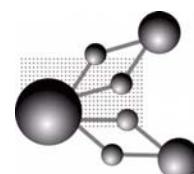
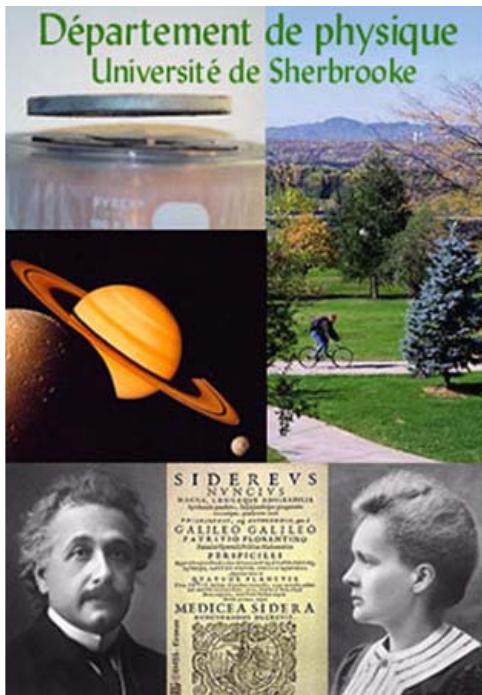


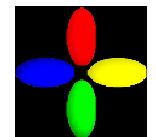
André-Marie Tremblay



CENTRE DE RECHERCHE SUR LES PROPRIÉTÉS
ÉLECTRONIQUES
DE MATÉRIAUX AVANCÉS

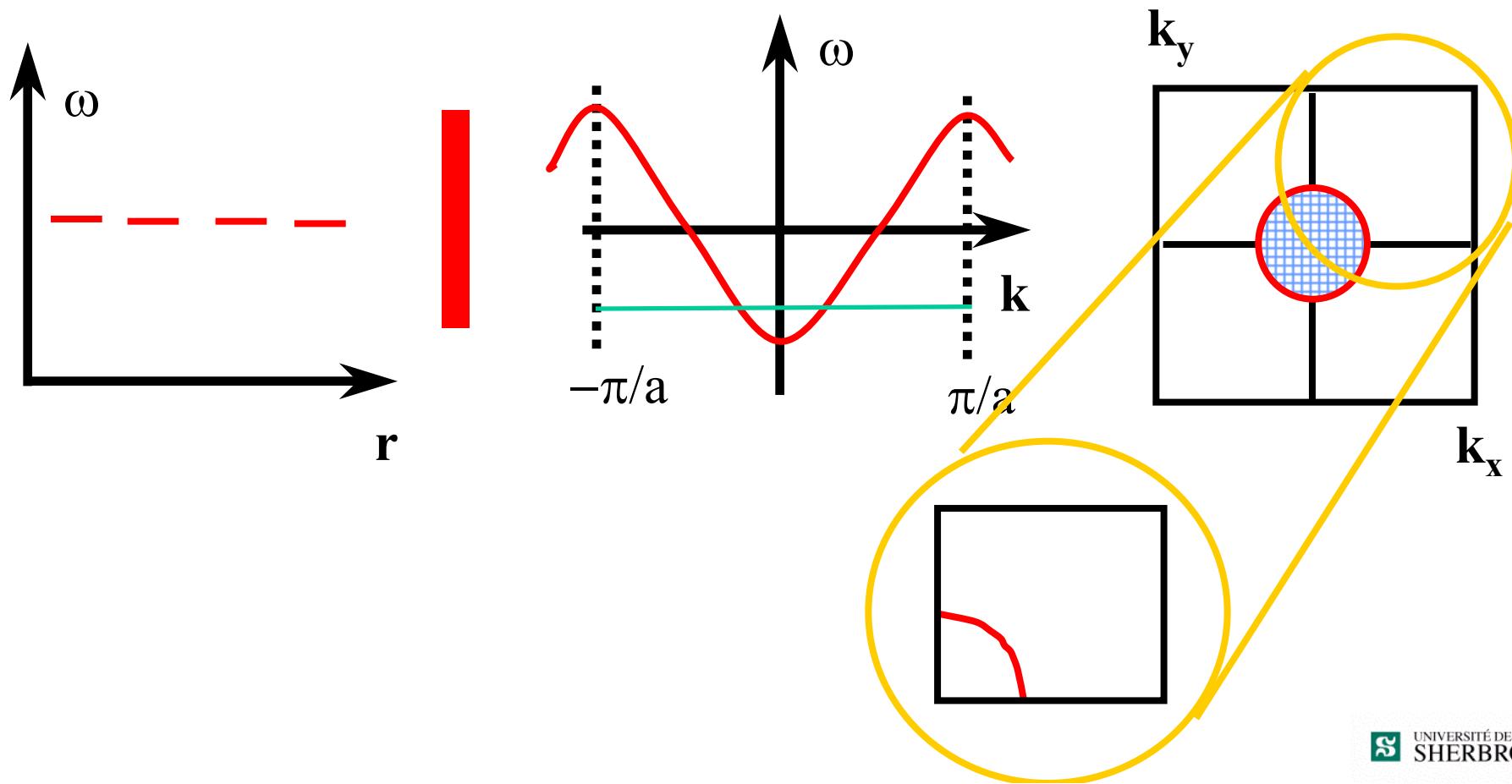


Sponsors:



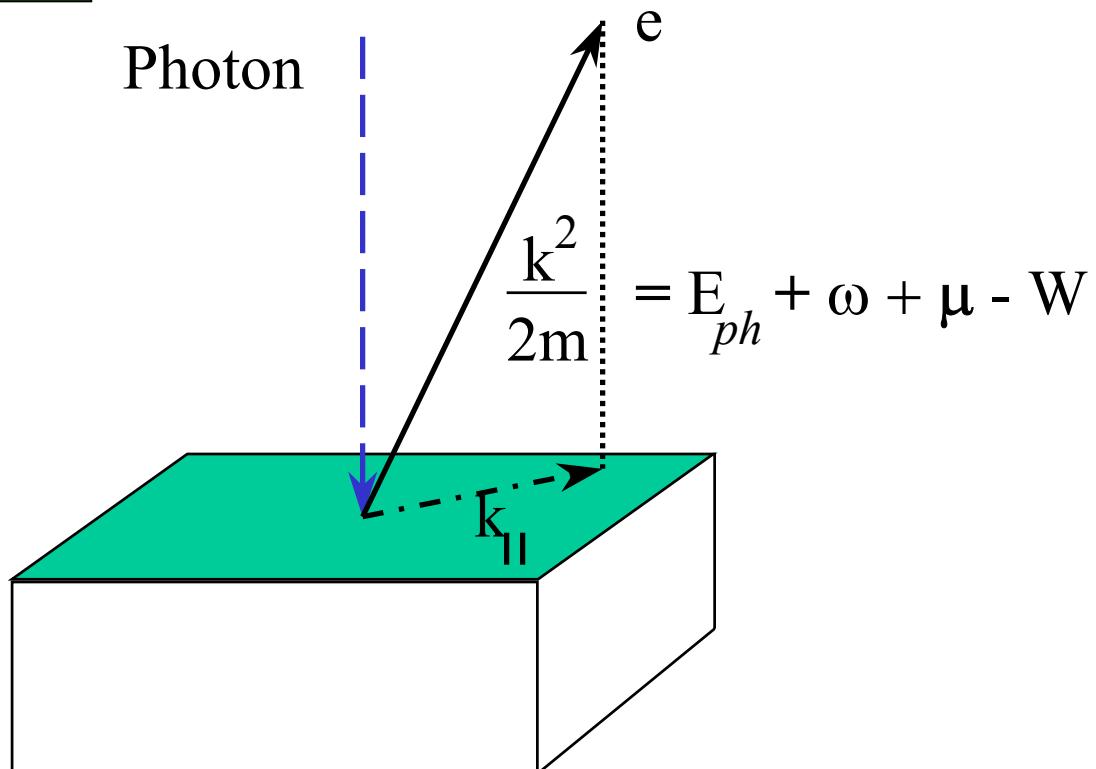
Two ways to destroy a Fermi liquid

Some basic Solid State Physics

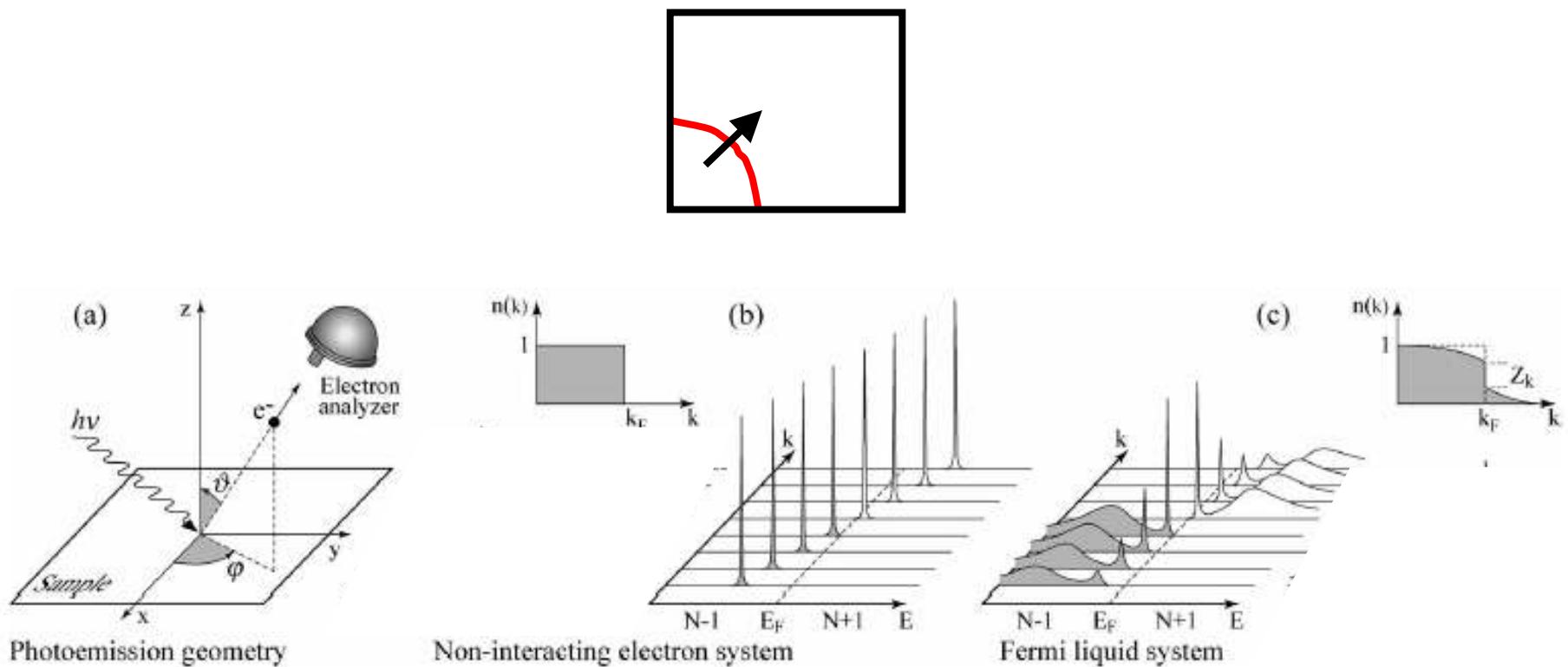


Measuring « band » properties in $d=2$

Photoemission



The Fermi liquid



Damascelli, Shen, Hussain, 2002.

A Fermi liquid in $d = 2$

$T\text{-TiTe}_2$

$U / W = 0.8$

Perfetti, Grioni et
al. Phys. Rev. B
64, 115102 (2001)

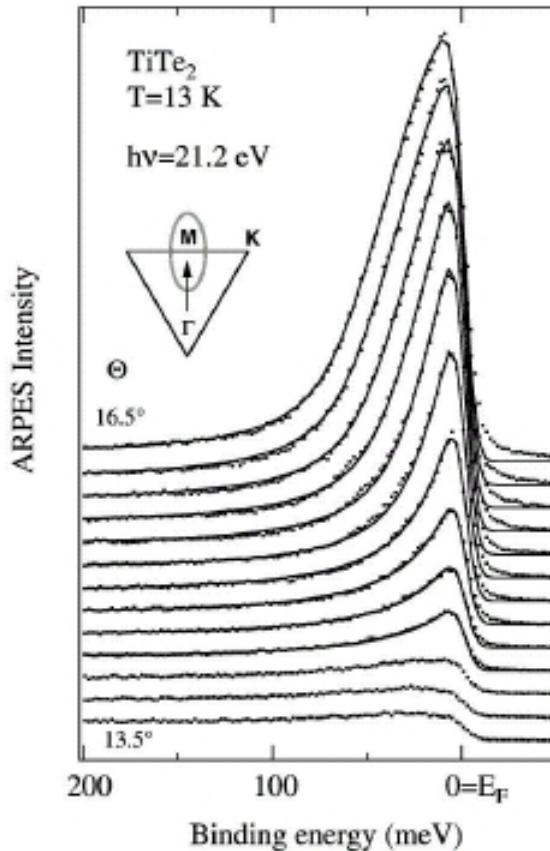
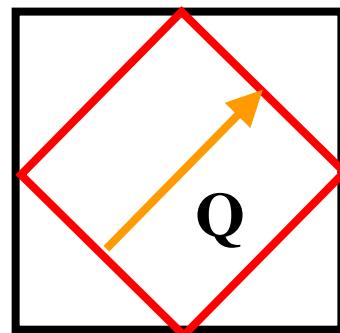


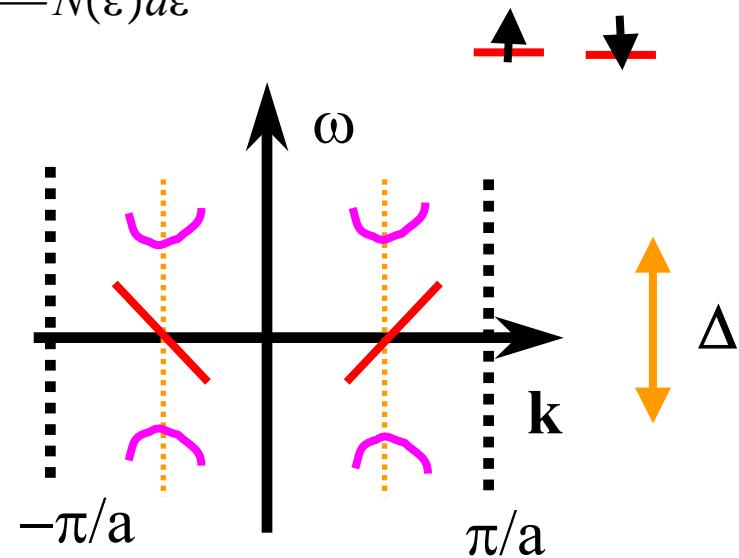
FIG. 1. High-resolution ARPES spectra of $1T\text{-TiTe}_2$ measured near the Fermi surface crossing along the high-symmetry ΓM direction ($\theta = 0$ is normal emission). The yellow lines are the results of Fermi liquid fits to the data with the parameters discussed in the text. The inset shows a portion of the Brillouin zone with the relevant ellipsoidal electron pocket.

Destroying the Fermi liquid at half-filling: Lattice + interactions

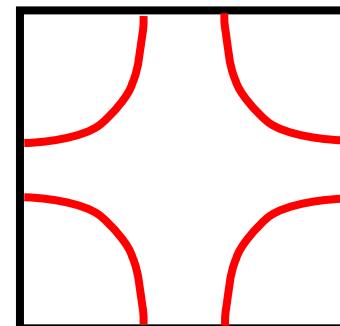
A-Long-range order



$$\begin{aligned}\chi &\propto \int \frac{f(\varepsilon) - f(-\varepsilon)}{2\varepsilon} N(\varepsilon) d\varepsilon \\ &\propto \int \frac{\tanh(\beta\varepsilon)}{2\varepsilon} N(\varepsilon) d\varepsilon\end{aligned}$$



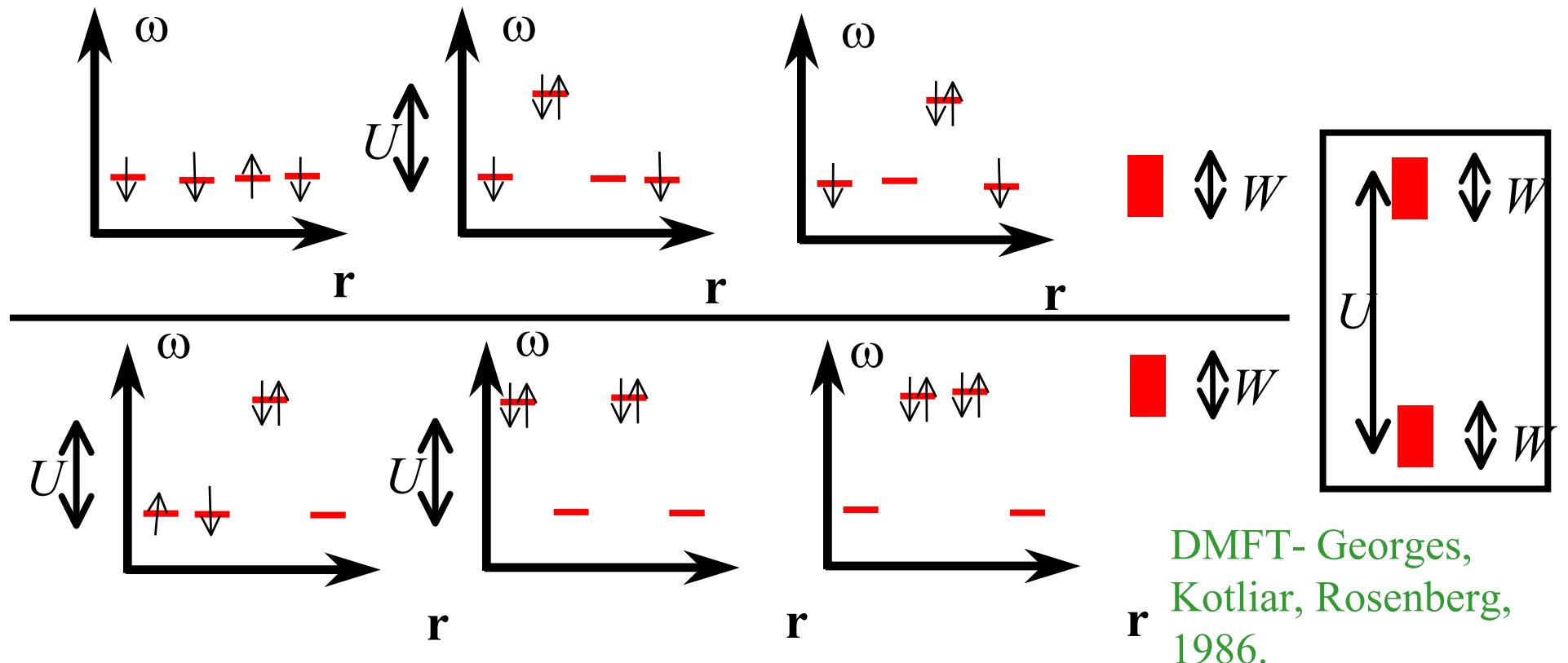
Introduce “frustration”



Will “resist” LRO until critical U

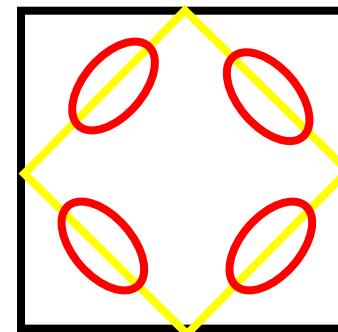
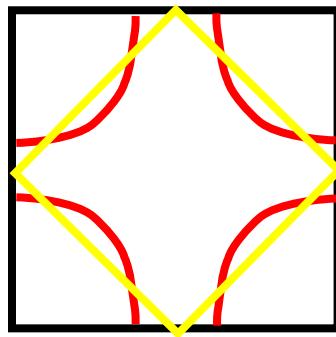
Destroying the Fermi liquid at half-filling: Lattice + interactions

B-Strong on-site repulsion (Mott transition)



Question: What happens away from $n = 1$?

A- Long-Range Order (U large enough)



Hole pockets:
Still FL

B- Mott transition : DMFT

$$\Sigma = f(\omega) \propto \frac{1}{\omega}$$

If gapped,

$$A = \frac{-2\Sigma''}{(\omega - \varepsilon_{\mathbf{k}} - \Sigma')^2 + \Sigma''^2} \text{ gapped everywhere}$$

Two ways to destroy a Fermi liquid

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II-Experimental results from cuprates

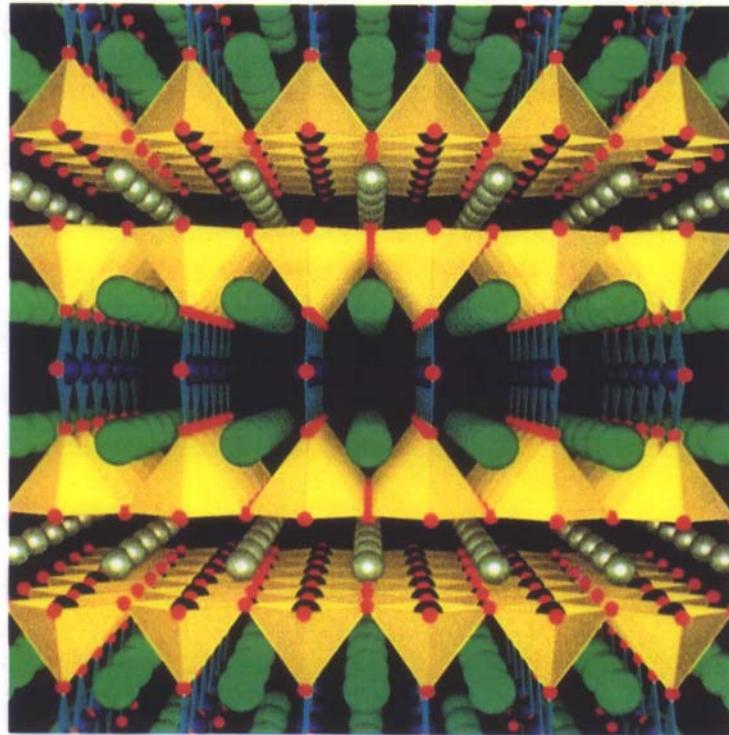
SCIENTIFIC AMERICAN

JUNE 1988
\$3.50

How nonsense is deleted from genetic messages.

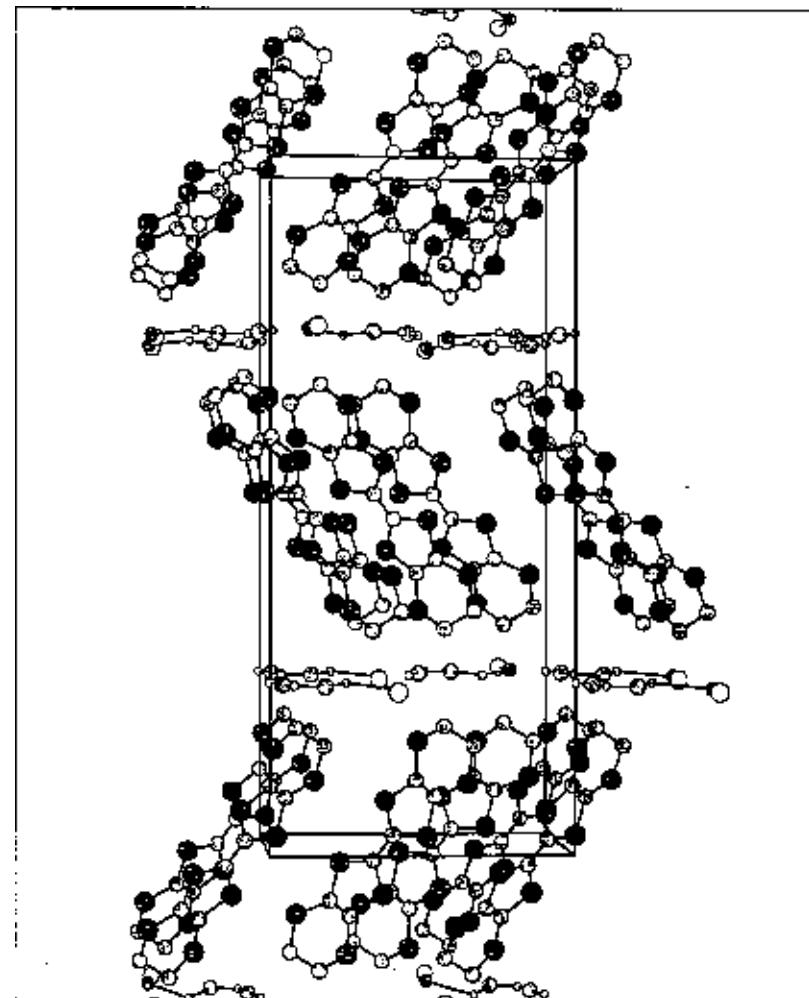
R for economic growth: aggressive use of new technology.

Can particle physics test cosmology?

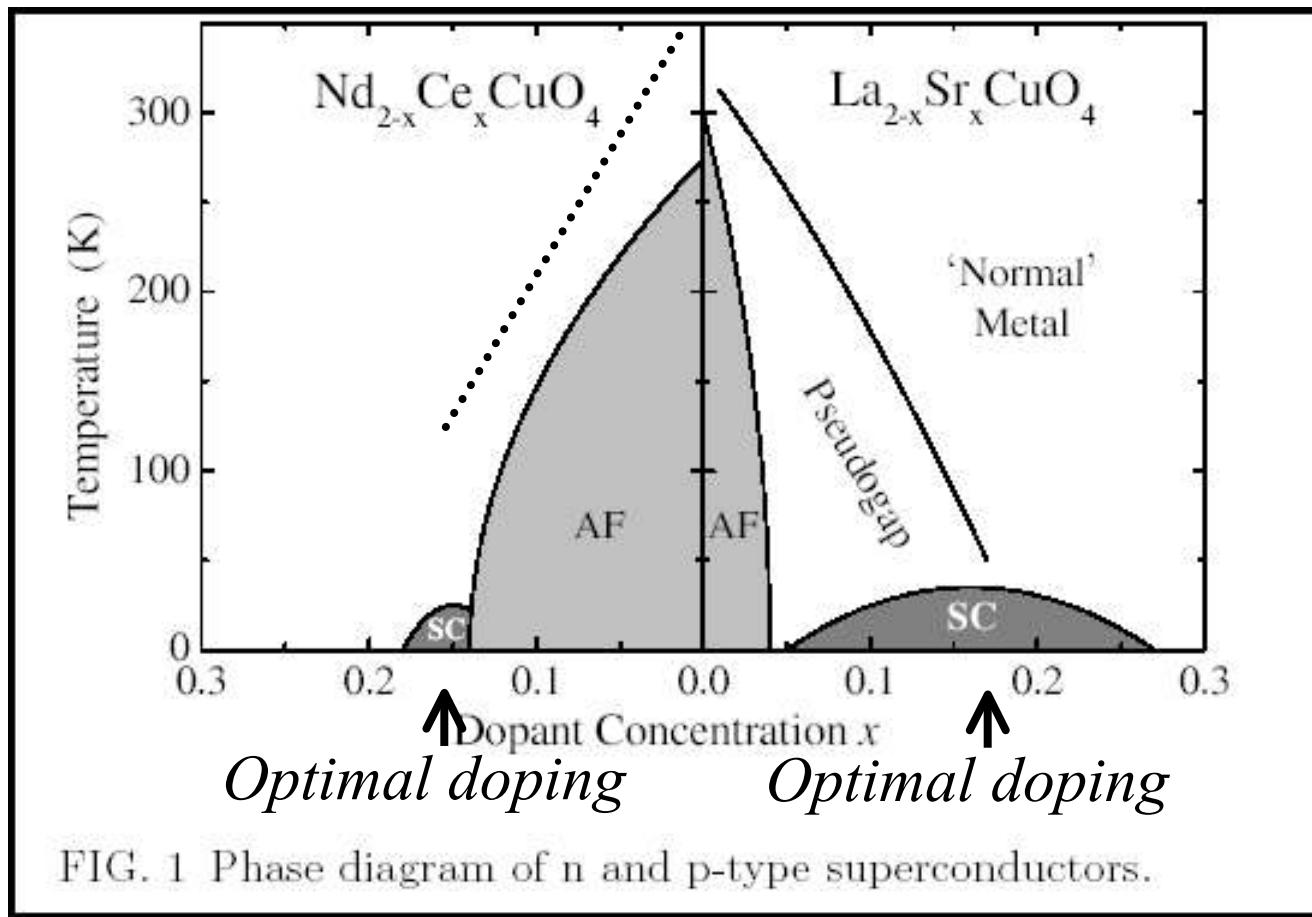


High-Temperature Superconductor belongs to a family of

$YBa_2Cu_3O_{7-\delta}$



Phase diagram



n , electron density

Damaselli, Shen, Hussain, 2002.

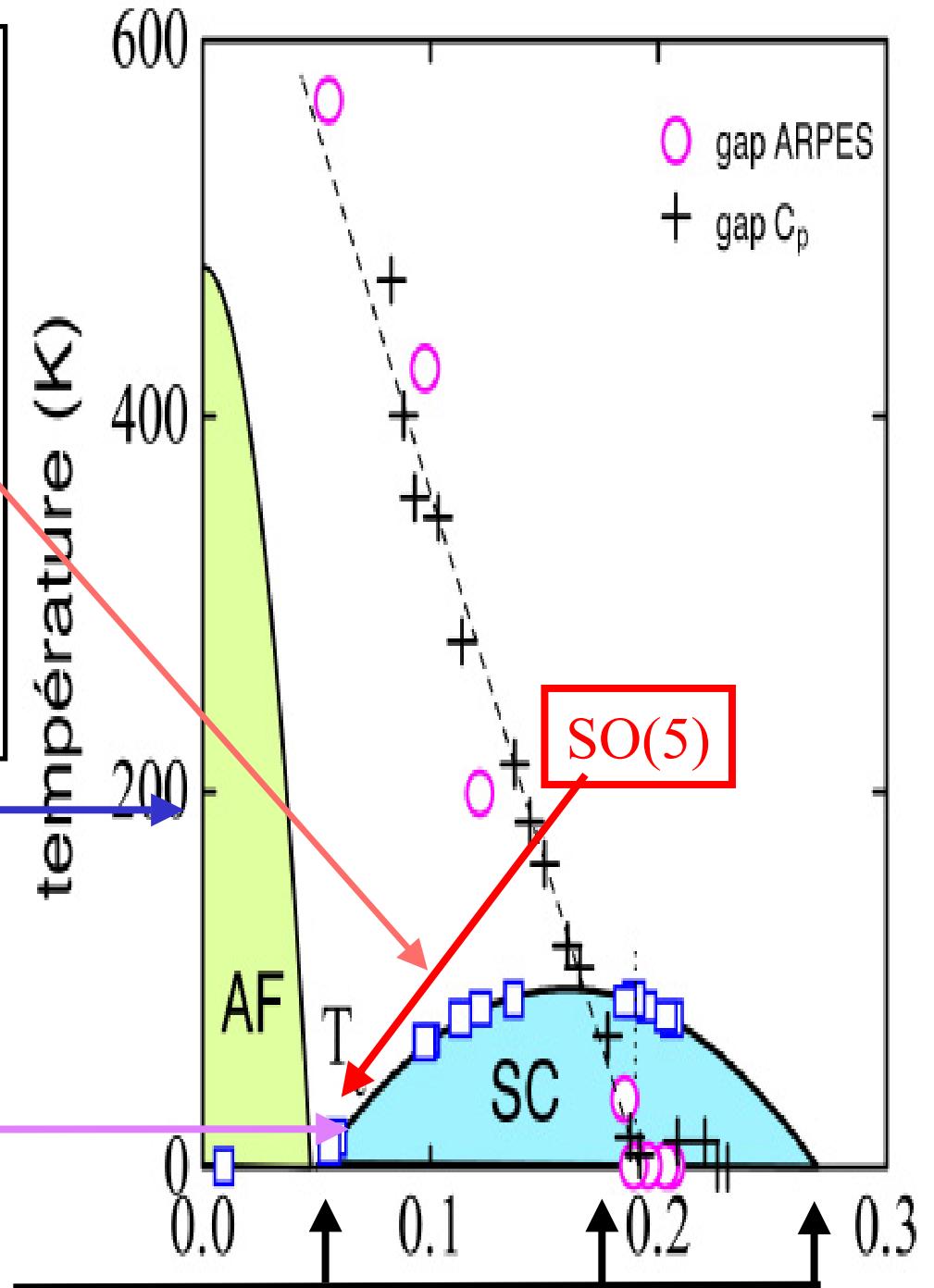
Pseudogap

- New Ising character phase?
 - RVB
 - Preformed pairs
 - Flux phase
 - D Density Wave
- Fluctuations?
 - SC, AFM, singlet...
- Stripes
- Spin-charge separation

$d = 3$ Néel T

« Mott » Physics explains
decreasing T_c
(Small ρ_s , Phase fluctuations)

Quantum critical points?

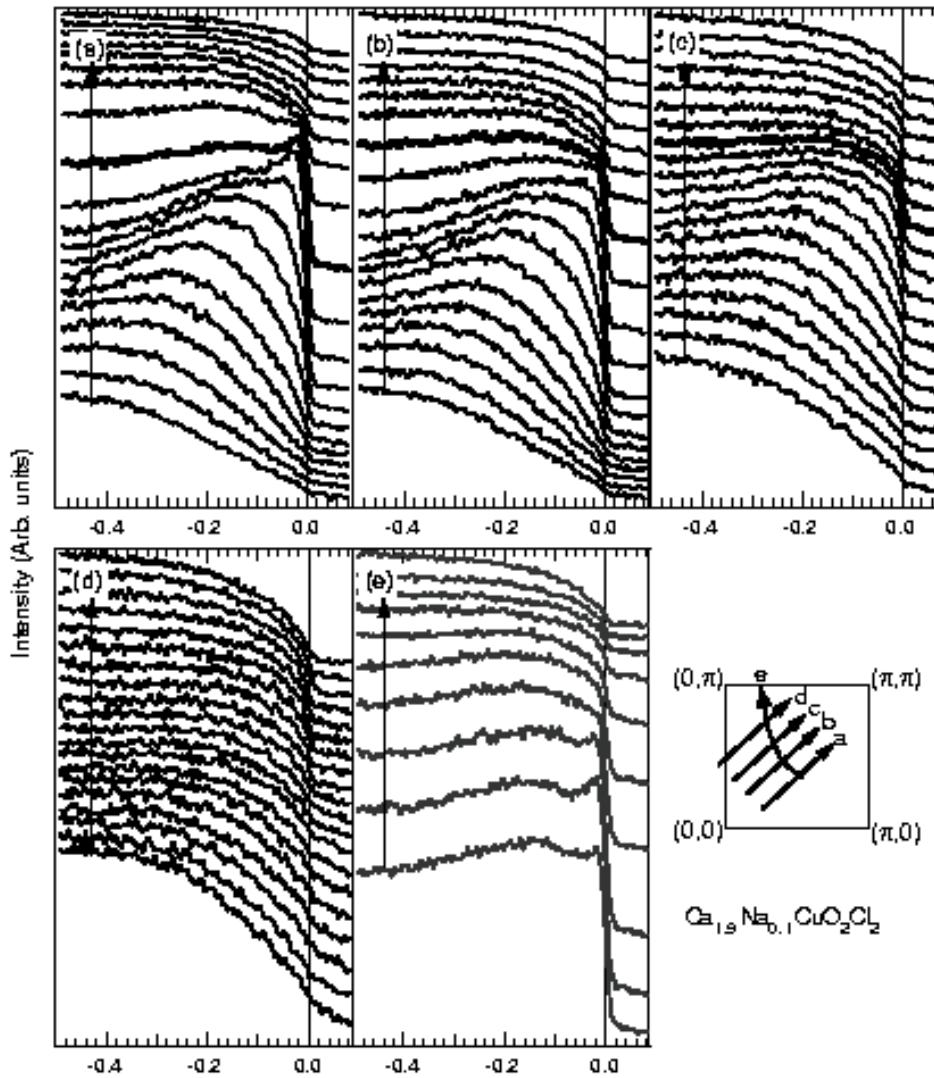


The normal state ($T > T_c$) of high temperature superconductors cannot be explained in the context of the band theory of metals or any of its extensions.

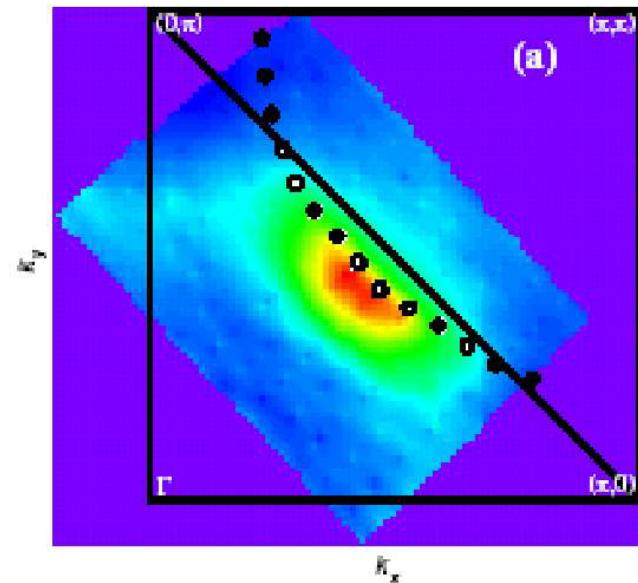
Two great mysteries:

1. The normal state (pseudogap).
2. The origin of the attraction leading to superconductivity (magnetic instead of phononic?)

Fermi surface, hole-doped case

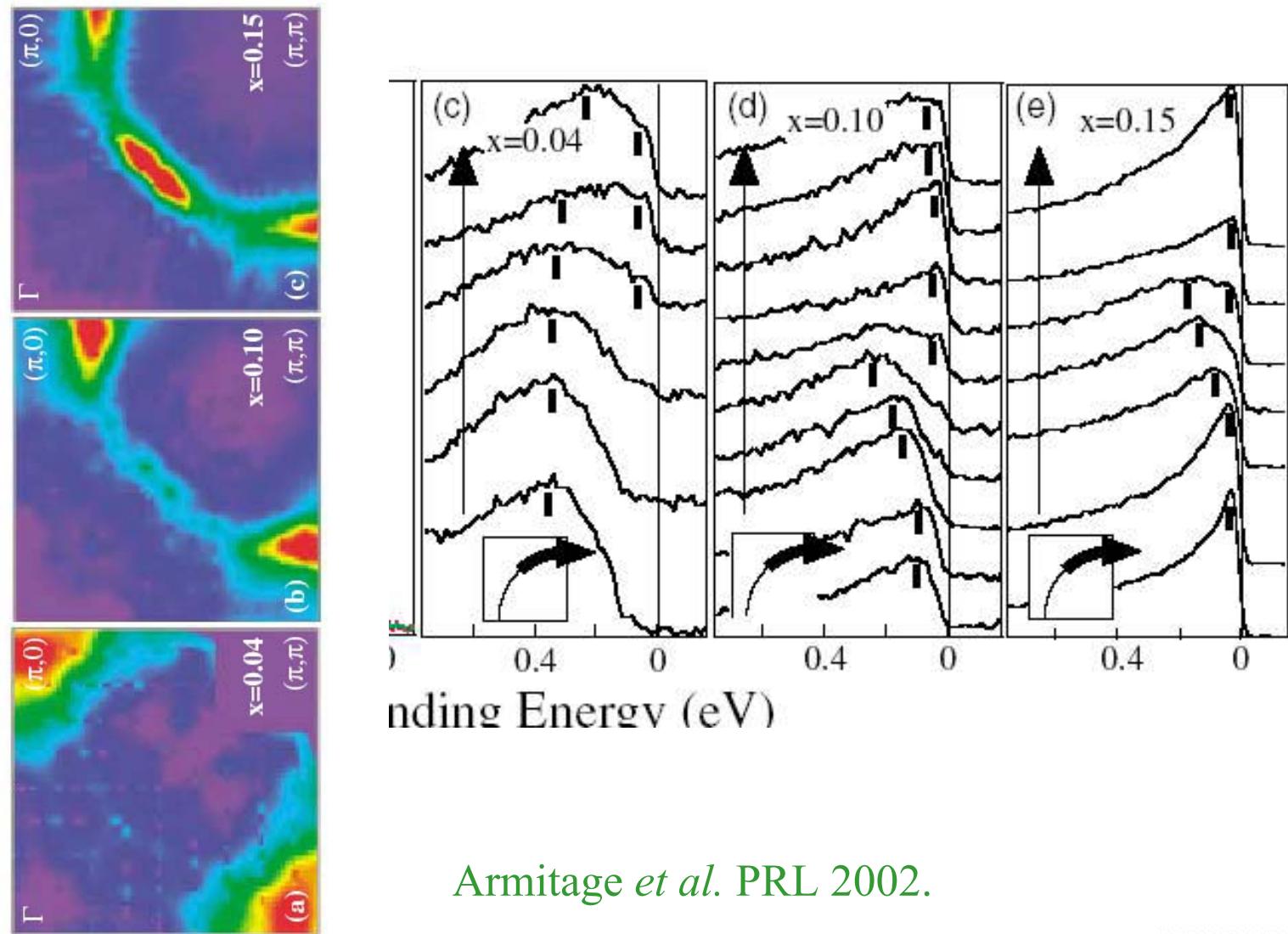


Hole-doped, 10%



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

Fermi surface, electron-doped case



Armitage *et al.* PRL 2002.

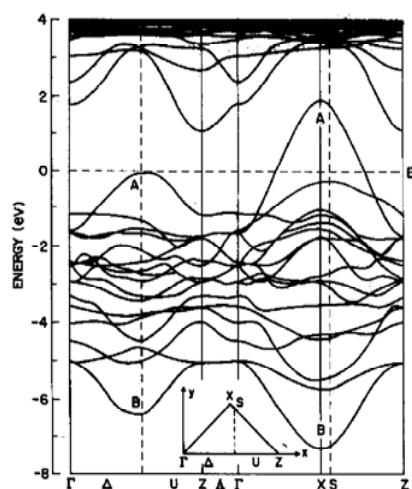
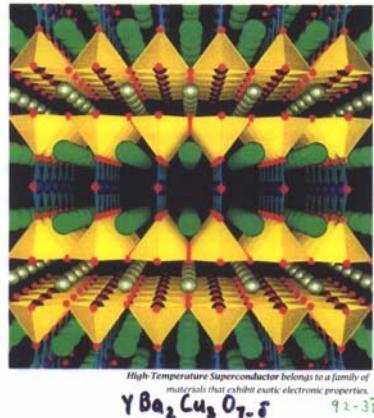
The « Hubbard model »

SCIENTIFIC
AMERICAN

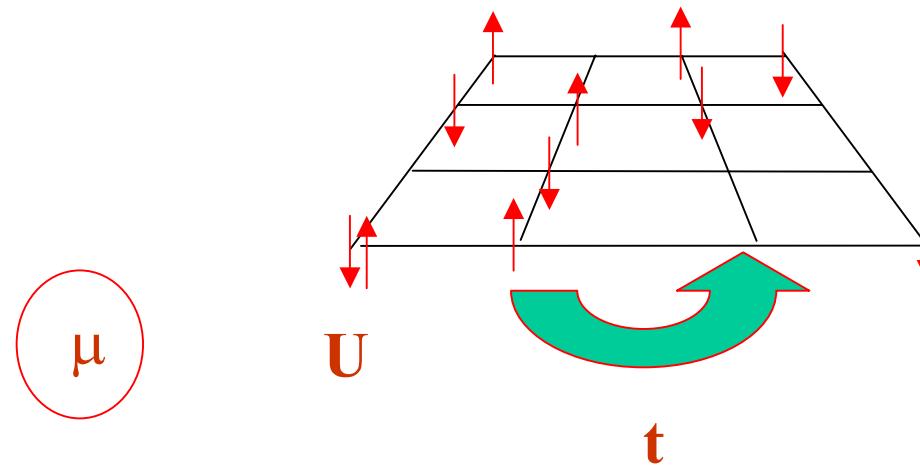
JUNE 1988
\$3.50

How nonsense is deleted from genetic messages.

Is for economic growth aggressive use of new technology.
Can particle physics test cosmology?



Simplest microscopic model for $Cu O$ planes.

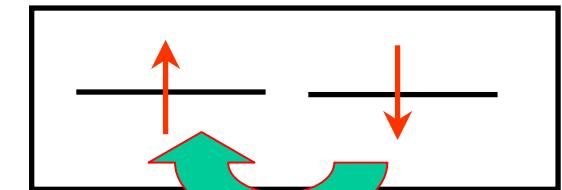
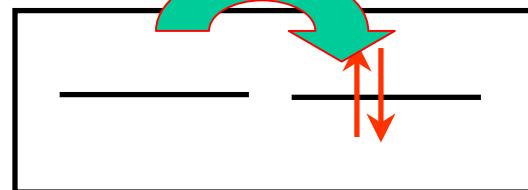
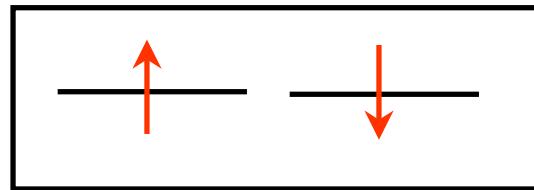
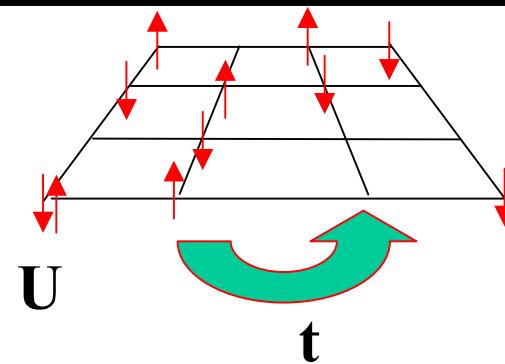


- Size of Hilbert space : 4^N ($N = 16$)
- With $N=16$, It takes 4 GigaBits just to store the states

Hubbard model (Kanamori, Gutzwiller, 1963) :

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

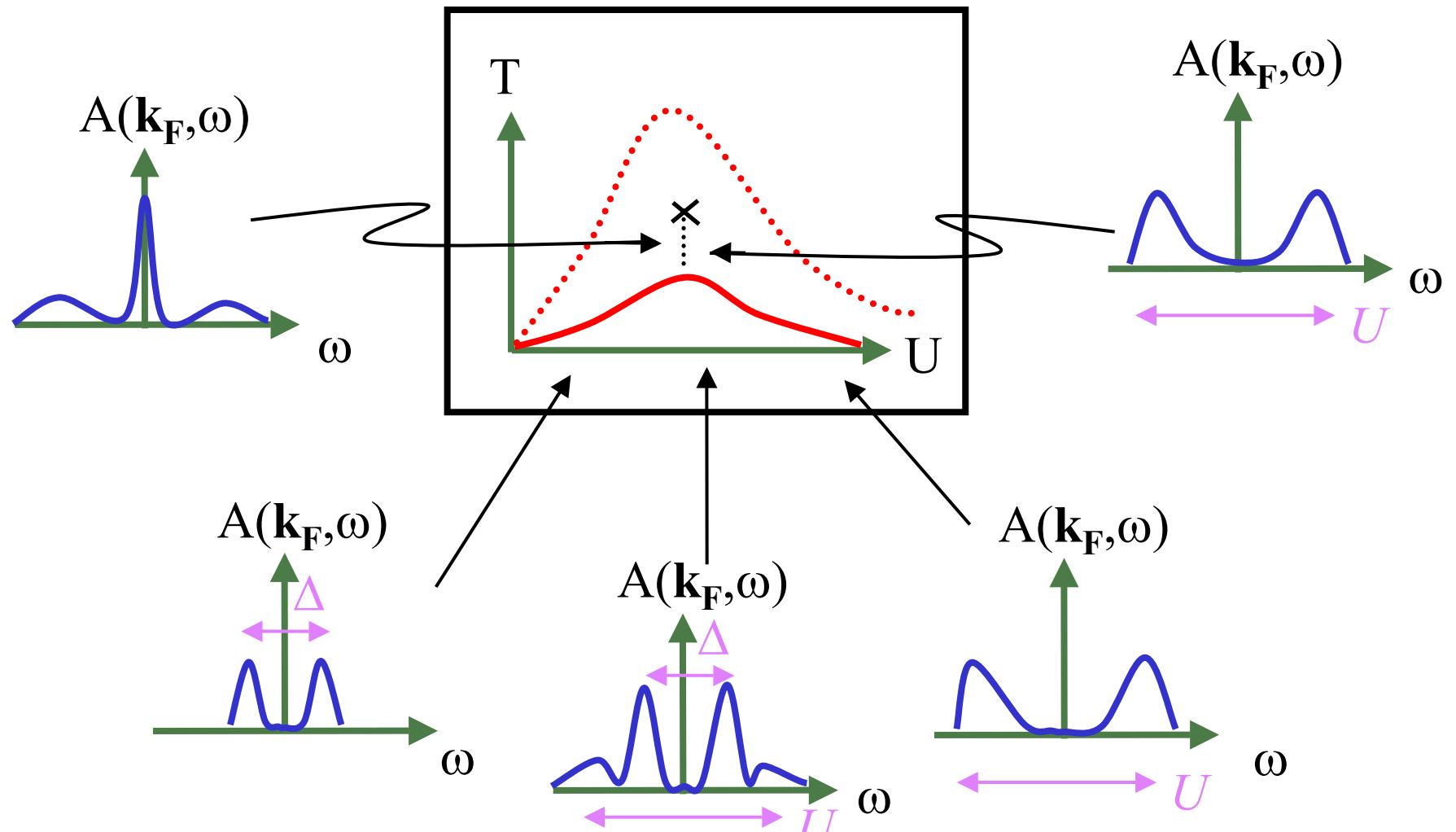
- Screened interaction U
- U, T, n (or $\delta=1-n$)
- $a = 1, t = 1, \hbar = 1$



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

- 2003 vs 1963: Numerical solutions to check analytical approaches

Weak vs strong coupling



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

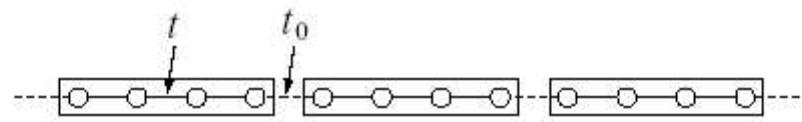
Mott transition

Two ways to destroy a Fermi liquid

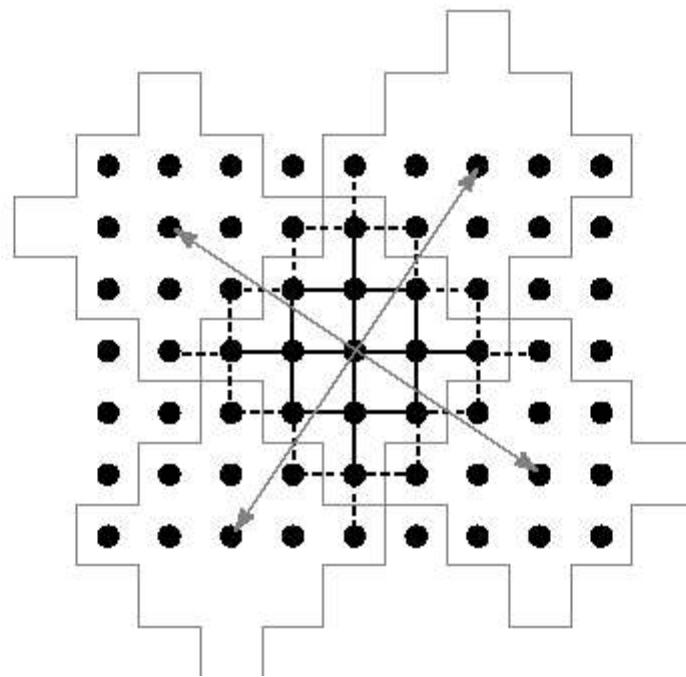
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Cluster Perturbation theory

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



Vary
cluster
shape and
size

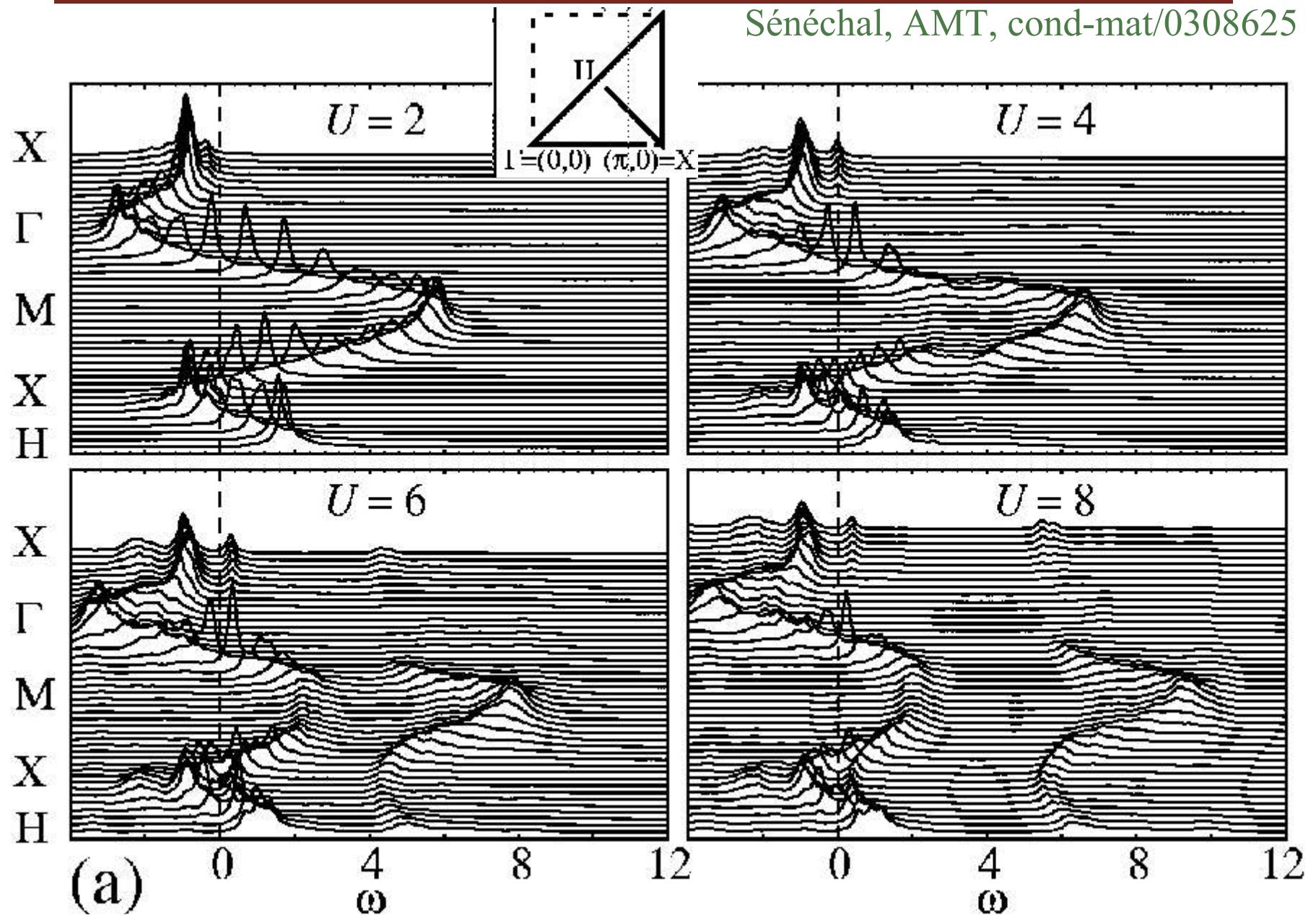


Sénéchal *et al.*
2000, 2002

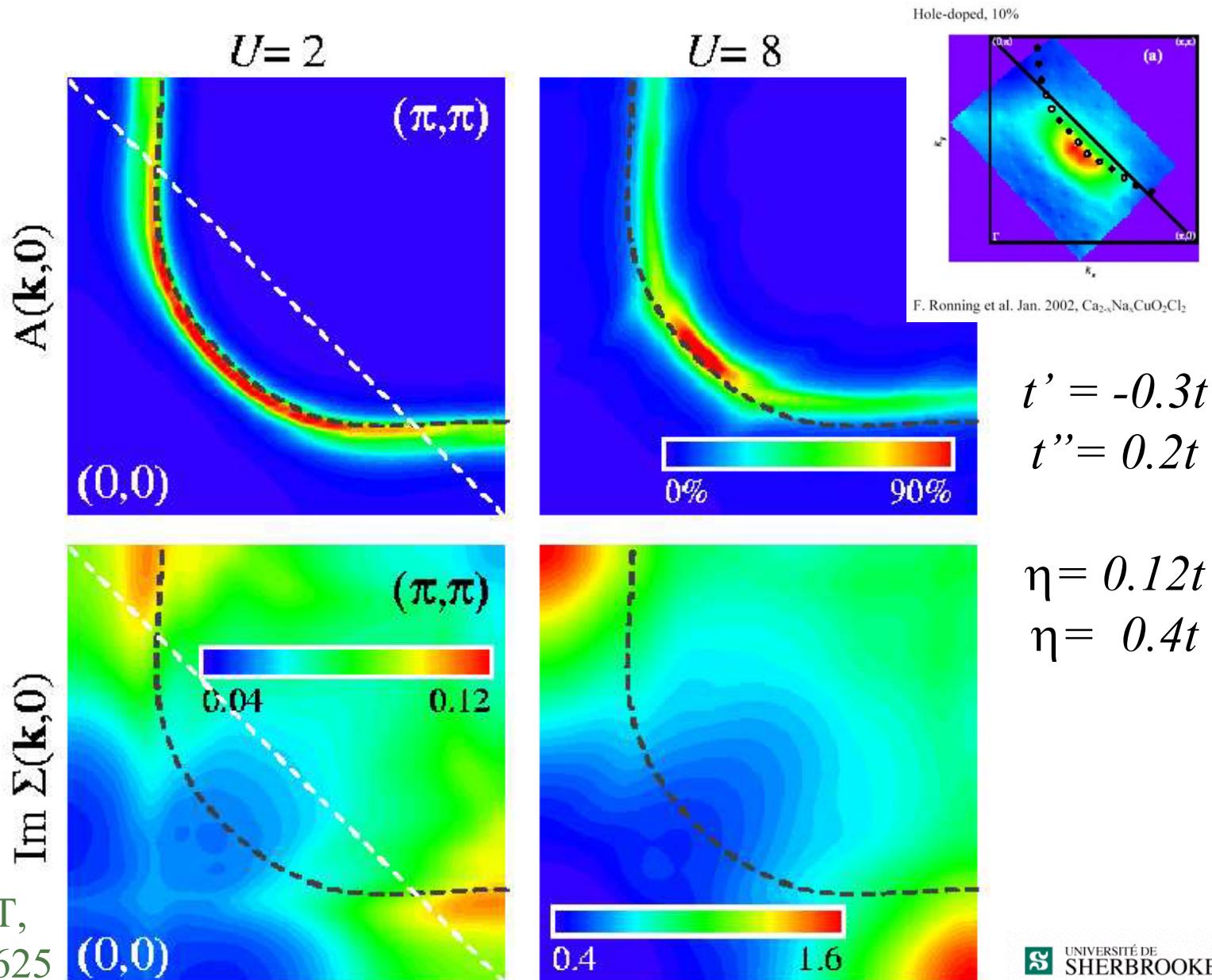
Tests: Spin-charge separation $d = 1$, and $U = \text{infinity}$

Hole-doped (17%)

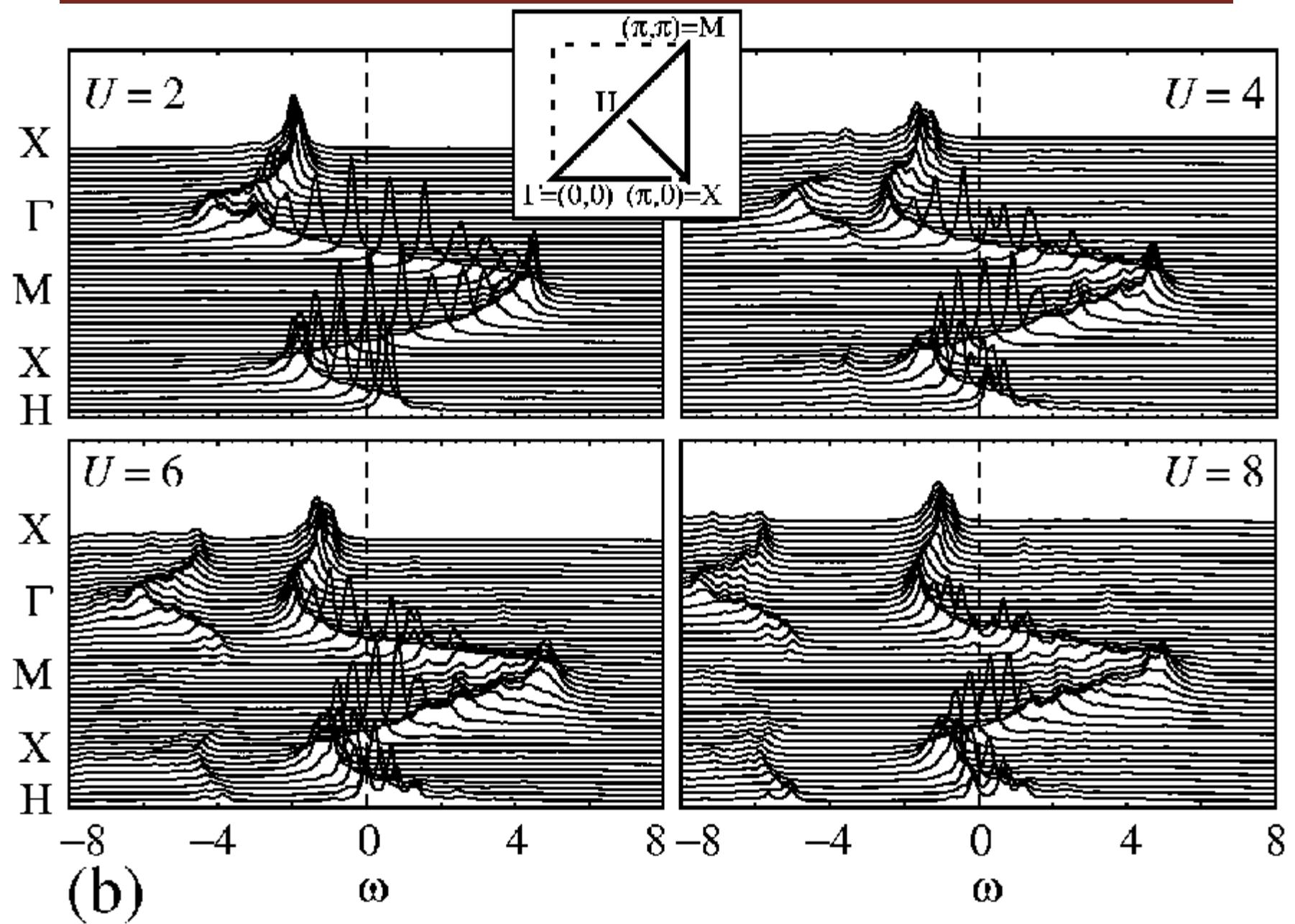
Sénéchal, AMT, cond-mat/0308625



Hole-doped (17%)

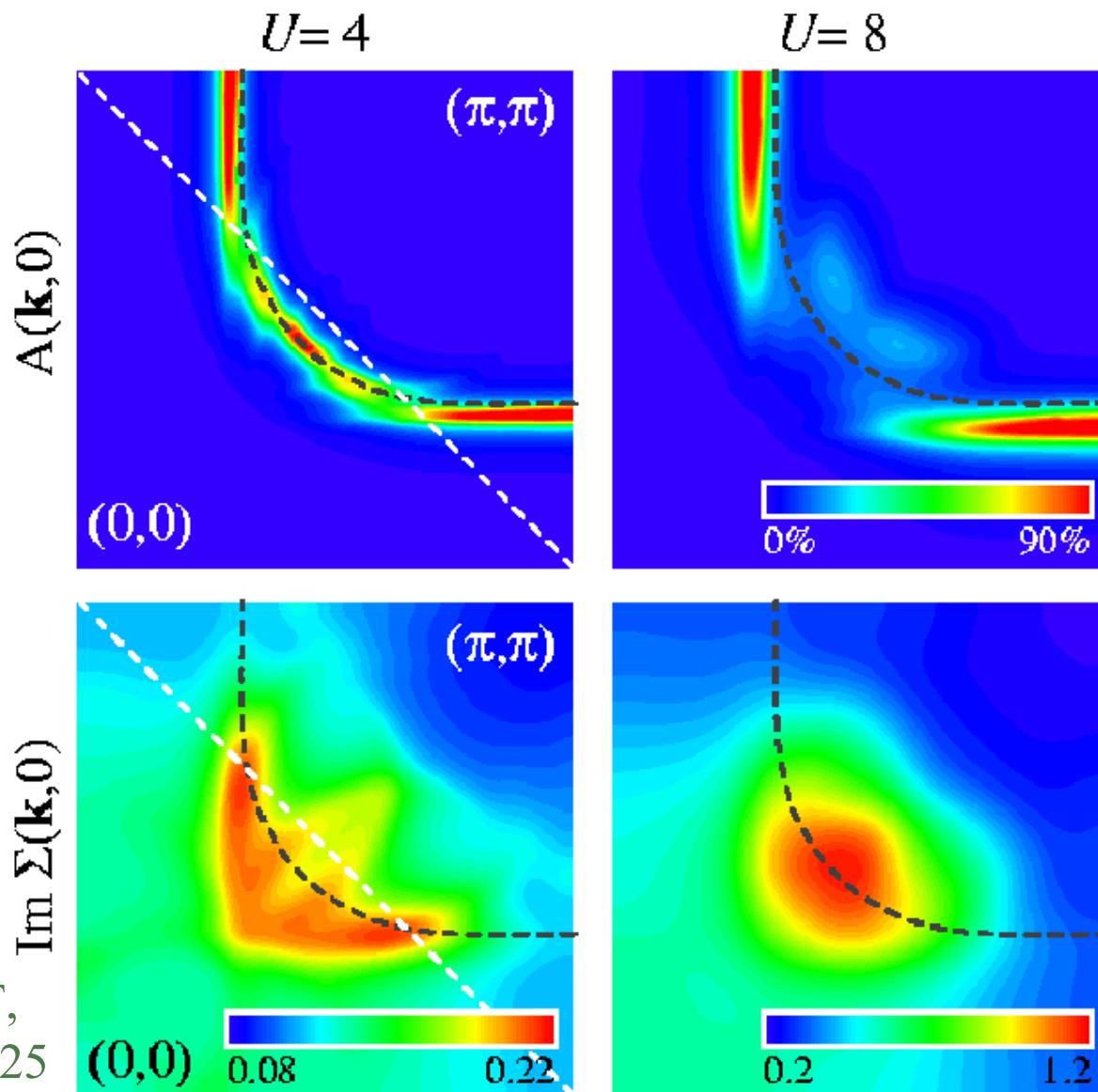


Electron-doped (17%)



(b)

Electron-doped (17%)

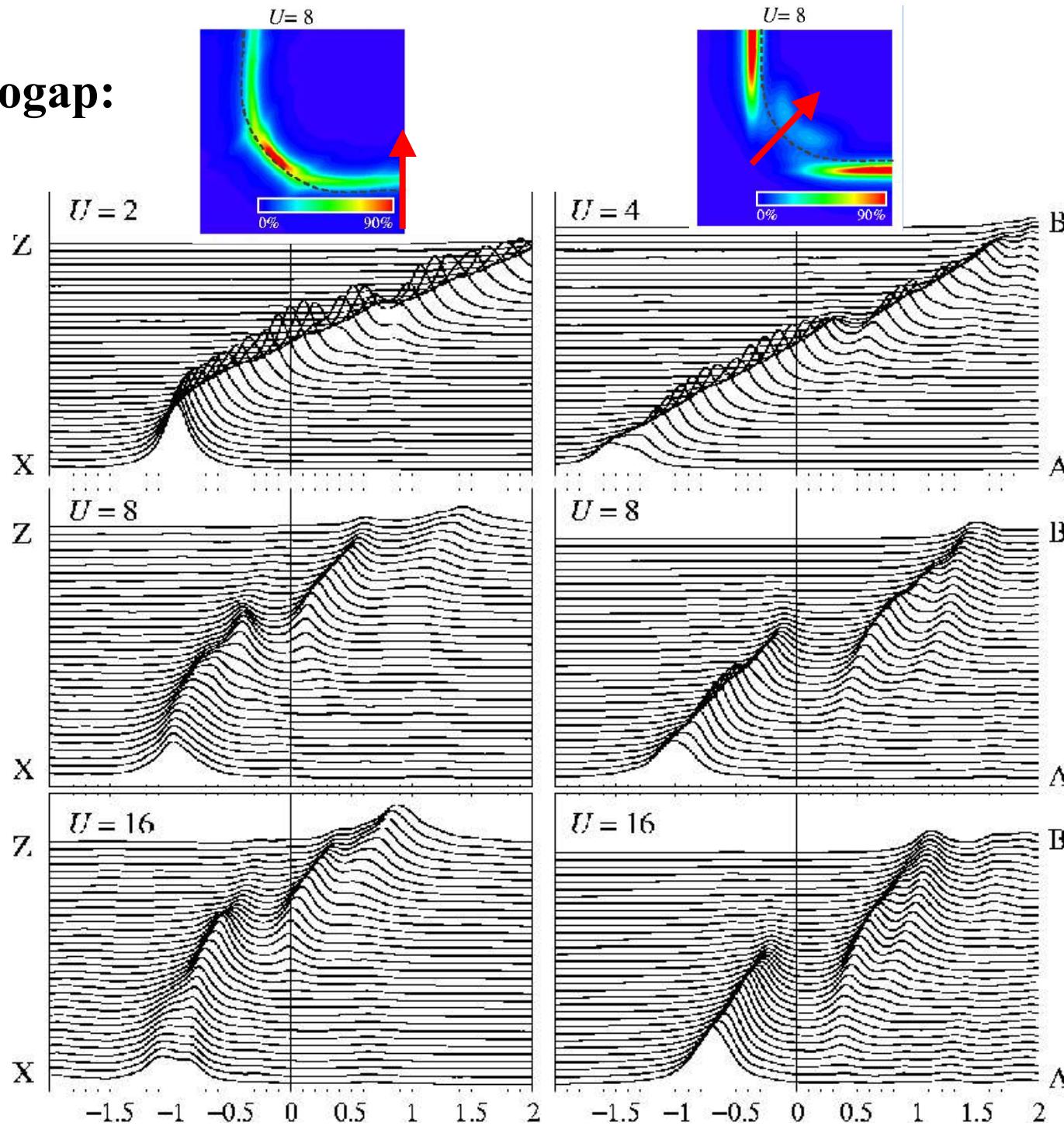


$$t' = -0.3t$$
$$t'' = 0.2t$$

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

Sénéchal, AMT,
cond-mat/0308625

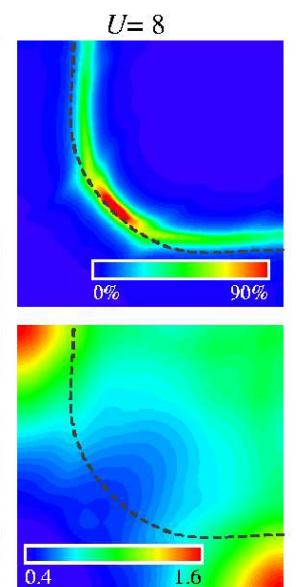
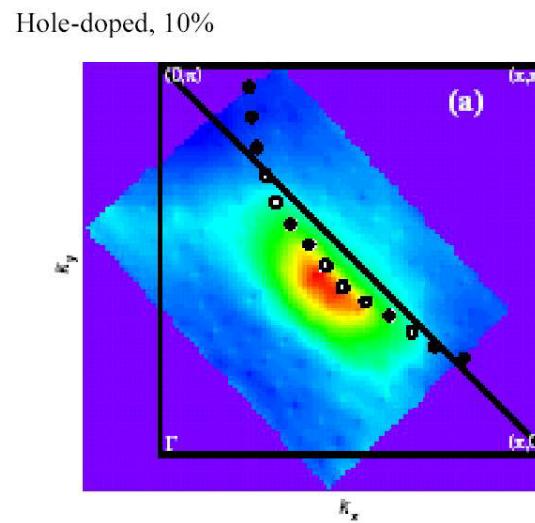
Pseudogap:



Sénéchal, AMT,
cond-mat/0308625

Strong coupling pseudogap

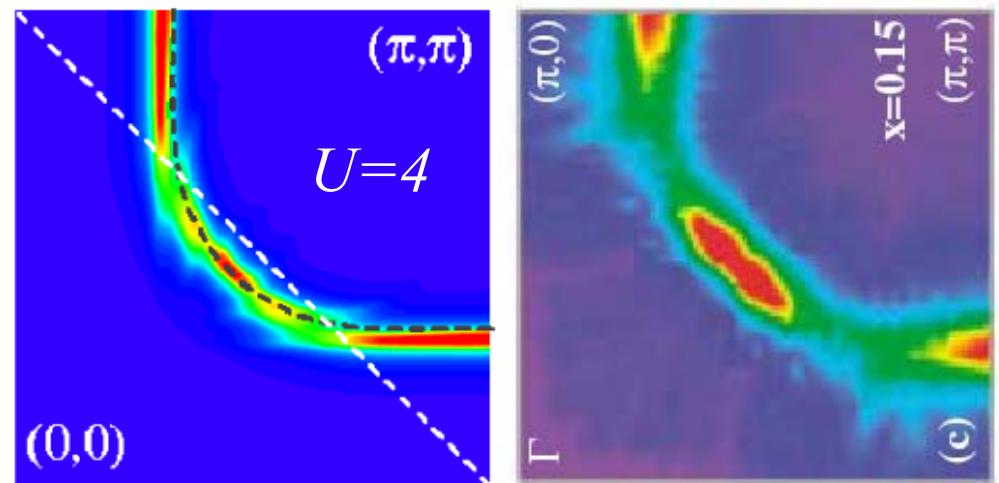
- When U is large enough, pseudogap is independent of cluster shape (and size) in CPT.
 - Short-range effect (few lattice spacings).
 - $\omega=0$ scattering largest at points separated by (π,π)
 - Scales like t .



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

Weak-coupling pseudogap

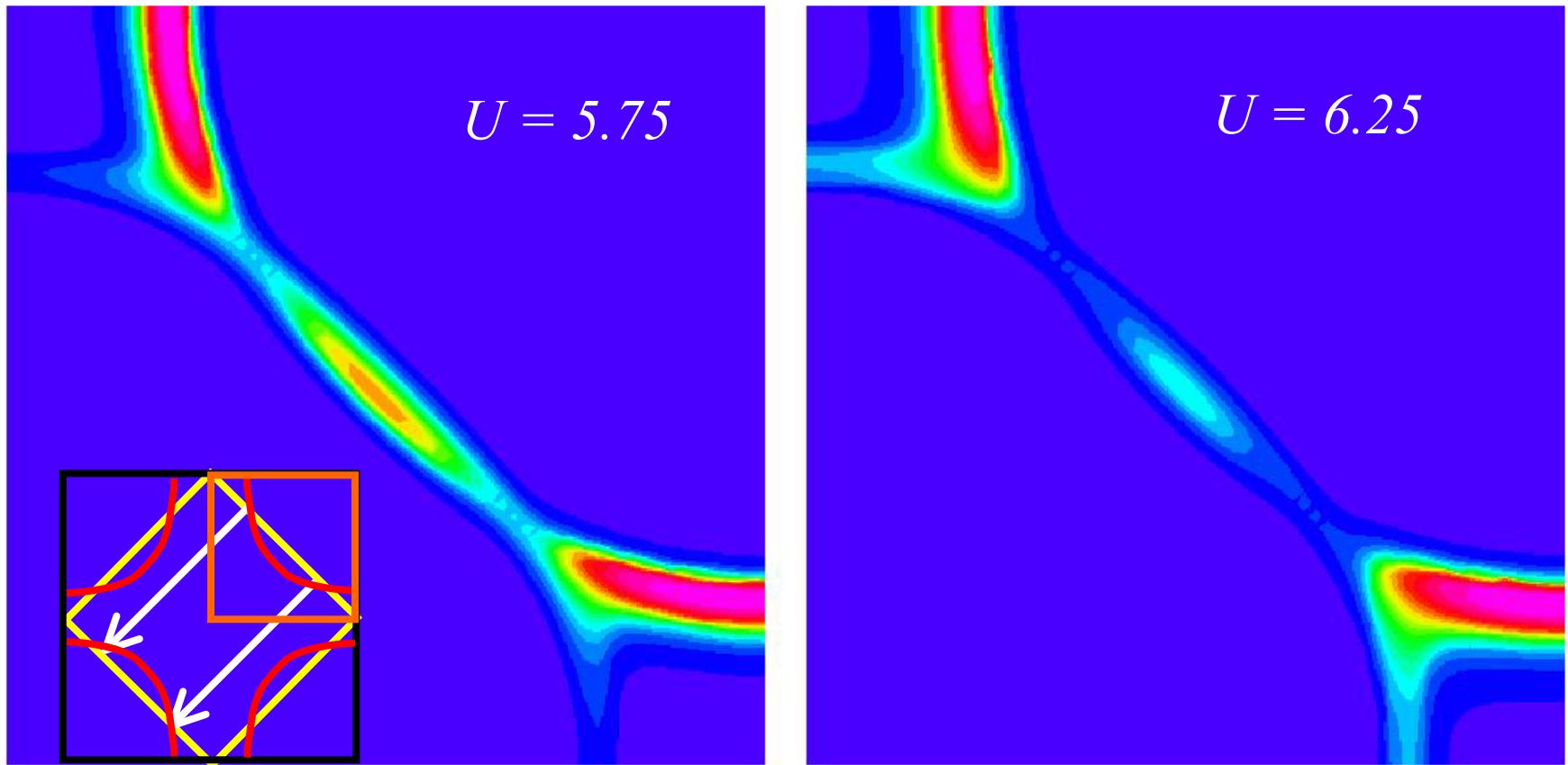
- In CPT
 - is mostly a depression in weight
 - depends on system size and shape.
- Coupling weaker because better screened $U(n)$.



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TPSC for electron-doped, 15%



$t' = -0.175, t'' = 0.05$

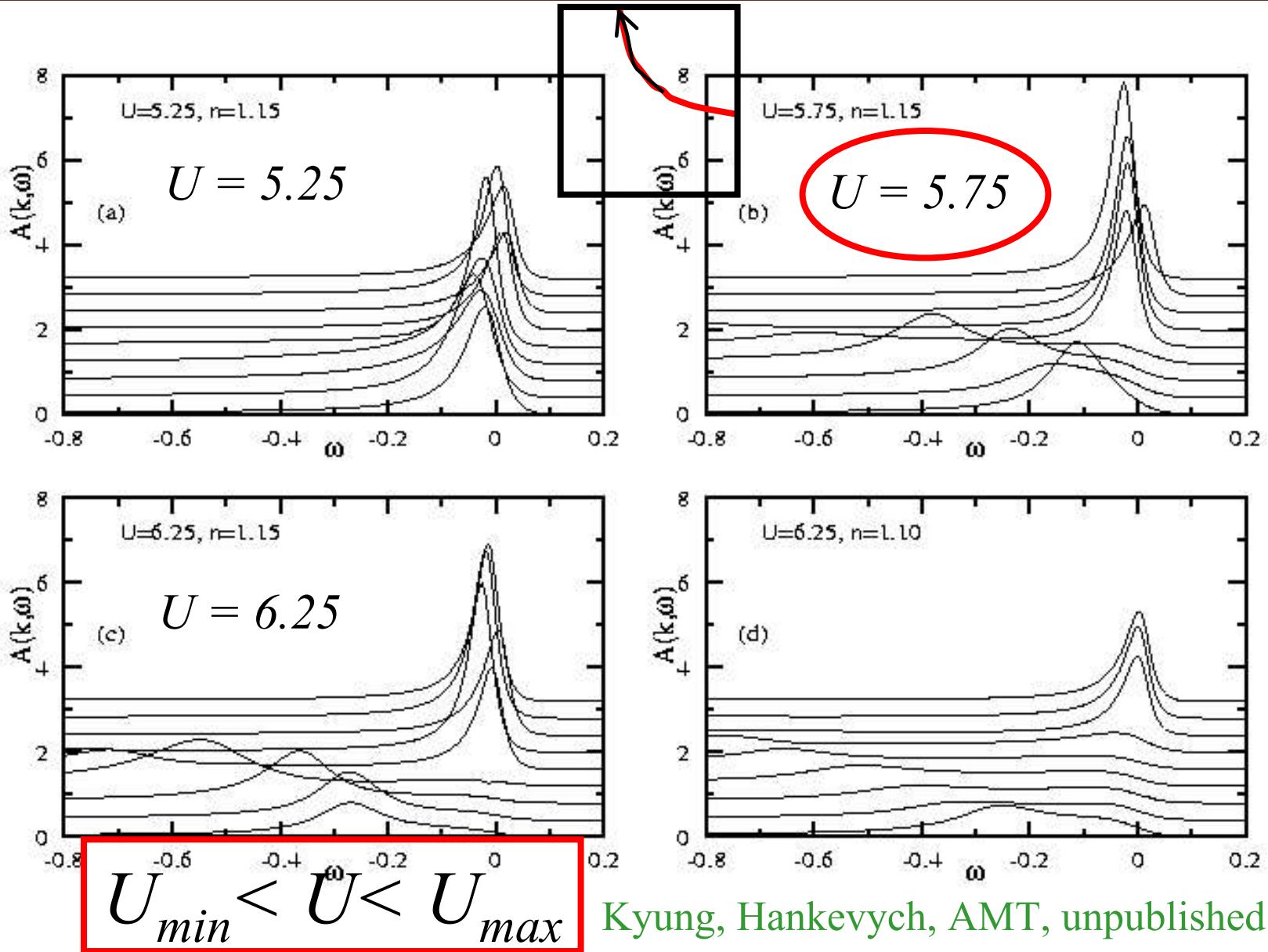
$n = 1.15$

$\beta = 40$

U cannot be too large to have three spots!

Kyung, Landry, AMT, cond-mat/0205165

Pseudogap or depression of weight?

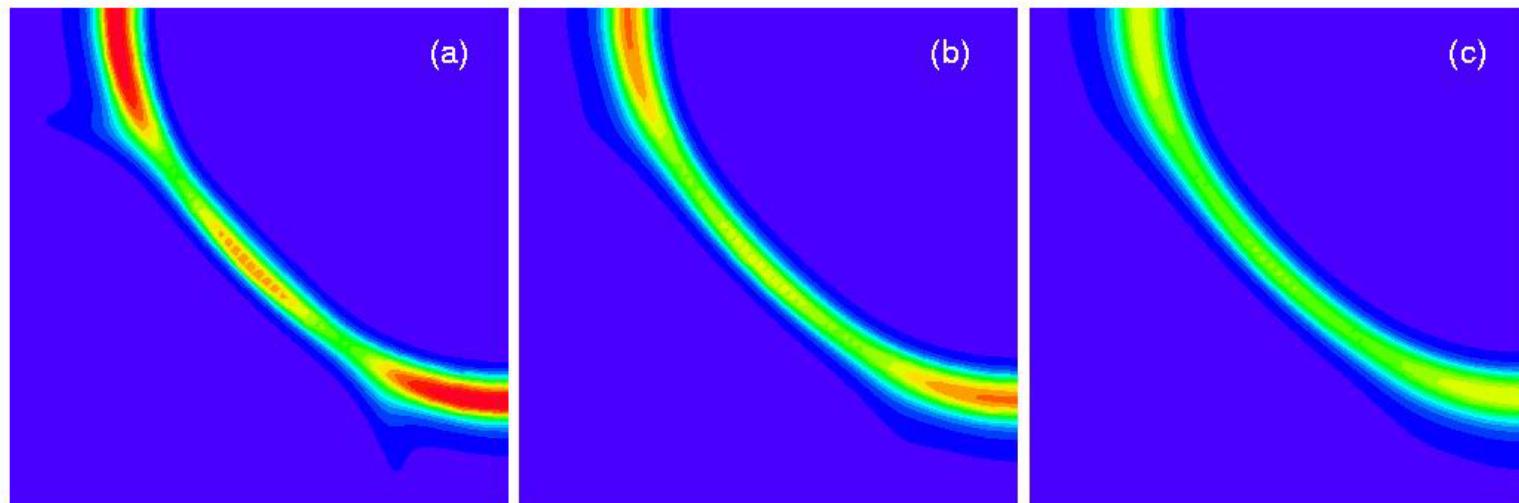


Temperature dependence

$\beta = 15$

$\beta = 10$

$\beta = 7.5$



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

Kyung, Hankevych, AMT, unpublished

Analytically :

$$\hbar\omega_{sf} \ll k_B T$$

effect of critical fluctuations on particles (RC regime)

Imaginary part: compare Fermi liquid, $\lim_{T \rightarrow 0} \Sigma_R''(\mathbf{k}_F, 0) = 0$

$$\Sigma_R''(\mathbf{k}_F, 0) \propto \frac{T}{v_F} \int d^{d-1} q_\perp \frac{1}{q_\perp^2 + \xi^{-2}} \propto \frac{T}{v_f} \xi^{3-d} \propto \frac{\xi}{\xi_{th}}$$

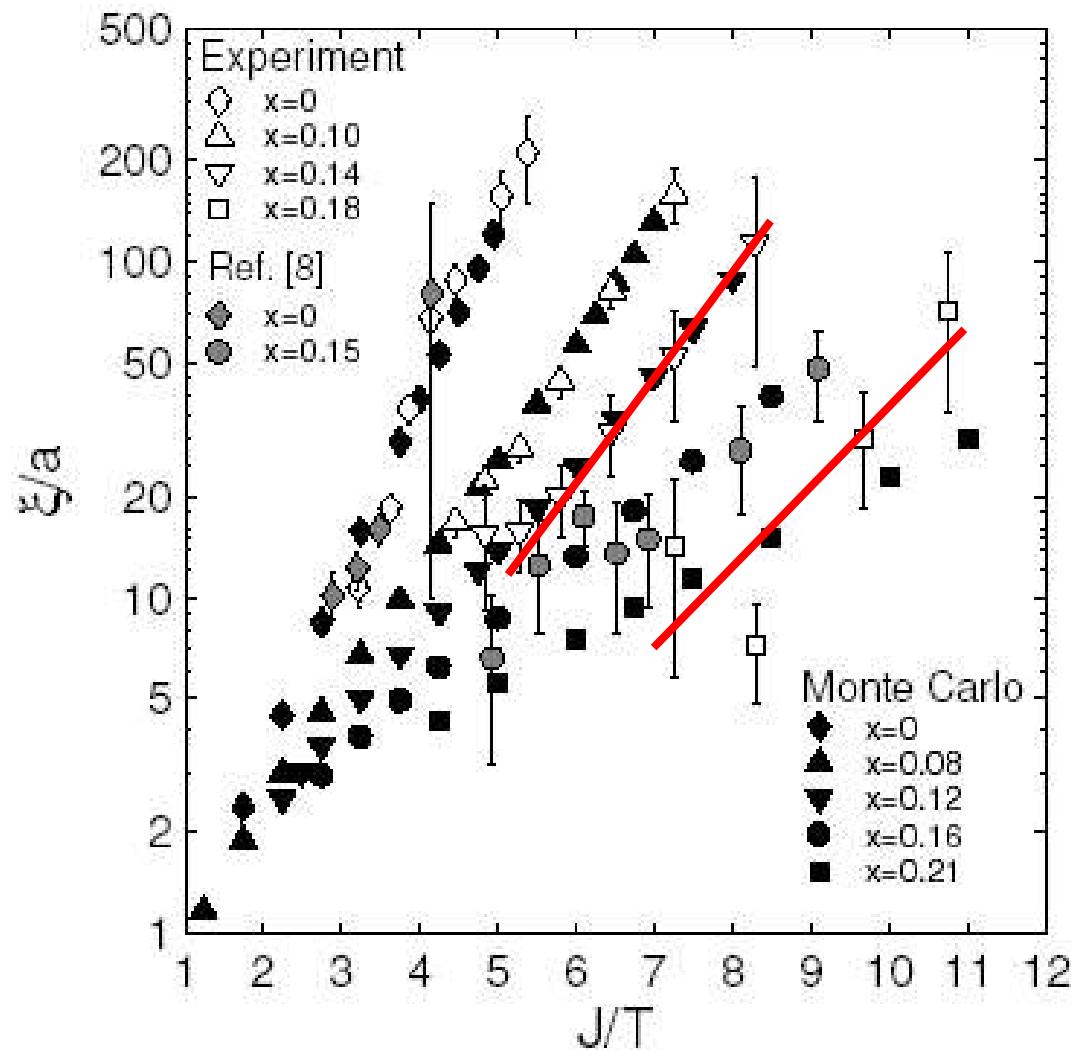
$$\text{Im } \Sigma^R(\mathbf{k}_F, 0) \propto -U\xi / (\xi_h \xi_0^2) > 1$$

Why leads to pseudogap

$$A(\mathbf{k}, \omega) = \frac{-2\Sigma_R''}{(\omega - \varepsilon_{\mathbf{k}} - \Sigma_R')^2 + \Sigma_R''^2}$$

Y.M. Vilk and A.-M.S. Tremblay, J. Phys. Chem. Solids **56**, 1769 (1995).
Y.M. Vilk and A.-M.S. Tremblay, Europhys. Lett. **33**, 159 (1996);

Long AFM correlation lengths (expt. NCCO)

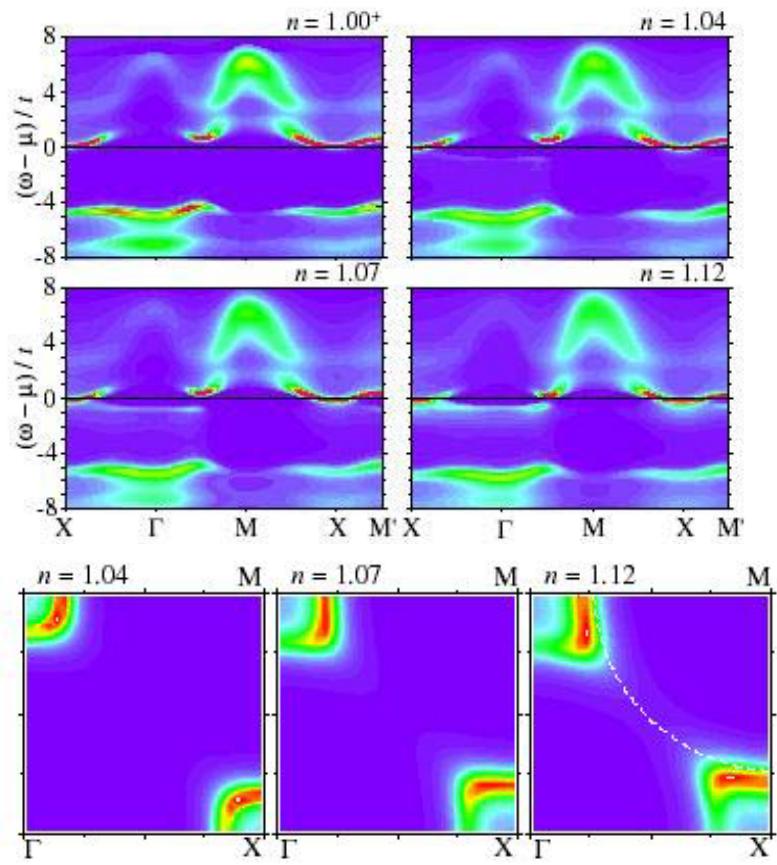
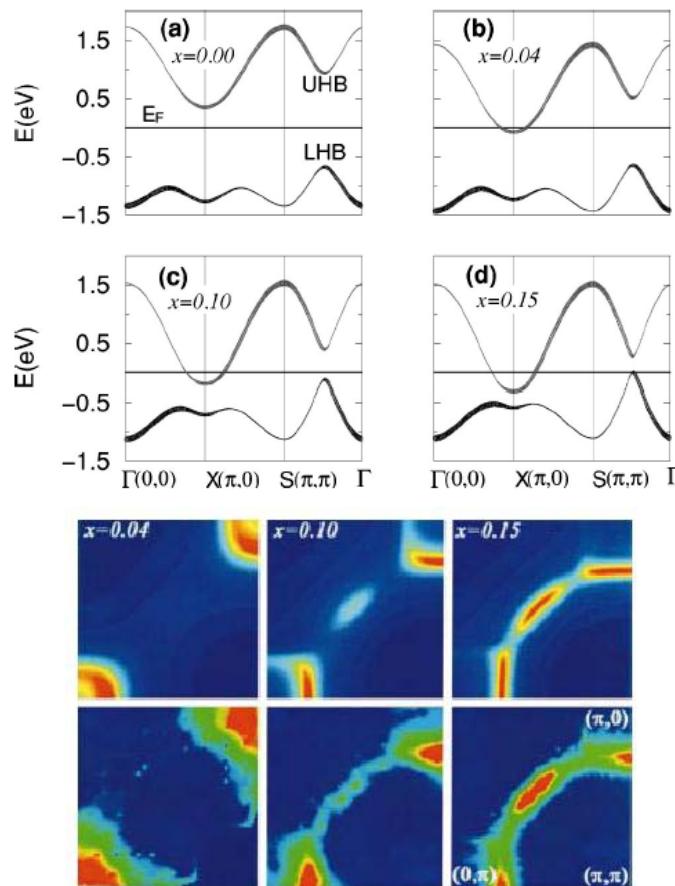


Experiment to do:
When do hot spots
disappear
with increasing T
In theory, $\xi \sim \xi_{\text{th}} \sim 5$ to 10

Vilk, PRB 97

Mang *et al.*
cond-mat/0307093

Contrast



Kusko, Markiewicz, Bansil, PRB 2002, Kusunose, Rice, cond-mat/0307053

Two-Particle Self-Consistent Approach

- How it works

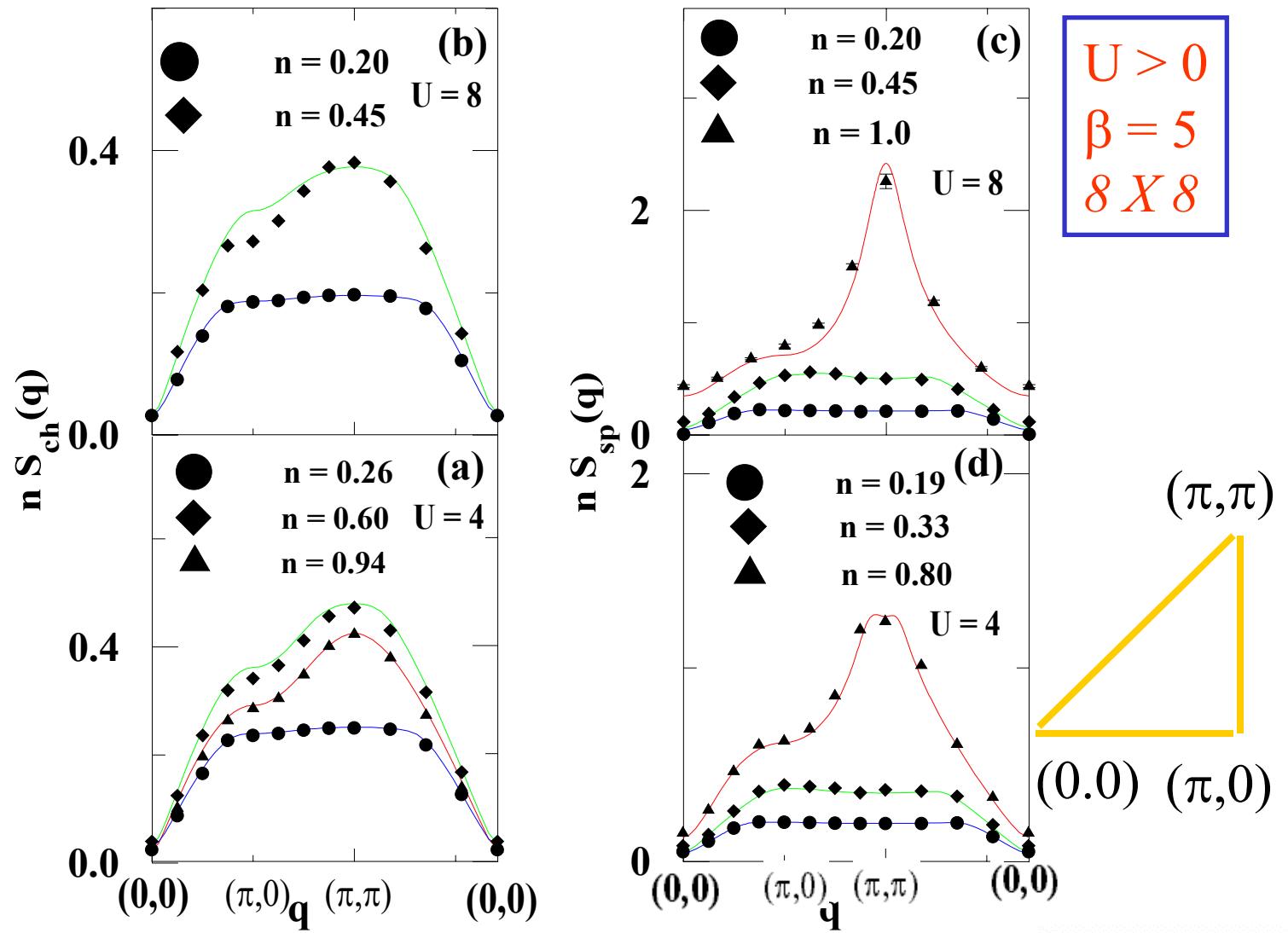
- General philosophy
 - Drop diagrams
 - Impose constraints and sum rules and try to satisfy them.
 - Pauli principle
 - Conservation laws
 - Mermin-Wagner theorem

Vilk, AMT J. Phys. I France, 7, 1309 (1997).

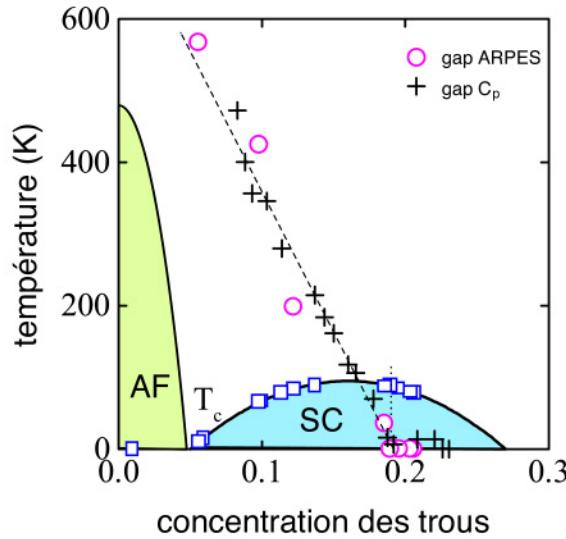
Proof that it works (comparisons with QMC)

Notes:

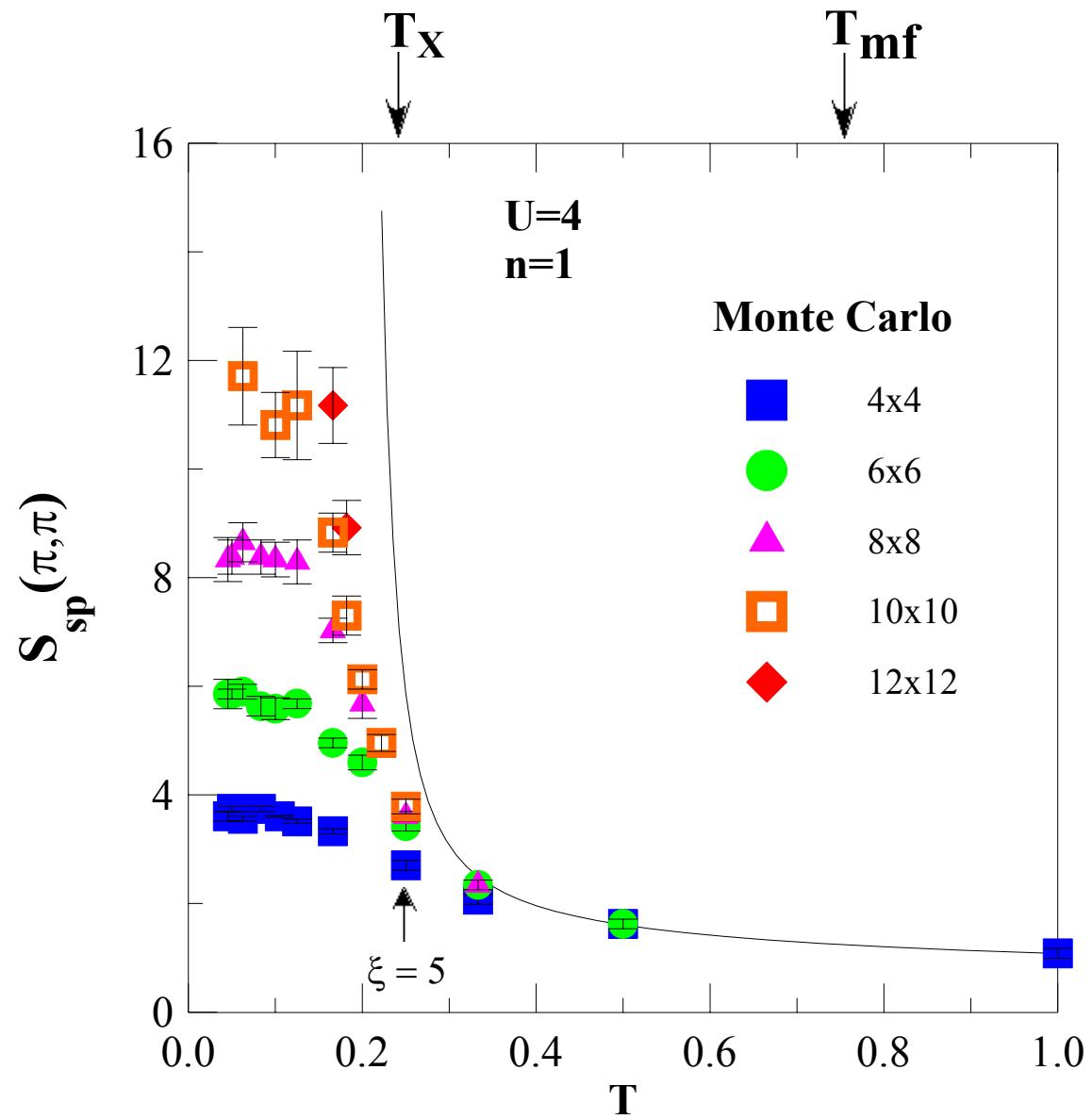
- F.L. parameters
- Self also Fermi-liquid



QMC + cal.: Vilk et al. P.R. B 49, 13267 (1994)



$$\xi \sim \exp(C(T) / T)$$



Calc.: Vilk et al. P.R. B **49**, 13267 (1994)

QMC: S. R. White, et al. Phys. Rev. **40**, 506 (1989).

$O(N = \infty)$ A.-M. Daré, Y.M. Vilk and A.-M.S.T Phys. Rev. B **53**, 14236 (1996)

A better approximation for single-particle properties (Ruckenstein)

$$1 \begin{array}{l} \\ \nearrow \\ \searrow \\ 3 \end{array} \rightarrow 2 = - \begin{array}{l} 1 \\ \nearrow \\ \searrow \\ 3 \end{array} \rightarrow 2 + \begin{array}{l} 1 \\ \leftarrow \\ \searrow \\ 3 \end{array} \begin{array}{c} \overline{2} \\ \overline{4} \\ \overline{3} \\ \overline{5} \end{array} \rightarrow 2$$

$$1 - \Sigma - 2 = 1 \quad 2 + 1 \quad \bar{5} \quad \frac{1}{2} \quad 2$$

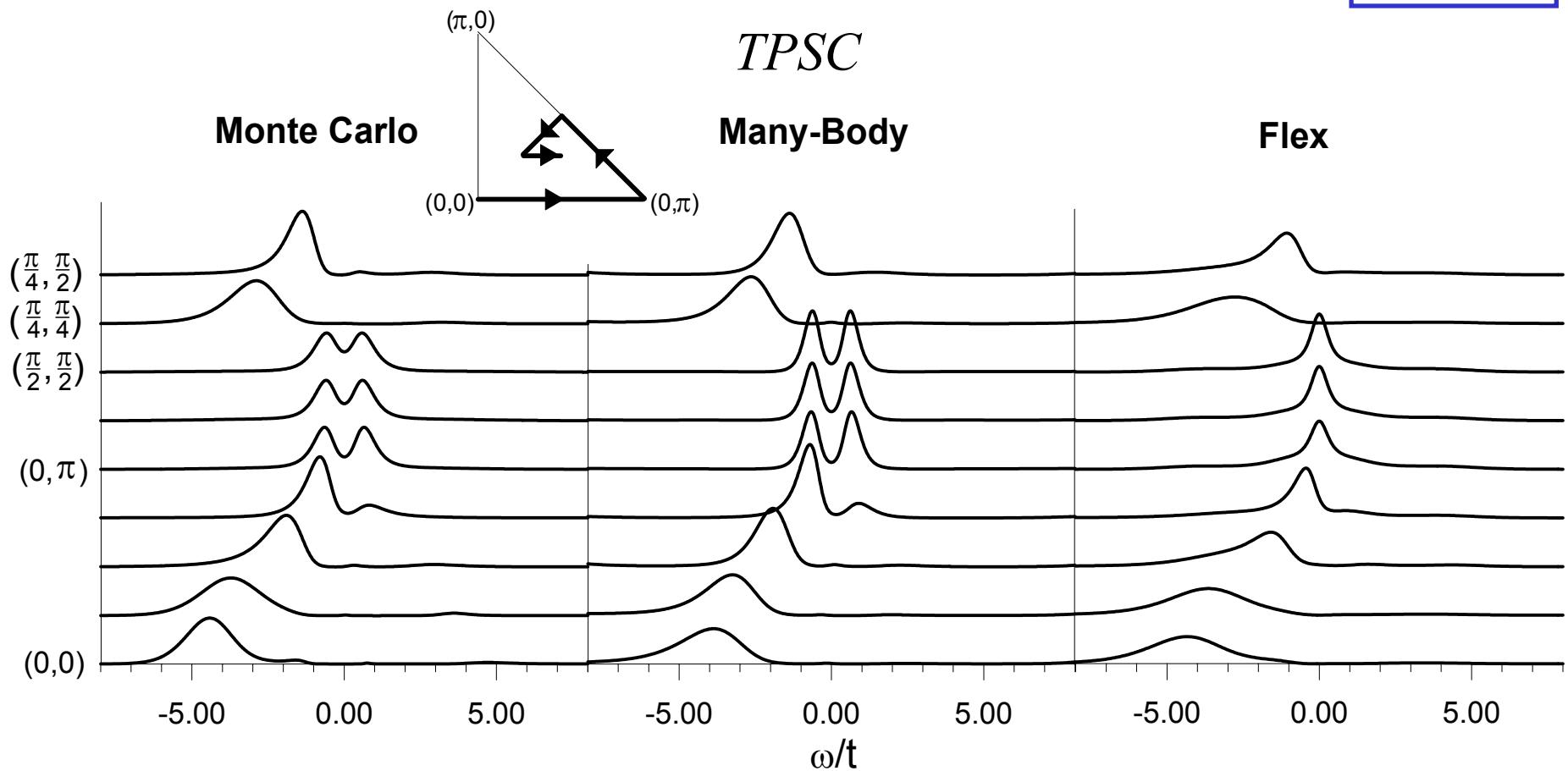
Y.M. Vilk and A.-M.S. Tremblay, J. Phys. Chem. Solids **56**, 1769 (1995).

Y.M. Vilk and A.-M.S. Tremblay, *Europhys. Lett.* **33**, 159 (1996);

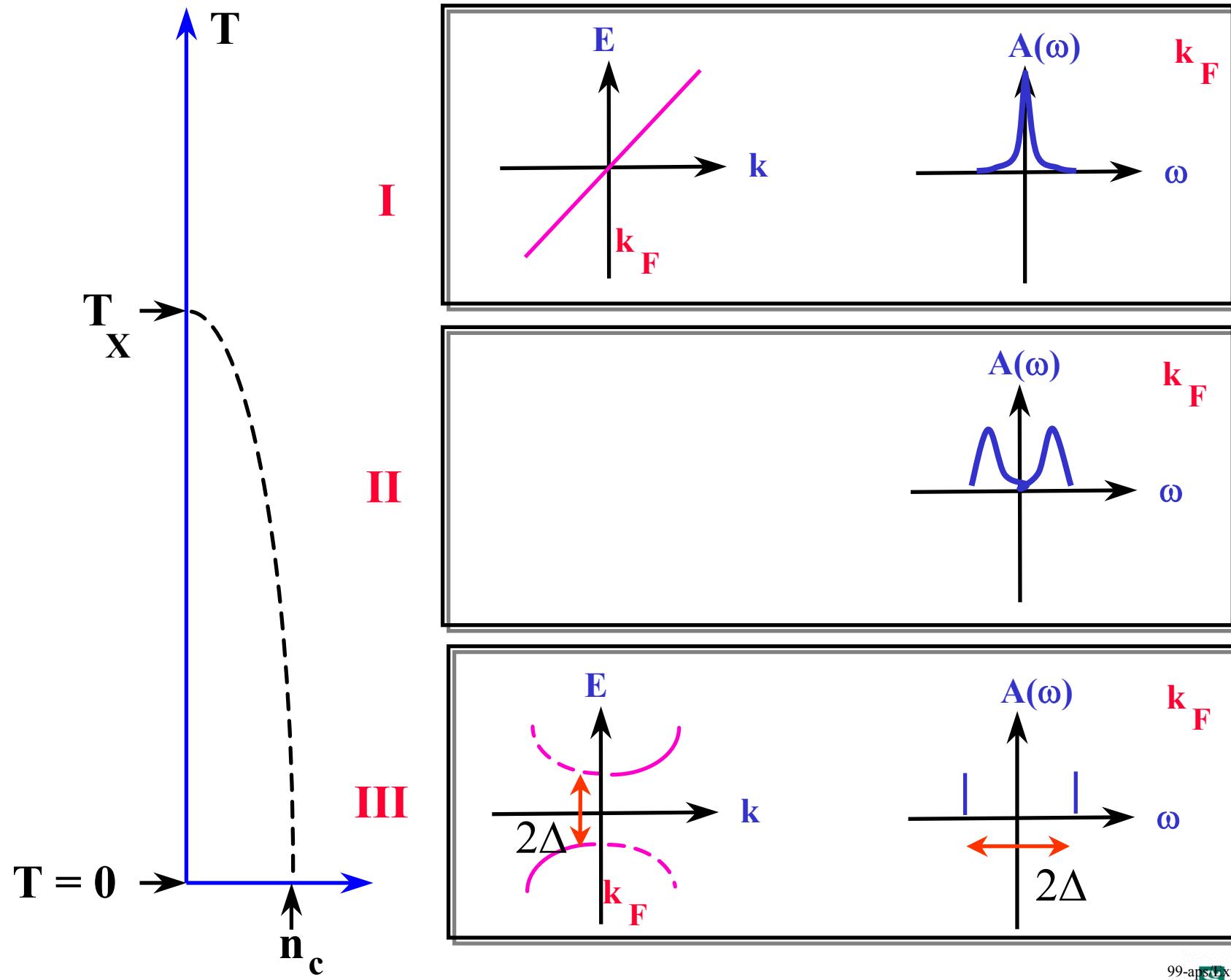
N.B.: No Migdal theorem

Proofs...

$$\boxed{U = +4}$$
$$\boxed{\beta = 5}$$



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

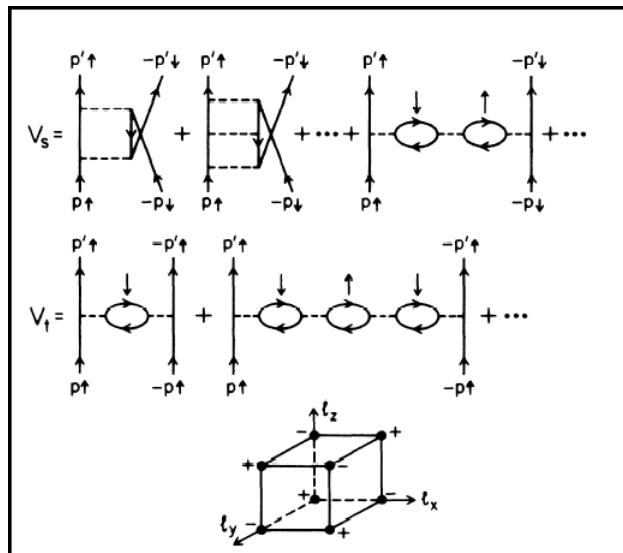


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A great prediction ? (Kohn-Luttinger mechanism)

d-wave superconductivity induced by antiferromagnetic fluctuations

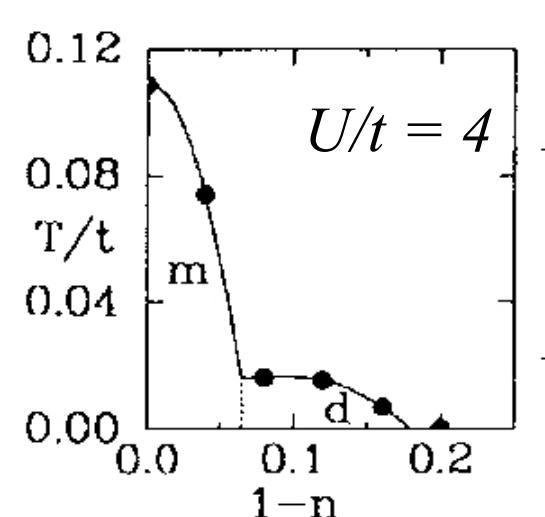


D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch
P.R. B **34**, 8190-8192 (1986).

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

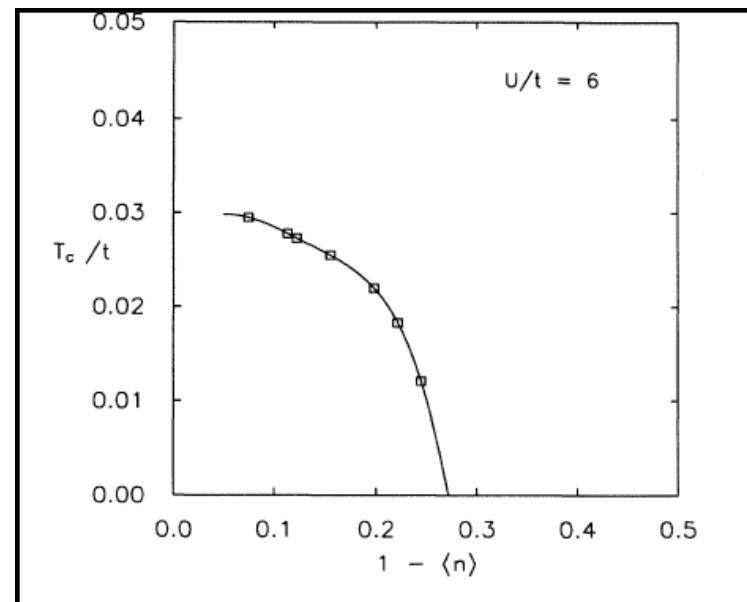
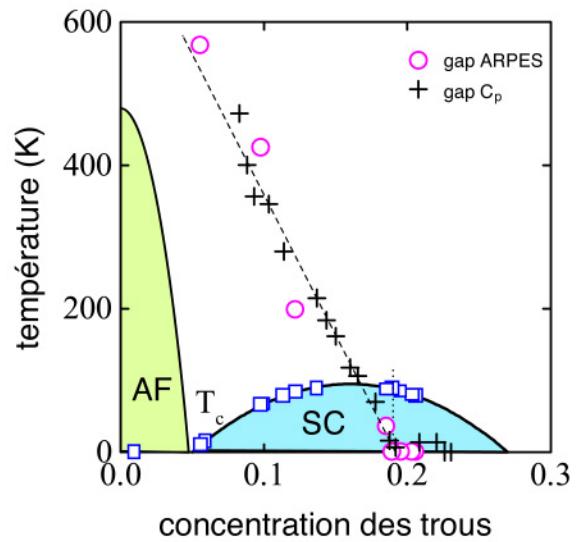
Miyake, Schmitt-Rink, and Varma
P.R. B **34**, 6554-6556 (1986)

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

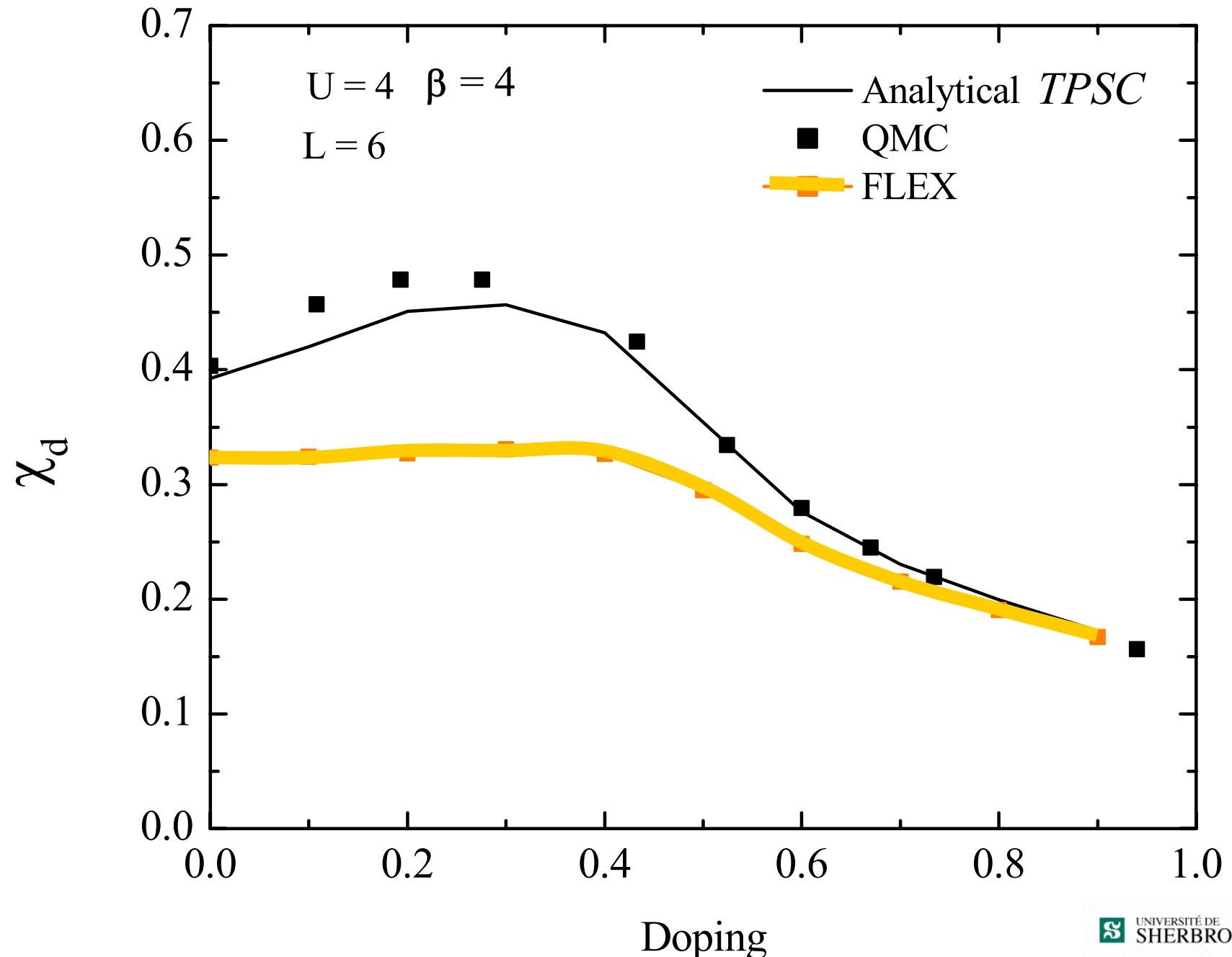


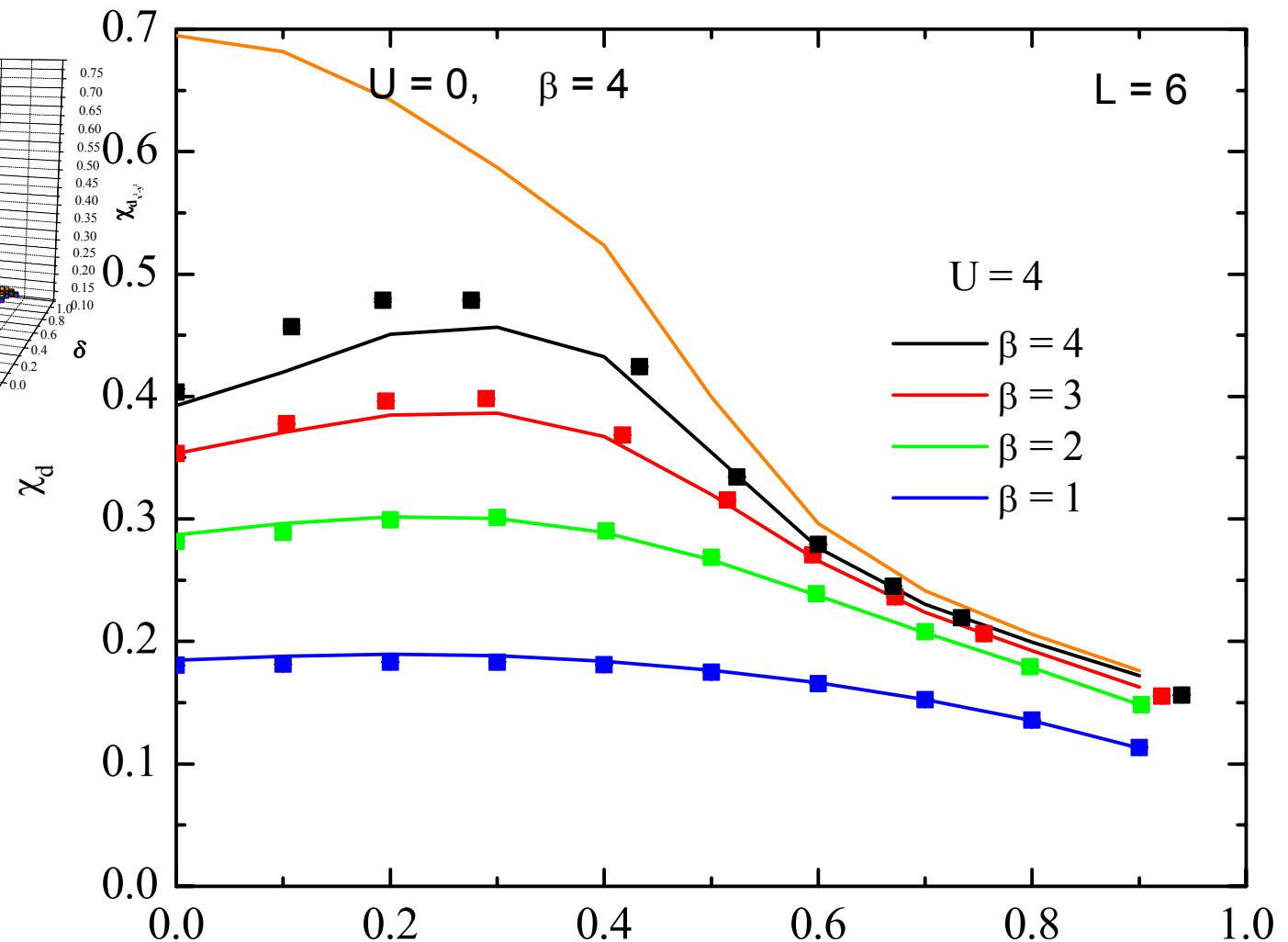
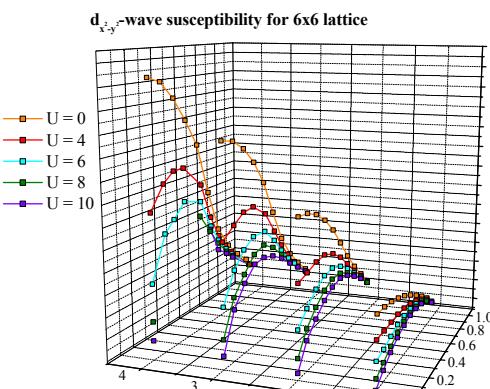
Bickers, Scalapino, White
P.R.L **62**, 961 (1989).

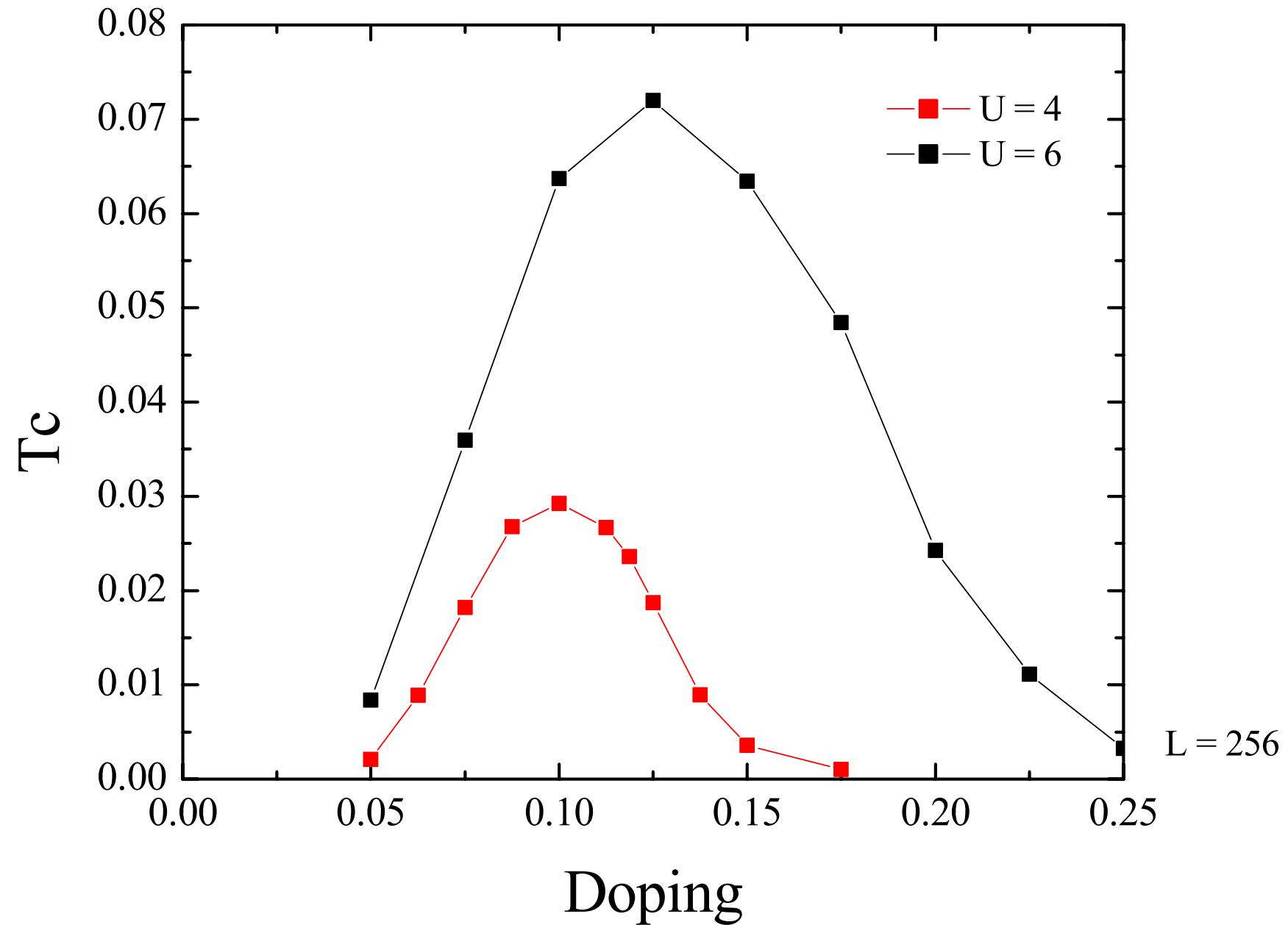
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Schmalian.



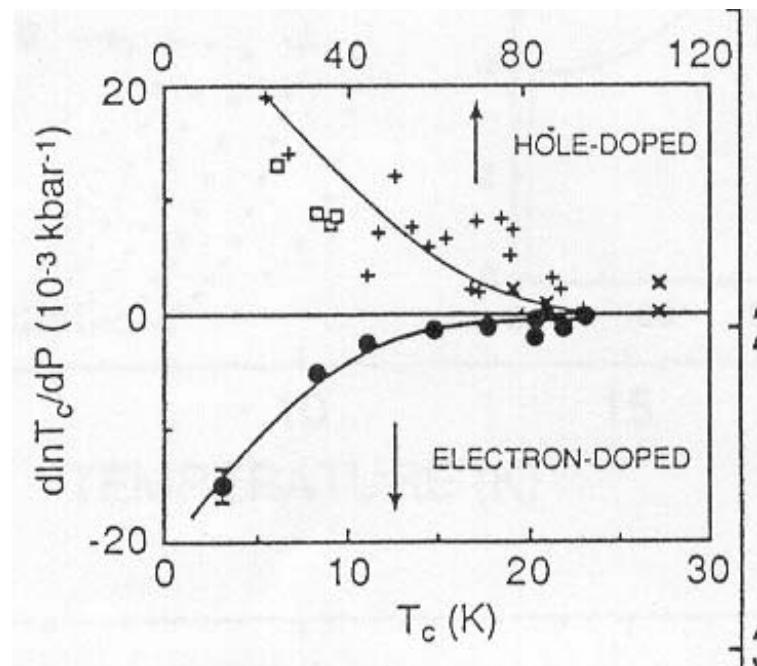
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Electron doped:



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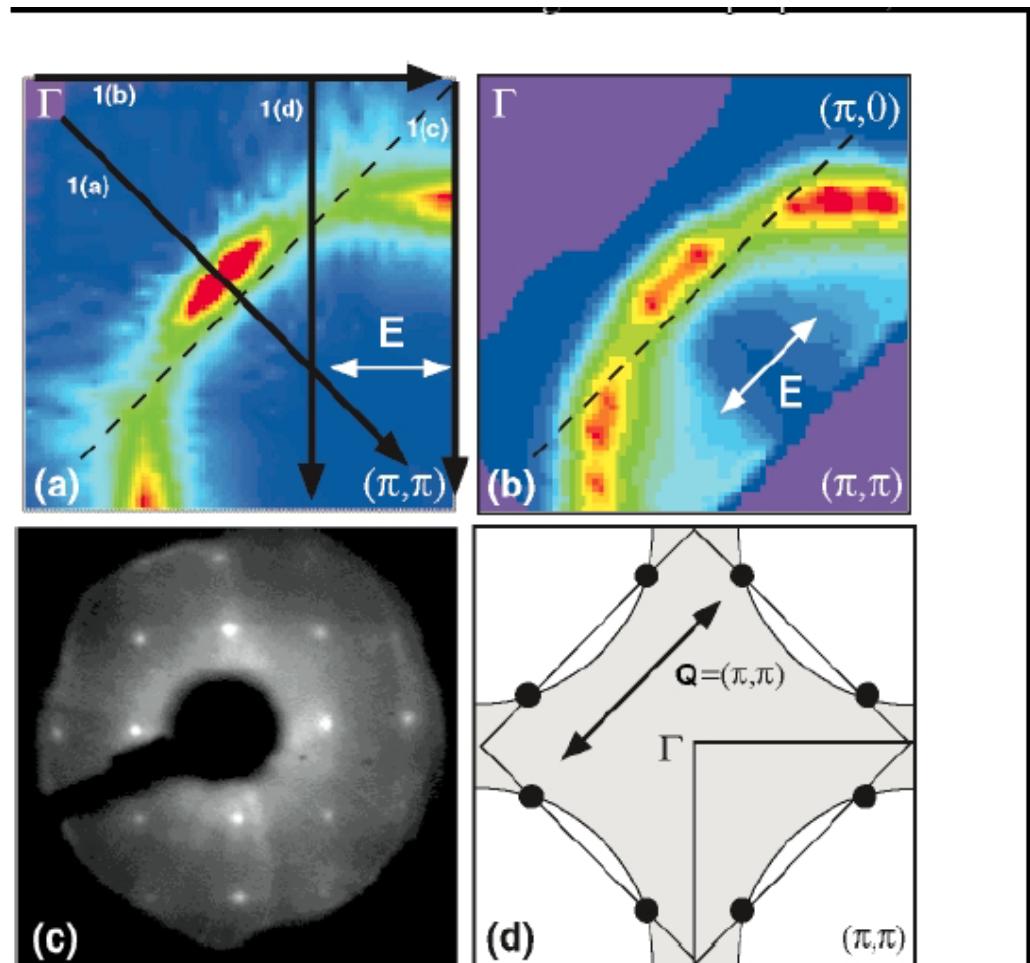
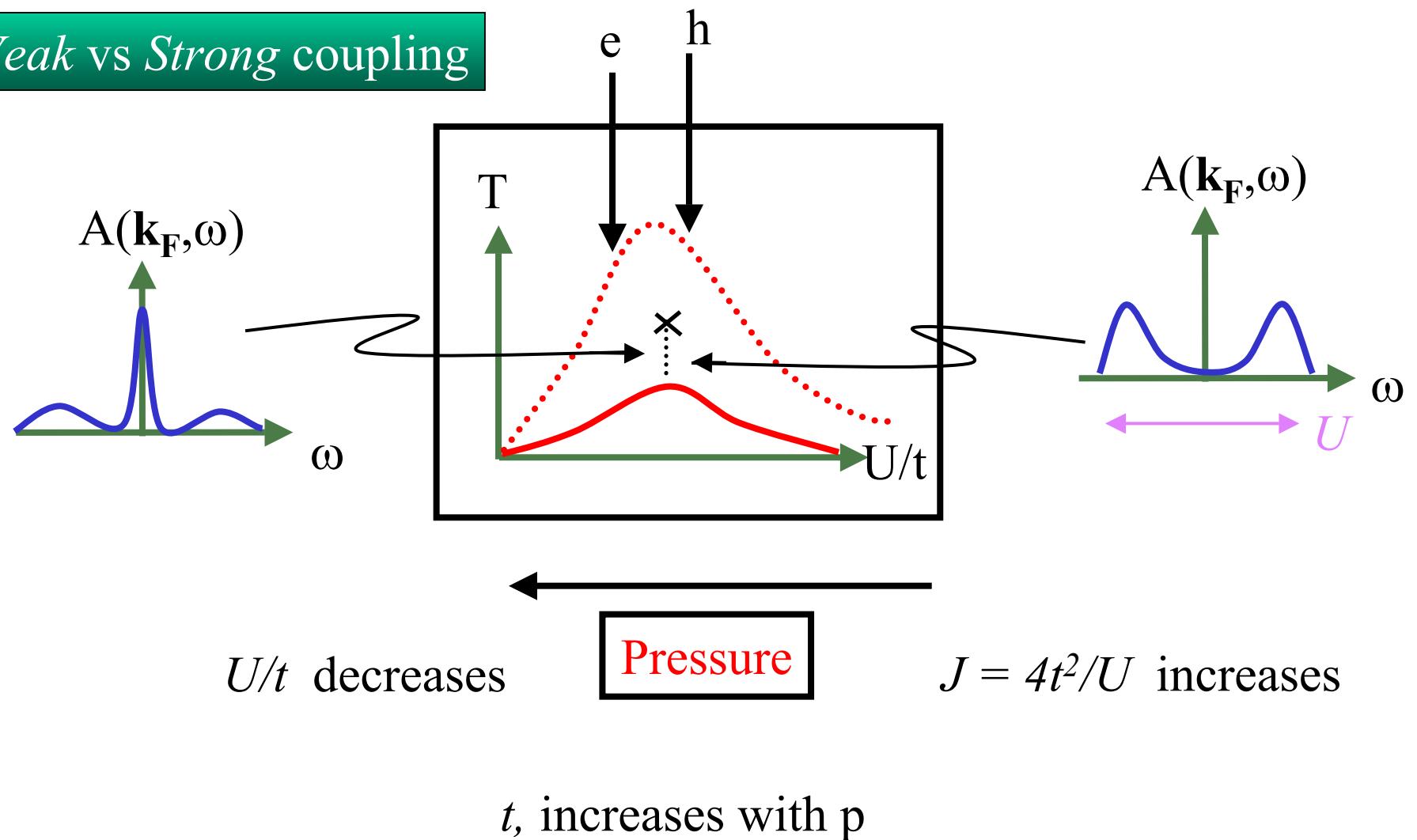


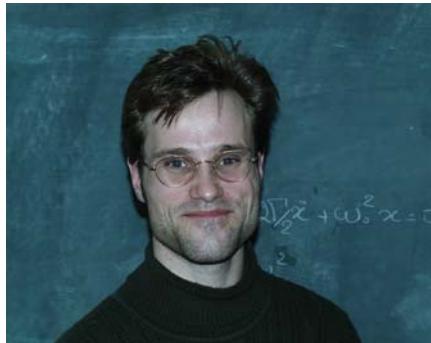
FIG. 2 (color). (a),(b) Fermi surface of the partial Brillouin zone of NCCO taken with $\hbar\omega = 16.5$ and 55 eV, respectively. The plotted quantity is a 30 meV integration about E_F of each EDC plotted as a function of \vec{k} . 16.5 eV data were taken over a Brillouin zone octant and symmetrized across the Γ to the (π, π) 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 (π, π) scattering.

Weak vs Strong coupling



VI- Conclusion

- Strong-coupling pseudogap
 - CPT (+ DCA + Phillips + ...) Mott gap sufficient but not necessary. Like Mott, short-range effect (but not zero range).
- Weak-coupling pseudogap
 - Electron-doped high T_c in this regime near optimal n .
 - Well explained by TPSC (Others need LRO)
 - Ratio ξ/ξ_{th} is important (precursor effect).
- Unified point of view (???) $\xi_{\text{th}} \rightarrow 1$ at strong coupling.
- AFM fluctuation exchange as source of d-wave superconductivity in electron-doped high-T_c. (Possibility of « complete » theory.)
 - Dome shape from AFM that can both help and hinder d-wave superconductivity.



Steve Allen

Liang Chen

Yury Vilk



François Lemay

Samuel Moukouri

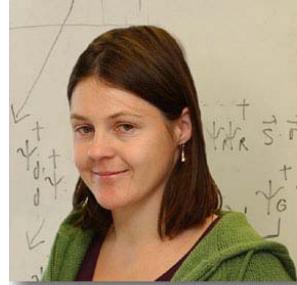


David Poulin



Hugo Touchette J.-S. Landry





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R. Côté



D. Sénéchal



Alexis Gagné-Lebrun

A-M.T. Alexandre Blais Vasyl Hankevych



Sébastien Roy

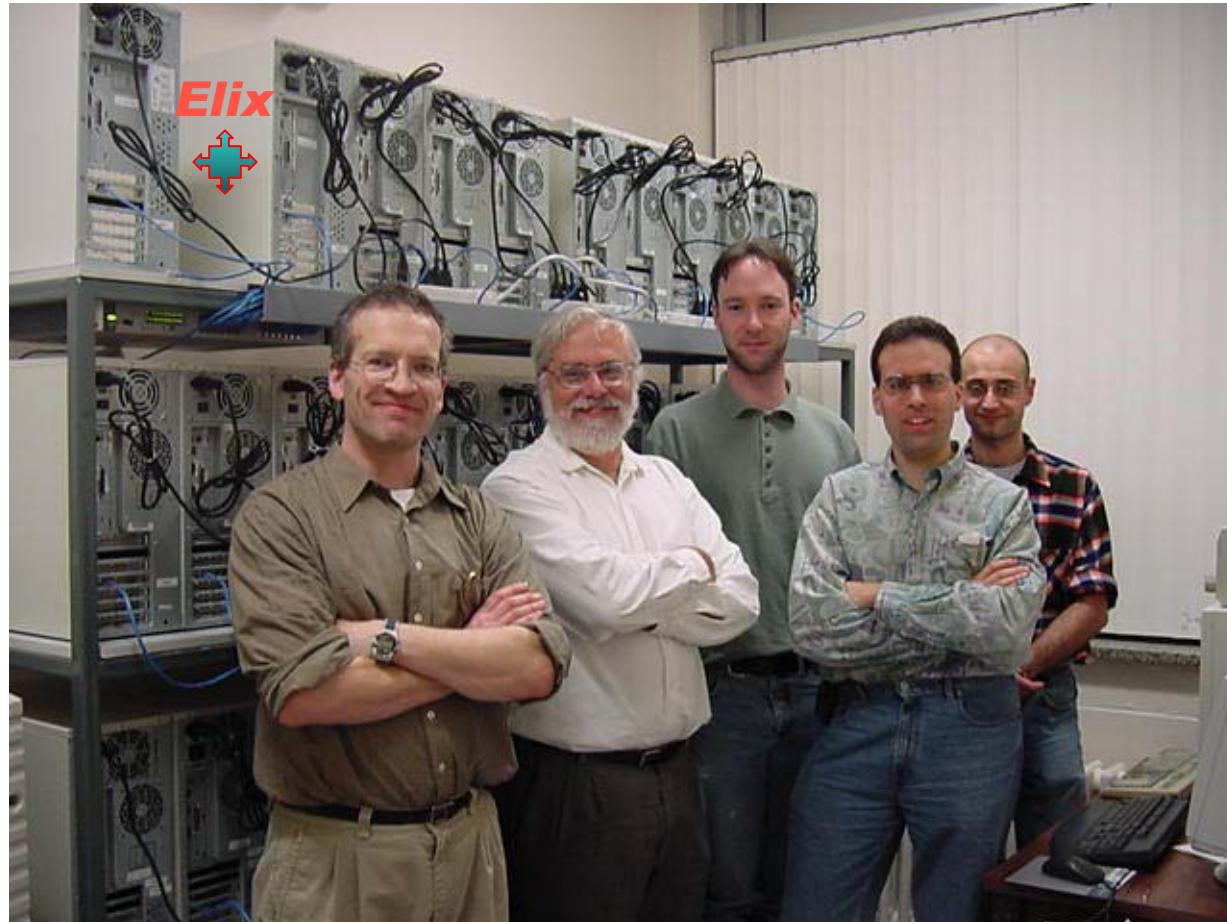
Sarma Kancharla

Bumsoo Kyung

Maxim Mar'enko

Michel Barrette

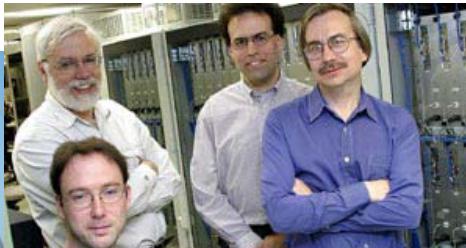
Mehdi Bozzo-Rey



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



Elix 2, april 2003



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

Elix2 vu de profil



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

C'est fini... .

enfin