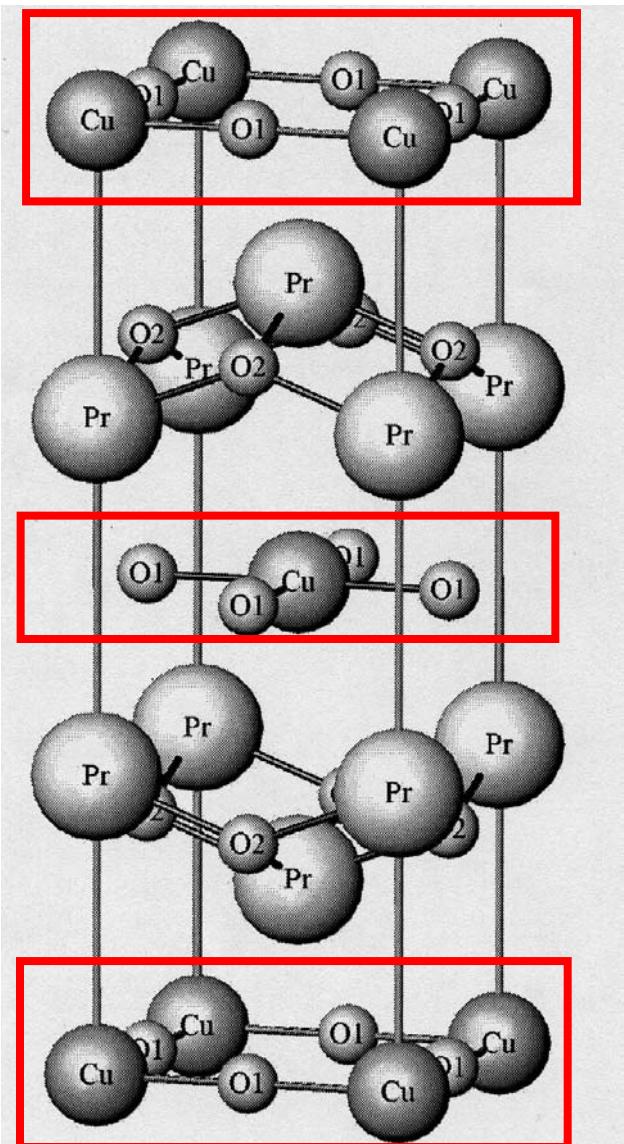


# CuO<sub>2</sub> planes



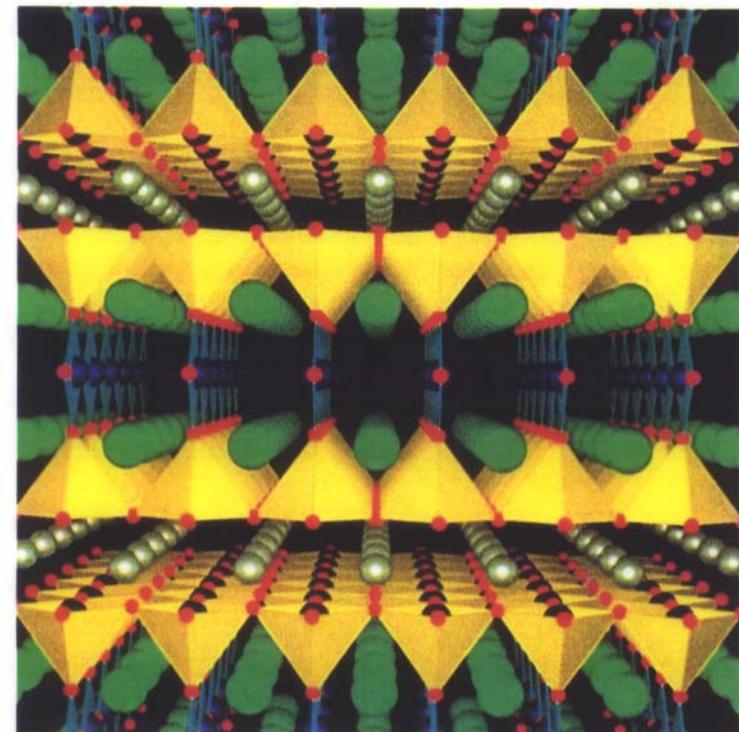
## SCIENTIFIC AMERICAN

*How nonsense is deleted from genetic messages.*

*R for economic growth: aggressive use of new technology.*

*Can particle physics test cosmology?*

JUNE 1988  
\$3.50



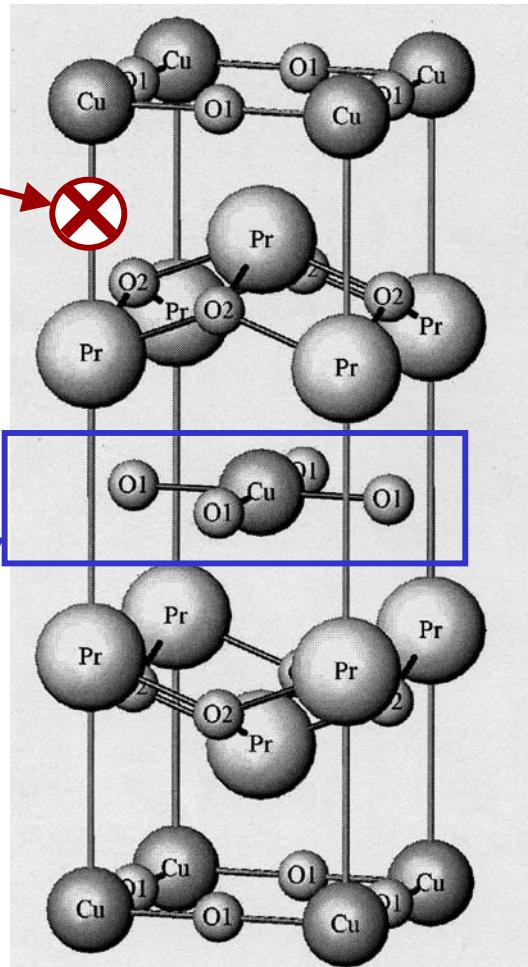
*YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub>*

# Different crystal structures

$\text{Pr}_2\text{CuO}_4$

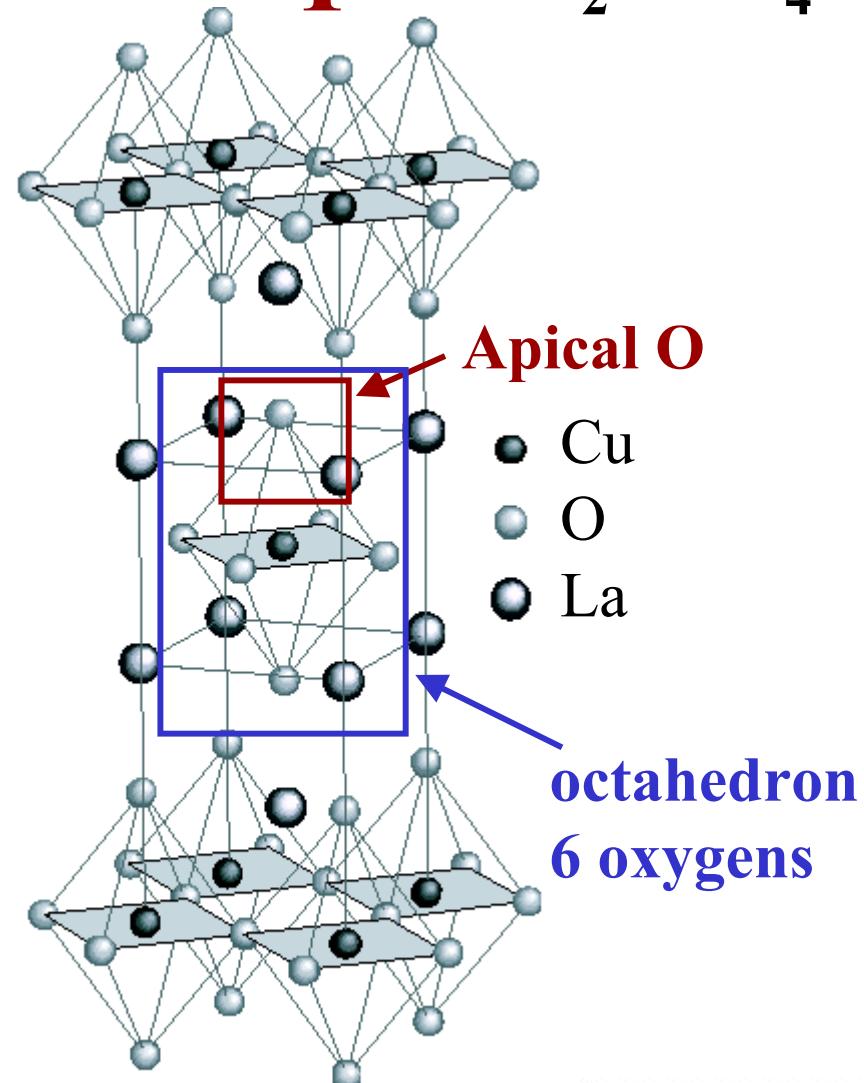
T'

No apical O!



Square  
4 oxygens

T  $\text{La}_2\text{CuO}_4$



octahedron  
6 oxygens

Figure provided by P. Fournier

# Phase diagram

Electron doping       $\longleftrightarrow$       Hole doping

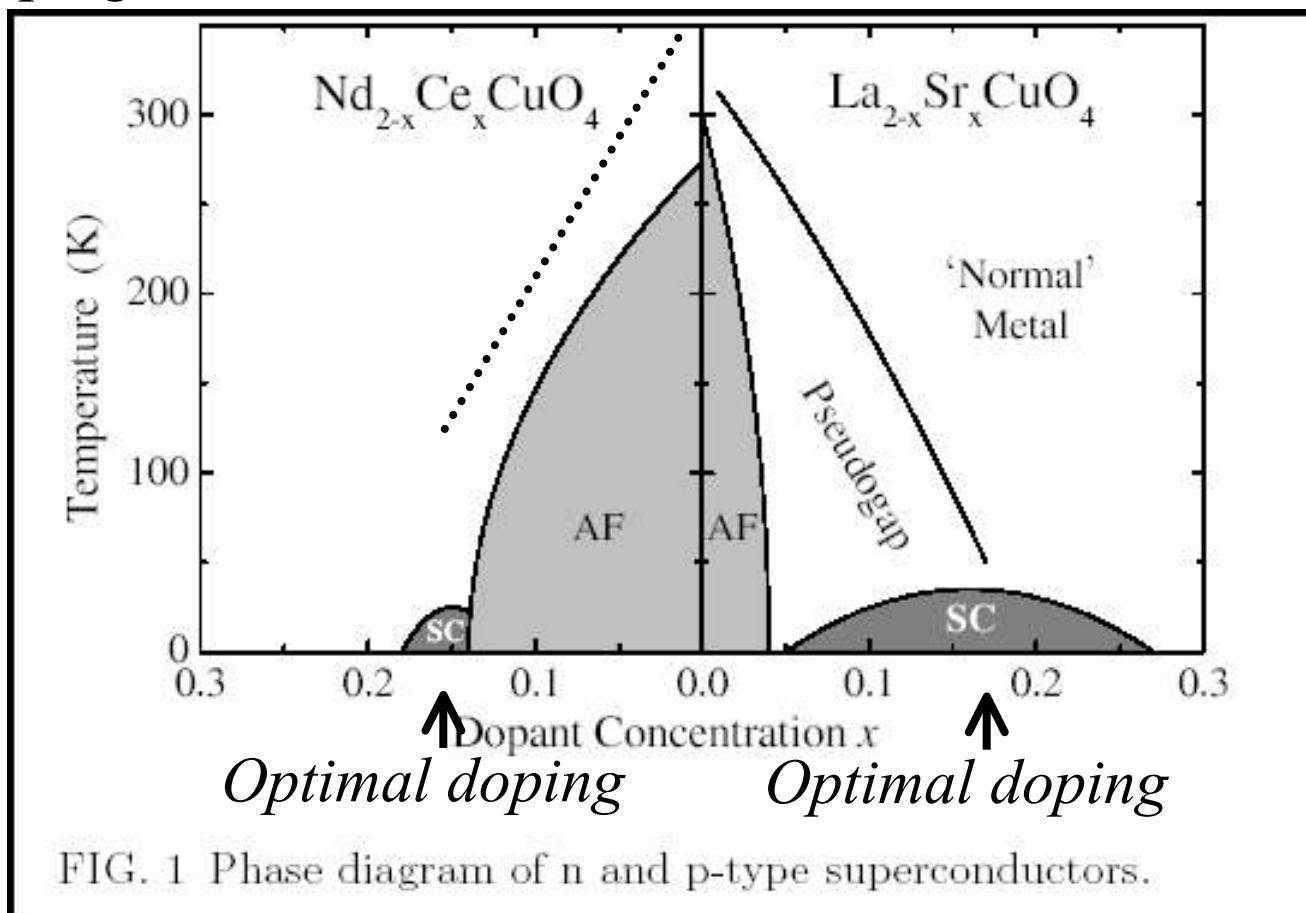
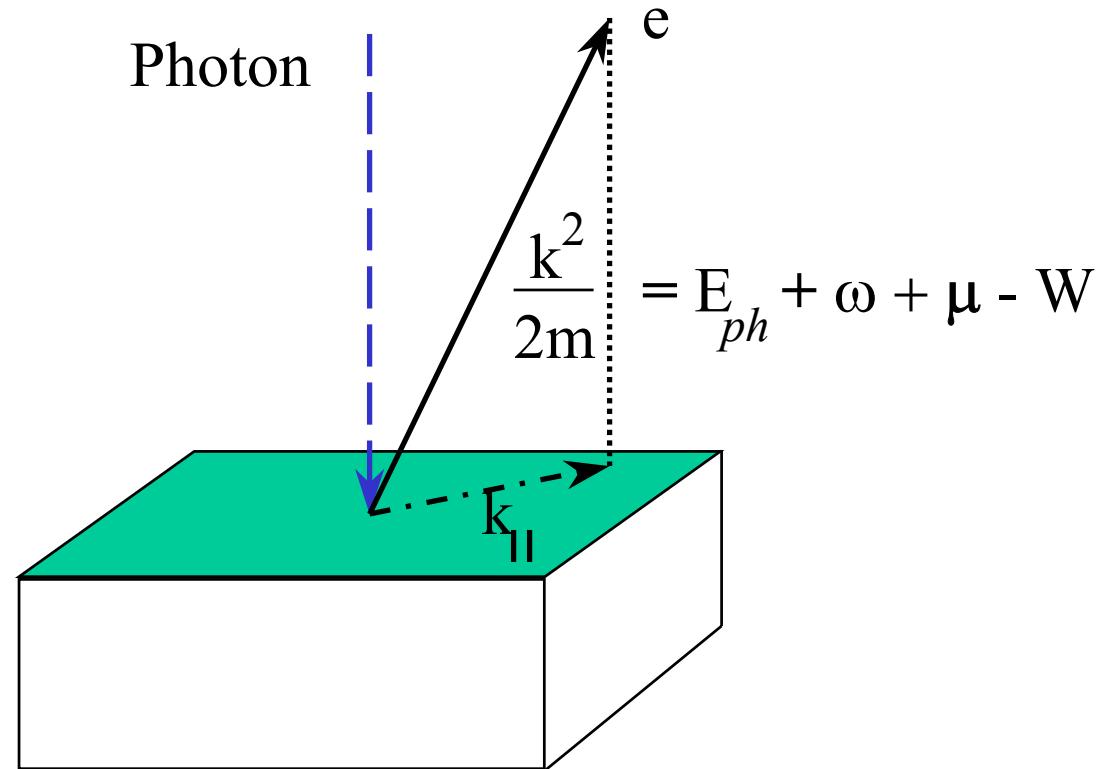


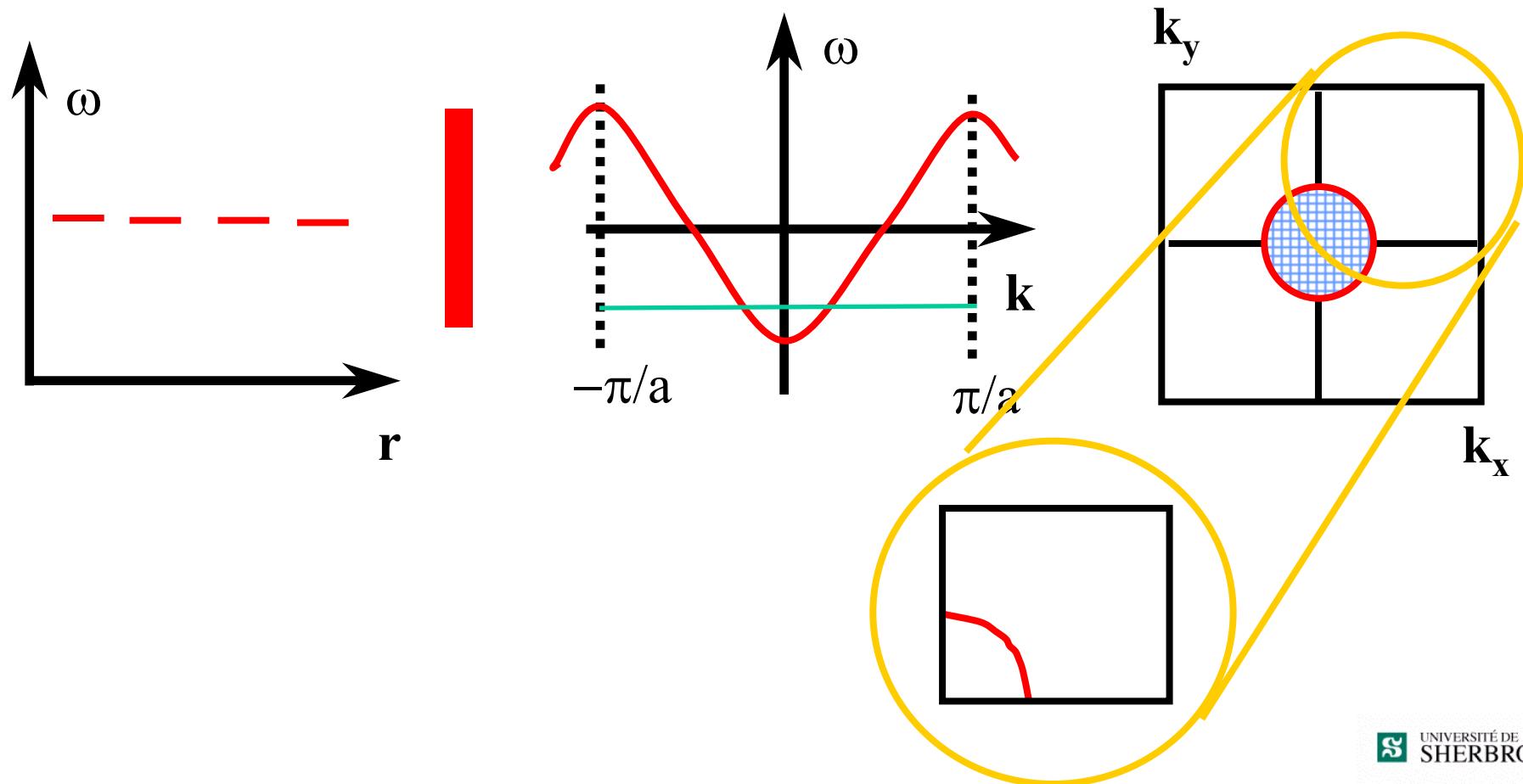
FIG. 1 Phase diagram of n and p-type superconductors.

# Electronic states in $d=2$

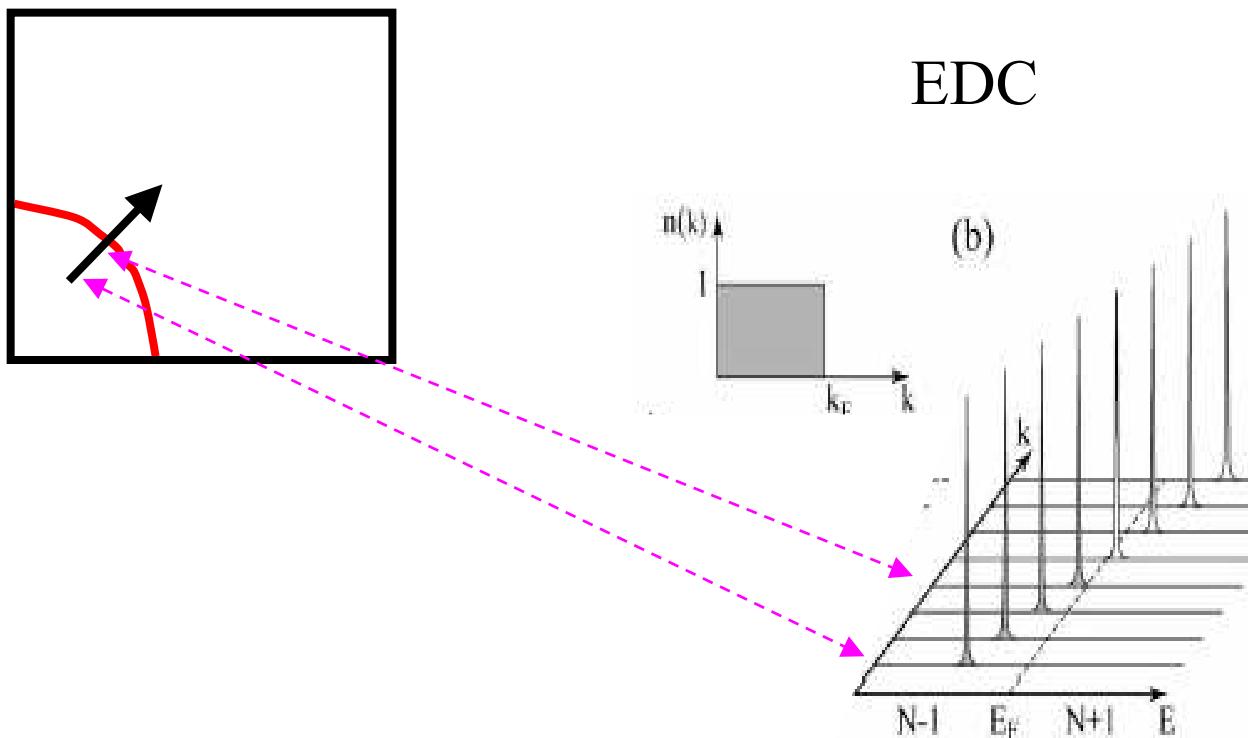
## Angle Resolved Photoemission Spectroscopy (ARPES)



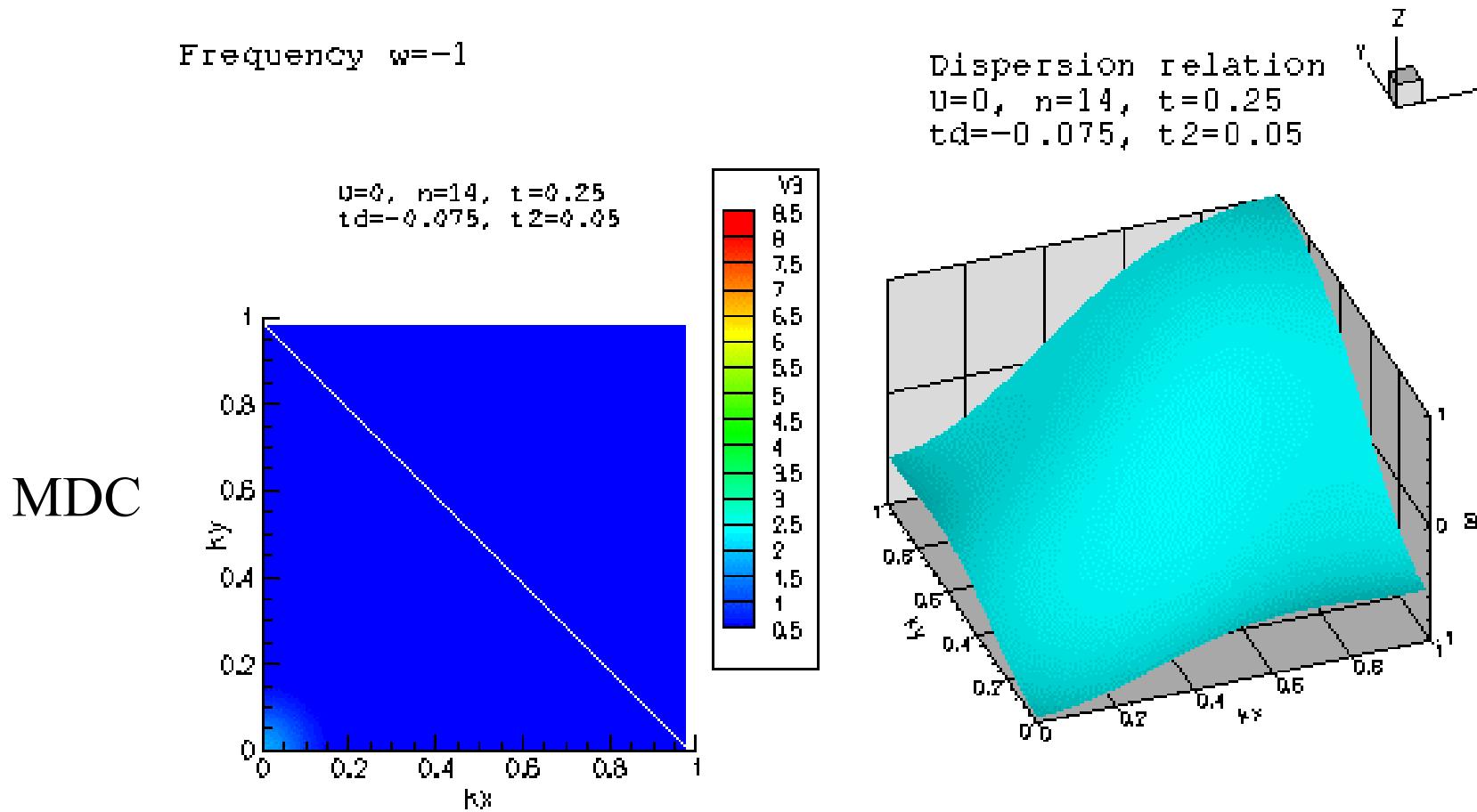
# Some basic Solid State Physics



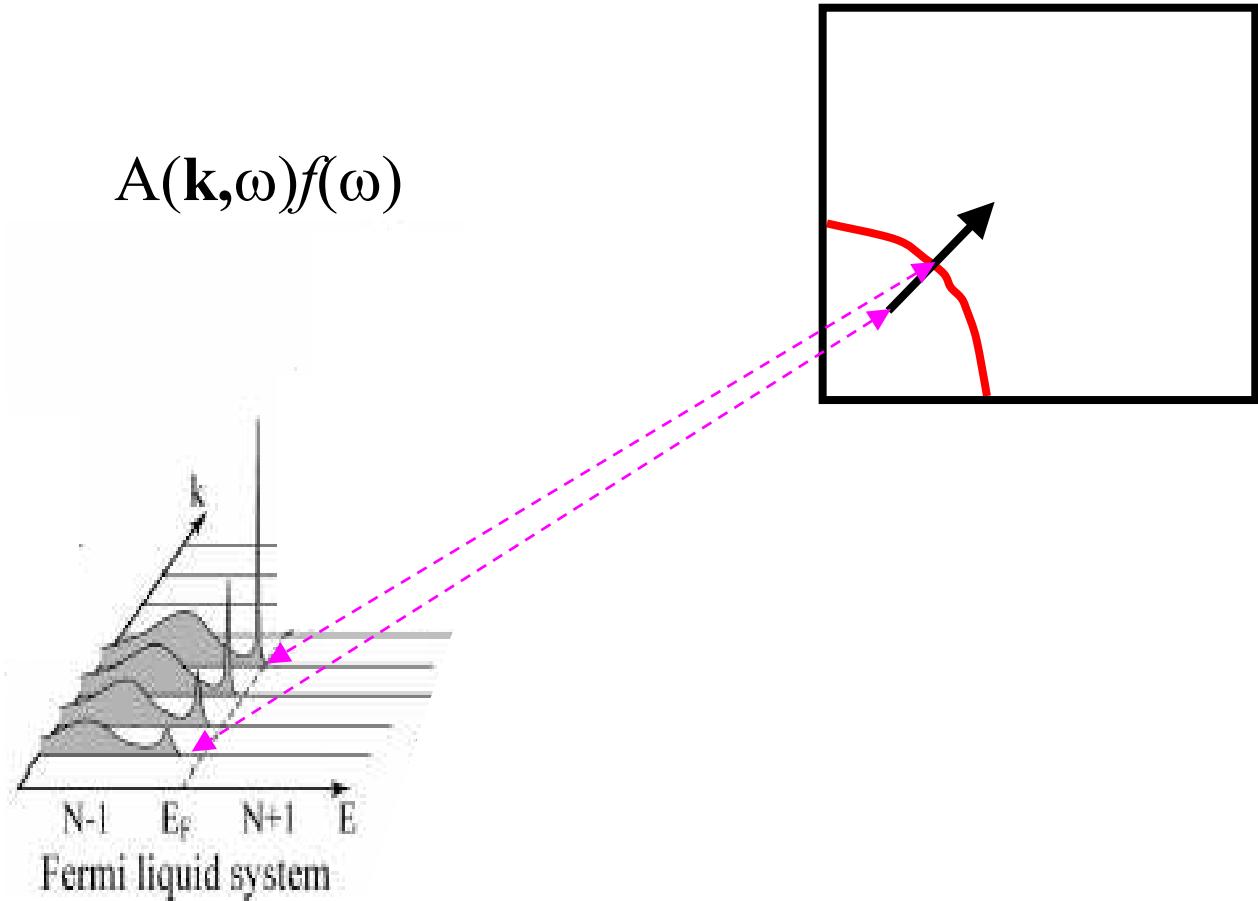
# The non-interacting case



# Electron-doped, non-interacting



# Interacting case: The Fermi liquid



# Quantum materials, strongly correlated electrons and high-temperature superconductivity

- I. Introduction
  - Fermi liquid
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- IV. Weak coupling pseudogap (QMC,TPSC)
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# Role of reduction in e-doped

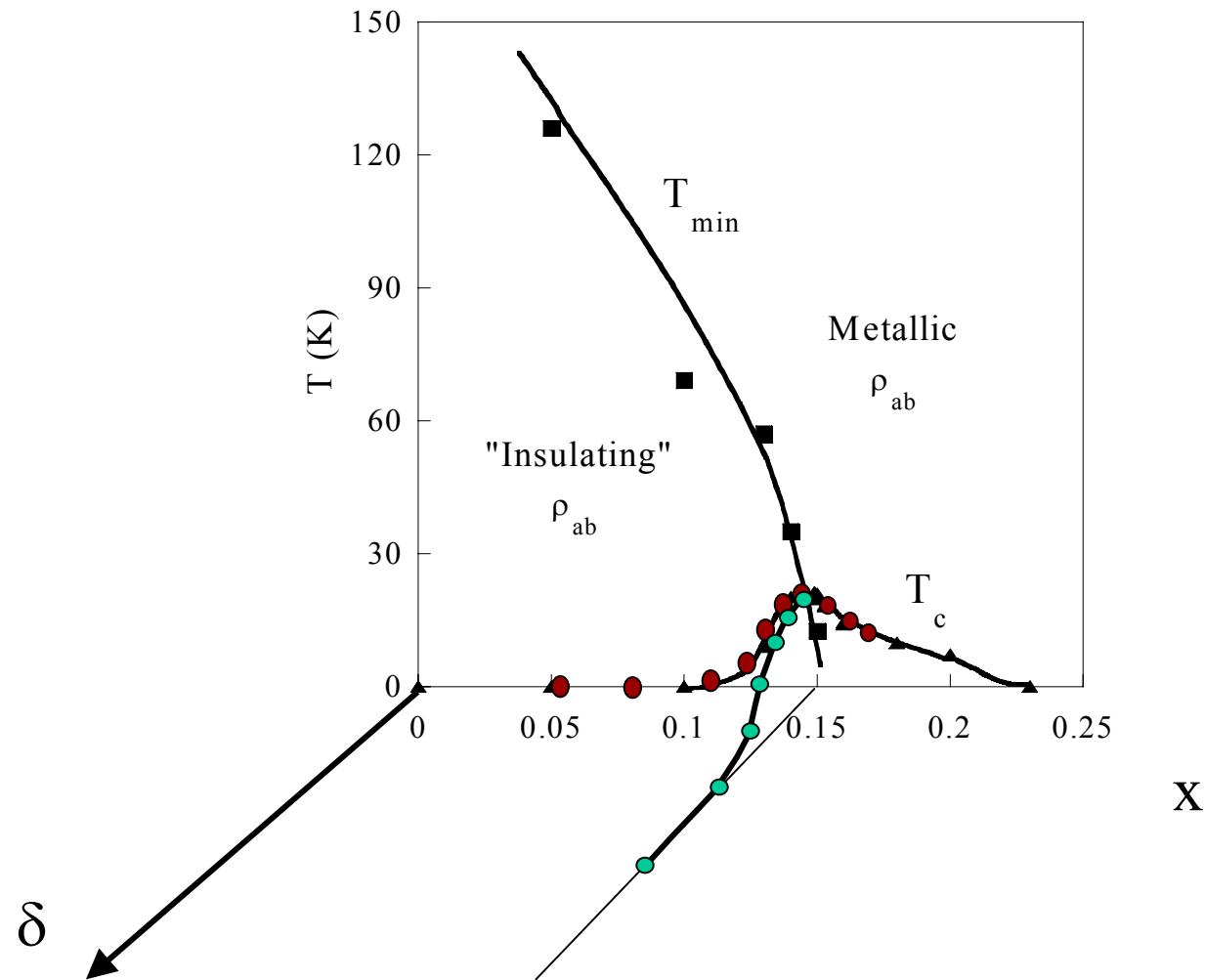
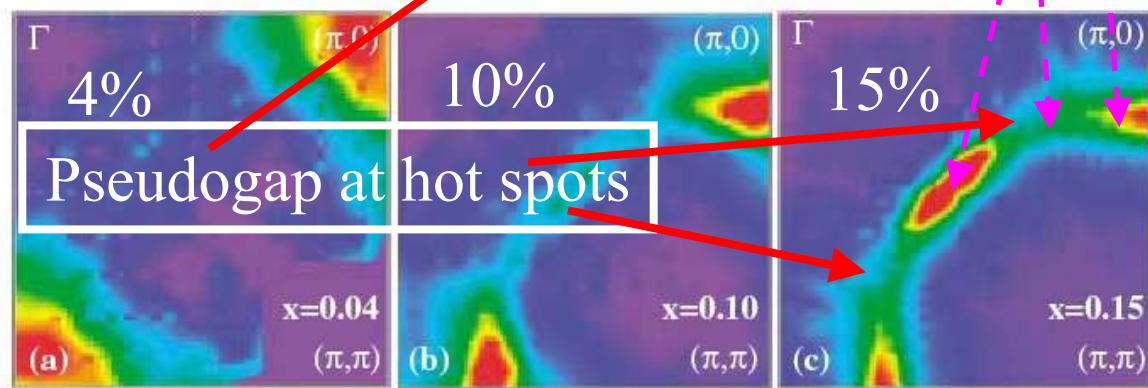
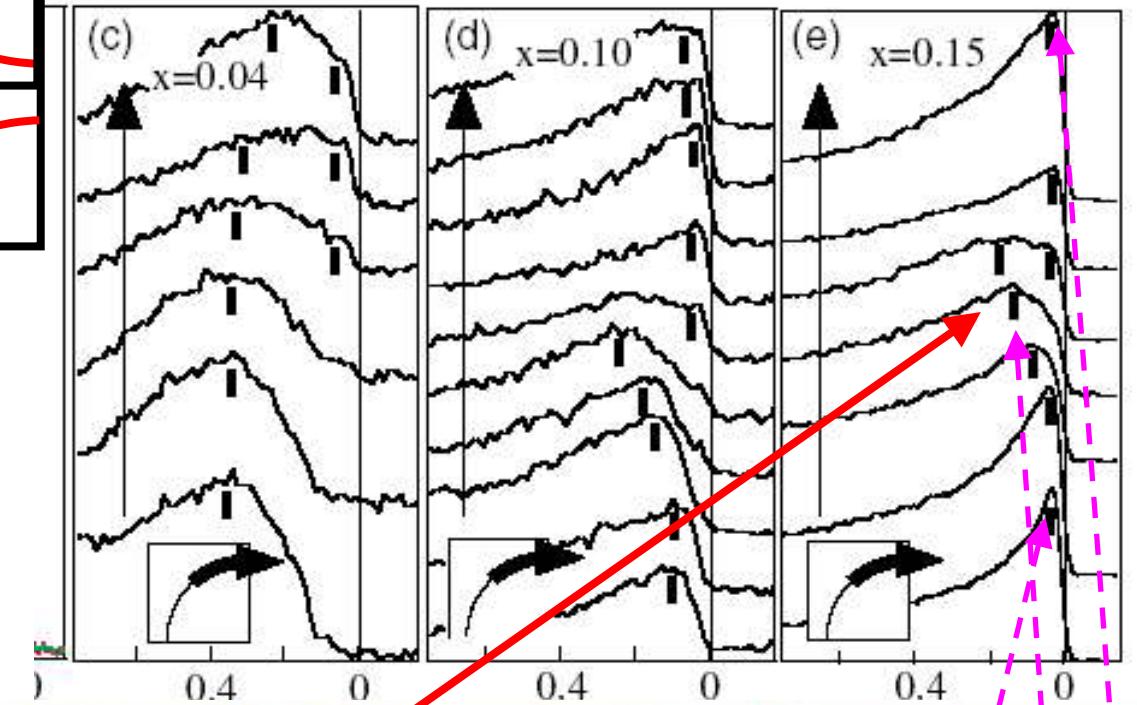
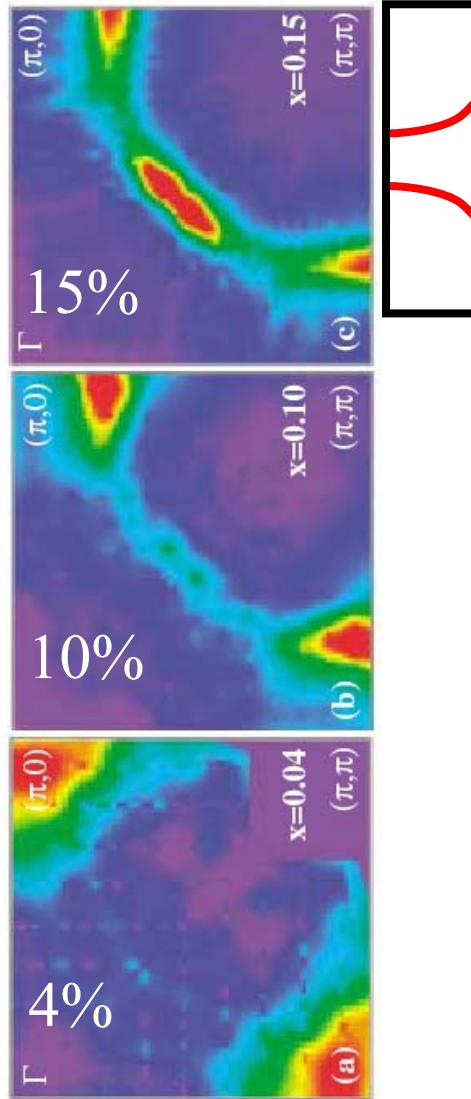


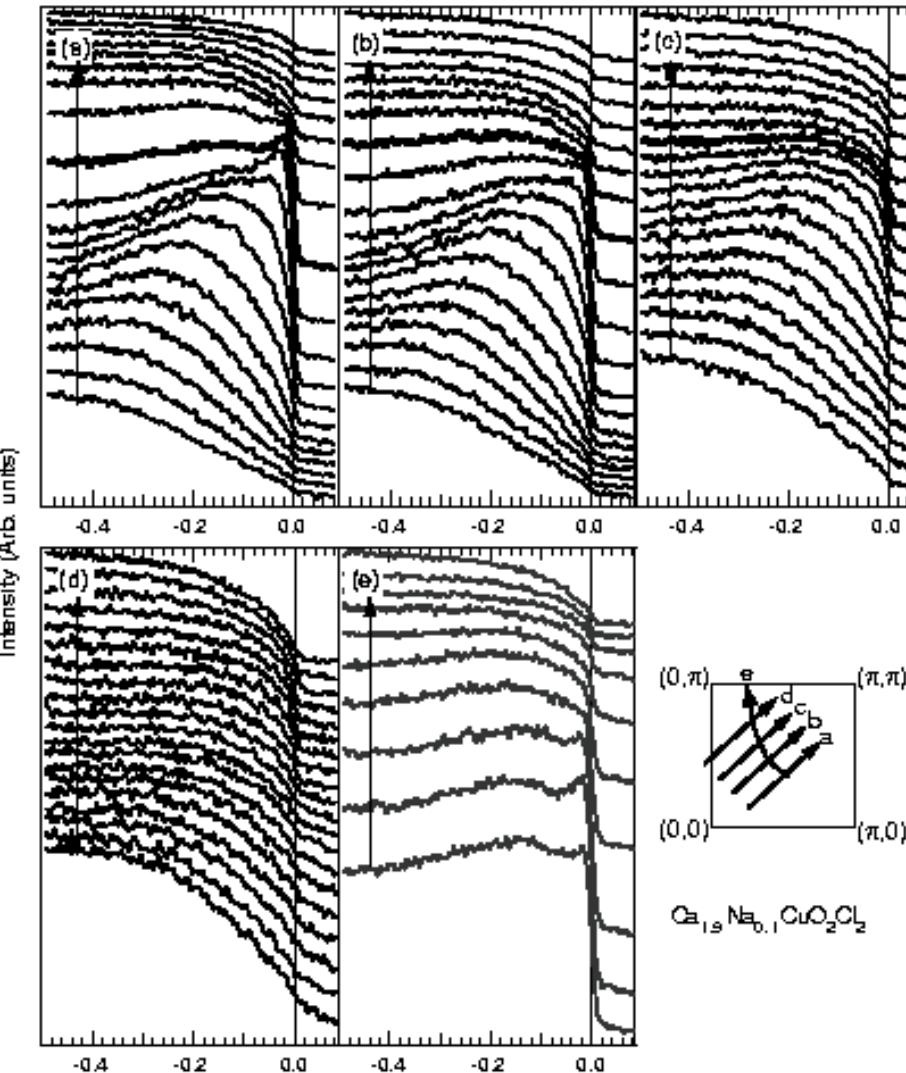
Figure provided by P. Fournier, + PRL 81, 4720 (1998).

# Fermi surface, electron-doped case

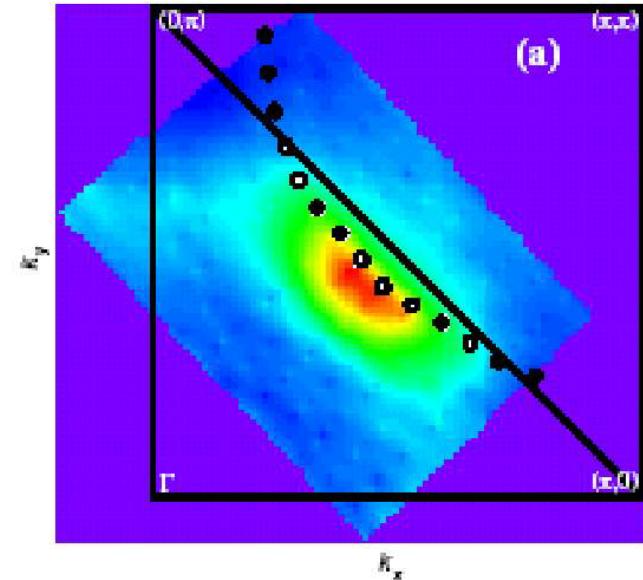
Armitage *et al.* PRL 87, 147003; 88, 257001



# Fermi surface, hole-doped case 10%



Hole-doped, 10%



F. Ronning et al. Jan. 2002,  $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

# The « Hubbard model »

**SCIENTIFIC  
AMERICAN**

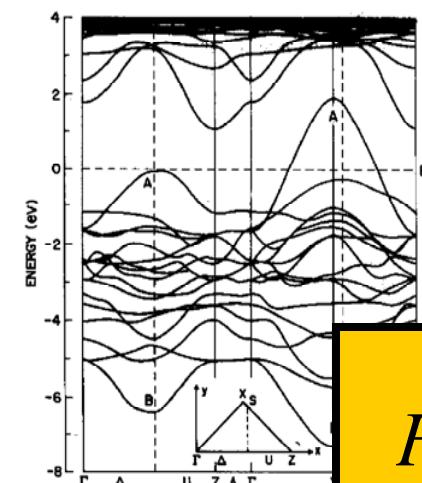
JUNE 1988  
\$3.50

How nonsense is deleted from genetic messages.  
R for economic growth: aggressive use of new technology.  
Can particle physics test cosmology?

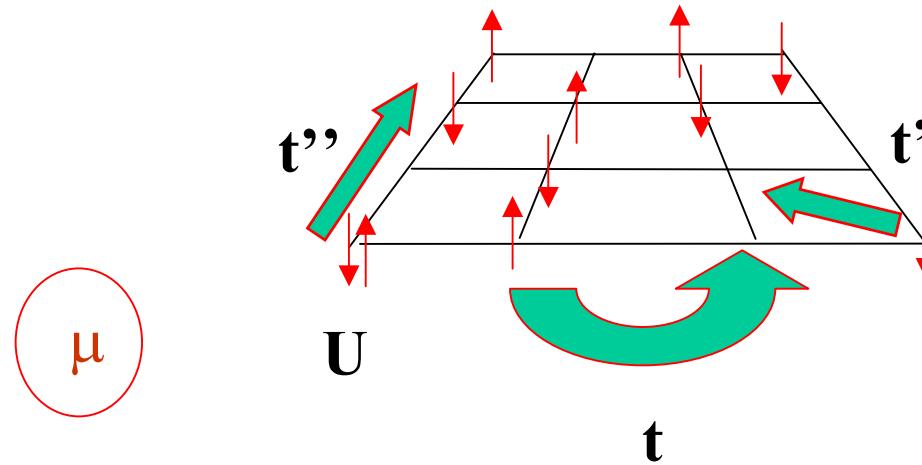


High-Temperature Superconductor belongs to a family of materials that exhibit exotic electronic properties.  
 $\gamma \text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$  9.2 - 37

LSCO



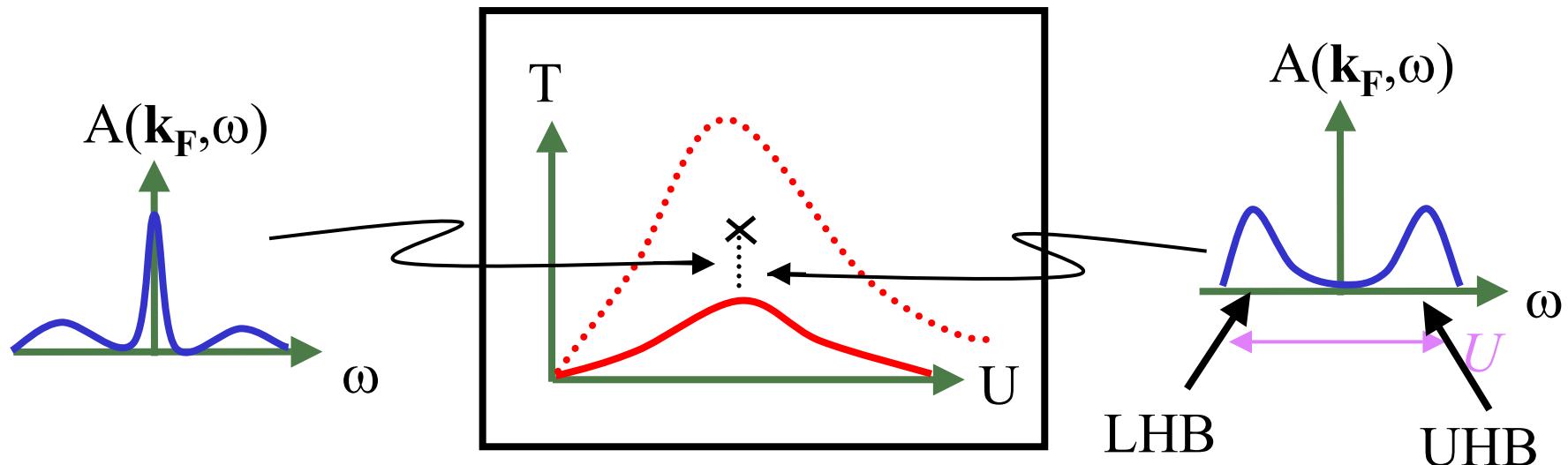
Simplest microscopic model for  $Cu$   $O$  planes.



- Size of Hilbert space :  $4^N$  ( $N = 16$ )
- With  $N=16$ , It takes 4 GigaBits just to store the states

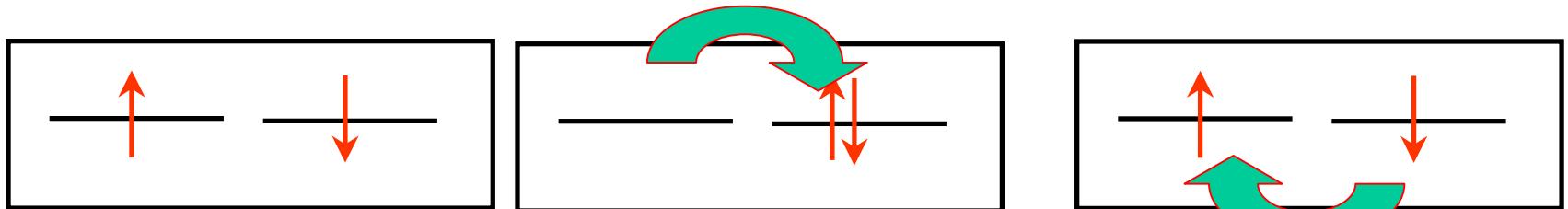
$$H = - \sum_{\langle ij \rangle \sigma} t_{ij} (c_{i\sigma}^\dagger c_{j\sigma} + c_{j\sigma}^\dagger c_{i\sigma}) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

## Weak vs strong coupling, $n=1$



$$U \sim 1.5W \quad (W = 8t)$$

Mott transition



Effective model, Heisenberg:  $J = 4t^2 / U$

# Question: quantitative and qualitative

- How do we go from a Mott insulator to a conductor as a function of doping?
- Hot spots and pseudogaps in the Hubbard model (like experiment) ?
- Close to understood in e-doped case.

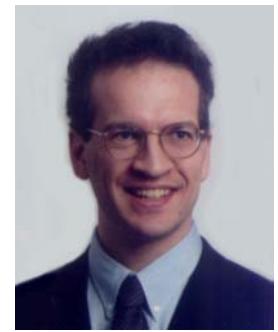
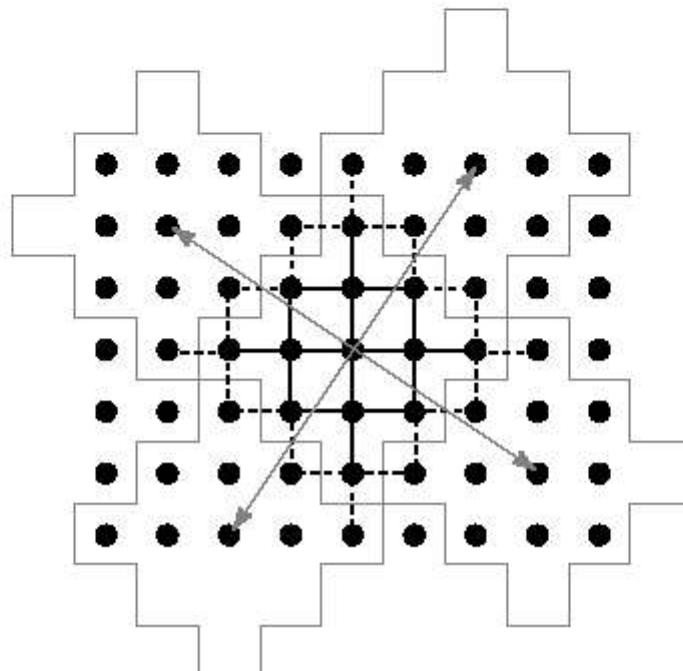
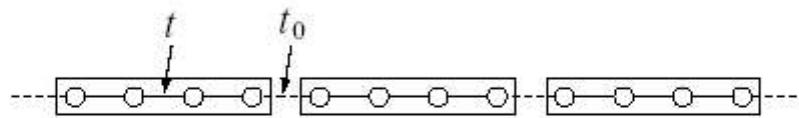
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# Cluster perturbation theory (CPT)

- ▶ Tile the lattice into identical clusters
- ▶ Solve exactly (numerically) within a cluster
- ▶ Treat inter-cluster hopping in perturbation theory

Vary  
cluster  
shape and  
size



$$t_{ab}^{mn} = t_{ab}^{(c)} \delta_{mn} + V_{ab}^{mn}$$

$$\hat{G}_0^{-1} = \omega - \hat{t} = \omega - \hat{t}^{(c)} - \hat{V}$$

noninteracting Green function      superlattice wavevector

## Basic CPT approximation :

$$\hat{G}^{-1}(\mathbf{K}, \omega) = \hat{G}^{(c)-1}(\omega) - \hat{V}(\mathbf{K})$$

CPT Green function

**Final Fourier transform :**

$$G_{\text{CPT}}(\mathbf{k}, \omega) = \frac{1}{L} \sum_{a,b=1}^L G_{ab}(\mathbf{k}, \omega) e^{-i\mathbf{k}\cdot(\mathbf{r}_a - \mathbf{r}_b)}$$

## Spectral function :

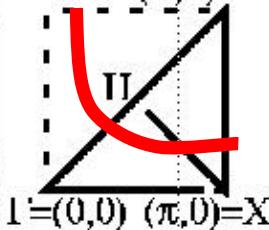
$$A(\mathbf{k}, \omega) = -2 \lim_{\eta \rightarrow 0^+} \text{Im} G(\mathbf{k}, \omega + i\eta)$$

# CPT

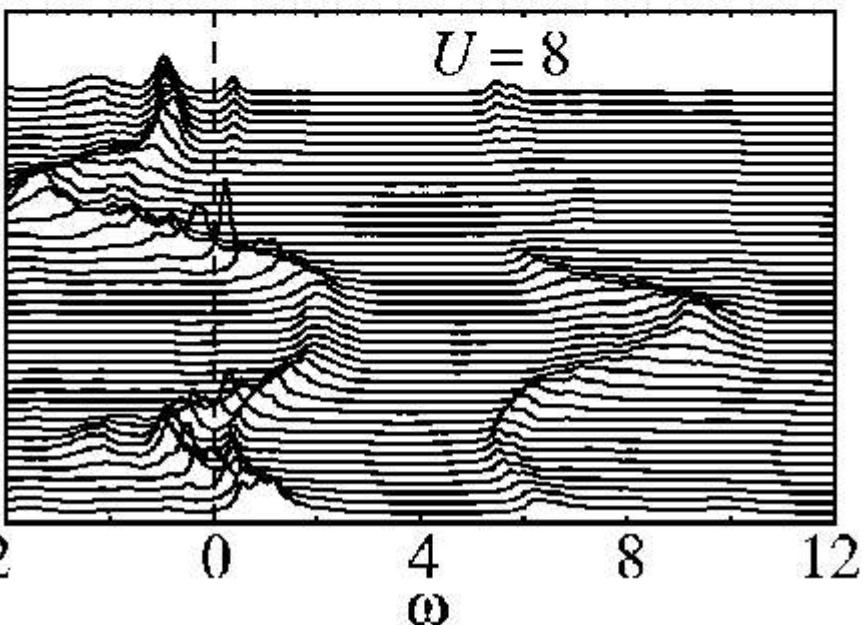
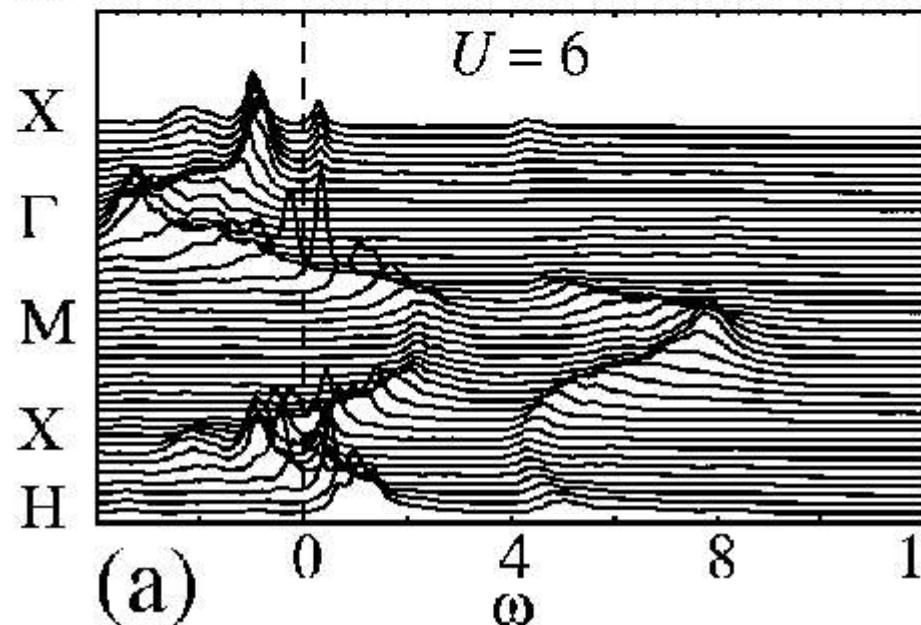
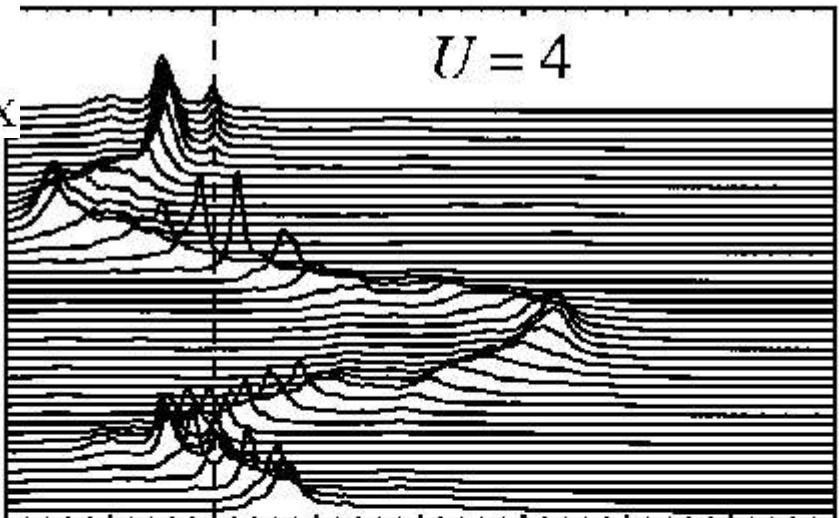
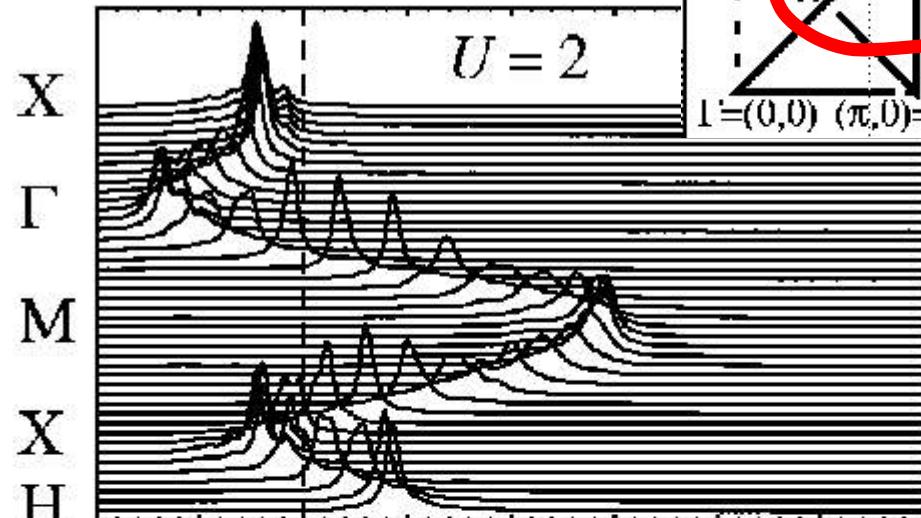
- Wave vector is continuous
  - Underlying cluster  $3 \times 4$  and  $4 \times 4$
- Exact for  $(t=0, U \text{ finite})$  and  $(U=0, t \text{ finite})$
- Finite energy resolution
  - Here about 40 meV (as in experiment).
- Tests:
  - spin-charge separation in  $d = 1$ .
  - $U=\text{infinity}$  limit.

# Hole-doped (17%)

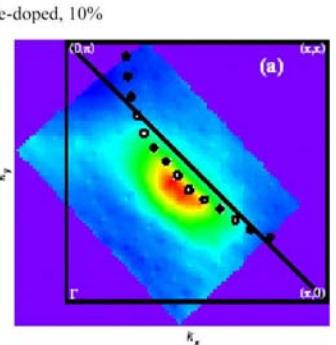
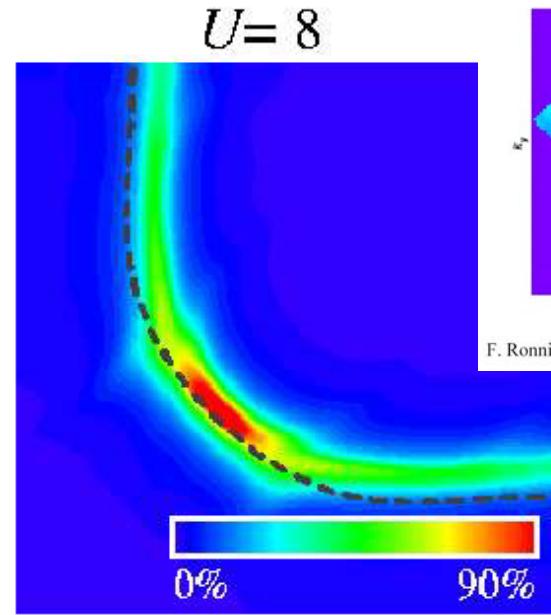
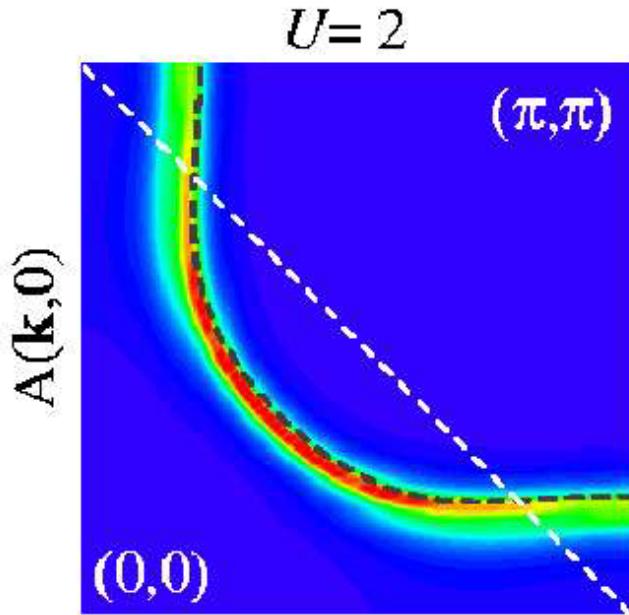
$$t' = -0.3t \quad , \quad t'' = 0.2t$$



Sénéchal, AMT, PRL **92**, 126401 (2004).



# Hole-doped (17%)

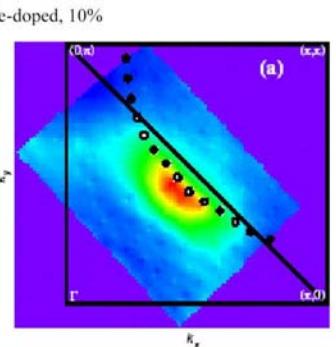
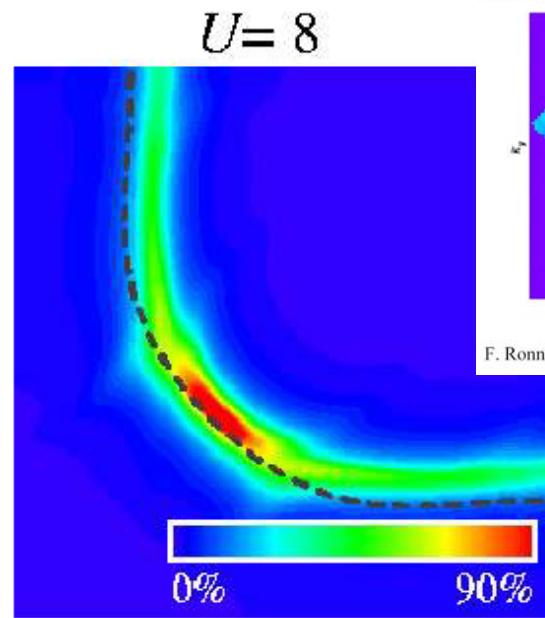
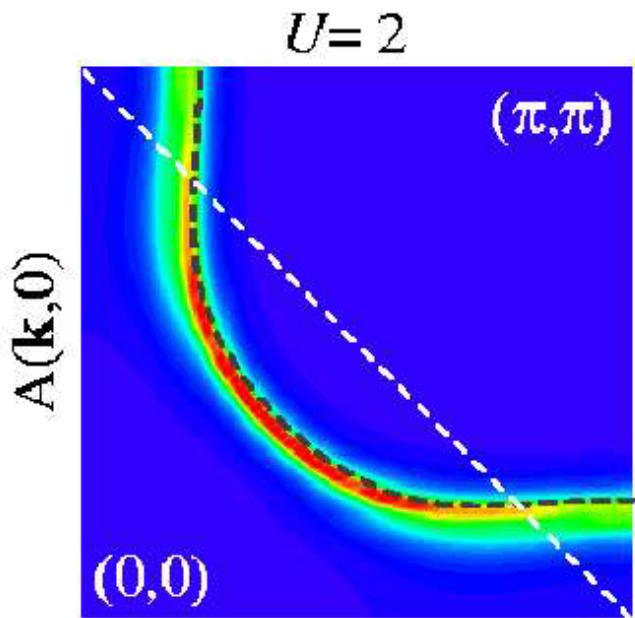


F. Ronning et al. Jan. 2002,  $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

$$t' = -0.3t$$
$$t'' = 0.2t$$

$$\eta = 0.12t$$
$$\eta = 0.4t$$

# Hole-doped (17%)

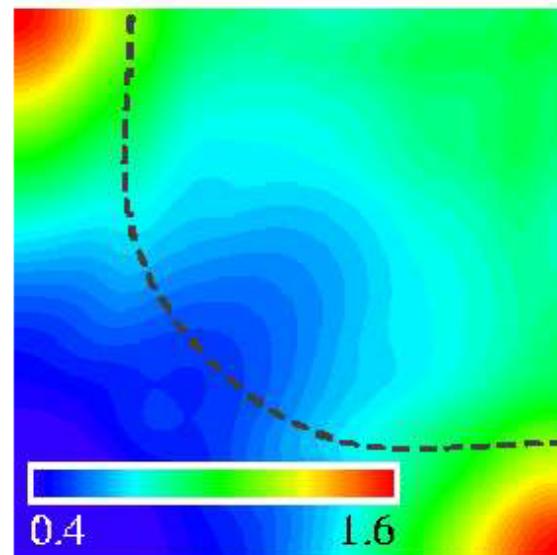


F. Ronning et al. Jan. 2002,  $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

$$t' = -0.3t$$
$$t'' = 0.2t$$

$$\eta = 0.12t$$
$$\eta = 0.4t$$

$\text{Im } \Sigma(\mathbf{k}, 0)$



Sénéchal, AMT, PRL 92, 126401 (2004).

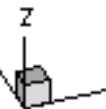
# Hole-doped 17%, $U=8t$

$U=8$

Frequency  $\omega=-1$

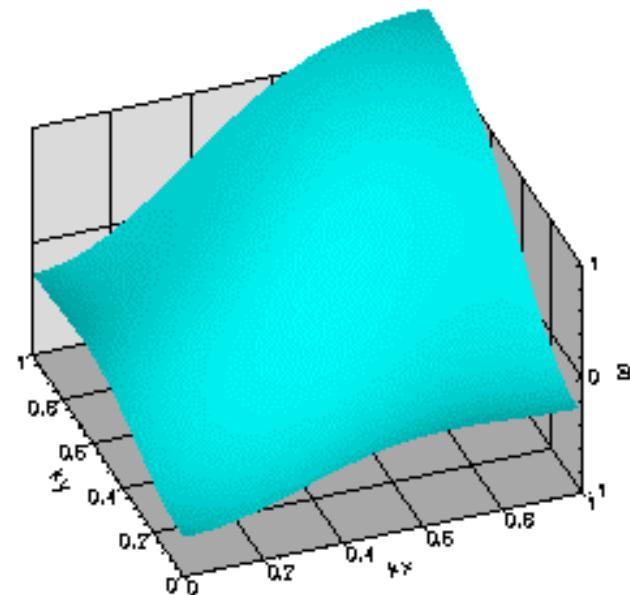
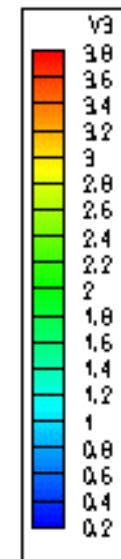
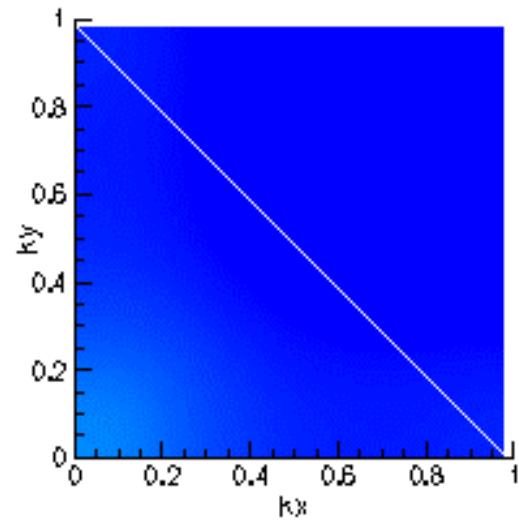
$U=2, n=10, t=0.25$   
 $t_d=-0.075, t_2=0.05$

Dispersion relation  
 $U=0, n=10, t=0.25$   
 $t_d=-0.075, t_2=0.05$



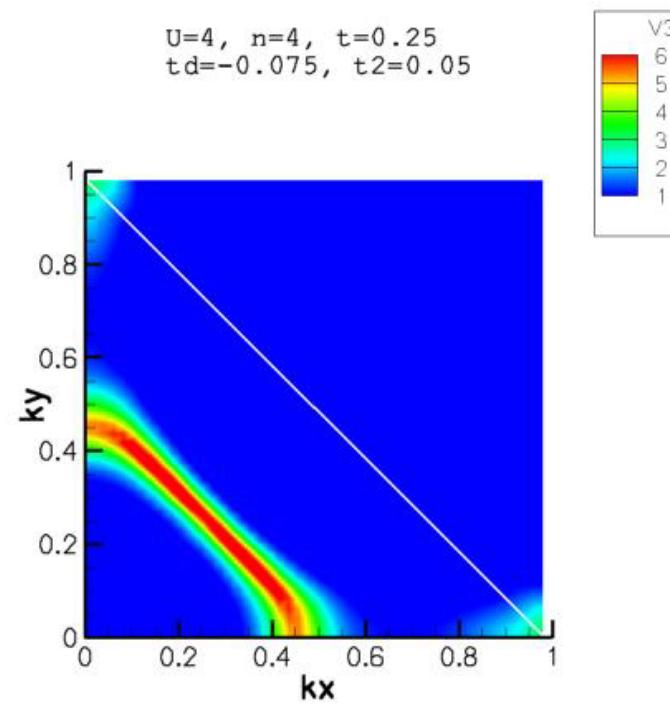
0%

90%

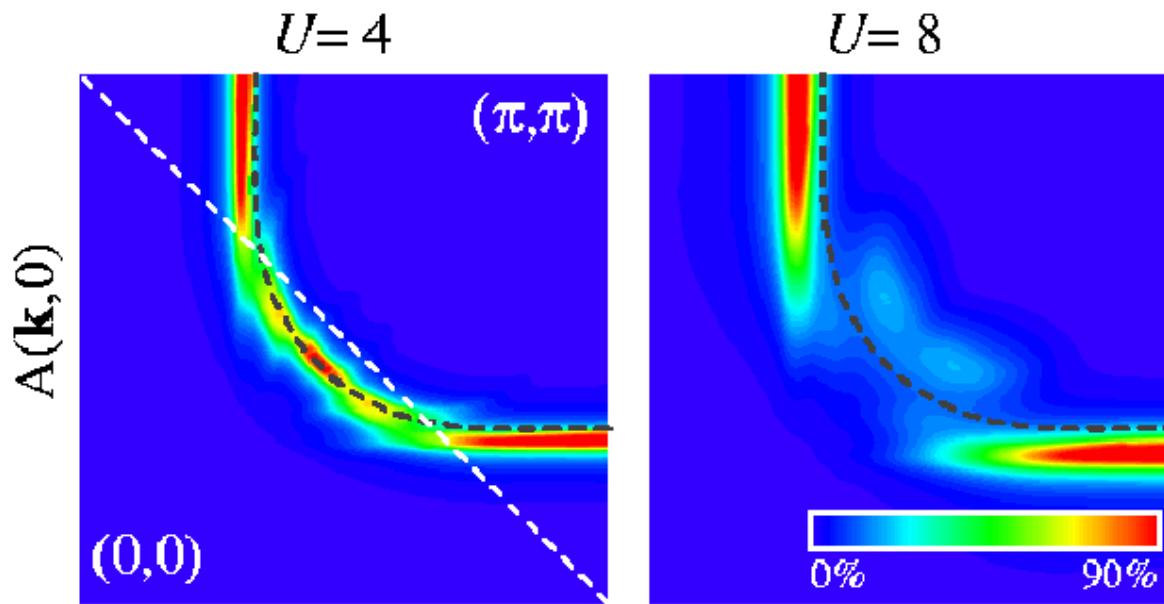


# Hole doped, 75%, $U = 16 t$

Frequency  $w=6.245e-17$



# Electron-doped (17%)

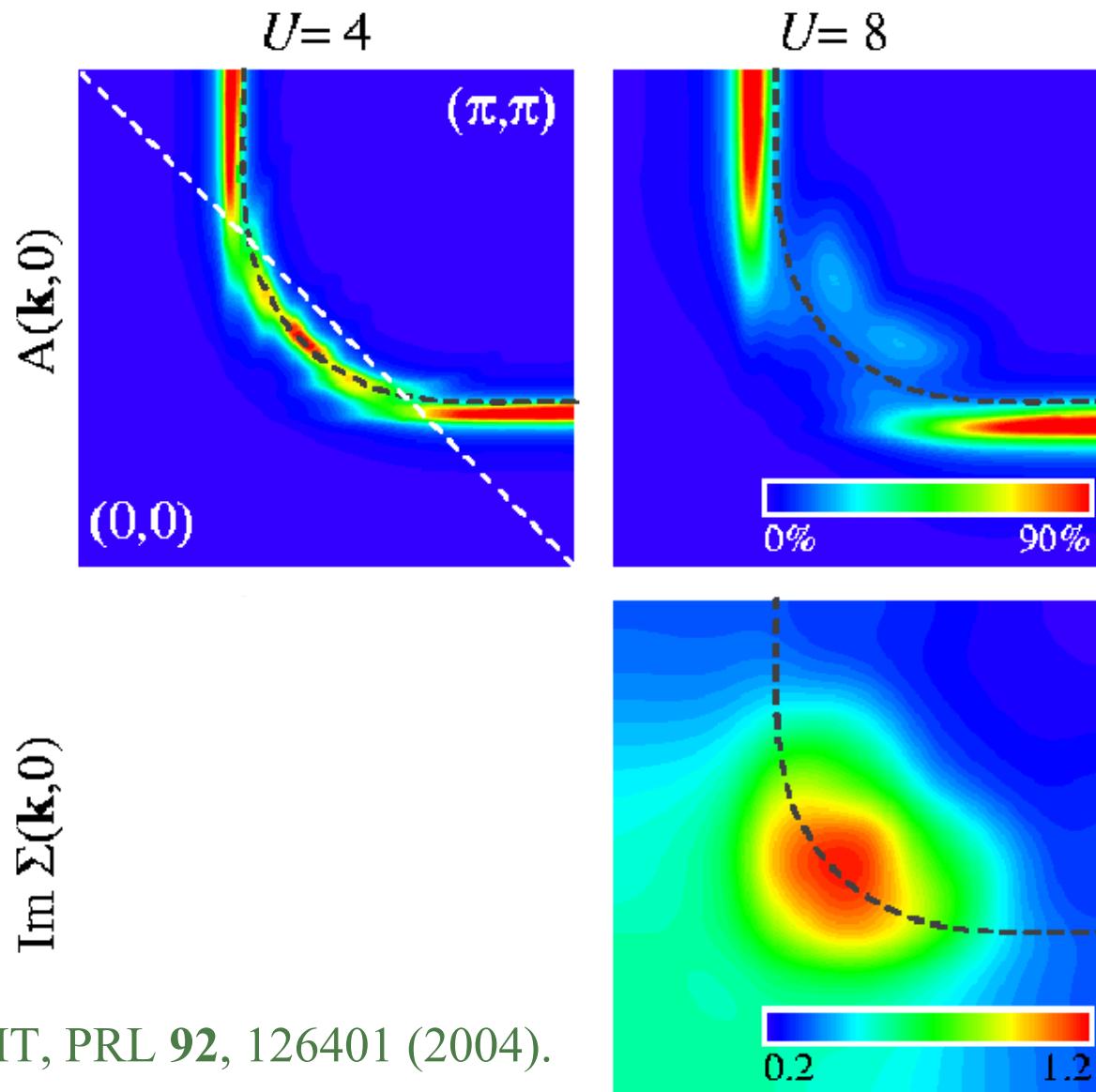


$$t' = -0.3t$$
$$t'' = 0.2t$$

$$\eta = 0.12t$$
$$\eta = 0.4t$$

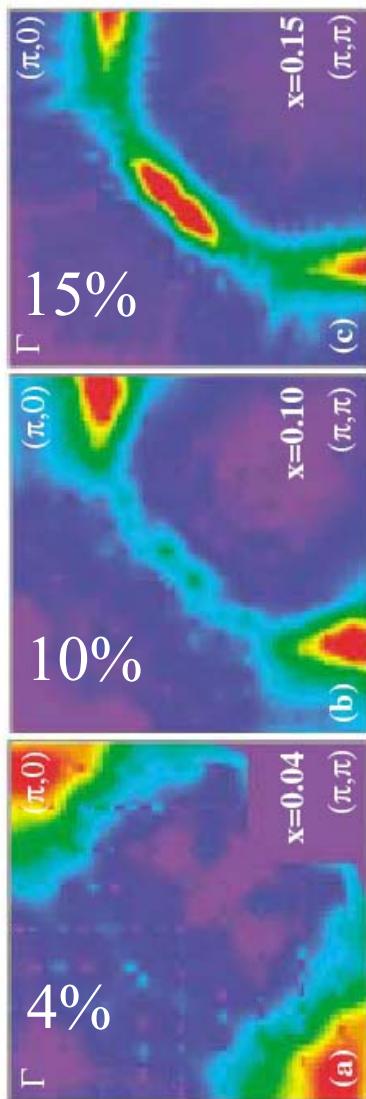
Sénéchal, AMT, PRL **92**, 126401 (2004).

# Electron-doped (17%)

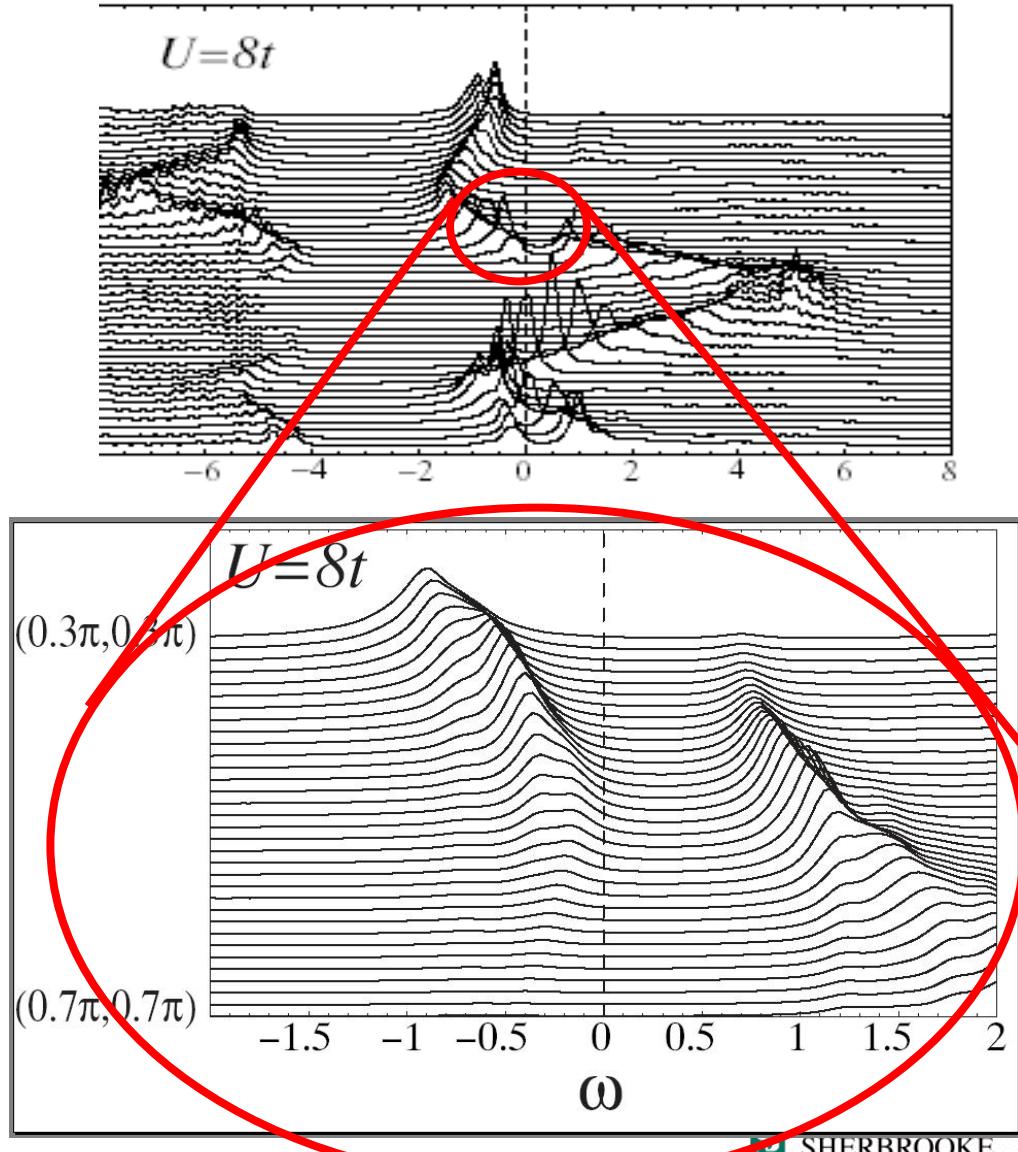


Sénéchal, AMT, PRL **92**, 126401 (2004).

# Electron-doped 12.5%, $U=8t$

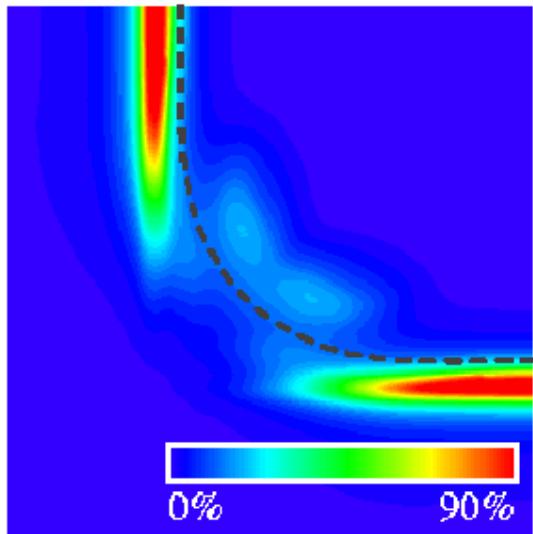


$4 \times 4$

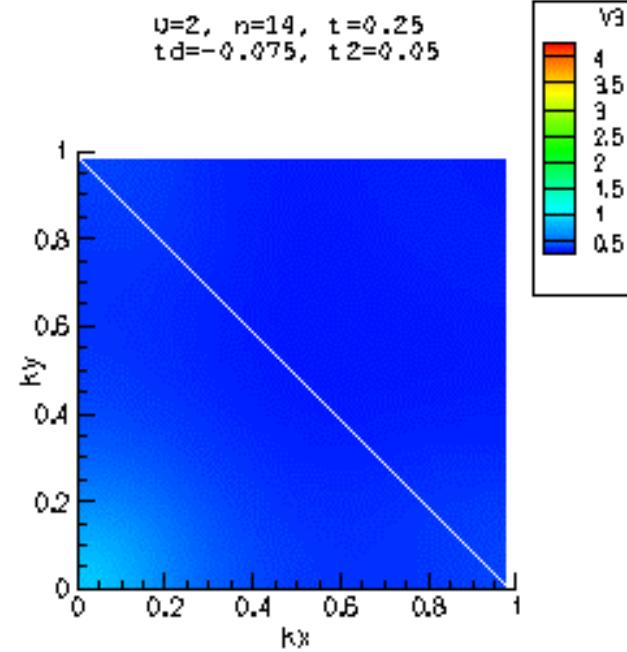


# Electron-doped, 17%, $U=8t$

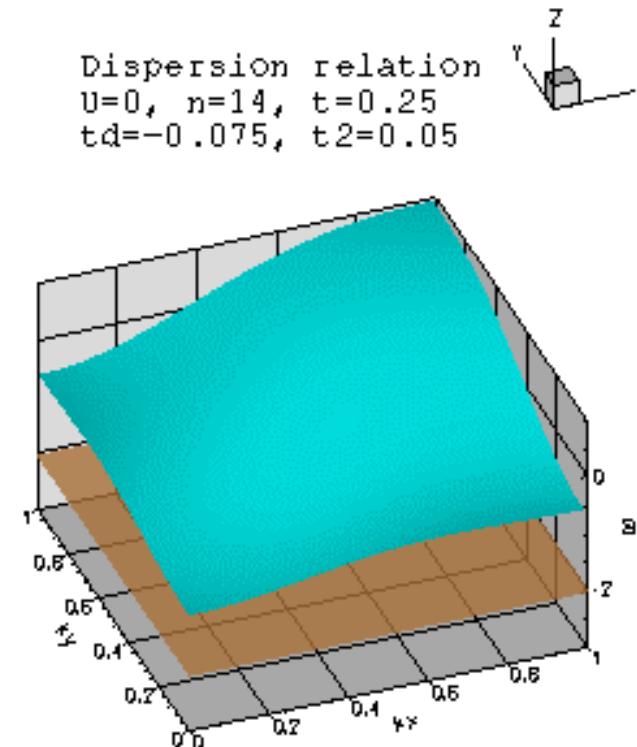
$U=8$



Frequency  $\omega=-2$

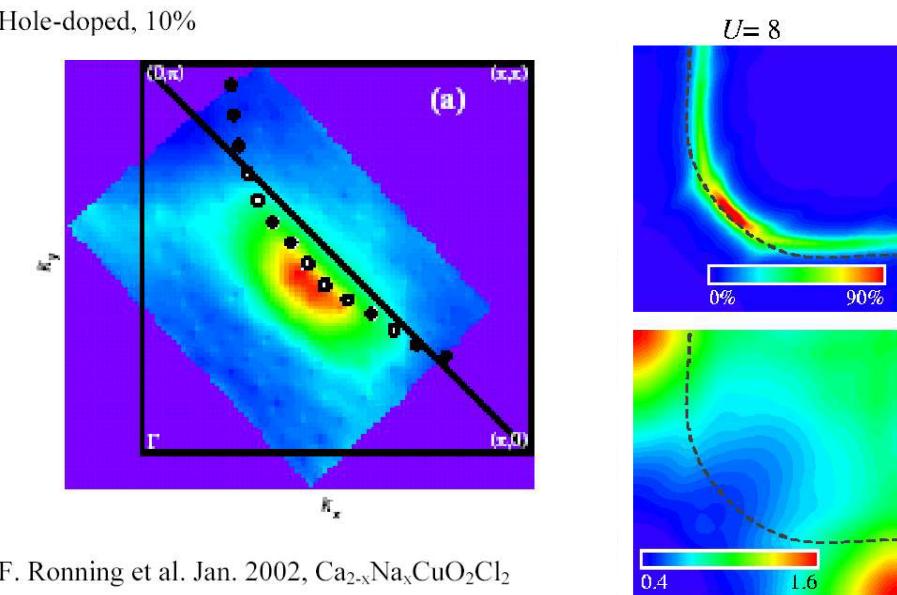


Dispersion relation  
 $U=0$ ,  $n=14$ ,  $t=0.25$   
 $t_d=-0.075$ ,  $t_2=0.05$



# Strong coupling pseudogap ( $U > 8t$ )

- Mott gap local (all  $k$ ) not tied to  $\omega=0$ .
- Pseudogap tied to  $\omega=0$  and only in regions nearly connected by  $(\pi,\pi)$ . (e and h),
- Pseudogap is independent of cluster shape (and size) in CPT.
- Not caused by AFM LRO
  - No LRO, few lattice spacings.
  - Not very sensitive to  $t'$
  - Scales like  $t$ .

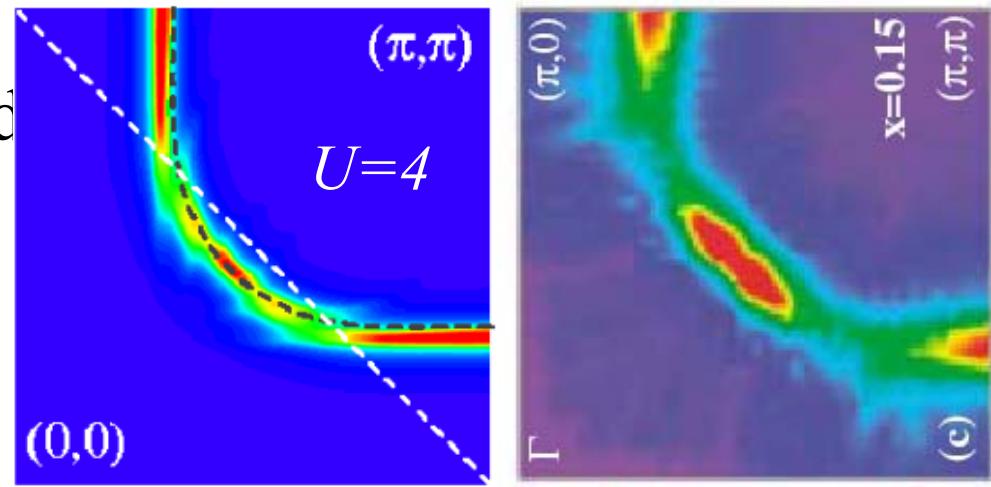
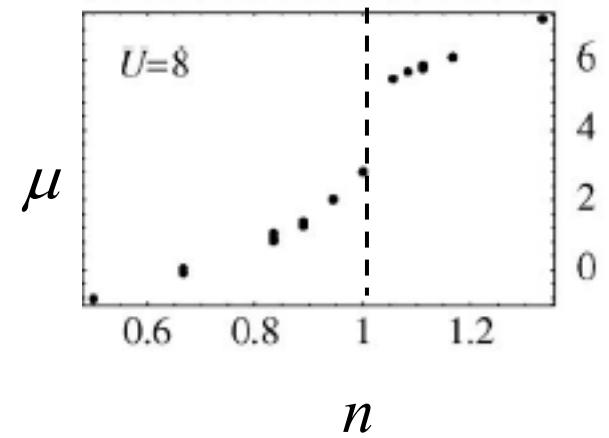


F. Ronning et al. Jan. 2002,  $\text{Ca}_{2-x}\text{Na}_x\text{CuO}_2\text{Cl}_2$

Sénéchal, AMT, PRL **92**, 126401 (2004).

# Weak-coupling pseudogap

- In CPT
  - is mostly a depression in weight
  - depends on system size and shape.
  - located precisely at intersection with AFM Brillouin zone
- Coupling weaker because better screened  
 $U(n) \sim d\mu/dn$

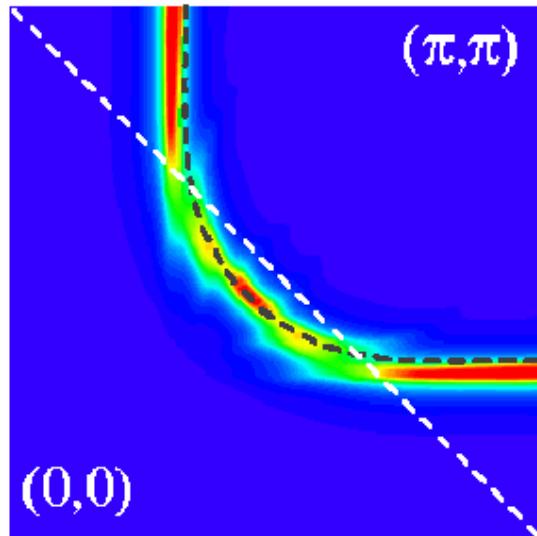


Sénéchal, AMT, PRL **92**, 126401 (2004).

# Electron-doped, 17%, $U=4t$

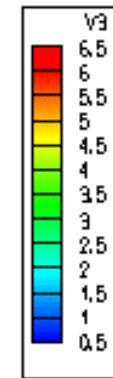
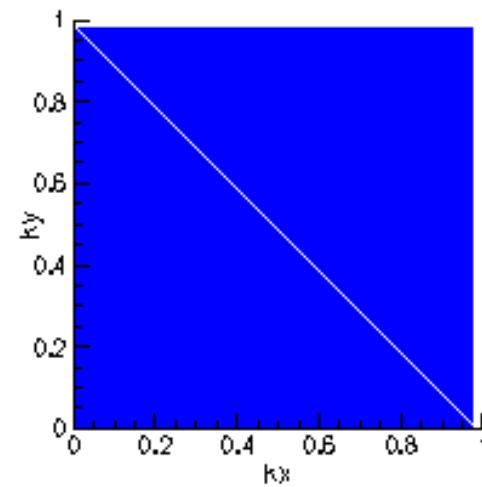
$U=4$

$A(\mathbf{k}, 0)$

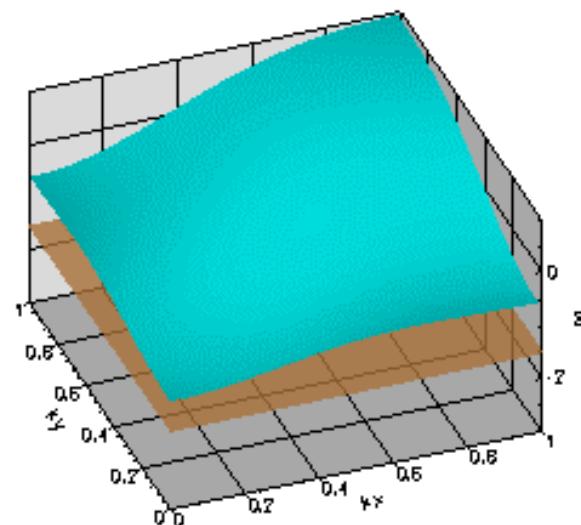
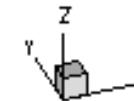


Frequency  $w=-1.5$

$U=1, n=14, t=0.25$   
 $t_d=-0.075, t_2=0.05$



Dispersion relation  
 $U=0, n=14, t=0.25$   
 $t_d=-0.075, t_2=0.05$



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Theory difficult even at weak to intermediate coupling!

- RPA
  - Mermin-Wagner
  - Pauli ~~X~~
- Moryia
  - Adjustable parameters:  $c$  and  $U_{eff}$
- FLEX
  - No pseudogap
  - Pauli ~~X~~

# Two-Particle Self-Consistent Approach ( $U < W$ )

- How it works

- General philosophy
  - Drop diagrams
  - Impose constraints and sum rules and ask to satisfy them.
    - Pauli principle
    - Conservation laws
    - Local moment and local density sum-rules
- Get for free:
  - Mermin-Wagner theorem
  - Kanamori-Brückner screening

Vilk, AMT J. Phys. I France, 7, 1309 (1997); Allen et al.in *Theoretical methods for strongly correlated electrons* also cond-mat/0110130

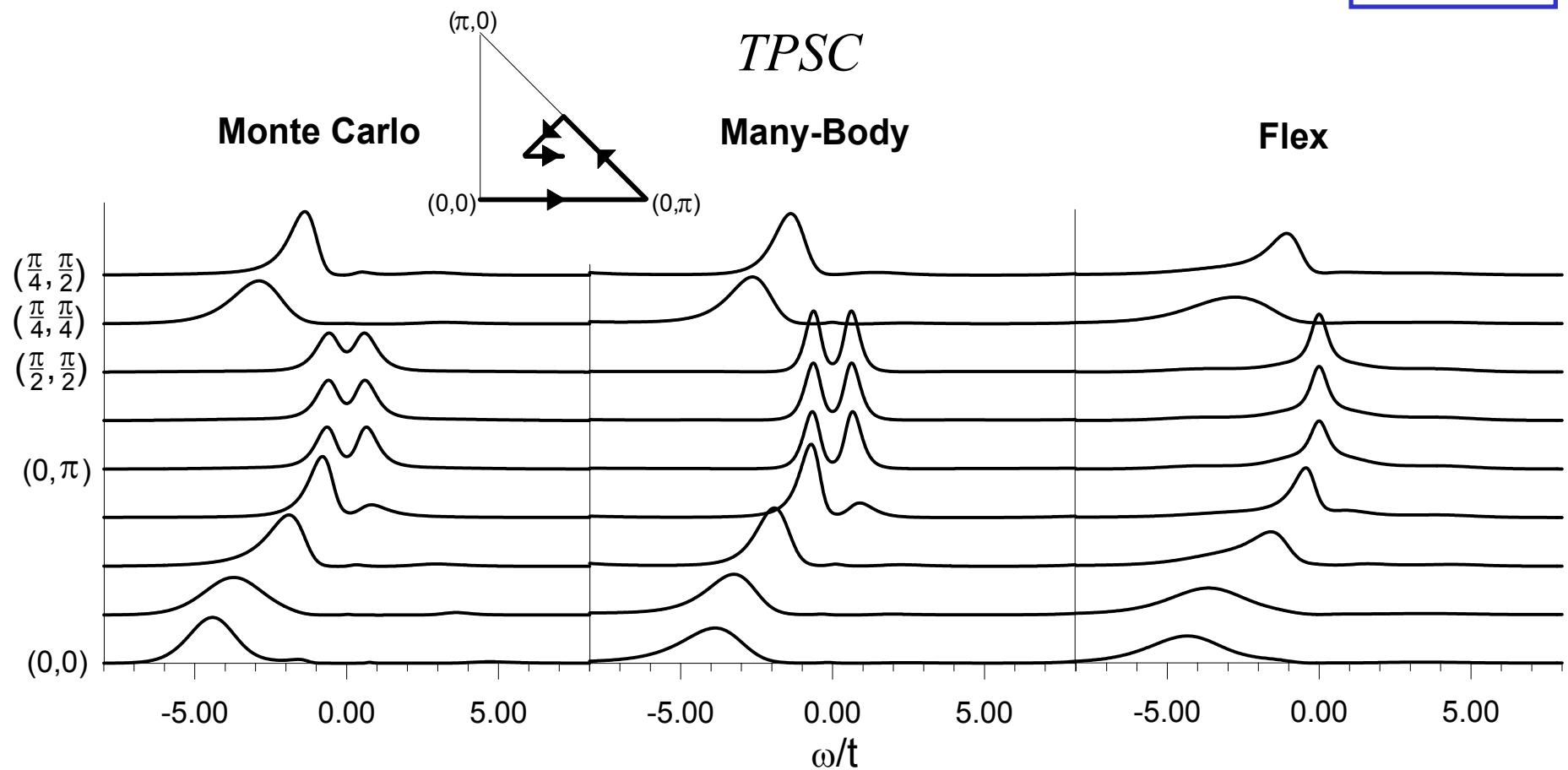
(Mahan, third edition)

# Quantum Monte Carlo

- **Use as benchmark for TPSC**
- Advantages
  - Sizes much larger than exact diagonalizations
  - As accurate as needed
- Disadvantages
  - Cannot go to very low temperature in certain doping ranges, yet low enough in certain cases to discard existing theories.

Proofs...

$U = +4$   
 $\beta = 5$



Calc. + QMC: Moukouri et al. P.R. B 61, 7887 (2000).

# TPSC approach: two steps

## I: Two-particle self consistency

1. Functional derivative formalism (conservation laws)

(a) analog of the Bethe-Salpeter equation:

$$\chi_{sp} = \frac{\delta G}{\delta \phi} = GG + GU_{sp}\chi_{sp}G$$

(b) spin vertex:  $U_{sp} = \frac{\delta \Sigma_\uparrow}{\delta G_\downarrow} - \frac{\delta \Sigma_\uparrow}{\delta G_\uparrow}$

(c) self-energy:

$$\Sigma_\sigma(1, \bar{1}; \{\phi\}) G_\sigma(\bar{1}, 2; \{\phi\}) = -U \langle c_{-\sigma}^\dagger(1^+) c_{-\sigma}(1) c_\sigma(1) c_\sigma^\dagger(2) \rangle_\phi$$

$\approx A_{\{\phi\}} G_{-\sigma}^{(1)}(1, 1^+; \{\phi\}) G_\sigma^{(1)}(1, 2; \{\phi\})$

2. Factorization

# TPSC...

$$U_{sp} = U \frac{\langle n_\uparrow n_\downarrow \rangle}{\langle n_\uparrow \rangle \langle n_\downarrow \rangle} \quad \text{Kanamori screening}$$

$$\chi_{sp}^{(1)}(q) = \frac{\chi_0(q)}{1 - \frac{1}{2}U_{sp}\chi_0(q)}$$

## 3. The F.D. theorem and Pauli principle

$$\frac{T}{N} \sum_q \chi_{sp}^{(1)}(q) = n - 2\langle n_\uparrow n_\downarrow \rangle$$

### II: Improved self-energy

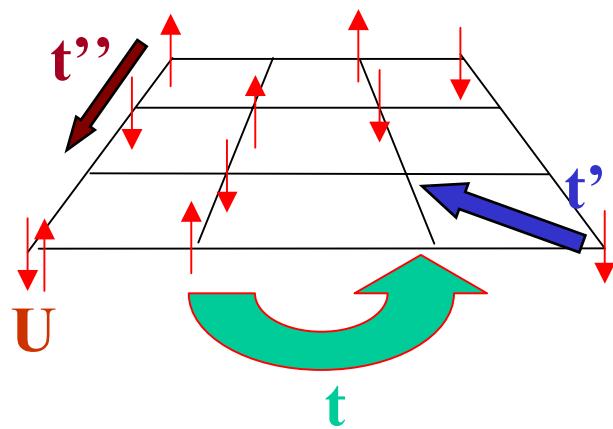
Insert the first step results

into exact equation:  $\Sigma_\sigma(1, \bar{1}; \{\phi\}) G_\sigma(\bar{1}, 2; \{\phi\}) = -U \langle c_{-\sigma}^\dagger(1^+) c_{-\sigma}(1) c_\sigma(1) c_\sigma^\dagger(2) \rangle_\phi$

$$\Sigma_\sigma^{(2)}(k) = Un_\sigma + \frac{U}{8} \frac{T}{N} \sum_q \left[ 3U_{sp}\chi_{sp}^{(1)}(q) + U_{ch}\chi_{ch}^{(1)}(q) \right] G_\sigma^{(1)}(k+q)$$

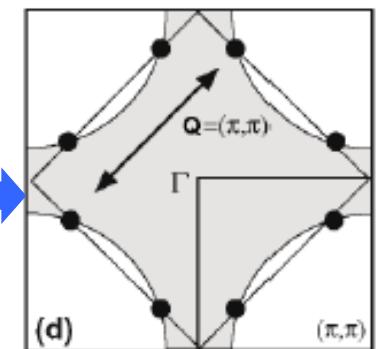
# The 2D Hubbard model

$$H = - \sum_{\langle ij \rangle \sigma} t_{ij} (c_{i\sigma}^\dagger c_{j\sigma} + c_{j\sigma}^\dagger c_{i\sigma}) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



*t' = -0.175t, t'' = 0.05t*  
*t = 350 meV, T = 200 K*

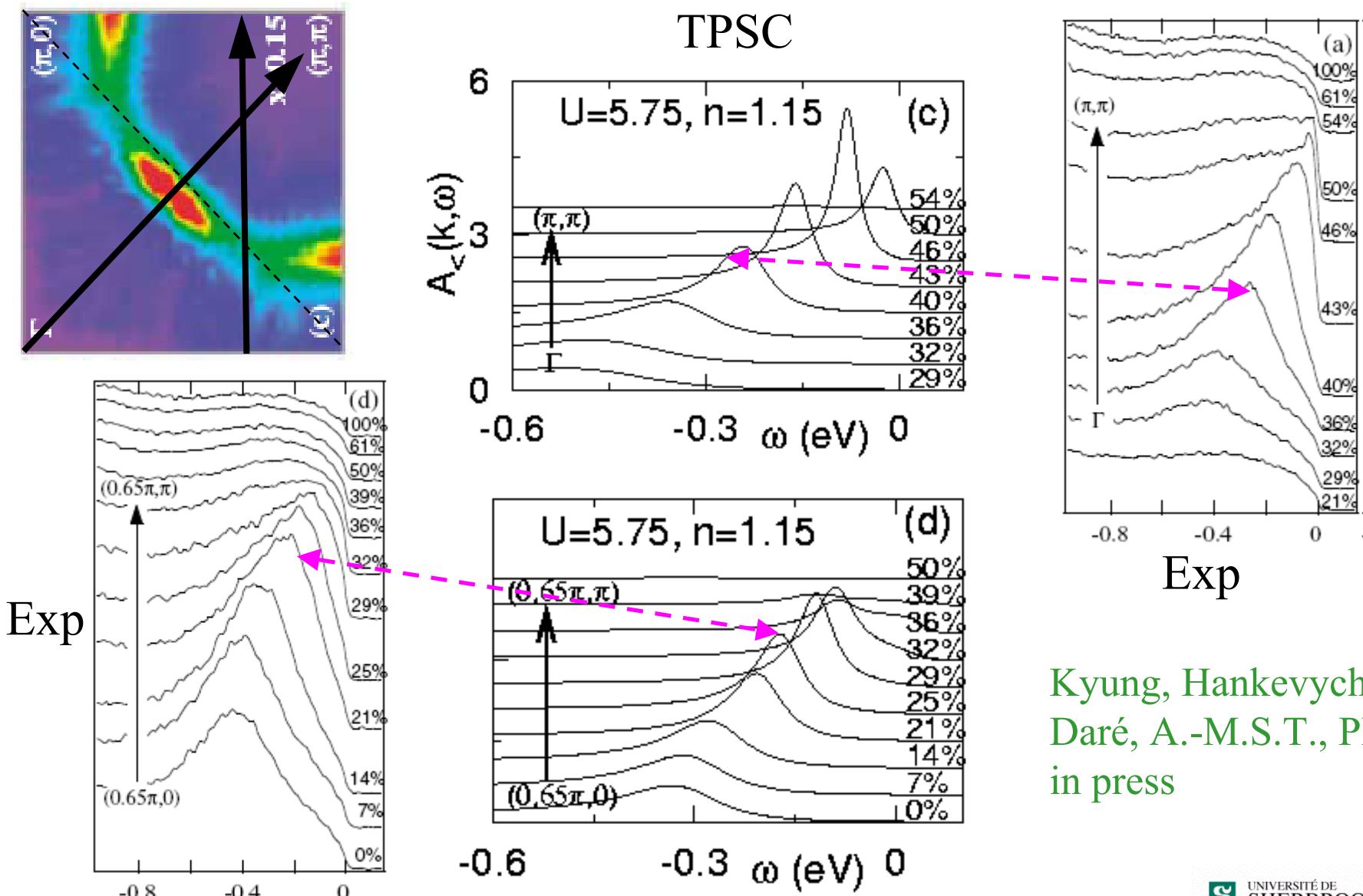
fixed



Weak coupling  $U < 8t$

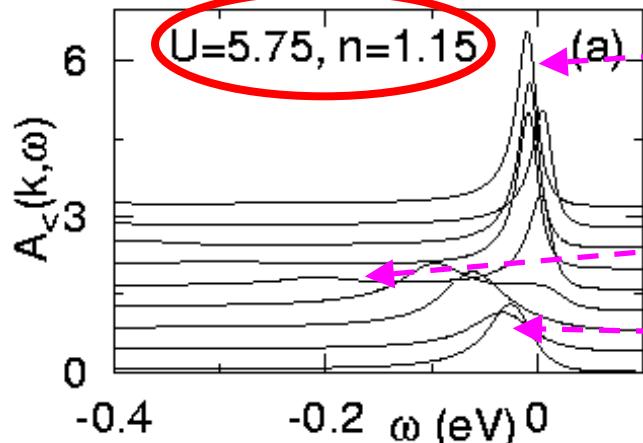
$n = 1 + x$  – electron filling

# 15% doped case: EDCs in two directions



Kyung, Hankevych,  
Daré, A.-M.S.T., PRL  
in press

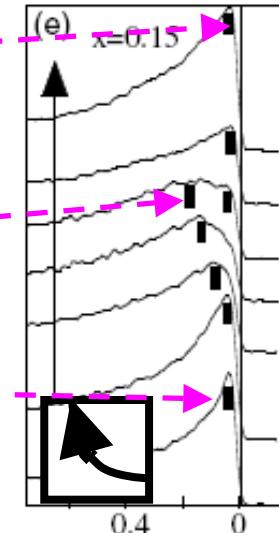
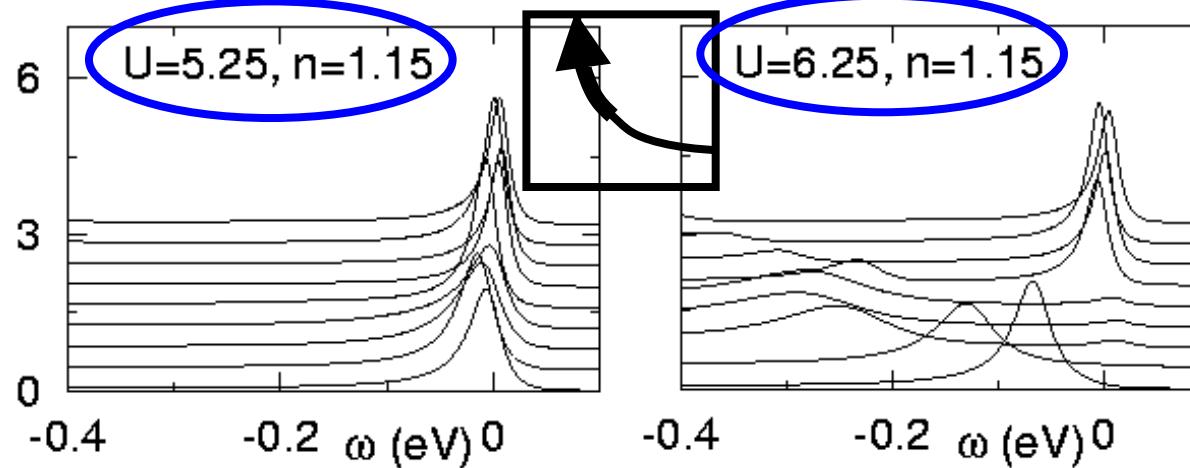
# 15% doping: EDCs along the Fermi surface TPSC



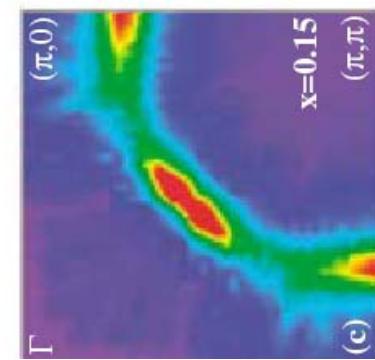
(a)

$$U_{min} < U < U_{max}$$

$U_{max}$  also from CPT

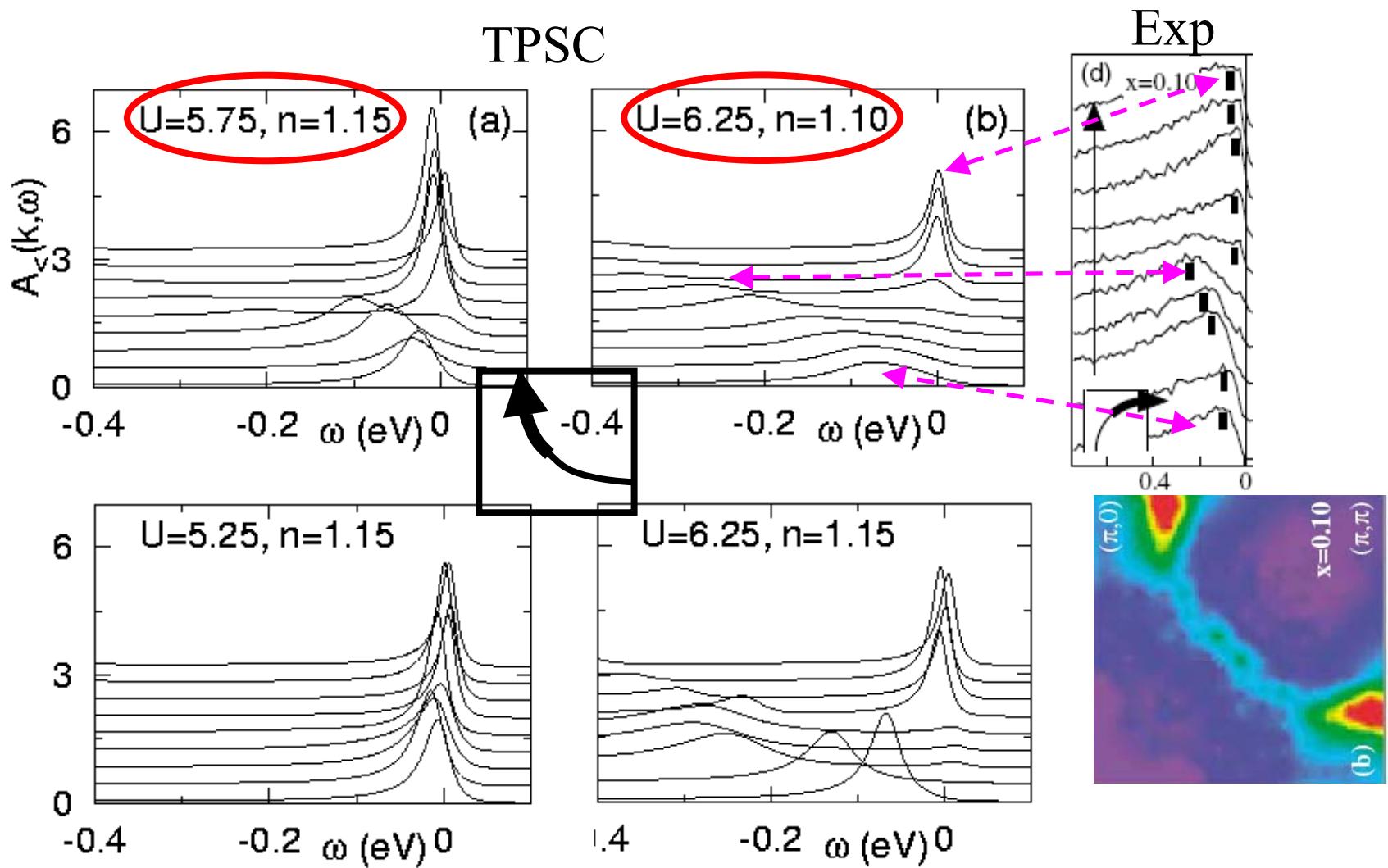


Exp



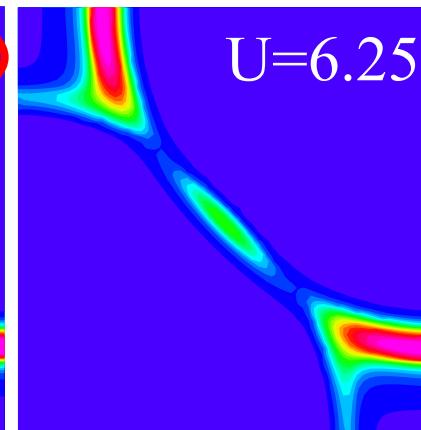
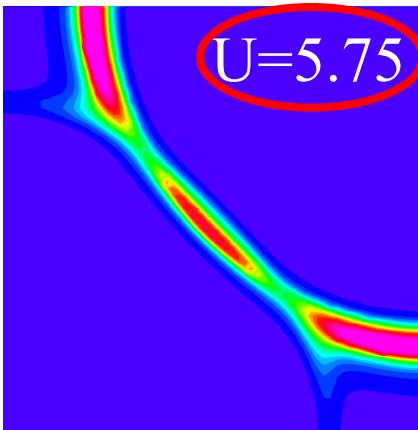
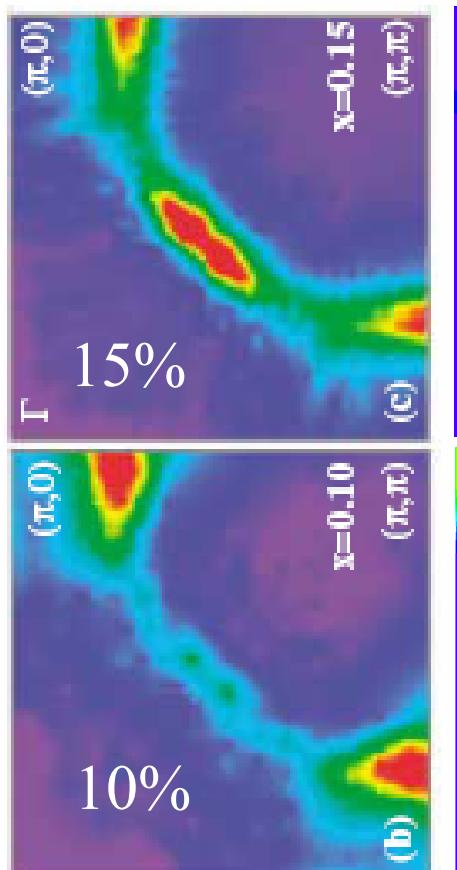
Kyung, Hankevych, Daré A.-M.S.T., PRL in press

# EDCs along the Fermi surface TPSC

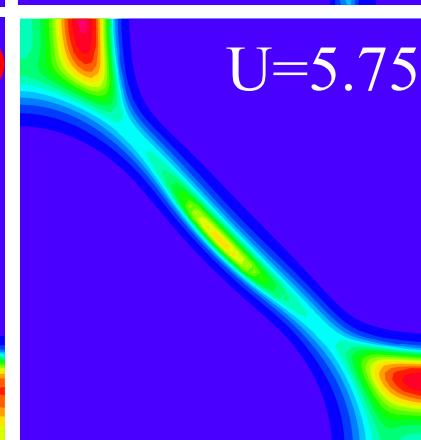
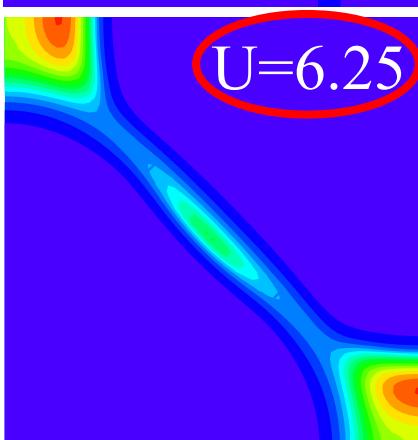
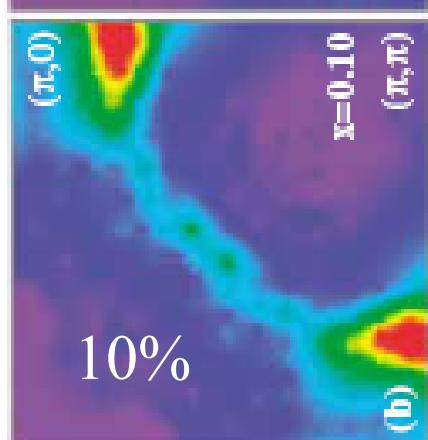


# Fermi surface plots

Hubbard repulsion  $U$  has to...

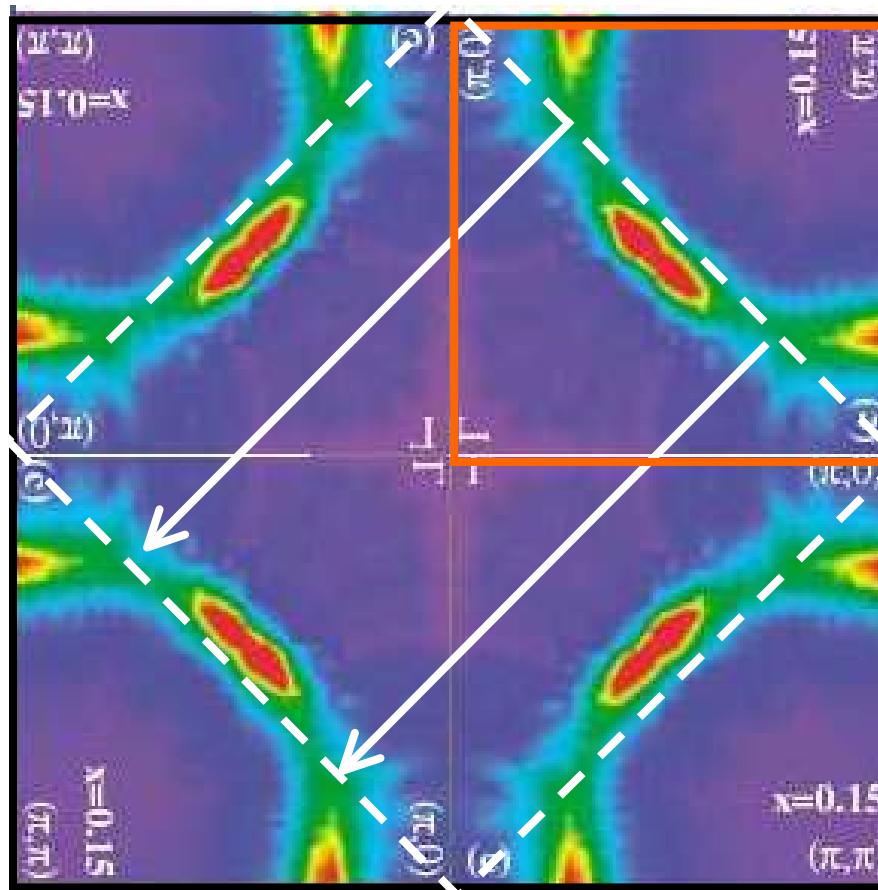


be not too large

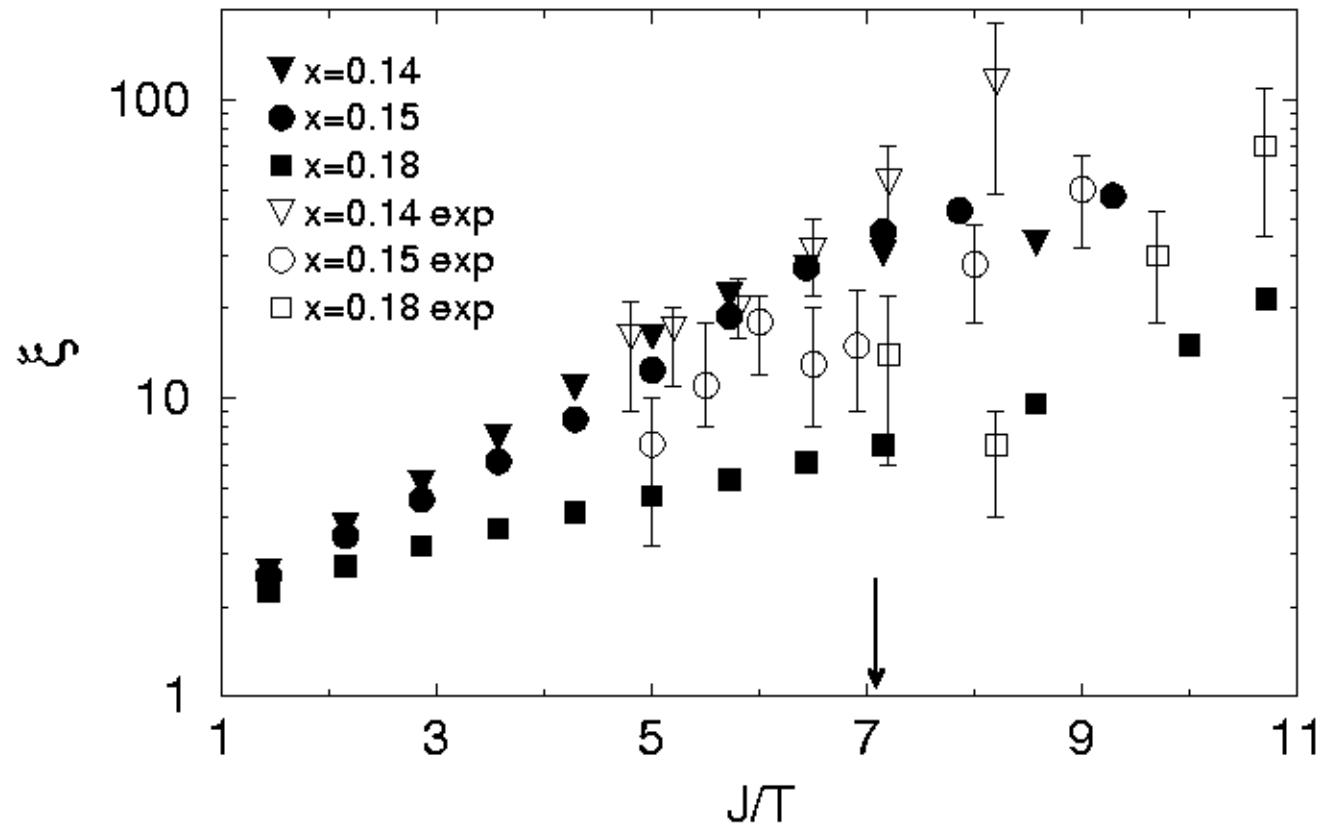


increase for  
smaller doping

# Hot spots from AFM quasi-static scattering



# AFM correlation length (neutron)



Expt: P. K. Mang et al., cond-mat/0307093, Matsuda (1992).

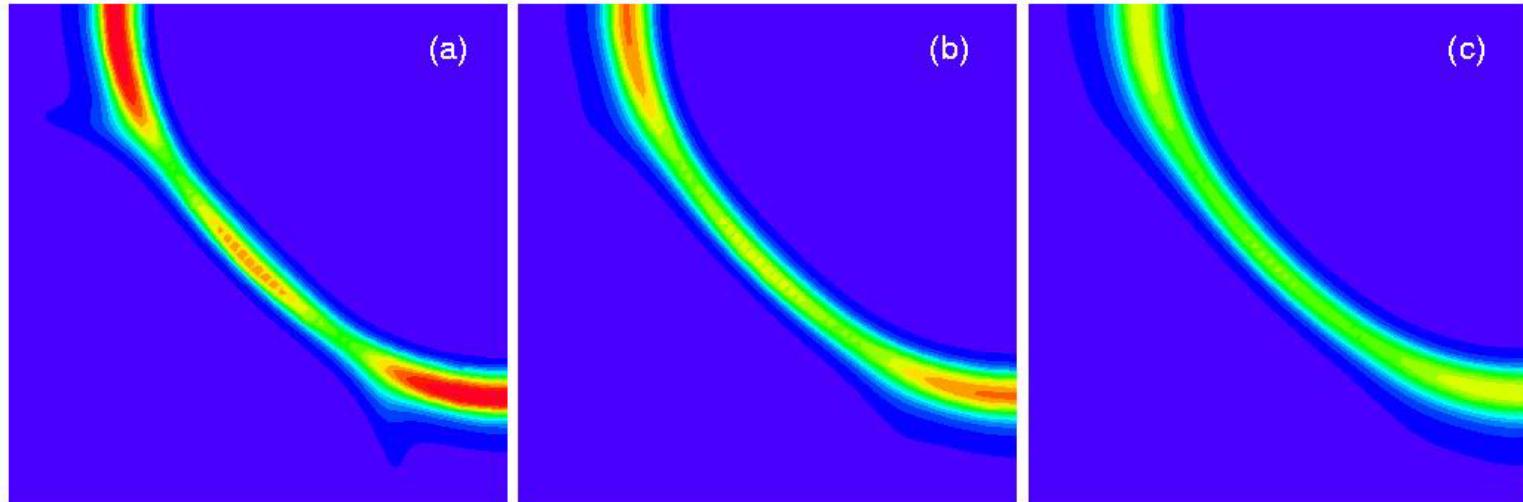
Theo: Kyung, Hankevych, Daré A.-M.S.T., PRL in press

# Temperature dependence of ARPES

$\beta = 15$

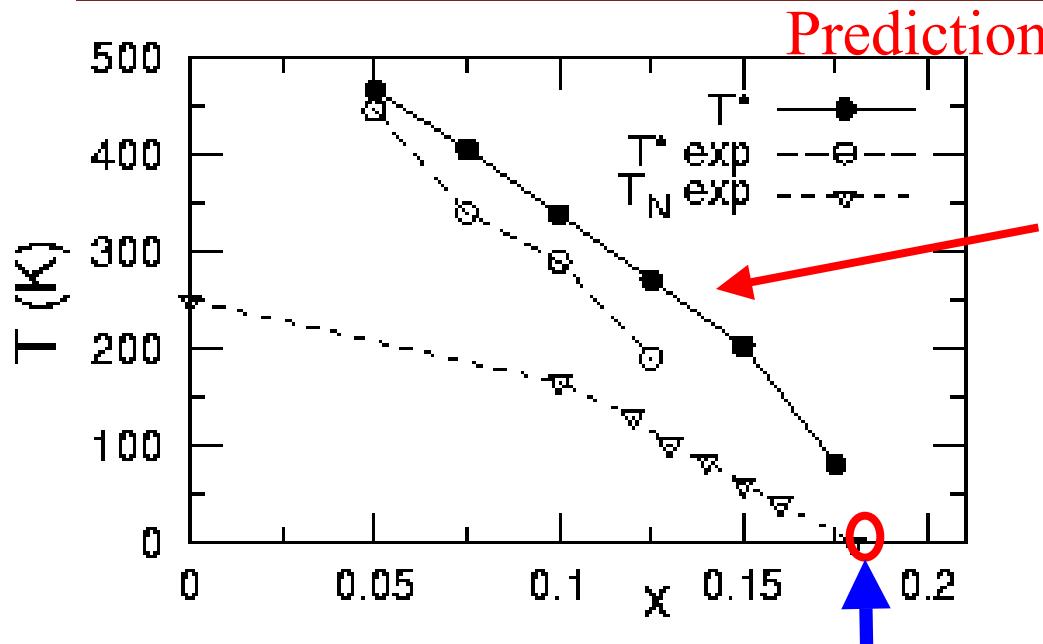
$\beta = 10$

$\beta = 7.5$



$U=5.75,$   
 $t'=-0.175, t''=0.05,$   
 $n = 1.15$

# Pseudogap temperature and QCP



Prediction

➤  $\xi \approx \xi_{th}$  at PG temperature  $T^*$ ,  
and  $\xi > \xi_{th}$  for  $T < T^*$

Prediction

supports further AFM  
fluctuations origin of PG

➤ ARPES to do:

when does PG disappear  
with increasing  $T$

Prediction QCP

may be masked by 3D transitions

➤  $\Delta_{PG} \approx 10k_B T^*$  comparable with optical measurements

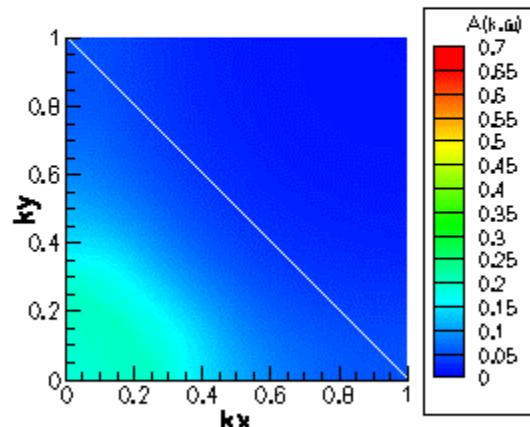
Kyung, Hankevych, Daré A.-M.S.T., PRL in press

Expt: Y. Onose et al., PRL (2001).

# Electron doped, 15% low $T=0.05t$

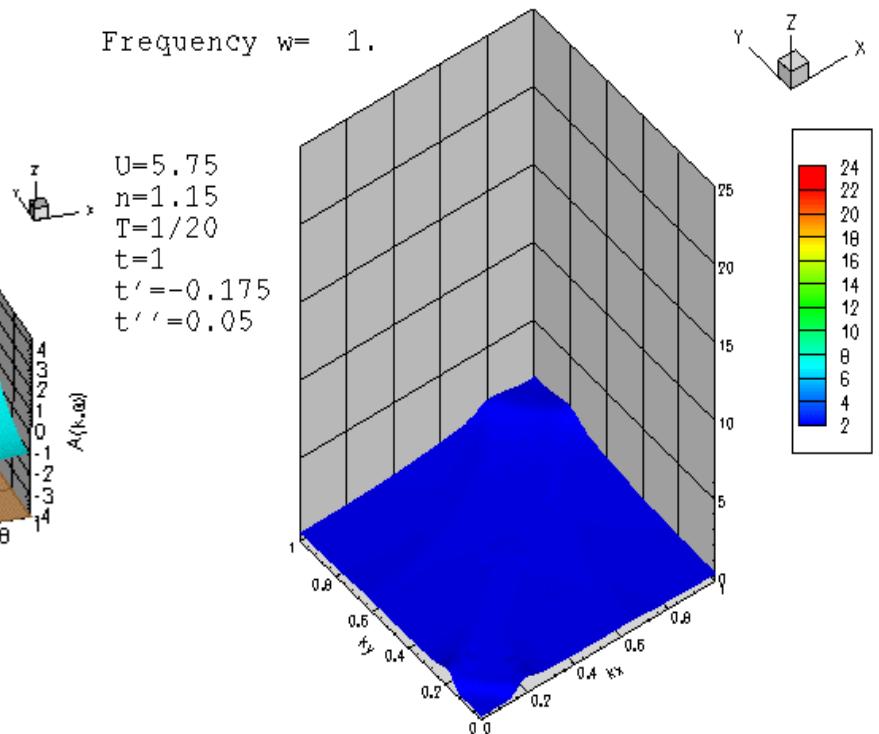
Frequency  $w = -4$ .

$U=5.75$ ,  $n=1.15$ ,  $T=1/20$   
 $t=1$ ,  $t'=-0.175$ ,  $t''=0.05$



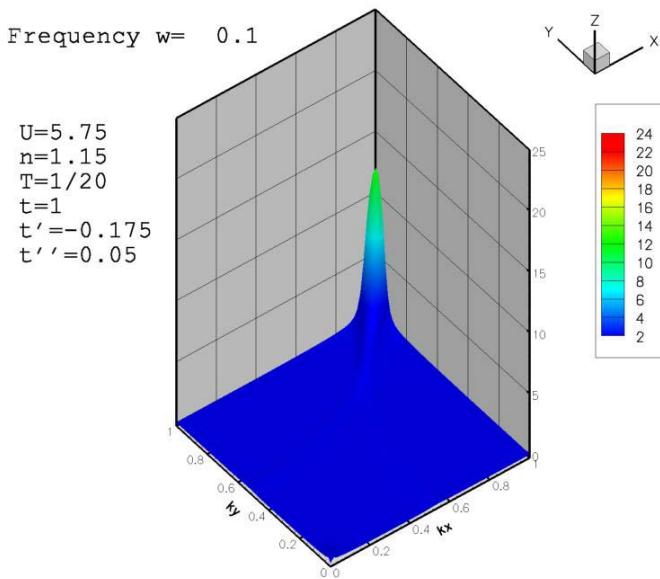
Frequency  $w = 1$ .

$U=5.75$   
 $n=1.15$   
 $T=1/20$   
 $t=1$   
 $t'=-0.175$   
 $t''=0.05$

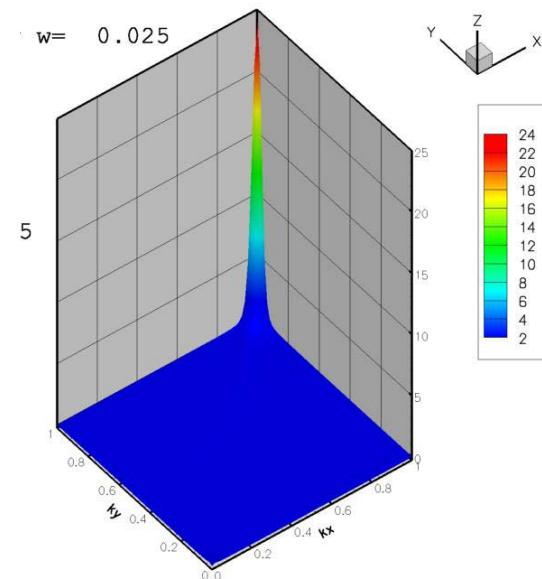


# Electron doped 15% low $T=0.05t$

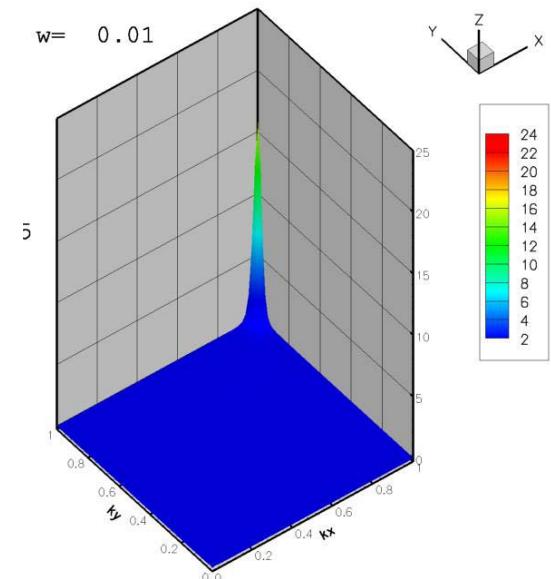
$\omega = 0.1t$



$\omega = 0.02t$



$\omega = 0.01t$

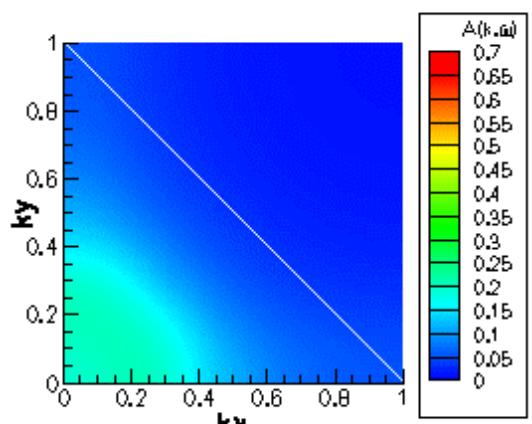


Prediction:  $\hbar \omega_{sf} \ll k_B T$  in pseudogap begins at  $T > T^*$

# Electron doped, 15%, high $T=0.2t$

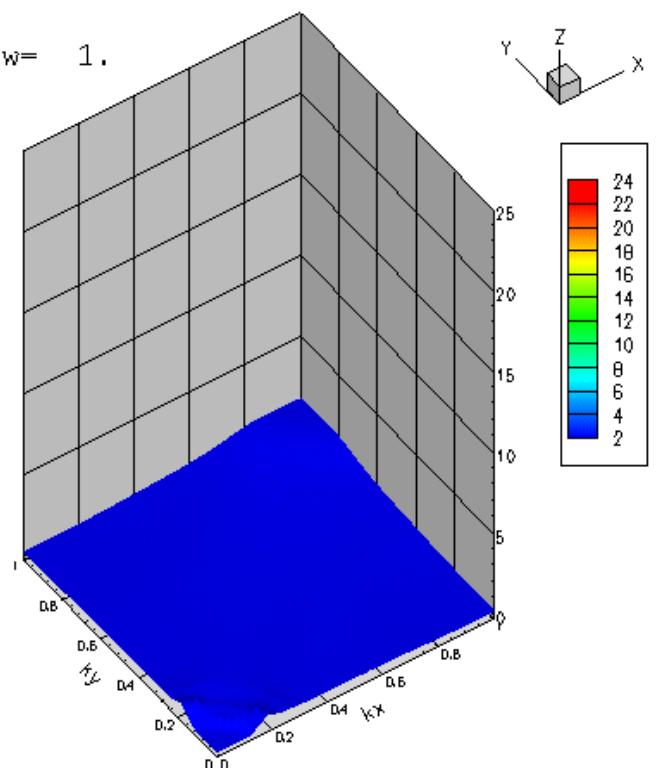
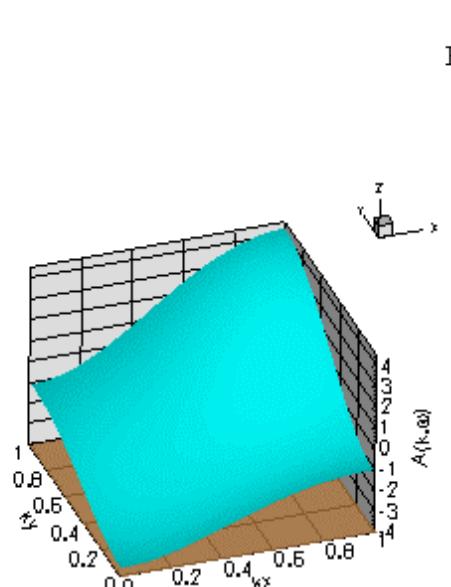
Frequency  $\omega = -4$ .

$U=5.75$ ,  $n=1.15$ ,  $T=1/5$   
 $t=1$ ,  $t'=-0.175$ ,  $t''=0.05$



Frequency  $\omega = 1$ .

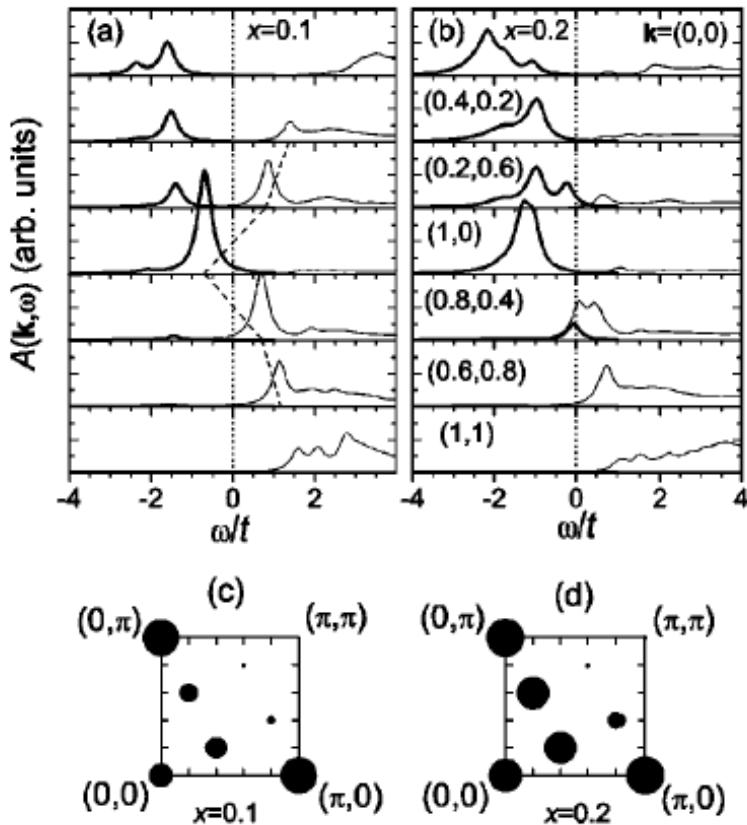
$U=5.75$   
 $n=1.15$   
 $T=1/5$   
 $t=1$   
 $t'=-0.175$   
 $t''=0.05$



# Precursor of SDW state (dynamic symmetry breaking)

- A.P. Kampf and J.R. Schrieffer, Phys. Rev. B **42**, 7967 (1990)
- Y.M. Vilk and A.-M.S. Tremblay, J. Phys. Chem. Solids **56**, 1769-1771 (1995).
- Y. M. Vilk, Phys. Rev. B **55**, 3870 (1997).
- J. Schmalian, *et al.* Phys. Rev. B **60**, 667 (1999).
- B.Kyung *et al.*, PRB **68**, 174502 (2003).
- Kyung, Hankevych, A.-M.S.T., in press
- R. S. Markiewicz, cond-mat/0308469.

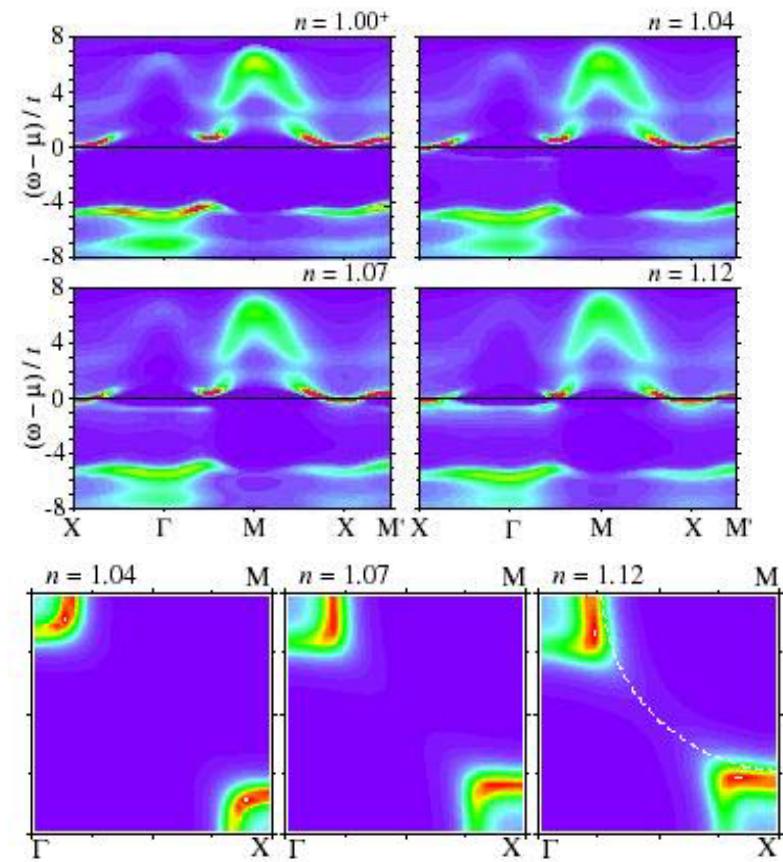
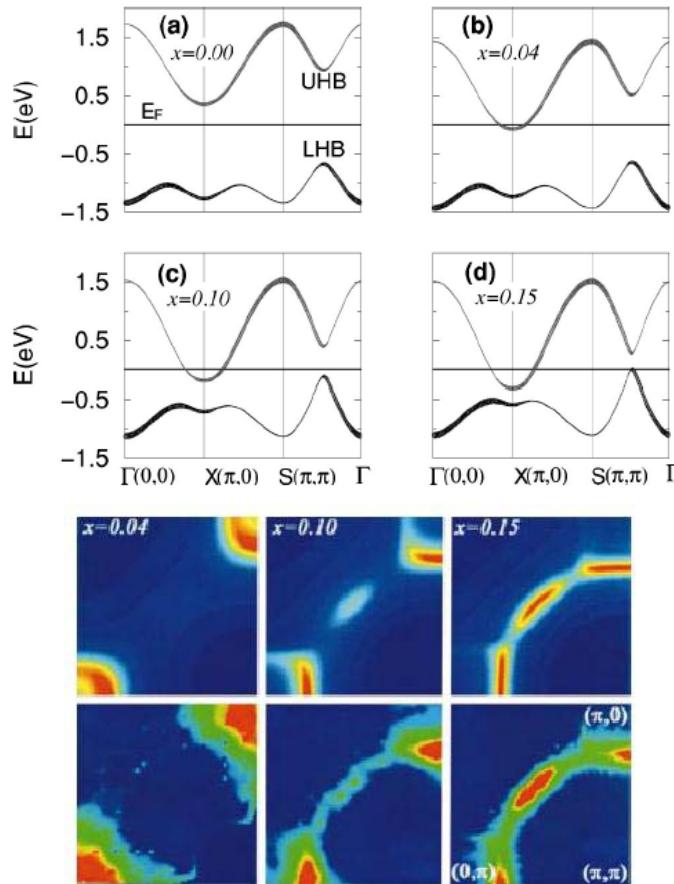
# Exact diagonalization for $t$ - $t'$ - $t''$ - $J$ model



- Absence of  $\omega=0$  excitations near  $(\pi/2, \pi/2)$  at optimal doping
- Small lattice size
- **Not applicable near optimal doping since no LHB**

T.Tohyama *et al.*, PRB **64**, 212505 (2001)

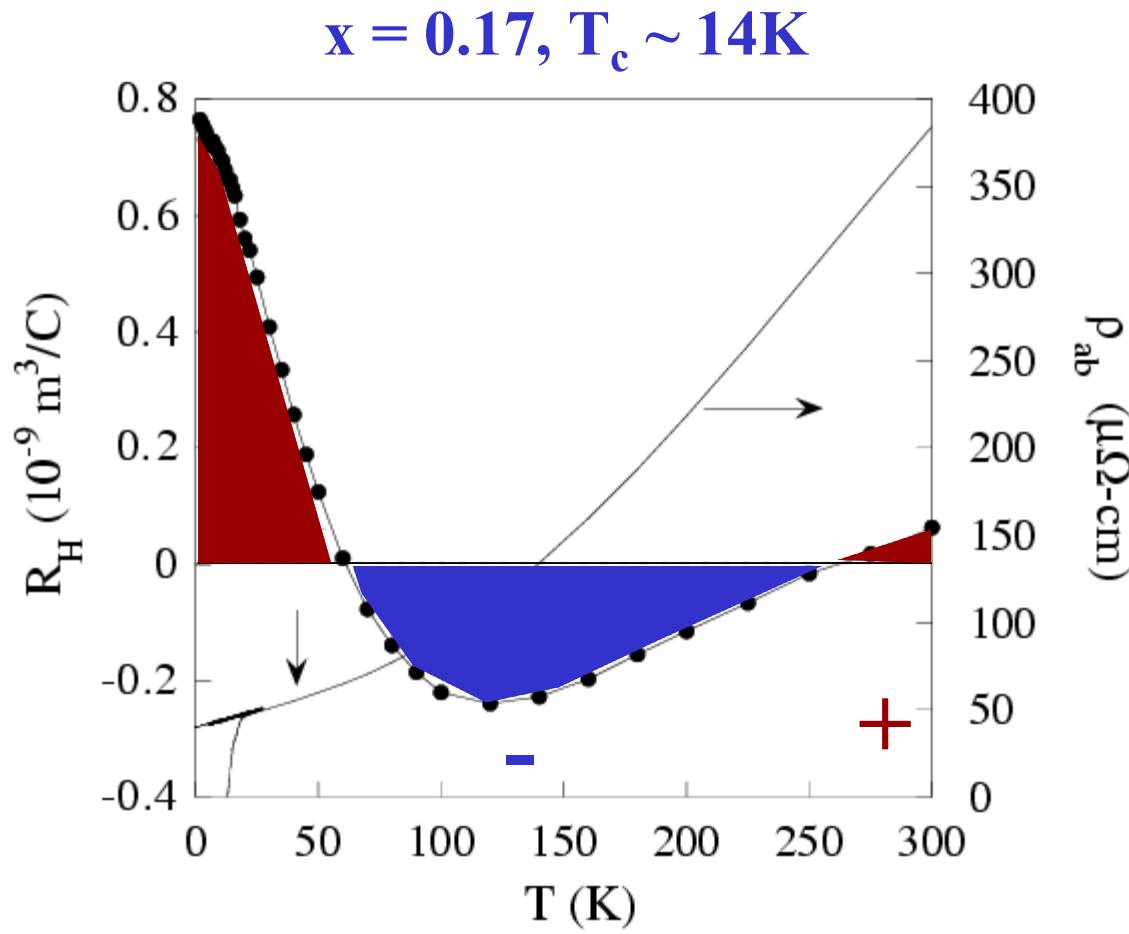
# Contrast



Kusko, Markiewicz, Bansil, PRB 2002,

Kusunose, Rice, Phys. Rev. Lett. (2003).

# Reduction introduces holes...



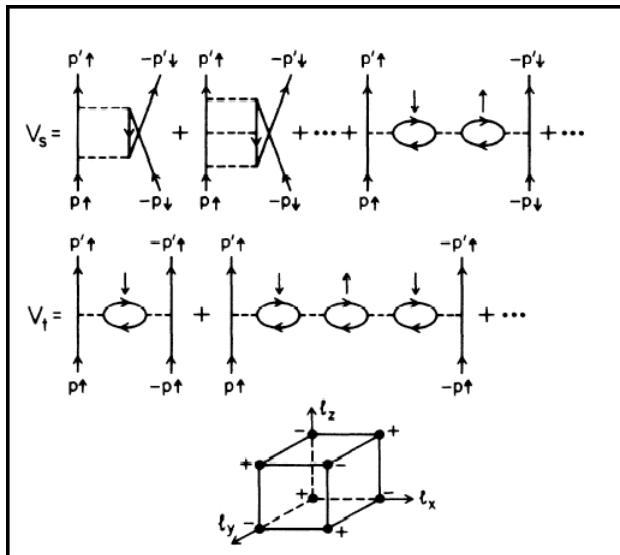
P. Fournier et al., Phys. Rev. Lett. **81**, 4720 (1998).

# Quantum materials, strongly correlated electrons and high-temperature superconductivity

- I. Introduction
  - Fermi liquid
- II. Experimental results from cuprates and model
- III. Strong and weak coupling pseudogap (CPT)
- IV. Weak coupling pseudogap (QMC,TPSC)
- V. **d-wave superconductivity**
- VI. Conclusion

# A great prediction ? (Kohn-Luttinger mechanism)

*d-wave* superconductivity induced by antiferromagnetic fluctuations

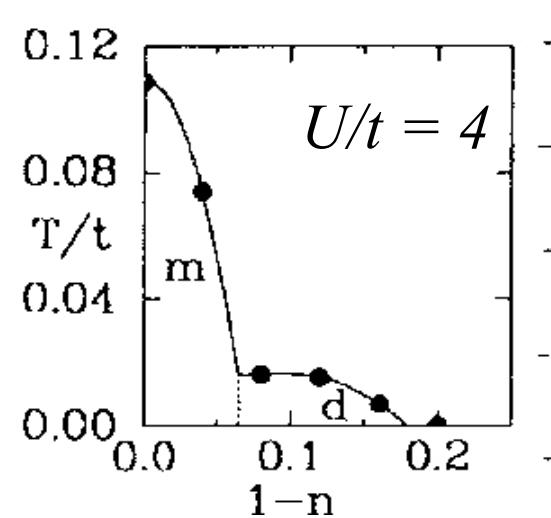


D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch  
P.R. B **34**, 8190-8192 (1986).

Béal-Monod, Bourbonnais, Emery  
P.R. B. **34**, 7716 (1986).

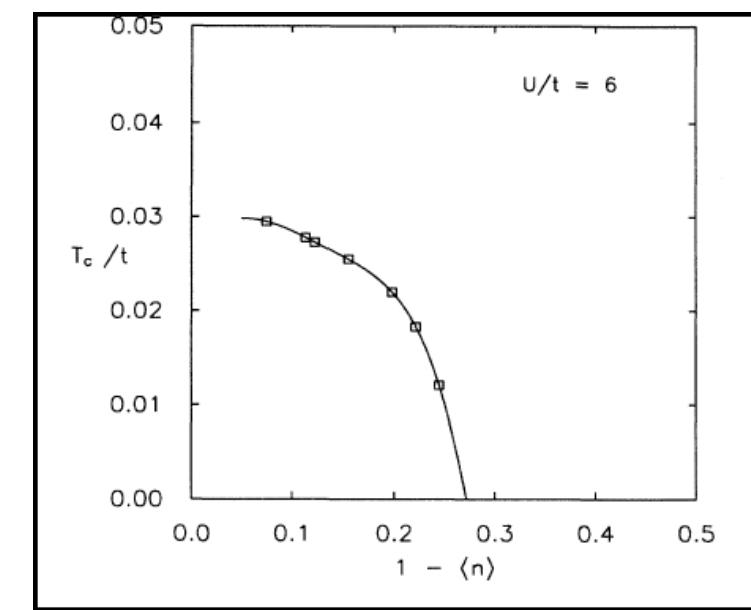
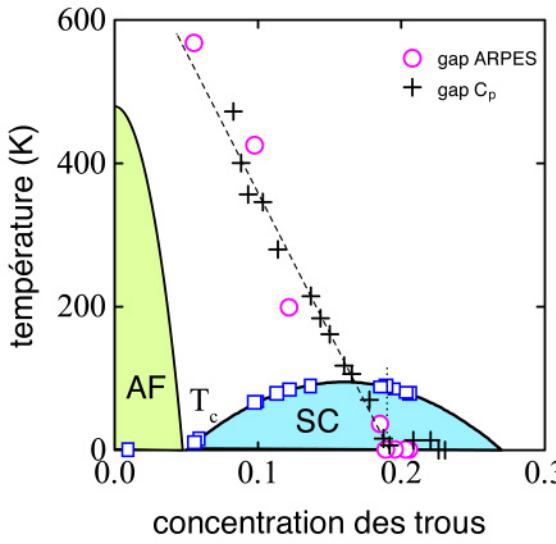
Miyake, Schmitt-Rink, and Varma  
P.R. B **34**, 6554-6556 (1986)

Kohn, Luttinger, P.R.L. **15**, 524 (1965).

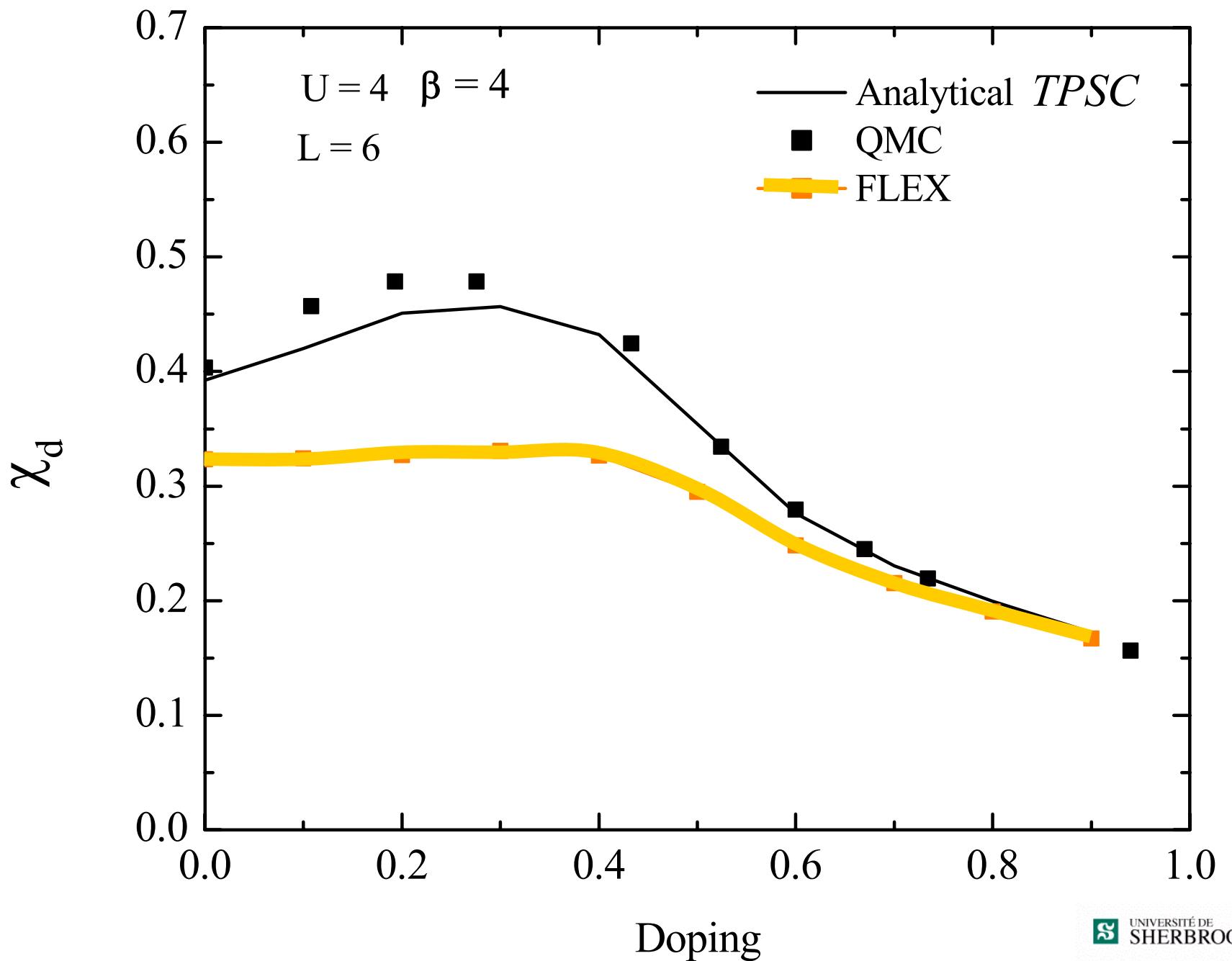


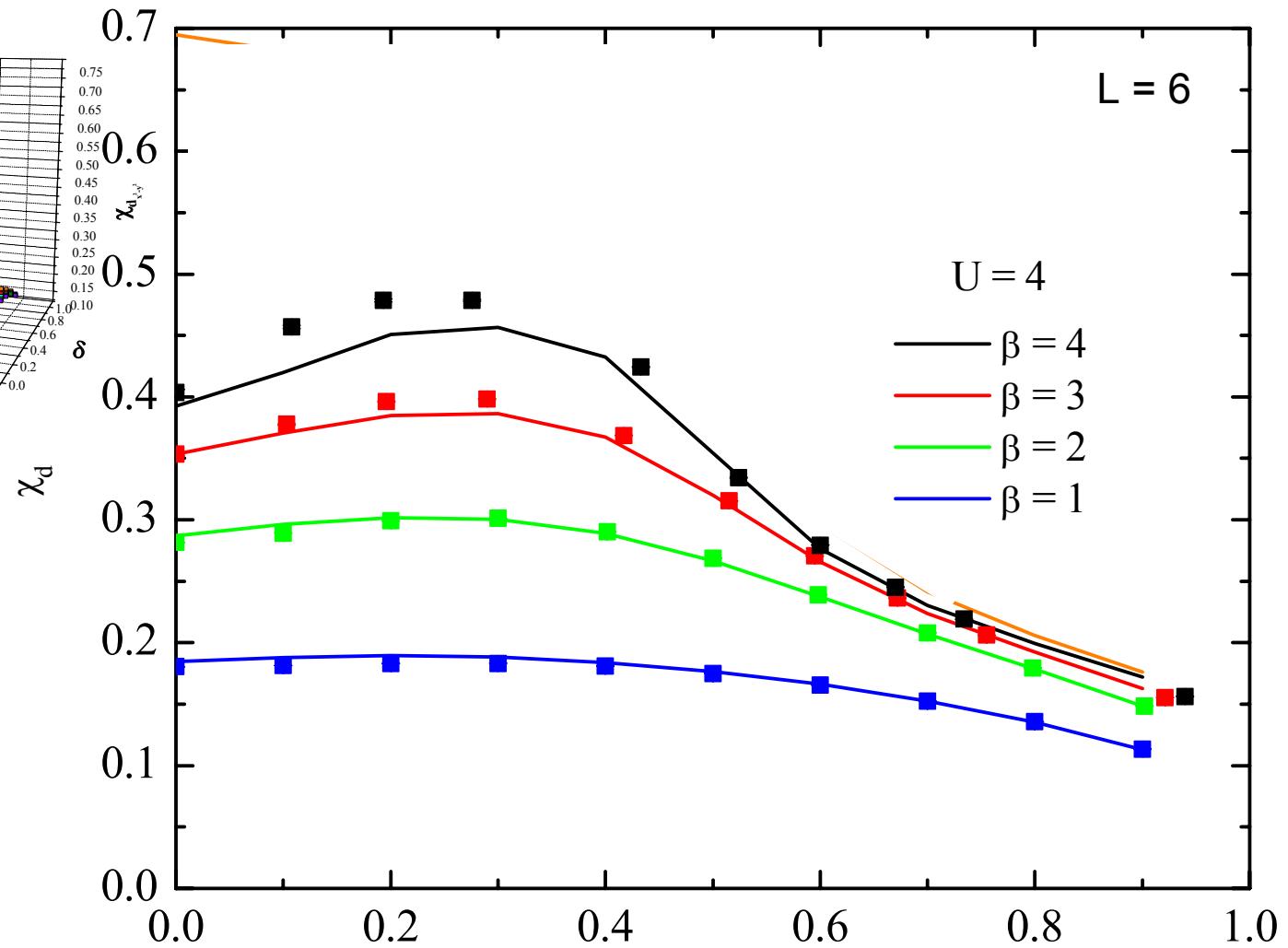
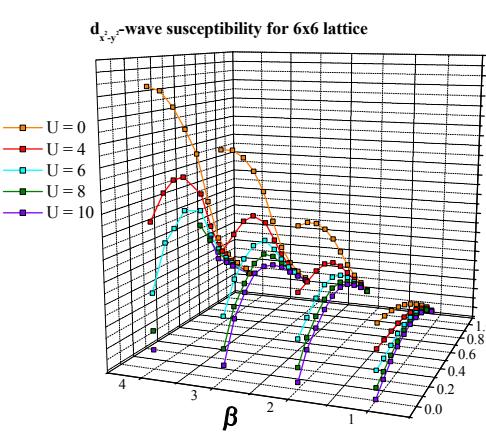
Bickers, Scalapino, White  
P.R.L **62**, 961 (1989).

Recent review by Chubukov, Pines,  
Schmalian.



C.-H. Pao and N.E. Bickers, Phys. Rev.  
B **51**, 16 310 (1995)

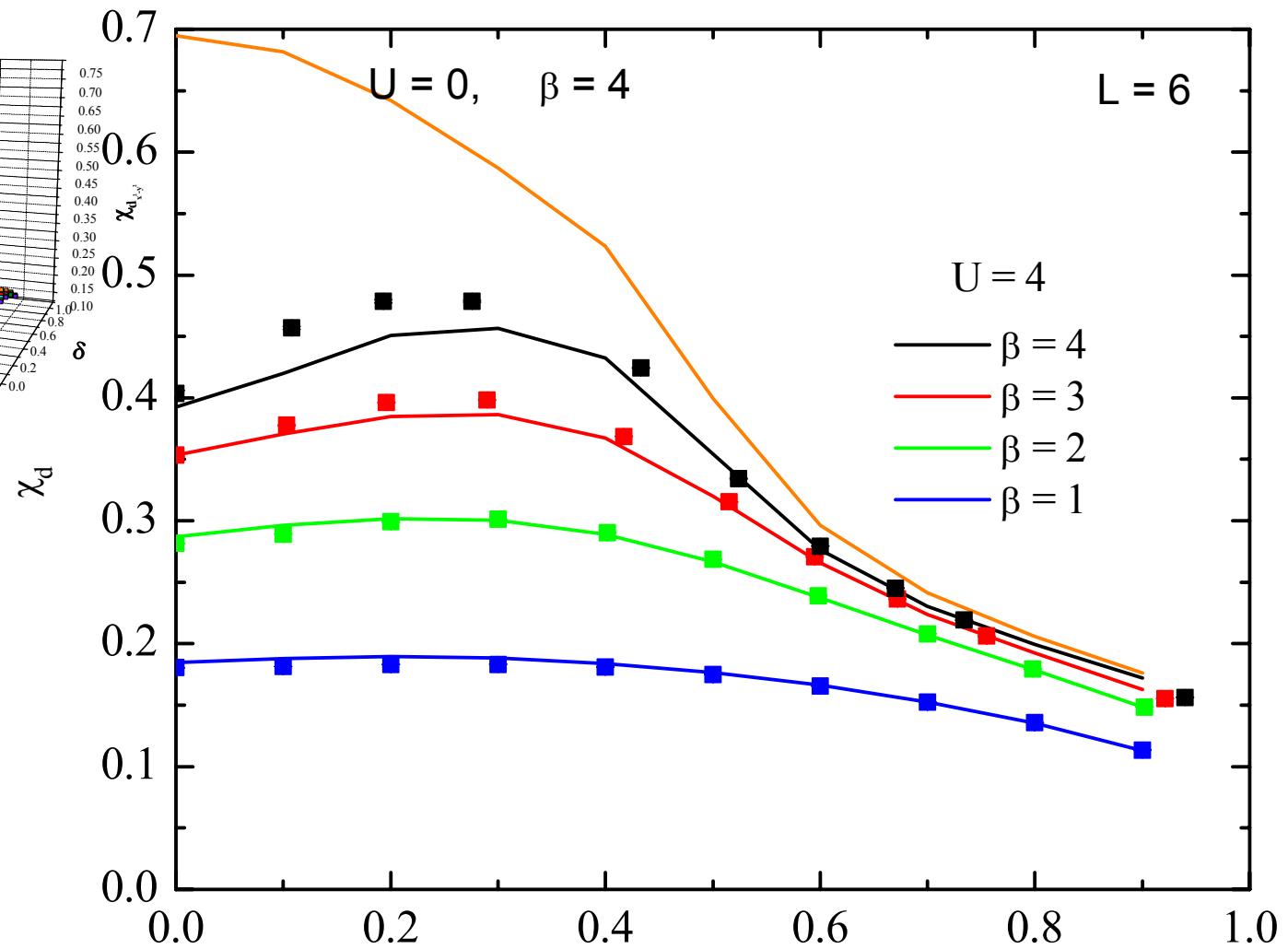
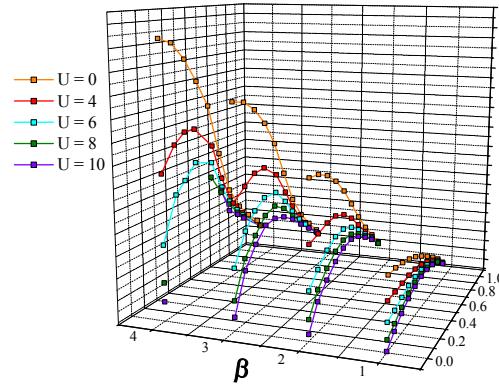


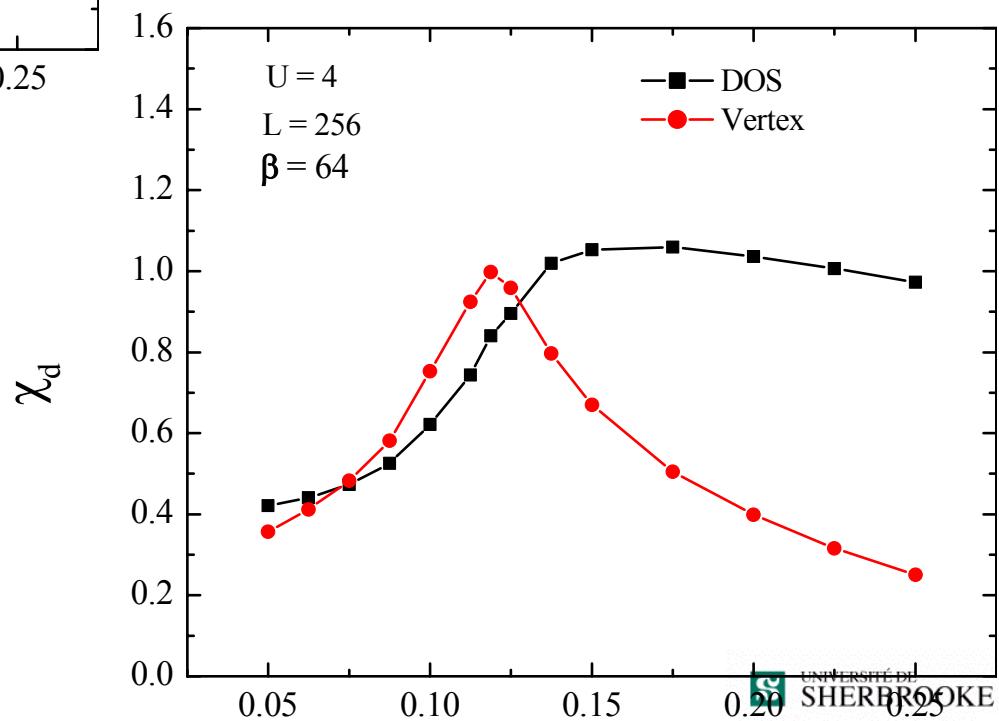
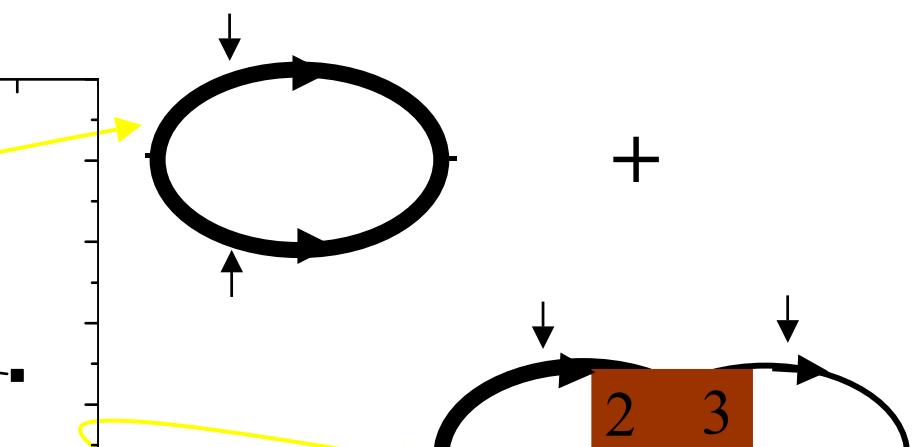
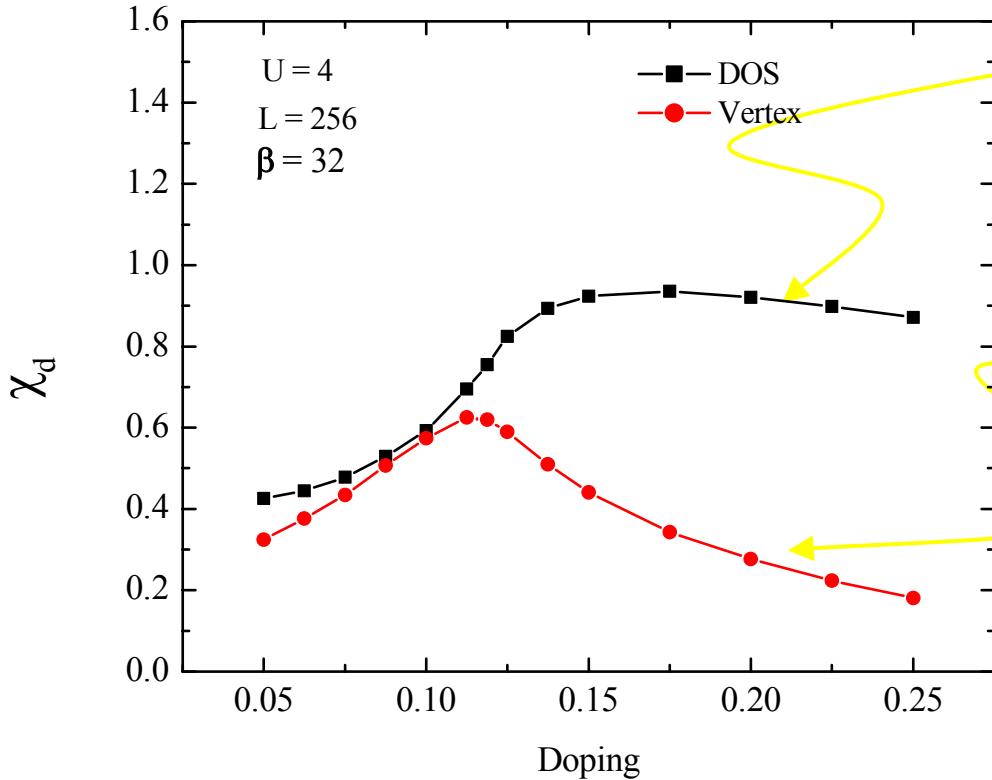


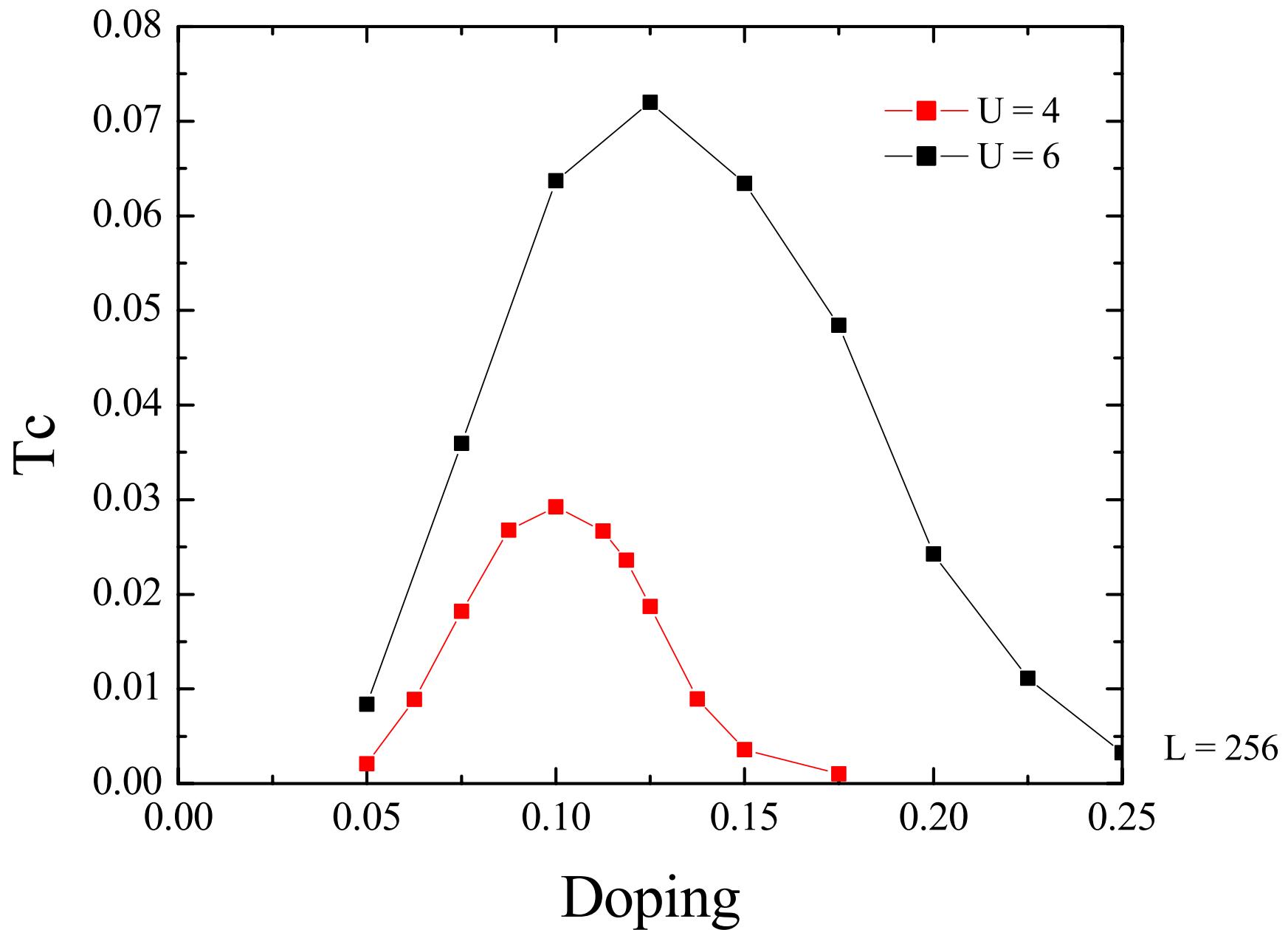
QMC: symbols.  
Solid lines analytical.

Doping  
Kyung, Landry, A.-M.S.T.

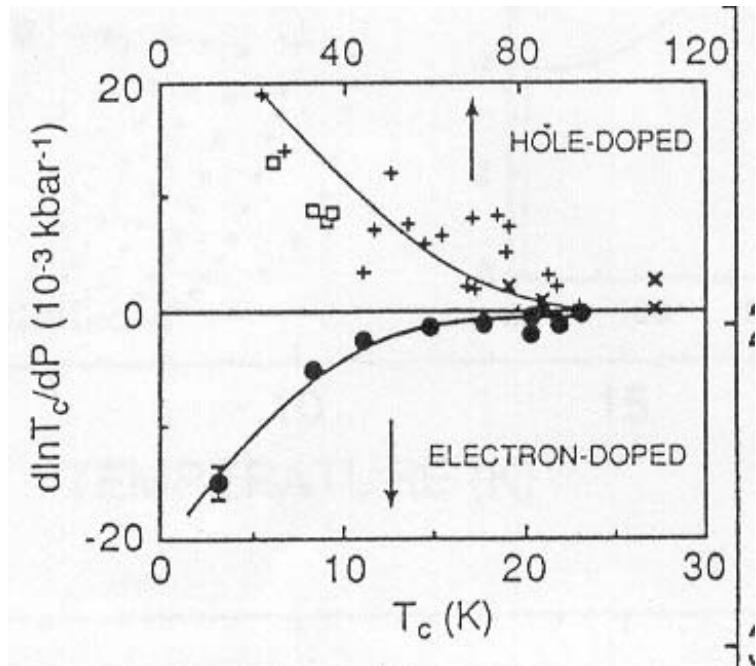
$d_{x^2-y^2}$ -wave susceptibility for  $6 \times 6$  lattice







Electron doped:



M.B. Maple  
MRS Bulletin,  
June 1990

Armitage et al.  
Phys. Rev. Lett.  
87, 147003 (2001)

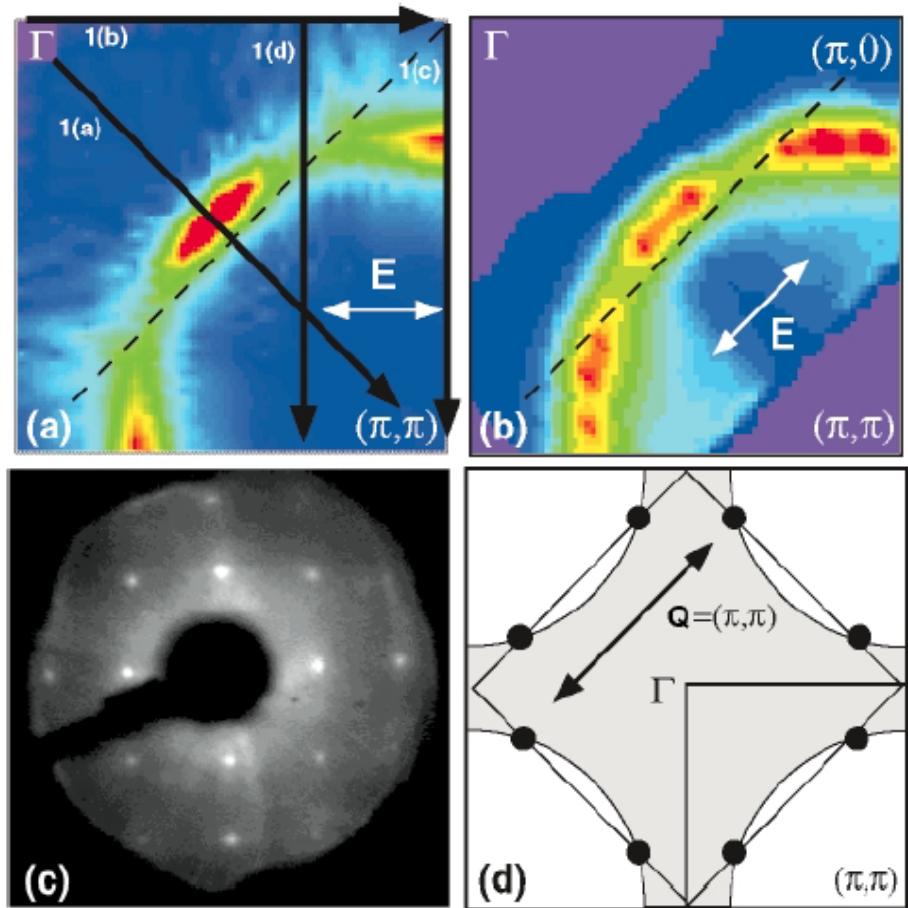
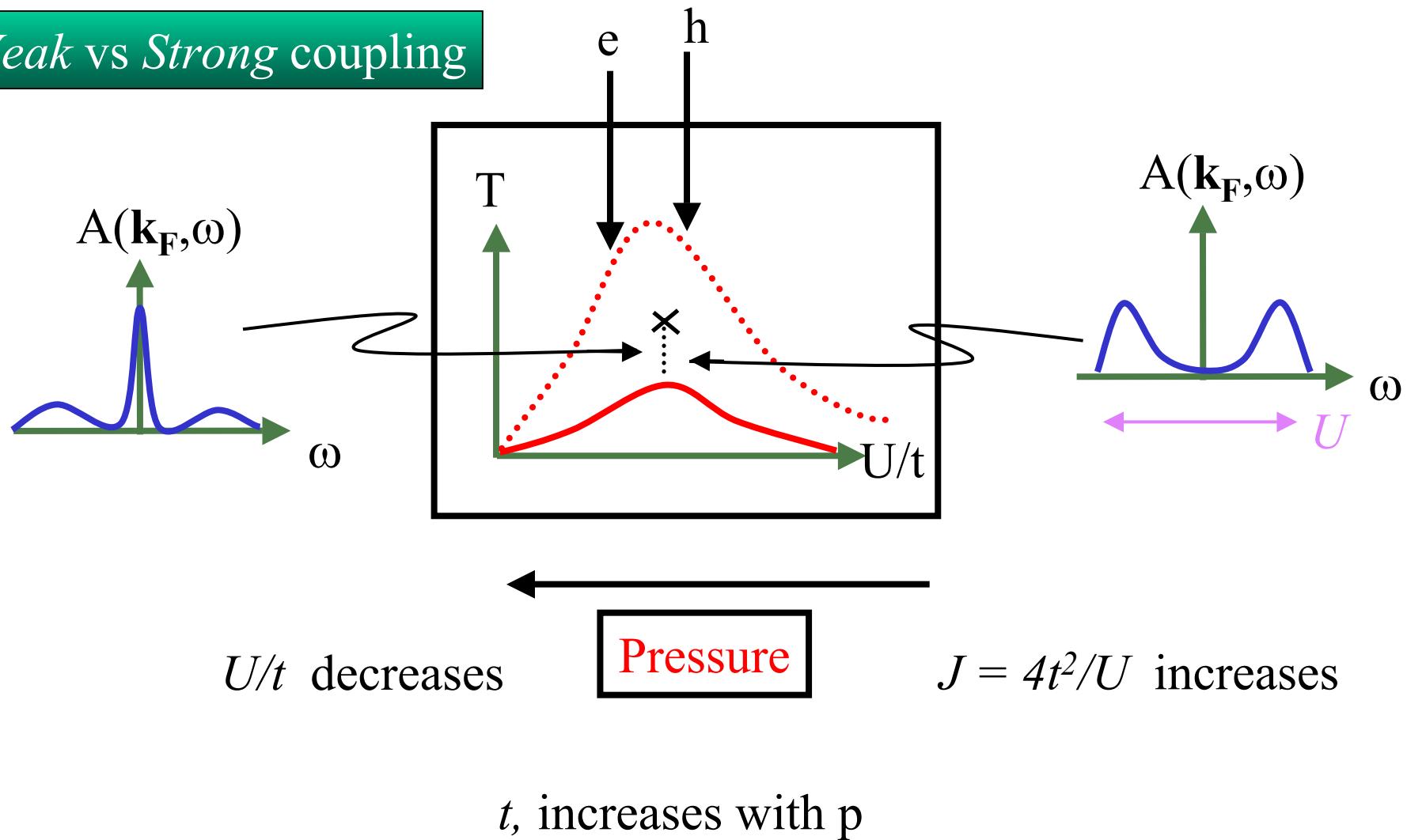


FIG. 2 (color). (a),(b) Fermi surface of the partial Brillouin zone of NCCO taken with  $\hbar\omega = 16.5$  and 55 eV, respectively. The plotted quantity is a 30 meV integration about  $E_F$  of each EDC plotted as a function of  $\vec{k}$ . 16.5 eV data were taken over a Brillouin zone octant and symmetrized across the  $\Gamma$  to the  $(\pi, \pi)$  line, while the 55 eV data were taken over a full quadrant [6]. The polarization direction is denoted by the double ended arrow. The dotted line is the antiferromagnetic Brillouin zone boundary. (c) LEED spectra of NCCO cleaved *in situ* at 10 K. (d) Schematic showing only those regions of FS near the black circles can be coupled with a  $(\pi, \pi)$  scattering.

## Weak vs Strong coupling



# VI- Conclusion

- One model, weak and strong coupling
- Strong-coupling pseudogap
  - h- or (e- very underdoped)
  - CPT (+ DCA + Phillips + ...) Like Mott, short-range effect (but not zero range). Scales like  $t$ .
- Weak-coupling pseudogap
  - Electron-doped high Tc in this regime near optimal  $n$ .
  - ARPES and neutron scattering are explained in detail by Hubbard model solved within TPSC
    - Only Hubbard parameters (no mode-coupling,  $U_{\text{eff}}$  etc.)
    - Remarkable (best?) agreement with experiment in high-Tc.

# Perspectives

- $\hbar\omega_{sf} \ll k_B T$  in pseudogap begins at  $T > T^*$
- $T^*(\delta)$  predicted for ARPES
- In EDC will appear when  $\xi/\xi_{\text{th}} \sim 1$  (precursor effect) in ARPES.
- No hot spots beyond QCP
- Speculation: going smoothly to strong coupling?  
 $\xi_{\text{th}} \rightarrow a$
- More studies of e-doped cuprates (great samples)

# Research projects

- Formal theoretical developments + applications (TPSC)
  - Thermodynamics
  - Optical conductivity, NMR and other response functions
  - Longer range screened interactions
  - Effect of disorder
  - Electron-phonon interactions
  - d-wave superconductivity

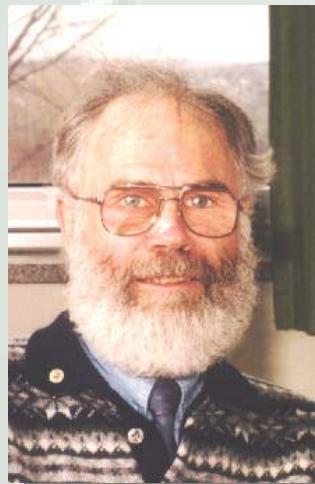
# Research projects

- QMC ( $n=1$ )
  - Thermodynamics
  - Effect of correlations on sound velocity
  - Effect of  $t'$  on fluctuation regime (attractive model)

# Theory



Claude Bourronnais



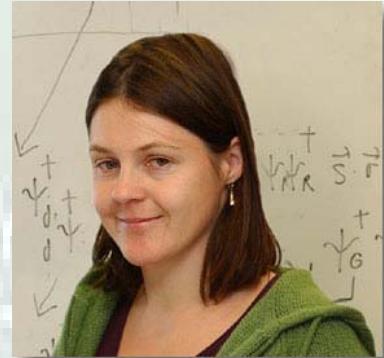
Laurent Caron



René Côté



David Sénéchal



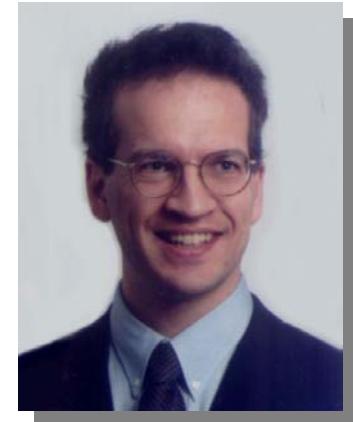
Karyn Le Hur



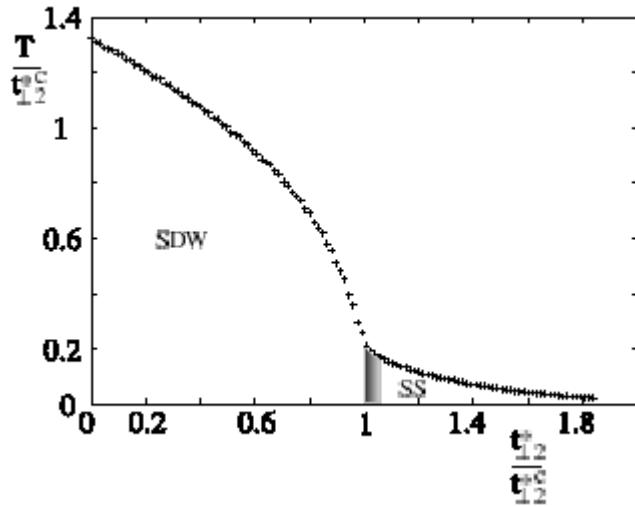
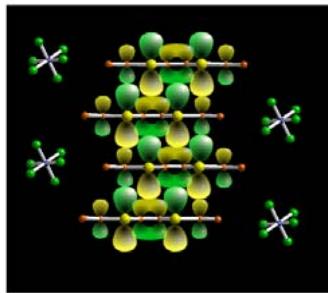
André-Marie Tremblay

# Variational Cluster Perturbation Theory

- What is the phase diagram of the Hubbard model in  $d=2$ ?
  - Square lattice, high-Tc
  - Frustrated lattice, organics
  - Mott vs Slater transition

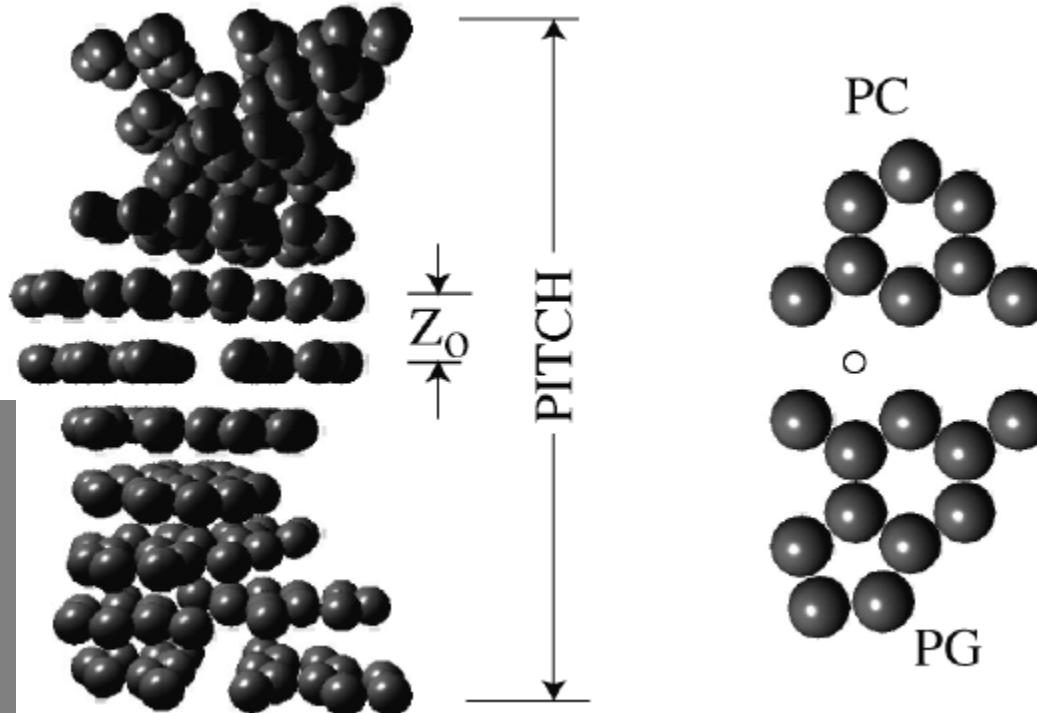
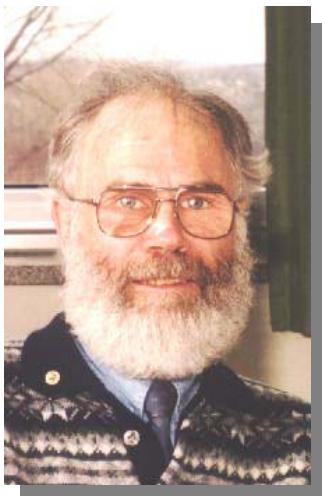


# In d~1, subtle interference effects



$$\begin{aligned} \frac{d\tilde{J}(k_\perp, k'_\perp)}{d\ell} = & - \frac{1}{N_\perp} \sum_{k''_\perp} \tilde{J}(k_\perp, k''_\perp) I_C(k''_\perp, k'_\perp, \ell) \tilde{J}(k''_\perp, k'_\perp) \\ & + \frac{1}{N_\perp} \sum_{k''_\perp} \tilde{J}(k_\perp, k''_\perp) I_P(k''_\perp, k'_\perp, t_{12}^*, \ell), \tilde{J}(k''_\perp, k'_\perp) \end{aligned}$$

# And even DNA



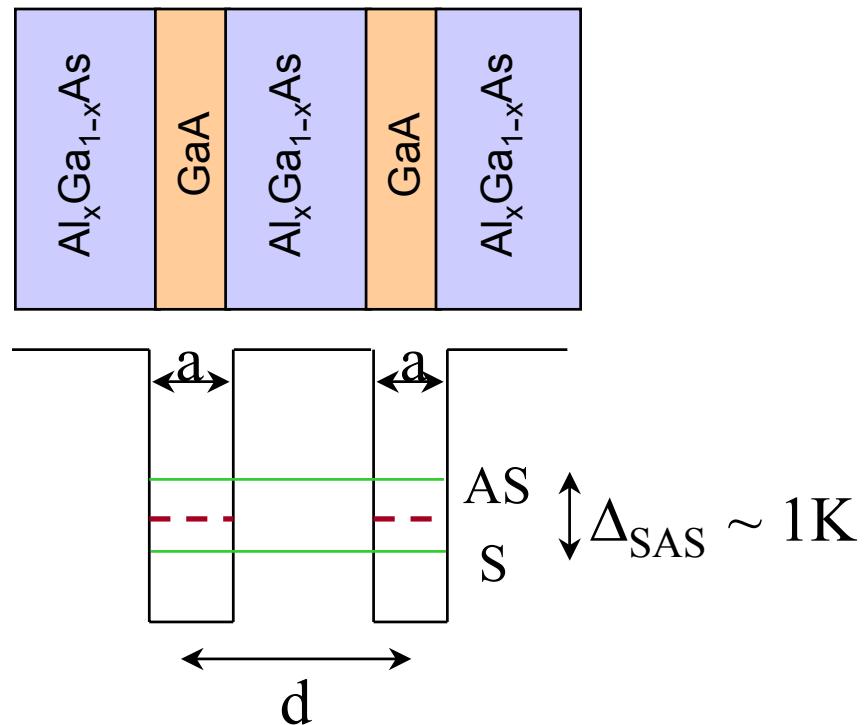
Elastic cross section and resonant capture increased around 15 eV

# Remarkable devices

Double wells:

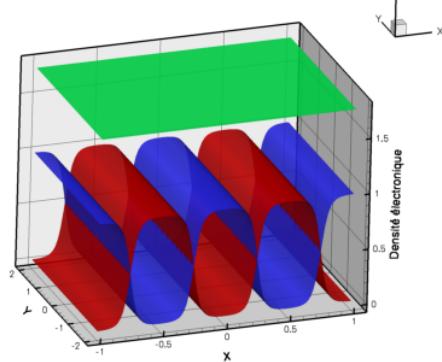
Textures in the electronic density:

Stripes  
Solitons (bimerons)  
(in the presence of  $\mathbf{B}$ )

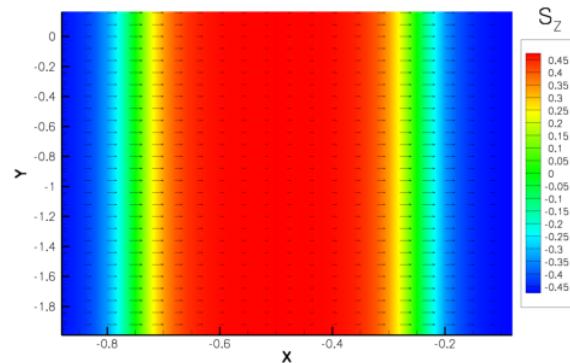


# Stripes and soliton networks

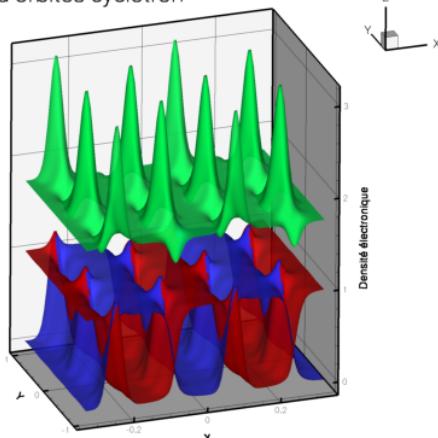
Niveau de Landau 2,  $\nu=1.00$   
Densité d'orbites cyclotron



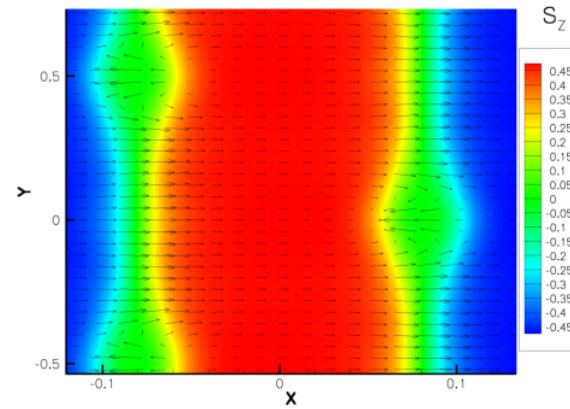
Représentation pseudospin



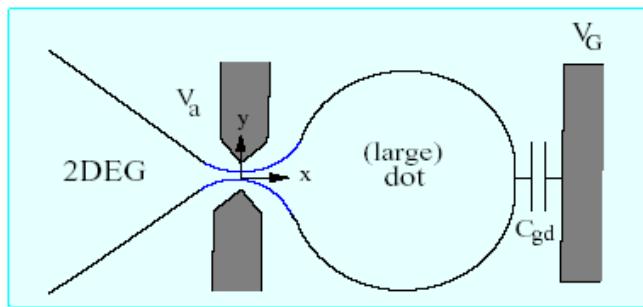
Niveau de Landau 2,  $\nu=1.10$   
Densité d'orbites cyclotron



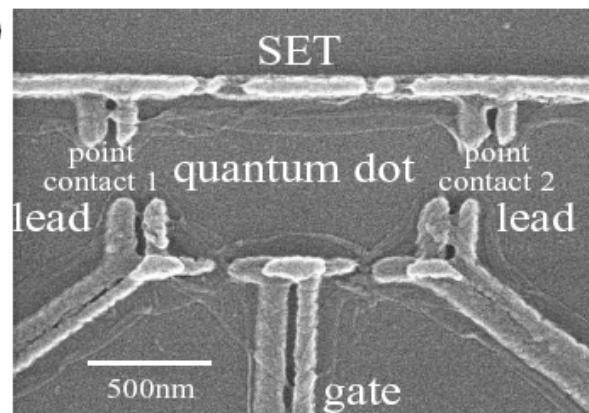
Représentation pseudospin



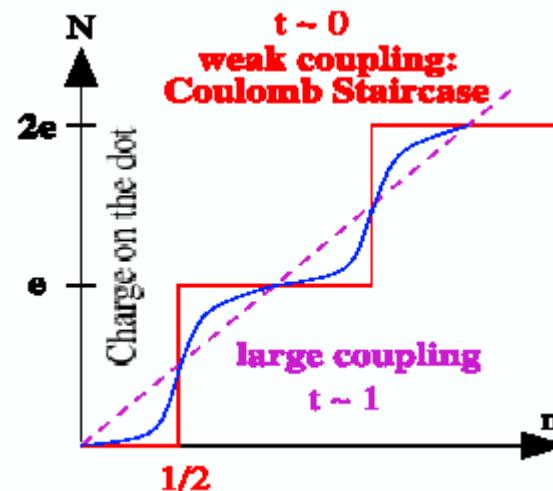
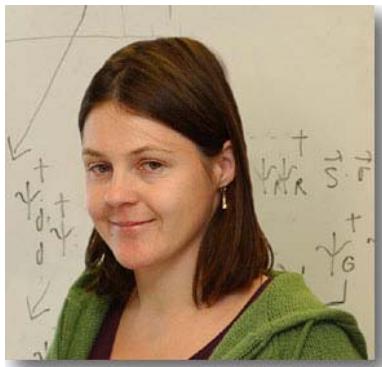
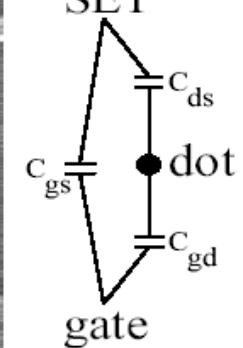
# Quantum devices



(a)

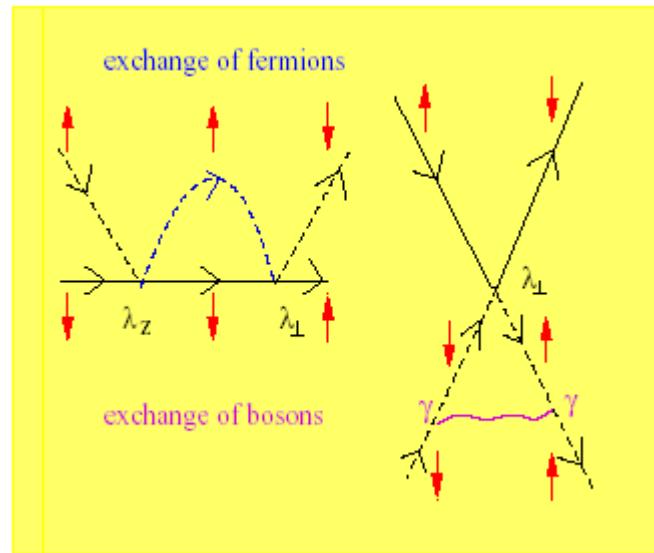
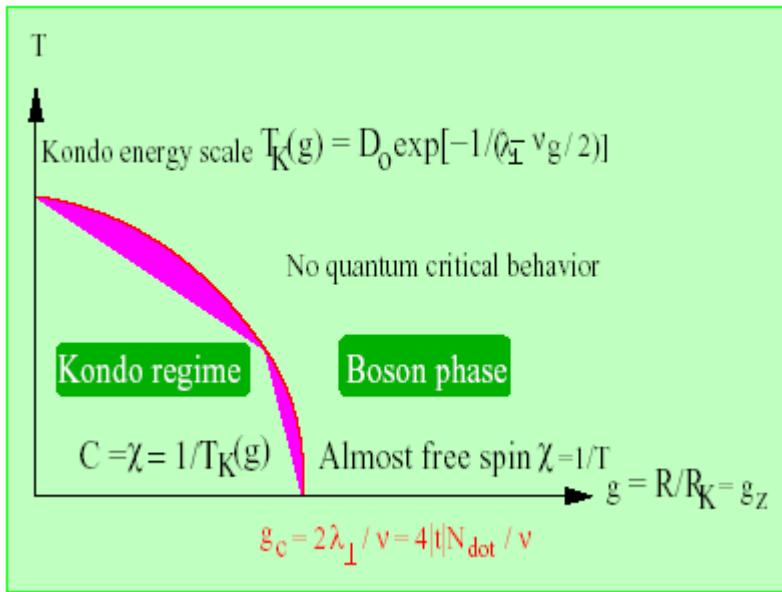


(b)



Version supra:  
(qubit)

# “Spin” coupled simultaneously to a boson and a fermion bath.

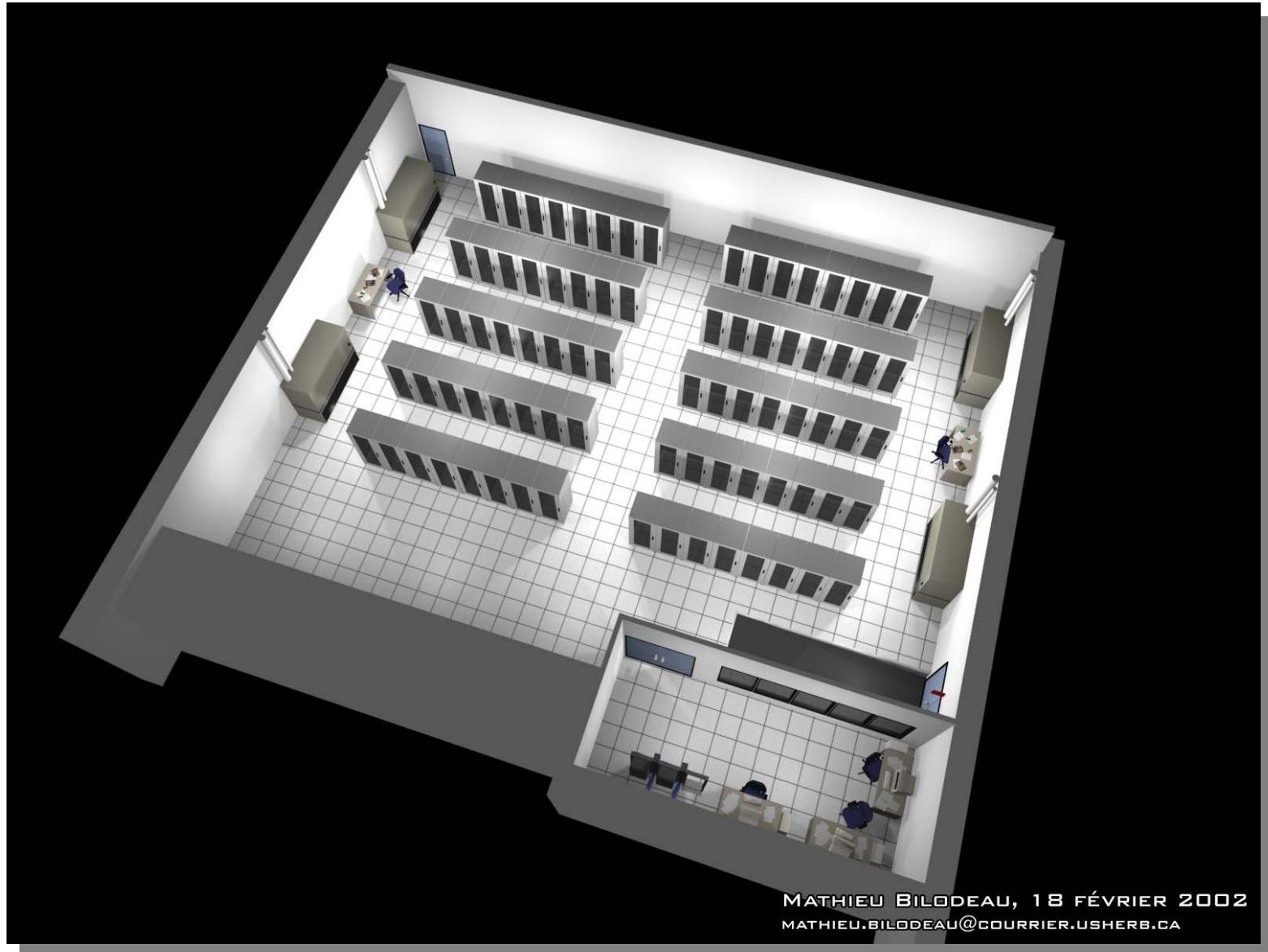


# From basic to applied

- Find or improve new analytic or numerical methods.
- Can the Hubbard model explain the phase diagram of high-temperature superconductors? (V-CPT)
- What is the mechanism for superconductivity in the organics and the high-temperature superconductors?
- What are the new elementary excitations for the two-dimensional electrons gas?
- Are there new quantum devices with new fundamental and useful properties?
- Bose condensation in optical traps?

# Powerful tools

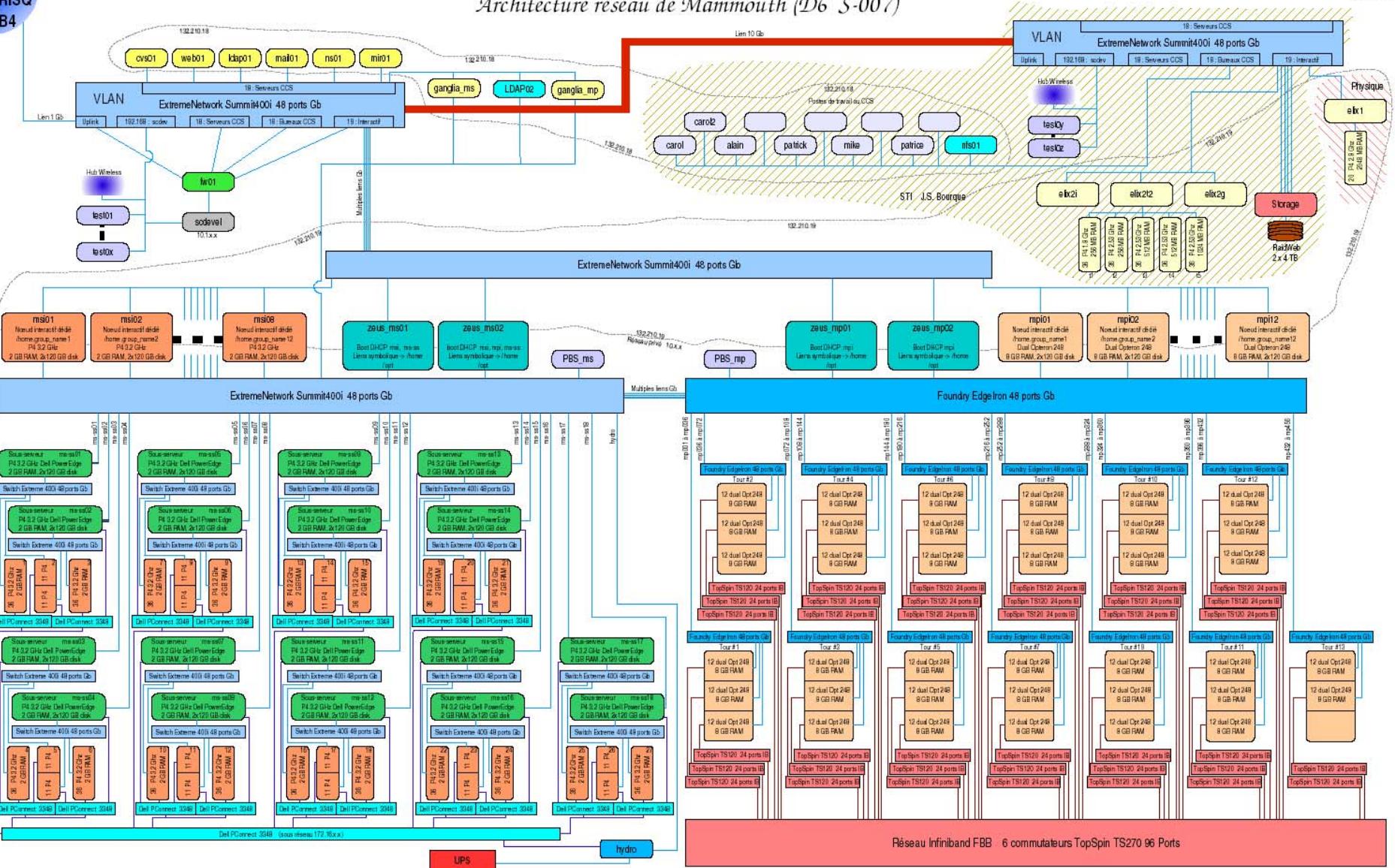
- Many-body theory and field theory
- Renormalization group (C.B., L.G.C., K. Le Hur)
- Self-consistent methods (R.C., A.-M.T.)
- Strong coupling perturbation theory (D.S., A.-M.T.)
- Cluster perturbation theory (+variational) (D.S.)



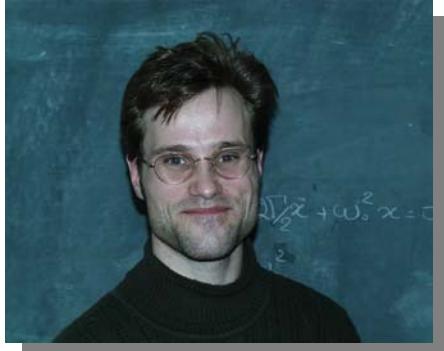
MATHIEU BILODEAU, 18 FÉVRIER 2002

MATHIEU.BILODEAU@COURRIER.USHERB.CA

# Architecture réseau de Mammouth ( $D6_S-007$ )

RISQ  
B4

Liang Chen Yury Vilk



Steve Allen



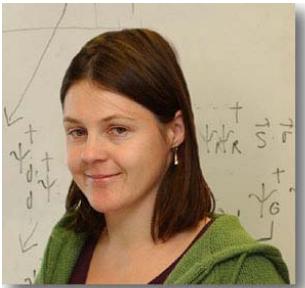
François Lemay

Samuel Moukouri



David Poulin Hugo Touchette J.-S. Landry M. Boissonnault

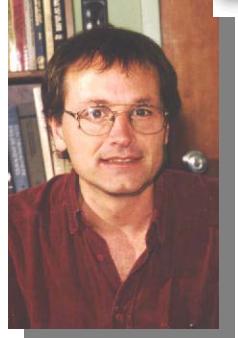




Alexis Gagné-Lebrun



A-M.T. Alexandre Blais Vasyl Hankevych

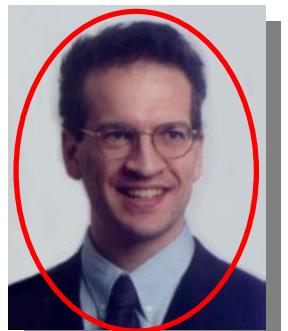


K. LeHur

C. Bourbonnais



R. Côté



D. Sénéchal

Sébastien Roy

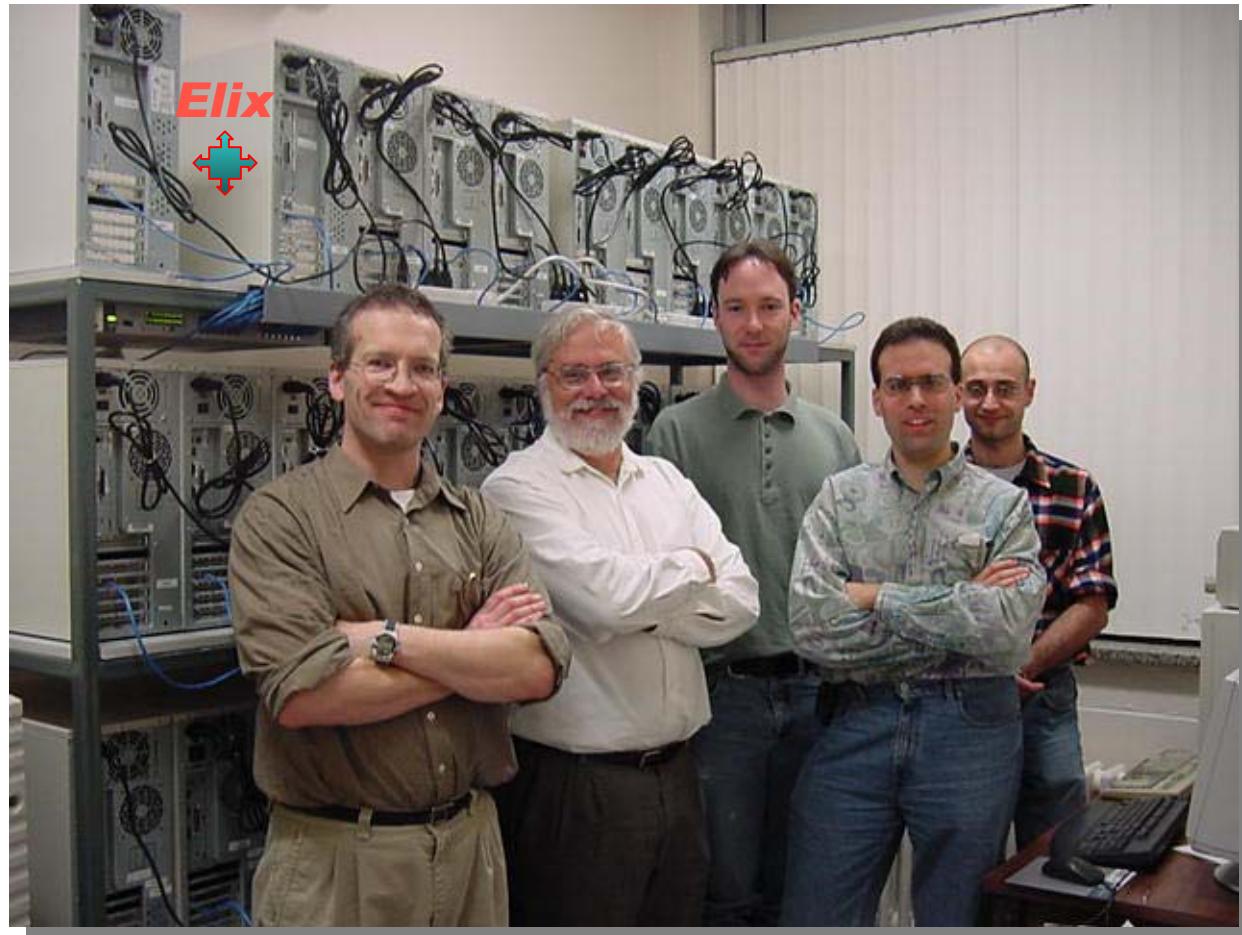
Sarma Kanchala

Bumsoo Kyung

Maxim Mar'enko

Michel Barrette

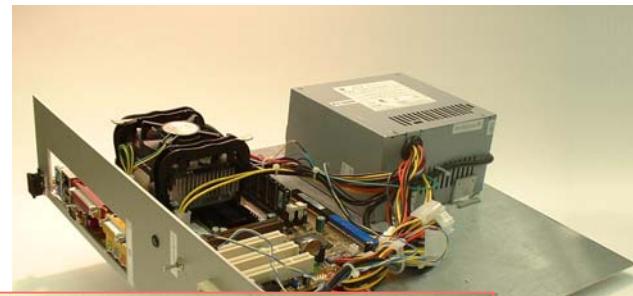
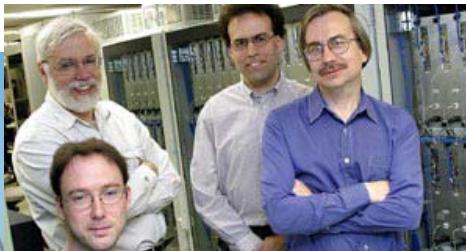
Mehdi Bozzo-Rey



David Sénéchal

A.-M.T.

Alain Veilleux



Un noeud d'Elix2

Carol Gauthier,  
analyste en Calcul  
du CCS en plein  
machinage d'un  
noeud d'Elix2



Elix2 vu de profil



De gauche à droite: Alain Veilleux, Michel Barrette, Jean-Phillipe Turcotte, Carol Gauthier, Patrick Vachon et le 1er noeud d'Elix

Equipe du CCS devant Elix2. Au fond: Patrick Vachon, Minh-Nghia Nguyen, David Lauzon, Michel Barrette, Mehdi Bozzo-Rey, Simon Lessard, Alain Veilleux. Au premier plan: Patrice Albaret, Karl Gaven-Venet, Benoît des Ligneris, Francis Giraldeau. Était absent de la photo: Jean-Philippe Turcotte, Carol Gauthier, Xavier Barnabé Thériault et Mathieu Lutfy





# Projet Mammouth

Réseau québécois  
de calcul de haute performance

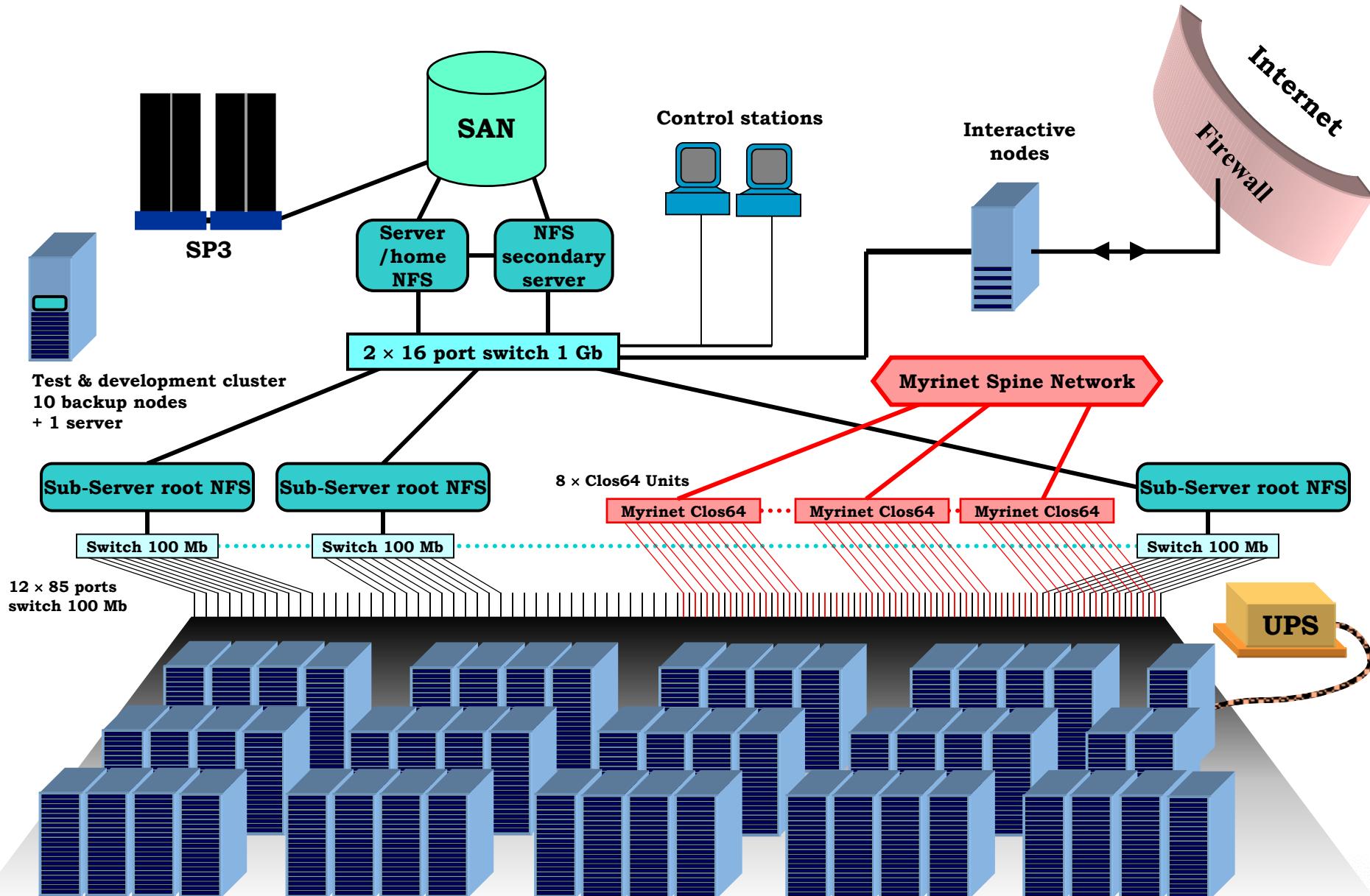
1024+50 CPUs Intel P4 2.2 GHz  
1 TBytes RAM  
22 TBytes Disk Space

1024 x 100 Mbit Ethernet  
512 x 2Gbit Myrinet  
55 Frames, 180 kW

IMSI  
INSTITUT DES MATERIAUX ET SYSTÈMES INTELLIGENTS  
INTELLIGENT MATERIALS AND SYSTEMS INSTITUTE

UNIVERSITÉ DE SHERBROOKE

Centre de calcul scientifique, IMSI  
Université de Sherbrooke



*C'est fini... .*

*enfin*