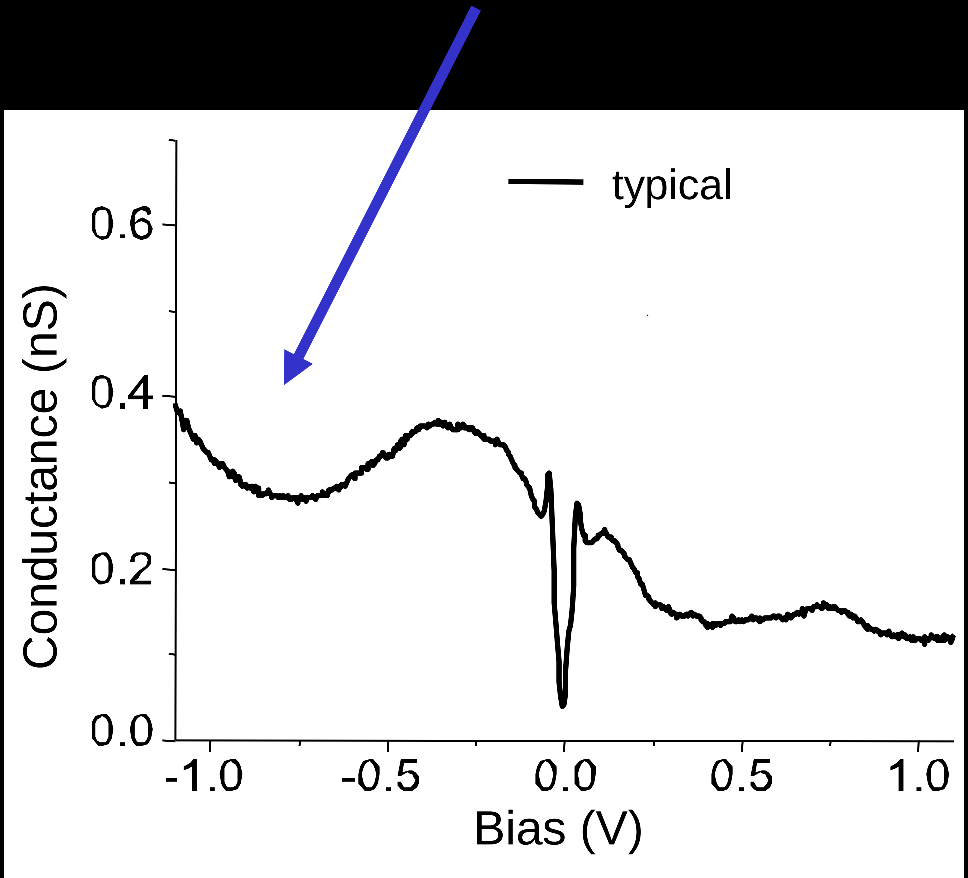
Identify dopant locations: Search for *impurity state* of O^{-2}



$Bi_2Sr_2CaCu_2O_{8+\delta}$

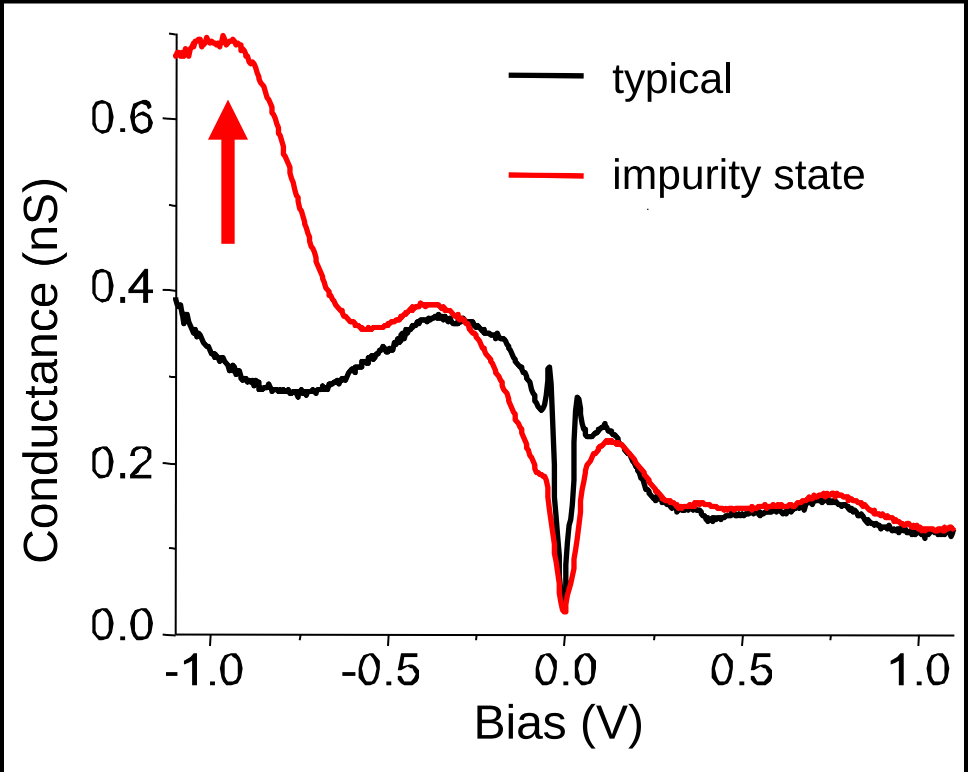
½ Unit Cell

Identify dopant locations: Search for *impurity state* of O^{-2}
=> additional filled states below E_f

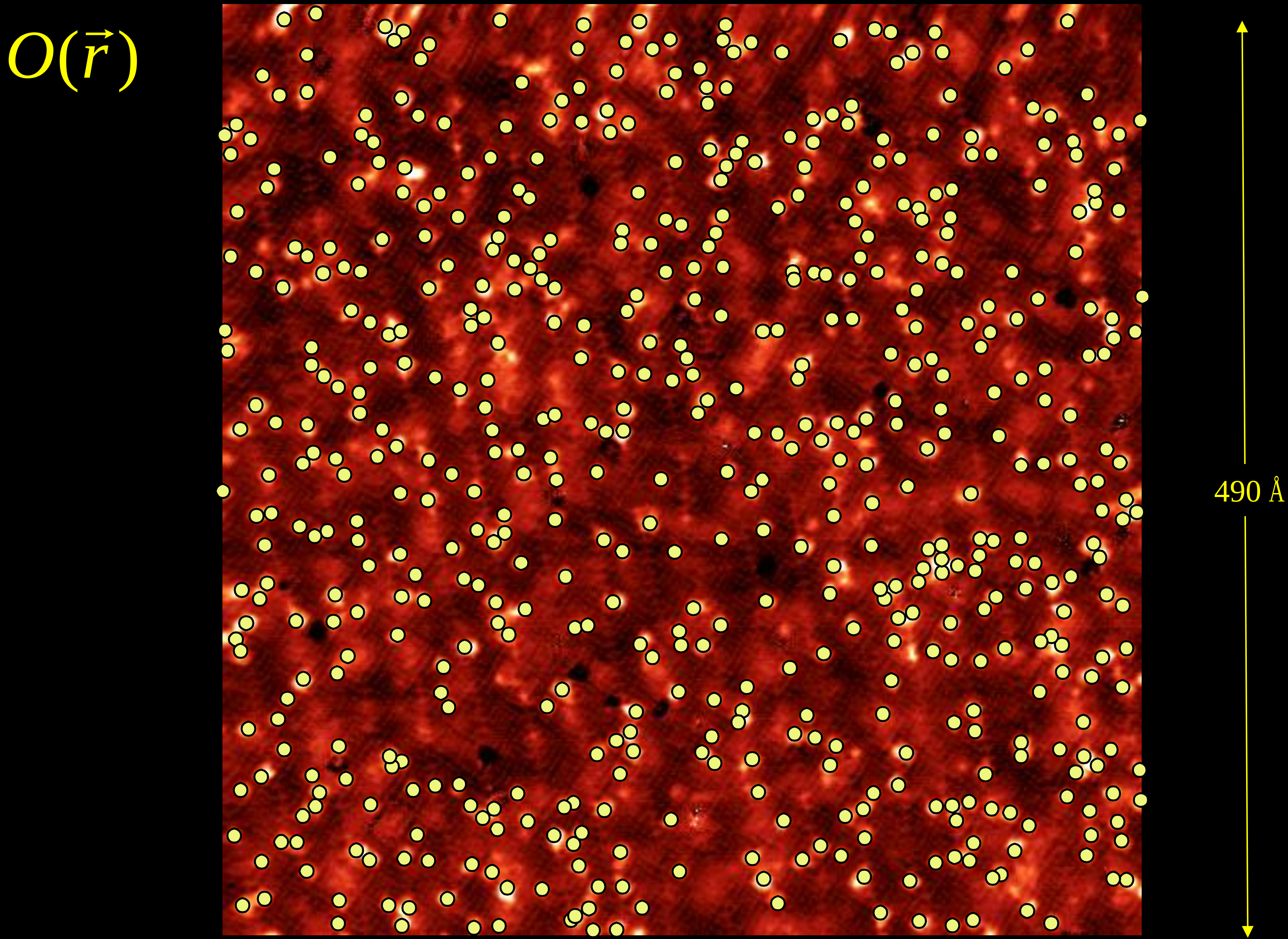


Discovered an *impurity state* below E_f

-0.96V peak

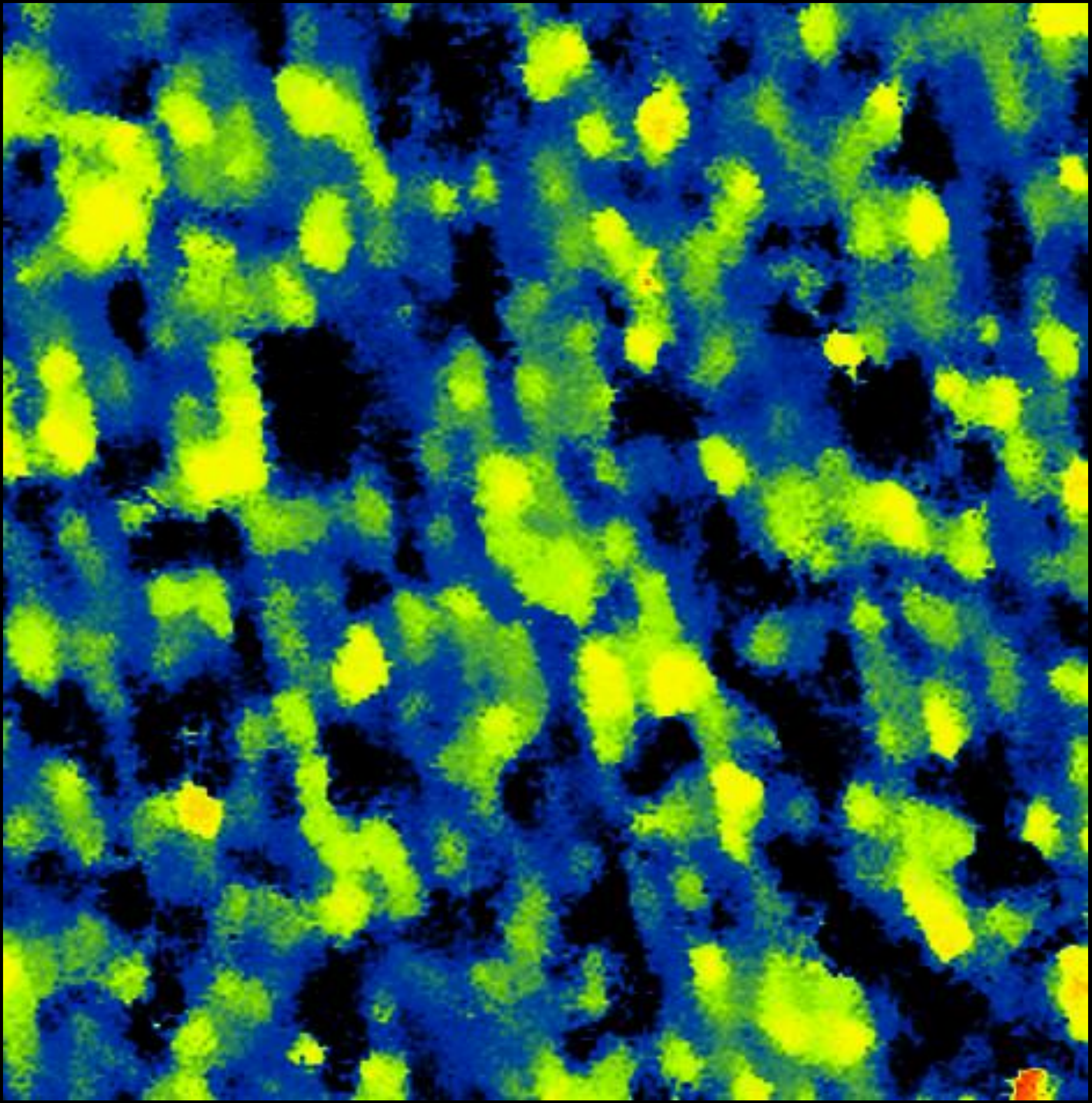


***Science* 309**, 1048 (2005)



Science *309*, 1048 (2005)

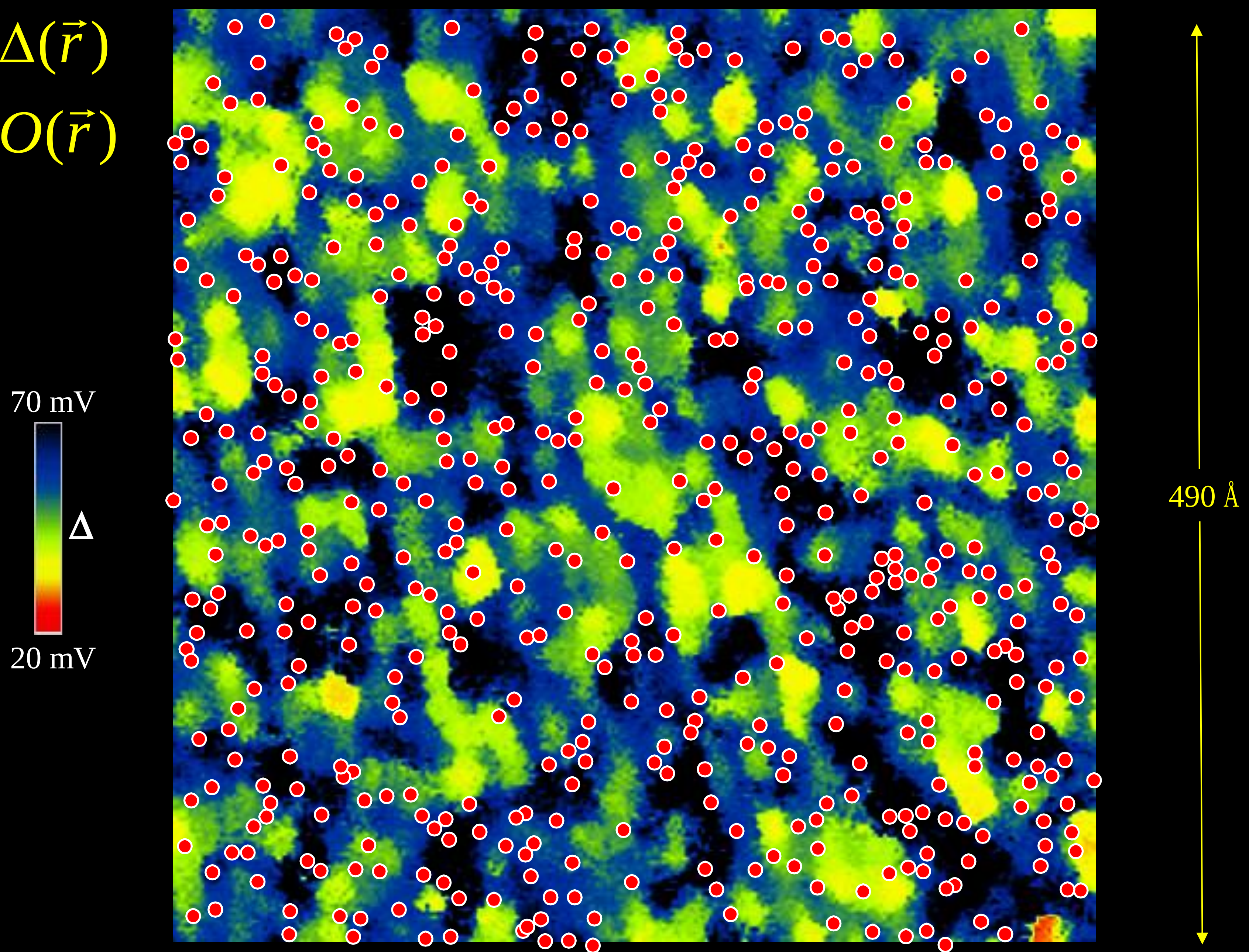
$\Delta(\vec{r})$



But do they cause the gap disorder?

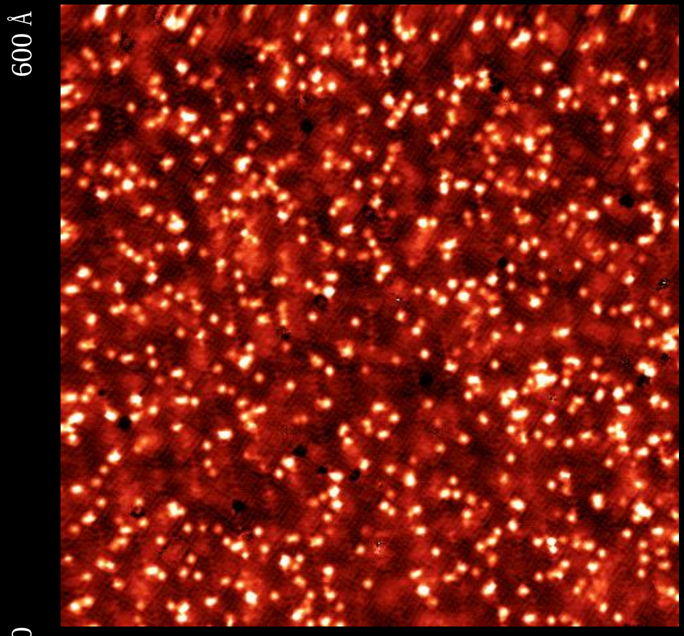
$\Delta(\vec{r})$

$O(\vec{r})$

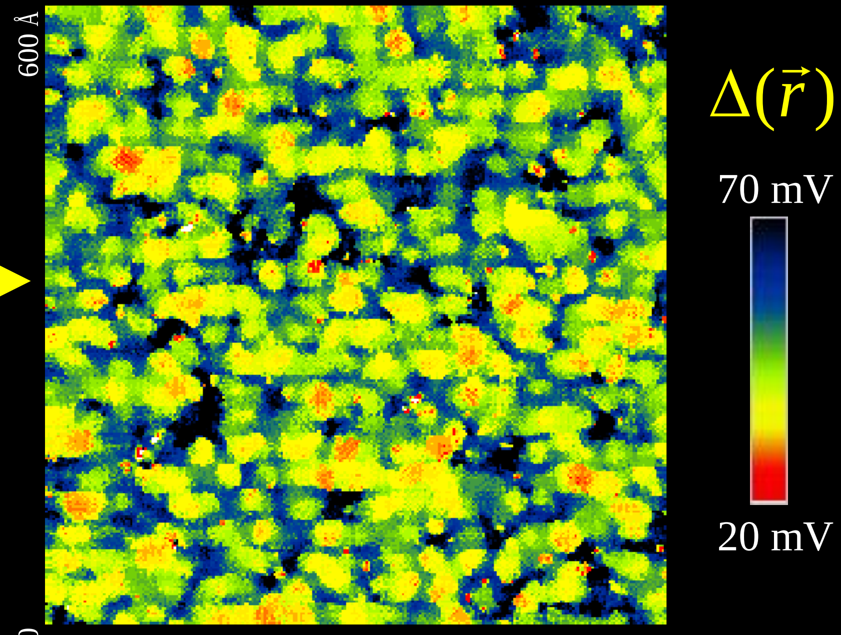


SC gap is increased where dopant oxygen atoms are located.

Dopant atoms



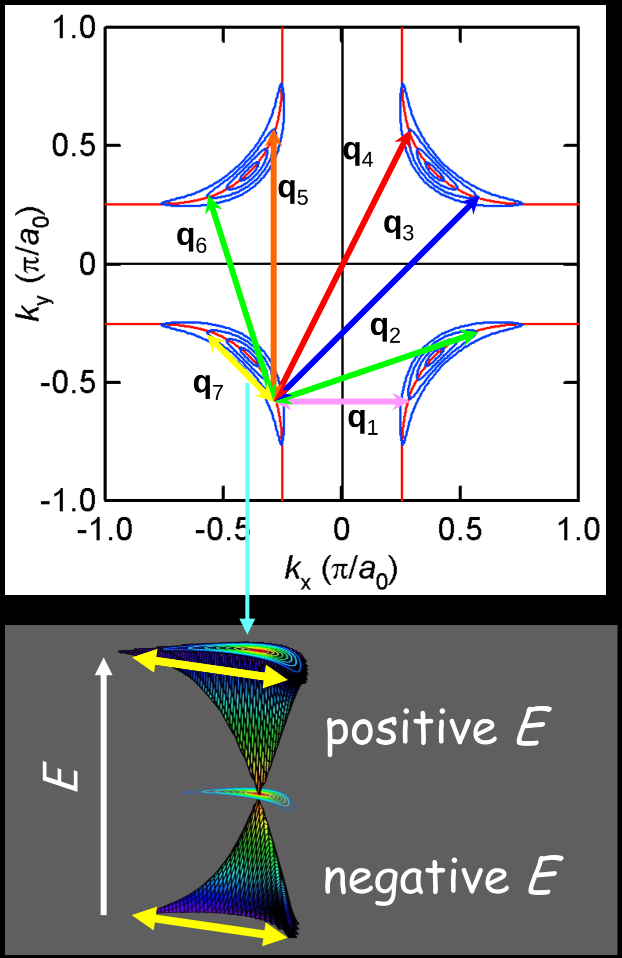
O^{2-} sites



Science 309, 1048 (2005)

$d_{x^2-y^2}$ Gap Function by QPI

Quasi-particle interference ~ "Octet" model



Quasi-particles that interfere are not excited from Fermi liquid, but from superconducting state.

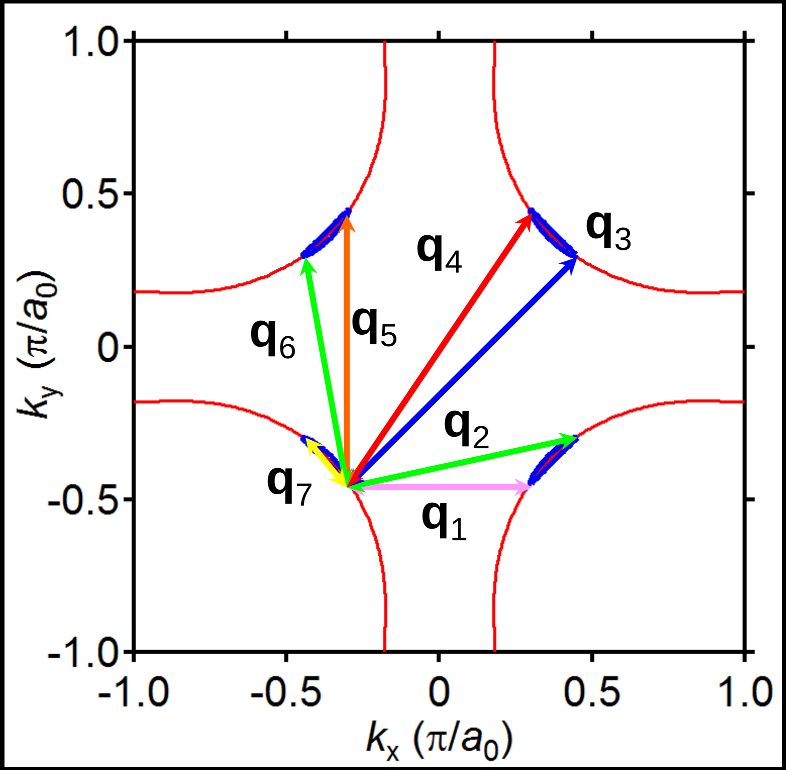
Bogoliubov quasi-particles

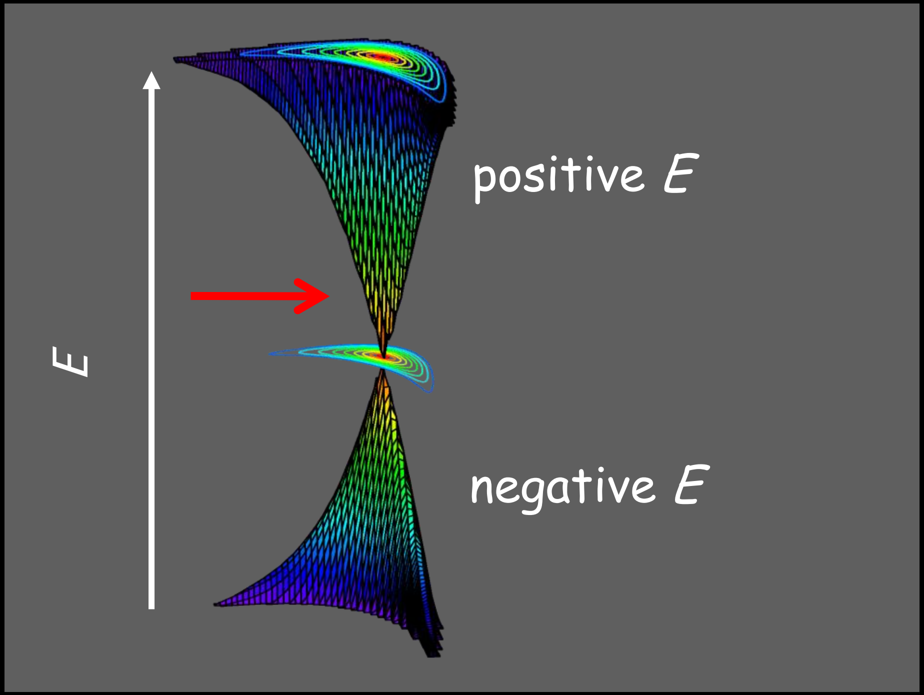
$$E(\mathbf{k}) = \sqrt{\varepsilon(\mathbf{k})^2 + \Delta(\mathbf{k})^2}$$

$$DOS \propto 1/\nabla E(\mathbf{k})$$

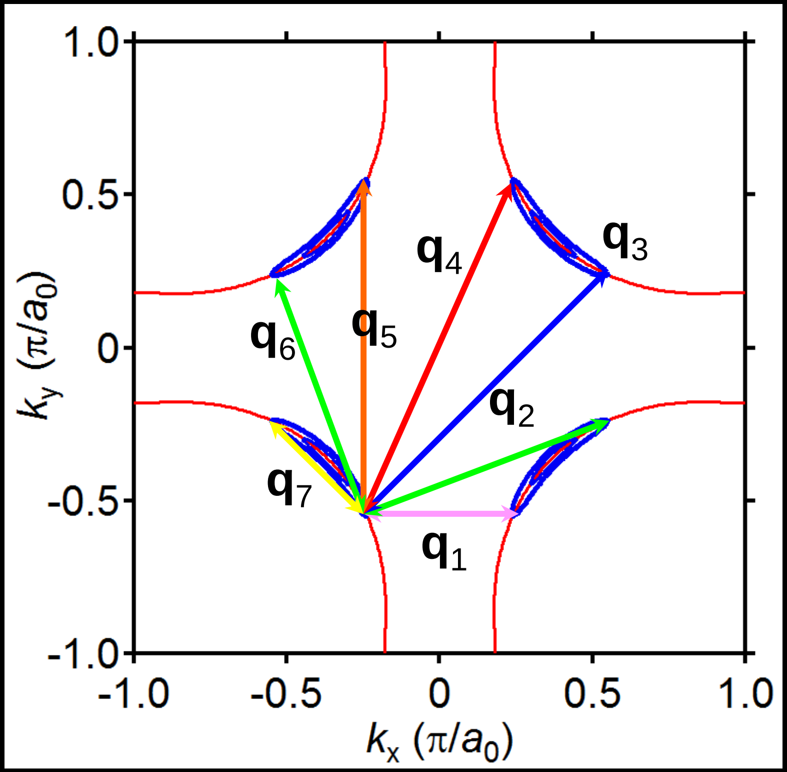
J. Hoffman *et al.*, Science **297**, 1148 (2002).
K. McElroy, *et al.*, Nature **422**, 592 (2003).

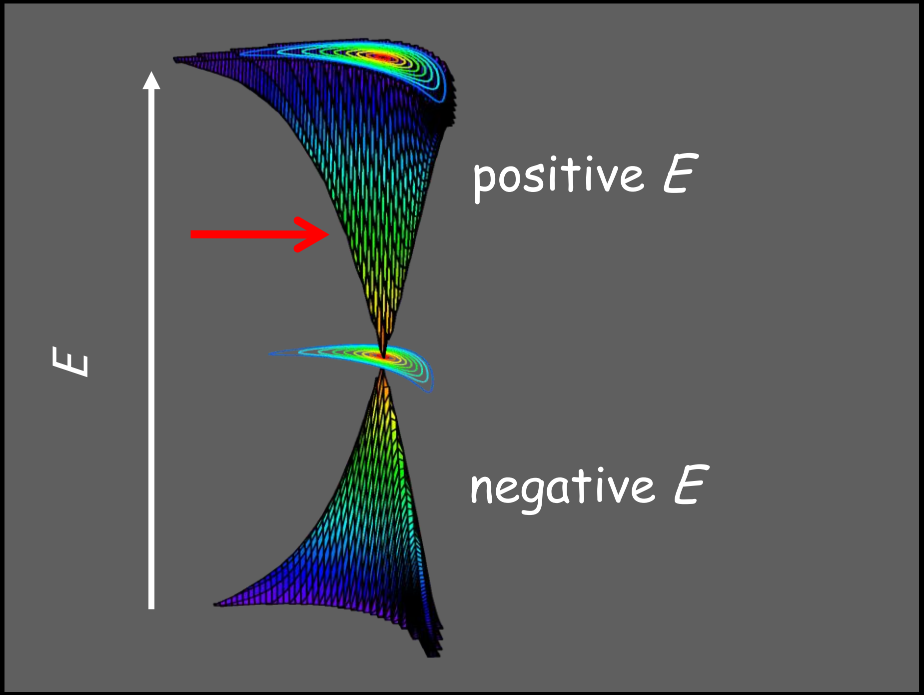
Quasi-particle interference ~ “Octet” model



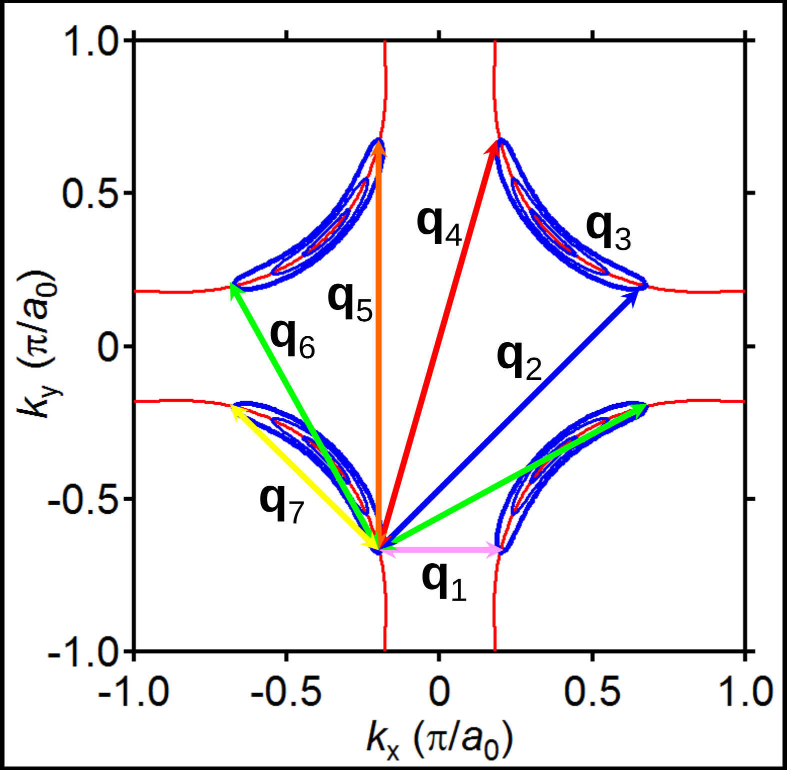


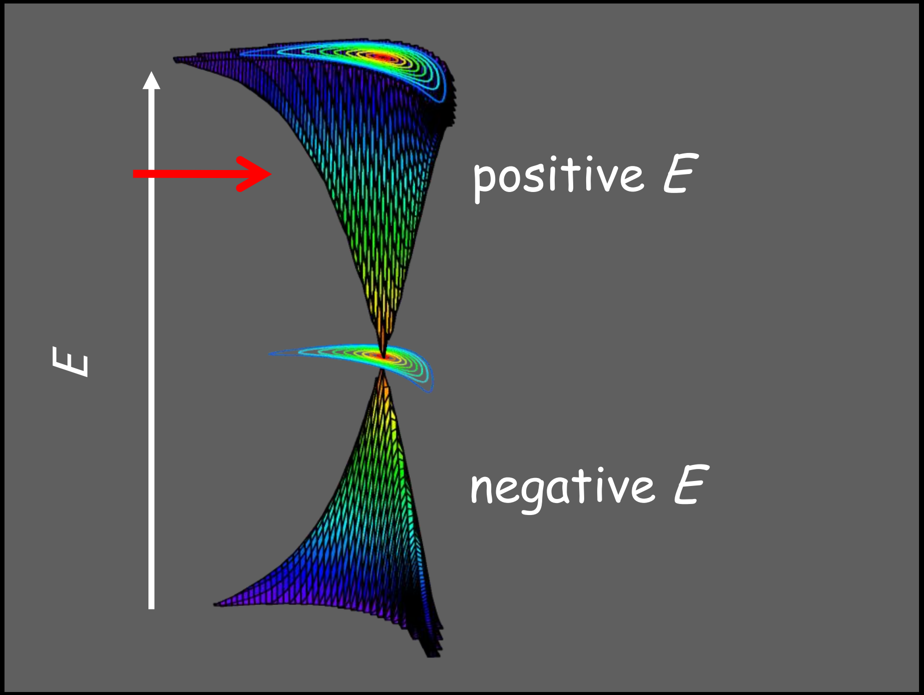
Quasi-particle interference ~ "Octet" model



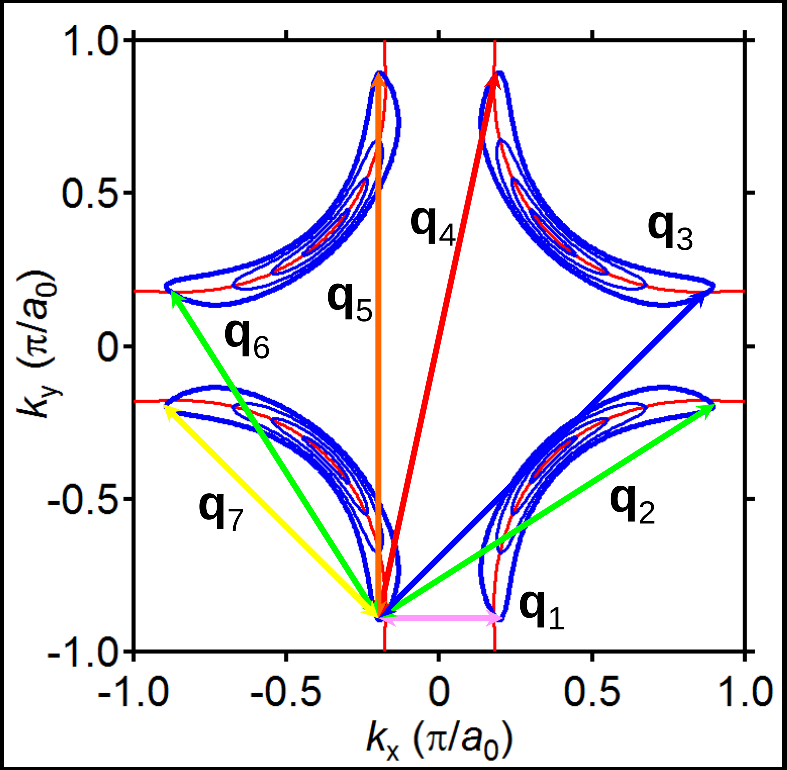


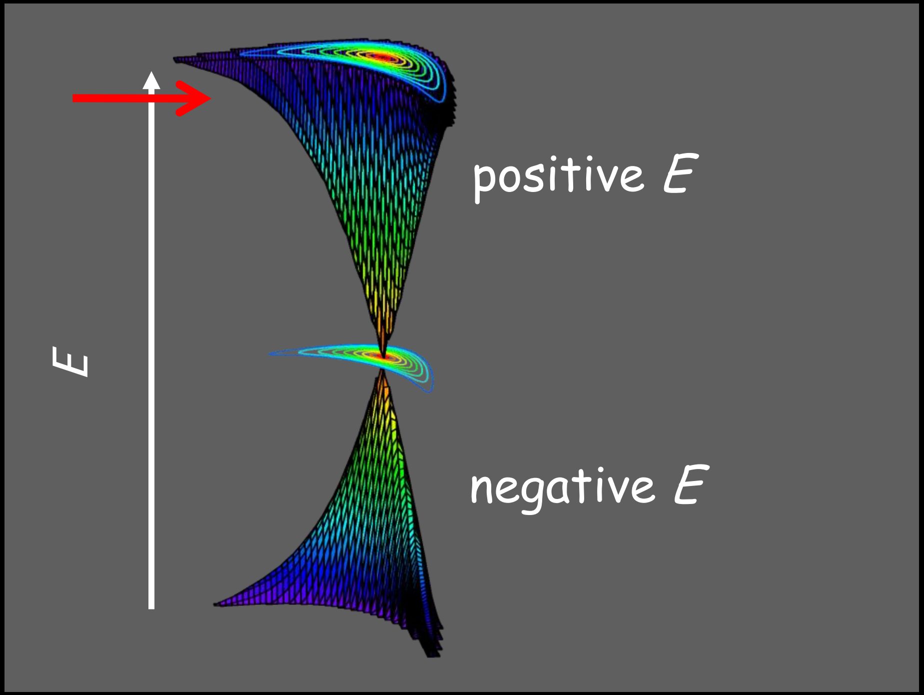
Quasi-particle interference ~ "Octet" model





Quasi-particle interference ~ "Octet" model

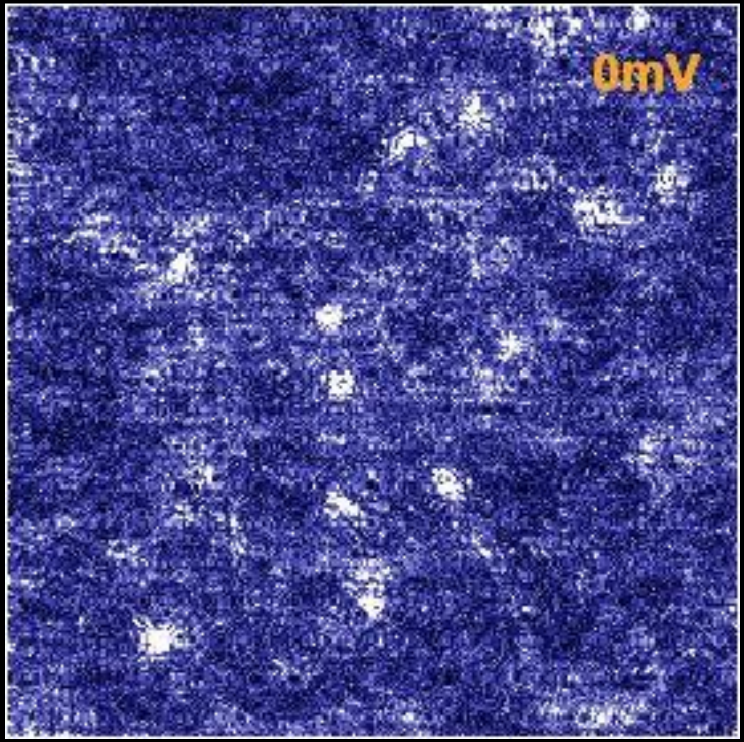




Quasiparticle Scattering Interference (QPI)

$Bi_2Sr_2CaCu_2O_{8+d}$

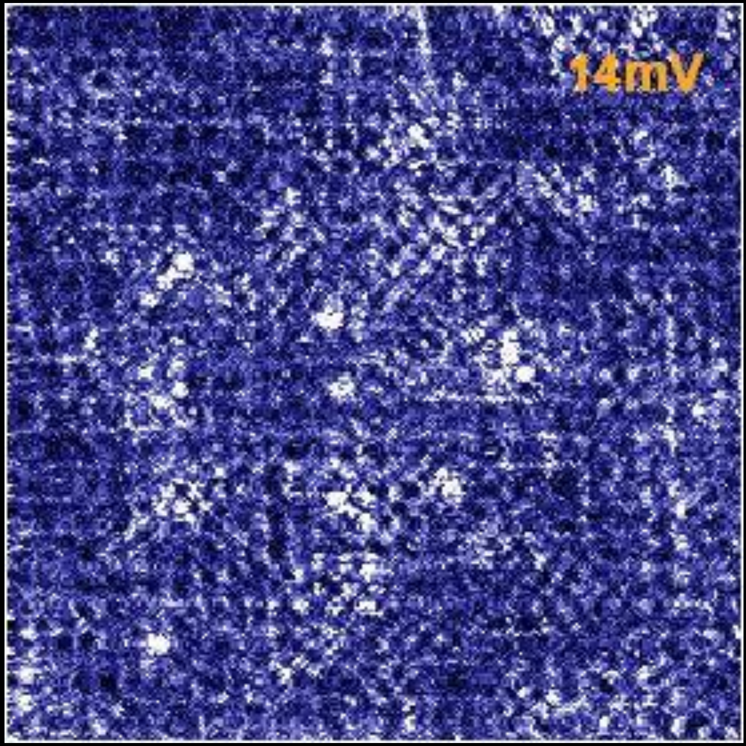
$g(\vec{r}, E)$



Quasiparticle Scattering Interference (QPI)

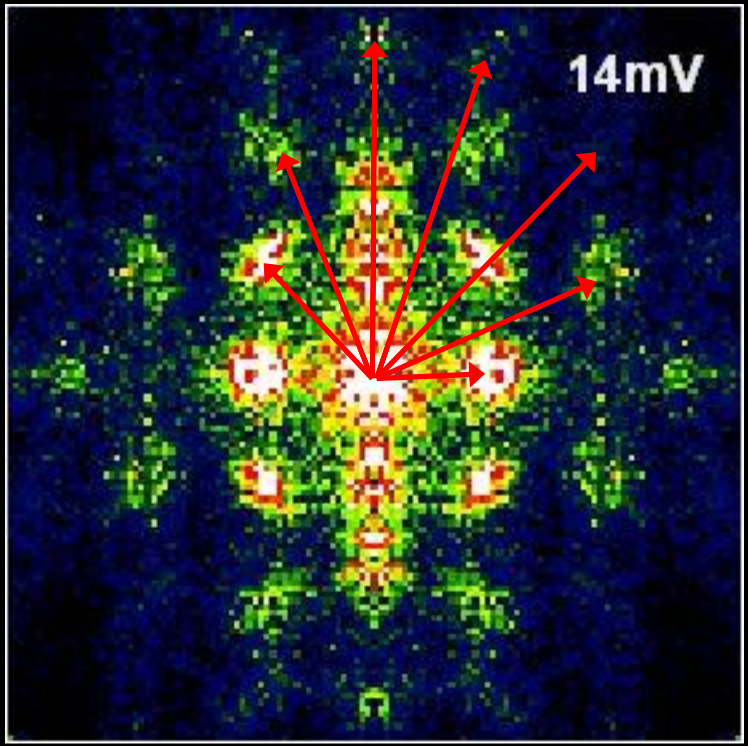
$Bi_2Sr_2CaCu_2O_{8+d}$

$g(\vec{r},E)$



FFT

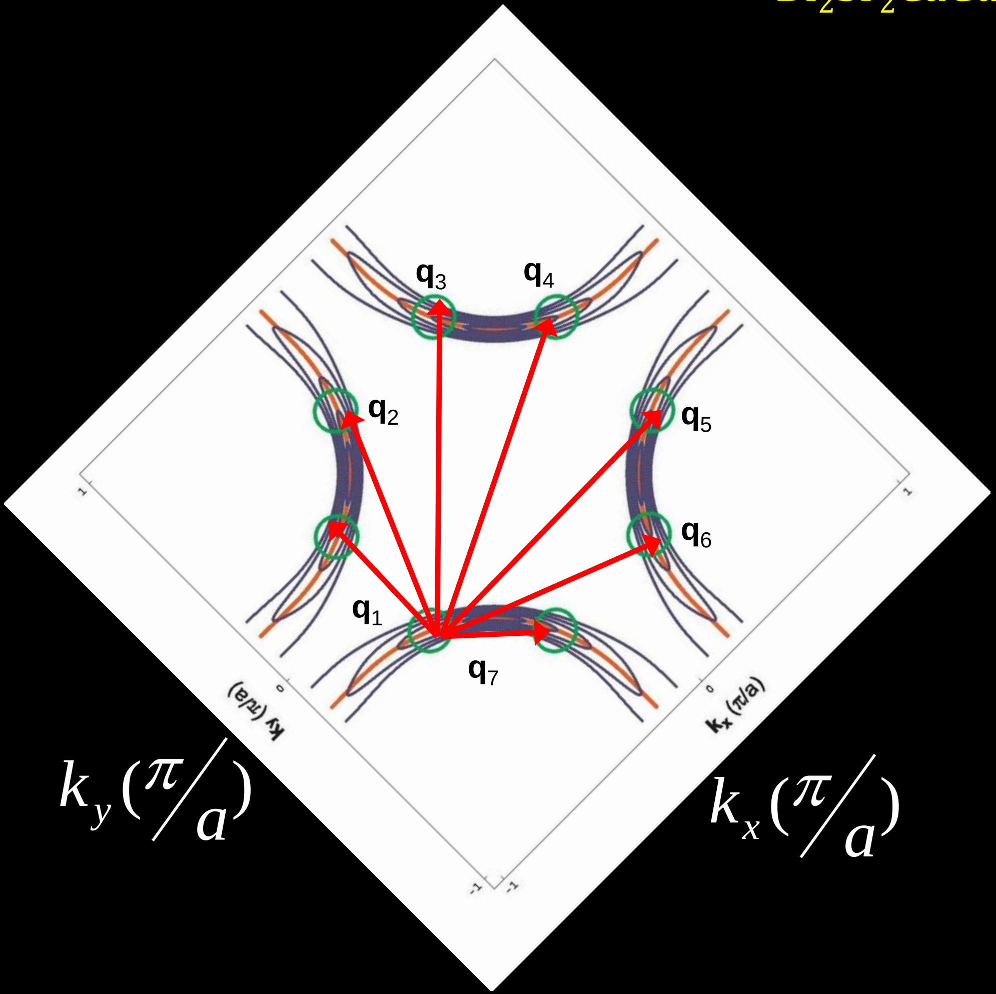
$\mathrm{FFT}[g(\vec{r},E)] \equiv g(\vec{q},E)$



J. E. Hoffman, *et al.*, Science **297**, 1148 (2002)
Q. Wang *et al.*, PRB **67**, 020511 (2003).
K. McElroy *et al.*, PRL **94**, 197005 (2005)

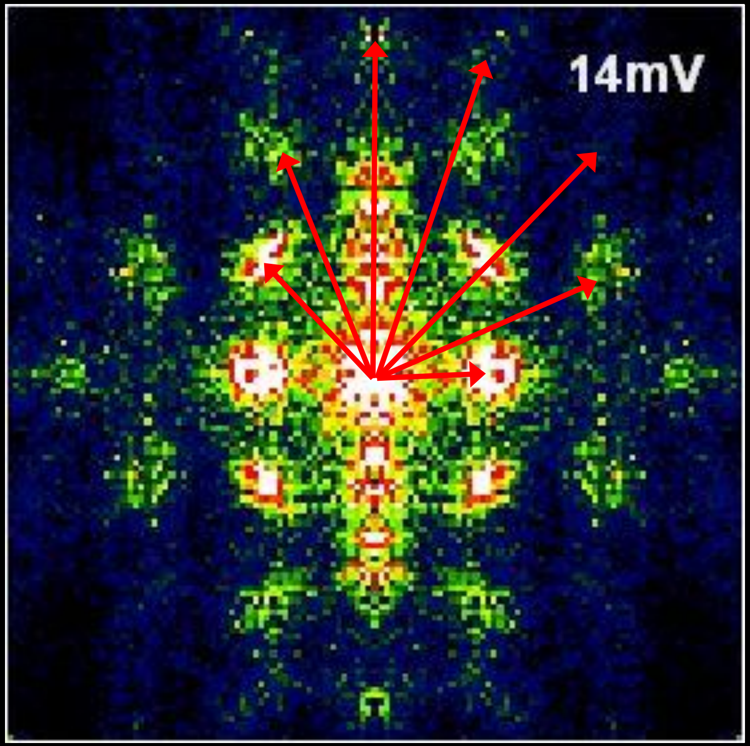
Quasiparticle Scattering Interference (QPI)

$Bi_2Sr_2CaCu_2O_{8+d}$



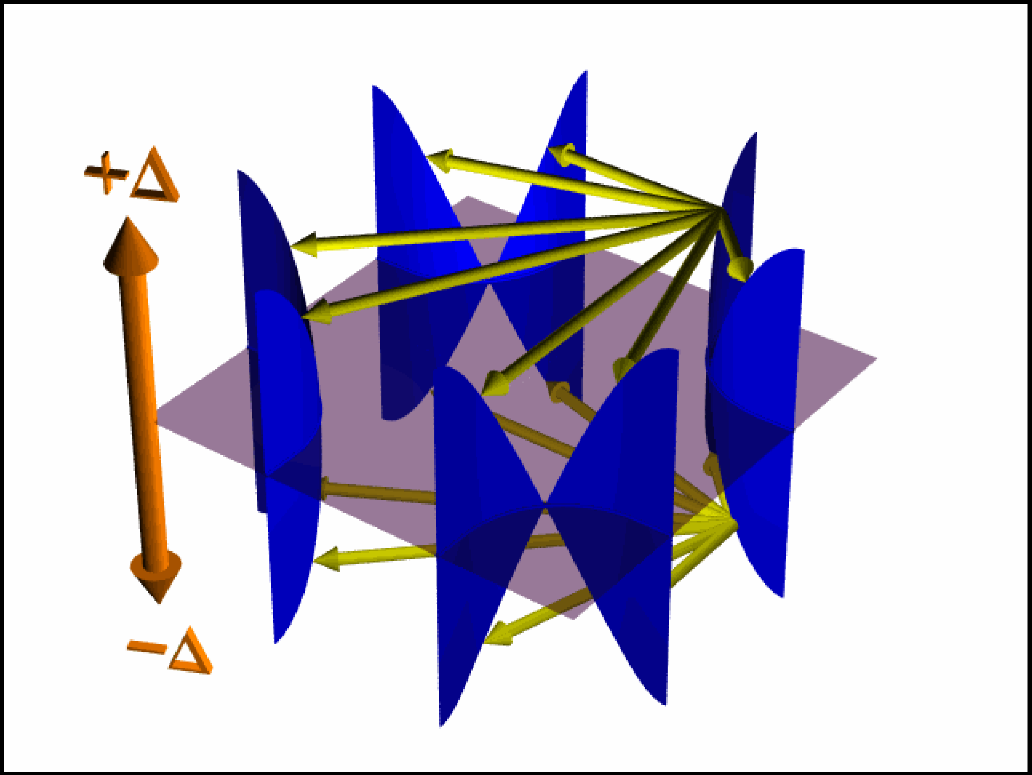
$k_y(\pi/a)$ $k_x(\pi/a)$

$$\mathrm{FFT}[g(\vec{r},E)] \equiv g(\vec{q},E)$$

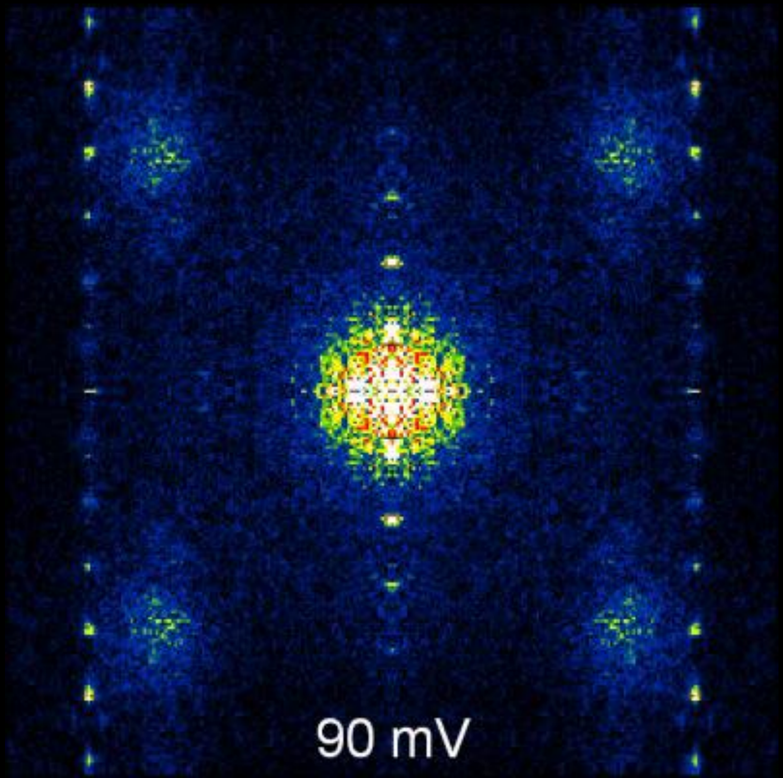


J. E. Hoffman, *et al.*, Science **297**, 1148 (2002)
Q. Wang *et al.*, PRB **67**, 020511 (2003).
K. McElroy *et al.*, Nature **422**, 592 (2003)

Anisotropic SC Gap Δ(*k*) from QPI



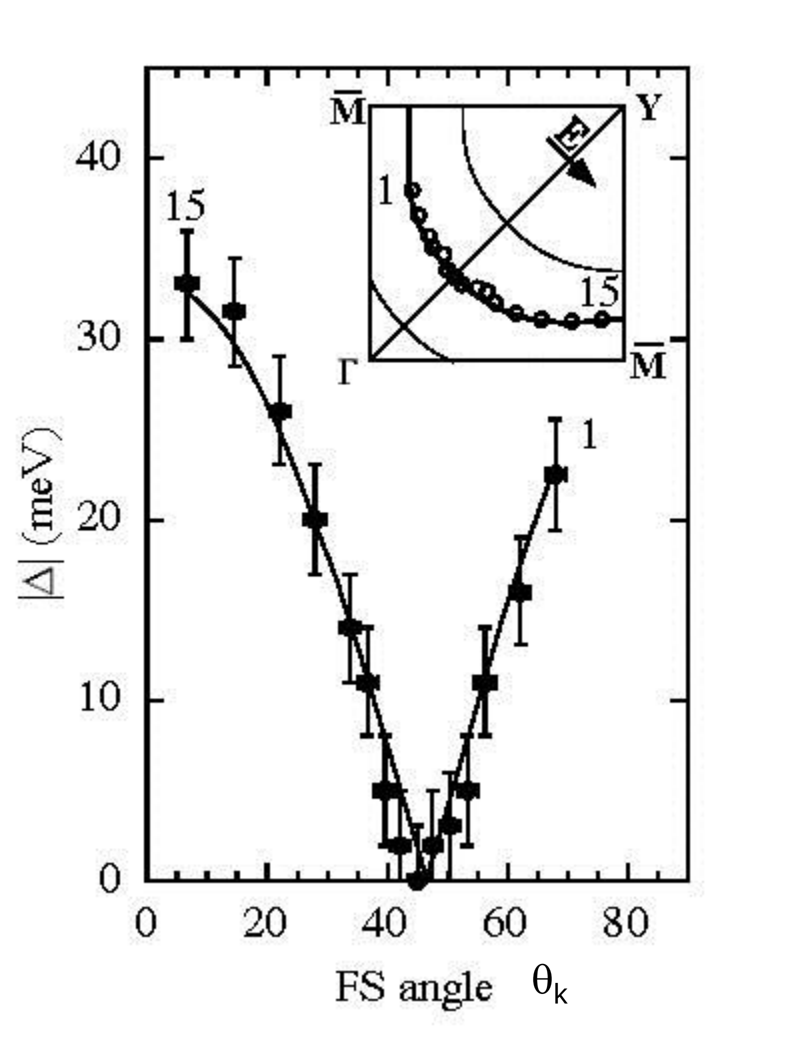
$g(q,E) \propto LDOS(q,E)$



D.-H. Lee, Phys. Rev. B **67**, 020511 (2003).
D. J. Scalapino, Phys. Rev. B **68**, 014508 (2003).
P.J. Hirschfeld *et al*., Phys. Rev. B **73**, 104511 (2006).

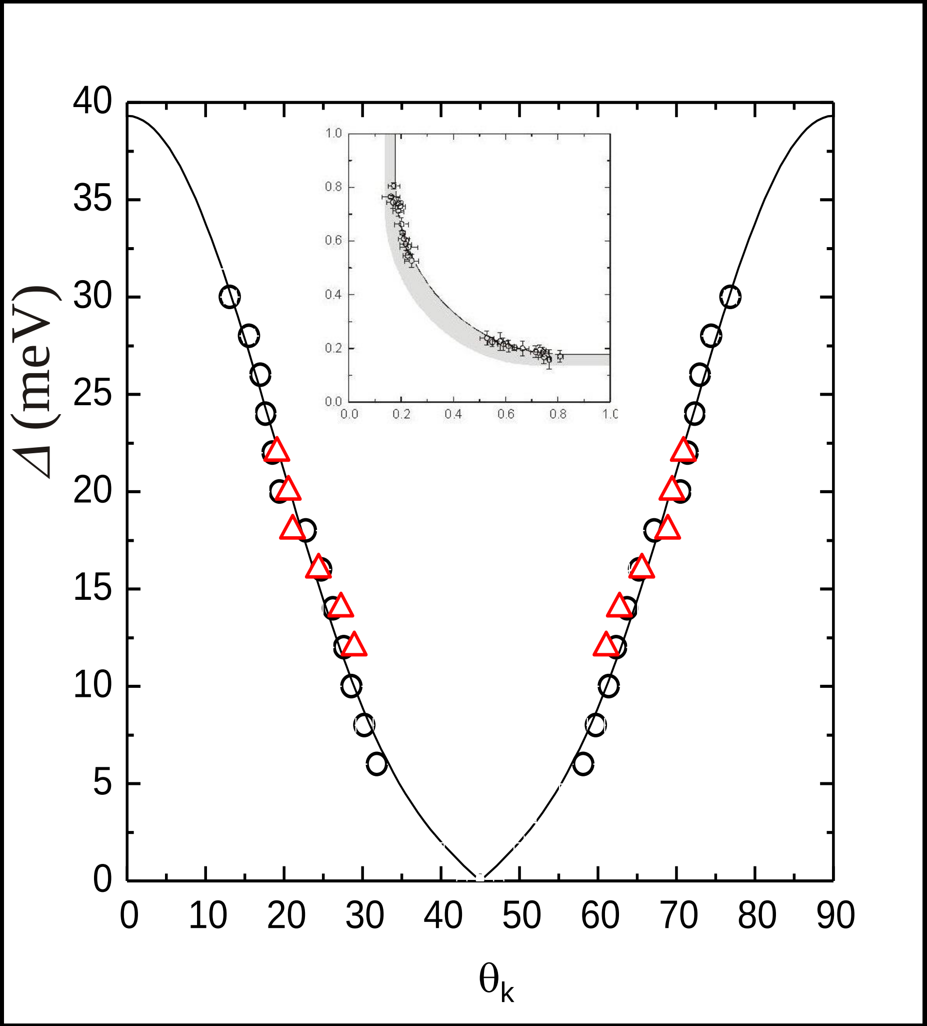
CuSC: Anisotropic SC Gap Δ(*k*) from QPI

ARPES



H. Ding *et al.*, PRB 54, 9678 (1996)
J. Mesot *et al.*, PRL 83, 840 (1999)

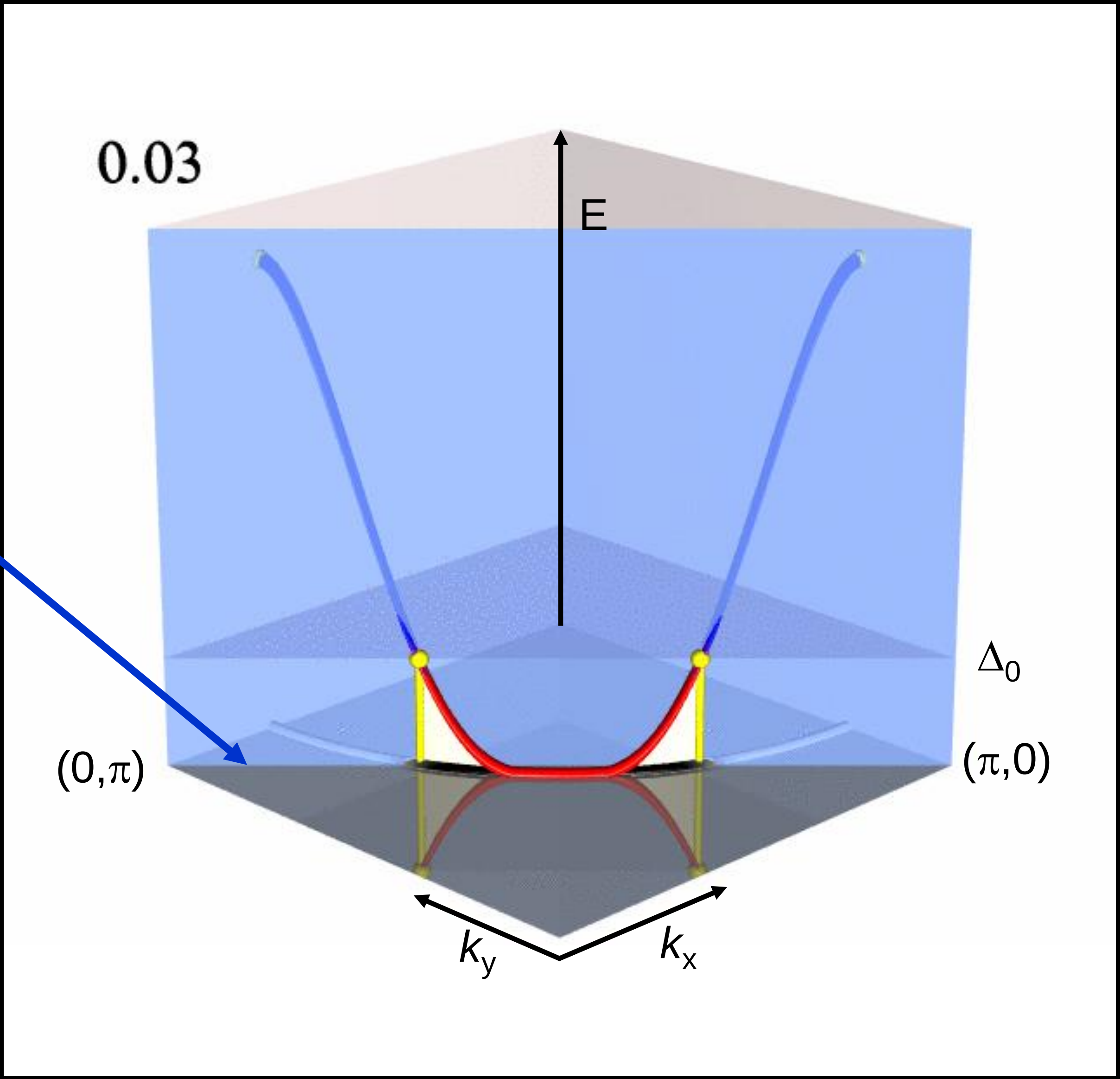
FT-STS



J. E. Hoffman *et al.*, Science 297, 1148 (2002)
K. McElroy *et al.*, Nature 422, 520 (2003)

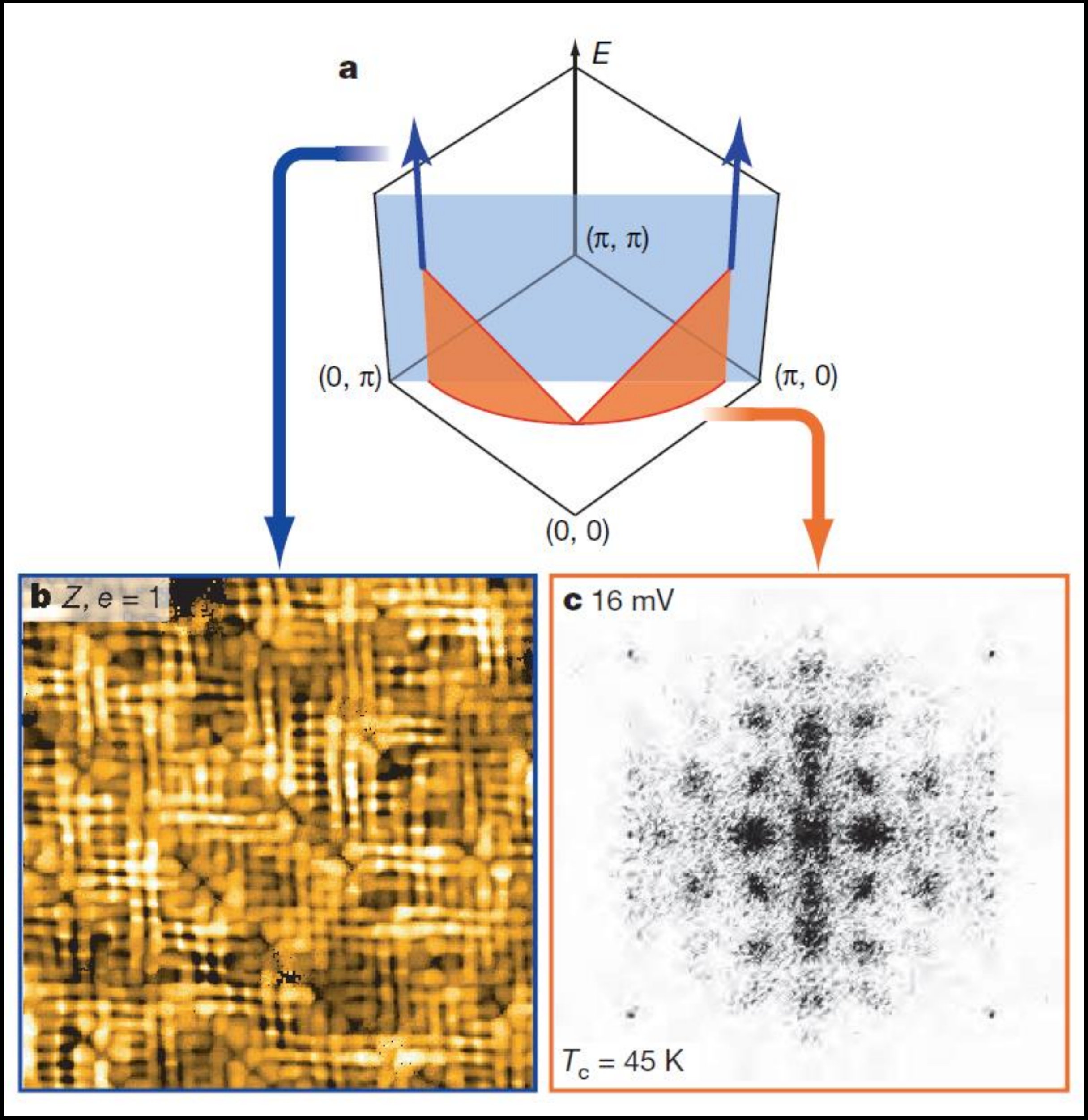
Doping Dependence of Coherent k-space QP & $\Delta(\vec{k})$

k-space boundary



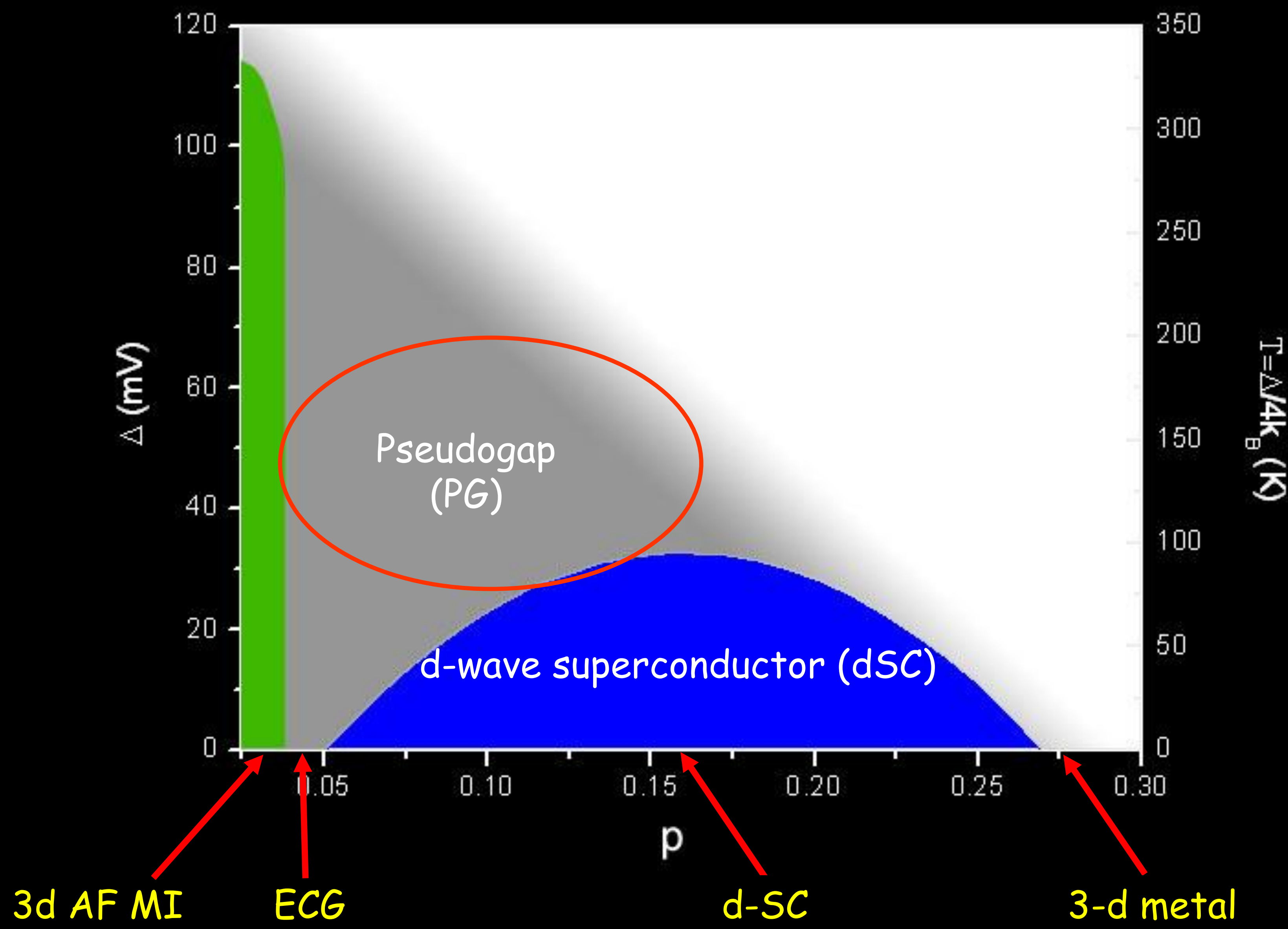
Y. Kohsaka *et al.*, Nature 454, 1072 (2008)

Bipartite electronic structure as p→ 0



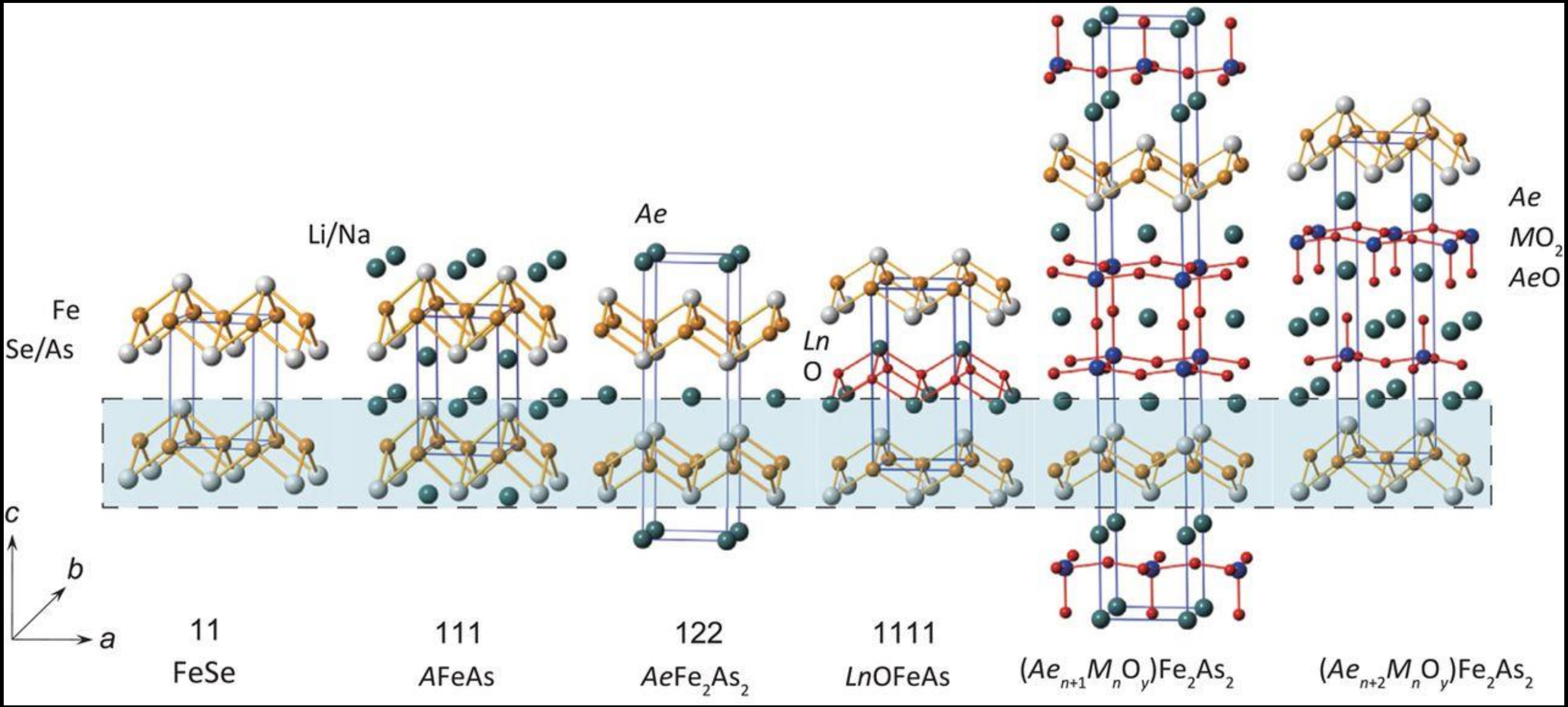
Y. Kohsaka *et al.*, Nature 454, 1072 (2008)

Schematic Phase Diagram of Hole-doped Cuprates



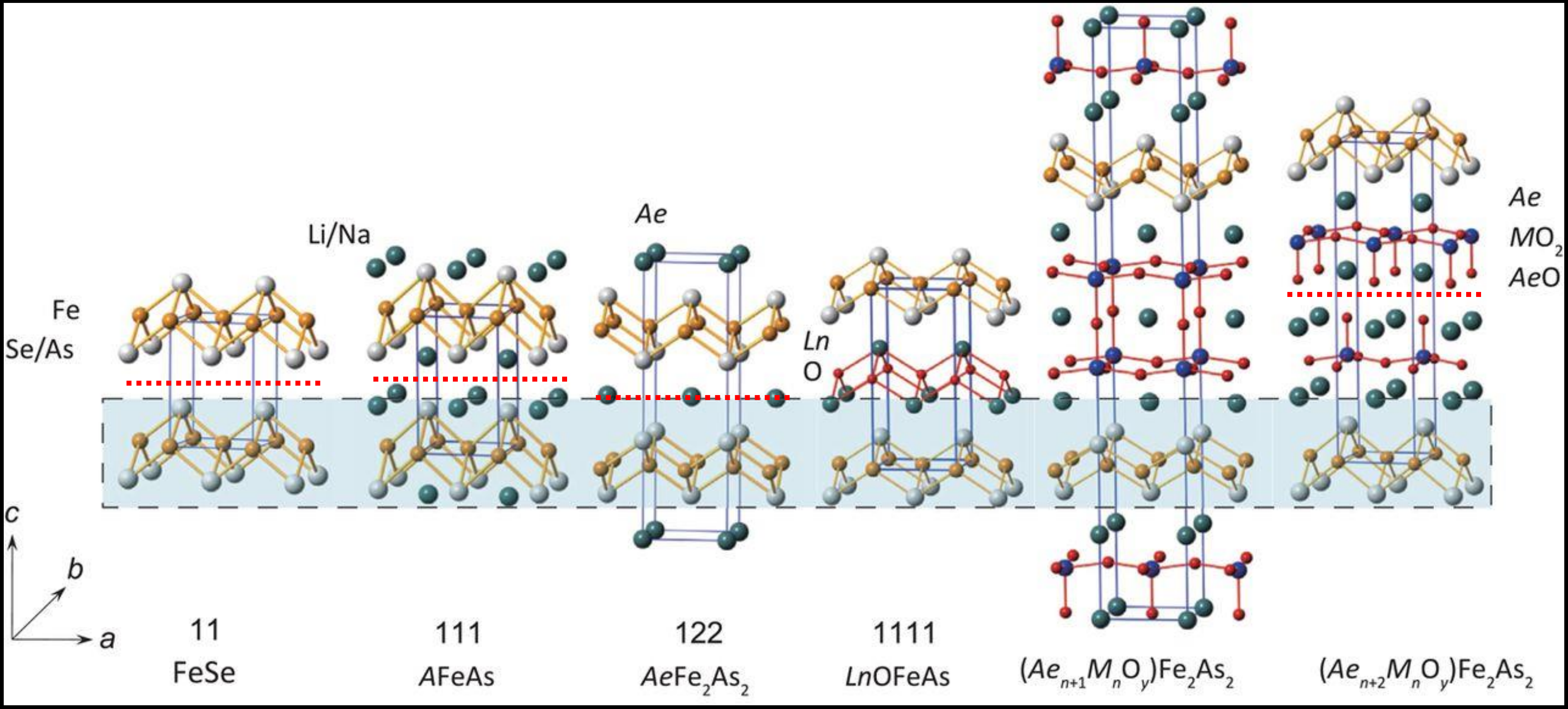
1. Introduction to conventional superconductivity
2. Introduction to scanning tunneling microscopy (STM)
3. High Tc Superconductor : Cuprates
4. High Tc Superconductor : Fe-based Compounds

FeSC Family



X.H. Chen *et al.*, National Science Review 1: 371–395 (2014)

FeSC Family



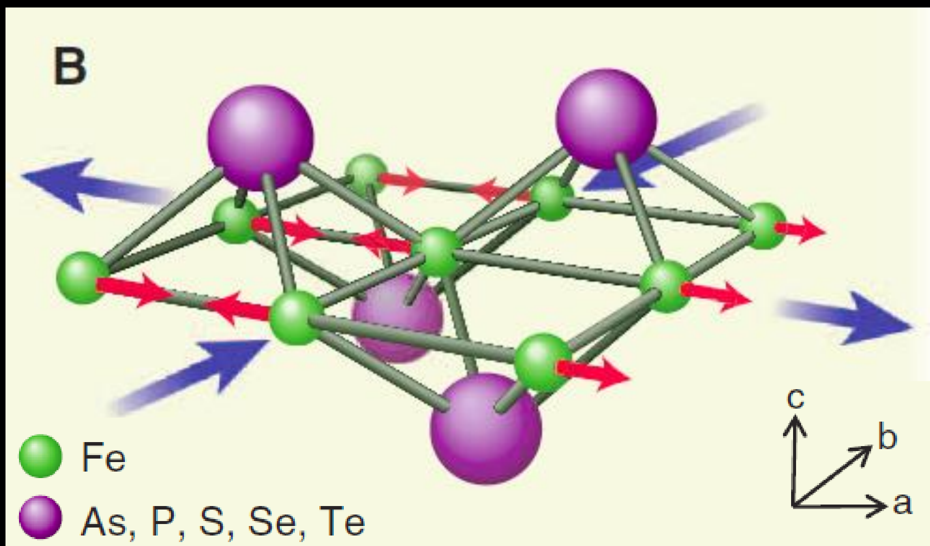
☺ ☺ 😐 😐

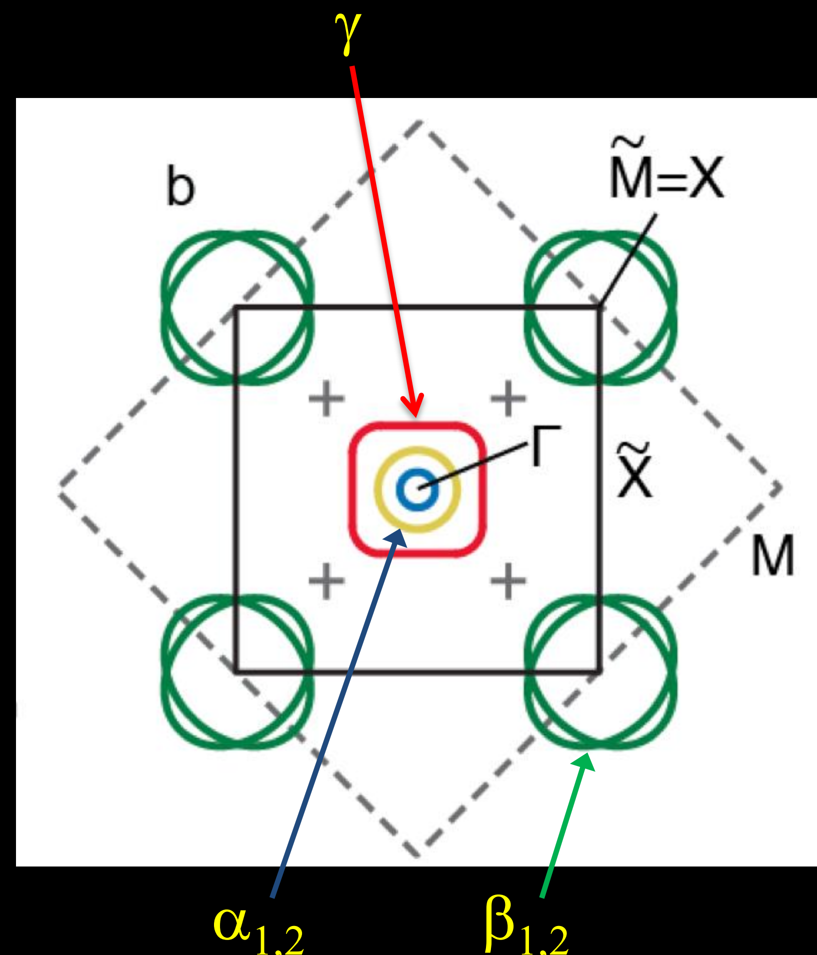
Glide plane : Good for STM/ARPES measurements

X.H. Chen *et al.*, National Science Review 1: 371–395 (2014)

FeSC : Complex Band Structure

SC layer with SDW ground state

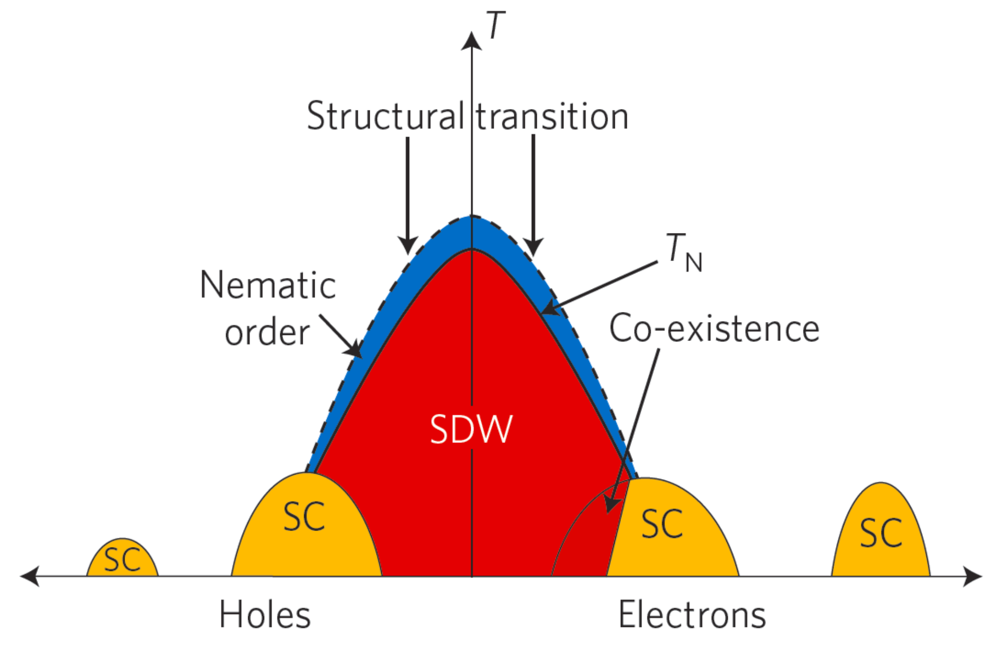




F. Wang *et al.*, Science 332, 200 (2011)
P. J. Hirschfeld *et al.*, Rep.Prog.Phys.**74**,124508 (2011)

FeSC Phase Diagram

FeSC

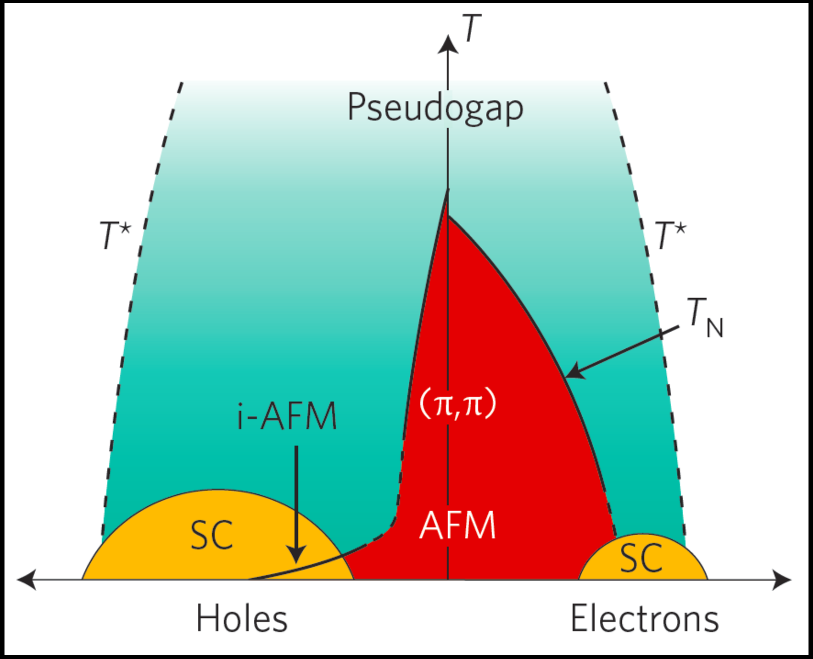


D.N. Basov *et al.*, NPhys **7**, 272 (2011)

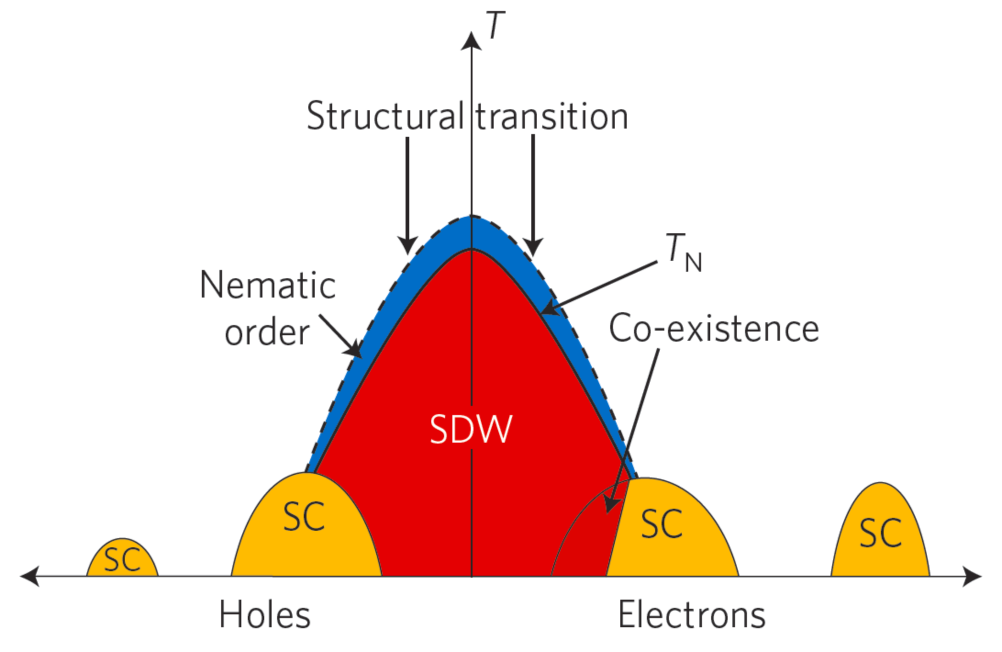
FeSC vs Cuprates : Phase Diagram

Many common electronic characteristics!
Both have antiferromagnetic 'parent' states.

Cuprates



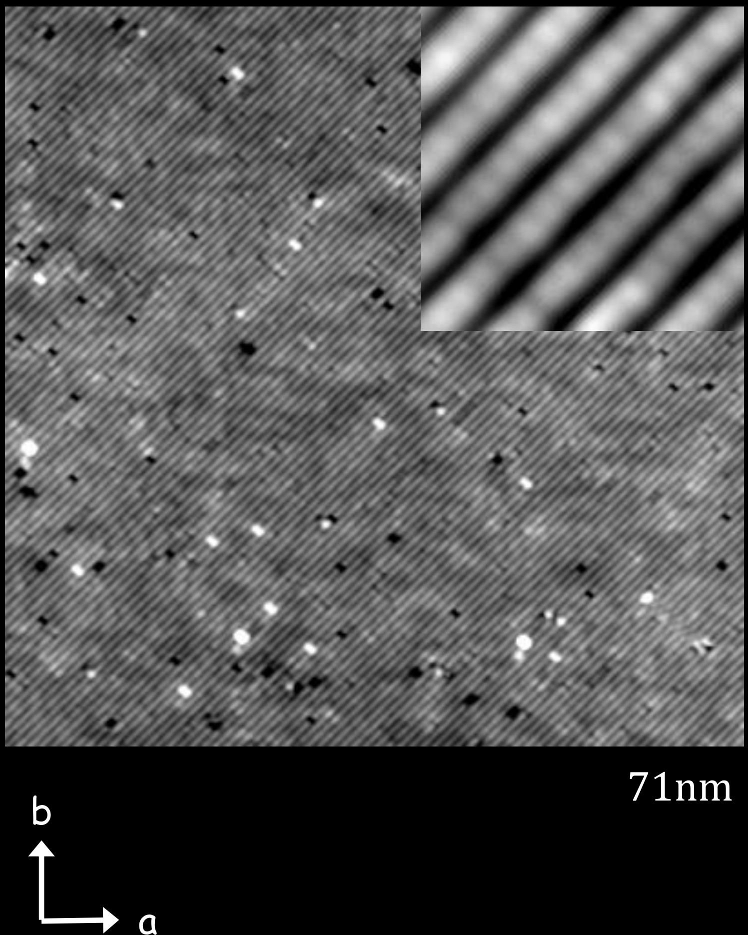
FeSC

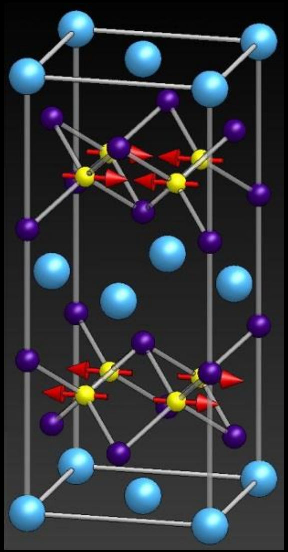


D.N. Basov *et al.*, NPhys **7**, 272 (2011)

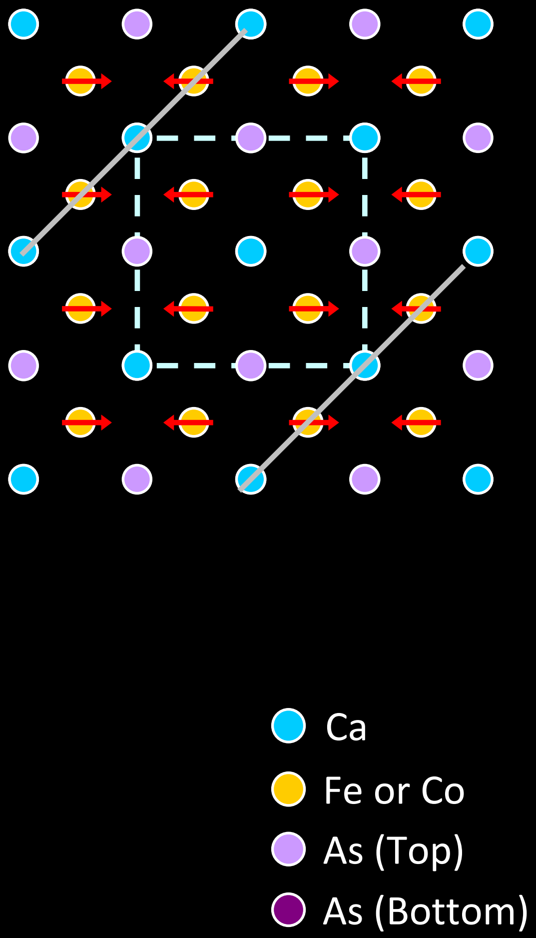
Direct Visualization of Electronic Nematicity in Underdoped $CaFe_2As_2$ (x=3.0%)

Topograph





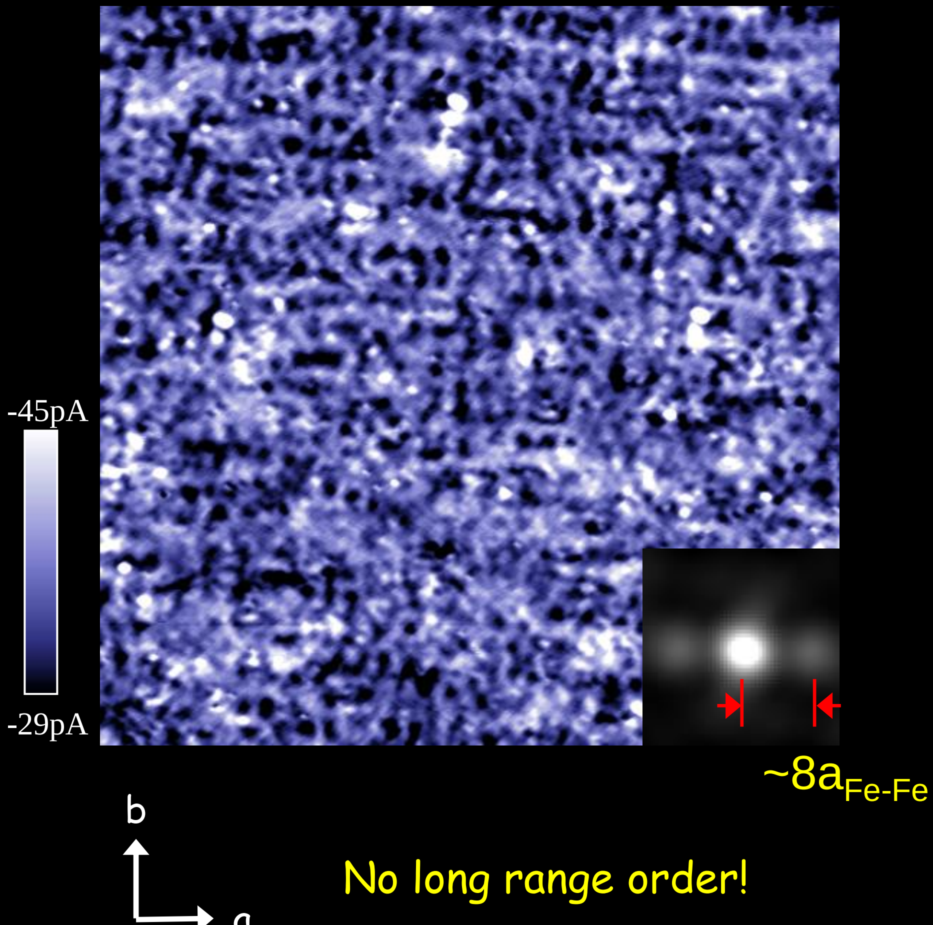
1x2 reconstruction



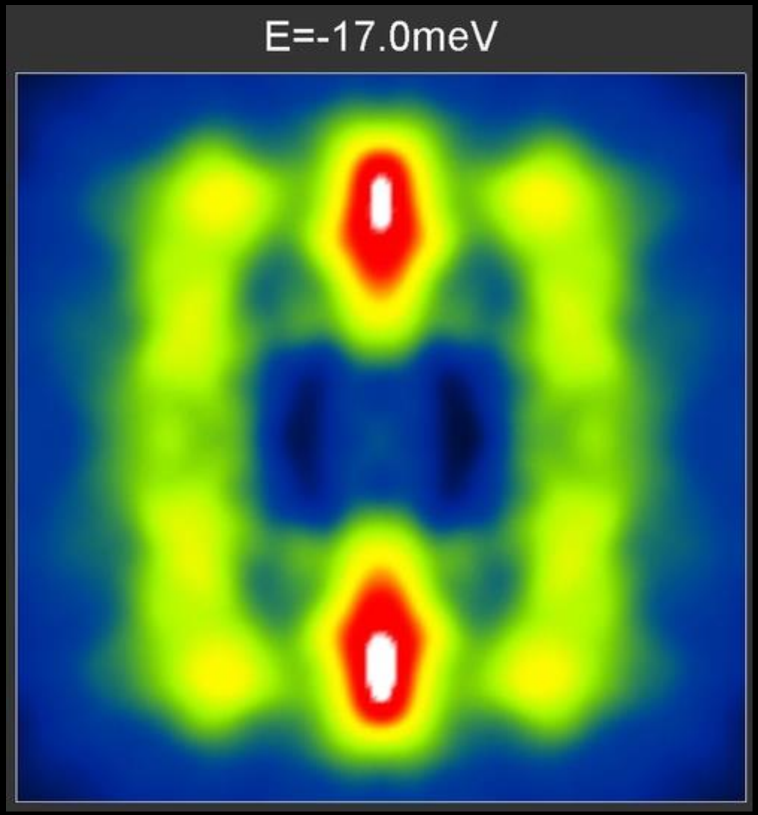
T.-M. Chuang *et al.*, Science **327**, 181 (2010)

Direct Visualization of Nematic Electronic Structure in Underdoped CaFe2As2 (x=3.0%)

Static $I(\vec{r}, E=50meV)$



Delocalized State, $LDOS(\vec{q}, E)$

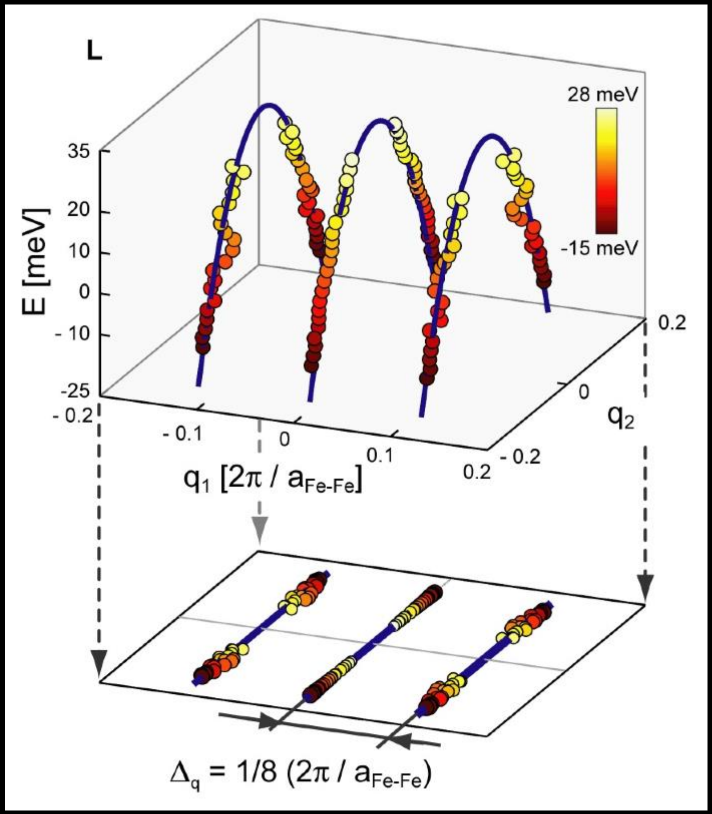


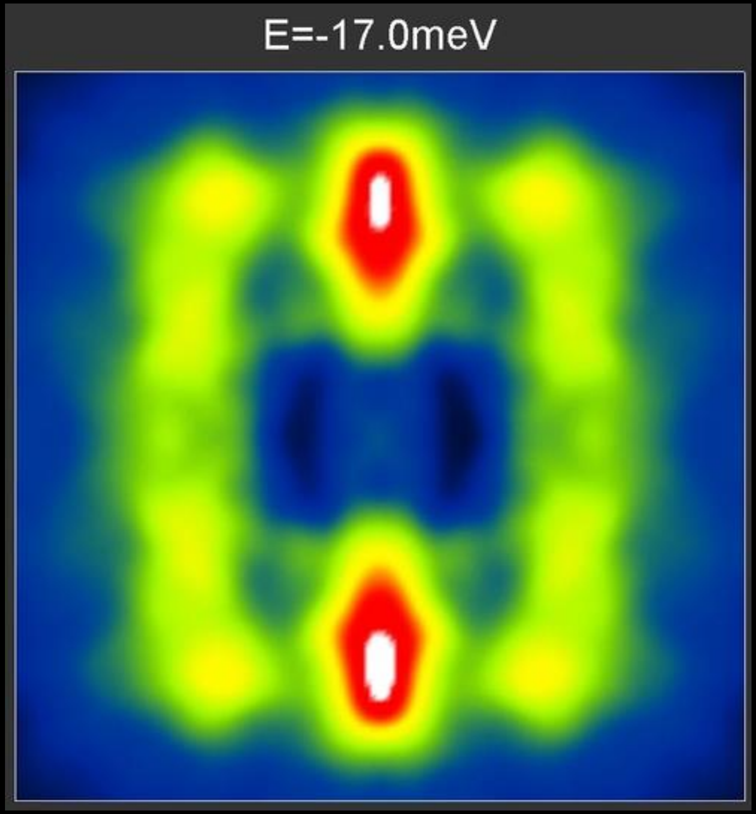
No long range order!

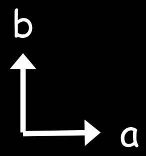
T.-M. Chuang *et al.*, Science **327**, 181 (2010)

Direct Visualization of Nematic Electronic Structure in Underdoped CaFe2As2 (x=3.0%)

Delocalized State, $LDOS(\vec{q}, E)$



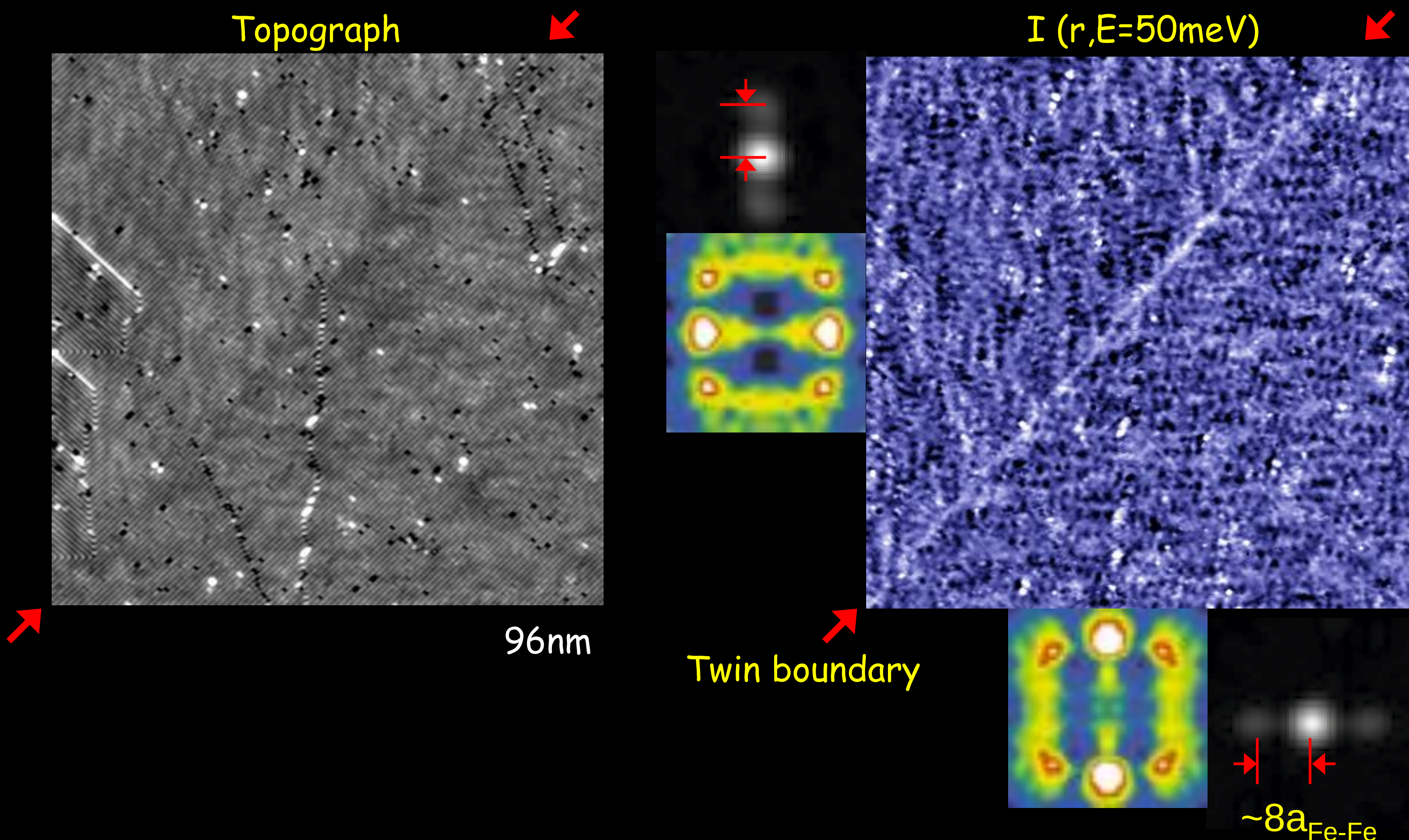




T.-M. Chuang *et al.*, Science **327**, 181 (2010)

Nematic Electronic Structure at Twin Domain Boundary

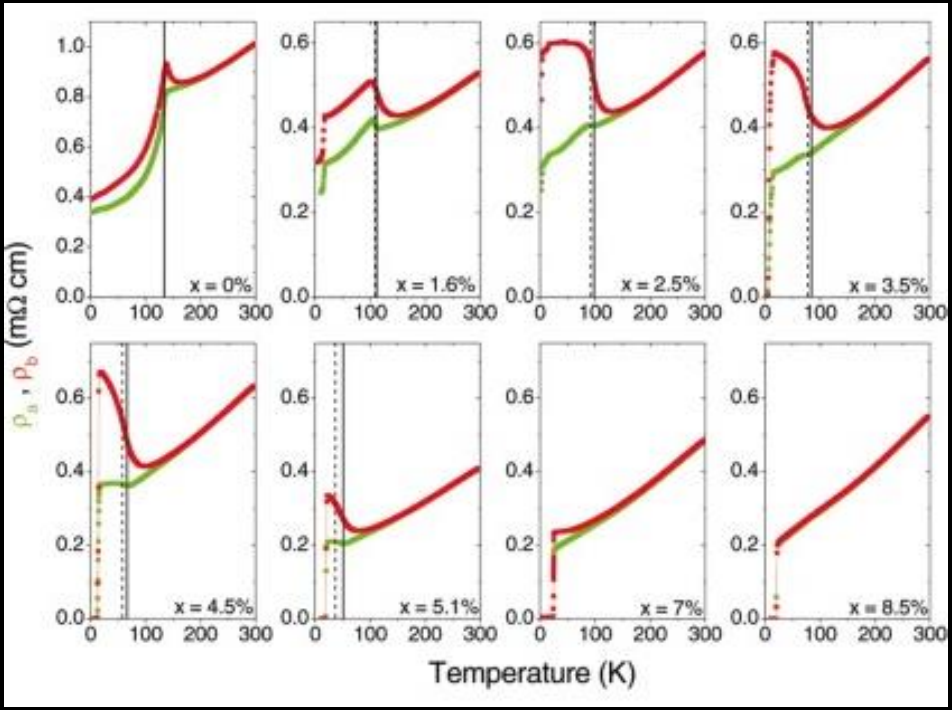
Surface reconstruction doesn't affect the nematic electronic structure.
Nematic electronic structure correlates to the crystal symmetry.



T.-M. Chuang *et al.*, Science **327**, 181 (2010)

Electronic Nematicity in Detwinned Single Crystals

$\rho_a < \rho_b$



DC electric transport:

J.H. Chu *et al.* Science **329**, 824-826 (2010).
M.A. Tanatar *et al.* PRB **81**, 184508 (2010).
S. Ishida *et al.* PRB **84**, 184514 (2010).
E.C. Blomberg *et al.* PRB **83**, 134505 (2011).
H.H. Kuo *et al*. PRB **84**, 054540 (2011).
J.J. Ying *et al.* PRL **107**, 067001 (2011).
J.H. Chu *et al.* Science **337**, 710 (2012).
A.F. Wang *et al*. New J. Phys. 15 043048(2013).

AC electric transport:

A. Dusza *et al.* EPL **93,** 37002 (2011).
M. Nakajima *et al.* PNAS **108**, 12238 (2011).
M. Nakajima *et al*. PRL **109**, 217003 (2012)

ARPES:

Q. Wang, *et al.* arXiv:1009.0271 (2010).
M. Yi *et al.*, PNAS **108**, 6878 (2011).
I.R. Fisher *et al.*, Rep. Prog. Phys. 74 124506 (2011)

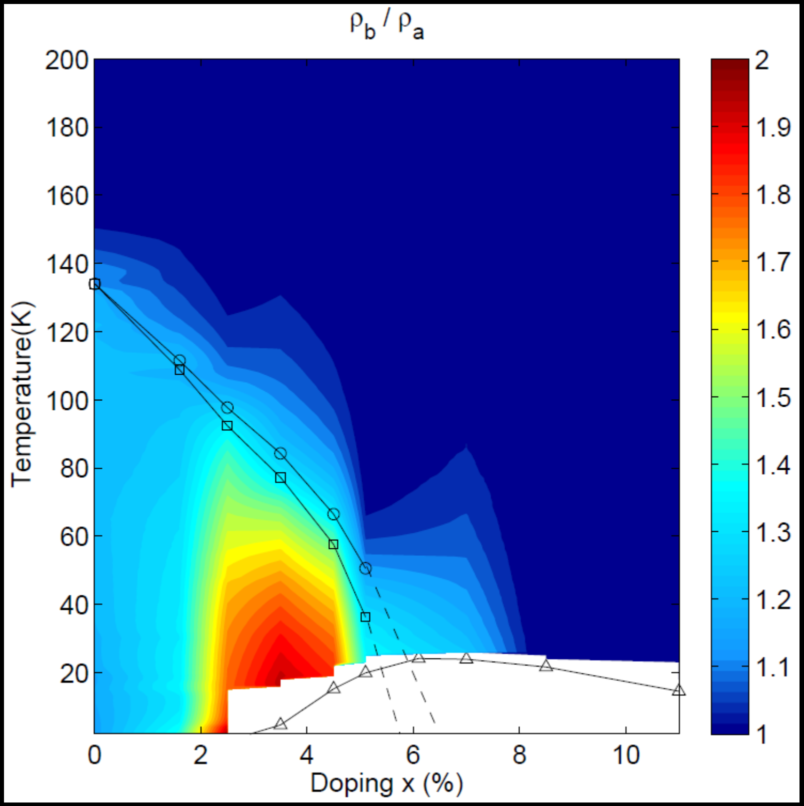
Magnetic torque:

S. Kasahara *et al.* Nature **486**, 382 (2012).

STM:

C.L. Song *et al.*, Science **332**, 1410 (2011).
X. Zhou *et al.* PRL. **106**, 087001 (2011).

In-plane Resistivity Anisotropy in Detwinned $Ba(Fe_{1-x}Co_x)_2As_2$



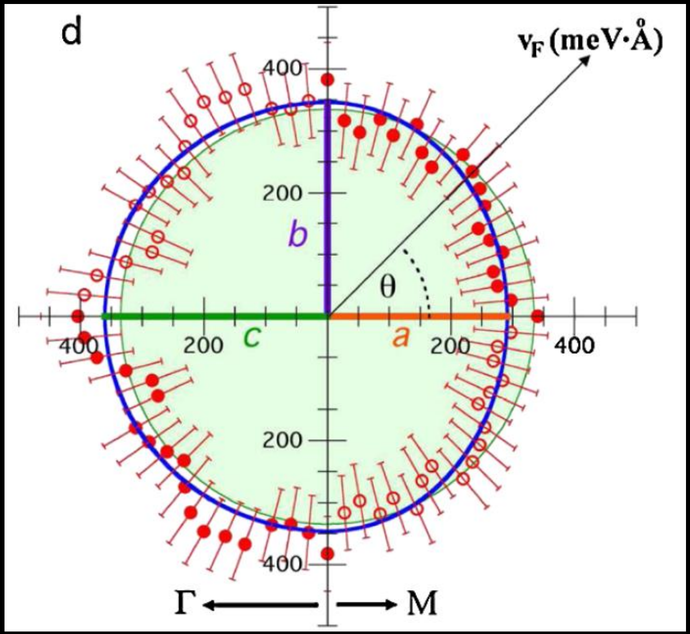
Crystalline anisotropy monotonically decreases with doping but nematicity does not !

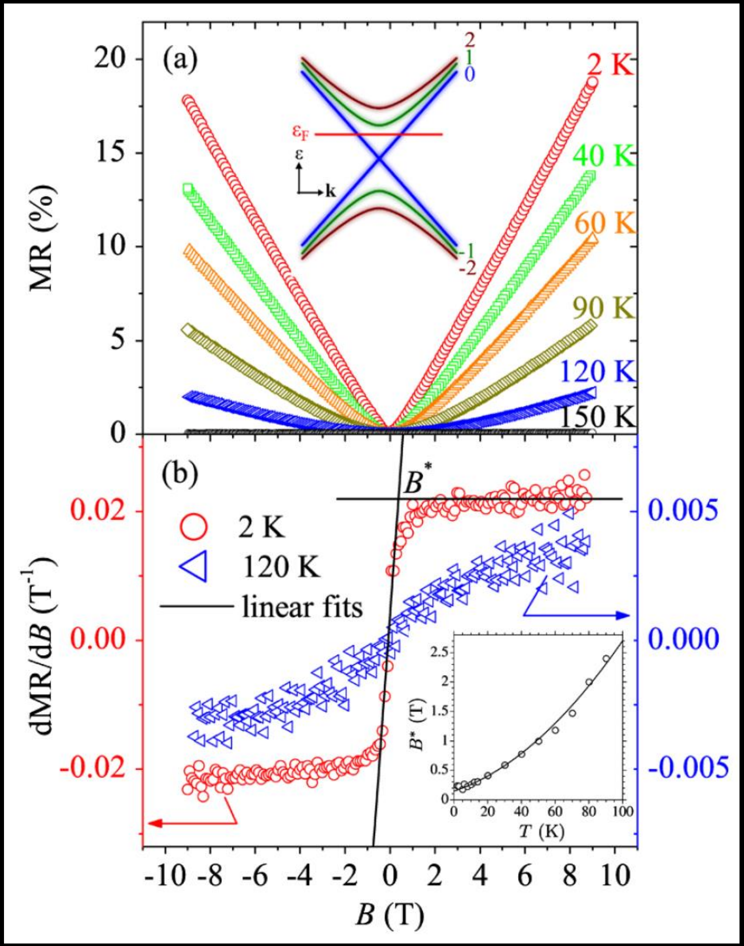
J.-H. Chu *et al.*, Science **329**, 824 (2010)
M. A. Tanatar *et al.*, PRB **81**,184508 (2010)

Doping Dependence of Transport Anisotropy?

Proposal by I.R. Fisher:
High mobility isotropic pocket "short-circuits" the aniostropic section of FS
H.-H. Kuo *et al.*, PRB 84, 054540 (2011)

Dirac pocket at Λ=(0.75π,0)





Alternative?

Theorectical Proposal : Impurity States

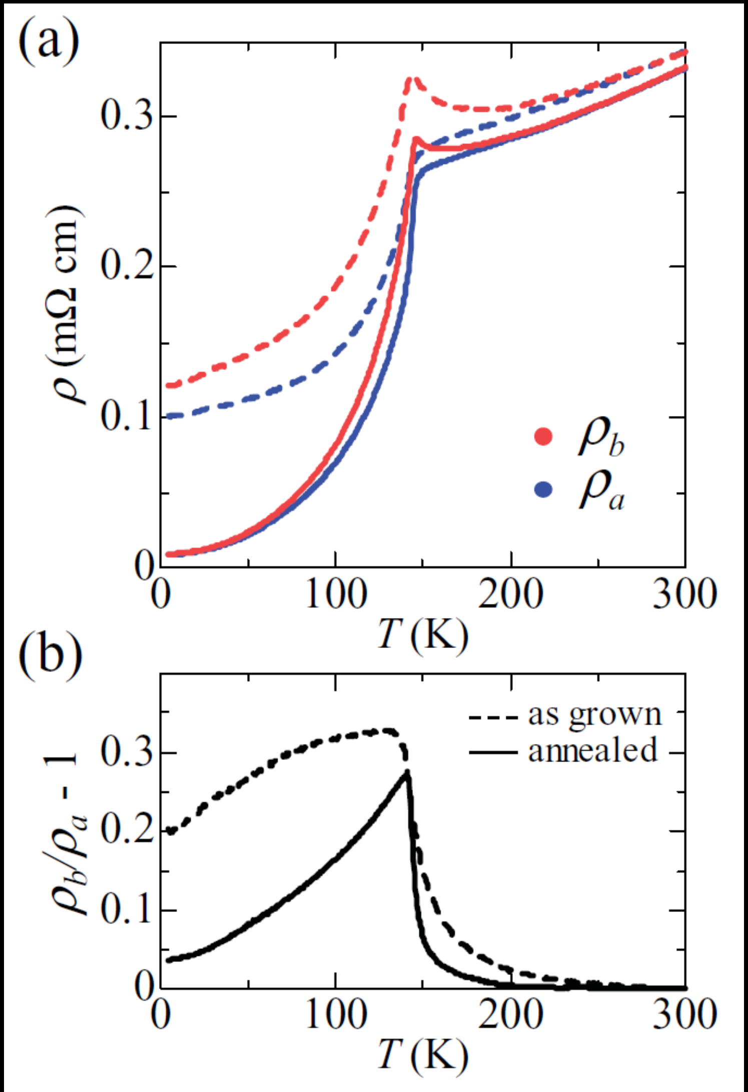
Impurity-induced nematic state from orbital fluctuation:
Y. Inoue *et al.*, PRB 85, 224506 (2012)

Ising nematic state from the scattering interference between impurities and spin fluctuation.
R.M. Fernandes *et al.*, PRL 107, 217002 (2011)

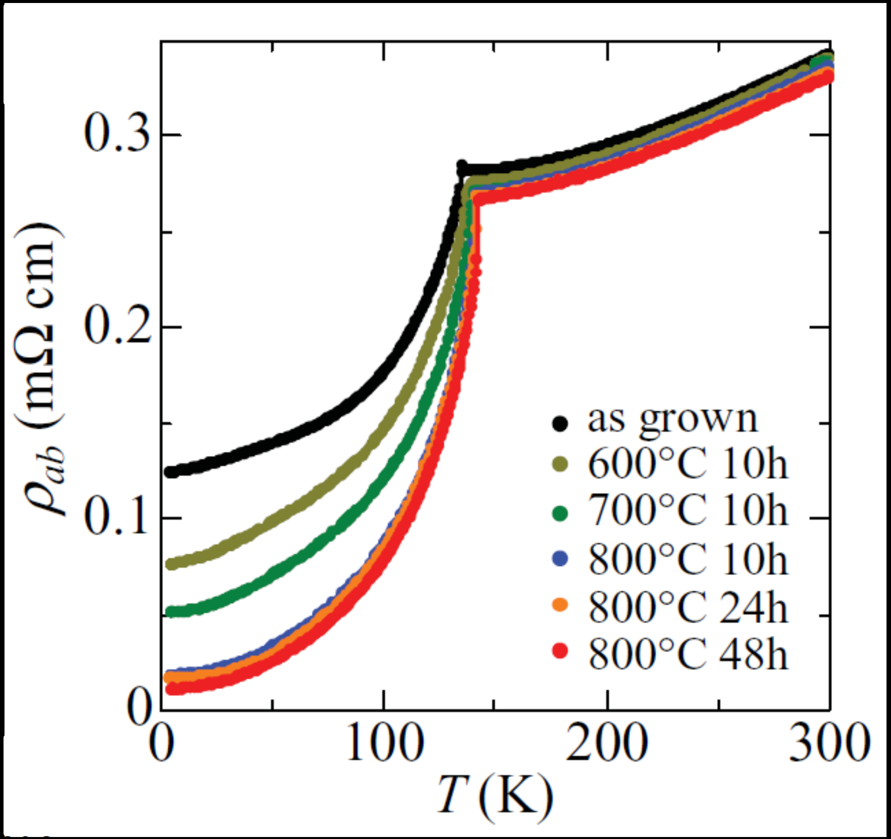
Impurity states determined by reconstructed nesting wavevector.
Jian Kang & Zlatko Tesanovic, PRB85, 220507(2012)

Diminishing Resistivity Anisotropy by Annealing

Defects and impurities play any role in transport anisotropy?



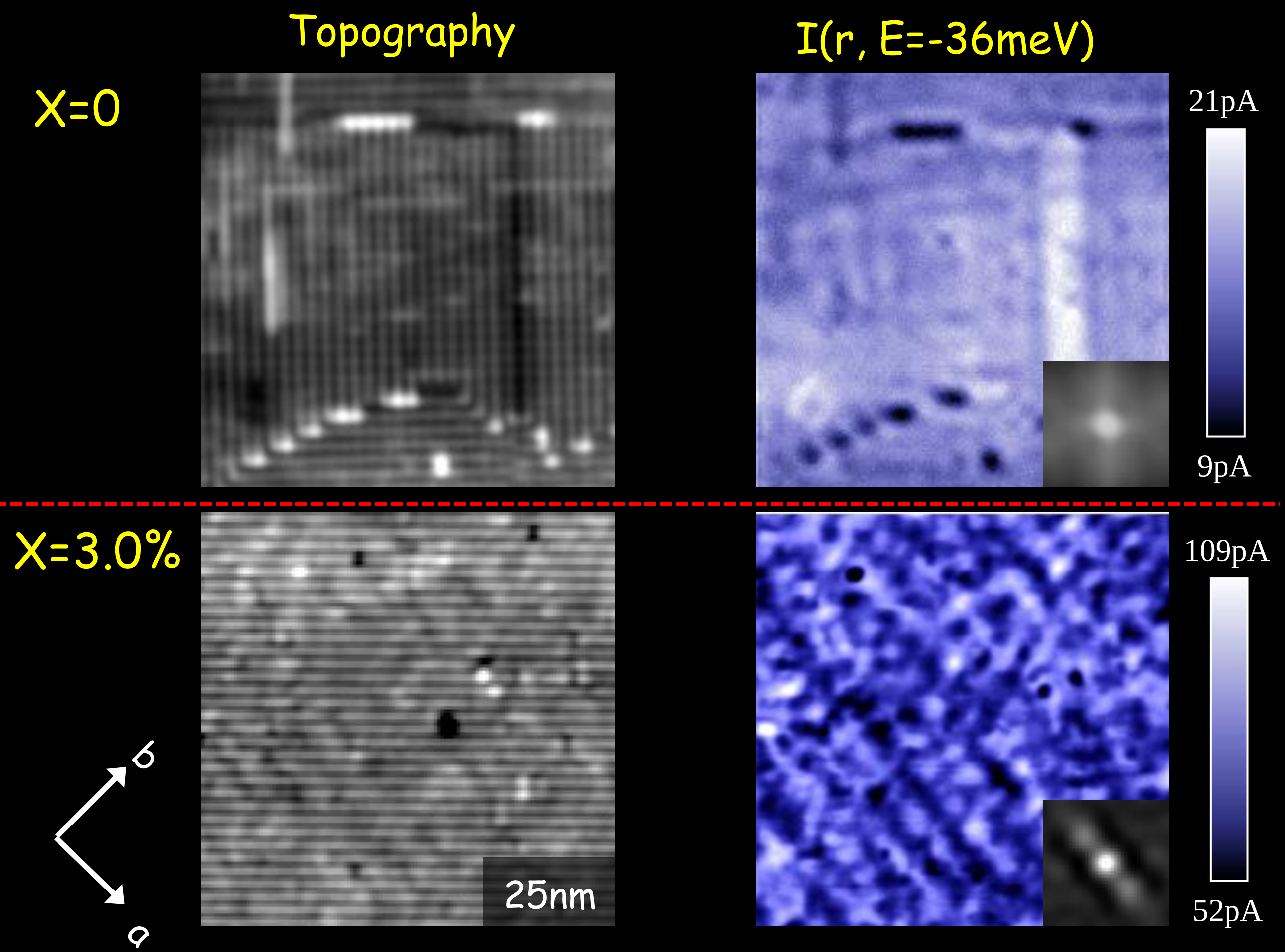
RRR improved a factor of 10.



M. Nakajima *et al*. PNAS **108**, 12238 (2011)
M. Nakajima *et al*. PRL **109**, 217003 (2012)

Doping Dependence of Electronic Structure in $Ca(Fe_{1-x}Co_x)_2As_2$

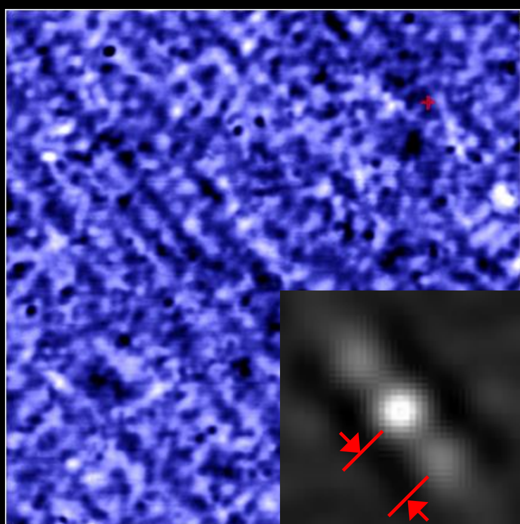
Co atoms induce nanoscale C_2-symmetric electronic structure.



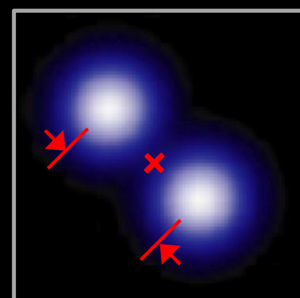
T.-M. Chuang *et al.*, Science **327**, 181 (2010)
M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Our Proposal : Anisotropic Impurity State

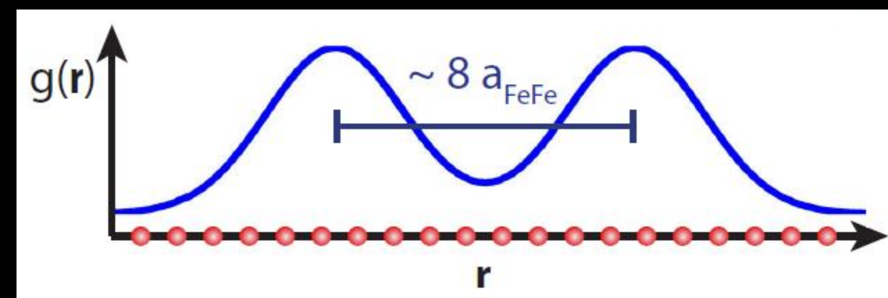
- Anisotropic electronic impurity state
- Separated by $8a_{Fe\text{-}Fe}$, aligned with AFM a-axis
- Distributed randomly



$\sim 8a_{Fe\text{-}Fe}$



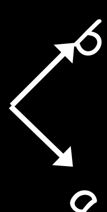
$\sim 8a_{Fe\text{-}Fe}$



$$g(\mathbf{r}) = \sum_{\mathbf{R_j} \in \mathscr{R}} \mathcal{N}(\mathbf{r} - \mathbf{R_j}),$$

$$\mathcal{N}(\mathbf{r}) = \mathcal{G}_\sigma(\mathbf{r}) + \mathcal{G}_\sigma(\mathbf{r} + \mathbf{d}),$$

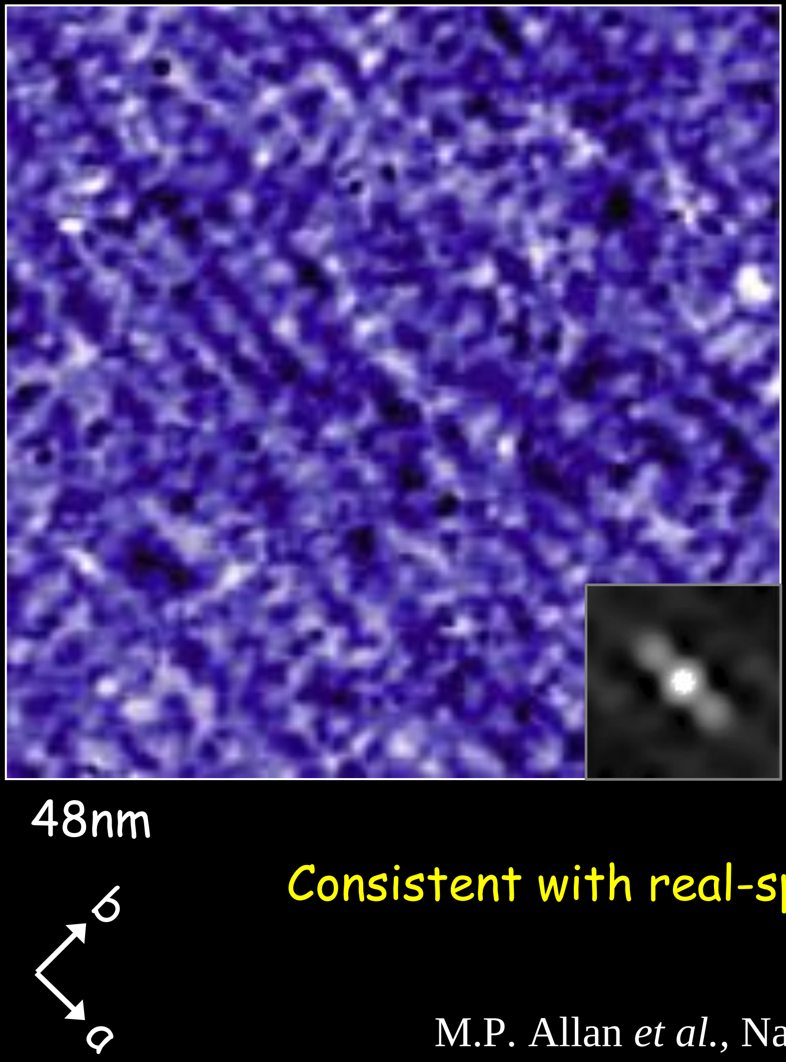
$$\mathcal{G}_\sigma(\mathbf{r}) = \left[a \cdot e^{-\frac{|\mathbf{r}|^2}{\sigma^2}}\right] \mathrm{mS},$$



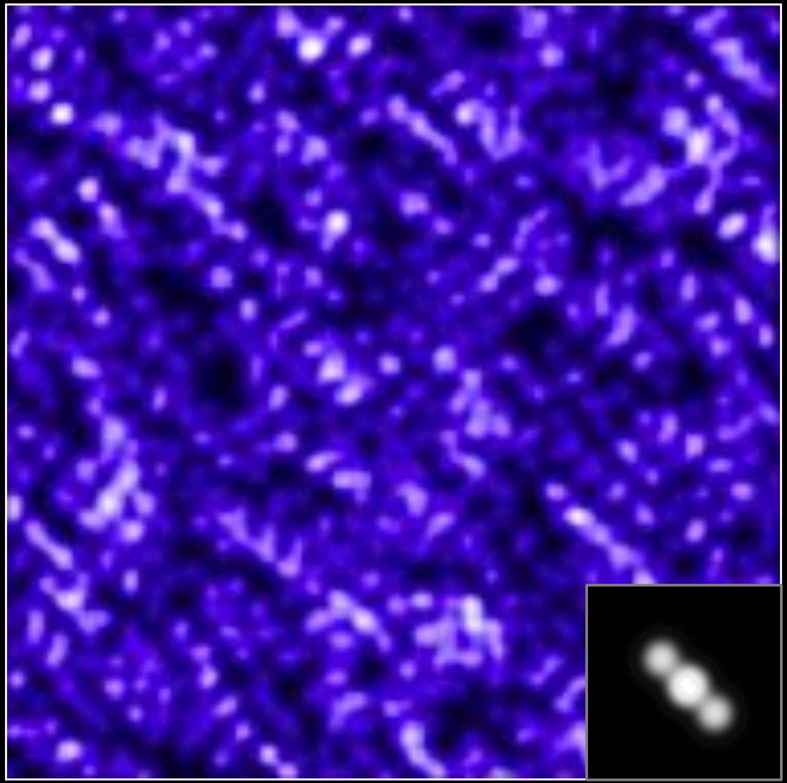
M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Static Nematic Electronic Structure vs Simulation

Data, $g(\boldsymbol{r}, E=-37meV)$



Simulation, 1000 impurities ~ 3% doping



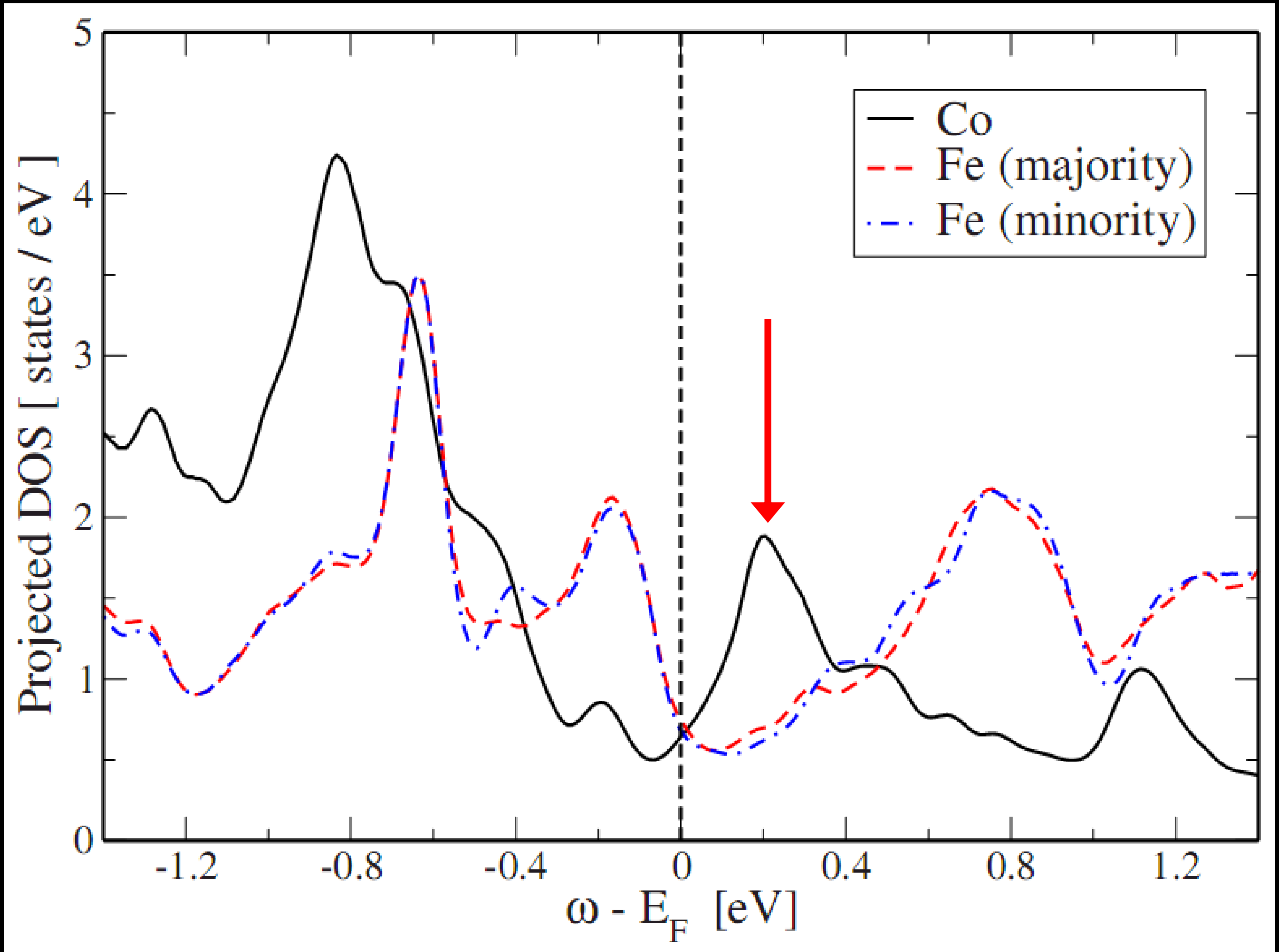
Consistent with real-space electronic structure.

M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Where Are Cobalt Dopant Atoms?

What Role Do They Play?

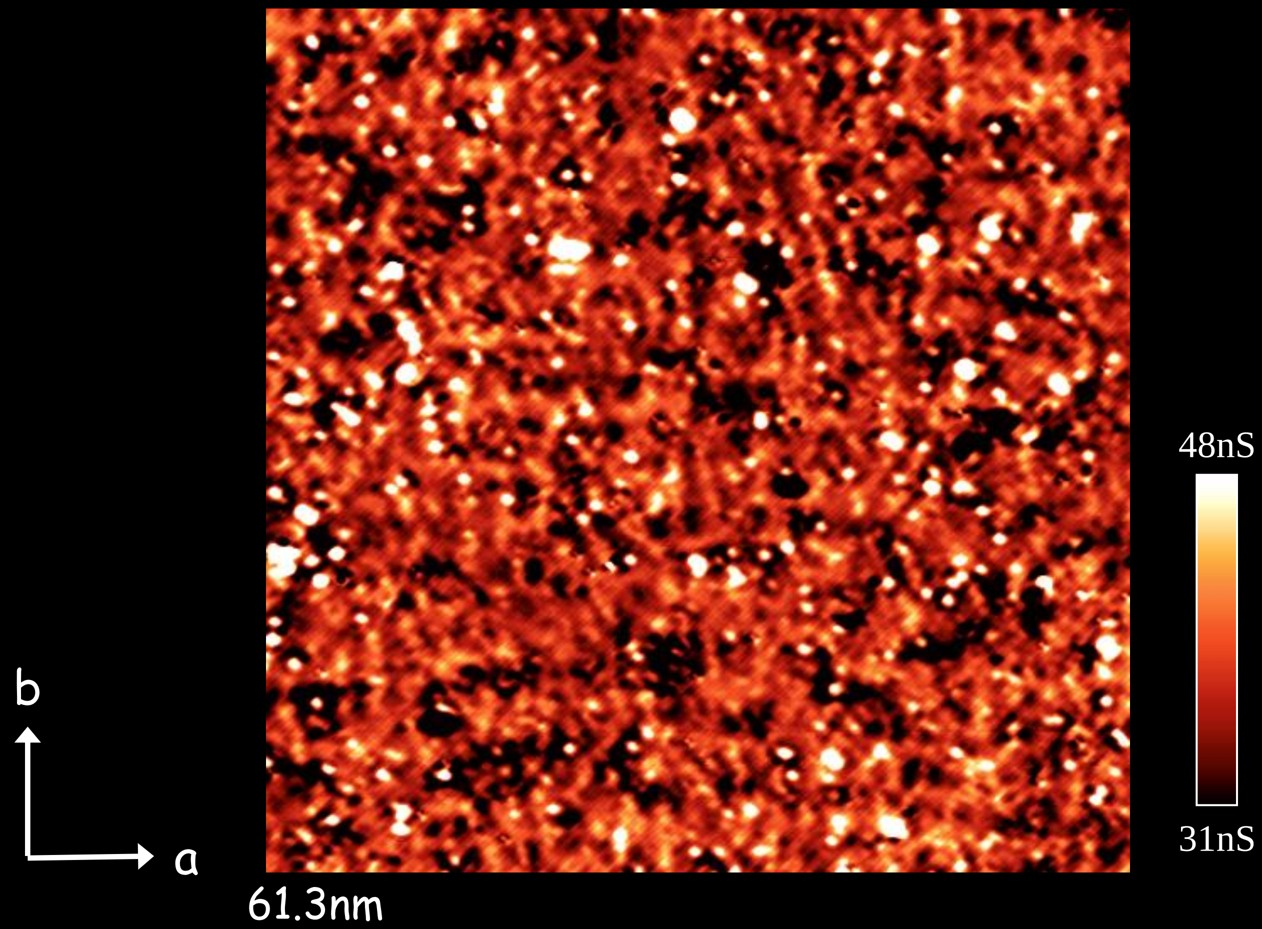
Atom-projected DOS for Co Dopants



A. F. Kemper *et al.*, PRB **80**, 104511 (2009)

Possible Identification of Co Dopants

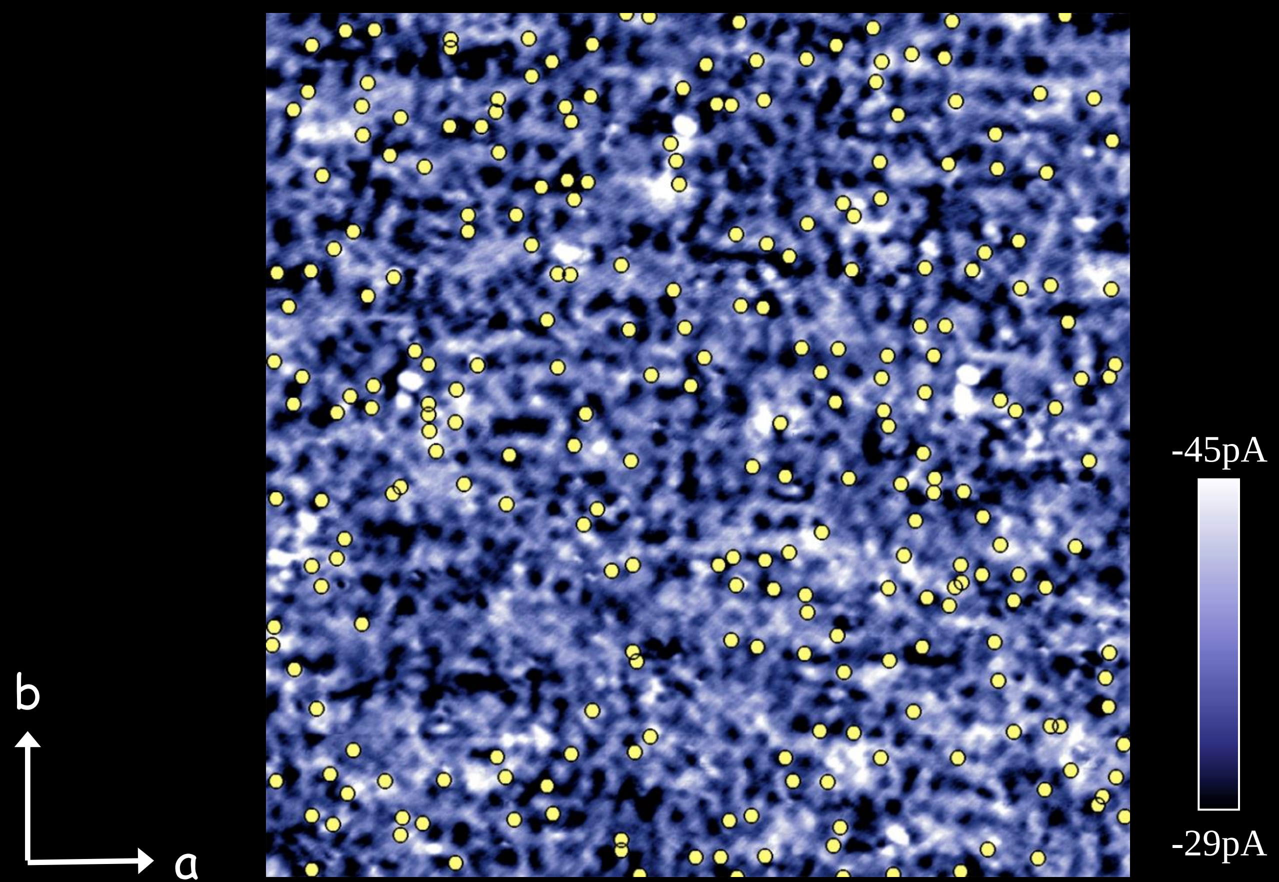
$g(\vec{r},+150mV)$



T.-M. Chuang *et al.*, Science **327**, 181 (2010)
M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Correlation between Co and Static Electronic Structure

$I(\vec{r},+50mV)$ + Co Dopants



Normalized cross-correlation=0.22

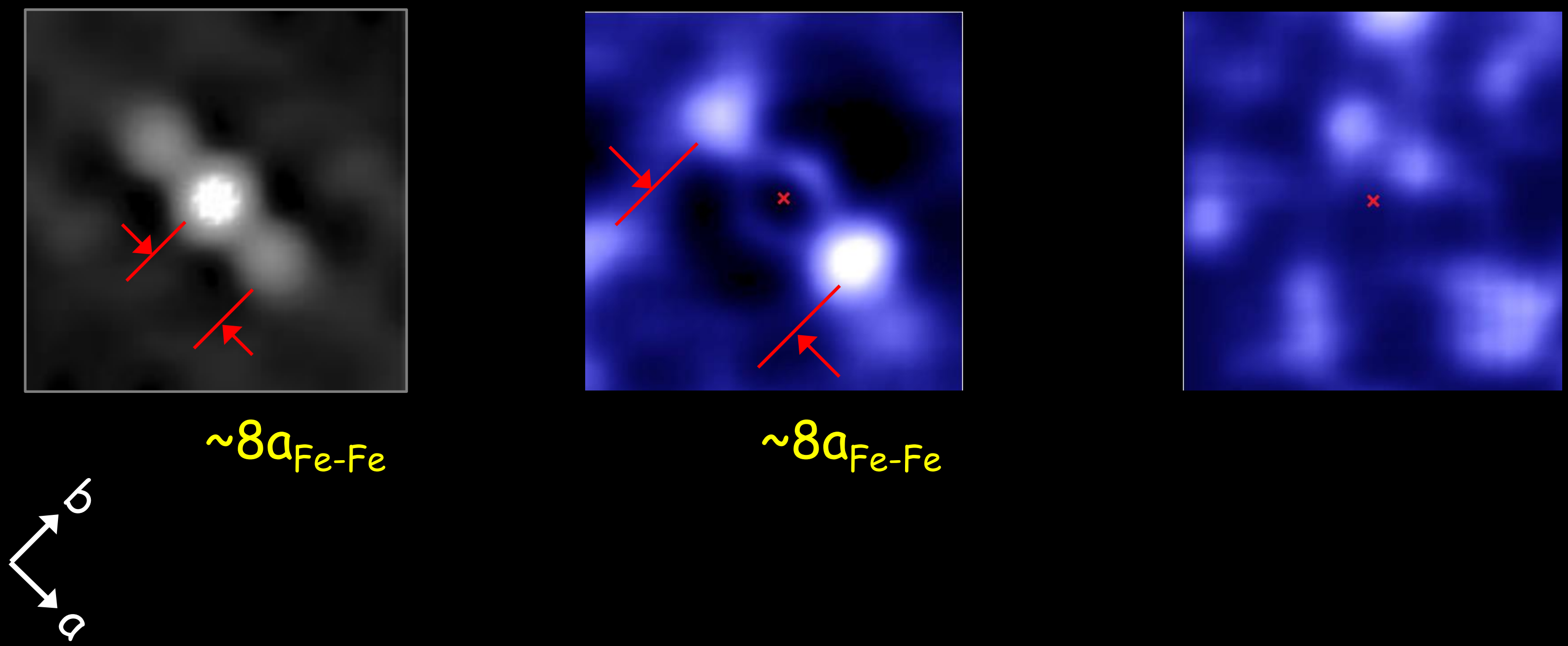
T.-M. Chuang *et al.*, Science **327**, 181 (2010)
M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Anisotropic Impurity States Induced or Pinned by Co Atoms

Autocorrelation of I-map

Averaged I-map around Co

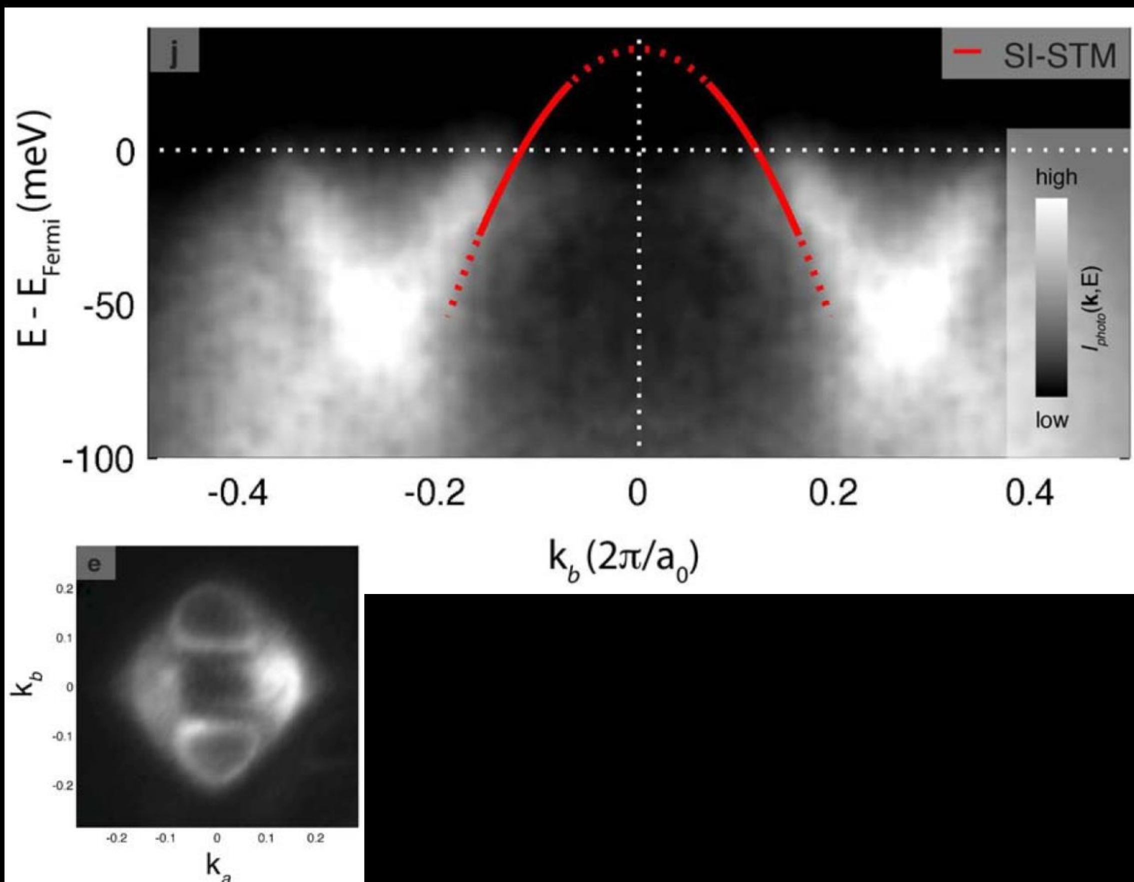
Averaged I-map away from Co

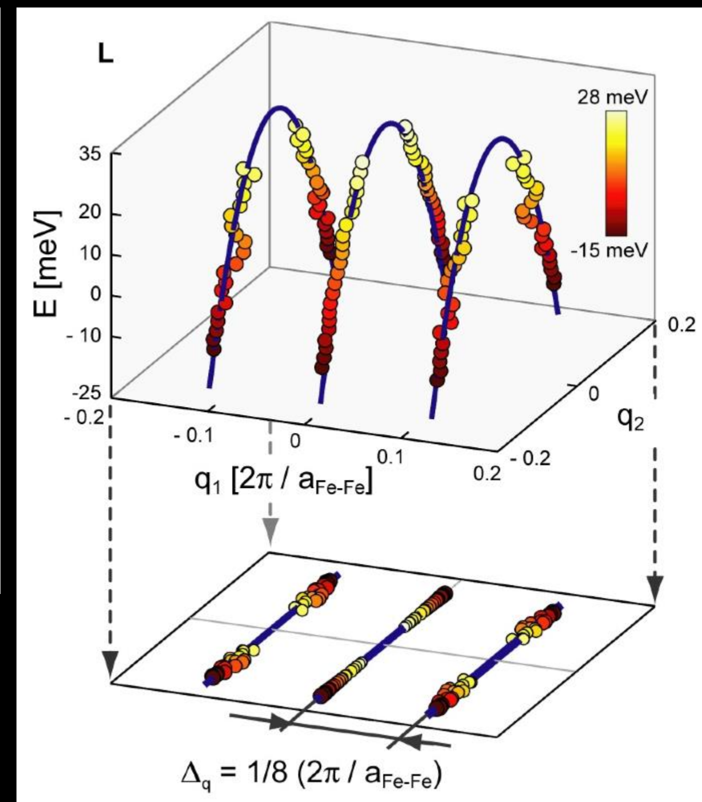


M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Reconcile QPI and ARPES

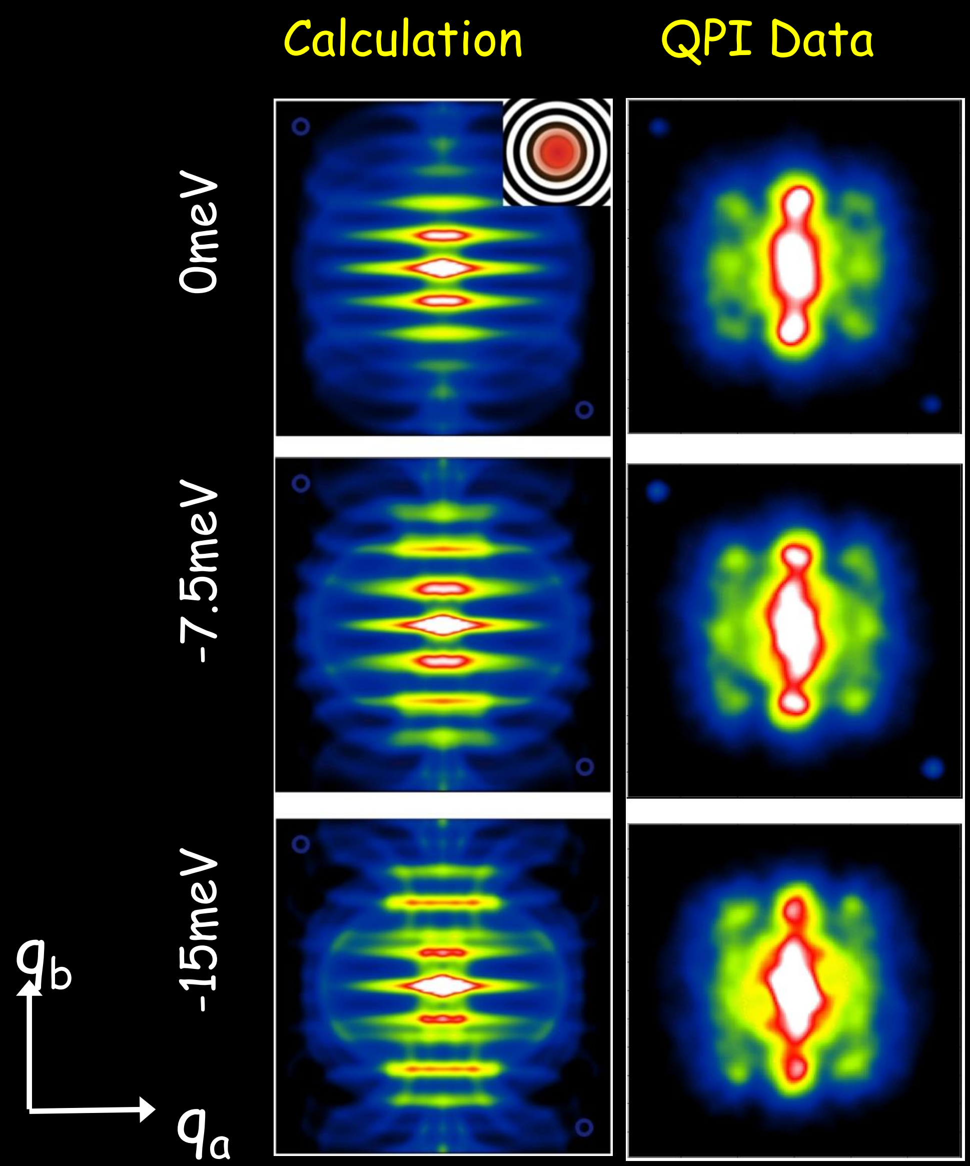
QPI from $\alpha 2$ band at Γ ⟷ Additional symmetry breaking?





M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Impact of Anistropic Impurity State on QPI



Power spectral density in differential conductance modulation

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

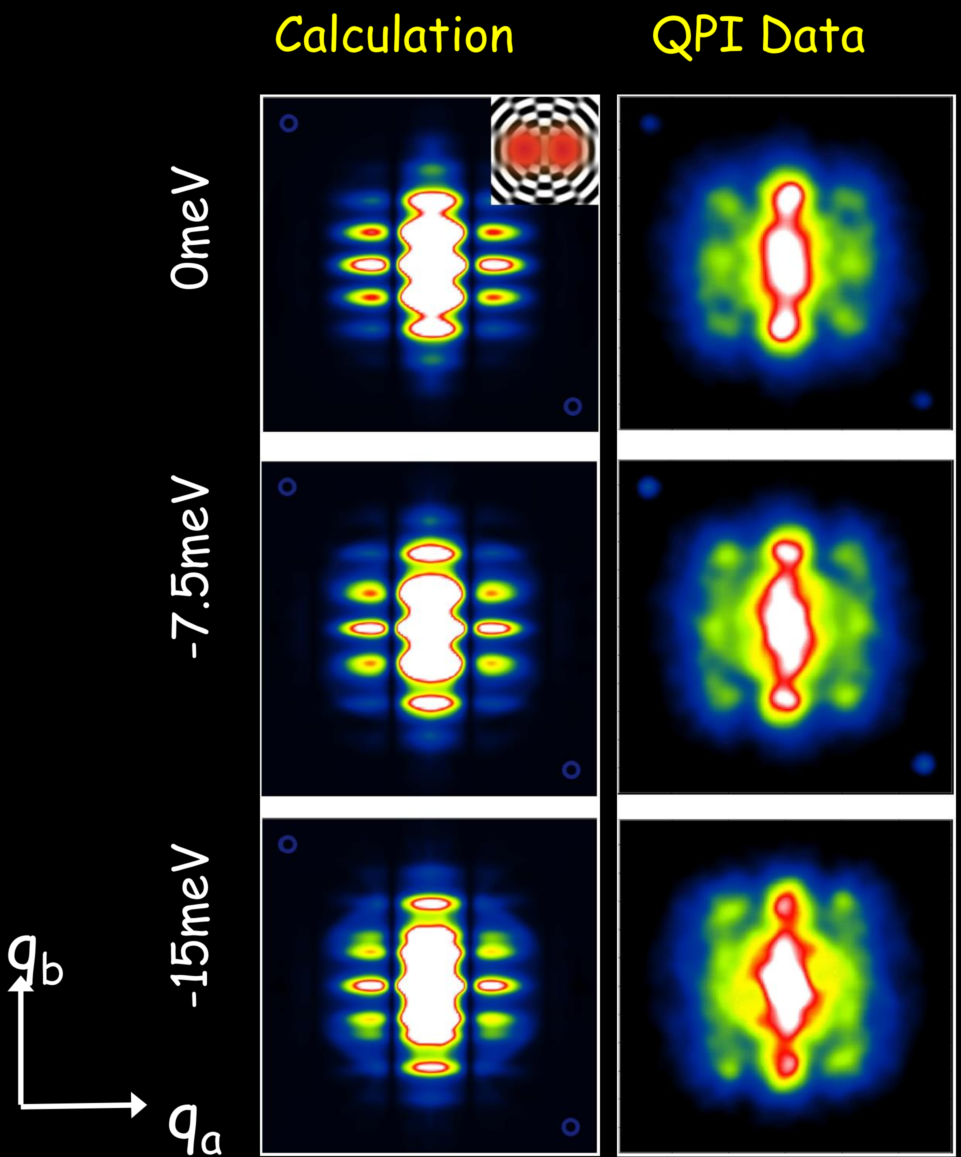
Bare QPI

Structure Factor : FFT of r-space scattering potential

Capriotti *et al.*, PRB 68, 014508 (2003)

M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Impact of Anistropic Impurity State on QPI



Power spectral density in differential conductance modulation

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Bare QPI

Structure Factor :
FFT of r-space scattering potential

Capriotti *et al.*, PRB 68, 014508 (2003)

M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Reconcile with Transport Anisotropy?

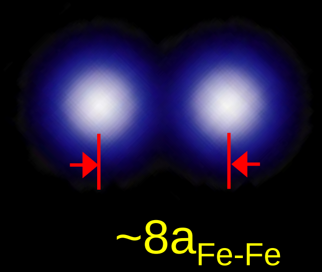
Scattering Rate in Born Approximation

Boltzman transport equation :

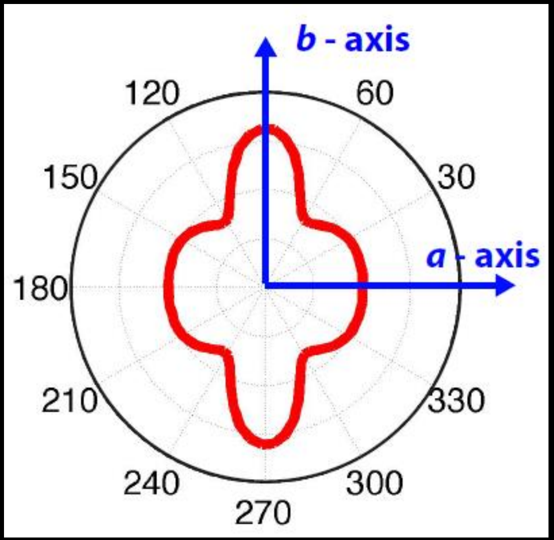
$$-\mathbf{v}_\mathbf{k} \cdot e \frac{\partial f^0_\mathbf{k}}{\partial E(\mathbf{k})} \mathbf{E} = \int \mathrm{d}\mathbf{k}' \, P(\mathbf{k} - \mathbf{k}') \left\{ (f_\mathbf{k} - f^0_\mathbf{k}) - (f_{\mathbf{k}'} - f^0_{\mathbf{k}'}) \right\}$$

Band structure

Scattering



Scattering probability



Scattering is anisotropic and q-dependent

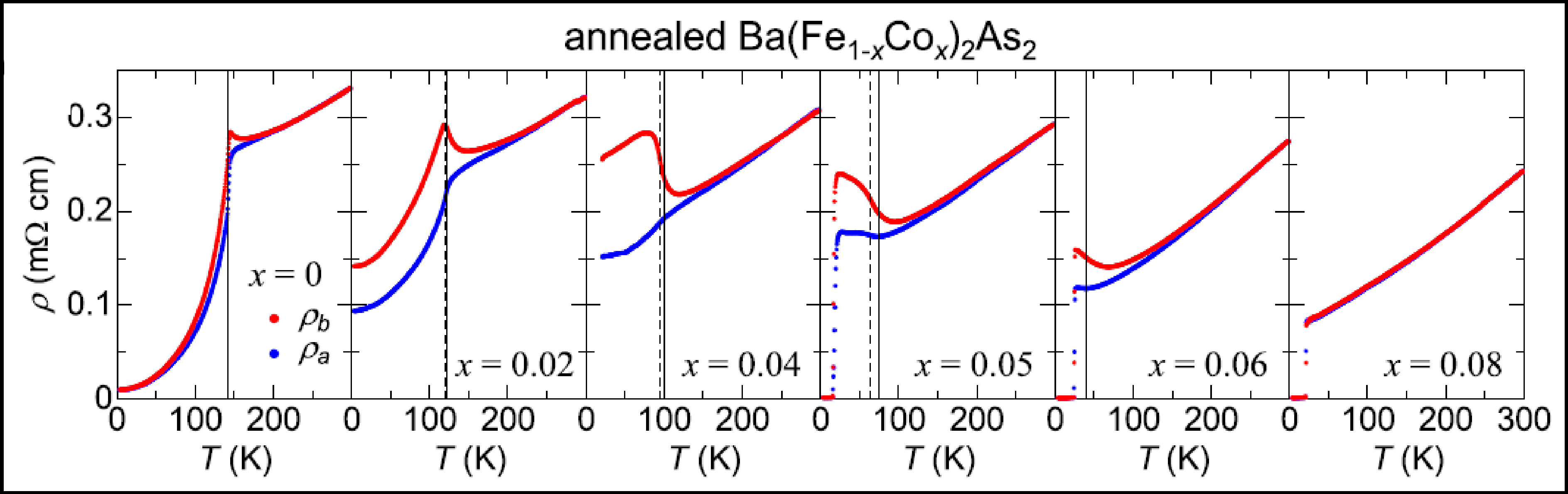
→ possible strong influence on transport.

Effective scattering rates also depend on the Fermi surface

M.P. Allan *et al.*, Nature Phys. 9, 220 (2013)

Consistent with Recent Transport Measurements

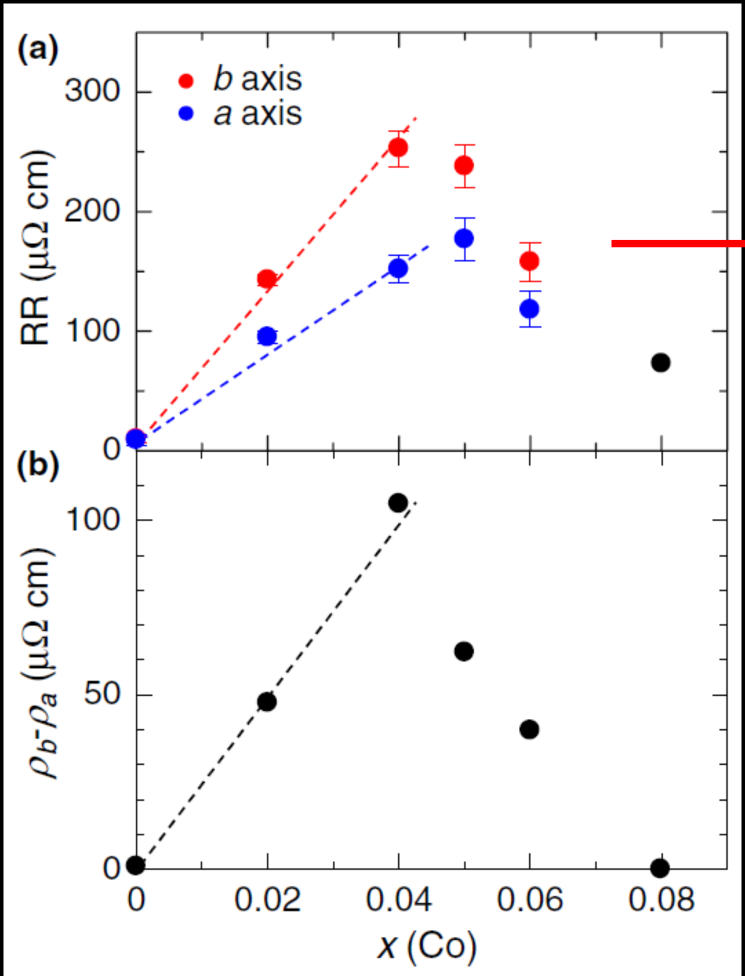
ρ_a and ρ_b show similar T dependence in the AFO phase.
→ T-dependent component of resistivity is nearly isotropic.



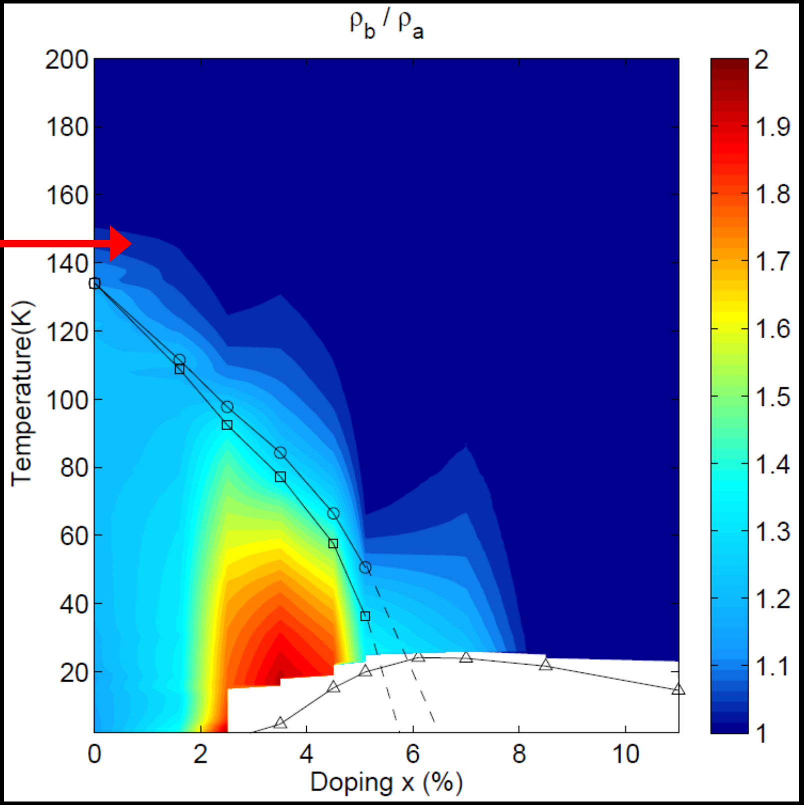
S. Ishida *et al*. PRL **110**, 207001 (2013)

Consistent with Recent Transport Measurements

The anisotropy in resistivity in AFO arises from the anisotropy in the residual component which increases in proportion to the Co concentration x.



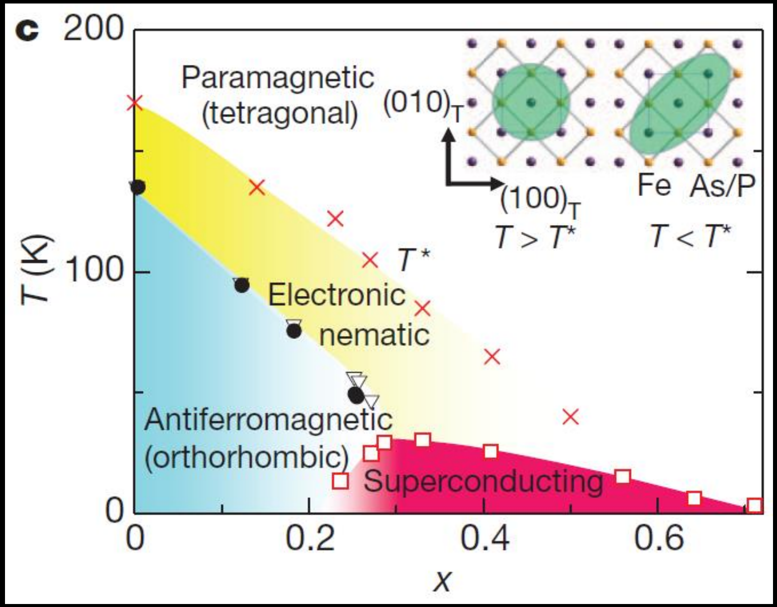
S. Ishida *et al*. PRL **110**, 207001 (2013)



J.-H. Chu *et al*., Science **329**, 824 (2010)

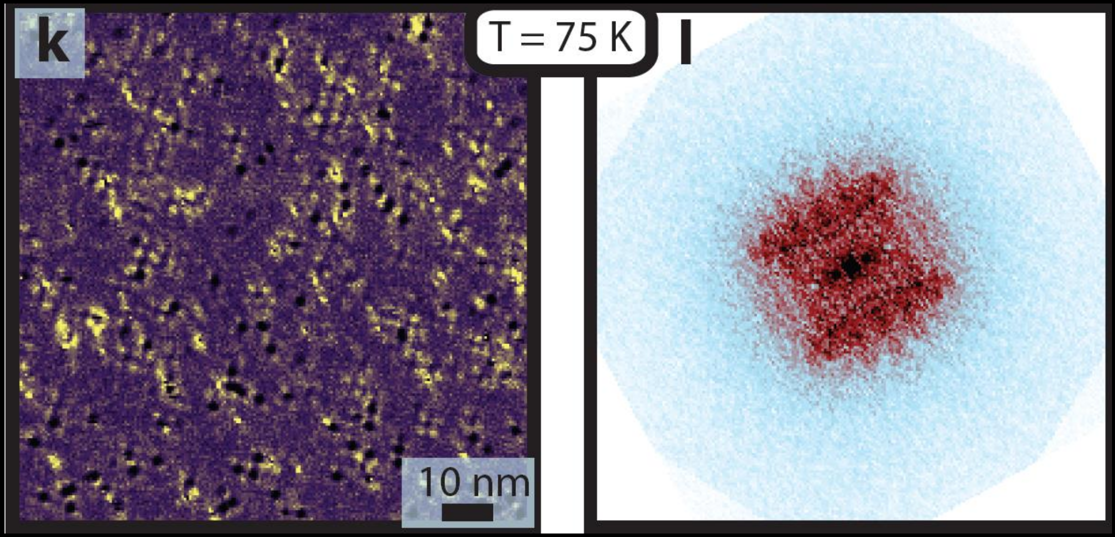
Nematicity above T_s and T_c

$BaFe_2(As_{1-x}P_x)_2$



S. Kasahara *et al.*, Nature **486**, 382 (2012)

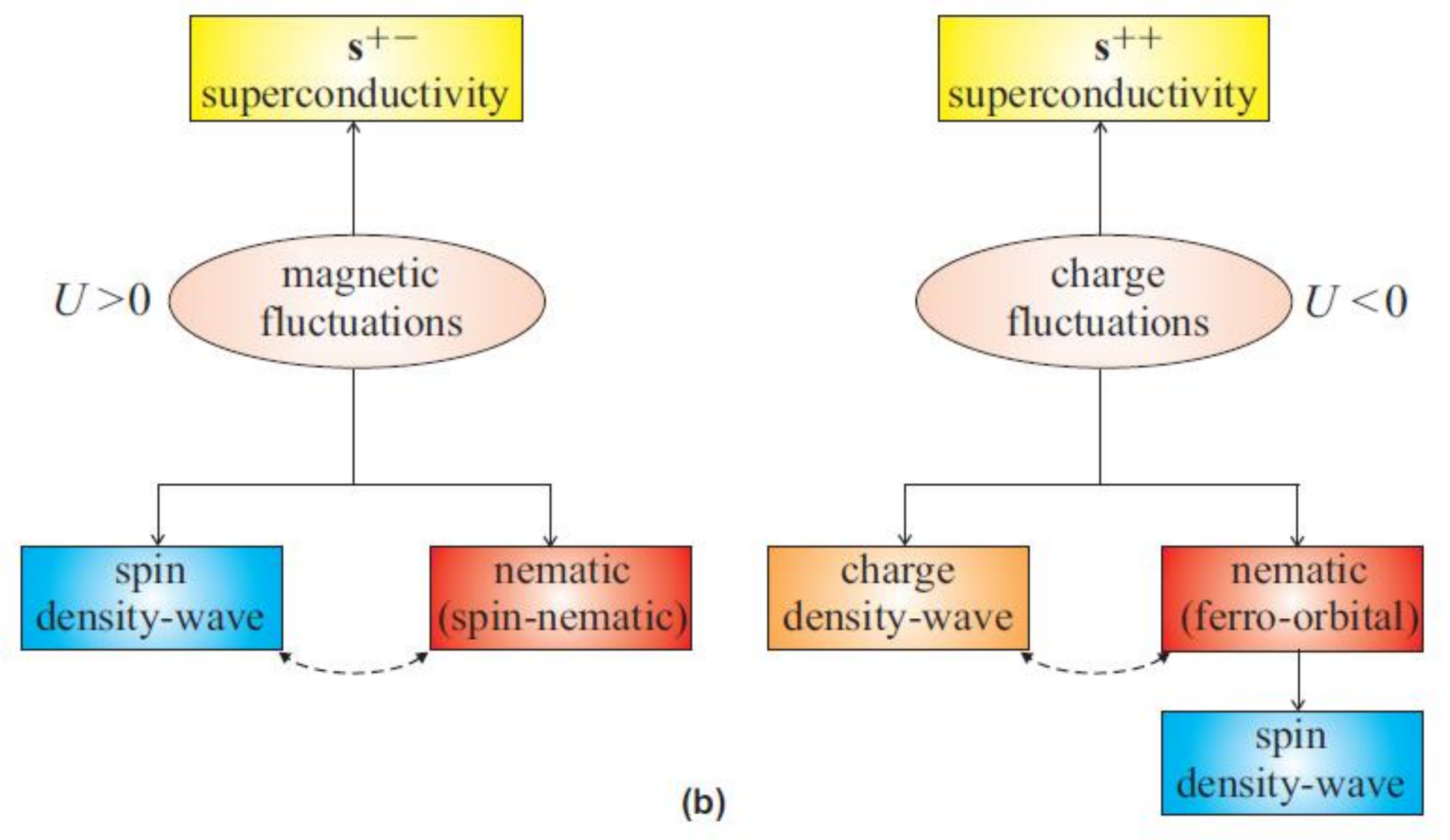
NaFeAs : T_s=52K, T_N=41K



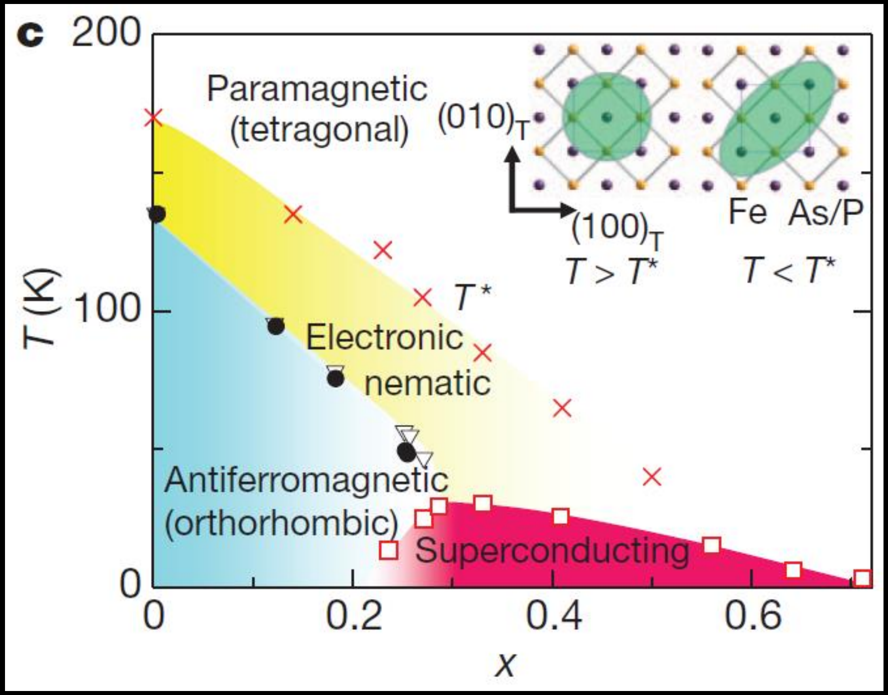
E. P. Rosenthal *et al.*, NatPhys 10, 225 (2014)

What drives the large nematic susceptibility?

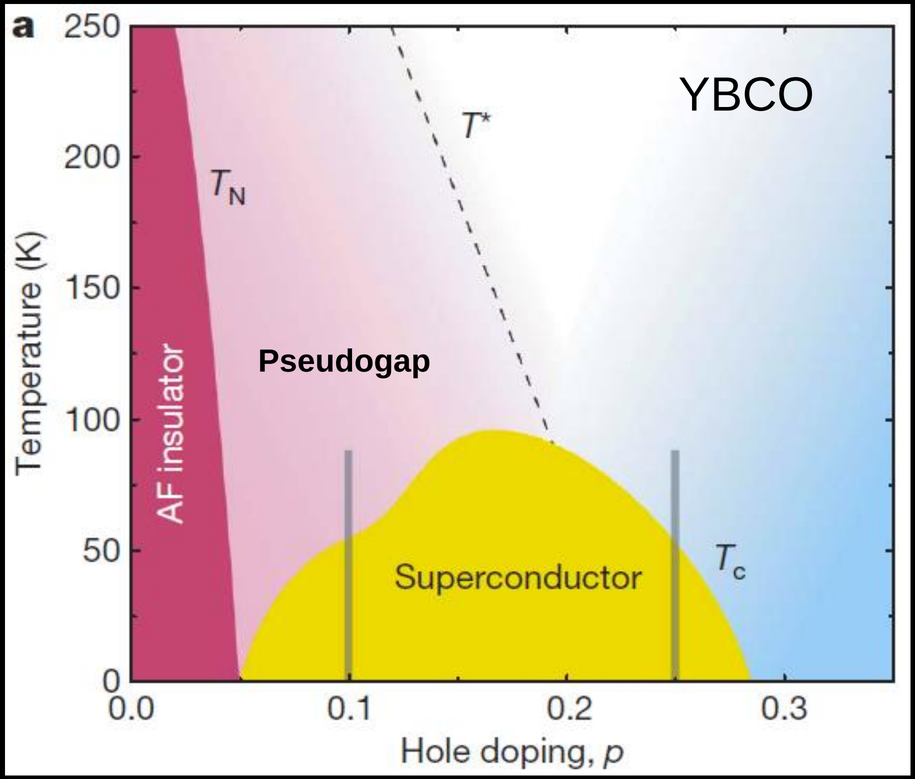
Nematicity Relevant to High T_c FeSC?



Nematicity Relevant to High T_c Superconductivity?



S. Kasahara *et al.*, Nature 486, 382 (2012)

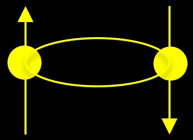


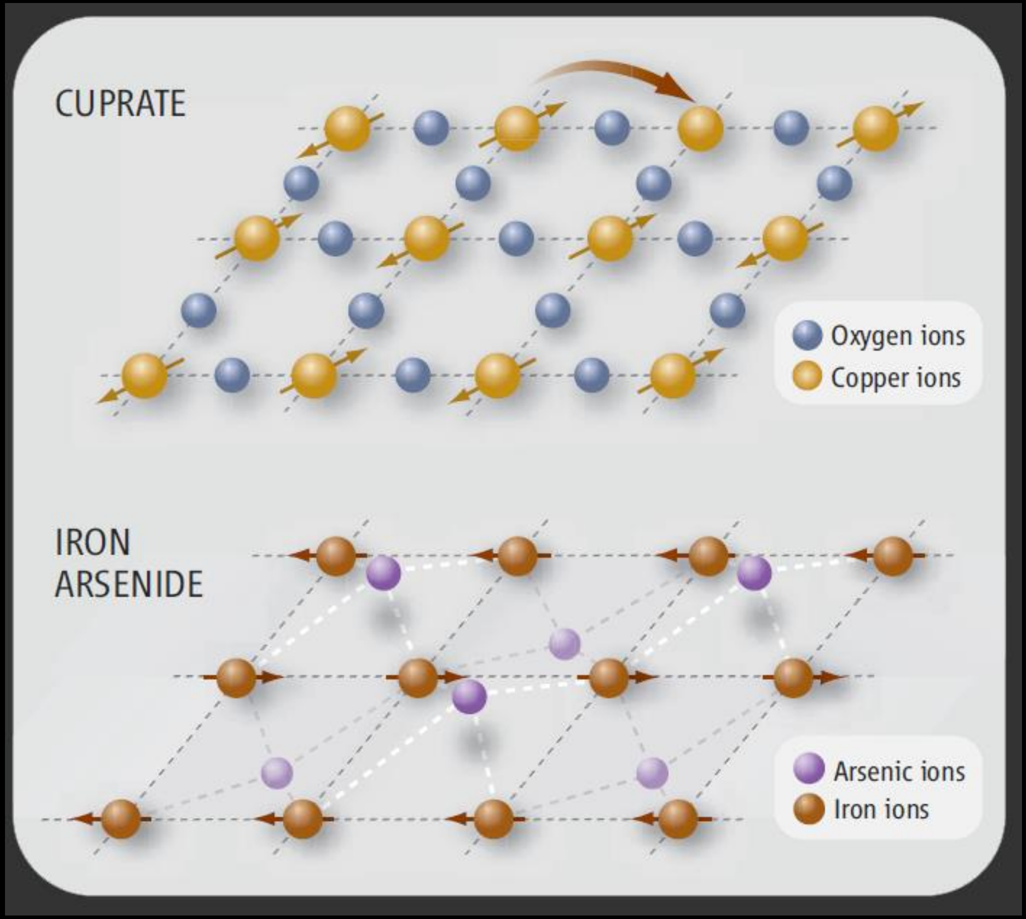
N. Doiron-Leyraud *et. al.*, Nature 447, 565 (2007)

FeSC vs Cuprates : Superconducting Layer

Both have antiferromagnetic 'parent' states.

Cooper pairing mediated by AF ?





$d_{x^2-y^2}$

5 d-orbitals

A. Cho, Science **320**, 870 (2008)

FeSC: Unconventional Superconductivity

1. The electron-phonon coupling is too weak to account for such high T_C.

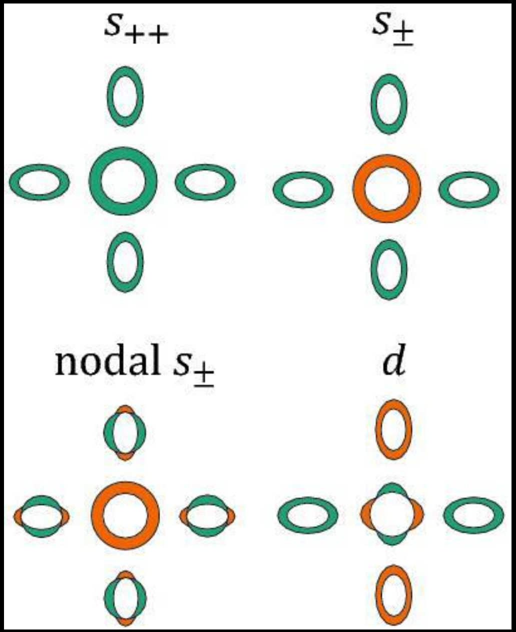
L. Boeri *et al.*, PRL 101, 026403 (2008)

2. Isotope effect on some materials shown to be negligible.

P.M. Shirage *et al.*, PRL 105, 037004 (2010)

3. Everything seems to work – doping / pressure / different structures

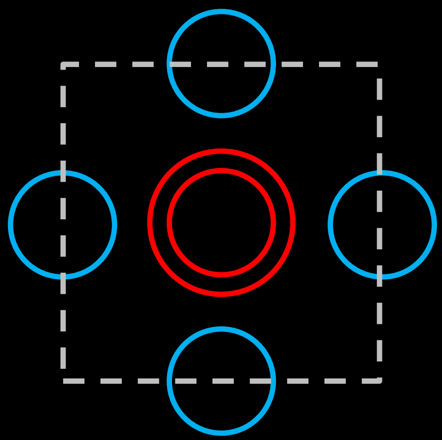
Possible pairing symmetries



FeSC: Candidates for Pairing Mechanism

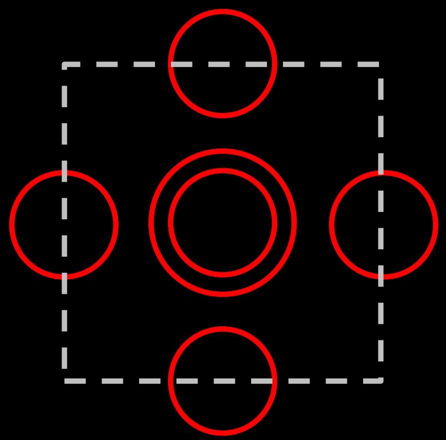
SDW suppression leads to SC
→ AF Spin Fluctuation Exchange.
→ S± OP symmetry

I. I. Mazin *et al*., PRL 101, 057003 (2008)
K. Kuroki *et al*., PRL 101, 087004 (2008)
K. Seo *et al*., PRL 101, 206404 (2008).



Orbital Fluctuation → S++ OP symmetry

H. Kontani *et al*., PRL **104**, 157001 (2010)



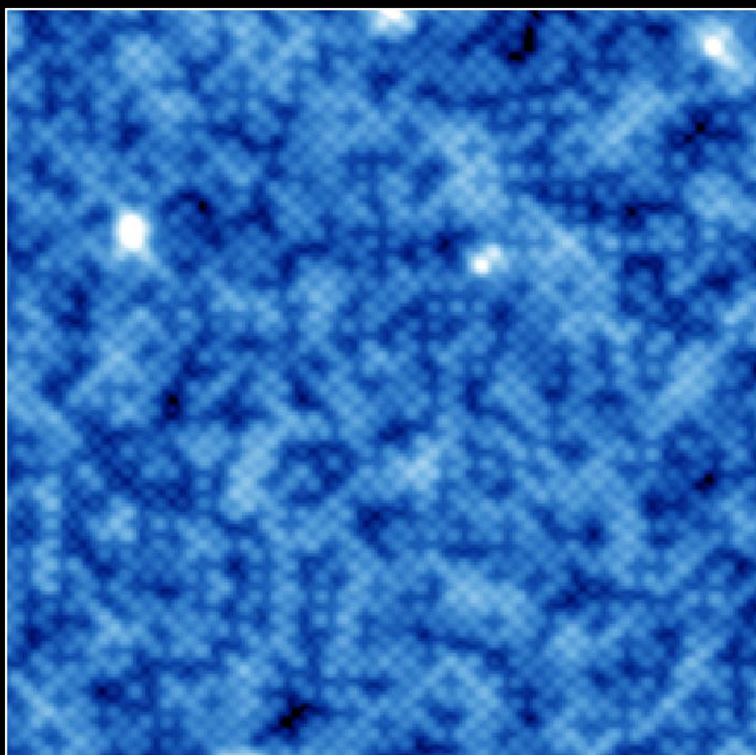
Gap symmetry?
Phase sensitive measurements required!

STM on an iron chalcogenide

T. Hanaguri *et al.*, Science 328, 474 (2010).

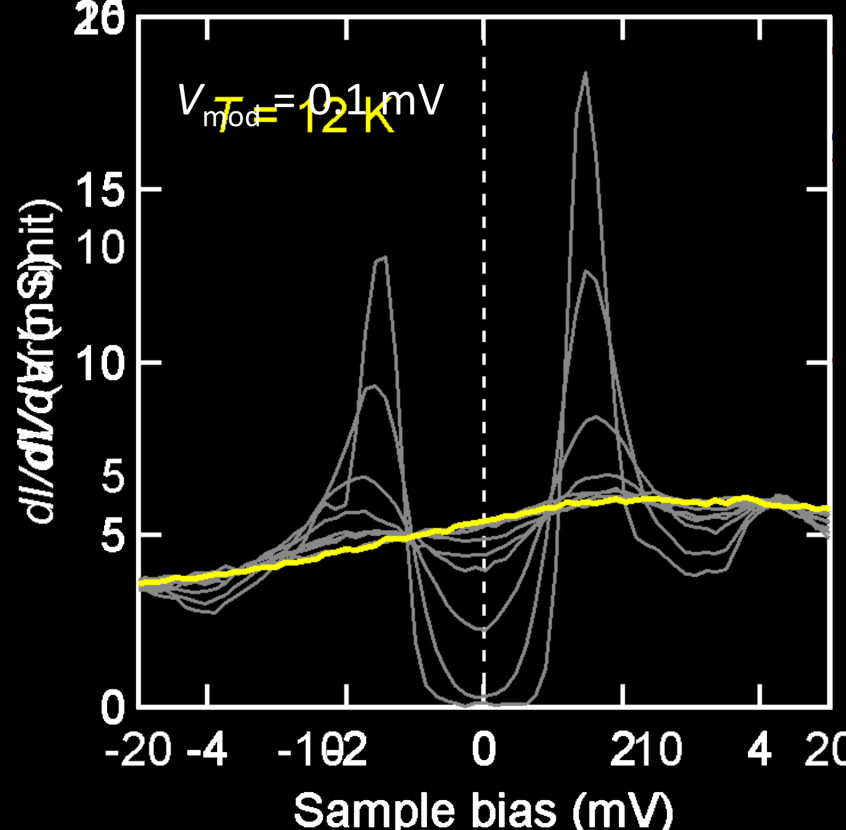
Fe (Se,Te) T_c = 13~14.5 K X'tals grown by Dr. Niitaka (RIKEN)

T ~ 1.5 K



19 nm × 19 nm, -20 mV/0.1 nA

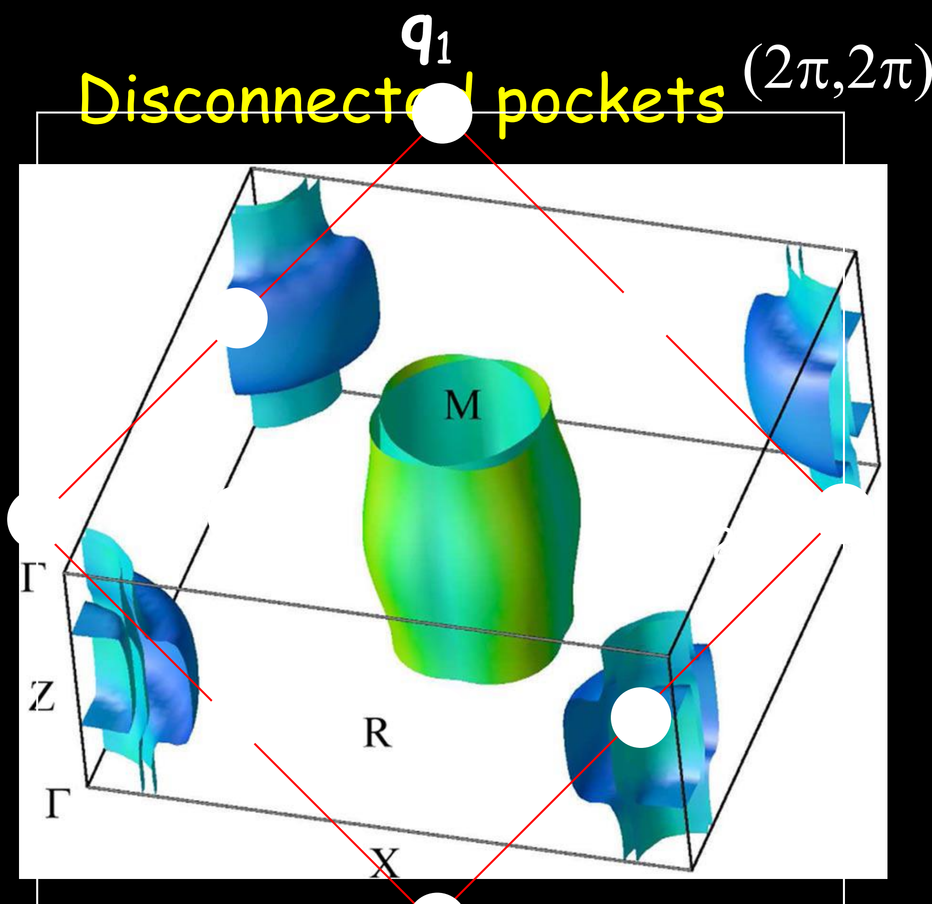
$2\Delta/T_c$ ~ 3.5



SC gap FULLY opens all over the FS pockets.

cf. F. Massee *et al.*, PRB 80, 140507(R) (2009), T. Kato *et al.*, PRB 80, 180507(R) (2009).

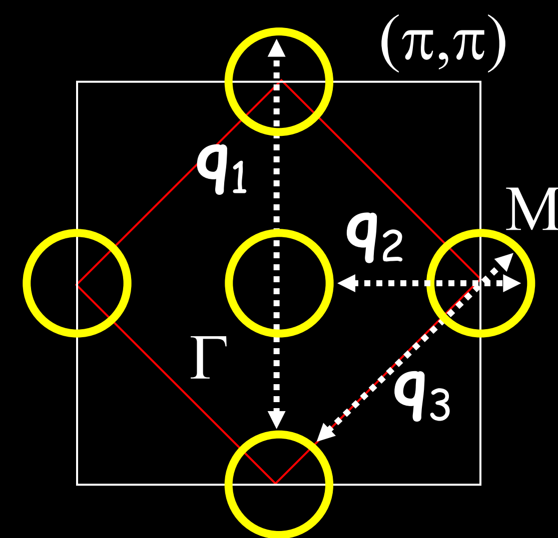
How will it work in iron-based SC?



D. J. Singh and M.-H. D PRL **100**, 237003 (2008).

q space

$E \sim \Delta$



k space

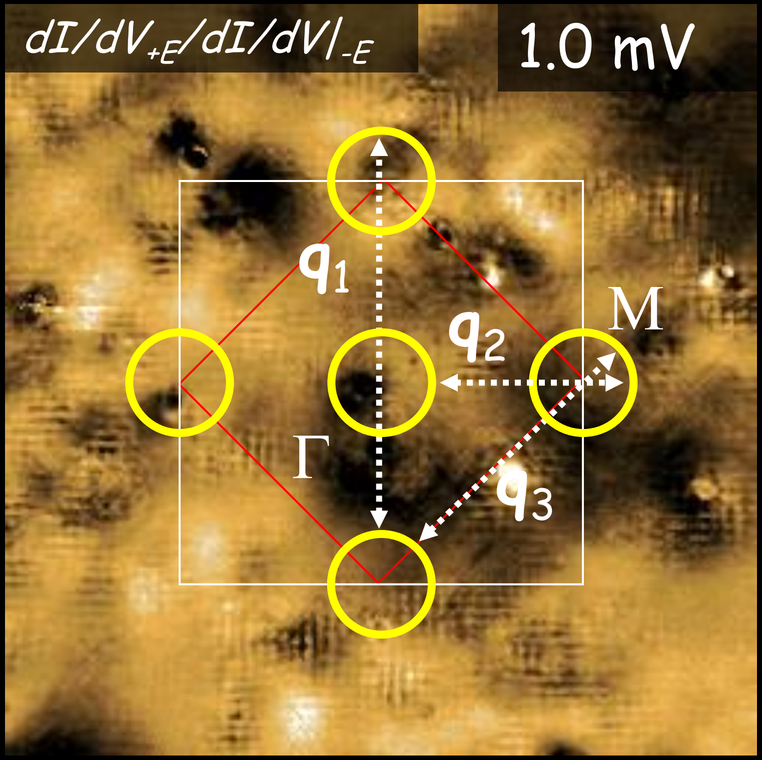
Inter-pocket scattering ⟷ Relationship between the pockets

QPI in an iron chalcogenide

T. Hanaguri *et al.*, Science **328**, 474 (2010).

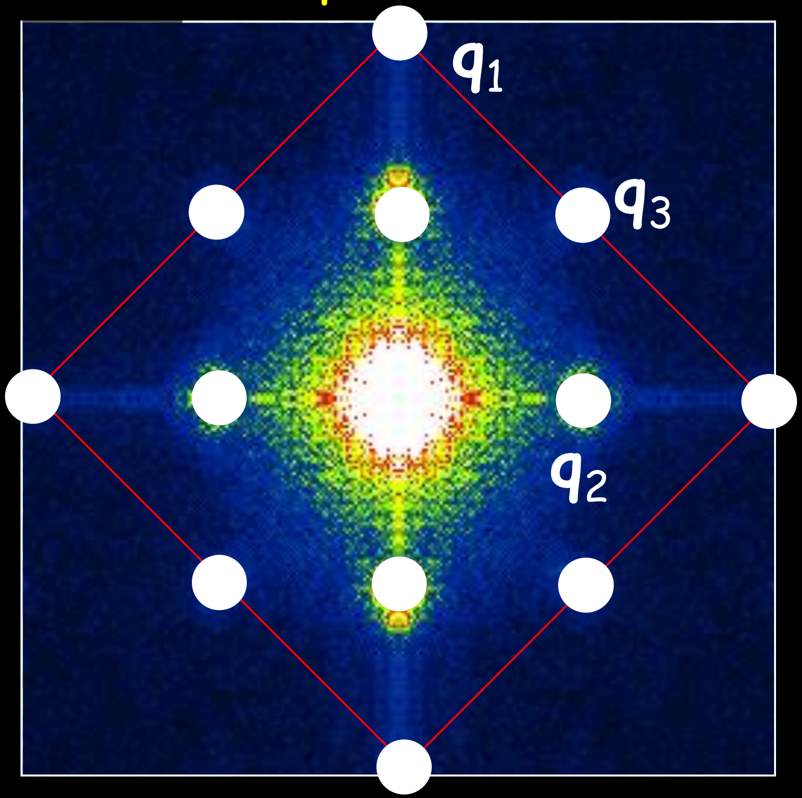
Fe(Se,Te) $T_c \sim 13$ K

$T \sim 1.5$ K



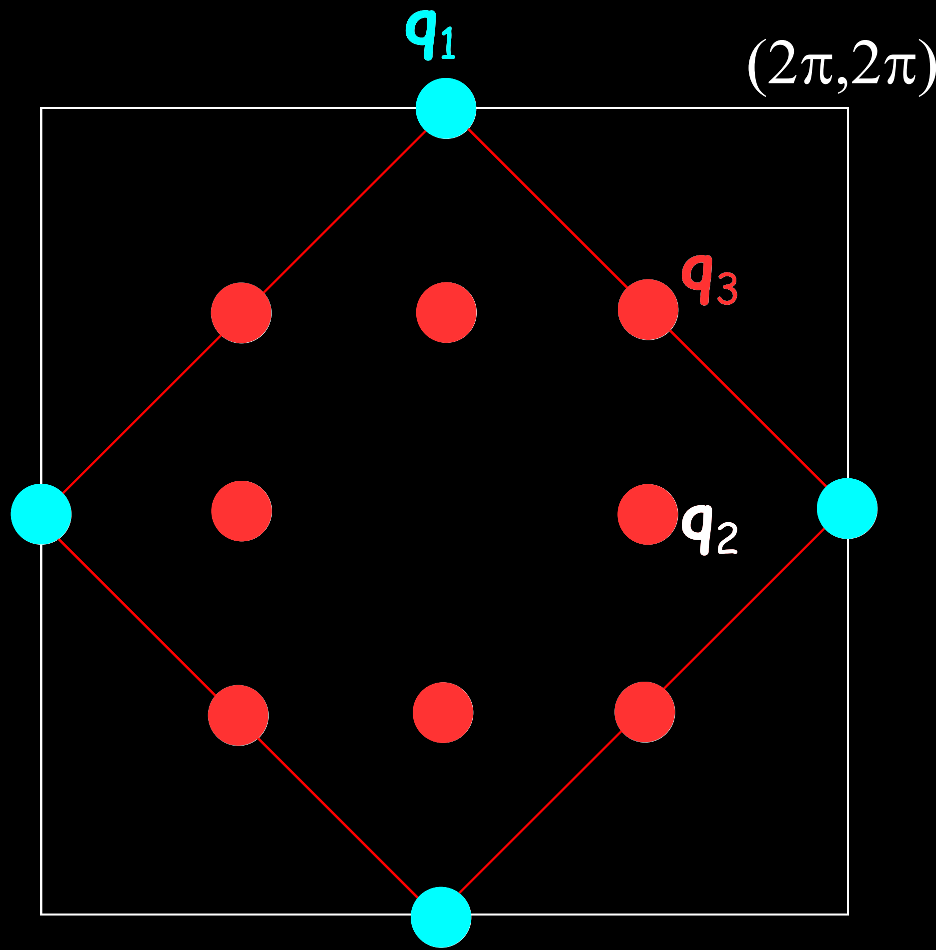
34 nm × 34 nm, -20 mV/0.1 nA

FT-*Z* map 1.0 meV



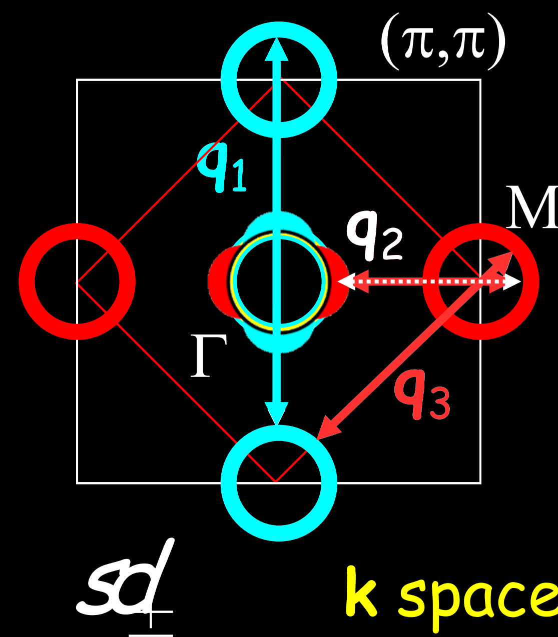
Inter-pocket scatterings are detected.

How to determine the phase?



q space

$E \sim \Delta$



k space

I. I. Mazin *et al.*, PRL **101**, 057003 (2008).
K. Kuroki *et al.*, PRL **101**, 087004 (2008).

- Sign-preserving scattering
- Sign-reversing scattering

cf.
F. Wang, H. Zhai and D. –H. Lee,
EPL **85**, 37005 (2009).
Yan-Yang Zhang *et al.*,
PRB **80**, 094528 (2009).
E. Plamadeala, T. Pereg-Barnea, and G. Refael
PRB **81**, 134513 (2010).

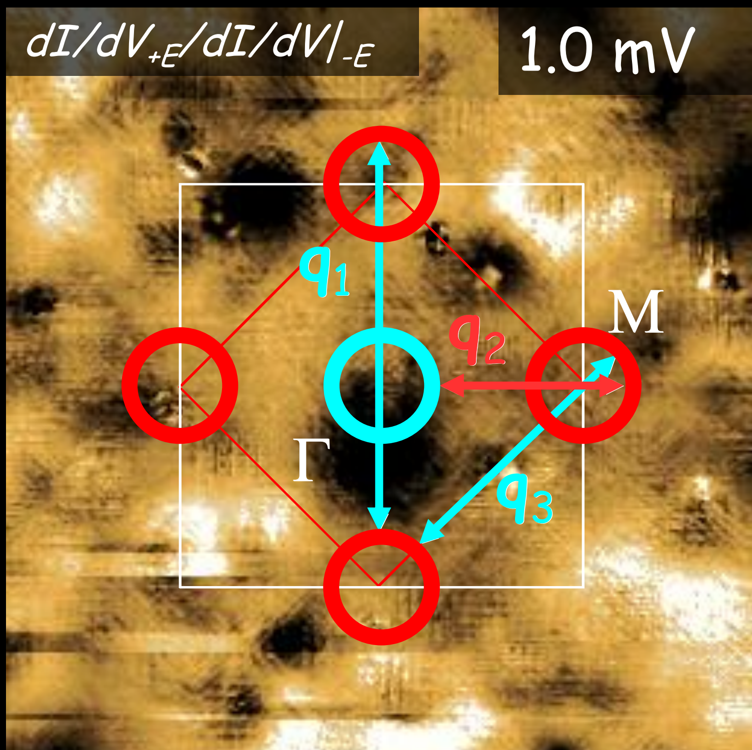
Phase-sensitive STM on an iron chalcogenide

T. Hanaguri *et al.*, Science **328**, 474 (2010).

$Fe_{1+x}(Se,Te)$ $T_c \sim 13$ K

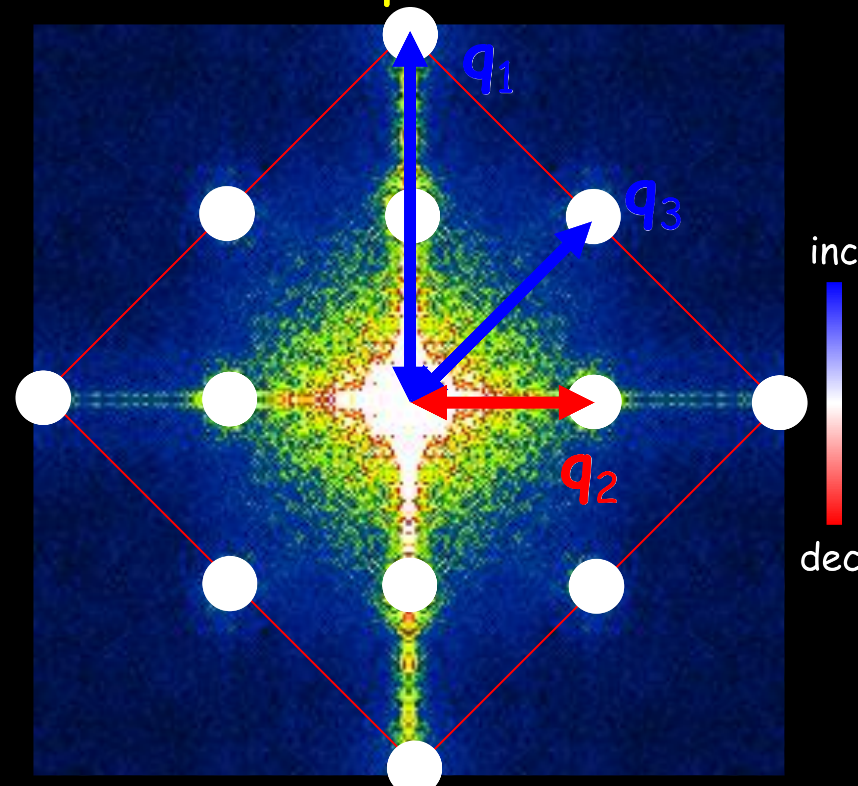
$B = 10$ T

$T \sim 1.5$ K



34 nm × 34 nm, -20 mV/0.1 nA

FT-*Z* map 1.0 meV



Evidence of $s_\pm$-wave symmetry: Spin fluctuation plausible.

Interpocket scatterings are detected.

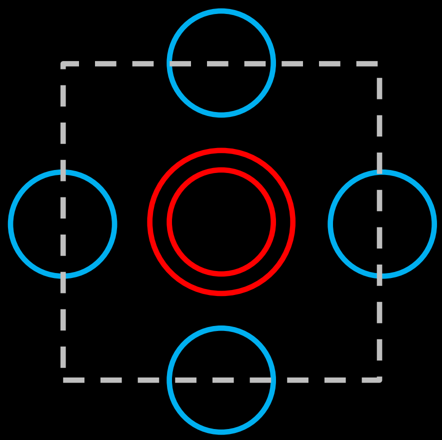
Summary of gap structure of iron-based SC

STM suggests $s_{\pm}$-wave gap in an FeSC!

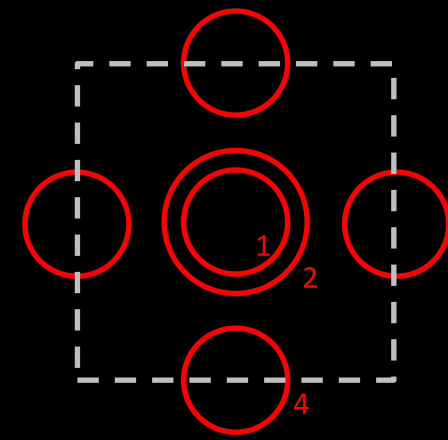
- Tunneling spectrum suggests that the superconducting gap fully opens over the Fermi surface.
- Inter-Fermi-pocket scatterings are identified in quasi-particle interference patterns, providing momentum-resolved information of the superconducting gap.
- Magnetic-field dependence of the quasi-particle interference pattern contains information on the phase of the superconducting gap function. The result on Fe(Se,Te) suggests $s_{\pm}$-wave superconductivity where the gap changes its sign between hole and electron pockets.

FeSC: SC Energy Gap Functions

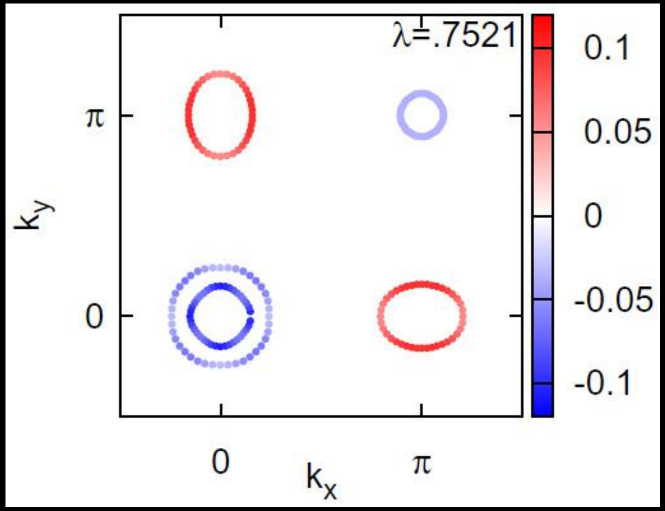
Spin Fluctuation → S± OP symmetry



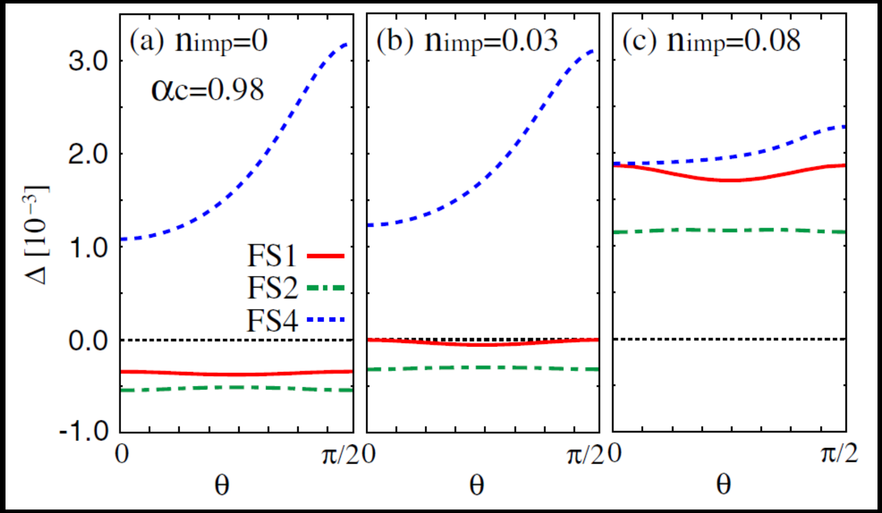
Orbital Fluctuation → S++ OP symmetry



Gaps show different anisotropy at different pockets!



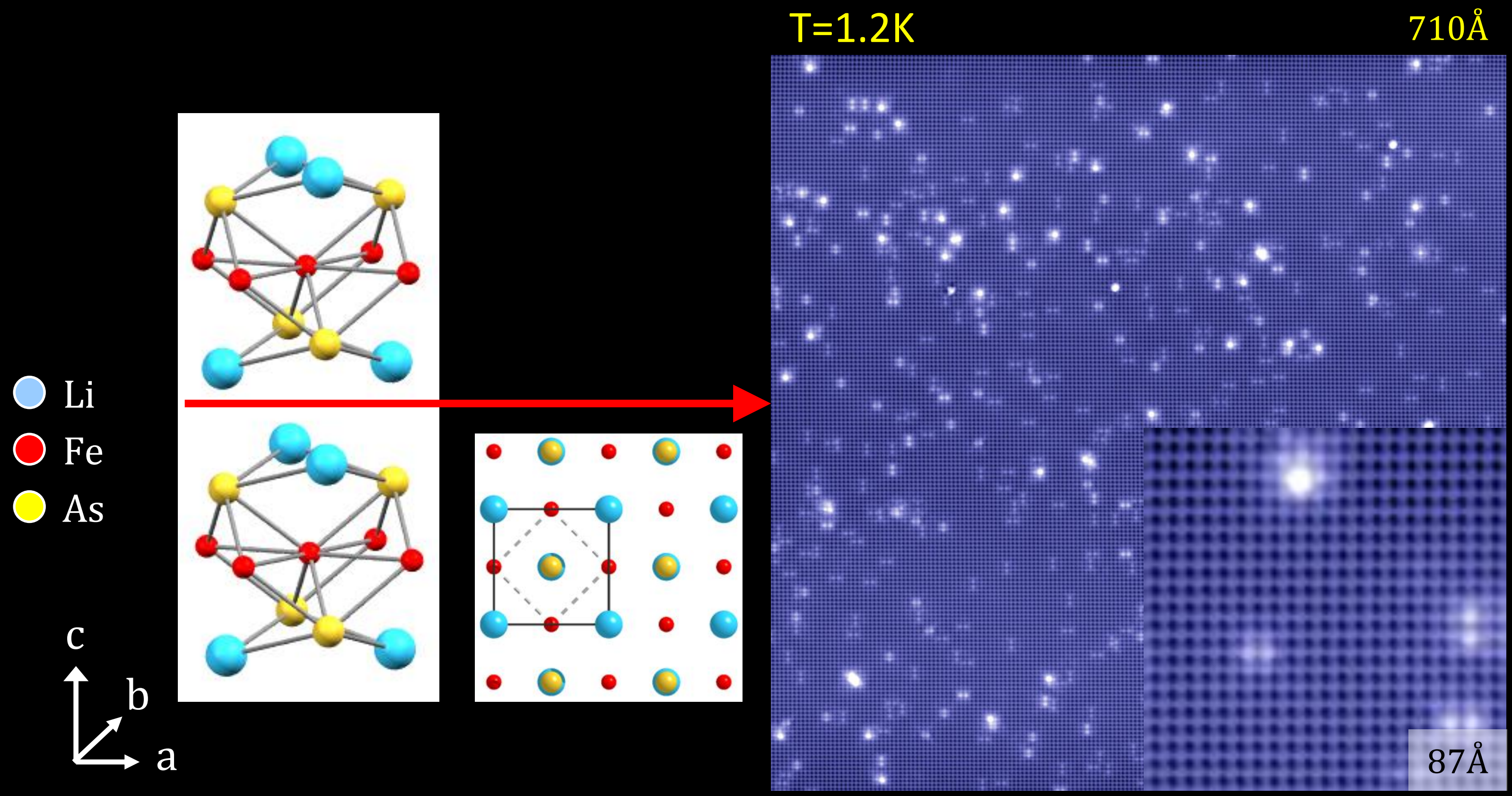
P. J. Hirschfeld *et al.*, Rep.Prog.Phys.**74**,124508 (2011)



H. Kontani *et al.*, PRL **104**, 157001 (2010)

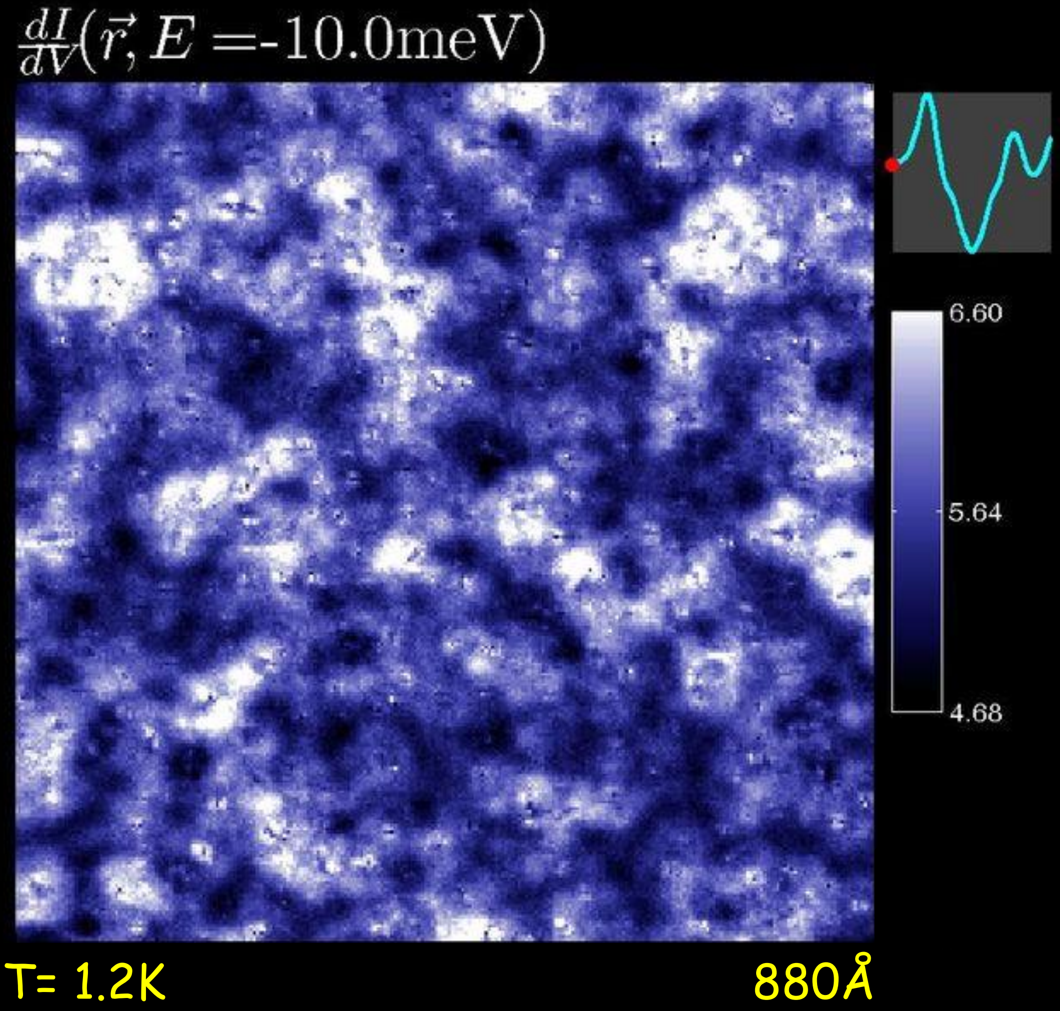
Our Samples : LiFeAs

Charge neutral cleaved surface :No surface states.
Ideal for STM / ARPES !
Large field of view necessary for intra-band QPI measurements!



M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

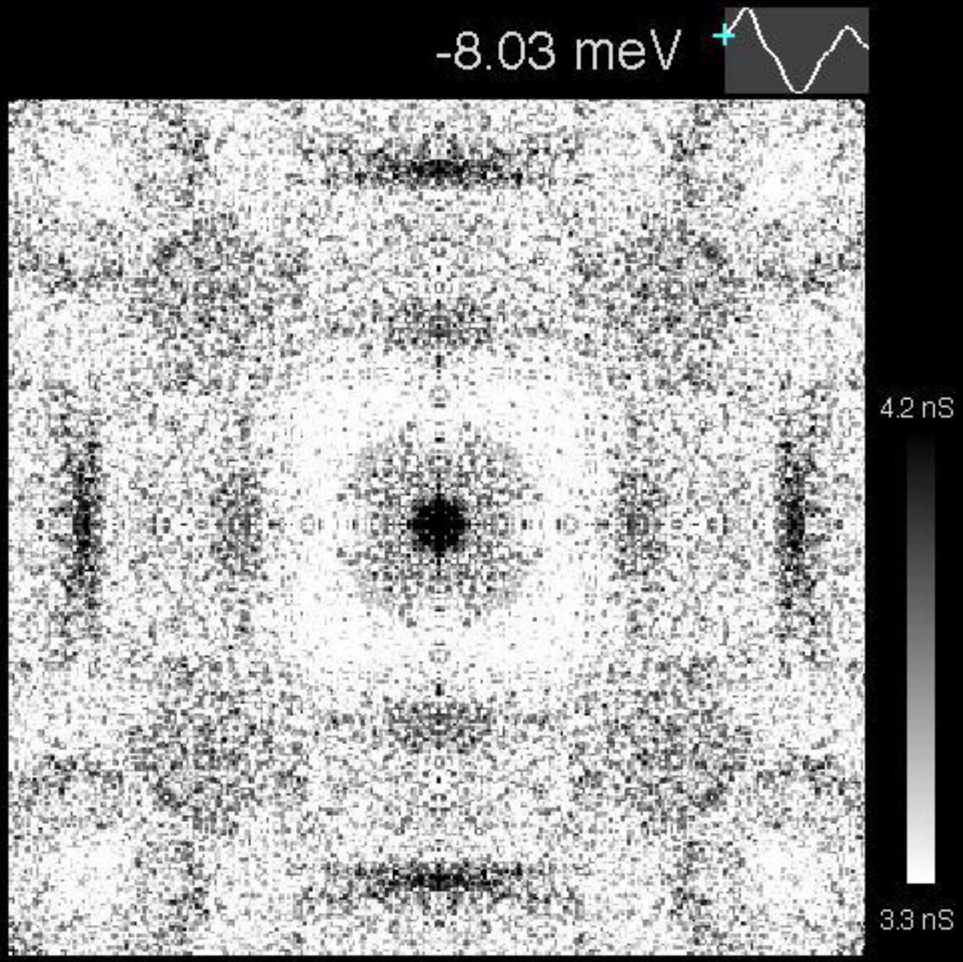
Spectroscopic Imaging, LDOS(r,E)



M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

Quasiparticle Interference, LDOS(q,E)

Fourier Transform of LDOS(r,E) → LDOS(q, E)

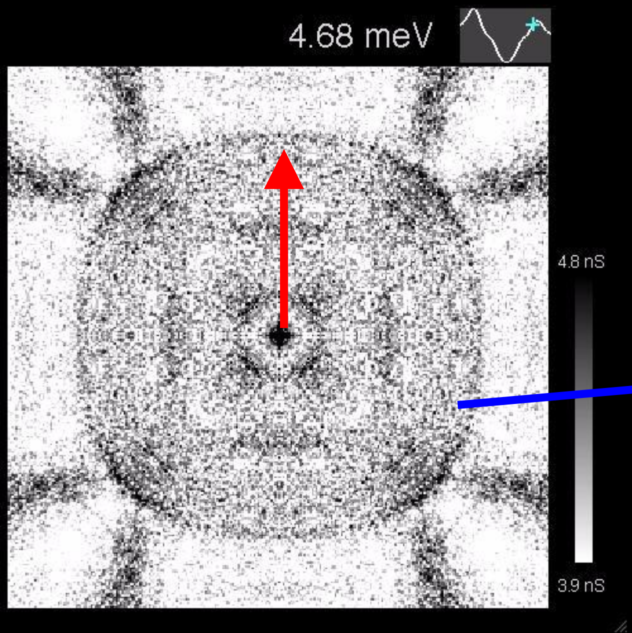


T= 1.2K

880Å

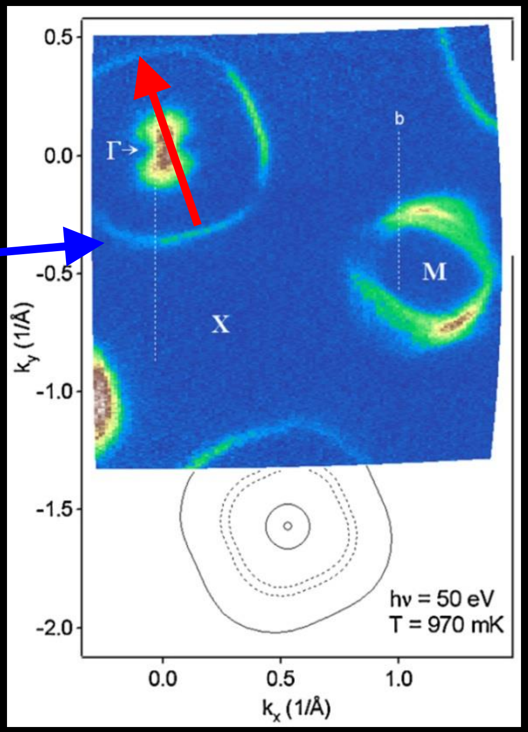
M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

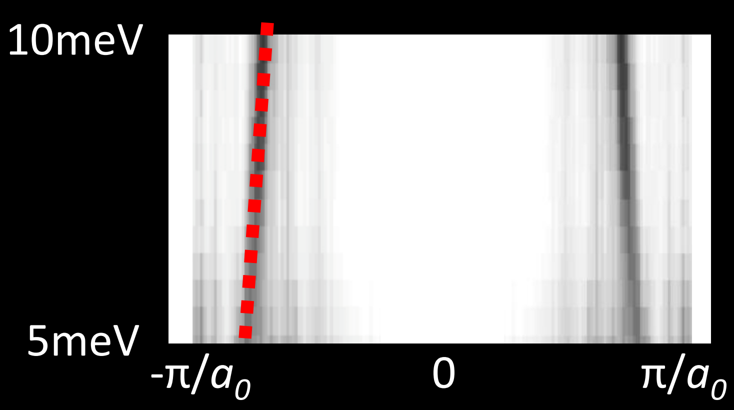
Band Identification by QPI above SC gap



γ band

Identification based on comparison with ARPES and LDA results.

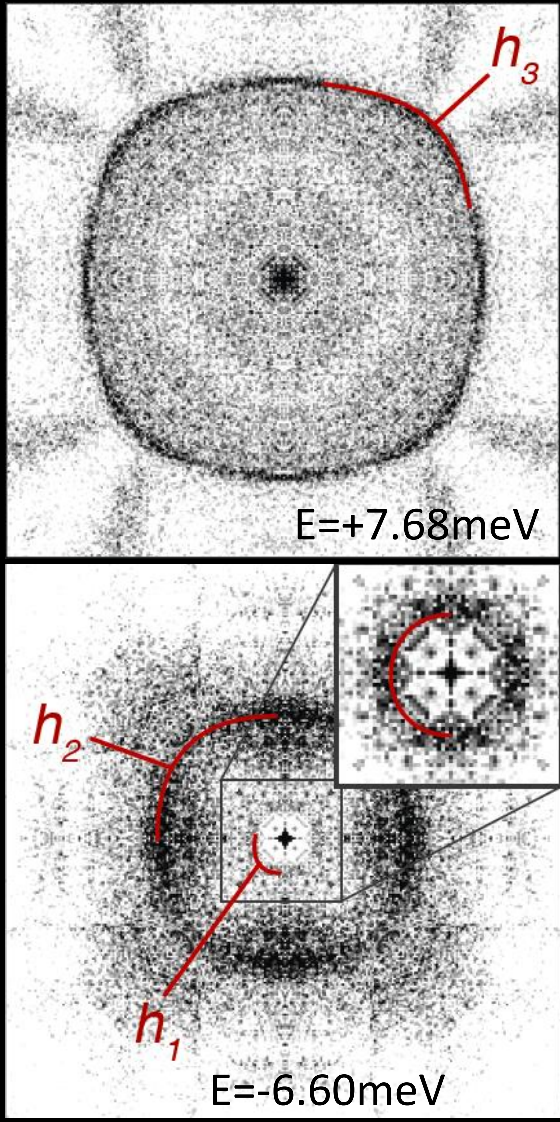


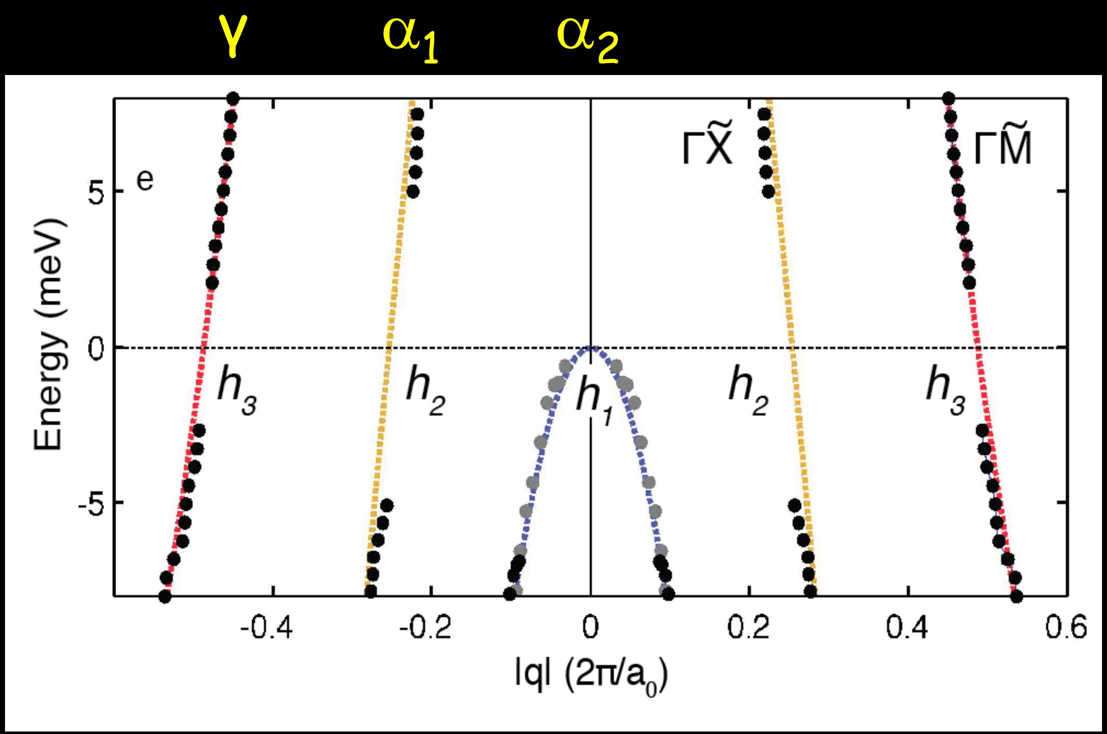


I.R. Shein *et al*., Solid State Comm.150, 152 (2010)
S.V. Borisenko *et al*., PRL 105, 067002 (2010)

M. P. Allan & A.W. Rost *et al*., Science **336**, 563 (2012)

Three hole-like bands: γ, α_2, α_1





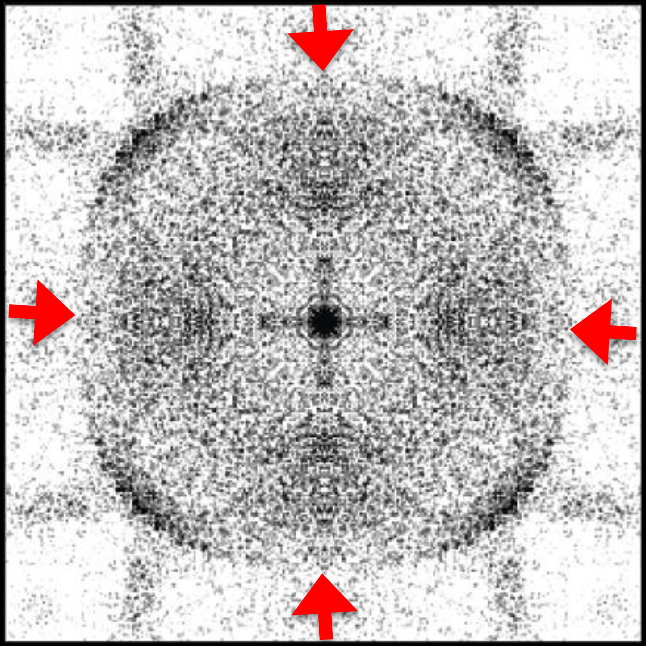
M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

Quasiparticle Interference, g(q,E) around SC Gap

Some QPI signals are suppressed.

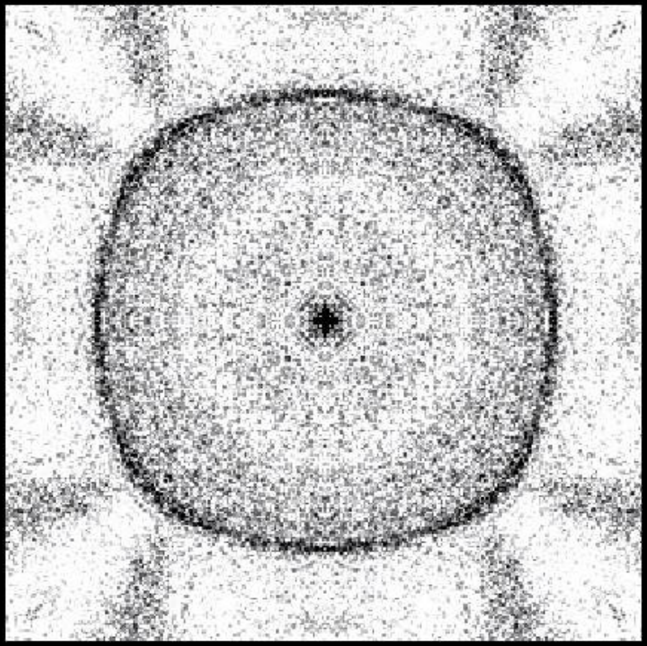
The SC gap at this Fermi sheet is anisotropic!

+2.00meV



T= 1.2K

+7.68meV



T= 1.2K

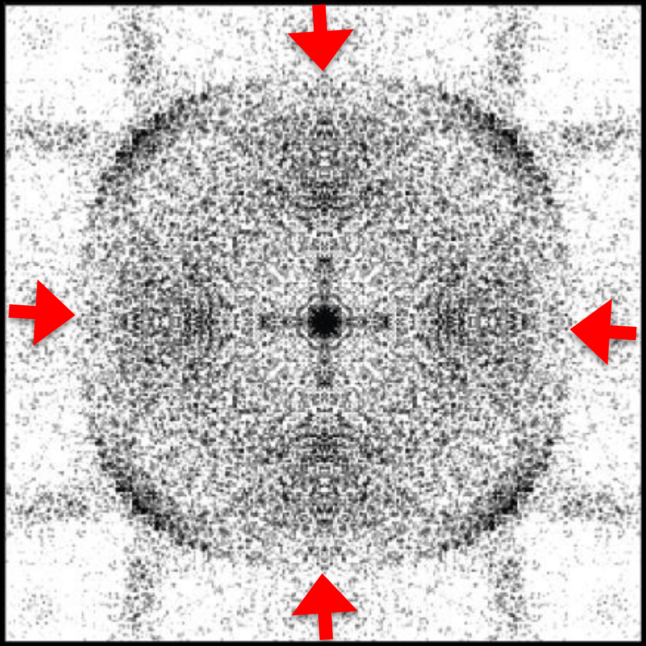
M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

Determination of Superconducting Energy-Gap Structure

How to obtain $\Delta_i(\boldsymbol{k})$?

q-space

+2.00meV

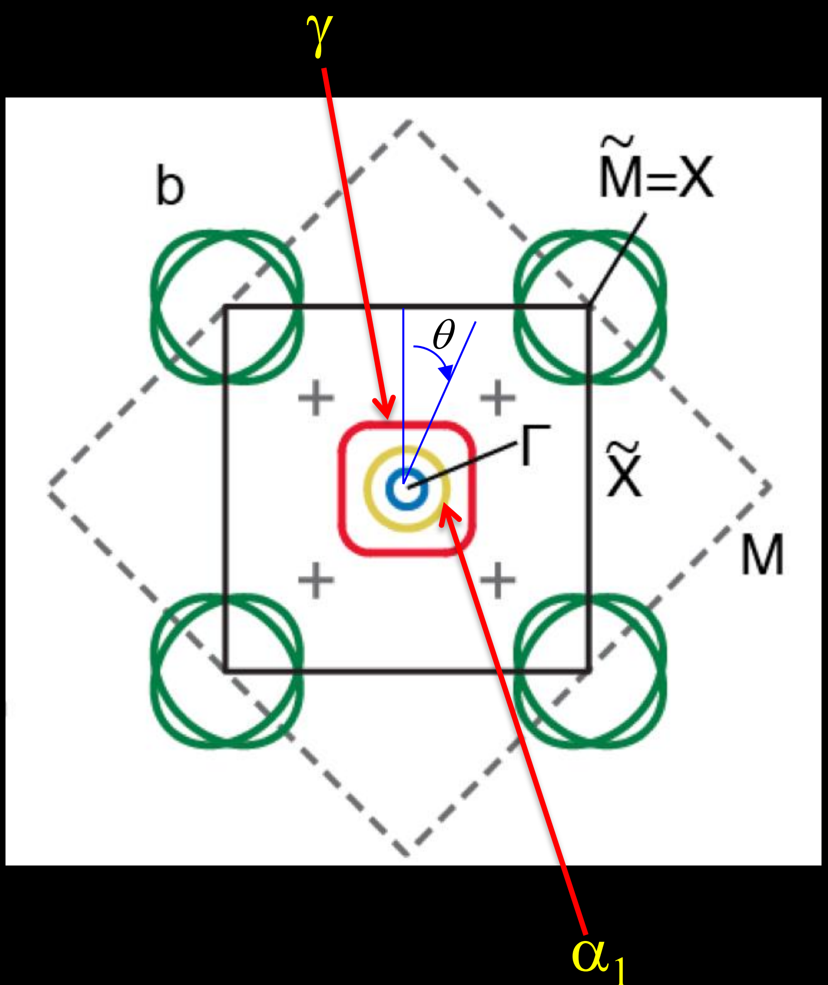


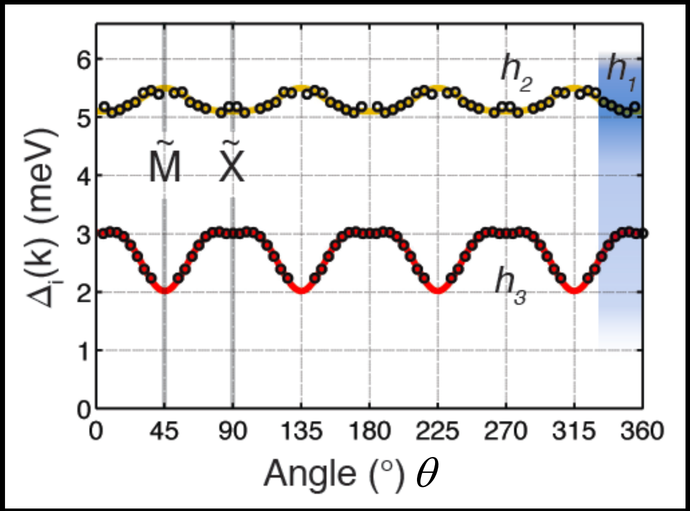
k-space

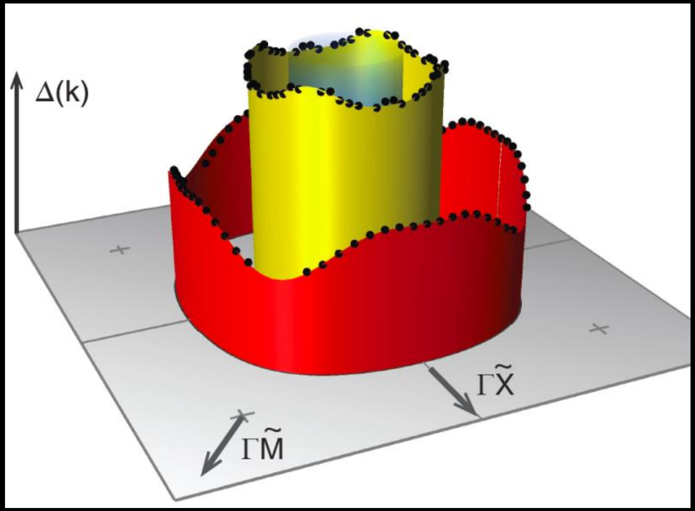
γ band + anisotropic gap

M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

Anisotropic Superconducting Energy-Gap Structure



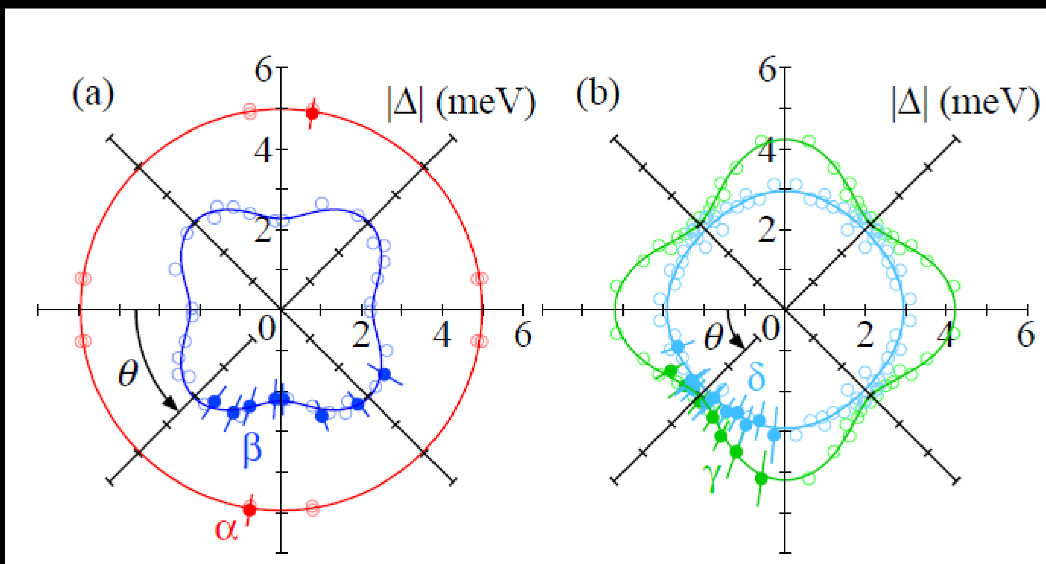




M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

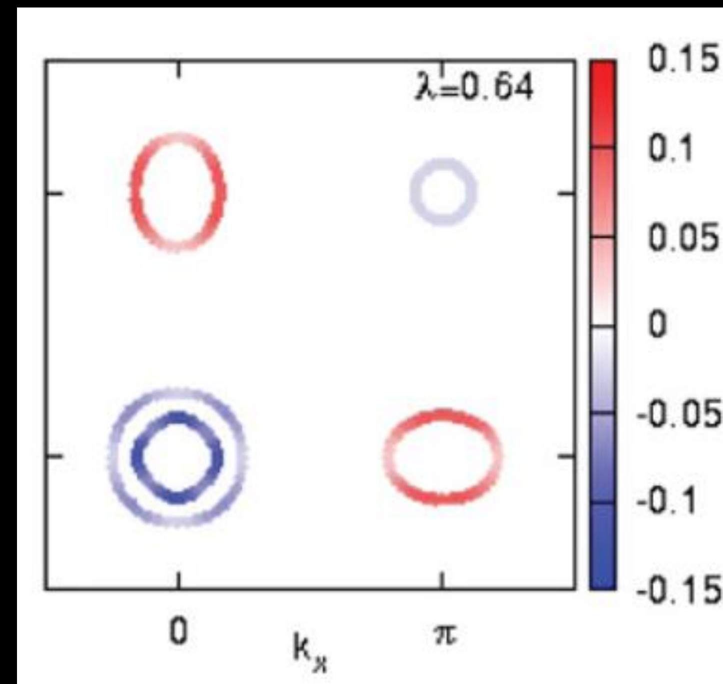
Two ARPES Groups Confirm Our Results

STM and ARPES are consistent around Γ.



S.V. Borisenko *et al.*, Symmetry 4, 251 (2012)
K. Umezawa *et al.* PRL 108, 037002 (2012)

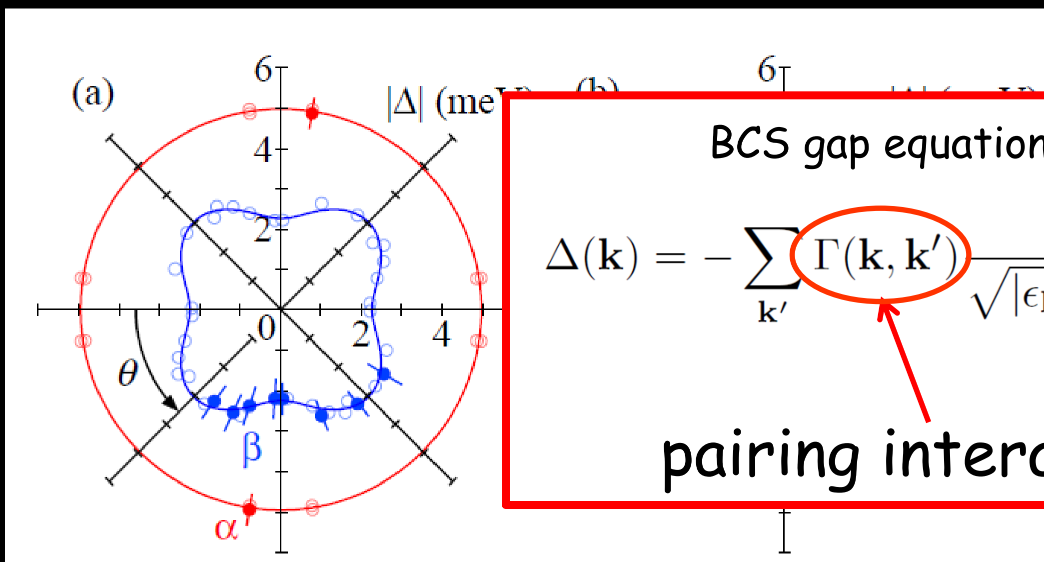
Consistent with AFSF theory.



P J Hirschfeld *et al.*, Rep.Prog.Phys.74, 124508 (2011)

Anisotropic SC Energy Gaps in LiFeAs by ARPES

STM and ARPES are consistent around Γ.



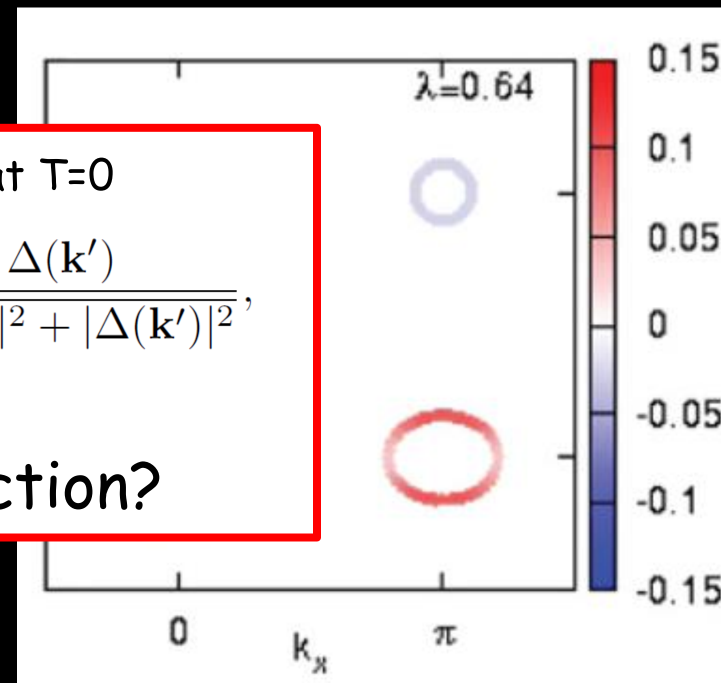
S.V. Borisenko *et al.*, Symmetry 4, 251 (2012)
K. Umezawa *et al.* PRL 108, 037002 (2012)

BCS gap equation at T=0

$$\Delta(\mathbf{k}) = -\sum_{\mathbf{k}'} \Gamma(\mathbf{k},\mathbf{k}') \frac{\Delta(\mathbf{k}')}{\sqrt{|\epsilon_{\mathbf{k}'}|^2 + |\Delta(\mathbf{k}')|^2}},$$

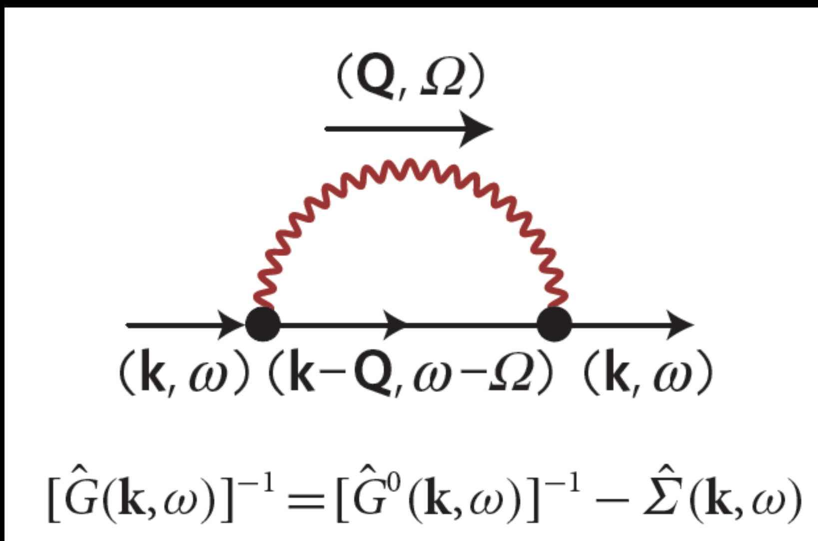
pairing interaction?

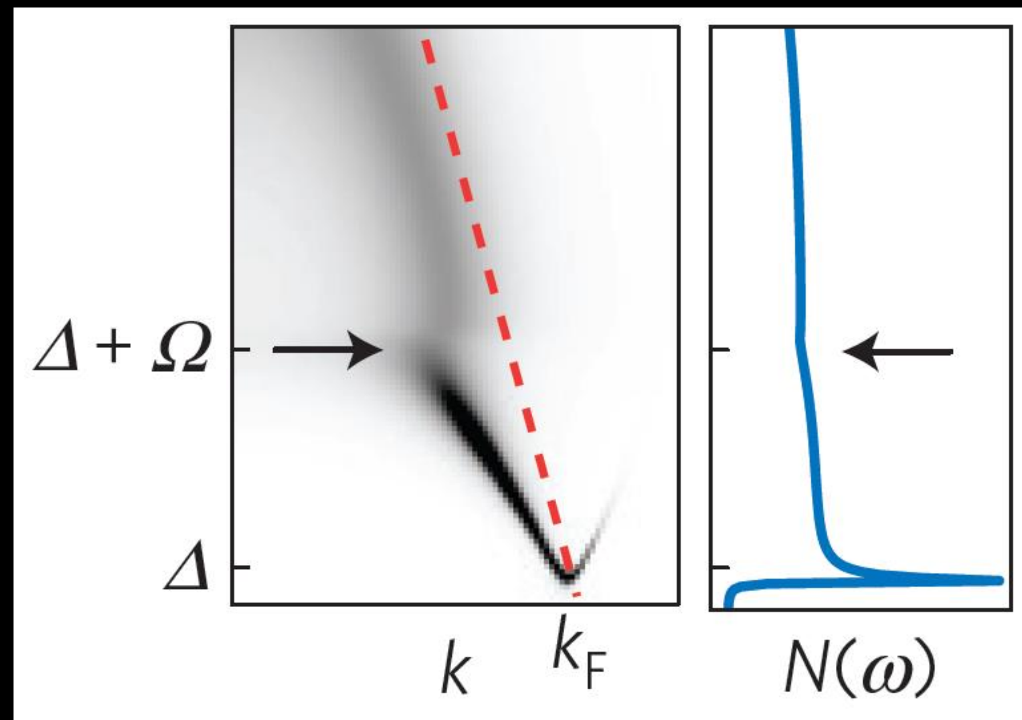
Consistent with AFSF theory.



P J Hirschfeld *et al.*, Rep.Prog.Phys.74, 124508 (2011)

Electron-Boson Interaction

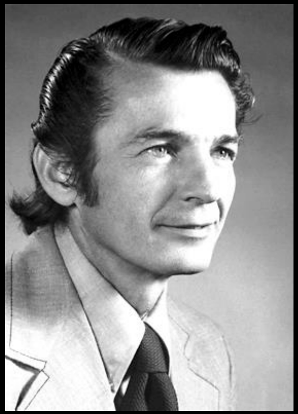




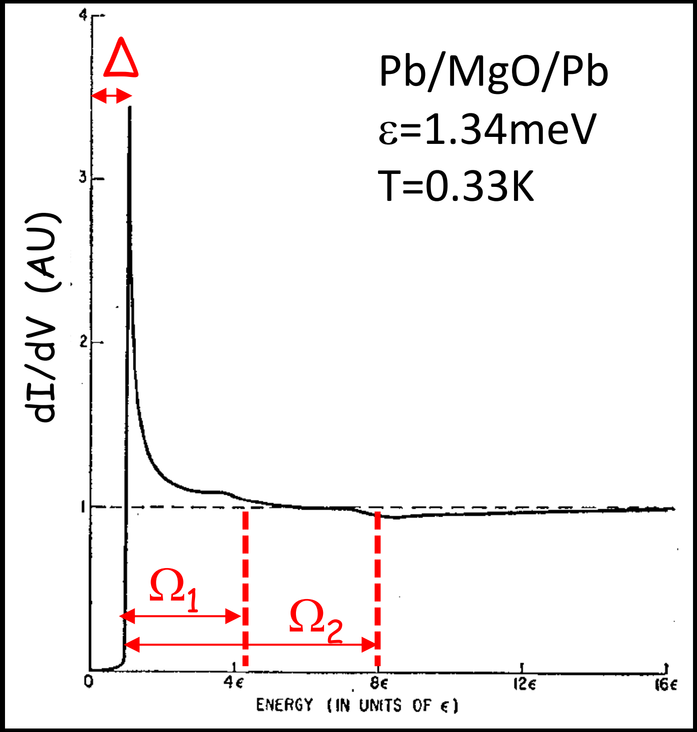
$Re\hat{\Sigma}(\vec{k},\omega) \rightarrow \vec{k}(\omega)$

$Im\hat{\Sigma}\left(\vec{k},\omega\right) \rightarrow \tau^{-1}(\vec{k},\omega)$

Superconductivity by Tunneling Spectroscopy



Ivar Giaever
Nobel Prize 1973

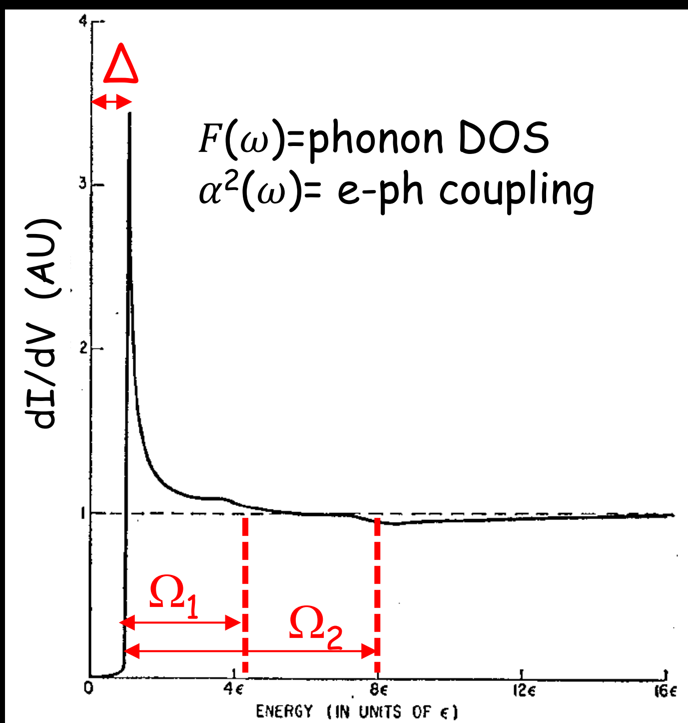


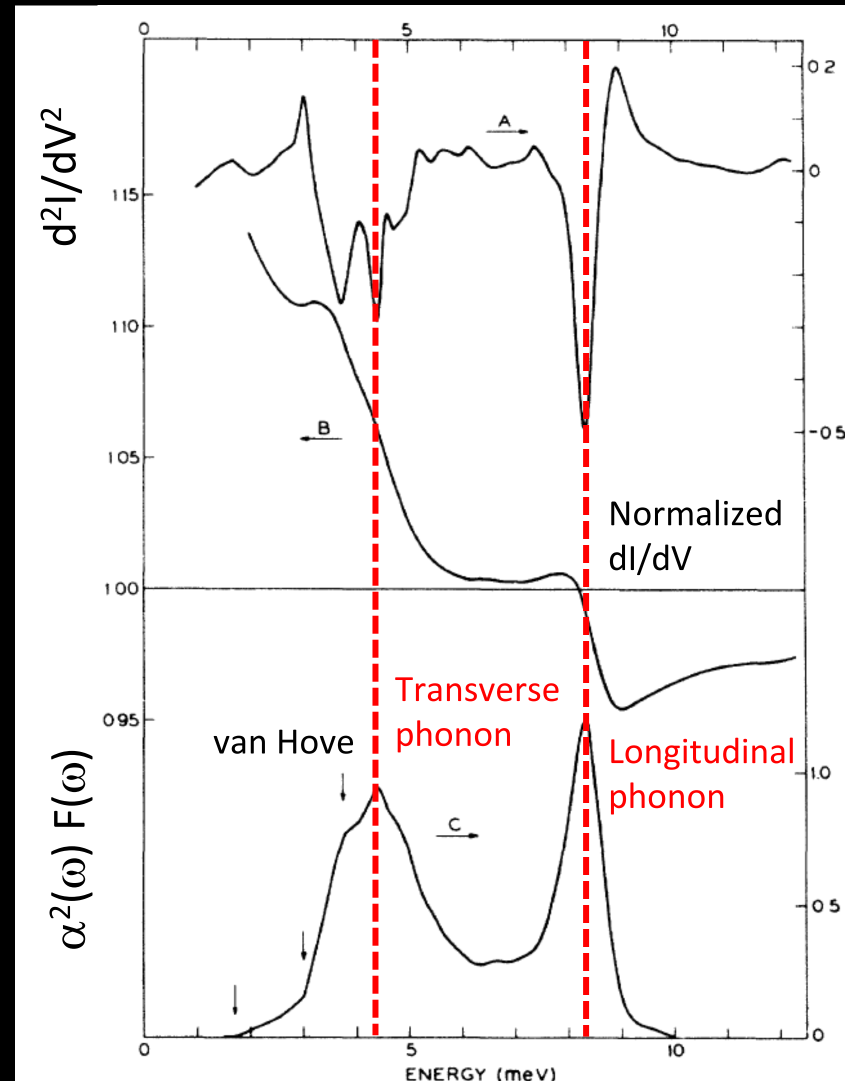
I. Giaever, Phys. Rev. 126, 941 (1962)

Electron-Phonon Interaction by Tunneling Spectroscopy

William McMillan

John Rowell

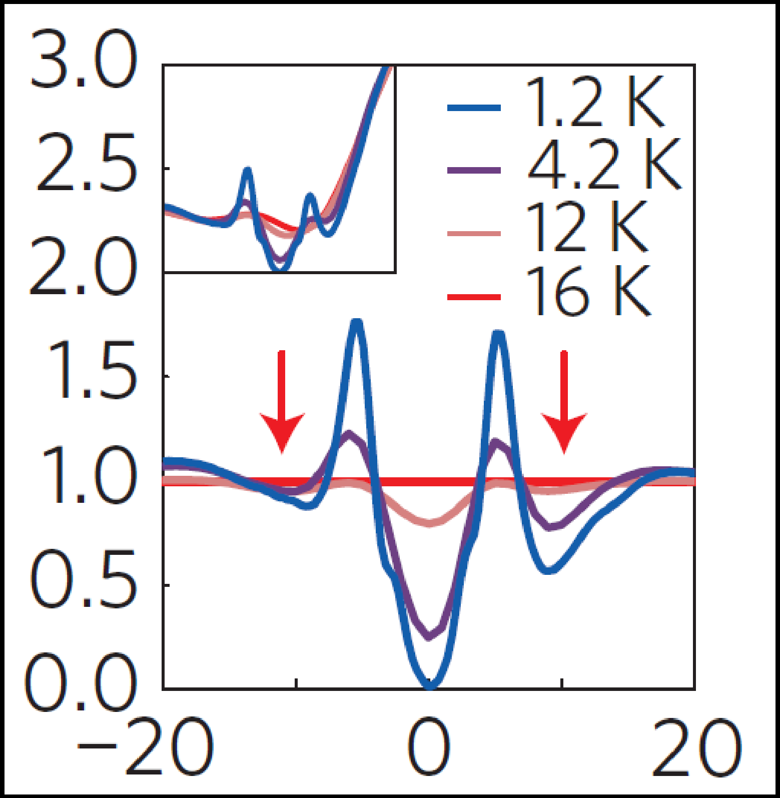




W.L. McMillan & J.W. Rowell, PRL 14, 108 (1965)

Atomic Visualization of Electron-Boson Coupling in FeSC

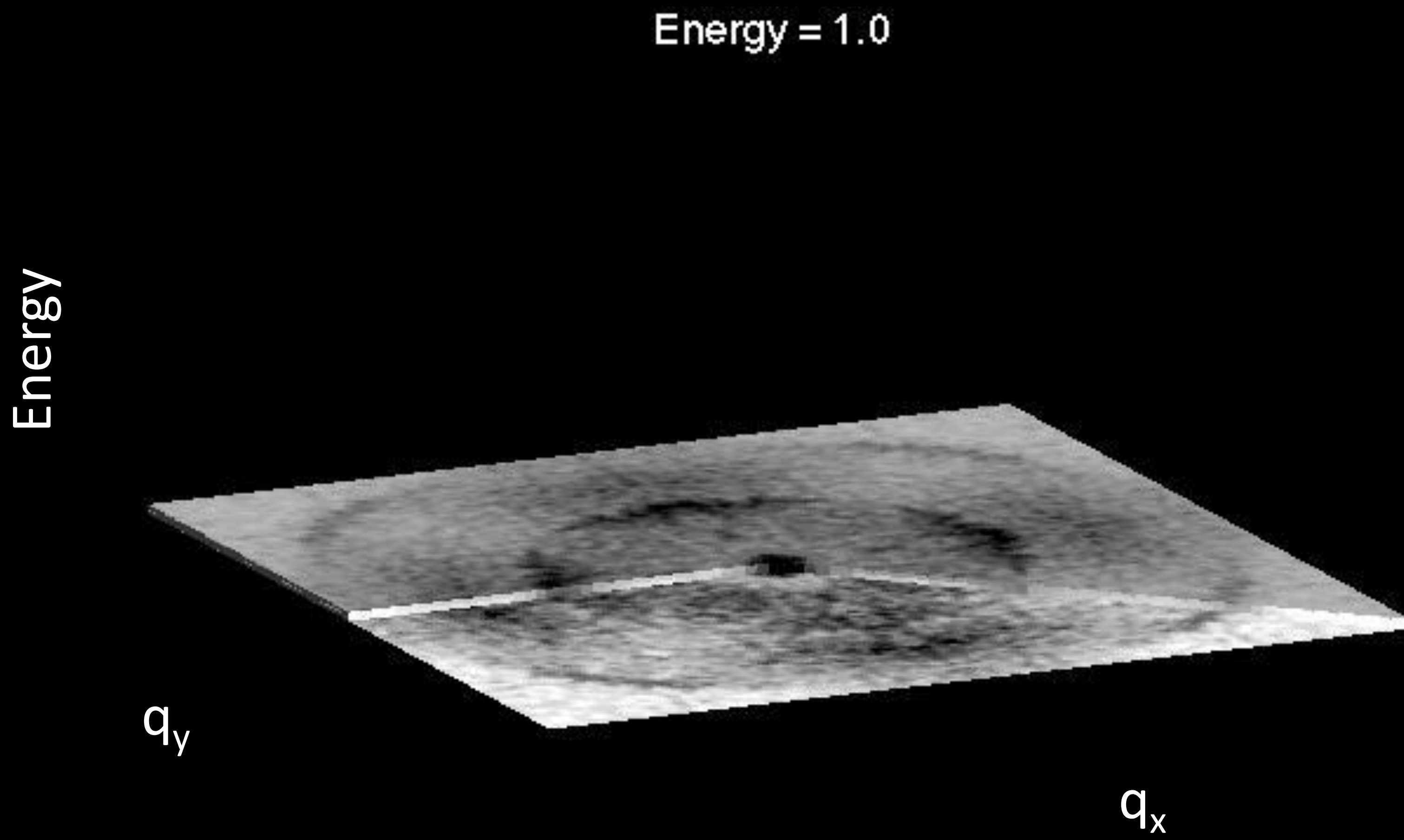
"Dip-hump" in spectrum of FeSC



Momentum info?

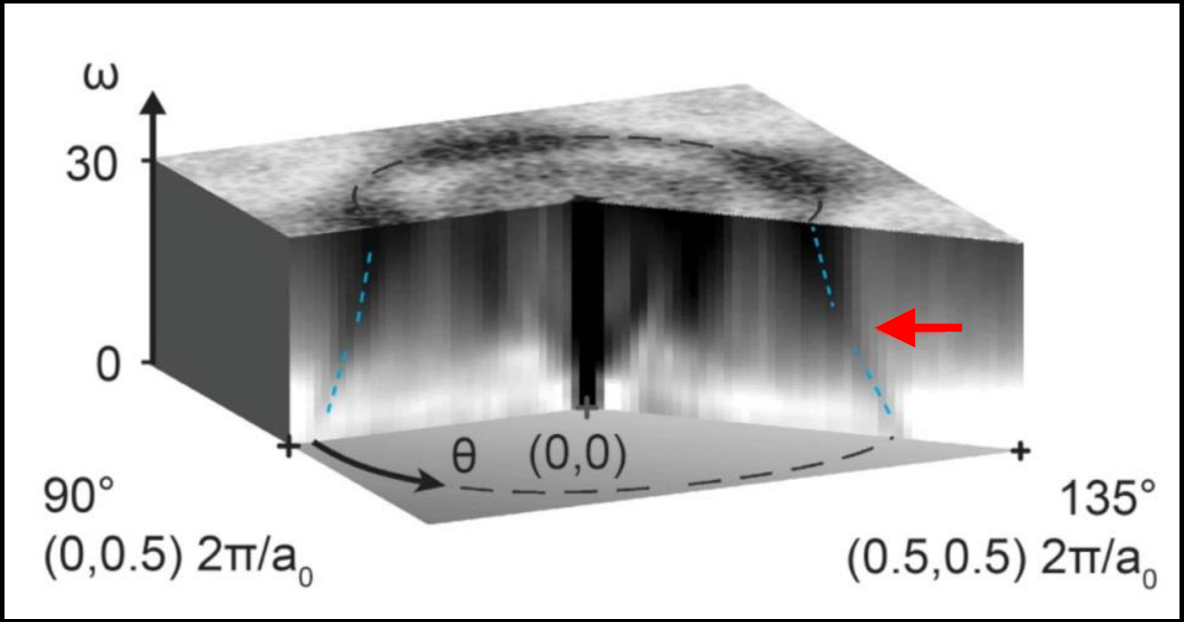
M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)
M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

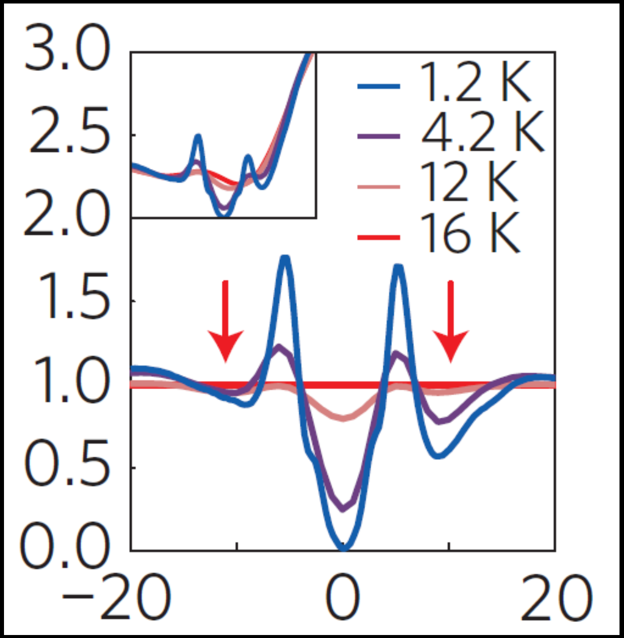
QPI in LiFeAs



M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

Atomic Visualization of Electron-Boson Coupling in FeSC

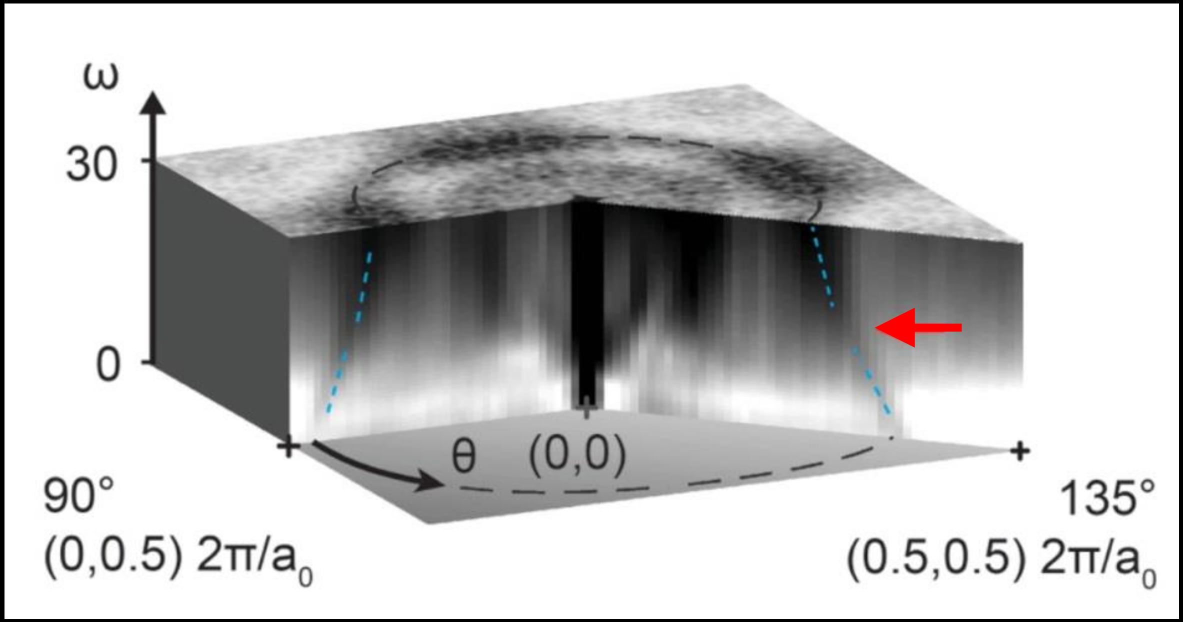


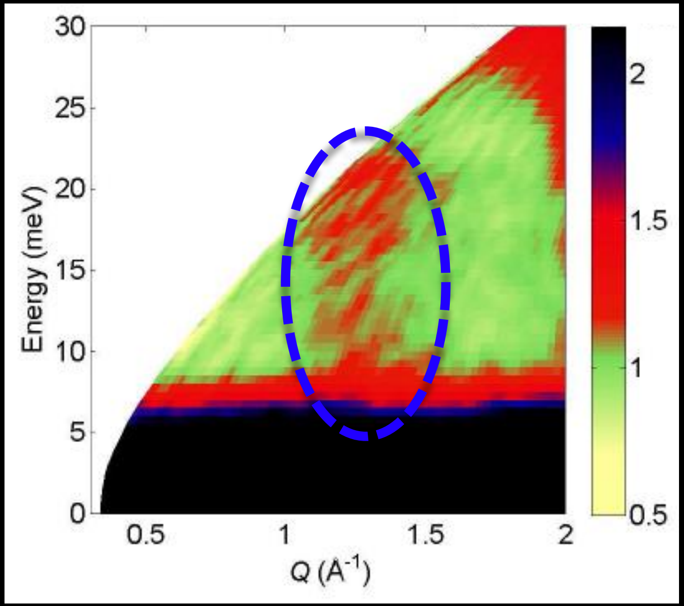


The change in dispersion occurs at the same energy as the 'traditional' Electron-Boson coupling signature in the spectrum.

M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

Atomic Visualization of Electron-Boson Coupling in FeSC





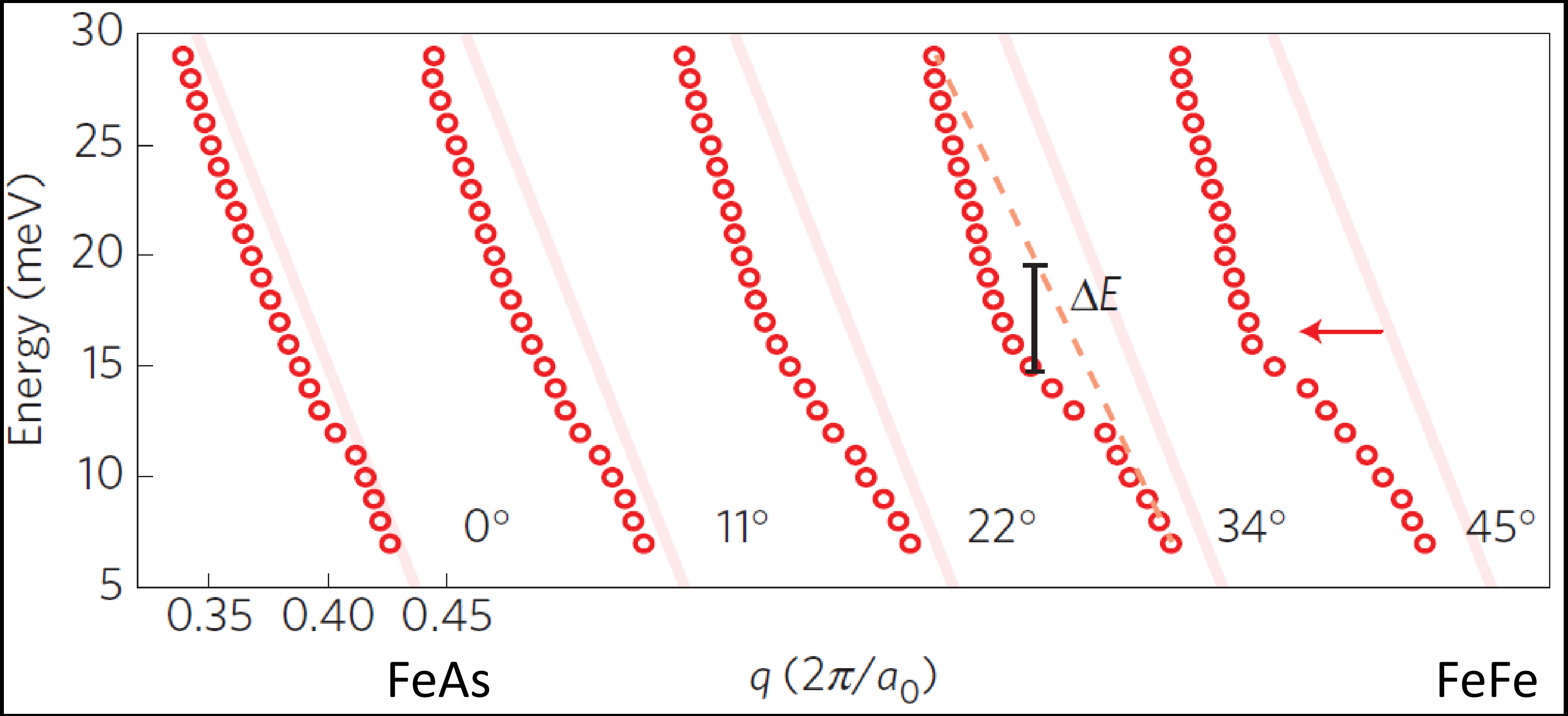
A.E. Taylor *et al.*, PRB 83, 220514 (2011)

The change in dispersion occurs at the same energy as the 'traditional' Electron-Boson coupling signature in the spectrum.

M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

Atomic Visualization of Electron-Boson Coupling in FeSC

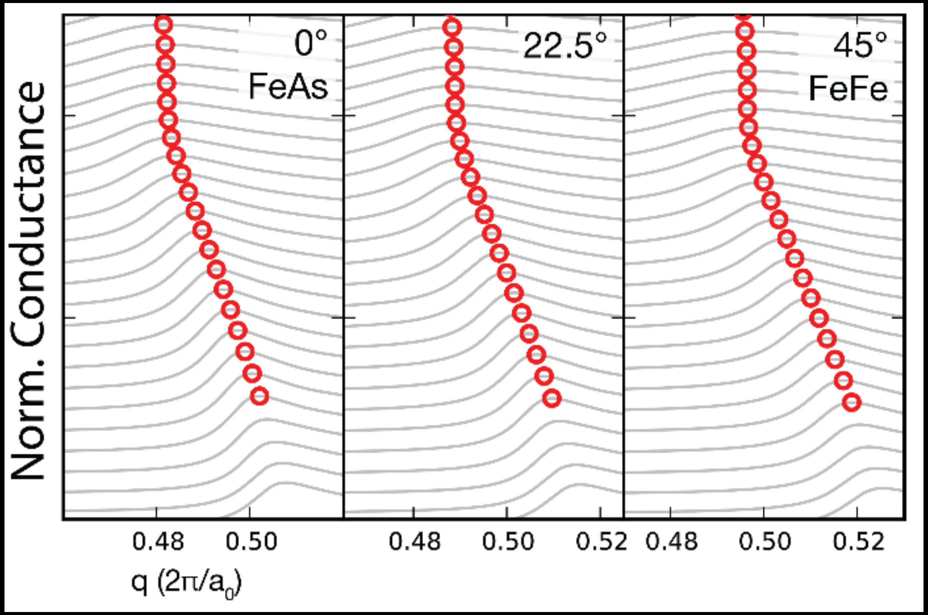
The self energy due to e-b coupling is strongly anisotropic



M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

Theoretical Calculation of E-B Couplings

d-orbital fluctuations by Fe Eg-phonon



M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

Theoretical Calculation of E-B Couplings

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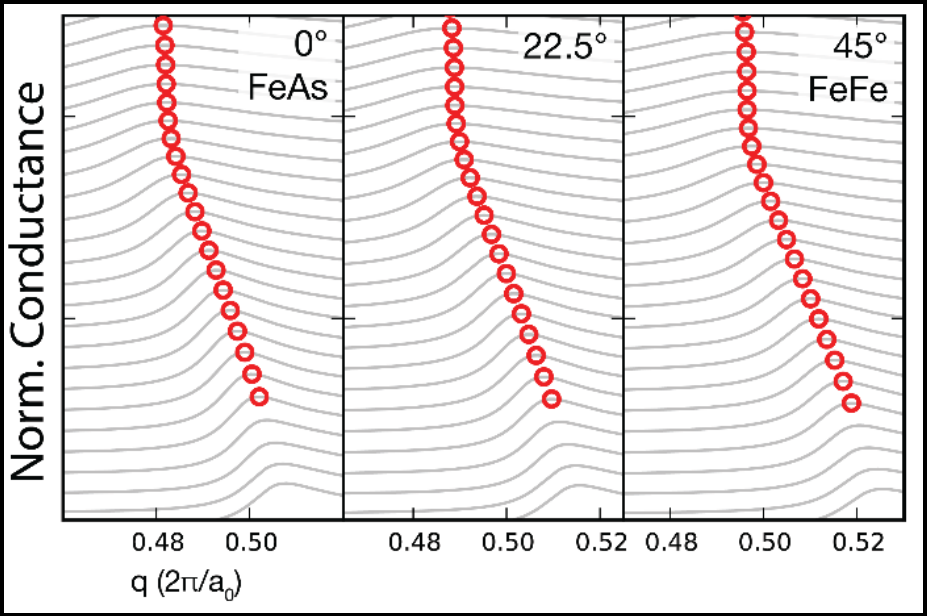
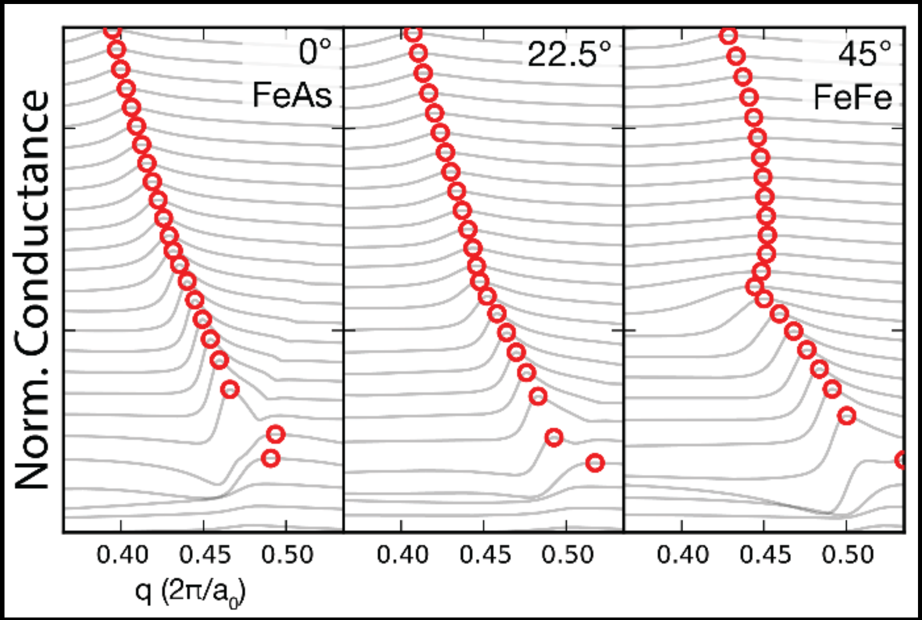


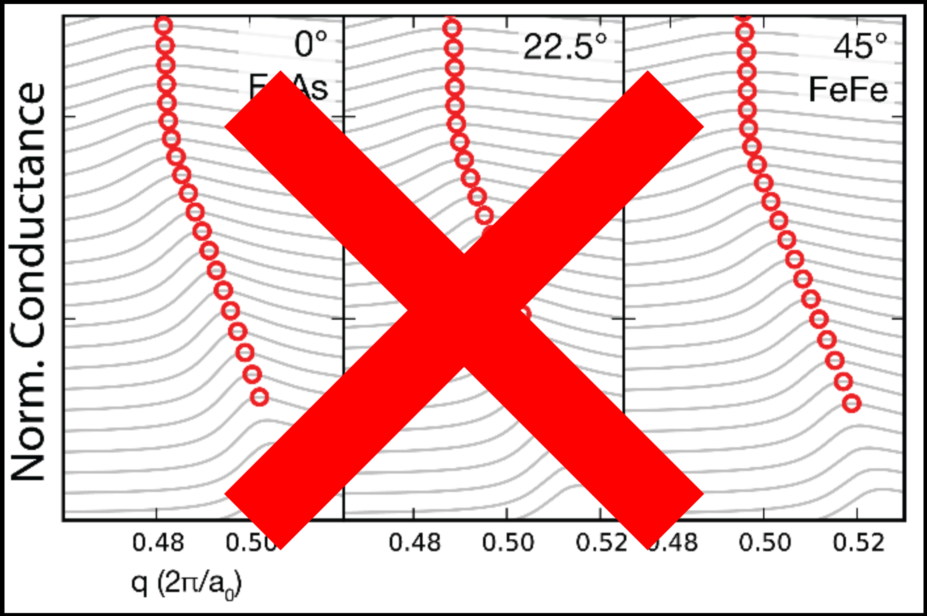
AF spin fluctuation



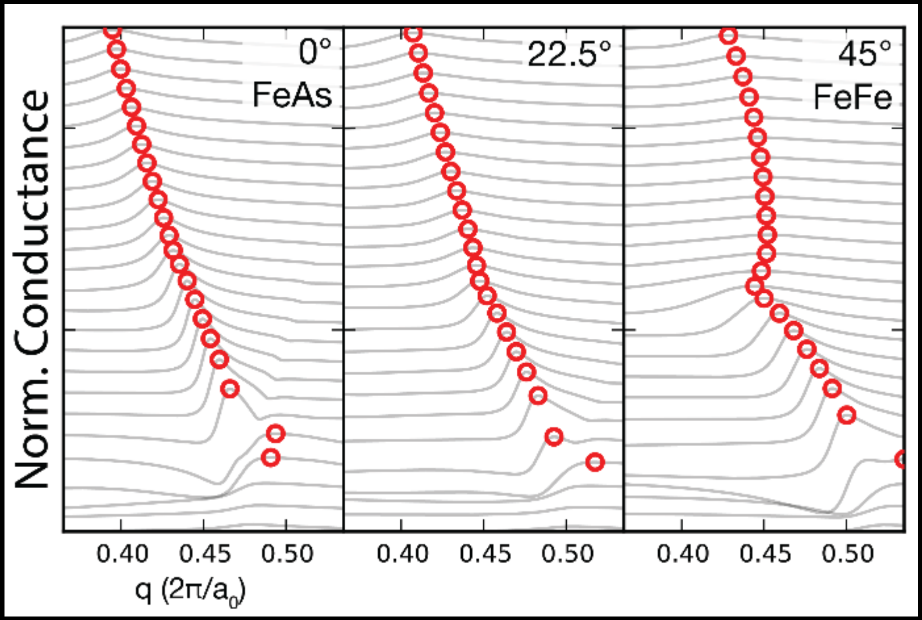
M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

Theoretical Calculation of E-B Couplings

d-orbital fluctuations by Fe Eg-phonon



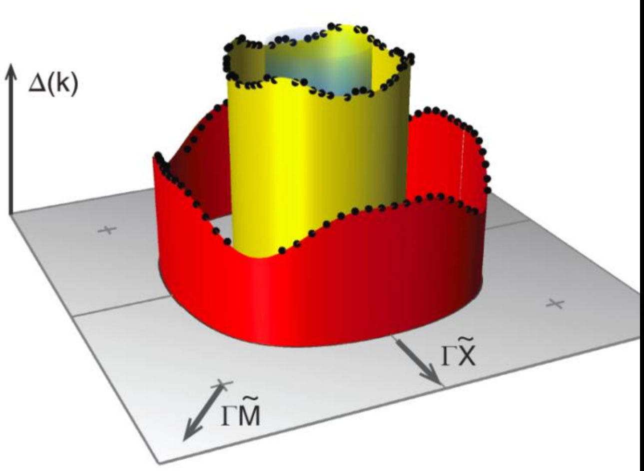
AF spin fluctuation

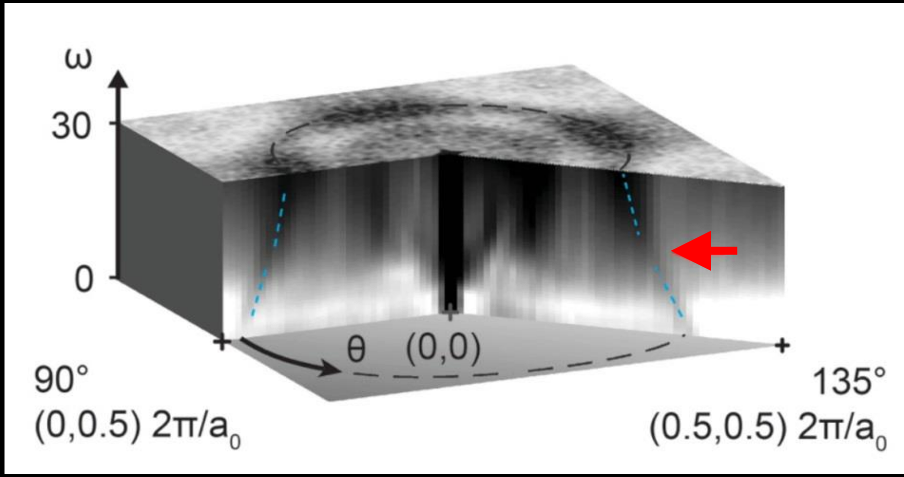


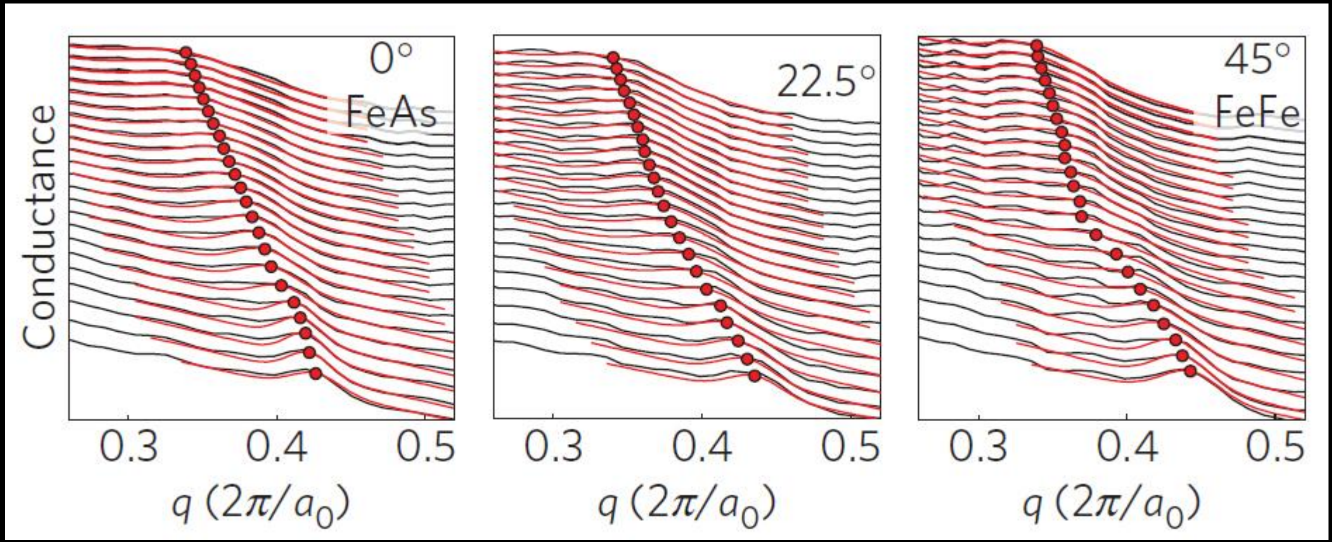
M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

"Fingerprint" of Pairing Mechanism in FeSC

Our experimental results support AF spin fluctuation pairing!







M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)