Mystery of HTSC: ARPES vs. Nature

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Navigation

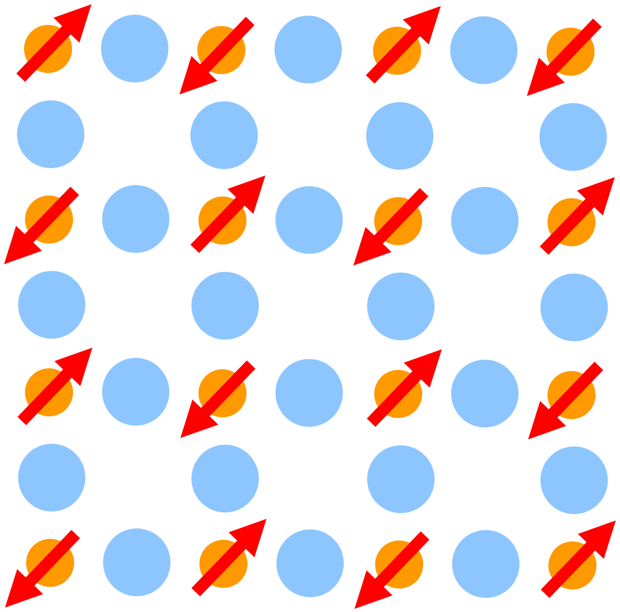
- HTSC are complex
- ARPES is simple
- ARPES in Dresden
- Complex structure *vs* complex physics
- What is complex: Antinodal region
- What is simple: Nodal region

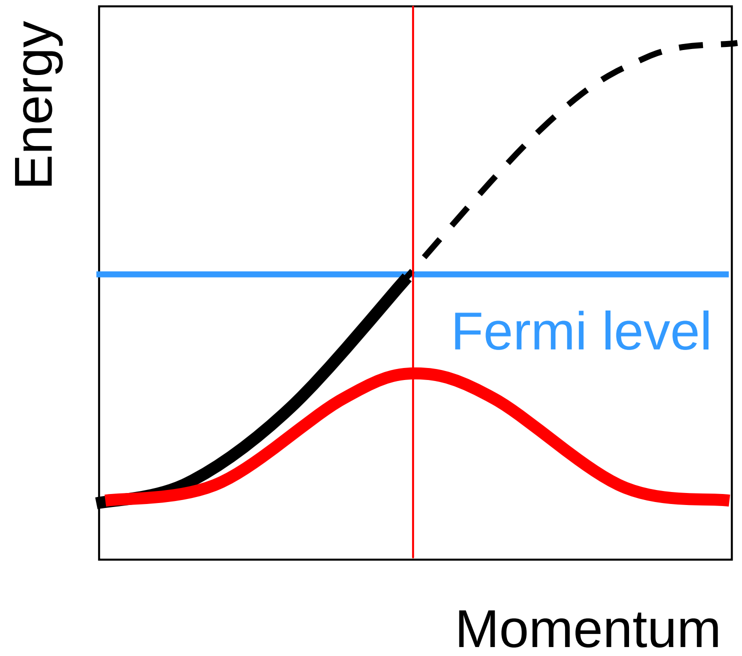
Introduction to HTSC physics

HTSC physics is complex

HTSC physics is located in simple CuO planes

...simple CuO planes

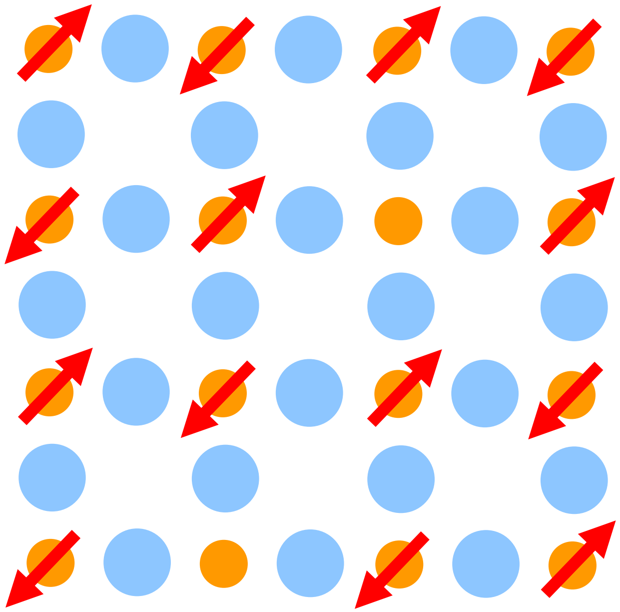


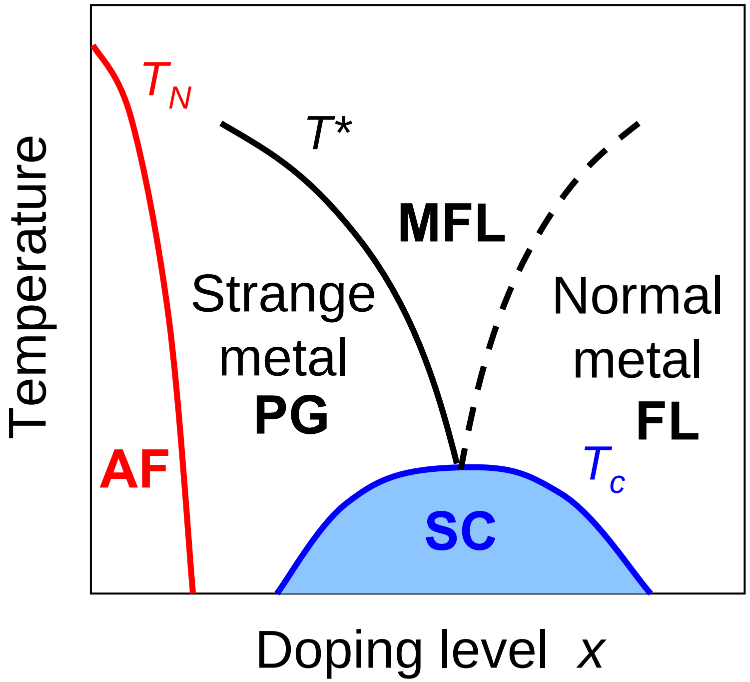


LDA $\Longrightarrow$ Simple metal

Experiment $\Longrightarrow$ Isolator - AF Mott isolator

Hole doping





FL – Fermi Liqiud

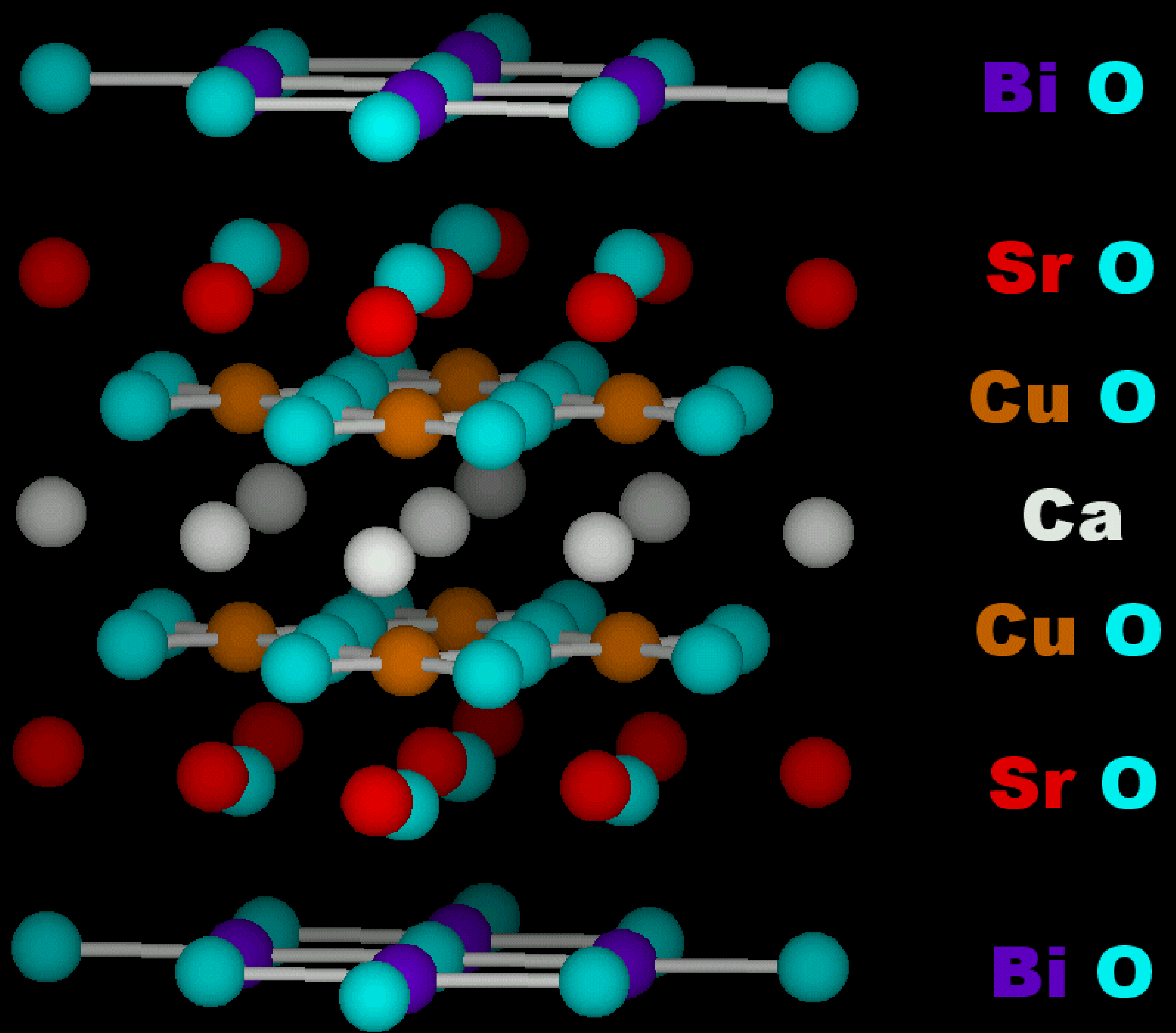
MFL – Marginal Fermi Liqiud

PG – Pseudo Gap state

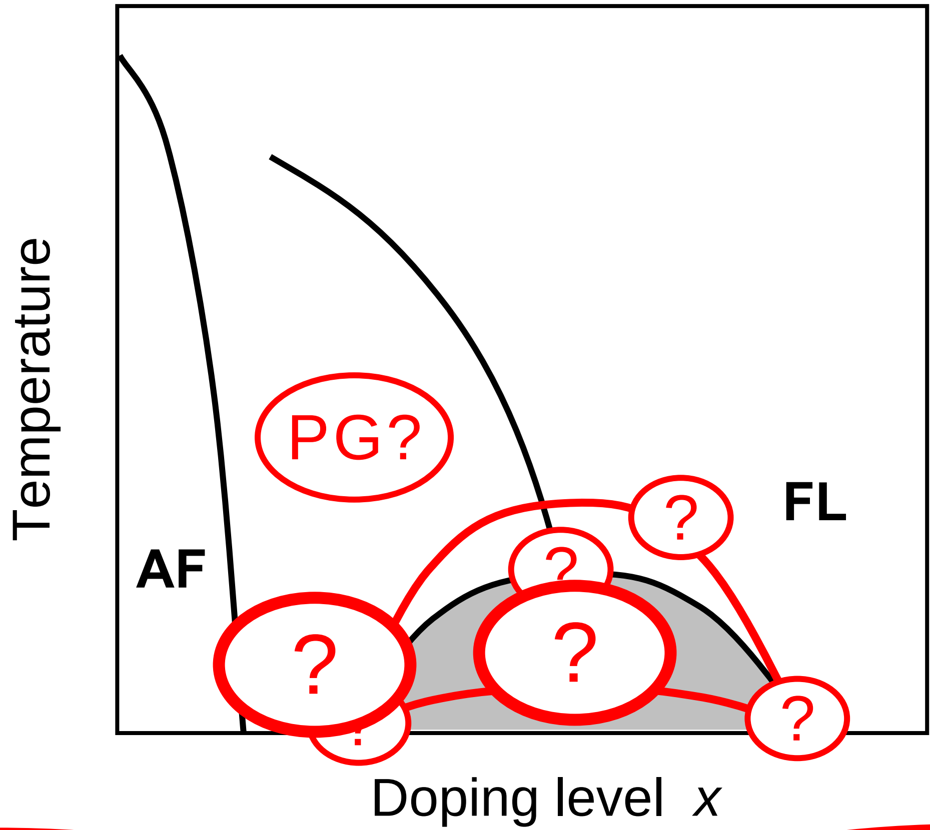
$Bi_2Sr_2CaCu_2O_{8+\delta}$

BSCCO

Bi-2212



Phase diagram: open questions



How does AF evolve into Metal?

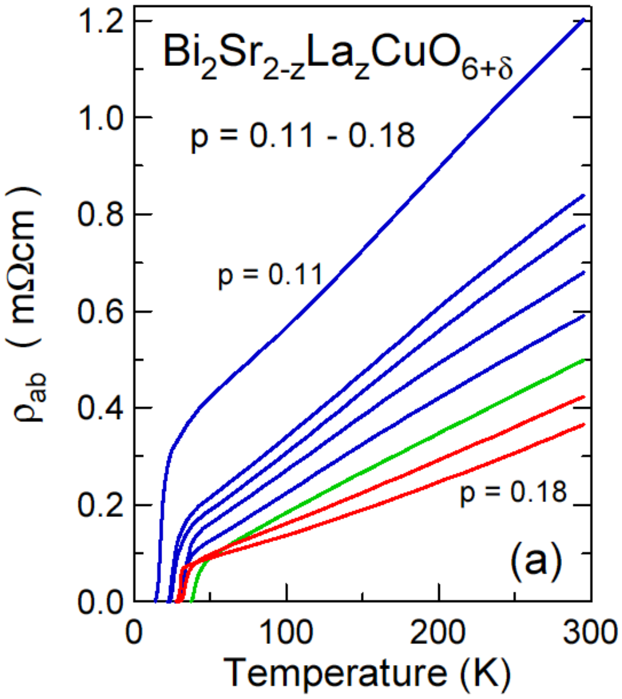
How does SC appear?

Complexity of properties

requires

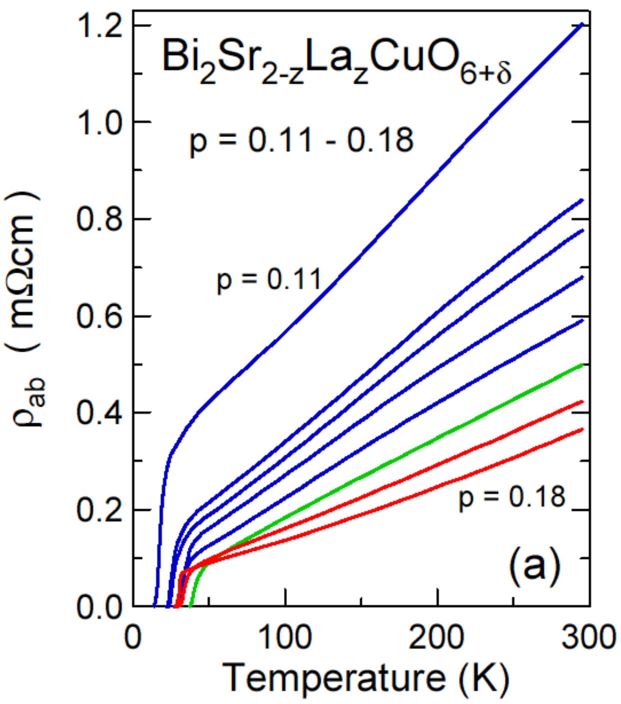
a powerfull experimental technique

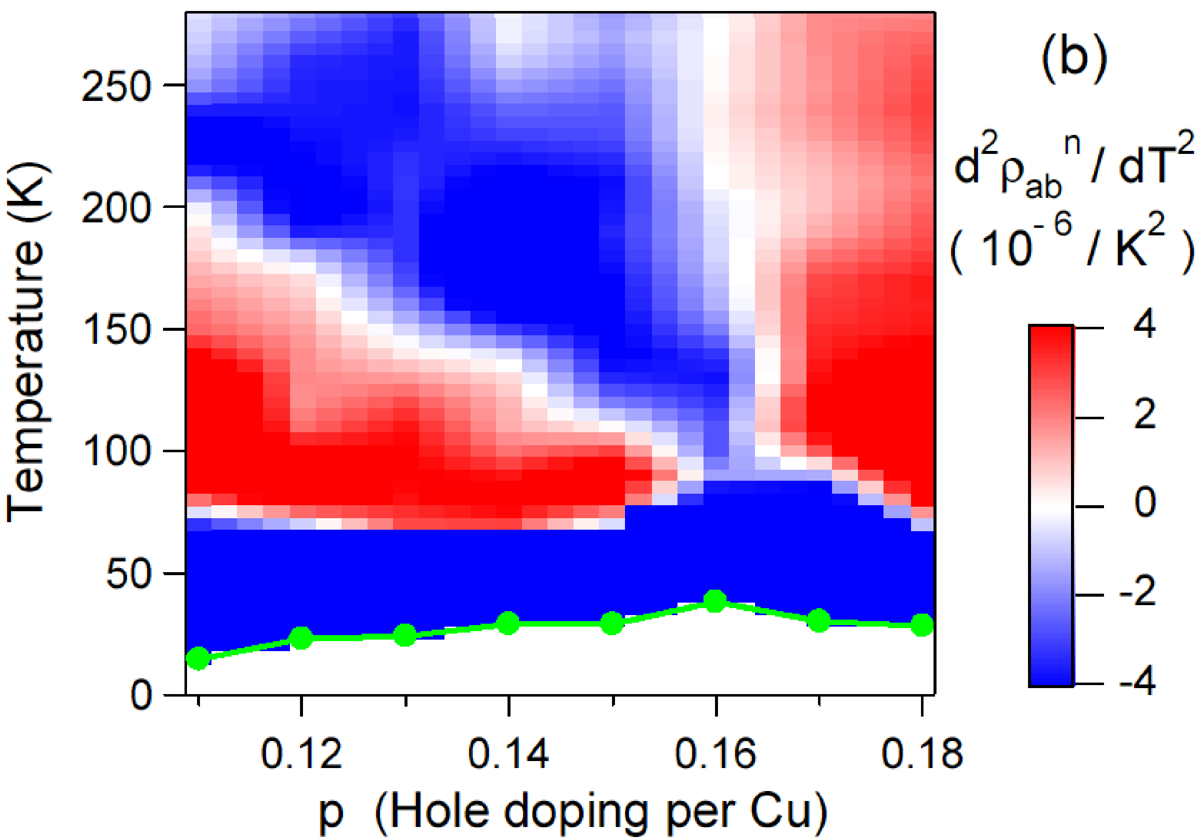
Phase diagram from a Mapping of the In-Plane Resistivity Curvature



Ando *PRL* 2004

Phase diagram from a Mapping of the In-Plane Resistivity Curvature

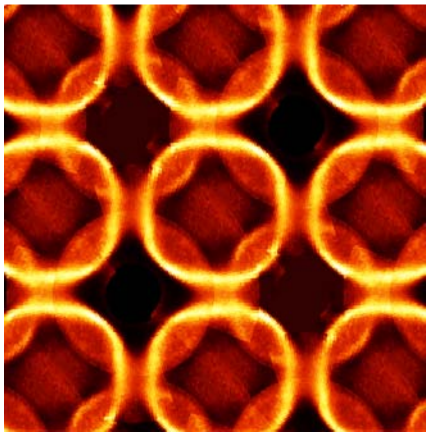


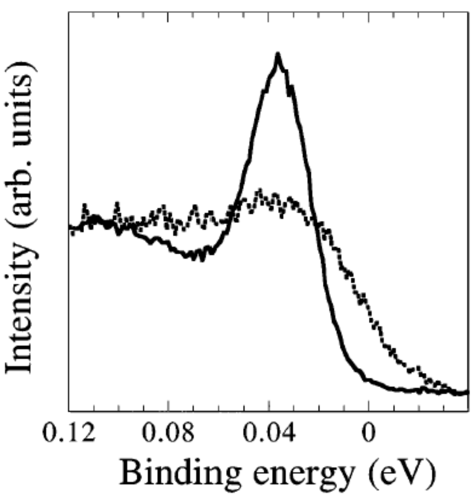


Ando *PRL* 2004

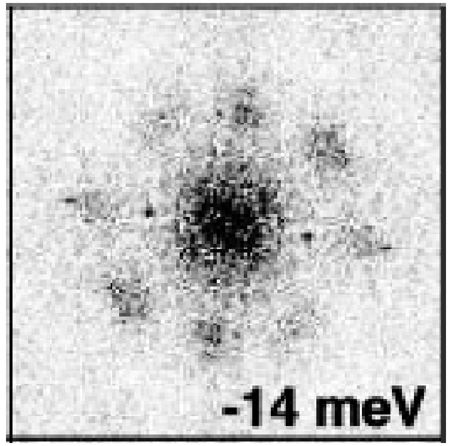
Modern momentum resolving techniques

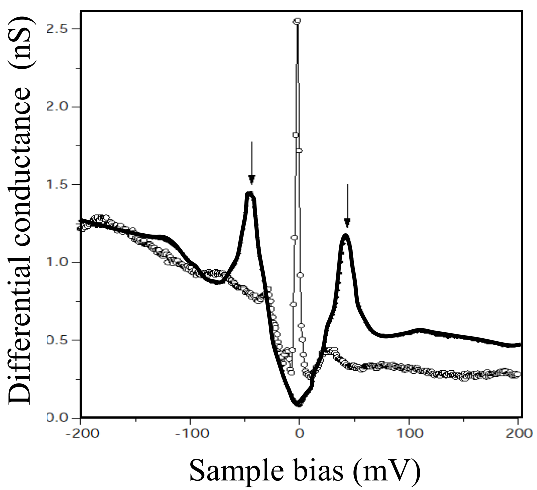
ARPES



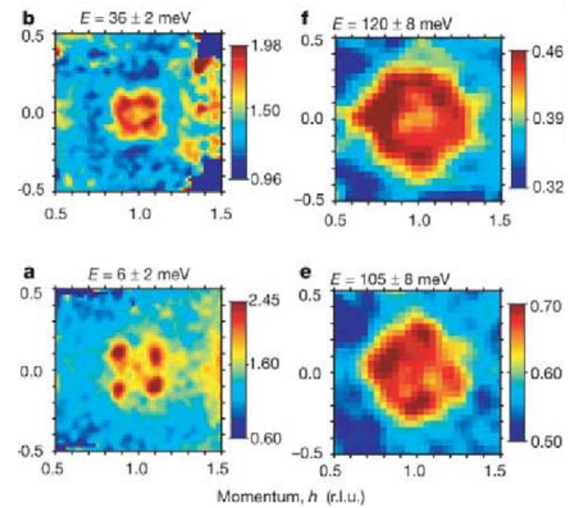


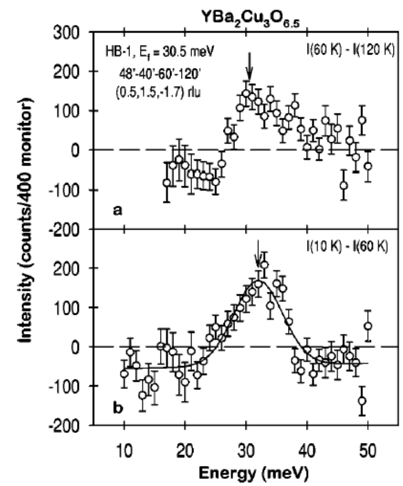
STS





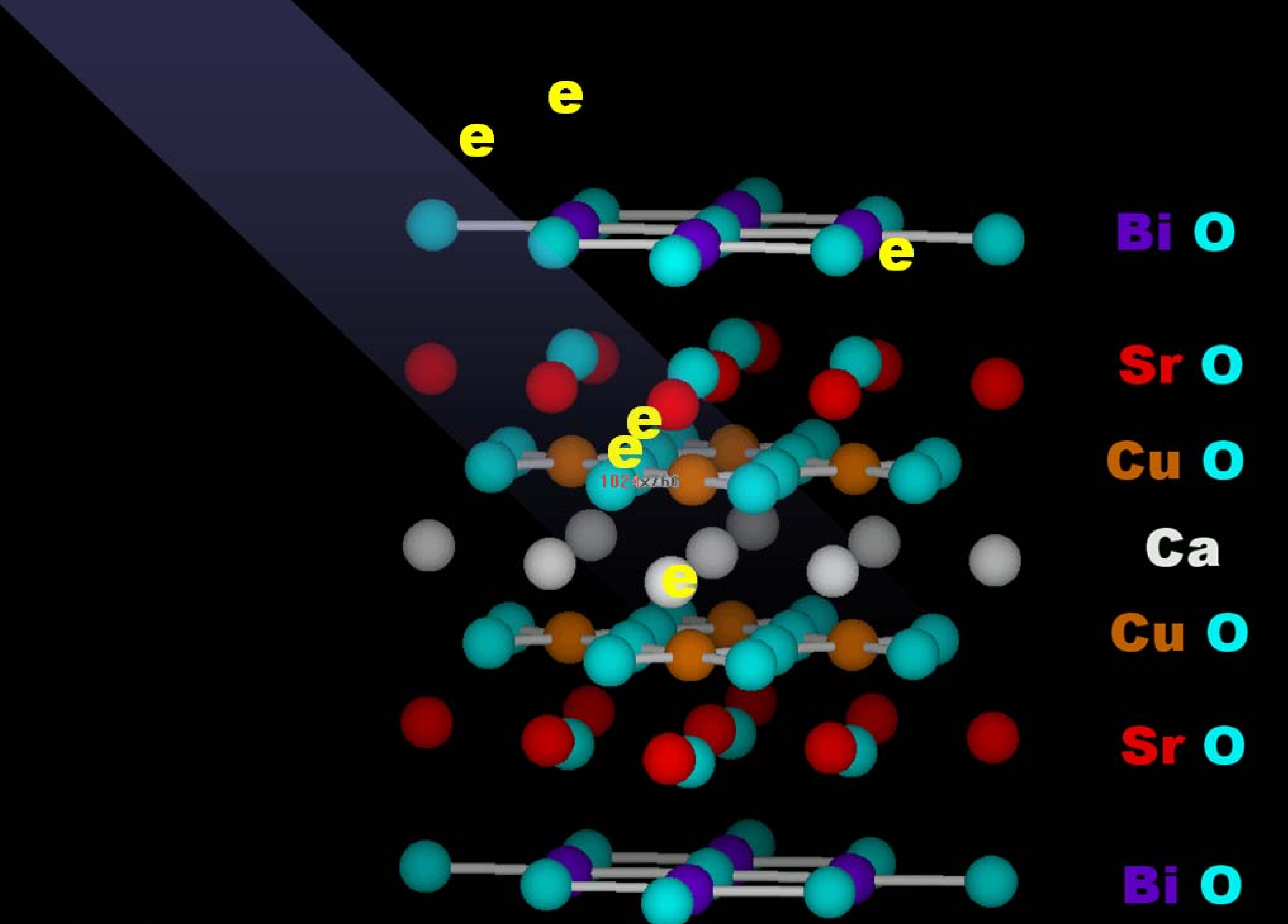
INS



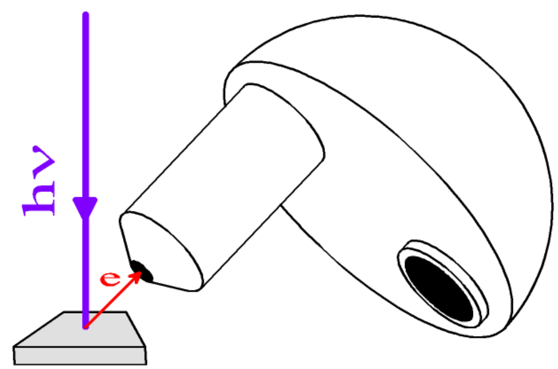


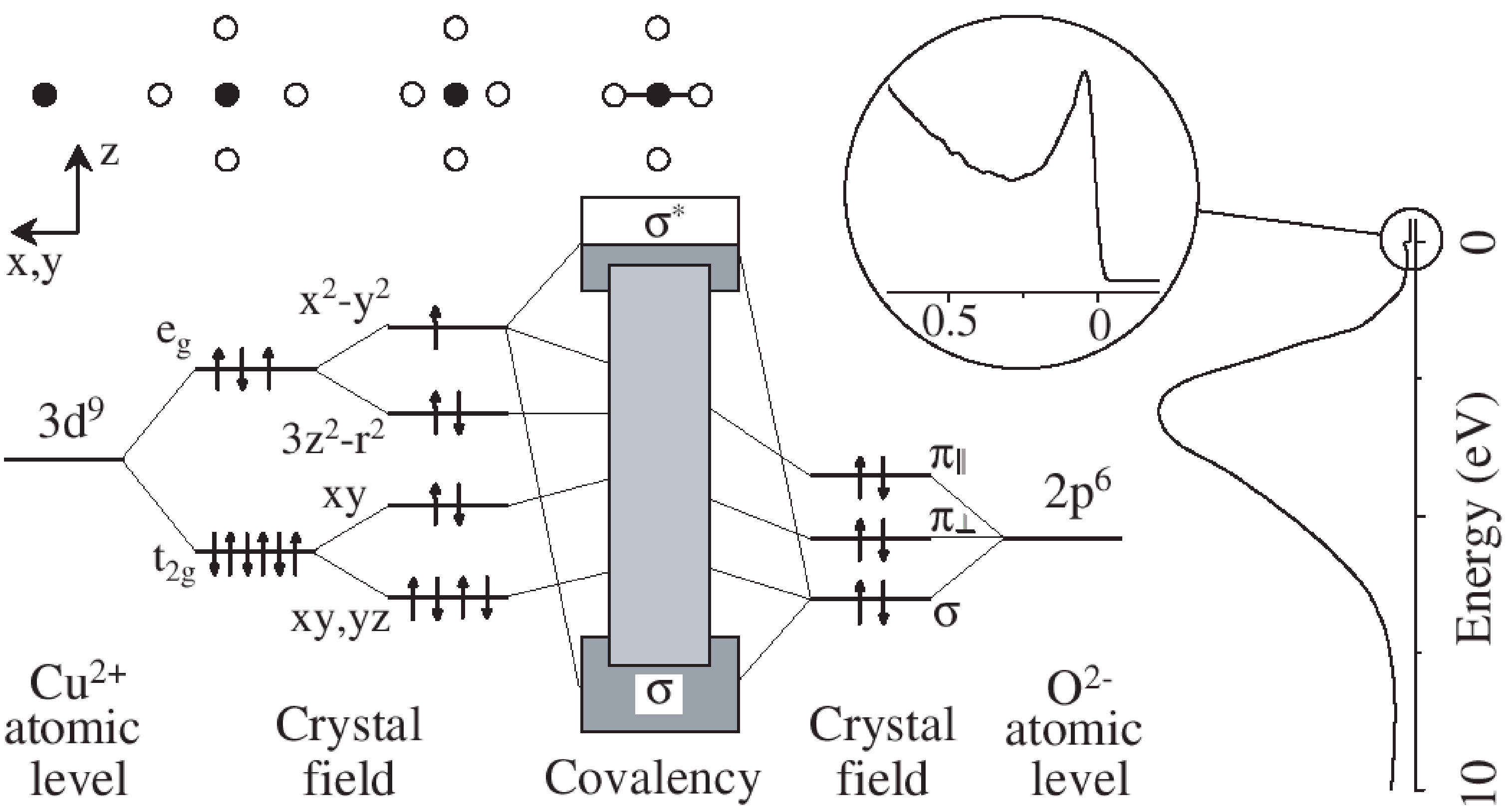
Introduction to ARPES

the most direct tool to explore the momentum-energy space of the electrons in solids

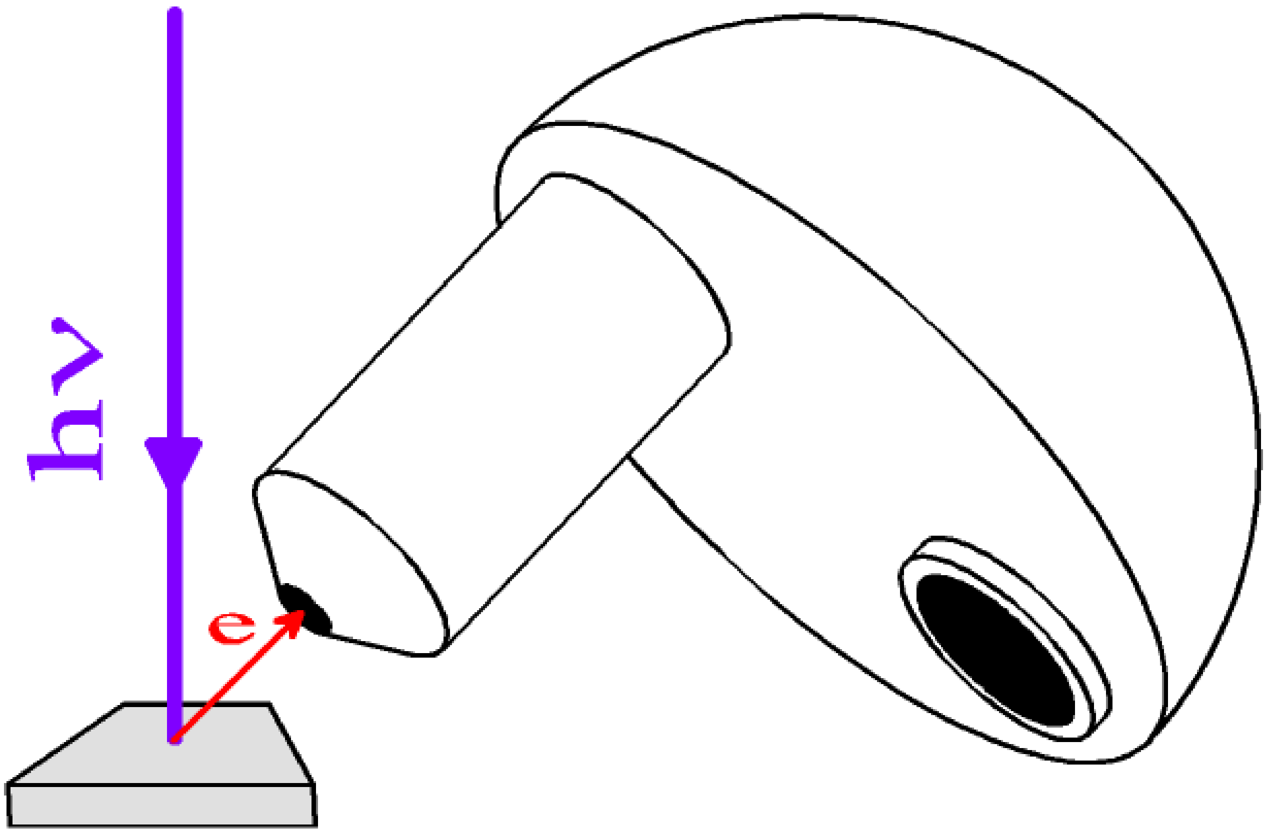

e
e
Bi O
e
Sr O
e
e
Cu O
Ca
e
Cu O
Sr O
Bi O

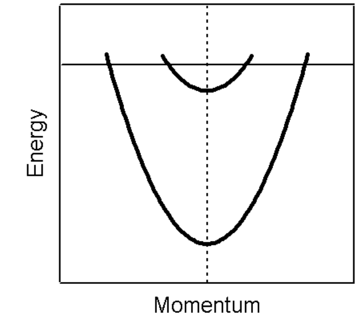
Photoemission Spectrum

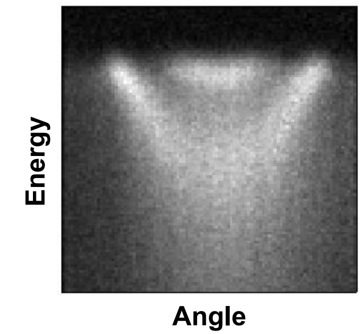




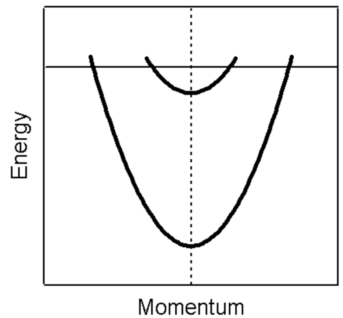
Angle-Resolved Photoemission (ARPES)

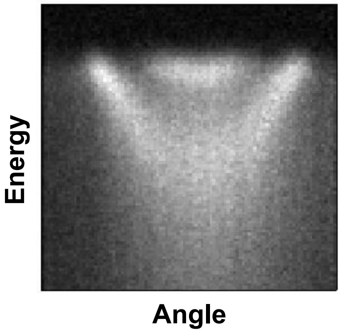


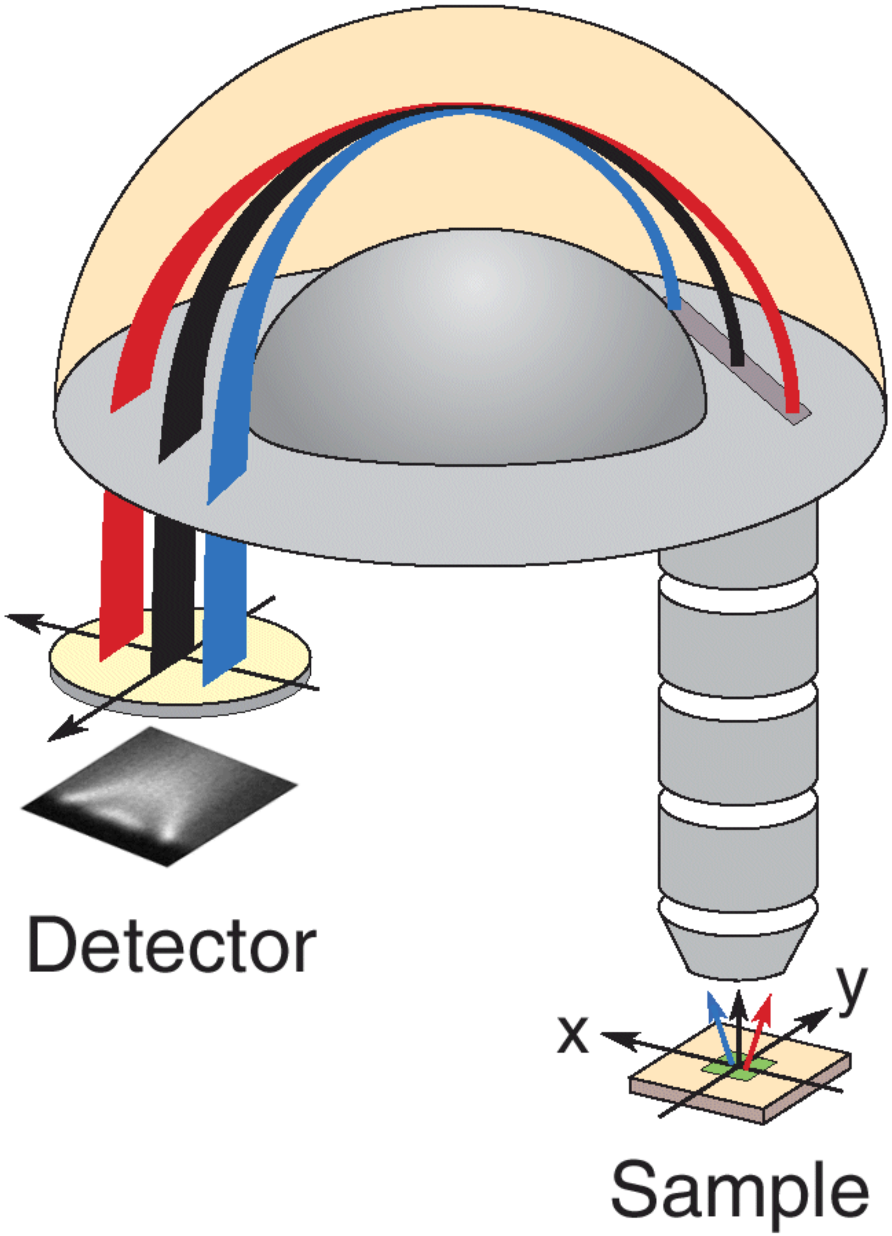




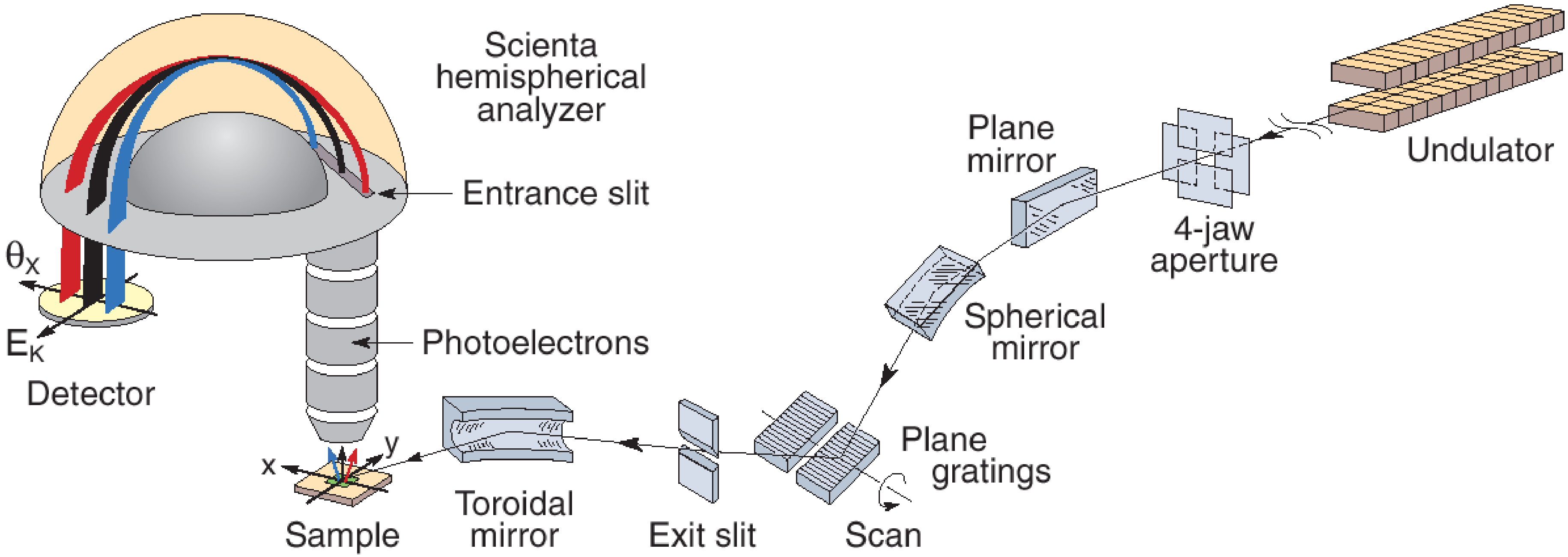
Angle Resolved Analyser





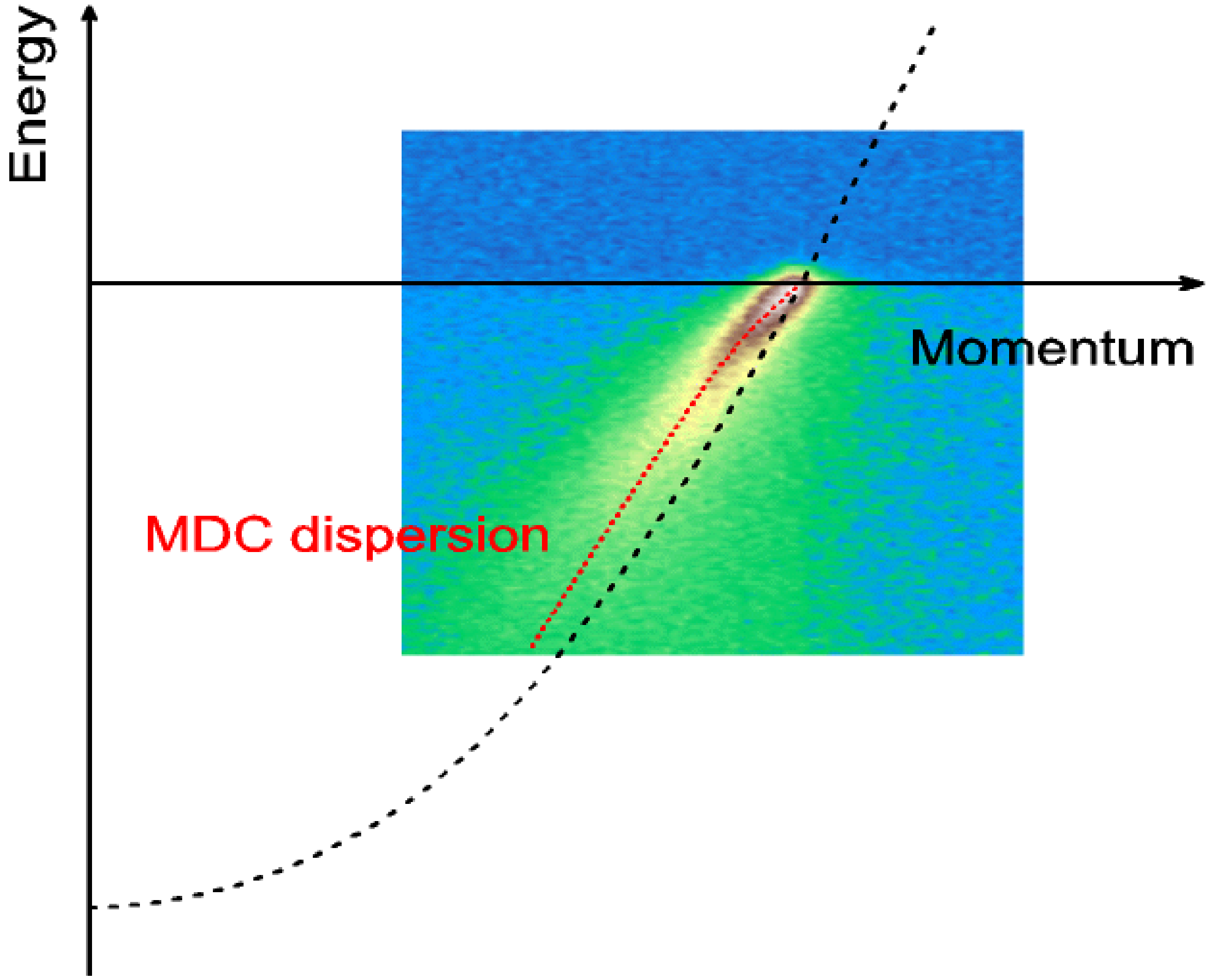


ARPES with Synchrotron Light



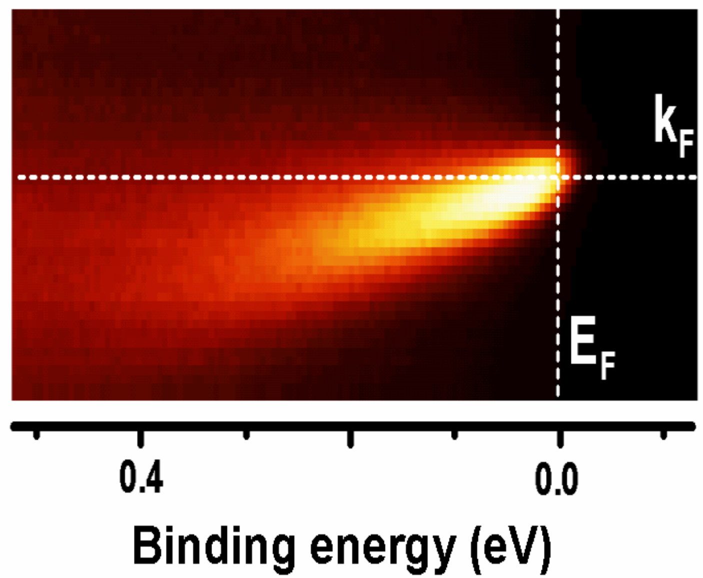
Damascelli *RMP* 2003

Basics: electron dispersion

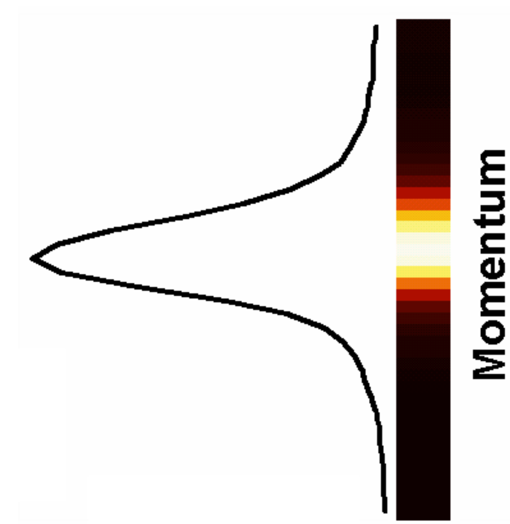


$$A(\mathbf{k},\omega)$$

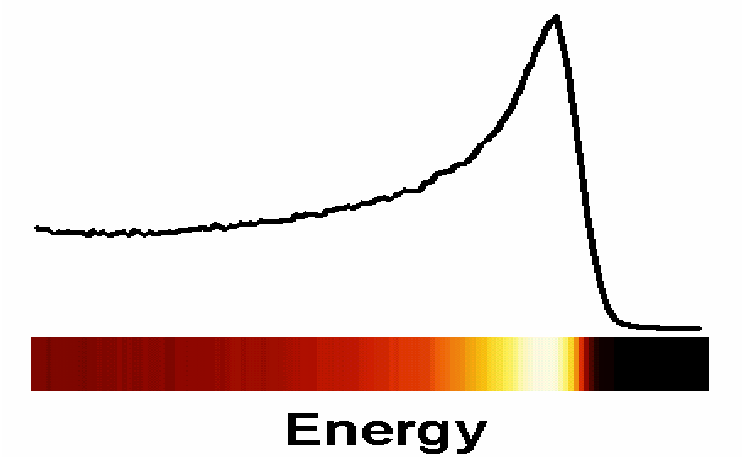
$I(k,\omega)$ - Energy Distribution Map



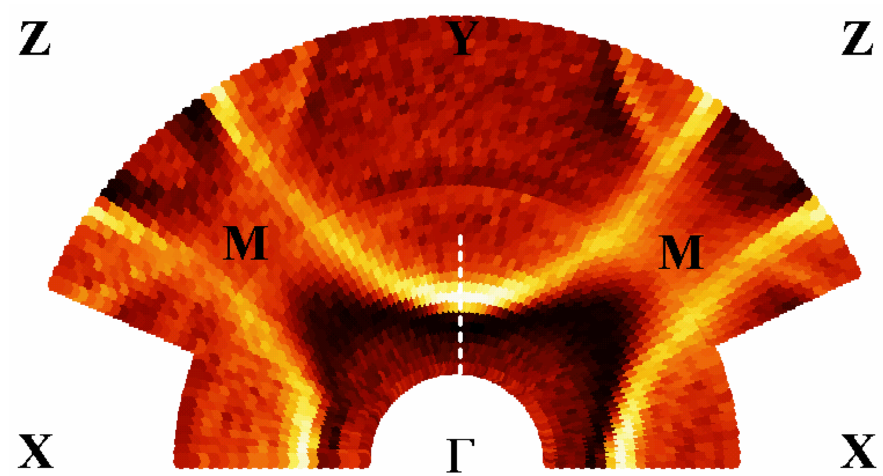
$I(k,\omega)$ - Momentum Distribution Curve



$I(k,\omega)$ - Energy Distribution Curve

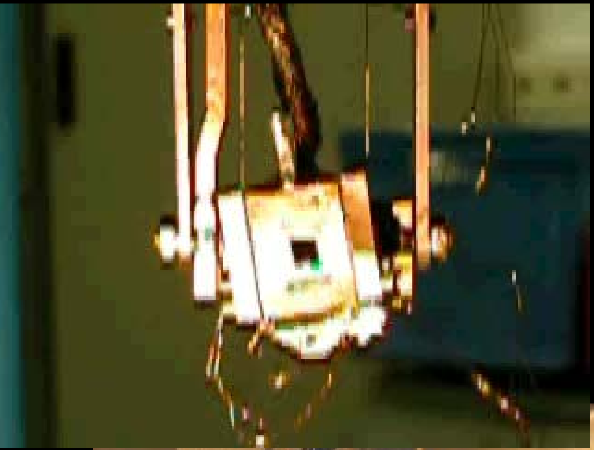


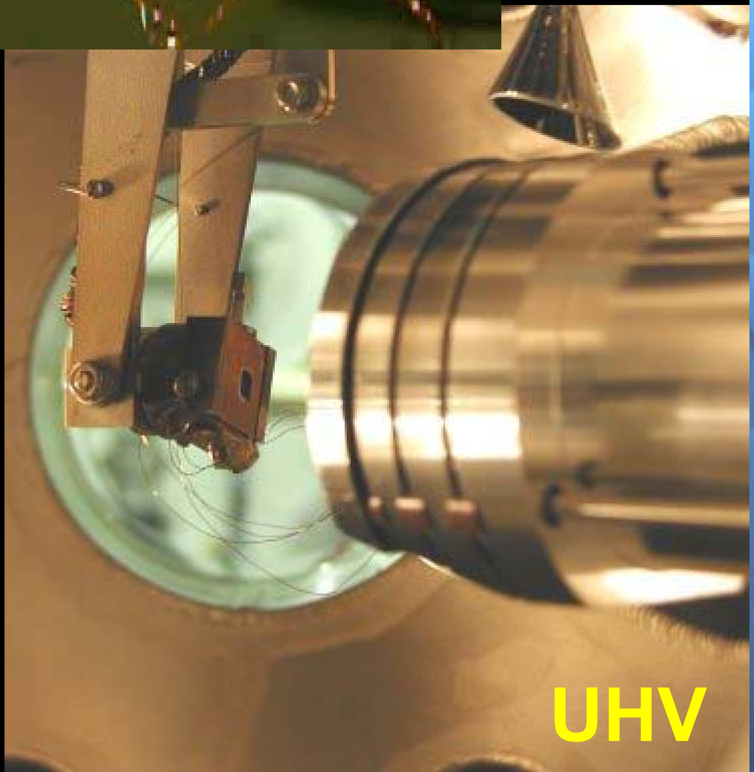
$I(k_x,k_y,\omega)$ - Momentum Distribution Map

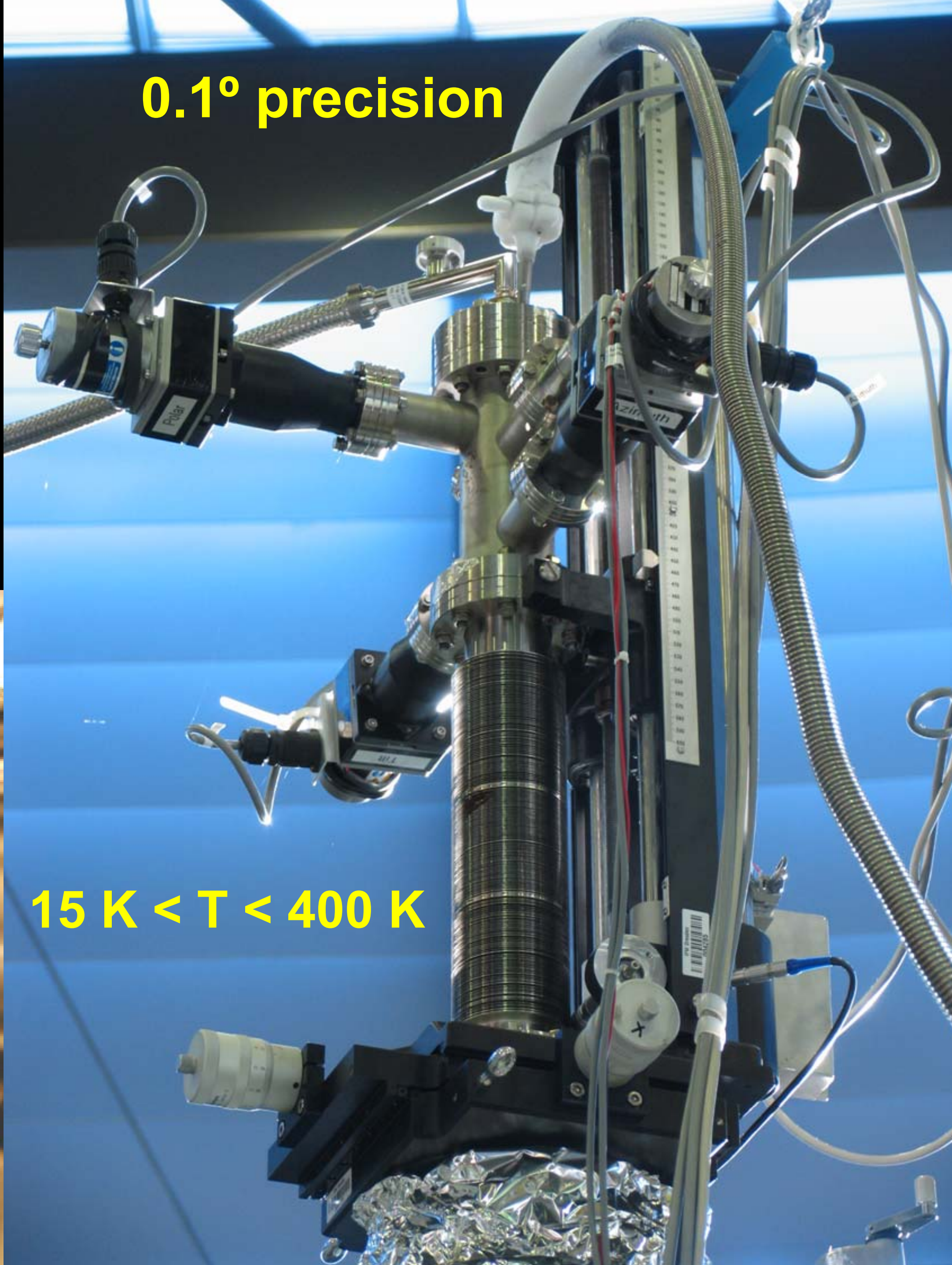


Borisenko *PRB* 2001

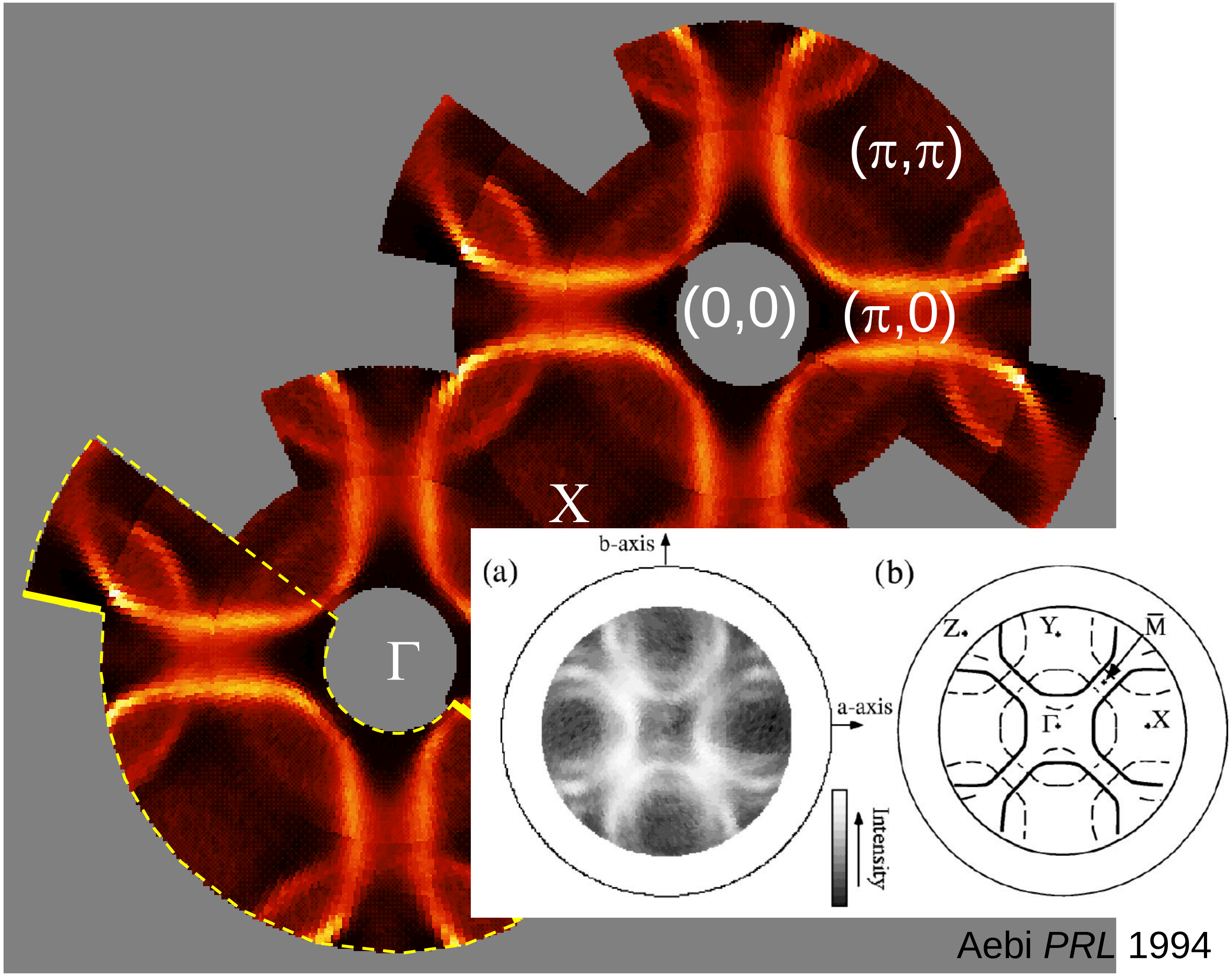
Precise Cryo-Manipulator



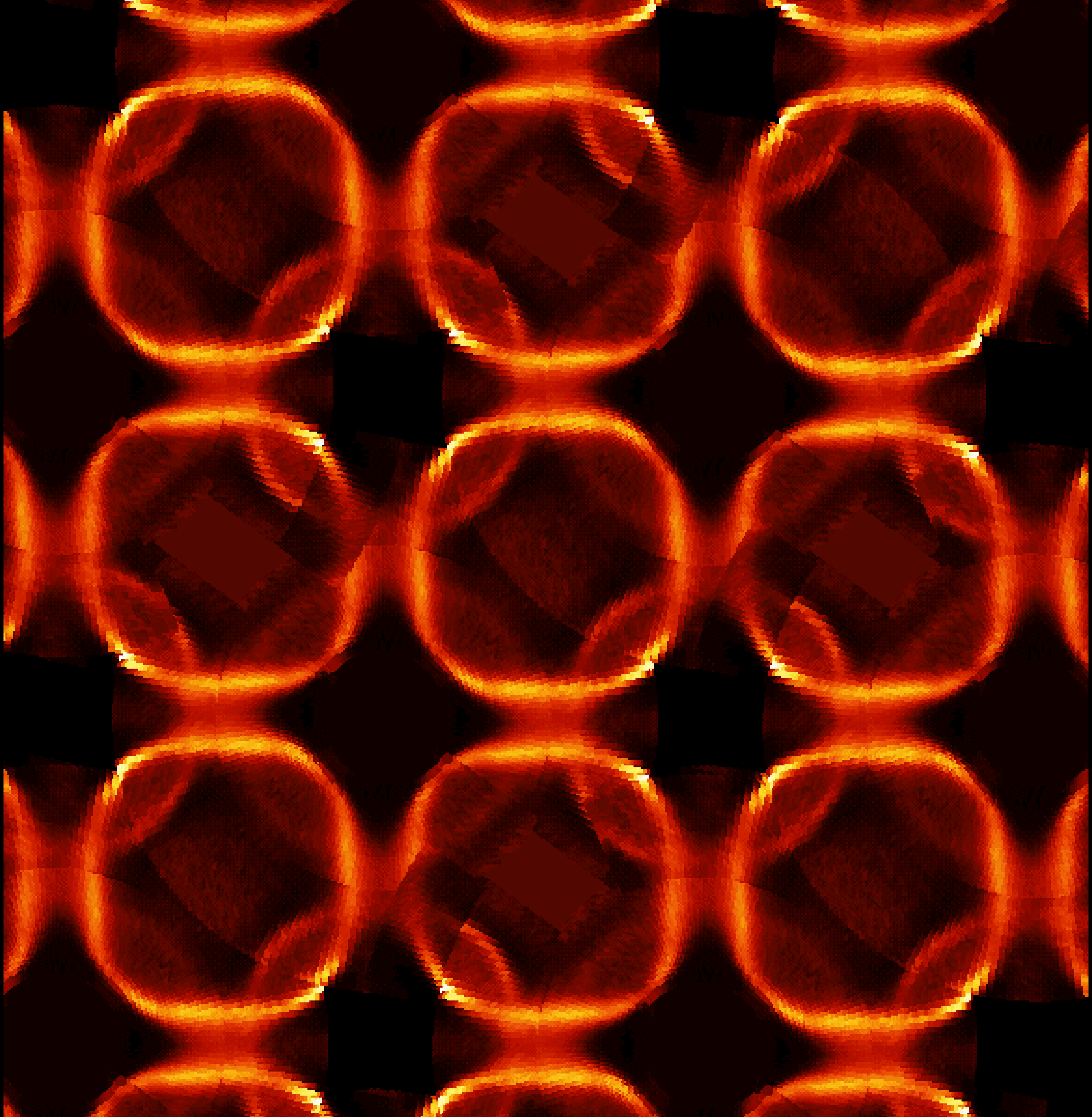




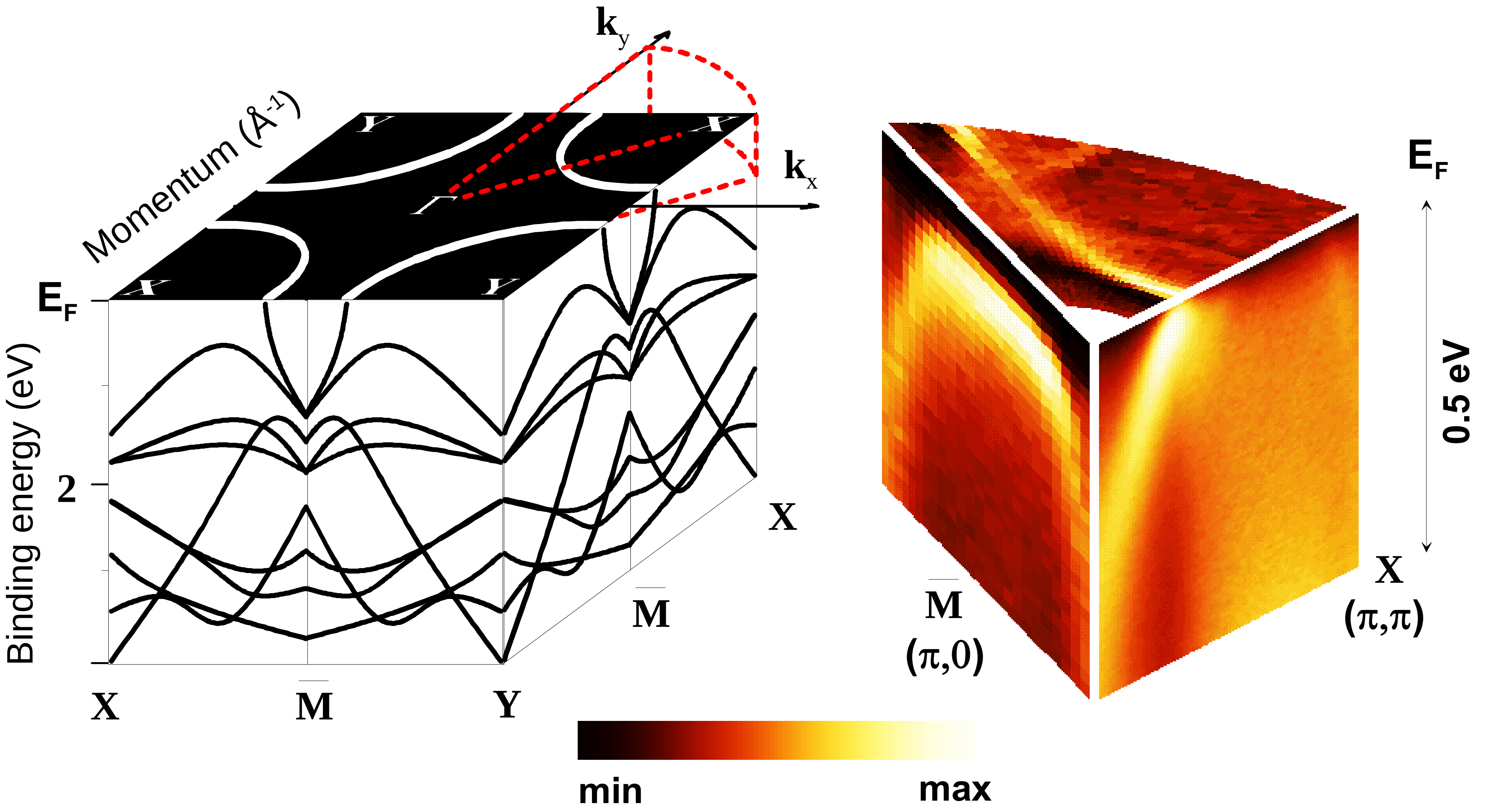
Fermi-surface map



Aebi *PRL* 1994

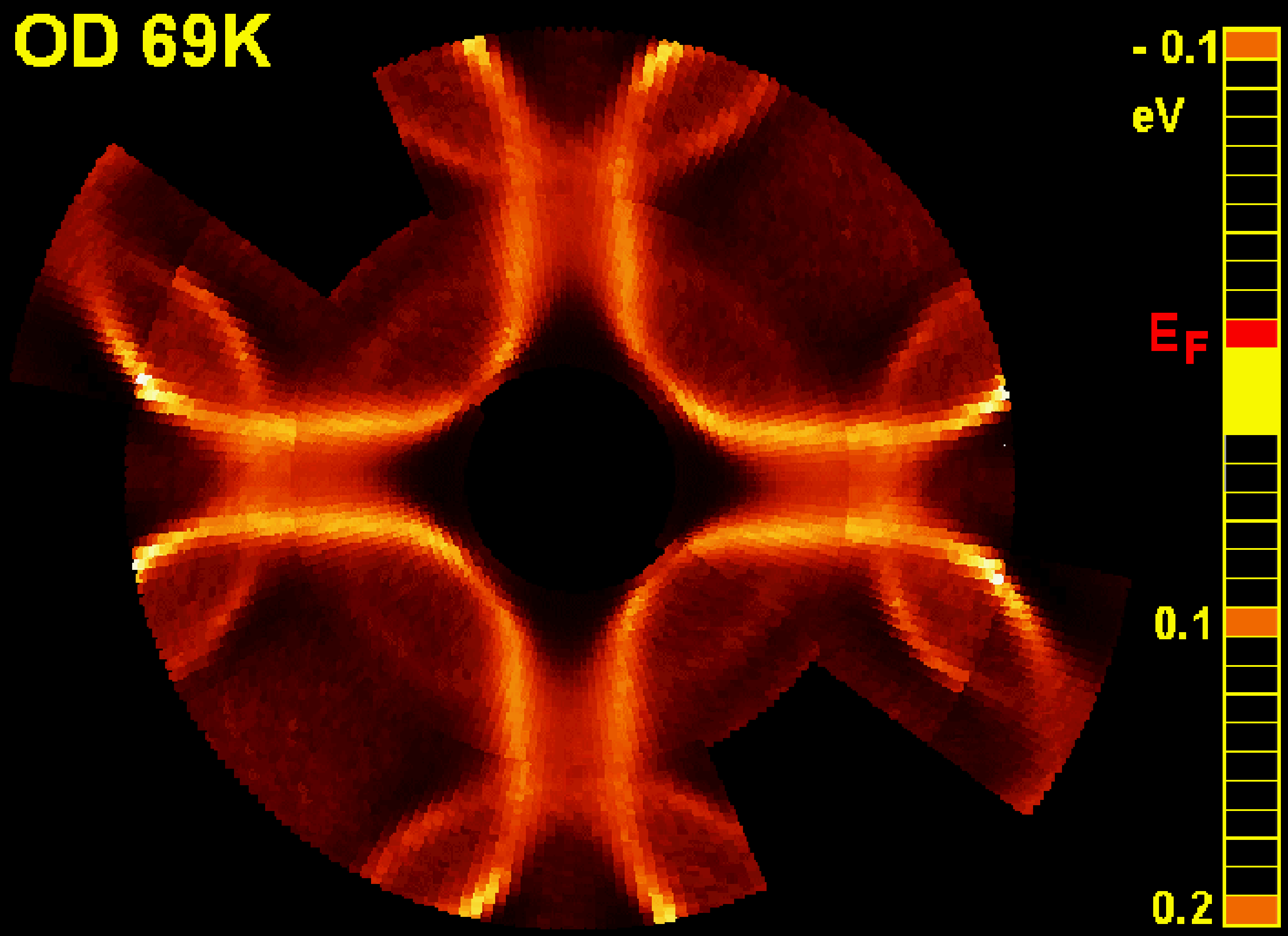


Momentum-energy space



Borisenko *PRB* 2001

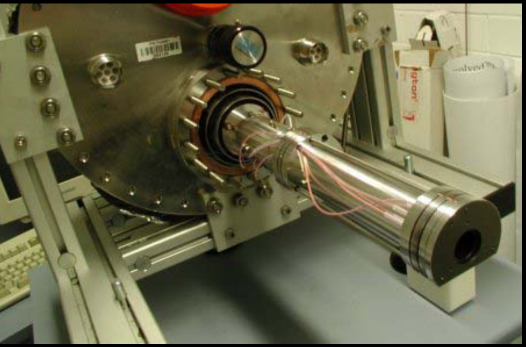
Momentum Distribution Map



300 K, 21.2 eV

Kordyuk 2000

Momentum-energy space explorer today



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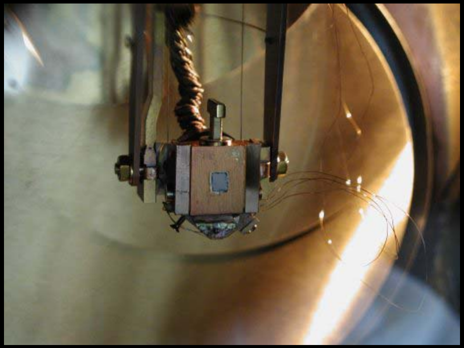

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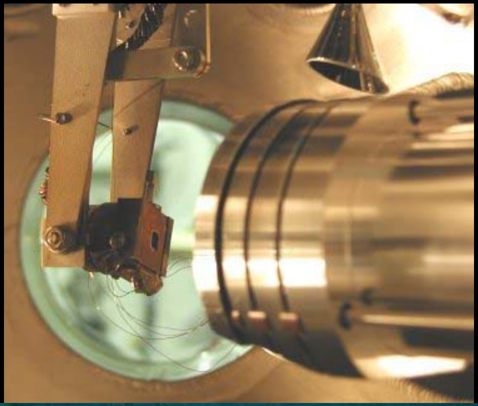

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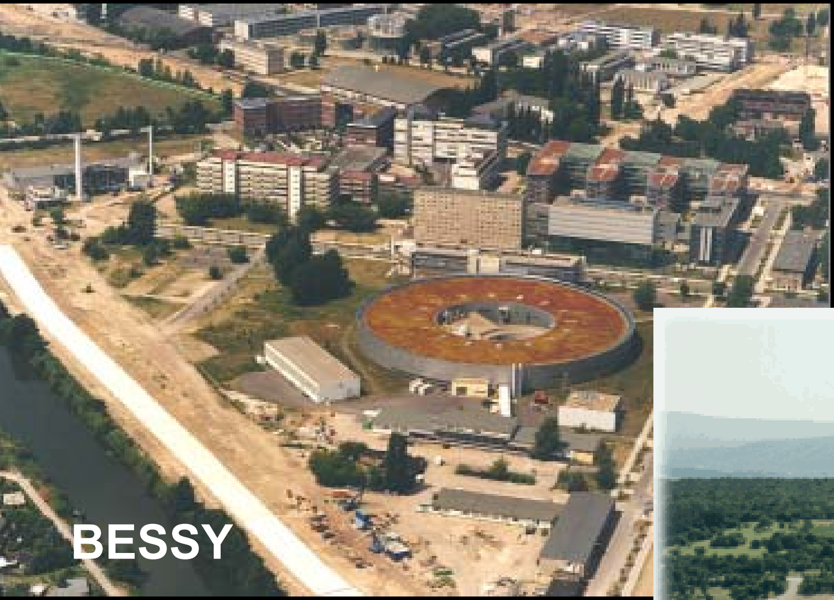
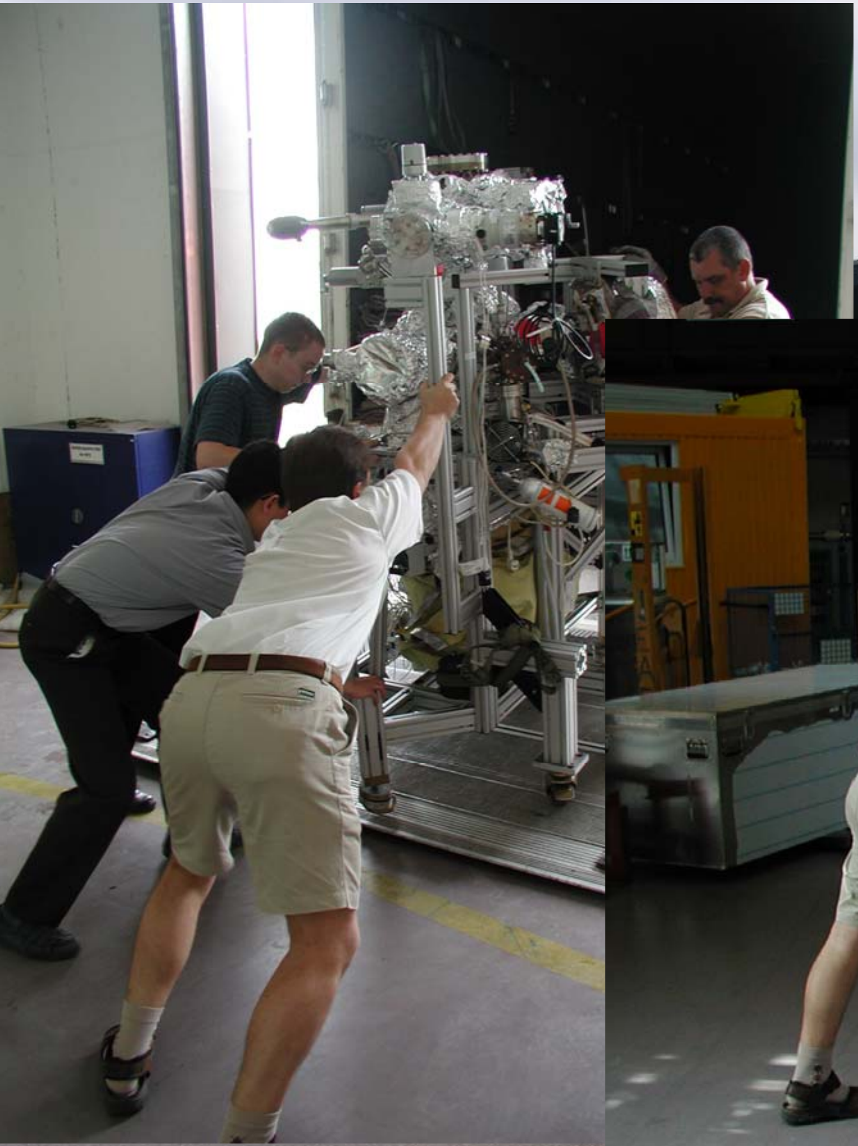
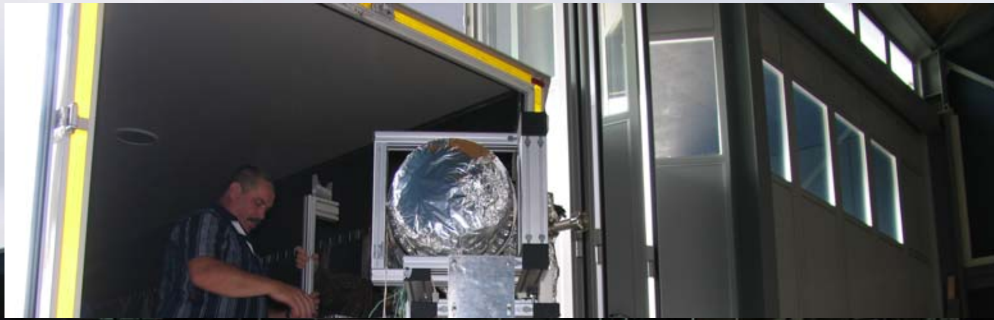


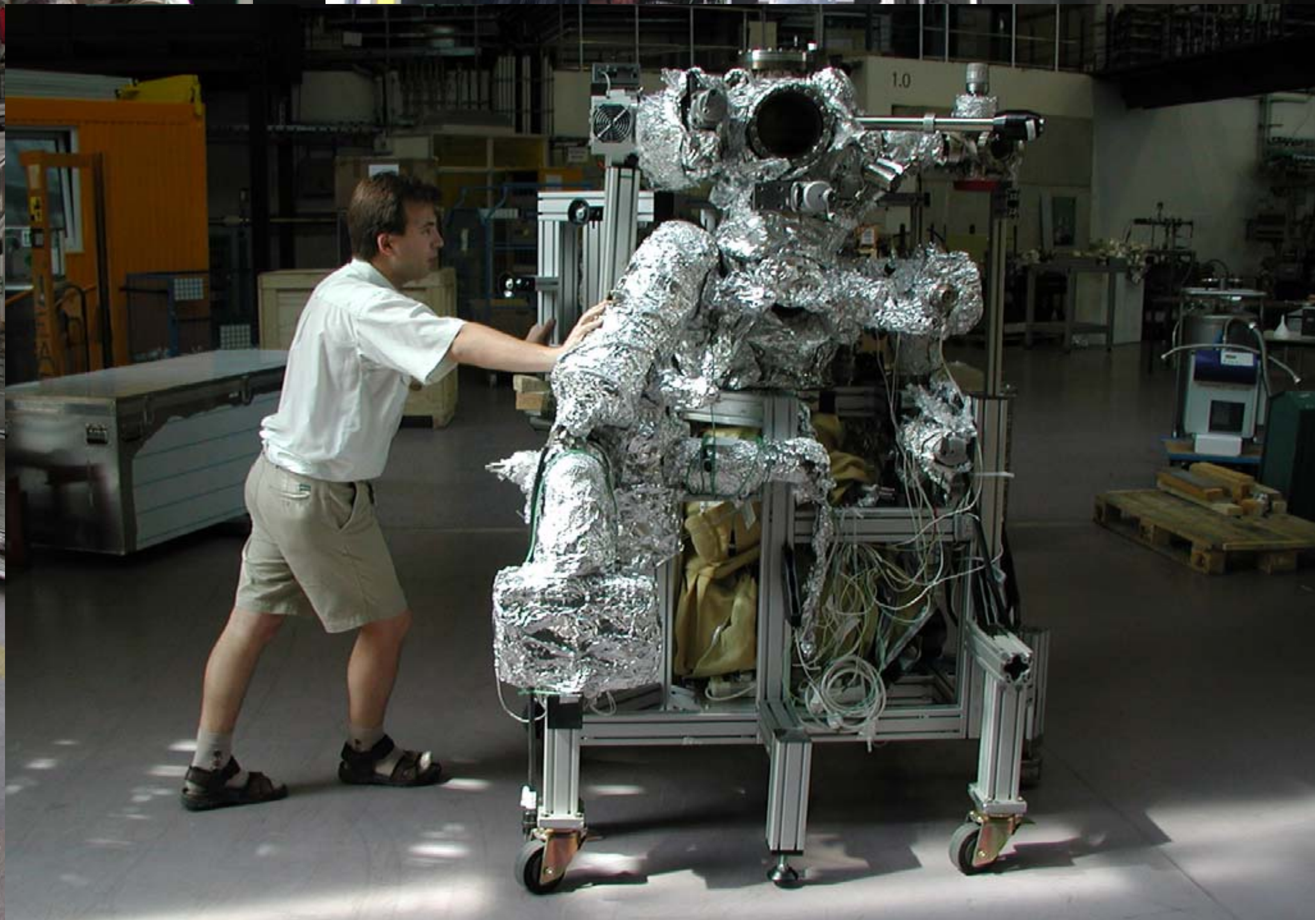
hν

more synchrotrons

...travelling chamber



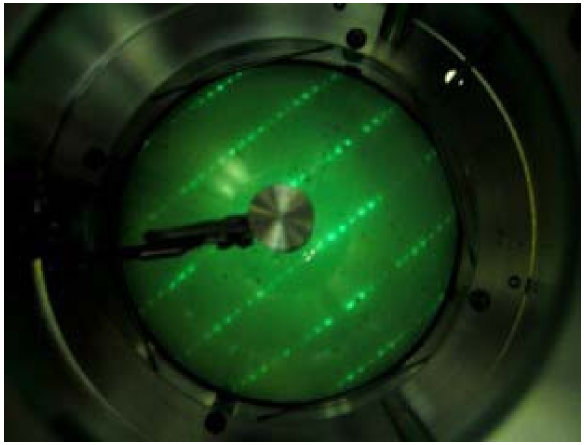


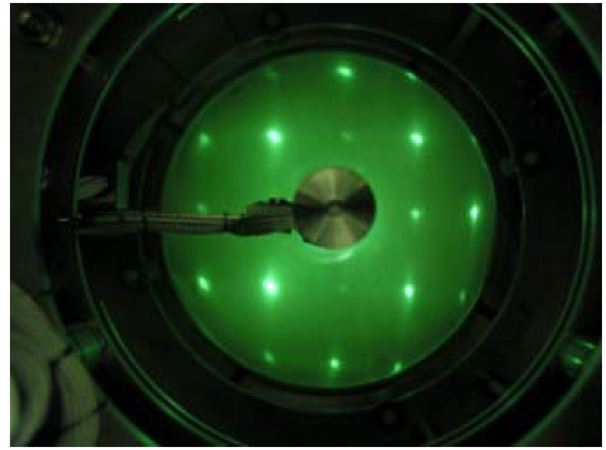


The advantages of our group

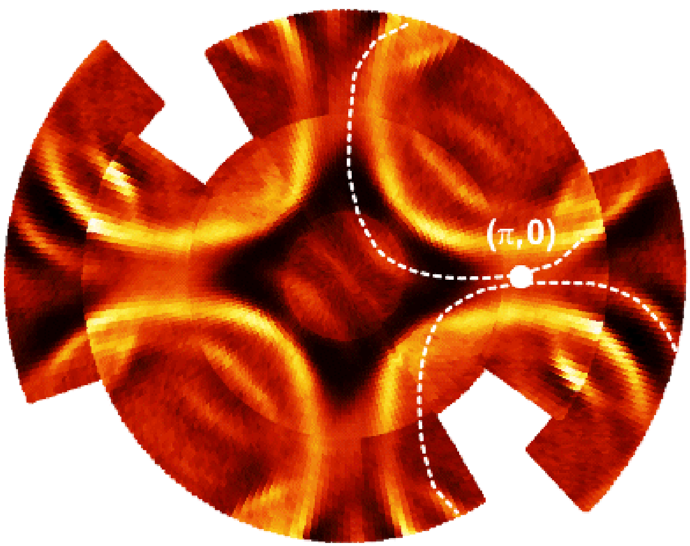
why Bi(Pb)-2212 is the best of the cuprates to be explored by ARPES

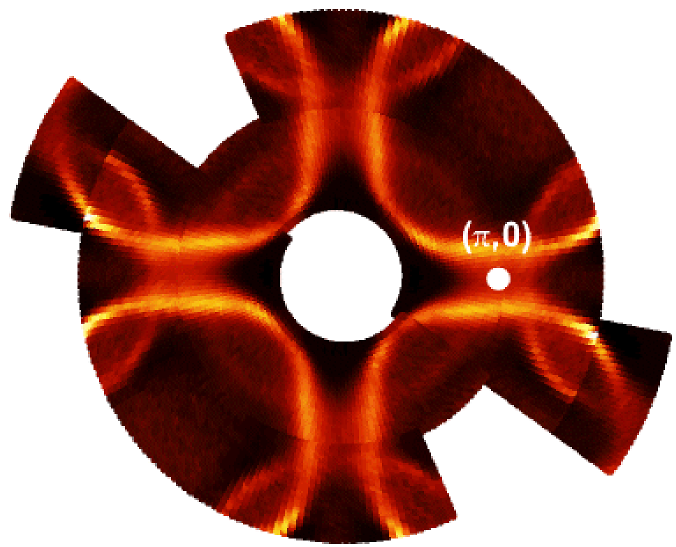
Pb or not Pb?



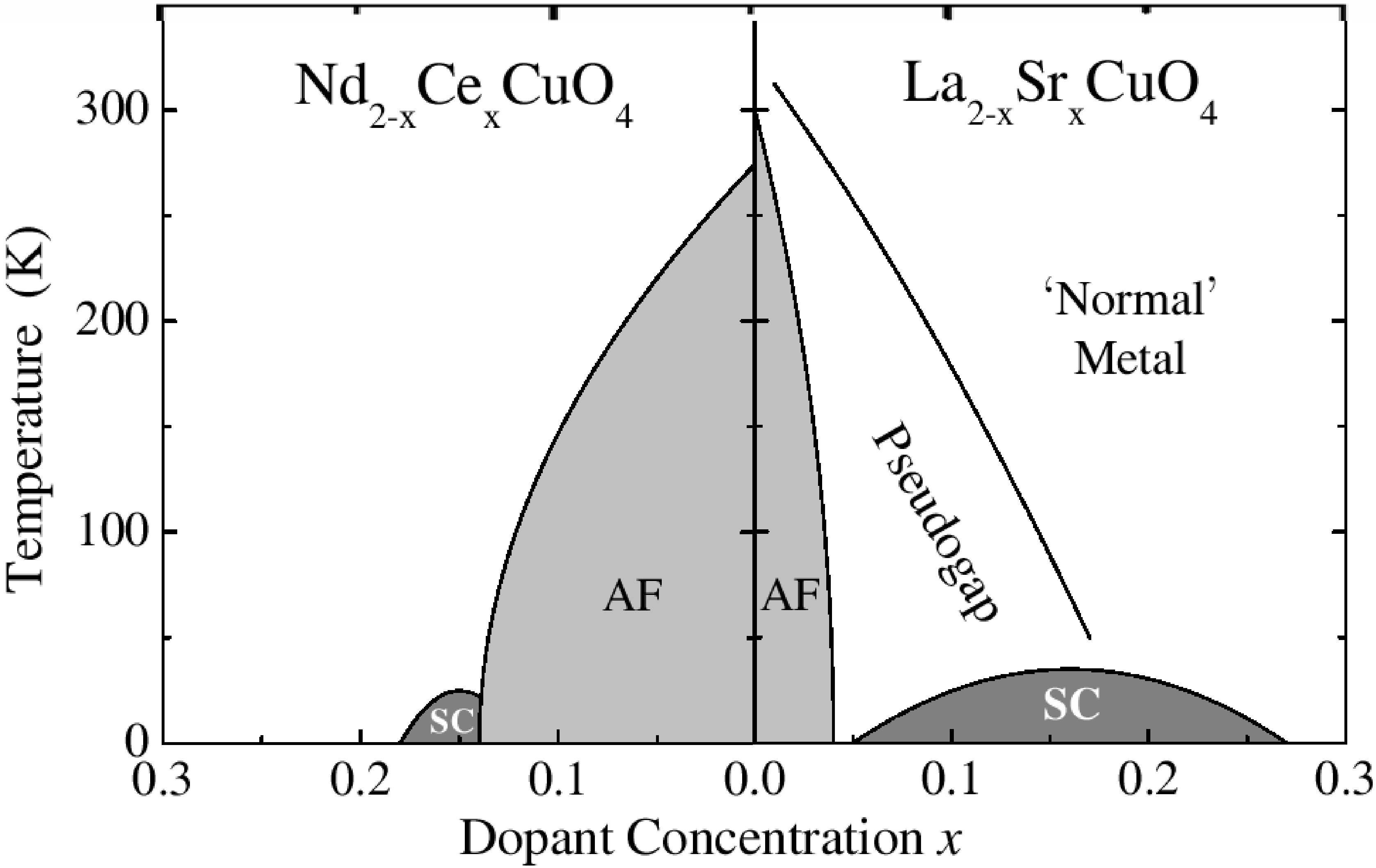


Bi2212 **Pb-Bi2212**

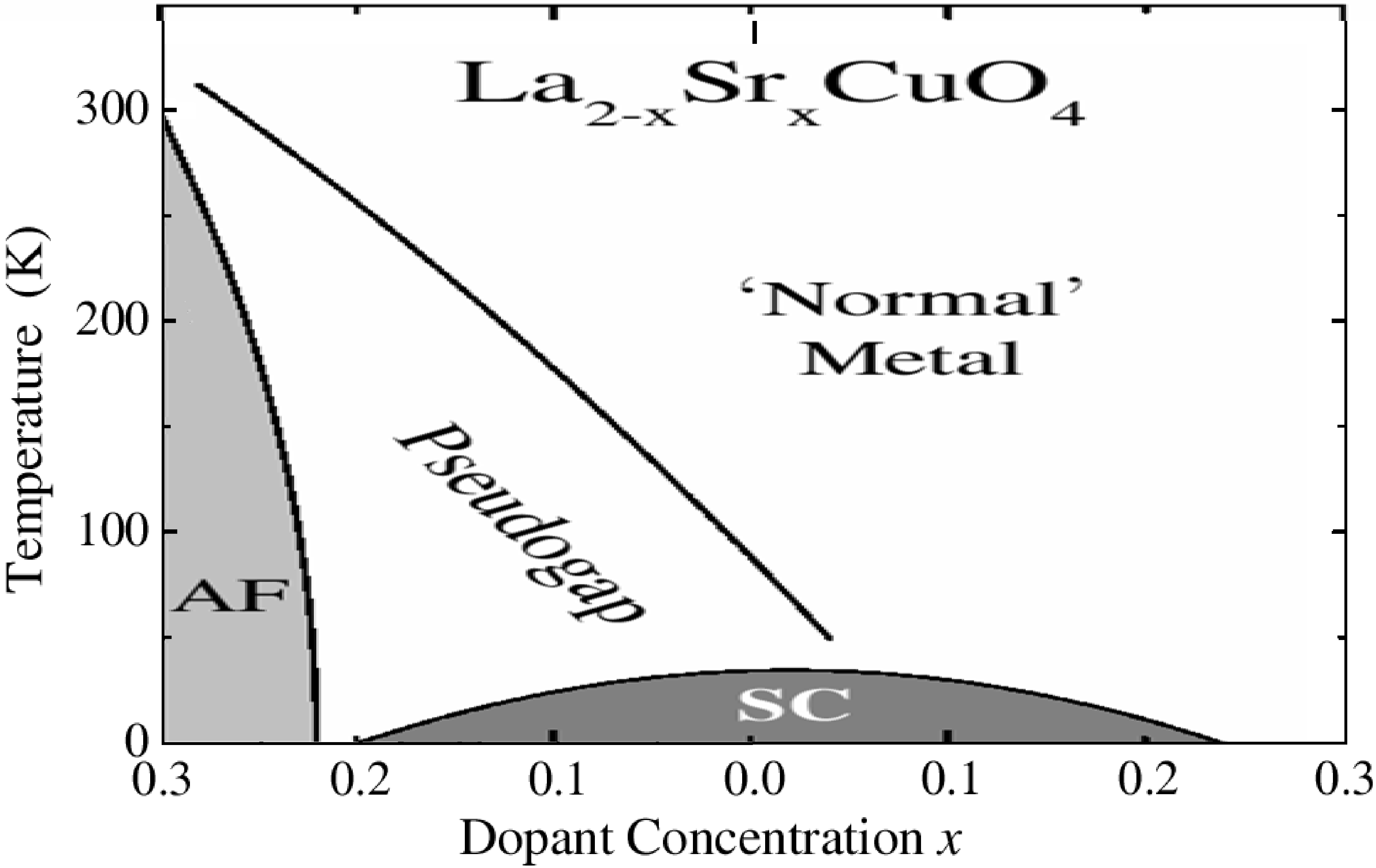




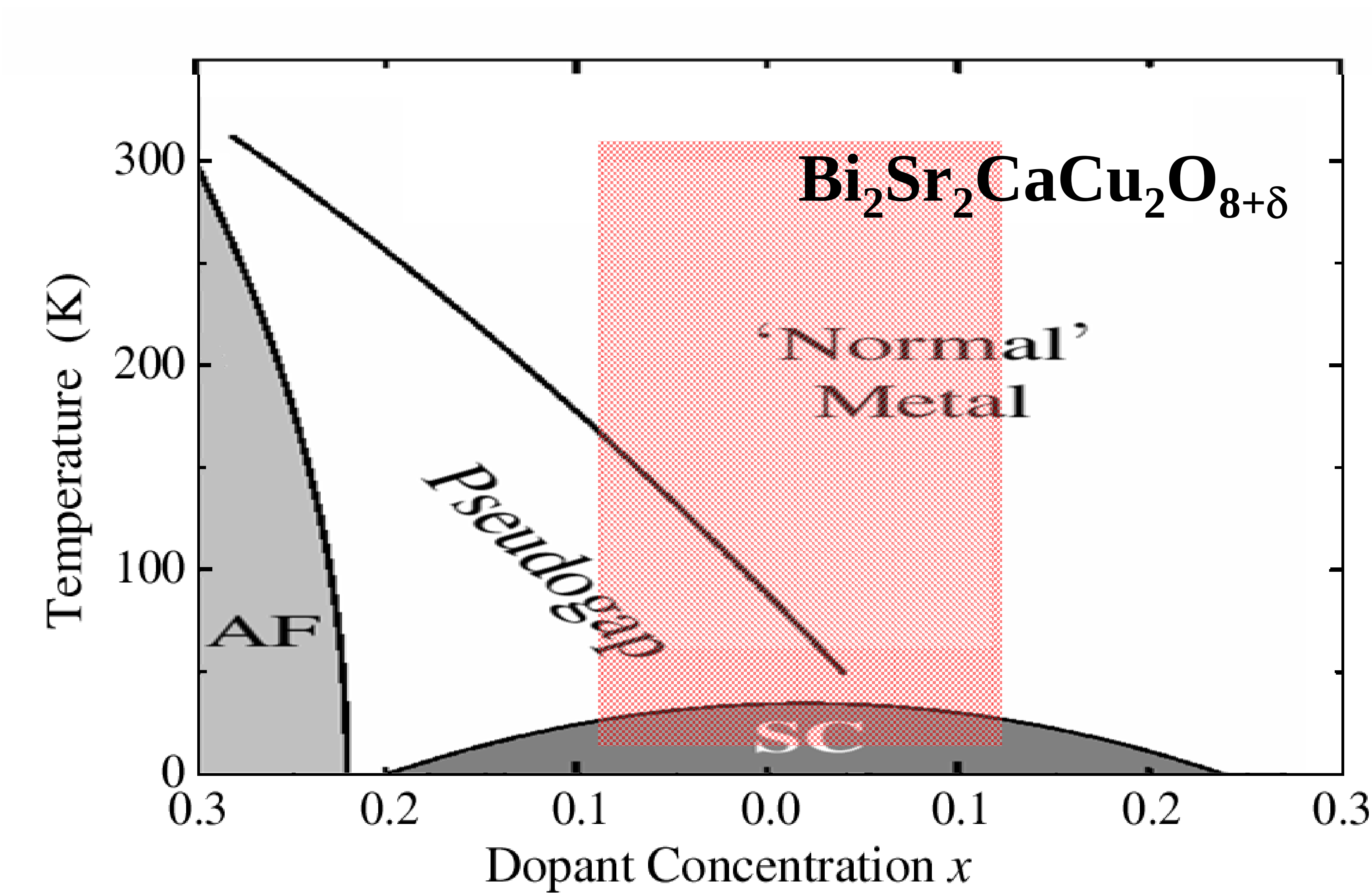
The region we explore



The region we explore

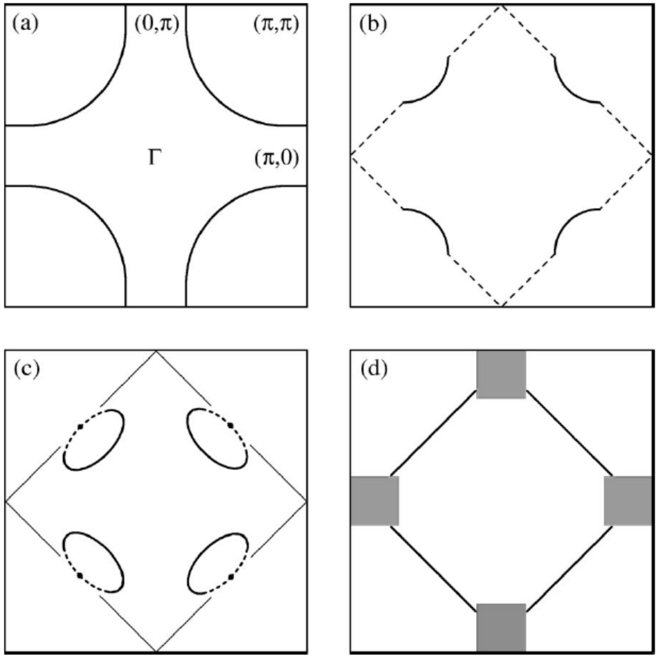


The region we explore

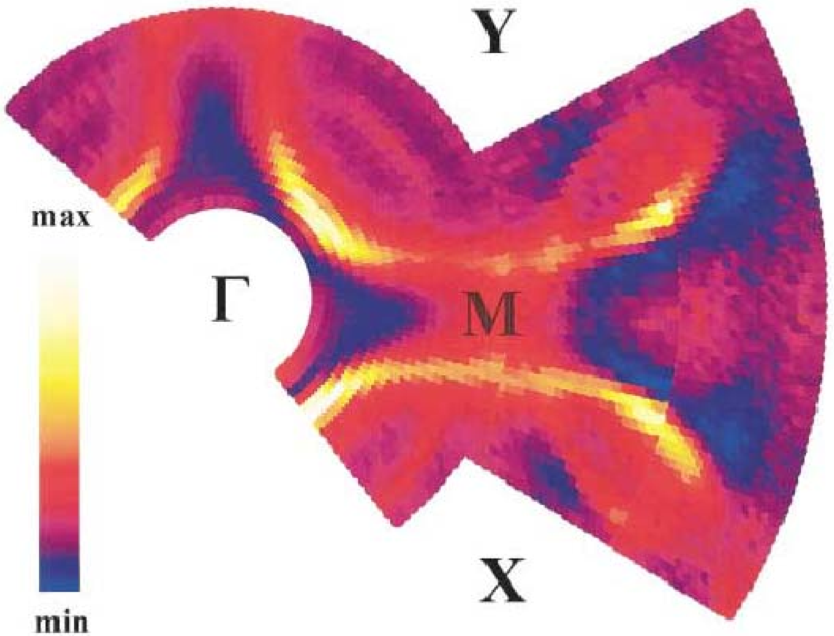


Complex structure
vs
complex physics

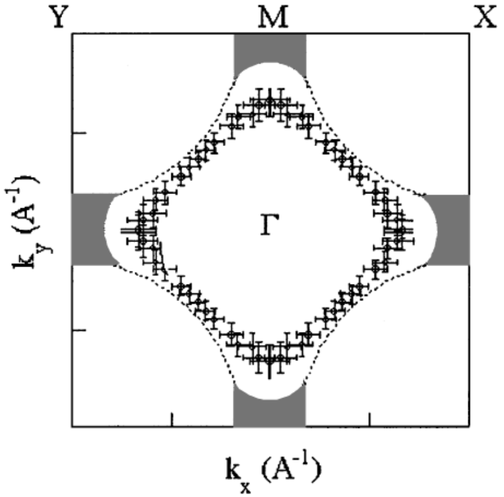
I. Fermi surface



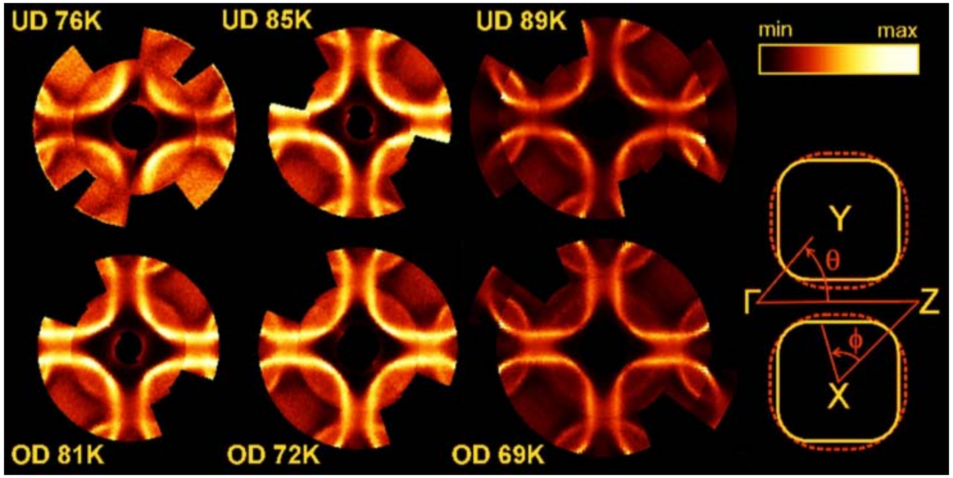
Damascelli *RMP* 2003



Borisenko *PRL* 2000

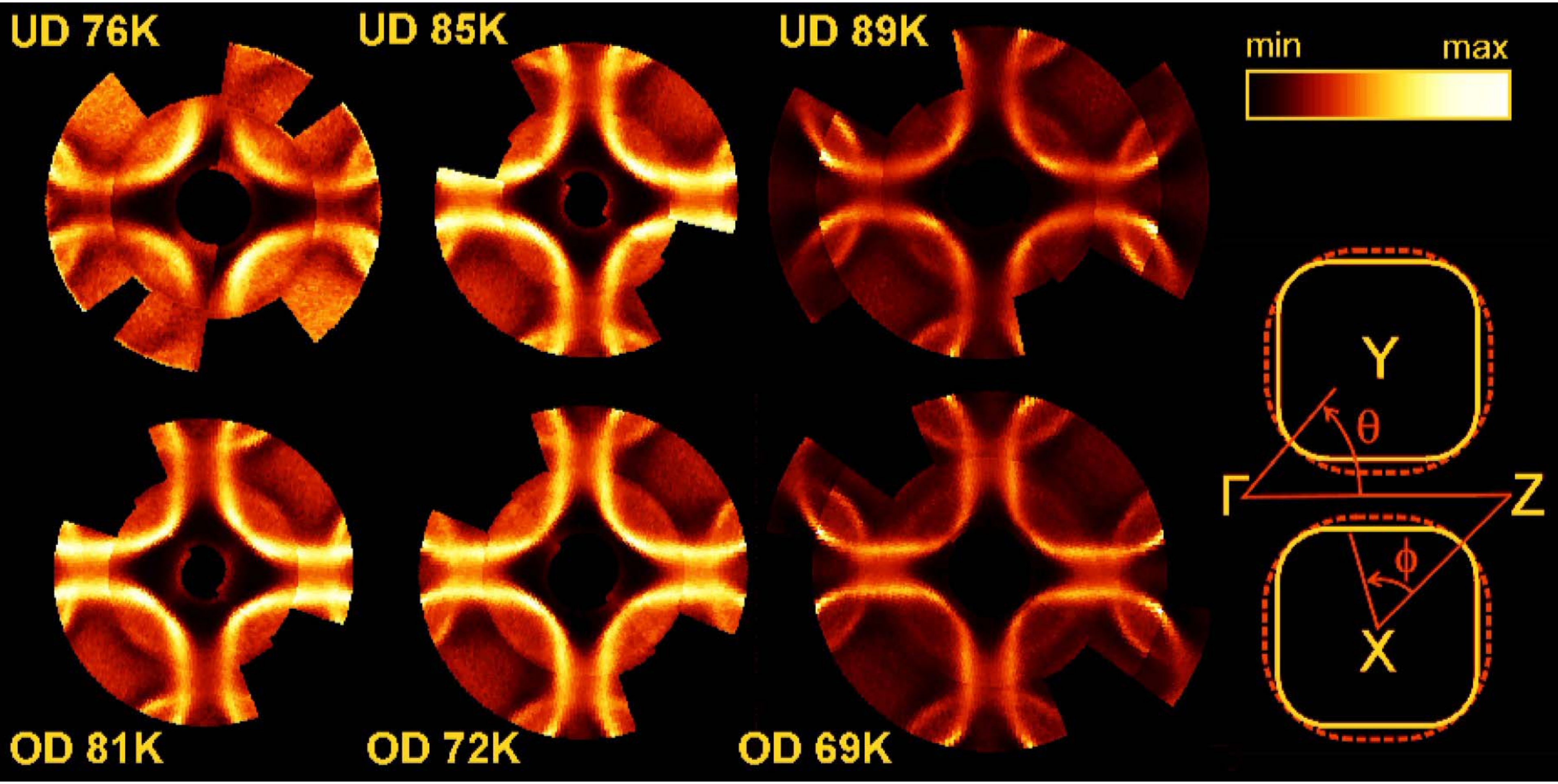


Bogdanov *PRL* 2000



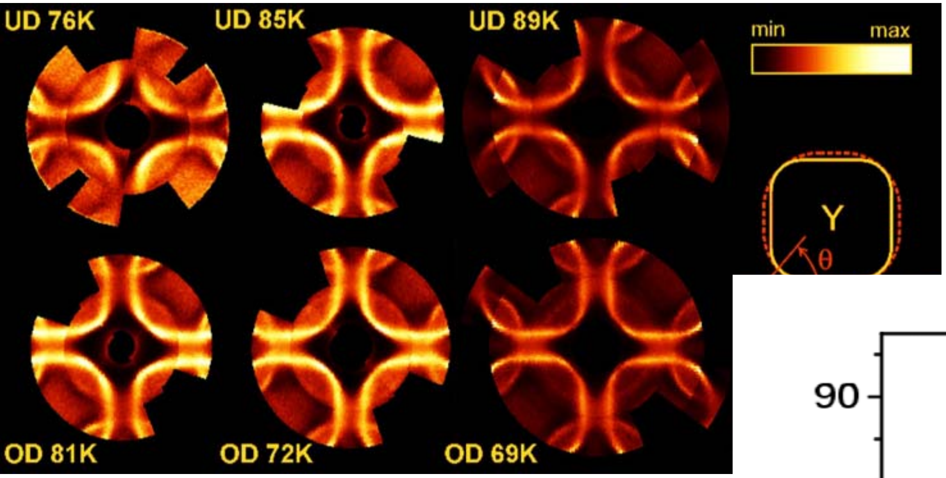
Kordyuk *PRB* 2002

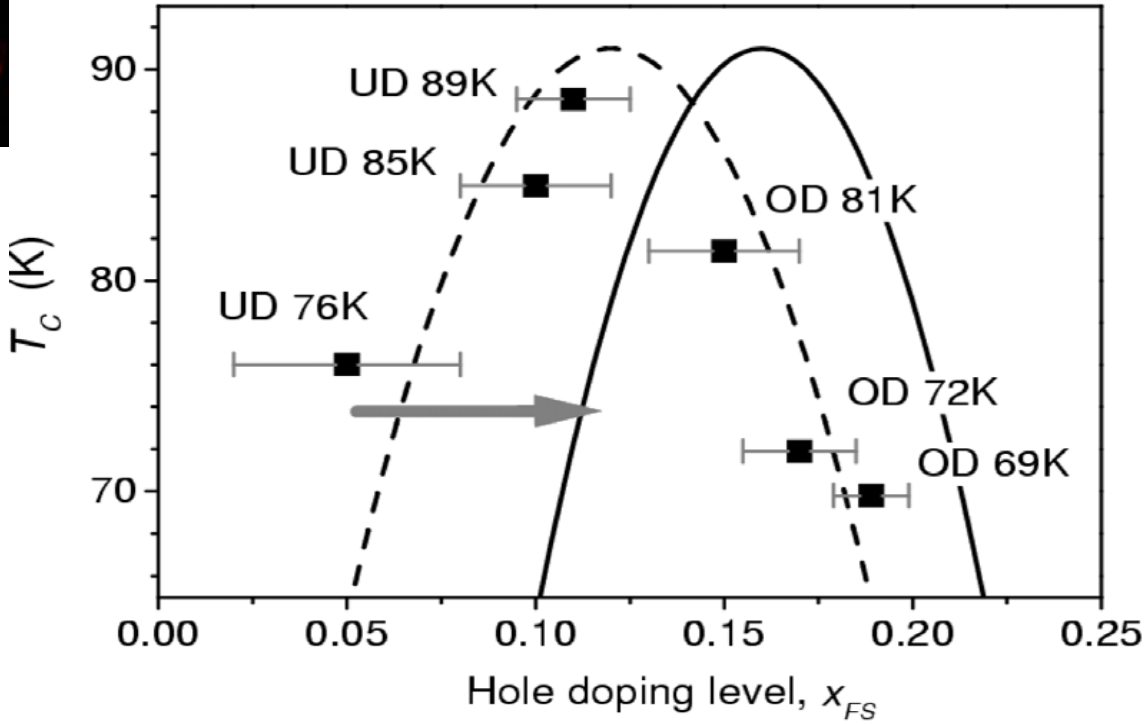
Fermi surface of Bi(Pb)-2212: doping dependence



Kordyuk *PRB* 2002

A set of superstructure-free Bi(Pb)-2212 in a wide doping range with known doping level





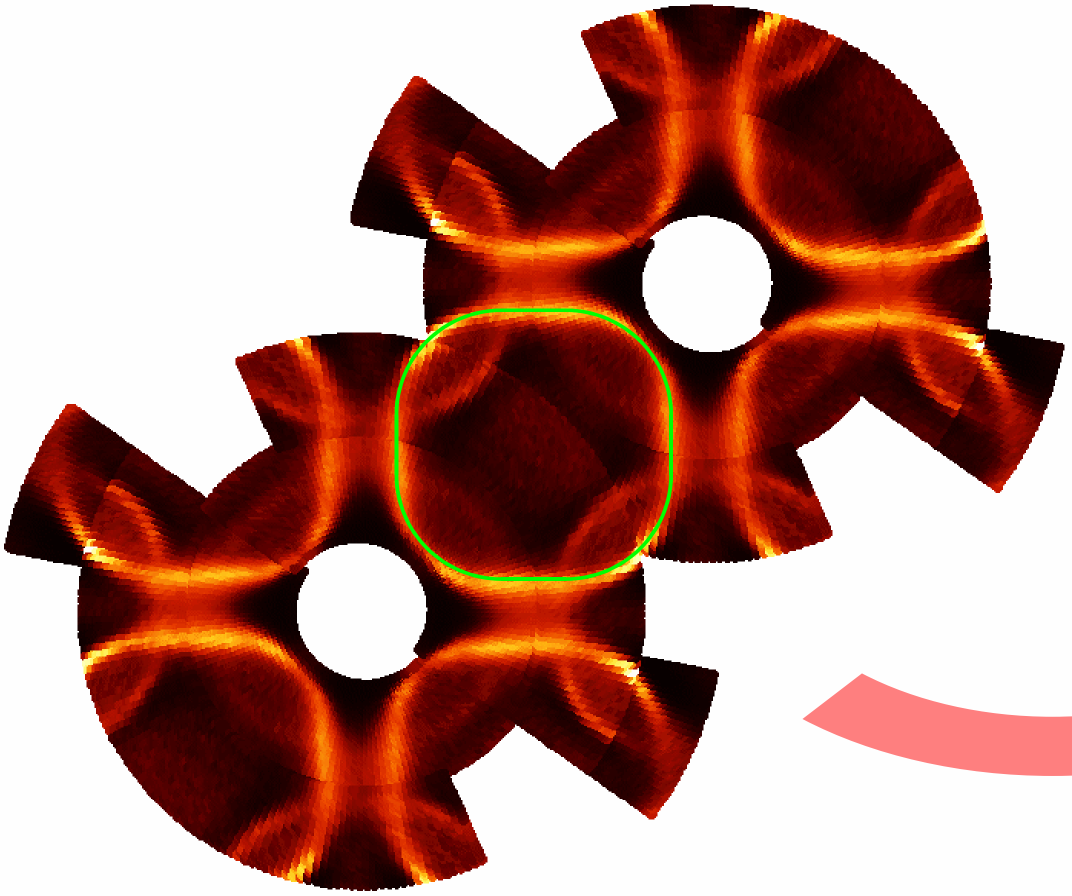
$$S_{FS} = (1 - x)/2$$

"Large Fermi surface"

Kordyuk *PRB* 2002

II. Band structure: TBF

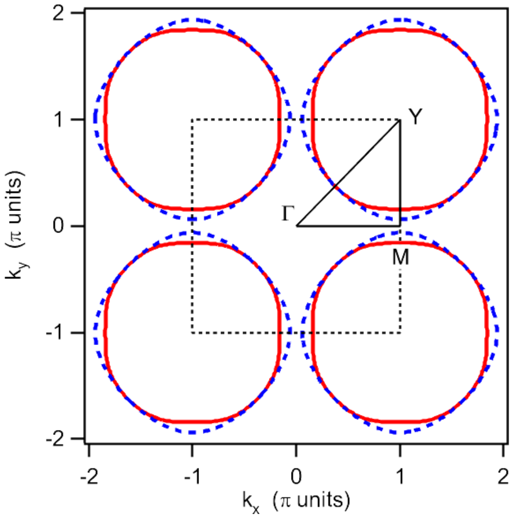
$$\varepsilon(k_x, k_y) = \Delta\varepsilon - 2t(\cos k_x + \cos k_y) + 4t' \cos k_x \cos k_y - 2t''(\cos 2k_x + \cos 2k_y)$$



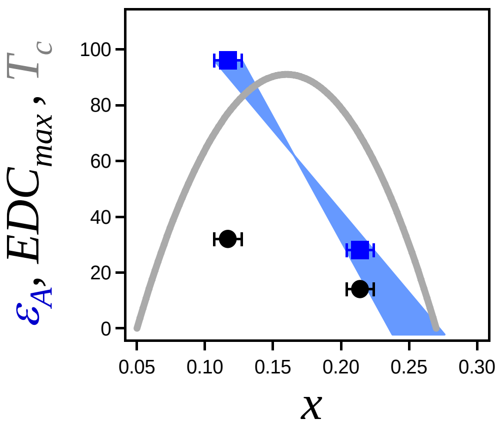
$$\Delta\varepsilon \approx 0.4\,\mathrm{eV}$$
$$t \approx 0.4\,\mathrm{eV}$$
$$t' \approx 0.1\,\mathrm{eV}$$
$$t'' \approx 0.05\,\mathrm{eV}$$

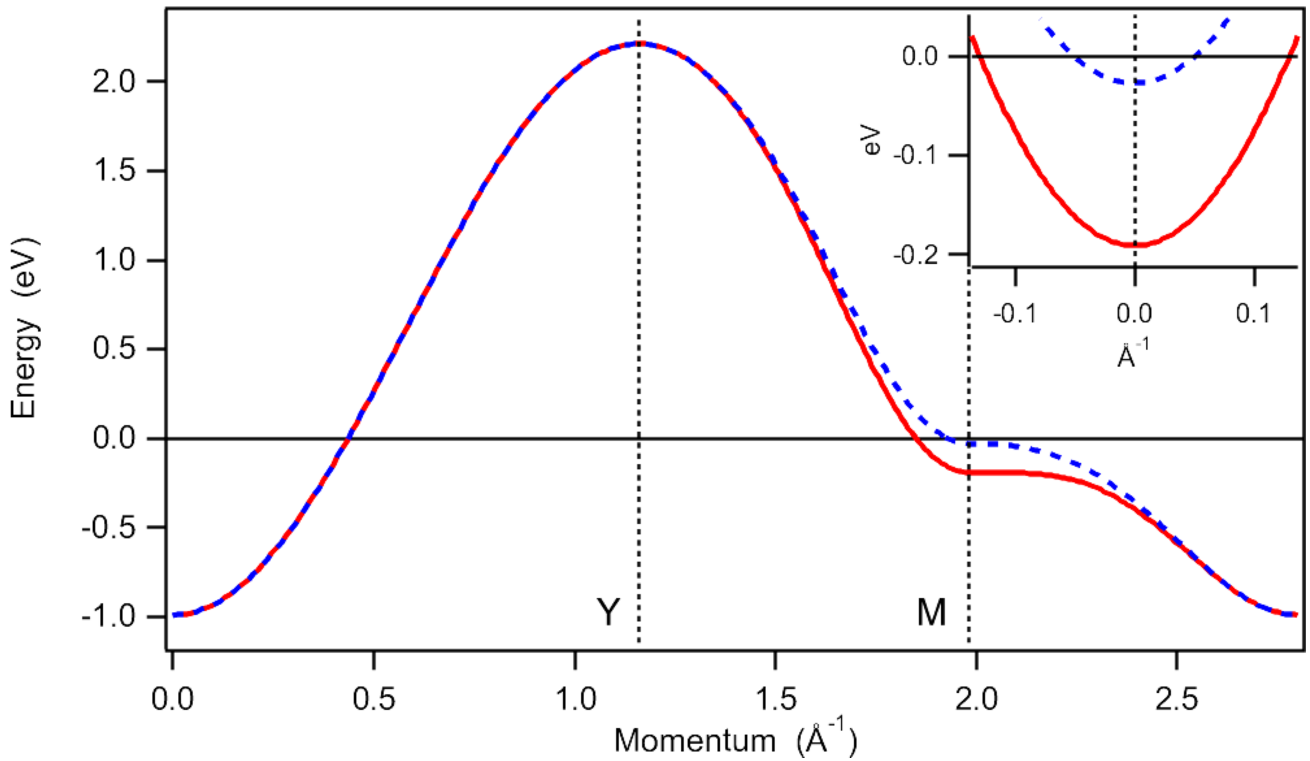
Kordyuk *PRB* 2003

Bare band structure



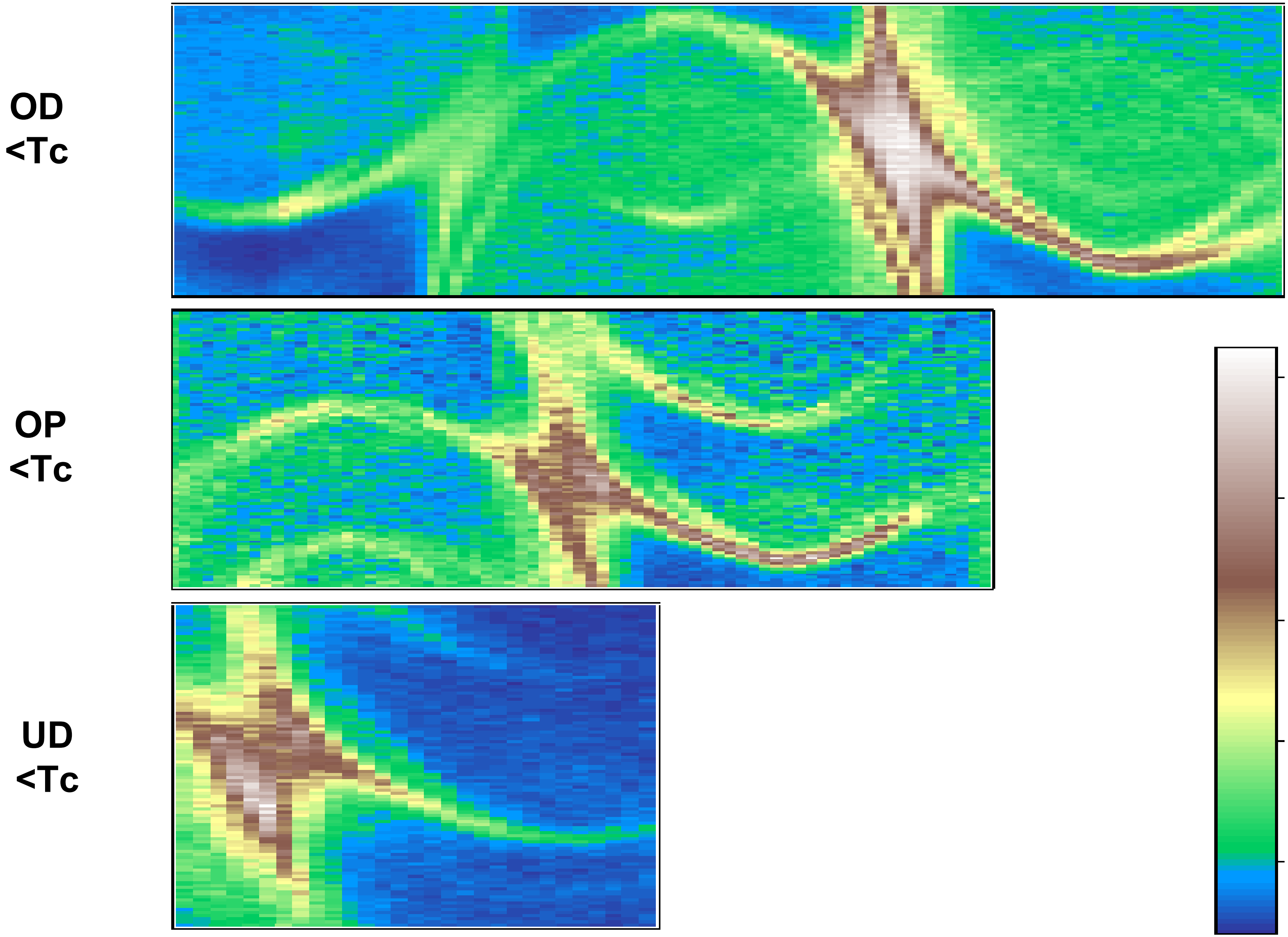
Sample	t (eV)	t' (eV)	t'' (eV)	$t_\perp$ (eV)	$\Delta\epsilon$ (eV)
OD 69 K	0.40	0.090	0.045	0.082	0.43
UD 77 K	0.39	0.078	0.039	0.082	0.29



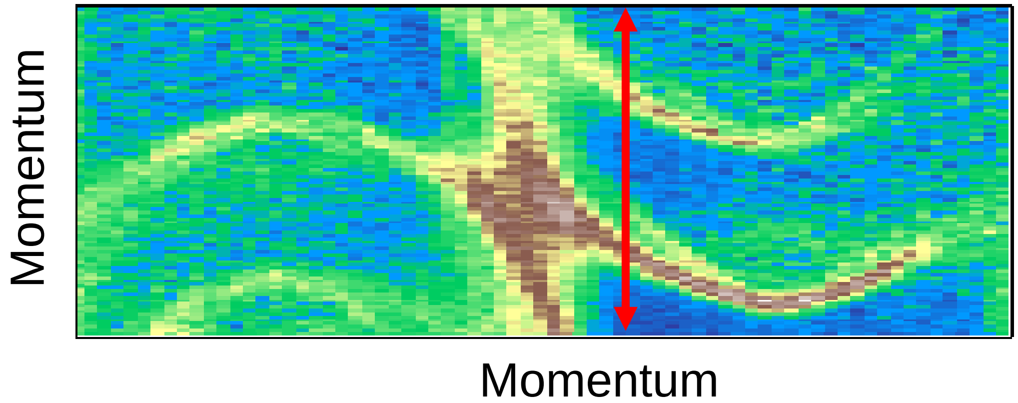


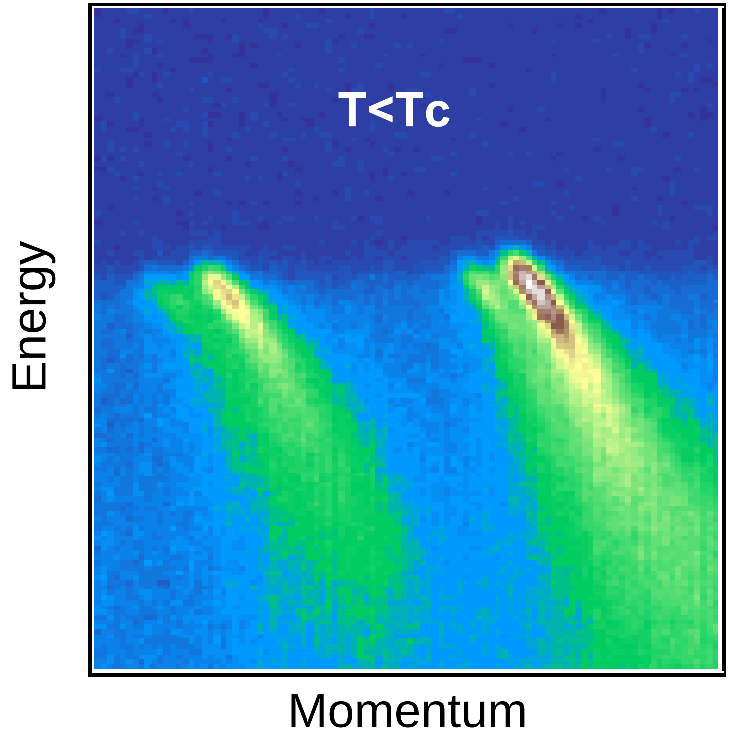
Kordyuk *PRB* 2003

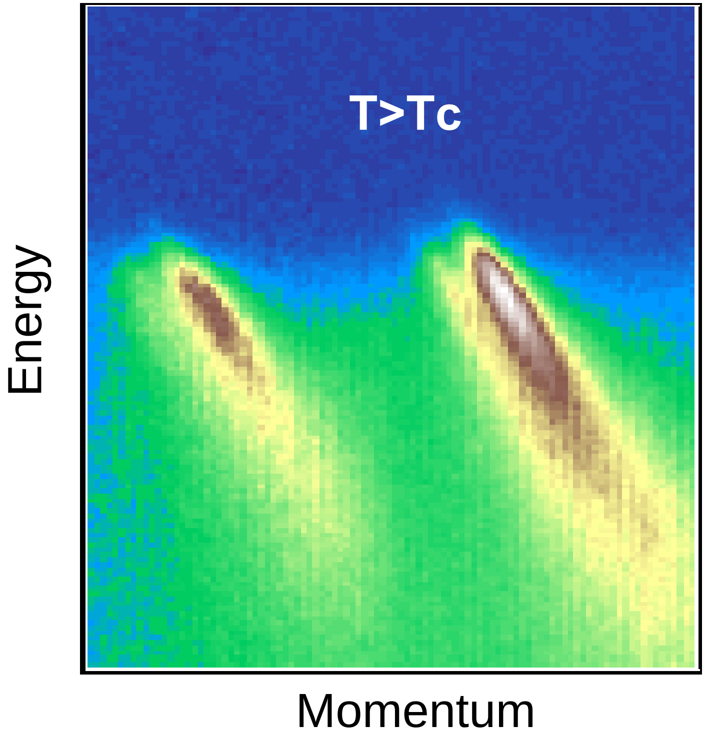
High precision Fermi surface mapping



Bilayer splitting in OP Bi-2212 in normal state







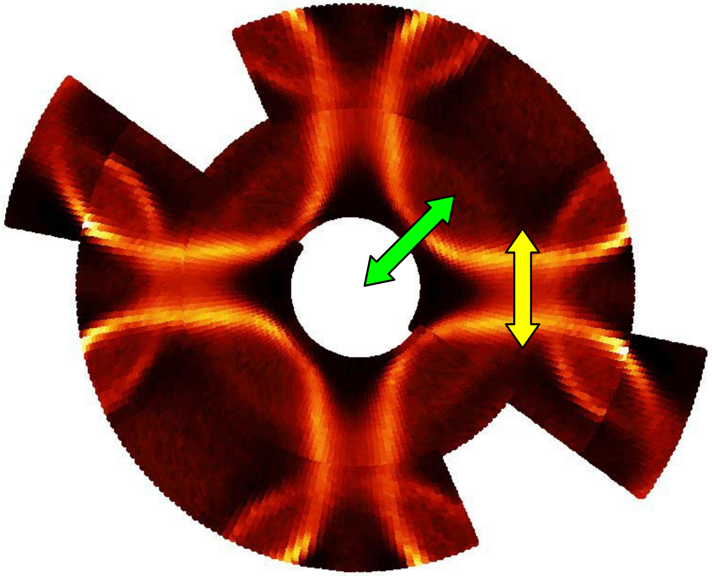
1. **Physics of HTSC is not so complex as believed but electronic structure is.**

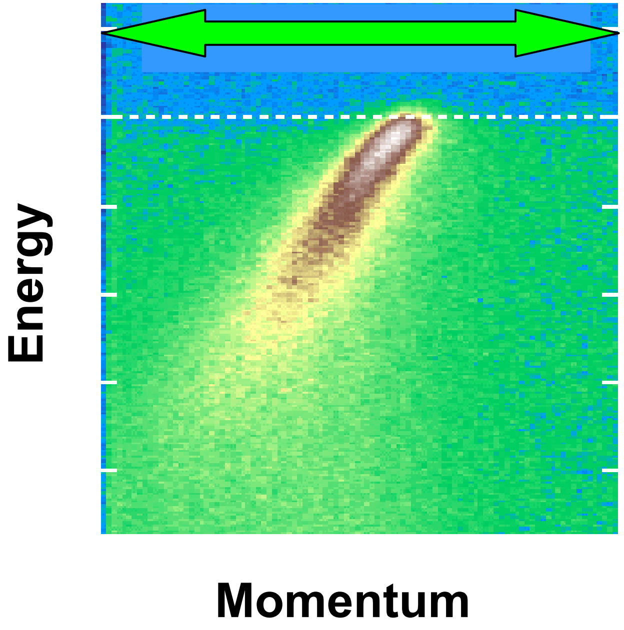
2. **Large Fermi surface and metallic behavior implies a phase separation.**

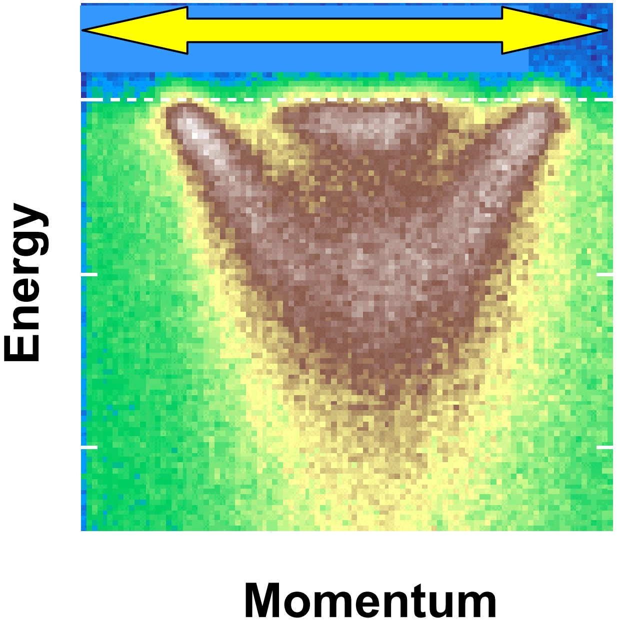
3. **The superconductivity which occurs in the metallic phase and is highly influenced by electronic structure.**

4. **What is complex then?**

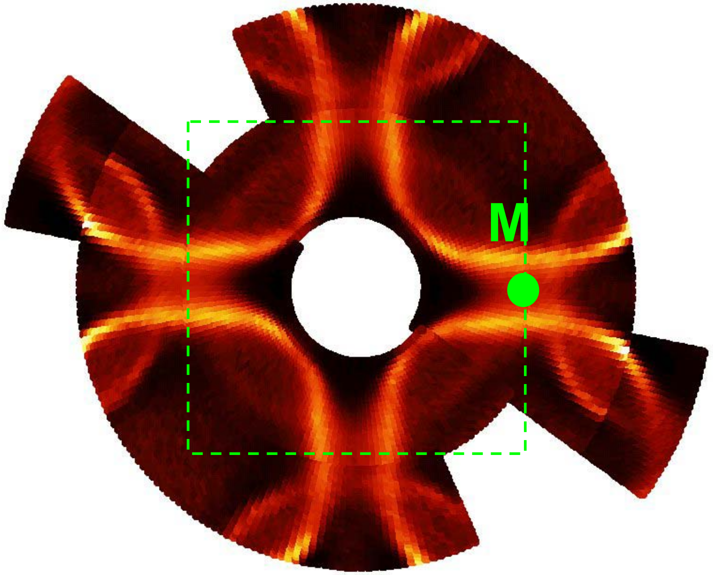
Key regions





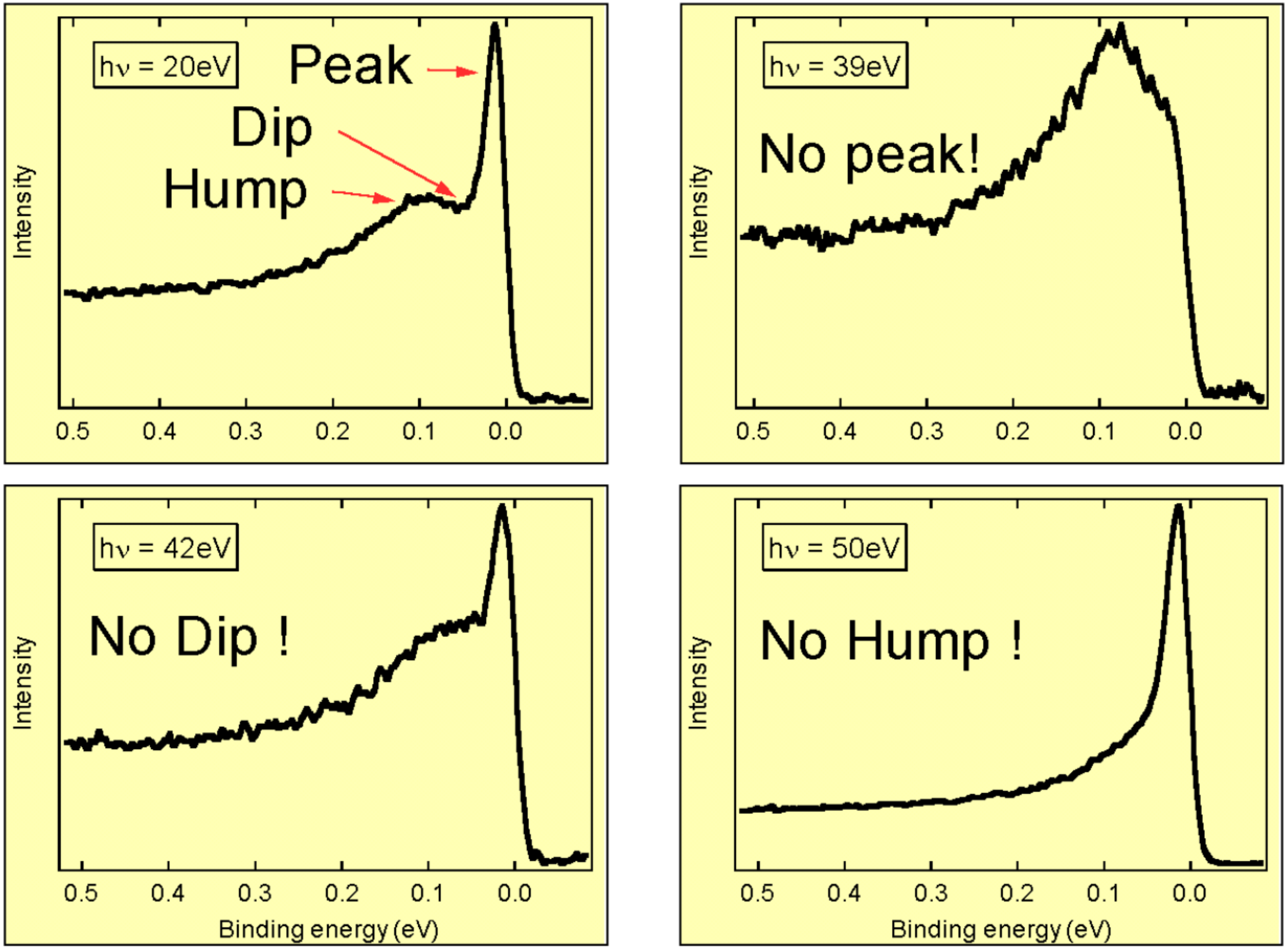


Saddle point



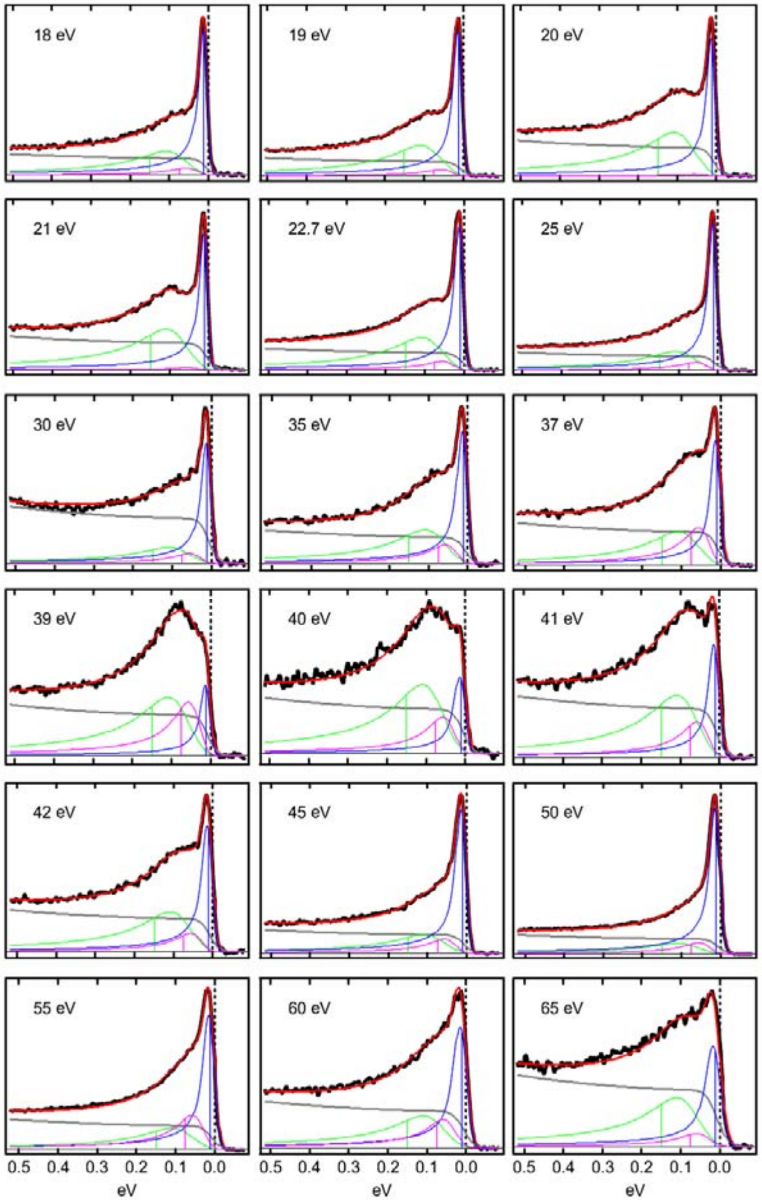
$(\pi,0)$

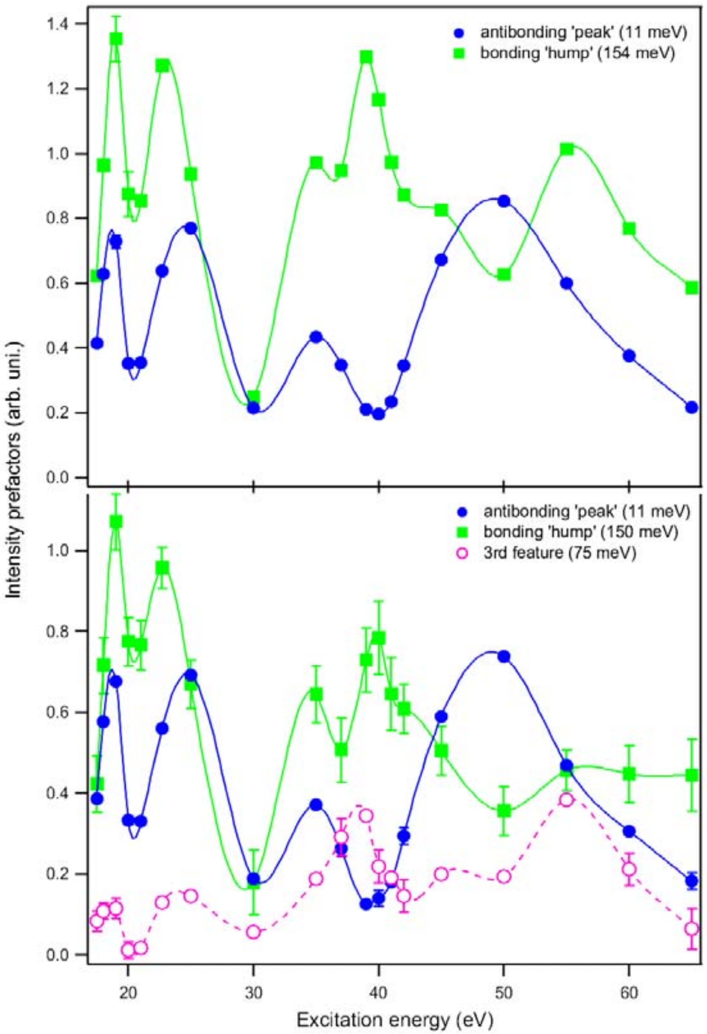
Excitation energy variation: PDH in OD



Kordyuk *PRL* 2002

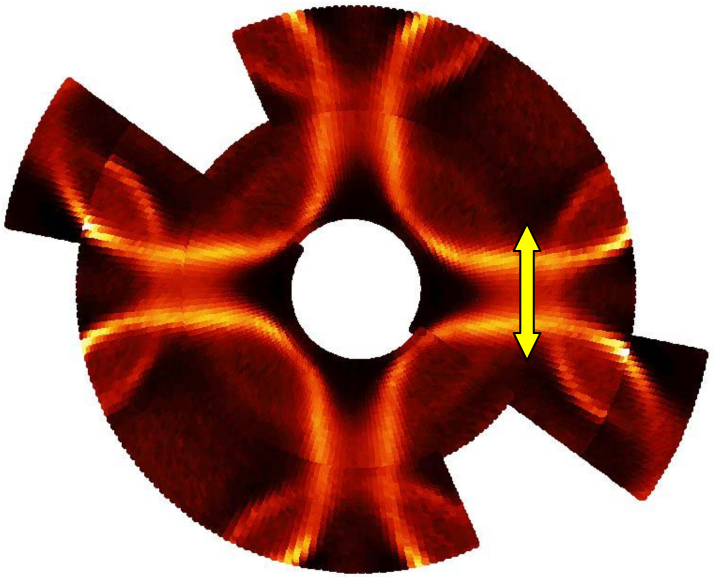
Excitation energy variation: PDH in OD



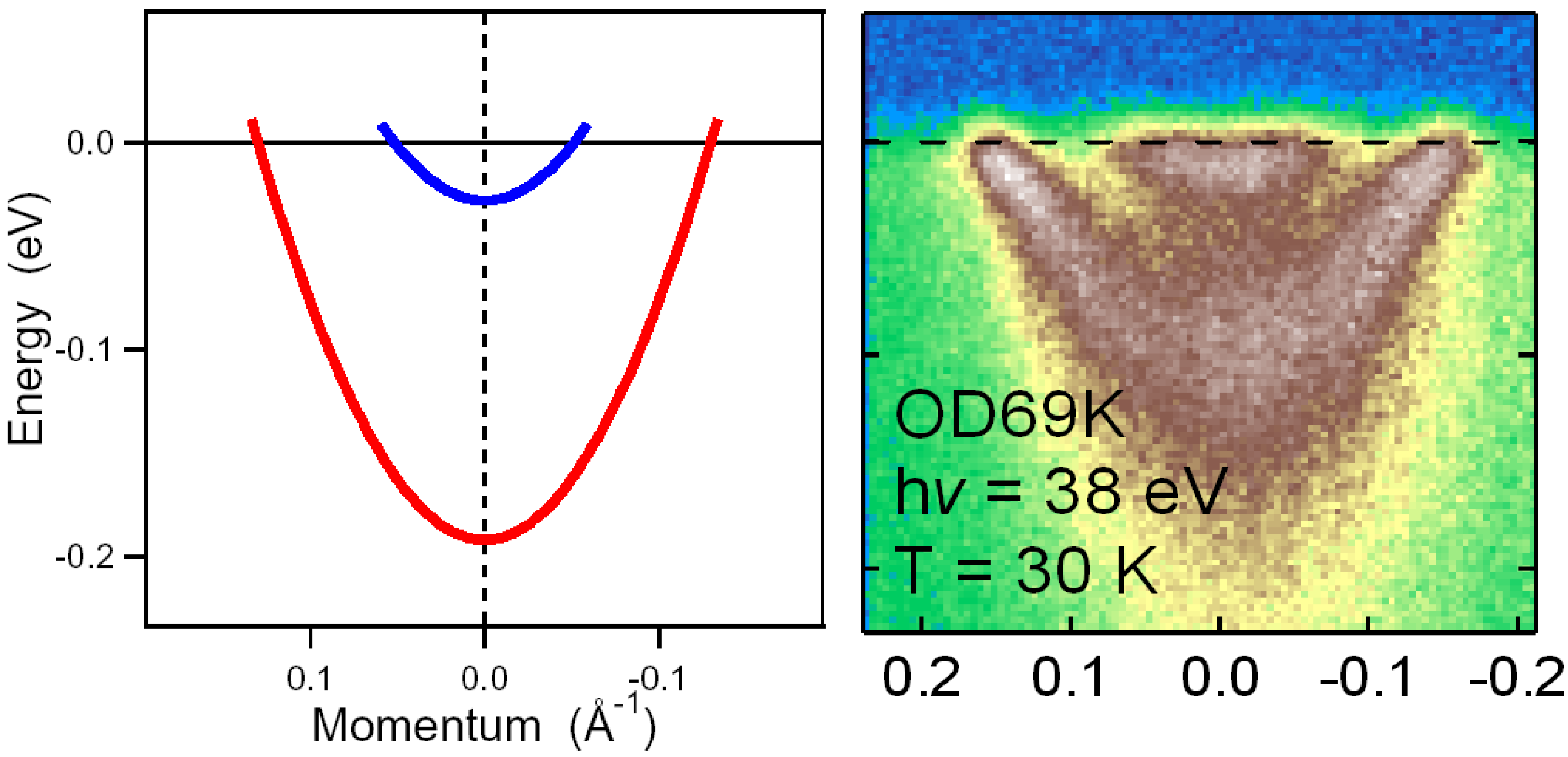


Kordyuk *PRL* 2002

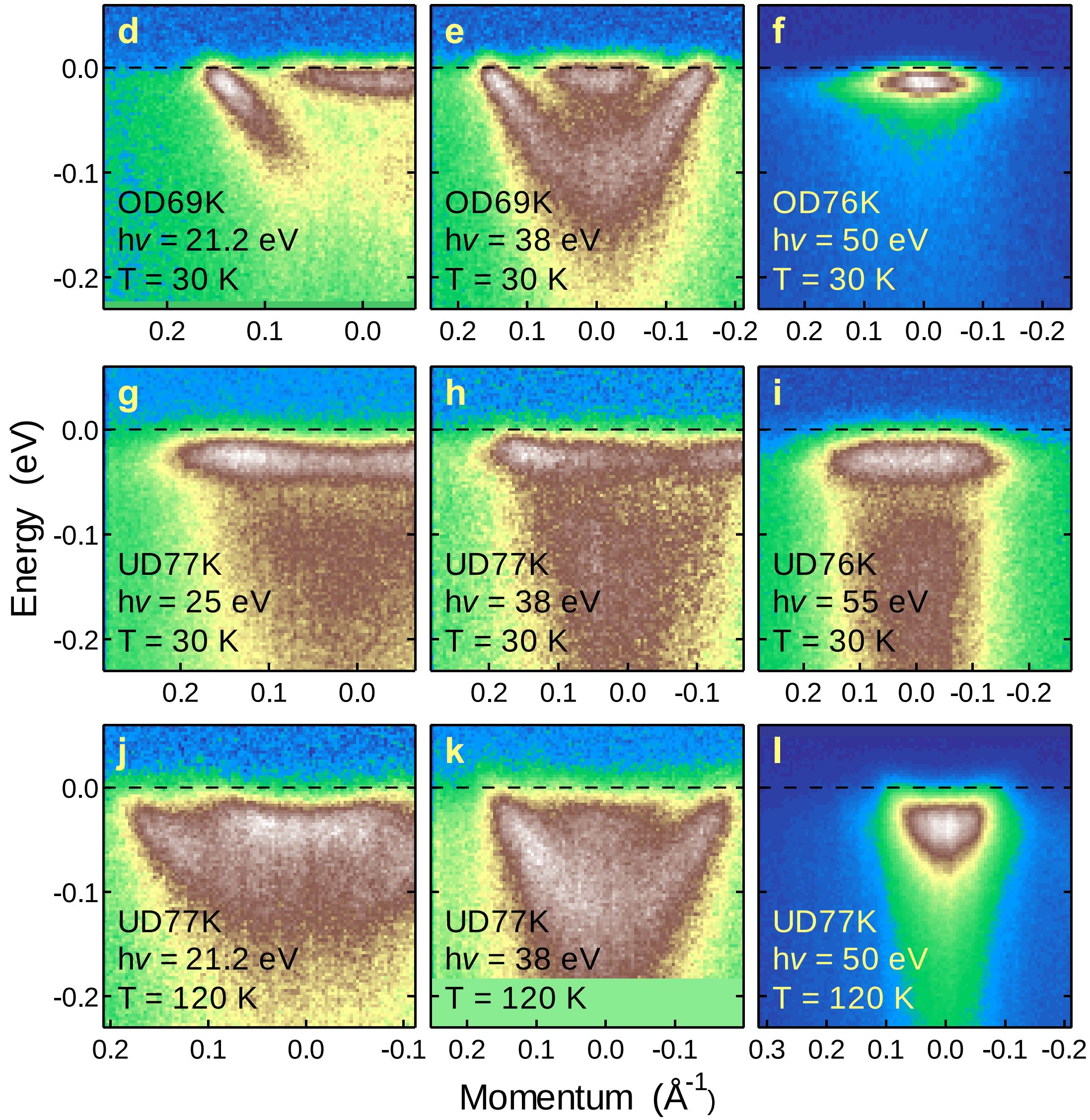
Antinodal region (XMY)



Antinodal or "XMY cut"

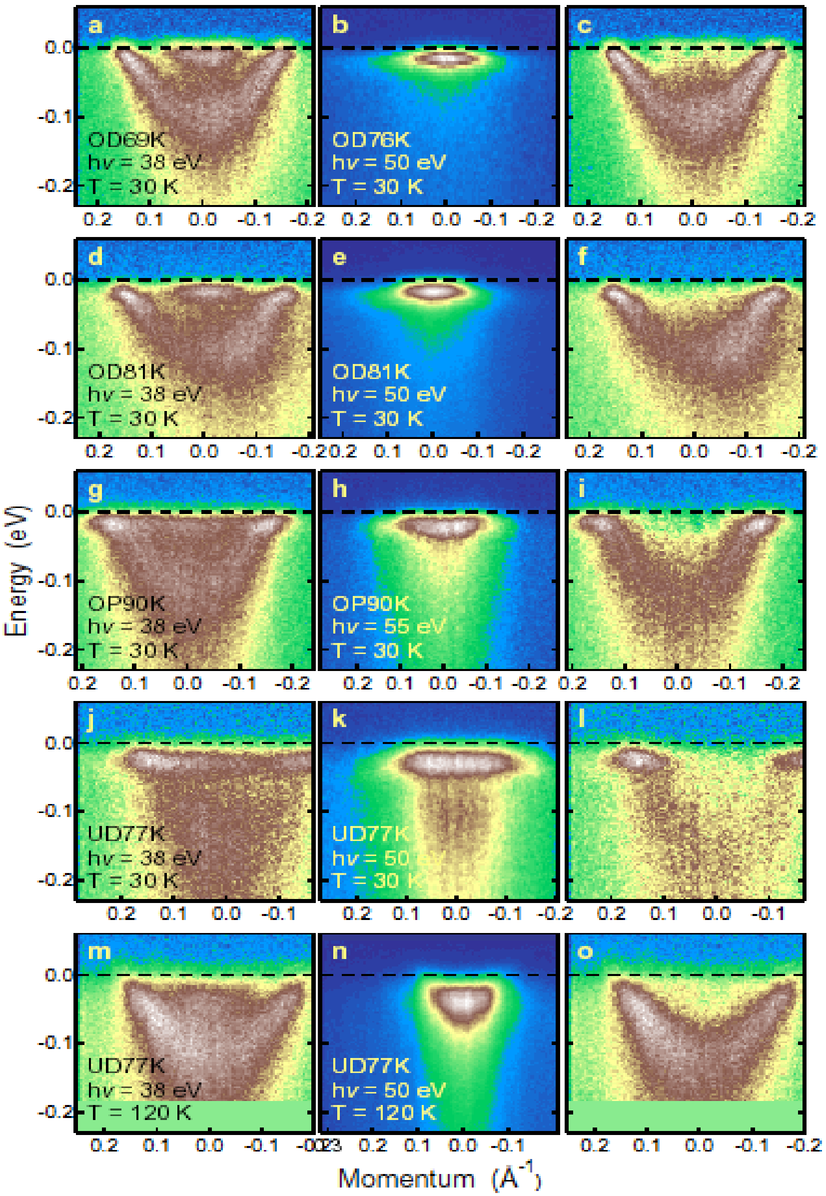


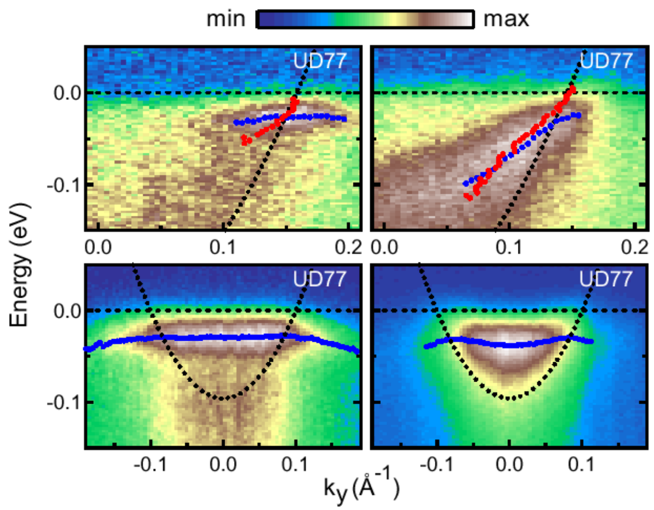
Interaction with a mode

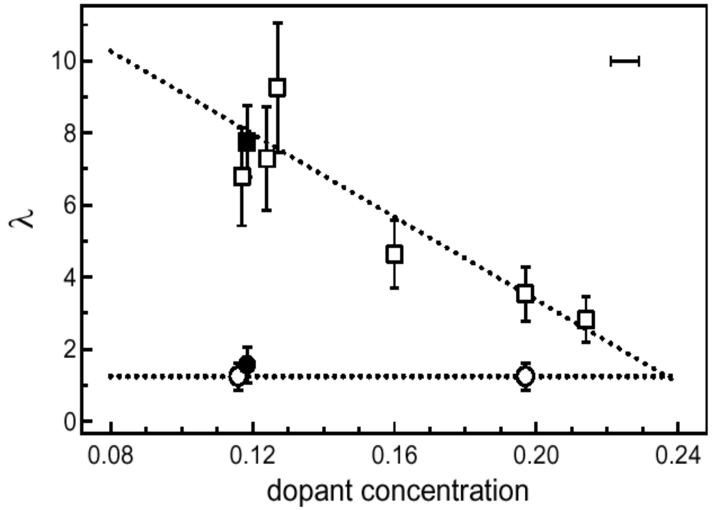


Borisenko *PRL* 2003

Interaction with a mode







Kim *PRL* 2003

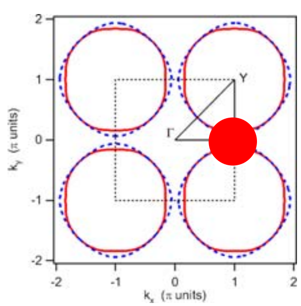
Antinodal electrons couple to ...

Doping dependence: UD↑
OD↓

Temperature dependence: $<T_c$

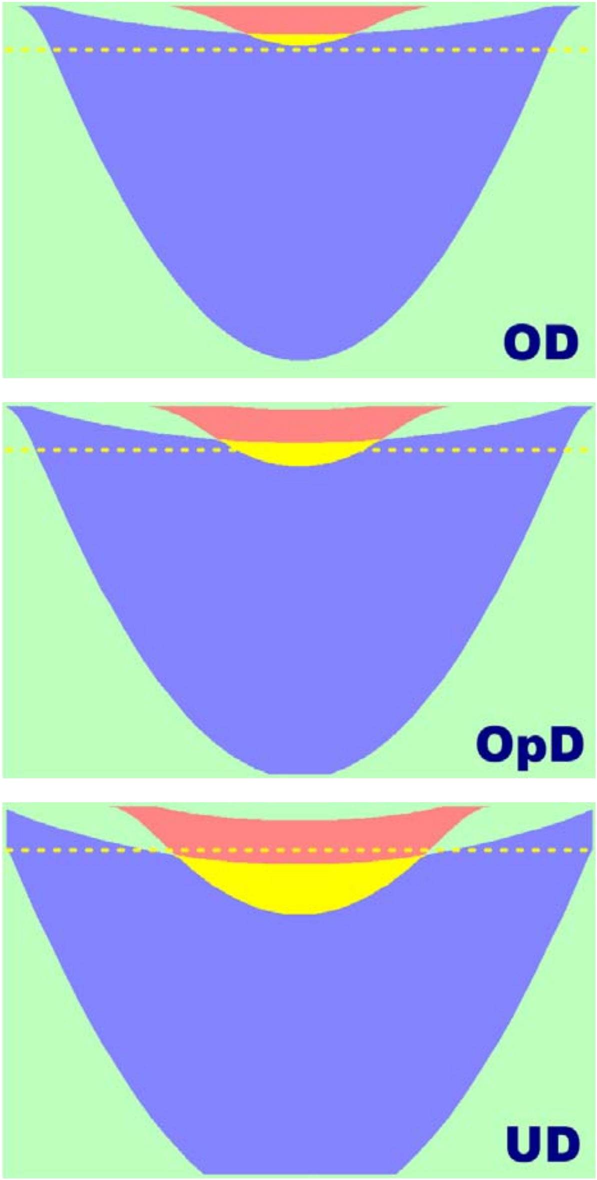
Energy ~ 40 meV

k-dependence:

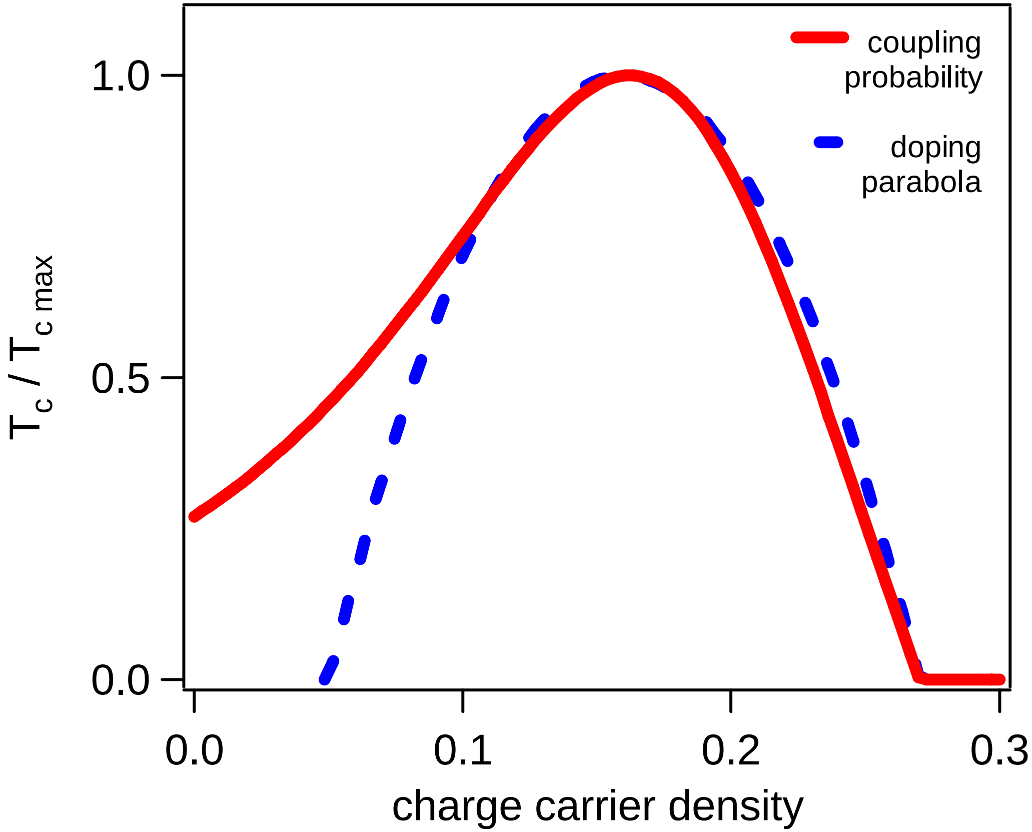


spin fluctuations

how it works

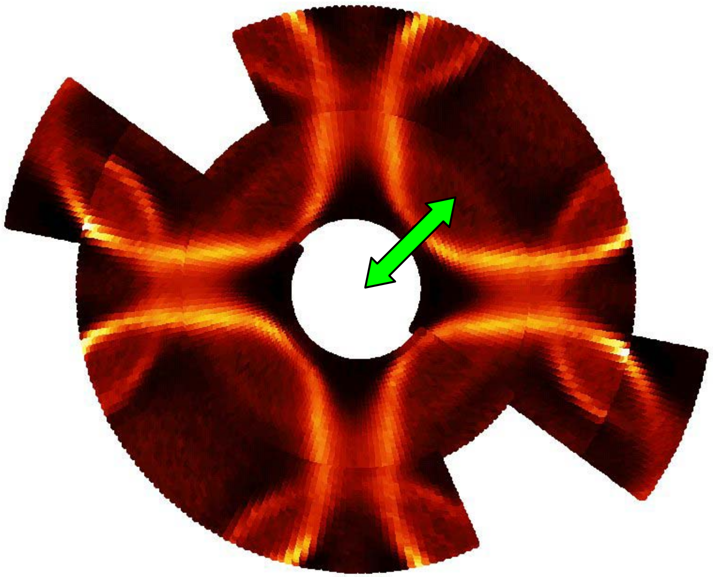


OD
OpD
UD

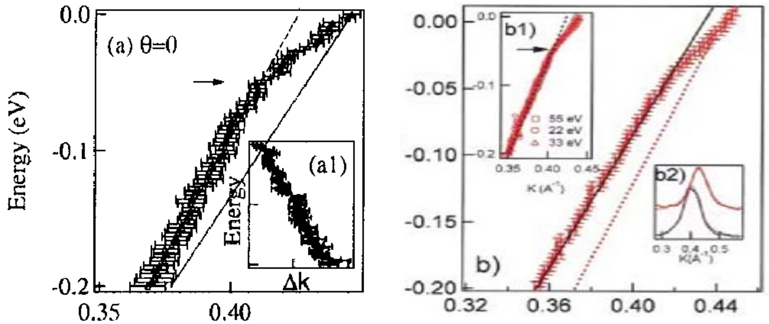


coupling probability
doping parabola
$T_c / T_{c\,max}$
1.0
0.5
0.0
0.0
0.1
0.2
0.3
charge carrier density

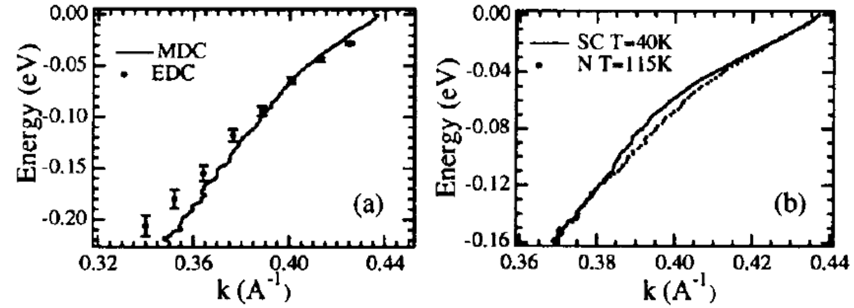
Nodal direction (GX)



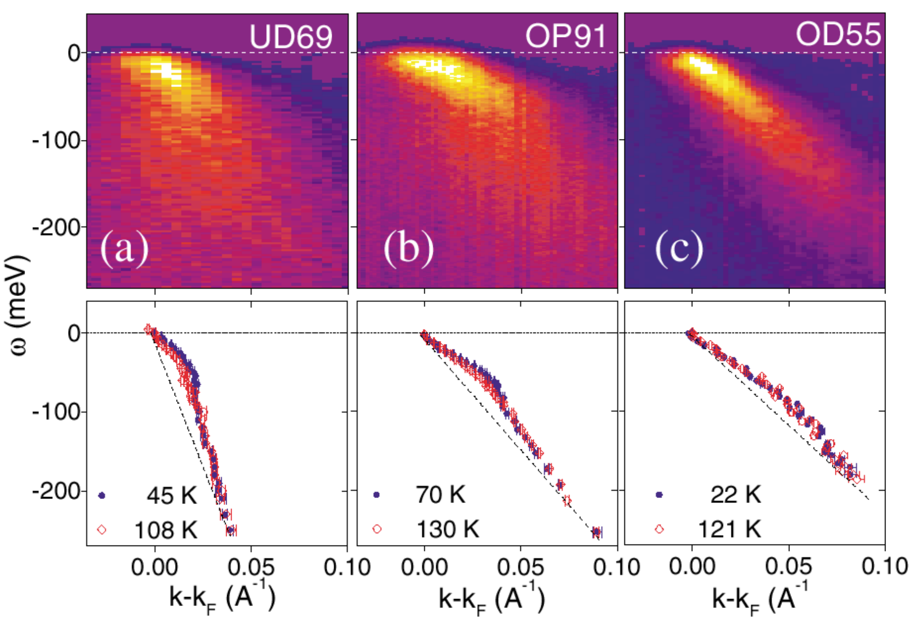
„Kinks“



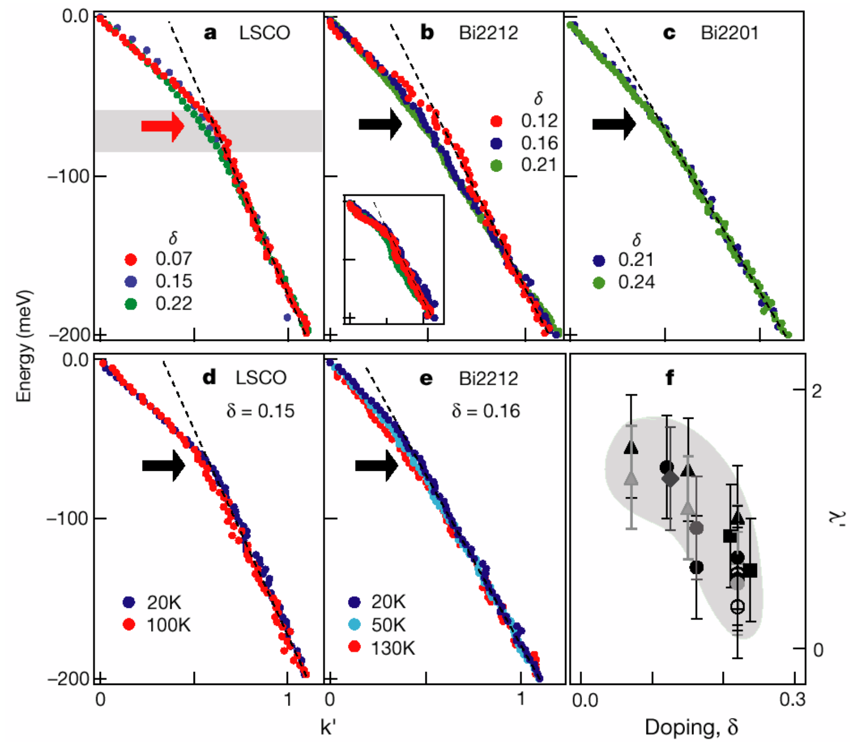
Bogdanov *PRL* 2000



Kaminski *PRL* 2001

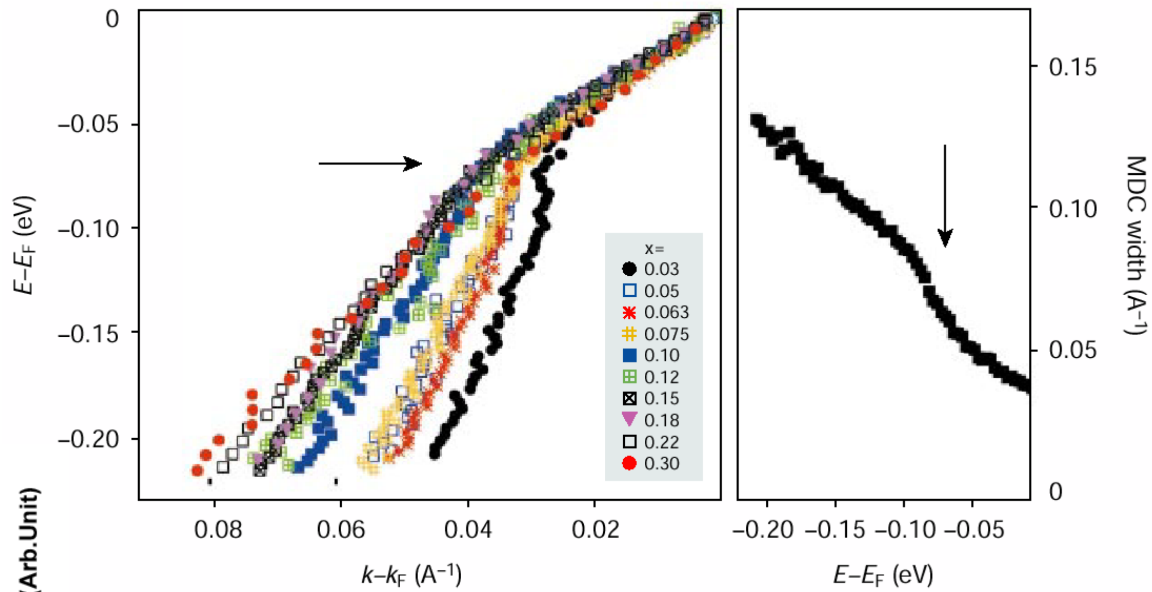


Johnson *PRL* 2001

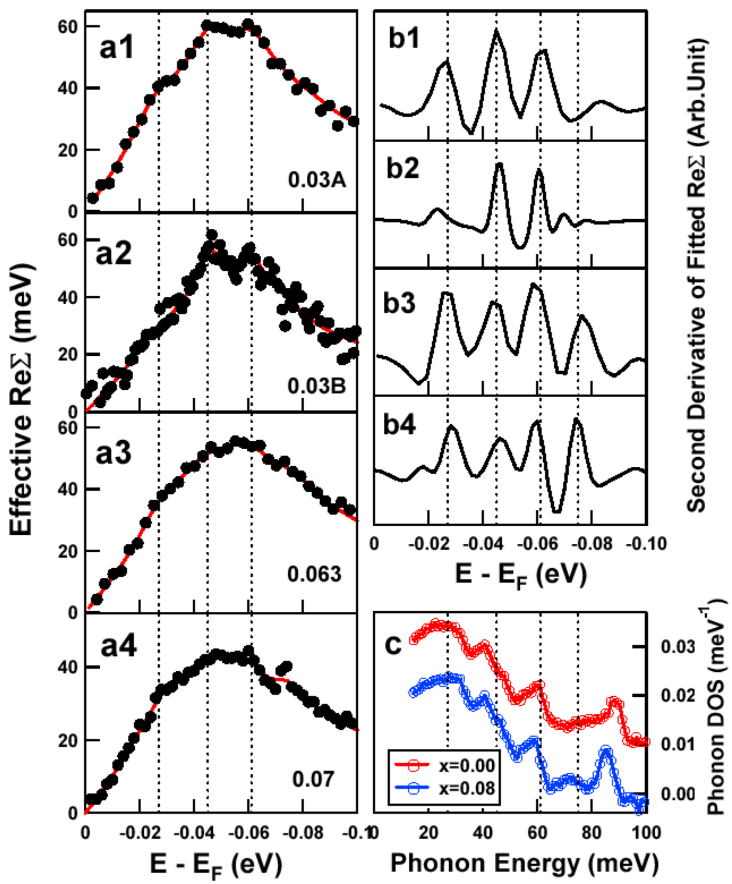


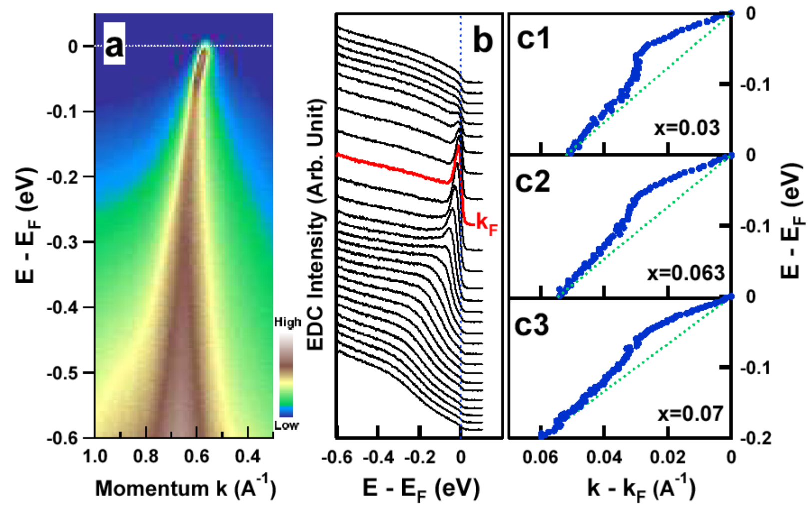
Lanzara *Nature* 2001

„Kinks“



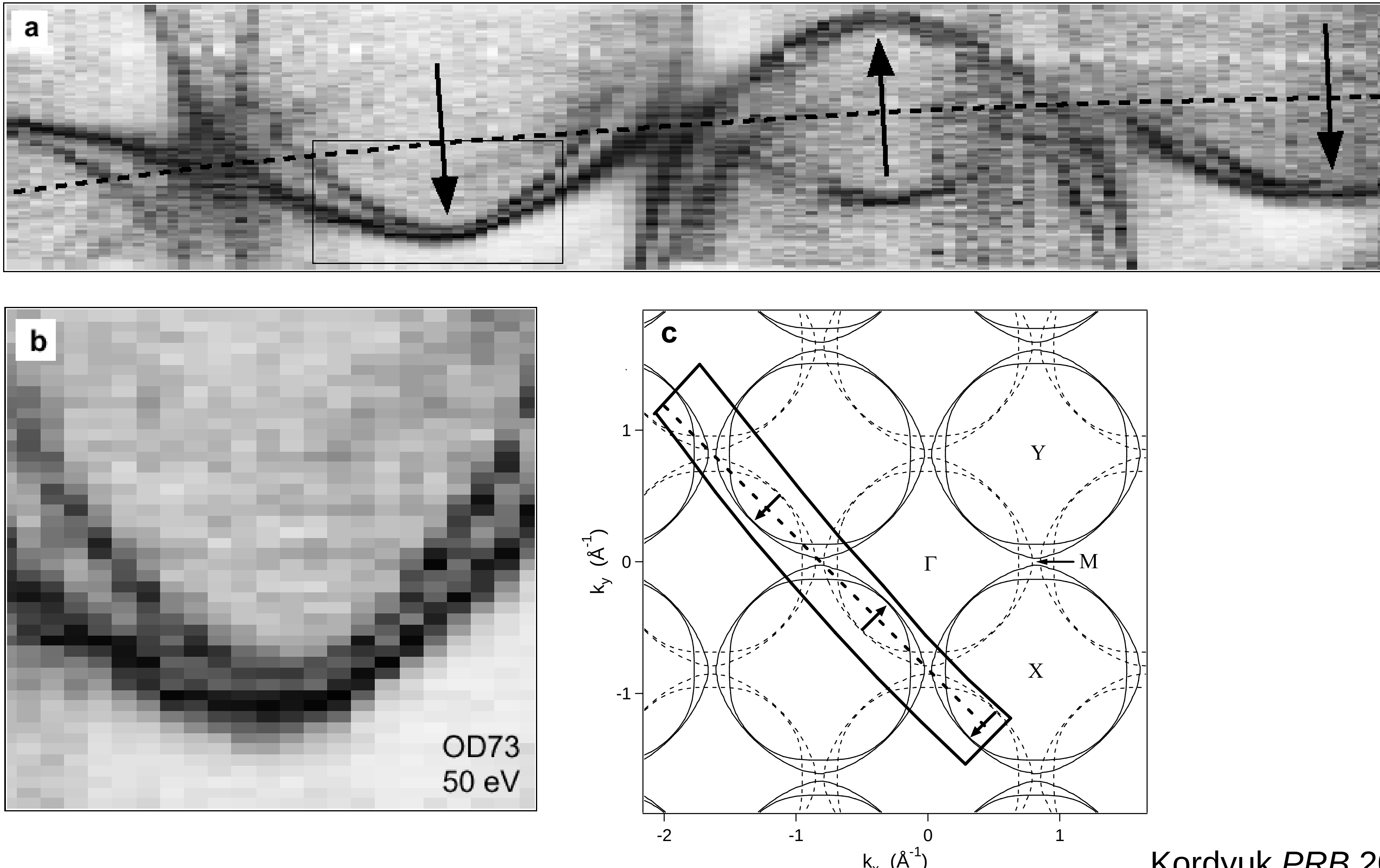
Zhou *Nature* 2003





Zhou *cond-mat* 2004

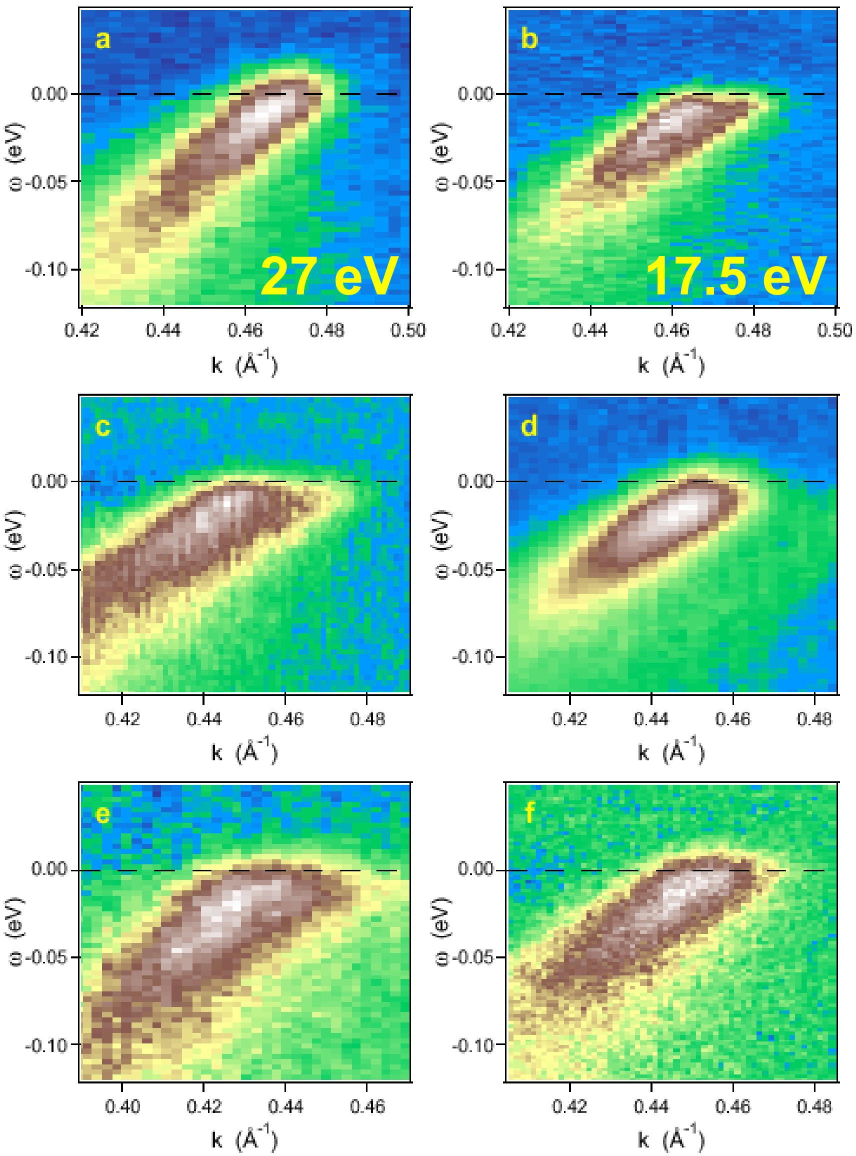
One complication: nodal splitting

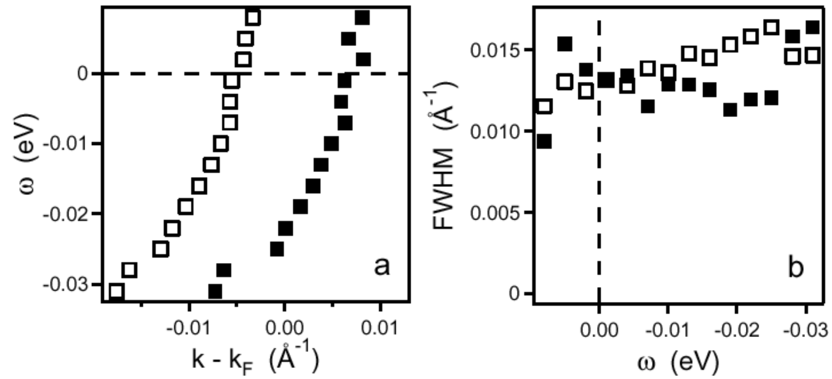


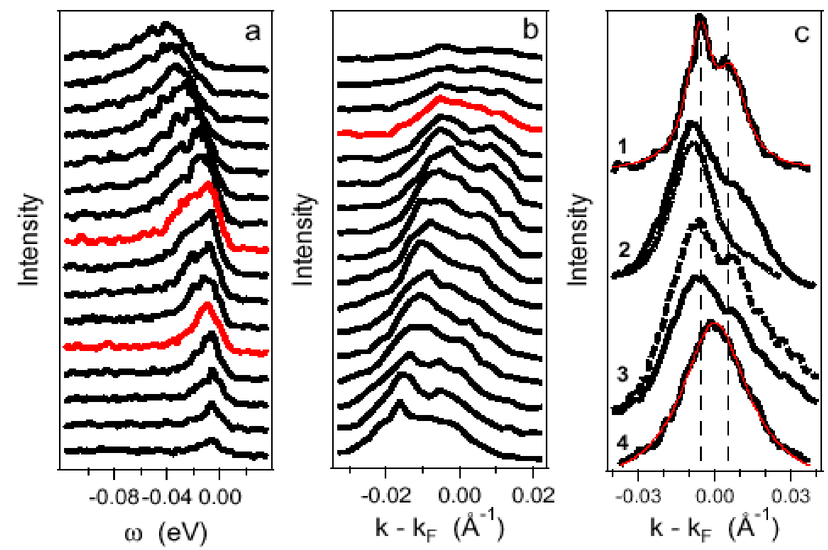
Kordyuk *PRB* 2004

Nodal splitting

Δk = 0.012 1/Å
$\Delta\varepsilon$ = 50 meV (bare!)







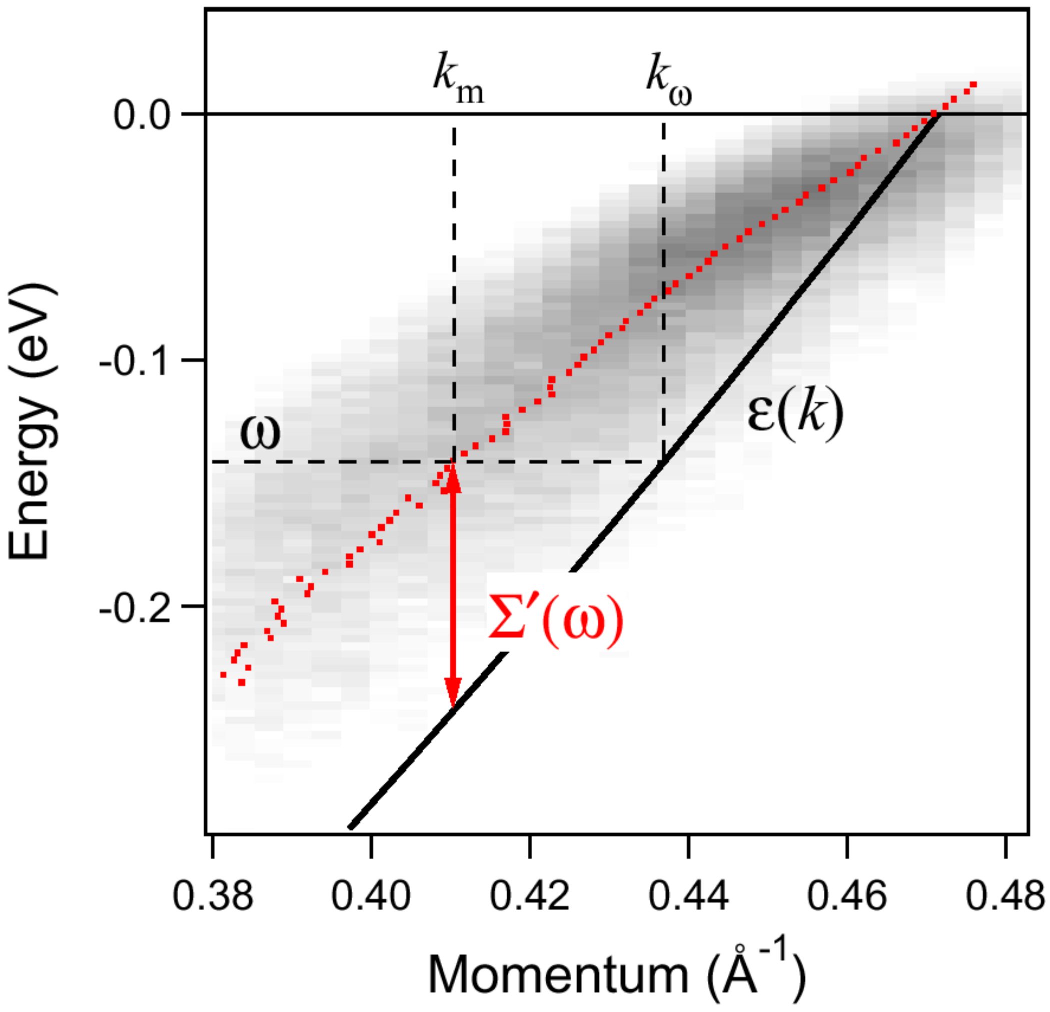
Kordyuk *PRB* 2004

Bare Dispersion

and

real Real Part of the Self-Energy (Renormalization)

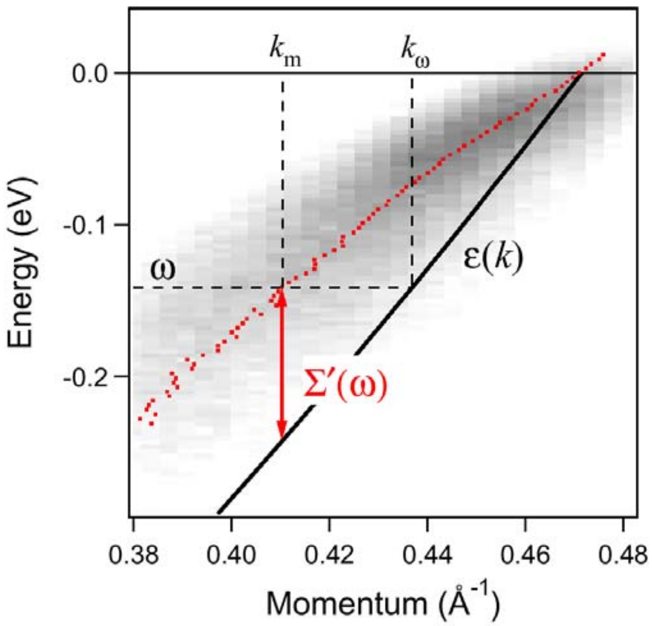
Bare dispersion



Kordyuk *cond-mat/0405696*

Self-energy approach

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



$$\Sigma'(\omega) = \omega - \varepsilon(k_m)$$

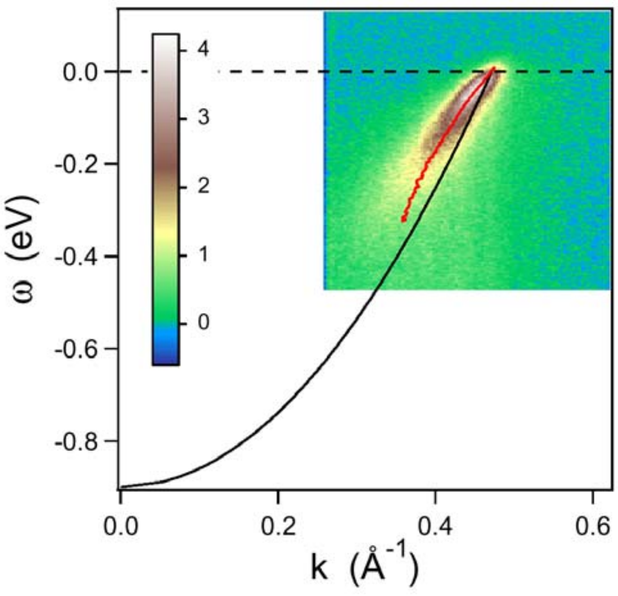
$$\Sigma''(\omega) = -v_F W(\omega)$$

Kordyuk *cond-mat/0405696*

Self-energy approach

$$\Sigma'(\omega) = \frac{v_F}{2}(k_m^2(\omega) - k_F^2) + \omega,$$

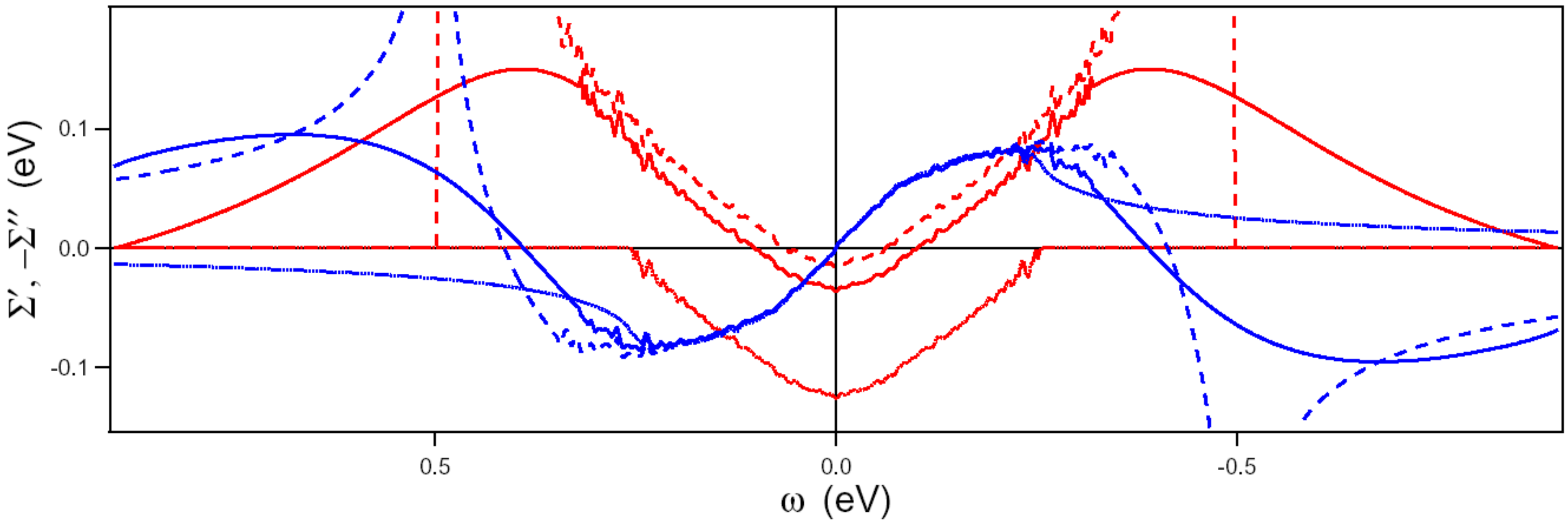
$$\Sigma''(\omega) = -v_F W(\omega)\sqrt{k_m^2(\omega) - W^2(\omega)}.$$

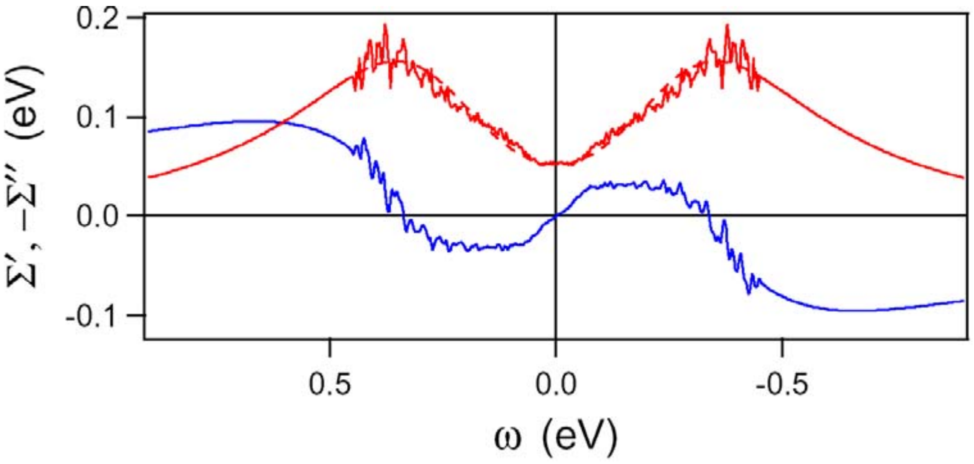


$$\Sigma'(\omega) = \mathrm{KK}\ \Sigma''(\omega)$$

Kordyuk *cond-mat/0405696*

Kramers-Kronig transform

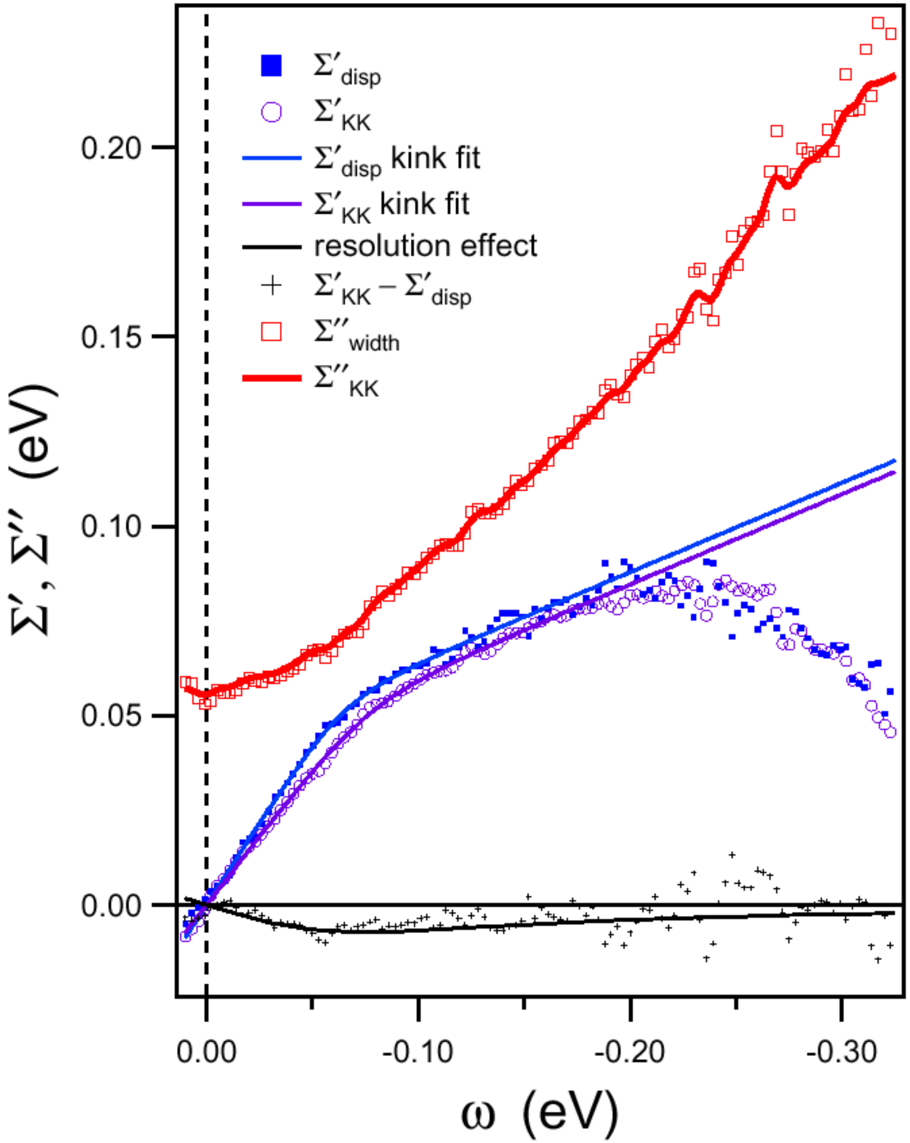


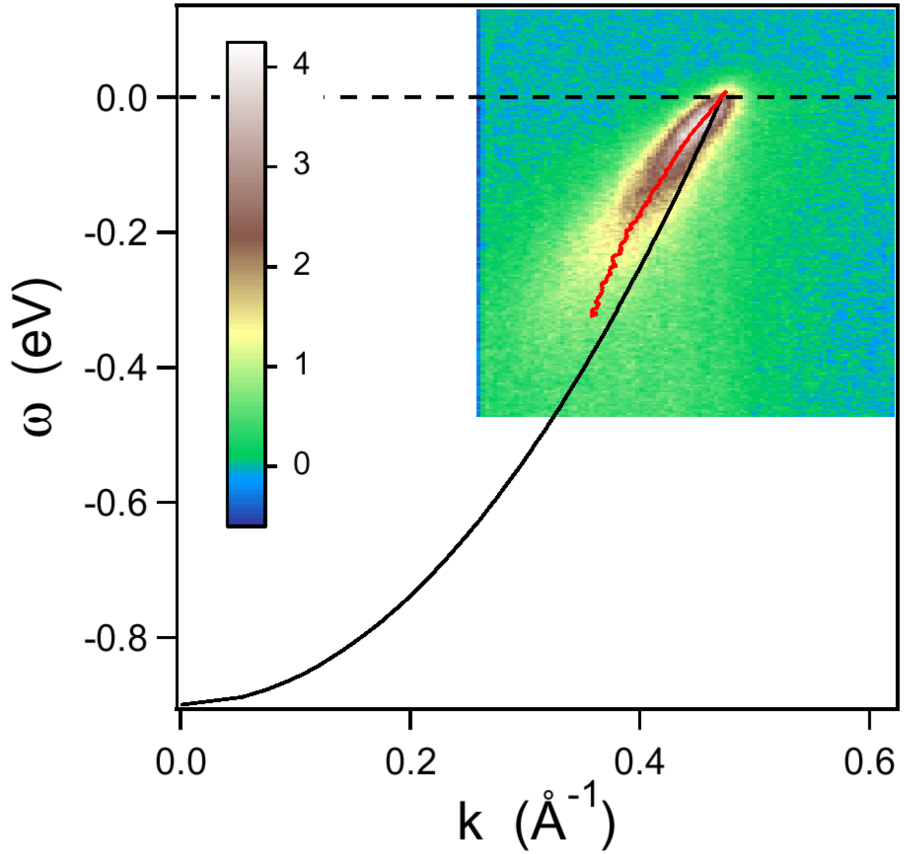


$$\Sigma'(\omega) = \mathrm{KK}\ \Sigma''(\omega)$$

Kordyuk *cond-mat/0409483*

Real Self-Energy



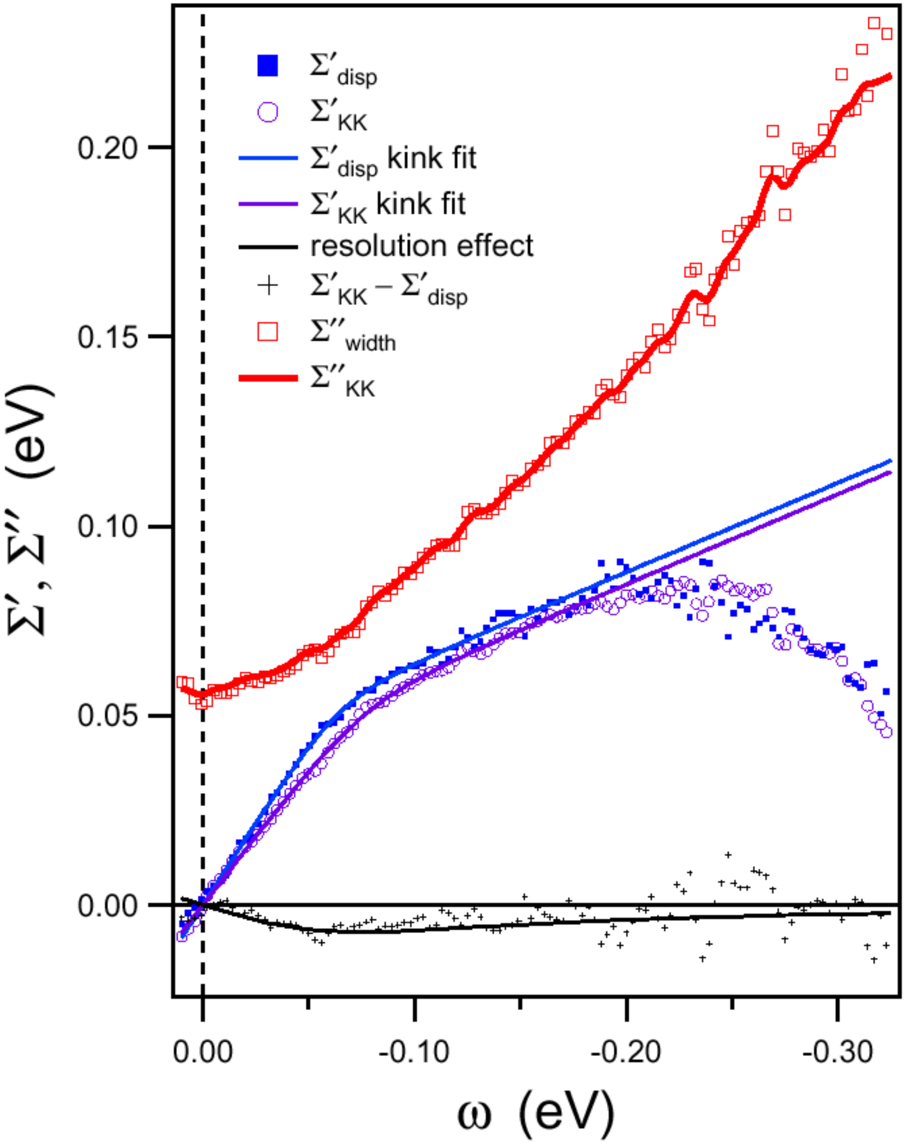


$$v_F = 3.82 \pm 0.17 \text{ eVÅ}$$

$$\lambda = 0.87 \pm 0.12$$

Kordyuk *cond-mat/0405696*

Bare dispersion



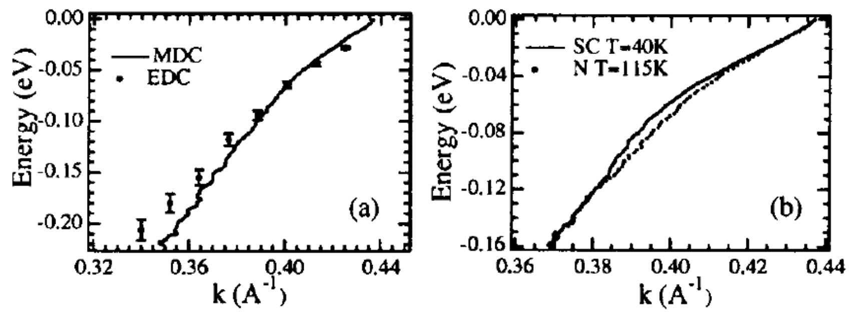
Self-consistency:
LDA + self-energy

Well defined quasi-particles

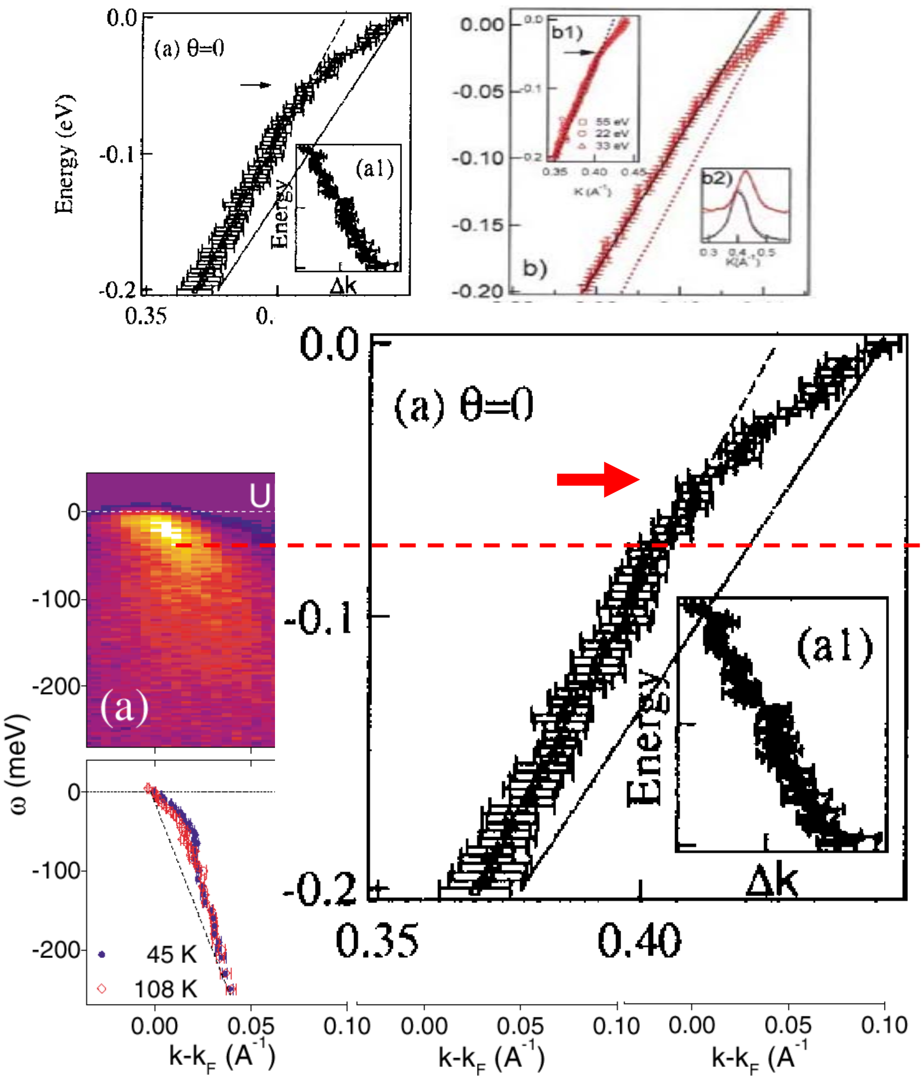
Kink phenomenology

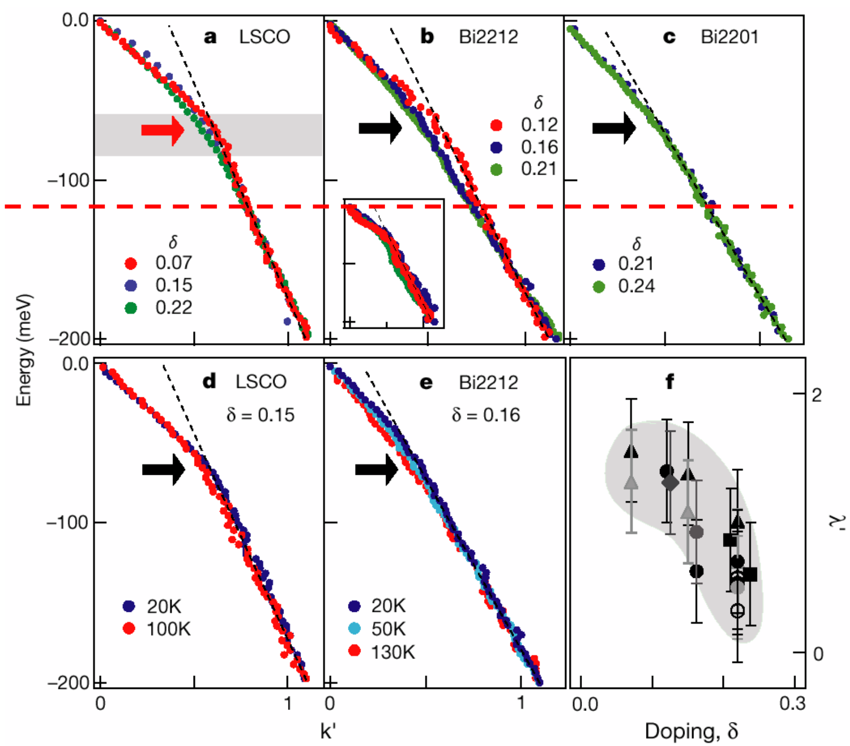
Kordyuk *cond-mat/0405696*

„Kinks“



Kaminski *PRL* 2001

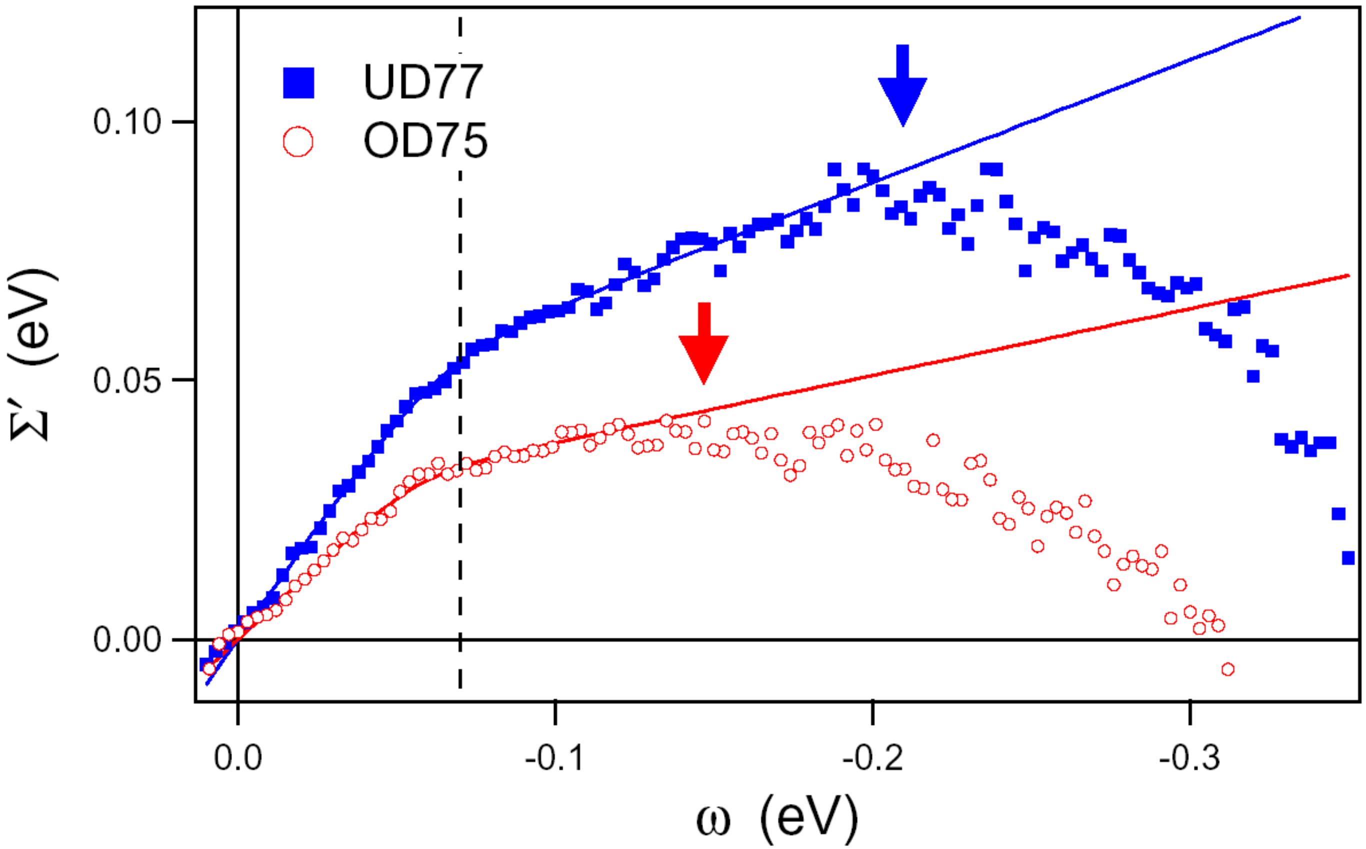




Johnson *PRL* 2001

Lanzara *Nature* 2001

Phenomenology of the kink



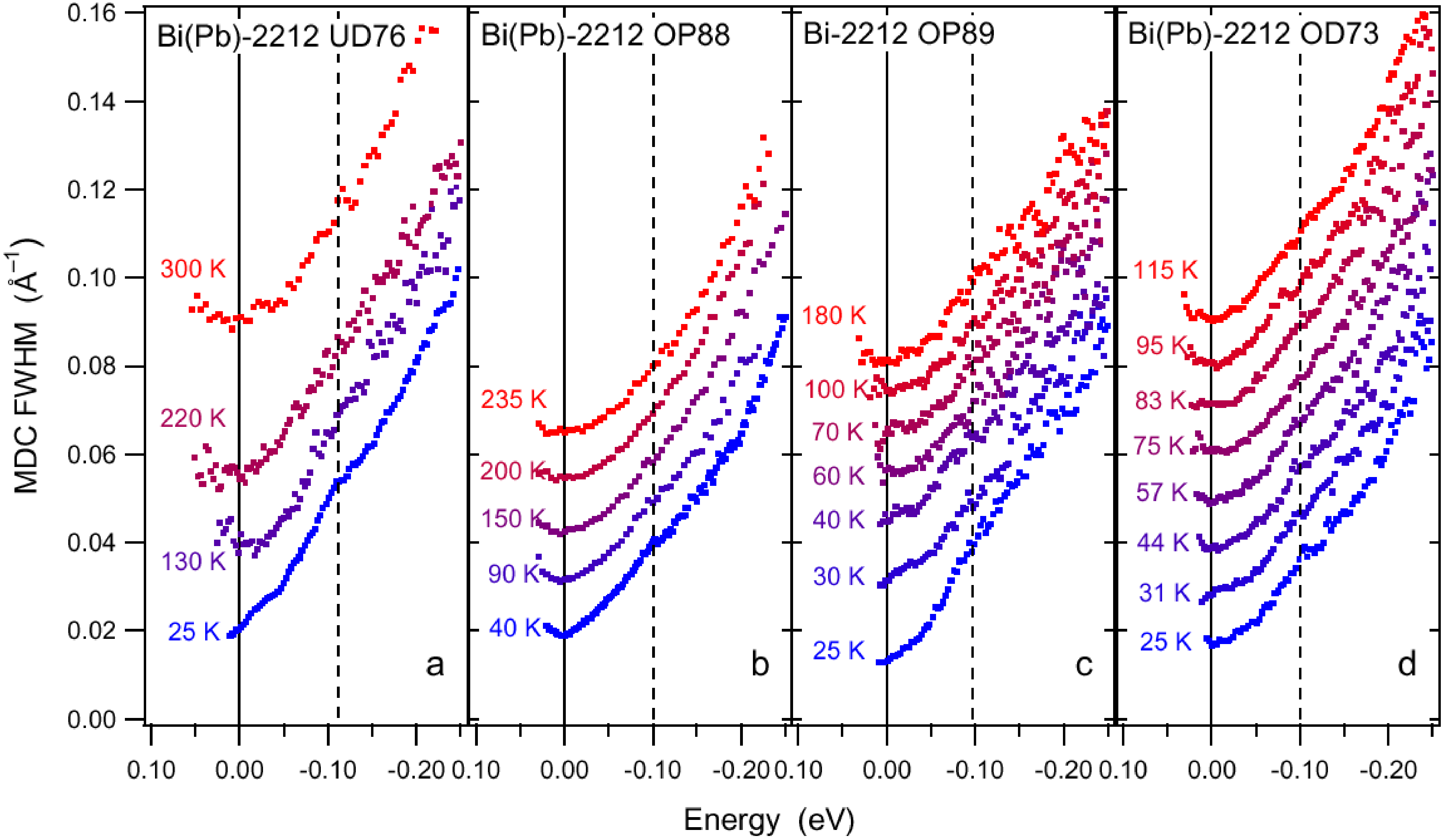
Kordyuk *cond-mat/0409483*

Imaginary Part of the Self-Energy

or

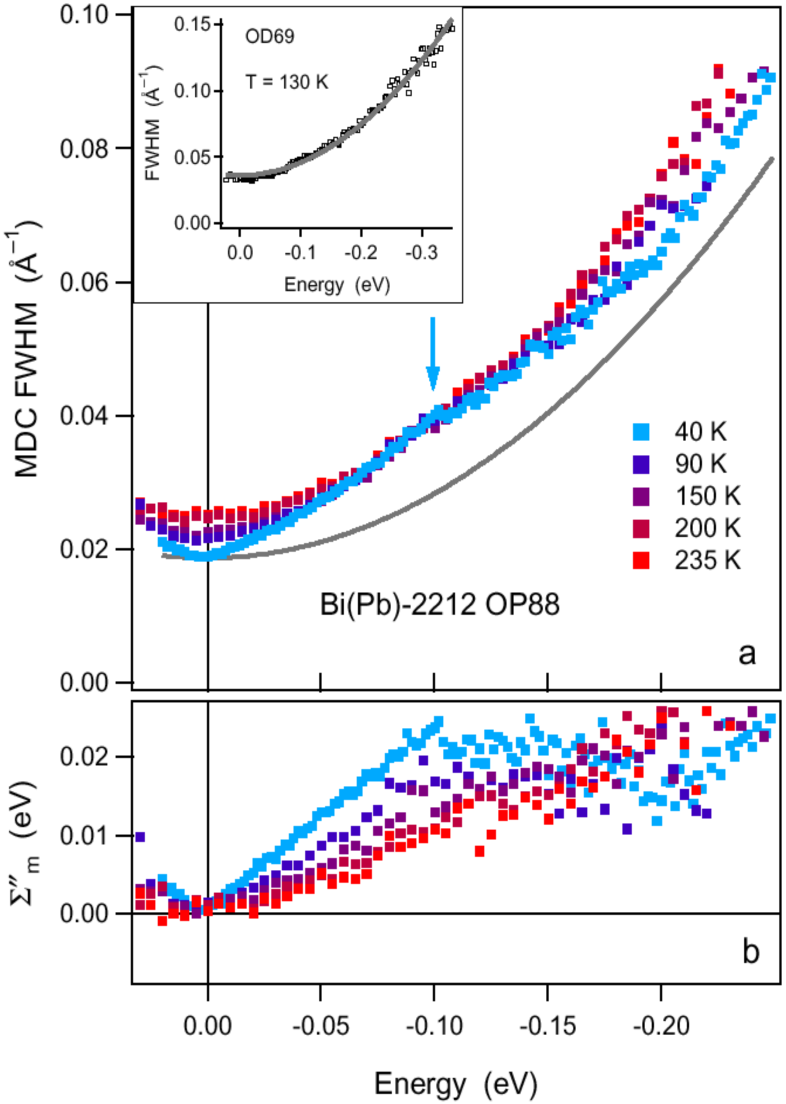
Quasiparticle Scattering Rate

Scattering rate kink



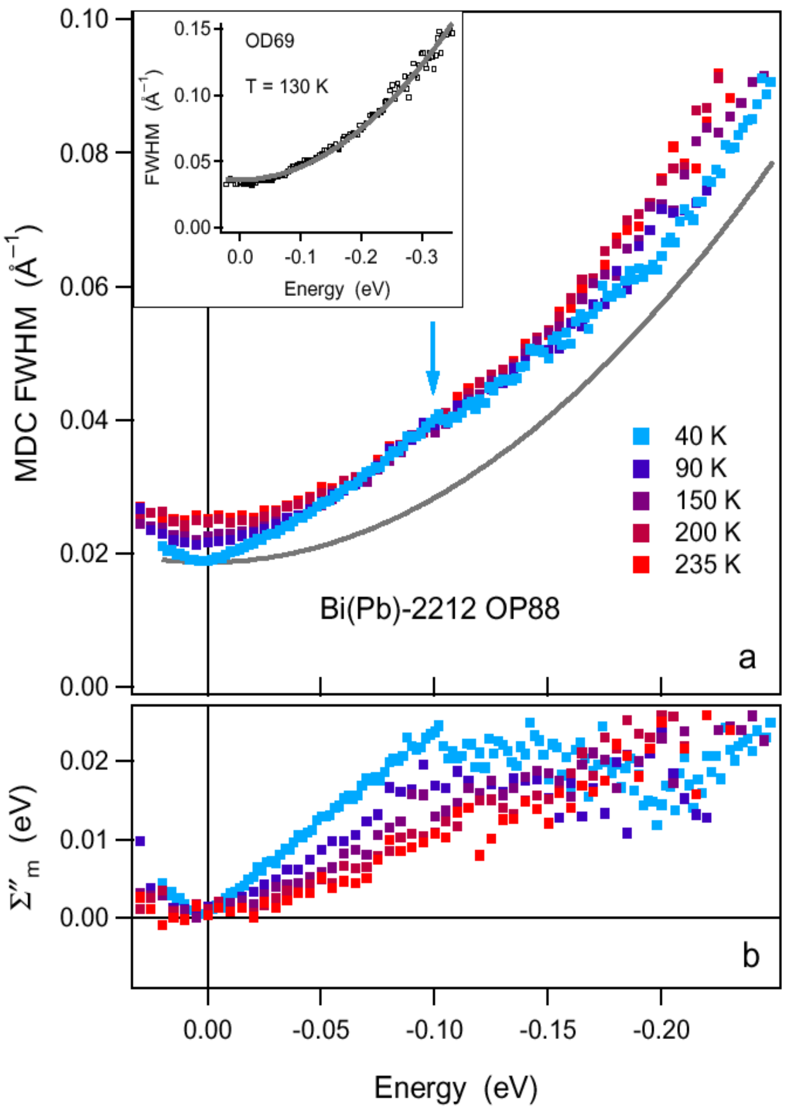
Kordyuk *PRL* 2004

Scattering rate: T-dependence

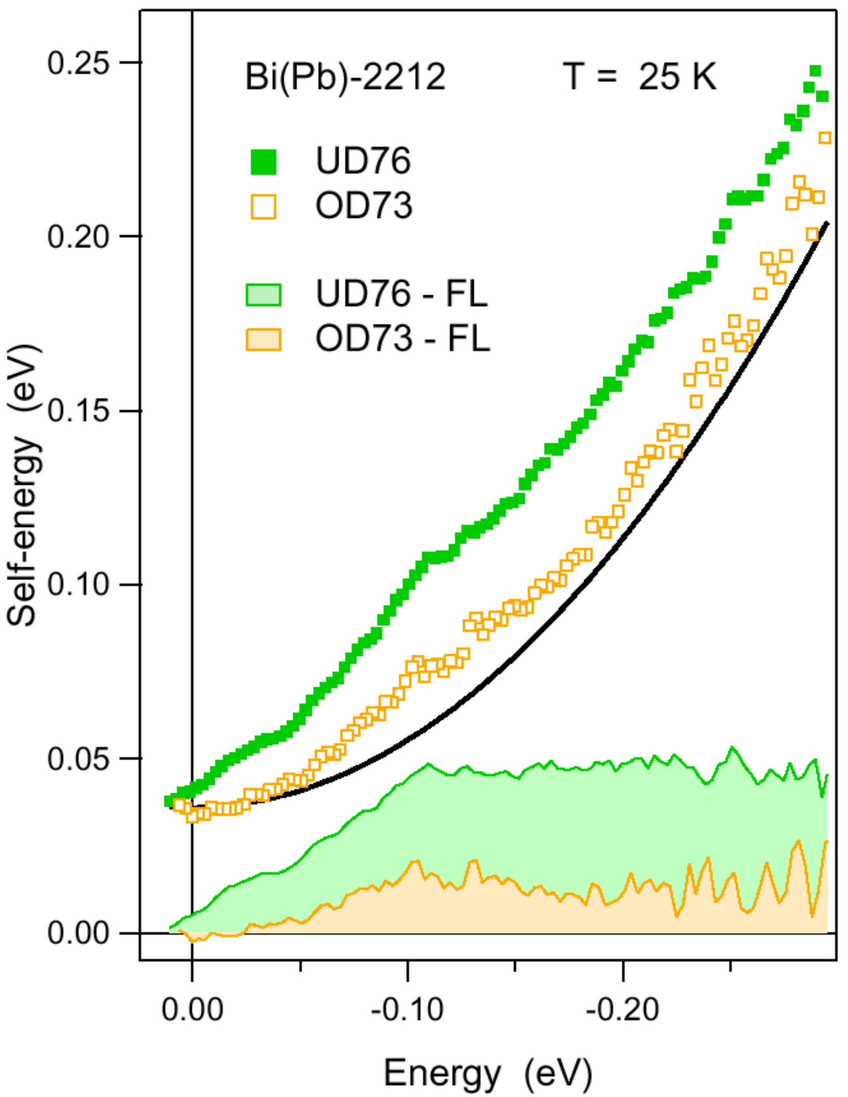


Kordyuk *PRL* 2004

T-dependence

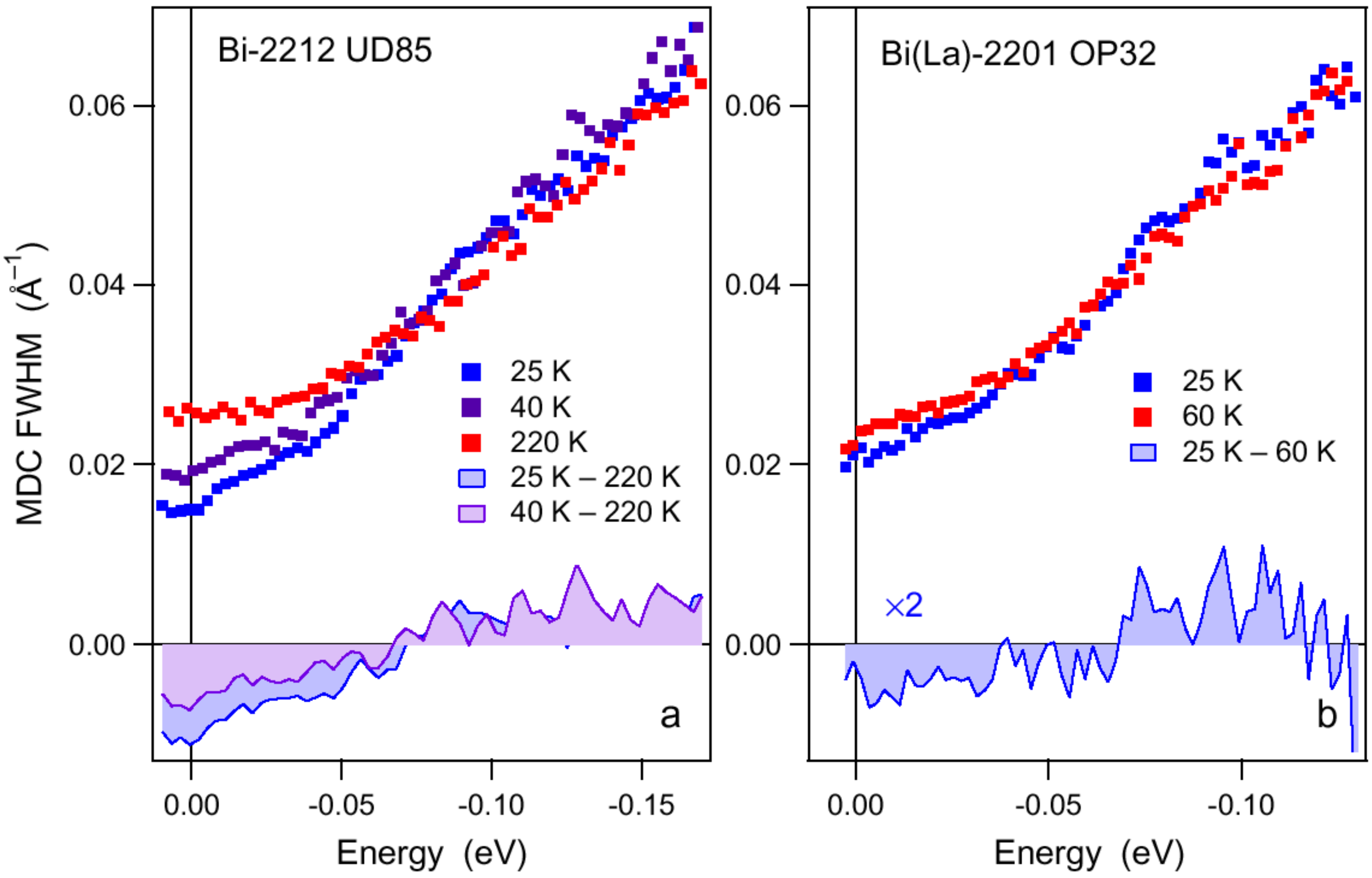


Doping dependence



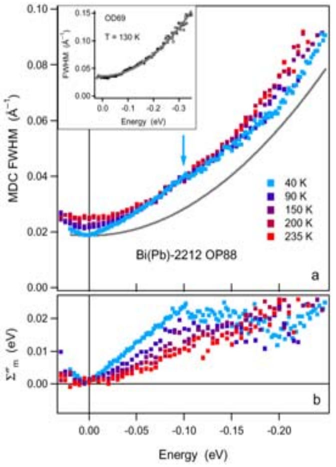
Kordyuk *PRL* 2004

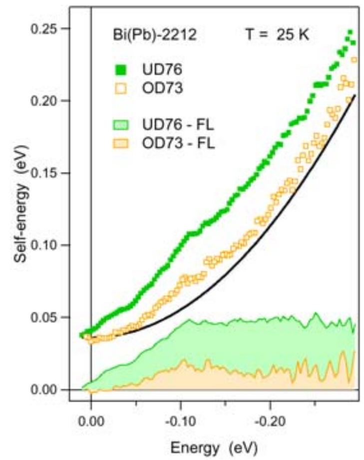
Scattering rate kink



Kordyuk *PRL* 2004

Scattering rate: Some conclusions

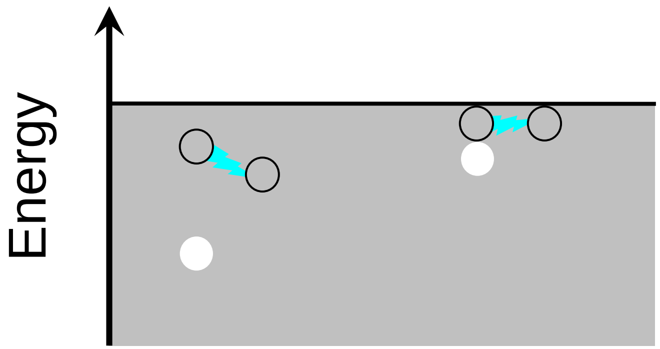


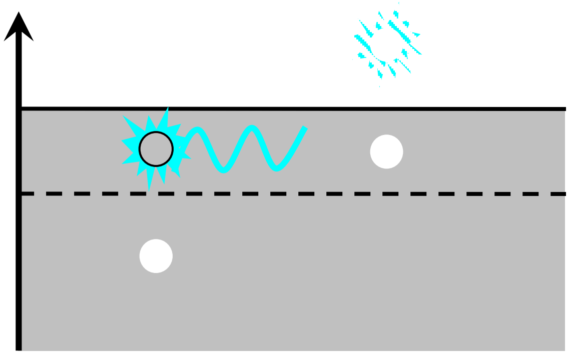


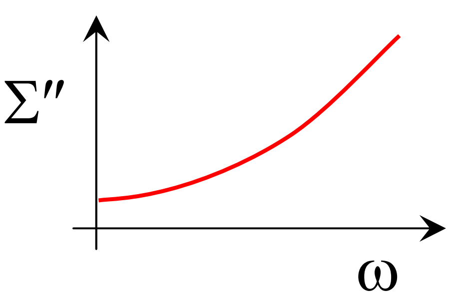
There are two channels:

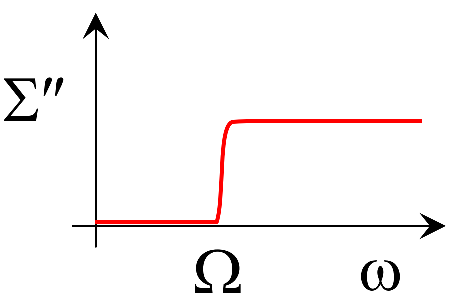
1st electron-electron scattering and

2nd electron-boson scattering



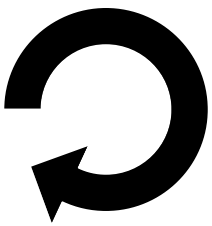


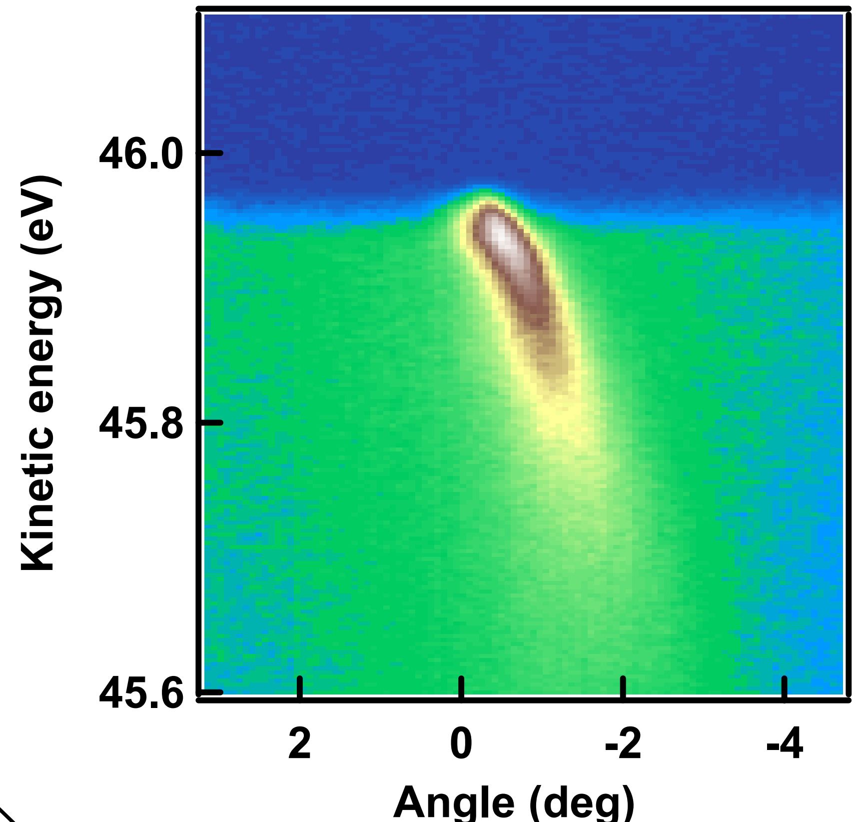


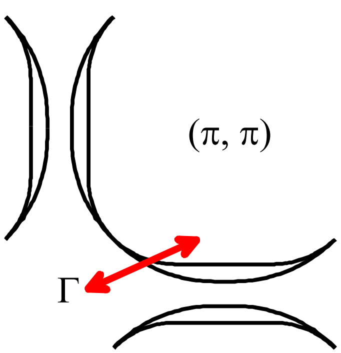


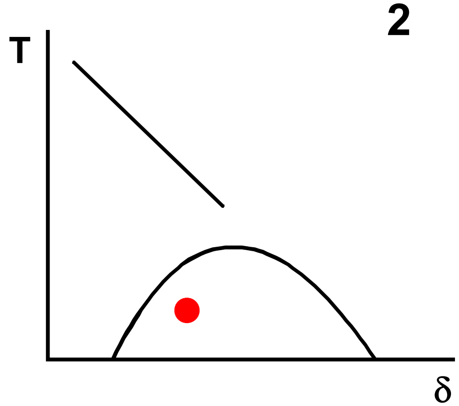
Parity

Circular dichroism in nodal region



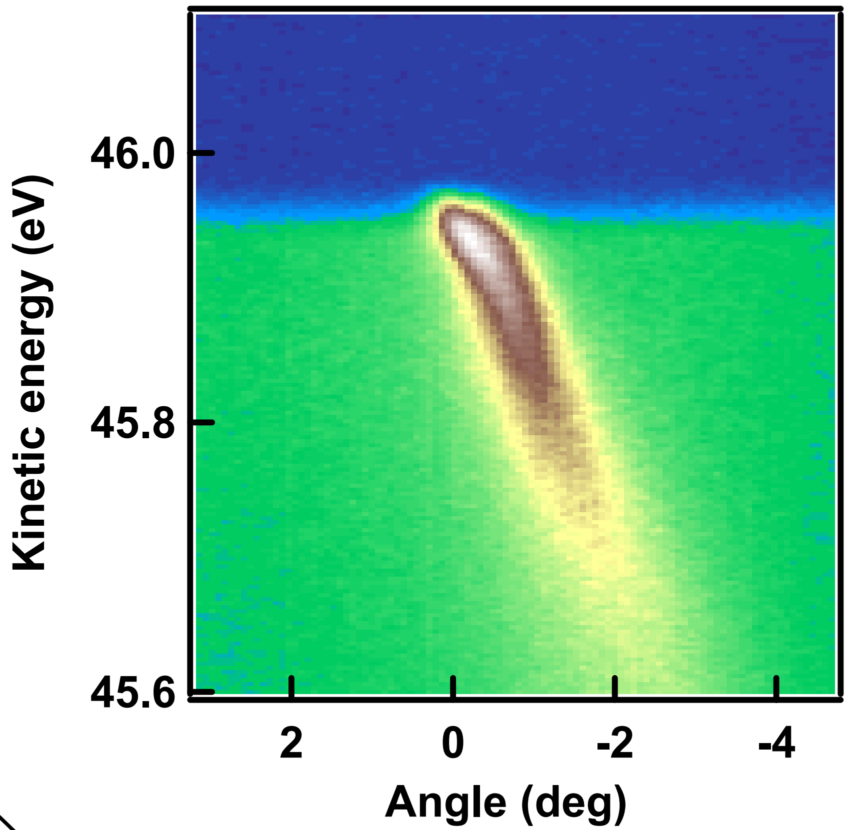


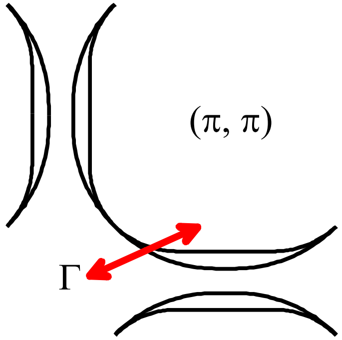


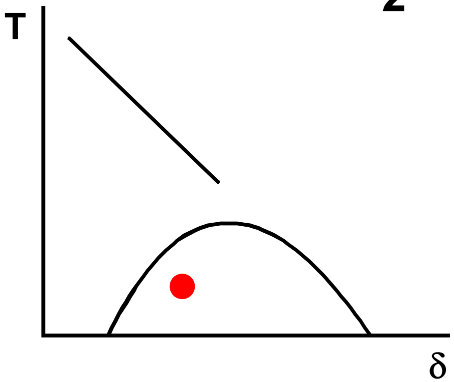


Borisenko 2004

Circular dichroism in nodal region

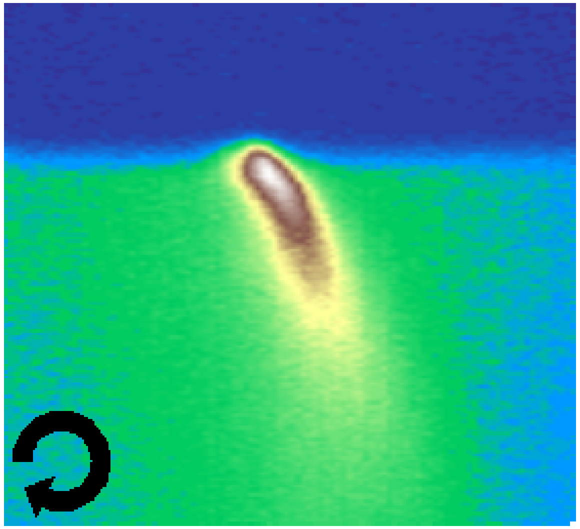


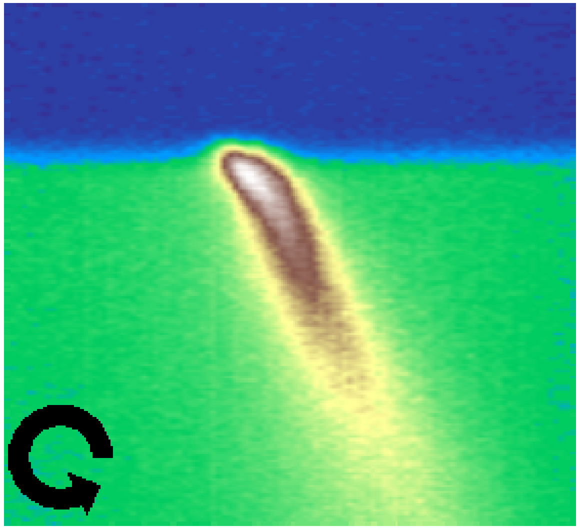


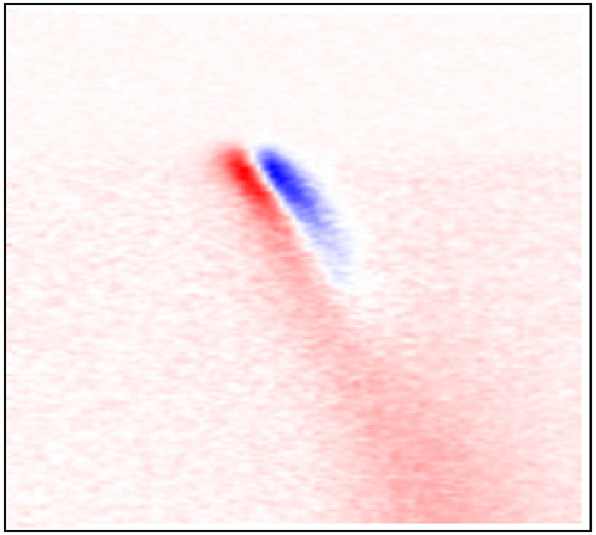


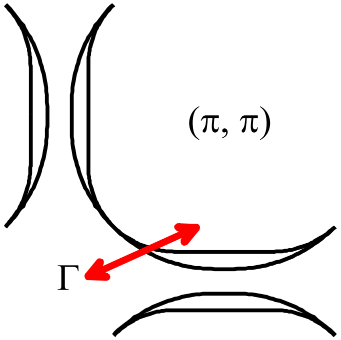
Borisenko 2004

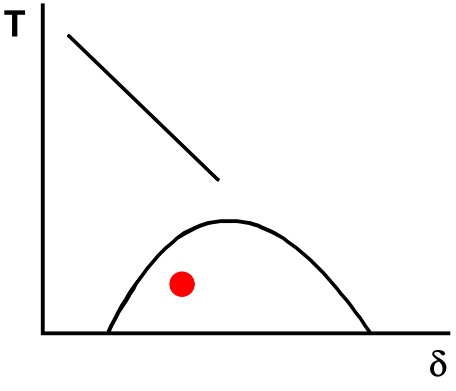
Circular dichroism in nodal region





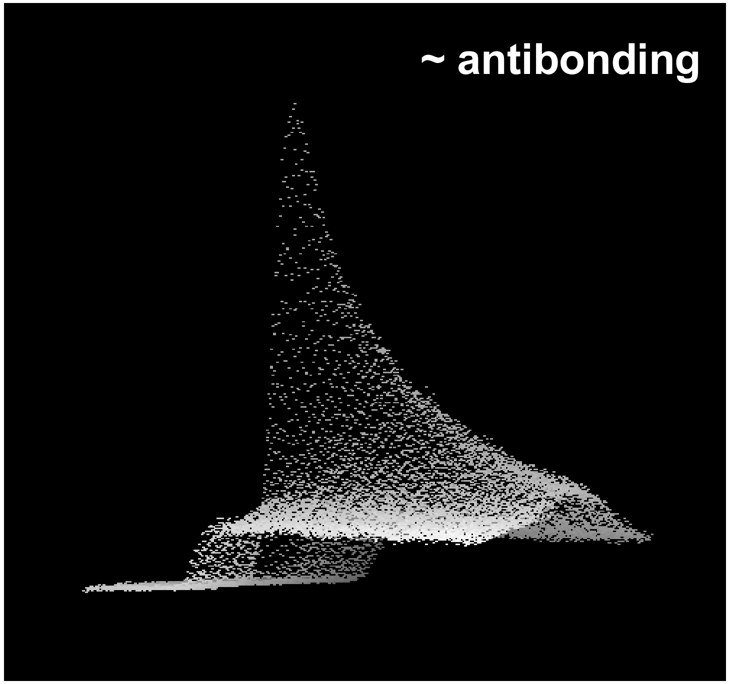


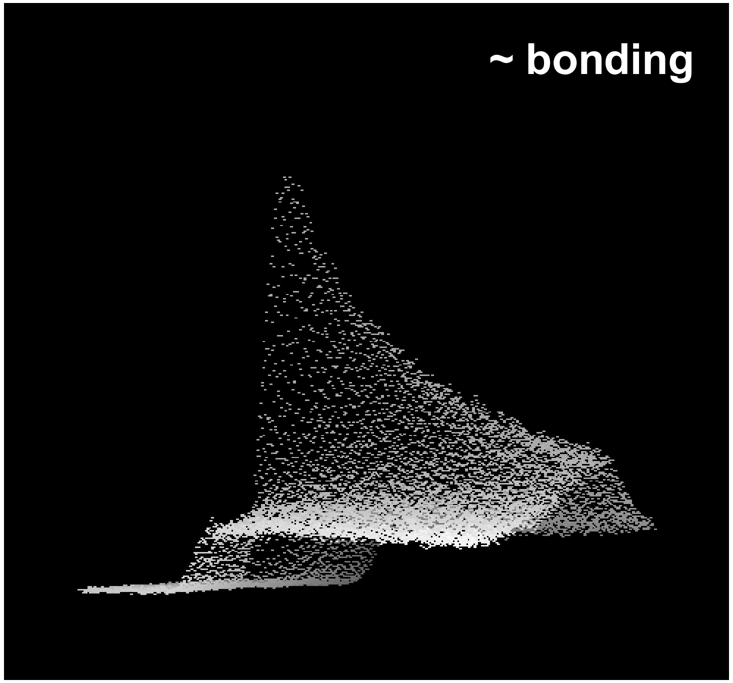


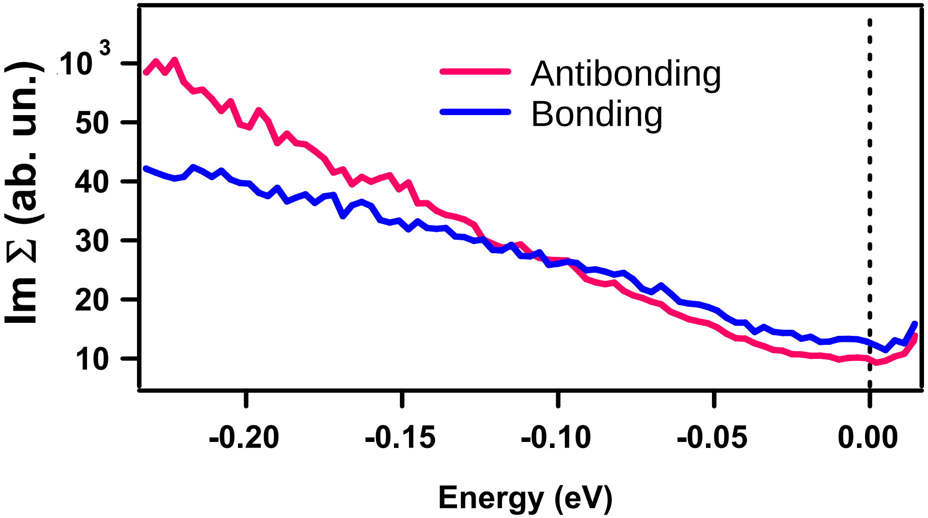


Borisenko 2004

Odd scattering







Borisenko 2004

Nodal electrons couple to ...

Doping dependence: **UD↑**
OD↓

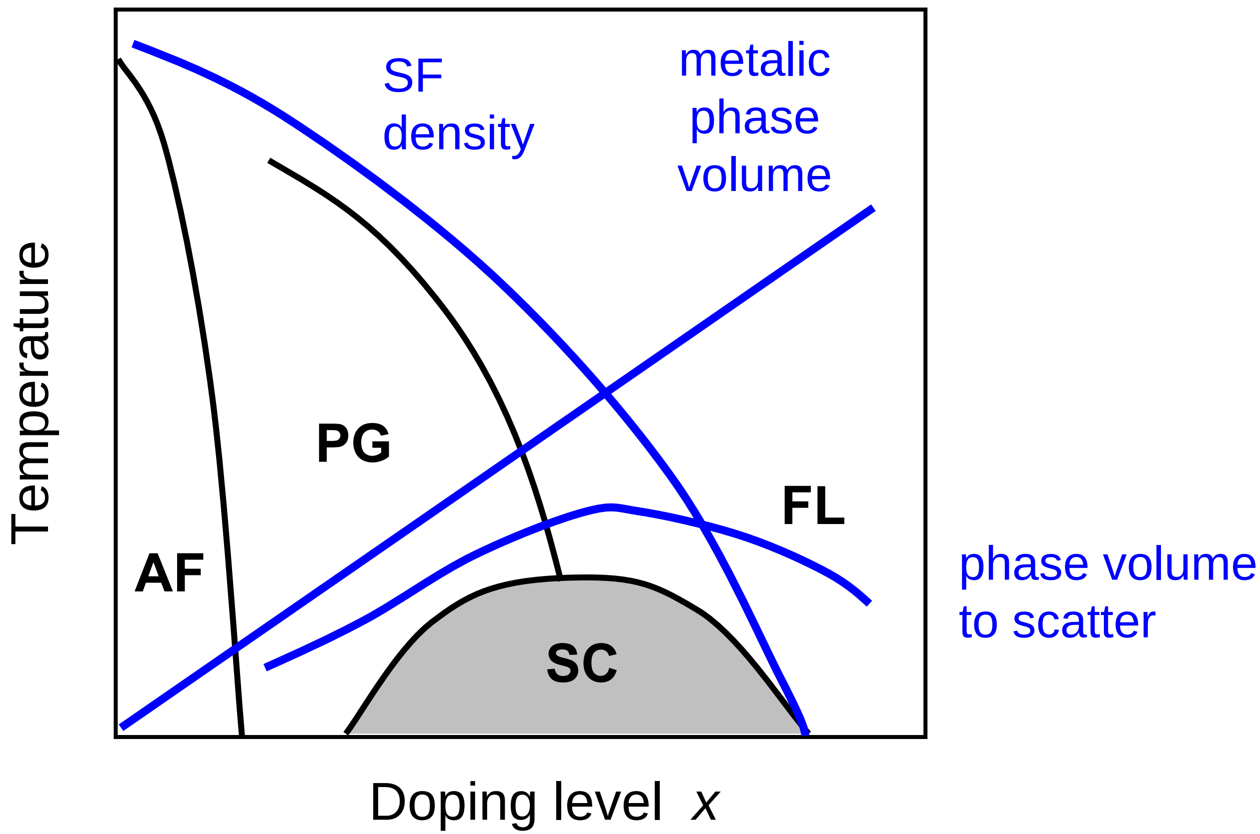
Temperature dependence:
< T_c for OD
< T* for UD

Parity: **odd boson**

spin fluctuations

Conclusions

- The spectral function analysis is applicable to the ARPES spectra from HTSC cuprates.
- Along the nodal direction well defined quasiparticles exist even for the underdoped Bi-2212 in the pseudogap state.
- Two channels in the scattering rate can be distinguished.
- The main doping independent contribution to the scattering can be well understood in terms of the conventional Fermi liquid model...
- ...while the additional doping dependent contribution has a magnetic origin.
- The magnetic contribution essentially increases with underdoping becoming dominant for the rest of the Brillouin zone and therefore determines the unusual properties of the cuprates in the superconducting and pseudo-gap phases.


SF
density
metalic
phase
volume
PG
FL
AF
SC
phase volume
to scatter
Temperature
Doping level x

Outlook

- Band structure
  - Increased accuracy
  - Lower doping level
  - AF $\leftrightarrow$ SC $\leftrightarrow$ Metal
- Shadow band
  - Origin
  - SB(x), SB(Tc)
- Mode(k,T,x,s)
  - Origin
  - Node ? Antinode
- Gaps
  - SG ? PG ? AFG
  - k-dependence

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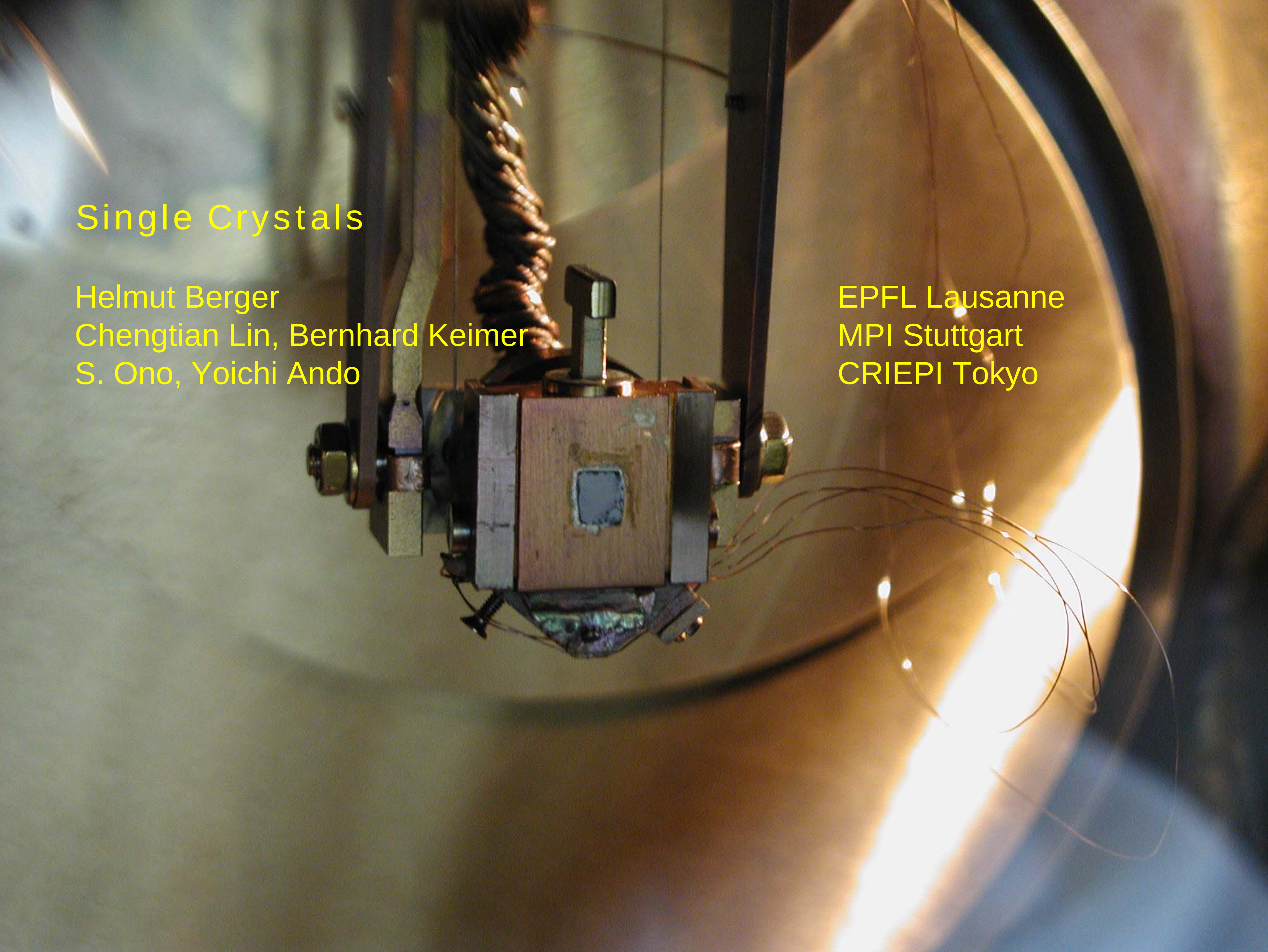
Single Crystals



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THE END