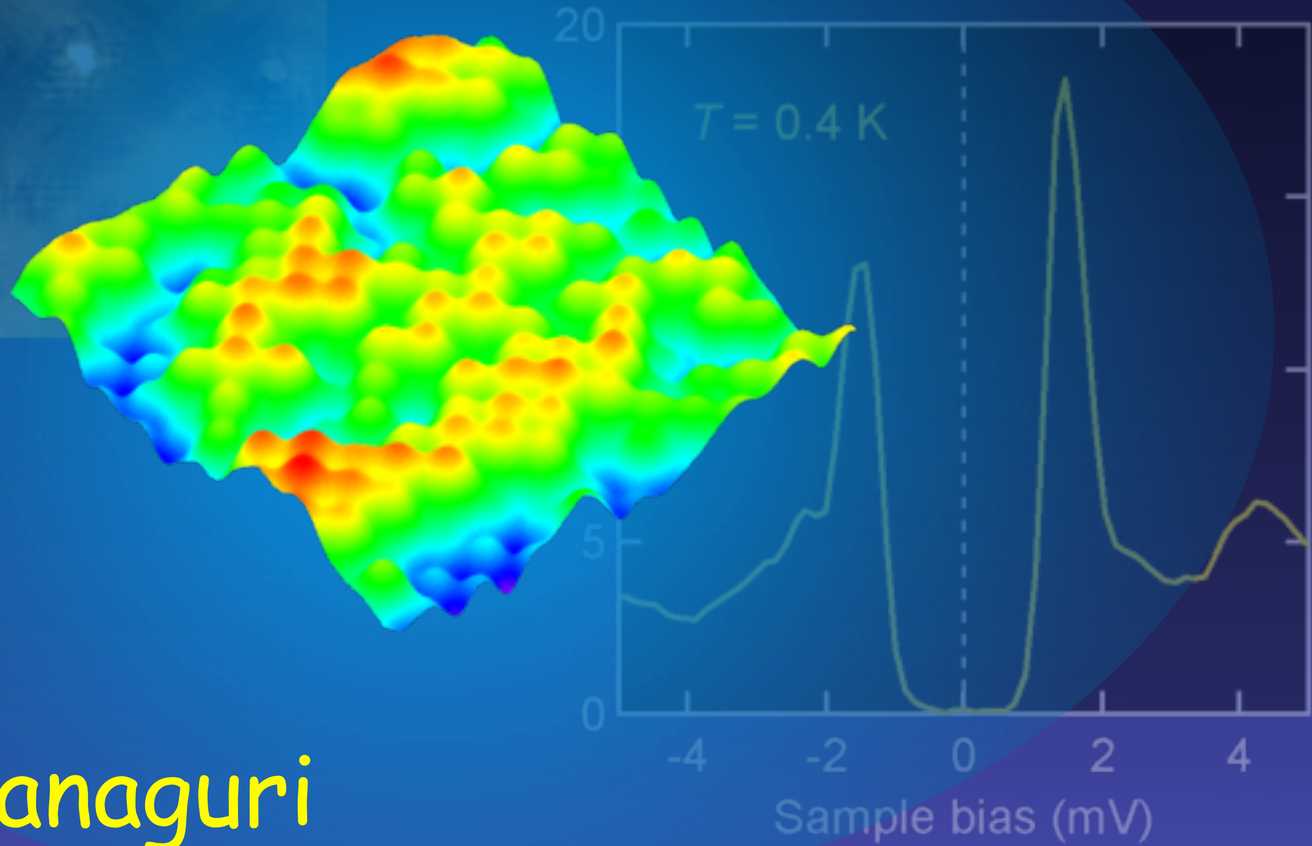
STM/STS studies on iron-based superconductors

~ superconducting-gap structure ~



RIKEN

Tetsuo Hanaguri

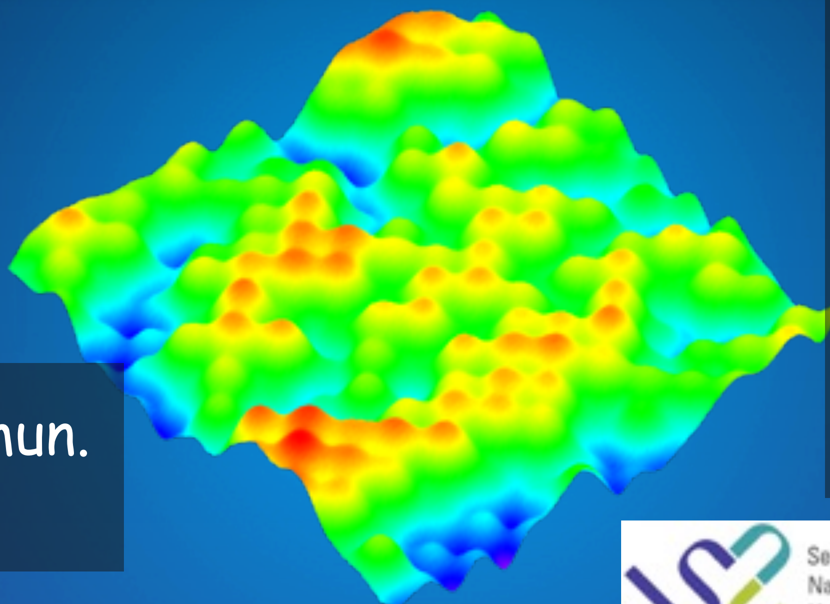
Collaborators

Fe(Se,Te)

RIKEN
S. Niitaka

U. Electro-Commun.
K. Kuroki

U. Tokyo/RIKEN
H. Takagi



LiFeAs

ISSP
K. Kitagawa
K. Matsubayashi
Y. Mazaki
Y. Uwatoko
M. Takigawa

SNU
Kee Hoon Kim

Outline

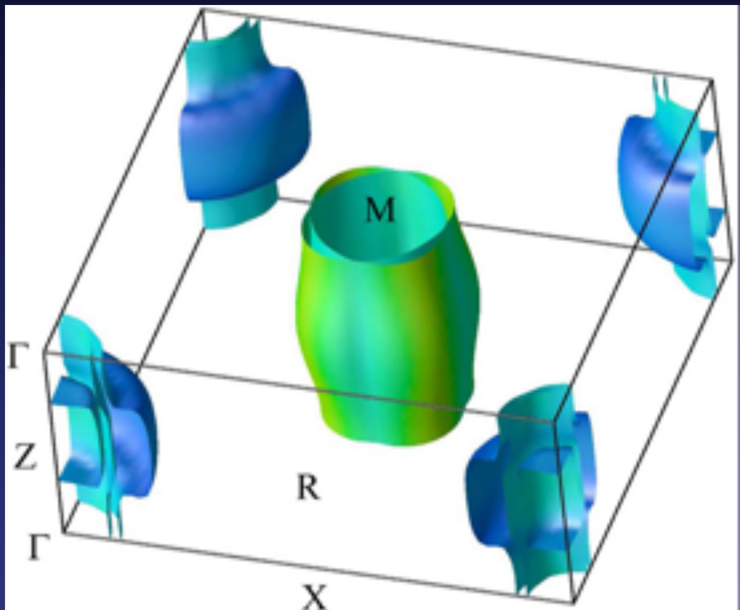
Gap structure of iron-based SC?

- Introduction
- Why STM?
- Results on iron-based superconductors
  - Phase-sensitive quasi-particle interference in Fe(Se,Te)
  - STM/STS studies of defect states in LiFeAs
- Summary and Prospects

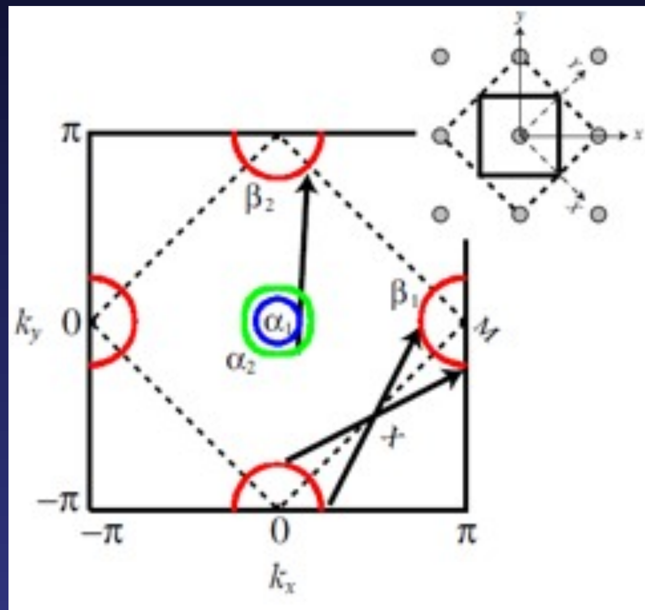
Gap structure of iron-based superconductors

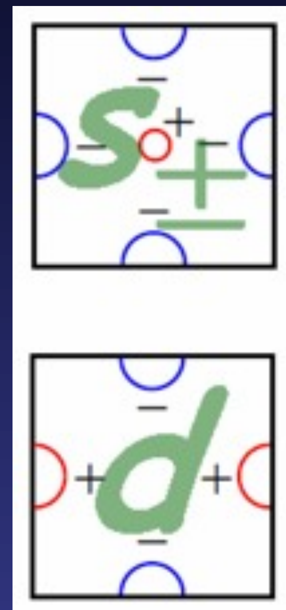
Disconnected Fermi surface pockets

cf. K. Kuroki and R. Arita, PRB **64**, 024501 (2001).



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





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

- Fully gapped or gapless?
- Sign reversal?

Experimental tests

Method	Material	Gap node	Symmetry
λ	$PrFeAsO_{1-y}$	gapped	$s_\pm$ or s_{++}
K. Hashimoto et al., PRL **102**, 017002 (2009).			
ARPES	$Ba_{0.6}K_{0.4}Fe_2As_2$	gapped	$s_\pm$ or s_{++}
H. Ding et al., EPL **83**, 47001 (2008).			
λ	LaFePO	nodal	nodal $s_\pm$ or d
J. D. Fletcher et al., PRL **102**, 147001 (2009).			
SC loop	$NdFeAsO_{0.88}F_{0.12}$	?	non s_{++}
C.-T. Chen et al., Nature Phys. **6**, 260 (2010).			
INS	$Ba_{0.6}K_{0.4}Fe_2As_2$	?	$s_\pm$
A. D. Christianson et al., Nature **456**, 930 (2008).			

Experimental tests

Method	Material	Gap node	Symmetry
λ	PrFeAsO		s_{++}

K. Hashimoto

A

H. D

			$s_{\pm}$ or d

J. D. Fletcher et al.,

SC loop	NdFeA $_{0.88}F_{0.12}$	?	non s_{++}

C.-T. Chen et al., Nature Phys 260 (2010).

INS	$Ba_{0.6}K_{0.4}Fe_2As_2$	?	$s_{\pm}$

A. D. Christianson et al., Nature **456**, 930 (2008).

Both **momentum** and **phase** resolutions are indispensable.

How STM can contribute to the issues?

- Nodal or fully gapped
- Distinguishing different FS pockets (**k** resolurion)
- Phase of the SC gap on each pocket

How STM can contribute to the issues?

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  ➡ Tunneling spectrum

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How STM can contribute to the issues?

- Nodal or fully gapped

  → **Tunneling spectrum**

- Distinguishing different FS pockets (**k** resolurion)

  → **Quasi-particle interference effect**
  (Fourier-transform STS)

- Phase of the SC gap on each pocket

How STM can contribute to the issues?

- Nodal or fully gapped

  ➡ **Tunneling spectrum**

- Distinguishing different FS pockets (**k** resolurion)

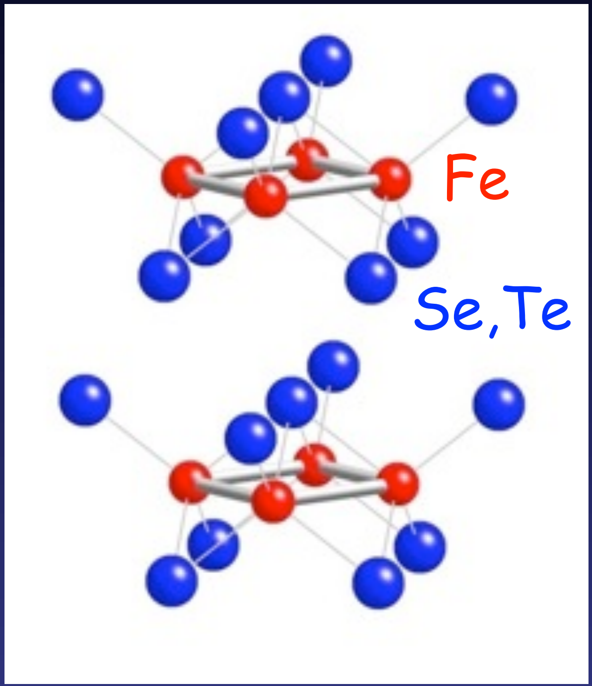
  ➡ **Quasi-particle interference effect**
  (Fourier-transform STS)

- Phase of the SC gap on each pocket

  ➡ **Coherence factors**

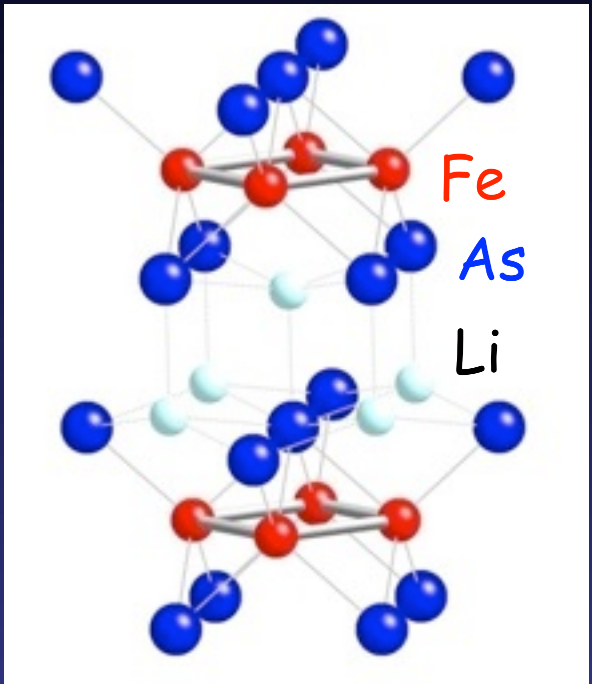
Surface MUST be neutral...

Fe (Se,Te) T_c ~ 13 K



Grown by
Dr. S. Niitaka
(RIKEN)

LiFeAs T_c ~ 16 K



Grown by
Dr. K. Kitagawa
Dr. K. Matsubayashi
(ISSP)

Nodal or fully gapped

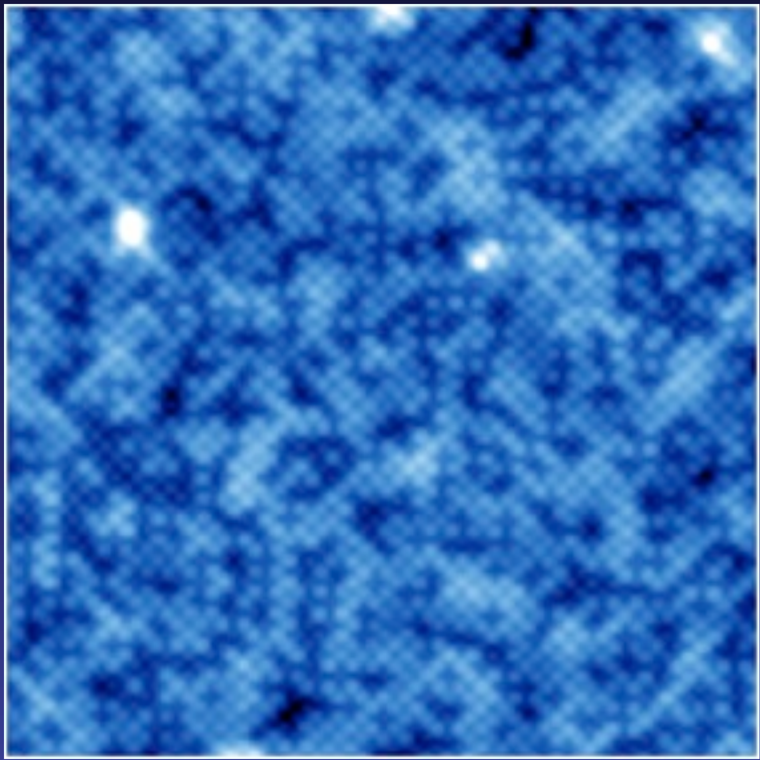
STM on an iron chalcogenide

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

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

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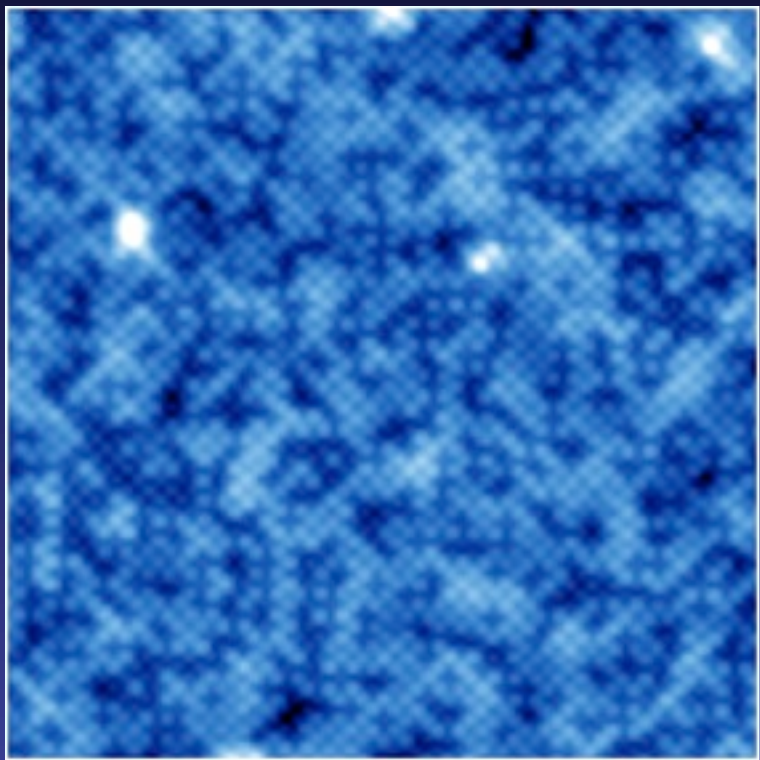

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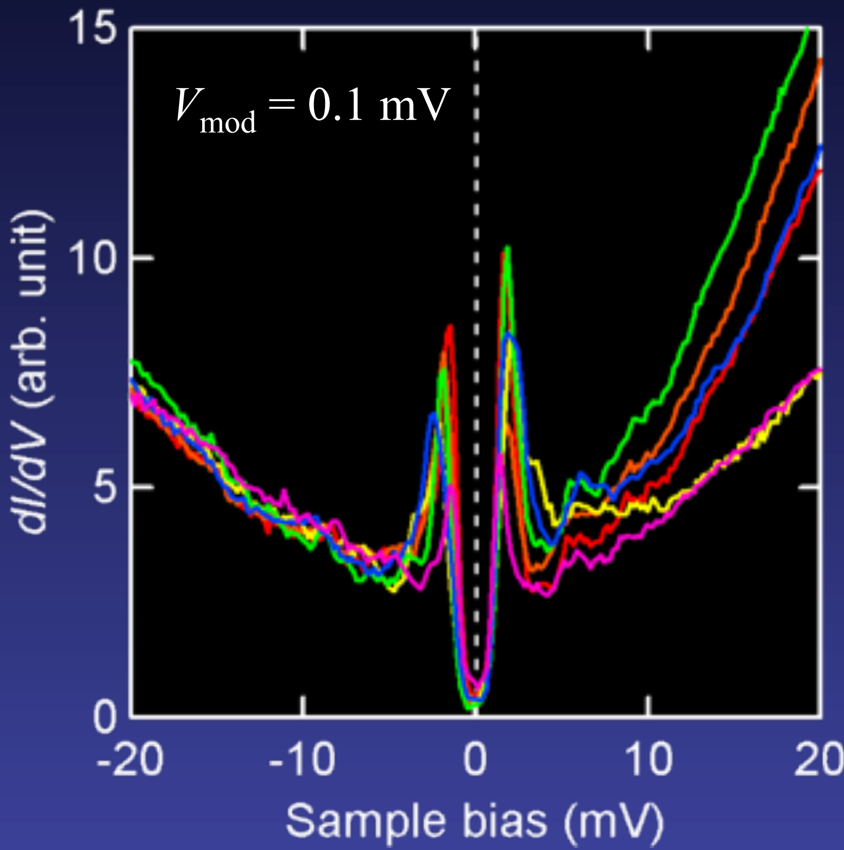

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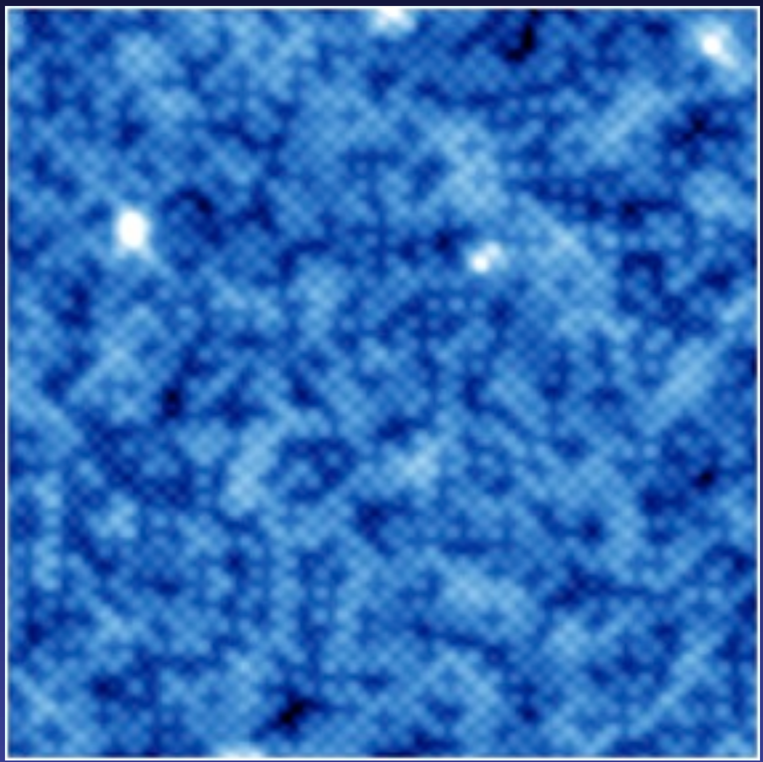

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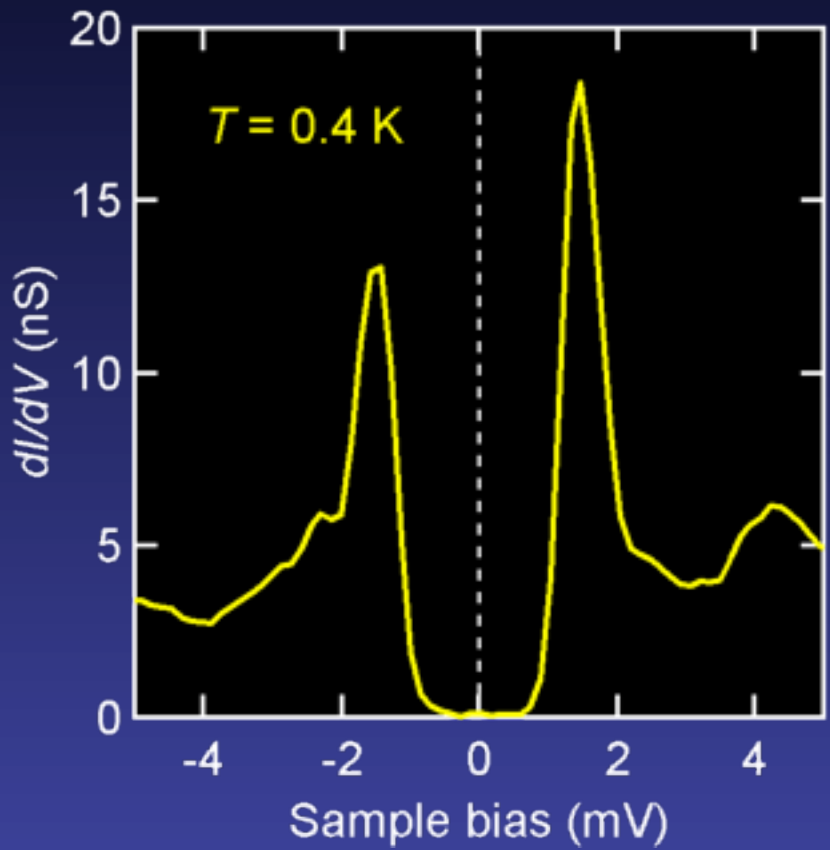

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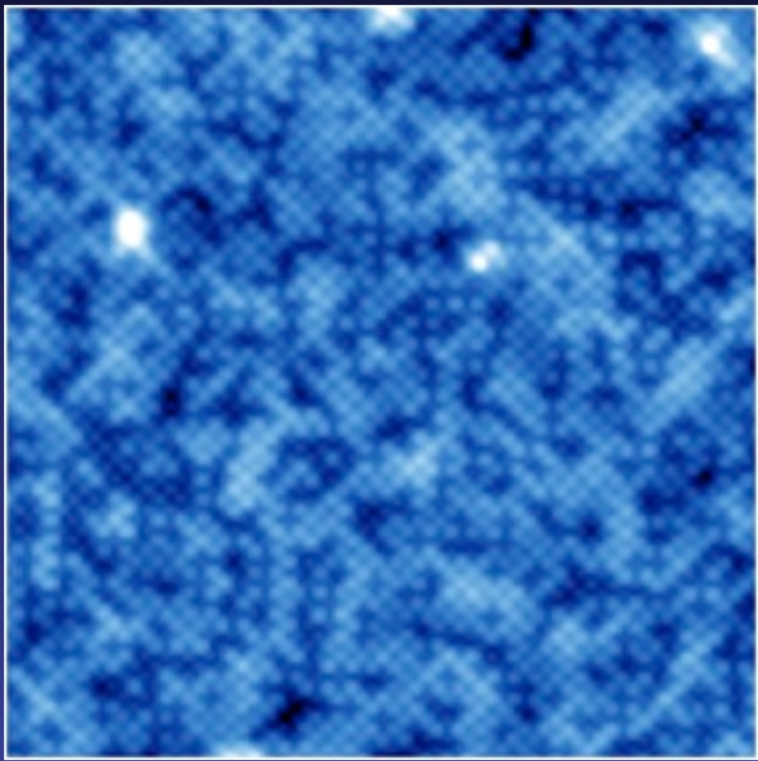

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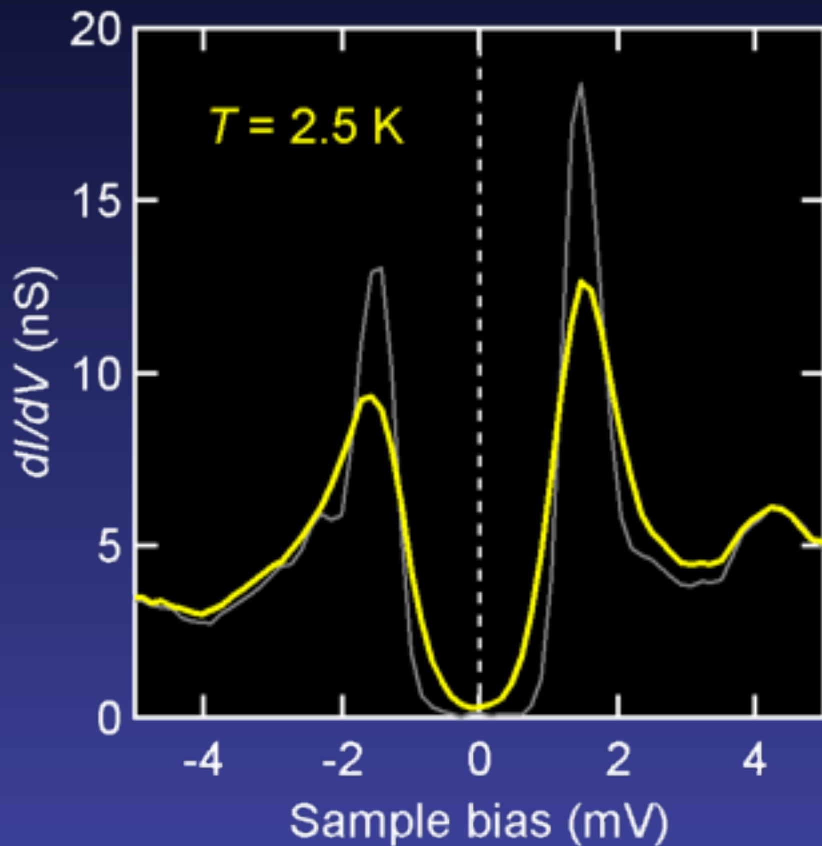

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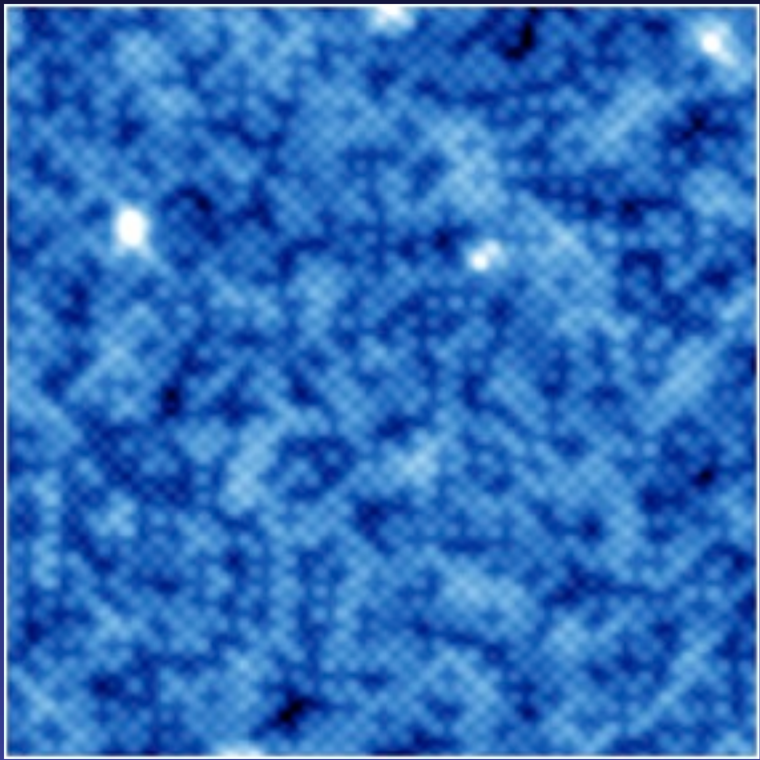

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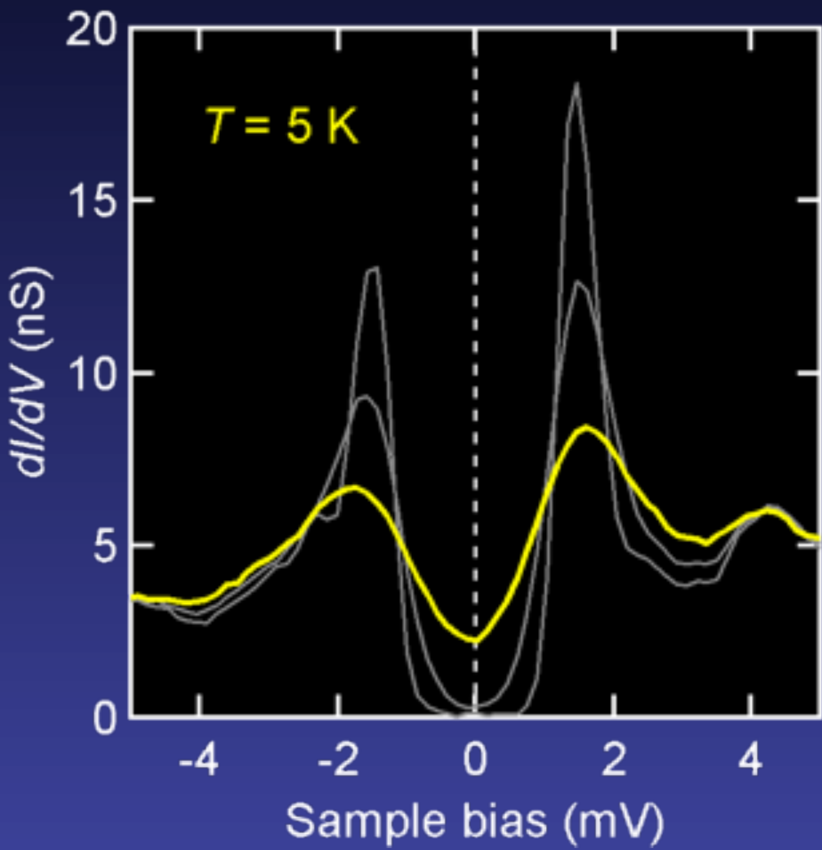

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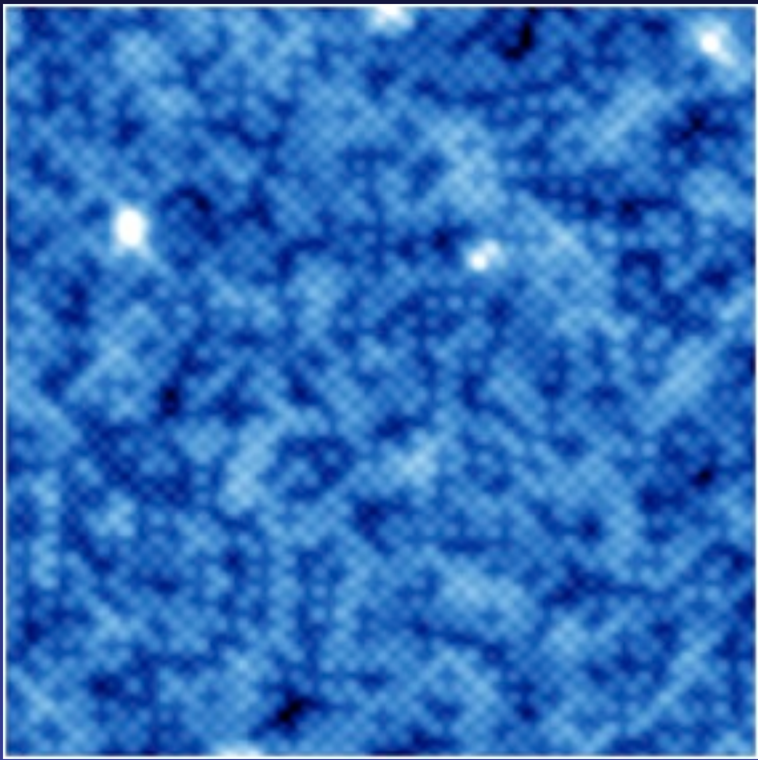

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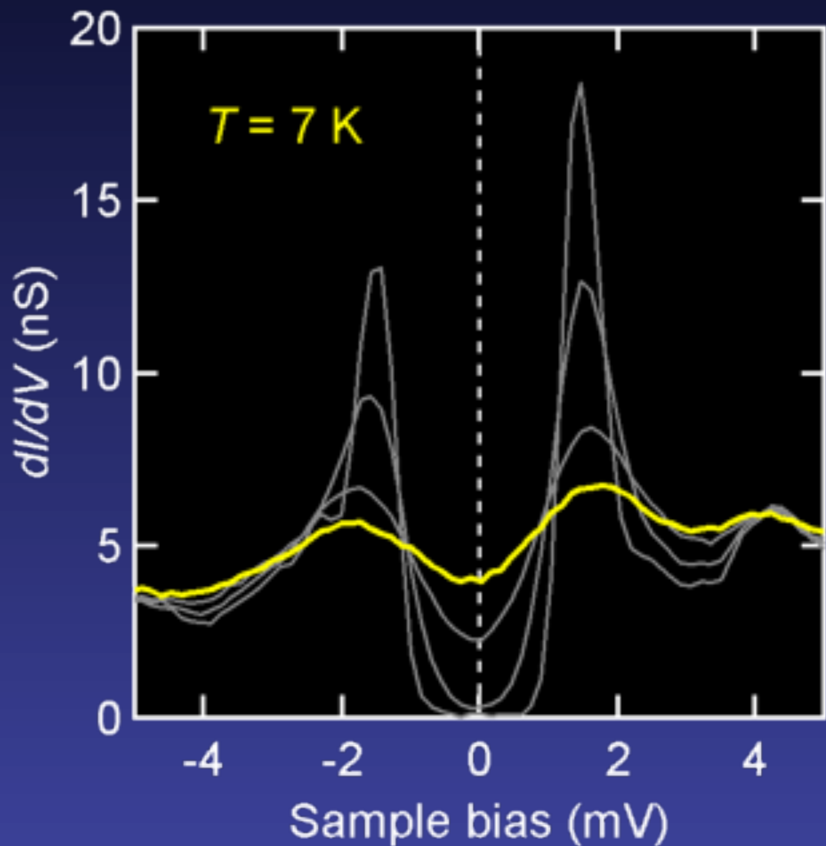

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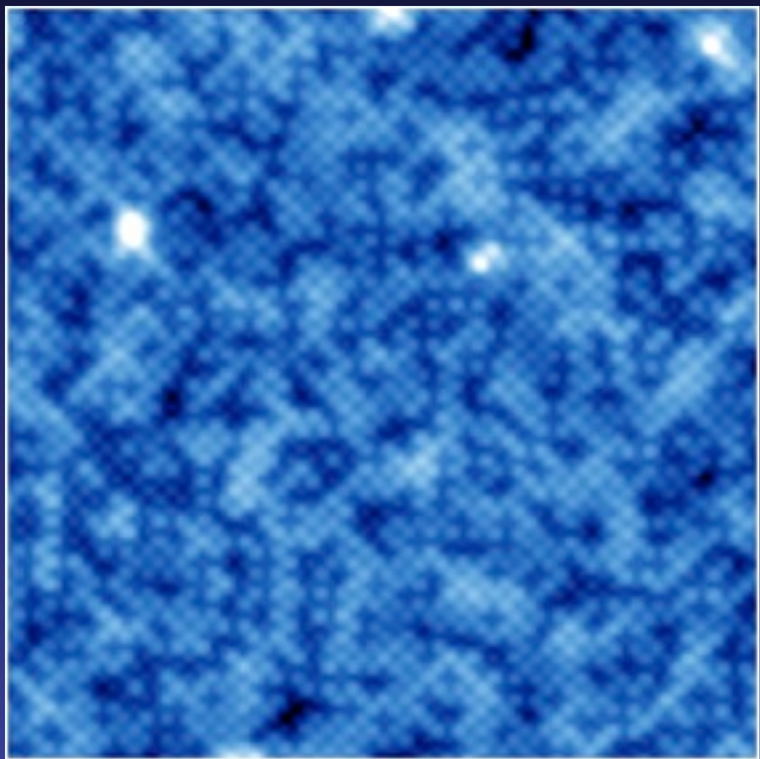

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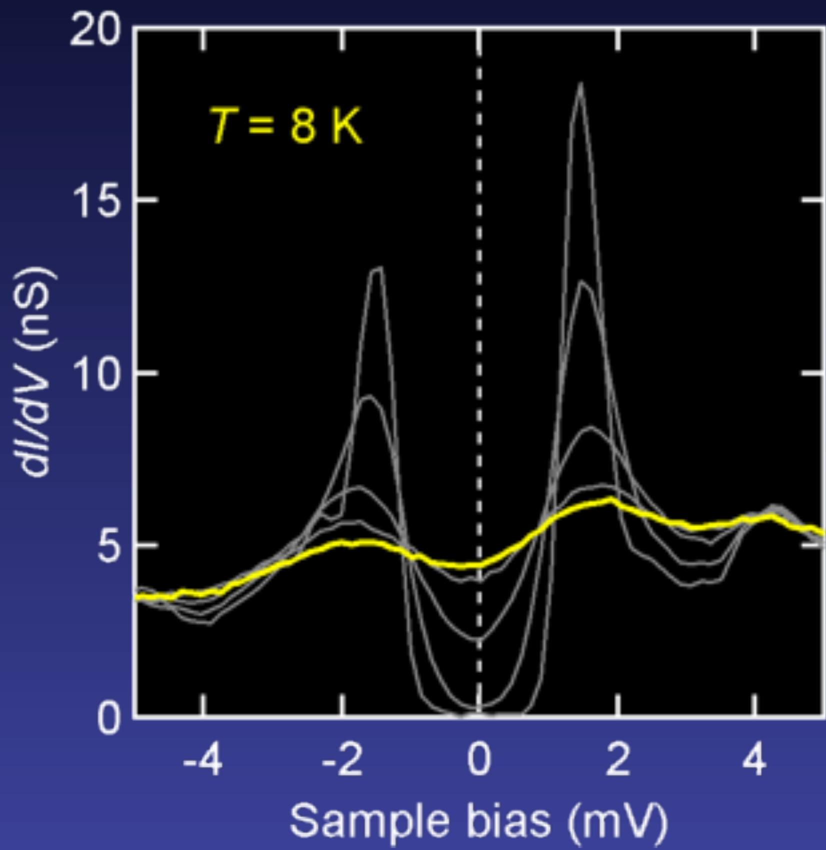

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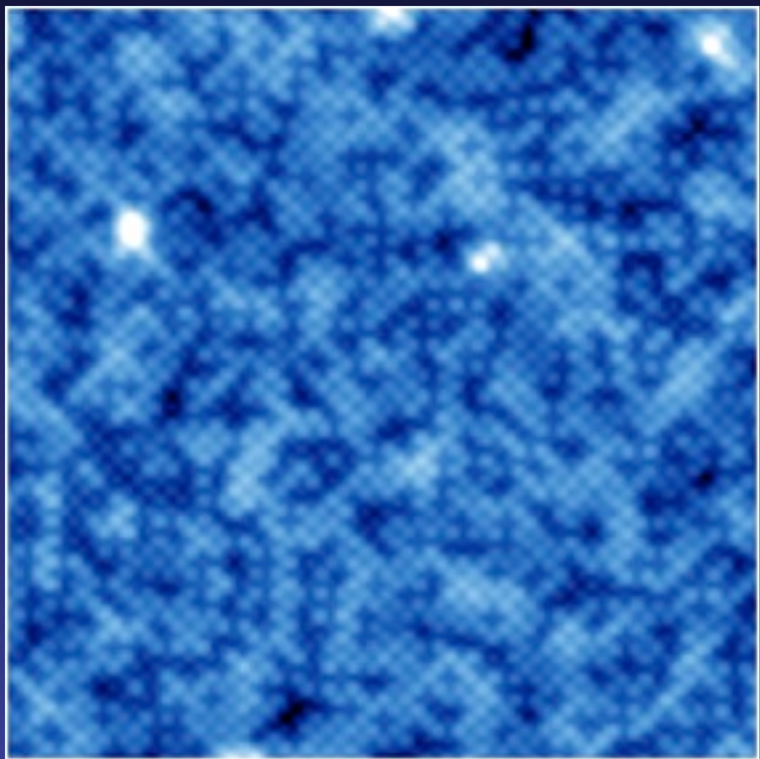

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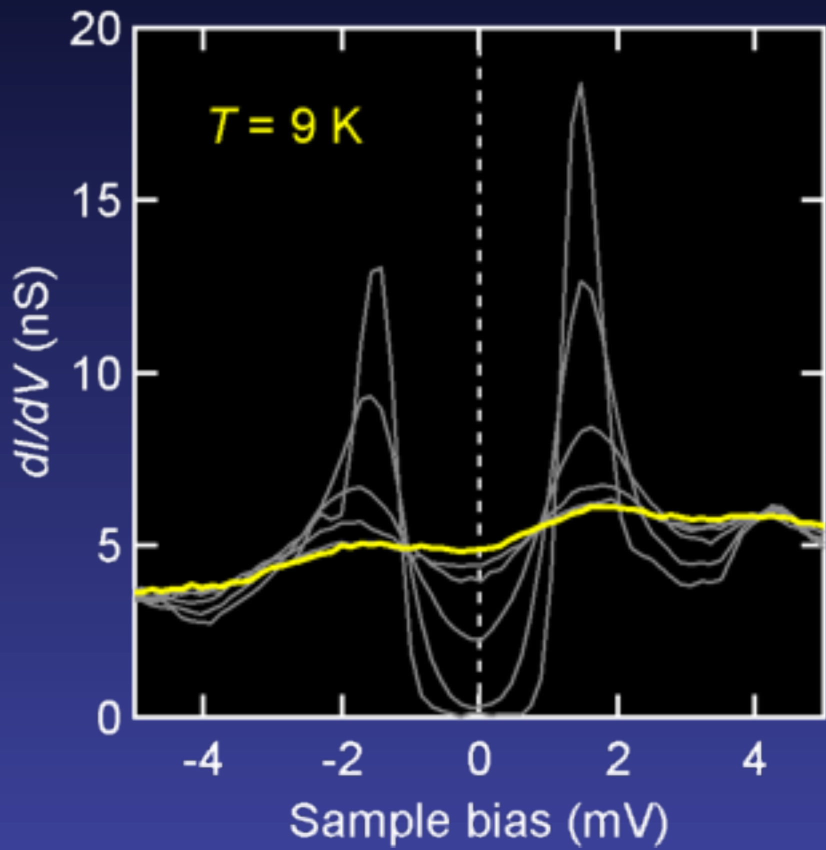

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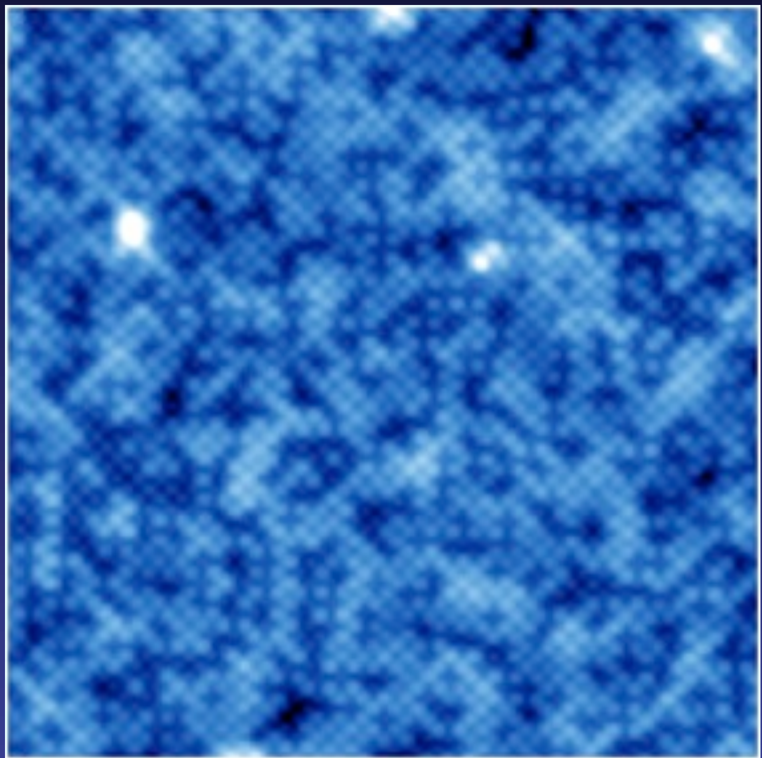

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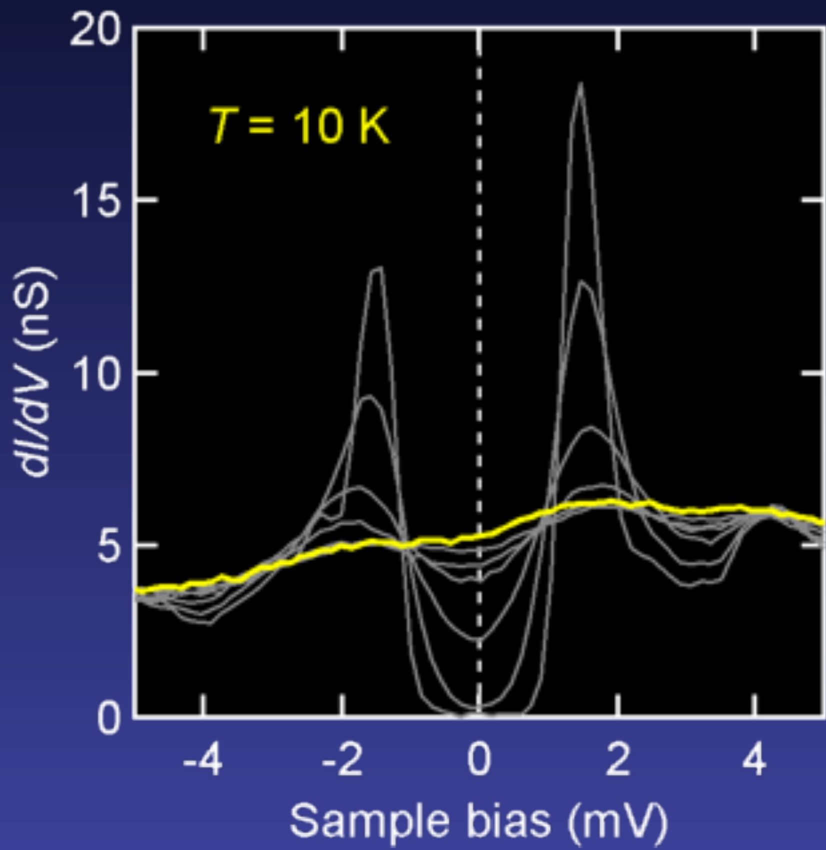

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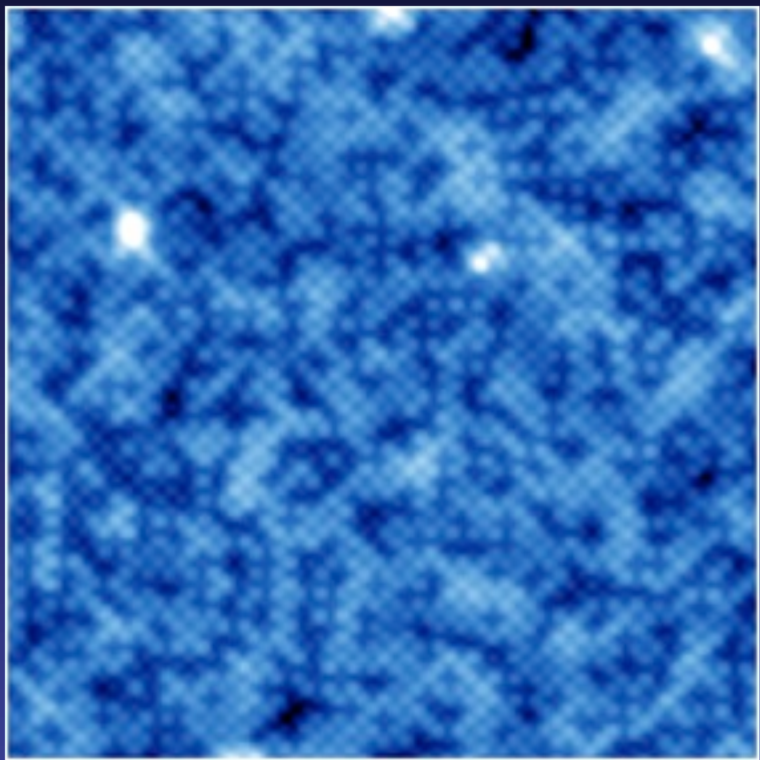

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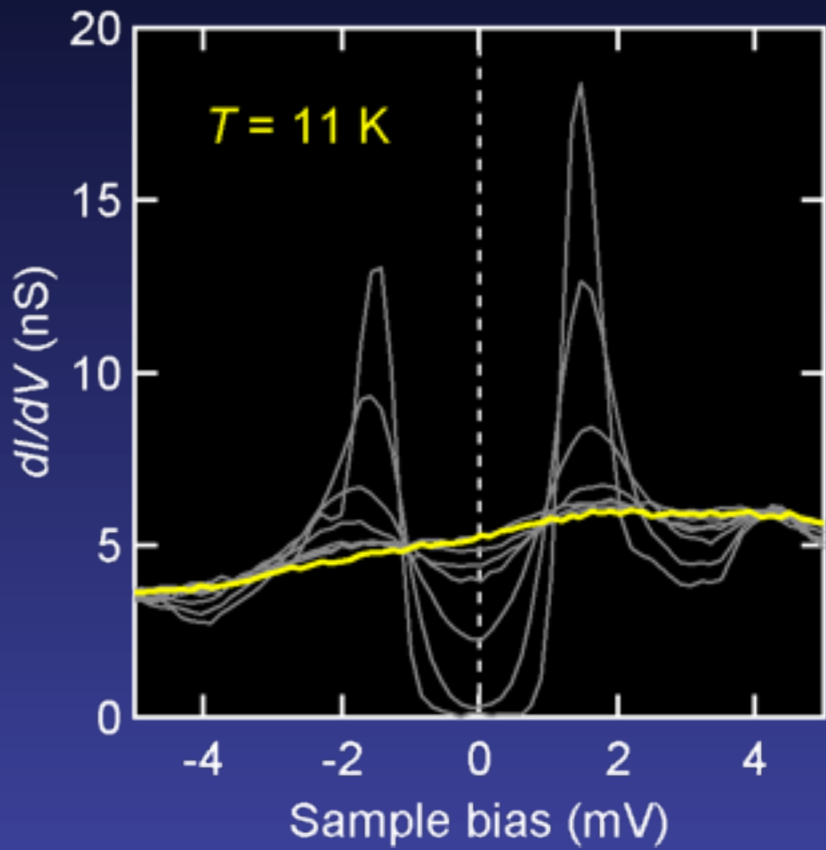

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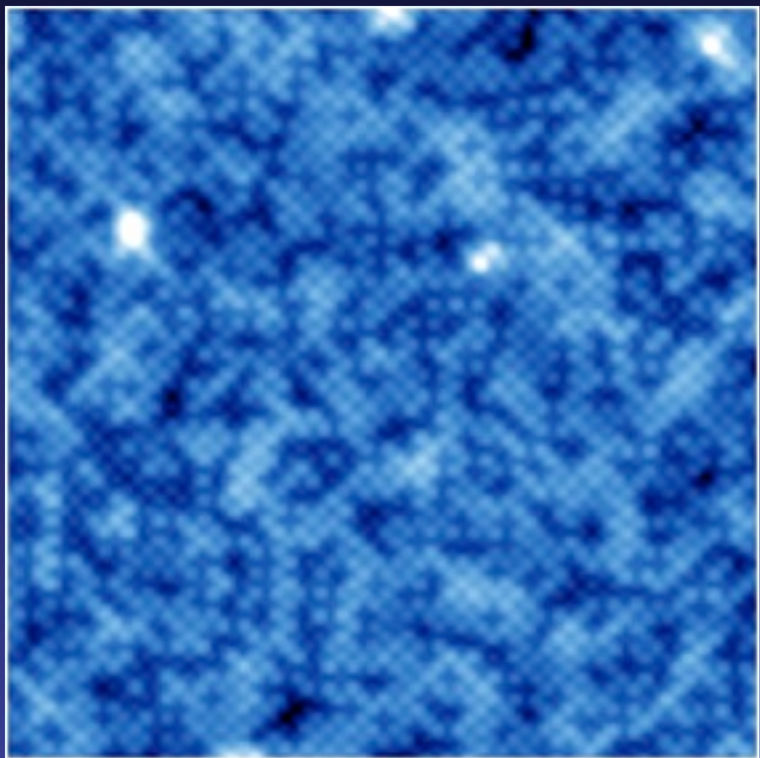

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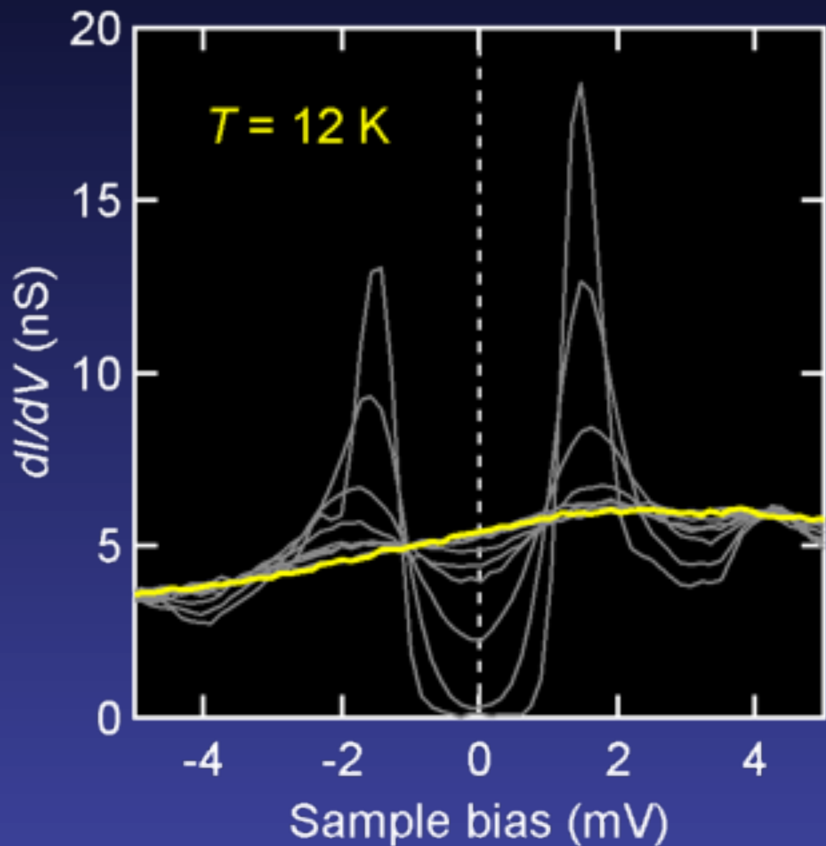

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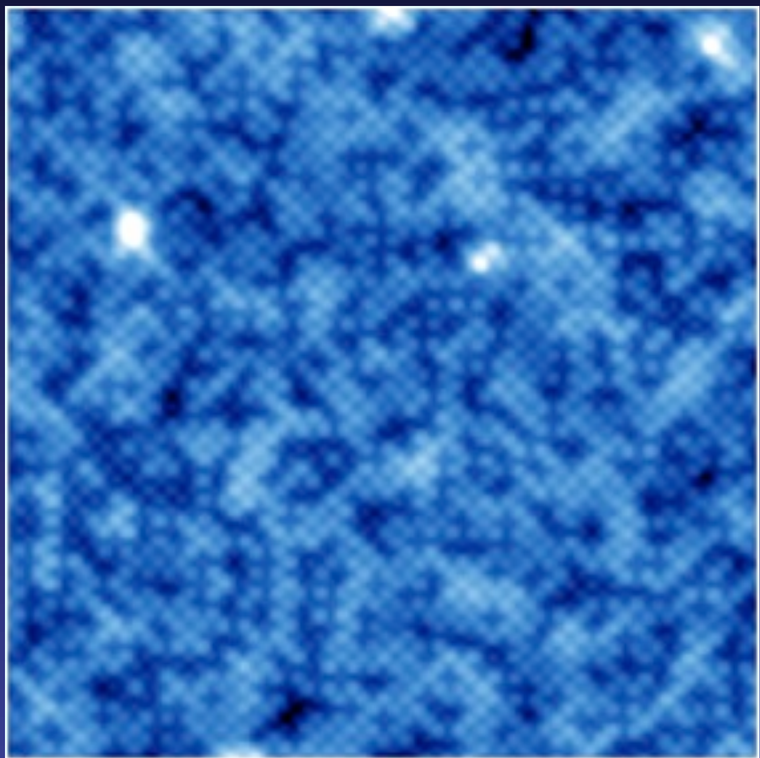
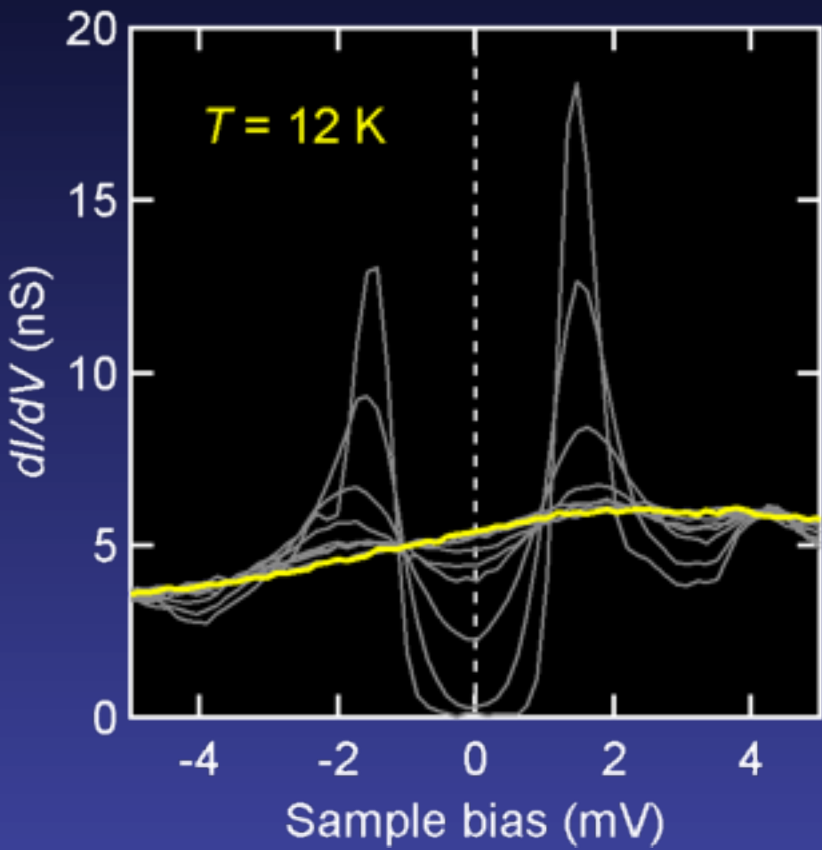


19 nm×19 nm, -20 mV/0.1 nA

$2\Delta/T_c$ ~ 3.5

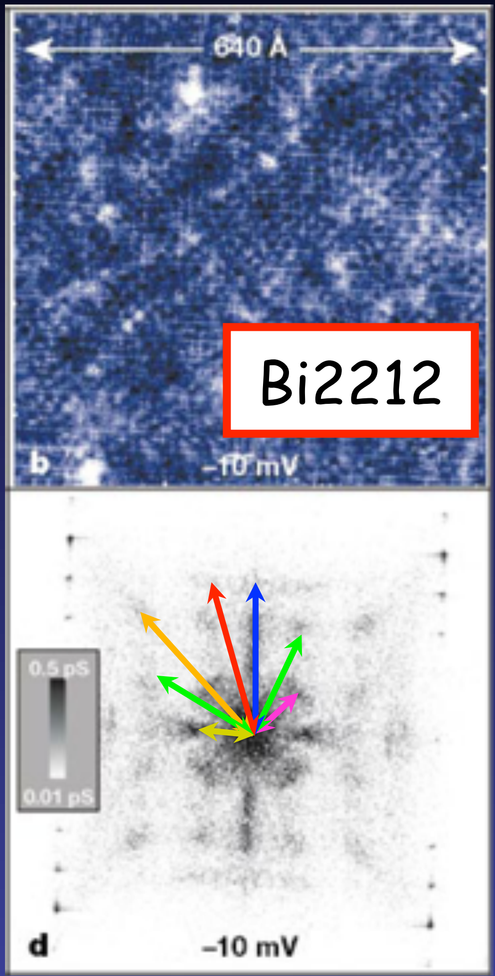


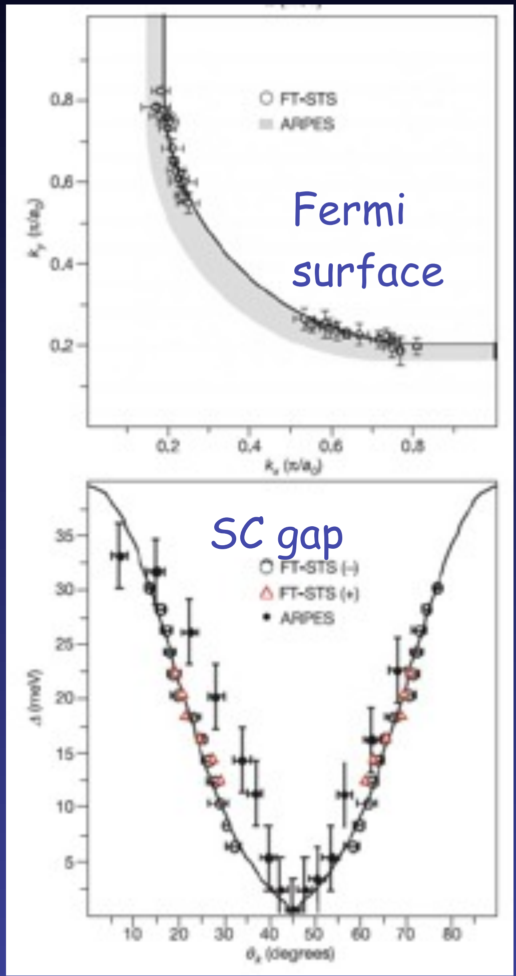
SC gap FULLY opens all over the FS pockets.

Distinguishing different FS pockets

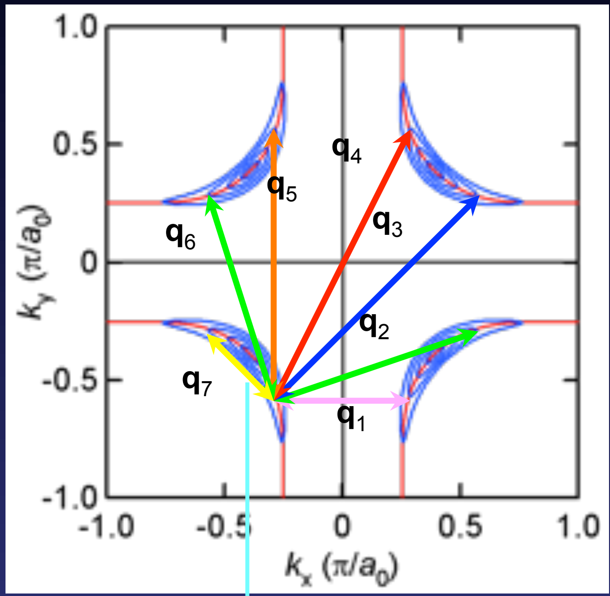
Quasi-particle interference ~ k-sensitive STM

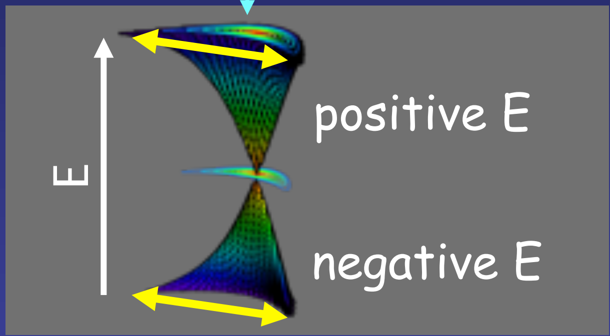
J. Hoffman et al., Science **297**, 1148 (2002).
K. McElroy, et al., Nature **422**, 592 (2003).





"Octet model"





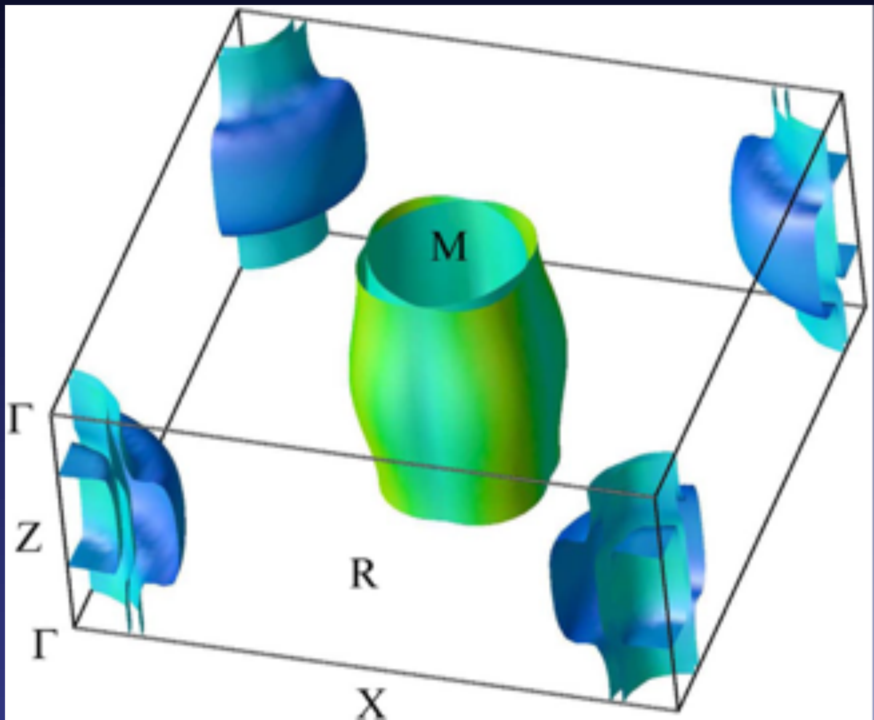
FS geometry & SC gap dispersion can be obtained through QPI.

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

Monday, January 24, 2011

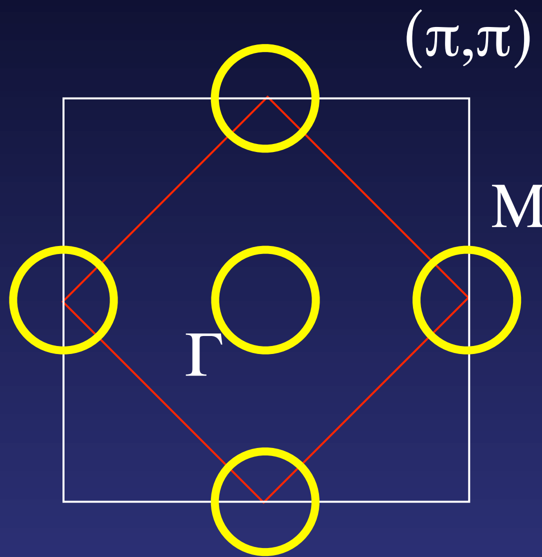
How will it work in iron-based SC?

Disconnected pockets



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

$E \sim \Delta$



k space

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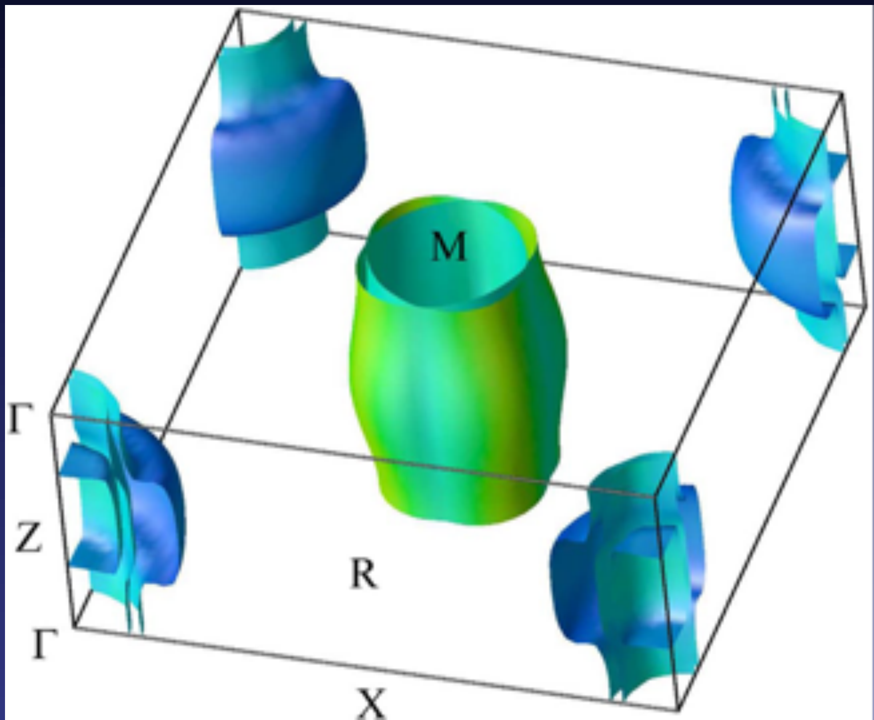

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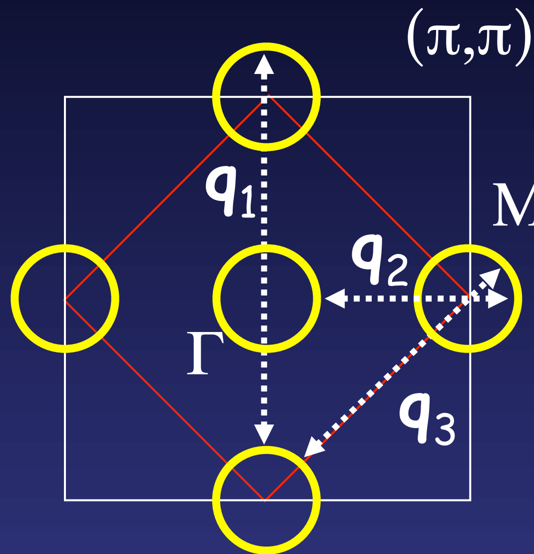

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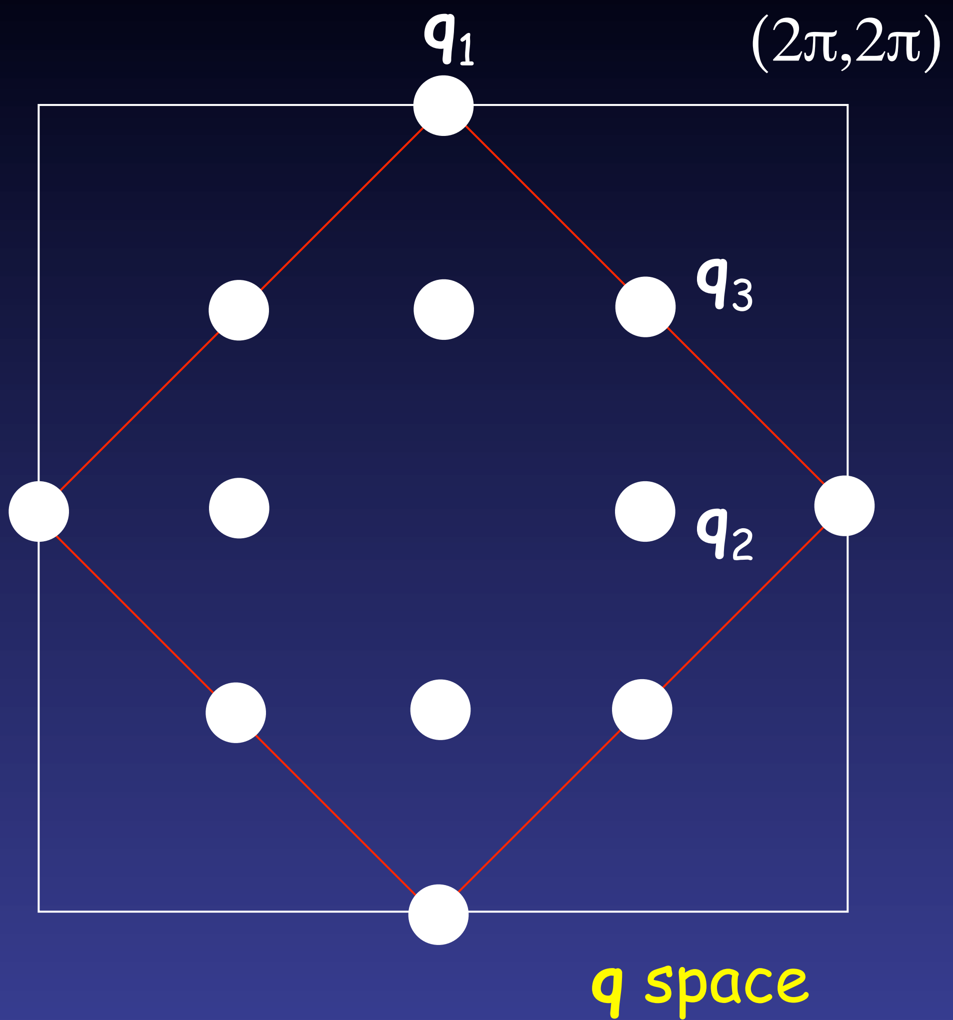

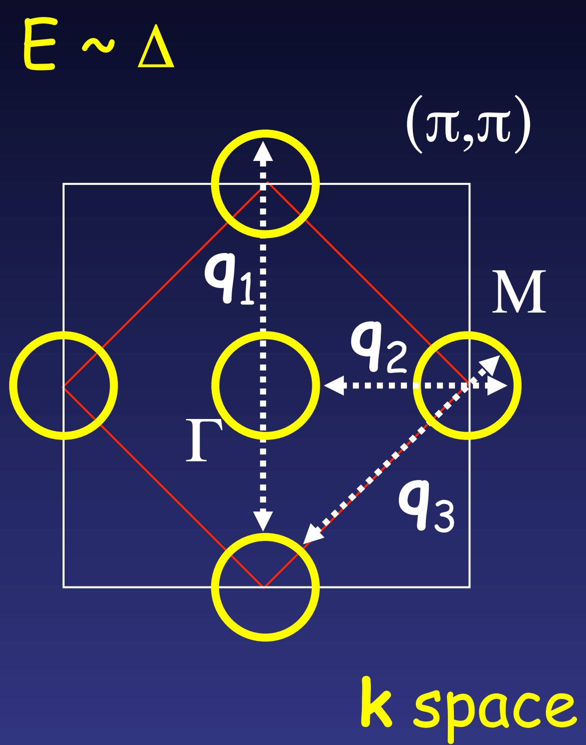

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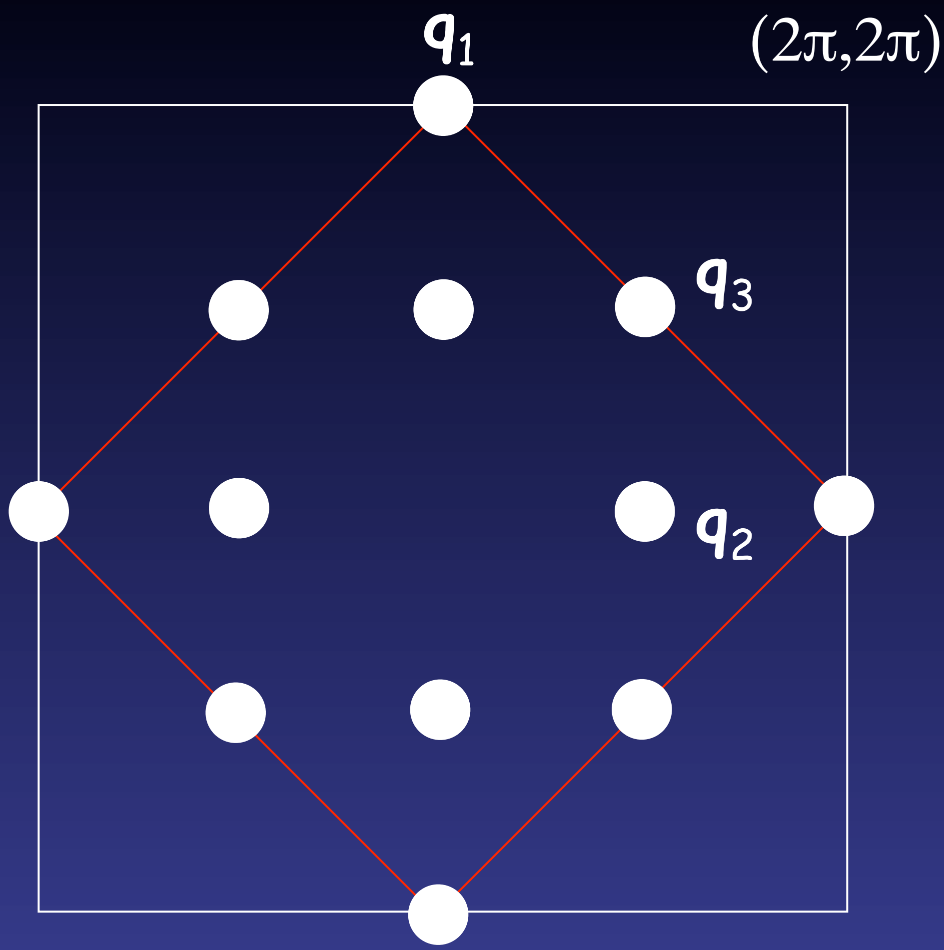
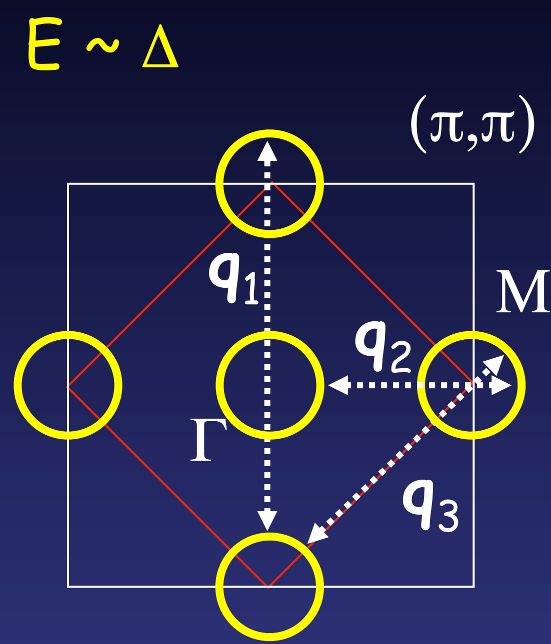


q space



k space

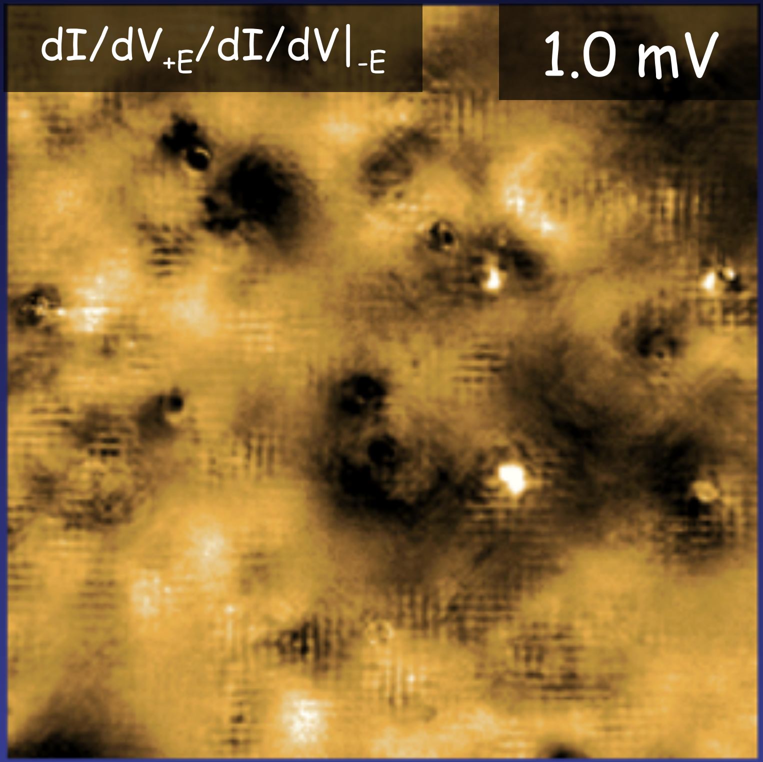
Inter-pocket scattering ⟷ Relationship between the pockets

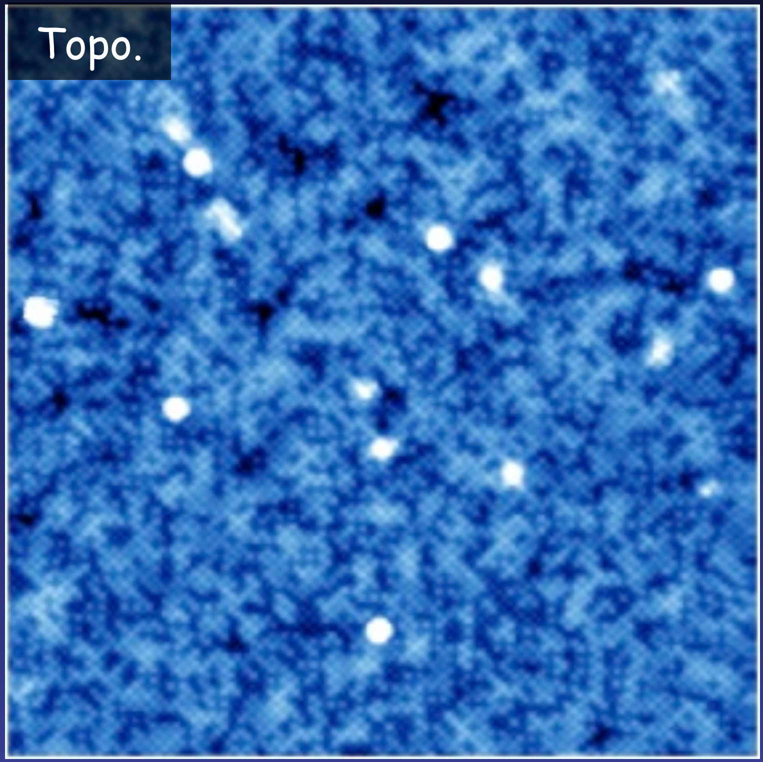
QPI in an iron chalcogenide

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

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

T ~ 1.5 K





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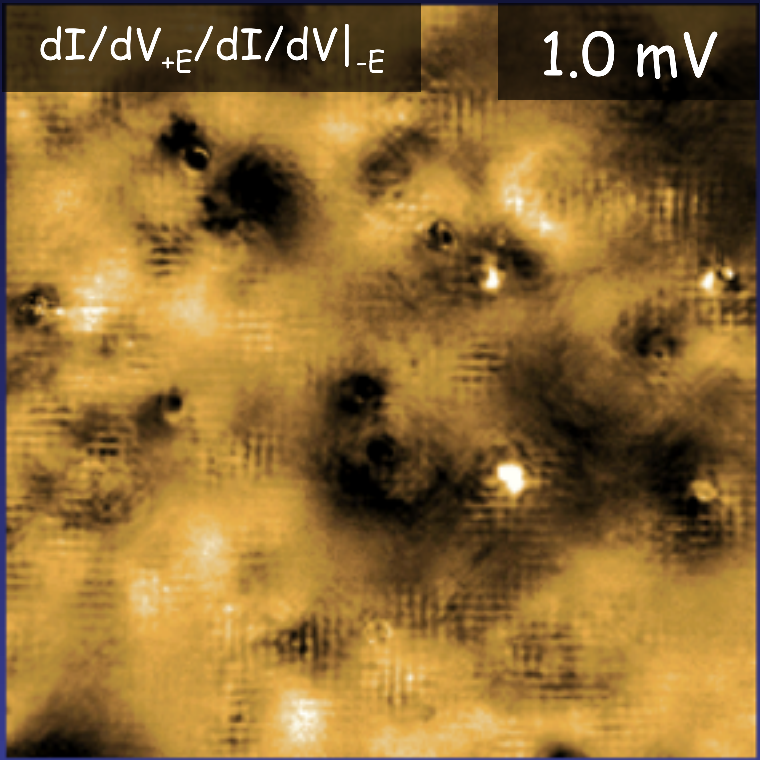

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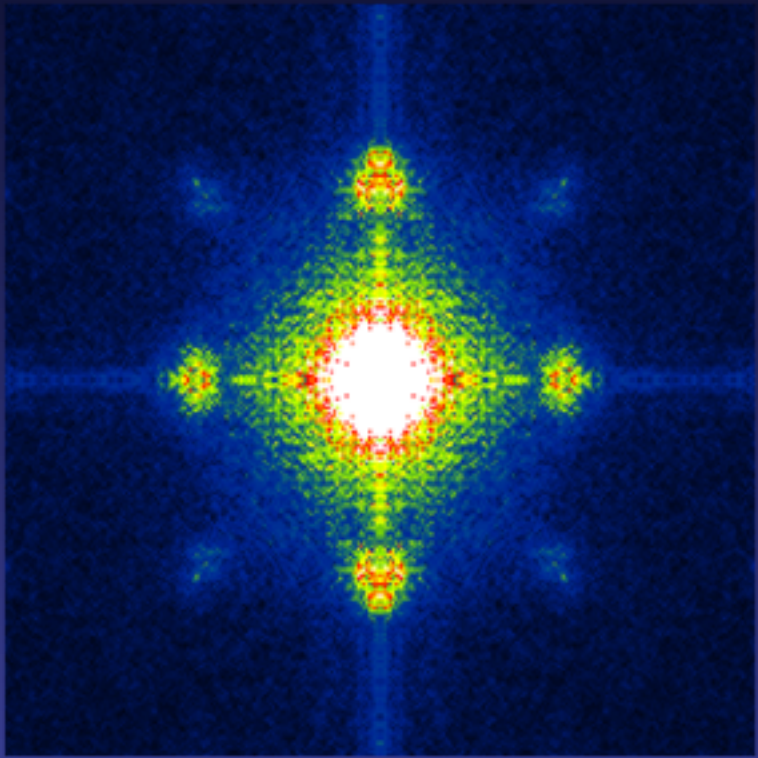
FT-Z map 1.0 meV



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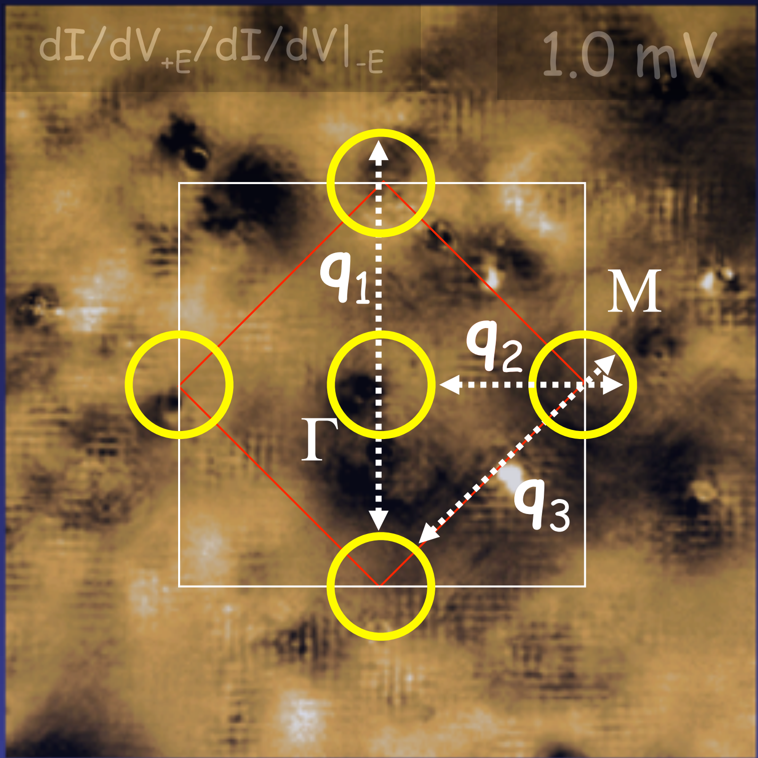

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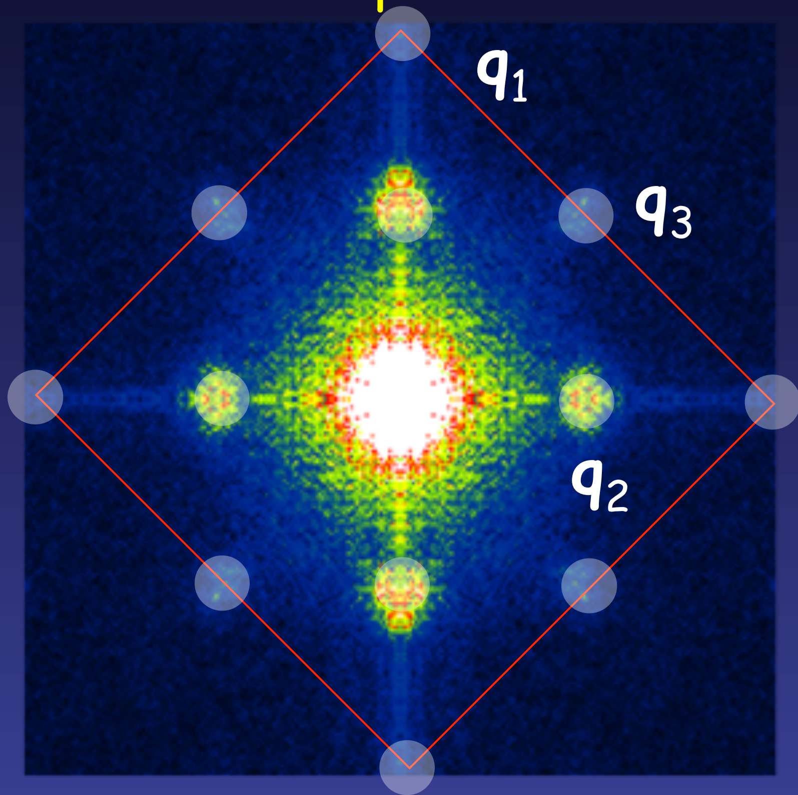

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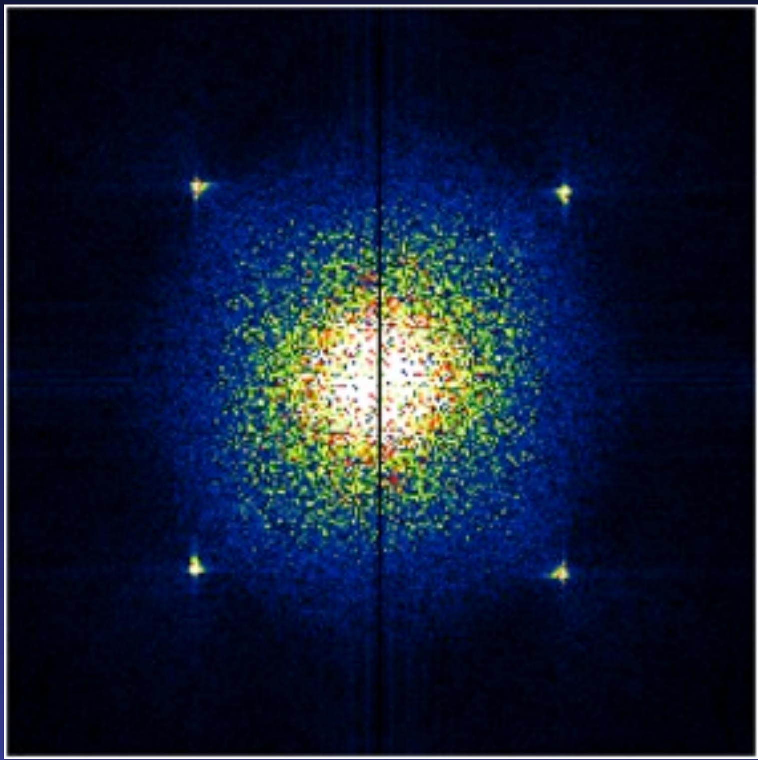
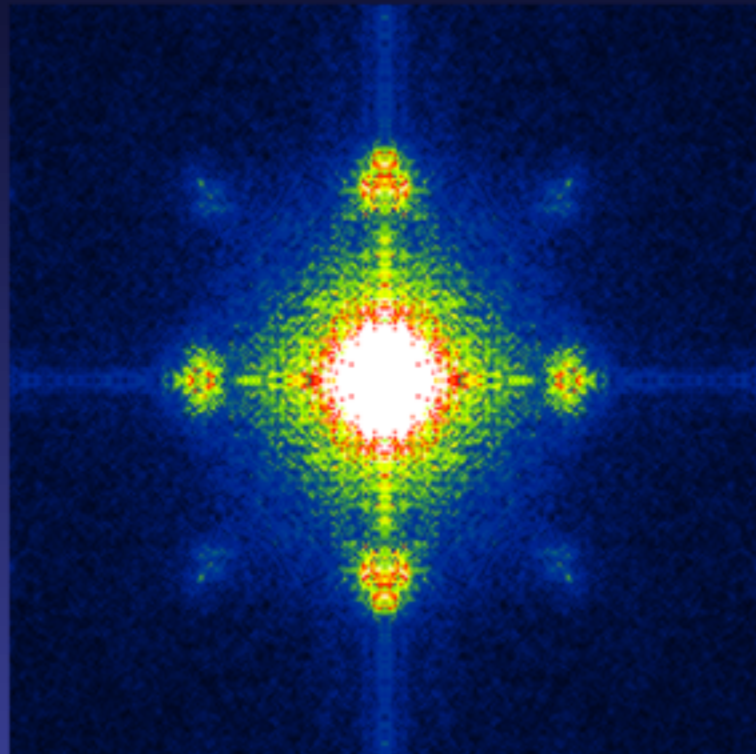
T ~ 1.5 K FT-topograph



FT-Z map 1.0 meV



cf. I.I. Mazin and D.J. Singh, arXiv:1007.0047v2, T. Hanaguri et al., arXiv:1007.0307.

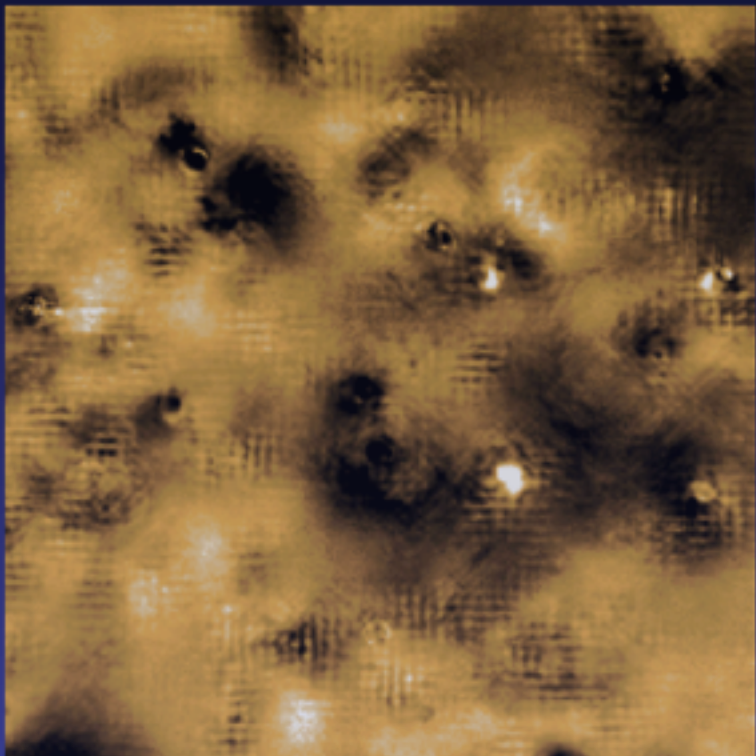
Peaks are much broader than the Bragg peak.

QPI in an iron chalcogenide

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

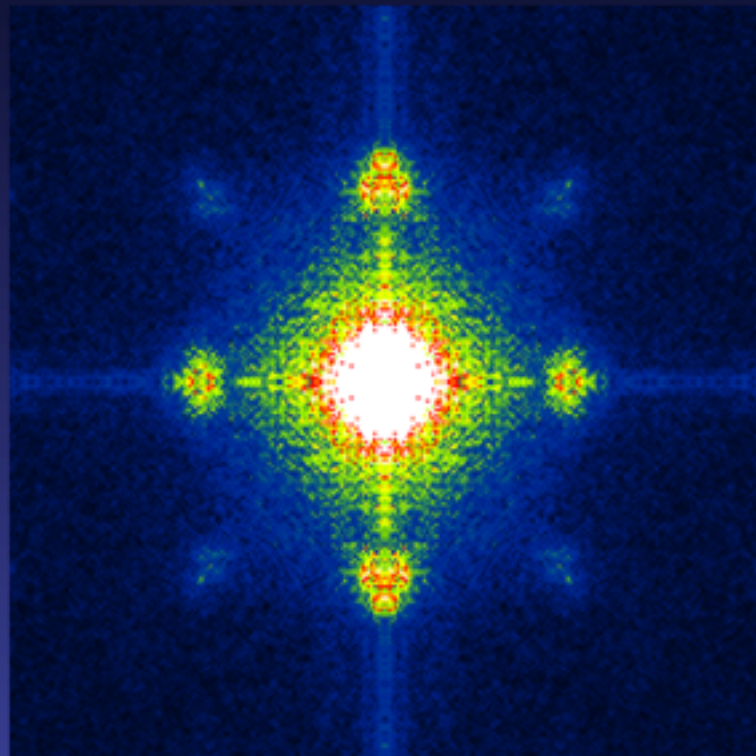
Fe(Se,Te) $T_c \sim 13$ K

T ~ 1.5 K



34 nm×34 nm, -20 mV/0.1 nA

FT-Z map 1.0 meV



Inter-pocket scatterings are detected.

Relative phase of SC gap between the pockets

Coherence factors in QPI ~ "extinction" rule

J. E. Hoffman, Thesis, http://physics.harvard.edu/~jhoffman/thesis/HoffmanThesis.pdf.

Q. -H. Wang and D. -H. Lee, PRB **67**, 020511(R) (2003).

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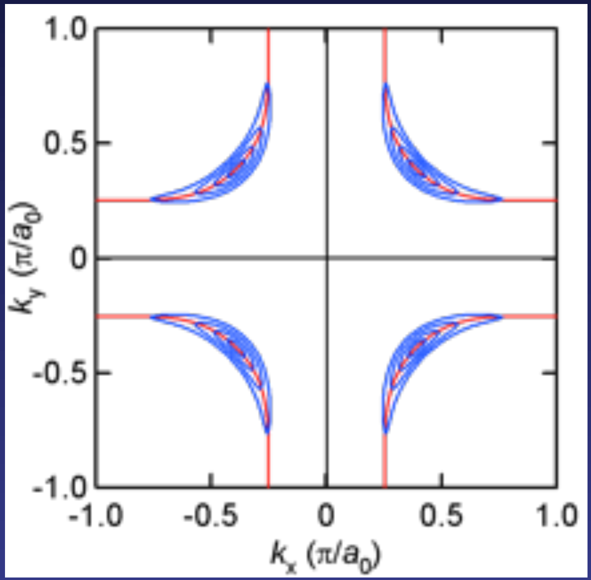
$$w(i \to f) \propto |V(\mathbf{k}_i, \mathbf{k}_f)|^2 JDOS(E, \mathbf{k}_i, \mathbf{k}_f)$$



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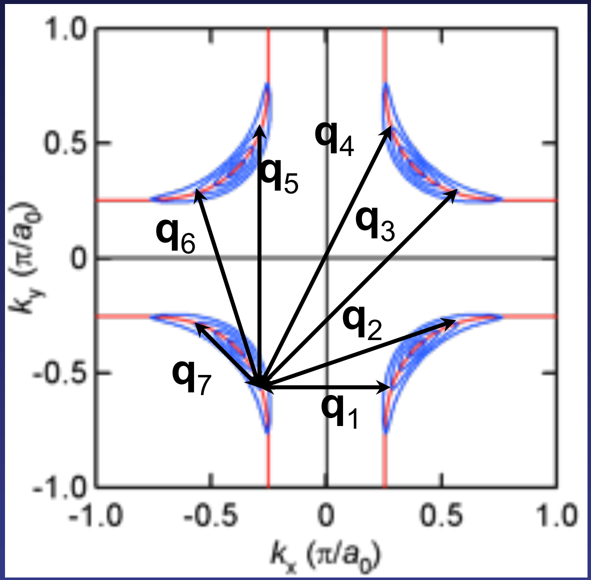

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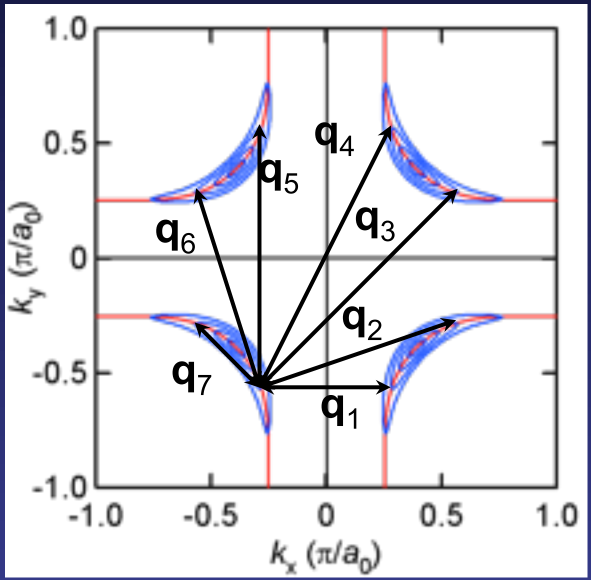

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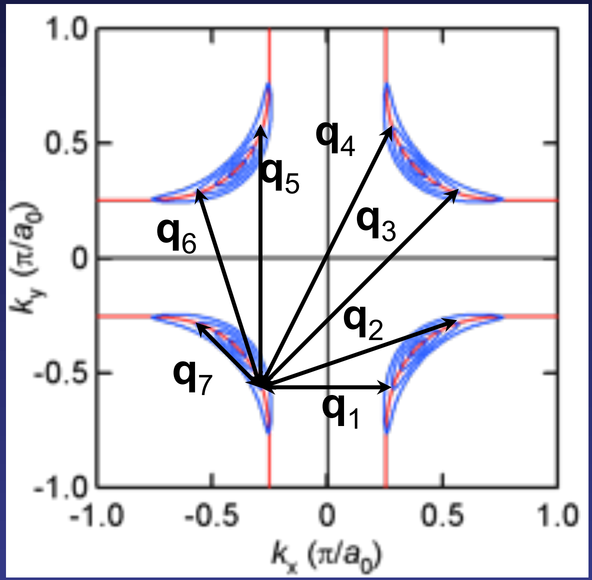
coherence factors

$$u_{\mathbf{k}} = \mathrm{sgn}(\Delta(\mathbf{k}))\sqrt{(1 + \epsilon(\mathbf{k})/E(\mathbf{k}))/2}$$

$$v_{\mathbf{k}} = \sqrt{1 - u_{\mathbf{k}}^2}$$



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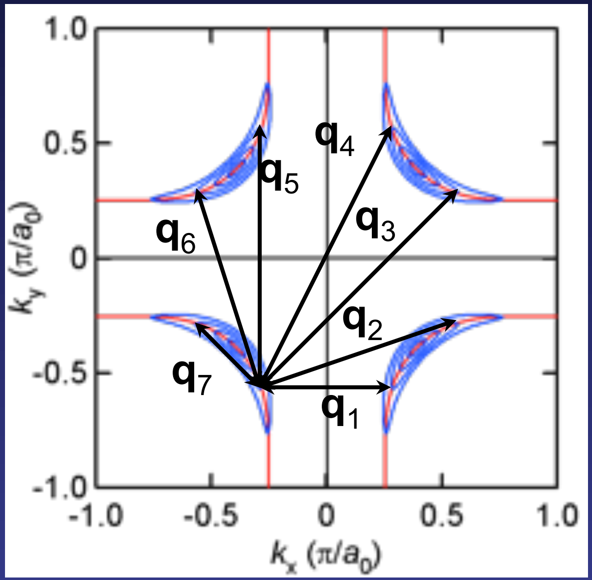

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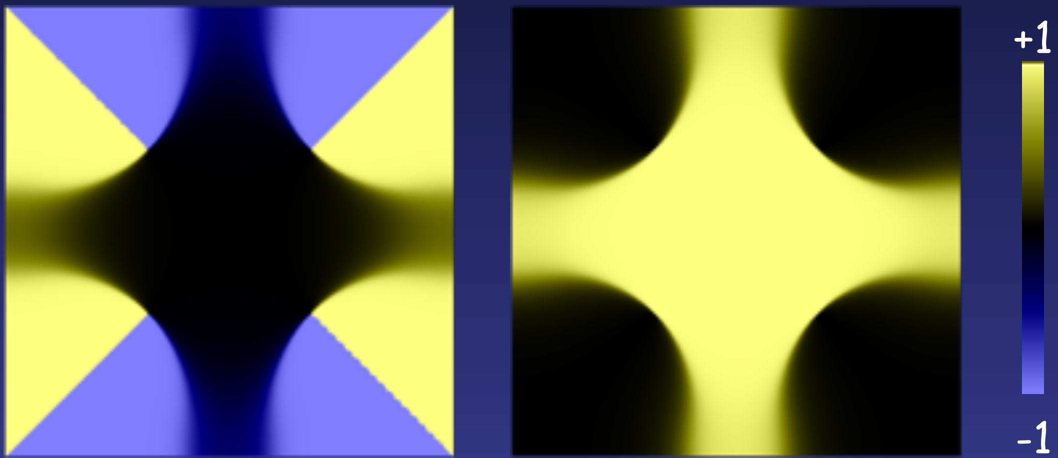
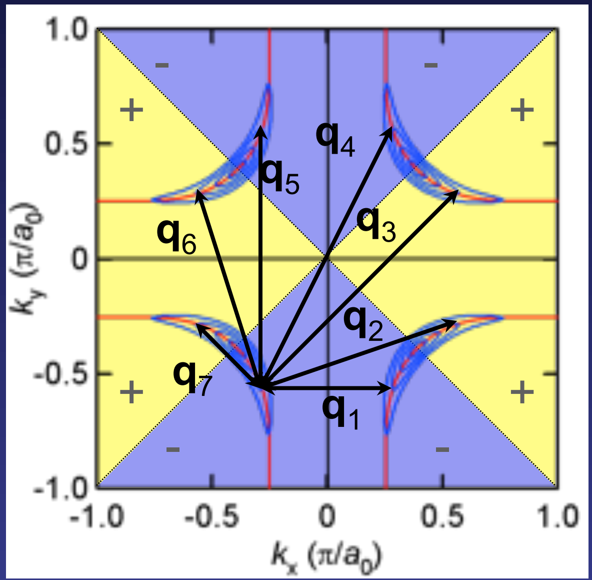
coherence factors



u_k v_k



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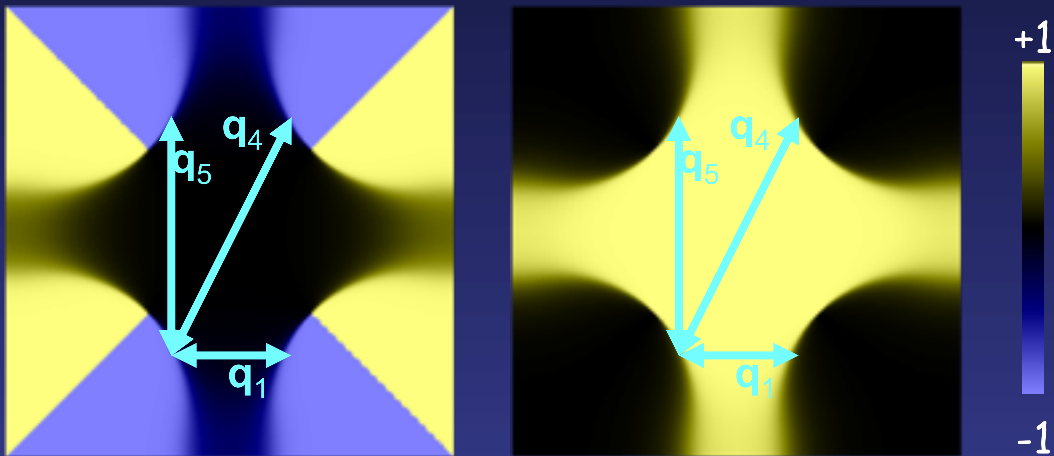
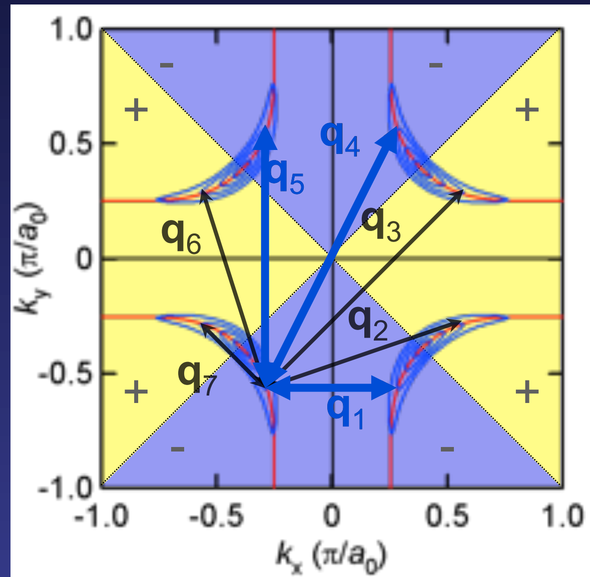
coherence factors



u_k v_k



sign-preserving scattering (q_1, q_4, q_5)

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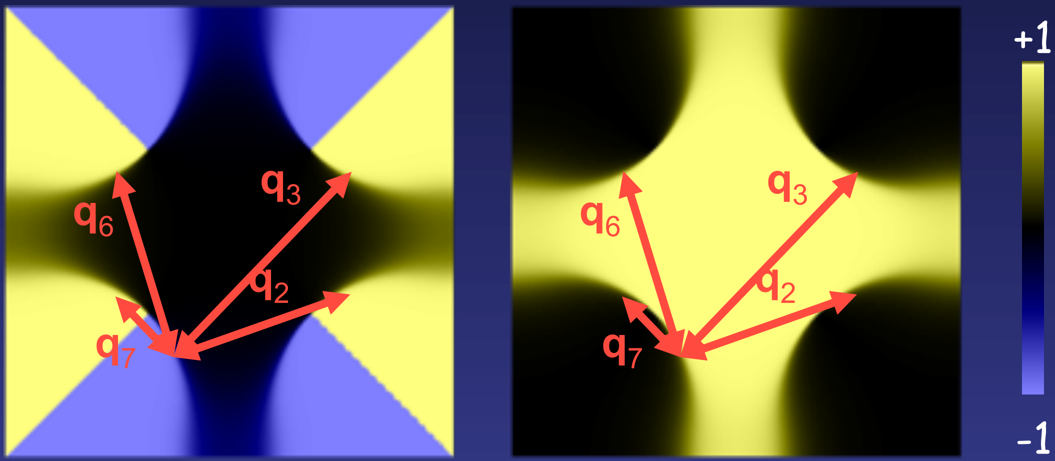
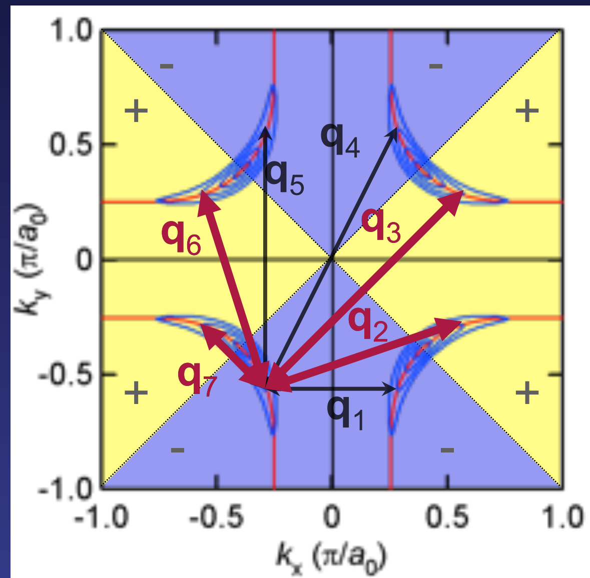
coherence factors



u_k v_k



sign-reversing scattering (q_2, q_3, q_6, q_7)

Coherence factors in QPI ~ “extinction” rule

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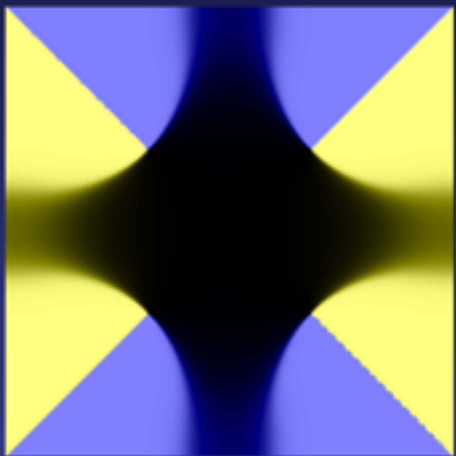
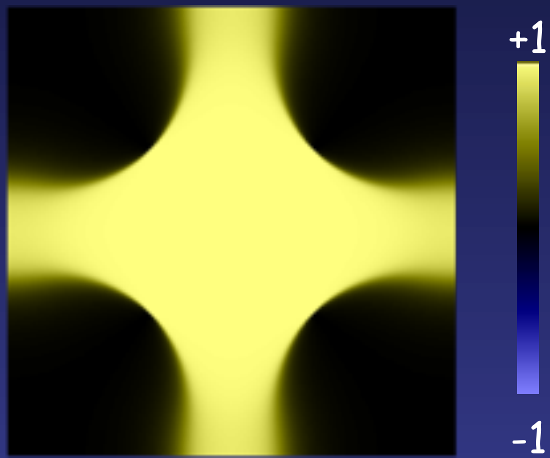
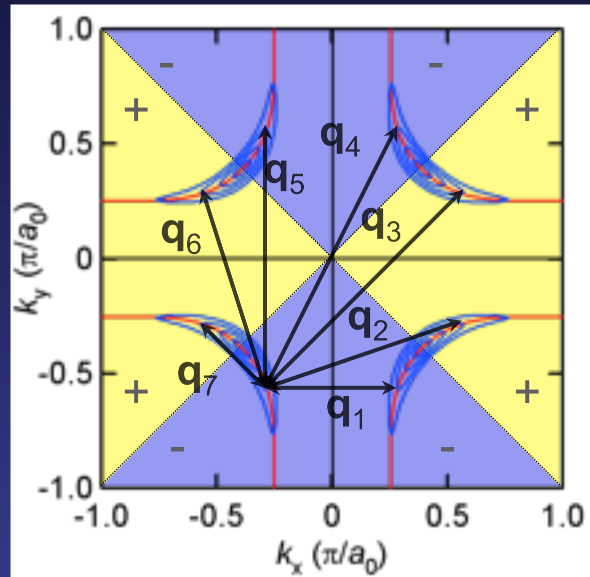
coherence factors



u_k



v_k



Scalar potential

$(uu'-vv')^2$

Coherence factors in QPI ~ "extinction" rule

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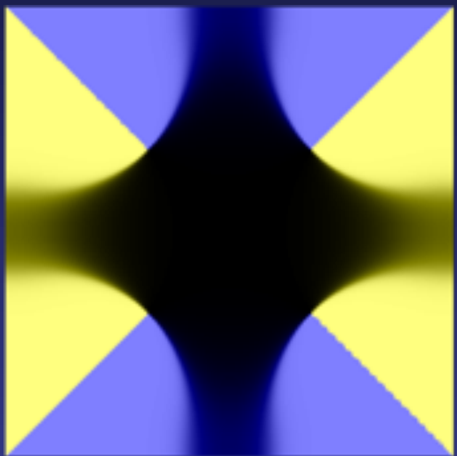
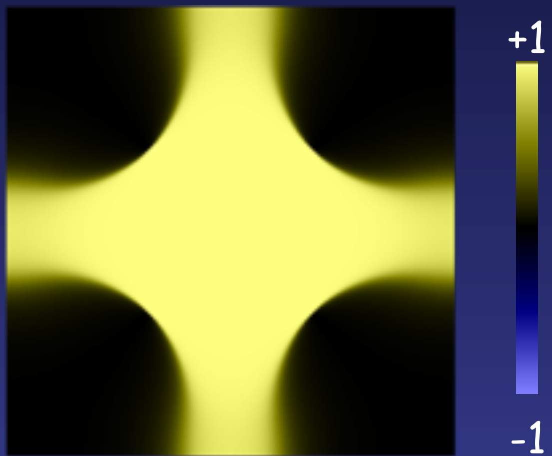
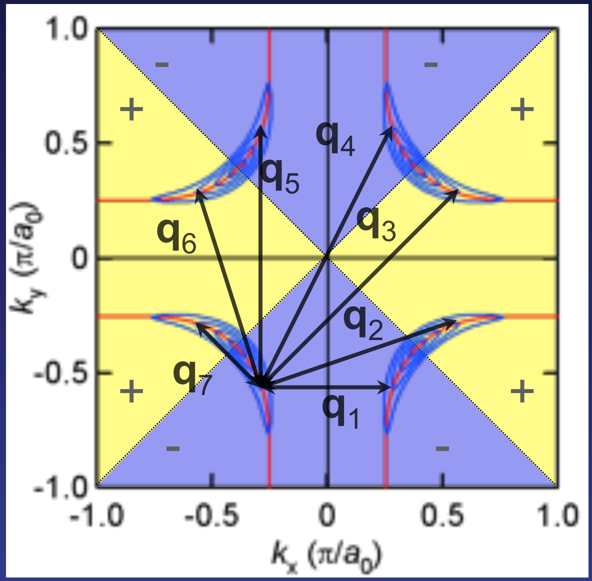
coherence factors



u_k



v_k



Scalar potential $(uu'-vv')^2$

~ 0 : for sign-preserving **q**'s

Coherence factors in QPI ~ "extinction" rule

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Q. -H. Wang and D. -H. Lee, PRB **67**, 020511(R) (2003).
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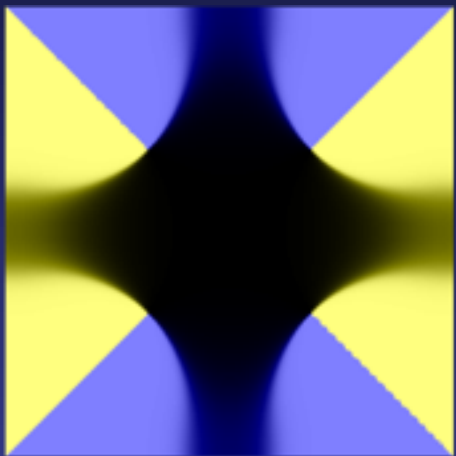
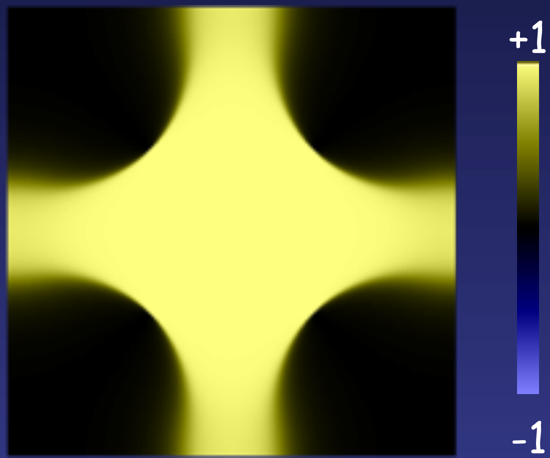
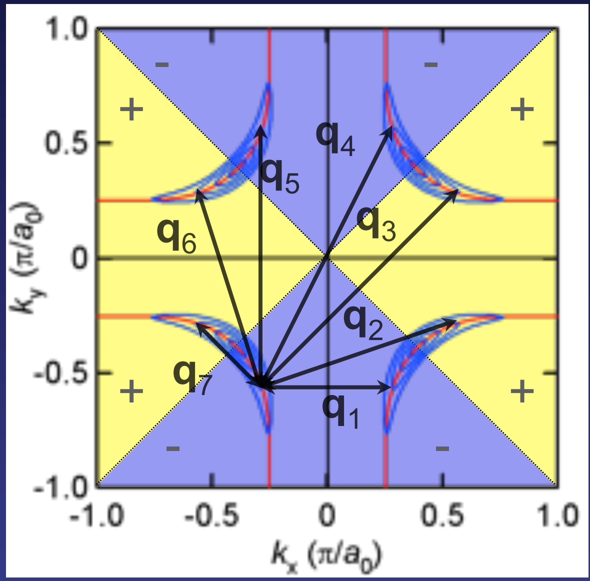
coherence factors



u_k



v_k



Scalar potential $(uu'-vv')^2$

~ 1 : for sign-reversing **q**'s

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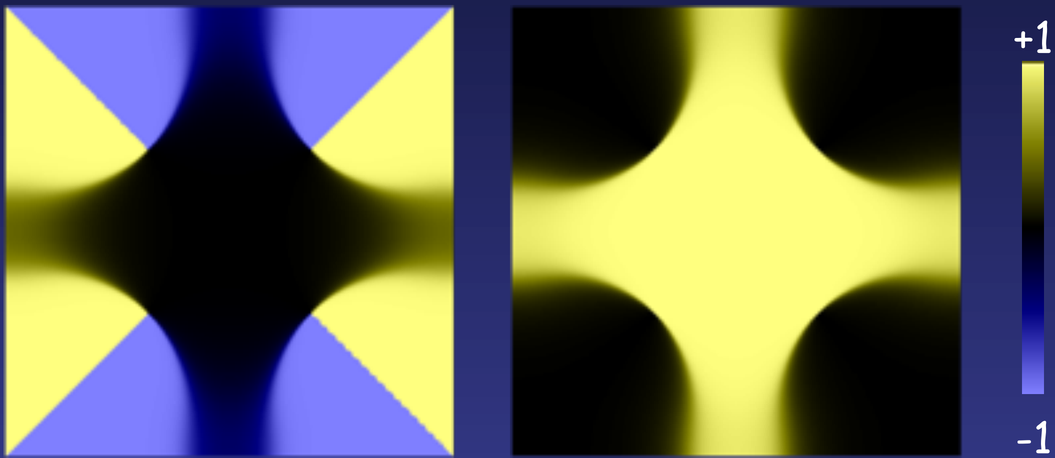
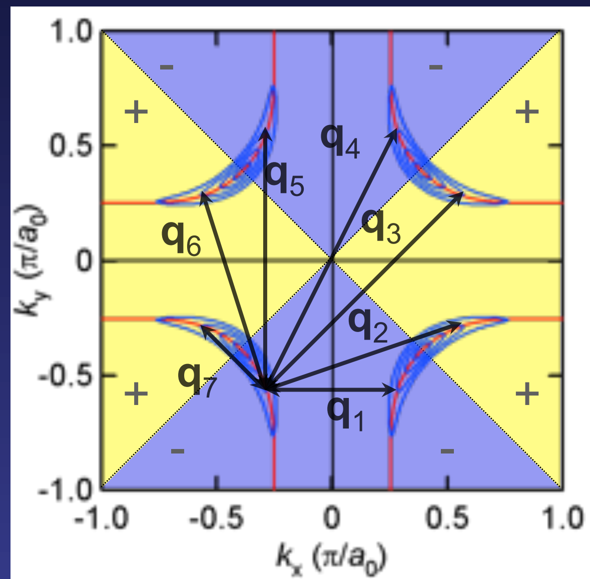


u_k v_k



Scalar potential $(uu'-vv')^2$: sign-reversing scattering (q_2, q_3, q_6, q_7)

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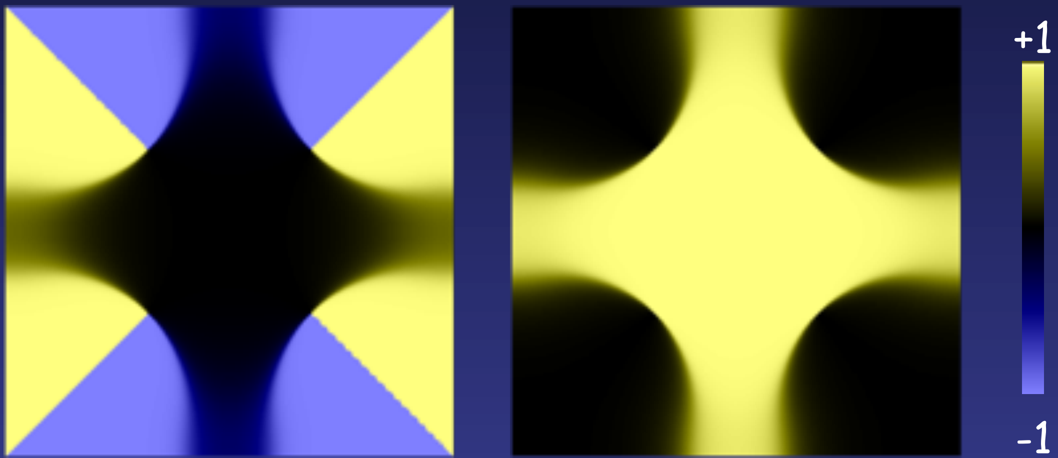
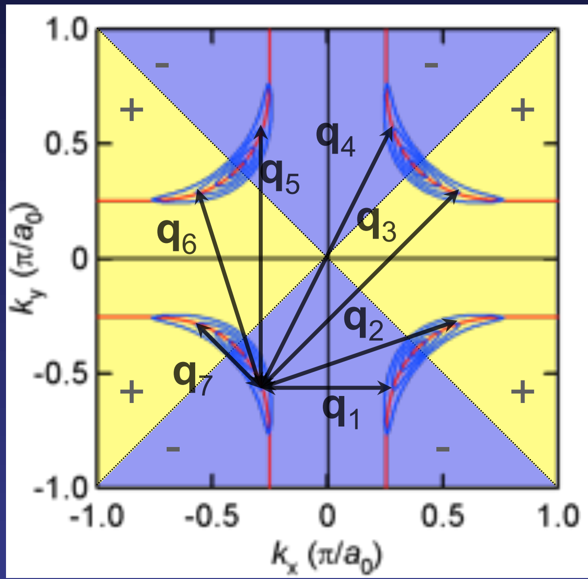
coherence factors



u_k v_k



Scalar potential $(uu'-vv')^2$: sign-reversing scattering (q_2, q_3, q_6, q_7)

Magnetic impurity $(uu'+vv')^2$: sign-preserving scattering (q_1, q_4, q_5)

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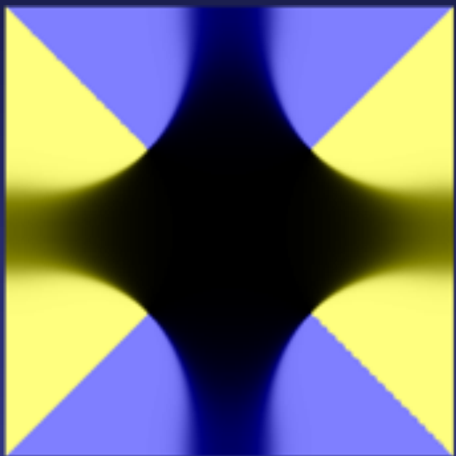
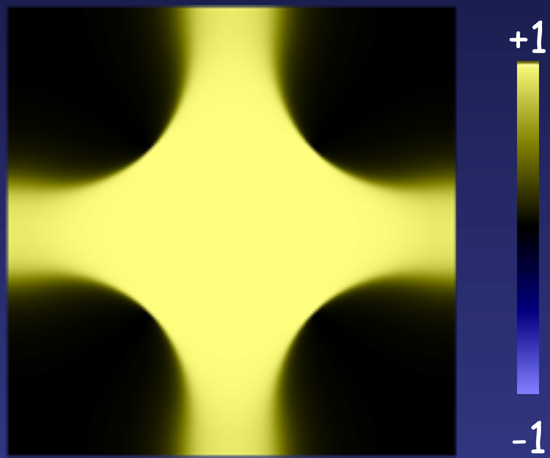
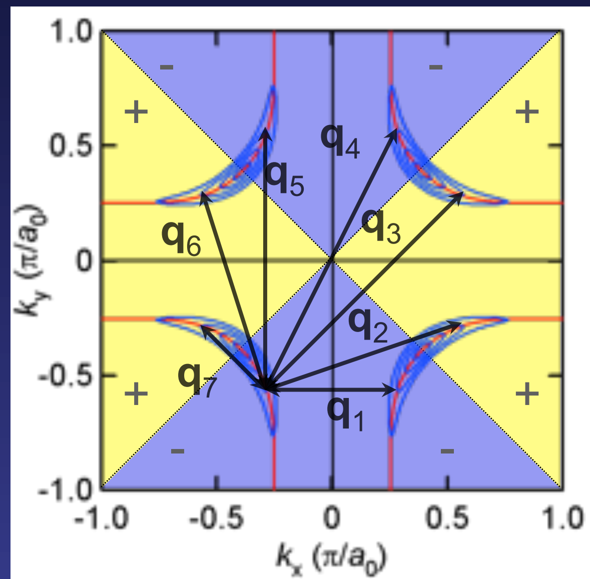
coherence factors



u_k



v_k



Scalar potential $(uu'-vv')^2$: sign-reversing scattering (q_2, q_3, q_6, q_7)

Magnetic impurity $(uu'+vv')^2$: sign-preserving scattering (q_1, q_4, q_5)

Δ inhomogeneity $(\Delta+\Delta')^2$: sign-preserving scattering (q_1, q_4, q_5)

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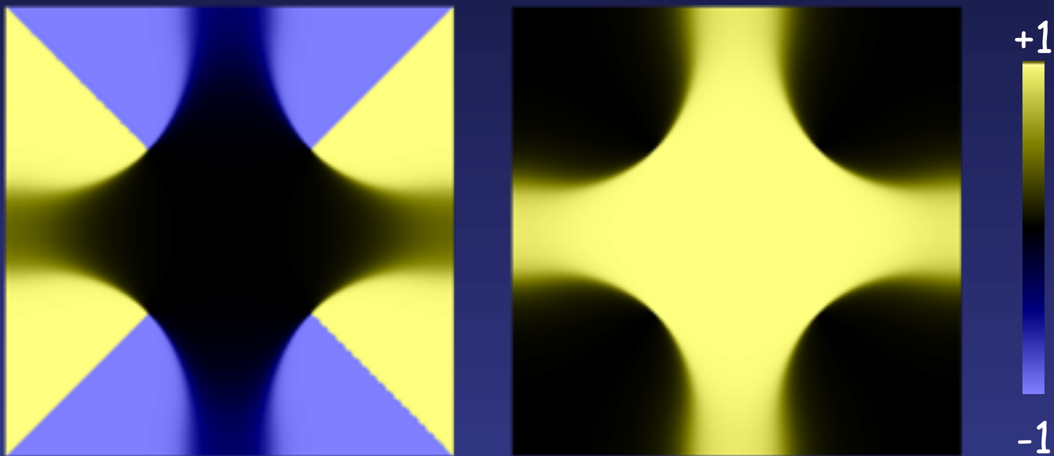
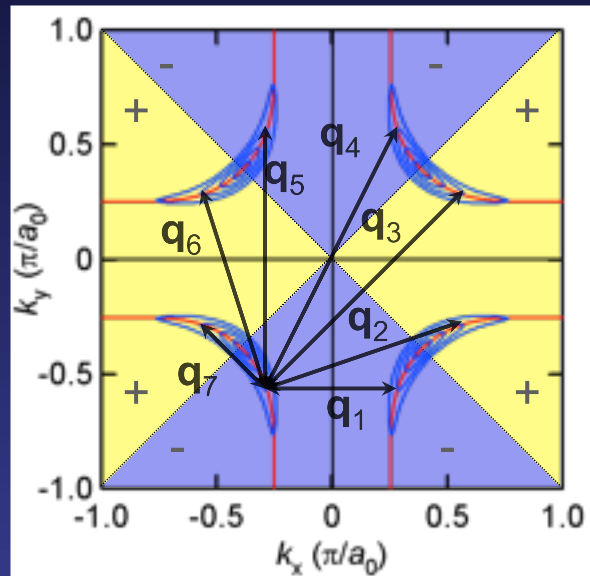
coherence factors



u_k v_k



Scalar potential	$(uu'-vv')^2$	: sign-reversing scattering	(q_2, q_3, q_6, q_7)
Magnetic impurity	$(uu'+vv')^2$	: sign-preserving scattering	(q_1, q_4, q_5)
Δ inhomogeneity	$(\Delta+\Delta')^2$	: sign-preserving scattering	(q_1, q_4, q_5)

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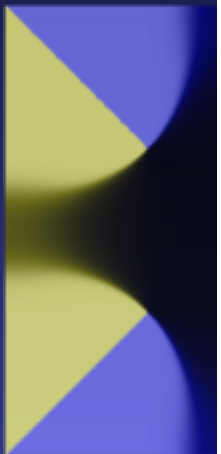
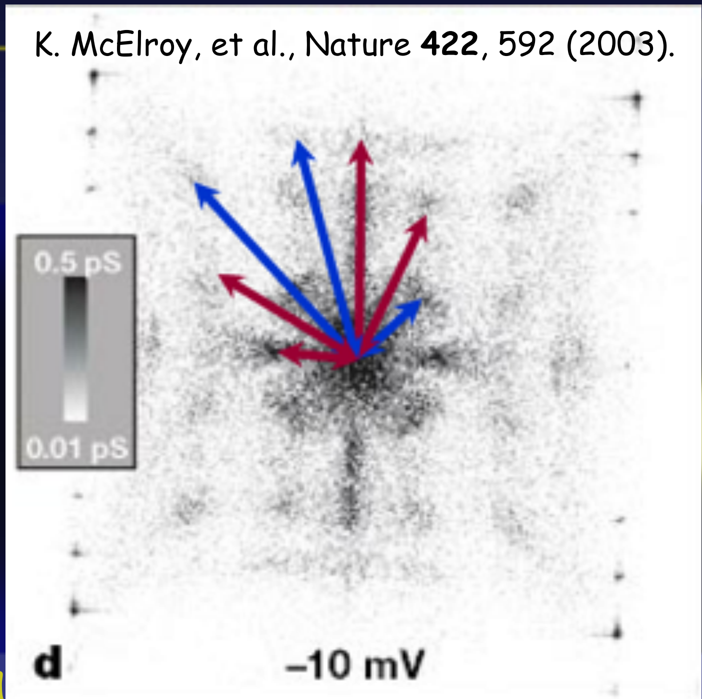
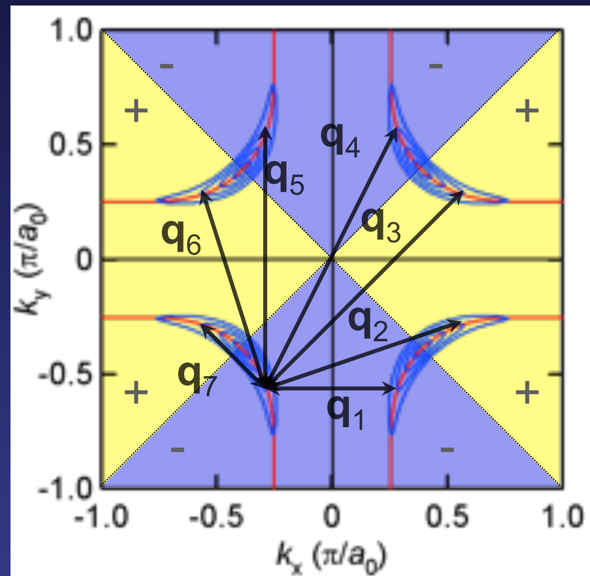
$w(i -$ … $|V(\mathbf{k}_i,\mathbf{k}_f)|^2 JDOS(E,\mathbf{k}_i,\mathbf{k}_f)$





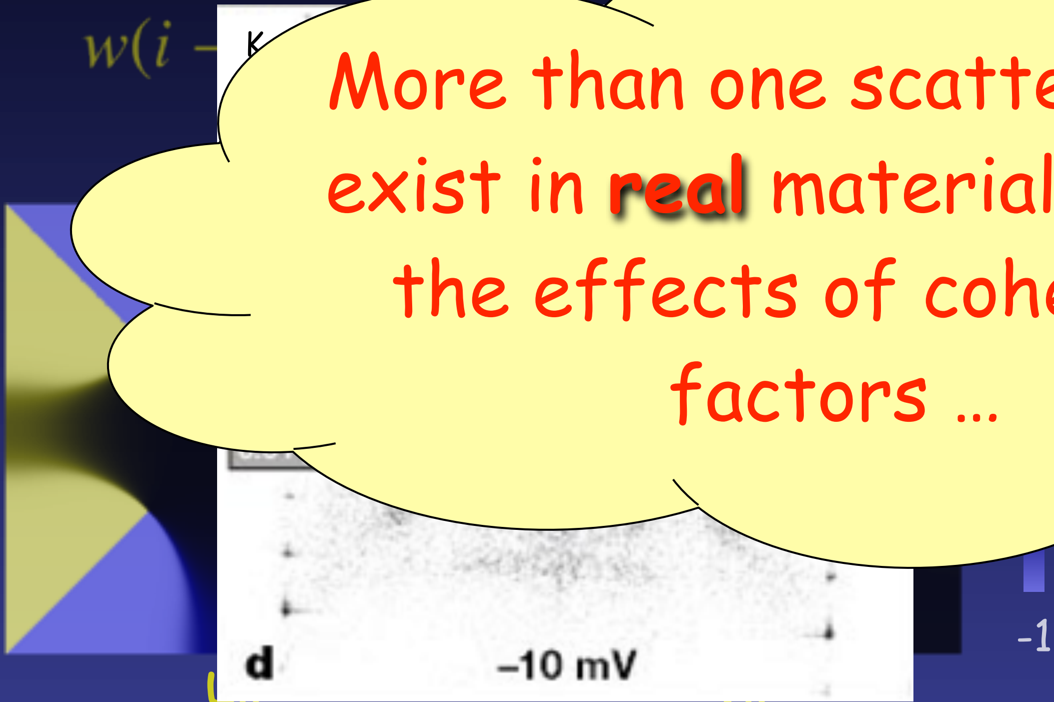


u_k

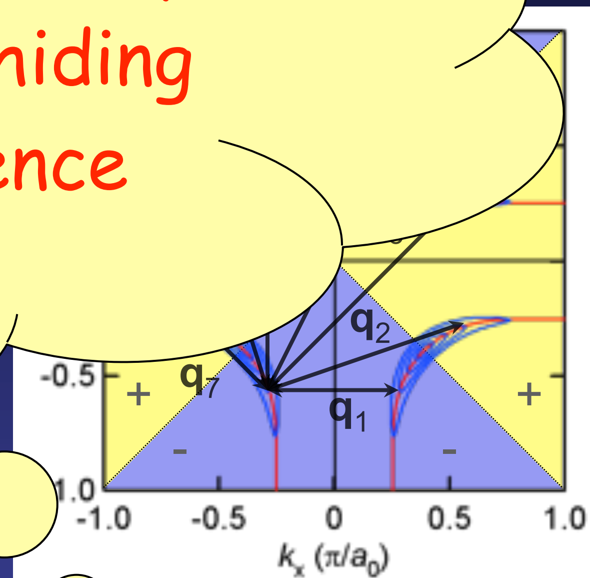
Scalar potential	$(uu'-vv')^2$	: sign-reversing scattering	(q_2, q_3, q_6, q_7)
Magnetic impurity	$(uu'+vv')^2$	: sign-preserving scattering	(q_1, q_4, q_5)
Δ inhomogeneity	$(\Delta+\Delta')^2$	: sign-preserving scattering	(q_1, q_4, q_5)

Coherence factors in QPI ~ "extinction" rule

J. E. Hoffman, Thesis, http://physics.harvard.edu/~jhoffman/thesis/HoffmanThesis.pdf.
Q. -H. Wang and D. -H. Lee, PRB **67**, 020511(R) (2003).
T. Pereg-Barnea and M. Franz, PRB **68**, 180506(R) (2003).
R. S. Markiewicz, PRB **69**, 214517 (2004).
T. Nunner et al., PRB **73**, 10451...



More than one scatterer may exist in **real** materials, hiding the effects of coherence factors ...



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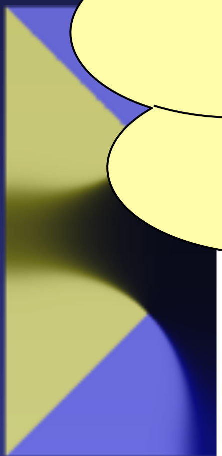
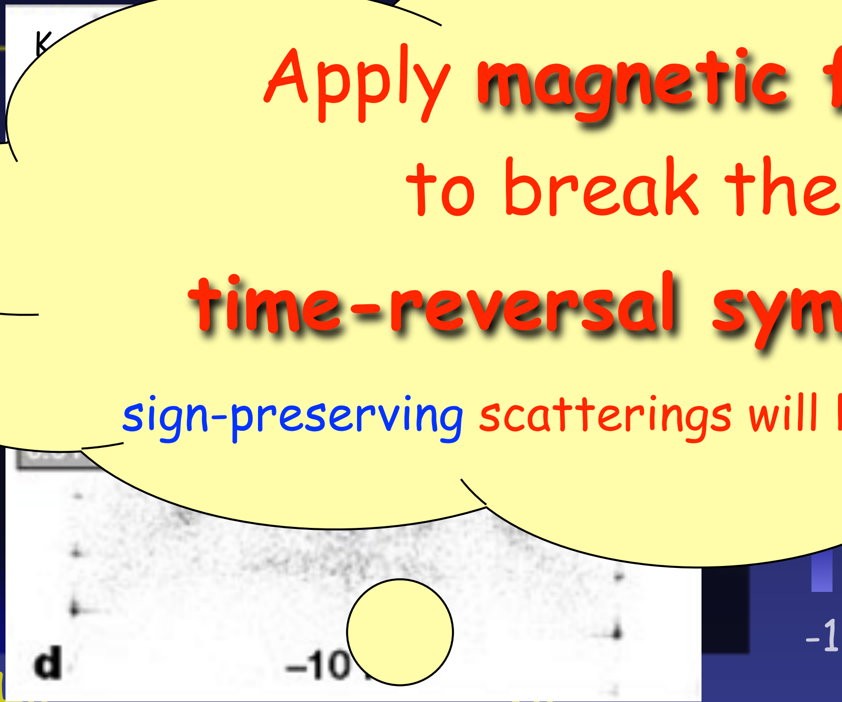
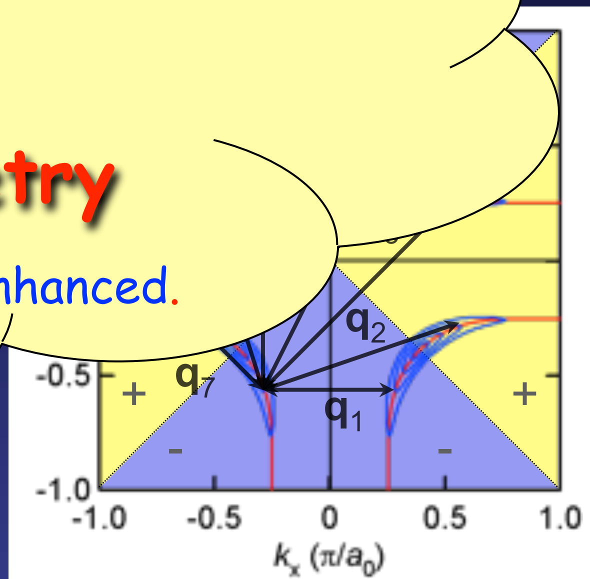






Apply **magnetic field**
to break the
time-reversal symmetry

sign-preserving scatterings will be enhanced.

Scalar potential (uu'-vv')^2 : sign-reversing scattering (q_2, q_3, q_6, q_7)

Magnetic impurity (uu'+vv')^2 : sign-preserving scattering (q_1, q_4, q_5)

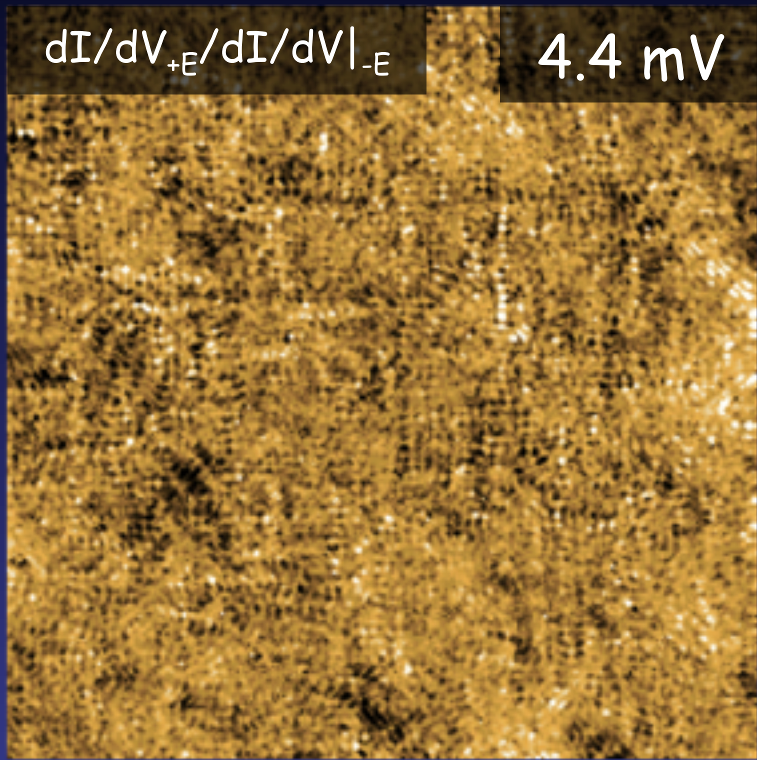
Δ inhomogeneity (Δ+Δ')^2 : sign-preserving scattering (q_1, q_4, q_5)

Phase-sensitive QPI in $Ca_{2-x}Na_xCuO_2Cl_2$

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

$x \sim 0.14$ ($T_c \sim 28$ K)

$V_{sample} = -0.1$ V, $I_t = 0.1$ nA, 45nm×45nm



QPI shows up in the dI/dV-ratio (Z) map !!

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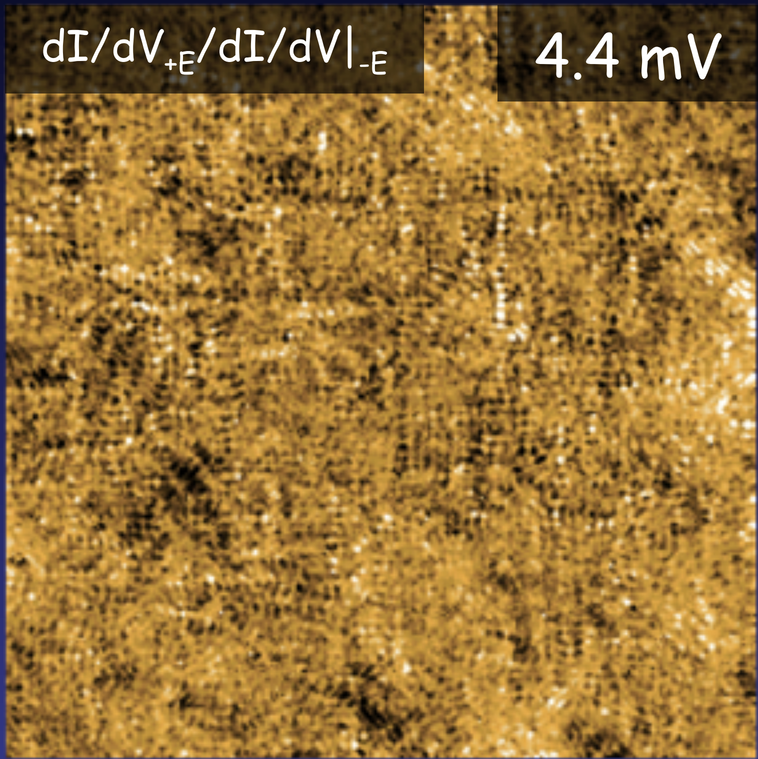
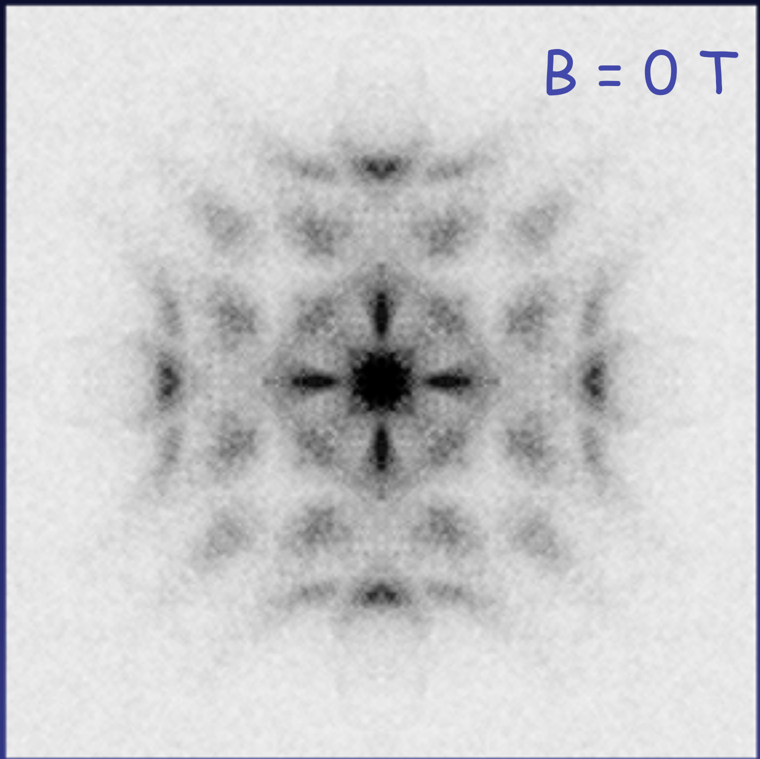


FT map 4.4 meV



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Monday, January 24, 2011

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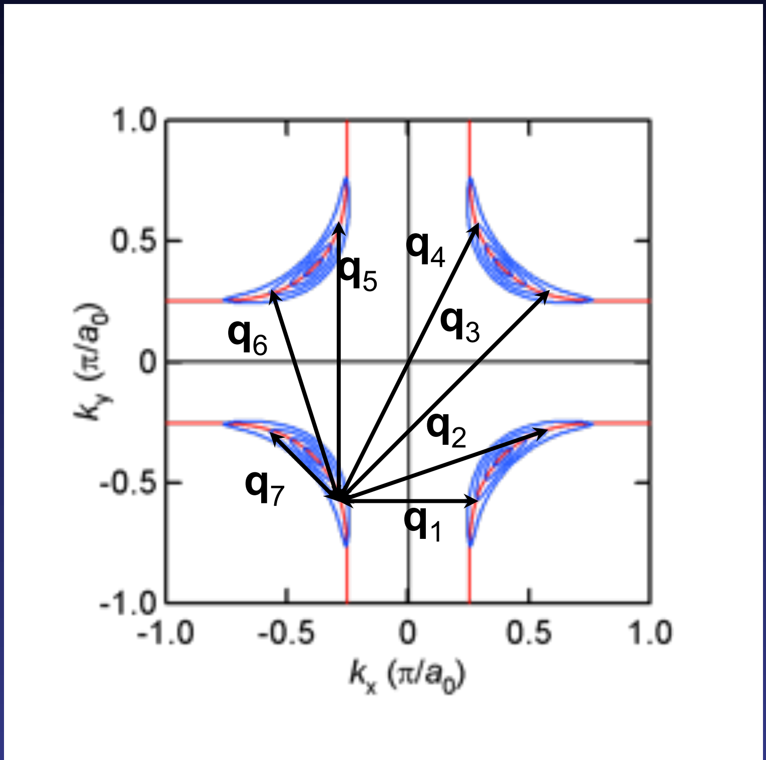

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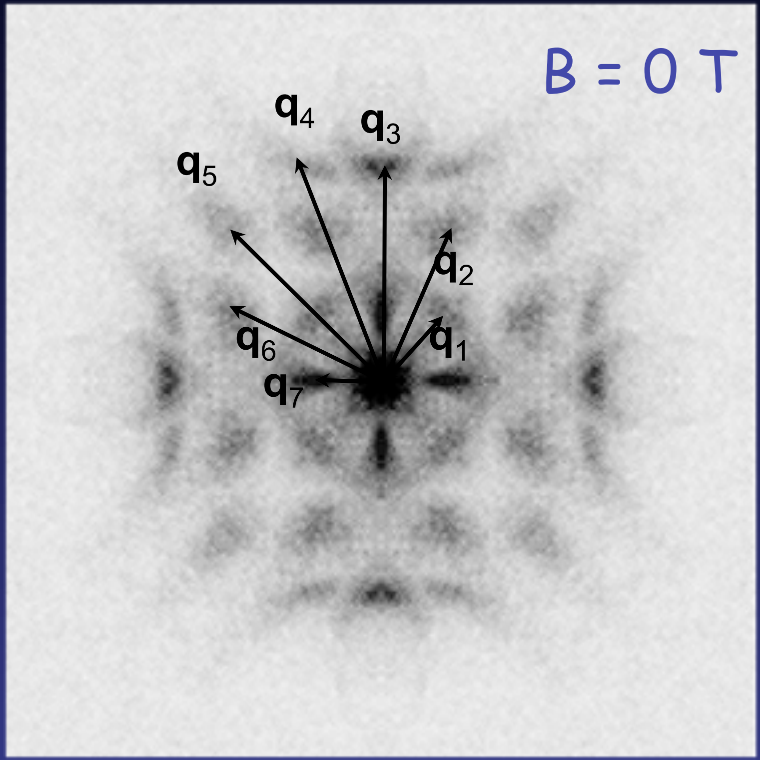

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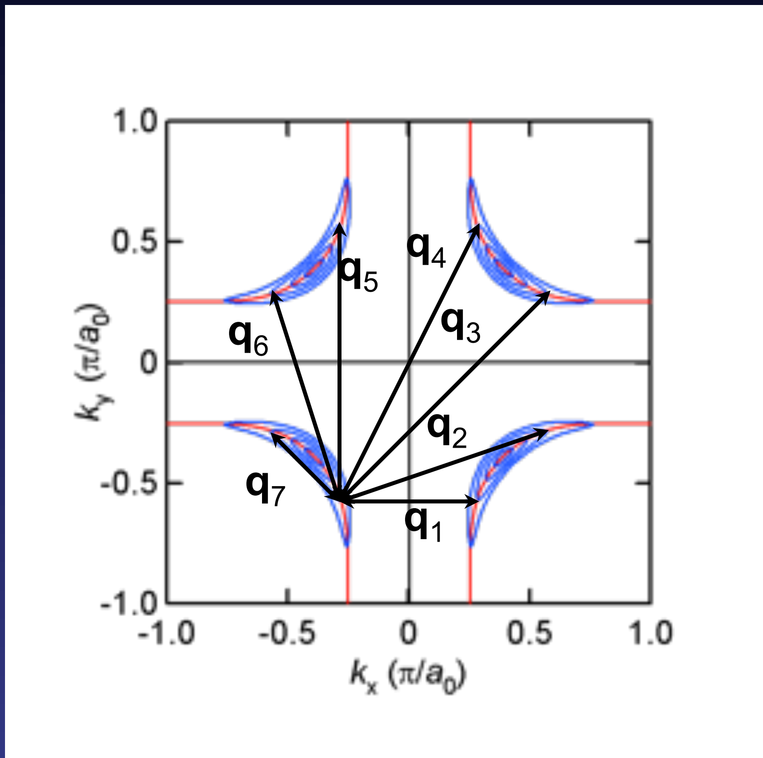

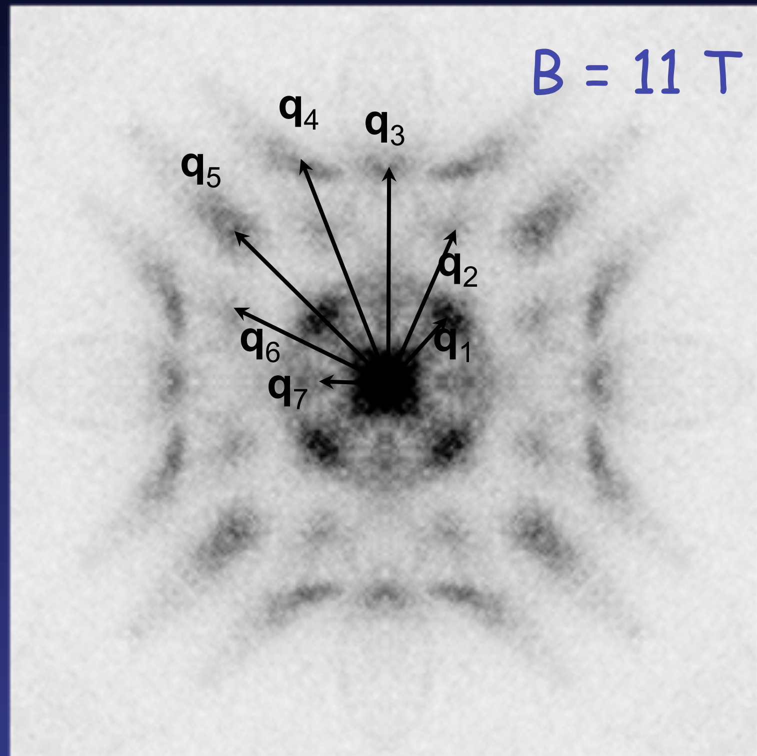

Magnetic field changes intensity of each spot.

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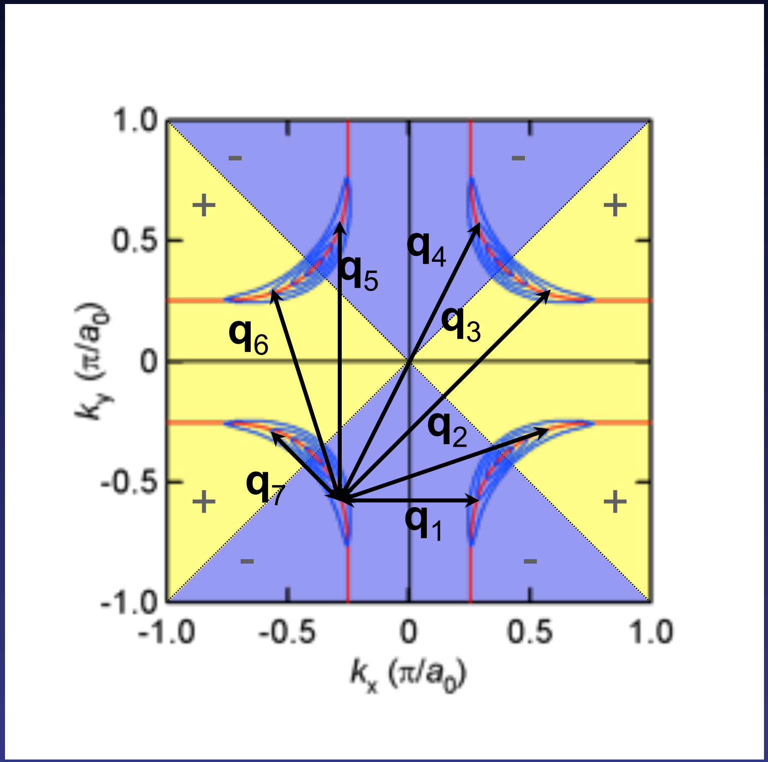
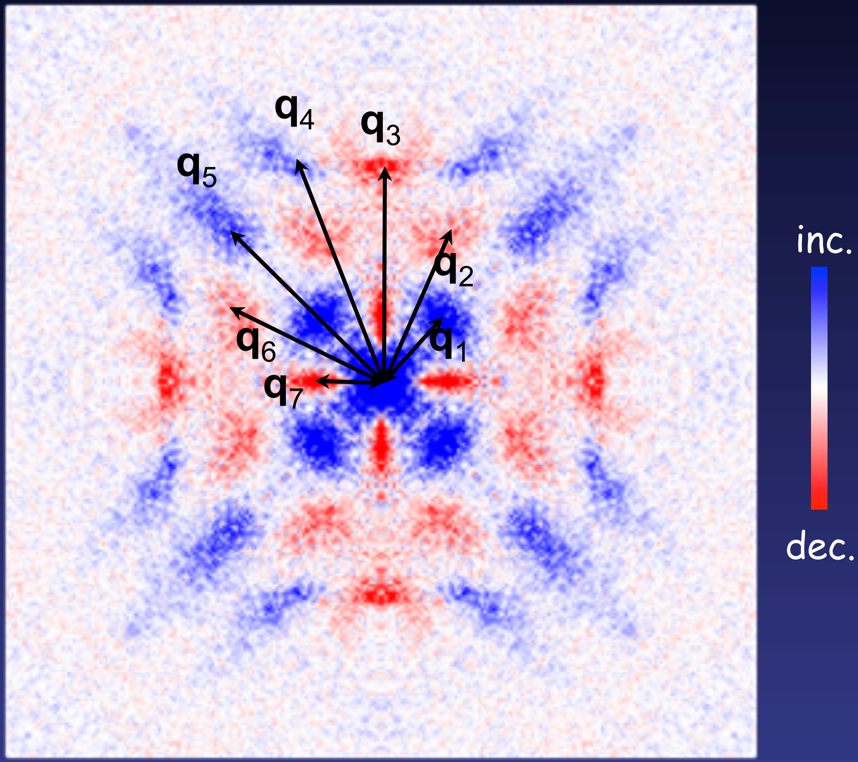


FT[Z(11T)]-FT[Z(0T)]



There are two kinds of scattering vectors.

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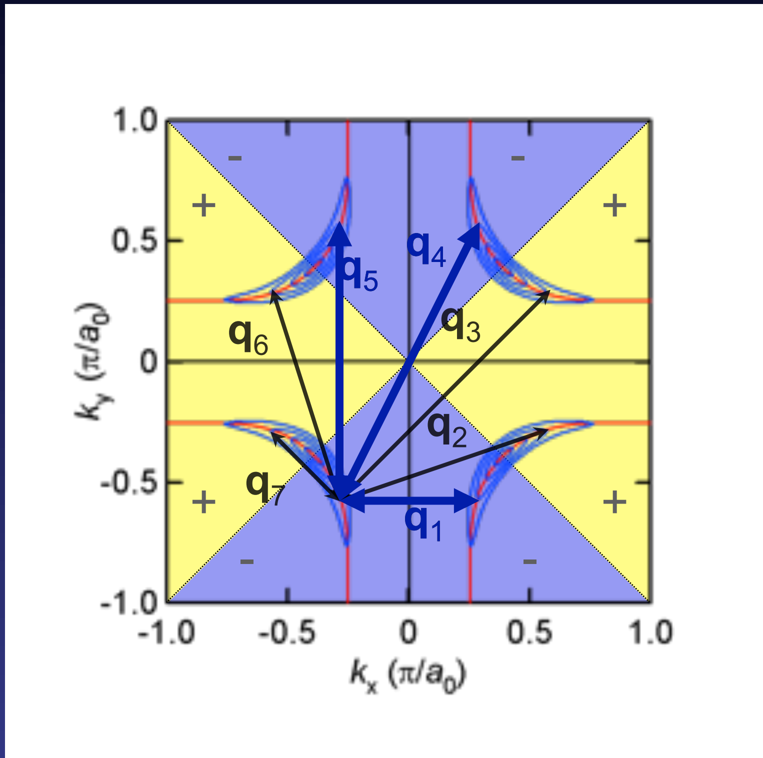

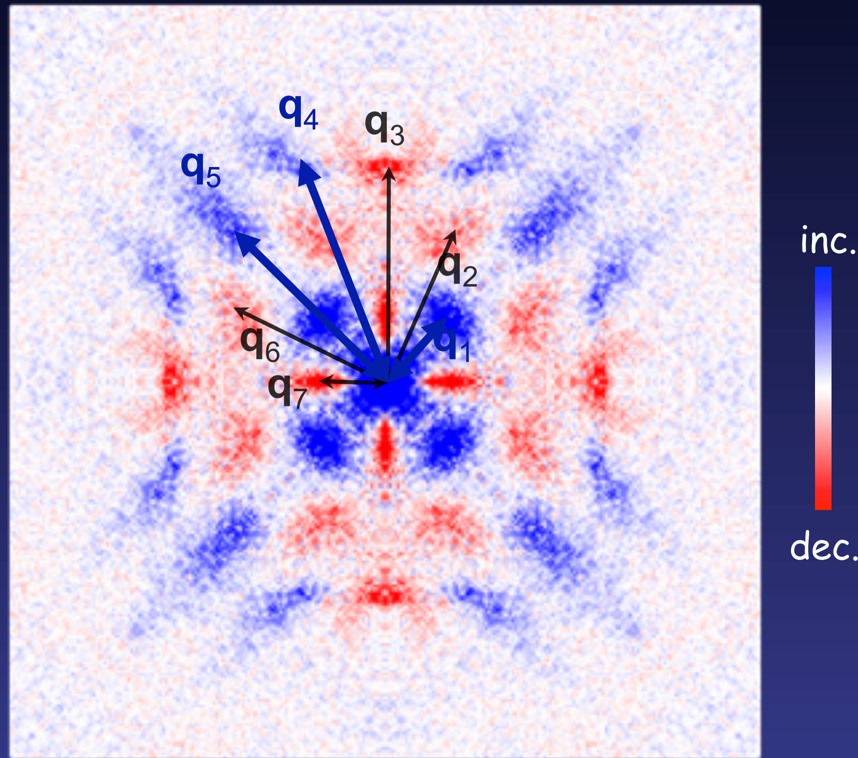

sign-preserving scattering (+,+) , (-,-) : Enhanced by B

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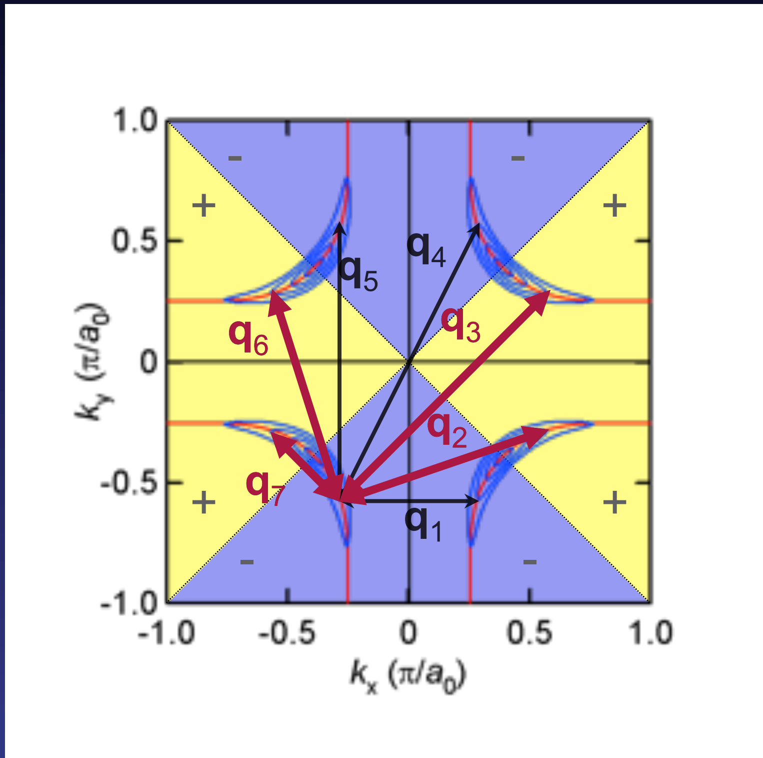
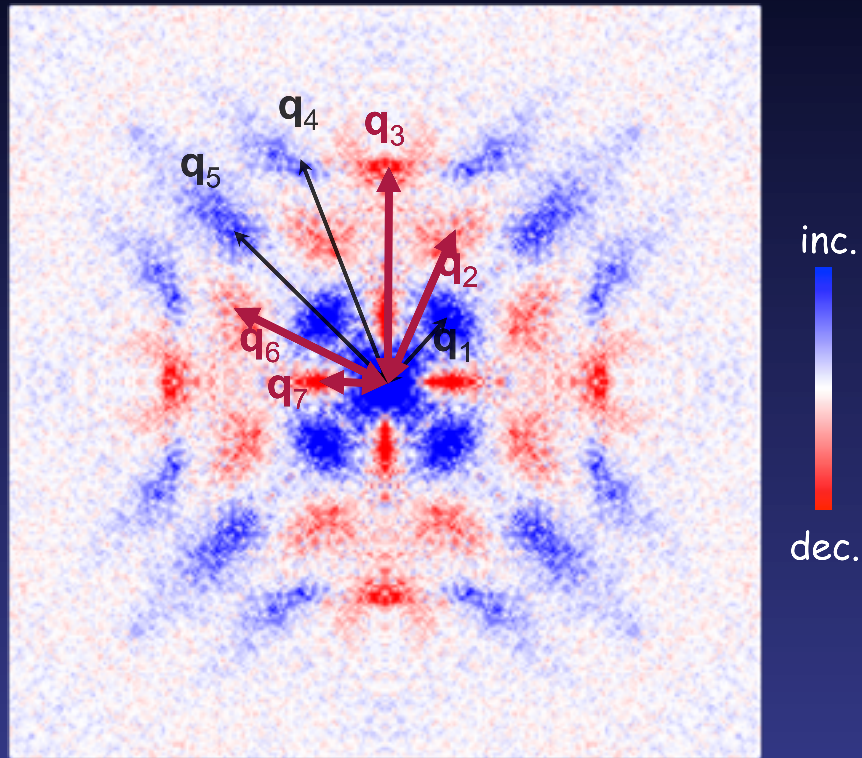


FT[Z(11T)]-FT[Z(0T)]



sign-preserving scattering (+,+) , (-,-) : Enhanced by B

sing-reversing scattering (+,-) , (-,+) : Suppressed by B

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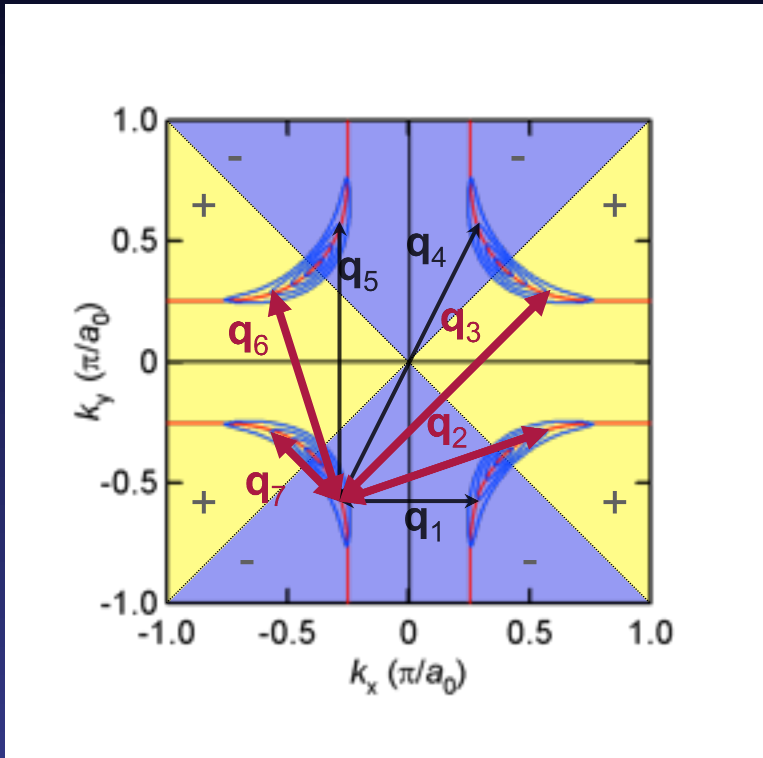

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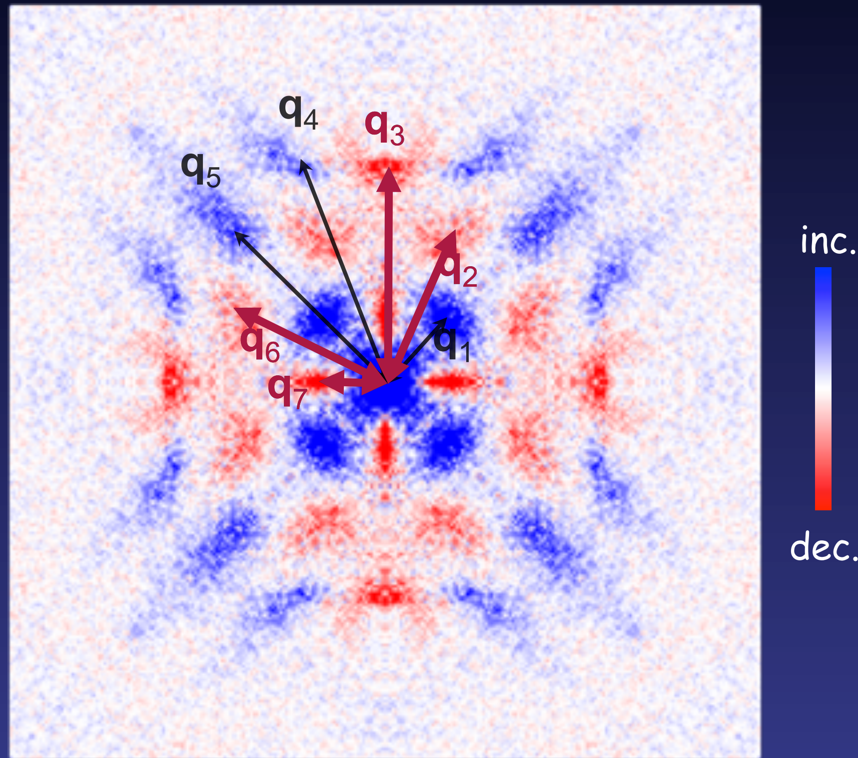

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Coherence effect highlights the phase!!

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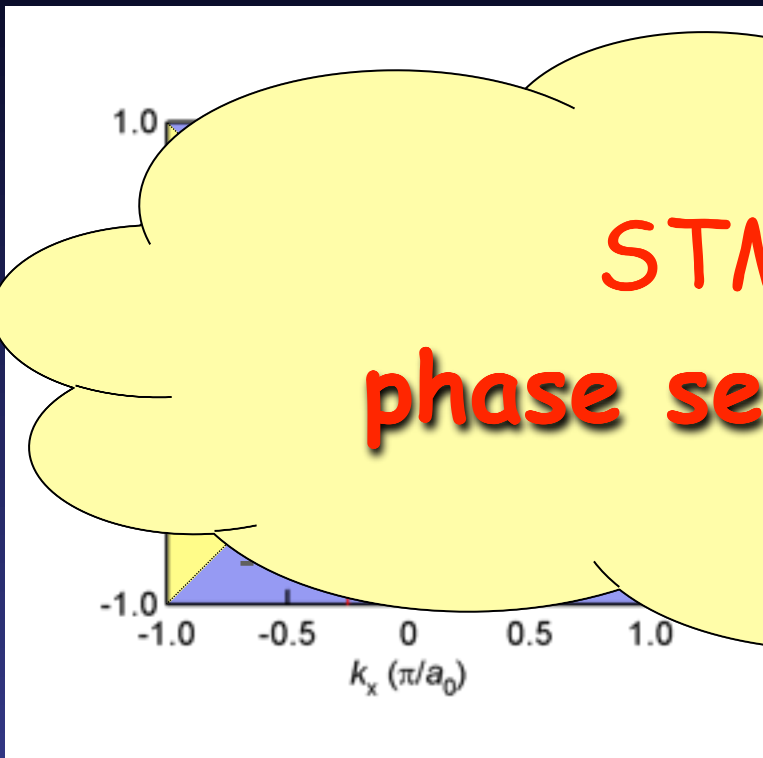


STM is

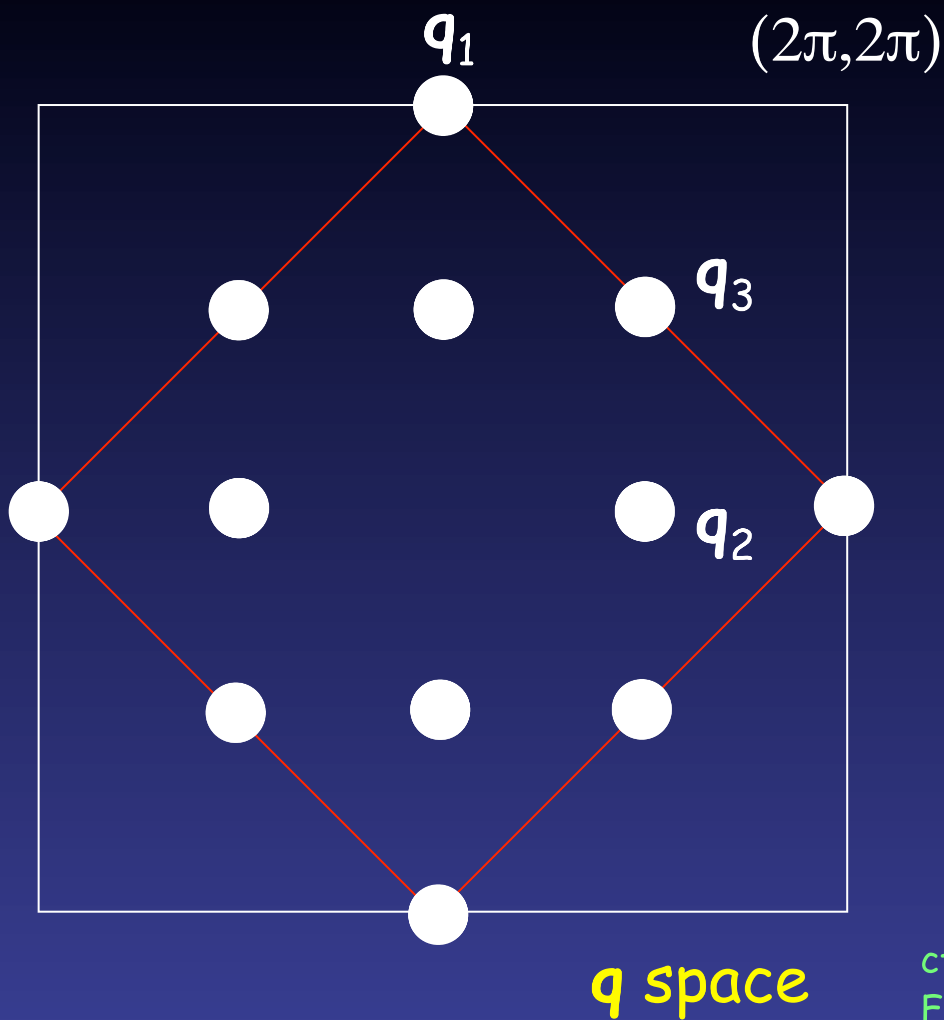
phase sensitive !!

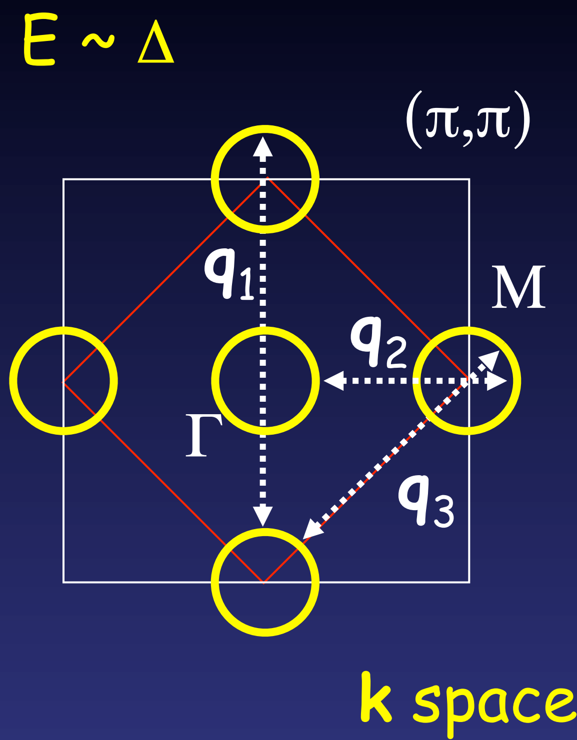
sign-preserving scattering (+,+) , (-,-) : Enhanced by B

sing-reversing scattering (+,-) , (-,+) : Suppressed by B

Coherence effect highlights the phase!!

How will it work in iron-based SC?





cf.
F. Wang, H. Zhai and D. -H. Lee,
EPL **85**, 37005 (2009).
Yan-Yang Zhang et al.,
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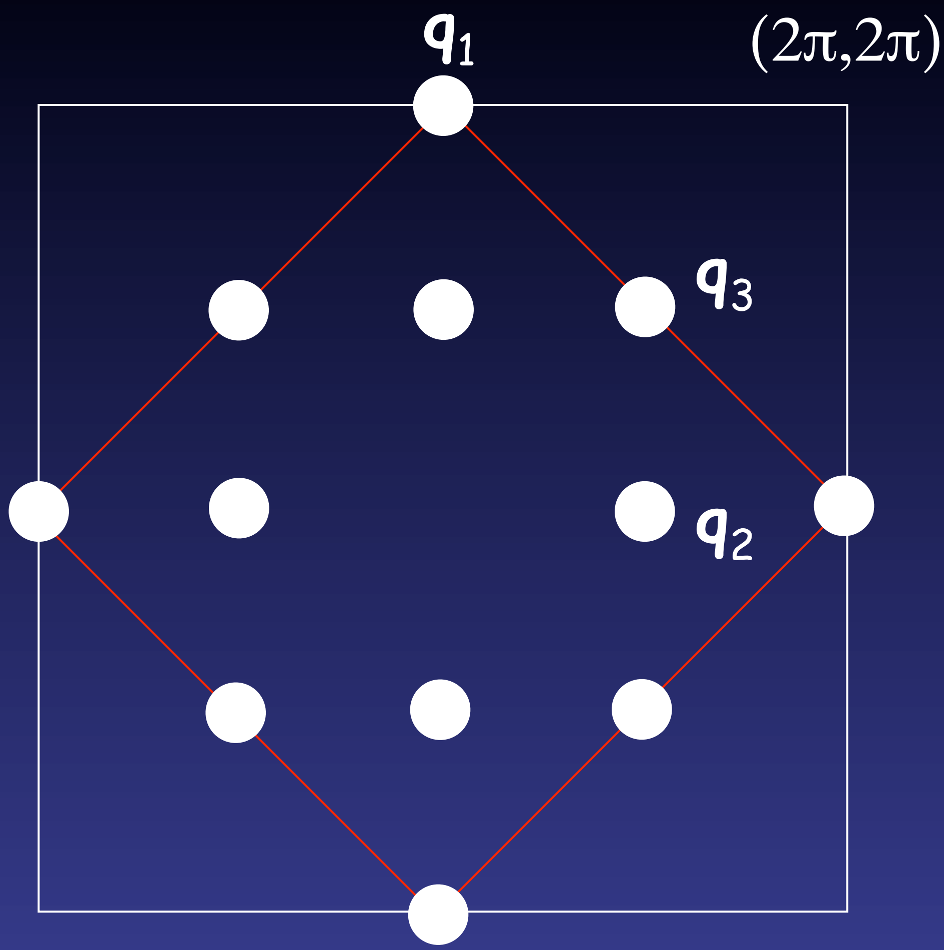
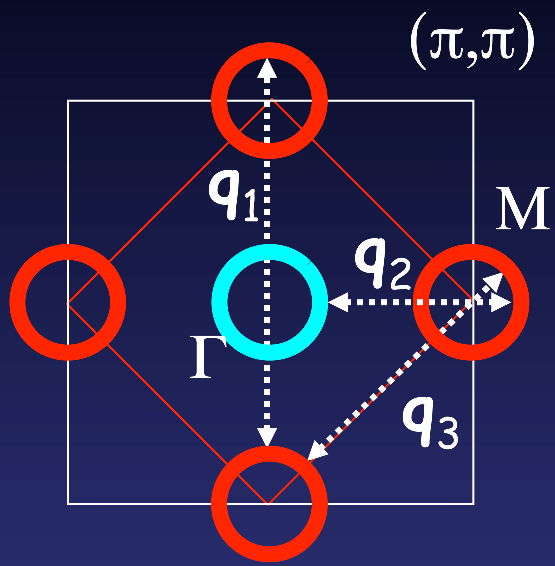


q space

$E \sim \Delta$



$s_{\pm}$

k space

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

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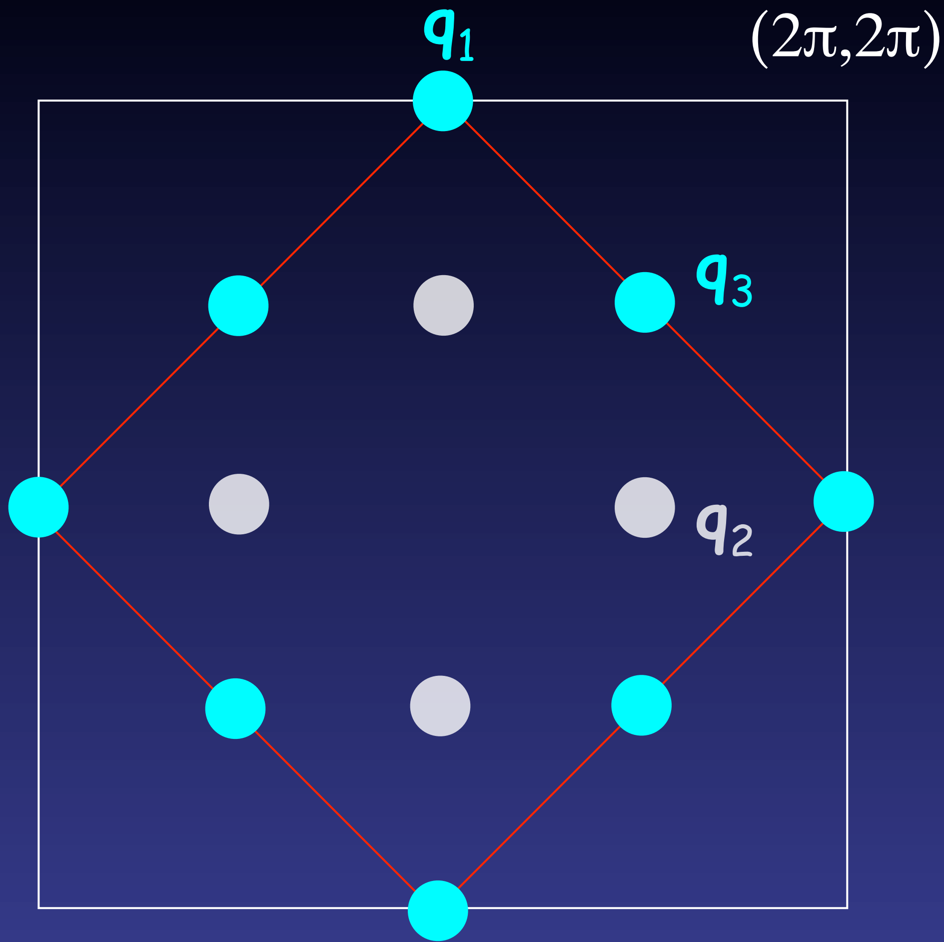
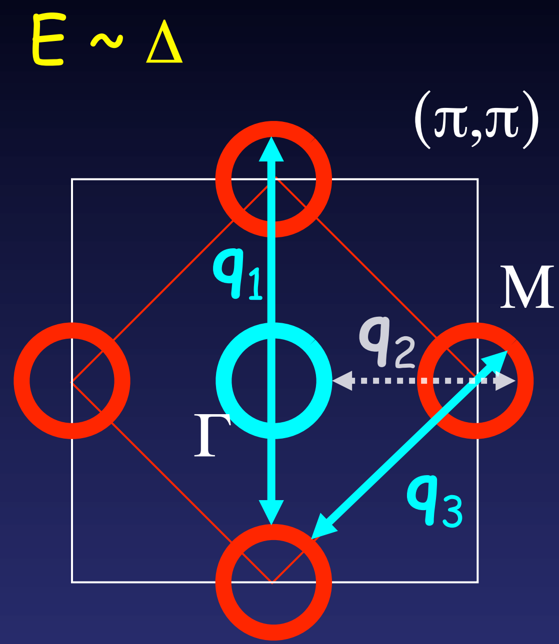


q space



$s_\pm$ k space

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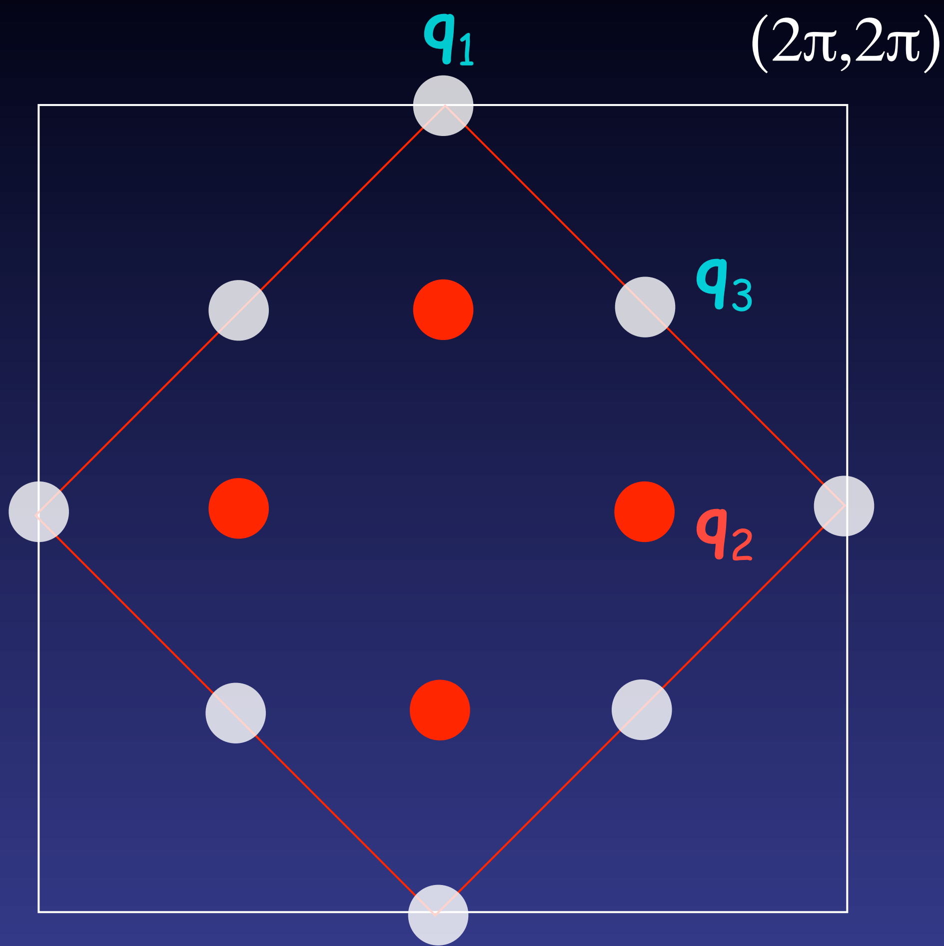
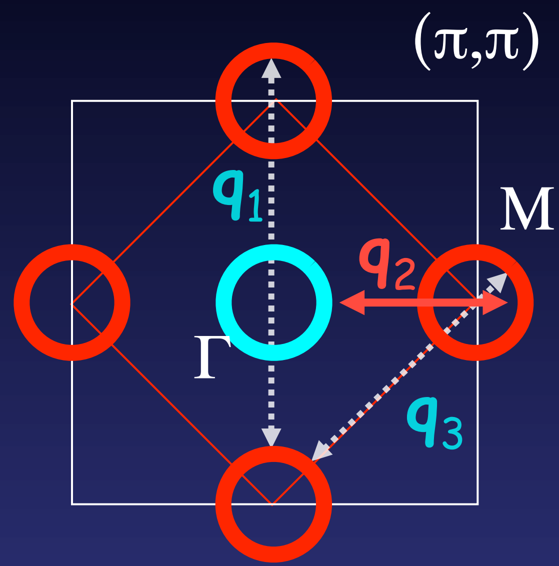


q space



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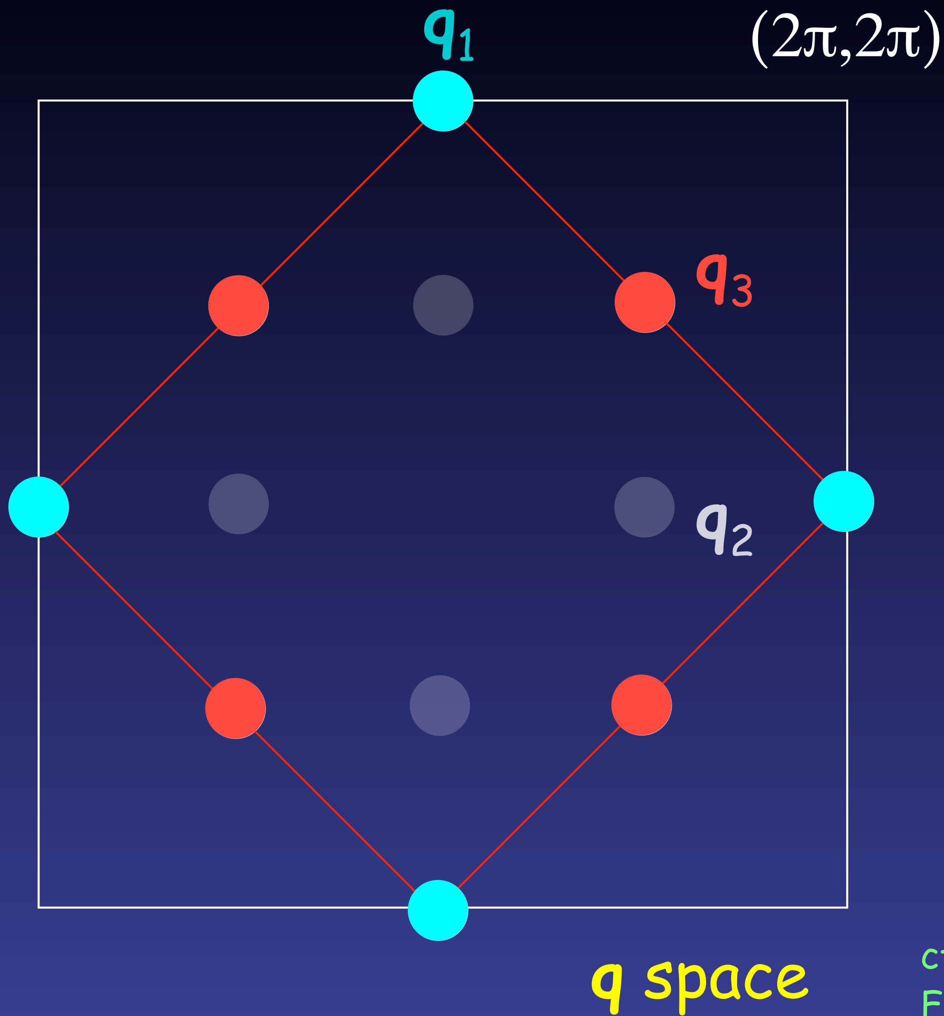

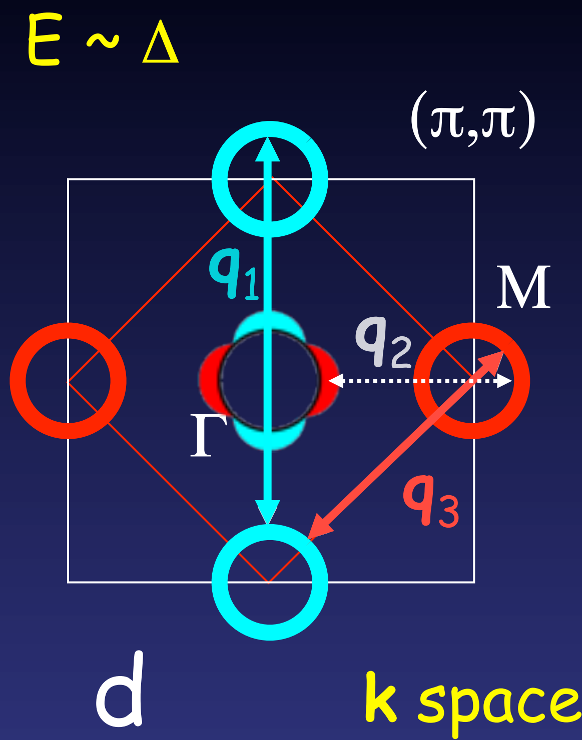

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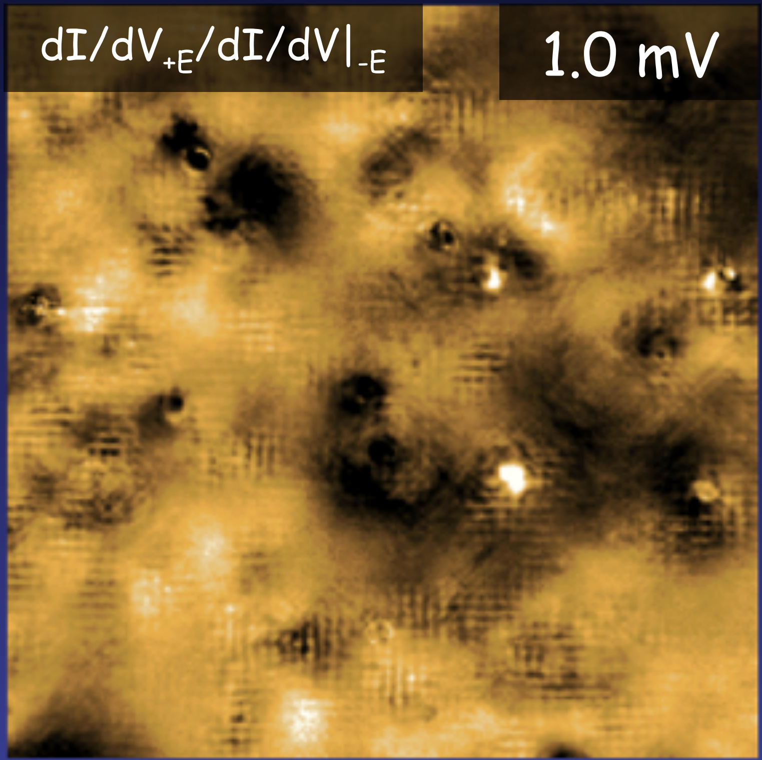
Phase-sensitive STM on an iron chalcogenide

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

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

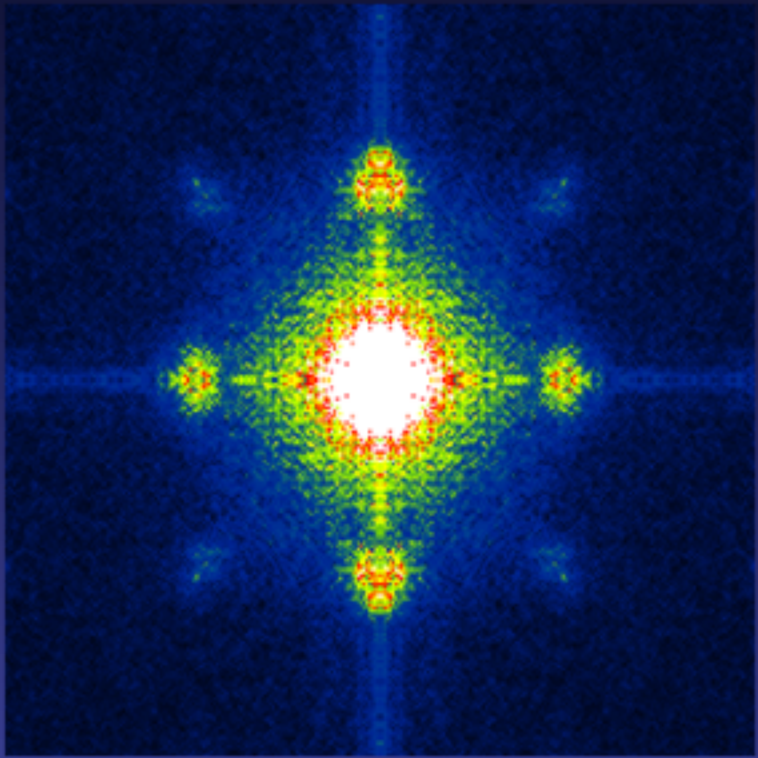
B = 0 T

T ~ 1.5 K



34 nm×34 nm, -20 mV/0.1 nA

FT-Z map 1.0 meV



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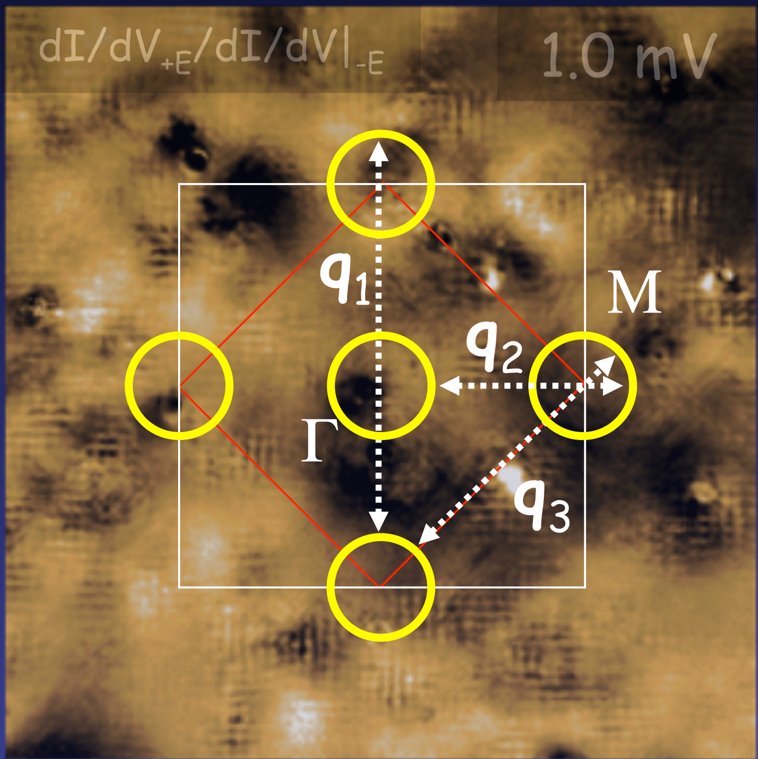

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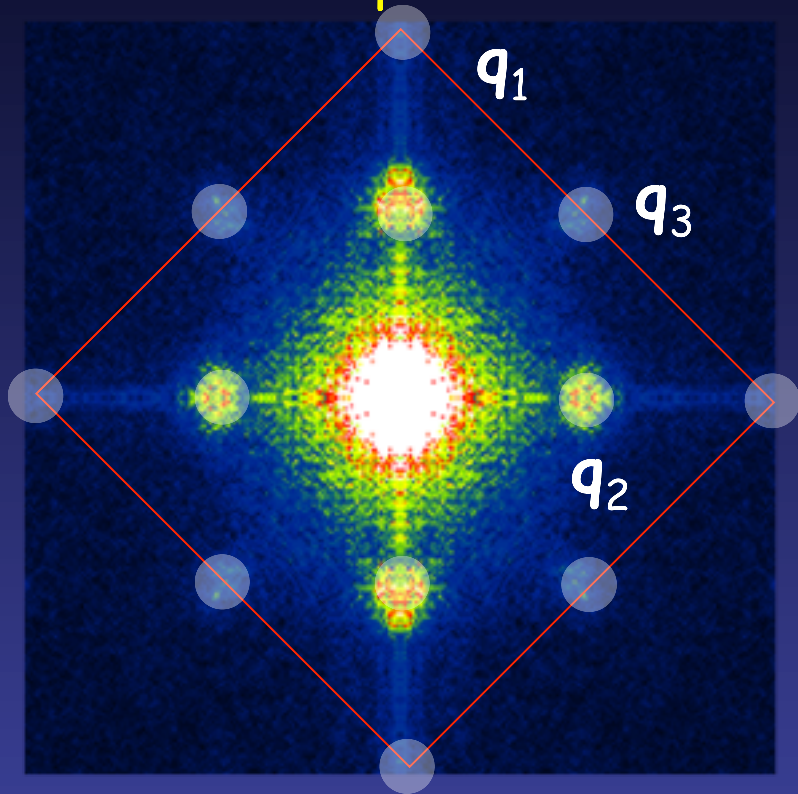

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Inter-pocket scatterings are detected.

Monday, January 24, 2011

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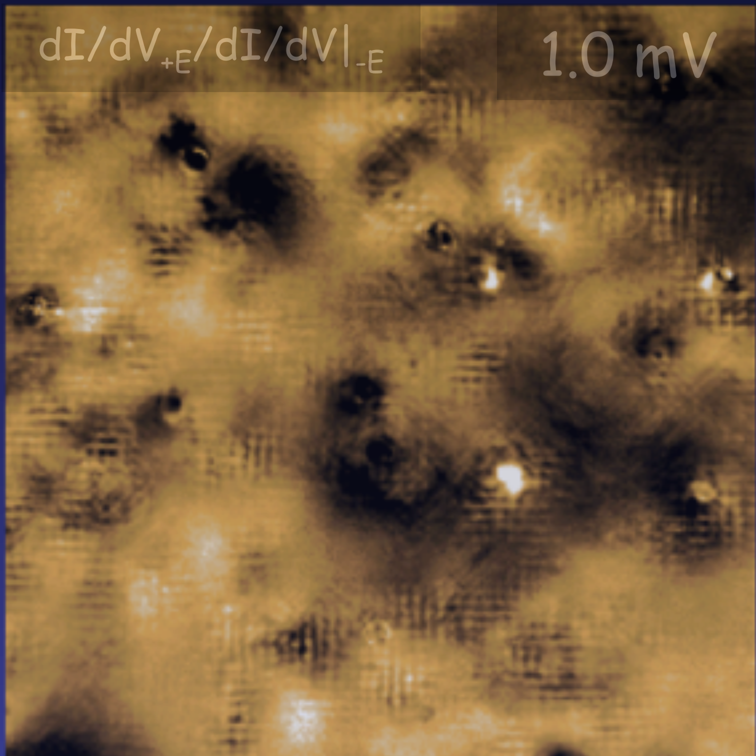

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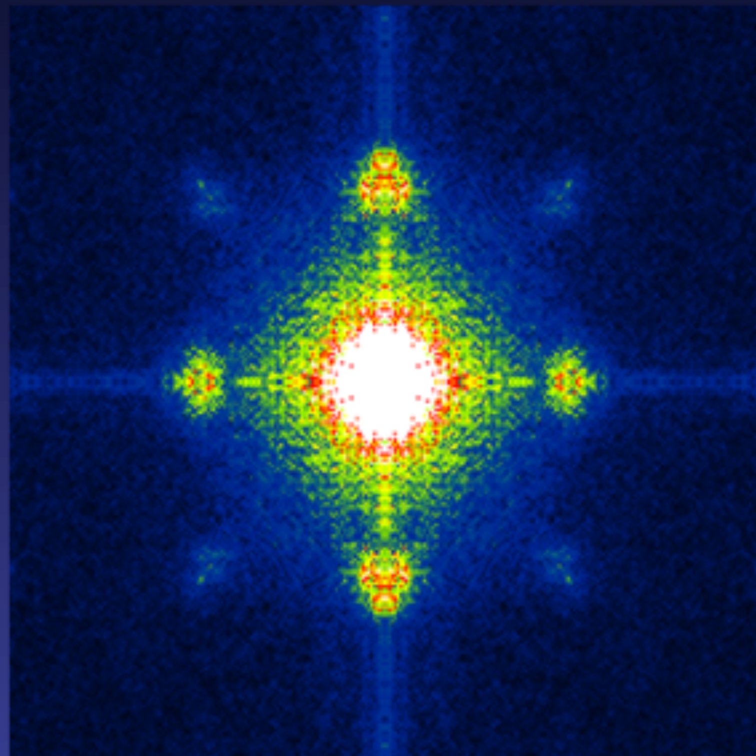

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T. Hanaguri et al., Science **328**, 474 (2010).

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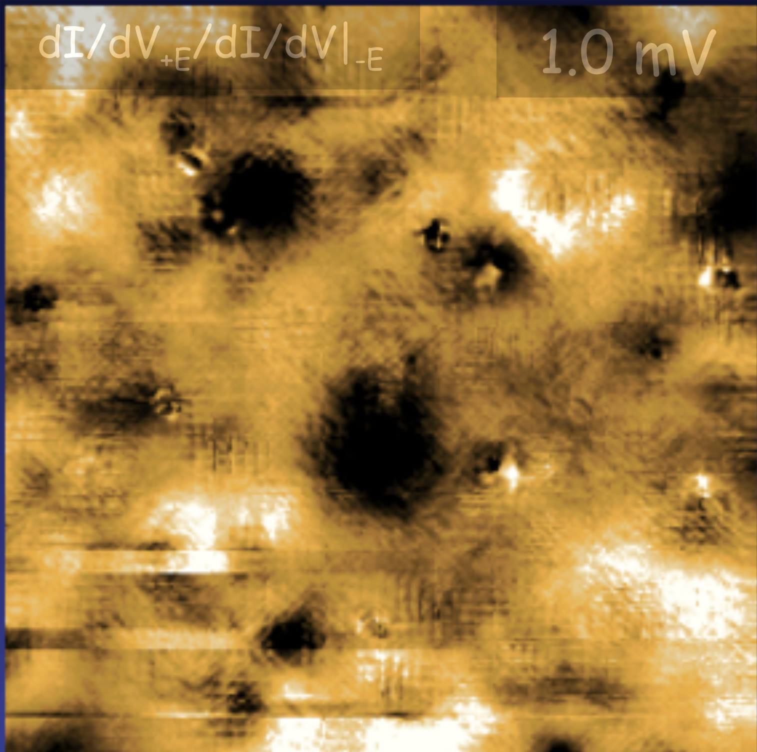
B = 10 T

T ~ 1.5 K



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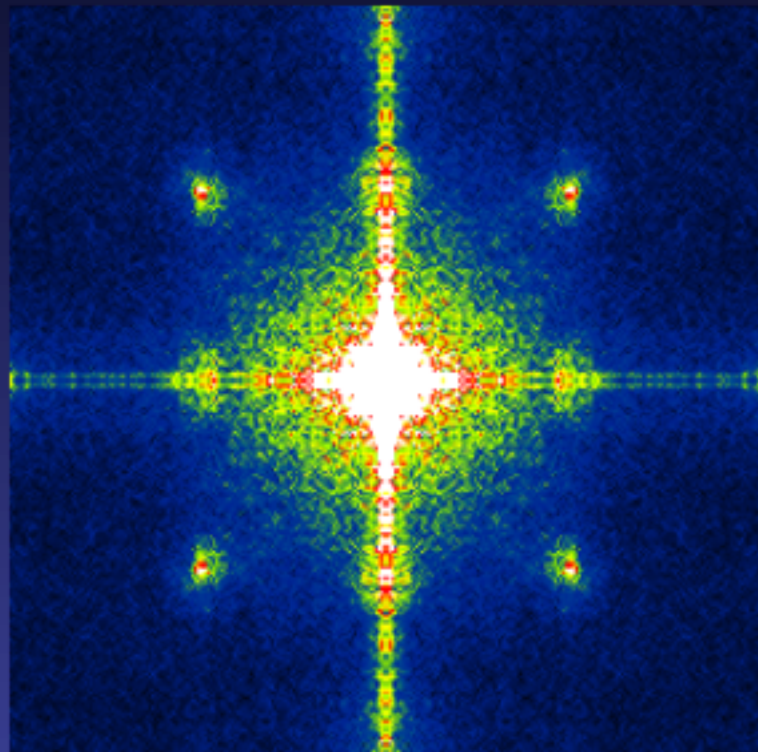

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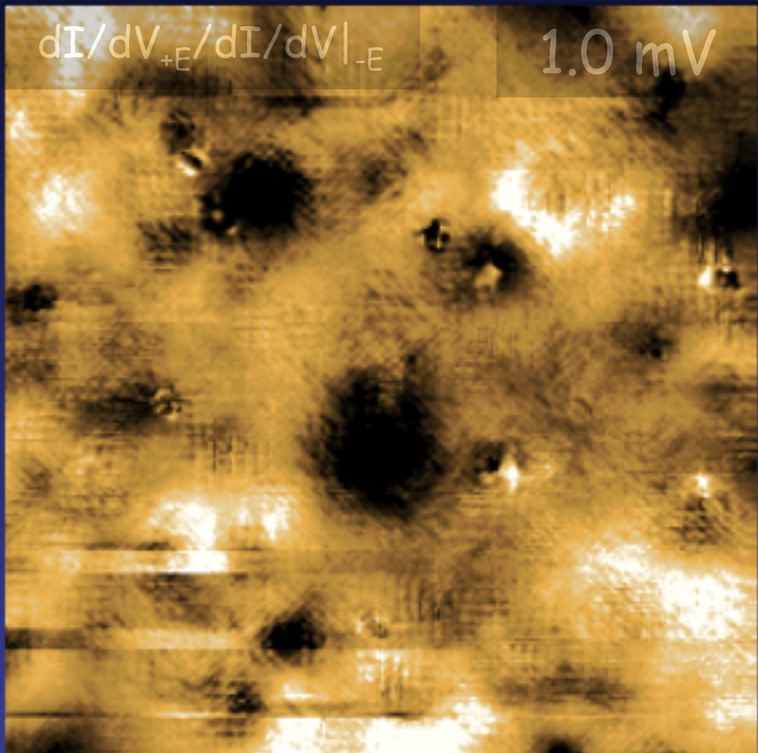
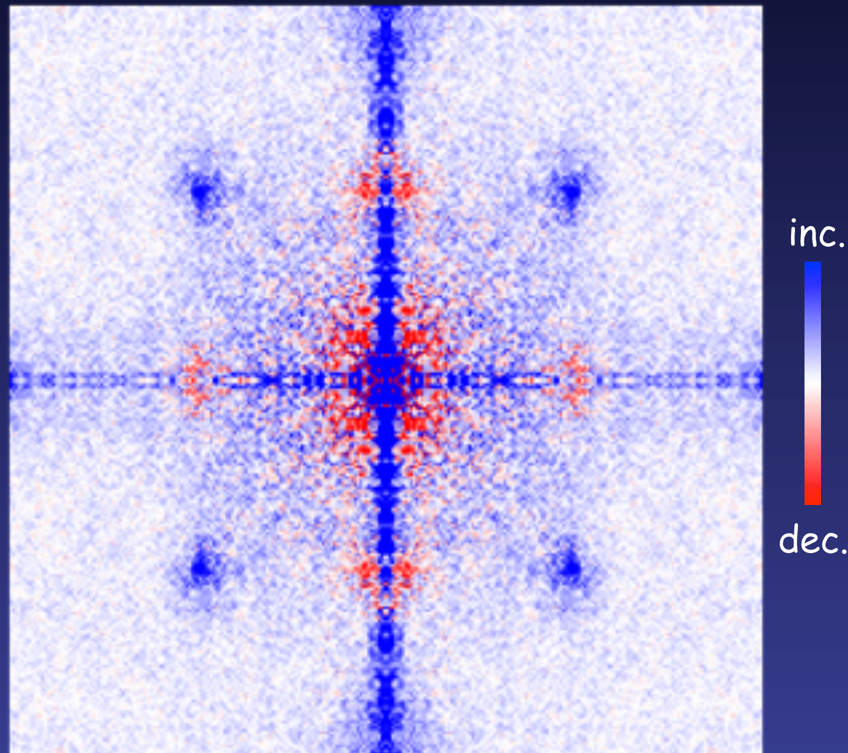


FT-Z map 1.0 meV



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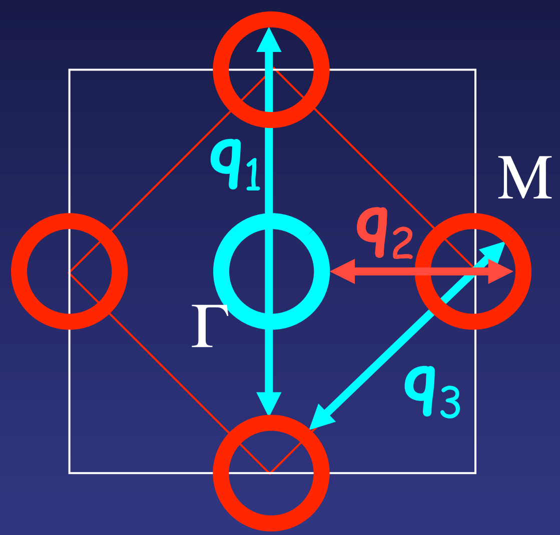
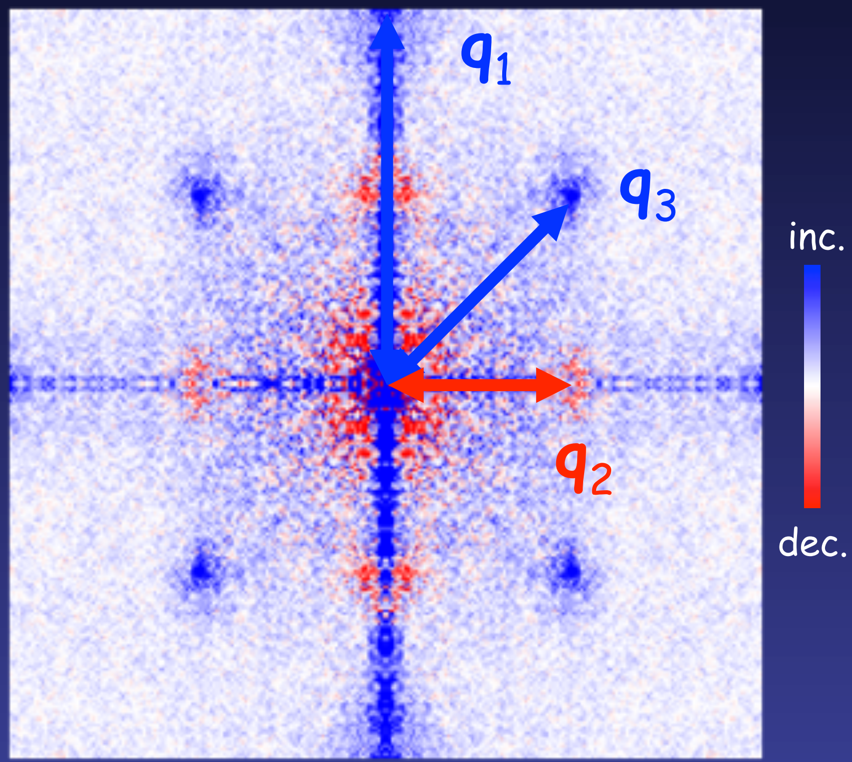


FT-Z map 1.0 meV



Strongly supports $s_{\pm}$-wave symmetry !!

Issues

- **Scattering centers?**
- **Impurity effect**

  - Does $s_{\pm}$-wave superconductivity really survive?

    M. Sato et al., JPSJ **79**, 014710 (2010).
    S. Onari and H. Kontani, PRL **103**, 177001 (2009).

  - Single impurity?

    S. H. Pan et al., Nature **403**, 746 (2000).
    E. W. Hudson et al., Nature **411**, 920 (2001).

- **Universality**

  - Various symmetries depending on band structures.

    K. Kuroki et al., PRB **79**, 224511 (2009).
    S. Graser et al., New J. Phys. **11**, 025016 (2009).

Issues

- **Scattering centers?**
- **Impurity effect**
  - Does $s_{\pm}$-wave superconductivity really survive?

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- **Universality**

  – Various symmetries depending on band structures.

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  S. Graser et al., New J. Phys. **11**, 025016 (2009).

LiFeAs

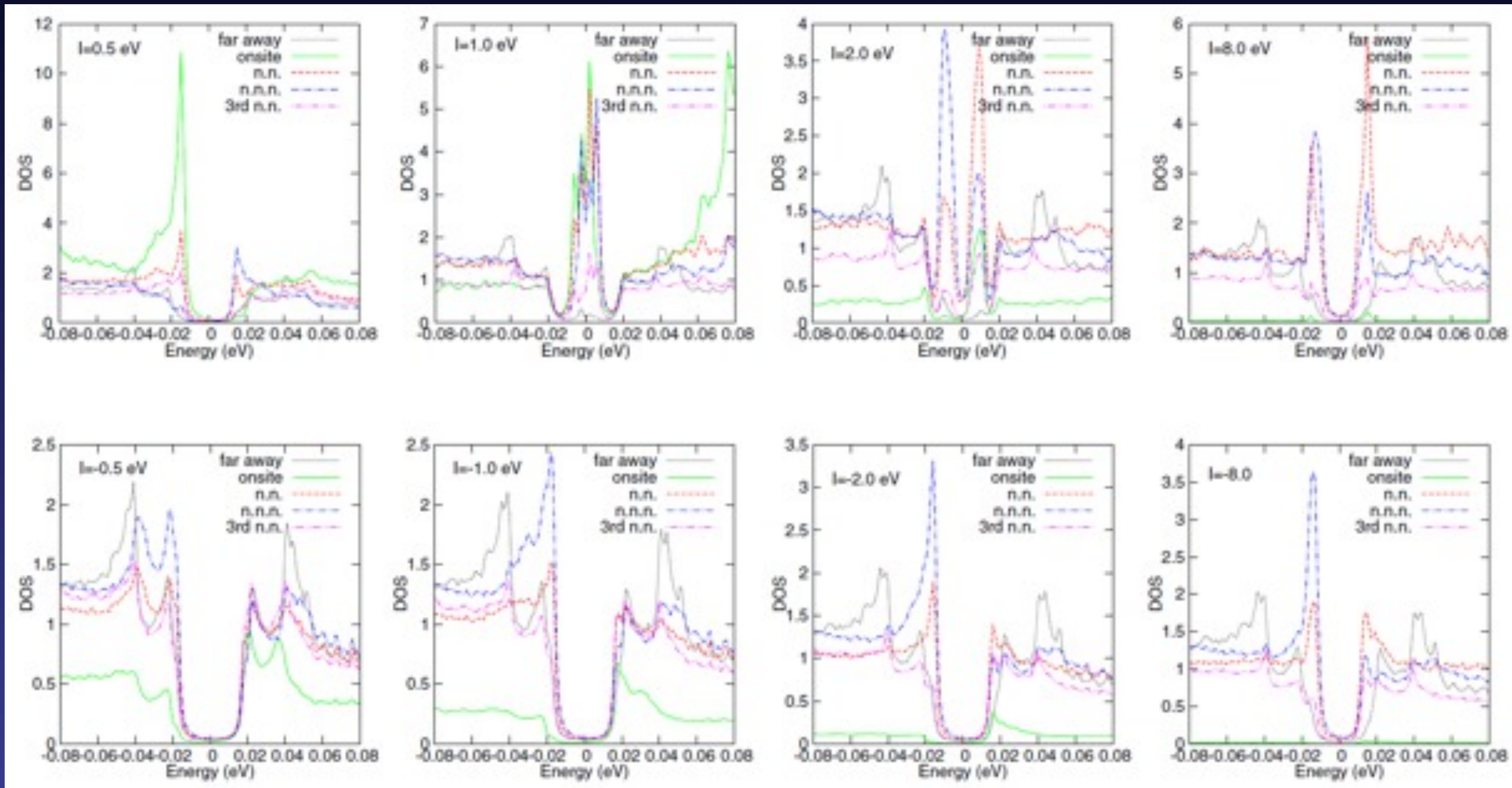
- Neutral surface
- Stoichiometric superconductor (clean !)

Issues ~ impurity effect

What about the effect of single impurity?

$s_{\pm}$

s_{++}



T. Kariyado and M. Ogata, JPSJ **79**, 083704 (2010).
See also, Y. Bang et al., PRB **79**, 054529 (2009), W. -F. Tsai et al., PRB **80**, 064513 (2009).

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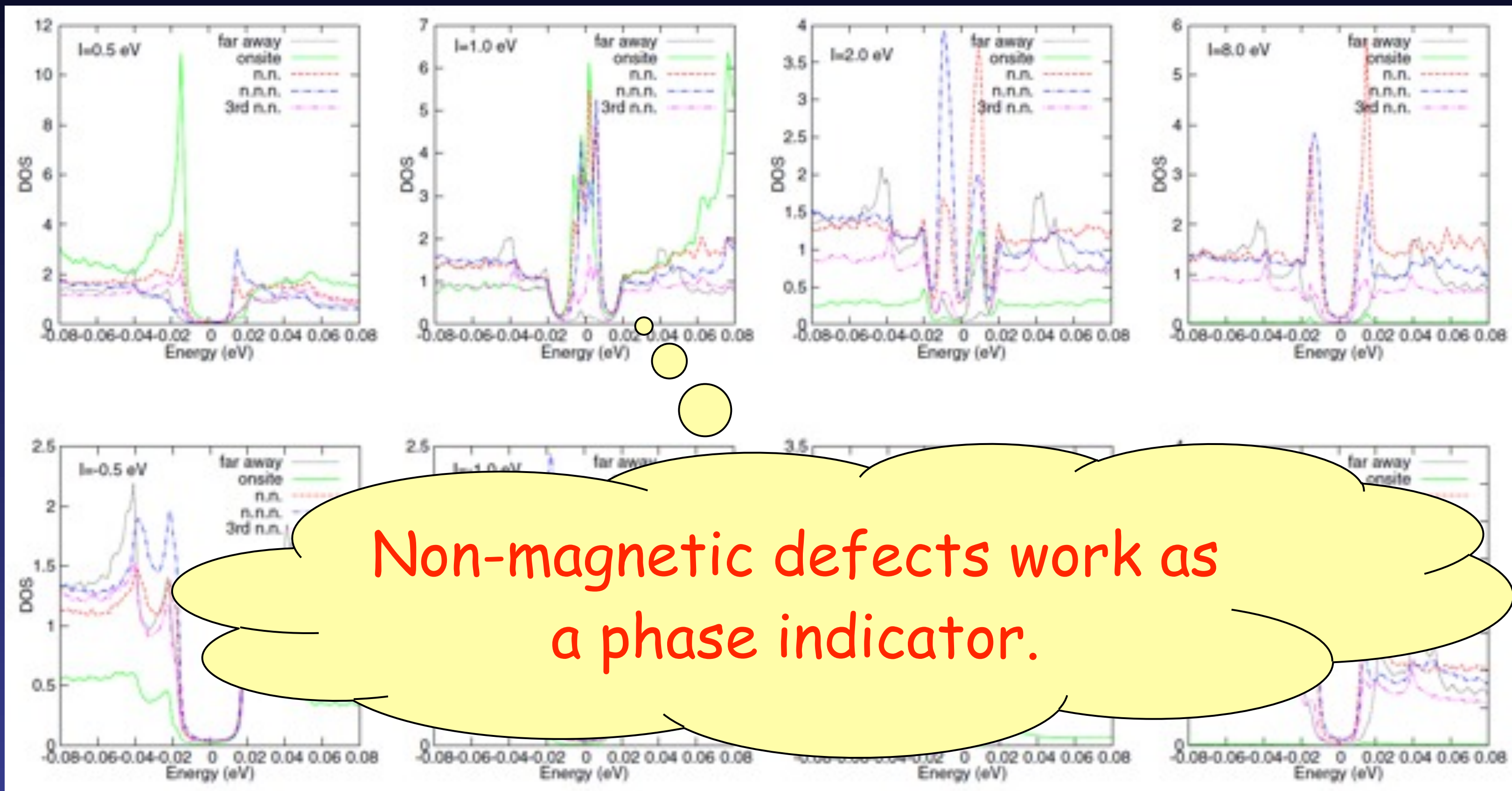

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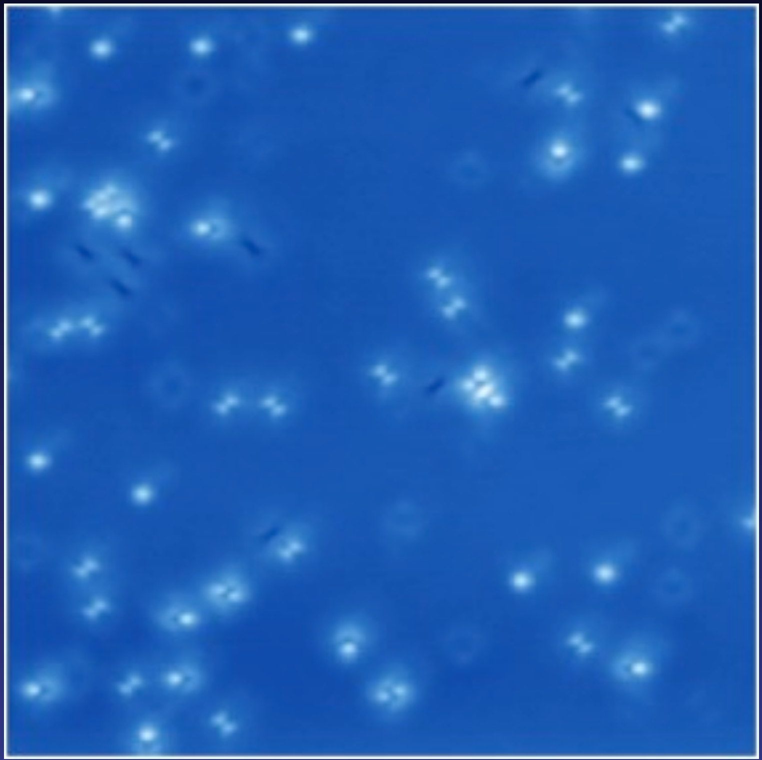
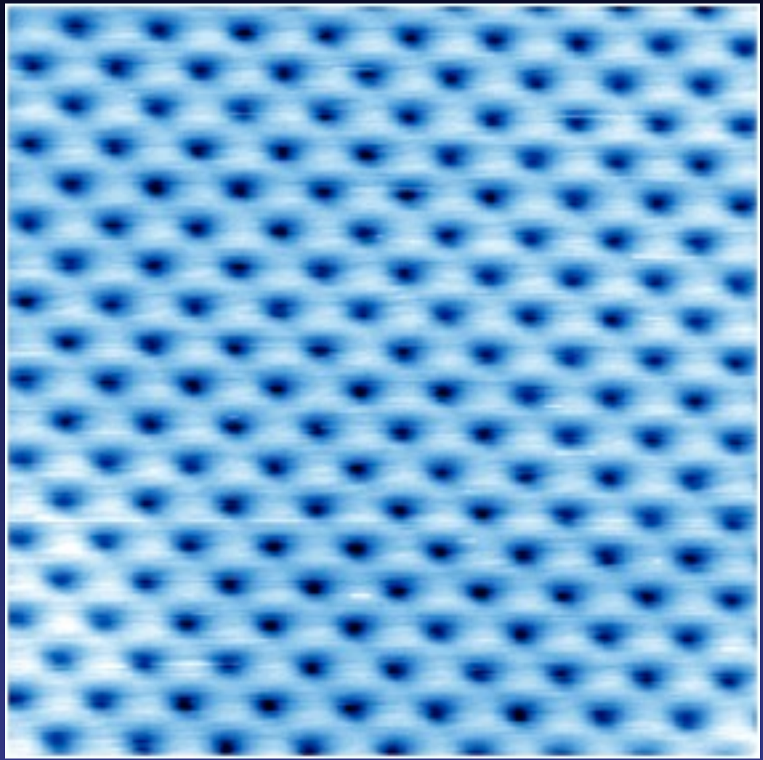
STM topograph of LiFeAs (T_c ~ 16 K)

T ~ 0.54 K



40 nm×40 nm, +50 mV/10 pA



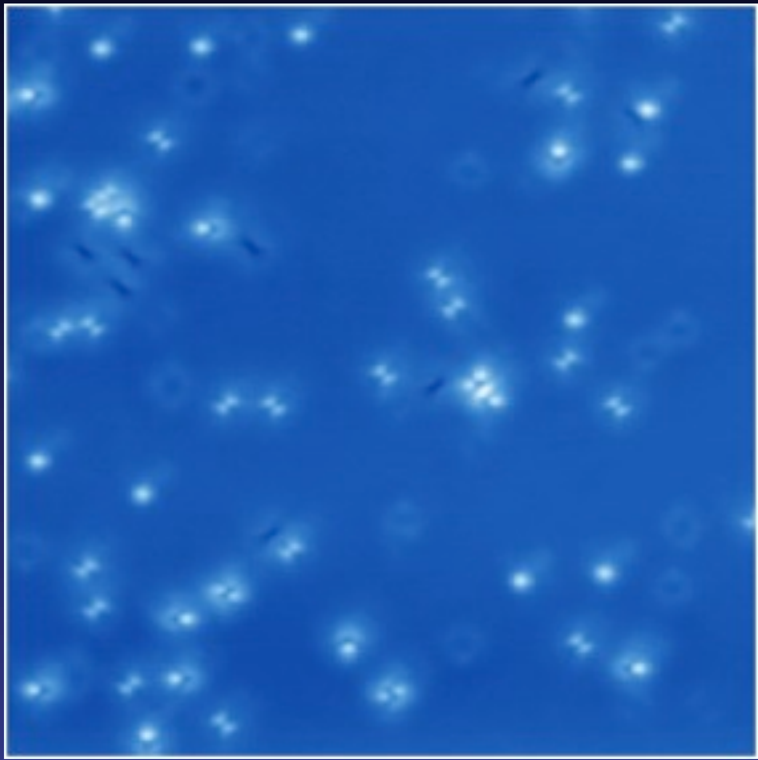
5 nm×5 nm, +20 mV/100 pA

Atomic lattice a ~ 3.8 Å (As or Li)

Variety of natural defects

Natural defects in LiFeAs

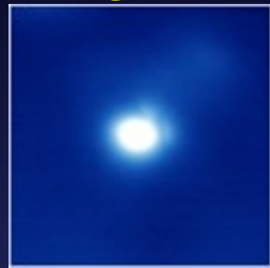
T ~ 0.54 K



40 nm×40 nm, +50 mV/10 pA

5 nm×5 nm, +50 mV/10 pA

"Dot"



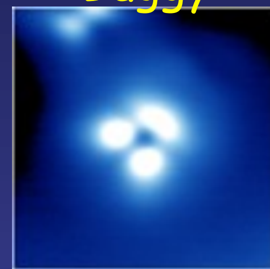
"Trench"

"Dumbbell"

"Clione"

"Yin-yang"

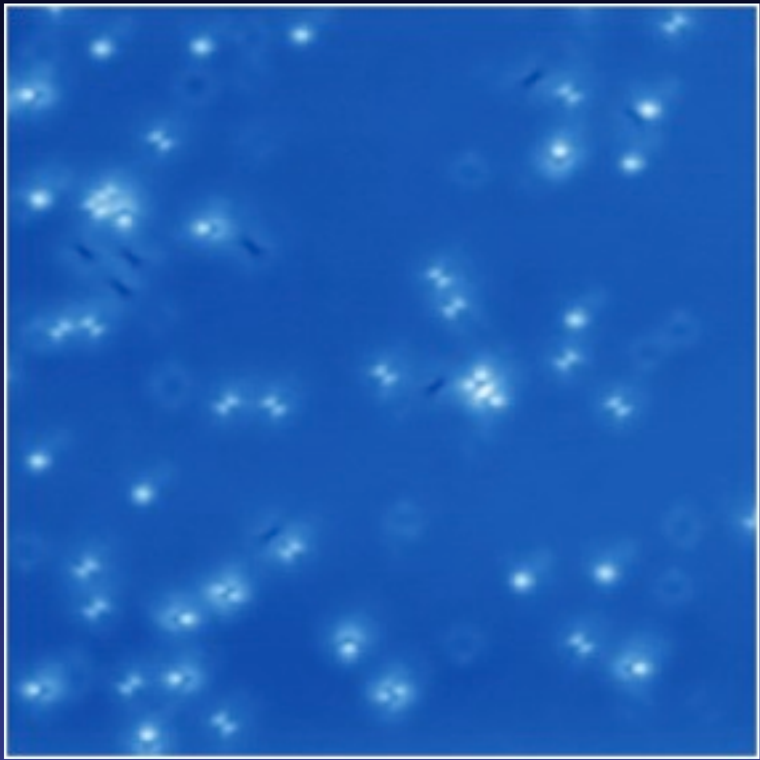
"Buggy"



At least 6 types of defects

Natural defects in LiFeAs

T ~ 0.54 K



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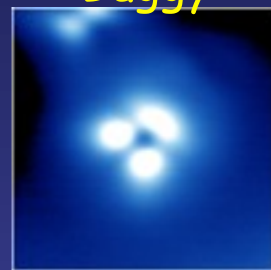
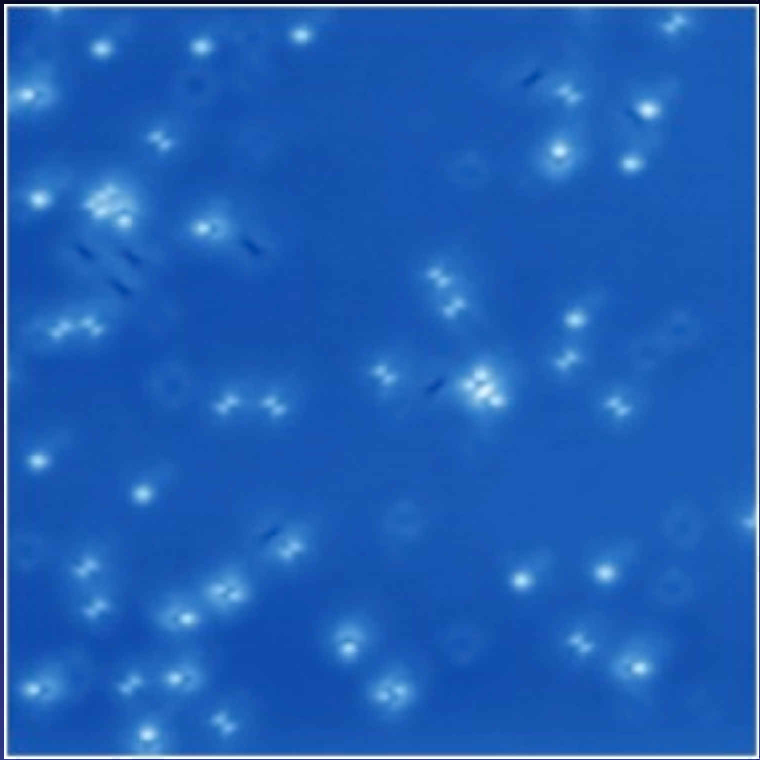


http://paraparadisezooeng.blog73.fc2.com/blog-category-27.html

At least 6 types of defects

Natural defects in LiFeAs

T ~ 0.54 K



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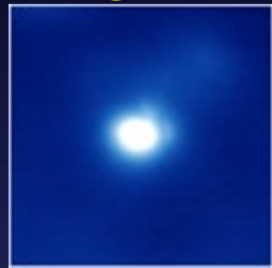

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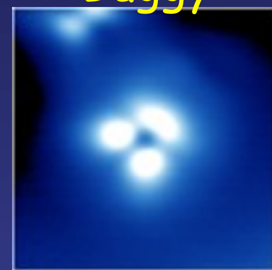
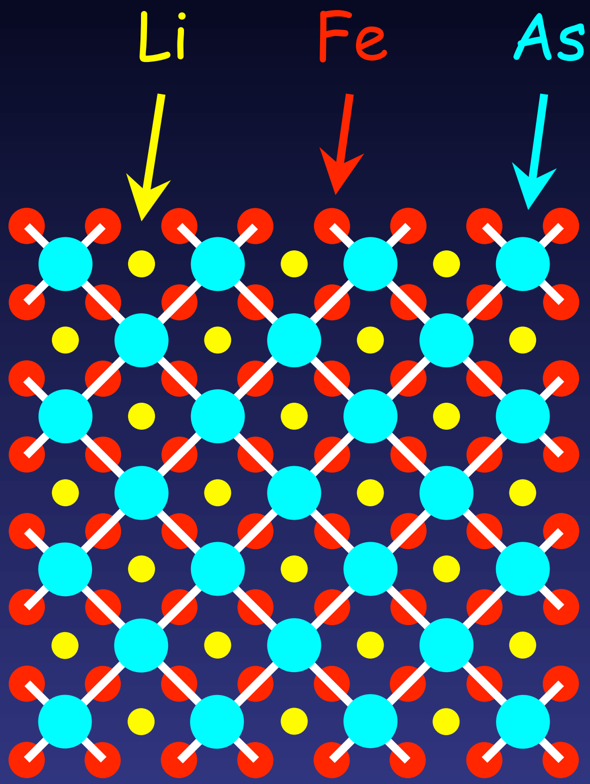
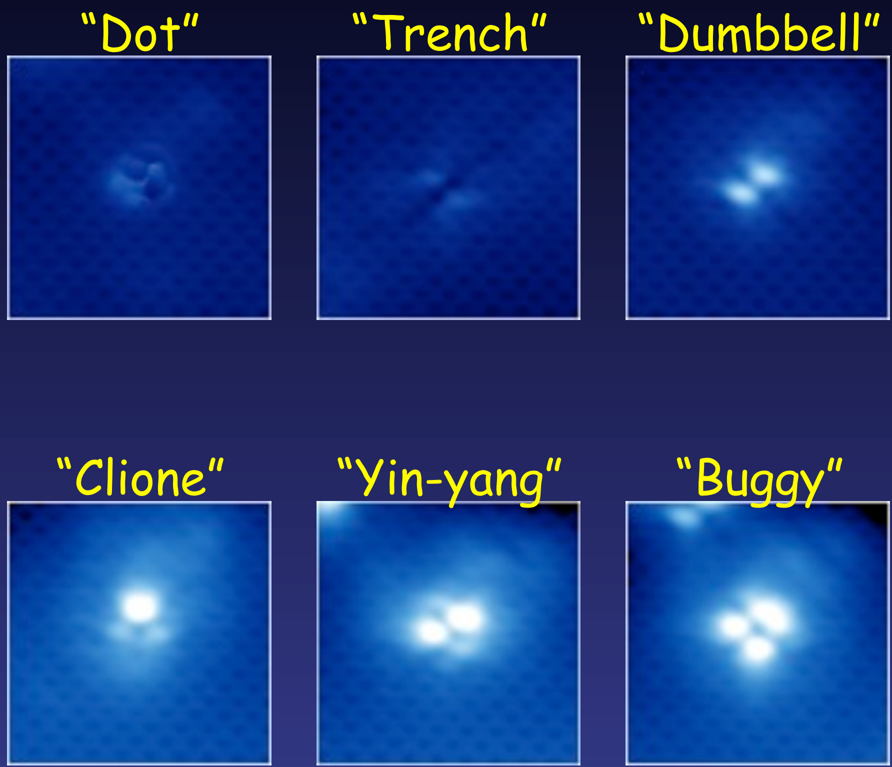


At least 6 types of defects

Site assignments for defects in LiFeAs



5 nm×5 nm, +20 mV/100 pA



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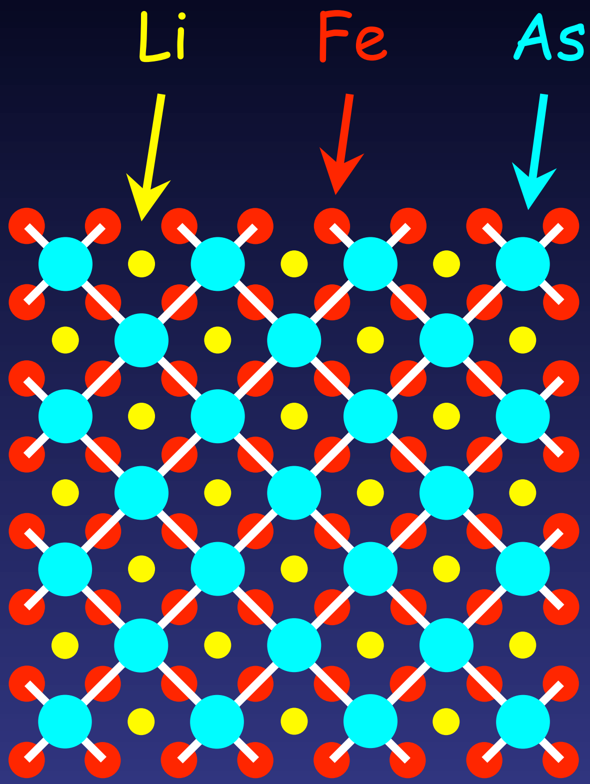

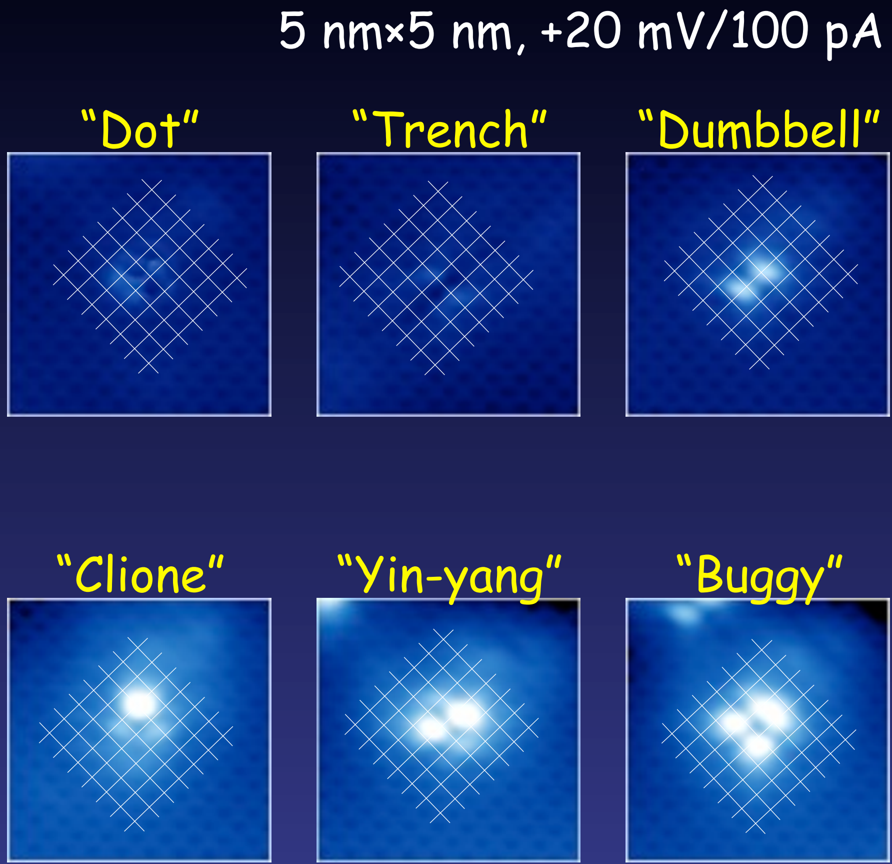

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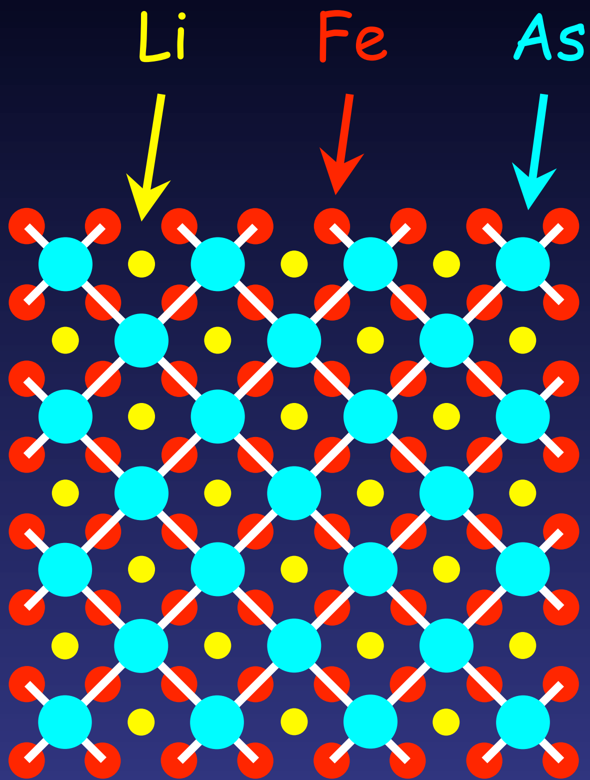

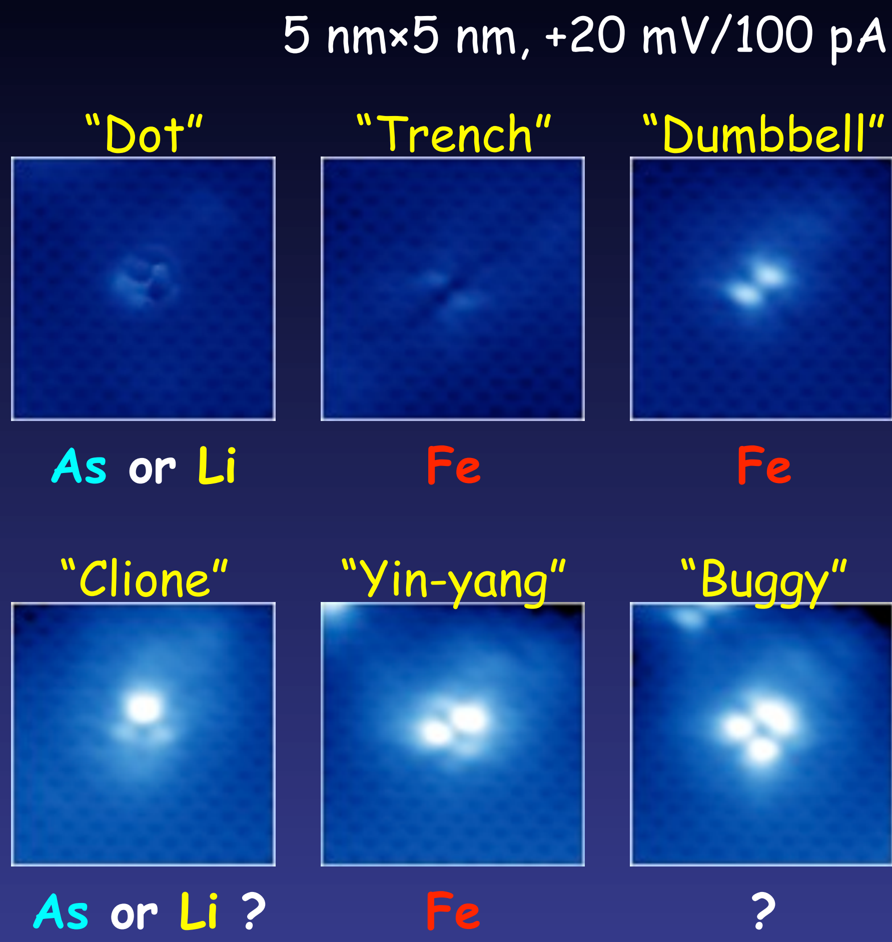

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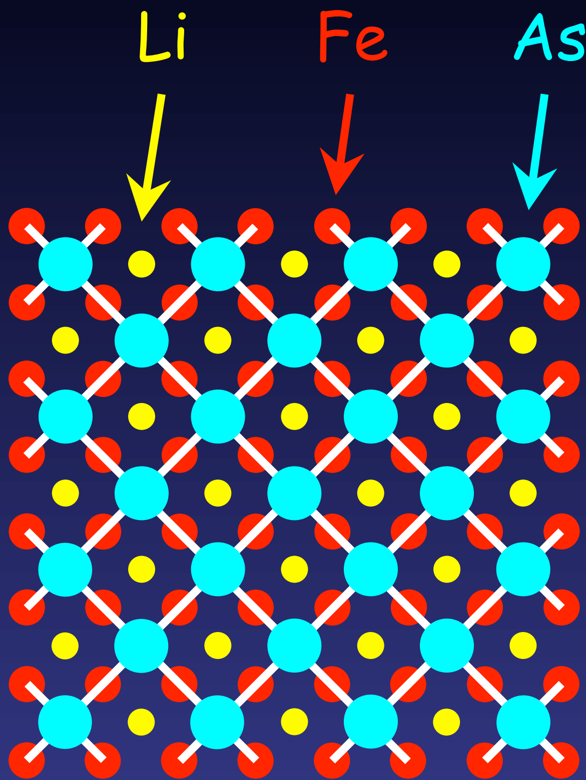


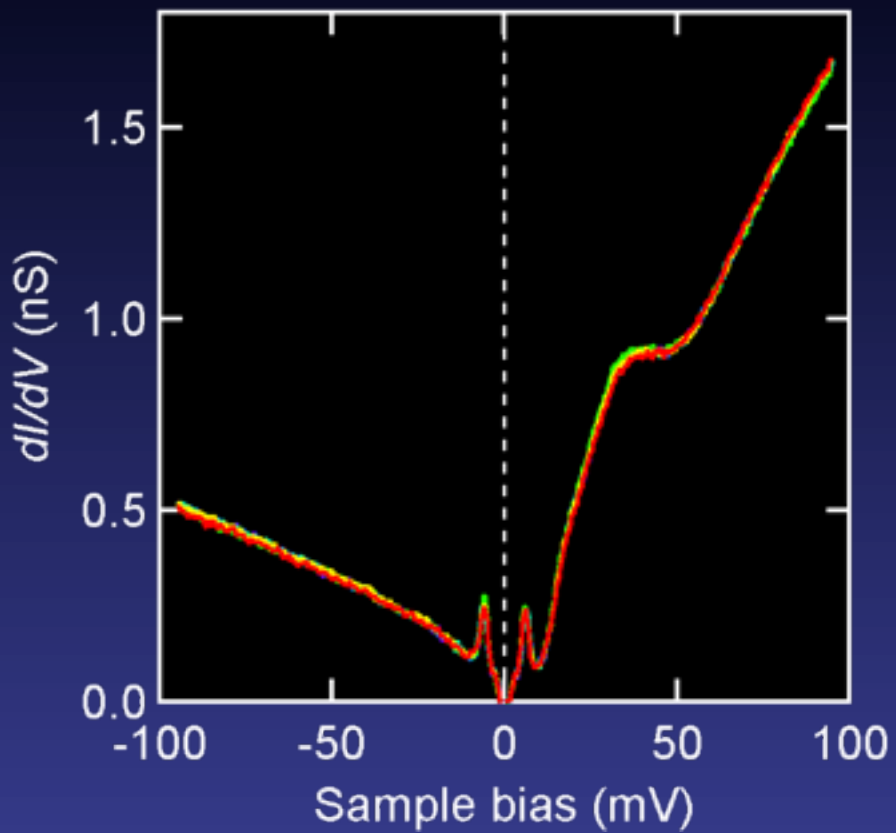
5 nm×5 nm, +20 mV/100 pA

Dot, Trench, Dumbbell : Local symmetry is preserved.

Clione, Yin-yang, Buggy : Local symmetry is broken.

Tunneling spectra of LiFeAs (T_c ~ 16 K)

T ~ 0.54 K



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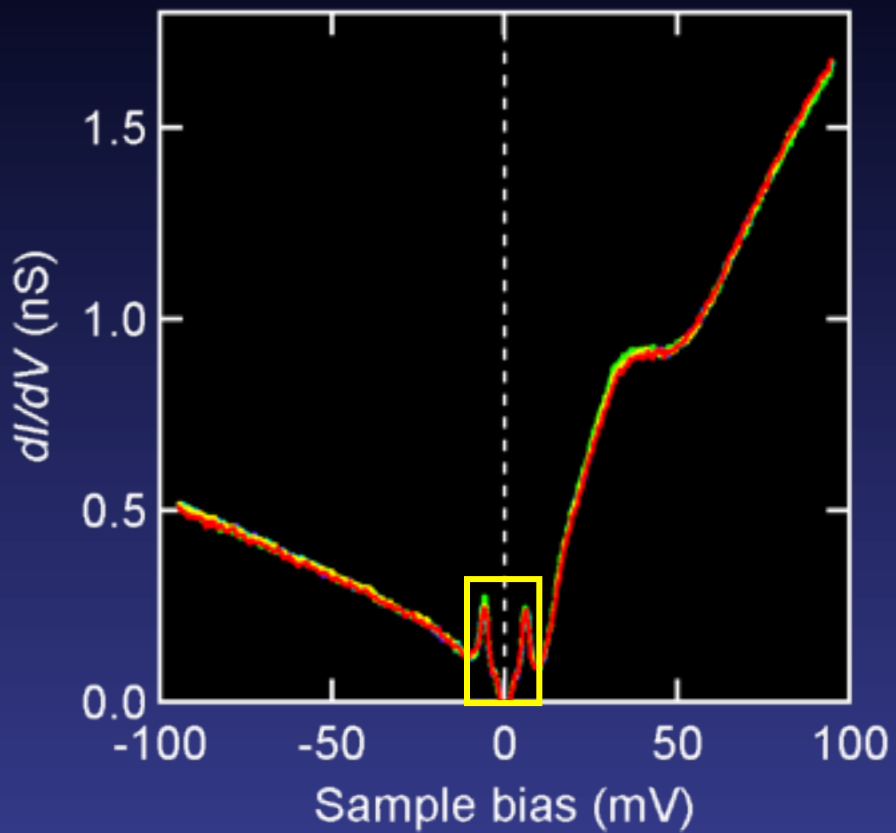

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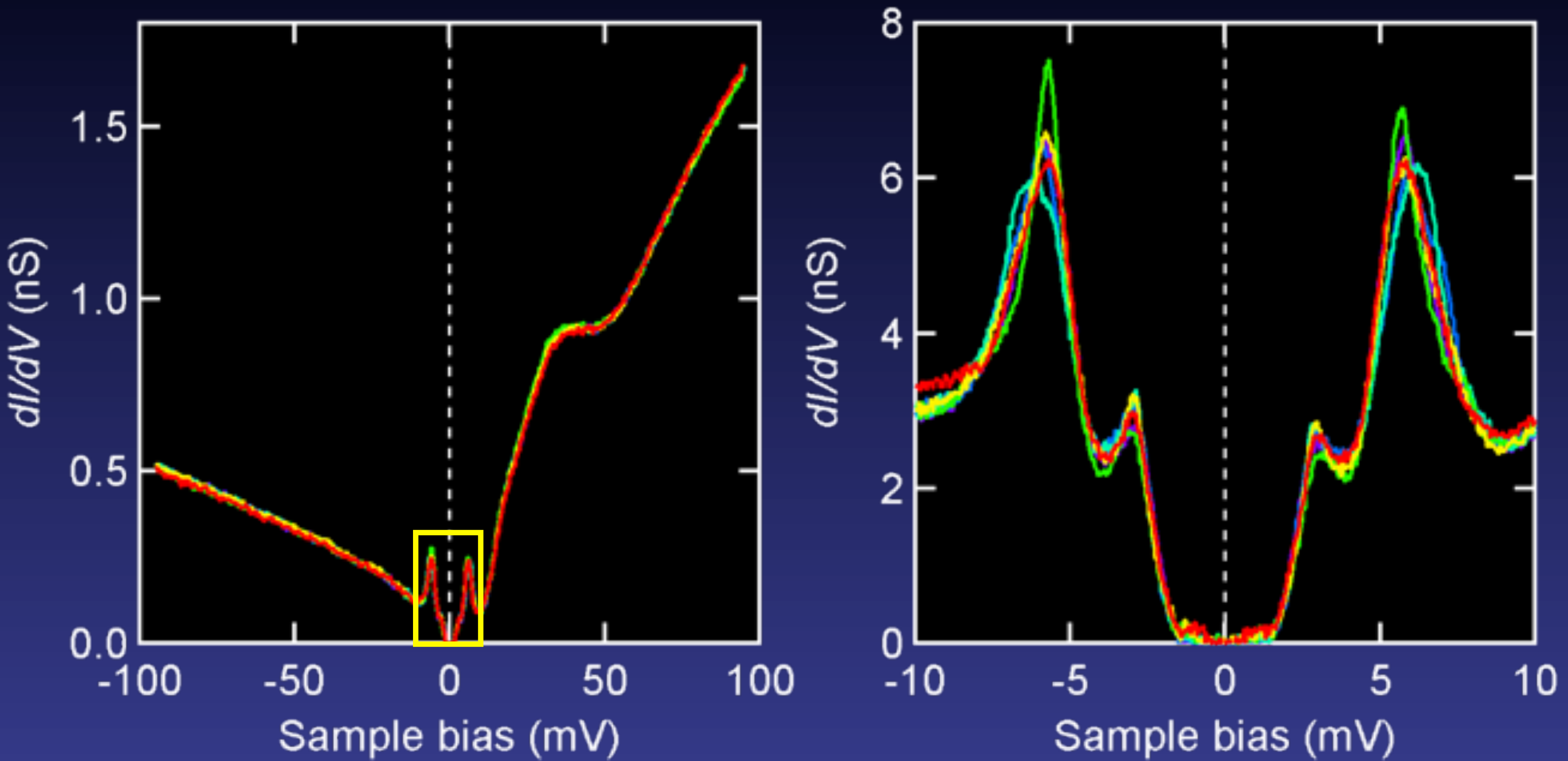

- Two gaps ($2\Delta/T_c$ ~ 3.6 and 8.3)
- No significant inhomogeneity

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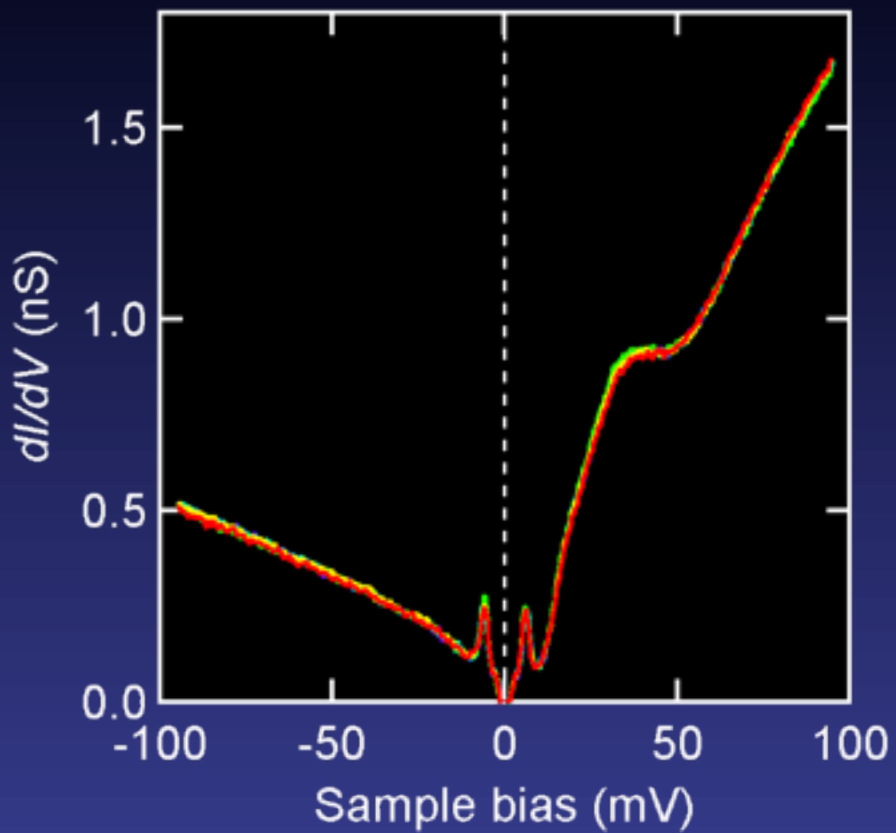
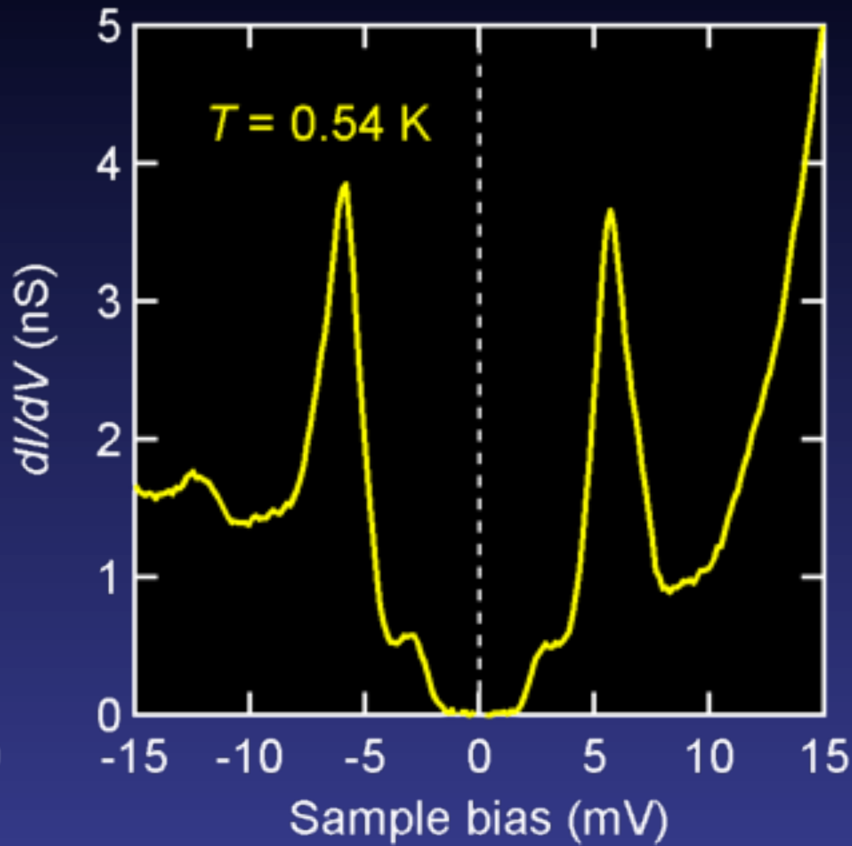
T ~ 0.54 K





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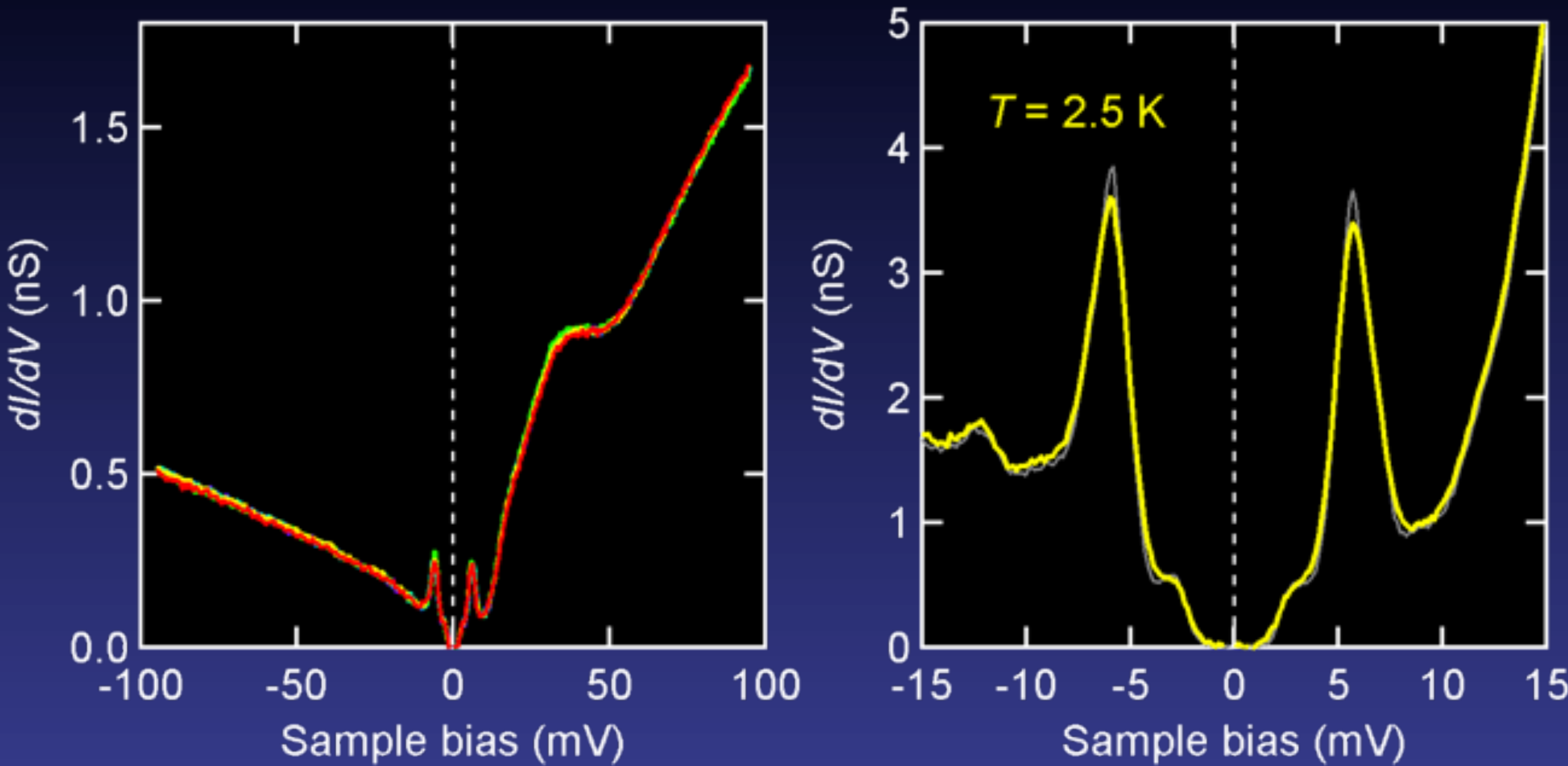

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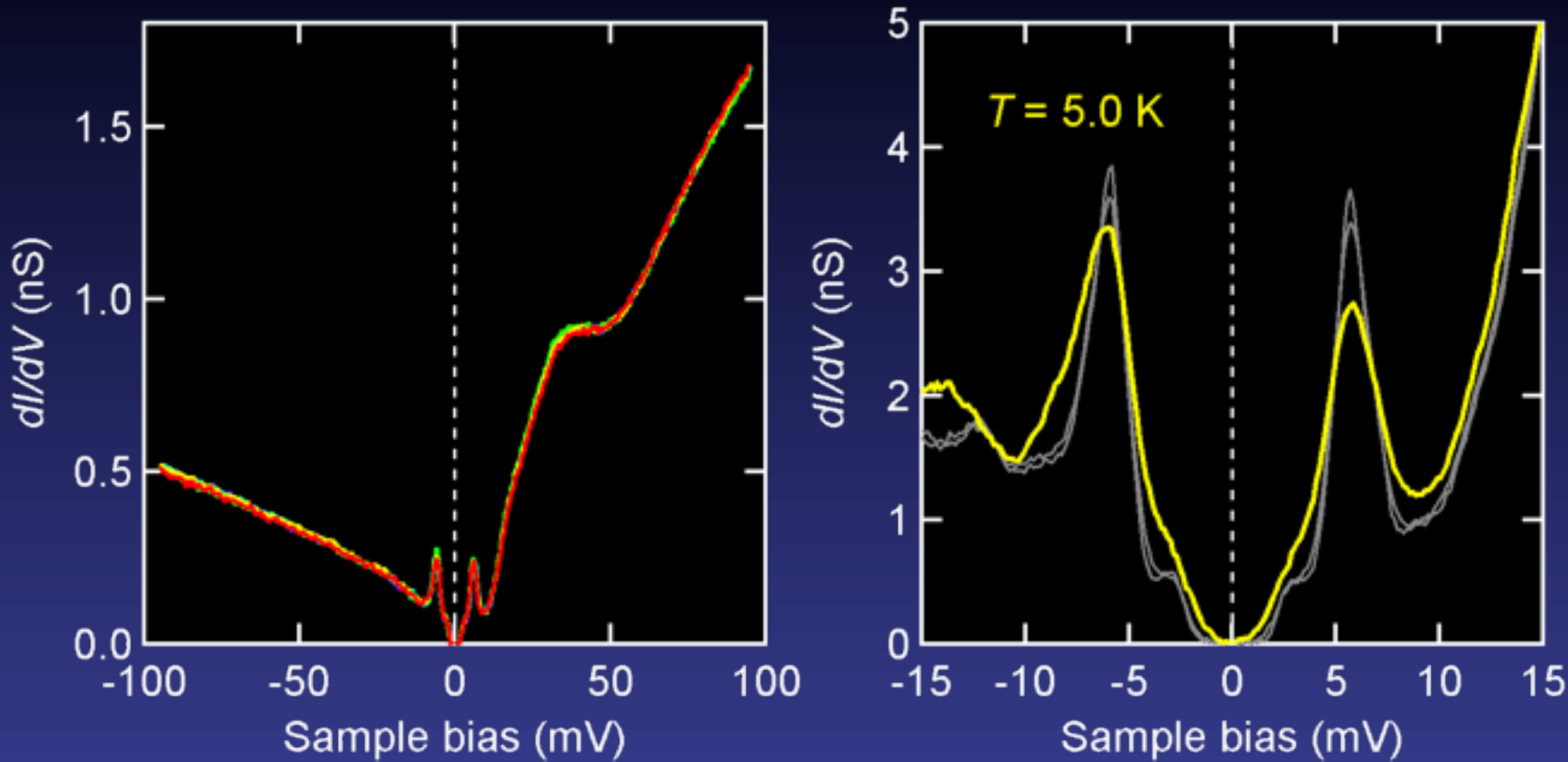

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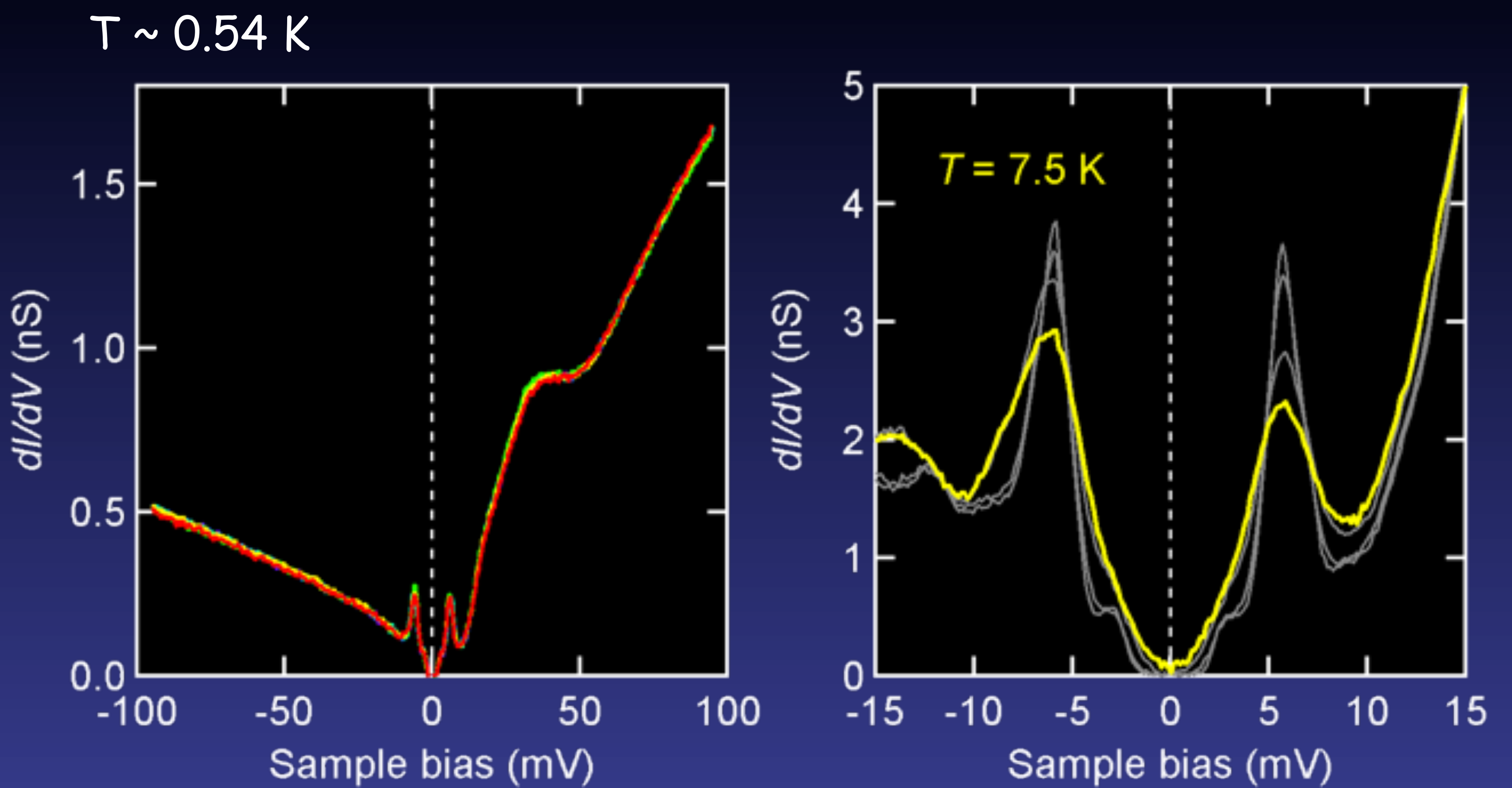

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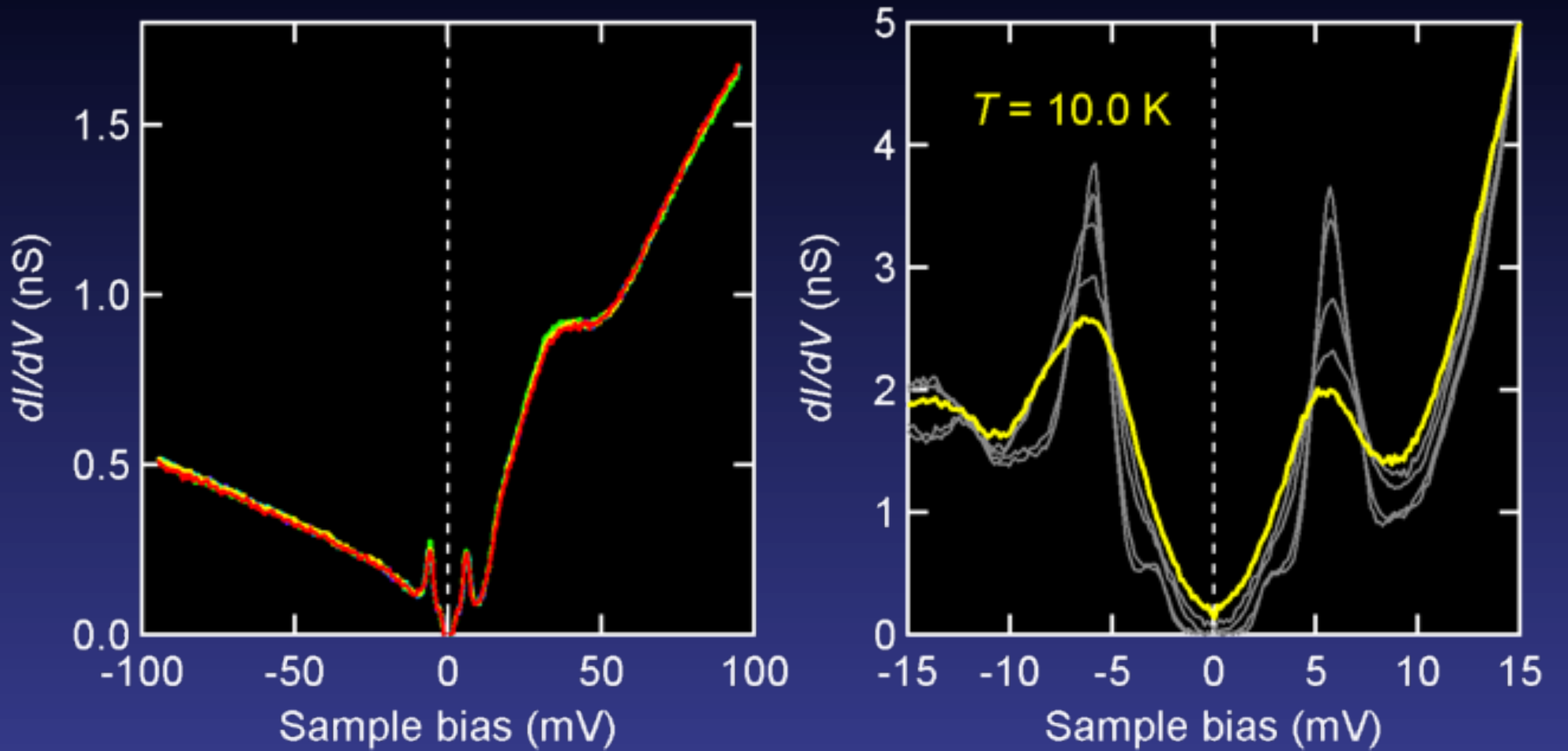

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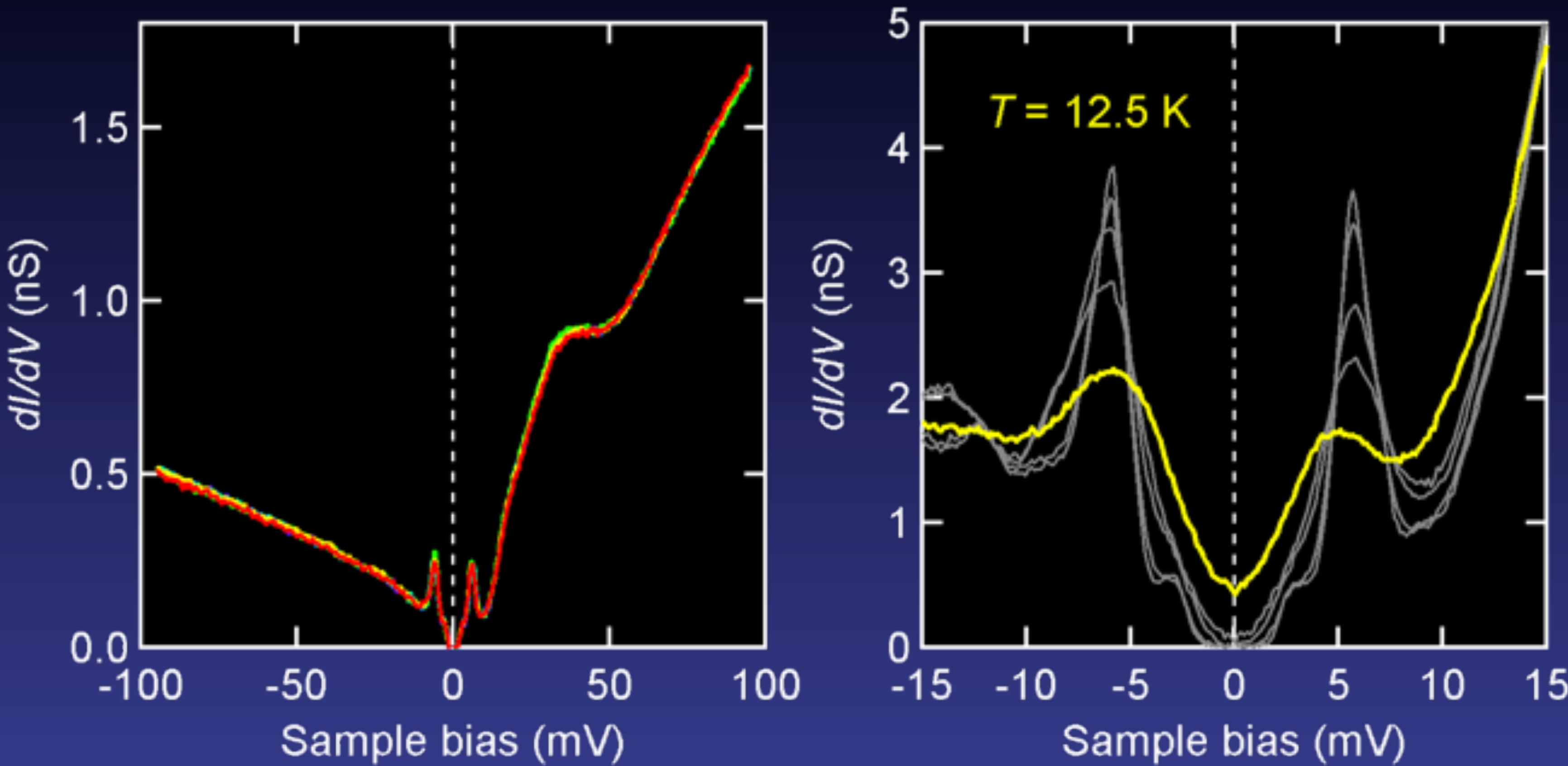

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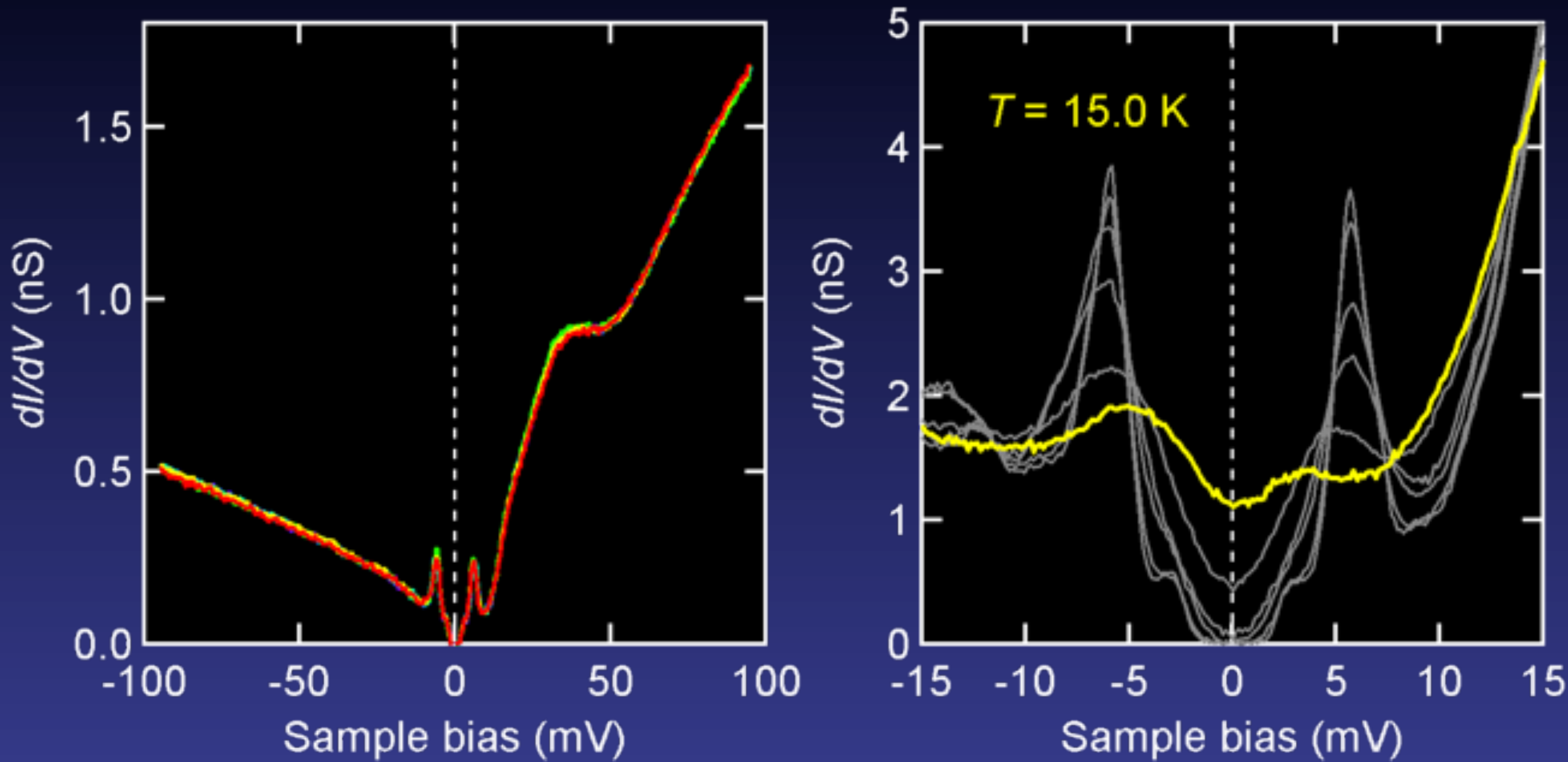

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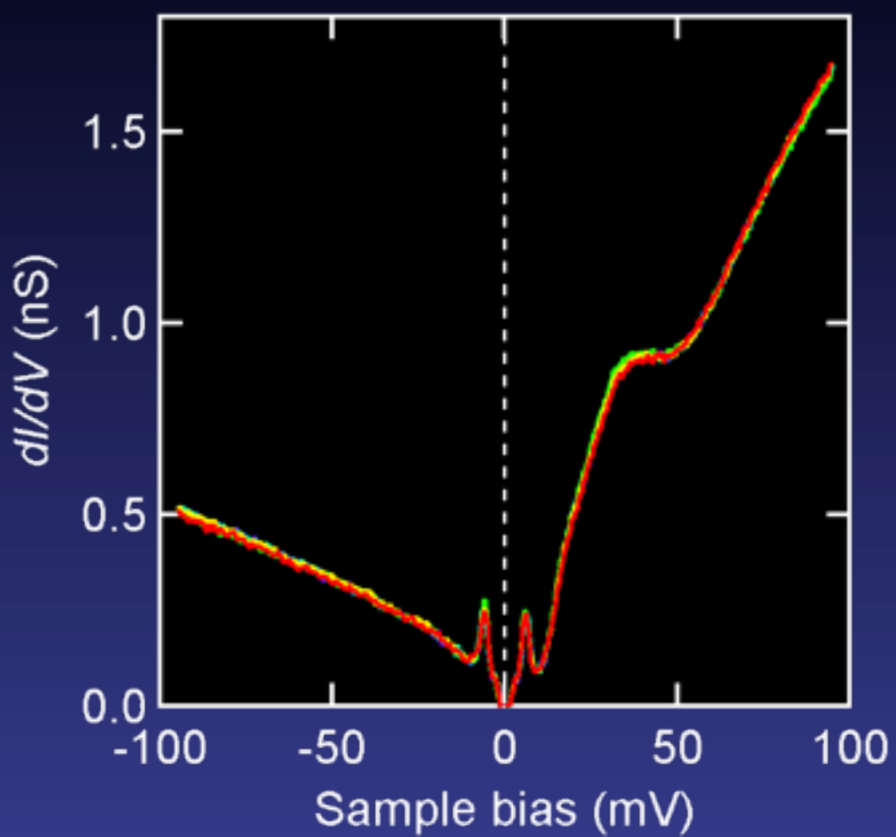

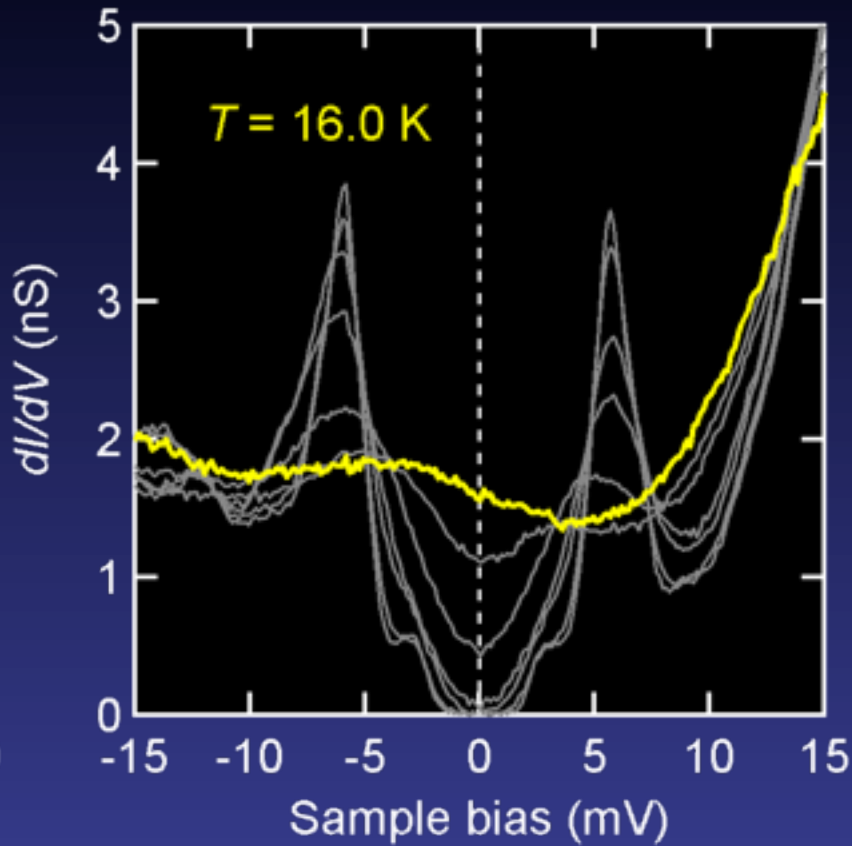

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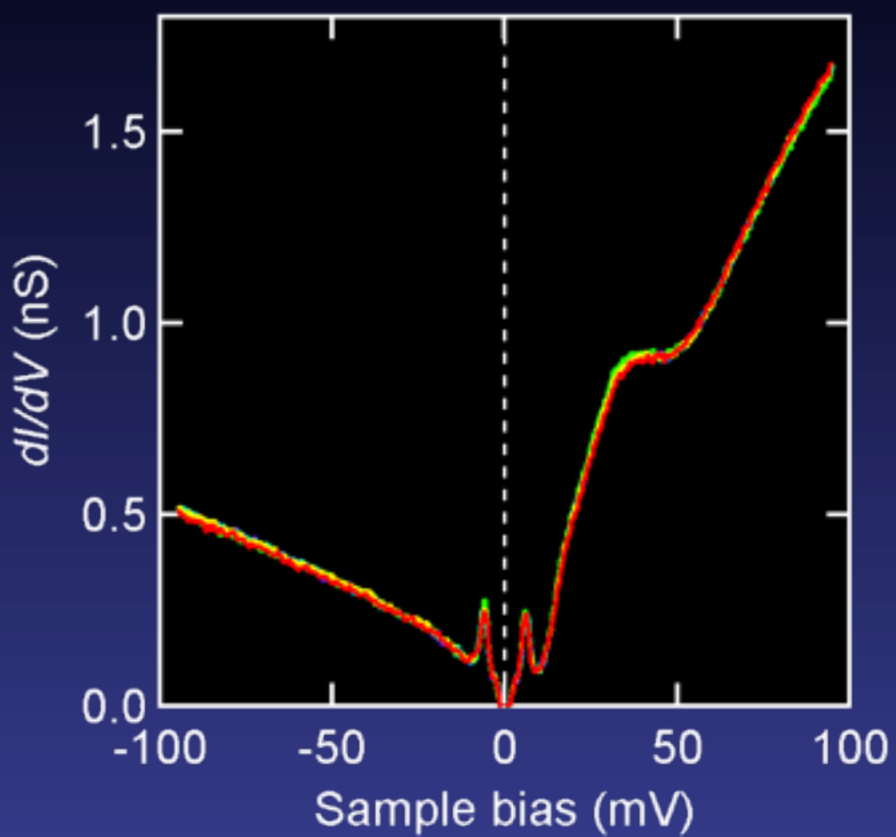
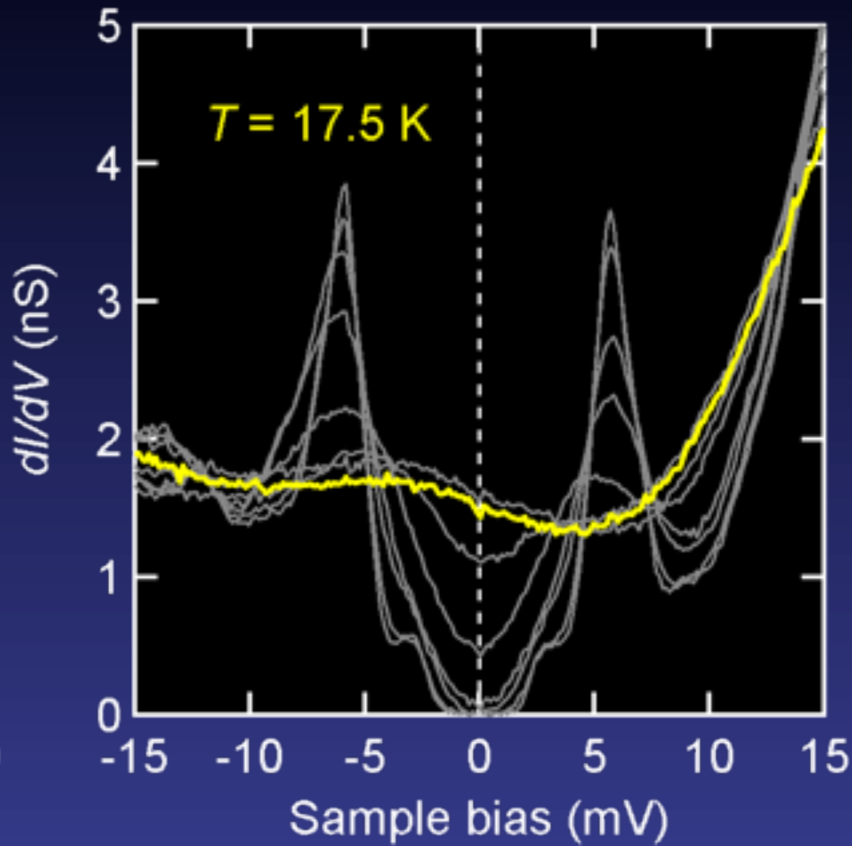




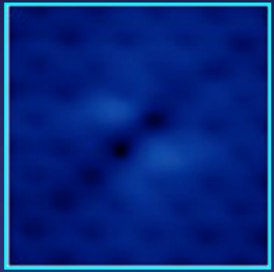
- Two gaps ($2\Delta/T_c$ ~ 3.6 and 8.3) disappear at T_c.
- No significant inhomogeneity

Tunneling spectra at the defects

symmetry-preserving defects

"Dot"

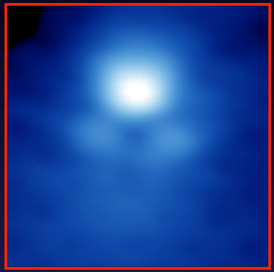
"Trench"



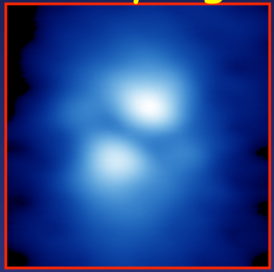
"Dumbbell"

symmetry-breaking defects

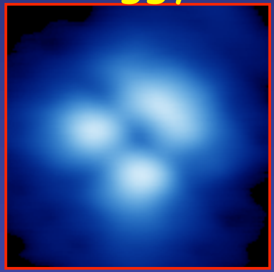
"Clione"



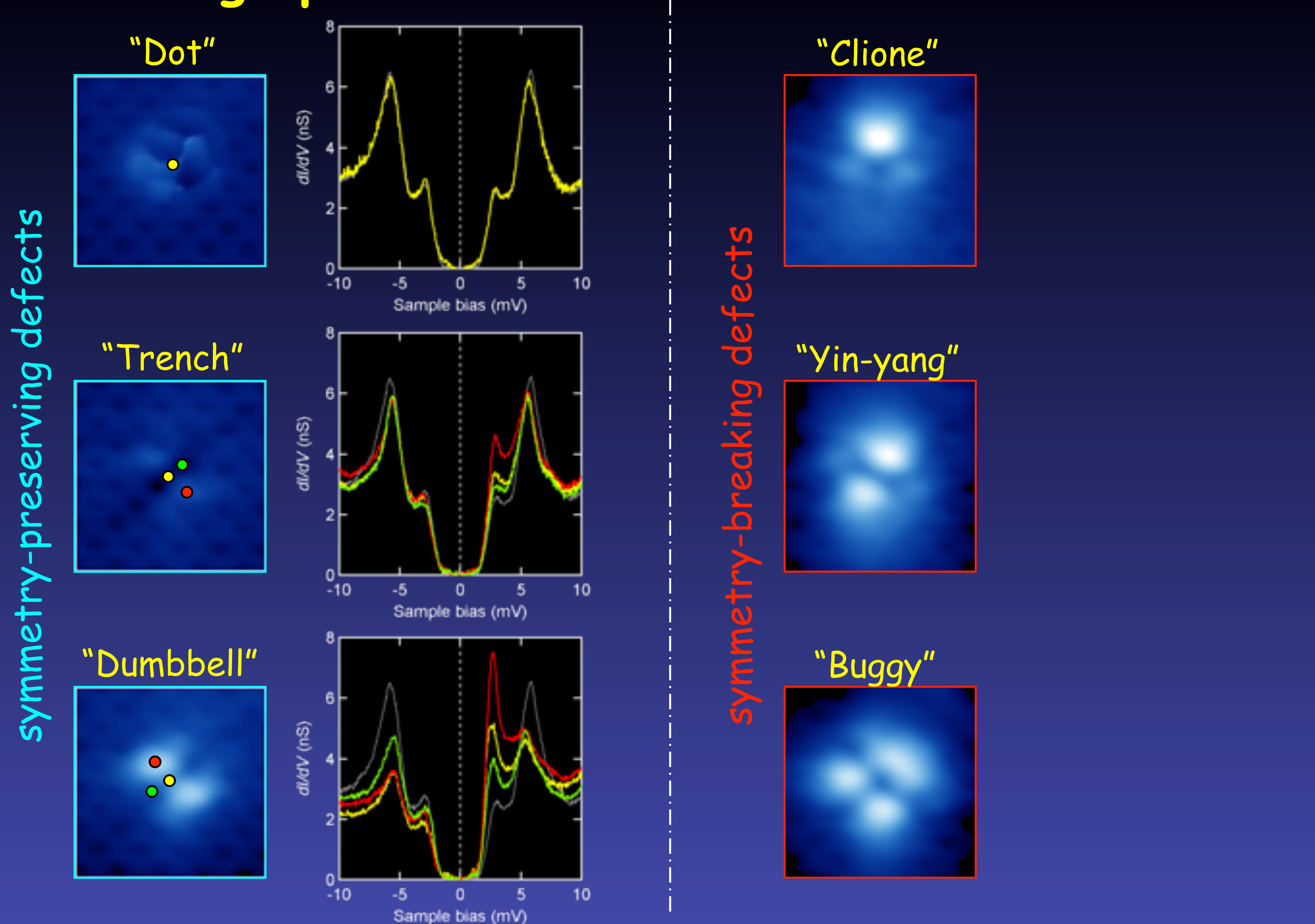
"Yin-yang"



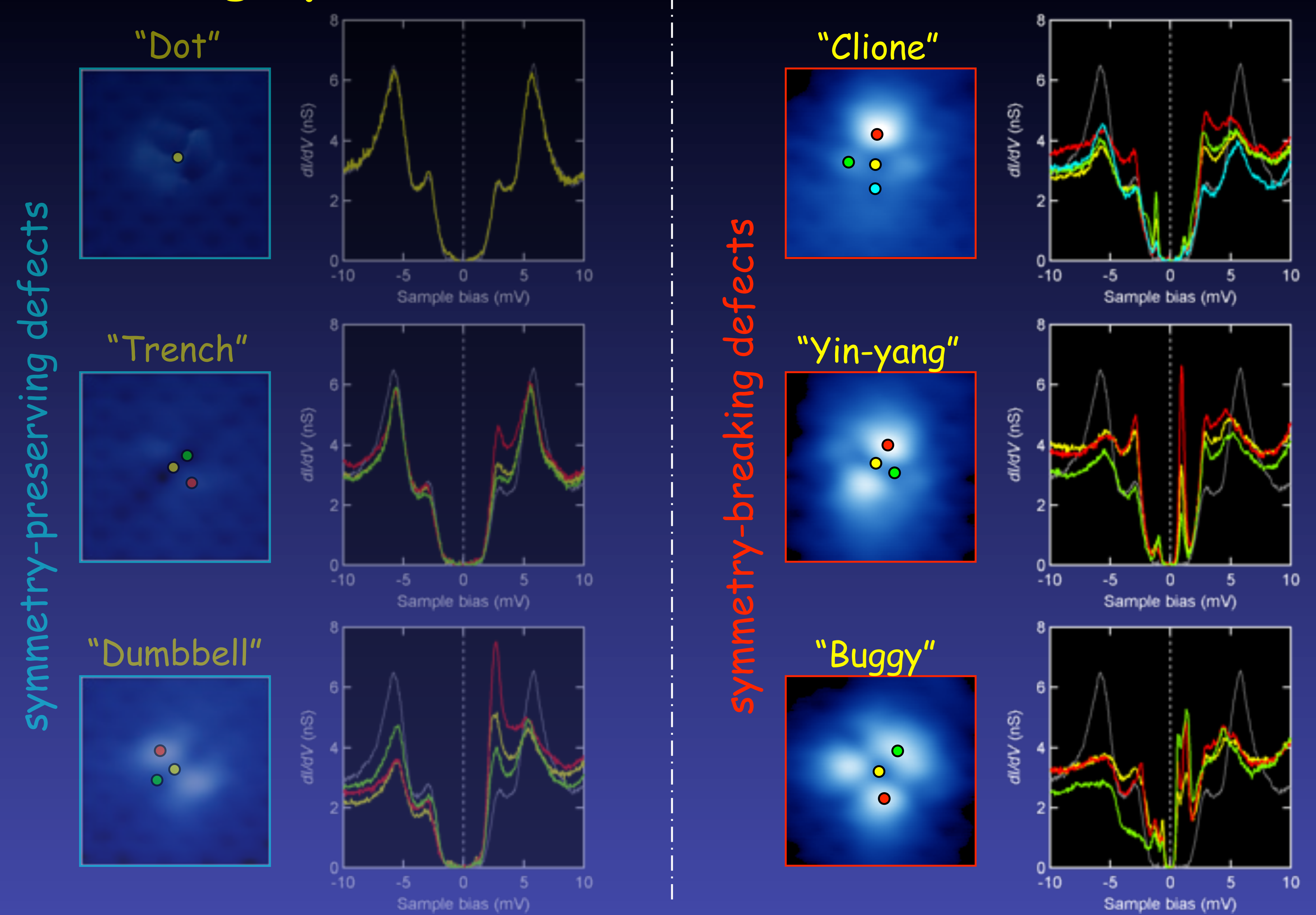
"Buggy"



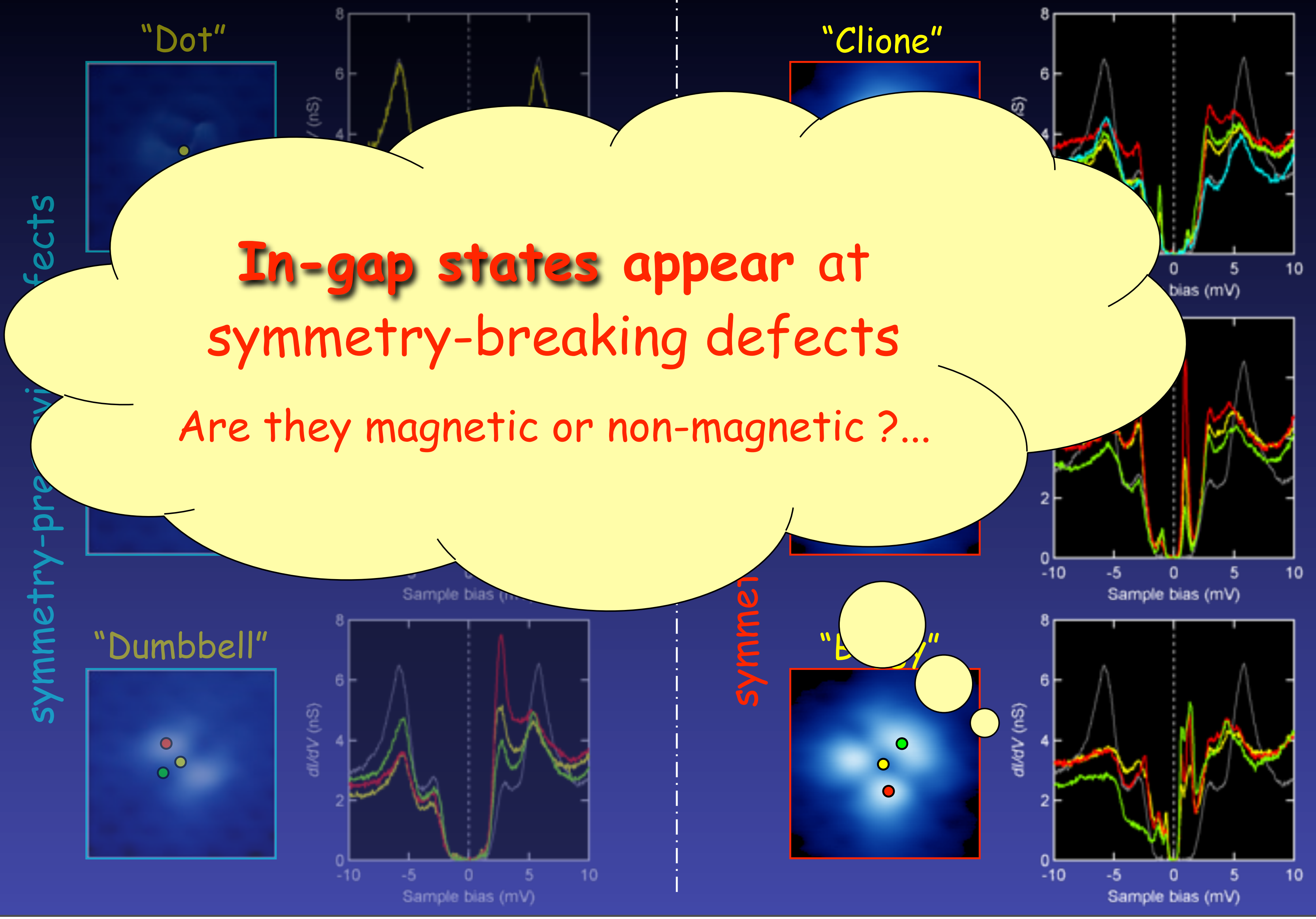
Tunneling spectra at the defects



Tunneling spectra at the defects



Tunneling spectra at the defects



In-gap states appear at
symmetry-breaking defects

Are they magnetic or non-magnetic ?...

Summary

- Tunneling spectra of Fe(Se,Te) and LiFeAs suggest that the **superconducting gap fully opens** over the Fermi surface.
- 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.
- In LiFeAs, **in-gap bound states** are formed at some of the defects which break local symmetry of the underlying lattice.

Prospects

- Larger field of view
- Intentionally-doped impurities (Sn, P,...)