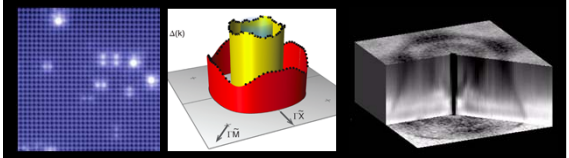
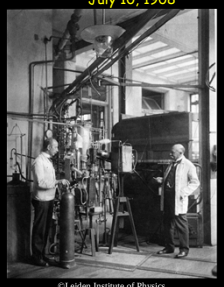
Atomic-scale Visualization of Cooper Pairing in Iron-based High Temperature Superconductors



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

First Helium Liquefaction in 1908

July 10, 1908



©Leiden Institute of Physics

Heike Kamerlingh Onnes
Nobel Prize, 1913

"Through Measurement to Knowledge"

Collaborators

Milan P. Allan, Andreas W. Rost, Freek Massee, Séamus Davis

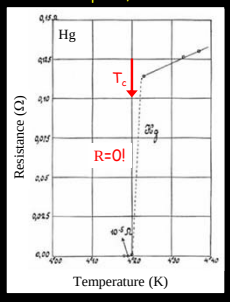
Kunihiro Kihou, Hiroshi Eisaki, Kyungmin Lee, Mark Fischer, Eun-Ah Kim

BROOKHAVEN NATIONAL LABORATORY

AIST

History of Conventional Superconductors

April 8, 1911



Heike Kamerlingh Onnes
Nobel Prize, 1913

"Through Measurement to Knowledge"

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

Acknowledgement

Discussion:

D.-H. Lee, T. Hanaguri, H. Takagi, S. Uchida, F. Baumberger, A. Carrington, M. J. Lawler, C. Putzke, J. Schmalian, Z. Tesanovic, R. Thomale, F. Wang, A. I. Coldea, P. C. Canfield, A. V. Chubukov, P. J. Hirschfeld, B. Keimer

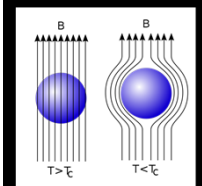
Support:

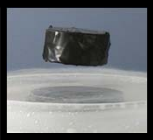
NSF, SUPA, EPSRC Engineering and Physical Sciences Research Council, JST

The Meissner Effect

- Superconductors are found to be perfect diamagnets in 1933.

Magnetic levitation





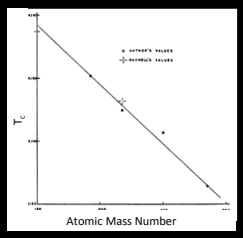
Walther Meißner (1882-1974)

Robert Ochsenfeld (1901-1993)

©PTB Berlin Institute

The Isotope Effect, 1950

- Isotope effect : $T_c \sim M^{-0.5}$
- Lattice vibration is a part of the superconducting process.
- A crucial step to a microscopic theory of superconductivity!



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

Matthias's Rules for Searching High T_c Superconductors

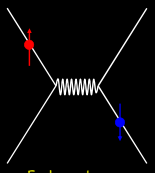
Bernd Matthias
By Joel Broida©

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)

Cooper Pairs and BCS Theory

Cooper Pairs



Exchange boson:
Lattice Vibration Mode

Nobel Prize 1972


John Bardeen


Leon Cooper


Robert Schrieffer

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

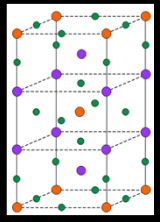
The Woodstock of Physics : Discovery of Cuprates

Nobel Prize in Physics 1987


J. Georg Bednorz


K. Alex Müller

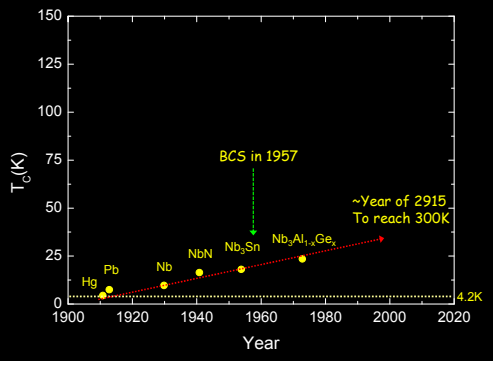
$La_{2-x}Ba_xCuO_4$



T_c~30K

J. G. Bednorz and K. A. Müller, Z. Phys. B **64**, 189 (1986)

History of Conventional Superconductors



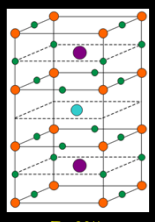
The Woodstock of Physics : Discovery of Cuprates

Superconductivity > 77K


C.W. Paul Chu
NCKU 1962


Maw-Kuen Wu

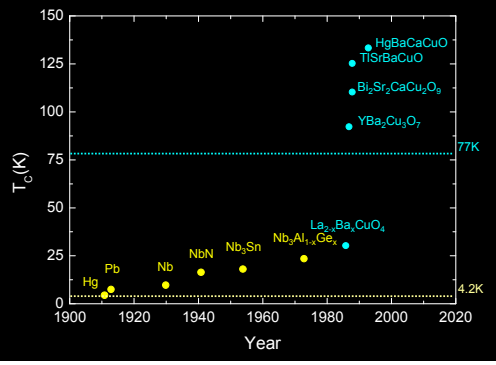
$YBa_2Cu_3O_{7-\delta}$



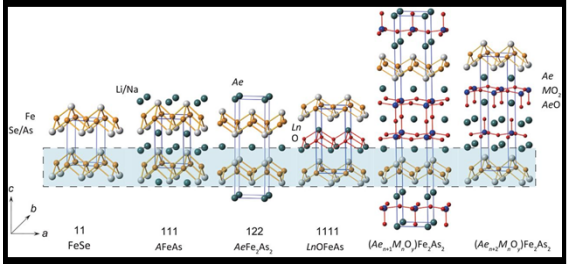
T_c~93K

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

History of Conventional and High T_C Superconductors



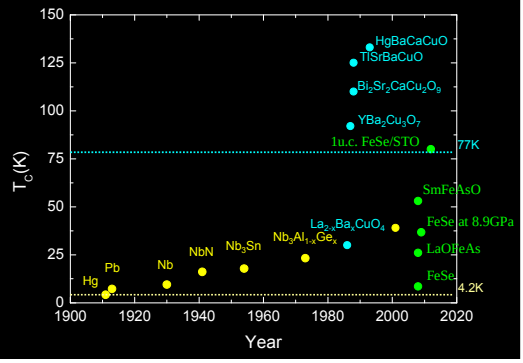
The Growing FeSC Family



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

High Tc Superconductors : Applications

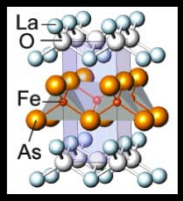
History of Conventional and High T_C Superconductors

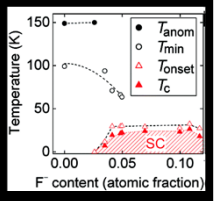


The Discovery of Fe-based Superconductors (FeSC)

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

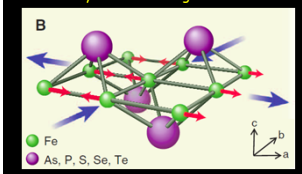


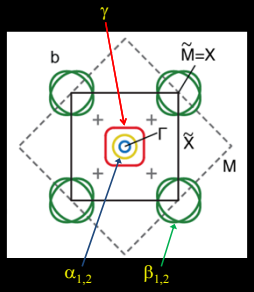


Y. Kamihara *et al.*, JACS. **128**, 10012 (2006)
T. Watanabe *et al.*, JACS. **46**, 7719 (2007)
Y. Kamihara *et al.*, JACS. **130**, 3296 (2008)

FeSC : Complex Band Structure

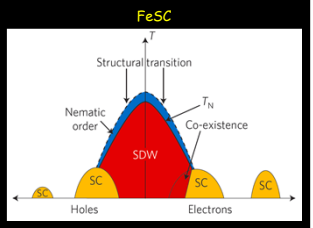
SC layer with SDW ground state





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

FeSC Phase Diagram

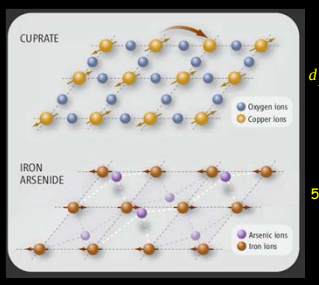


D.N. Basov *et al.*, NPhys **7**, 272 (2011)

FeSC vs Cuprates : Superconducting Layer

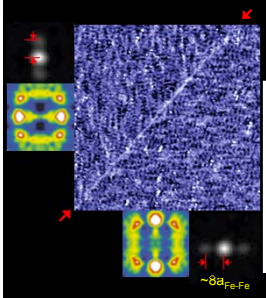
Both have antiferromagnetic 'parent' states.

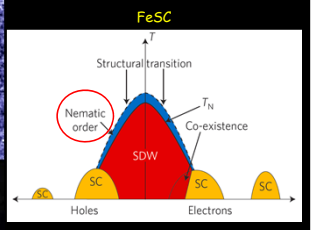
Cooper pairing mediated by AF ?



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

FeSC Phase Diagram





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

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

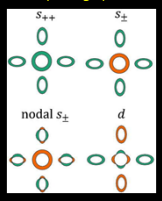
FeSC: Unconventional Superconductivity

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

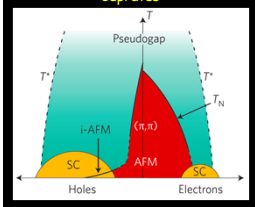
Possible pairing symmetries



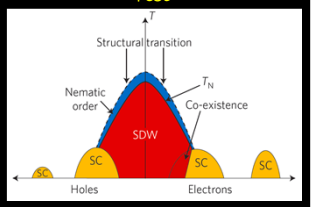
FeSC vs Cuprates : Phase Diagram

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

Cuprates



FeSC

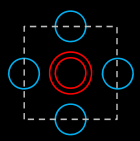


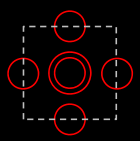
D.N. Basov *et al.*, NPhys **7**, 272 (2011)

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)

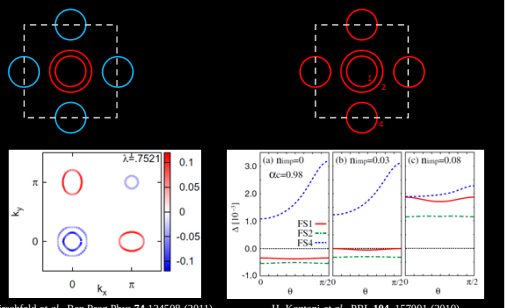




FeSC: SC Energy Gap Functions

Spin Fluctuation → S± OP symmetry

Orbital Fluctuation → S++ OP symmetry



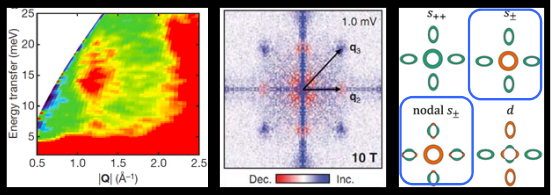
P. J. Hirschfeld et al., Rep.Prog.Phys.**74**,124508 (2011)

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

Quasiparticle Scattering Interference (QPI) for Superconductivity in Momentum-Space by Scanning Tunneling Microscope (STM)

FeSC: Pairing Mechanism S± OP Symmetry

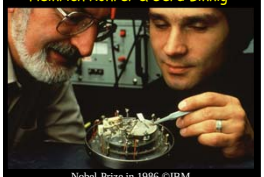
S± pairing symmetry is favored!



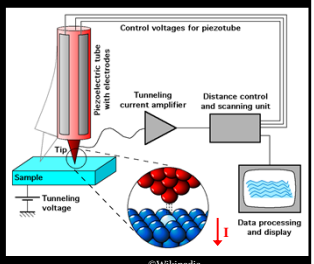
A. D. Christianson *et al.*, Nature 456, 930 (2008)
T. Hanaguri *et al.*, Science 328,474 (2010)

Scanning Tunneling Microscopy (STM)

Heinrich Rohrer & Gerd Binnig



Nobel Prize in 1986 ©IBM



©Wikipedia

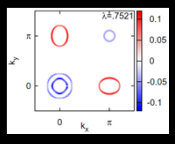
FeSC: Pairing Mechanism?

To understand the pair mechanism, knowledge to both gap symmetry and structure are essential !

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 — bare dispersion

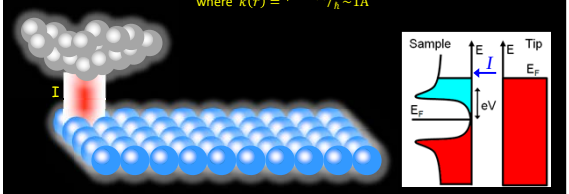


Review:
F. Wang, D.H. Lee, Science 332, 200 (2011)
P. J. Hirschfeld et al., Rep.Prog.Phys.**74**,124508 (2011)

Tunneling Current

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

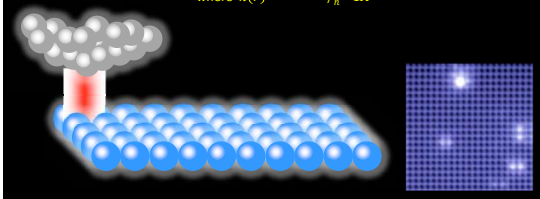
where $\kappa(\vec{r}) = \sqrt{2m\emptyset(\vec{r})}/\hbar \sim 1\text{Å}^{-1}$



Constant Current Topography

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

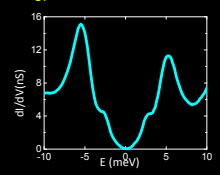
where $\kappa(\vec{r}) = \sqrt{2m\phi(\vec{r})}/\hbar \sim 1\text{Å}^{-1}$

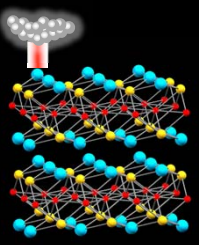


Scanning Tunneling Spectroscopy (STS) Mapping

Atomic resolution energy resolved conductance images, g(r,E) ∝ LDOS(r,E)

Energy resolution ≤ 0.35meV at T=1.2K

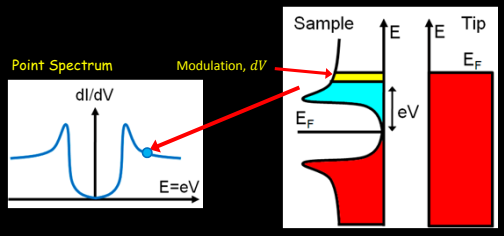




LiFeAs

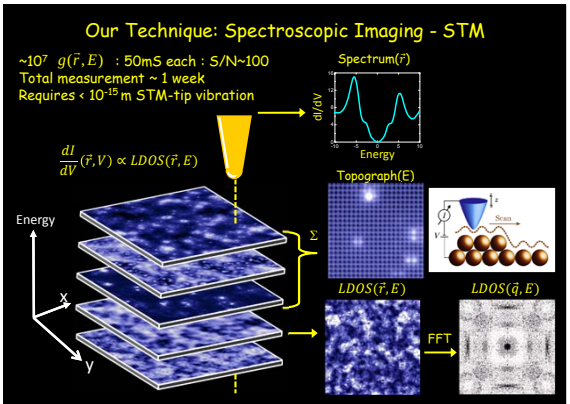
Tunneling Spectroscopy

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



Our Technique: Spectroscopic Imaging - STM

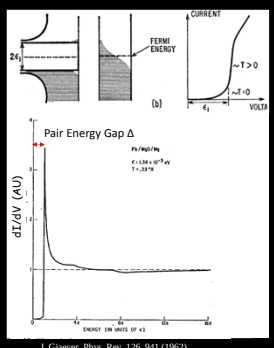
~10^7 $g(\vec{r},E)$: 50mS each : S/N~100
Total measurement ~ 1 week
Requires < 10^{-15} m STM-tip vibration



Tunneling in Superconductors: Energy Gap

Ivar Giaever

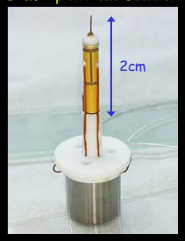
Nobel Prize 1973
©Schenectady Museum



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

Our Resolution and Stability

STM Tip on Piezo Scanner

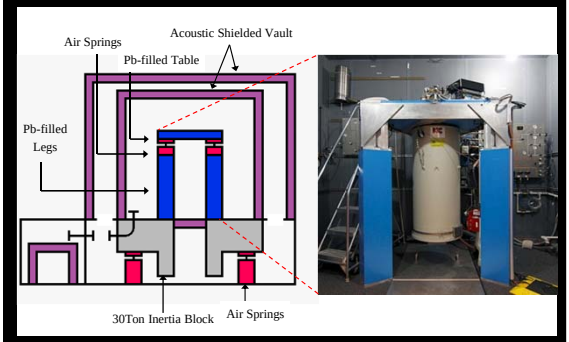


Taipei 101

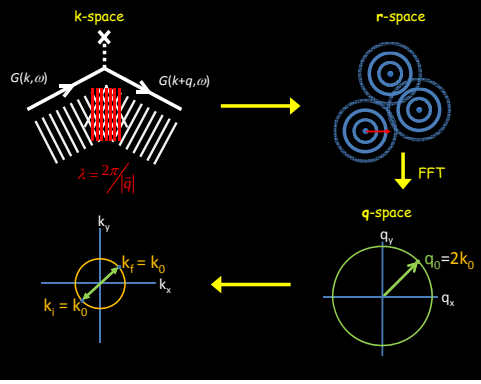
@Wikipedia

<0.5pm/2cm → 13nm/509m!

Ultra Low Vibration Lab @ Cornell University



QPI on Simple Metals

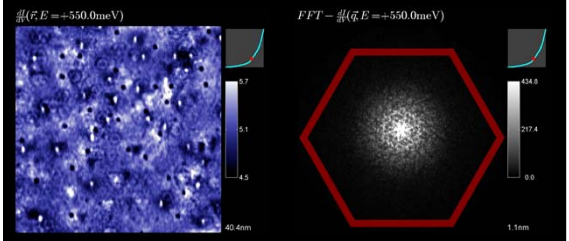


1.6K-9Tesla Cryogenic UHV STM @ Academia Sinica

100% Homemade!

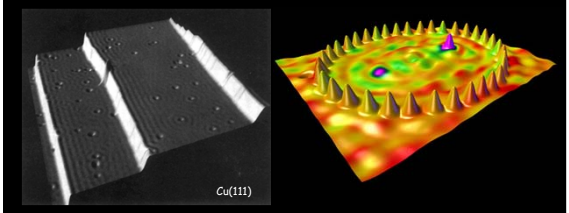
http://www.phys.sinica.edu.tw/~chuangtm/

Spectroscopy Map on Rashba BiTeI



In preparation

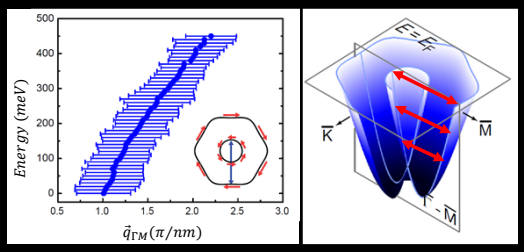
Quasiparticle Scattering Interference (QPI) on Simple Metals



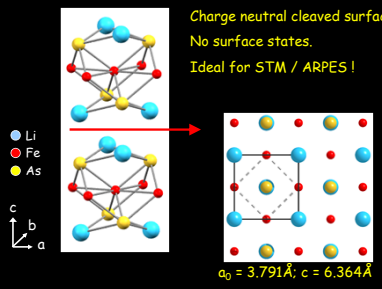
M.F. Crommie *et al.*, Nature 363, 524 (1993)

H. C. Manoharan *et al.*, Nature **403**, 512 (2000)

Determination of Band Structures from QPI



Our Samples : Superconducting LiFeAs



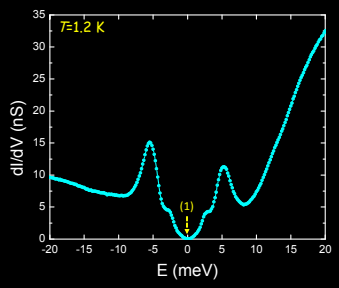
Charge neutral cleaved surface.
No surface states.
Ideal for STM / ARPES !

a_0 = 3.791Å; c = 6.364Å

J. H. Tapp *et al.*, PRB **78**, 060505 (2008)
X.C. Wang *et al.*, Solid State Comm. 148 ,538 (2008)
A. Lankau *et al.*, PRB **82**, 184518 (2010)

Single Tunneling Spectrum, T=1.2K

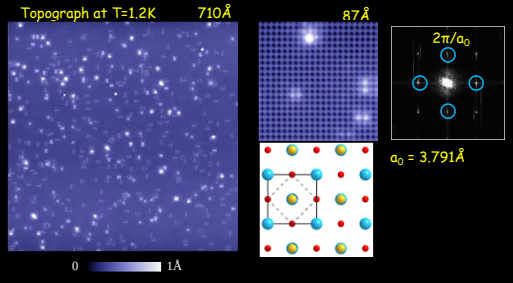
(1) Flat spectrum at zero bias.
Excludes the possible existence of nodes in the SC gap.



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

Our Samples : LiFeAs

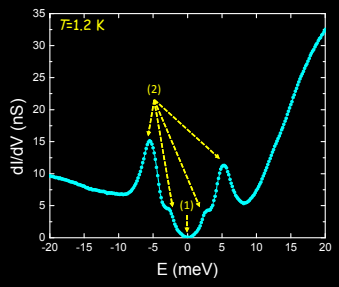
Large field of view necessary for intra-band QPI measurements!



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

Single Tunneling Spectrum, T=1.2K

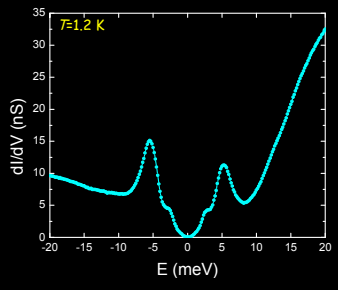
(2) Coherence peaks:
- At least two different Fermi surface gaps
- Indication of variation in the gap magnitudes.



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

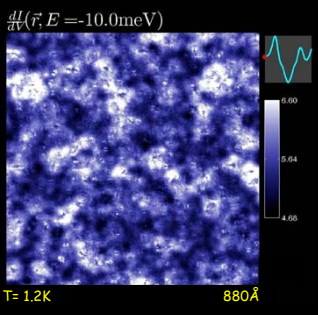
Single Tunneling Spectrum, T=1.2K

$\frac{dI}{dV} \propto LDOS(E = eV)$ with energy resolution of ≤ 350μeV!



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

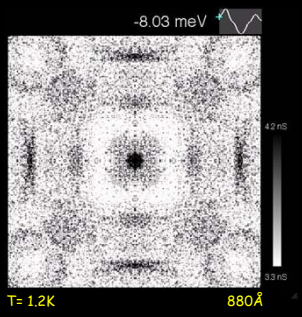
Spectroscopic Imaging, LDOS(r,E)



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

Quasiparticle Interference, LDOS(q,E)

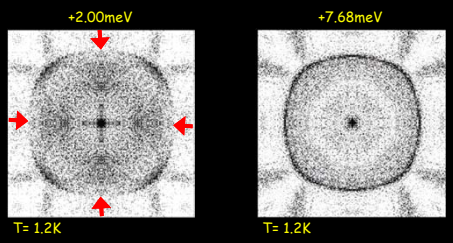
Fourier Transform of LDOS(r,E) → LDOS(q, E)



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

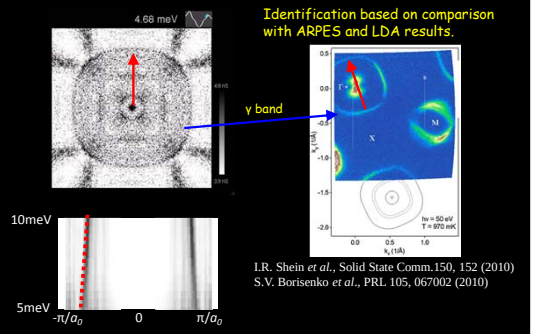
Quasiparticle Interference, g(q,E) around SC Gap

Some QPI signals are suppressed.
The SC gap at this Fermi sheet is anisotropic!



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

Band Identification by QPI above SC gap



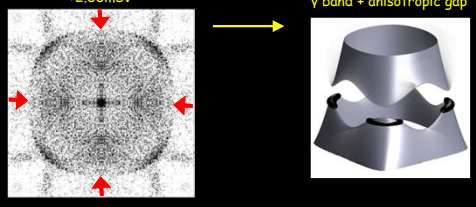
Identification based on comparison with ARPES and LDA results.

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)

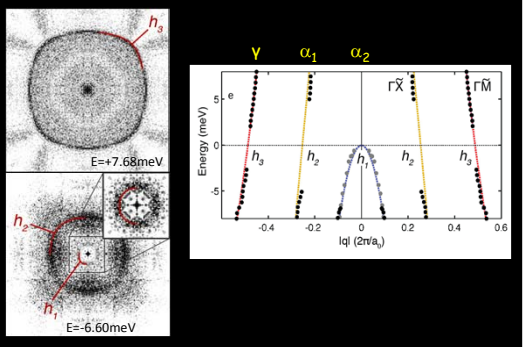
Determination of Superconducting Energy-Gap Structure

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



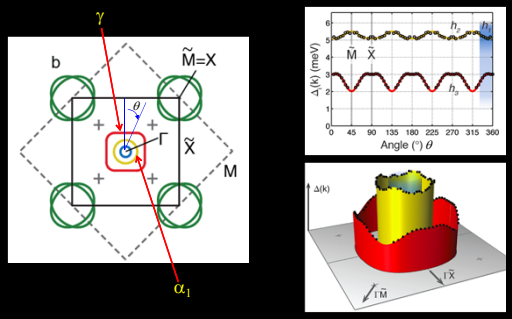
M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

Three hole-like bands: γ, α_2, α_1



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

Anisotropic Superconducting Energy-Gap Structure

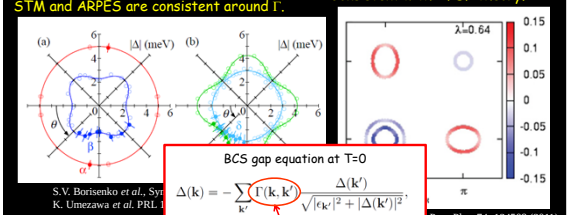


M. P. Allan & A.W. Rost *et al.*, Science **336**, 563 (2012)

Anisotropic SC Energy Gaps in LiFeAs by ARPES

STM and ARPES are consistent around Γ.

Consistent with AFSF theory.



S.V. Borisenko *et al.*, Sy
K. Umezawa *et al.* PRL 1

BCS gap equation at T=0

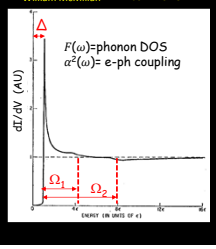
$$\Delta(\mathbf{k}) = -\sum_{\mathbf{k}'} \Gamma(\mathbf{k},\mathbf{k}') \frac{\Delta(\mathbf{k}')}{\sqrt{|\epsilon_{\mathbf{k}'}|^2 + |\Delta(\mathbf{k}')|^2}}$$

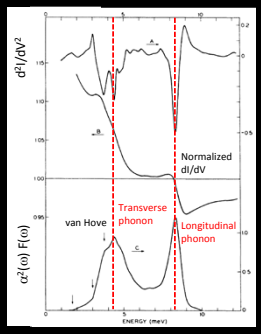
pairing interaction?

.Prog.Phys.74, 124508 (2011)

Electron-Phonon Interaction by Tunneling Spectroscopy

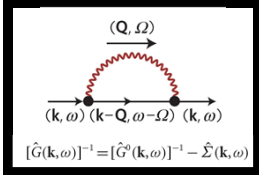
William McMillan John Rowell





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

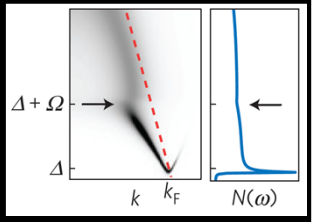
Electron-Boson Interaction



$$[\hat{G}(\mathbf{k},\omega)]^{-1} = [\hat{G}^0(\mathbf{k},\omega)]^{-1} - \hat{\Sigma}(\mathbf{k},\omega)$$

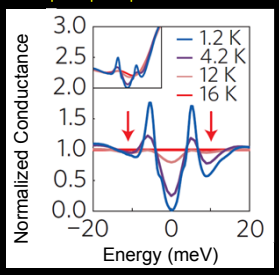
$$Re\Sigma(\vec{k},\omega) \rightarrow \vec{k}(\omega)$$

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



Atomic Visualization of Electron-Boson Coupling in FeSC

"Dip-hump" in spectrum of FeSC

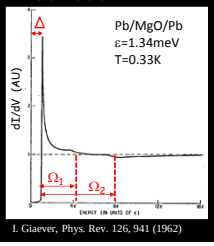


Momentum info?

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)

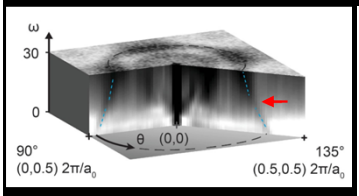
Superconductivity by Tunneling Spectroscopy

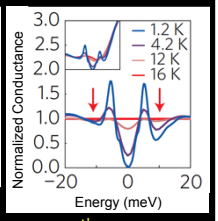
Ivar Giaever
Nobel Prize 1973



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

Atomic Visualization of Electron-Boson Coupling in FeSC

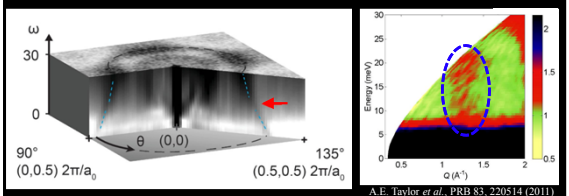




The change in dispersion occurs at the same energy as the 'traditional' Electron-Boson coupling signature in the spectrum.

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)

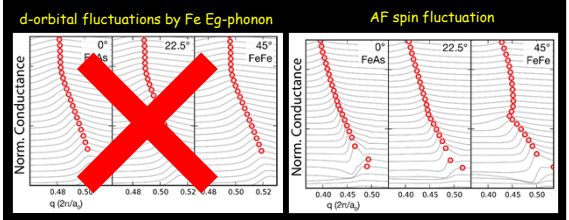
The change in dispersion occurs at the same energy as the 'traditional' Electron-Boson coupling signature in the spectrum.

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

Theoretical Calculation of E-B Couplings

d-orbital fluctuations by Fe Eg-phonon

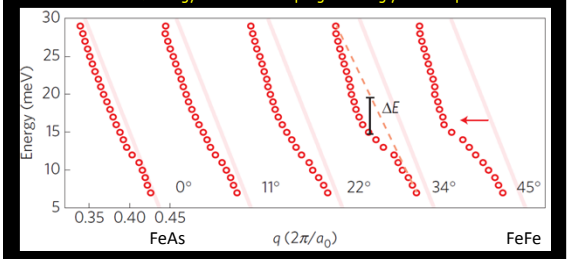
AF spin fluctuation



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

Atomic Visualization of Electron-Boson Coupling in FeSC

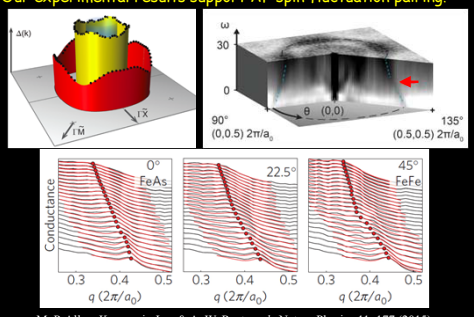
The self energy due to e-b coupling is strongly anisotropic



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

Pairing Mechanism in FeSC

Our experimental results support AF spin fluctuation pairing!



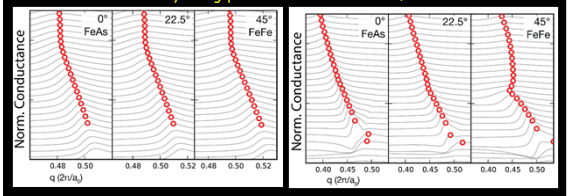
M. P. Allan, Kyungmin Lee & A. W. Rost *et al.*, Nature Physics 11, 177 (2015)

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

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)