Ultra-low temperature ARPES on strontium ruthenates

Volodymyr Zabolotnyy, IFW Dresden, Institute for Solid State Research

Electronic Structure and Electron Spectroscopies 2013

Thanks to:

D. V. Evtushinsky
A. A. Kordyuk
J. Maletz
J. Trinkauf
J. Geck
S. V. Borisenko
B. Büchner

M. Couco
A. Veccione
R. Fittipaldi

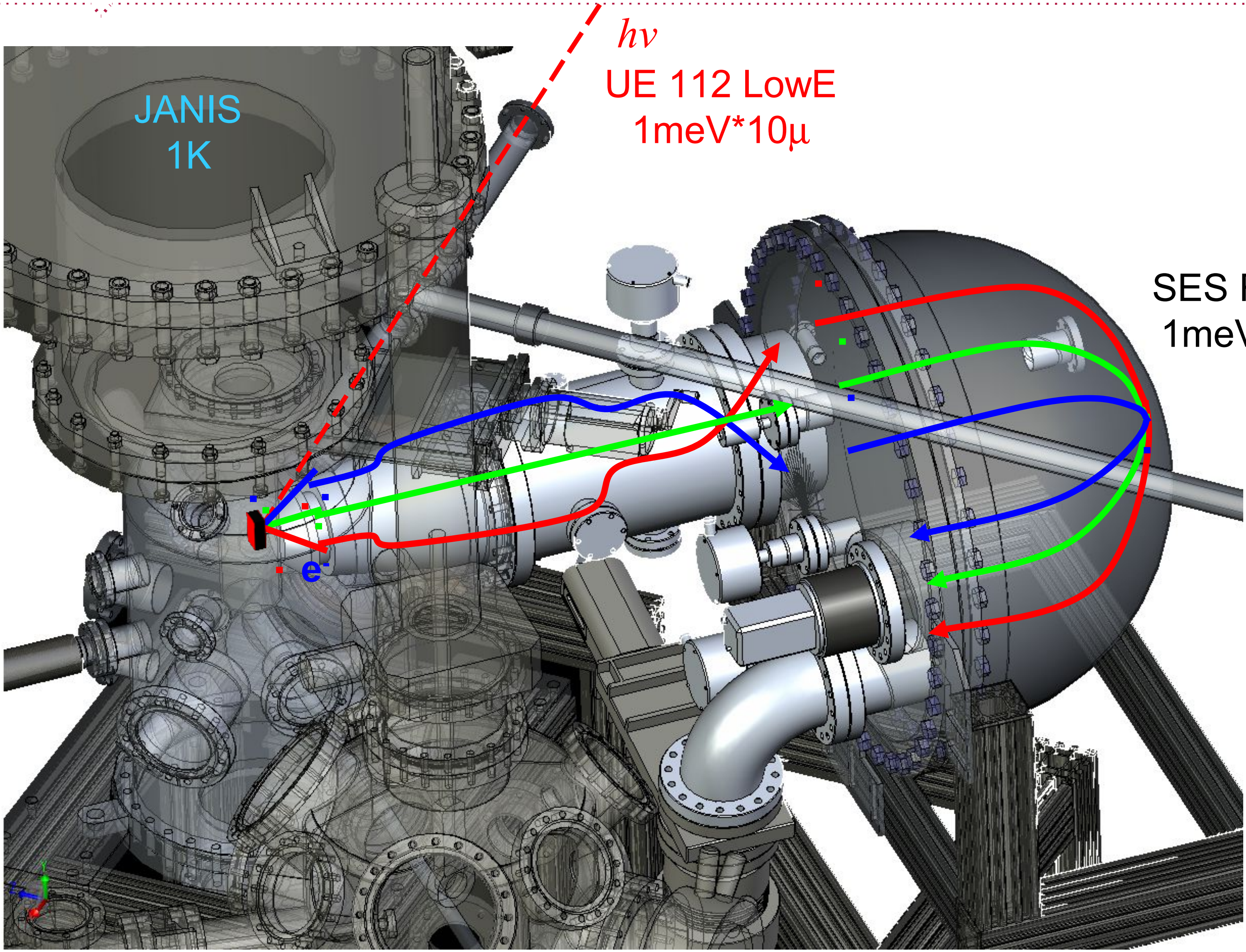
A. Varykhalov
E. Rienks
S. Thirupathaiah
O. Schwarzkopf
R. Follath

T. K. Kim

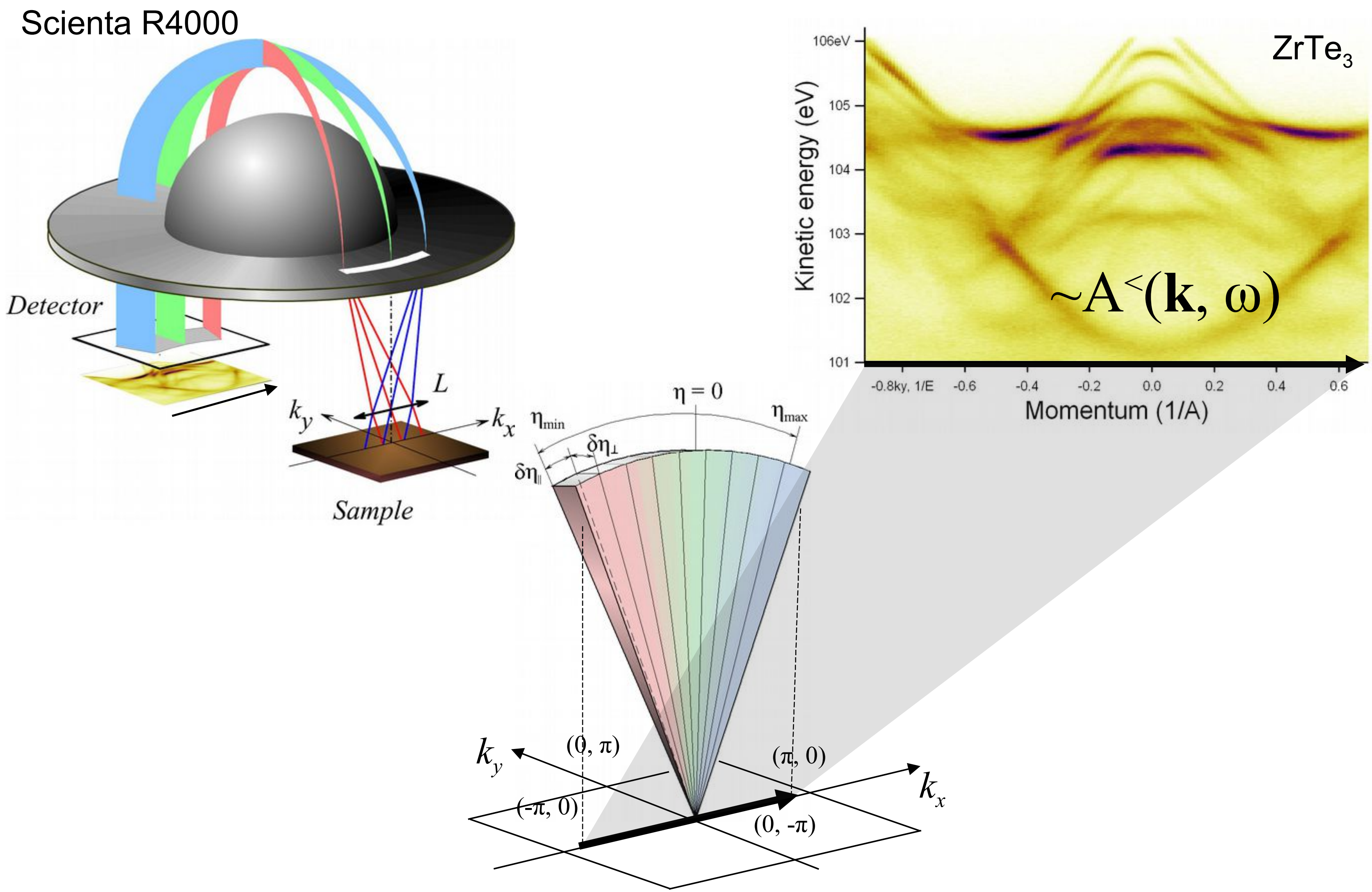
E. Carleschi
B. Doyle

DFG Research Unit 538

BESSY 1³ station

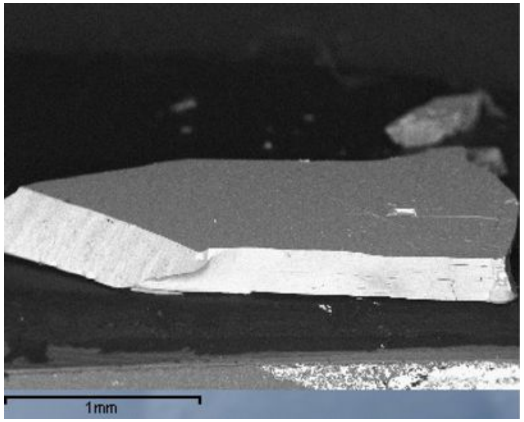


Photoemission principle

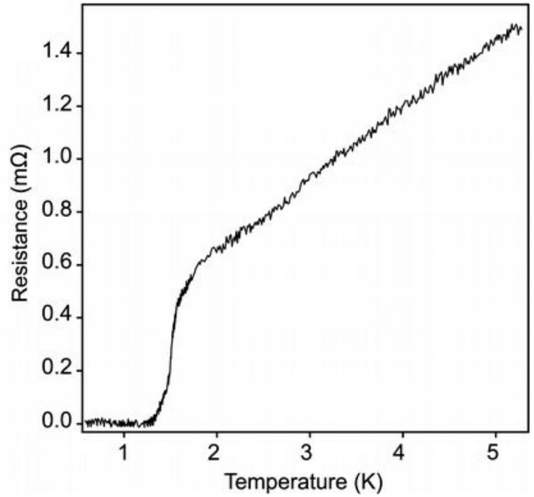


Crystal growth & quality

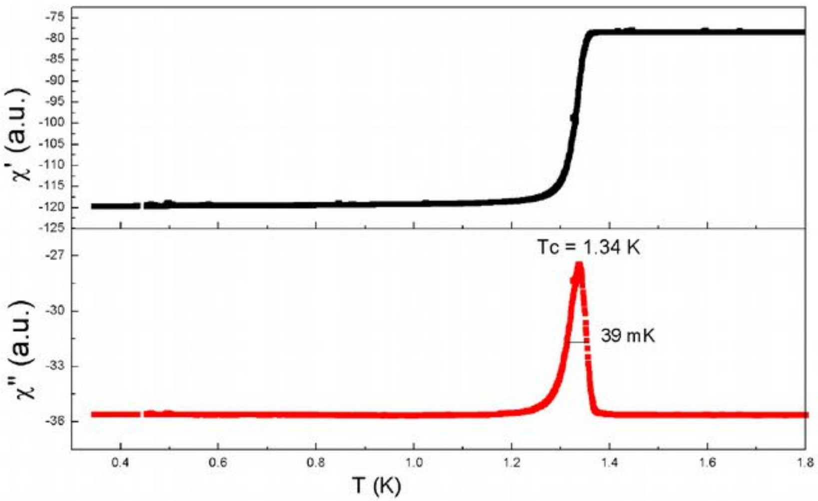
Microscopy



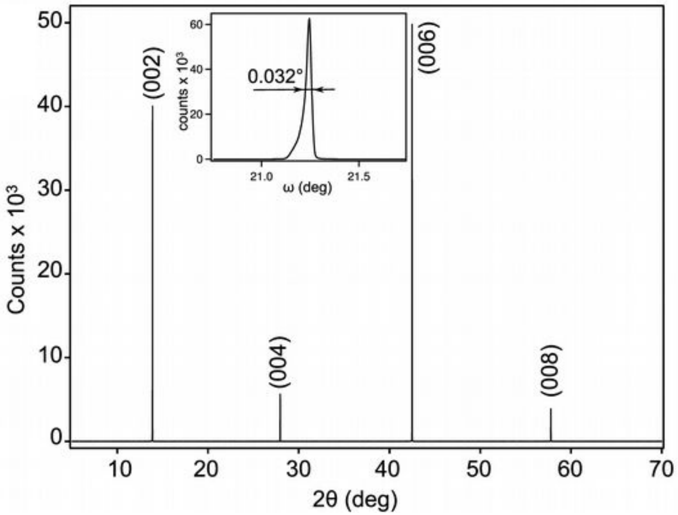
Resistivity



AC susceptibility

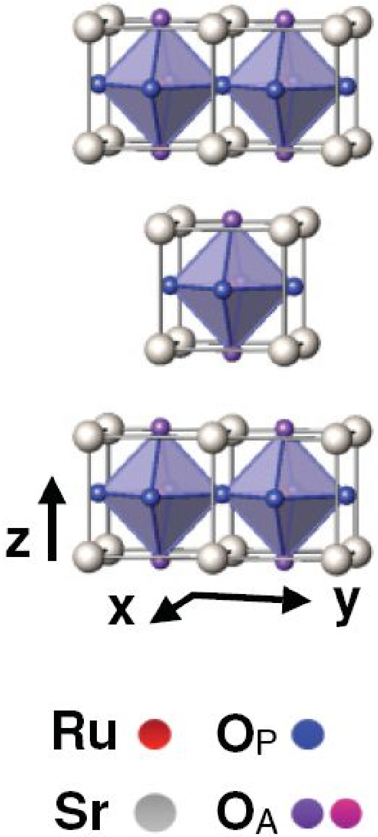


X-Ray diffraction

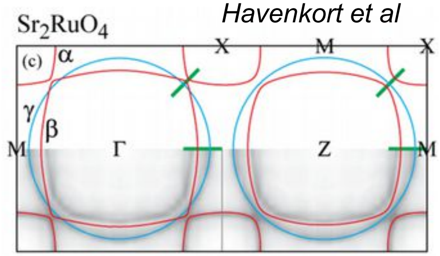


R. Fittipaldi

Electronic structure: summary of available data

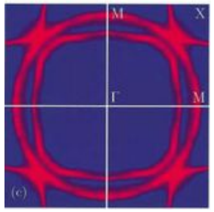


Havenkort et al



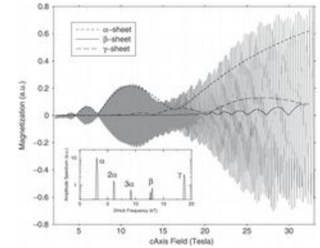
Band structure calculations

Damascelli et al

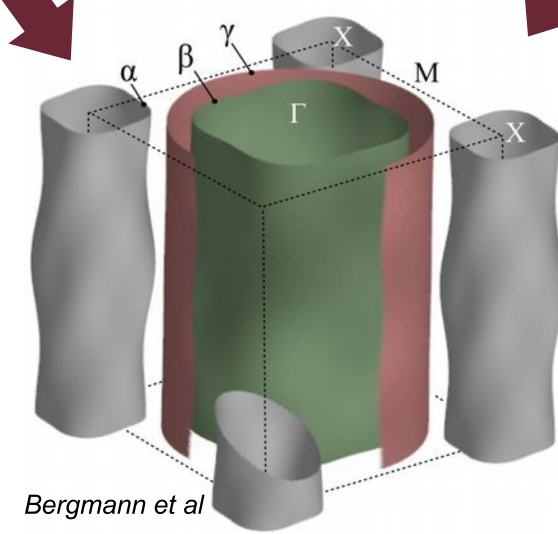


ARPES

Bergmann et al



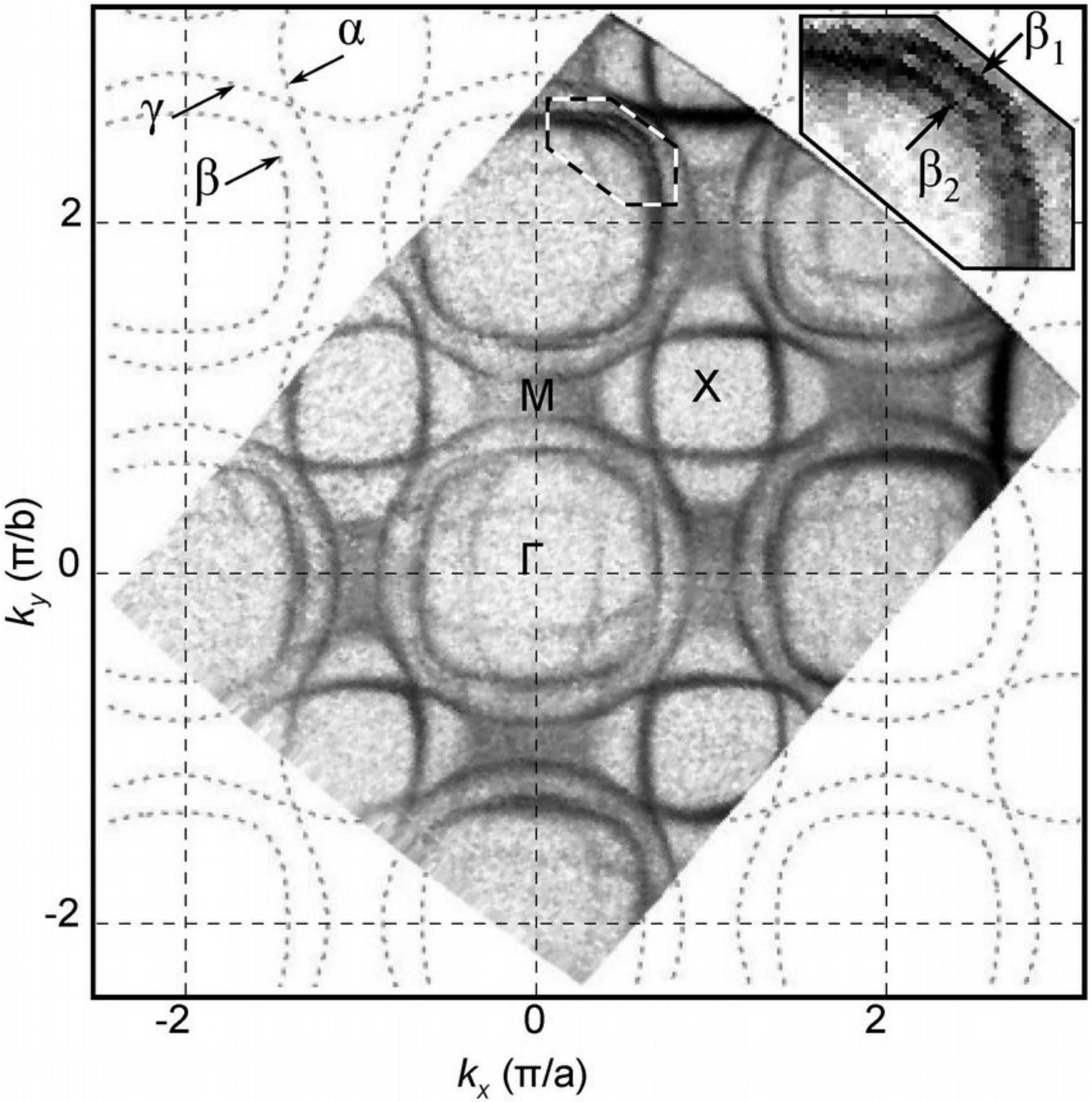
dHvA



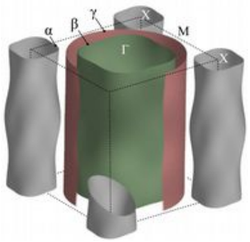
Bergmann et al

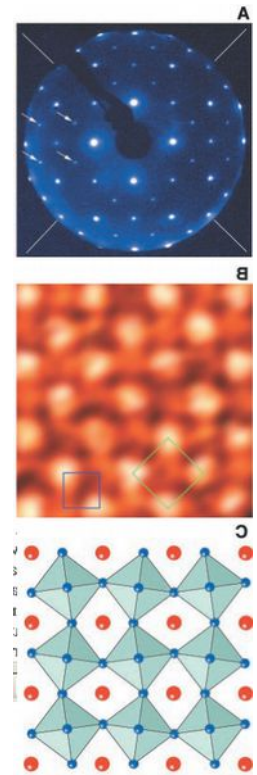
k_z corugations exagerated 15 times

ARPES Fermi surface



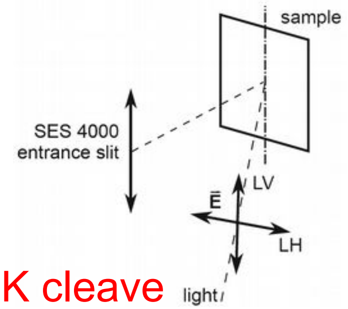
Zabolotnyy et al. New J. Phys. 14, 063039 (2012)



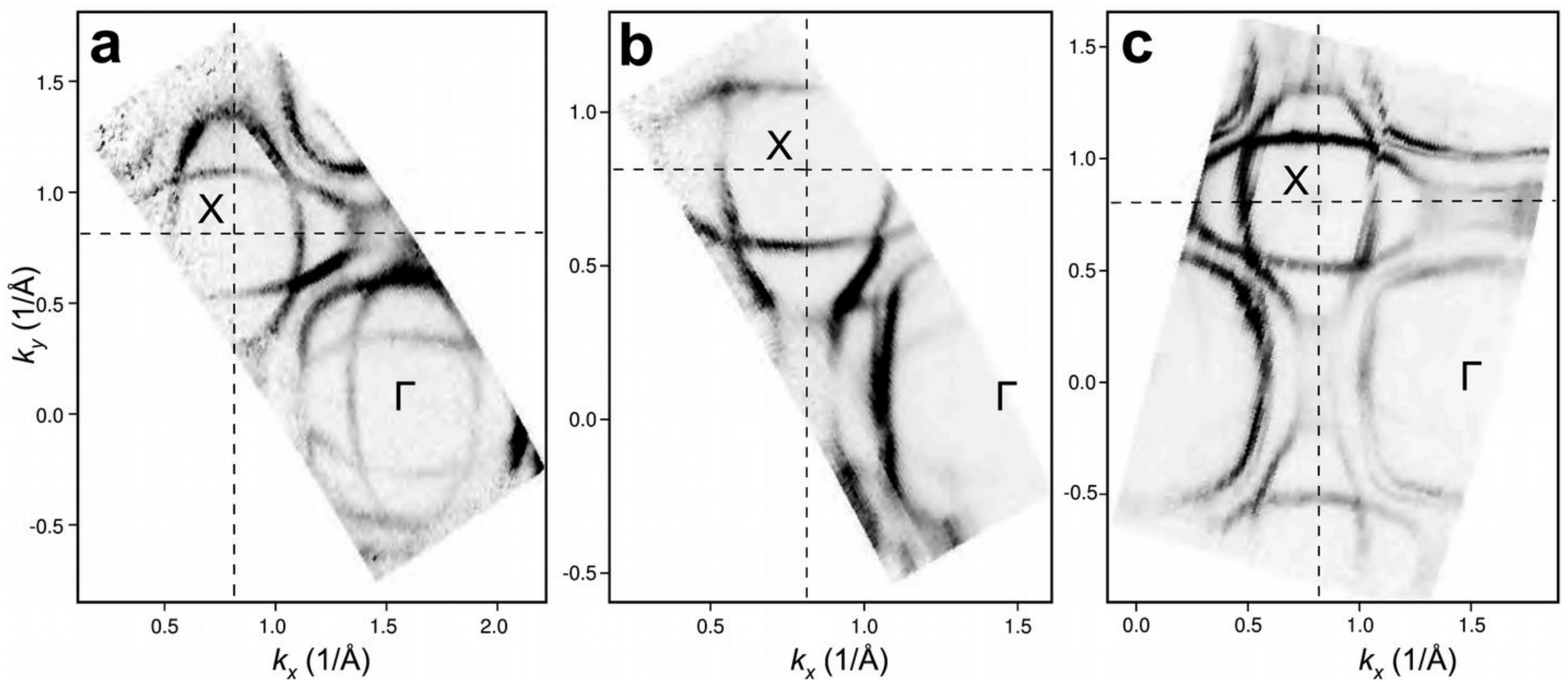


Matzdorf 289, 746 (2000)

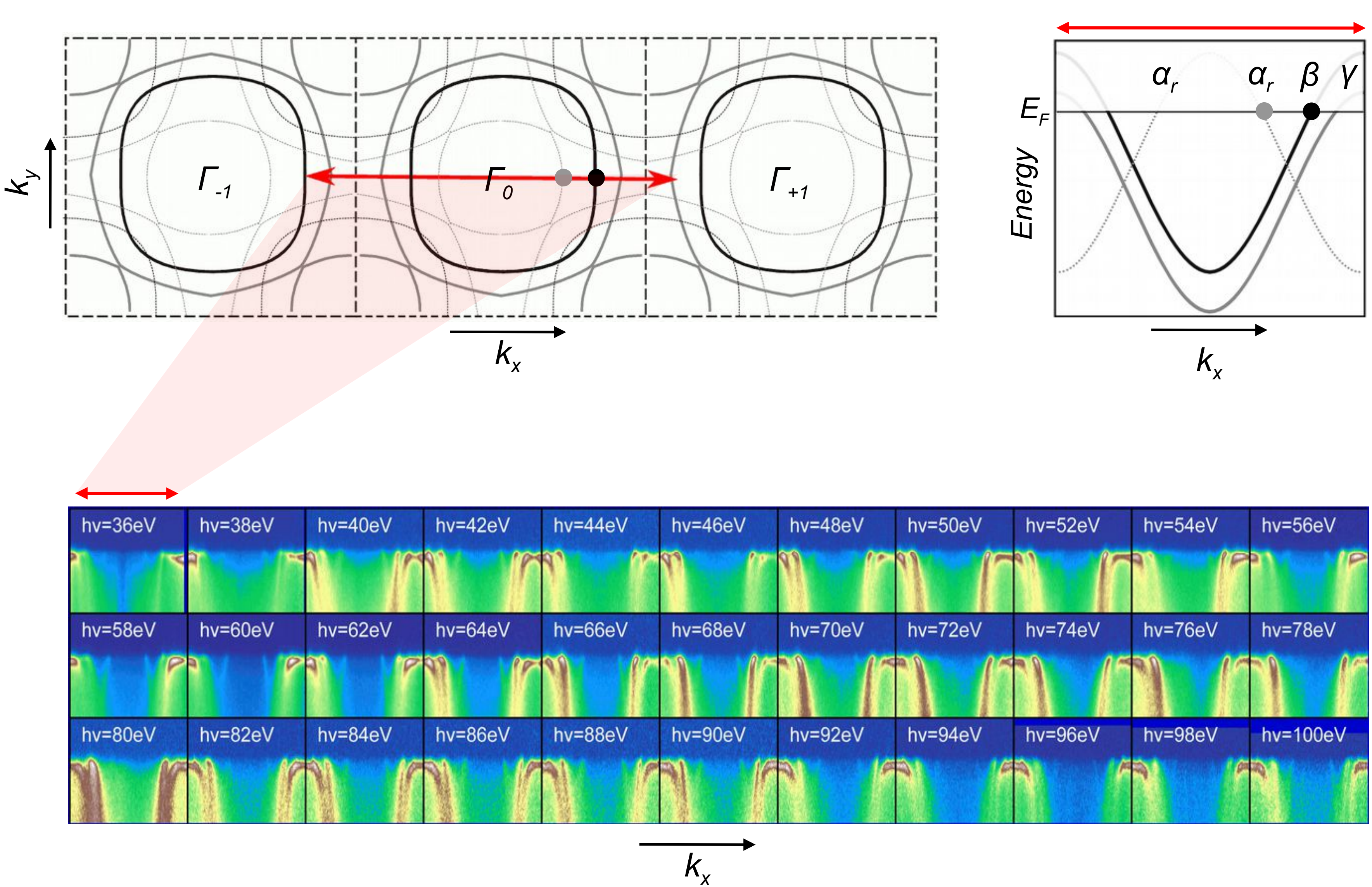
Surface aging not a panacea



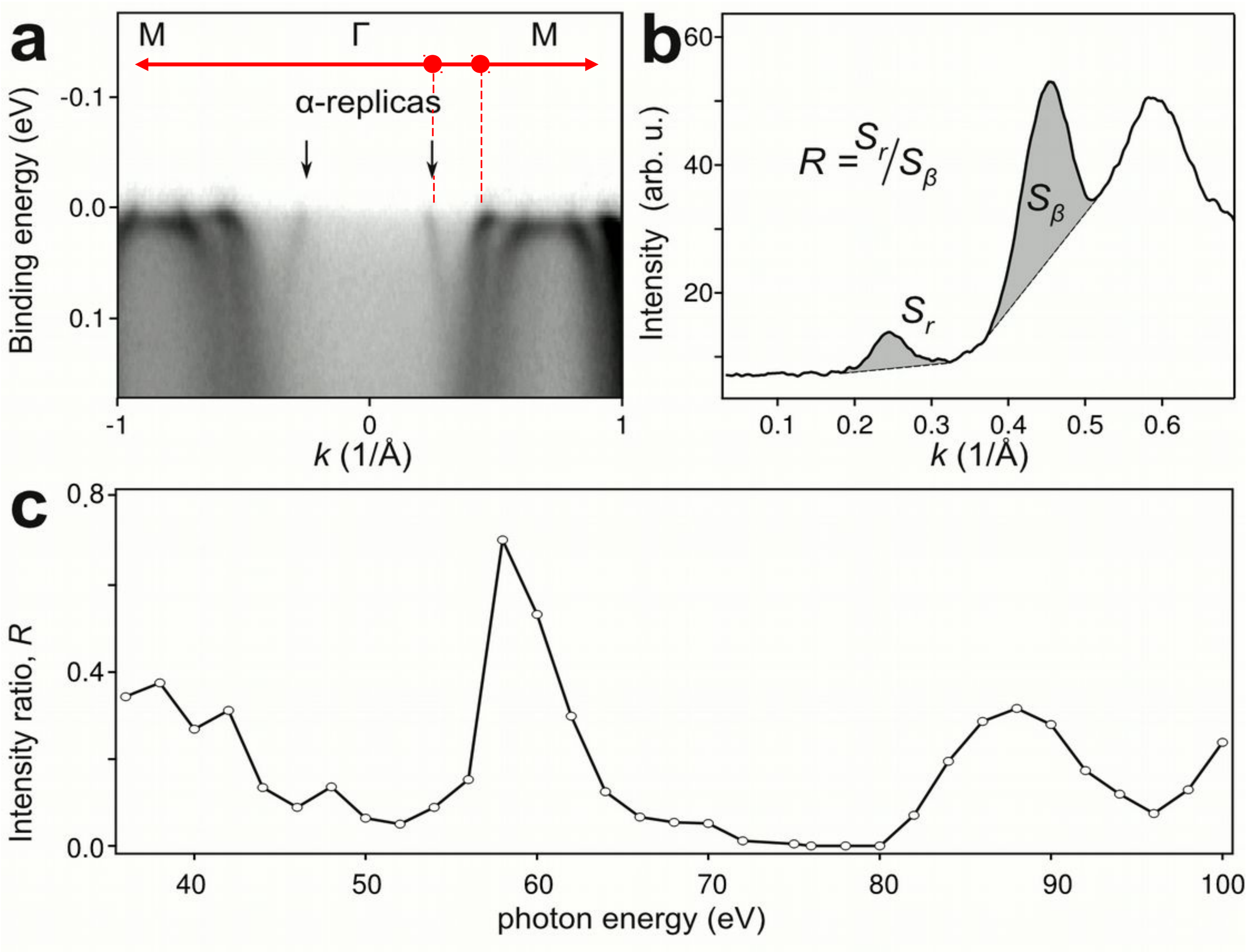
40K cleave	40K cleave	300K cleave
hv=80ev, LV	*hv*=50ev, LH	*hv*=80ev, LH



Systematic hv-dependence



Systematic hv-dependence



Surface emission

General case

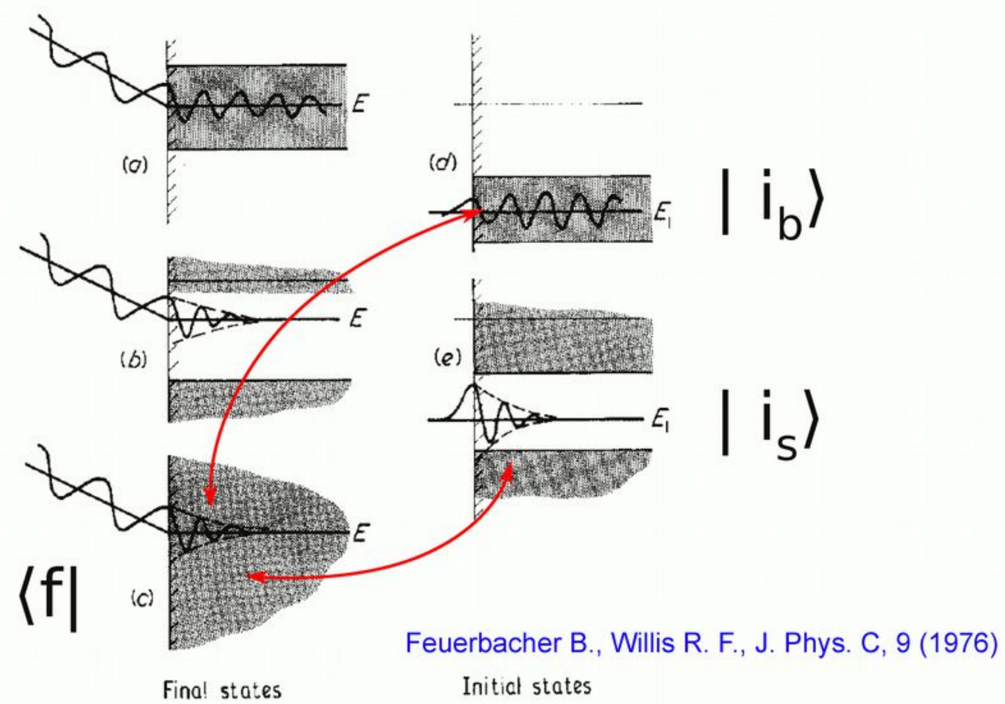
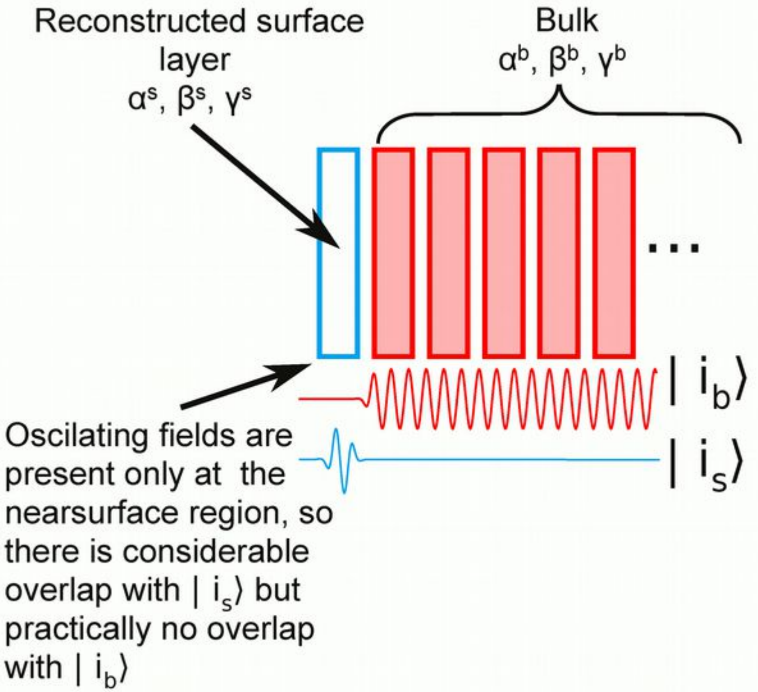


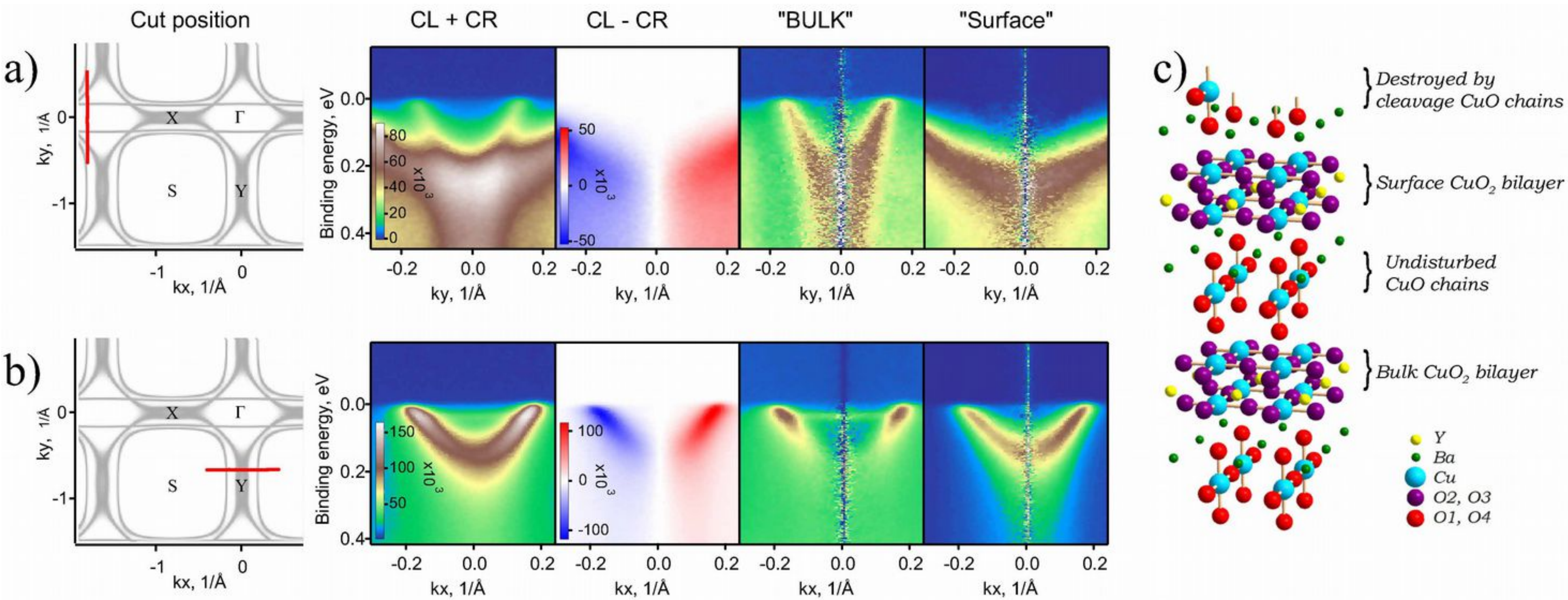
Figure 5. Wavefunctions involved in the photoelectric effect in the incoming-wave picture. Left side, final states, (*a*) propagating 'bulk' final state for low damping, (*b*) evanescent state in a band gap and (*c*) the strong damping case. Right side, initial states, (*d*) propagating 'bulk' state and (*e*) localized surface state.

Layered Sr_2RuO_4



$$M \sim \langle f | A\nabla + \mathrm{div}A | i_{b/s} \rangle$$

Circular dichroism on YBCO

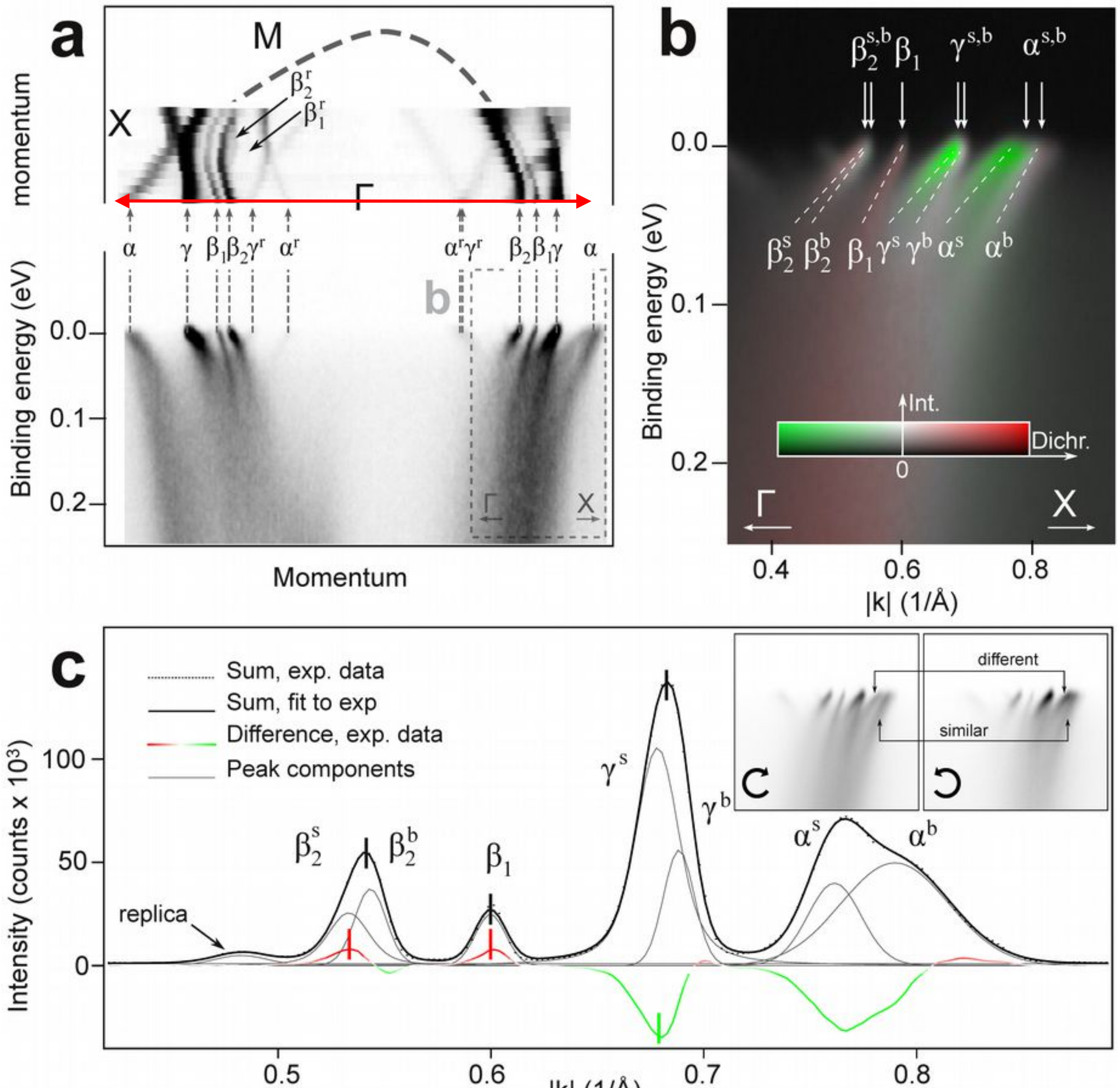


Zabolotnyy et al. PRB 76, 024502 (2007)

superconducting bulk

overdoped surface

Circular dichroism on Sr_2RuO_4

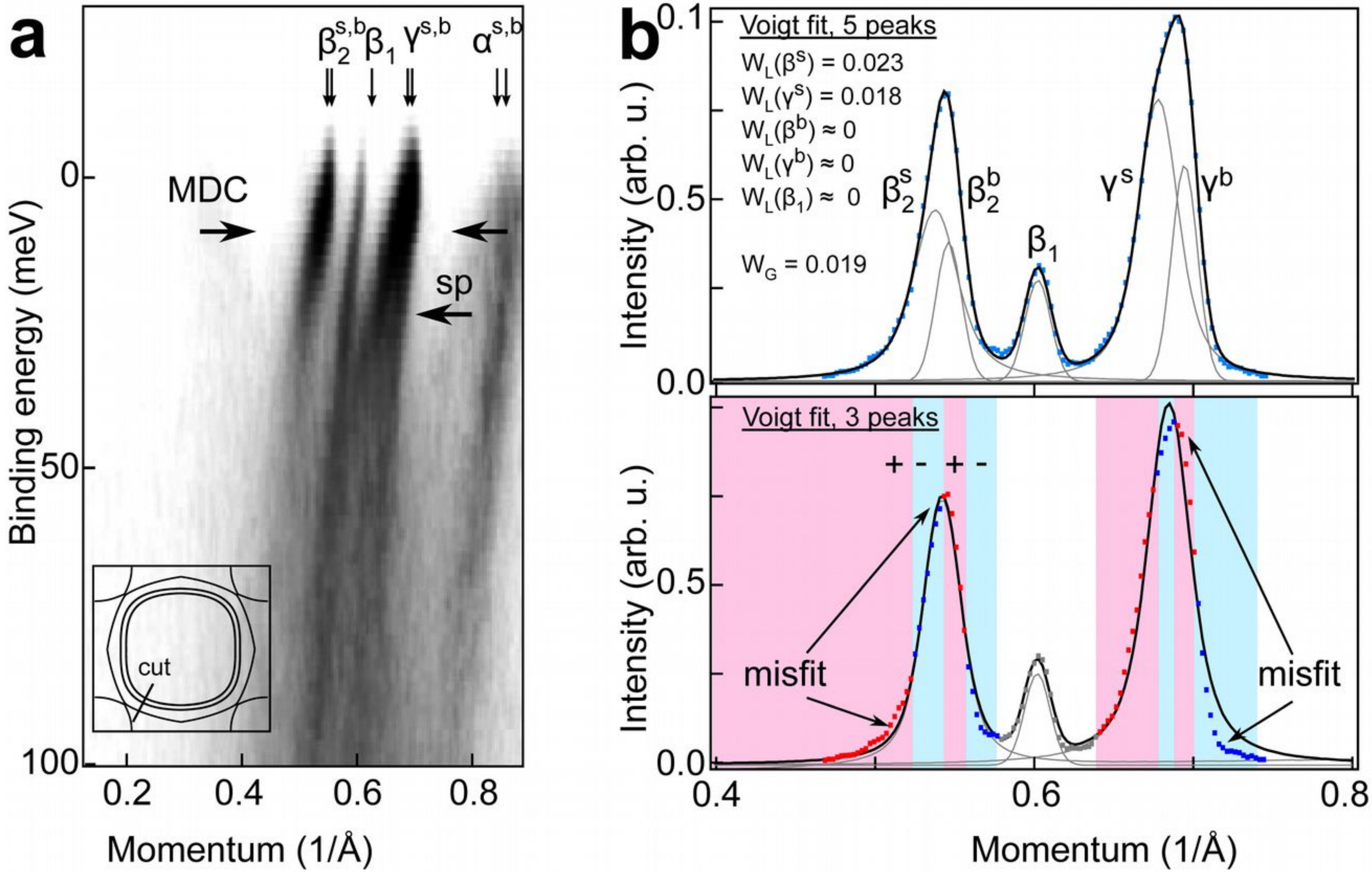


Surface: lower velocity + dichroism

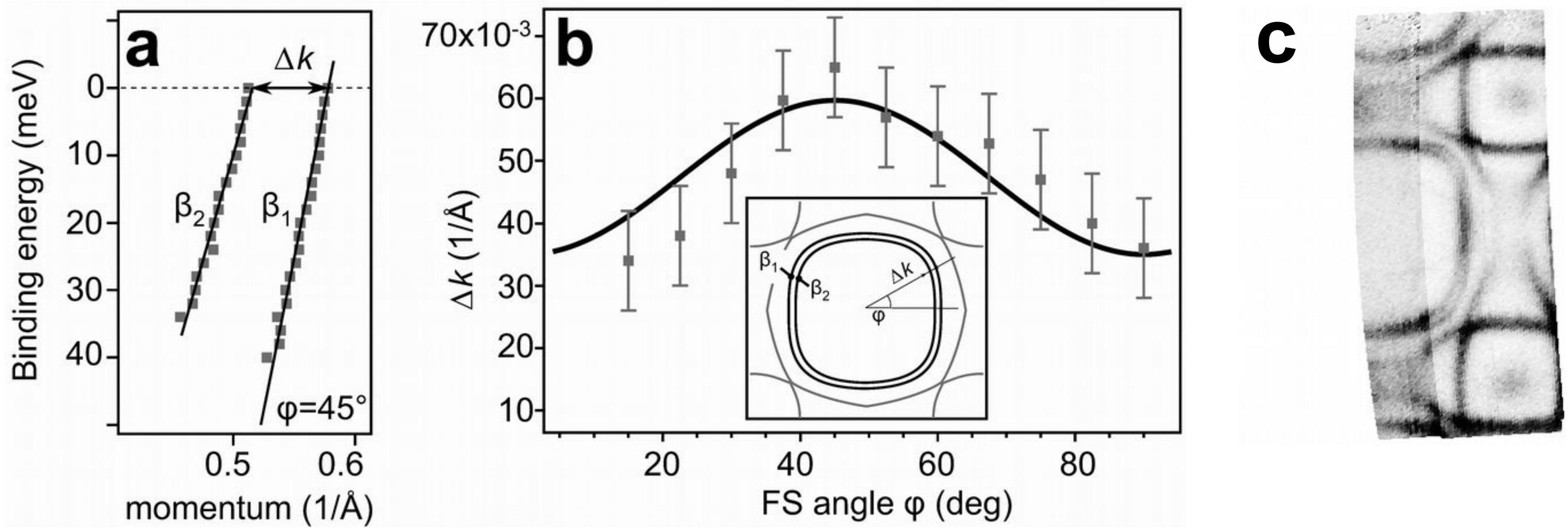
Bulk: higher velocity + no dichroism

Zabolotnyy et al. New J. Phys. 14, 063039 (2012)

Line shape analysis



β-band splitting



The outer pocket β_1 is more “square” like

Spin-Orbit and Rashba effect

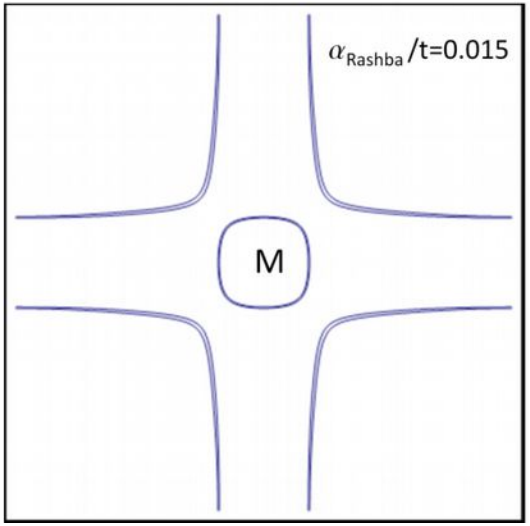
Spin–Orbit in the bulk: spin degeneracy remains, just shifts in energy

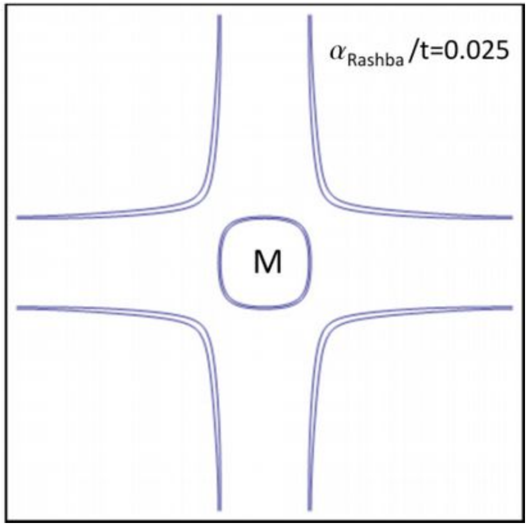
Spin–Orbit at the surface: broken symmetry, lifted spin degeneracy

$$\left[c^{+}_{yz,\uparrow} \quad c^{+}_{xz,\uparrow} \quad c^{+}_{yz,\downarrow} \quad c^{+}_{xz,\downarrow}\right]$$

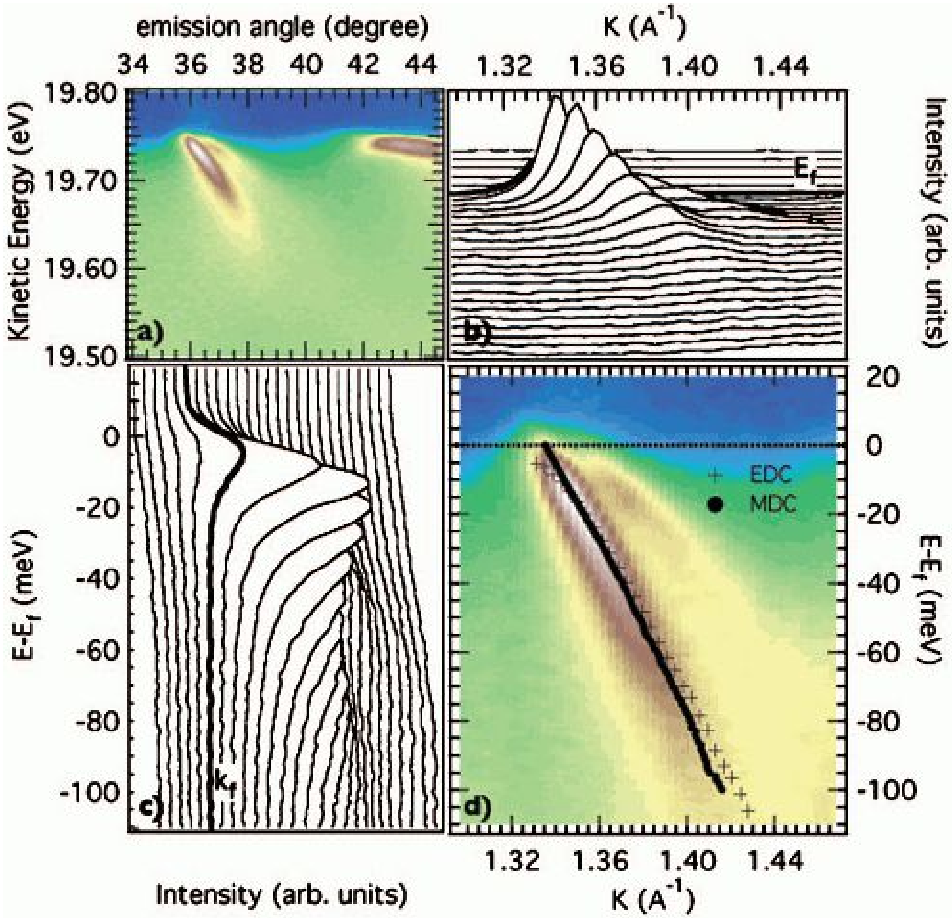
$$\widetilde{H} = \begin{bmatrix} \varepsilon_1 & g & r & 0 \\ g & \varepsilon_2 & 0 & r \\ \bar{r} & 0 & \varepsilon_1 & g \\ 0 & \bar{r} & g & \varepsilon_2 \end{bmatrix}$$

$$\varepsilon_1 = -2t\cos(k_y) - \mu$$
$$\varepsilon_2 = -2t\cos(k_x) - \mu$$
$$g = -4t_1 \sin(k_x)\sin(k_y)$$
$$r = \alpha\left[\sin(k_y) + i\sin(k_x)\right]$$
$$\bar{r} = \alpha\left[\sin(k_y) - i\sin(k_x)\right]$$

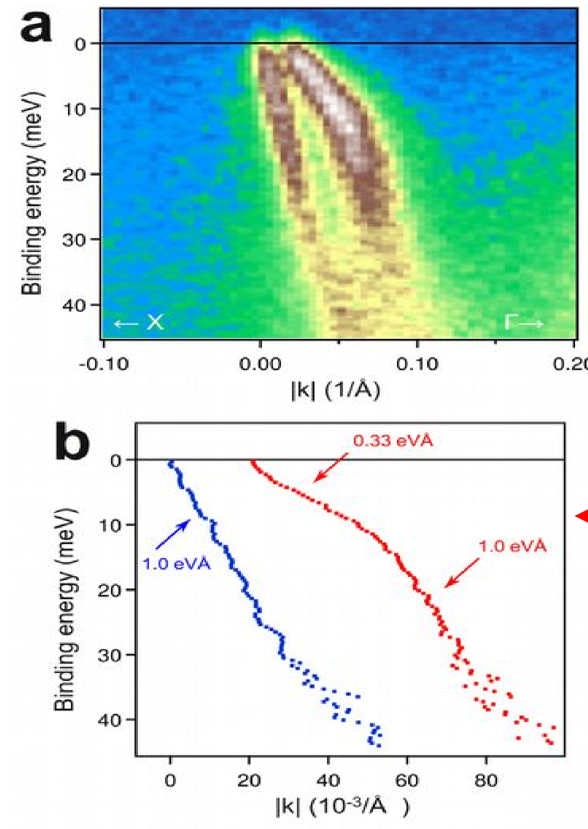




α-pocket, surface cf bulk, El-ph coupling



Ingl et al PRB 72, 205114 (2005).



5 meV kink

ARPES kink & bulk phonons

LATTICE DYNAMICS AND ELECTRON-PHONON COUPLING… PHYSICAL REVIEW B **76**, 014505 (2007)

15 meV= 3.6THz

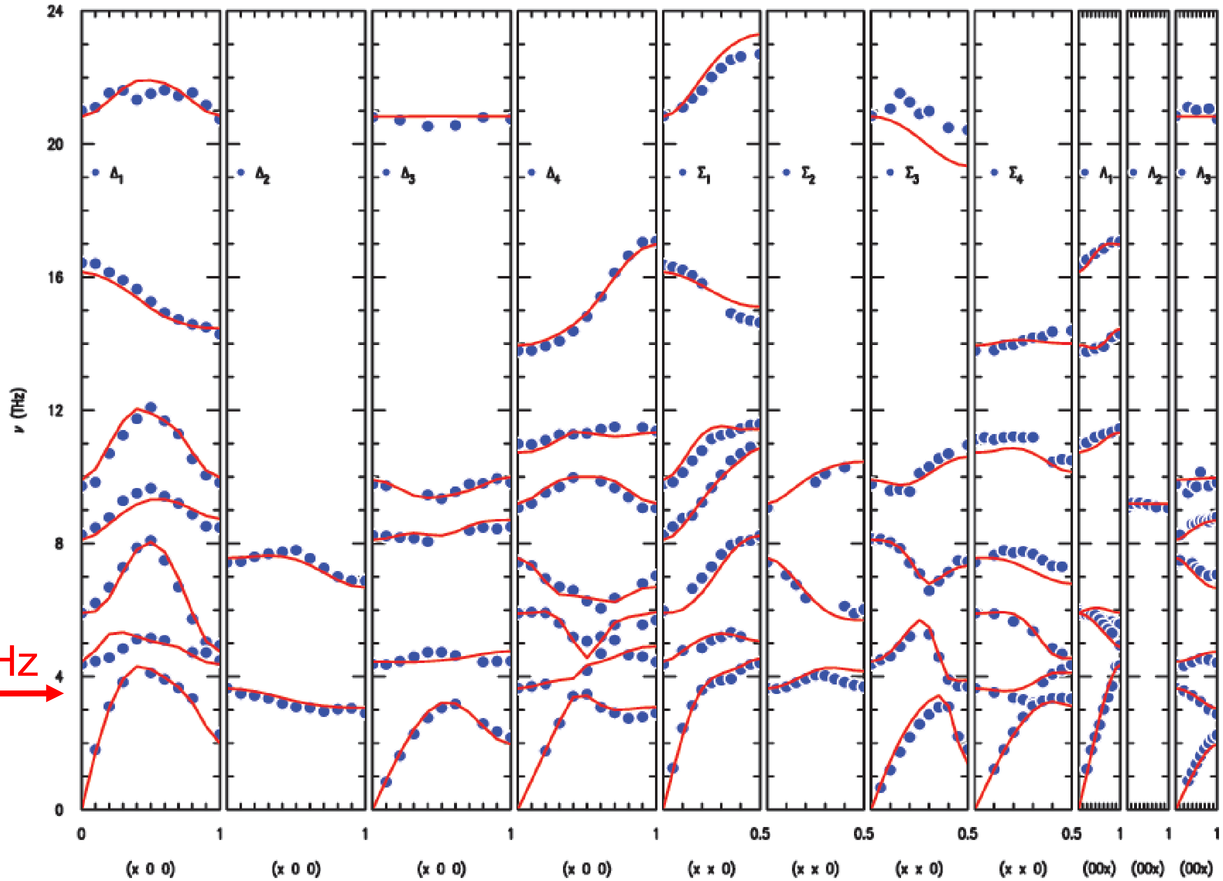
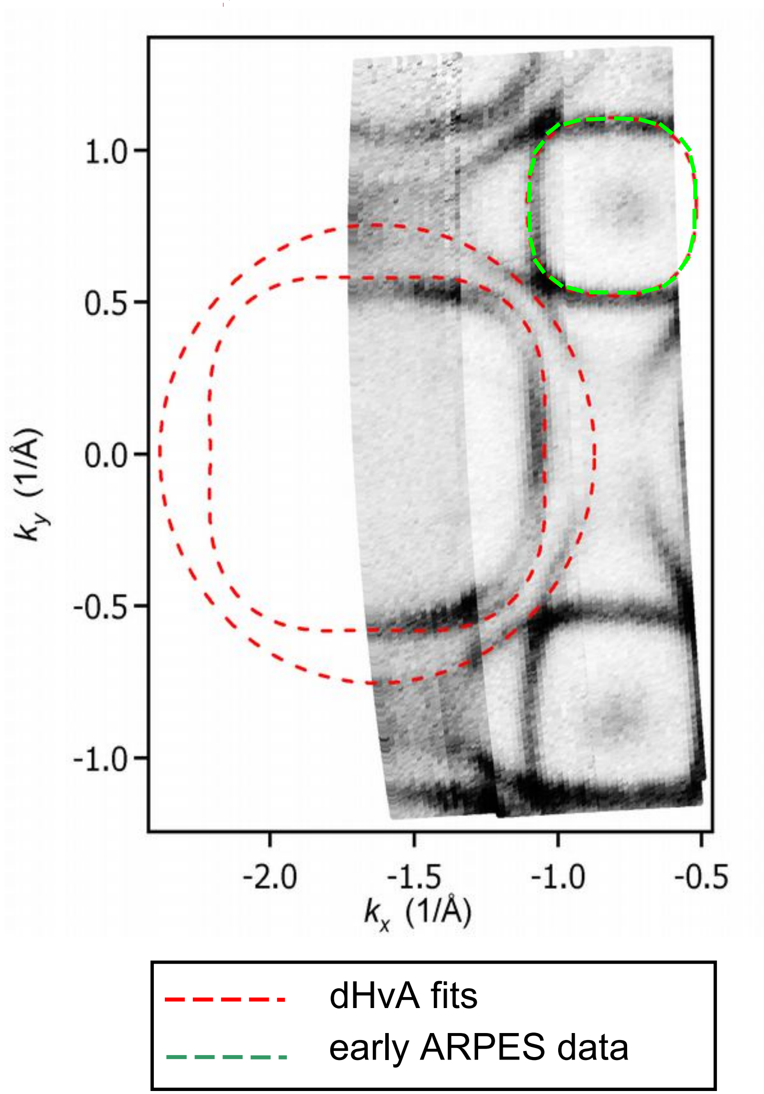
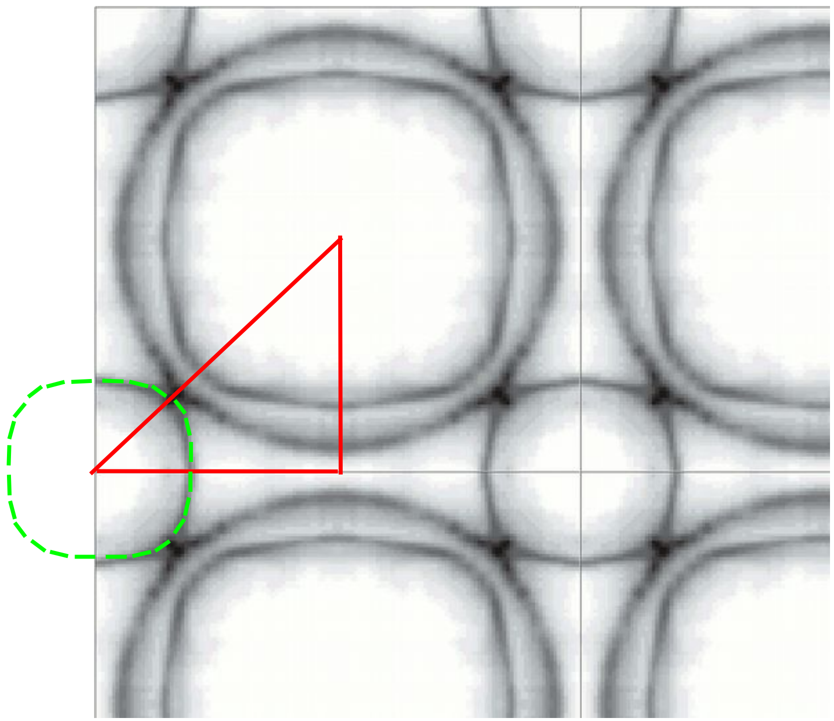


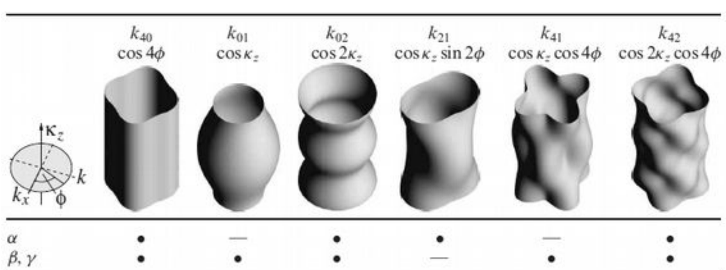
FIG. 2. (Color online) Phonon dispersion in Sr_2RuO_4, symbols denote the measured frequencies and lines those calculated with the lattice dynamical model. We show the phonon dispersion along the main symmetry directions [100], [110], and [001], separated according to the irreducible representations, see text and Table I.

Werner et al PRB 76, 014505 (2007).

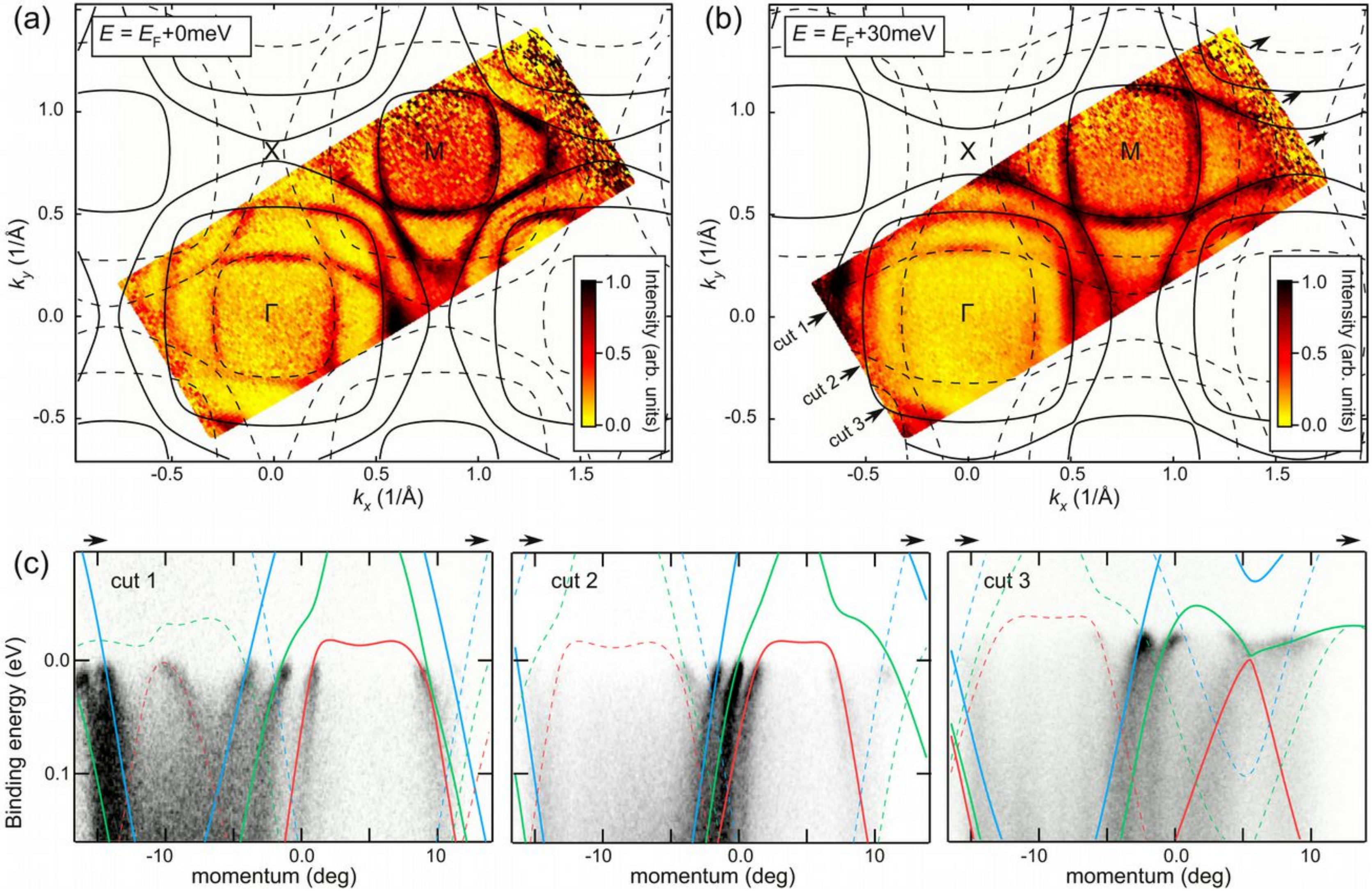
Comparison to dHvA FS fits





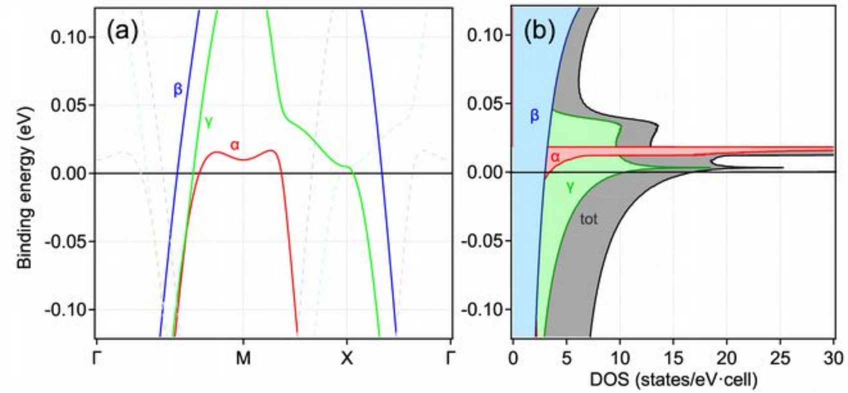


TB model



(a)
$E = E_F$+0meV
X
M
Γ
k_y (1/Å)
k_x (1/Å)
Intensity (arb. units)
(b)
$E = E_F$+30meV
cut 1
cut 2
cut 3
(c)
cut 1
cut 2
cut 3
Binding energy (eV)
momentum (deg)

TB model, comparison to other methods

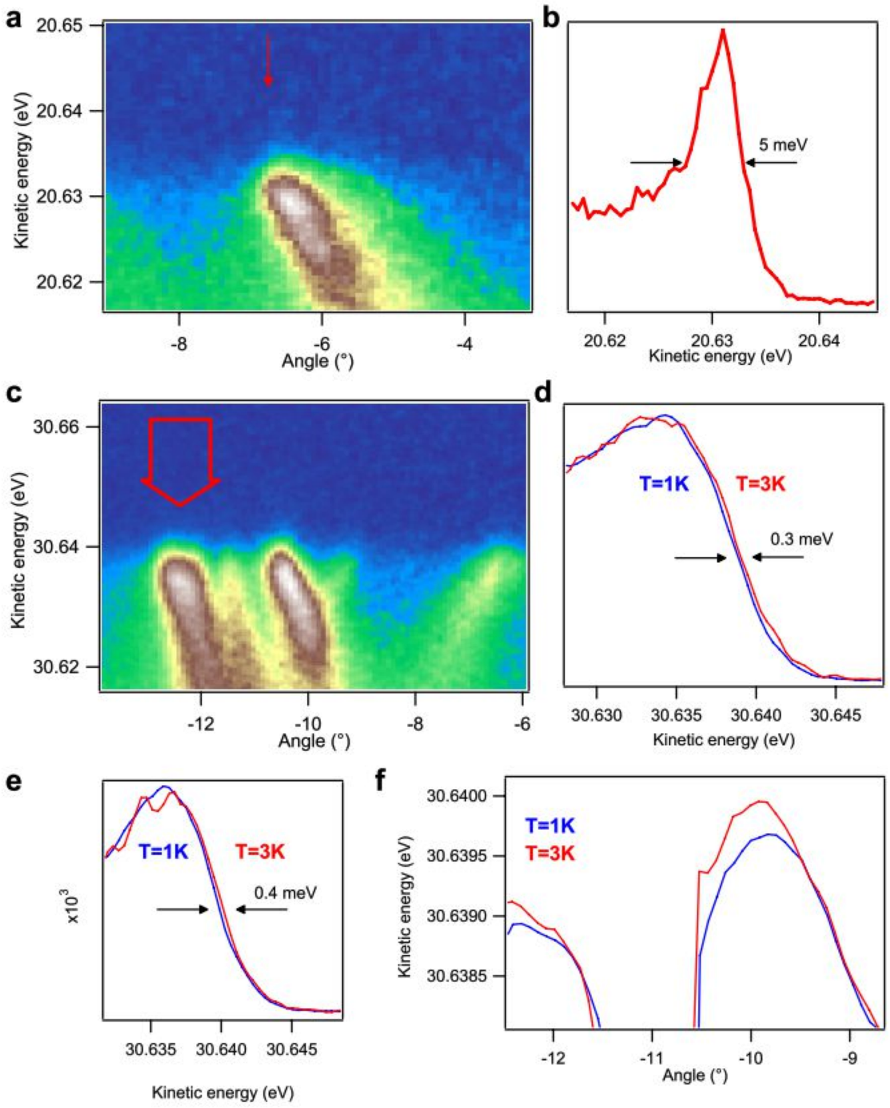


$$\hbar\Omega_{xx} = \sqrt{\sum_{i=\alpha,\beta,\gamma} \frac{e^2}{L_a L_b L_c \epsilon_0} \left\langle f_k \frac{\partial^2 E^{(i)}}{\partial k_x \partial k_x} \right\rangle_{\mathrm{BZ}}}$$

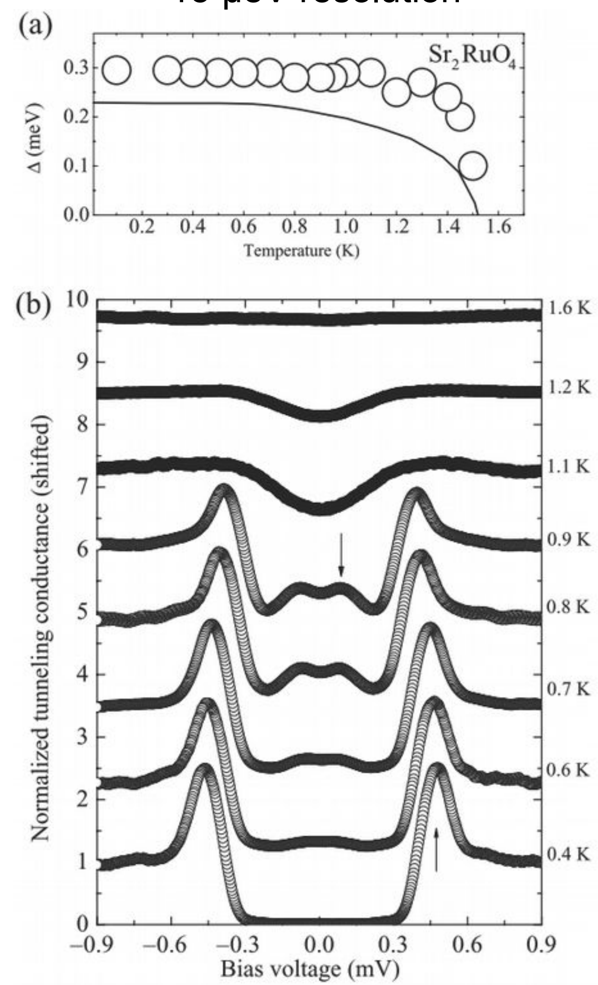
$$\hbar\Omega_{xx} = 1.3\,\mathrm{eV}$$

mass type	α	β	γ	total	year
(this study)	5.4	4.8	16.7	26.9	
Cyclotron thermodynamic [15, 75]	3.3	7.0	16.0	26.3	2001
Cyclotron thermodynamic [72]	3.4	7.5	14.6	25.5	1998
Cyclotron thermodynamic [76]	3.4	6.6	12.	22.0	1998
Cyclotron thermodynamic [77]	3.2	6.6	12.0	21.8	1996
Cyclotron resonance [15]	2.1	4.3	5.8	12.2	2003
Cyclotron resonance [78]	4.3	5.8	9.7	19.8	2000

Superconducting gap

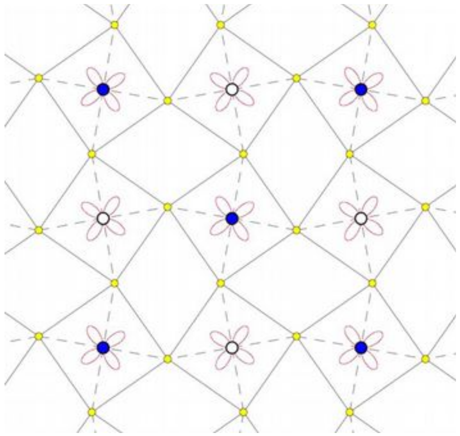


Al-Sr_2RuO_2 STM,
15 μeV resolution



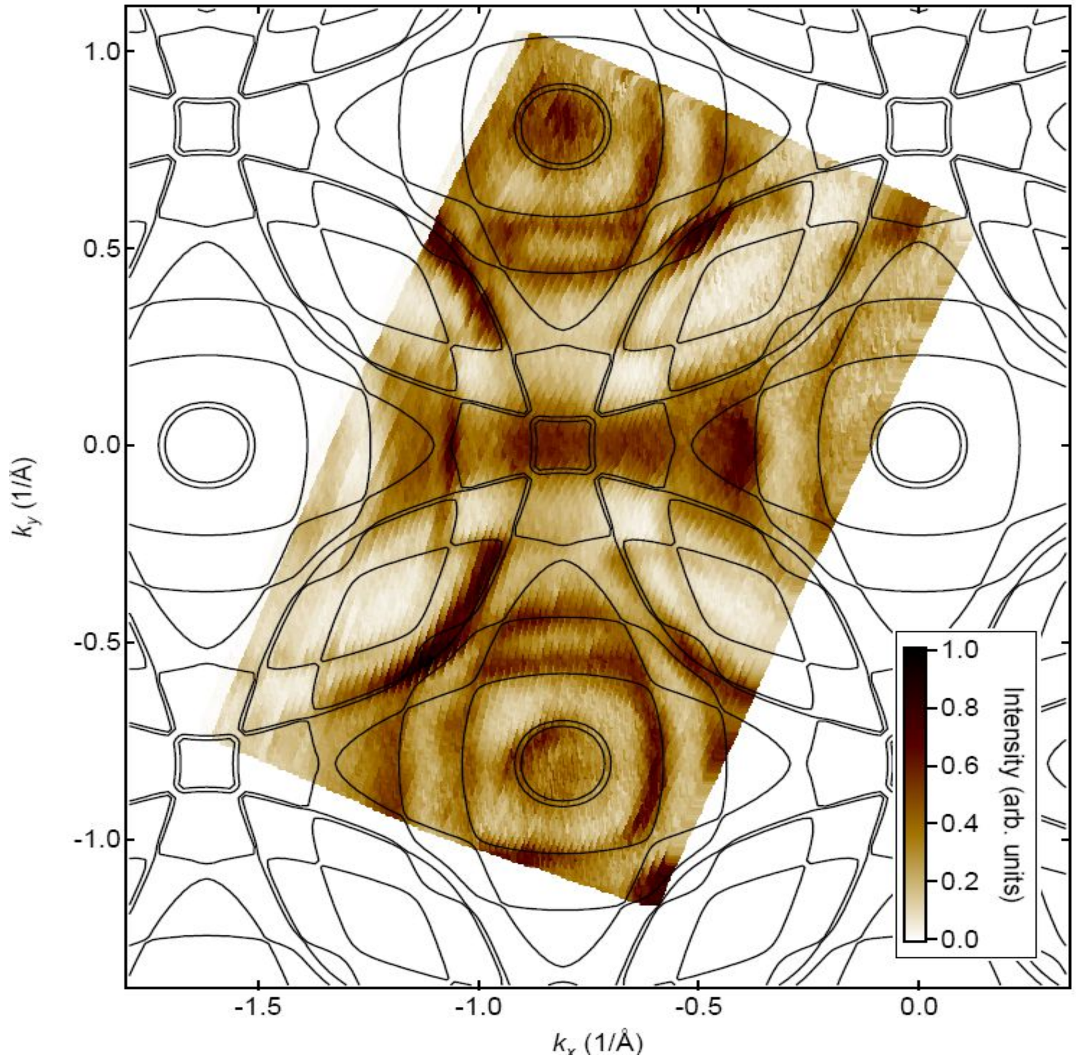
Suderow et al. NJP 11, 093004 (2009)

Double-layered ruthenate: $Sr_3Ru_2O_7$



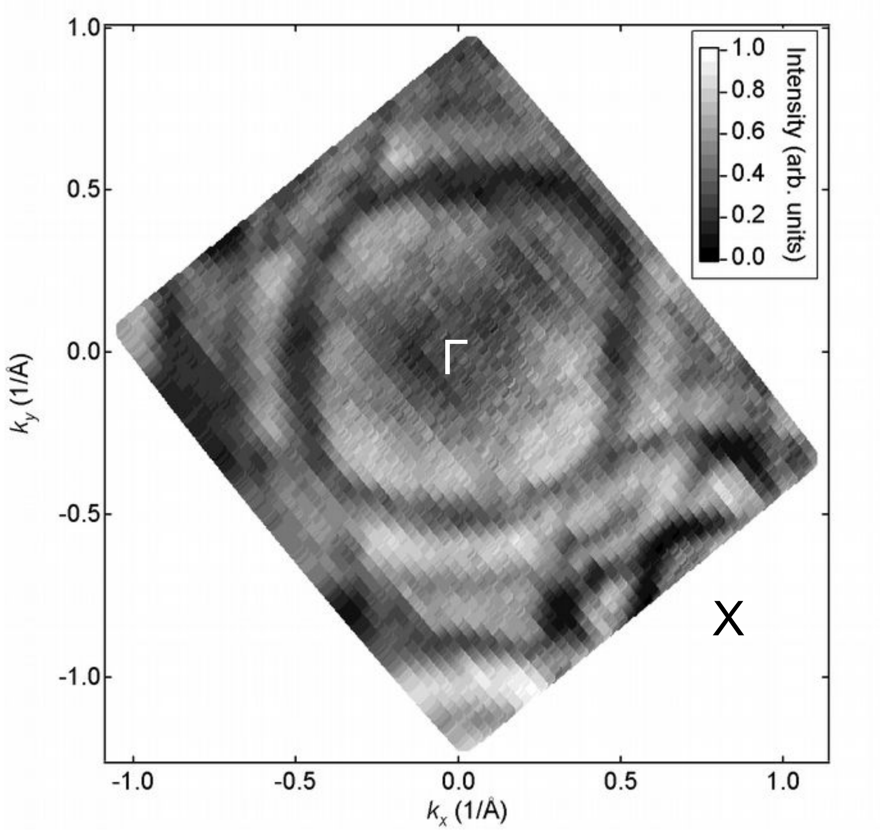
$$\mathcal{H}_{\vec{k}} = \begin{pmatrix} \hat{L}_s^{+}(\vec{k}) & -\hat{G}^{\dagger}(\vec{k}) & \hat{B}_1^{\dagger} & \hat{B}_2^{\dagger} \\ -\hat{G}(\vec{k}) & \hat{L}_s^{+}(\vec{k}+\vec{Q}) & \hat{B}_2^{\dagger} & \hat{B}_1^{\dagger} \\ \hat{B}_1 & \hat{B}_2 & \hat{L}_s^{-}(\vec{k}) & \hat{G}^{\dagger}(\vec{k}) \\ \hat{B}_2 & \hat{B}_1 & \hat{G}(\vec{k}) & \hat{L}_s^{-}(\vec{k}+\vec{Q}) \end{pmatrix}$$

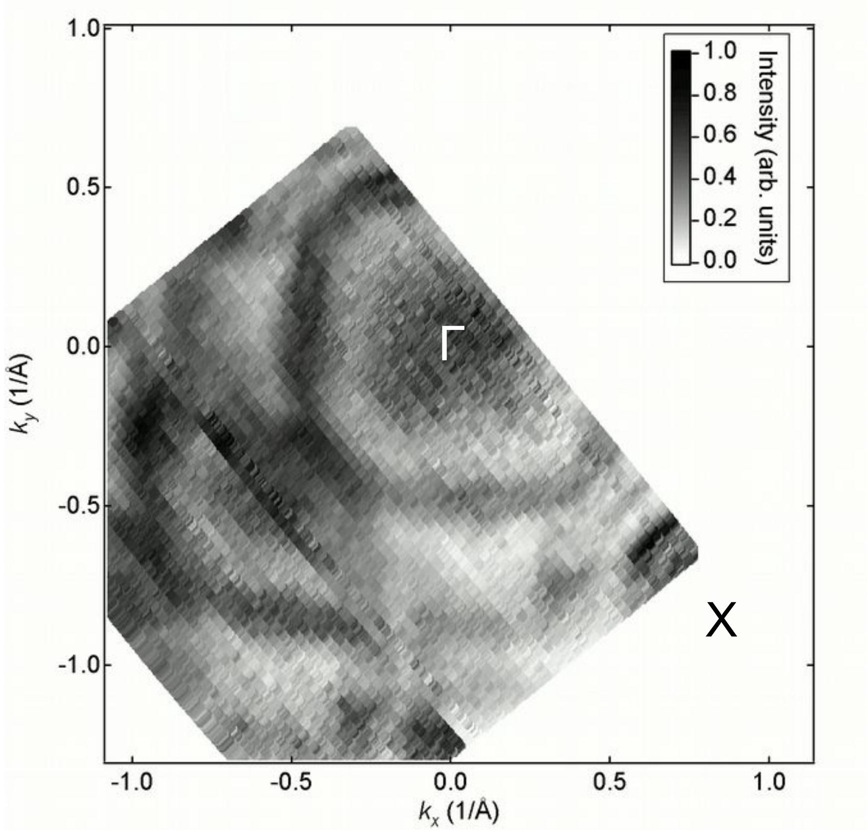
Wei-Cheng Li et al. B 81, 184403 2010



Tri-layered ruthenate: $Sr_4Ru_3O_{10}$

Sr_2RuO_4 : 3 × 1 × 1 = 3 bands
$Sr_4Ru_3O_{10}$: 3 × 3 × 2 = 18 bands





Summary

- Splitting of the surface β band, presumably due to spin-orbit interaction
- Enhanced renormalization of surface bands
- Enhanced electron phonon coupling for the surface band
- TB-model parametrizing quasiparticle dispersion in Sr_2RuO_4 consistent with bulk measurements.

Thank you for your attention