Title: New Superconductors

Date: Nov 26, 2008 02:00 PM

URL: http://pirsa.org/08110002

Abstract: The discovery and understanding of superconductivity has provided important paradigms for physics, including spontaneous gauge symmetry breaking and the Anderson-Higgs mechanism. More recent discoveries in superconductivity have given us examples of doped Mott insulators, still an unsolved theoretical problem, as well as superconductors which spontaneously break time reversal symmetry and which support Majorana fermions and non-Abelian statistics. The latter are of potential interest to quantum computing. This talk will review our current understanding of, and the open issues related to, these new supercondutors, including the high T_c cuprates, iron pnictides, and strontium ruthenate.

New Superconductors

Catherine Kallin

McMaster University

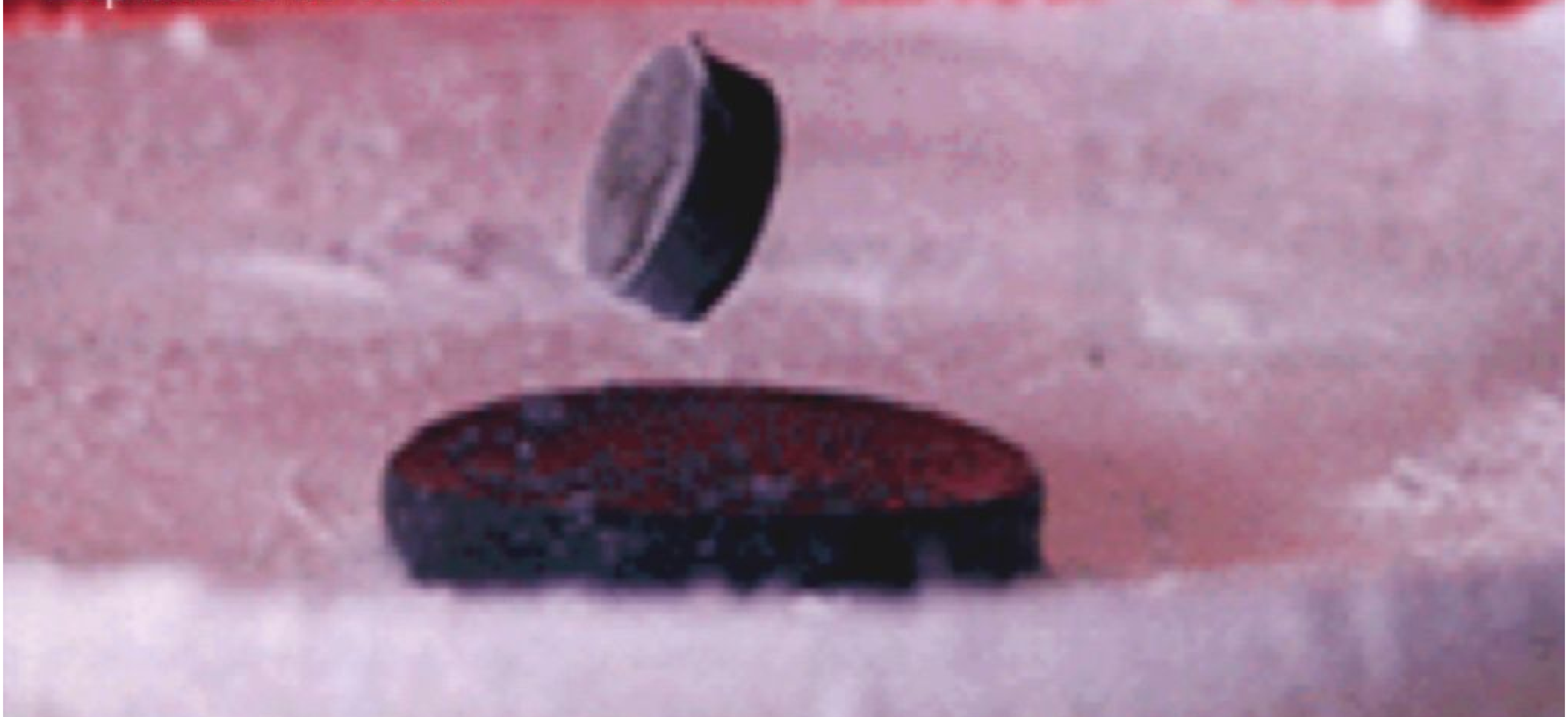
Perimeter Institute, November 2008

Outline

- Brief introduction to Superconductivity
- High T_c cuprates
- Iron superconductors
- Superconductors with spontaneous TRSB

Superconductivity

Superconductor: perfect conductivity and diamagnetism
Discovered in 1911 in Hg by Kamerlingh Onnes
Explained in 1957



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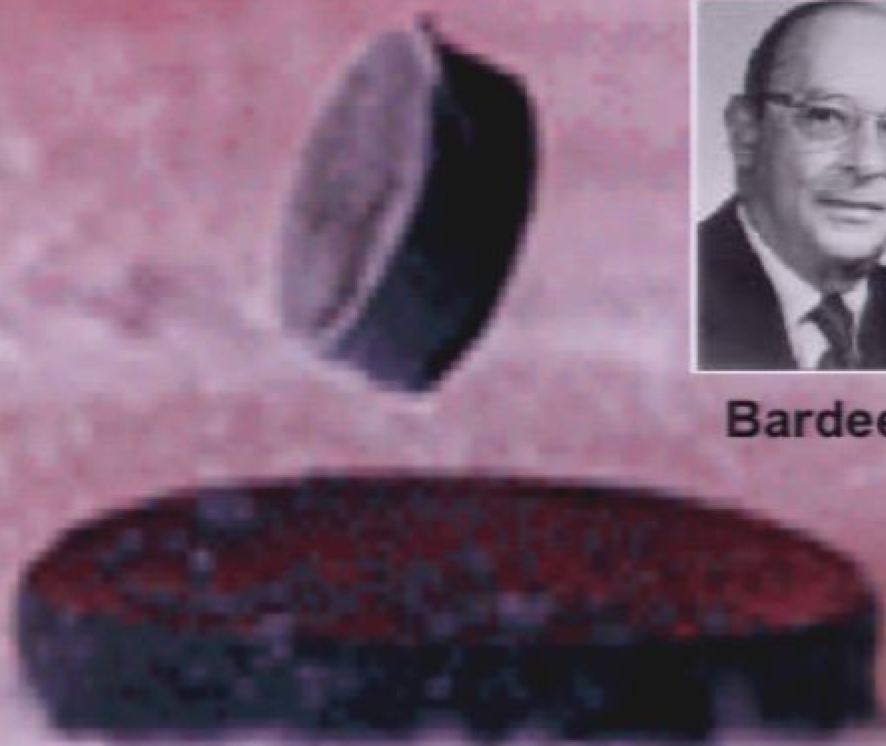

Bardeen Cooper Schrieffer

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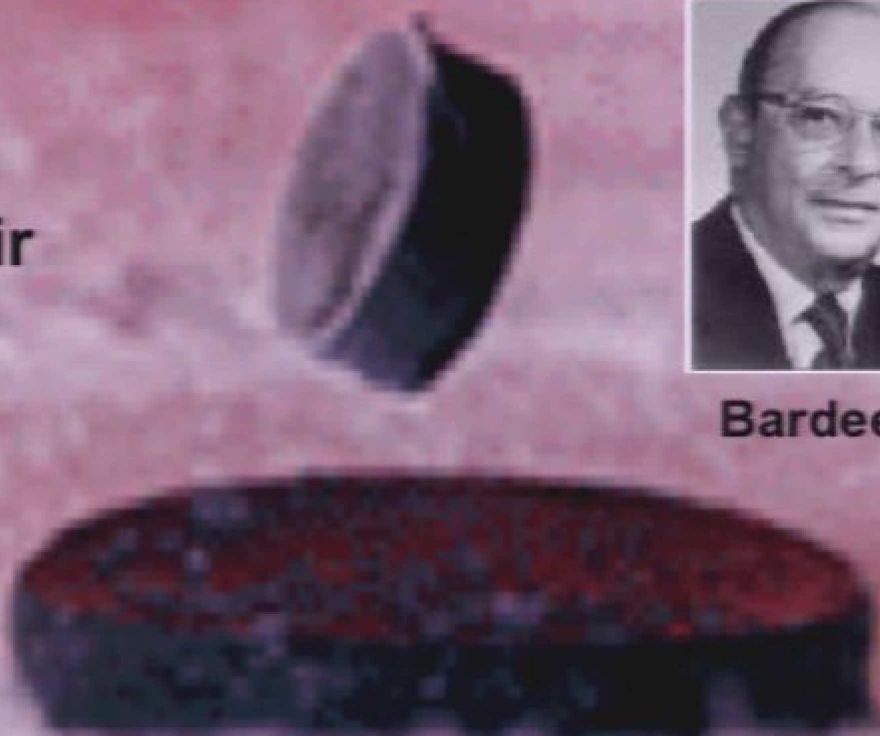
Electrons pair



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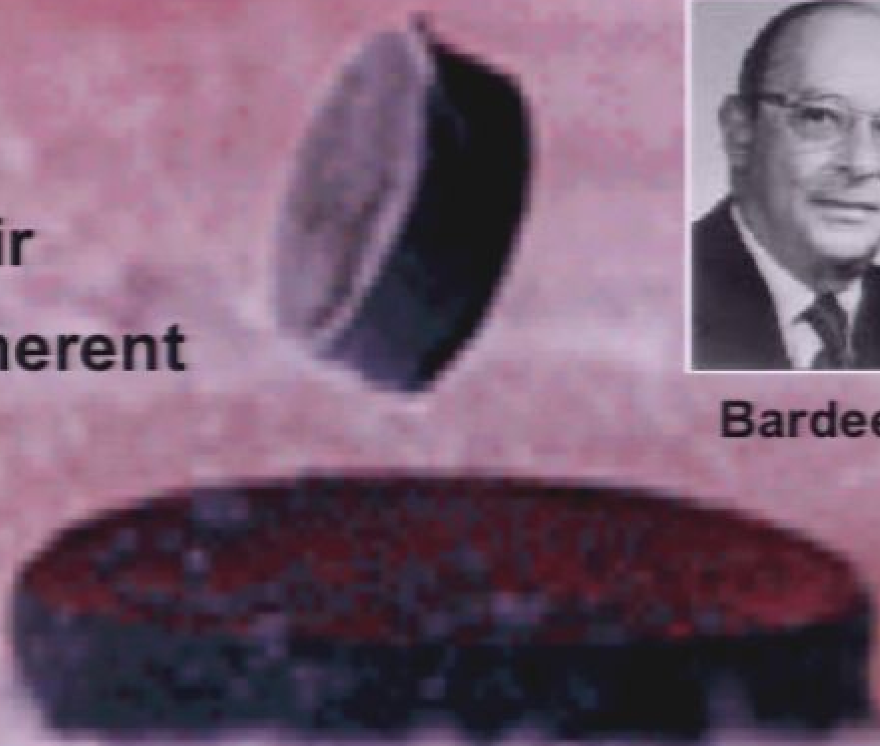
Pairs are coherent



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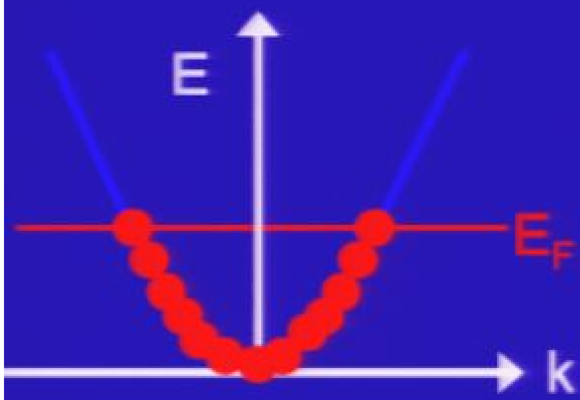
Superconductivity is described by an order parameter which measures the fraction of coherent pairs. Same phase for all Cooper pairs: $\langle \psi_{\uparrow}(r)\psi_{\downarrow}(r) \rangle$

Superconductivity & SSB

Two major paradigms of condensed matter physics:

- Fermi liquid theory



Fermi surface obeying Luttinger's theorem
states enclosed unchanged by interactions.

Quasiparticles with same charge/spin.

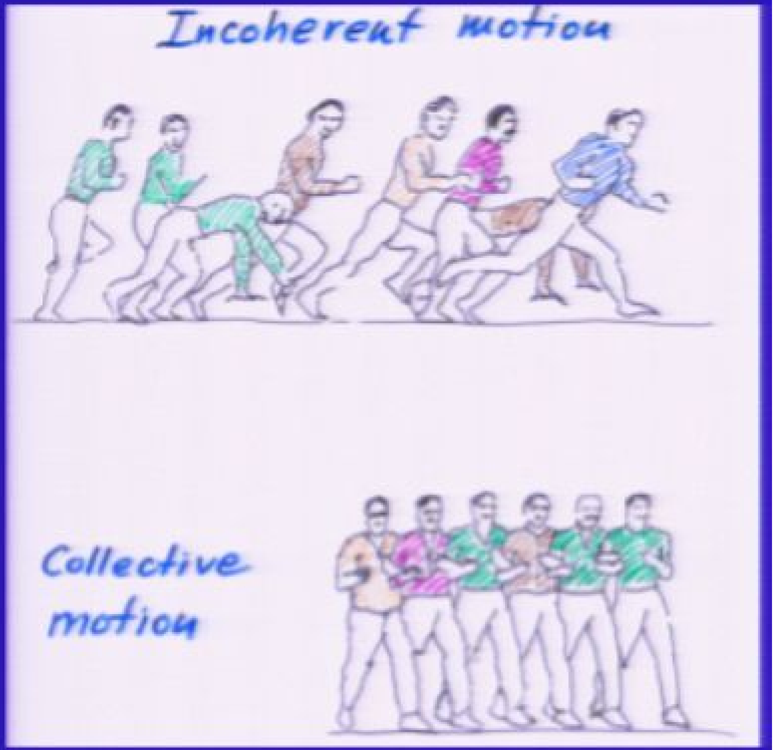
- Spontaneous Symmetry Breaking

- local order parameter (e.g. $\langle \mathbf{m}_i \rangle$ for a ferromagnet)
- Goldstone mode (if continuous symmetry broken, e.g. spinwaves)
- examples: solids, charge and spin order

Superconductivity

Superconductivity fit into SSB with "broken gauge symmetry" → phase coherence, order parameter $\langle \psi_{\uparrow}(r)\psi_{\downarrow}(r) \rangle$.

No Goldstone mode due to Higgs mechanism.
[Analogous to E-W symmetry breaking]



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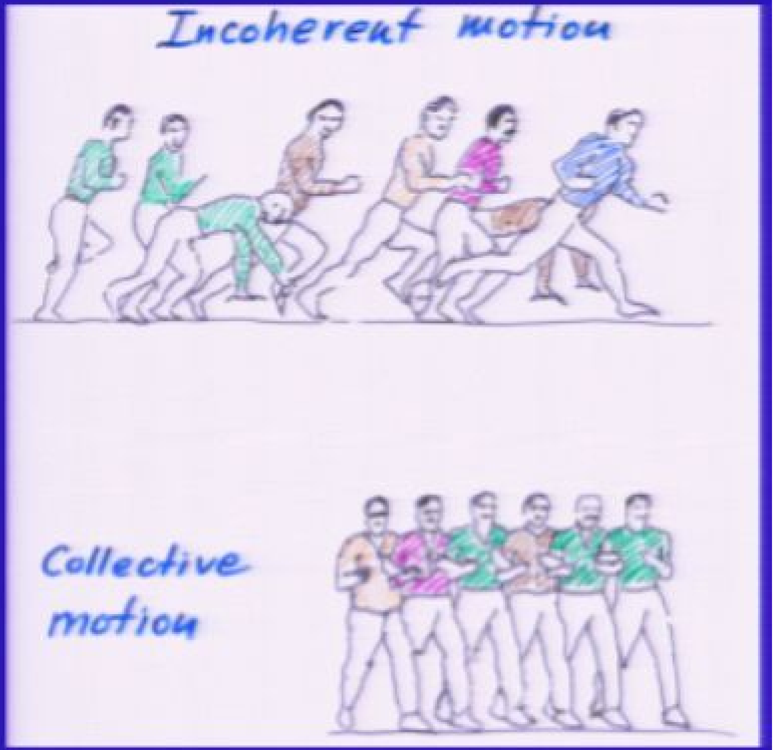
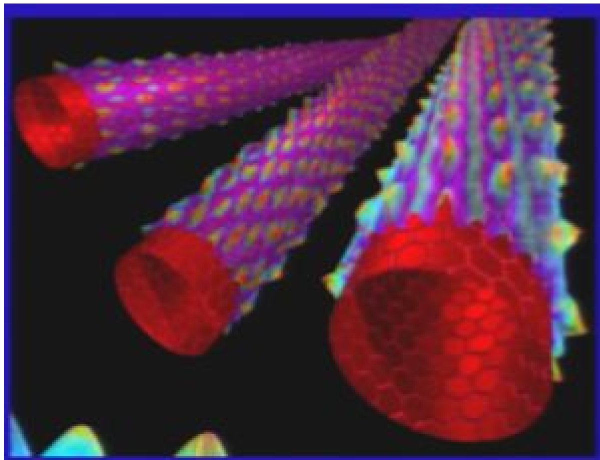


Much of CM in last two decades focused on materials and models exhibiting states which do not fit into the paradigms of spontaneous symmetry breaking or Fermi liquids – particularly those with topological order

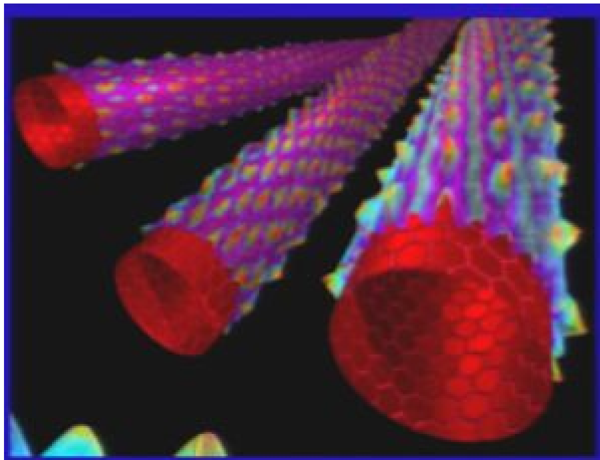


Topological Order

In 1d, FLT breaks down and SSB order destroyed by quantum fluctuations.

d>1: require strong interactions, frustration, degeneracy or nontrivial band structure to stabilize states with topological order. E.g. quantum Hall states.

- no local order parameter, but a quantum order (Wen)
- gs degeneracy which depends on topology
- edge states in finite geometry
- exhibit fractionalization (e.g. spin-charge separation)



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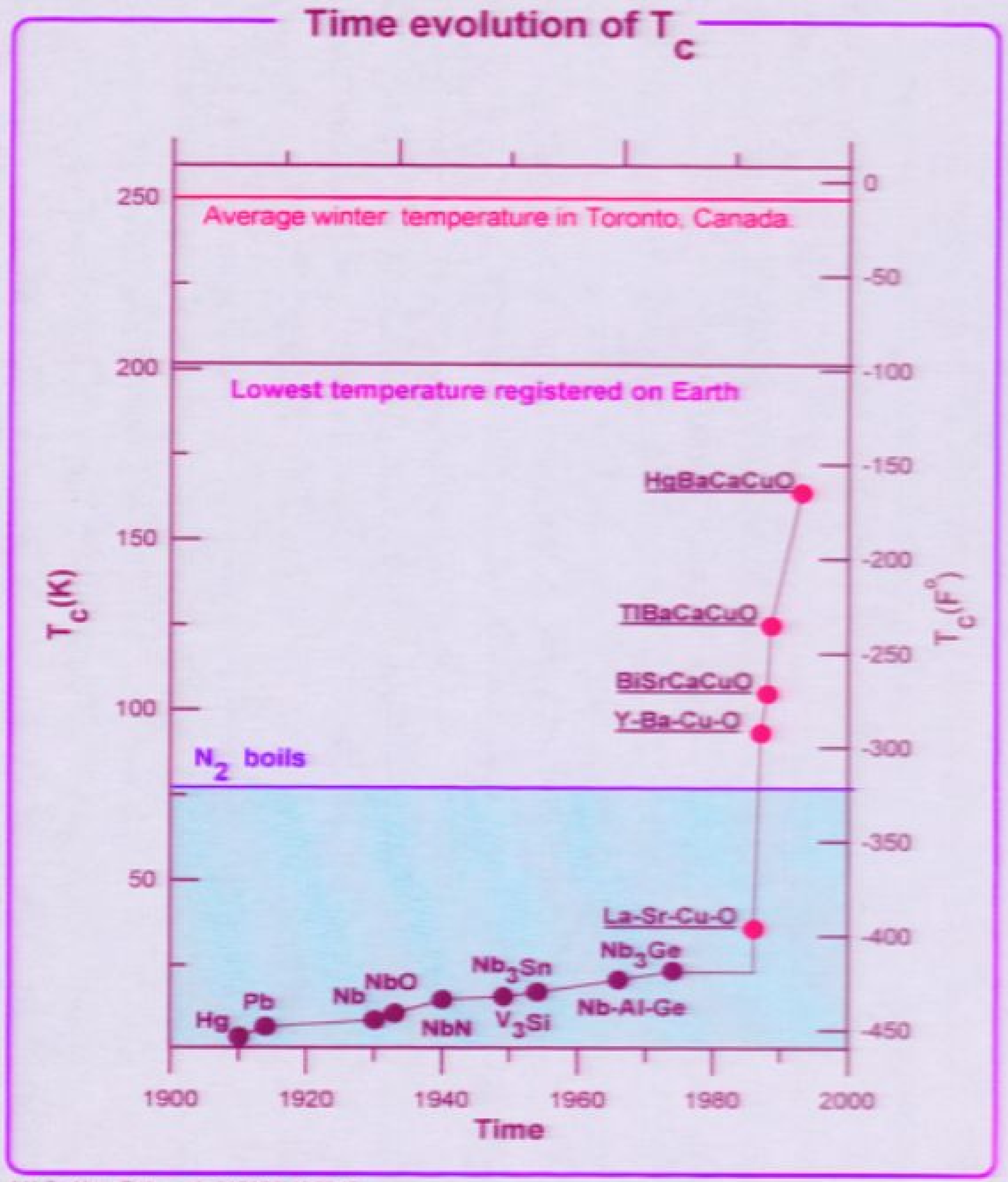
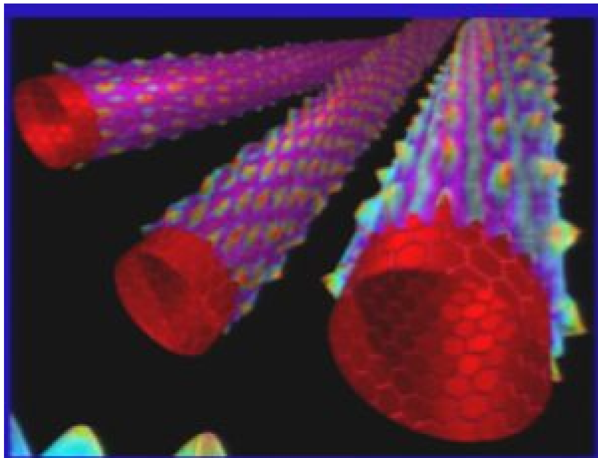
Superconductivity now understood as example of topological order, with (gapped) edge states, spin-charge separation.
[T. H. Hansson, V. Oganesyan, S. L. Sondhi, 2004.]



High Temperature Superconductivity in the Cuprates

High transition temperatures

Strong electron correlations



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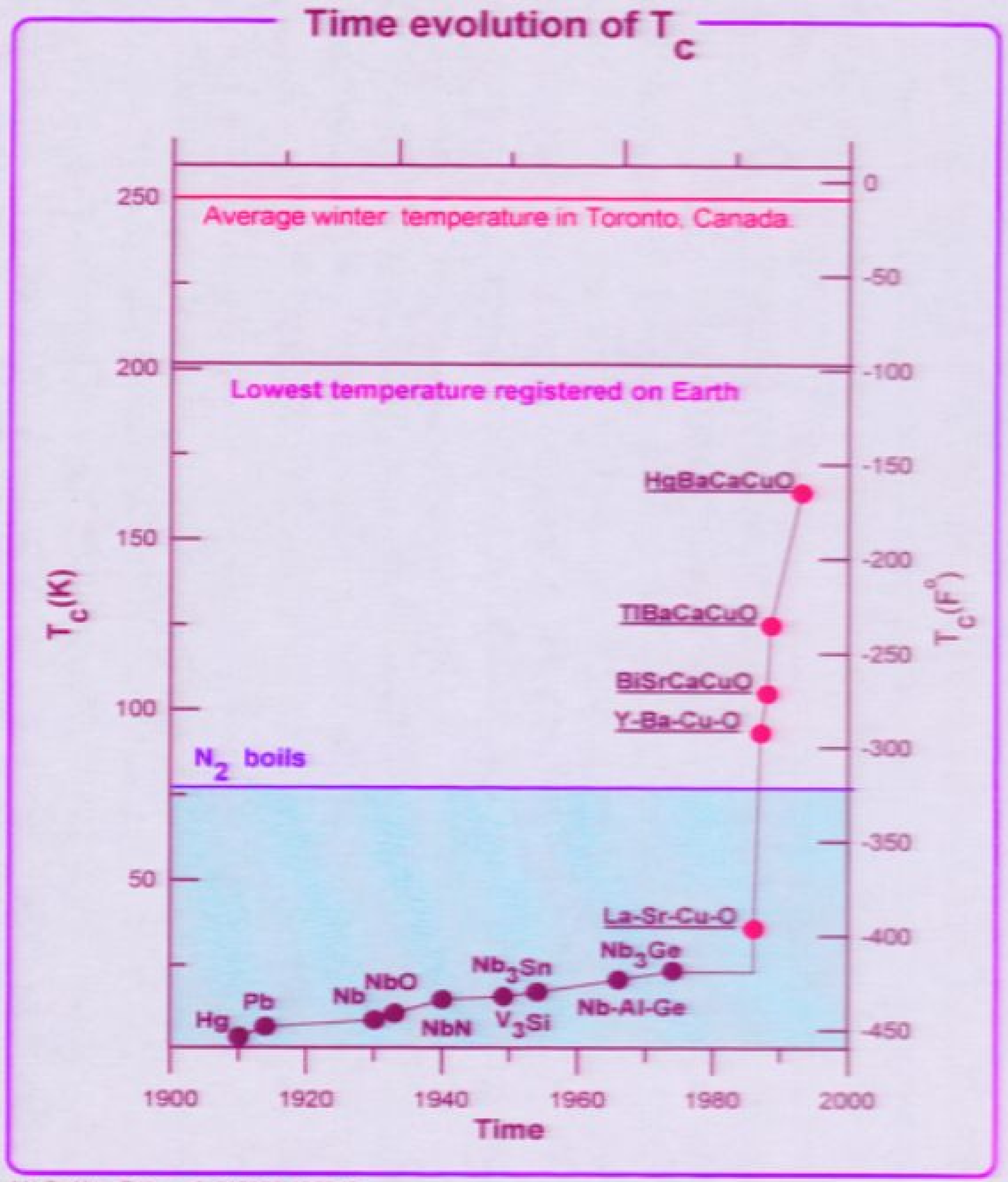

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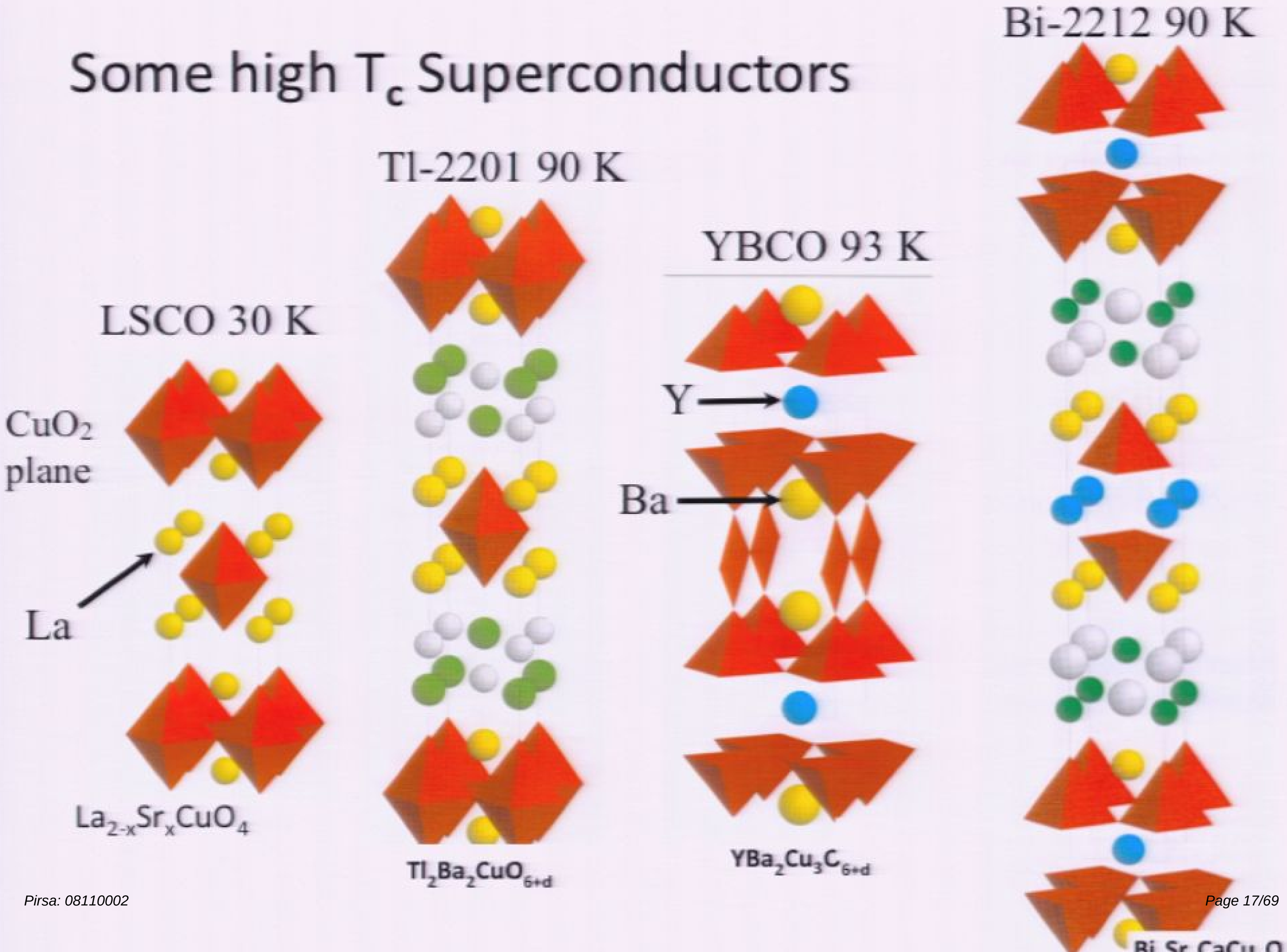
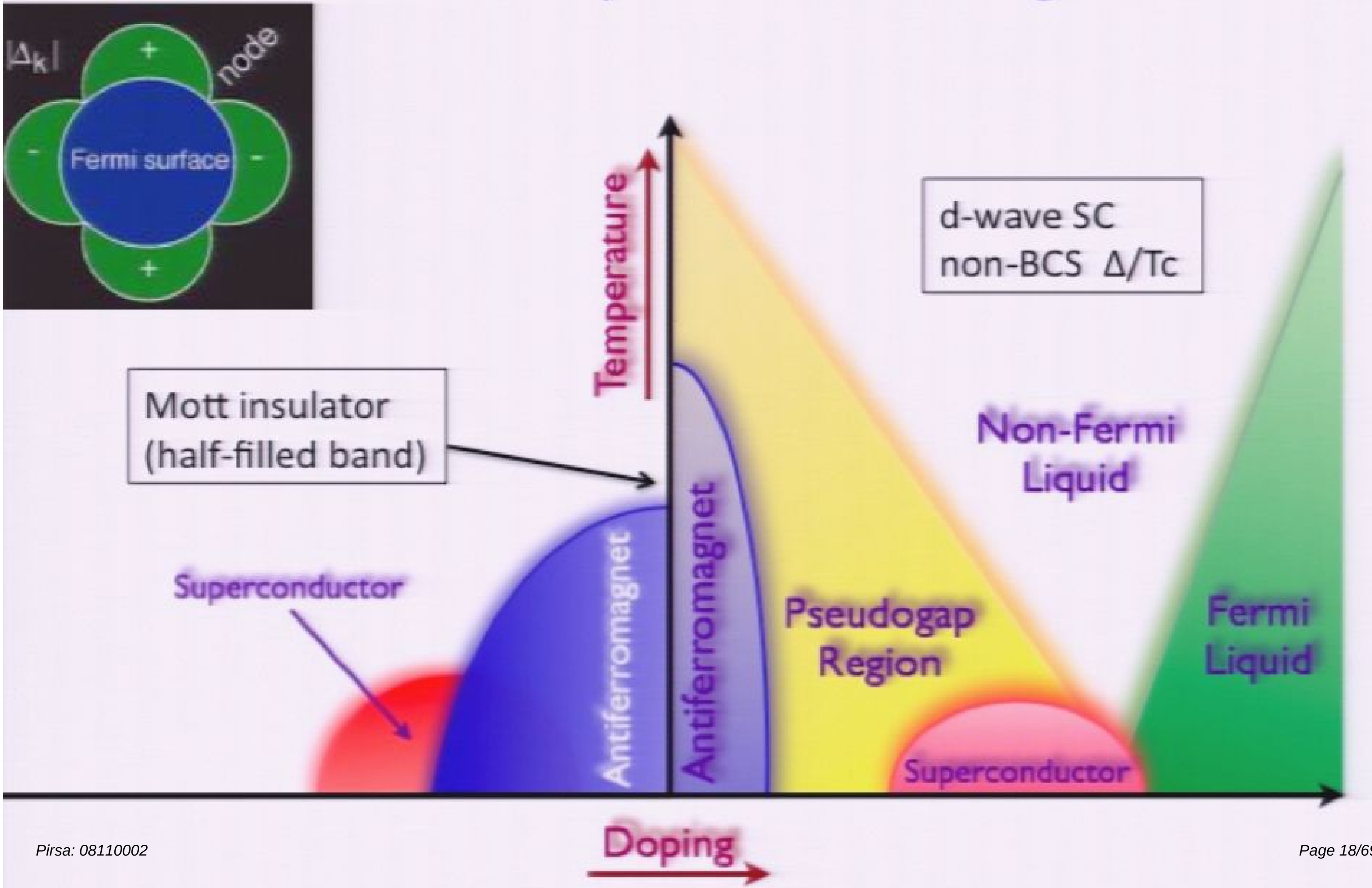
Some high T_c Superconductors



Generic Cuprate Phase Diagram



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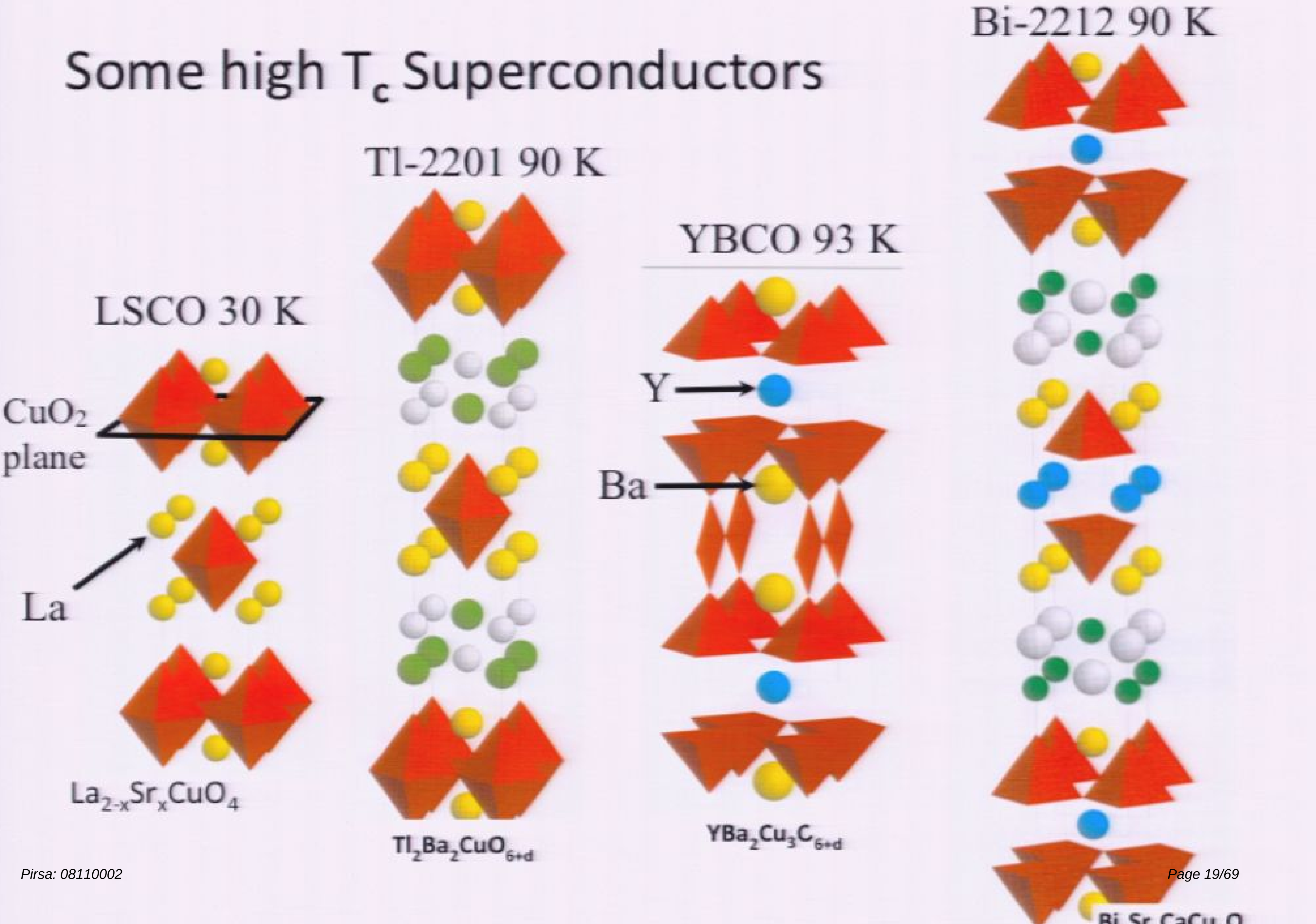

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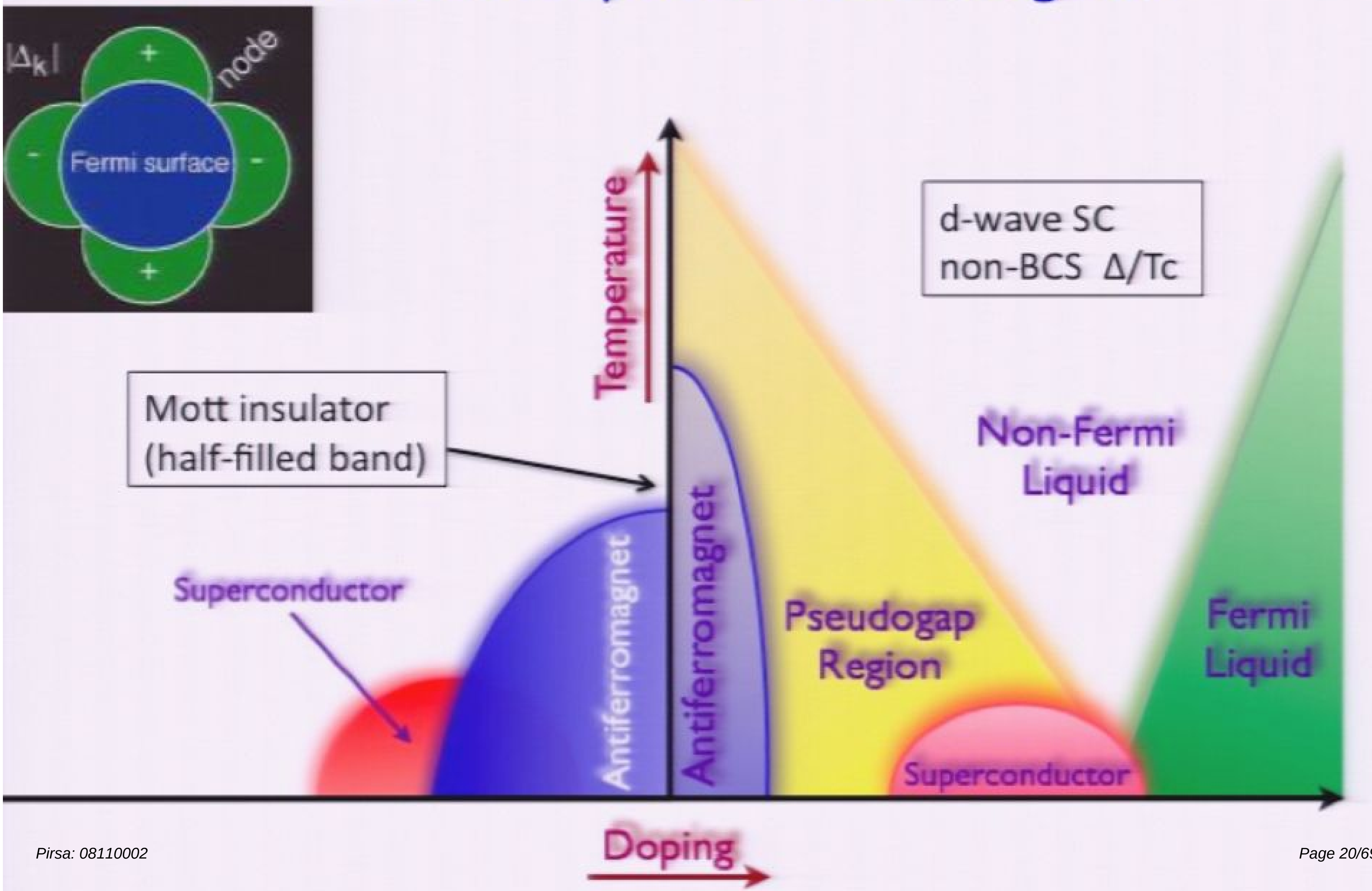

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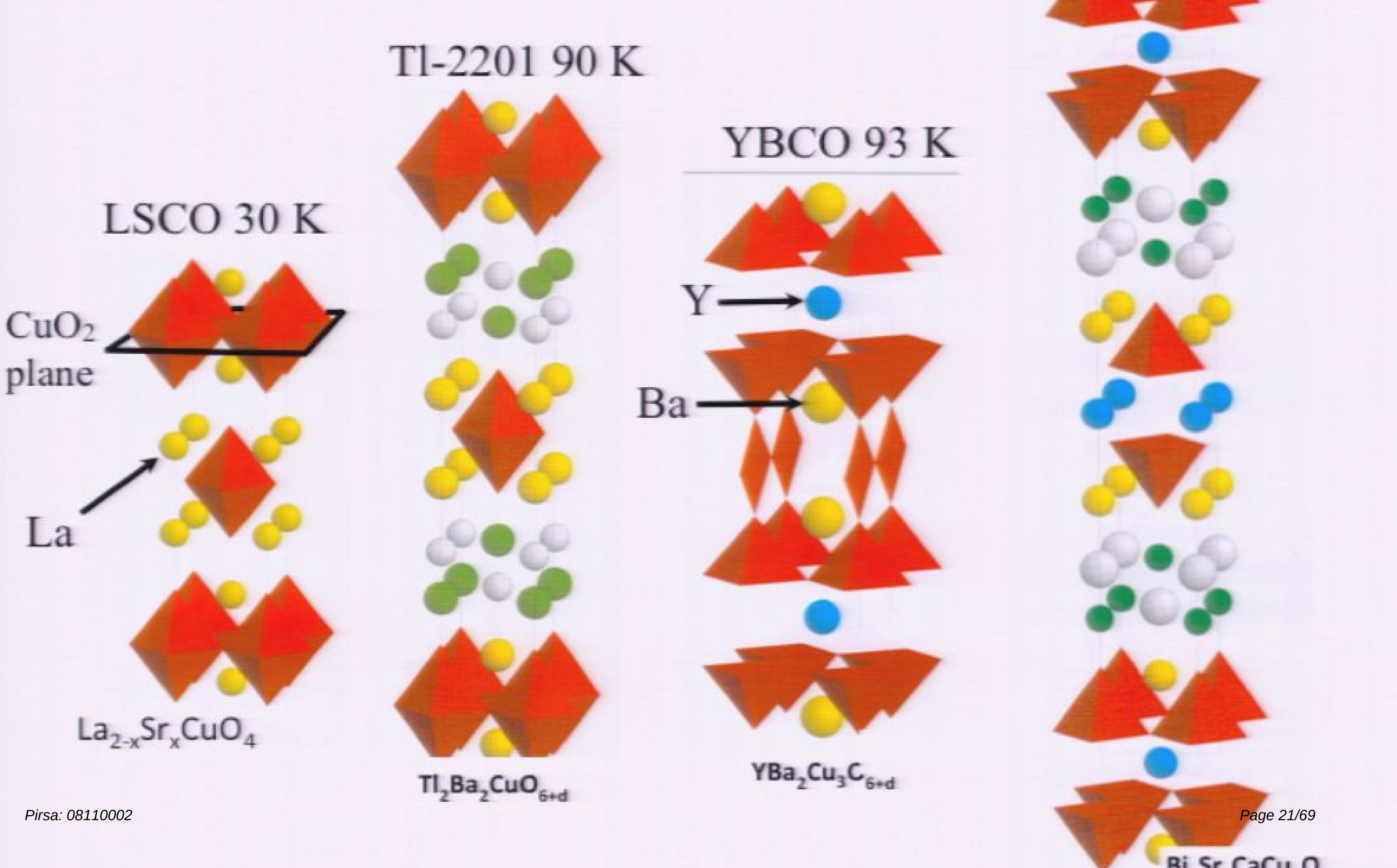

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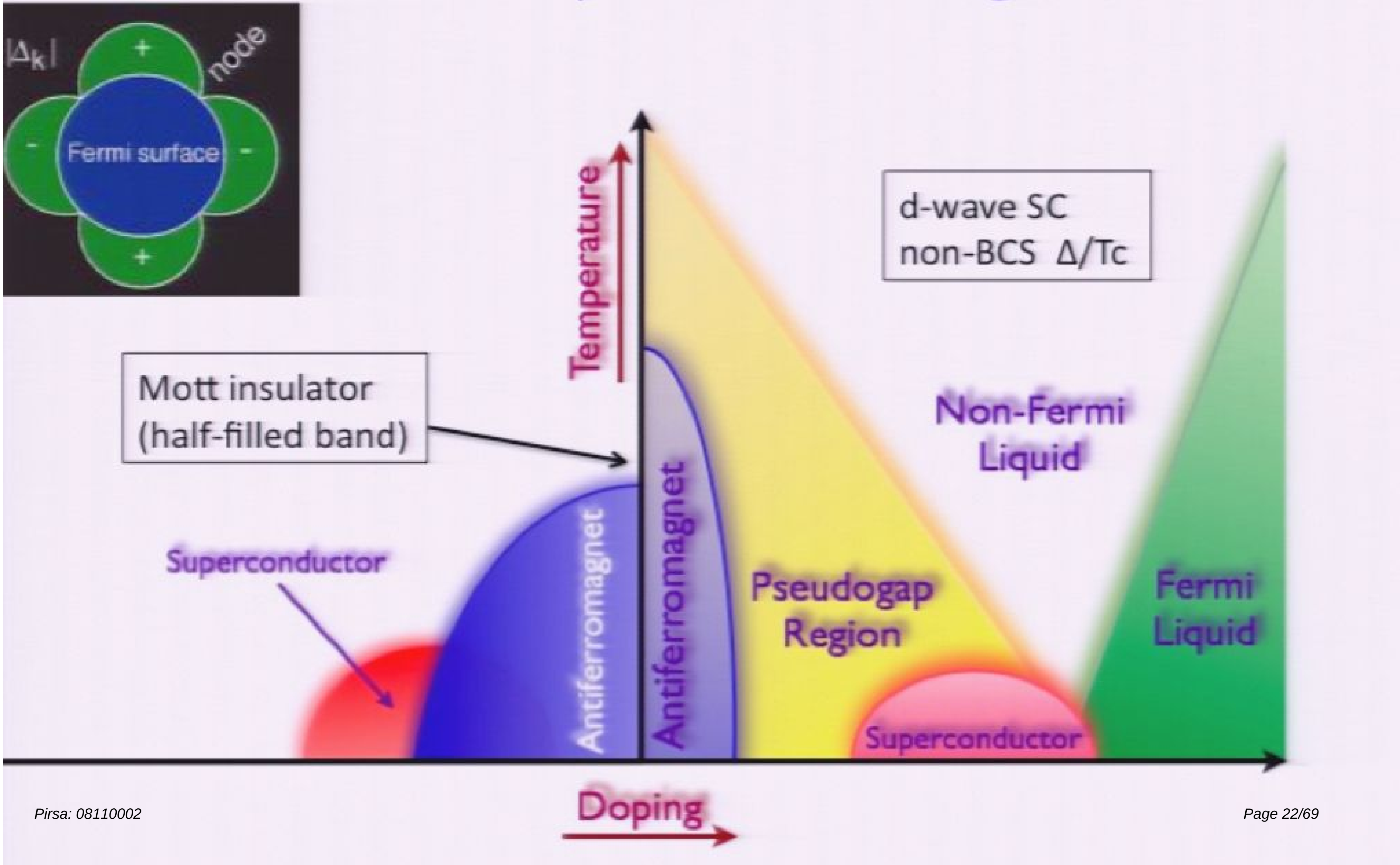
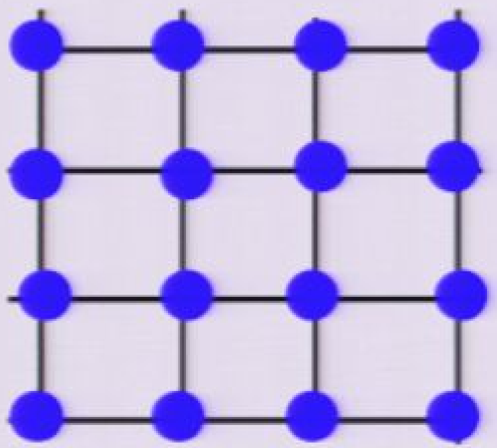


Mott insulator



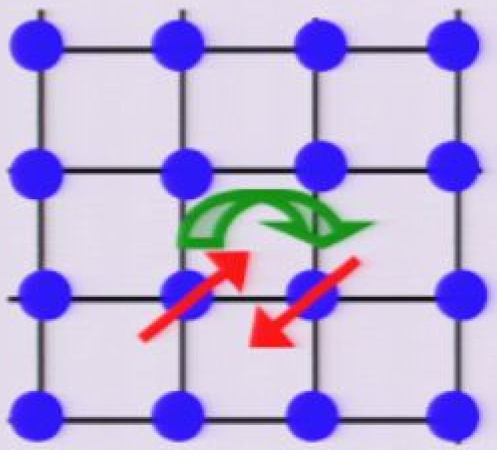
1 electron per site → band theory would predict a metal (half filled band)

large onsite Coulomb energy U → electrons can't move → Mott insulator with charge gap U

$$\boxed{H = t\sum_{i\delta\sigma} c^{+}_{i\sigma} c_{i+\delta,\sigma} + U\sum_{i} n_{i\uparrow} n_{i\downarrow}}$$

Doped Mott Insulator

Mott insulator



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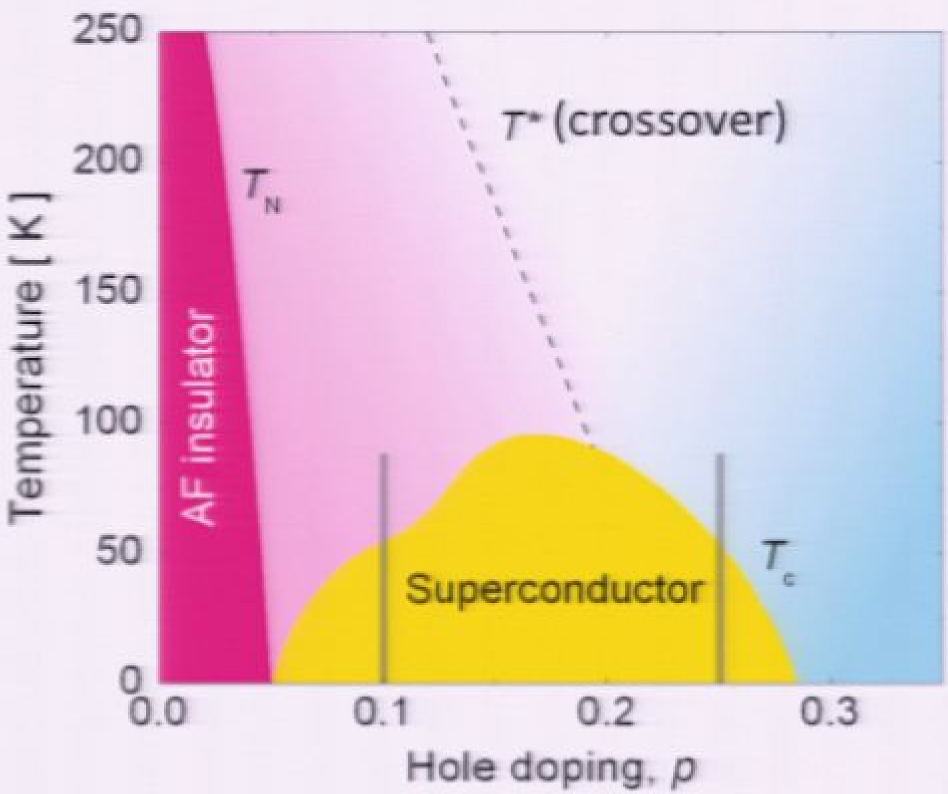
Doped Mott Insulator

Goal: Explain all universal properties in the insulating, pseudogap and superconducting phases within a single theory which can make verifiable predictions.



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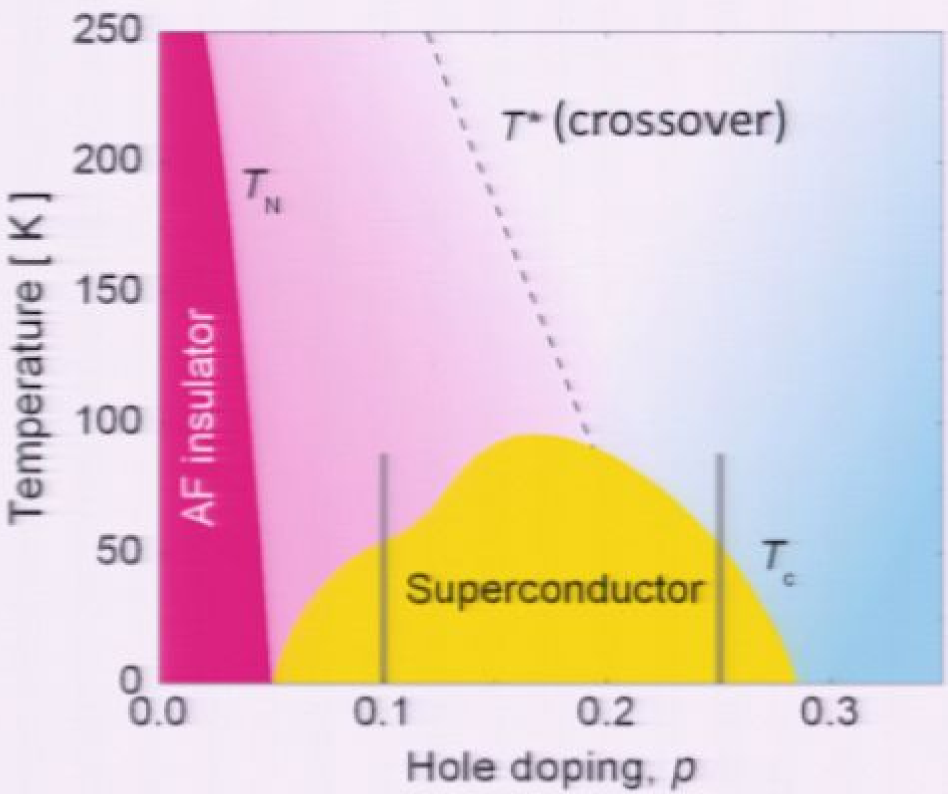
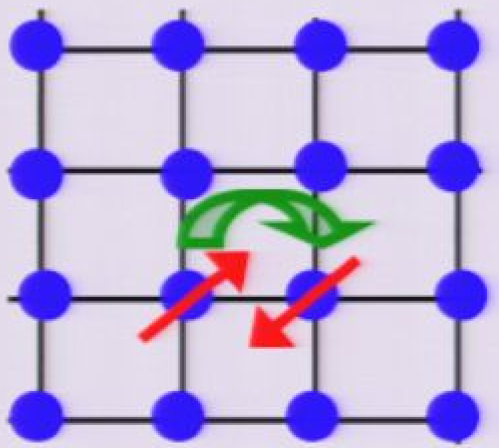


Pseudogap: Key as it connects AF and d-SC phases and exists over wide temperature and doping region. Problem of doped Mott insulator.

- Preformed pairs
- AF and/or SC fluctuations
- Stripes and fluctuations
- DDW, Π-flux
- orbital currents ....

Mott insulator



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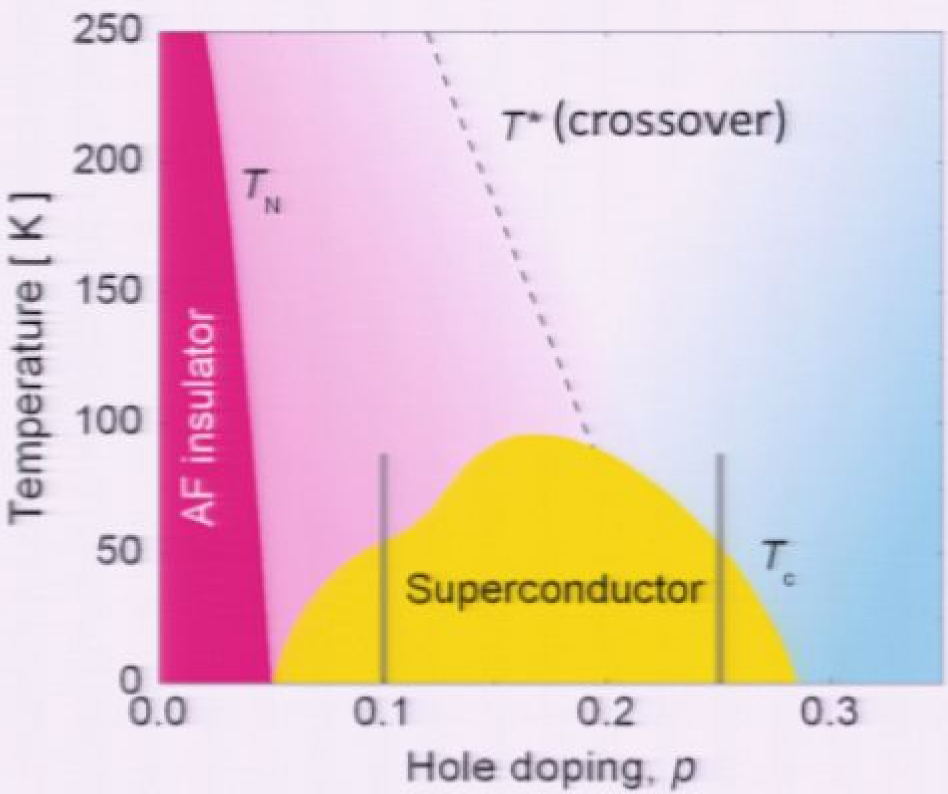

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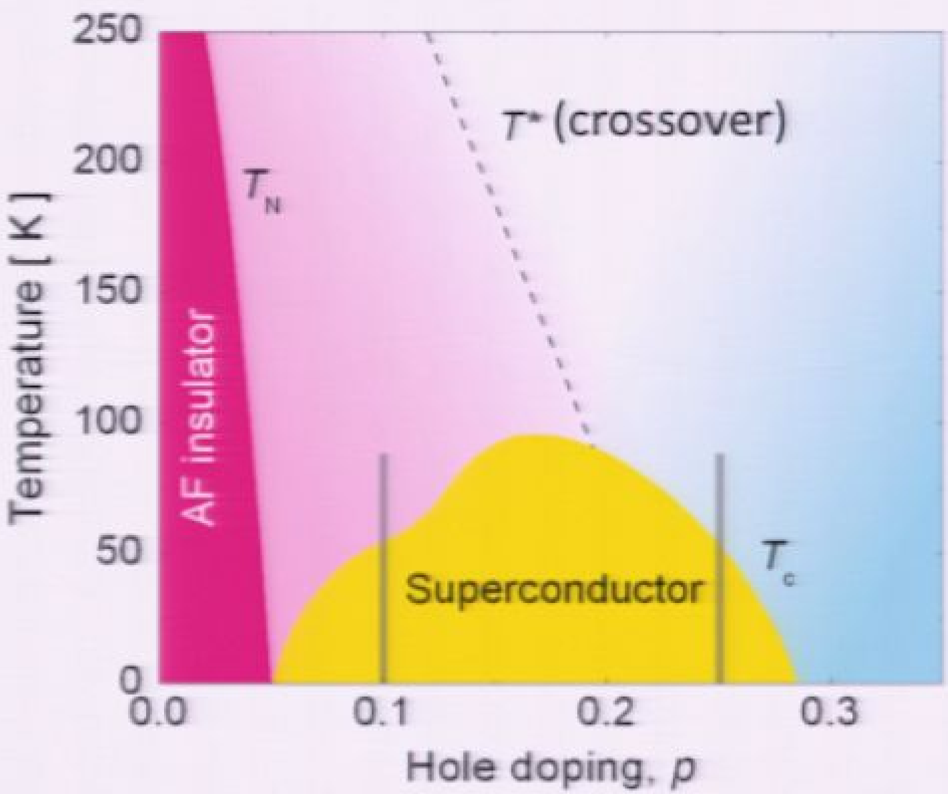

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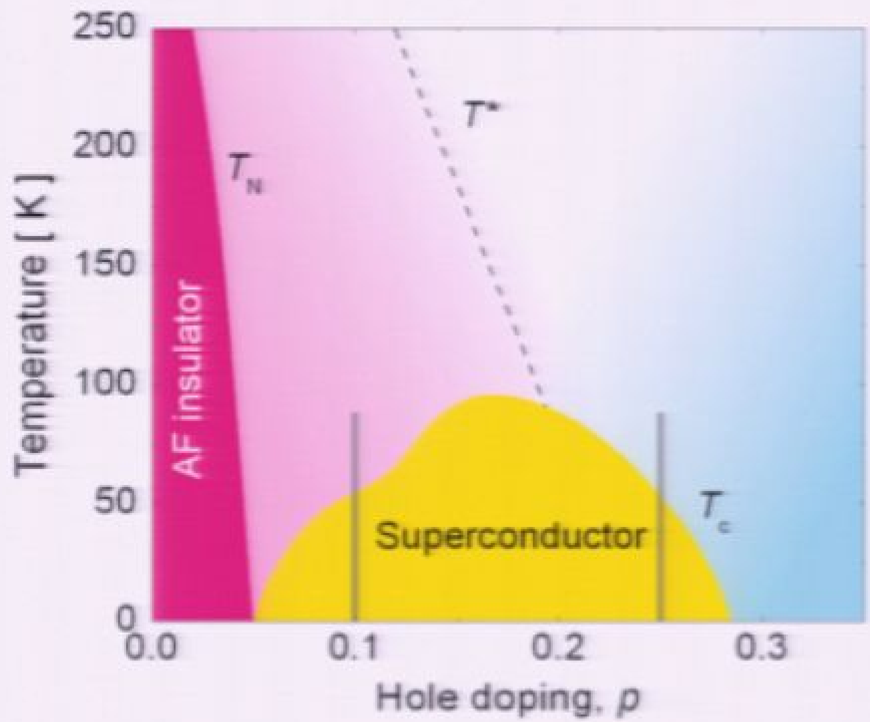

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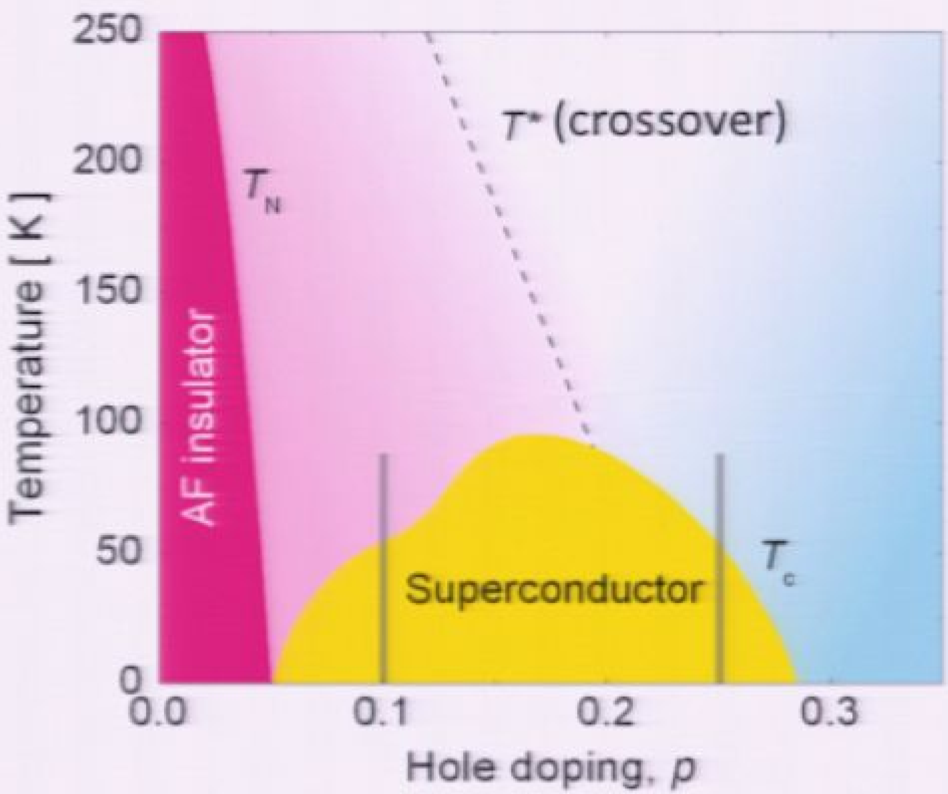

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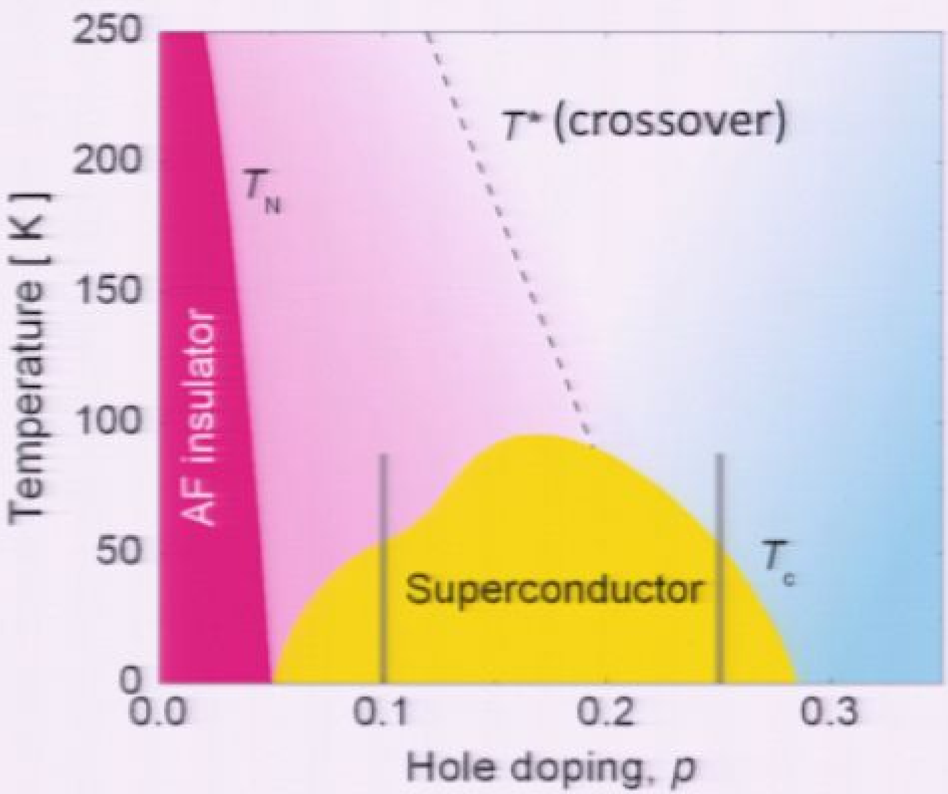

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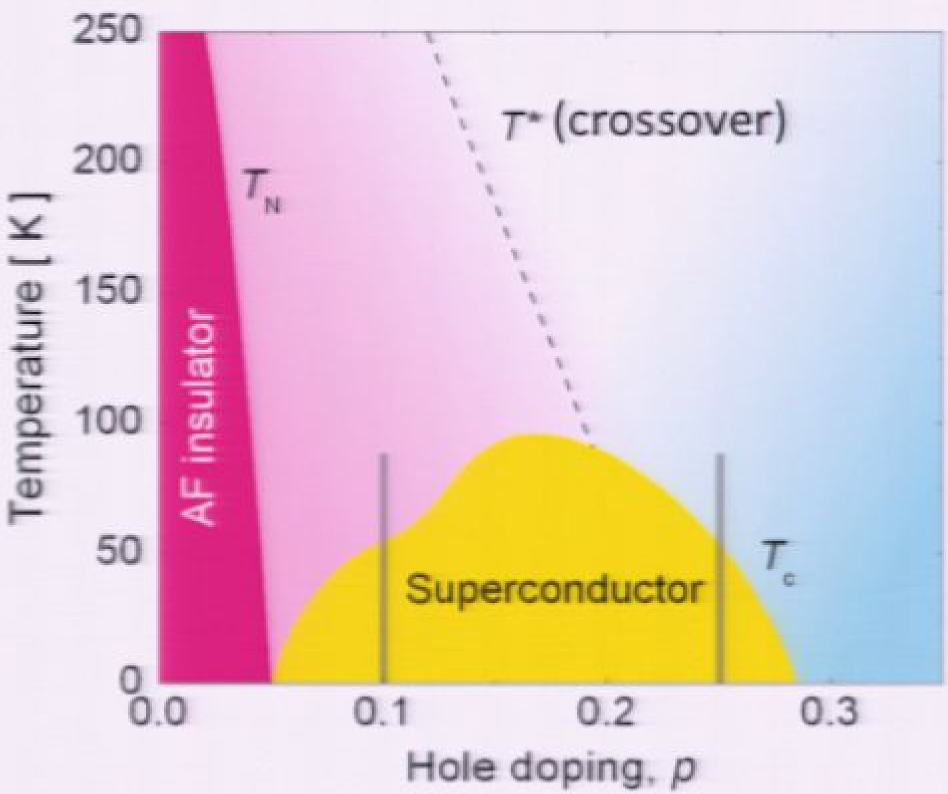

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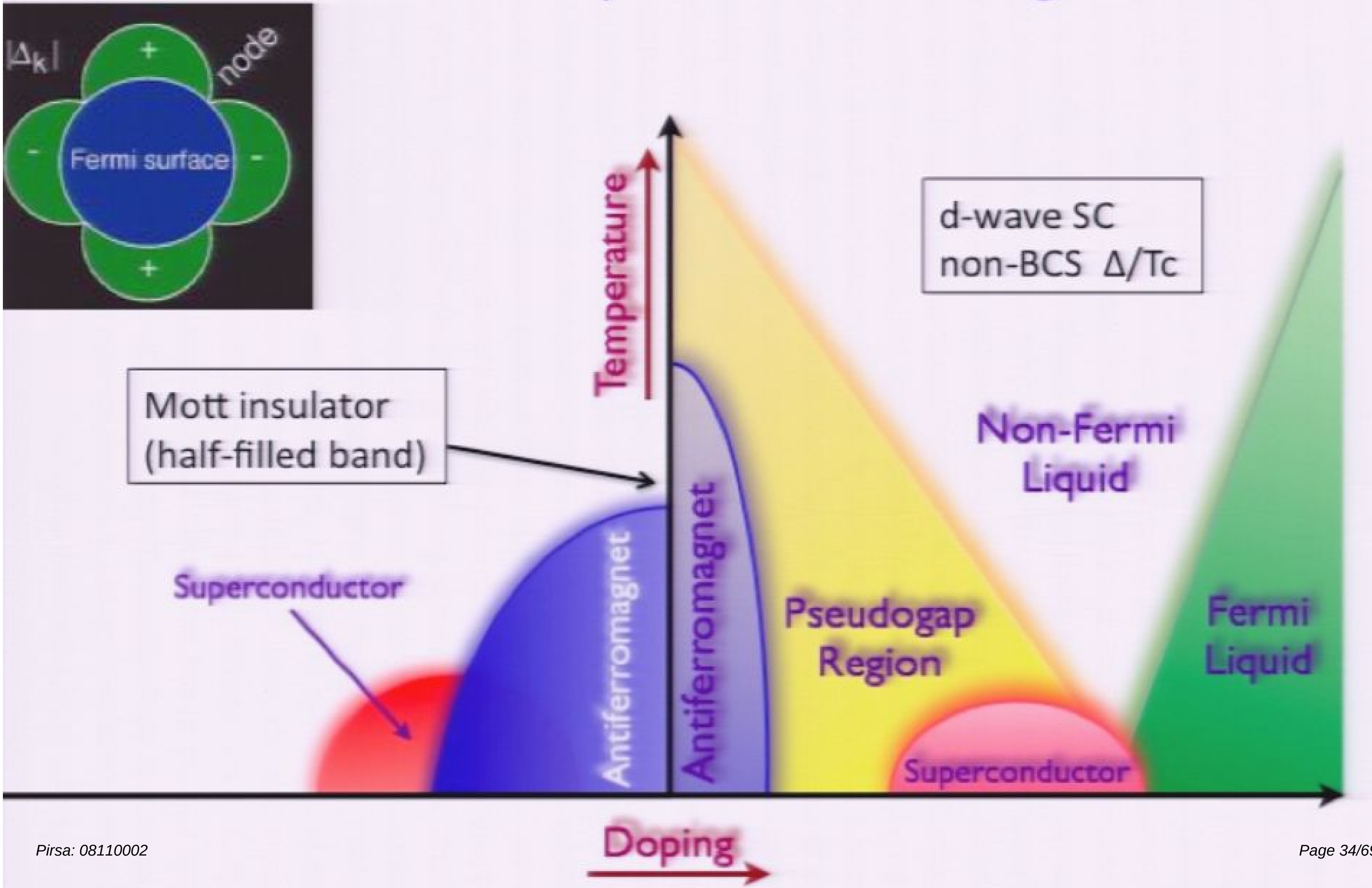

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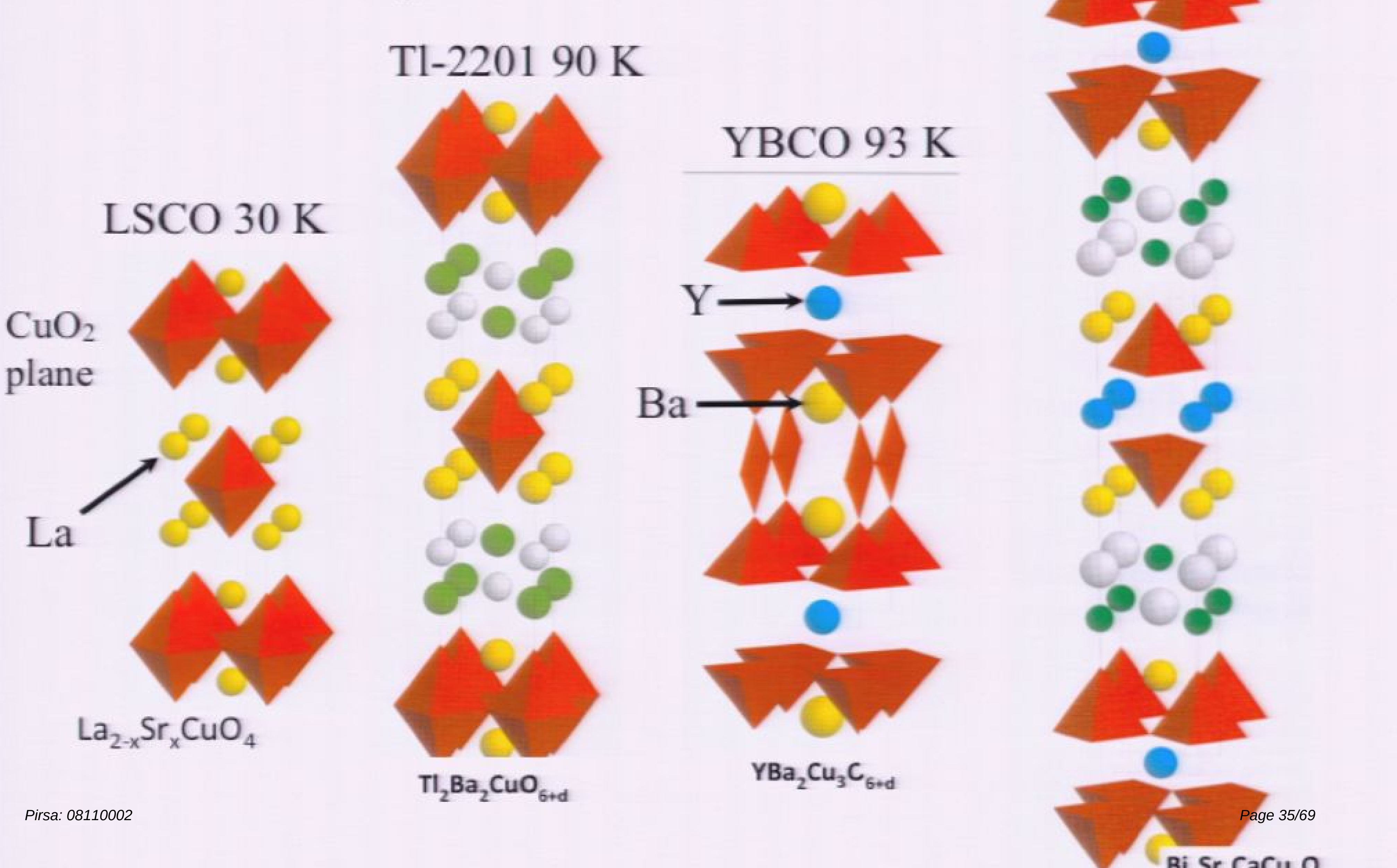

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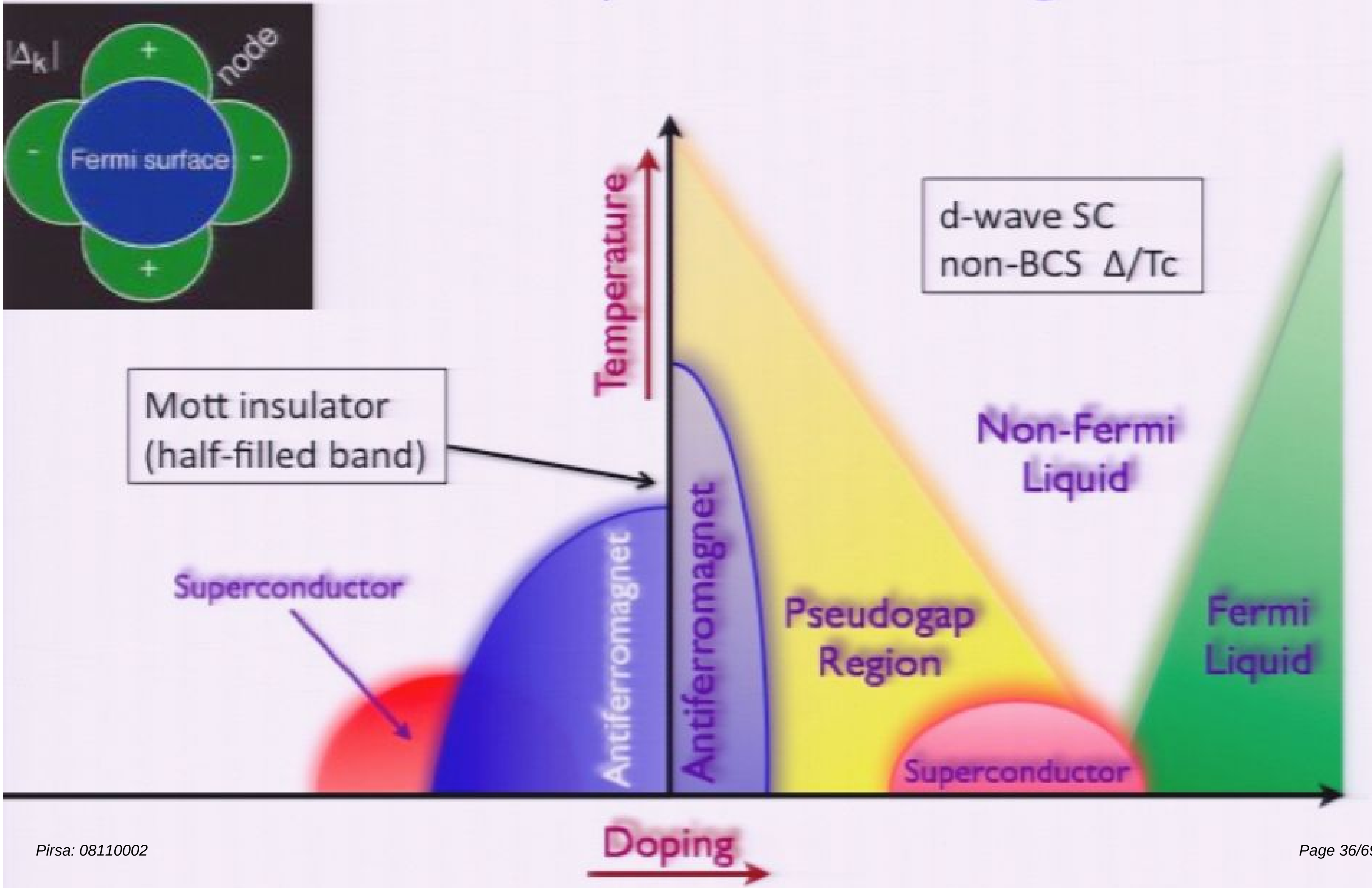

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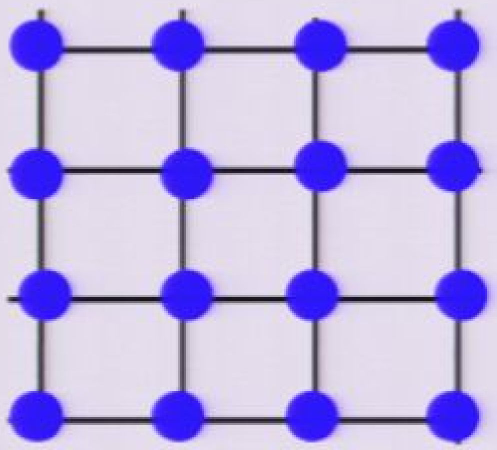

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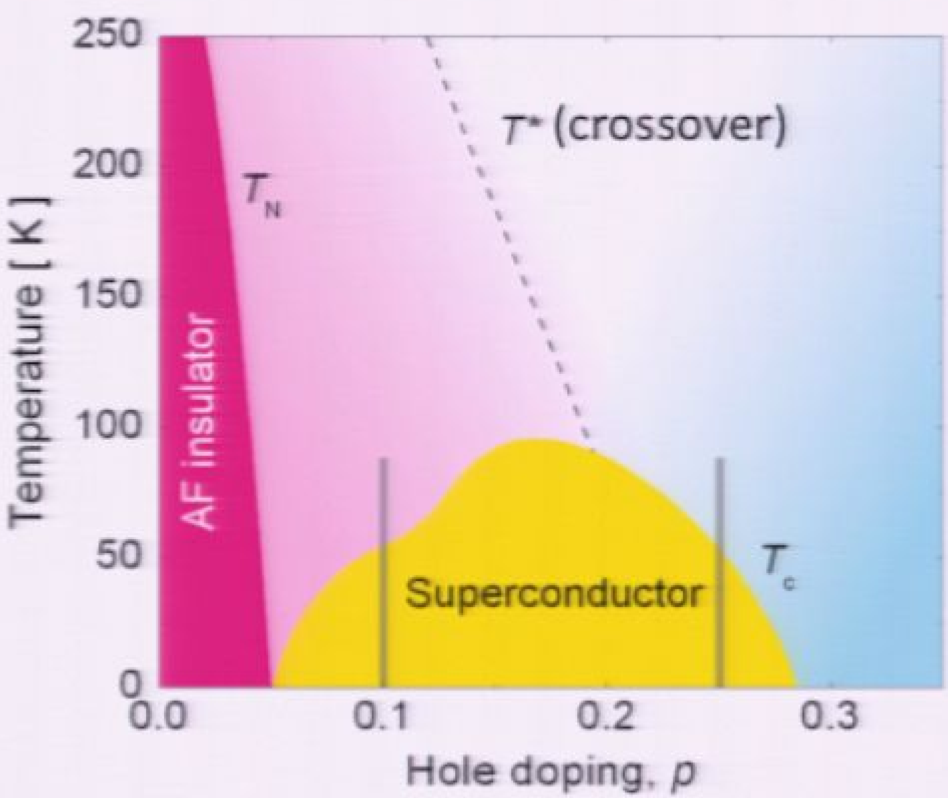
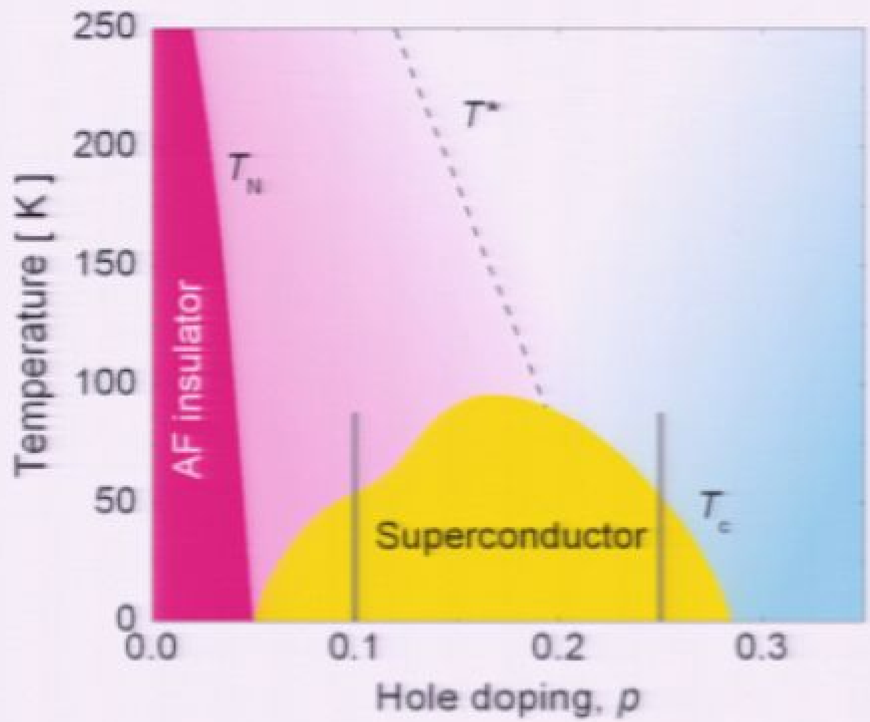


Fermi surface of hole-doped cuprates



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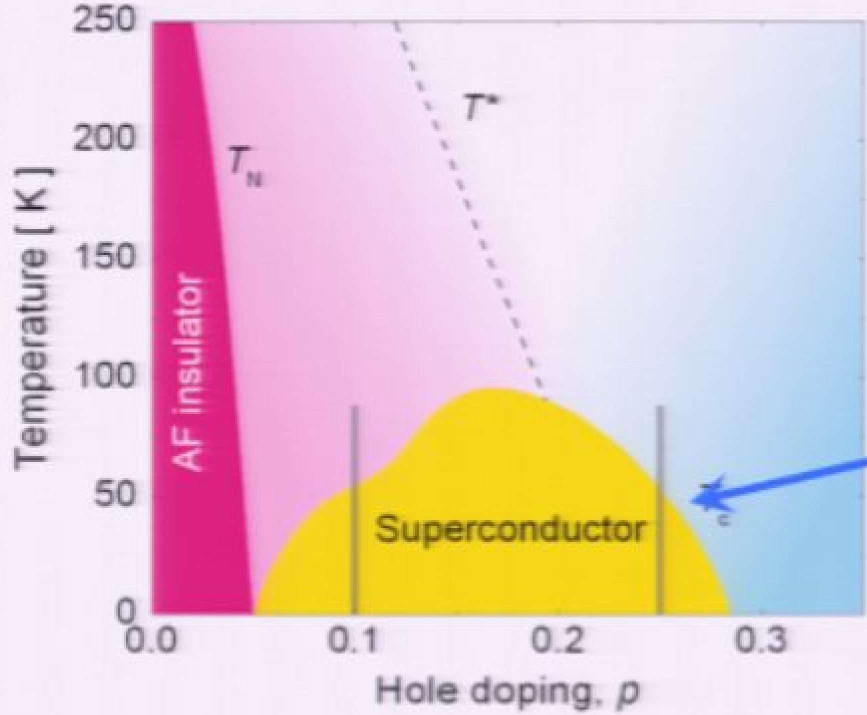
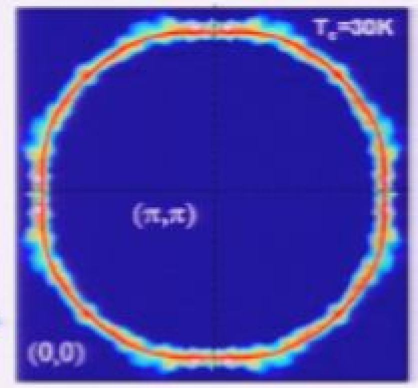
$n = 1+p$





M. Platé et al., PRL 2005

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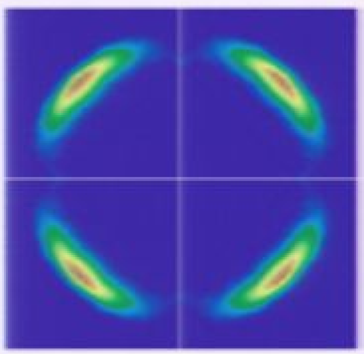
Fermi "arcs"



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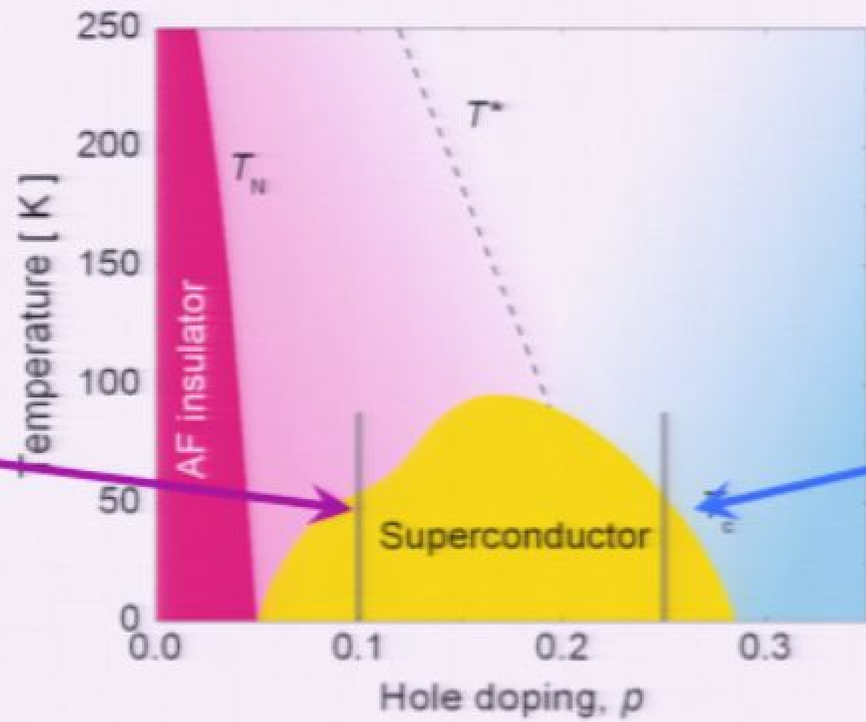

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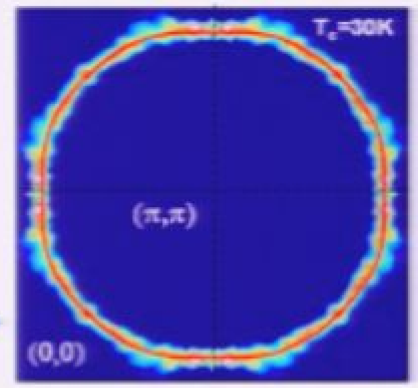

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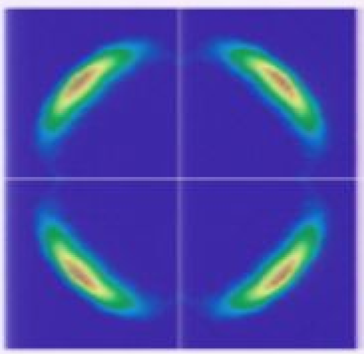

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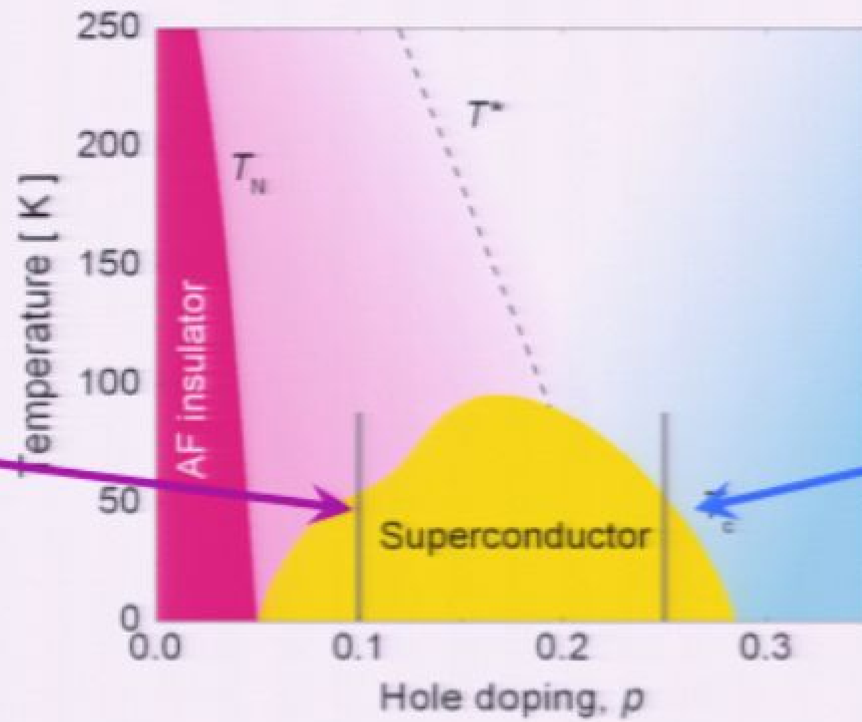

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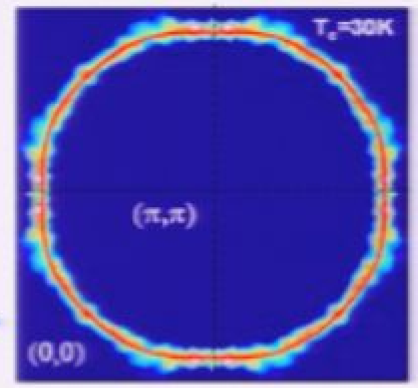

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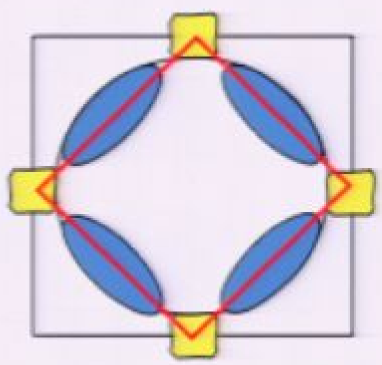
Recent SdH and dHvA measurements give information about the Fermi surface in the pseudogap phase



N. Doiron-Leyraud et al., Nature 2007

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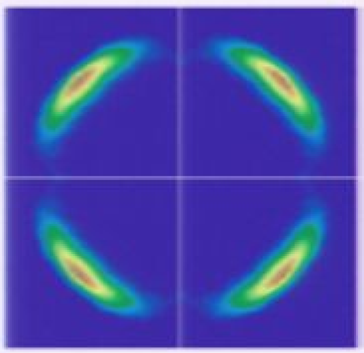

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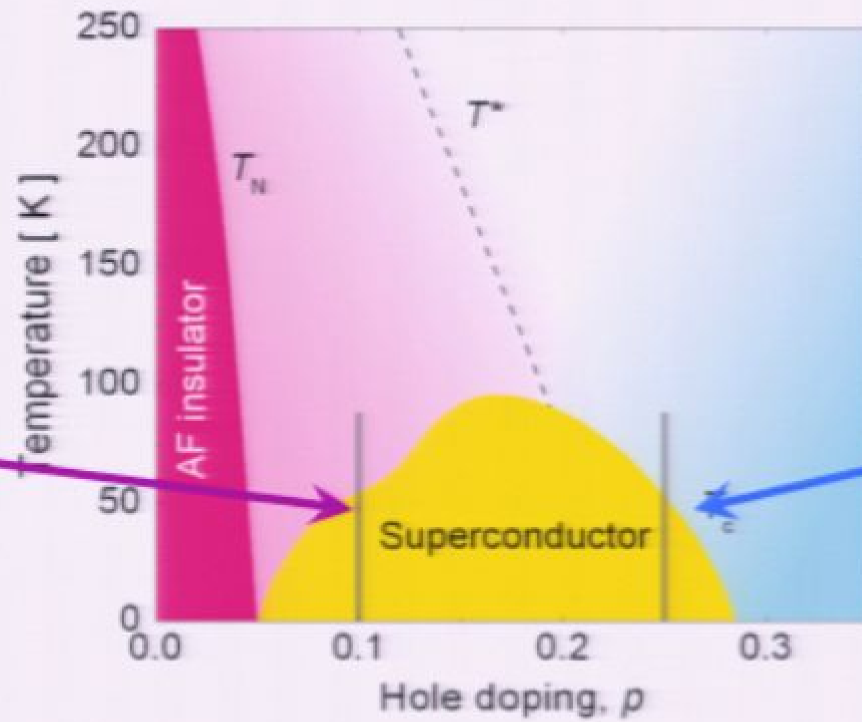

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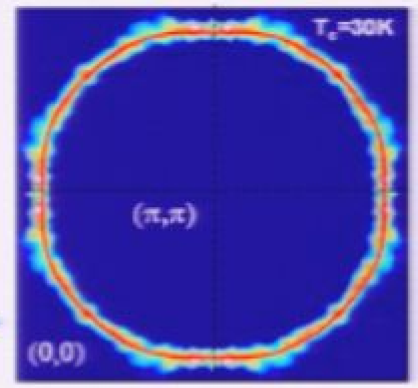

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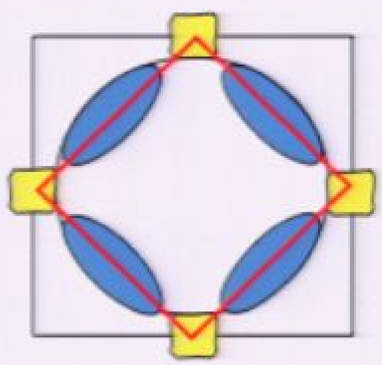

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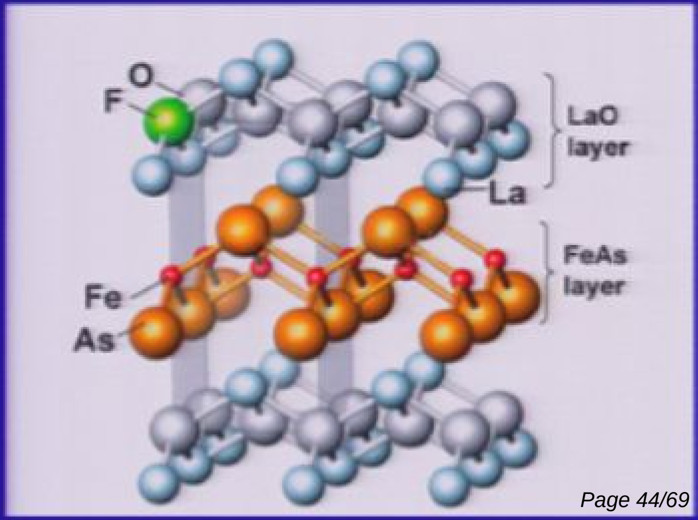
Nature of pseudogap phase still open question

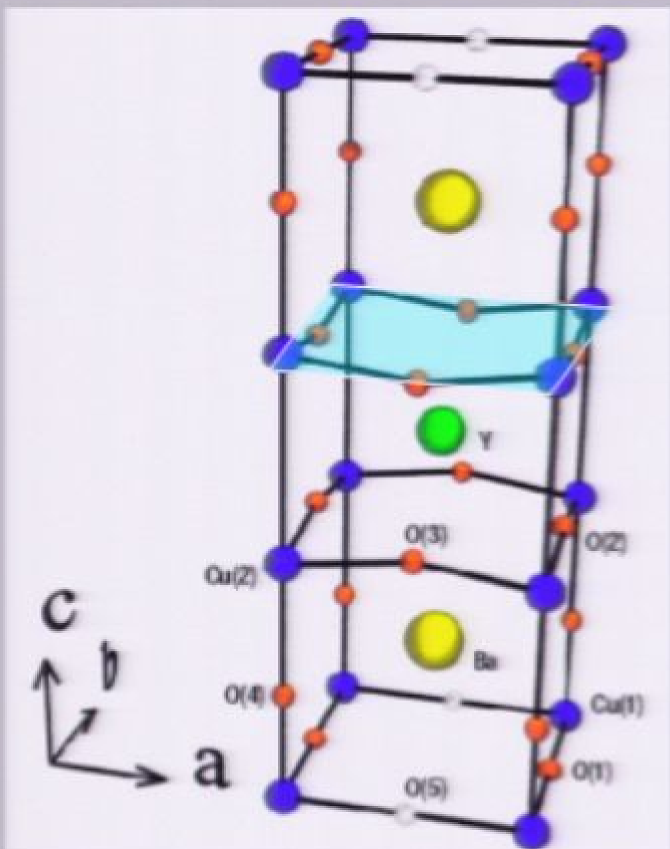
Iron Superconductors

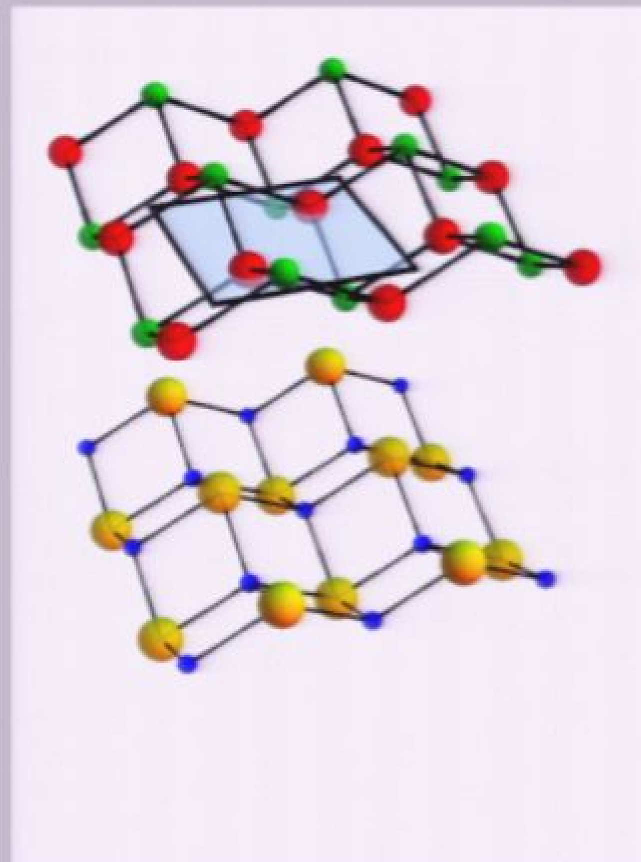
26K $LaO_{1-x}F_xFeAs$ (Hosono, February 2008)
43K $SmO_{1-x}F_xFeAs$ (Chen, March 2008)
52K $PrO_{1-x}F_xFeAs$ (Zhao, March 2008)
55K $PrO_{1-x}F_xFeAs$ grown under pressure (Zhao, April 2008)

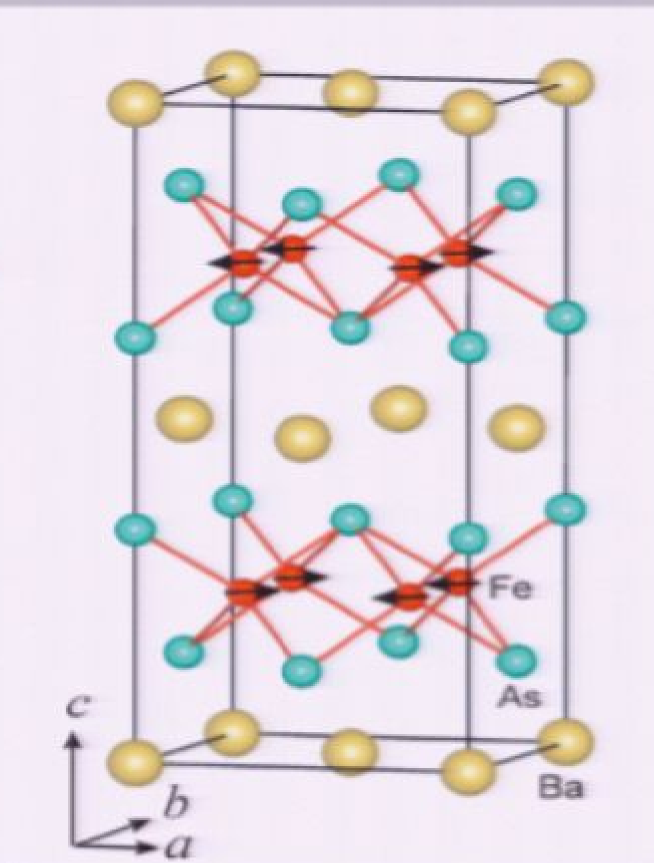
111: ROFeAs, LiFeAs R=Ce,Pr,Nd,Sm,...
122: $(Ba,K)Fe_2As_2$, $(Sr,A)\ Fe_2As_2$ A=K,Cs



Cu-oxides versus Fe-pnictides







Both have d-electrons in key role (Cu vs Fe)
Both are layered (CuO2 vs FeAs)
Both have AF and SC in close proximity
Both are poor metals

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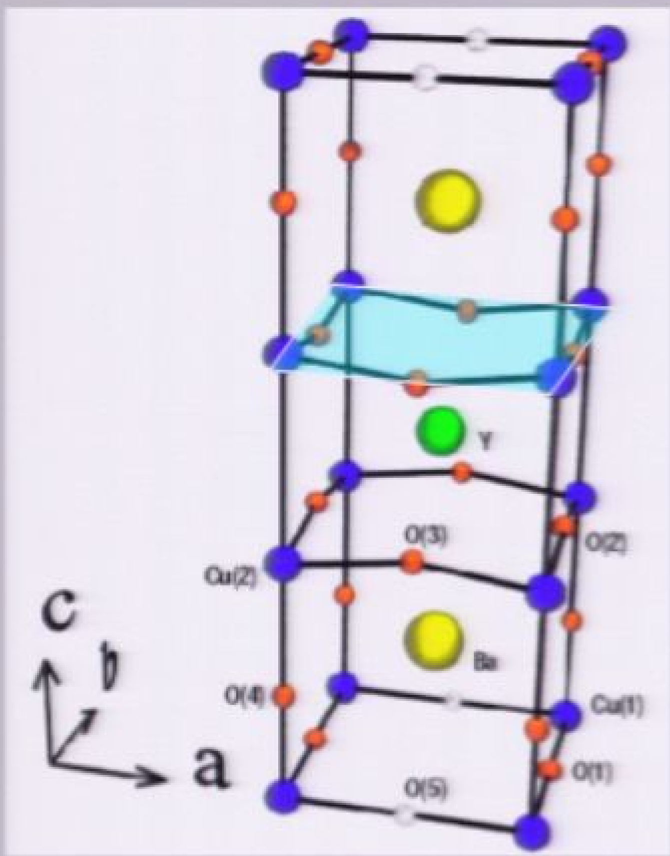
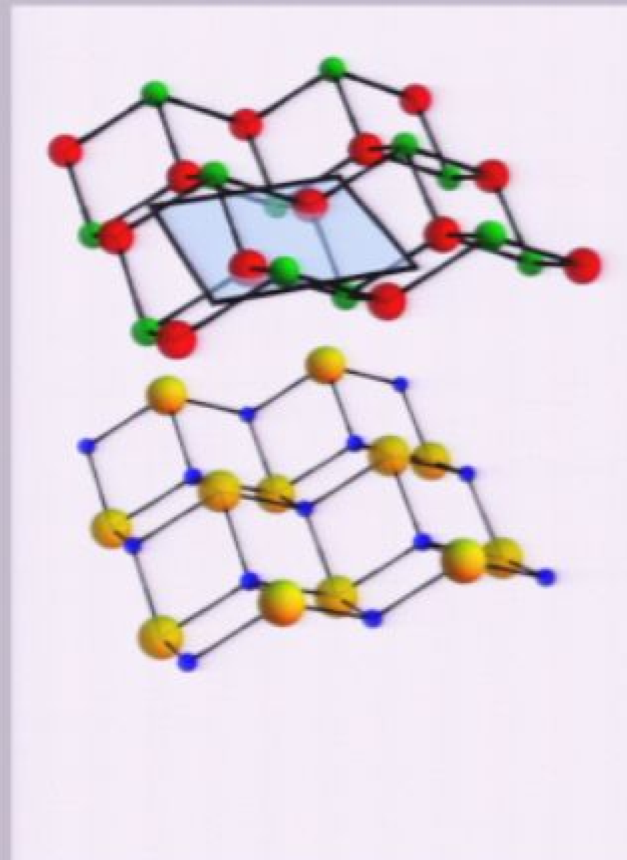
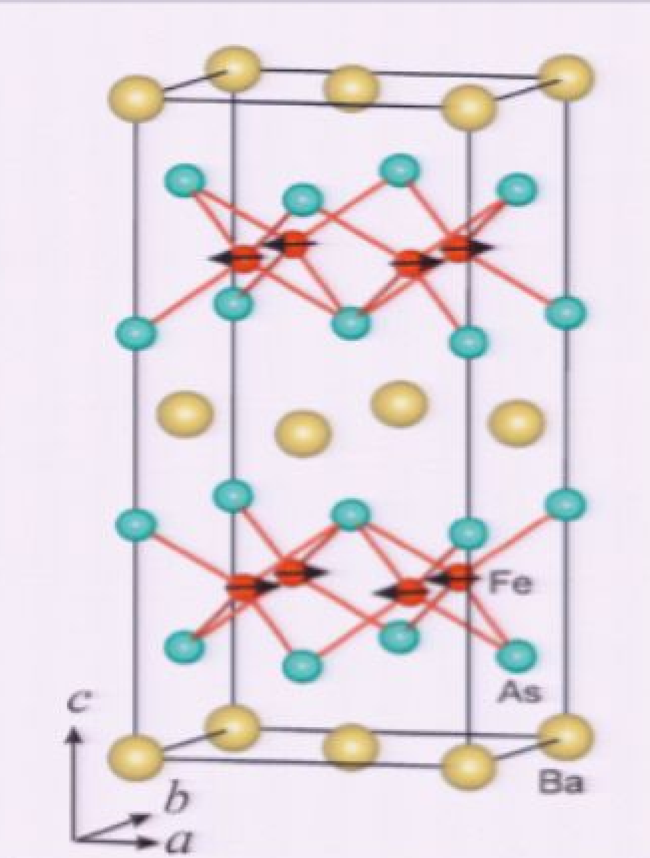




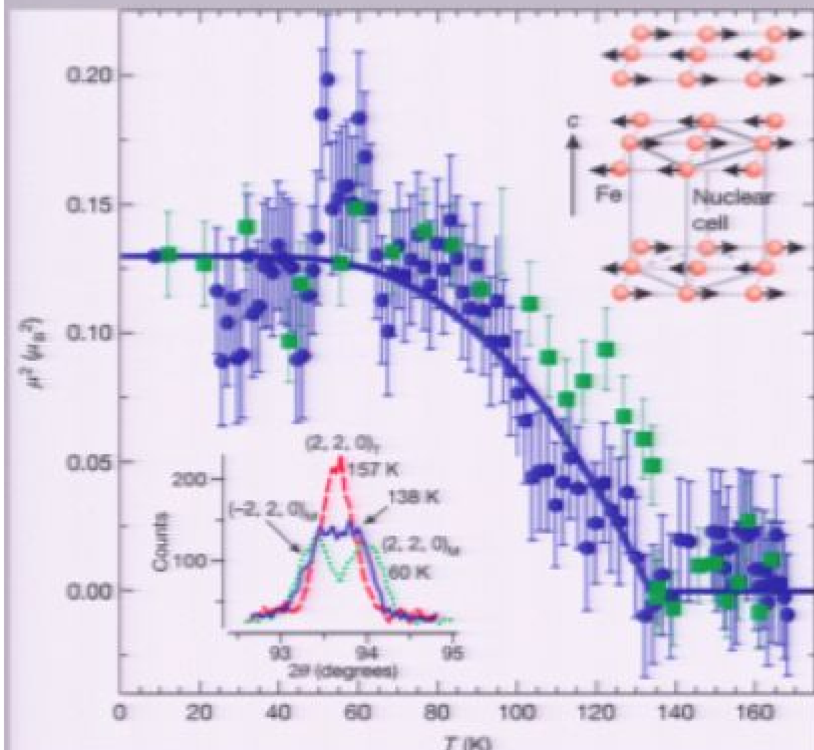


Both have d-electrons in key role (Cu vs Fe)
Both are layered (CuO2 vs FeAs)
Both have AF and SC in close proximity
Both are poor metals

However, there are also differences which may be important.

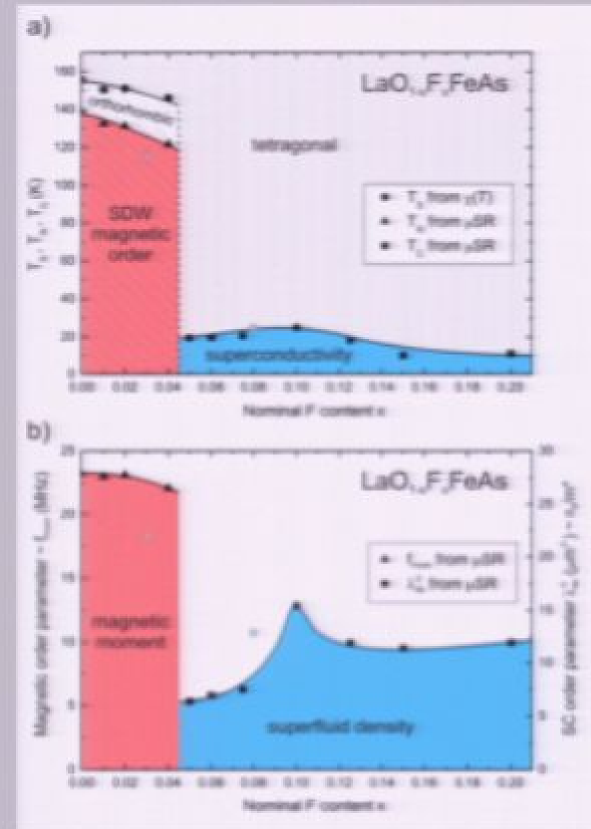
Phase diagram of Fe-pnictides

C. de la Cruz, *et al.*, Nature **453**, 899 (2008)



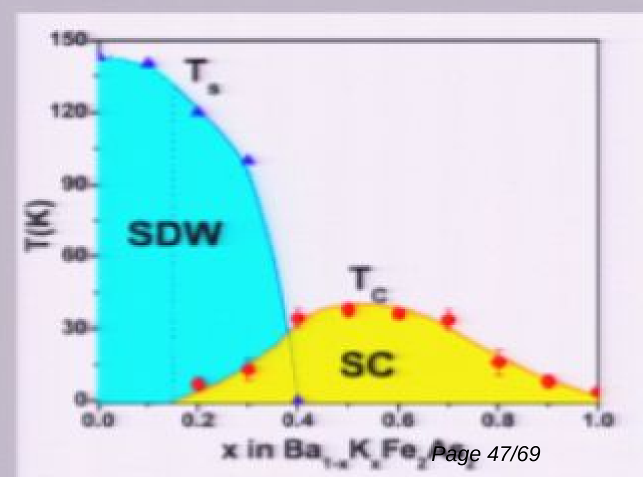
Small moment (in plane) → no Hunds rule

Like CuO_2, phase diagram FeAs has SDW (AF) in proximity to the SC state.



H. Chen, *et al.*, arXiv/0807.3950

SC coexists with SDW (AF) in 122 compounds →



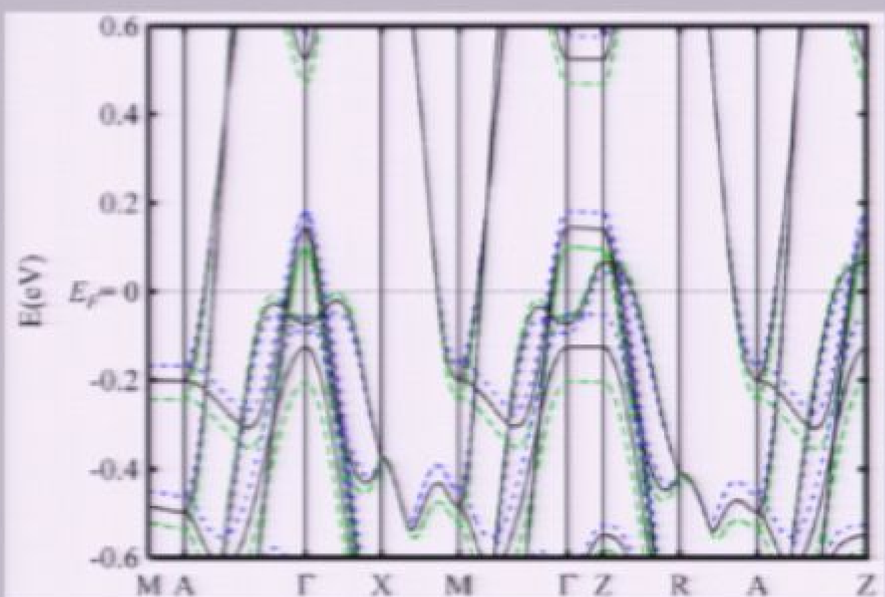
Key Difference:
odd versus even number of d-electrons

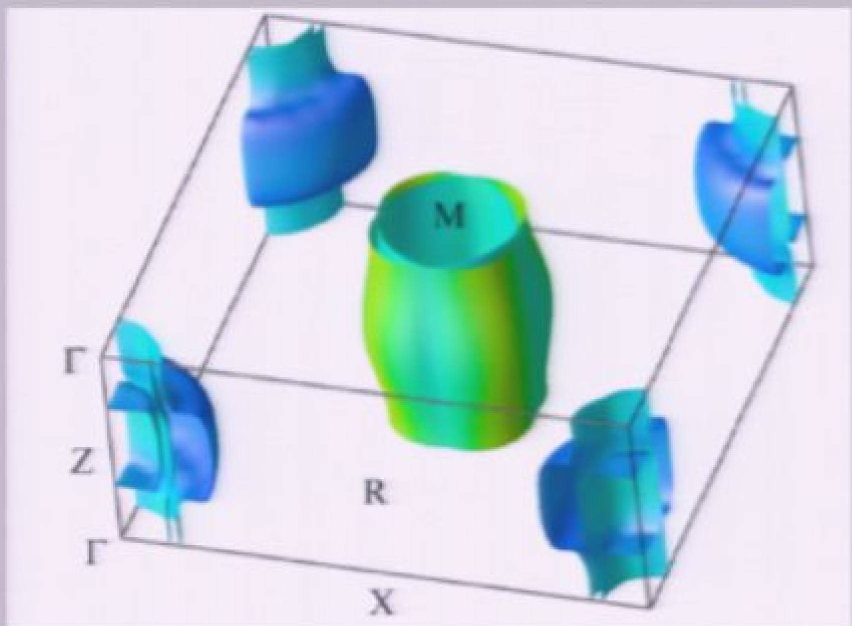
$Cu^{2+} \rightarrow 3d^9$
$Fe^{2+} \rightarrow 3d^6$

→ In CuO_2 start with half-filled single band

→ In FeAs nearly full or empty bands

Undoped FeAs bands are nearly full or nearly empty → no insulating phase → less correlated than cuprates





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

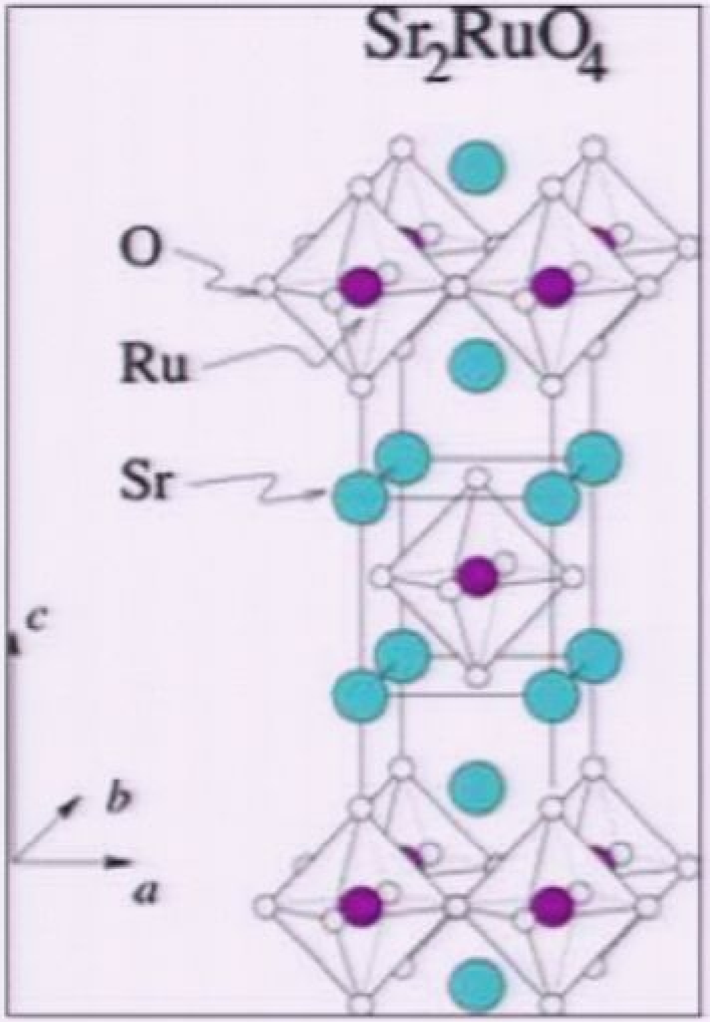
Theory of Fe SC

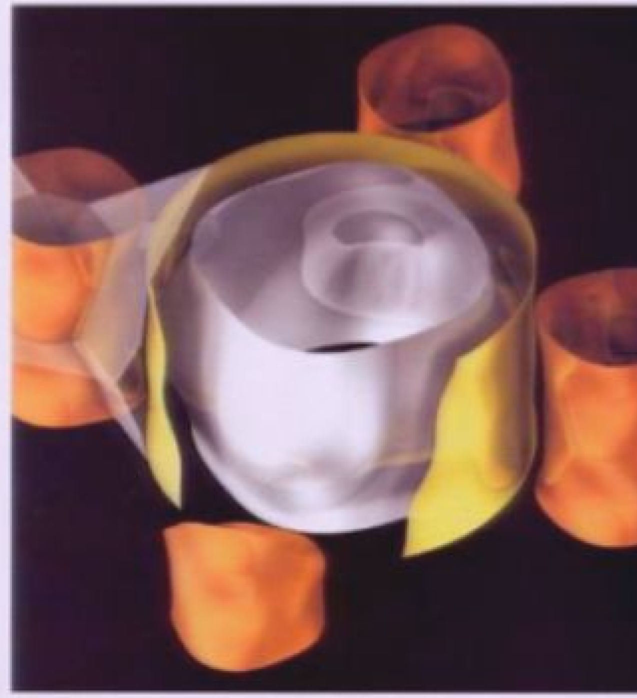
- Not compatible with only phonons (Haule, Shim, Kotliar)
- Phonons (intraband) and e-e interactions (interband) – Tesanovic (s-wave, but gaps on different bands may have opposite sign)
- Many electron correlation theories (AF fluctuations, some with large U → s-wave or d-wave)

→ Different than cuprates? U not as important?

- Accurate techniques are available (unlike early days of cuprate SC) but still need to still need high quality single crystals (some crystals are available).

Strontium Ruthenate

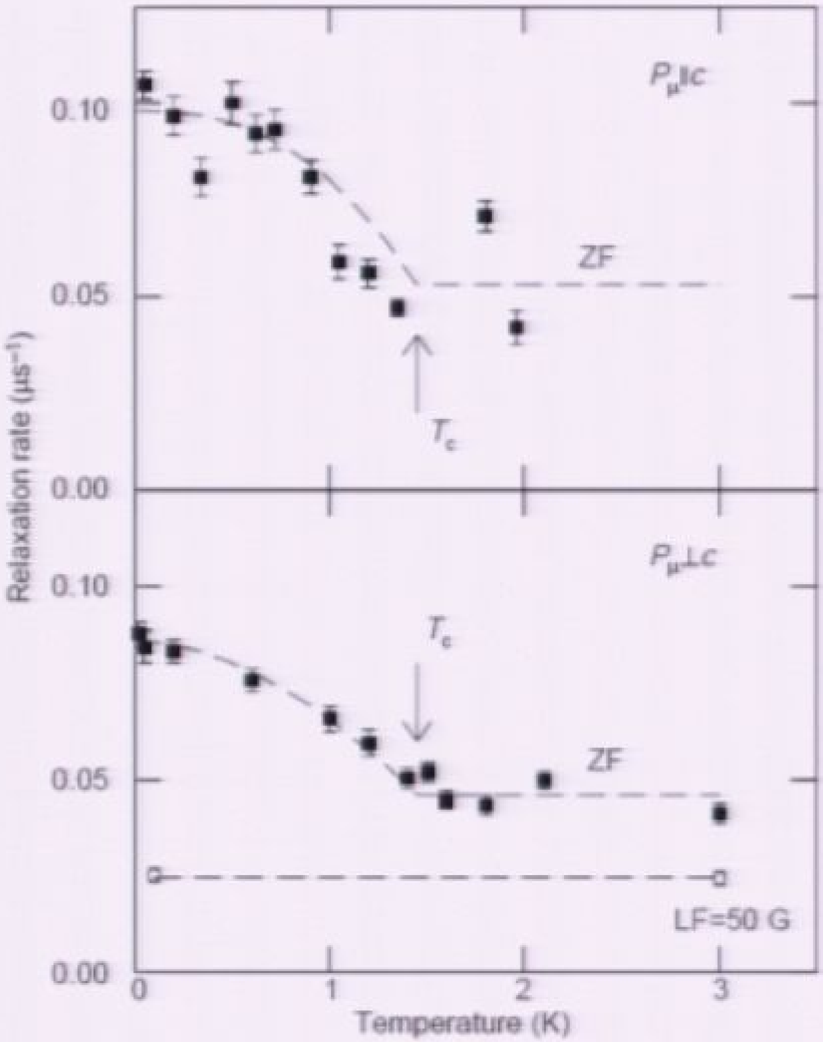




- Discovered in 1994 (Maeno)
- Same structure as cuprates
- Quasi-two-dimensional; multiband
- $T_c \leq 1.5K$, strongly disorder dependent

  → unconventional pairing

ZF-muSR Decay Rate vs Temperature: Evidence for TRSB in SC State

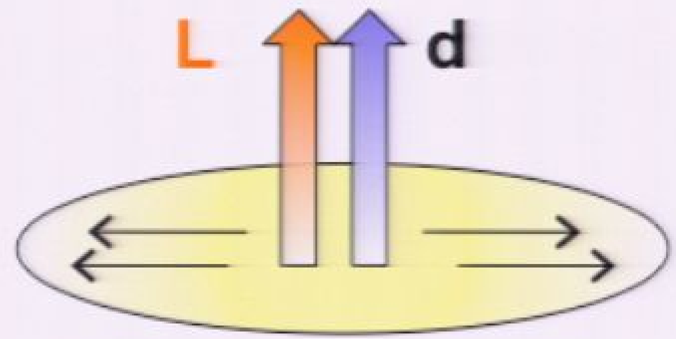


Luke et al., Nature **394**, 558 (1998).

- Spontaneous field seen below T_c, for P_m//c, //a. B_{loc}~1G.
- NMR sees evidence for triplet pairing (spin susceptibility constant thru T_c) → p-wave.
- These and crystal symmetry point to chiral p-wave superconductivity

Introduction to p_x+ip_y SC

$$S=1 \Rightarrow |\uparrow\uparrow\rangle, \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle+|\downarrow\uparrow\rangle\right), |\downarrow\downarrow\rangle$$



$$\Delta(\mathbf{k}) = i\{\mathbf{d}(\mathbf{k})\cdot\boldsymbol{\sigma}\}\sigma_y$$

2x2 matrix in s,s'. $d \parallel z \leftrightarrow S_z=0$
or equal spin pairing in xy plane

Both d-vector and L aligned along c-axis

equal spin pairing in ab-plane

$$\boxed{\mathbf{d}(\mathbf{k}) = \begin{cases} \Delta_0(k_x+k_y)\hat{\mathbf{z}} \\ \Delta_0(k_x \pm ik_y)\hat{\mathbf{z}} \end{cases} \rightarrow \begin{array}{ll} \Delta = \Delta_0\left|k_x+k_y\right| & \text{nodes} \\ \Delta = \Delta_0\sqrt{k_x^2+k_y^2} & \text{gap} \end{array}}$$

Breaks time-reversal symmetry

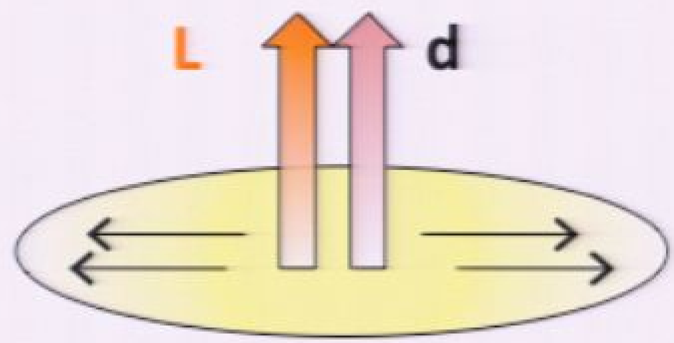
$$\vec{L} = \hbar\hat{\mathbf{z}}$$

k_x+ik_y degenerate with k_x-ik_y

→ can have domains

Chiral p-wave Superconductivity

$$\mathbf{d}(\mathbf{k}) = \Delta_0 \hat{\mathbf{z}}(k_x \pm i k_y)$$



Each Cooper pair carries angular momentum ħ and the BCS SC state carries ang mom $\langle L_z \rangle = \hbar N/2$

- analogous to A phase of He-3
- topological state → Moore-Read QH state (Read & Green, 1999)
- Majorana zero modes at edges and vortex cores
- rotated d-vector → isolated Majorana zero modes

Zero modes = Majorana Fermions

$$H\psi_n = \begin{pmatrix} h & \Delta \\ \Delta^+ & -h^T \end{pmatrix} \begin{pmatrix} u_n \\ v_n \end{pmatrix} = E_n \psi_n \rightarrow \quad H = \sum_n E_n \gamma_n^+ \gamma_n$$

$$\text{where} \quad \gamma_n^+ = \sum_i (u_n a_i^+ + v_n a_i)$$

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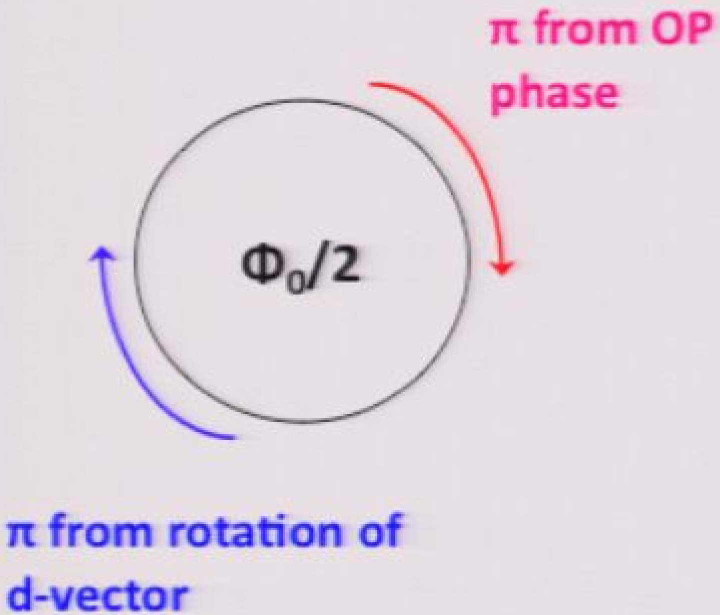
Majorana Fermion

Can have **one** Majorana zero mode at vortex

(requires spinless fermions, or d-vector in xy-plane)

chiral p-wave and quantum computing



d-vector perpendicular to z

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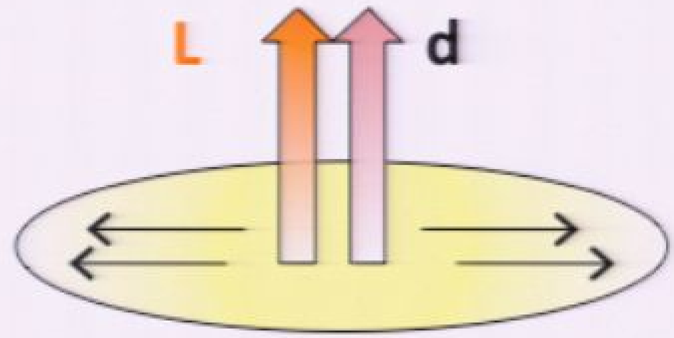

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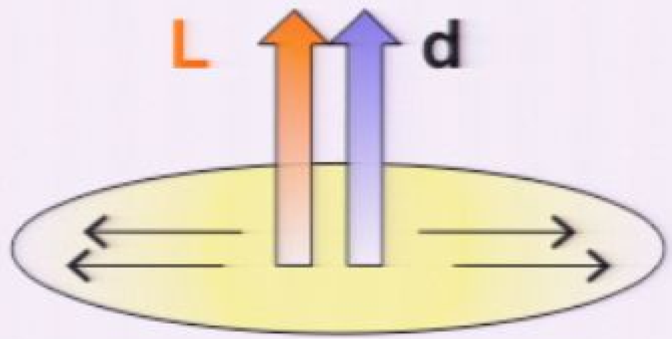

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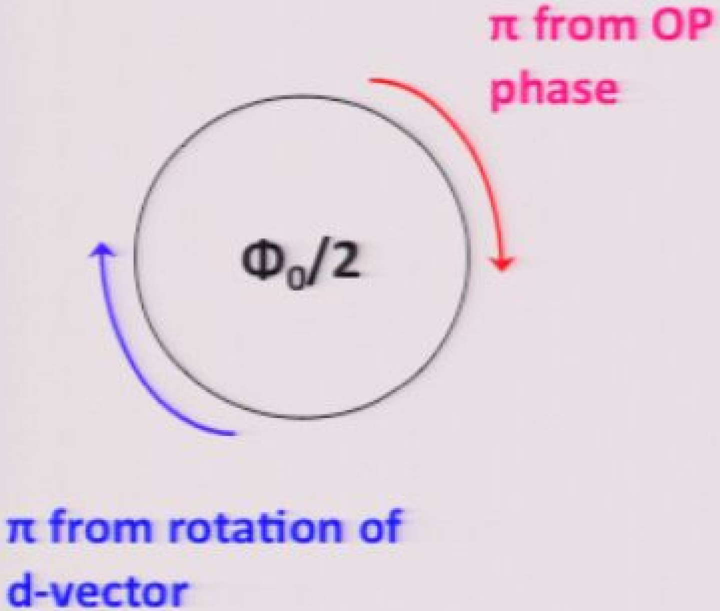

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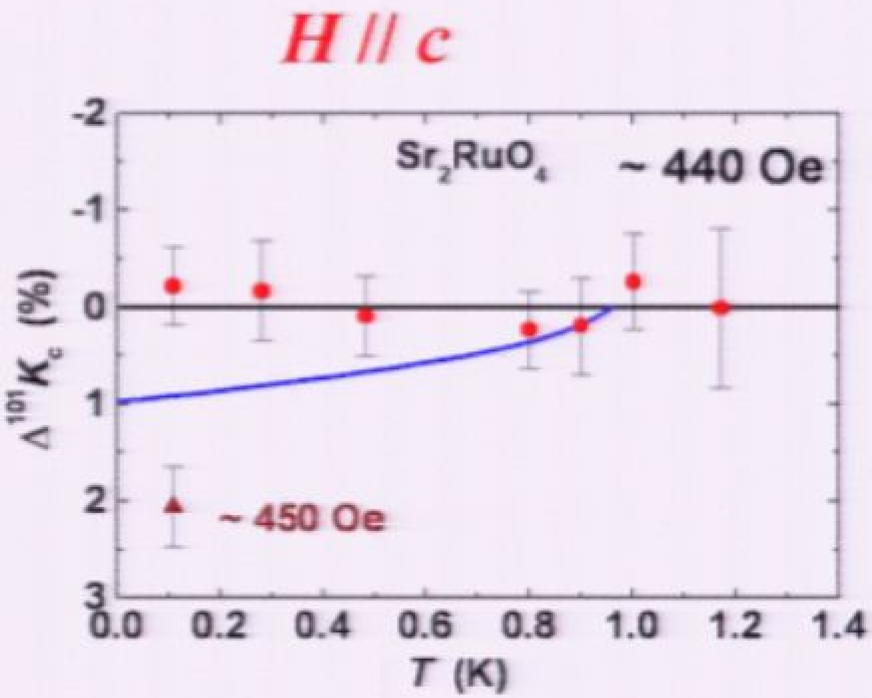


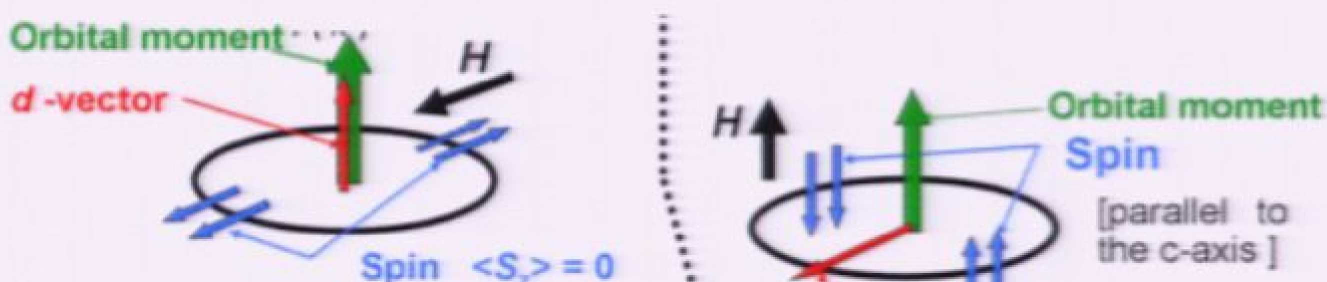
More recent NMR with H | c also found no supression of Knight shift below Tc

→ triplet with spins along c ?

→ not necessarily same orbital state

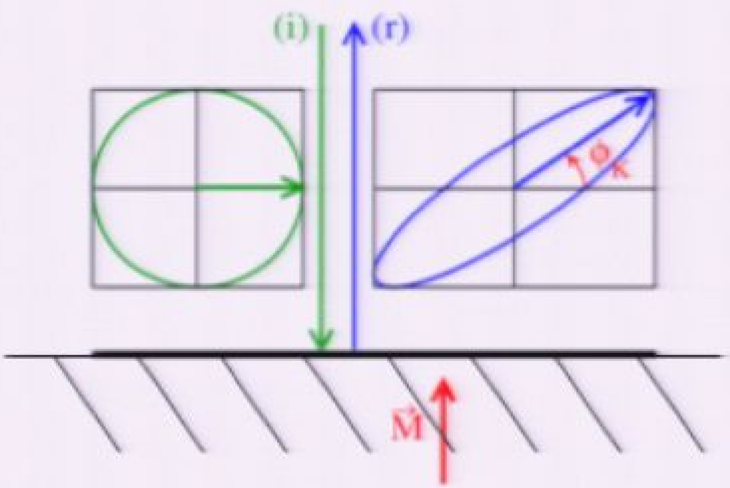
→ NMR lineshapes broader

[From Ishida (KITP 2007)]



$d = z\Delta_0(\sin k_x + i \sin k_y)$ (A state)

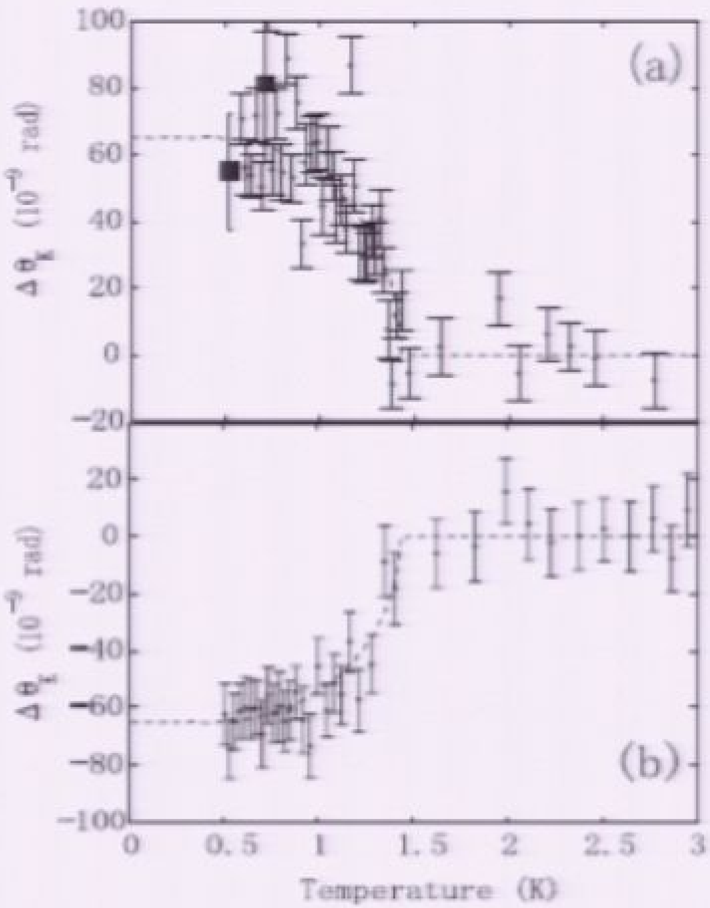
Polar Kerr effect



Linearly polarized light is reflected as elliptically polarized light, with rotation of polarization axis by Kerr angle

Measure magnetization perpendicular to surface in FM

Requires broken time-reversal symmetry



Cooled in (a) 93 G (b) -43 G
[ω=0.8ev; Θ=60 nanorads]

J. Xia, Y. Maeno, P.T. Beyersdorf, M.M. Fejer, A. Kapitulnik, PRL 97, 167002 (2006).

Clean chiral p-wave SC has $\sigma_{xy}(k,\omega)\rightarrow 0$ for $k\rightarrow 0$, although interesting signatures at finite k.

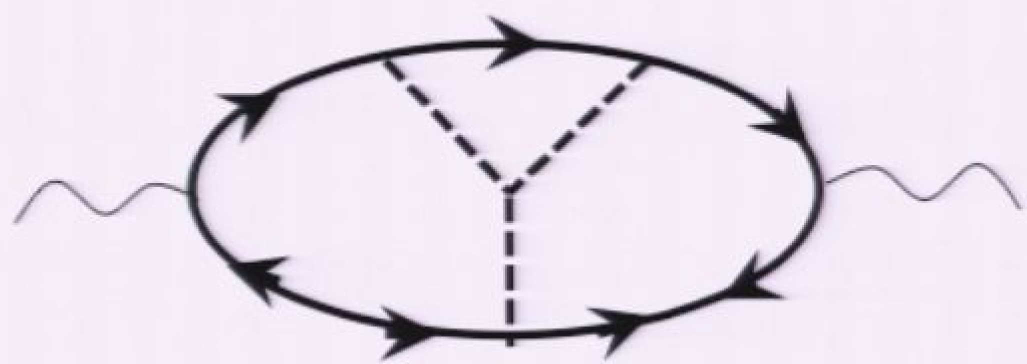
One can show lowest disorder contribution ($n_i U^2$) also vanishes.

Goryo identified diagrams of order $n_i U^3$ (skew scattering) which contribute.

$\mathrm{Tr}[\tau_3 G(p)G(k)]=2i\Delta^2\sin\theta$

$\rightarrow \sin^2\theta$ $\rightarrow$ **nonzero, only for l=1 !**

~ comparable to experiment; a bit small & likely to be reduced



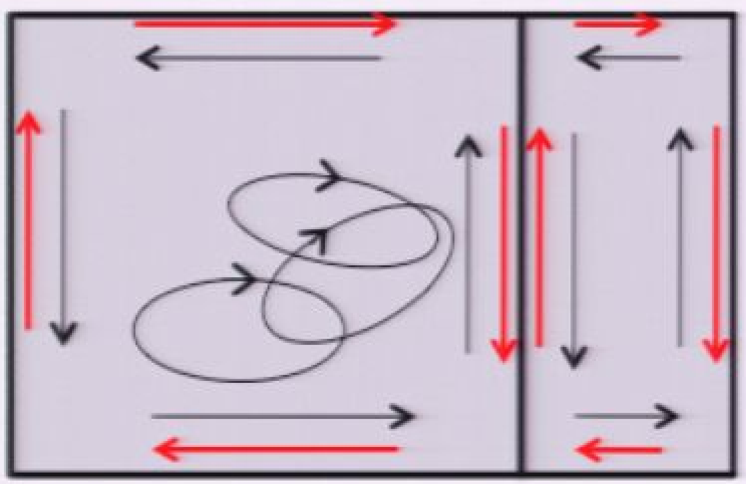
Explanation? Test by studying disorder and frequency dependence of Kerr effect.

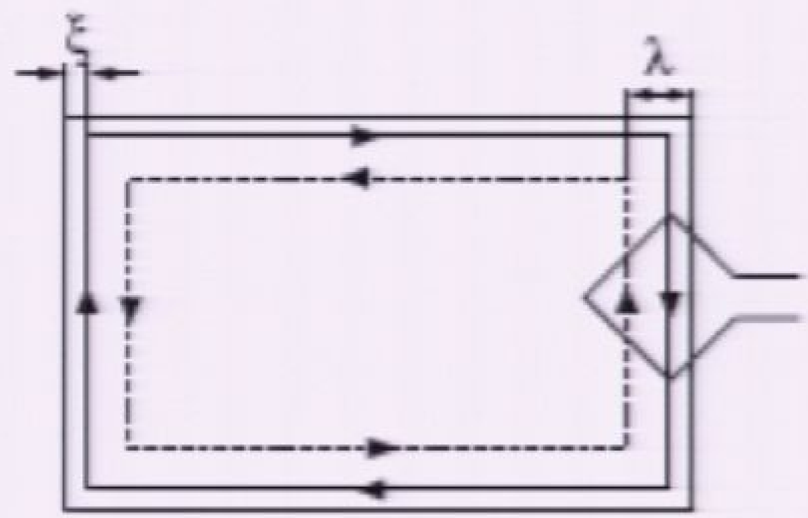
$$\sigma_{xy}^{(v)}(\omega) = \gamma_{BCS}^2 \left(1-\frac{T}{T_c}\right)\frac{l_i}{\xi_0}\left(\frac{\epsilon_F}{\pi\tau_0}\right)^{3/2}\frac{\sigma_{xy}^{(0)}}{(\omega+i/\tau_0)^3}$$

Jun Goryo, arXiv:0806.0548

Spontaneous equilibrium supercurrents flow at the edges and domain walls (related to macroscopic angular momentum of the chiral p-wave state). These are screened by counterflowing supercurrents.

Stone and Roy (2004)
Matsumato and Sigrist (1999)



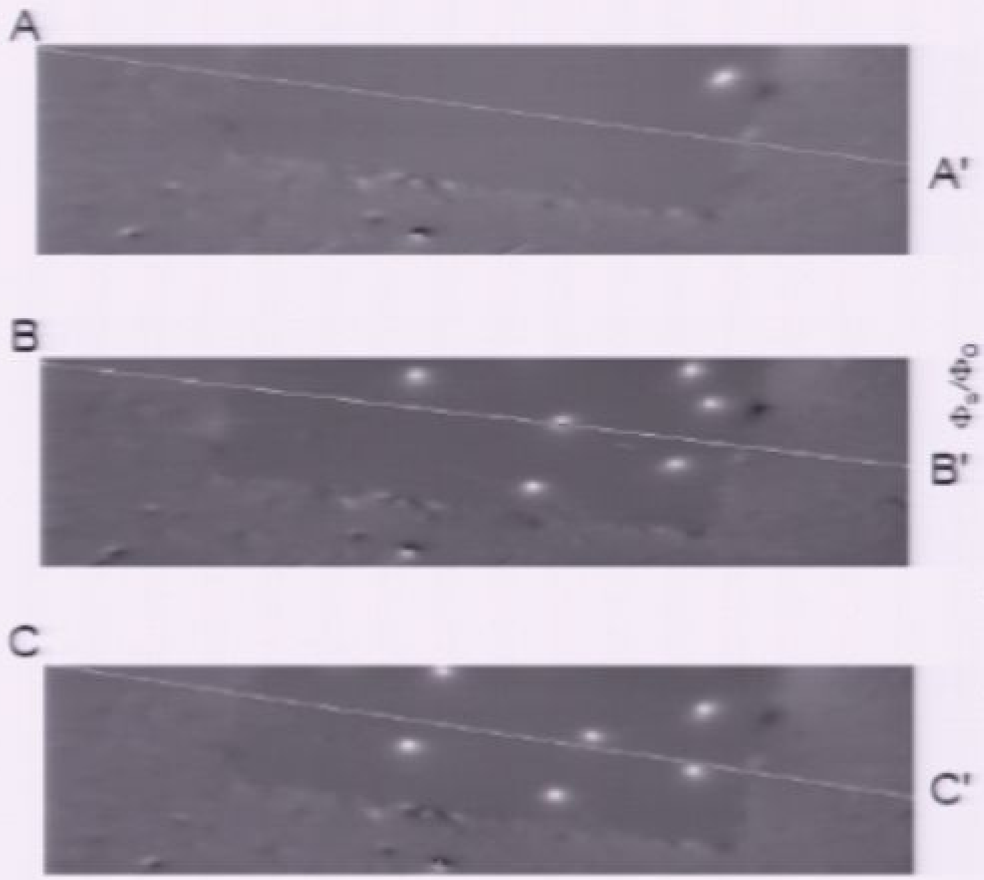


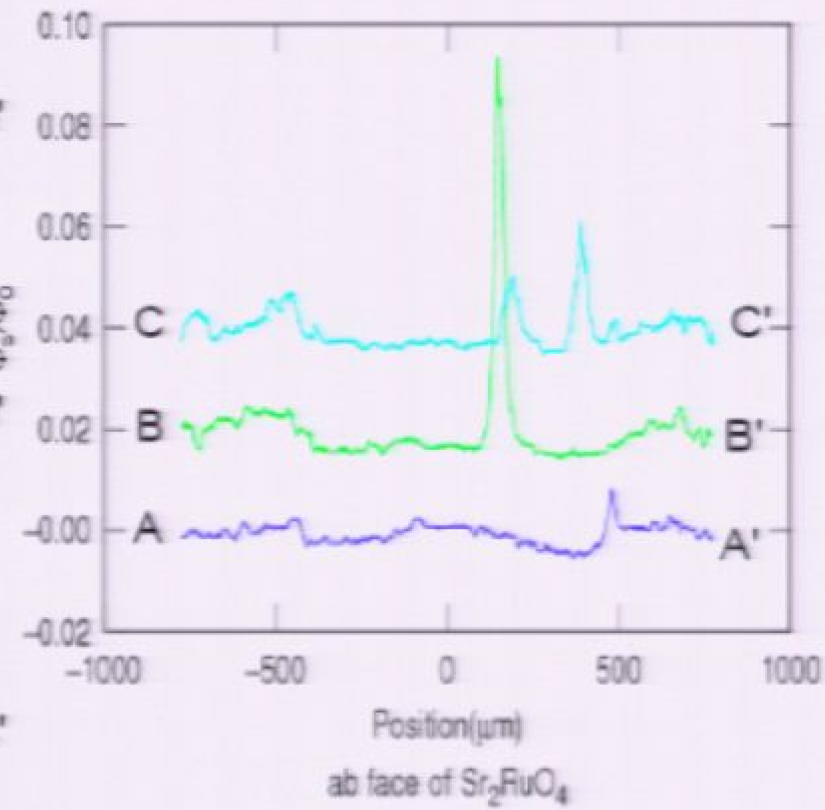
Can detect the field due to these currents with scanning SQUID microscopy

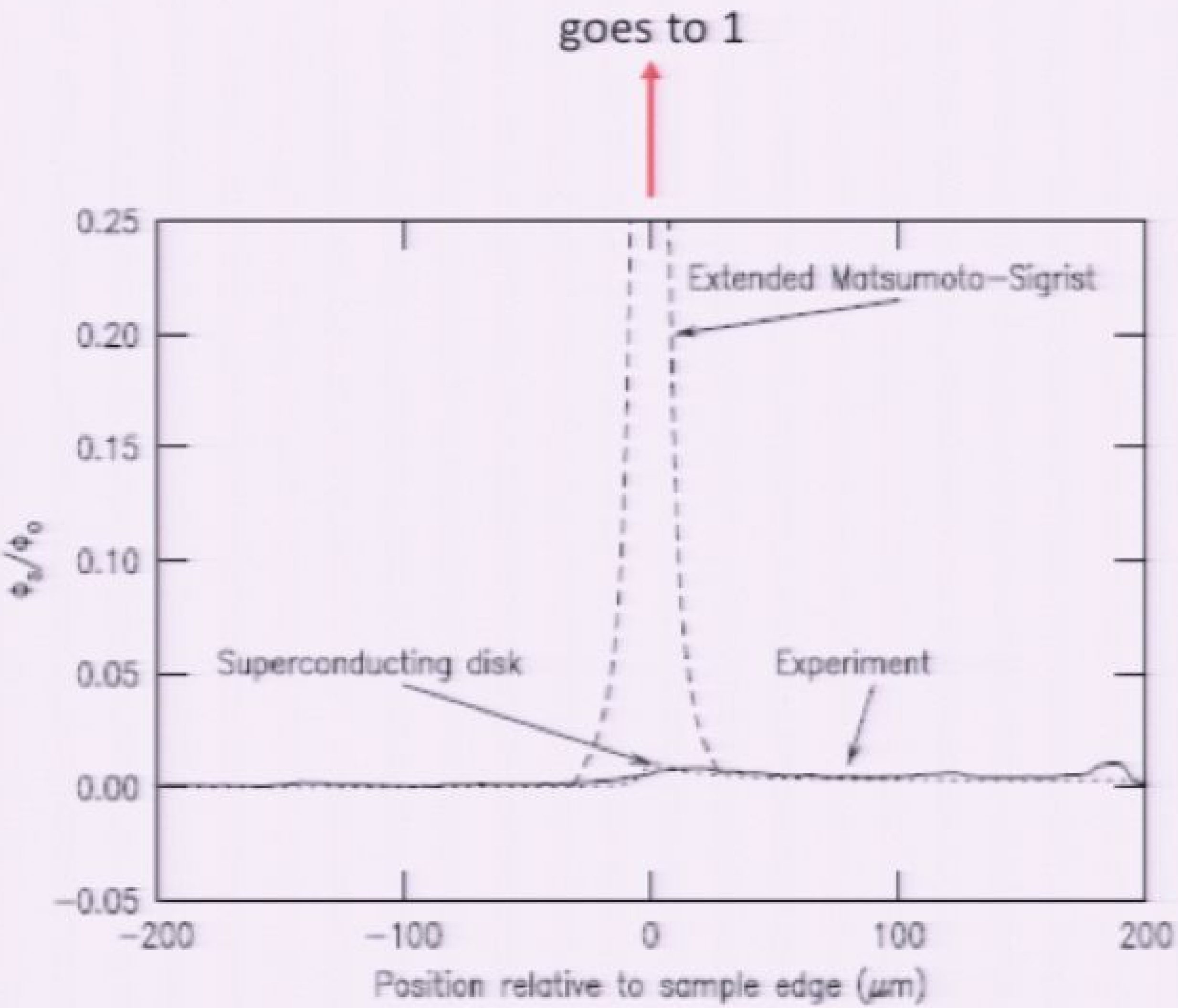
Fig. 5. Electric currents (solid lines) of the chiral edge states along the inner and outer edges of Sr_2RuO_4. The dashed lines show superfluid counterflow. The rectangular coil on the right represents a SQUID pickup loop.

Scanning SQUID microscopy: search for edge and domain currents

J.R. Kirtley, C. Kallin, C. Hicks, E.A. Kim, Y. Liu, K.A. Moler, Y. Maeno, PRB (2007).






goes to 1
Extended Matsumoto–Sigrist
Superconducting disk
Experiment
Φ_s/Φ_0
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−200
−100
0
100
200
Position relative to sample edge (μm)

No (weak) spontaneous edge currents ←→chiral p-wave?

- Rough and pairbreaking surfaces cause little suppression
- Alternative to BCS wave function proposed by Leggett

$$|\psi_{\mathrm{BCS}}\rangle = \prod_k (u_k + v_k a_{k\uparrow}^+ a_{-k\downarrow}^+)|0\rangle \qquad u_k = |u_k|,\ v_k = |v_k| e^{i\phi_k}$$

$$|\psi_N\rangle = \sum_p f_p (\Omega_+)^p (\Omega_-)^p |\mathrm{FS}\rangle \qquad \Omega_+ = \sum_{k>k_f} \frac{v_k}{u_k} a_k^+ a_{-k}^+ \quad \Omega_- = \sum_{k<k_f} \frac{u_k}{v_k} a_{-k} a_k$$

$$L_{\mathrm{BCS}} = N\hbar/2 \quad \Leftrightarrow \quad L_{\mathrm{Leggett}} = \left(\frac{\Delta}{E_f}\right)^2 N\hbar/2$$

Time Reversal Symmetry Breaking

Experiment	TRSB?	Domain size [limit >0.3μ]
muSR (Luke & Ishida)	Yes	< 2 μ
Kerr rotation (Kapitulnik)	Yes	> 50 μ with field cooling ~ > 15-20 μ in ZFC
Scanning Hall Probe (Moler)	No	< 1 μ
SQUID (Kirtley)	No	< 2 μ
Tunneling (van Harlingen)	Yes	< 1 μ ~0.5 μ dynamic
Tunneling (Liu) Corner junctions	Parity Yes	>10-50 μ

Conclusion

- In SRO questions remain about symmetry and angular momentum of BCS state. Compelling evidence for chiral order, but lack of edge supercurrents puzzling. Note Leggett's wave function would also give very reduced muSR signal.

- In cuprates, Hubbard model yields many competing orders and many signatures seen in the pseudogap phase. Still much to understand about this phase and connection to high Tc.

- Fe superconductors – field is moving rapidly but nature of superconductivity and connection to cuprates still under debate.