Direct spectroscopic evidence for phase competition between the pseudogap and superconductivity

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SLAC National Accelerator Laboratory

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outline

1. Introduction
2. Pseudogap as a distinct phase
3. Competition between the pseudogap and superconductivity
4. Summary

collaborators

- **ARPES**
  - R.-H. He, I. M. Vishik, Y. He, S. Chen, K. Tanaka, R. G. Moore, D. H. Lu, Z.-X. Shen (Stanford/SLAC)
  - A. Fujimori (U. Tokyo), Z. Hussain (LBNL)

- **Samples (Bi2201, Bi2212)**
  - Y. Yoshida, M. Ishikado, H. Eisaki (AIST)
  - K. Fujita, S. Ishida, S. Uchida (U. Tokyo)
  - T. Sasagawa (Tokyo Institute of Technology)

- **Theory**
  - B. Nowadnick, B. Moritz, T. P. Devereaux (Stanford/SLAC)

- **RIXS**
  - G. Ghiringhelli, G. Dellea, A. Amorese, C. Mazzoli, L. Braicovich (Politecnico di Milano)
  - W.-S. Lee (SLAC)
  - K. Kummer, N. B. Brookes (ESRF)

POLITECNICO DI MILANO SPIN ESRF CNISM SIMES BERKELEY LAB ALS UNIVERSITY OF NORTH DAKOTA JAEA AIST

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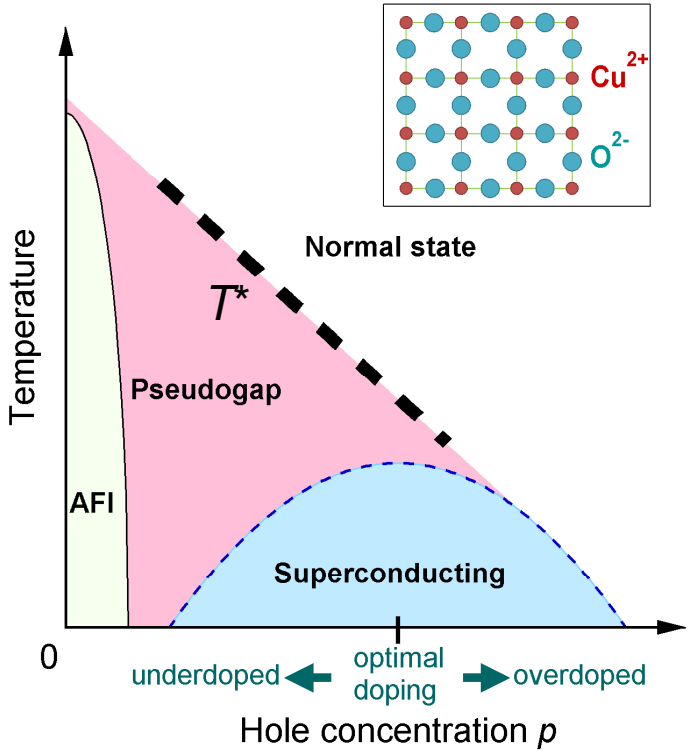
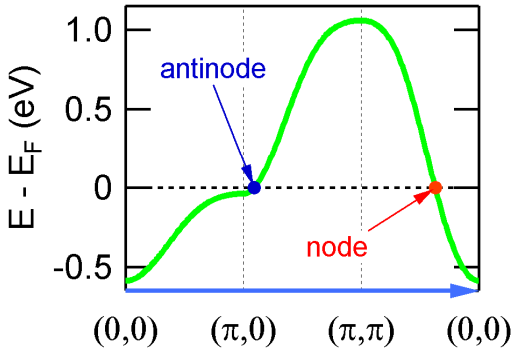
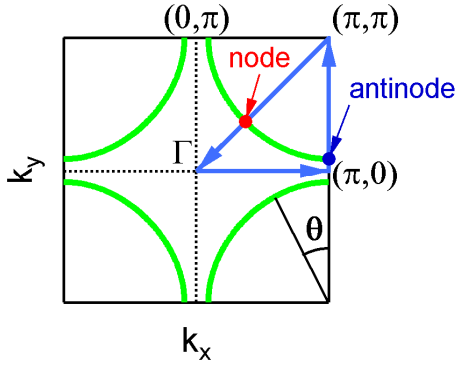
cuprate phase diagram and electronic structure







The nature of the pseudogap

- Different from SC?
- Crossover or phase transition?
- Electronic symmetry?
- Interplay between PG and SC?
- QCP?

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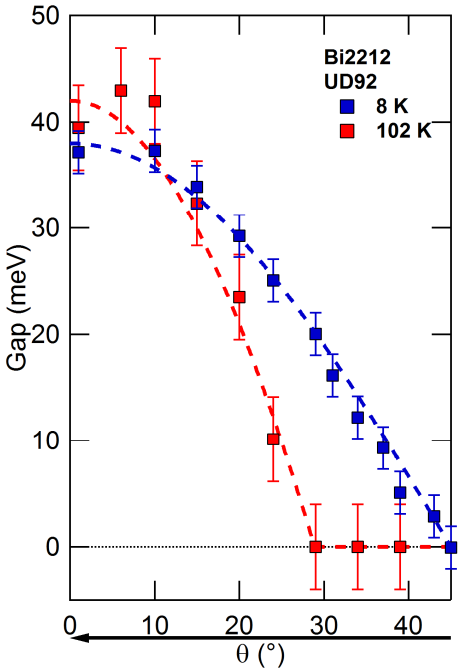
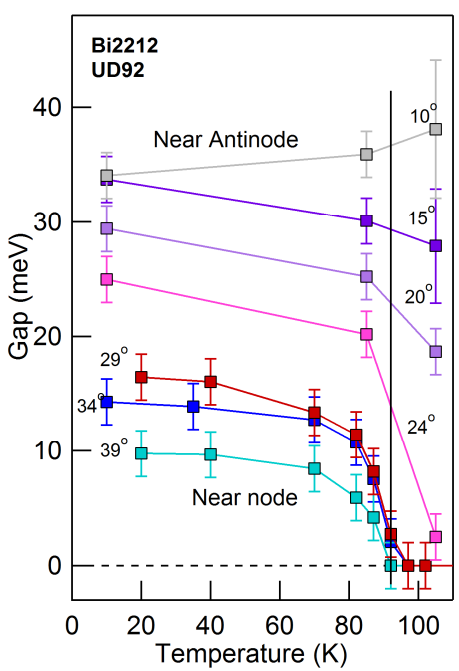
energy gaps – nodal-antnodal dichotomy

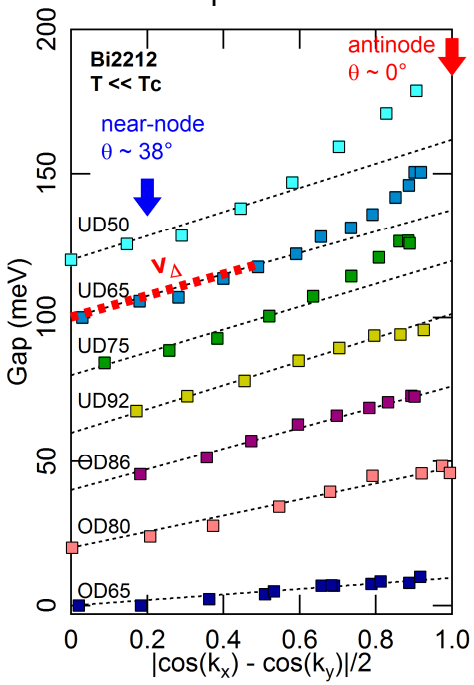
momentum dependence

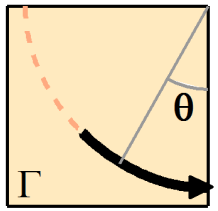


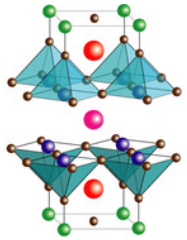
temperature dependence



doping dependence







Bi2212: K. Tanaka *et al.*, *Science* **314**, 1910 (2006)
Bi2212: W. S. Lee *et al.*, *Nature* **450**, 81 (2007)
LBCO: R. H. He *et al.*, *Nat. Phys.* **5**, 119 (2009)
LSCO: T. Yoshida *et al.*, *Phys. Rev. Lett.* **103**, 037004 (2009)
Bi2201: R. H. He* and M. Hashimoto* *et al.*, *Science* **331**, 1579 (2011)
Bi2201: M. Hashimoto *et al.*, *Phys. Rev. B* **86**, 094504 (2012)
Bi2212: I. M. Vishik *et al.*, *PNAS* **109**, 18332 (2012)
Review: M. Hashimoto *et al.*, *Nat. Phys.* **10**, 483 (2014)

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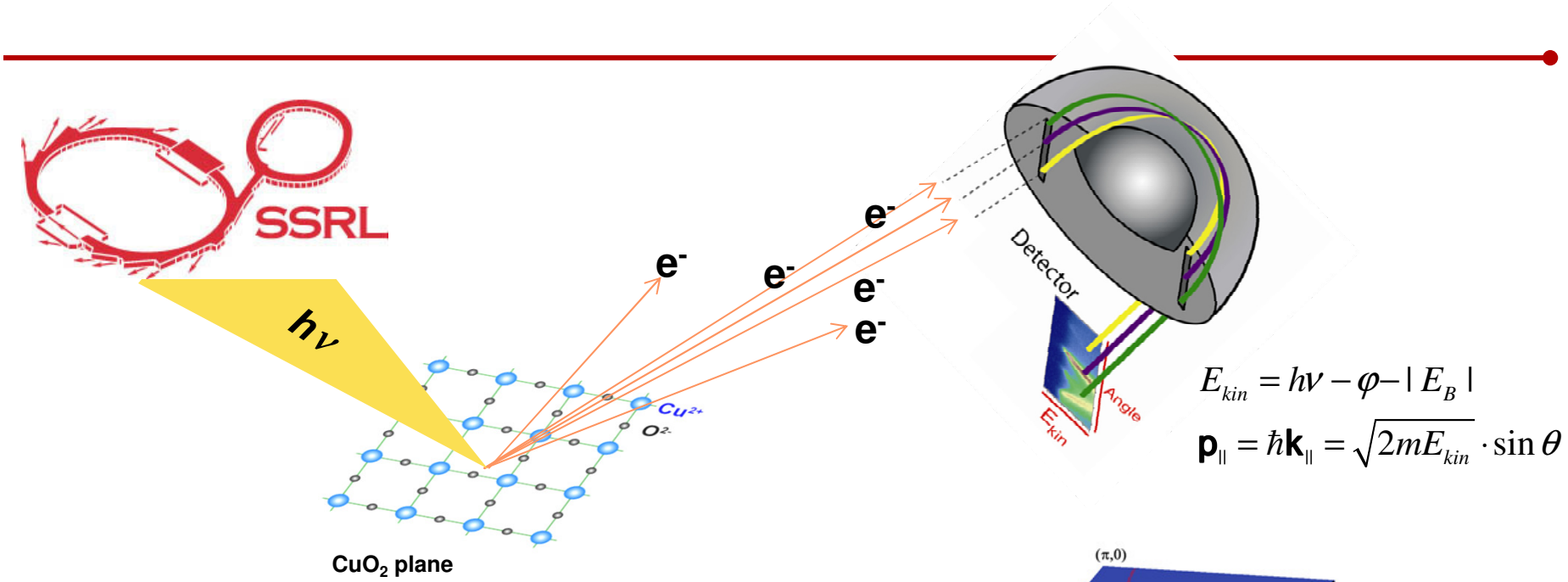
ARPES

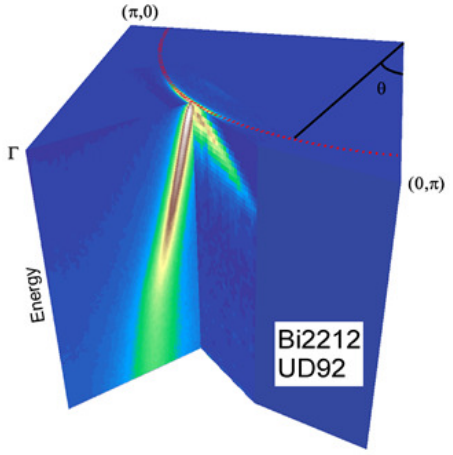


$$E_{kin} = h\nu - \varphi - |E_B|$$

$$\mathbf{p}_{||} = \hbar\mathbf{k}_{||} = \sqrt{2mE_{kin}} \cdot \sin\theta$$

ARPES directly measures spectral function A(*k*,ω)

- band dispersion and Fermi surface
- spectral energy gap
- correlation effect
- …
- $I(\mathbf{k},\omega) \sim A(\mathbf{k},\omega)f(\omega,T) \rightarrow A(\mathbf{k},\omega) \sim I(\mathbf{k},\omega)/f(\omega,T)$



I. M. Vishik *et al.*, *Phys. Rev. Lett.* **104**, 207002 (2010)

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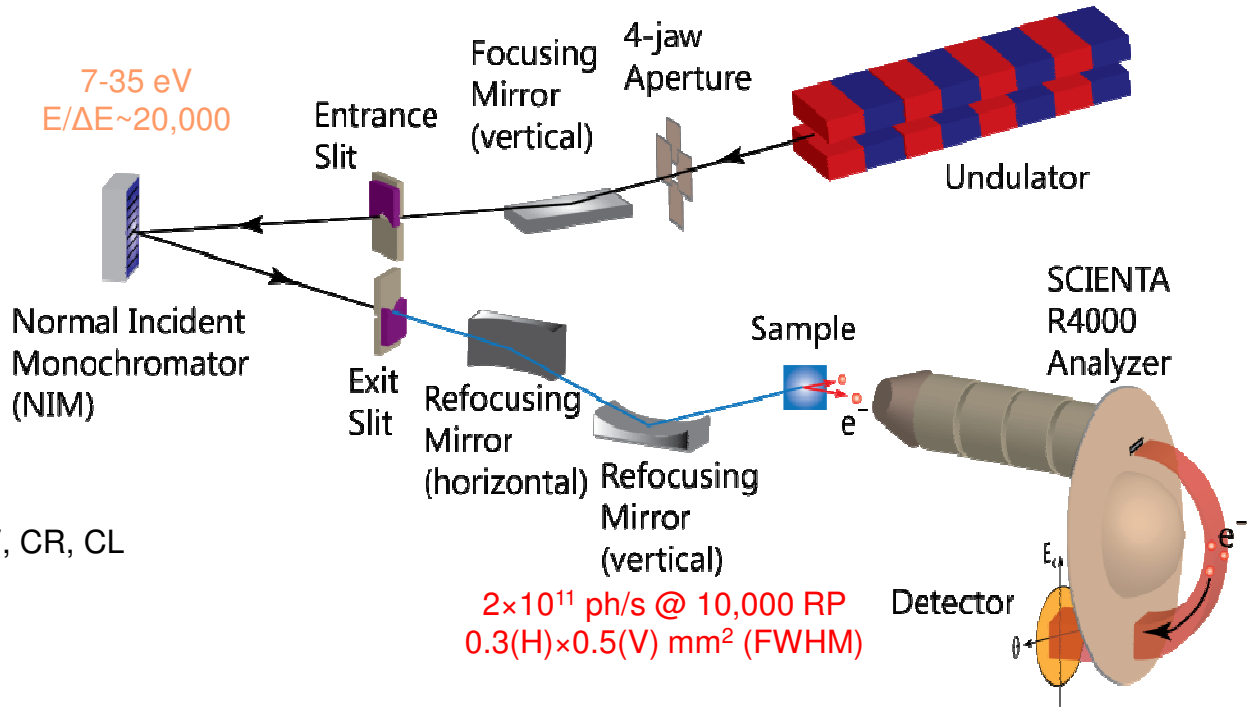
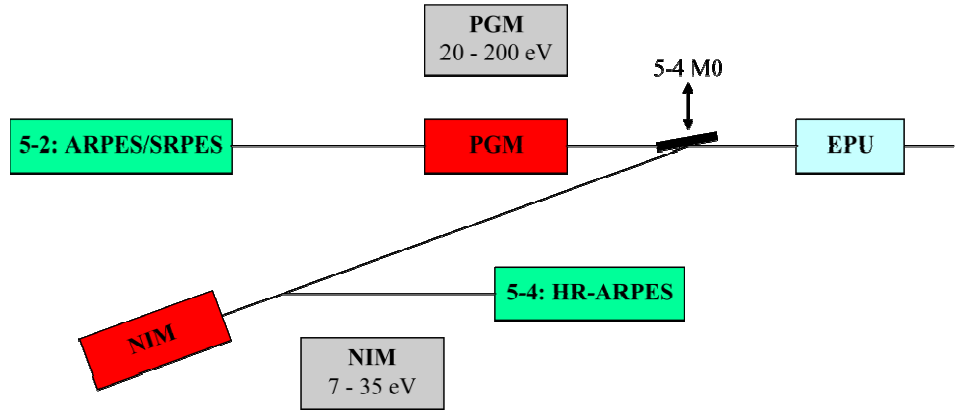
Beam Line 5-4 at SSRL

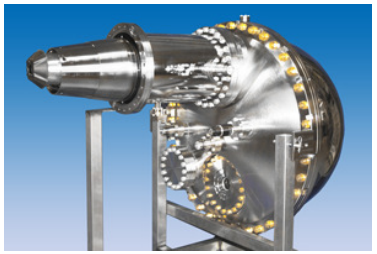


- NIM branch line
  - 7-35 eV
  - polarization, LH, LV, CR, CL
  - *E*/Δ*E* ~ 20,000
- UHV < 3×10^{-11} Torr
- Scienta R4000 analyzer
  - ~few to 10 meV energy resolution
- 5-axis manipulator
  - 6 - 400 K
- complementary to new branch line 5-2

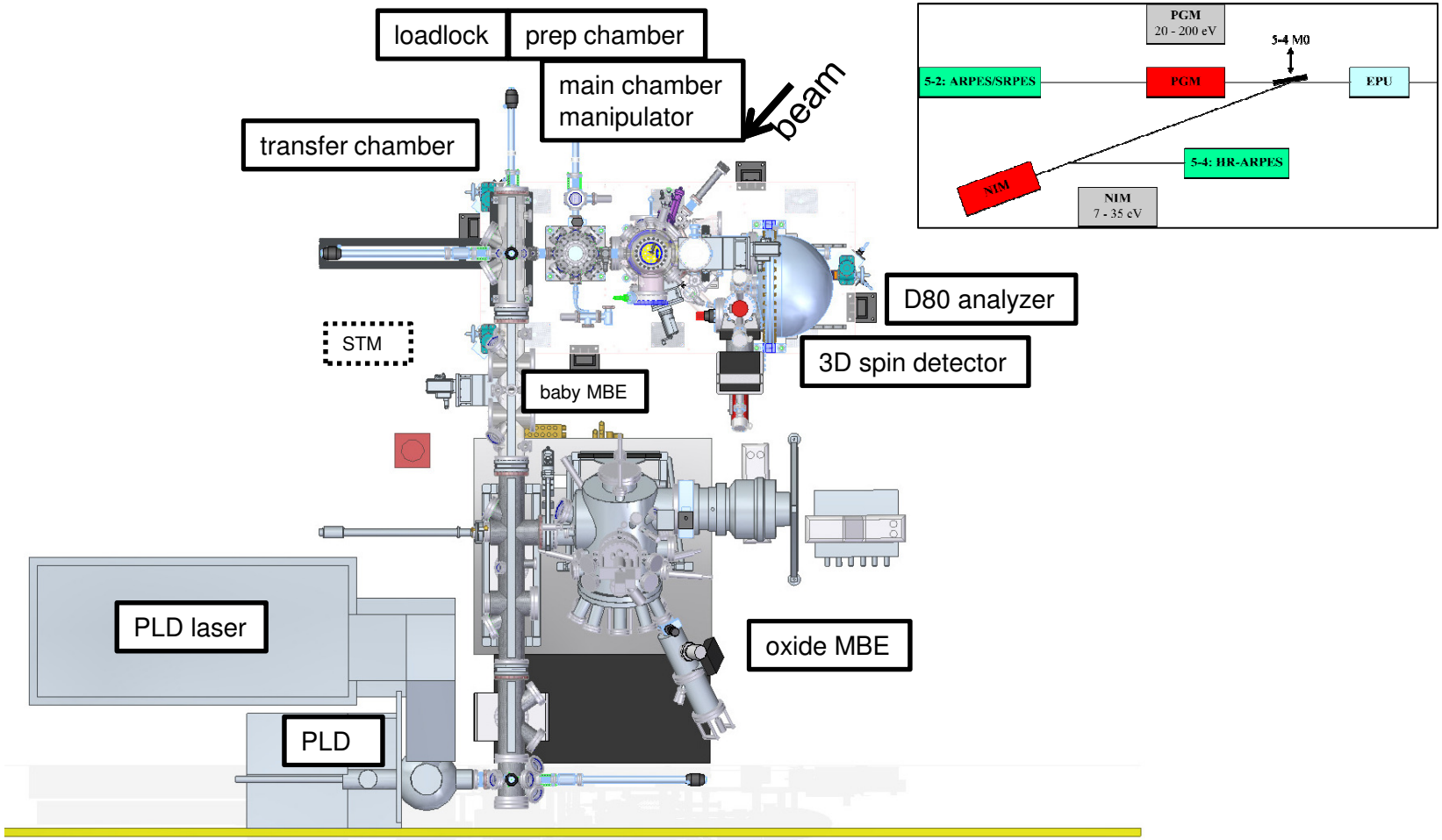
new Beam Line 5-2 at SSRL

- PGM branch line
  - 20 – 200 eV
  - small beam size: < 50 (H) x 20 (V) micron
  - polarization control (LH, LV, CR, CL)
  - $E/\Delta E$ > 25000
- Scienta D80 analyzer
  - *Ø80 mm MCP detector*
  - *3D mini Mott spin detector*
  - < few meV energy resolution
- 6-axis manipulator
  - < 10 K
  - compatible with sample holders for thin films
- complementary to the existing NIM branch line





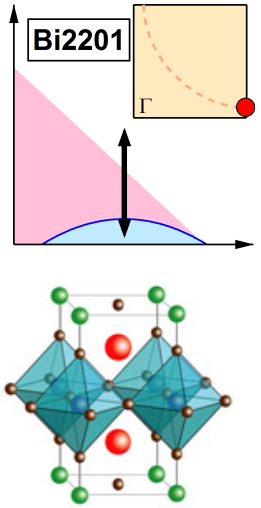
new Beam Line 5-2 at SSRL

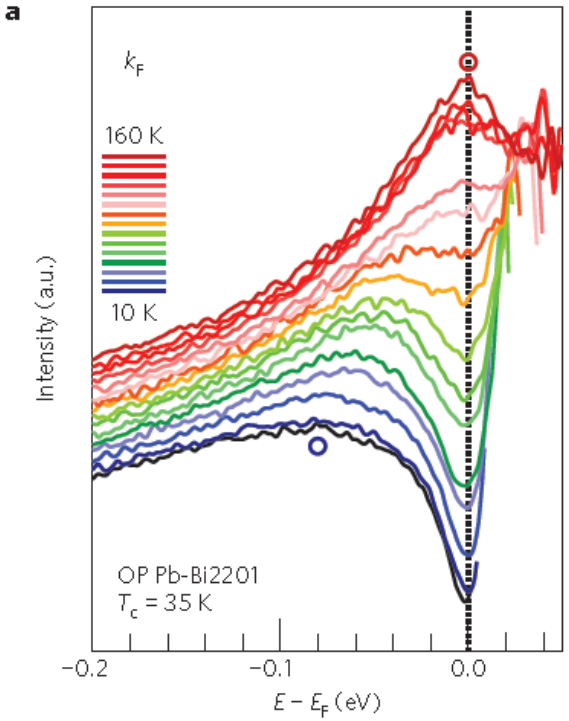


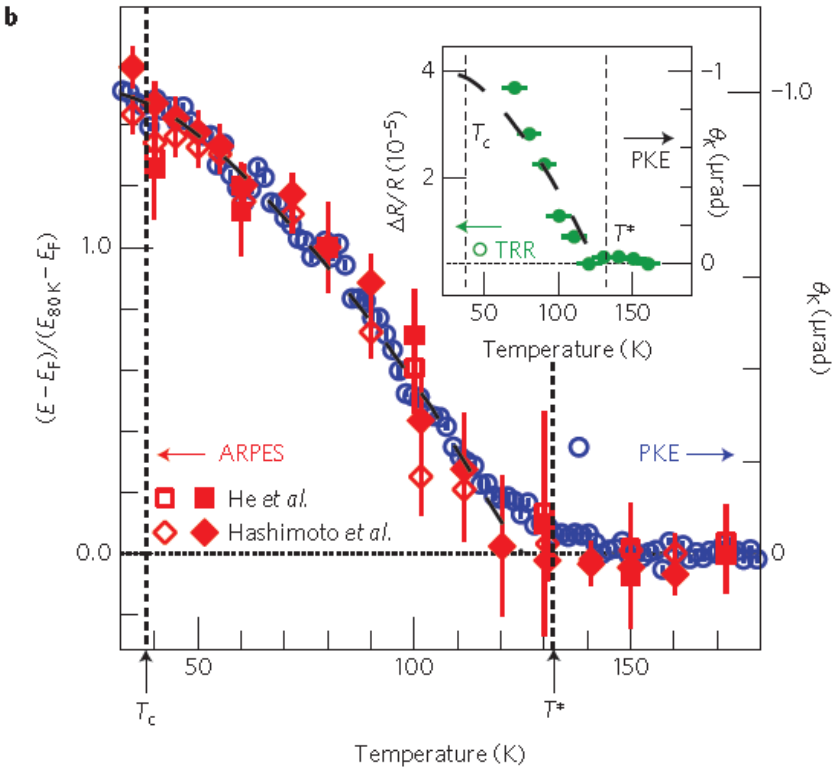
outline

1. Introduction
   - cuprates
   - energy gap
   - ARPES
   - ARPES Beam Lines at SSRL
2. Pseudogap as a distinct phase
3. Interplay between the pseudogap and superconductivity
4. Summary

pseudogap phase transition







Kerr effect: A. Kapitulnik
TRR: J. Orenstein
Theory: S. Kivelson

- M. Hashimoto* and R. H. He* *et al.*, *Nat. Phys.* **6**, 414 (2010)
- R. H. He* and M. Hashimoto* *et al.*, *Science* **331**, 1579 (2011)

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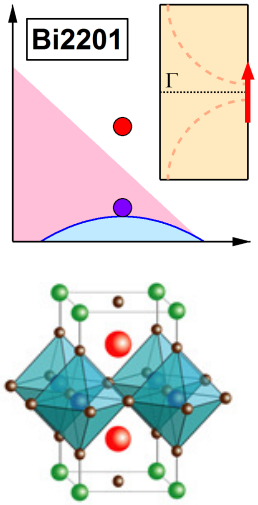
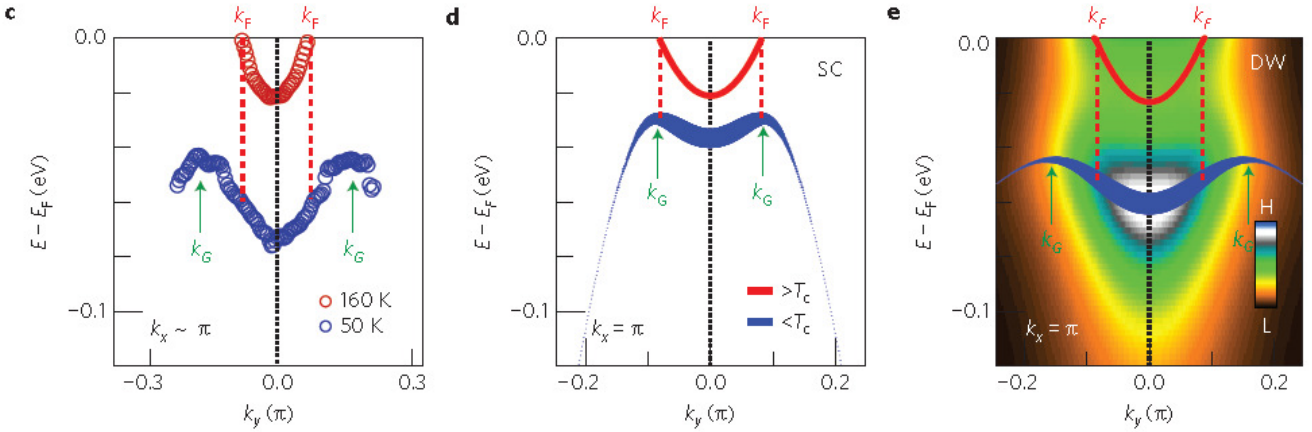
symmetry breaking below pseudogap temperature



Experiment SC gap density wave gap



- back-bending momentum ≠ k_F
- different from SC gap
- consistent with density wave
- not perfect nesting

M. Hashimoto* and R. H. He* *et al.*, *Nat. Phys.* **6**, 414 (2010)

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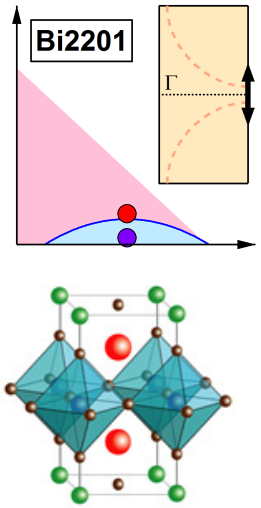
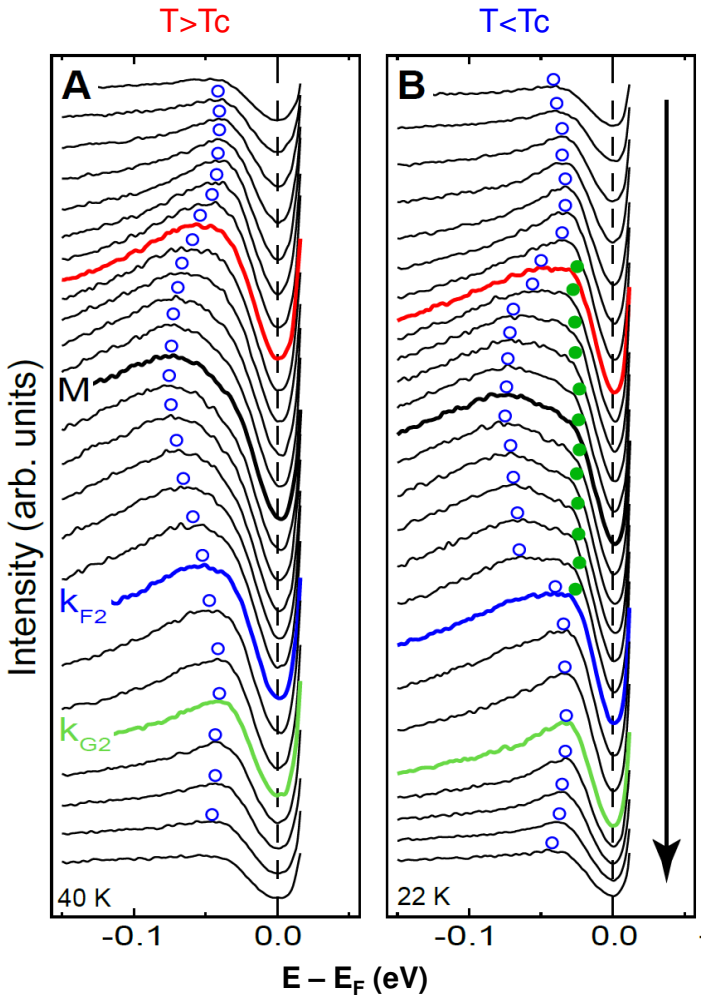
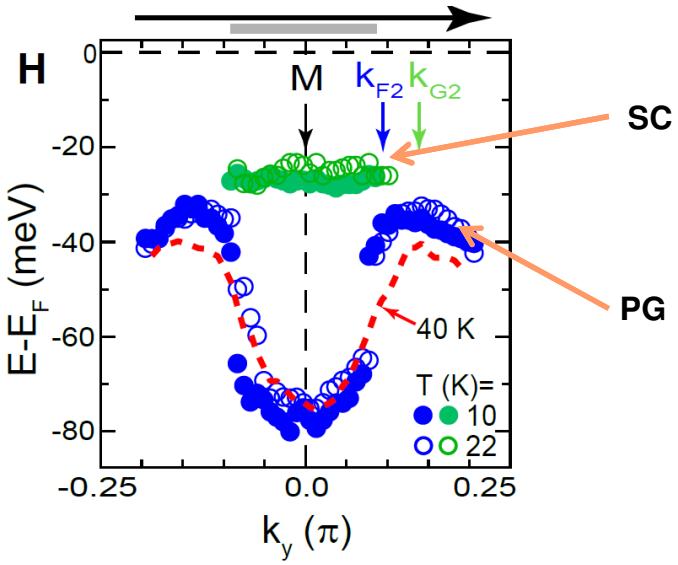
coexistence of pseudogap and superconductivity







- SC and PG coexist
- SC is distorted by PG

R. H. He* and M. Hashimoto* *et al.*, *Science* **331**, 1579 (2011)

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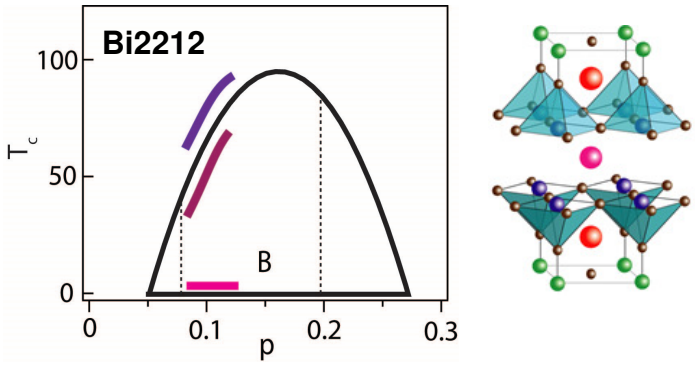
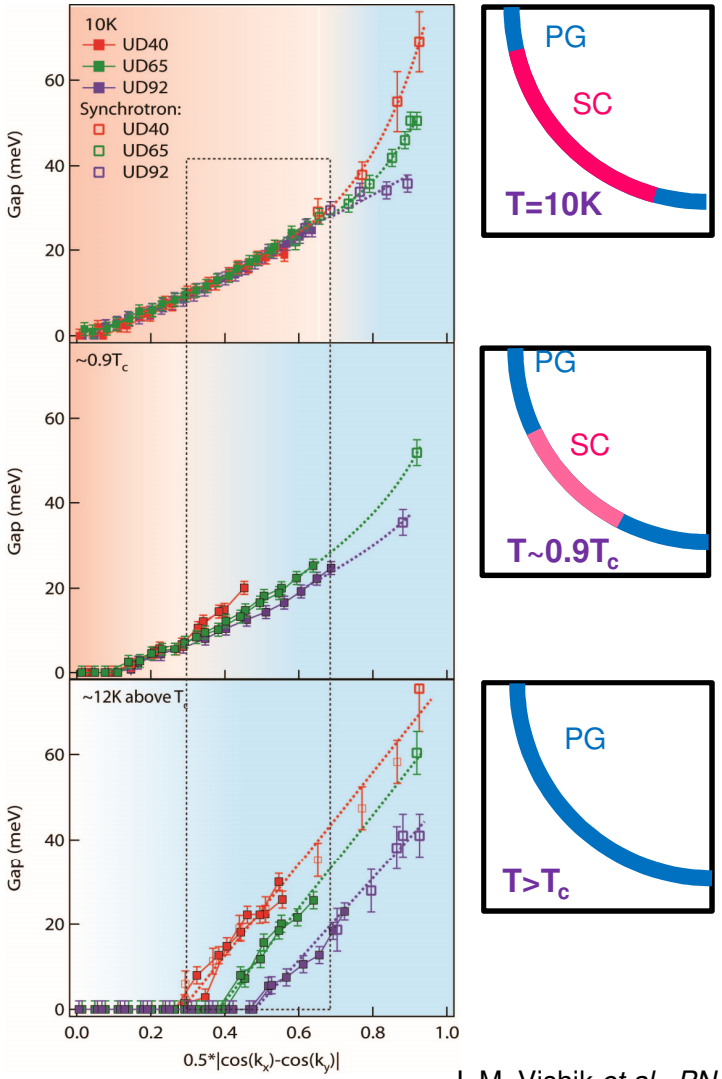
momentum dependent pseudogap suppression





Intermediate momenta

- $T << T_c$

doping ***independent*** SC gap

- $T > T_c$

doping ***dependent*** PG

I. M. Vishik *et al.*, *PNAS* **109**, 18332 (2012)

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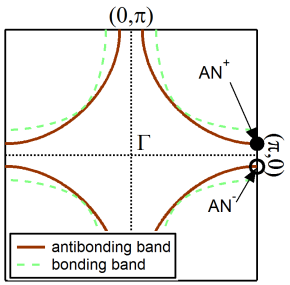
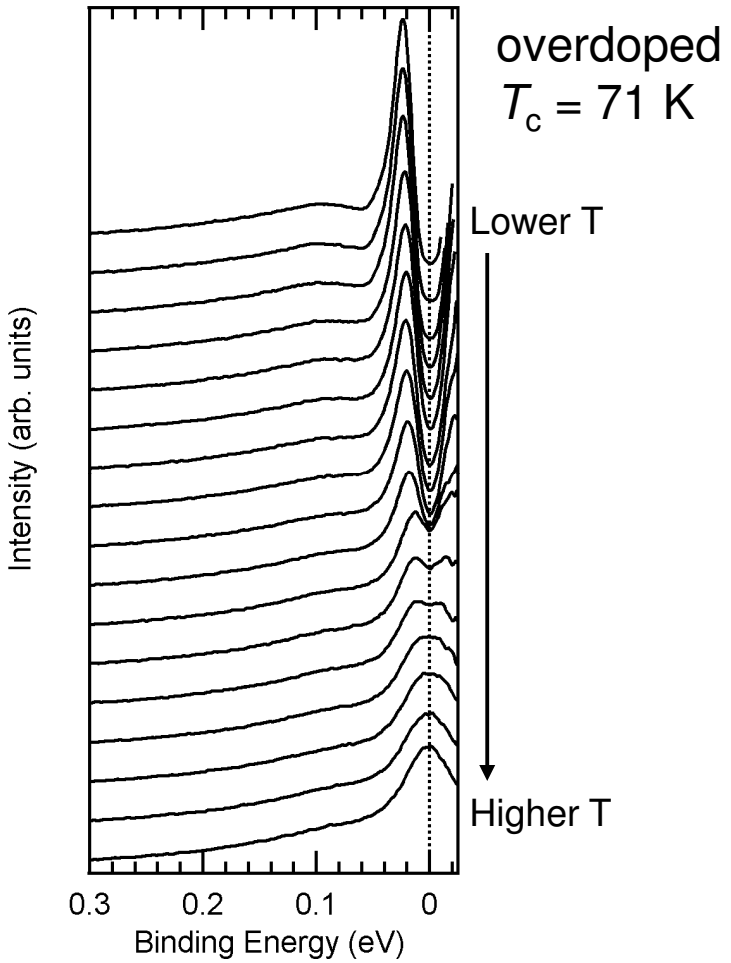
Bi2212 antinodal spectra





M. Hashimoto *et al.*, *Nat. Mat. advance online publication*

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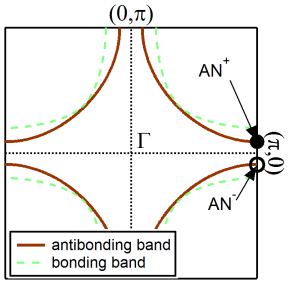
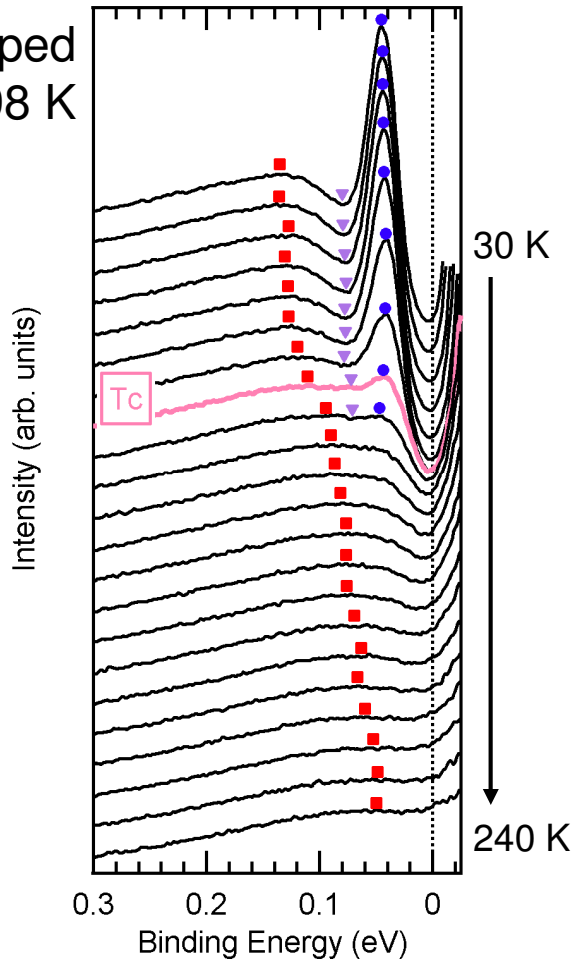
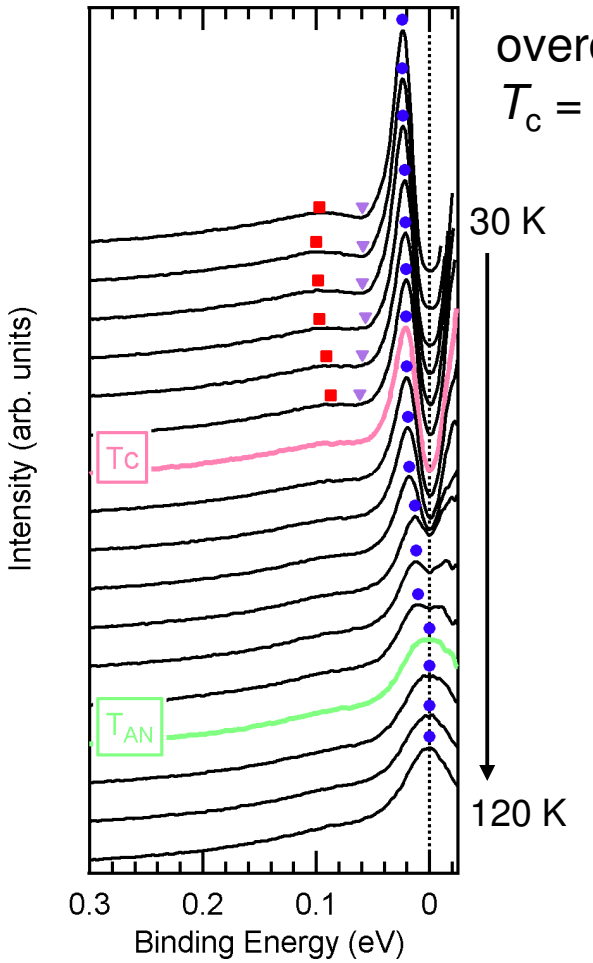
Bi2212 antinodal spectra

optimally doped
T_c = 98 K





overdoped
T_c = 71 K



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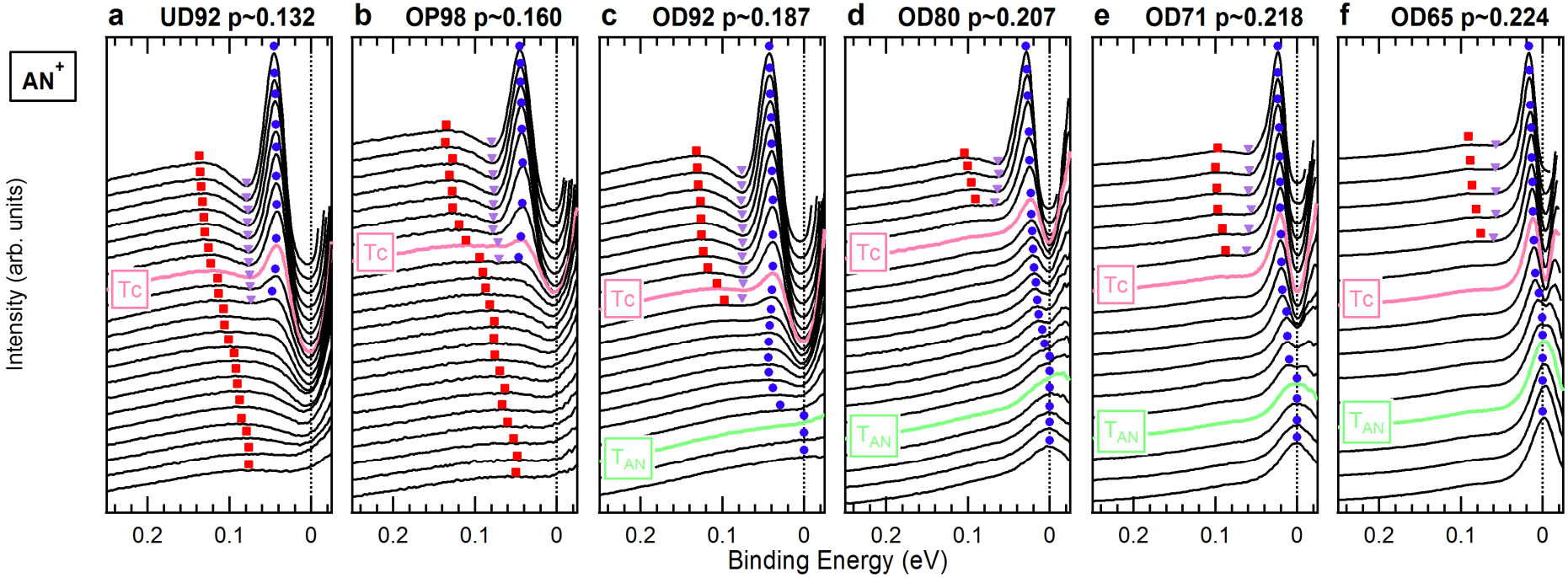
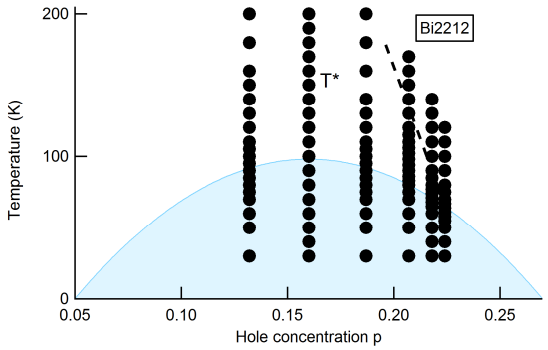
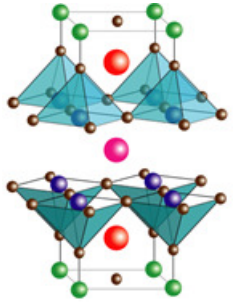
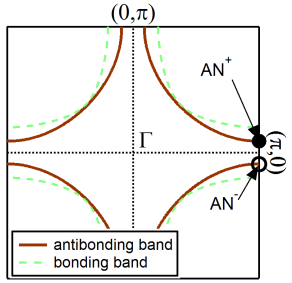
Bi2212 antinodal spectra









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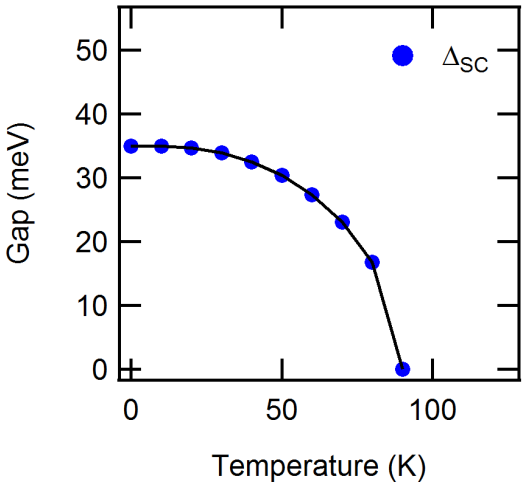
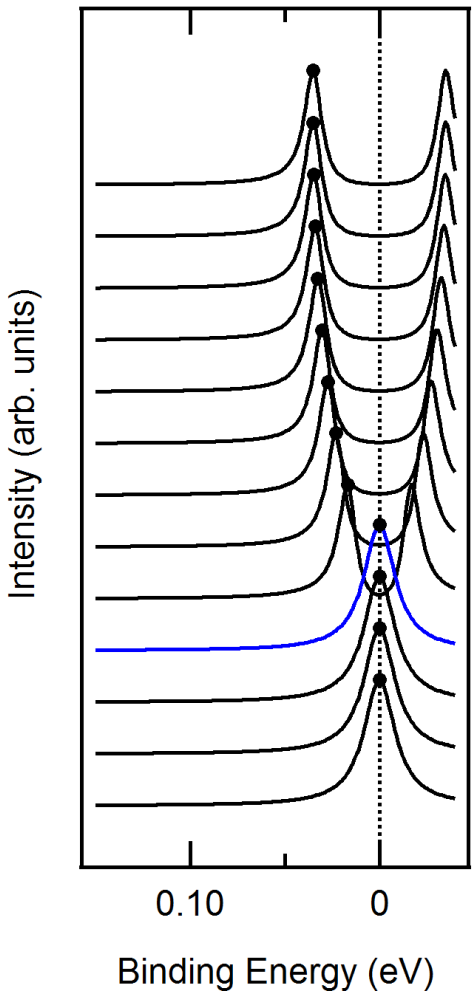
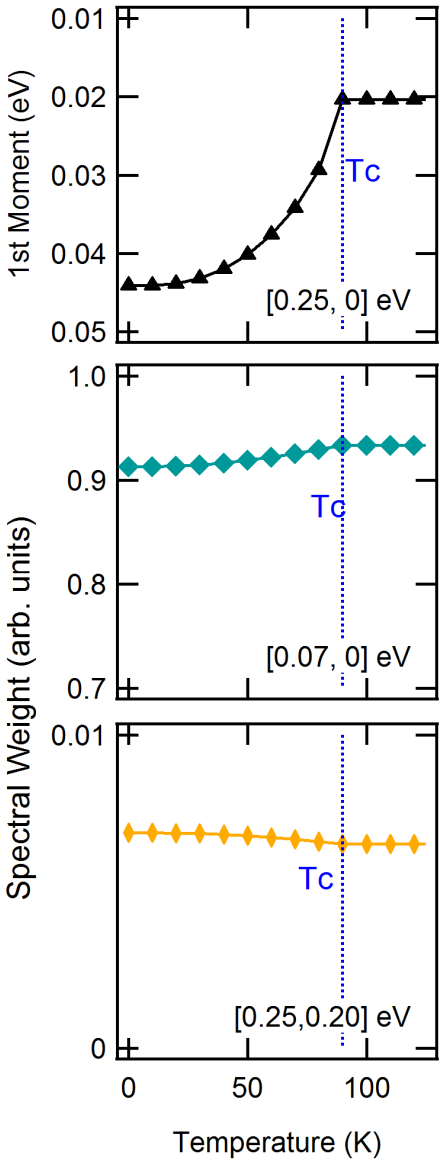
what happens to the spectral weight when sc gap opens?







Center of Mass

Spectral Intensity near E_F

Spectral Intensity away from E_F

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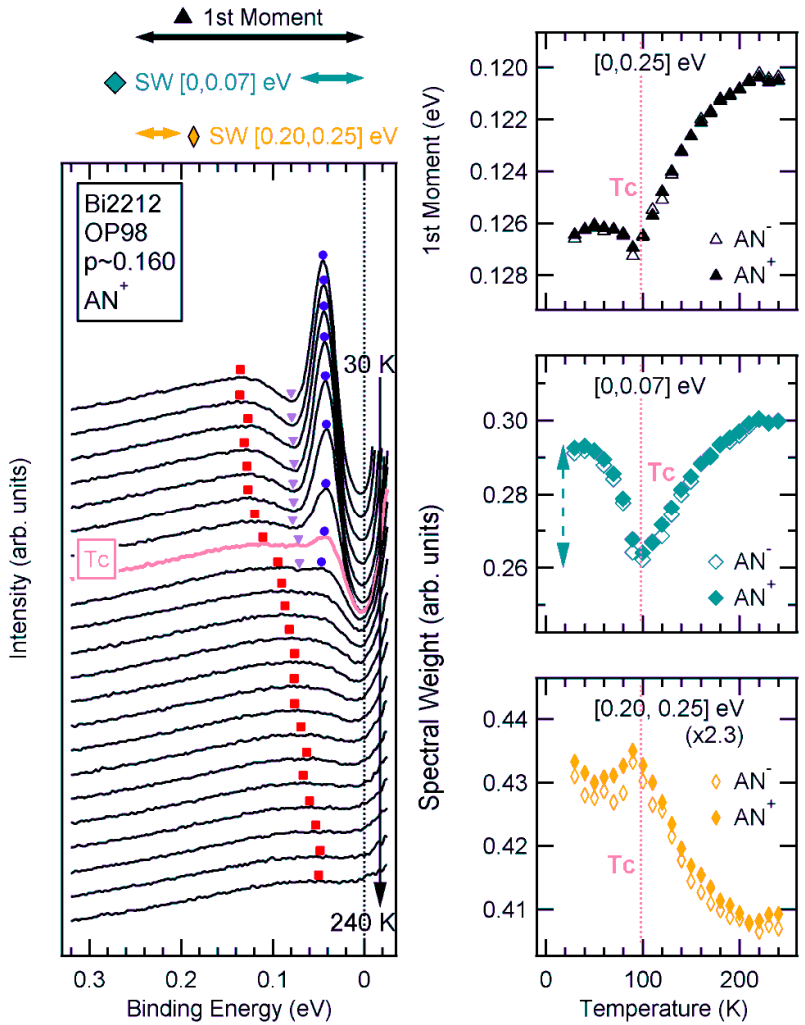
phase competition in spectral weight



- singularity at T_c in the spectral weight
- singularity not evident in the spectral lineshape

M. Hashimoto *et al.*, *Nat. Mat. advance online publication*

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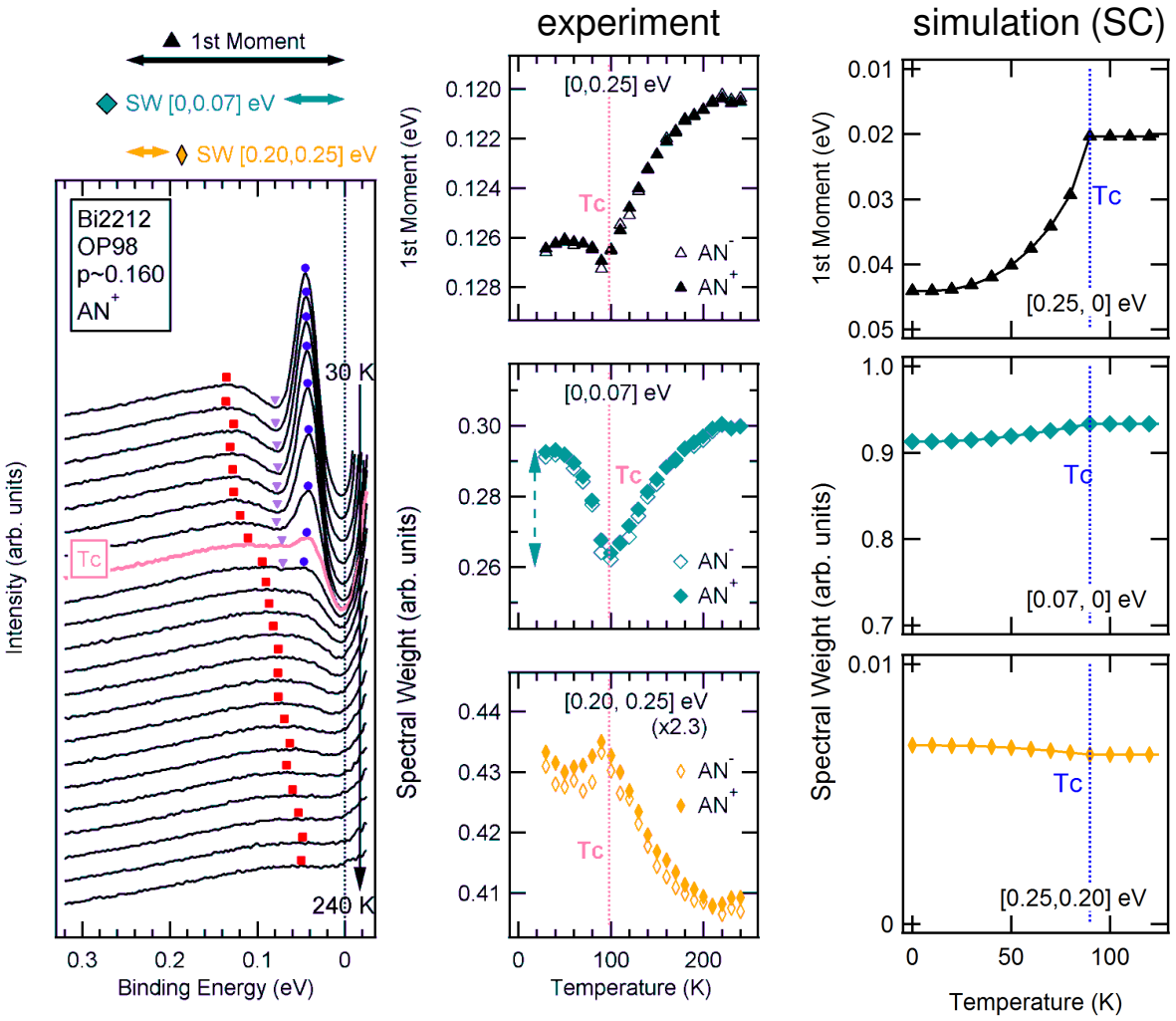
phase competition in spectral weight



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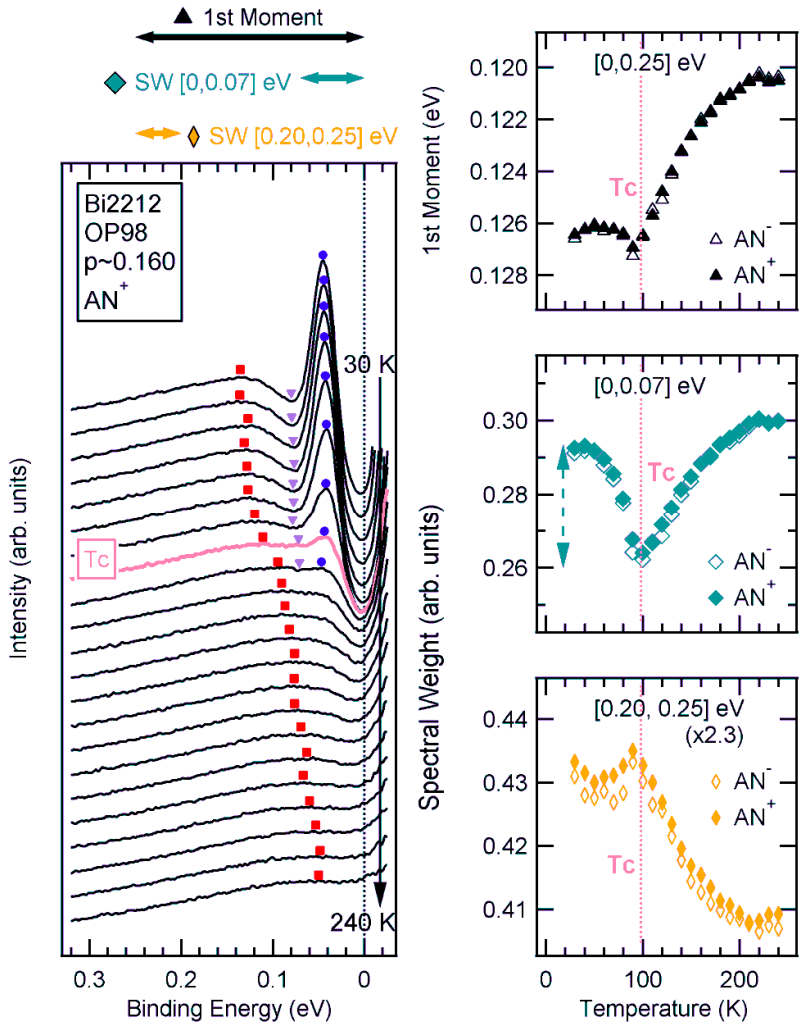
phase competition in spectral weight



- singularity at T_c in the spectral weight
- singularity not evident in the spectral lineshape
- SC alone cannot explain the spectral weight singularity
- PG spectral weight is taken away by SC, suggesting phase competition

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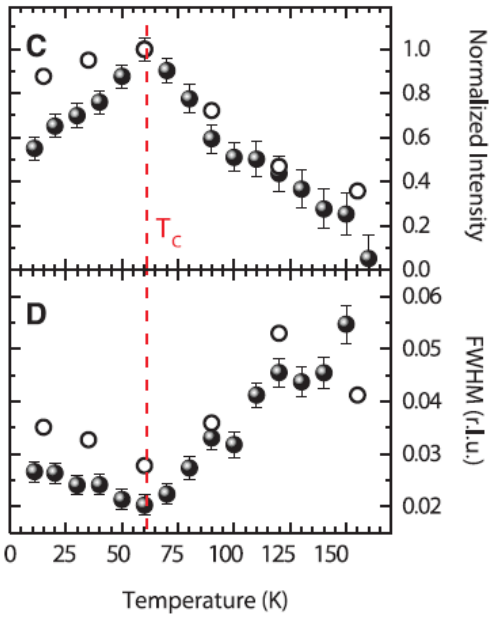
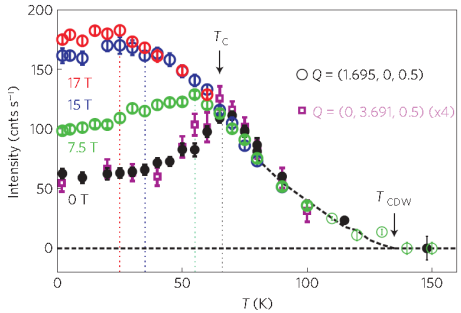
phase competition in cuprates

YBCO

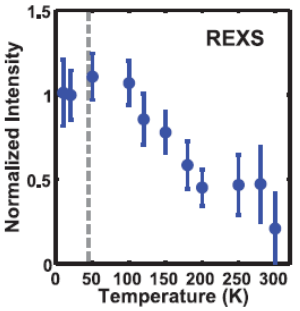


G. Ghiringhelli *et al.*,
Science **337**, 821 (2012)

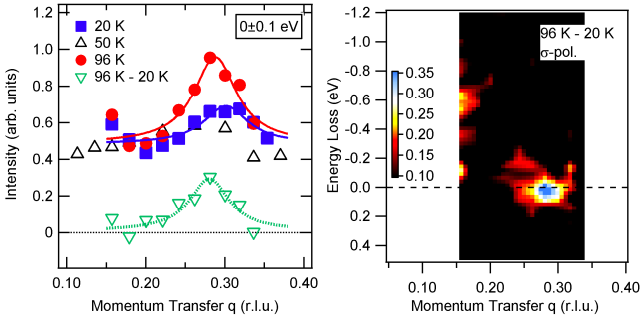


J. Chang *et al.*,
Nat Phys **8**, 871 (2012)

Bi2212



E. H. da Silva Neto *et al.*,
Science **343**, 393 (2014)



M. Hashimoto *et al.*, *Phys. Rev. B* **89**, 220511 (2014)

- Charge ordering suppressed below T_c
- Pseudogap ~ charge ordering?
- Spectroscopic signature?

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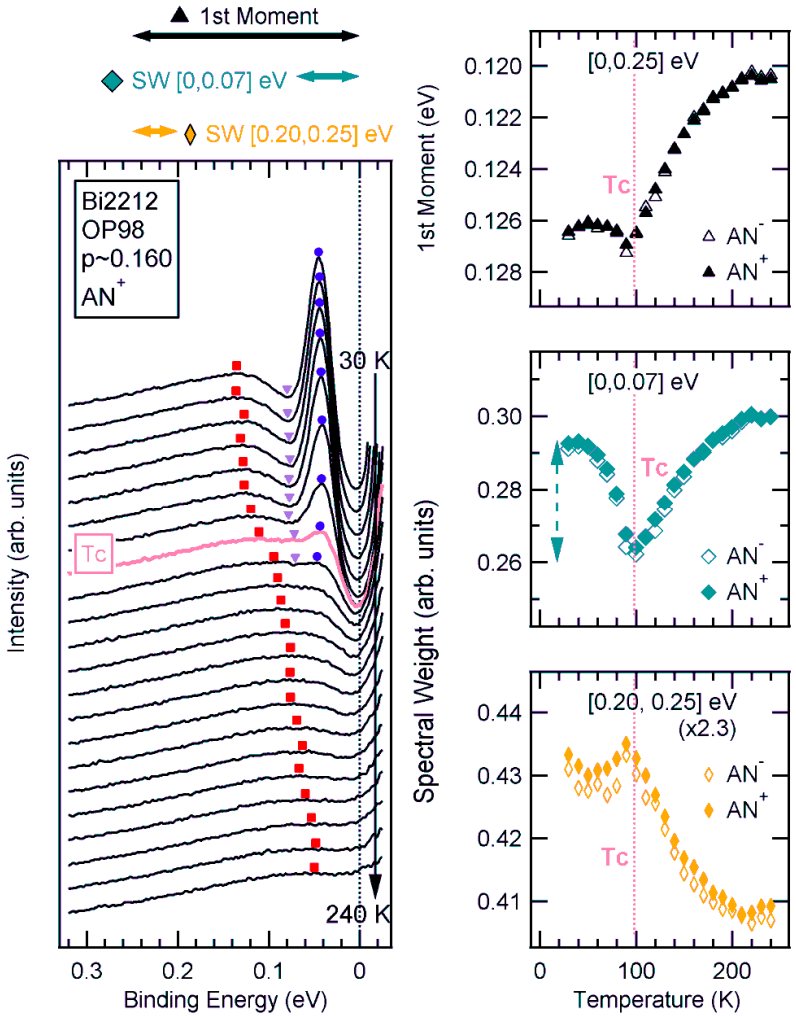
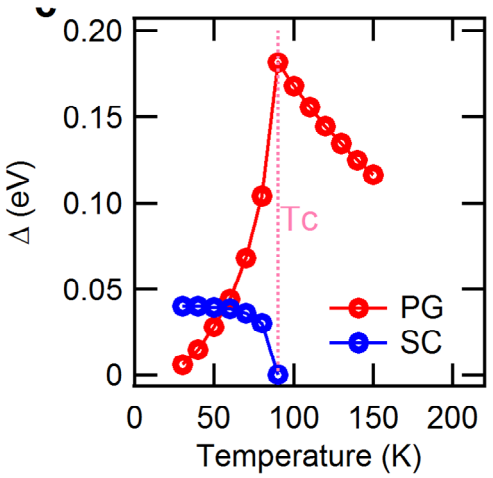
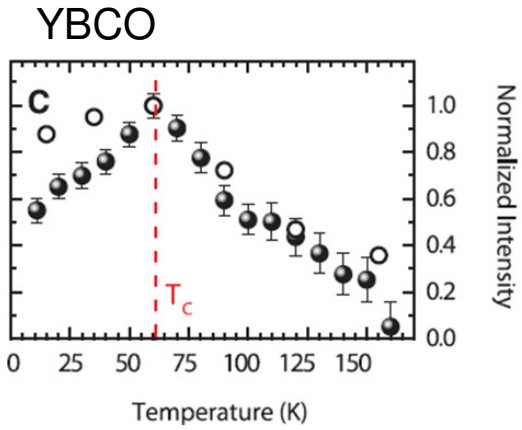
phase competition in spectral weight







G. Ghiringhelli *et al.*, *Science* **337**, 821 (2012)

M. Hashimoto *et al.*, *Nat. Mat. advance online publication*

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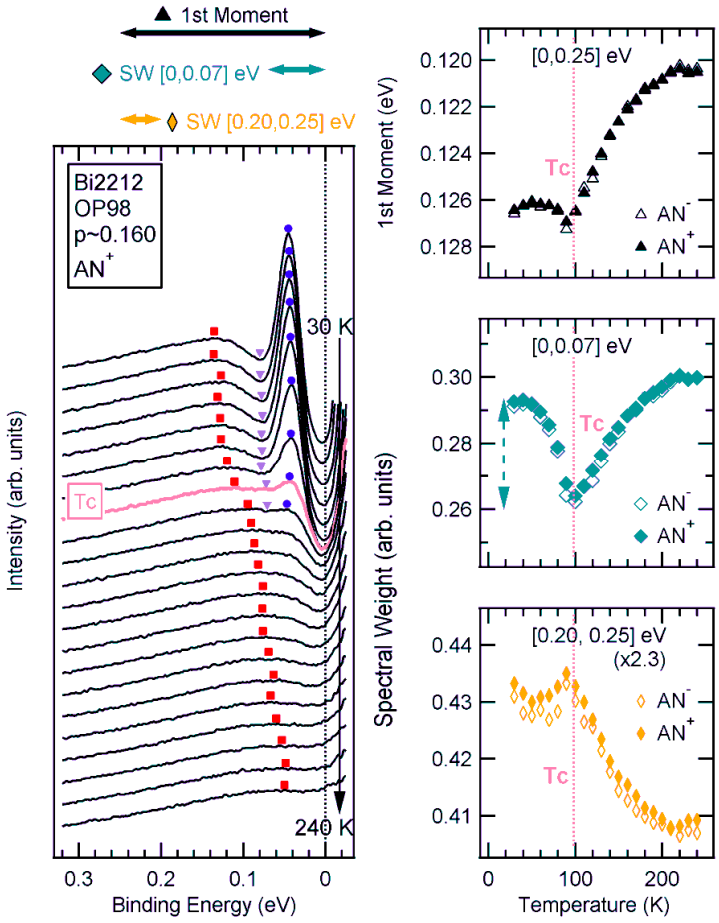
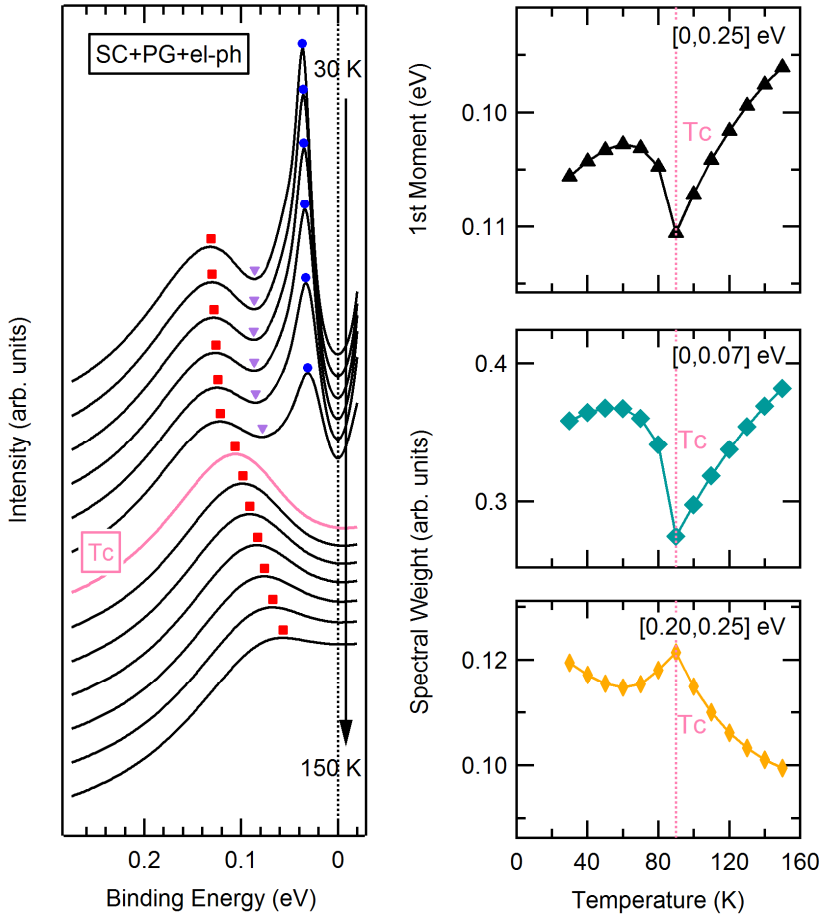
comparison with simulation

experiment



theory



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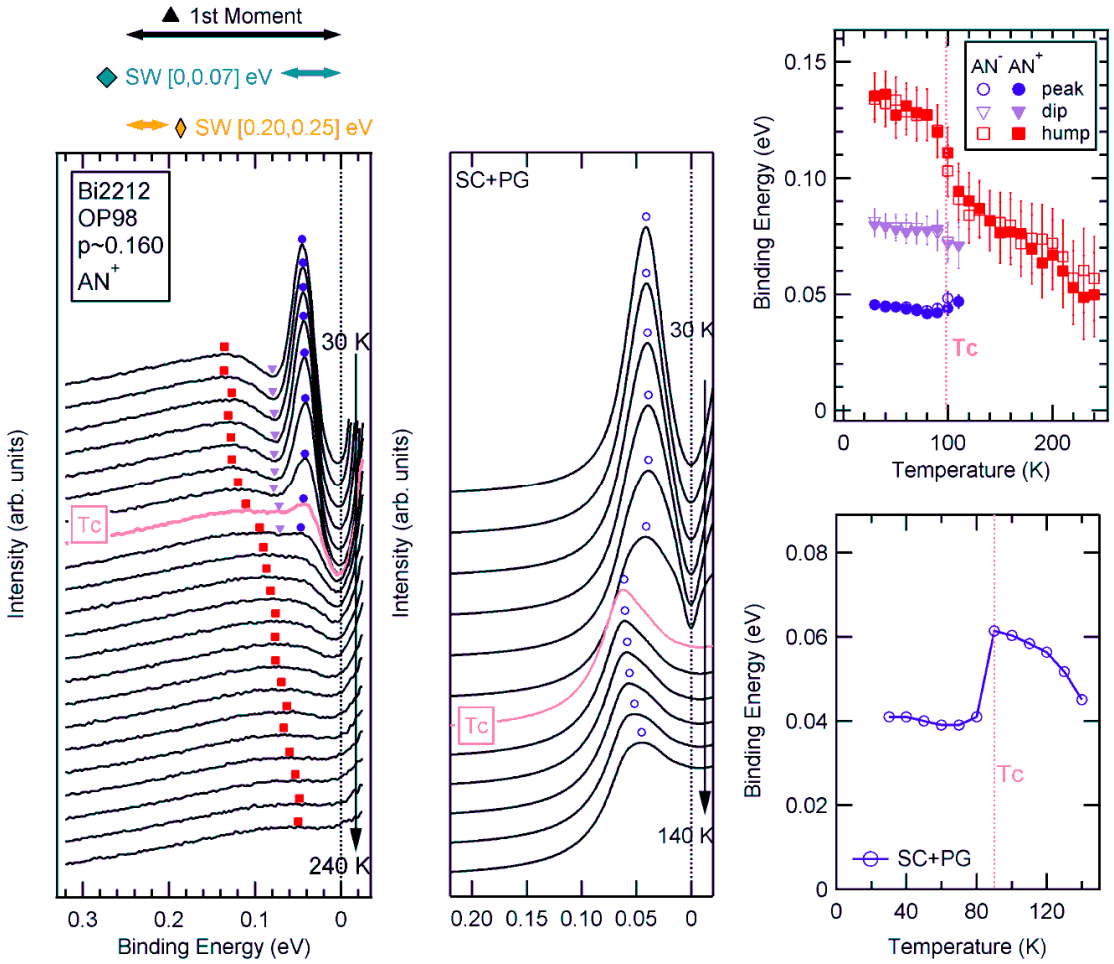
simulation: SC + PG (CDW)



Particularly, dip and hump feature below T_c is hard to explain...

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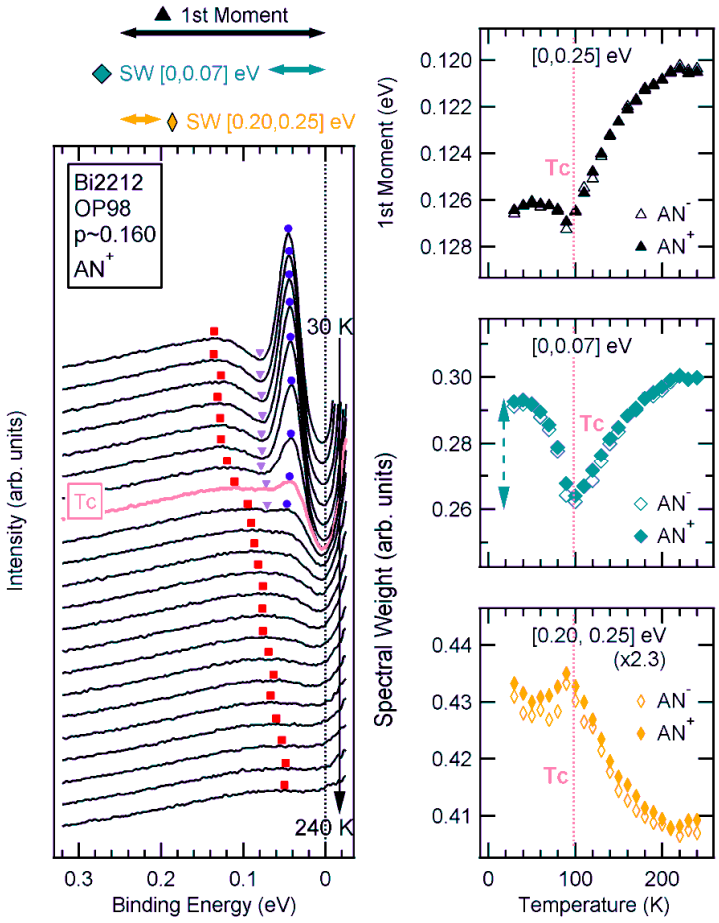
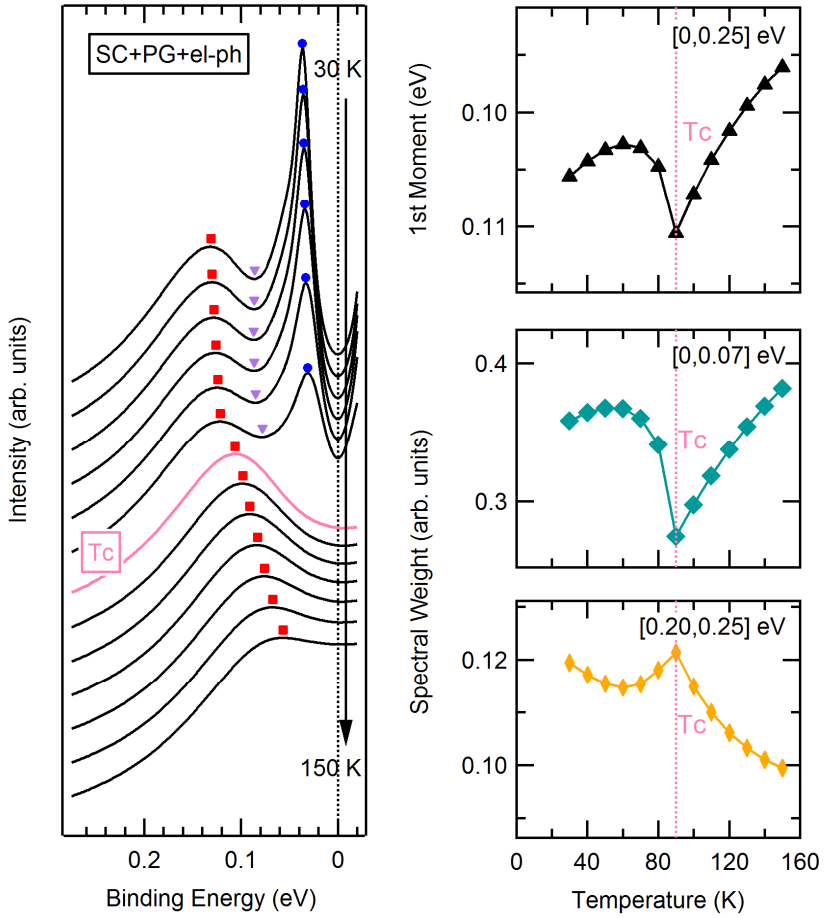
comparison with simulation

experiment



Theory (CDW + SC + el-ph)



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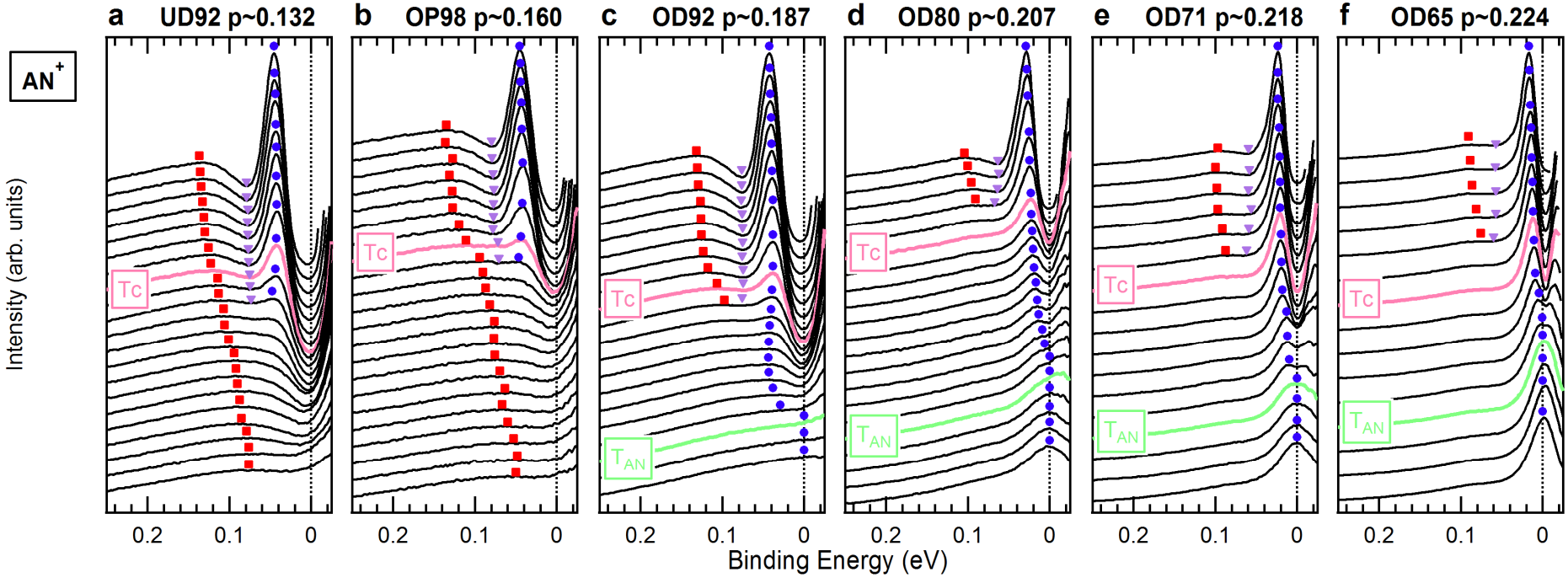
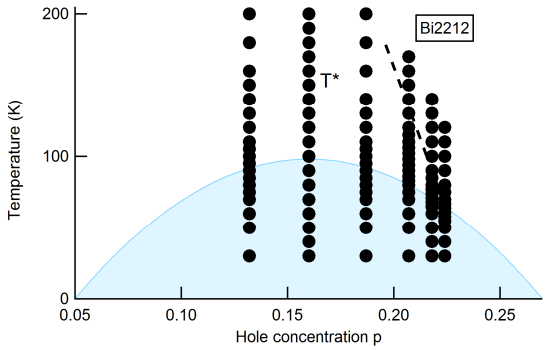
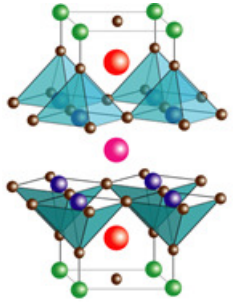
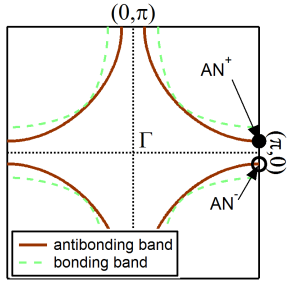
Bi2212 antinodal spectra









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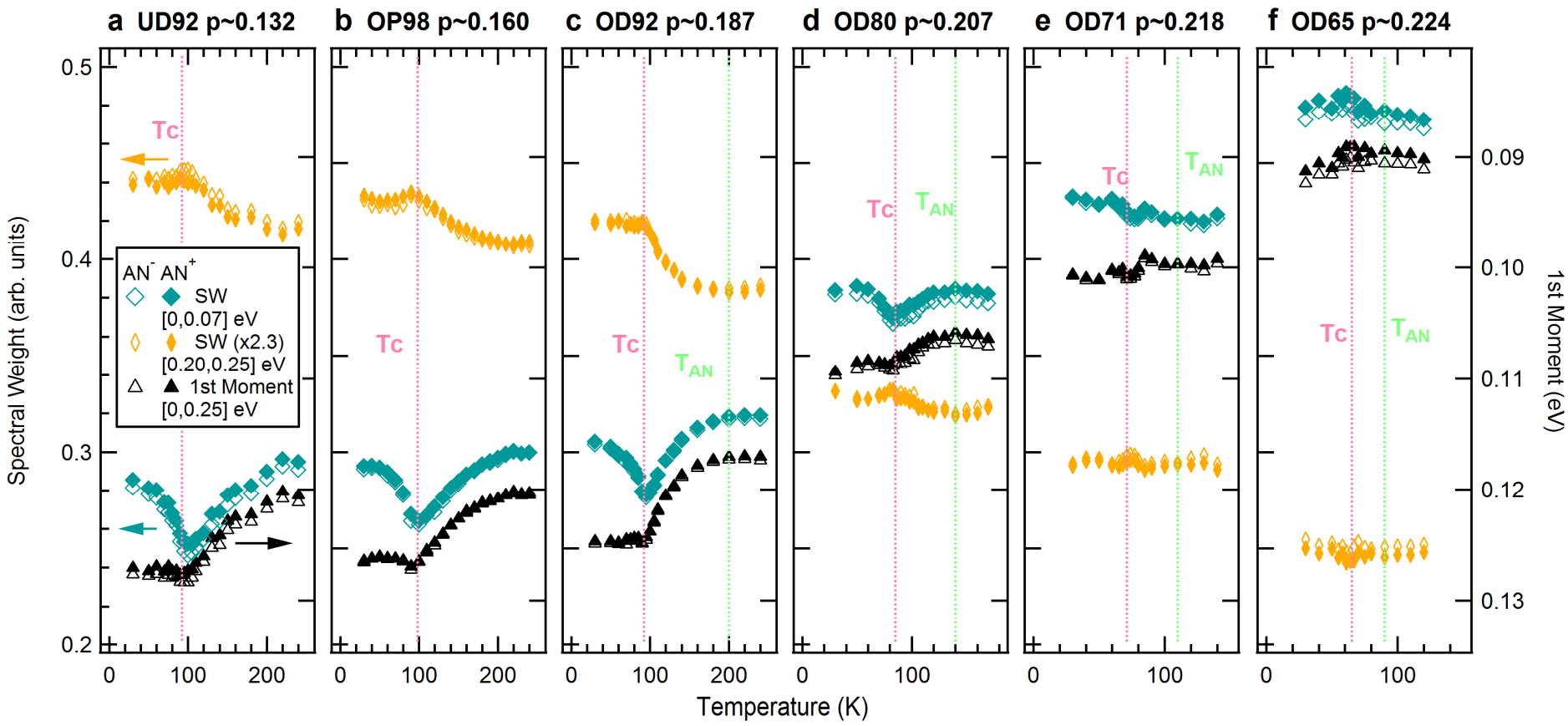
doping dependence of the phase competition



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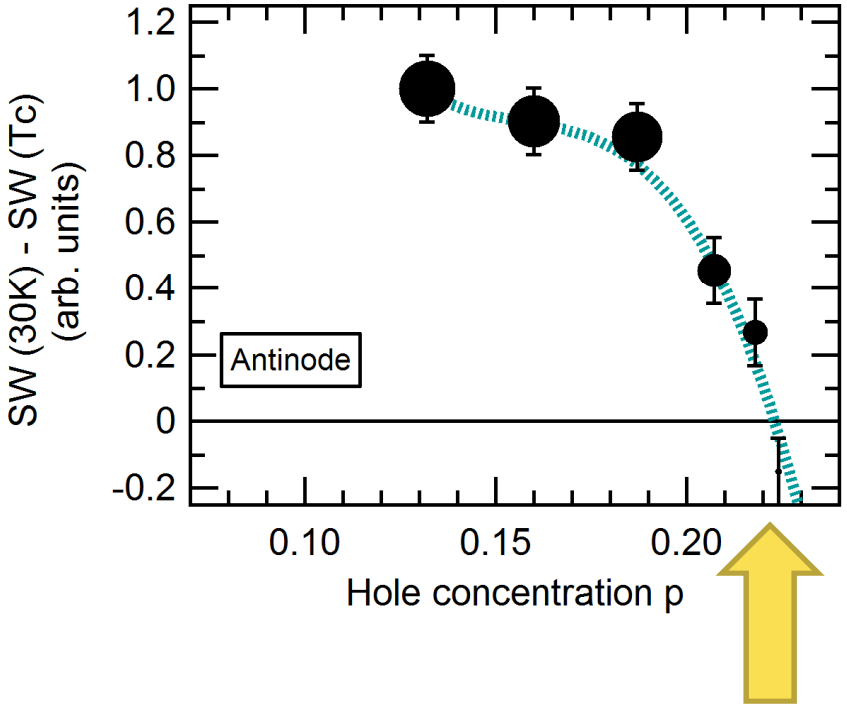
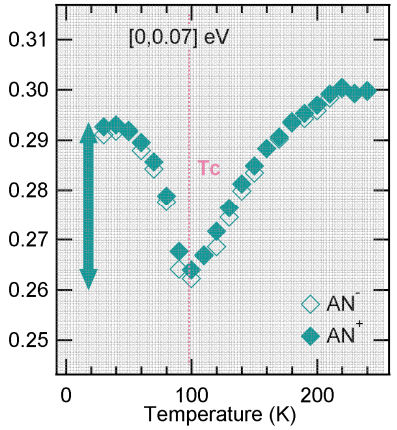
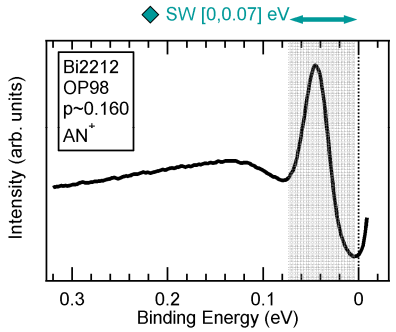
pseudogap critical point ($T \sim T_c$)







Phase competition up to at least p~0.22 at ~T_c

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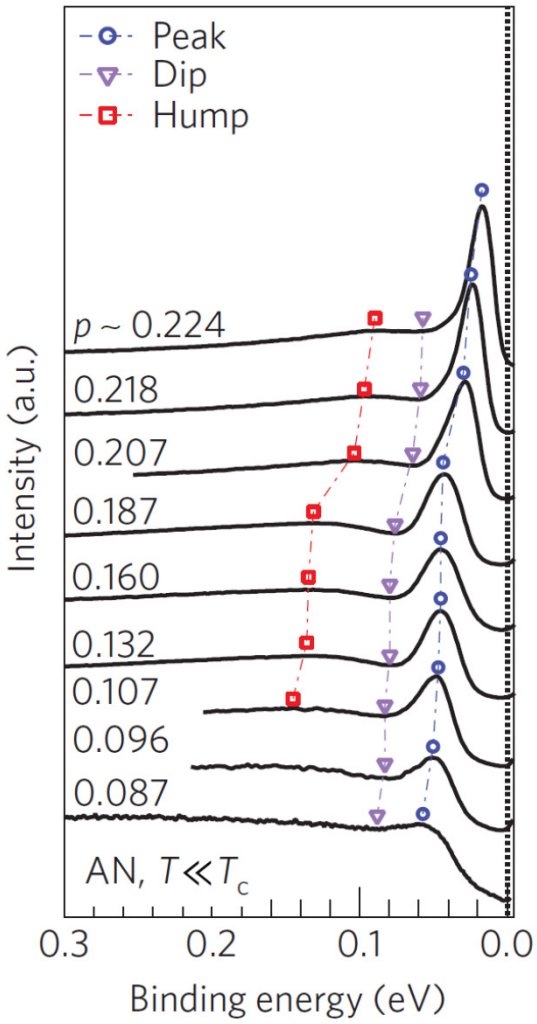
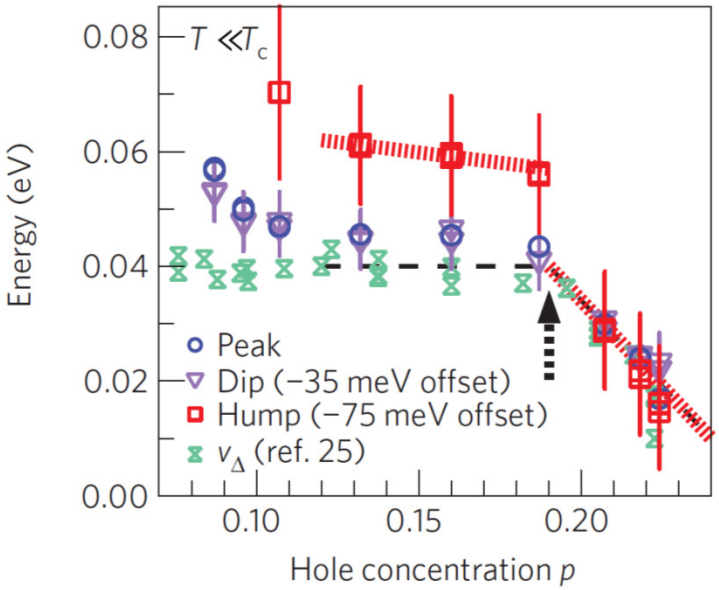
pseudogap critical point (T << Tc)





- T~T_c

Phase competition up to p~0.22

- T<<T_c

Critical point at p~0.19
Hump related with the pseudogap

v_Δ: I. M. Vishik *et al.*, *PNAS* **109**, 18332 (2012)
M. Hashimoto *et al.*, *Nat. Mat. advance online publication*

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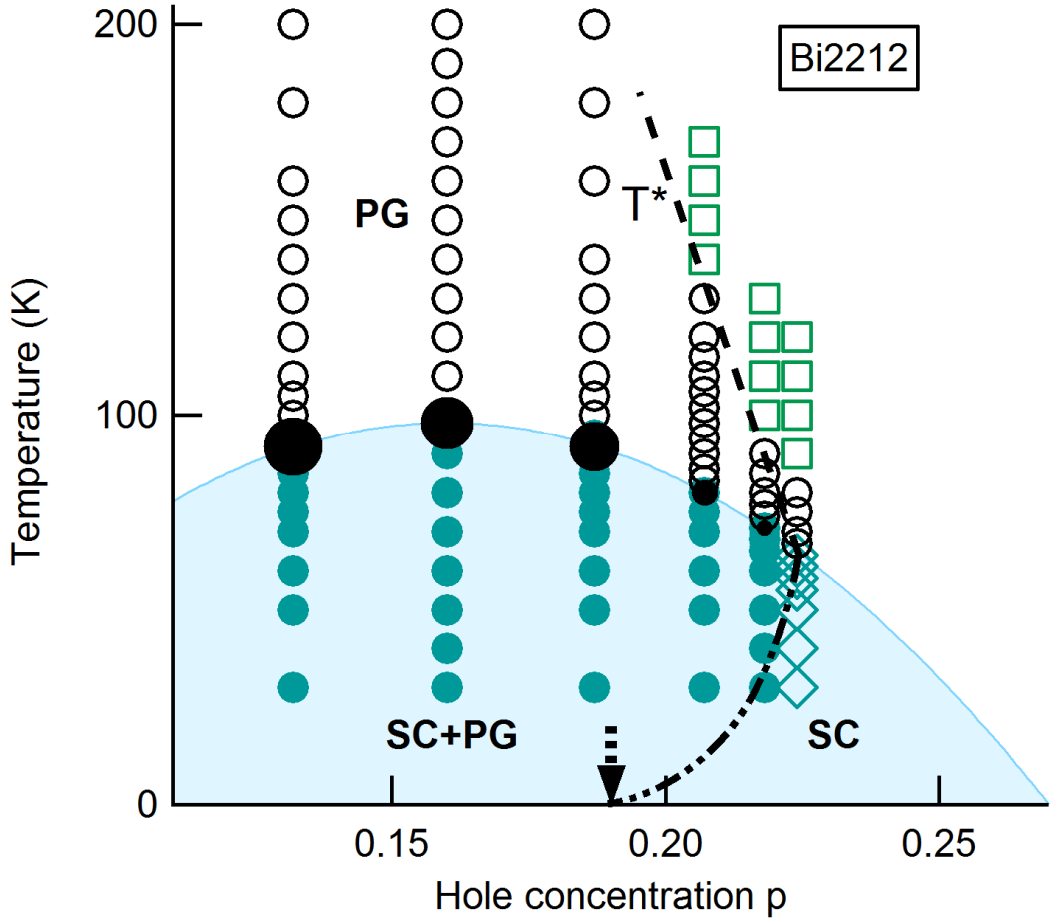
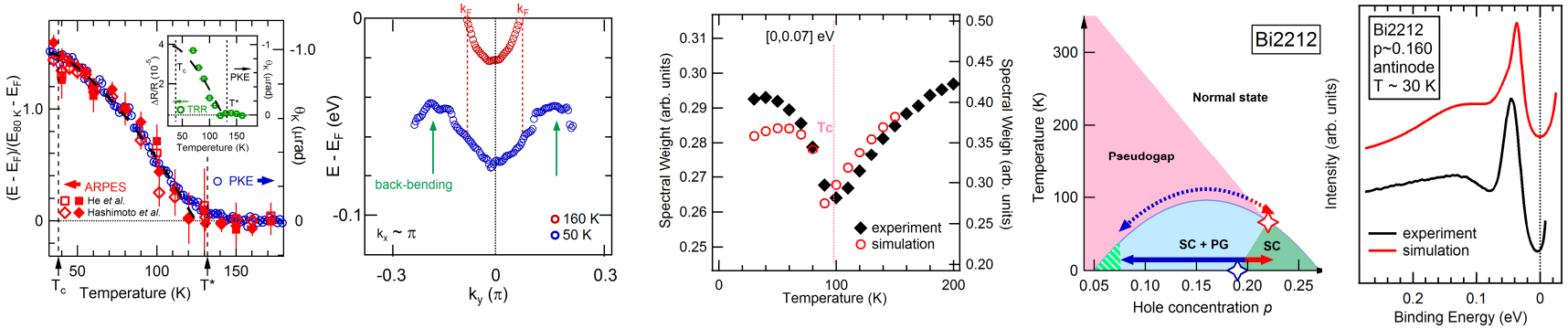
phase diagram



c.f. I. M. Vishik *et al.*, *PNAS* **109**, 18332 (2012)
M. Hashimoto *et al.*, *Nat. Mat. advance online publication*

summary

- Broken symmetry at $T < T^*$ and (rounded) phase transition at T^*
- Competition between the order parameters for SC and PG
- Experiment ≈ Simulation: PG + SC + el-ph



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- ❖ M. Hashimoto, I. M. Vishik, R.-H. He, T. P. Devereaux, Z.-X. Shen, *Nat. Phys.* **10**, 483 (2014)
- ❖ M. Hashimoto *et al.*, *Nat. Mat. advance online publication*

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