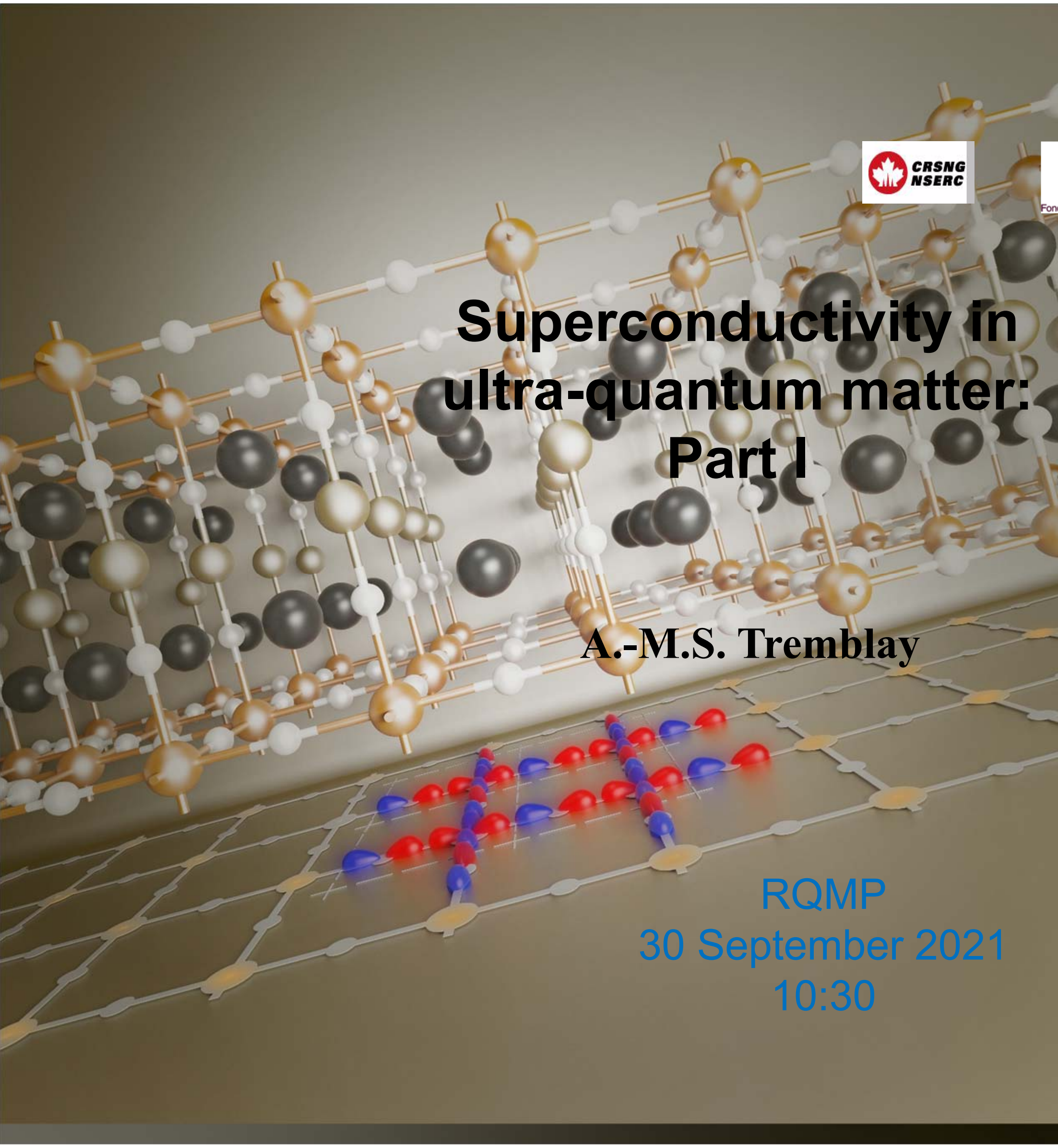
Journée nationale de la vérité et de la réconciliation

UDEMNOUVELLES | LE 27 SEPTEMBRE 2021 | CHRISTINE FORTIER

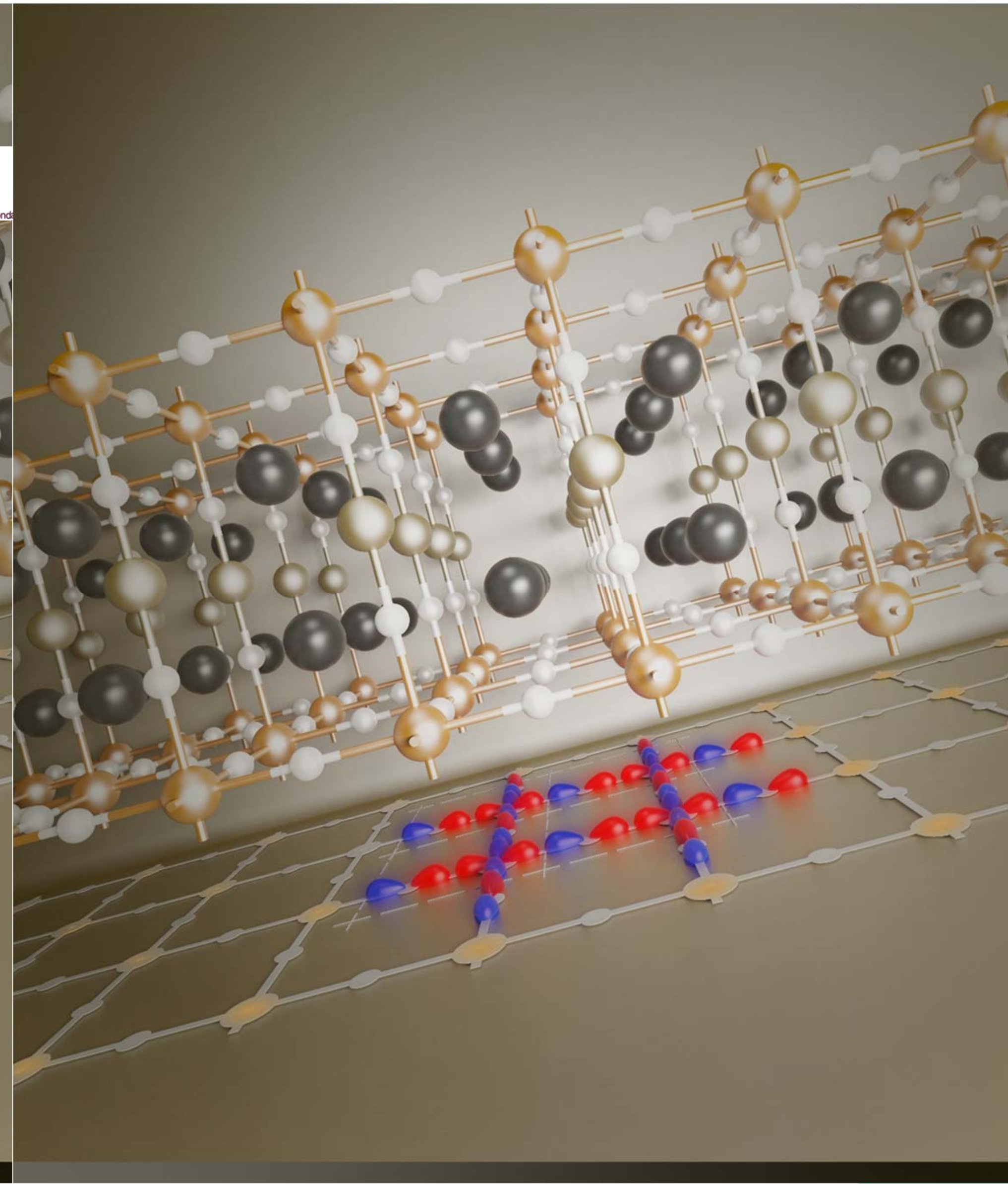


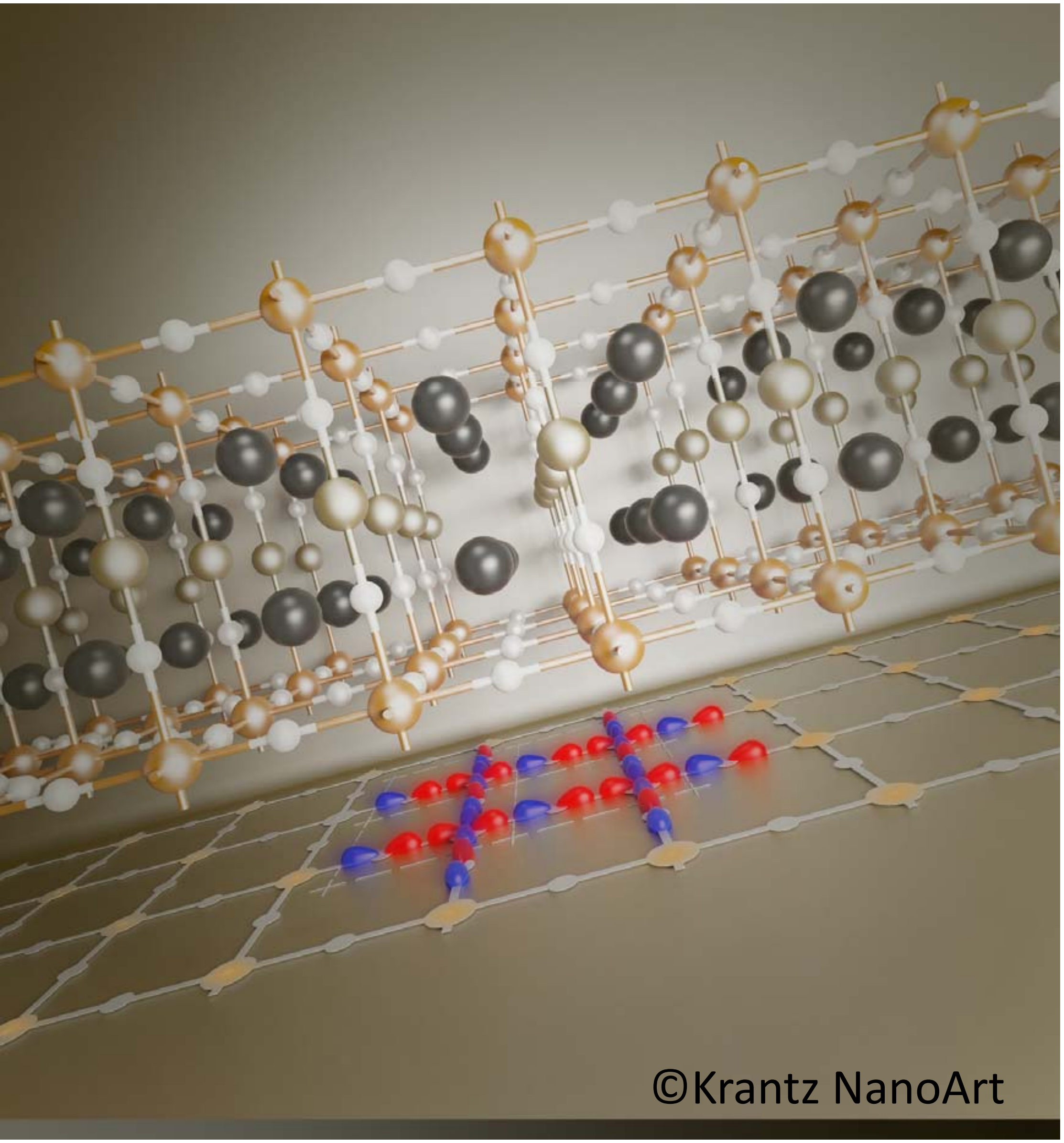
CRSNG NSERC

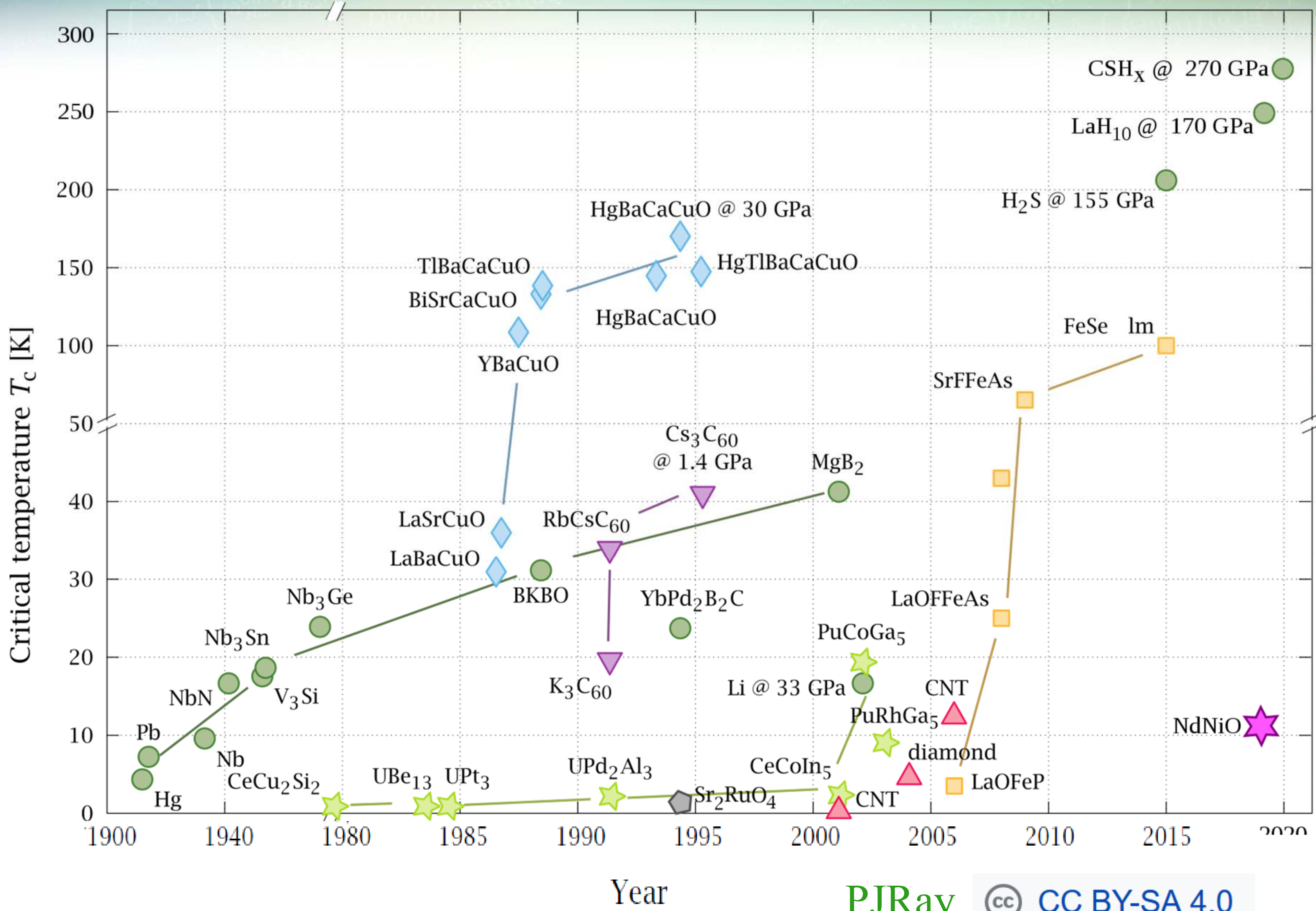
Superconductivity in ultra-quantum matter: Part I

A.-M.S. Tremblay

RQMP
30 September 2021
10:30

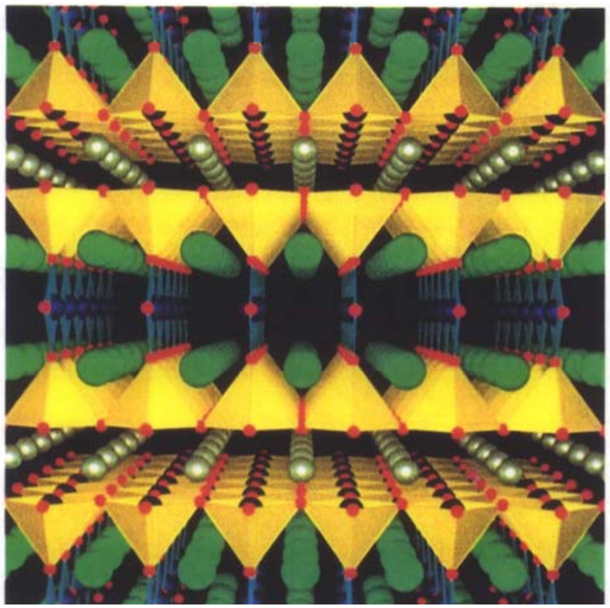


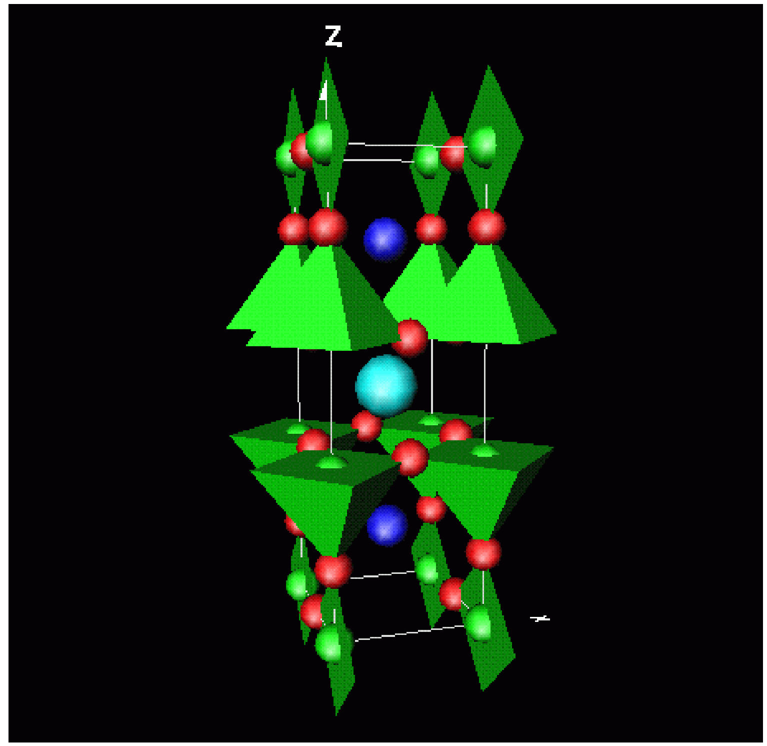

©Krantz NanoArt



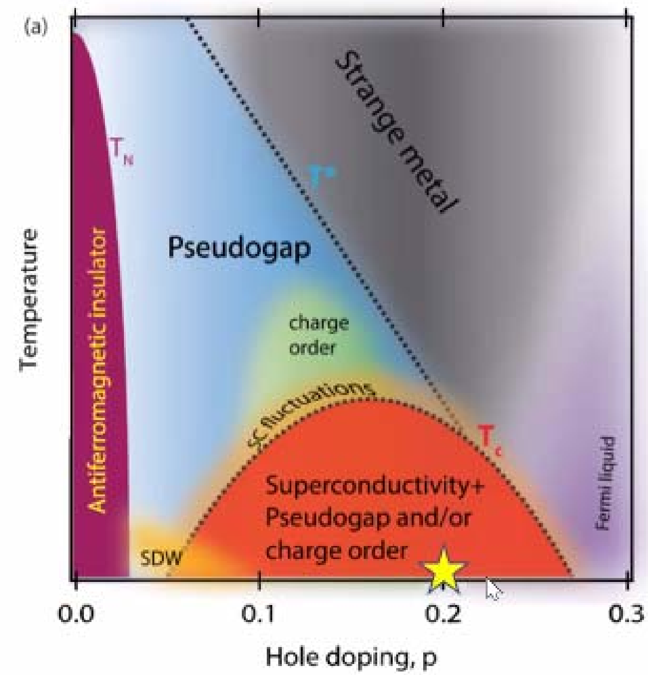
Critical temperature T_c [K]
Year
300
250
200
150
100
50
40
30
20
10
0
1900
1940
1980
1985
1990
1995
2000
2005
2010
2015
2020
CSH_x @ 270 GPa
LaH_{10} @ 170 GPa
H_2S @ 155 GPa
HgBaCaCuO @ 30 GPa
TlBaCaCuO
HgTlBaCaCuO
BiSrCaCuO
HgBaCaCuO
YBaCuO
FeSe
lm
SrFFeAs
Cs_3C_{60}
@ 1.4 GPa
MgB_2
LaSrCuO
$RbCsC_{60}$
LaBaCuO
BKBO
Nb_3Ge
$YbPd_2B_2C$
LaOFFeAs
Nb_3Sn
$PuCoGa_5$
NbN
V_3Si
K_3C_{60}
Li @ 33 GPa
CNT
$PuRhGa_5$
Pb
NdNiO
Nb
diamond
$CeCu_2Si_2$
UBe_{13}
UPt_3
UPd_2Al_3
$CeCoIn_5$
Hg
Sr_2RuO_4
CNT
LaOFeP

Atomic structure



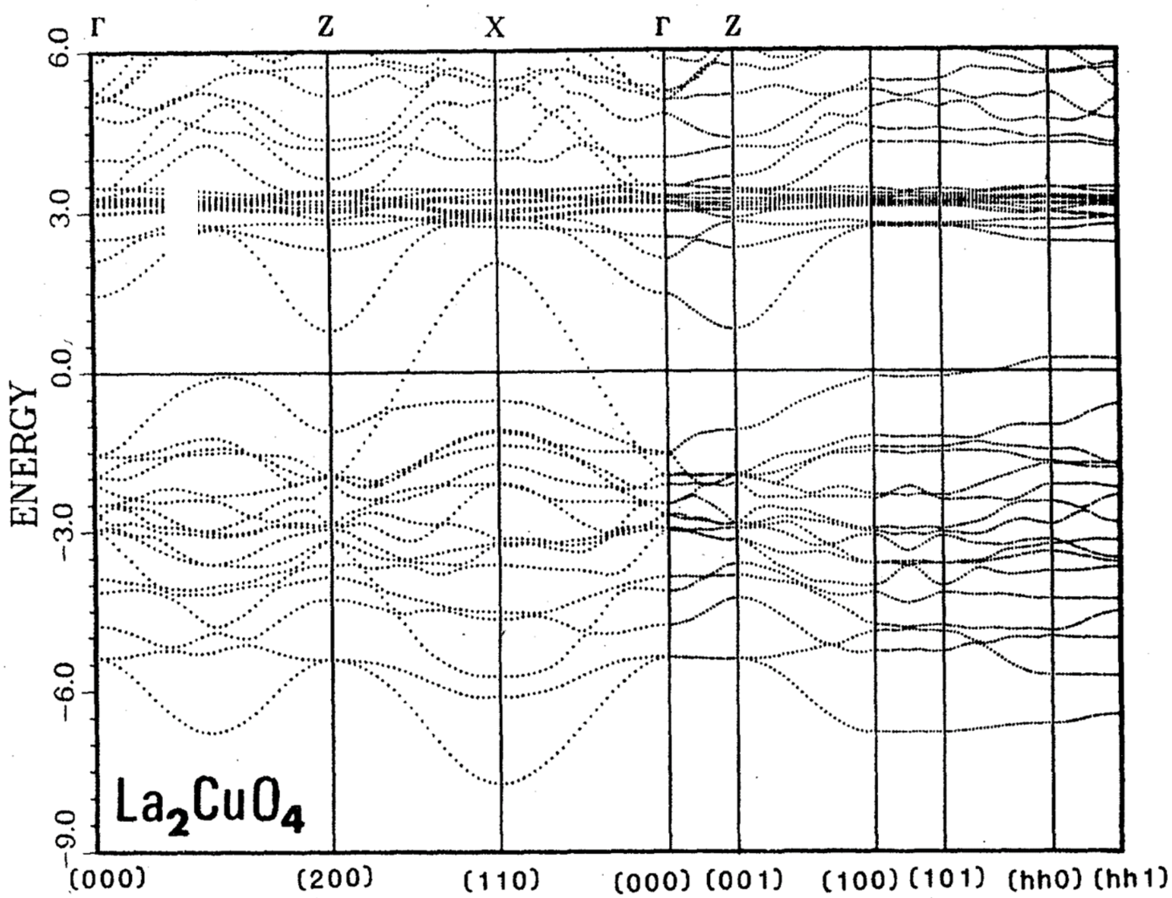


- Who ordered this?



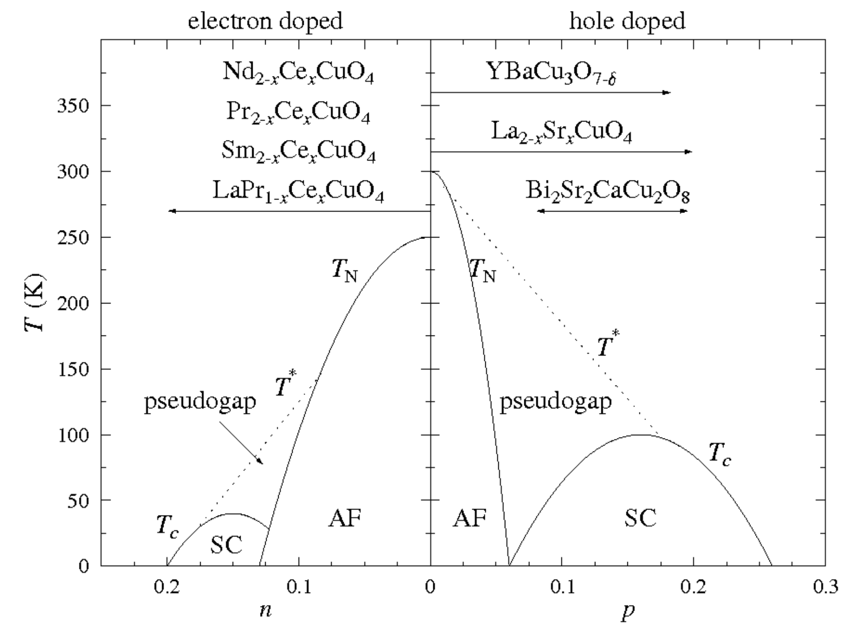
Vishik, Rep. Prog. Phys. (2018)

Band structure for high Tc



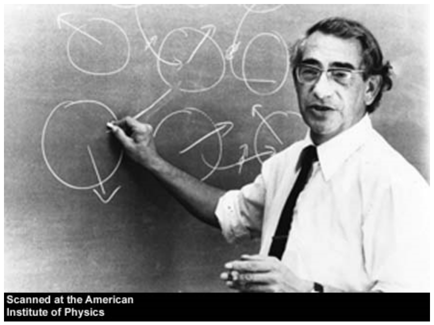
W. Pickett, Rev. Mod. Phys. 1989

"Universal" phase diagram

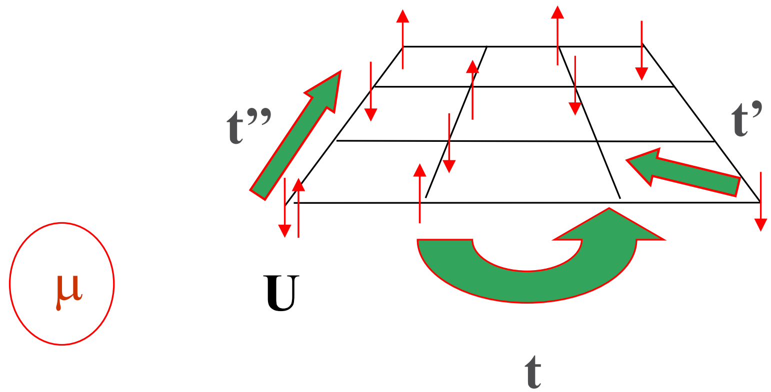


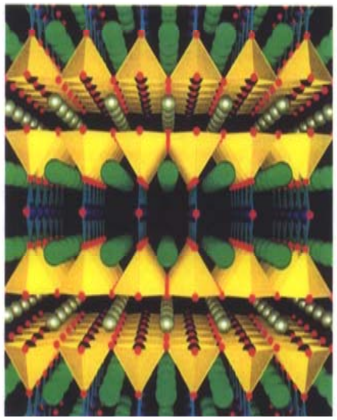
Public Domain,
https://en.wikipedia.org/w/index.php?curid=21641300

Hubbard model



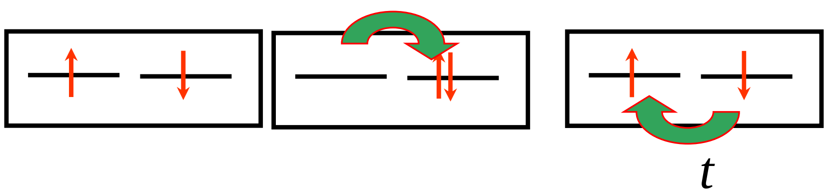
1931-1980





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

Spin 1/2

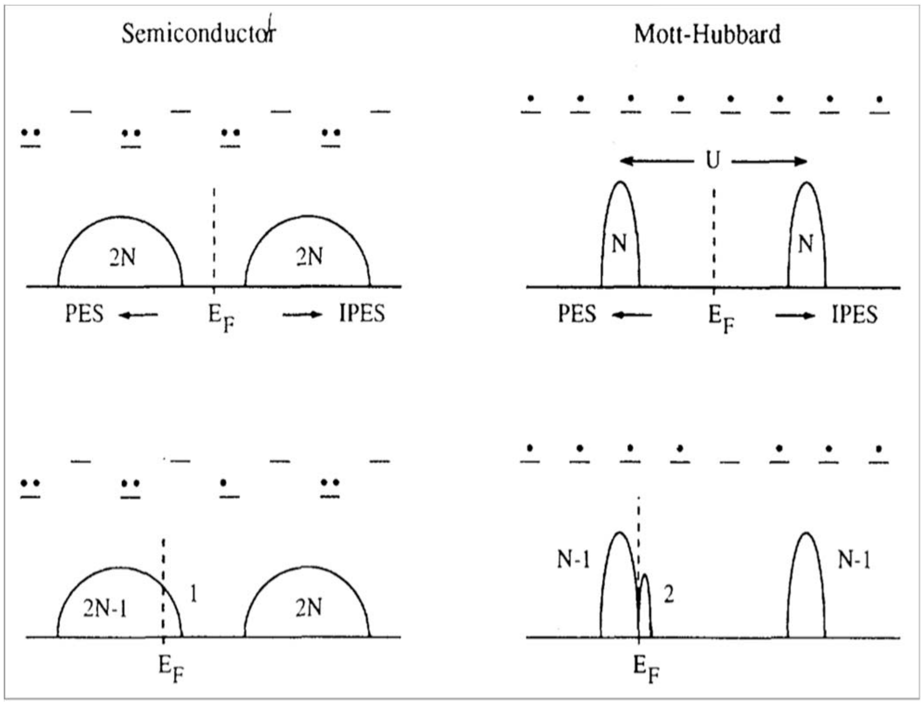


Effective model, Heisenberg: $J = 4t^2/U$

Attn: Charge transfer insulator

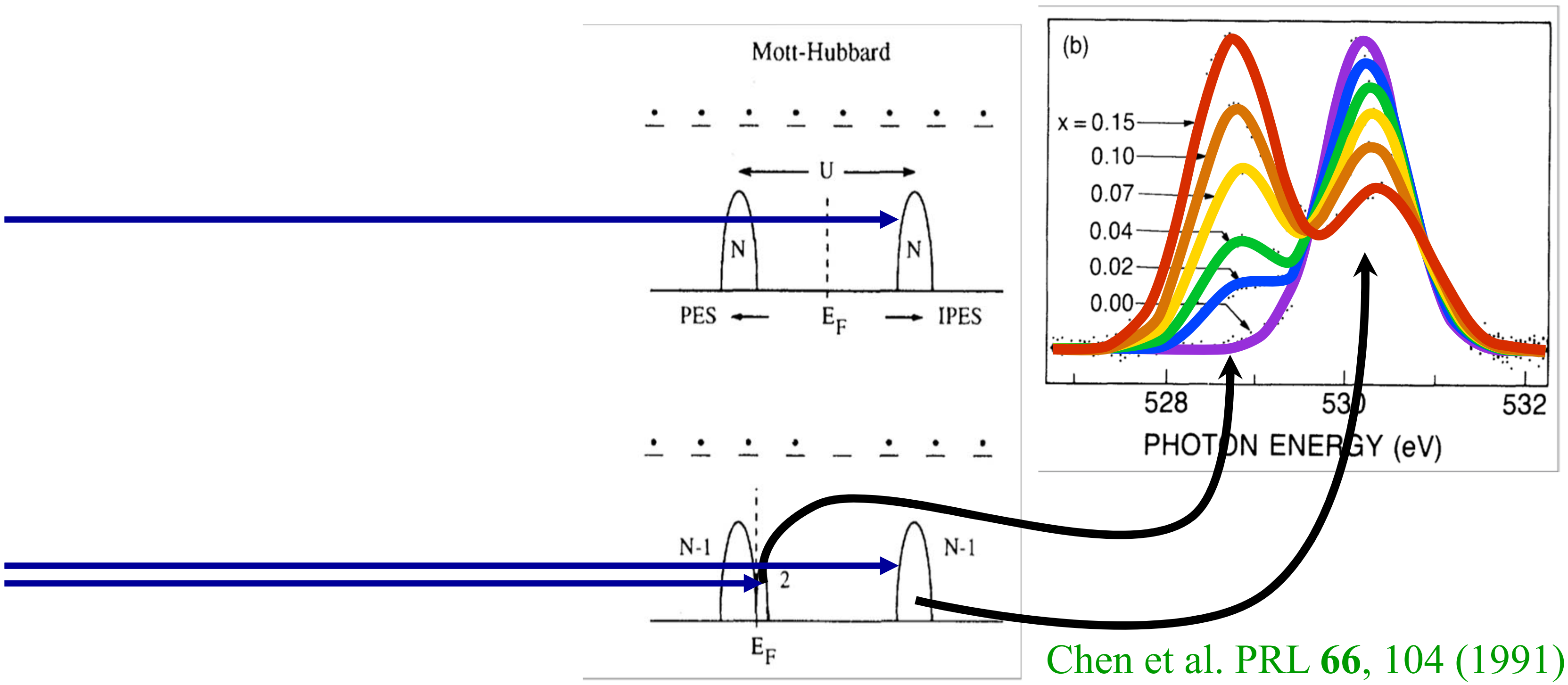
Mott Insulator : X-Ray absorption

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



Mott Insulator : X-Ray absorption

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



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

Take home messages

- Most of the main features of the phase diagram follow from the Hubbard model.
- This physics is continuously connected to the Mott transition at half-filling
- We need to look beyond traditional tools of solid state physics to work this out.

Minuterie

- 10 Minutes

Outline

- Method

- One-band Hubbard model
  - Phase diagram
  - Pseudogap
  - d-wave superconductivity
  - A phase transition at the heart of the phase diagram

- Three-band Hubbard model : oxygen can probe the details
  - Pseudogap
  - d-wave superconductivity

Method : The precursors

Hohenberg-Kohn : Exchange correlation

Kohn-Sham : Basis set

Density Functional Theory

Method

Metzner, Vollhardt PRL **62**, 324 (1989)
Georges, Kotliar, PRB **45,** 6479 (1992)
Jarrell PRL **69,** 168 (1992)
Review: Georges, Kotliar, Krauth, Rozenberg, RMP **68**, 13 (1996)

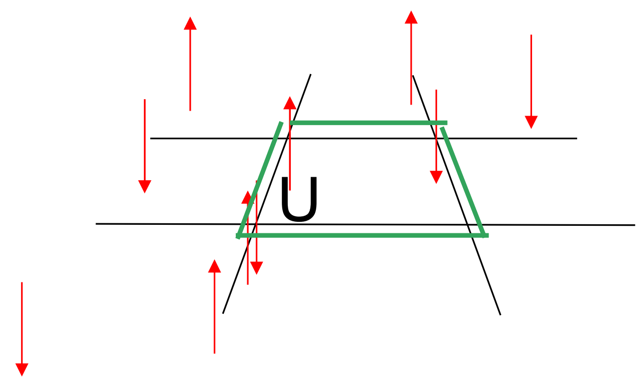
Dynamical Mean-Field Theory : DMFT

For additionnal physical intuition: Compare with more analytical approaches

- Pseudogap
  - Wei Wu, Scheurer, Chatterjee, Sachdev, Georges, Ferrero PRX 8, 021048 (2018)
  - Scheurer, Chatterjee, Wu, Ferrero, Georges, Sachdev, PNAS **115**, E3665 (2018).

Localized and delocalized pictures

Localized



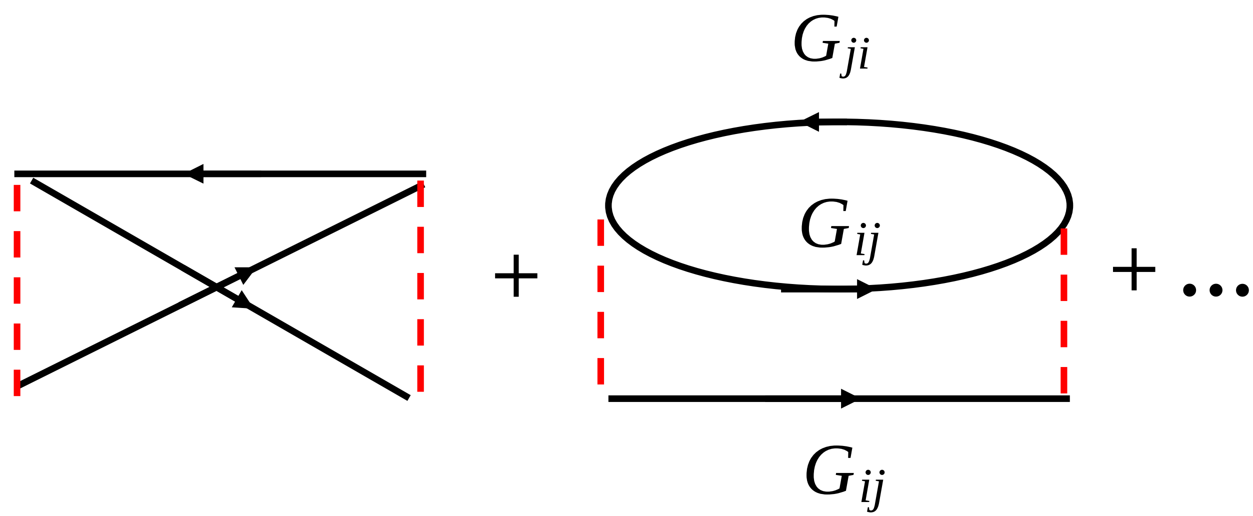
Lichtenstein *et al.*,PRB 2000
Kotliar *et al.*, PRB 2000
M. Potthoff, EJP 2003

REVIEWS
Maier, Jarrell et al., RMP. (2005)
Kotliar *et al.* RMP (2006)
AMST *et al.* LTP (2006)

$$(G^{-1})_{ij} = (G_0^{-1})_{ij} - \Sigma_{ij}$$

Skeleton expansion for the Anderson impurity problem

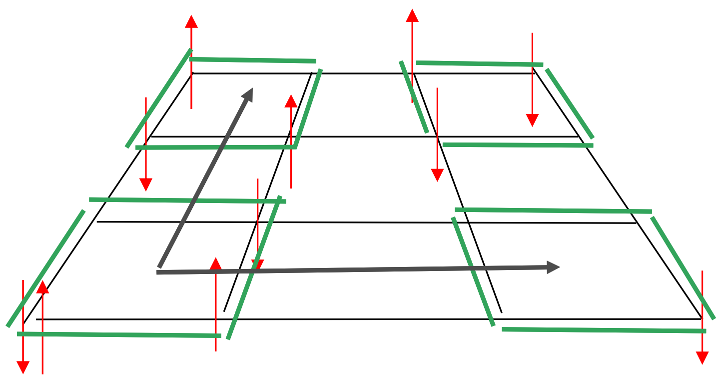
$$\Sigma_{ij} = $$



$$(G^{-1})_{ij} = (G_0^{-1})_{ij} - \Sigma_{ij}$$

Localized and delocalized pictures

Delocalized

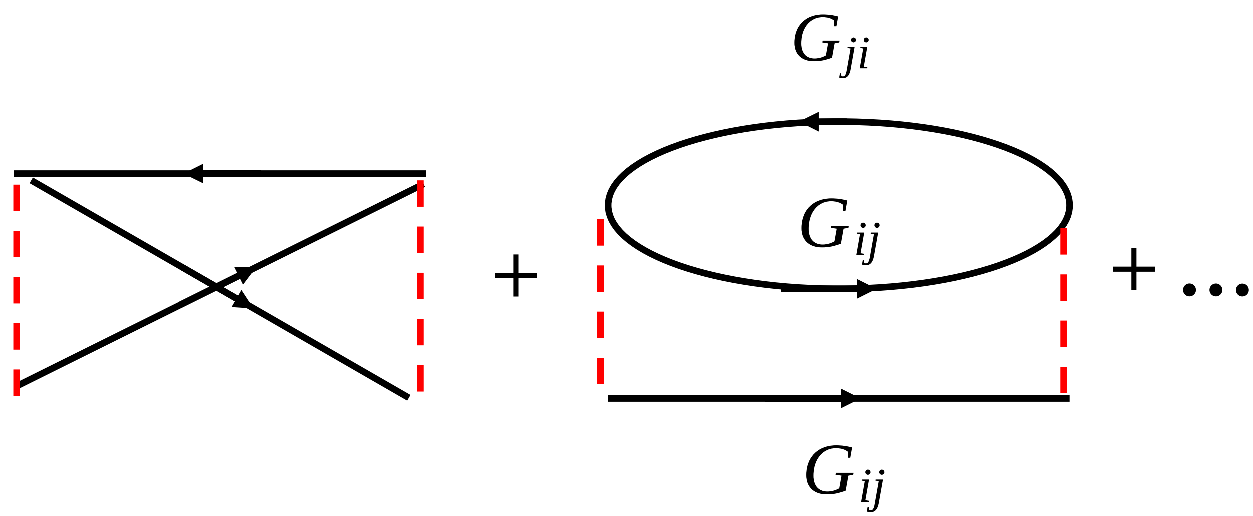


$$\mathbf{R} \rightarrow \tilde{k}$$

$$G_{ij}\left(\tilde{k}\right) = \left(\frac{1}{(i\omega_n+\mu)I-\varepsilon\left(\tilde{k}\right)-\Sigma}\right)_{ij}$$

Skeleton expansion for the connected clusters

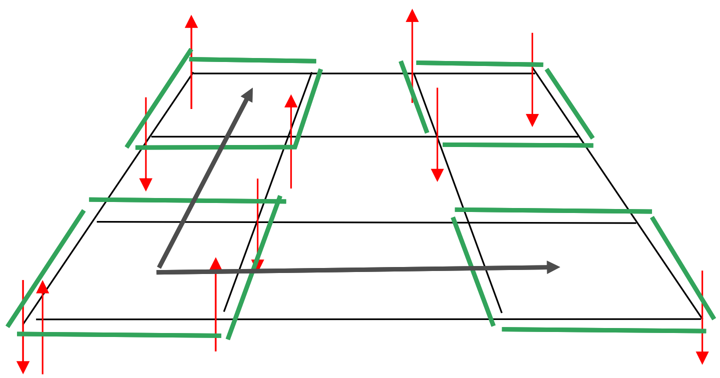
$$\Sigma_{ij} =$$



$$G_{ij}(\tilde{k}) = \left(\frac{1}{(i\omega_n + \mu)I - \varepsilon(\tilde{k}) - \Sigma} \right)_{ij} \longrightarrow G_{ij} = \int \frac{d^d\tilde{k}}{(2\pi)^d} G_{ij}(\tilde{k})$$

Localized and delocalized pictures C-DMFT

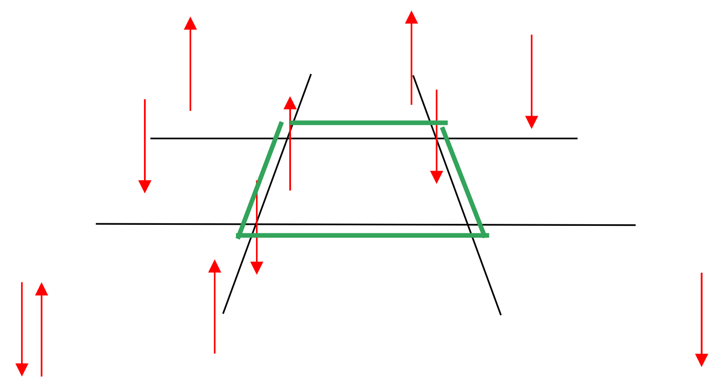
Delocalized



$\mathbf{R} \longrightarrow \tilde{k}$

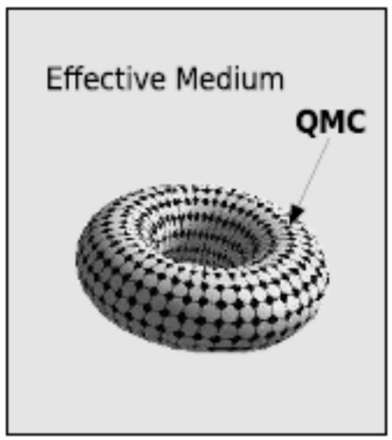
$$G_{ij} = \int \frac{d^d\tilde{k}}{(2\pi)^d} \left(\frac{1}{(i\omega_n+\mu)I-\varepsilon\left(\tilde{k}\right)-\Sigma} \right)_{ij}$$

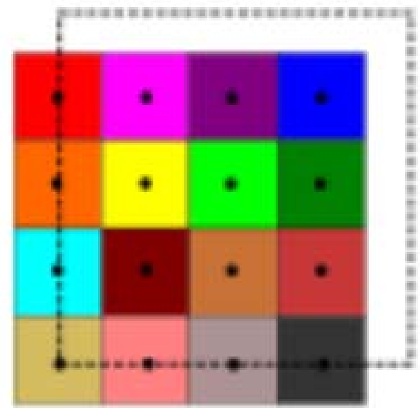
Localized



$$(G^{-1})_{ij} = (G_0^{-1})_{ij} - \Sigma_{ij}$$

Dynamical cluster approximation (DCA)

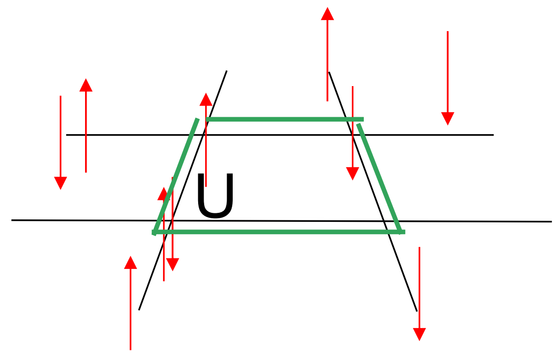




Hettler …Jarrell…Krishnamurty PRB **58** (1998)

Impurity solvers

Impurity solver (Exact diagonalisation)



Caffarel, Krauth, PRL **72** 1545 (1994)

QCM David Sénéchal

Impurity solver : continuous-time quantum Monte Carlo

$$Z = \int \mathcal{D}[\psi^\dagger, \psi]\, e^{-S_c - \int_0^\beta d\tau \int_0^\beta d\tau' \sum_{\mathbf{K}} \psi^\dagger_{\mathbf{K}}(\tau)\Delta_{\mathbf{K}}(\tau,\tau')\psi_{\mathbf{K}}(\tau')}$$

Hybridization expansion :

Werner Millis PRB **74**, 155107 (2006)
Werner Millis B **75**, 085108 (2007)
Haule, PRB **75**, 155113 (2007)
Sémon, Sordi, AMST PRB **89**, 165113 (2014)
Sémon, Yee, Haule, AMST PRB **90**, 075149 (2014)

triqs   **ALPSCore / CT-HYB**   **iQIST**   **ComCTQMC**

Impurity solver : continuous-time quantum Monte Carlo

$$S = \int_0^\beta \mathrm{d}\tau \mathrm{d}\tau' \sum_{\sigma=\uparrow,\downarrow} \xi^*_\sigma(\tau) \left[g_{0\sigma}^{-1}(\tau-\tau')\right] \xi_\sigma(\tau') + U \int_0^\beta \mathrm{d}\tau \left(n_\uparrow(\tau) n_\downarrow(\tau) - \frac{n_\uparrow(\tau) + n_\downarrow(\tau)}{2} \right)$$

CT-AUX : Gull, Werner, Parcollet, Troyer, 2008, Europhys. Lett. **82**, 57003 (2008)

DCA++

Review of these methods

Gull, Millis, Lichtenstein, Rubtsov, Troyer, Werner RMP **83,** 349 (2011)

Some groups using these methods for cuprates

- Europe:
  - Georges, Parcollet, Ferrero, Civelli, Wu (Paris)
  - Lichtenstein, Potthoff, (Hamburg) Aichhorn (Graz), Liebsch (Jülich) de Medici (Grenoble) Capone (Italy)
- USA:
  - Gull (Michigan) Millis (Columbia)
  - Kotliar, Haule (Rutgers)
  - Jarrell (Louisiana)
  - Maier, Okamoto (Oakridge)
- Japan
  - Imada (Tokyo) Sakai, Tsunetsugu, Motome

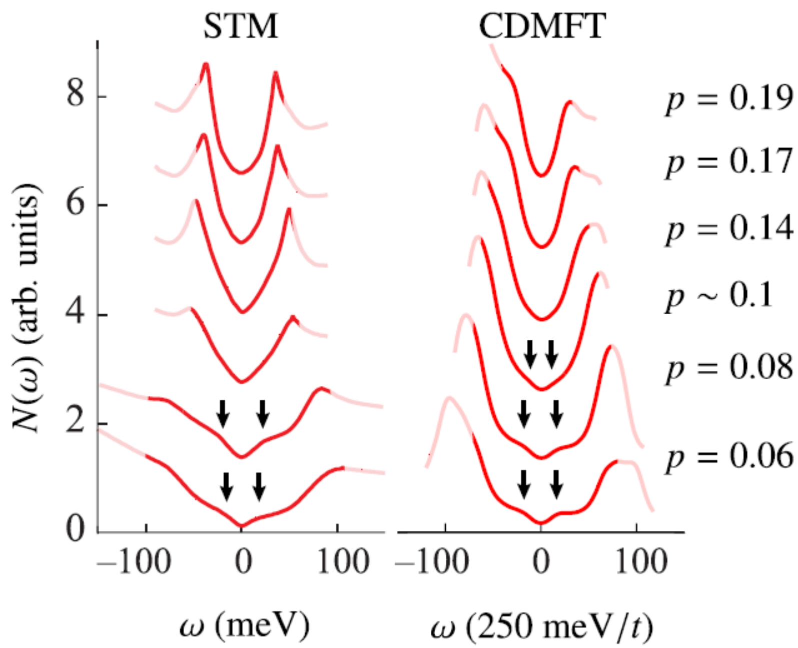
Critique

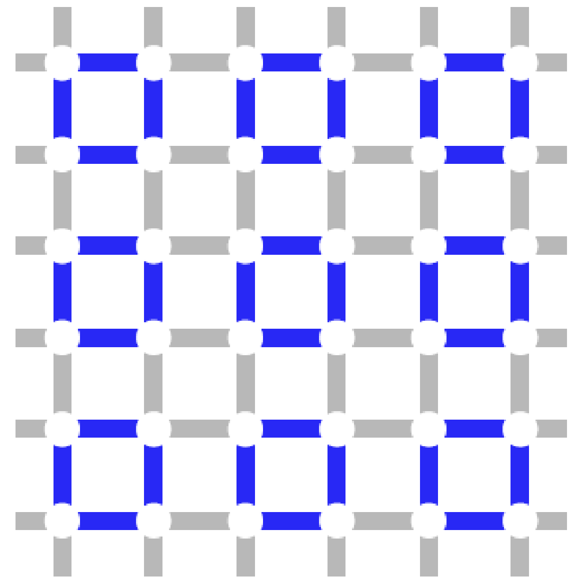
+ and -

- Long range order:
  - No mean-field factorization on the cluster
  - Symmetry breaking allowed in the bath
- Included exactly:
  - Short-range dynamical and spatial correlations

- Missing:
  - Long wavelength p-h and p-p fluctuations
  - Hence good when the corresponding correlation lengths are small

Possible artefacts





Verret, Roy, Foley, Charlebois, Sénéchal, A.-M.S.T, RPB **100**, 224520 (2019)

STM Kohsaka, … Davis, Nature (London) **454**, 1072 (2008).

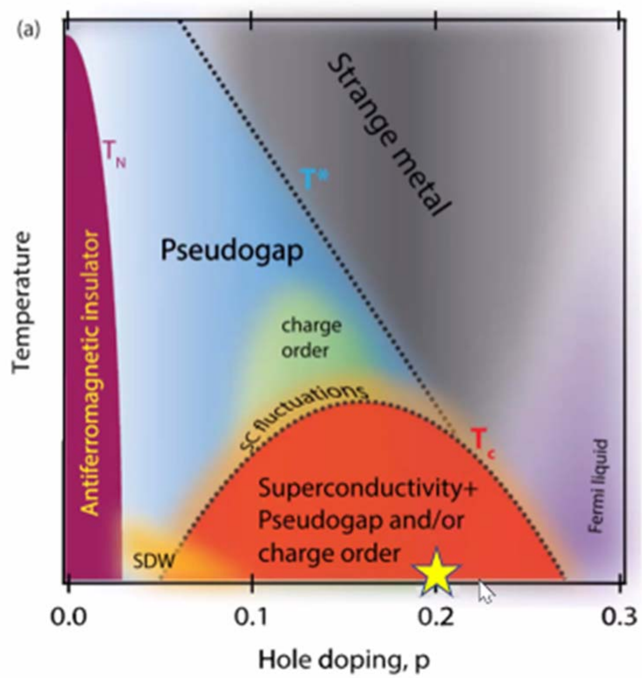
What to do

- Exact in the infinite size limit of the cluster
  - Compare different cluster sizes
  - Compare real-space (CDMFT) and momentum space (DCA) clusters

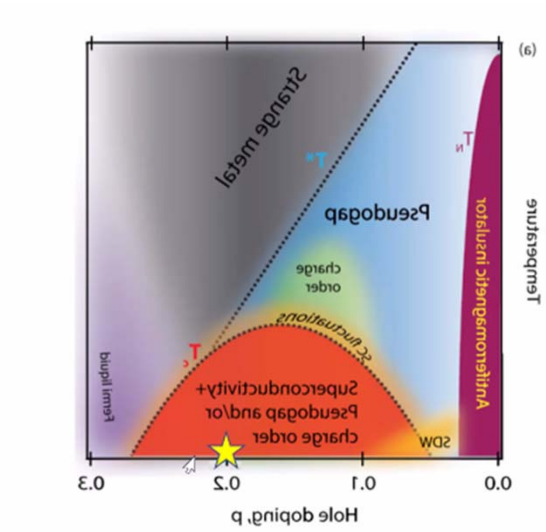
Minuterie

- 10 Minutes
- 6 minutes = 16 minutes

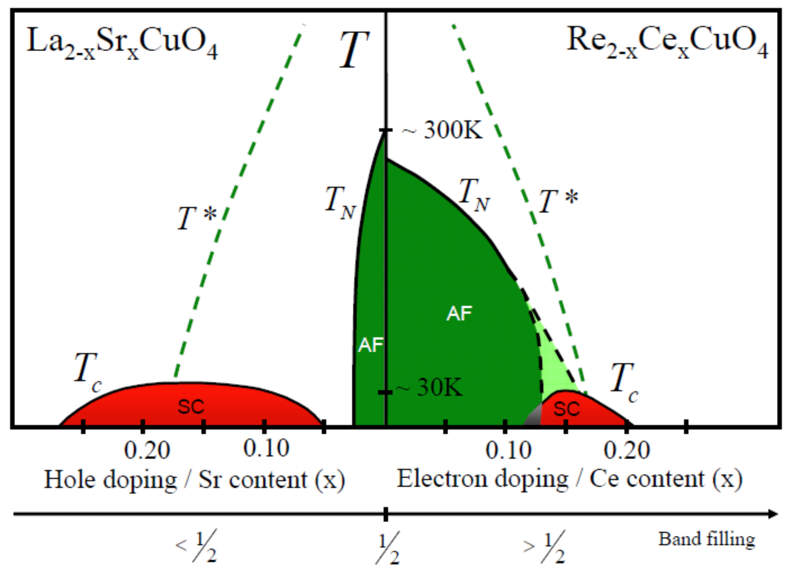
Back to our problem: Phase diagram

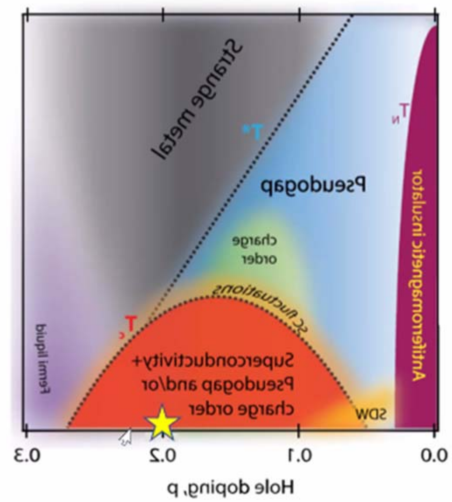


Vishik, Rep. Prog. Phys. (2018)

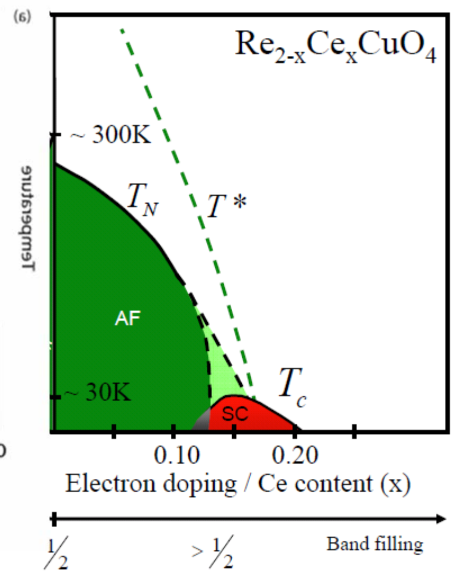


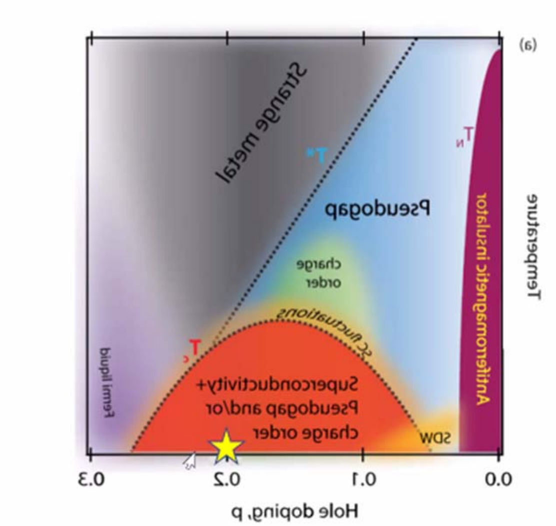
Vishik, Rep. Prog. Phys. (2018)



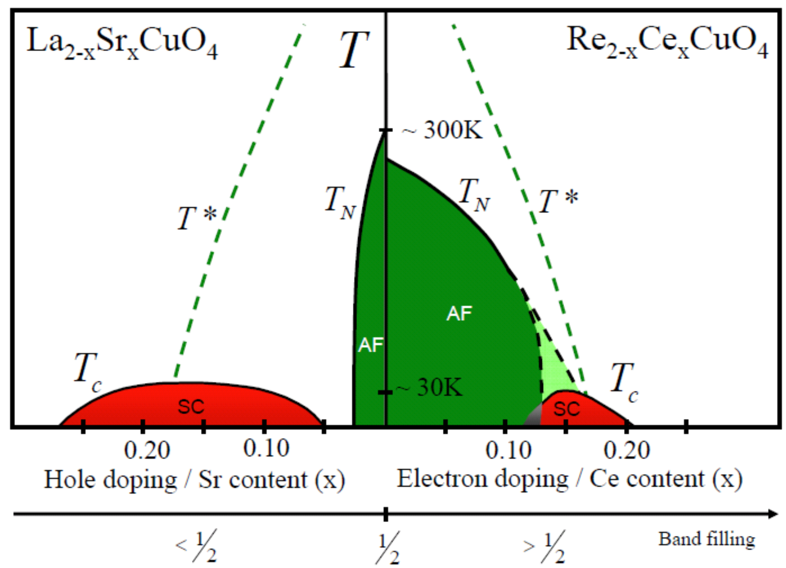


Vishik, Rep. Prog. Phys. (2018)



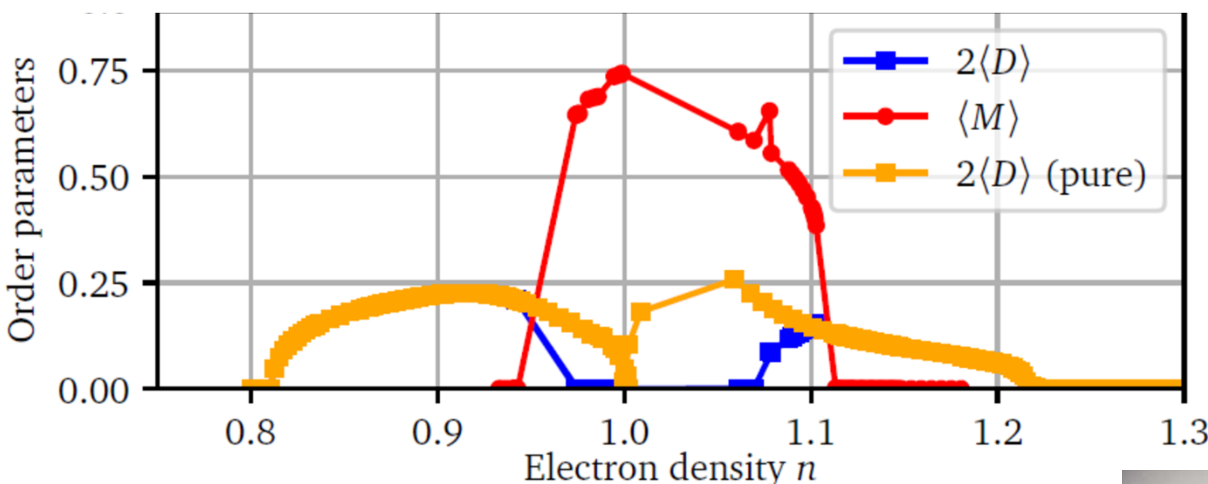


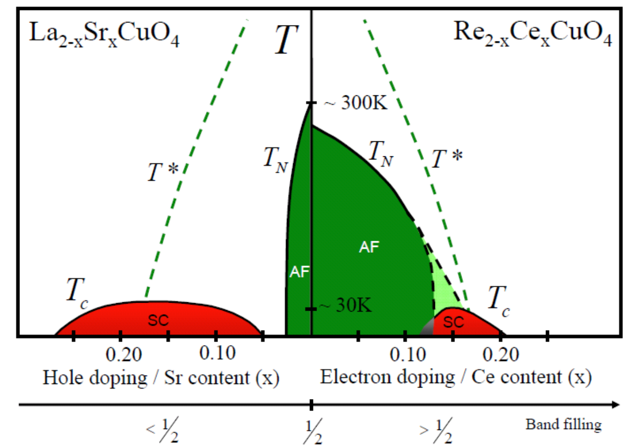
Vishik, Rep. Prog. Phys. (2018)



A bird's eye overview of the *T = 0* phase diagram

$U = 8t, t' = -0.3t, t'' = 0.2t$





A. Foley *et al.* Phys. Rev. B **99**, 184510 (2019)
S. S. Kancharla, *et al.* Phys. Rev. B **77**, 184516 (2008)
D. Sénéchal, *et al.* Phys. Rev. Lett. **94**, (2005)
M. Jarrell *et al.* EPL **56** 563, (2001)

A. Foley

S. Verret

D. Sénéchal

CDMFT 4 sites

Competing ground states

PHYSICAL REVIEW X **10**, 031016 (2020)

Absence of Superconductivity in the Pure Two-Dimensional Hubbard Model

Mingpu Qin,[1,2,*] Chia-Min Chung,[3,4,*] Hao Shi,[5] Ettore Vitali,[6,2] Claudius Hubig,[7]
Ulrich Schollwöck,[3,4] Steven R. White,[8] and Shiwei Zhang[5,2]

PRL **113**, 046402 (2014) PHYSICAL REVIEW LETTERS week ending 25 JULY 2014

Competing States in the *t*-*J* Model: Uniform *d*-Wave State versus Stripe State

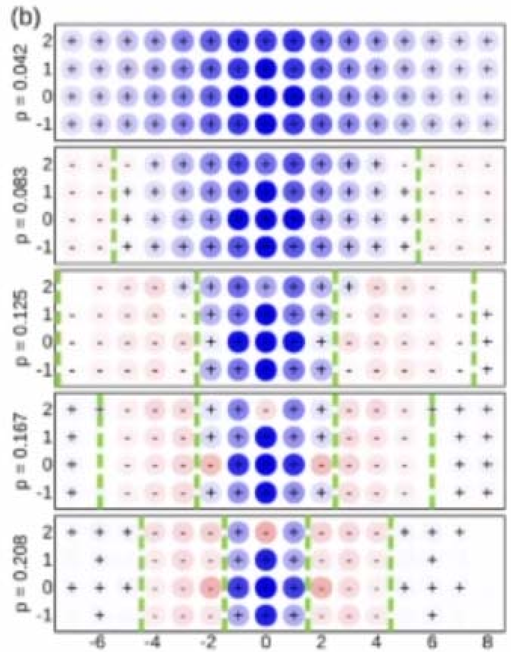
Philippe Corboz,[1,2] T. M. Rice,[1] and Matthias Troyer[1]

Competing ground states

ARTICLE OPEN

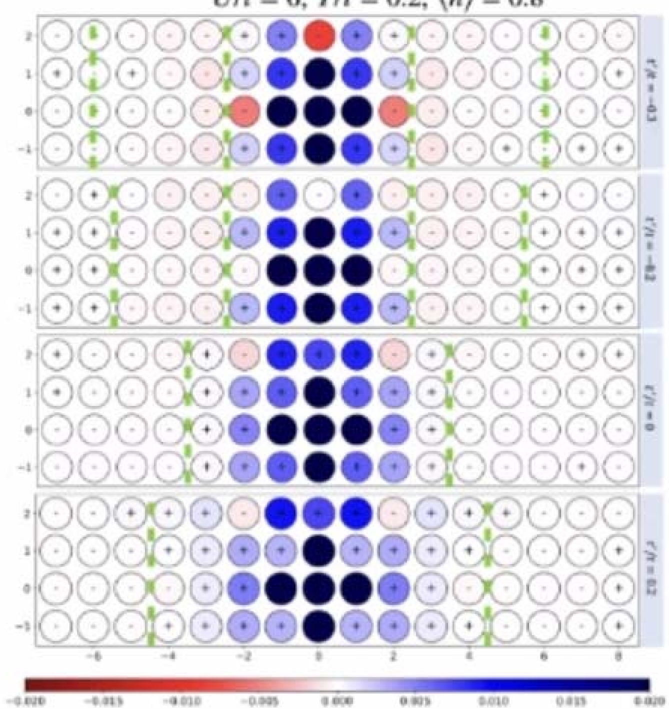
Stripe order from the perspective of the Hubbard model

Edwin W. Huang[1,2], Christian B. Mendl[3], Hong-Chen Jiang[2], Brian Moritz[2,3] and Thomas P. Devereaux[2,4]



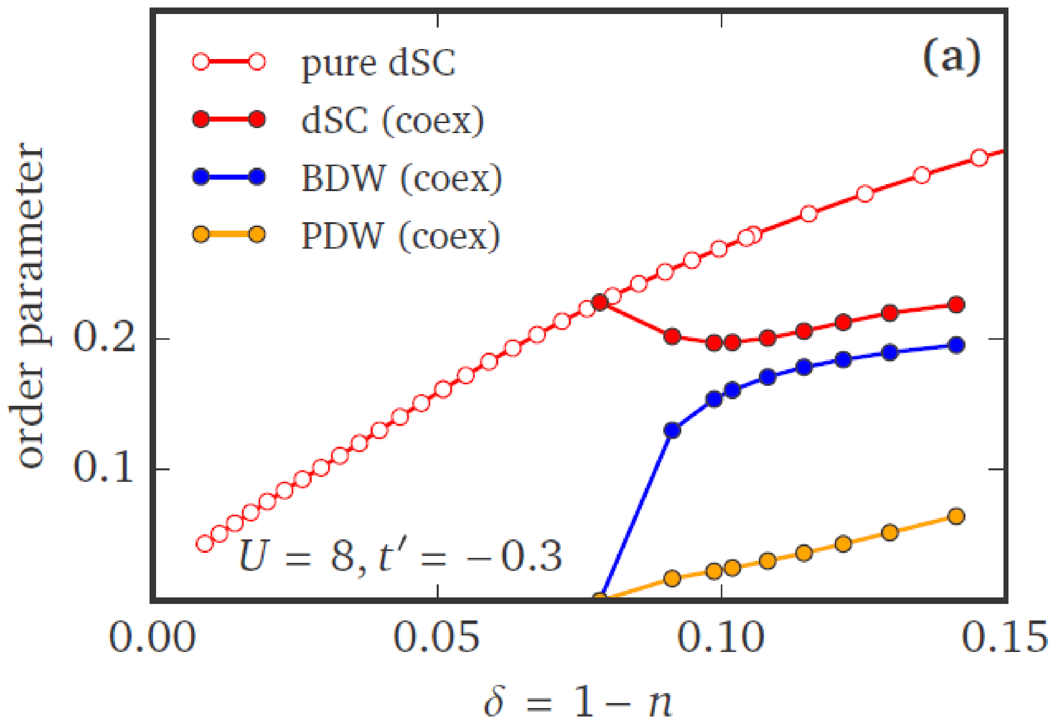
DQMC on 16 x 4 Hubbard:
$U/t = 6, t'/t = -0.25, T/t = 0.22$

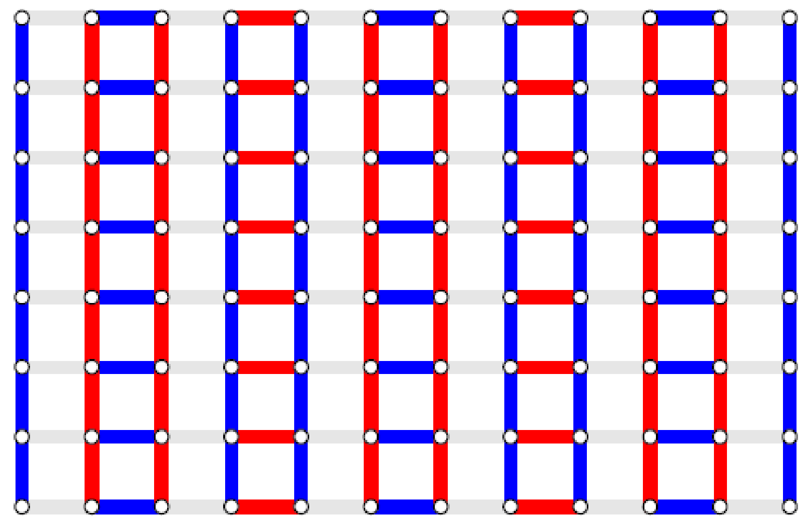
DCA (16 x 4 cluster)
$U/t = 6,\ T/t = 0.2,\ \langle n \rangle = 0.8$



P. Mai, S. Karakuzu, S. Johnston & TAM, in preparation

Competing states





VCA

Faye Sénéchal, PRB **95** (2017)

J.-P. Faye Latyr

D. Sénéchal

Minuterie

- 10 minutes
- 6 minutes
- 3 minutes = 19

Minuterie

- 10 minutes
- 6 minutes
- 3 minutes
- 4 minutes
- 5 minutes = 28

Pseudogap


Alexis Reymbaut

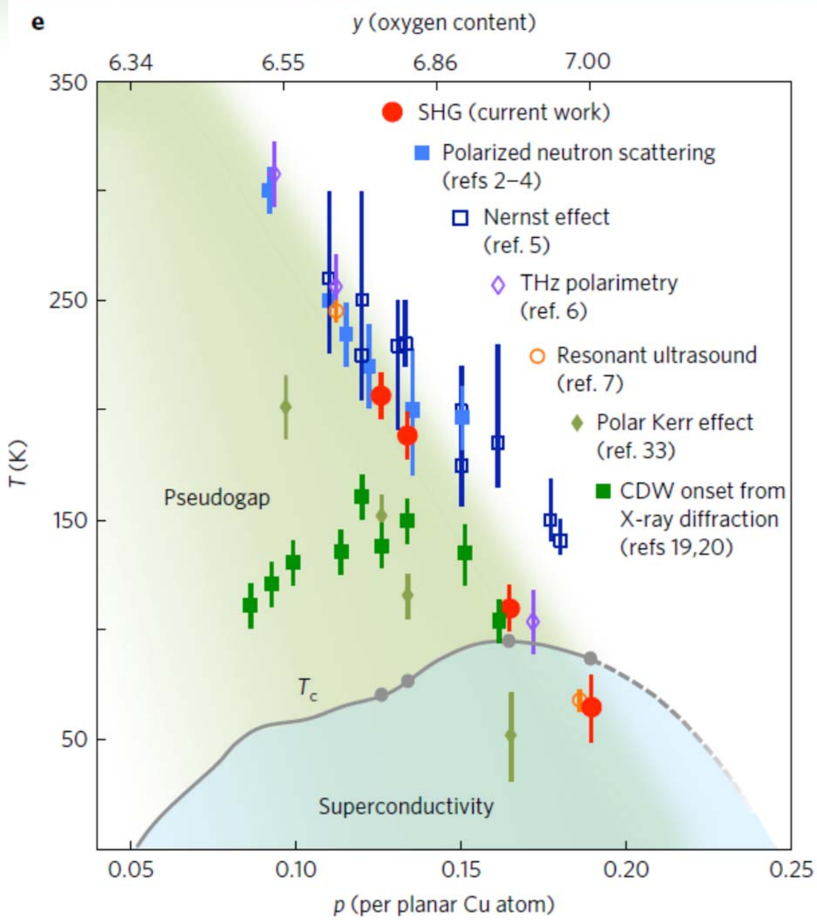

Simon Bergeron


Maxime Charlebois


Patrick Sémon

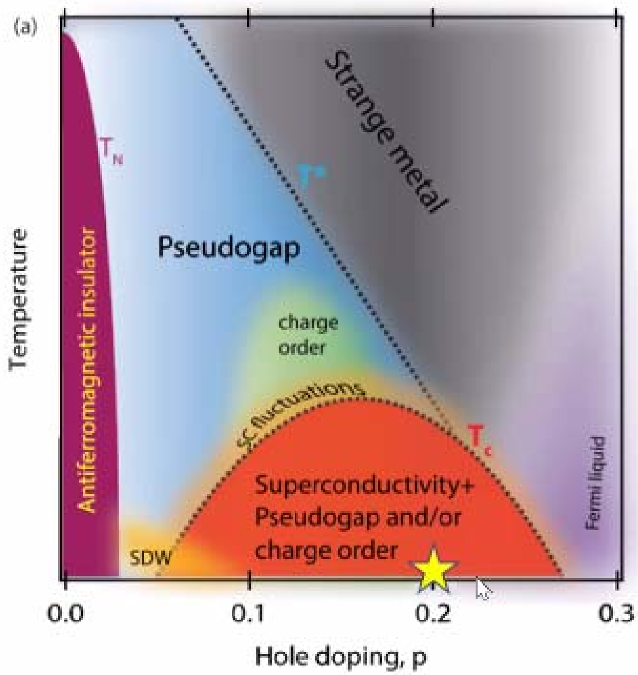

Marion Thénault

Reymbaut, *et al.*
Phys. Rev. Research **1**, 023015 (2019)

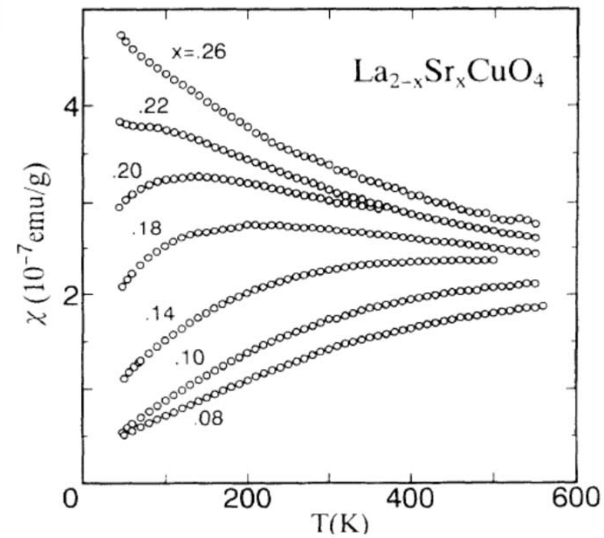


Zhao *et al.* Nat. Phys. 13, 250 (2017).

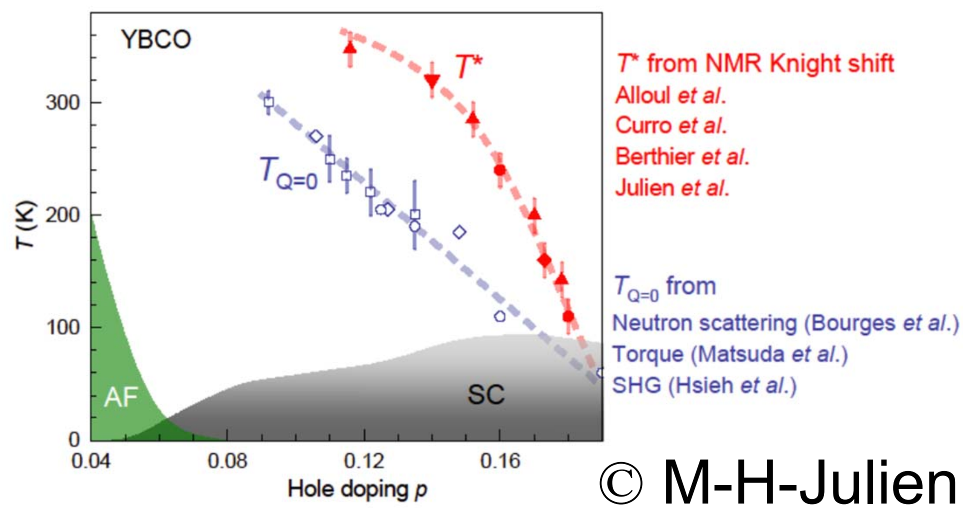
Pseudogap



Vishik, Rep. Prog. Phys. (2018)



Nakano *et al.* Phys. Rev. B **49**, 16000 (1994)
Alloul *et al* (1989)



© M-H-Julien

Knight shift (Q=0 spin susceptibility)

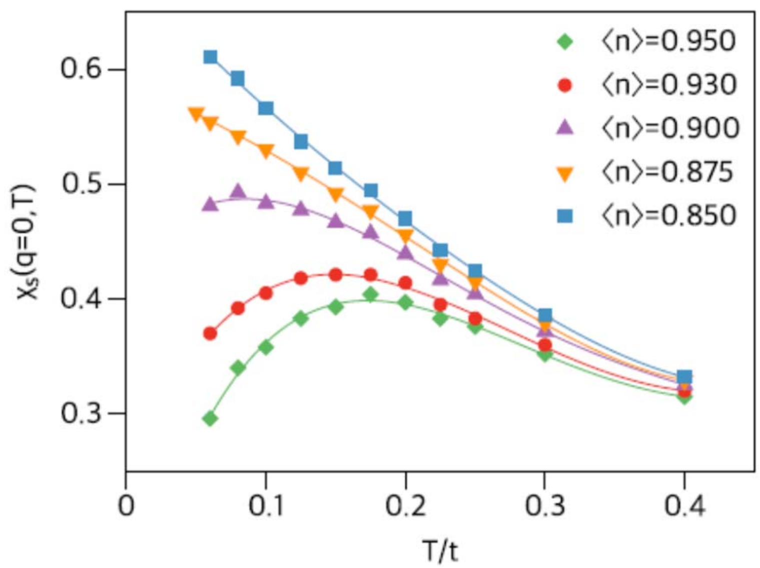
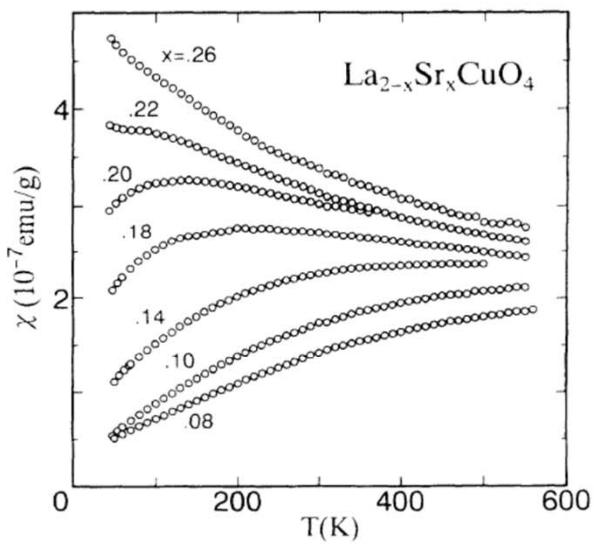


Fig. 3 Temperature and doping dependence of the $q = 0$ spin susceptibility. At the smaller dopings (larger filling $\langle n \rangle$), $\chi_s(T)$ exhibits a peak in the temperature dependence indicating the opening of a PG

DCA 12 sites, *t'=0, U = 7*

T.A. Maier, D.J. Scalapino, npj Quantum Materials (2019)

Comparison



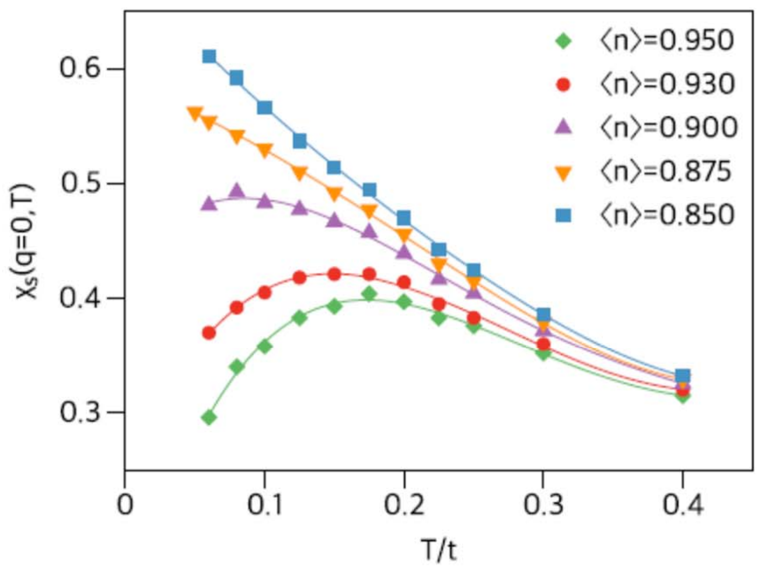
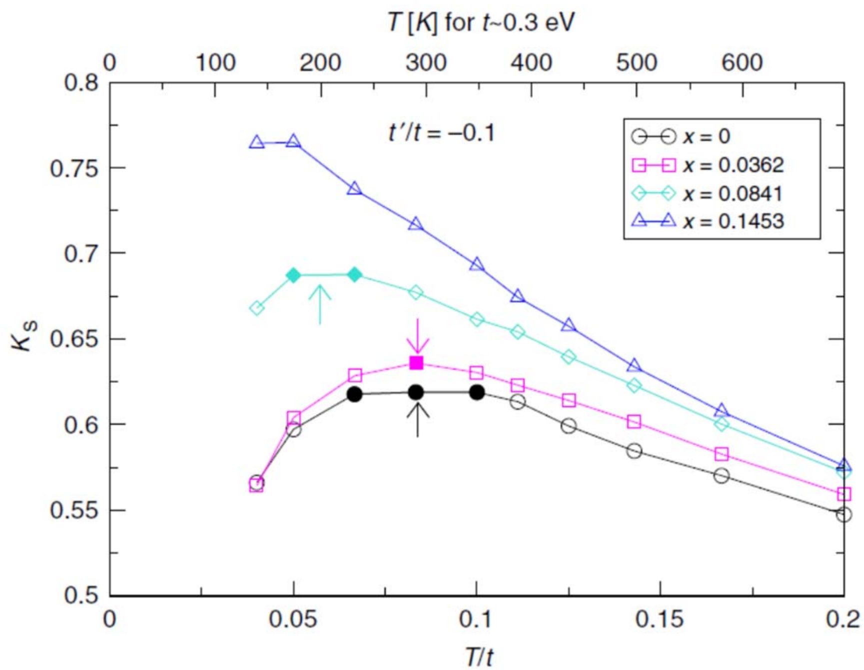


Fig. 3 Temperature and doping dependence of the $q = 0$ spin susceptibility. At the smaller dopings (larger filling $\langle n \rangle$), $\chi_s(T)$ exhibits a peak in the temperature dependence indicating the opening of a PG

Knight shift

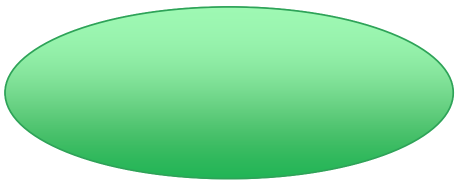


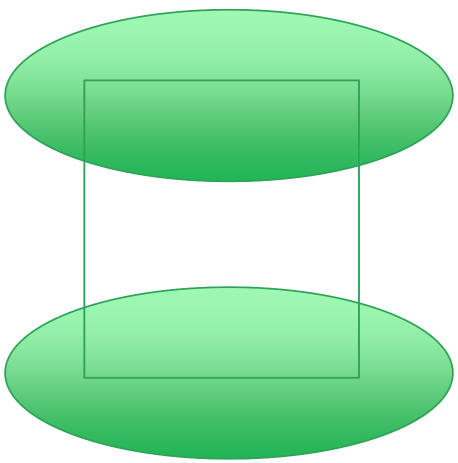
DCA 8 sites, *U = 6, t' = -0.1t*

Chen, LeBlanc, Gull, Nature Com. Apr. 2017

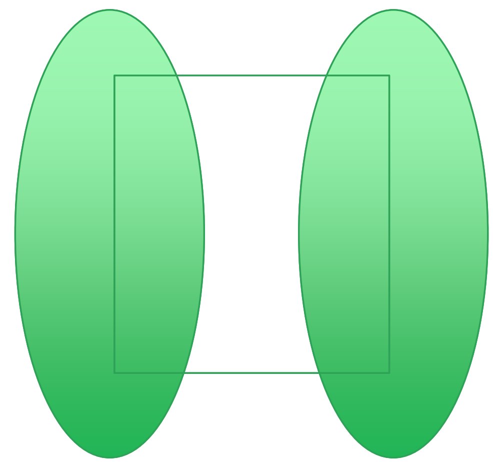
See also Jarrell *et al.* 2001, 2002

Physical origin of the pseudogap

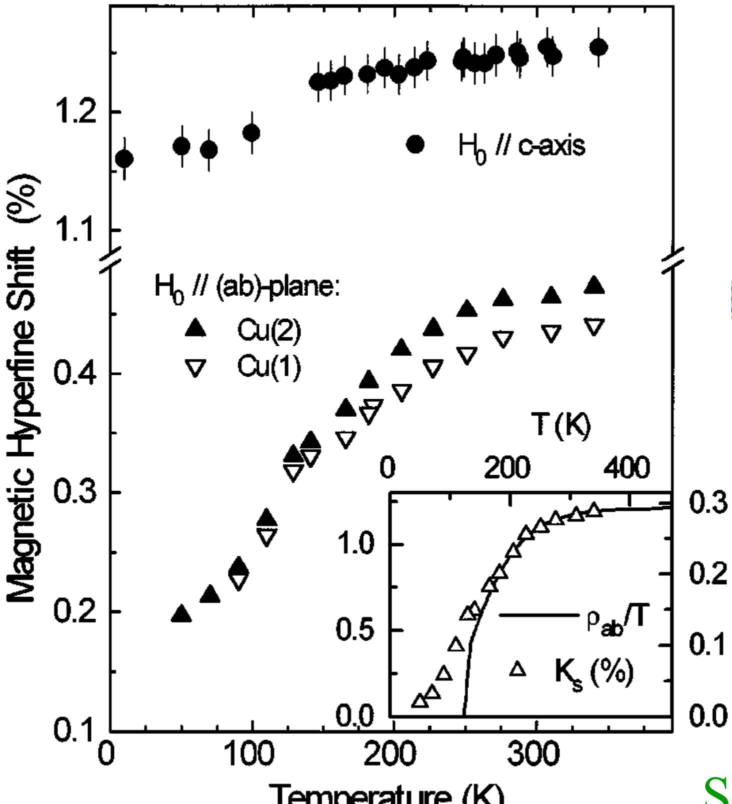
 = $\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$



-

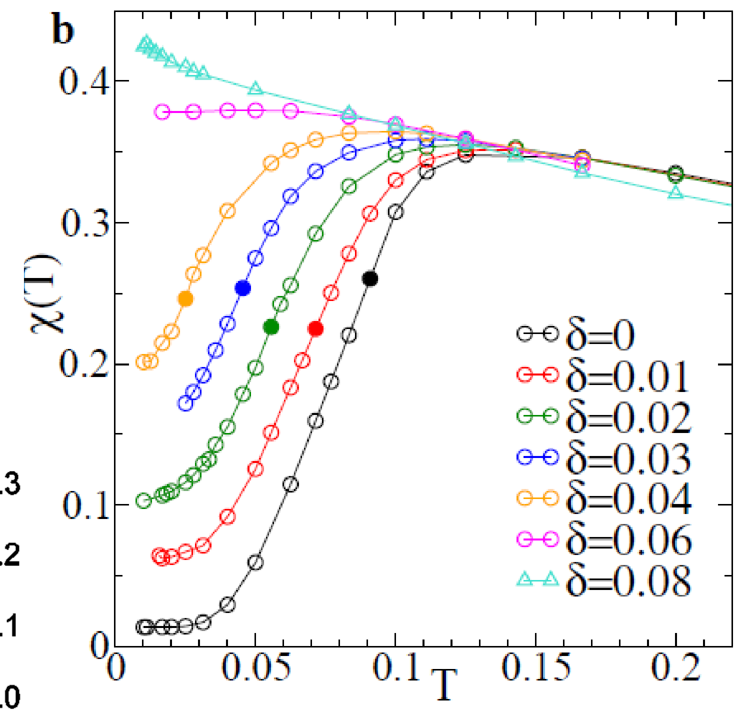


Spin susceptibility



Underdoped Hg1223

Julien et al. PRL **76,** 4238 (1996)

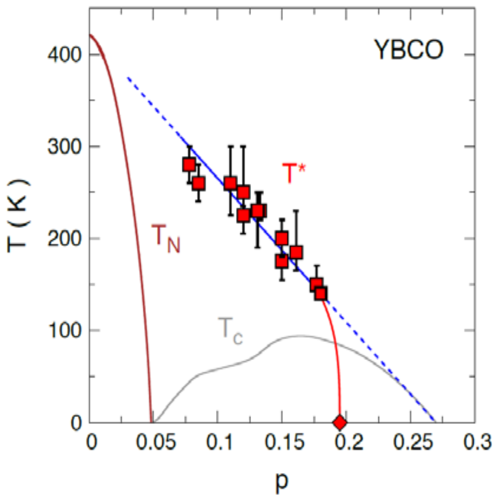


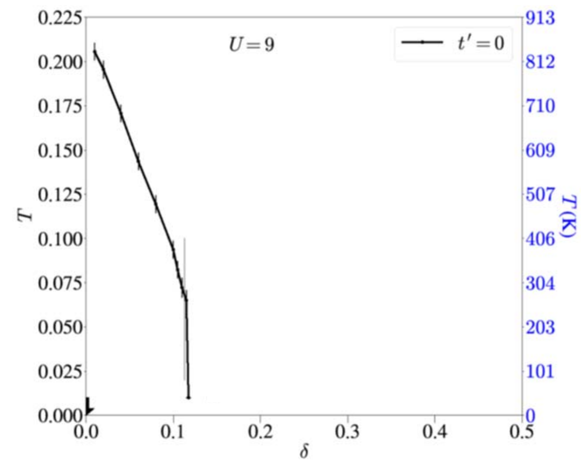
Sordi et al., Sci. Rep. 2 547 (2012);

U = 6.2 , t'=0

Experiments and *T**

G.Sordi et al. Phys. Rev. B **87**, 041101(R) (2013)





Cyr-Choinières et al. Phys. Rev. B **97**, 064502

p

A. Reymbaut, M. Thénault, L. Fratino, G. Sordi,
P. Sémon, AMT, Phys. Rev. Research **1**, 023015 (2019)

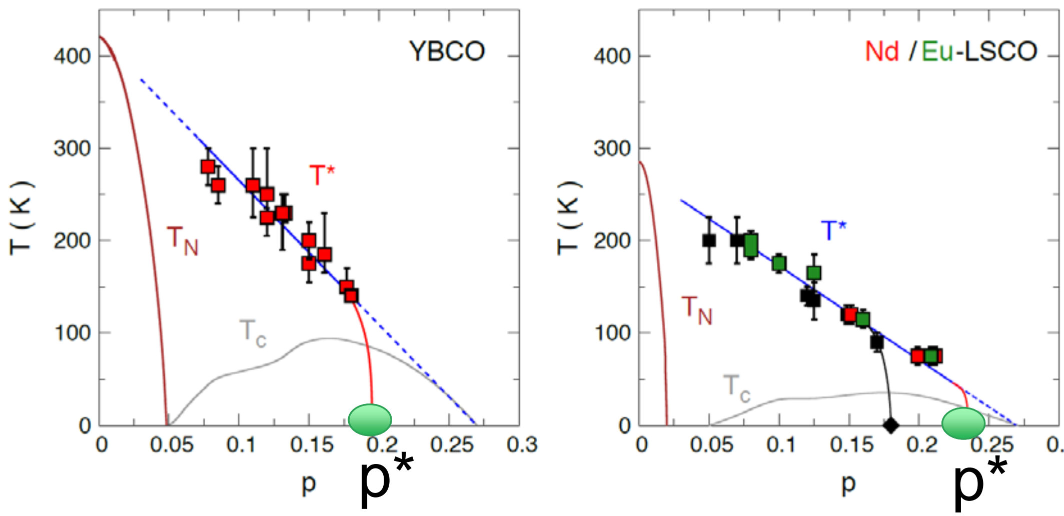
W Wu, A Georges, M Ferrero Phys. Rev. X 8, 021048 (2018).

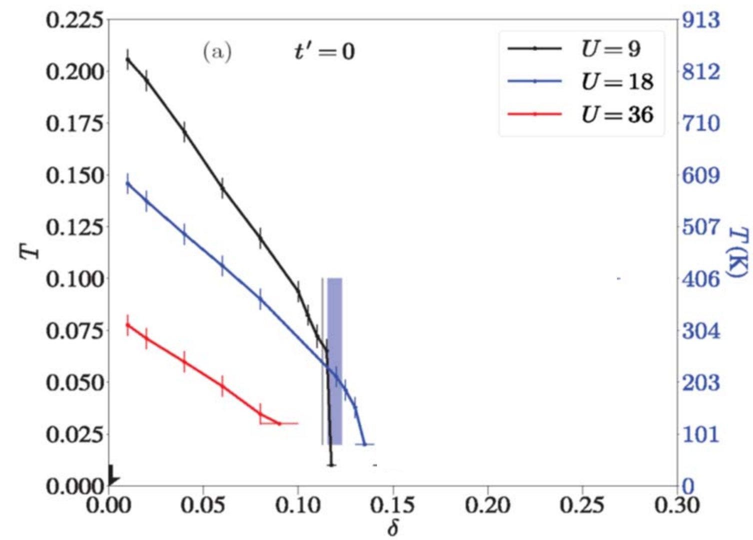
Bragança, Sakai, Aguiar, Civelli, PRL **120**, 067002 (2018)

Experiments and *T**

$$k_{\mathrm{B}} T^* \sim J$$

$J = 4t^2/U$





p

Cyr-Choinières et al. Phys. Rev. B **97**, 064502

A. Reymbaut, M. Thénault, L. Fratino, G. Sordi,
P. Sémon, AMT, Phys. Rev. Research **1**, 023015 (2019)

W Wu, A Georges, M Ferrero Phys. Rev. X 8, 021048 (2018).

Bragança, Sakai, Aguiar, Civelli, PRL **120**, 067002 (2018)

Entropy maximum

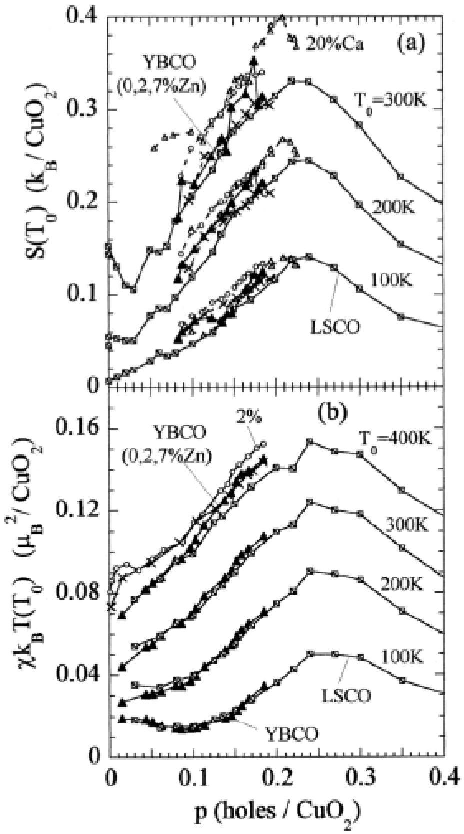


Fig. 14. (a) Entropy $S(T_0)$ (in k_B/CuO_2) at fixed $T = T_0$ vs p, reflecting spectral weight within fixed energy windows $\sim E_F \pm 2k_B T_0$ for LSCO and YBCO (0, 2, 7% Zn and 20% Ca). (b) $\chi k_B T(T_0)$ (in μ_B^2/CuO_2) at fixed $T = T_0$ vs p for LSCO and YBCO(0, 2, 7% Zn).

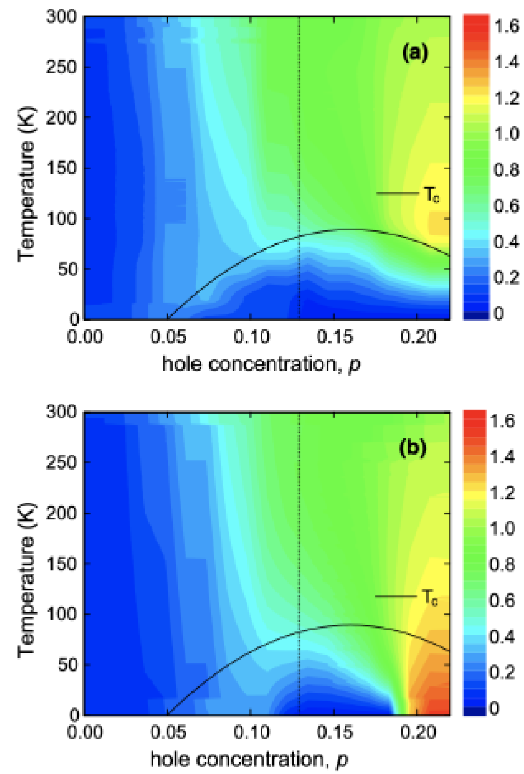
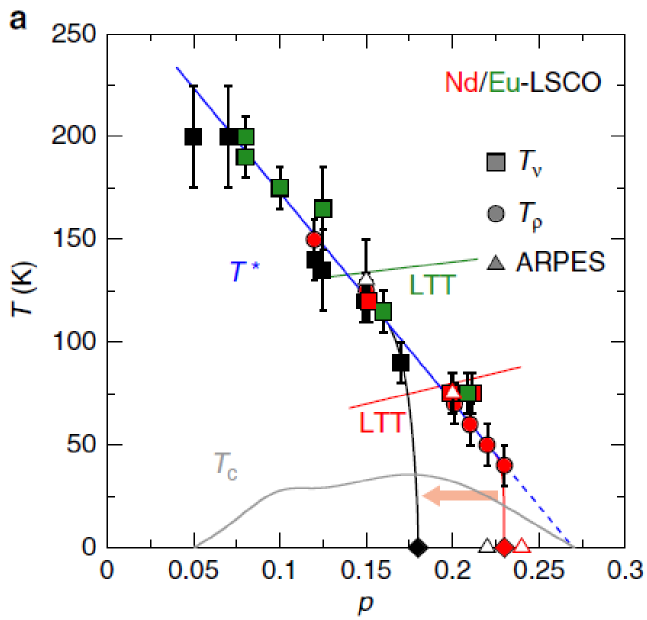


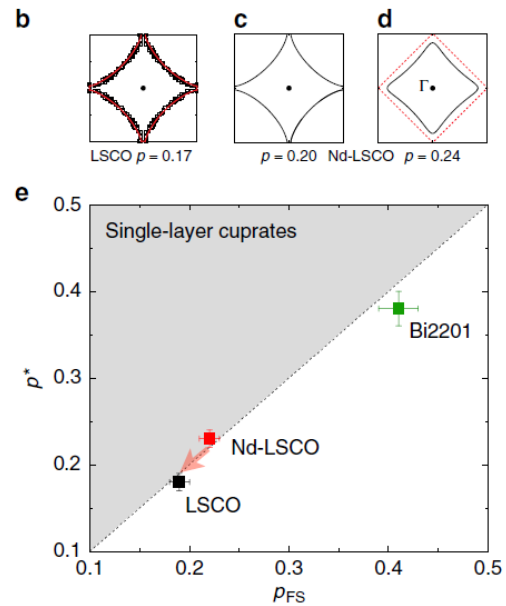
Fig. 2. False color contour plot of $S(T)/T$ for (a) the real superconducting HTS system and (b) for the normal-state extrapolated to $T = 0$. The plots are a composite of Bi-2212 data for $p > 0.13$ and Y-123 data for $p < 0.13$. The crossover is marked by the vertical dashed line.

Tallon, Loram (2001)
Physica C: Supercon 349(1):53–68.
Tallon, *et al.* (2004)
Physica C: Supercon. 415(1):9–14.

Results : effect of *t'* on *T**



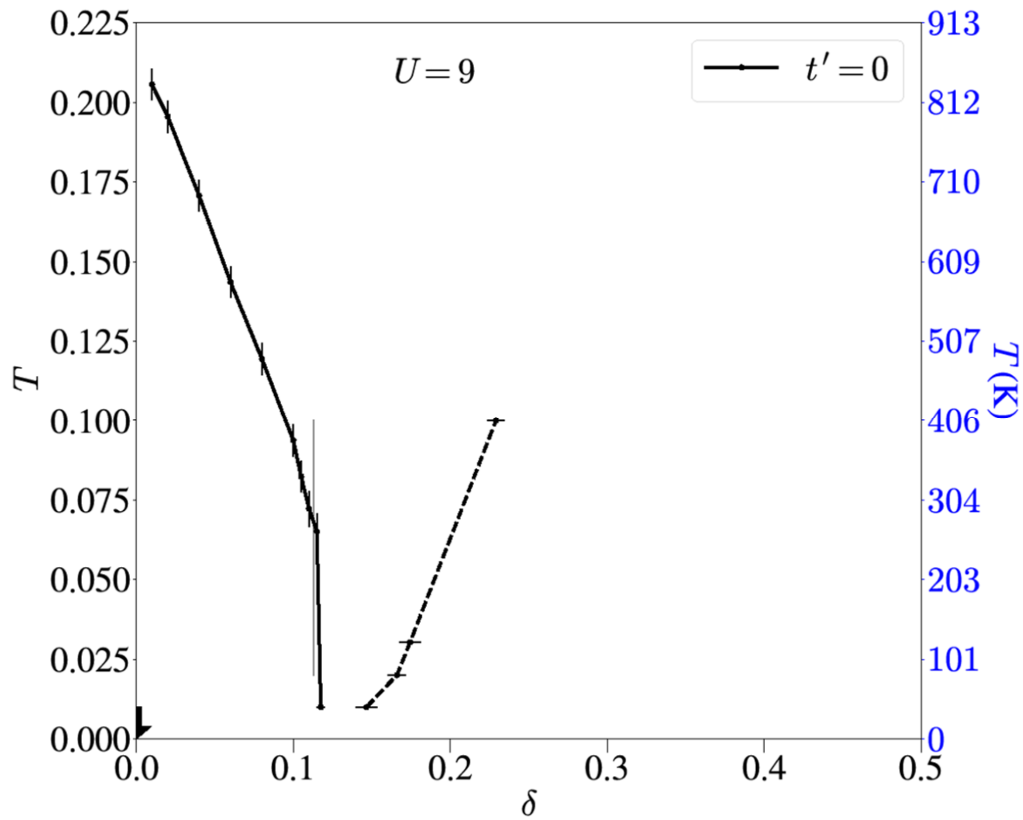
Doiron-Leyraud *et al.*
Nature Comm. **8** 2044



$$p^* < p_{fs}$$

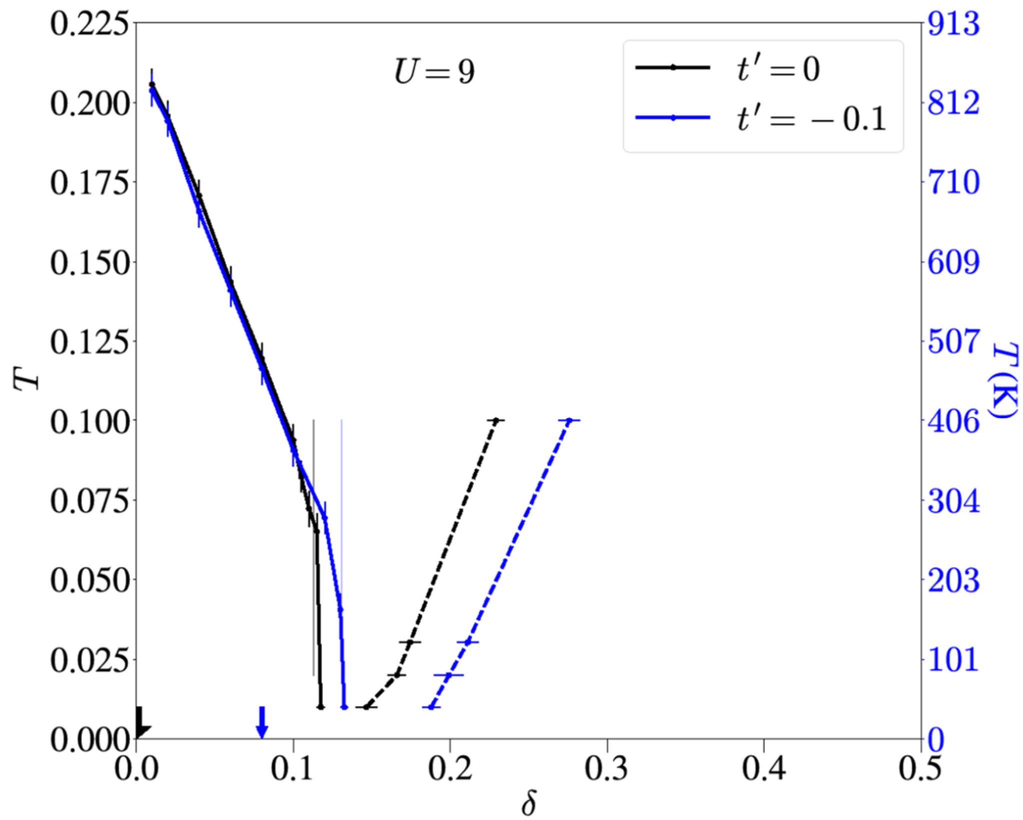
Doiron-Leyraud *et al.*
Nature Comm. **8** 2044

Effect of *t'*



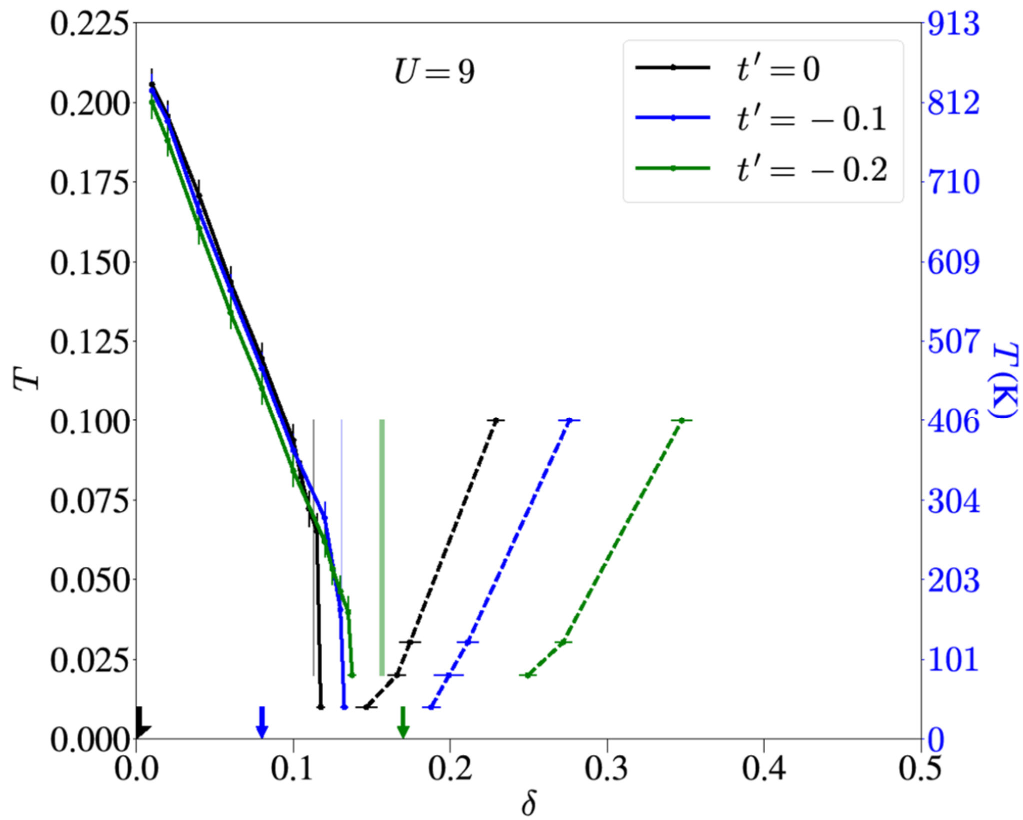
A. Reymbaut *et al.*
Phys. Rev. Research **1**, 023015 (2019)

Effect of *t'*



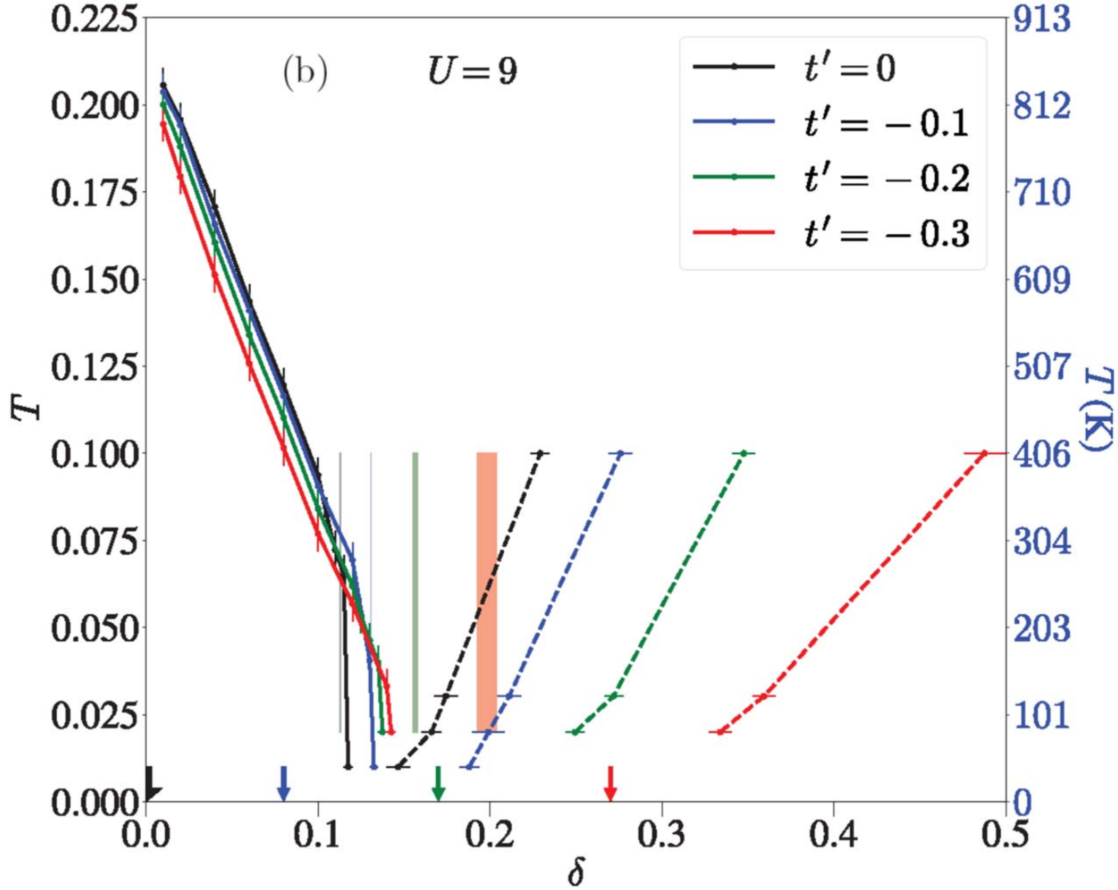
A. Reymbaut *et al.*
Phys. Rev. Research **1**, 023015 (2019)

Effect of *t'*



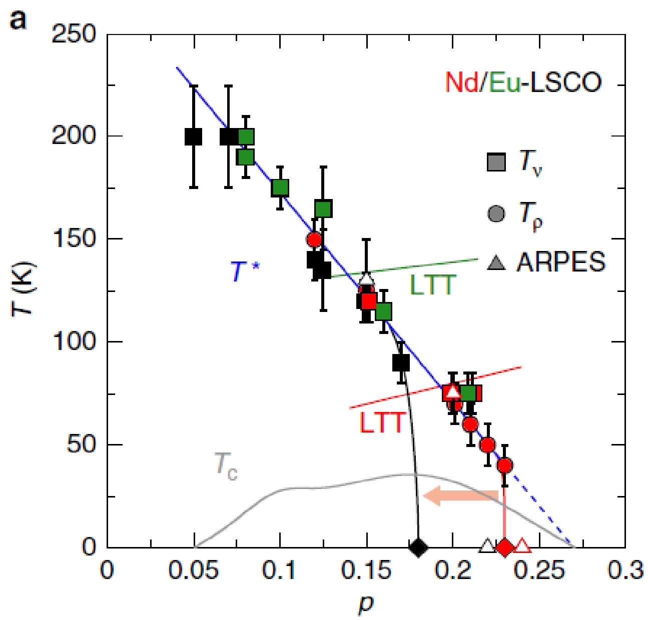
A. Reymbaut *et al.*
Phys. Rev. Research **1**, 023015 (2019)

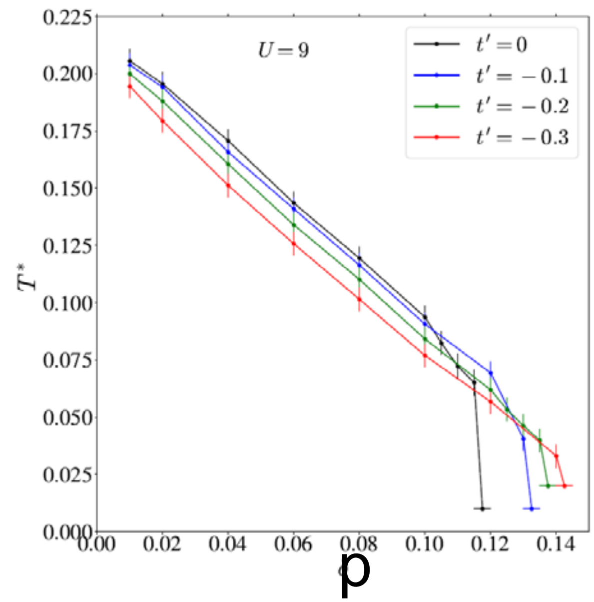
Effect of *t'*



A. Reymbaut *et al.*
Phys. Rev. Research **1**, 023015 (2019)

Results : effect of *t'* on *T**

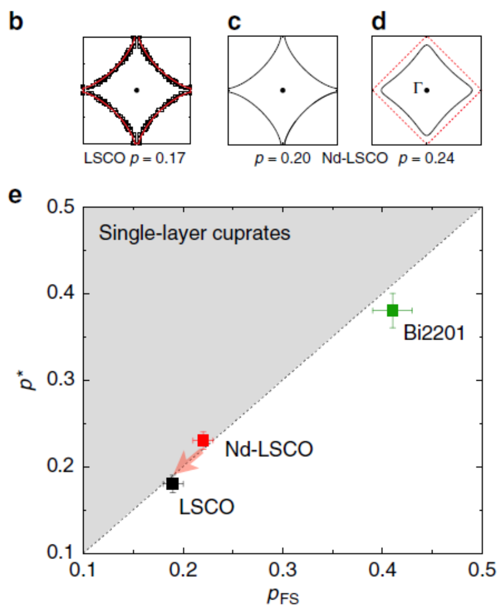




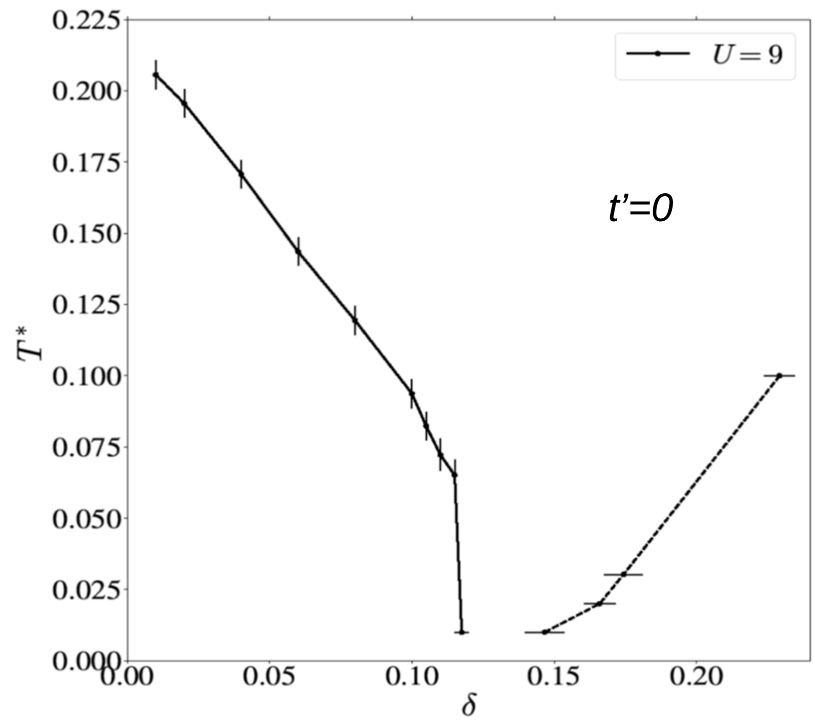
Doiron-Leyraud *et al.*
Nature Comm. **8** 2044

A.Reymbaut, *et al.*
Phys. Rev. Research **1**, 023015 (2019)

Results: van Hove singularity



$p^* < p_{fs}$



p^* p_{fs}

Doiron-Leyraud *et al.*
Nature Comm. **8** 2044

A.Reymbaut, *et al.*
Phys. Rev. Research **1**, 023015 (2019)
W Wu, A Georges, M Ferrero Phys. Rev. X 8, 021048 (2018).

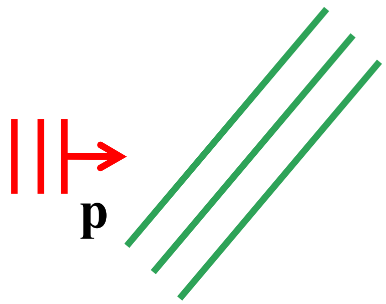
Minuterie

- 10 minutes
- 6 minutes
- 3 minutes
- 4 minutes = 23

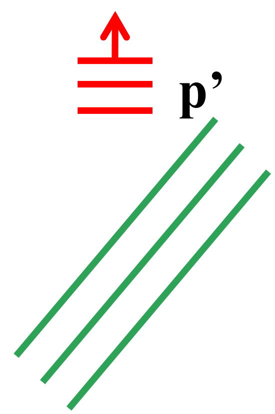
d-wave superconductivity

Superconductivity

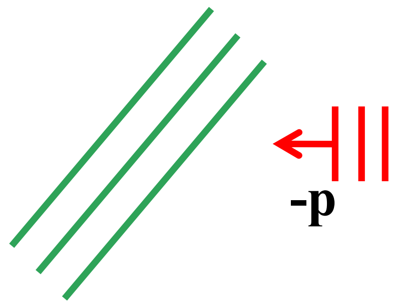
Attraction mechanism in the metallic state



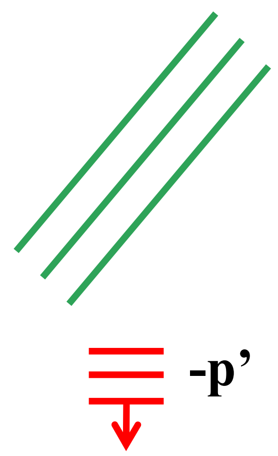
Attraction mechanism in the metallic state



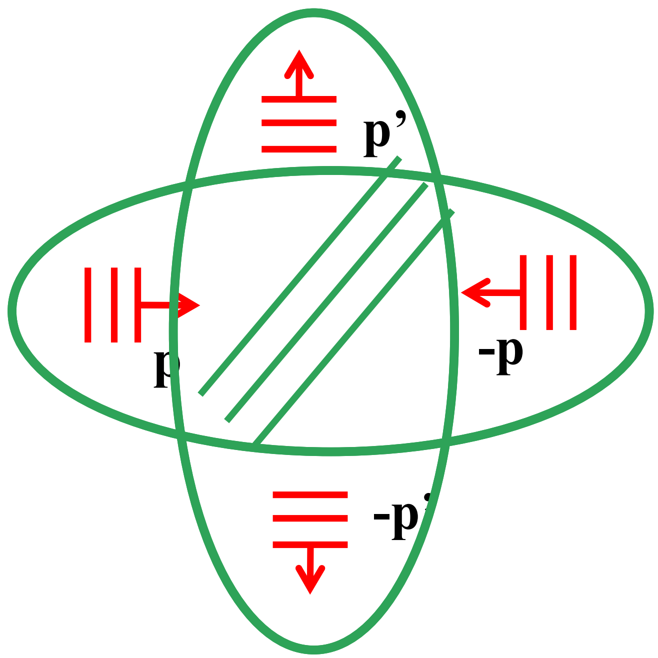
Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



#1 Cooper pair, #2 Phase coherence

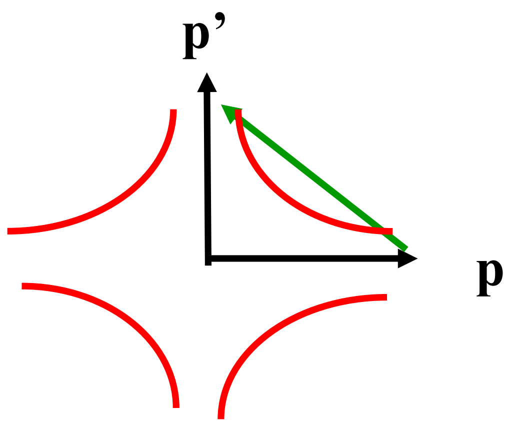
$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow}$$

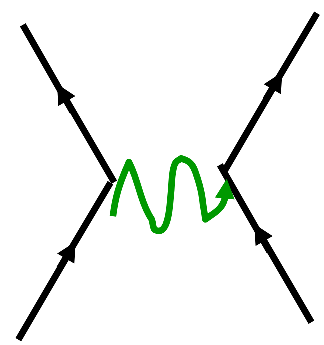
$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \left\langle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} \right\rangle \left\langle \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \quad \right\rangle$$

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

Cartoon « BCS » weak-coupling picture

$$\Delta_{\mathbf{p}} = -\frac{1}{2V}\sum_{\mathbf{p}'} U(\mathbf{p}-\mathbf{p}')\frac{\Delta_{\mathbf{p}'}}{E_{\mathbf{p}'}}\left(1-2n\left(E_{\mathbf{p}'}\right)\right)$$



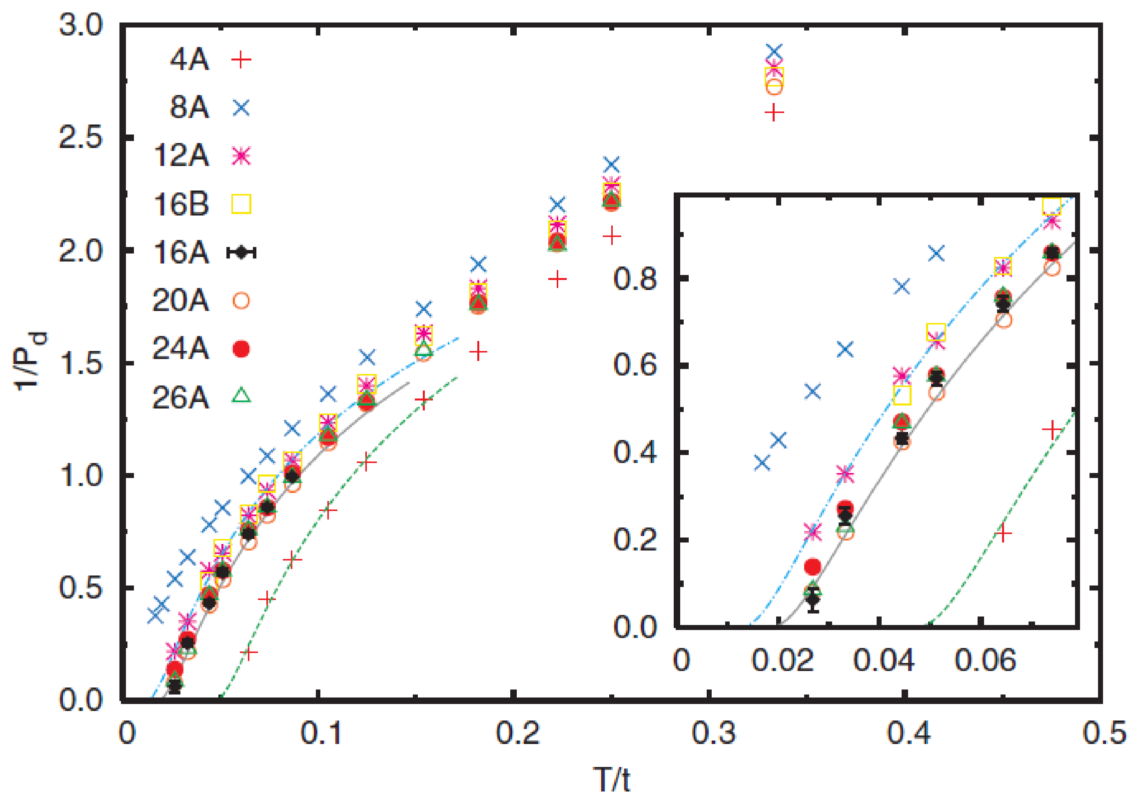


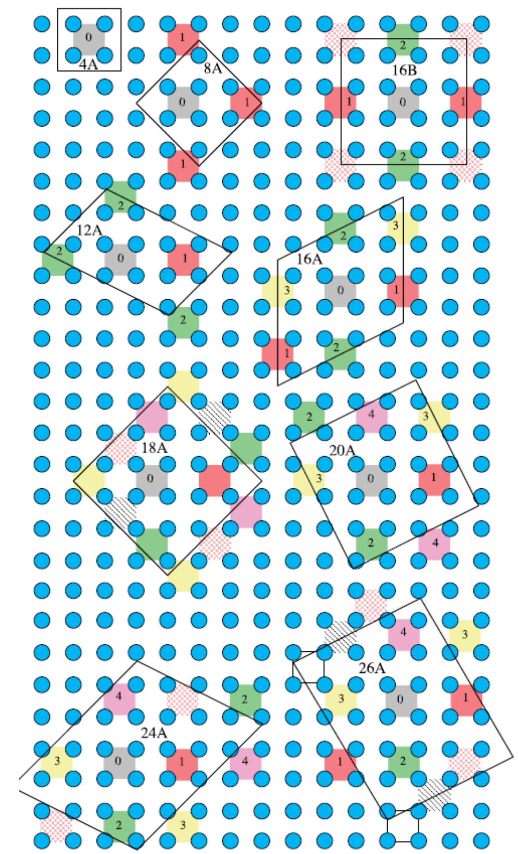
Exchange of spin waves?
Kohn-Luttinger
T_c with pressure

P.W. Anderson Science 317, 1705 (2007)

Béal–Monod, Bourbonnais, Emery P.R. B. **34**, 7716 (1986).
D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch P.R. B **34**, 8190-8192 (1986).
Kohn, Luttinger, P.R.L. **15**, 524 (1965).

Exchange of spin waves, *U = 4t doping 10%*





Maier, Jarrell, Schulthess, Kent, White PRL **95,** 237001 (2005)

A cartoon strong correlation picture

$$J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j = J\sum_{\langle i,j\rangle}\left(\frac{1}{2}c_i^{\dagger}\vec{\sigma}c_i\right)\cdot\left(\frac{1}{2}c_j^{\dagger}\vec{\sigma}c_j\right)$$

$$d = \langle\hat{d}\rangle = 1/N\sum_{\vec{k}}(\cos k_x - \cos k_y)\langle c_{\vec{k},\uparrow}c_{-\vec{k},\downarrow}\rangle$$

$$H_{MF} = \sum_{\vec{k},\sigma}\varepsilon(\vec{k})c^{\dagger}_{\vec{k},\sigma}c_{\vec{k},\sigma} - 4Jm\hat{m} - Jd(\hat{d}+\hat{d}^{\dagger}) + F_0$$

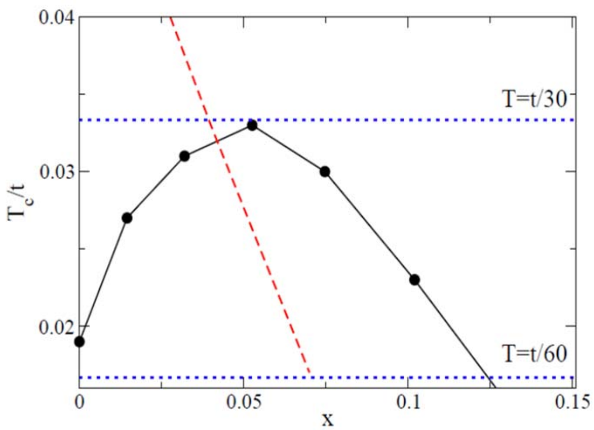
Pitaevskii Brückner:
Pair state orthogonal to repulsive core of Coulomb interaction

P.W. Anderson Science 317, 1705 (2007)

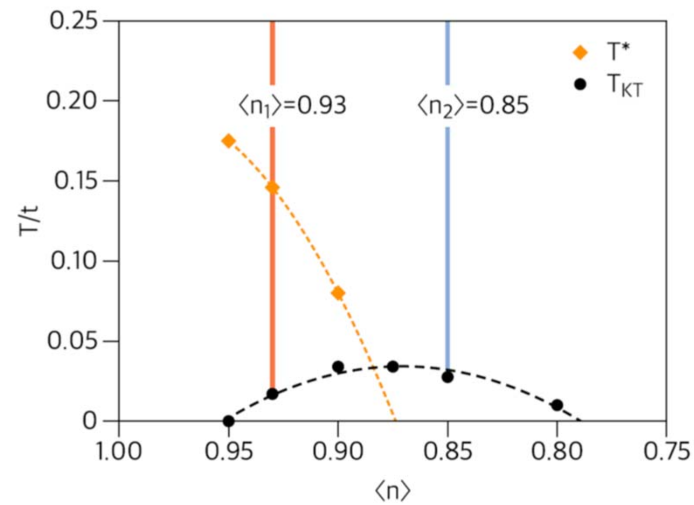
Miyake, Schmitt–Rink, and Varma P.R. B **34**, 6554-6556 (1986)

More sophisticated Slave Boson: Kotliar Liu PRB 1988

Superconducting transition temperature



E. Gull and A. J. Millis
Phys. Rev. B 88, 075127

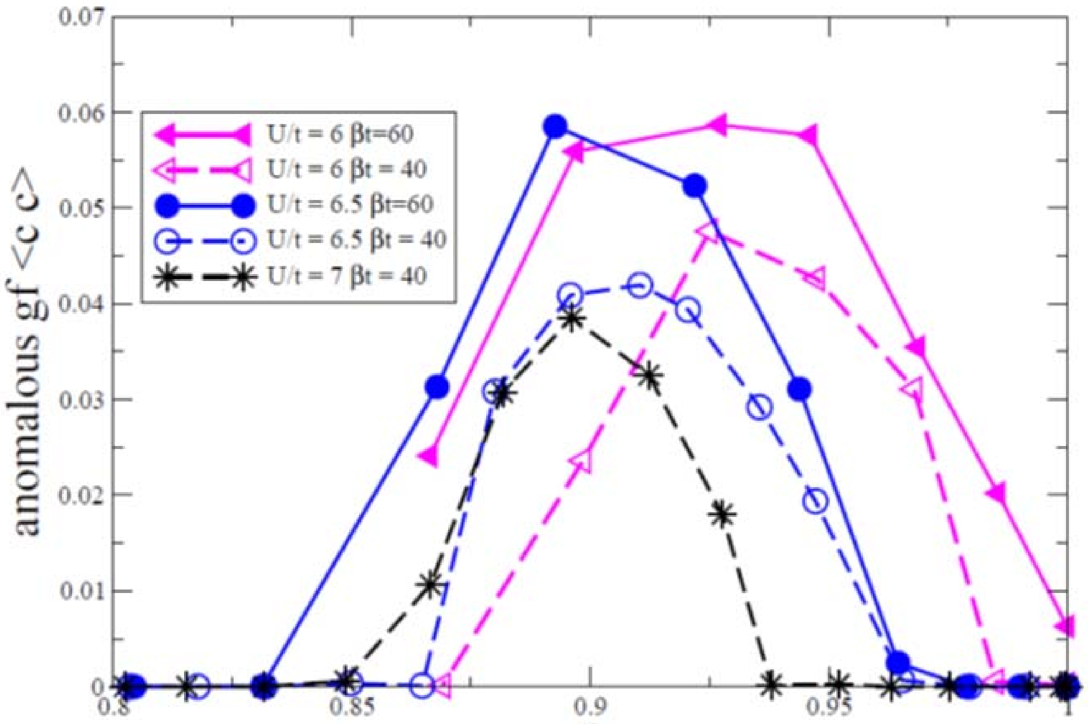


T.A. Maier, D.J. Scalapino, npj Quantum Materials (2019)

DCA, 8 sites, $U/t = 6$ and $t'=0$

DCA, 12 sites, $U/t = 7$ and $t'/t = -0.15$

$t' = 0$ DCA, 8 site



Gull *et al.* Phys. Rev. Lett. **110**, 216405 (2013)

d-wave in mean-field

$$\hat{\mathcal{H}}_{modèle\ t-J} = -t \sum_{\langle i,j \rangle\ \sigma} \hat{P}\left(\hat{c}^{\dagger}_{i\sigma}\hat{c}_{j\sigma} + c.h\right)\hat{P} + J\sum_{\langle i,j \rangle}\left(\hat{\vec{S}}_i.\hat{\vec{S}}_j - \frac{1}{4}\hat{n}_i\hat{n}_j\right)$$

$$\begin{aligned}
J\hat{S}^z_i\hat{S}^z_j &= J(\hat{n}_{i\uparrow} - \hat{n}_{i\downarrow})(\hat{n}_{j\uparrow} - \hat{n}_{j\downarrow}) \\
&= J(\hat{c}^{\dagger}_{i\uparrow}\hat{c}_{i\uparrow} - \hat{c}^{\dagger}_{i\downarrow}\hat{c}_{i\downarrow})(\hat{c}^{\dagger}_{j\uparrow}\hat{c}_{j\uparrow} - \hat{c}^{\dagger}_{j\downarrow}\hat{c}_{j\downarrow}) \\
&= -J(\hat{c}^{\dagger}_{i\downarrow}\hat{c}_{i\downarrow}\hat{c}^{\dagger}_{j\uparrow}\hat{c}_{j\uparrow} + \hat{c}^{\dagger}_{i\uparrow}\hat{c}_{i\uparrow}\hat{c}^{\dagger}_{j\downarrow}\hat{c}_{j\downarrow}) + \ldots \\
&= -J(\hat{c}^{\dagger}_{j\uparrow}\hat{c}^{\dagger}_{i\downarrow}\hat{c}_{i\downarrow}\hat{c}_{j\uparrow} + \hat{c}^{\dagger}_{i\uparrow}\hat{c}^{\dagger}_{j\downarrow}\hat{c}_{j\downarrow}\hat{c}_{i\uparrow}) + \ldots
\end{aligned}$$

Hartree-Fock :

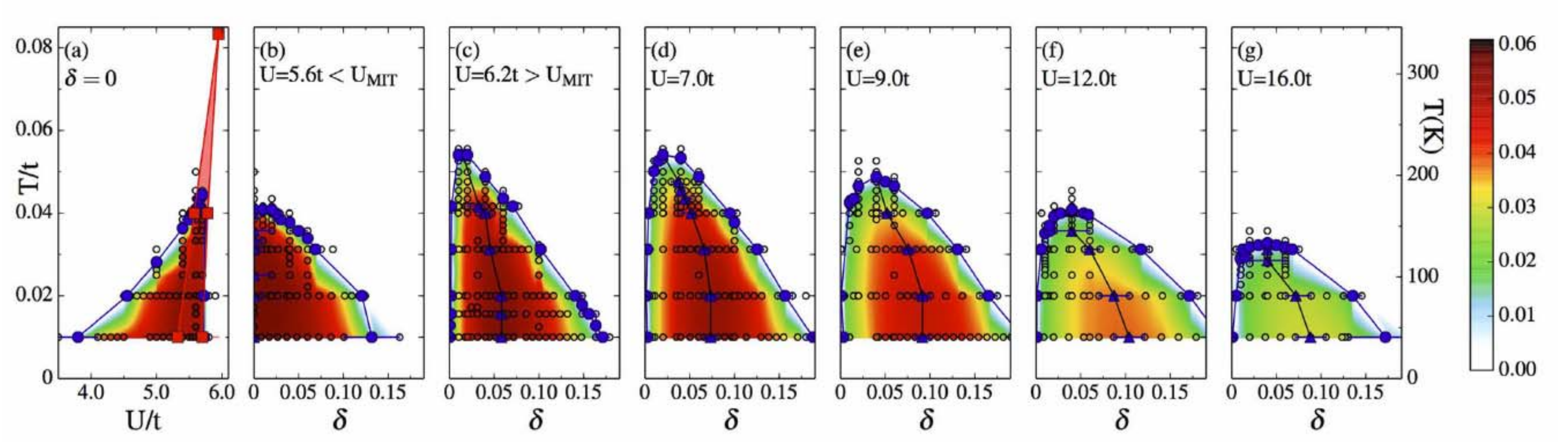
$$d^* = \langle \hat{c}^{\dagger}_{j\uparrow}\hat{c}^{\dagger}_{i\downarrow}\rangle_{\mathcal{H}_{modèle\ t-J}}$$

$$\langle J\hat{S}^z_i\hat{S}^z_j\rangle = -2J\, d^*d + \ldots$$

Miyake, Schmitt–Rink et Varma, PRB **34**, 6554-6556 (1986)

Anderson, Baskaran, Zou et Hsu, PRL **58**, 26 (1987)

T_c controlled by *J*, CDMFT *2x2*



Fratino et al.
Sci. Rep. **6**, 22715

Some experiments that suggest $T_c < T_{pair} < T^*$

T. Kondo *et al*. PRL **111** (2013)

Kondo, Takeshi, et al. Kaminski Nature Physics 2011, ***7***, 21-25

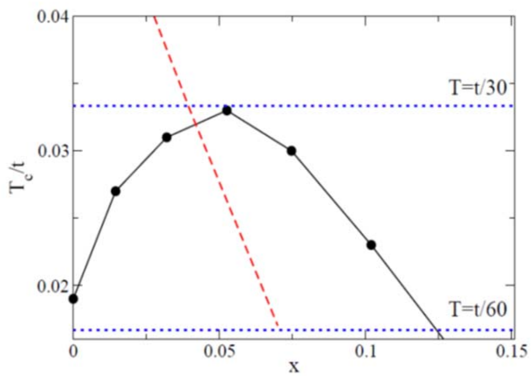
A. Pushp, Parker, … A. Yazdani, Science **364**, 1689 (2009)

Lee …Tajima (Osaka) https://arxiv.org/pdf/1612.08830

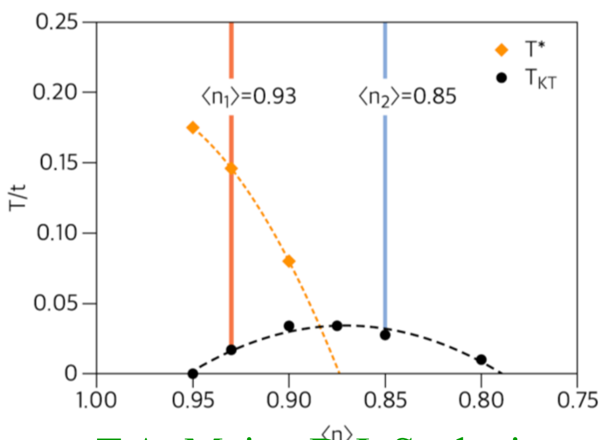
Patrick M. Rourke, et al. Hussey Nature Physics **7,** 455–458 (2011)

Lee et al. J. Phys. Soc. Jpn. 86, 023701 (2017)

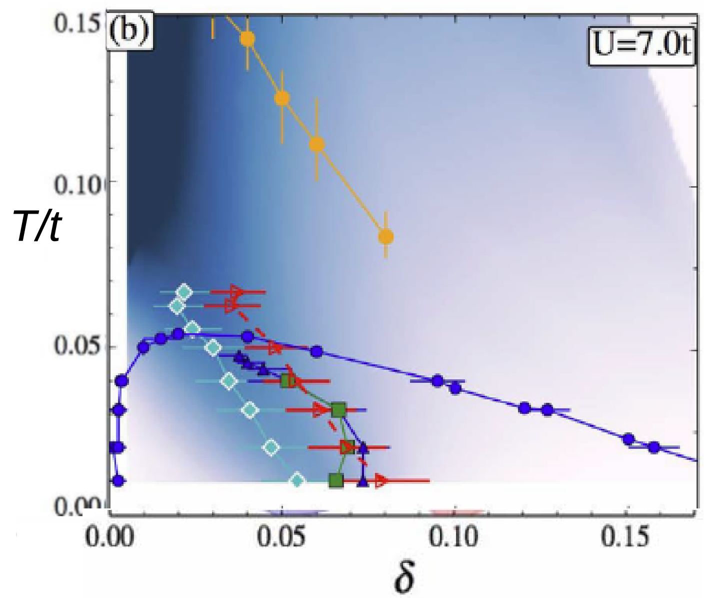
Phase diagram



E. Gull and A. J. Millis
Phys. Rev. B 88, 075127

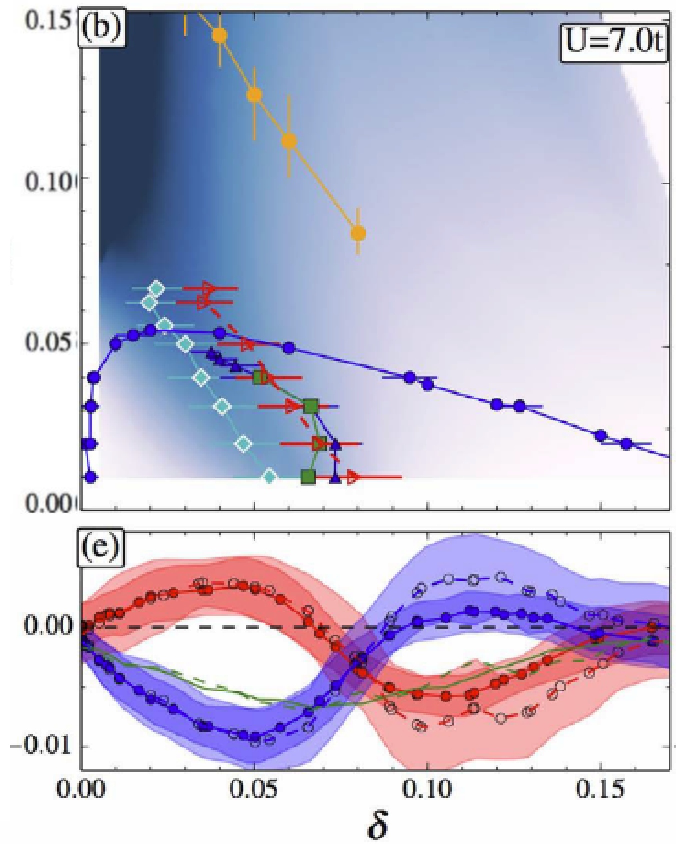


T.A. Maier, D.J. Scalapino, npj Quantum Materials (2019)



Fratino et al.
Sci. Rep. **6**, 22715

Condensation energy

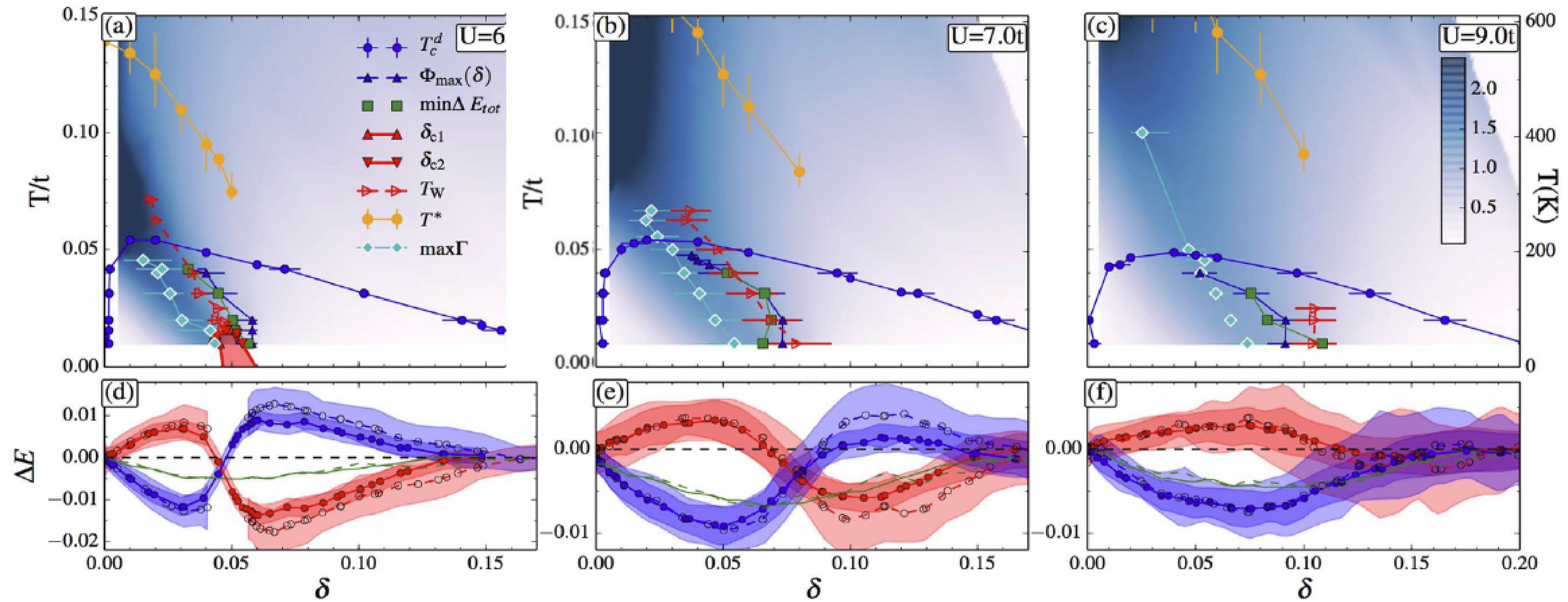


Fratino et al.
Sci. Rep. **6**, 22715

Theory, see also Jarrel PRL (2004), Gull Millis PRB (2014)
Experiments: Bontemps, Santander-Syro Van der Marel …

Condensation energy

Fratino et al.
Sci. Rep. **6**, 22715



Theory, see also Jarrel PRL (2004), Gull Millis PRB (2014)
Experiments: Bontemps, Santander-Syro Van der Marel …

Minuterie

- 10 minutes
- 6 minutes
- 3 minutes
- 4 minutes
- 5 minutes
- 9 minutes = 37

D. Sénéchal

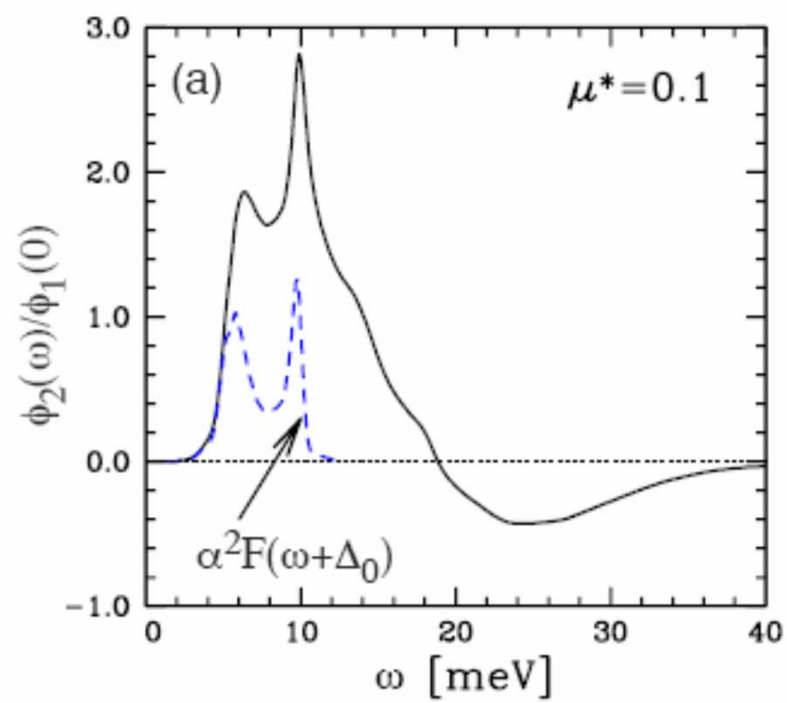
Bumsoo Kyung

The glue

Kyung, Sénéchal, Tremblay, Phys. Rev. B **80,** 205109 (2009)
Sénéchal, Day, Bouliane, AMST, Phys. Rev. B **87**, 075123 (2013)
A. Reymbaut *et al*. PRB **94** 155146 (2016)

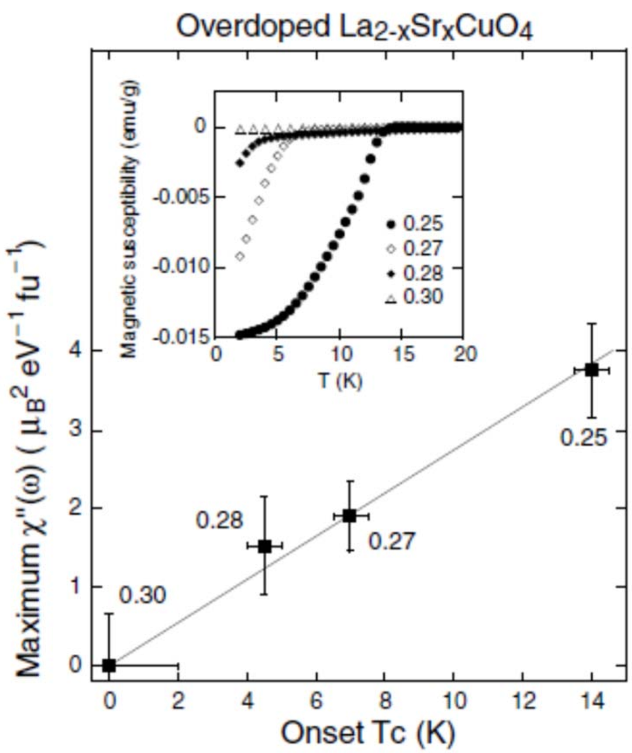
Im Σ_{an} and electron-phonon in Pb

Maier, Poilblanc, Scalapino, PRL (2008)

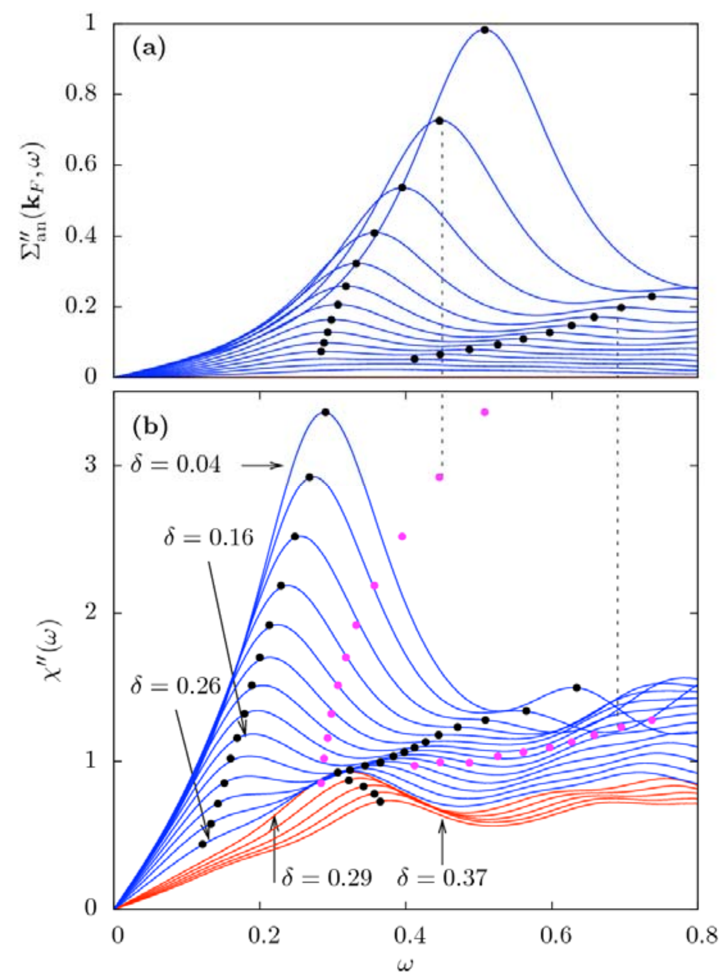


The glue CDMFT 2x2, T=0

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



Wakimoto … Birgeneau
PRL (2004)



The glue and neutrons

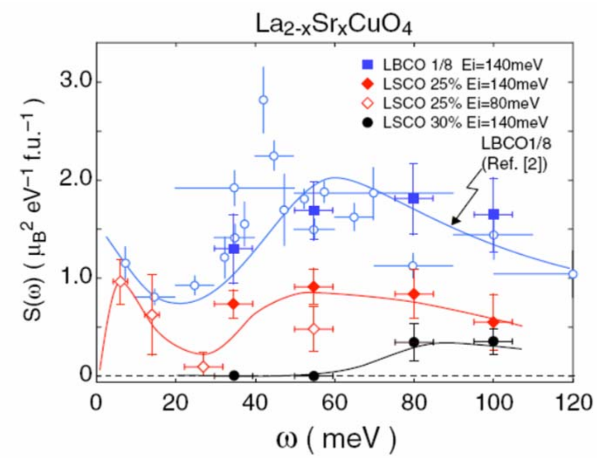
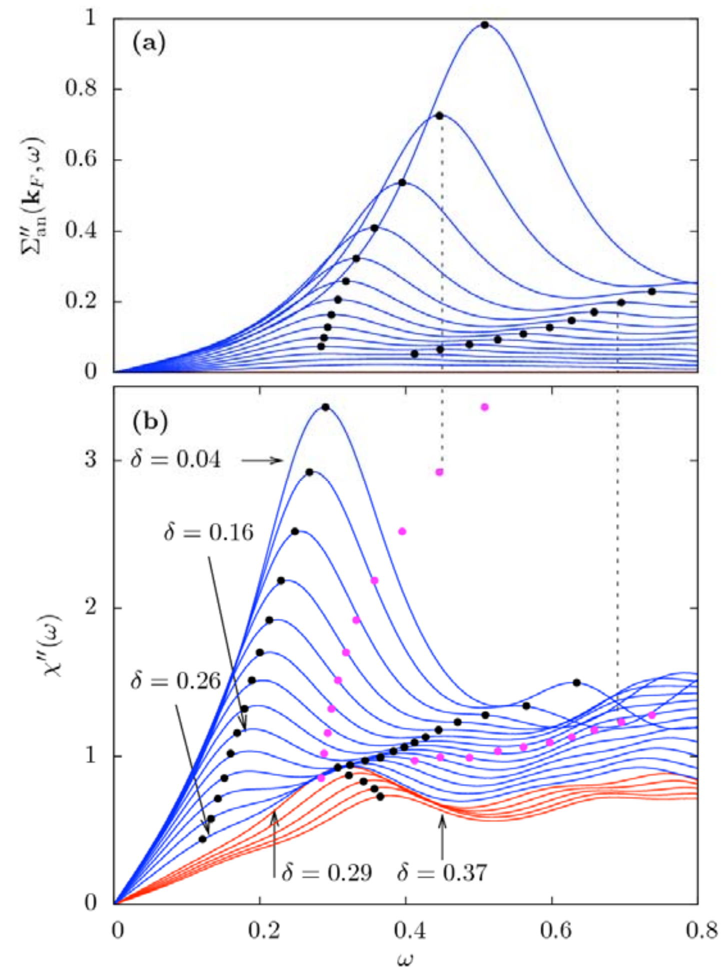


FIG. 3 (color online). **Q**-integrated dynamic structure factor $S(\omega)$ which is derived from the wide-H integrated profiles for LBCO 1/8 (squares), LSCO $x = 0.25$ (diamonds; filled for $E_i =$ 140 meV, open for $E_i = 80$ meV), and $x = 0.30$ (filled circles) plotted over $S(\omega)$ for LBCO 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)



Minuterie

- 10 minutes
- 6 minutes
- 3 minutes
- 4 minutes
- 5 minutes
- 9 minutes
- 3 minutes = 40

Giovanni Sordi

Patrick Sémon

Kristjan Haule

A phase transition at the heart of the phase diagram (and its relation to Mott)

G. Sordi, *et al*. Scientific Reports 2, 547 (2012)

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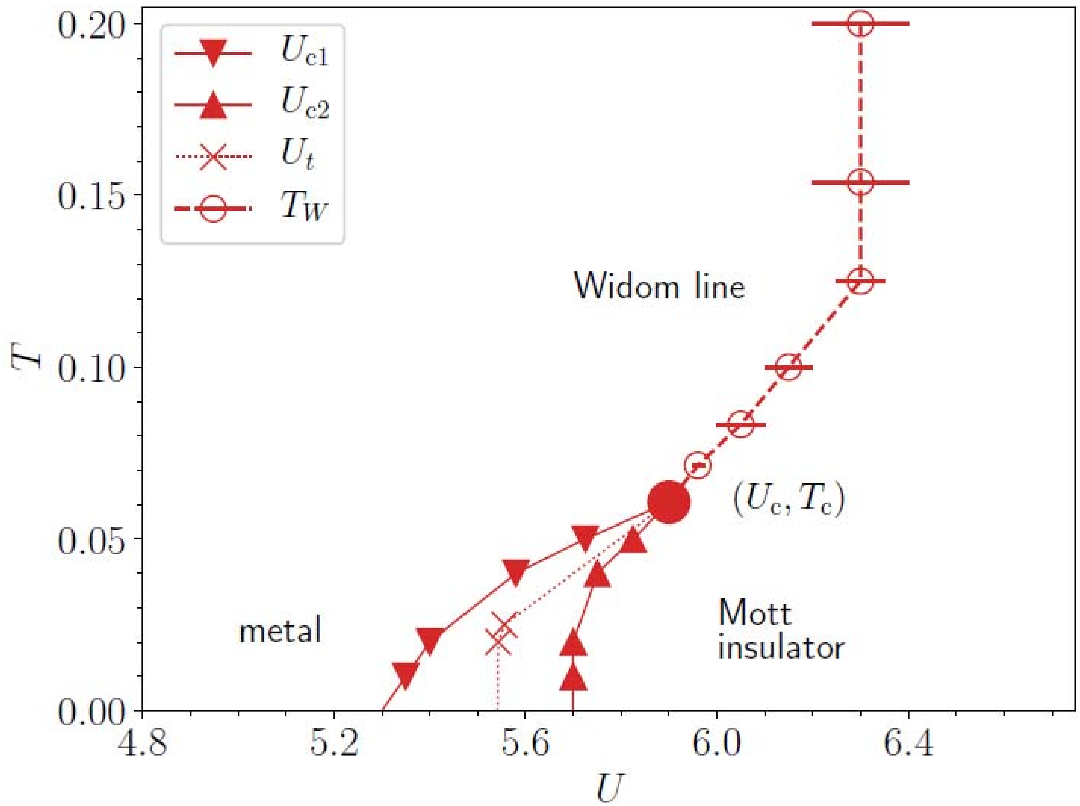
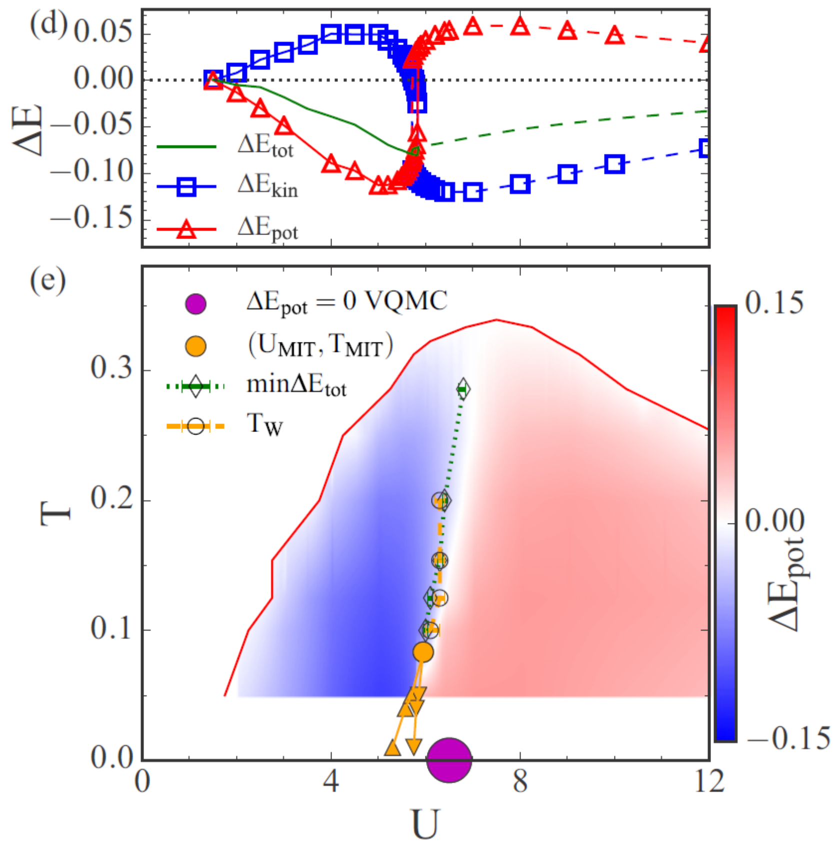
Mott transition at half-filling, CDMFT 2 x 2



Walsh, Sémon, Poulin, G. Sordi, AMST, PRB **99**, 075122 (2019)

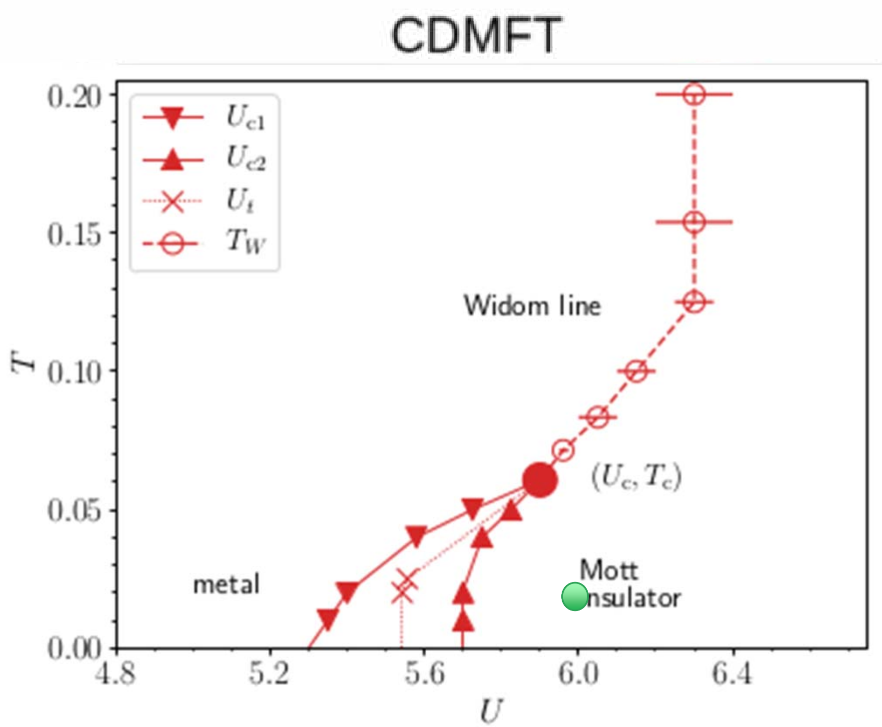
Park, Haule, Kotliar, Phys. Rev. Lett. **101**, 186403 (2008)

Change in potential energy due to large ξ

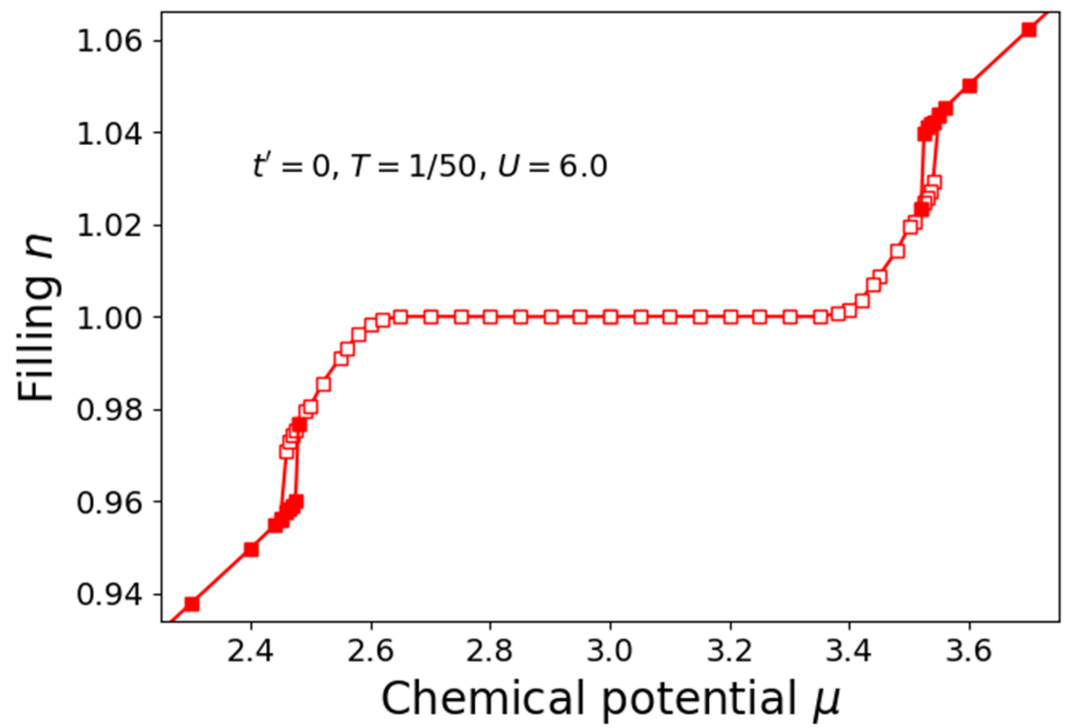


Fratino, Sémon, Charlebois, Sordi, AMST, PRB **95**, 235109 (2017)

Mott and Sordi transition: CDMFT 2 x 2

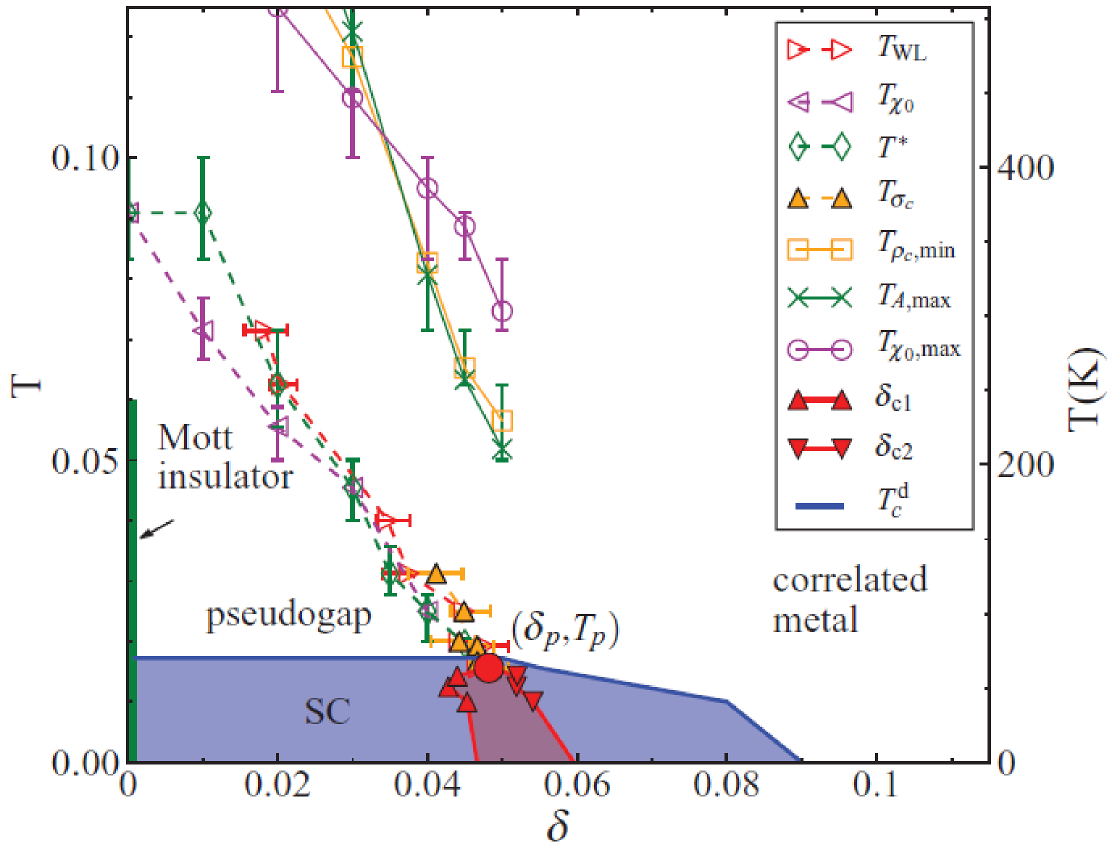


C. Walsh, Phys. Rev. Lett., 122 : 067203 – Feb 2019



G. Sordi, PhysRevB.84.075161 – August 2011

Widom line and its precursor



Not in *d=1*

J. P. L. Faye and D. Sénéchal
Phys. Rev. B **96**, 195114

Sordi, Sémon, Haule, AMST, PRB **87**, 041101(R) (2013)

Sordi, Haule, AMST, PRB **84**, 075161 (2011)

Sordi, Haule, AMST, PRL**104**, 226402 (2010)

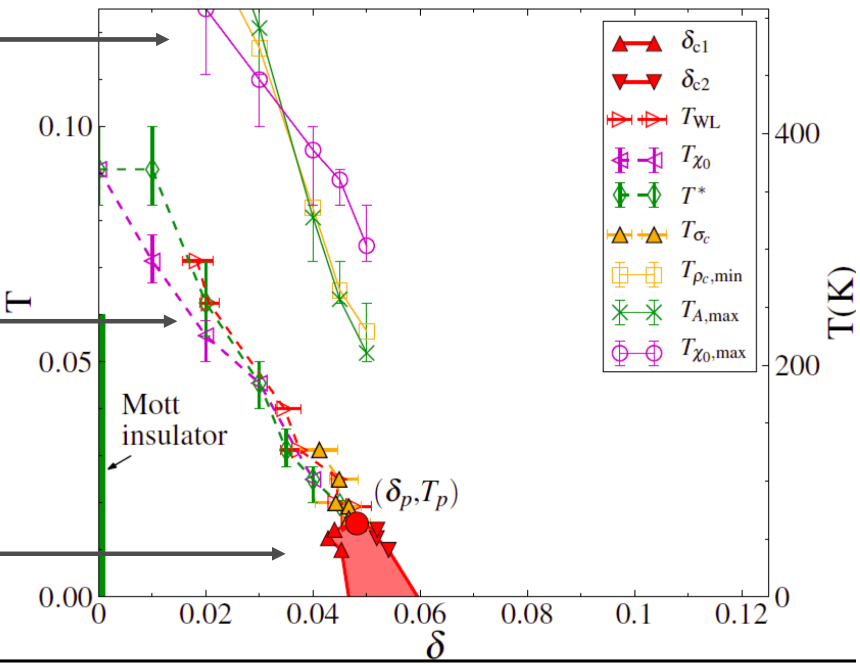
Two crossover lines


Giovanni Sordi   Patrick Sémon

T*

Widom line

Sordi transition

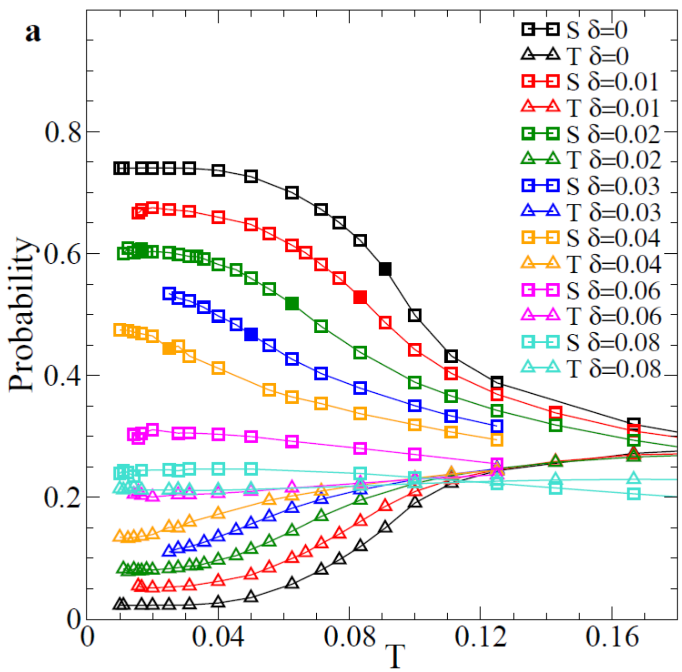


Not in *d=1*

J. P. L. Faye and D. Sénéchal
Phys. Rev. B **96**, 195114

G. Sordi et al. Phys. Rev. Lett. 108, 216401/1-6 (2012)
G.Sordi et al. Phys. Rev. B 87, 041101(R)/1-5 (2013)
P. Sémon, G. Sordi, *et al.*, Phys. Rev. B **89**, 165113/1-6 (2014)

Physics: Plaquette eigenstates



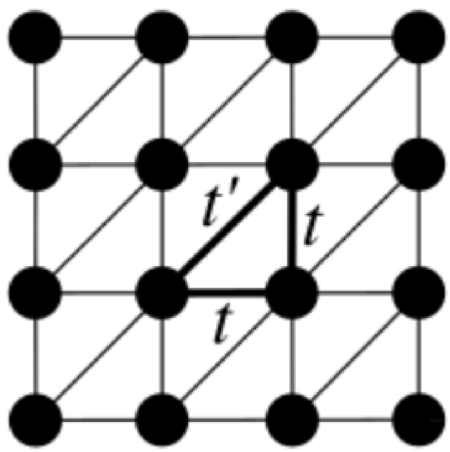
U = 6.2; t' = 0

Sordi et al., Sci. Rep. 2 547 (2012);

See also:

Michel Ferrero, P. S. Cornaglia, L. De Leo, O. Parcollet, G. Kotliar, A. Georges
PRB **80**, 064501 (2009)

Anisotropic triangular lattice



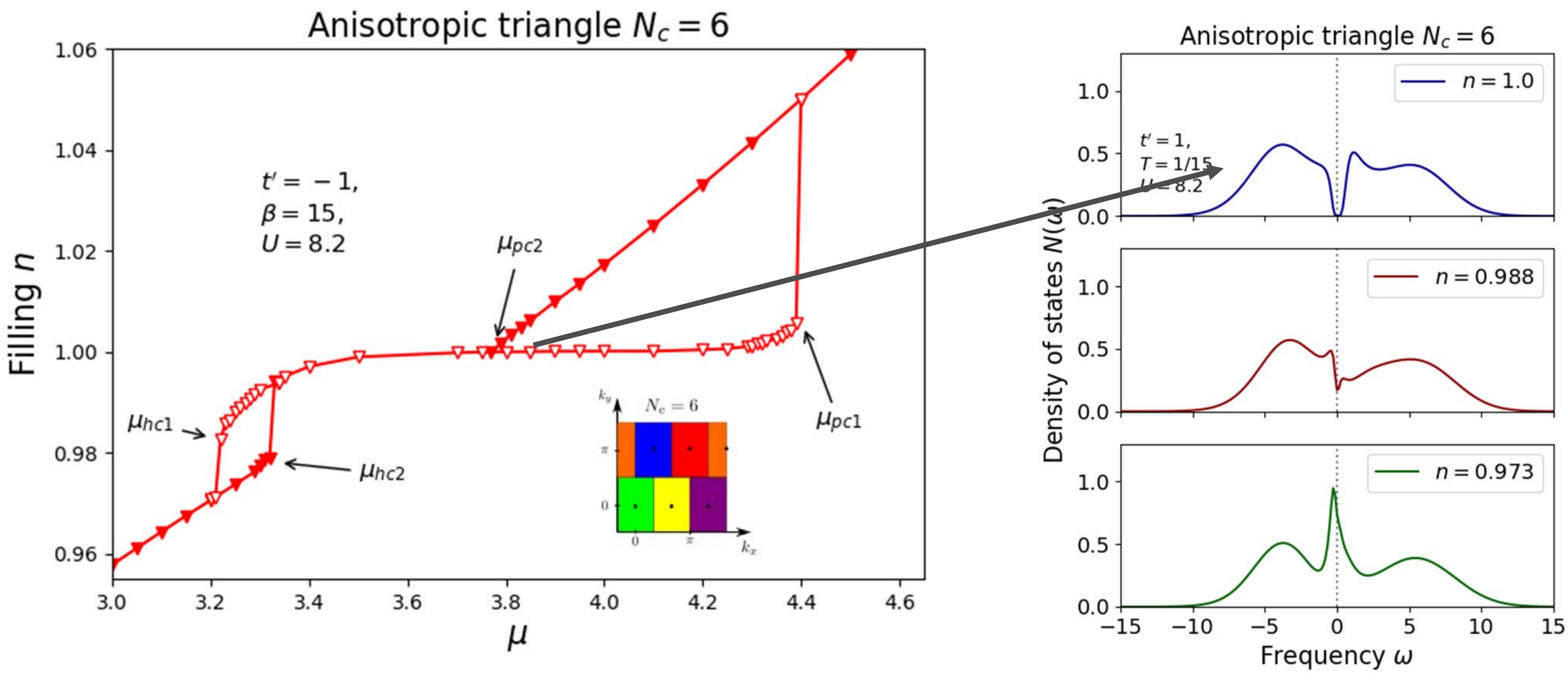
Pierre-Olivier Downey

Maxime Charlebois

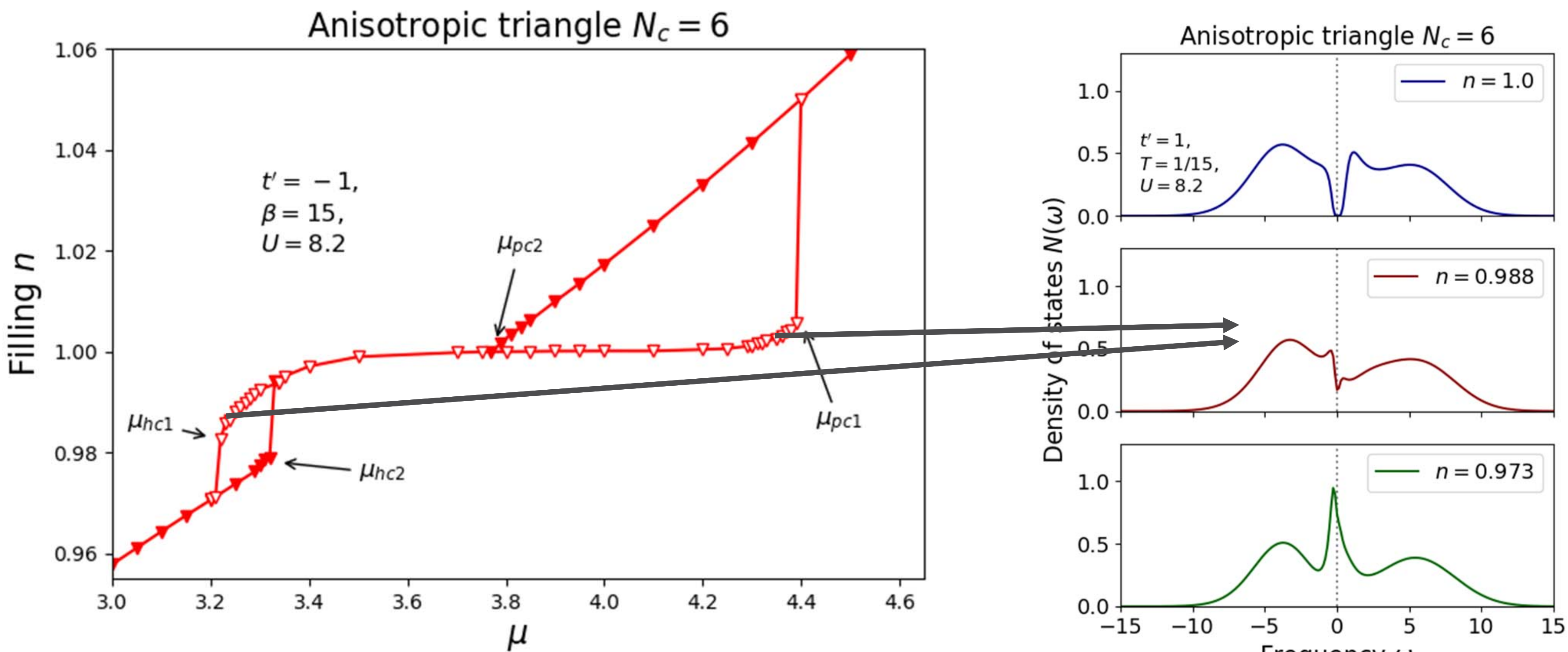
Charles-David Hébert

Olivier Gingras

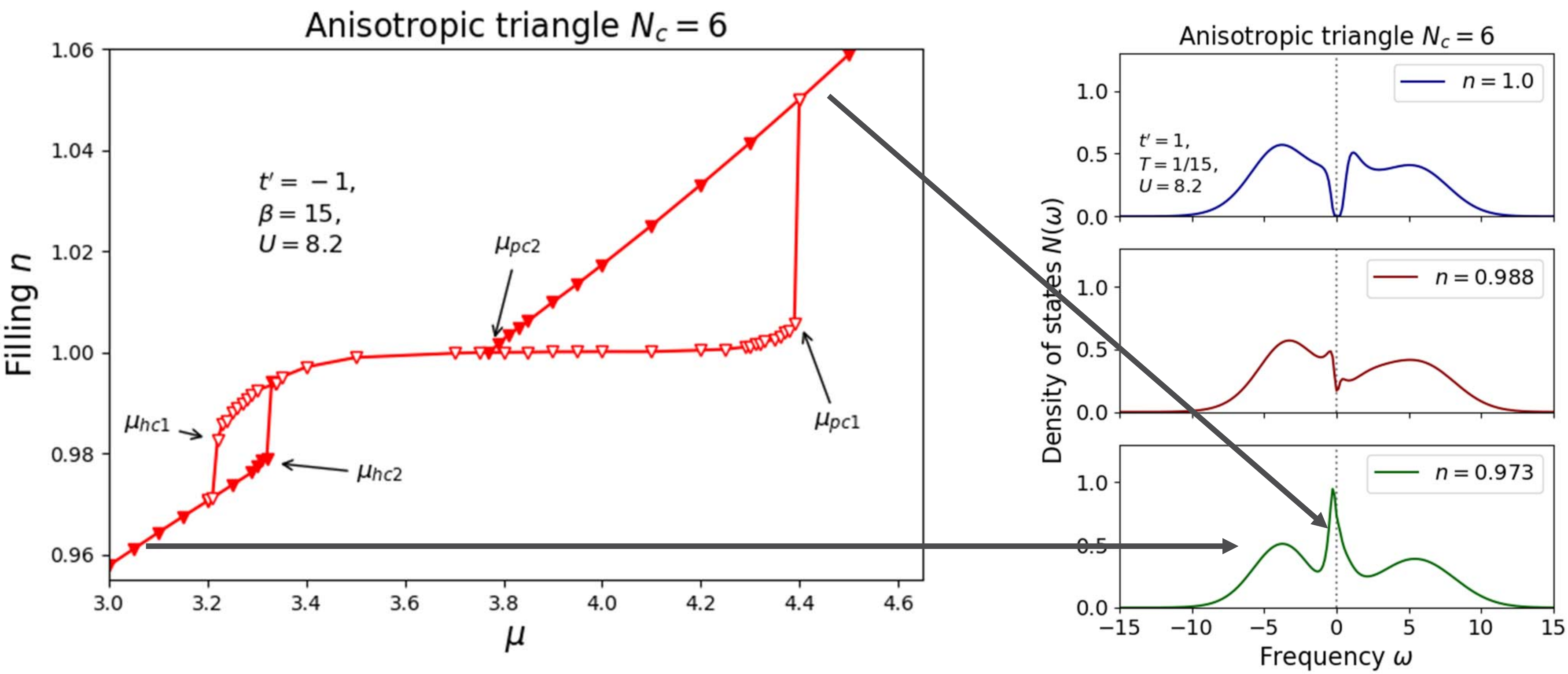
Same Physics on the triangular lattice



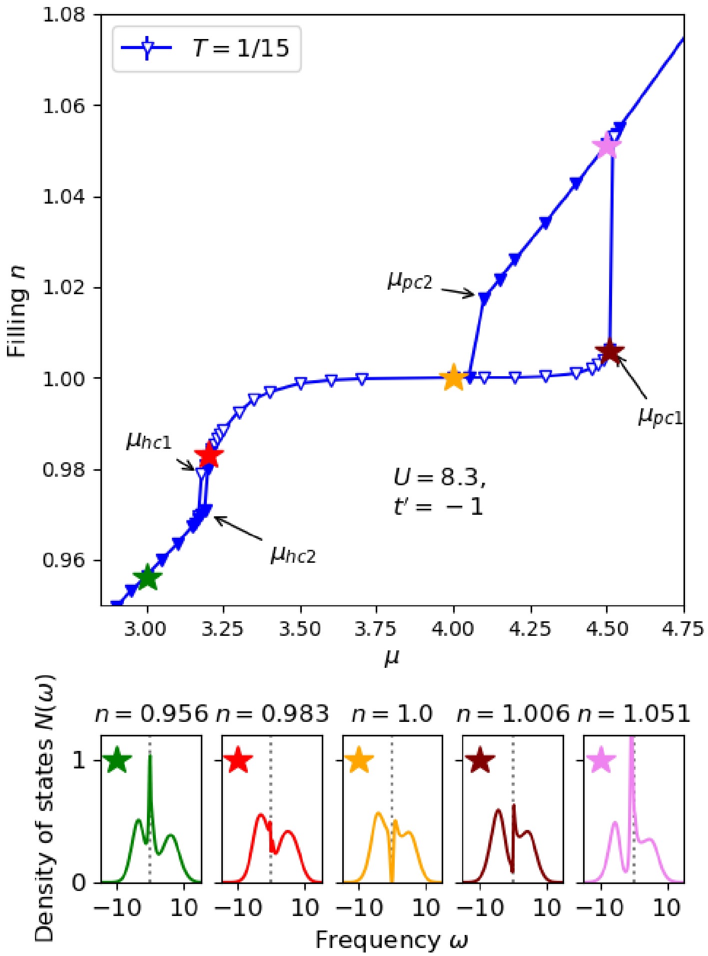
Same Physics on the triangular lattice



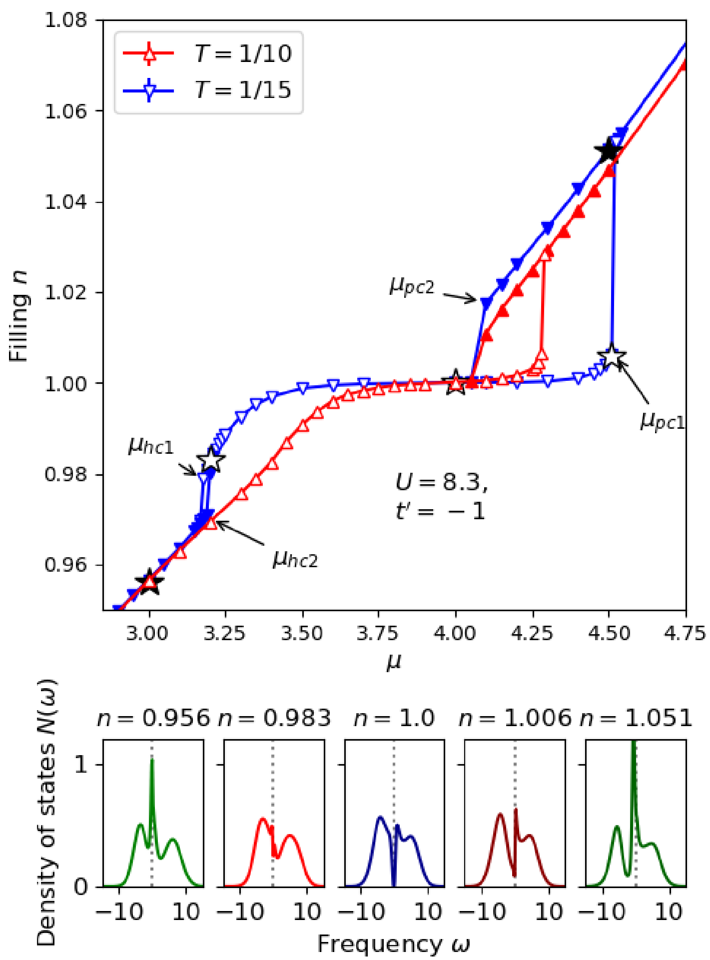
Same Physics on the triangular lattice



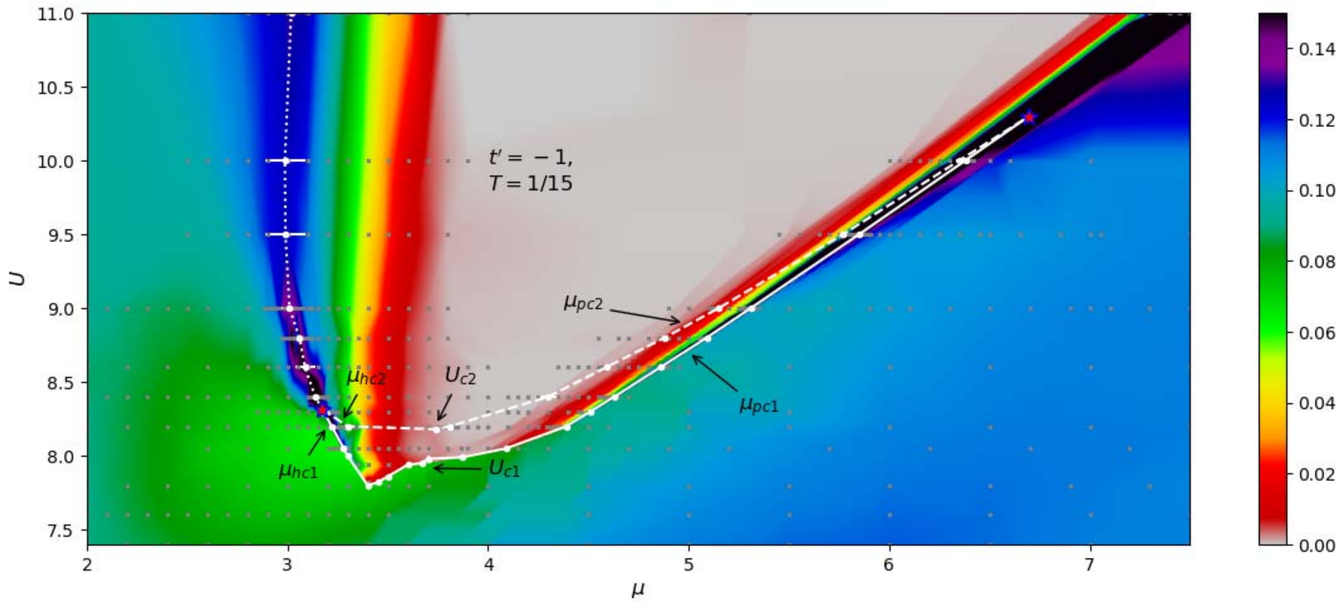
Triangular lattice with DCA, 6 patches

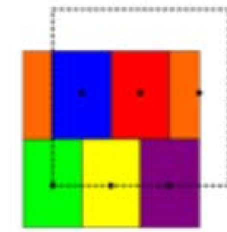


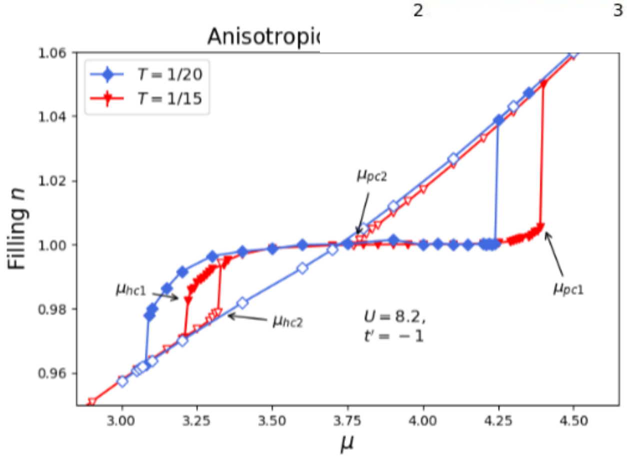
Some Physics on the triangular lattice



Mott and Sordi transition on the triangular lattice DCA, N=6



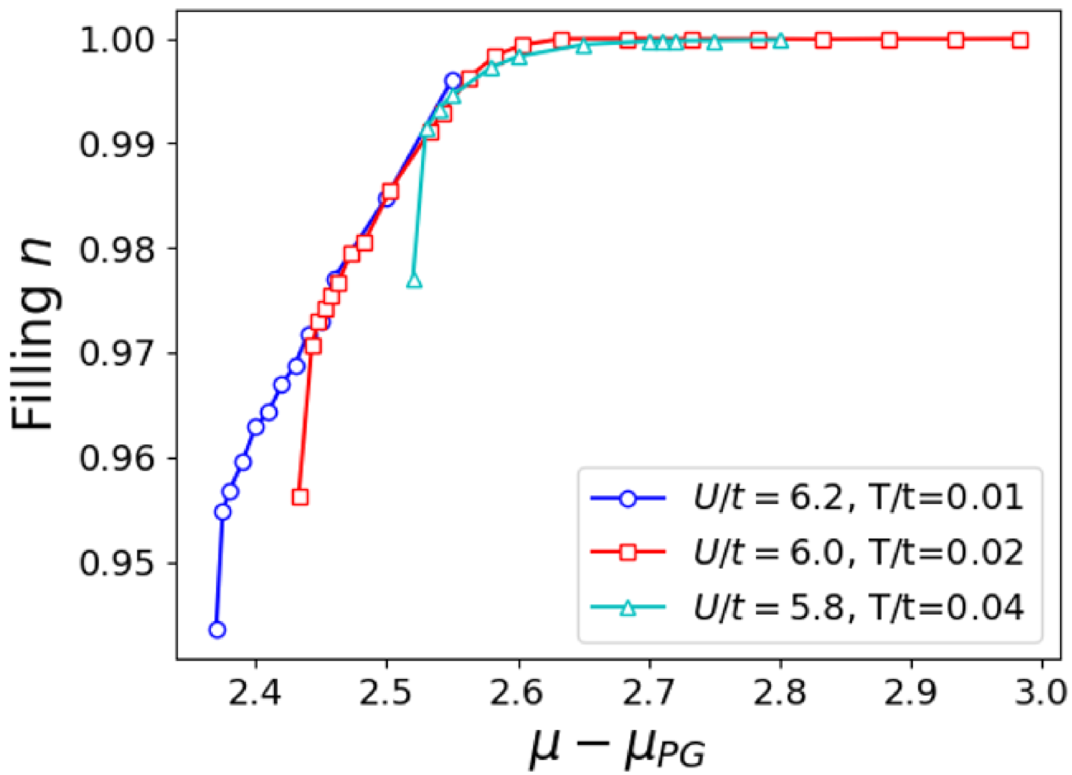




(Topological) stability

Depends on

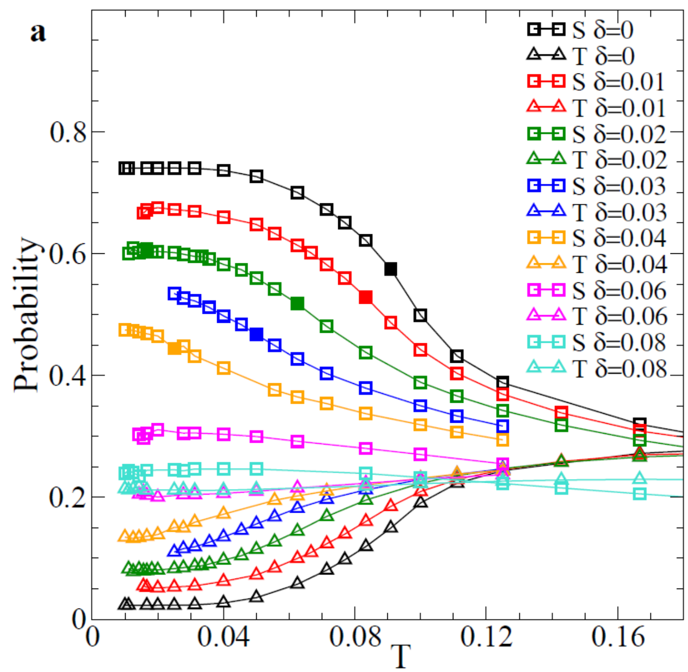
- Cluster
- Large changes in t'



Another *Fermi Surface Reconstruction without Symmetry Breaking*

- Gazit, Assaad, Sachdev Phys. Rev. X 10, 041057

Physics: Plaquette eigenstates



U = 6.2; t' = 0

Sordi et al., Sci. Rep. 2 547 (2012);

See also:

Michel Ferrero, P. S. Cornaglia, L. De Leo, O. Parcollet, G. Kotliar, A. Georges
PRB **80**, 064501 (2009)

Quantum Critical point
Back to square lattice

Yang, … Zaanen, and Jarrell PRL **106**, 047004 (2011)

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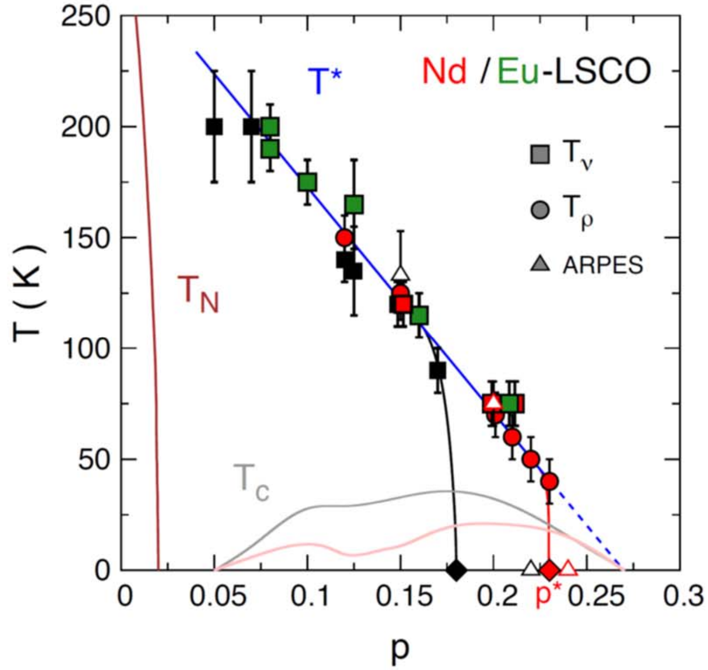
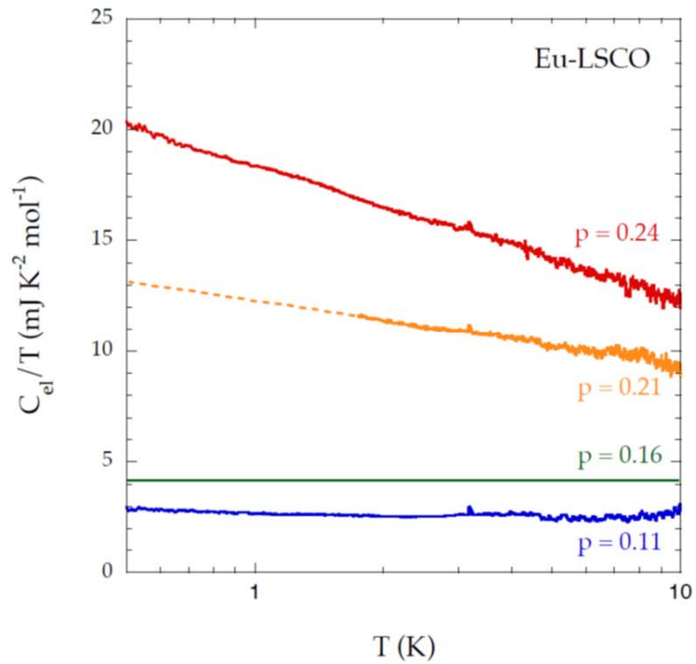
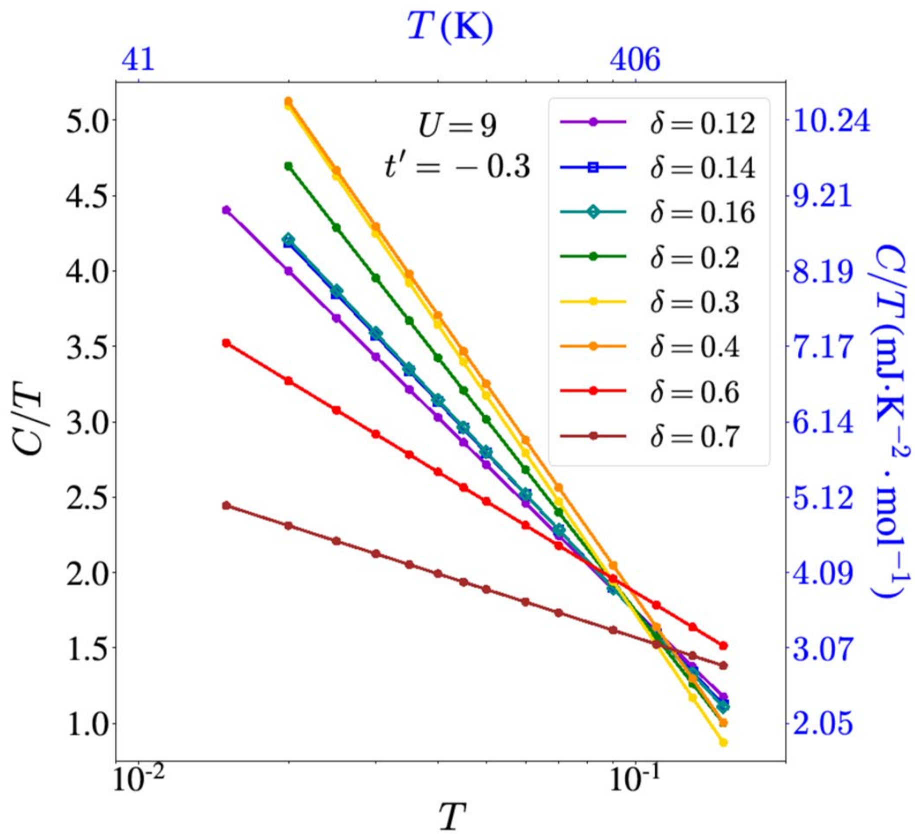
Specific heat in the strange metal phase





B. Michon, C. Girod, Taillefer, Klein, Nature 567, 218 (2019)

Specific heat in the strange metal phase



A.Reymbaut, *et al.* Phys. Rev. Research **1**, 023015 (2019)

See also for C_v Maximum: Sordi, Walsh, Sémon, and A.-M.S.T, PRB **100**, 121105(R) (2019)

Summary Conclusion

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Summary

- Intrinsic to the doped Mott insulator
  – Pseudogap
  – First-order transition – QCP
  – d-wave superconductivity
    - Short-range spin fluctuations (J)
    - Role of charge-transfer gap and of oxygen-hole doping

- Other effects that have not been discussed ***V >> J***
  – Reymbaut, Charlebois, Fellous Asiani, Fratino, Sémon, Sordi A.-M.S.T. PRB **94**, 155146 (2016)
- Other experiment consistent with doped Mott picture
  – Frachet, … Leboeuf, Julien Nat. Phys. 10.1038/s41567-020-0950-5

Entanglement properties

- Sharp variation in the entanglement-related properties and not broken symmetry phases characterizes the onset of the pseudogap phase at finite temperature.
  - Walsh, Sémon, Poulin, Sordi, A.-M.S.T. PRX QUANTUM **1**, 020310 (2020)

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Merci

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