Deconfined quantum criticality and the underdoped cuprates

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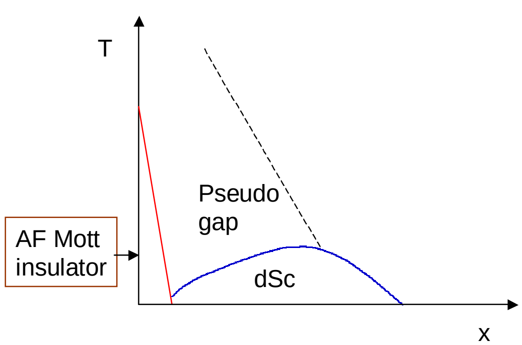
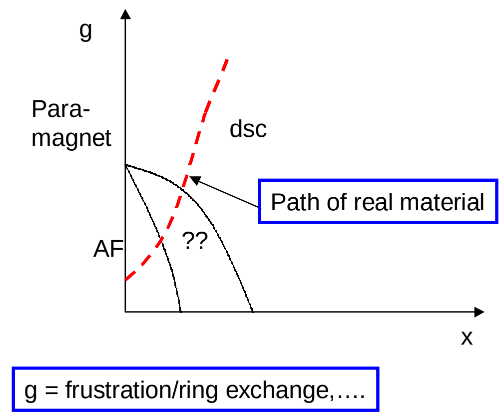
T.S, Lee, cond-mat/0406066
Levin, T.S, cond-mat/0405702
Hermele et al, cond-mat/0404751

Cuprate phase diagram



Nature of pseudogap, and dSc at low non-zero doping?

Old idea: view as doped paramagnetic Mott insulator



What paramagnet? Some hints from experiments

- Softening of neutron resonance mode with decreasing x

- consider paramagnets proximate to Neel state

i.e potentially separated by 2nd order transition.

- Gapless nodal quasiparticles in dSC

- consider paramagnets with gapless spin excitations.

Candidate states – gapless spin liquids

Rough description: Gapless spin-1/2
nodal spinons coupled to deconfined gauge fields.
(Eg: Z_2 spin liquid with nodal spinons and gapped visons)

Can spin liquid states be reached from conventional
collinear Neel by second order transitions?

Orthodox answer: No!

Claim in this talk: Orthodox answer needs to be revisited.

Are the cuprates doped gapless spin liquids?

Natural (old) questions:

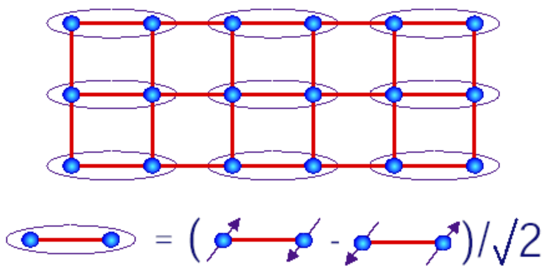
- Is the question meaningful?
- How to tell? (TS,Lee,condmat/0406066)

Revisit – exploit insights from study of deconfined criticality at Neel-VBS transition.

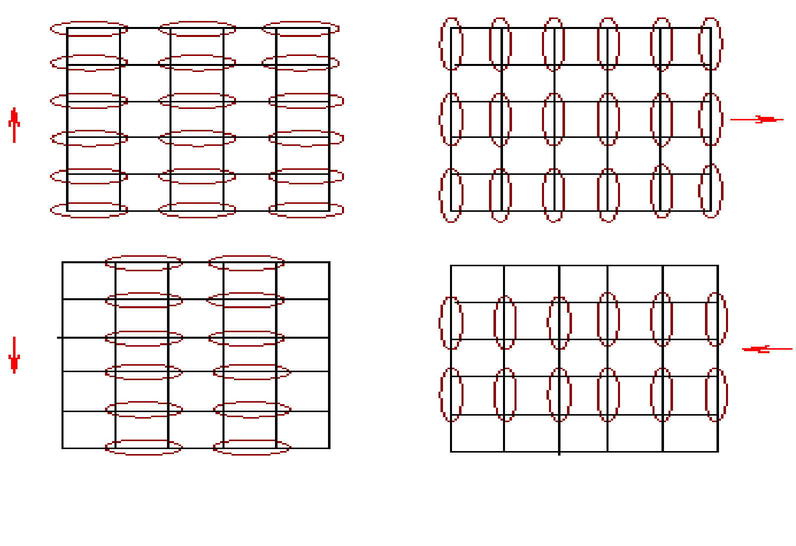
Deconfined criticality again – now from the valence bond solid(VBS) side

(Levin, TS, cond-mat/0405702)

Valence bond solid with spin gap.



Discrete Z_4 broken symmetry



Neel-Valence Bond Solid transition

- Naïve approaches fail

Attack from Neel ≠Usual O(3) fixed point in D = 3

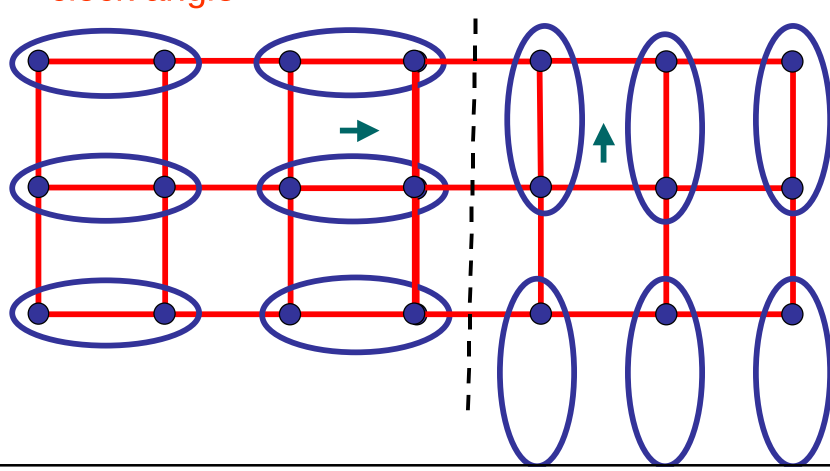
Attack from VBS ≠ Usual Z_4 fixed point in D = 3 (= XY universality class).

Why do these fail?

Topological defects carry non-trivial quantum numbers!

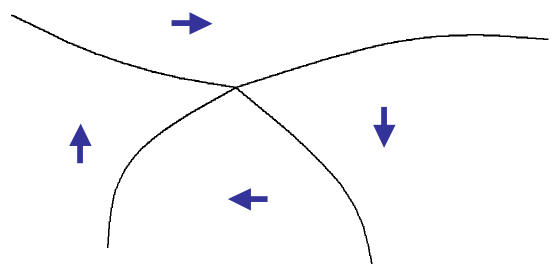
Topological defects in Z_4 order parameter

- Domain walls – elementary wall has π/2 shift of clock angle



Z_4 domain walls and vortices

- Walls can be oriented; four such walls can end at point.
- End-points are Z_4 vortices.

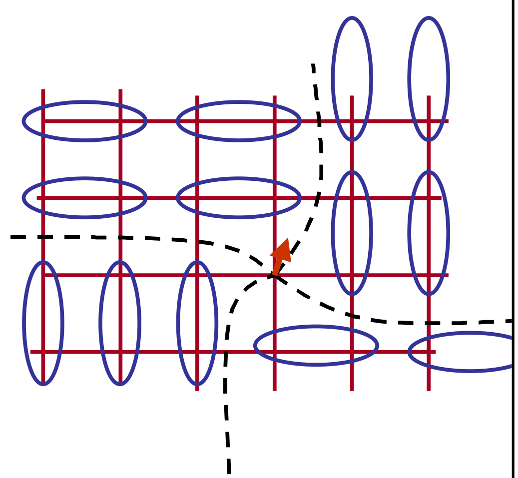


Z_4 vortices in VBS phase

Vortex core has an unpaired spin-1/2 moment!!

Z_4 vortices are ``spinons''.

Domain wall energy confines them in VBS phase.



Disordering VBS order

- If Z_4 vortices proliferate and condense, cannot sustain VBS order.

- Vortices carry spin =>develop Neel order

Z_4 disordering transition to Neel state

- As for usual (quantum) Z_4 transition, expect clock anisotropy is irrelevant.

(confirm in various limits).

Critical theory: (Quantum) XY but with vortices that carry physical spin-1/2 (= spinons).

Alternate (dual) view

- Duality for usual XY model (Dasgupta-Halperin)

Phase mode - ``photon''

Vortices – gauge charges coupled to photon.

Neel-VBS transition: Vortices are spinons

=> Critical spinons minimally coupled to fluctuating non-compact U(1) gauge field.

Proposed critical theory ``Non-compact CP_1 model''

$$S = \int d^2x d\tau \, |(\partial_\mu - i a_\mu) z|^2 + r |z|^2 + u |z|^4 + (\varepsilon_{\mu\nu\lambda} \partial_\nu a_\lambda)^2$$

z = two-component spin-1/2 spinon field

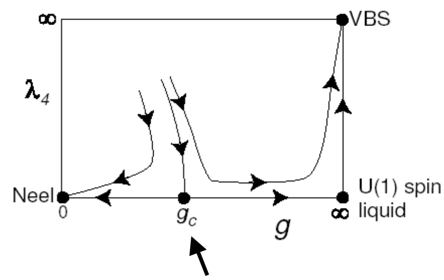
a_μ = non-compact U(1) gauge field.

Distinct from usual O(3) or Z_4 critical theories.

Reobtain same result as by attack from Neel state!

Renormalization group flows

Clock anisotropy
= quadrupled monopole
fugacity

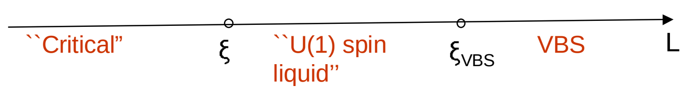


Deconfined critical fixed point

Monopoles are ``dangerously irrelevant''.

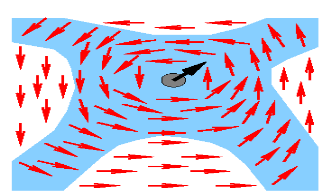
Precise meaning of deconfinement:
Conservation of gauge flux ⬄
Extra emergent global (topological) U(1) symmetry associated with skyrmion conservation

Two diverging length scales in paramagnet



$\xi_{VBS} \sim \xi^{\kappa}$ diverges faster than ξ

Spinons confined in either phase but `confinement scale' diverges at transition.



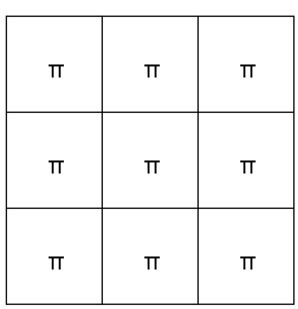
Pertinent lessons

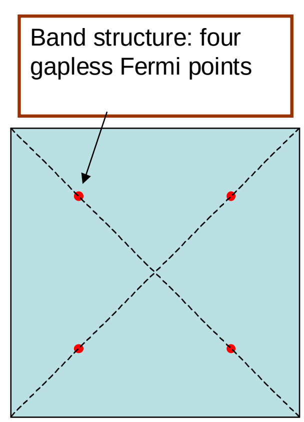
- Lesson 1: Gapless spinons may kill confinement in U(1) gauge theories in d = 2.
- Lesson 2: Even unstable spin liquids may control broad intermediate regime near certain quantum transitions.

Application to cuprates: theory of gapless U(1) spin liquids

- Affleck-Marston '88, Marston'91: Flux phase of large-N spin models.

Mean field: Half-filled tight binding band of fermionic spinons with π-flux through each plaquette.





Low energies: massless Dirac theory in D = 2+1.

Beyond mean field

Describe by fermionic massless Dirac spinons coupled to compact U(1) gauge field

Ultimate fate?? Confinement??

- Doped versions: Lee, Nagaosa, Wen, ……..

(1996 - ….)

Mostly ignore compactness (and hence possibility of confinement).

Stability of gapless U(1) spin liquids (Affleck-Marston pi-flux phase)

Hermele et al, cond-mat/0404751

- Analyse in limit of large number 2N of Dirac spinons (appropriate for SU(N) spin model).

- First ignore monopole events in space-time

⇒ Gauge flux exactly conserved.

Low energy theory is critical with no relevant perturbations (non-compact QED_3) : conformally invariant with power law spin correlations.

$$\mathcal{L} = \bar{\psi}_j \gamma^\mu (\partial_\mu + i a_\mu) \psi_j + \frac{1}{8\pi e^2} (\epsilon_{\mu\nu\lambda} \partial_\nu a_\lambda)^2.$$

Monopoles

- Break flux conservation symmetry

Careful consideration: monopoles irrelevant at low energy critical fixed point for large enough N.

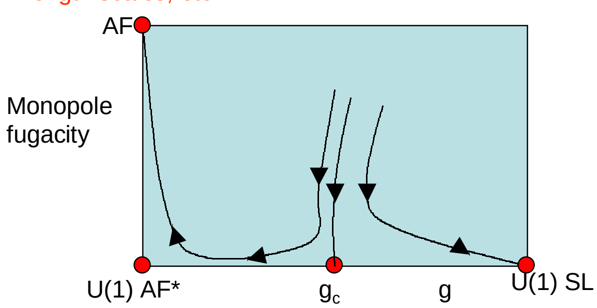
⇒ Deconfined critical phase

Precise meaning of ``deconfinement": extra global topological U(1) symmetry associated with gauge flux conservation.

Second order transition to Neel

(induce by increasing strength of quartic spinon interaction)

- Spin density wave of spinons
- Monopoles continue to be irrelevant at critical point to Neel.
- Spinons gapped in Neel phase => monopoles no longer irrelevant, cause confinement to yield conventional Neel state.
- Deconfined critical point with dangerous irrelevant monopoles, 2 diverging length scales, etc.



General lesson I

- Stable gapless U(1) spin liquids exist in D = 2+1 (at least for SU(N) models and N > some N_{c1}).

N_{c1} possibly smaller than 2, not known at present*.

$N_{c1} < 2$ => appealing description of cuprates as doped U(1) spin liquids.

*Indications from numerics: $N_{c1}<4$ (Assaad, cond-mat/0406…)

Alternate possibility

(or how Z2 and U(1) spin liquids may give each other 2nd lives)

Z_2 spin liquid with nodal spinons and gapped Z_2 vortices (visons) – clearly stable even for SU(2) spin models.

?? 2nd order transition to conventional collinear Neel state ??

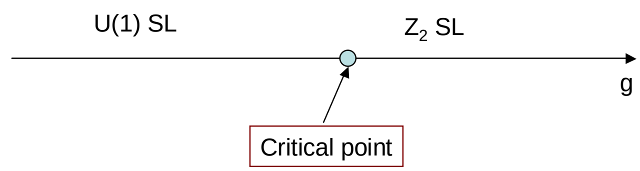
Z2 state: Higgs phase of compact U(1) gauge theory coupled to charge-2 boson (spinon pair) field.

Neel: some confined phase of same theory.

Confinement transition from gapless Z_2 SL

Transition where spinon pair field gets gapped.

First ignore monopoles: Phase with gapped spinon pair described by non-compact QED_3 for spinons (i.e the U(1) SL)



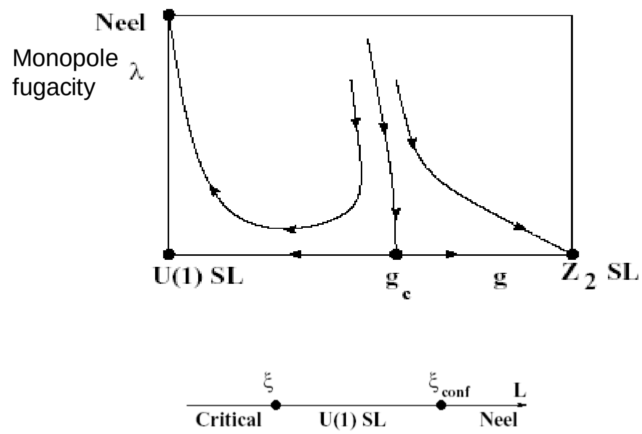
Z_2 SL –Neel transition

- Expect monopole scaling dim at critical point > at U(1) SL fixed point

⇒Can get situation where monopoles are irrelevant at critical point but relevant at U(1) SL fixed point (for $N_{c2} < N < N_{c1}$)

⇒Possibility of direct 2nd order transition from Z_2 SL to conventional collinear Neel.

A deconfined critical point again



General lesson II

- Can possibly reach Z_2 spin liquid with nodal spinons by direct second order transition from conventional Neel state.
- The (unstable) gapless U(1) spin liquid controls a large intermediate length scale regime in Neel state near the transition.

Summary, conclusions, etc - I

- Gapless spin liquids exist as stable phases

in D = 2+1.

They may be accessed from conventional Neel by second order transitions.

Needed: Numerics to determine N_{c1}, N_{c2}

Summary, conclusions -II

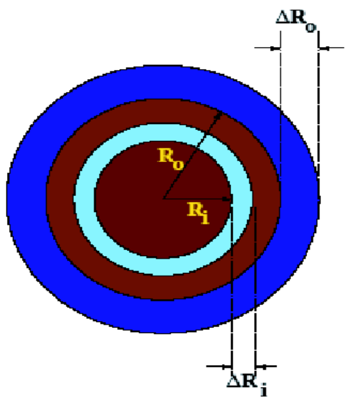
- U(1) SL with ``gapless Dirac spinons'' apparently plays an important role whether it is stable or not.

Are the cuprates doped U(1) spin liquids?

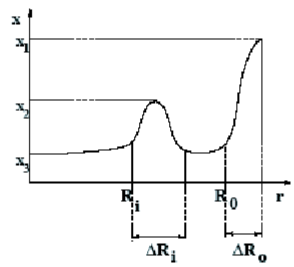
How to tell?

Detect conserved U(1) gauge flux!

Gauge flux detector



Cuprate sample with spatially modulated doping as below



Gauge flux detection

- Start with outer ring superconducting and trap an odd number of hc/2e vortices

(choose thin enough so that there is no physical flux).

- Cool further till inner annulus goes superconducting.

- For carefully constructed device will spontaneously trap hc/2e vortex of either sign in inner annulus.

How does it work?

- Odd hc/2e vortex inside outer ring => π flux of internal gauge field spread over the inner radius.
  (Lee, Wen, 2001)

- If inner annulus sees major part of this internal flux, when it cools into SC, it prefers to form a physical vortex.

- For best chance, make both SC rings thinner than penetration depth and device smaller than roughly a micron.