“s”-wave pseudogap in underdoped cuprates

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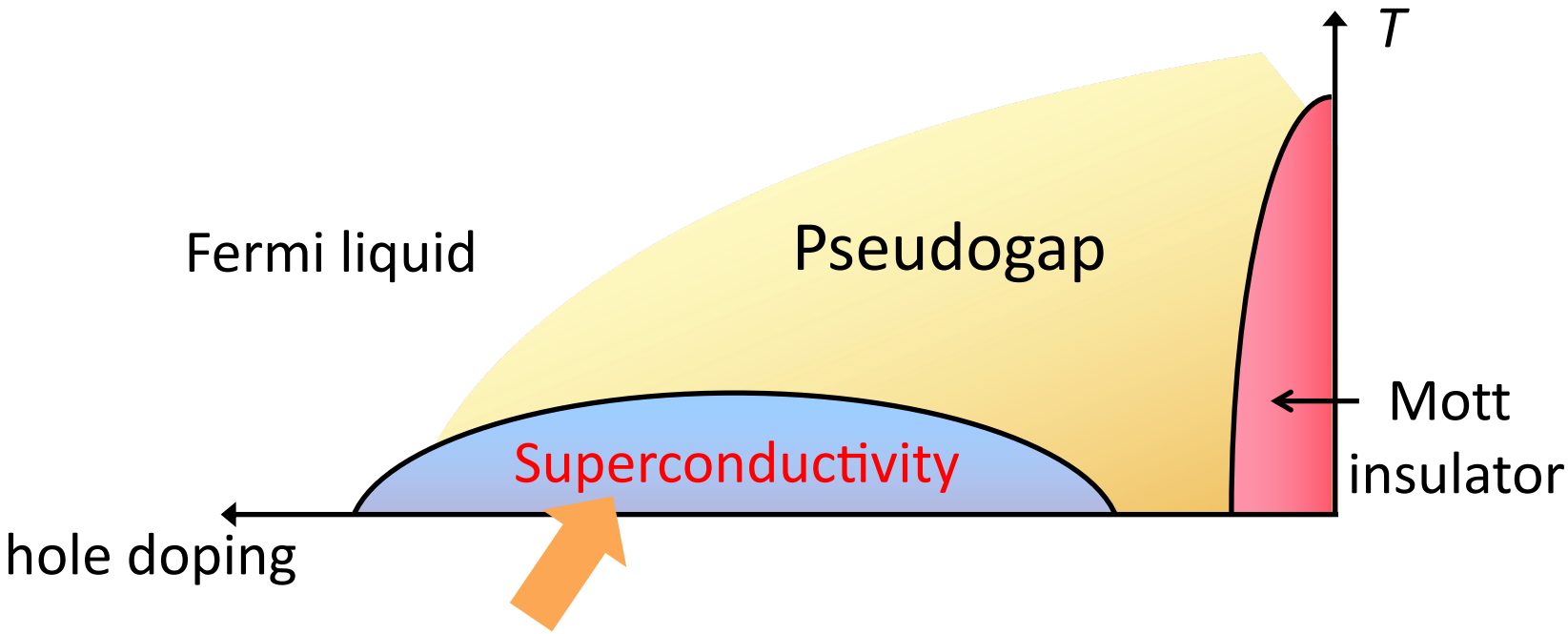
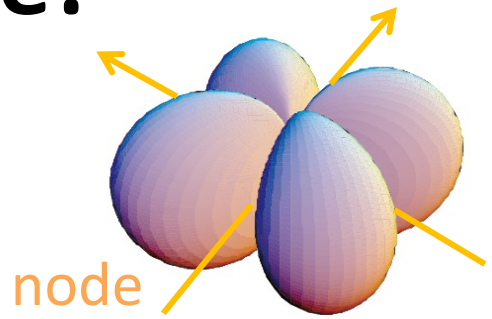
S.S., S. Blanc, M. Civelli *et al*., PRL **111**, 107001 (2013)

Cuprates are *d*-wave superconductor



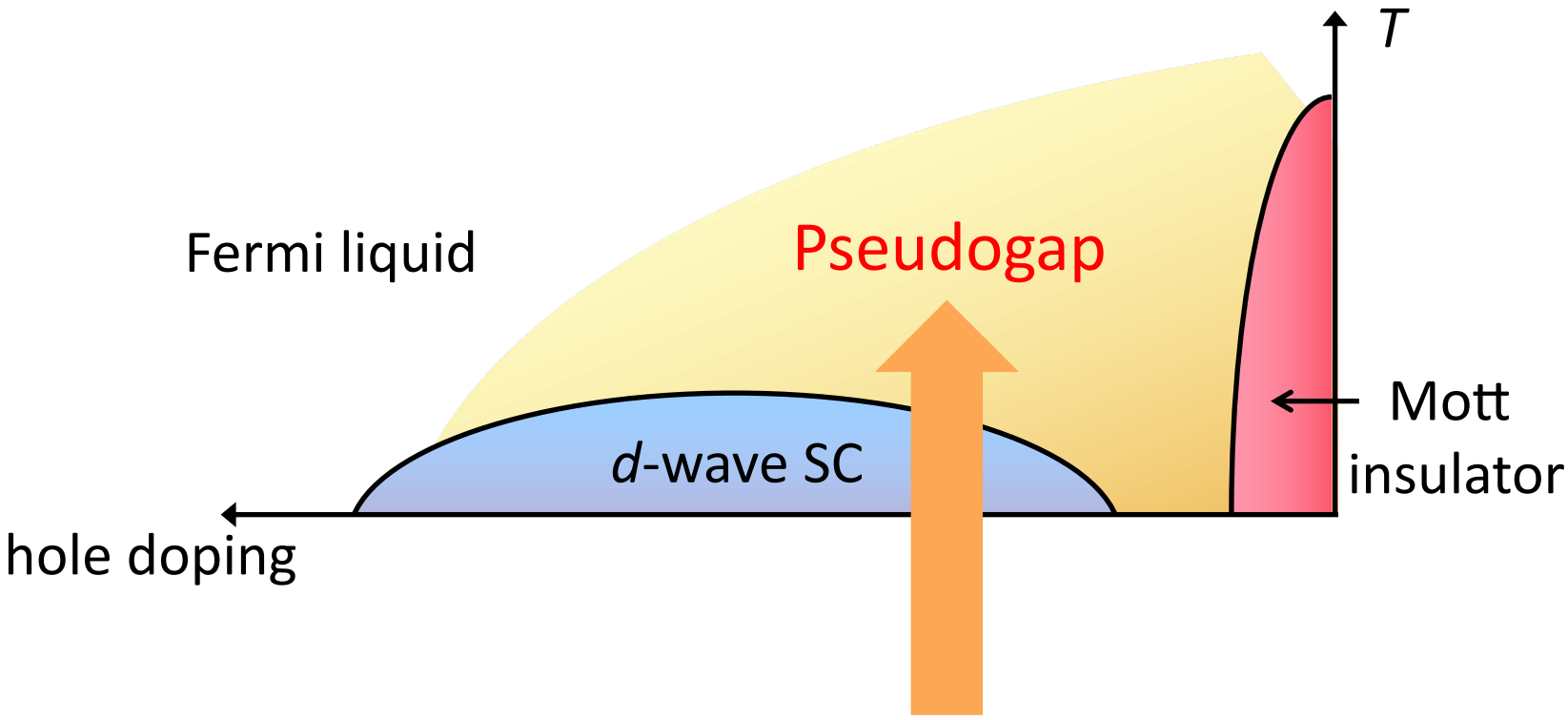
SC gap is *d* wave!



Firm evidence by SQUID

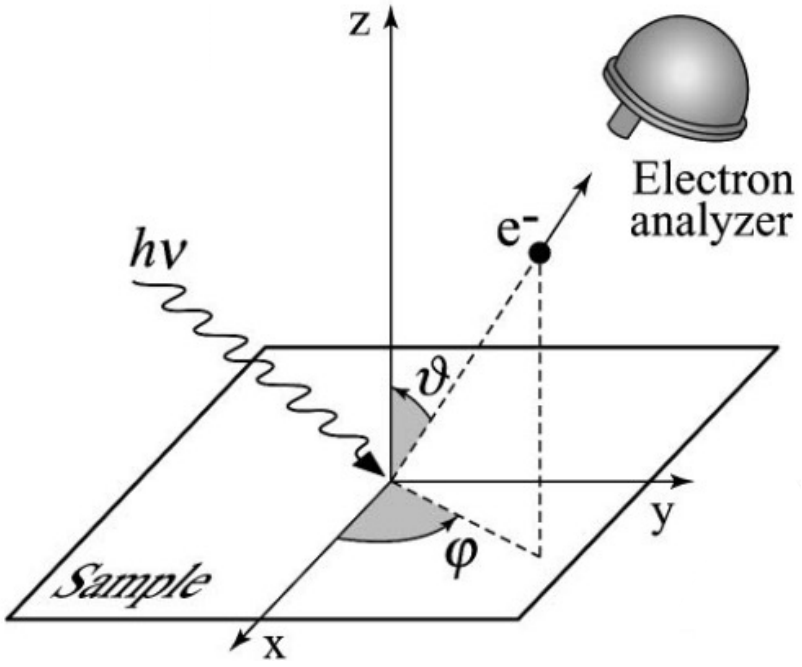
[Wollman *et al.*, PRL'93; Tsuei *et al.*, PRL'94]

Pseudogap has been *assumed* to be *d* wave



No phase-sensitive evidence for the pseudogap structure.

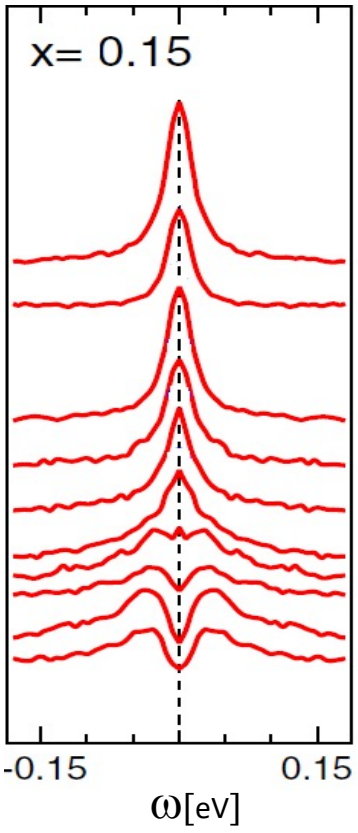
Pseudogap observed in angle-resolved photoemission spectroscopy (ARPES)



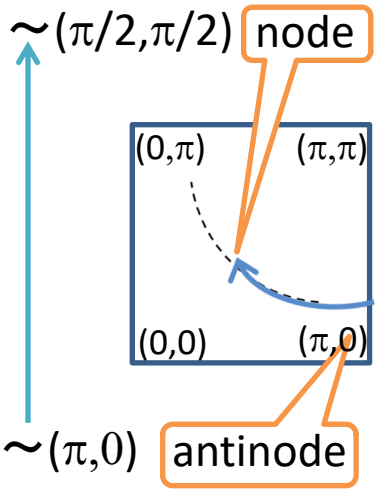
Damascelli, Hussain and Shen, RMP'03

Occupied part of the electronic spectra $A(\mathbf{k},\omega)$ is measured.

k-dependent gap



$La_{2-x}Sr_xCuO_4$, PG state
[Yoshida *et al.*, JPCM'07]

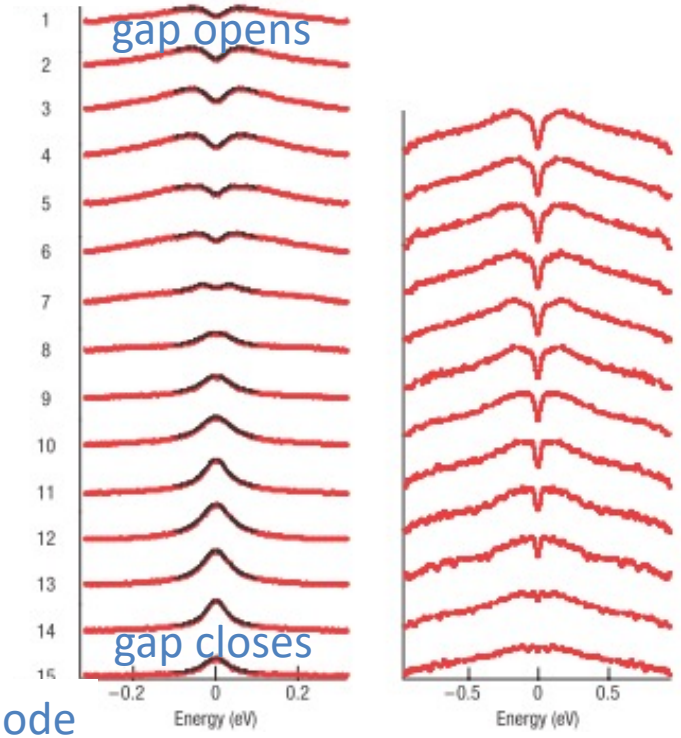


cf. Norman *et al.*, Nature'98

ARPES "evidence" of *d*-wave pseudogap

According to ARPES,
PG also looks like d-wave...

Antinode



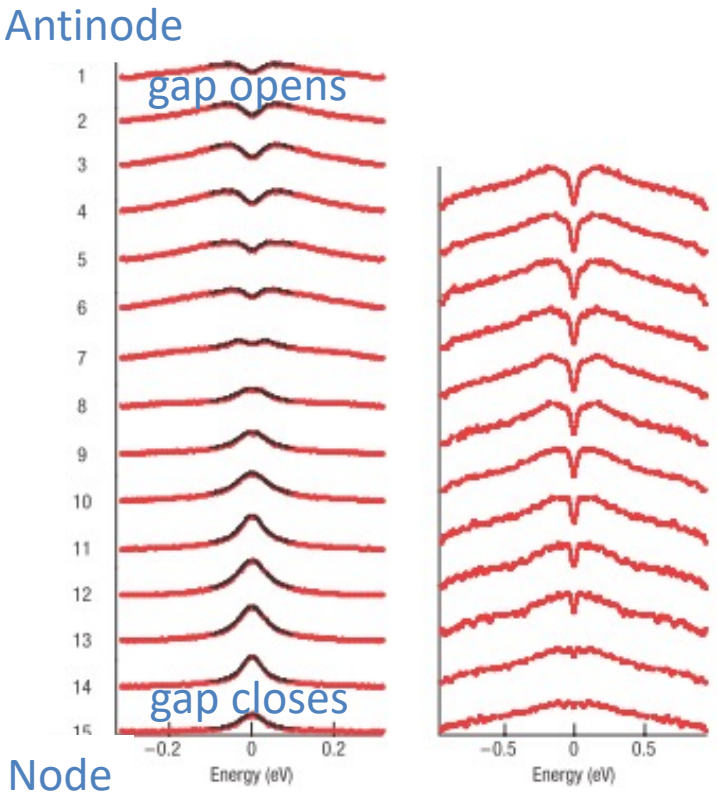
Node

T_c=90K, T=140K

T_c=25K, T=55K

ARPES "evidence" of *d*-wave pseudogap

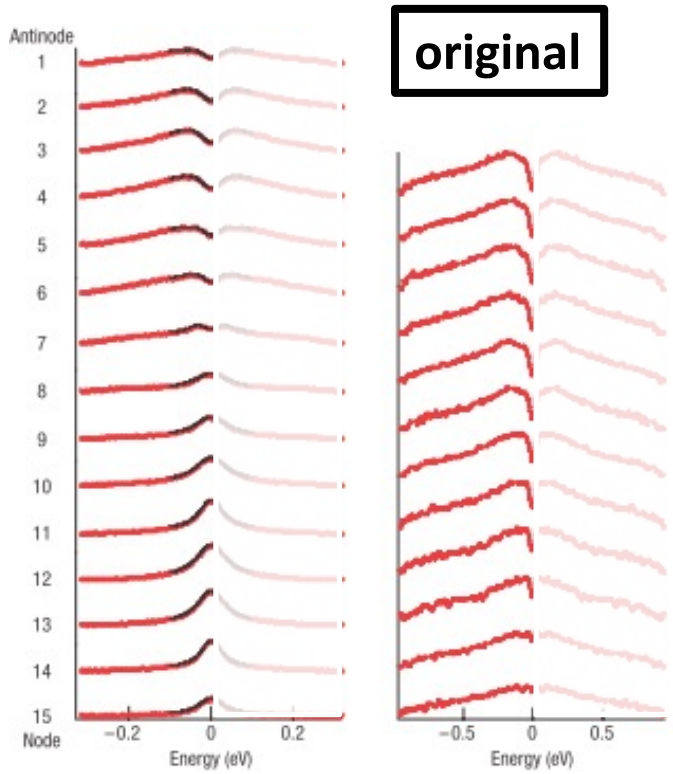
According to ARPES,
PG also looks like d-wave...



T_c=90K, T=140K T_c=25K, T=55K

symmetrization

But, these are "symmetrized" spectra:



Bi2212 [Figure from Kanigel *et al.*, Nat. Phys.'06]

Nothing is actually known about above E_F

Numerical results

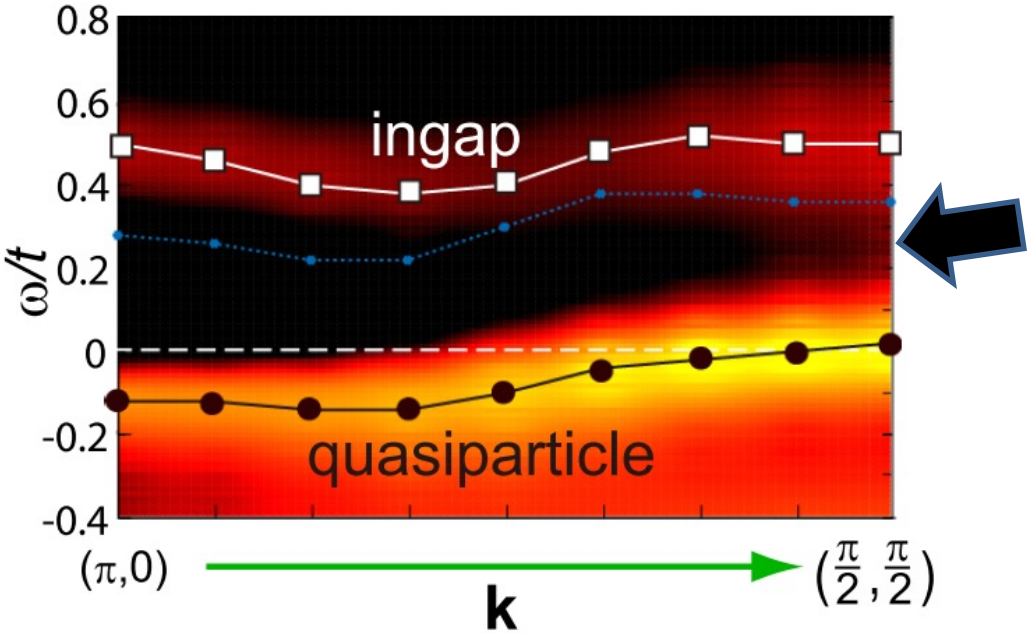
2D Hubbard model (5% doping)

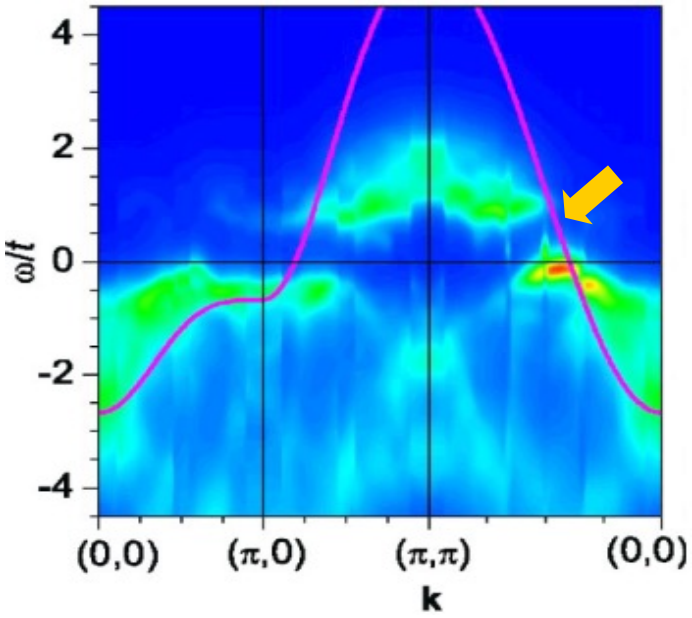
4x4 CDMFT [SS, S. Blanc, M. Civelli *et al.*, PRL **111**, 107001 (2013)]

2D *t-J* model (10% doping)

20-site exact diagonalization [T. Tohyama, PRB **70**, 174517 (2004)]

$A(\mathbf{k},\omega)$



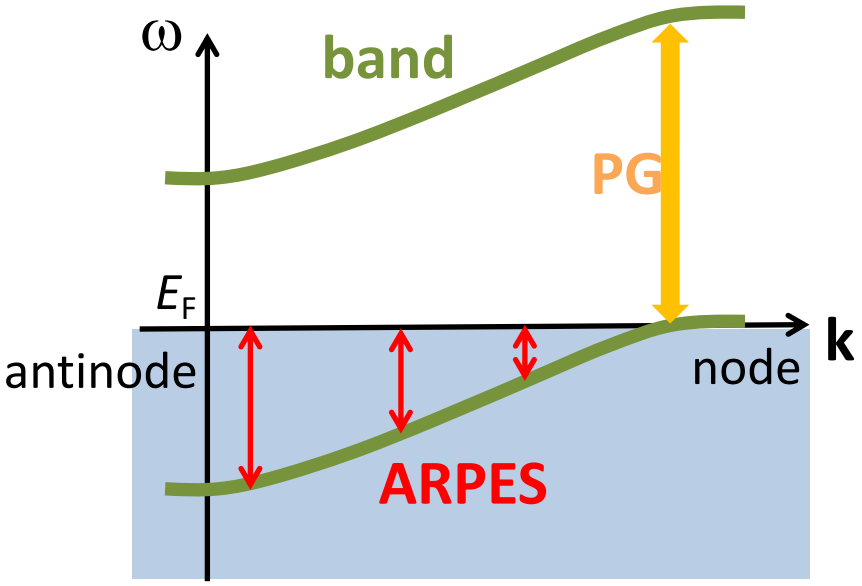


- *Gap opens at every **k**.*
- *Energy position of the gap depends on **k**.*

"s"-wave gap

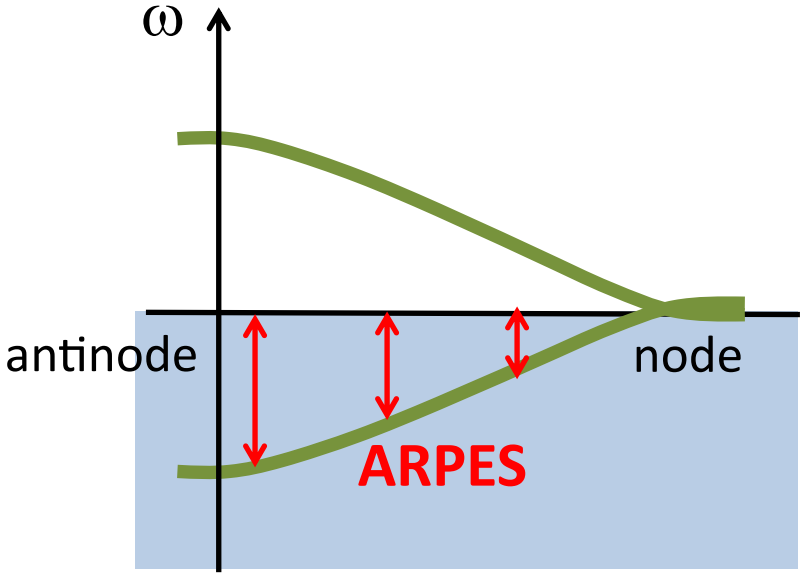
Numerically obtained

"*s*"-wave PG



Often assumed

***d*-wave PG**



Compared to *d*-wave PG,

- similar below E_F
- different above E_F

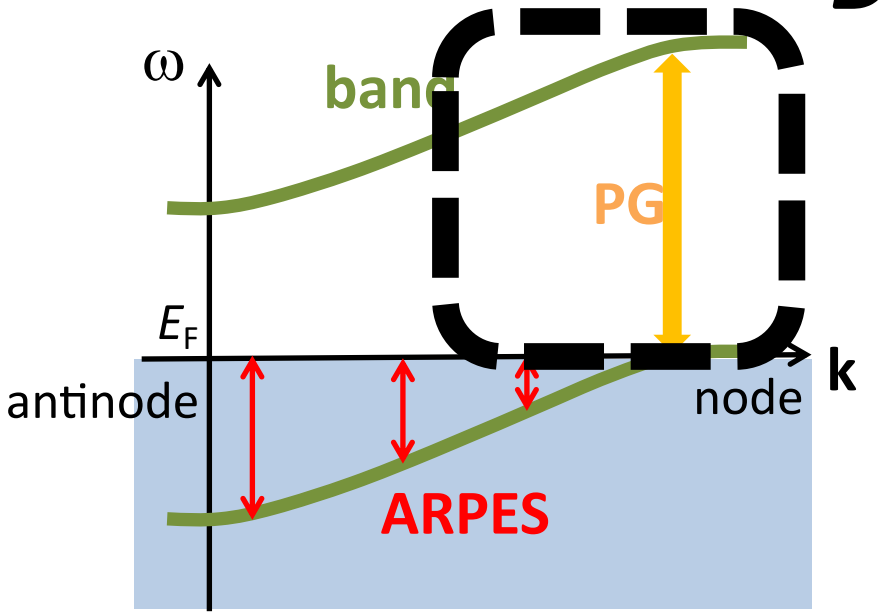
Numerically obtained

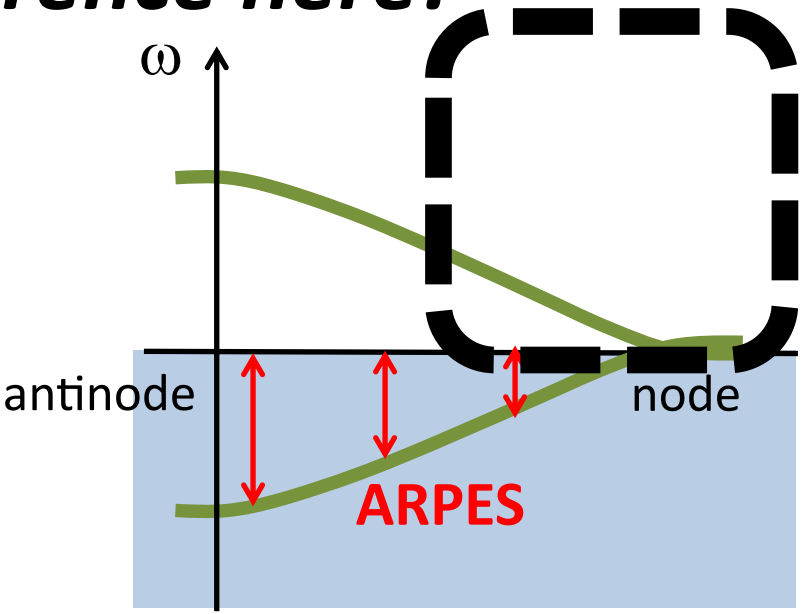
"*s*"-wave PG

Often assumed

d-wave PG

Difference here!





Compared to *d*-wave PG,

- similar below E_F
- different above E_F

***Unoccupied* spectra in the *nodal* region for underdoped cuprates**

k-resolved unoccupied spectra are elusive

Possible in principle by inverse ARPES, though improvement of energy resolution is necessary.

ARPES

k-resolved *occupied* spectra

→ Analysis of high-*T* data can give information of unoccupied spectra slightly above E_F .

$$I(\mathbf{k},\omega) \propto \int A(\mathbf{k},\omega') f(\omega') R(\omega-\omega')\, \mathrm{d}\omega'$$

STM

k-*integrated* occupied and unoccupied spectra.

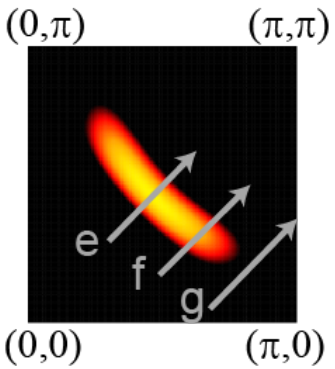
→ A consequence of **k**-resolved spectra can be discussed.

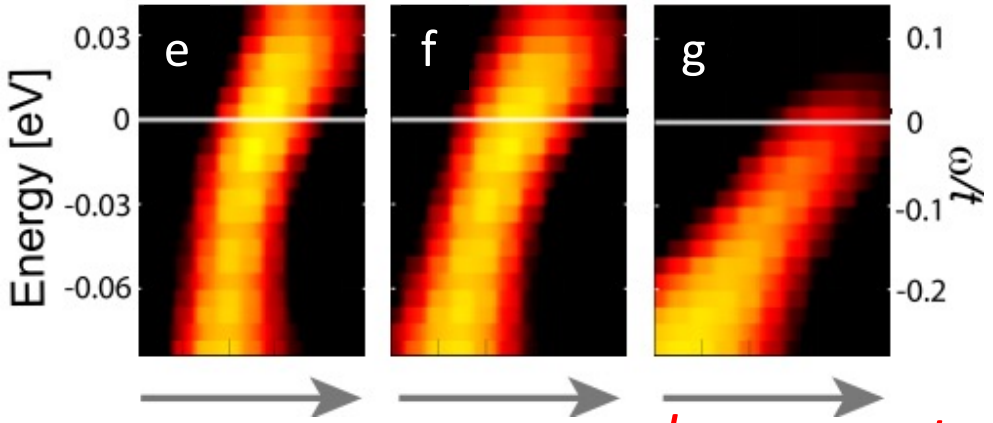
$$\frac{dV}{dI} \sim \mathrm{DOS}(\omega) = \int d\mathbf{k}\, A(\mathbf{k},\omega)$$

Indication in ARPES

CDMFT

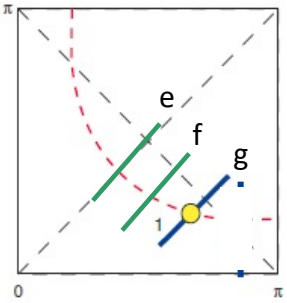
t=0.3eV
5% doping
U=8t
T=0.06t



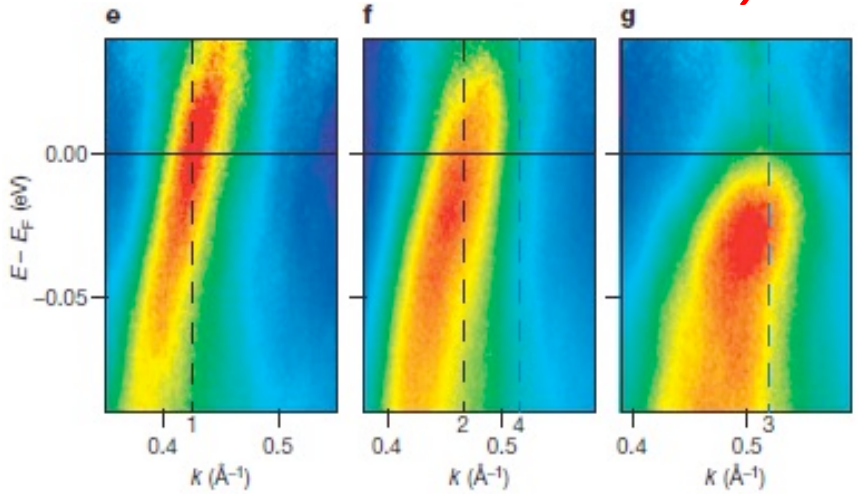


e-h asymmetry!

ARPES



$$I(\mathbf{k},\omega) \propto \int A(\mathbf{k},\omega') f(\omega') R(\omega-\omega')\, \mathrm{d}\omega'$$



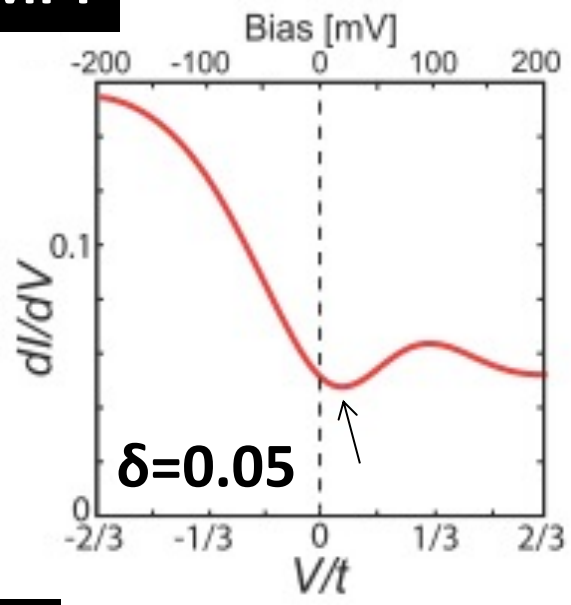
Bi2212 (UD65K), *T*=140K [Yang *et al.*, Nature'08]

Analysis of high-T data

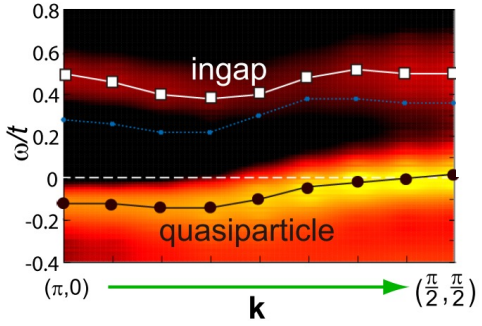
→ Strong e-h asymmetry consistent with "s"-wave PG.

Indication in STM

CDMFT

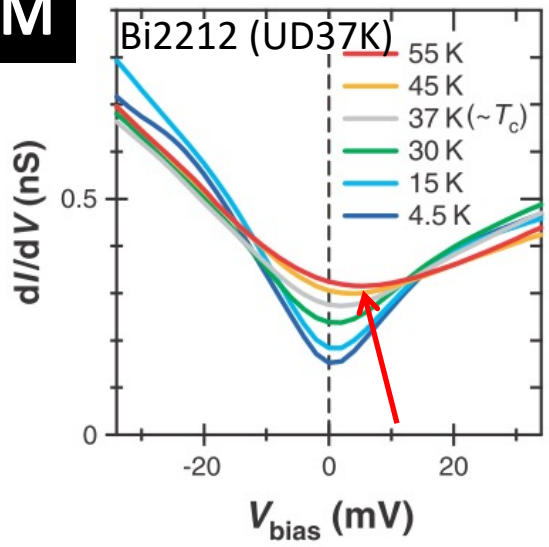


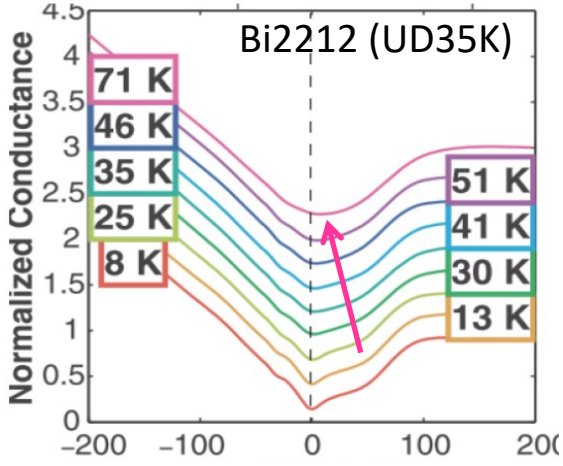
Bottom shift to positive-energy side

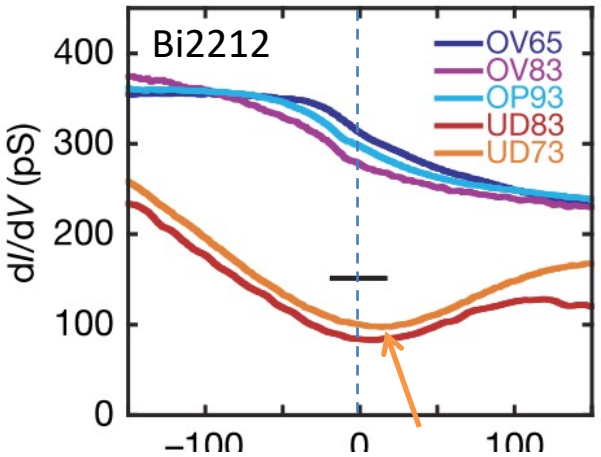


Bottom shift is expected for "*s*"-wave PG.

STM



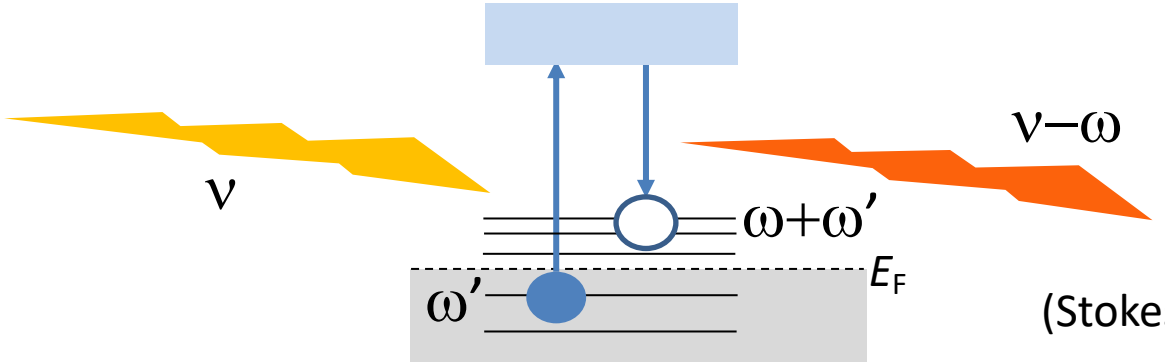




Similar shift in underdoped samples!

[Lee *et al*., Science'09] [Pushp *et al*., Science'09] [Gomez *et al*., Nature'07]

Electronic Raman Spectroscopy

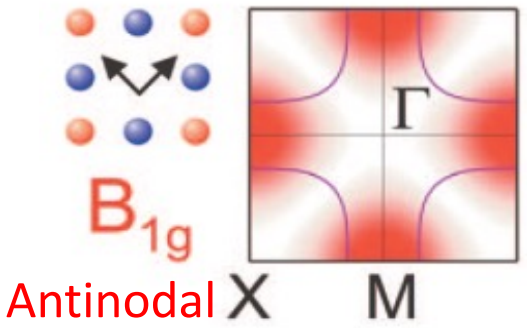


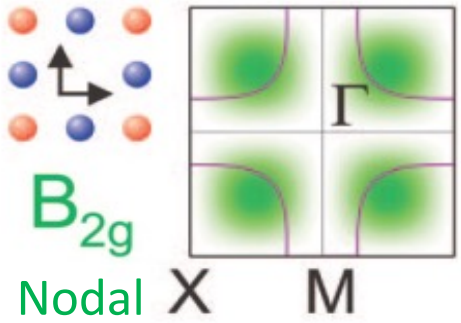
(Stokes process)

First approximation:

$$\chi''(\omega) \propto \int d\mathbf{k}\, \gamma_\mu{}^2(\mathbf{k}) \int d\omega' A(\mathbf{k},\omega') A(\mathbf{k},\omega+\omega')[f(\omega') - f(\omega+\omega')]$$

contributed from both occupied and unoccupied spectra.



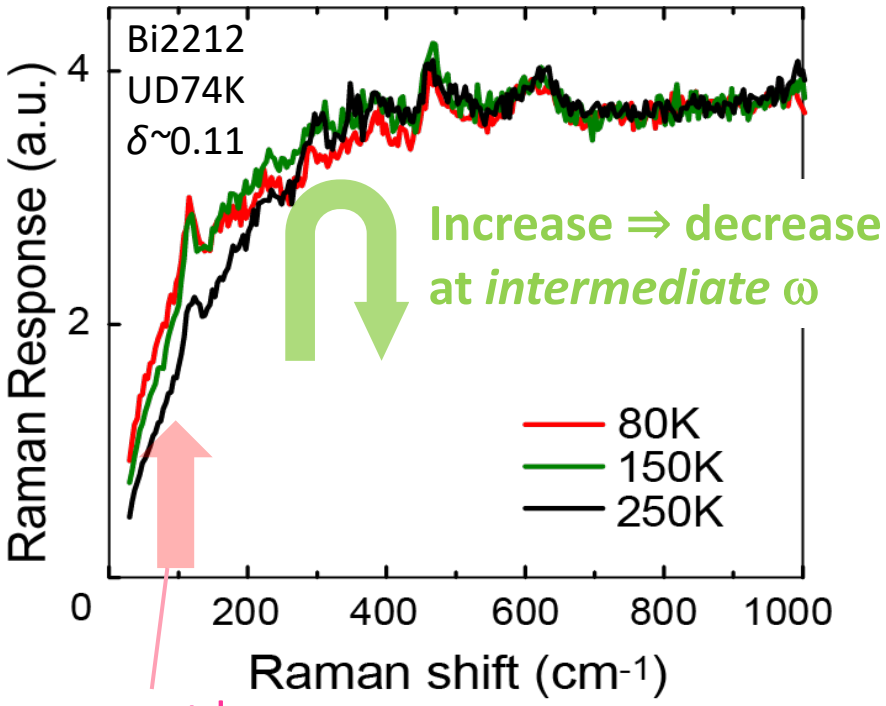


[Devereaux and Hackl, RMP'07]

Light polarization gives momentum-space selectivity.

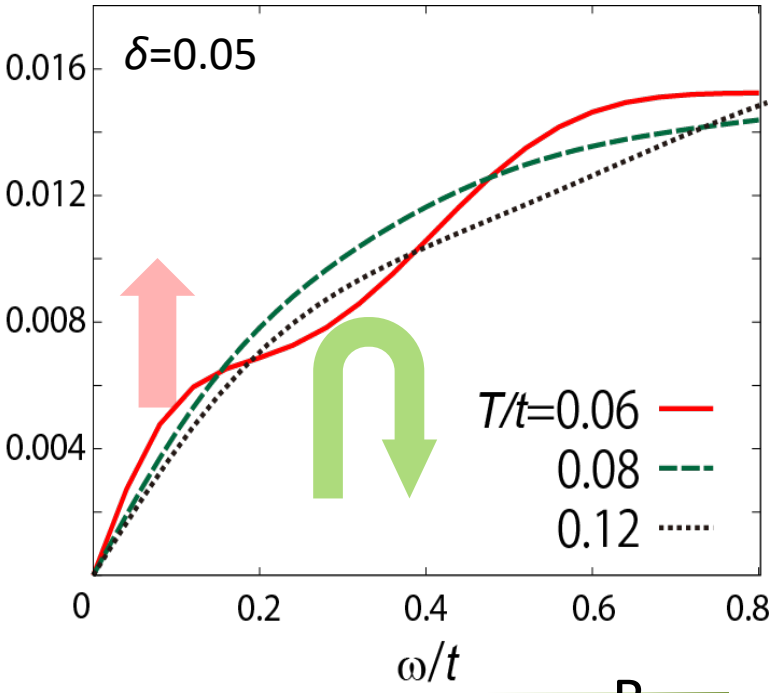
B_{2g} (nodal) Raman response

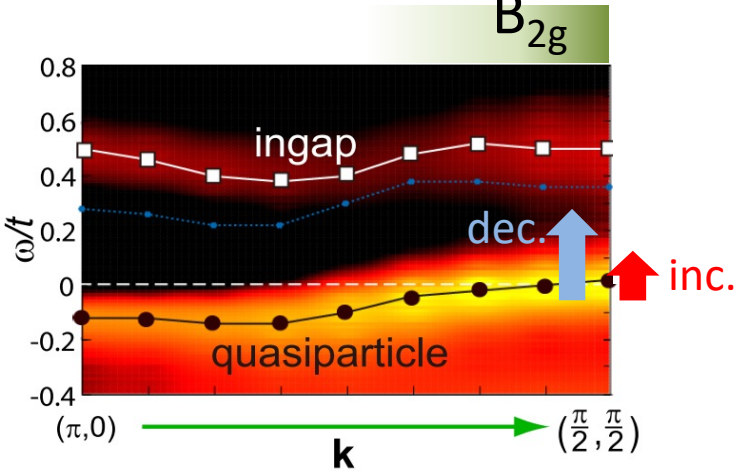
Experiment



Increases at low ω.
(Metallic behavior)

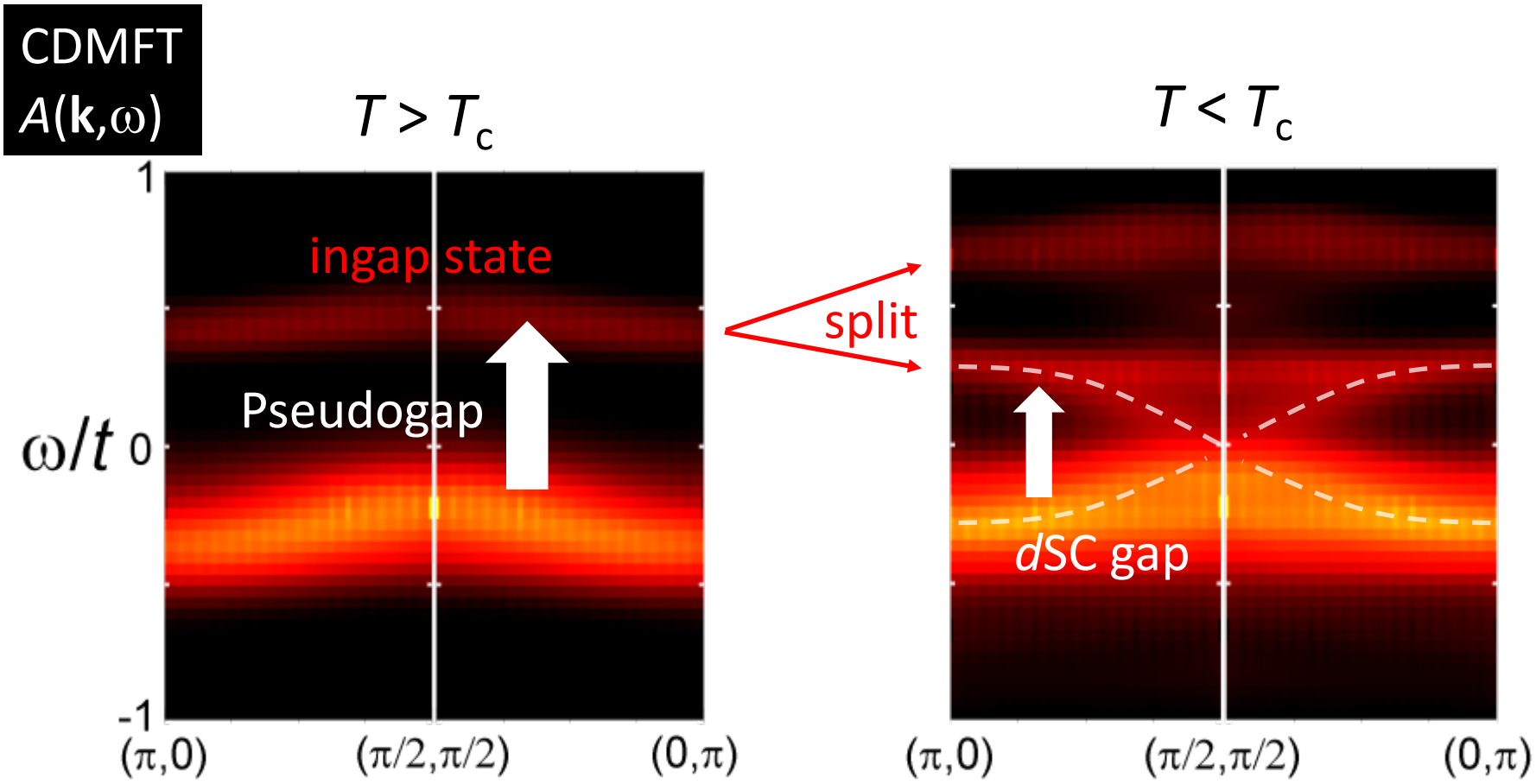
CDMFT





The intermediate-ω depression in B_{2g} Raman signals the gap in the nodal region above E_F.

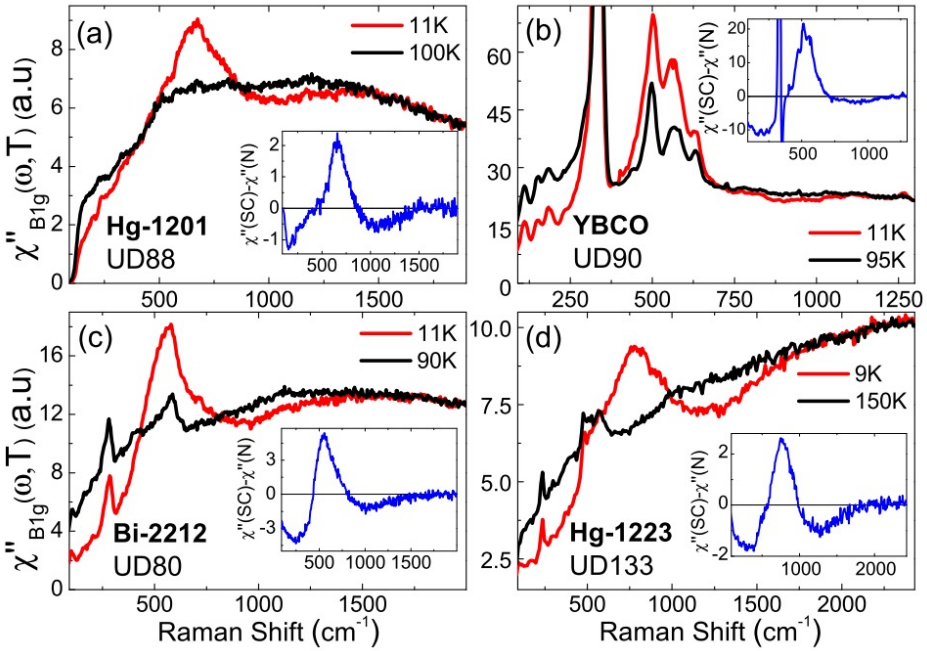
How can s-wave PG be reconciled with d-wave SC?

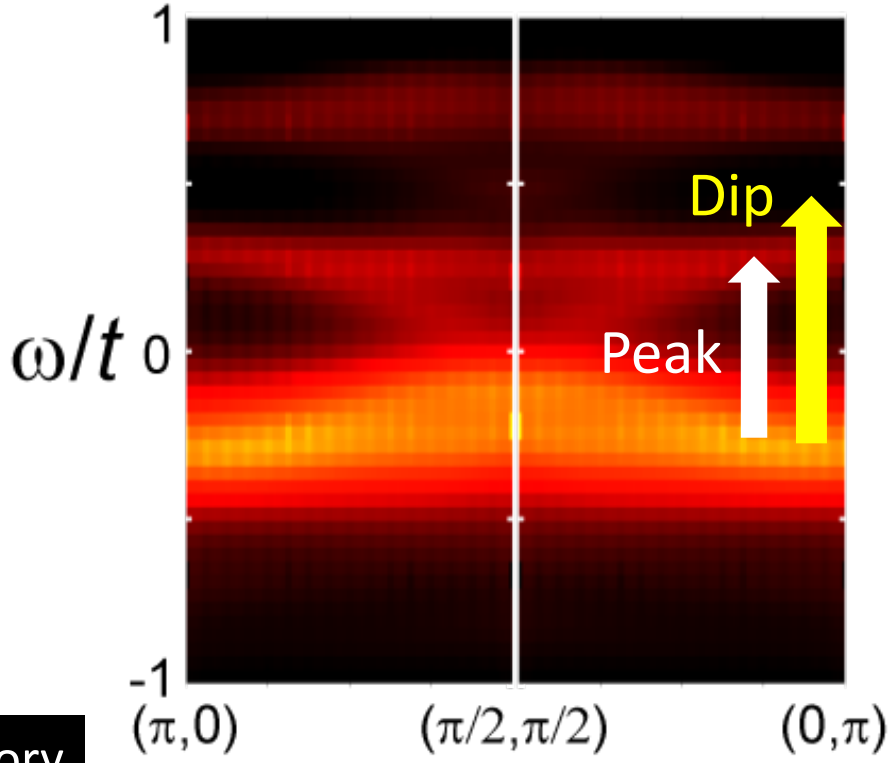


SC gap appears inside PG!

SS, S. Blanc, M. Civelli *et al.*, PRL **111**, 107001 (2013)
SS, M. Civelli, M. Imada, PRL **116**, 057003 (2016).
B. Loret, SS *et al.*, PRL **116**, 197001 (2016)

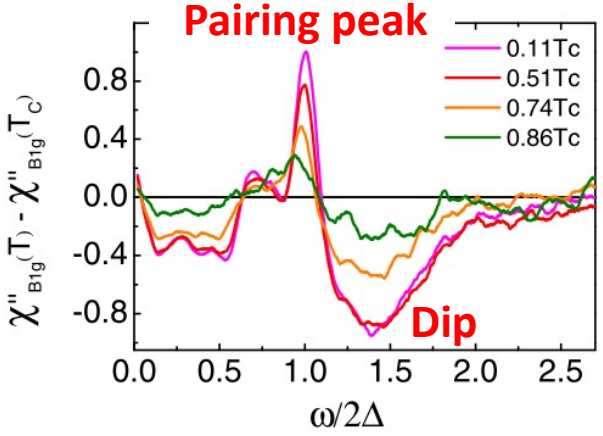
Peak-dip structure in B_{1g} Raman response



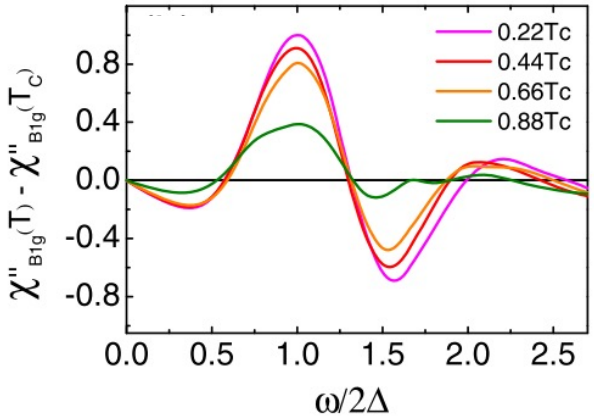


Hg-1223

Experiment

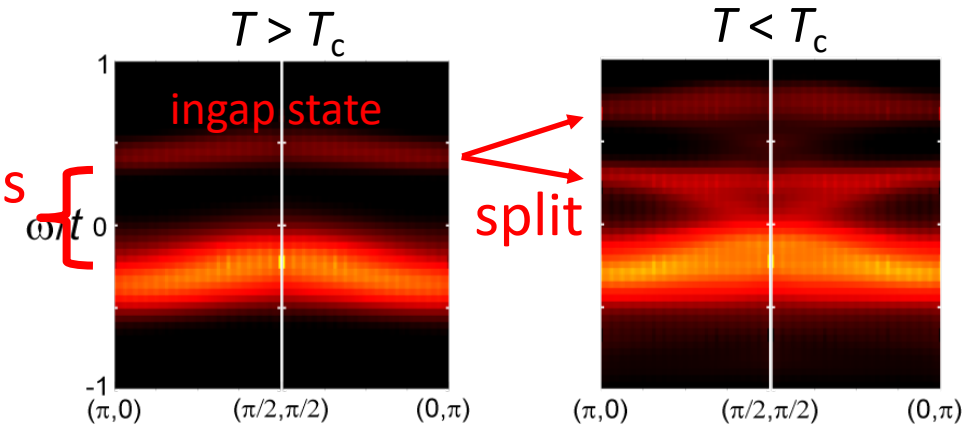


Theory



B. Loret, SS *et al.*,
PRL **116**, 197001 (2016);
PRB **96**, 094525 (2017)

Strong scattering is present inside PG



- *Why and how does the ingap peak split?*
- *Under the strong scattering due to PG, how can the Bogoliubov peaks emerge?*

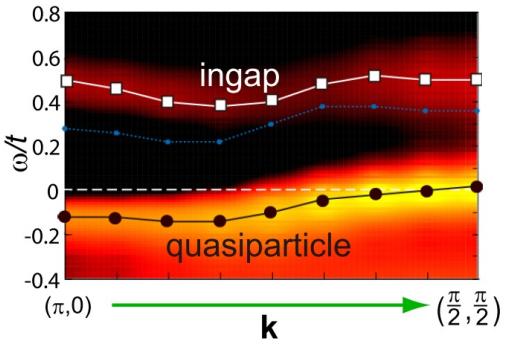
- *Below T_c, the scattering (normal self-energy) is cancelled out by a contribution from anomalous self-energy.*

SS, M. Civelli, M. Imada, PRL **116**, 057003 (2016);
Another slides (hiddenfermion.pdf).

Summary

“*s*”-wave pseudogap

- Finite gap even at the node but above E_F.
- The gap below E_F is *d*-wave like.



	d-wave PG	“*s*”-wave PG
Numerical simulation (2D Hubbard, t-J)		✔
ARPES (occupied spectra)	✔	✔
ARPES (E-h asymmetry)		✔
STM (E-h asymmetry)		✔
B_{2g} Raman (Finite-energy dip)		✔
B_{1g} Raman	✔	✔