Strongly Correlated Superconductivity

A.-M. Tremblay

G. Sordi, D. Sénéchal, K. Haule,

S. Okamoto, B. Kyung, M. Civelli

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St-John's, 16 June 2011

VERITATEM IN CHARITATE

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The race for absolute zero temperature

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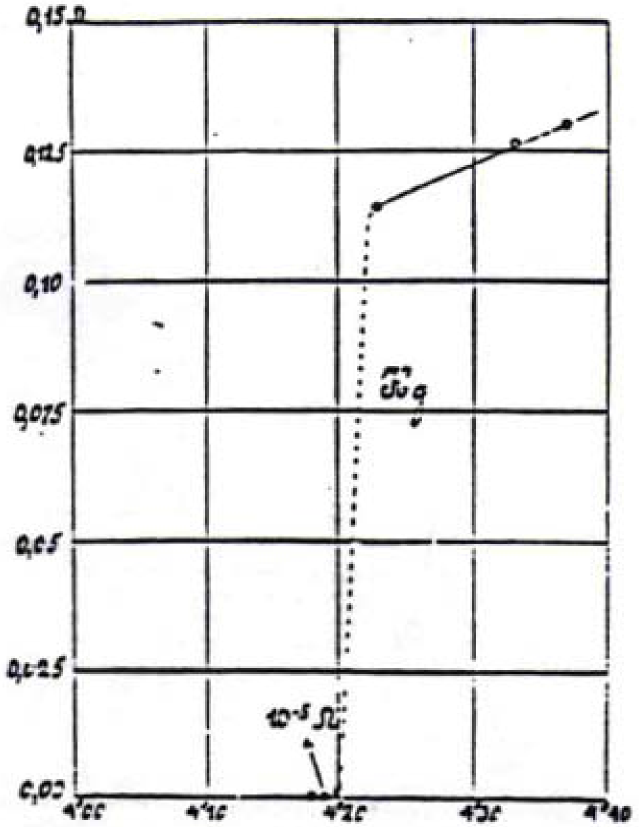
On the way towards the target *T=0*

- What happens to electrical resistance?

8 April 1911



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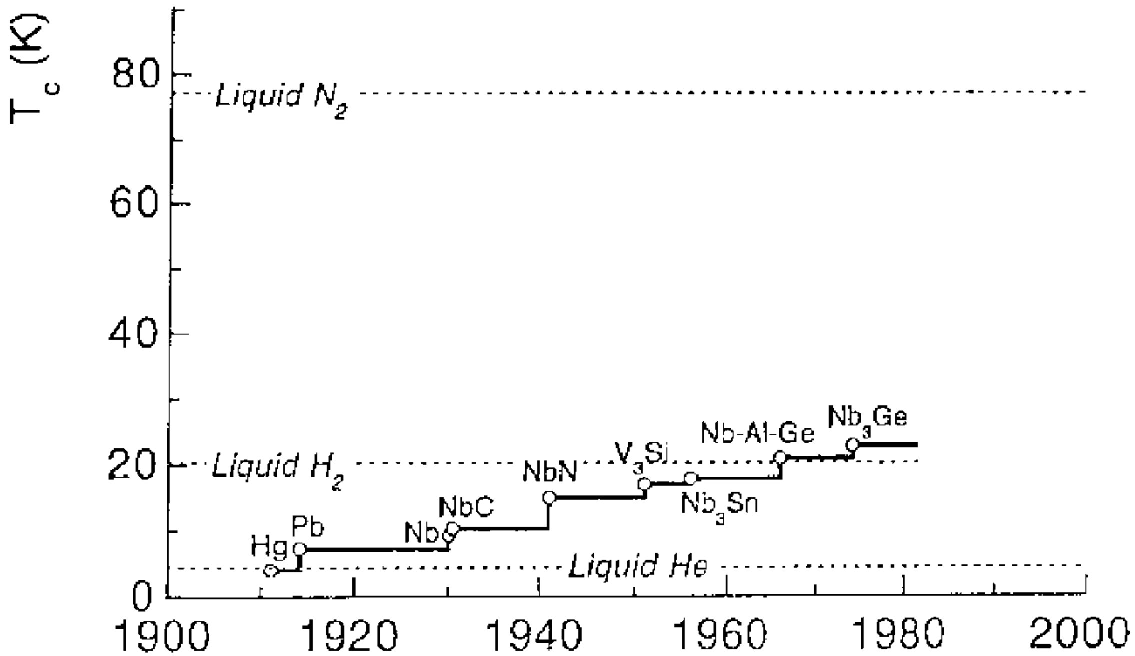
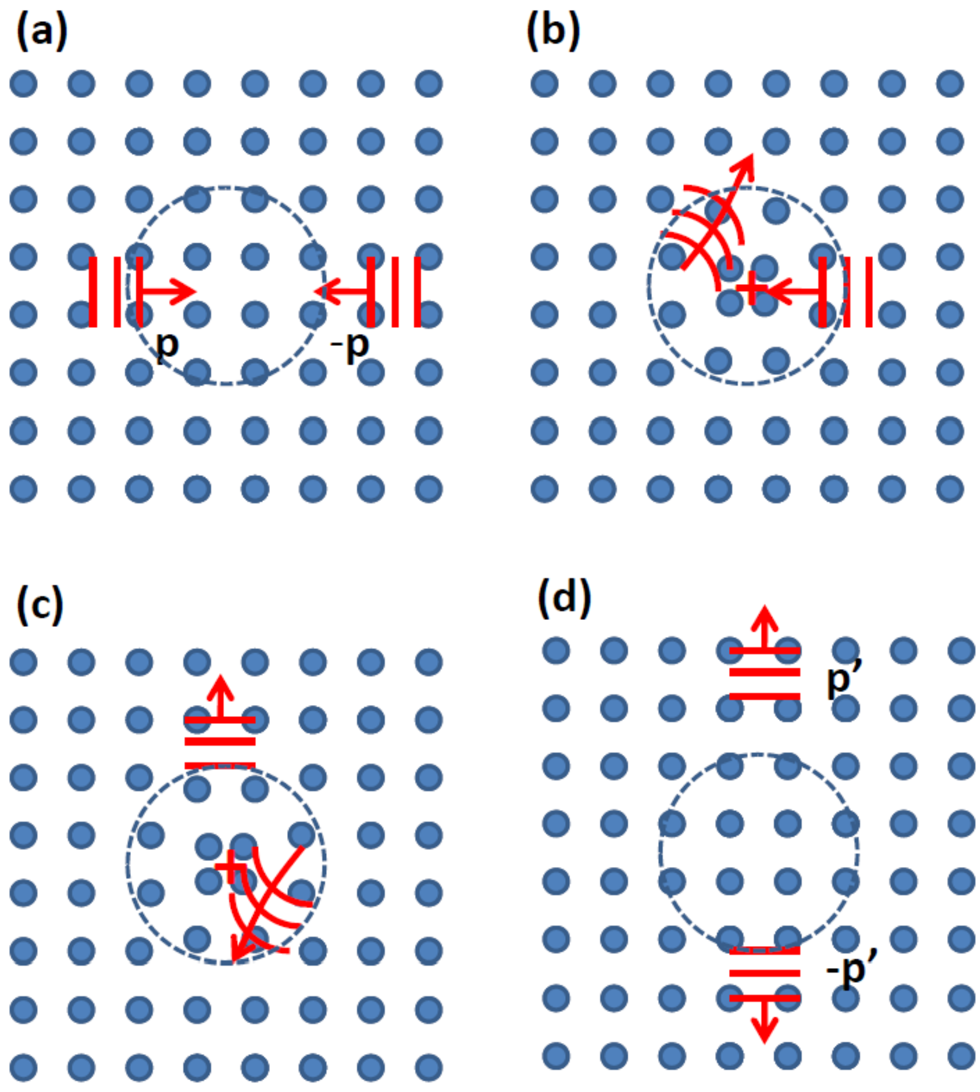
Inching our way to room temperature



Attraction mechanism in the metallic state



#1 Cooper pair, #2 Phase coherence

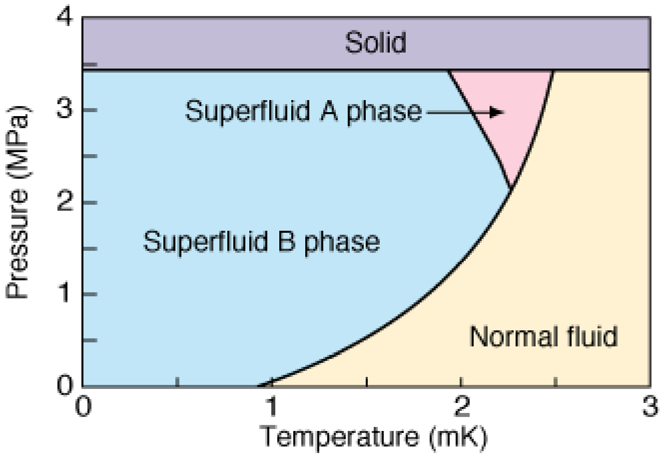
$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow}$$

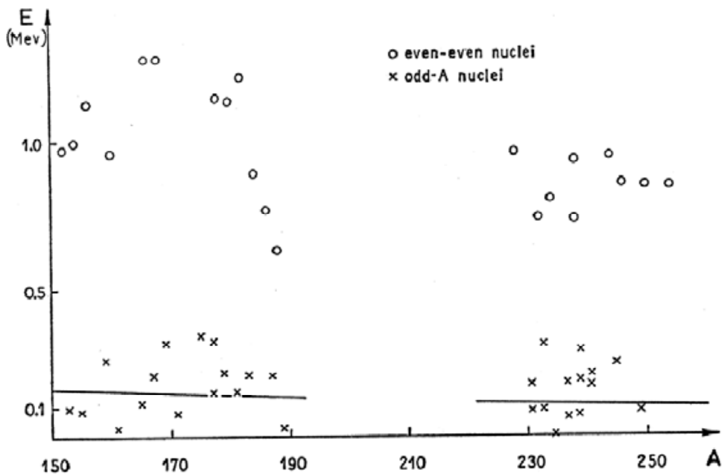
$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \left(\langle \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \rangle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} + \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \left\langle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} \right\rangle \right)$$

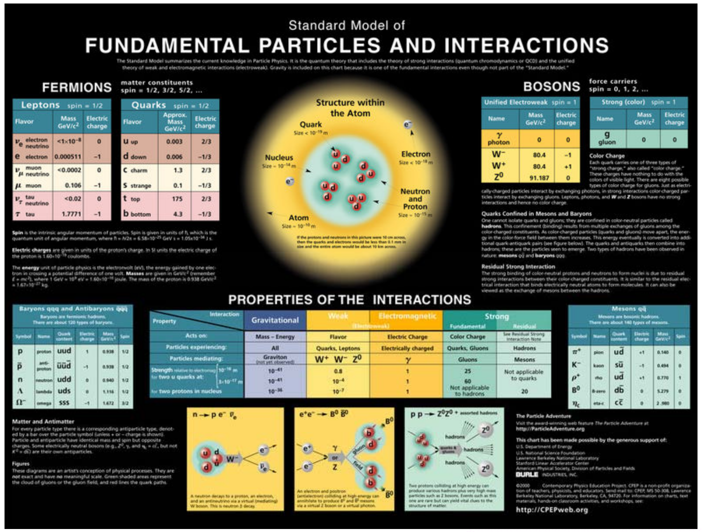
$$|\mathrm{BCS}(\theta)\rangle = \ldots + e^{iN\theta} |N\rangle + e^{i(N+2)\theta} |N+2\rangle + \ldots .$$

Superconductivity everywhere

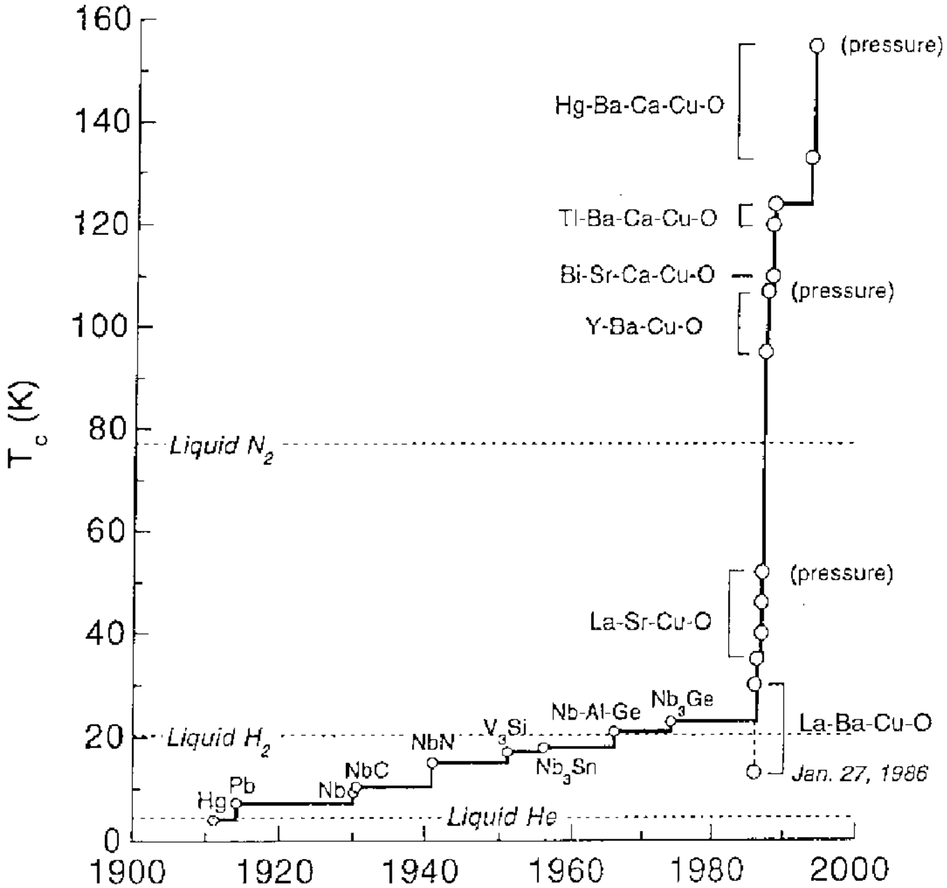
Superconductivity everywhere



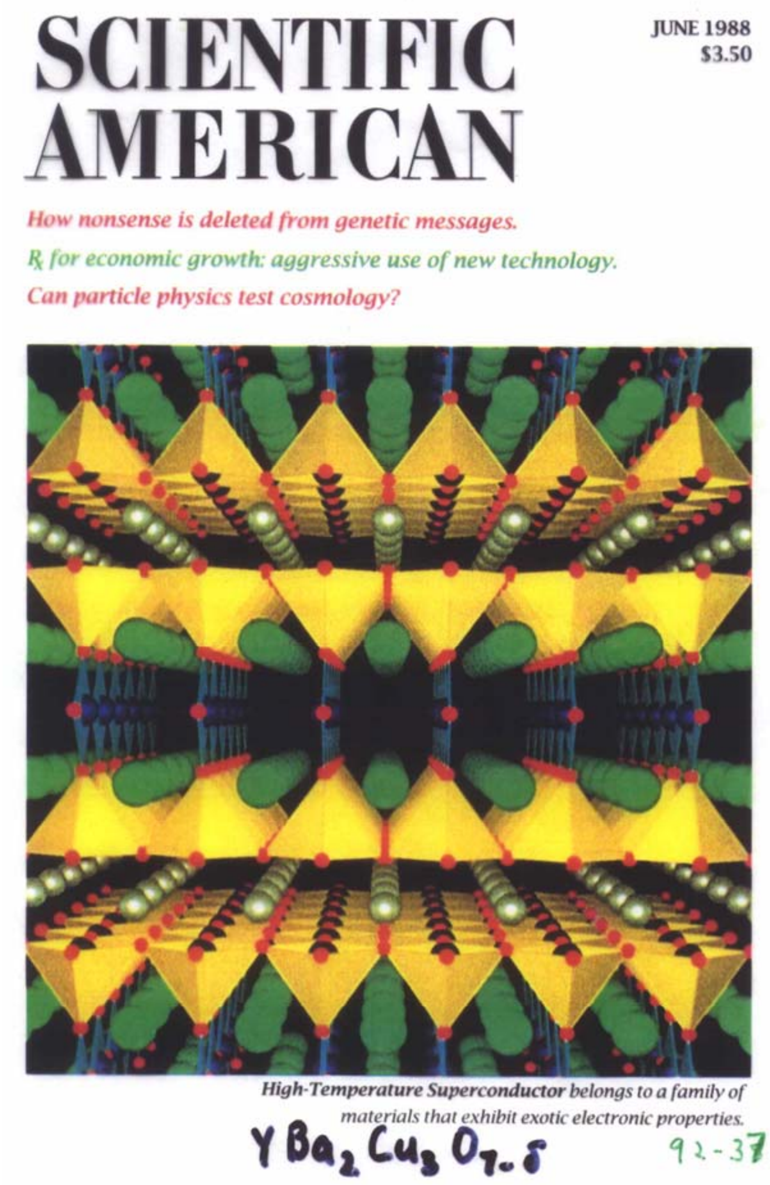


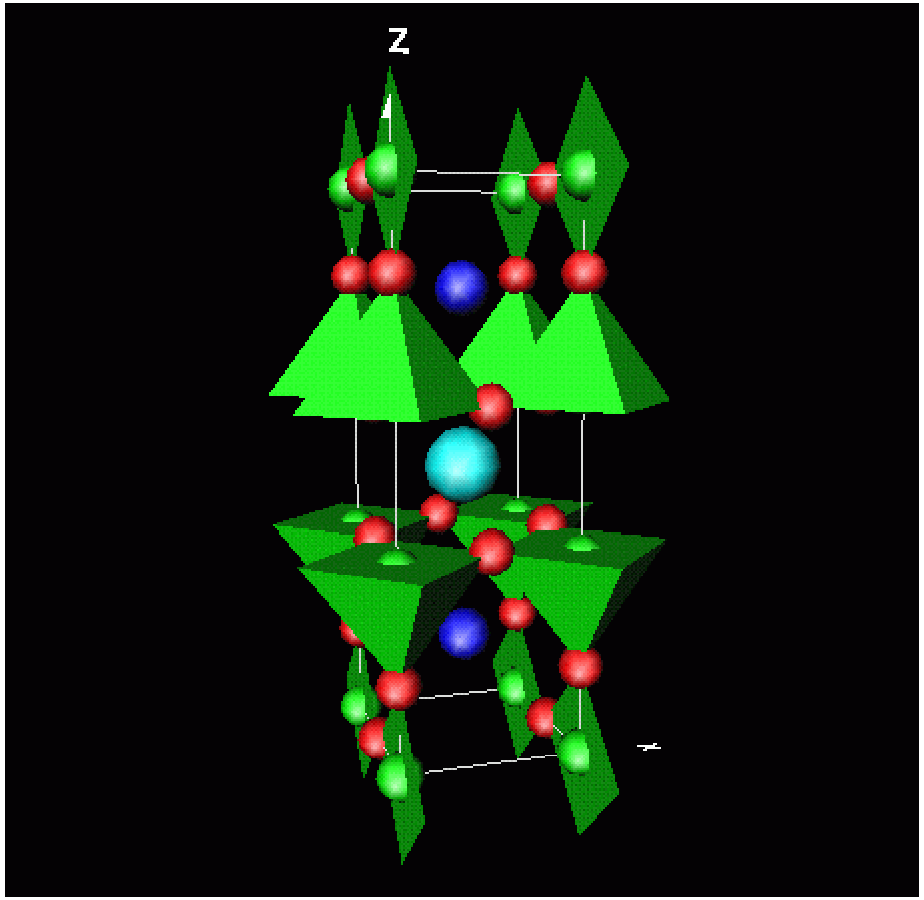


Inching our way to room temperature



High-temperature superconductors





What is special

- TM (not Cu, Au,Fe)
- Cubic
- Stay away from
  - O
  - Magnets
  - Insulators

- Cu
- Layered
- Stay close to
  - O
  - Magnets
  - Insulators

Superconductivity
in the presence of repulsion

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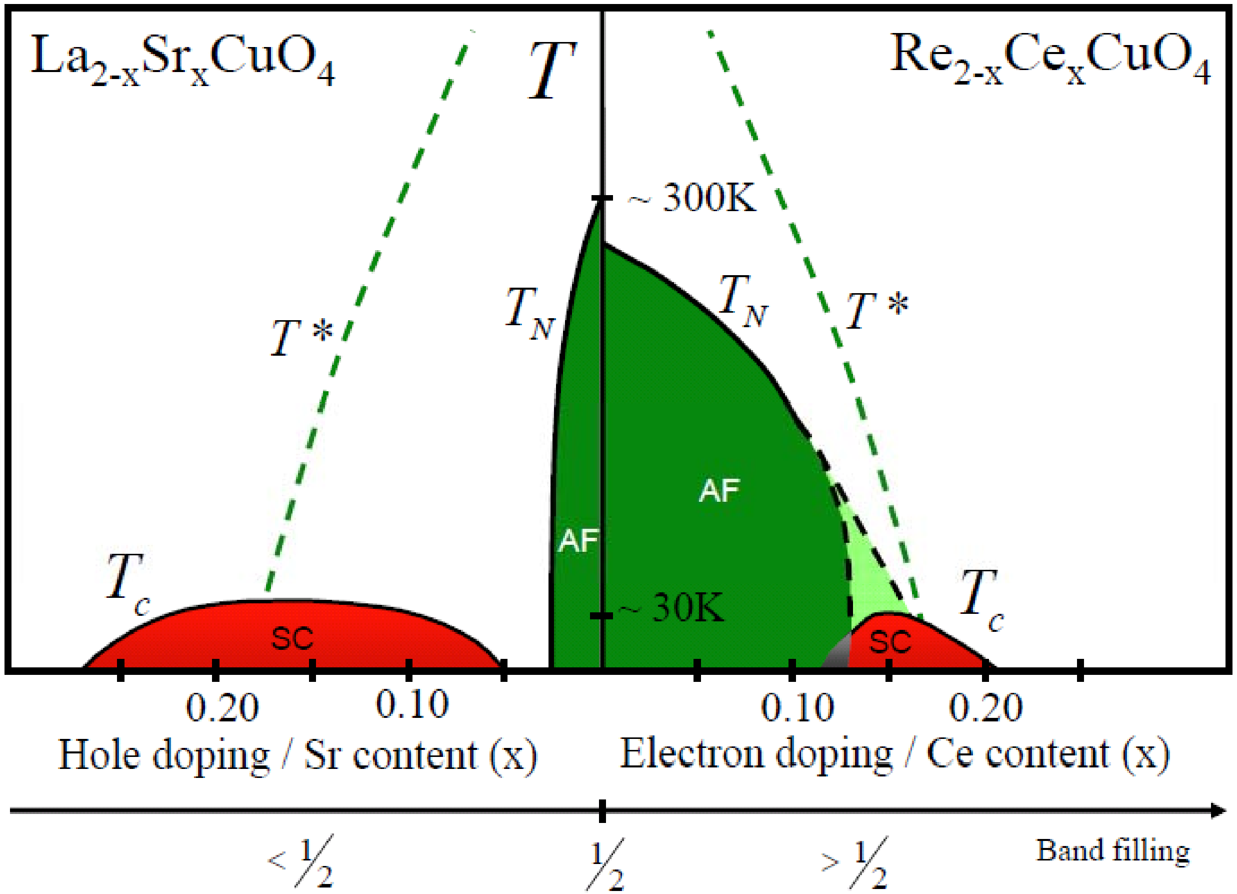
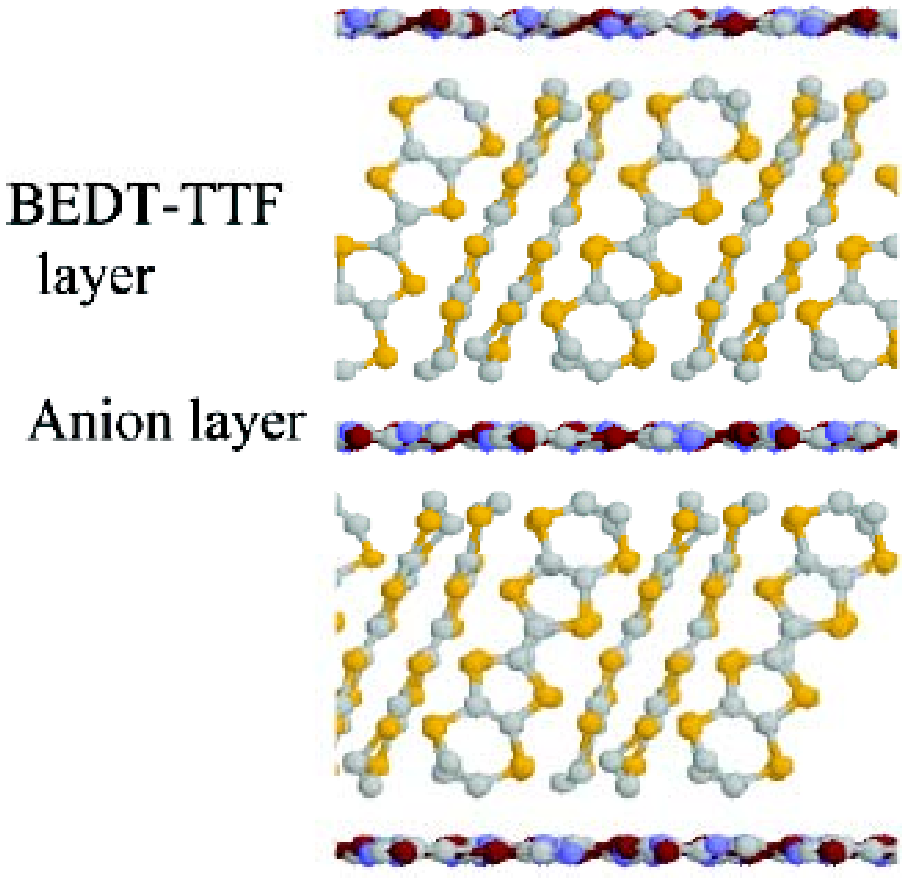
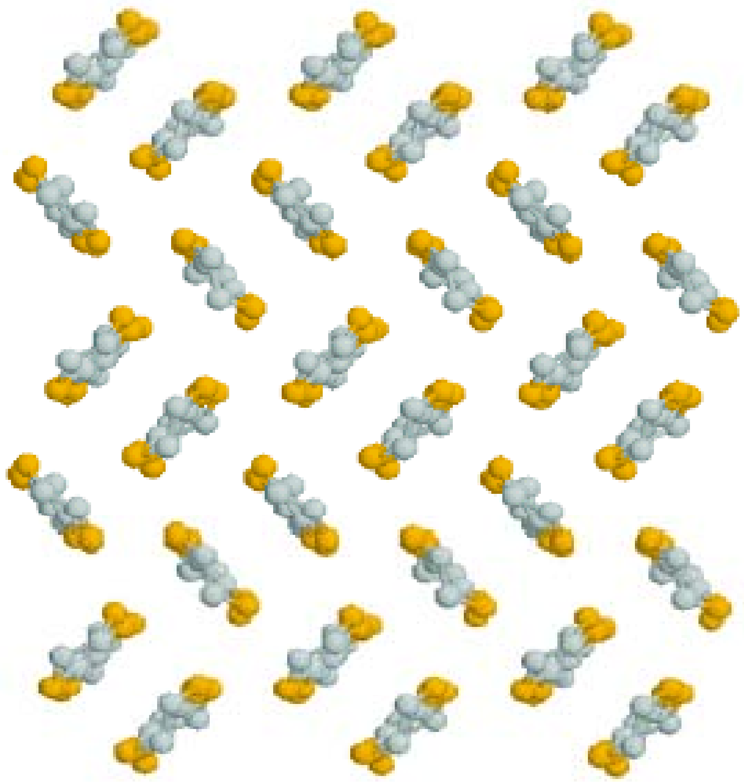
Phase diagram



Armitage, Fournier, Greene, RMP (2009)

Layered organic conductors(κ–BEDT-X family)





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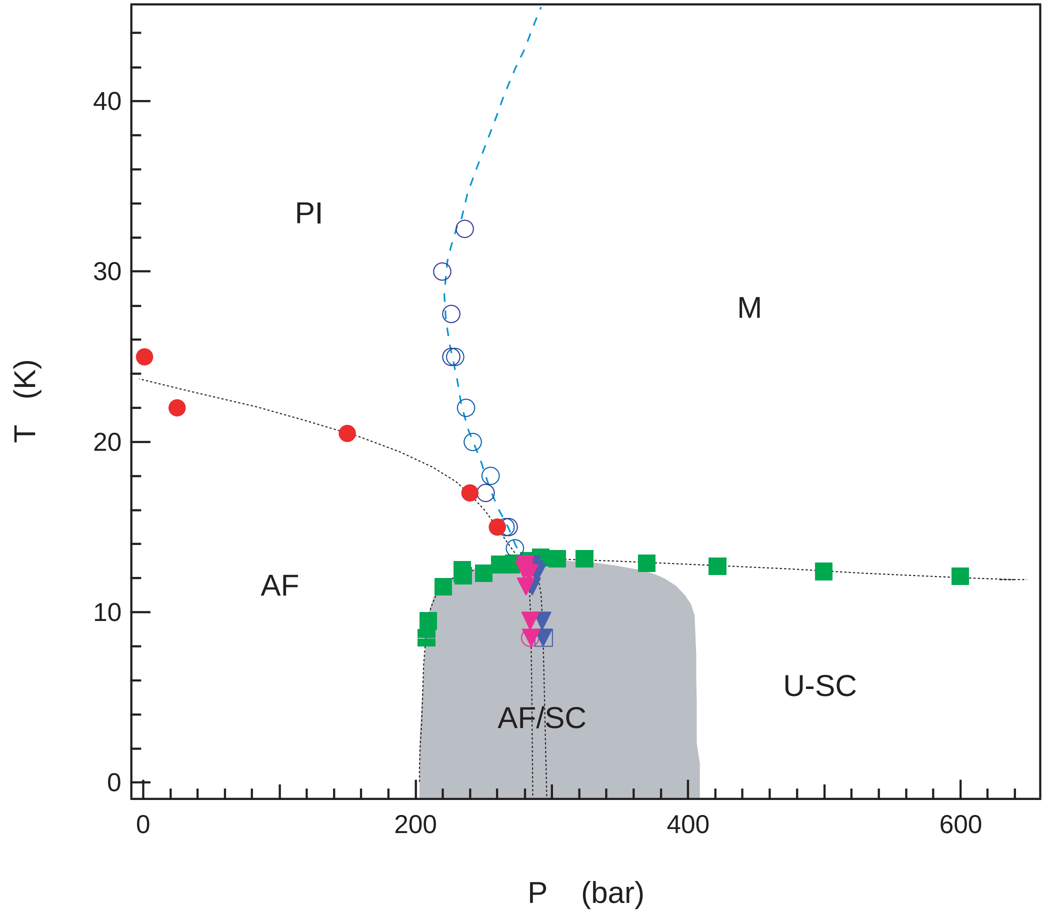
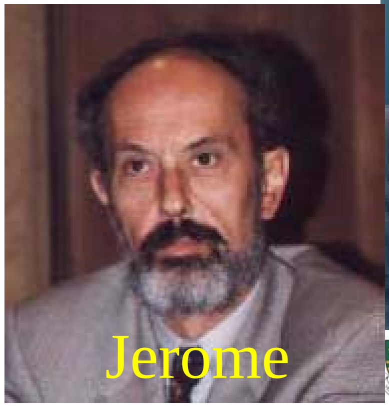
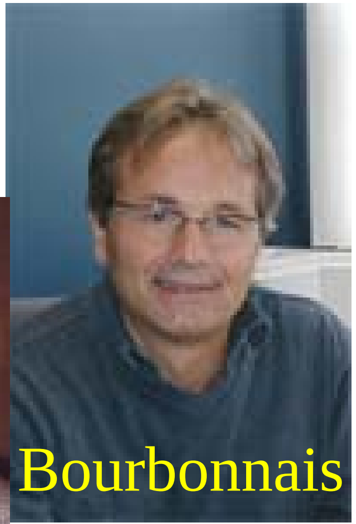
Experimental phase diagram BEDT-X



Phase diagram (X=Cu[N(CN)$_2$]Cl)

S. Lefebvre et al. PRL **85**, 5420 (2000), P. Limelette, et





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Heavy fermions $CeMnI_5$

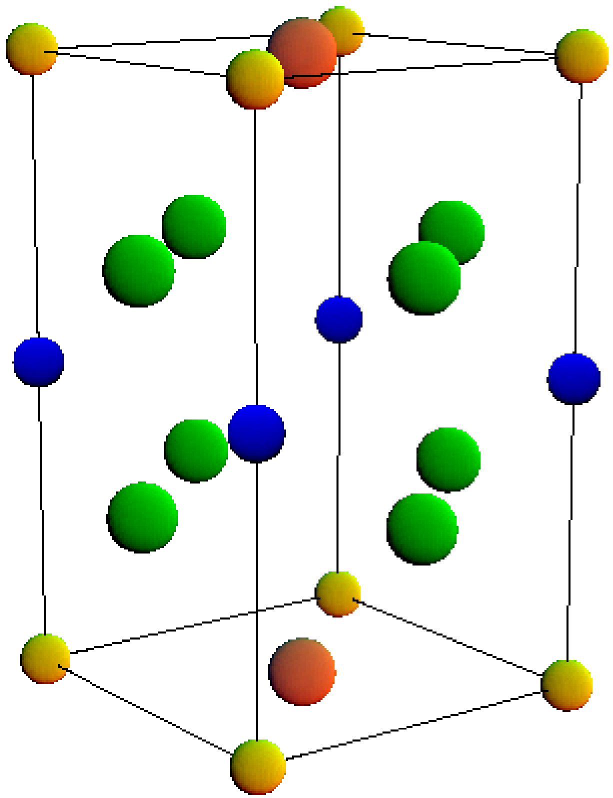

Figure 1. The structure of the $CeMIn_5$ materials. The Ce (Wykyoff position 1a) atoms are yellow, the In(1) (1c) atoms are orange, the In(2) (4i) are green, and the M atoms are blue (1b). Details of the structural parameters can be found in [10]. **Hyperfine interactions in the heavy fermion $CeMIn_5$ systems** N J Curro

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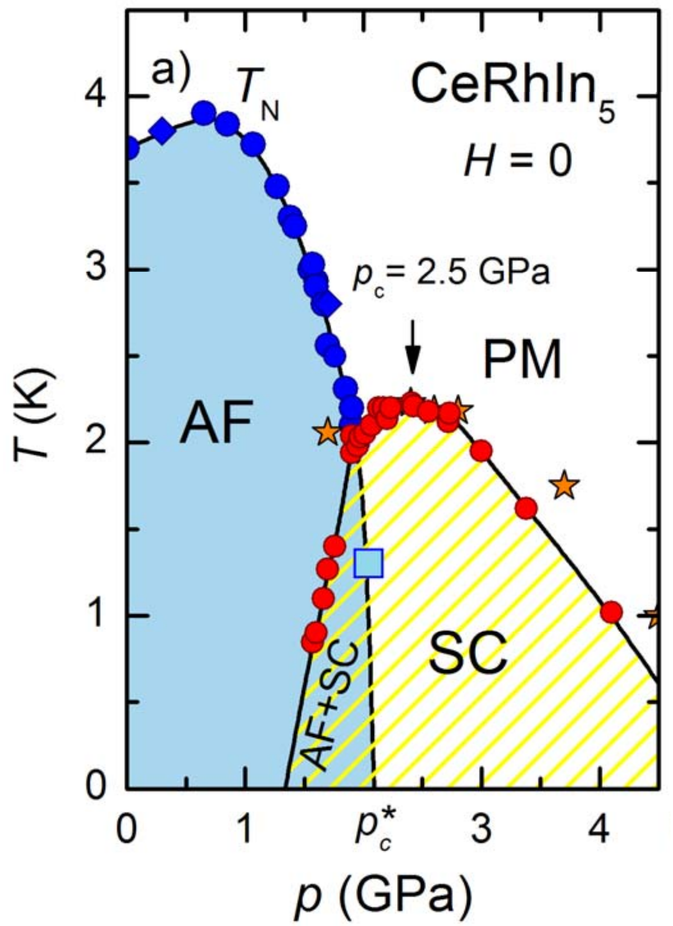
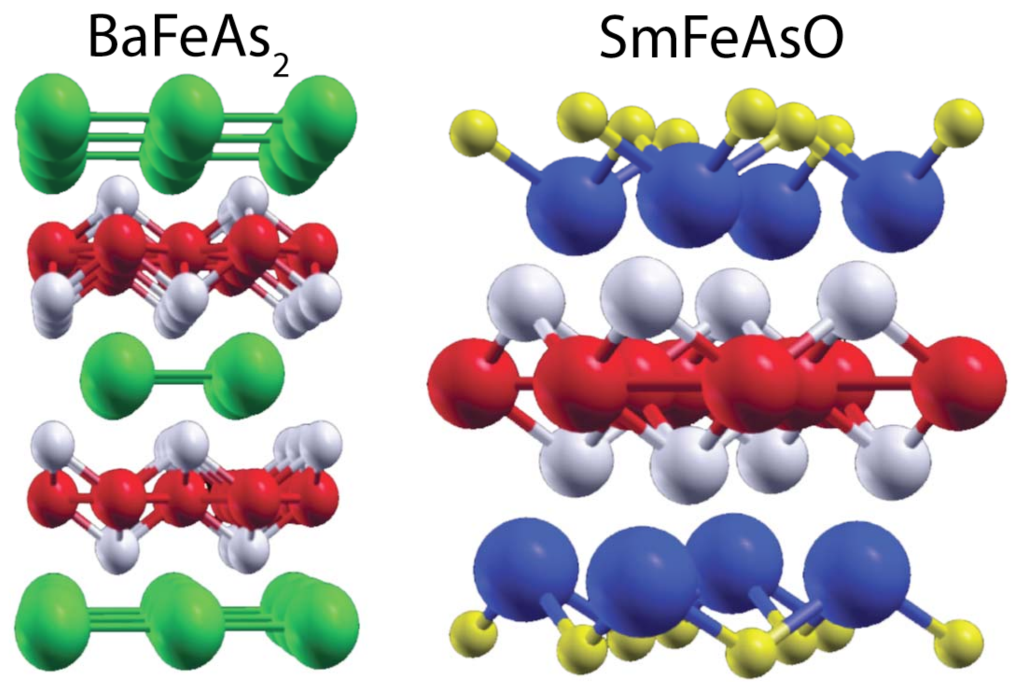
115 (in 2000)



http://inac.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_visu.php?id_ast=525

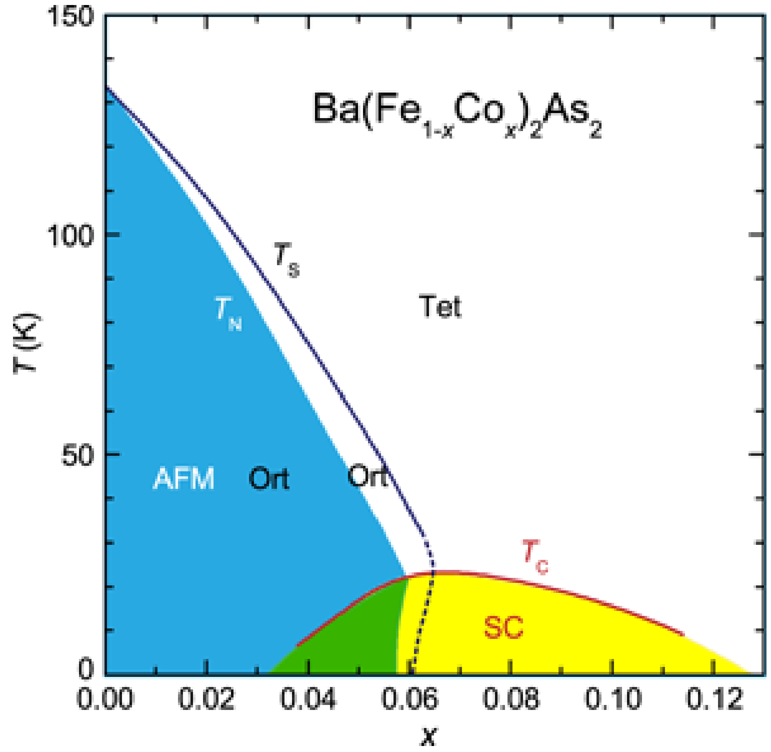
Pnictides (2008)



[redacted]

http://www.stanford.edu/~tpd/research_hightc.html

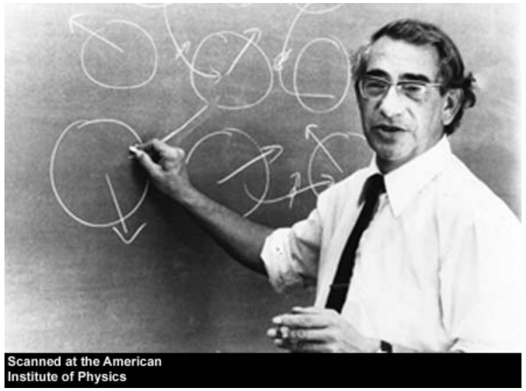
Pnictides



http://physics.aps.org/articles/v3/41

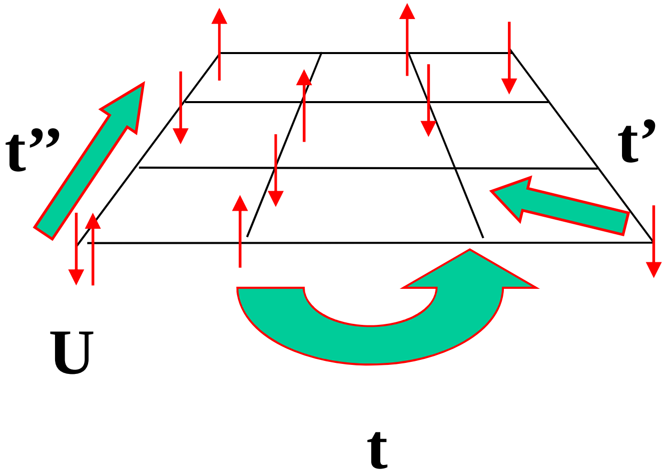
Antiferromagnetism means repulsion

Hubbard model



1931-1980

μ

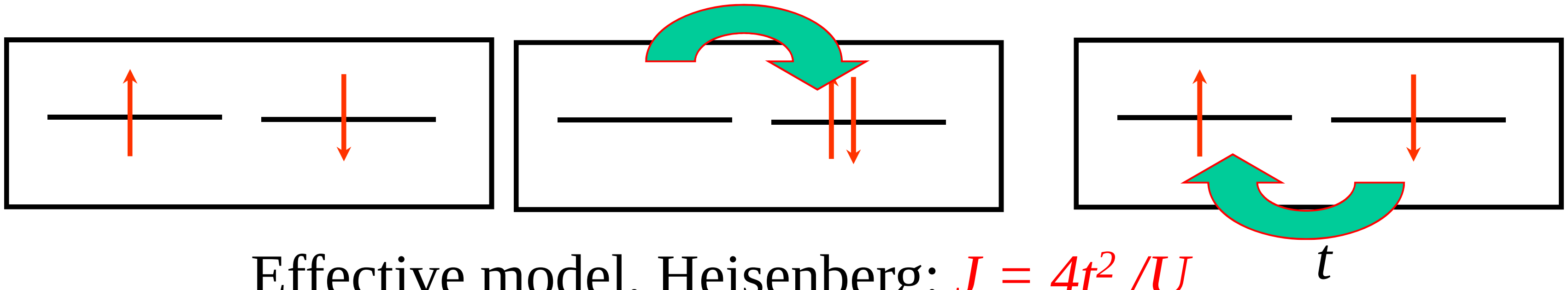


$$H = -\sum_{<ij>\sigma} t_{i,j} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

Weak coupling

Strong coupling

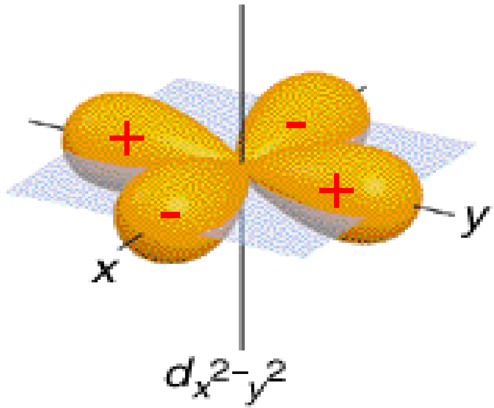
Antiferromagnetism and repulsion



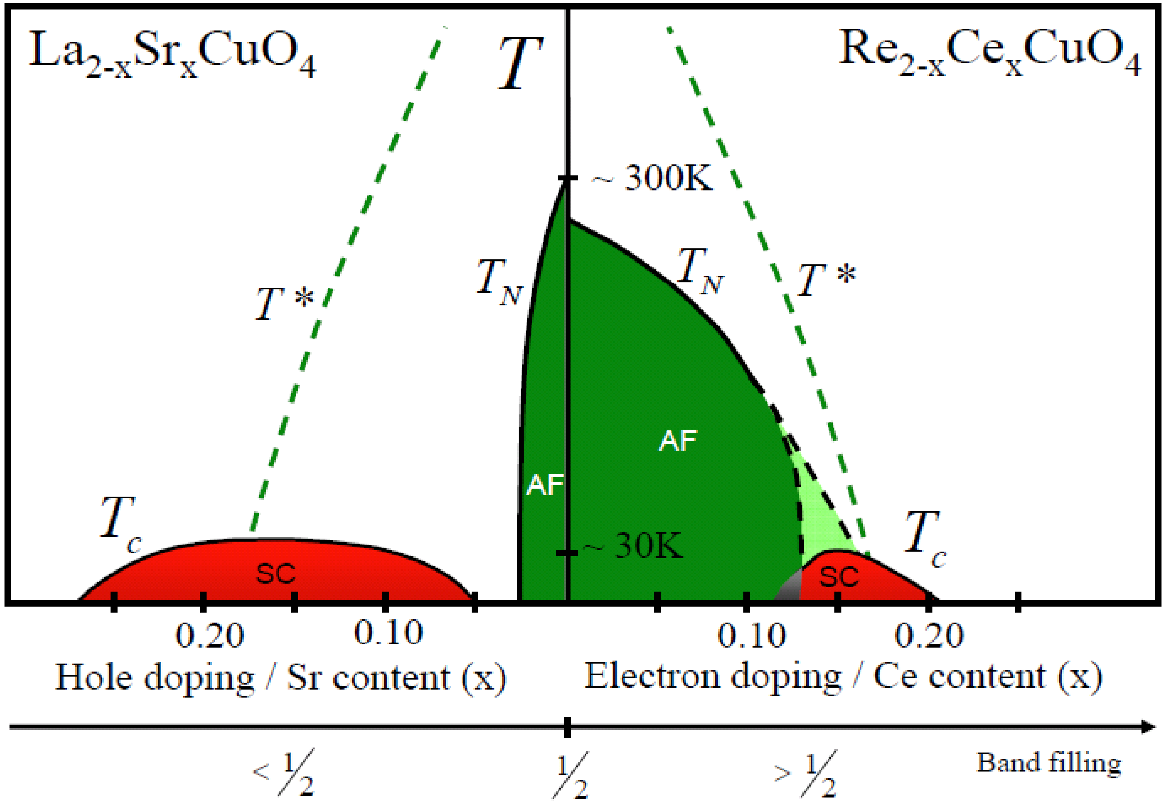
Effective model, Heisenberg: $J = 4t^2/U$

Superconductivity with repulsion

$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow}$$



Weak to intermediate coupling



Armitage, Fournier, Greene, RMP (2009)

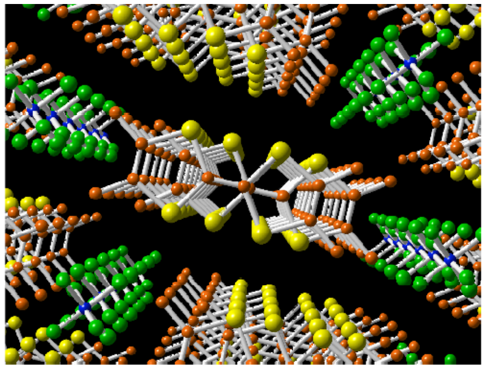
FLEX, Bickers, Scalapino

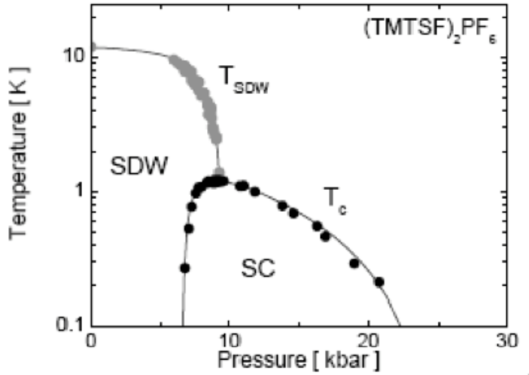
Two-particle self-consistent approach, Vilk, Kyung,A.-M.S.T.

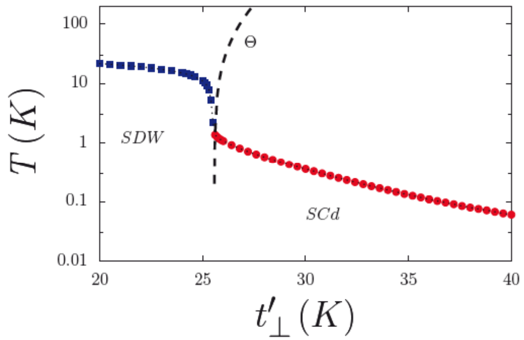
Weak to intermediate coupling

- Renormalization group

Claude Bourbonnais



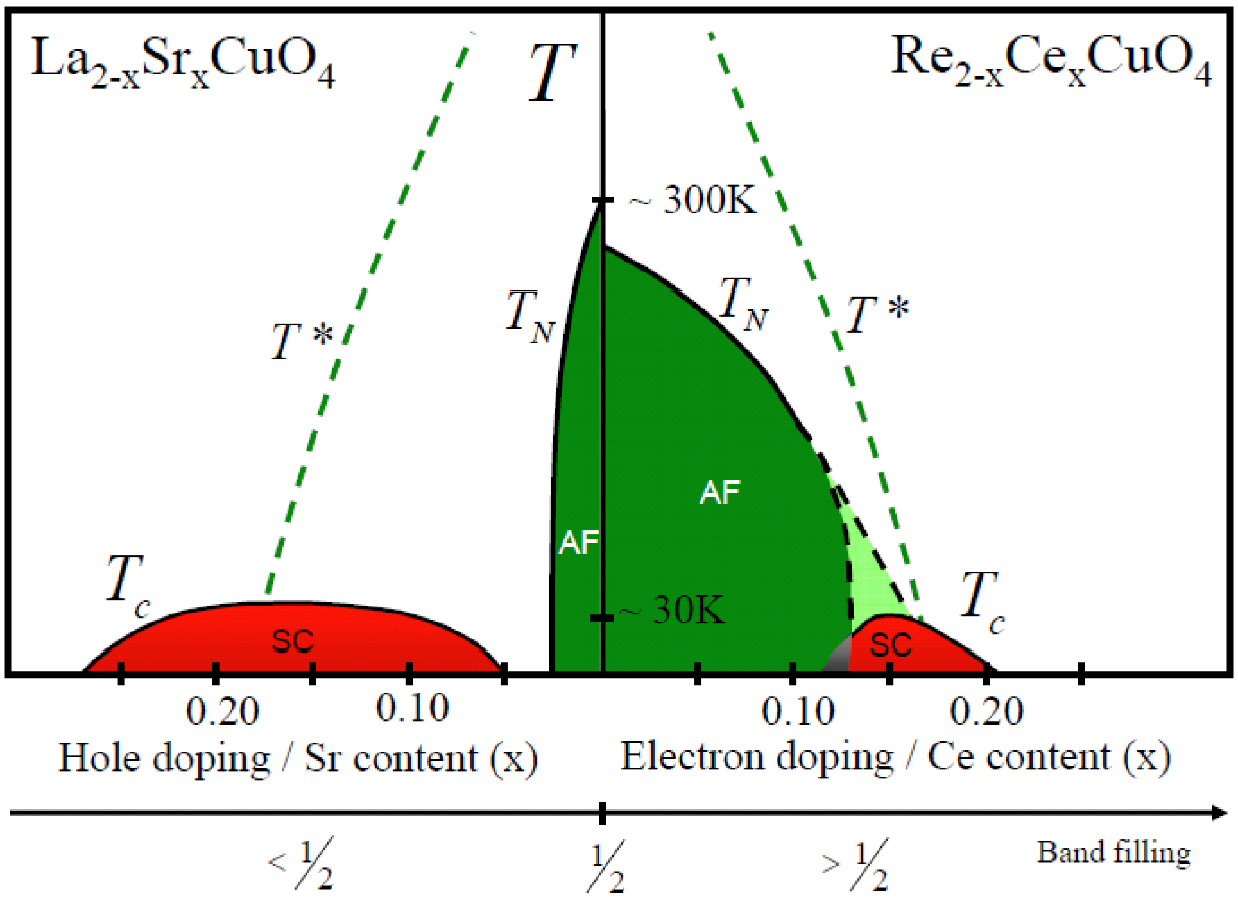




Strong correlations

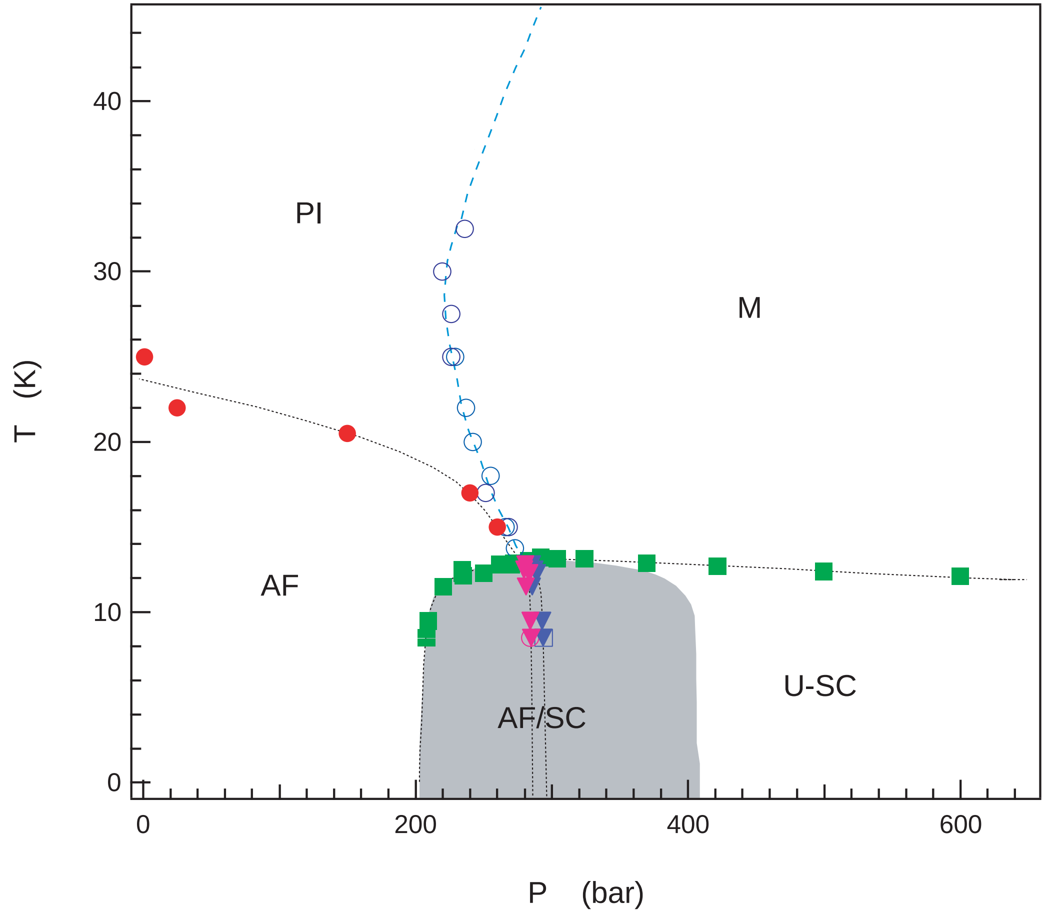
Phase diagram

Insulator even if $n=1$



Armitage, Fournier, Greene, RMP (2009)

Experimental phase diagram BEDT-X



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S. Lefebvre et al. PRL **85**, 5420 (2000), P. Limelette, et

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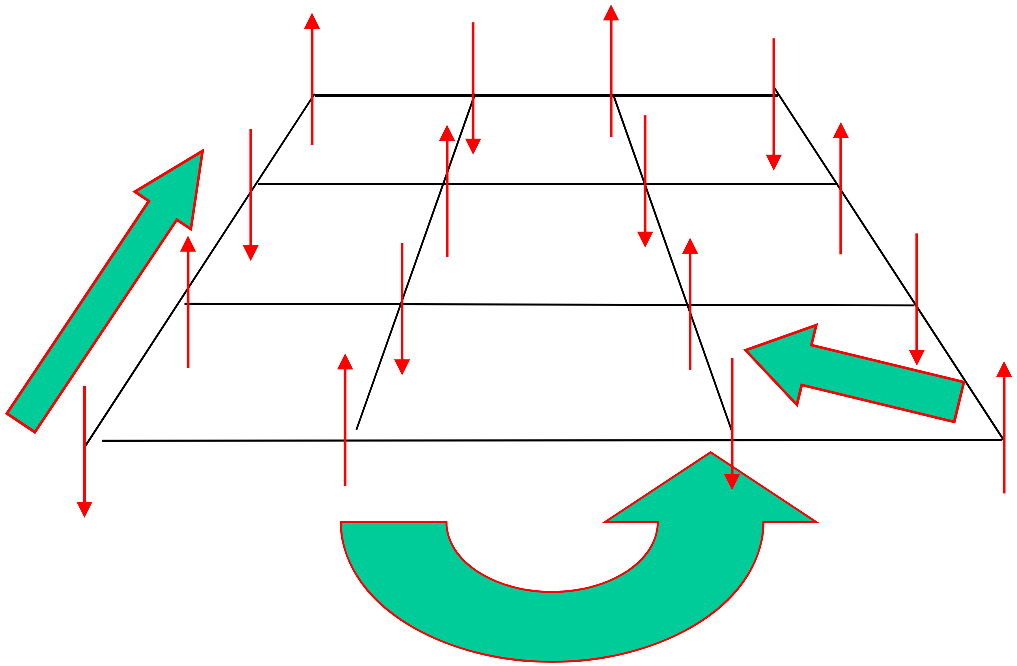
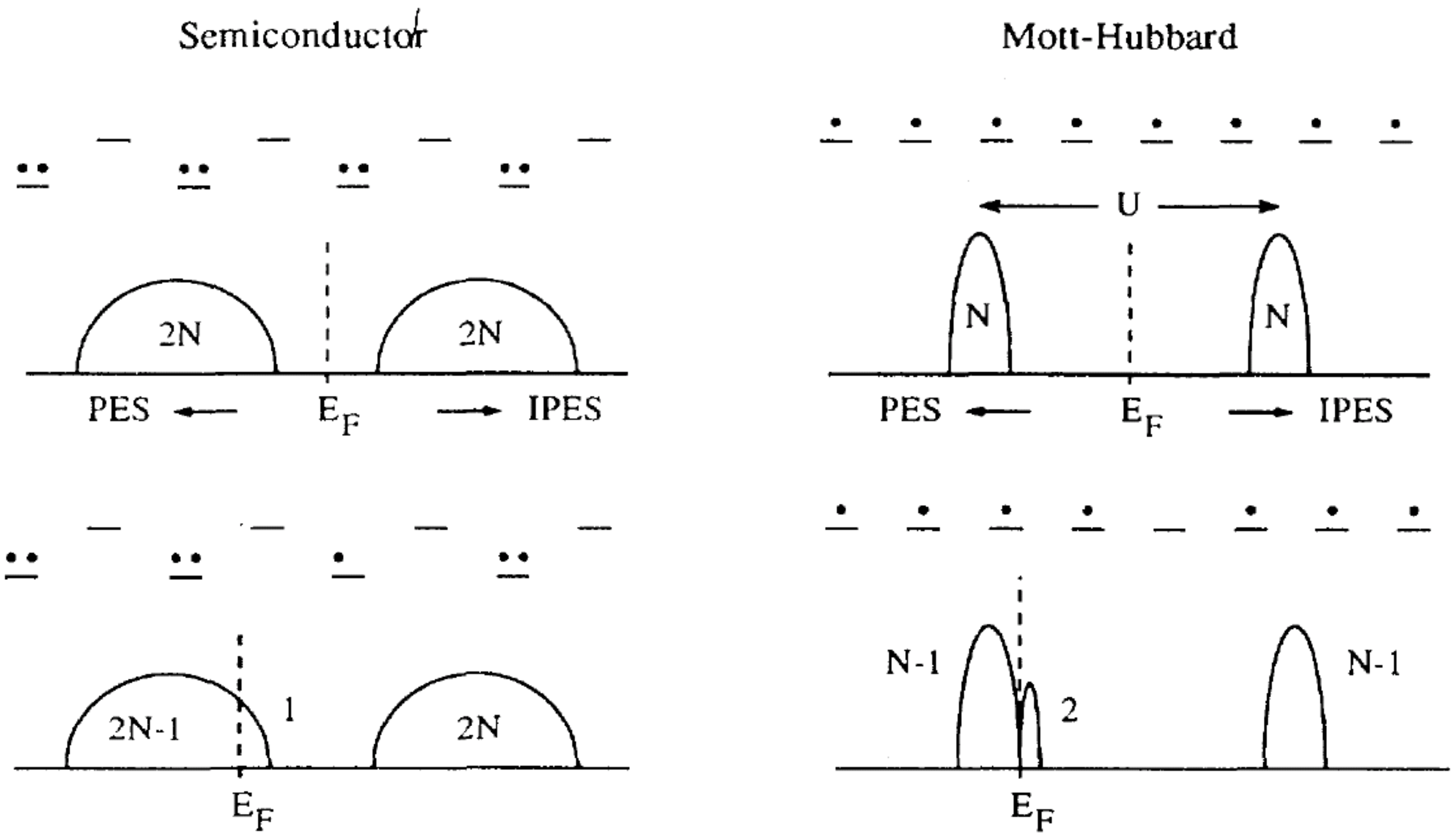
A quantum traffic jam (A.P.): Mott insulator



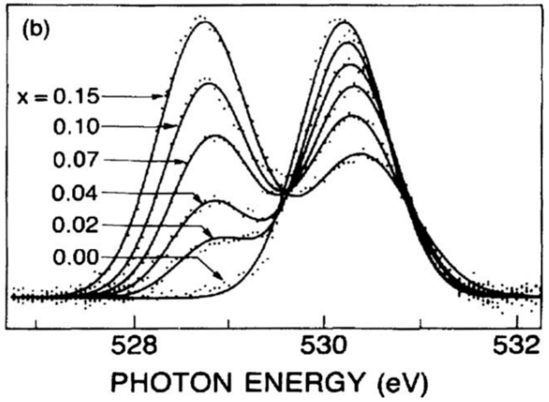
Spectral weight transfer



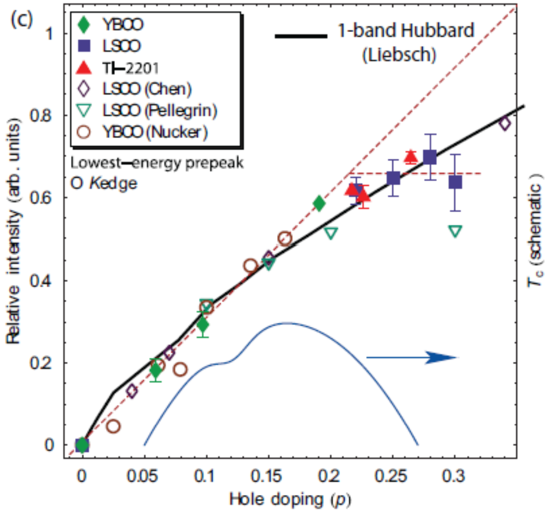
Meinders *et al.* PRB **48**, 3916 (1993)

Cuprates as doped Mott insulators

Experiment: X-Ray absorption



Chen et al. PRL **66**, 104 (1991)



Peets et al. PRL **103**, (2009), Phillips, Jarrell arXiv

Number of low energy states above ω = 0 scales as *2x* +

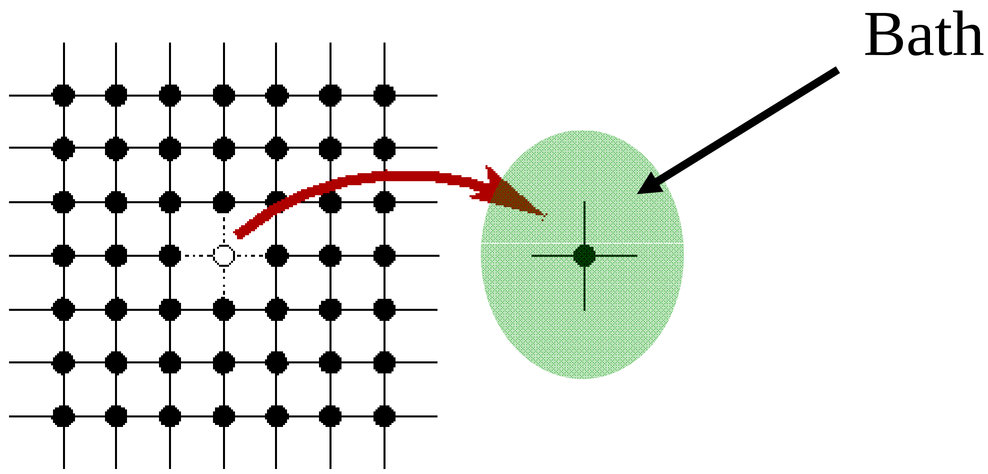
Not as 1+x as in Fermi liquid

Meinders *et al.* PRB **48**, 3916 (1993)

Theoretical method

Mott transition and Dynamical Mean-Field Theory. The beginnings in *d = infinity*

- Compute scattering rate (self-energy) of impurity problem.
- Use that self-energy (ω dependent) for lattice.
- Project lattice on single-site and adjust bath so that single-site DOS obtained both ways be equal.



W. Metzner and D. Vollhardt, PRL (1989)
A. Georges and G. Kotliar, PRB (1992)
M. Jarrell PRB (1992)

DMFT, (*d = 3)*

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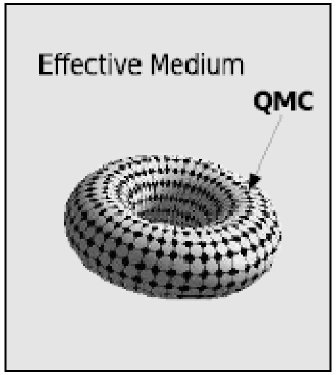
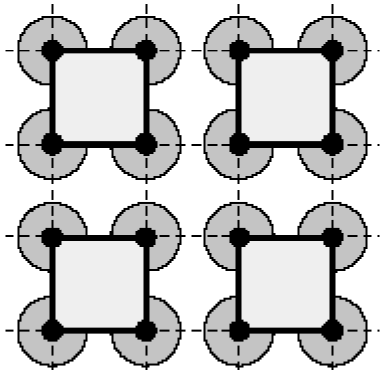
2d Hubbard: Quantum cluster method

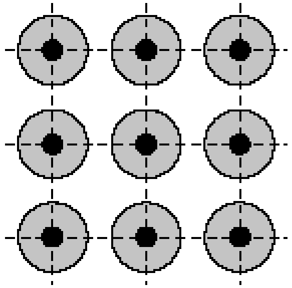


DCA

C-DMFT



DMFT



Hettler …Jarrell…Krishnamurty PRB **58** (1998)
Kotliar et al. PRL **87** (2001)
M. Potthoff *et al.* PRL **91,** 206402 (2003).
Maier, Jarrell et al., Rev. Mod. Phys. **77**, 1027 (2005)

Solving cluster in a bath problem

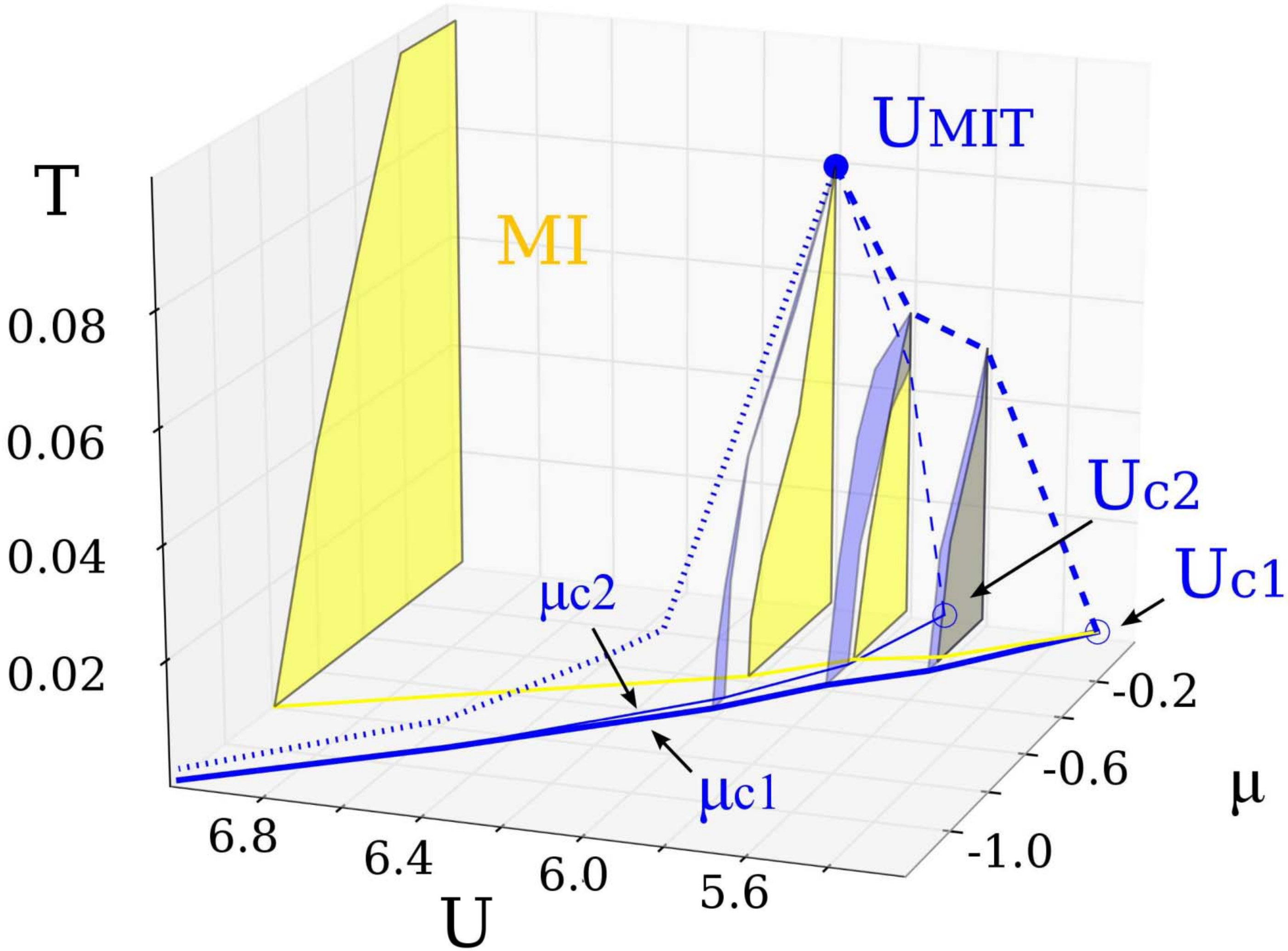
- Continuous-time Quantum Monte Carlo calculations to sum all diagrams generated from expansion in powers of hybridization.

  – P. Werner, A. Comanac, L. de' Medici, M. Troyer, and A. J. Millis, Phys. Rev. Lett. **97**, 076405 (2006).

  – K. Haule, Phys. Rev. B **75**, 155113 (2007).

The « normal » state

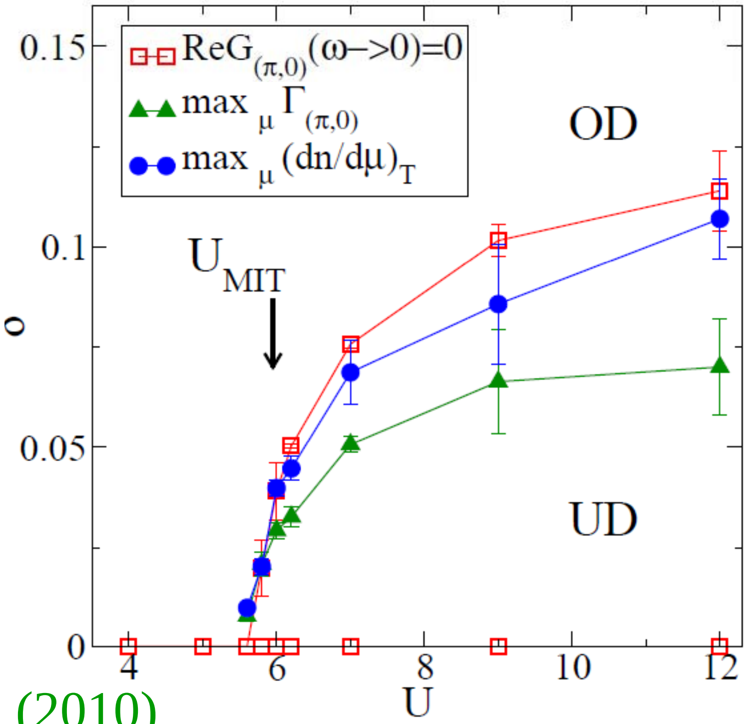
Normal state phase diagram



Mott felt away from *n* = *1*

Giovanni Sordi

Kristjan Haule



G. Sordi, K. Haule, A.-M.S.T PRL, **104**, 226402 (2010)
and arXiv:1102.0463

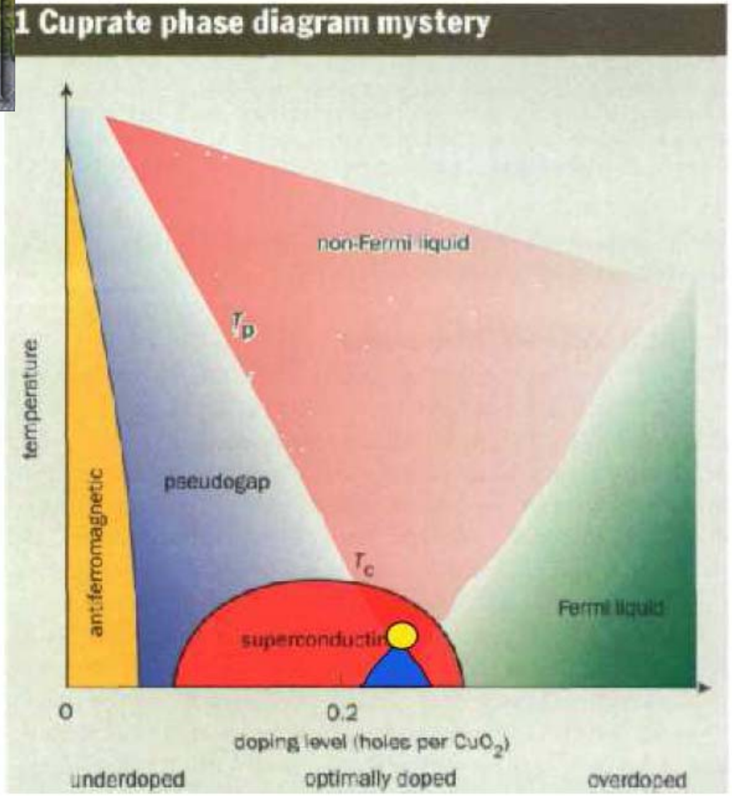
- first order transition at finite doping between two metals
- it is associated to Mott physics: all signatures of the first order transition can be traced back to Mott critical point

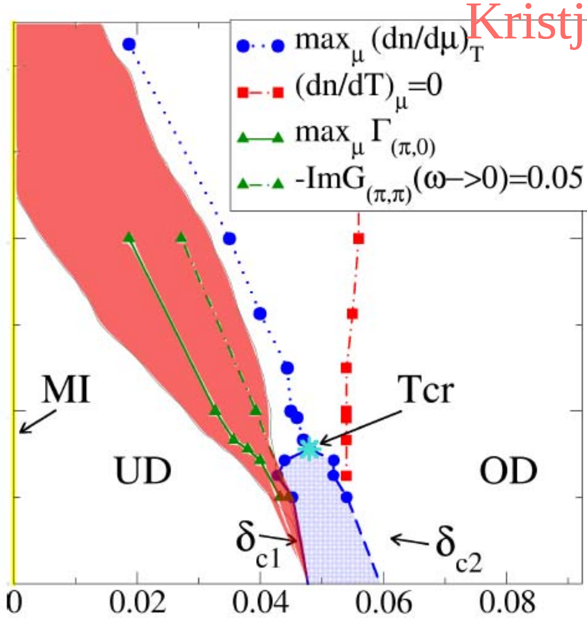
$\Rightarrow$ signature of the Mott transition in the 2D Hubbard model extends way beyond half filling!

Beneath the dome

Giovanni Sordi

Kristjan Haul





criticality originates from

first order transition at finite doping

coming from influence of Mott physics well beyond half filling!

G. Sordi, K. Haule, A.-M.S.T PRL, **104**, 226402 (2010)
and arXiv:1102.0463

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Strongly Correlated Superconductivity

Phase diagram

Exact diagonalization as impurity solver (*T=0*).

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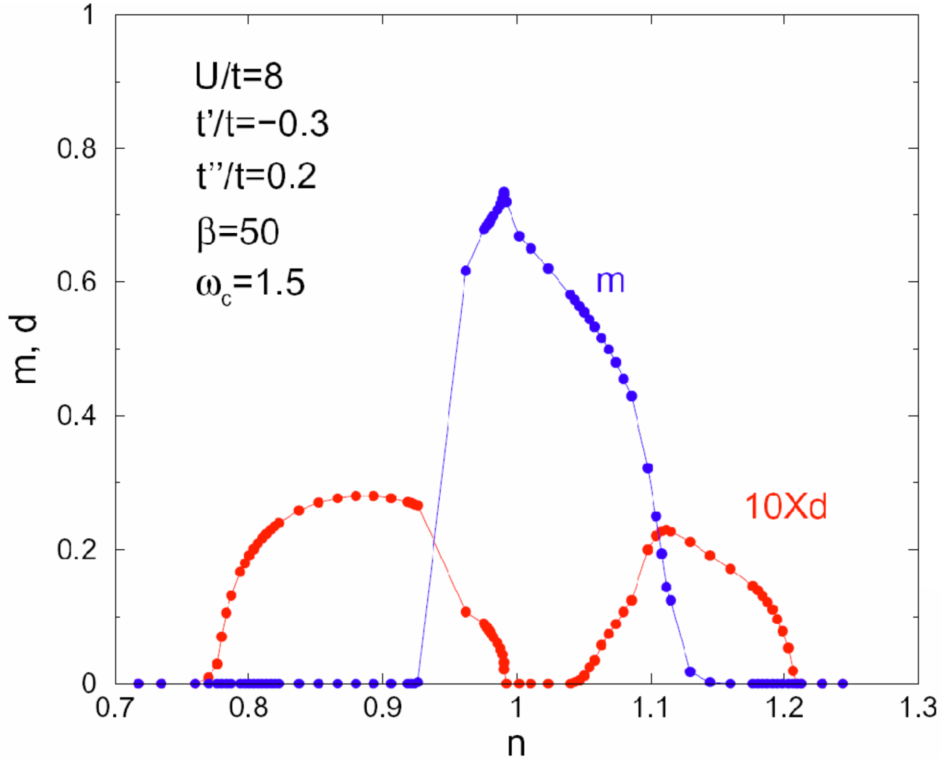
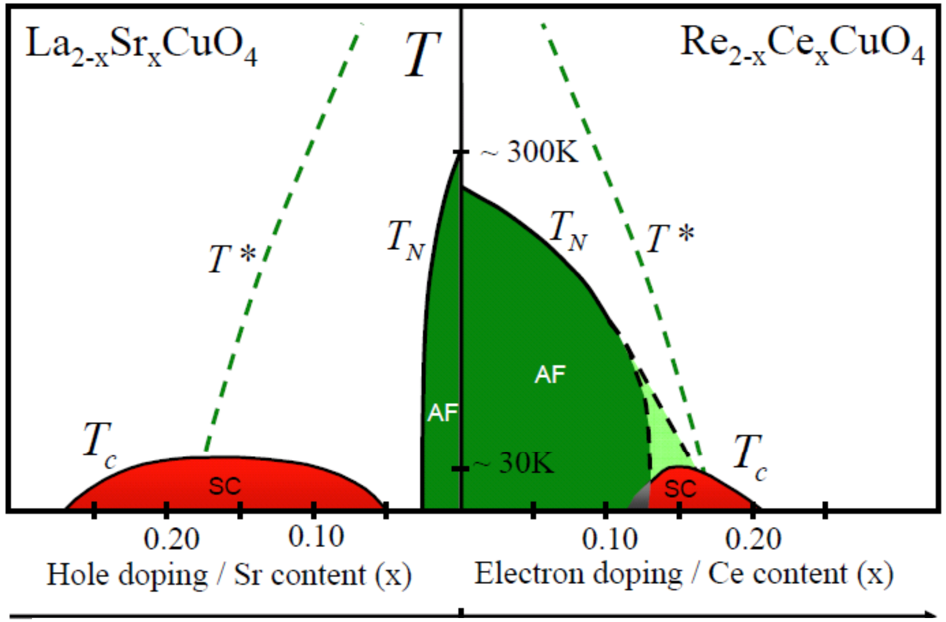
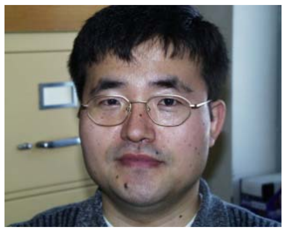
CDMFT global phase diagram



Kancharla, Kyung, Civelli, Sénéchal, Kotliar AMST Phys. Rev. B (2008)



Armitage, Fournier, Greene, RMP (2009)



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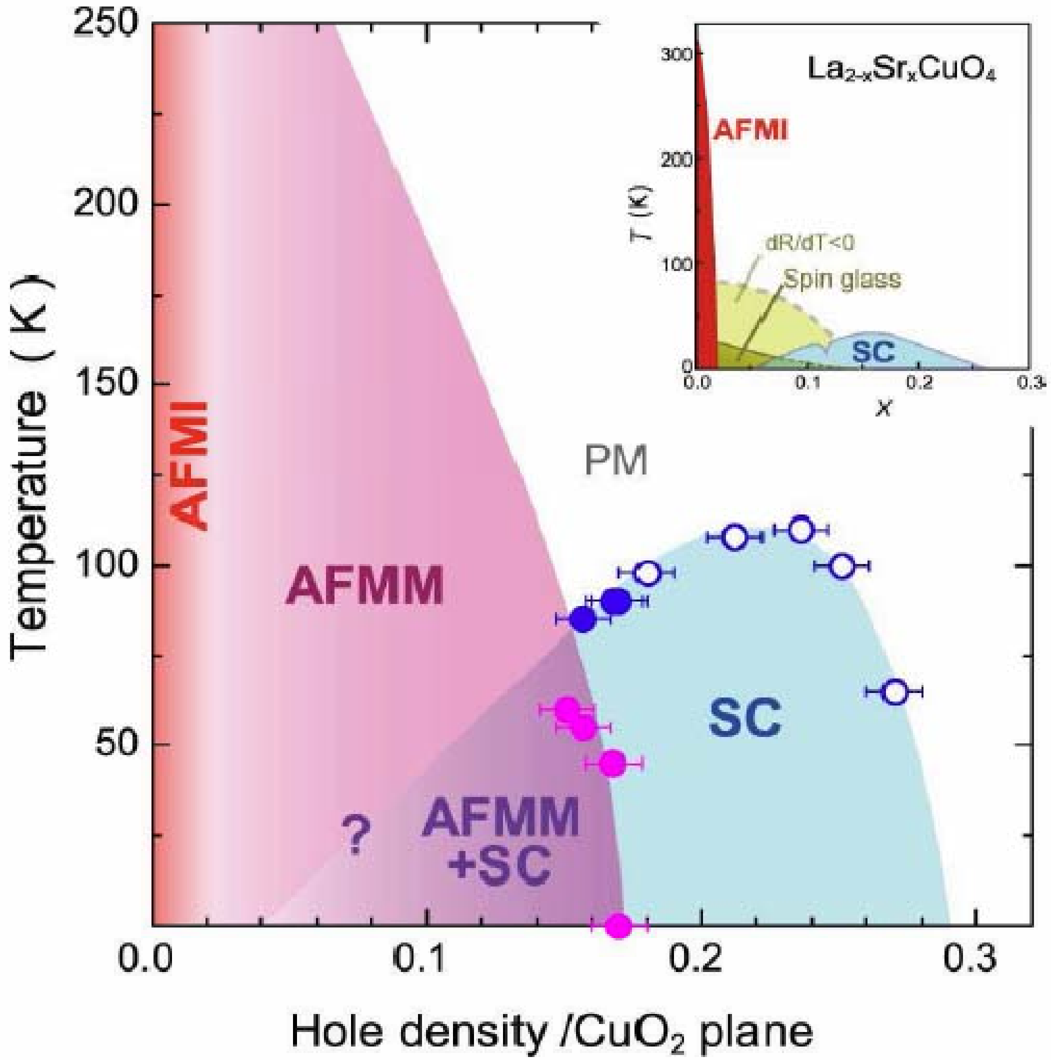
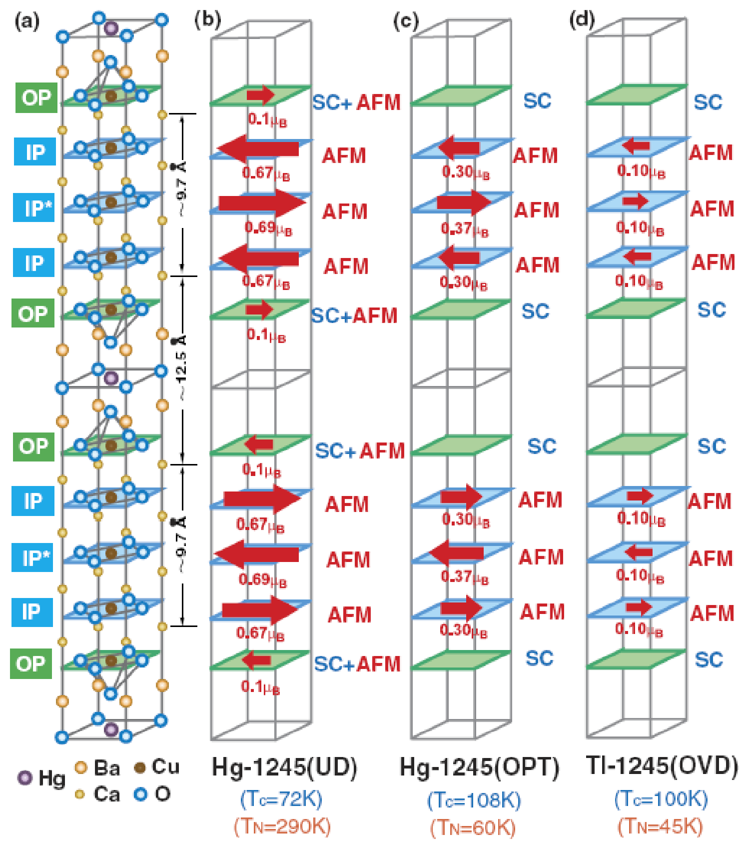
Consistent with following experiment

H. Mukuda, Y. Yamaguchi, S. Shimizu, … A. Iyo JPSJ **77**, 124706 (2008)





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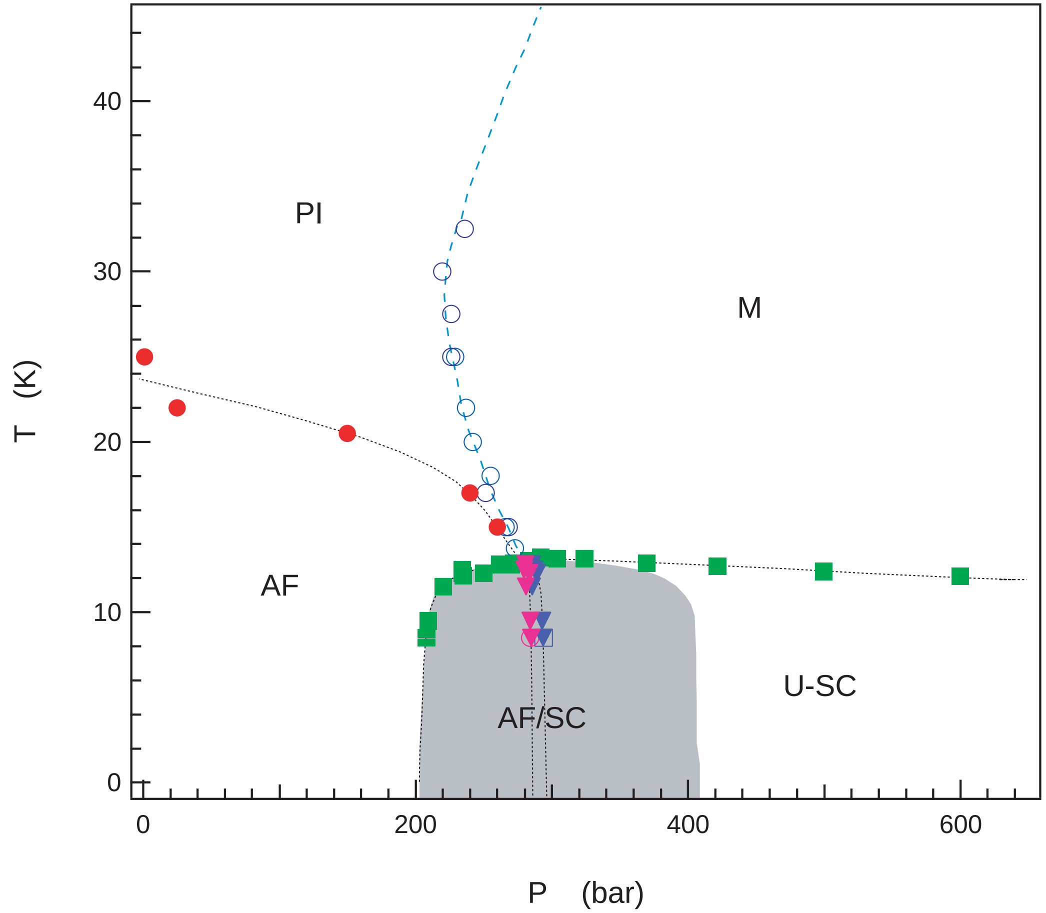
Experimental phase diagram BEDT-X



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S. Lefebvre et al. PRL **85**, 5420 (2000), P. Limelette, et

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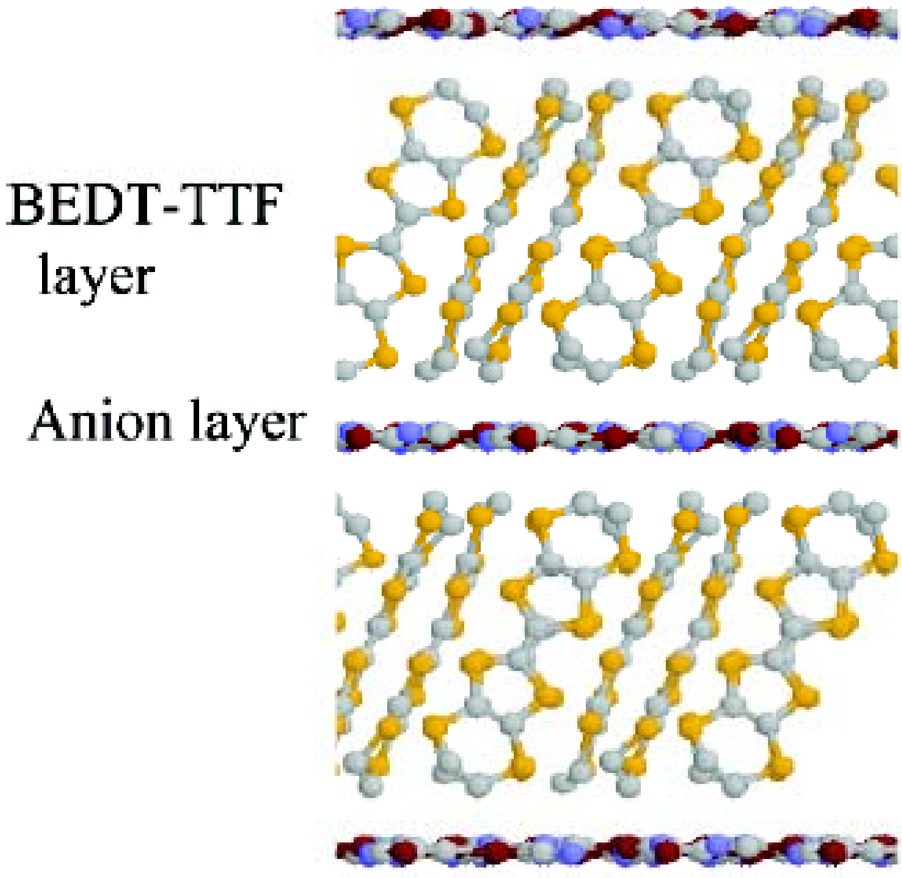
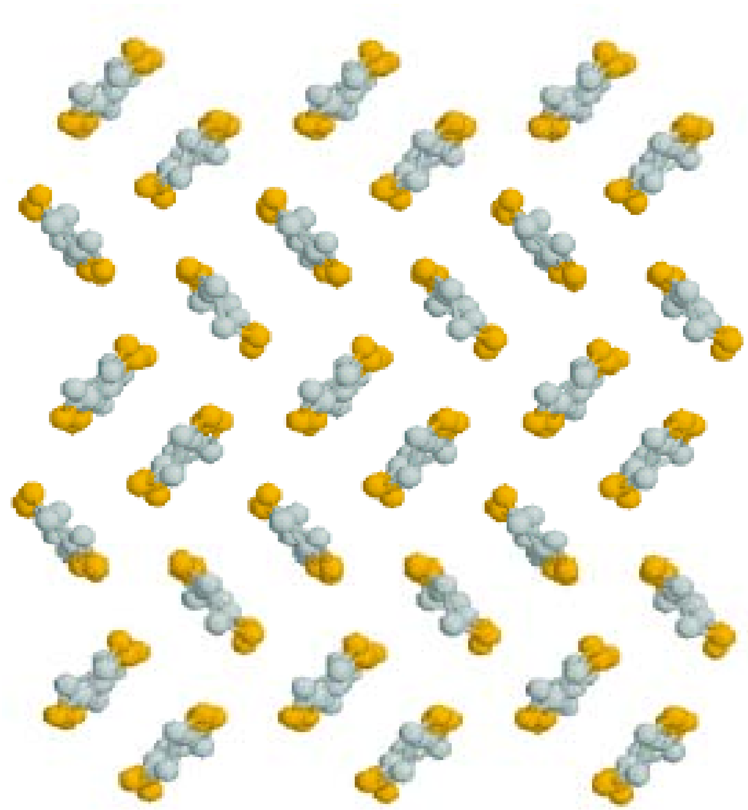
Layered organics (κ–BEDT-X family)





$t \approx 50\ \text{meV}$

$\Rightarrow U \approx 400\ \text{meV}$

$t'/t \sim 0.6 - 1.1$

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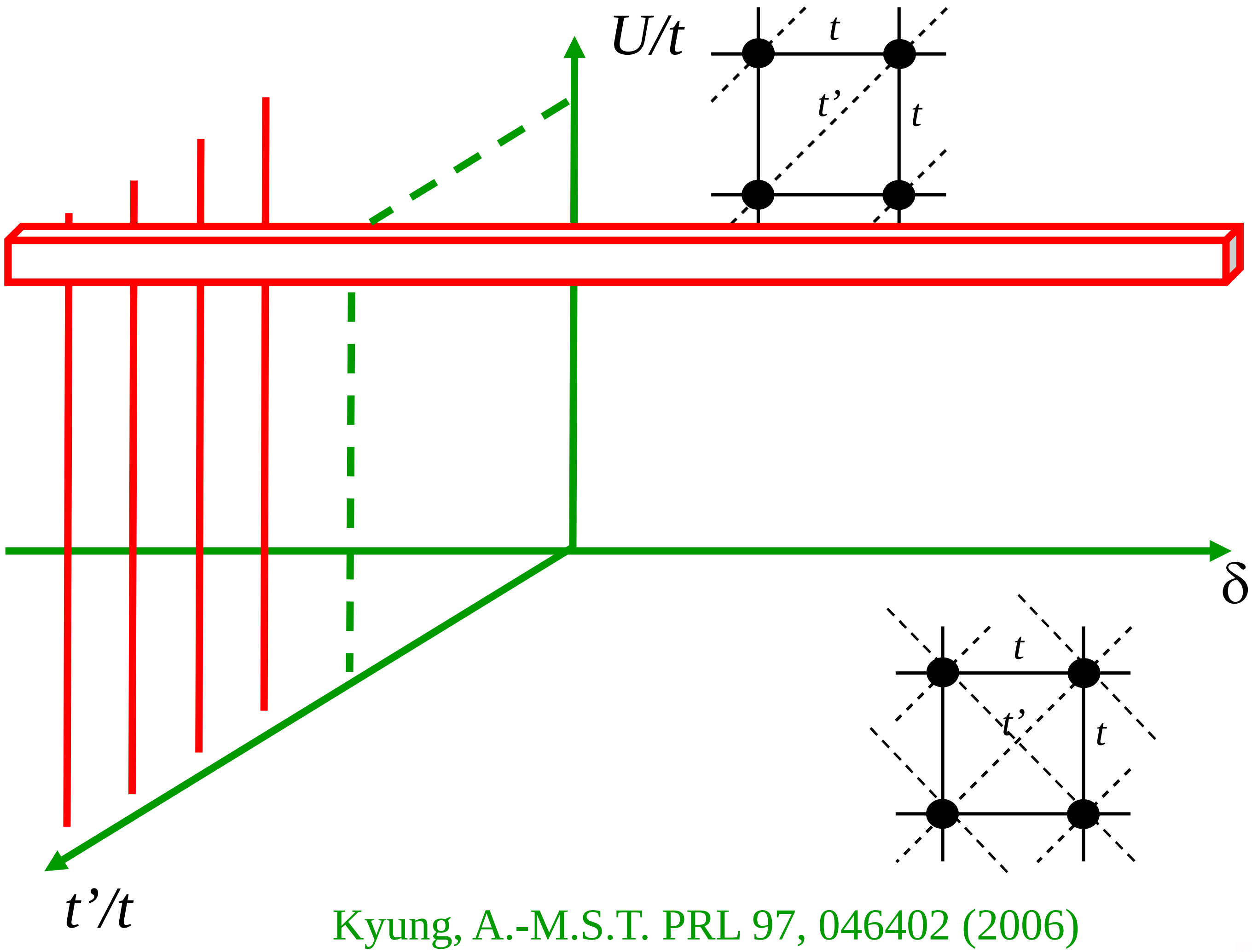
Perspective

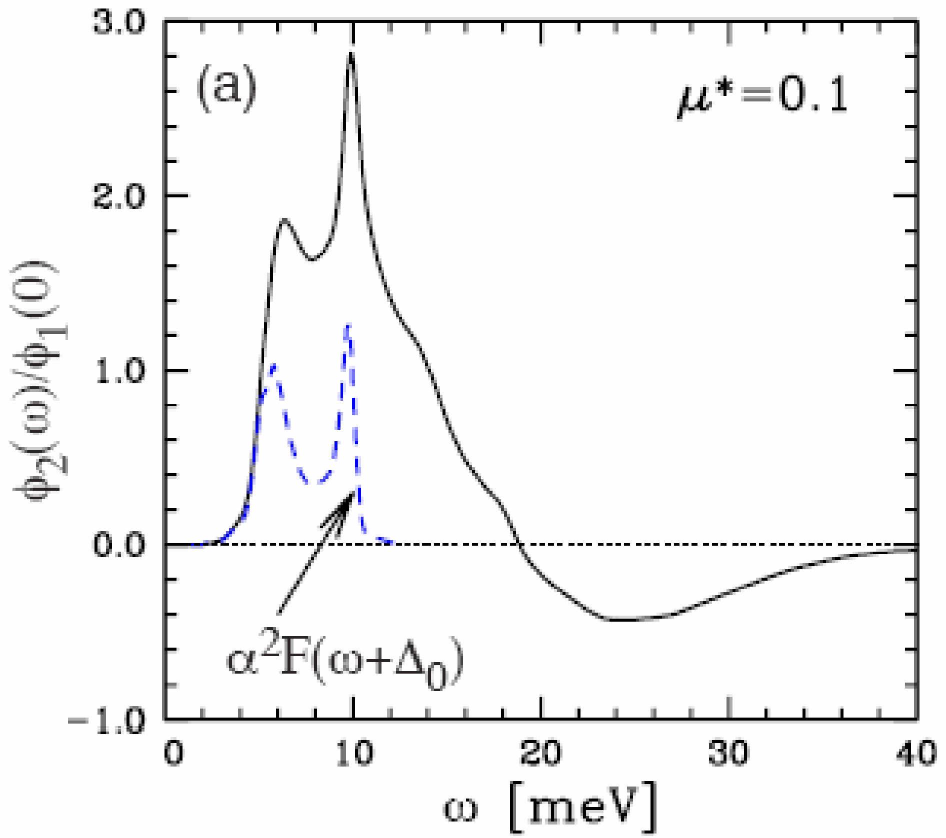


Kyung, A.-M.S.T. PRL 97, 046402 (2006)

The glue

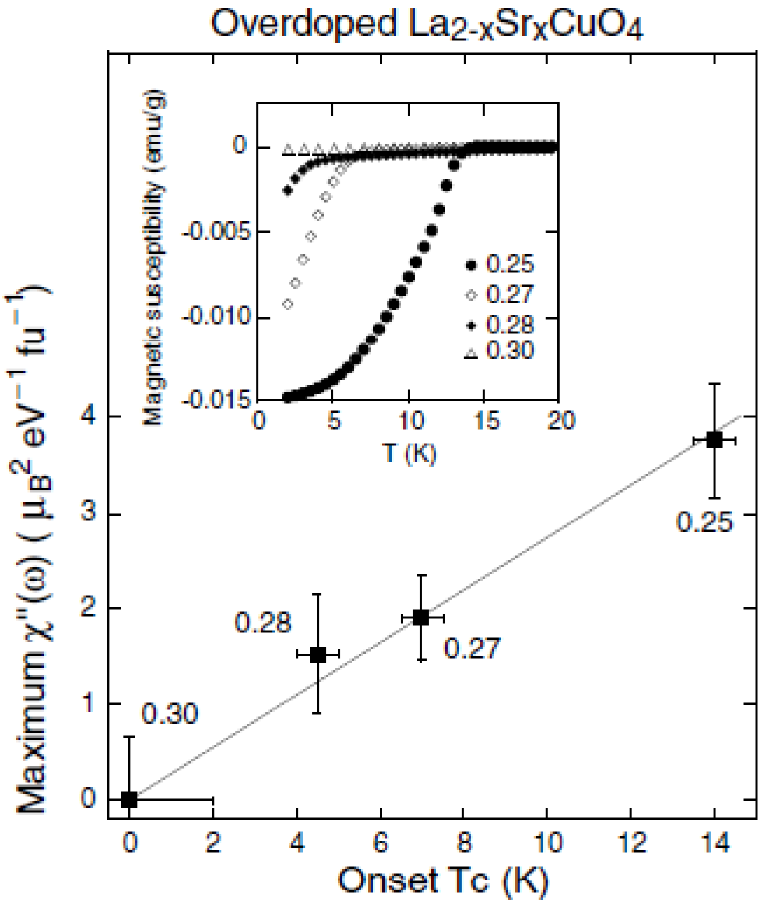
Im Σ_{an} and electron-phonon in Pb

Maier, Poilblanc, Scalapino, PRL (2008)

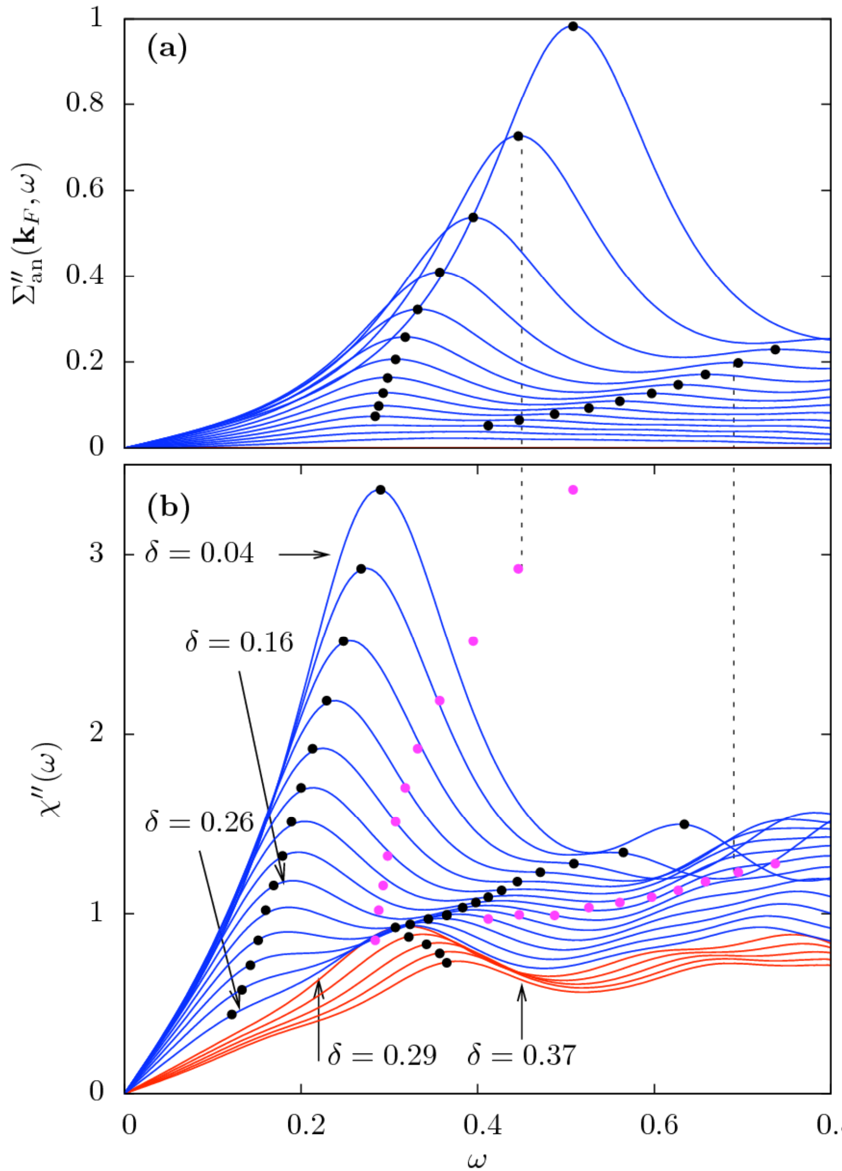


The glue

Kyung, Sénéchal, Tremblay, Phys. Rev. B **80,** 205109 (2009)



Wakimoto … Birgeneau PRL (2004)



The glue and neutrons

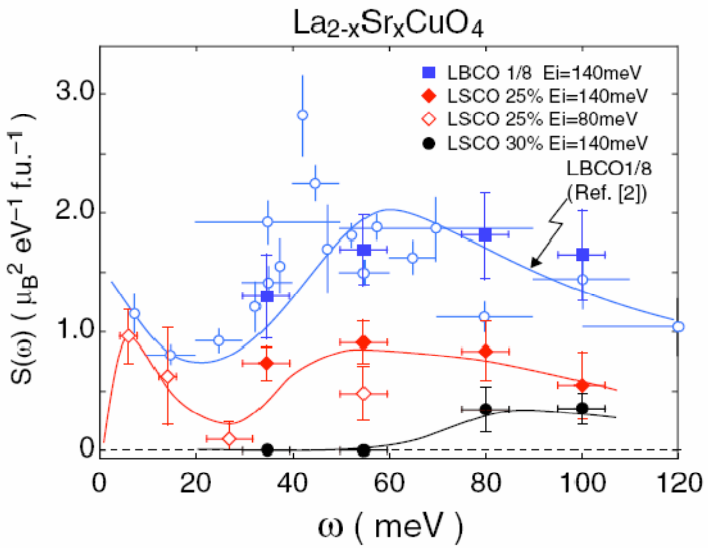
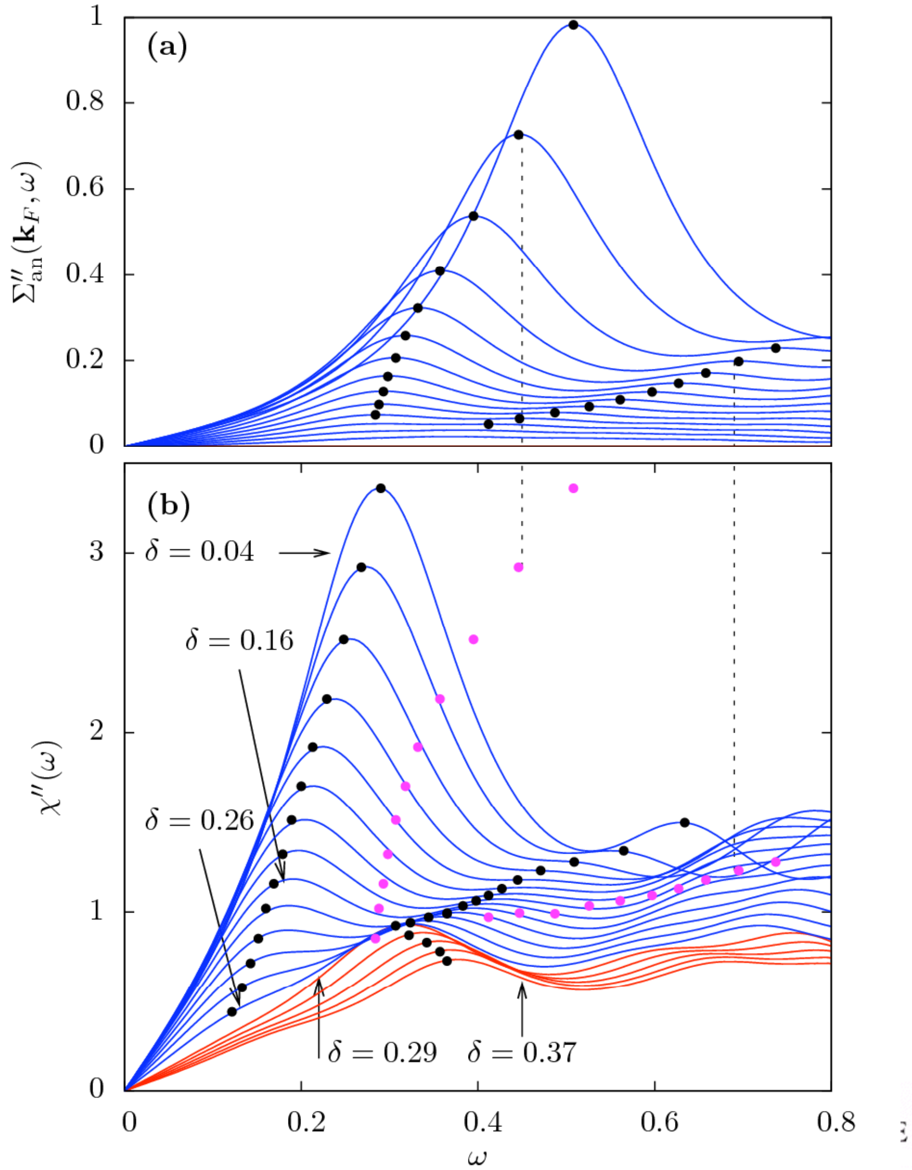
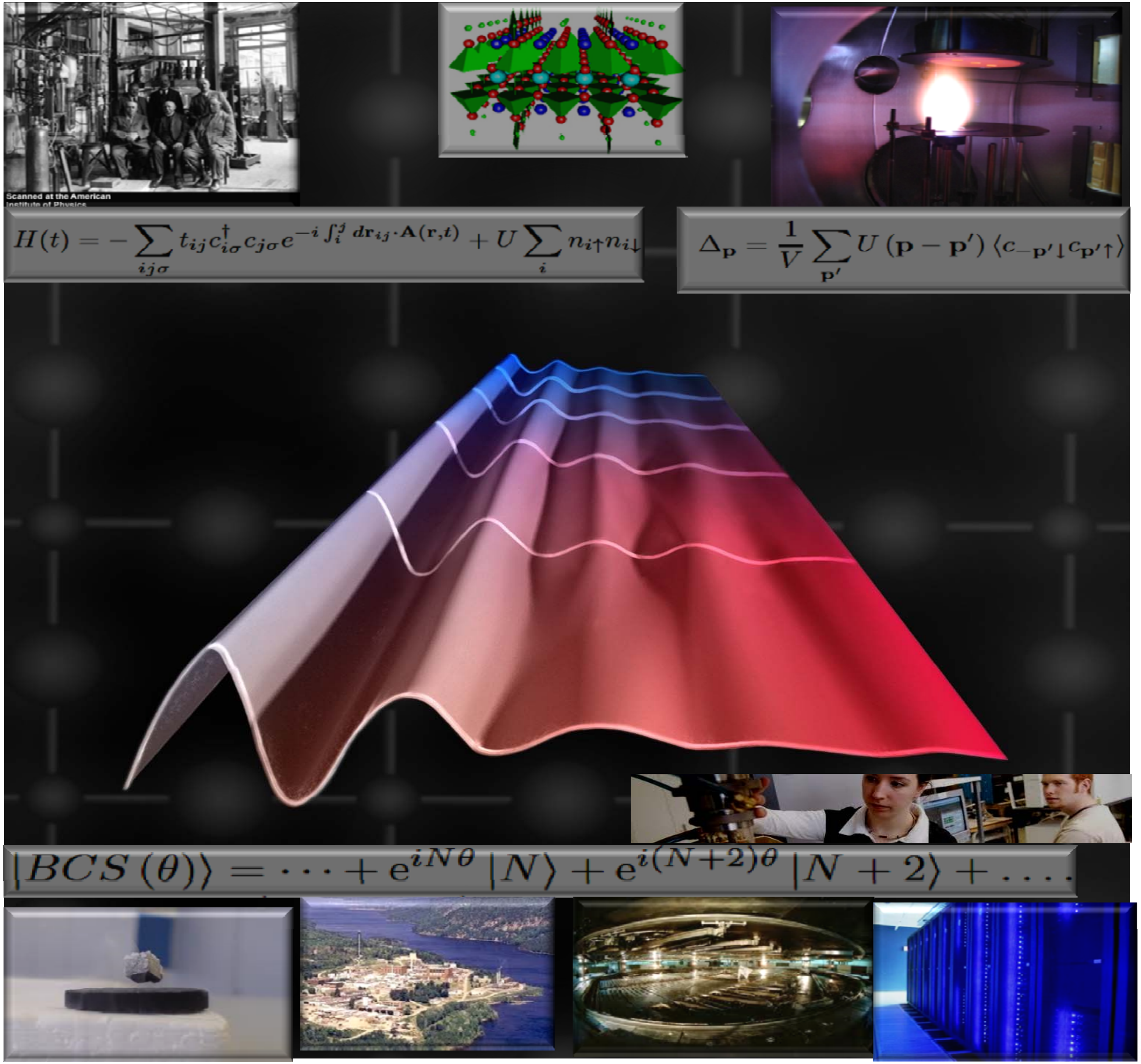


FIG. 3 (color online). **Q**-integrated dynamic structure factor $S(\omega)$ which is derived from the wide-H integrated profiles for LBCO 1/8 (squares), LSCO $x = 0.25$ (diamonds; filled for E_i = 140 meV, open for E_i = 80 meV), and $x = 0.30$ (filled circles) plotted over $S(\omega)$ for LBCO 1/8 (open circles) from [2]. The solid lines following data of LSCO $x = 0.25$ and 0.30 are guides to the eyes.



Wakimoto … Birgeneau PRL (2007);
PRL (2004)



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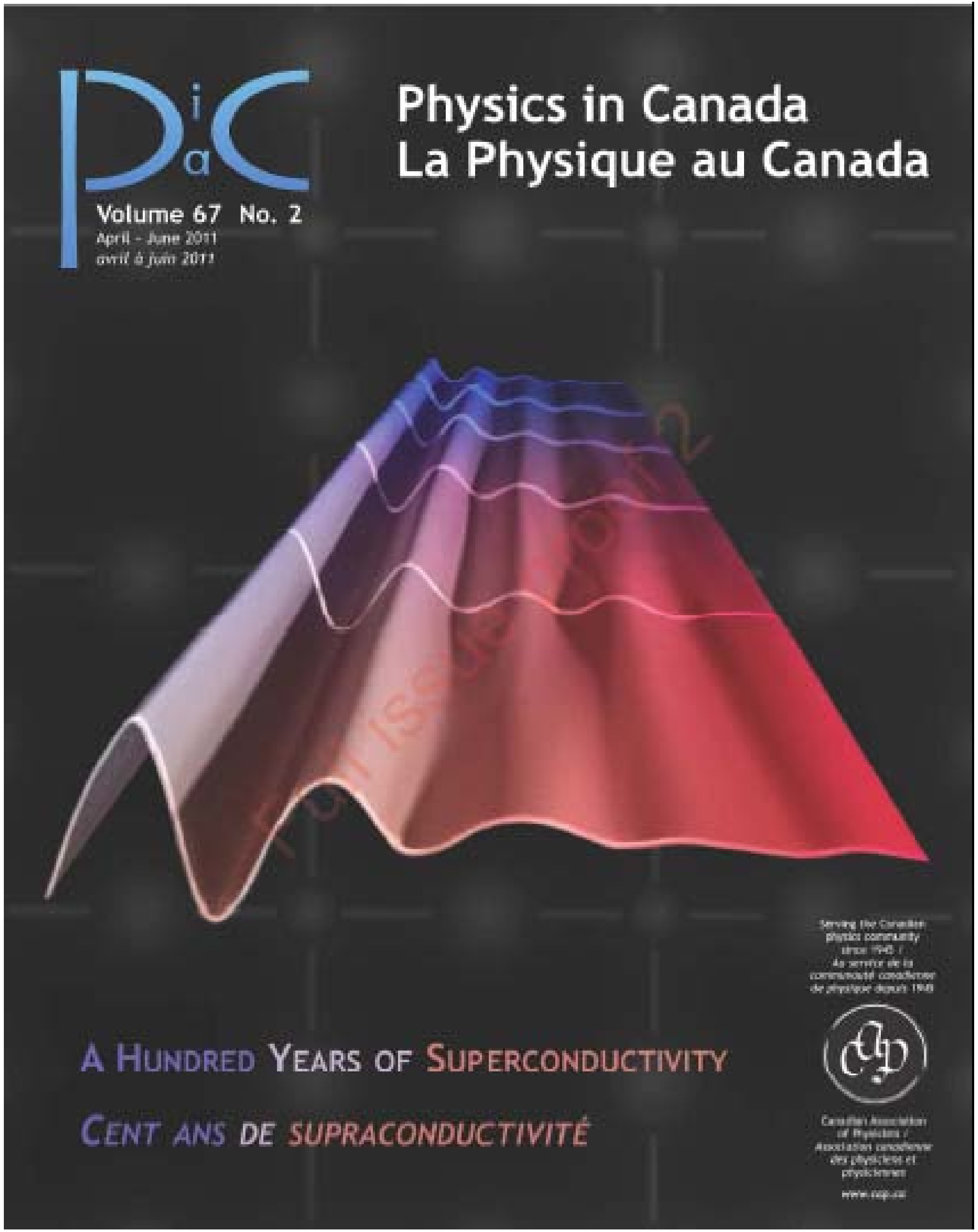

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The dream

room-temperature superconductors

50–50

They would transform the grid—if they can exist at all *By Michael Moyer*

You can build a coal-fired power plant just about anywhere. Renewables, on the other hand, are finicky. The strongest winds blow across the high plains. The sun shines brightest on the desert. Transporting that energy into cities hundreds of kilometers away will be one of the great challenges of the switch to renewable energy.

The most advanced superconducting cable can move those megawatts thousands of kilometers with losses of only a few percent. Yet there is a catch: the cable must be kept in a bath of liquid nitrogen at 77 kelvins (or −196 degrees Celsius). This kind of deployment, in turn, requires pumps and refrigeration units every kilometer or so, greatly increasing the cost and complexity of superconducting cable projects.

Superconductors that work at ordinary temperatures and pressures would enable a truly global energy supply. The Saharan sun could power western Europe via superconducting cables strung across the floor of the Mediterranean Sea. Yet the trick to making a room-temperature superconductor is just as much of a mystery today as it was in 1986, when researchers constructed the first superconducting materials that worked at the relatively high temperatures of liquid nitrogen (previous substances needed to be chilled down to 23 kelvins or less).

Two years ago the discovery of an entirely new class of superconductor—one based on iron—raised hopes that theorists might be able to divine the mechanism at work in high-temperature superconductors [see "An Iron Key to High-Temperature Superconductivity?" by Graham P. Collins; SCIENTIFIC AMERICAN, August 2009]. With such insights in hand, perhaps a path toward room-temperature superconductors would come into view. But progress has remained slow. The winds of change don't always blow on cue.

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http://www.physique.usherbrooke.ca/taillefer/Vulgarisation.html

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To do

- Work with what we have
  - Quantum computer (SC vs laser)
- Improve theoretical methods
- Guide the search for new materials
  - AFM
  - U
  - There does not seem to be a fundamental law prohibiting room temperature superconductivity
- Design heterostructures

Main collaborators

Giovanni Sordi

David Sénéchal

Kristjan Haule

Sarma Kancharla

Gabi Kotliar

Bumsoo Kyung

Marcello Civelli

Satoshi Okamoto

Massimo Capone

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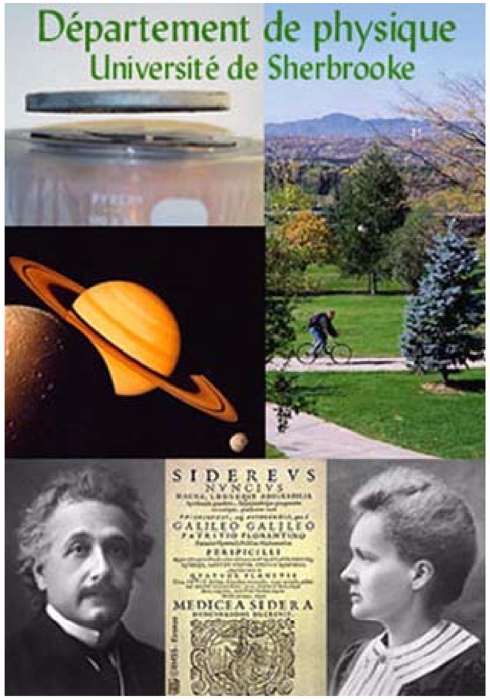

André-Marie Tremblay

CANADA RESEARCH CHAIRS
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Merci

Thank you