Are the cuprates doped spin liquid Mott insulators?

T. Senthil (IISc (India) and MIT(USA))

Meaning of the question?
How might we find answers?
Don't we already know?

T.Senthil, Patrick Lee, cond-mat/0406066
M.Hermele, T. Senthil, and M.P.A. Fisher, cond-mat/0502215

Other relevant work:
M. Hermele, T. Senthil, M.P.A. Fisher, P.A. Lee, N. Nagaosa, X.G. Wen, PR B 04

Are the cuprates doped spin liquid Mott insulators?

- ``Obvious'' answer: No!

Undoped material has antiferromagnetic order – not a spin liquid.

However ``obvious'' answer may be too quick……..

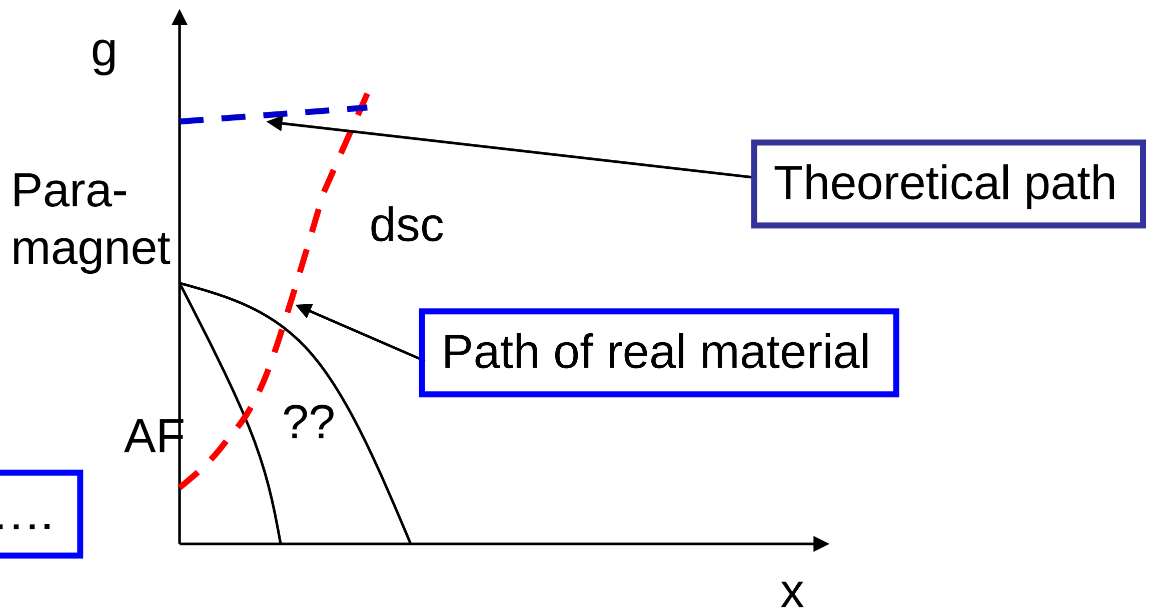
Aspects of underdoped phenomenology (at not too low doping or temperature)

- Charge transport is by holes
- No magnetic long range order (AF LRO quickly destroyed by hole motion)
- Existence of spin gap

Perhaps useful to view as doped paramagnetic (spin liquid) Mott insulator.

Further theoretical bonus: Superconductivity a natural outcome of doping paramagnetic Mott states

(old RVB notion – Anderson, Kivelson et al, Kotliar-Liu,………)

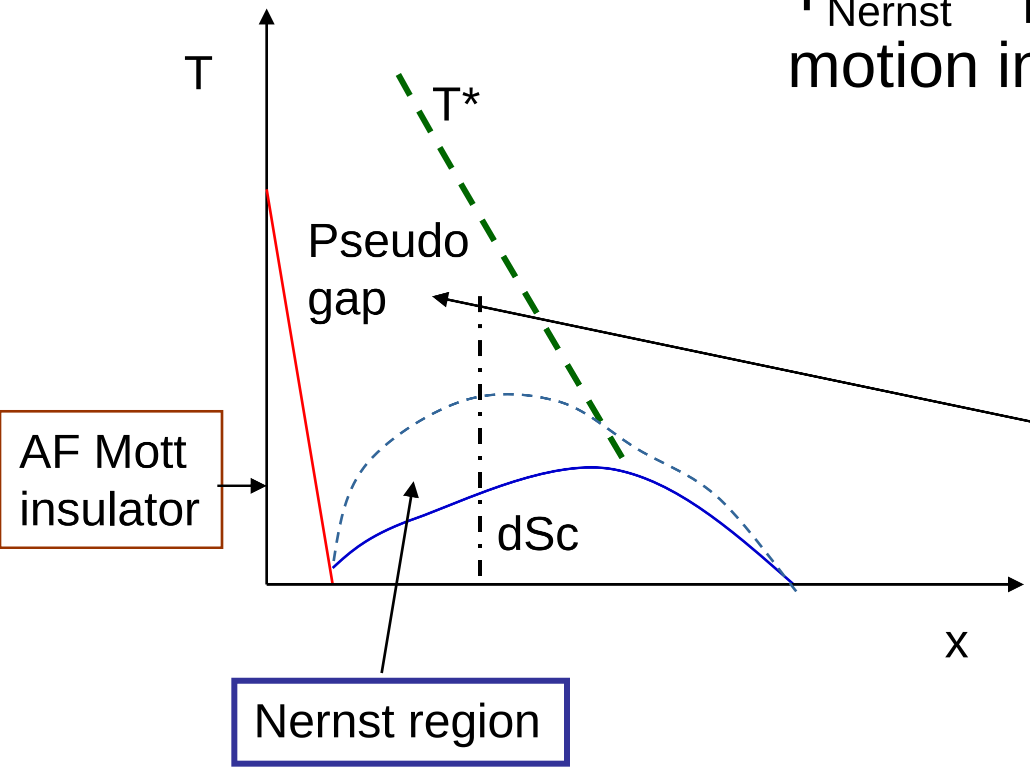


g = frustration/ring exchange,….

Where might be the spin liquid?

T*≈ spins pair into valence bond singlets

T_{Nernst} ≈ phase coherent charge motion in background of paired spins



Spin physics in

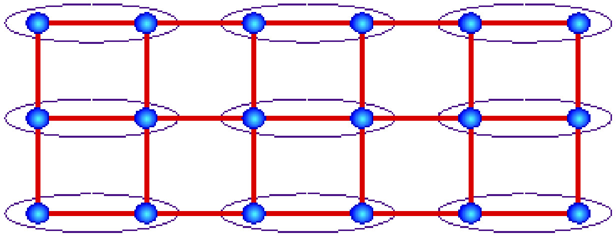
<u>high-T pseudogap regime</u>

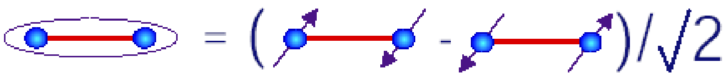
- reflect character of hypothesized ``parent” spin liquid.

What paramagnet to ``dope"?

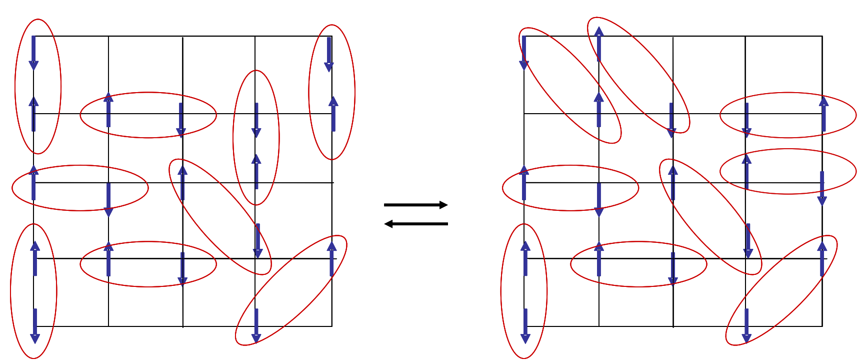
Theoretical candidates

1. Valence bond solid (spin Peierls) states





2. Various kinds of RVB spin liquids



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 2^{nd} order transition.

- Gapless nodal quasiparticles in dSC

- consider paramagnets with gapless spin excitations.

Tight constraints

=> Only few candidates: ``gapless spin liquids''

Example of spin liquid with nodal spinons

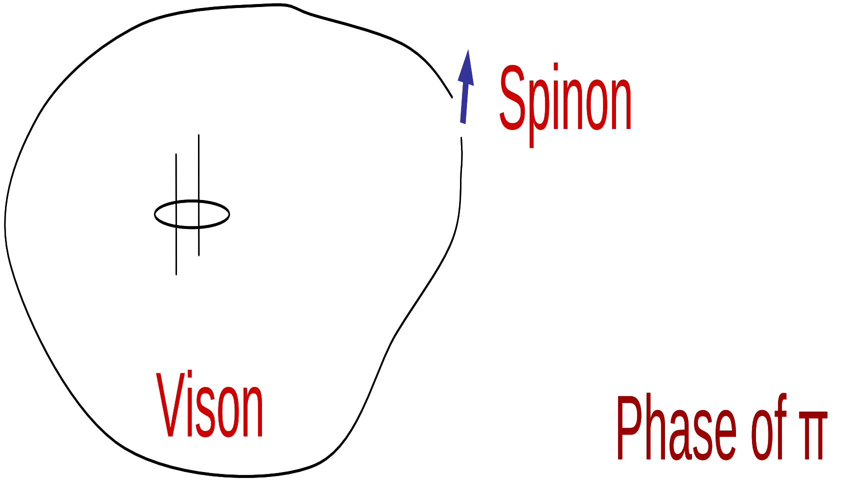
Gapless Z_2 spin liquid (TS, Fisher):

Conserved Z_2 gauge flux (= ``vison'').

Doping a Z_2 spin liquid – attractive theory of cuprates but apparently not supported by experiments

(eg: no evidence for visons or their consequences

– Bonn-Moler flux-trapping and other experiments).



Are there any other alternatives??

Alternate possibility: gapless U(1) spin liquids

- Affleck-Marston ’88, Kotliar ’88: d-wave RVB state

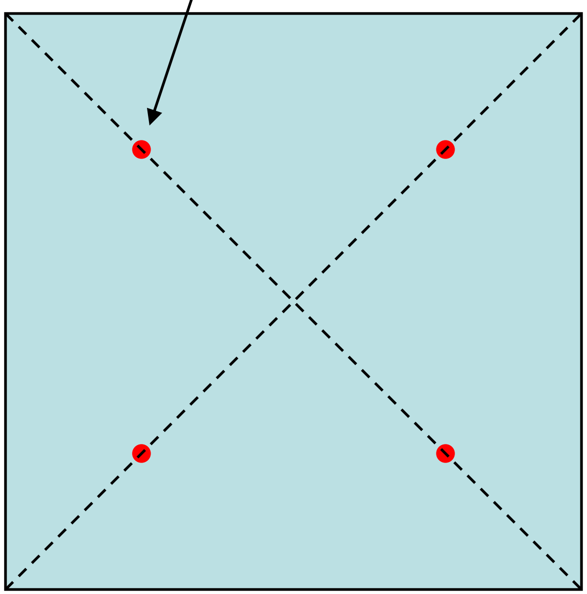
Mean field: Spinons (f) with hopping and d-wave pairing.

$$H = -\chi \sum_{\langle rr' \rangle} \left(f_r^{\dagger} f_{r'} + h.c.\right)$$

$$+ \sum_{\langle rr' \rangle} \Delta_{rr'} \left(f_{r\uparrow} f_{r'\downarrow} - f_{r\downarrow} f_{r'\uparrow}\right) + h.c.$$

$\Delta_{rr'}$: d-wave

Band structure: four gapless Fermi points



Low energies: gapless Dirac spinons in D = 2+1.

Beyond mean field

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

Stable to confinement (at least within systematic 1/N expansion)
(Hermele et al 04)

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

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

dRVB ``algebraic" spin liquid (Rantner,Wen)

Numerics: Evidence for such a phase in SU(4) Hubbard model.
(Assaad, 04)

Doping the dRVB algebraic spin liquid

- U(1) gauge theory with holons and spinons

(Lee, Wen, Nagaosa, Ng, Ivanov,……)

- Projected BCS wavefunctions:

$$P_G \, | \text{d-wave BCS} \rangle$$

(Zhang, Gros, Ogata, Paremekanti, Randeria, Trivedi, Lee,………)

How to tell?

Search for unique signatures in structure of parent spin liquid.

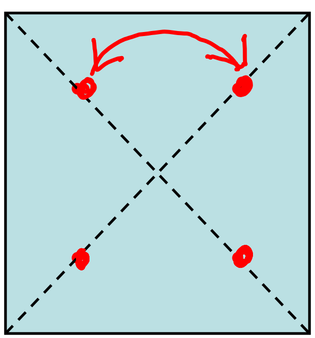
Low energy structure of the dRVB algebraic spin liquid

- SU(2) spin rotation

  +

rotation between 2 spinon nodes

enlarge* → SU(4)



Hermele, TS, Fisher '05
See also Herbut '02
Tesanovic et al '02

$\psi \to U\psi, \quad U \in SU(4)$

$\psi = \psi_{a\alpha}, \quad \alpha = \uparrow, \downarrow; \; a = 1, 2 = \text{node index}$

*evidence from large-N

Other symmetries

- Hidden non-trivial U(1) symmetry: conservation of internal gauge flux*

$$\frac{\partial b}{\partial t} = -\vec{\nabla} \times \vec{e}$$

$$\Rightarrow \frac{d}{dt}\left(\int d^2x \, b\right) = 0 \quad \text{(upto boundary effects)}$$

$(\vec{e}, b)$: internal "electromagnetic" field

*Irrelevance of space-time ``magnetic monopoles”.

- Scale invariance and SU(4), $U_{flux}(1)$ symmetries should hold (approximately) in the doped system

- possibly visible in experiments as unique signatures.

dRVB algebraic spin liquid –mother of many competing orders

Slow power-law spin correlations at (π,π) (Rantner,Wen'01)

$$e^{iQ\cdot r}\langle S_r \cdot S_0 \rangle \sim \frac{1}{r^{1+\eta}}$$

Exact SU(4) symmetry at low energies
``unification" of several other competing orders

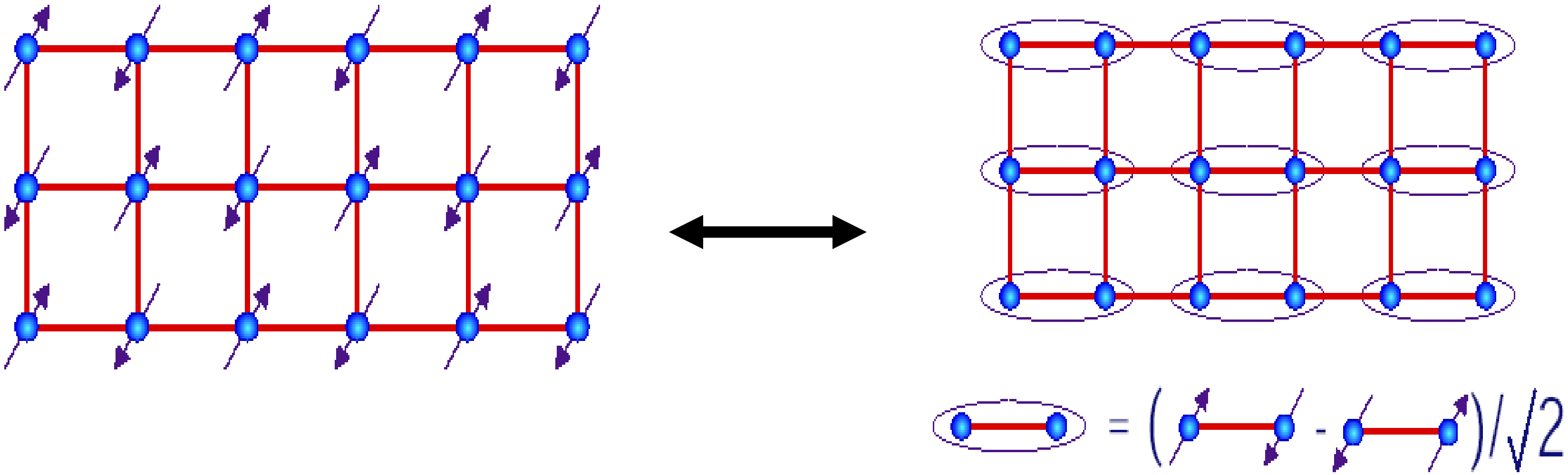
- identical slow power law for variety of other correlations (Hermele et al, 05)

$$\underbrace{e^{iQ\cdot r}\vec{S}_r}_{\text{Neel}}, \quad \underbrace{(-1)^x \vec{S}_r \cdot \vec{S}_{r+x}, \quad (-1)^y \vec{S}_r \cdot \vec{S}_{r+y}}_{\text{Dimer}}$$

$$\underbrace{(-1)^x \vec{S}_r \times \vec{S}_{r+y}, \quad (-1)^y \vec{S}_r \times \vec{S}_{r+x}}_{\text{Vector spin chirality}}, \ldots \text{other unusual operators}$$

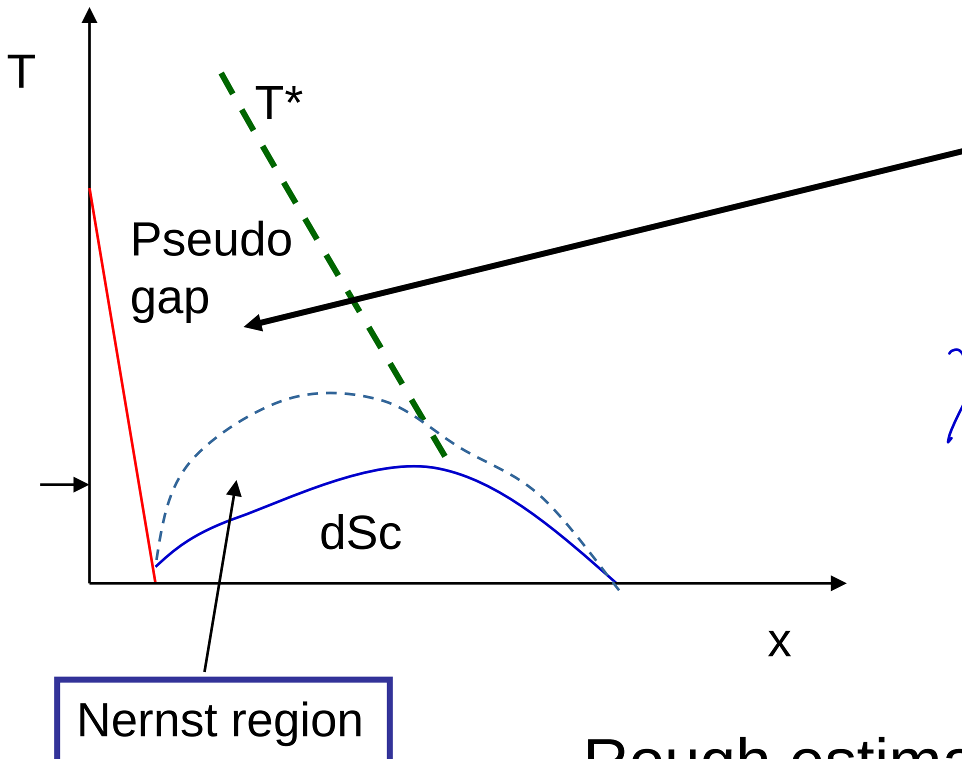
Example – Neel and dimer correlations

- SU(4) rotates Neel to dimer



Both have same slow power law correlations

Probing the pseudogap for the dRVB spin liquid



- Simplest:

Look for scaling in spin correlations near (π,π)

$$\chi''(q,\omega,T) \sim \frac{1}{T^{2-\eta}} f\left(\frac{|q-Q|}{T}, \frac{\omega}{T}\right)$$

Rough estimate: $\eta \approx 0.5$ (projected wavefunctions)

Ivanov, Paremekanti et al.

More subtle: similar scaling in dimer and other correlations

Prior scaling sightings in (π,π) spin response

- Keimer et al ’91: Very lightly doped LSCO
- Bao et al (talk on 5/28): Li-doped La2CuO4
- Stock et al ‘05: Very underdoped YBCO at low T
- Dai et al (talk on 5/28): e-doped cuprate

- Mostly different parameter regimes from high-T pseudogap
- Mostly unconventional: see ω/T scaling but no sign of scaling in q.

To what extent is there conventional scaling in high-T pseudogap regime?

Gauge flux conservation

Conservation of gauge flux of undoped spin liquid

approximately true at finite-T in doped normal state; justifies use of slave particle degrees of freedom.

=> Crucial experiment: directly detect the gauge flux.

How to detect gauge flux?

- Use non-trivial structure of superconducting vortex.

- SC obtained by condensing charge-e holons

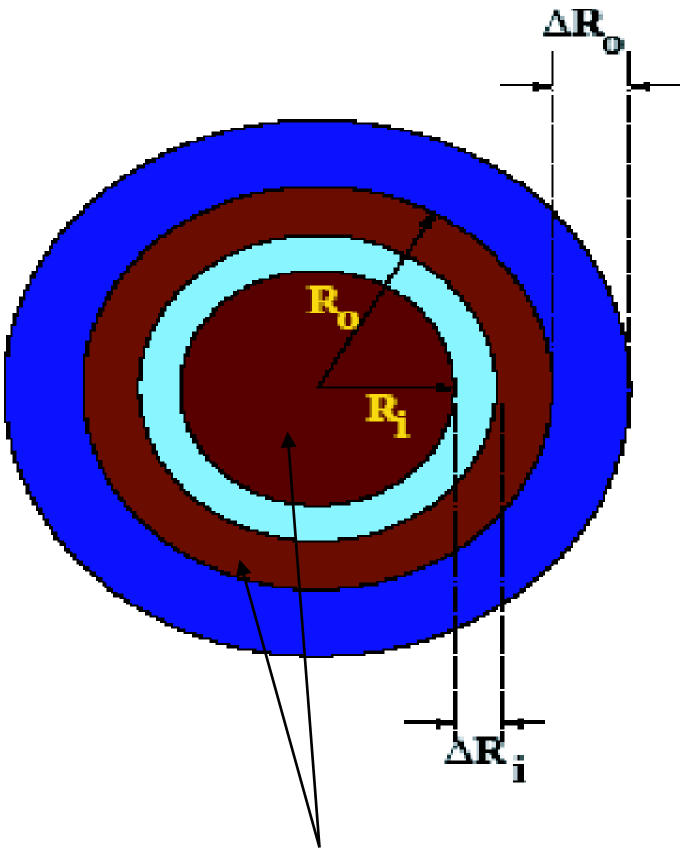
but has hc/2e vortices (Lee,Wen'01)

Possible due to coupling to gauge field

- gauge flux of π in the vortex core.

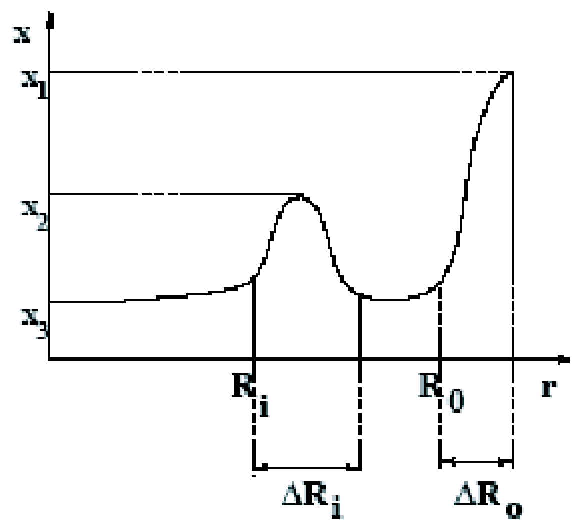
An idea for a gauge flux detector

TS, Lee, cond-mat/0406066



Cuprate sample with spatially modulated doping as below

Pseudogap material



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.

- 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.

Summary

- Cuprates as doped spin liquid Mott insulators
- plausible interesting point of view.

- Spin liquid physics most likely to reveal itself in high-T pseudogap regime.

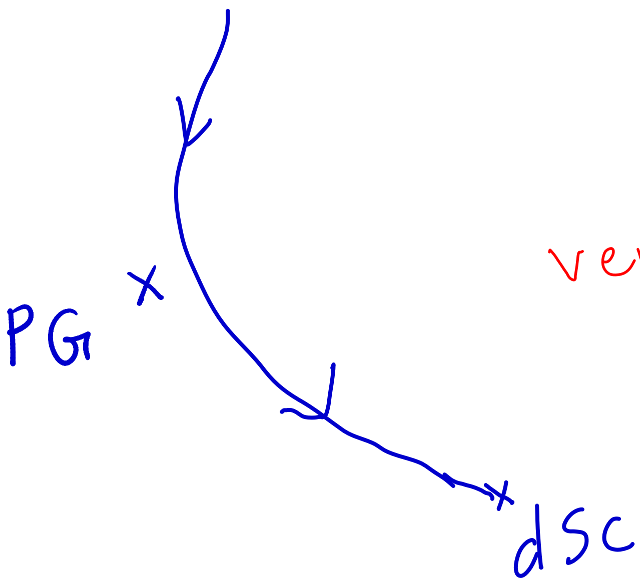
- Nontrivial structure of dRVB state – unique signatures possibly visible in experiments

- Gauge flux conservation – crucial approximate symmetry.

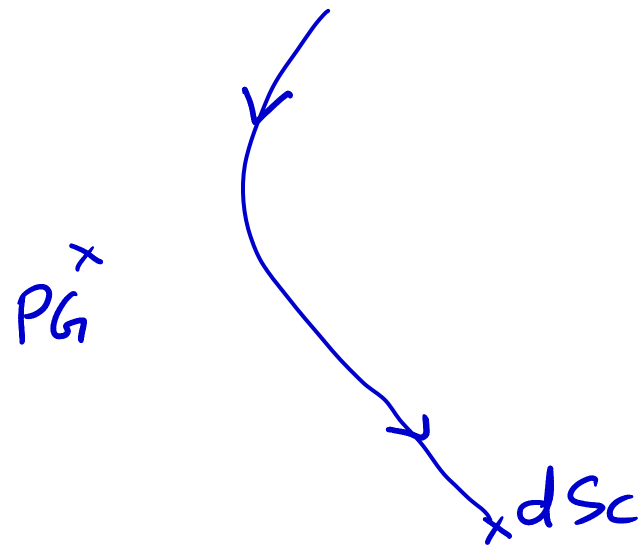
Possible detection through unusual flux trapping effect.

Prospects

- Pseudogap – unstable fixed point en route to superconductivity



versus



Optimistic view

Clean tests in experiment

Pessimistic view

No clean tests.

Will we ever definitively understand?