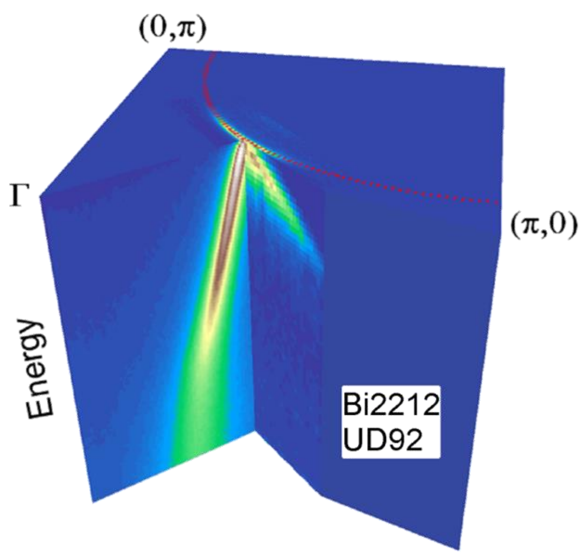
Low energy excitations in cuprates: an ARPES perspective

Inna Vishik

Beyond (Landau) Quasiparticles: New Paradigms for Quantum Fluids

Jan. 15, 2014



Acknowledgements

➢ **Shen Group**

- Professor Zhi-Xun Shen
- Dr. Makoto Hashimoto, Dr. Wei-Sheng Lee, Yu He

➢ **Theory**

- Prof. T. Devereaux (Stanford, SLAC)
- Prof. S. Johnston (UT Knoxville)

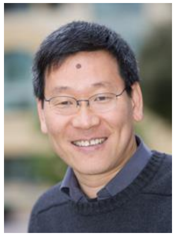
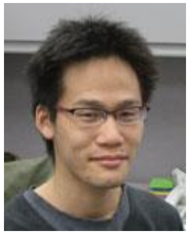
➢ **Bi2212 Samples**

•Prof. T. Sasagawa (Tokyo Institute of Technology)

•Prof. S. Uchida, K. Fujita, S. Ishida (University of Tokyo)

•M. Ishikado (Japan Atomic Energy Agency)

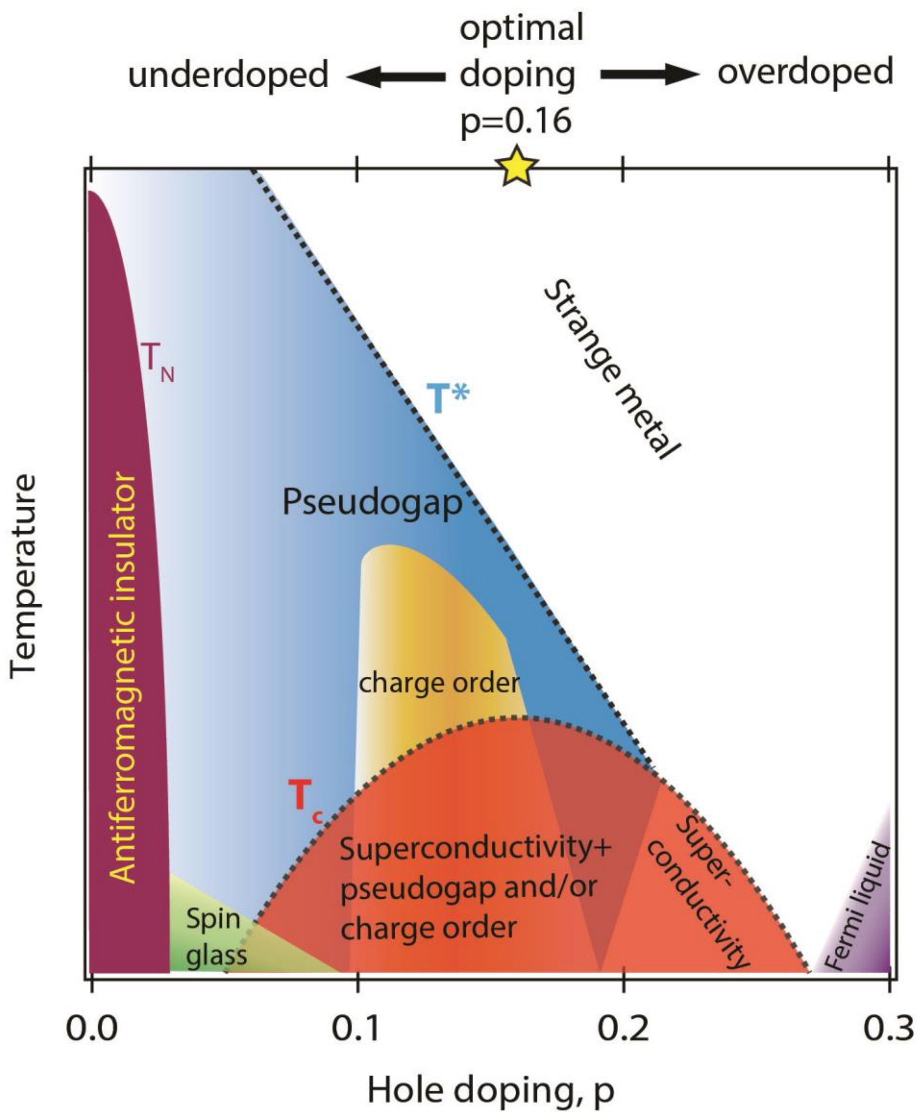
•Y. Yoshida, H. Eisaki (Nanoelectronics Research Institute, AIST)

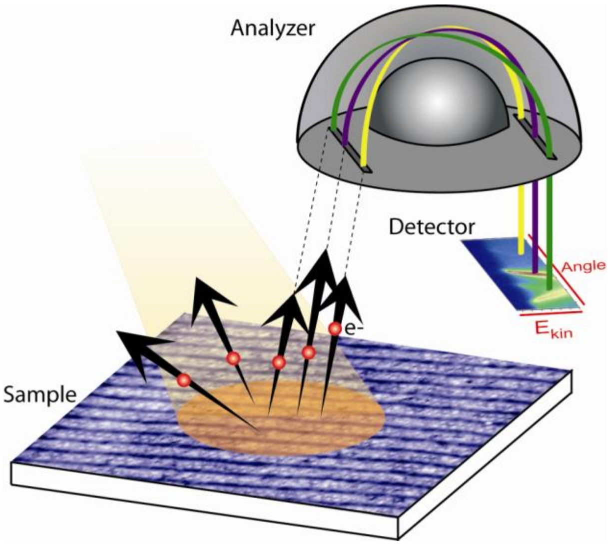


U.S. DEPARTMENT OF ENERGY

A complex phase diagram



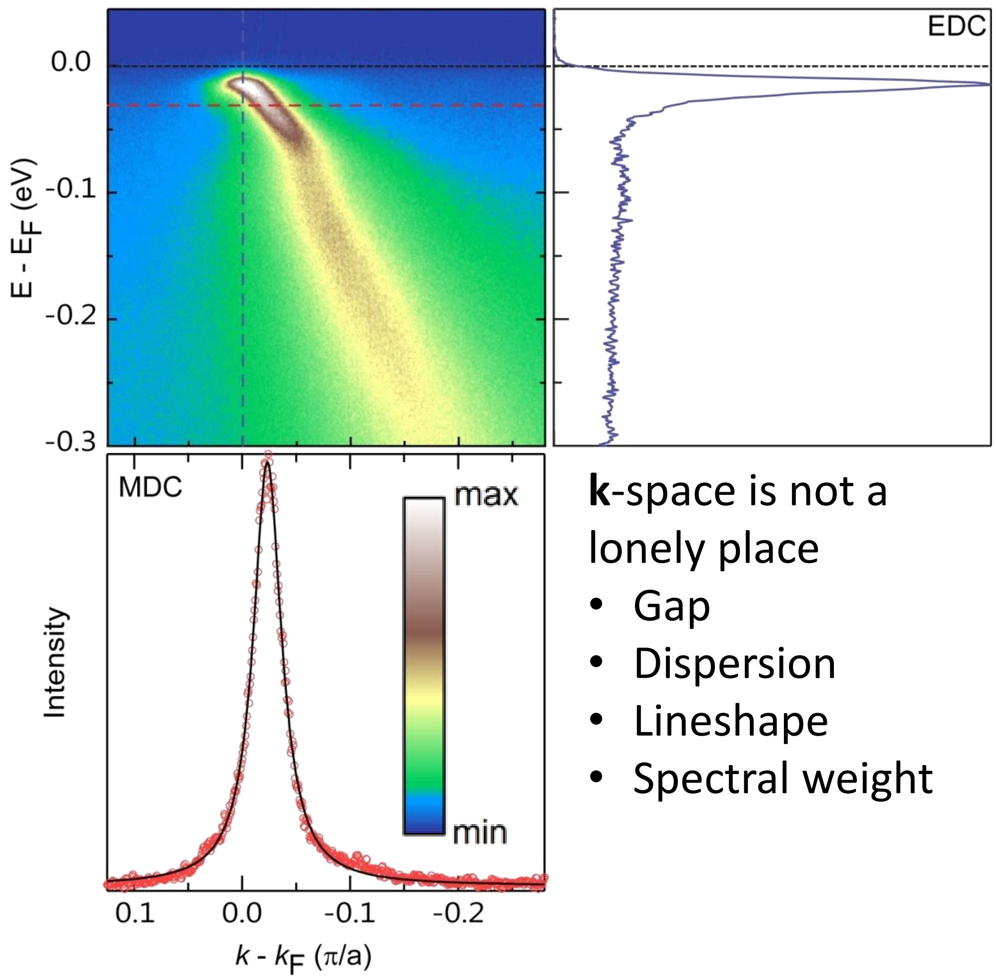
Motivation: phenomenology as starting point for microscopic theory



Angle-resolved photoemission spectroscopy

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

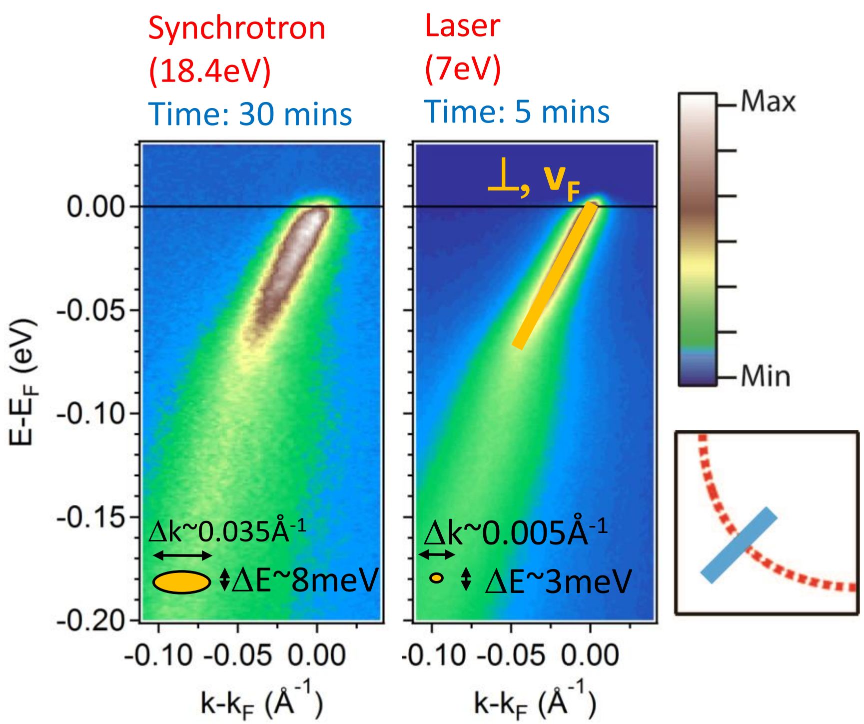
$$\mathbf{p}_{\parallel} = \hbar \mathbf{k}_{\parallel} = \sqrt{2mE_{kin}} \cdot \sin\theta$$

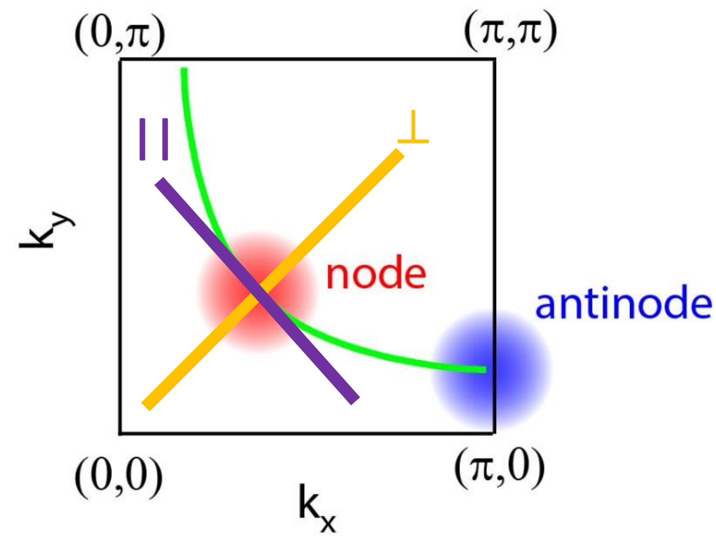


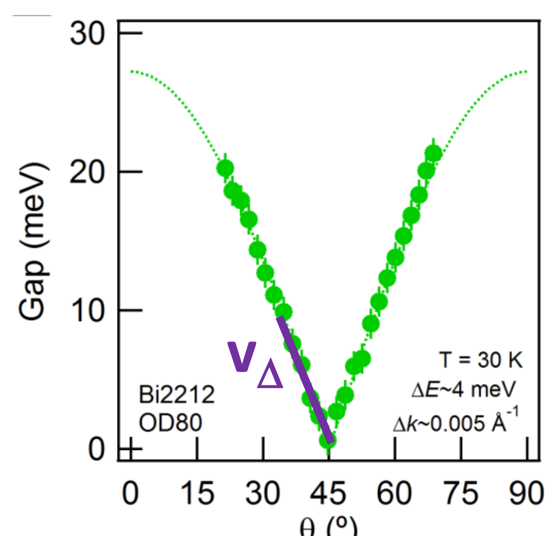
k-space is not a lonely place

- Gap
- Dispersion
- Lineshape
- Spectral weight

Laser ARPES: unprecedented access to low energy excitations



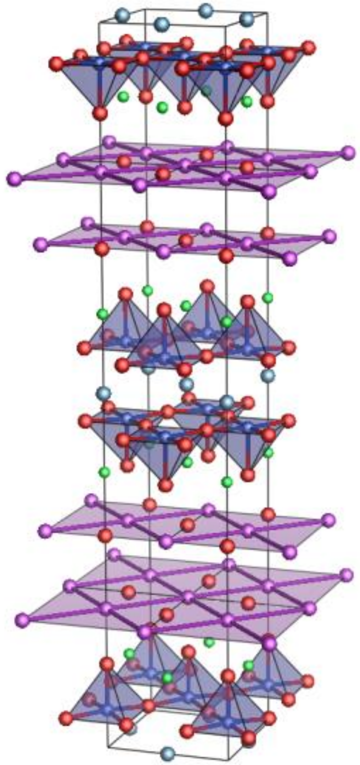




7eV Laser ARPES

- Energy resolution
- Momentum resolution
- Data collection efficiency

Outline



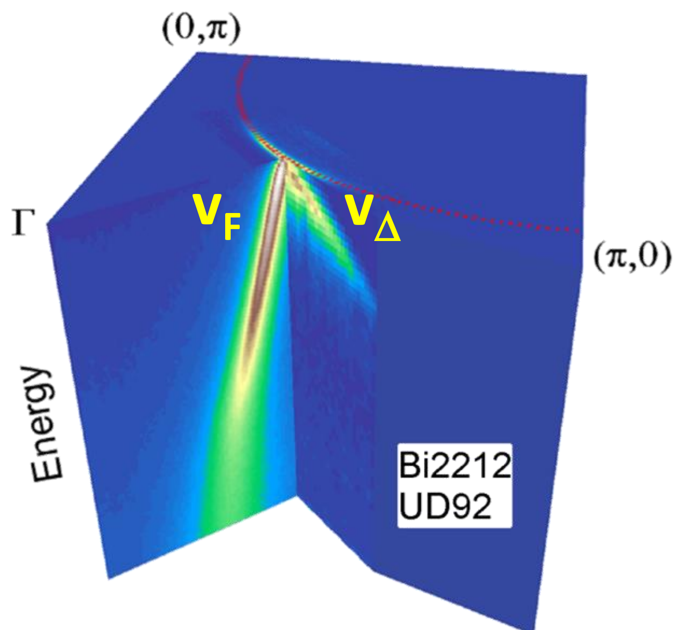
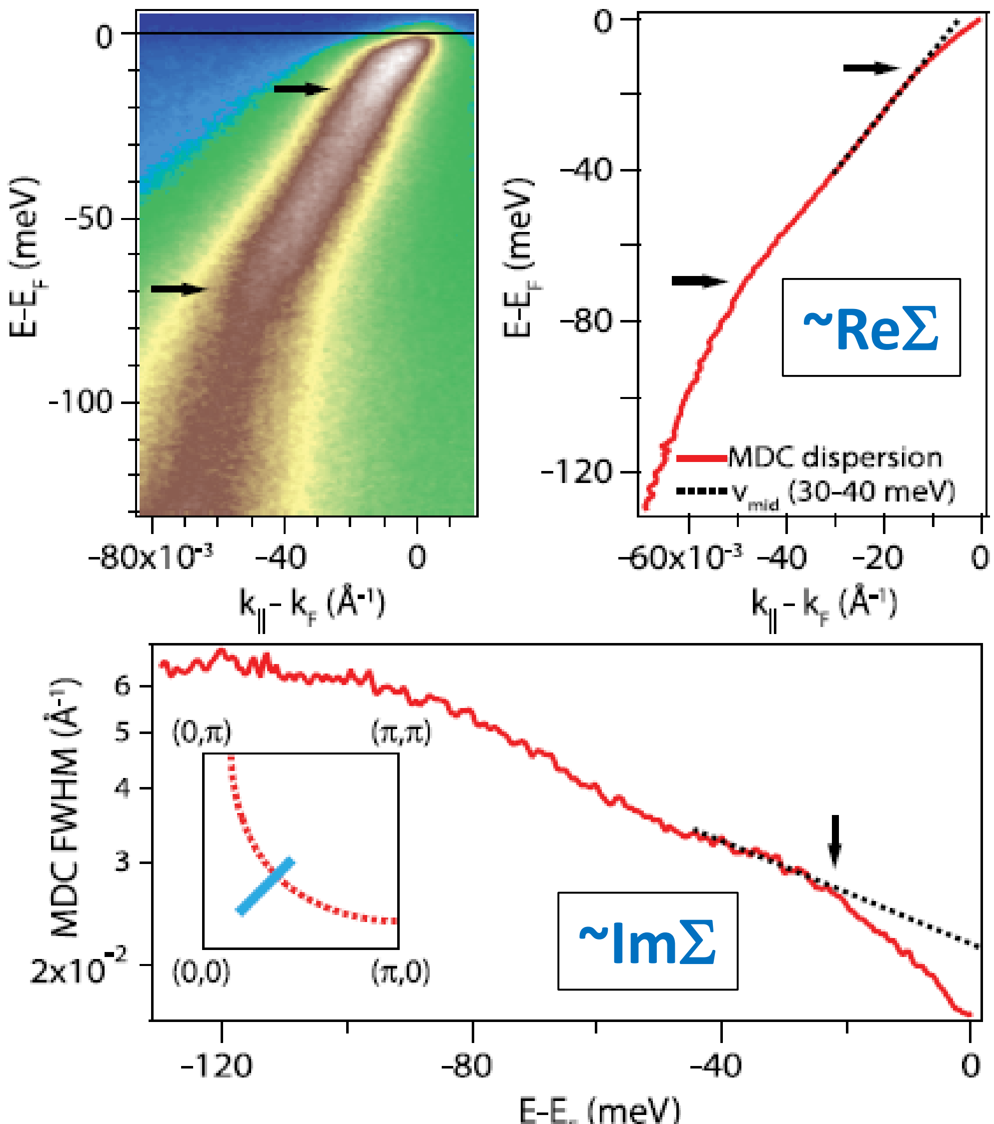


Image: B. Moritz

1. Low energy kink, v_F→Connection to bulk probes
2. Trisected superconducting dome→Fingerprints of quantum phases which coexist with superconductivity

First laser ARPES discovery: low energy (ω~10 meV) kink



Shen group and collaborators

- **Expt: Vishik *et al.* PRL 104, 207002 (2010)**
- **Theory+ Expt: S. Johnston , I. M. Vishik *et al.* PRL 108 166404 (2012)**

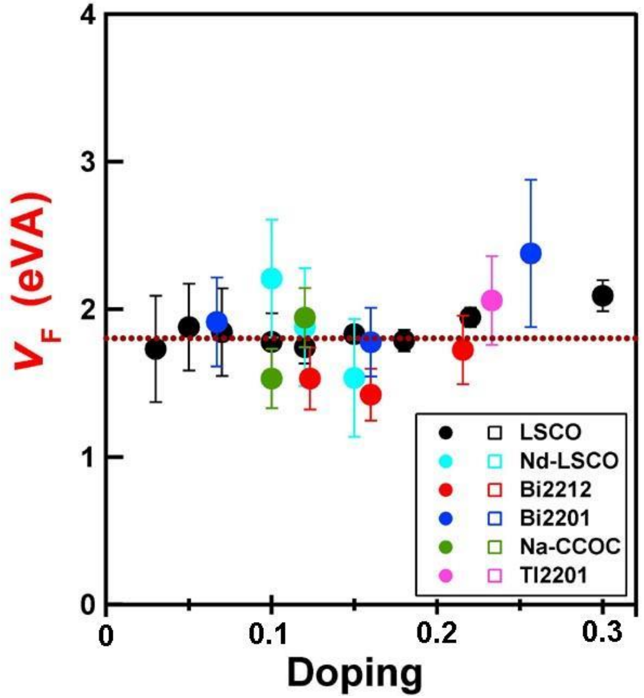
Other groups:

- Rameau *et al.* Phys. Rev. B **80** (2009)
- Plumb *et al*. Phys. Rev. Lett. **105** (2010)
- Anzai *et al.* Phys. Rev. Lett. **105** (2010)
- Kondo *et al.* Phys. Rev. Lett. **110** (2013)

- Present in ReΣ and ImΣ
- Observed in underdoped Bi-2212 and Bi-2201
- Kink gets stronger with underdoping

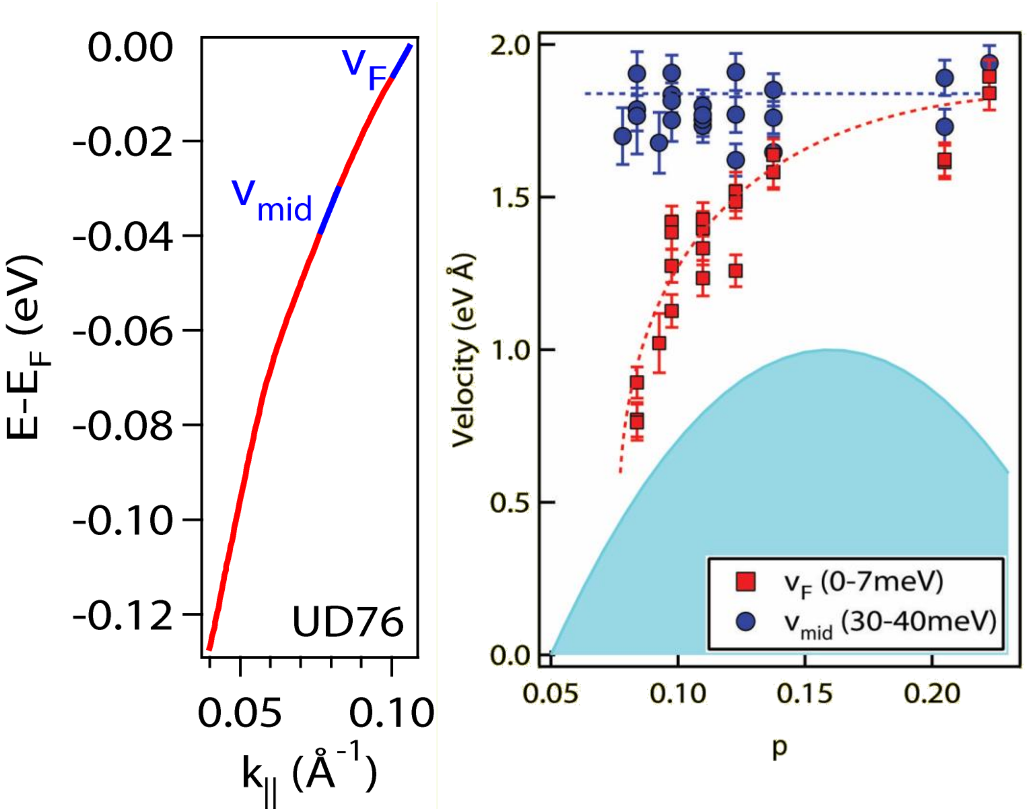
Consequence: doping *dependent* v_F

ΔE=20meV:
Universal nodal v_F



X. J. Zhou,, *et al.*, Nature **423**, 398 (2003)

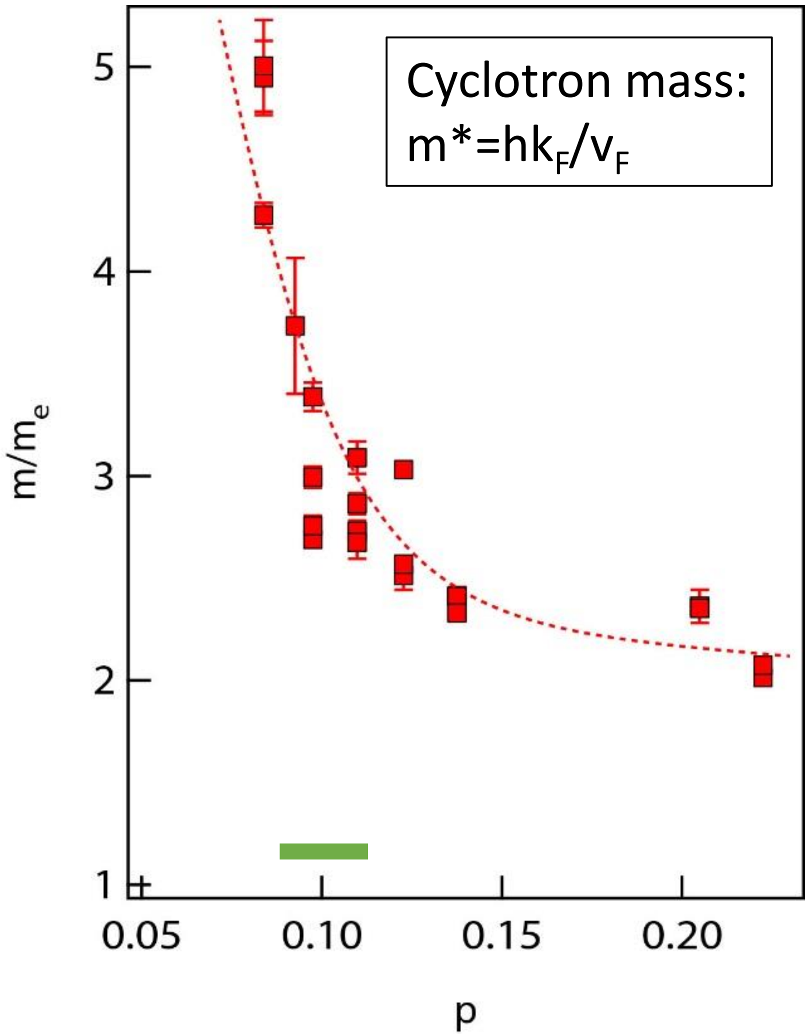
ΔE=3meV:
doping dependent v_F



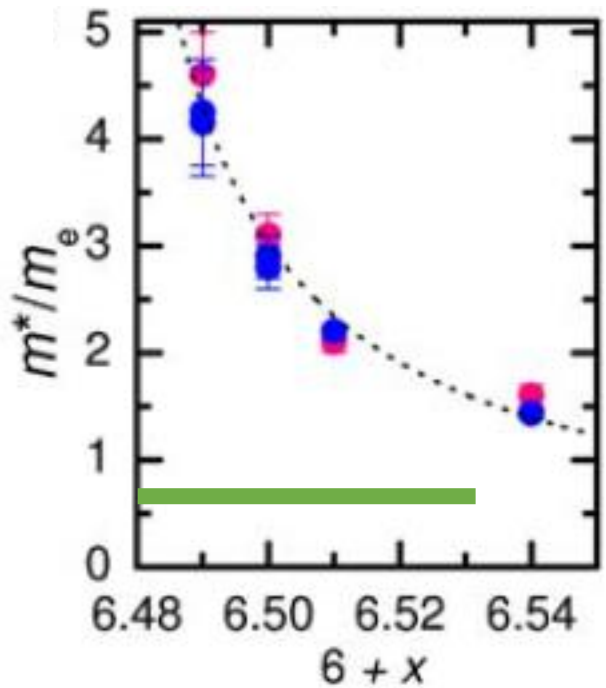
Vishik *et al.* PRL 105 **104**, 207002 (2010)

Diverging m*

ARPES: Bi2212



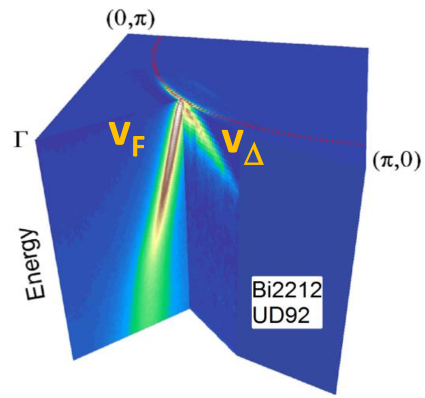
Quantum Oscillations: YBCO



Sebastian *et al.* PNAS **107** 6175 (2010)

Thermodynamics in cuprates

Thermodynamics at T=0, determined by v_F and v_Δ

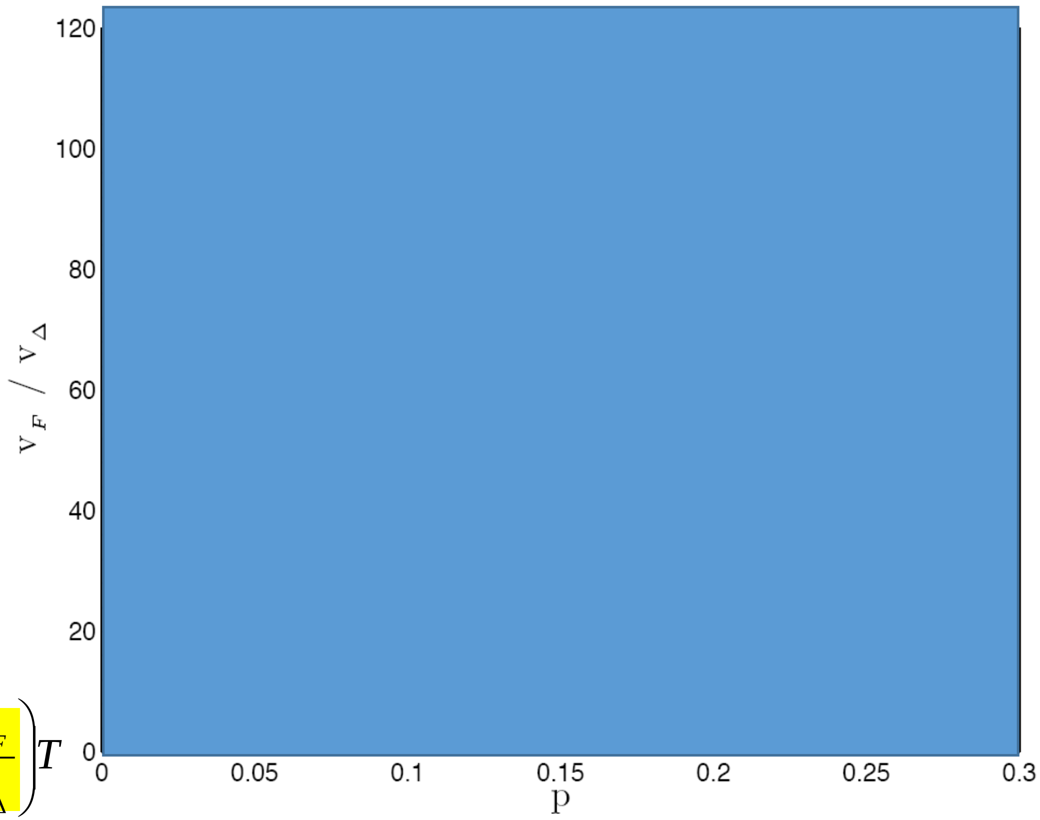


DOS: $$N(E) = \frac{2}{\pi\hbar^2}\frac{1}{v_F v_\Delta}E$$

Superfluid Density: $$\frac{\rho_s(T)}{m} = \frac{\rho_s(0)}{m} - \frac{2\ln 2}{\pi}\frac{k_B}{\hbar^2}\frac{n}{d}\alpha^2\left(\frac{v_F}{v_\Delta}\right)T$$

Electronic Specific Heat: $$C_{el}(T) \propto \frac{n}{d}\left(\frac{1}{v_F v_\Delta}\right)T^2$$

Thermal conductivity: $$\frac{\kappa_0}{T} = \frac{k_B^2}{3\hbar}\frac{n}{d}\left(\frac{v_F}{v_\Delta} + \frac{v_\Delta}{v_F}\right) \approx \frac{k_B^2}{3\hbar}\frac{n}{d}\frac{v_F}{v_\Delta}$$

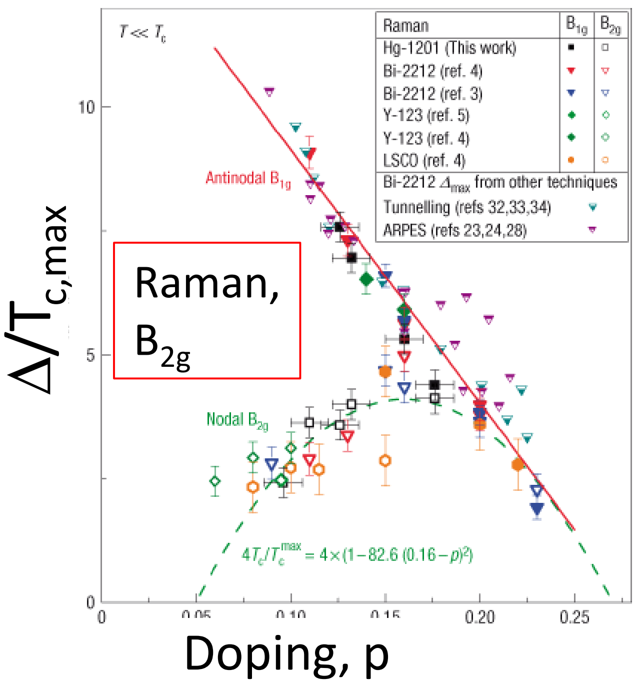


$YBa_2Cu_3O_7$ (YBCO): Taillefer Group, To be published

Quantitative agreement between bulk thermodynamic probe and surface spectroscopy

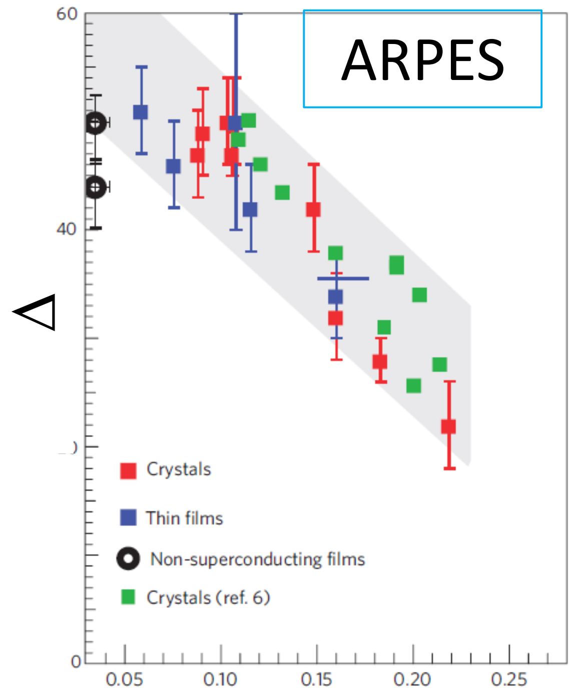
Recent Disputes about doping dependence of near-nodal superconducting gap

$\Delta \propto T_c$



M. Le Tacon, *et al.* Nat. Phys. **2**, 537 (2006)

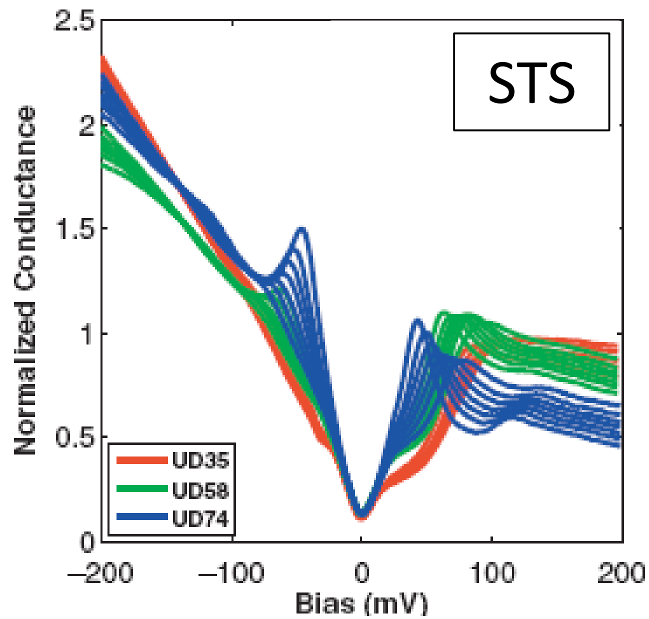
$\Delta \propto T^*$



Doping, p

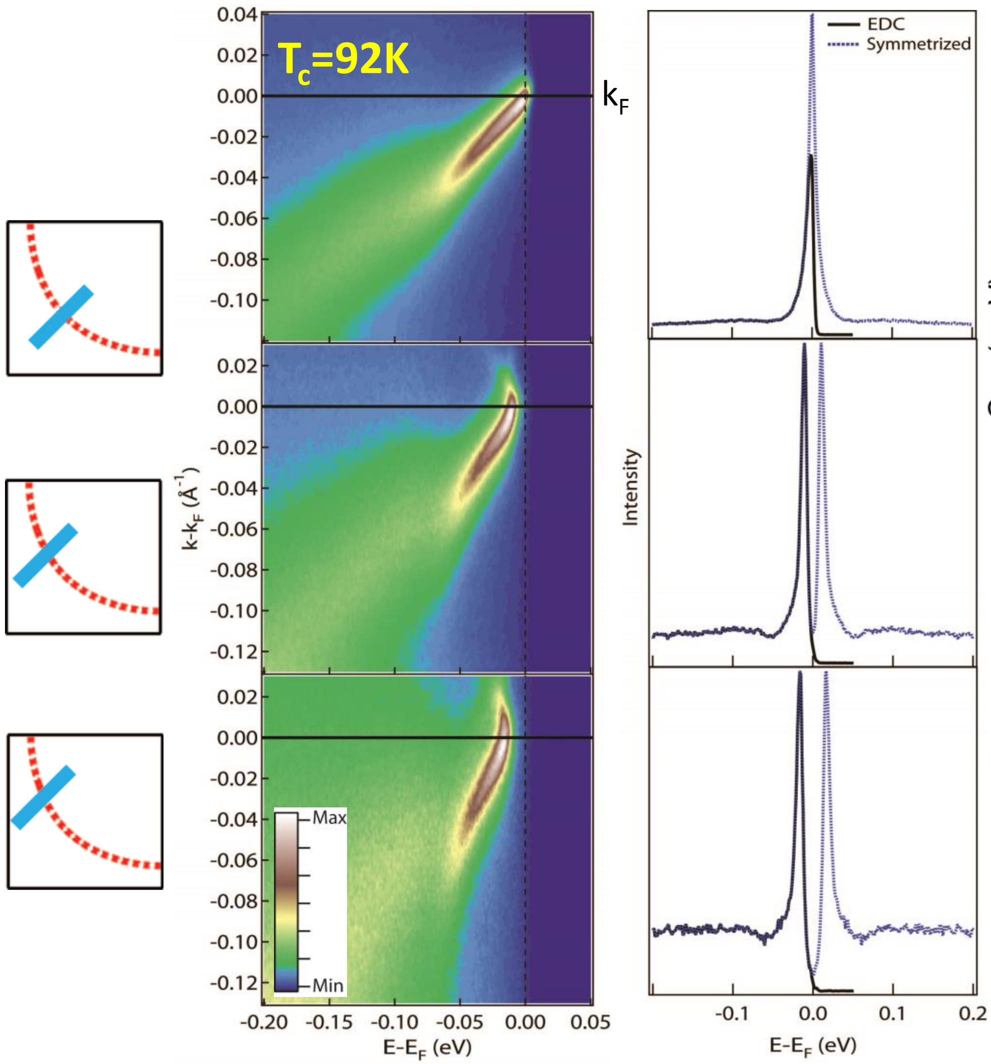
Chaterjee *et al.* Nat. Phys. **6**, 99 (2009)

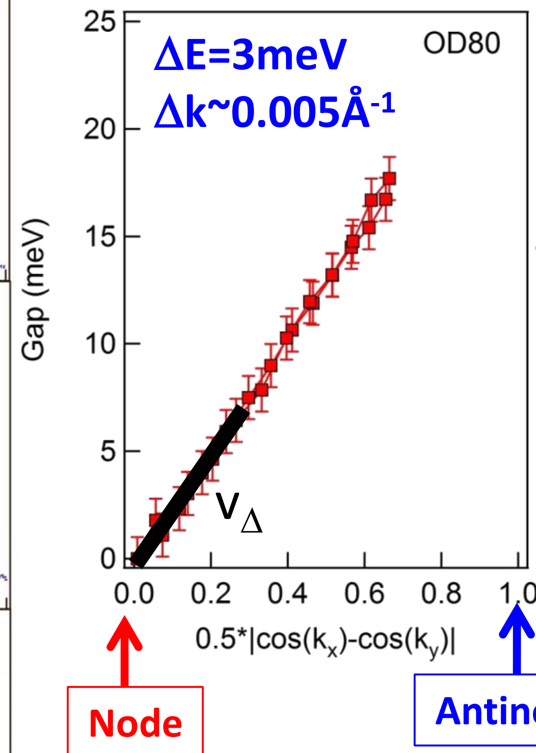
$\Delta = const$

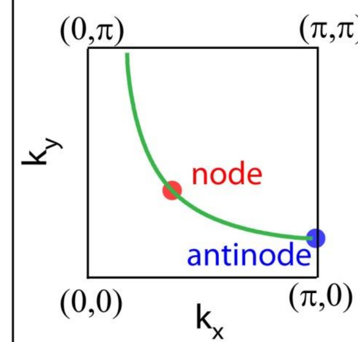


Pushp *et al. Science* **324,** 1689 (2009)

Gap measurements, extracting v_Δ







Expected for *d*-wave superconductor:

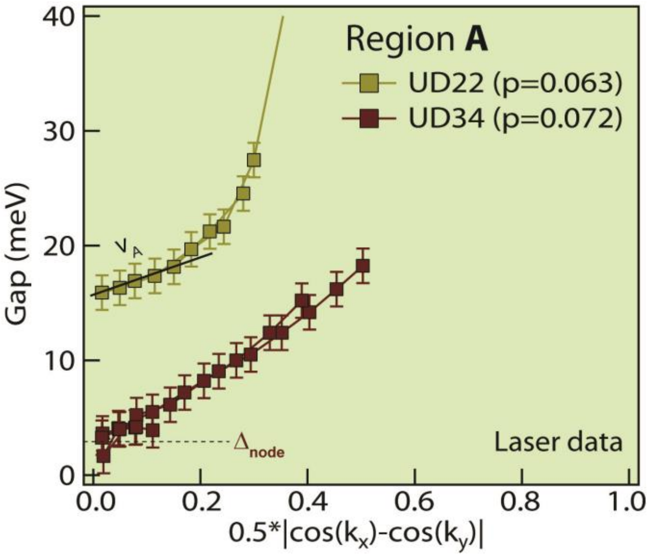
$$v_\Delta \propto T_c$$

Norman model: $\Sigma(\mathbf{k},\omega) = -i\Gamma_1 + \Delta^2 / [(\omega + i0^+) + \varepsilon(\mathbf{k})]$

Norman *et al.* Phys. Rev. B **57**, R11093 (1998)

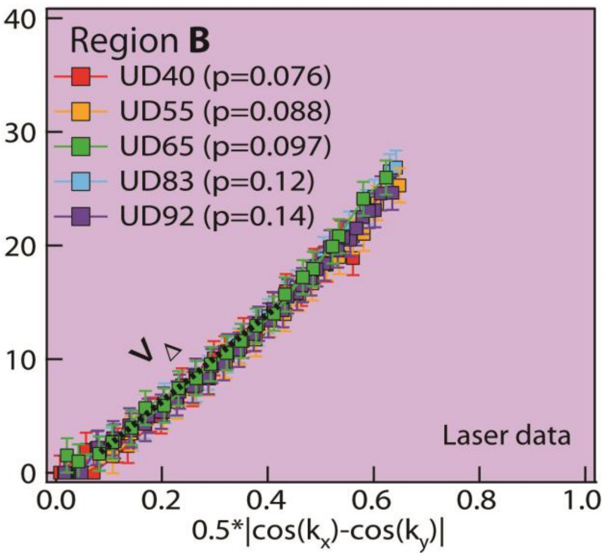
Bi-2212, T=10K: three phase regions in superconducting dome

p<0.076



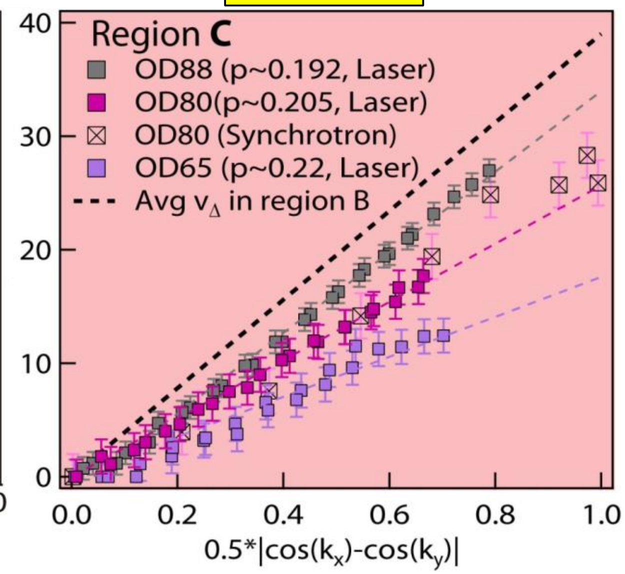
Fully gapped Fermi surface

0.076<p<0.19



Doping-independent v_Δ

p>0.19

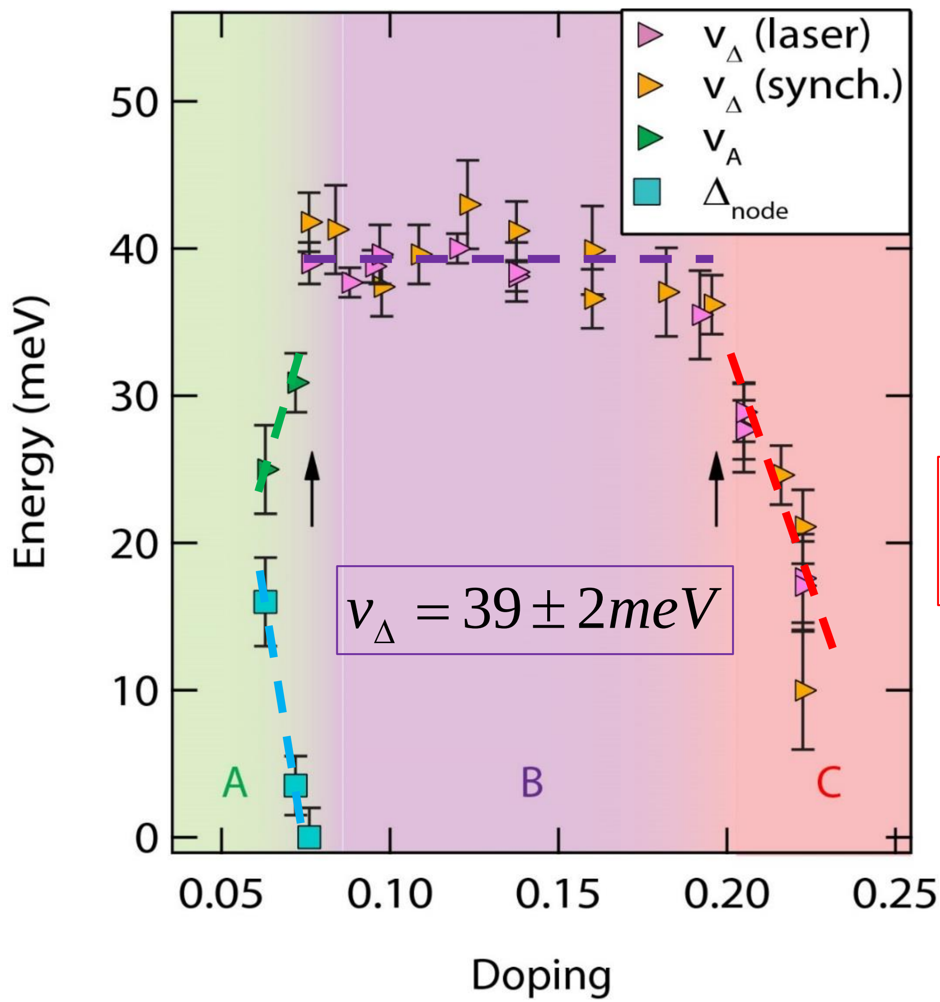


$v_\Delta \propto T_c$

Vishik *et al.* PNAS **109** 18332-18337 (2012)

ARPES: three phase regions (10K)

- Δ_{node} grows with underdoping
- v_A decreases with underdoping



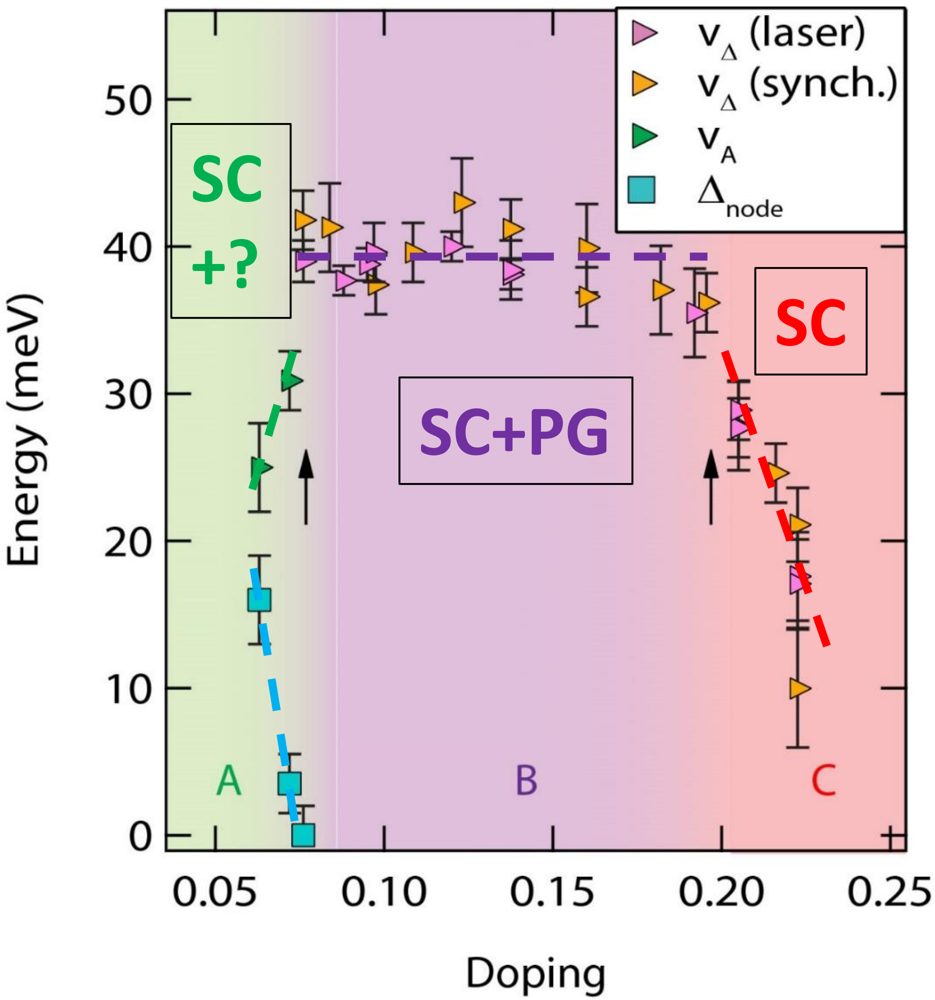
$$\frac{\Delta}{k_B T_c} = 3.7 \pm 0.4$$

I. M. Vishik *et al.* PNAS **109** (45) 18332 (2012)

Trisected superconducting dome: interpretations

?=:

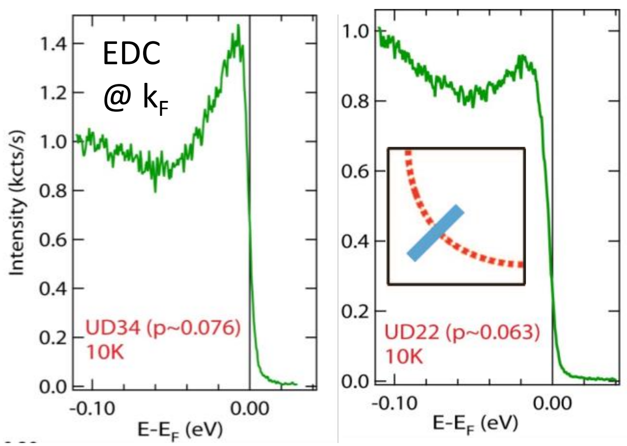
- Spin glass
- SDW
- Coulomb gap
- Lifshitz transition
- $d_{x2-y2}+id_{xy}$ SC+ SDW (A. Gupta *et al.* arXiv:**1401.0617v1**)
- Topological SC (Y.-M. Lu *et al.*, arXiv:**1311.5892v1**)
- Fulde-Ferrell-Larkin-Ovchinnikov (T. Das, arXiv:**1312.0544v1**)

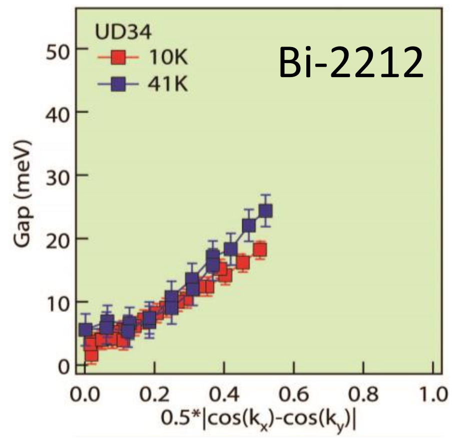


I. M. Vishik *et al.* PNAS **109** (45) 18332 (2012)

Phase region A: summary of ARPES data

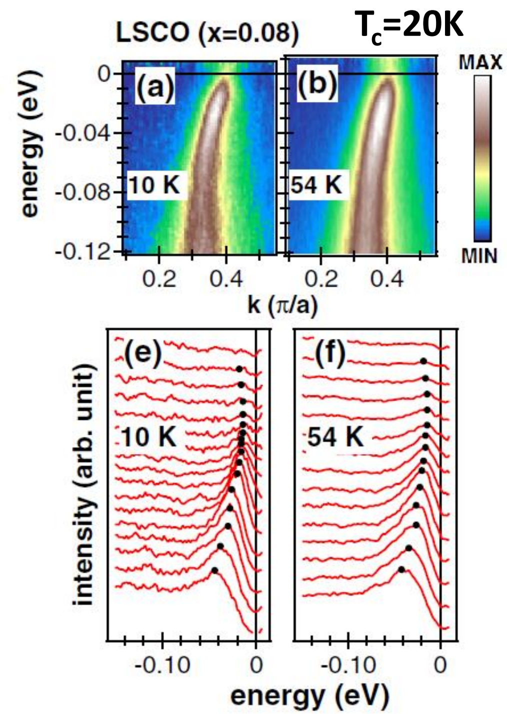
Bi-2212





- ➢ Energy well-defined from EDC
- ➢ Gap persists $T>T_c$

Vishik *et al.* PNAS **109** 18332-18337 (2012)



- ➢ No comment: DOS at E_F, e-h symmetry

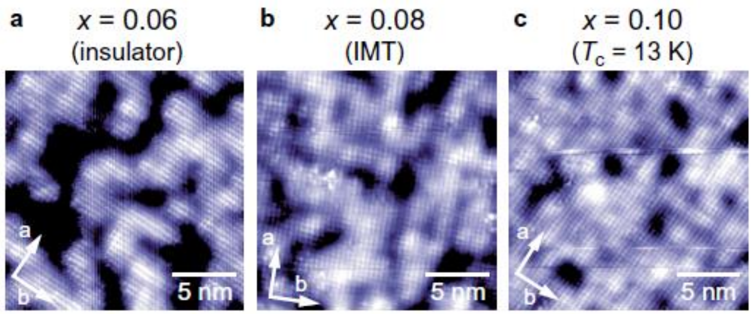
•$Ca_{2-x}Na_xCuO_2Cl_2$: K. M. Shen *et al. PRB (2004)*

•$La_{2-x}Sr_xCuO_4$ (LSCO): E Razzoli *et al. PRL* (2013)

- ➢ Observed in other cuprates at SC dopings

Phase region A: summary of other experiments

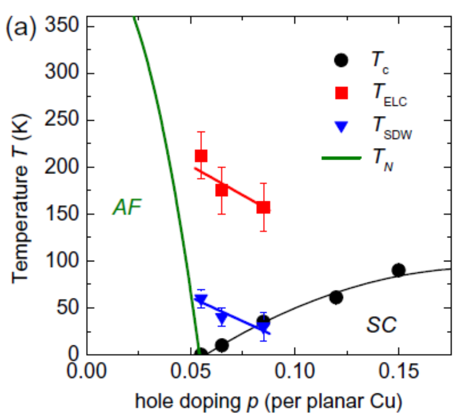
Na-CCOC



Kohsaka *et al.* PRL **93** (2004)

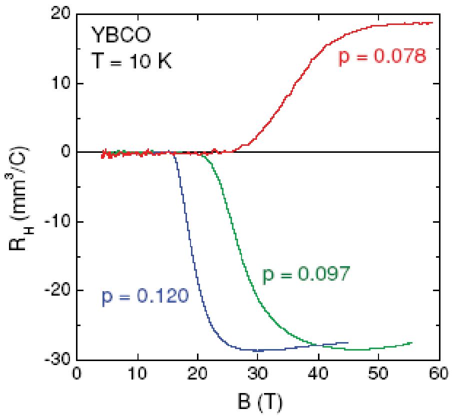
➢ STS: Percolation of conductive patches

➢ Neutron: spin correlations near (π,π)



Haug *et al.* NJP (2010)

➢ Transport: change in Fermi surface

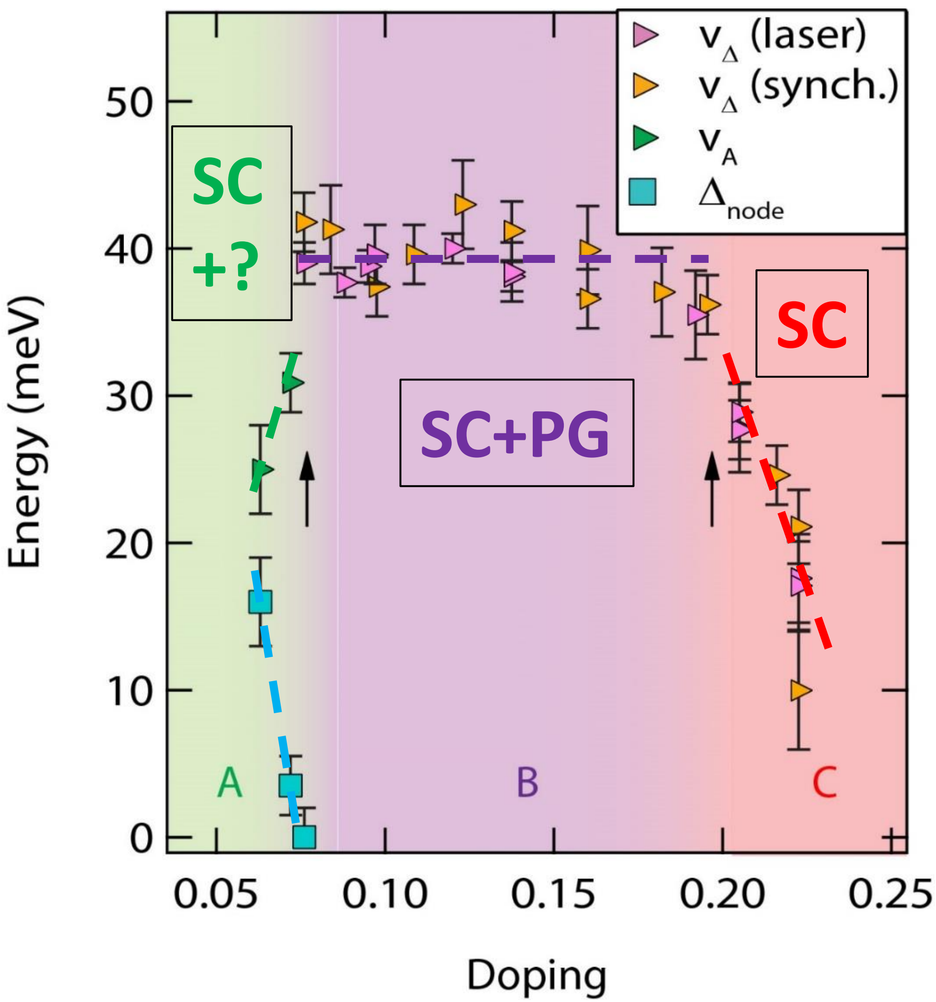


LeBoeuf *et al.* PRB (2011)

➢ ARPES (Bi-2212) and quantum oscillations (YBCO): diverging m*

- Sebastian *et al.* PNAS **107** 6175 (2010)
- Vishik *et al.* PRL **104** (2010)

Phase region B



Why?

•Expected behavior for *d*-wave superconductor in region C

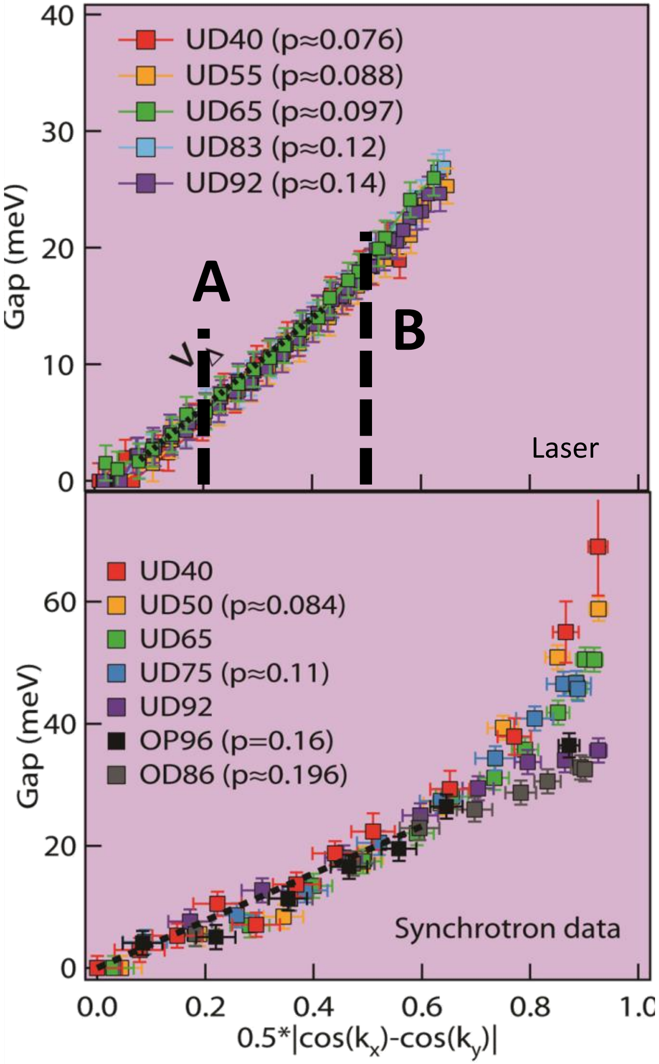
•ARPES data: Superconductivity/pseudogap coexistence

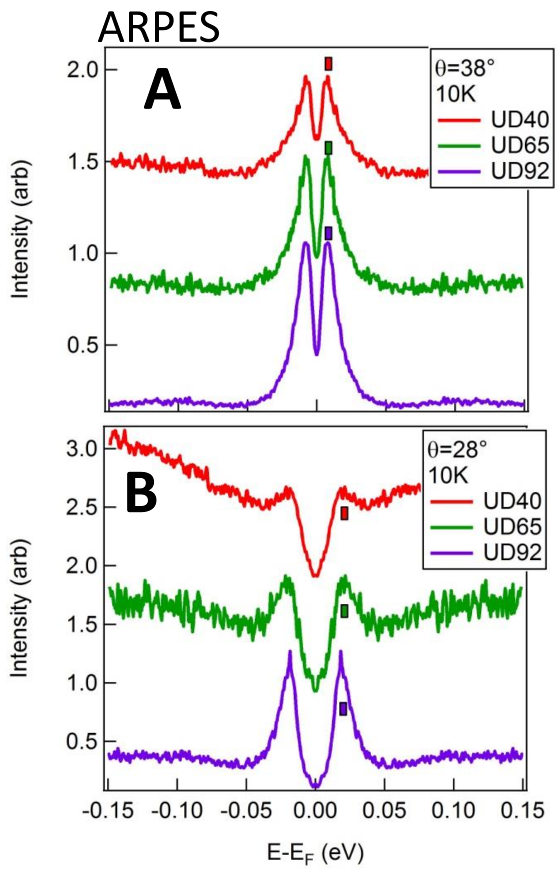
•Other experiments (London penetration depth, STM)

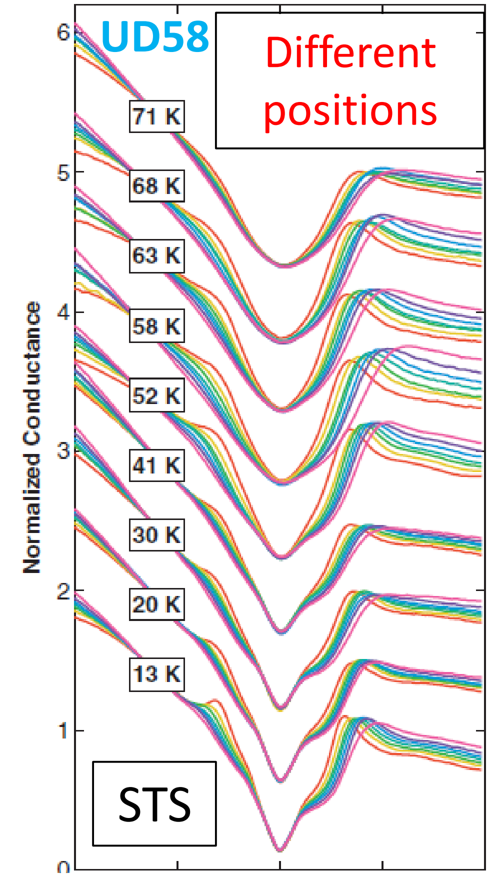
Open question:
Why is v_Δ doping-independent?

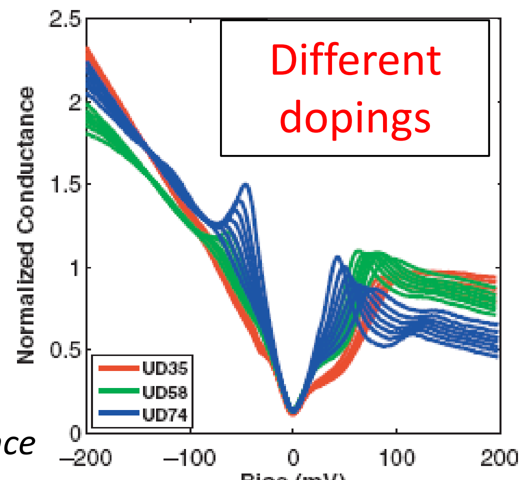
I. M. Vishik *et al.* PNAS **109** (45) 18332 (2012)

Phase region B: raw data





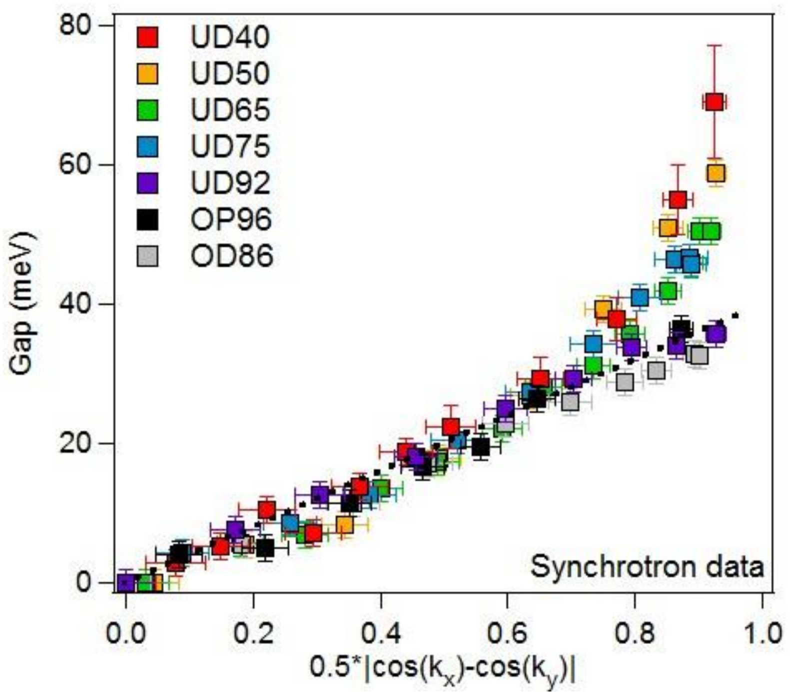




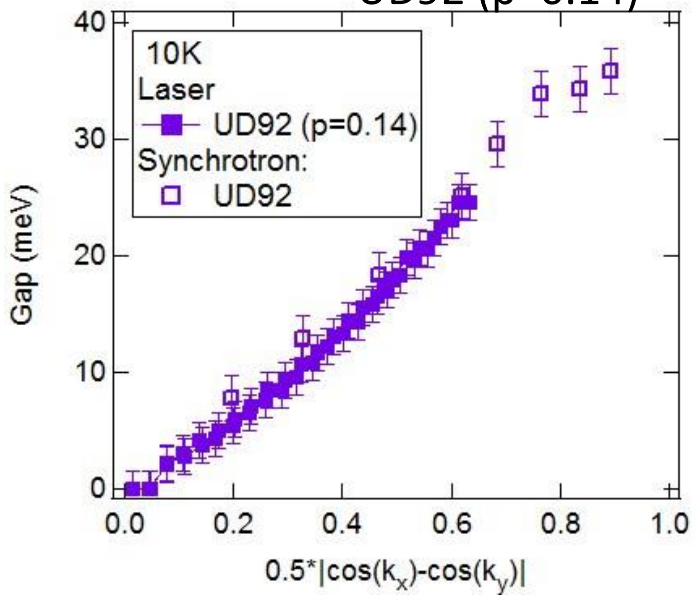
Pushp *et al. Science* **324,** 1689 (2009)

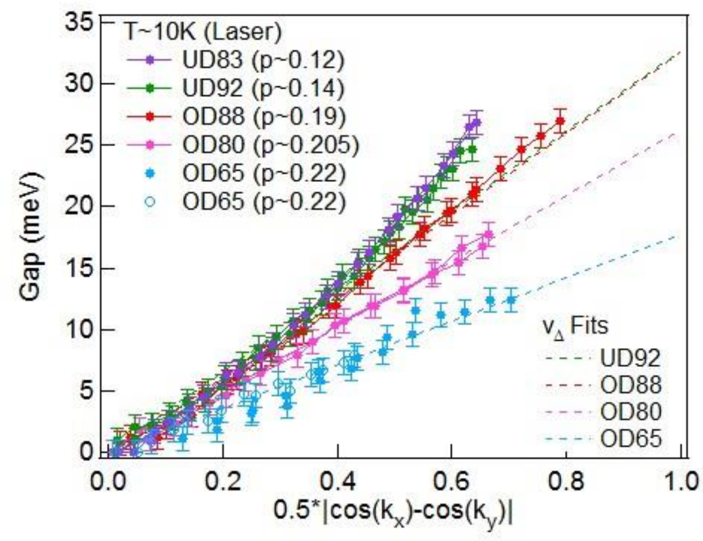
Manifestations of pseudogap below T_c: ARPES

Deviation from simple *d*-wave form becomes more pronounced with underdoping



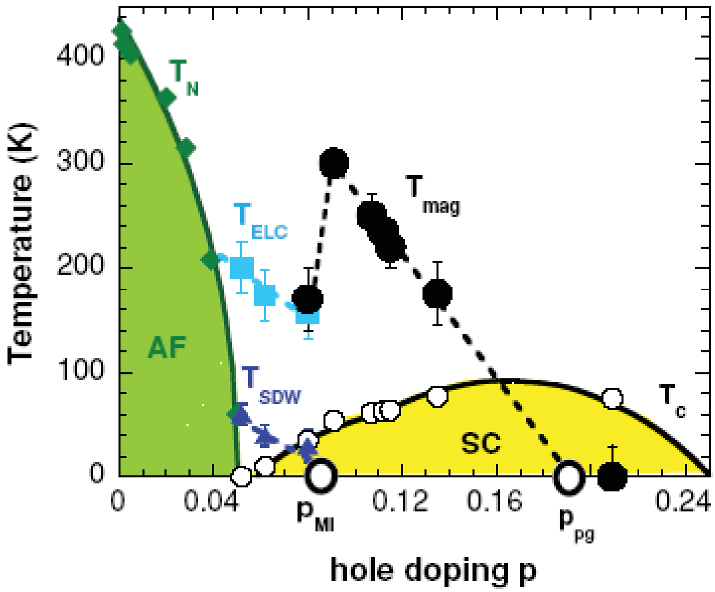
UD92 (p~0.14)





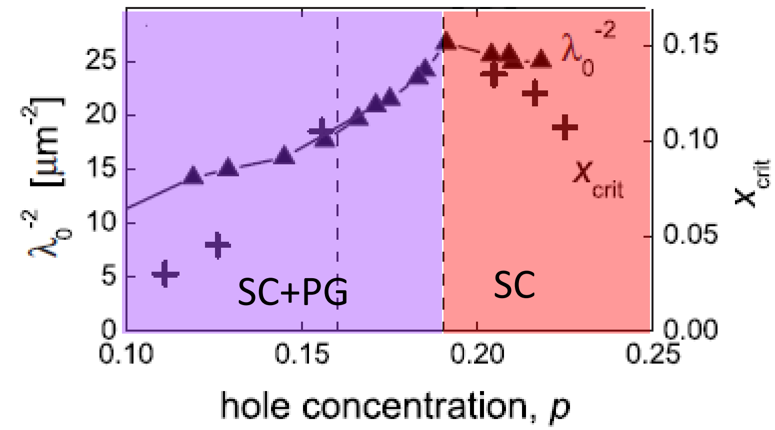
19% critical point + PG/SC coexistence

Extrapolation



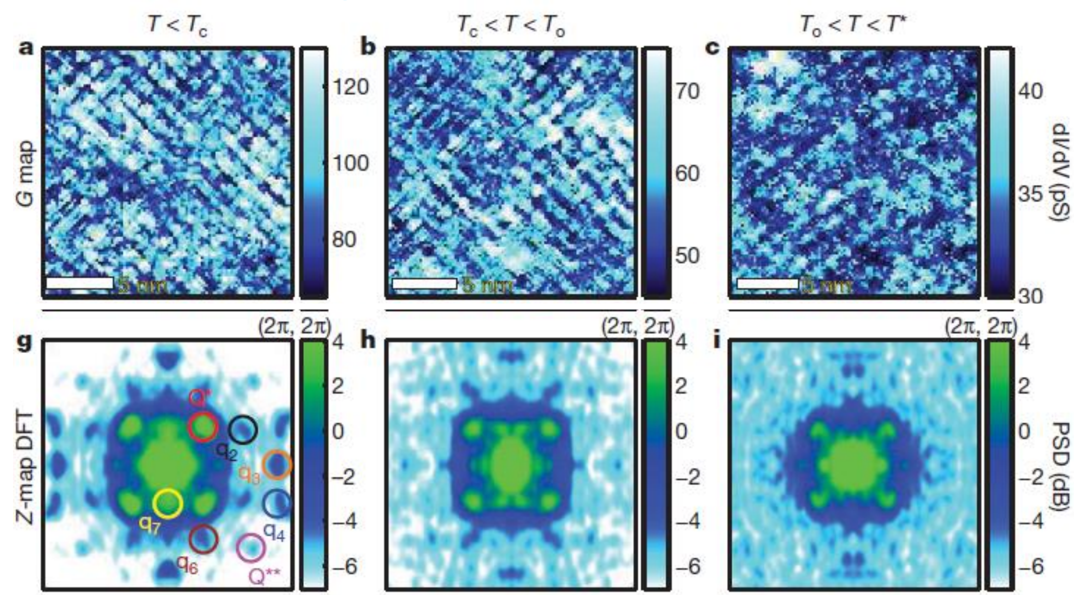
Baledent *et al.* PRB **83**, 104504 (2011)

Something happens



Storey *et al.* PRB **76,** 060502R (2007)

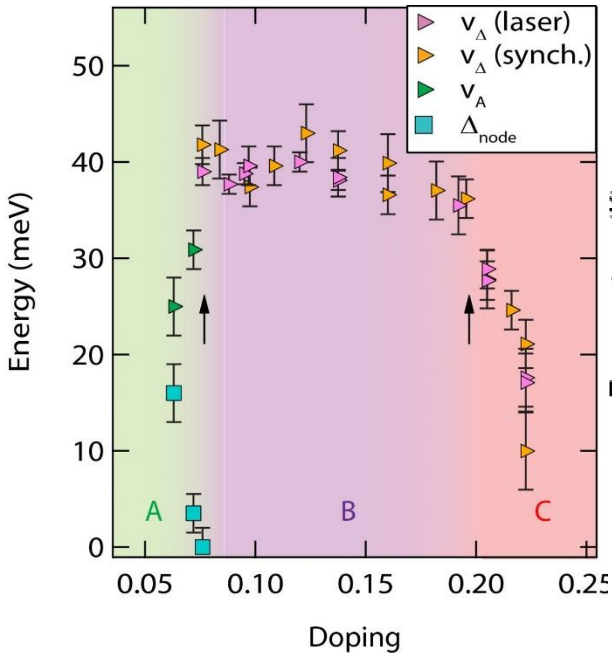
Something exists 0<T<T*



Parker *et al.* Nature **678** (2010)

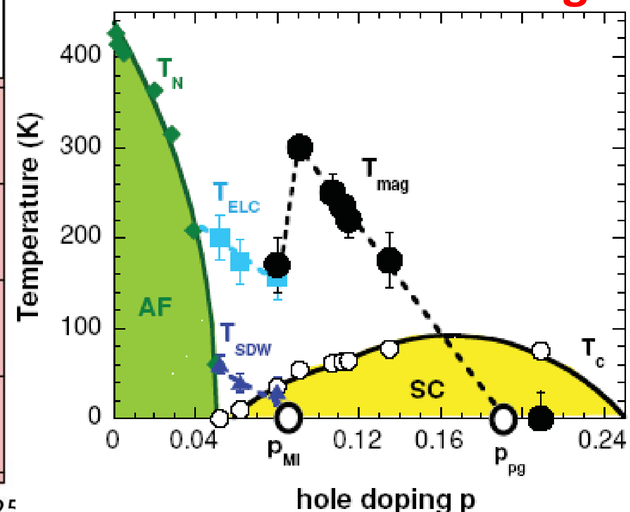
Ubiquitous trisected superconducting dome

➢ **ARPES**



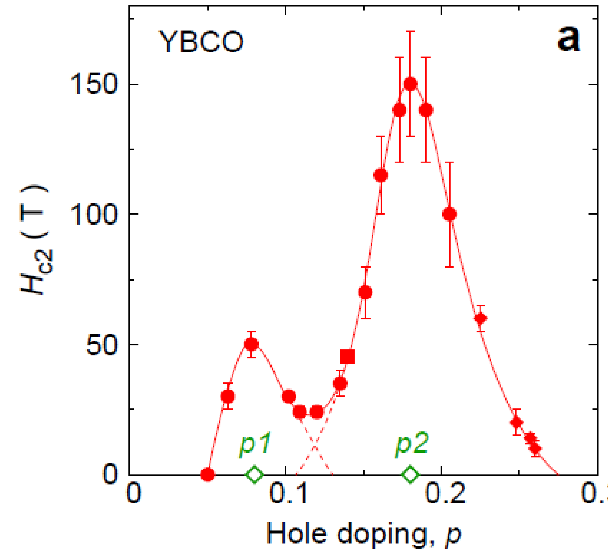
I. M. Vishik *et al.* PNAS **109** 18332 (2012)

➢ **Neutron scattering**



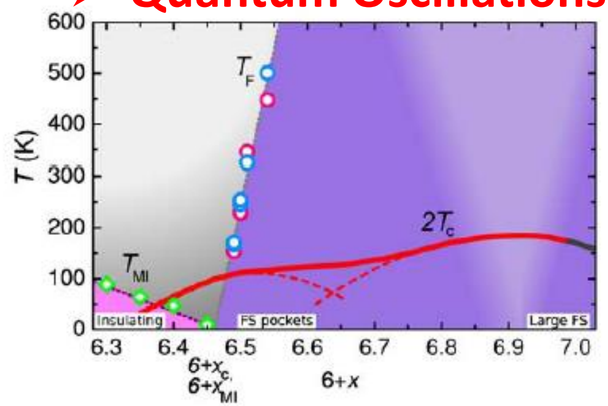
Baledent *et al.* PRB **83**, 104504 (2011)

➢ **Thermal conductivity**



Grissonnanche *et al. To appear in Nat. Comm. (2014)*

➢ **Quantum Oscillations**

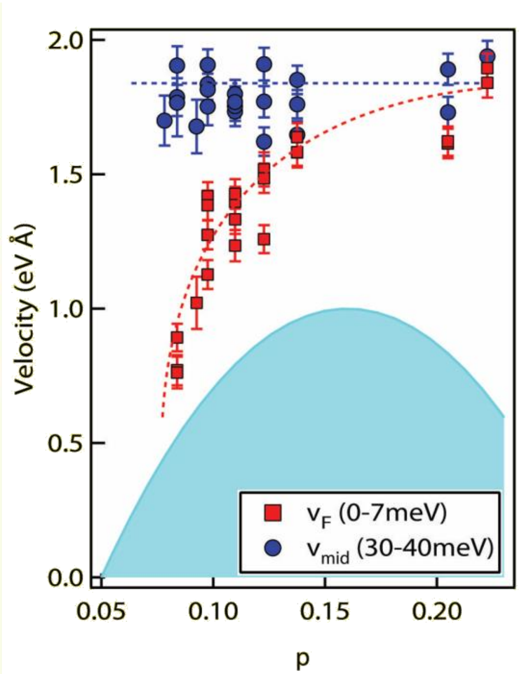


Sebastian *et al.* PNAS **107**, 6175 (2010)

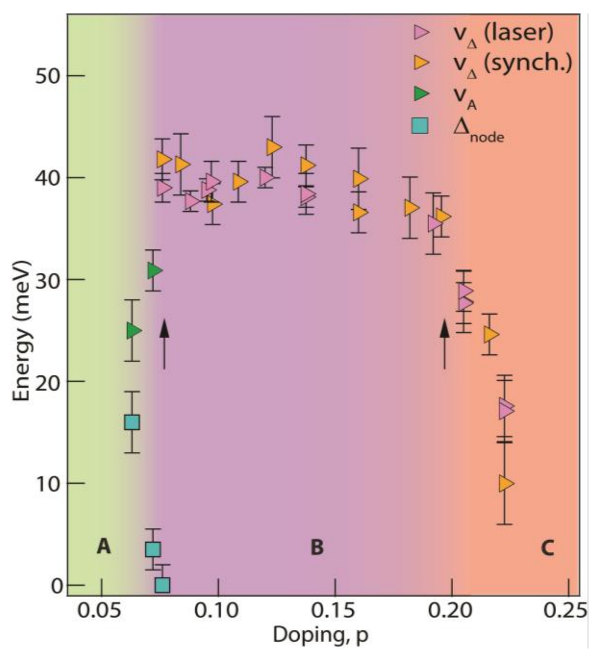
Conclusions

Laser ARPES provides unprecedented access to low energy excitations in near-nodal region

- Low energy kink
- 3 phase regions in SC dome



Vishik *et al.* PRL 105 **104**, 207002 (2010)



I. M. Vishik *et al.* PNAS **109** (45) 18332-18337 (2012)

Open questions:

- How to explain distinct physics on underdoped edge of SC dome?
- Why is v_Δ doping-independent over broad doping range?