Emergence of quantum phases in novel materials

SUPERCONDUCTIVITY II

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BIBLIOGRAPHY (BOOKS)

Collection of reviews

- Conventional SPC "Superconductivity" Edited by Parks. 1968.
- Conventional and unconventional SPC "Superconductivity" 2008 (Fe SPC not included)

"Many-body physics" Piers Coleman

"Introduction to superconductivity" Tinkham

SPC history:

"Superconductivity: a very short introduction" S. Blundell

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OUTLINE

- **Superconductivity**
  - Properties (zero resistivity, Meissner effect)
  - Understanding (pairing, BCS, Ginzburg-Landau)
  - Electron-phonon interaction (conventional superconductivity)
- **Unconventional superconductivity (unsolved)**
  - What are the new issues.
  - What are the proposals.

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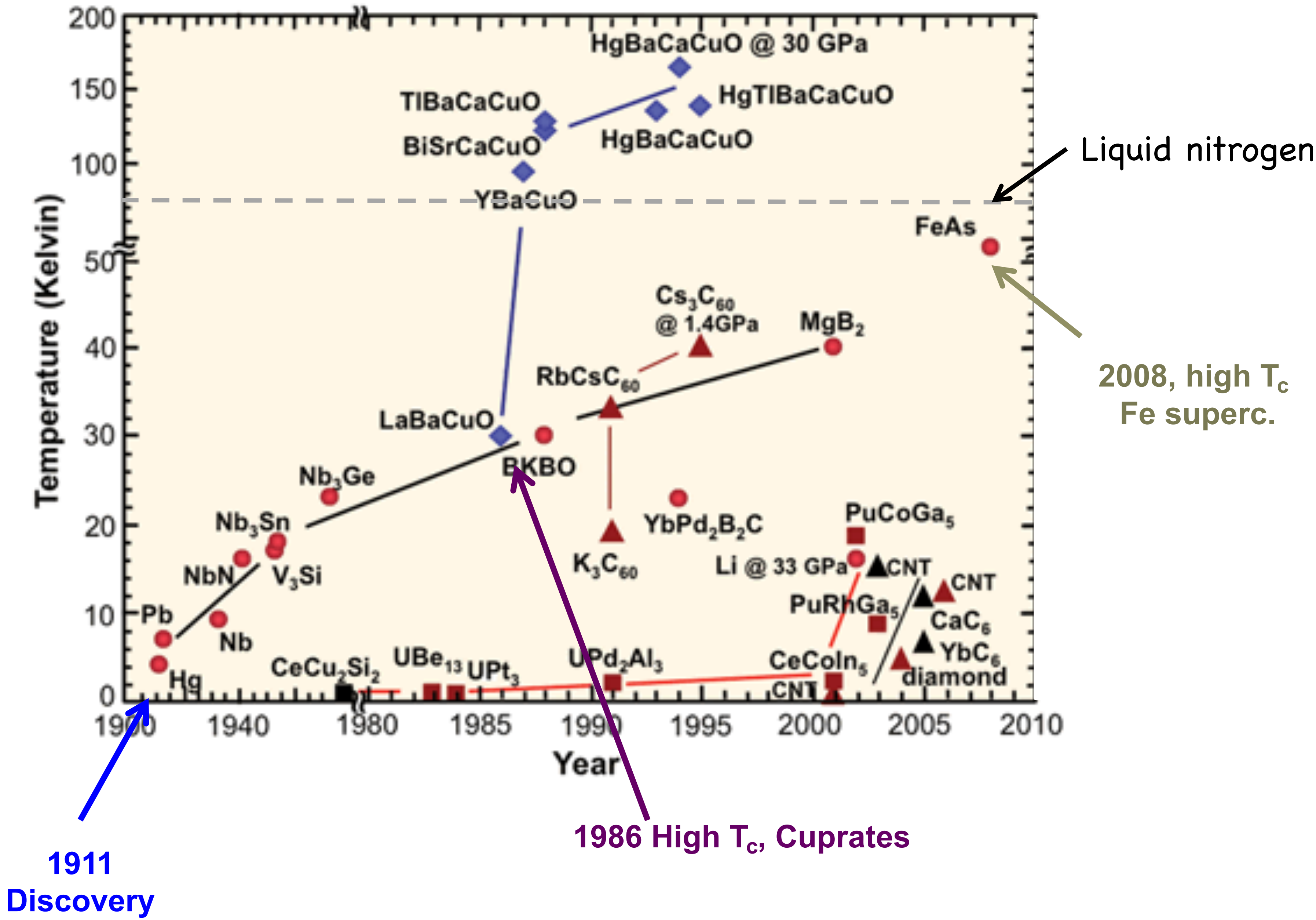

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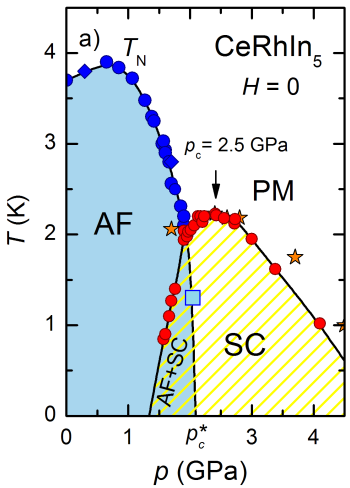
MATTHIAS'S RULES ?

Theory predicted superconductivity in hydrogen compounds (Ashcroft) and semiconductors (Cohen).

$SrTiO_3$ (T_c=0.3K); H_2S (T_c=200K)

AF supercond.

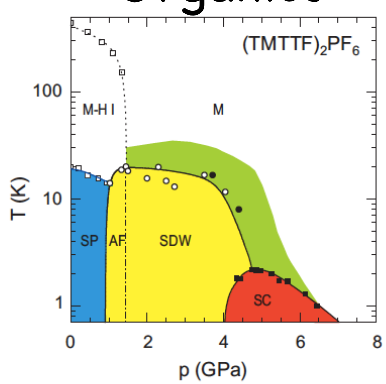
Heavy fermions



AF+SPC
Coexistence

Oxides
Insulators
Magnetism

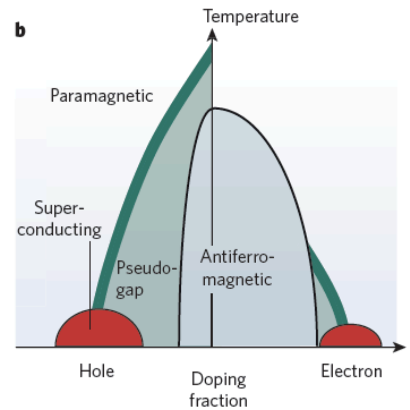
Organics



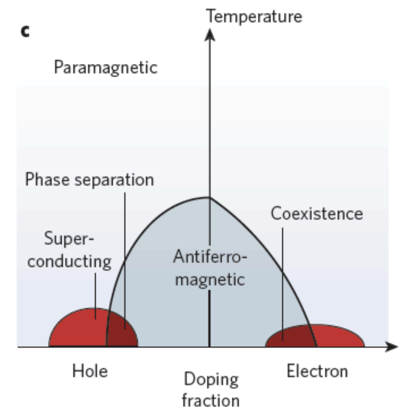
Eur. Phys. JB 21, 175

High T_c

Cuprates

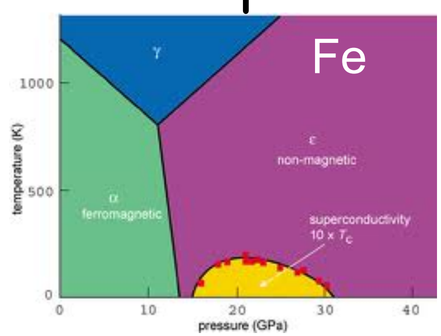


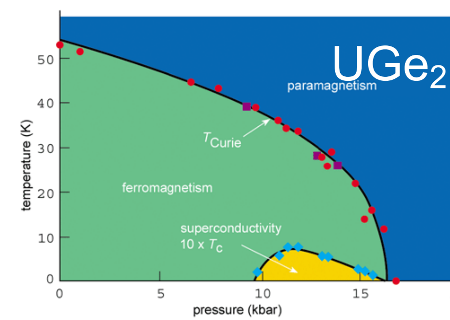
Fe-superconductors



Nature 464, 183 (2010)

FM superconductors





Physics World, Jan 2002

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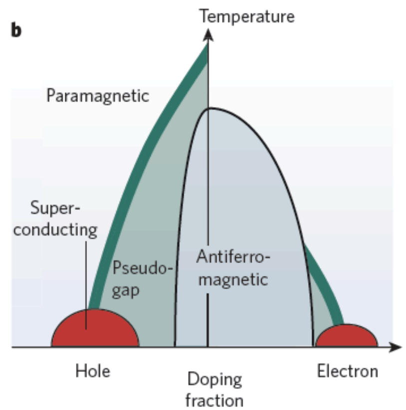
UNCONVENTIONAL SUPERCONDUCTORS

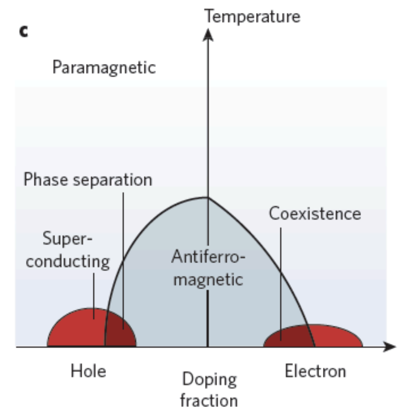
Not driven by conventional phonons.

High T_c

Cuprates

Fe-superconductors

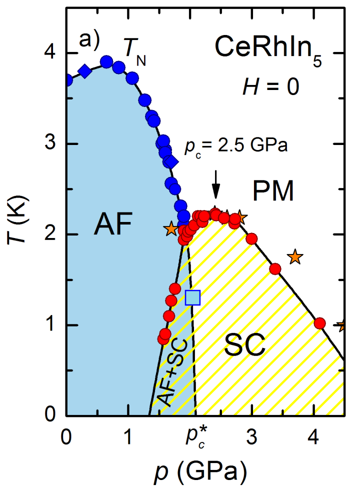




Nature 464, 183 (2010)

AF supercond.

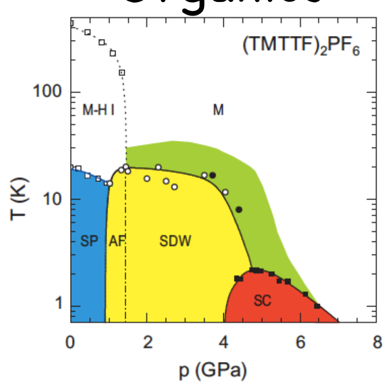
Heavy fermions



AF+SPC Coexistence

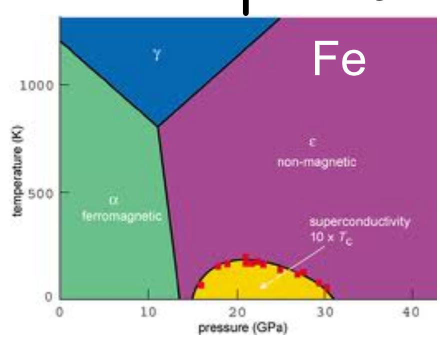
Oxides
Insulators
Magnetism

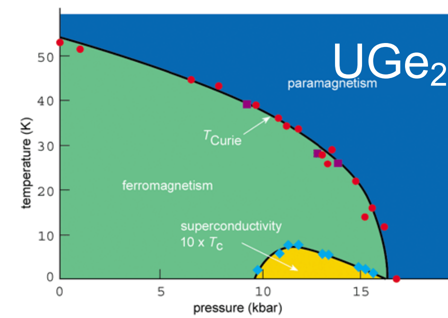
Organics



Eur. Phys. JB 21, 175

FM superconductors





Physics World, Jan 2002

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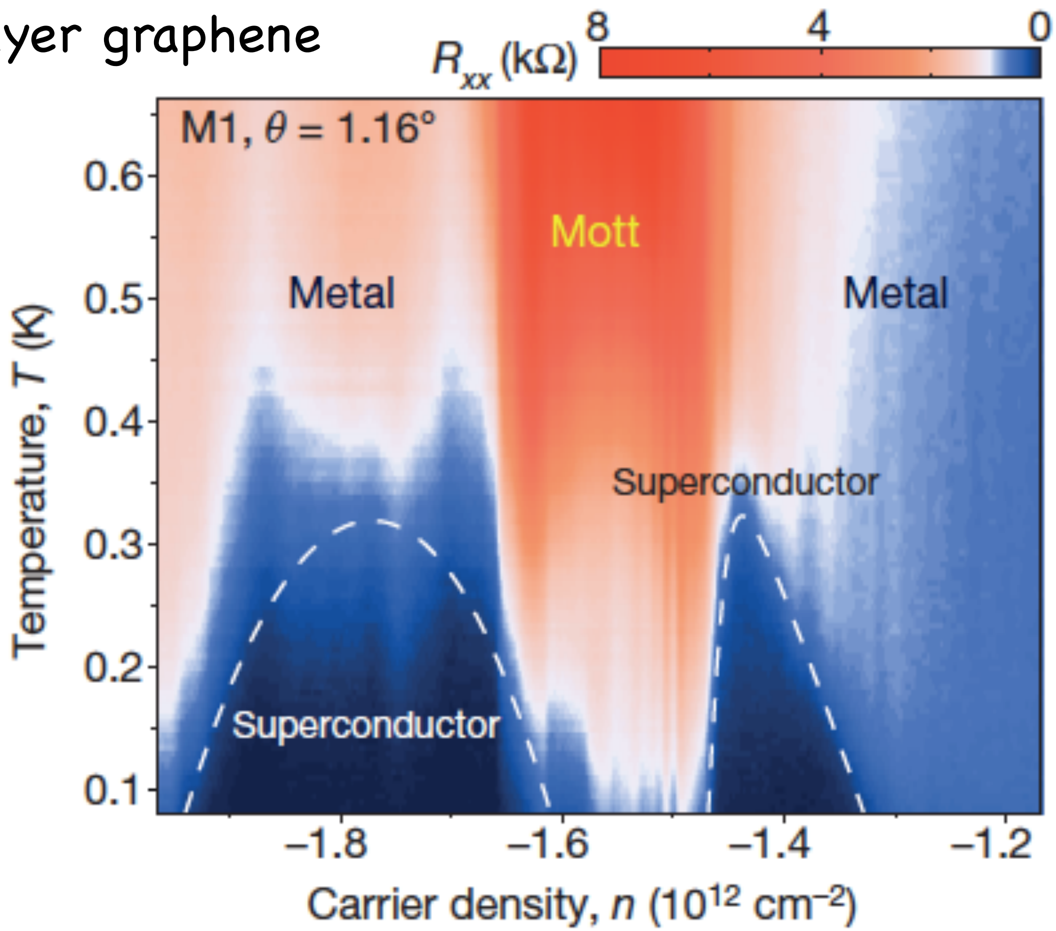
UNCONVENTIONAL SUPERCONDUCTORS

Not driven by conventional phonons?

Magic angle twisted bilayer graphene



Cao et al, Nature 556, 43 (2018); 556, 80 (2018)

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UNCONVENTIONAL SUPERCONDUCTORS

The "normal" state is more complicated

- Proximity or coexistence with magnetism
- Strong correlations.
  - Competing orders (stripes).
  - Is there a Fermi surface? Doped Mott insulator. Non-Fermi liquid behaviour. Pseudogap phase in cuprates.
- Low dimensionality, anisotropies.

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UNCONVENTIONAL SUPERCONDUCTORS

The superconducting state is different

The pairing function Δ_k may

- Be non-isotropic (including nodes, sign changes)
- Have a finite orbital momentum (p, d)
- Be spin-triplet

- High superconducting T_c
- $\lambda >> \xi$ (type II)
- Anisotropies

$$\frac{2\Delta}{k_B T_c} >> 3.53$$

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Many theories.
2 distinct approaches to the problem:

- Stay within BCS but a new pairing (glue) mechanism is needed (maybe spin fluctuations, some kind of electron-phonon interaction).

- Start from the Mott state (no boson exchange required) and see how to gain energy from pairing
  - Resonating valence bonds
  - Kinetic energy driven
  - Quantum criticality…

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Many theories.
2 distinct approaches to the problem:

- Stay within BCS but a new pairing (glue) mechanism is needed (maybe spin fluctuations, some kind of electron-phonon interaction).

  A: We know how to deal with it.
  D: Usually there is no Fermi surface. Note: Fe superconductors are not Mott insulators; their AF state is a metal.

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Many theories.
2 distinct approaches to the problem:

- Start from the Mott state
  - Resonating valence bonds
  - Kinetic energy driven
  - Quantum criticality…

A: It seems, in principle, more self-consistent.
D: We need to properly treat the Mott state first!!

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Is it possible to have a universal theory of superconductivity?

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Assume BCS is valid for non-conventional superconductors. Then we need some attractive interaction but we don't have the help of phonons anymore! Moreover, we have a very strong electron-electron repulsive interaction.

Is there a way around it??

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PAIRING SYMMETRY

$$\psi(\vec{r}_1 s_1, \vec{r}_2 s_2) = \varphi(\vec{r}_1, \vec{r}_2)\chi(s_1, s_2)$$

Spatial Spin

Pair wavefunction must be antisymmetric

Spin singlet → even parity orbital wave function s, d
Spin triplet → odd parity orbital wave-function p, f

s-wave: conventional spc
d-wave: cuprates

p-wave Superfluidity in ^{3}He

UPt_3	p-wave	0.51K
Sr_2RuO_4	currently under revision!	0.93K

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SUPERFLUIDITY IN ^{3}HE (1972)

T_c=2.7 mK

Pairing cannot be mediated by the lattice. Nuclear forces are strongly repulsive in the core → no s-wave possible. Need of wavefunctions that vanish at r→0.

One possibility is mediation by ferromagnetic spin fluctuations: FM paramagnons (FM fluctuations suppress s-wave and enhance p-wave pairing).

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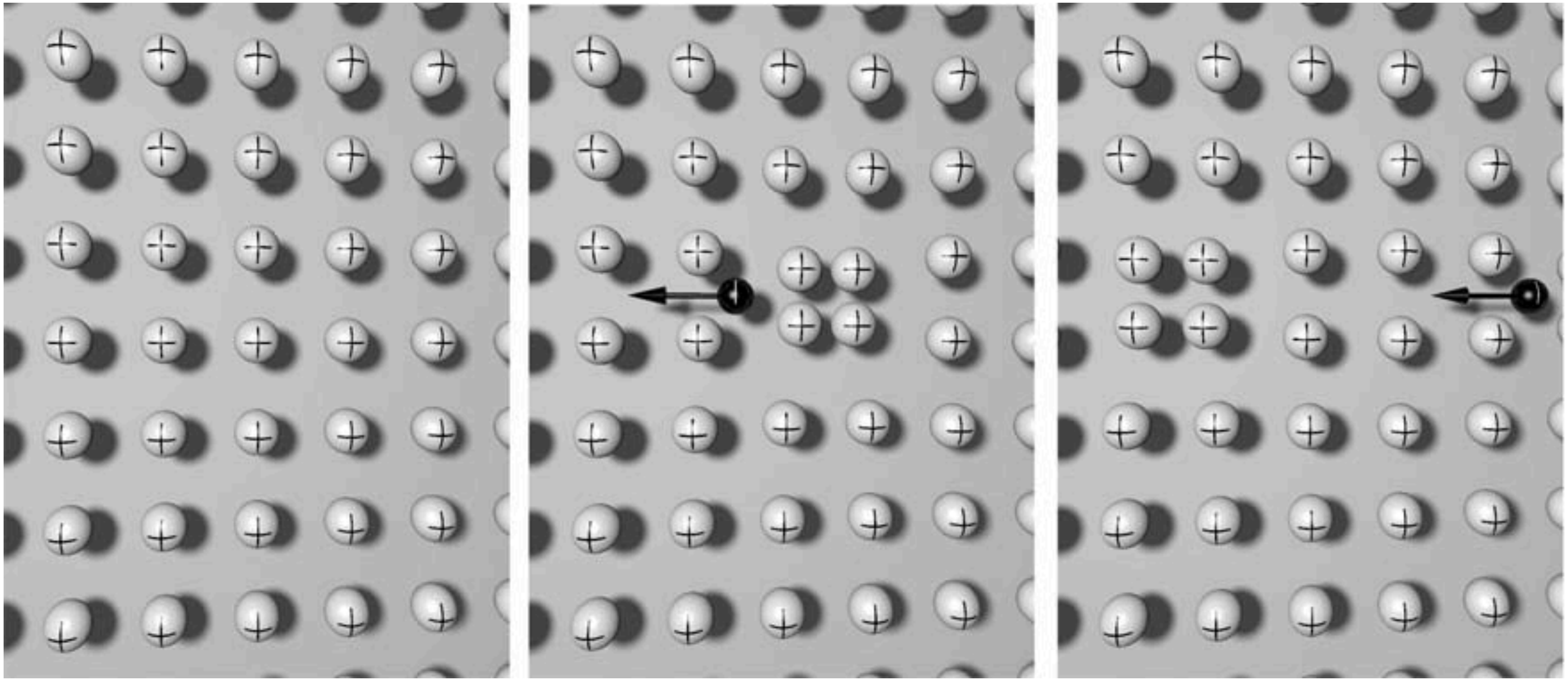
Rev. Mod. Phys. 69, 645

SUPERFLUIDITY IN ^{3}HE

Attractive interactions by ferromagnetic fluctuations:

FM clouds are formed which attract the ^{3}He quasiparticles (something like magnetic polarons instead of lattice polarons)



Blundell's book

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High angular momentum pairing (p-wave)was proposed for ^3He as a way to overcome the short range repulsion (Pitaevskii 1959)

What about non-conventional superconductors?

Mostly singlet pairs with mainly d-wave symmetry.

In iron superconductors both s and d are postulated.

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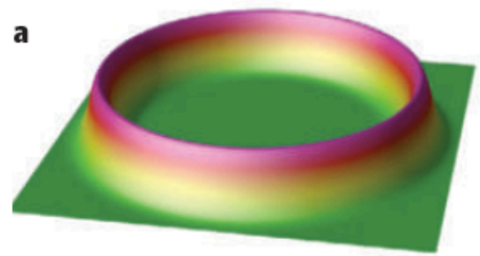
S-WAVE

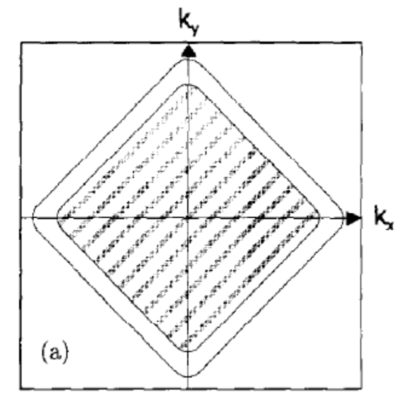
Gap equation from BCS (T=0)

$$\Delta_k = -\frac{1}{\Omega}\sum_{kk'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}}$$

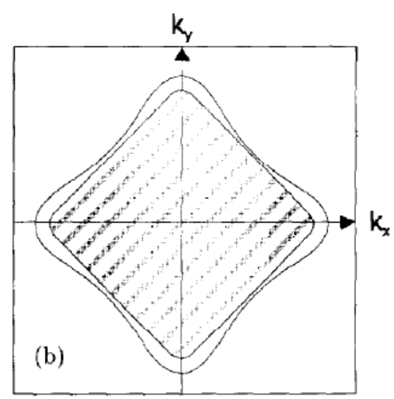
For $V_{kk'}$ constant and attractive: isotropic gap $\Delta_k = \Delta$

s wave gap
(spherical symmetry)





More generally, s-wave gap may be anisotropic with no sign changes.



Scalapino, Phys. Rep. 250,329 (1995)

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D-WAVE

Gap equation from BCS (T=0)

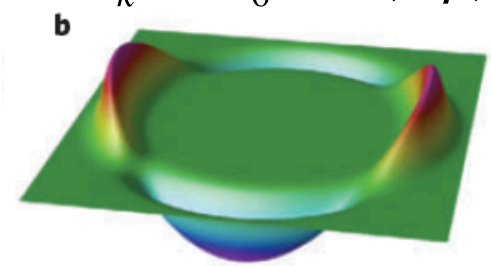
$$\Delta_k = -\frac{1}{\Omega}\sum_{kk'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}}$$

Repulsive $V_{kk'}$ ⟷ Anisotropic Δ_k with sign change!

$$\mathrm{sign}(\Delta_{\mathbf{k}}) = -\mathrm{sign}(V_{\mathbf{k},\mathbf{k}'})\mathrm{sign}(\Delta_{\mathbf{k}'}).$$

For instance, d-wave

$$\Delta_k = \Delta_0 \cos(2\phi)$$



The gap has nodes and sign changes

An anisotropic pair potential leads to an anisotropic gap

$$V_{kk'} = -V_0 \gamma_k \gamma_{k'}$$

$$\Delta_k = \gamma_k \Delta_0$$

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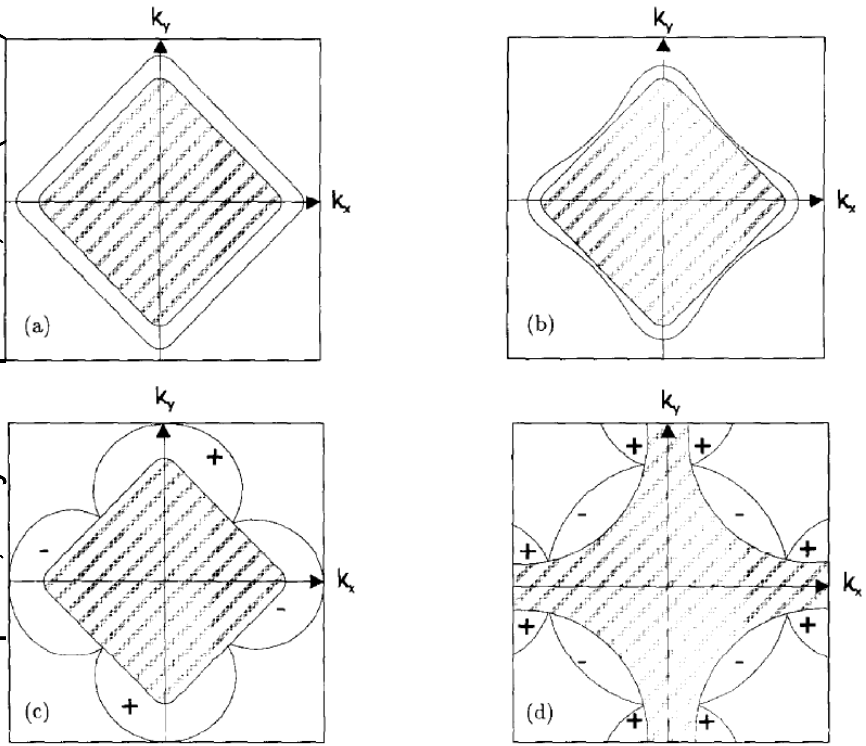
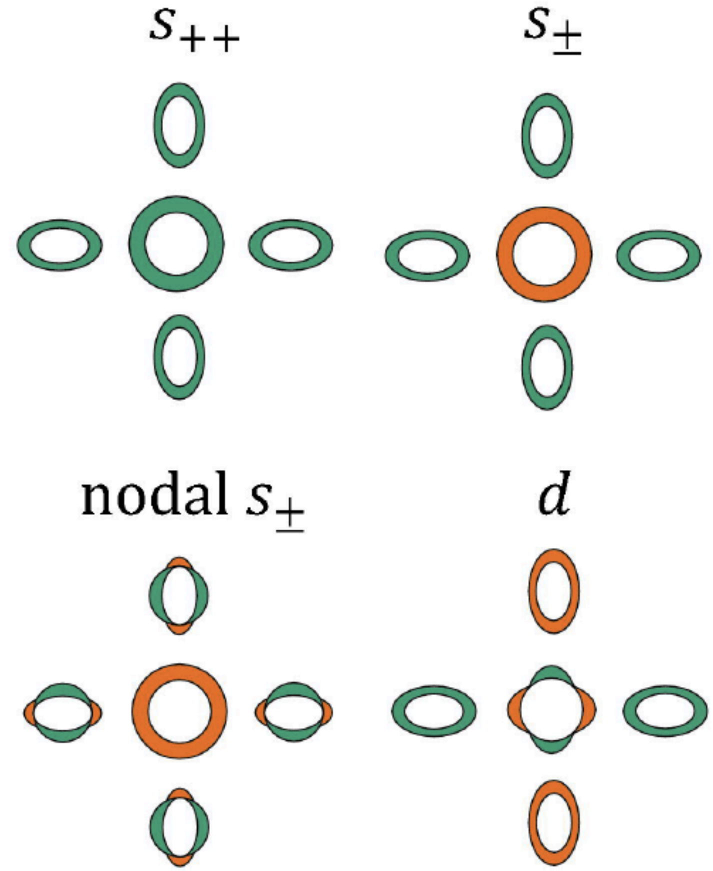
GAP SYMMETRIES…

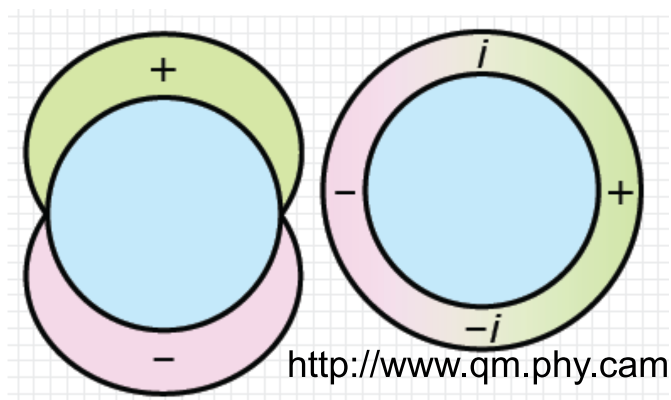
Scalapino, Phys. Rep. 250,329 (1995)



Hirshfield et al. 1106.3712



Non-isotropic gaps lead to sensitivity of unconventional SPC to non-magnetic impurities



http://www.qm.phy.cam.ac.uk/teaching/

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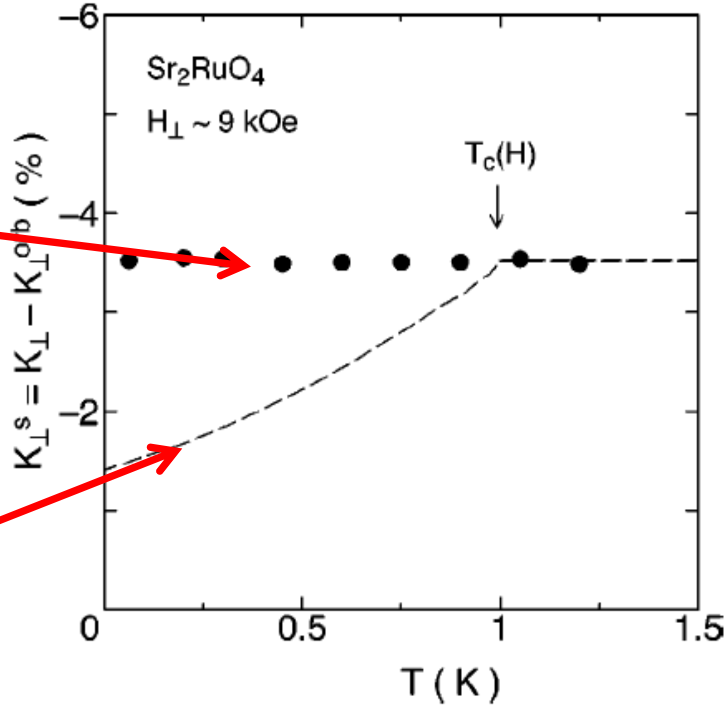
SINGLET-TRIPLET

From Knight shift experiments

triplet

Singlet
(spin quenching
at low T)



PRB 63, 060507 (2001)

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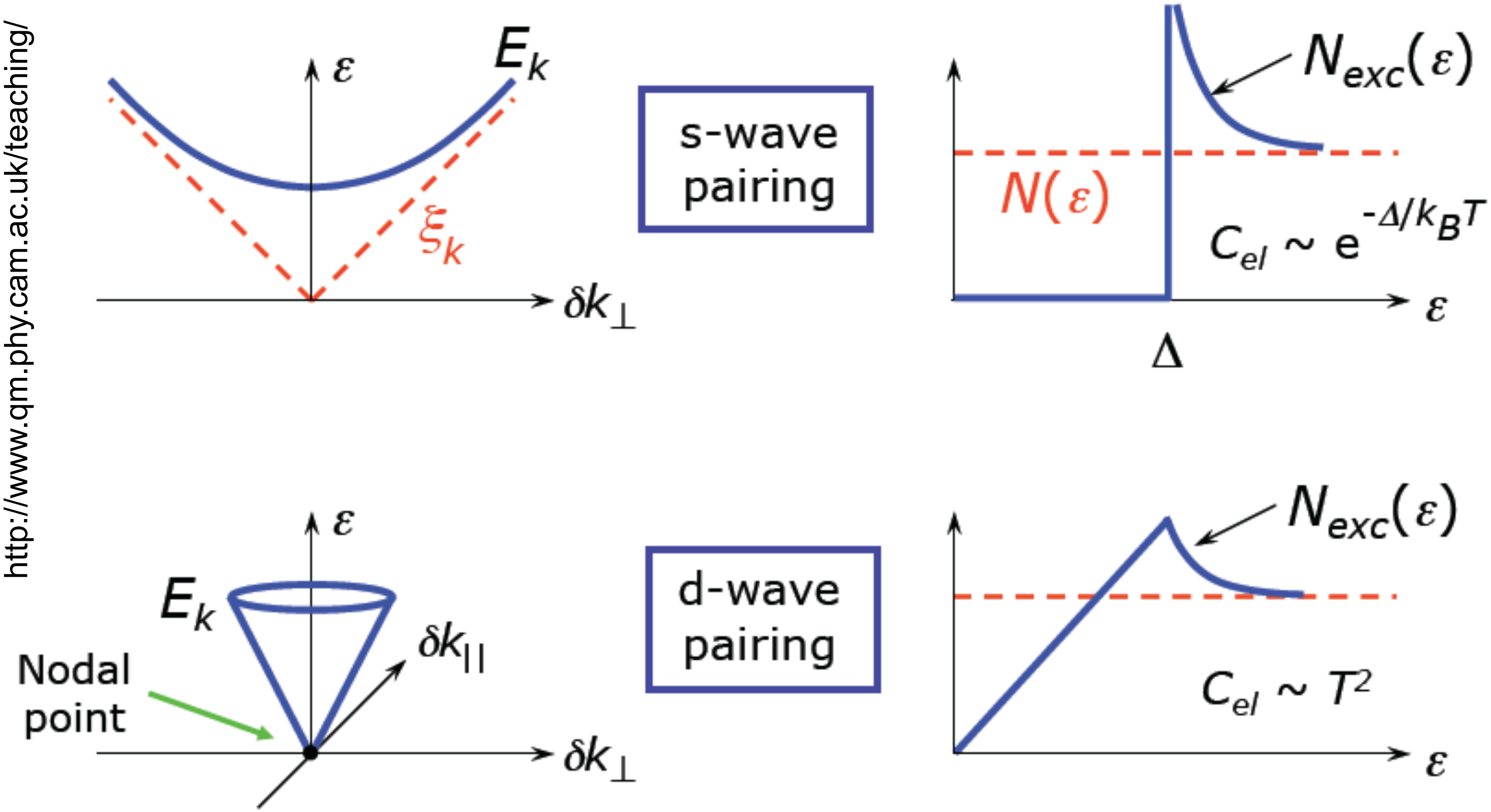
NODES VERSUS NODELESS

http://www.qm.phy.cam.ac.uk/teaching/



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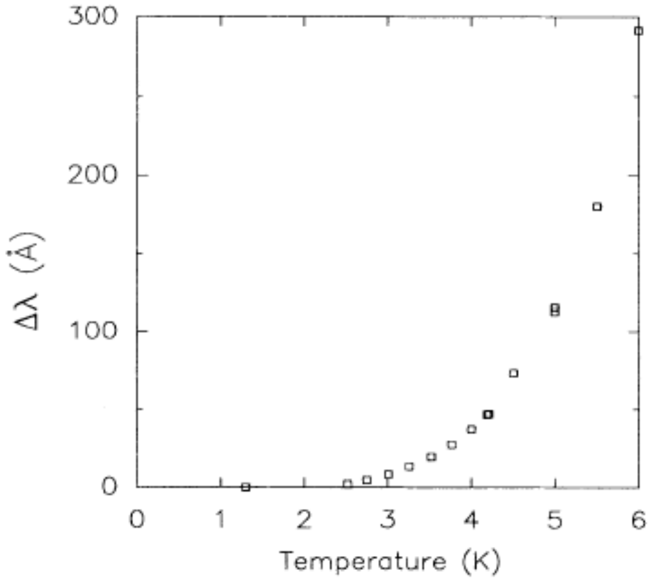
Without nodes: activated behavior (λ, specific heat…)
With nodes: power law behaviors

Gap without nodes

London penetration length within BCS

$$\frac{\Delta\lambda(T)}{\lambda(0)} \sim 3.33\left(\frac{T_c}{T}\right)^{1/2} \exp(-1.76T_c/T)$$

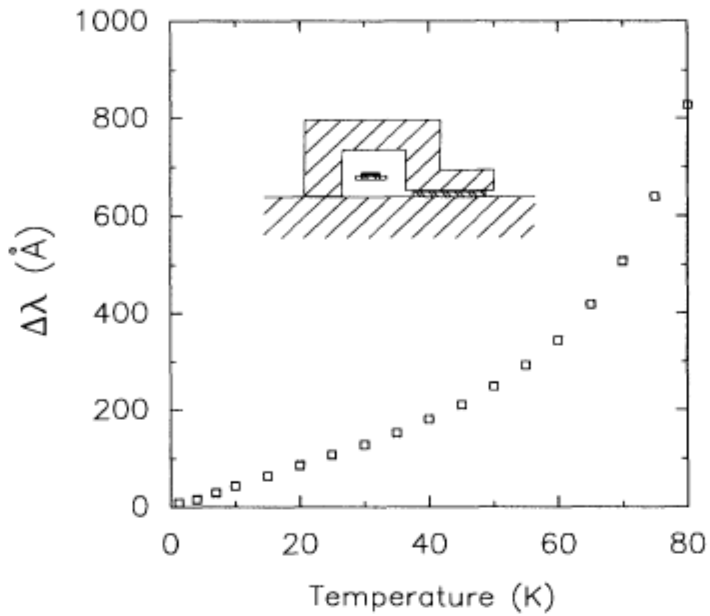


$Pb_{0.95}Sn_{0.05}$

PRL 70, 3999 (1993)

Gap with nodes

Power law dependencies



$YBa_2Cu_3O_{6.95}$

(no phase information)

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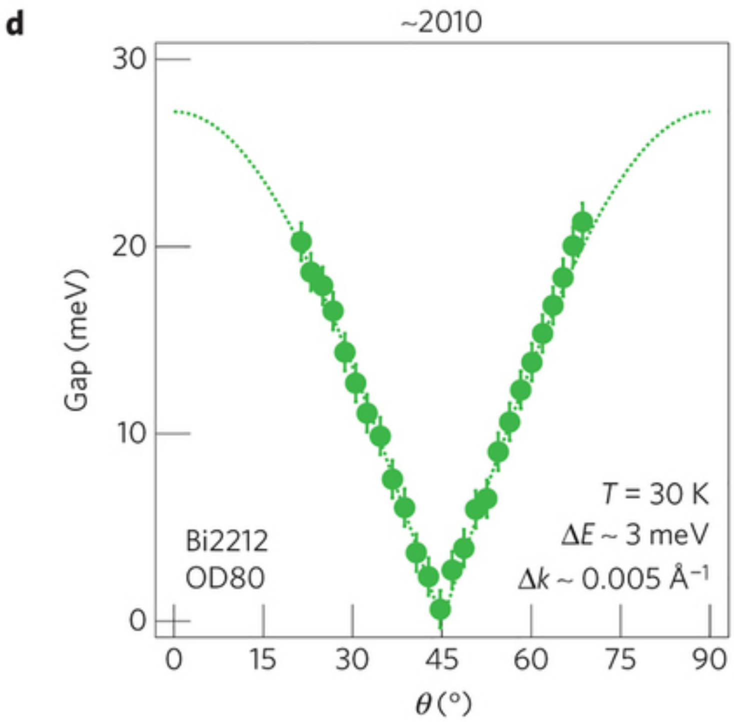
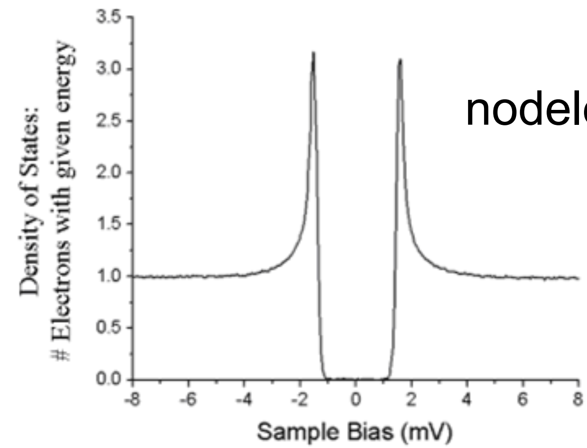
ARPES

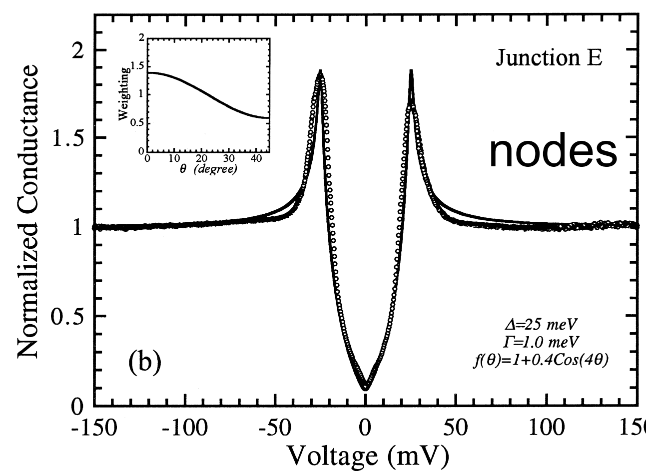


Nature Physics 10, 483–495 (2014)

(no phase information)

TUNNELING SPECTROSCOPY





www.personal.psu.edu/ewh10 Physica C 320, 9

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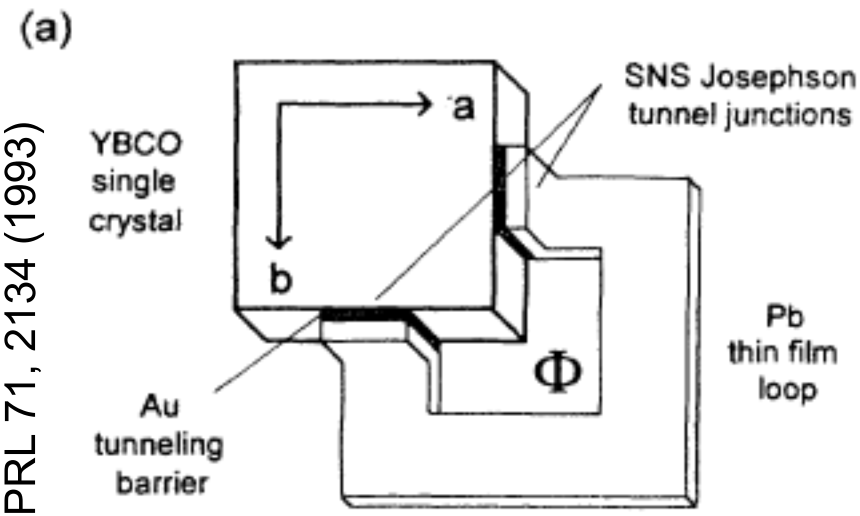
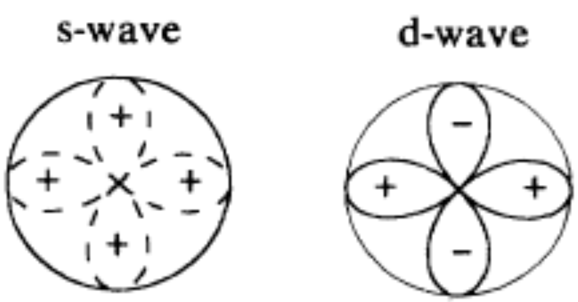
SENSITIVITY TO THE PHASE: JOSEPHSON EFFECT

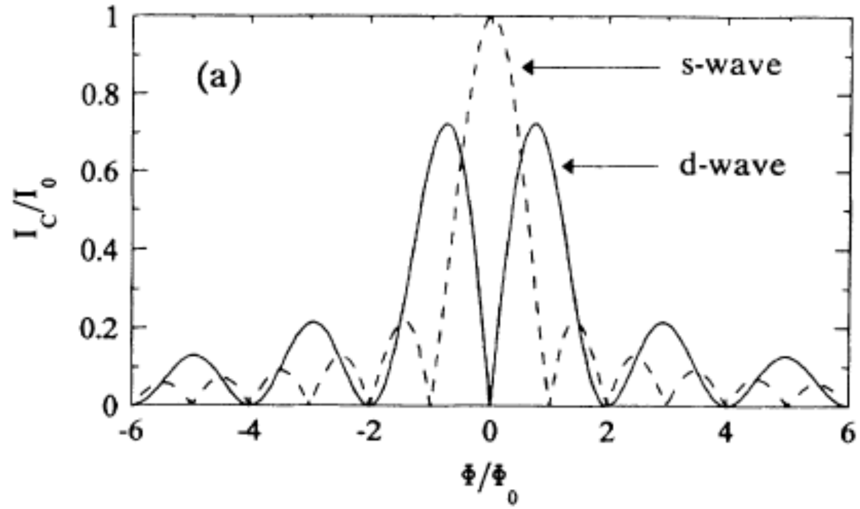
$$I_s = I_c \sin \Delta\varphi$$

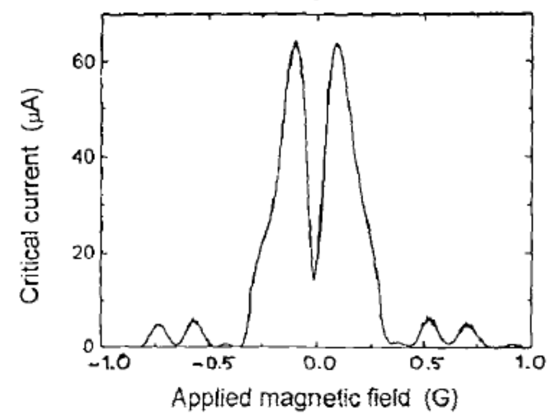
PRL 71, 2134 (1993)





Calculated critical current





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A FEW WORDS ABOUT THE MATERIALS

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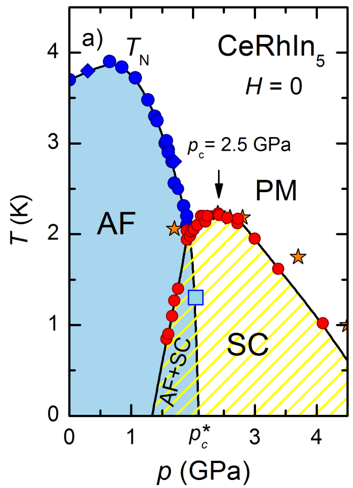
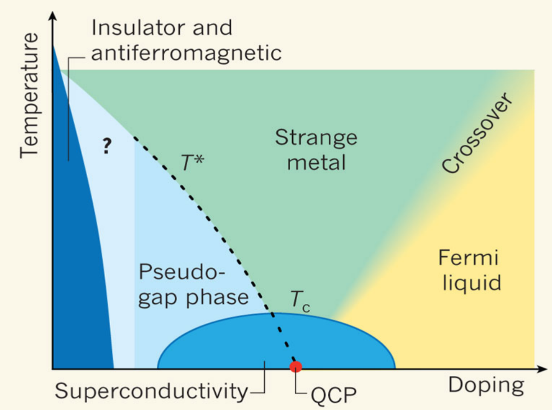
SOME TYPICAL PHASE DIAGRAMS

Heavy fermions

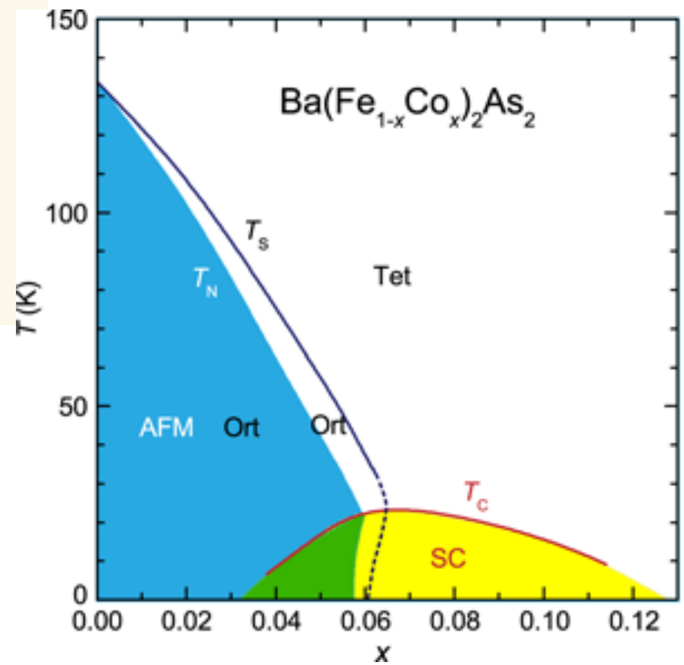


Cuprates



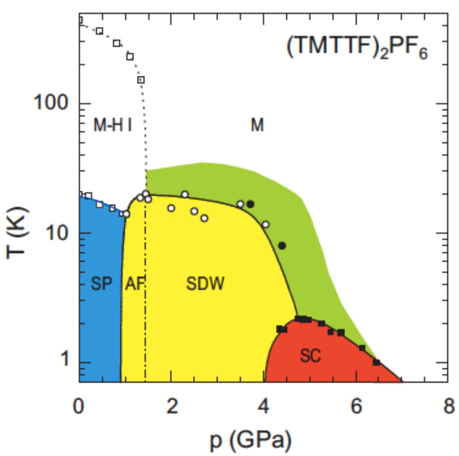
Nature 468, 184–185

Fe-superconductors



Nandi et al, PRL 104, 057006 (2010)

Organics



Eur. Phys. JB 21, 175

In common: (AF)magnetic phases

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HEAVY FERMIONS (1979)

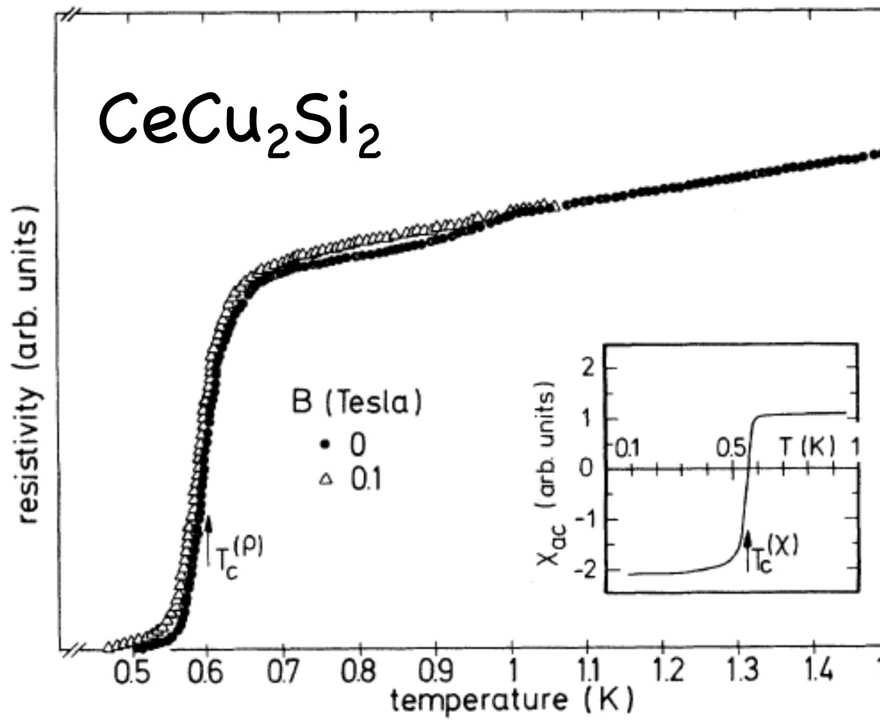
"Our experiments demonstrate for the first time that superconductivity can exist in a metal in which many-body interactions, probably magnetic in origin, have strongly renormalized the properties of the conduction-electron gas."

PRL 43, 1892 (1979)

Coexisting AF + SPC

Reentrant SPC due to competition with Kondo

Quantum criticality
Nat. Phys. 4, 186



PRL 43, 1892 (1979)

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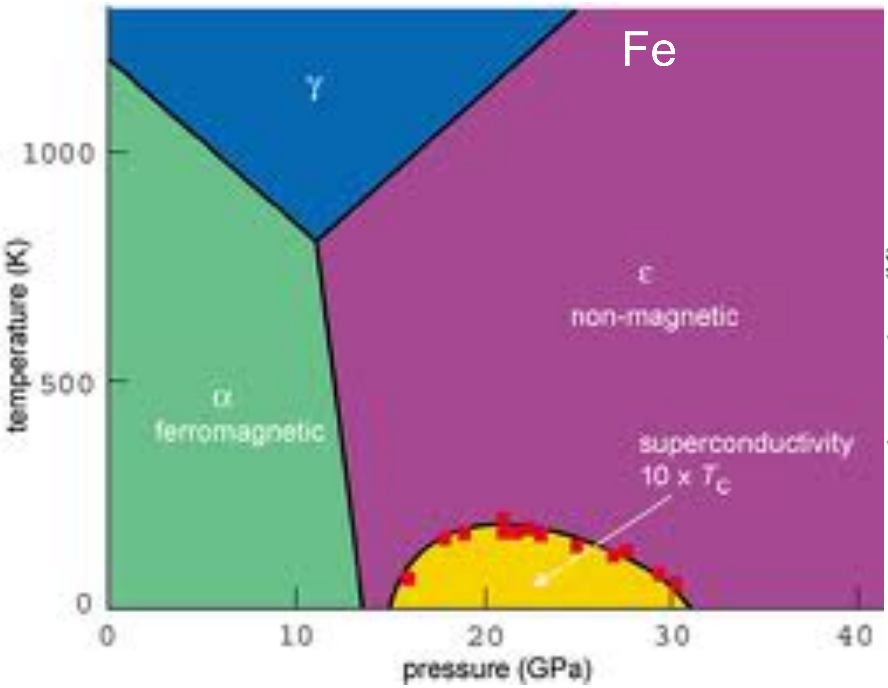
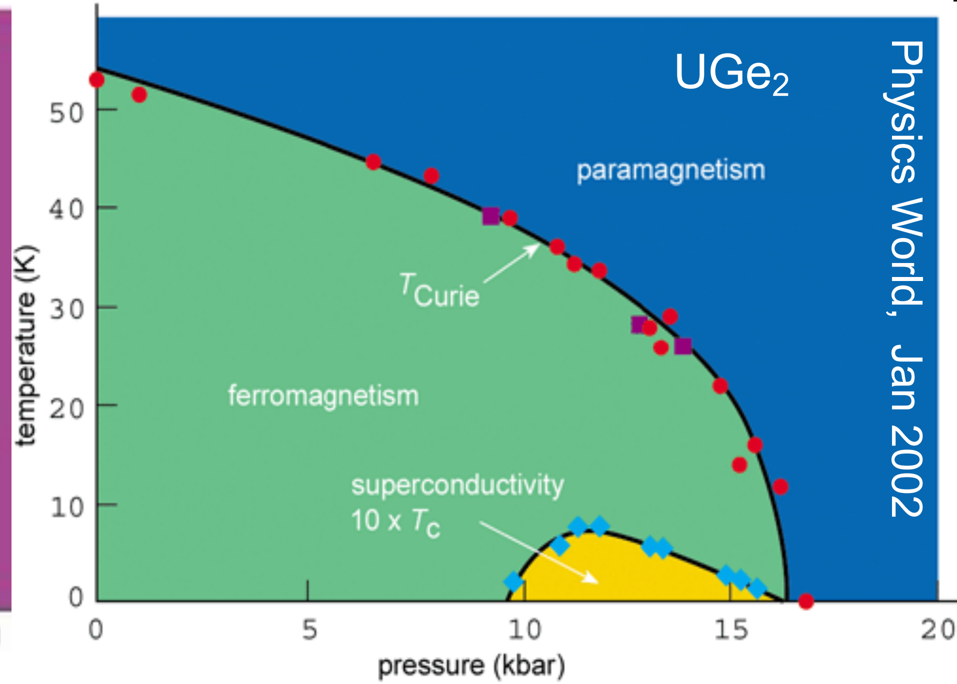
FERROMAGNETIC SUPERCONDUCTORS





Physics World, Jan 2002

Proximity of quantum critical point can lead to coexistence

Triplet pairing?

PRL 94, 097003 (2005)

CUPRATES

Layers of CuO_2. Different related structures. But note!: SPC requires coherence in 3dim.

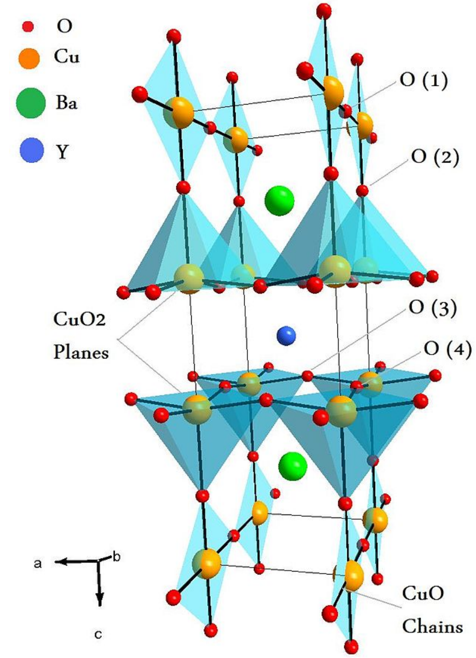
Highest Tc 134K (at ambient pressure). Tc increases with number of CuO2 planes in the unit cell (up to n=3).

Pairs were found to be singlets.

d-wave pairing was proposed in the cuprates early on.

Scalapino, Phys. Rep. 250, 329 (1995)

Undoped cuprates are correlated insulators and AF (π,π).



wikipedia

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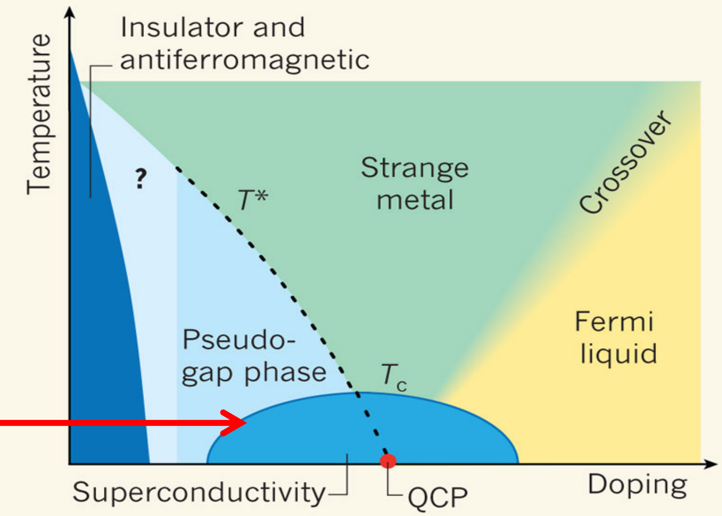
PSEUDOGAP

Spin quenching sets up at T*.

underdoped



Nature 468, 184–185

Origin?: spin-singlet formation (Anderson), pairing with short range order (preformed pairs), antiferromagnetic fluctuations, charge density wave

Is it due to fluctuations or is it a new phase (with a related broken symmetry)? Transition or crossover?

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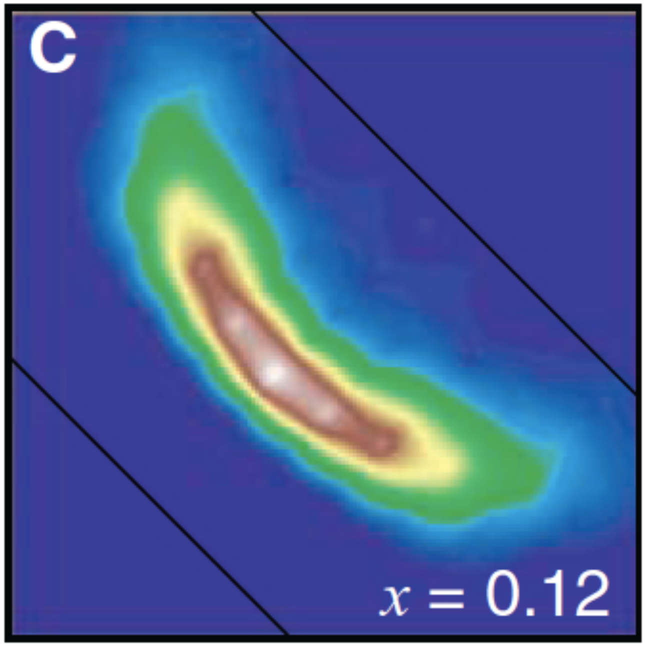
PSEUDOGAP

In other words:
Is it a precursor or a competing phase?



Science 307, 901

Norman, cond-mat:0507031
http://www.msd.anl.gov/files/msd/cuprates-columbia.pdf

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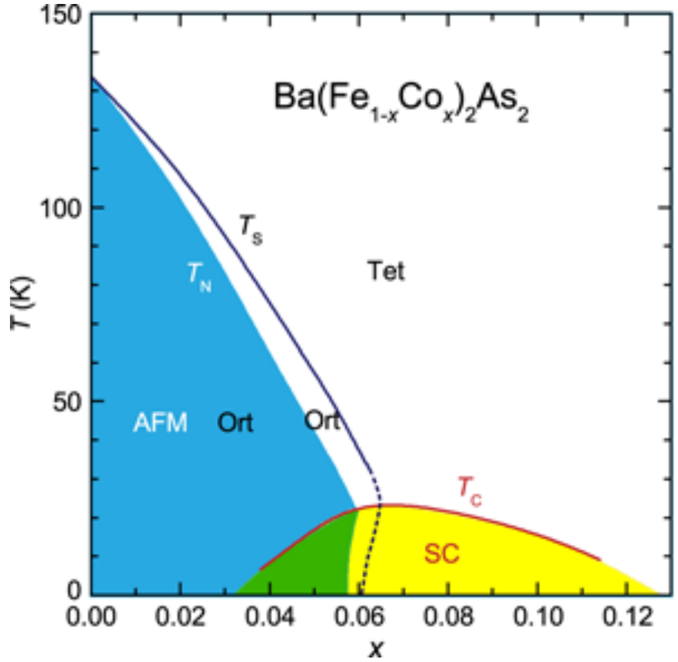
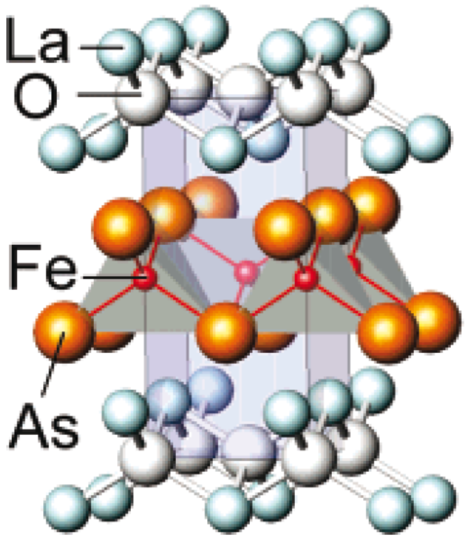
FE BASED SUPERCONDUCTORS

Many different families discovered, all sharing a Fe plane



Nandi et al, PRL 104, 057006 (2010)



An important breakthrough because it could help understand cuprates

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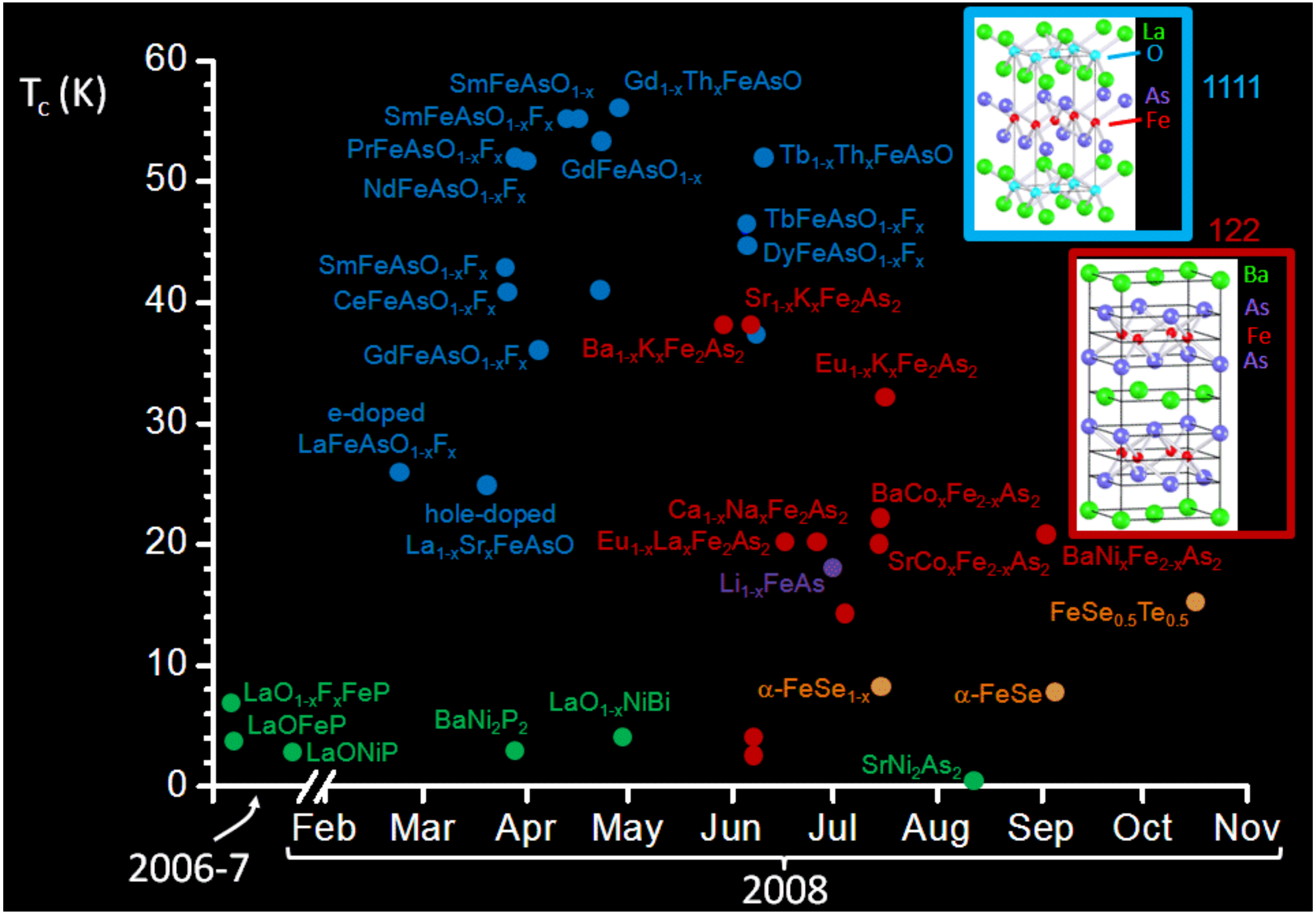

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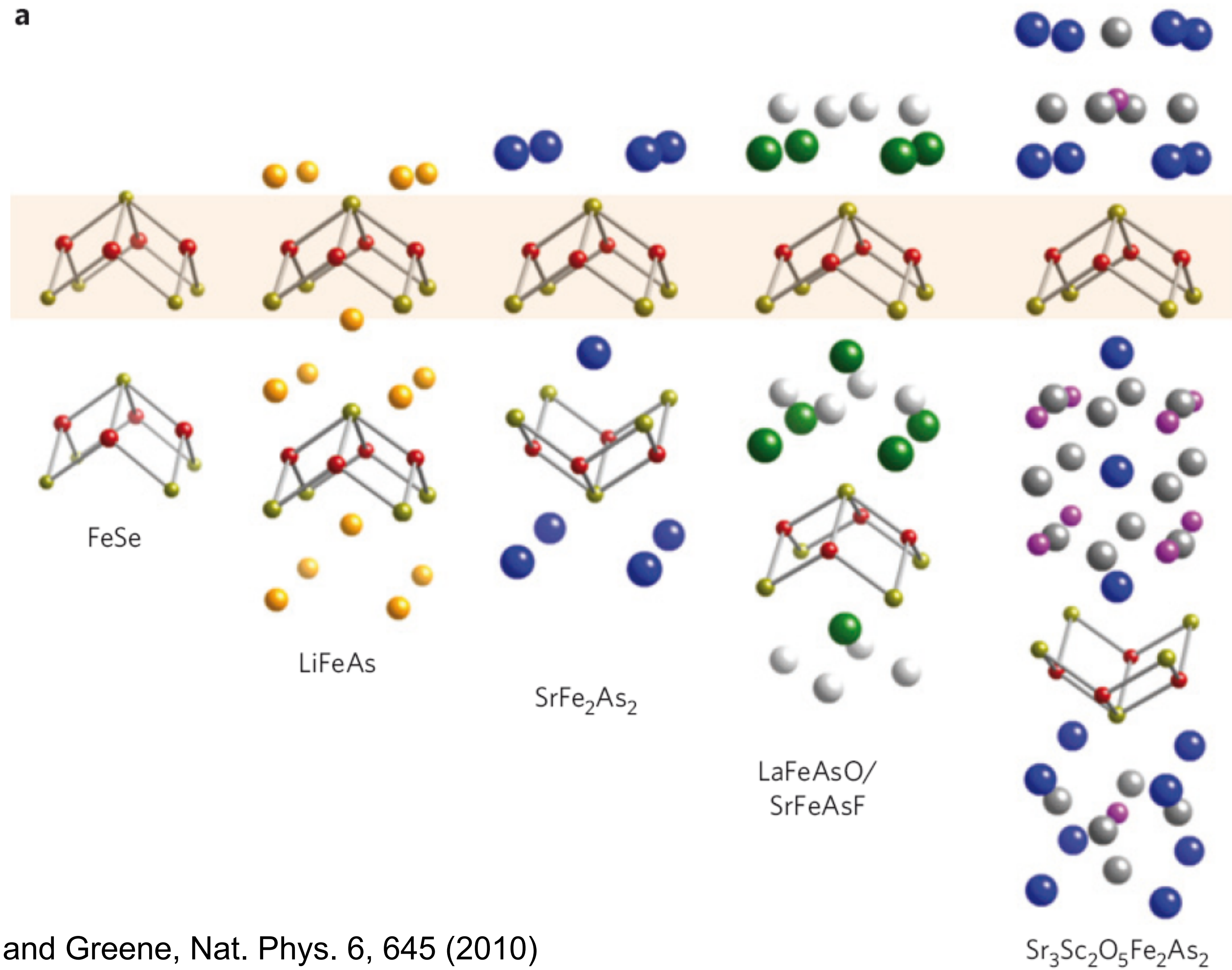
Fe-As or Fe-Se planes



Paglione and Greene, Nat. Phys. 6, 645 (2010)

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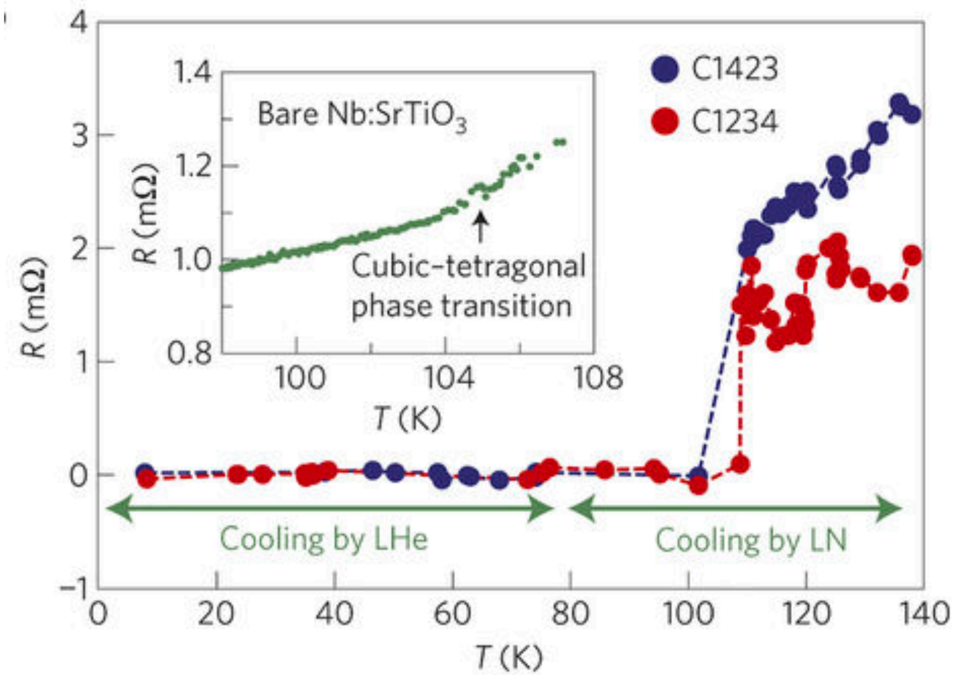
HIGHEST TC IN FE SUPERCONDUCTORS

Single layer FeSe on $SrTiO_3$

(interface superconductivity)



Nature Materials 14, 285–289 (2015)

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FE BASED SUPERCONDUCTORS

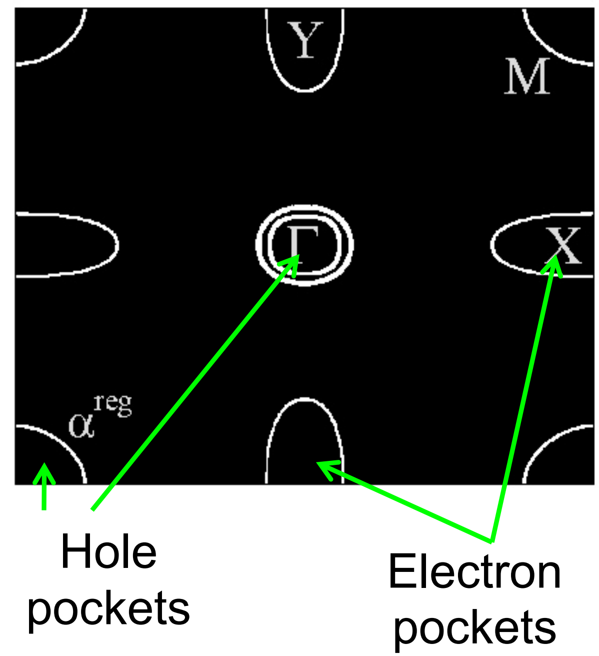
Differences with cuprates:

- The AF state is metallic (not Mott insulator): Hund metal (correlations).
- Multiorbital system (more than 1 gap possible)
- SPC can be achieved without chemical doping.
- More 3dim-like (less anisotropy in c-direction)

Proposed mechanisms for superconductivity

- Spin fluctuations (π,0)
- Orbital fluctuations

Extended BZ (1 Fe unit cell)



Gap symmetry

Family	Full gap	Highly anisotropic	Strong nodal
1111	$PrFeAsO_{1-y}$[52K] [293] SmFeAs(O,F)[55K] [295]	LaFeAs(O,F)[26K] [214] NdFeAs(O,F) [214]	LaFePO[6K] [203, 204, 294]
122	$(Ba,K)Fe_2As_2$[40K] [146, 236, 296, 242] $Ba(Fe,Co)_2As_2$ [OP,23K] [238, 208]	$Ba(Fe,Co)_2As_2$ [OD] [238, 241]* $Ba(Fe,Ni)_2As_2$ [297]* $Ba(Fe,Co)_2As_2$ [UD] [241]*	KFe_2As_2 [4K] [211, 309] $BaFe_2(As,P)_2$[OP,31K] [205, 149] $(Ba,K)Fe_2As_2$ [UD] [242]
111	LiFeAs [18K] [298, 258]		LiFeP [6K] [299]
11		Fe(Se,Te) [27K] [231, 246]	

arXiv:1106.3712

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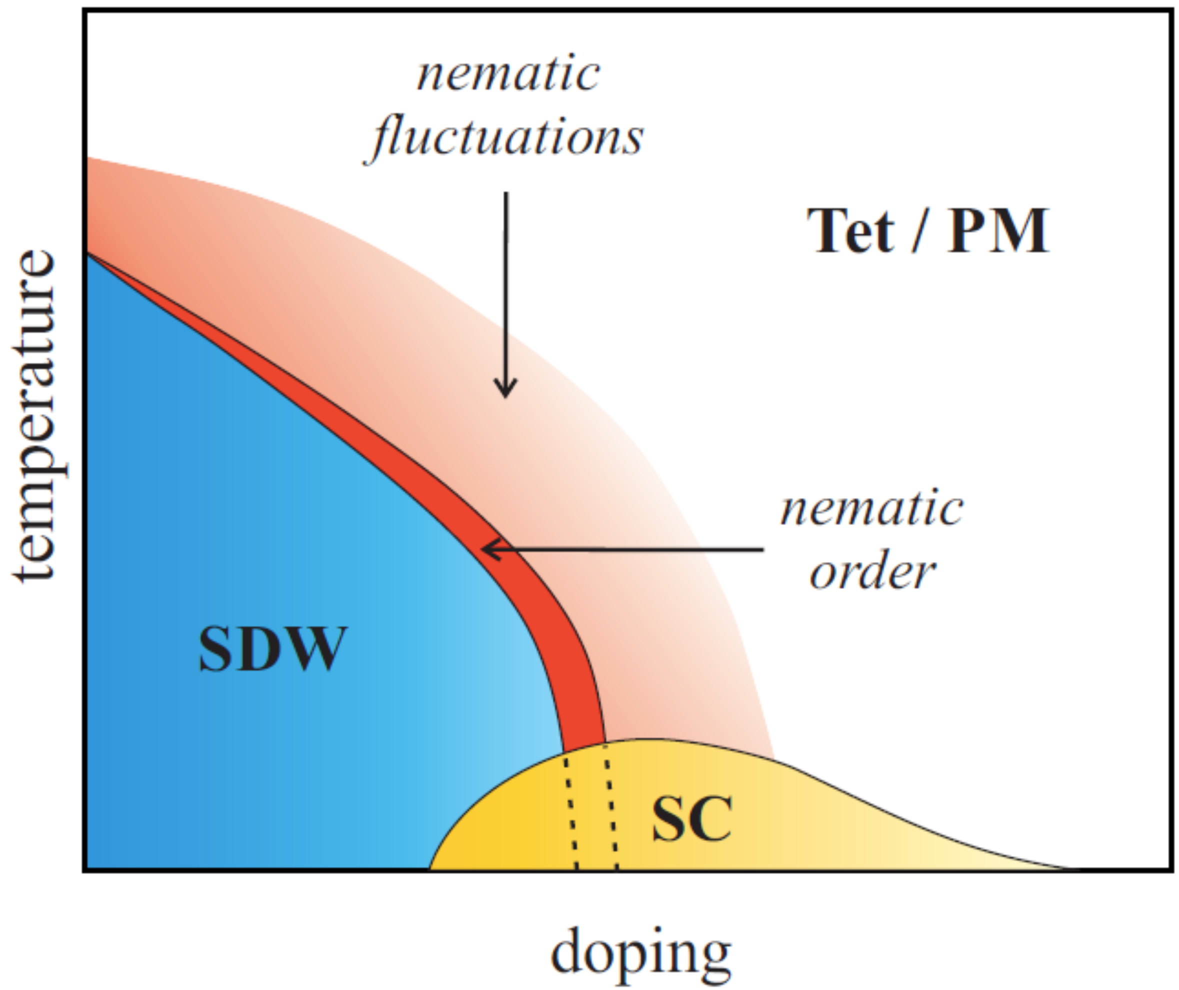
FE BASED SUPERCONDUCTORS

Role of <u>nematicity</u>?

Breaks the tetragonal symmetry.

Related to magnetic fluctuations.

Nematic order postulated for the pseudogap in cuprates.



http://www.ifsc.usp.br/coloquio/2013/Fernandes.pdf

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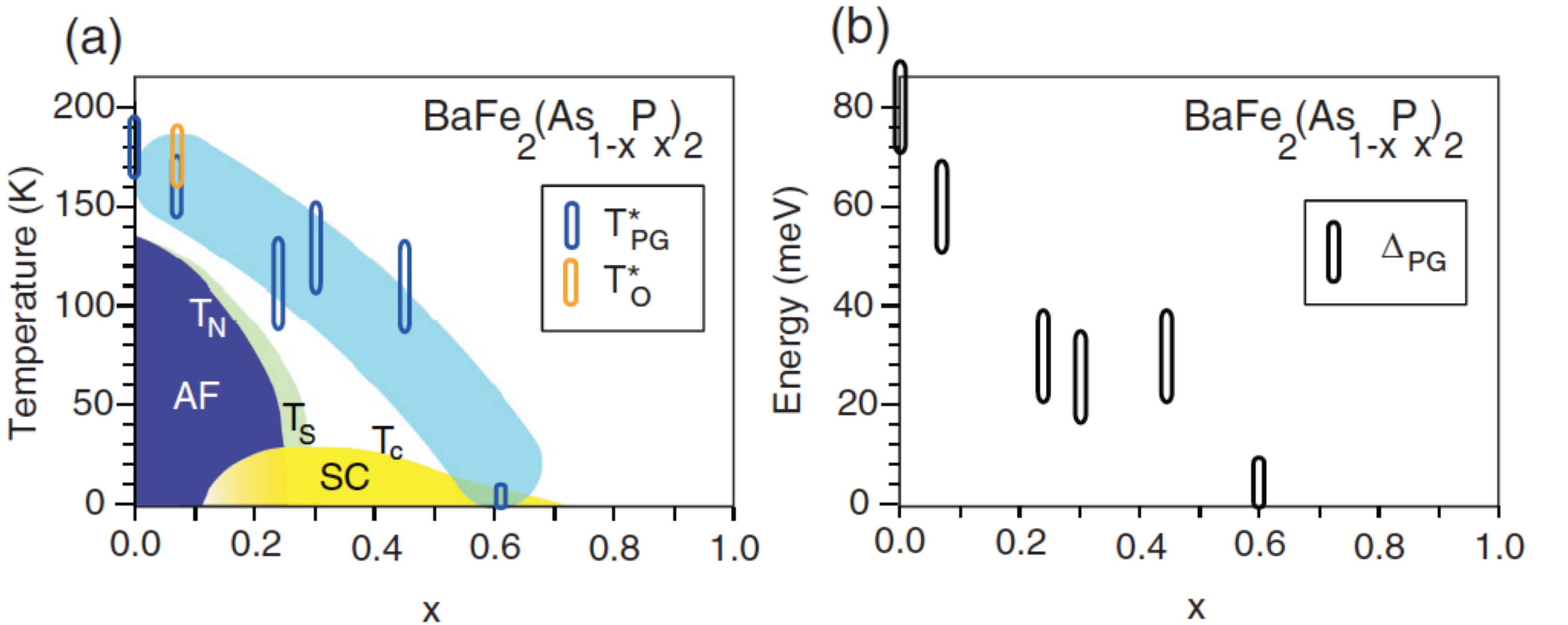
FE BASED SUPERCONDUCTORS

Pseudogap

Gap opening due to spin fluctuations:
Nat. Comm. **2**, 392 (2011)



Accompanied by orbital ordering. PRB 89, 045101 (2014)

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MECHANISMS

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SPIN-FLUCTUATION MECHANISM

Spin fluctuations play the role of phonons (à la BCS).

The "normal" state can be described as a nearly AF Fermi liquid (unconventional Fermi liquid close to an AF instability).

Note: calculating the effective interaction is not trivial because vertex corrections can be important (Migdal's theorem doesn't apply)

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SPIN-FLUCTUATION MECHANISM

If the magnetic susceptibility has a peak at q (remember nesting) the interaction is also peaked at q and positive.

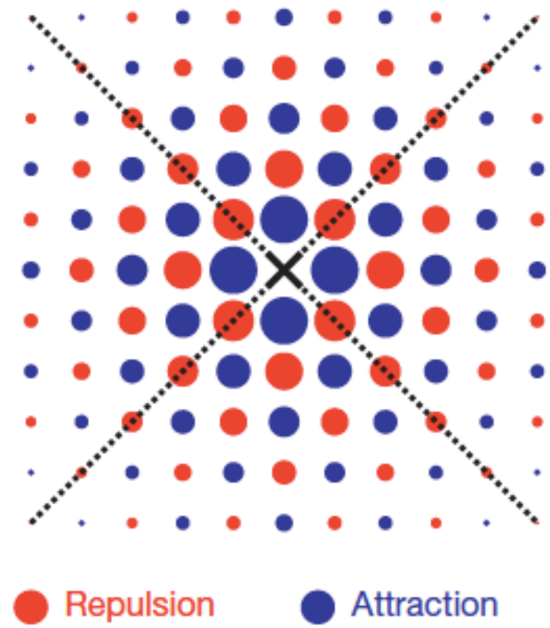
$$\Gamma_s(\boldsymbol{k},\boldsymbol{k}') = \frac{3}{2}U^2\frac{\chi_0(\boldsymbol{q})}{1-U\chi_0(\boldsymbol{q})}$$

If you look at the interaction in real space

It changes sign with position!!

Attractive interaction by space avoidance

q=(π,π)



Nature 450, 1177 (2007)

Scalapino, Phys. Rep. 1995
Hirshfield et al. 1106.3712

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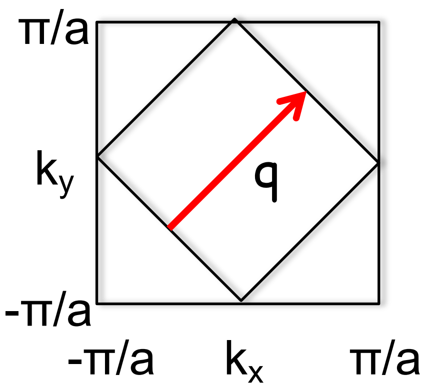
SPIN-FLUCTUATION MECHANISM

Square lattice at half-filling:



At q=(π,π) the spin susceptibility is maximal (nesting)

$$V_{k,k'} = V_{k-k'} = V_q \propto \chi_q > 0 \qquad q = (\pi,\pi)$$

To fullfil the gap equation, you need an anisotropic gap such that

$$\Delta_k = -\frac{1}{\Omega}\sum_{kk'} V_{kk'} \frac{\Delta_{k'}}{2E_{k'}}$$

$$\mathrm{sign}(\Delta_{\mathbf{k}}) = -\mathrm{sign}(V_{\mathbf{k},\mathbf{k}'})\mathrm{sign}(\Delta_{\mathbf{k}'}).$$

d-wave

$$\Delta_k = \frac{\Delta_0}{2}(\cos k_x - \cos k_y)$$

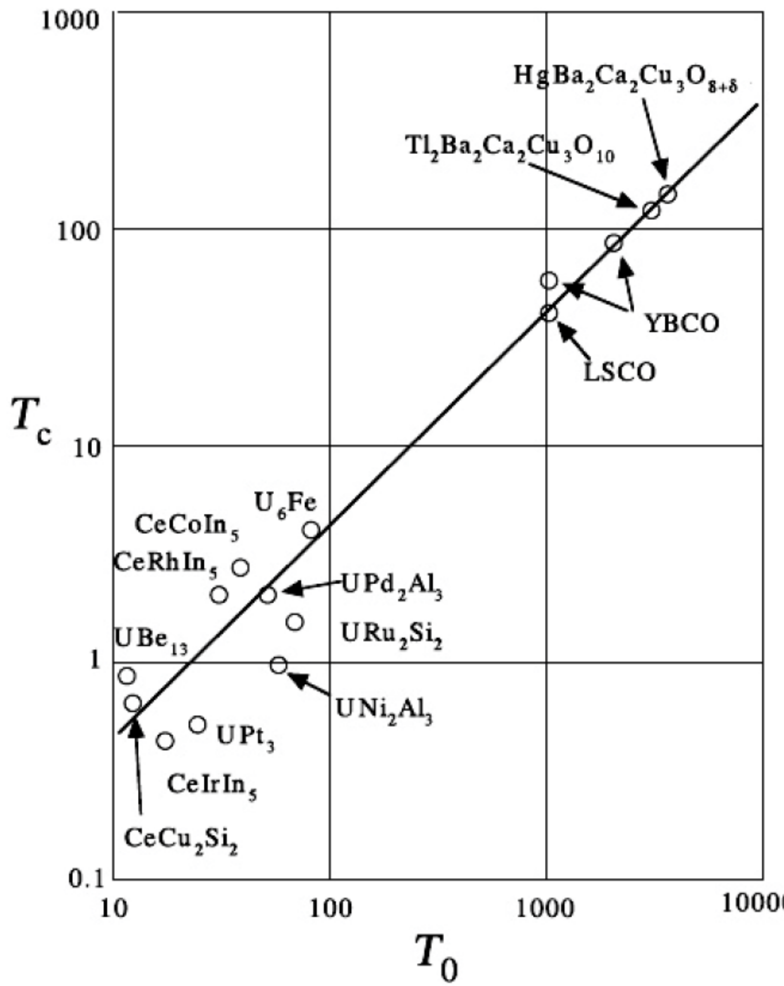
$$\Delta_{k+(\pi,\pi)} = \frac{\Delta_0}{2}(-\cos k_x + \cos k_y) = -\Delta_k$$

Scalapino, Phys. Rep. 1995
Hirshfield et al. 1106.3712

SPIN-FLUCTUATION MECHANISM

Correlation between Tc and a typical energy scale of spin fluctuations.

In the Scalapino approach, the t-J model is the basis for understanding.



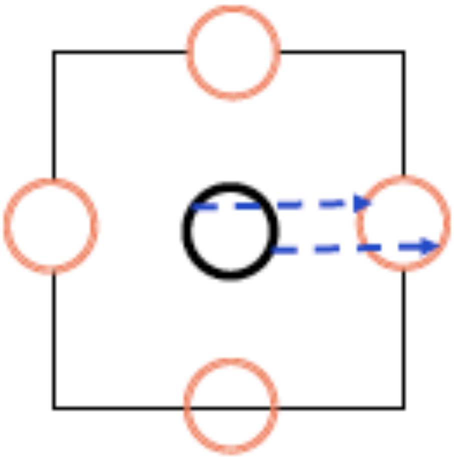
Moriya-Ueda, Rep. Prog. Phys. 66, 1299 (2003)

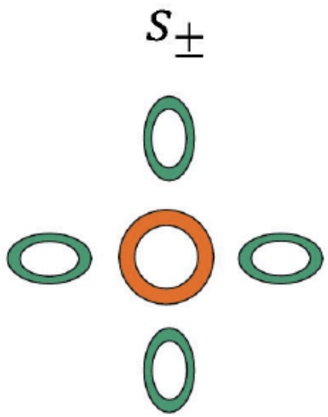
Scalapino, Rev. Mod. Phys. 84, 1383 (2012)

SPIN-FLUCTUATION MECHANISM

For a murtiorbital system (as Fe-superconductors)

For instance, spin fluctuations related to nesting between electron and hole pockets: $q=(\pi,0)$





This would lead to an $s_{\pm}$

(as the order parameter averages to zero on the Fermi surface, you also get "Coulomb avoidance")

arXiv:0901.4790

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ELECTRON-PHONON

Not discarded!

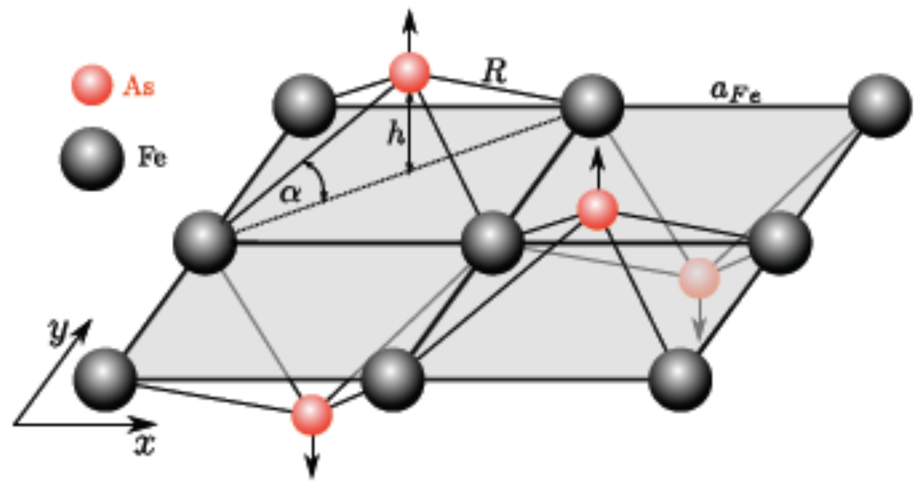
For cuprates: Phys. Rev. Lett. 105, 257001

Maybe coupled to other degrees of freedom?

For Fe-superconductors

Spin-phonon?

Adv. in Cond. Matt. Phys. 2010, 164916 (2010)



PRB 88, 165106 (2013)

Orbital fluctuations induced by electron-phonon.

PRL 104, 157001

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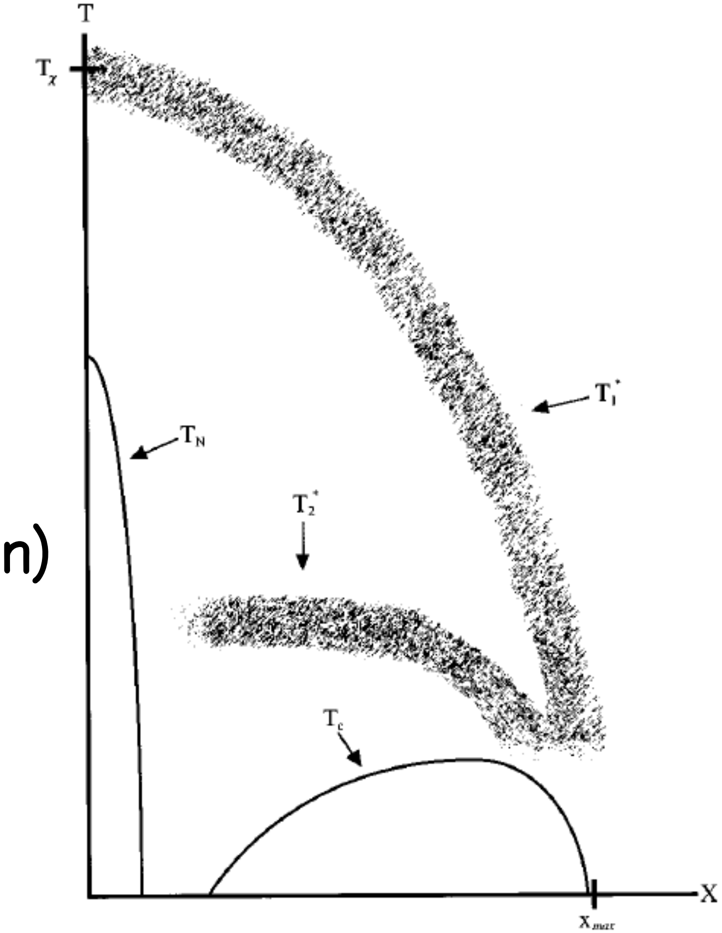
KINETIC ENERGY DRIVEN MECHANISM

Carlson et al, Chapter 21

Different energy scales involved for underdoped cuprates



T*: Phase transition or crossover
(no exp. evidence of phase transition)

$T_c < T^*_{pair} < T^*_{stripe}$

PRB 56, 6120

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KINETIC ENERGY DRIVEN MECHANISM

Carlson et al, Chapter 21

Different energy scales involved for underdoped cuprates

At T^*_{stripe}: stripe formation. Stripes are rivers of charge where holes can move (gain kinetic energy in 1dim). In between, AF regions where the carriers are localized.

At T^*_{pair}: local pairing (spin-gap) within the 1DEGs (stripes). Pairs can tunnel to neighboring 1DEG (which in principle has another k_F). This way the system gains kinetic energy in a perpendicular direction as well. There is finite Δ but not fixed phase.

At T_c: phase coherence sets in (Josephson coupling between stripes) → superconductivity.

$$T_c < T^*_{pair} < T^*_{stripe}$$

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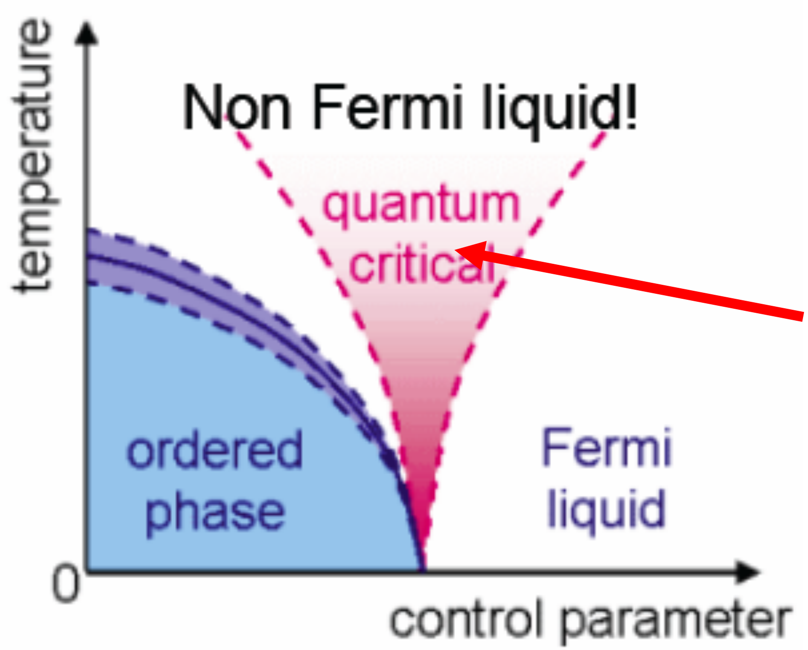
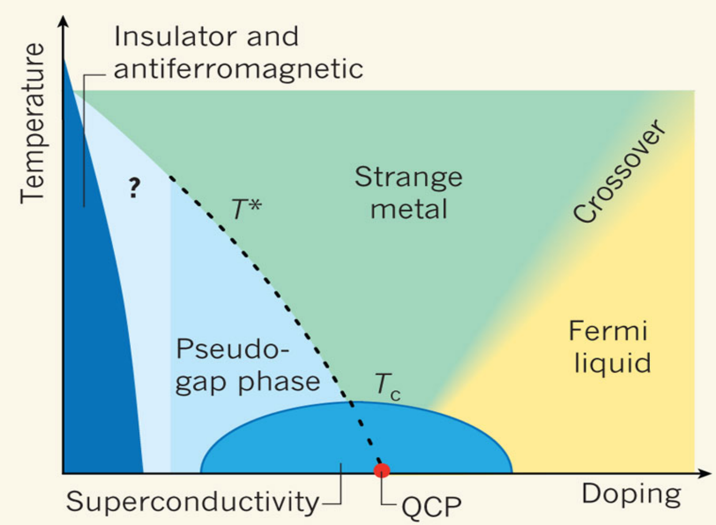
QUANTUM PHASE TRANSITIONS



Region in which termal and quantum fluctuations are equally important

Transition at T=0 with consequences for T>0.

Divergence of time coherence.



Nature 468, 184–185

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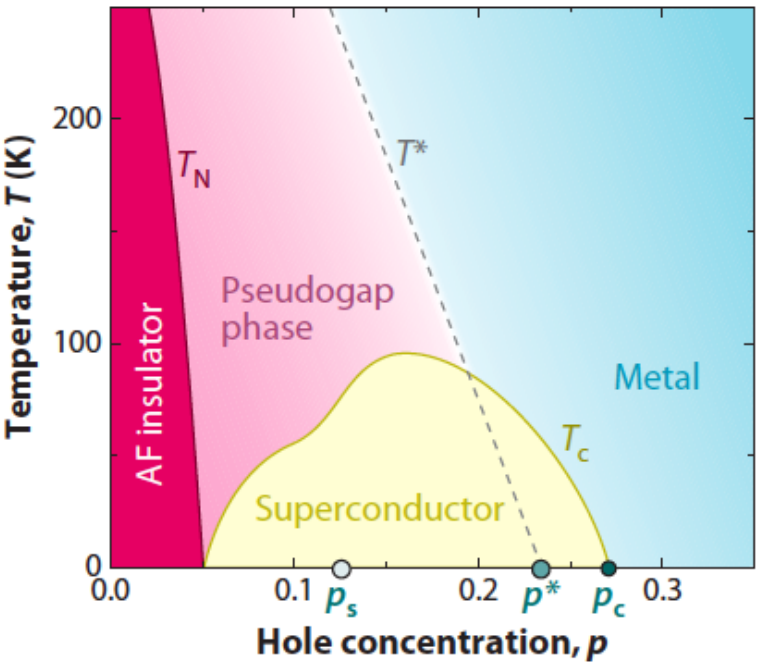
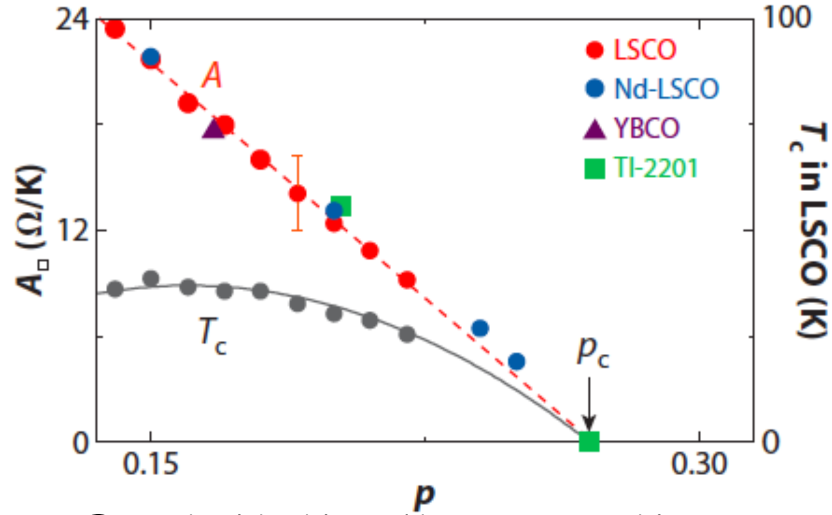
Taillefer Annu Rev Cond Matter Phys (2010)





Resistivity linear with T above the spc phase appears at p_c (doping at the Quantum Critical Point).

Linear T resistivity coming from fluctuations in the pseudogap phase (spin density wave order).

In organic spc and Fe pnictides, similar phenomena coming from spin fluctuations.

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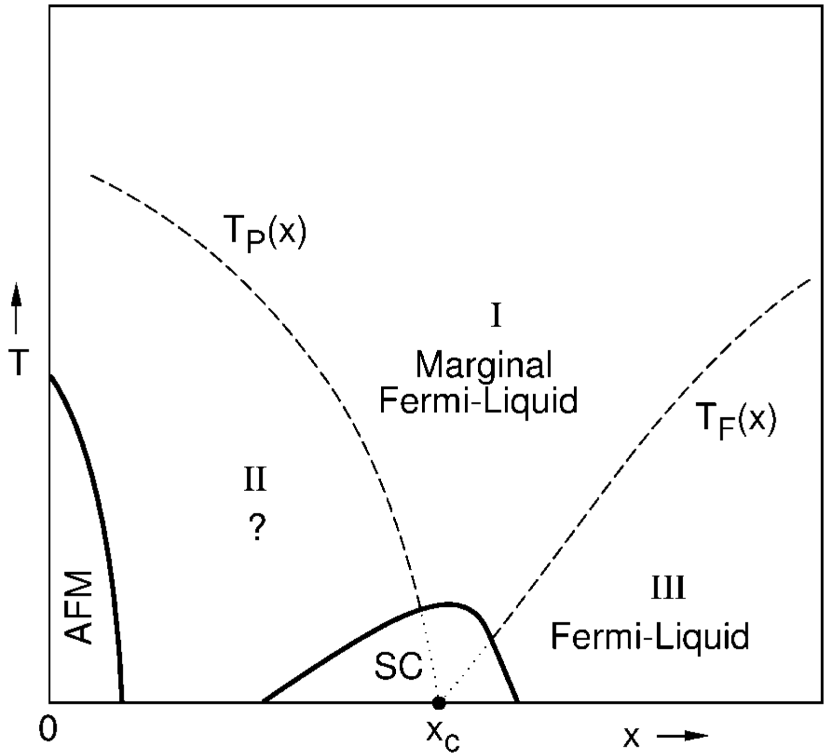
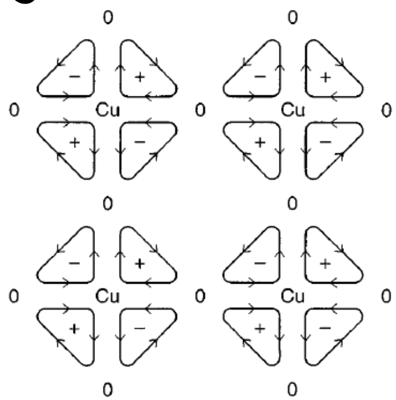
HIDDEN ORDER

Idea: the pseudogap phase is in fact a gapped phase (pseudo in experiment due to imperfections or dynamic effects)



PRL 83, 3538

Circulating currents, PRB 55, 14554



Charge order PRL 87, 056401

d-density wave PRB 63, 094503

Nematic phase arXiv:1404.0362

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RESONATING VALENCE BONDS

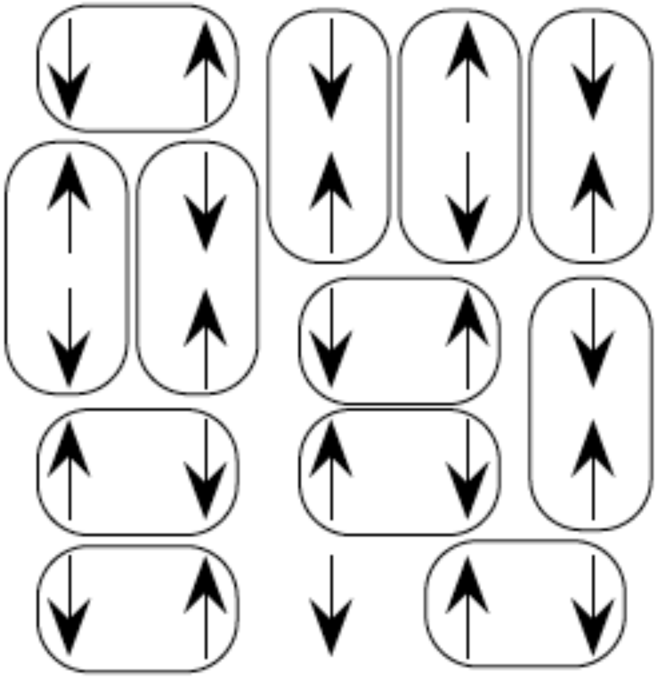
(Anderson)

Mottness from the start.

Pairing scale very large (related to T*)

Quantum fluctuations destroy long range order leading to a spin liquid of singlets.

However, spin liquid not found on cuprates.



http://www.msd.anl.gov/files/msd/cuprates-columbia.pdf

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POST HIGH T_C PRINCIPLES TO FIND SPC

MAZIN, NATURE 464, 183 (2010)

- Layered structures
- Carrier density should not be too high (compared to conventional metals)
- Transition metals of the fourth period (3d) are good
- Magnetism is essential
- Proper Fermi surface geometry is essential (in relation to spin excitations)

Corollary: work with solid state chemists (you need complex chemical compounds)

…. Really?

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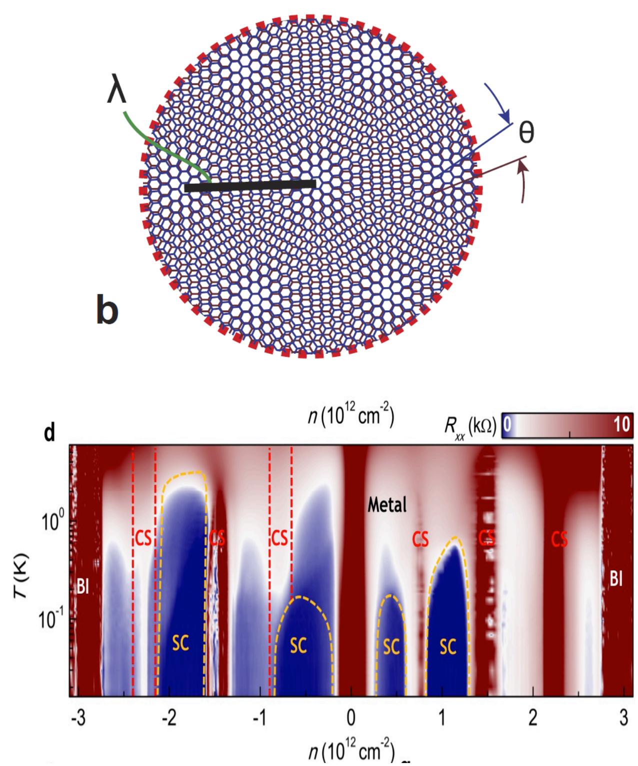
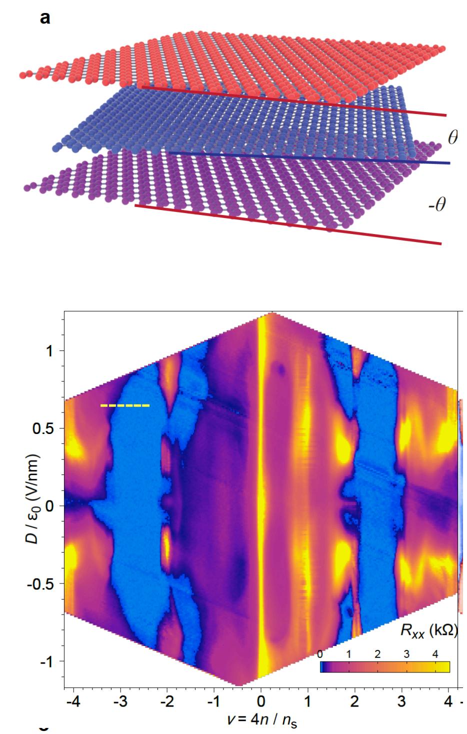
SUPERCONDUCTIVITY IN MULTILAYERED GRAPHENE (2018-)

Twisted bilayer graphene



Cao et al, Nature 556, 80 (2018);
Nature 556, 43 (2018)
Lu, et al Nature 574, 653 (2019)

Mirror-symmetric twisted trilayer graphene



Park et al, Nature 590, 249 (2021)

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CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

OUTLINE

- **Superconductivity**
  - Properties (zero resistivity, Meissner effect)
  - Understanding (pairing, BCS, Ginzburg-Landau)
  - Electron-phonon interaction (conventional superconductivity)
- **Unconventional superconductivity (unsolved)**
  - What are the new issues.
  - What are the proposals.

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