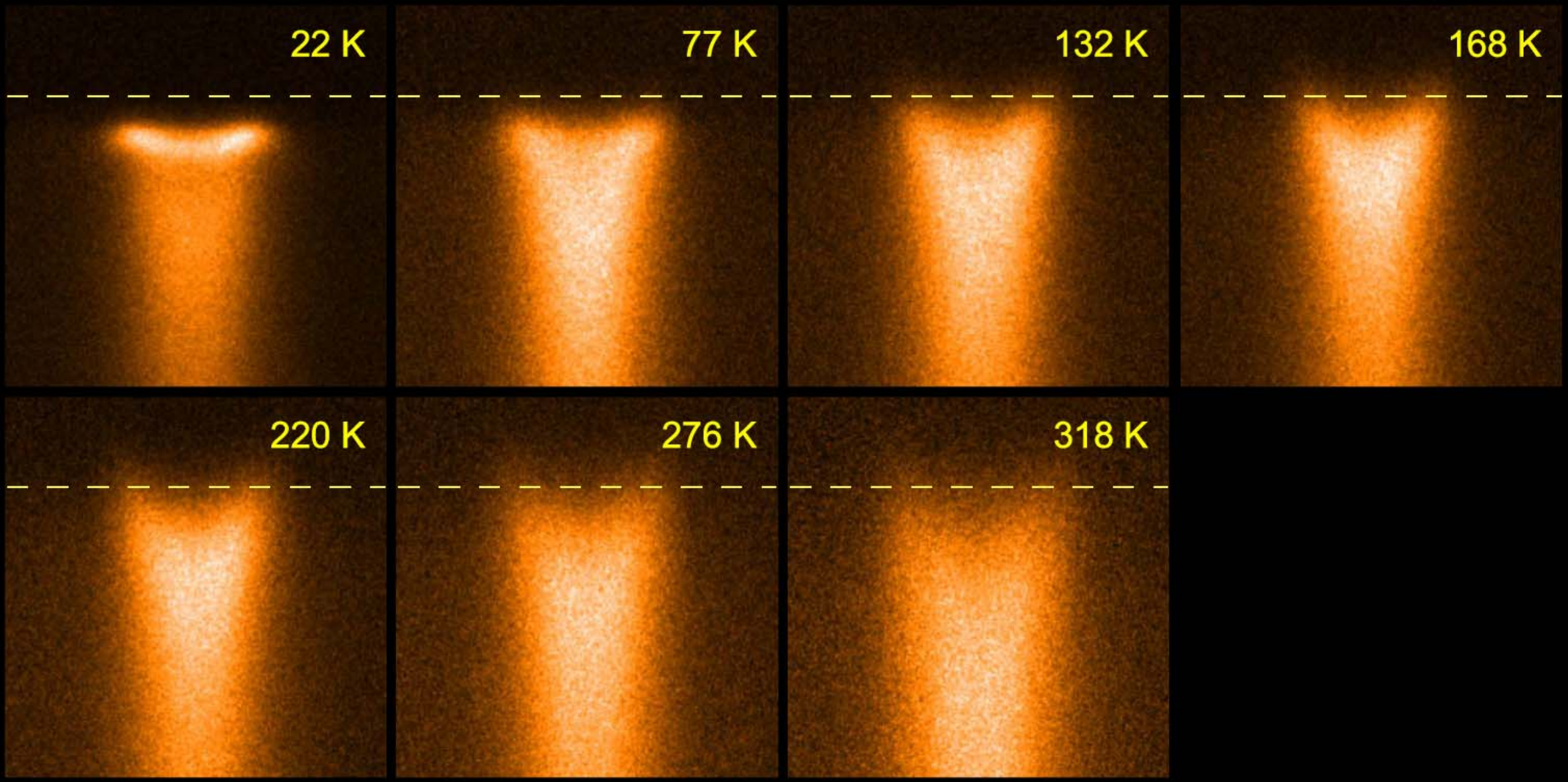
Electrons in cuprates: view by ARPES



A. A. Kordyuk
IFW Dresden & IMP Kiev

Intro

Occam's razor:

"entities should not be multiplied beyond necessity"

Eq.1:

HTSC = LDA + Self-energy + PG

Outline

I. LDA +

II. Self-energy structure

III. Self-energy origin: ARPES and INS

IV. Pseudo-gap

Outline

I. LDA +

II. Self-energy structure

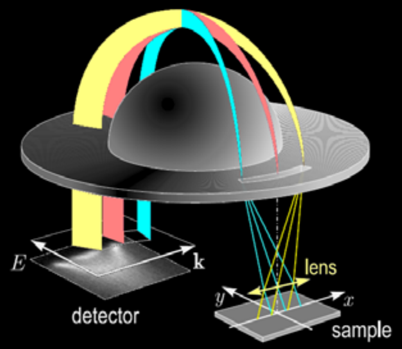
III. Self-energy origin: ARPES and INS

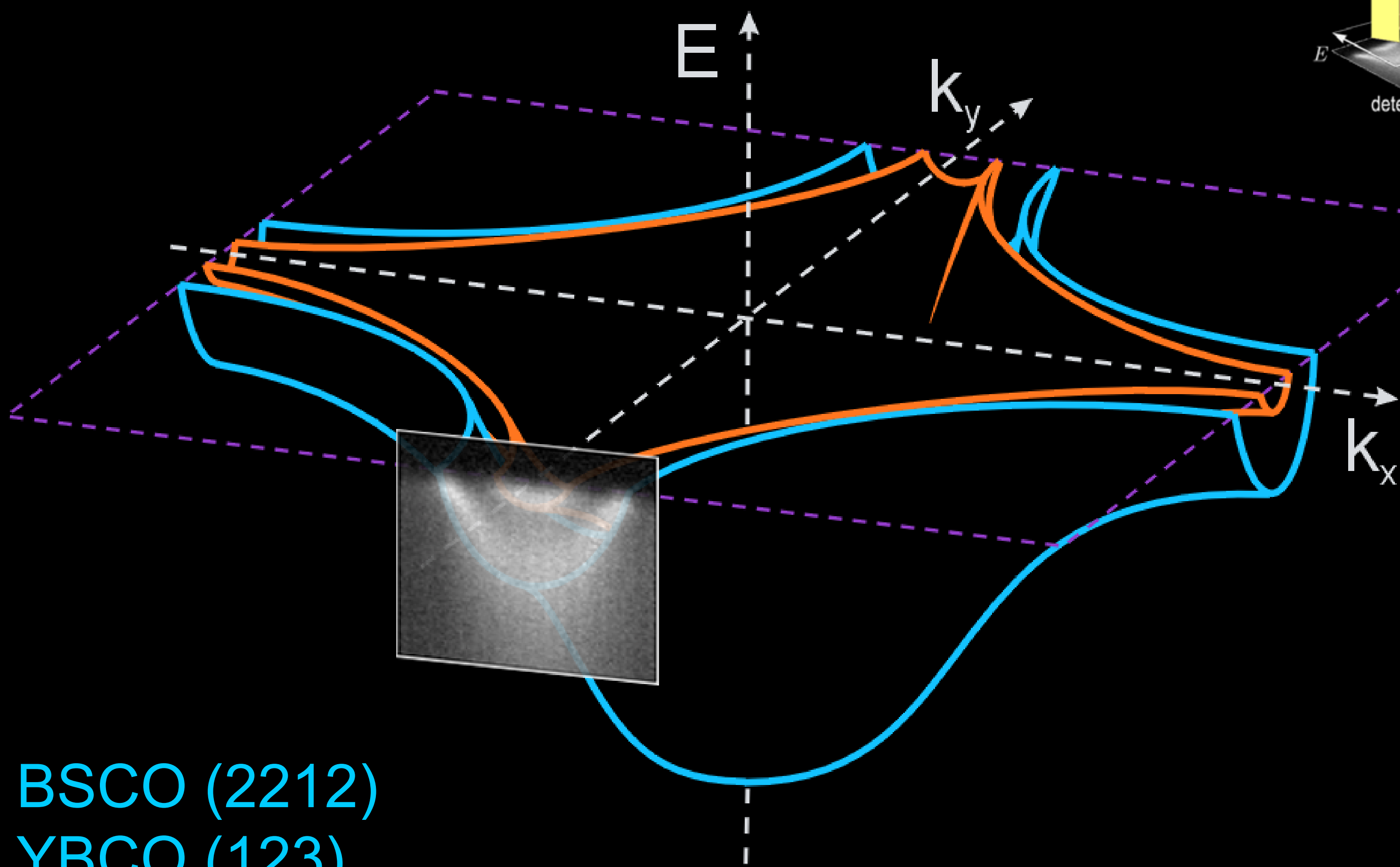
Dahm *Nature Phys.* **5**, xxx (2009)

IV. Pseudo-gap

Kordyuk *PRB* **79**, 020504(R) (2009)

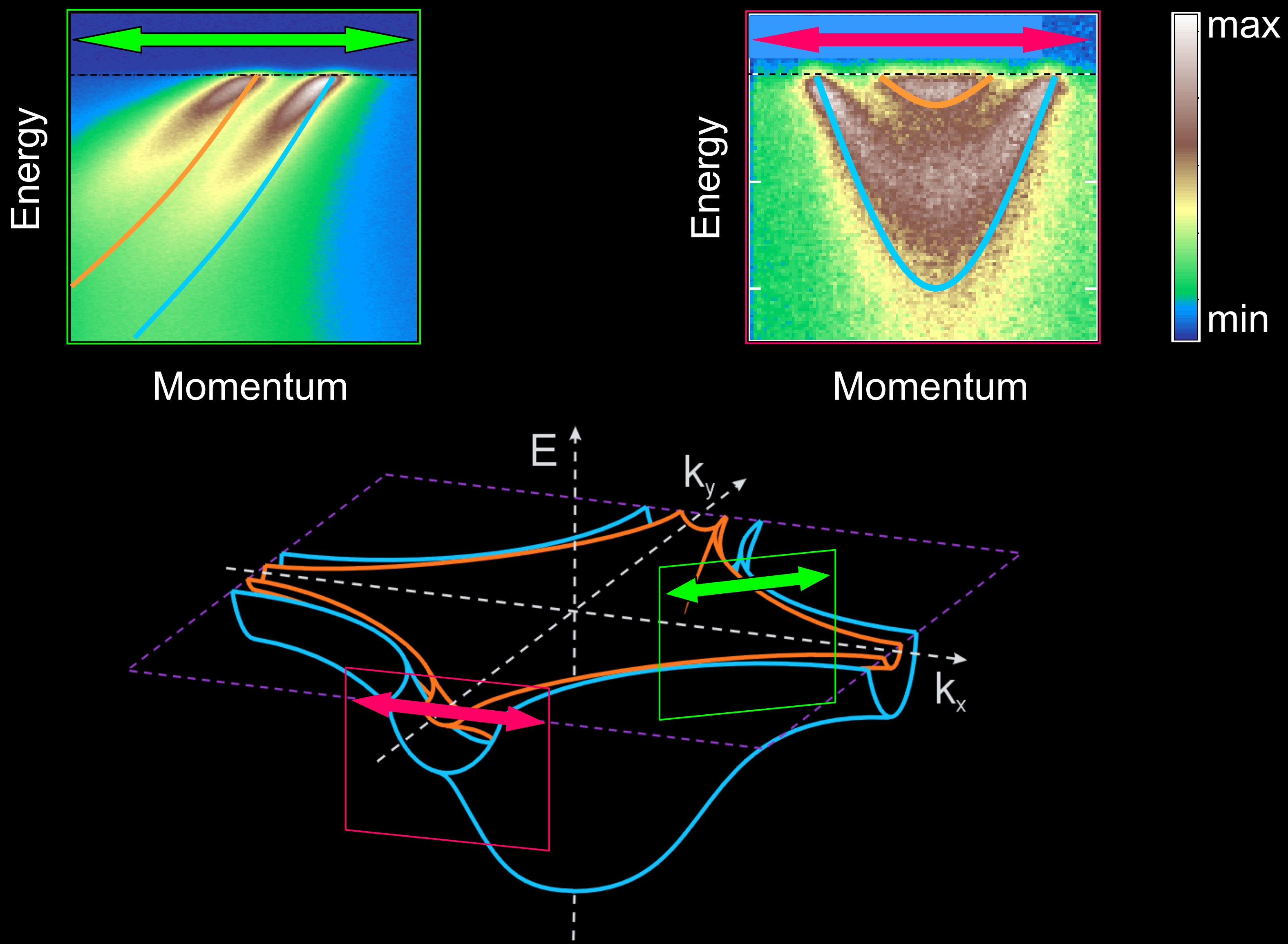
HTSC = LDA + Self-energy + PG



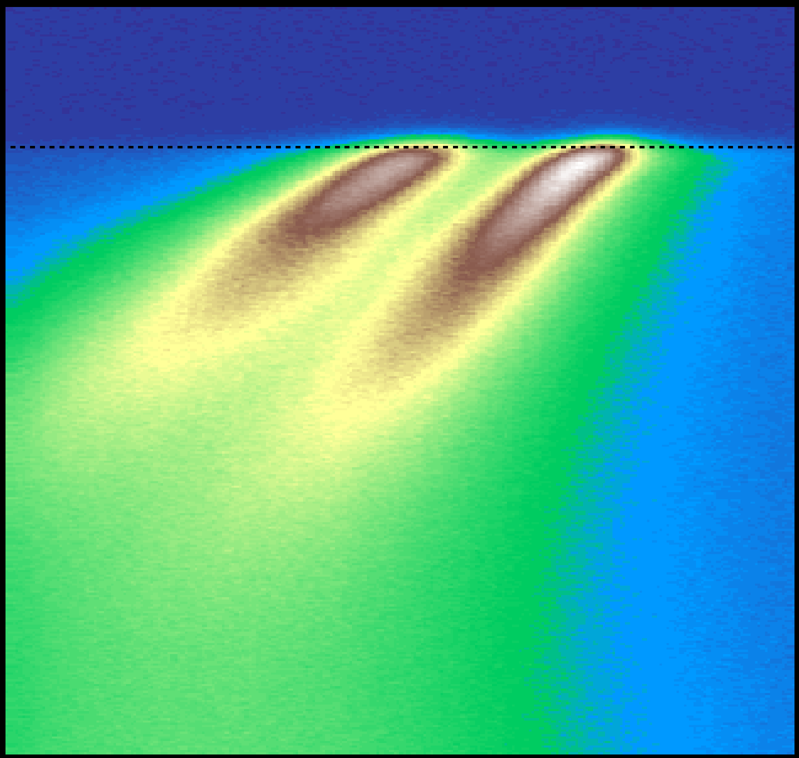


BSCO (2212)
YBCO (123)

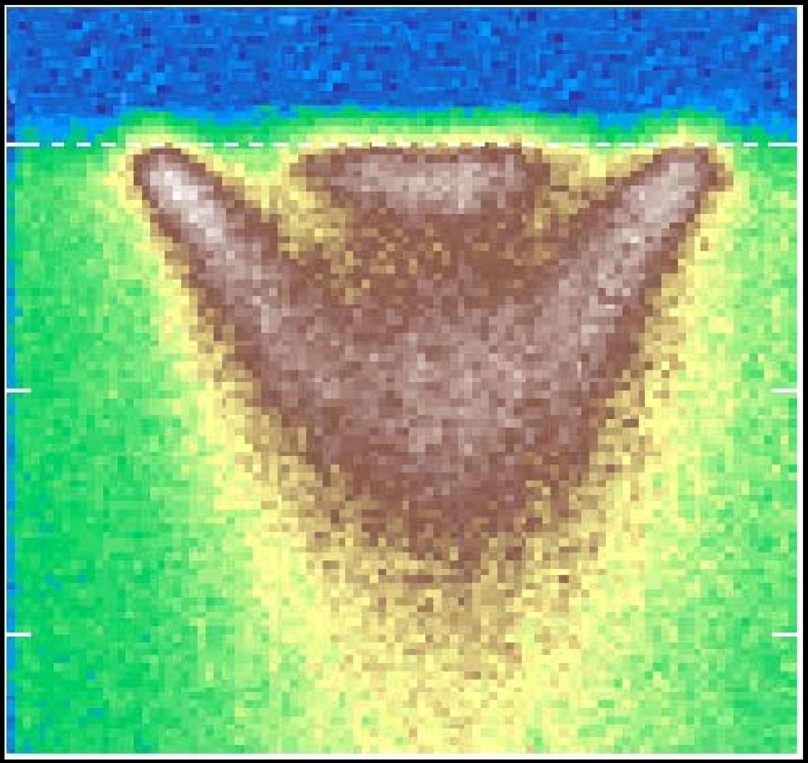
HTSC = LDA + quasiparticles?



HTSC = LDA + quasiparticles?



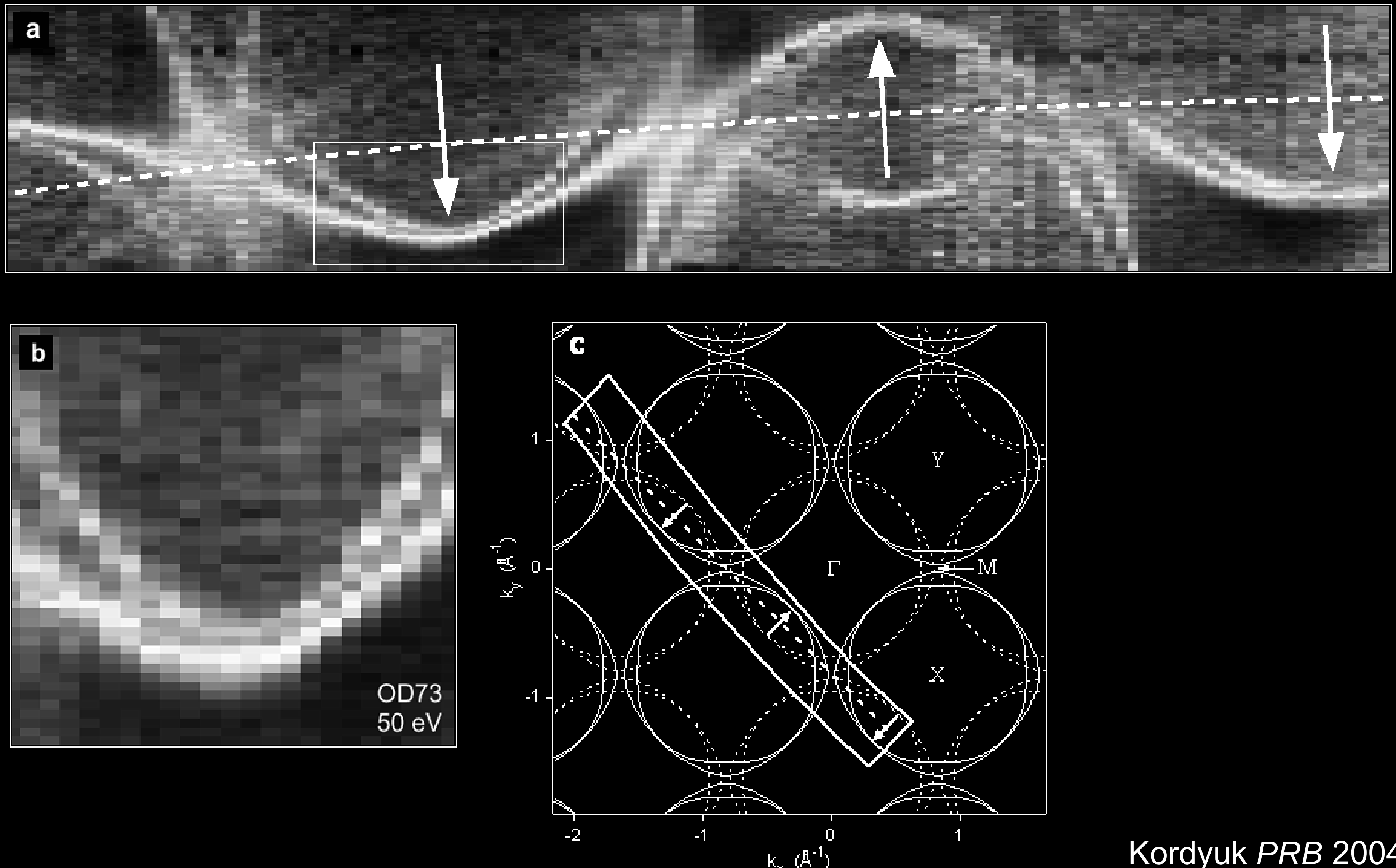
2006



2002

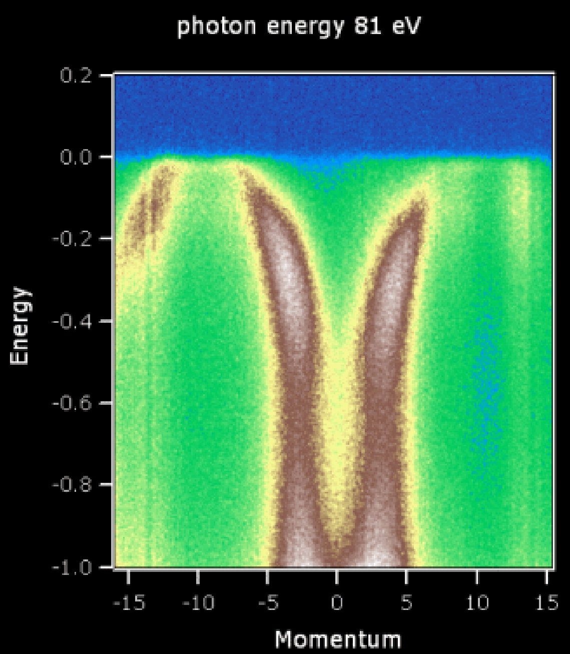
Borisenko *PRL* 2003

Photon energy – an important tool

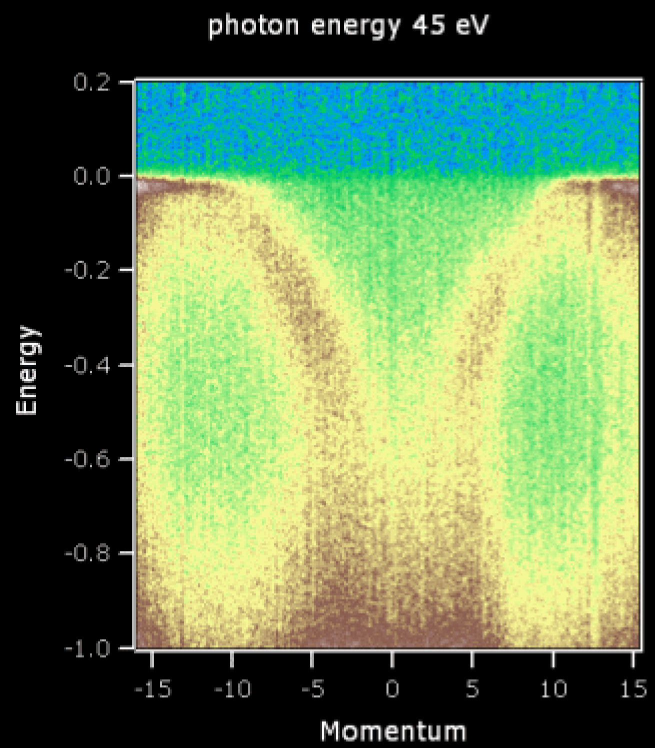


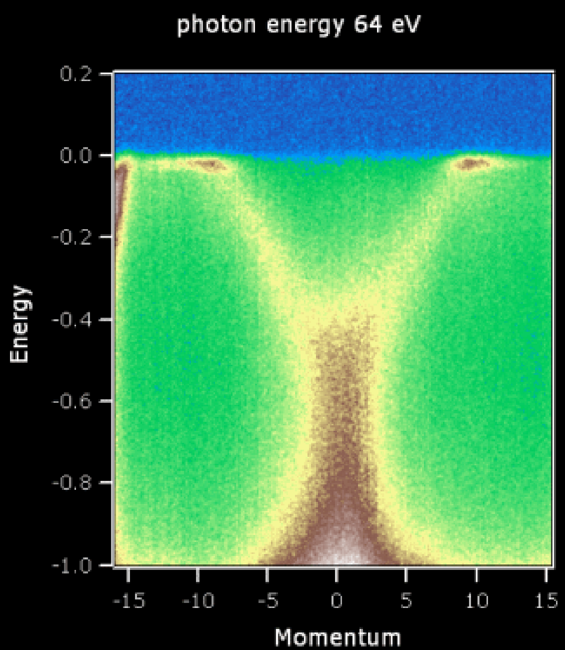
Kordyuk *PRB* 2004

Photon energy – an important tool



„Waterfalls“



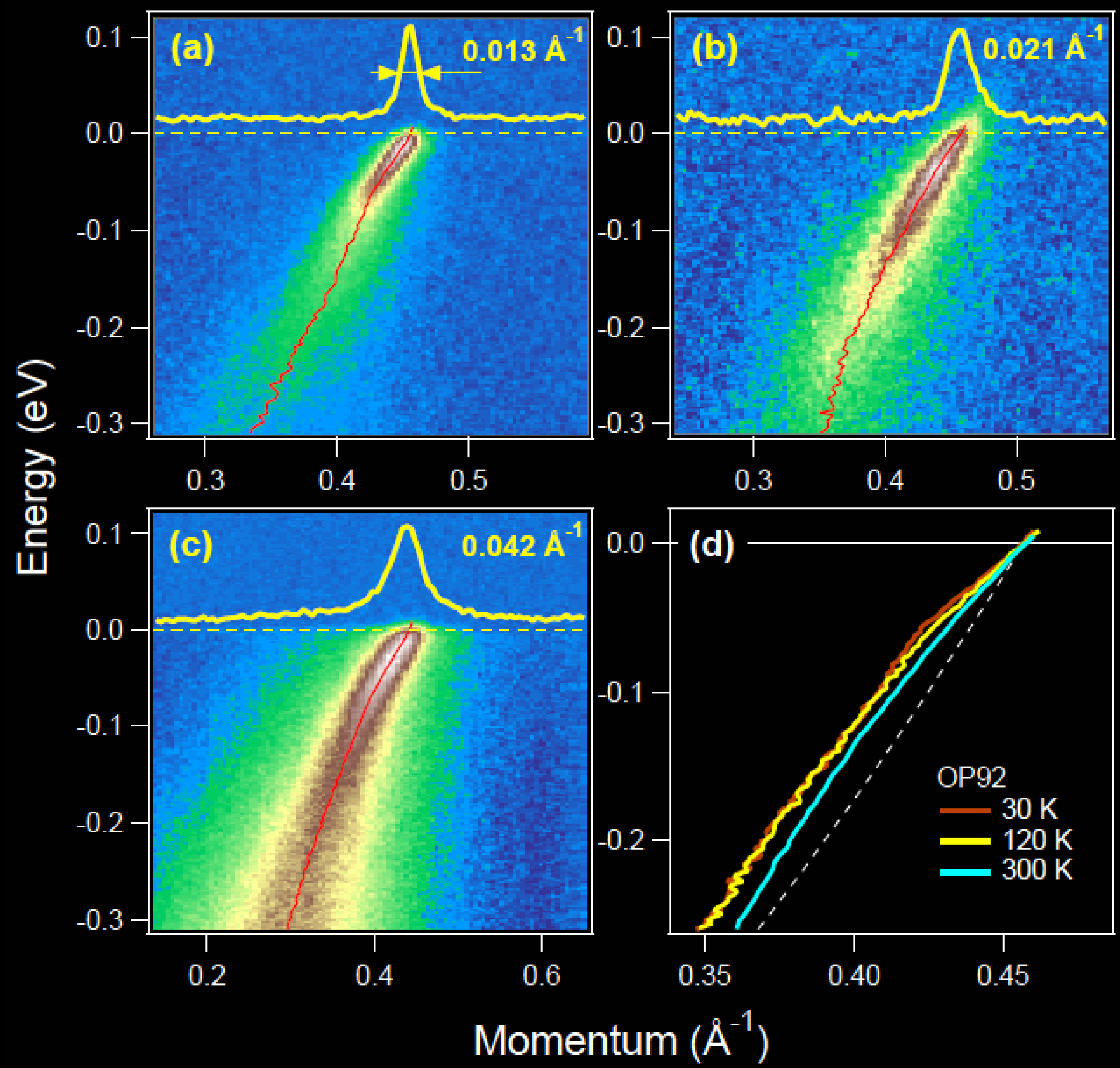


„Champagne glass“

Inosov *PRL* 2007, *PRB* 2008

HTSC = LDA + quasiparticles

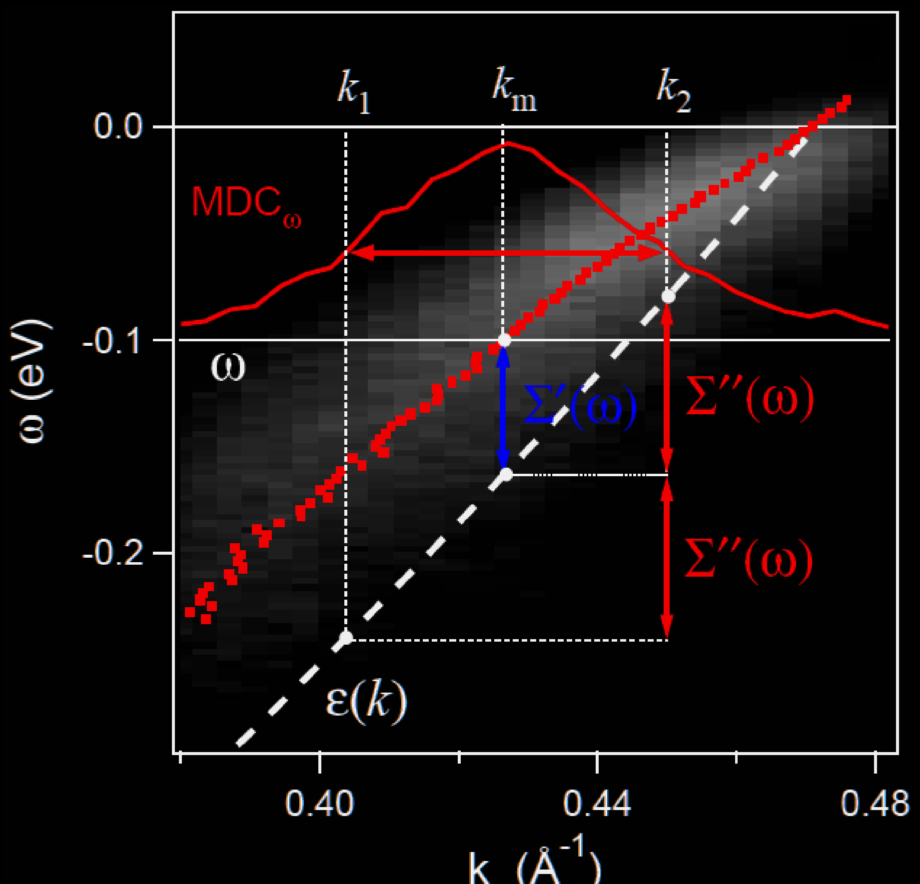
hv = 27 eV



Kordyuk *PRL* 2006

Quasiparticles ?

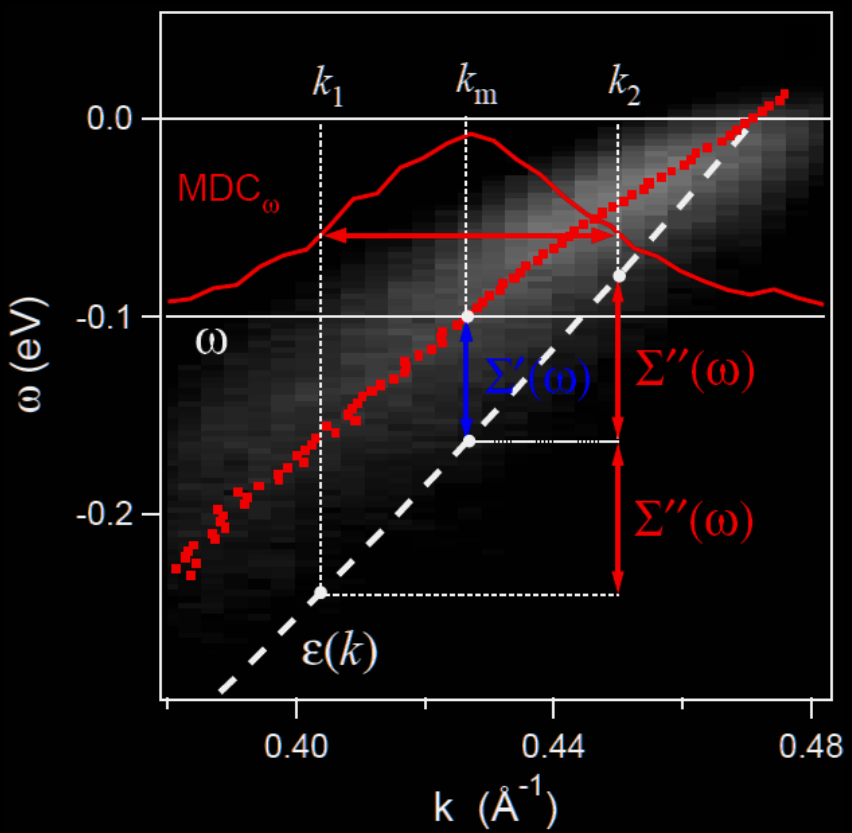
$$A(\omega, \mathbf{k}) = -\frac{1}{\pi} \frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}$$

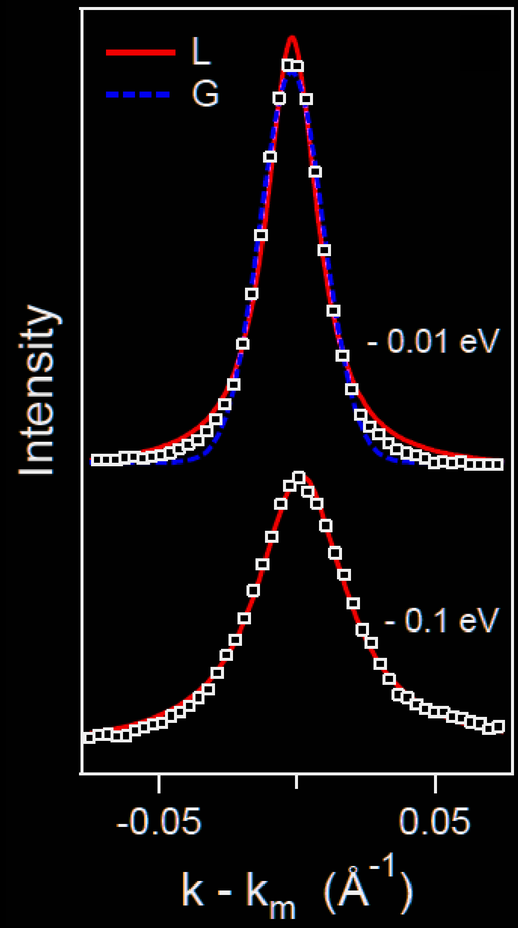


$$\Sigma'(\omega) = \omega - \varepsilon(k_m)$$

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

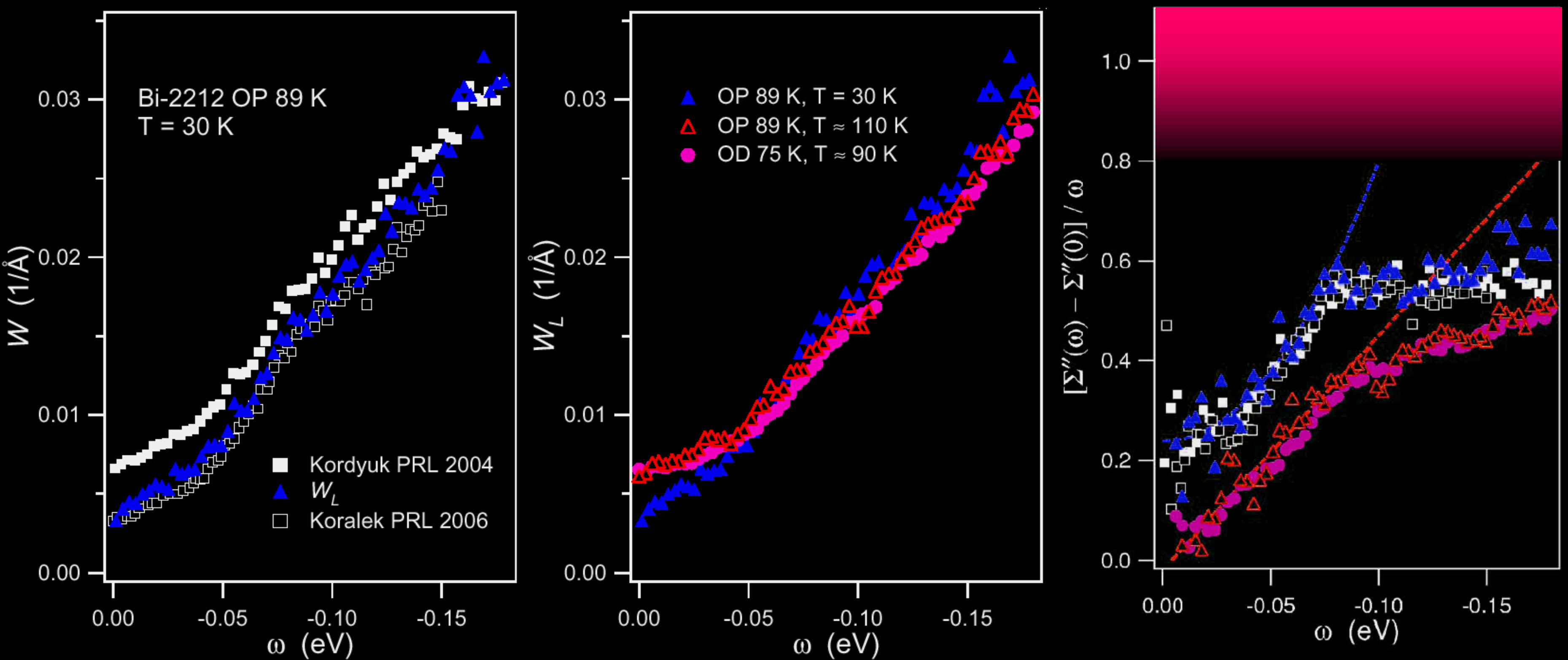
Quasiparticles ?





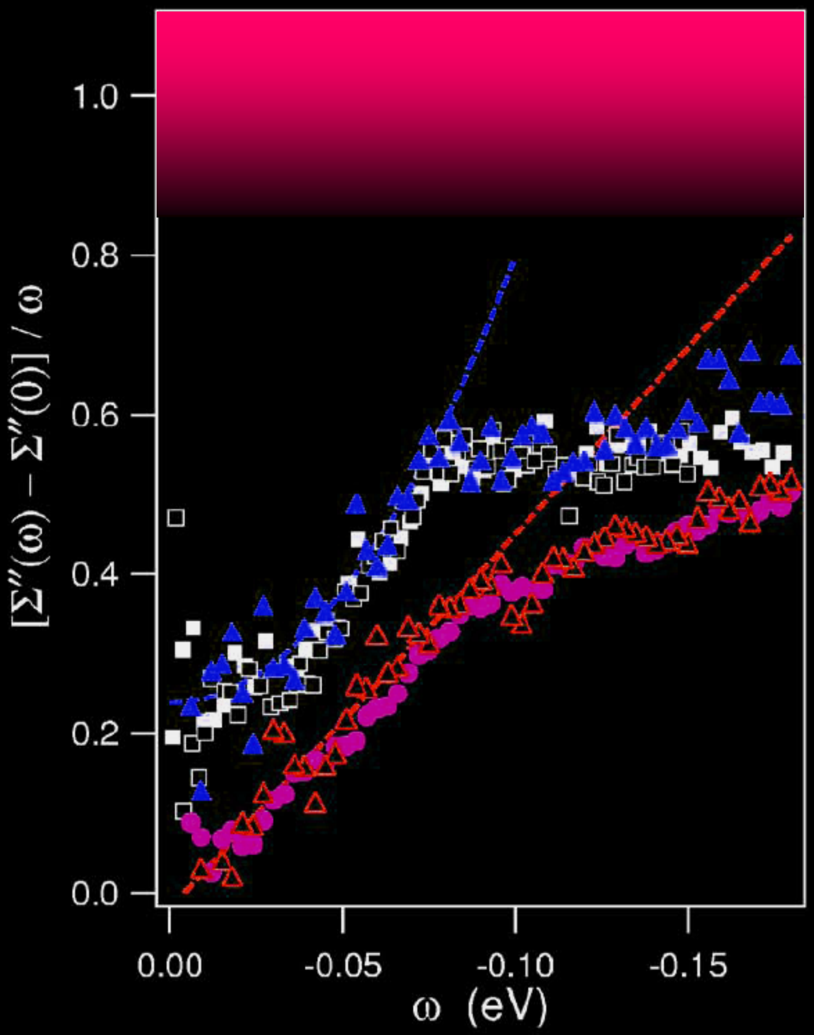
Voigt profile = Lorentzian ⊗ Gaussian

Quasiparticles ?



Evtushinsky *PRB 2006*

well or not well defined quasiparticles ?

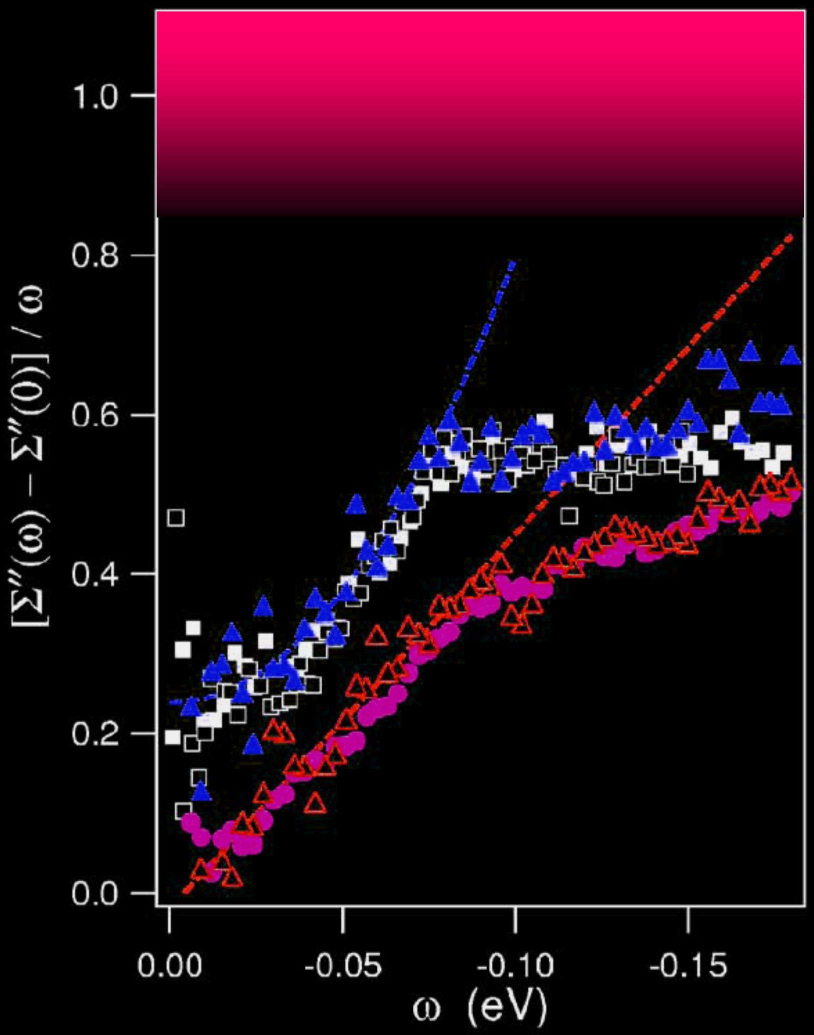


$\Sigma''(\omega) << \omega$

▲ OP 89 K, T = 30 K
△ OP 89 K, T ≈ 110 K
● OD 75 K, T ≈ 90 K

Evtushinsky *PRB 2006*

well or not well defined quasiparticles ?



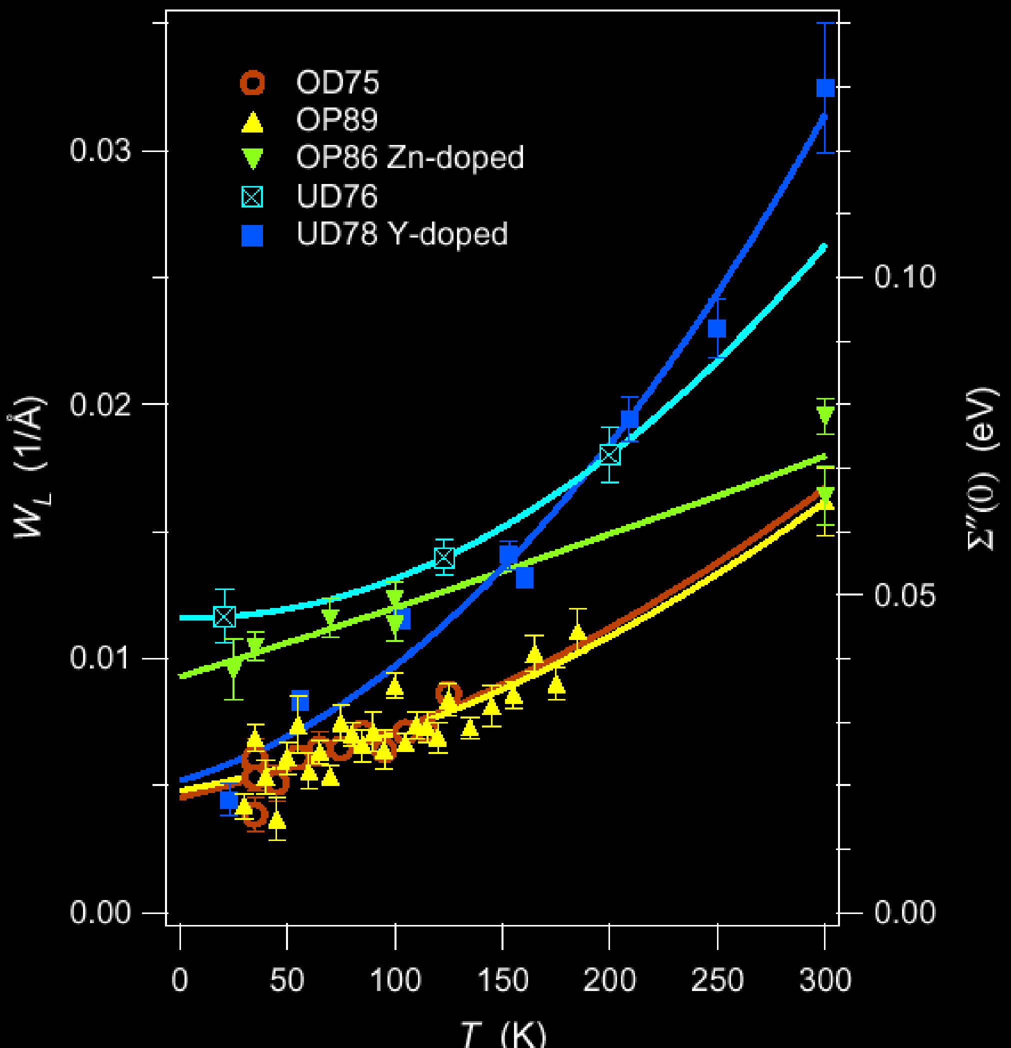
$$\Sigma''(\omega) - \Sigma''(0) \ll \omega$$

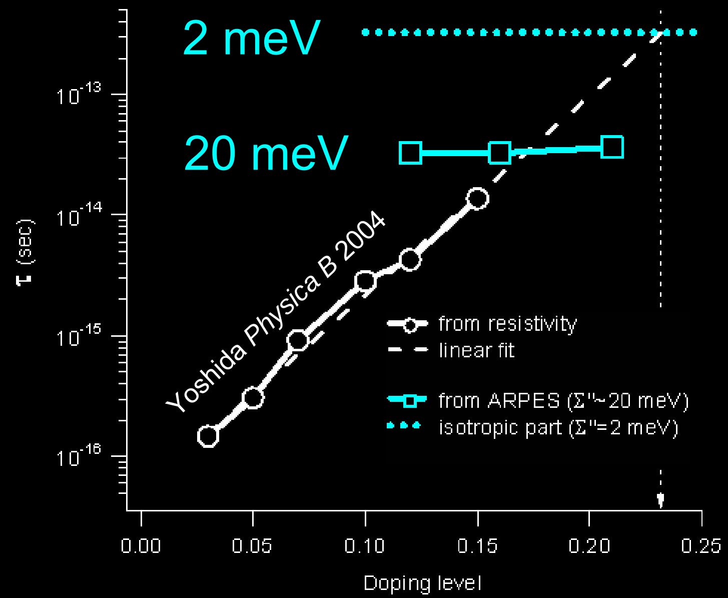
$$\frac{\Sigma''(\omega) - \Sigma''(0)}{\omega} \ll 1$$

OP 89 K, T = 30 K
OP 89 K, T ≈ 110 K
OD 75 K, T ≈ 90 K

Evtushinsky *PRB 2006*

HTSC = LDA + quasiparticles

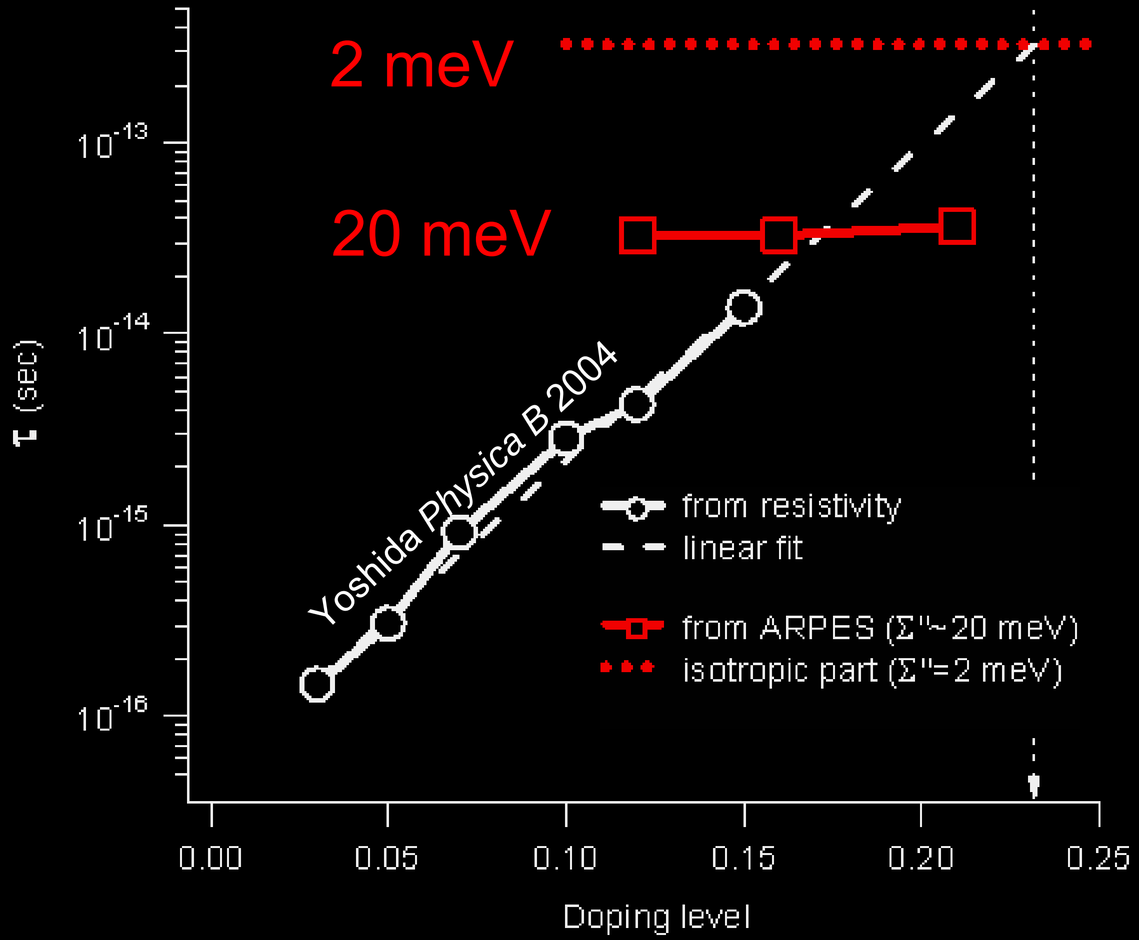




$$\rho_0 = \frac{m^*}{ne^2\tau} \approx \frac{k_F}{ne^2\eta}\frac{\Sigma''_{im}}{v_r}$$

Evtushinsky *PRB 2006*

HTSC = LDA + quasiparticles



n(*x*) problem

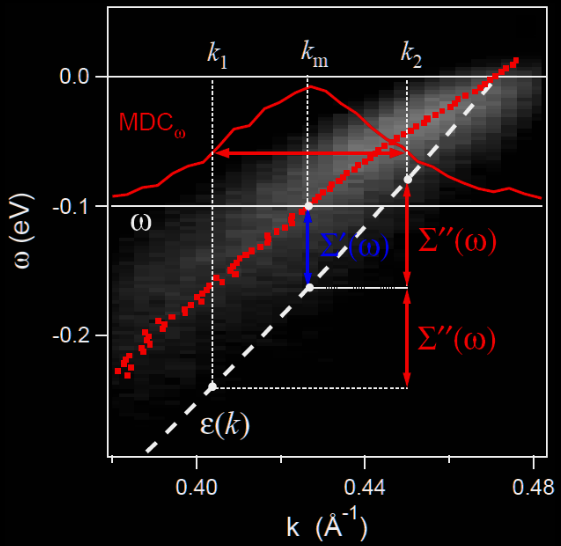
?

inhomogeneity

localization

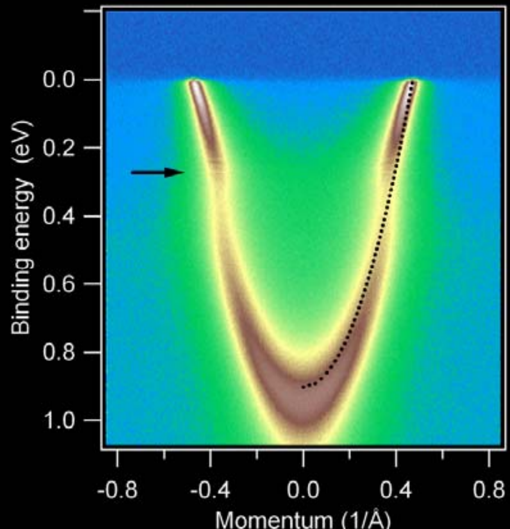
PG

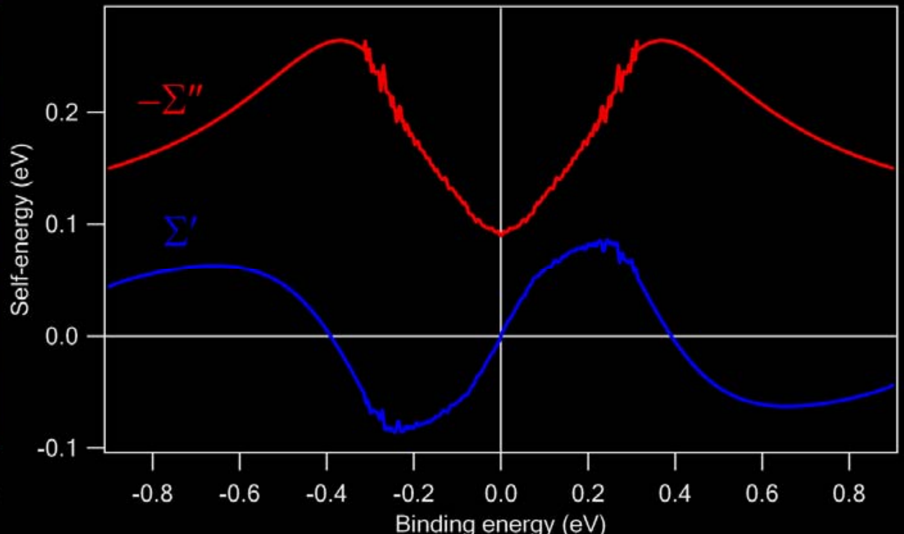
Self-energy structure



self-consistency means:

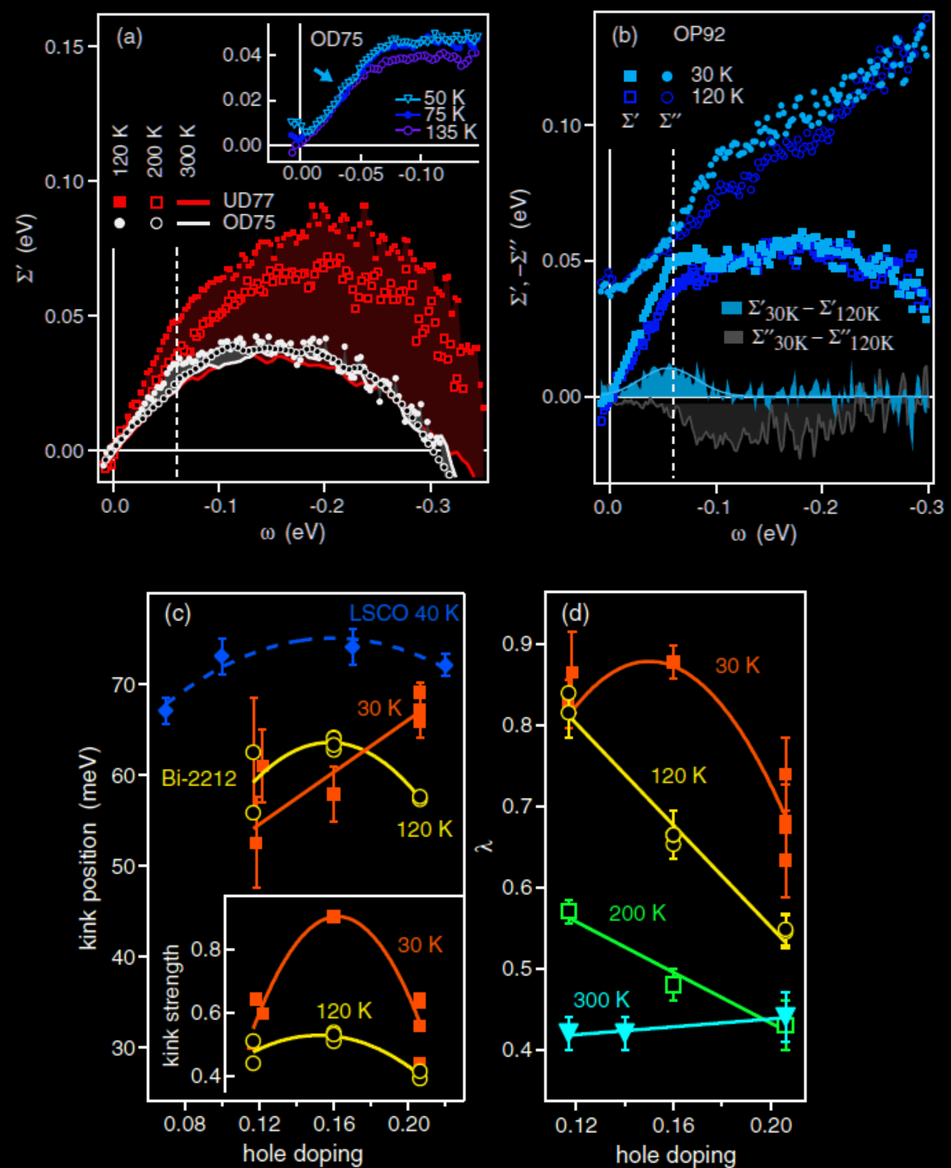
$$\Sigma' = \mathrm{KK}\ \Sigma''$$

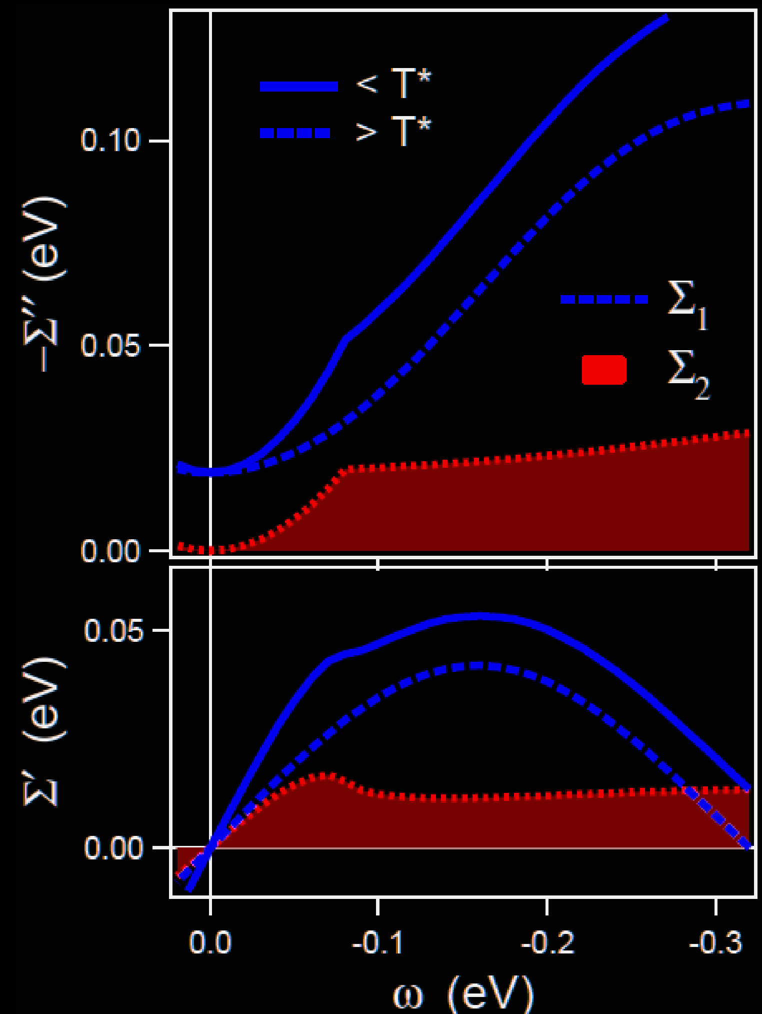




Kordyuk *PRB* 2005

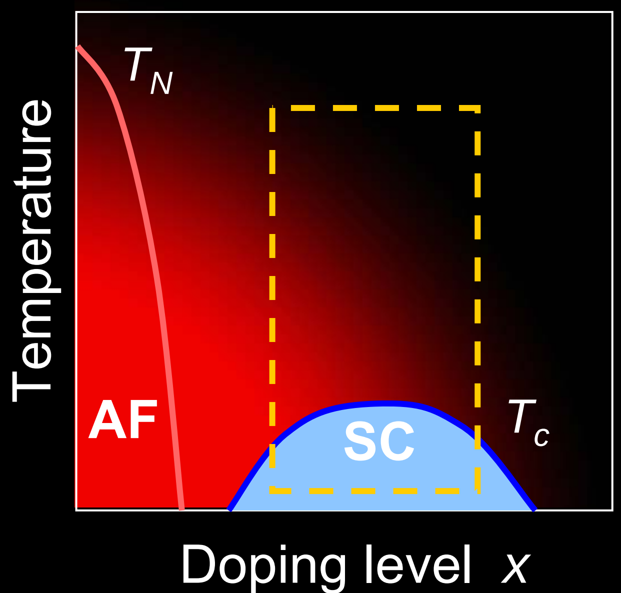
Self-energy structure: two channels

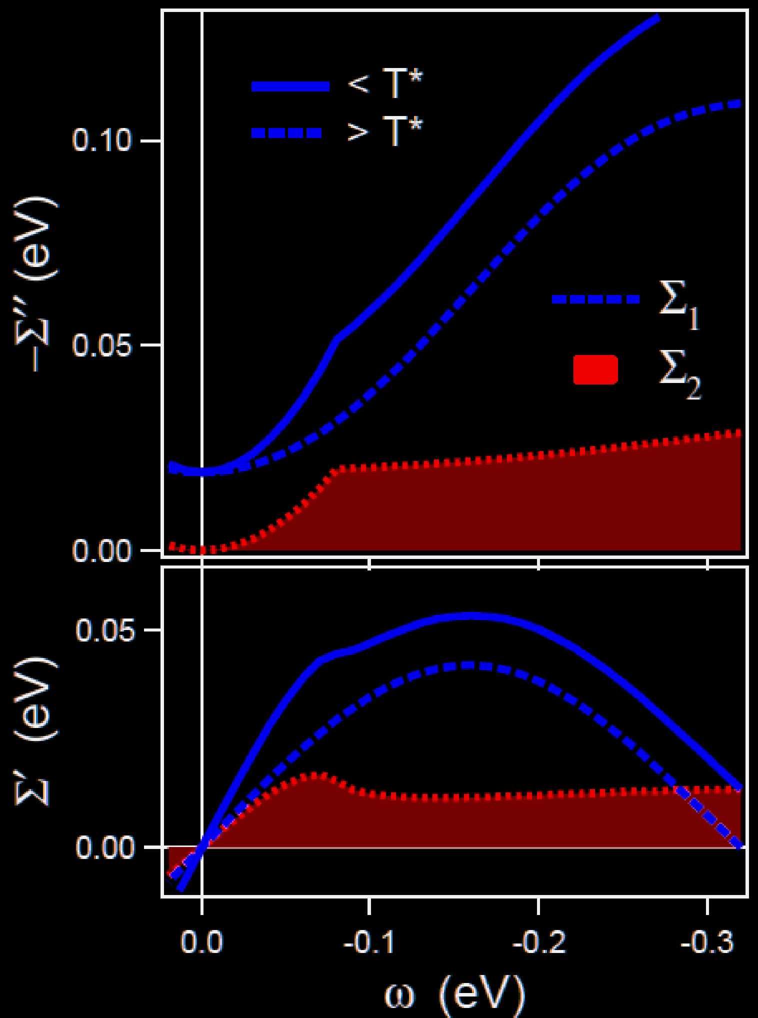




Kordyuk *PRL* 2004; *PRL* 2006

Self-energy structure: two channels



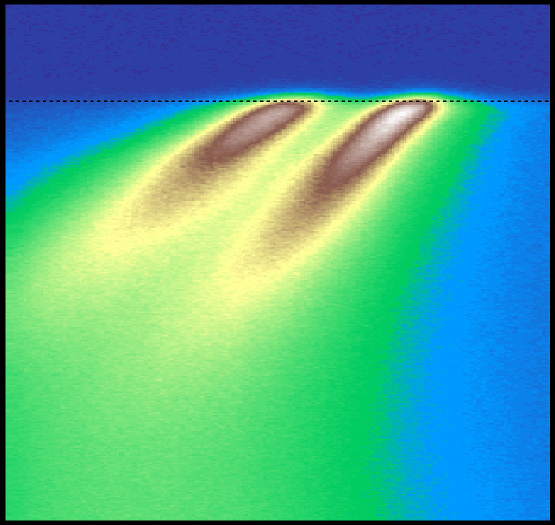


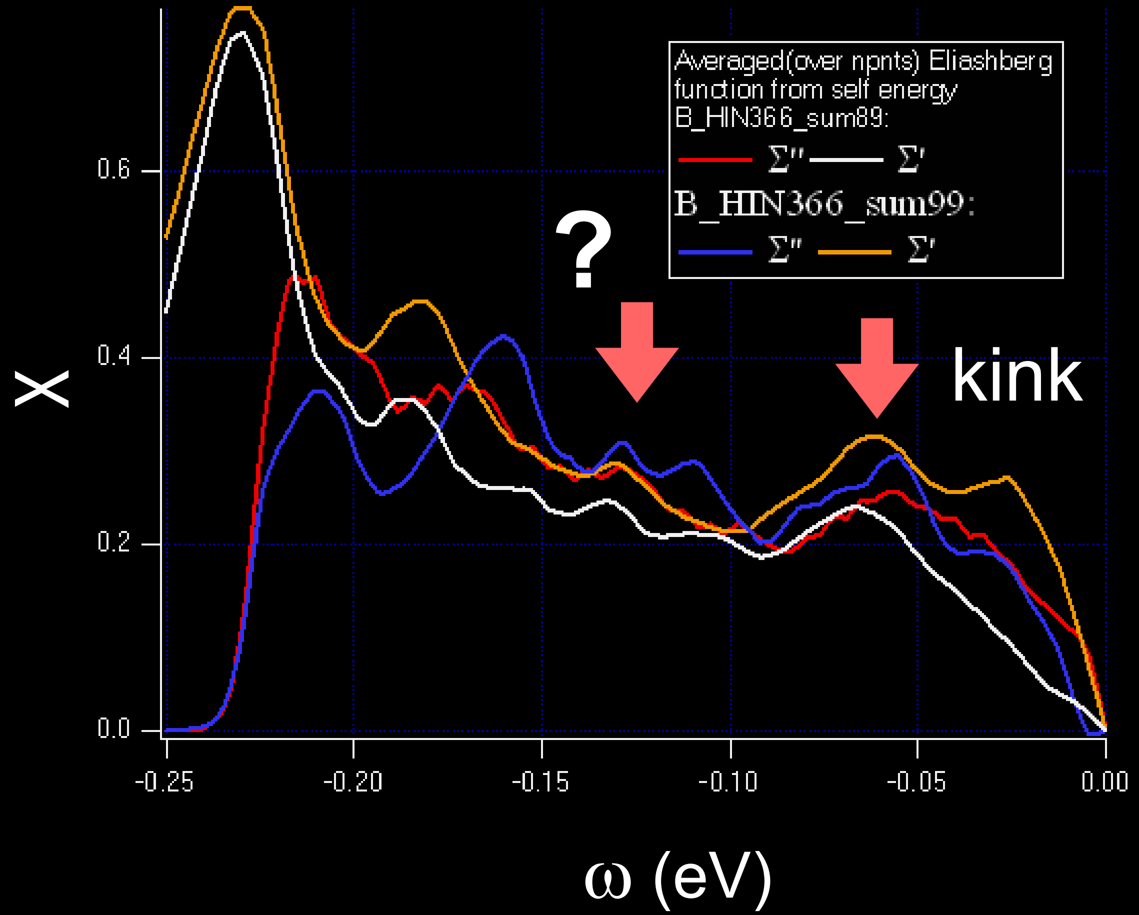
the only channel which reveals some energy scale is critically doping dependent
→ spin fluctuations

Kordyuk *PRL* 2004; *PRL* 2006

Self-energy structure: Eliashberg function

$G \star \chi = \Sigma$





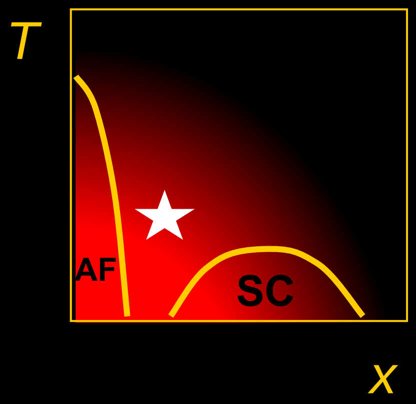
Evtushinsky 2007

Self-energy structure

1. Self-energy = **CHARGE** + MAGNETIC

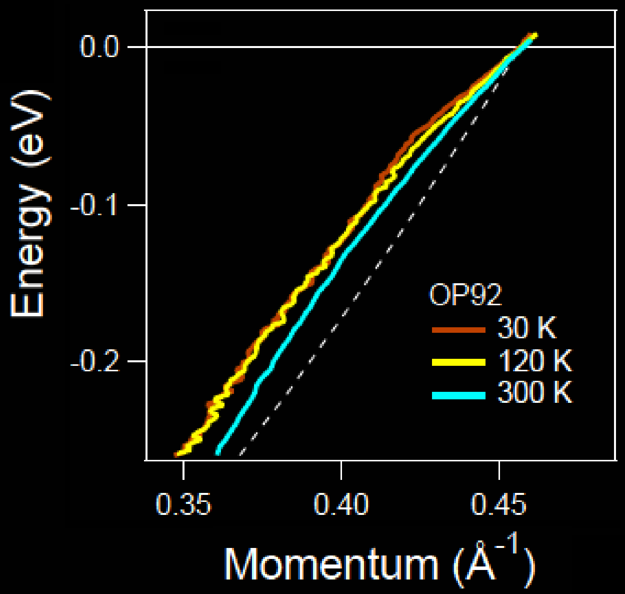
Self-energy structure

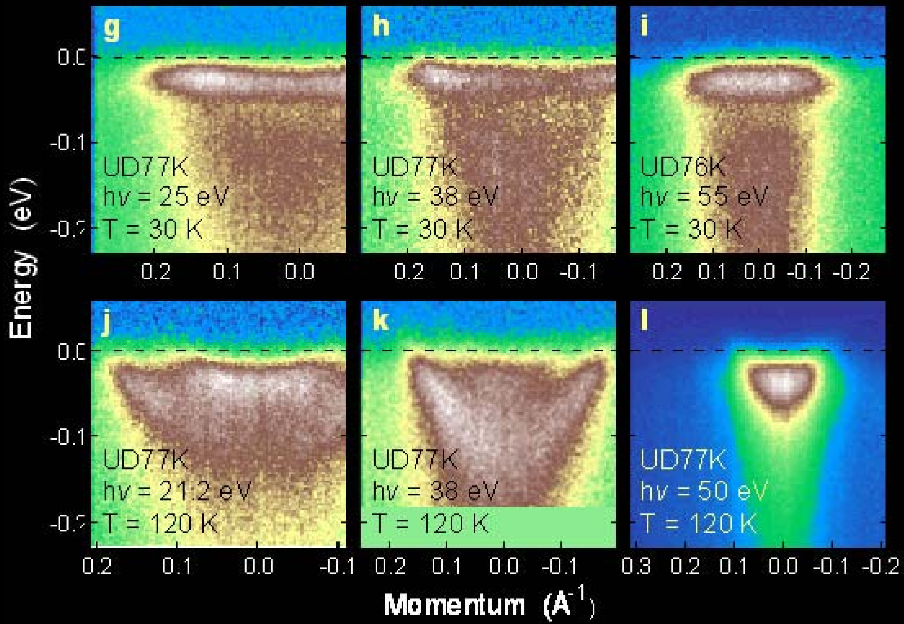
1. Self-energy = **CHARGE** + **MAGNETIC**



Self-energy structure

1. Self-energy = **CHARGE** + MAGNETIC
2. MAGNETIC (ω AND k AND T) ?

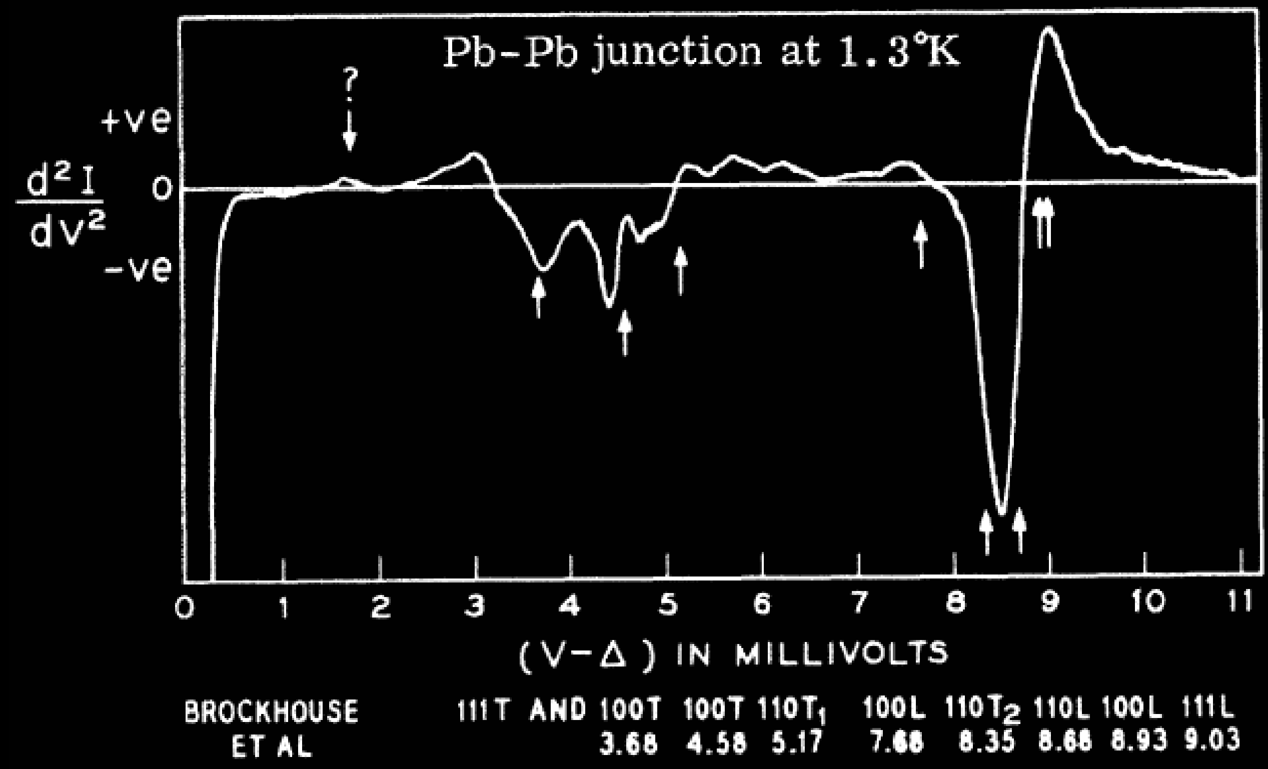




Self-energy origin

ARPES and INS

Story of "fingerprints"



"fingerprints" of the phononic spectrum
in tunneling differential conductance
by Rowell *PRL* 1963

Eliashberg equations

$$\Delta(\omega)=\frac{1}{Z(\omega)}\int_0^{\omega_c} d\omega'\ \mathrm{Re}\left\{\frac{\Delta(\omega')}{(\omega'^2-\Delta^2(\omega'))^{1/2}}\right\}[K_+(\omega',\omega)-N(0)U_c]$$

$$[1-Z(\omega)]\omega=\int_0^{\infty} d\omega'\ \mathrm{Re}\left\{\frac{\omega'}{(\omega'^2-\Delta^2(\omega'))^{1/2}}\right\}K_-(\omega',\omega)$$

$$K_\pm(\omega,\omega')=\sum_\lambda\int_0^{\infty} d\nu\ \alpha_\lambda^2(\nu)F_\lambda(\nu)\left[\frac{1}{\omega'+\omega+\nu+i\delta}\pm\frac{1}{\omega'-\omega+\nu-i\delta}\right]$$

el-ph coupling constant

phonon DOS

Scalapino *PR* 1966

What about HTSC?

✓ d-wave gap +
anisotropic electronic structure +
anisotropic spectra of phonons
or magnons

---

require
momentum resolved
experimental techniques: ARPES, INS

Constituents of quasiparticle spectrum

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

$$G_0(\mathbf{k},\omega) \qquad \Sigma(\mathbf{k},\omega) \;\; \& \;\; \Delta(\mathbf{k},\omega)$$

bare electrons Green function

self-energy

superconducting gap

Constituents of quasiparticle spectrum

bare Green function: $G_0(\mathbf{k}, \omega)$ from ARPES

self-energy: $\Sigma(\mathbf{k}, \omega)$ from ARPES and INS

$$G_0^{-1} + \underbrace{G \star \chi}_{= \Sigma} = G^{-1}$$

'bosonic' spectrum: $\chi(\mathbf{q}, \Omega)$ from INS

Constituents of quasiparticle spectrum

bare Green function: $G_0(\mathbf{k}, \omega)$ from ARPES

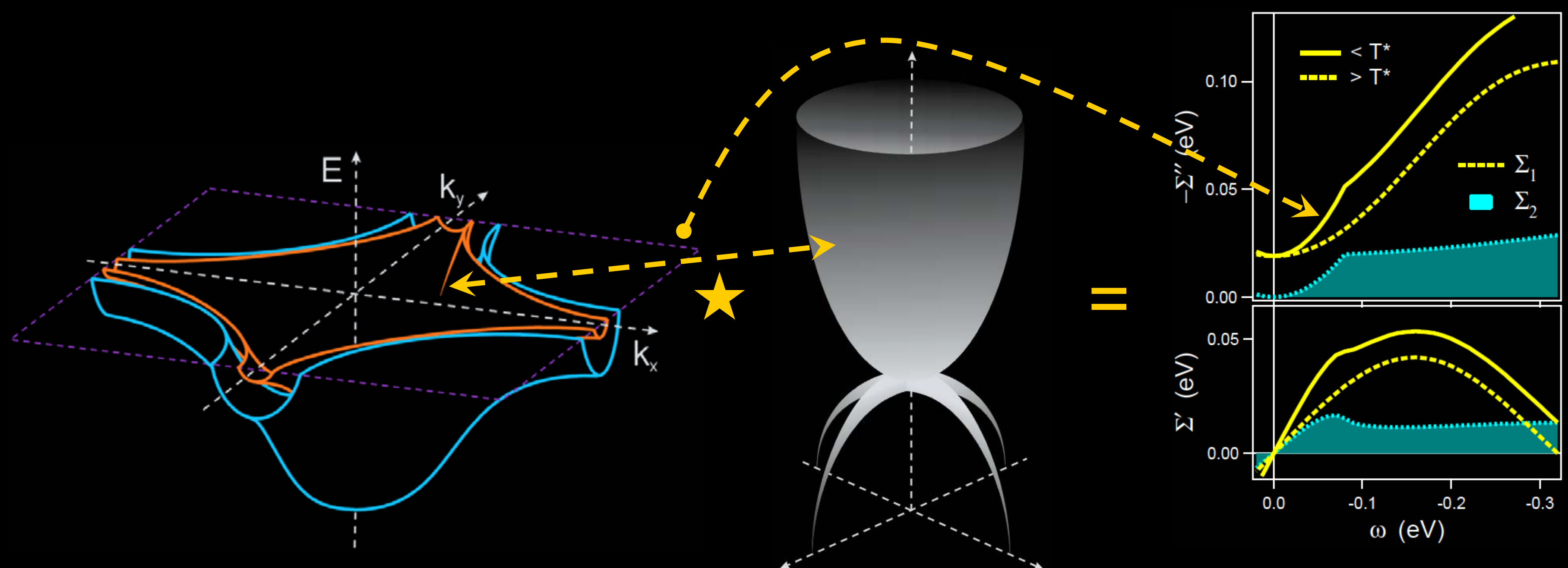
self-energy: $\Sigma(\mathbf{k}, \omega)$ from ARPES

$$G_0^{-1} + \overbrace{G \star \underbrace{G \star G}_{=\ \chi(\mathbf{q},\Omega)}}^{=\ \Sigma(\mathbf{k},\omega)} = G^{-1}$$

ittinerant SF: $\chi(\mathbf{q}, \Omega)$ from INS and ARPES

Spin-fluctuations: ARPES and INS

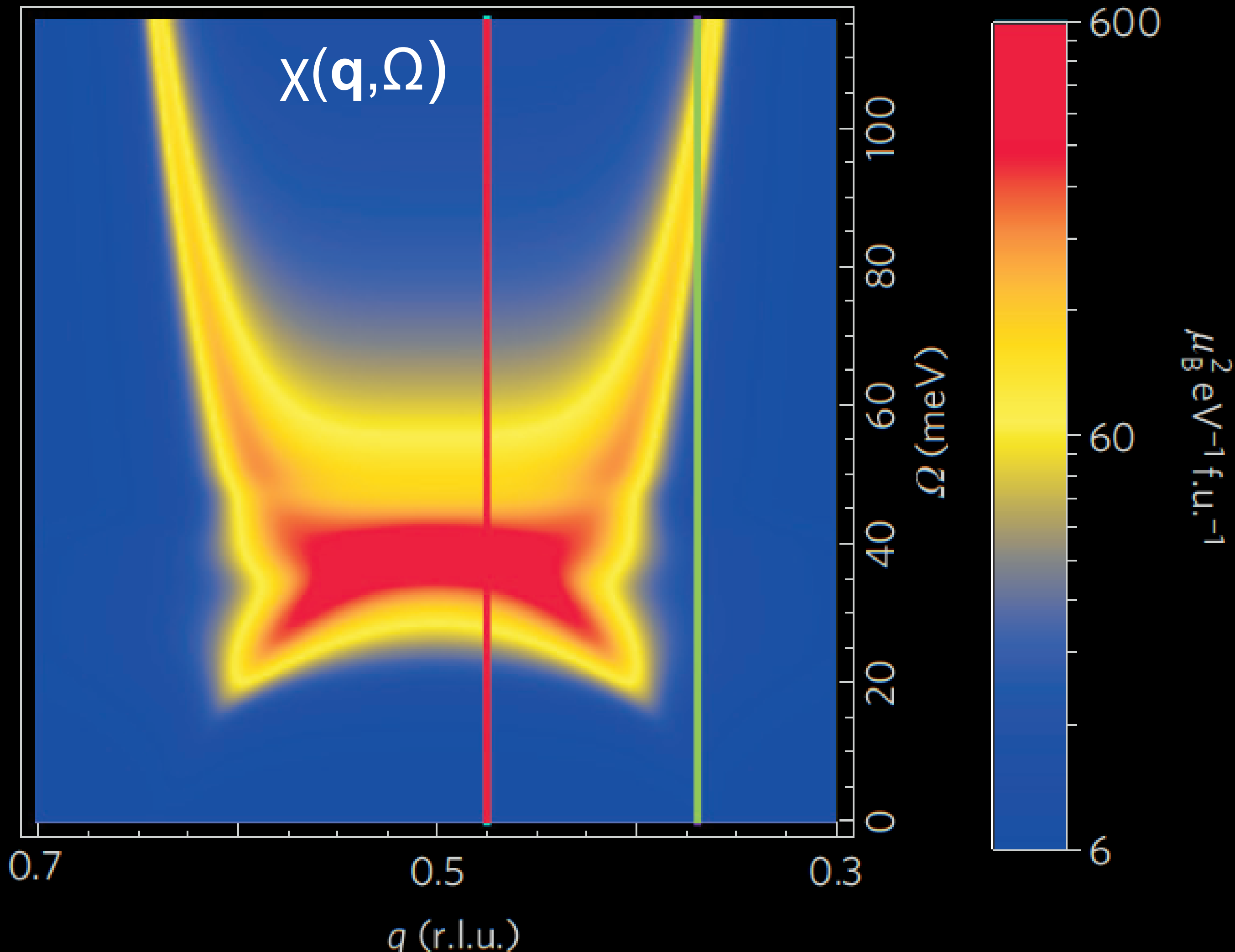
$$G_0^{-1} + G \star \chi = G^{-1}$$



$G_0(k, \omega)$ $\chi(q, \Omega)$ $\Sigma(k, \omega)$

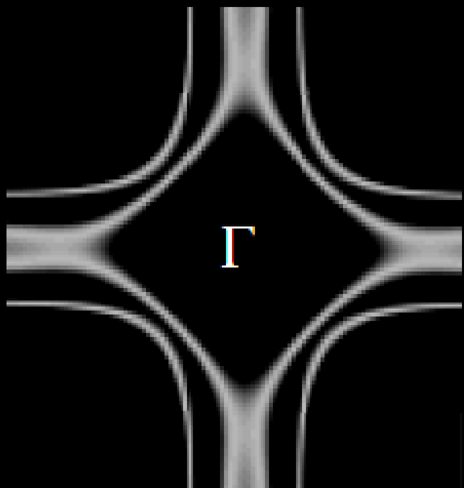
IFW (ARPES) + Hinkov & Keimer (INS) + Dahm & Scalapino 2006

Spin-fluctuations: ARPES and INS

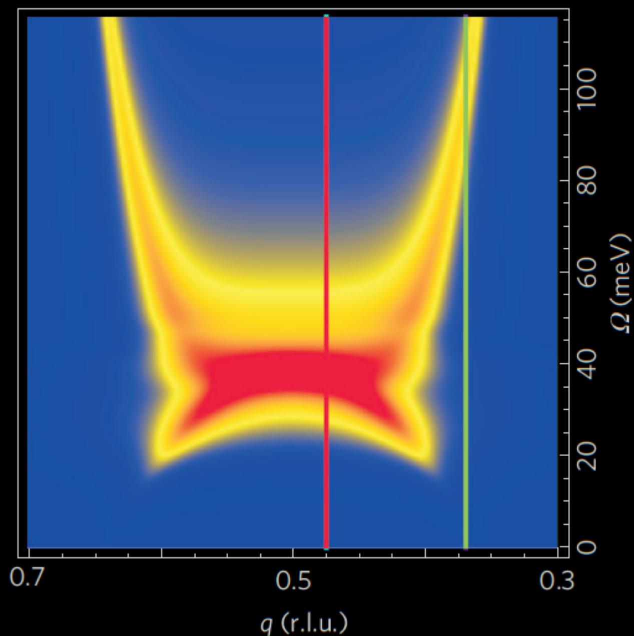


Dahm *Nature Phys.* (2009)

Spin-fluctuations: ARPES and INS



★



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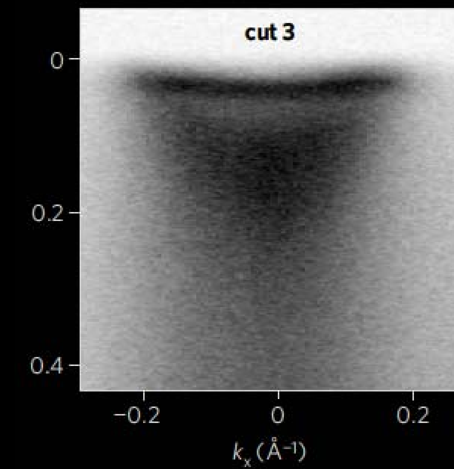
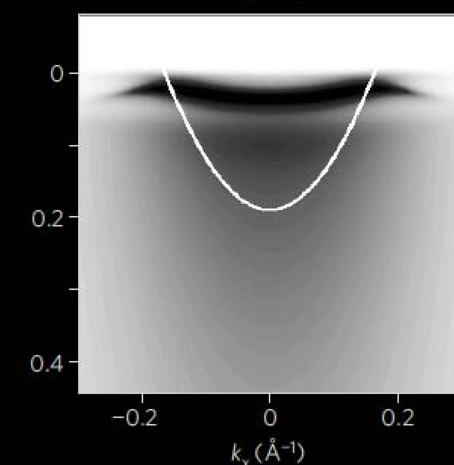
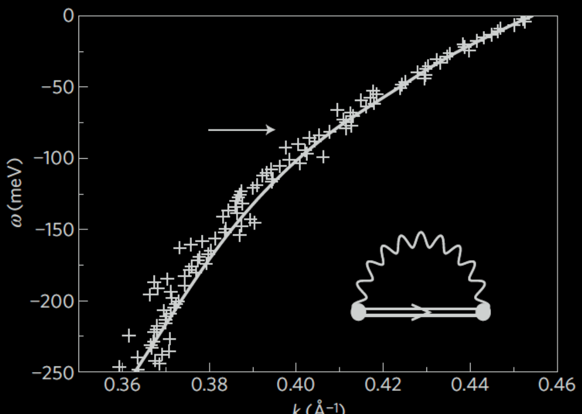
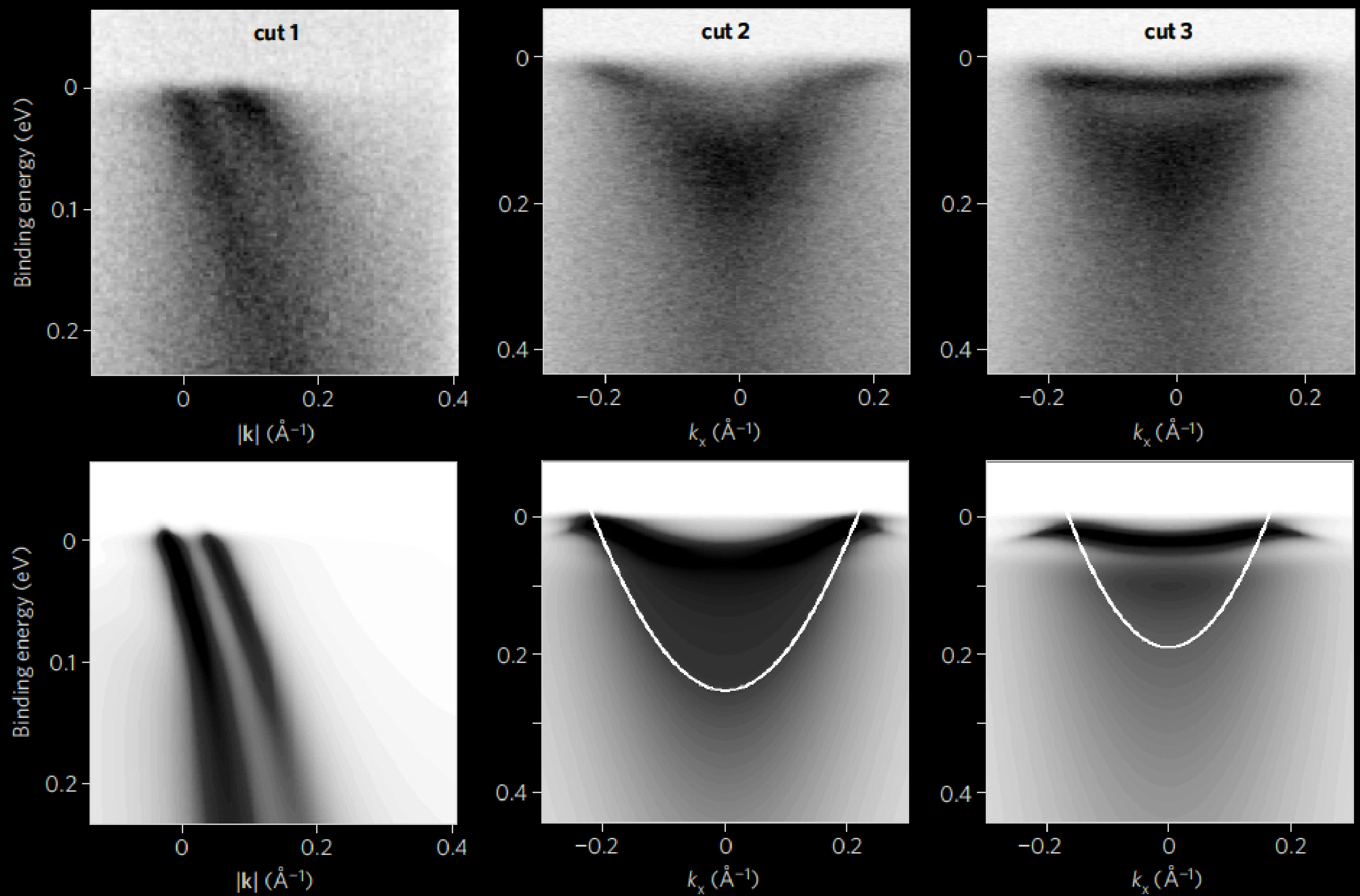






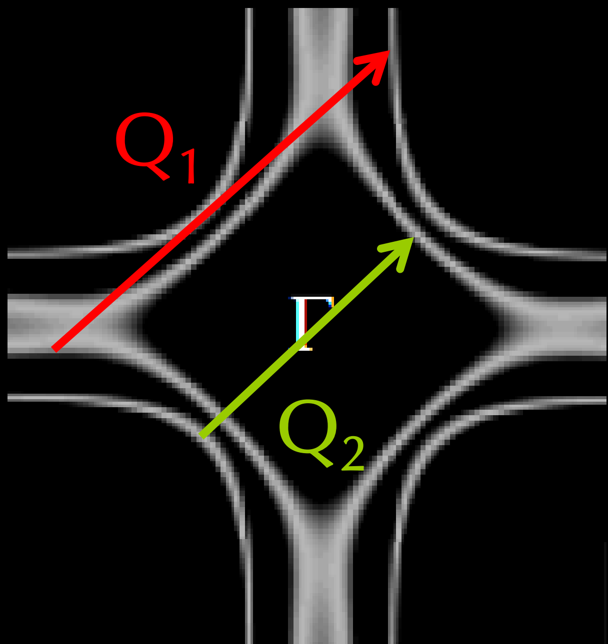
Dahm *Nature Phys.* (2009)

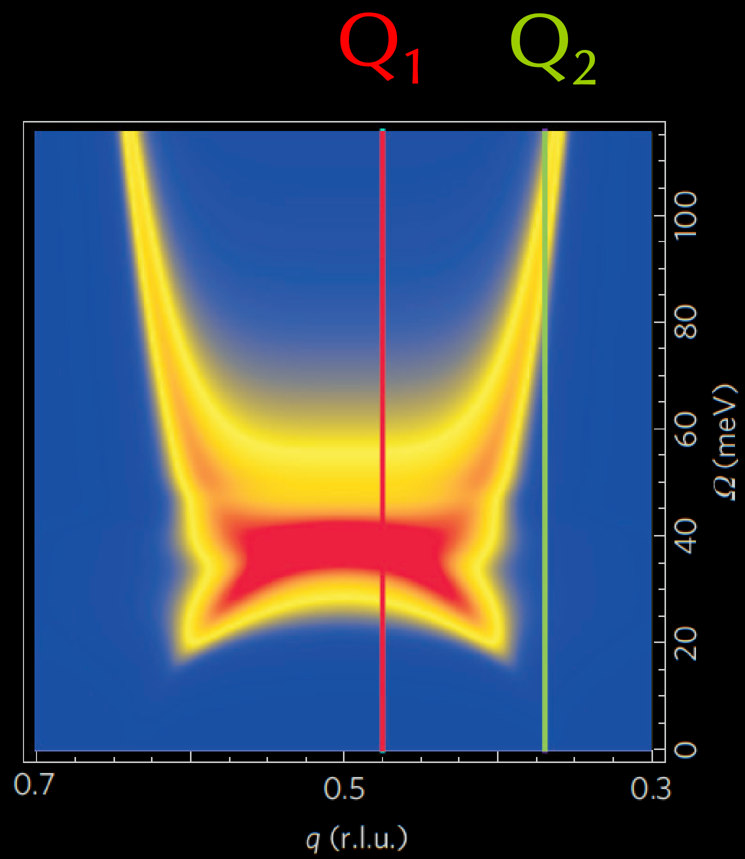
Spin-fluctuations: ARPES and INS



Dahm *Nature Phys.* (2009)

Spin-fluctuations: ARPES and INS

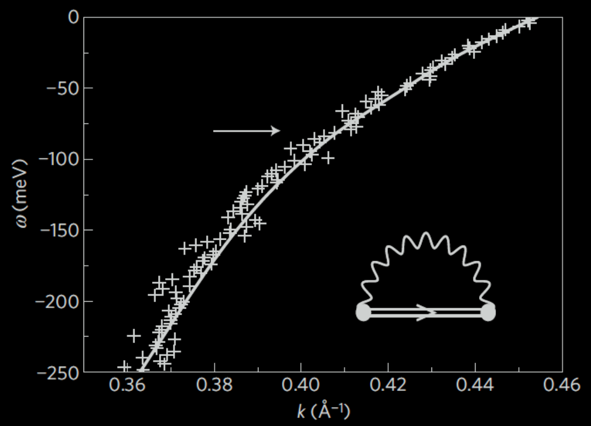




Dahm *Nature Phys.* (2009)

Spin-fluctuations: ARPES and INS

$$V_{\text{eff}}(\mathbf{Q},\Omega) = \frac{3}{2}\,\bar{U}^2\,\chi(\mathbf{Q},\Omega)$$



$$\bar{U} = 1.59\,\text{eV}$$

$$\lambda_d = 1.39$$

$$\boxed{T_c = 174\,\text{K}}$$

Dahm *Nature Phys.* (2009)

General conclusions

1. Spin-fluctuations well describe one-particle spectra in YBCO.

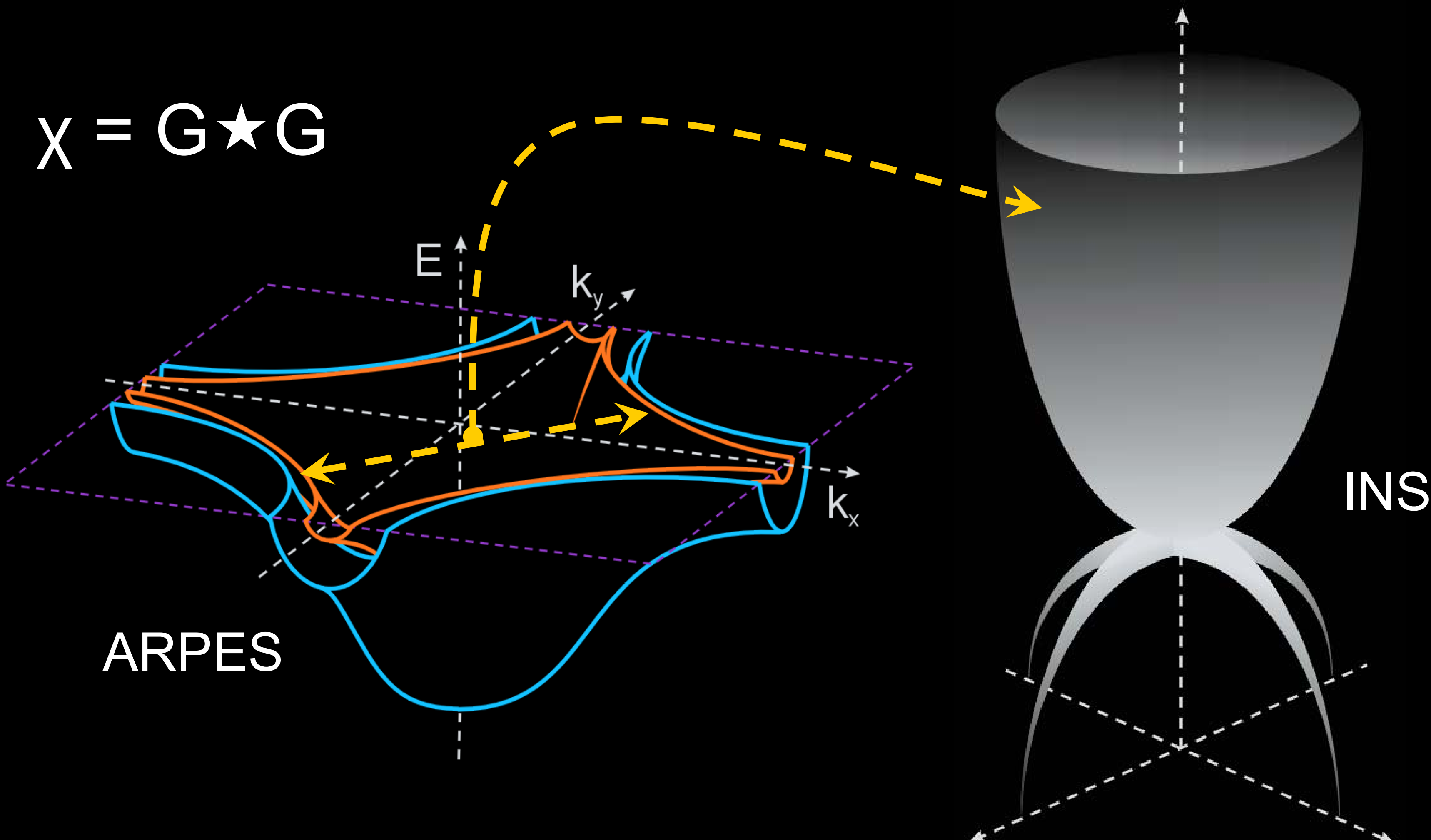
2. In particular, they solve the kink puzzle.

3. $T_c > 150$ K:
   spin fluctuations have sufficient strength to mediate high-temperature superconductivity.

PG ?

Is it itinerant?

$\chi = G \star G$



Is it itinerant?

bare spin susceptibility (Lindhard function):

$$\chi_0(\mathbf{Q}, i\Omega_n) = \frac{1}{\pi^2} \int \sum_m G(\mathbf{k}, i\omega_m) G(\mathbf{k}+\mathbf{Q}, i\omega_m + i\Omega_n) \mathrm{d}\mathbf{k}$$

dynamic spin susceptibility (RPA):

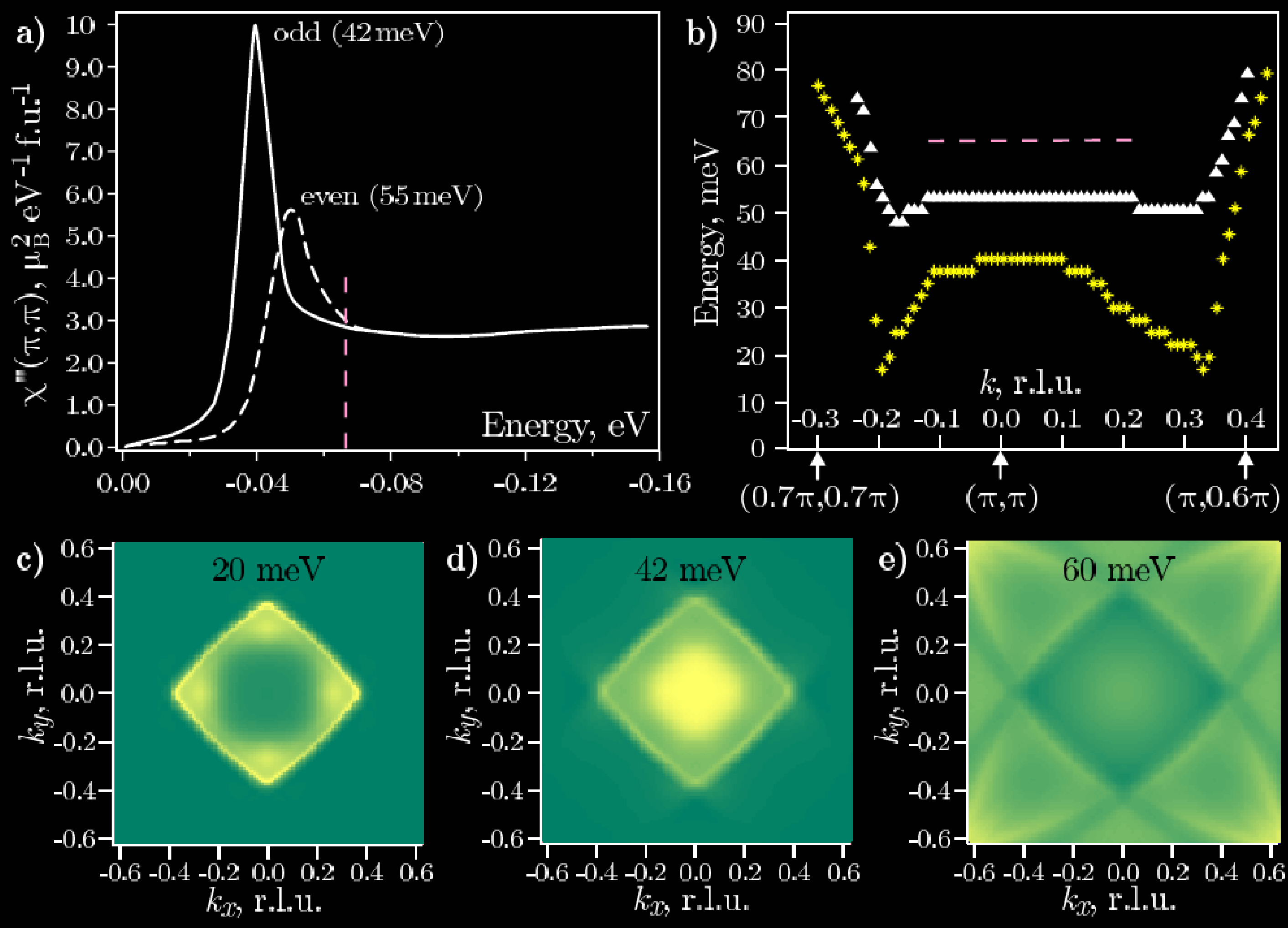
$$\chi^{\mathrm{o,e}}(\mathbf{Q}, \Omega) = \chi_0^{\mathrm{o,e}}(\mathbf{Q}, \Omega) / [1 - J_Q^{\mathrm{o,e}} \chi_0^{\mathrm{o,e}}(\mathbf{Q}, \Omega)]$$

effective Hubbard interaction:

$$J_Q^{\mathrm{o,e}} = -J_{\parallel}(\cos Q_x + \cos Q_y) \pm J_{\perp}$$

Inosov *PRB 2007*

Is it itinerant?



Inosov *PRB 2007*

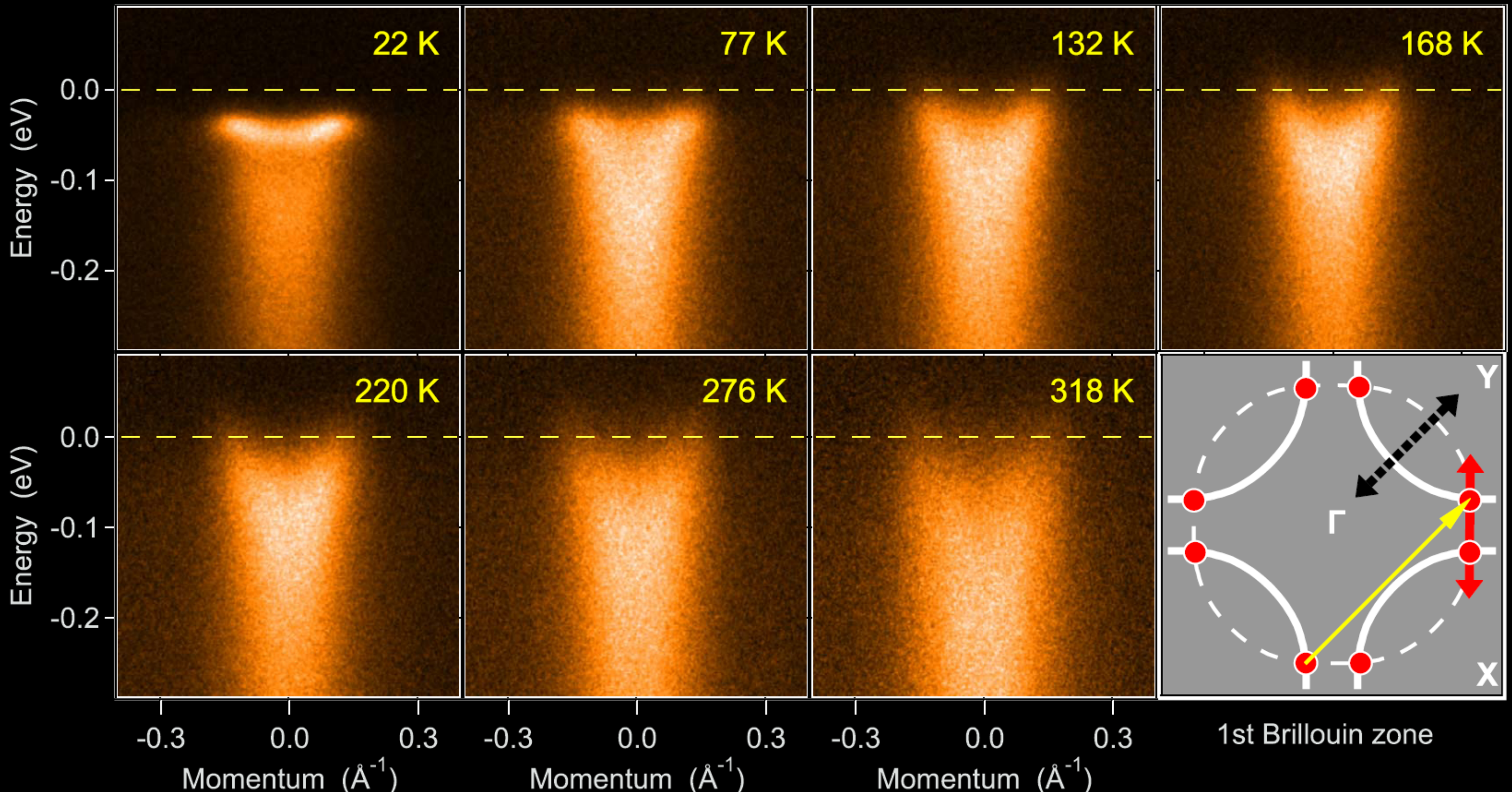
$$\Sigma(\mathbf{k},\omega) = \overbrace{G_0^{-1} + G \star G \star G}^{}$$

$$G_0^{-1} + \overbrace{G \star G \star G}^{\Sigma(\mathbf{k},\omega)} = G^{-1}, \qquad G \star \underbrace{G \star G}_{=\,\chi(\mathbf{q},\Omega)}$$

PG ?

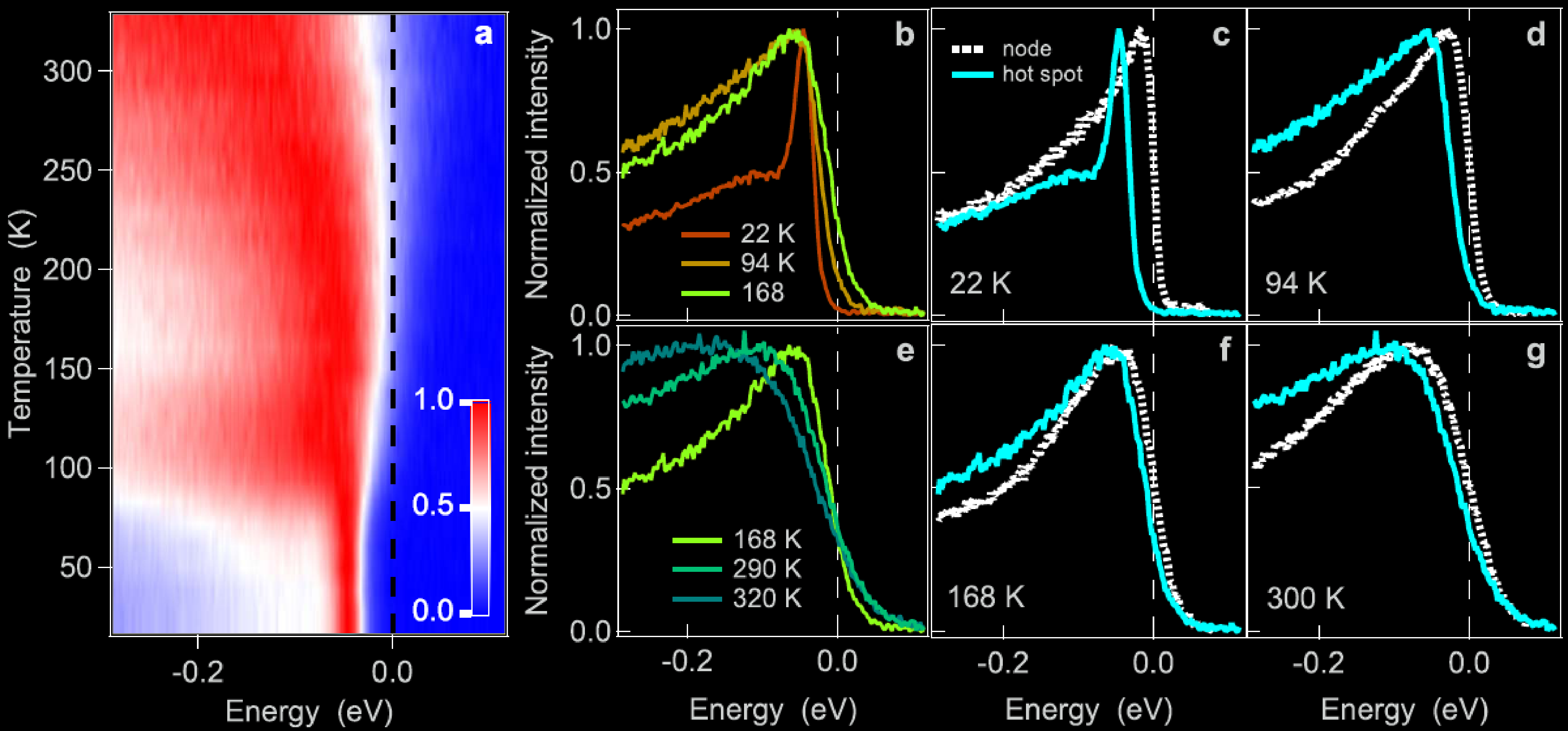
Pseudo-gap in BSCCO

Non-monotonic pseudo-gap in BSCCO



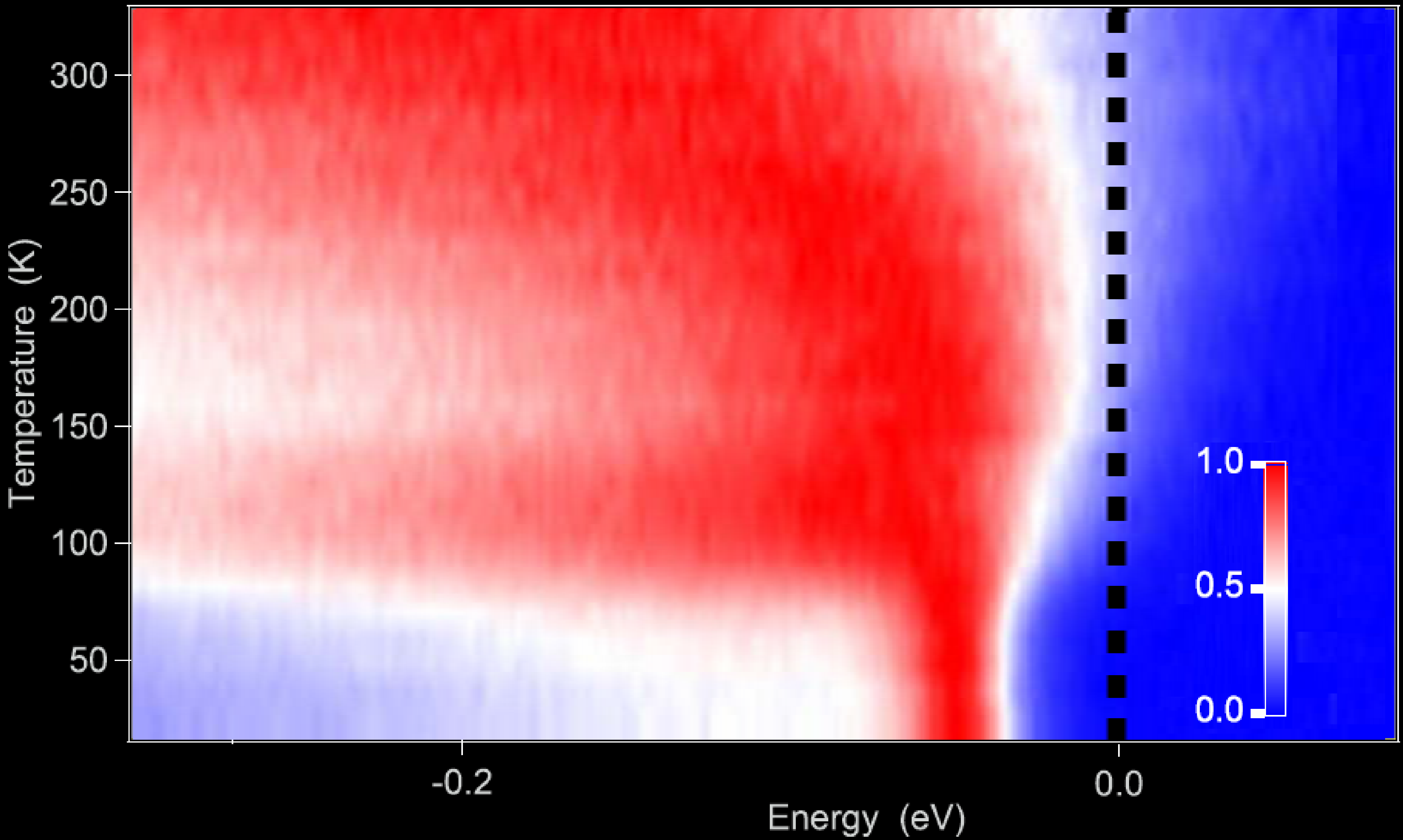
Kordyuk *PRB* (2009)

Non-monotonic pseudo-gap in BSCCO



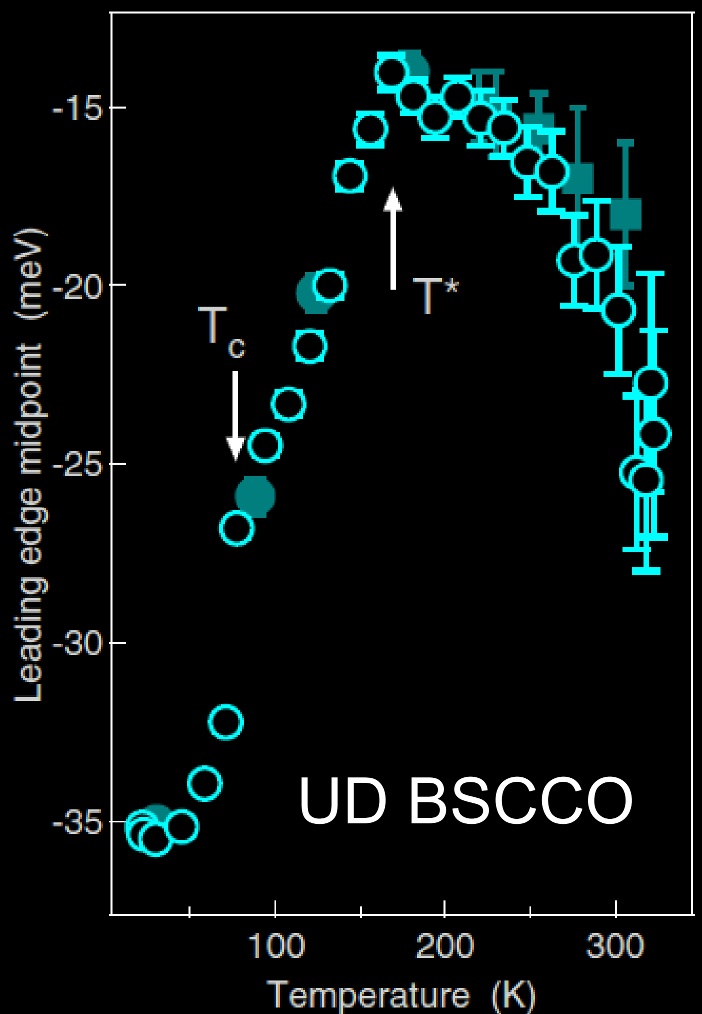
Kordyuk *PRB* (2009)

Non-monotonic pseudo-gap in BSCCO

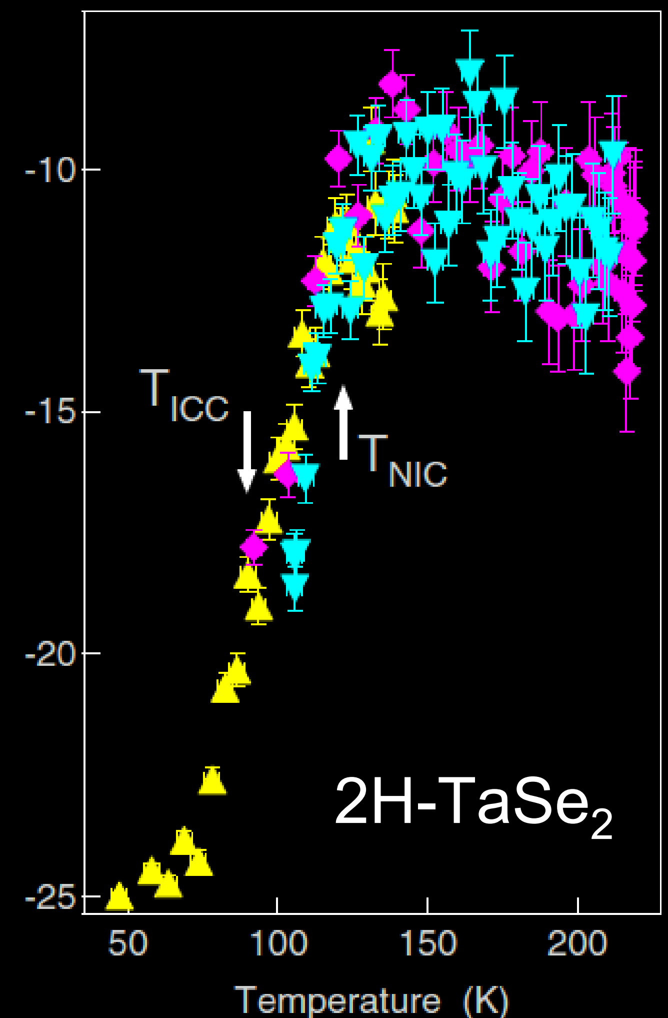


Kordyuk *PRB* (2009)

Non-monotonic pseudo-gap in BSCCO

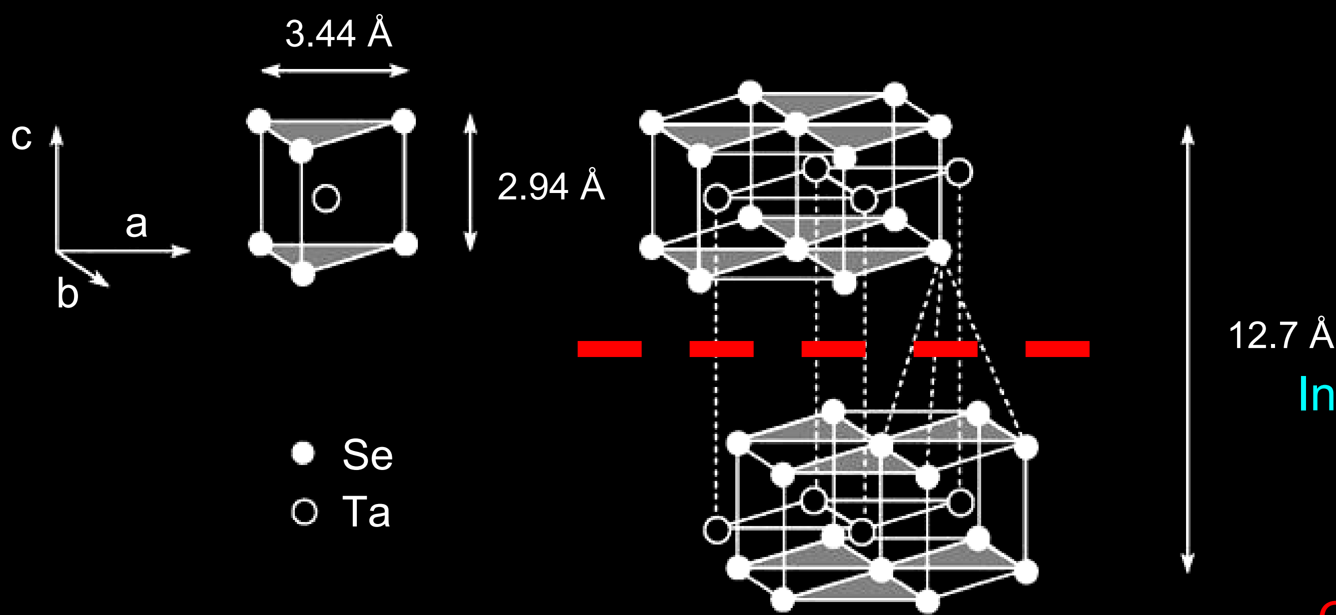


Kordyuk *PRB* (2009)



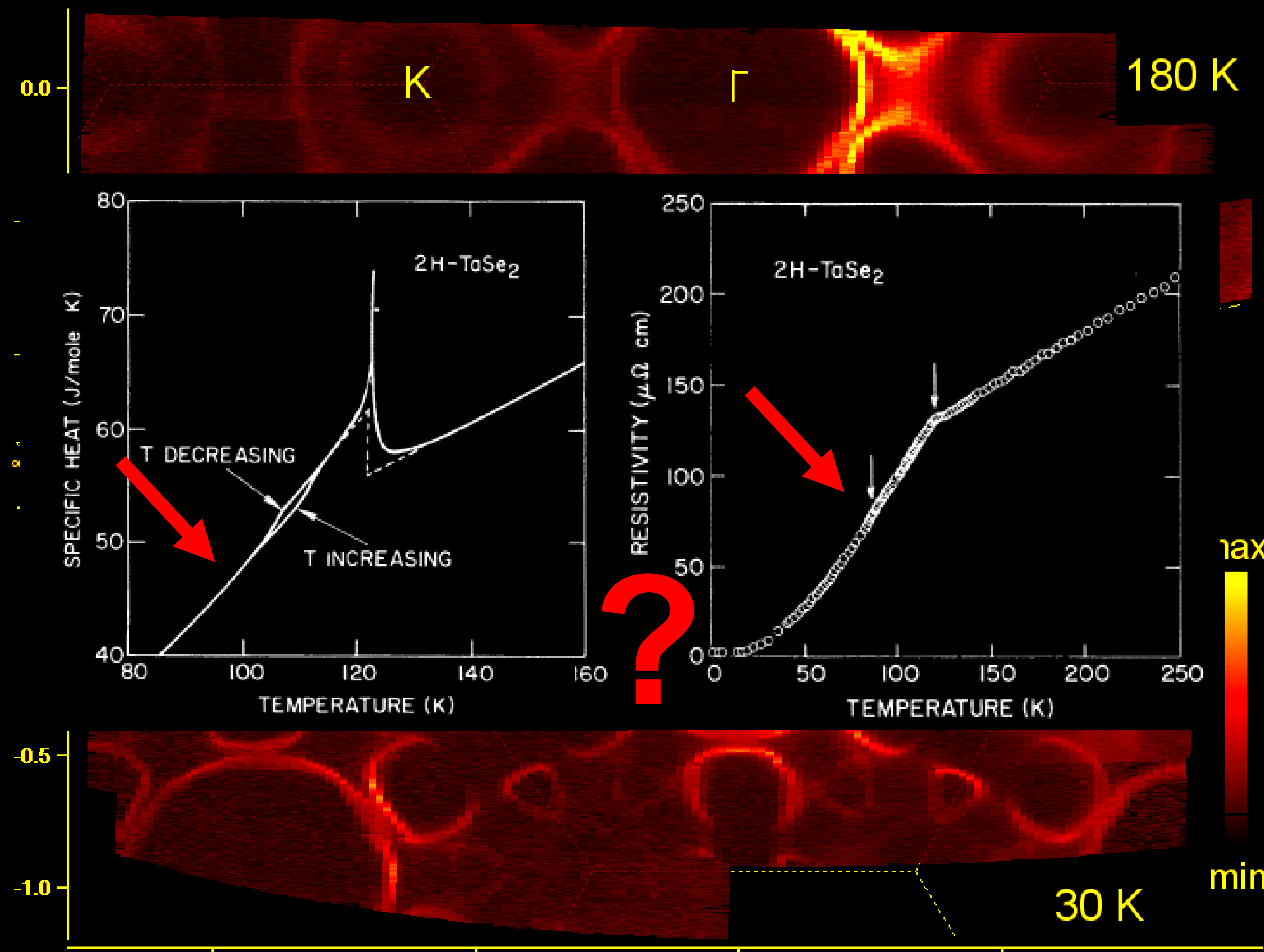
Borisenko *PRL* (2008)

2H-$TaSe_2$ crystal structure, CDW transitions



- 2nd-order transition to an incommensurate CDW at T_{NIC} = 122 K
- 1st-order lock-in transition to a 3x3 commensurate CDW at T_{ICC} = 90 K

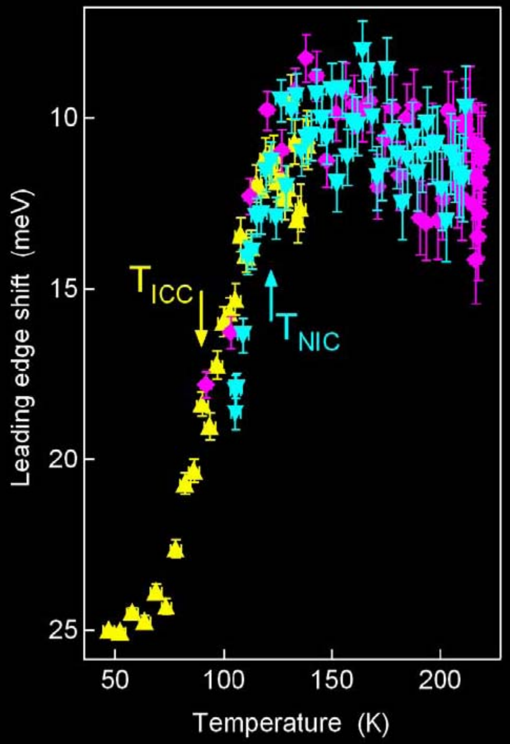
Fermi surface: commensurate CDW state

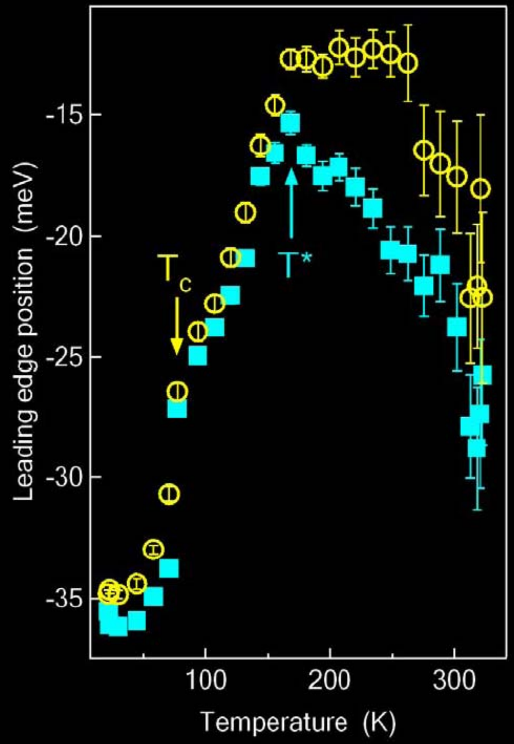


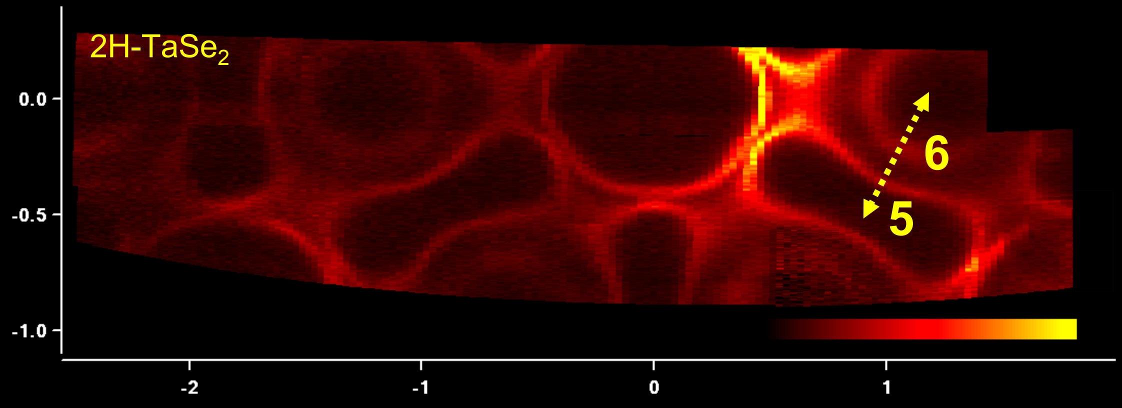
Borisenko *PRL* 2008

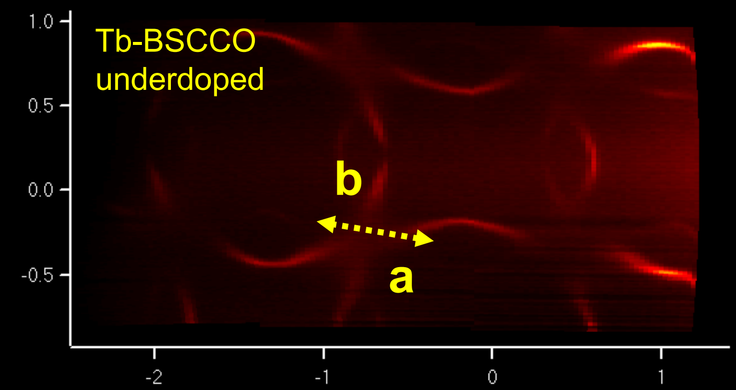
Craven & Meyer *PRB* 1977

Pseudogap in 2H-$TaSe_2$ and Tb-BSCCO

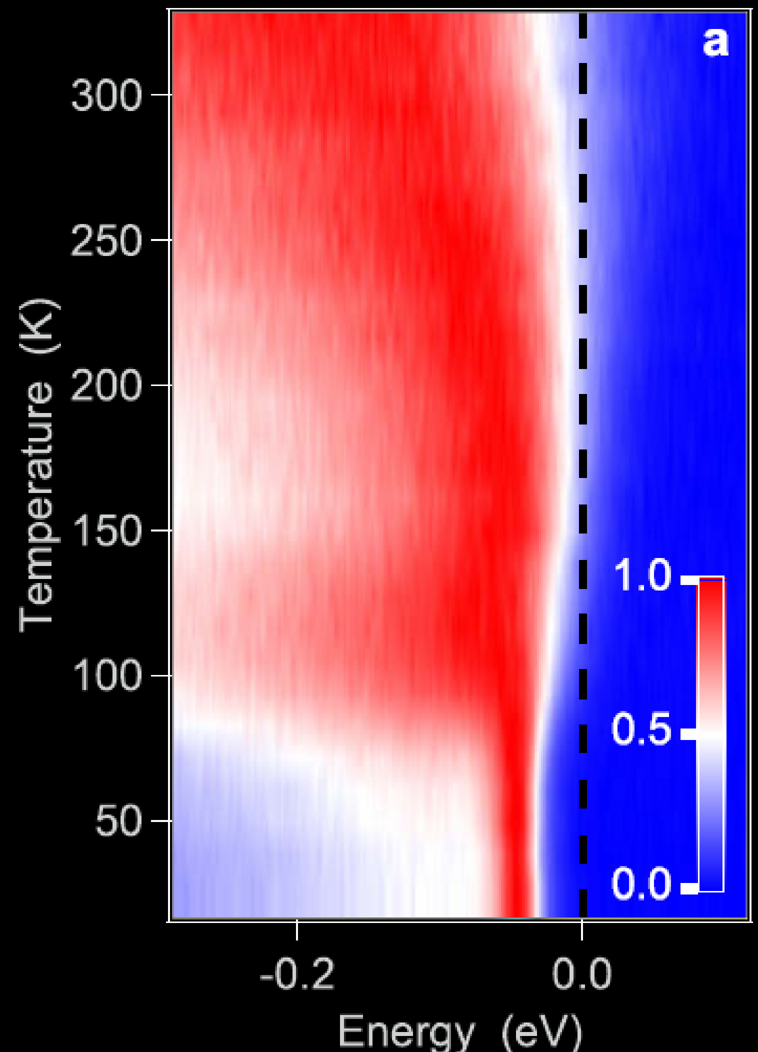


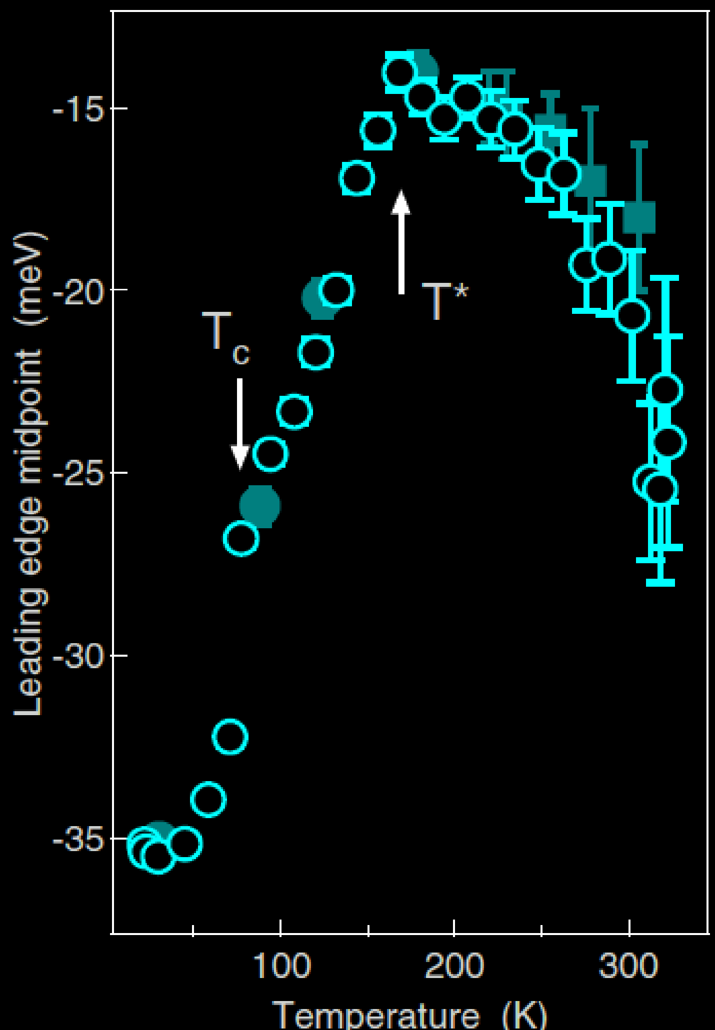






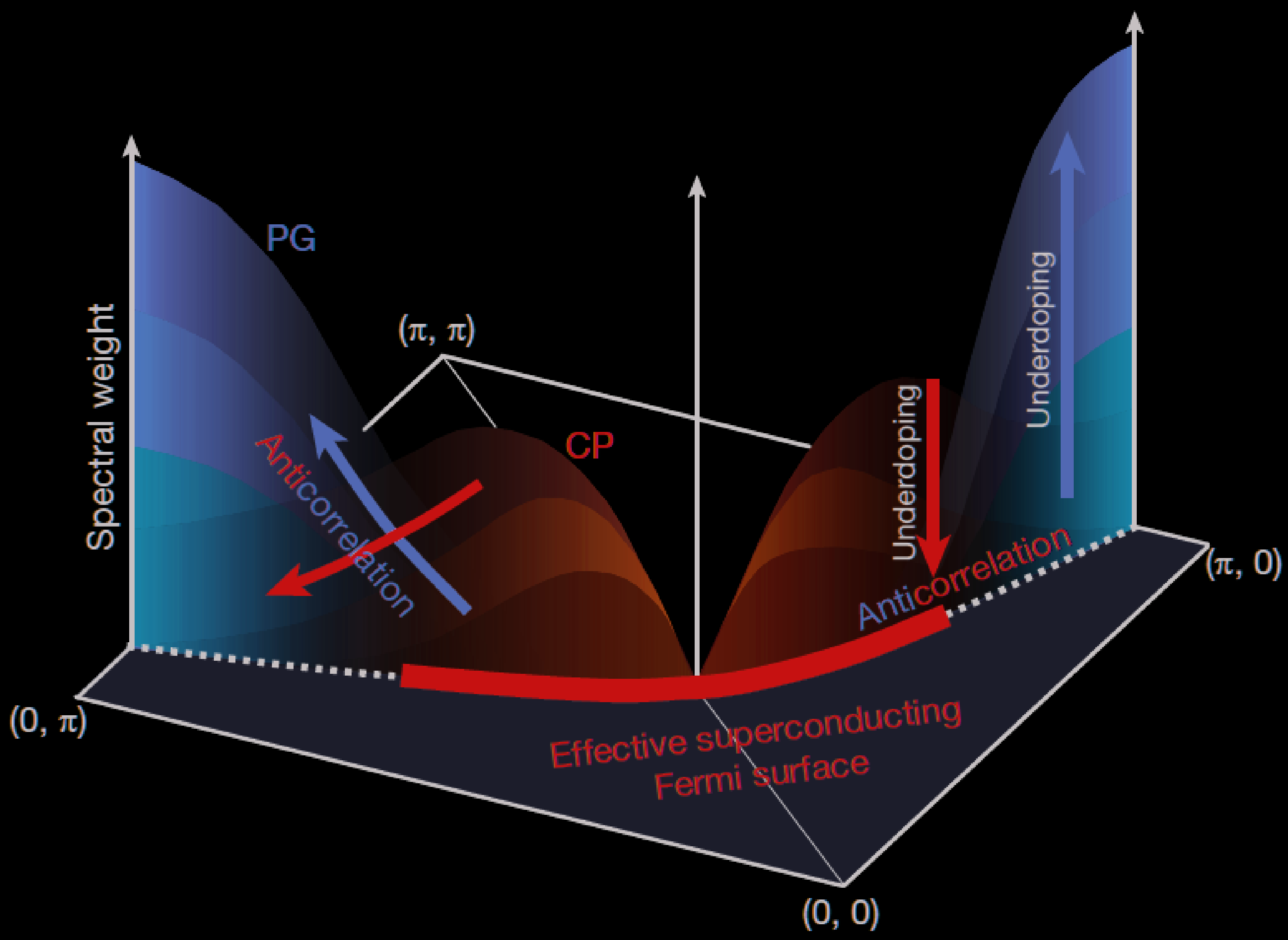
Non-monotonic pseudo-gap in BSCCO





Kordyuk *PRB* (2009)

Pseudo-gap competes with SG



Kondo *Nature* (2009)

General conclusions

1. HTSC = LDA + PG + Self-energy = $\underset{\text{spectrum}}{\text{QP}}$

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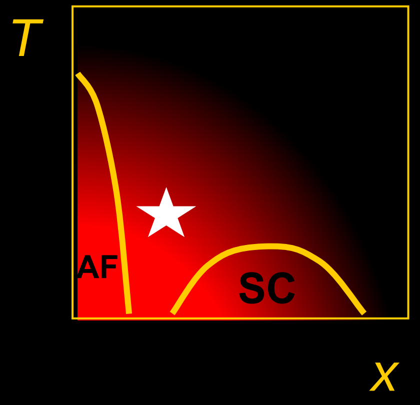
2. Self-energy = **CHARGE** + **MAGNETIC** + phonons

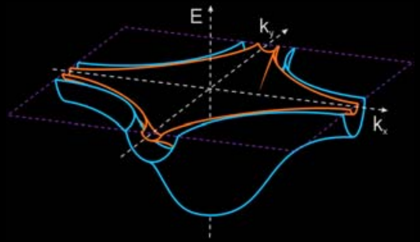


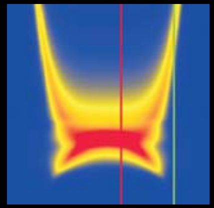
General conclusions

1. HTSC = LDA + PG + Self-energy = QP spectrum

2. Self-energy = **CHARGE** + MAGNETIC

3. MAGNETIC = QP spectrum ★ SF spectrum





General conclusions

1. HTSC = LDA + PG + Self-energy = QP spectrum
2. Self-energy = **CHARGE** + **MAGNETIC**
3. **MAGNETIC** = QP spectrum ★ SF spectrum ⇒ T_c = 150 K

General conclusions

1. HTSC = LDA + PG + Self-energy = QP spectrum
2. Self-energy = **CHARGE** + MAGNETIC
3. MAGNETIC = QP spectrum ★ SF spectrum ⇨ T_c = 150 K
4. PG = Electron density modulation =

   = incommensurate xDW (x = C, D, S...)

Outlook

1. xDW in cupates: x = C, D, S or ... ?

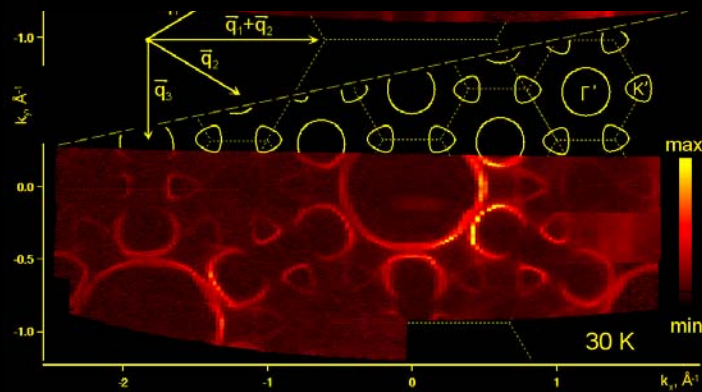
2. How xDW competes with SC ?

3. What is PG origin at hight T ?

4. How general is DW in 2D ?

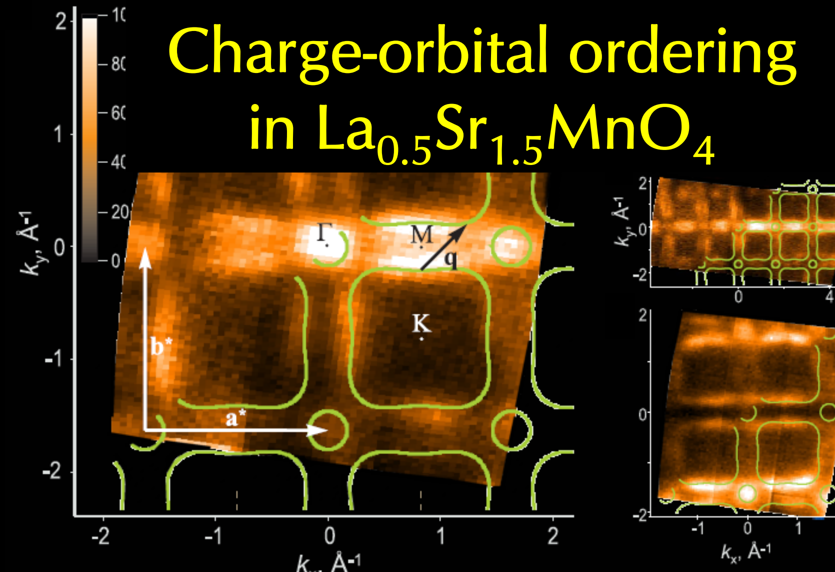
How general is DW in 2D ?

CDW crossovers in dichalcogenides



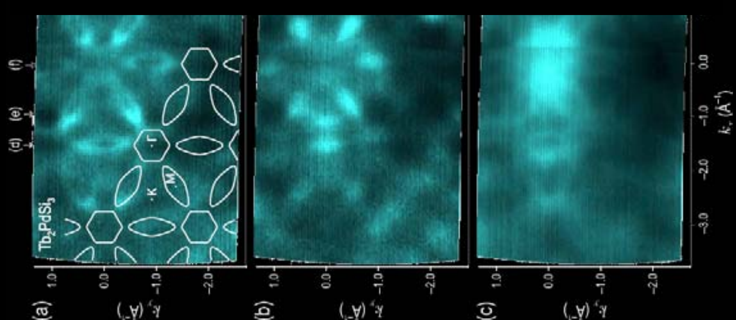
Borisenko *PRL* 2008
Evtushinsky *PRL* 2008

Charge-orbital ordering in $La_{0.5}Sr_{1.5}MnO_4$



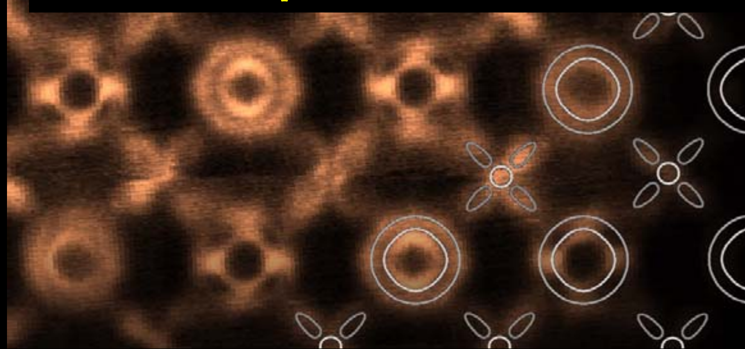
Evtushinsky 2008

Nesting-driven magnetic ordering in rare earth silicides



Inosov *PRL* 2009

(π, π) electronic order in pnictides



Zabolotnyy *Nature* 2009
Evtushinsky *PRB* 2009

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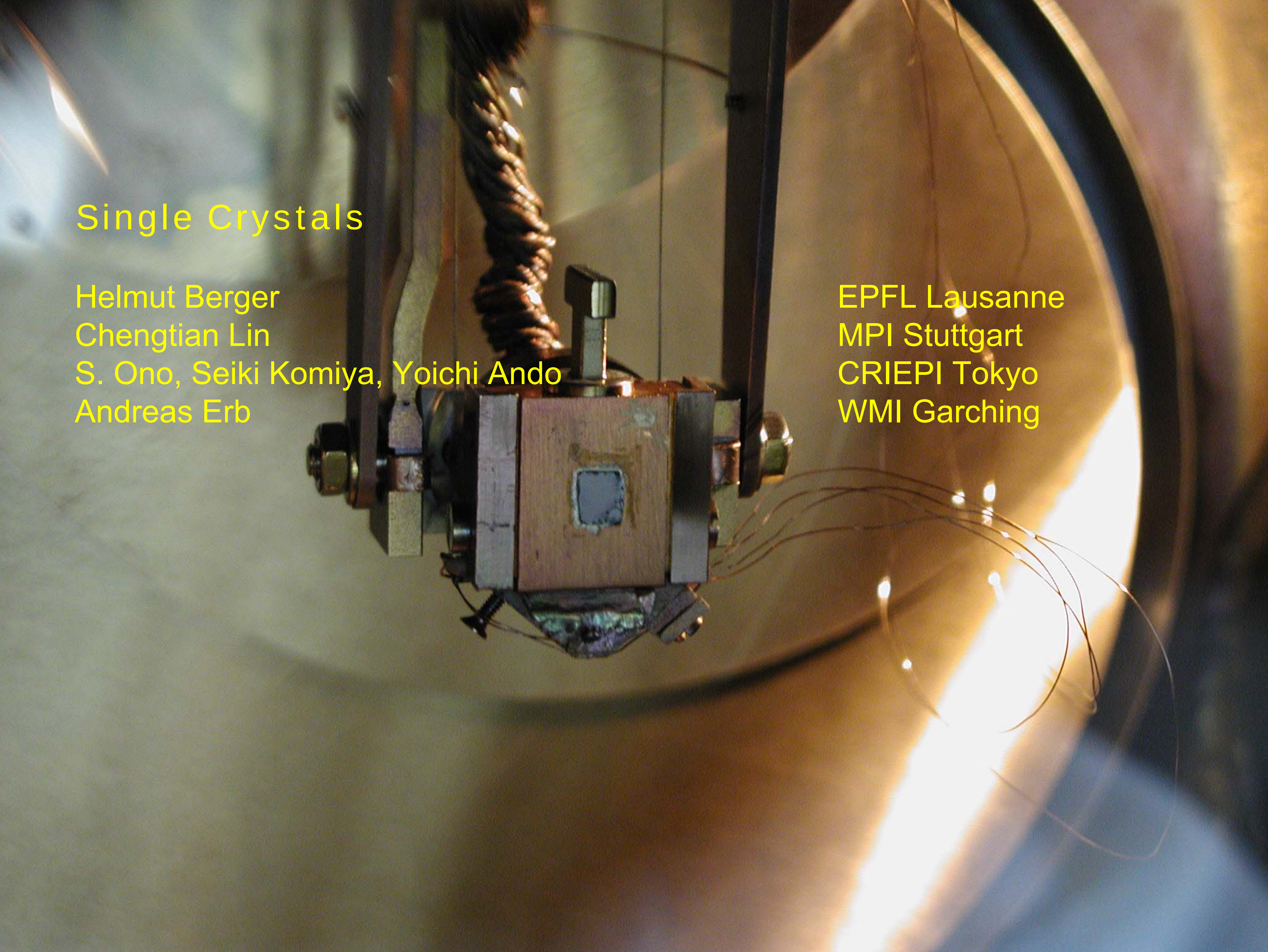

Single Crystals

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