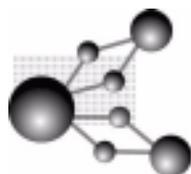


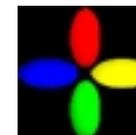
André-Marie Tremblay



CENTRE DE RECHERCHE SUR LES PROPRIÉTÉS
ÉLECTRONIQUES
DE MATÉRIAUX AVANCÉS



Sponsors:



Electronic correlations, fluctuations and pseudogap.

1. Motivation, model

2. The standard approach :

- what it is
- a qualitatively incorrect result
- limitations of the approach

3. A non-perturbative approach ($U > 0$ and $U < 0$)

- Proof that it works
- How it works

4. Results:

- Mechanism for pseudogap
- Spectral weight rearrangement

5. Conclusion.

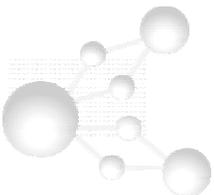


1. Motivation, model

Theory of solids

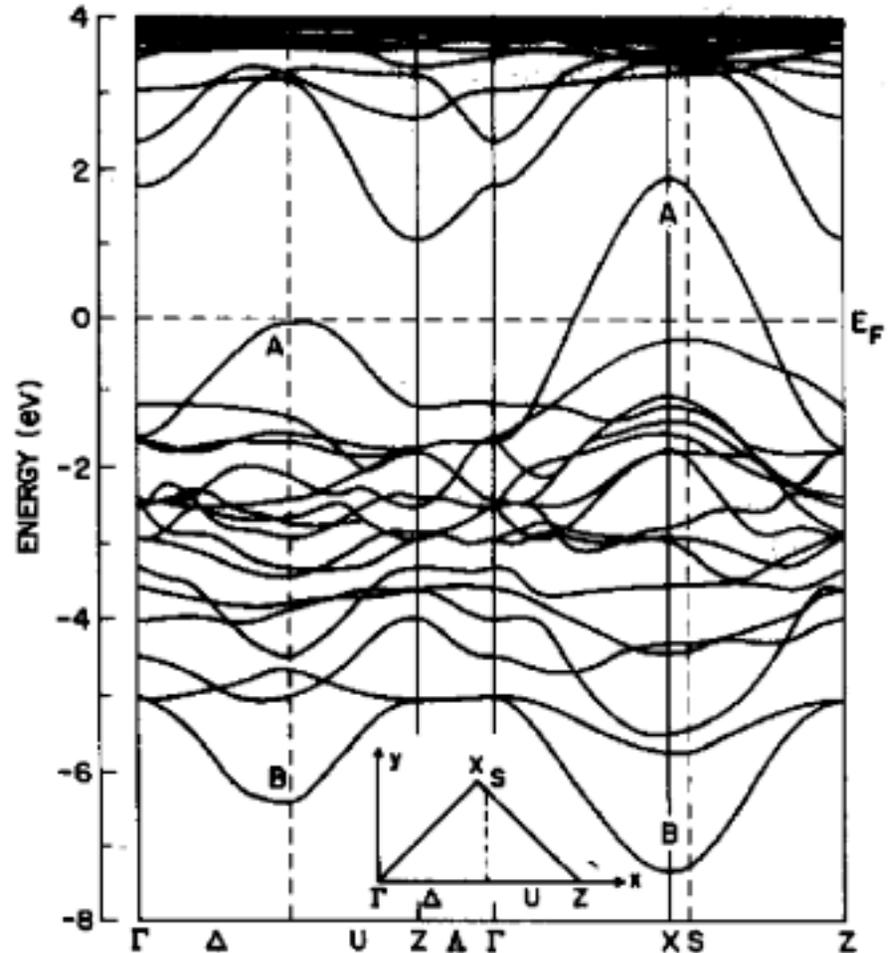
$$H = \text{Kinetic} + \text{Coulomb}$$

- Many new ideas and concepts needed for progress (Born-Oppenheimer, H-F, Bands...)
- Successful program
 - Semiconductors, metals *and superconductors*
 - Magnets
- Is there anything left to do?
 - Unexplained materials: High Tc, Organics...
 - Strong correlations:
strong interactions, low dimension



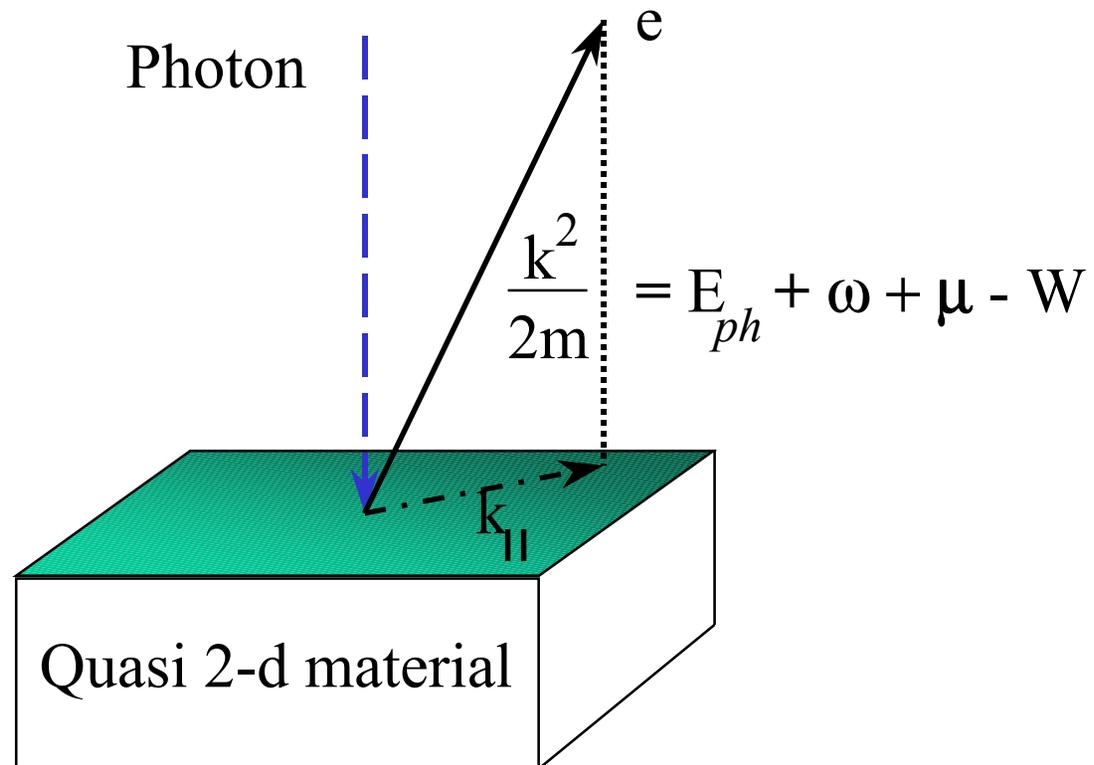
The standard approaches :

Quasiparticles, Fermi surface
and Fermi liquids
- LDA (Nobel prize 1998)



L.F. Mattheiss, Phys. Rev. Lett. 58, 1028 (1987).

Angle-Resolved Photoemission (ARPES)



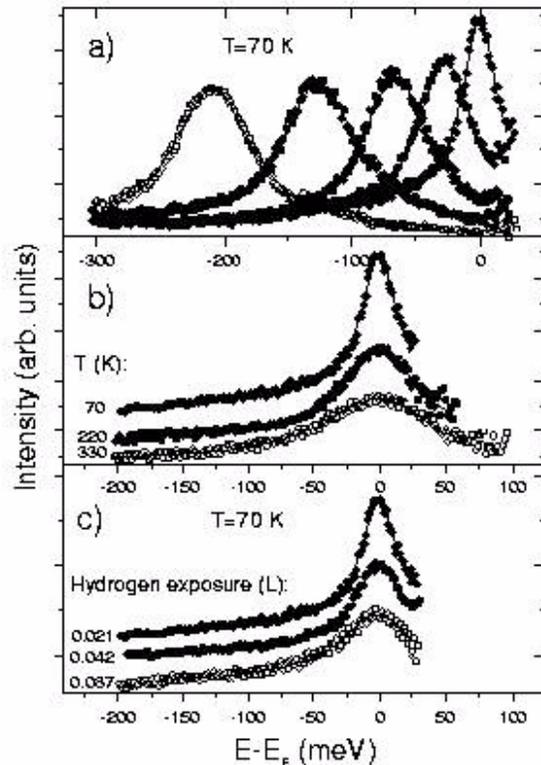


FIG. 2. Spectral intensity as a function of binding energy for constant emission angle, normalized to the experimentally determined Fermi cut-off. Data are symbols, while lines are fits to the Lorentzian peaks with a linear background. The dependence on the binding energy (a), temperature (b), and hydrogen exposure (c) is shown.

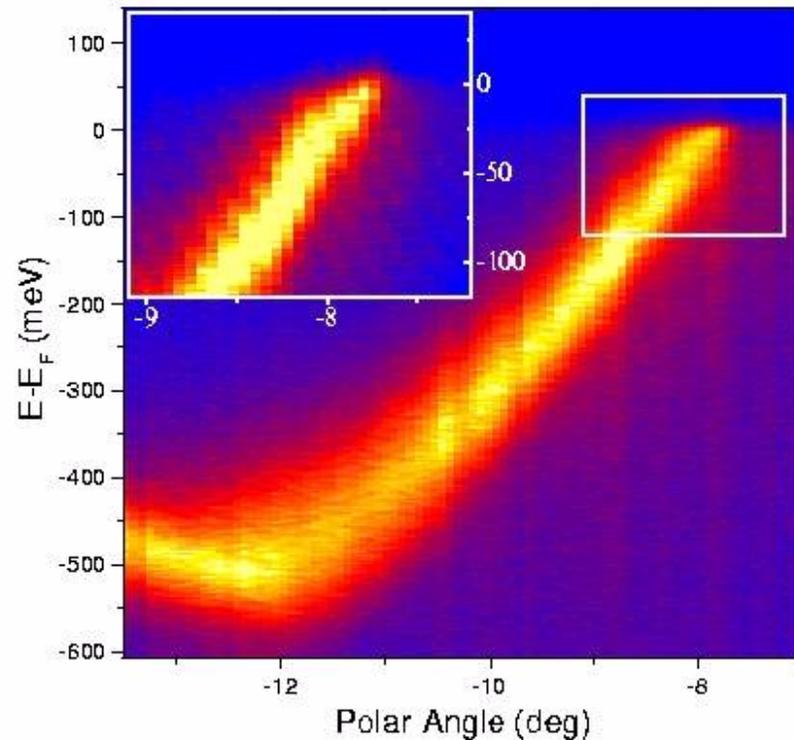


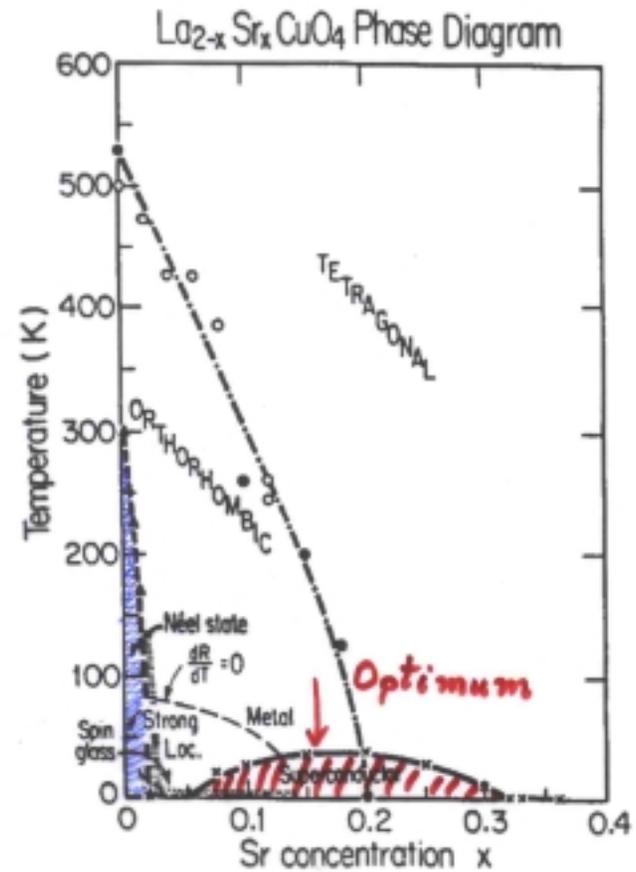
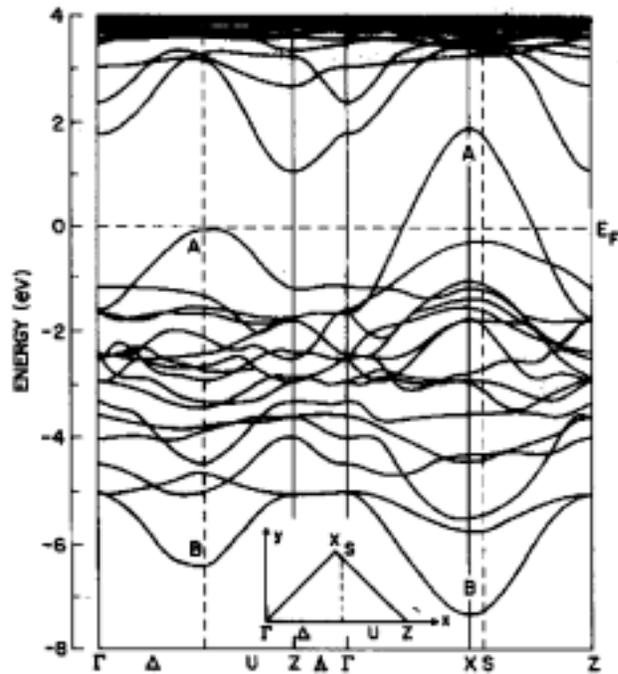
FIG. 1. ARPES intensity plot of the Mo(110) surface recorded along the $\bar{\Gamma} - \bar{N}$ line of the SBZ at 70 K. Shown in the inset is the spectrum of the region around k_F taken with special attention to the surface cleanliness.

T. Valla, A. V. Fedorov, P. D. Johnson, and S. L. Hulbert
P.R.L. **83**, 2085 (1999).



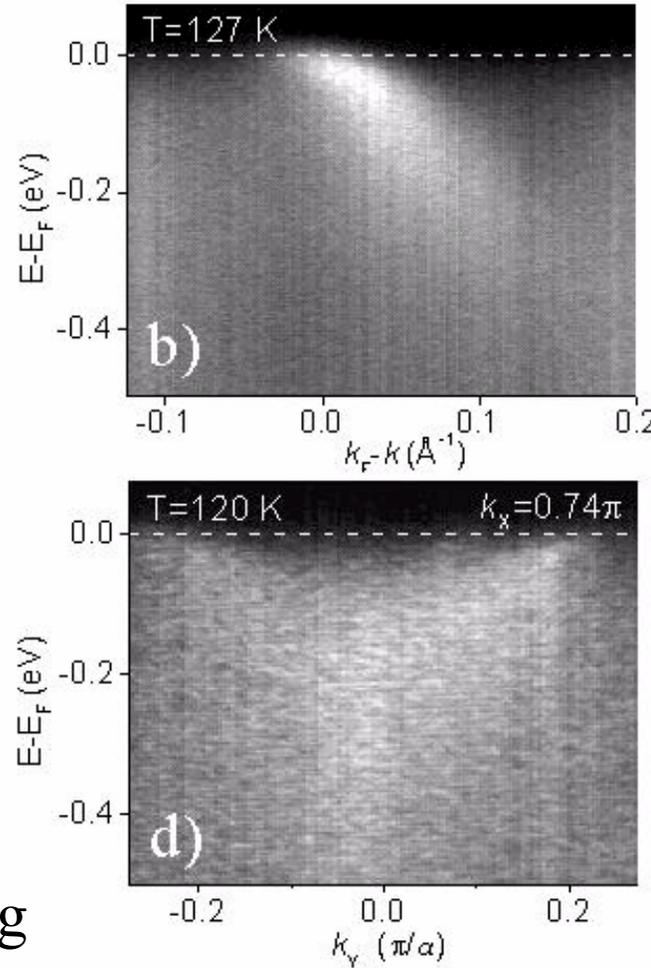
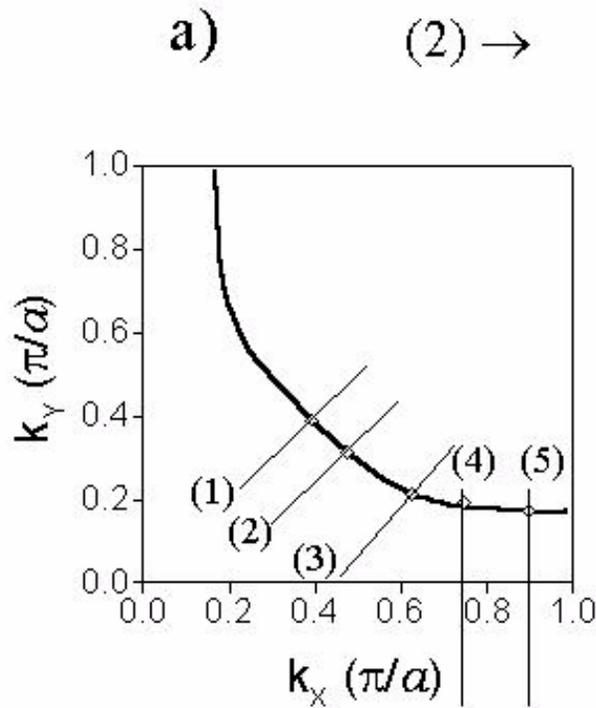
$$n = 1,$$

Metal according to band
AFM insulator in reality



BISCCO at optimal doping

Normal



Pseudogap

- $d=2$ partial disappearing
act of the Fermi surface,
doping away from $n = 1$

A. V. Fedorov, T. Valla, P. D. Johnson et al. P.R.L. **82**, 2179 (1999)

Microscopic model

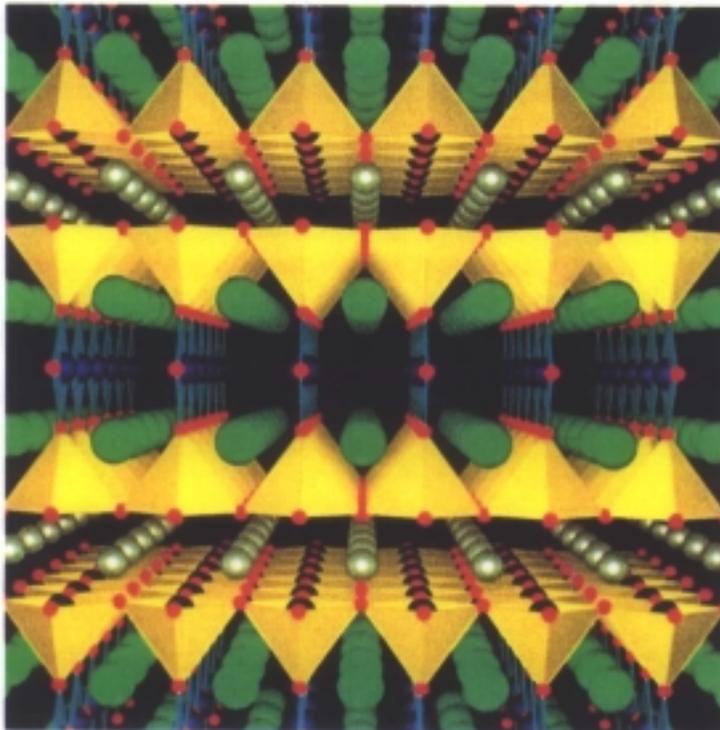
SCIENTIFIC AMERICAN

JUNE 1988
\$3.50

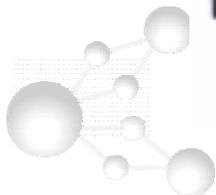
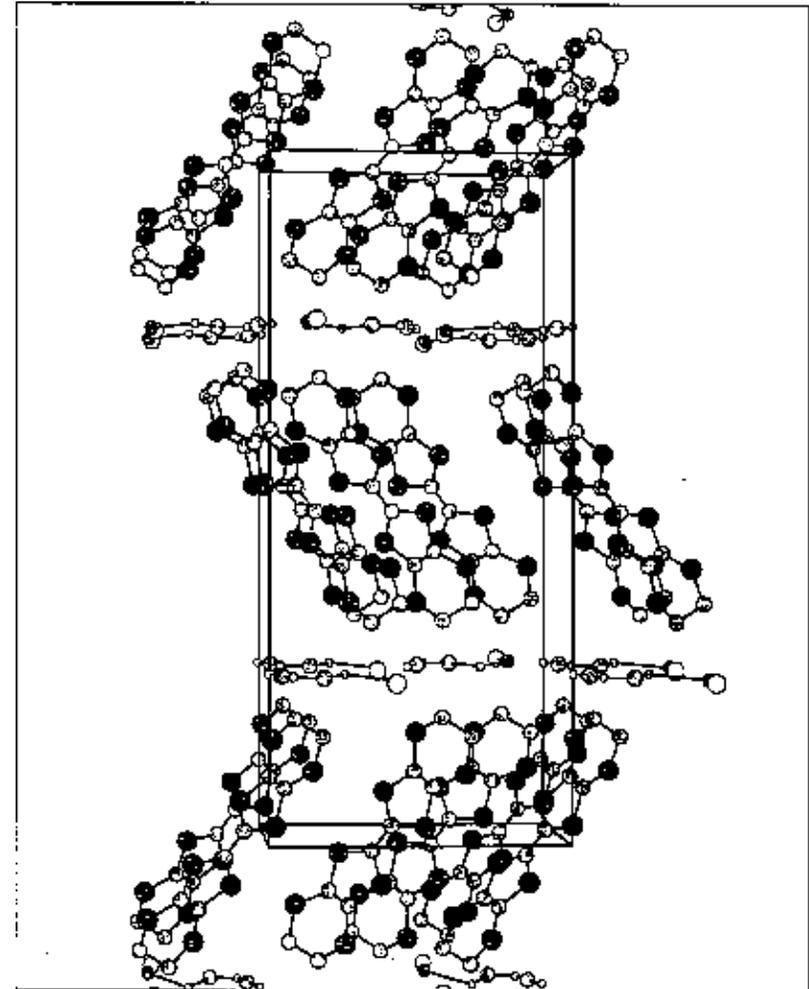
How nonsense is deleted from genetic messages.

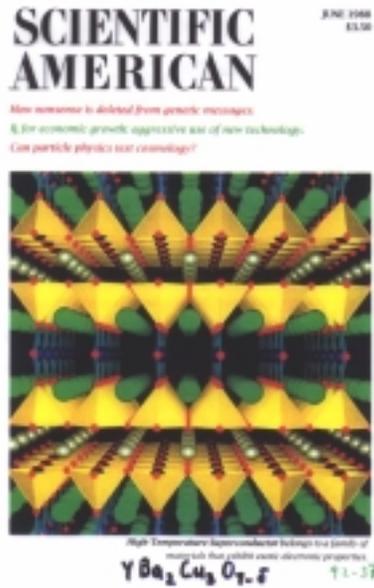
R&D for economic growth: aggressive use of new technology.

Can particle physics test cosmology?



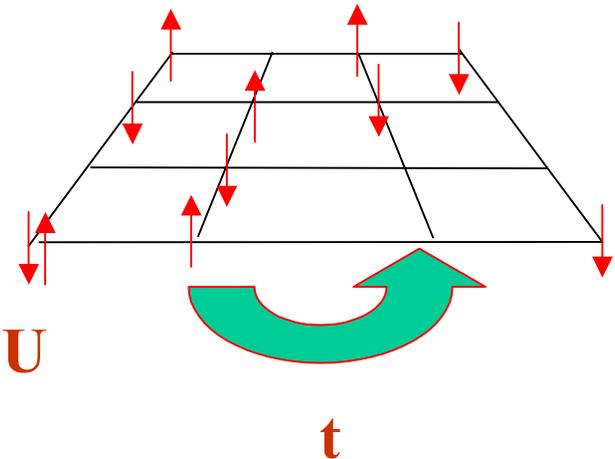
High-Temperature Superconductor belongs to a family of materials that exhibit exotic electronic properties.





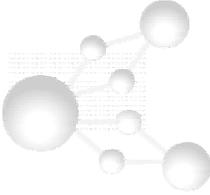
Simplest microscopic model for Cu O planes.

μ



• Size of Hilbert space : 4^N (N = 16)

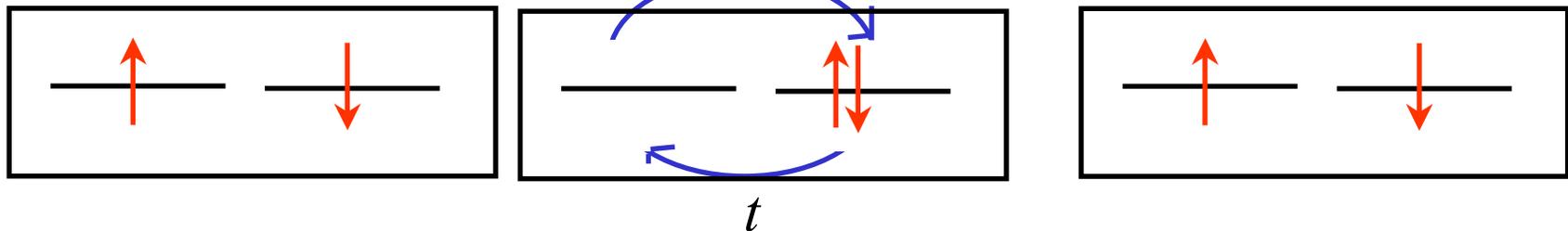
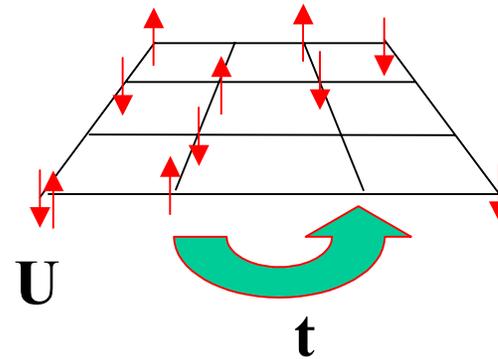
• Compute
$$\frac{\text{Tr}\left[Oe^{[-H/k_B T]}\right]}{\text{Tr}\left[e^{[-H/k_B T]}\right]}$$



Hubbard model (Kanamori, Gutzwiller, 1963) :

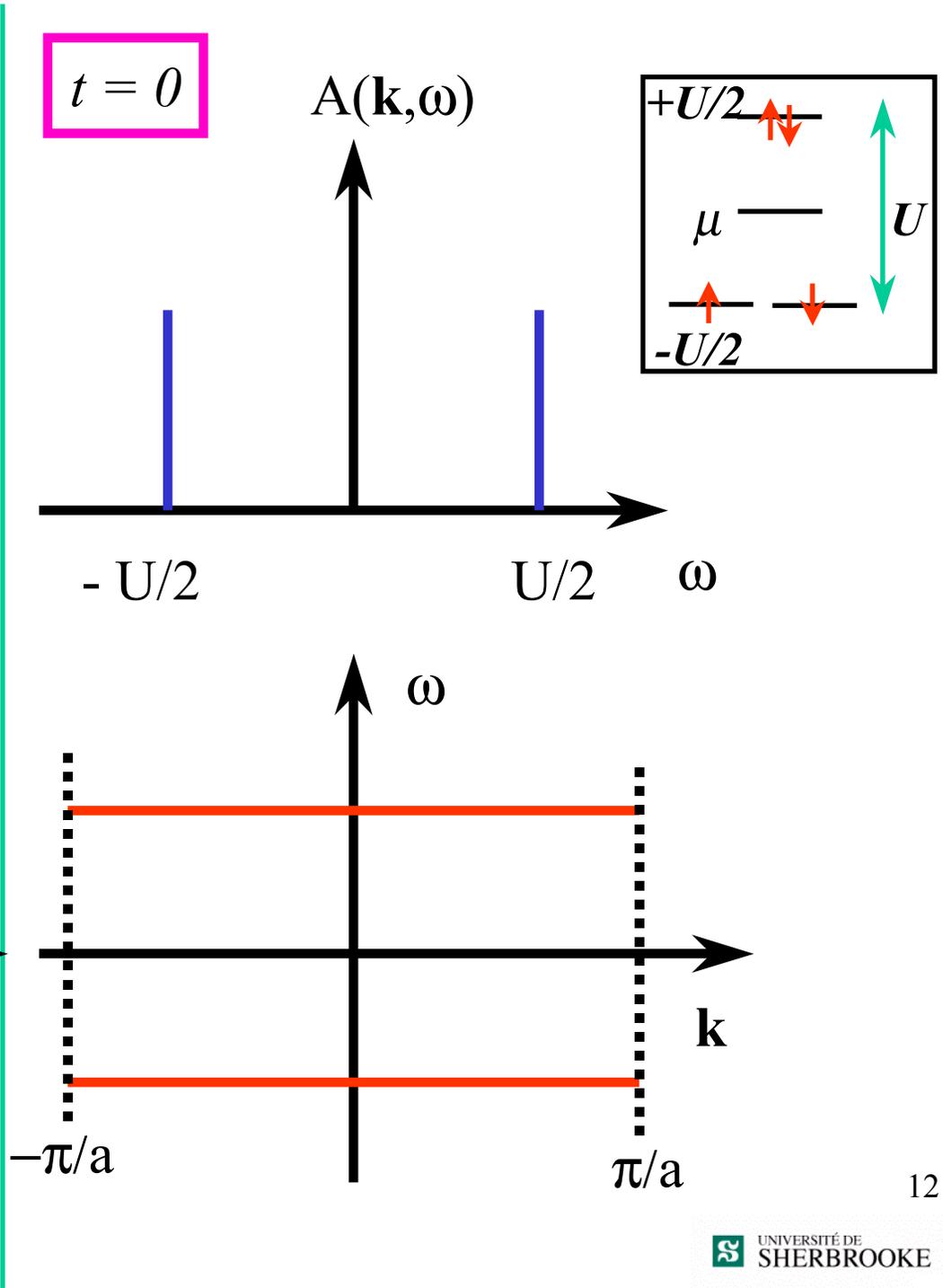
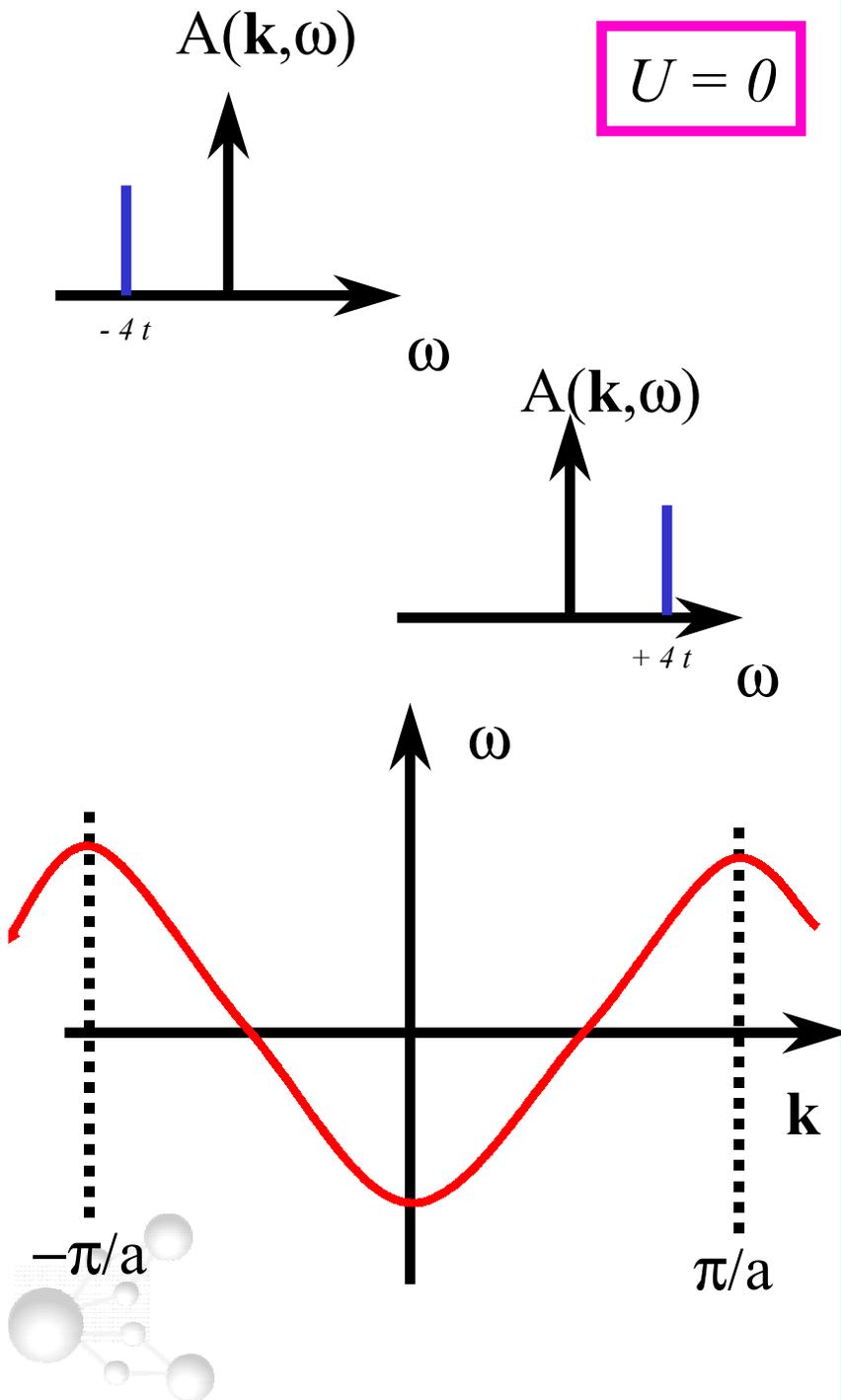
$$H = - \sum_{\langle ij \rangle \sigma} t_{i,j} (c_{i\sigma}^\dagger c_{j\sigma} + c_{j\sigma}^\dagger c_{i\sigma}) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

- Screened interaction U
- U, T, n
- $a = 1, t = 1, \hbar = 1$

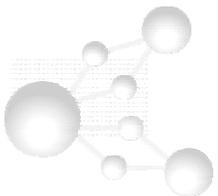
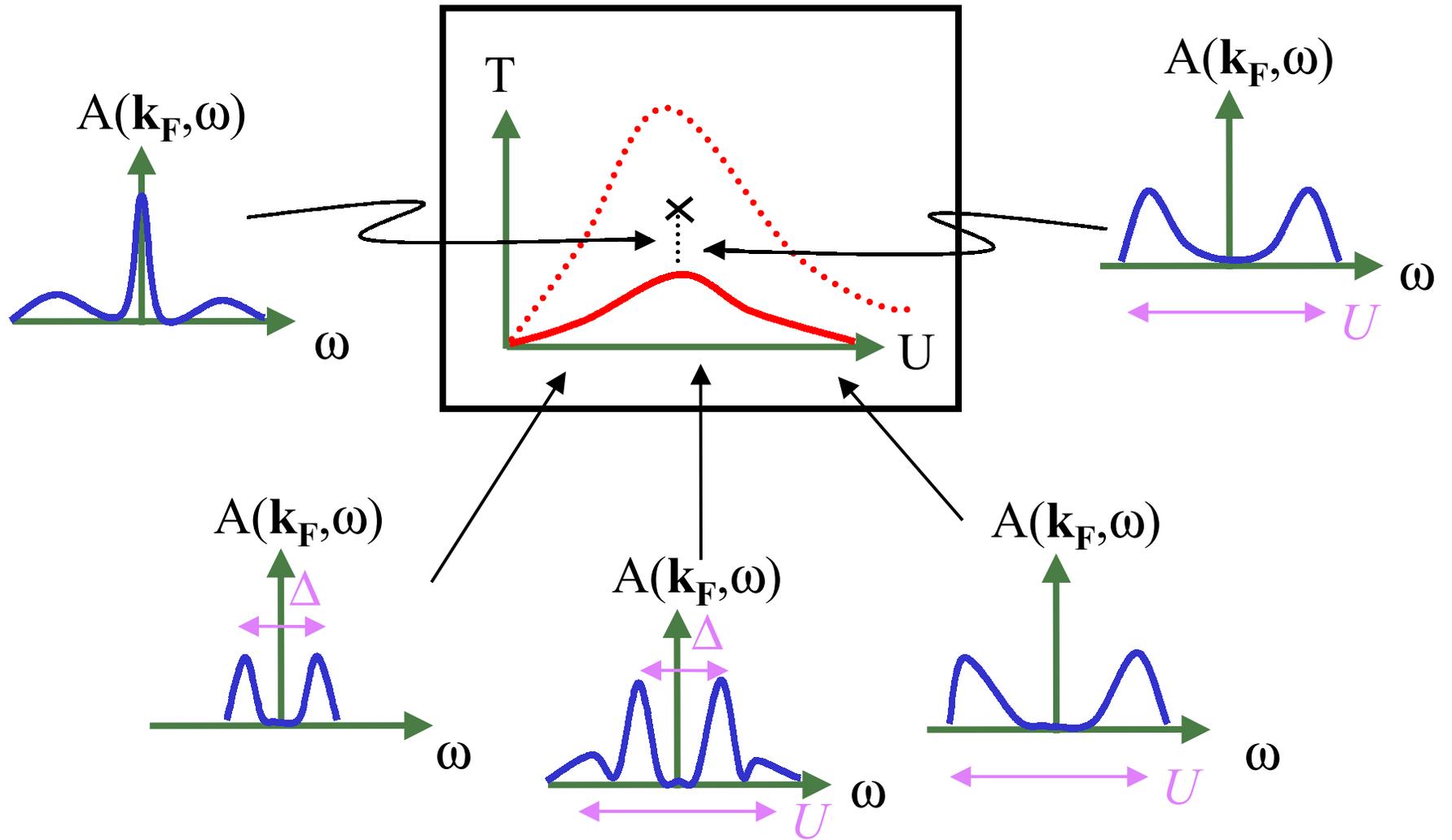


- 2001 vs 1963: Numerical solutions to check analytical approaches

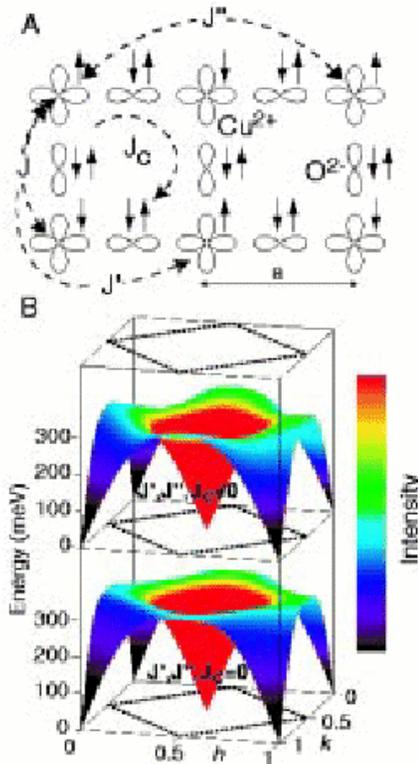




Weak vs strong coupling



High T_c are at « intermediate » coupling:
 $U = 8t, \quad t \sim 300 \text{ meV}$



$$n = 1$$

Low energy excitations, spin waves are detected by neutron scattering.

They are bidimensional.

← Experimental spin-wave dispersion

← Heisenberg, $H = J \sum \mathbf{S}_i \cdot \mathbf{S}_j$

FIG. 1. (color) **A** The CuO₂ plane showing the atomic orbitals (Cu 3d_{x²-y²} and O 2p_{x,y}) involved in the magnetic interactions. J , J' and J'' are the first-, second- and third-nearest-neighbor exchanges and J_c is the cyclic interaction which couples spins at the corners of a square plaquette. Arrows indicate the spins of the valence electrons involved in the exchange. **B** Lower surface is the dispersion relation for $J=136$ meV and no higher-order magnetic couplings or quantum corrections. The upper surface shows the effect of the higher-order magnetic interactions determined by the present experiment. Color is spin-wave intensity.

R. Coldea PRL **86**, 5377 (2001)



Pseudogap

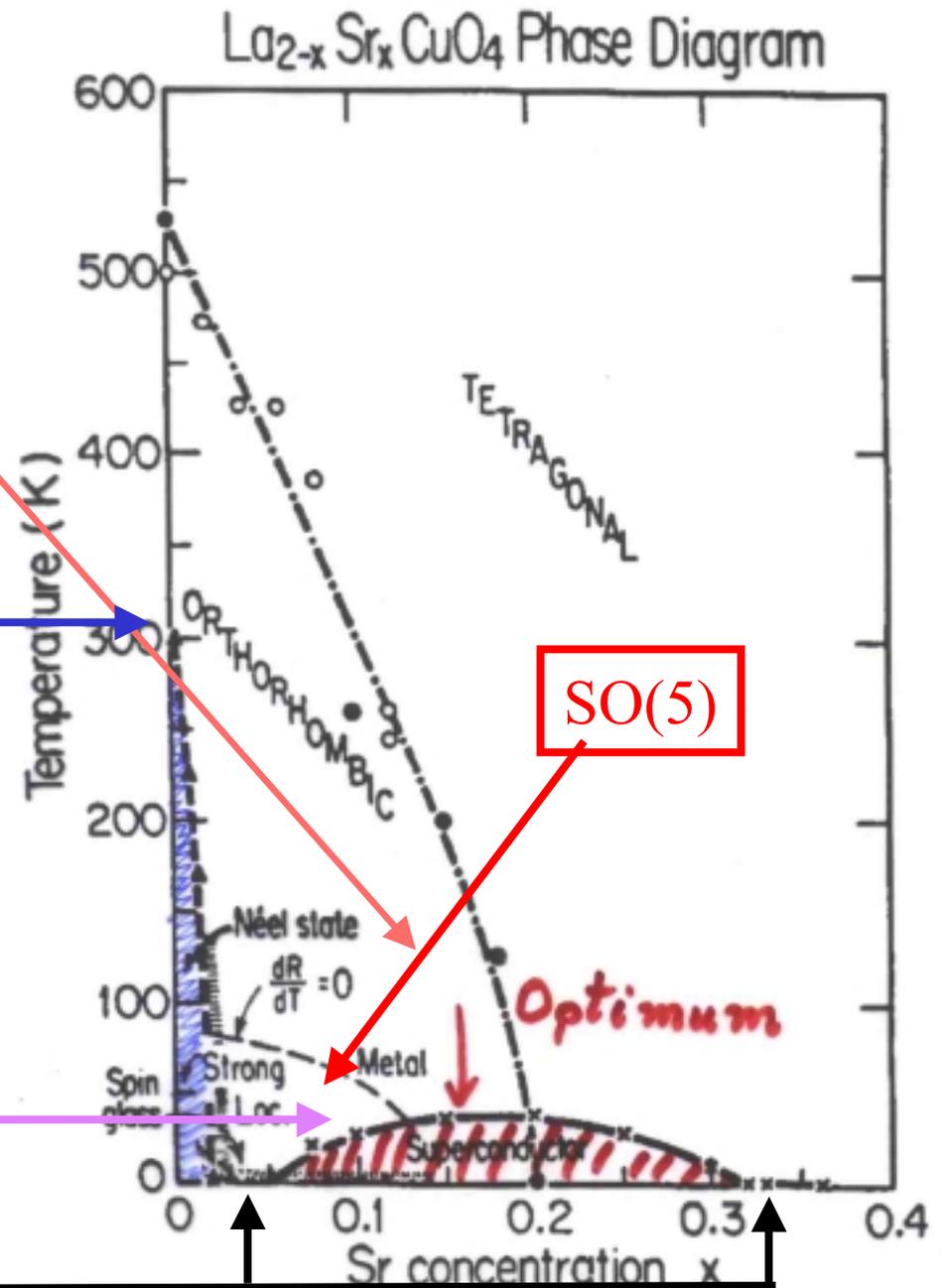
- New Ising character phase?
 - RVB
 - Preformed pairs
 - Flux phase
 - D Density Wave
- Fluctuations?
 - SC, AFM, singlet...

$d = 3$ Néel T

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

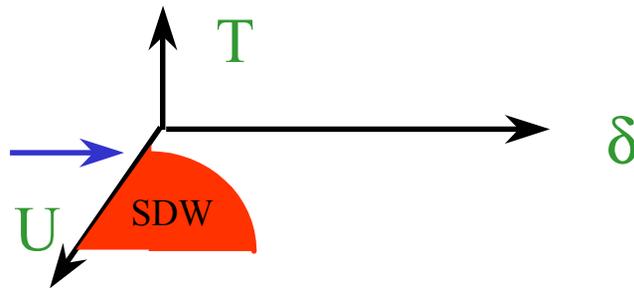


Quantum critical points

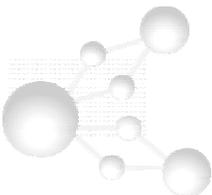


Motivation

- Here, $-W < U < W$ with ($W = \delta t$)
- Relevant for high T_c where $U > W$?
- A question of threshold (and continuity)



- Importance of quantitative predictions
 - Location of QCP
 - No ferromagnetism
- Effective $U < 0$ model may be not too strongly interacting
- Suppose we find new quasiparticles in strong coupling. How do we study residual interactions?
- Do we give up calculating Landau parameters?
 - How to predict when the theory is bad?
- Standard method gives qualitatively incorrect results



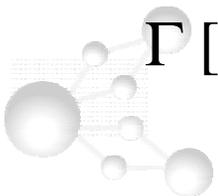
2. The standard approach :

- what it is (FLEX, self-consistent T-matrix ...)

$$\Phi [G] = \text{Diagram 1} + \frac{1}{2} \text{Diagram 2} + \dots$$

$$\Sigma [G] = \delta\Phi [G] / \delta G = \text{Diagram 3} + \text{Diagram 4} + \dots$$

$$\Gamma [G] = \delta\Sigma [G] / \delta G = \text{Diagram 5} + \dots$$



2. The standard approach :

- what it is (FLEX, self-consistent T-matrix ...)

- Thermodynamically consistent:

$$dF/d\mu = \text{Tr}[G]$$

- Satisfies Luttinger theorem

(Volume of Fermi surface at $T = 0$ preserved)

- Satisfies Ward identities (conservation laws):

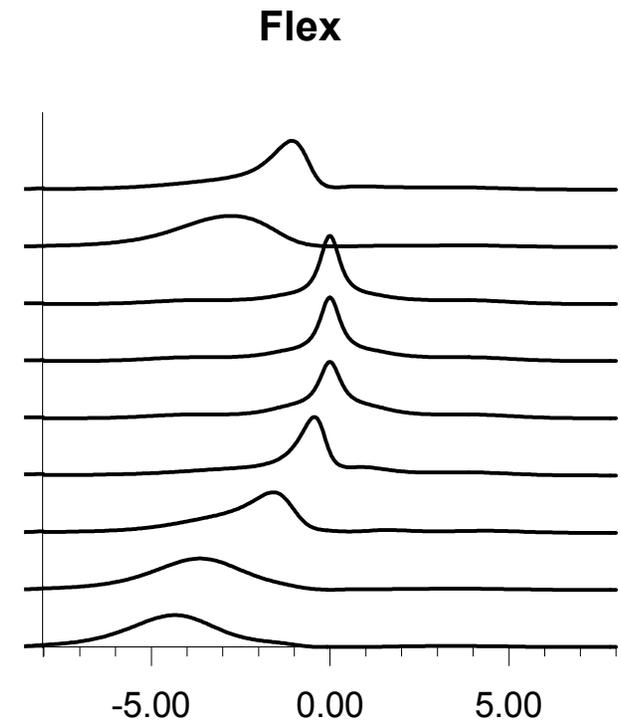
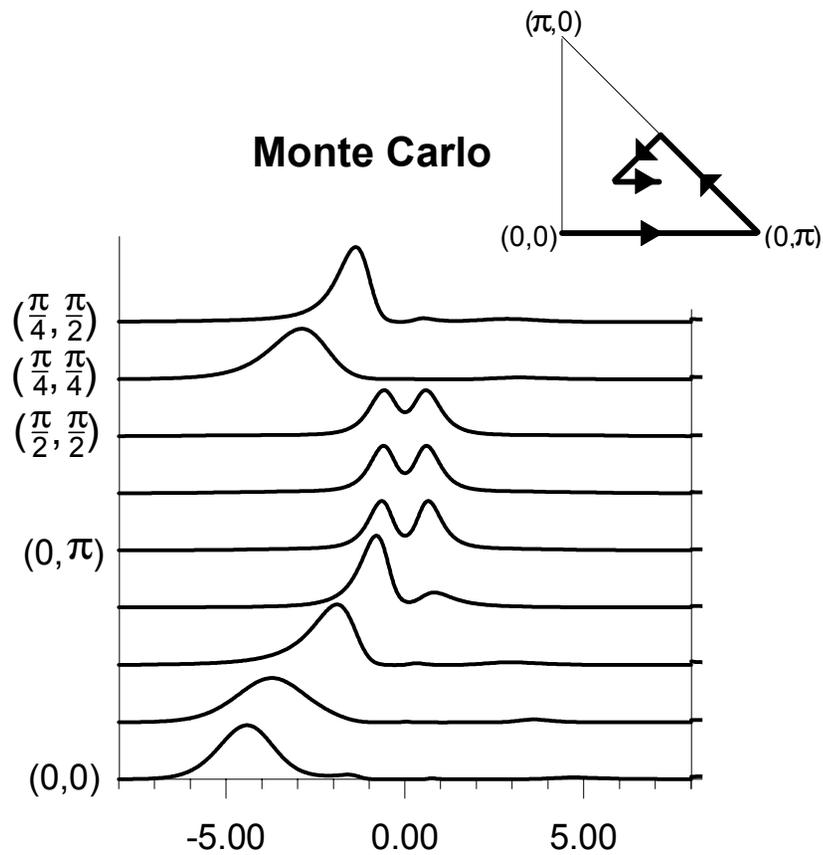
$G_2(1,1;2,3)$ appropriately related to $G(1,2)$



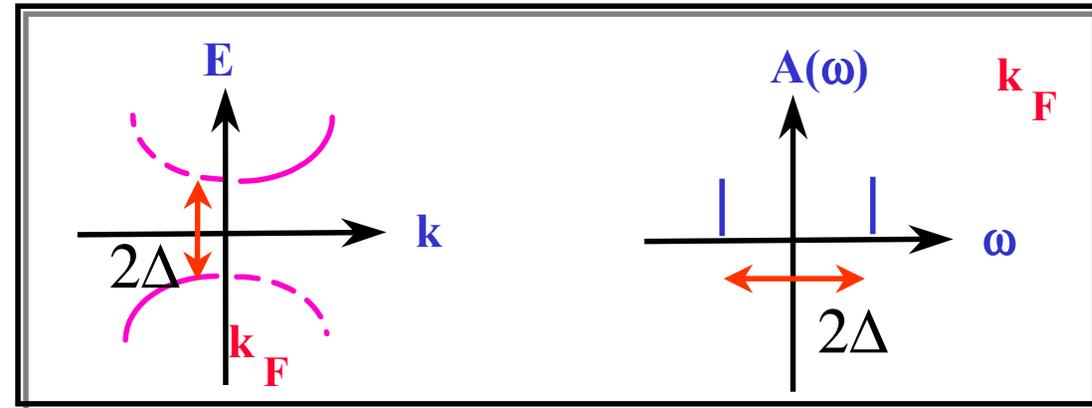
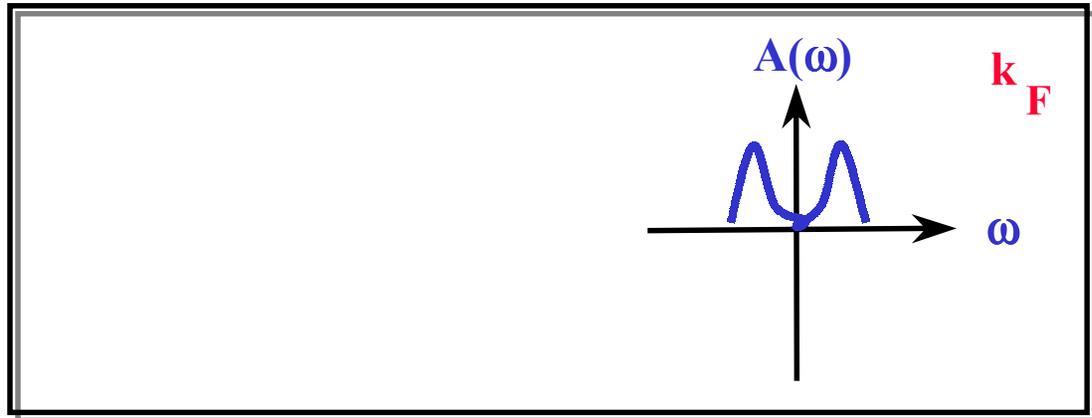
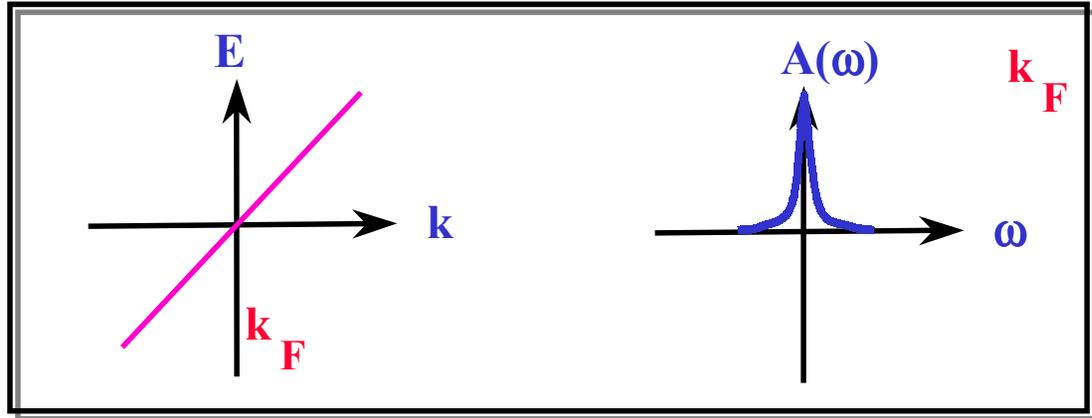
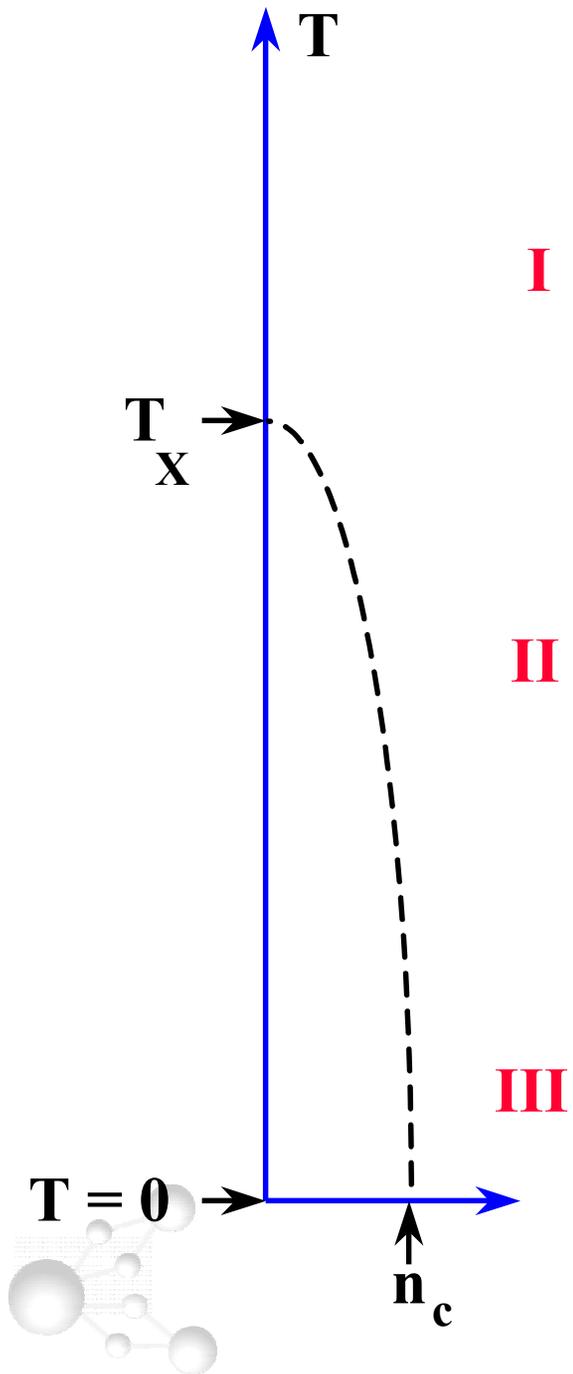
2. The standard approach :

- a qualitatively incorrect result

$U = +4$
 $T = 0.2$
 $n=1$
 8×8



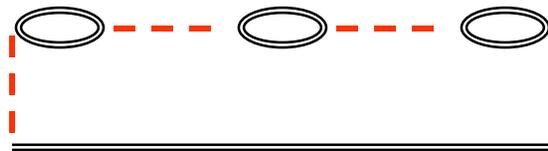
Calc. + QMC: Moukouri et al. P.R. B 61, 7887 (2000).



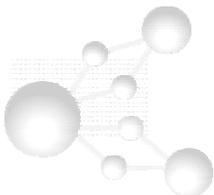
2. The standard approach :

- limitations of the approach

- Integration over coupling constant of potential energy does not give back the starting Free energy.
- The Pauli principle in its simplest form is not satisfied (It is used in defining the Hubbard model in the first place)
- There is an infinite number of conserving approximations (How do we pick up the diagrams?)
- Inconsistency:
Strongly frequency-dependent self-energy, constant vertex



No Migdal theorem, so
vertex corrections should be
included



Singular



$$\Sigma(\mathbf{k}_F, ik_n) \approx \frac{U T}{4 N} \sum_{\mathbf{q}} U_{sp} \chi_{sp}(\mathbf{q}, 0) \frac{1}{ik_n - \tilde{\epsilon}_{\mathbf{k}+\mathbf{q}} - \Sigma(\mathbf{k}_F + \mathbf{q}, ik_n)}$$

$$\Sigma(ik_n) = \frac{\Delta^2}{ik_n - \Sigma(ik_n)}$$

$$\text{Re}\Sigma^R(\omega) = \frac{\omega}{2} - \frac{\omega}{2|\omega|} \theta(|\omega| - 2\Delta) (\omega^2 - 4\Delta^2)^{1/2}$$

$$\text{Im}\Sigma^R(\omega) = -\frac{1}{2} \theta(2\Delta - |\omega|) (4\Delta^2 - \omega^2)^{1/2}$$

Non Fermi-liquid but not singular at $\omega = 0$

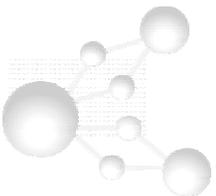
Vilk, et al. J. Phys. I France, 7, 1309 (1997).



2. The standard approach :

- problem...

- We do not know how to properly solve even the «standard model» for heavy fermions (Coleman).
- Lee-Rice-Anderson simpler approach seems qualitatively better, why?
- GW approach to improve band structure calculations?



3. An approach for both $U > 0$ and $U < 0$

- Proofs that it works

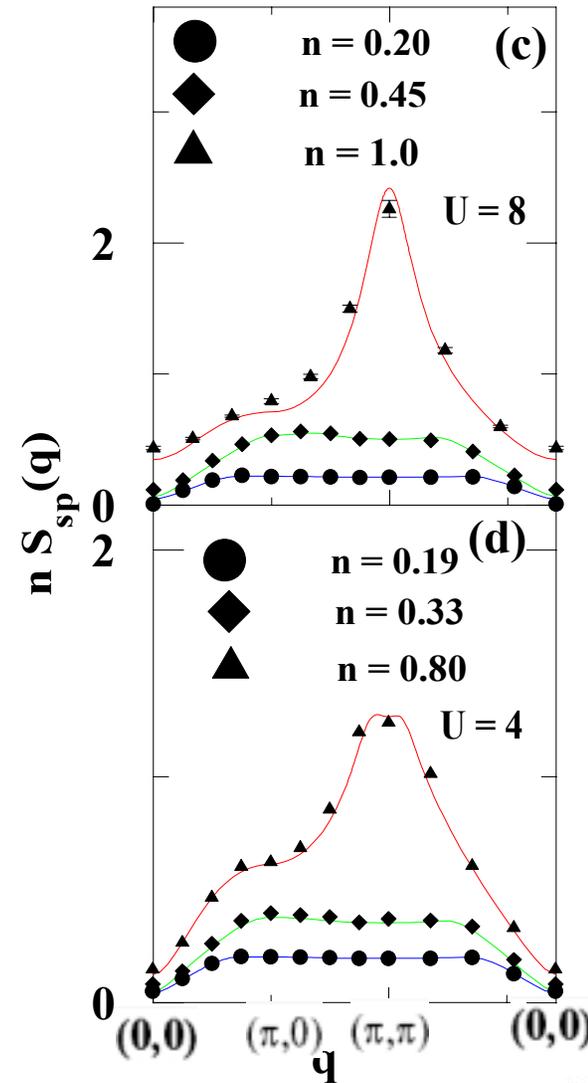
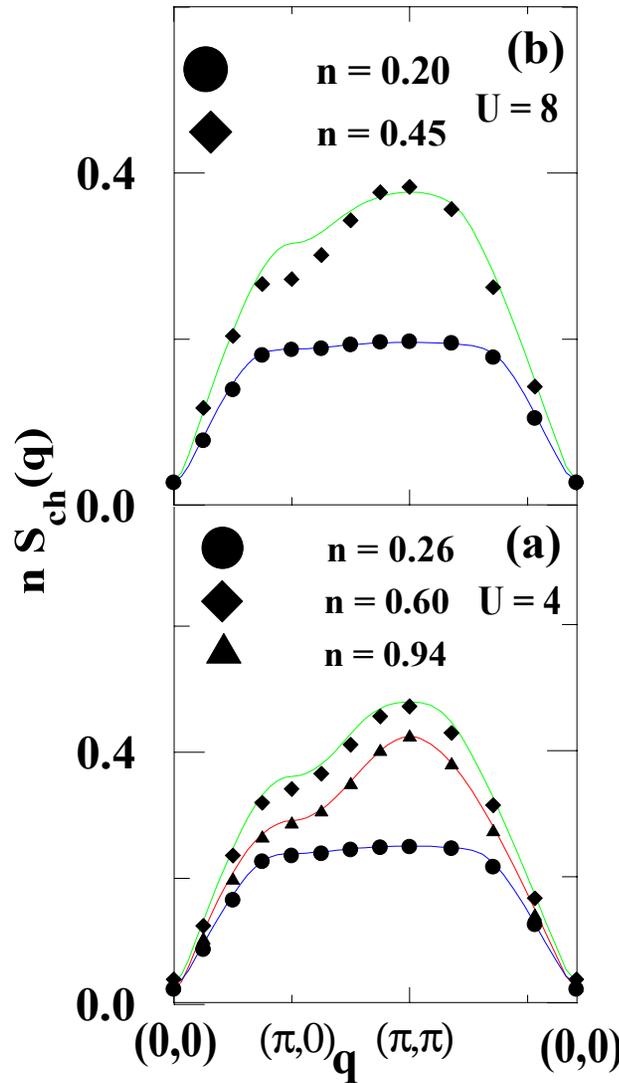
Notes:

-F.L.

parameters

-Self also

Fermi-liquid

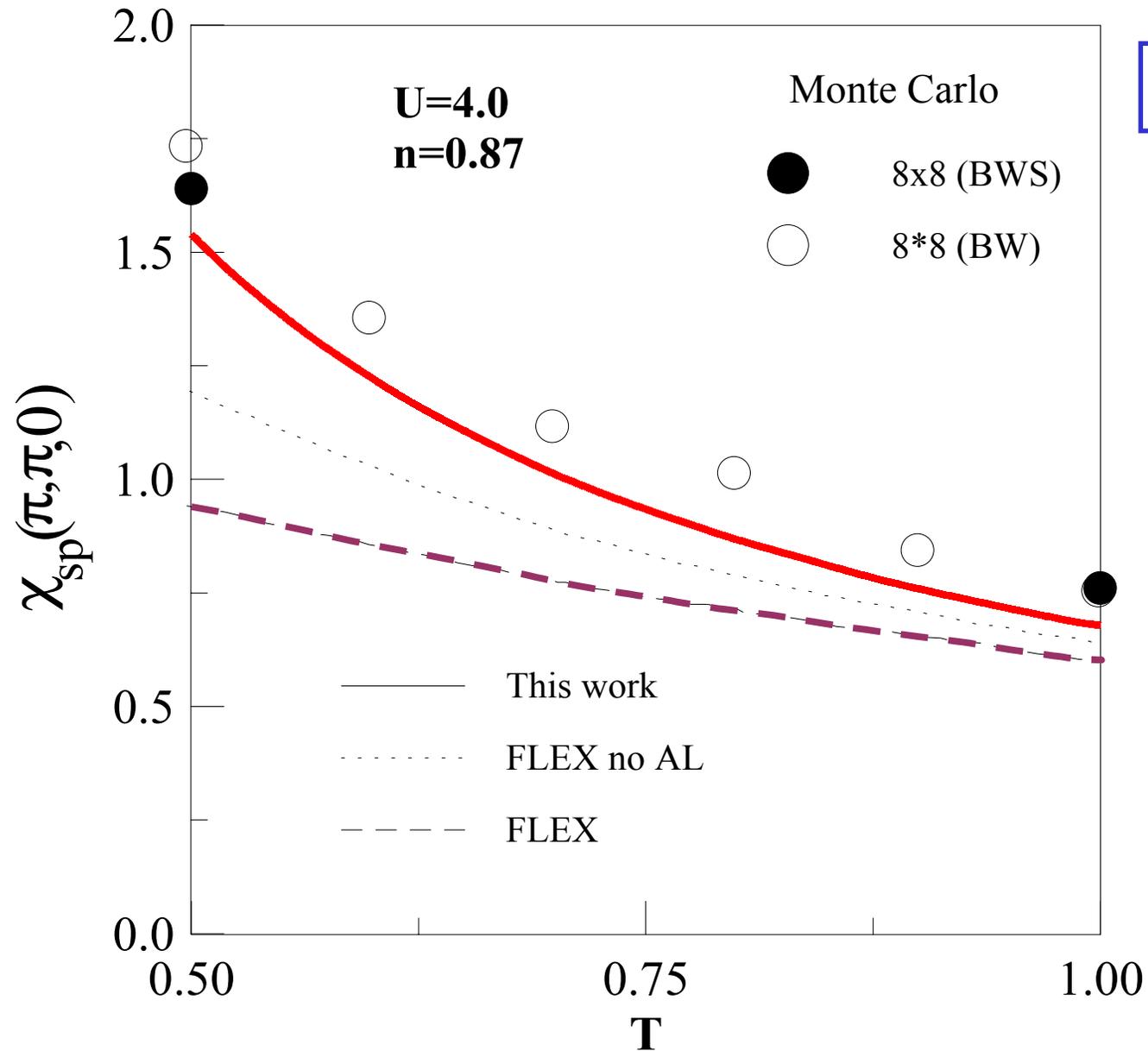


$U > 0$



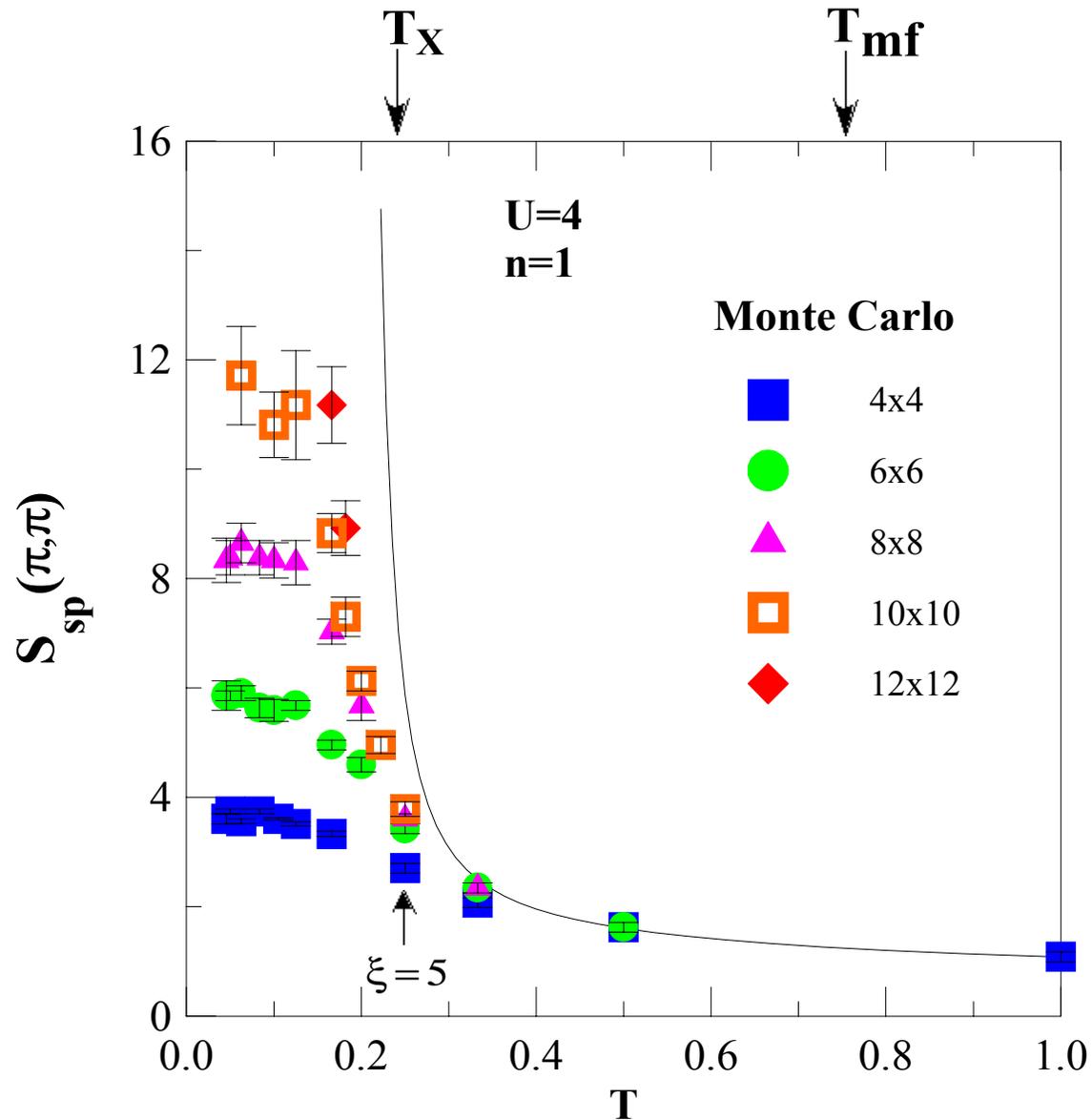
QMC + cal.: Vilks et al. P.R. B **49**, 13267 (1994)

Proofs...



Calc.: Vilk, et al. J. Phys. I France, 7, 1309 (1997).

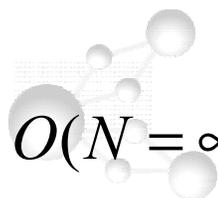
QMC: Bulut, Scalapino, White, P.R. B 50, 9623 (1994).



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

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

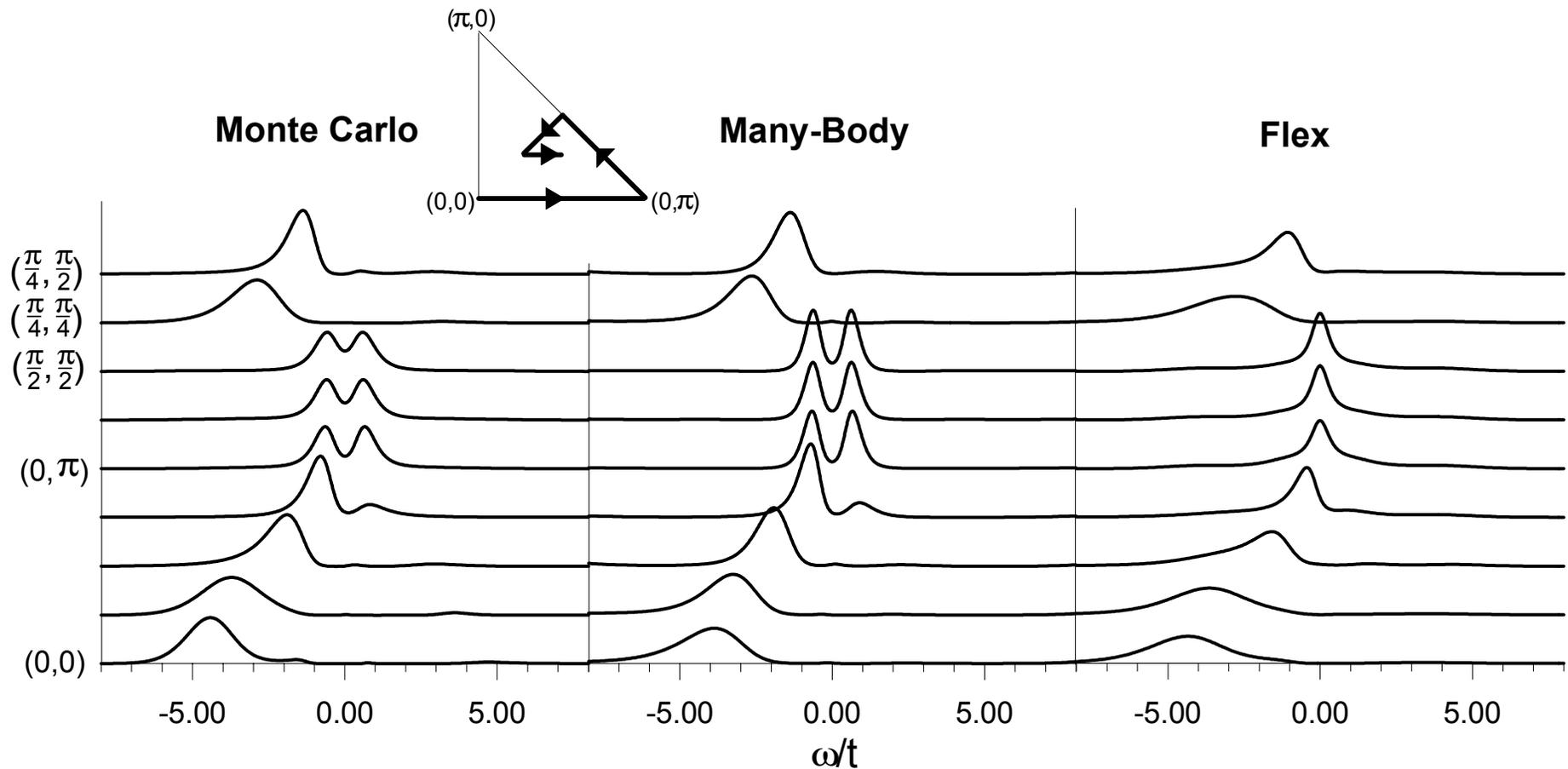
QMC: S. R. White, et al. Phys. Rev. **40**, 506 (1989).



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

Proofs...

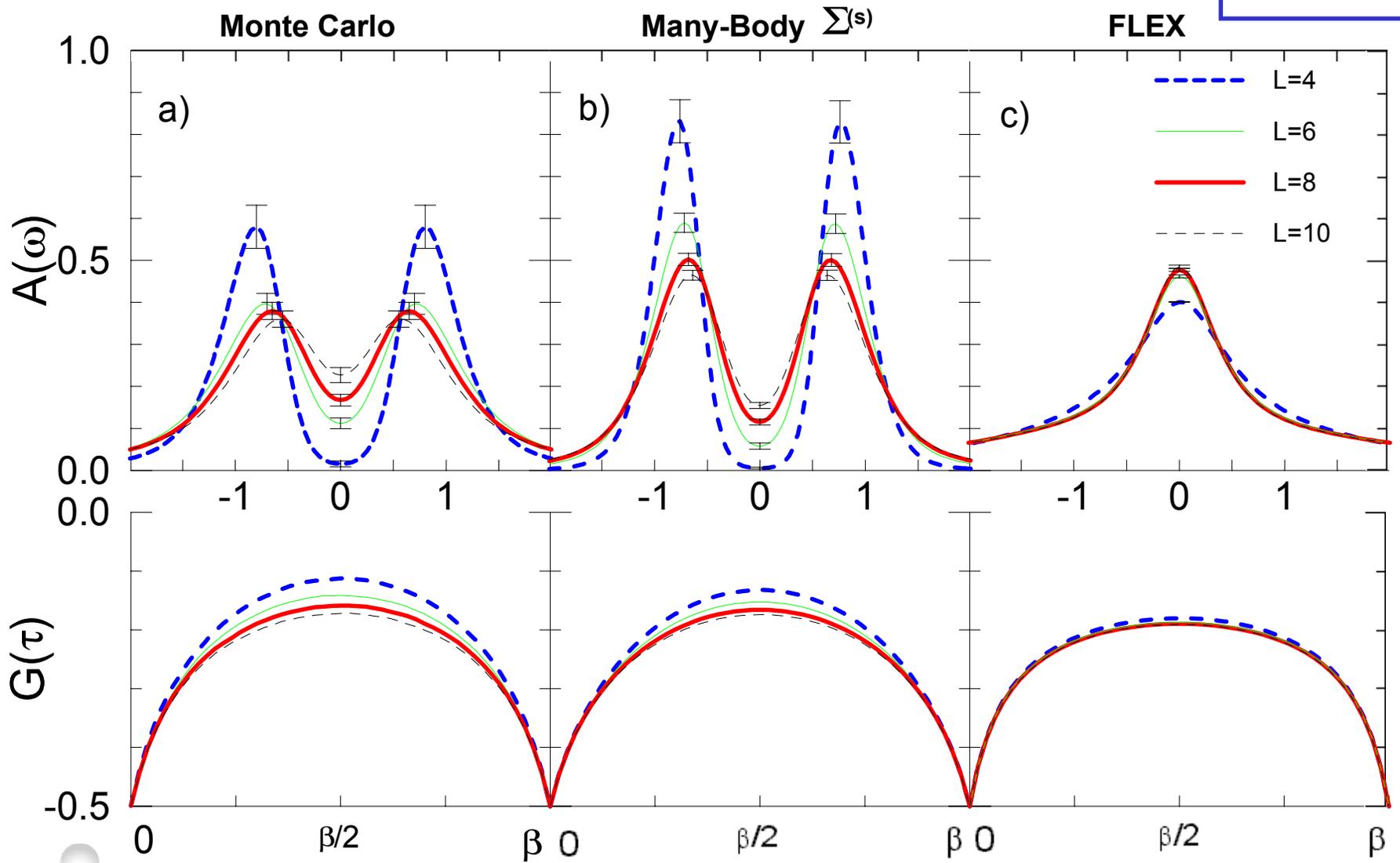
$$U = +4$$



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

Proofs...

$$U = +4$$



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

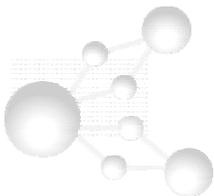
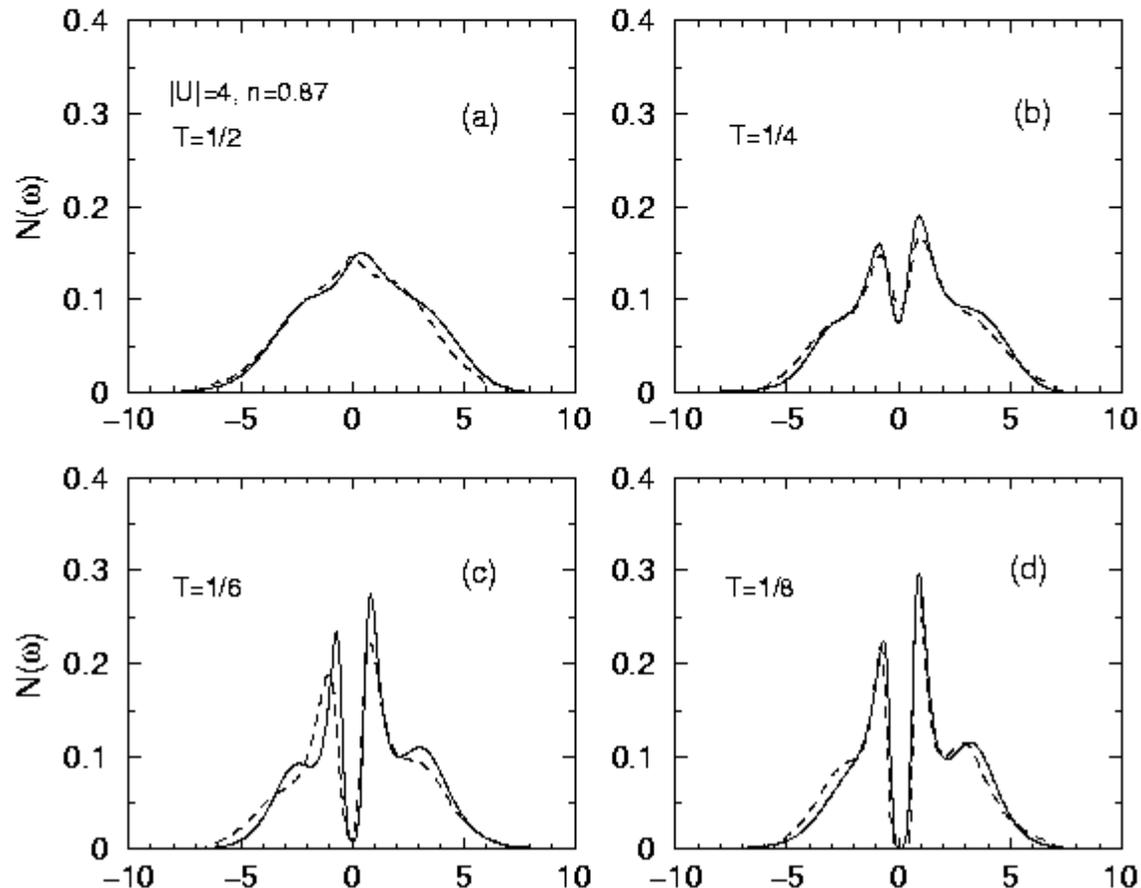
Moving to the attractive case....

$$U = -4$$

Calc. : Kyung et al. cond-mat/0010001

QMC : Moreo, Scalapino, White, P.R. B. **45**, 7544 (1992)

Proofs...

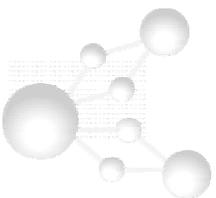
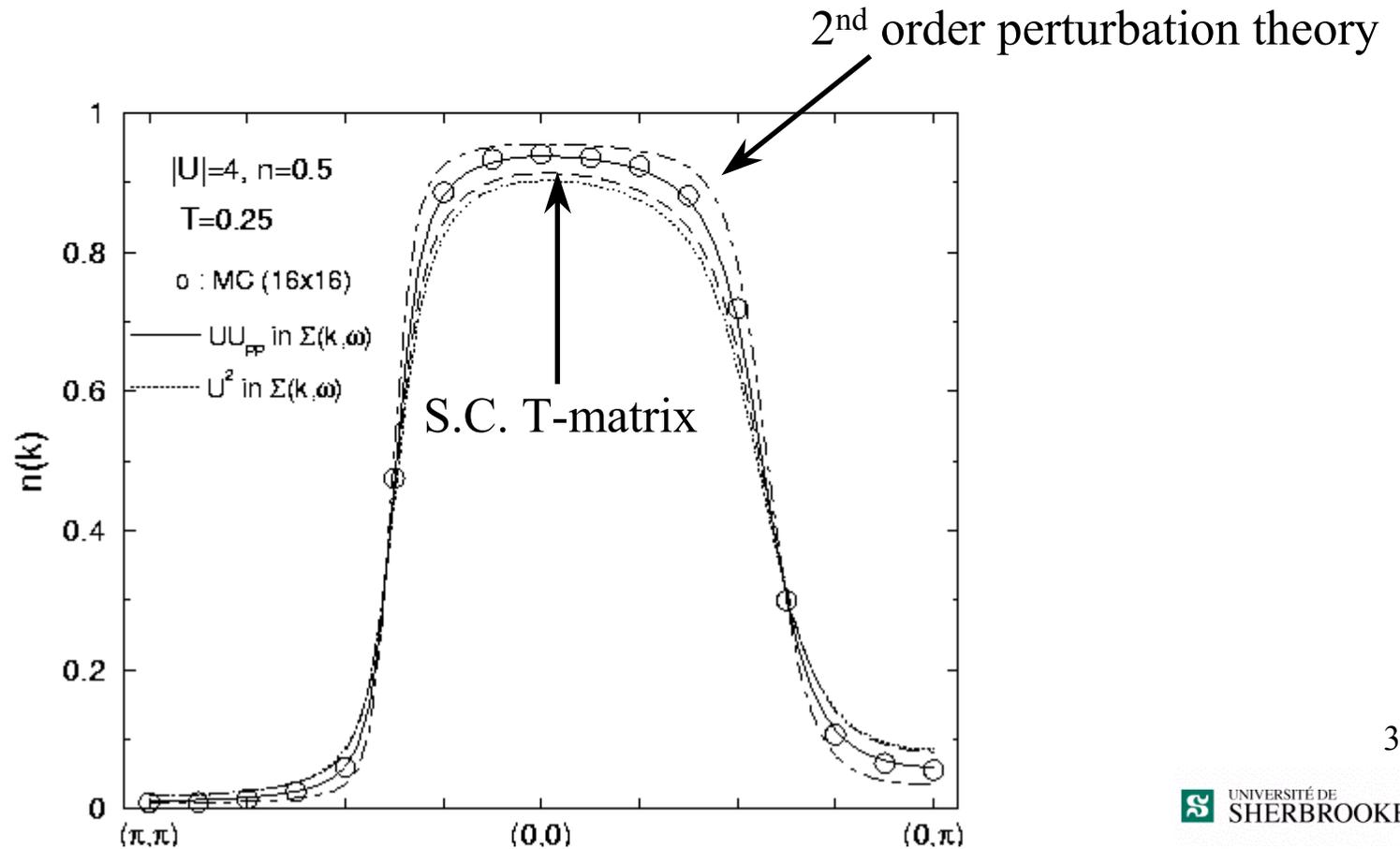


Proofs...

$$U = -4$$

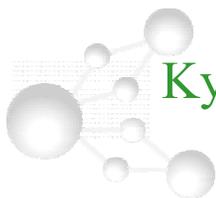
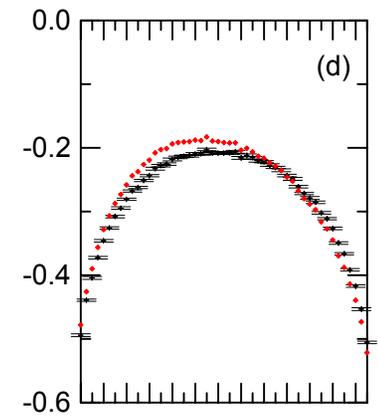
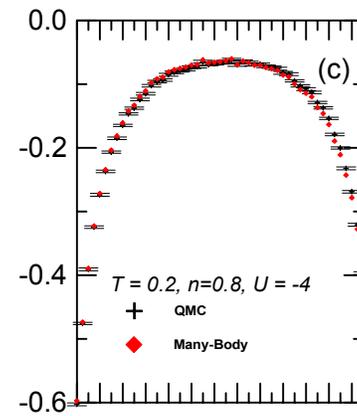
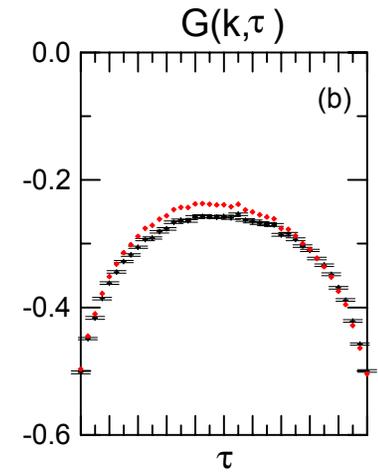
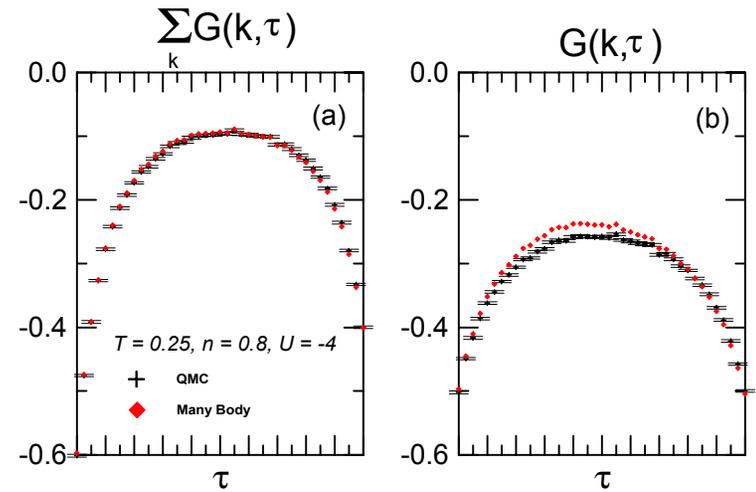
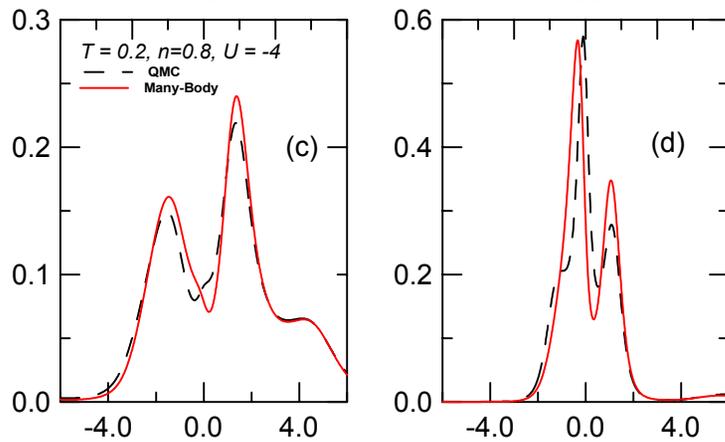
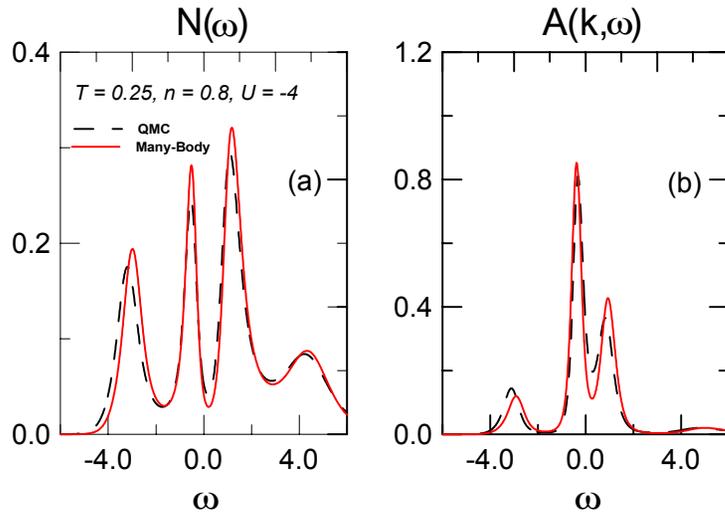
Calc. : Kyung et al. cond-mat/0010001

QMC : Trivedi and Randeria, P.R. L. **75**, 312 (1995)



Proofs...

$$U = -4$$



3. An non-perturbative approach for both $U > 0$ and $U < 0$

Reminder:

Generating function, with source field

$$Z[\phi] = \text{Tr} \left[\mathbb{T}_\tau \left(e^{-\psi_\sigma^\dagger(\bar{1}) \phi_\sigma(\bar{1}, \bar{2}) \psi_\sigma(\bar{2})} \right) \right]$$

Propagator in the presence of the source field

$$G_\sigma(1, 2; \{\phi\}) = - \left\langle \psi_\sigma(1) \psi_\sigma^\dagger(2) \right\rangle_\phi = - \frac{\delta \ln Z[\phi]}{\delta \phi_\sigma(2, 1)}$$

Equation of motion and definition of self-energy

$$\left(G_0^{-1} - \phi \right) G = 1 + \Sigma G \quad ; \quad G^{-1} = G_0^{-1} - \phi - \Sigma$$

where, from the commutator of the interacting part of H :

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



Response functions :

$$GG^{-1} = 1$$

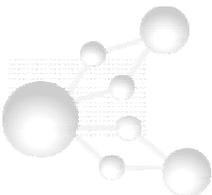
$$\frac{\delta G}{\delta \phi} G^{-1} + G \frac{\delta G^{-1}}{\delta \phi} = 0$$

Using $G^{-1} = G_0^{-1} - \phi - \Sigma$

$$\frac{\delta G}{\delta \phi} = -G \frac{\delta G^{-1}}{\delta \phi} G = G \wedge G + G \frac{\delta \Sigma}{\delta \phi} G$$

Legendre transform of Z is $\Phi[G]$ and $\Sigma[G] = \delta \Phi[G] / \delta G$. We have the RPA equation in particle-hole channel, (or Bethe-Salpeter in particle-particle)

$$\frac{\delta G}{\delta \phi} = G \wedge G + G \left[\frac{\delta \Sigma}{\delta G} \frac{\delta G}{\delta \phi} \right] G$$



Vertices appropriate for spin and charge responses

$$U_{sp} = \frac{\delta \Sigma_{\uparrow}}{\delta G_{\downarrow}} - \frac{\delta \Sigma_{\uparrow}}{\delta G_{\uparrow}} \quad ; \quad U_{ch} = \frac{\delta \Sigma_{\uparrow}}{\delta G_{\downarrow}} + \frac{\delta \Sigma_{\uparrow}}{\delta G_{\uparrow}}$$



Hartree-Fock as an example of use of this formalism:

As an example, consider Hartree-Fock (N.B. all in external field ϕ . Take $\phi = 0$ at the end only.)

$$\Sigma_{\sigma}^H(1, \bar{1}) G_{\sigma}^H(\bar{1}, 2) = U G_{-\sigma}^H(1, 1^+) G_{\sigma}(1, 2)$$

$$\Sigma_{\sigma}^H(1, 2) = U G_{-\sigma}^H(1, 1^+) \delta(1 - 2)$$

$$\frac{\delta \Sigma_{\uparrow}(1, 2)}{\delta G_{\downarrow}(3, 4)} = U n_{-\sigma} \delta(1 - 2) \delta(3 - 1) \delta(4 - 2)$$



First step: Two-Particle Self-Consistent

$$\Sigma_{\sigma}^{(1)}(1, \bar{1}) G_{\sigma}^{(1)}(\bar{1}, 2) = A G_{-\sigma}^{(1)}(1, 1^+) G_{\sigma}^{(1)}(1, 2)$$

where A depends on external field and is chosen such that the exact result

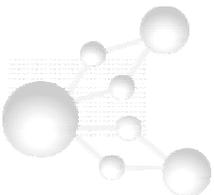
$$\Sigma_{\sigma}(1, \bar{1}) G_{\sigma}(\bar{1}, 1^+) = U \langle n_{\uparrow} n_{\downarrow} \rangle$$

is satisfied. One finds

$$A = U \frac{\langle n_{\uparrow} n_{\downarrow} \rangle}{\langle n_{\uparrow} \rangle \langle n_{\downarrow} \rangle}$$

Functional derivative of $\langle n_{\uparrow} n_{\downarrow} \rangle / (\langle n_{\uparrow} \rangle \langle n_{\downarrow} \rangle)$ drops out of spin vertex

$$U_{sp} = A = U \frac{\langle n_{\uparrow} n_{\downarrow} \rangle}{\langle n_{\uparrow} \rangle \langle n_{\downarrow} \rangle}$$



To close the system of equations, while satisfying conservation laws and the Pauli principle

$$\langle (n_{\uparrow} - n_{\downarrow})^2 \rangle = \langle n_{\uparrow} \rangle + \langle n_{\downarrow} \rangle - 2 \langle n_{\uparrow} n_{\downarrow} \rangle$$

$$\frac{T}{N} \sum_{\tilde{q}} \frac{\chi_0(q)}{1 - \frac{1}{2} U_{sp} \chi_0(q)} = n - 2 \langle n_{\uparrow} n_{\downarrow} \rangle \quad (1)$$

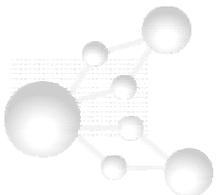
Recall

$$U_{sp} = U \frac{\langle n_{\uparrow} n_{\downarrow} \rangle}{\langle n_{\uparrow} \rangle \langle n_{\downarrow} \rangle} \quad (2)$$

To have charge fluctuations that satisfy Pauli principle as well,

$$\frac{T}{N} \sum_q \frac{\chi_0(q)}{1 + \frac{1}{2} U_{ch} \chi_0(q)} = n + 2 \langle n_{\uparrow} n_{\downarrow} \rangle - n^2 \quad (3)$$

(Bonus: Mermin-Wagner theorem)



Second step: improved self-energy

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

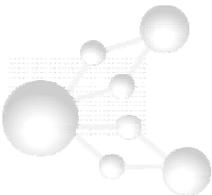
$$\Sigma_{\sigma} (1, \bar{1}) G_{\sigma} (\bar{1}, 2) = -U \left[\frac{\delta G_{\sigma} (1, 2)}{\delta \phi_{-\sigma} (1^{+}, 1)} - G_{-\sigma} (1, 1^{+}) G_{\sigma} (1, 2) \right]$$

Last term is Hartree Fock ($\lim \omega \rightarrow \infty$). Multiply by G^{-1} , replace lower energy part results of TPSC

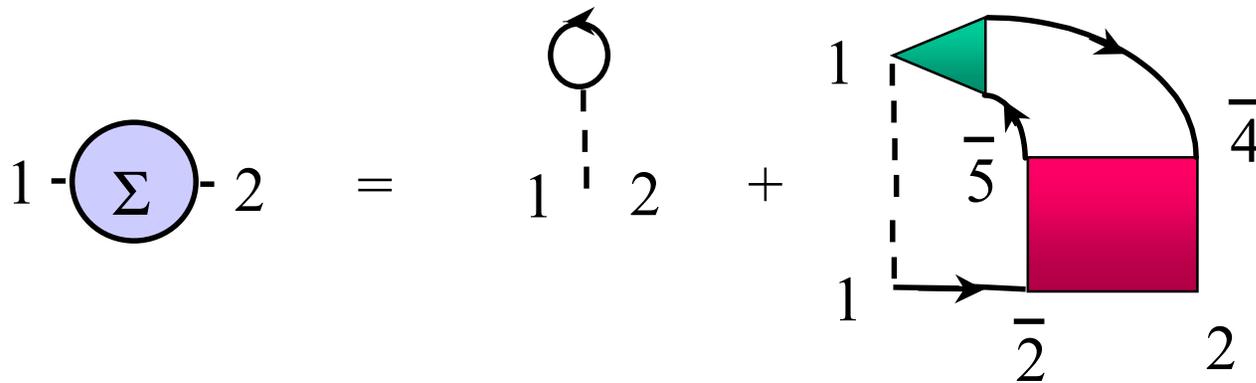
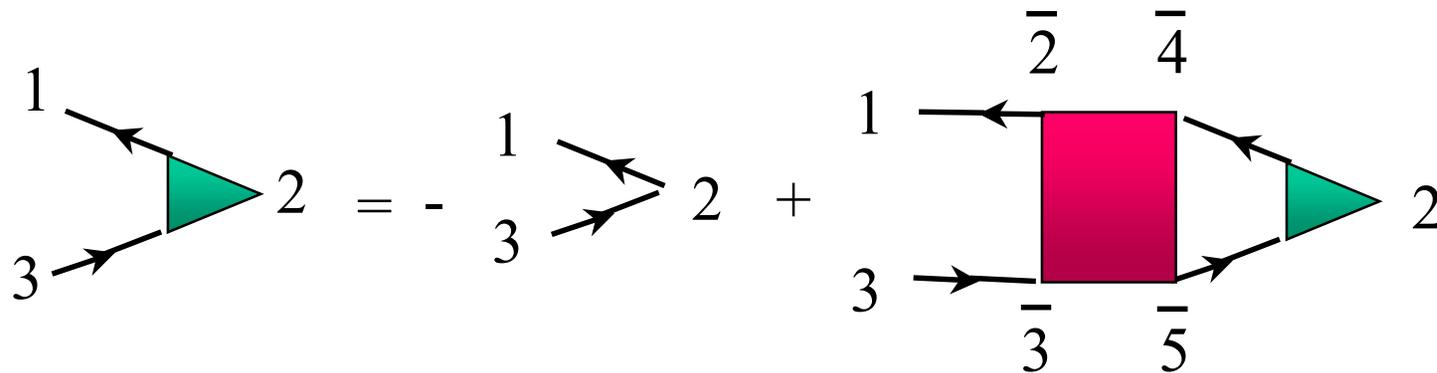
$$\Sigma_{\sigma}^{(2)} (1, 2) = U G_{-\sigma}^{(1)} (1, 1^{+}) \delta (1 - 2) - U G^{(1)} \left[\frac{\delta \Sigma^{(1)}}{\delta G^{(1)}} \frac{\delta G^{(1)}}{\delta \phi} \right]$$

Transverse+longitudinal for crossing-symmetry

$$\Sigma_{\sigma}^{(2)} (k) = U n_{-\sigma} + \frac{U T}{8 N} \sum_q \left[3 U_{sp} \chi_{sp}^{(1)} (q) + U_{ch} \chi_{ch}^{(1)} (q) \right] G_{\sigma}^{(1)} (k + q). \quad (4)$$



What about single-particle properties? (Ruckenstein)



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



N.B.: No Migdal theorem

Results of the analogous procedure for $U < 0$

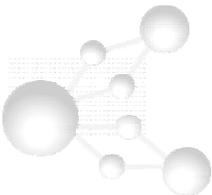
$$U_{pp} = U \frac{\langle (1 - n_{\uparrow}) n_{\downarrow} \rangle}{\langle 1 - n_{\uparrow} \rangle \langle n_{\downarrow} \rangle}. \quad (5)$$

$$\chi_p^{(1)}(q) = \frac{\chi_0^{(1)}(q)}{1 + U_{pp} \chi_0^{(1)}(q)} \quad (6)$$

$$\frac{T}{N} \sum_q \chi_p^{(1)}(q) \exp(-iqn_0^-) = \langle \Delta^\dagger \Delta \rangle = \langle n_{\uparrow} n_{\downarrow} \rangle \quad (7)$$

$$\Sigma^{(1)} \simeq \frac{U}{2} - \frac{U_{pp} (1 - n)}{2} \quad (8)$$

$$\Sigma_{\sigma}^{(2)}(k) = U n_{-\sigma} - U \frac{T}{N} \sum_q U_{pp} \chi_p^{(1)}(q) G_{-\sigma}^{(1)}(q - k) \quad (9)$$



Satisfies Pauli principle and generalization of f -sum rule

$$\int \frac{d\omega}{\pi} \text{Im} \chi^{(1)}(\mathbf{q}, \omega) = \langle [\Delta_{\mathbf{q}}(0), \Delta_{\mathbf{q}}^{\dagger}(0)] \rangle = 1 - n \quad ; \quad \forall \mathbf{q} \quad (10)$$

$$\int \frac{d\omega}{\pi} \omega \text{Im} \chi^{(1)}(\mathbf{q}, \omega) = \left[\frac{1}{N} \sum_{\mathbf{k}} (\varepsilon_{\mathbf{k}} + \varepsilon_{-\mathbf{k}+\mathbf{q}}) (1 - 2 \langle n_{\mathbf{k}\uparrow} \rangle) \right] \quad (11)$$

$$-2 \left(\mu^{(1)} - \frac{U}{2} \right) (1 - n) \quad ; \quad \forall \mathbf{q} \quad (12)$$

Internal accuracy check (For both $U > 0$ and $U < 0$).

$$\frac{1}{2} \text{Tr} [\Sigma^{(2)} G^{(1)}] = \lim_{\tau \rightarrow 0^-} \frac{T}{N} \sum_k \Sigma_{\sigma}^{(2)}(k) G_{\sigma}^{(1)}(k) e^{-ik_n \tau} = U \langle n_{\uparrow} n_{\downarrow} \rangle$$

Check : $\boxed{\text{Tr} [\Sigma^{(2)} G^{(1)}] \sim \text{Tr} [\Sigma^{(2)} G^{(2)}]}$



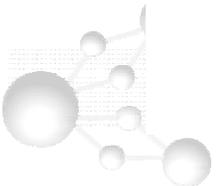
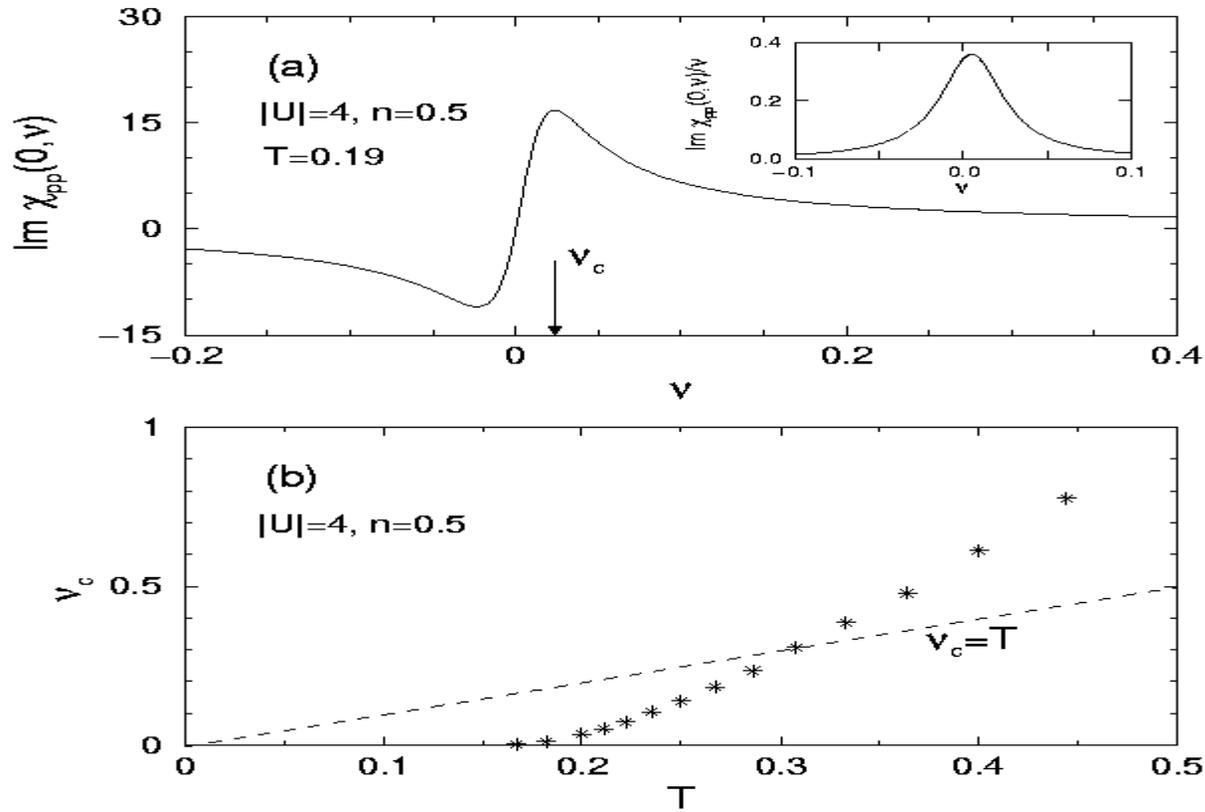
4. Results:

- Mechanism for pseudogap

$$U = -4$$

- (analogous to $U > 0$) : *Vilk et al. Europhys. Lett. 33, 159 (1996)*
Pines, Schmalian (98)

- Enter the renormalized-classical regime. N.B. $d = 2$

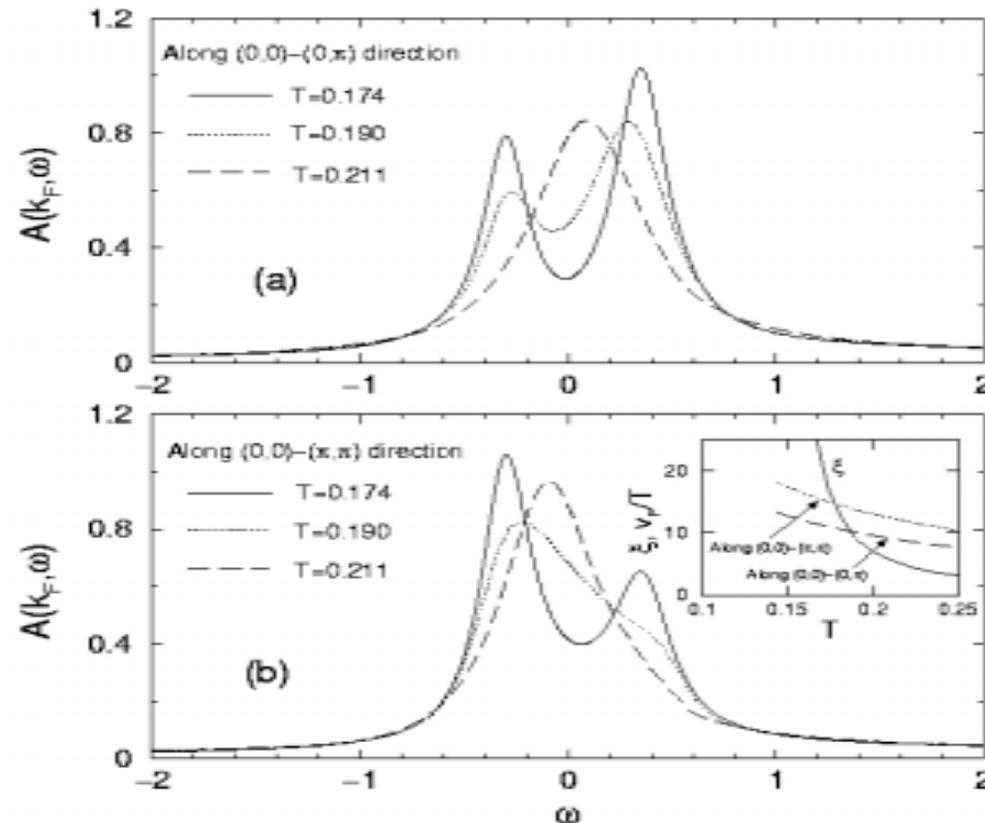


4. Results:

- Mechanism for pseudogap

$$U = -4$$

- Pairing correlation length larger than single-particle thermal de Broglie wavelength (v_F/T)



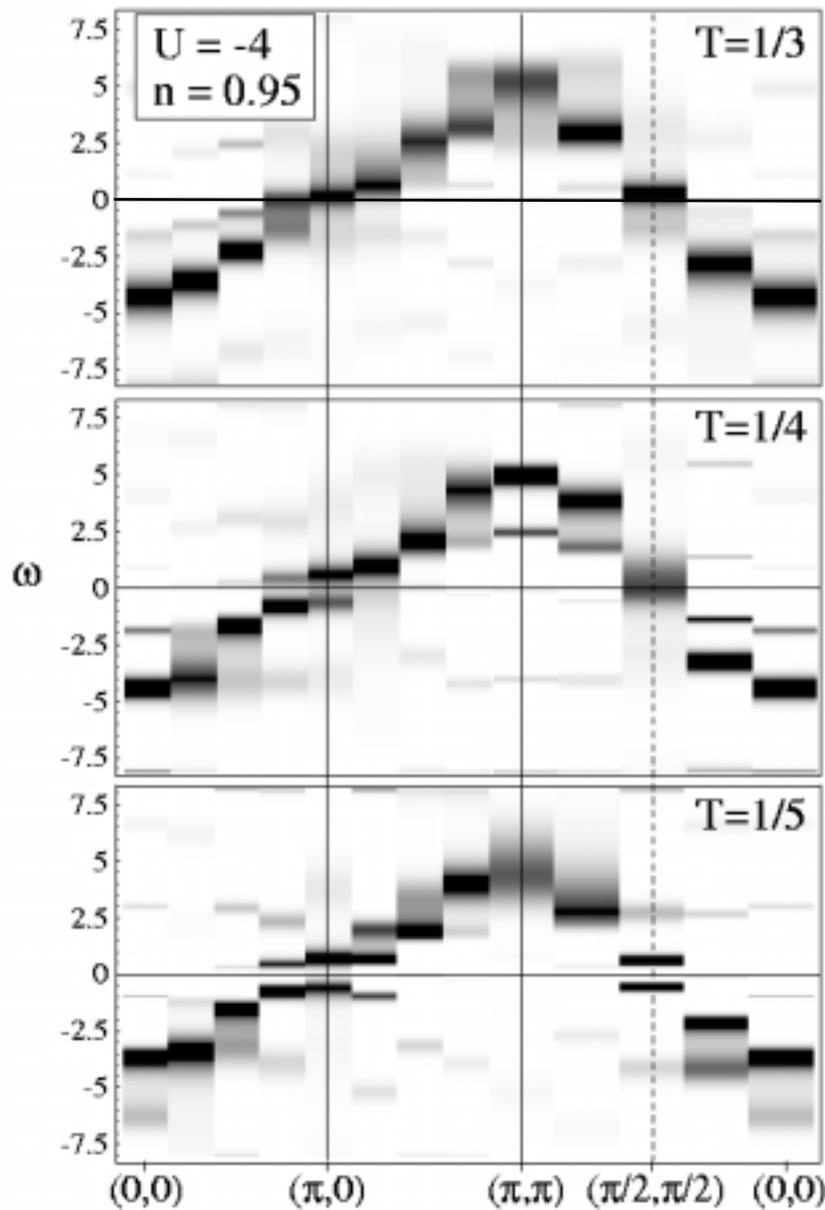
$$\xi \sim 1.3 \xi_{th}$$



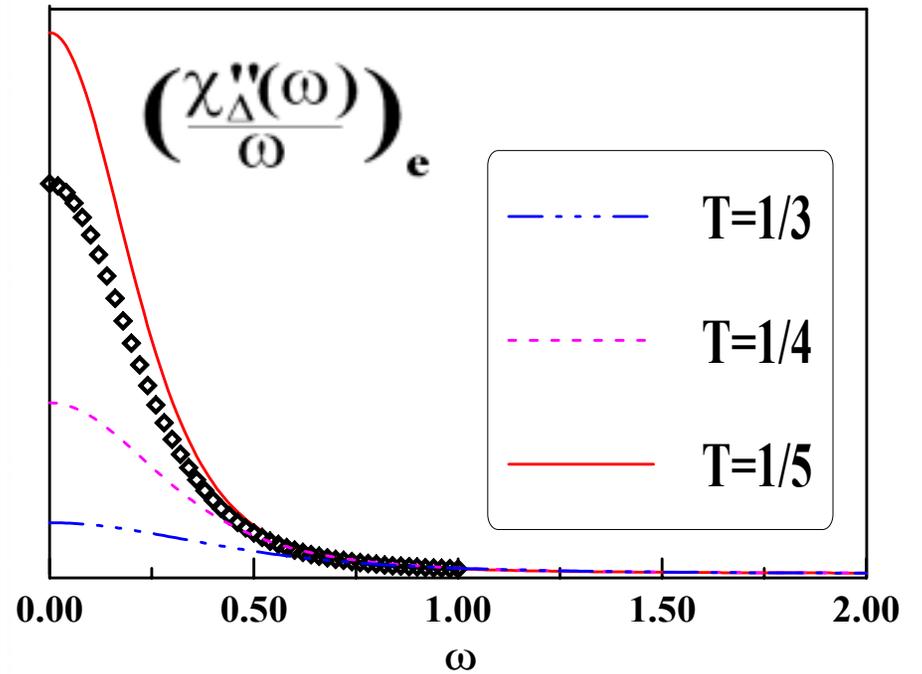
Mechanism for pseudogap formation in the attractive model:

$$U = -4$$

$d = 2$ is crucial



Even part of the pair susceptibility at $q = 0$, for different temperatures



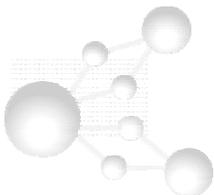
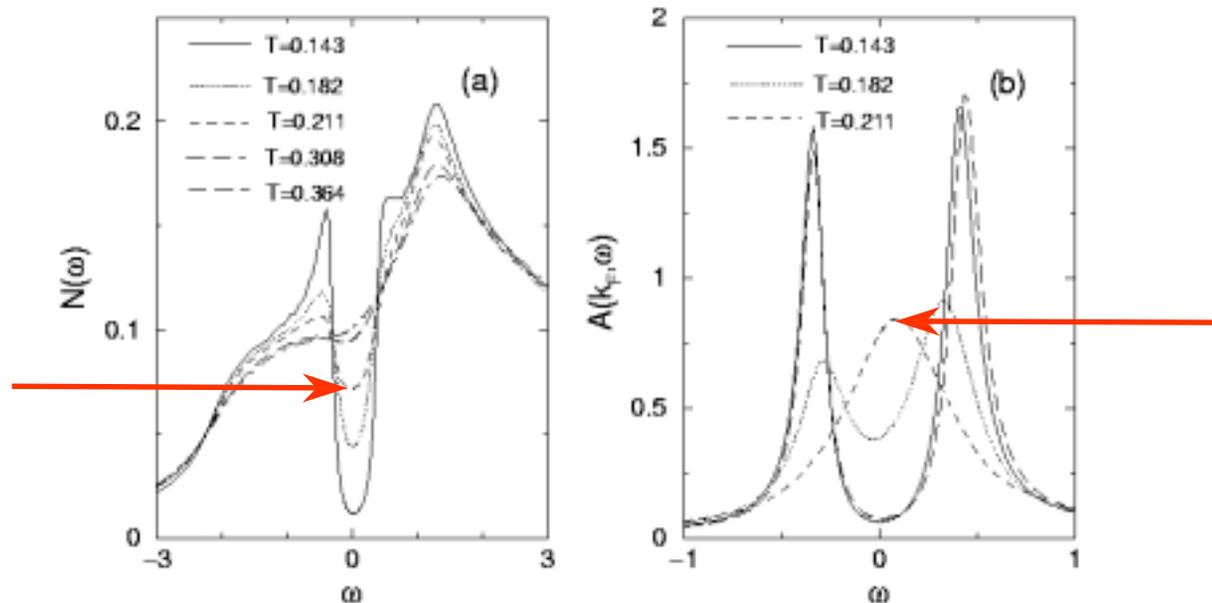
Allen, et al. P.R. L **83**, 4128 (1999) 44

4. Results:

- Spectral weight rearrangement

$$U = -4$$

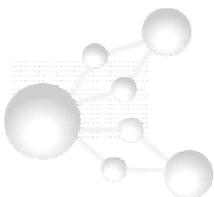
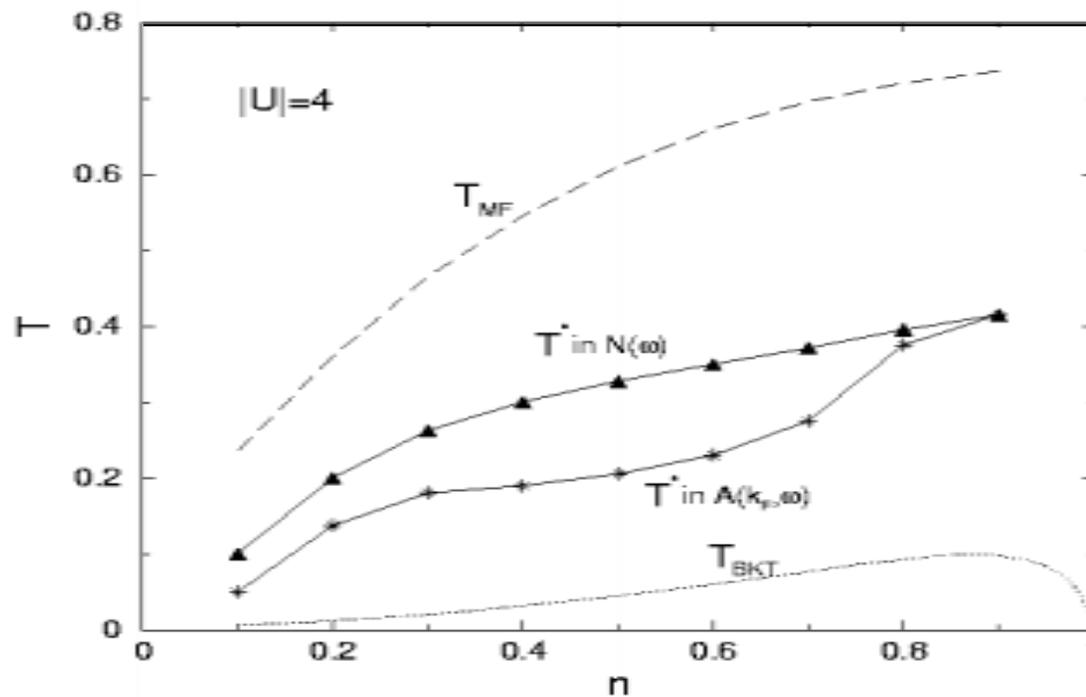
- Pseudogap appears first in total density of states
- Fills in instead of opening up
- Rearrangement over huge frequency scale compared with either T or ΔT . ($\Delta T \sim 0.03$, $T \sim 0.2$, $\Delta\omega \sim 1$)



4. Results:

- Crossover diagram

$$U = -4$$



5. Conclusion

$$U > 0$$

- Renormalized classical regime for spin fluctuations in pseudogap regime?

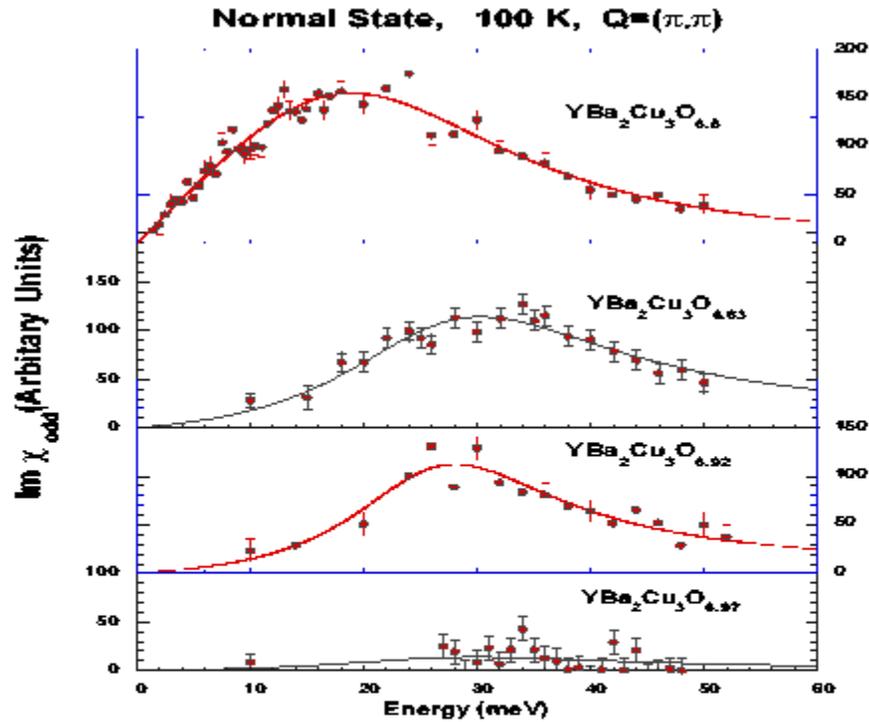
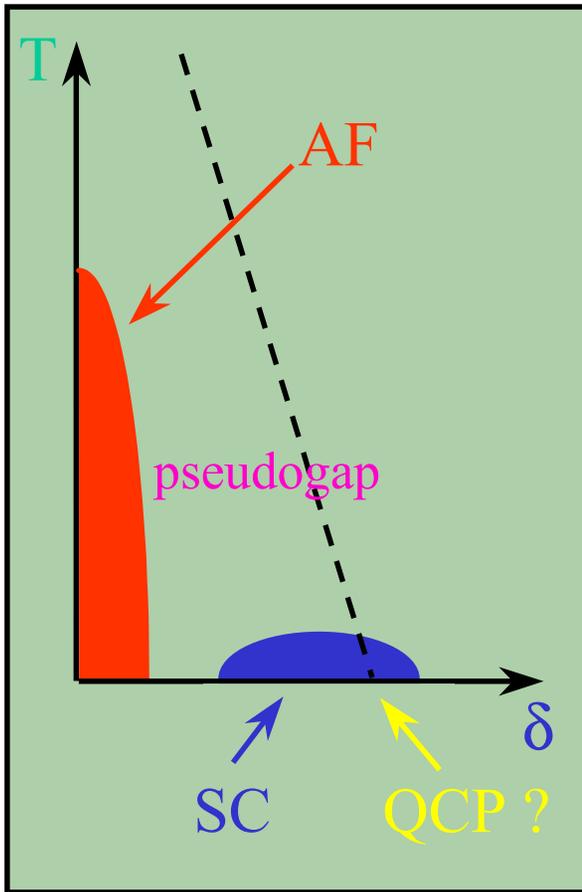


Figure 2: Normalized imaginary part of the spin susceptibility at the AF wavevector in the normal state, at $T = 100$ K, for four oxygen contents in YBCO ($T_c = 15, 35, 91, 92.5$ K for $x = 0.5, 0.53, 0.92, 0.97$ respectively). These curves have been normalized to the same units using standard phonon calibration¹⁴ (100 counts in the vertical scale roughly correspond to $\sim 350 \mu_B^2/eV$ in absolute units) (from¹⁰).

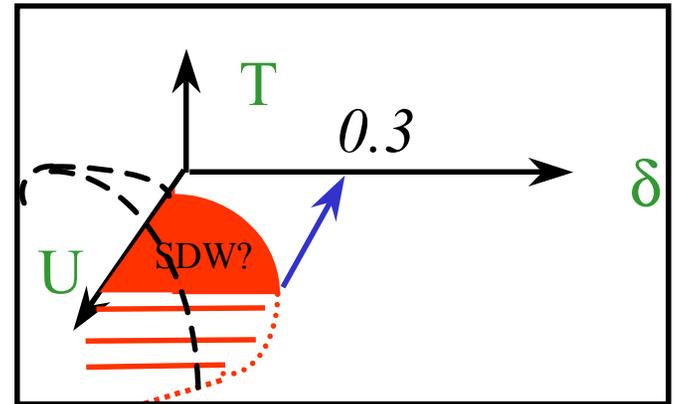
Philippe Bourges cond-mat/0009373



$$U > 0$$

- Quantum critical point, $d = 2$:
 - Instability at incommensurate q
 - Largest doping : 0.315

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



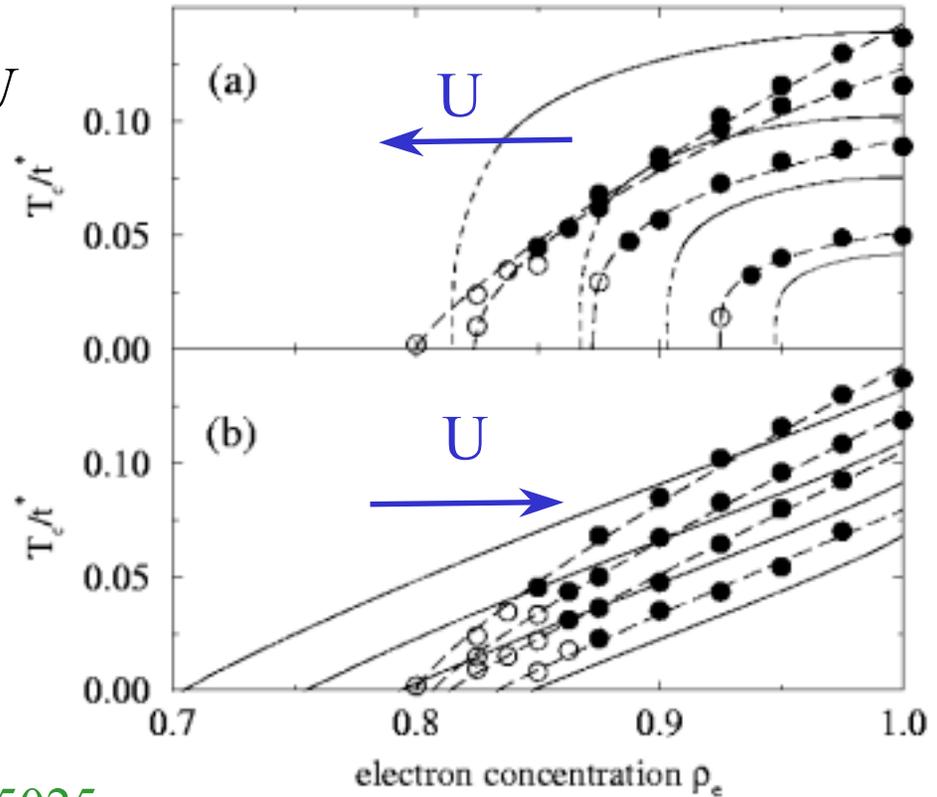
- Decreases with increasing U

$$U < W$$

$$d = \text{infinity}$$



$$U > W$$



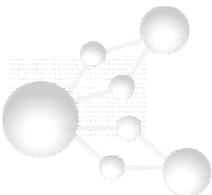
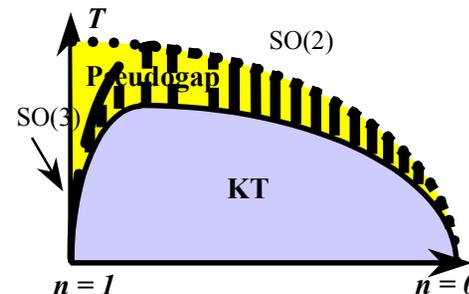
Freericks, Jarrell cond-mat/9405025

$$U < 0$$

Pairing-fluctuation induced pseudogap

- Slightly Overdoped High-Tc Superconductor $\text{TlSr}_2\text{CaCu}_2\text{O}_{6.8}$
Guo-qing Zheng et al., P. R. L. 85, 405 (2000)
 - Pseudogap in Knight shift and NMR relaxation strongly H dependent, contrary to underdoped (up to $23 T$).
- Underdoped in a range $\Delta T \sim 15 K$ near T_c see evidence for renormalized classical regime (KT behavior).
Corson et al. Nature, 398, 221 (1999).
- Higher symmetry group creates large range of T where there is a pseudogap.

Allen et al. P.R.L. 83, 4128 (1999)





Steve Allen



François Lemay

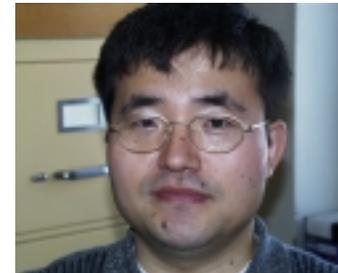


David Poulin

Liang Chen



Yury Vilk



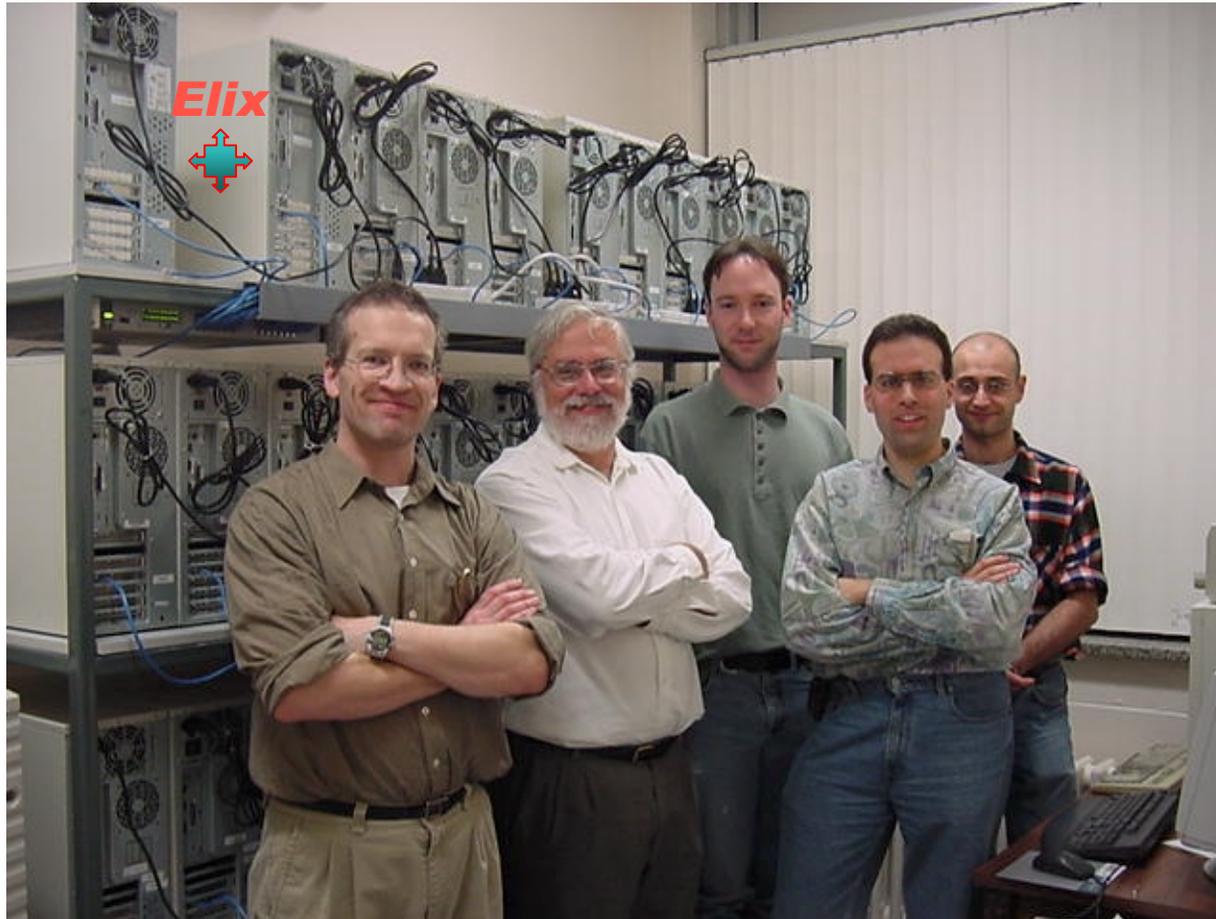
Bumsoo Kyung Samuel Moukouri



Hugo Touchette

Michel Barrette

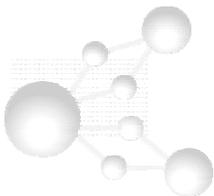
Mehdi Bozzo-Rey



David Sénéchal

A.-M.T.

Alain Veilleux





Sébastien Roy Alexandre Blais



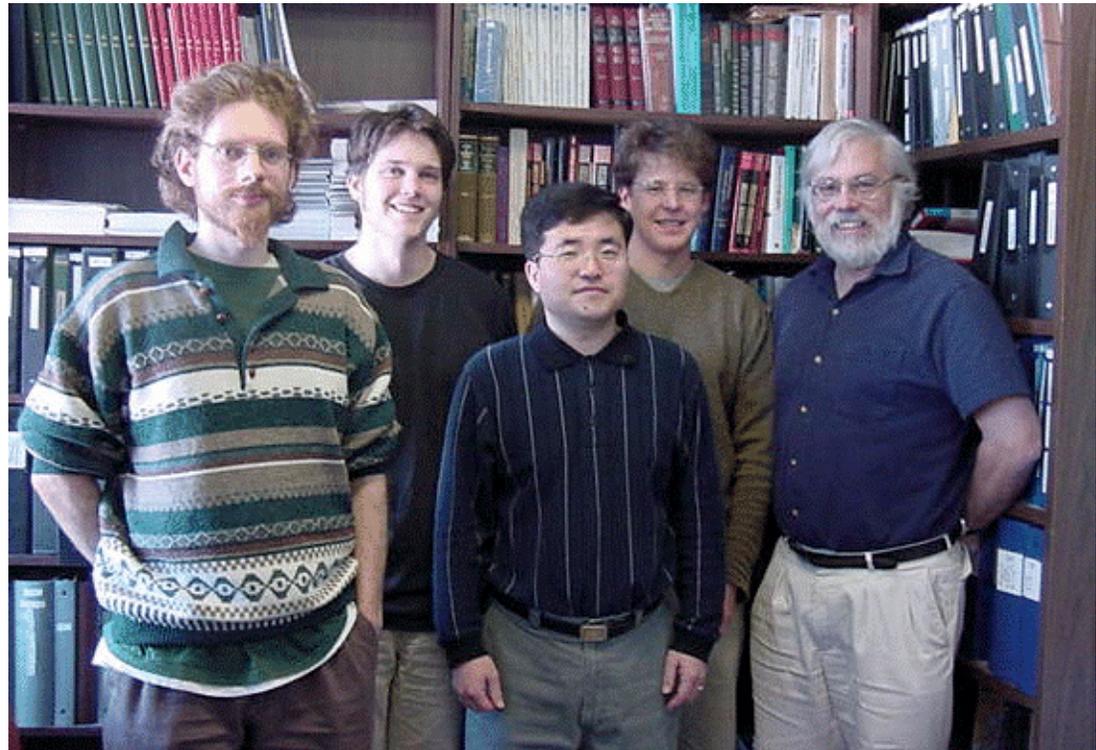
Claude Bourbonnais



R. Côté



D. Sénéchal



Jean-Sébastien Landry

A-M.T.

Bumsoo Kyung



- How can we understand electronic systems that show both localized and extended character?
- Why do both organic and high-temperature superconductors show broken-symmetry states where mean-field-like quasiparticles seem to reappear?
- Why is the condensate fraction in this case smaller than what would be expected from the shape of the would-be Fermi surface in the normal state?
- Are there new elementary excitations that could summarize and explain in a simple way the anomalous properties of these systems?
- Do quantum critical points play an important role in the Physics of these systems?
- Are there new types of broken symmetries?
- How do we build a theoretical approach that can include both strong-coupling and $d = 2$ fluctuation effects?
- What is the origin of d-wave superconductivity in the high-temperature superconductors?

