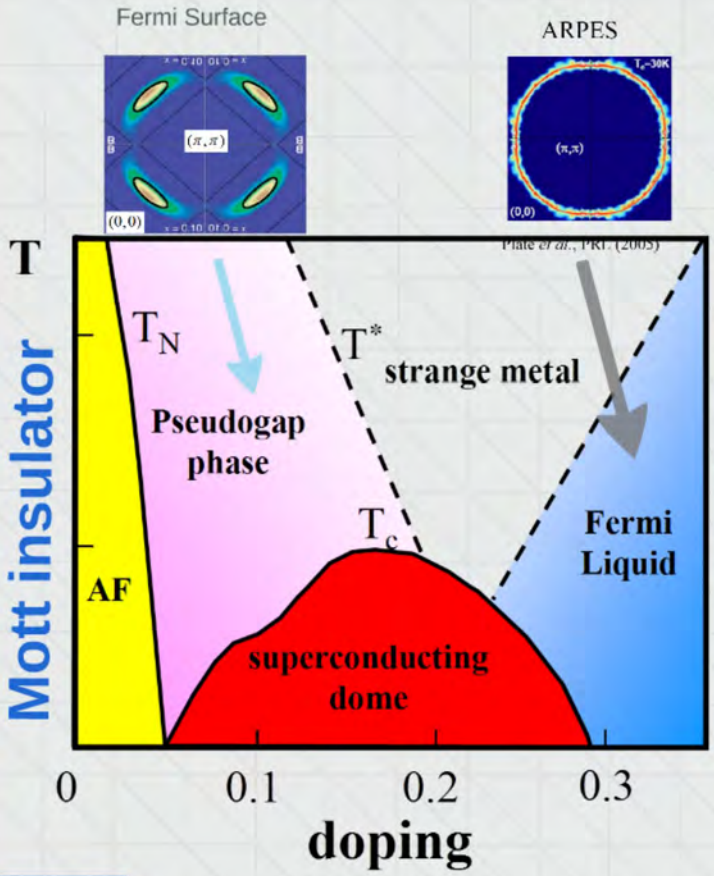
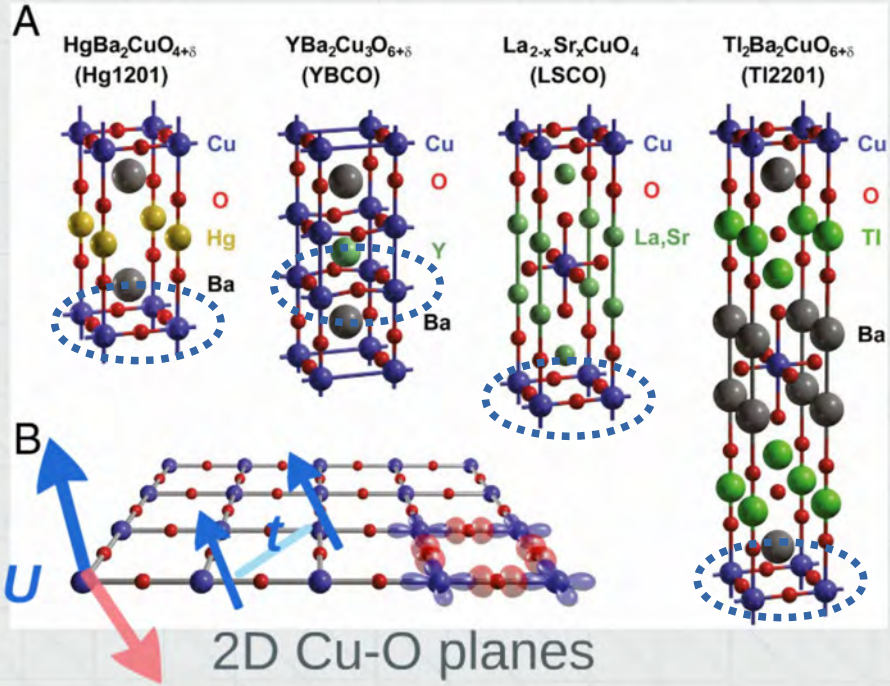
Pseudo-Gap to the Extreme

Marcello Civelli

Cuprates

1986 Bednorz and Muller



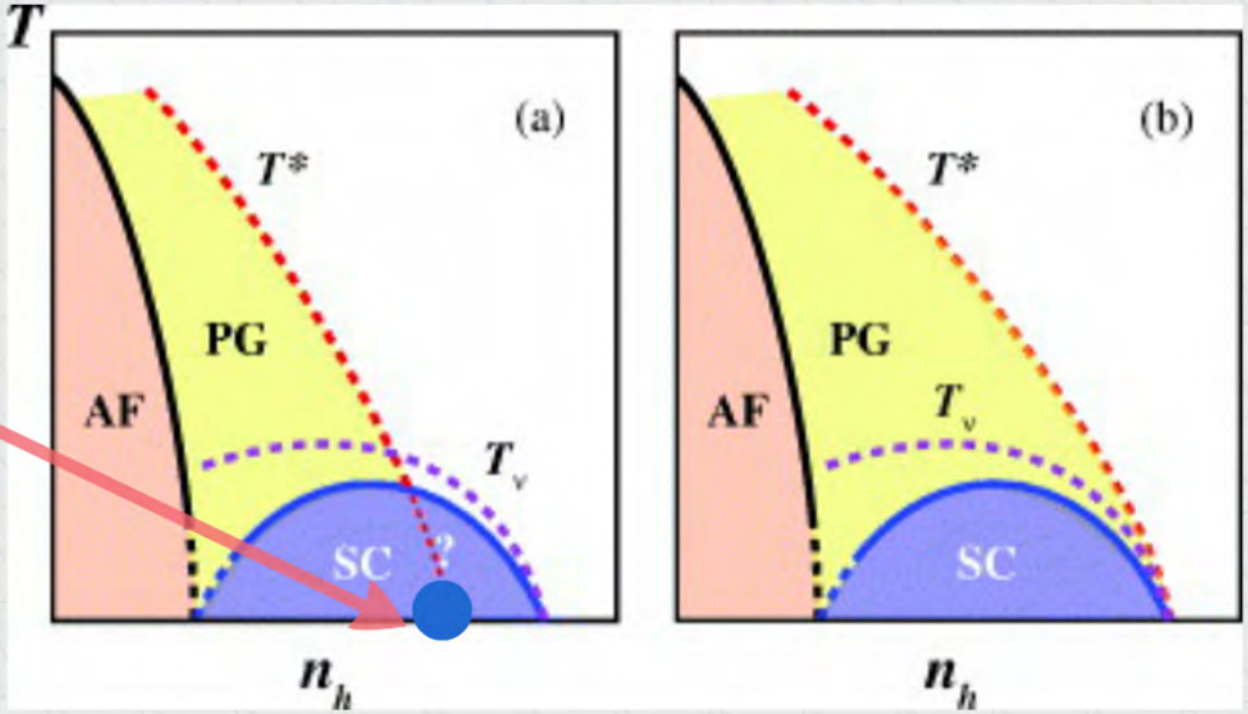


PSEUDOGAP IS AN UNCONVENTIONAL (BAD) METAL

PseudoGap vs SupraGap: a long-standing open issue

Competing orders

Quantum critical point



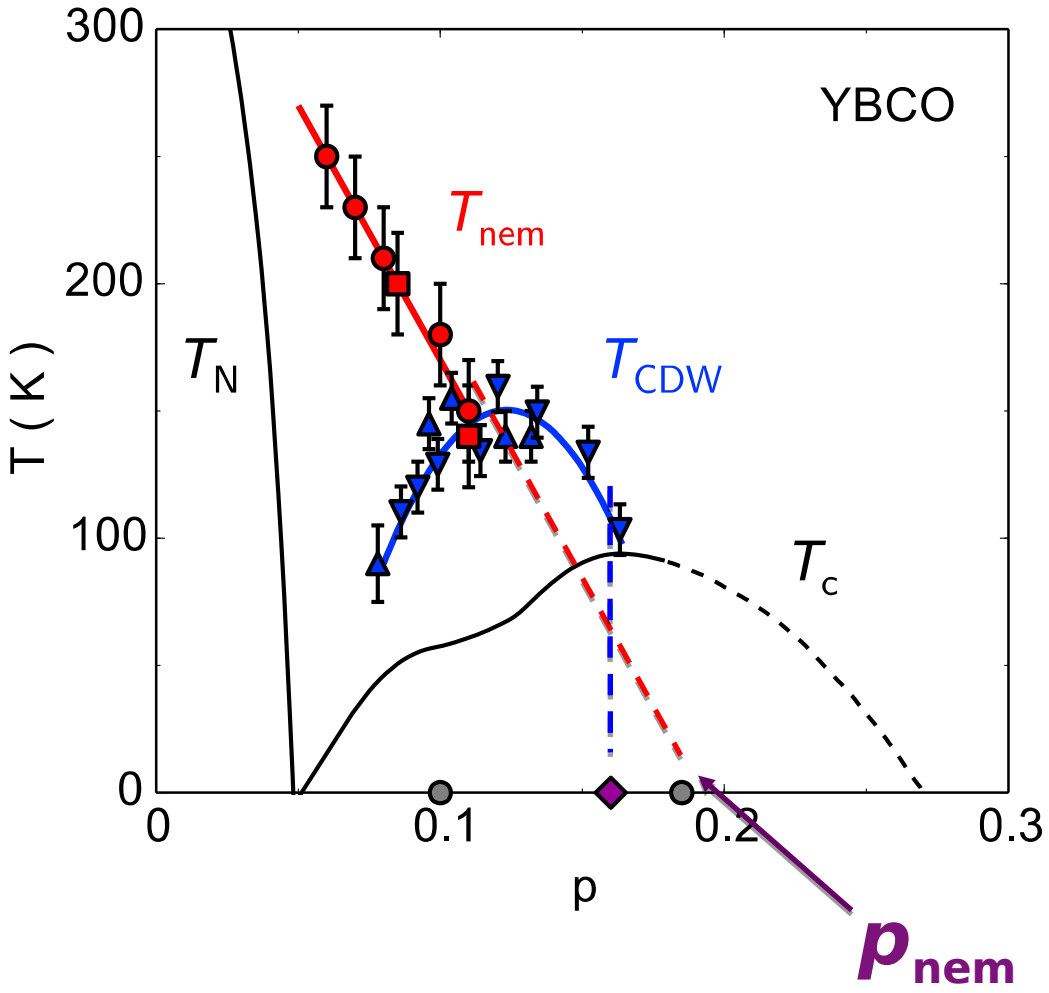
Anderson's RVB

"preformed" Cooper pairs

H. Alloul et al. EPL 91 37005 (2010)

IS THE HIGH-Tc MECHANISM BURIED ALREADY IN THE NORMAL PG PHASE ? CAN WE UNDERSTAND PG ?

PG phase: the longstanding search for a hidden order



COMPETING ORDERS :

CDW,
SDW,
loop currents,
Nematicity …. ?

Cyr-Choinière *et al.*, arXiv:1504.06972 (2015)

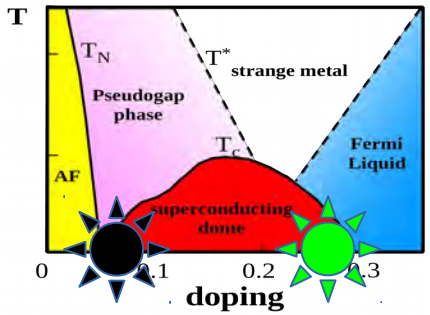
OUTLINE

Cluster DMFT :

1) WE DO NOT NEED A BROKEN ORDER TO EXPLAIN PG

2) PG vs SuperConductivity (different beasts? friends ?...):

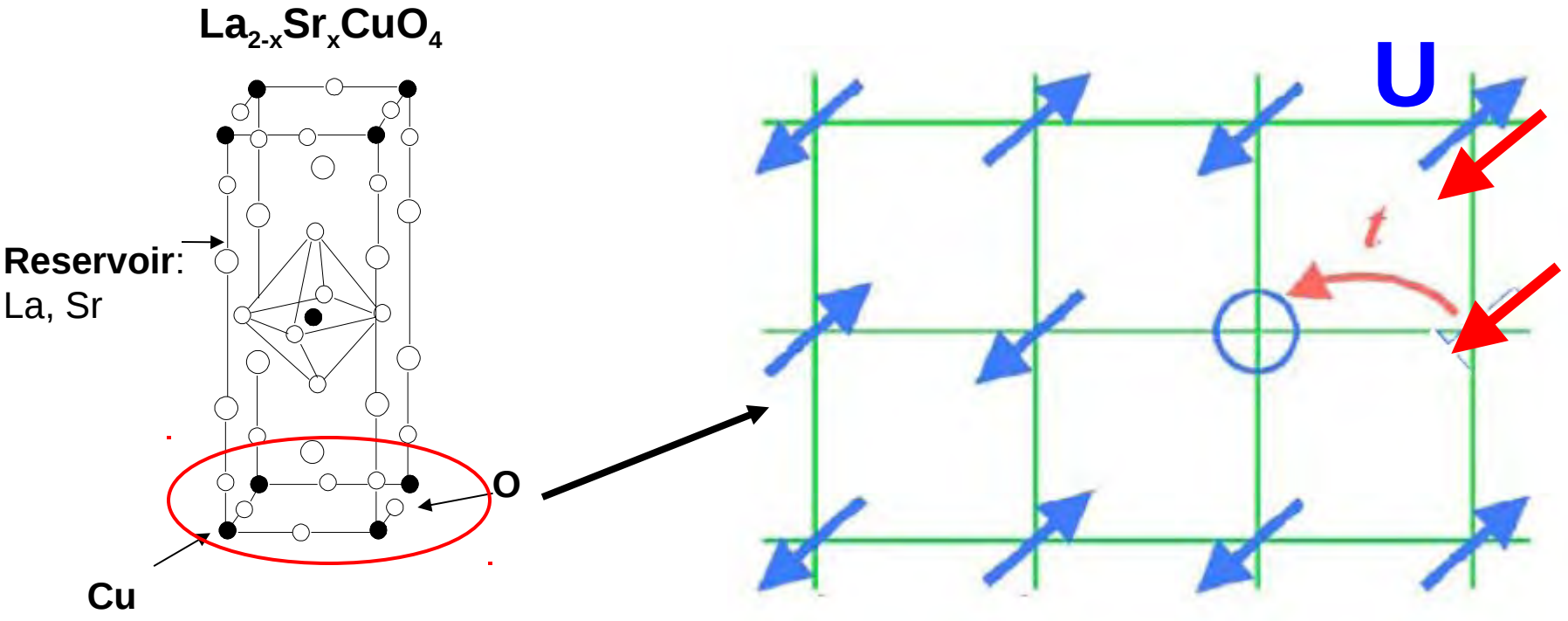
FOCUS ON EXTREMES OF THE DOME



- **Low doping: <u>non-nodal PG</u> vs <u>nodal SC gap</u> theory as compared to Raman experiments…**
- **High doping: Raman collapse of PG at a VanHove Sing.**

<u>CAN the interplay between PG and SC BOOST UP TC ?</u>.

Theoretical play-ground model

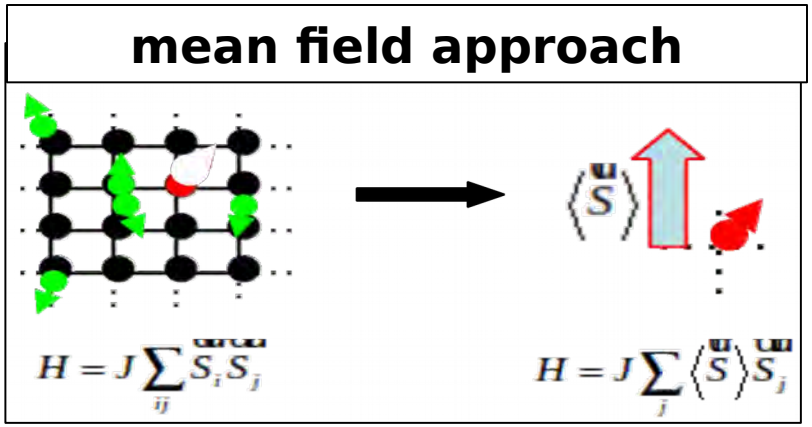


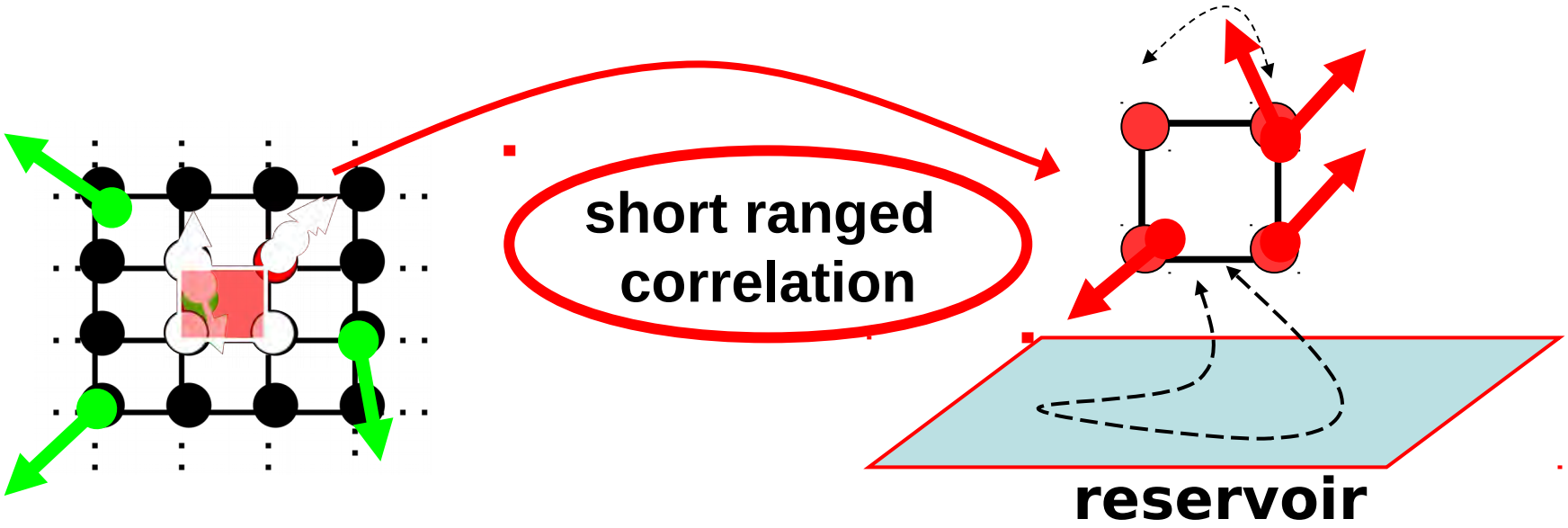
2D Hubbard Model

$$H = \underline{-t} \sum_{ij\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + \underline{U} \sum_{i} n_{i\downarrow} n_{i\uparrow}$$

The CLUSTER (2x2) DMFT

Th. Maier et al. , Rev. of Mod. Phys. 77,1027 ‘05; G. Kotliar et al., Rev. of Mod. Phys. 78, 865 ‘06.





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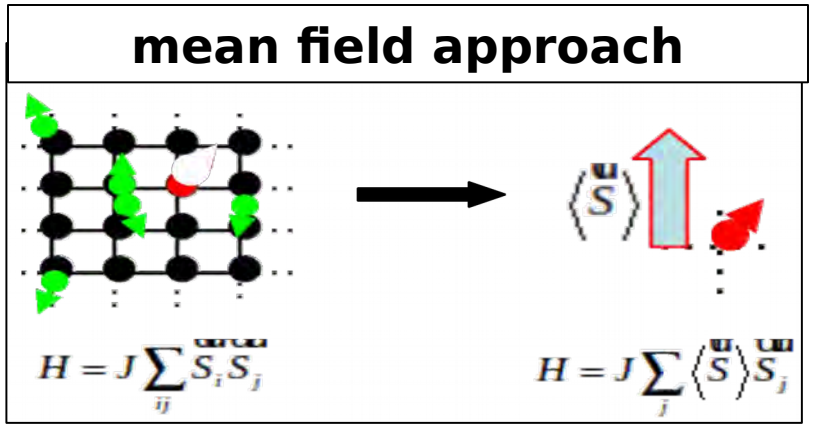
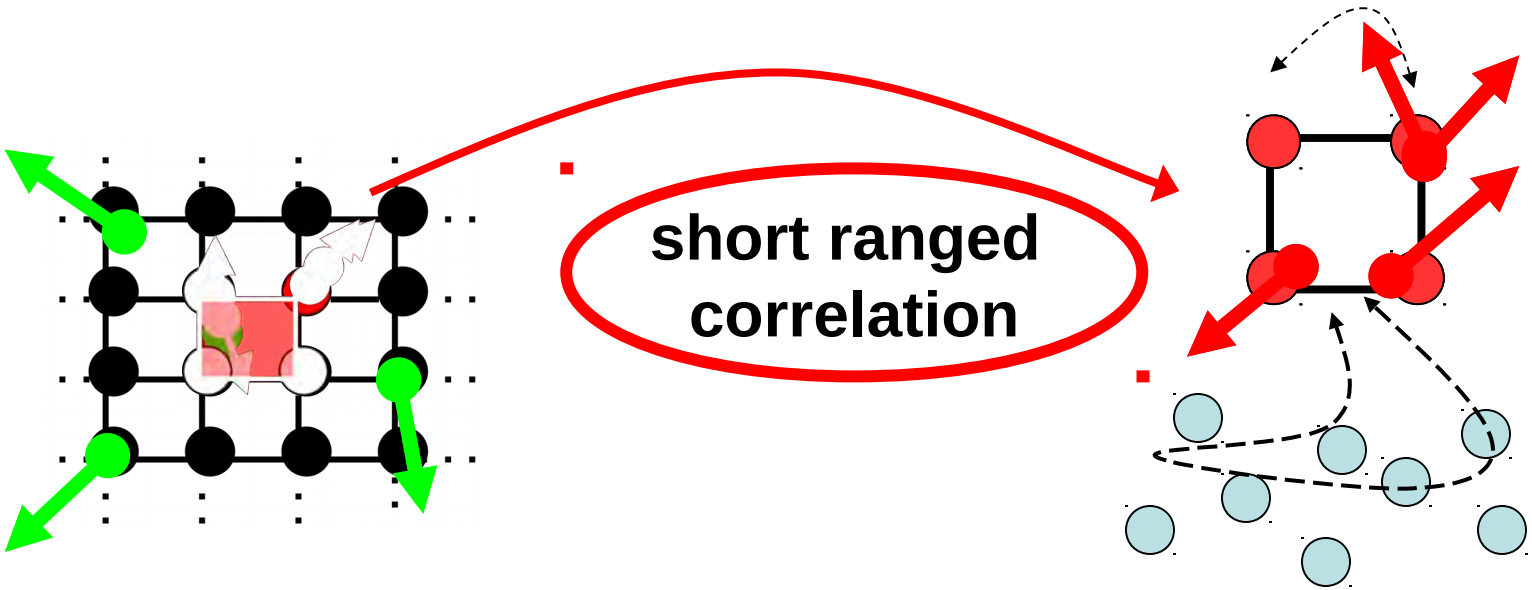




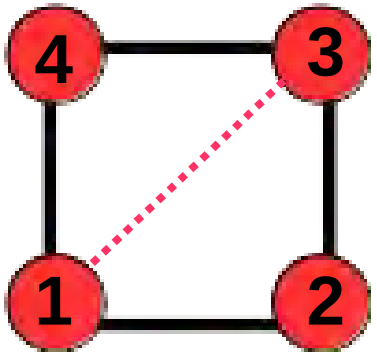
The CLUSTER (2x2) DMFT implemented with EXACT DIAGONALIZATION, Krauth & Caffarel ‘94

The CLUSTER (2x2) DMFT

GOAL: the one-article propagator → SPECTRAL FUNCTION

$$G(k,\omega)=\langle\langle c^{\dagger}_{-k\sigma} c_{k\sigma}\rangle\rangle(\omega) \qquad A(k,\omega)=-\Im\, G(k,\omega)$$

$$G_{loc}(\omega)=\langle\langle c^{\dagger}_{1\sigma} c_{1\sigma}\rangle\rangle(\omega)$$
$$G_{n.n}(\omega)=\langle\langle c^{\dagger}_{1\sigma} c_{2\sigma}\rangle\rangle(\omega)$$
$$G_{n.n.}(\omega)=\langle\langle c^{\dagger}_{1\sigma} c_{3\sigma}\rangle\rangle(\omega)$$



CDMFT (2x2) gives energy ω and approximate k-dependence:

$$G(k,\omega)=G_{loc}.+G_{n.n}(\cos k_x+\cos k_y)+G_{n.n.n}\cos(k_x)\cos(k_y)$$

DMFT sinlge site

Delicate point !

Normal state

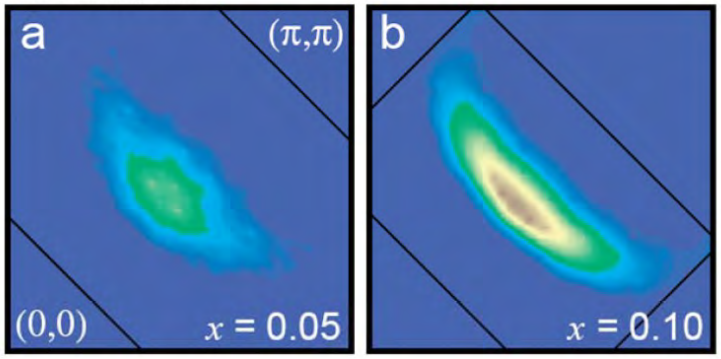
PSEUDOGAP and Fermi arcs

Civelli et al: PRL 95, 106402 (2005)

$$A\left(k,\omega=0\right)$$

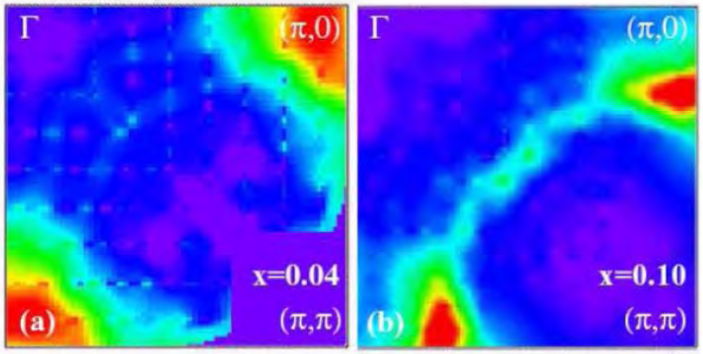
ARPES Experiments

hole doped



K.M. Shen et al., Science '04

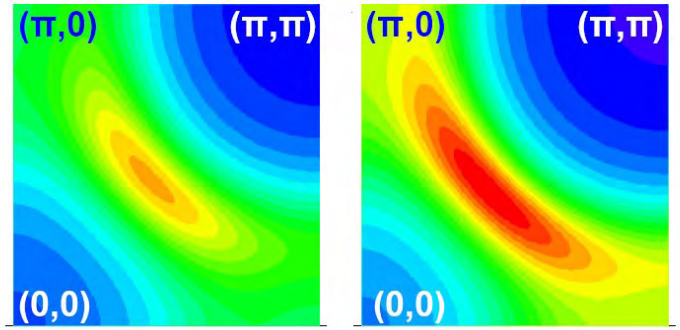
e- doped



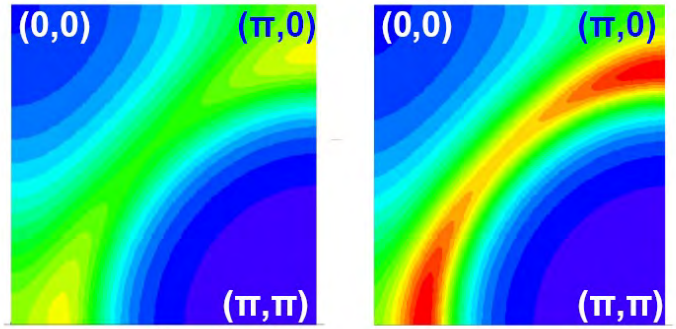
N.P. Armitage et al., PRL '02

CDMFT Theory

hole doped

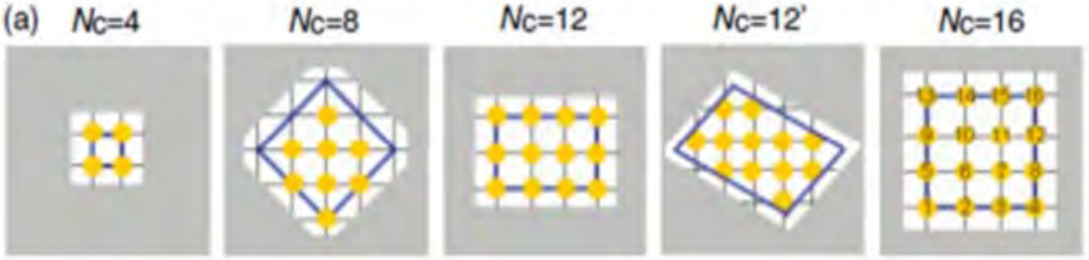


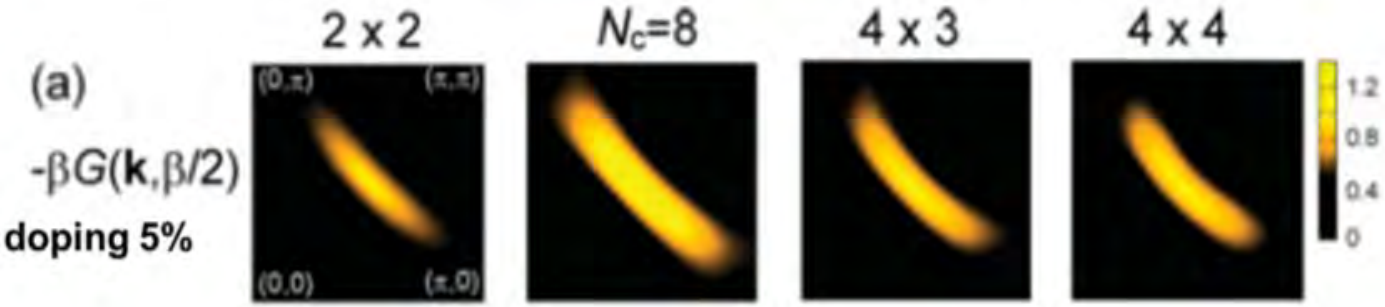
e- doped



Increasing the cluster size

Shiro Sakai et al. PRB 85, 035102 (2012)
CDMFT + Continuous Time QMC





The Pseudogap is a solid feature!

Many groups have been developing **CDMFT (DCA)** to study the **normal and SC state of the 2D Hubbard Model**

Mark Jarrell and co-woekers (DCA, large clusters)
G. Kotliar and K. Haule group in Rutgers (CDMFT)

A.-M. Trambley recently in collaboration with
G. Sordi and K. Haule (CDMFT CTQMC)

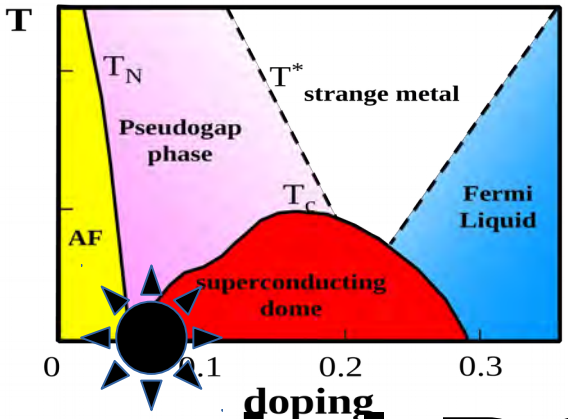
A.J. Millis and E. Gull (DCA CTQMC)

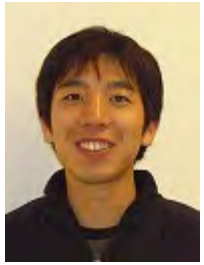
A. Georges, O. Parcollet, M. Ferrero (from small to large cluster....CTQMC and DCA)

S. Sakai and M. Imada (CDMFT, ED, CTQMC...

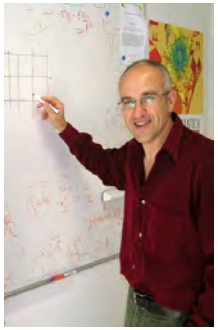
Everybody agrees on the gross picture of the PG

Underdoped side





Non-nodal PG v.s. d-wave nodal SC gap



S. Sakai et al.

Phys. Rev. Lett. 111, 107001 (2013)

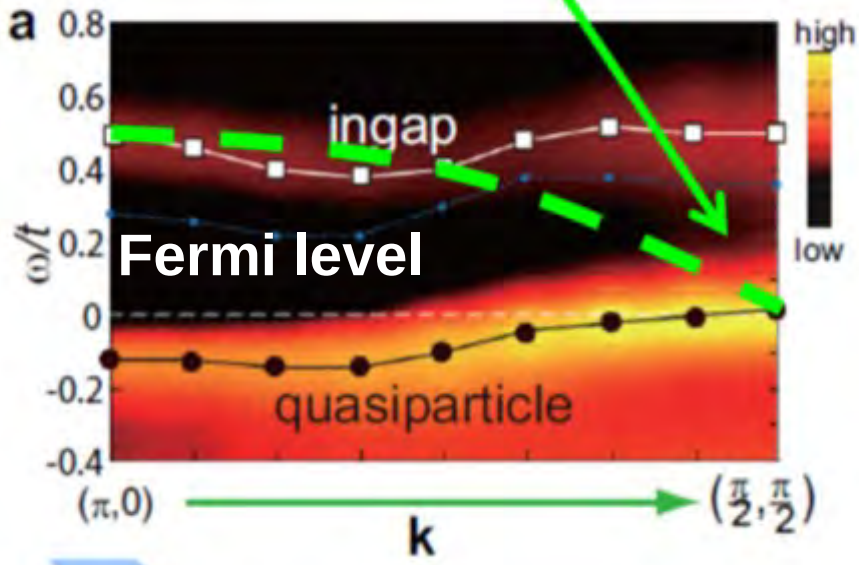
Experiments : Sacuto group Paris 7

PG abd SC gap have different structures in the nodes and different particle-hole symmetry

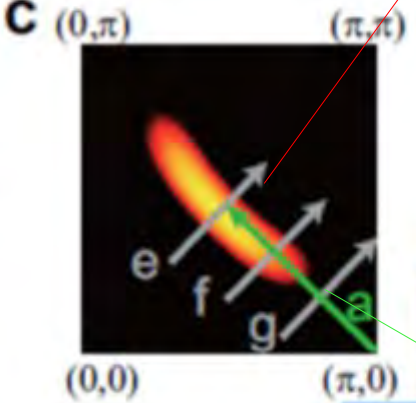
If the gap were d-wave,

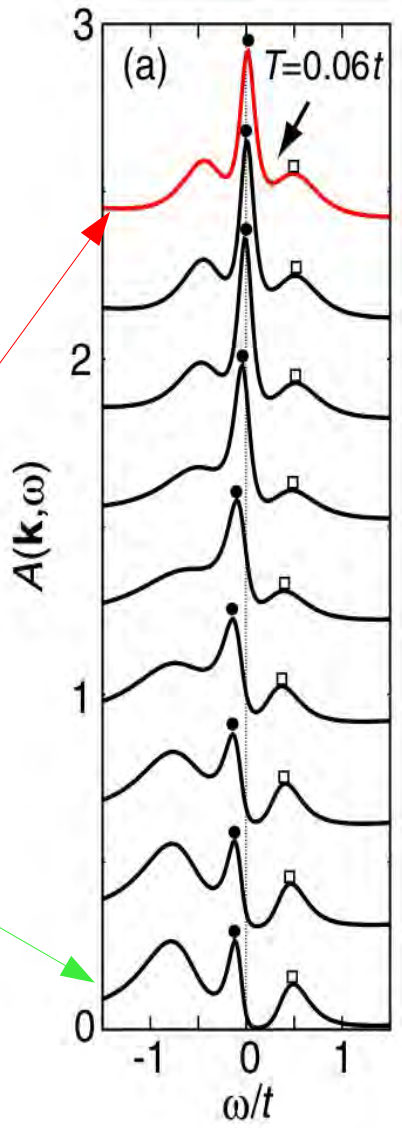
Nodes are expected!

$A(k_a,\omega)$

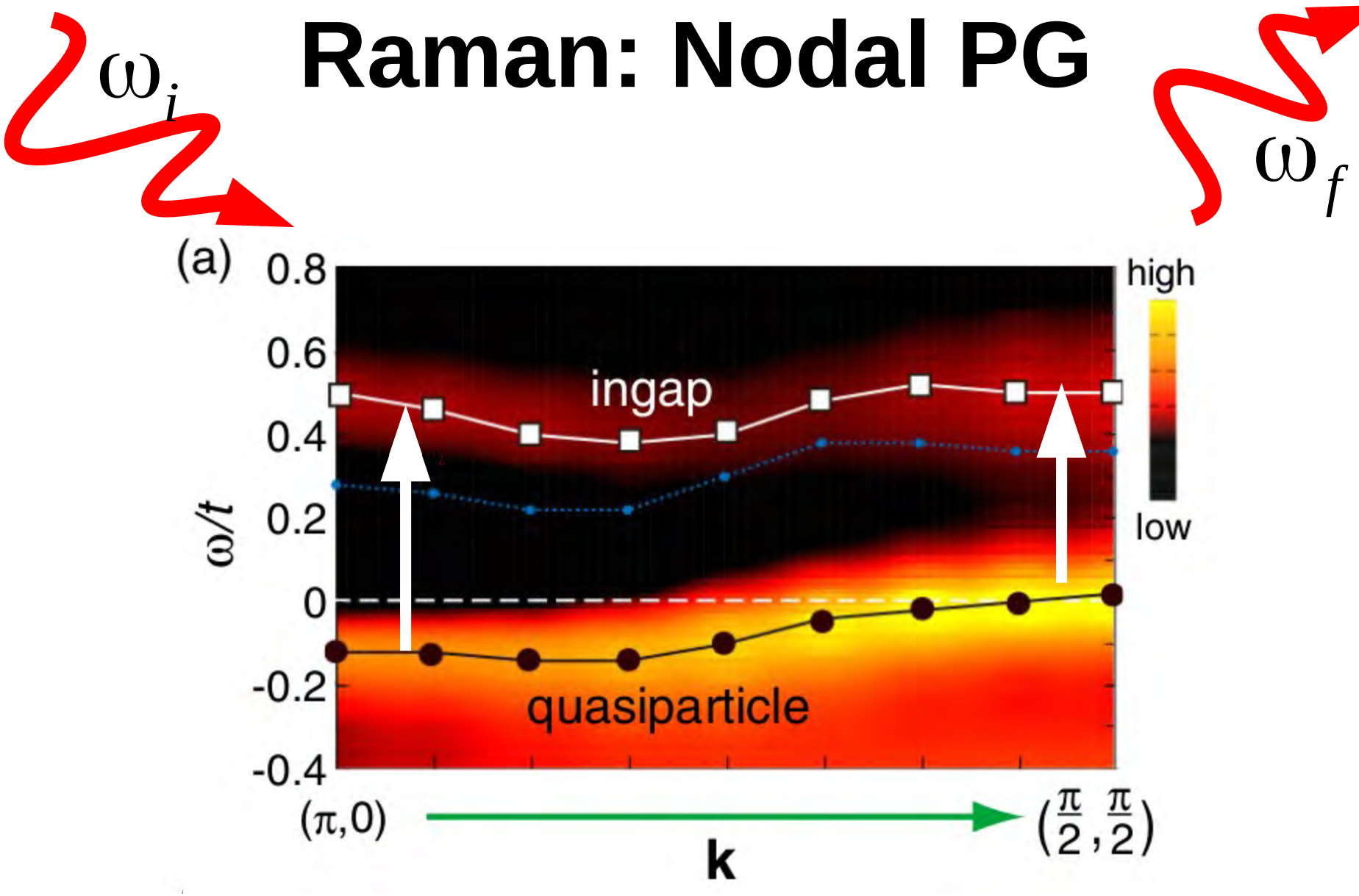


$A(k,\omega=0)$





Raman: Nodal PG

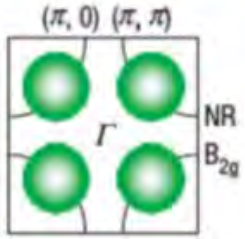


RAMAN RESPONSE :

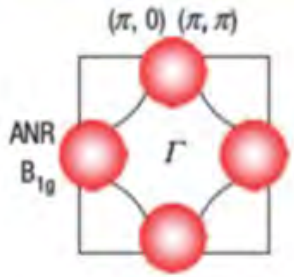
1) Polarized light sees different regions of k-space

2) Access the $\omega > 0$ unoccuppied spectrum

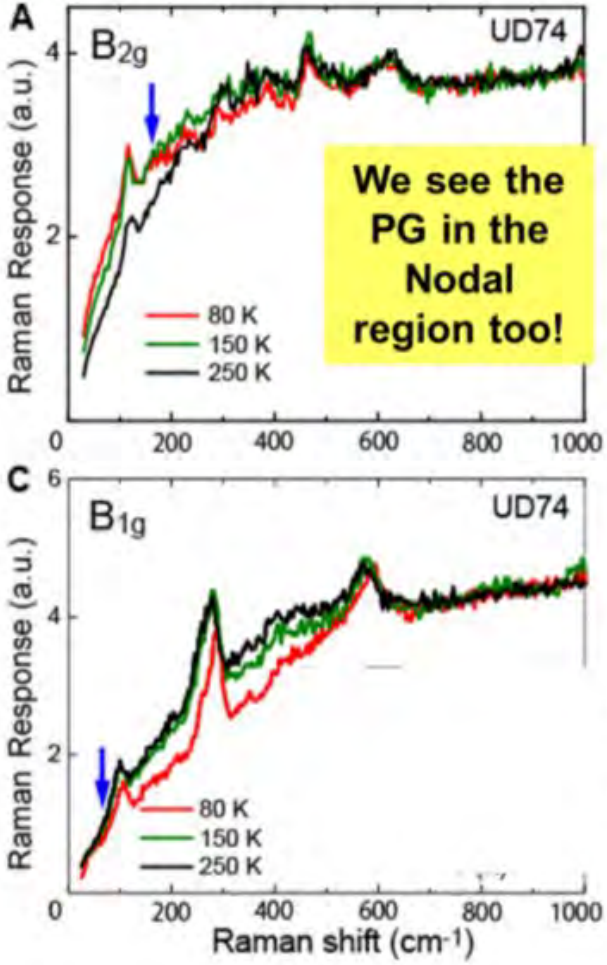
B2g response



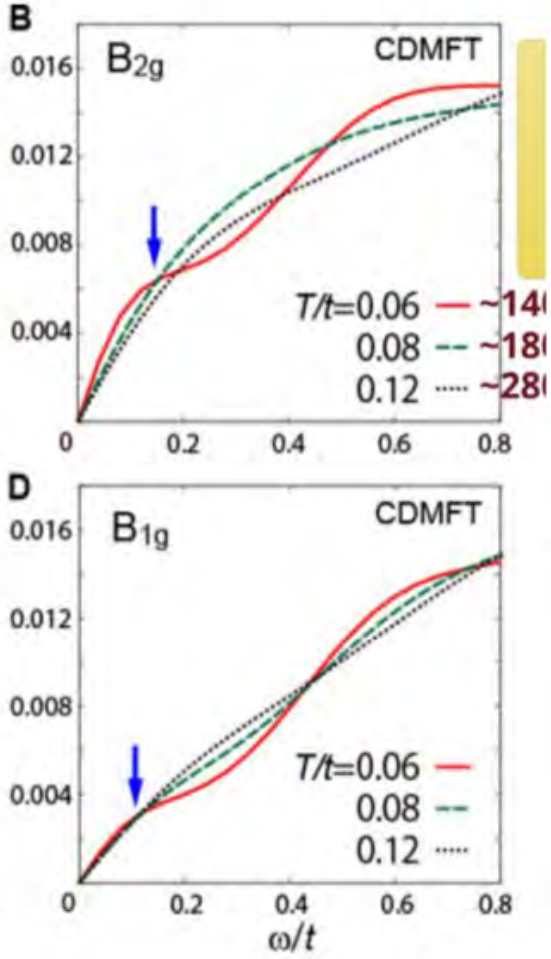
B1g response



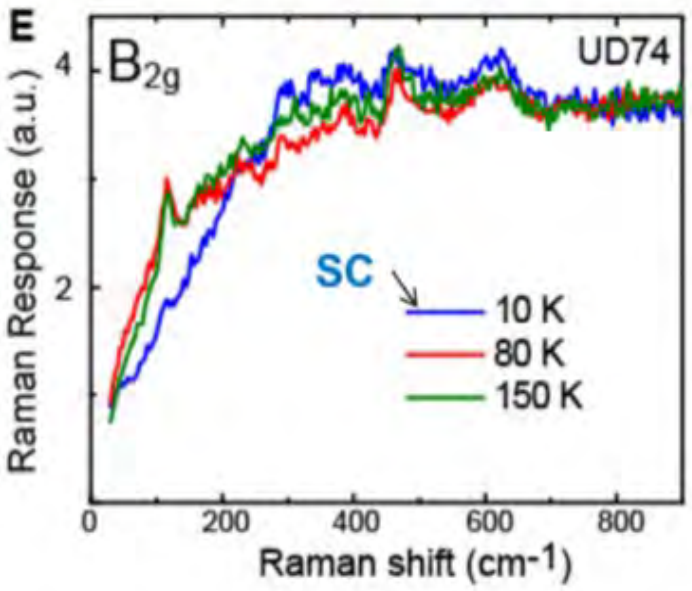
Experiment Bi2212

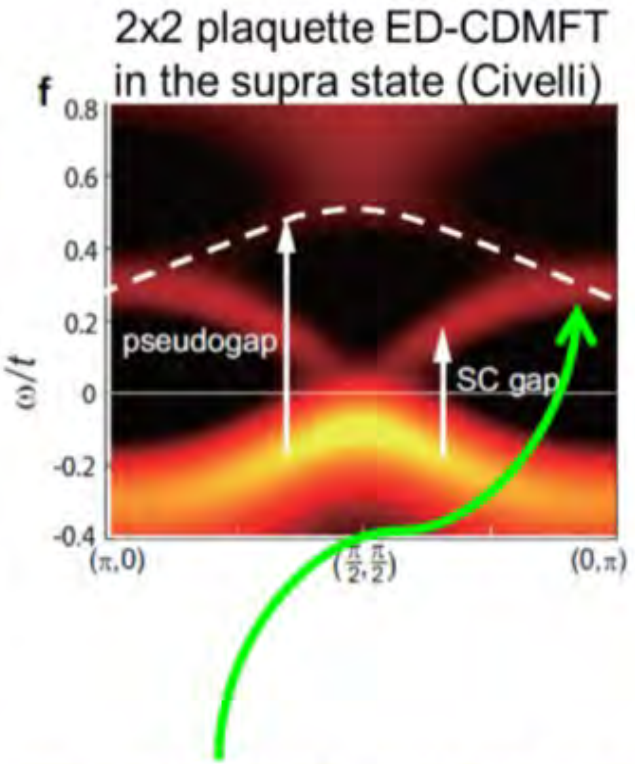


CDMFT Theory



Pseudo and superconducting gaps in Raman B2g (nodes) Alain Sacuto SQUAP group ay Paris 7

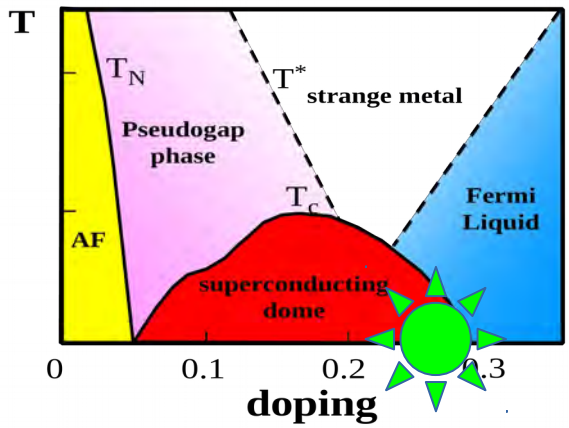




The opening of the SC d-wave gap (Bogoliubov bands formation) appears to insert electronic states within the s-wave pseudogap *at the nodes* (B2g Raman)

See also recent arXiv I. Gull, Olivier Parcollet, A. J. Millis, 16-site DCA
In the superconducting state

Overdoped side



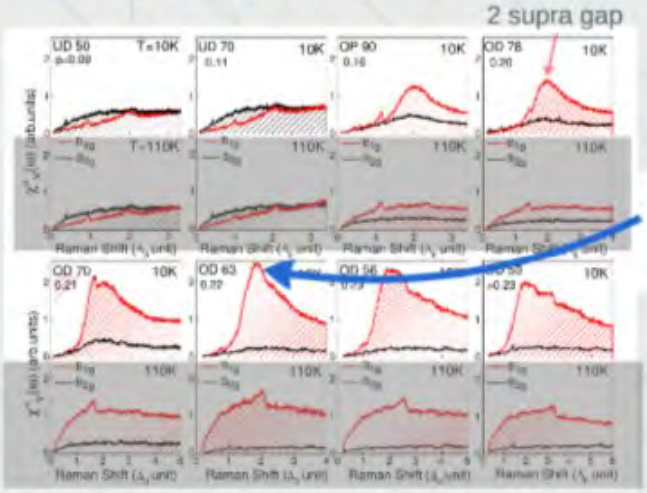
Collapse of the PG @ a Lifshitz transition

Raman experiments of the SQUAP gropu at Paris Diderot (**Benhabib**, Sacuto...)
Theoretical interpretation : I. Paul, Paris Diderot
Physical Review Letters 114, 147001, 2015

Experiments by the Squap team, Paris Diderot

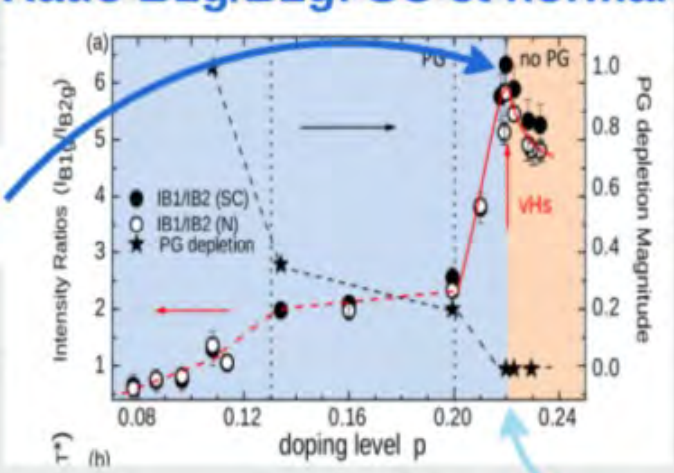
S. Benhabib et al. PRL 114, 147001, 2015

At pc ~ 0.22 we see an unexpected maximum in the Raman response !
Sacuto group @ Paris 7

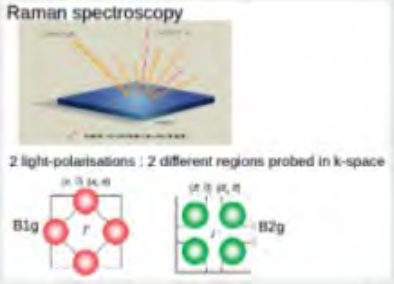


maximum here
p=0.22

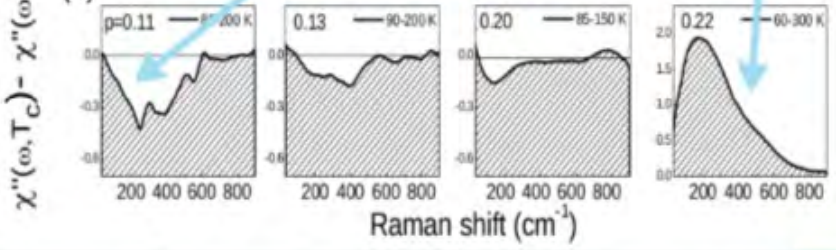
Ratio B1g/B2g: SC et normal



PG disappears!

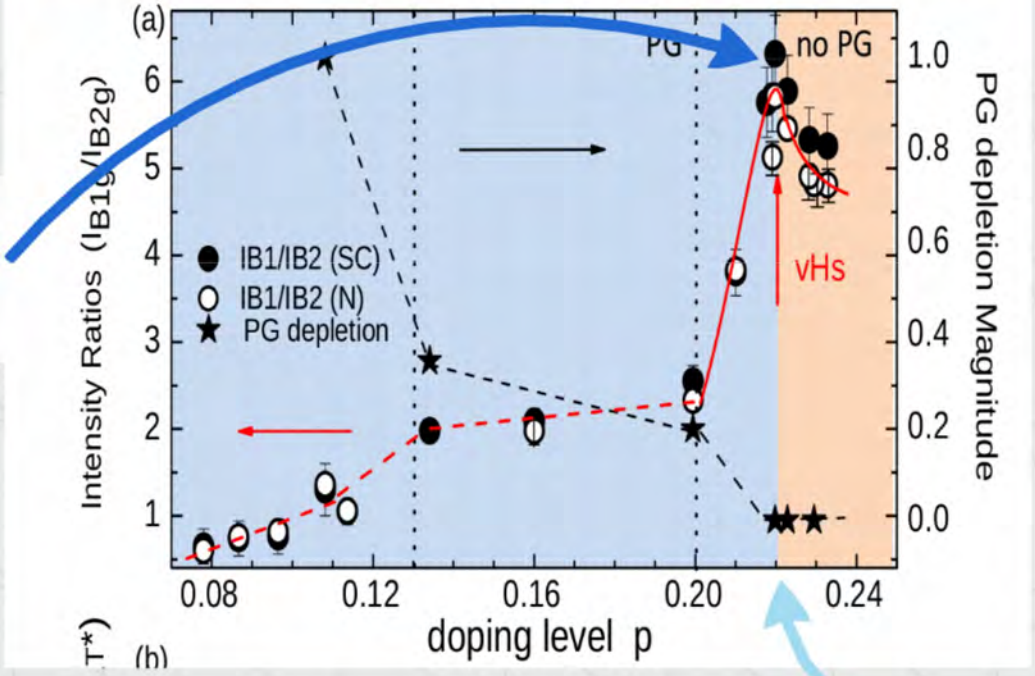


pseudogap



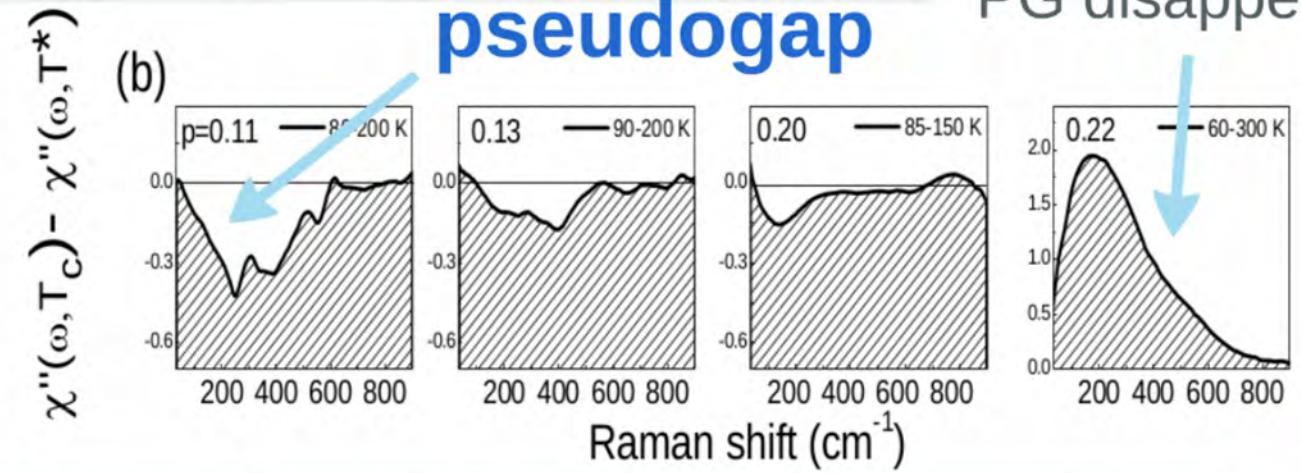
Ratio B1g/B2g: SC et normal

- maximum here p=0.22



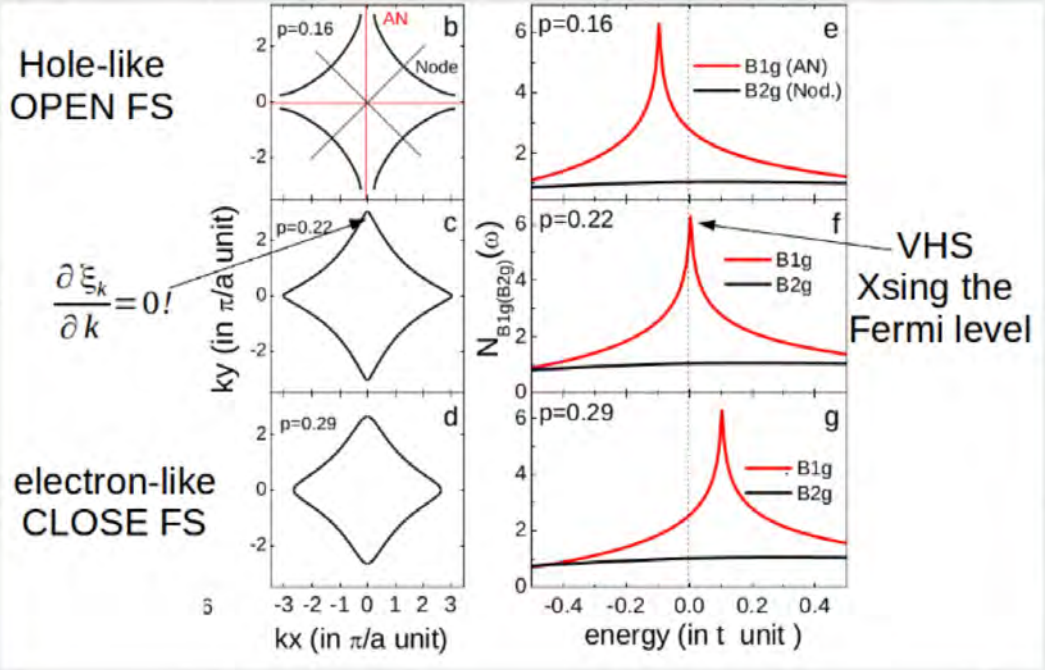
PG disappears!

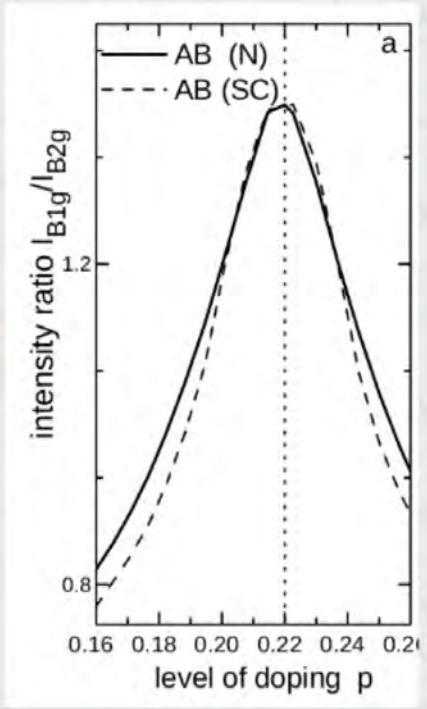
pseudogap



Theory: Vhs and Lifshitz transition

tight-binding Model of Bi2212, collab. with I. Paul





S. Benhabib et al. PRL 114, 147001, 2015

CONCLUSIONS

Van hove singularity can explain the maximum in the B1g reponse !!

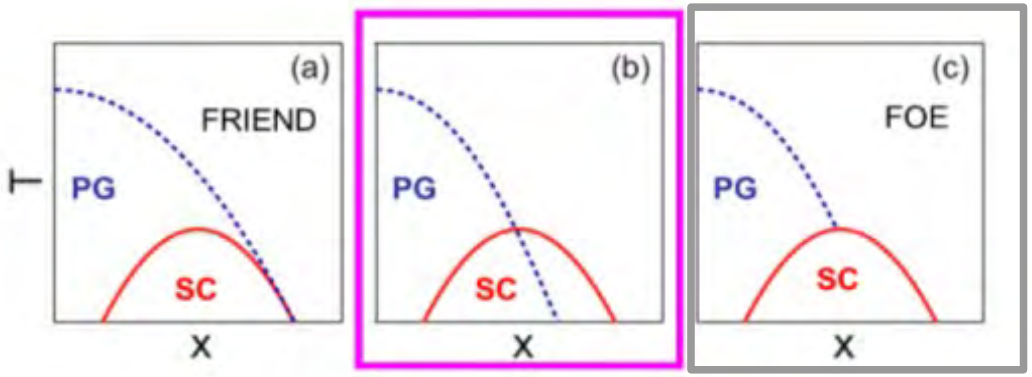
This point marks a change in topology of the Fermi surface (Lifshitz transition), no QCP needed

The SC seems not much affected by this transition (and this explains the differences among different materials...)

SC and PG are different animals!! (but no QCP needed)

Conclusions:
PG and SC looks having a different structure

The pseudogap: friend or foe of high Tc?
Norman, Pines, Kallin (2005)



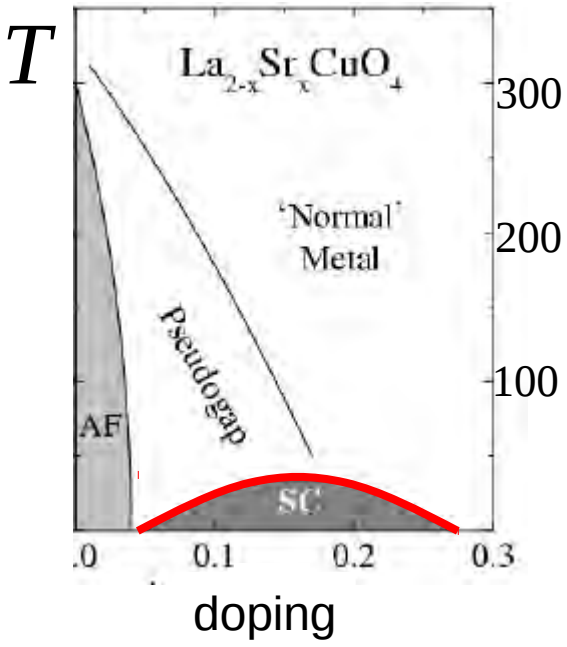
Competing scenarios!

Shiro Sakai et al. arXiv: 1207.5070

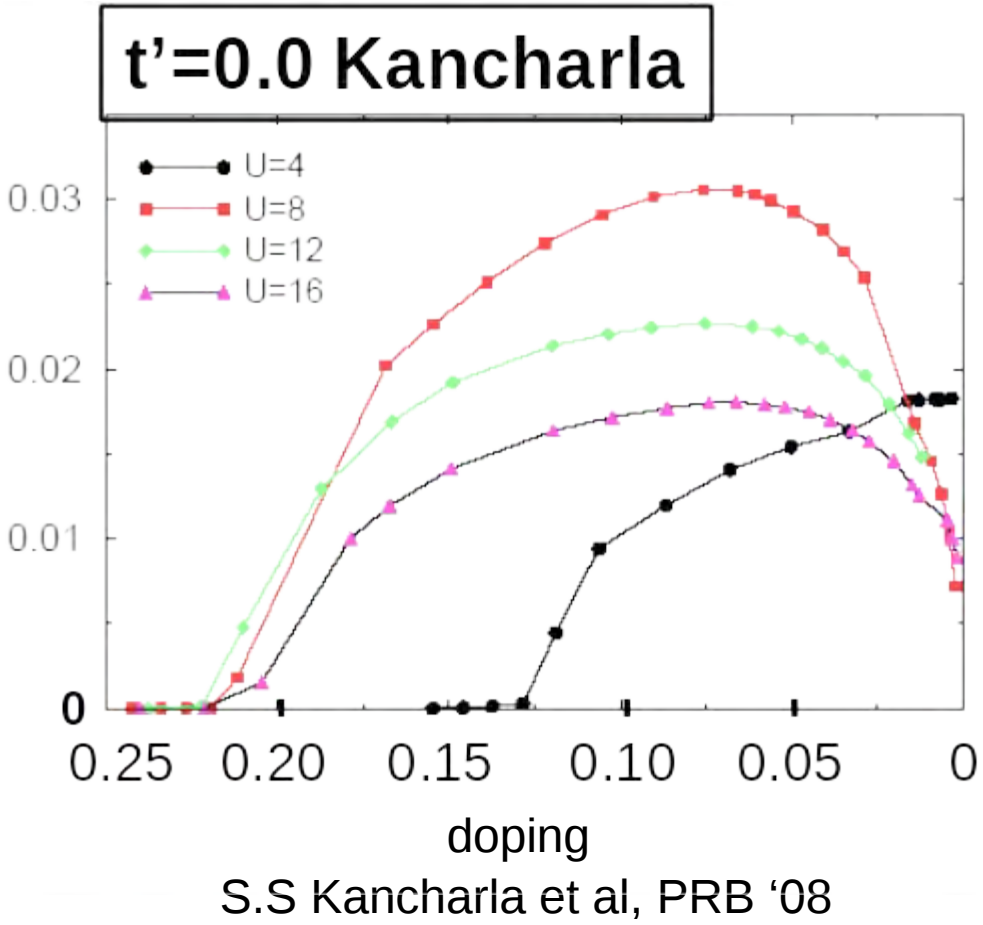
PG and Superconducting state

Superconducting d-wave state!

order parameter in the Hubbard Model $\phi = \langle c1\uparrow\ c2\downarrow \rangle$



$\Phi = \langle c_{1\uparrow} c_{2\downarrow} \rangle$



S.S Kancharla et al, PRB '08

Sordi-Tremblay-Haule CDMFt CTQM
Phys. Rev. B 87, 041101(R) (2013)

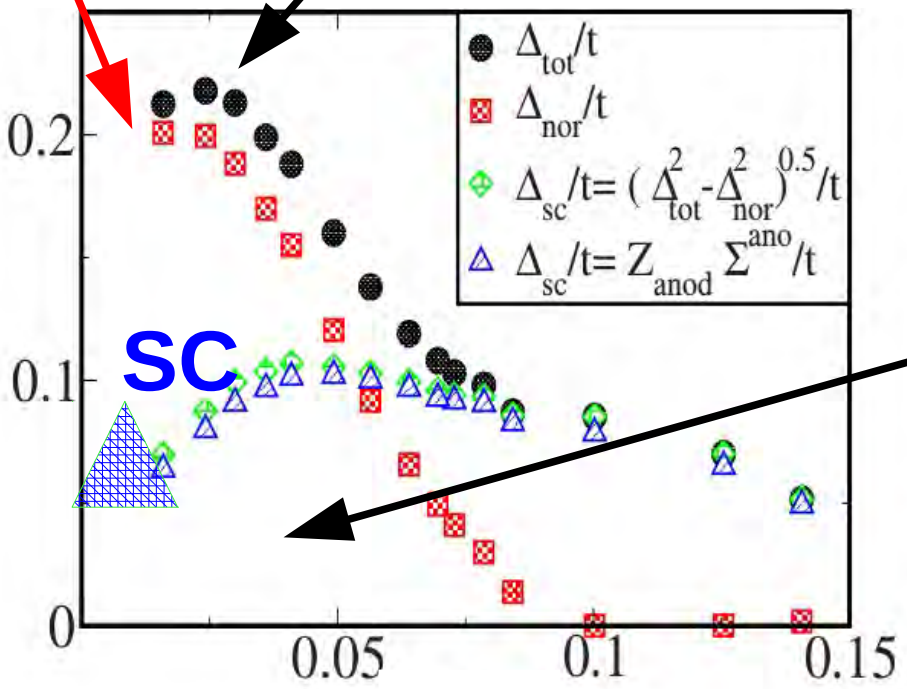
PG co-existing with SC

In the underdoped side

Total gap

PG

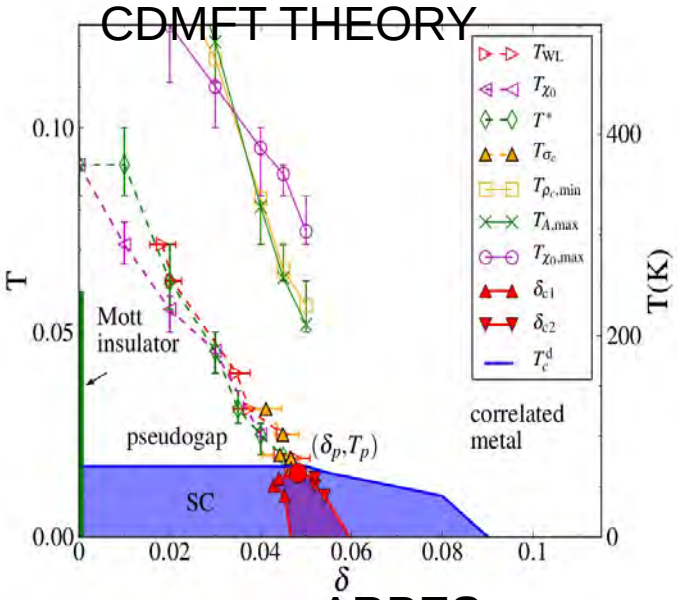
CDMFT T=0



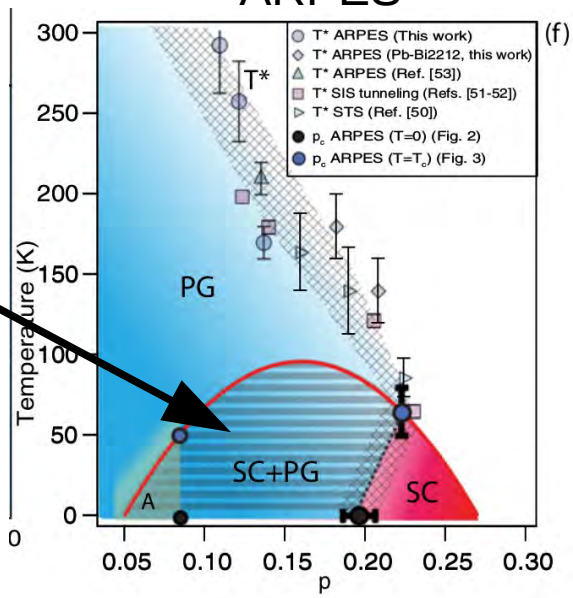
Civelli PRB 2009

PG + SC

CDMFT THEORY



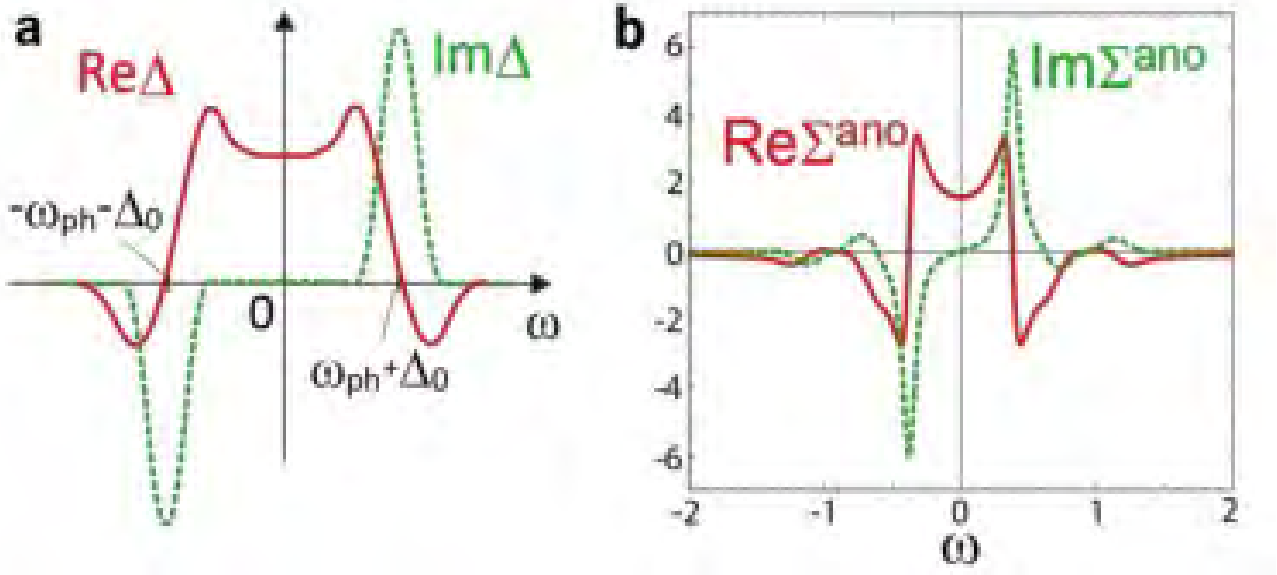
ARPES



Vishik et al. | PNAS | 2012 | vol. 109 | no. 45

Pairing function (2x2 cdmft U=8t)

Sakai, Civelli, Imada, http://arxiv.org/pdf/1411.4365.pdf

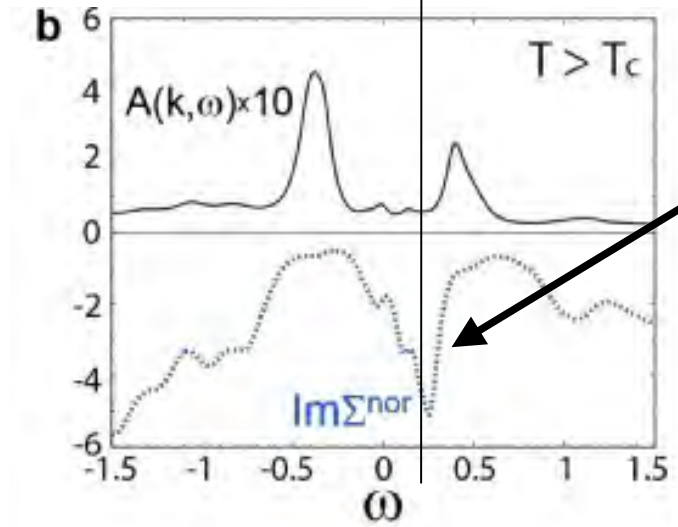


The peak in ImΣano is in standard (Migdal-Eliashberg) theory associated to the boson mediating the pairing interaction

$$\mathrm{Re}\Delta(\mathbf{k},\omega=0)=\frac{2}{\pi}\int_0^{\infty}\frac{\mathrm{Im}\Delta(\mathbf{k},\omega')}{\omega'}d\omega'$$

Phonos, spin-density waves,...

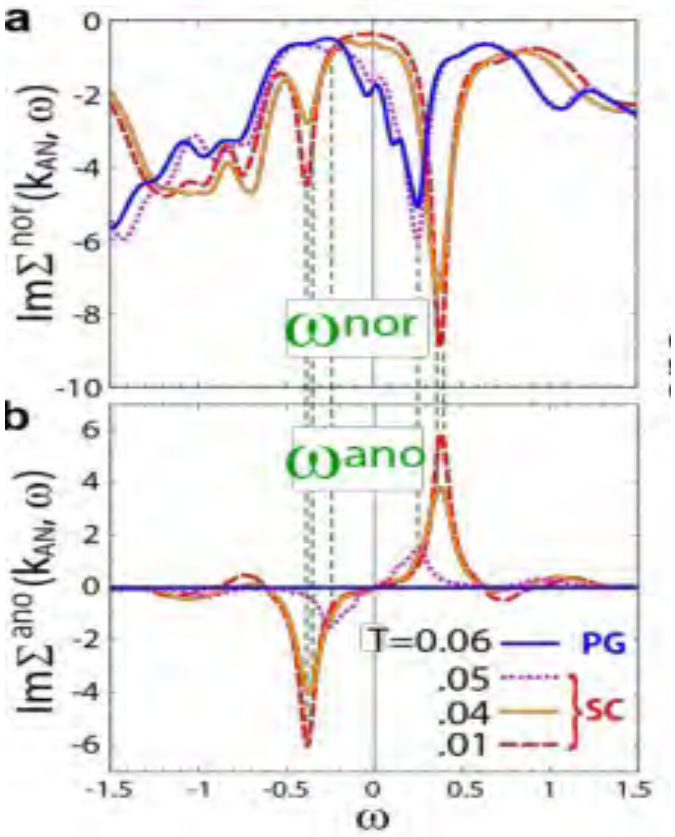
CDMFT+ ED (with temperature)



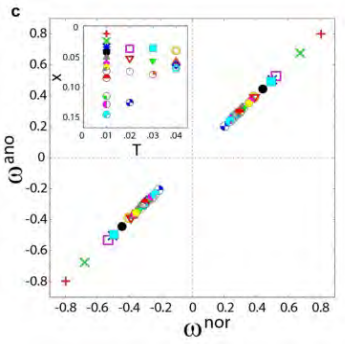
The peak in ImΣnor is responsible for the pseudogap in A(k,ω)

Peak in $Im\Sigma_{ano}$ has been seen already in CDMFT

Haule and Kotliar PRB 76 2007
Maier Poilblanc Scalapino PRL 2008
Civelli PRL 2009
Kyung, Senechal, Trambley PRB 2009
Millis and Gull PRL 2013, PRB 2015 **BUT**

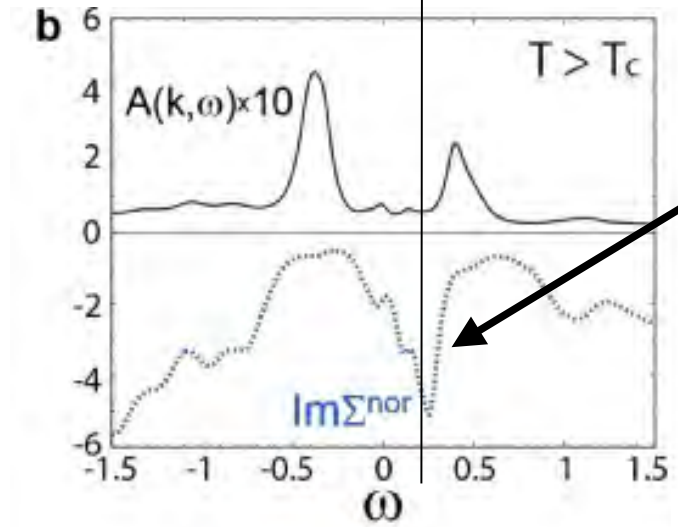


Sakai, Civelli, Imada arXiv :1411.4365



The peak in ImΣnor and ImΣano are the SAME

CDMFT+ ED (with temperature)



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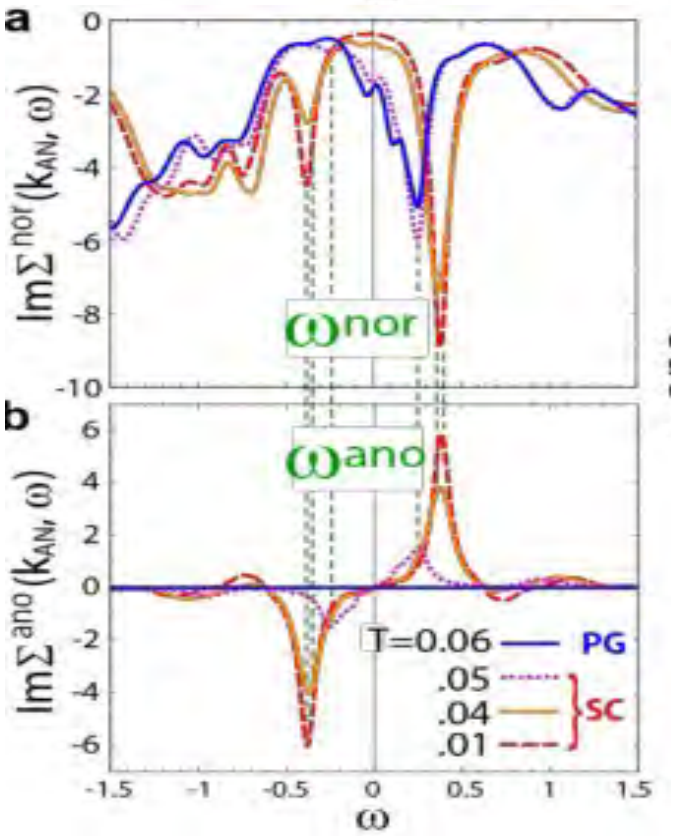
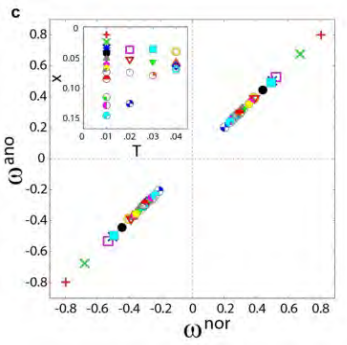


Sakai, Civelli, Imada arXiv :1411.4365



The peak in ImΣnor and ImΣano are the SAME

Mechanism driving the PG drives the H-Tc ?

$$\Re\,\Sigma_{ano}(k,\omega=0)=\frac{1}{\pi}\int\frac{\Im\,\Sigma_{ano}(k,\omega')}{\omega'}\,d\omega'$$

1) **A peak in ImΣ_{ano} can push up Re$\Sigma_{ano}(\omega=0)$,**

the peak comes from the PG

$$\Delta(k,\omega)=\frac{\Sigma_{ano}(k,\omega)}{\left(1-\frac{\Sigma_{nor}(k,\omega)-\Sigma_{nor}(k,-\omega)^{\dagger}}{2\omega}\right)}$$

$$\Delta(k,\omega)=Z(k,\omega)\,\Sigma_{ano}(k,\omega)$$

2) **A peak in ImΣ_{nor} implies $Z\rightarrow 0$, destroys Δ** (Anderson ?

Interpretation in terms of « hidden fermion » by M. Imada

Sakai, Civelli, Imada arXiv :1411.4365

CONCLUSIONS

1) Cluster DMFT :

WE DO NOT NEED A BROKEN ORDER TO EXPLAIN PG, which comes from Mott physics (pole in Σ_{nor})

2) PG and SC are competing (in overdoped and underdoped sides, agreement with Raman....)

3) The origin of the PG creates peaks in the pairing function which can boost Tc

4) At the same time PG=MOTT, quasiparticles and SC are bound to go down approaching the Mott insulator

PG friend AND foe of H-Tc