Stay Away from Theorists

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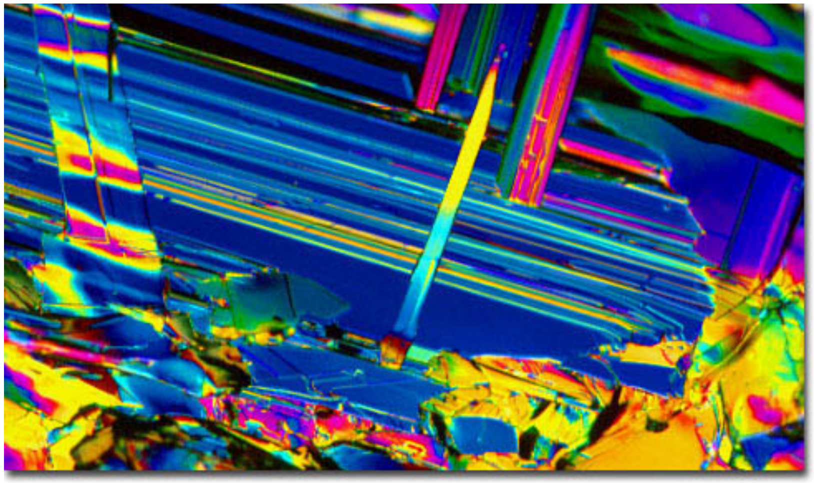


Science 332, 196 (2011)

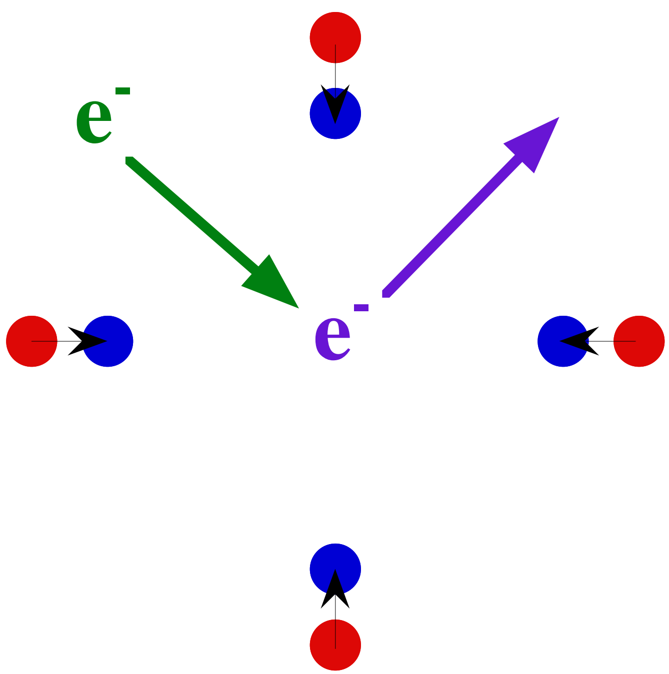
IBM Almaden – Oct. 17, 2012

Rules of B. Matthias for discovering new superconductors

1. high symmetry is best
2. peaks in density of states are good
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators
6. stay away from theorists

From Steve Girvin's lecture (Boulder Summer School 2000) courtesy of Matthew Fisher

Everything You Wanted to Know About Pair Formation
(But Were Afraid to Ask)

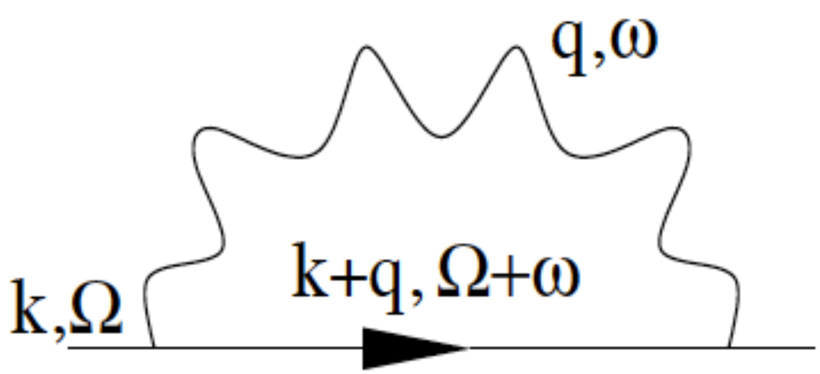


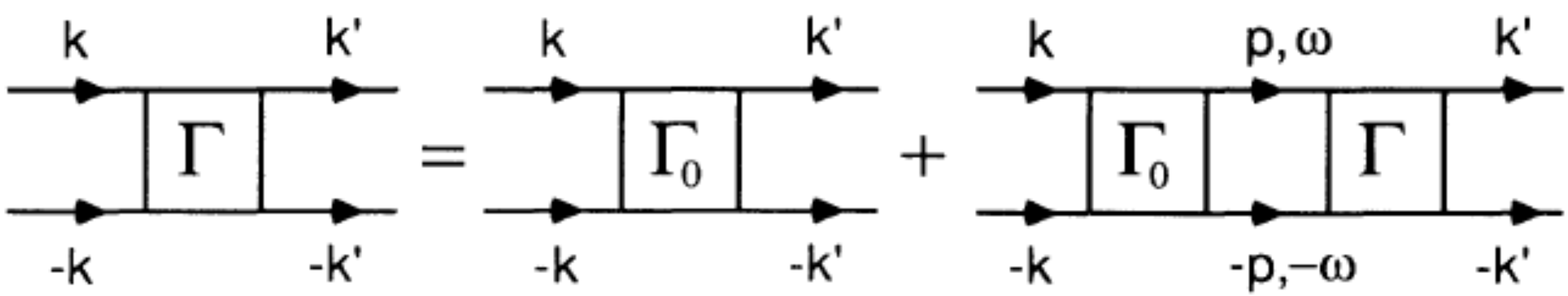
(the electron-phonon case)

1. 1st e^- attracts + ions
2. Ions shift position from red to blue
3. 1st e^- moves away
4. 2nd e^- sees + ion hole and moves to former position of 1st e^-

Interaction is local in space
(s-wave pairs, L=0, S=0)
but retarded in time
(T_c << Debye frequency)

In conventional electron-phonon theory, we rapidly went from a weak coupling treatment – BCS - to a strong coupling theory – Eliashberg - in just a few years because of the utility of Migdal's theorem





Unfortunately, this didn't help us much!

1. Didn't predict buckeyballs
2. Didn't predict MgB_2
3. Predictions based on MgB_2 (Li_xBC, etc.) didn't pan out
4. Heavy fermion superconductors unexpected
5. Cuprates as well
6. Pnictides too
7. And we can only imagine what's next …

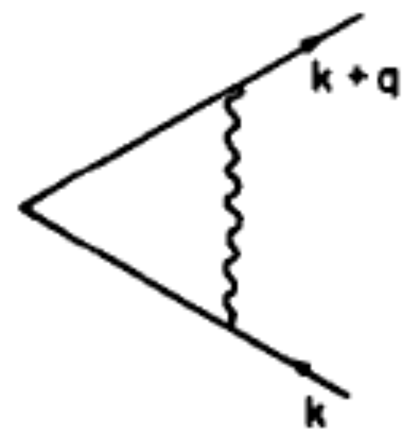
So, what do we mean by unconventional superconductivity?

1. An order parameter that changes sign as a function of ***k***

2. A pairing mechanism different from electron-phonon theory

Examples

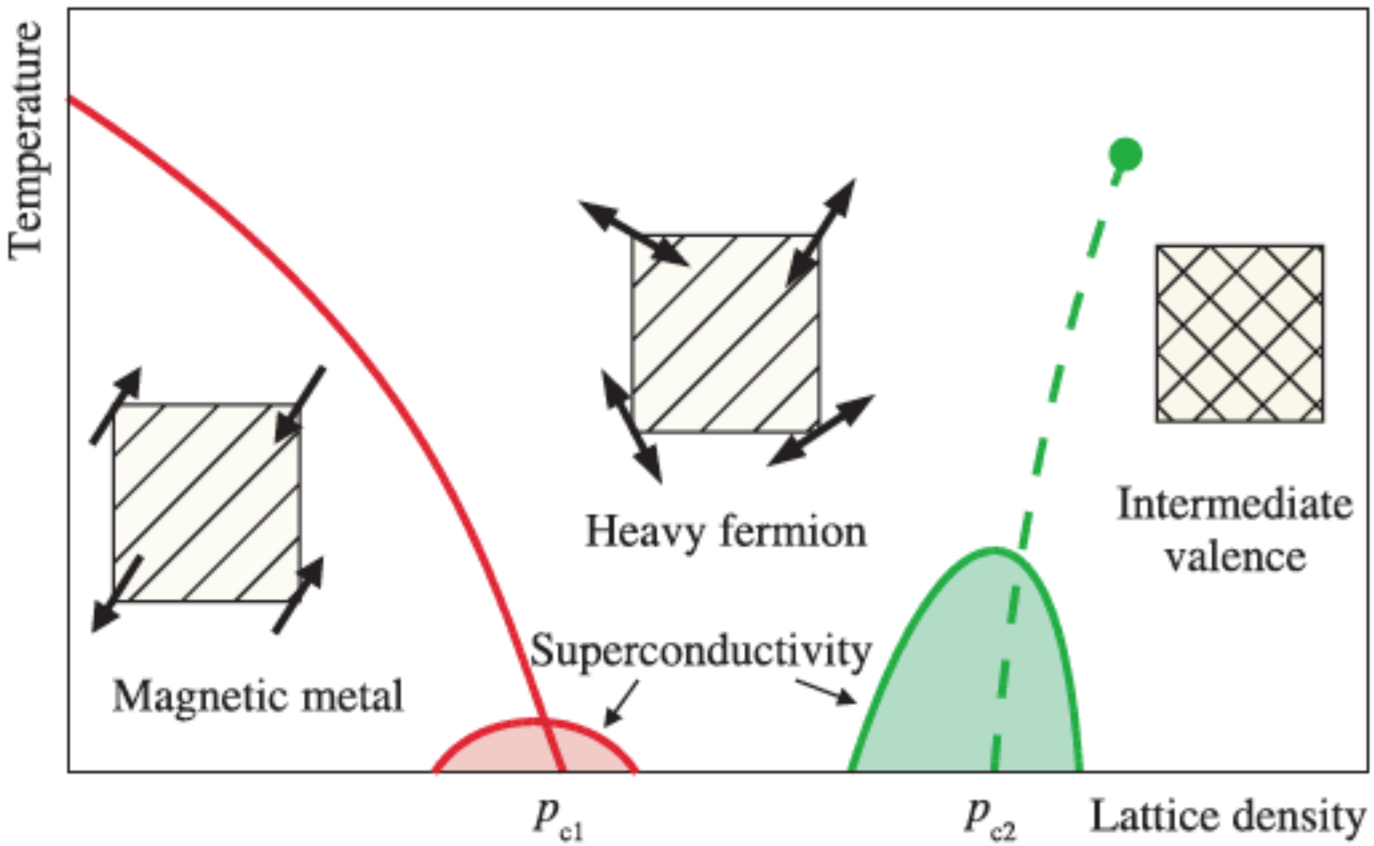
- superfluid ^3He
- heavy fermion superconductors
- organic superconductors
- cuprate superconductors
- iron arsenide superconductors



As pointed out by Hertz, Levin and Beal-Monod (SSC 1976), there is no Migdal theorem for electron-electron theories

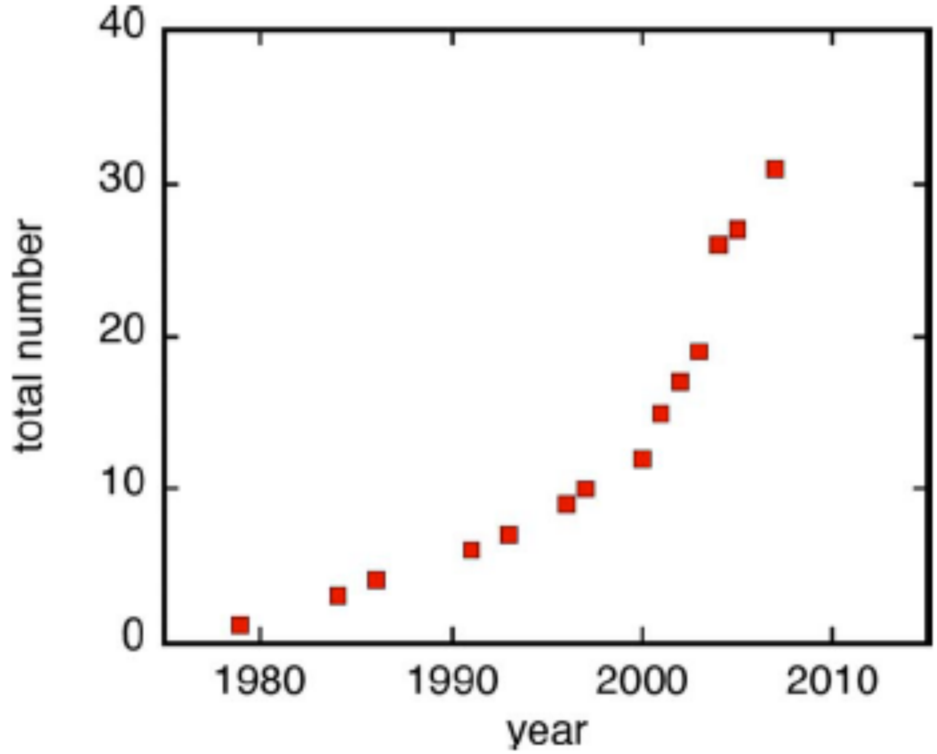
Heavy Fermion Superconductors

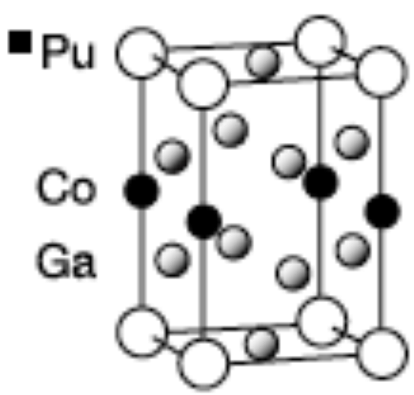
$CeCu_2Si_2$ – Steglich, PRL 1979
UBe_{13} – Bucher, PRB 1975; Ott, PRL 1983
UPt_3 – Stewart, PRL 1984
U_2PtC_2 – Matthias, PNAS 1969

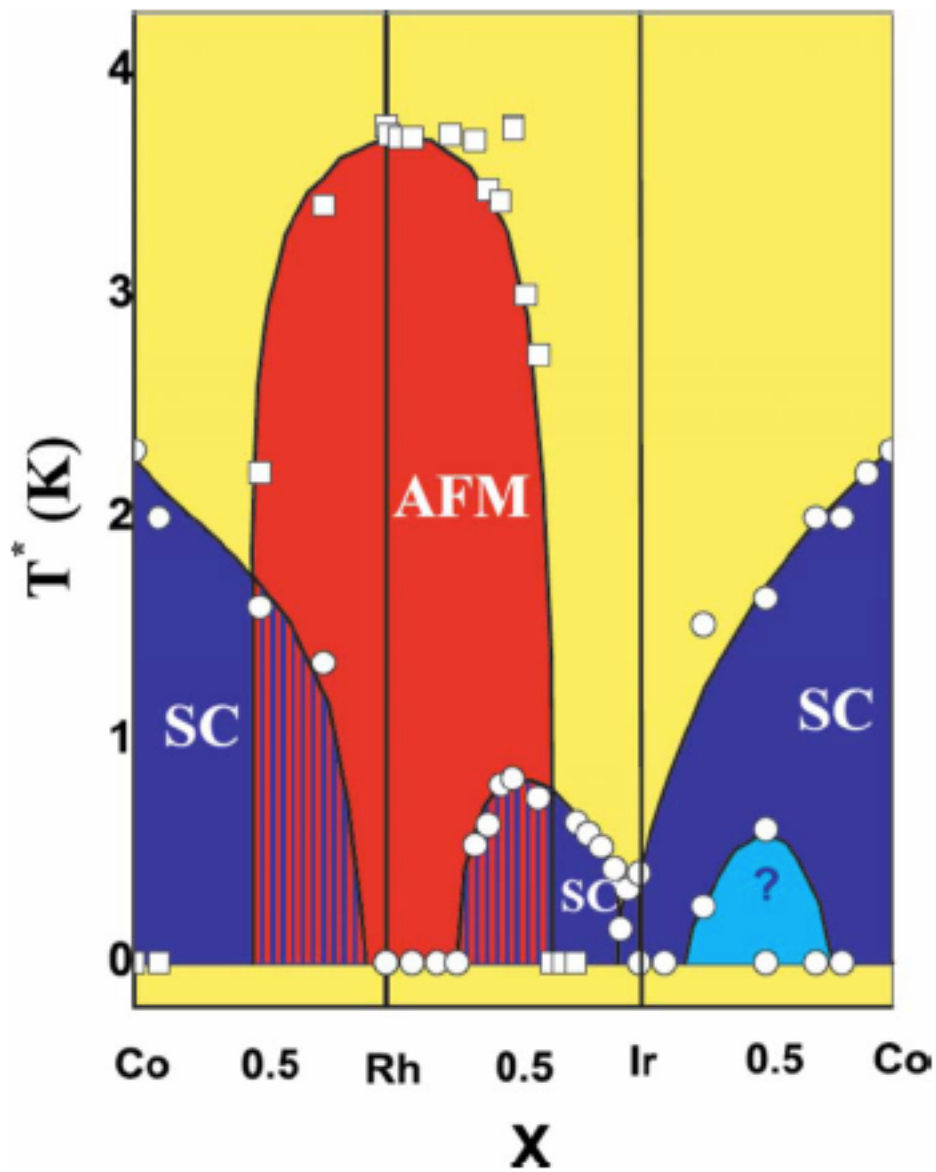


Yuan *et al.*, Science (2003)

$CeMIn_5$ - LANL group – PRL 2000, EPL 2001, JPCM 2001
$PuCoGa_5$ – LANL group – Nature 2002 (T_c = 18.5 K !)



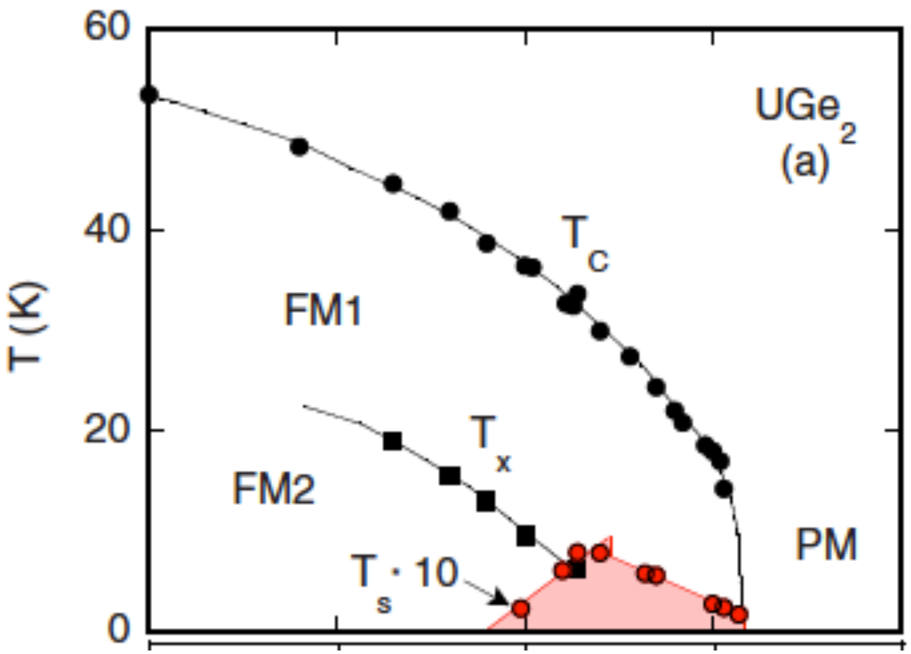




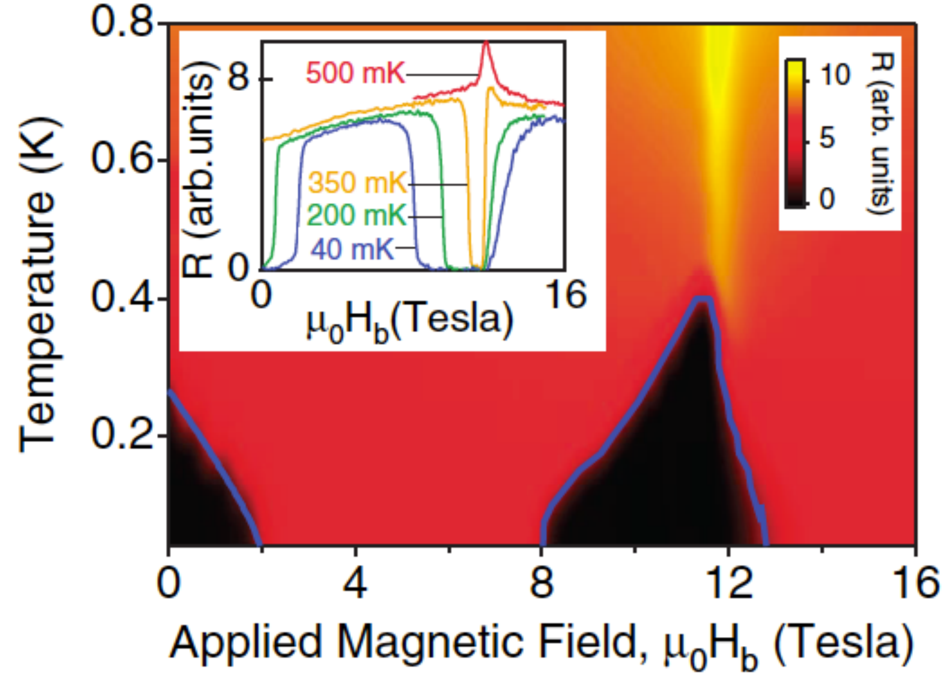
Pfleiderer, RMP (2009)

Ferromagnetic Superconductors

UGe_2 – Saxena, Nature 2000; URhGe – Aoki, Nature 2001

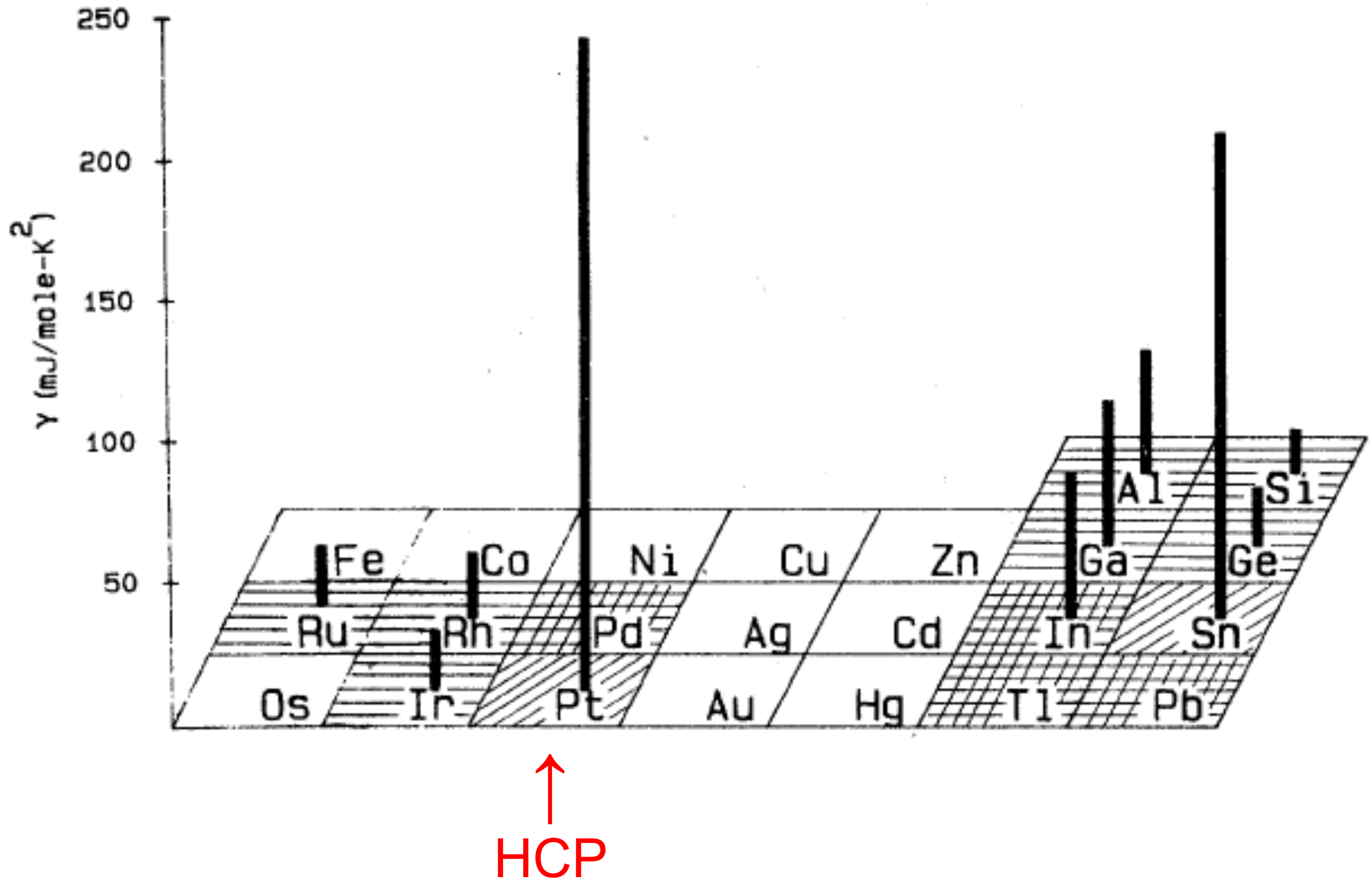


Pfleiderer & Huxley, PRL (2002)



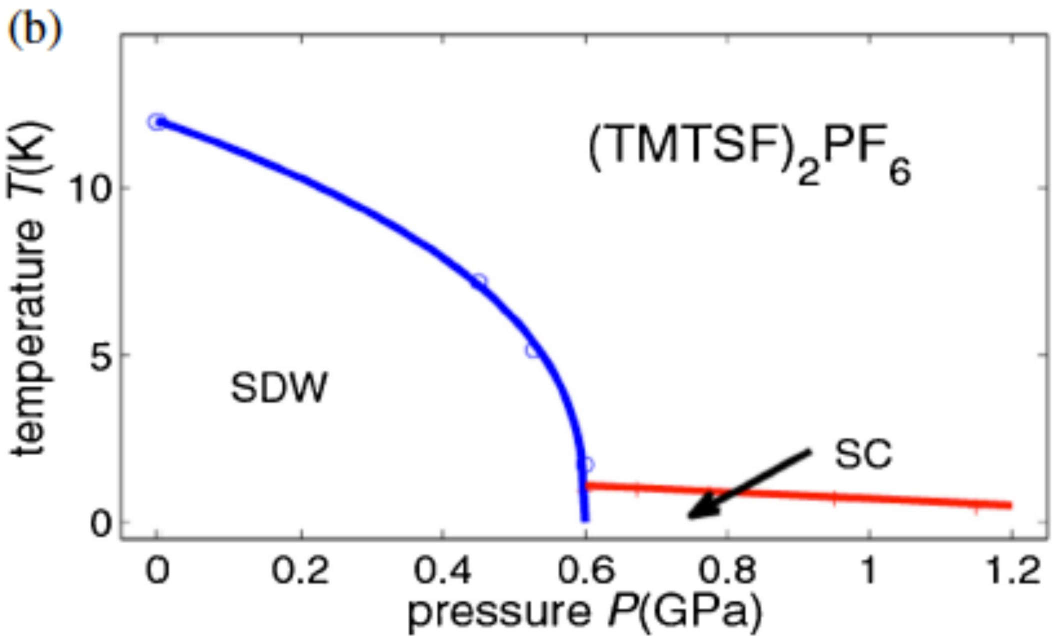
Levy *et al.*, Science (2005)

UX_3 – most of them $AuCu_3$ cubic structure expect
UPd_3 – dHCP (localized f electrons, quadrupole order)
UPt_3 – HCP (itinerant f, heavy fermion superconductor

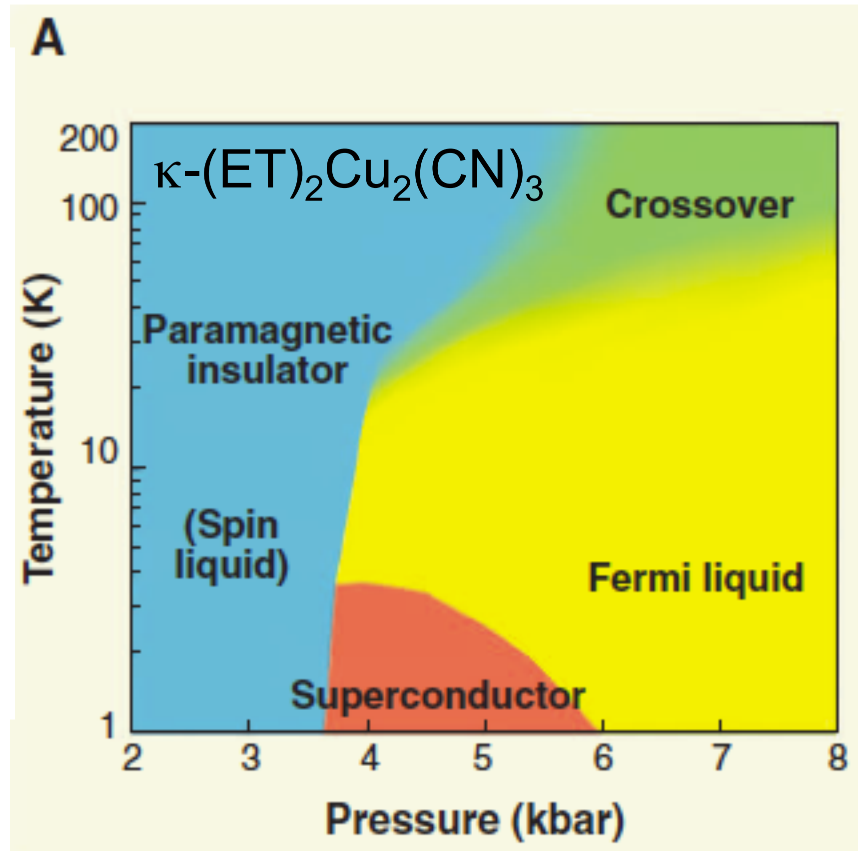


Koelling *et al.*, PRB (1985)

Organic Superconductors

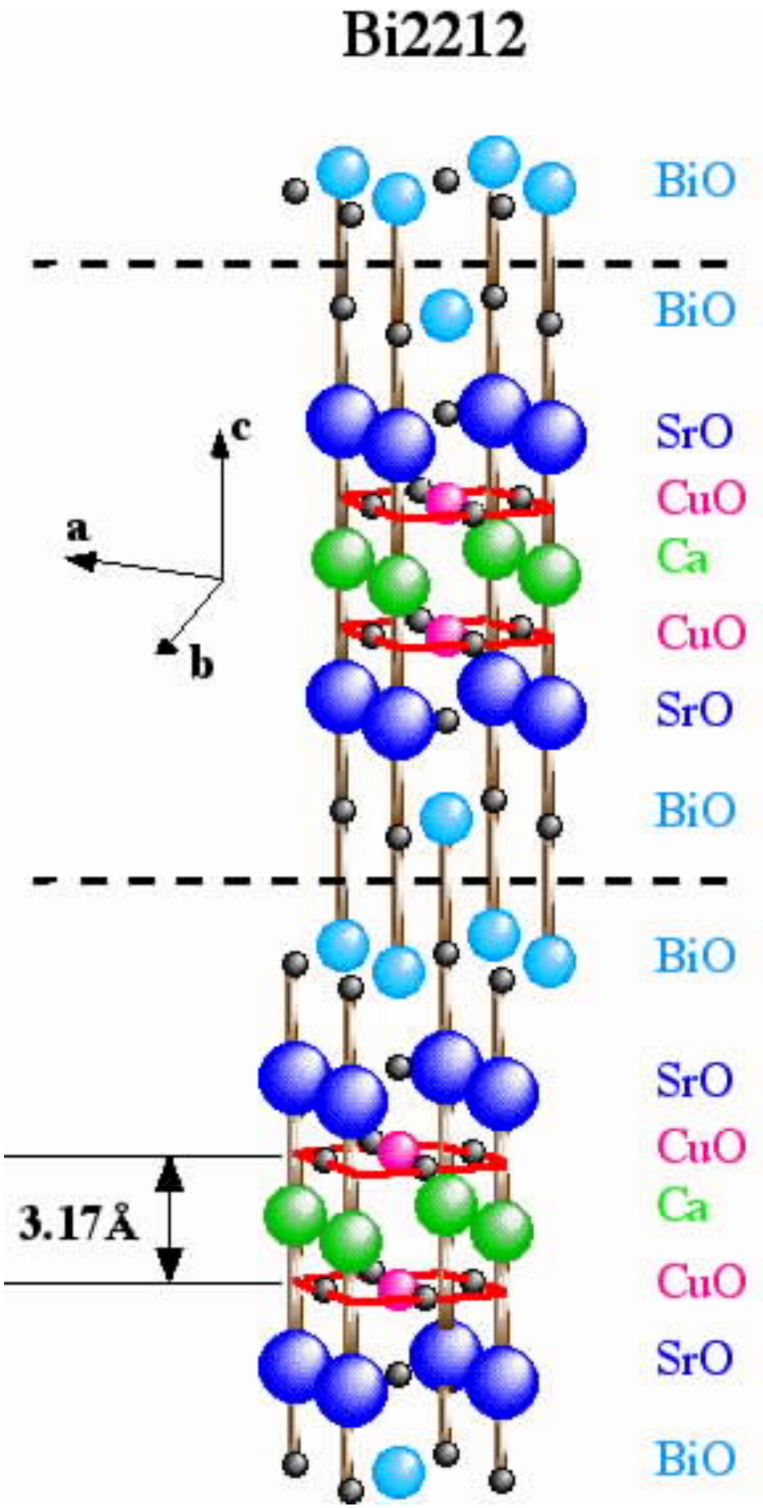


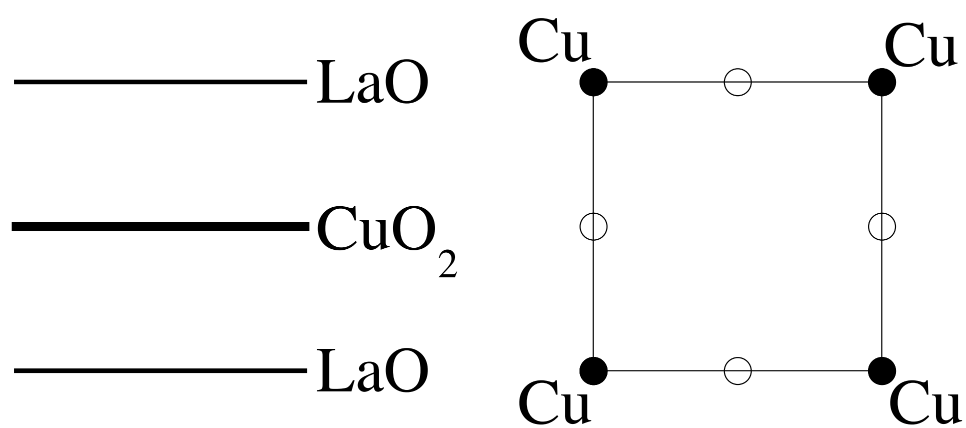
Ardavan *et al.*, JPSJ (2012)

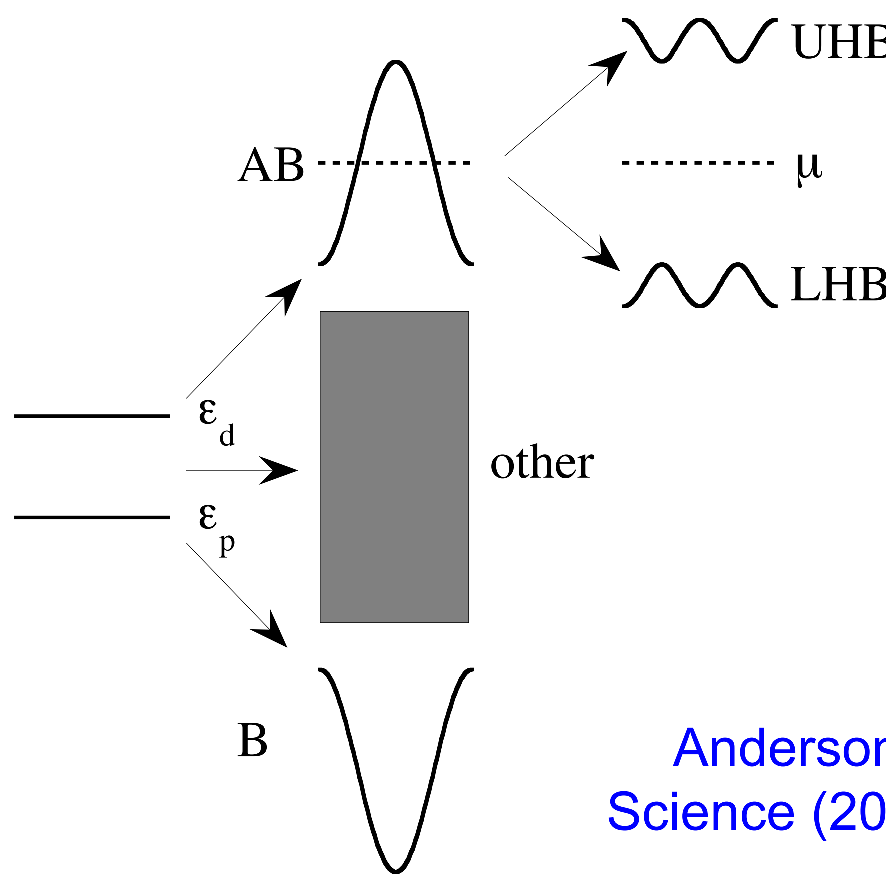


Kurosaki *et al.*, PRL (2005)

Electronic Structure of Cuprates

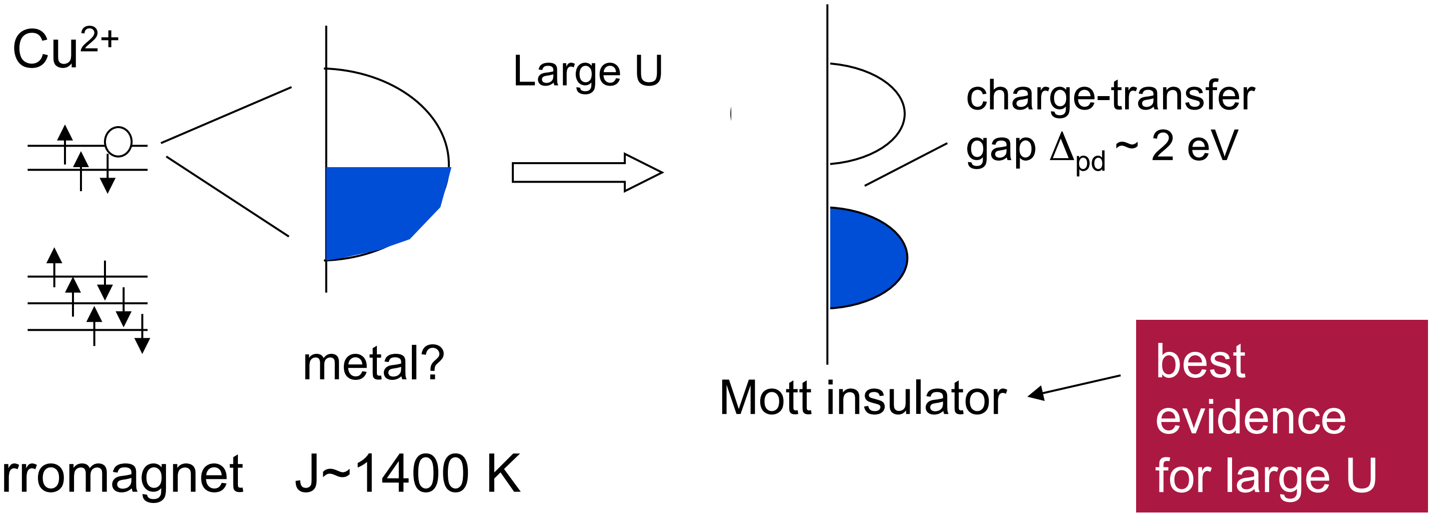




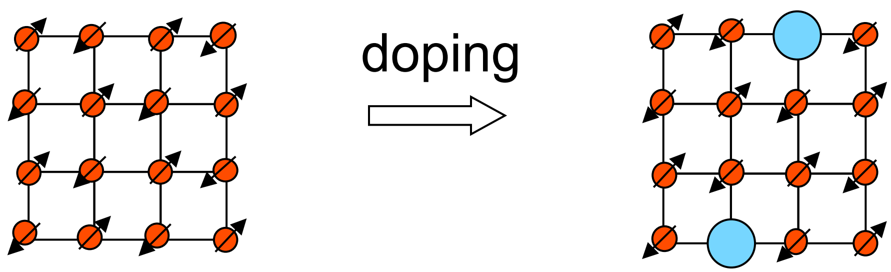


Anderson
Science (2007)

Short tutorial on cuprates



antiferromagnet J~1400 K

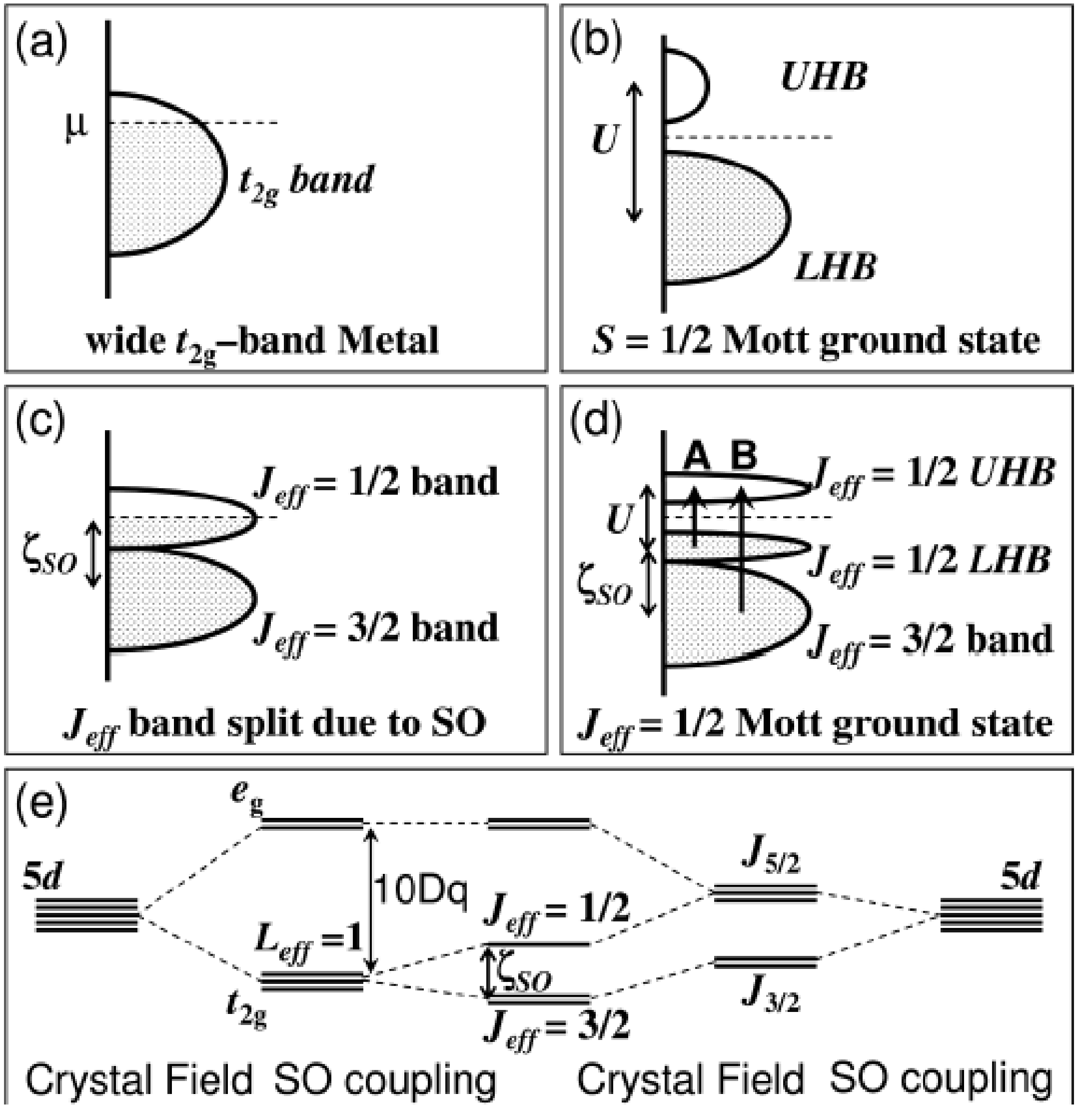


$$H = -t \sum_{i,j,\sigma} c^{+}{}_{i\sigma}\, c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$ Hubbard

$t = 0.3$ eV, $U = 2$ eV, $J = 4t^2/U = 0.12$ eV

(slide from PWA)

Iridates - spin-orbit plus d^5 configuration leads to a half filled band



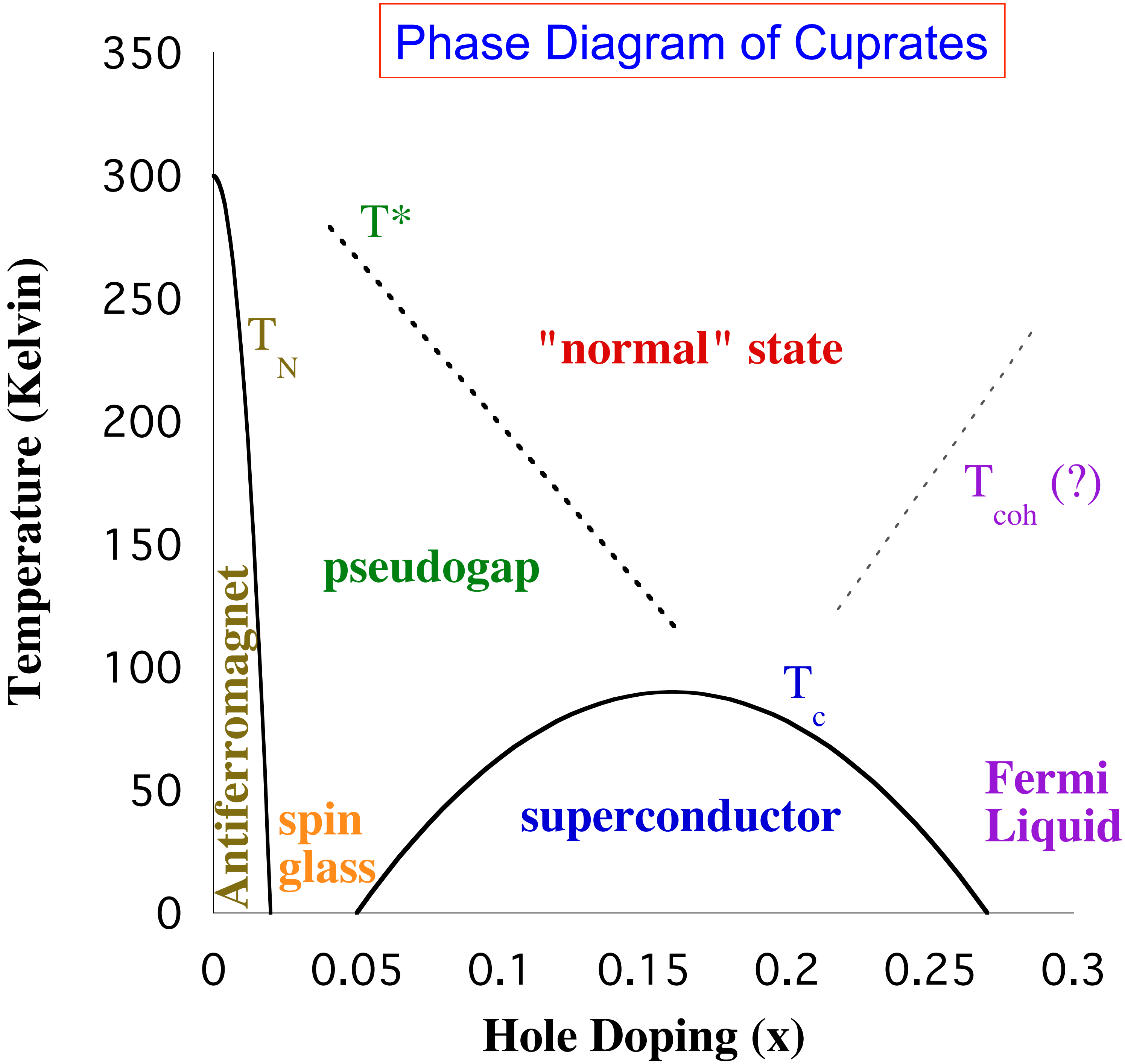
Kim *et al.*, PRL (2009)

Cuprates are Mott insulators, have a half filled band, and a large superexchange J

So are iridates!

If doped, will they be high T_c superconductors?

Wang & Senthil, PRL (2011)



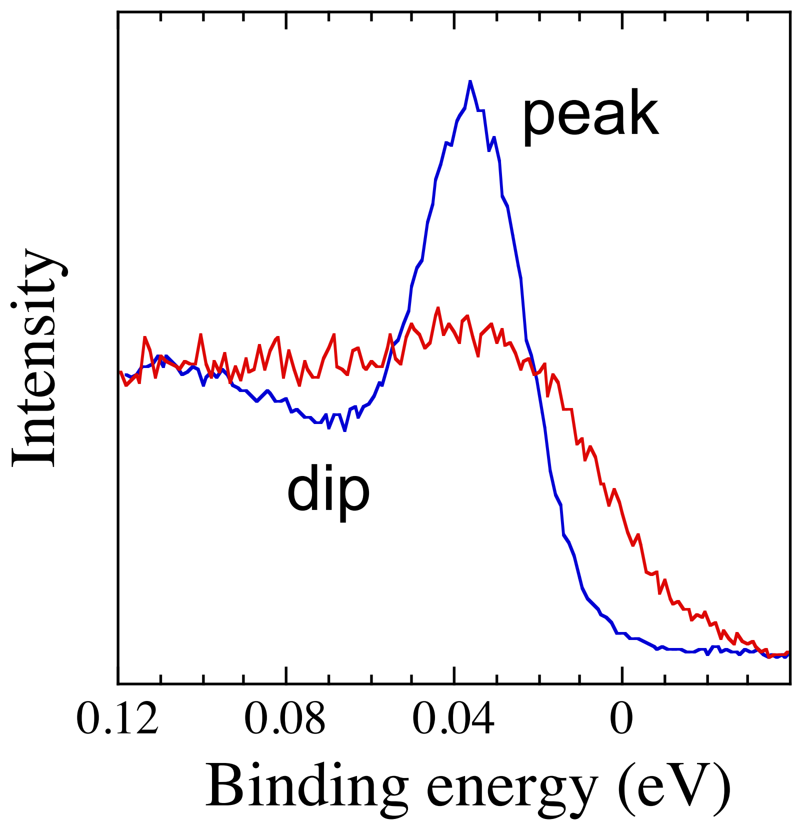
Phase Diagram of Cuprates
350
300
250
200
150
100
50
0
Temperature (Kelvin)
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
"normal" state
T_N
pseudogap
T_{coh} (?)
Antiferromagnet
T_c
Fermi Liquid
spin glass
superconductor

Cuprates have
d-wave pairs
(L=2, S=0)

van Harlingen;
Tsuei & Kirtley -
Buckley Prize -1998

Artwork by
Gerald Zeldin (2000)

Photoemission spectrum above and below T_c at momentum $\boldsymbol{k} = (\pi,0)$ for Bi2212

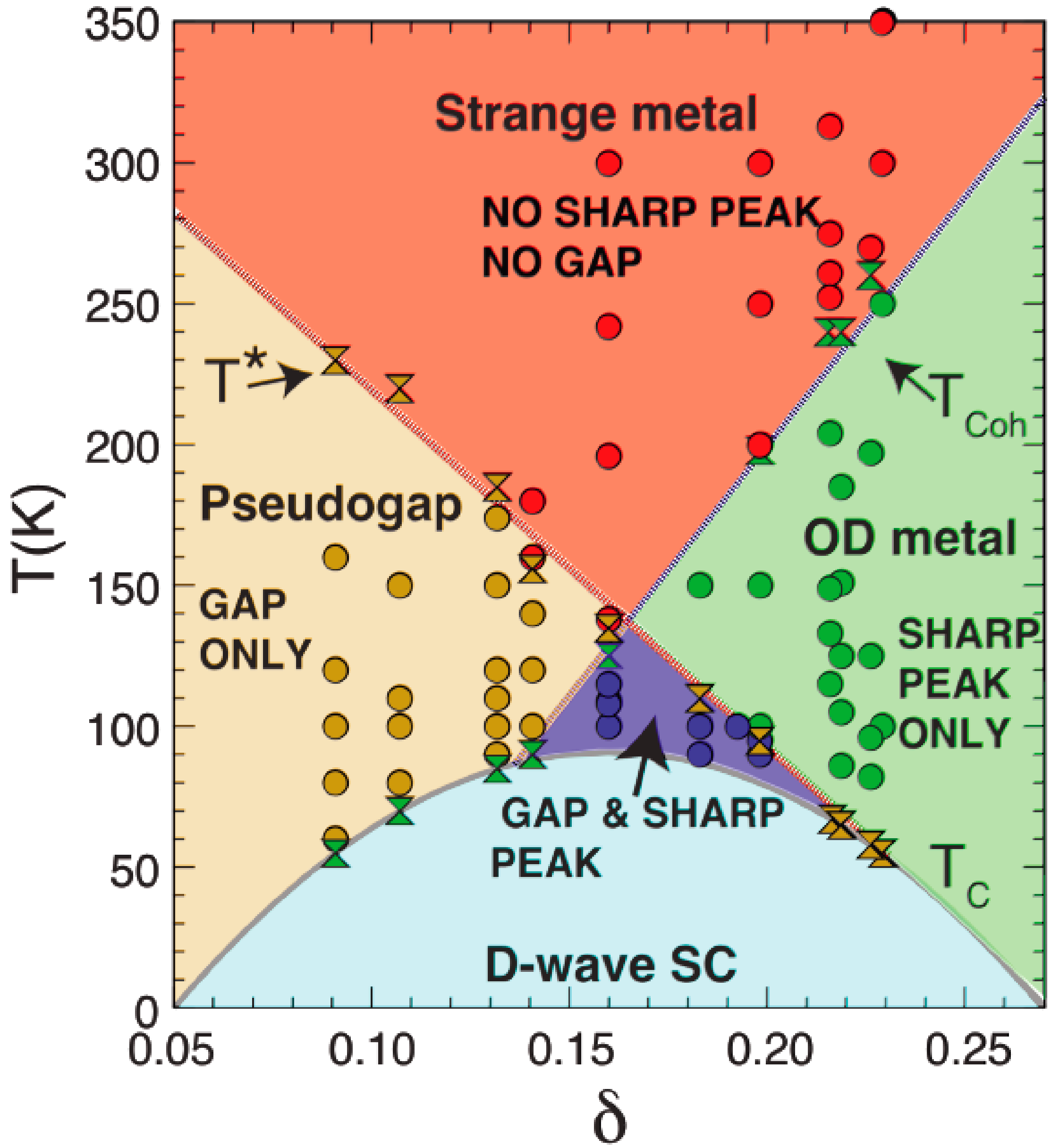


Incoherent normal state

Coherent superconductor

Norman *et al.*, PRL (1997)

Electronic Phase Diagram Based on Antinodal Spectra

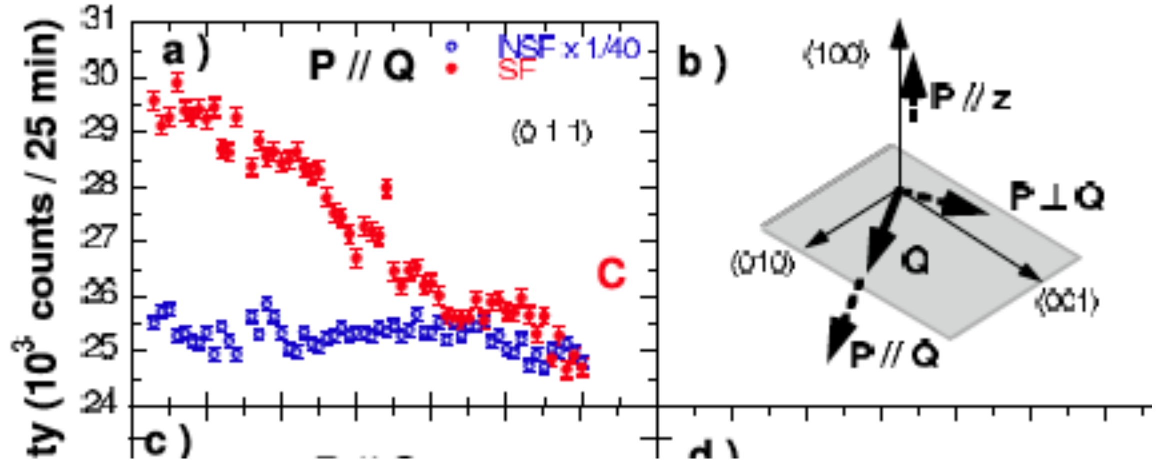


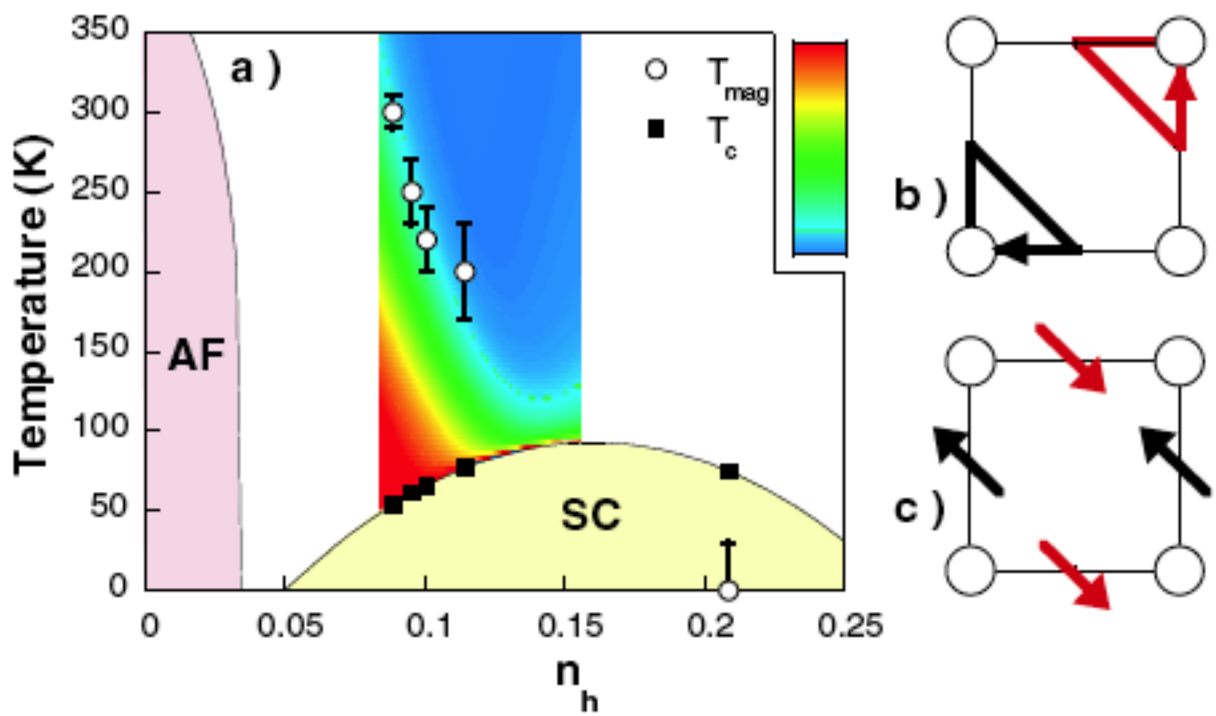
Chatterjee *et al.*, PNAS (2011)

What is the Pseudogap Due to?

1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?

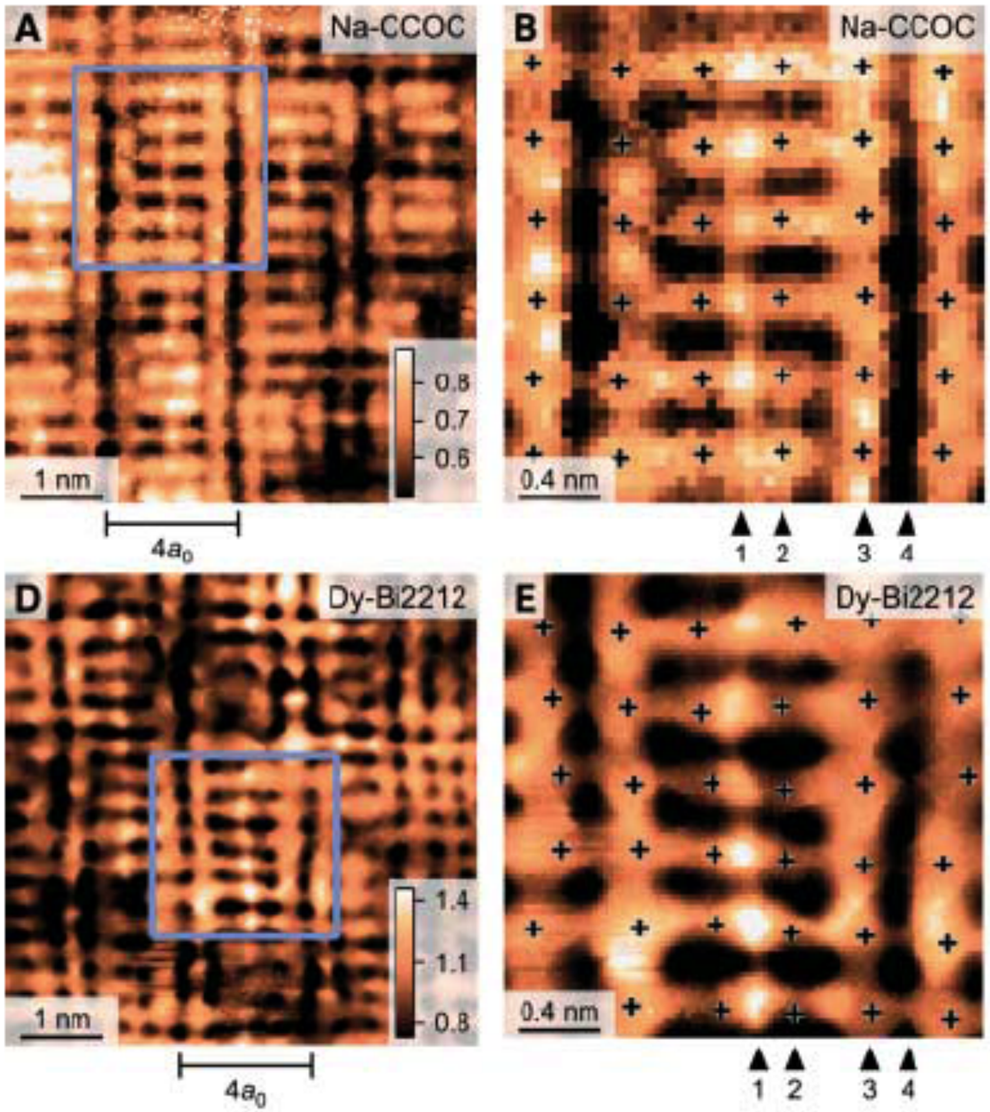
Orbital moments above T_c in the pseudogap phase (Bourges, Greven)

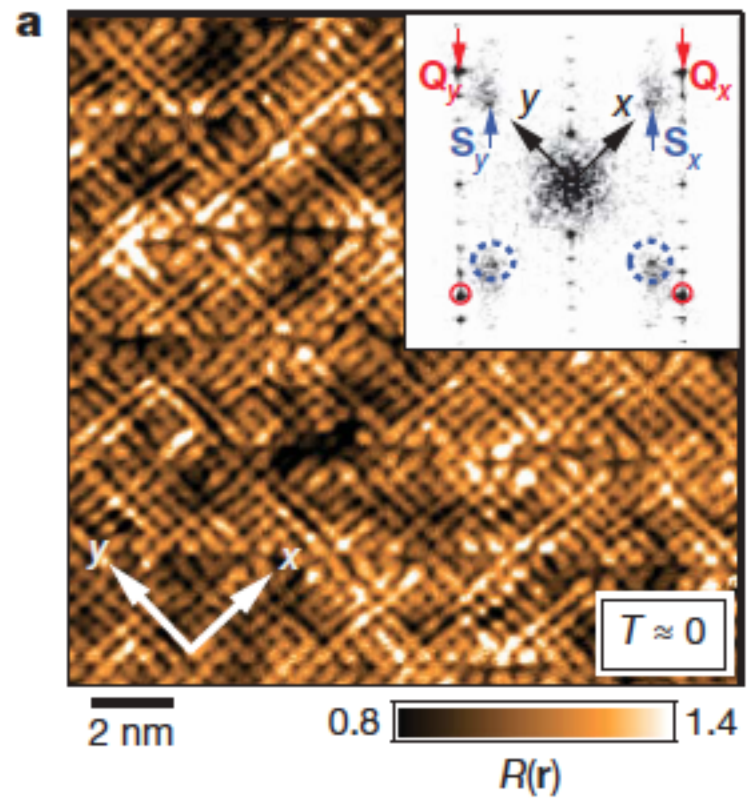




Fauque *et al.* PRL (2006)

hole density shows a "4a period bond centered electronic glass"
& the pseudogap exhibits a nematic anisotropy

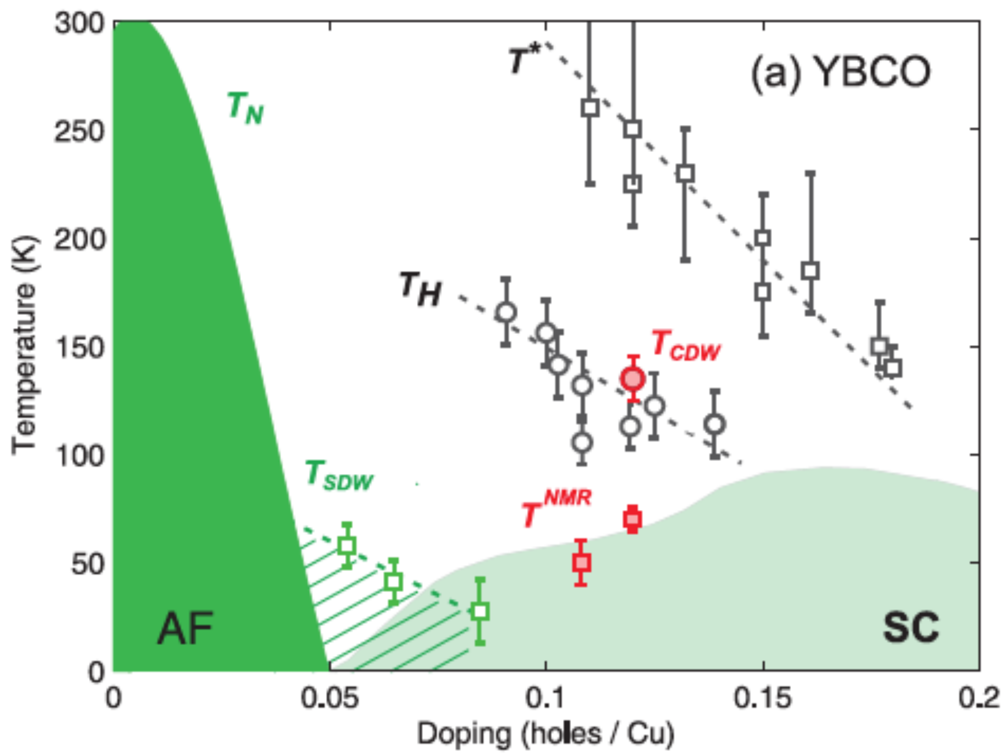




Kohsaka *et al.*, Science (2007)

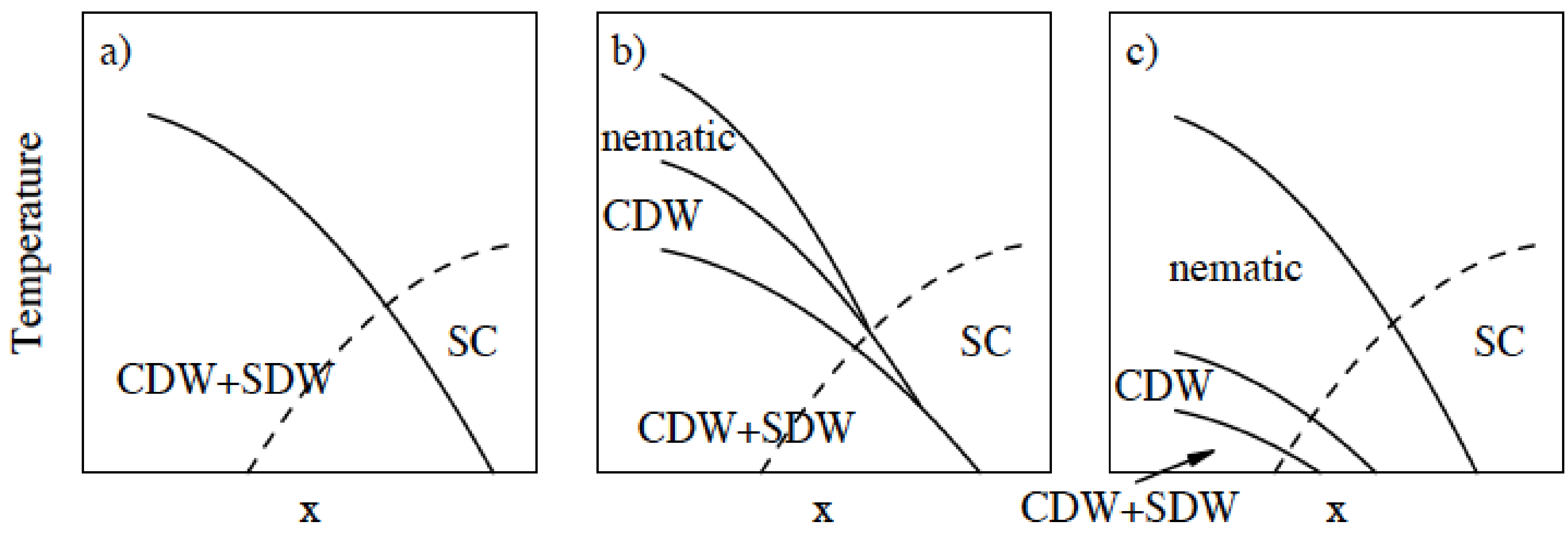
Lawler *et al.*, Nature (2010)

Is the Pseudogap a Nematic Phase?



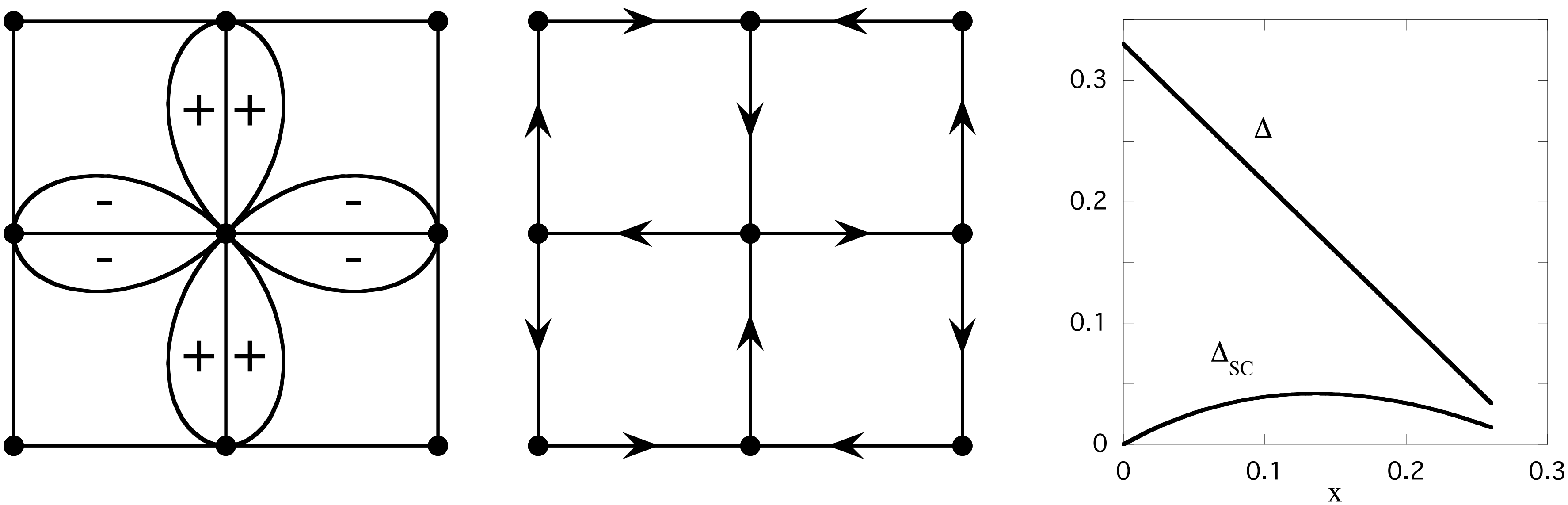
Chang *et al.*, Nat Phys (2012)

Vojta, Adv. Phys. (2009)



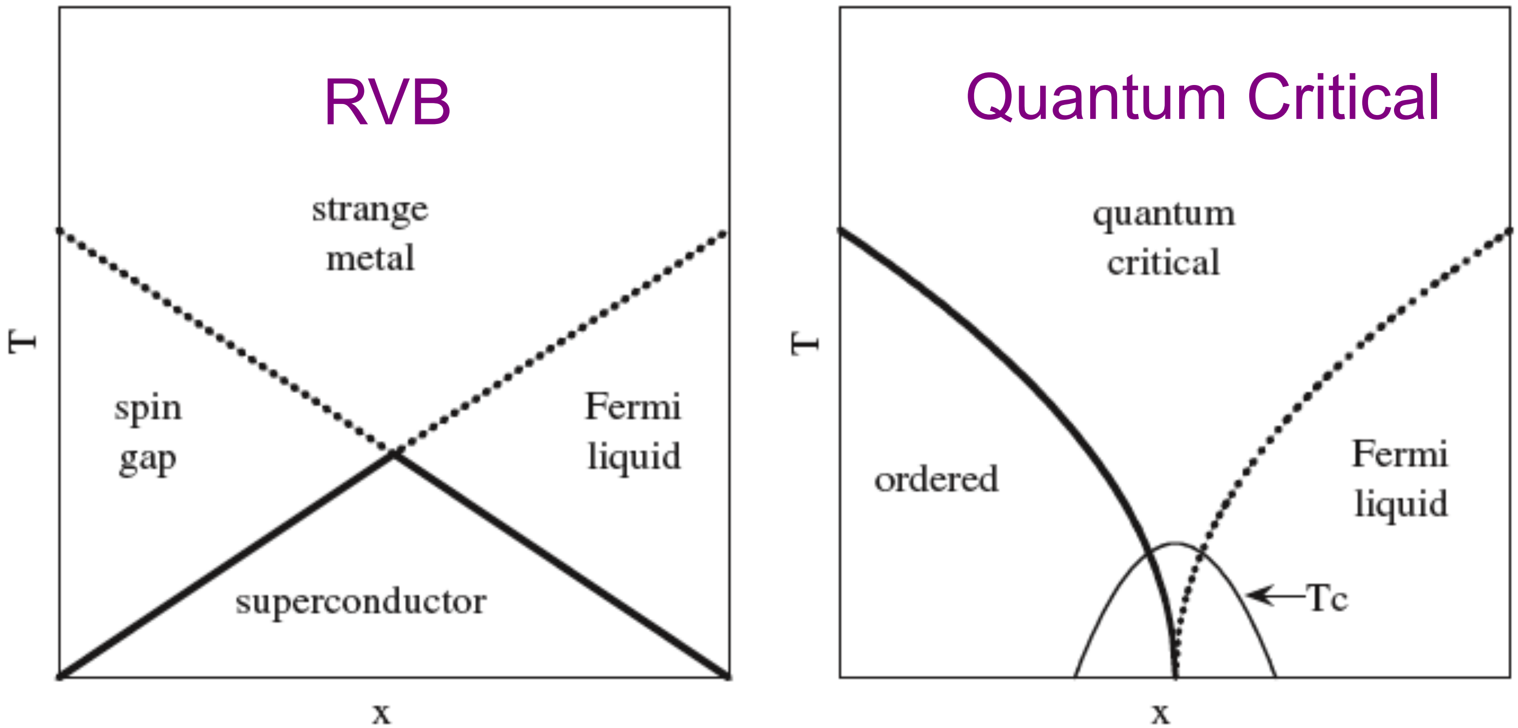
RVB Model (Anderson, Lee & Nagaosa, Randeria & Trivedi, etc.)

It postulates a liquid of spin singlets rather than a Neel lattice

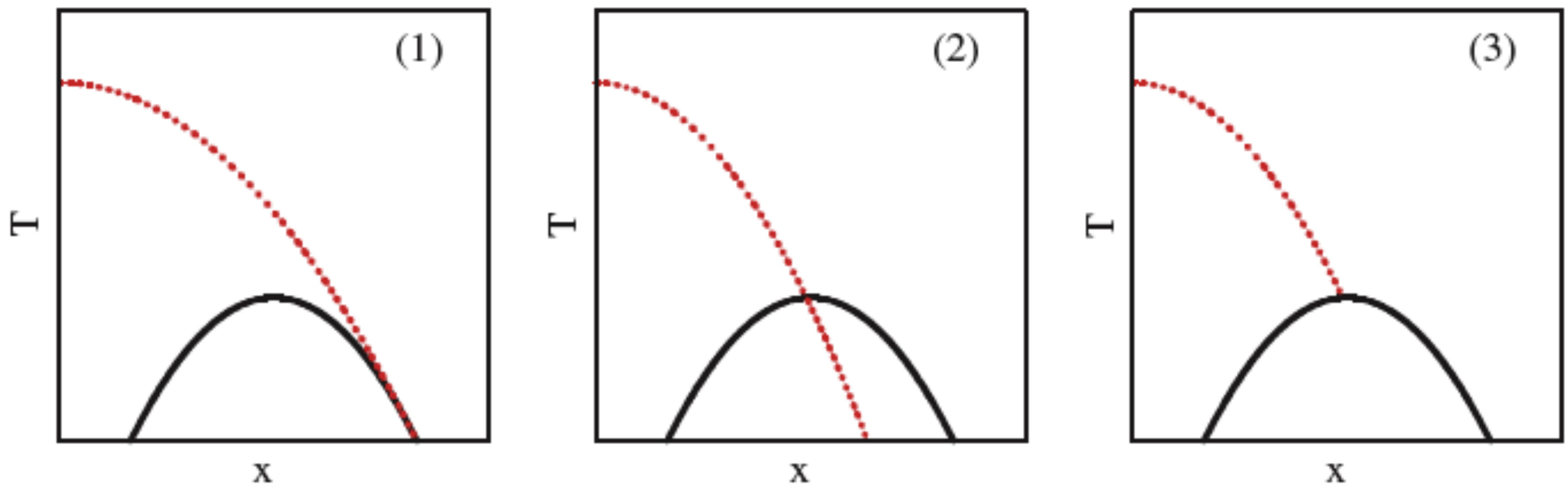


Pseudogap phase corresponds to a d-wave pairing of spins (left). At half filling, this is quantum mechanically equivalent to a staggered flux state (middle). The spin gap, Δ, is not equivalent to the superconducting order parameter, Δ_{sc} (right).

Two Theories of the Cuprate Phase Diagram



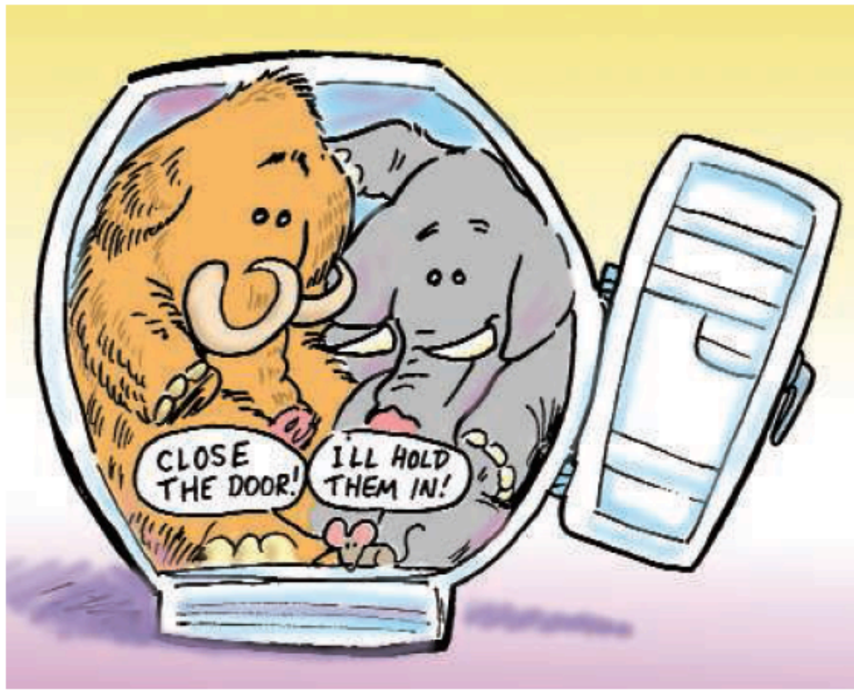
Relation of T* to T_c



What is the origin of pairing?

Is there a pairing glue?

Is it instantaneous?

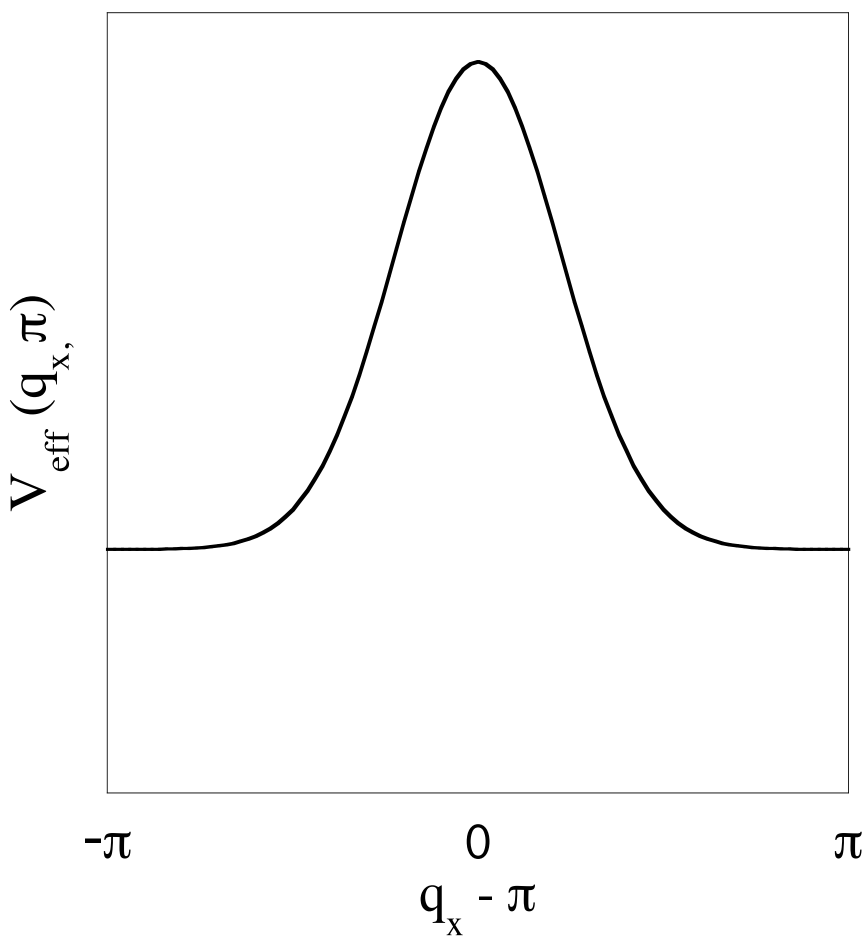


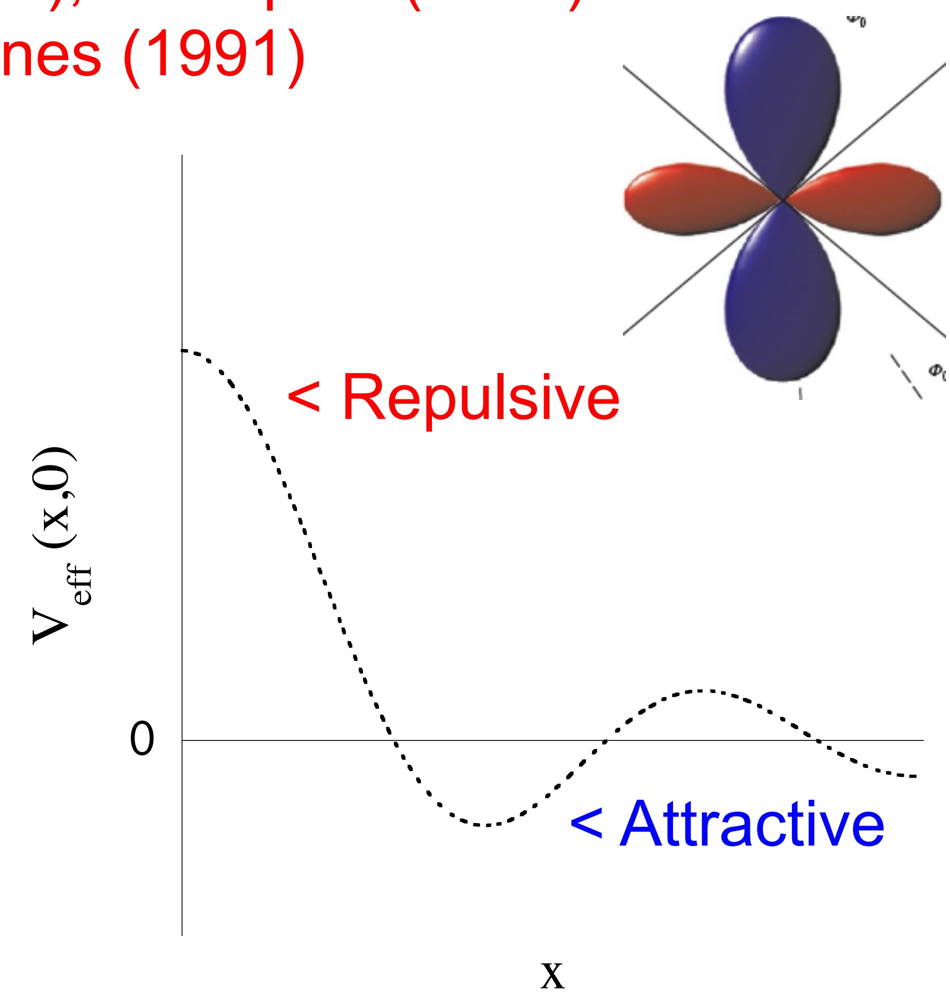
"We have a mammoth and an elephant in our refrigerator— do we care much if there is also a mouse?"

Anderson, Science (2007)

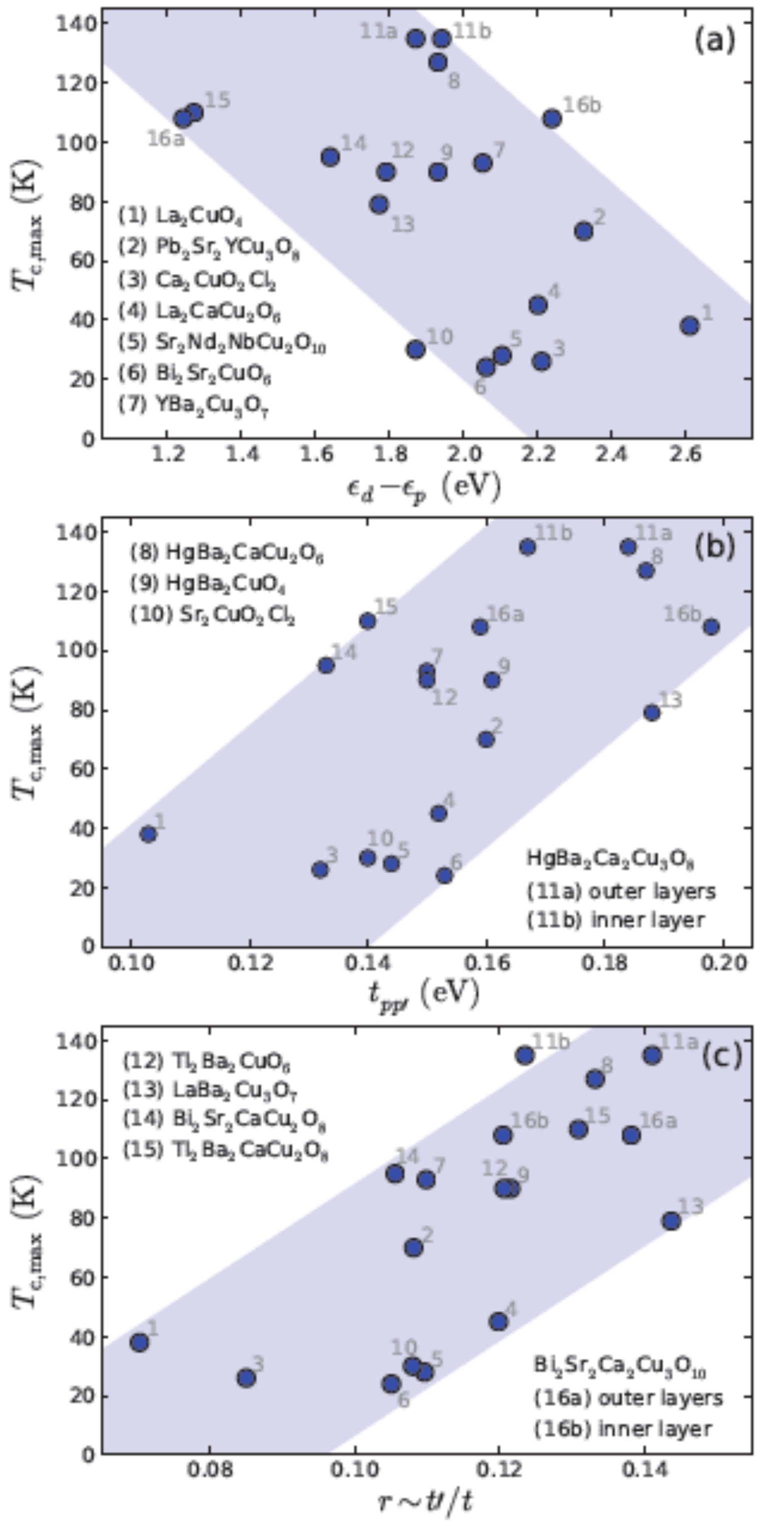
Antiferromagnetic spin fluctuations can lead to d-wave pairs (an e^- with up spin wants its neighbors to have down spins)

Heavy Fermions - Varma (1986), Scalapino (1986)
High T_c - Scalapino (1987), Pines (1991)

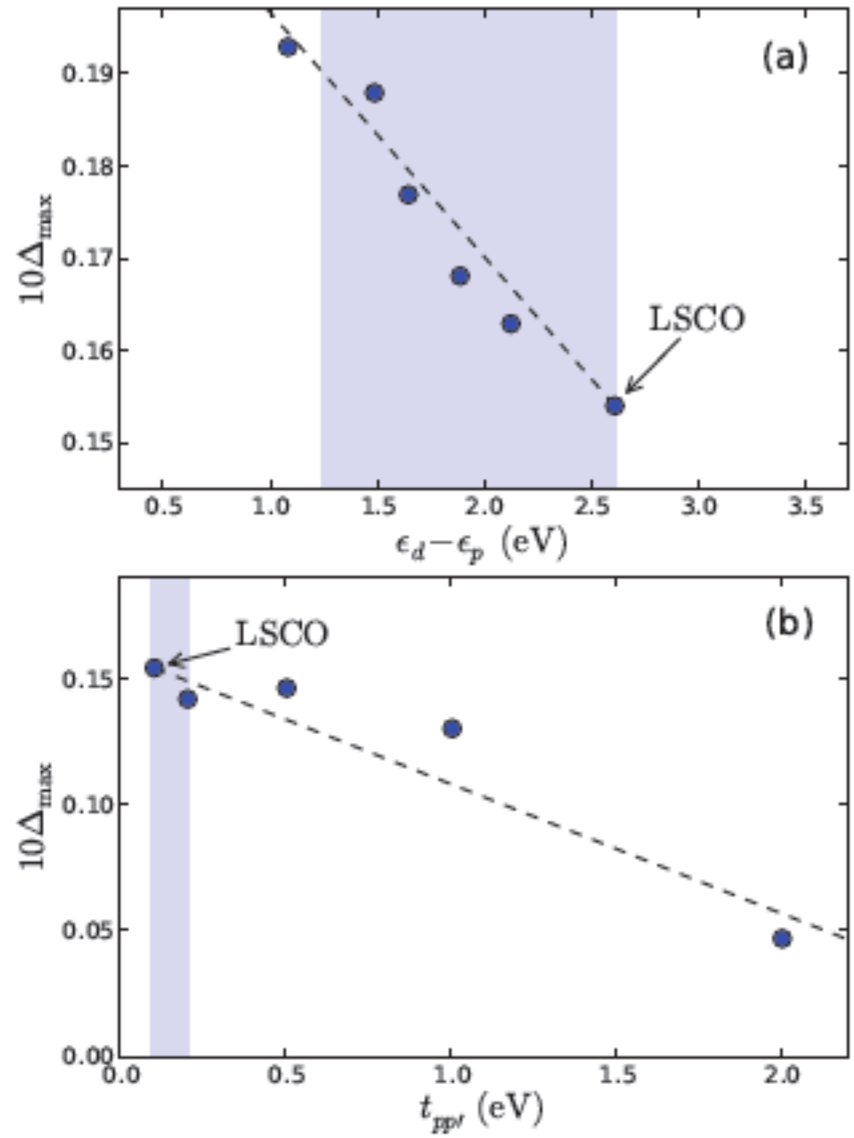




(plots from Doug Scalapino)

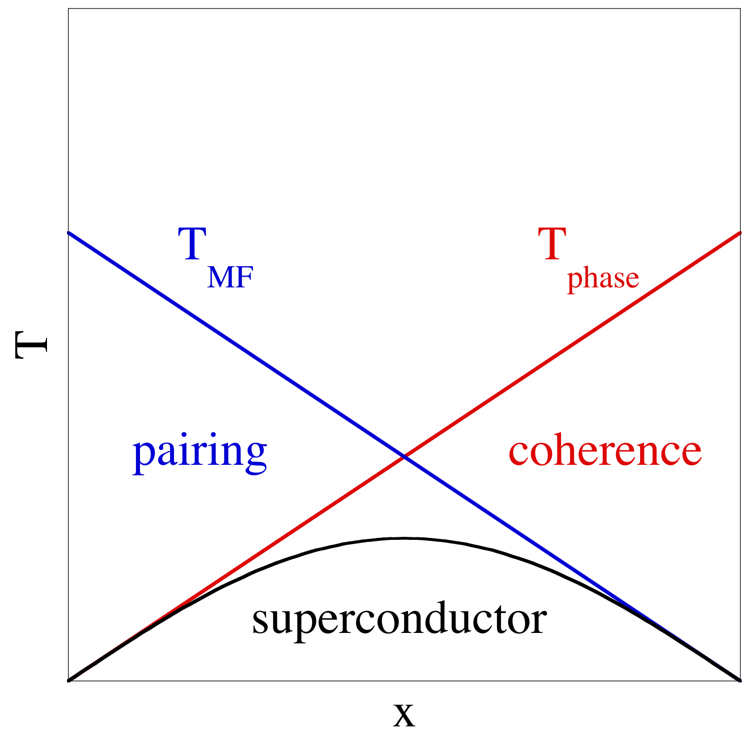


Cluster DMFT



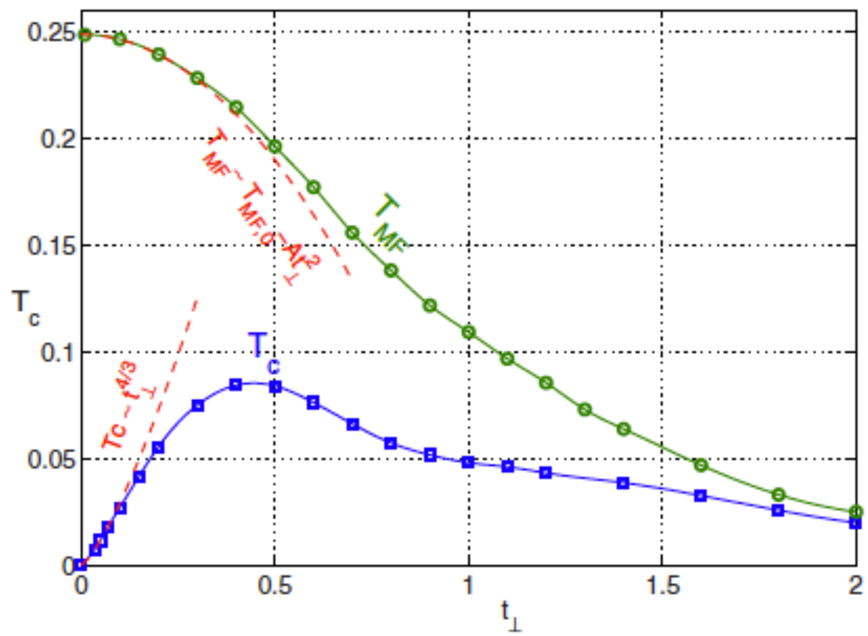
Weber *et al.*, arXiv (2011)

"Emery-Kivelson" picture
Nature (1995)

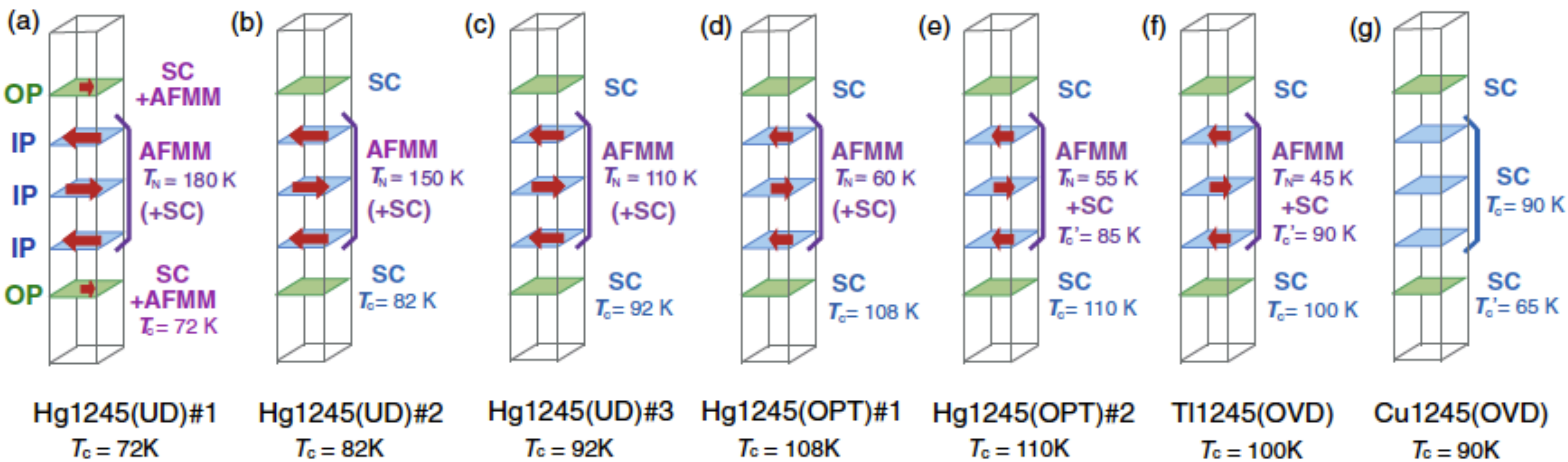


Pairing occurs below mean field transition temperature
Coherence occurs below phase ordering temperature
Superconductivity occurs only below both temperatures

Composite Systems – A route to high T_c

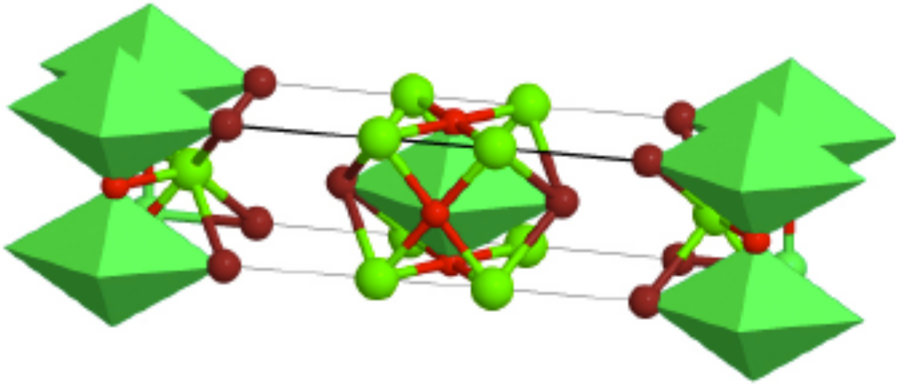


Berg *et al.*, PRB (2008)

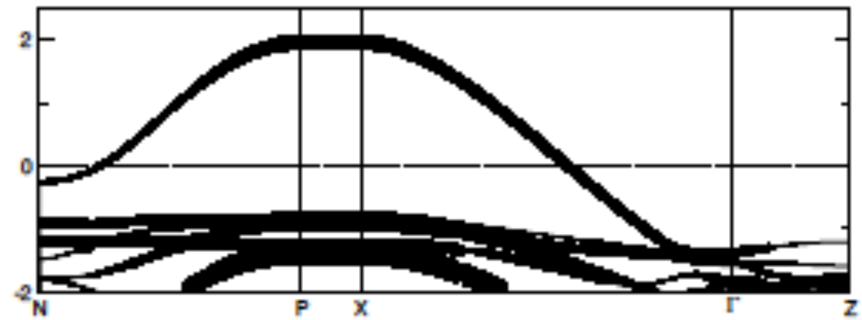


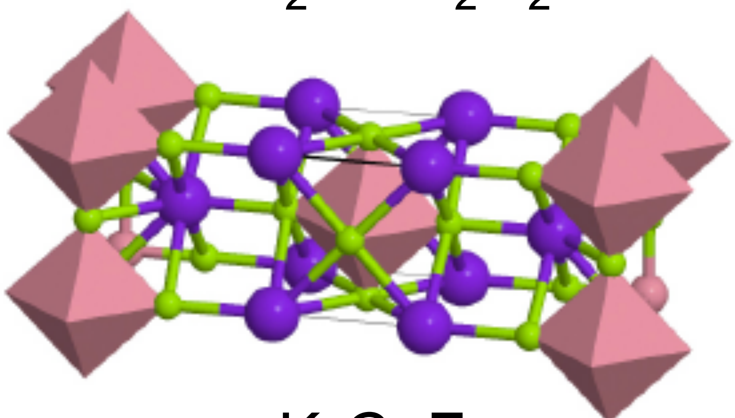
Mukuda *et al.*, JPSJ (2012)

Data Mining

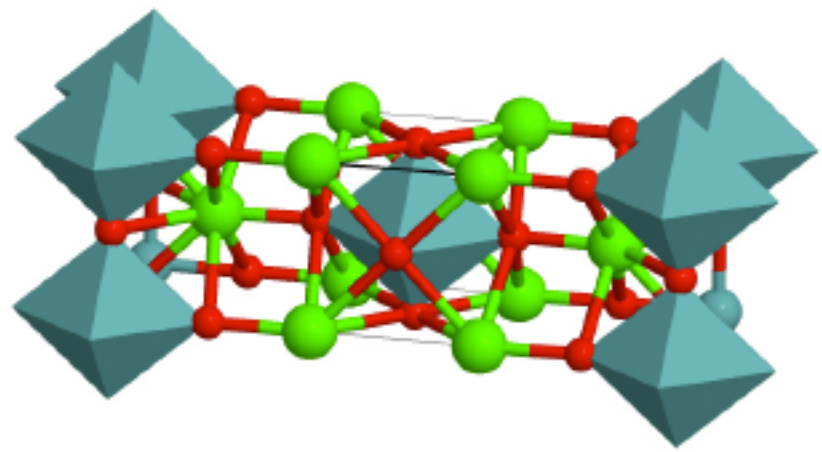


$Ca_2CuBr_2O_2$

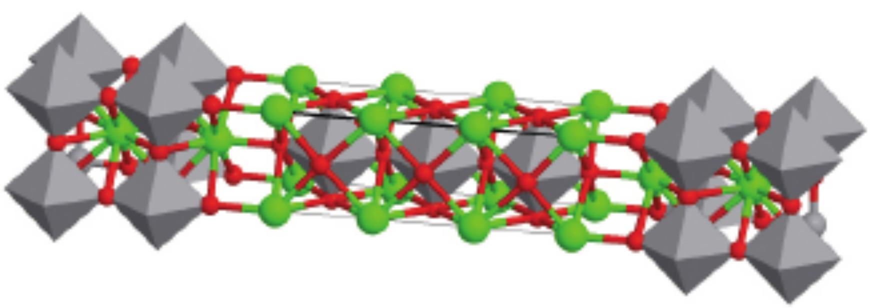




K_2CoF_4



Sr_2MoO_4



$Sr_4V_3O_{10}$

Klittenberg & Eriksson, arXiv (2011)

Iron arsenide and chalcogenide superconductors

There are a number of different crystal structures

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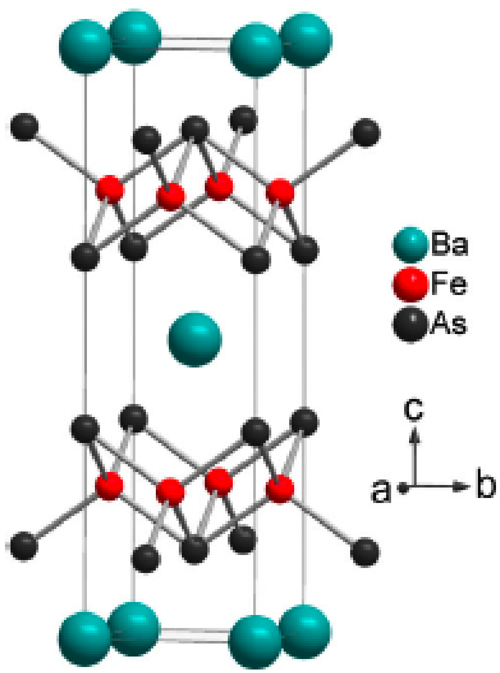

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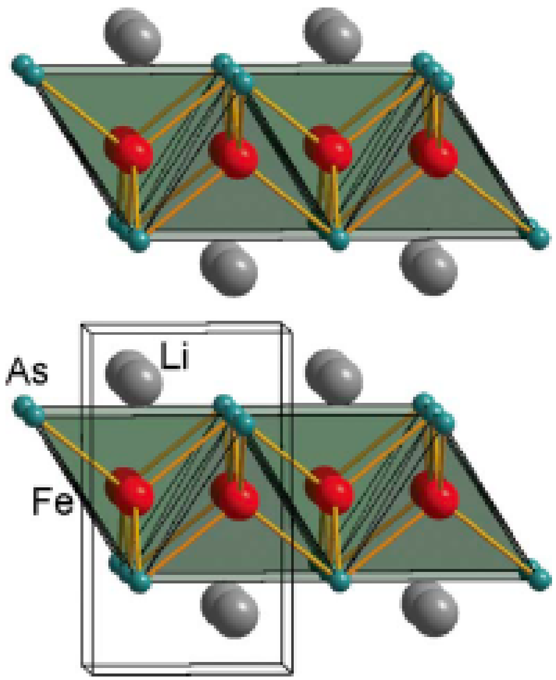

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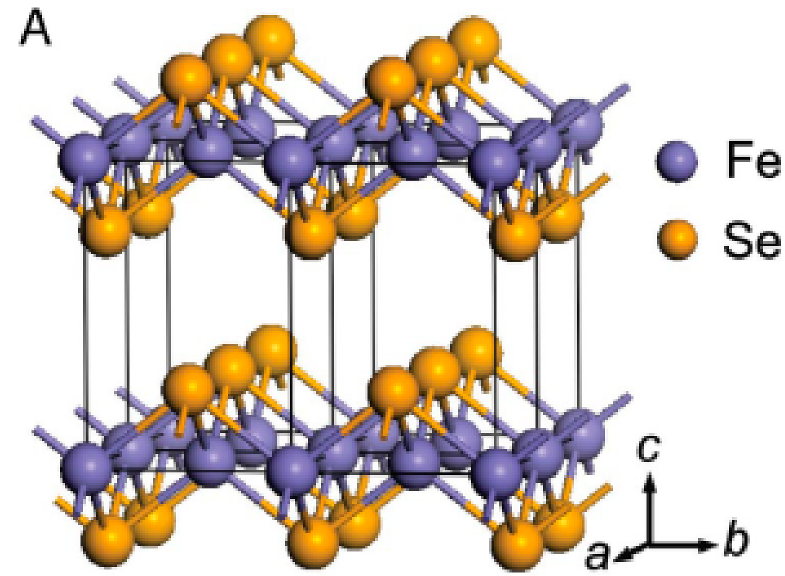
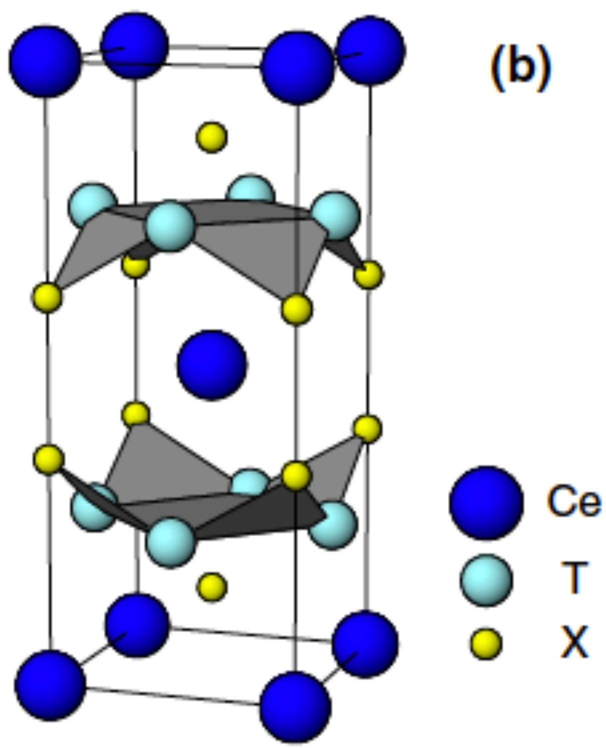


Tapp *et al.*, PRB (2008)

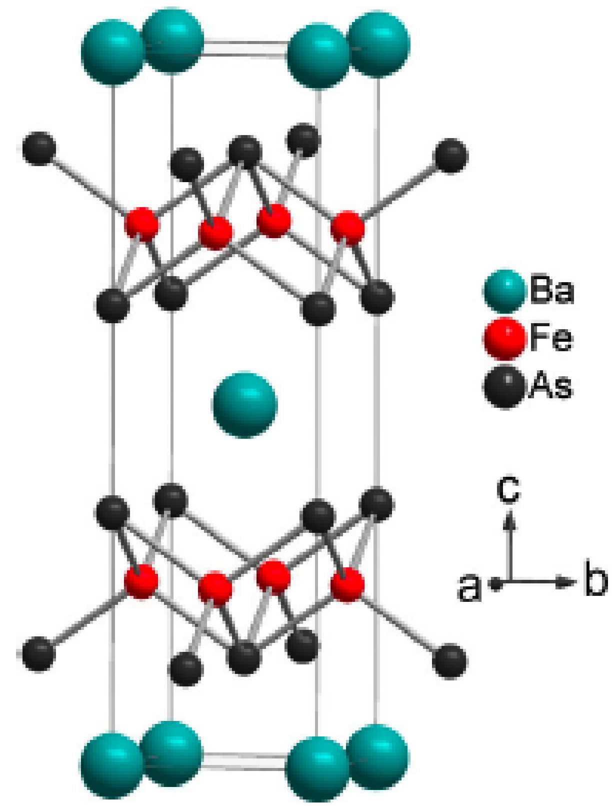
Rotter *et al.*, PRL (2008)

Hsu *et al.*, PNAS (2008)

$ThCr_2Si_2$ crystal structure seems to be ubiquitous

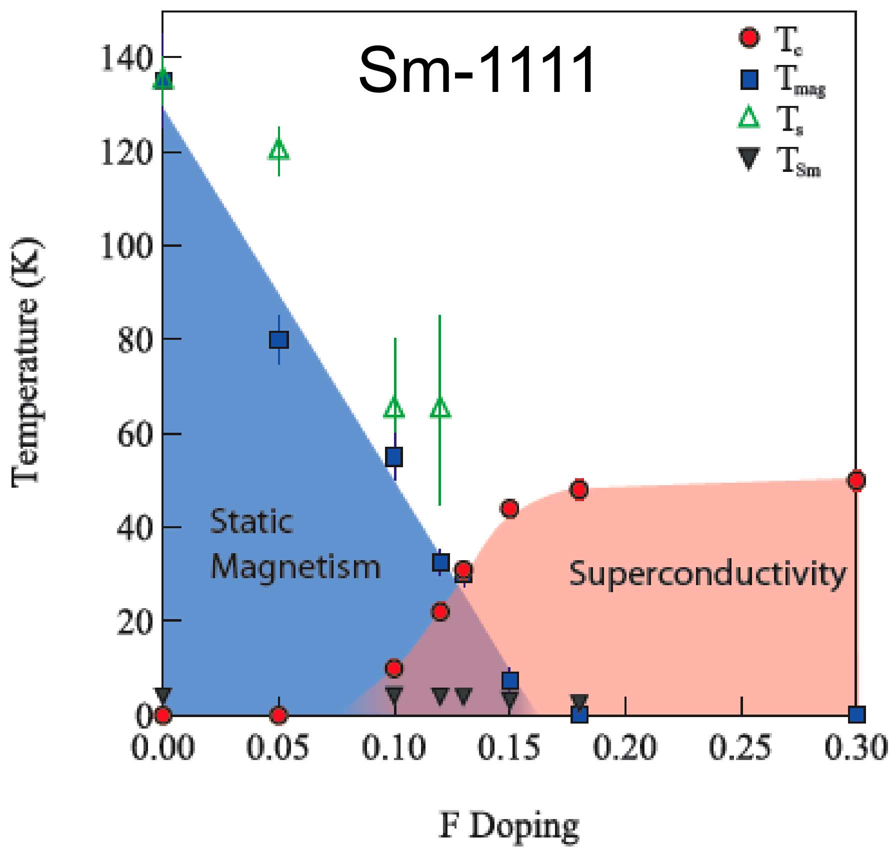


$CeCu_2Si_2$

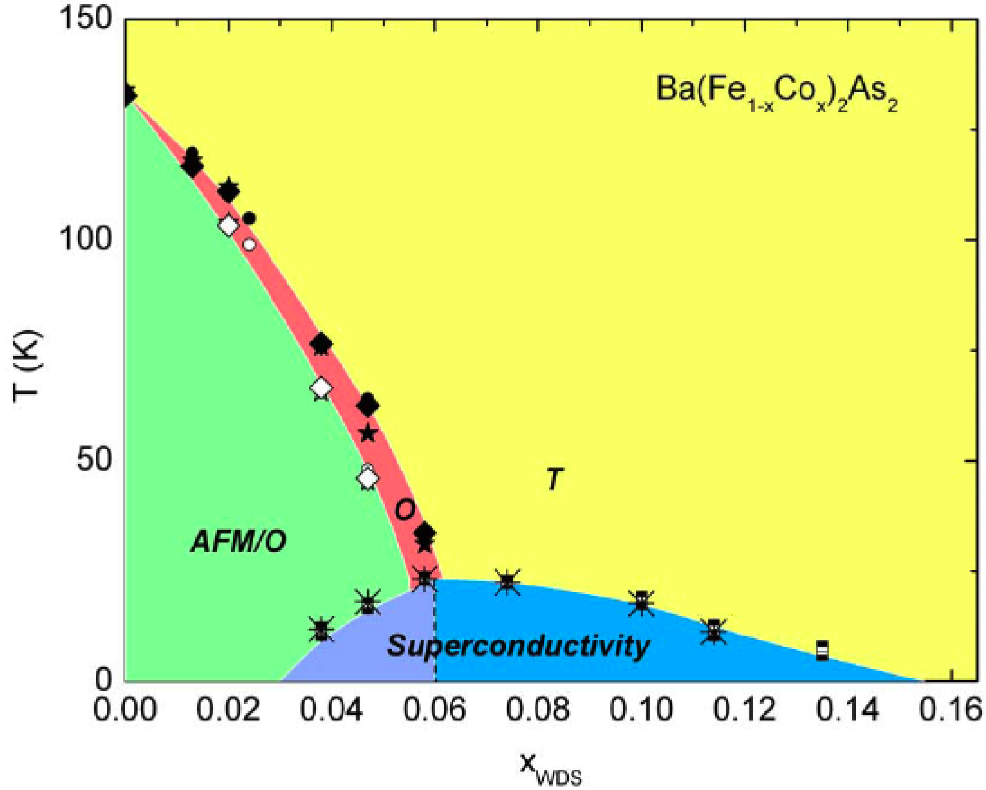


$BaFe_2As_2$

Coexistence of superconductivity & magnetism

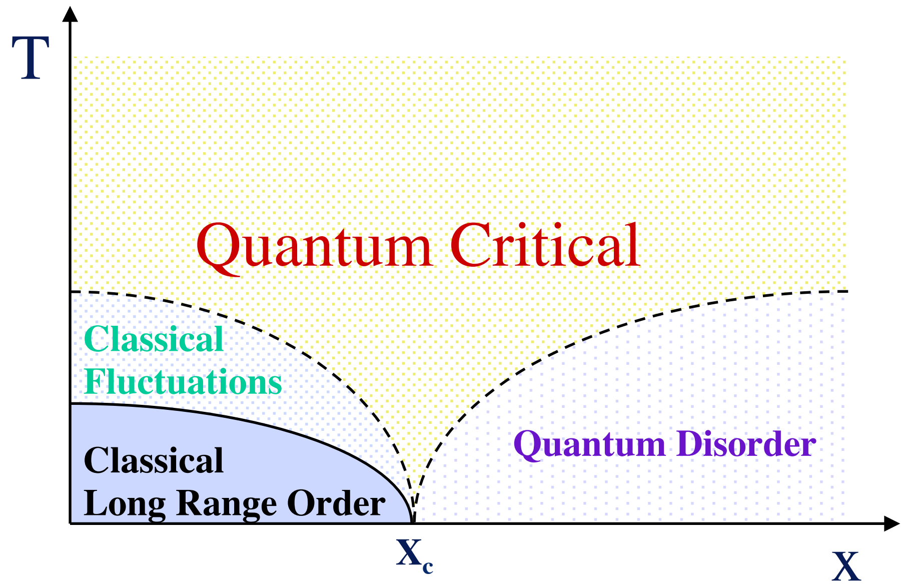


Drew *et al.*, Nat. Mater. (2009)



Canfield & Budko, ARCMP (2010)

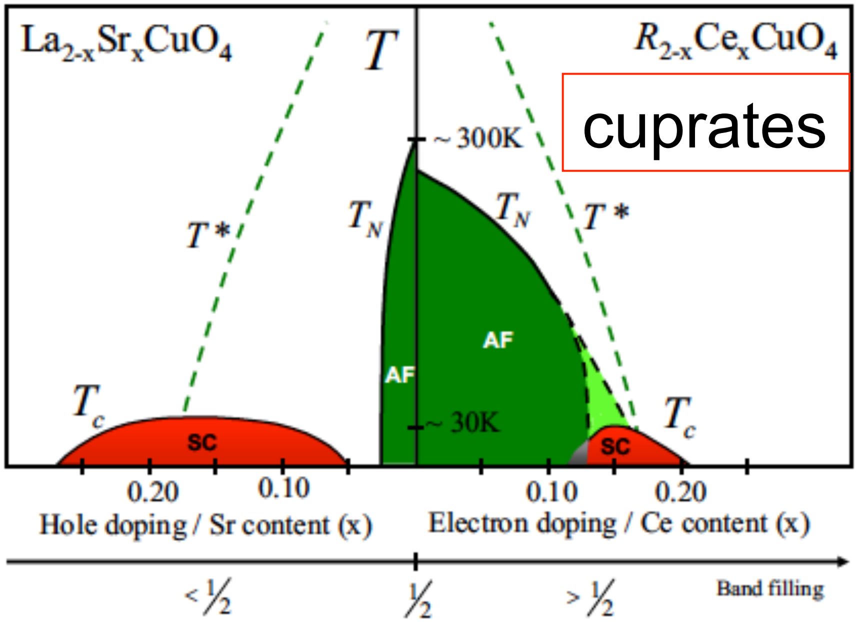
Quantum Critical Scenario



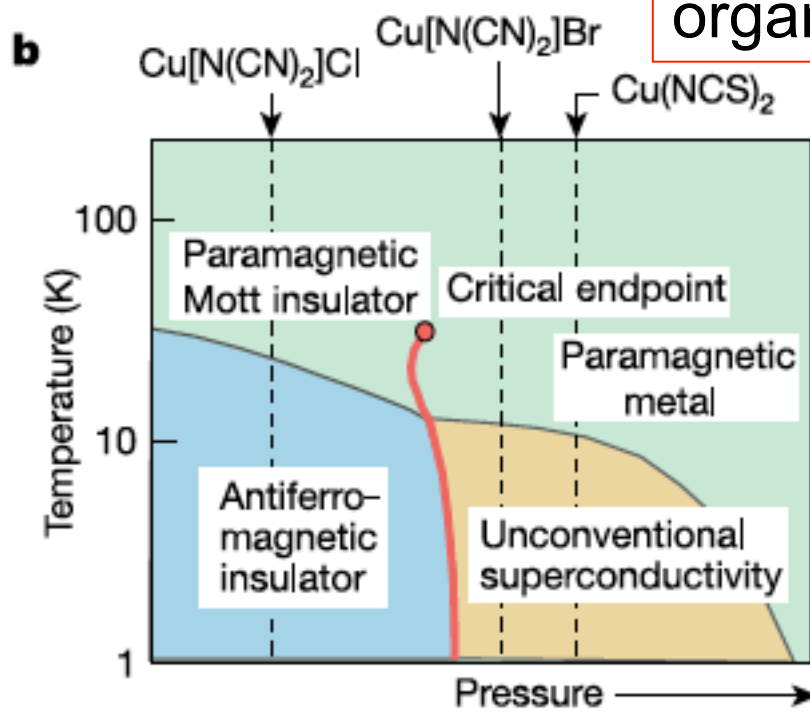
In a quantum critical scenario, an “ordered” phase exists on one side of the critical point, the corresponding “quantum disordered” phase (Fermi liquid) is on the other side.

Similarity of Phase Diagrams

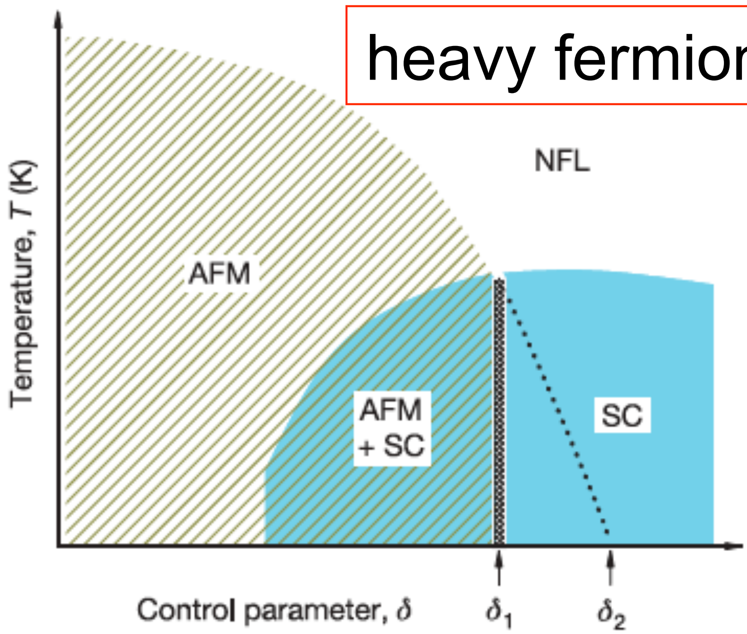
cuprates



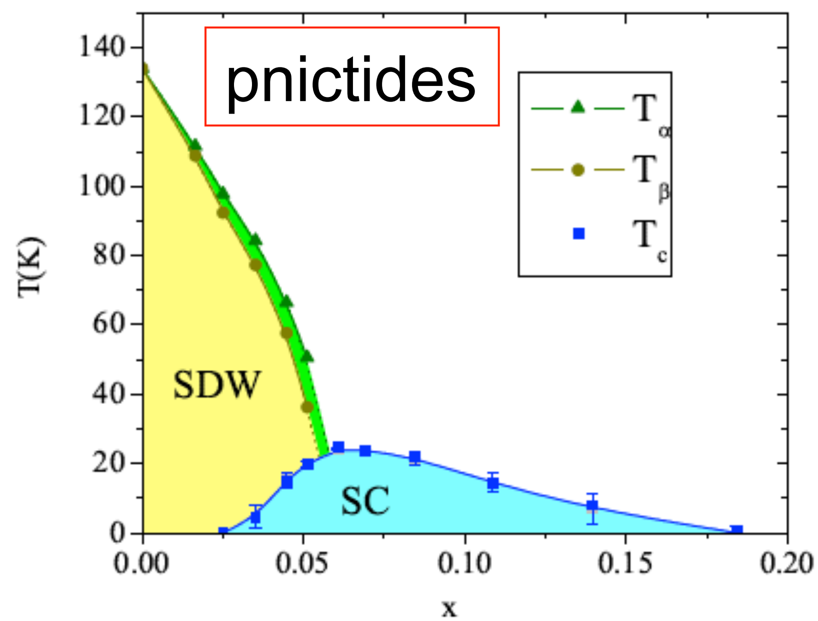
organics



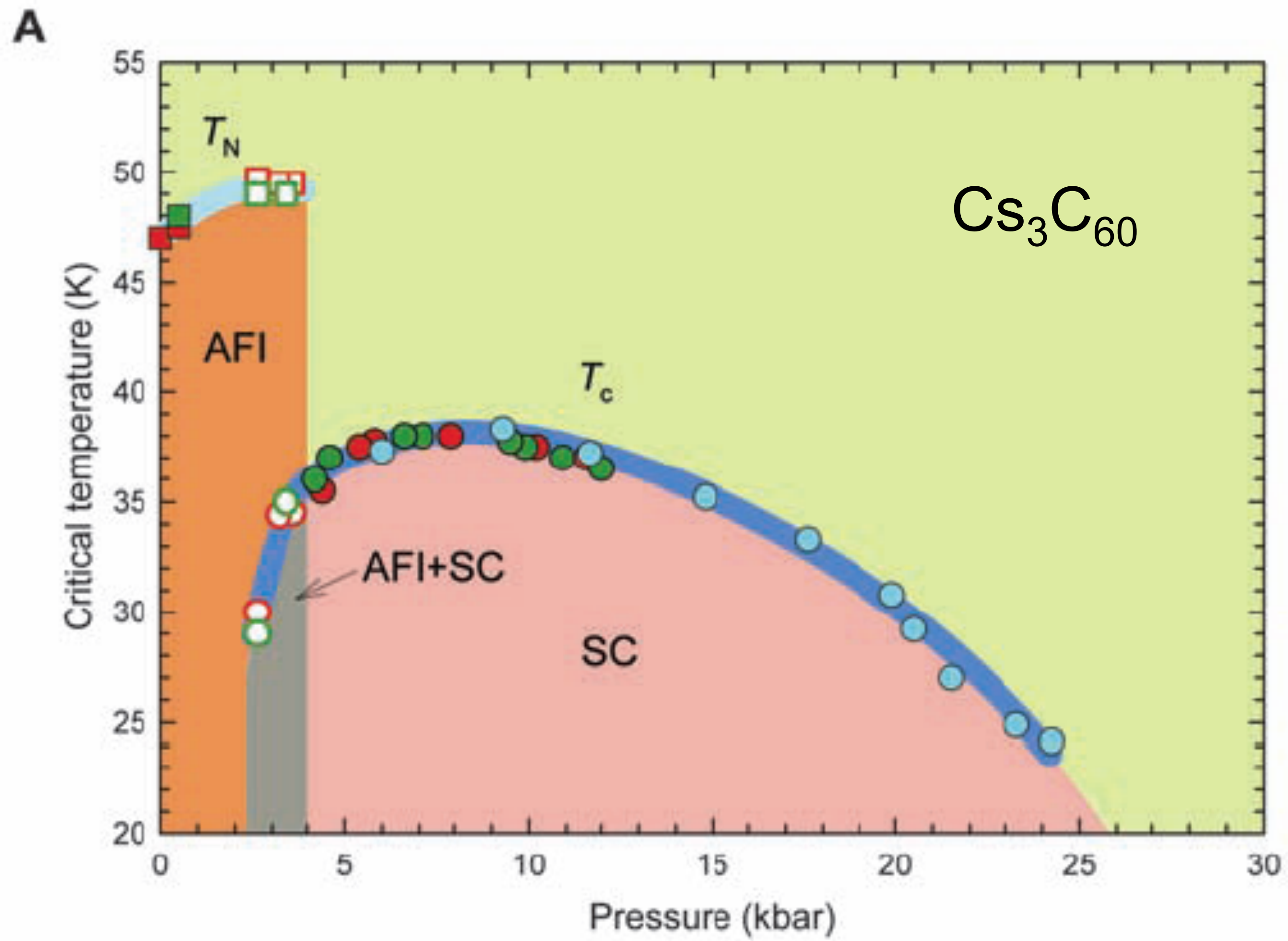
heavy fermions



pnictides

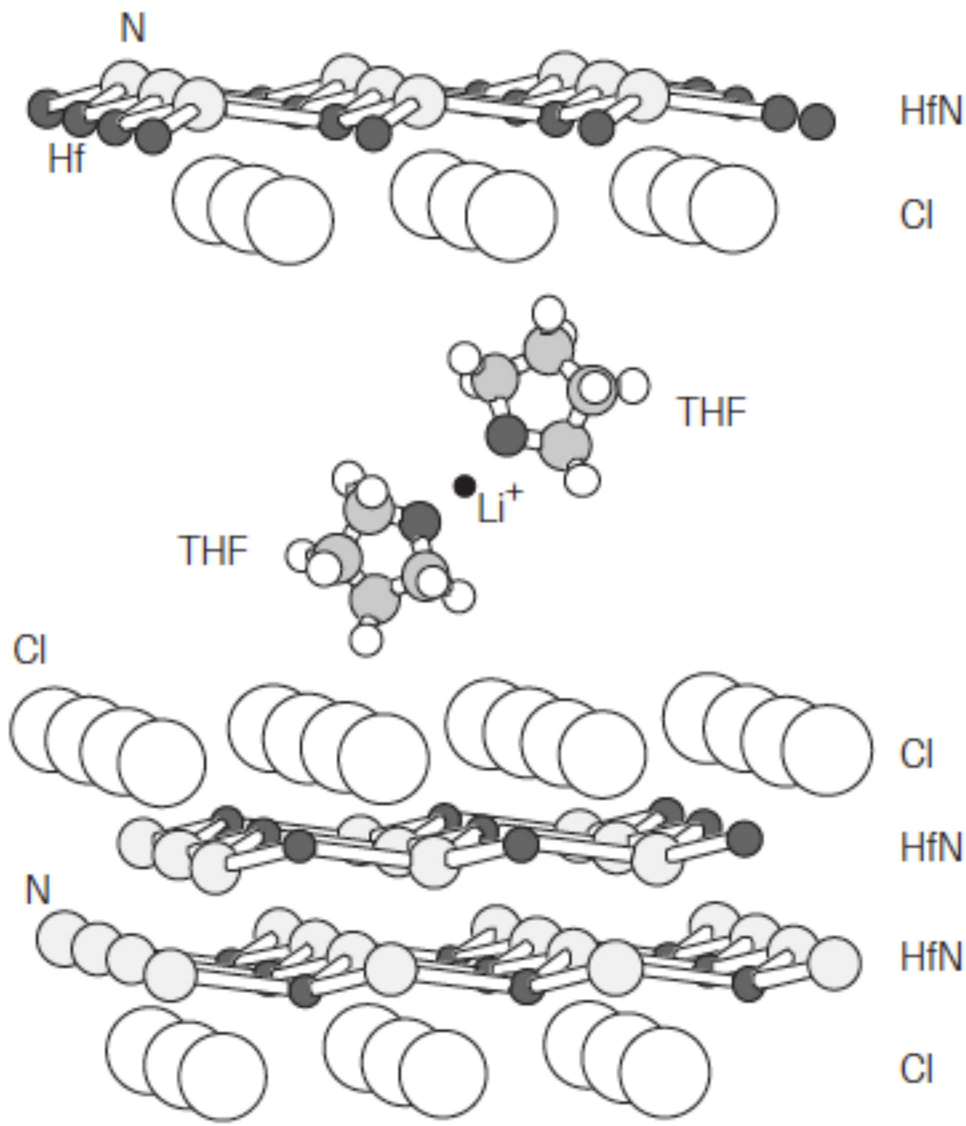


Even Buckeyballs have a Similar Phase Diagram



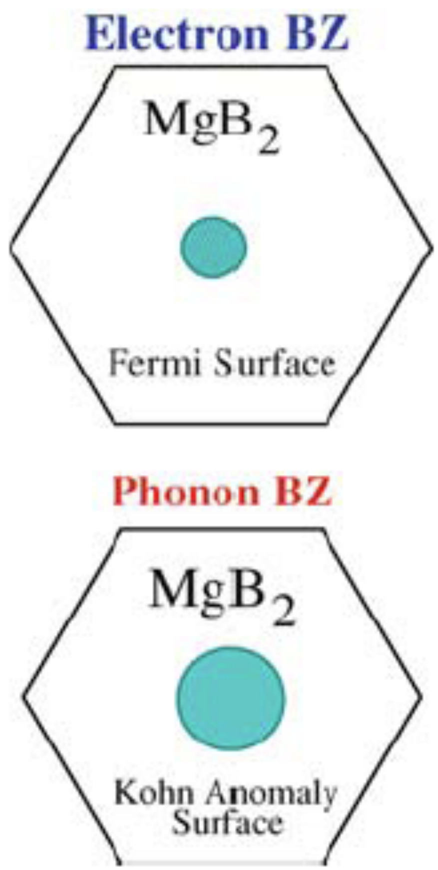
Takabayashi *et al*., Science (2009)

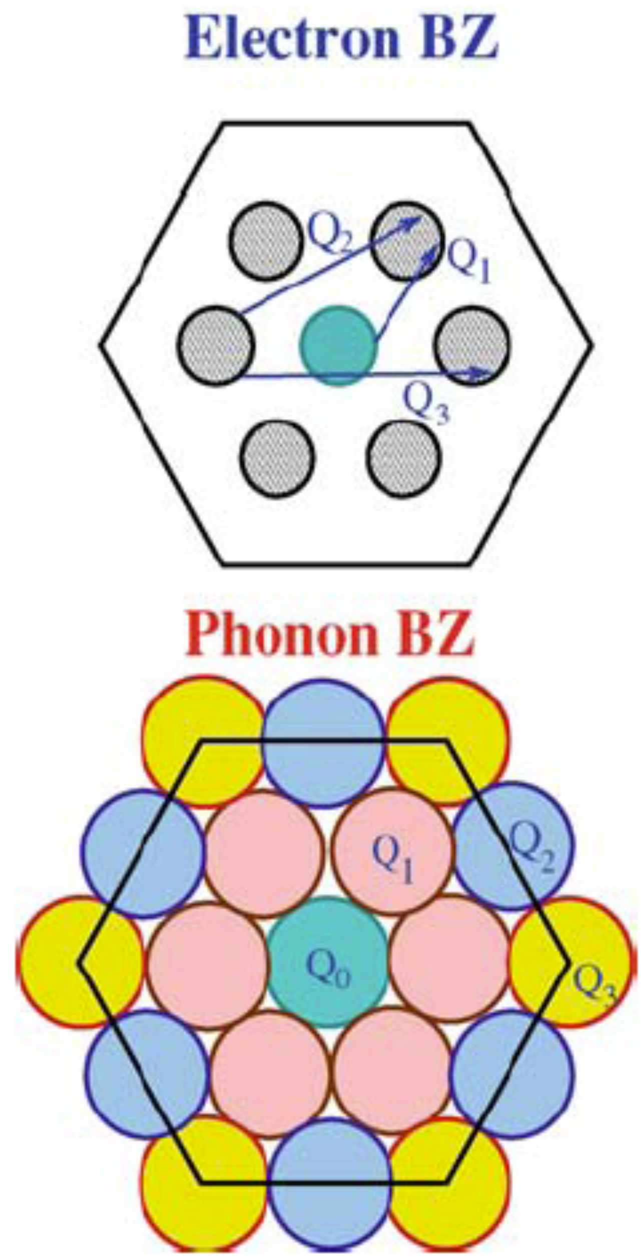
26K superconductivity in layered hafnium nitride



Yamanaka *et al.*, Nature (1998)

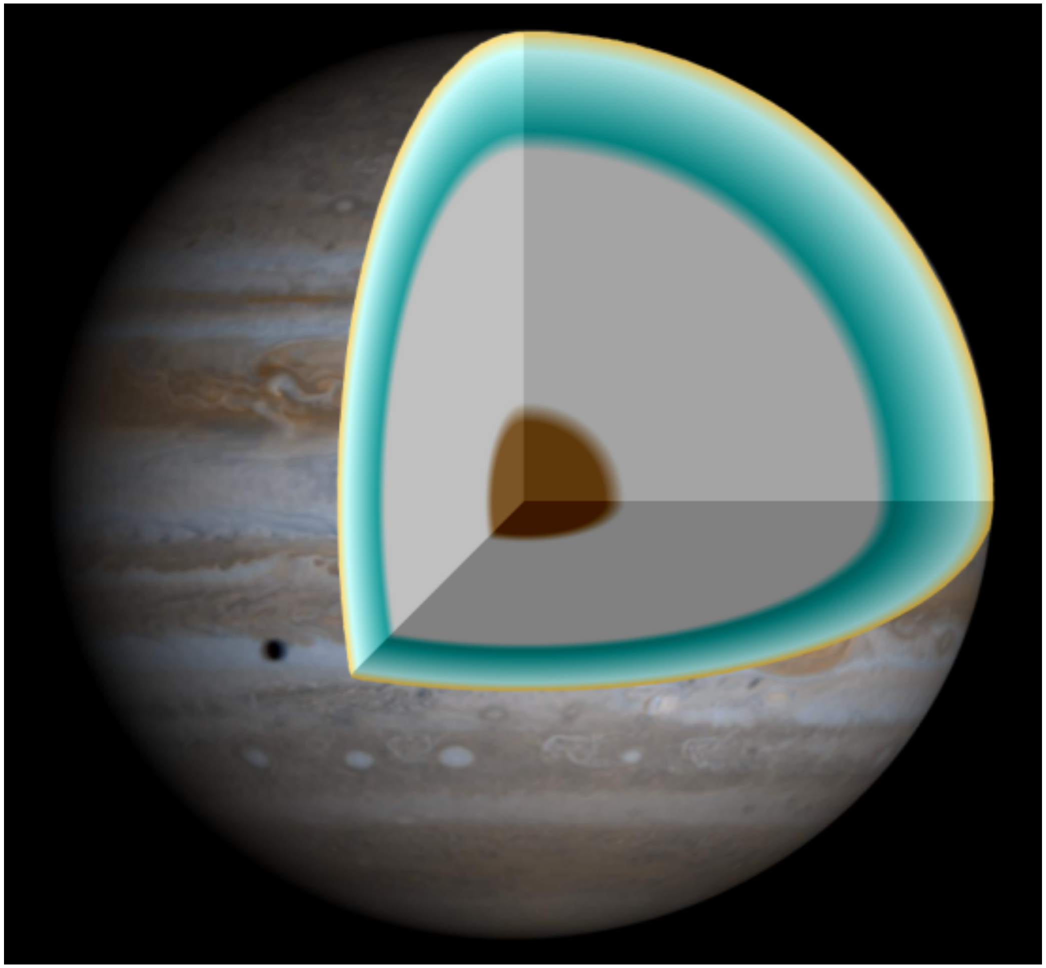
Filling up the Brillouin Zone





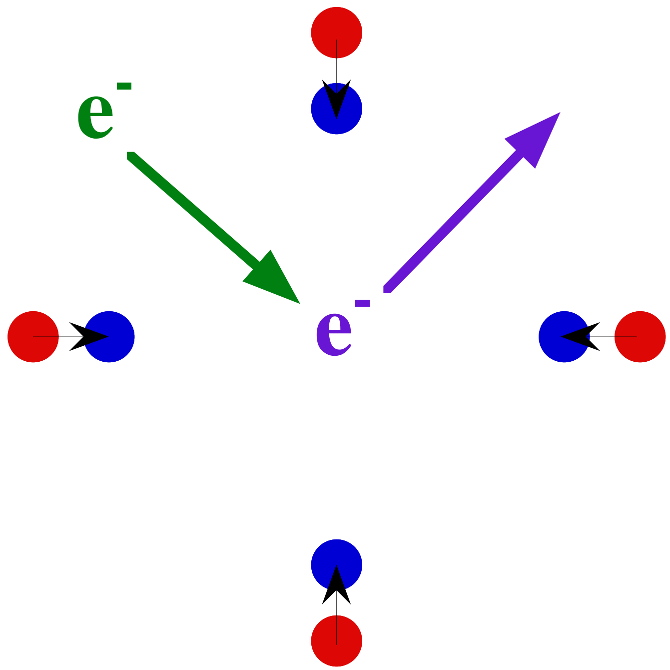
Pickett, J Supercond (2006)

Metallic Hydrogen: A High T_c Superconductor?



Ashcroft, PRL (1968)

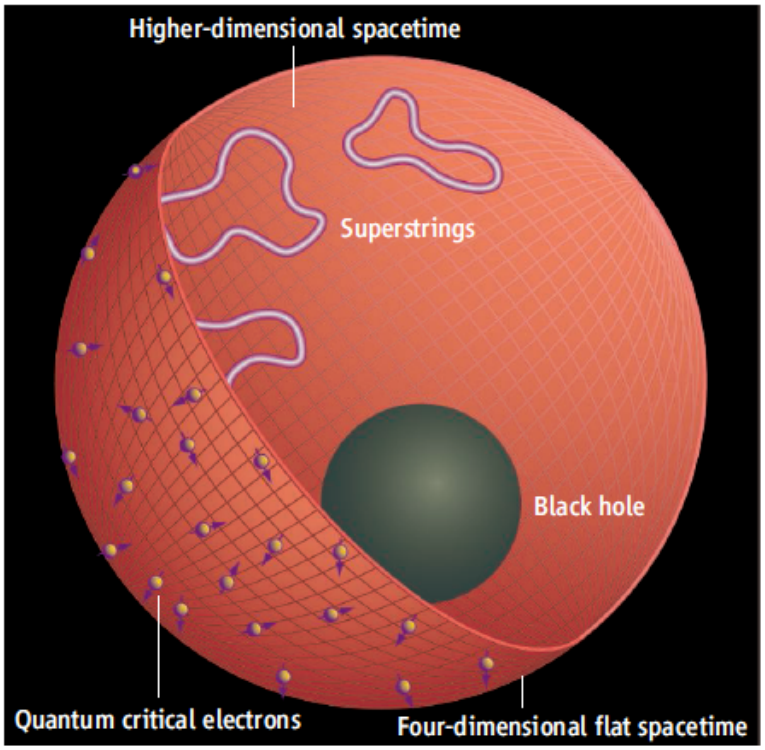
Super High T_c Superconductivity?



Replace ions by heavy holes (leading to a high effective ω_D)

Abrikosov, JETP Lett. (1978)

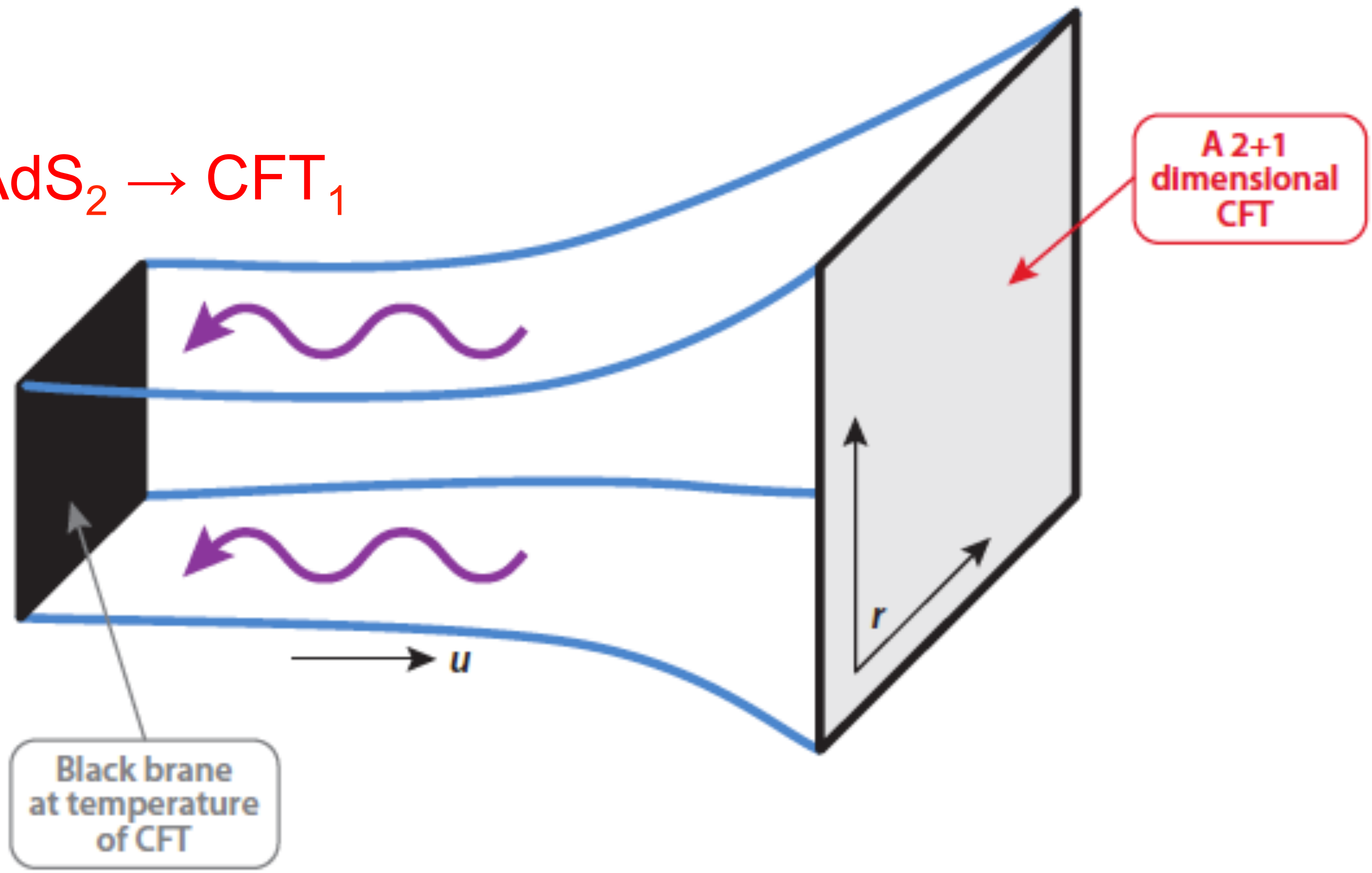
Holographic approach to high temperature superconductors?



Hartnoll, Science (2008)

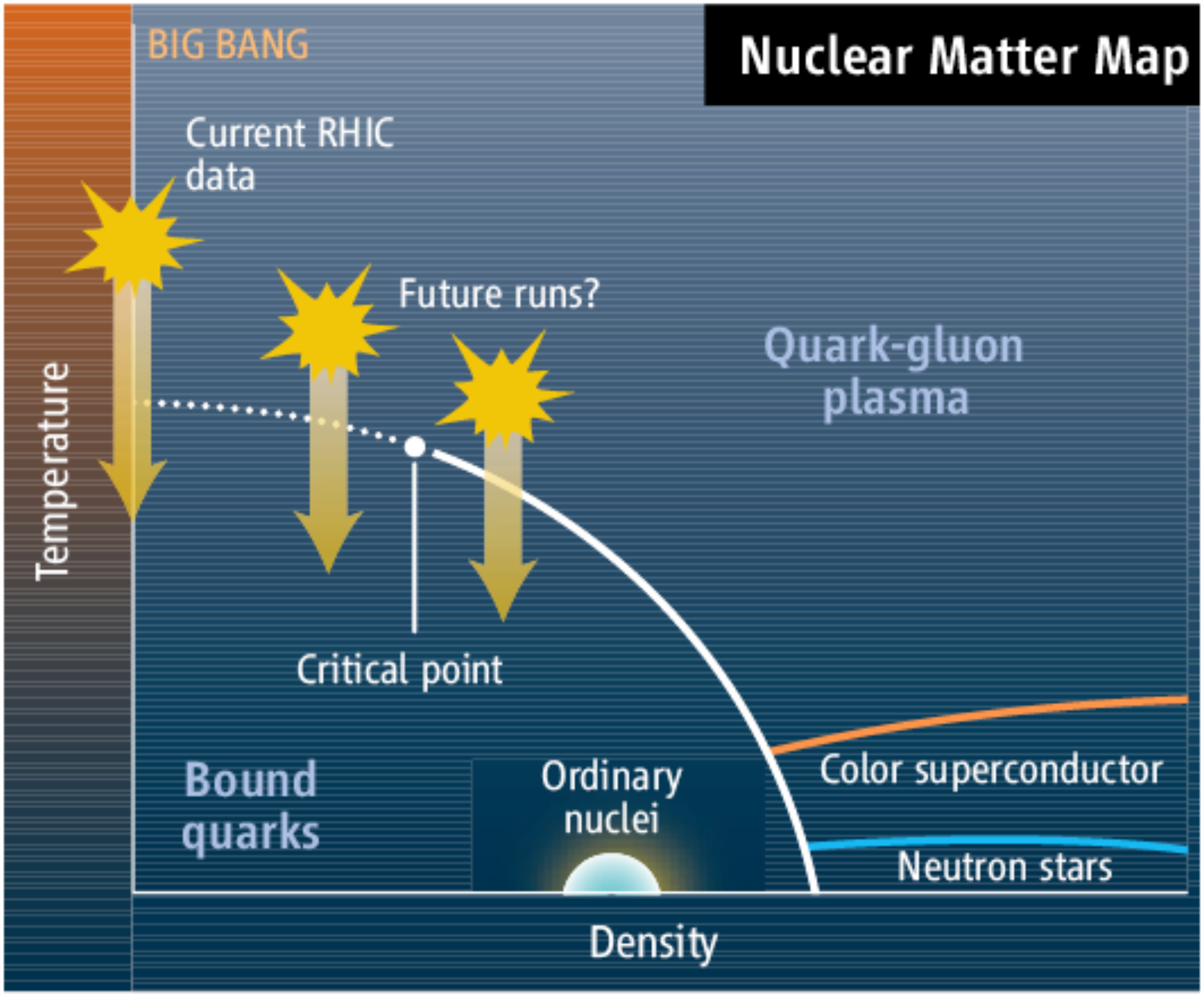
Holographic Approach – AdS/CFT

$AdS_2 \rightarrow CFT_1$



Gubser, Hartnoll, Horwitz, Lee, Liu, McGreevy, Phillips, Sachdev, Zaanen, …
Sachdev, ARCMP (2012)

Connection to Other Fields
(Cold Atoms, Nuclear Matter, …)



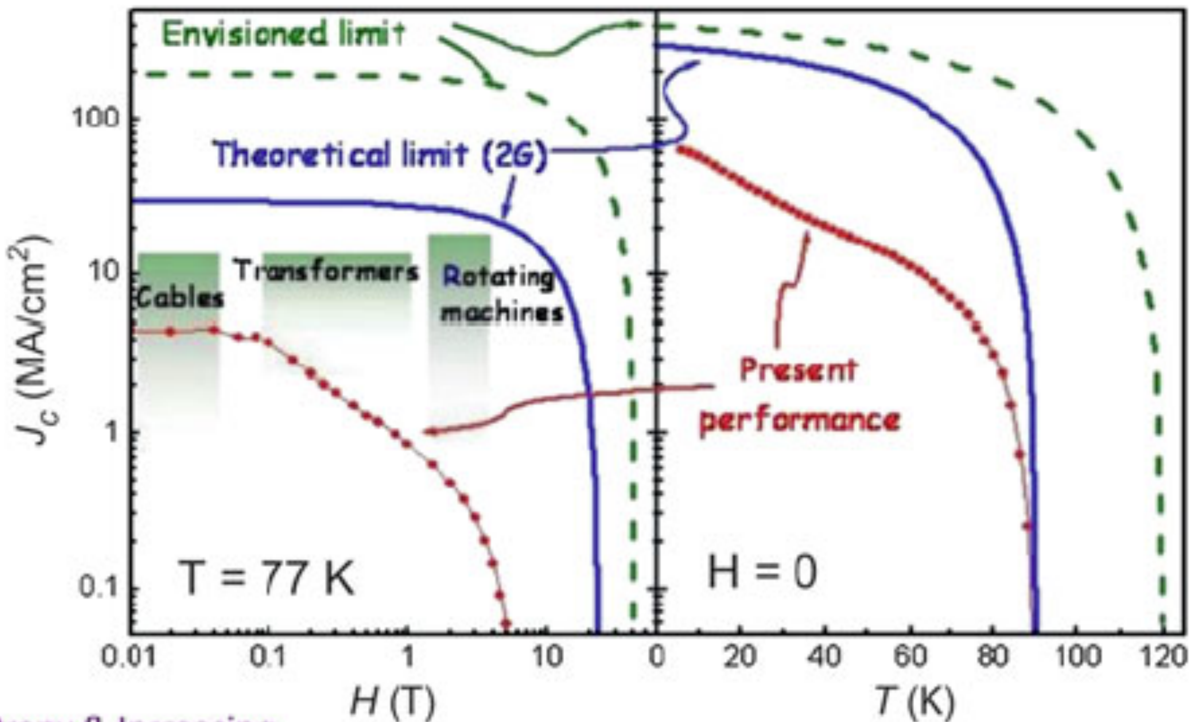
An increased T_c leads to a reduced phase stiffness

$$\frac{T_\phi}{T_p} \propto \frac{n_s^* v_F}{\gamma T_p^2}$$

$$T_c = \min\{T_\varphi, T_p\}$$

$$J_c \propto n_s^* T_p$$

$$\gamma = \sqrt{\frac{M}{m}}$$



Decreasing Anisotropy & Increasing Pair Density (Cumulative) →

Increasing Pairing Interaction - T_p ↓

T_p	T_c $\frac{J_c}{J_c^{YBCO}}$	$\gamma \to 1$	n_s^* x 2	n_s^* x 10
90 K (YBCO)	90 K 1	90 K 1	90 K 2	90 K 10
180 K	72 K 2	180 K 2	180 K 4	180 K 20
270 K	54 K 3	270 K 3	270 K 6	270 K 30
360 K	36 K 4	180 K 4	360 K 8	360 K 40

Beasley, MRS Bull (2011)

I leave you with some "infamous" Bernd Matthias quotes:

I also want to begin with a friendly introduction because the rest of my talk will not be so friendly – *1969 Spring Superconducting Symposium (NRL, 1969)*

The electron-phonon interaction always reminds me of the man who is looking for his keys under a street light and his friends say "but you didn't lose them here, you lost your keys over there". "I know, but it is too dark over there." – *ditto*

the first symposium on organic superconductors is being held in Hawaii. To my knowledge, this is the first symposium ever to be held on a nonexistent subject. – *Superconductivity, ed. Frank Chilton (North Holland, 1971), p . 69*

the success of the 5f electron superconductivity mechanism in being able to predict even ferromagnetism is in my opinion fairly convincing evidence of the magnetic rather than vibrational interaction – *ditto*

That of course leads you to Green's functions and the absence of any further predictions. – *Science and Technology of Superconductivity (Plenum, 1973)*

Unless we accept this fact and submit to a dose of reality, honest and not so honest speculations will persist until all that is left in this field will be these scientific opium addicts, dreaming and reading one another's absurdities in a blue haze. - *Comments Solid State Physics, 3, 93 (1970)*