# A gauge glue between spin and charge in cuprates

P.A. Marchetti
University of Padova

joint project with Su Zhao-Bin and Yu Lu
(happy birthday!)

Collaborators: J. Froehlich,
J.H. Dai, G. Qin, L. De Leo, G. Orso,
F. Ye, A. Ambrosetti, R. Zaetta

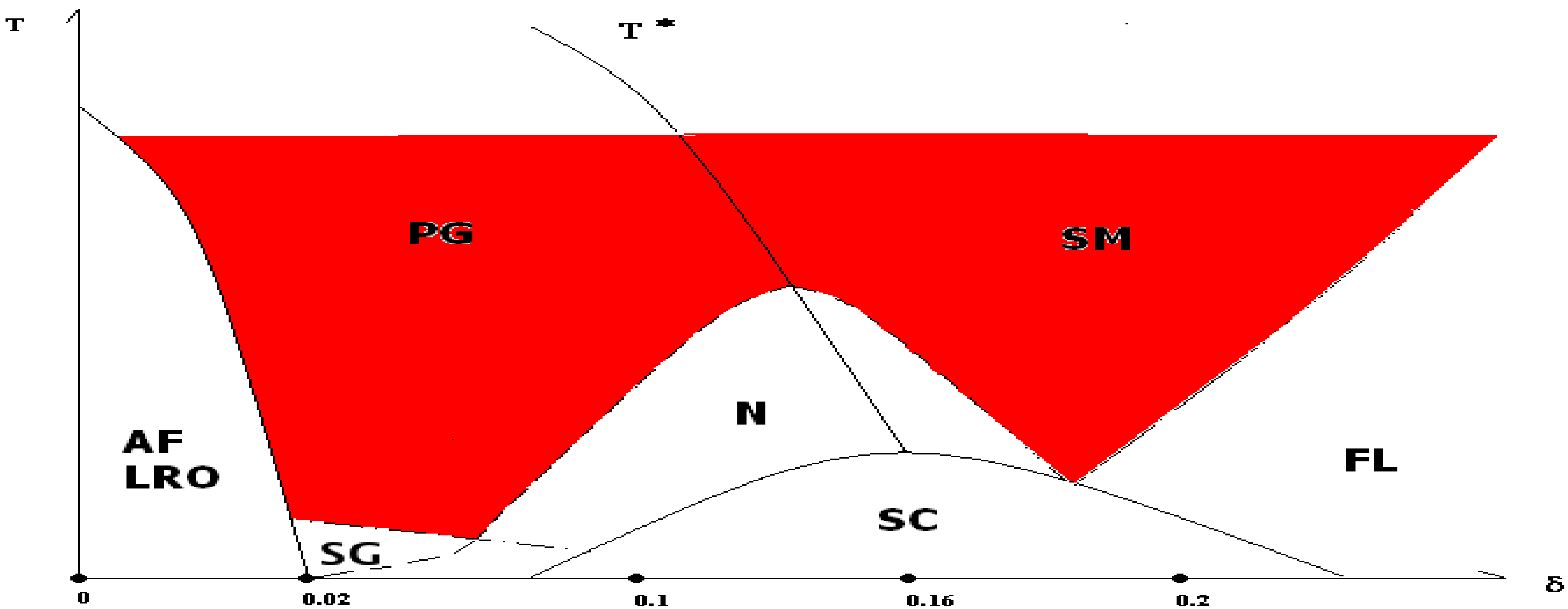
# Aim

Discuss some experimental features of transport and thermodynamic properties of the normal state of hole-doped cuprates suggesting the existence of an emergent "gauge glue" between spin and charge degrees of freedom of the electron.

# Outline

- Phase diagram and model adopted
- Experimental features addressed: metal–insulator crossover of in–plane resistivity and electronic entropy and specific heat
- Where the “gauge glue” come from
- Interpretation of experiments in terms of “gauge glue”

# "Phase diagram" and model




- red=region considered here

PG =PseudoGap
SM=Strange Metal
SG="Spin-Glass"
FL=Fermi-Liquid like
N=Nernst

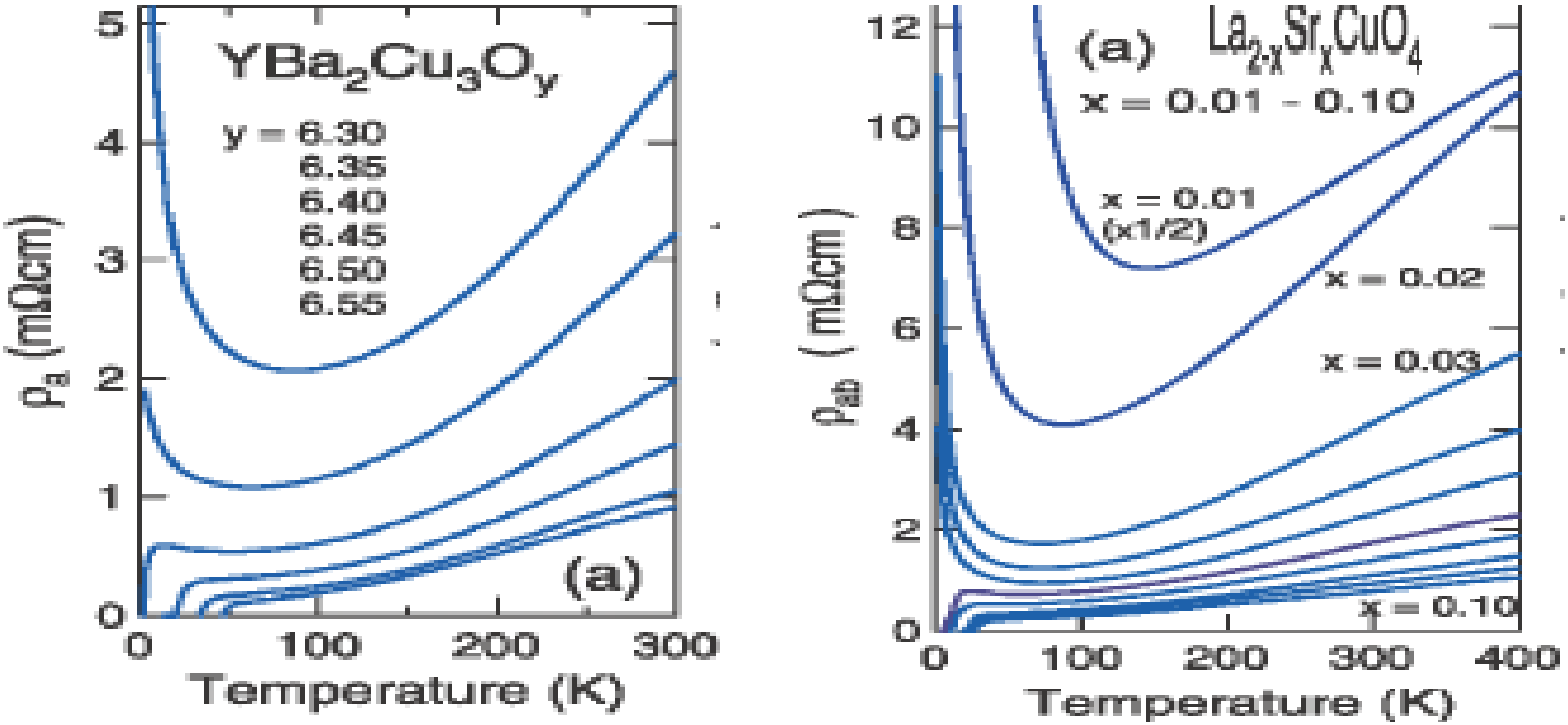
- MODEL: t-J in 2D

  $H=\sum_{ij} P_G[-t\, c_i c_j + J\, S_i S_j + h.c.] P_G$

  in square lattice

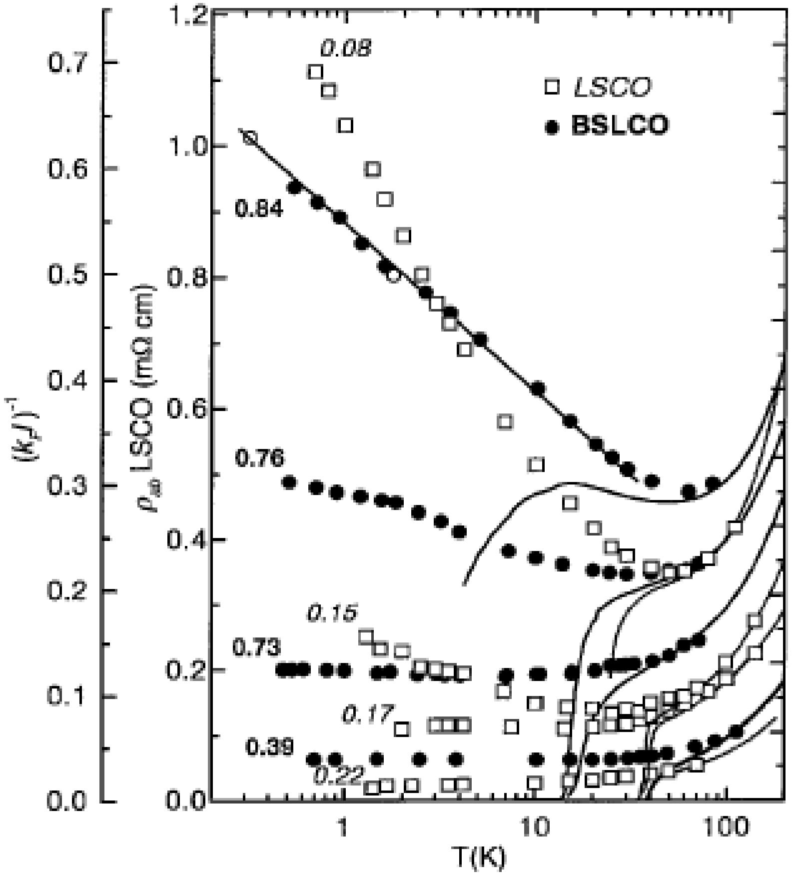
- $P_G$=Gutzwiller projection eliminating double occupation

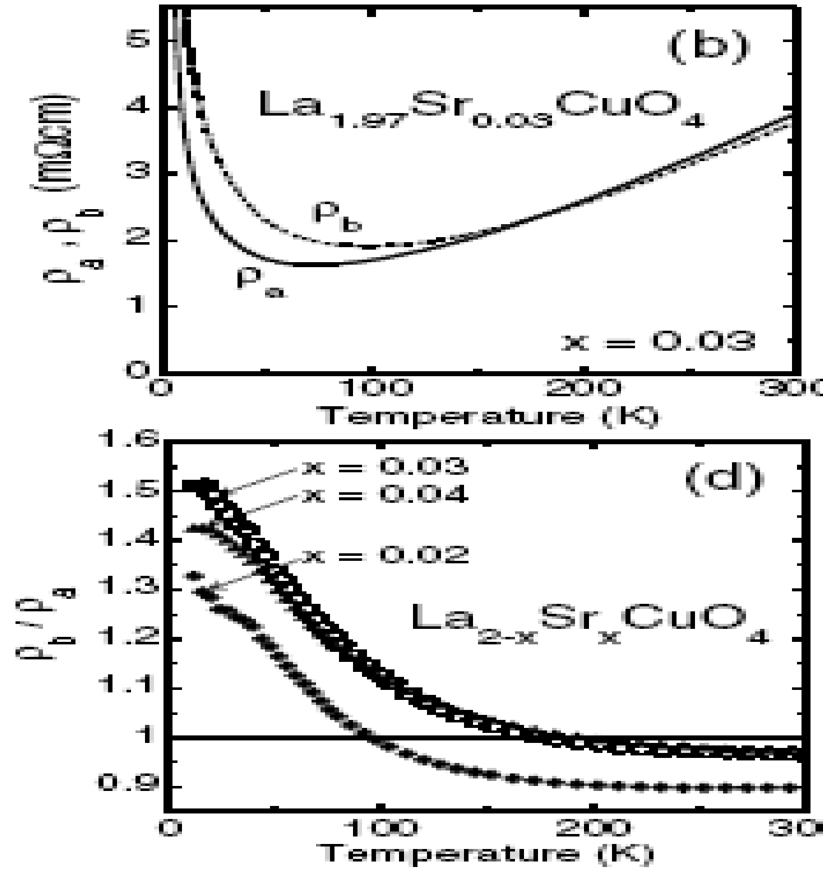
# Metal–insulator crossover (MIC)




- (Y. Ando et al. PRL 2004)

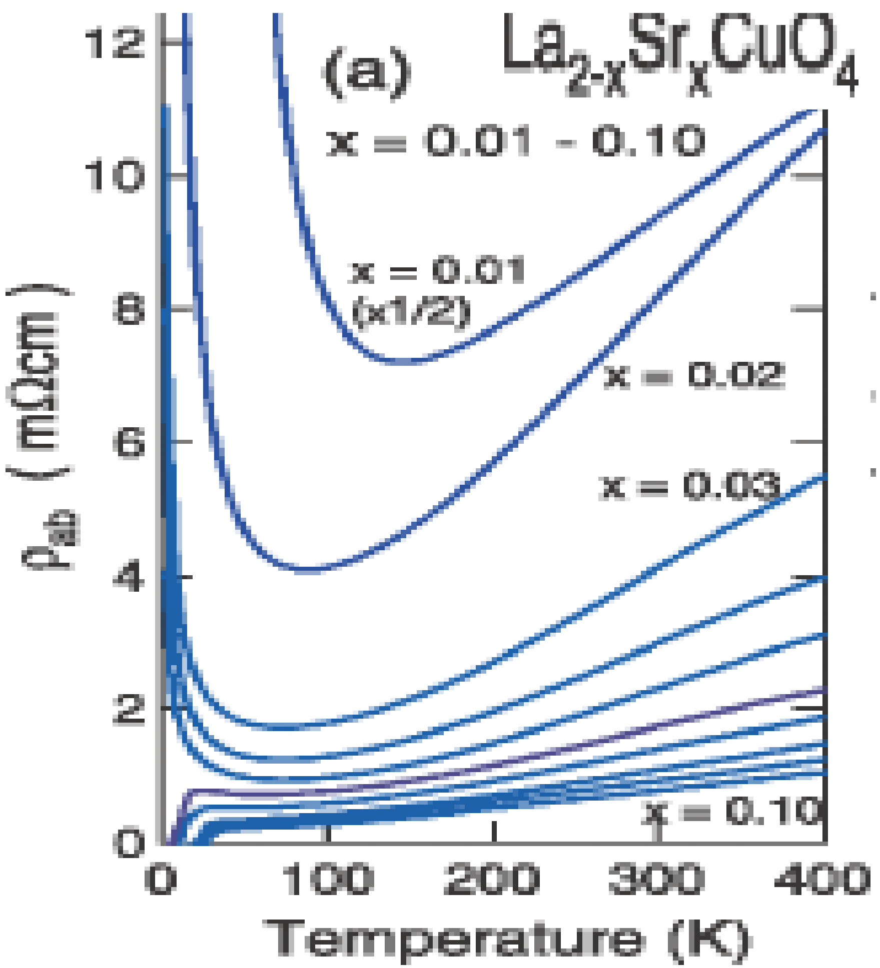
# MIC not due to disorder localization



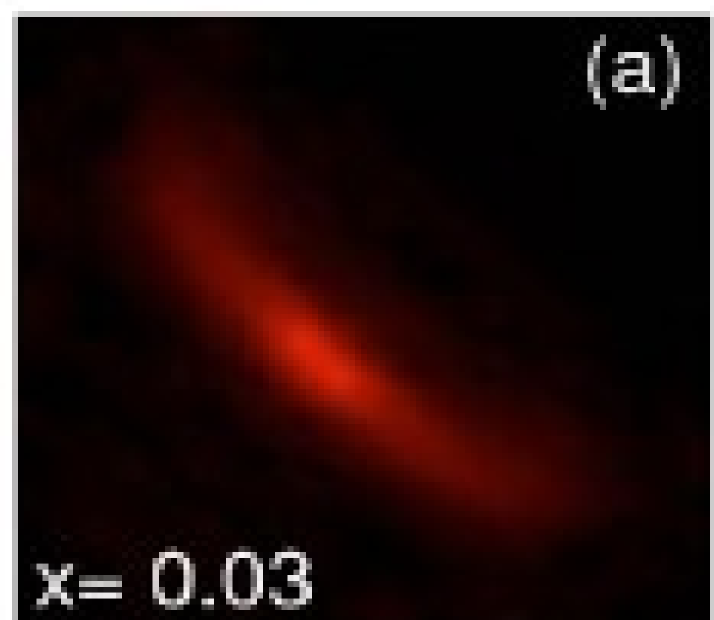

- S. Ono et al PRL 2000 : MIC well above (and below) Ioffe-Regel limit ($k_F \ell \sim 1$) expected for disorder loc.
- Y. Ando et al PRL 2002: different MIC temperatures for a, b directions: incompatible with standard localization, anisotropy too small for 1D structures

# Insulating ρ and Fermi "surface"

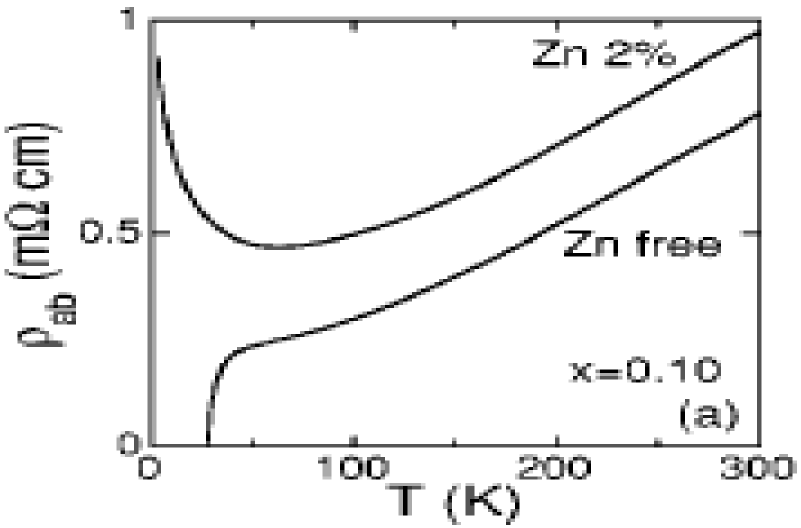



- If MIC is not due to disorder–localization (plausible however at lower T), how to reconcile gapless FS "arcs" with insulating resistivity?

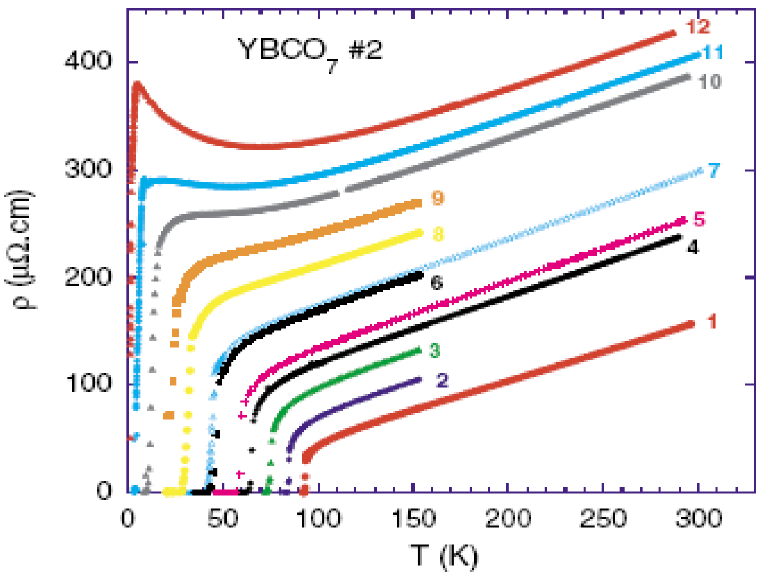
- LSCO ARPES T.Yoshida et al PRB 2006



# Dependence on impurities



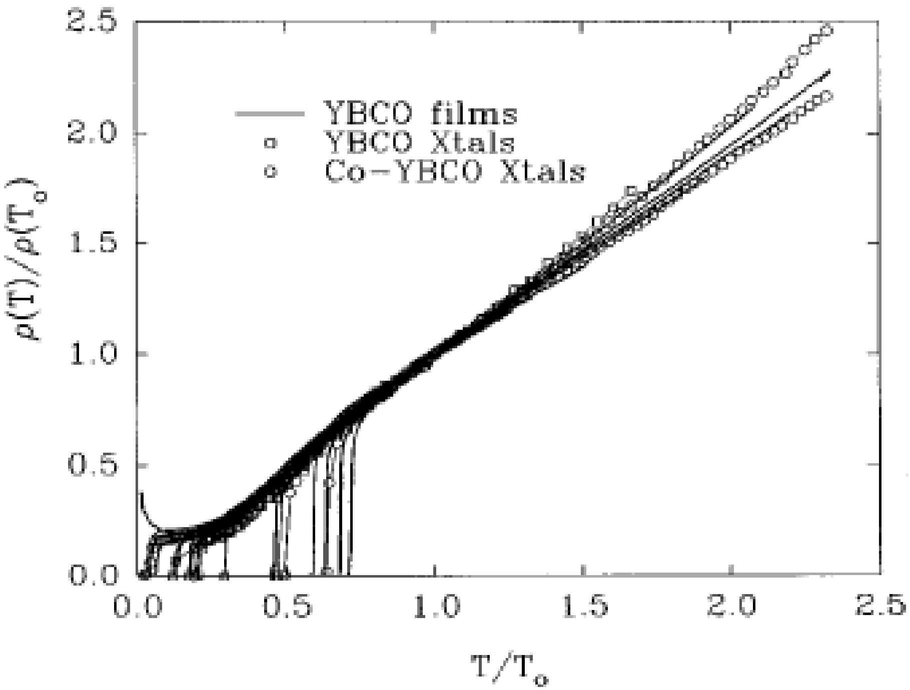

- LSCO S. Komiya et al. PRB 2004

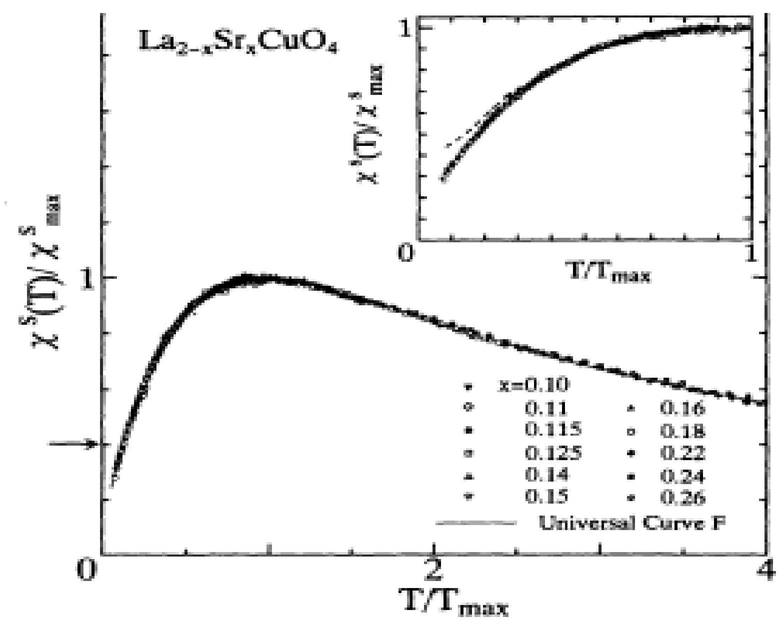



- For magnetic impurities two effects:
- Upward shift with slope unaffected for T>>MIC ->Matthiessen rule satisfied -> FL-like
- Near MIC shape affected ->Matthiessen rule violated

YBCO F. Rullier-Albenque et al PRL 2003

# Universality

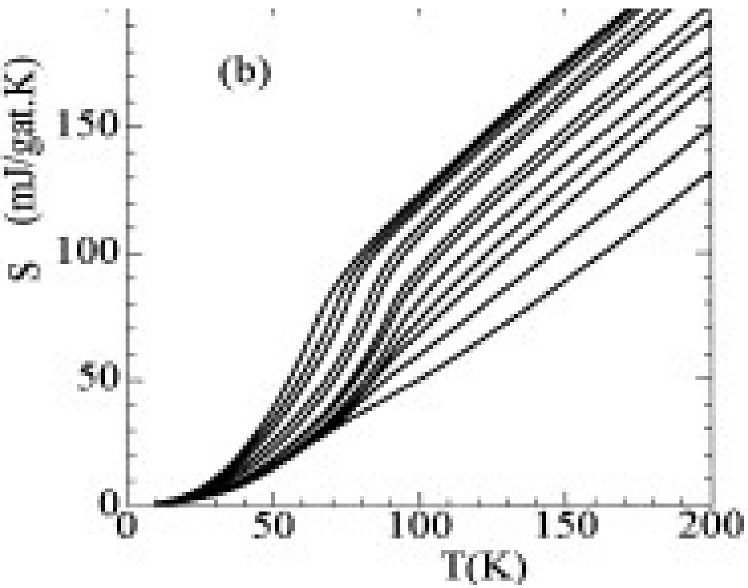


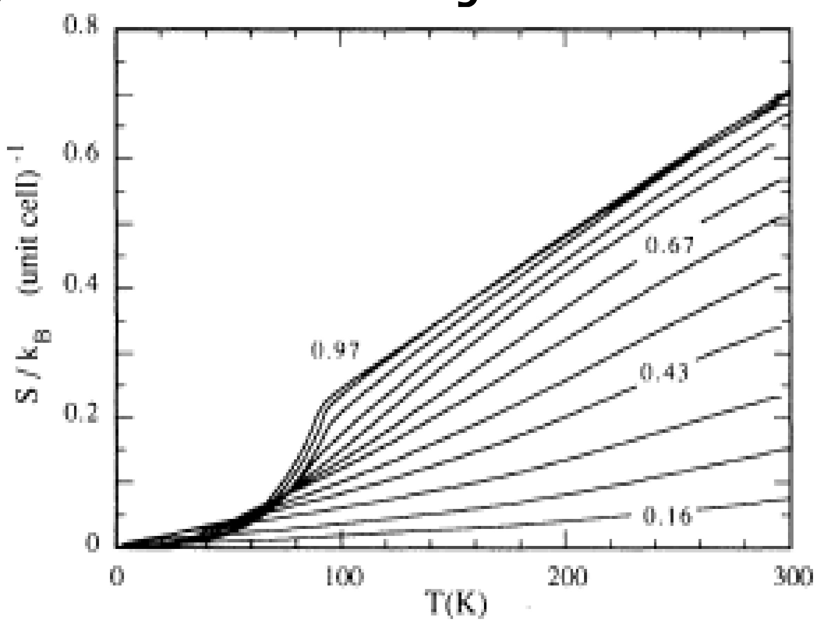

- Universality of resistivity with impurity term removed, in terms of T/T* ( B. Wuyts et al PRB 1996); where comes from?
- Similar universality for other quantities; in uniform magnetic susceptibility related to spin dof (Heisenberg model at moderate T)

T. Nakano et al PRB 1994

# Electronic entropy



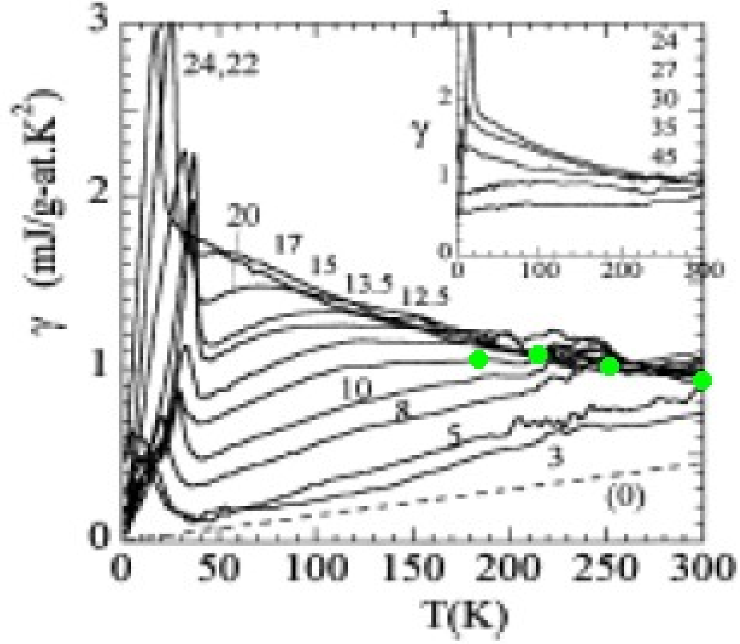

- Y-Pb doped Bi2212: JW Loram et al JPCS 2001



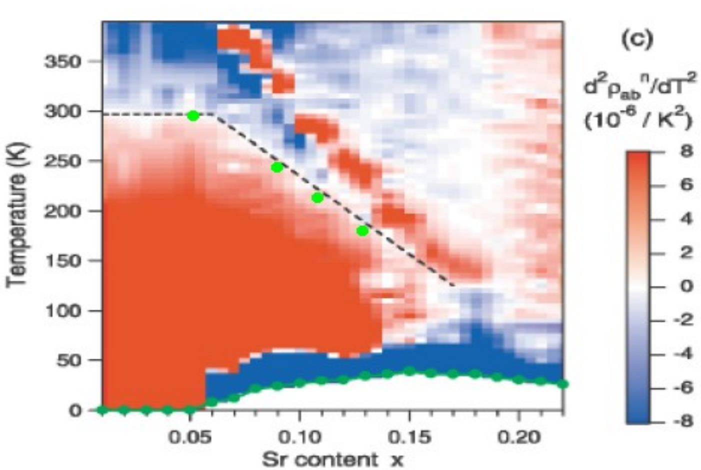

- Linear in T at moderate temperatures -> Fermi liquid-like
- Anomalous feature: negative intercept of extrapolation to T=0 in PG ->Negative contribution?
- Slope increasing at low doping then saturating at higher dopings

YBCO : JW Loram et al PRL 1993

# Electronic specific heat coefficient




- LSCO JW Loram et al JPCS 2001

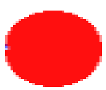
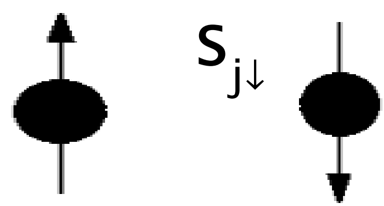



- Decreasing T in NS:
- First increase up to T* (identified by inflection point of resistivity)
- Then decrease (as for undoped ->spin waves) with roughly the same slope at different dopings
- For non super-conducting samples there is an upturn at lowest T

(Y. Ando et al PRL 2004)

# Origin of the gauge "glue"

- We propose an interpretation of the discussed experimental features in terms of an emergent "gauge glue" between spin and charge dof. But where this "glue" comes from?
- t-J : NO-DOUBLE OCCUPATION ->Fixed site j alternatives: hole; spin up, spin down

 $h_j$ (holon) ; $s_{j\uparrow}$  $s_{j\downarrow}$ (spinon)

- Electron $c_{j\alpha}=h^*_j s_{j\alpha}$
- Redundant dof (Anderson, Baskaran ,Kivelson, ..Lee,Nagaosa...):

  $h_j \to h_j\, e^{i\Lambda_j}$, $s_{j\alpha} \to s_{j\alpha}\, e^{i\Lambda_j}$ $e^{i\Lambda_j}$ =U(1) group element

- EMERGENT LOCAL U(1) GAUGE SYMMETRY(unphysical)

# The gauge field

- It is convenient to introduce emergent U(1) gauge field $A_\mu$ (not independent, no new dof: $A_\mu \sim s_\alpha{}^* \partial_\mu s_\alpha + \ldots$) coupled to h and s to explicitly realize local U(1) gauge symmetry
- Gauge fixing $A_\mu$ -> elimination of unphysical gauge dof
- $A_\mu$ gauge fixed ~ $A_\perp$ (vector transverse), $A_0$ (scalar)
- $A_0$ is purely constraint field: enforces "Gauss law of holon+spinon density conservation"
- The field $A_\mu$ will provide our "gauge glue" between charge and spin dof of the electron

# Statistics for holons and spinons

- Slave boson: h boson, $s_\alpha$ fermion ->$c_\alpha$= h*$s_\alpha$ fermion
- But in 2D more possibilities: one can add fluxes (like in LRO for FQHE) to h and s (Chern-Simons)

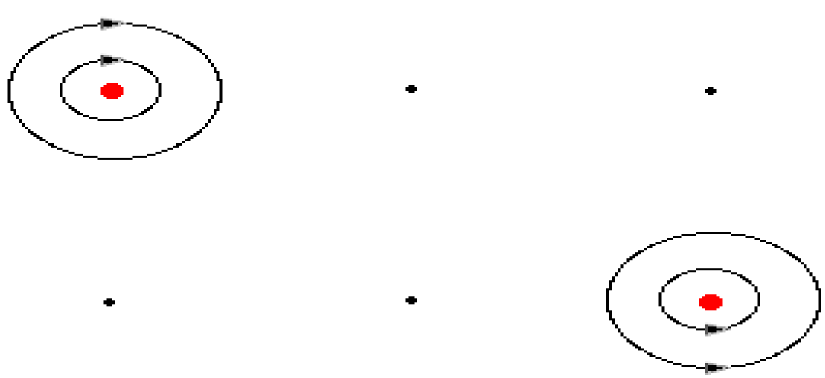
$$c = e^{-i\Phi_h} h^* \qquad e^{i\Phi_s} s$$

U(1) charge dof SU(2) spin dof

with statistical compensation $e^{-i\Phi_h} e^{i\Phi_s} \sim 1$ ;
if h* s fermion-> c fermion

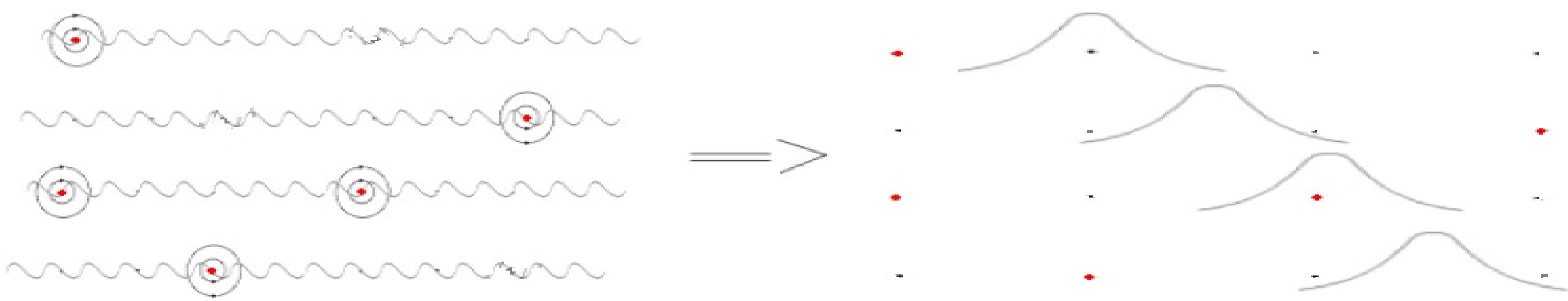
# Optimize spin flux

- Our strategy: choose h spinless fermion (hence s boson) -> no-double occupation automatically satisfied by Pauli principle; then find optimal "charge" and "spin" fluxes $\Phi_h$ , $\Phi_s$ in Mean Field compatible with statistics
- Effect of optimal spin flux $\Phi_s$ : to attach a spin vortex to the holon positions (empty sites) with opposite chirality in the two Neel sublattices



# Optimal spin flux -> Short Range AF

- Gapless spinons (~spin waves) of Heisenberg AF model (->undoped) travelling through gas of spin vortices centered on empty sites (induced by $\Phi_s$ ) in MF acquire a gap m ($<\Phi_s^2>$ s*s=m s*s)



- Doping: LongRangeAF->ShortRangeAF (via magnon formation by spinon binding)
- m~ J ( δ | ln δ| )$^{1/2}$
  density of empty sites long range tail of vortices
- Neutron experiments in LSCO (B. Keimer et al 1992) AF correlation length $\xi_{AF}$~1/ √ δ

# Optimize charge flux

- Fixed the spin flux, in MF for s
  -> MF Hamiltonian for h:
  $H \sim \sum_{ij} -t\, h_i^* h_j\, e^{i\Phi_h}$ = spinless fermions hopping in 2D square lattice in presence of a “magnetic” flux $\Phi_h$
- Lieb's theorem: at $\delta=0$ flux optimizing energy is $\pi$ per plaquette (peculiar consequence of Pauli principle in 2D bipartite lattices)
- Diamagnetism: for $\delta$ sufficiently large and finite T optimal flux per plaquette is 0
- Numerical simulations (using Harper's equation)-> for T sufficiently large only $\pi$ and 0 flux are optimal

# Optimal charge flux->SM-PG crossover

- Conjecture: 0 ->$\pi$ flux transition in holon MF leads via t-J model to the StrangeMetal -> PseudoGap crossover in phase diagram of cuprates (T* line viewed as the region of formation of the flux lattice ~slave boson flux phase Lee-Nagaosa)
- Dispersion relations for holons ( $\Phi_h$-> Haldane-Wu semion statistics : allowed double occupation in k)
  SM E~ $-t\,(\cos k_x + \cos k_y)$ $k_F \sim (1-\delta)$ ~band FS
  PG E~ $-t\,(\cos k_x^2 + \cos k_y^2)^{1/2}$ $k_F \sim \delta$ small FS
  pockets near ( $\pm\pi/2$, $\pm\pi/2$)
- Hofstadter phenomenon of Fermi surface reduction for holons (not yet of electrons!)

# The "gauge glue" at work

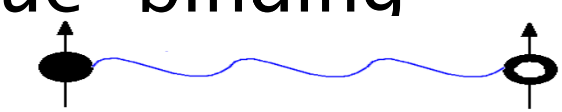
- Inserting gauge fluctuations ($A_\mu$) necessary because physical objects are gauge invariant ->Effects from eikonal resummation:

- Finite holon FS ->$A_\perp$ transverse is a gapless diffusive mode dominated by Reizer singularity with momentum scale $Q \sim (T k_F^2)^{1/3}$

- Coupling A to spinons provides an effective dissipative term correction to the mass :

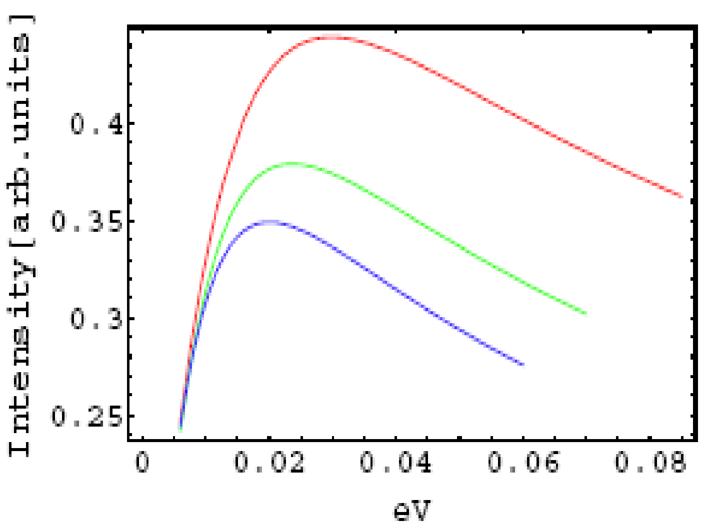
$$m \to (m^2 + i\, c\, T\, k_F)^{1/2} = M + i\ \Gamma \qquad \text{PG}$$

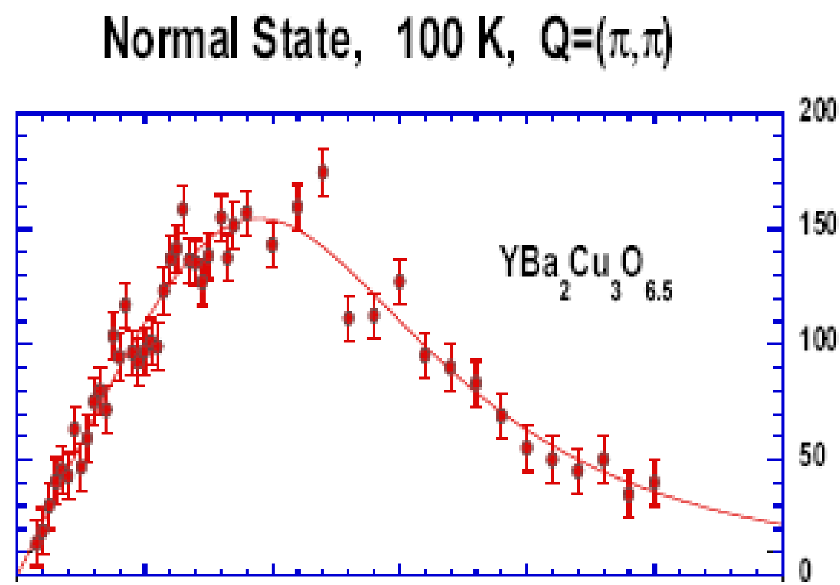
$$\to m + i\, c\, T\, k_F\, Q / m^2 = m + i\ \Gamma \qquad \text{SM}$$

- A acts at low energy as a "gauge glue" binding
  spinon-antispinon -> magnon 
  spinon-holon -> electron 
  resonances with inverse life-time $\Gamma$

# Effect of gauge glue on magnon: ShortRangeAF but no spin gap

- Dissipative term introduced by $A_\perp$ -> magnon can move by thermal diffusion at low T -> spin fluctuations are not gapped (as m suggests)
- Check: dynamical spin susceptibility at AF point



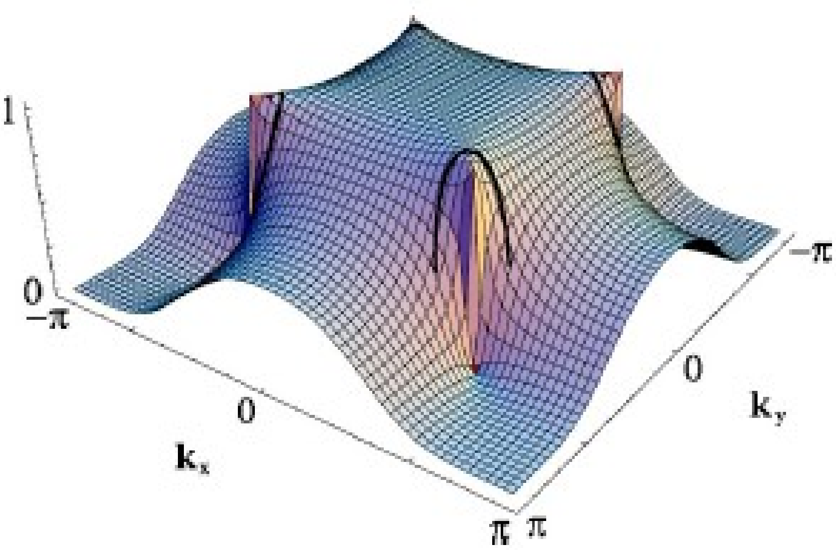

SRAF -> diffusion crossover (P.Bourges 1999)

(from top $\delta$ =0. 04,0.07,0.1)

# Effect of gauge glue on electron: electron Fermi Surface

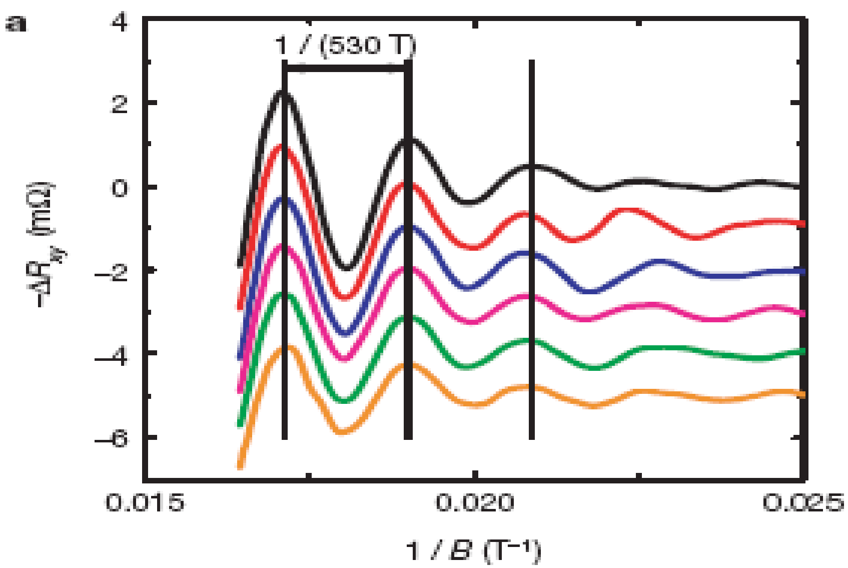
- Momenta near holon FS: binding ->electron FS
- SM : holon band FS ->electron band FS
- PG : small holon pocket FS -> small electron pocket FS near ( $\pm\pi/2$, $\pm$ $\pi/2$), but reconstruction of electron from holon-spinon->reduction of spectral weight outside MBZ (mimicks, but not exactly, Fermi arcs)

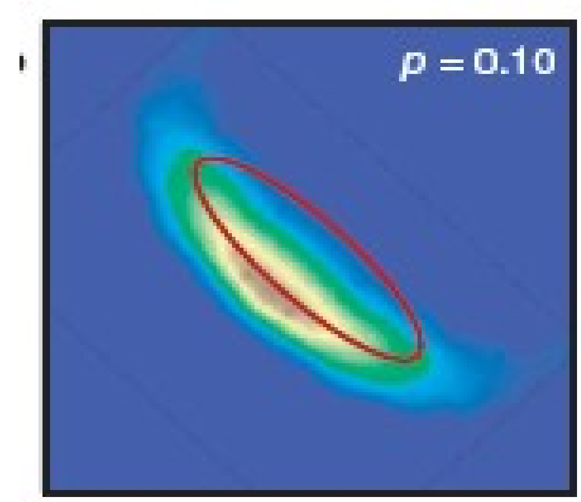
Spectral weight in PG
PA Marchetti et al PRB 2004



# Small Fermi Surface in PG?

- Reduction of spectral weight recovers full lattice translational symmetry for the physical electron even in PG. Recently explained in terms of Projective Gauge Symmetry (XG Wen 2002, R Kaul et al 2007)
- Is this small FS in PG the one of quantum oscillations in YBCO (N. Doiron-Leyraud et al 2007) and Y124 (AF. Bangura et al , E A Yelland et al 2007) ?



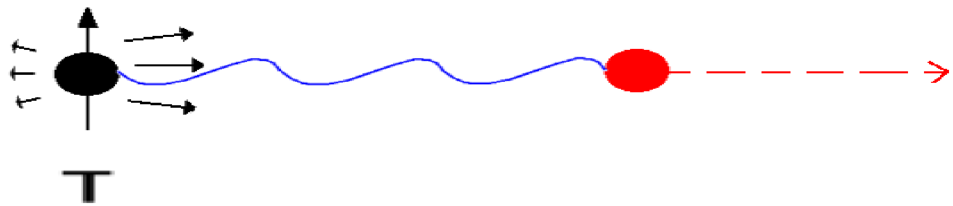

N Doiron-Leyraud et al Nature 2007

# Gauge interpretation of MIC

- Ingredients: spinon is massive but can thermally diffuse, holon has FS, physical electron is gauge invariant and there is a gauge string between spinon and holon
- The electromagnetic field is coupled to the physical electron -> to move the electron one should move the spinon and the (gapless) holon , but due to its gap the spinon can move only by thermal diffusion-> solves the puzzle of FS coexisting with insulating resistivity
- Calculation of resistivity via Kubo formula and Ioffe-Larkin rule (<-gauge invariance)

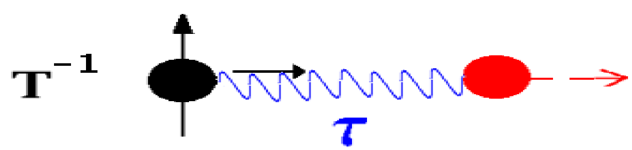
# MIC: the basic gauge mechanism

- T<MIC SRAF dominates, basic time scale is set by spinon diffusion ~T conductivity σ ▲ as T ▲




  Possible evidence for a SRAF origin of MIC (muon spin rotation JE Sonier et al PRB 2007)

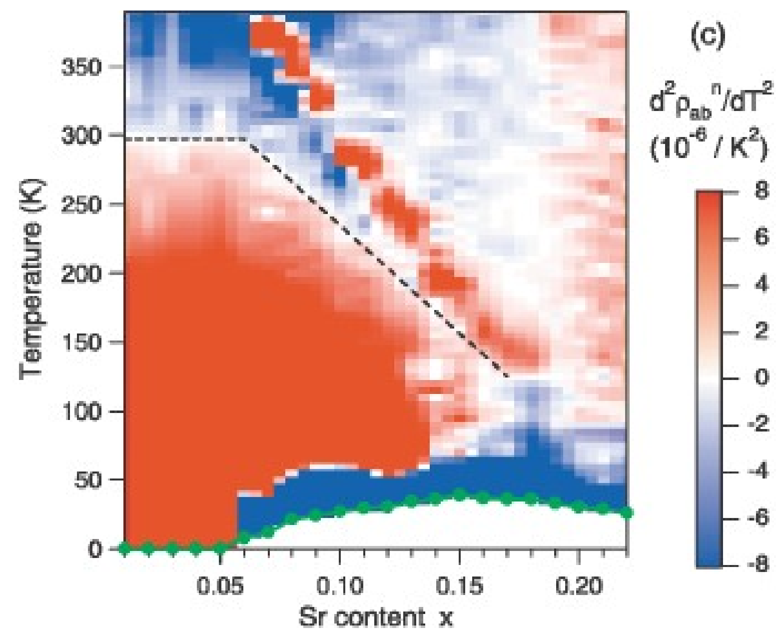
- T>MIC basic time scale is scattering time against gauge fluctuations ~ Drude-like $\sigma \sim \tau \sim T^{-\alpha}$ ▼ as T ▲




- Limit of eikonal treatment: at T $\lesssim$50-20K gauge interaction too weak ->SG?

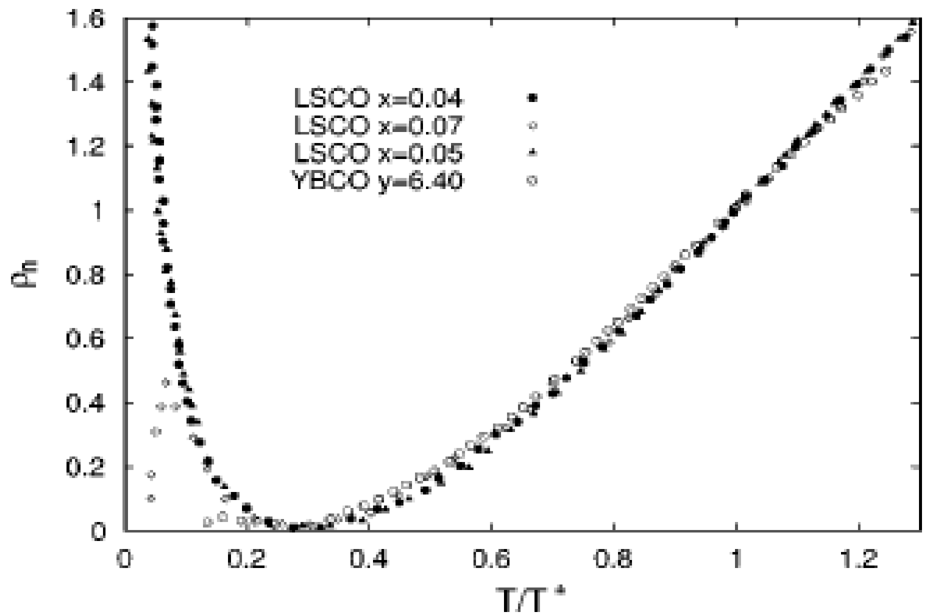
# Gauge MIC : features

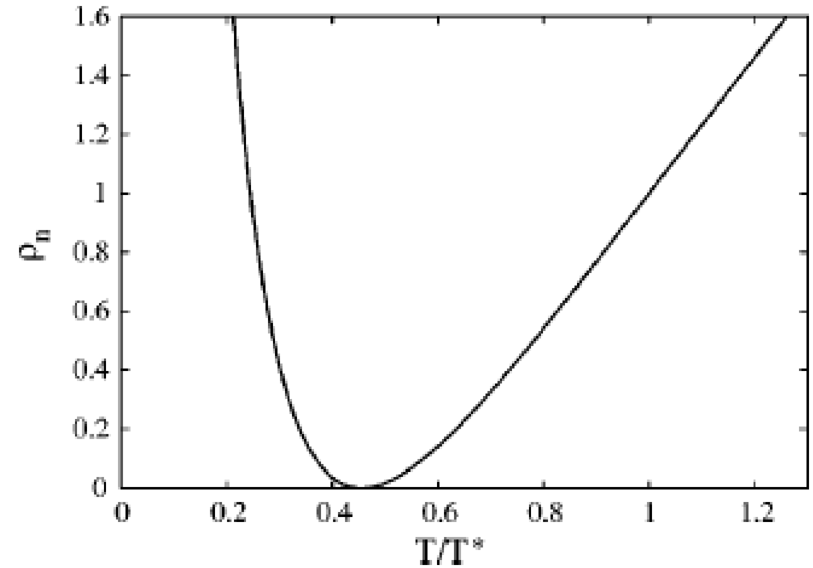
- Coexistence with gapless FS: Even if $\rho$ is insulating for T<MIC holon still has FS -> electron has FS "arcs" (due to spectral weight reduction)
- Impurities: $\rho$ is dominated by spinons -> most sensitive to magnetic impurities; non-magnetic ones act on Fermi liquid holons, thus obeying Matthiessen rule
- PG: inflection point of $\rho$ due to square root in $\Gamma$ $\sim \mathrm{Im}\,(m^2 + i\, c\, T\, k_F)^{1/2}$
- SM: no square root in $\Gamma \sim T^{4/3}$ -> no inflection point ; $m < \Gamma$ -> Drude-like behaviour $\sigma \sim \tau \sim T^{-1}$ -> resistivity linear in T



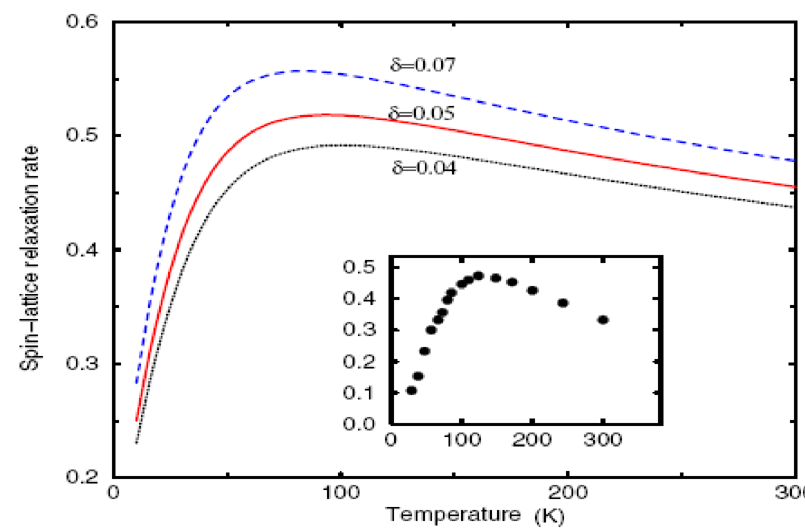
# Gauge MIC: universality

- Dominating spinon (->spin) contribution $\rho \sim c_1(\delta)\ \rho_n(T/T^*) + c_2(\delta)$, $T^*$=inflection point$\sim m^2/k_F$, $\rho_n$ universal function



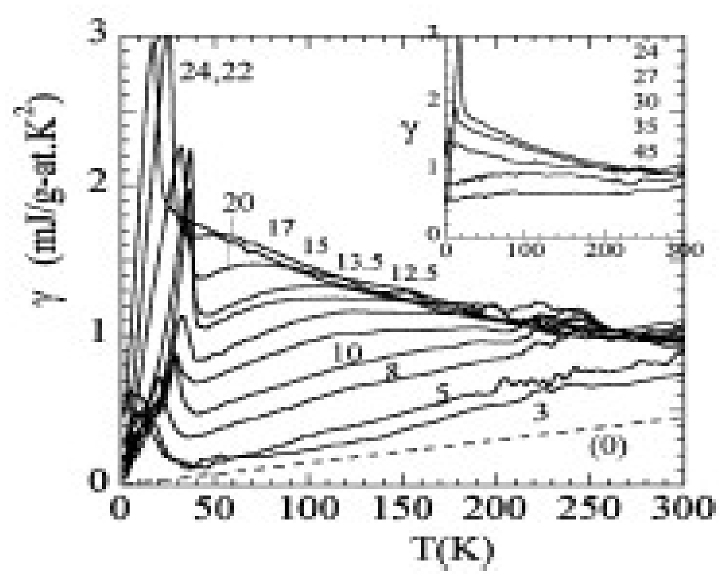

- Crossover SRAF -> diffusion, same e.g. in $^{63}(1/T_1T)$




Marchetti et al JPCM 2000 , PRB 2004

# Gauge interpretation of specific heat

- Contributions: massive spinons (irrelevant at low T), Fermi liquid holons with $k_F \sim \delta$ in PG, $\sim 1-\delta$ in SM, transverse gauge acting as gapless diffusive mode (Reizer), scalar gauge acting as "constraint field"




SM: $k_F \sim 1-\delta$ ->saturation decrease in T due to $A_\perp$, $\gamma \sim T^{-1/3}$

-> upturn due to $A_\perp$, $\gamma \sim T^{-1/3}$ PG: $k_F \sim \delta$ ->increase

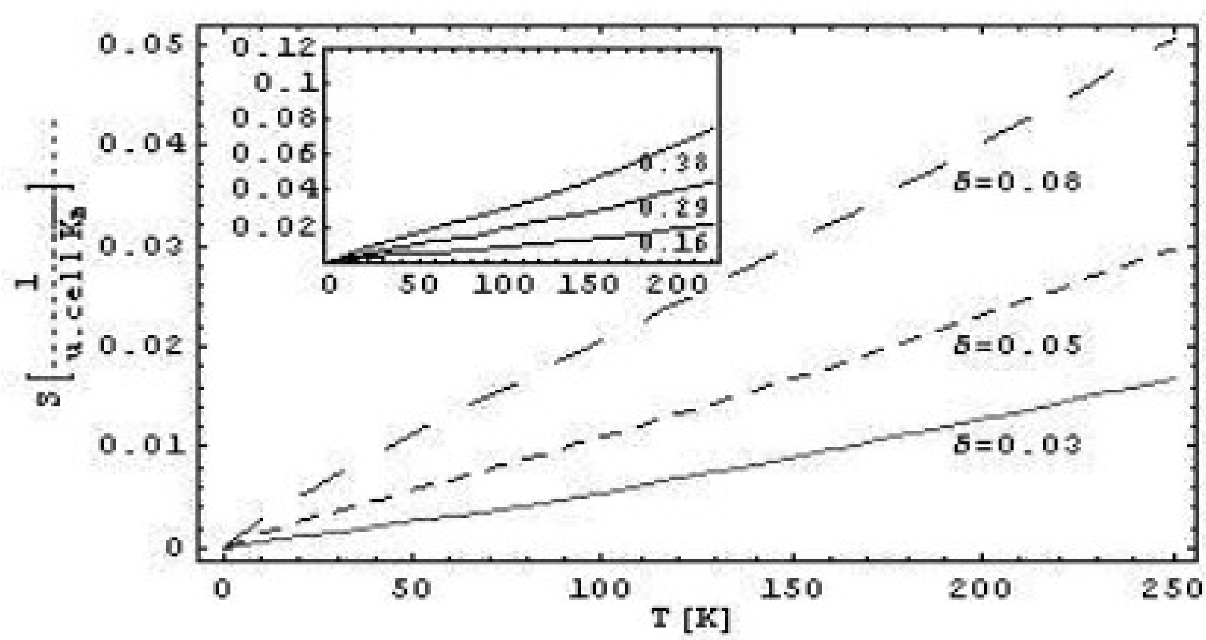
- $A_\perp$ enhances $\gamma$ at low T in PG and then in SM

# Gauge interpretation of entropy

- $A_0$ acts constraining -> reduces dof -> negative contribution to entropy (also Hlubina et al 1992 in slave boson)

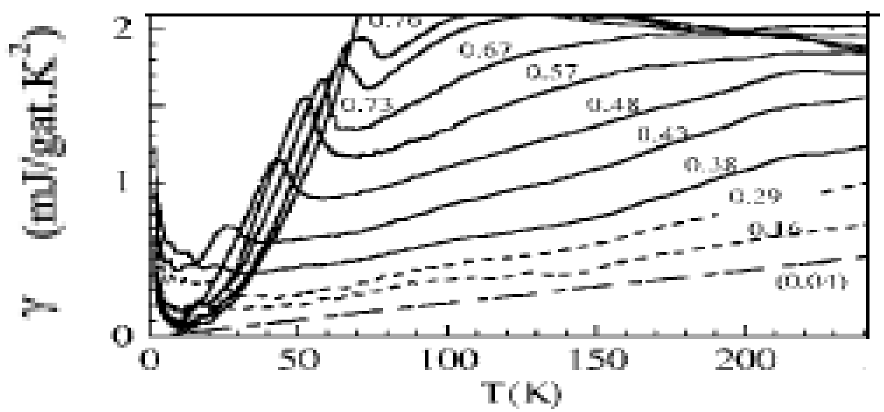
$$S \sim -T/v_F + c\,T^2/v_F^2$$

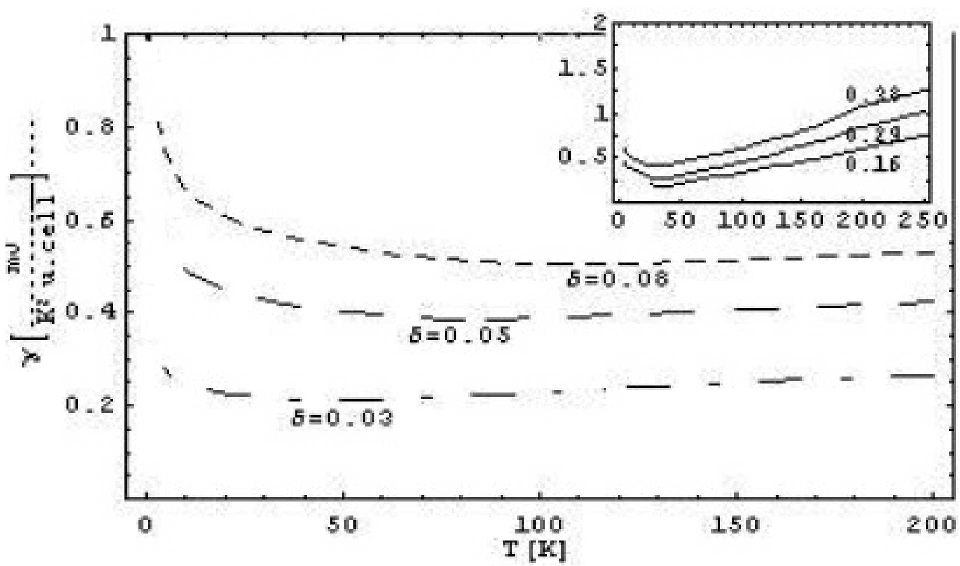
- First term: constraint-> negative intercept of entropy at T=0 in PG because dominating at moderate T



# Gauge interpretation of rising γ

- $S \sim -T / v_F + c\, T^2 / v_F^2$ , second term: thermally relaxing constraint -> linear T rising in γ with doping -independent slope
- replaces the spin-wave contribution of undoped AF, removed by spinon gap

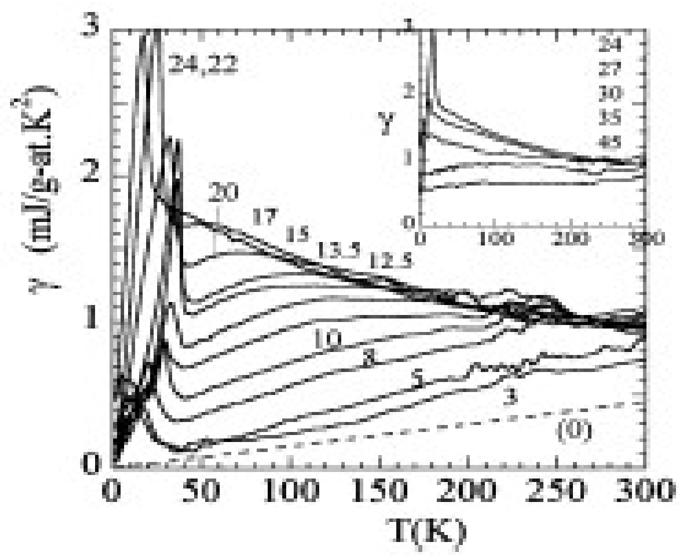


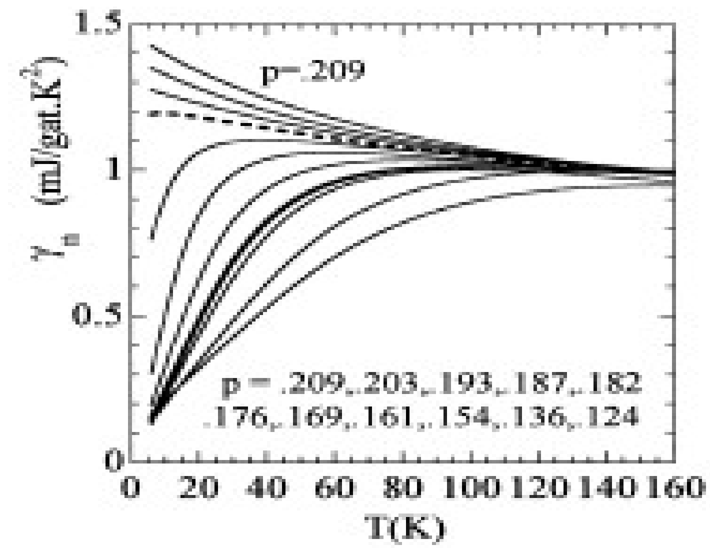




- YBCO JW Loram et al JPCS 2001

# Not Just DOS increase with T

- Presumably effect of linear rising in T of γ is enhanced by increasing DOS with T, due to destruction of holon-holon pairing (not taken into account here), but this cannot be the only source: curves in γ are approximately parallel not converging near T~0 as for DOS increase.




DOS increase-extrapolation
JW Loram et al JPCS 2001

# Conclusions

- Many detailed features both of Metal-Insulator Crossover and of entropy in the normal state of hole-doped cuprates can be interpreted in terms of a composite structure of the electron given by a massive spinon bound to a gapless fermionic holon by a string of emergent "gauge glue".
- Gauge fluctuations allow Short Range AF without spin gap
- Many crossovers in PG are attributed to a competition between SRAF and thermal diffusion induced by the gauge string
- The crossover PG-SM could be explained as a change of holon FS inducing one on the electron FS (perhaps partially masked by pairing effects)