Quest for new superconductors

…or superconductivity entering the Iron Age

Igor Mazin, Naval Research Laboratory, Washington D. C.

As coarse as my own wits are, I have been privileged to wear the boots of the Sagacious and be clad in the robes of the Virtuous.

The Supplication of Daniel the Prisoner, a Russian monk, XIII century.

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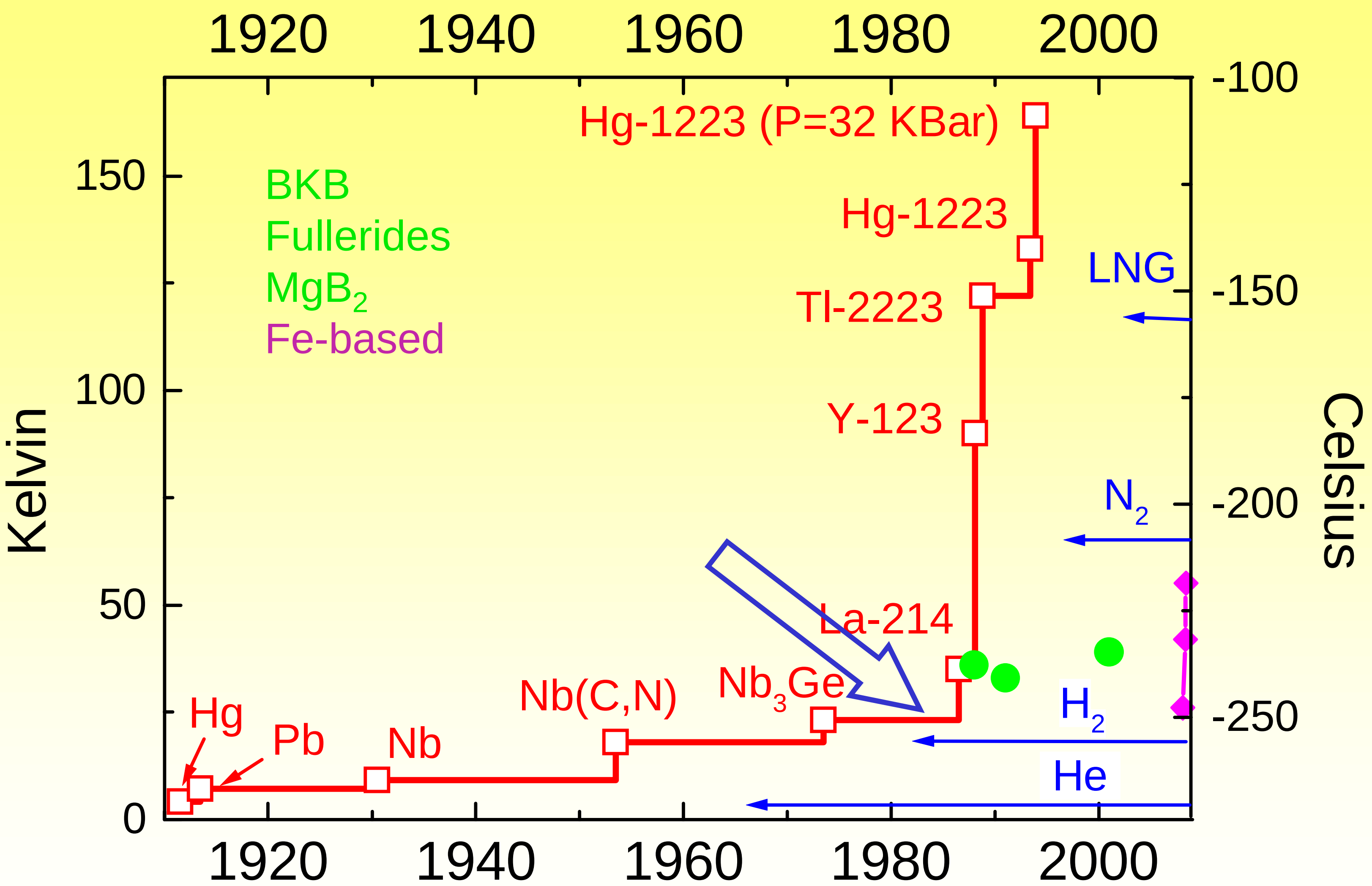
Vitaly Ginzburg and high temperature superconductivity: Personal reminiscences

Igor I. Mazin *

A brief history of superconductivity



…in search of a theory of primeness…

• 1, 3, 5, 7 are all prime. *Ergo*, all odd numbers are prime.

• 9 is not prime! *This is an experimental error. To test this, let us look at more odd numbers:*

• 11 is prime and so is 13. The hypothesis has been confirmed and demonstrated it's predictive power!

Any correct theory of primeness should be able to explain why all odd numbers are prime.

…and any correct theory of s/c must explain why the maximum Tc is limited by 30 K (as of 1985)

…in search of a theory of primeness…

B.T. Matthias, Science **144** (1964) 373: *Why has it been relatively easy, within the last 10 years, to reach transition temperatures of 17? to 18?K in many intermetallic systems and impossible to raise this value even by as little as half a degree?*

M.L. Cohen, P.W. Anderson, Comments on the maximum superconducting transition temperature, in: D.H. Douglass (Ed.), Superconductivity in d- and f-Band Metals, AIP, New York, 1972

$$T_c \approx \theta \exp\{-1/[\lambda/\cancel{(1+\lambda)} - \mu^*]\}$$

$$\mu^* = \mu/[1+\mu \ln(E/\theta)]$$

$$\lambda = \mu$$

$T_c(\max) = E \exp(-4-3/\lambda)$

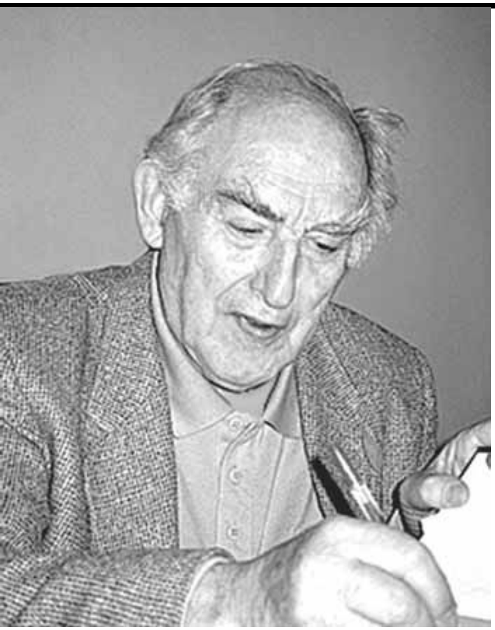
$T_C(\max)$~10-30 K for λ~1-2

$E \exp(-3/\lambda)$

$T_C(\max)$~50 times higher.

OK, let $\lambda(\max)$ be ½…

…in search of a theory of primeness…



Timeline

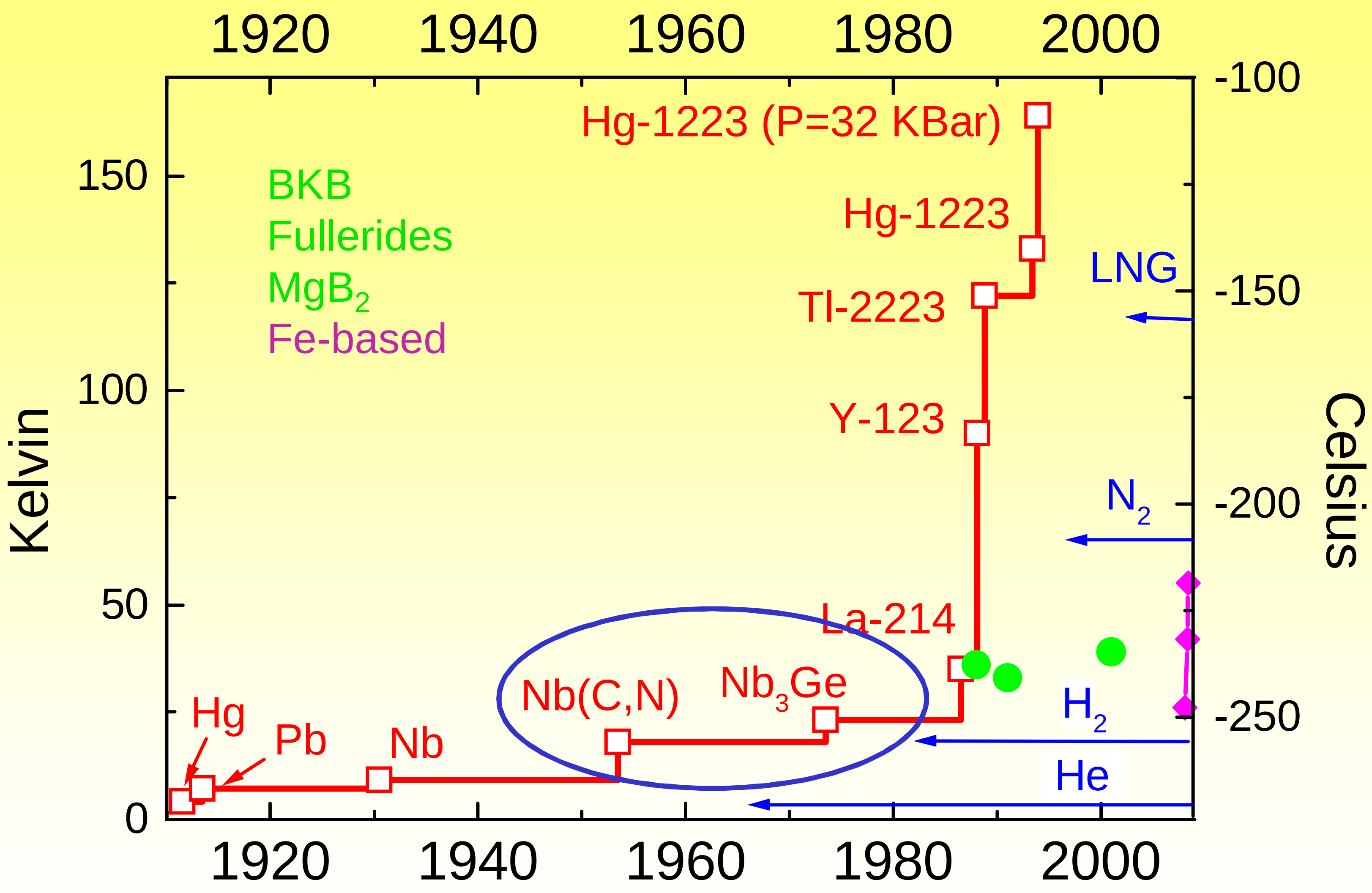
1964: Matthias poses his challenge

1972: Anderson responds

1976: I come to the V.L.'s group as a student

1978-1981: Dolgov-Kirzhnits-Maksimov

$$\lambda = \mu$$



1920
1940
1960
1980
2000
-100
-150
-200
-250
150
100
50
0
Kelvin
Celsius
Hg-1223 (P=32 KBar)
Hg-1223
Tl-2223
Y-123
La-214
BKB
Fullerides
MgB2
Fe-based
LNG
N2
H2
He
Nb(C,N)
Nb3Ge
Hg
Pb
Nb

Berndt Matthias' rules

Six rules for a successful search for new superconductors

1 . A high symmetry is good; cubic symmetry is the best.

2. A high density of electronic states is good.

3. Stay away from oxygen.

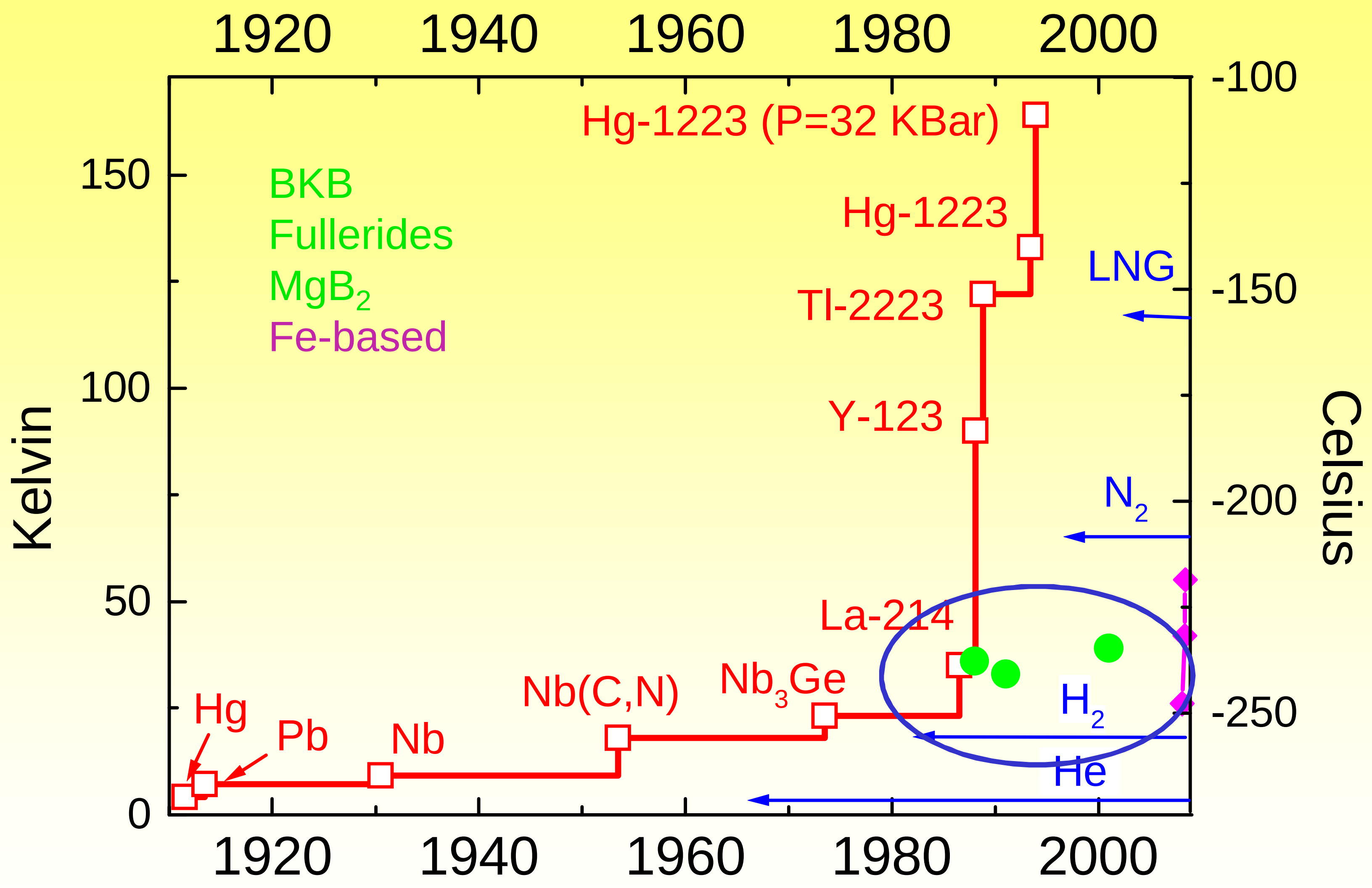
4. Stay away from magnetism.

5. Stay away from insulators.

6. Stay away from theorists.

All these rules (with possible exception of #6) have been proven wrong in cuprates

Are cuprates unique?



Basic Research Needs for Superconductivity (DOE, 2006)

11000 years ago: Wolf domesticated

…4000 years… different wolf species domesticated; various dog breeds created and improved

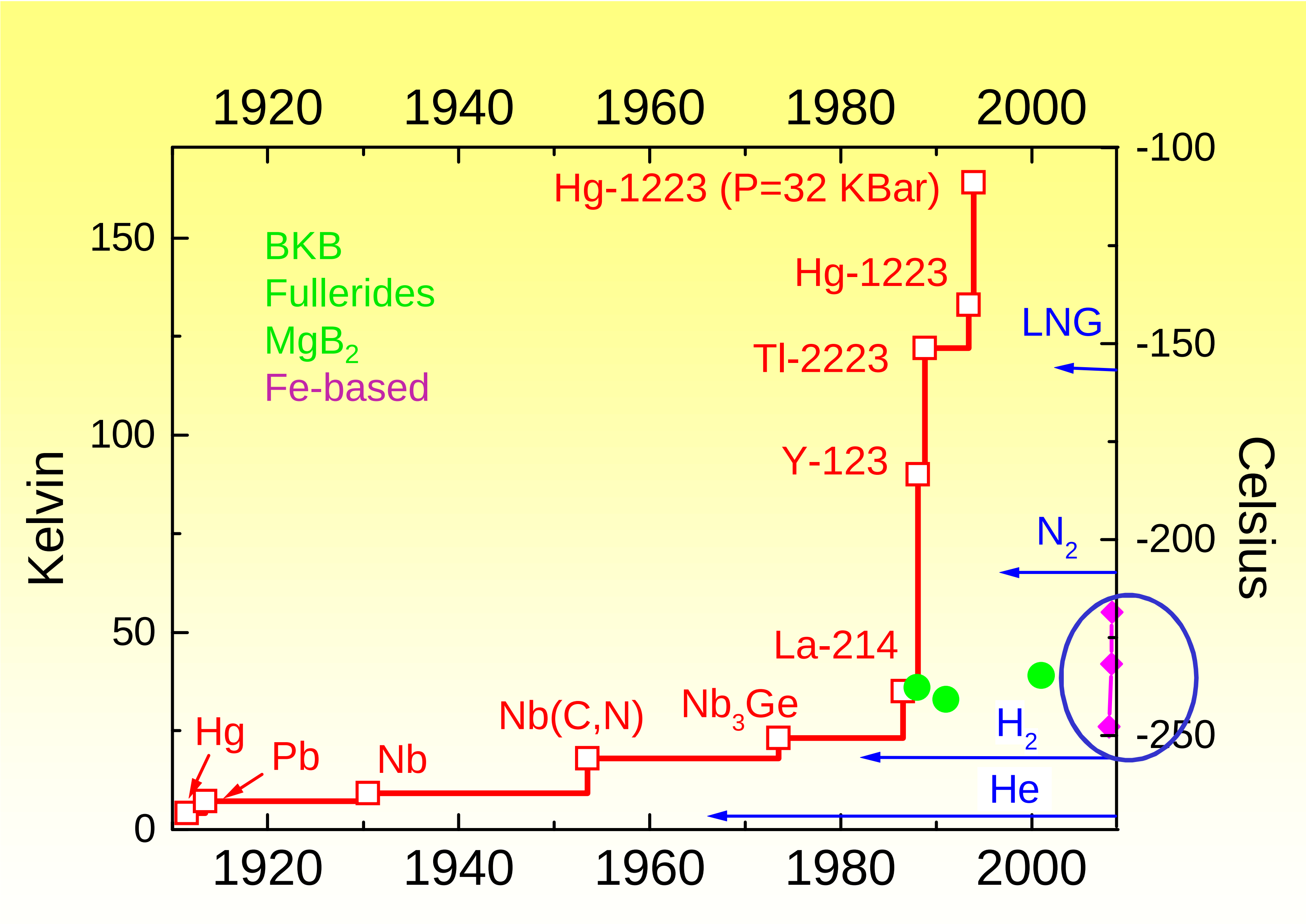
7000 years ago: Goat domesticated

Sheep, cattle, chicken, swine, ass domesticated within, presumably, the next 1000 years.

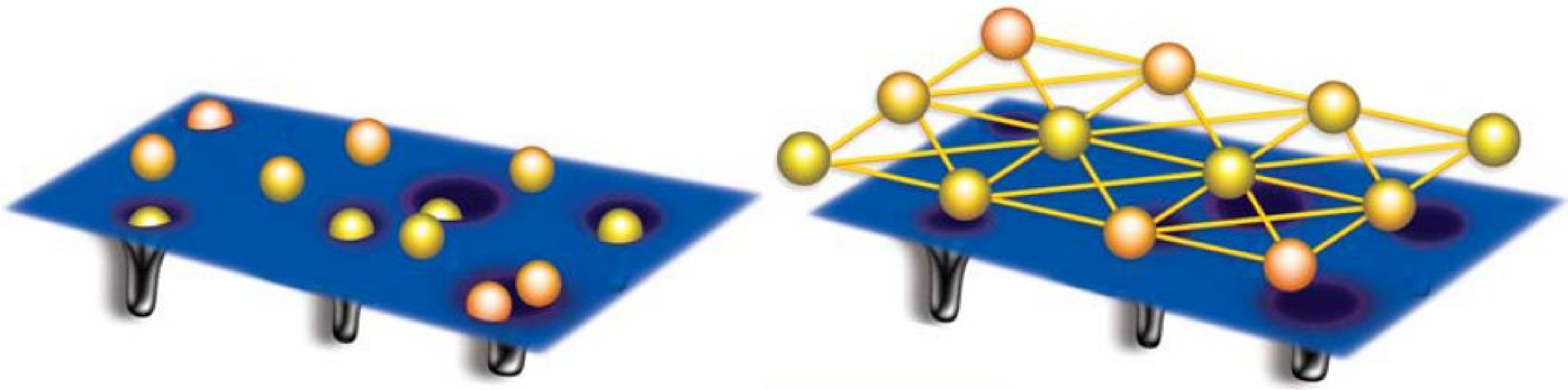
Wh our Cur r Status?

Wh our Basi ence Challenge?

Goat discovered?

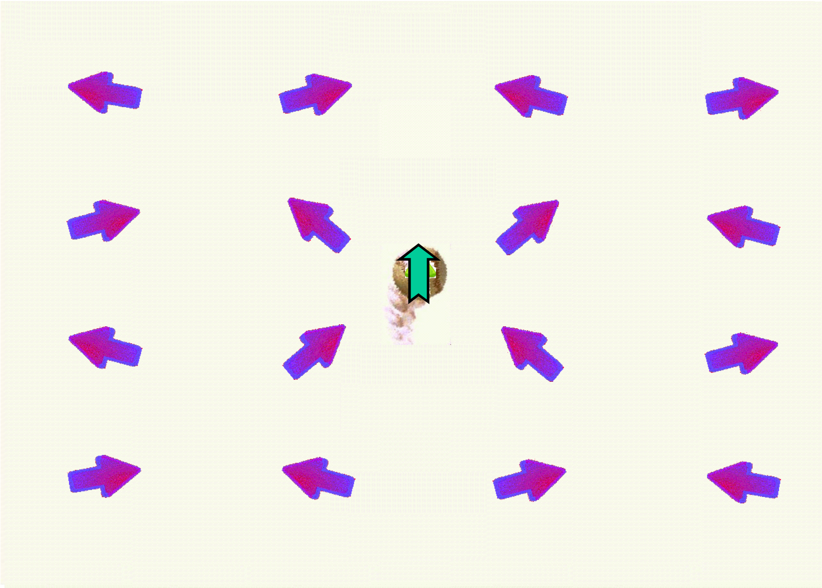


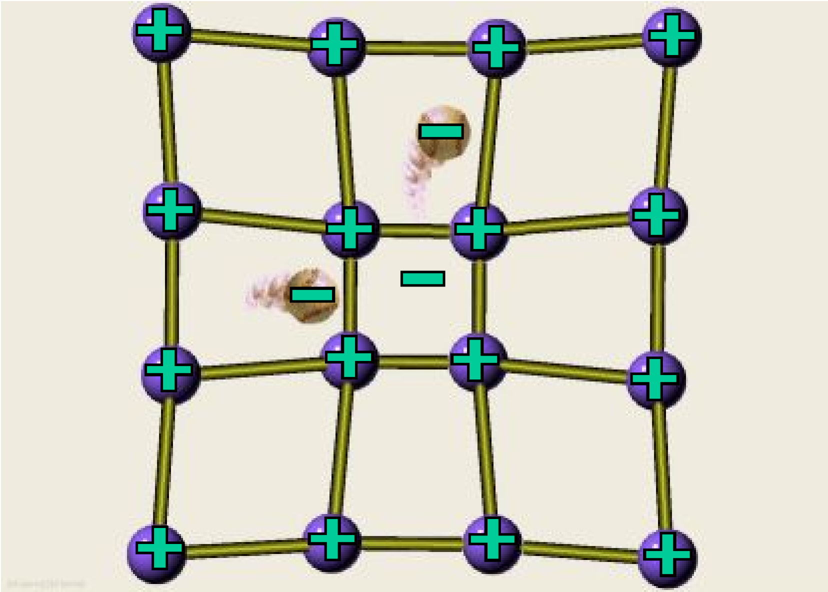
BCS basics



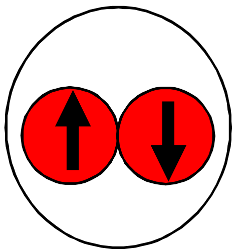
1. Macroscopically coherent state
2. Pairing (to go from the Fermi statistics to the Bose statistics)
3. Pairing interaction
   - *Not necessarily phonons*
   - *Not necessarily attraction*
4. Excitation gap (robustness)

Pairing interaction: phonons vs. spin fluctuations



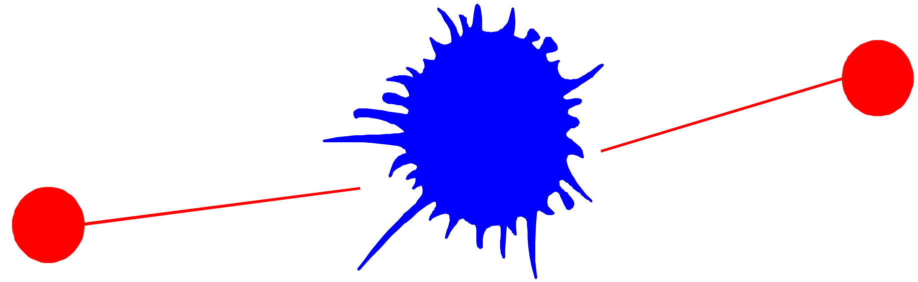


Superconductivity and spin fluctuations

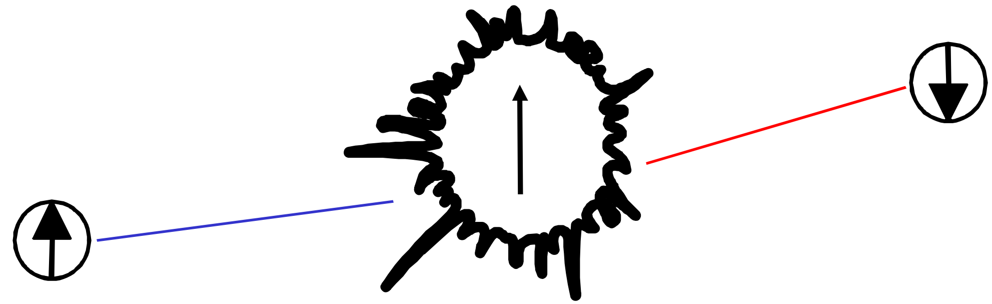


singlet

charge fluctuations (phonons) mediate attraction; spin fluctuations mediate repulsion



2nd electron - charge polarization cloud - 1st electron

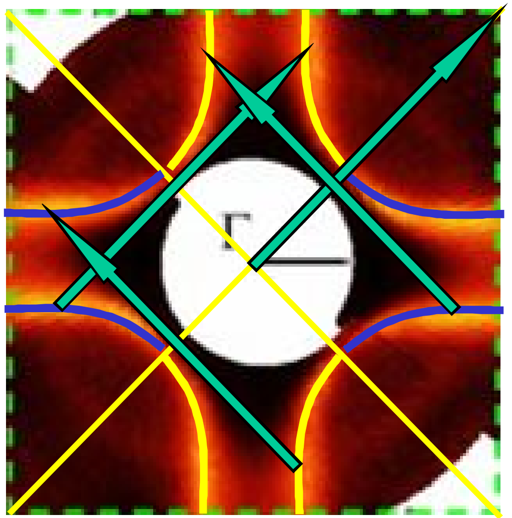


2nd electron - spin polarization cloud - 1st electron

$$\Delta_{\mathbf{k}\alpha} = \sum_{\mathbf{q}\beta} V_{\mathbf{kq},\alpha\beta} \Delta_{\mathbf{q}\beta} F(\Delta_{\mathbf{q}\beta}, T)$$

If $\Delta_{\alpha\mathbf{k}}$ and $\Delta_{\mathbf{k}\beta}$ have opposite sign, a negative (repulsive) V can still be pairing.

How does it work in high-Tc cuprates?



Fermi surface of BSCCO measured by ARPES (http://en.wikipedia.org/wiki/Fermi_surface)

Parent compounds have checkerboard antiferromagnetism. Superexchange interaction is peaked at Q=(π,π)

It is perfectly well matching the fermiology of high-Tc cuprates

There are two ingredients in this recipe: (1) Fermiology and (2) momentum dependence of spin-fluctuations

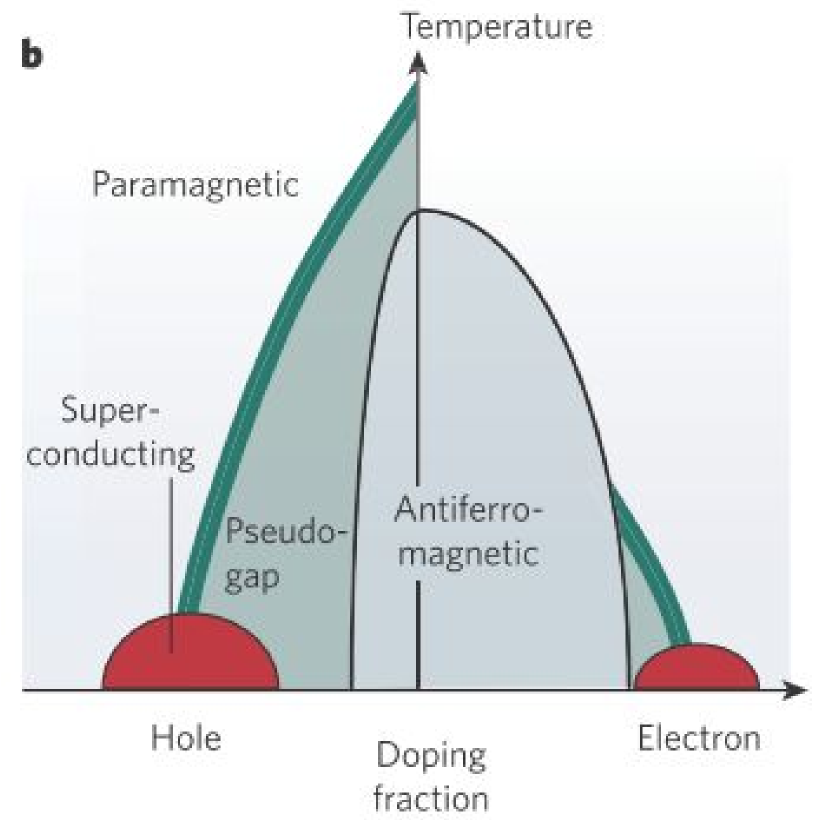
$$\Delta_{\mathbf{k}\alpha} = \sum_{\mathbf{q}\beta} V_{\mathbf{kq},\alpha\beta} \Delta_{\mathbf{q}\beta} F(\Delta_{\mathbf{q}\beta}, T)$$

If $\Delta_{\alpha k}$ and $\Delta_{k\beta}$ have opposite sign, a negative (repulsive) *V* can still be pairing.

The cuprates duel: pairing glue – yes or no?

Two schools of thoughts:

1. Pairing glue, most likely magnetic.
   - Superconductivity emerges from "outside", from Fermi liquid.
   - Modified Eliashberg theory.
   - Proponents: Ginzburg, Maksimov, Pines, Scalapino,…



2. Completely novel mechanisms
   - Superconductivity emerges from the Mott-Hubbard state
   - Pairing creates energy gain for all electrons (in different ways in different theories).
   - Proponents: Anderson (RVB, IPT, …), Laughlin (Gossamer s/c), …

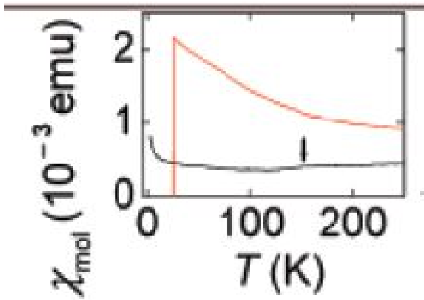
Pairing glue proponents celebrate

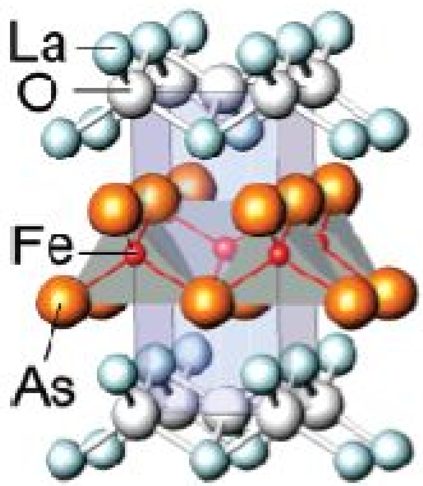
J|A|C|S
COMMUNICATIONS

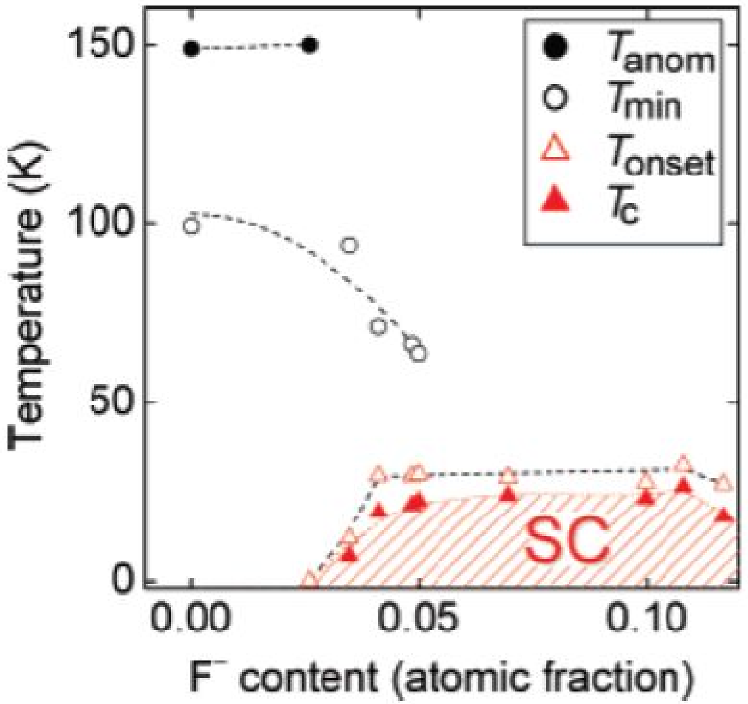
Published on Web 02/23/2008

Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ ($x = 0.05-0.12$) with $T_c = 26$ K (soon up to 57 K)

Yoichi Kamihara,[*,†] Takumi Watanabe,[‡] Masahiro Hirano,[†,§] and Hideo Hosono[†,‡,§]

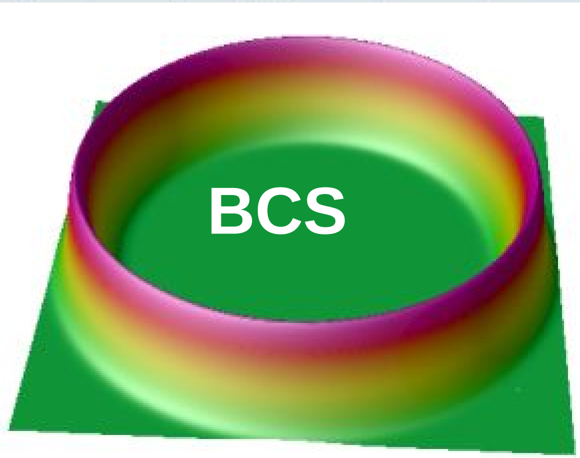


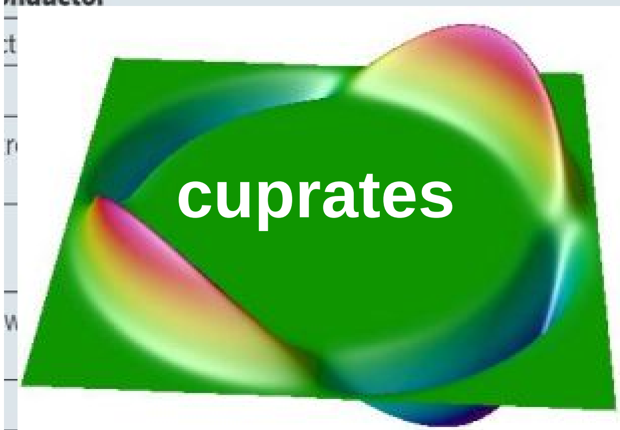


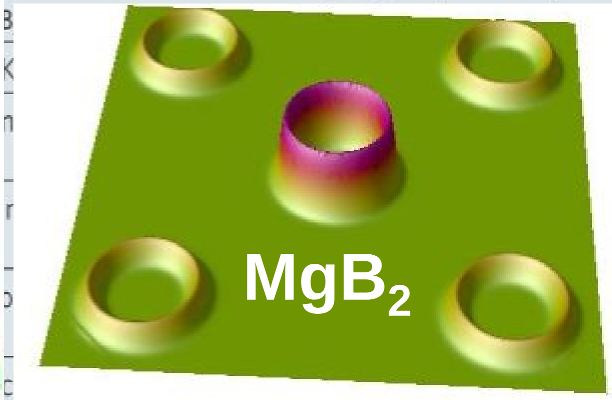


Comparison with other high-T_c materials

Ta… …nductor





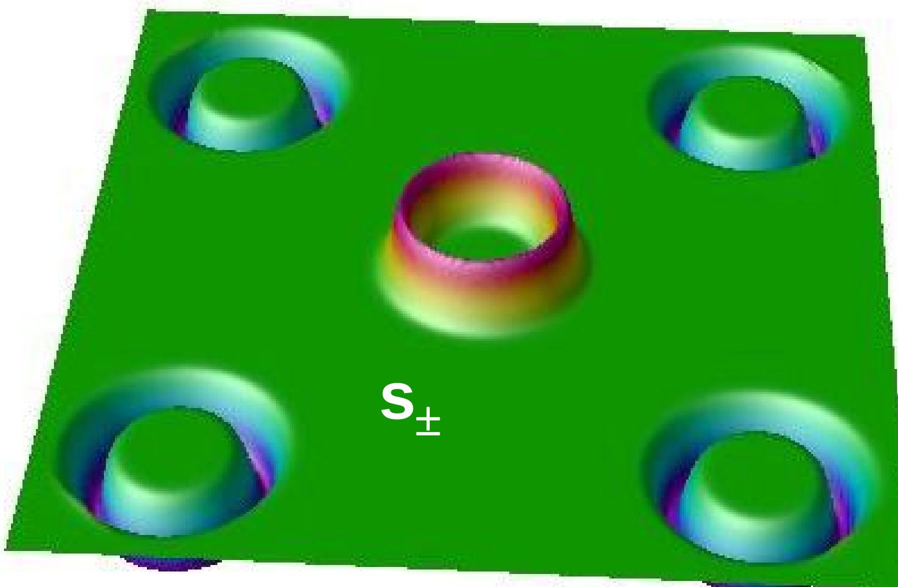


Dimensionality	Three dimensional	Two dimensional	Three dimensional	Variable

From *I. I. M* … …y review).

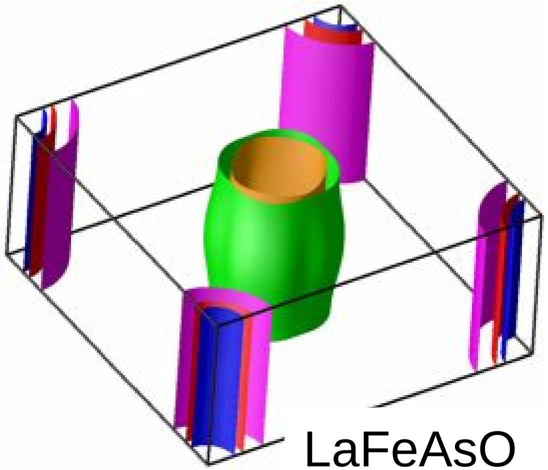
Other revie… …, J. Paglione and R.L. Green…

… 469, 614 (2009).

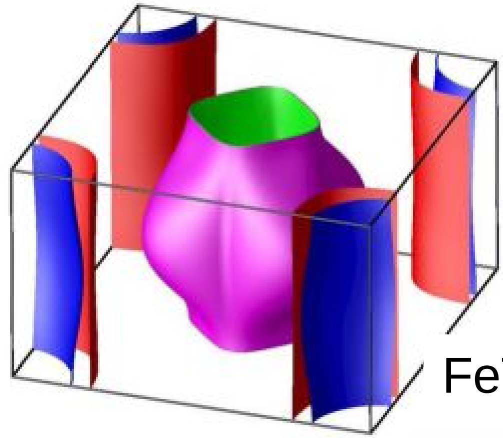


In some … …cuprates and MgB_2.
In many … …new paradigm.

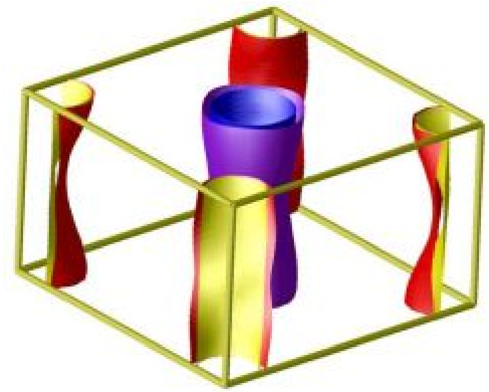
Fe-based superconductirs: Fermiology



LaFeAsO

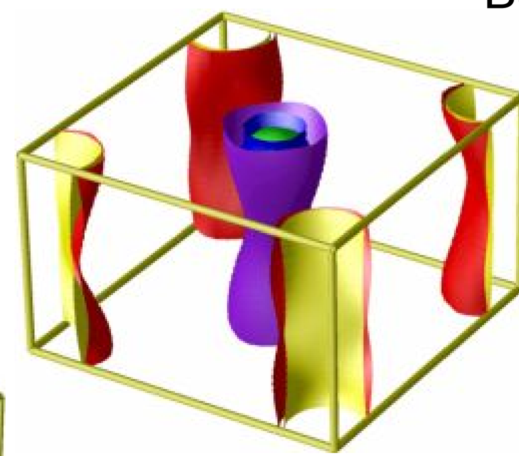


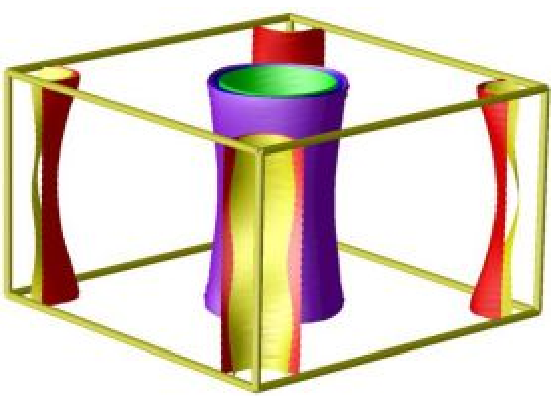
FeTe



$BaFe_2As_2$

Ba122 – 10%e





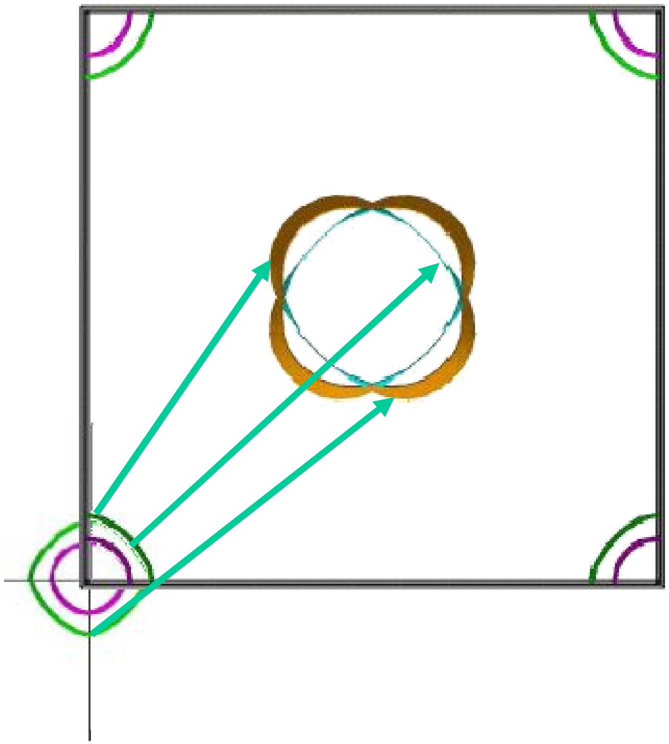
Ba122 – 10%h

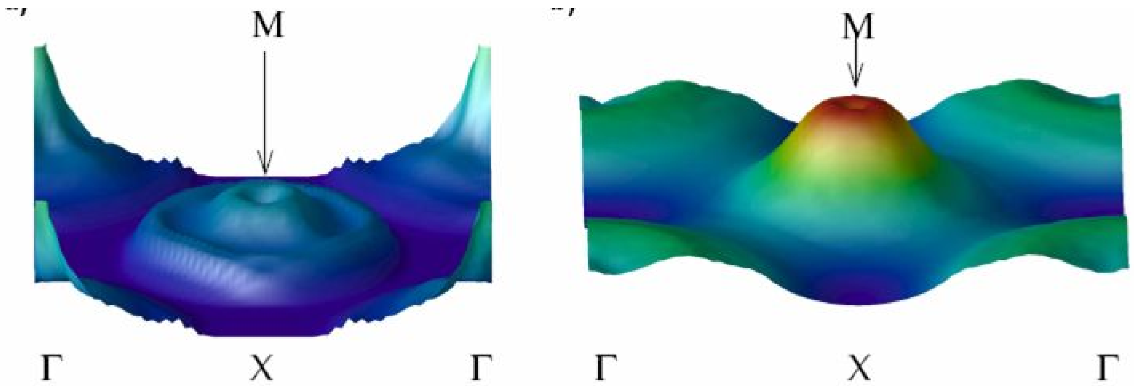
In all actual materials there is some “poor” nesting of the Fermi surfaces .

ingredient 2 – spin fluctuation

$$\mathrm{Re}\,\chi_0(\mathbf{q},\omega\to 0)=\sum_{\mathbf{k}}\frac{f_{\mathbf{k+q}}-f_{\mathbf{k}}}{\varepsilon_{\mathbf{k+q}}-\varepsilon_{\mathbf{k}}}$$

$$\frac{\mathrm{Im}\,\chi_0(\mathbf{q},\omega)}{\omega}\Big|_{\omega\to 0}=\sum_{\mathbf{k}}\delta(\varepsilon_{\mathbf{k+q}}-E_F)\delta(\varepsilon_{\mathbf{k}}-E_F)$$





$\mathrm{Im}\ \chi_0(\mathbf{q},\omega)/\omega|_{\omega\to 0}$ $\mathrm{Re}\ \chi_0(\mathbf{q},0)$

fully pairing for the $s_{\pm}$ state (sharp nesting not needed)

FOUND EXPERIMENTALLY!

Experimental status

Pairing symmetry:

- definitely singlet

- nearly definitely not *d*

- most likely sign-changing

- strong evidence for $s_{\pm}$ (even though only indirect so far)

Pairing glue, after all?

There is infinite number of incorrect theories, correctly describing the finite number of experimental facts.

(ascribed to Niels Bohr)

The concept of pairing glue appears to work reasonably well in both cuprates and pnictides (even predictively!), as opposed to all other methodologies, despite the drastic difference between the two families – a big feather in the pairing glue proponents' hat.

“Iron age” Matthias rules

1 . A high symmetry is good; cubic symmetry is the best.

new rule: ***Layered structures are good***

2. A high density of electronic states is good.

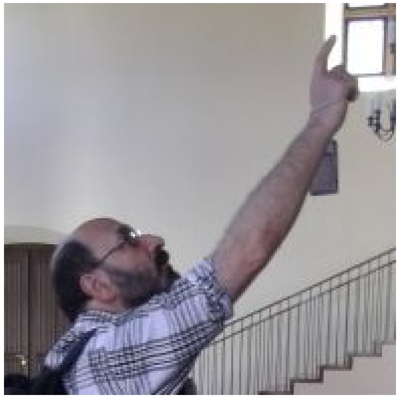
new rule: ***the carrier density should not be too high (compared with, say, conventional metals)***

3. Stay away from oxygen.

new rule: ***3d metals (V, Cr, Mn, Fe, Co, Ni, Cu) are good.***

4. Stay away from magnetism.

new rule: ***magnetism is essential***



5. Stay away from insulators.

new rule: ***proper Fermi surface geometry is essential (it must match the structure of the spin excitations***)

6. Stay away from theorists.

new rule: ***enlist theorists, at least to compute the Fermi surfaces*** (I hope theorists are more useful than this but do not dare to insist).

Physics authors/titles Oct 2005 (200 skipped) - Microsoft Internet Explorer

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The theoretical oriented scientist cannot be envied, because nature, i.e. the experiment, is a relentless and not very friendly judge of his work. In the best case scenario it only says "maybe" to a theory, but never "yes" and in most cases "no". If an experiment agrees with theory it means "perhaps" for the latter. If it does not agree it means "no". Almost any theory will experience a "no" at one point in time - most theories very soon after they have been developed.

Title: Theoretical remark on the superconductivity of metals

Authors: Albert Einstein