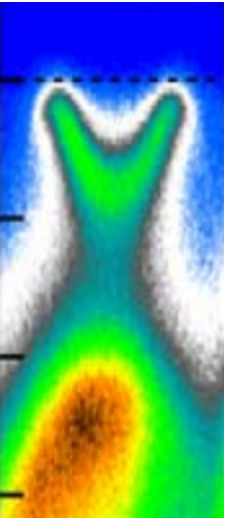
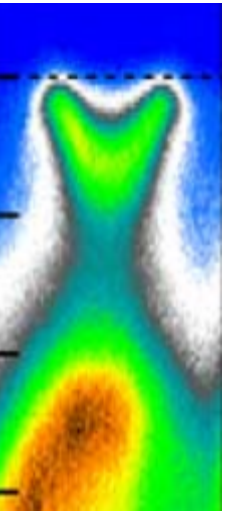




Electronic Origin of High-Temperature Superconductivity in Single-Layer FeSe Superconductor*

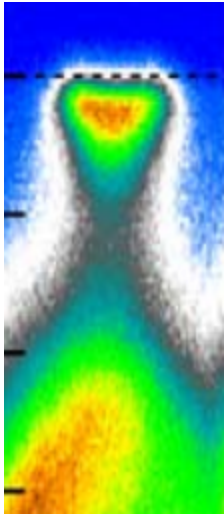
Team #1 - Jyoti Aneja, Brian Busemeyer,
Mindy Cartolano, David Casavant

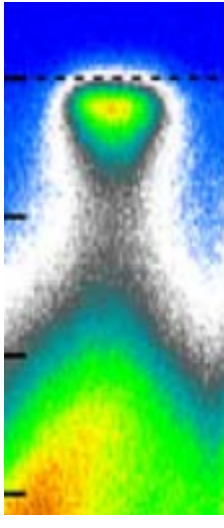
Physics 596 Journal Club Presentation
November 22, 2013

*Liu, D., *et al.* Electronic origin of high-temperature superconductivity in single-layer FeSe superconductor. *Nat. Commun.* 3:931 doi: 10.1038/ncomms1946 (2012).

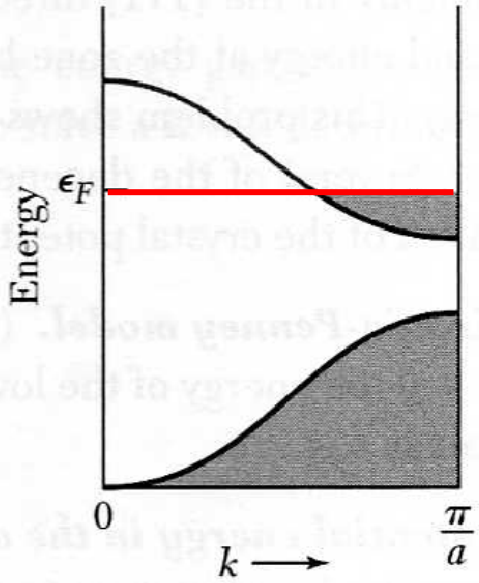
Outline

- Background
  - Fermi surfaces
  - Superconductivity
- Article summary
  - Methods
  - Results
- Critique of Paper
- Conclusions
- Citation Analysis





Fermi Surfaces Depict Conduction States in k-space



Along one dimension...

Kittel, 2005, John Whiley & Sons, 8e, 181

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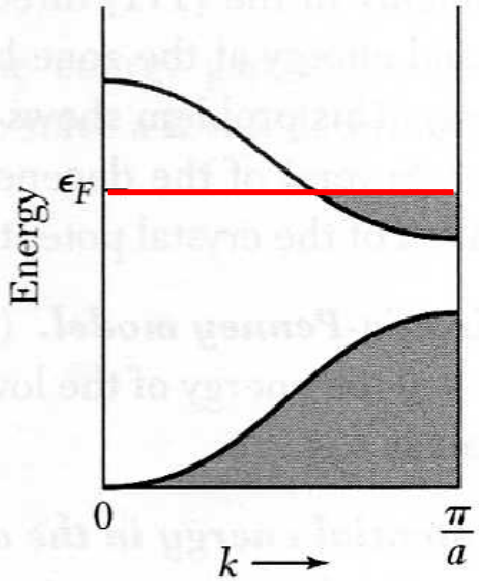

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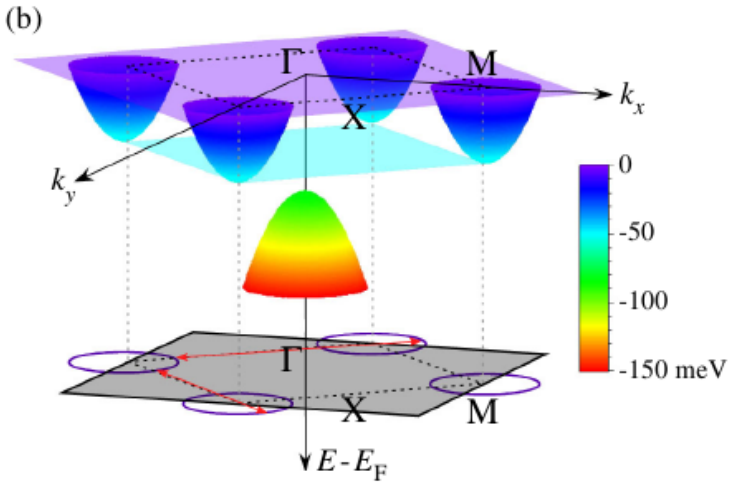

...in two dimensions...

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PRL **106,** 187001 (2011)

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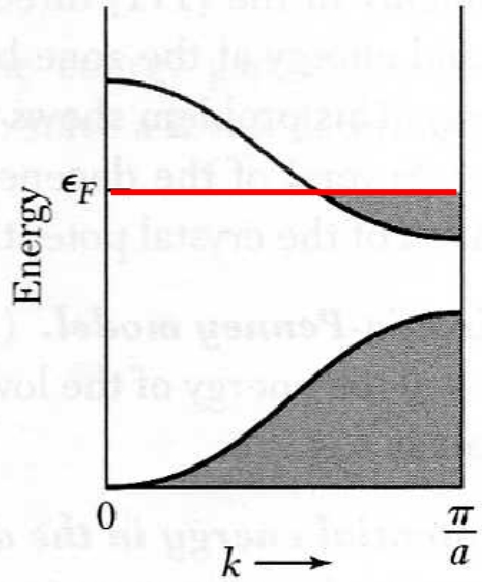

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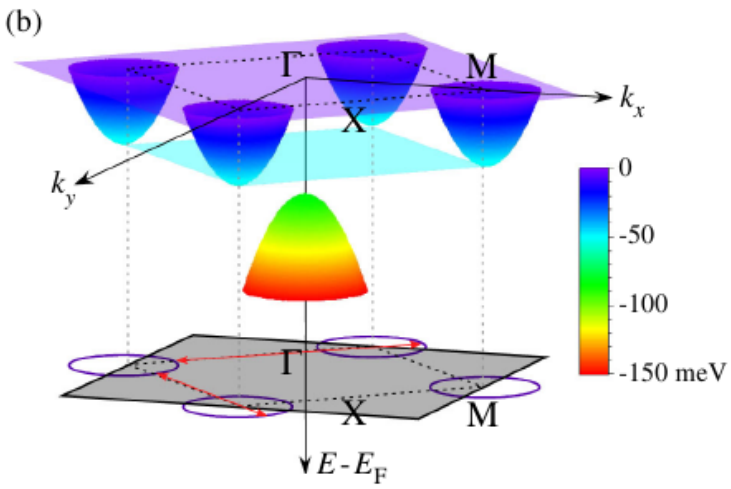

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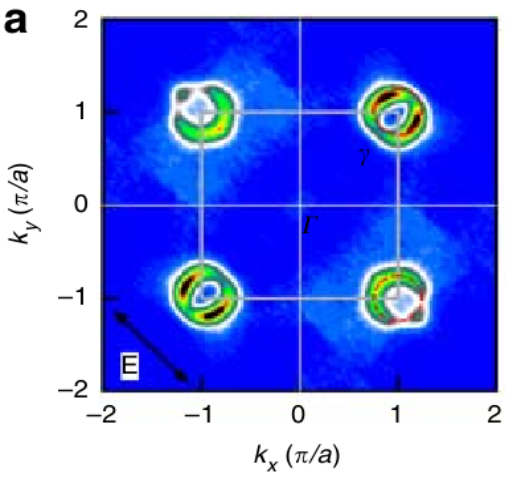
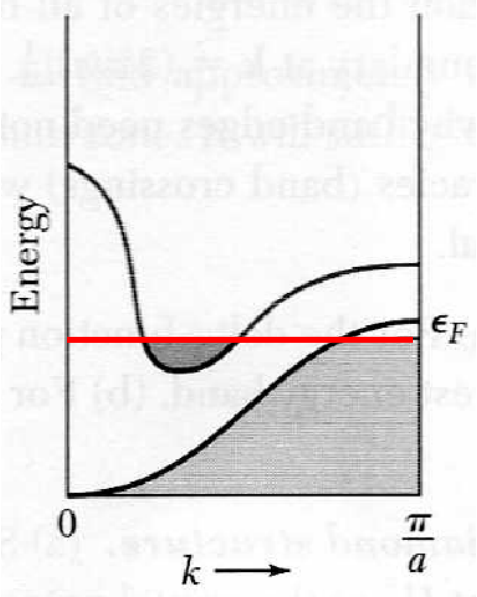


...intersecting with Fermi energy.

Kittel, 2005, John Whiley & Sons, 8e, 181

PRL **106,** 187001 (2011)

Another Kind of Fermi Surface:



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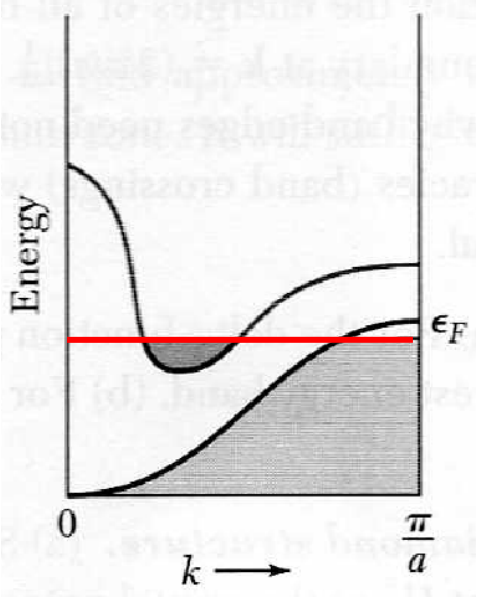

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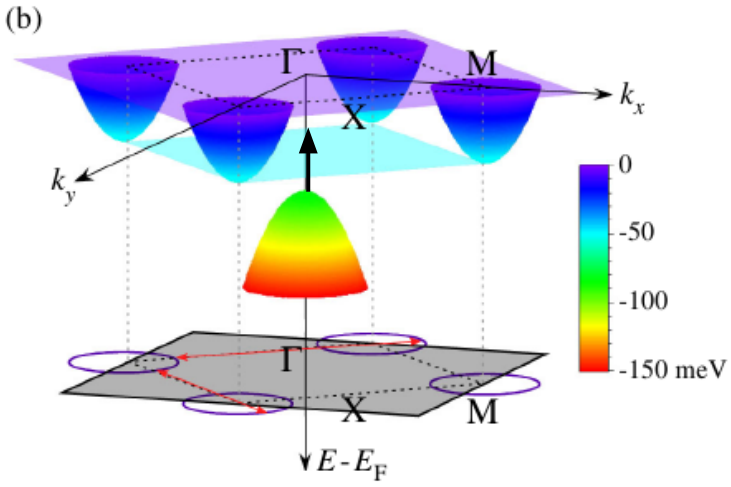

...if surfaces are positioned right...

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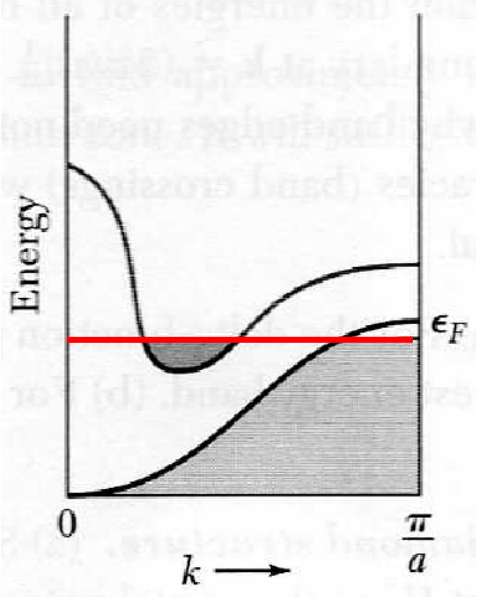

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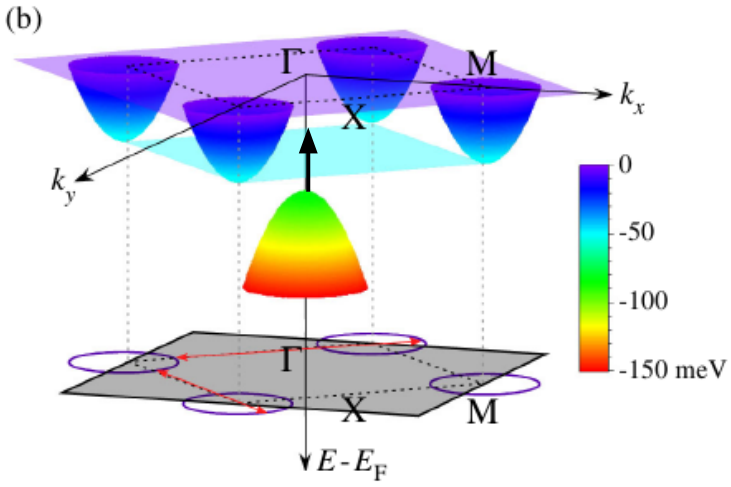

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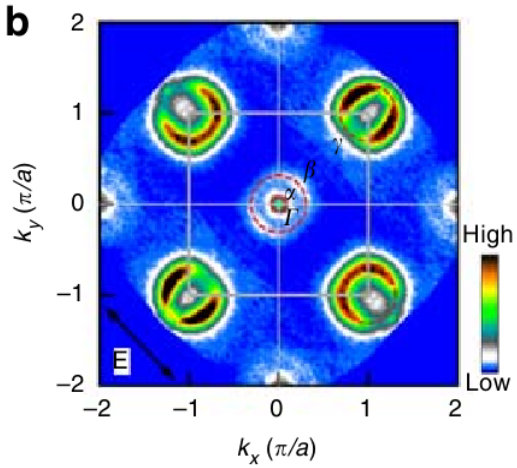

...see extra circle in center.

Brief review: Connecting Iron-based Superconductivity and Magnetism

Table 1 | Properties of different classes of superconductor

Property	Conventional superconductors	Copper oxides	MgB_2	Iron-based superconductors
T_c (maximum)	<30 K	134 K	39 K	56 K
Correlation effects	None (nearly-free electrons)	Strong local electronic interaction	None (nearly-free electrons)	Long-range (non-local) magnetic correlations
Relationship to magnetism	No magnetism	Parent compounds are magnetic insulators	No magnetism	Parent compounds are magnetic metals
Order parameter	One band, same-sign *s* wave	One band, sign-changing *d* wave	Two band, same-sign *s* wave	Two band, presumably sign-changing *s* wave
Pairing interaction	Electron–phonon	Probably magnetic (no consensus)	Electron–phonon	Presumably magnetic
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NATURE|Vol 464|11 March 2010|doi:10.1038/nature08914

Conventional superconductors: Electron-phonon interactions lead to Cooper pairing

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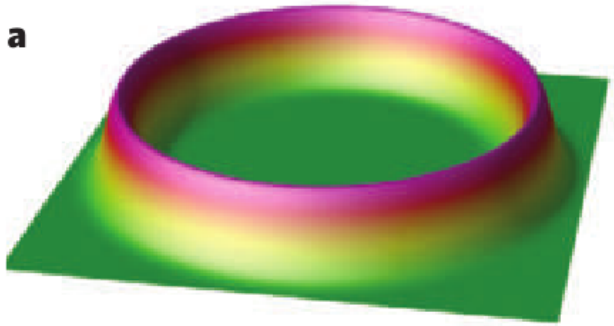
Conventional superconductors: Electron-phonon interactions lead to Cooper pairing

Unconventional superconductors: Antiferromagnetism suggests magnetic interactions are involved.

“Nesting picture” : magnetic interactions require a k-vector connecting parts of Fermi surface with opposite sign in order parameter.

Aforementioned Symmetries of the Fermi Surface and Order Parameter:



s-wave (conventional superconductivity)

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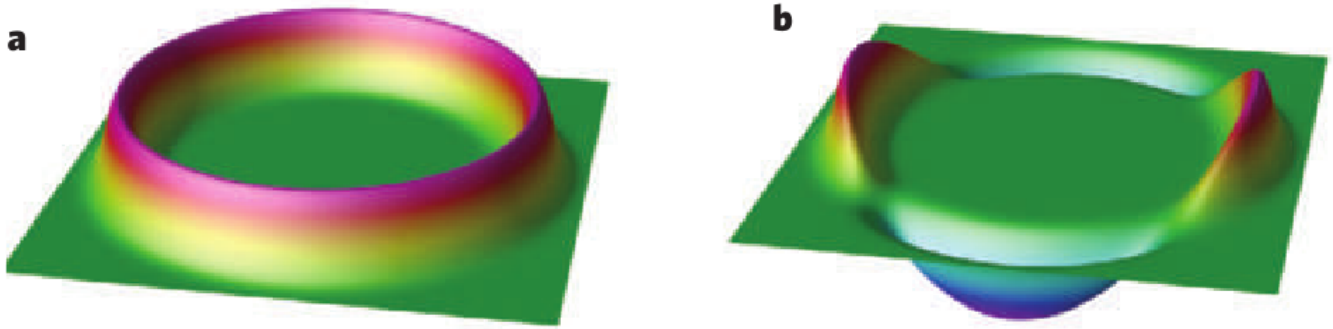

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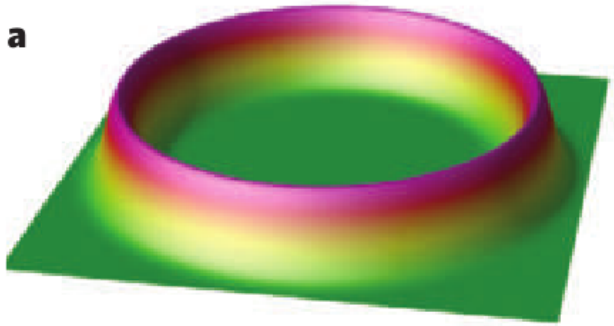

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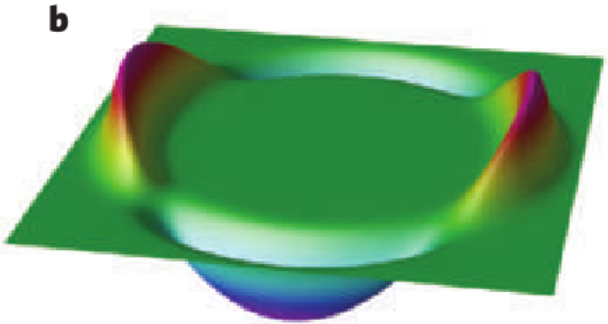

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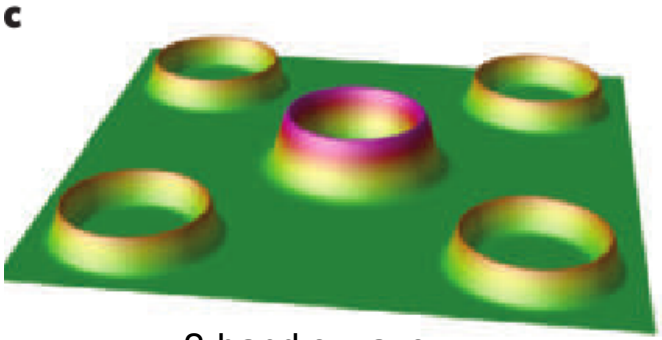

2-band s-wave

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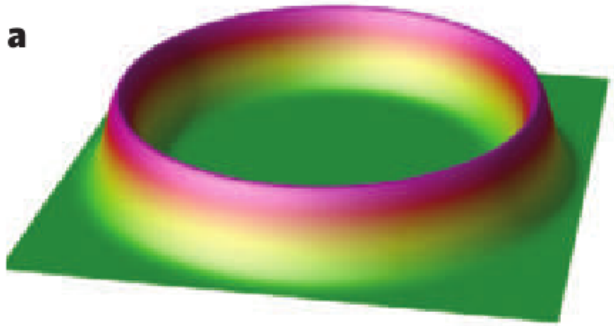

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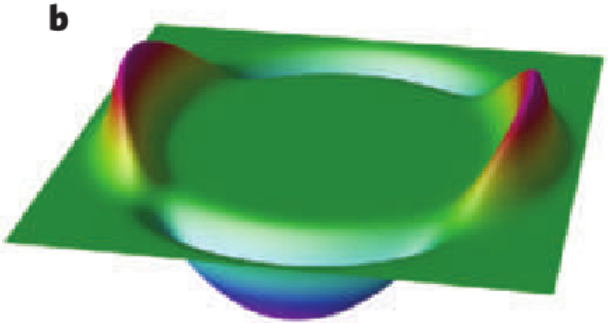
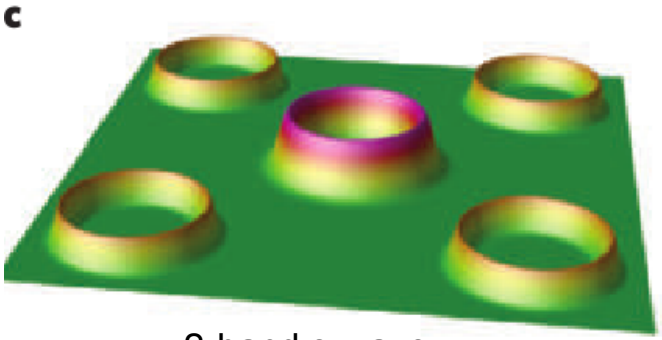


d-wave



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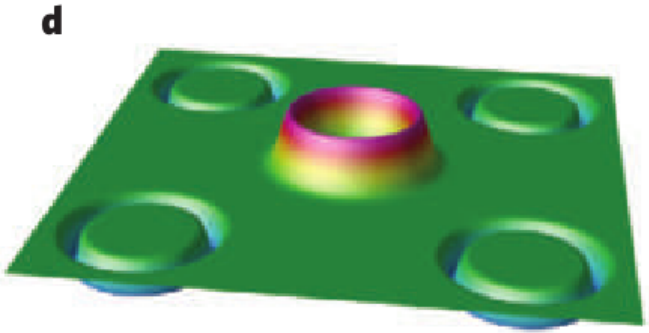

2-band s(+/-) -wave

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Of All the High-T_c Fe-based Superconductors, Why Study Monolayer FeSe?

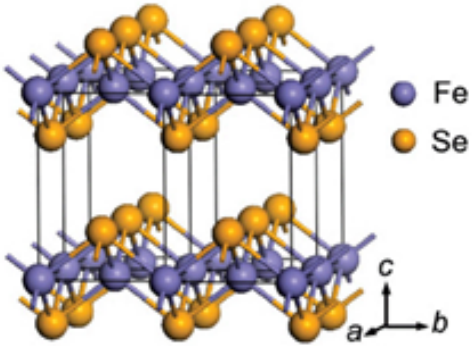


Image from Pnas.org

- Simple crystal structure: a single FeSe layer
- 2D electronic structure

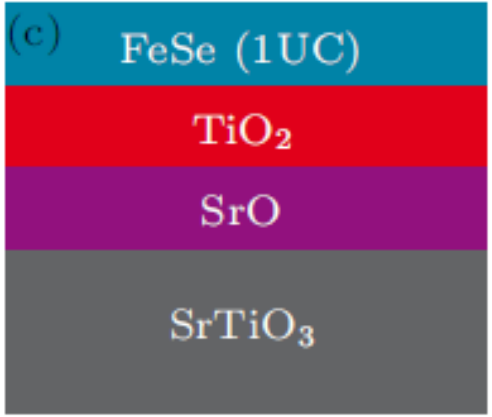
  ⟶ Entire 3D momentum space doesn't need to be probed

- Superconducting phase is pure, as opposed to $A_x Fe_{2-\gamma} Se_2$ superconductors which contain many coexisting phases.
- FeSe is a building block for Fe-based superconductors

Sample Preparation: Molecular Beam Epitaxy

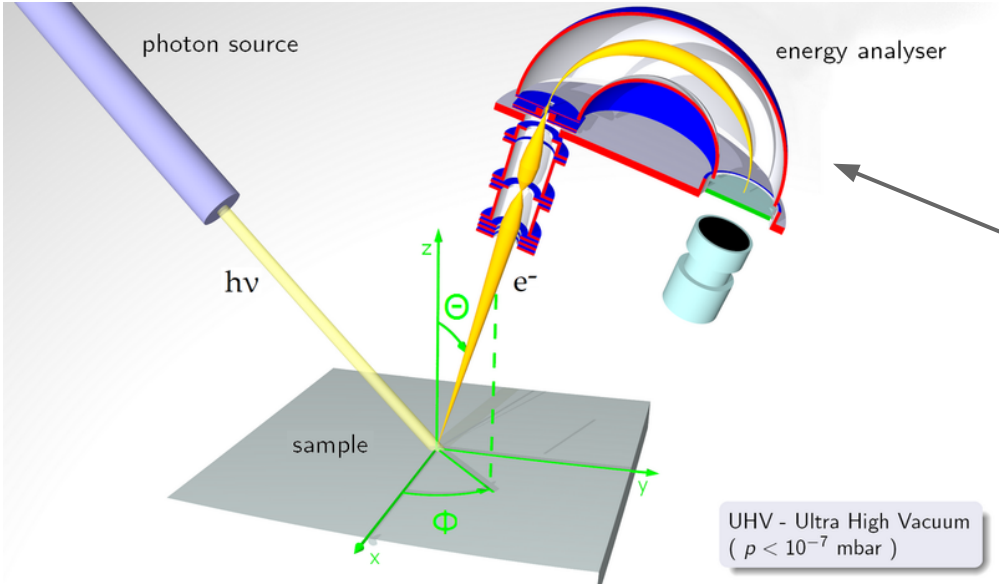
- The single-layer FeSe is grown on a STO substrate*
- Se molecular beam etching to produce an atomically smooth STO surface

STO:



*Wang, Q. Y. *et al. Chine. Phys. Lett.* **29**, 037402 (2012).

High-resolution Angle-Resolved Photoemission (ARPES) Measurements



Goal: measure energy and momentum of outgoing electron

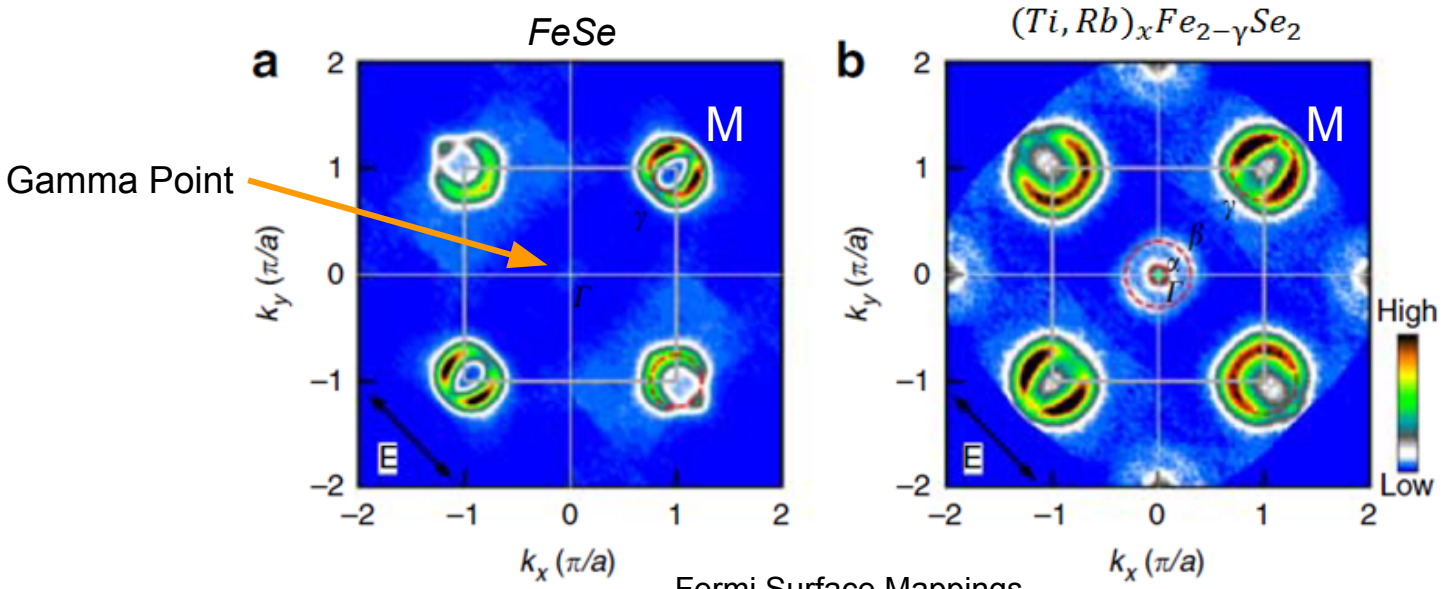
$$E = \hbar\omega - E_{k_f} - \phi.$$

$$\hbar k_{i\parallel} = \hbar k_{f\parallel} = \sqrt{2mE_f}\sin\theta$$

Image courtesy of Wikipedia

Distinguishing Features of Electronic Structure

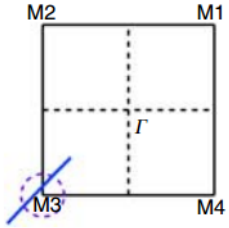
- Electron-like Fermi surface sheet around M
- Lacks a hole-like Fermi-surface around the gamma point
- Rules out 2-band s-wave order parameter symmetry: requires scattering between hole-like bands near gamma and electron-like bands near M

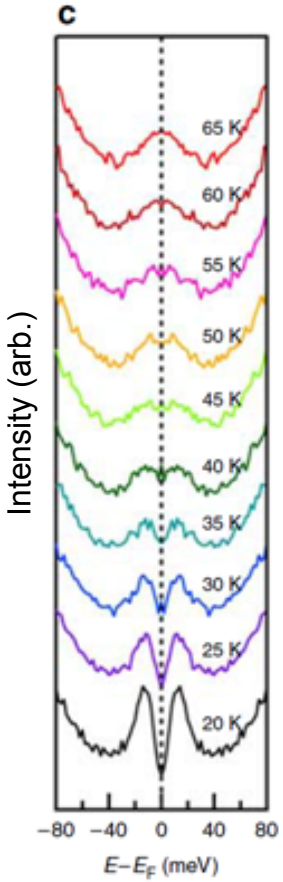


Fermi Surface Mappings

T_c Inferred From Measurement of the Superconducting Gap

- The superconducting gap is inferred from photoemission spectra along a cut at the M3 point.

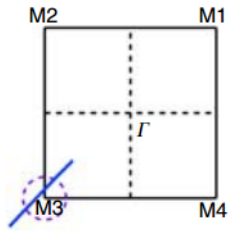


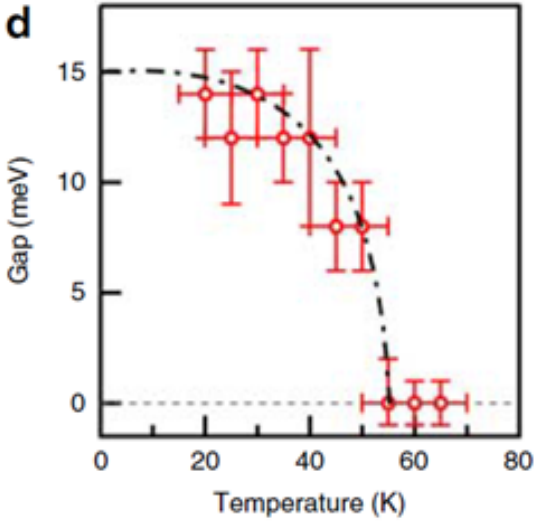


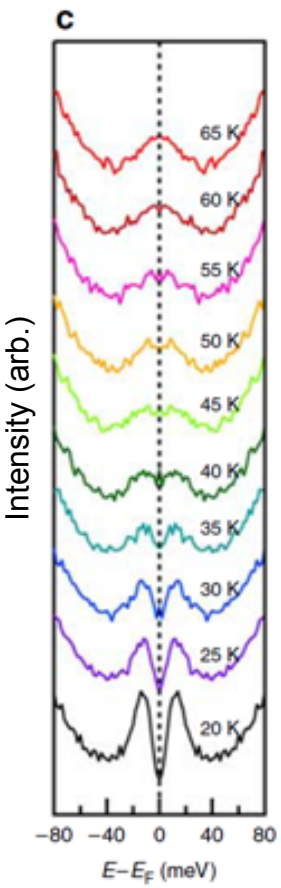
Symmetrized photoemission spectra

T_c Inferred From Measurement of the Superconducting Gap

- The superconducting gap is inferred from photoemission spectra along a cut at the M3 point.
- The gap size is measured to be ≈ 15 meV at 20K.
- Vanishing gap at high temperatures indicates $T_c = 55 \pm 5$ K



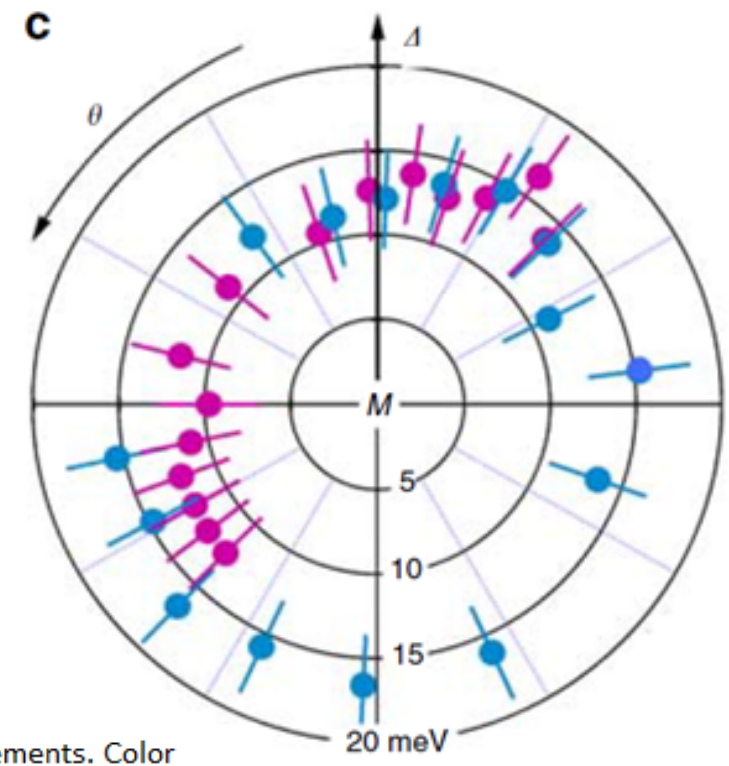




Symmetrized photoemission spectra

Evidence for a Nodeless Superconducting Gap

- Photoemission spectra are obtained for different momenta
  - Done independently for two samples
- The gap is nearly isotropic, indicating that there is no node
- Rules out d-wave order parameter symmetry



Superconducting gap measurements. Color corresponds to the sample measured.

Critique 1: T_c Cannot be Measured Directly

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- Superconducting gap closes at T_c for other Fe-based superconductors
  (PRL 106, 107001 (2011),
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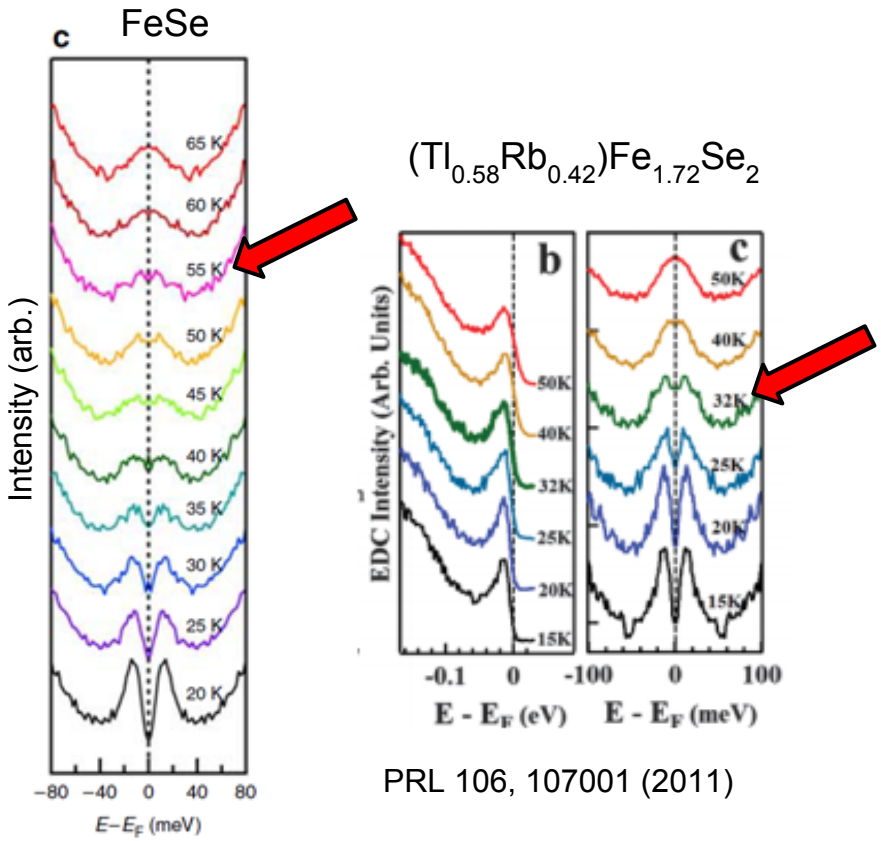

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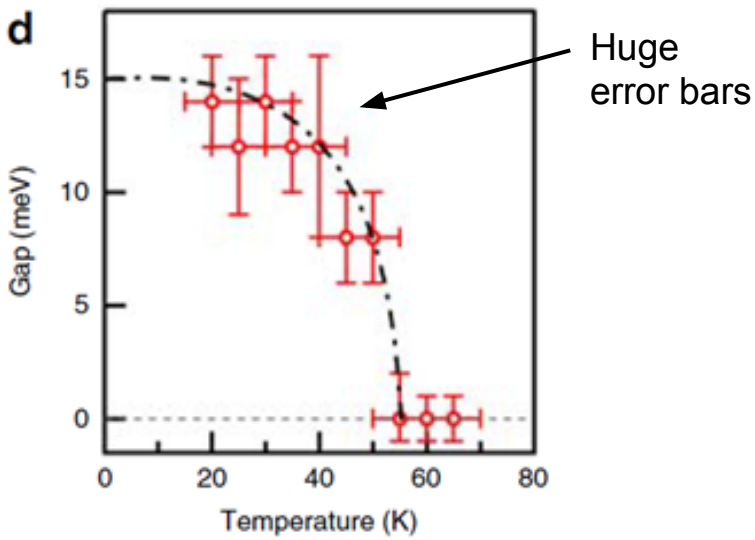

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$$= (15\ \text{meV}) \times \left(\frac{32\ \text{K}}{9.7\ \text{meV}}\right) \approx \boxed{50\ \text{K}}$$

Critique 2: Different Gap Sizes Measured

(13 ± 2 meV vs. 15 ± 2 meV)

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- Different post-annealing conditions could change the superconducting phase

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- Different post-annealing conditions could change the superconducting phase

- Both samples show no gap at Fermi surface (no effect on nodeless superconducting gap conclusion)

Critique 3:
Lack of a Two-Gap Structure Disagrees with Previous Tunneling Measurements*

*Wang, Q. Y. *et al. Chine. Phys. Lett.* **29**, 037402 (2012).

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Lack of a Two-Gap Structure Disagrees with Previous Tunneling Measurements*

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Lack of a Two-Gap Structure Disagrees with Previous Tunneling Measurements*

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  - No signature of a 2D electron gas in the interface

- How does annealing to substrate change FeSe structure?
  - Lattice mismatch may cause strain which increases superconductivity

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Critique 4: Style of the Paper

- The authors do address potential points of controversy well

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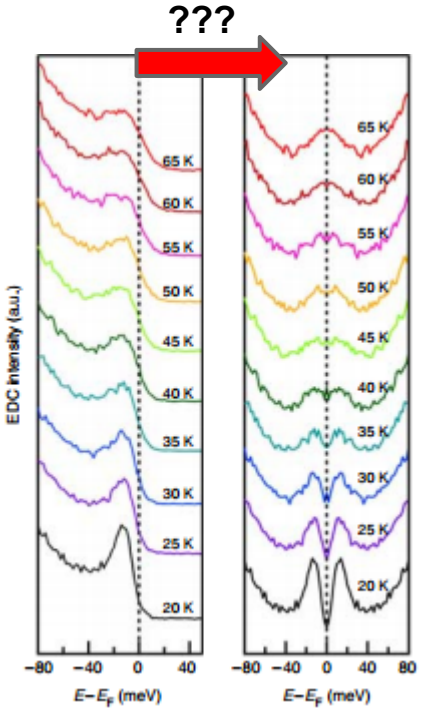
- Figure descriptions could be too brief for a non-expert audience
  - Example: missing a reference to explain symmetrized data



Critique 4: Style of the Paper

- The authors do address potential points of controversy well

- Figure descriptions could be too brief for a non-expert audience
  - Example: missing a reference to explain symmetrized data

Image from www.fdjtool.com

- Grammar
  - “They will shed lights on understanding the superconductivity mechanism and exploring new superconductors with higher T_c in the Fe-based superconductors.” (DOI: 10.1038/ncomms1946)

Paper Conclusions

- Single-layer FeSe has a much simpler structure, but is likely to have one of highest T_c 's of the Fe-based superconductors

- Measurements show lack of a hole-like Fermi surface at gamma point and a nodeless, isotropic superconducting gap

- Current theories for the superconducting mechanism need to be modified to describe all the results presented in this paper

Citation Analysis

- Since publication in July 2012, the paper has been cited
  - 17 times (Google Scholar)
  - 16 times (Scopus)

- Because FeSe has the simplest crystal structure of the Fe-based superconductors discovered so far, it is considered to be the essential building block for superconductivity in the Fe-based compounds. As such, the paper has been applied and cited by both theoretical and experimental groups.

Theory

“S_4 Symmetric Microscopic Model for Iron-Based Superconductors”, “Mechanism for Odd Parity Superconductivity in Iron-Based Superconductors” :Jiangping Hu, Ningning Hao et al

The more recent paper in Nature **“Superconductivity: Fewer atoms, more information”** : Sergey Borisenko, talks about how monolayer FeSe might be an ideal model system for testing theoretical ideas.

Experiment

“**Superconductivity and magnetism in 11-structure iron chalcogenides in relation to the iron pnictides**” : David Joseph Singh

“Single crystal growth and characterization of tetragonal $FeSe_{1-x}$ superconductors” :Dmitriy Chareev et al.

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Thank you for listening!