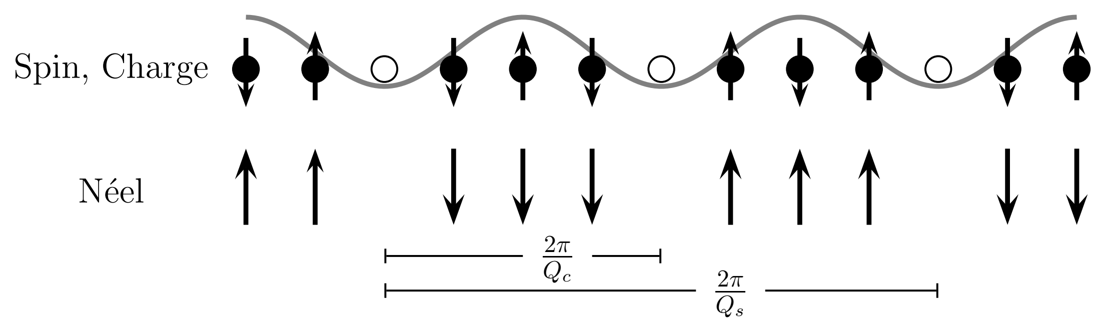
Quantum Melting of Stripes

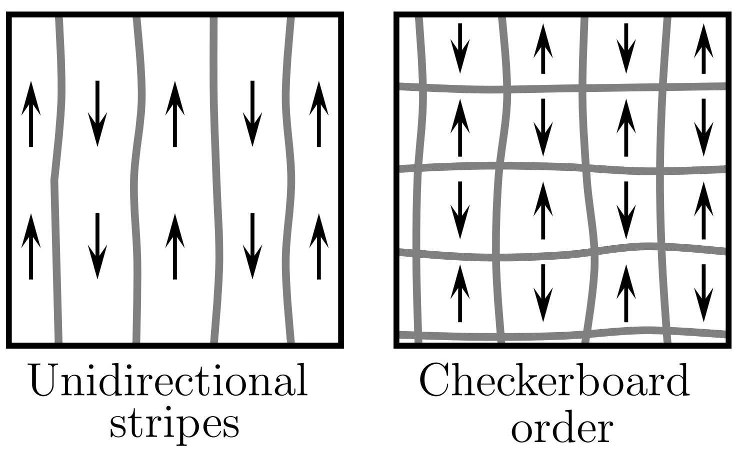
David Mross and T. Senthil (MIT)

D. Mross, TS, PRL 2012
D. Mross, TS, PR B (to appear)

Varieties of Stripes



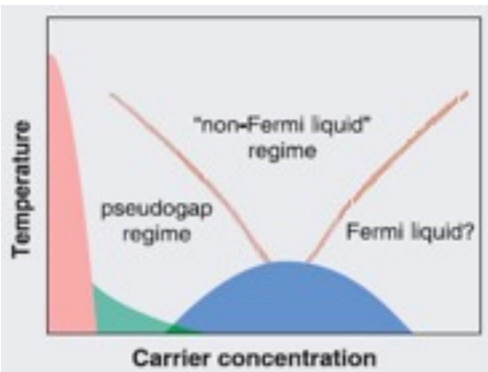
``Anti-phase" stripes, common in La-based cuprates.



Usually stripe means unidirectional order;
bidirectional checkerboard order is a close cousin.
I will use `stripe' for both.

Typically spin stripe implies charge stripe (Landau argument) but charge stripe does not imply spin order.

Stripes and the underdoped cuprates



Stripes/broken translation invariance seem remarkably common in almost all families of underdoped cuprates.

La-based cuprates: original stripe materials;
static charge and spin stripes in some cases.

Bi-2201, Bi2212: broken translation symmetry in many STM studies.

YbCO: 1. Dynamic incommensurate spin fluctuations in neutrons (Eg, Stock, Buyers et al, 2004)

2. High field NMR (Julien et al, 11).

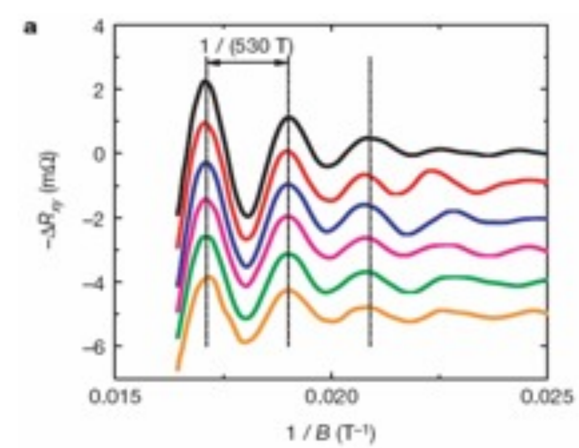
3. Most recent - charge ordering in X-ray; no obvious relation to incommensurate spin fluctuations (Ghiringelli et al, Science 2012, Chang et al, arxiv 1206.4333, Hawthorn et al, arxiv 1207.3667).

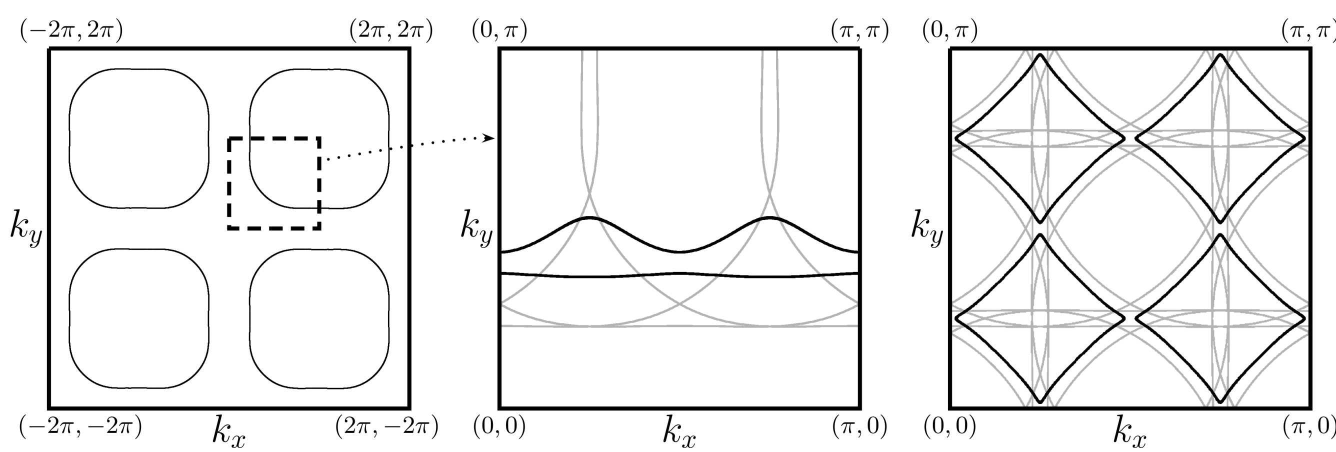
Stripe order and quantum oscillations

Stripe/broken translation presumably play a crucial role in determining electronic structure of B-field induced ``normal" state.

Must incorporate in theory of observed quantum oscillations.

Reconstruction of Fermi surface.

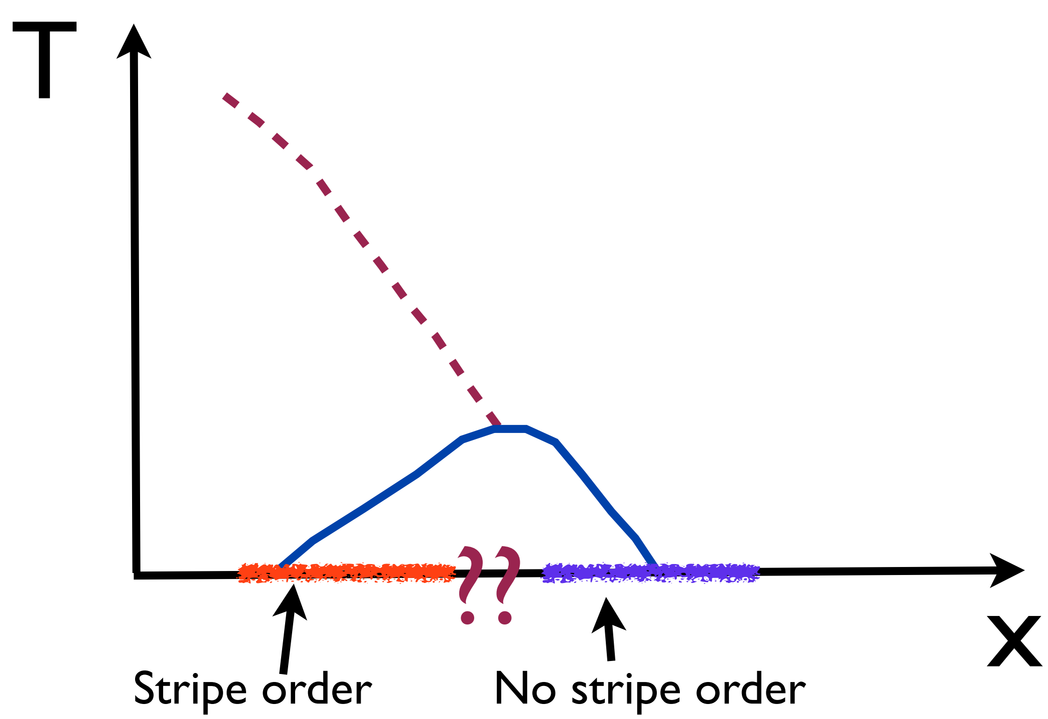




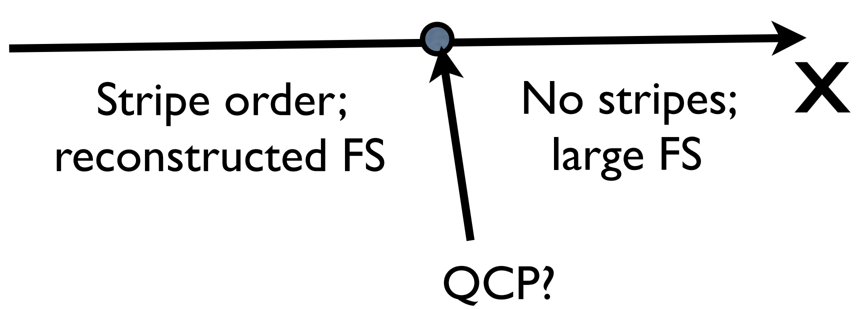
Stripes: Evolution with doping

No reported stripe ordering in overdoped cuprates.

Evolution from under to overdoping accompanied by loss of stripe order.

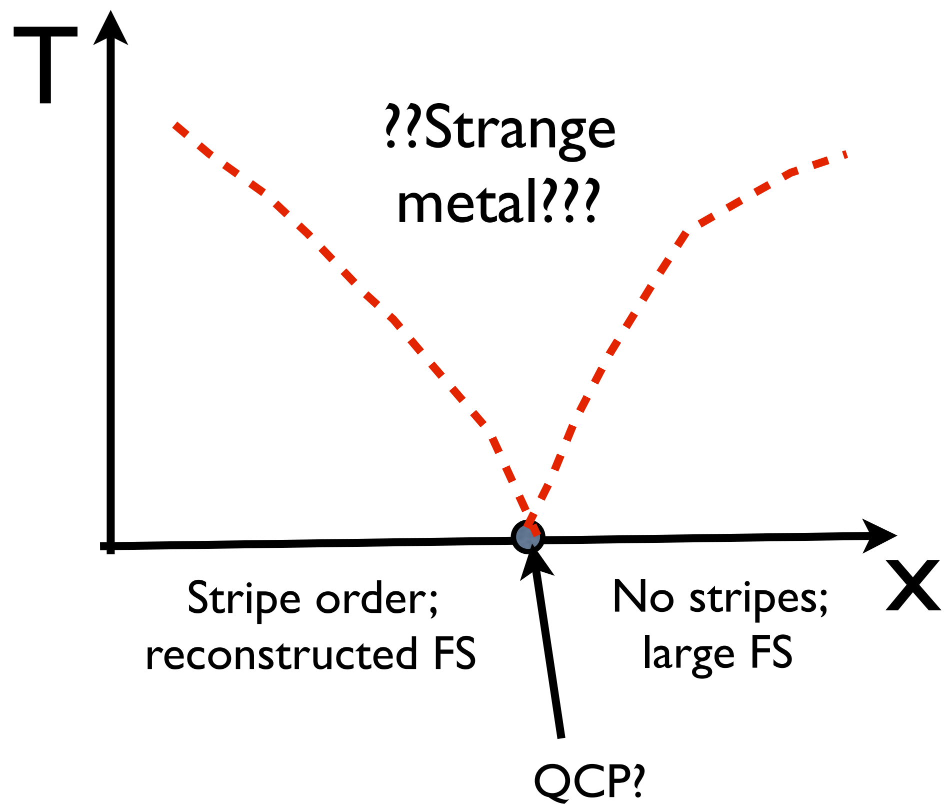


A possible evolution of ``underlying normal'' ground state



Stripe criticality - a savior?

Could a stripe onset quantum critical point around optimal doping in the ``underlying normal'' state control physics of strange metal?



L. Taillefer,.......

(last 2 years)

Challenge: Theory of stripe melting, quantum criticality, and Fermi surface reconstruction in a metal

Theory of onset of stripe order in a metal?

Weak coupling approach: couple Fermi surface to stripe order parameter.

Dynamics of stripe order parameter dominated by Landau damping of p/h pairs of Fermi surface at low energies.

Old theory: ``Hertz-Millis'', z = 2 criticality, upper critical dimension 2

Modern developments (Abanov, Chubukov, 2004; Metlitski, Sachdev, 2010);

Stripe fluctuations couple increasingly strongly to Fermi surface excitations at low energy in 2d.

Standard 1/N expansion methods spiral out of control.

No reliable description of low energy physics.

Critical stripe fluctuations in experiment?

Very little known.

Exception: famous old experiment (Aeppli et al, Science 1997).

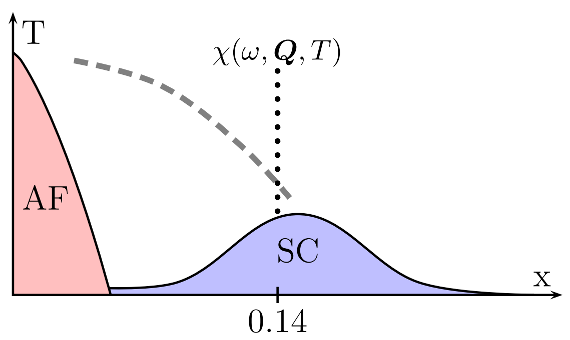
Nearly Singular Magnetic Fluctuations in the Normal State of a High-T_c Cuprate Superconductor

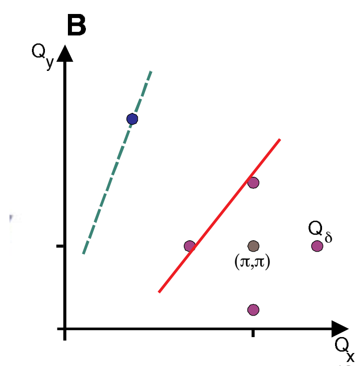
G. Aeppli, T. E. Mason,* S. M. Hayden, H. A. Mook, J. Kulda

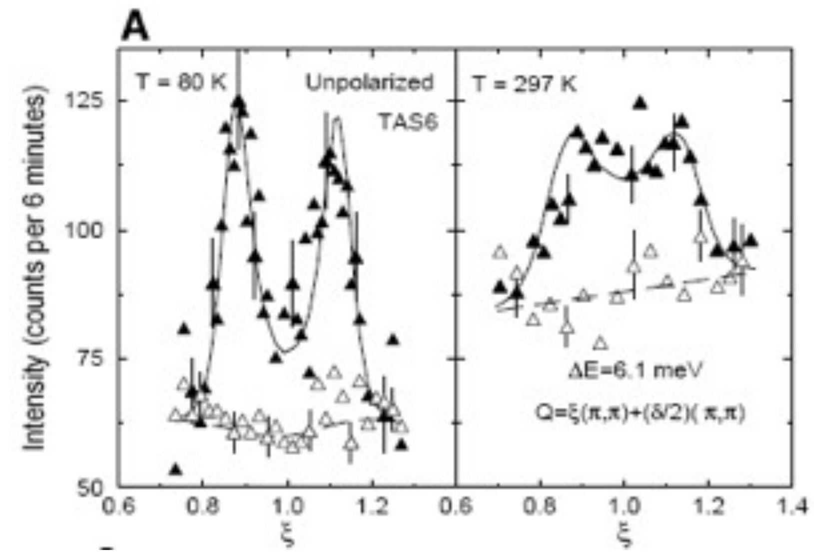
Polarized and unpolarized neutron scattering was used to measure the wave vector– and frequency-dependent magnetic fluctuations in the normal state (from the superconducting transition temperature, $T_c = 35$ kelvin, up to 350 kelvin) of single crystals of $La_{1.86}Sr_{0.14}CuO_4$. The peaks that dominate the fluctuations have amplitudes that decrease as T^{-2} and widths that increase in proportion to the thermal energy, k_BT (where k_B is Boltzmann's constant), and energy transfer added in quadrature. The nearly singular fluctuations are consistent with a nearby quantum critical point.

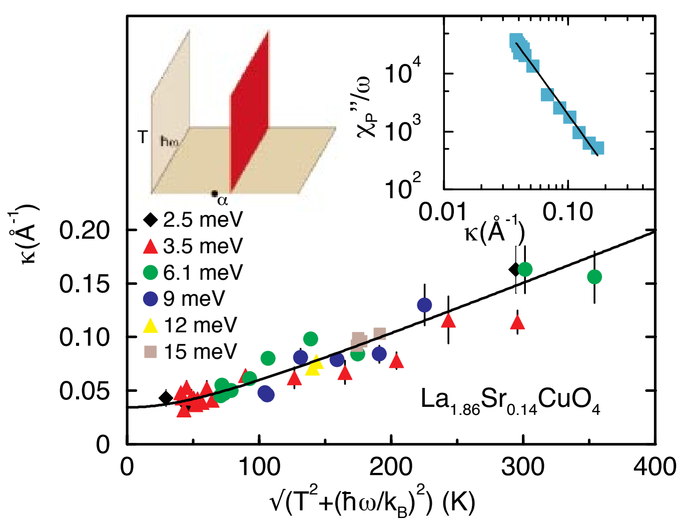
Critical stripe fluctuations in experiment?

Aeppli et al, 1997





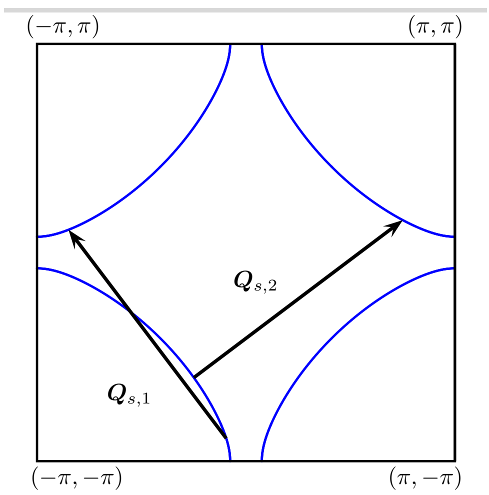




QC scaling with z = 1

z = 1 in a metal??

Usually AF spin fluctuations get Landau damped by coupling to particle-hole excitations of Fermi surface.



$$\chi(\mathbf{q},\omega) = \frac{1}{\omega^2 - v^2|\mathbf{q}-\mathbf{Q}|^2} \rightarrow \frac{1}{\omega^2 + i\gamma\omega - v^2|\mathbf{q}-\mathbf{Q}|^2}$$

Drives z away from 1.

More qualitative: Near doping x = 0.14, ARPES pseudogap temperature ≈150 K.
Stripe fluctuations evolve smoothly without noticing the pseudogap.

J. Tranquada, Handbook of Superconductivity, 2006.

``One suprising experimental observation is the minimal amount of damping of the magnetic excitations in underdoped cuprates, especially in the normal state. One would expect the continuum of electron-hole excitations to cause significant damping [90]. Could it be that the antiphase relationship of spin correlations across a charge stripe acts to separate the spin and charge excitations in a manner similar to that in a one-dimensional system [281, 282]?"

Contrast with ``standard" theory

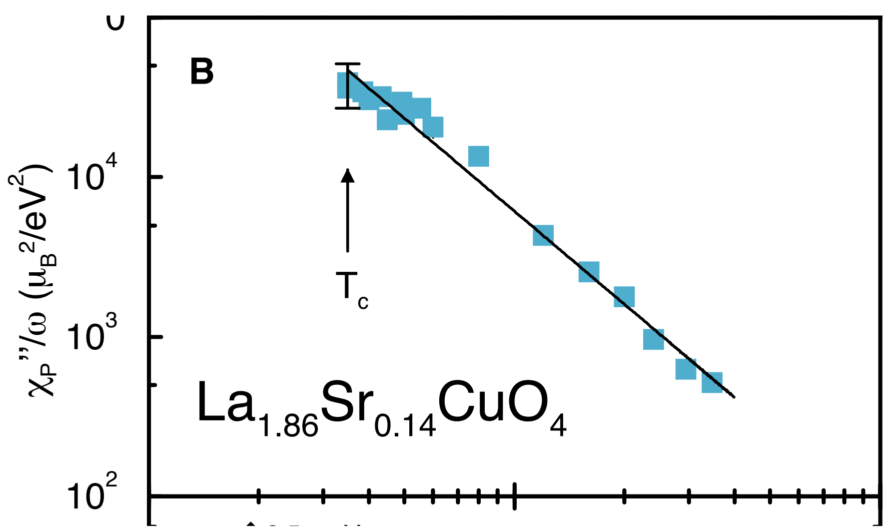
Experiment: Stripe fluctuations do not notice Fermi surface or its pseudogapping; apparent decoupling of stripes and electrons.

Standard Theory:
Old version (Hertz, Millis, ...) Stripe fluctuations strongly Landau damped by Fermi surface at low energy.

Modern version(Abanov, Chubukov, Metlitski, Sachdev): Coupling to Fermi surface even stronger than in Hertz-Millis.

Other surprises in Aeppli 1997 experiment

T-dependence of peak height:
large anomalous exponent?



$$\frac{\chi_P''}{\omega} \sim \frac{1}{T^2}$$

Usual quantum critical scaling: $\eta \approx 1$.

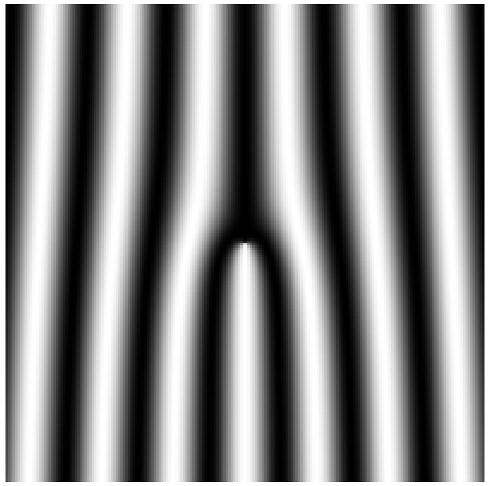
Large η uncommon for Landau QCPs
but common at non-Landau QCPs
(eg, deconfined criticality, TS et al 2004).

This talk: Alternate approach to stripe onset transition

Start from the stripe ordered phase and describe quantum melting of stripe order.

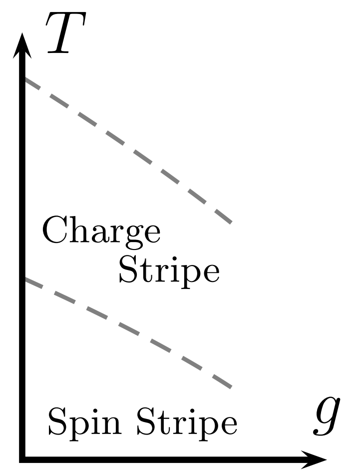
Stripe order reconstructs band structure `large' Fermi surface.

Melt stripes by proliferating topological defects = dislocations in stripe pattern.



Stripe melting: A possible phase diagram

1. Thermal melting: usually spin stripe melts first.



Stripe melting: A possible phase diagram

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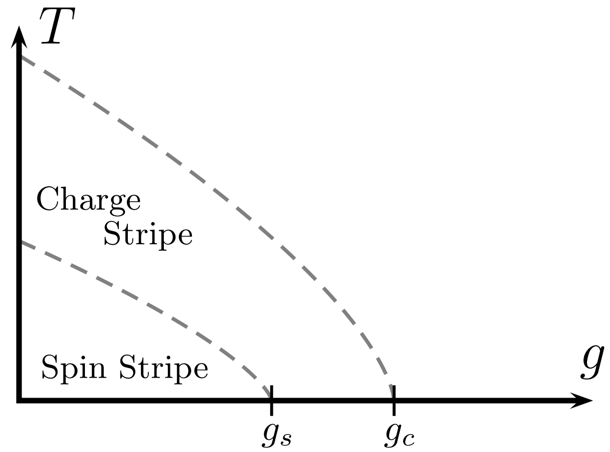
2. Expect spin stripe melting QPT occurs before charge stripe melting QPT.



Stripe melting: A possible phase diagram

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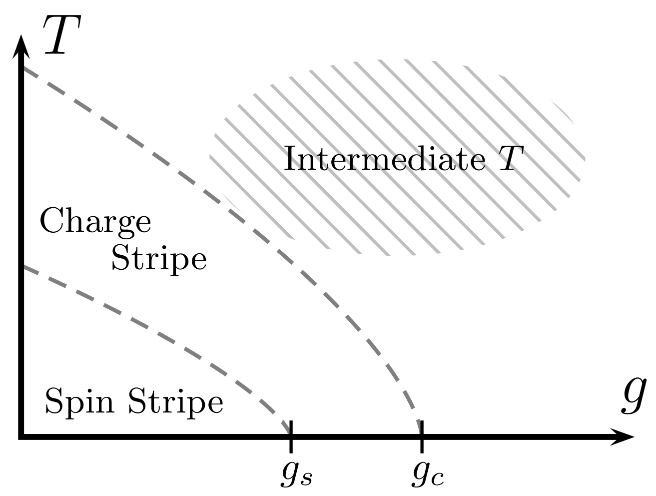
3. Intermediate T spin physics: quantum multicritical point where both spin and charge stripes simultaneously melt.



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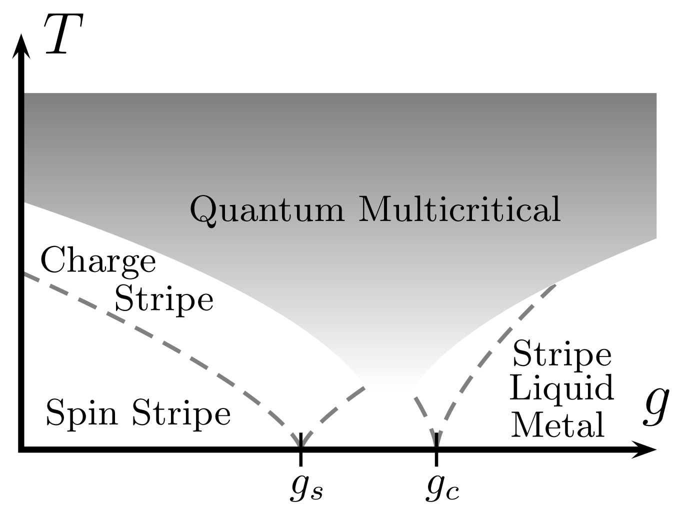

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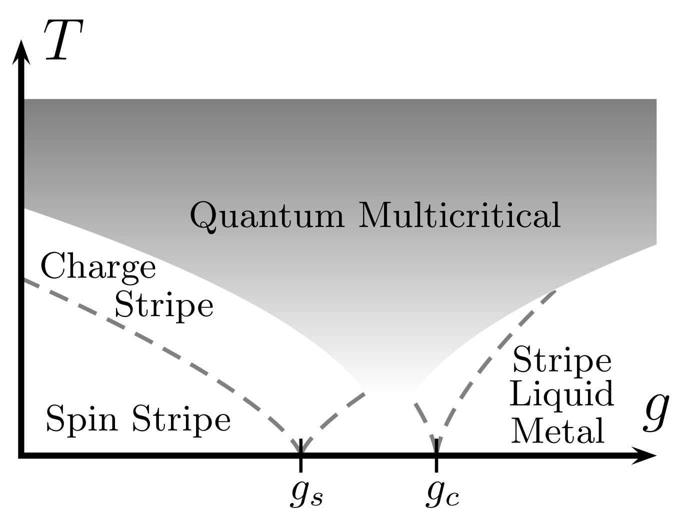
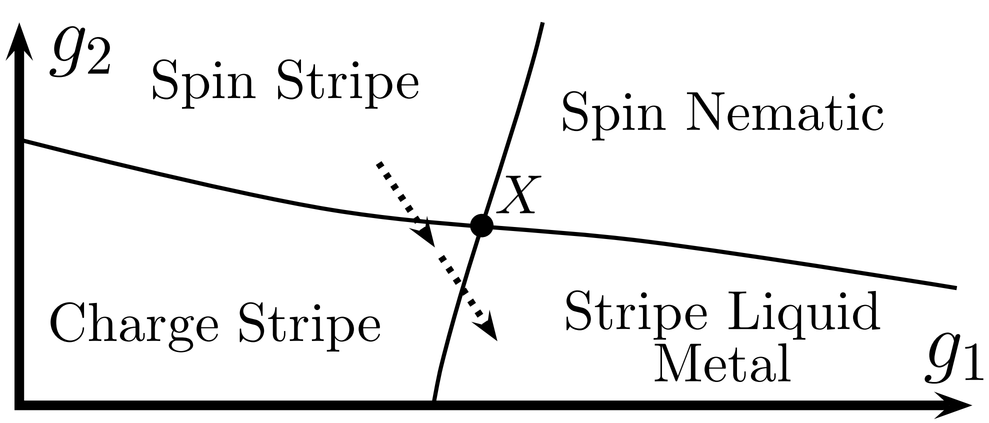
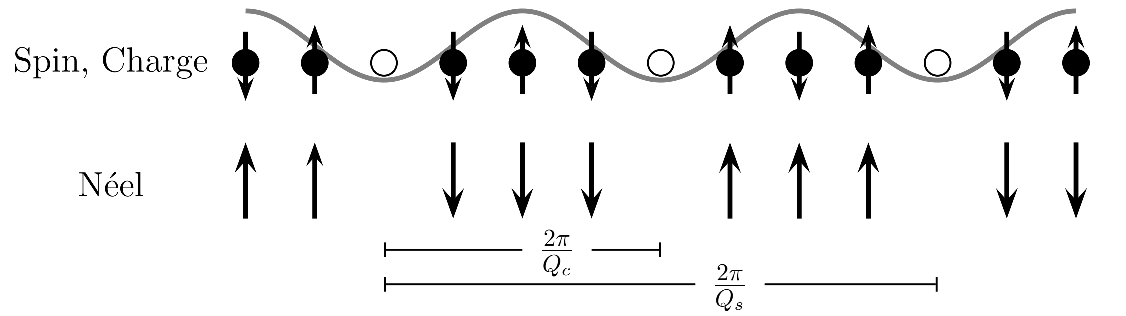




Zero temperature phase diagram

Stripe order parameters



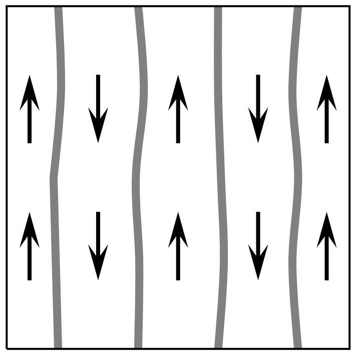
$$\vec{S}_r \sim e^{i\mathbf{Q}.\mathbf{r}} e^{i\theta_s} \vec{N} + c.c$$

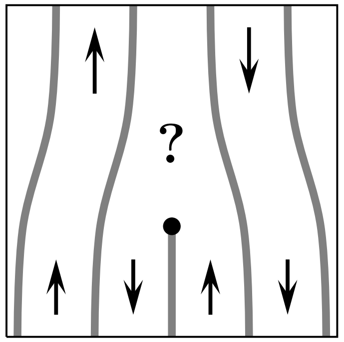
Stripe order parameter $= e^{i\theta_s}\vec{N}$.
θ_s: stripe displacement
$\vec{N}$: local Neel vector.
Charge stripe order parameter $= e^{2i\theta_s}$.

Both stripe order parameters are composites of fields $b = e^{i\theta_s}$, $\vec{N}$.
Formulation in terms of $b, \vec{N}$ has Z_2 "gauge" redundancy $(b, \vec{N} \to -b, \vec{N})$.

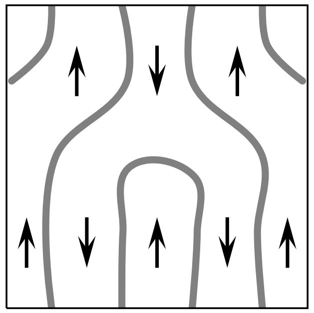
Dislocations in stripe phases

Example: uniaxial charge stripes with (at least short ranged) collinear spin order.





Spin order is frustrated at a single dislocation.



Spin order not frustrated at a double dislocation.

Proliferate single dislocations: conventional Fermi liquid; transition not understood.

This talk: proliferate doubled dislocations.

Quantum melted phase

Proliferate doubled dislocations to melt stripe order

Restore Landau quasiparticles at large Fermi surface
(visible in dHvA, ARPES, transport,.....)

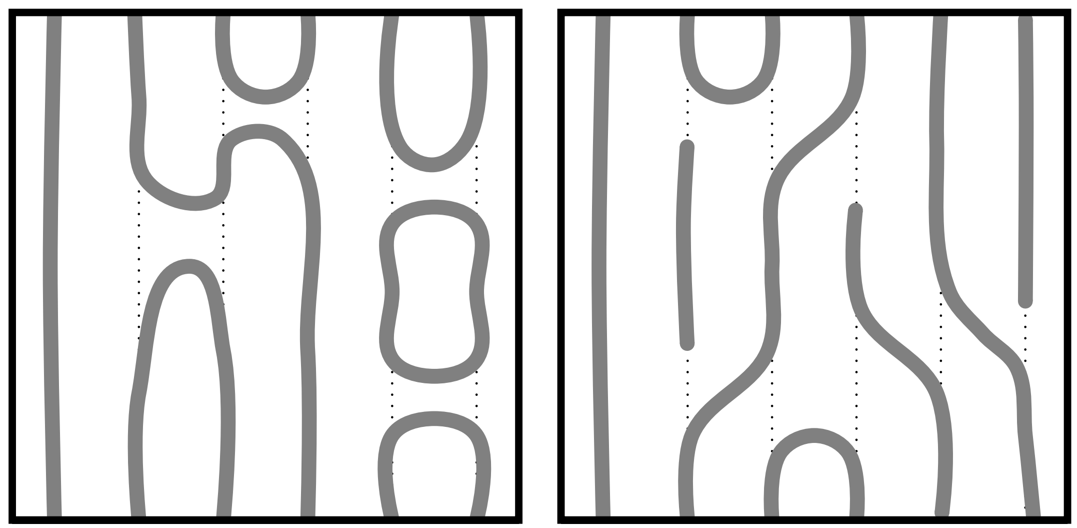
but stripe fluctuations
are ``fractionalized'' (Zaanen, 1999, Sachdev, Morinari, 2002).

Characterize as stripe loop metal.

Very subtle distinction from ordinary FL
(surely not visible to any current experimental probe).

Might this be the overdoped cuprate metal???

Stripe loop metals

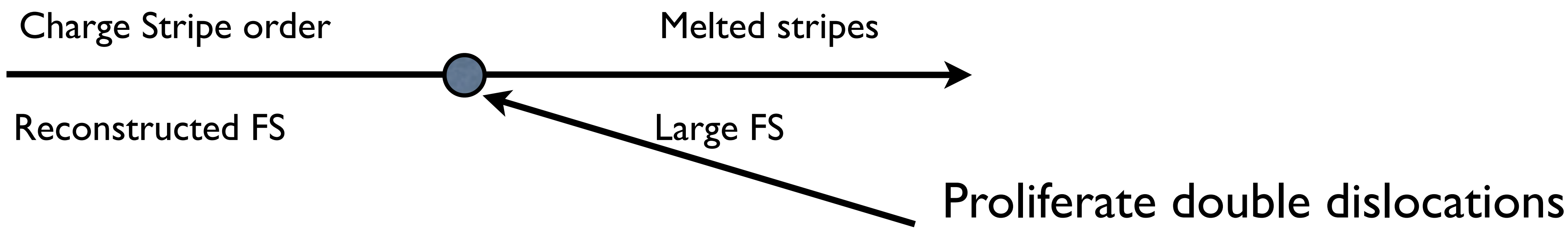


Stripe Loop Metal   Regular fluctuating stripes

Distinction from conventional FL well hidden from all current experimental probes.

Theory of continuous stripe melting

Strategy: initially ignore Fermi surface and obtain critical theory; then include perturbatuvely to test for RG relevance.



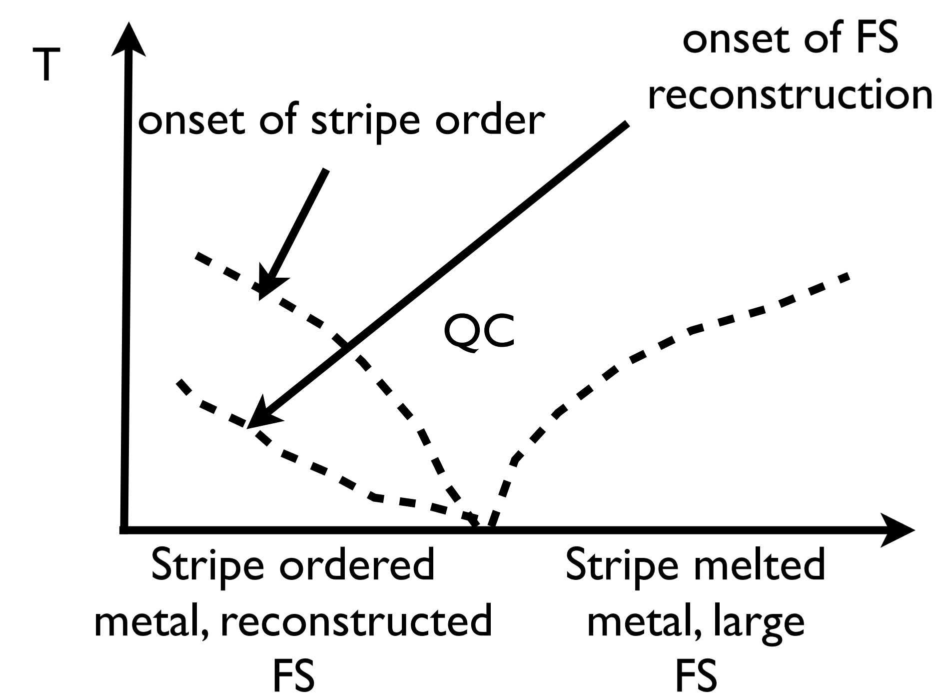
Charge stripe melting by doubled dislocation proliferation is an XY transition for the fractional stripe order parameter b (XY* transition).

Physical stripe order parameter b^2 has large anomalous dimension.

* No ``chemical potential'' term for XY order parameter due to lattice reflection symmetry.

Theory of a continuous stripe melting transition

Consequences of large anomalous dimension :



1. Lattice pinning of stripe order parameter irrelevant at critical point (even for commensurate stripes).

2. Landau damping and other coupling to Fermi surface also irrelevant at criticality!

Critical stripe fluctuations are strongly coupled but tractable.

Coupling to Fermi surface dangerously irrelevant: in stripe ordered state, scale of stripe ordering parametrically different from scale of Fermi surface reconstruction.

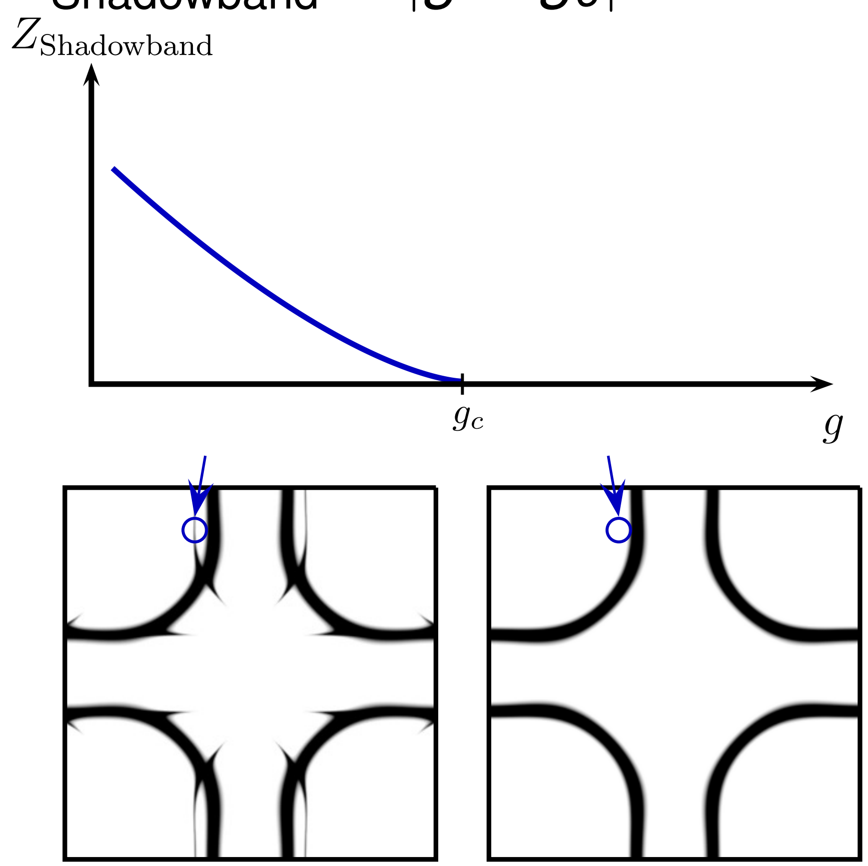
Single electron physics Fermi liquid like even at critical point.

Fermi surface reconstruction

In stripe ordered phase reconstructed Fermi surface has a shadow portion coming from folding. How is this shadow Fermi surface destroyed o approaching stripe melting?

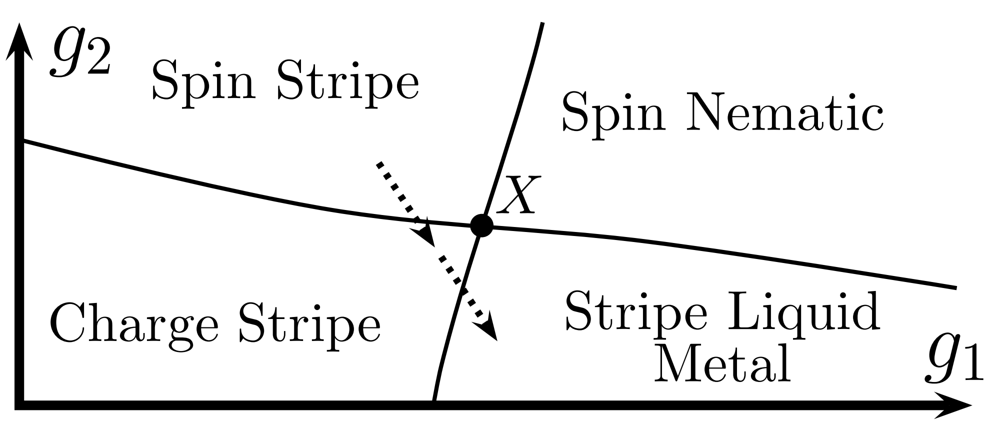
Spectral weight on shadowbands

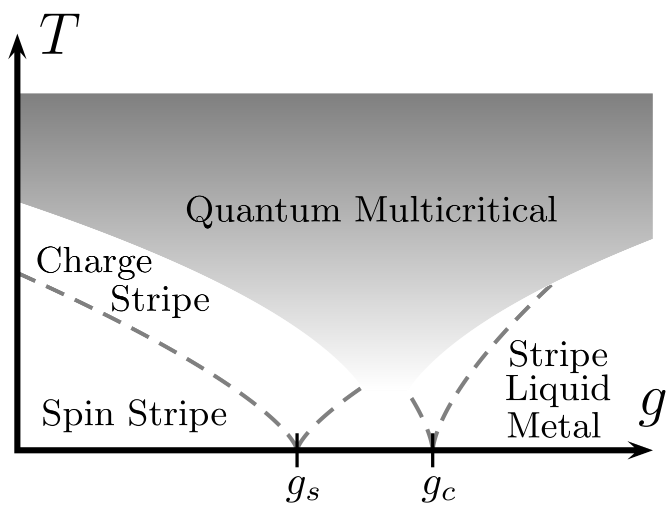
$Z_{\text{Shadowband}} \sim |g - g_c|^{\nu(z+\eta)}$



Theory of Multicritical point

Intermediate T spin physics: quantum multicritical point where both spin and charge stripes simultaneously melt.





Theory of Multicritical point

Both $b, \vec{N}$ simultaneously critical.

$$S[b,\vec{N}] = \int d\tau d^2 r \mathcal{L}_b + \mathcal{L}_N + \mathcal{L}_{bN} \quad (1)$$

$$\mathcal{L}_b = |\nabla b|^2 + \frac{1}{v_c^2}|\partial_\tau b|^2 + r_b|b|^2 + u_b|b|^4 \quad (2)$$

$$\mathcal{L}_N = |\nabla \vec{N}|^2 + \frac{1}{v_s^2}|\partial_\tau \vec{N}|^2 + r_N|\vec{N}|^2 + u_N|\vec{N}|^4 \quad (3)$$

$$\mathcal{L}_{bN} = v|b|^2|\vec{N}|^2. \quad (4)$$

v irrelevant at 'decoupled' $O(3) \times XY$ fixed point.

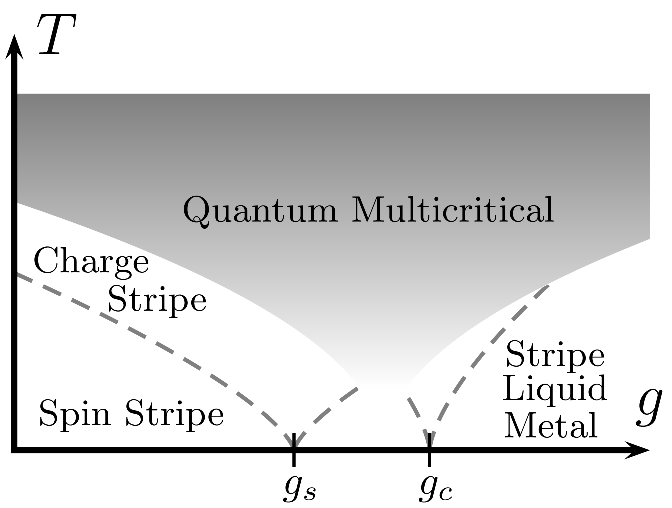
Theory of multicritical point (cont'd)

Physical spin/charge stripe order parameters $b\vec{N}, b^2$ have large anomalous dimension $\eta_s \approx 1.08, \eta_c \approx 1.49$.

Landau damping by Fermi surface fluctuations irrelevant.

Strongly coupled critical stripe fluctuations survives presence of Fermi surface and is unaffected by it.

Relation to experiment



1. In intermediate-T region, critical stripe fluctuations decouple from Fermi surface.

2. Critical dynamics with z = 1.

3. Exponents $z = 1, \eta_s \approx 1.08$
=> $\frac{\chi_P"}{\omega} \sim \frac{1}{T^{1.92}}$.
(Compare with $\frac{1}{T^2}$ behavior in Aeppli et al 1997).

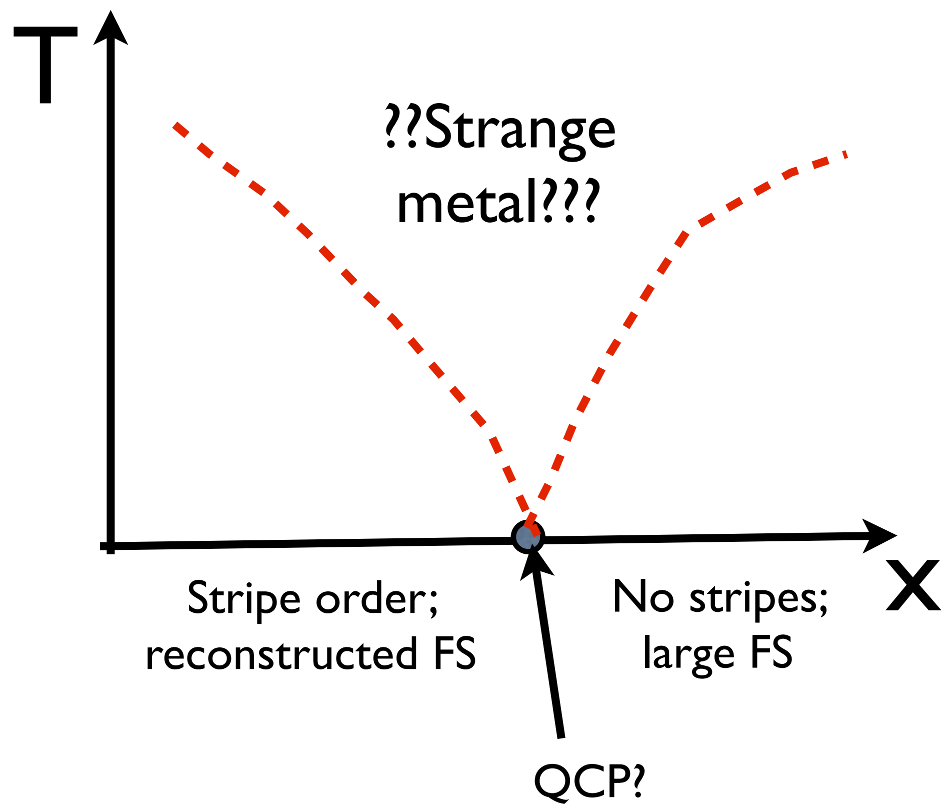
Predictions:

1. Criticality of charge stripe fluctuations (measure thru STM?)

2. Spin quadrupole fluctuations (how to measure?)

Stripe criticality - a savior?

Could a stripe onset quantum critical point around optimal doping in the ``underlying normal" state control physics of strange metal?



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(last 2 years)

Our theory explains stripe sector but does not destroy electron quasiparticle.

NOT a viable theory of strange metal.
Strange metal due to other physics possibly coexistent with our theory of stripe fluctuations.

Summary/conclusions/comments

1. Stripe fluctuations in cuprates very unusual - apparently blind to Fermi surface excitations.

Unusual criticality near optimal doping.

2. Theory explanation - stripe fluctuations controlled by proximity to non-Landau quantum (multi)critical point.

Was Aeppli et al 1997 the first observation of non-Landau quantum criticality?

3. This is the only concrete and tractable theory of quantum stripe melting and Fermi surface reconstruction I know.

4. Stripe melting apparently does not explain strange metal.