Investigation of the mechanism for high temperature superconductivity using single crystals of CLBLCO

Gil Drachuck and Amit Keren
Technion – Physics Department

Collaborations

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  Institute Laue-Langevin, Grenoble, **France**
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  Technion - Israel Institute of Technology, Haifa, **Israel**

Outline

- **Why $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$?**
- The role of disorder in CLBLCO?
- The relationship between J and T_c^{max} in cuprates.
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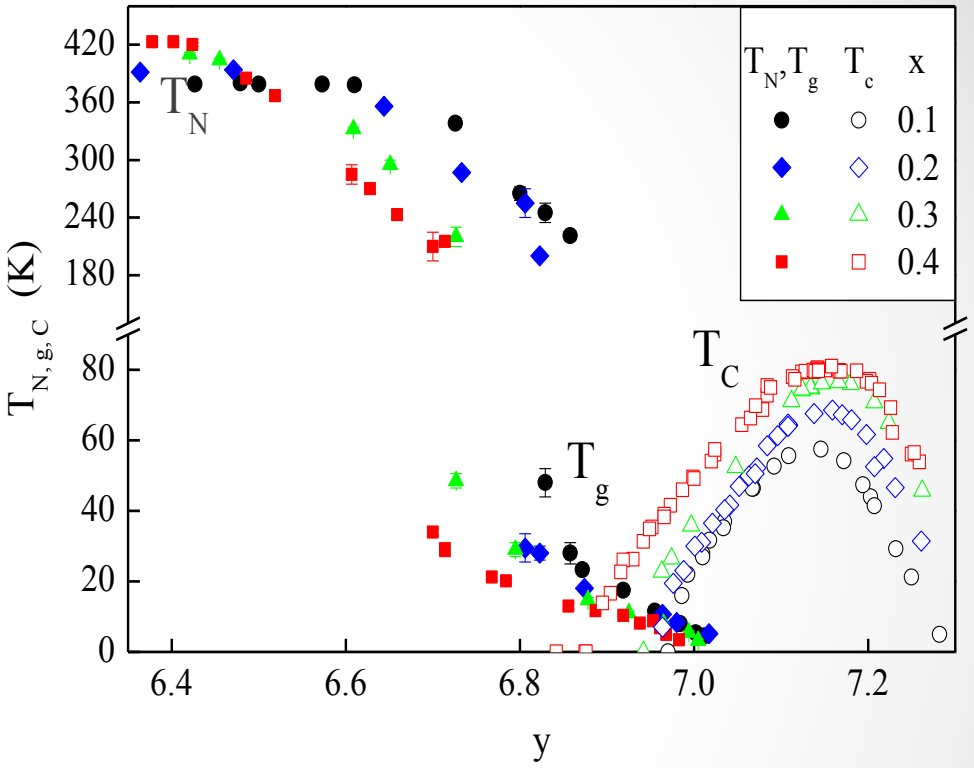
Why $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$?

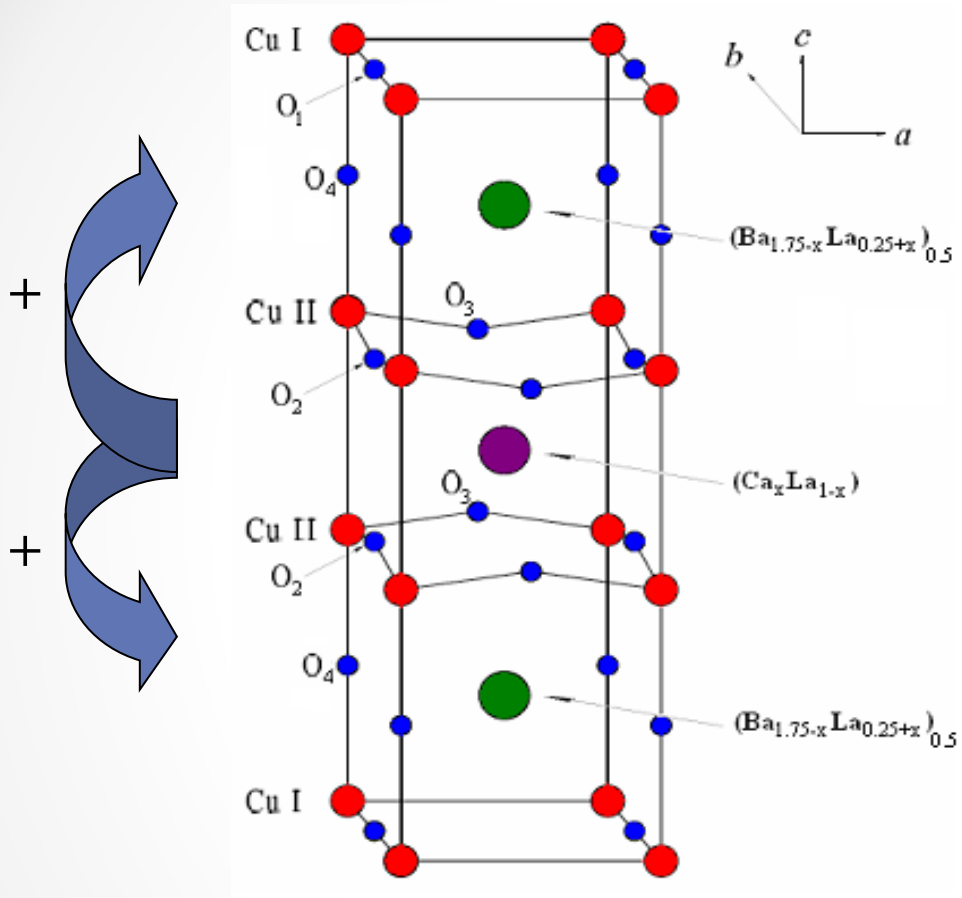
- $YBa_2Cu_3O_y$ structure.
- 2 planes per unit cell.
- Tetragonal at all x and y.
- Over doping is possible.
- T_c variation of 30%.
- Valance Ca=Ba=2, La=3.



- The **family (or x)** with the highest T_c has the highest T_N at zero doping.

CLBLCO allows T_c and T_N variations, with minimal structural changes.

The role of x in $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$

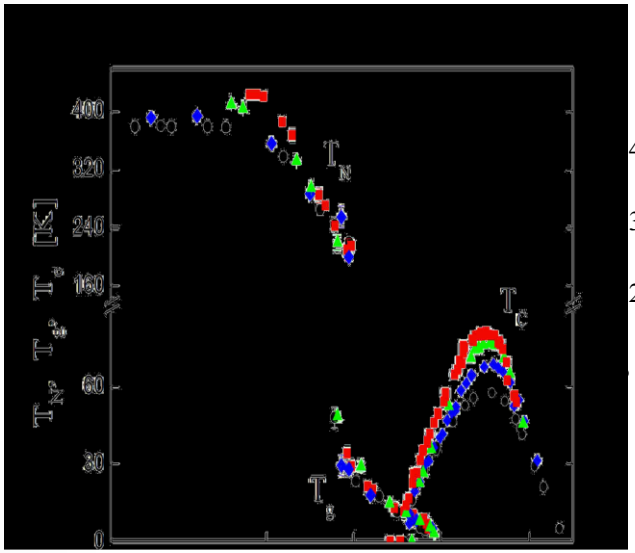


- Crystal structure does not change (remains tetragonal).
- Unit cell parameter does not change (<1%)
- Total Charge does not change

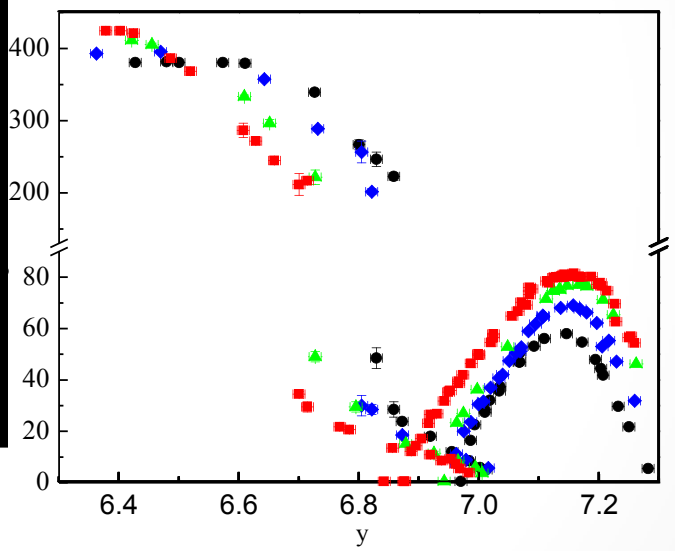
•Positive change is moving from between the CuO2 planes with increasing x.

• This changes the **oxygen position** and **buckling angle** thus increases orbital overlaps.

The Scaling "miracle"

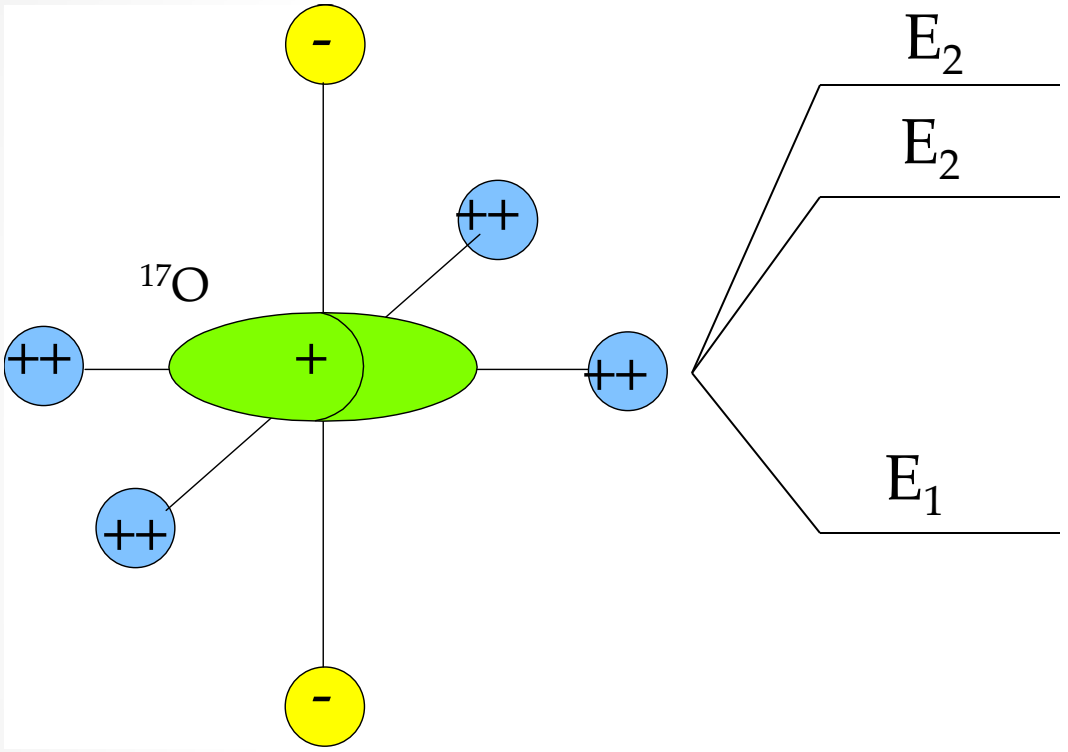


K(x) × y



- Stretching the oxygen axis of each family by factor of ***K(x)*** creates identical critical doping levels and untangle the phase diagram.

The meaning of scaling; ^{17}O NQR



Sensitive to electric Field gradent

Variations in the resonance frequency $^{17}\nu_Q$ measures charge variations of the nuclear environment.

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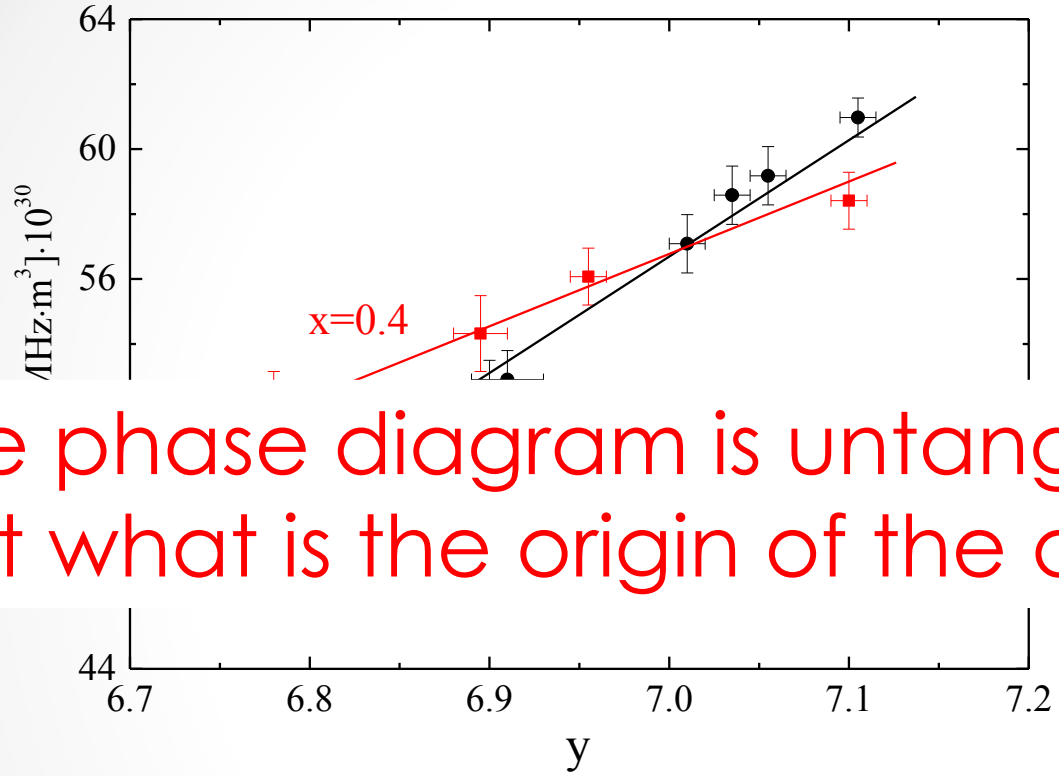
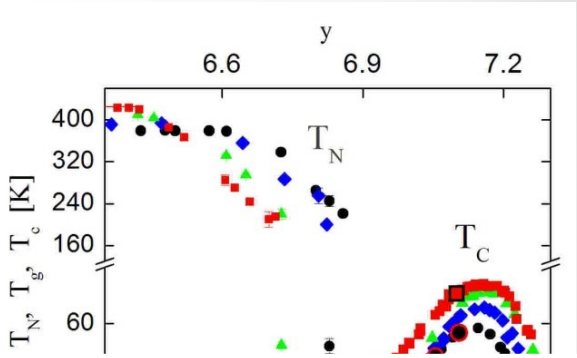
Determination of K(x)





The phase diagram is untangled
but what is the origin of the difference in Tc?

- The slopes' ratio is equal to *K(0.4)/K(0.1)*.
- The scaling parameter *K(x)* is an <u>in-plane</u> doping efficiency factor.

Eran Amit and Amit Keren

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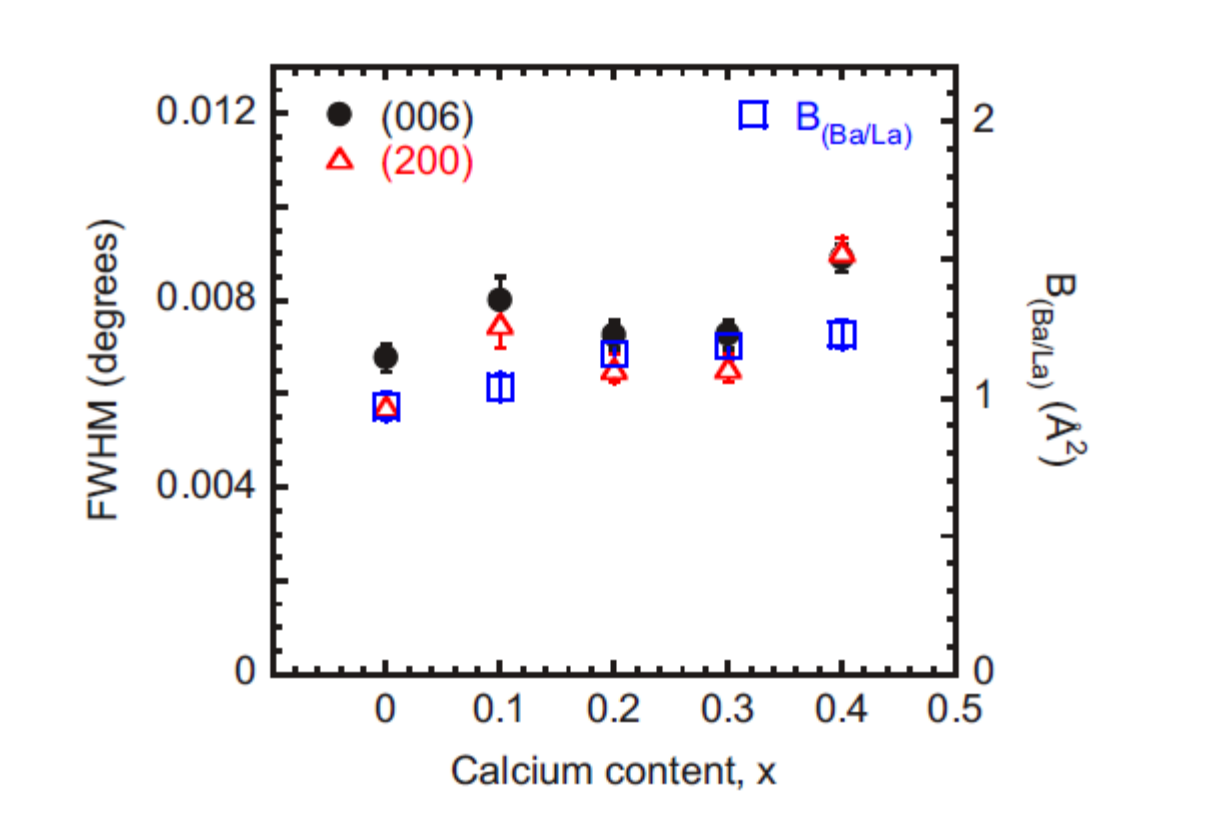
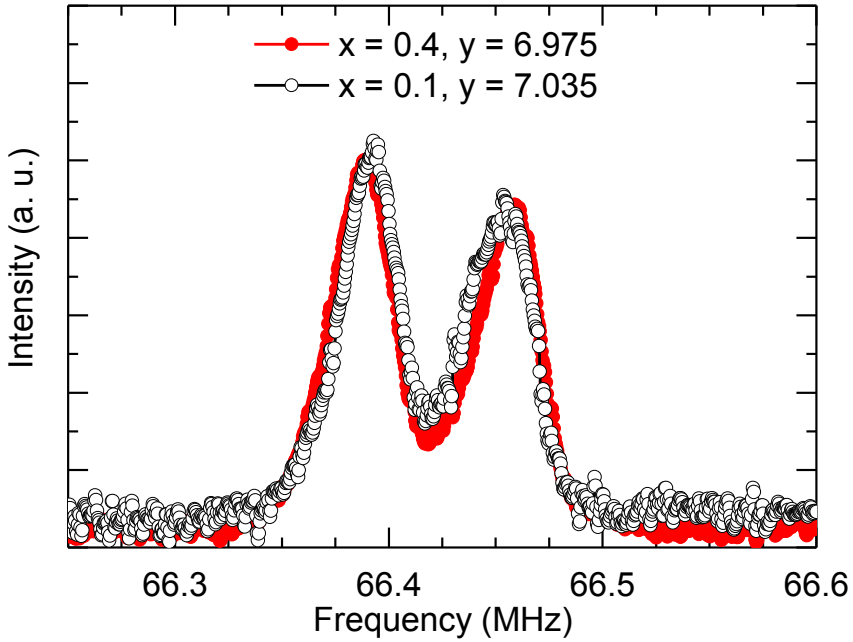
Disorder Issues: High Resolution X-ray

Disorder is *x* independent.



- Agrestini…Bianconi, JPCS **75,** 259 (2014) showed equal line widths for the different families on powder sample.

Disorder Issues: ^{17}O NMR



- T. Cvitanic (Phys. Rev. B **90**, 054508) showed identical NMR line widths for powder samples.

The difference in Tc is not induced by disorder… So what else could it be?

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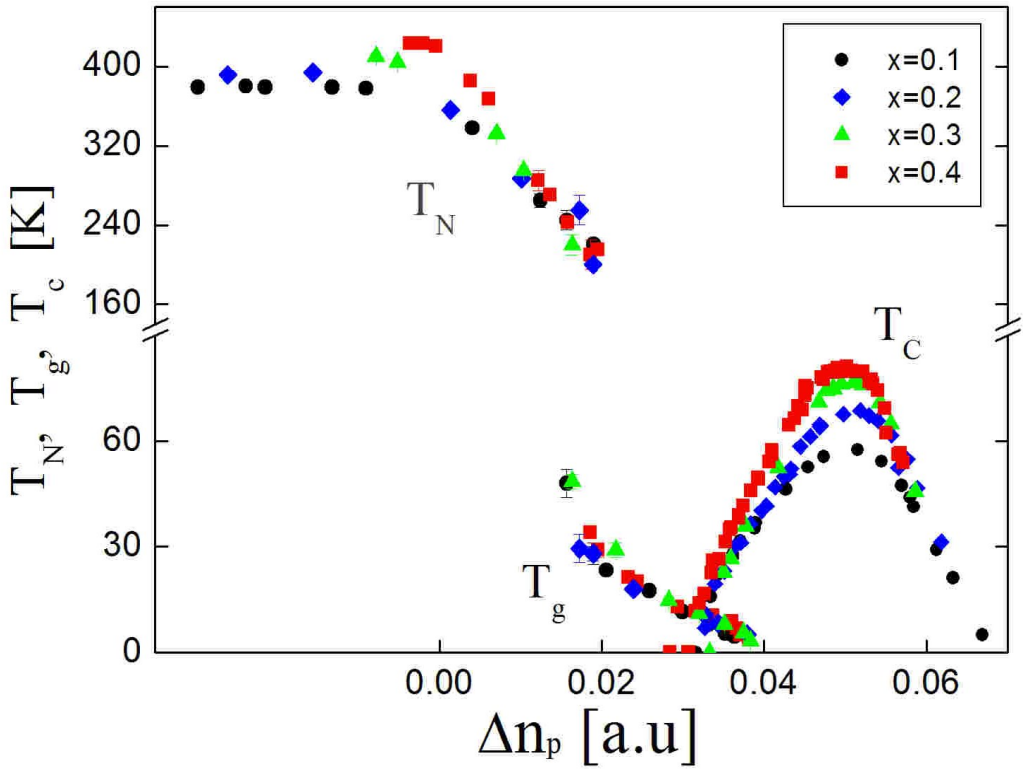
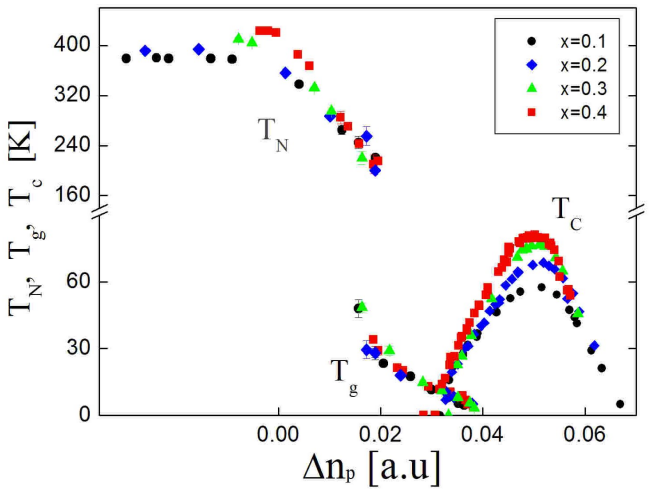
Connecting the energy scales

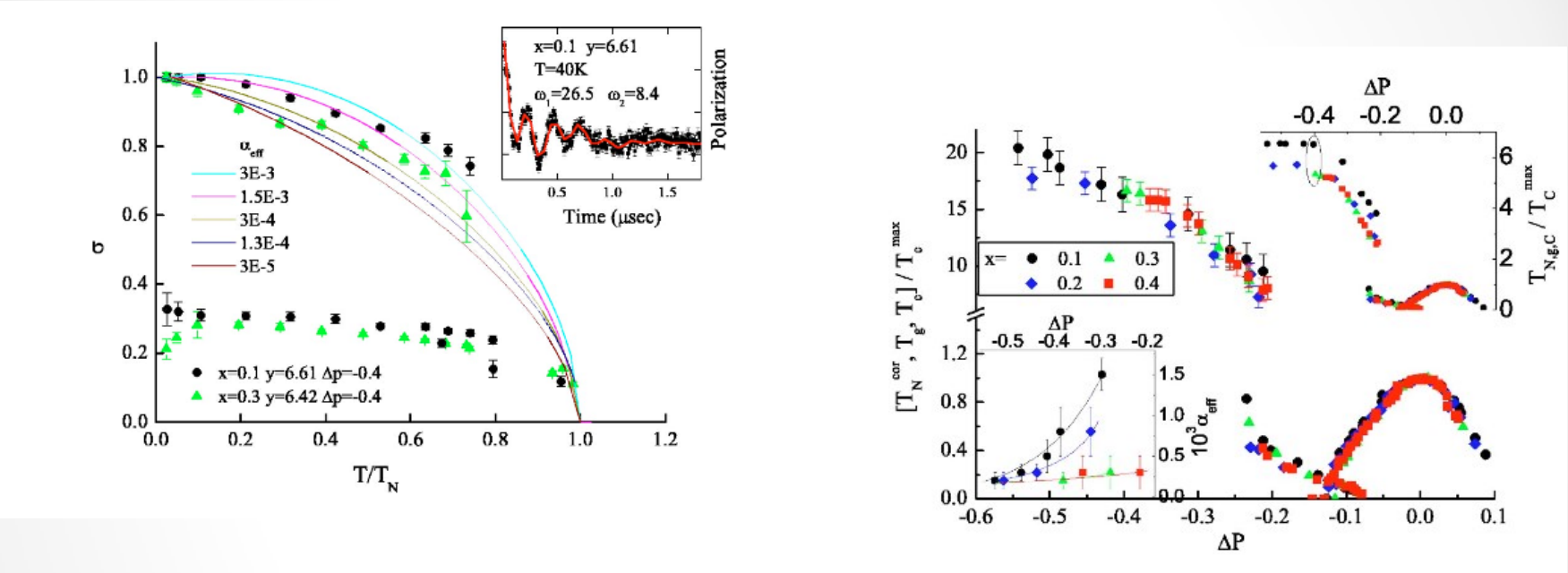




- In the untangled diagram T_N and T_c^{max} are correlated, but not proportional.
- However, T_N is not an Hamiltonian parameter.
- J We had to be extract from T_N.

Early determination of J

muSR frequency ∝ magnetic moment



•The magnetization of CLBCO in the AF phase was measured via muSR.

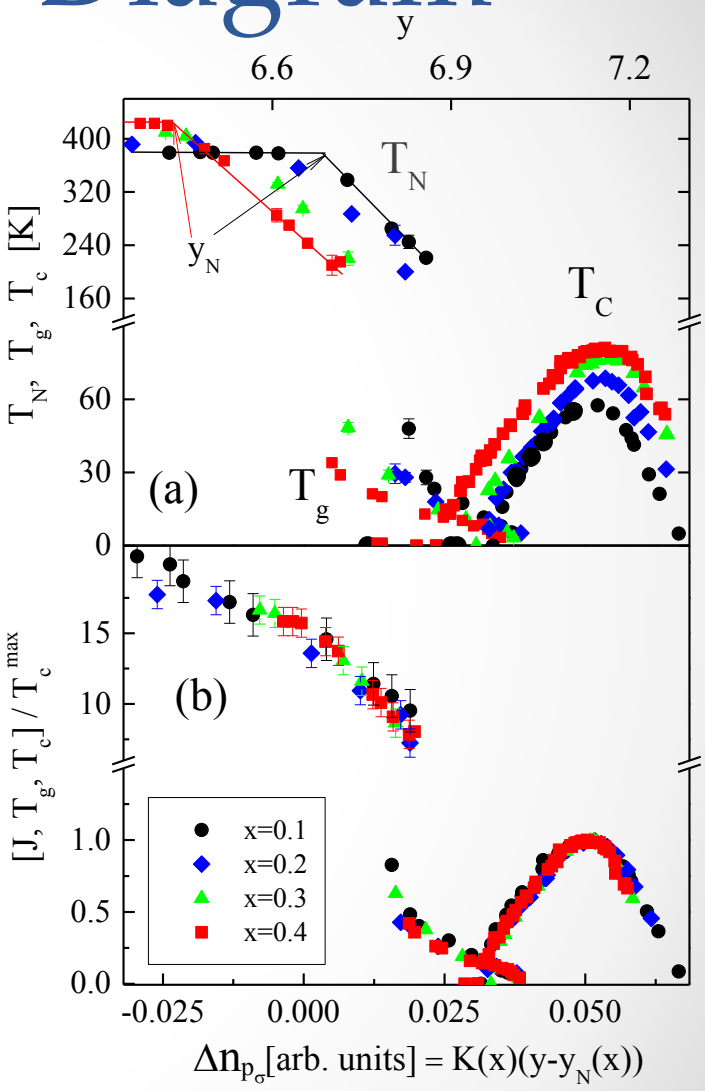
•The in-plane J was extracted using a fit to a mean field theory taking anisotropy into account.

$$T_N^{cor} = T_N / t_N\left(\alpha_{eff}\right) = J$$

•**Now the phase diagram is untangled and proportional**

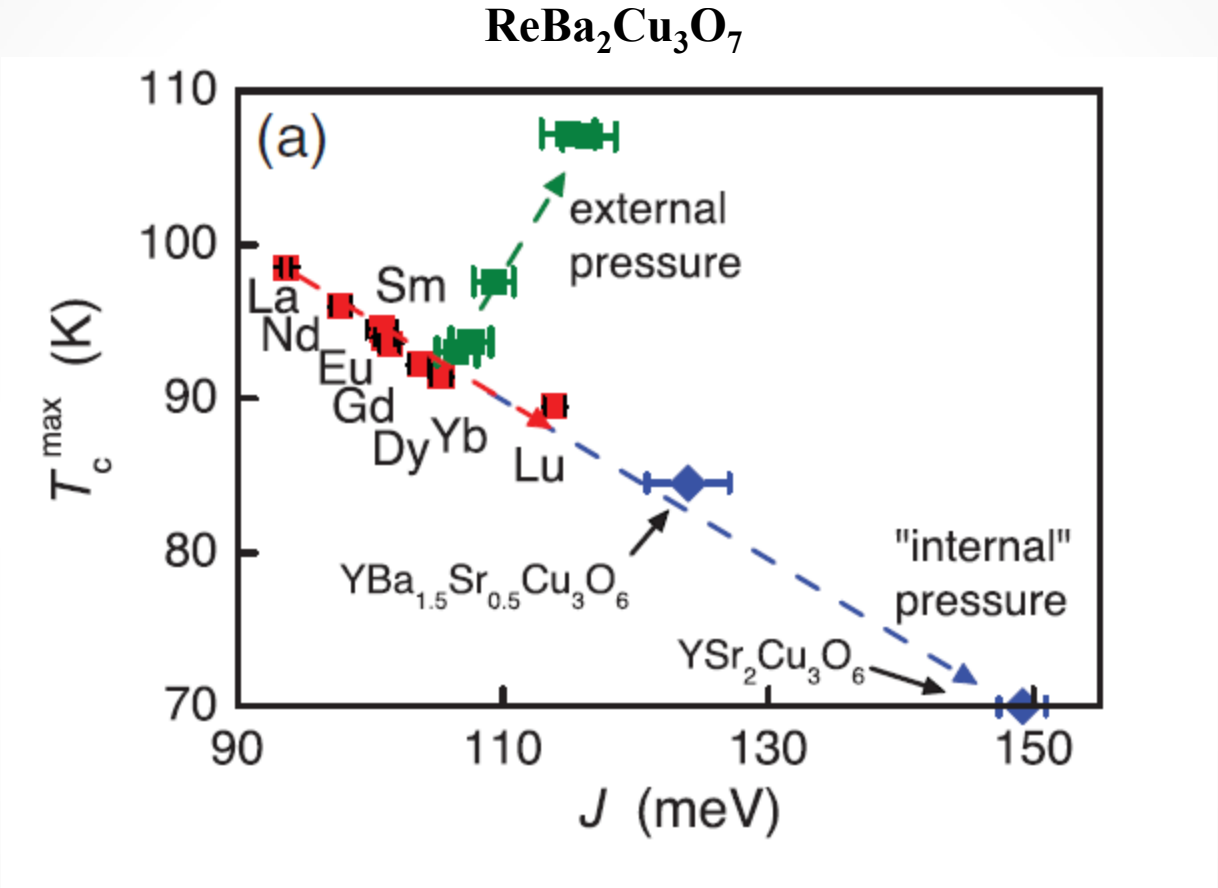
The Unified Phase Diagram

- Drawbacks:
  - **Powder Measurements. Let's grow a crystal.**
  - **Does the scenario hold for optimal doping? Probe *t* with ARPES.**
  - ***J* is extracted from T_N using theoretical calculations and not measured directly. Measure with Raman scattering.**
  - **Maybe we are wrong all together?**



$$T_c^{max} \propto J$$

Is J and Tc corrlated in all cuprates?



- Mallet…Tallon *et al.* PRL **111**, 237001 (2013) presented the "central paradox" of the cuprates.
- Internal vs external pressure.
-

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From powder to crystal

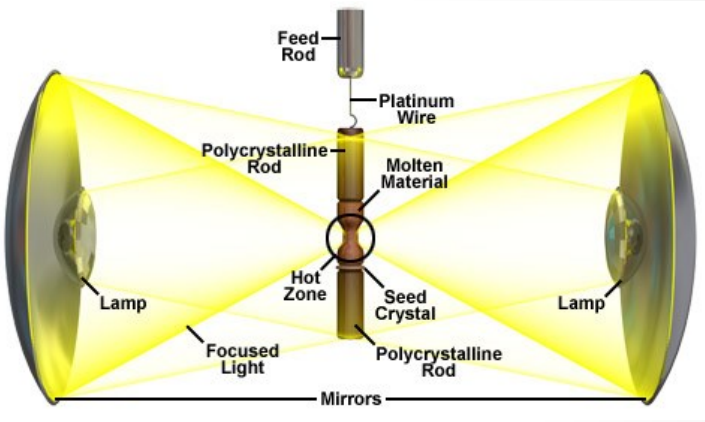
- The phase diagram, and all the data we had from CLBLCO was measured on powder samples.

- All major techniques in condensed matter require high quality single crystals (Neutron Scattering, ARPES, Raman, etc.)

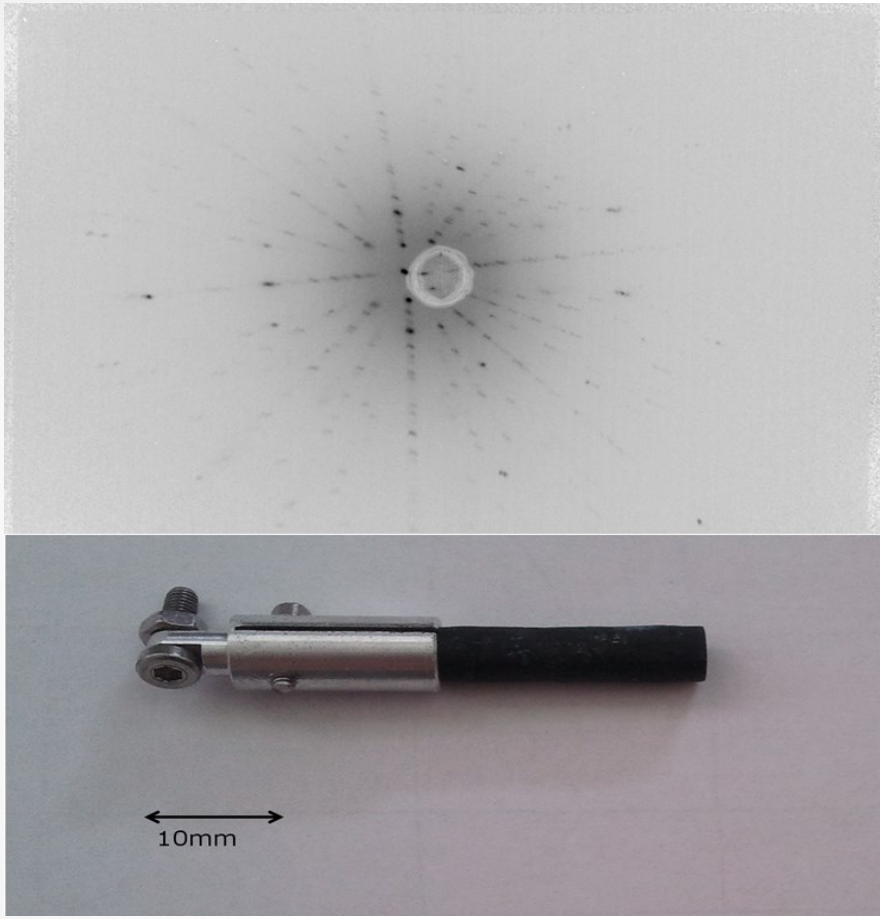
It took a great effort to grow them,
and now we are the only group in the world with crystals of CLBLCO.

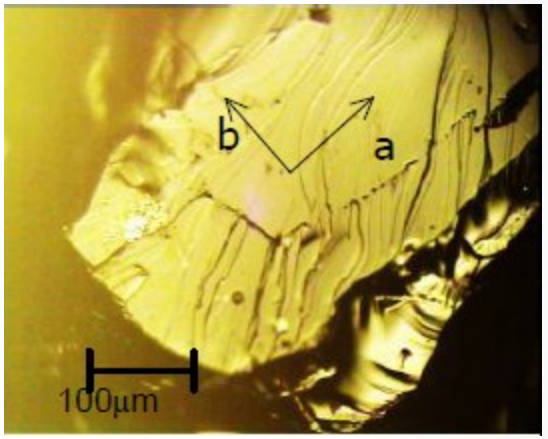
The Crystal growth technique we use

Traveling Solvent Floating Zone Method (Crystal Systems Corp. Japan) image furnace. It is in operation in our laboratory since 2007.



The CLBLCO Crystal





The crystals can be oriented and cleaved.

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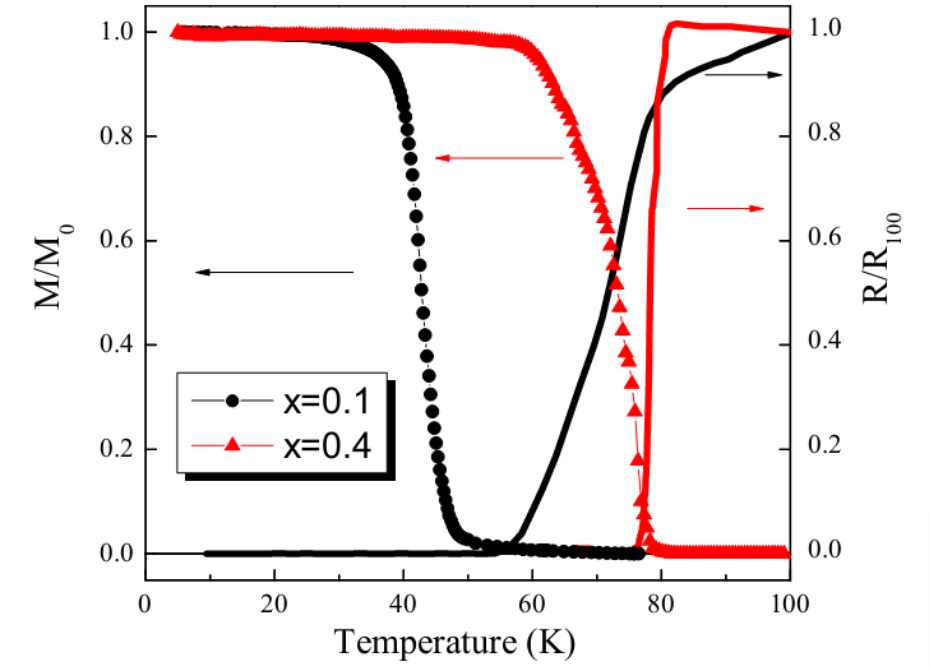
J Supercond Nov Magn (2012) 25:2331–2335

Bulk superconducting measurements

- Resistivity and susceptibility are in good agreement with the measurements done on powder samples.



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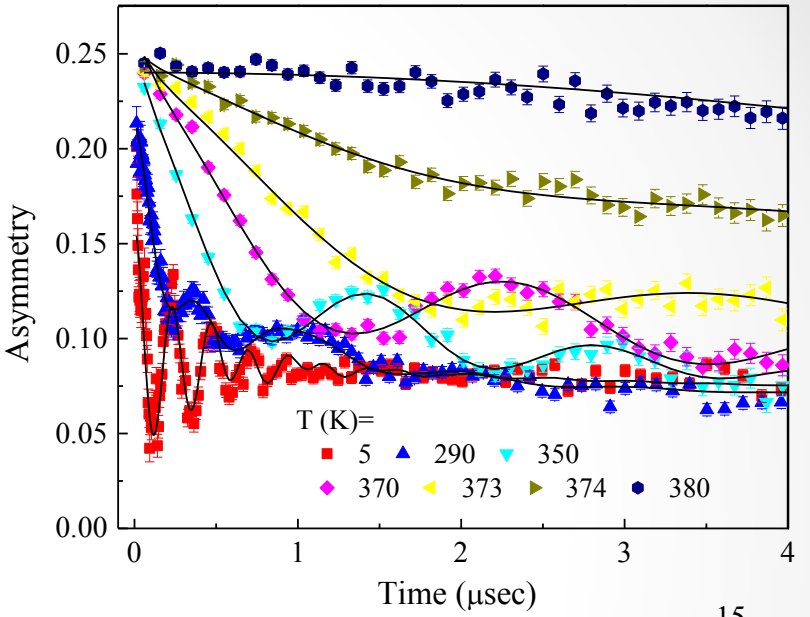
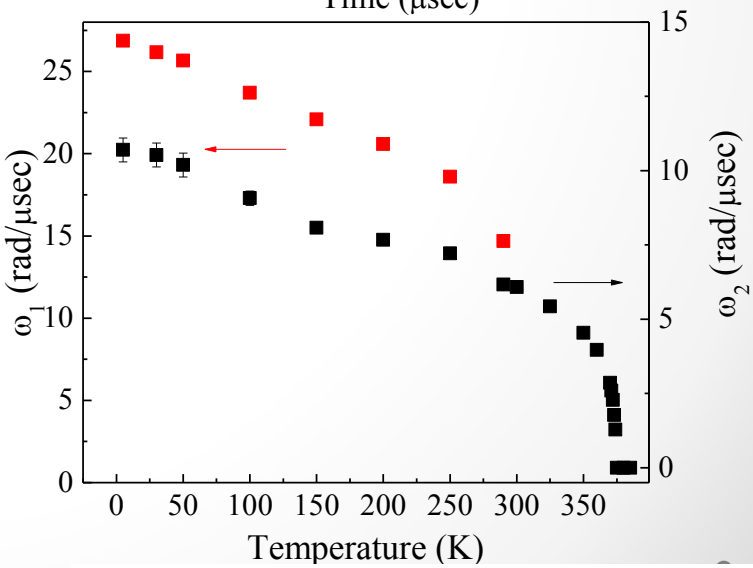
Bulk magnetic measurements

- CLBLCO x=0.1 annealed in Argon.
- μSR frequency corresponds to AF magnetic order parameter.
- Néel temperature is 375K which is the same as for powder.

The grown crystals and powders have the same physical properties (T_c,T_N).





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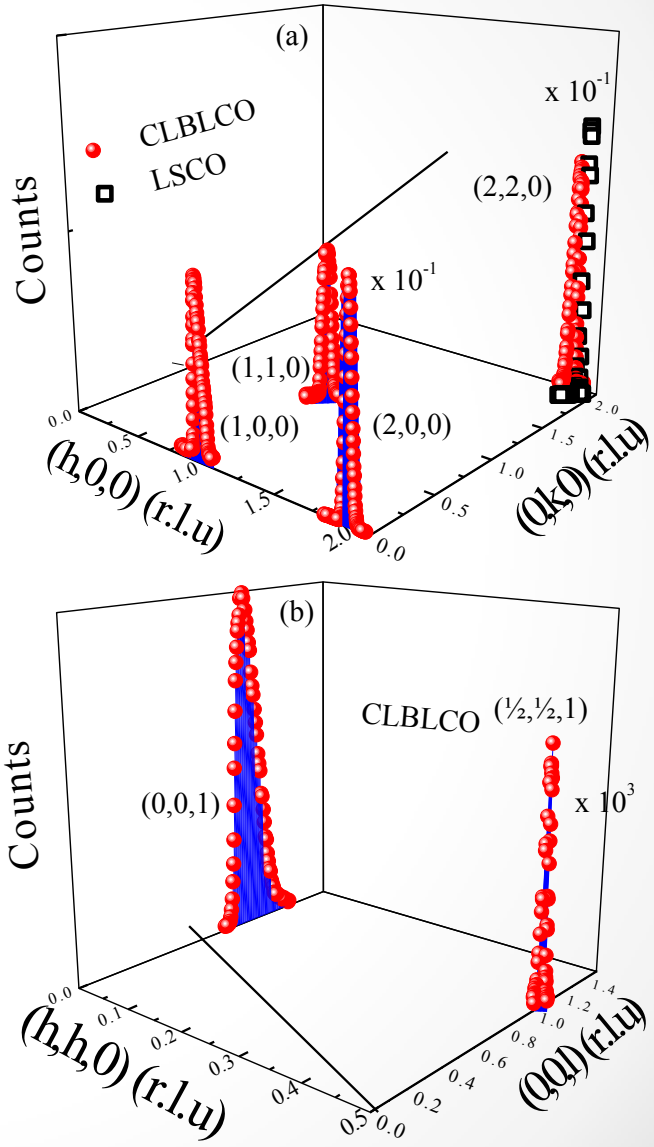
Elastic Neutron Scattering

- Elastic neutron scattering performed on a CLBLCO x=0.1 crystal.
- A variety of nuclear Bragg peaks were detected.
- The AF peak **(½, ½,1)** was detected.

Unfortunately efforts to measure J with magnetic inelastic neutron scattering were unsuccessful (for now at least..).



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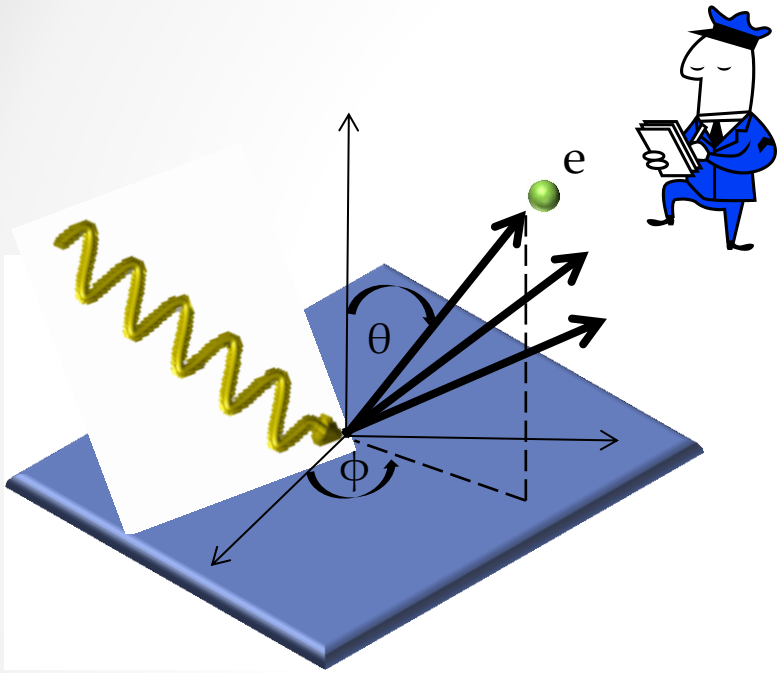
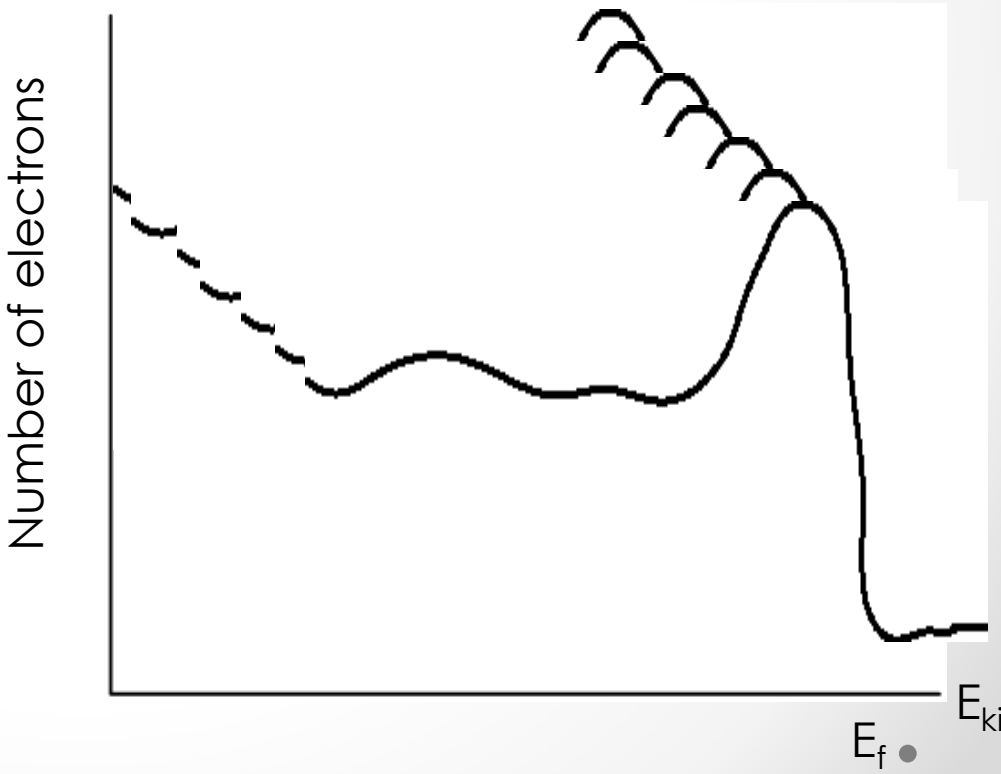
ARPES:
Angle Resolved Photo Emission Spectroscopy



Good for measuring: the Fermi surface
The band structure, The SC gap.

Energy Distribution Curve (EDC)

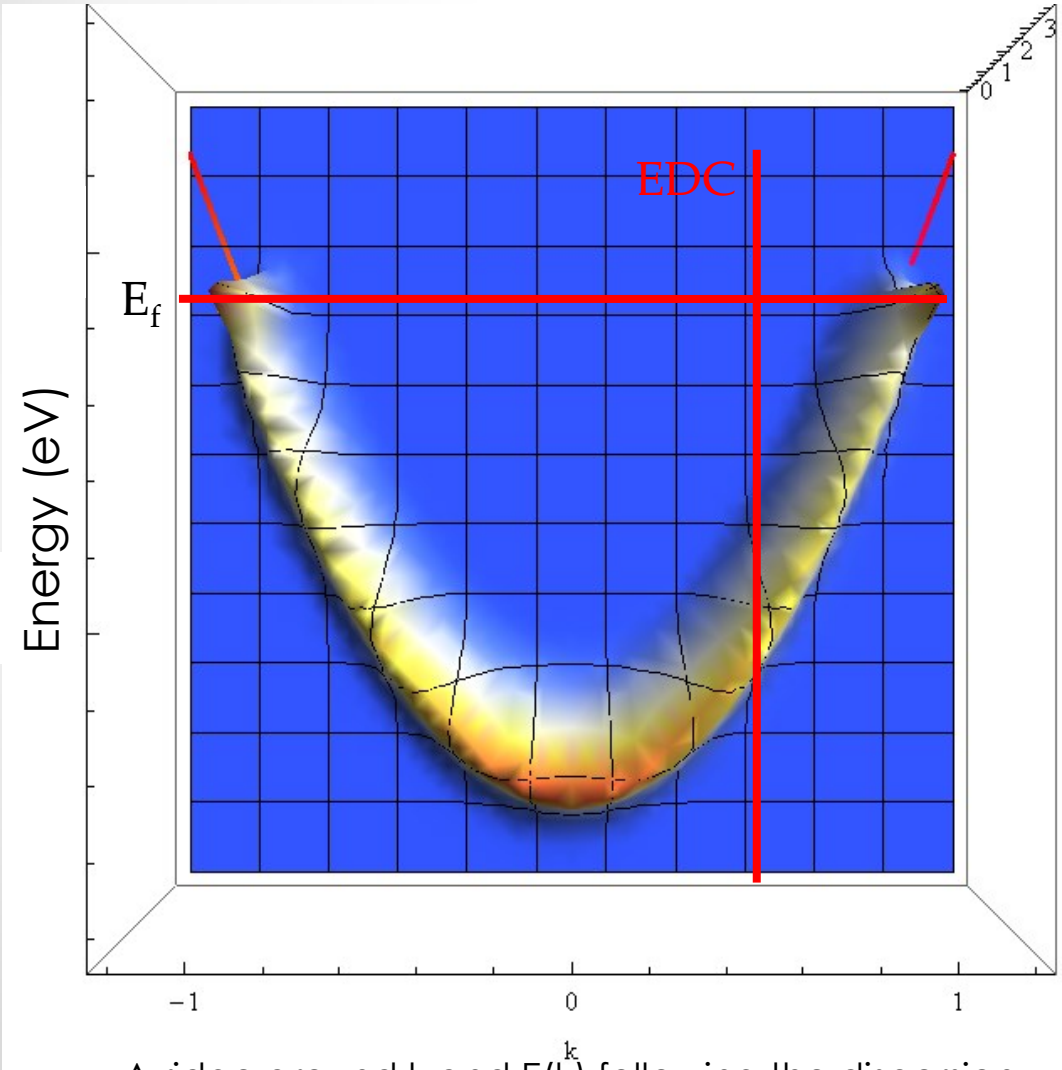


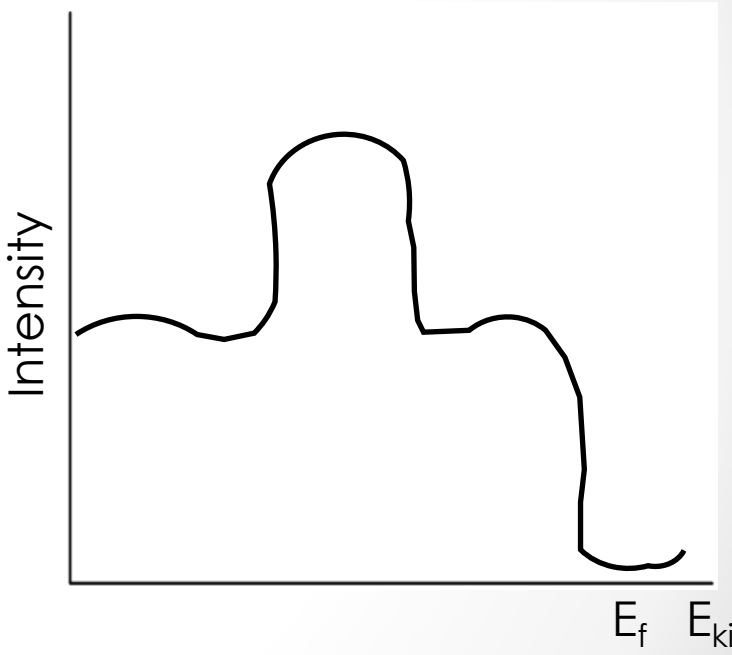
$$E_k = h\nu - \phi - |E_B(k)|$$

$$k^i_{||} = k^f_{||} = \frac{1}{\hbar}\sqrt{2mE_k}\sin\theta$$

Angle Resolved Photo Emission Spectroscopy

Typical data set



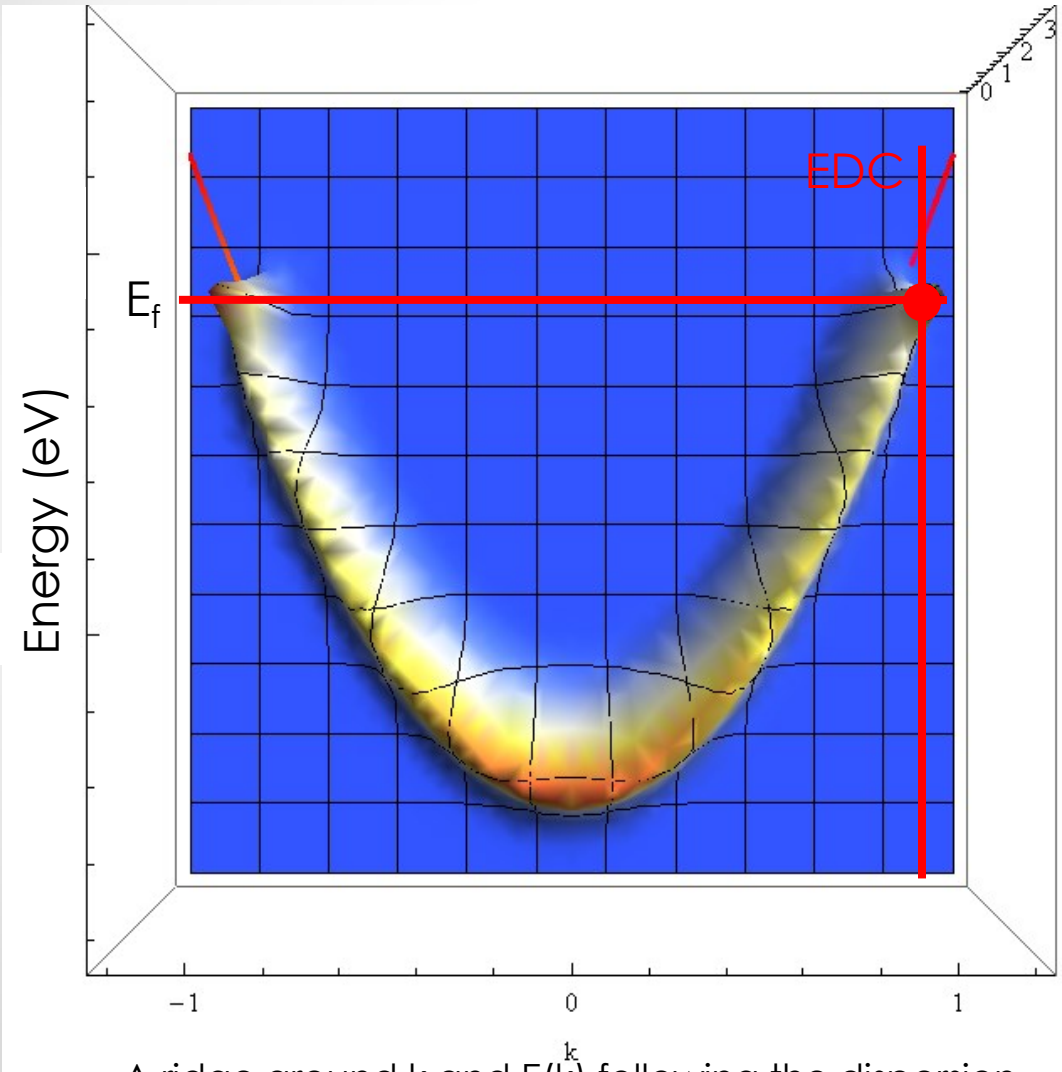


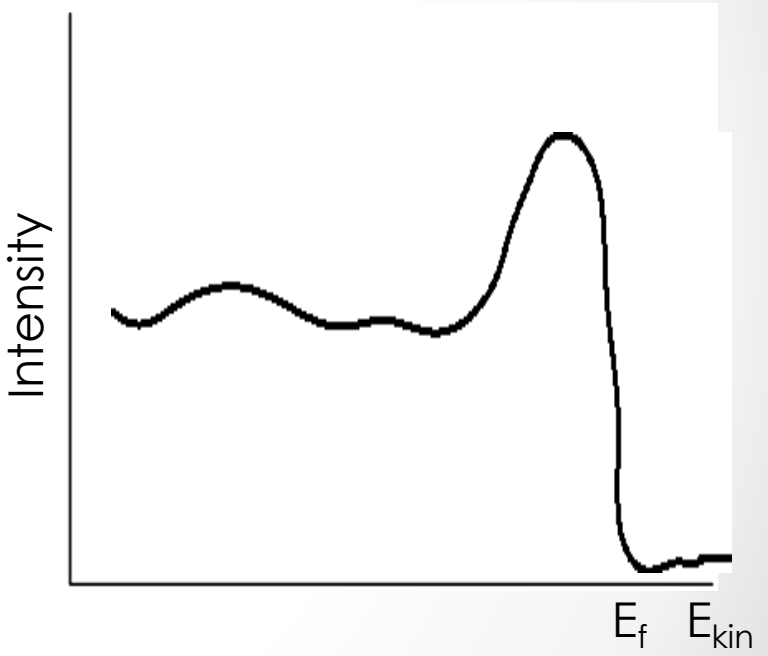
- A ridge around k and E(k) following the dispersion

EDC = Energy Distribution Curve
Constant k

Angle Resolved Photo Emission Spectroscopy

Typical data set

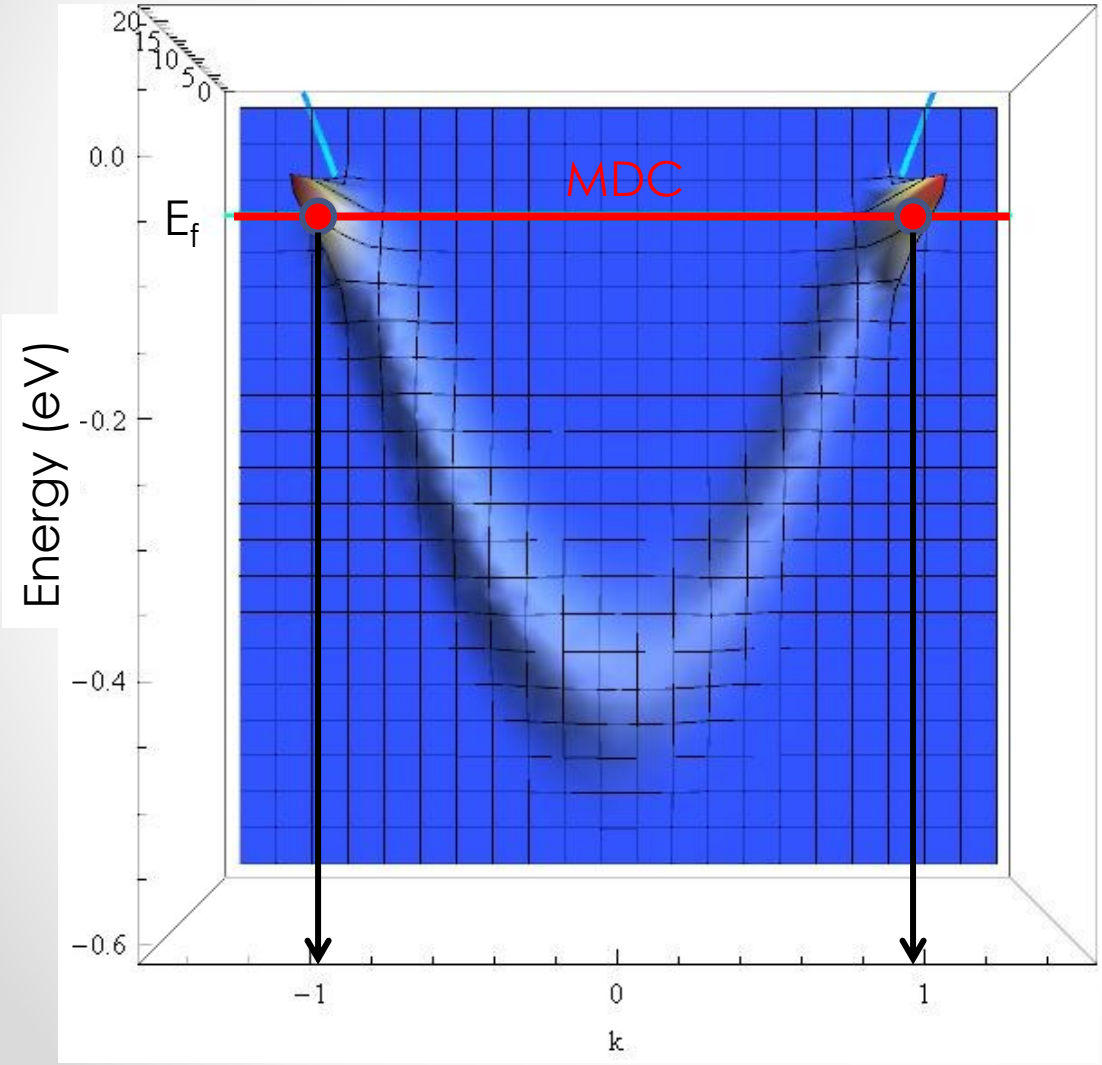




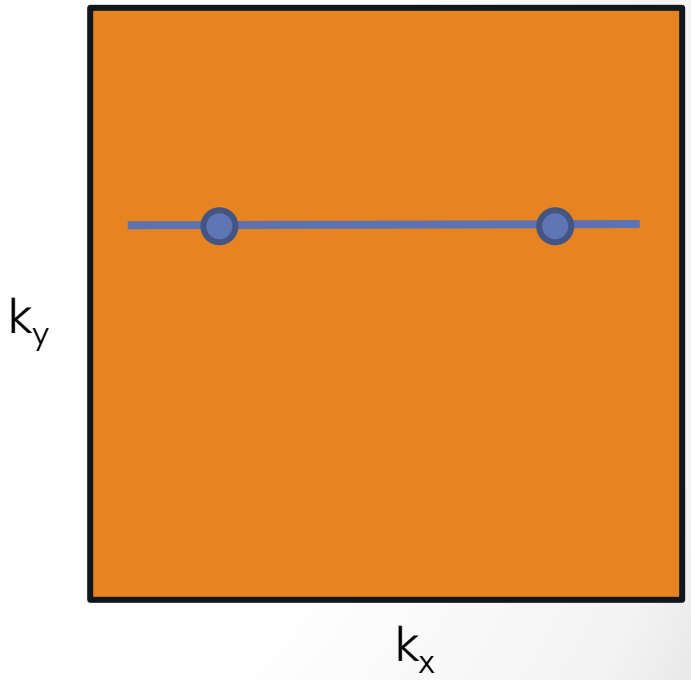
- A ridge around k and E(k) following the dispersion

EDC = Energy Distribution Curve
Constant k

Fermi Surface



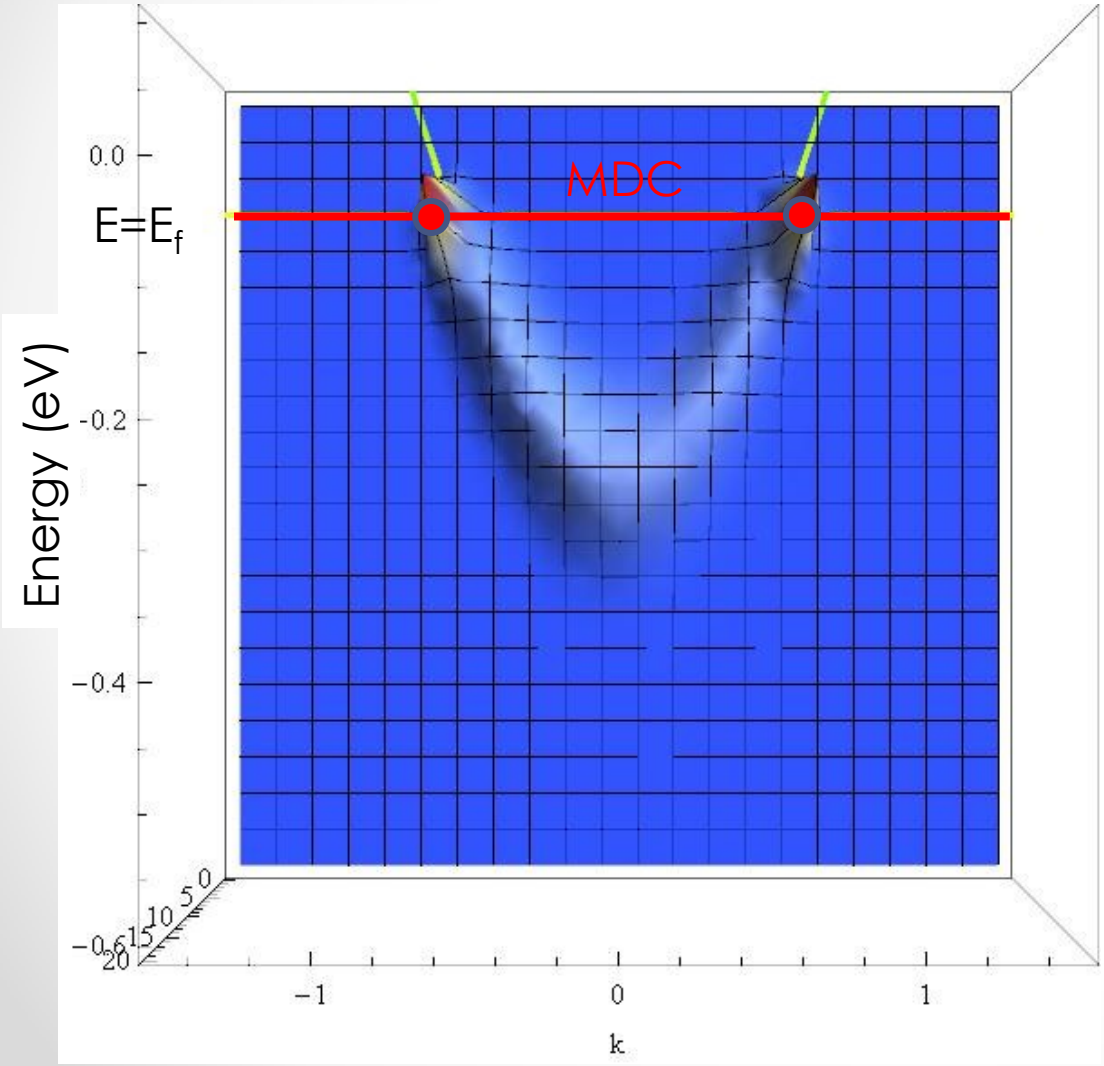
Fermi Surface



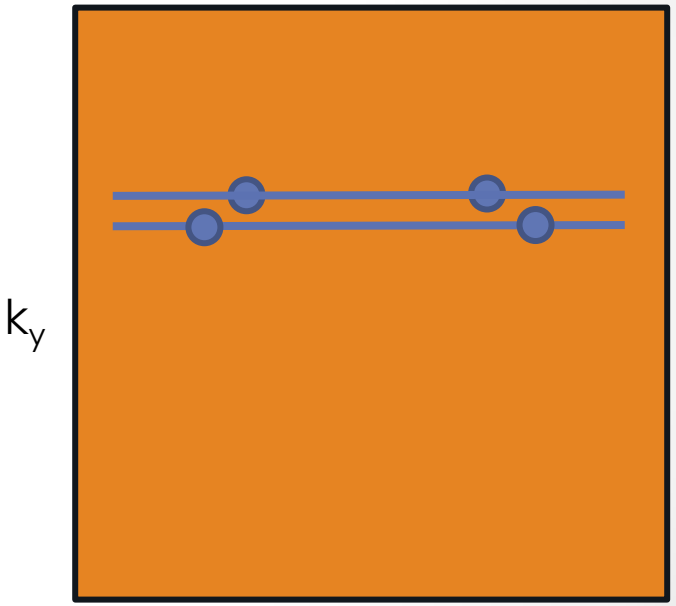
Intensity map at the Fermi Level

MDC = Momentum Distribution Curve
Constant E

Fermi Surface

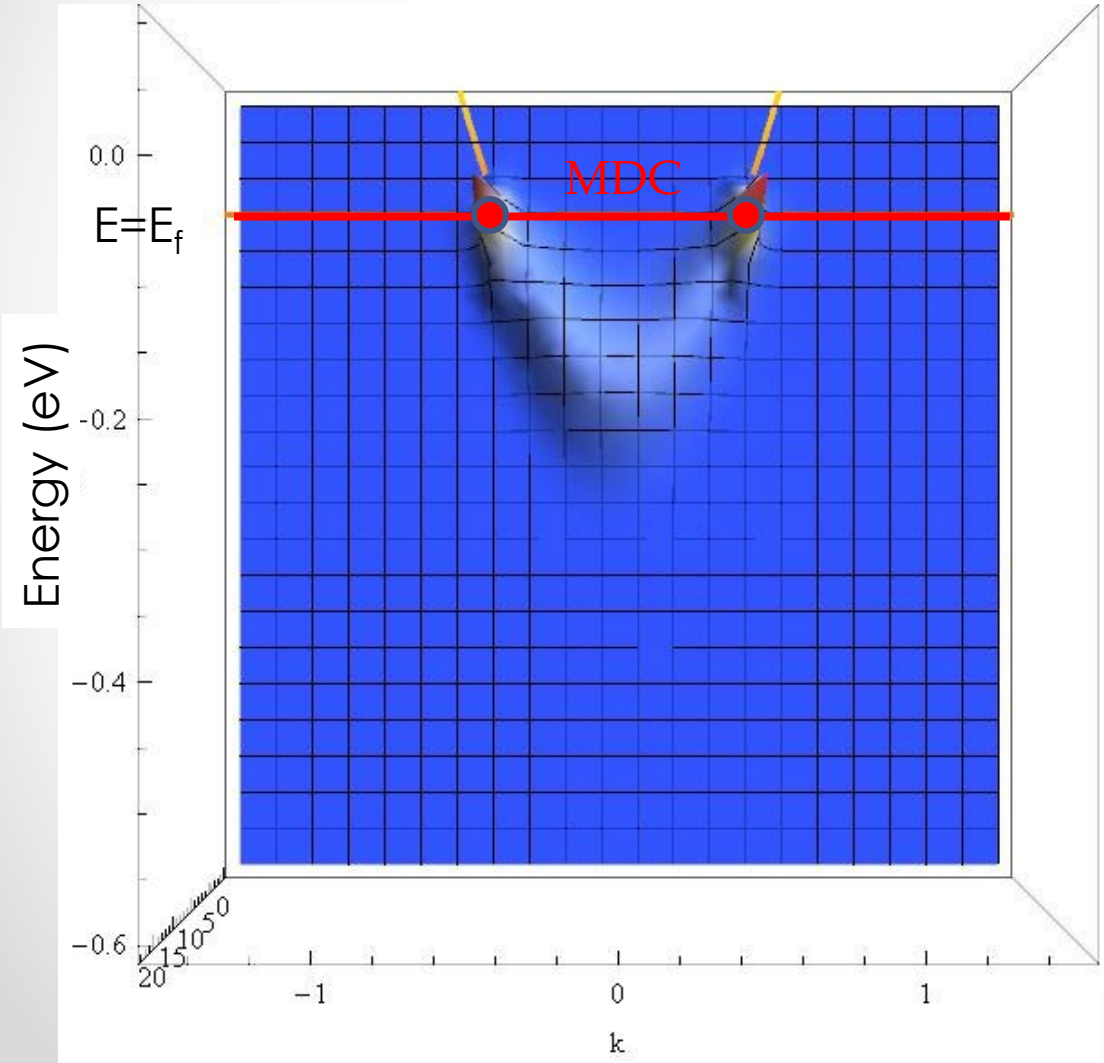


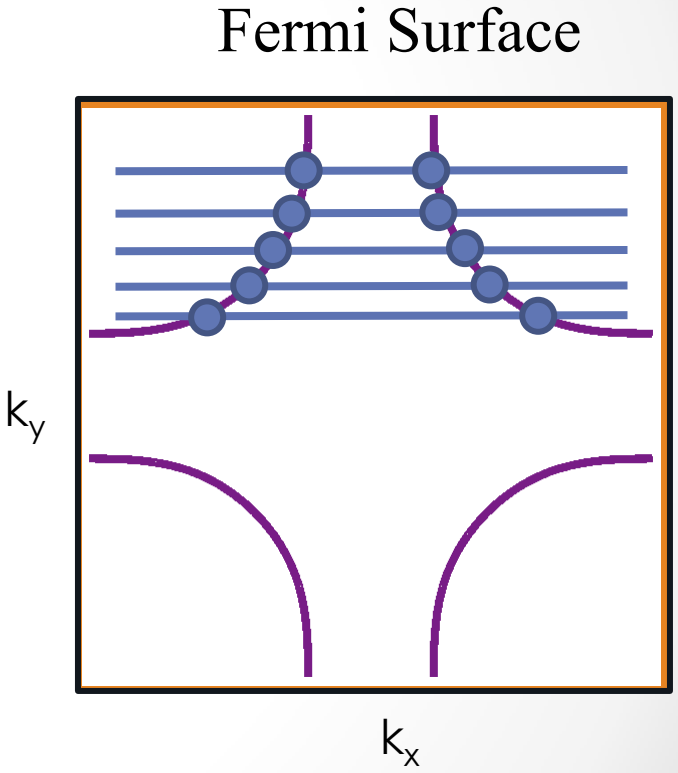
Fermi Surface



Intensity map at $E=E_f$

Fermi Surface

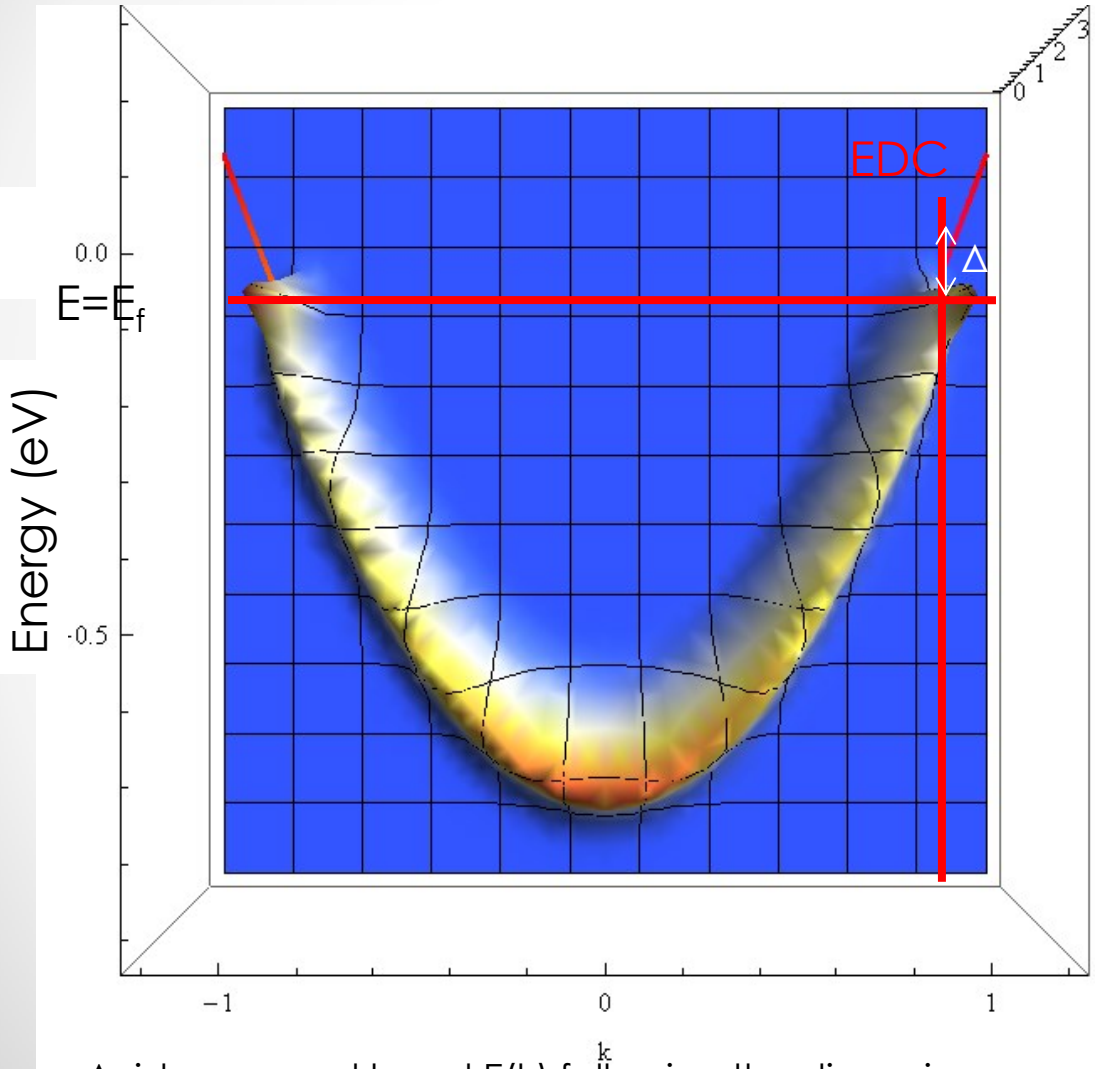


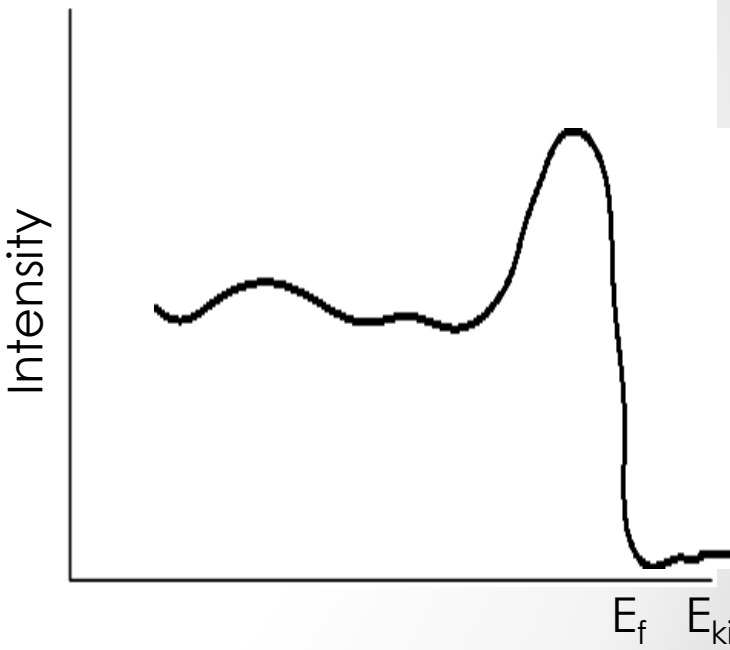


Intensity map at E=E$_f$

Measuring a gap

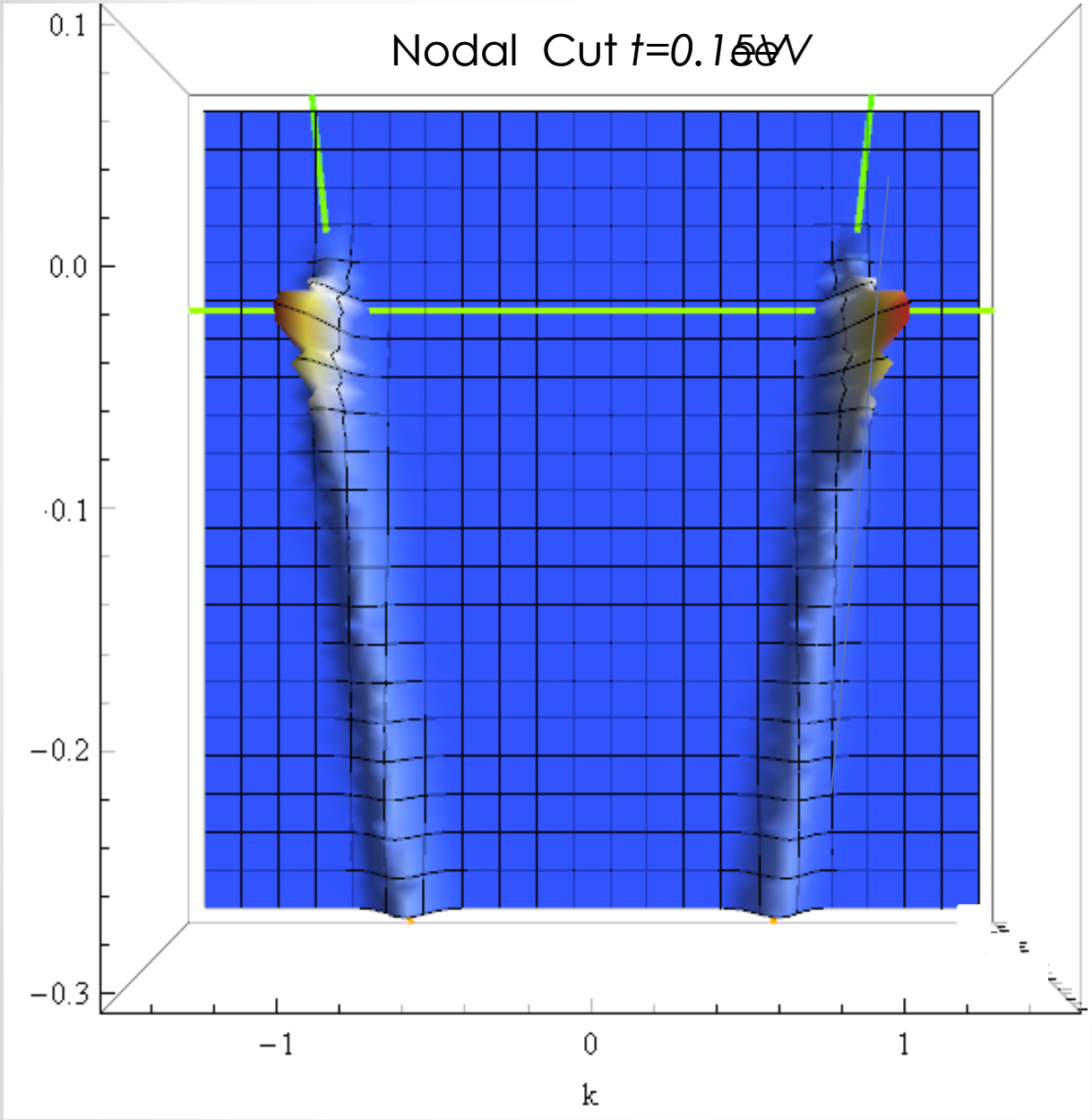
Typical data set





- A ridge around k and E(k) following the dispersion

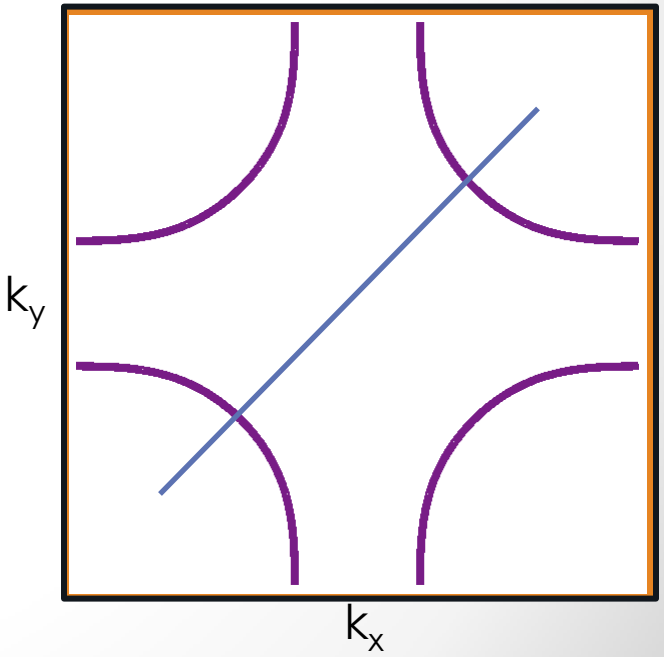
Nodal Fermi Velocity



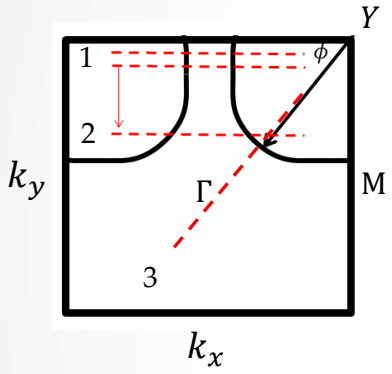
Fermi Velocity

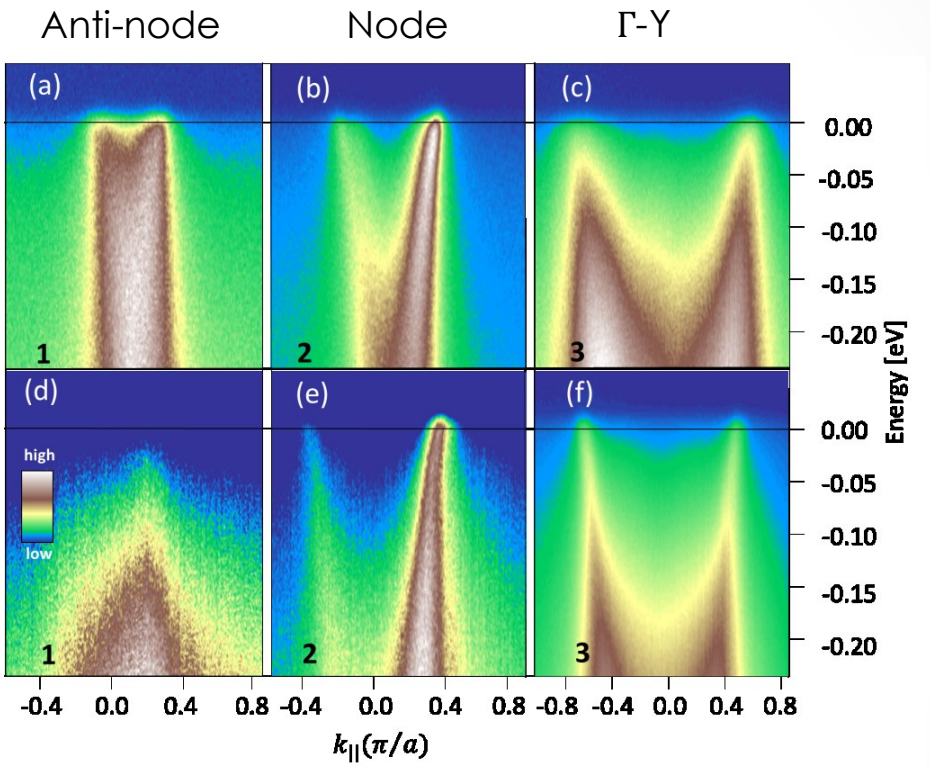
$$v_F = \frac{\partial E}{\partial k} \propto t$$

Fermi Surface



ARPES Raw data





CLBLCO $x = 0.1$

CLBLCO $x = 0.4$

- Data is presented from the anti-node to the node first.
- A gap is observed at *x=0.4*.
- We focus on the Γ-Y direction.

- **Gil Drachuck , *et al.***

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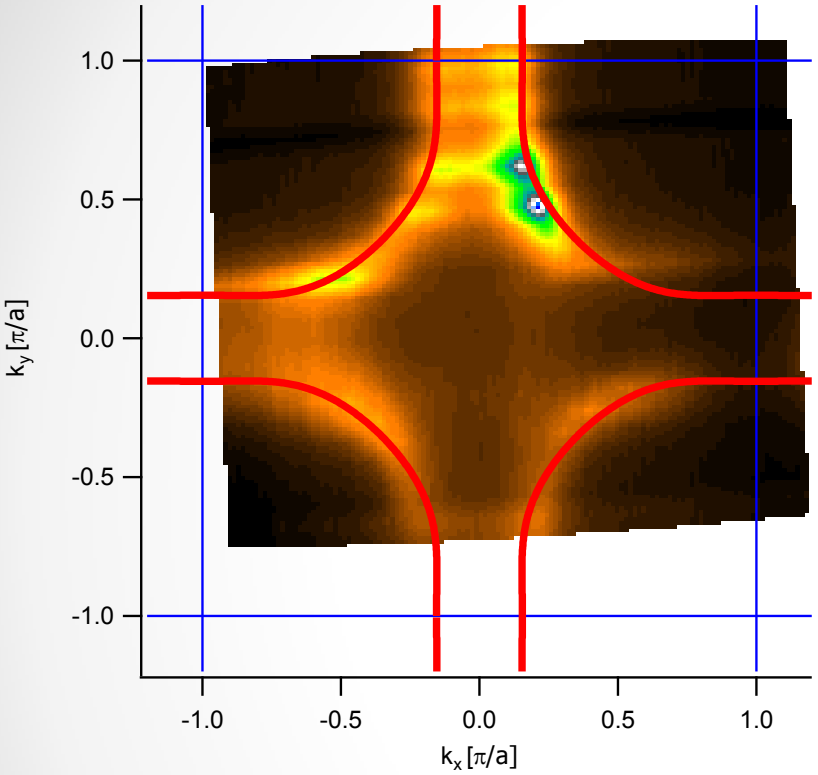
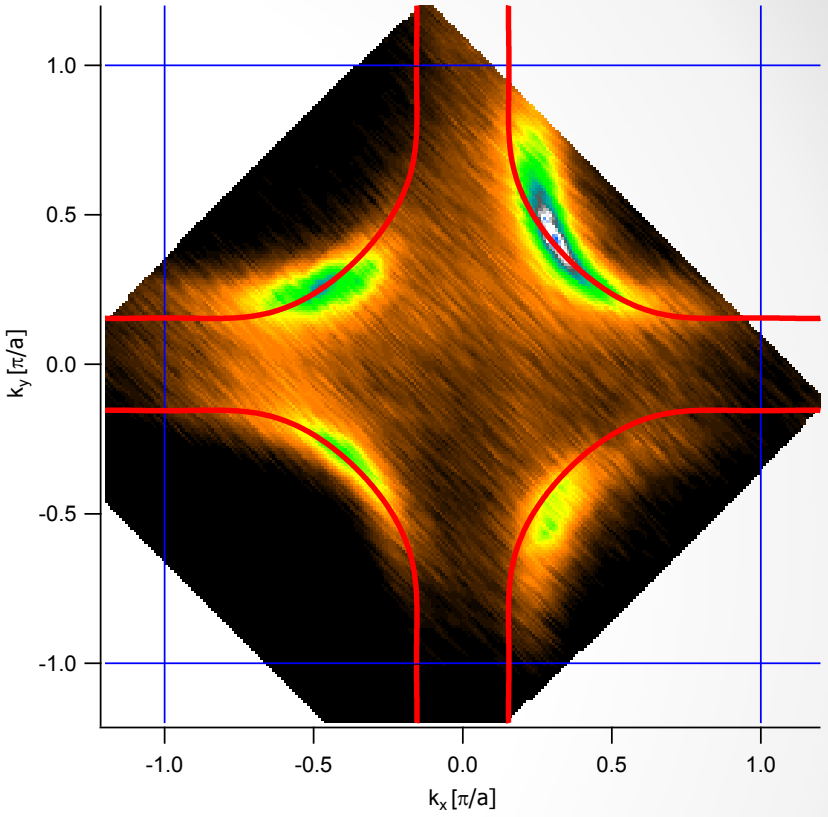
The Fermi Surface of CLBLCO



$x = 0.1$



$x = 0.4$

- The doping of the surface appears independent of the preparation doping of the bulk crystal, and is the same for both families.
- The surface is of CLBLCO **overdoped**.

- **Gil Drachuck , *et al.***

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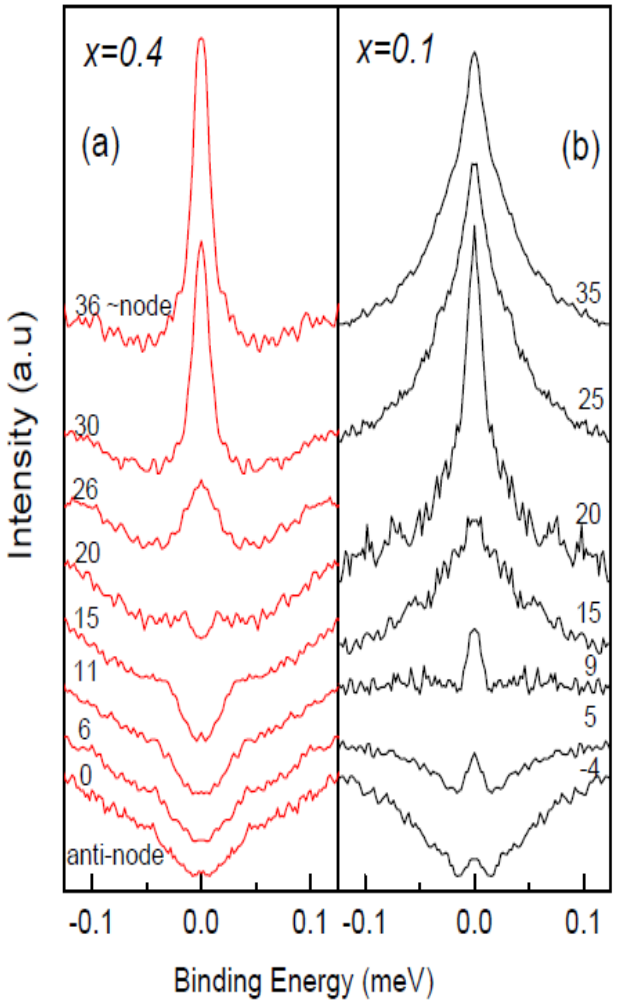
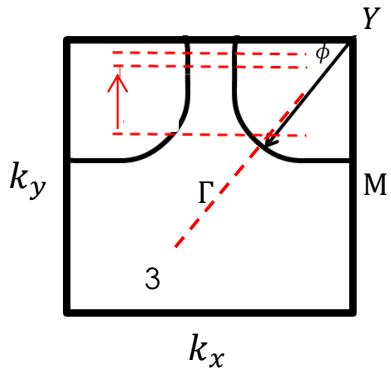
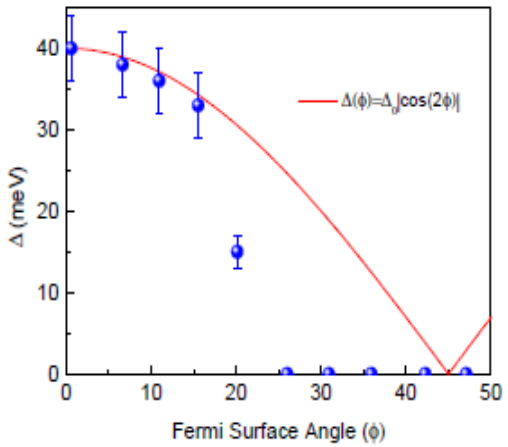
Gap in CLBLCO





CLBLCO $x = 0.4$



- At the same doping there is a gap **only for the x=0.4 family**.
- The gap has a resemblance to the psudogap, but the for sample on the overdoped side.
- Work in progress…

- **Gil Drachuck , *et al.***

PHYSICAL REVIEW B **89**, 121119(R) (2014)

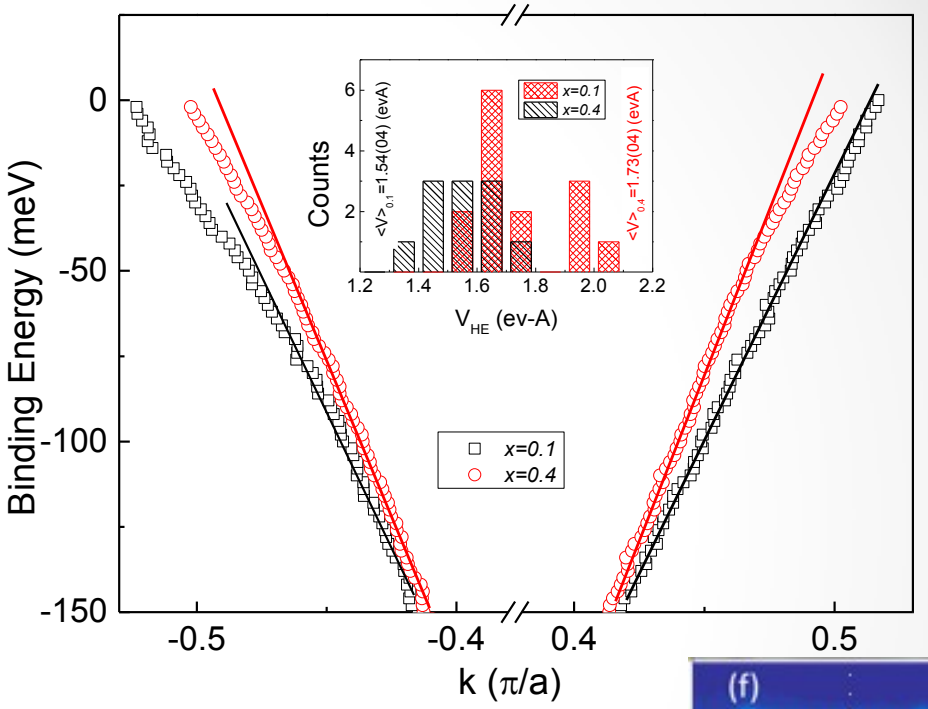
Nodal velocity

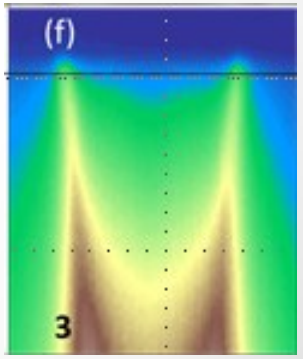
- The Fermi velocity is higher for x=*0.4*.
- After averaging over samples we found:

$$\frac{\langle V \rangle_{0.4}}{\langle V \rangle_{0.1}} = \frac{1.73\ eVA}{1.54\ eVA}$$

- Since $J \propto t^2 \propto V_F^2$ the ratio of velocities agrees with the ratio of *J*'s (25% difference)

.





Conclusions from the **underdoped** side survives to the **overdoped** side.

- **Gil Drachuck , *et al.***

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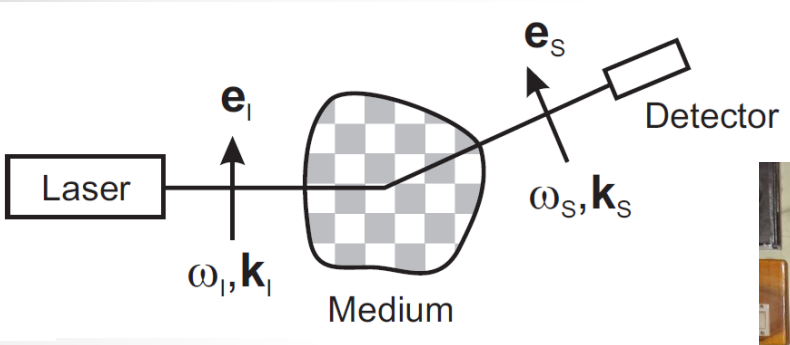
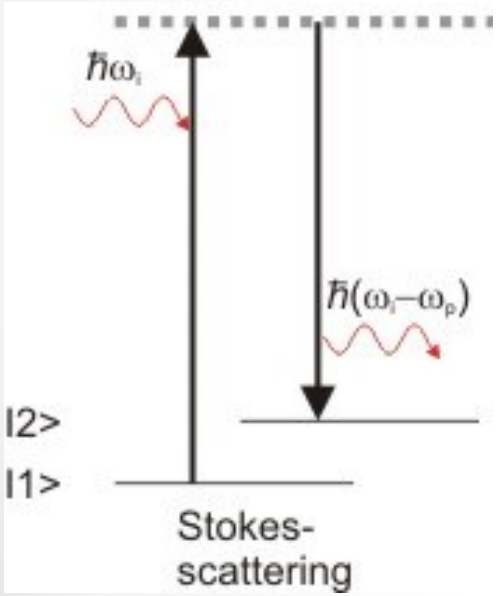
Outline

- Why $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$?
- The role of disorder in CLBLCO?
- The relationship between J and T_c^{max} in cuprates.
- Crystal Growth of CLBLCO
- ARPES in CLBLCO
- **Raman Scattering in CLBLCO in CLBLCO**
- Summary

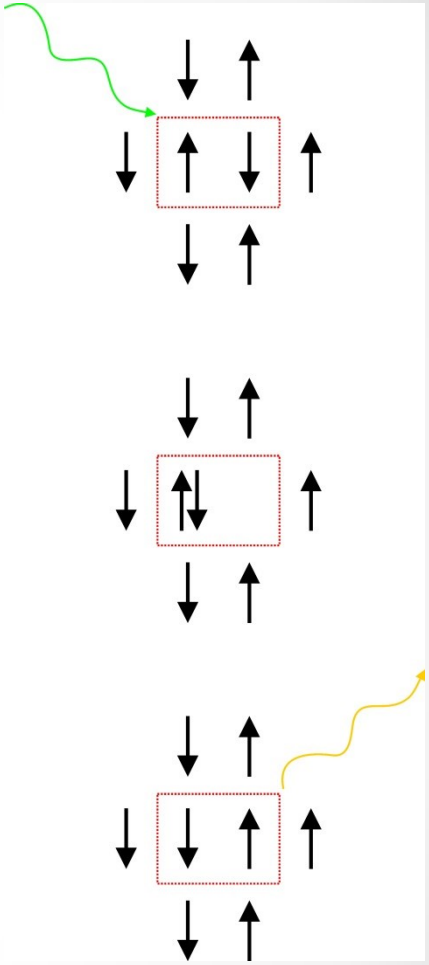
Two magnon Raman scattering





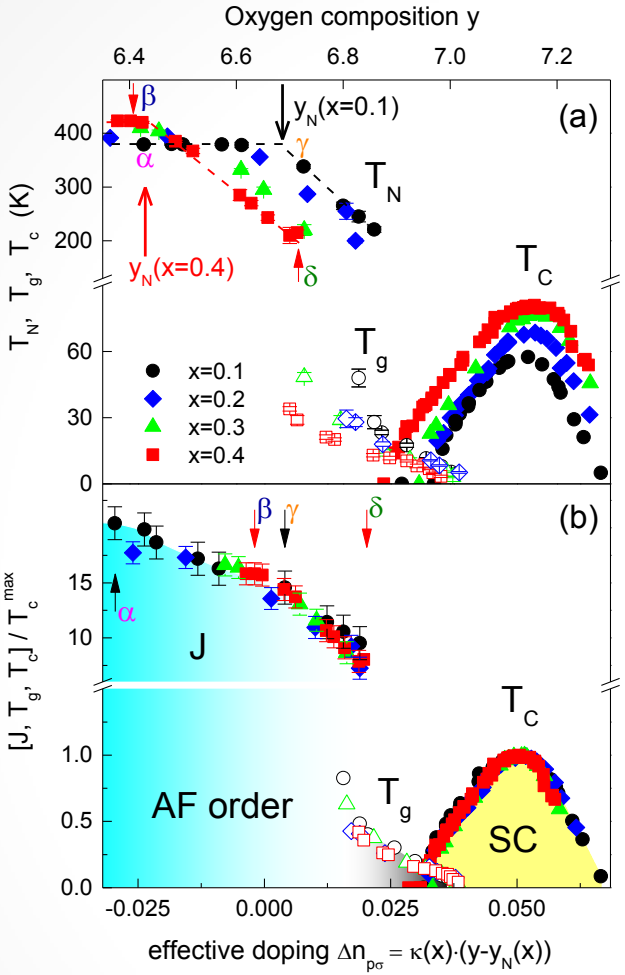
K. Y. Choi, Elsevier (2005)

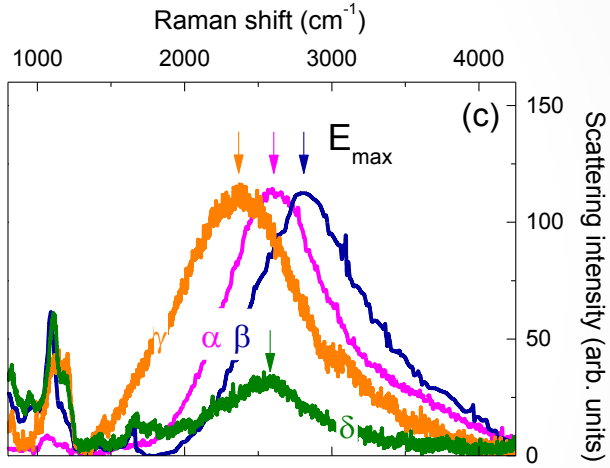
$\omega_s = \omega_i - \Omega$



$E_{mag} = 3J$

Raw Data





- The 2M-Raman peak is sensitive to doping and family.
- At the same doping it is more energetic for *x=0.4* than for *x=0.1*.

- Dirk Wulferding , *et al.*

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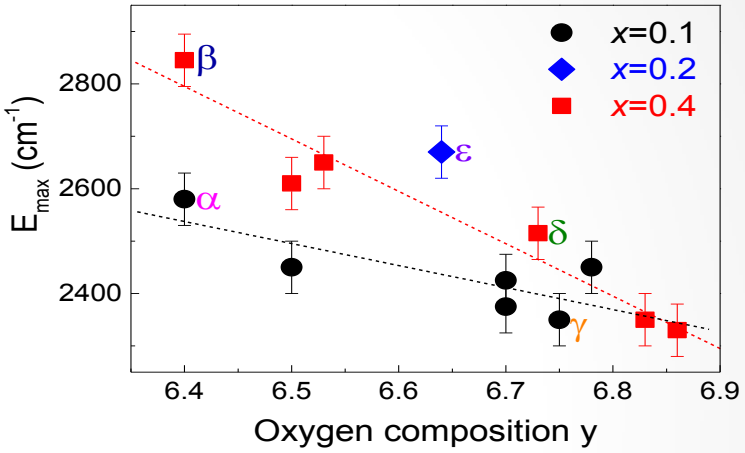
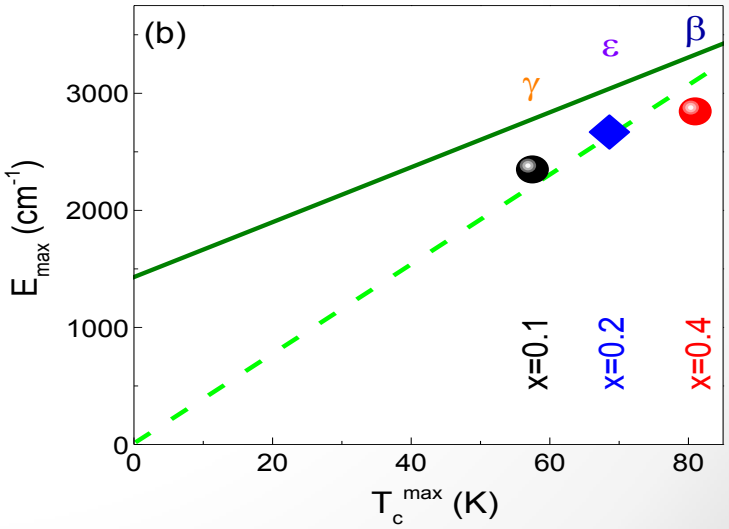
Doping and Family dependence

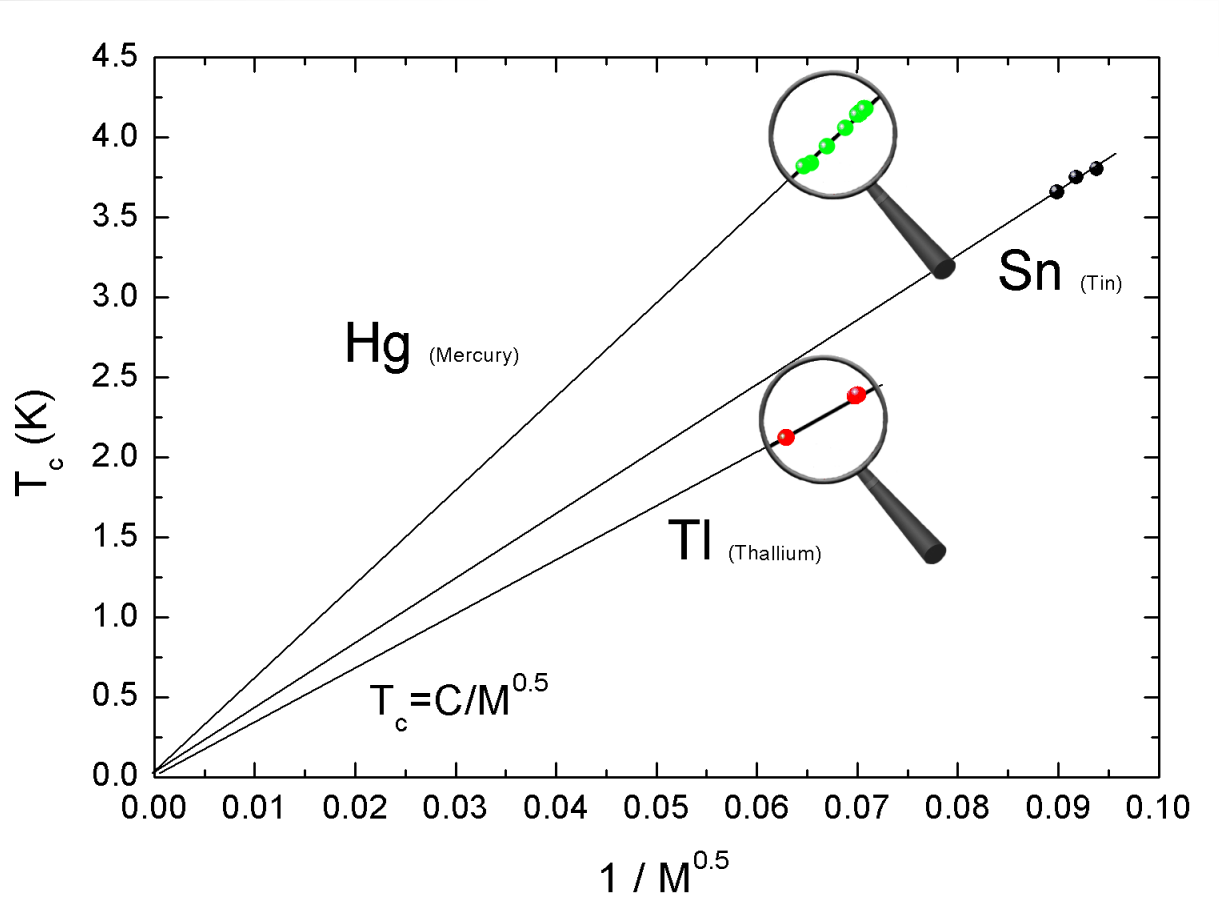
- It is essential to compare the 2M-Raman peak at equal doping.
- **In this case, $E_{max} = 3J$, is proportional to T_c^{max}.**





- Dirk Wulferding *et al.*

The Isotope Effect in BCS



C. A. Reynolds et. al., Phys. Rev. 84, 691 (1950).

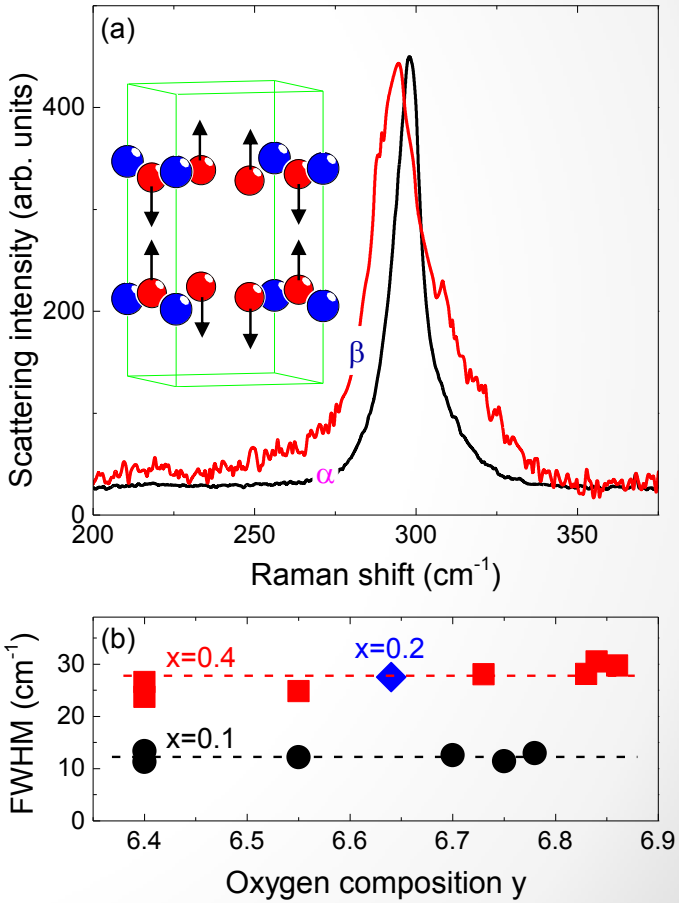
B. Serin et al., Phys. Rev. 86, 162 (1952).

E. Maxwell et al., Phys. Rev. 95, 333 (1954).

- Maximum 4% variation of T_C in Sn.
- The (0,0) point is important.

Addressing the disorder with Raman

- The width of a phonon peak in Raman is a good measure for disorder in the sample
- The most pronounced phonon is narrower for x=0.1 (**family with lowest Tc**).
- This is true for all doping, and is sample independent.



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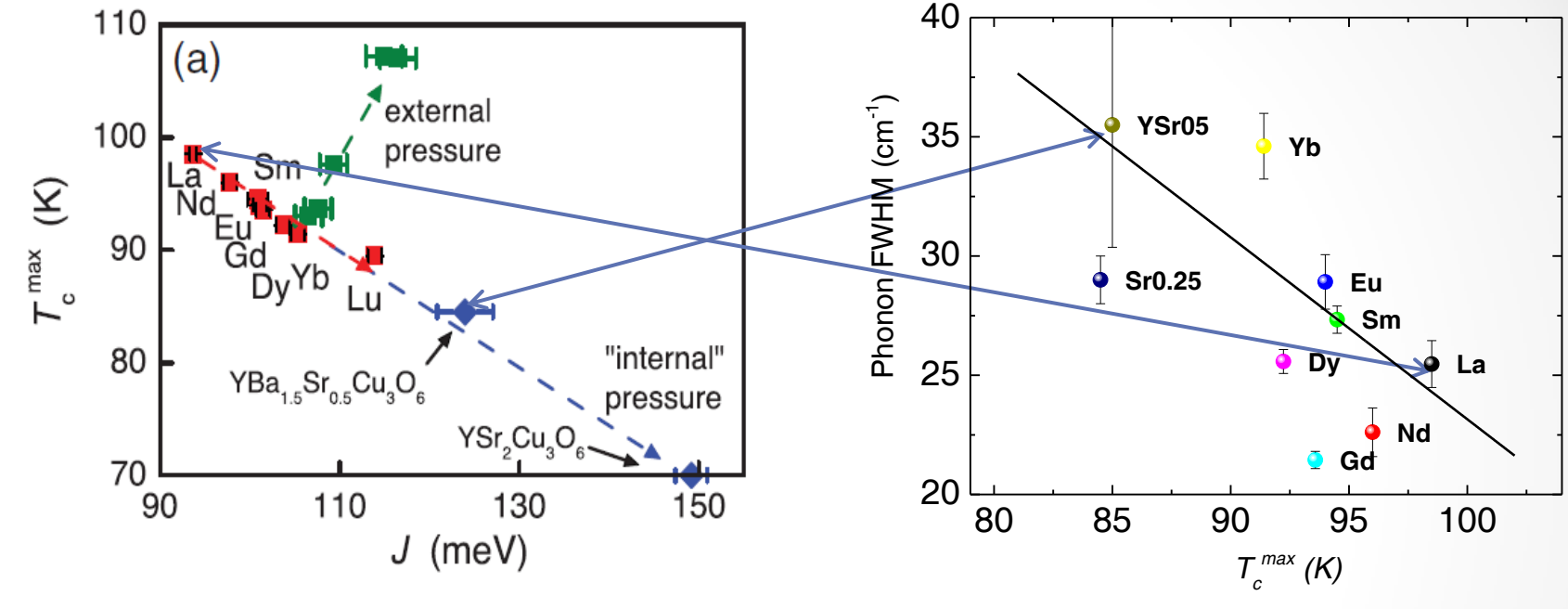
Problems with The ReBa2Cu307 study



- The FWHM of magnon Raman peak increases with decreasing T_c.
- **One cannot separate effect of disorder from coupling.**

Outline

- Why $(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$?
- The role of disorder in CLBLCO?
- The relationship between J and T_c^{max} in cuprates.
- Crystal Growth of CLBLCO
- ARPES in CLBLCO
- Raman Scattering in CLBLCO in CLBLCO
- **Summary**

Summary

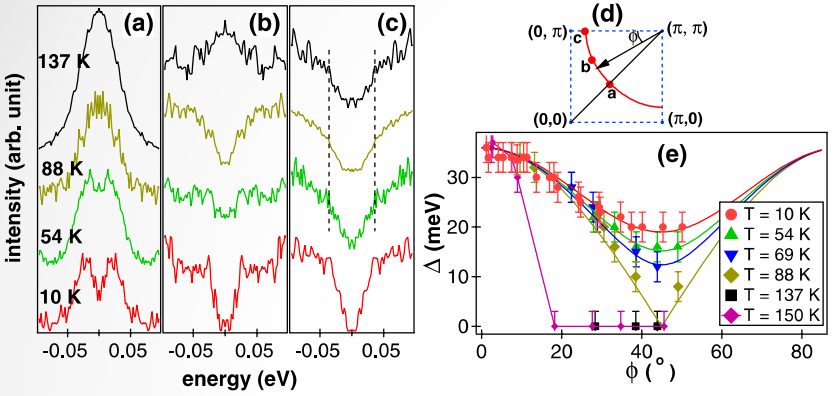
- We were able to grow large crystals of CLBLCO.
- The grown crystals have the same physical properties as the previously measured powders.
- We measured the Fermi Surface of CLBLCO.
- We have shown that T_c^{max} is proportional to $\boldsymbol{V_f}$ and thereby to the hopping integral $\boldsymbol{t}$.
- We measured $\boldsymbol{J}$ with a direct probe and found it to be roughly proportional to T_c^{max} .
- The difference in T_c^{max} between CLBLCO is unrelated to disorder.
- We are happy to collaborate and provide samples.

THE END

Thank You

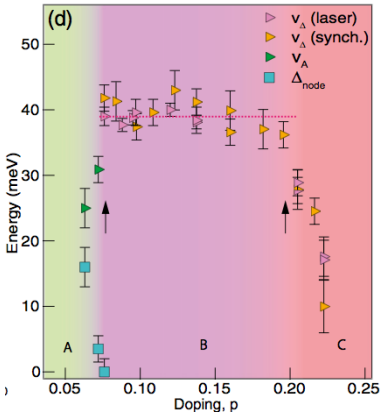
The motivation for this work

LSCO



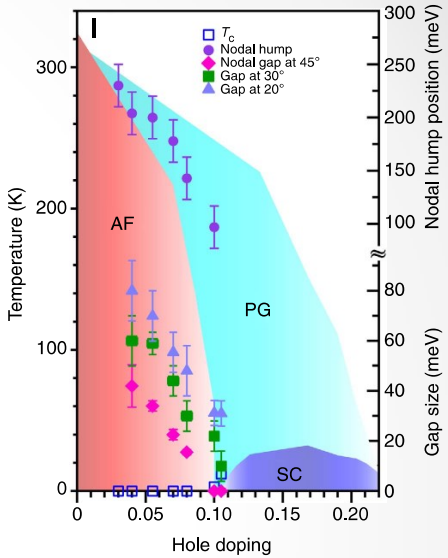
Razolli et al. 2013

Bi2212



Vishik et al. 2012

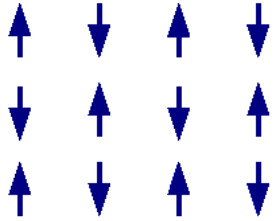
La-Bi2201

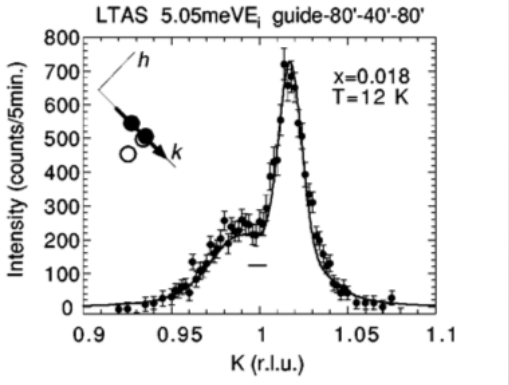


Y.Y Peng et al. 201

- Under-doped cupratse have a fully gapped Fermi surface, **d-wave + nodal gap**, in LSCO, Bi-2212 and La-Bi2201, even for non-superconducting samples.
- Under-doped cuprates are not simple antiferromagnets. A Spin Density Wave (SDW) develops on top of the AF order.

AF



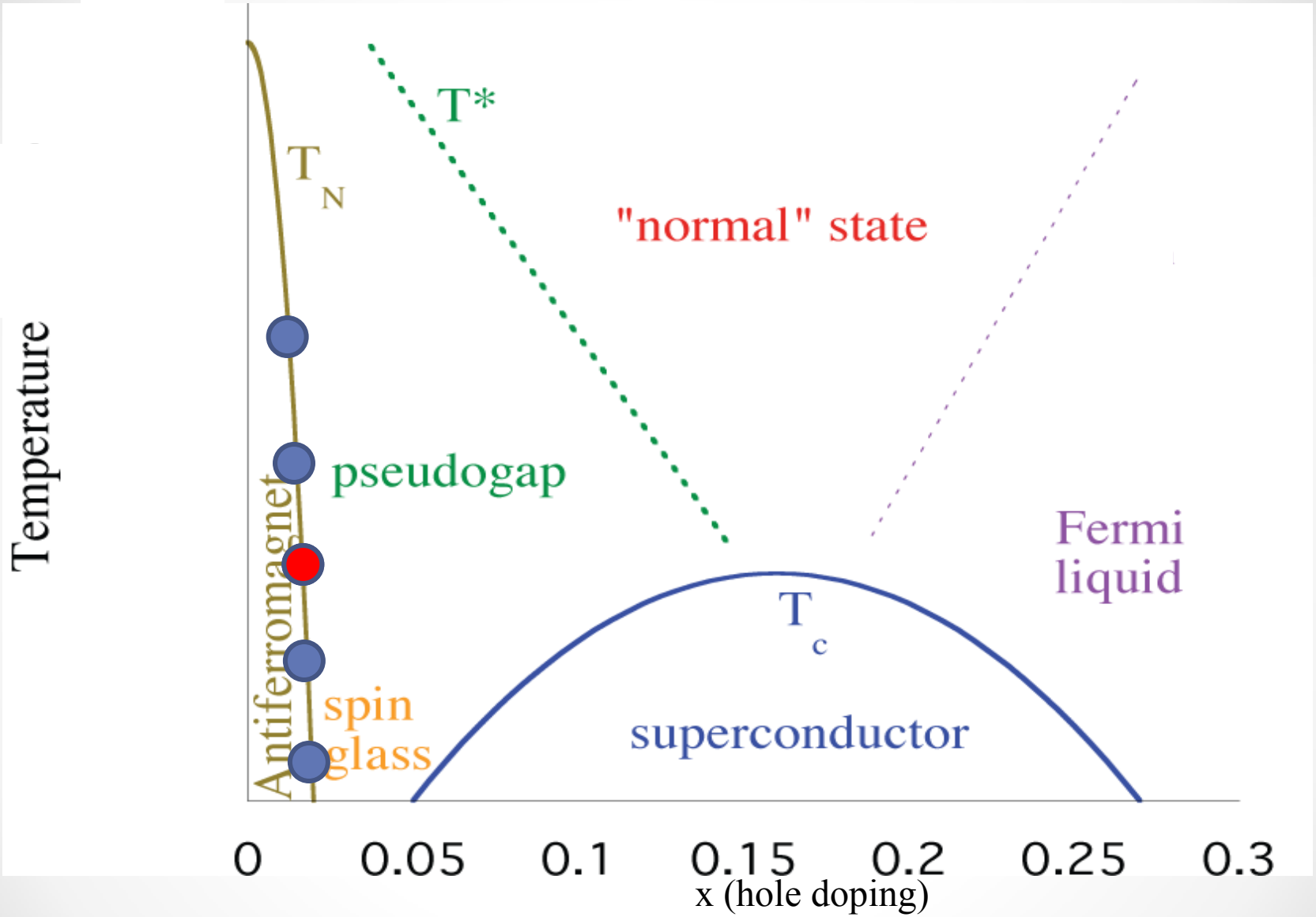


Matsuda et al. 2002

In this work

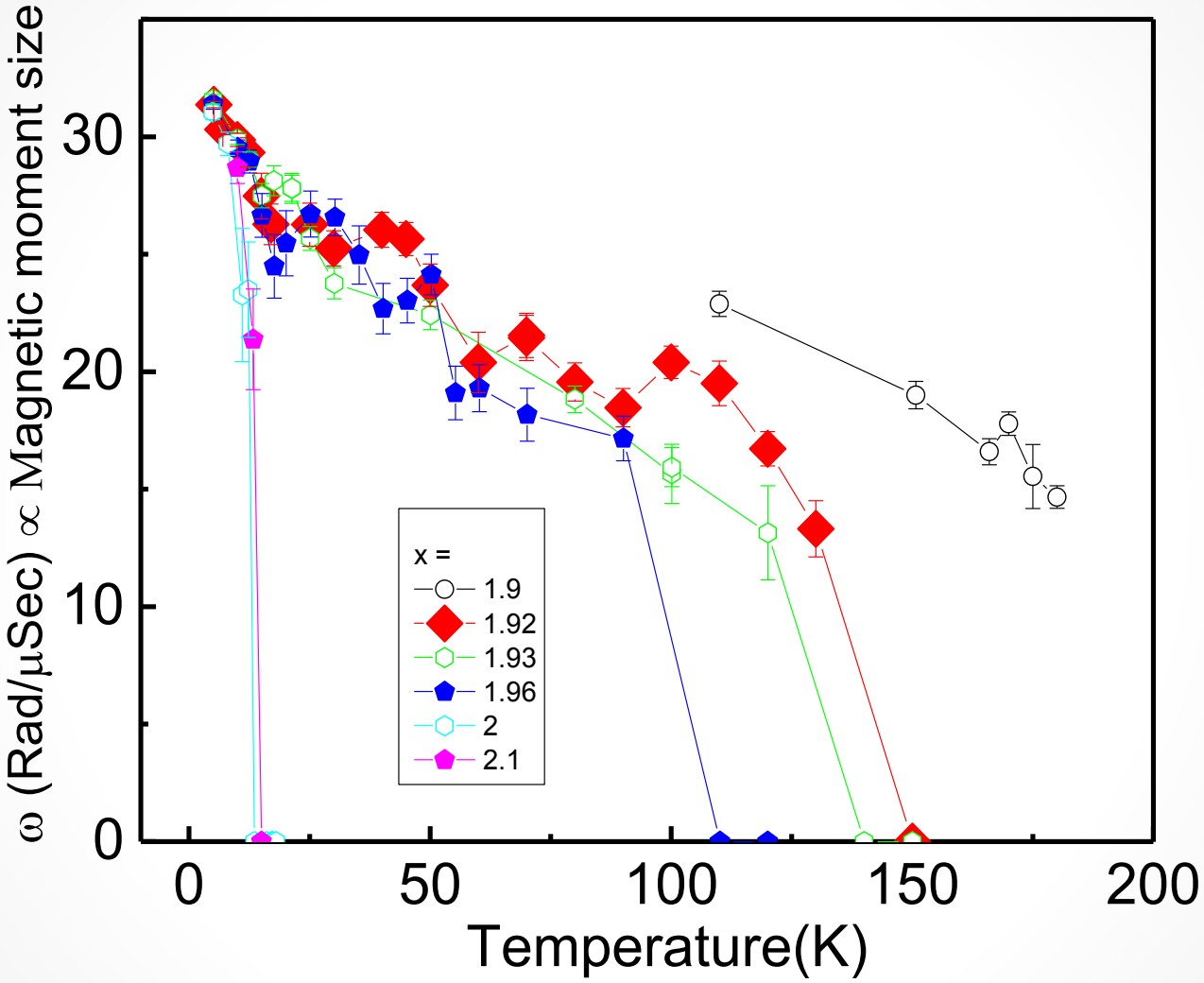
- We wanted to explore the relationship between the gap at the Fermi surface and magnetic order in underdoped LSCO.
- We combined **ARPES**, **neutron scattering and muSR** on one unique crystal of **$La_{2-x}Sr_xCuO_4$** in the antiferromagnetic phase.
- We found that the formation of the nodal gap is due to the spin density wave and not the AFM order.

Attempted Samples



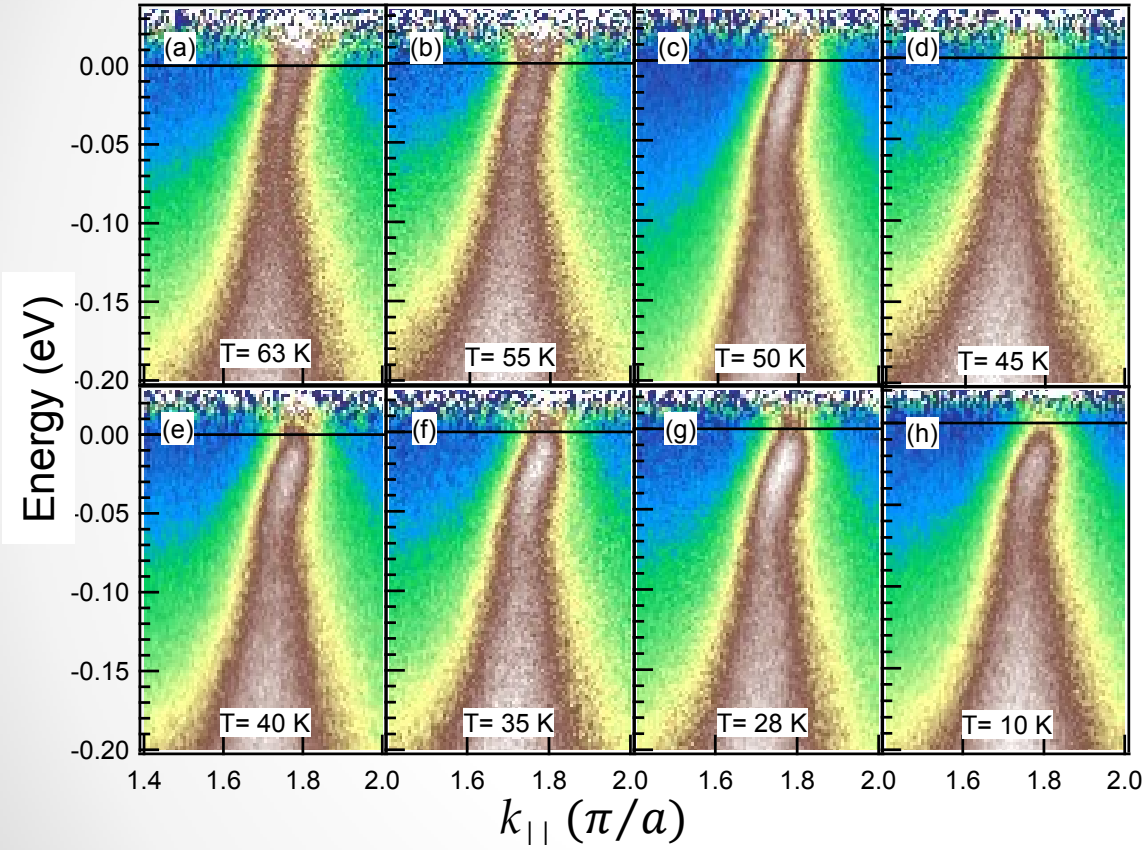
- We have grown a series of LSCO crystals with 1.9<x<2.1% for an ARPES and neutron scattering investigation.

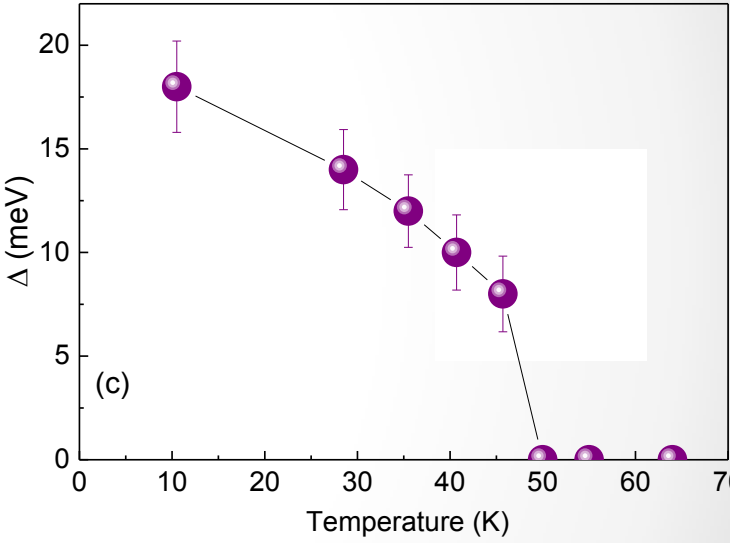
μSR Results

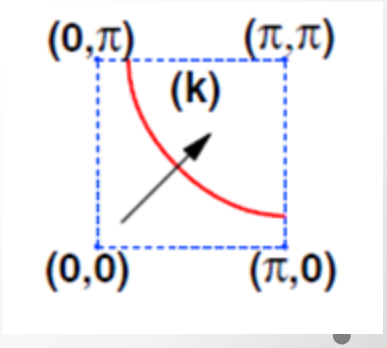


samples with x=1.92-1.96% answered our criteria.
The sample with **x=1.92%** "did the trick"

The Nodal gap in $La_{2-x}Sr_xCuO_4$ (x = 1.92%)

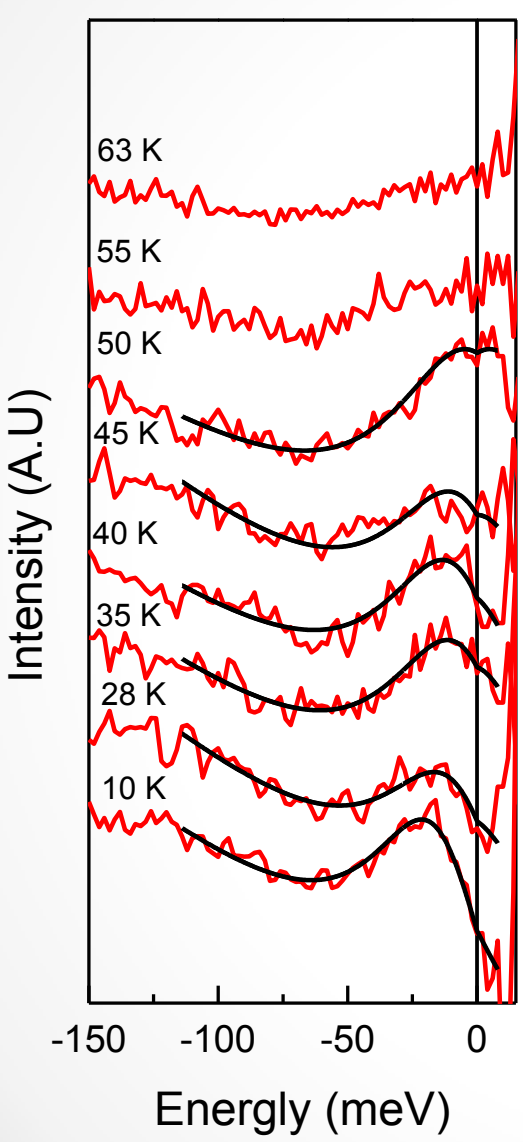


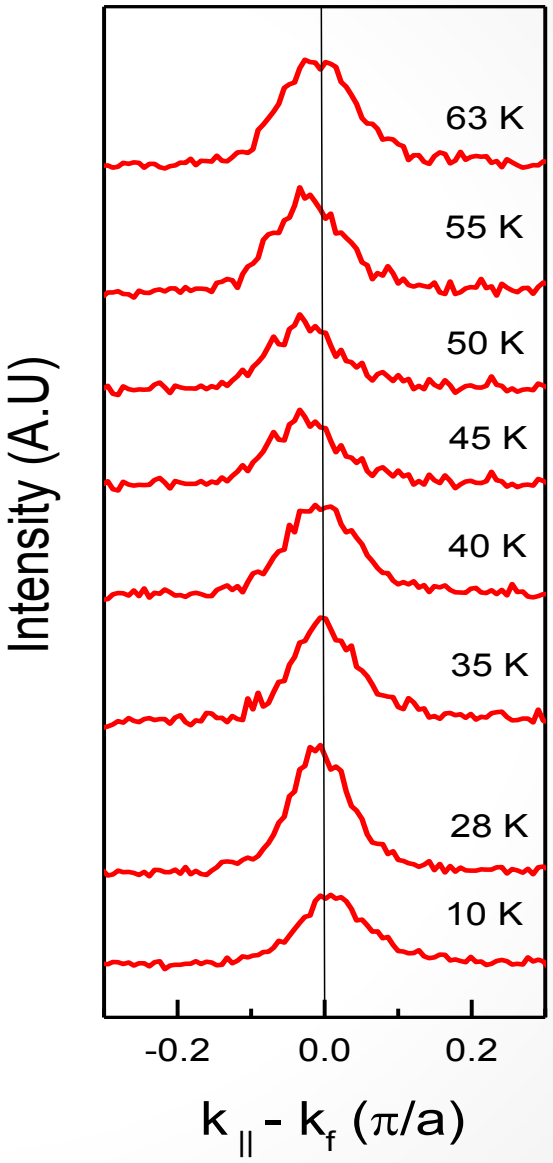




We follow the evolution of the nodal spectra
A nodal gap appears at T=45K.

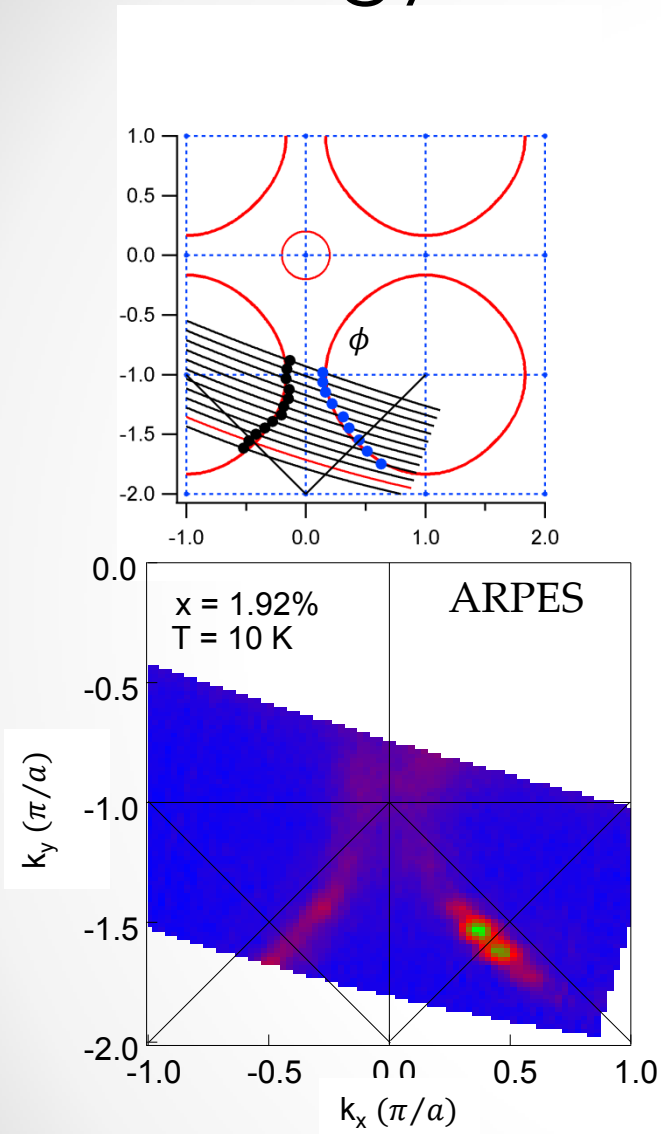
EDC and MDC temperature dependence

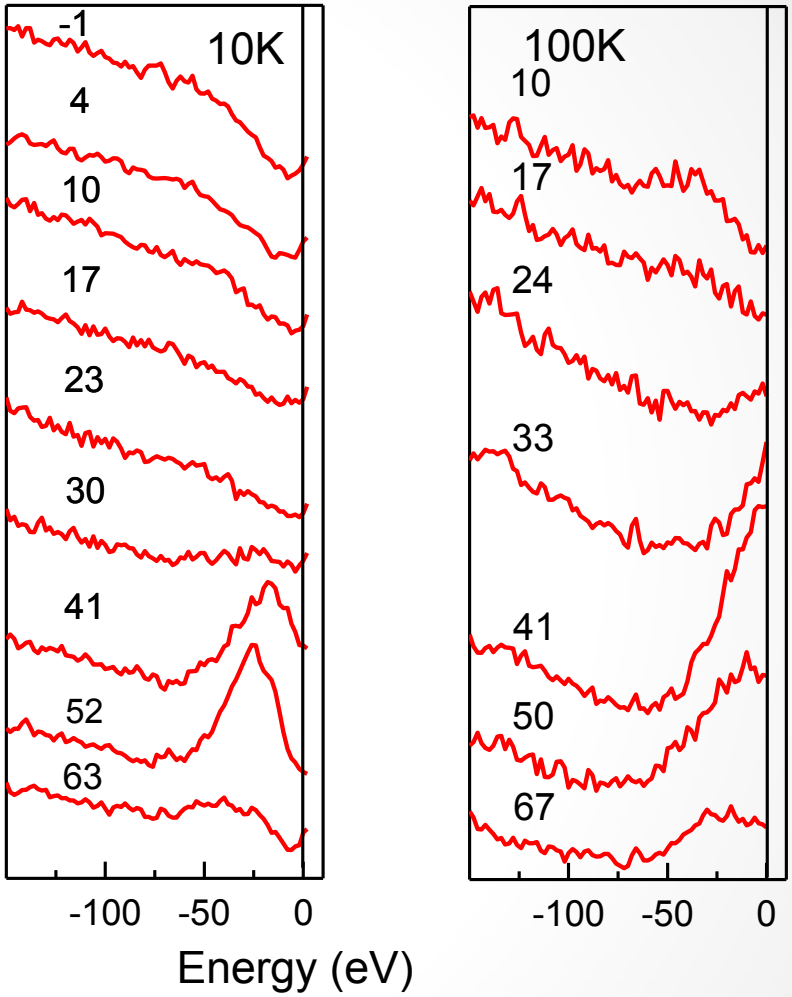




k_F does not change when the gap opens.

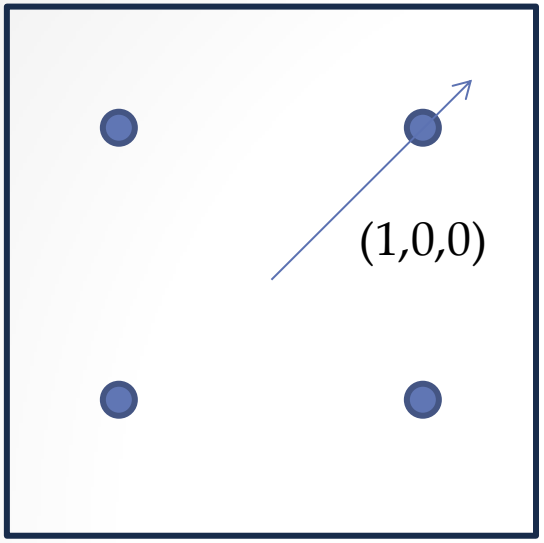
Energy Distribution Cut (EDC) at k_f

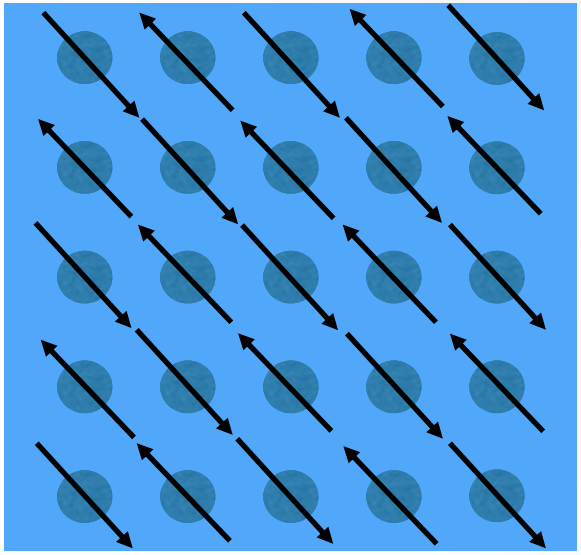




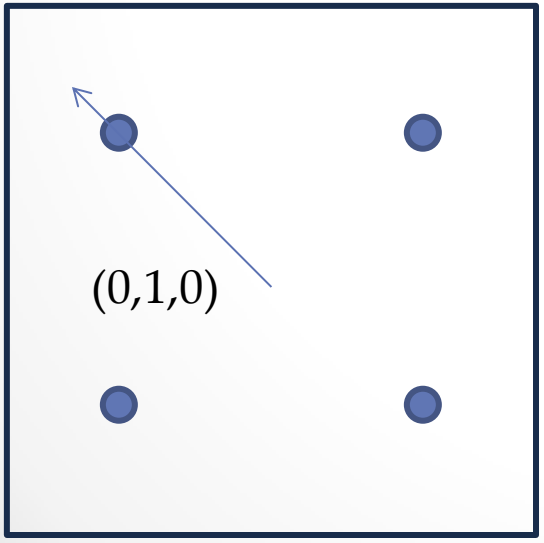
The FS is fully gapped at 10K and has a fermi-arc at 100K.

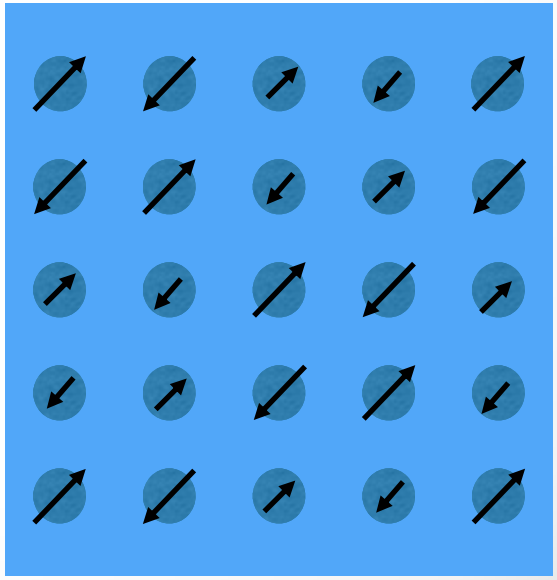
Neutrons scatter when $\vec{Q} \perp \vec{S}$





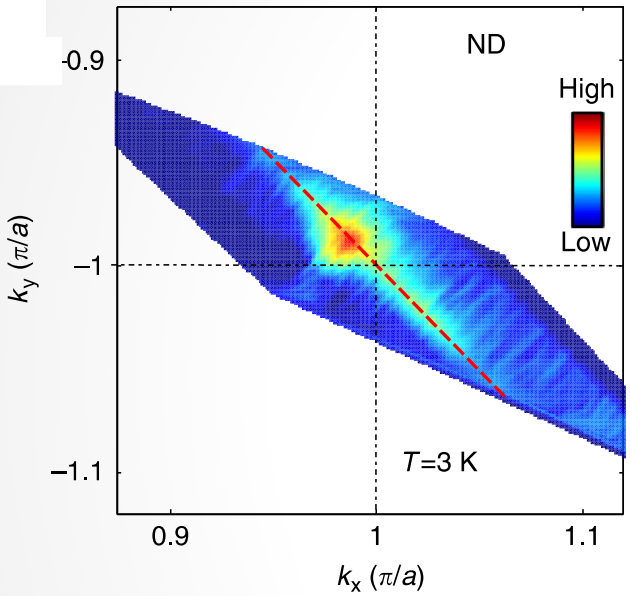
π, π



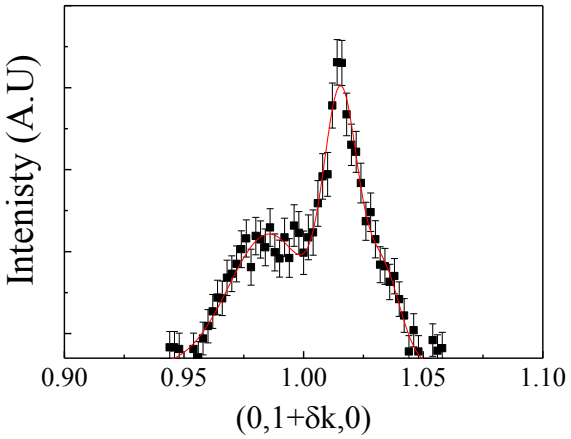


Ic SDW

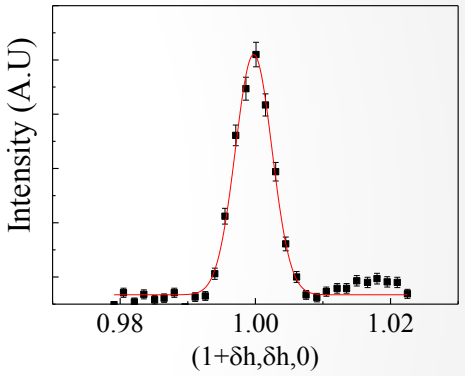
The magnetic structure of $La_{2-x}Sr_xCuO_4$ (x=1.92%)

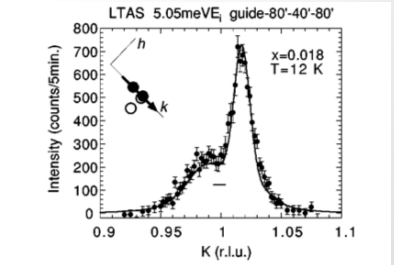


Incommensurate SDW Signal



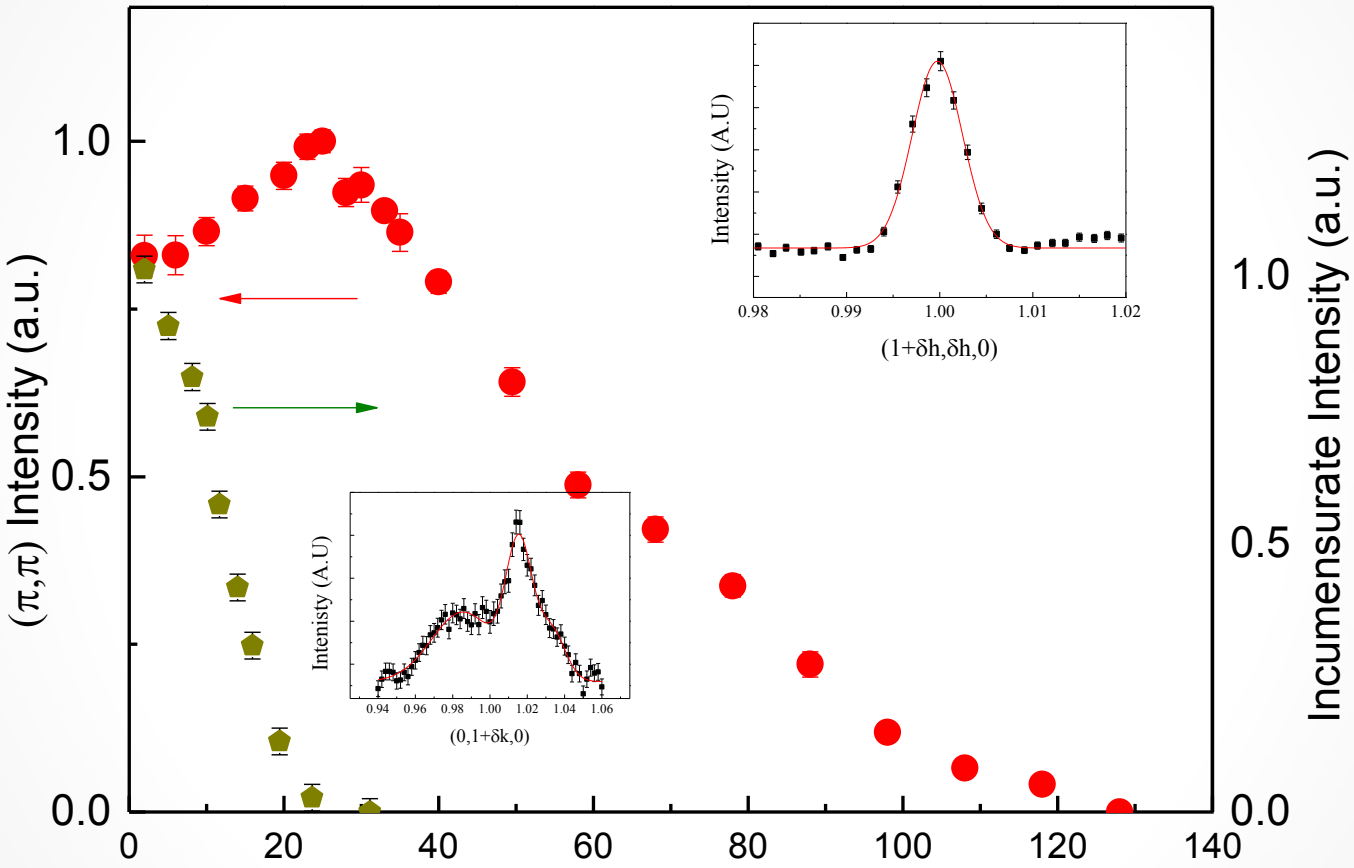
Commensurate (π,π) Signal





- The sample is antiferromagnetic with a diagonal spin stripes (SDW).
- We followed the temperature dependence of the magnetic order.

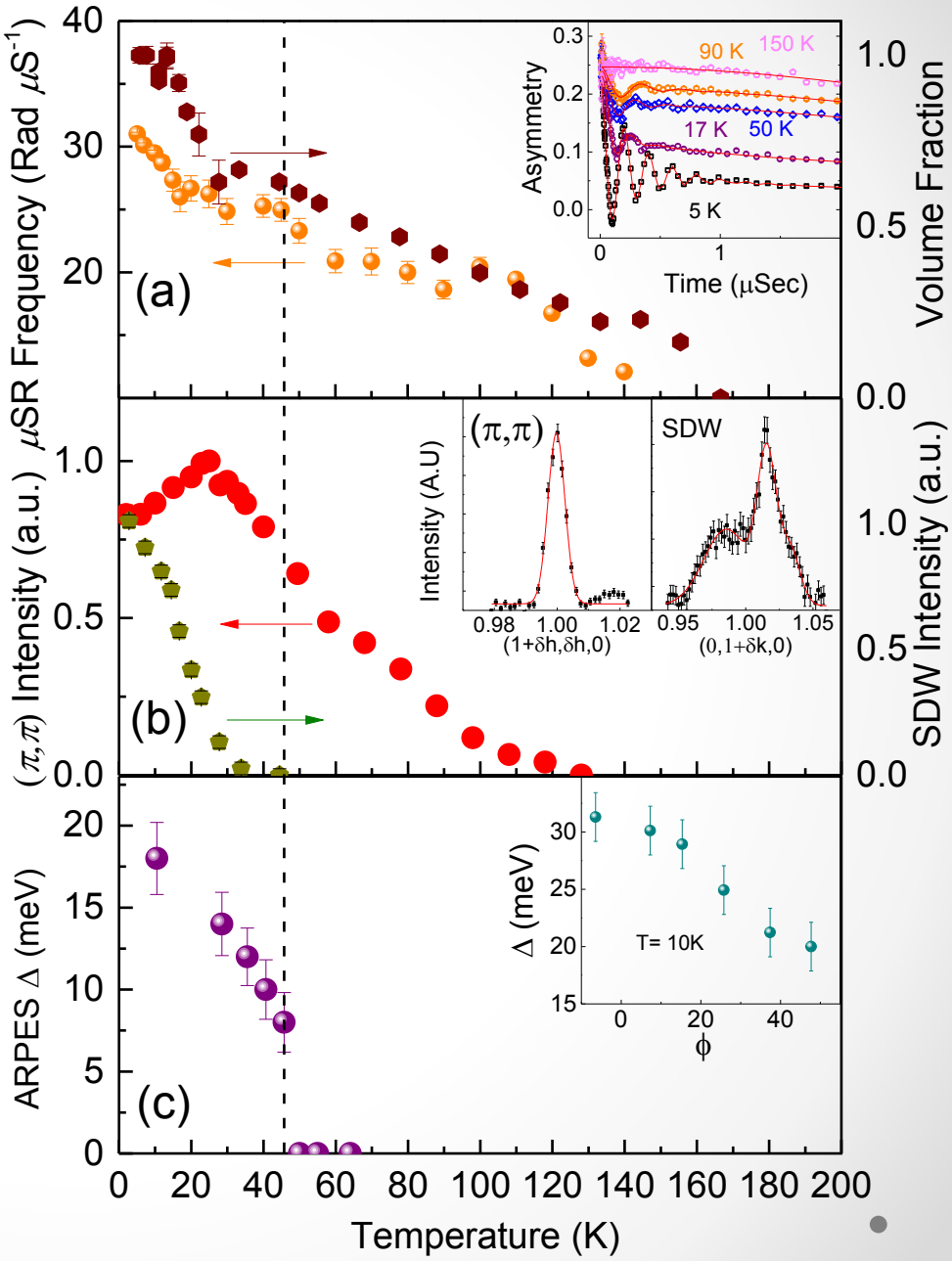
Neutron scattering summary



Commensurate magnetism appears at 130K
Spin Density Wave (SDW) appears at 30K

Results Summary

- The AF magnetic transition begins at 140K
- Commensurate magnetism is well developed when the gap opens.
- An incommensurate SDW forms at ~40K the same T as the gap opening.
- The Nodal gap opens at T~45K



Conclusions

- We find that a nodal gap opens well below the commensurate ordering at 140 K, but close to the spin density wave ordering temperature.

- Our measurements demonstrate that the origin of the newly discovered nodal gap in cuprates is the SDW, and not the AFM order.

The Collaboration

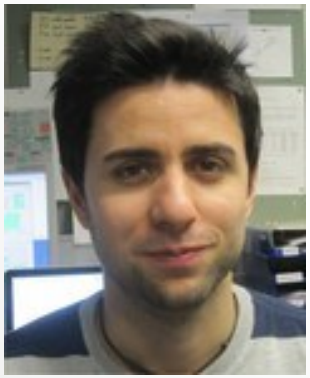
Technion-Israel Institute of Technology, Israel

A. Keren

A. Kanigel

G. Bazalitski

Paul Scherrer Institute (PSI), Switzerland



E. Razzoli

M. Shi

C. Niedermayer

THE END

Thank You