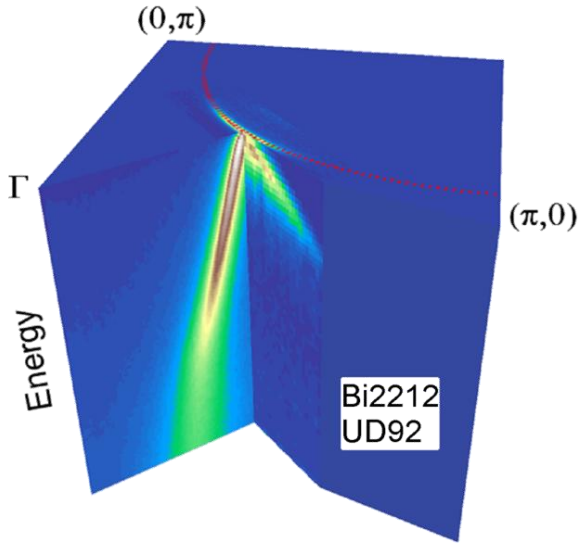
Momentum space imaging of cuprate superconductors

Inna Vishik

Nov. 10, 2014

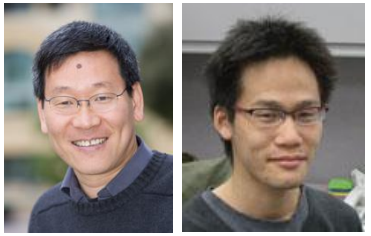
KITP



Acknowledgements

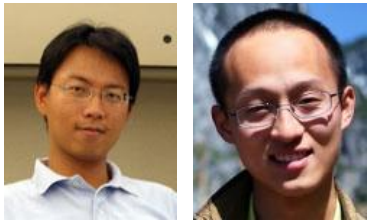
➢**Shen Group**

- 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)

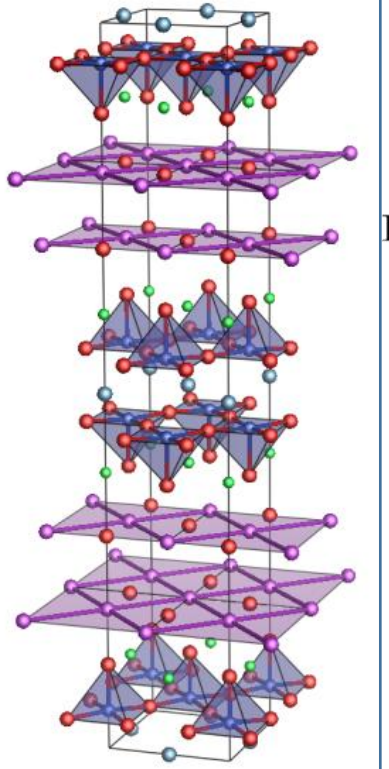
•Prof. S. Uchida, K. Fujita, S. Ishida (University of Tokyo)

•M. Ishikado (Japan Atomic Energy Agency)

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

U.S. DEPARTMENT OF ENERGY

Outline



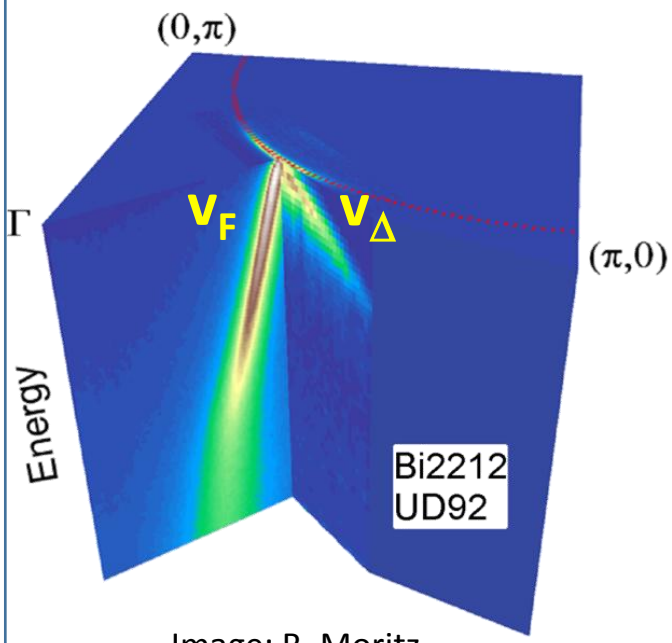
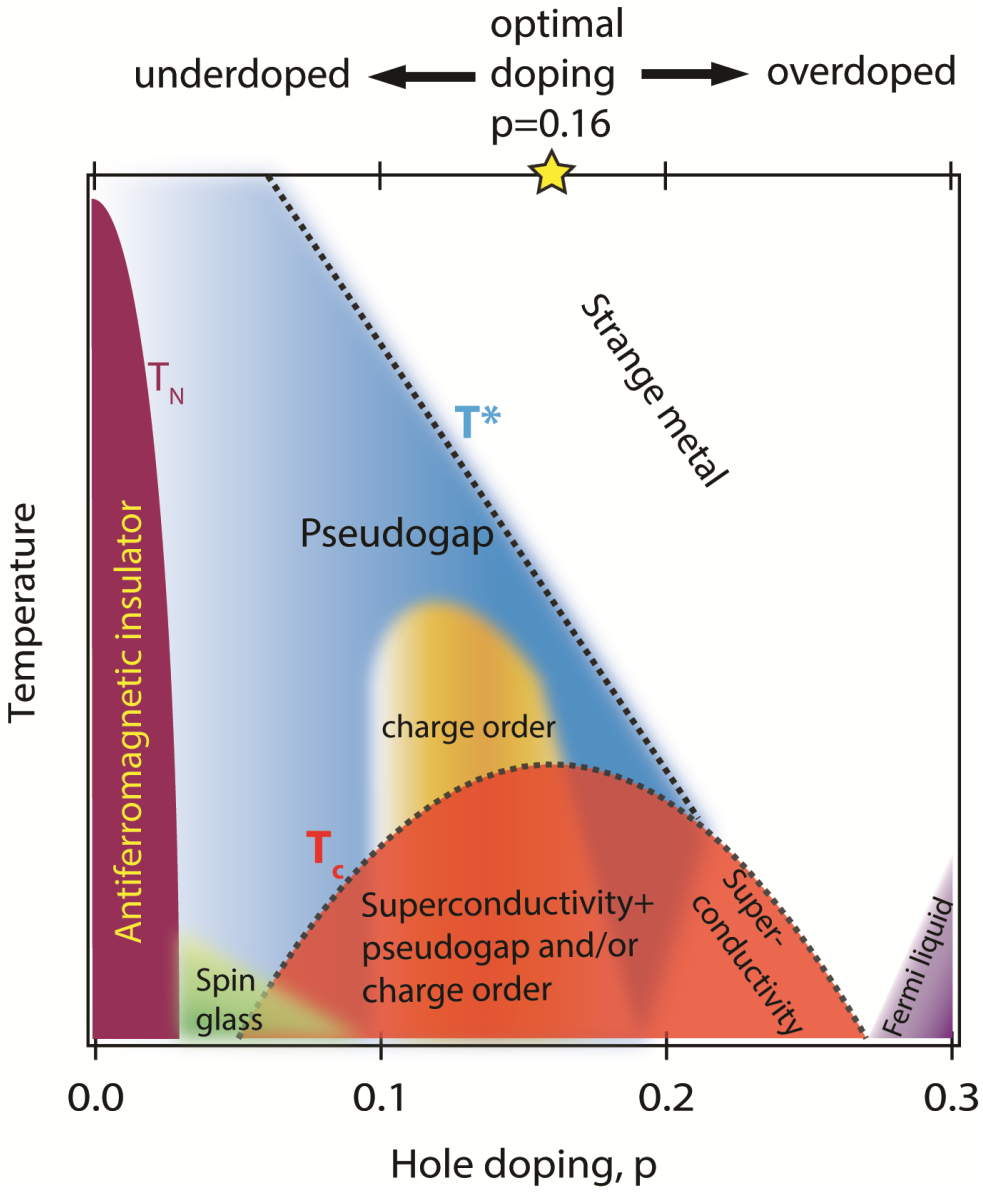


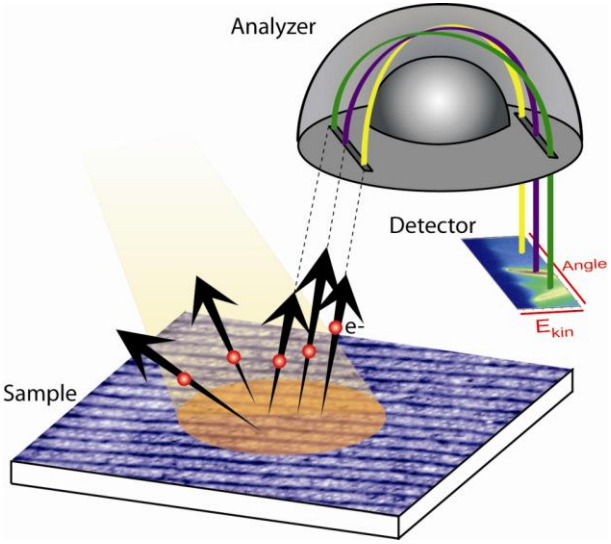
Image: B. Moritz

1. Low energy kink, v_F
2. Fully gapped state in deeply underdoped regime
3. Doping dependence of v_Δ

A complex phase diagram



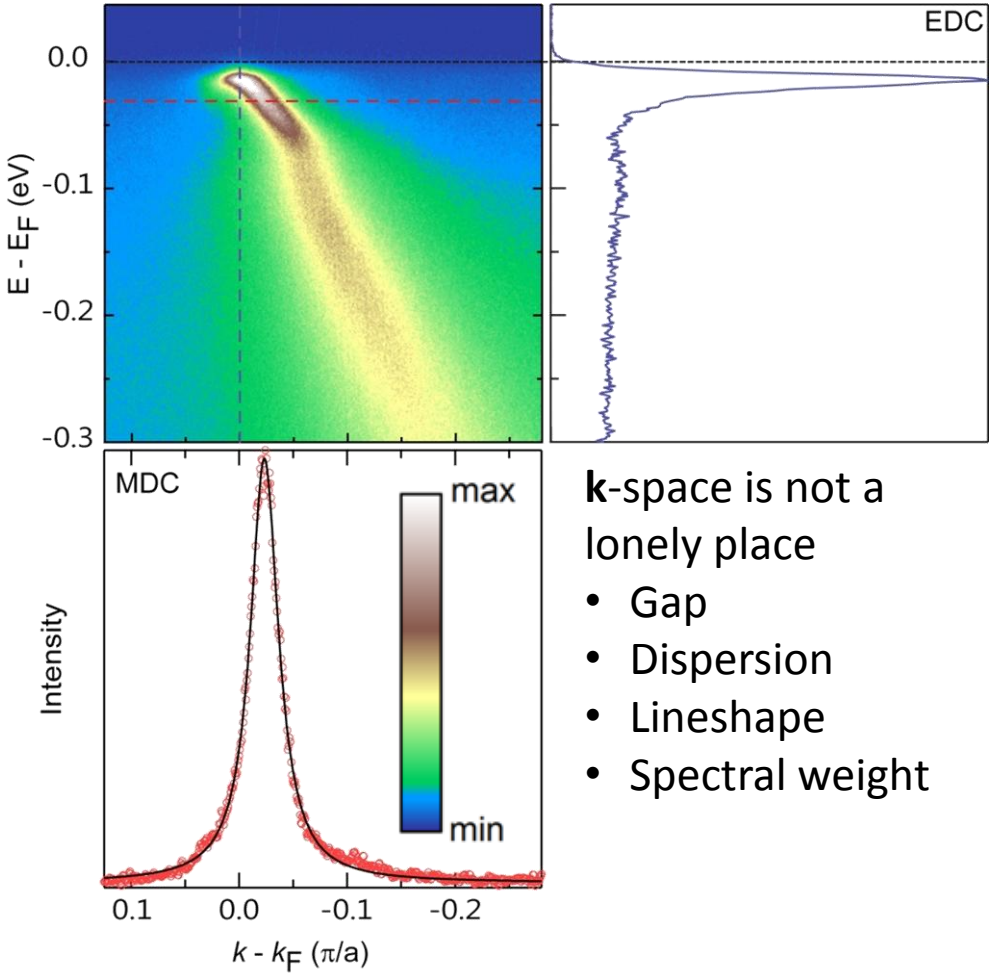
ARPES introduction



Angle-resolved photoemission spectroscopy

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

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

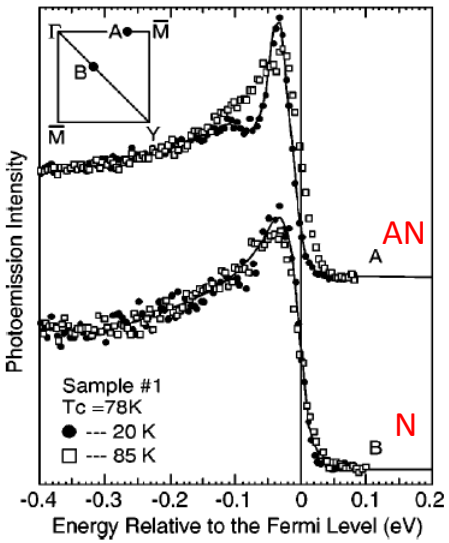


k-space is not a lonely place

- Gap
- Dispersion
- Lineshape
- Spectral weight

Evolution of experimental technology

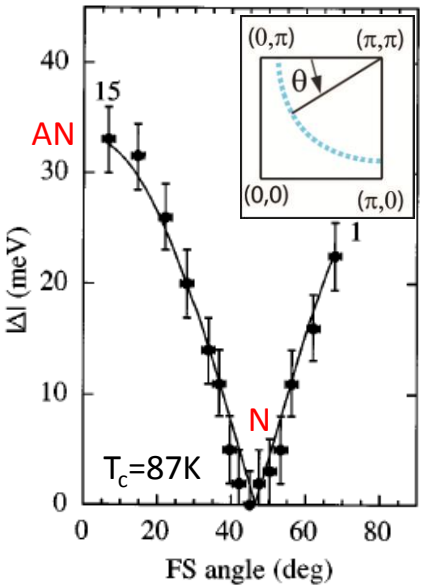
ΔE=30meV



Shen *et al.* PRL **70** (1993)

6 hrs/k

ΔE=17meV

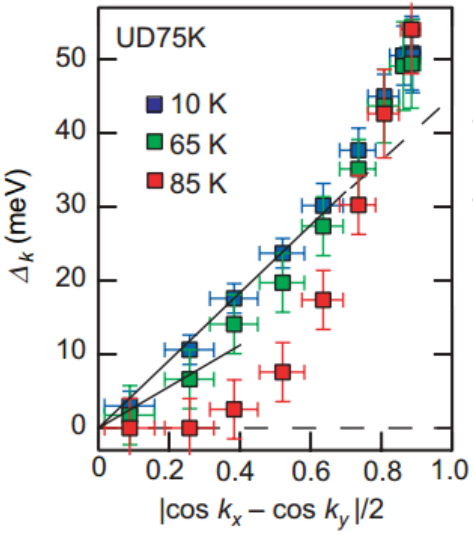


Ding *et al.* PRB **54** (1996)

1 hr/k

Synchrotron

ΔE=6-10meV

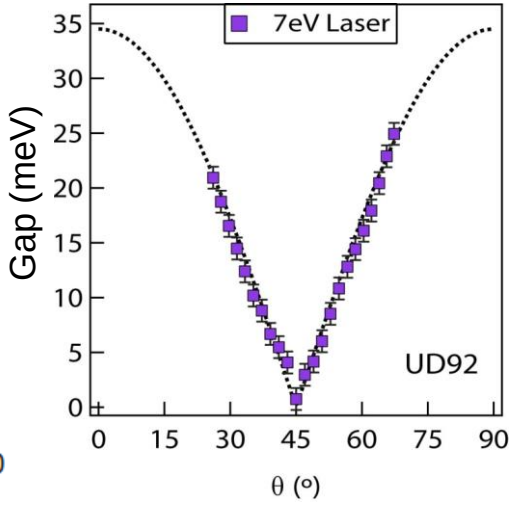


Lee *et al.* Nature **450** (2007)

30 min/k

Laser

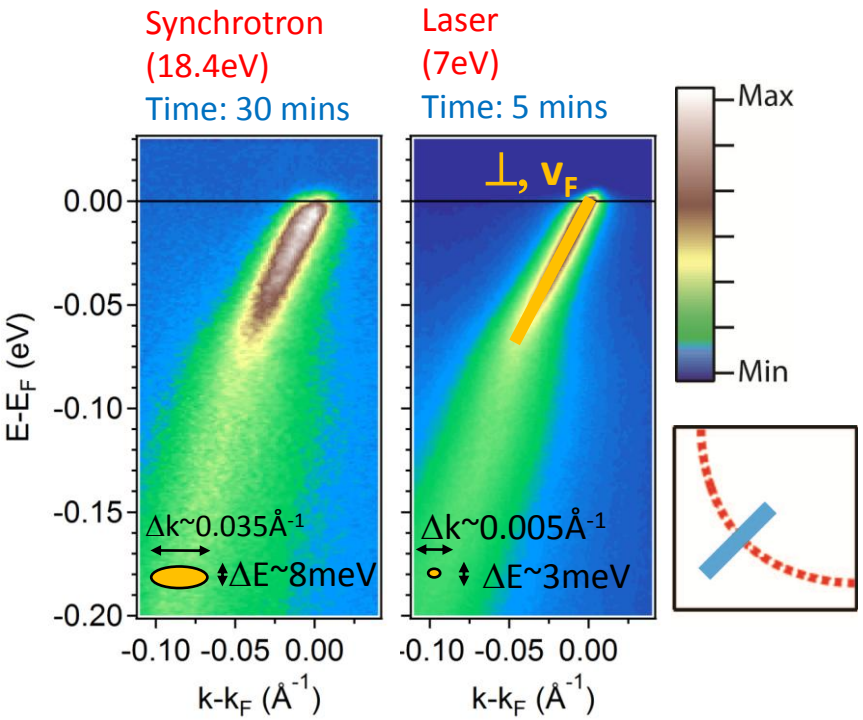
ΔE=1-3meV

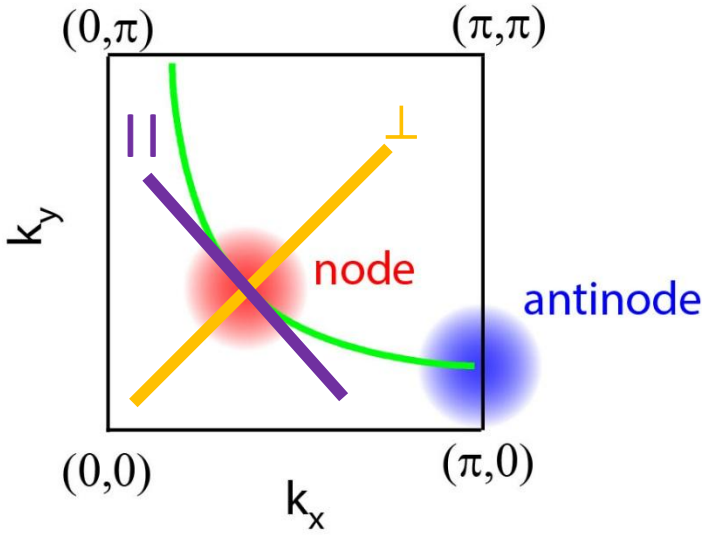


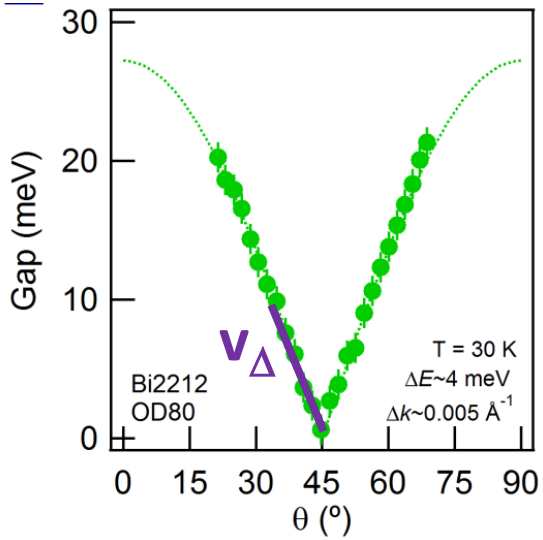
Vishik *et al.* PNAS **(2012)**

5 min/k

Laser ARPES: unprecedented access to low energy excitations



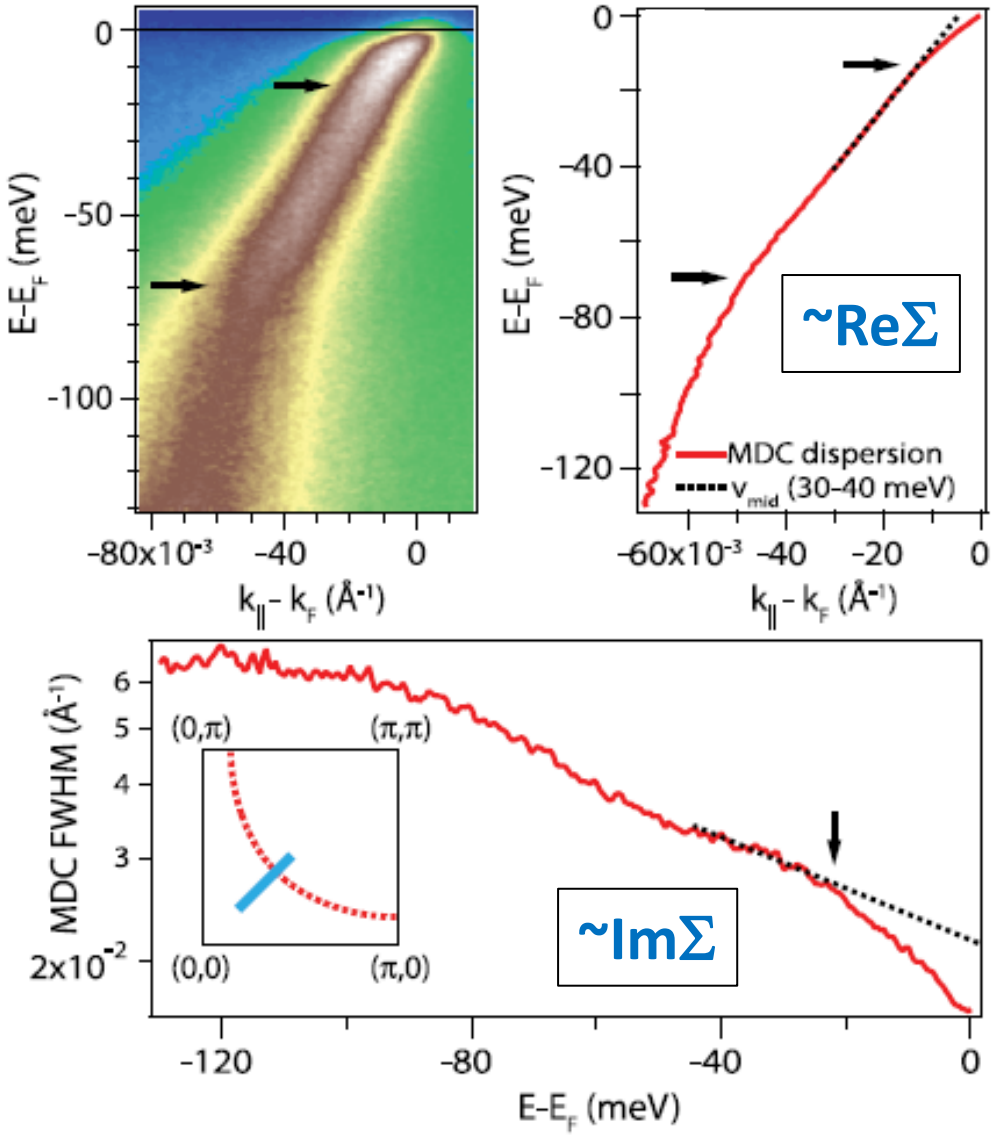




7eV Laser ARPES

- Energy resolution
- Momentum resolution
- Data collection efficiency

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



Shen group and collaborators

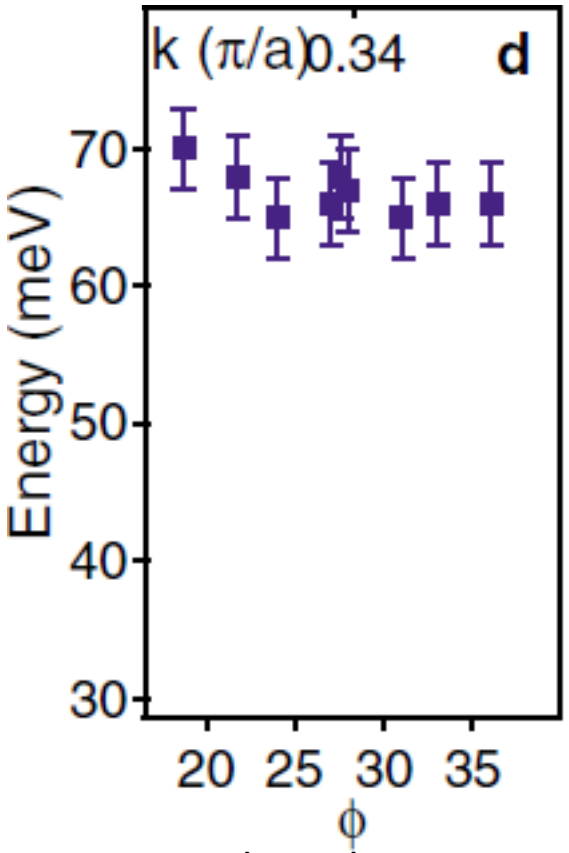
- **Expt: Vishik *et al.* PRL 104, 207002 (2010)**
- **Theory+ Expt: S. Johnston , I. M. Vishik *et al.* PRL 108 166404 (2012)**

Other groups:

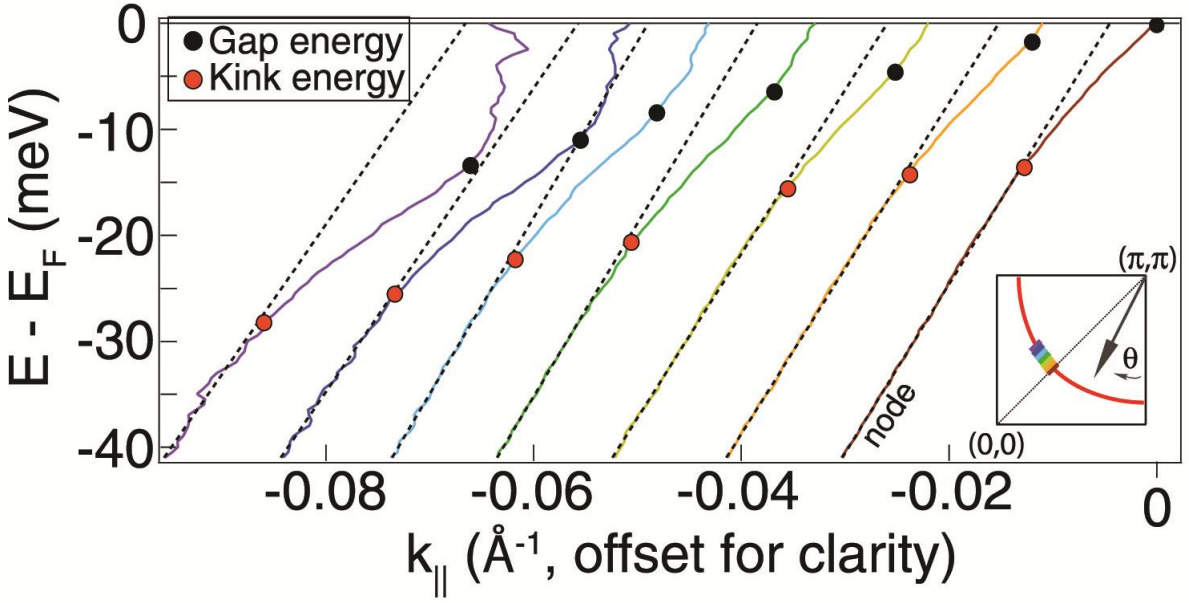
- Rameau *et al.* Phys. Rev. B **80** (2009)
- Plumb *et al*. Phys. Rev. Lett. **105** (2010)
- Anzai *et al.* Phys. Rev. Lett. **105** (2010)
- Kondo *et al.* Phys. Rev. Lett. **110** (2013)

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

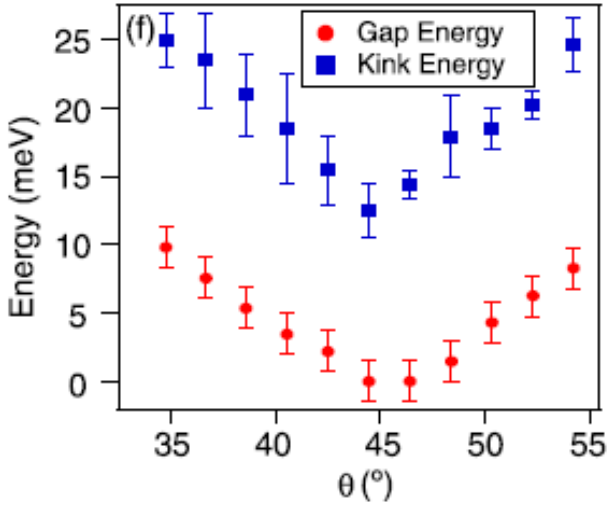
Momentum dependence



Cuk et al, PRL **93** 117003 (2004)

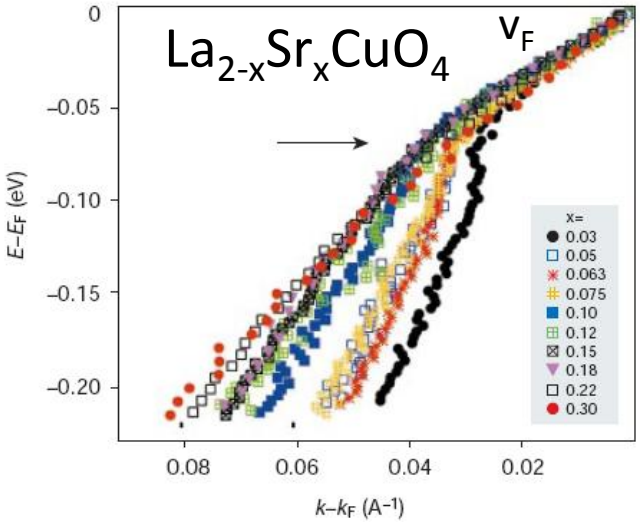


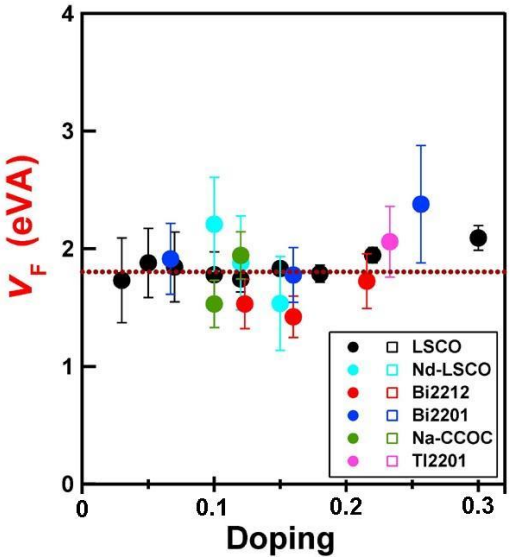
S. Johnston , I. M. Vishik *et al.* PRL **108** 166404 (2012)



Consequence: doping *dependent* v_F

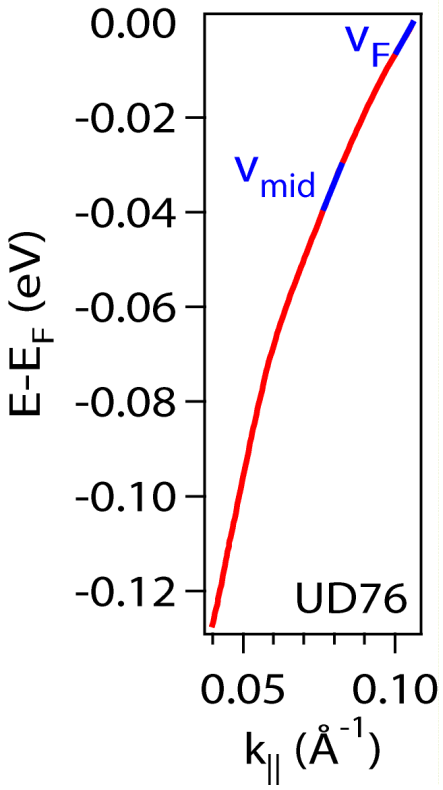
ΔE=20meV: Universal nodal v_F

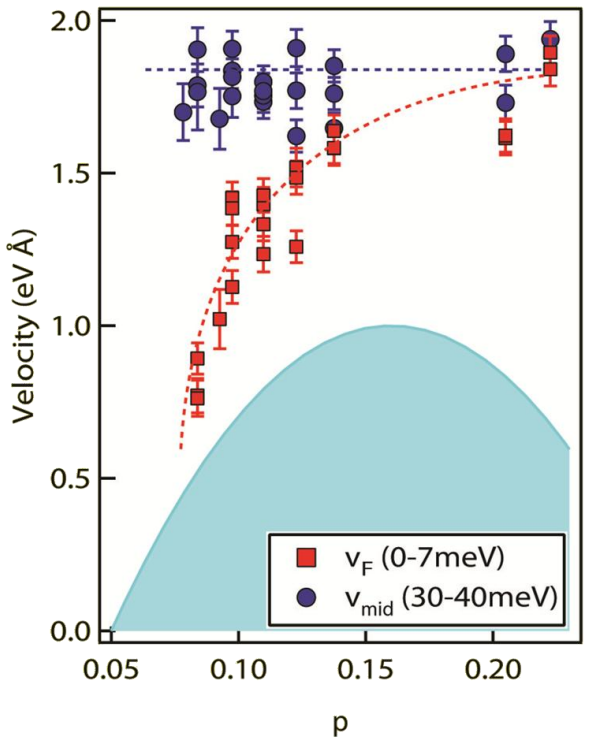




X. J. Zhou,, *et al.*, Nature **423**, 398 (2003)

ΔE=3meV: doping dependent v_F

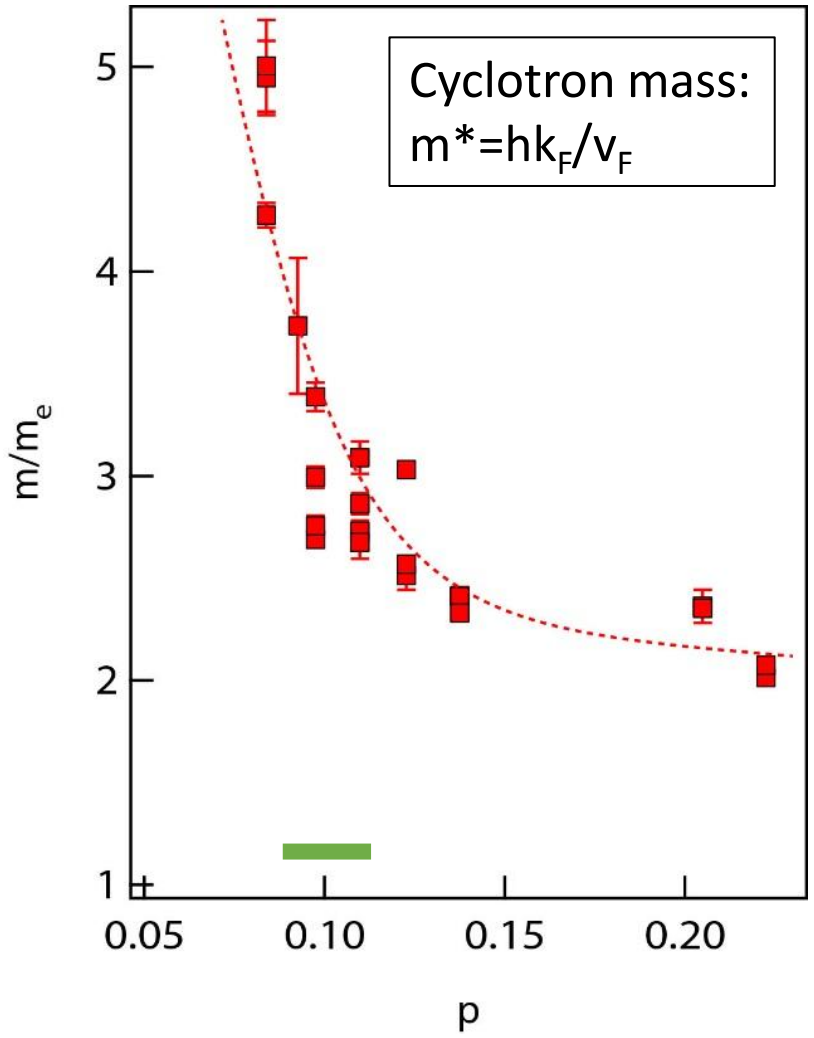




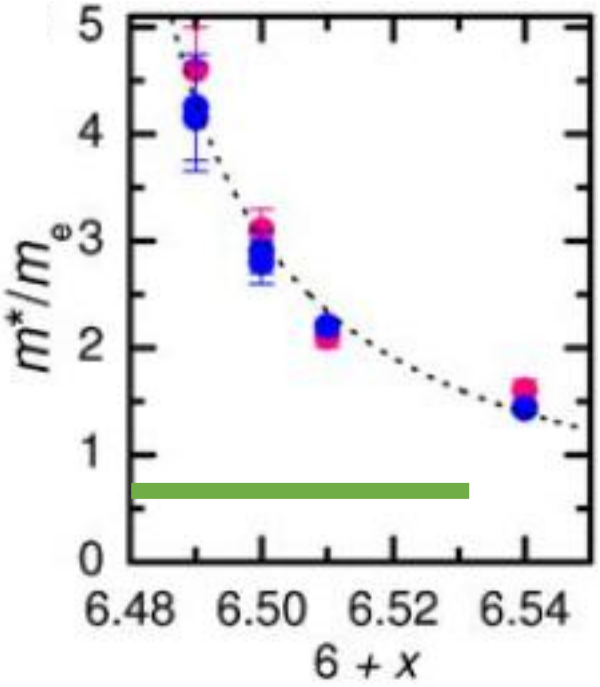
Vishik *et al.* PRL 105 **104**, 207002 (2010)

Diverging m*

ARPES: Bi2212

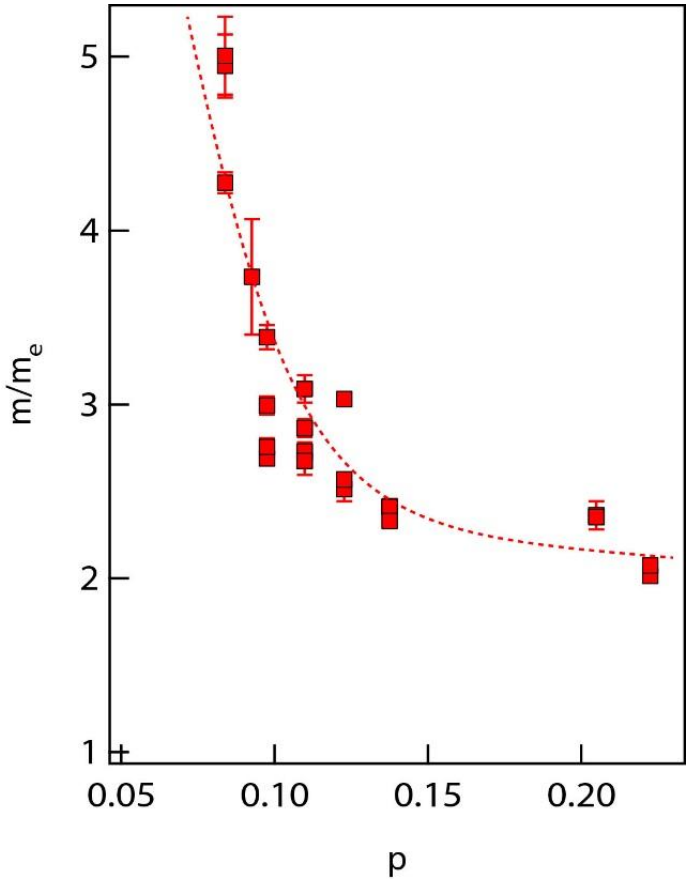


Quantum Oscillations: YBCO

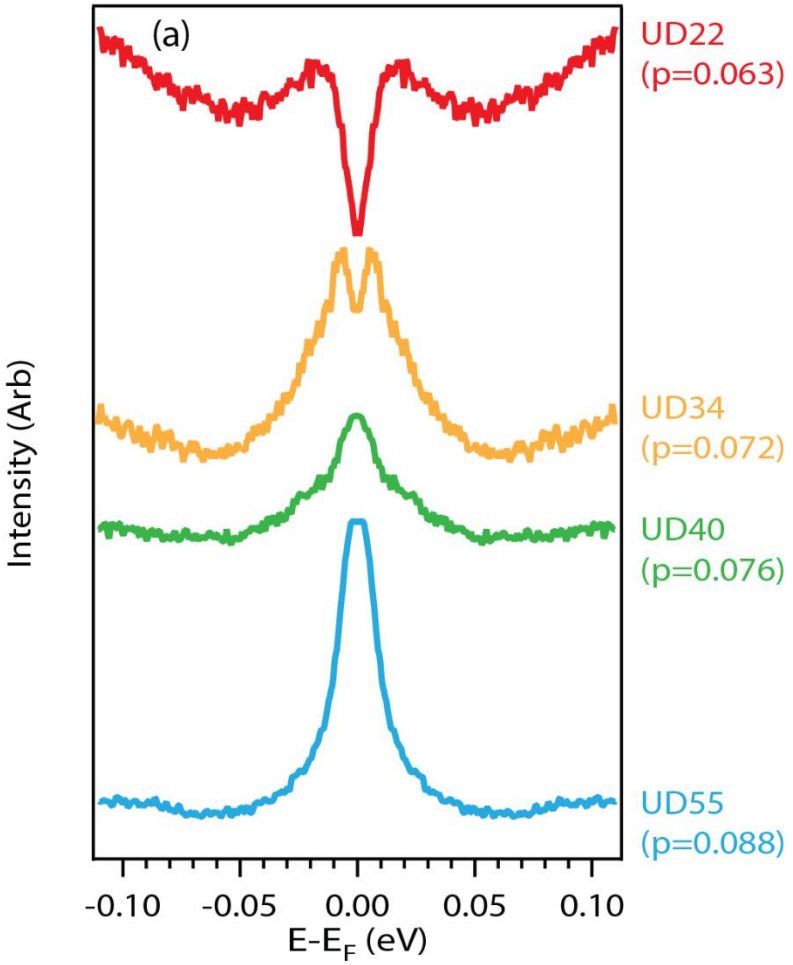


Sebastian *et al.* PNAS **107** 6175 (2010)

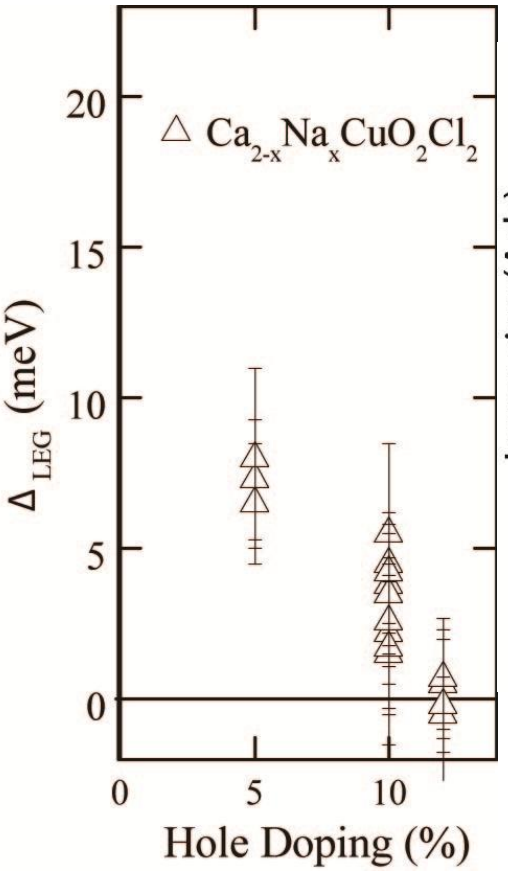
What happens at lower dopings?



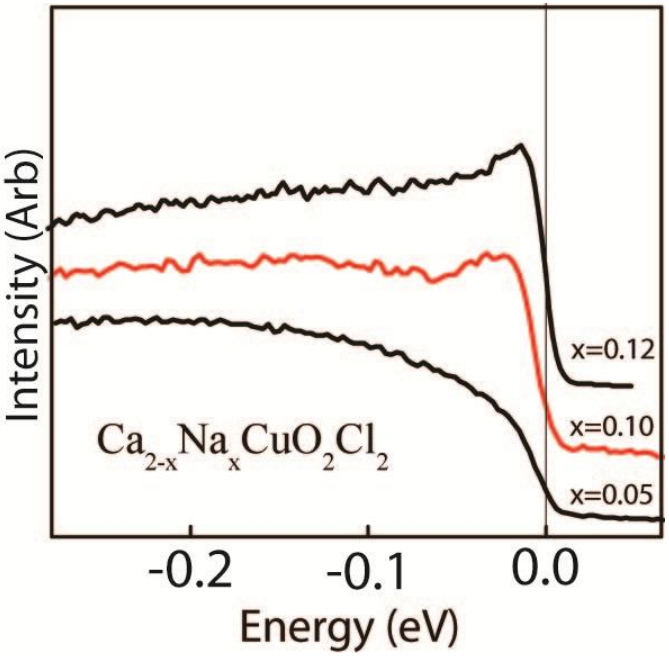
Nodal EDCs (symmetrized), T=10K



History



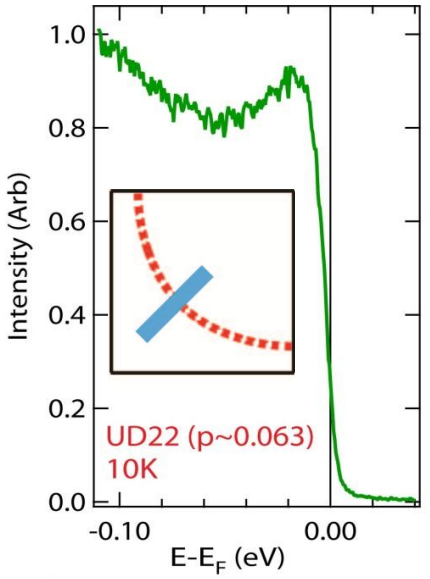
Na-CCOC (2004)



K. M. Shen *et al.* PRB **69** (2004)

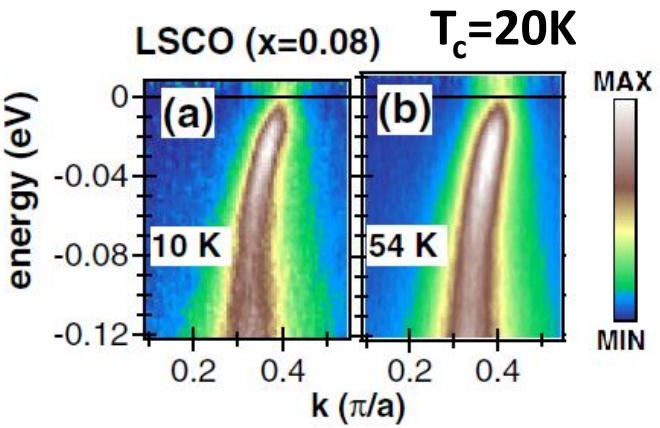
No comment
- e/h symmetry
- DOS at E_F

Bi-2212 (2012)



Vishik *et al.* PNAS **109** (2012)

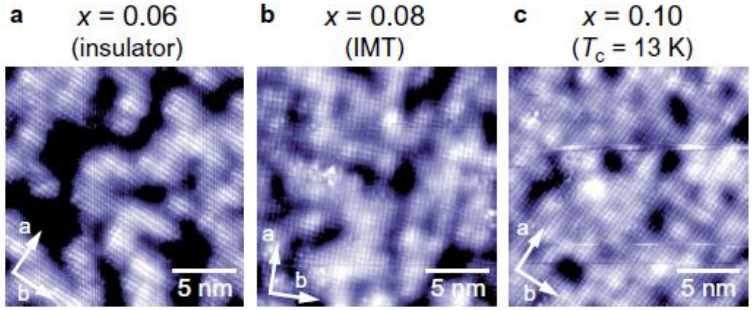
LSCO (2013)



E Razzoli *et al.* PRL **110** (2013)

Summary of other experiments

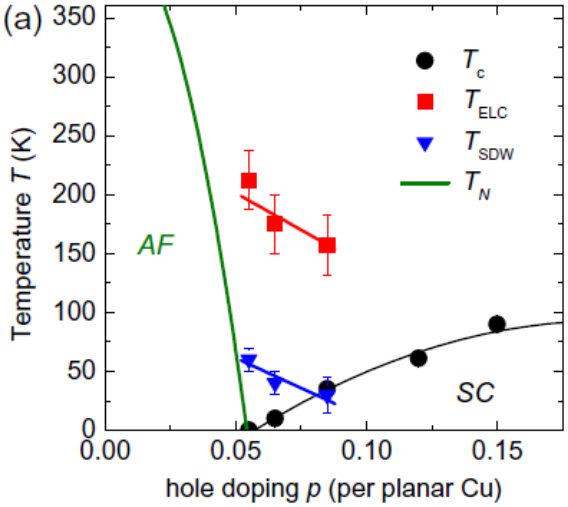
Na-CCOC



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

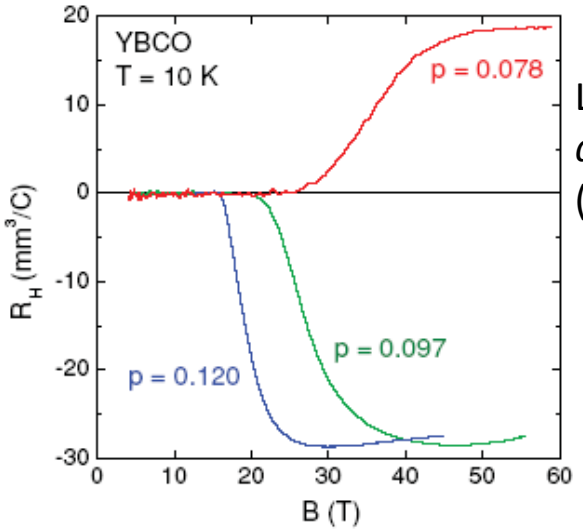
➢ STS: Percolation of conductive patches

➢ Neutron: spin correlations near (π,π)



Haug *et al.* NJP (2010)

➢ Transport: change in Fermi surface



LeBoeuf *et al.* PRB (2011)

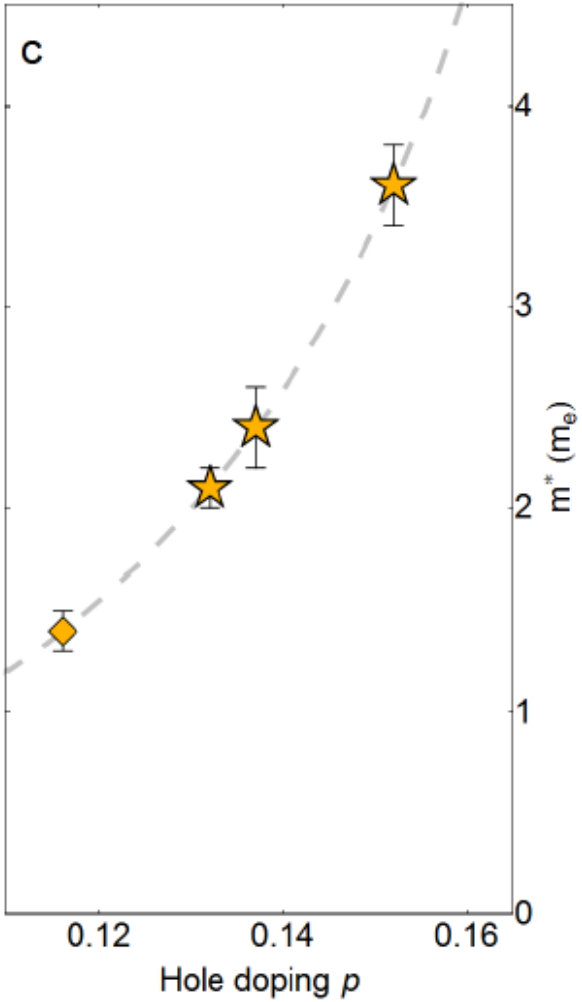
➢ ARPES (Bi-2212) and quantum oscillations (YBCO): diverging m*

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

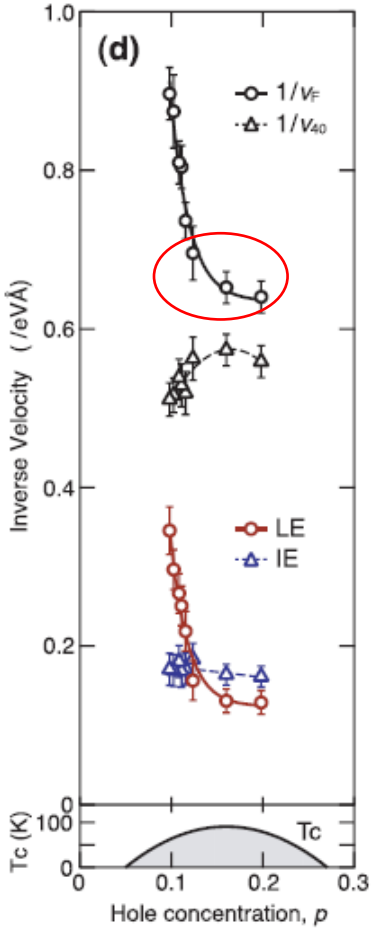
Recent theoretical proposals

- $d_{x2-y2}+id_{xy}$ SC+ SDW (A. Gupta *et al.* arXiv:**1401.0617v1**)
- Topological SC (Y.-M. Lu *et al.*, Nature Physics **10** (2014))
- Fulde-Ferrell-Larkin-Ovchinnikov (T. Das, arXiv:**1312.0544v1**)

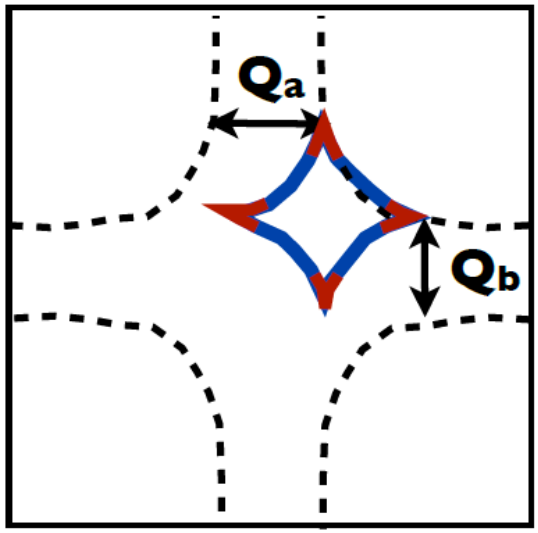
Another diverging m*



Ramshaw *et al.*
arXiv:1409.3990v1



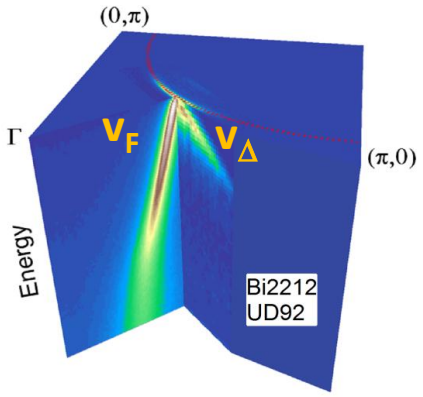
Anzai *et al.* PRL
105 (2010)



T. Senthil arXiv:1410.2096v1

Bi-2212 and YBCO: the nodes agree

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

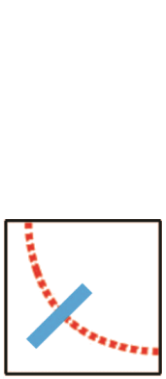
Electronic Specific Heat: $C_{el}(T) \propto \frac{n}{d}\left(\frac{1}{v_F v_\Delta}\right)T^2$

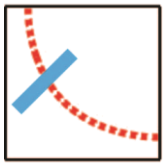
Thermal conductivity: $\frac{\kappa_0}{T} = \frac{k_B^2}{3\hbar}\frac{n}{d}\left(\frac{v_F}{v_\Delta} + \frac{v_\Delta}{v_F}\right) \approx \frac{k_B^2}{3\hbar}\frac{n}{d}\frac{v_F}{v_\Delta}$

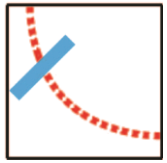
$YBa_2Cu_3O_7$ (YBCO): Taillefer Group, Samuel René De Cotret, To be published

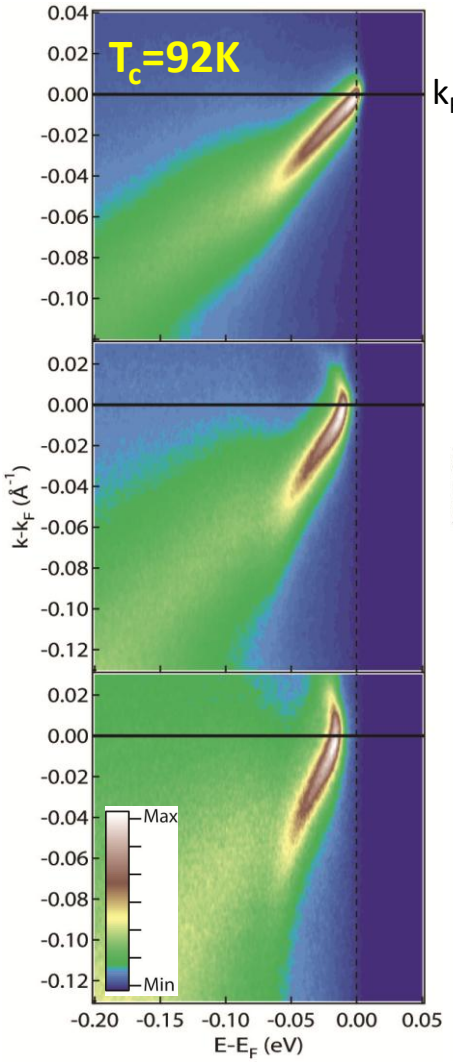
Quantitative agreement between bulk thermodynamic probe and surface spectroscopy of nodal properties

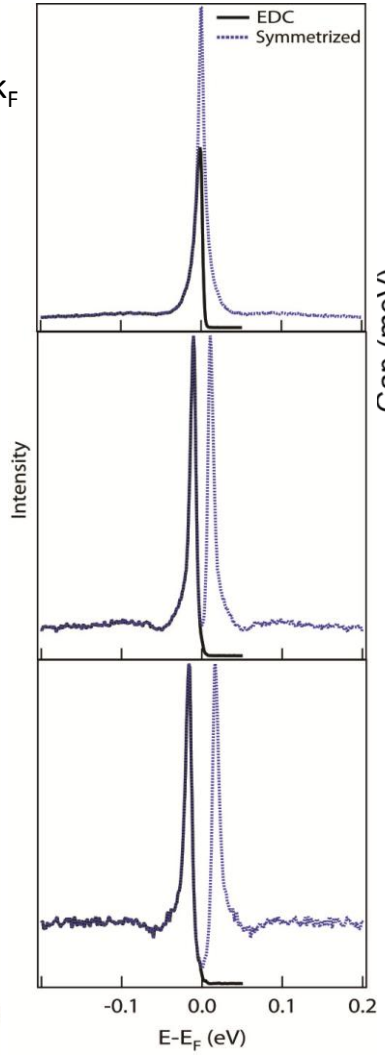
Gap measurements, extracting v_Δ

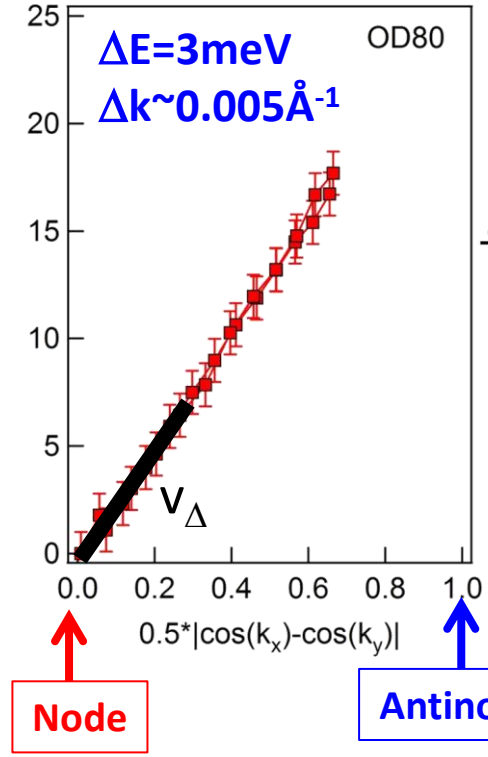


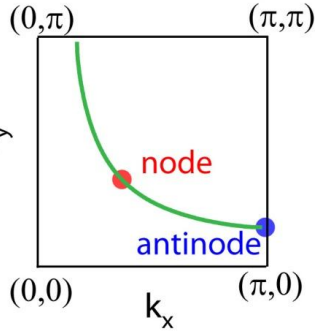












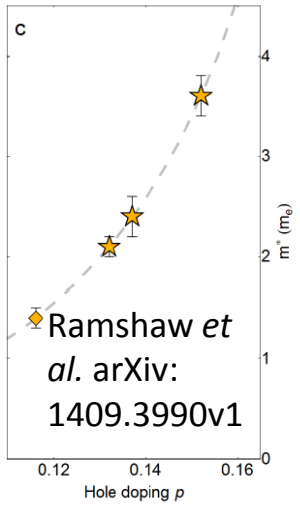
Expected for *d*-wave superconductor:

$$v_\Delta \propto \Delta_0 \propto T_c$$

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)

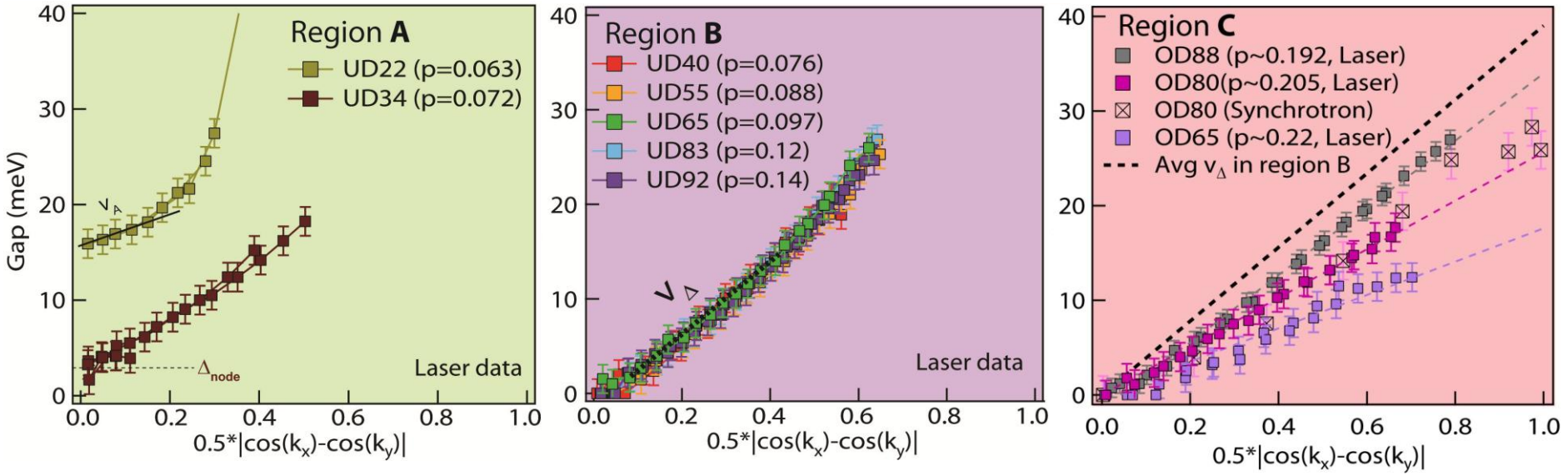
Bi-2212, T=10K: two potential critical points manifest in near-nodal gaps



p<0.076

0.076<p<0.19

p>0.19



Fully gapped Fermi surface

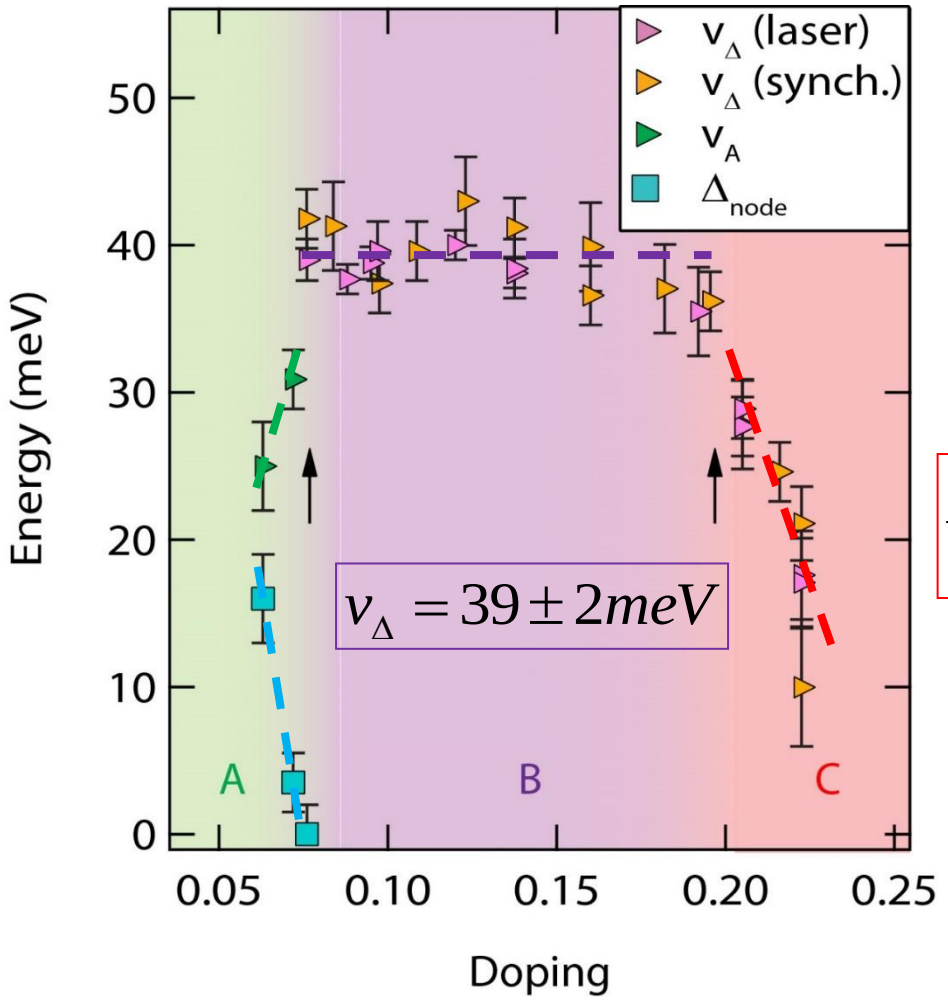
Doping-independent v_Δ

$v_\Delta \propto T_c$

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

ARPES: three phase regions (10K)

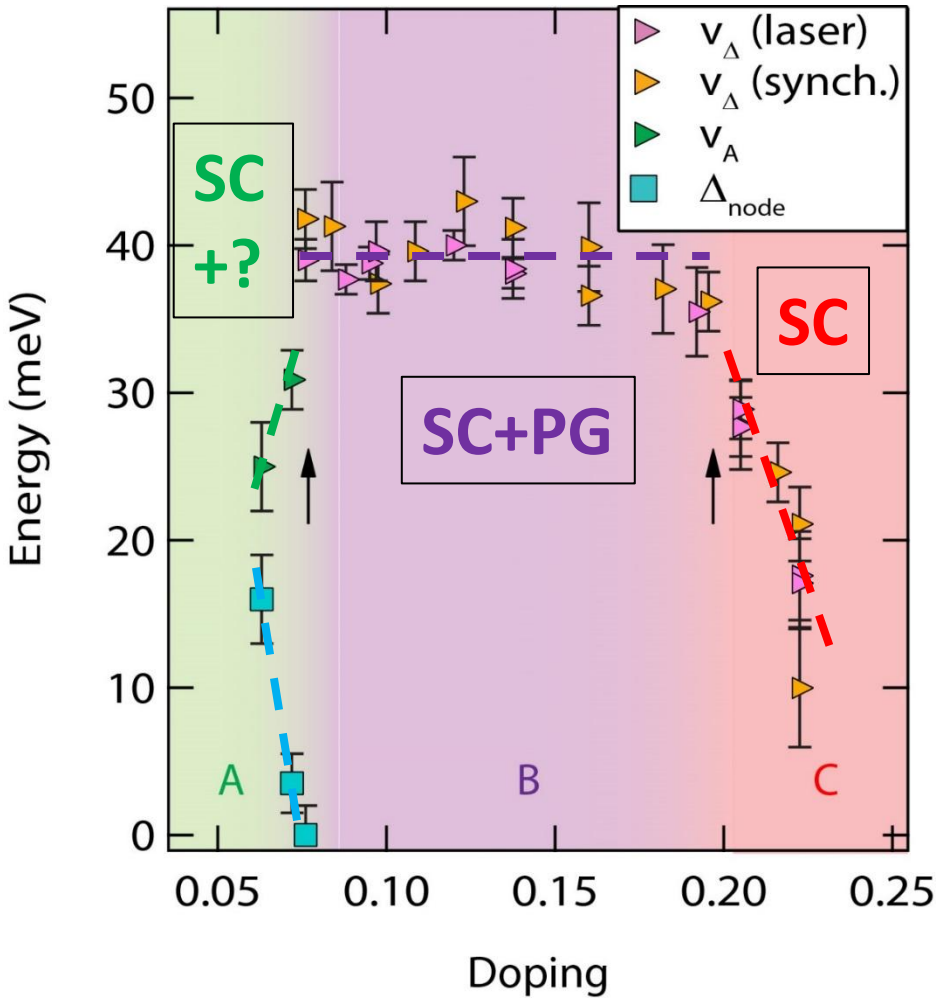
- Δ_{node} grows with underdoping
- v_A decreases with underdoping



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

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

Trisected superconducting dome: interpretations

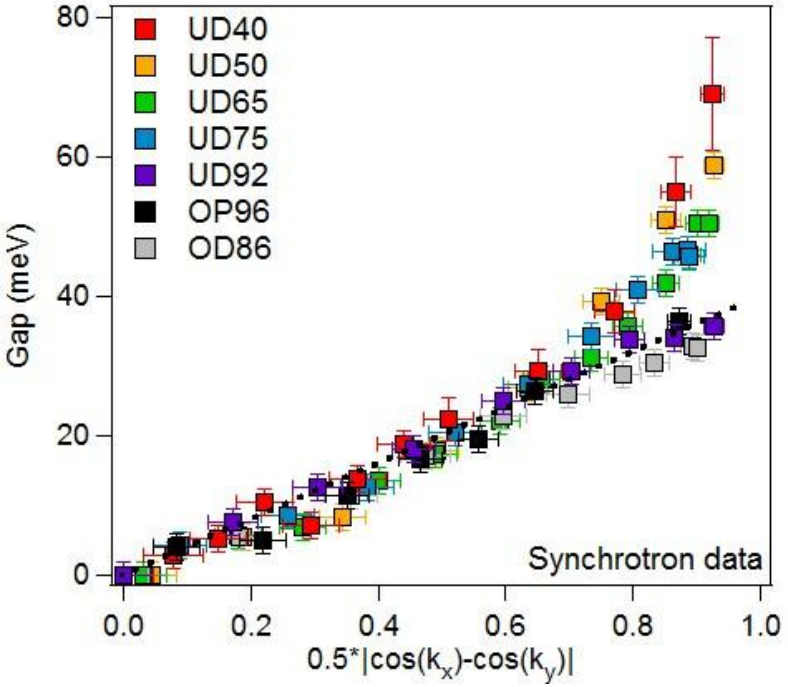


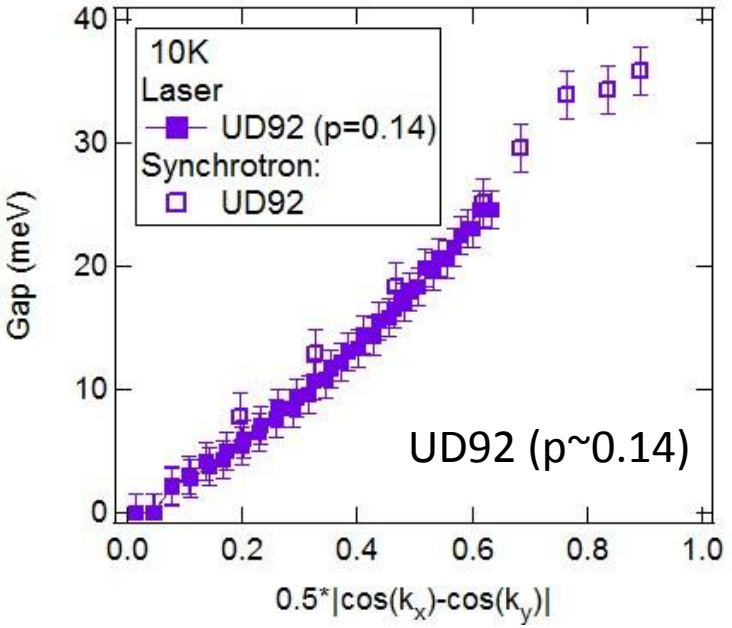
Open question: Why is v_Δ doping-independent?

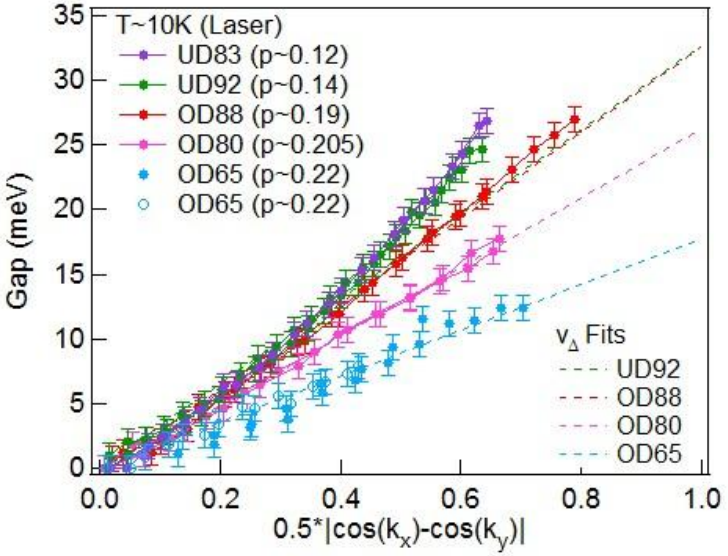
I. M. Vishik *et al.* PNAS **109** (45) 18332 (2012)

Manifestations of pseudogap below T_c: ARPES

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

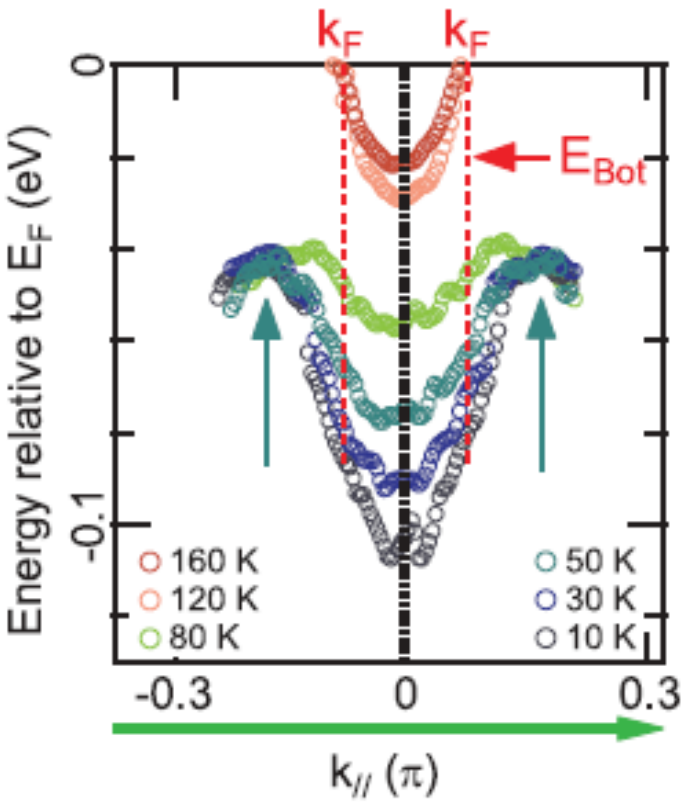




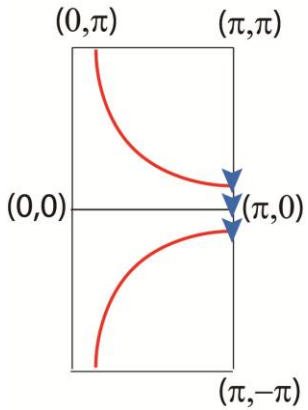


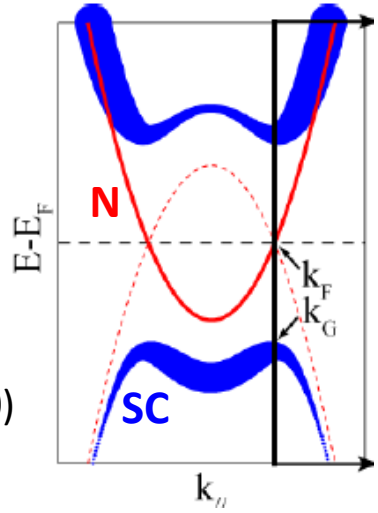
Charge order in ARPES

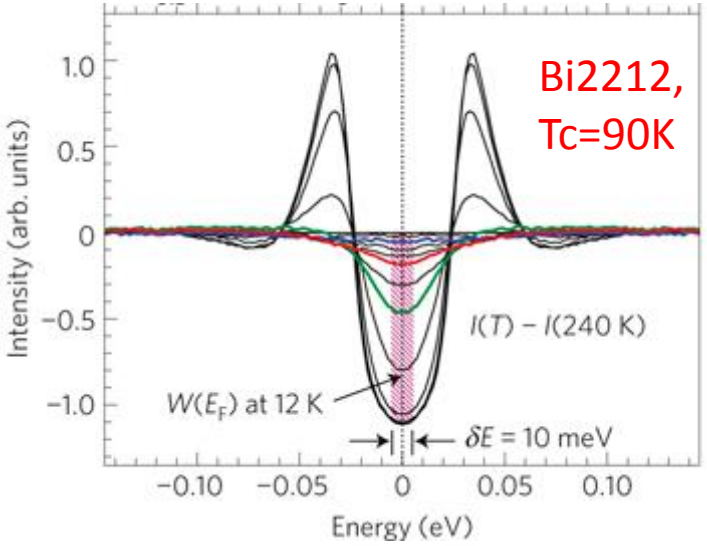
Pb-Bi2201 T_c=34K, T^* =125±10 K

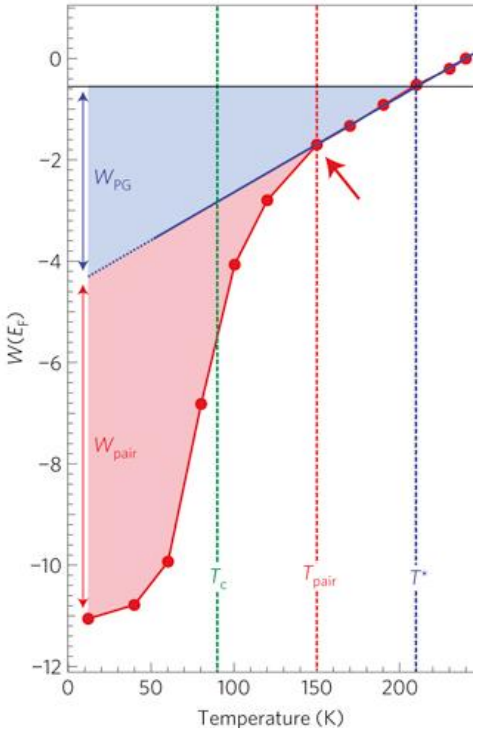


Hashimoto *et al.* Nat. Phys **6,** 414 (2010)



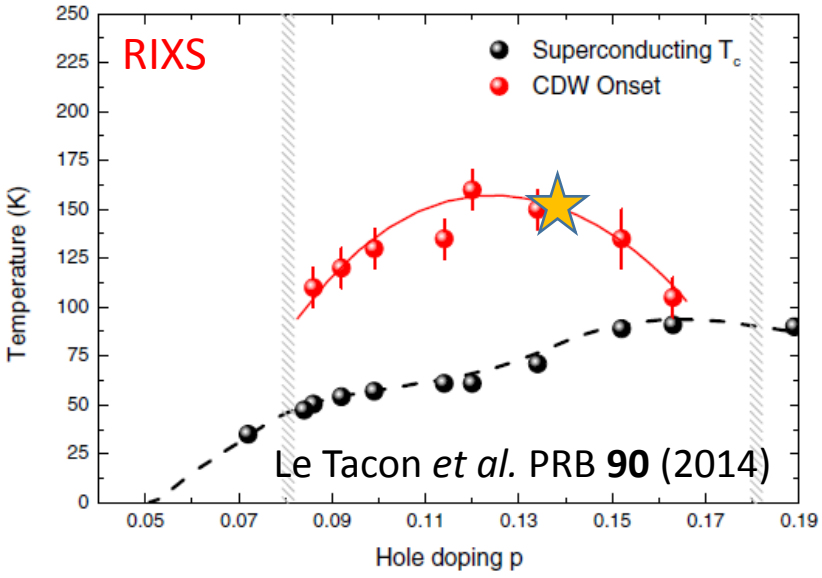


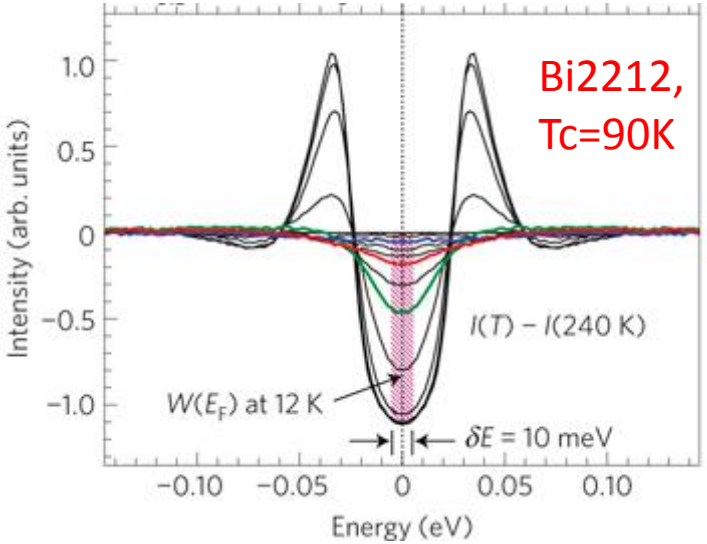


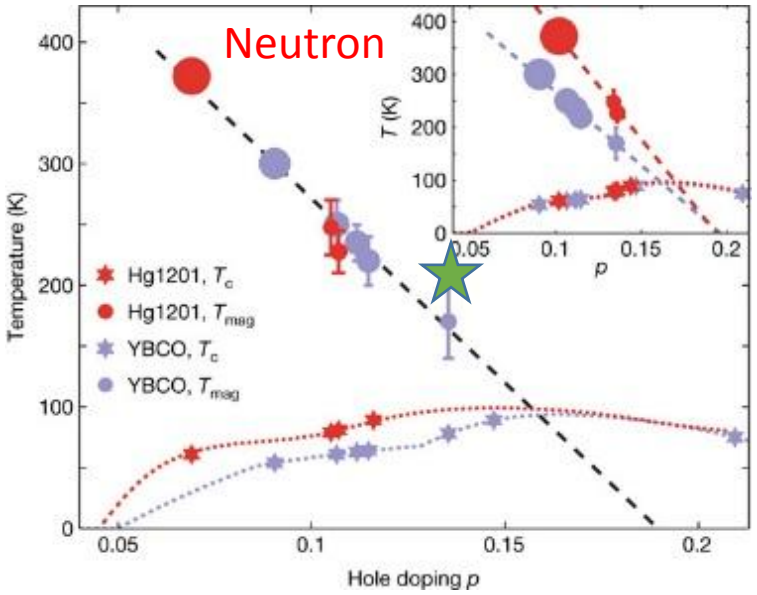


Kondo et al, Nat. Phys. **7** (2011)

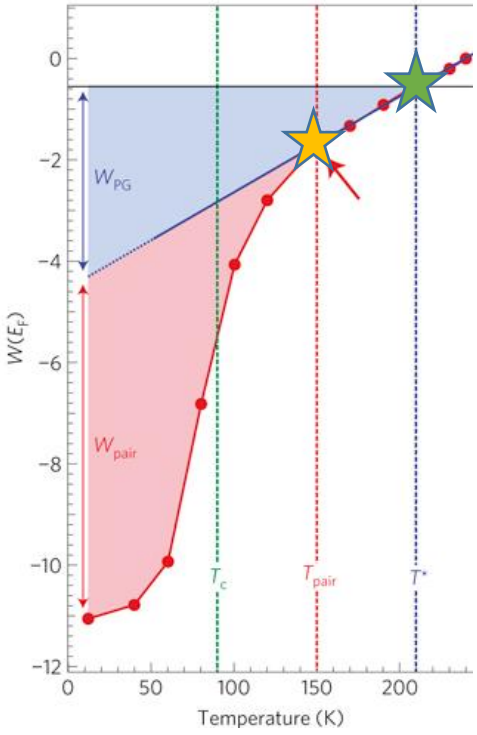
Charge order in ARPES







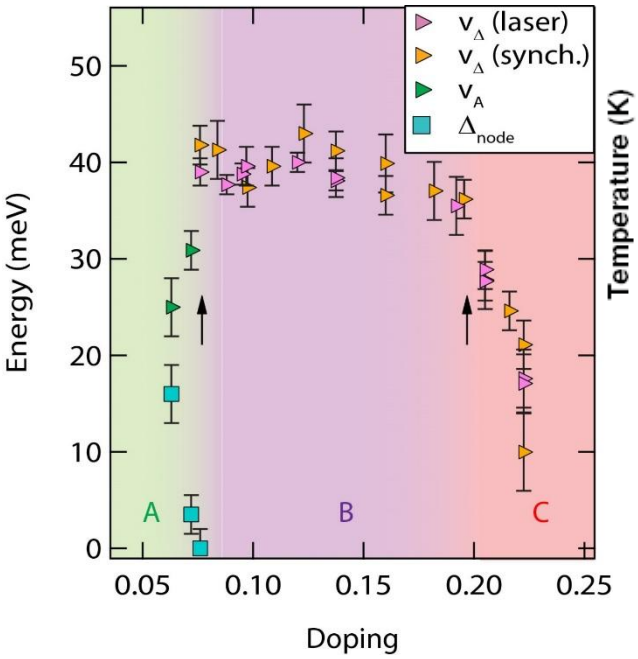
- Y. Li *et al.* Nature **455** (2008)
- Faugue *et al.* PRL **96** (2006)



Kondo et al, Nat. Phys. **7** (2011)

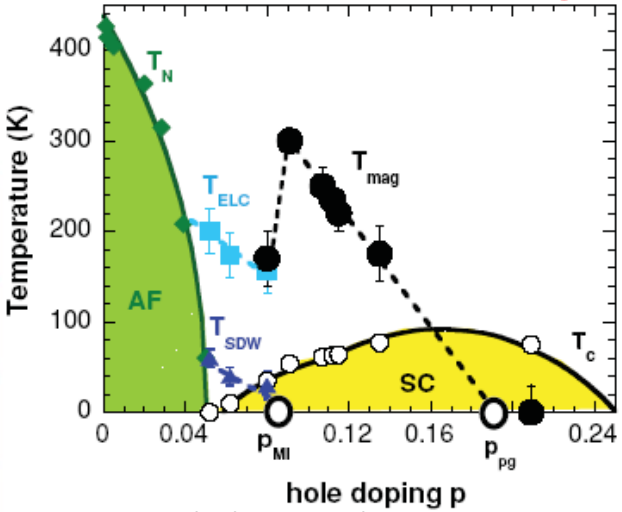
Ubiquitous trisected SC dome

➢ ARPES



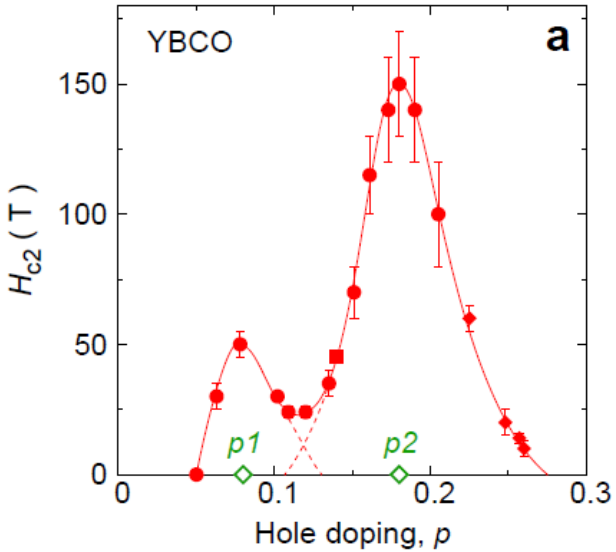
I. M. Vishik *et al.* PNAS **109** 18332 (201

➢ Neutron scattering



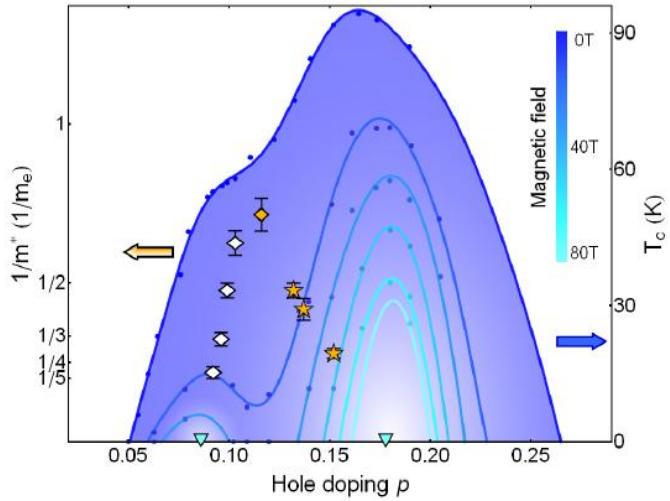
Baledent *et al.* PRB **83**, 104504 (2011)

➢ Thermal conductivity



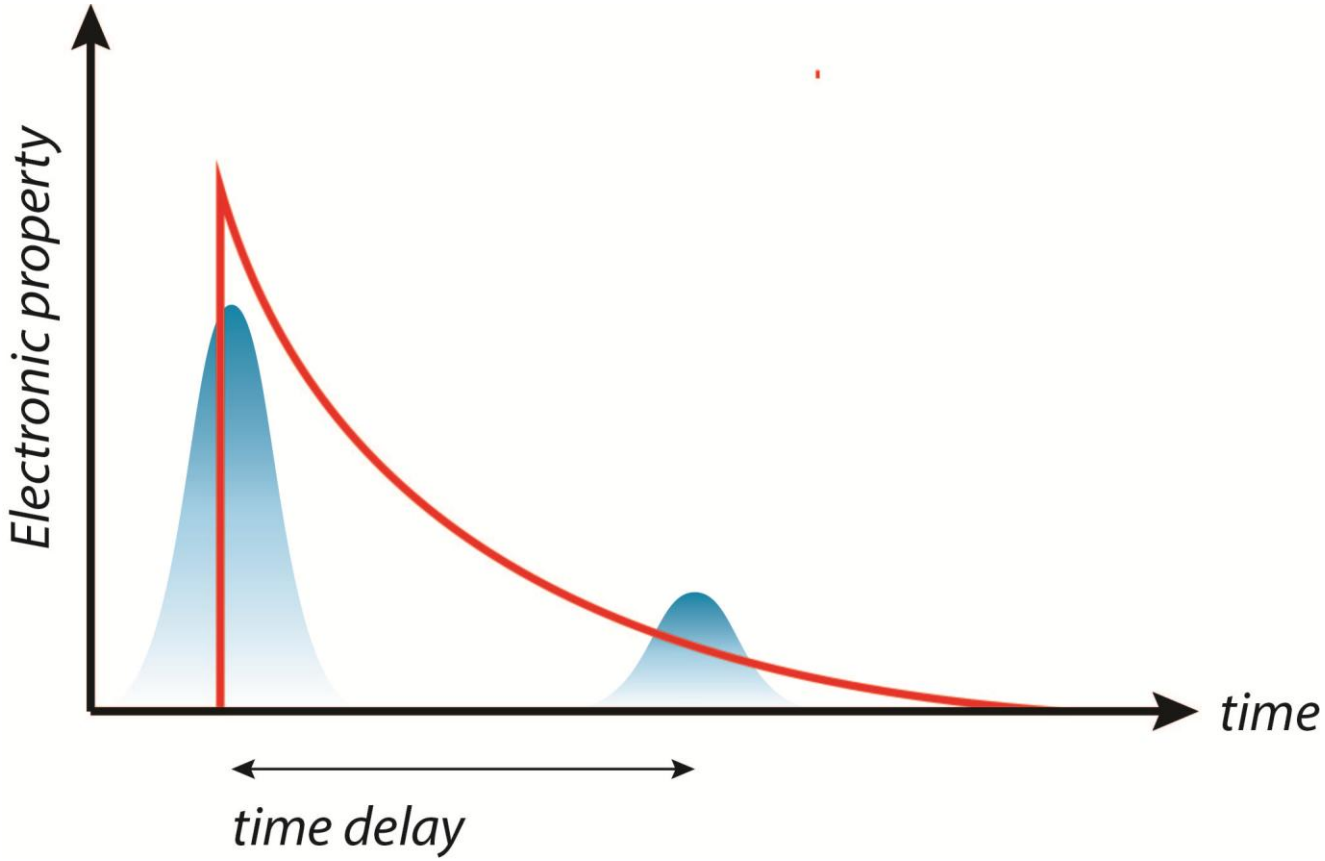
Grissonnanche *et al. To appear in Nat. Comm. (2014)*

➢ Quantum Oscillations



Ramshaw *et al.* arXiv:1409.3990v1

Advertisement: new pump-probe experiments



Prof. Nuh Gedik

Pump probe experiments

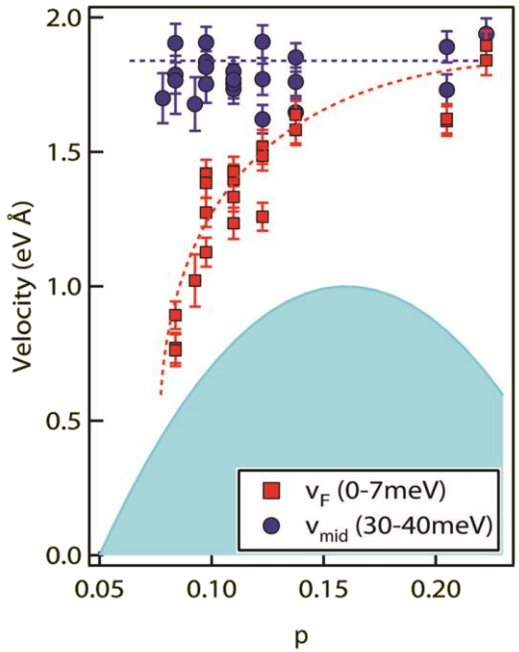
$CeCoIn_5$

Electron-doped cuprate

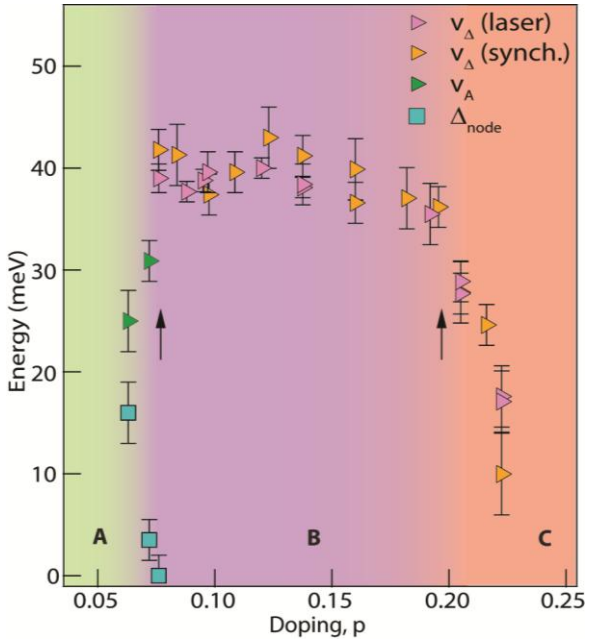
Conclusions

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?