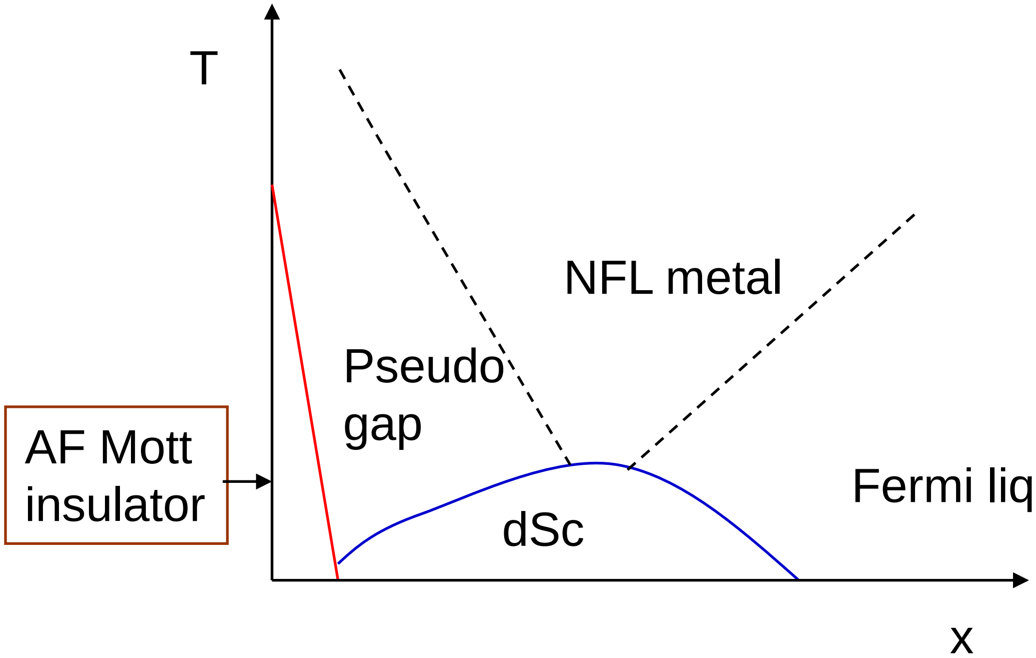
Neel order, quantum spin liquids, and quantum critical scaling in underdoped cuprates

T. Senthil (Indian Institute of Science (India) and MIT(USA))

Pouyan Ghaemi, T. Senthil, cond-mat/0509066
T. Senthil and Patrick Lee, PR B 05

Other relevant work:
M. Hermele, T. Senthil, M.P.A. Fisher, P.A. Lee, N. Nagaosa, X.G. Wen, PR B 04
M. Hermele, T. Senthil, M.P.A. Fisher, PR B 05

Cuprate phase diagram



This talk: focus on underdoped side at not too low doping/temperature

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

Some simple ideas

Qualitative cartoon picture of the pseudogap.

Underdoped side strongly affected by proximity to Mott insulator.

$\Rightarrow$ As x decreases electrons spend increasing amount of time staying localized next to each other

Superexchange can then operate and bind the electron spins into singlets.
(Requires electrons to sit next to each other for times >> 1/J)

If x large enough electronic configuration will change too rapidly for superexchange to do its job

=> lose the pseudogap with increasing doping.

Some simple ideas (cont'd)

<u>Qualitative picture of superconductivity</u>

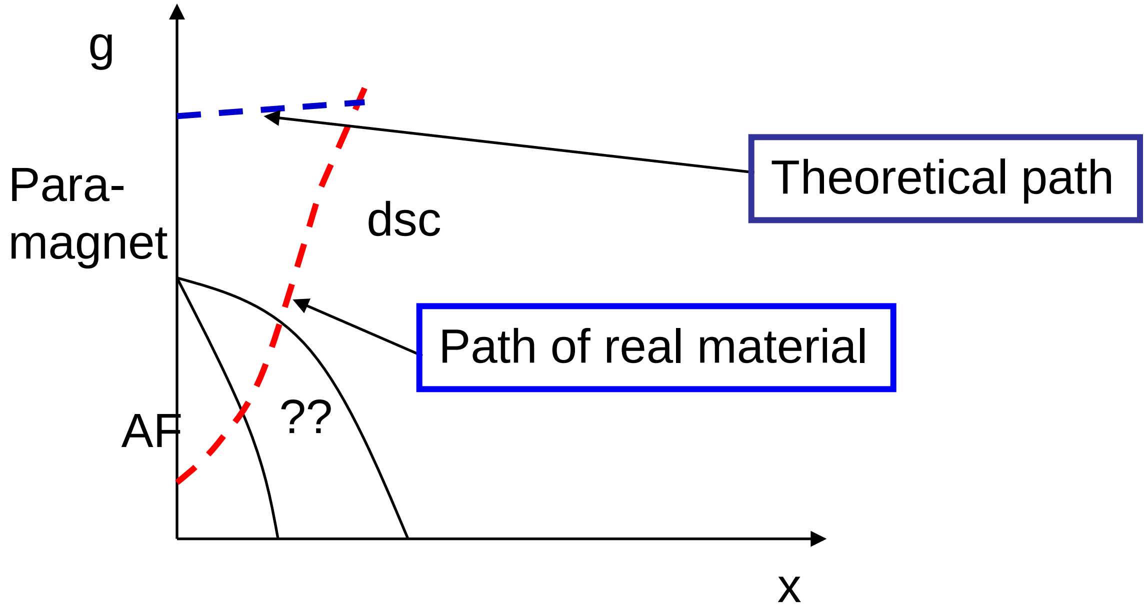
Singlet valence bonds ≈ Cooper pairs

Non-zero doping: Cooper pairs have room to move and condense at low temperature (old `RVB' notion: Anderson, Kivelson et al)

Equivalently holes move coherently in background of paired spins

==> Within this picture regard as doped `spin liquid' Mott insulator

Theoretical strategy behind spin-liquid based approach



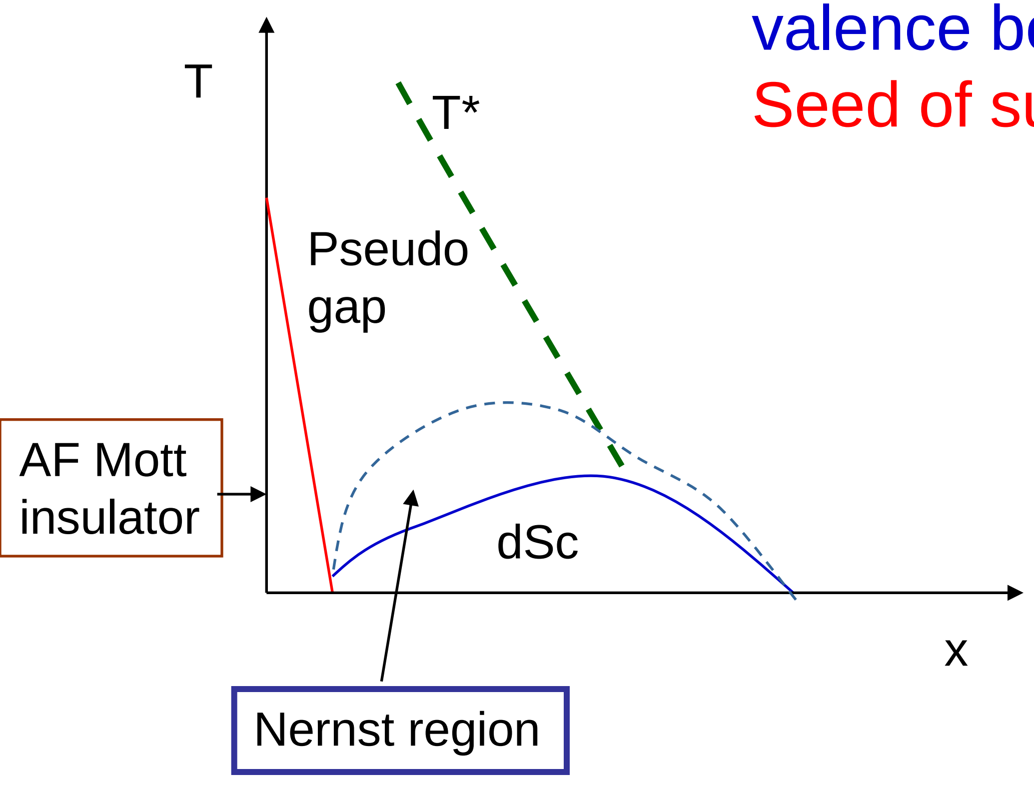
g = frustration/ring exchange,….

T*≈ spins pair into valence bond singlets

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

Structure and (quantum) dynamics of valence bond singlets?

Seed of superconductivity?

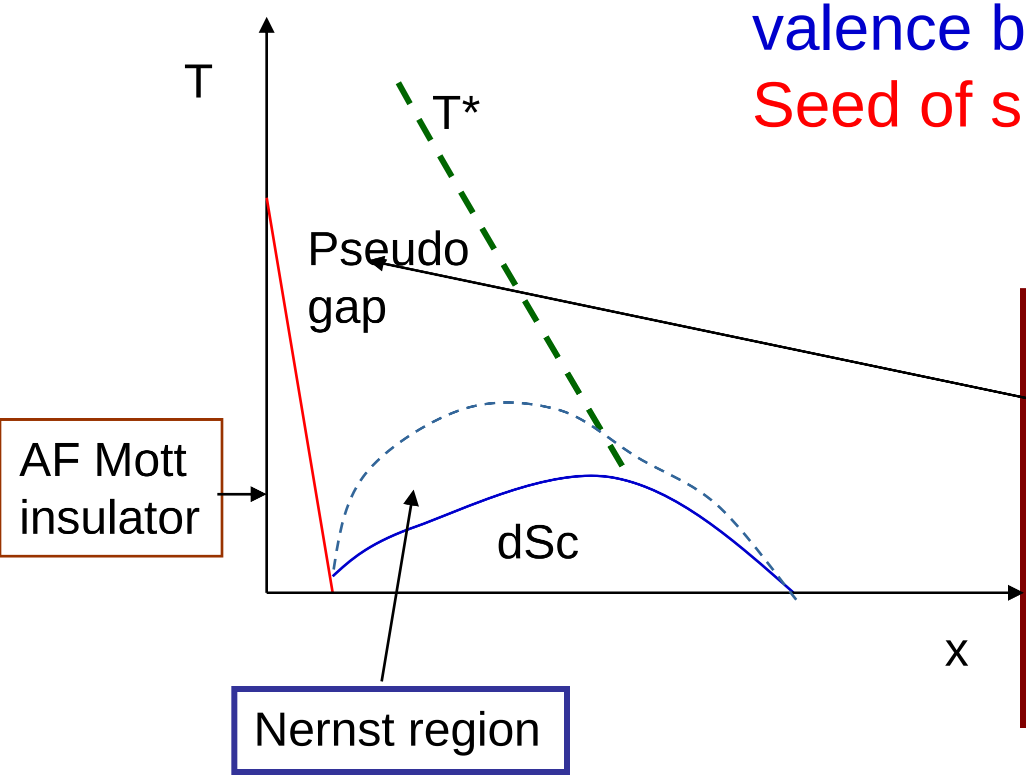


T*≈ spins pair into valence bond singlets

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

Structure and (quantum) dynamics of valence bond singlets?

Seed of superconductivity?



Spin physics in

high-T pseudogap regime

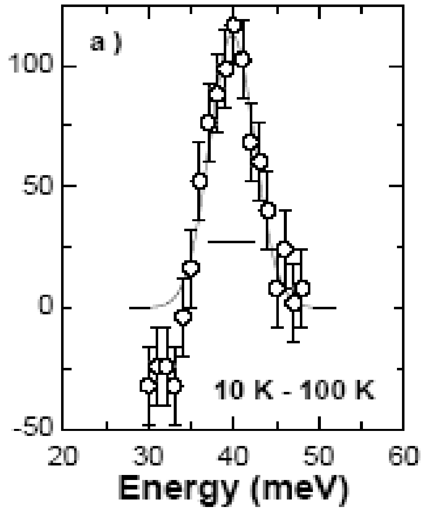
- reflect character of hypothesized ``parent”
spin liquid.

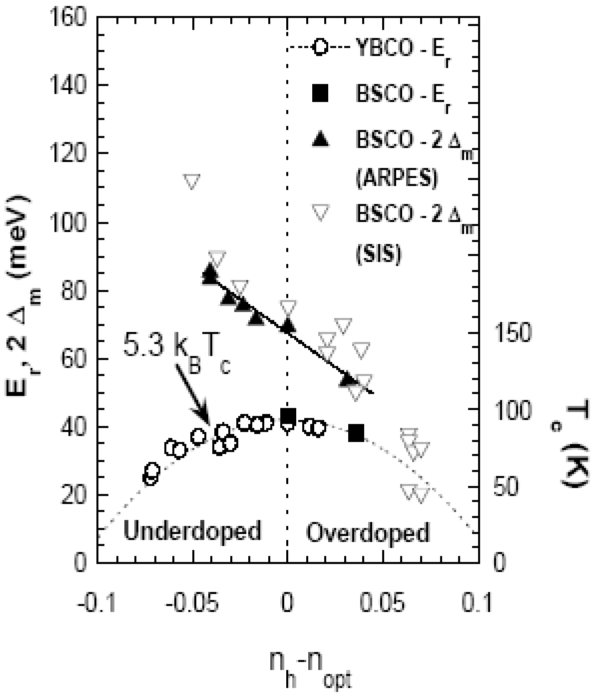
What about antiferromagnetism?

What about antiferromagnetism?

- Hints from experiment – neutron resonance peak that softens with decreasing doping

Optimally doped YBCO at (π, π)





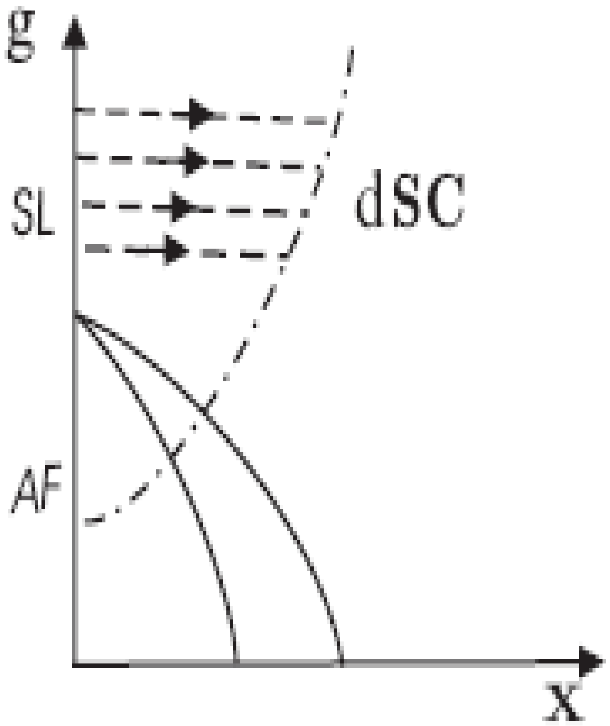
Interpret: soft mode of magnetic long range order?

Morr, Pines '98
M. Vojta et al '00

Resonance as soft mode:
implications for spin liquid based approach

Parent spin liquid connected to Neel through second order phase transition.

Decreasing x
==> corresponding parent states are closer to transition
to Neel.



Old quantum magnetism folklore

- Collinear Neel not connected to spin liquid thru 2nd order transition in 2d
- Noncollinear Neel → spin liquid can result.

Theoretical basis: Large-N calculations, quantum dimer models, etc.

Apparent difficulty for spin liquid based approach in cuprates…….

Old quantum magnetism folklore

- Collinear Neel not connected to spin liquid thru 2^{nd} order transition in 2d
- Noncollinear Neel – spin liquid can result.

Theoretical basis: Large-N calculations, quantum dimer models, etc.

Apparent difficulty for spin liquid based approach in cuprates…….

REVISIT

Hints from experiment for certain kind of parent spin liquid which escapes this restriction. Folklore did not consider this kind!

Guidance from experiments

- Many different experiments: Gapless nodal quasiparticles in superconducting state that survive at lowest dopings.

- Suggests studying parent spin liquids which already have built-in nodal excitations that can evolve into fermionic quasiparticles with doping.

- Such spin liquids exist (at least in theoryland!)

Most attractive current possibility: gapless U(1) spin liquids

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

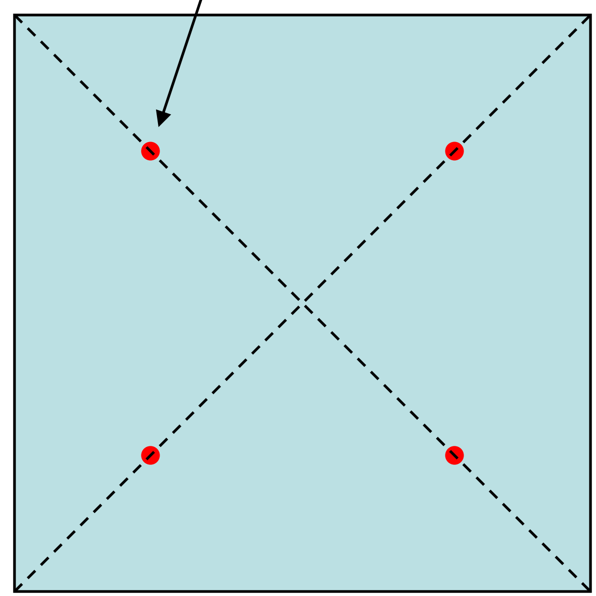
Mean field: Spinons (f) with hopping and d-wave pairing.

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

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

($\Delta_{rr'}$: 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:

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

This talk:

1. How to tell?

Search for unique signatures in structure of parent spin liquid.

2. Accomodating magnetism and the resonance peak.

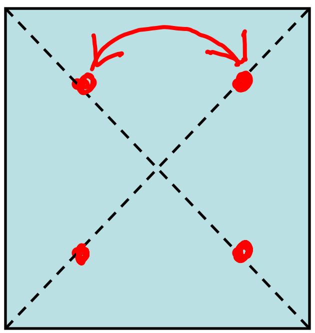
Low energy structure of the dRVB algebraic spin liquid

- SU(2) spin rotation

  +

rotation between 2 spinon nodes

enlarge* → SU(4)



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

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

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

*evidence from large-N

Other symmetries

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

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

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

$(\vec{e}, b)$: 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

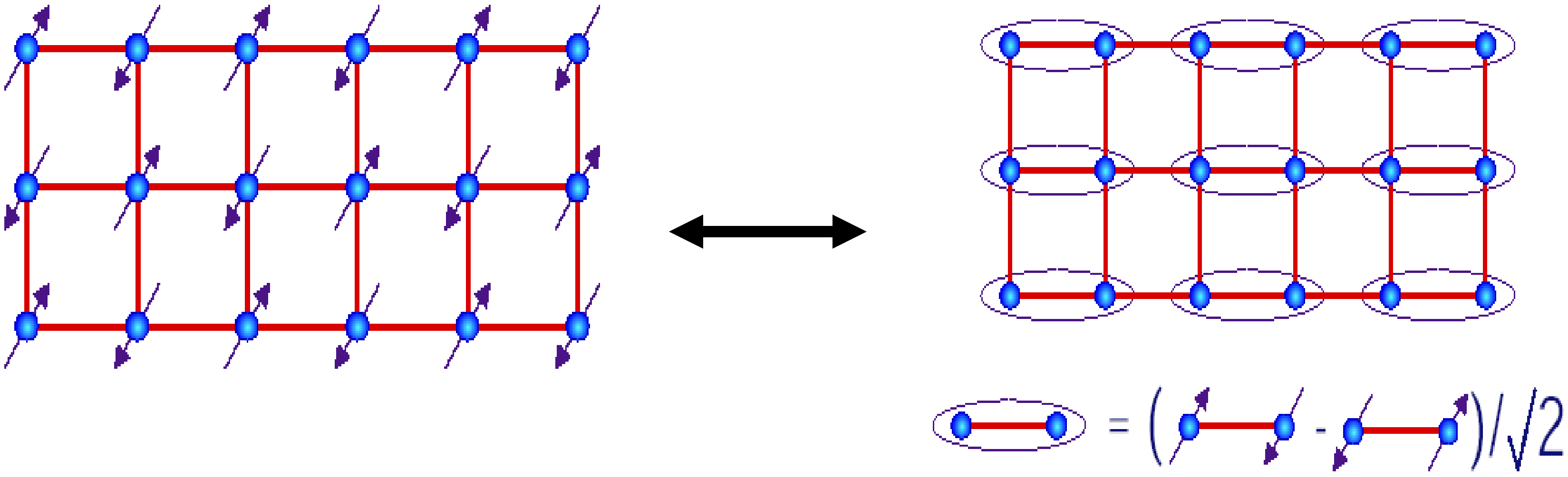
- identical slow power law for variety of other correlations (Hermele et al, 05)

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

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

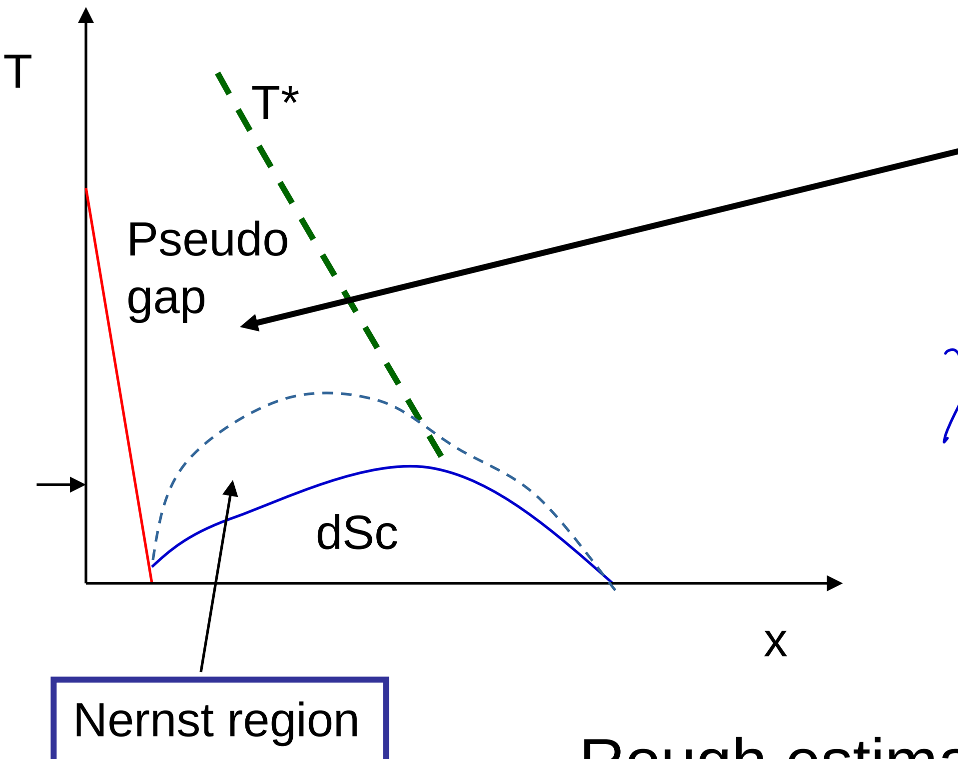
Example – Neel and dimer correlations

- 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

Some implications of scaling

$$\chi''_L(\omega, T) = \int d^2q \; \chi''(q, \omega, T)$$

$$\sim \omega^{\eta} F(\omega/T)$$

$$\Rightarrow \left(\frac{1}{T_1 T}\right)_{Cu} \sim \frac{1}{T^{1-\eta}}$$

But static uniform susceptibility $\chi_u \sim T$

$(\Rightarrow$ Knight shift $K \sim T)$

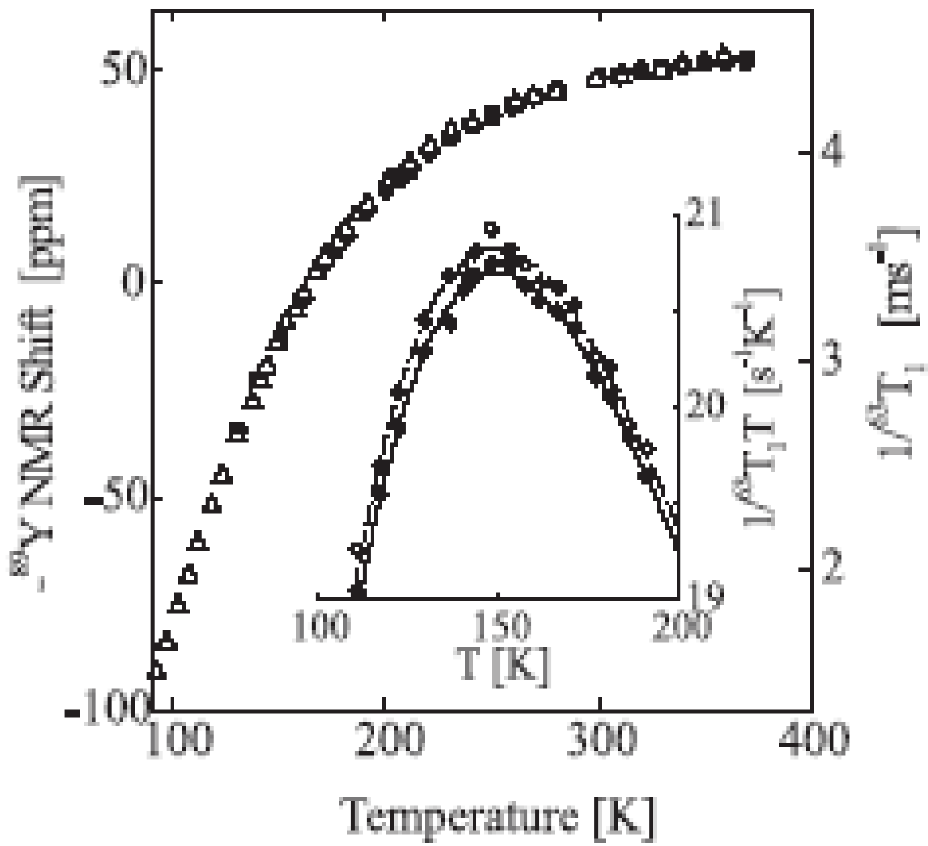
Evidence from NMR?

Underdoped $YBa_2Cu_4O_8$

$K \searrow$ as $T \searrow$

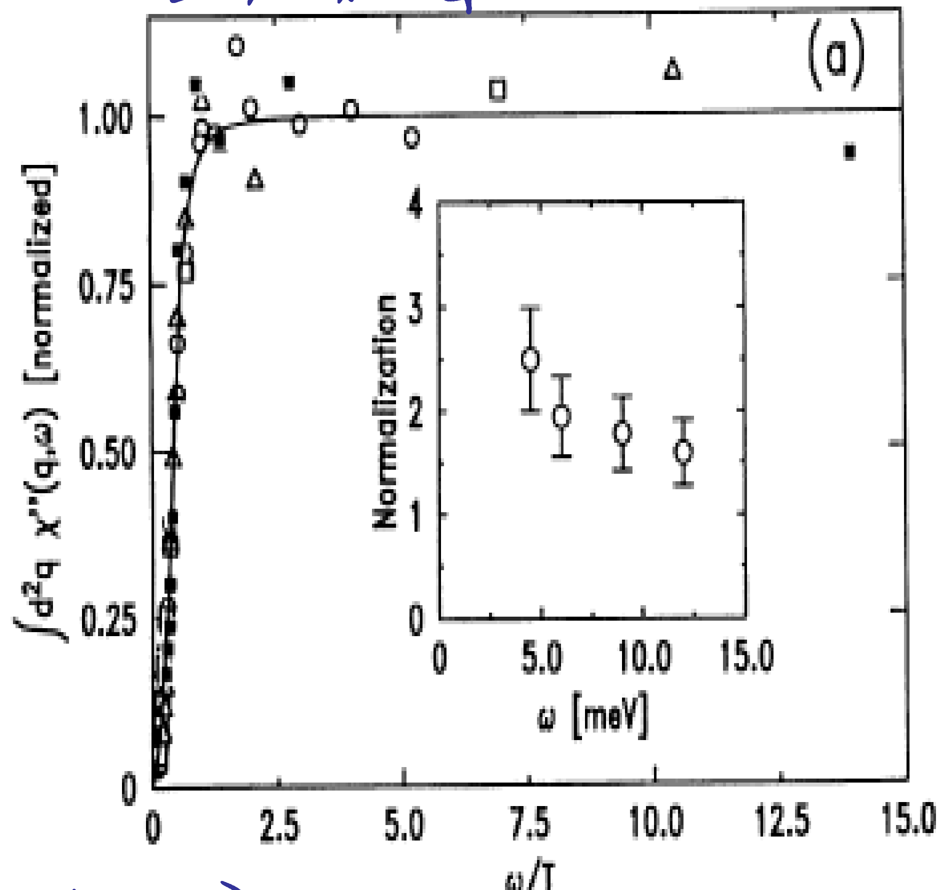
$\left(\frac{1}{T_1 T}\right)_{Cu} \nearrow$ as $T \searrow$

for $T \gtrsim 150$ K



Scaling in inelastic neutron scattering?

$La_{2-x}Sr_xCuO_4$ Keimer et. al. '91

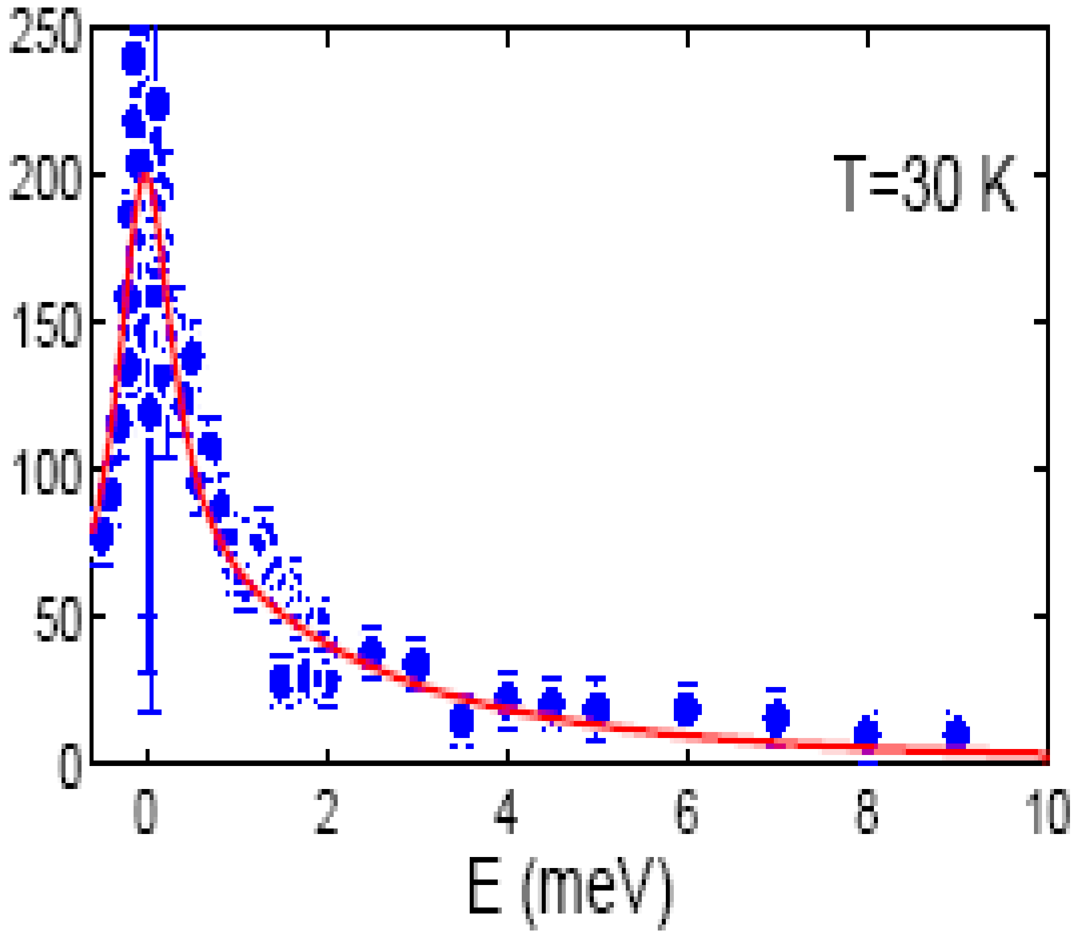


$\chi_L''(\omega, T) \sim \omega^\eta F(\omega/T)$

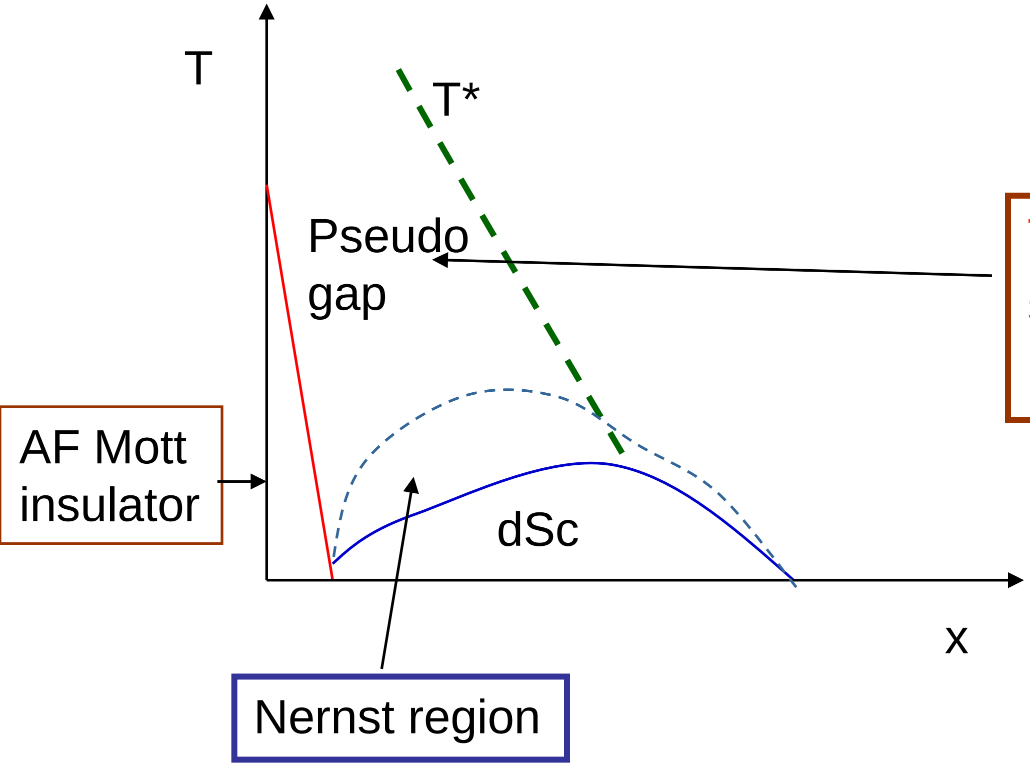
Prefactor decreases with ω unlike "critical" scaling form!

Similar data on $LaCu_{2-x}Li_xO_4$ (Bao et. al. 2002), underdoped YBCO (Stock et. al. 2005)

Inelastic neutron scattering in very underdoped YBCO (Tc = 18 K)



Issue for future experiments



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

Accomodating magnetism and the resonance peak -second order Neel-spin liquid transition

Mean field theory

$$H_{MF} = -\sum_{\langle rr' \rangle} t_{rr'} \left(f_r^\dagger f_{r'} + h.c. \right) + \Delta_{rr'} \left(f_{r\uparrow} f_{r'\downarrow} - f_{r\downarrow} f_{r'\uparrow} \right)$$

$$- \frac{4N}{g} \sum_r f_r^\dagger \sigma^z f_r$$

$$N = \epsilon_r \left\langle f_r^\dagger \frac{\sigma^z}{2} f_r \right\rangle \qquad \left(\epsilon_r = (-1)^{x+y} \right)$$

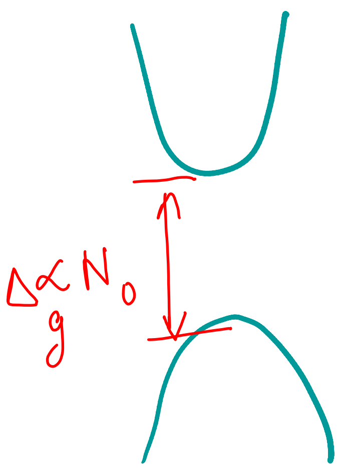
$= 0$ for $g <$ some g_c

$\neq 0$ for $g > g_c$

Mean field description of Neel state

Neel ordering – a spin density wave formed out of spinons

Mean field spectrum



Spinons gapped by (π, π) Neel order

– no spinons at low energy!

Beyond mean field in Neel state

Perturbative fluctuations - (i) gapless spin waves

(ii) gapless photon

$$S_{eff} \sim \int d^3x \left(\partial_\mu \vec{N}_\perp\right)^2 + \left(\epsilon_{\mu\nu\lambda}\partial_\nu a_\lambda\right)^2$$

Also spinons only gapped, still part of spectrum!

$\Rightarrow$ NOT the conventional magnetic state

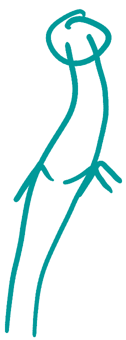
- a "fractionalized" antiferromagnet (U(1) AF*)

IS THIS A PROBLEM?

Beyond mean field (cont'd)

Spinon confinement

Include space-time monopoles of U(1) gauge field



2π -flux

Standard calculation

- photon gets a gap
- spinons "confined", disappear from spectrum!

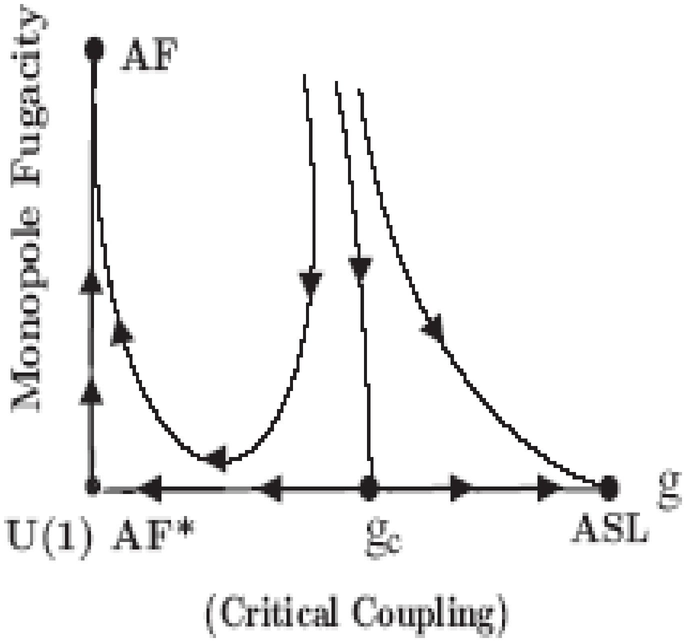
$\Rightarrow$ Recover conventional antiferromagnetic state!

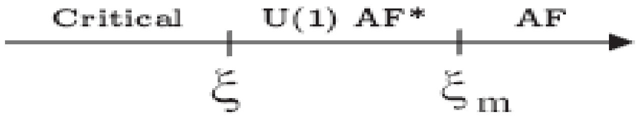
Neel-spin liquid transition

Crucial assumption: Monopoles irrelevant both at ASL and critical fixed points.

⇒monopoles dangerously irrelevant in Neel side.

⇒two diverging length/time scales





Critical properties

Continuum field theory

$$S = \int d^3x \; \bar{\psi}\left(i\partial\!\!\!/ - a\!\!\!/\right)\psi + i\lambda \vec{N}\cdot\bar{\psi}\frac{\vec{\sigma}^{\mu^2}}{2}\psi + \left(\epsilon_{\mu\nu\lambda}\partial_\nu a_\lambda\right)^2$$

$$+ \left(\partial_\mu \vec{N}\right)^2 + r\vec{N}^2 + u\vec{N}^4$$

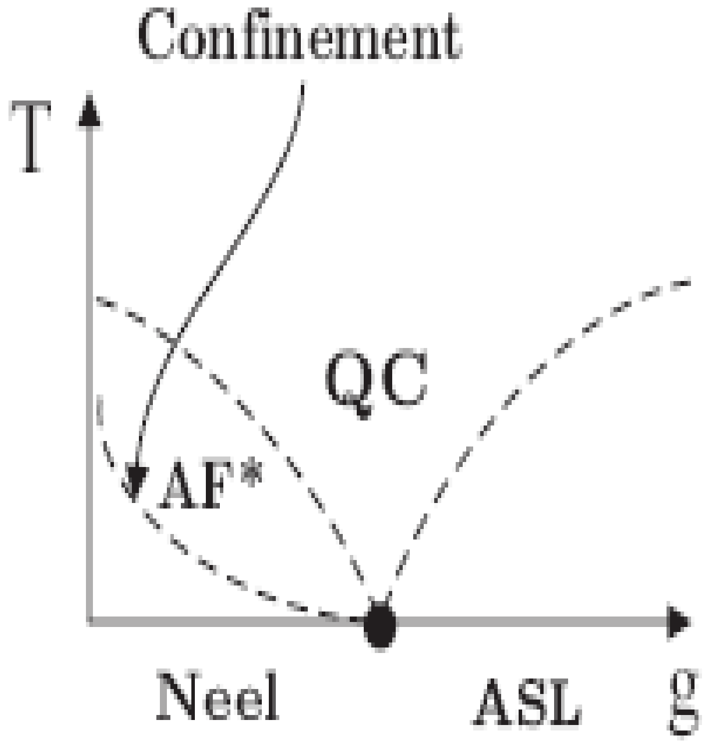
Study by ϵ-expansion – exponents etc to $o(\epsilon)$

Note: (i) Critical fixed point relativistic at $o(\epsilon)$

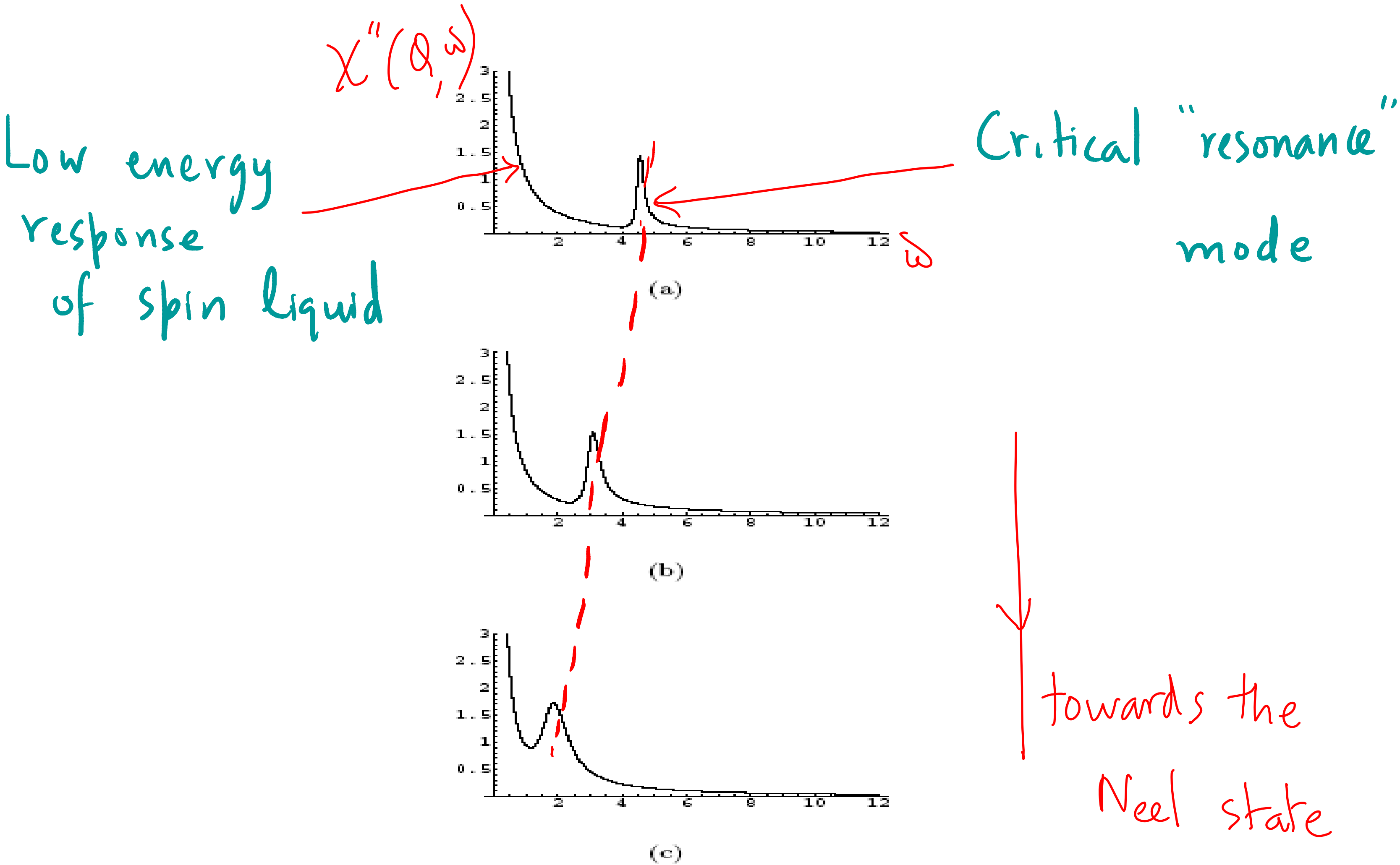
(ii) Symmetry $SU(2) \times U(1) \times U(1)_{\text{gauge}}$ at critical fixed point

$SU(2)$ ↗ spin; $U(1)$ ↗ "VBS"

Phase diagram/crossovers



Precursor fluctuations in spin liquid

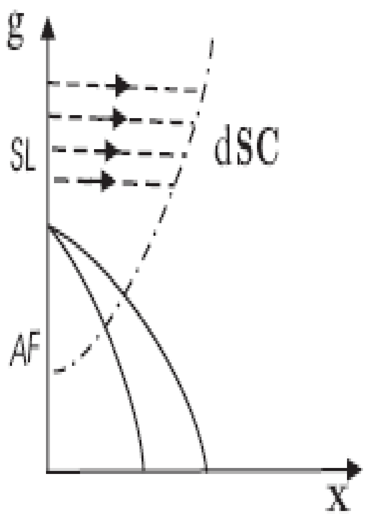


Connection to experiments
- resonance peak in doped system

Spinons → fermionic "BCS" quasiparticles of dSC

Gauge field gapped due to holon condensation

⇒ in magnetic response (π, π) peak is prominent & softens as $x \searrow$



Background - "particle-hole" continuum of fermionic quasiparticles (well described by RPA (Eg: Abanov, Chubukov '99, Norman '00, ...))

Resonance peak as triplet `exciton' of spinons

- Two previous interpretations of resonance

(i) soft mode of magnetic LRO in insulator (Morr, Pines '98, M. Vojta et. al. '00)

Natural explanation of doping dependence; difficulties with incomennsurate structure below the peak.

(ii) triplet spin exciton of weakly interacting fermionic BCS quasiparticles

Understand incommensurate structure as p/h triplet continuum; resonance is bound state but doping dependence not so naturally understood.

(Abanov, Chubukov '99, Normand, ...)

Our interpretation – unified version of these two (best of both worlds)

A triplet exciton of spinons

$\Rightarrow$ incommensurate structure, resonance and doping dependence all understood at least qualitatively.

Cuprates as doped dRVB spin liquids - pros and cons

PROS	CONS
Build in proximity to Mott -	
Existence of spin gap	
dSc with nodal quasiparticles	
	Connection to antiferromagnetism
	Nature of charge transport in non-SC state
	Doping dependence of
	Fermi arcs in ARPES
	Recovering band structure
Understand phonon effects?	

Summary

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

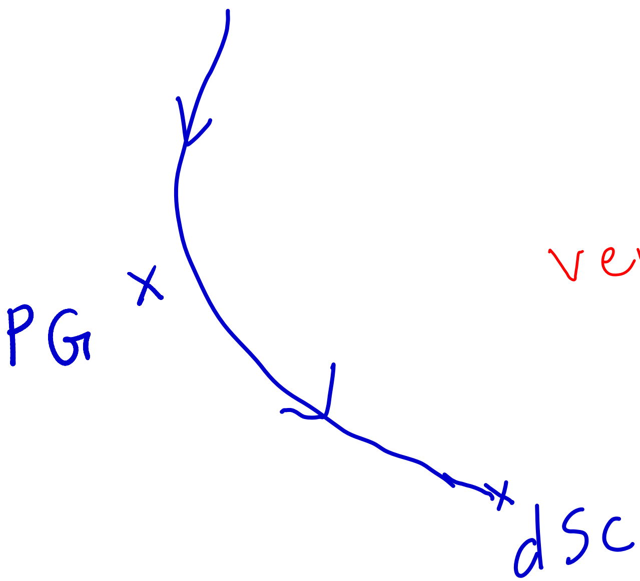
- Spin liquid physics most likely to reveal itself in high-T pseudogap regime.

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

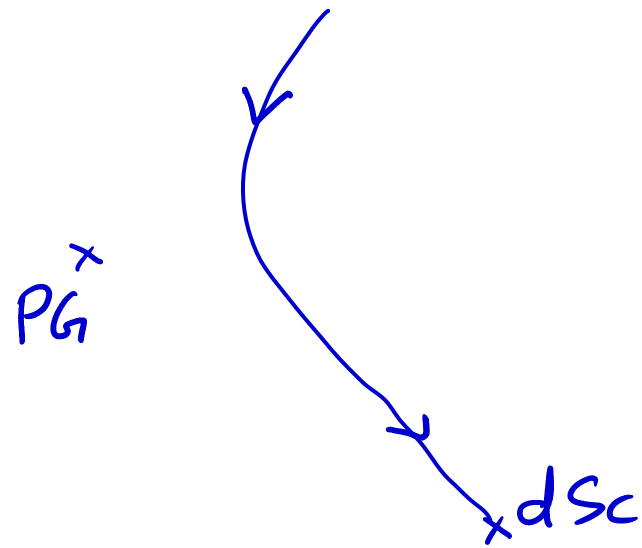
- Neutron resonance peak – key connection to antiferromagnetism.

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?