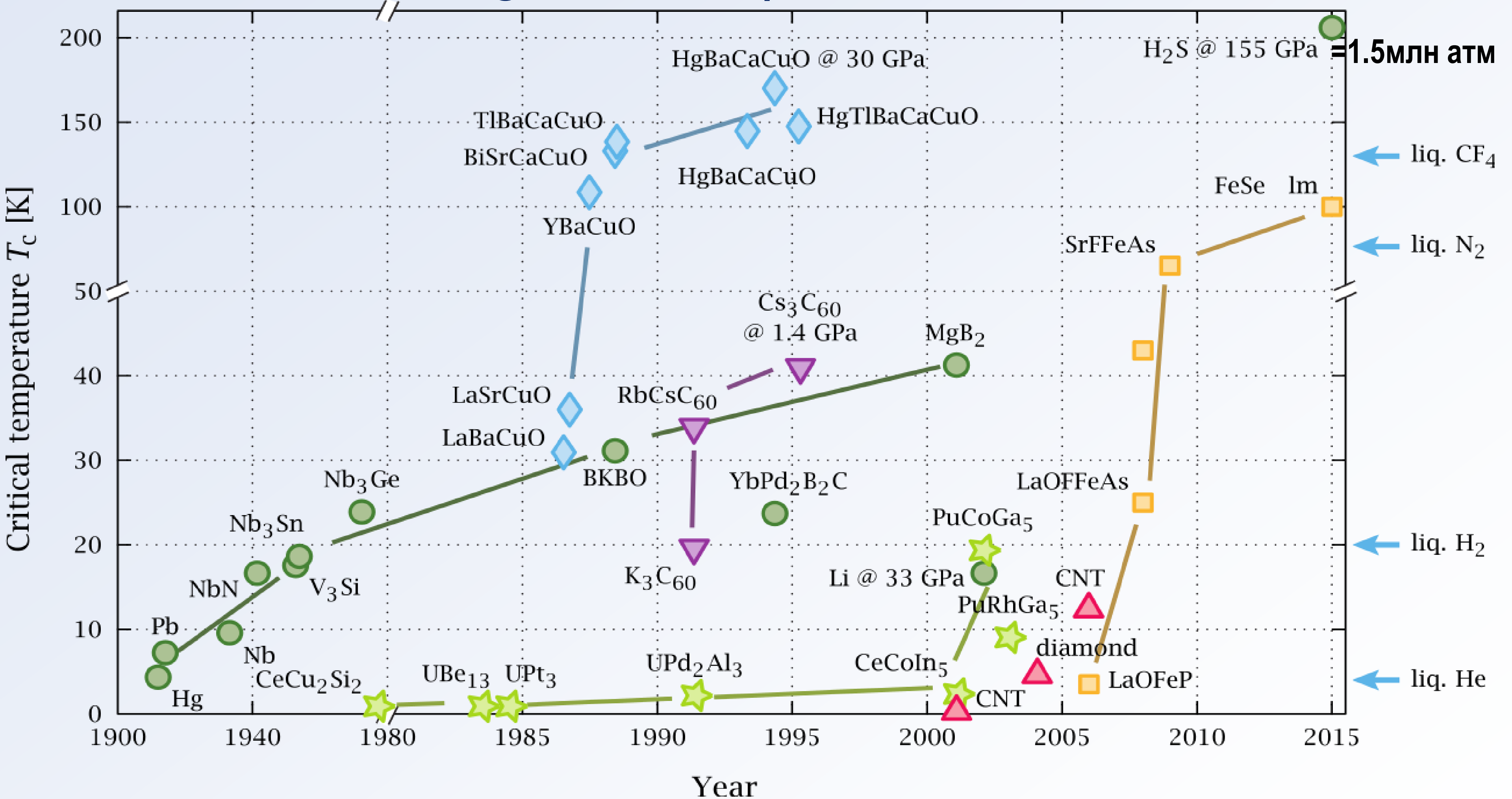
The importance of the problem of high-temperature superconductivity

The discovery of superconductivity at room temperature will lead to a technological revolution comparable to the invention of computers.

Even now, despite the need for cooling, superconductors are used in engineering, including:

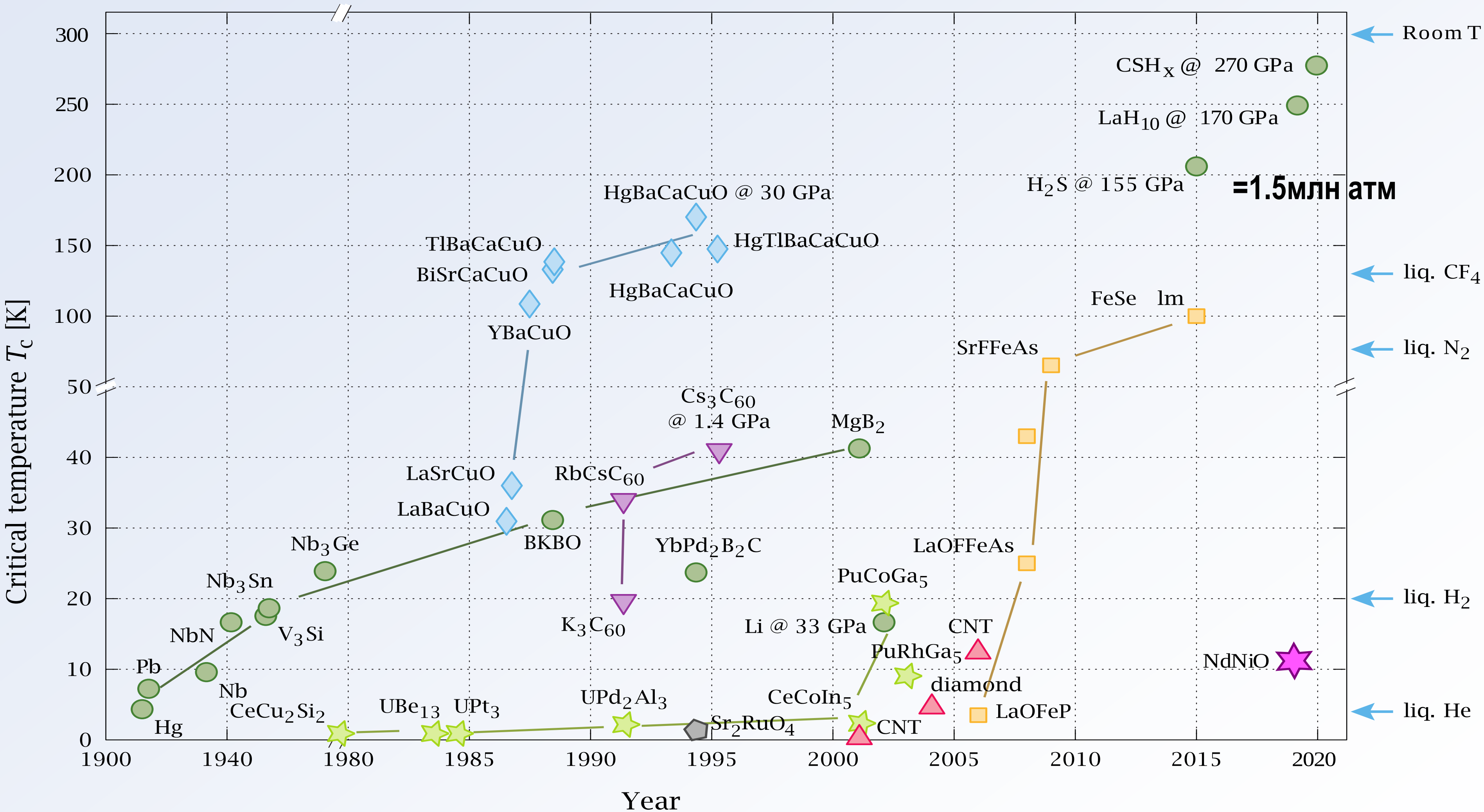
1. Production of SQUID-based sensitive magnetometers.
2. Fast digital electric circuits.
3. Powerful superconducting electromagnets used in scientific research, medical devices for magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR), magnetocontact fusion reactors (for example, tokamak) and beam controllers, and focusing magnets used in particle accelerators.
4. Power cables with low losses.
5. Radio and microwave filters (e.g., for base stations of mobile phones, for military ultra-sensitive /selective receivers, etc).
6. High-speed short-circuit current limiters.
7. Magnets of rolling guns and magnetic cannons.

High-Tc superconductors



Unfortunately, now the discovery of high-Tc superconductors occurs most often by accident: it is not clear in advance what structure or chemical formula should be achieved in order to increase Tc. => we need to better understand the known high-Tc superconductors

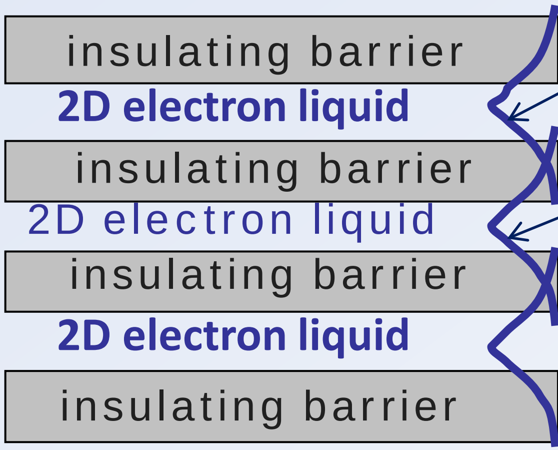
High-Tc superconductors



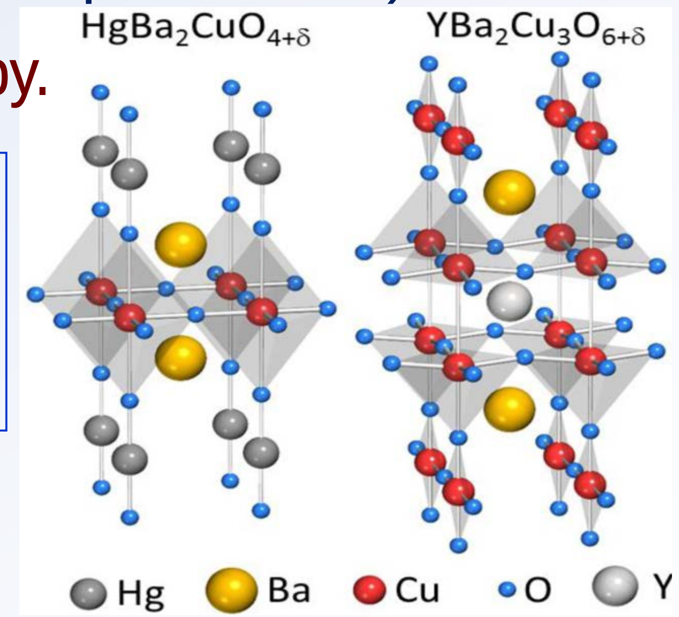
Unfortunately, now the discovery of high-Tc superconductors occurs most often by accident: it is not clear in advance what structure or chemical formula should be achieved in order to increase Tc. => we need to better understand the known high-Tc superconductors

The common features of all high-temperature superconductors (at ambient pressure)

1. Layered crystal structure, => strong anisotropy.

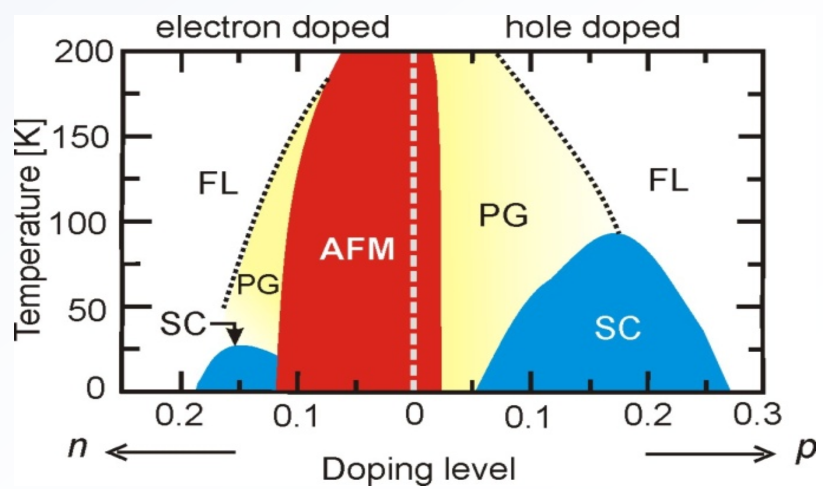


Interlayer hopping integral t_z and the interlayer conductivity are small: $\sigma_{zz} << \sigma_{xx}$

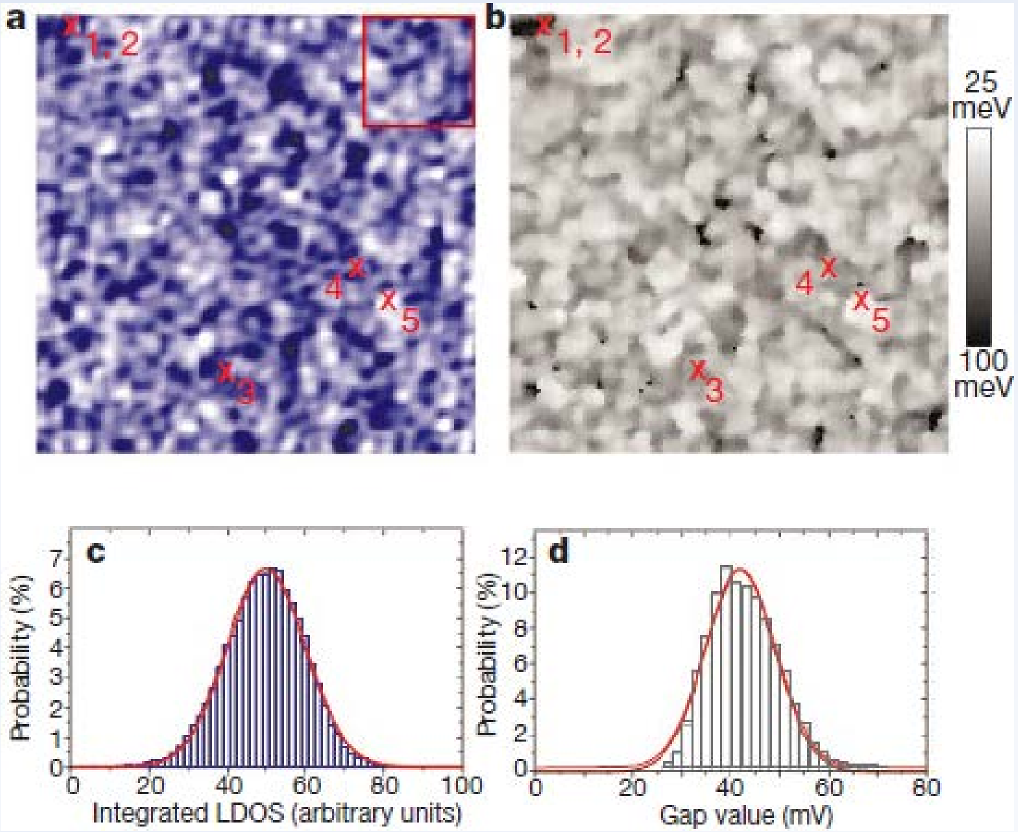


2. The spatial inhomogeneity for superconductors with the highest Tc (cuprates, iron-based), due to doping or interplay with density wave

3. Strong electron correlations and competition of superconductivity with other types of electronic ordering: charge or spin density waves, antiferromagnetism, etc ..



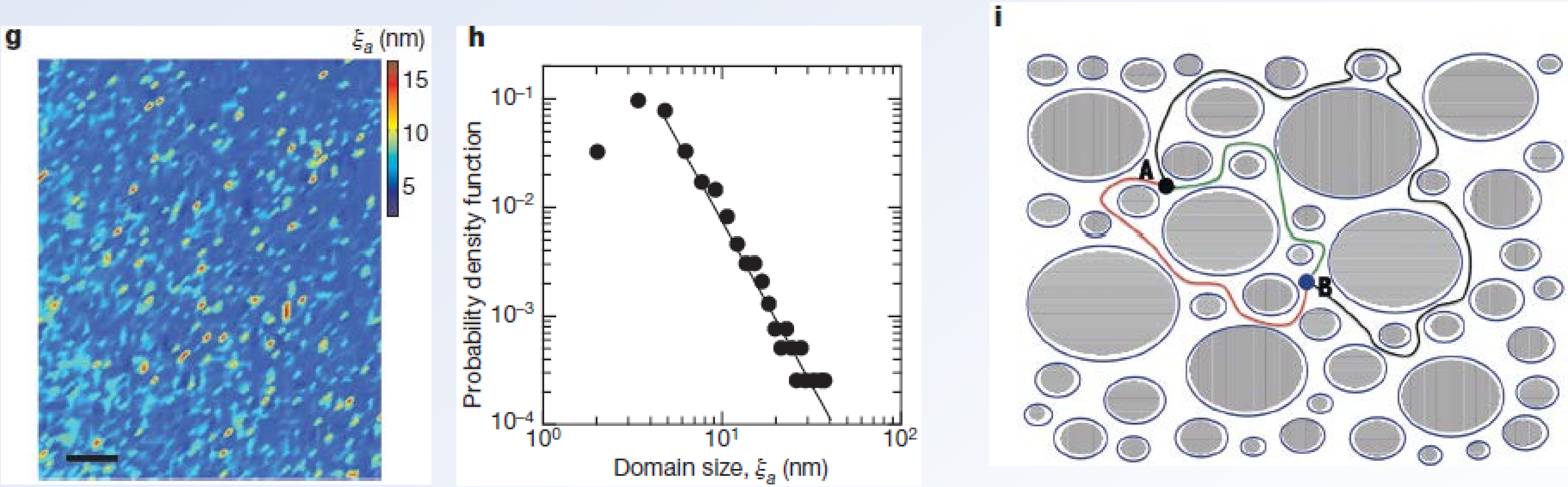
Spatial inhomogeneities in BISCCO [NATURE 413, 282 (2001)]



A LDOS map and superconducting gap map with their associated statistical results. a) 600x600A LDOS map obtained on a single crystal $Bi_2Sr_2CaCu_2O_{8+x}$ doped with a very dilute concentration (0.2%) of Zn atoms. The crystal has a superconducting transition temperature of 84 K, with a transition width of 4 K. It clearly displays an inhomogeneous structure. b) Superconducting gap map, obtained simultaneously with the integrated LDOS map on the same location, showing the spatial variation of the superconducting energy gap.

The local gap values are extracted from the corresponding local differential conductance spectra. c, d) show the statistical distributions of the integrated LDOS and the magnitude of the superconducting gap. Each of them exhibits a gaussian-like distribution (fitting function displayed in red). The fit of the gap distribution (42 meV mean; ~20 meV FWHM) shows it to be slightly skewed.

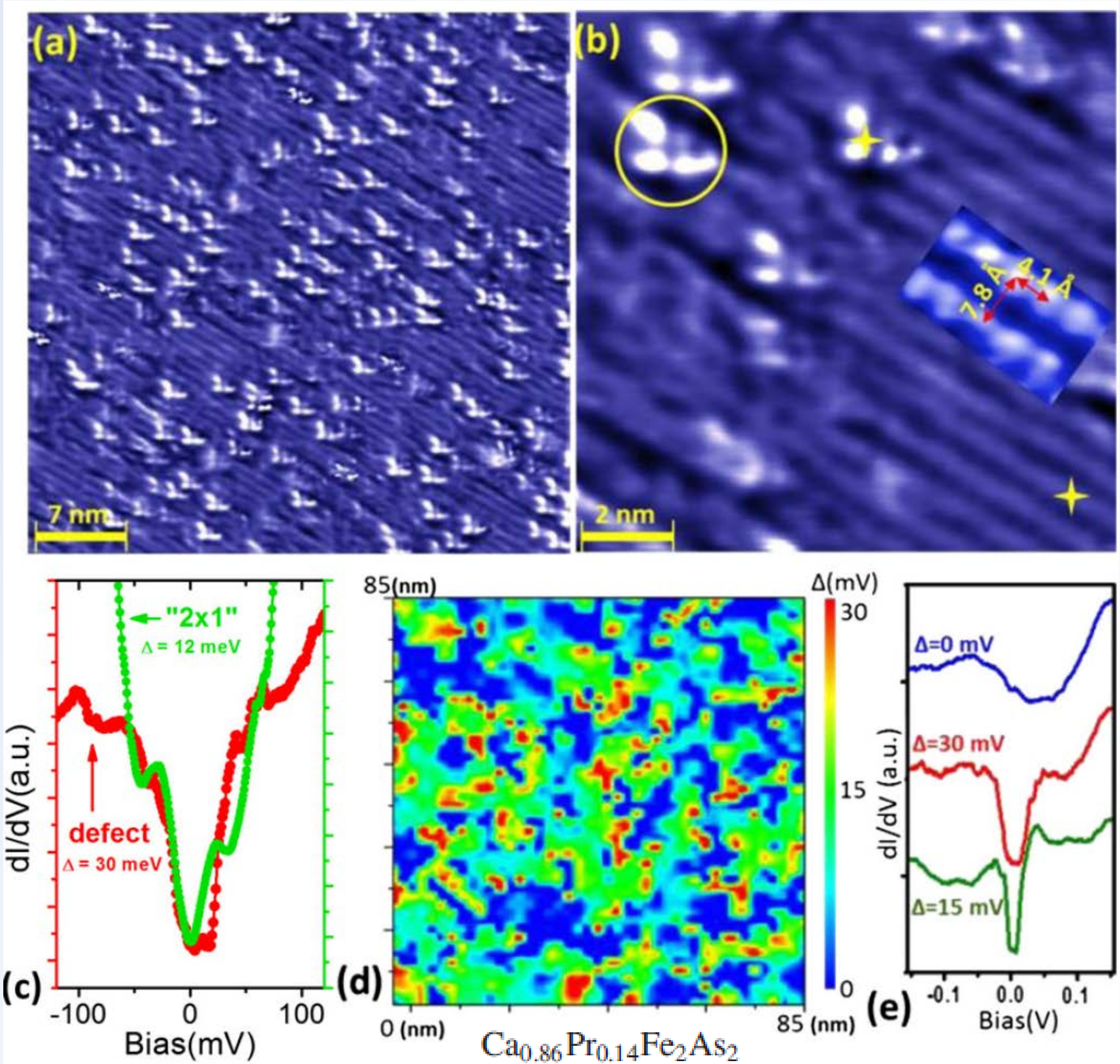
Inhomogeneity of charge-density-wave order and quenched disorder in a high-T_c superconductor $HgBa_2CuO_{4+y}$



Spatial map (g) and probability density function (h) of the CDW-puddle size. Scale bar in g, 10mm. i, A schematic of non-equivalent paths for the superconducting current, running in the interface space between CDW puddles, connecting point A to point B.

G. Campi et al., Nature 525, 359–362 (2015)

Spatial heterogeneities in Fe-based superconductors



PRL 112, 047005 (2014)

Therefore, the study of high-Tc superconductivity onset in the form of isolated islands is very important !

ARPES (Angle resolved photoemission spectroscopy)

Main idea:

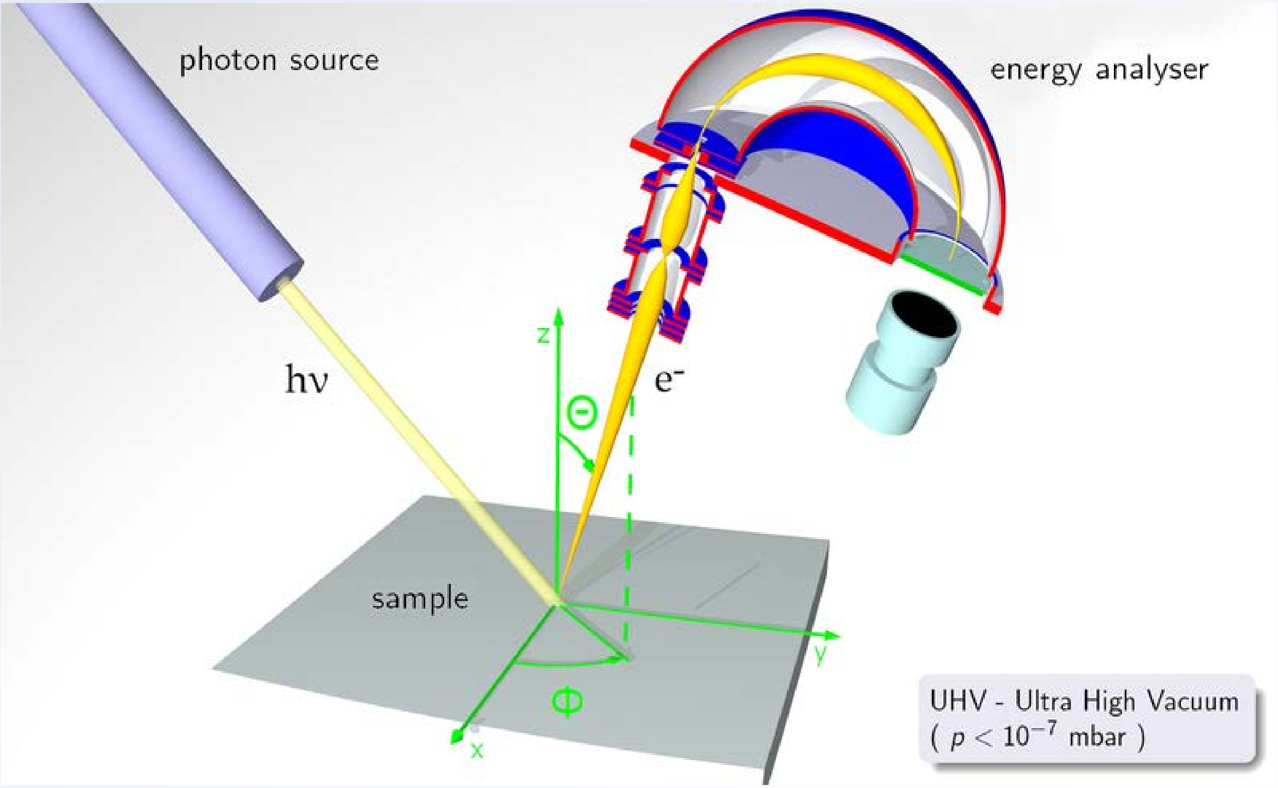
$$E = \hbar\omega - E_k - \phi$$

E_k = kinetic energy of the outgoing electron — can be measured.

$\hbar\omega$ = incoming photon energy - known from experiment, ϕ = known electron work function.

Angle resolution of photoemitted electrons gives their momentum.

Rev.Mod.Phys. 75, 473 (2003)



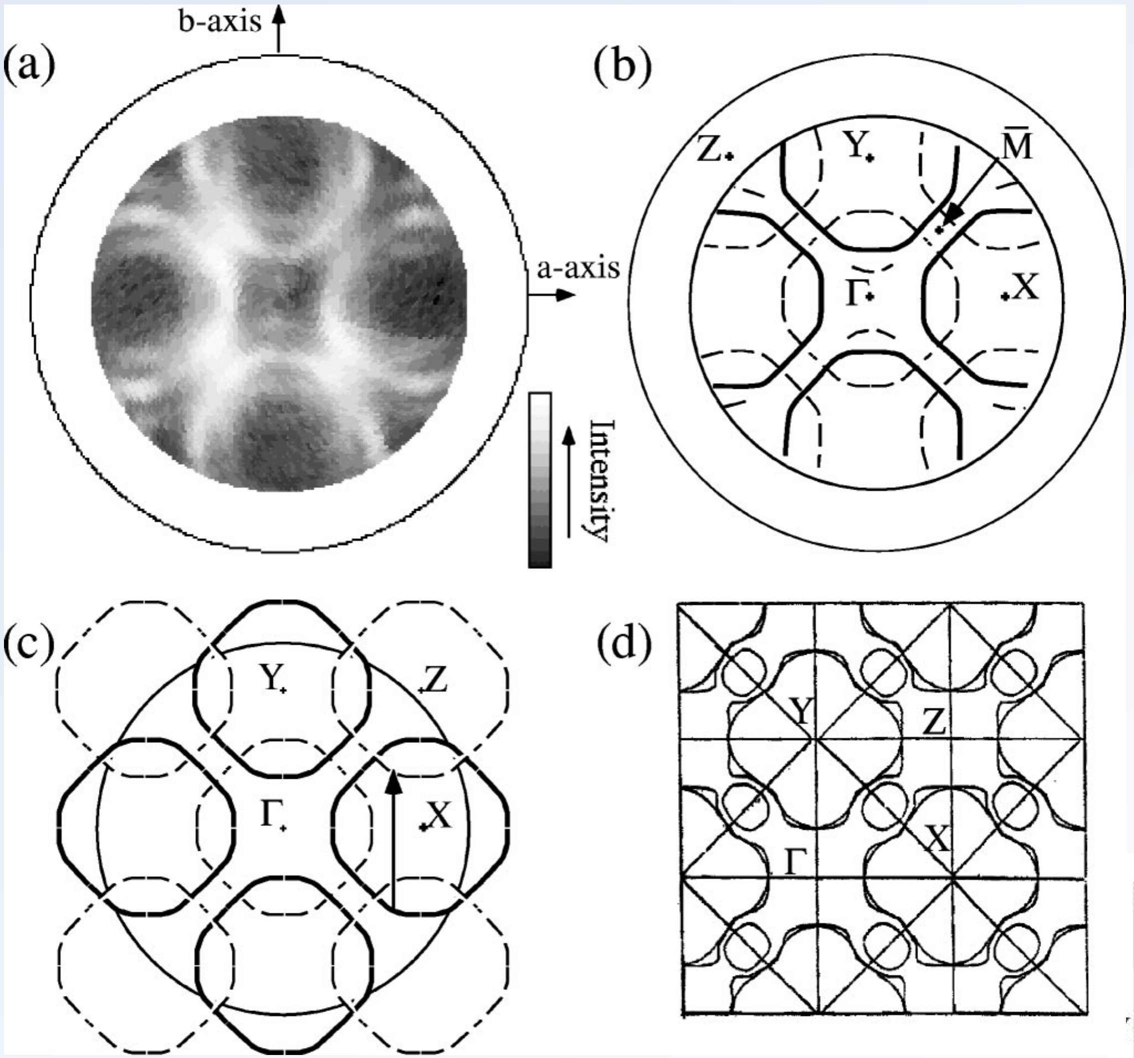
The photocurrent intensity is proportional to a one-particle spectral function multiplied by the Fermi function: $I(\mathbf{k},\omega) = A(\mathbf{k},\omega) f(\omega)$

$$A(\omega,\mathbf{k}) = -\frac{1}{\pi}\frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}.$$

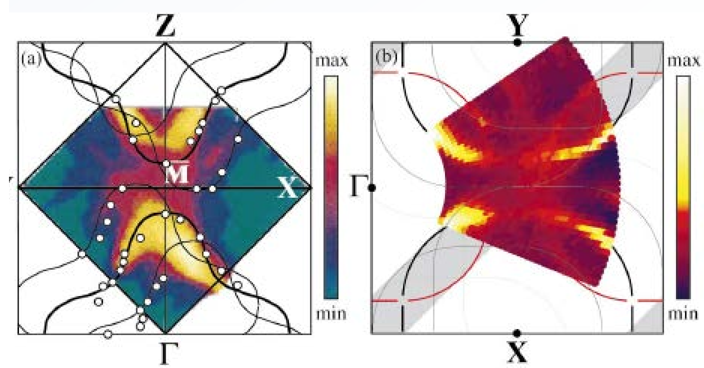
Therefore can find out information about *E(k)*

Drawbacks: 1) Often unavailable; 2) Only surface electrons participate; 3) Low resolution (>10meV) => ambiguous interpretation.

ARPES data and Fermi-surface shape

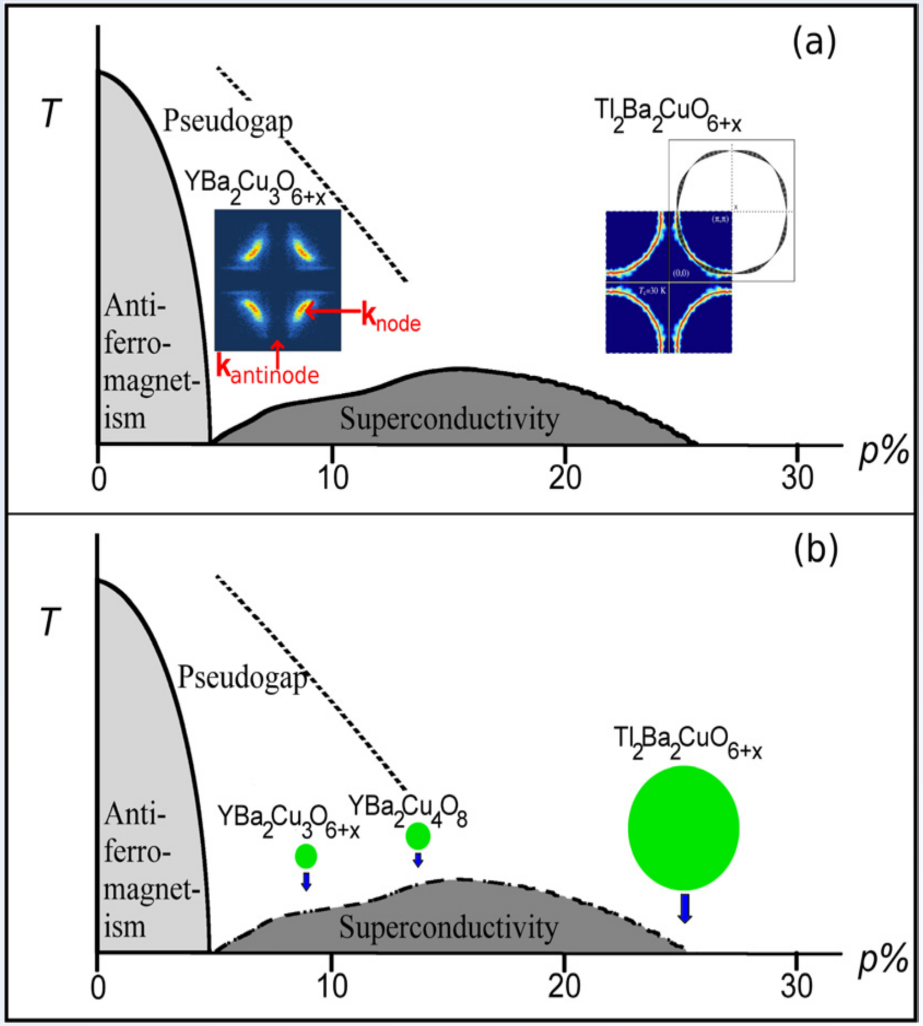


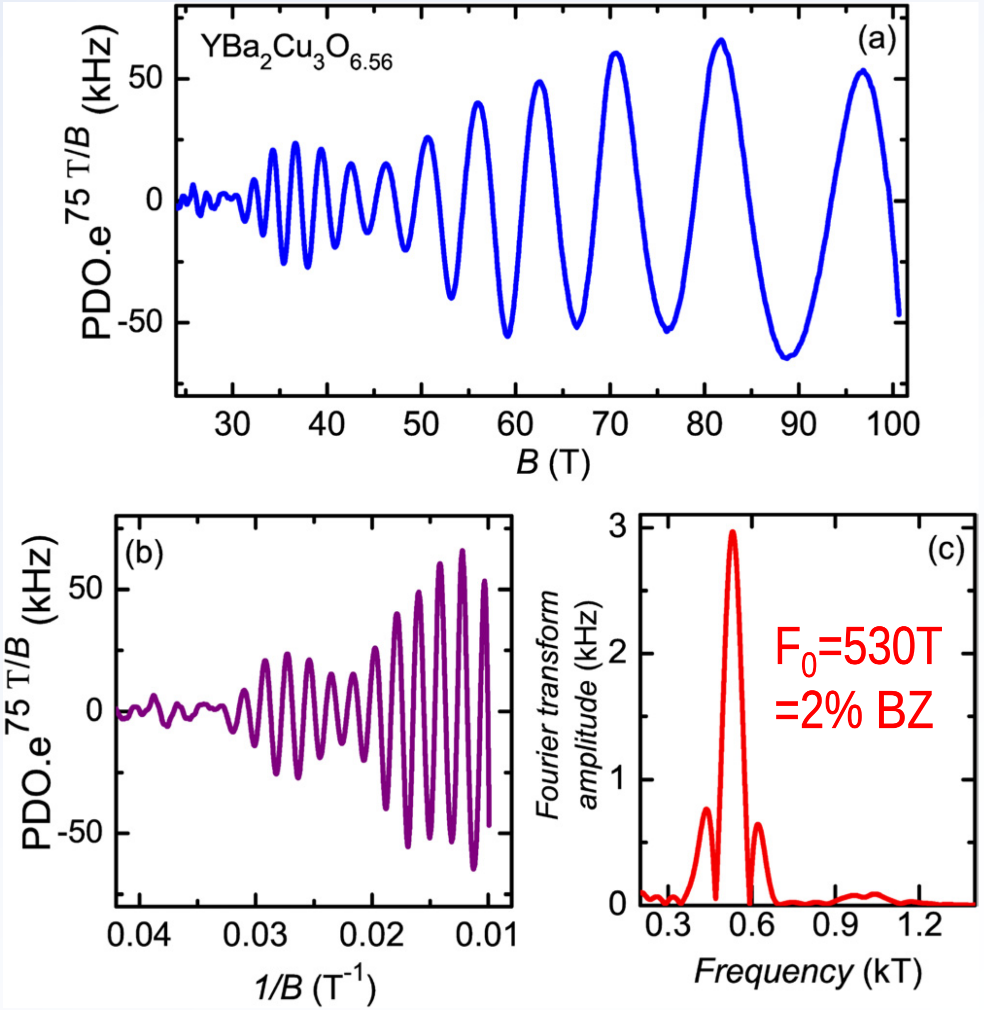
The Fermi surface of near optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (a) integrated intensity map (10-meV window centered at *EF*) for Bi2212 at 300 K obtained with 21.2-eV photons (HeI line); (b),(c) superposition of the main Fermi surface (thick lines) and of its (p,p) translation (thin dashed lines) due to backfolded shadow bands; (d) Fermi surface calculated by Massidda *et al.* (1988).



Drawback 3: Low resolution
=> ambiguous interpretation

Quantum oscillations observed in YBCO cuprates high-Tc superconductors

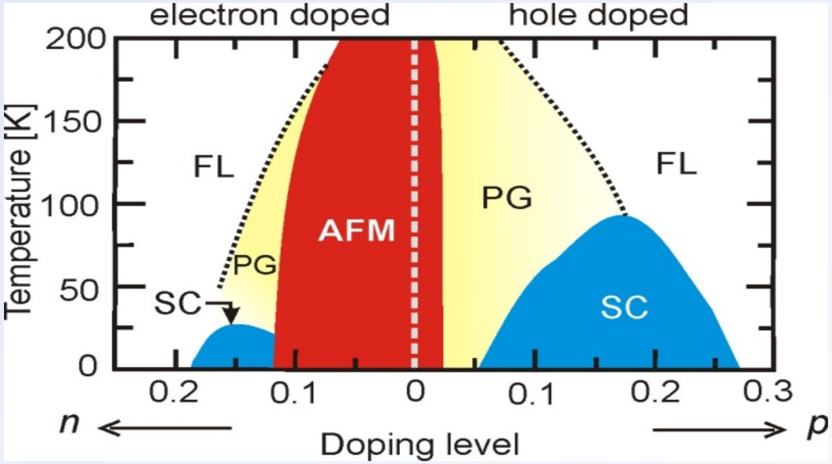




Phase diagram and magnetic quantum oscillations of YBCO cuprate superconductors [Figs. are taken from review S.E. Sebastian et al., Rep. Prog. Phys. 75, 102501 (2012)]

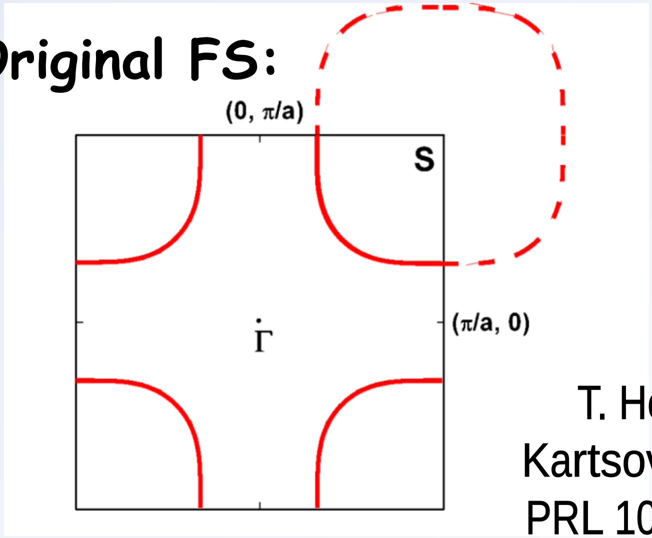
Fermi-surface reconstruction in electron-doped cuprate superconductors

$Nd_{2-x}Ce_xCuO_4$ (NCCO)



For hole-doped YBCO it does not work, because (1) size of hole pocket is larger than 2% of BZ 2) AFM order is absent at doping level p>0.03.

Original FS:

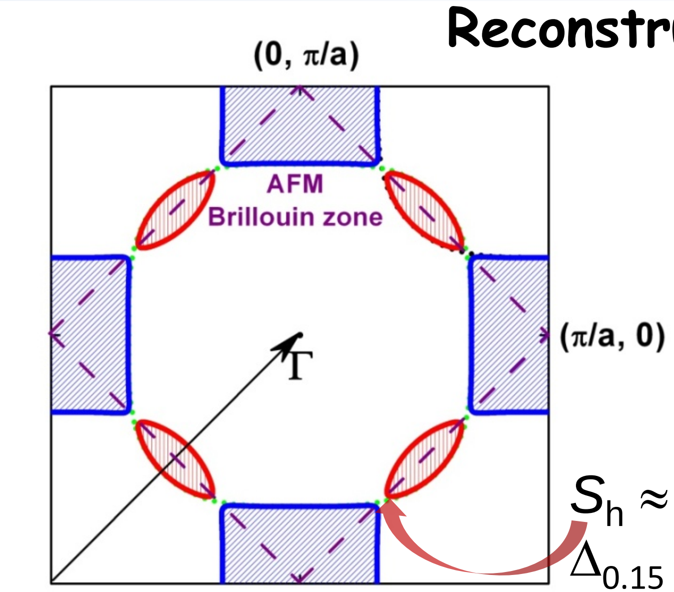


$\underline{n = 0.17}$

$S_h = 41.5\%$ of S_{BZ}

T. Helm, M. Kartsovnik et al., PRL 103, 157002 (2009)

Reconstructed FS:



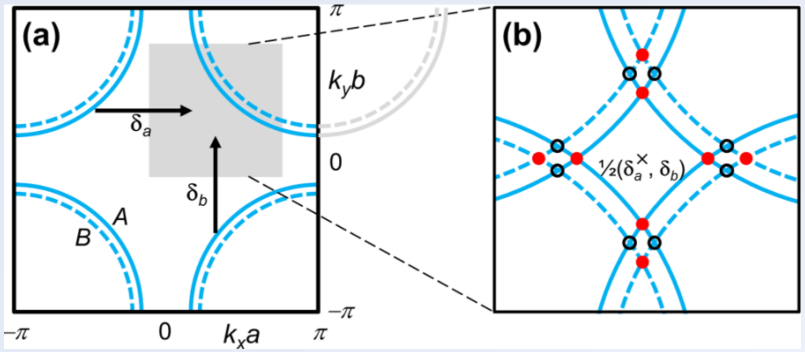
$\underline{n = 0.15 \text{ and } 0.16}$

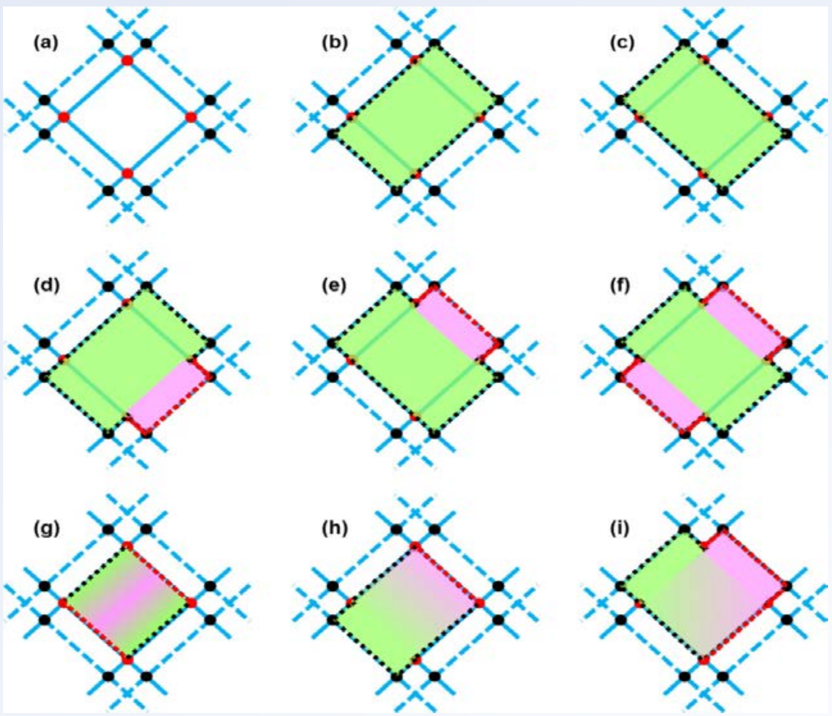
$S_h \approx 1.1\%$ of S_{BZ};

$\Delta_{0.15} \approx 64$ meV;

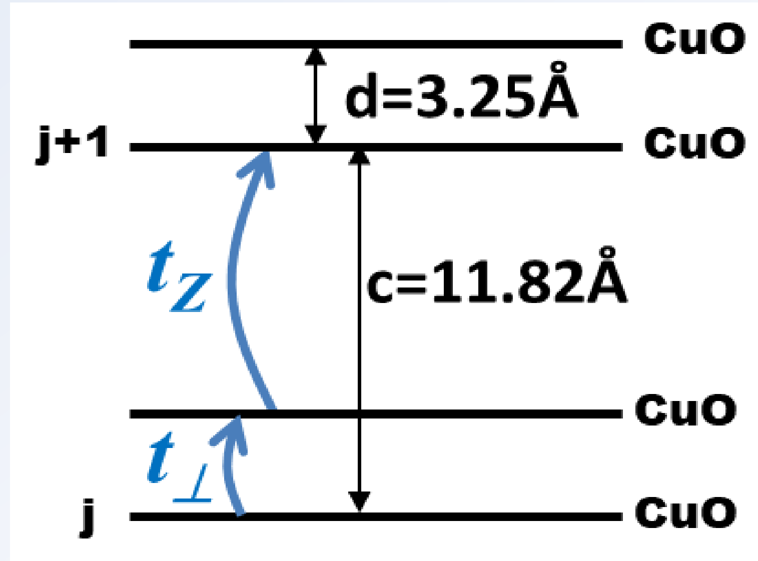
$\Delta_{0.16} \approx 36$ meV

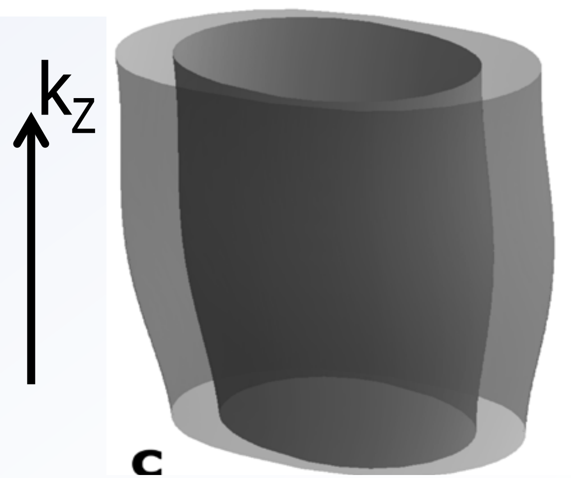
FS reconstruction by CDW predicts 2 closed pockets due to bilayer splitting





A.K.R.Briffa et al., Phys. Rev. B 93, 094502 (2016)

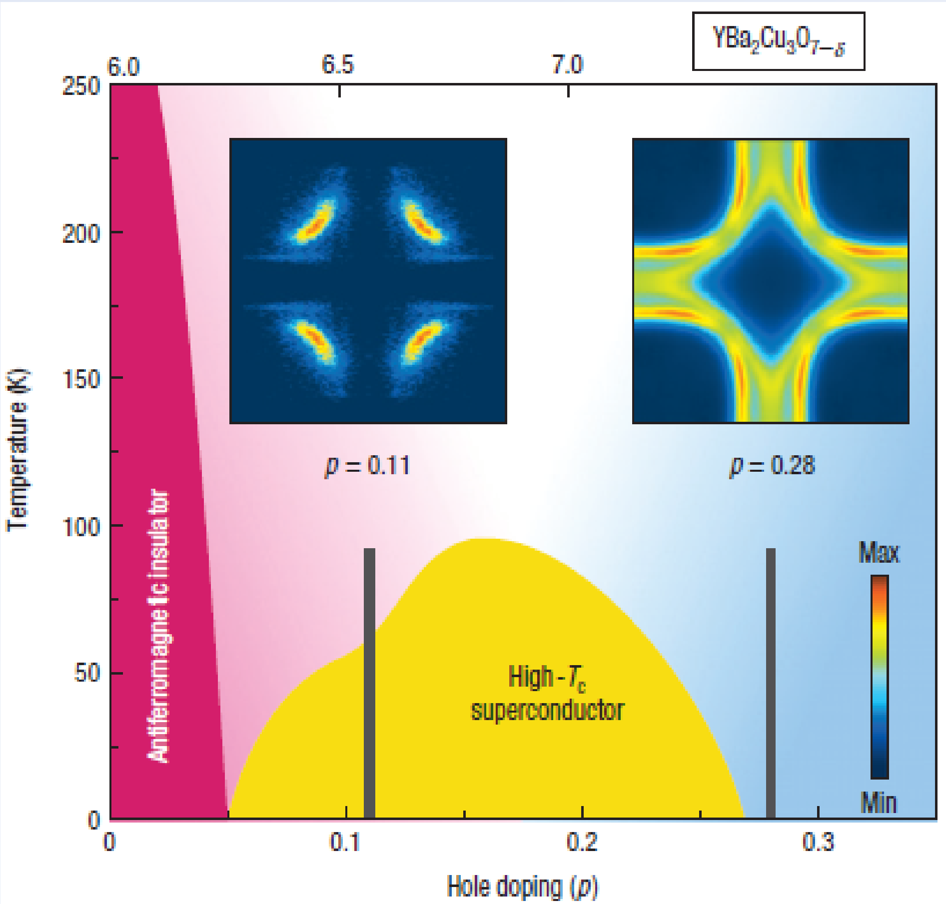




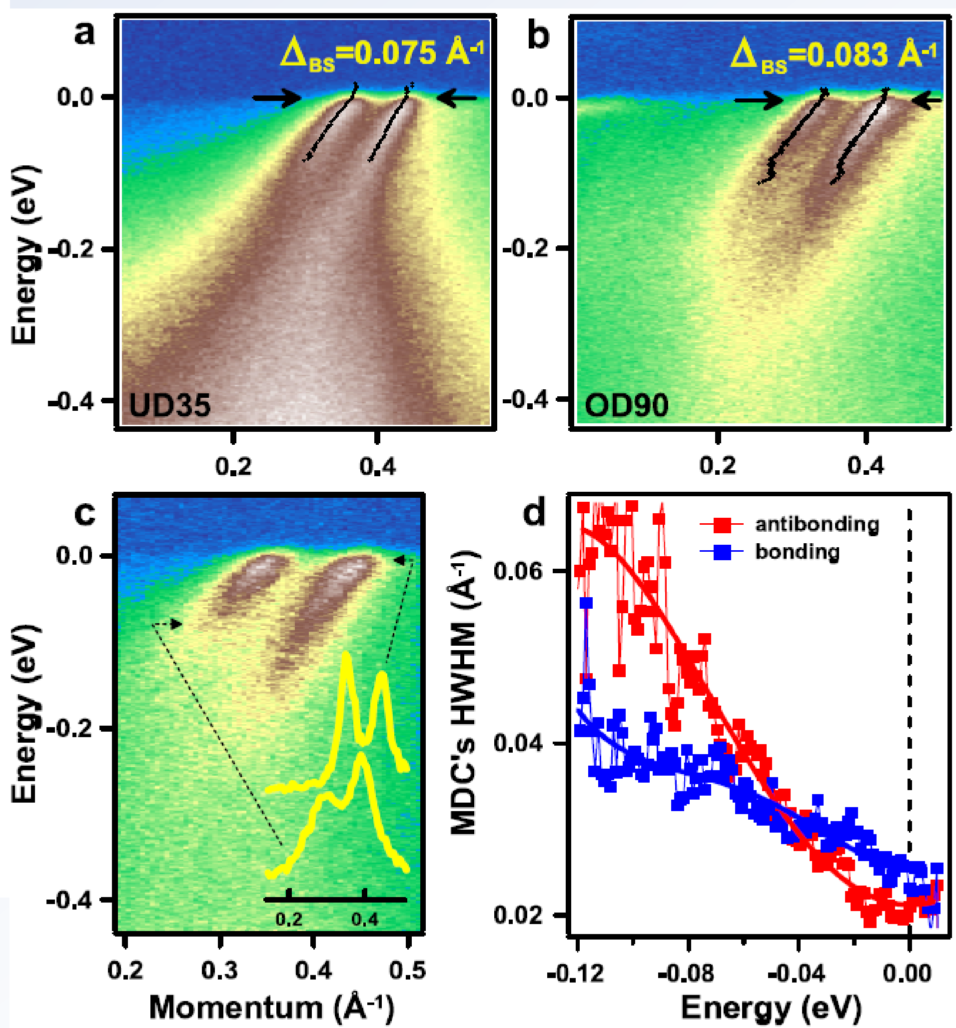
Schematic FS view

Bilayer-split Fermi surface [PG & TZ, JETP Lett. 106, 361 (2017)]

ARPES data (underdoped YBCO)



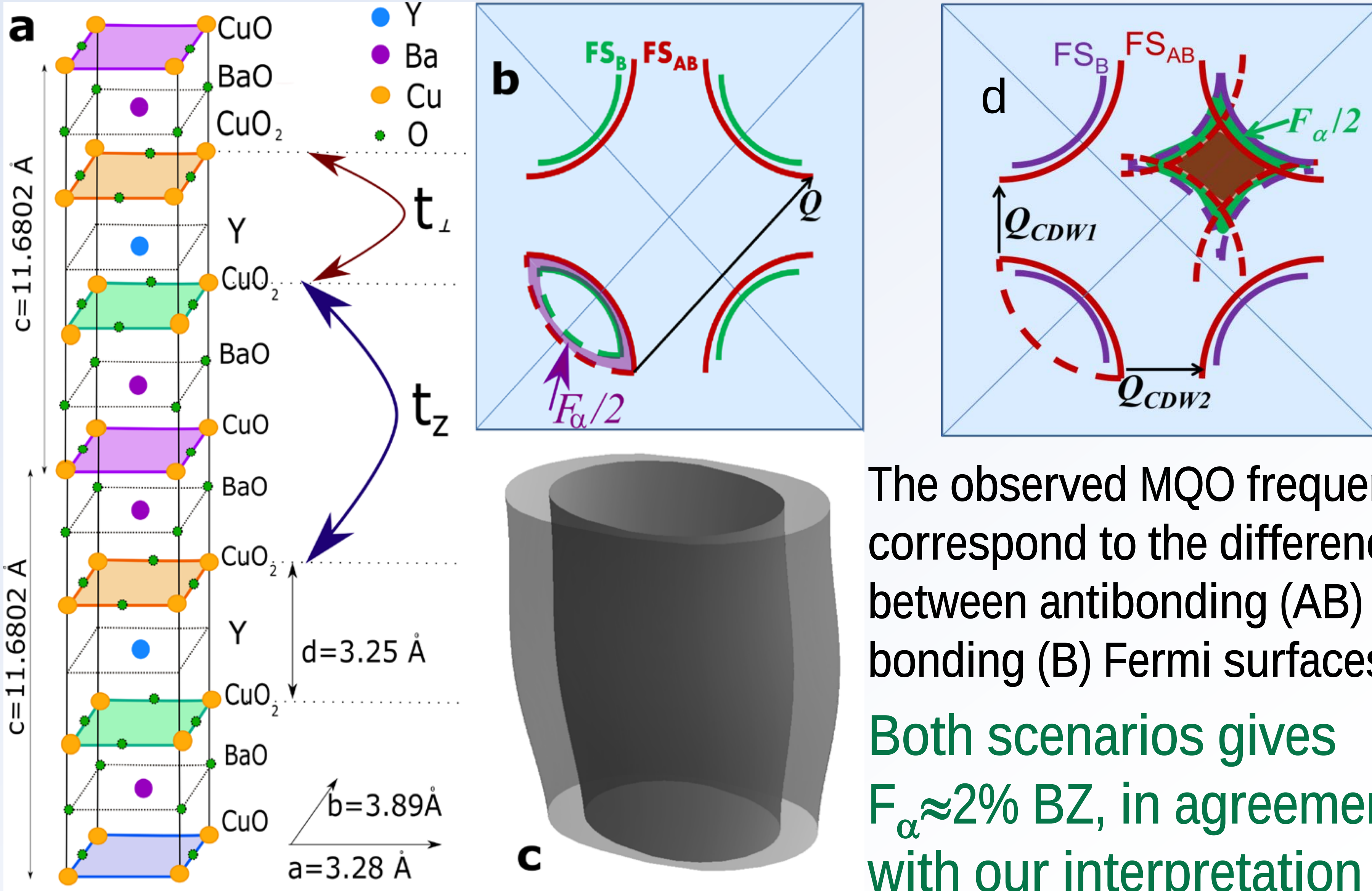
Phase diagram of YBCO by ARPES
M.A. Hossain et al., Nature Physics **4**, 527–531 (2008)



Bilayer splitting observed by ARPES
S.V. Borisenko et al., PRL **96,** 117004 (2006)

Our model indeed gives ~2% of the BZ !

Geometrical interpretation of observed magnetic oscillation frequencies in YBCO



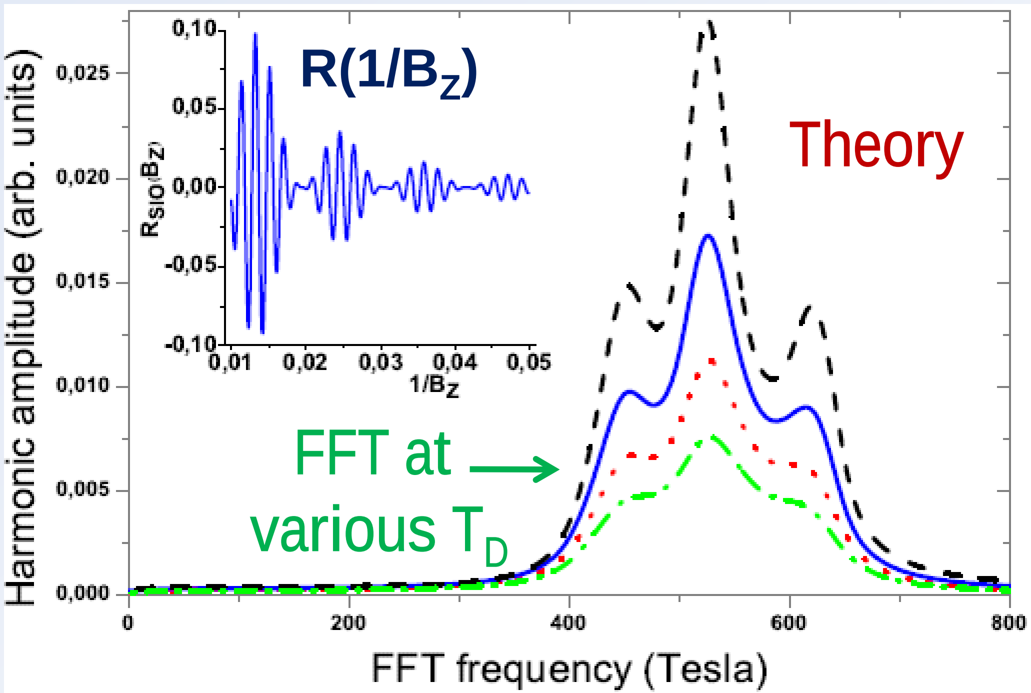
The observed MQO frequency correspond to the difference between antibonding (AB) and bonding (B) Fermi surfaces.

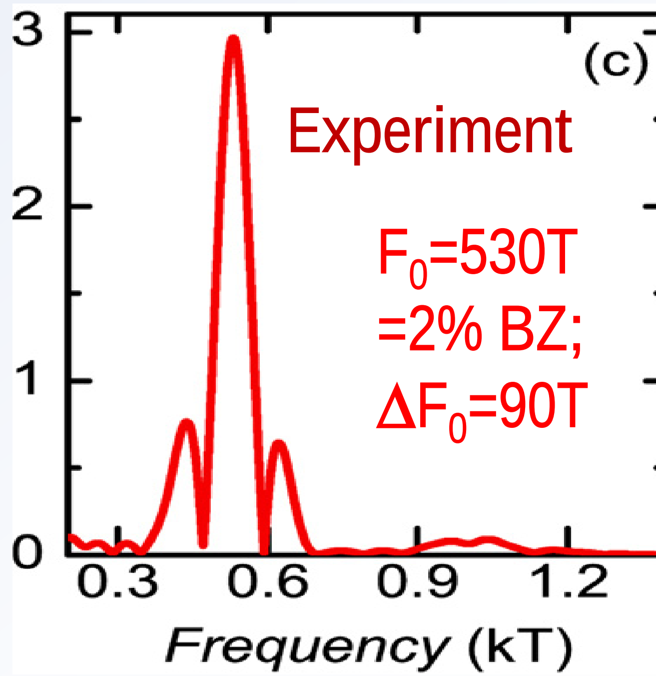
Both scenarios gives $F_{\alpha}\approx 2\%$ BZ, in agreement with our interpretation !

Results, comparison with experiment, and discussion

The slowly oscillating term in conductivity

$$\sigma_{SIO}(B_z) \propto J_0^2\left(2\pi\frac{\Delta F_c}{B_z}\right)\cos\left(4\pi\frac{\Delta F_\perp}{B_z}\right)R_D^2$$

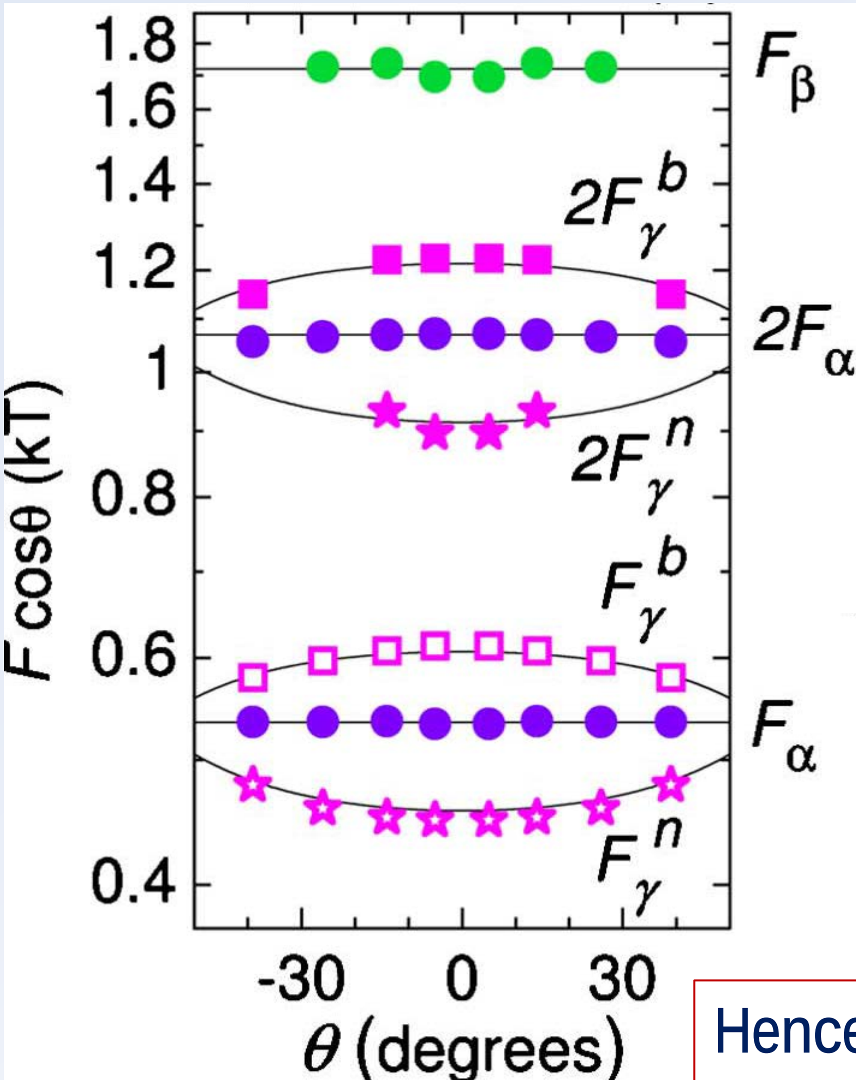




With increasing of Dingle temperature or with decreasing field range, two side peaks disappear, as they do in experiments in lower fields.

If the proposed interpretation is valid, and F_0 gives the bilayer splitting and one needs to look for fundamental frequency F_β and for very low frequency $2\Delta F_c$

Angular dependence of three MQO frequencies



The split frequency fits the angular dependence, $\Delta F_c \cos\theta \propto J_0(k_F c^\star \tan\theta)$ suggesting that it originates from k_z dispersion, i.e. $\Delta F_c = 2t_z B/\hbar\omega_c \approx 90T$ Then $\Delta F_\perp = t_\perp B/\hbar\omega_c \approx 530T$ is reasonable for bilayer splitting.

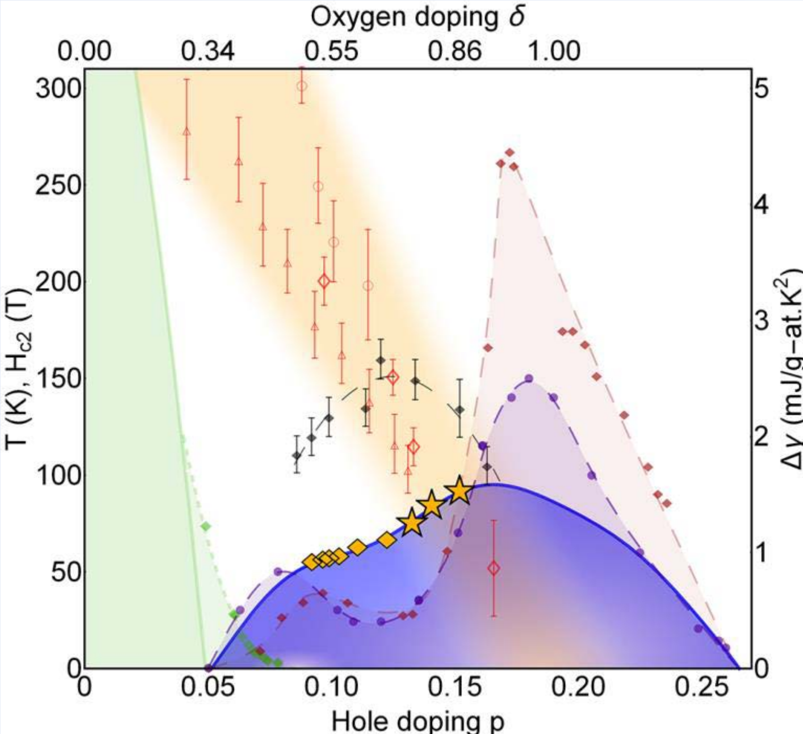
The first Yamaji angle $\theta_{Yam} \approx 43^\circ$ corresponds to the FS pocket area $\sim\pi k_F^2$ = 6% of BZ and to $F_\beta \approx 1.6$kT rather than to stronger $F_\alpha \approx 530$T. => The most prominent frequency F_α does not correspond to FS pocket.

Hence, the angular dependence of three MQO frequencies confirms the proposed scenario.

S.E. Sebastian et al., PRB 81, 214524 (2010)

P.D. Grigoriev, T. Ziman, JETP Lett. 106, 361; Phys. Rev. B 96, 165110 (2017)

Doping-dependence of MQO frequencies in YBCO is weak, contrary to m*



B. J. Ramshaw, S. E. Sebastian, et al., Science **348**, 317 (2015)