Anisotropy of magnetic response in high-temperature superconductors

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«Conventional» superconductors:

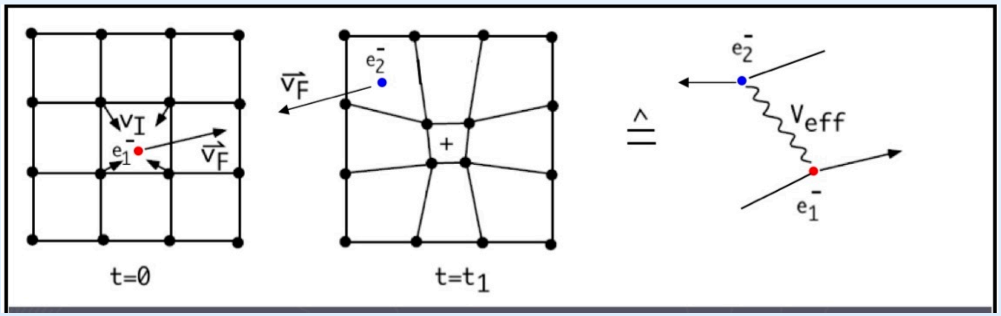
model (theory) BCS
1957: J.Bardeen, L.Cooper, R.Schrieffer

principal ingredient – Cooper pairs (L.Cooper, 1956)

***attraction* of two electrons** exchanging a virtual phonon

or **electron-phonon interaction**

relation of spectral and superconducting characteristics



$$k_B T_C = 1.14\,\hbar\omega_D \cdot \exp\left(-\frac{1}{\lambda - \mu^*}\right)$$

$$\lambda = \frac{N_{el}\langle J^2\rangle}{\langle M\omega^2\rangle} = \frac{el - phon}{ion - ion}$$

retardation effect
helps reducing the Coulomb repulsion

SC-gap function

$$\Delta_k = -\sum_{k'} \frac{V_{kk'}\Delta_{k'}}{2\sqrt{\varepsilon_{k'}^2 + \Delta_{k'}^2}}$$

electron pairs in BCS
have zero spin and orbital momenta
(the most symmetric state):
L=0, S=0

BCS:

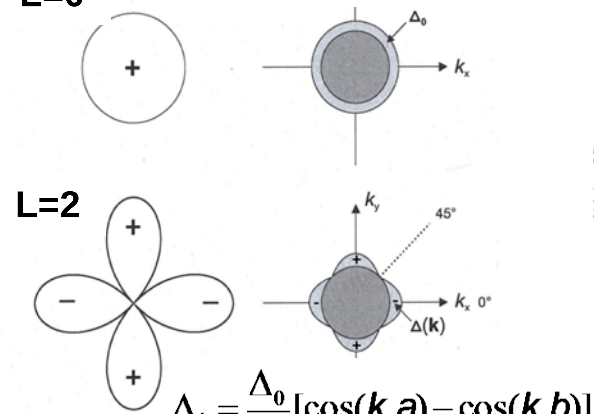
$V < 0$, $\Delta = const > 0$

«Uncvonventional» SC state in HTSC is experimentally proved

L=0

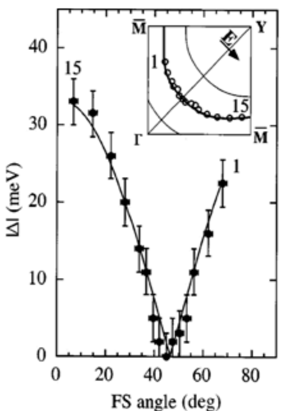
$$\Delta_k = const = \Delta_0$$

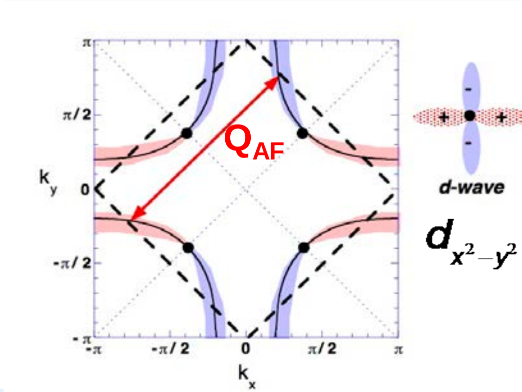
L=2



$$\Delta_k = \frac{\Delta_0}{2}[\cos(k_x a) - \cos(k_y b)]$$

d-wave gap function: ARPES (1996)





For such gap symmetry

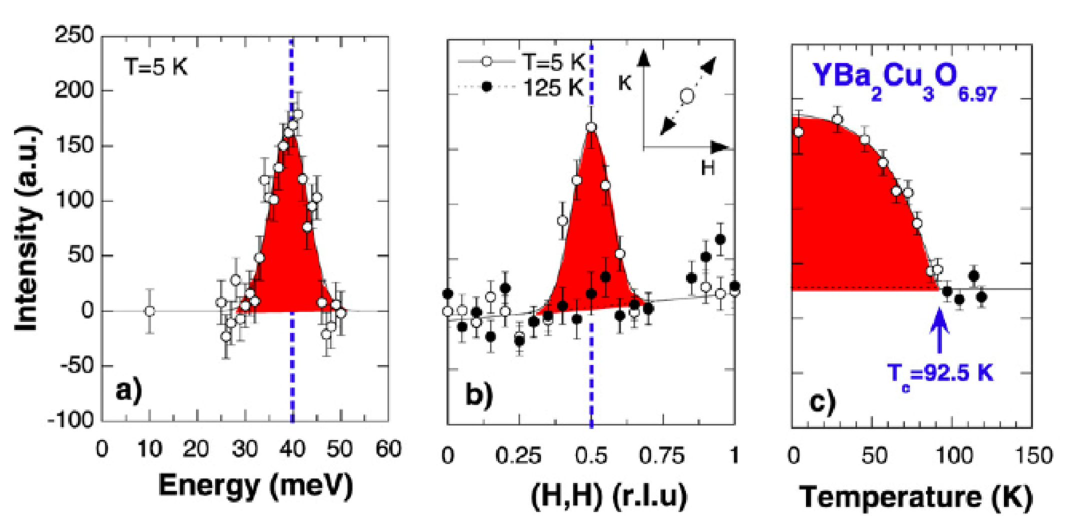
χ''(Q,ω)

in the SC state has increased value at certain Q (AFM-vector Q_{AF}) in the plane

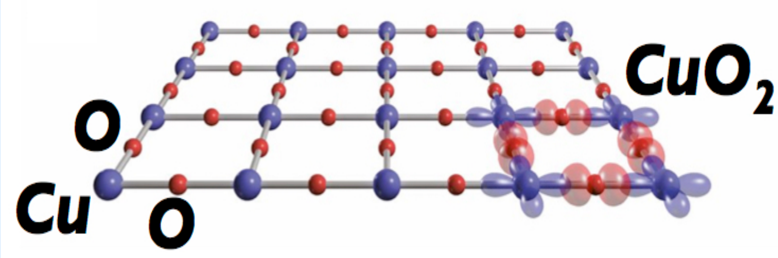
L=2
d-wave pairing

$$Intensity \sim \chi''_{gap}(Q,\omega) \sim \sum_k \{1 - \frac{\Delta_k \Delta_{k+Q} + \varepsilon_k \varepsilon_{k+Q}}{\sqrt{\Delta_k^2 + \varepsilon_k^2}\sqrt{\Delta_{k+Q}^2 + \varepsilon_{k+Q}^2}}\} F(k, Q, \omega)$$

The spin (or magnetic) resonance is observed by INS



Common to all cuprates: the CuO_2 crystal layers



Cuprates: complex oxides with a layered crystal structure

The layers CuO_2 are responsible for the main SC properties while the other layers stabilize the crystal structure and serve charge "reservoirs"

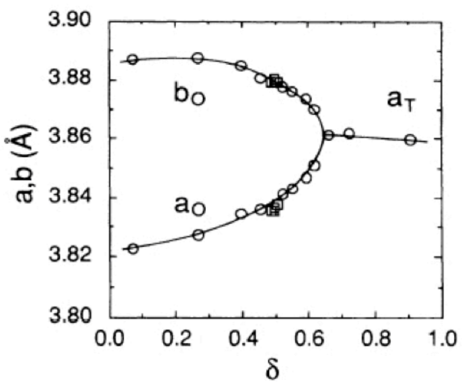
Perovskite-like layered structures

$ABO_3=(AO) + (BO_2)$

$YBa_2Cu_3O_{6+x}$ =

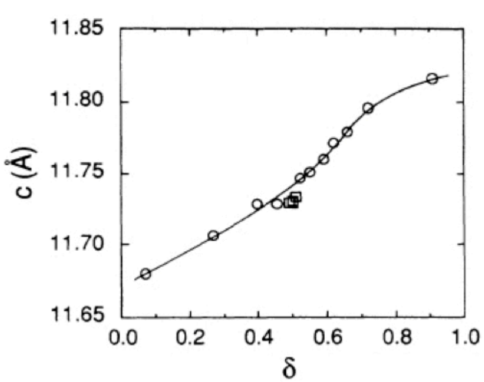
Y + 2(BaO) + 2(CuO_2) + 1(CuO_x)

ambient T

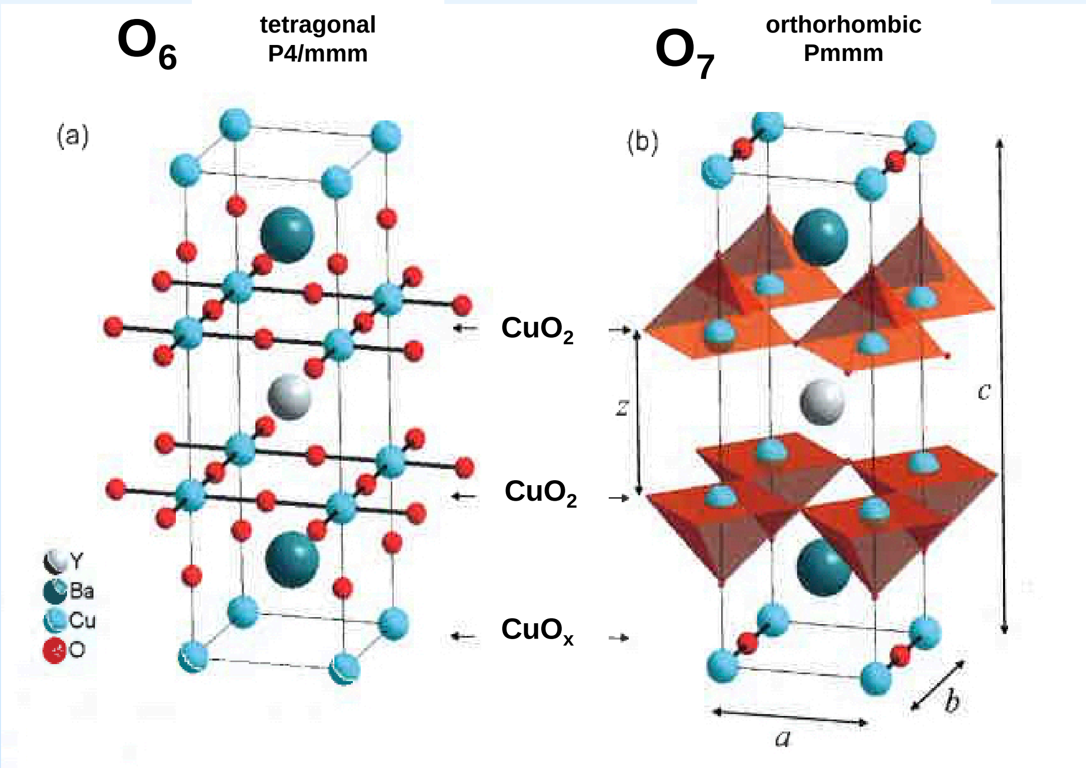


a)

$YBa_2Cu_3O_{7-\delta}$ δ=1-x



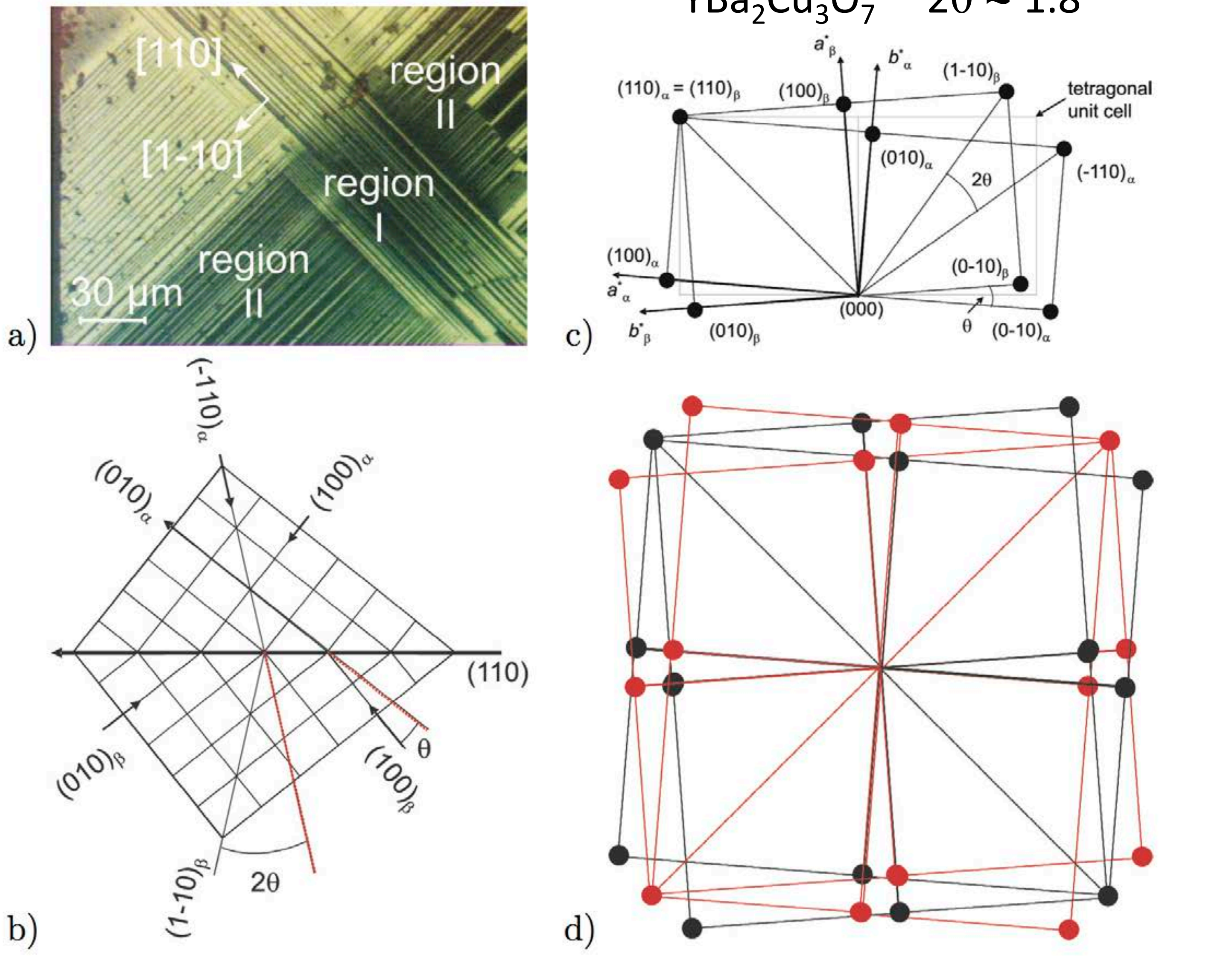
b)



All are tetragonal at high temperatures (>500 K)
tetra-ortho phase transition is doping dependent

Orthorhombic structures: elastic domains

$YBa_2Cu_3O_7$ $2\theta \approx 1.8^o$



Preparing single-domain (detwinned) samples

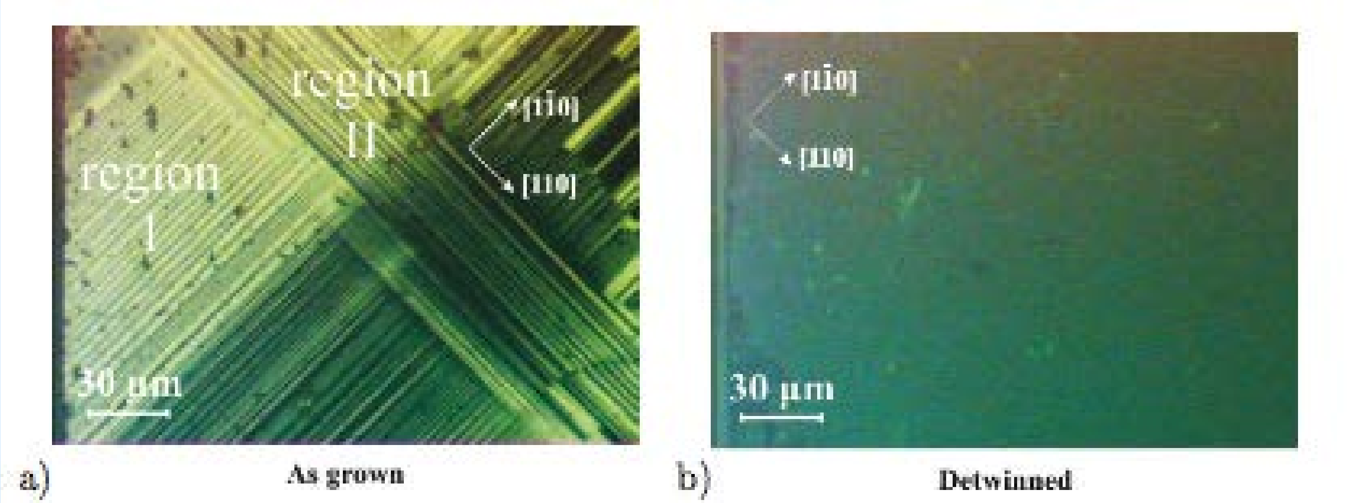
As grown crystals are first annealed in appropriate atmosphere in order to reach the desired doping content

Then crystals, one after another are compressed with a uniaxial mechanical force (~0.5 kbar) applied along <100> ("*a*" or "*b*") at high temperature in the tetragonal phase while keeping a controlled atmosphere around the crystals

then cooled through the tetra-ortho transition keeping the force

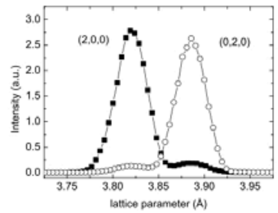
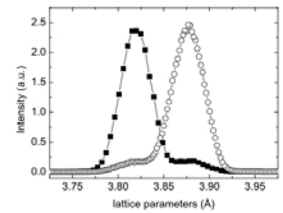
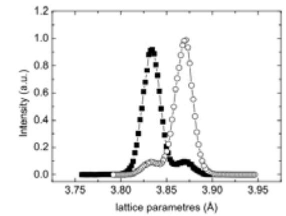
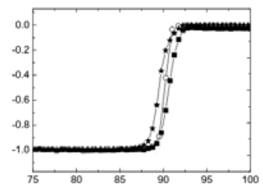
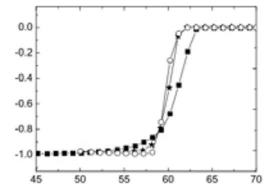
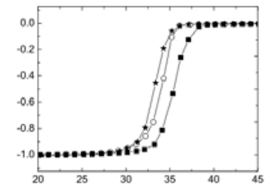
and at last the force is released at ambient temperature

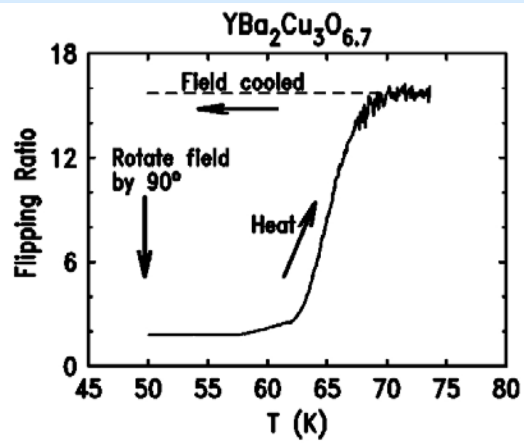
appropriate sample size – several cubic mm
not enough for INS – composed samples from individually characterized crystals

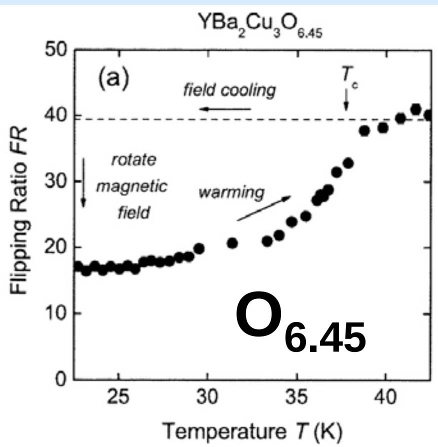


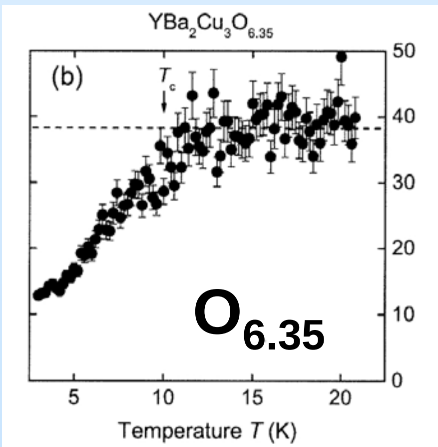
Preparing single-domain (detwinned) samples

neutron beam characterization

Nominal composition	$YBa_2Cu_3O_{6.85}$	$YBa_2Cu_3O_{6.6}$	$YBa_2Cu_3O_{6.45}$
p_h	0.148	0.12	0.085
mass (g)	1.3	2.9	2.0
majority domain	95%	94%	92%
elastic scans			
$T_{c,\mathrm{mid}}(K)$ [ΔT_c (K)]	90 [2]	61 [2]	35 [3]
typical curves			
$E_{\mathrm{resonance}}$ (meV)	41	38	20 (?)







Objects for research: single crystals

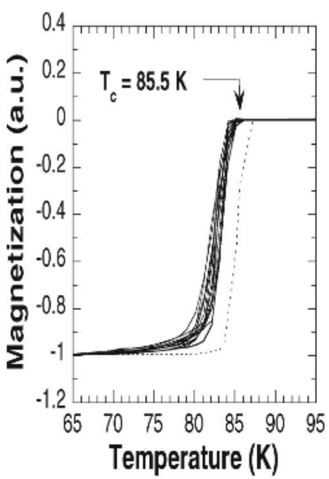
good to have ~1 см^3

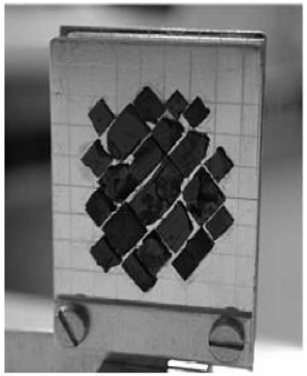
In the great majority of cases it is not possible
in particular for new materials such as HTSC

«composed» samples: 0.06-0.45 см^3,

quality (mosaic spread) :   1^o - 2^o

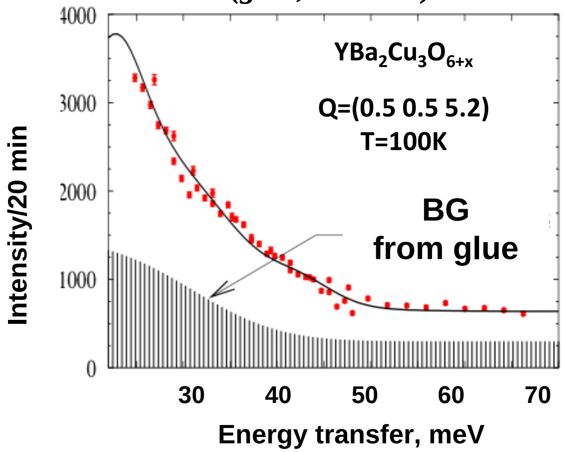
8, 60, 80, 120, 180, 250(!)
small single crystals

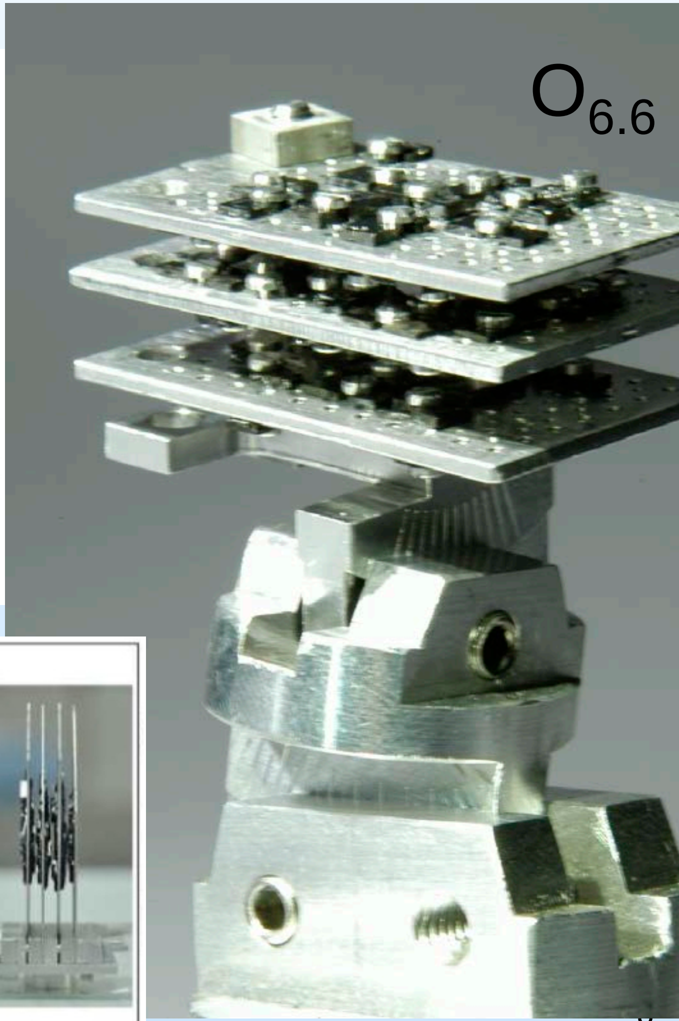




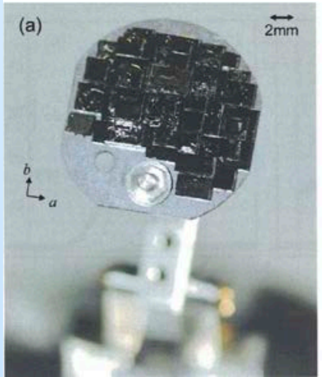
$(YCa)Ba_2Cu_3O_6$

reducing background
(glue, Al -> Si)



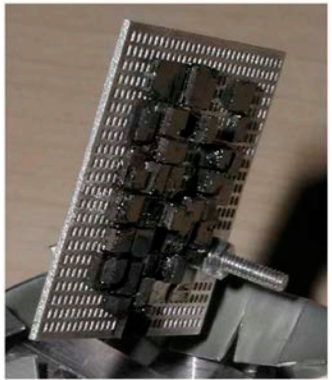


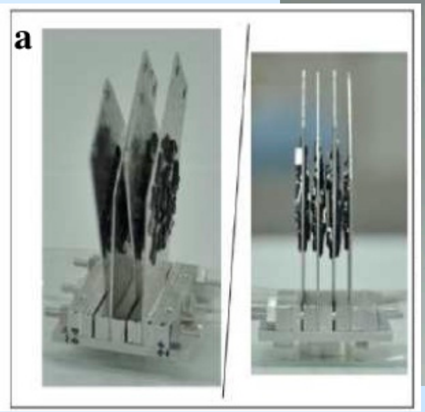
$YBa_2Cu_3O_{6.35}$



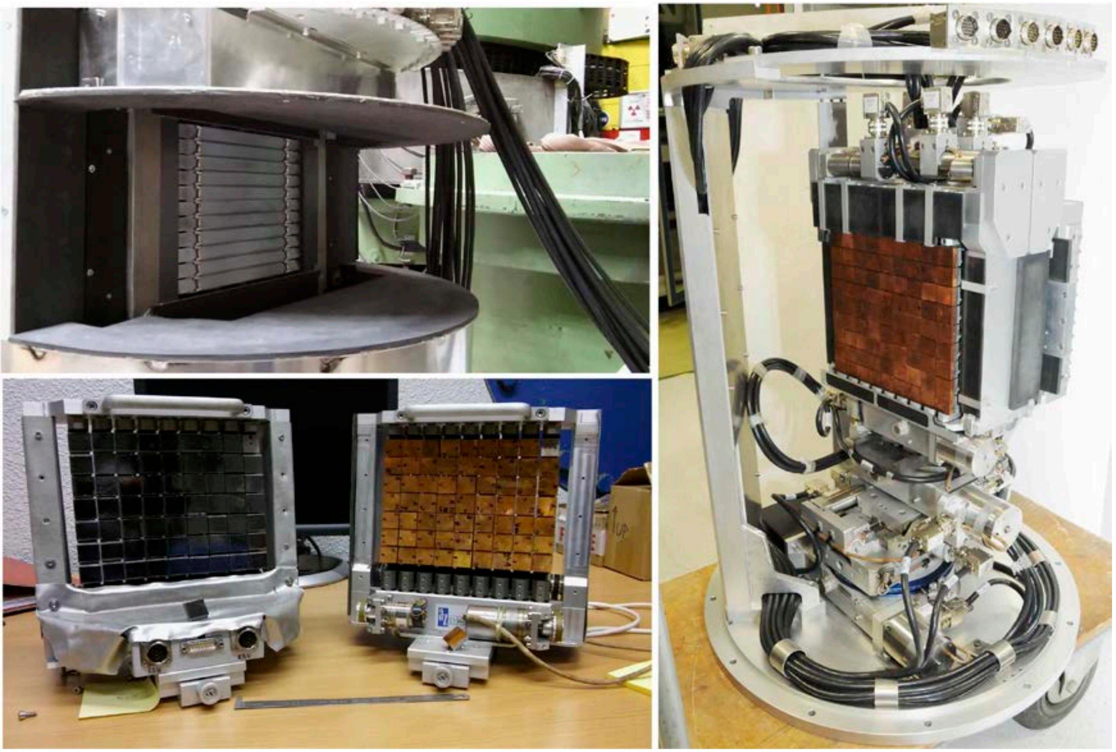
$YBa_2Cu_3O_{6.40}$

$YBa_2Cu_3O_{6.45}$





Experimental equipment



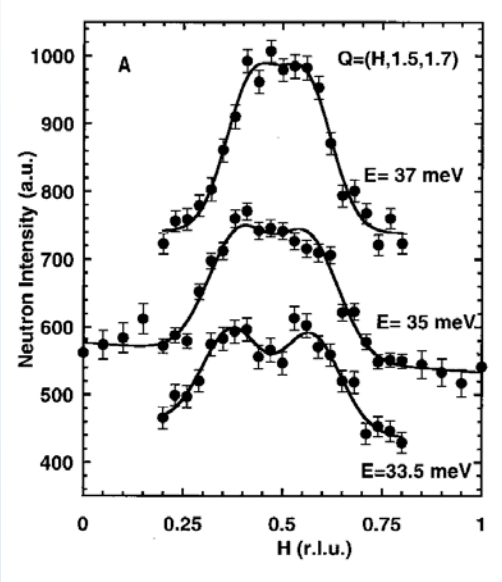
“On the-floor”
distances – meters
divergences - degrees

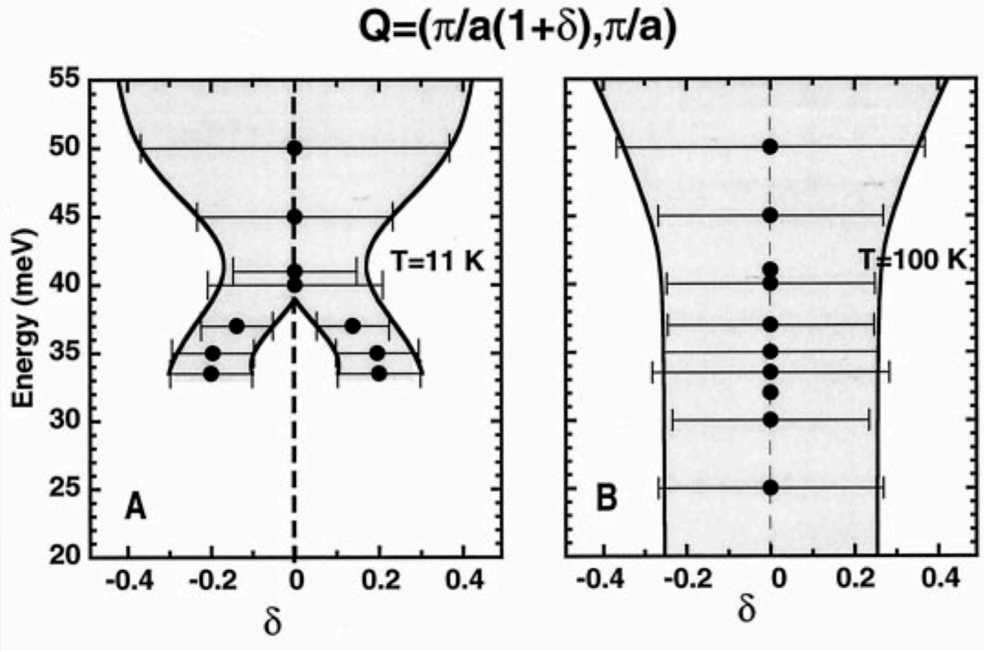
weight of the moving modules – up to tons
precision of positioning – 0.01 degree

neutron polarization analysis

Dispersion of the resonance intensity

$YBa_2Cu_3O_{6.85}$





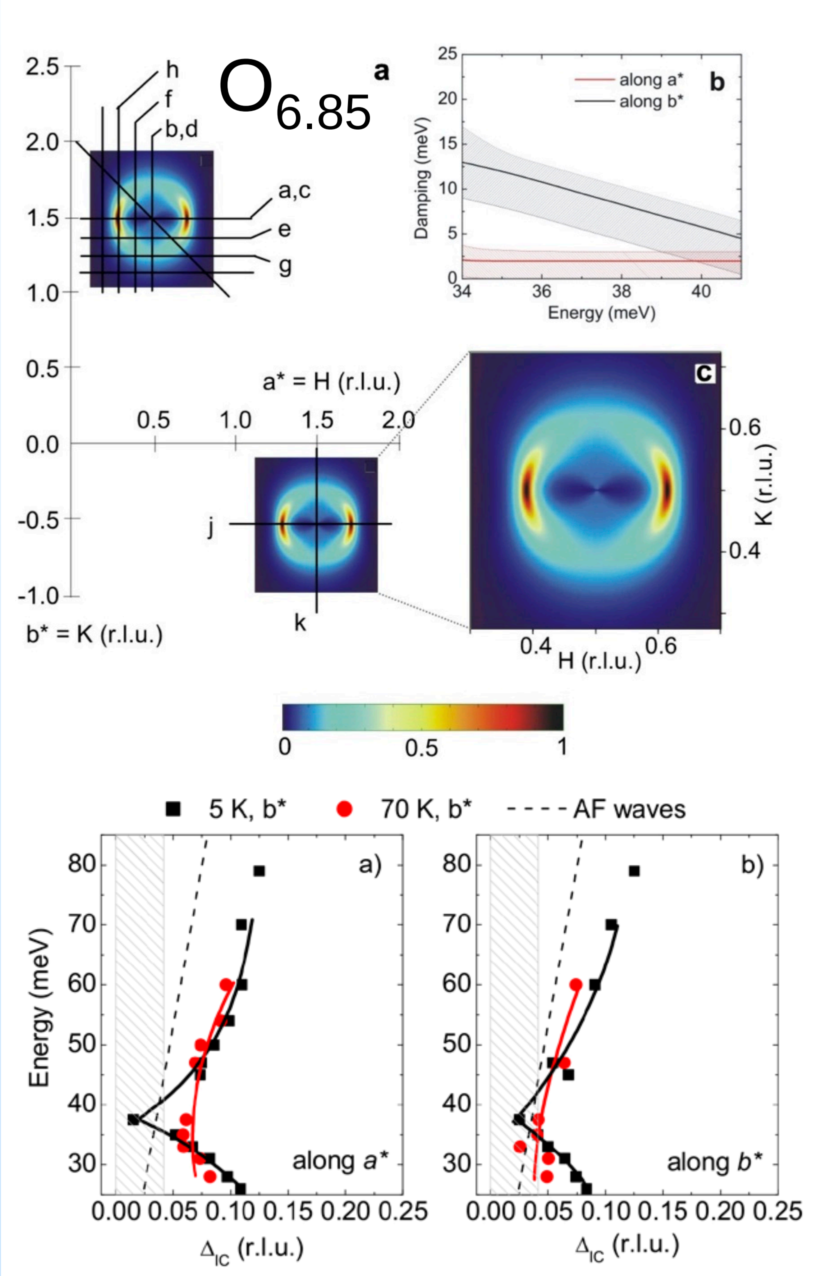
incommensurability of the signal below T_c

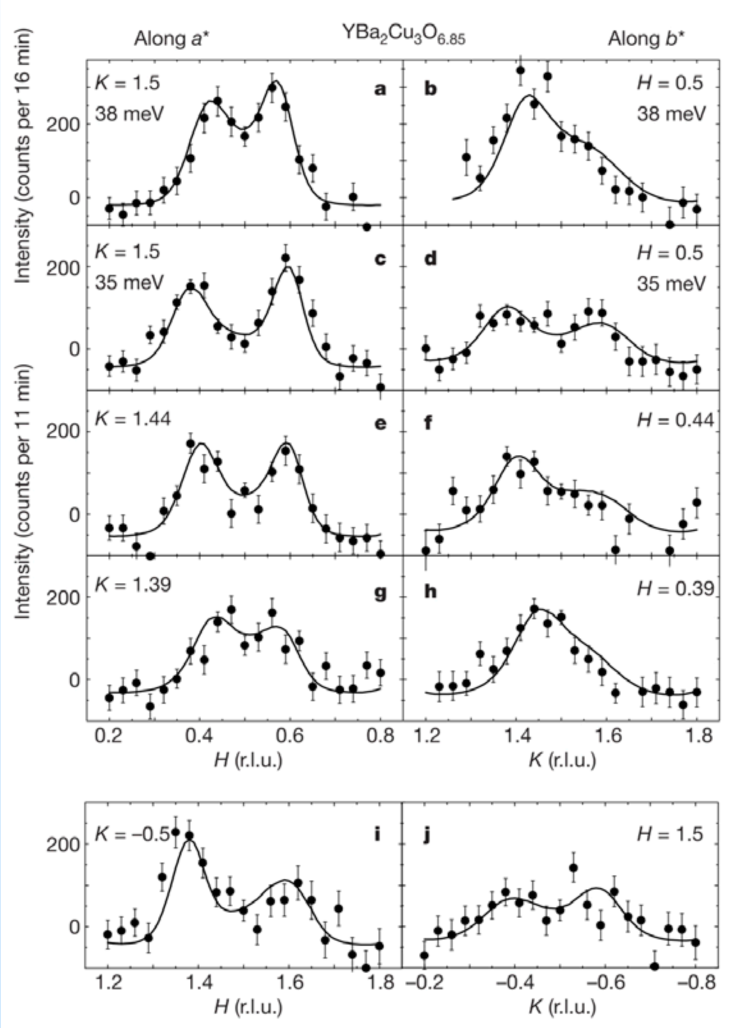
cannot be related to pinned “stripes”

more detailed analysis on detwinned samples

Magnetic resonance in cuprates

anisotropy in the plane CuO_2 and dispersion of the resonance intensity



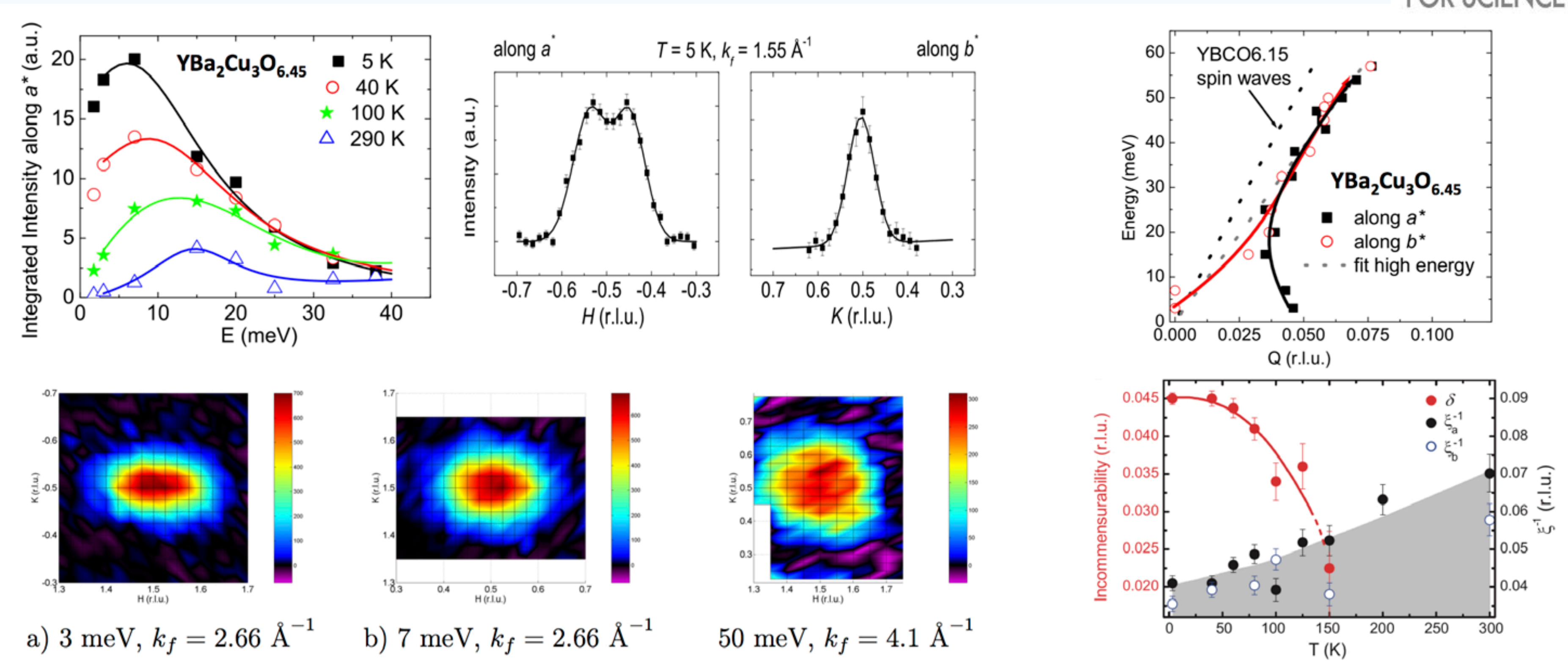


Anisotropy of the forms “X” and “Y” (below and above Tc)

nematic electron correlations: 2D

Magnetic resonance in cuprates

anisotropy in the plane CuO_2 and the resonance dispersion



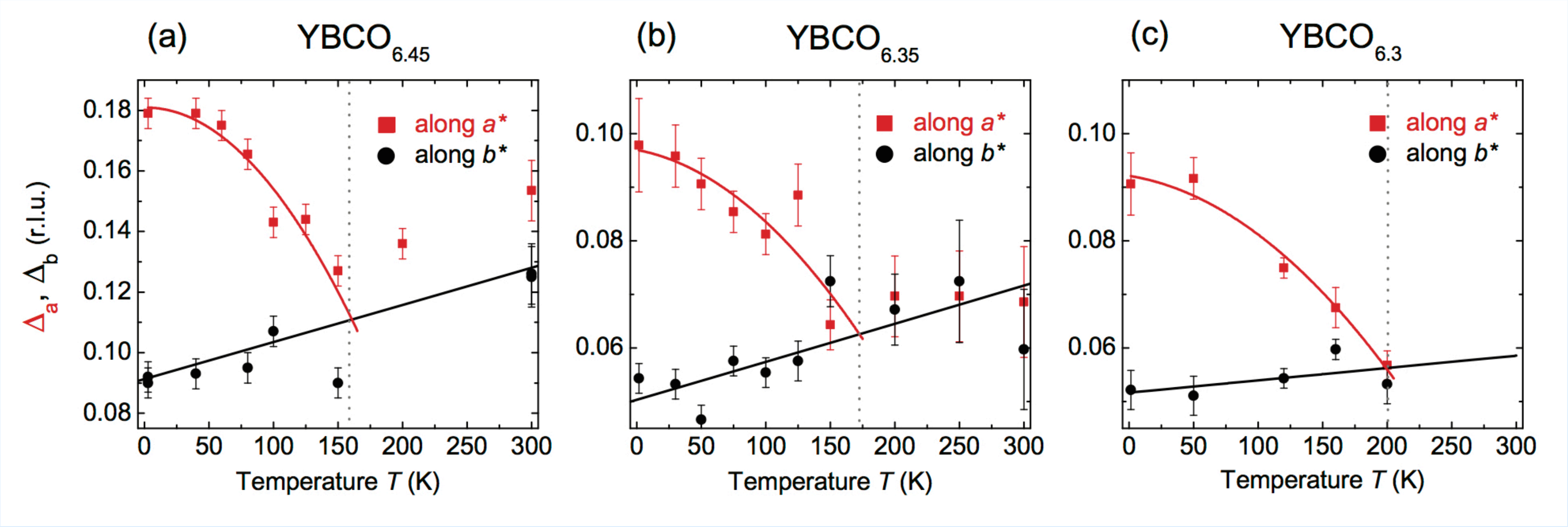
anisotropy in the plane increases at lower energies

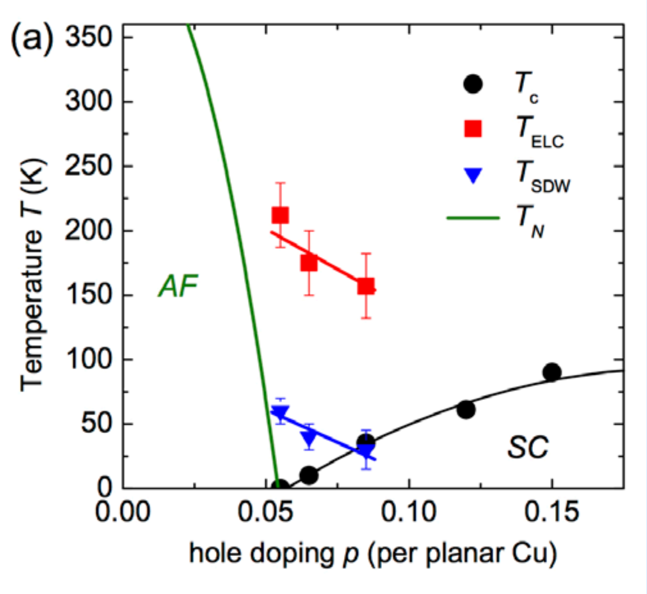
and

with reducing doping "x" in $YBa_2Cu_3O_{6+x}$

Magnetic resonance in cuprates

anisotropy in the plane CuO_2 and the resonance dispersion





Fe-based SC

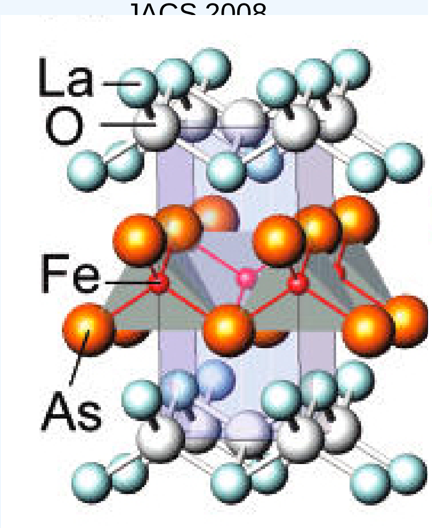
(from 2008 – pnictides, then selenides)

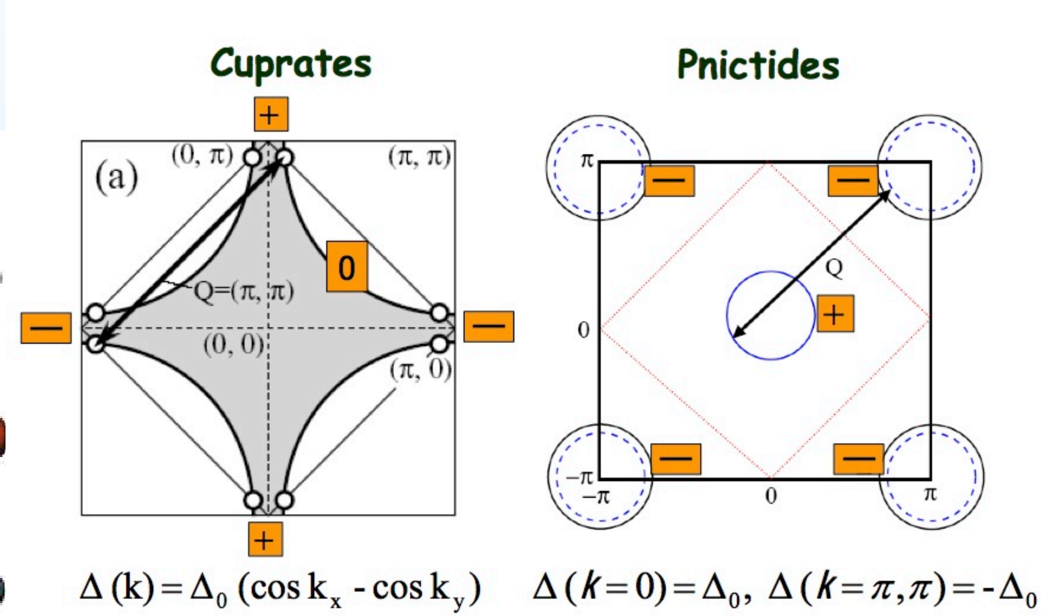
resemble cuprates: layered structures, Magnetic AFM layers, several structure types, phase diagrams alike

LaOFeAs

Kamihara *et al*

JACS 2008



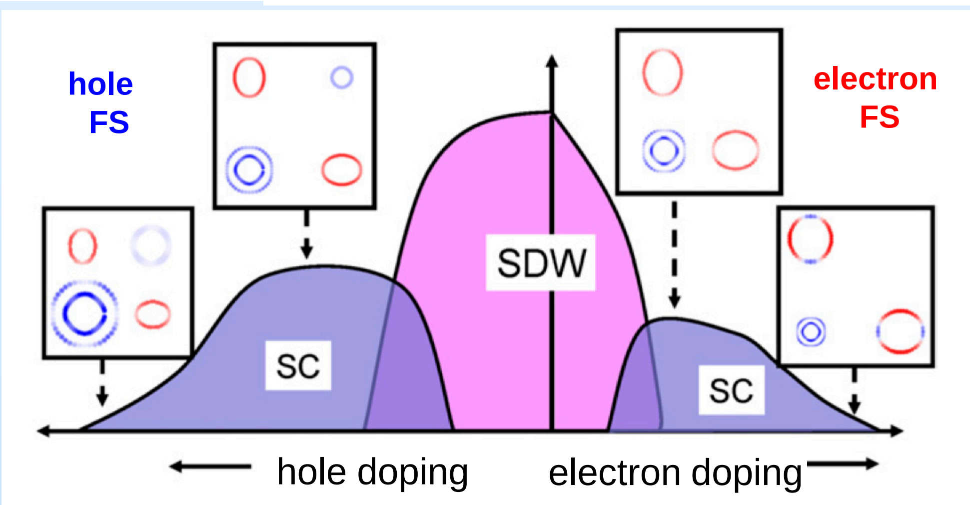


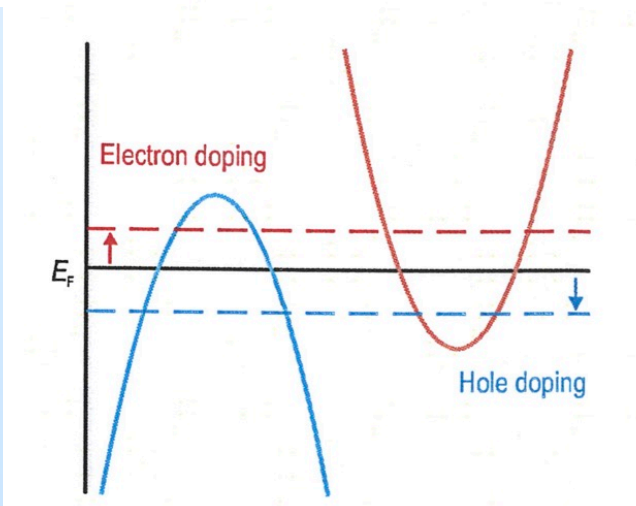
Resonance:

interband transitions between distinct parts of the Fermi surface with different signs of the SC-gap function:

$\Delta(\mathbf{k}) = -\Delta(\mathbf{k}+\mathbf{Q}_{AF})$

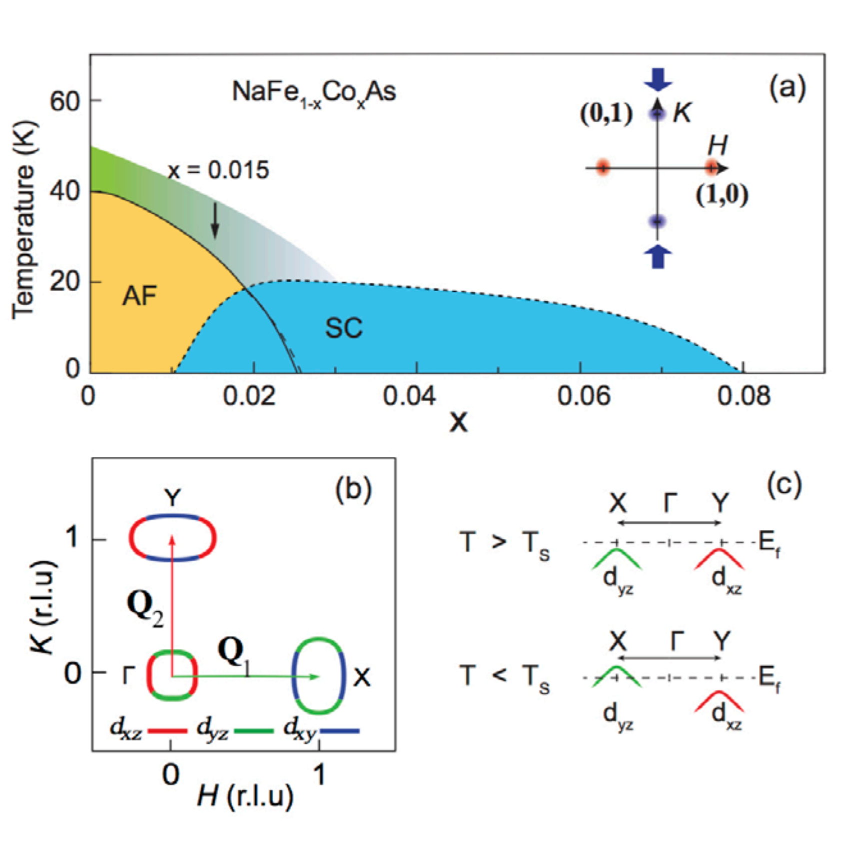
so called $S^{\pm}$ pairing

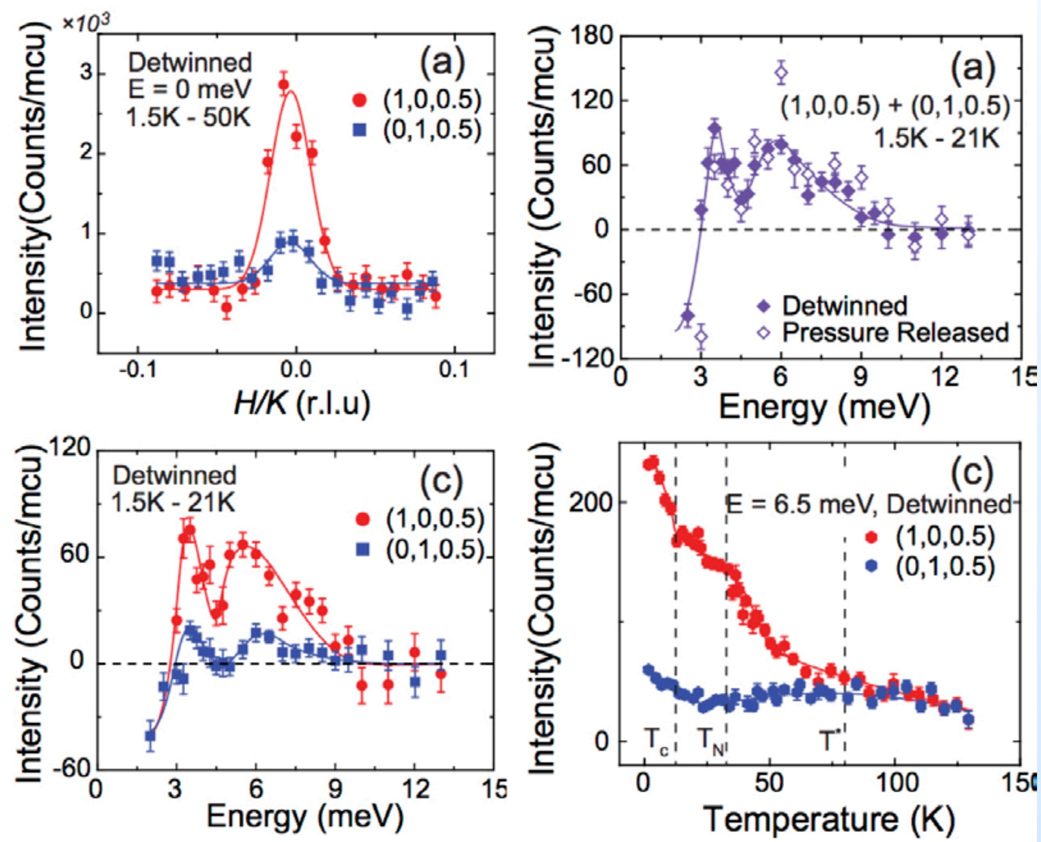




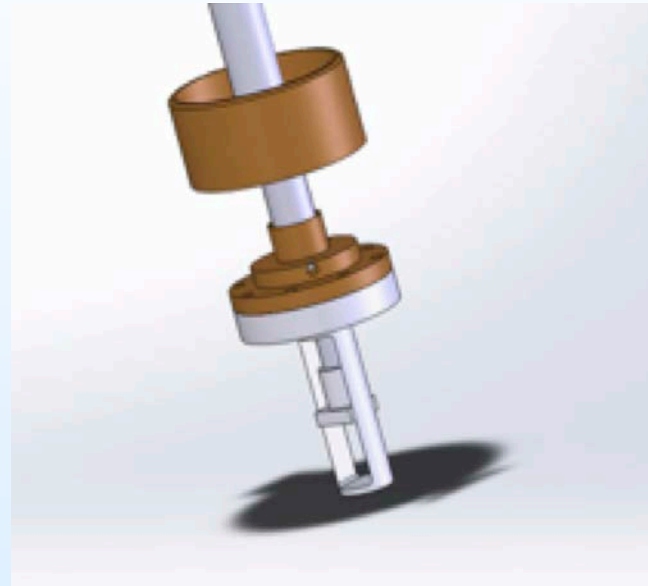
Anisotropy of the magnetic resonance in the 111 family Na(FeCo)As

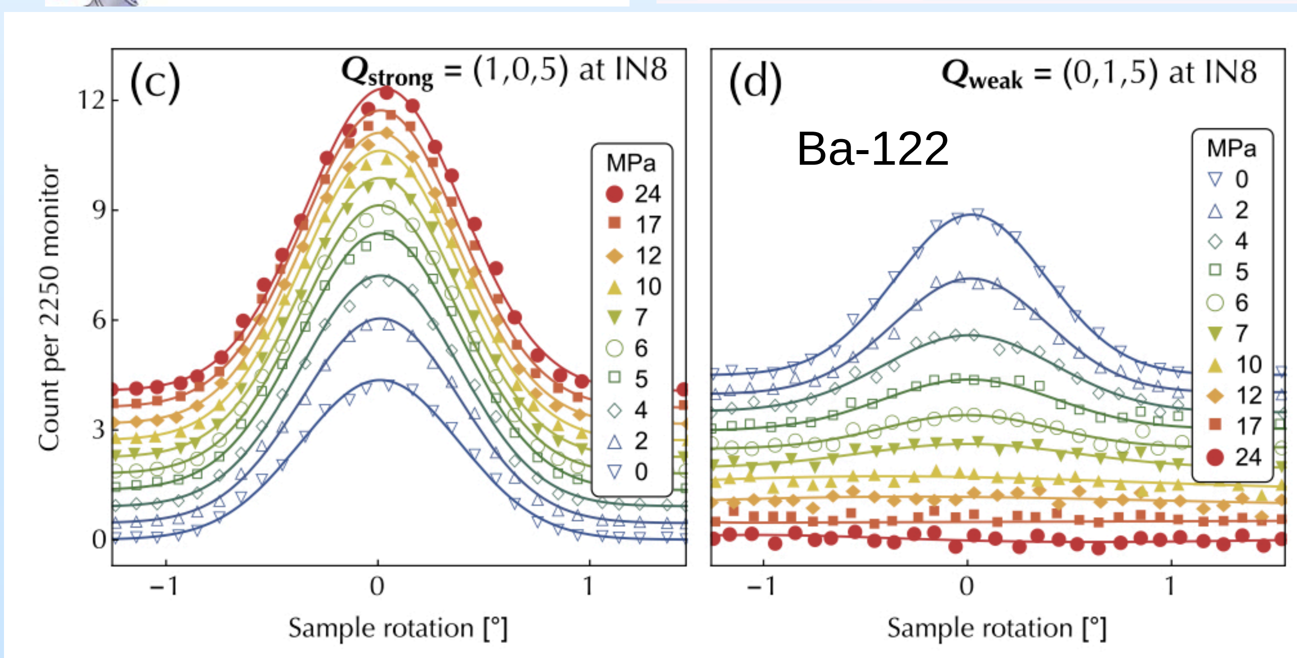
lifting of the orbital degeneration under uniaxial stress



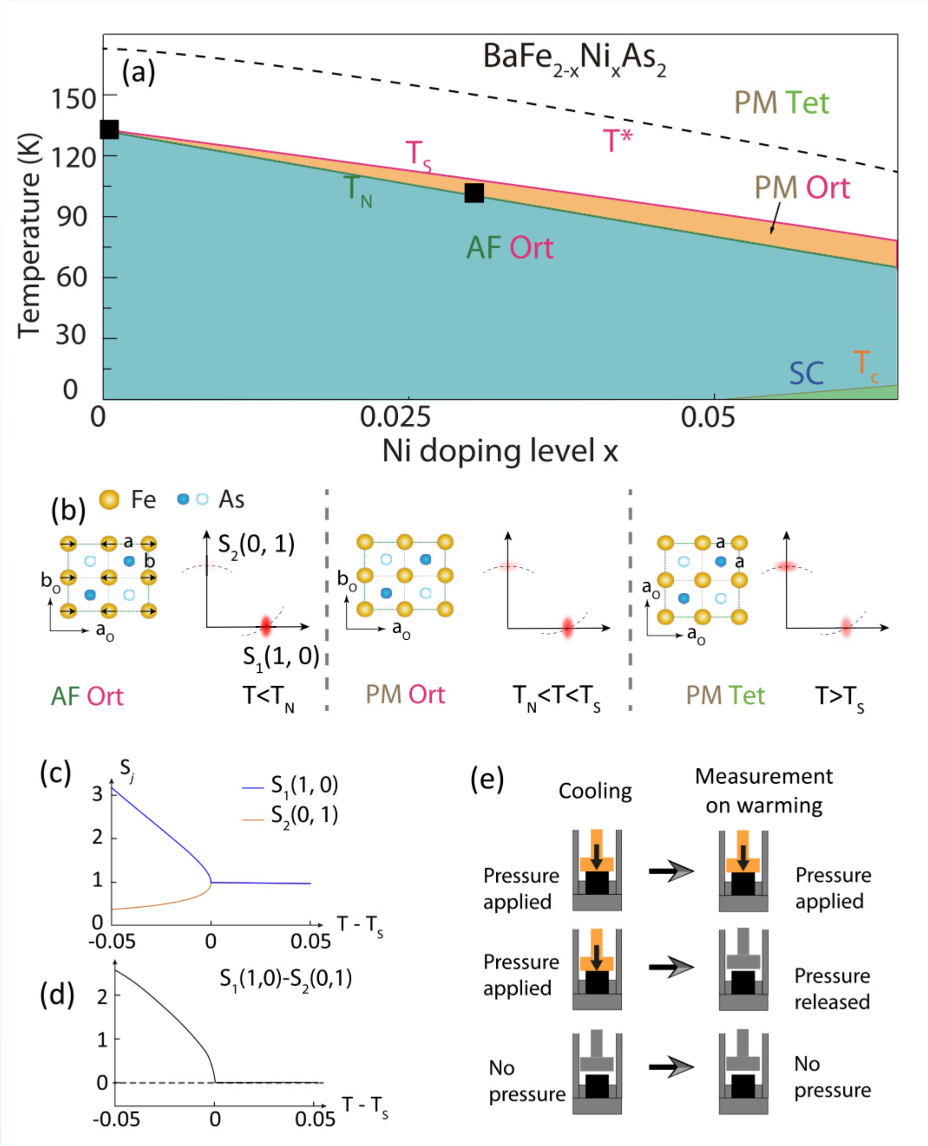


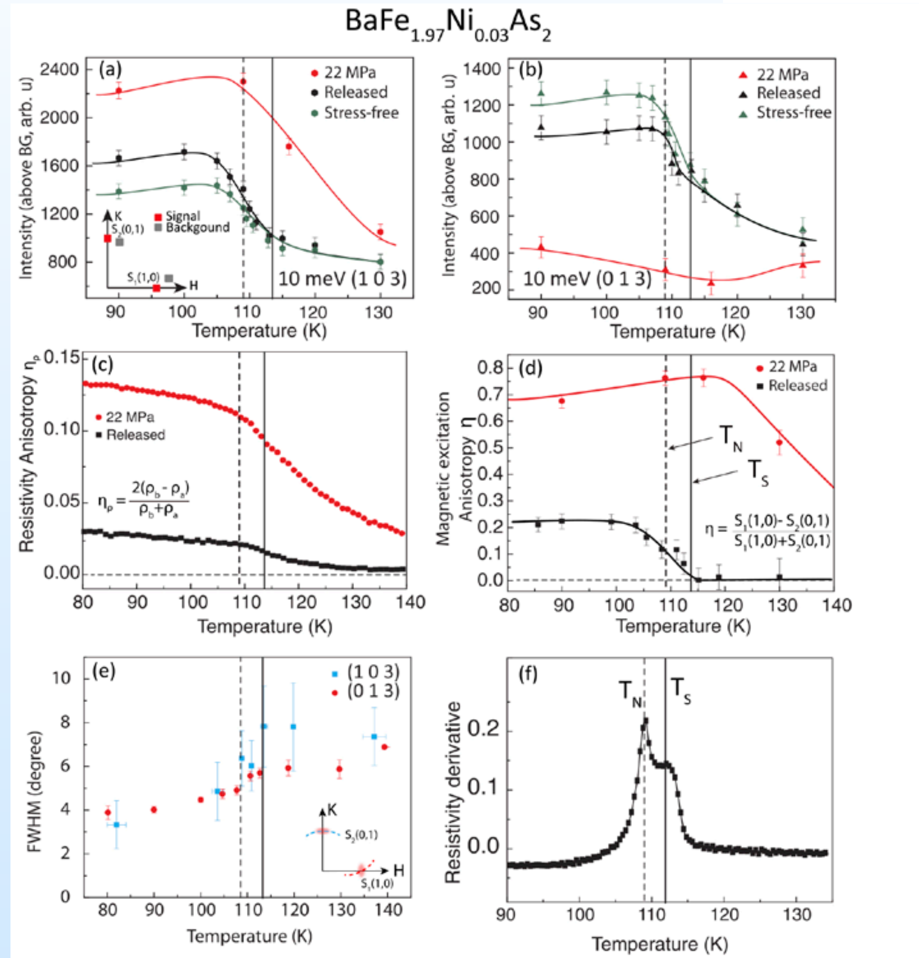
"*In-situ*" detwinning under uniaxial stress at low temperature





“*In-situ*” detwinned Ba-122





Anisotropy begins at structural transition (Ts

Conclusion

Anisotropy of magnetic fluctuations is well developed in the orthorhombic phases of copper- and iron-based unconventional superconductors

Anisotropy of magnetic fluctuations is supportive of the theories generating nematic order in the 2D electronic liquid

the "broken symmetry" low-temperature phases correspond to reduced rotational and not translational symmetry

ВТСП на основе железа

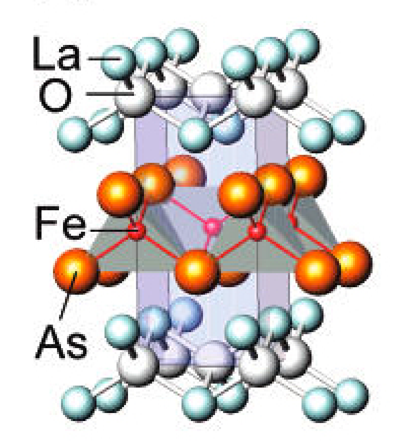
(с 2008 года – пниктиды, и затем - селениды)

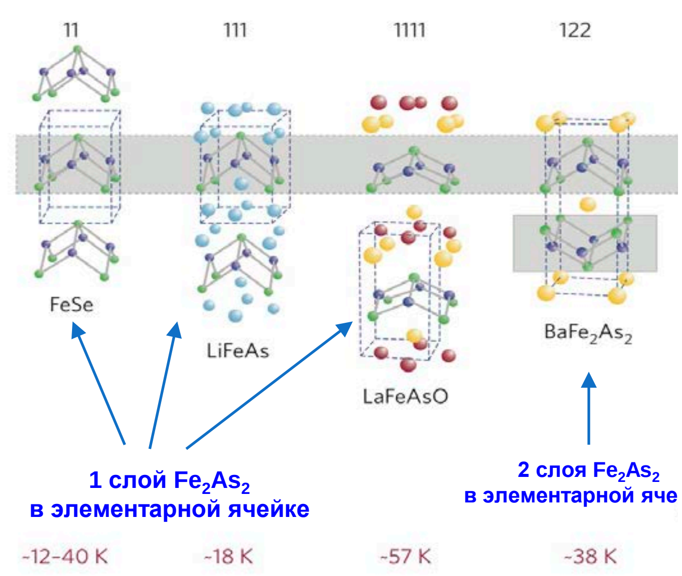
во многом похожи на купраты:

структуры со слоями, есть магнитно-активные слои с AFM взаимодействием

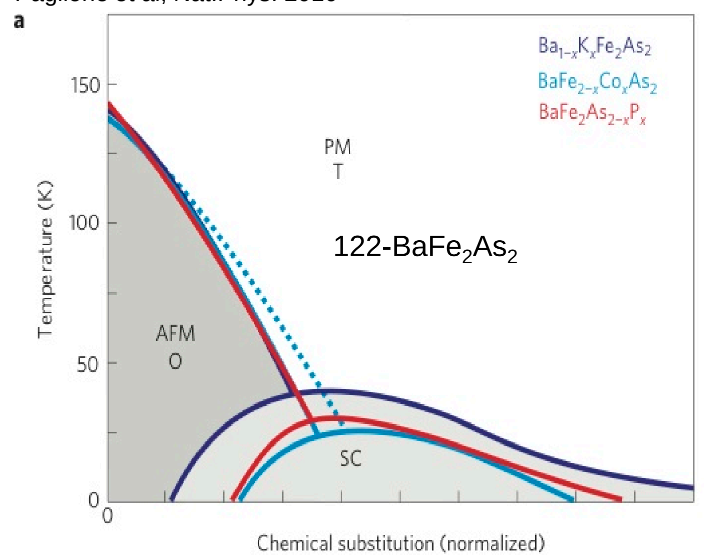
несколько типов структур, подобные фазовые диаграммы

LaOFeAs
Kamihara *et al*
JACS 2008





Paglione et al, Nat.Phys. 2010



Слоистые структуры, но с тетраэдрической, не планарной координацией

Другие различия: недопированные соединения – не изоляторы, а металлы, хотя и «плохие»

Допирование в Fe-based: все типы возможны, электронные, дырочные, изовалентные, за счет изменения расстояний под давлением. Можно широко замещать Fe, тогда как в купратах СП быстро деградирует при замещении Cu (1%).

Купраты более однородны внутри семейства, а Fe-based могут сильно отличаться по свойствам

Fe based более сложные: много-зонные, много-орбитальные, много-щелевые

Вдвое более плотное «заселение» магнитных ионов Fe в слоях:

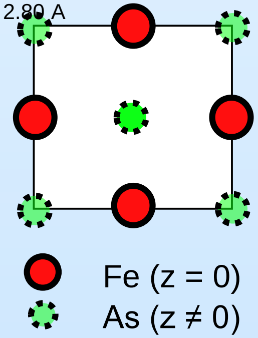
Fe2As2 против CuO2

с примерно одинаковым размером ячейки

Metal iron (bcc):
a = 2.866 A
Fe-Fe = 2.480 A

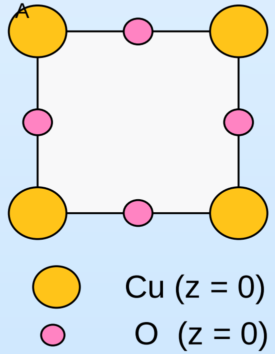
Magnetic moment
Fe = 2.2 μ_B

Fe$_2$As$_2$: Fe-Fe = 2.70 - 2.80 A



Spin Fe^{2+} (d^6):
S=2
Magnetic moment Fe
0.1 - 3.4 μ_B

CuO$_2$: Cu-Cu = 3.85 - 4.0 A

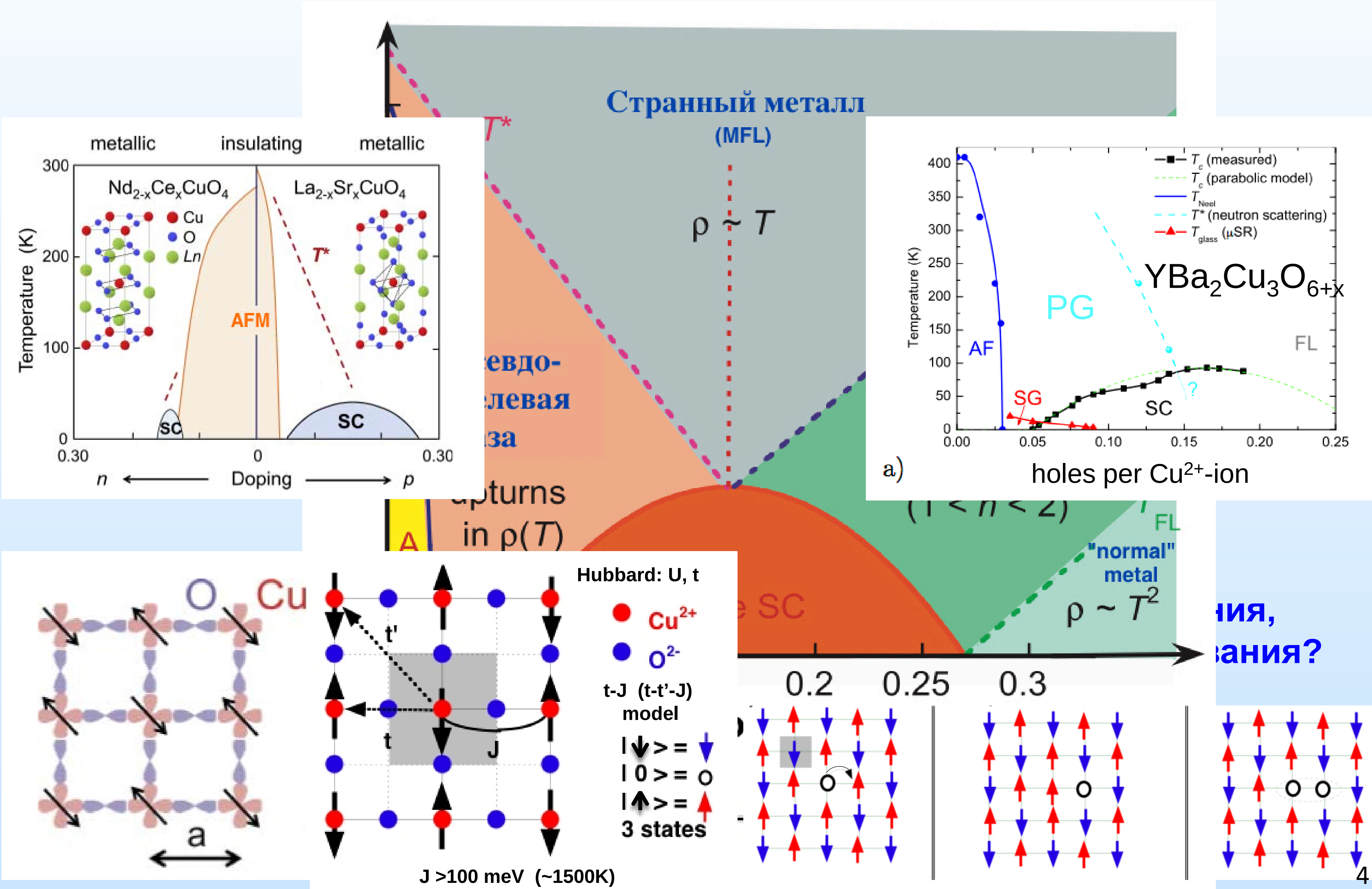


Spin Cu:
S=1/2
Magnetic moment Cu
~ 0.5 μ_B

Широкая вариация T_N и моментов

Фазовые диаграммы

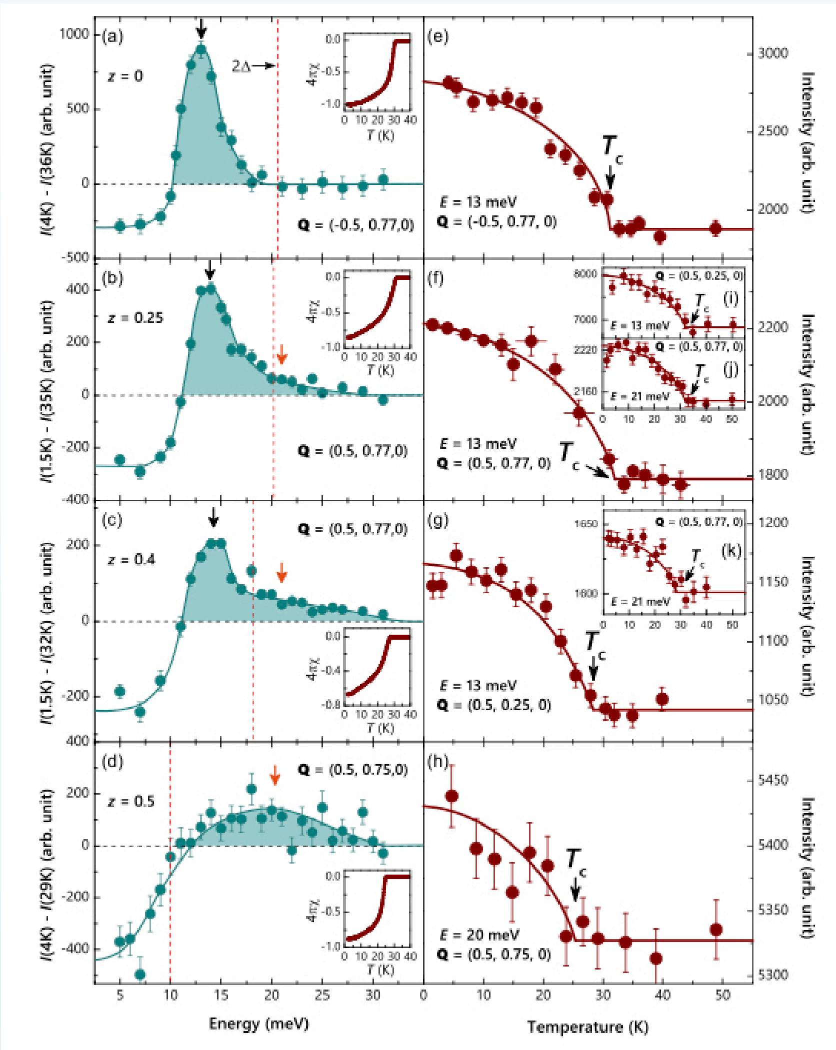
Общее: СП возникает при зарядовом допировании (электронном или дырочном) плоскостей CuO_2



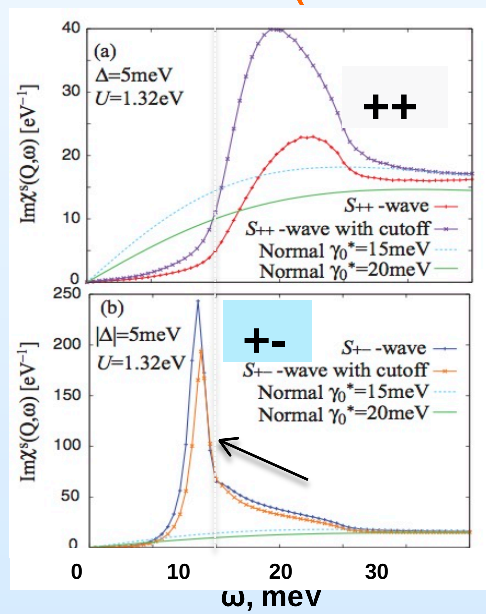
Полученные данные: пример

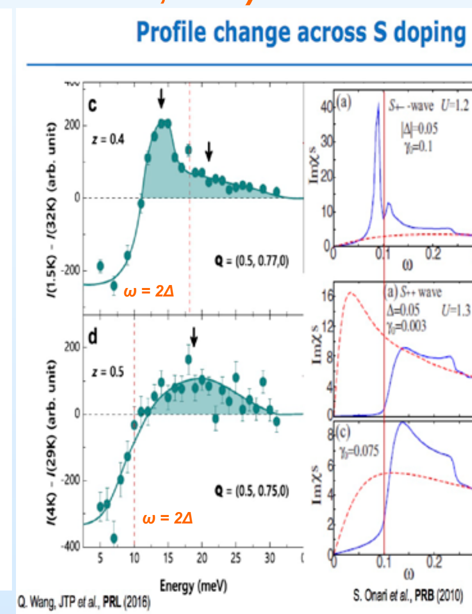
магнитное рассеяние в S-замещенных селенидах

Изменение типа спаривания в одном семействе $K_xFe_2(Se_{1-z}S_z)$
при легировании серой – малые изменения Tc, подобные свойства



Наблюдаемые изменения похожи на то, что было рассчитано для S^{+-} и S^{++} магниткных откликов (S.Onari *et al* PRB 2010, 2011)



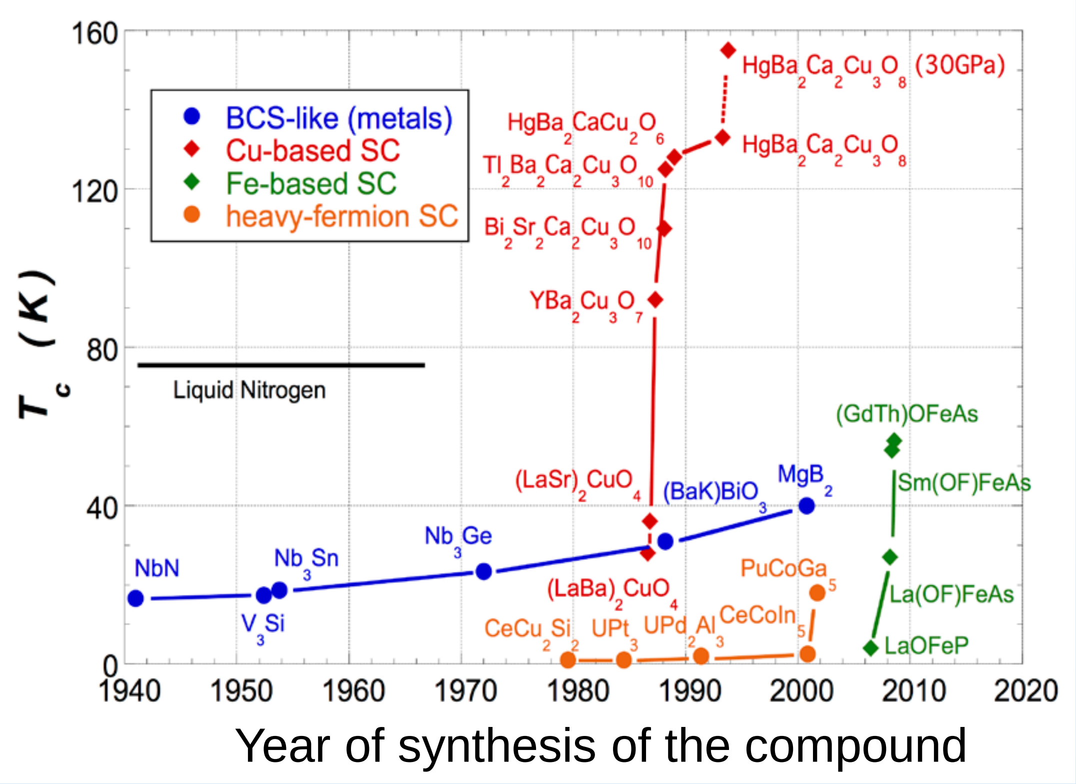


По мере увеличения содержания серы магнитный резонанс возникающий, по имеющимся преставлениям, в симметрии S^{+-}, прогрессивно исчезает и замещается «нерезонансным» поведением, характерным для симметрии S^{++}.
Мы интерпретируем это как плавный переход от одного типа спаривания к другому.

High-Temperature Superconductors (HTSC) from 1986: Tc > 30 K

NEUTRONS FOR SCIENCE

HTSC Cu-based: oxides
HTSC Fe-based: pnictides and chalcogenides



«Unconventional» superconductors
ceramics materials

different from

«conventional», «usual» superconductors
known earlier in metals and intermetallics

new mechanism of superconductivity