Quantum criticality beyond the Landau-Ginzburg-Wilson paradigm

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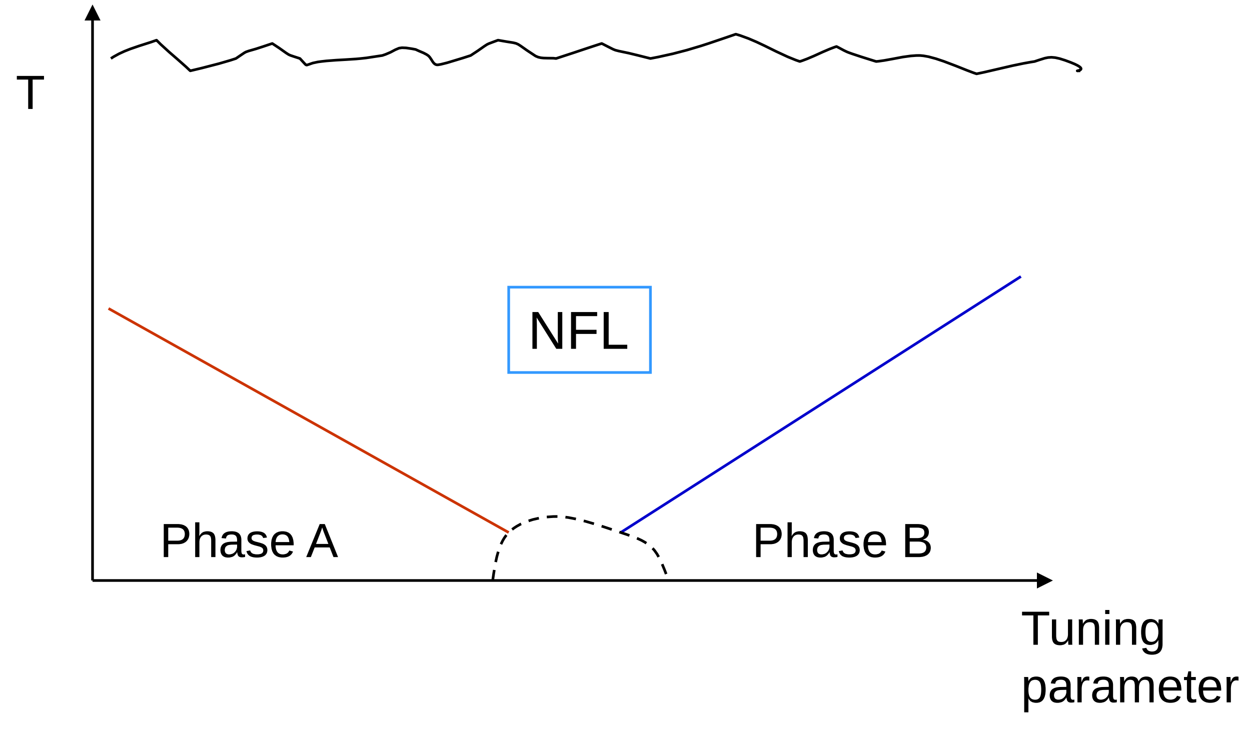
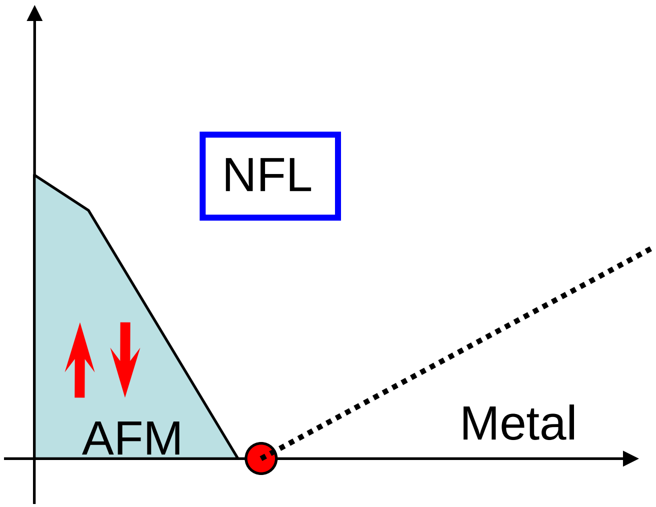
Competing orders and non-fermi liquids(NFL) in correlated electron systems



Example: Magnetic ordering in heavy electron systems

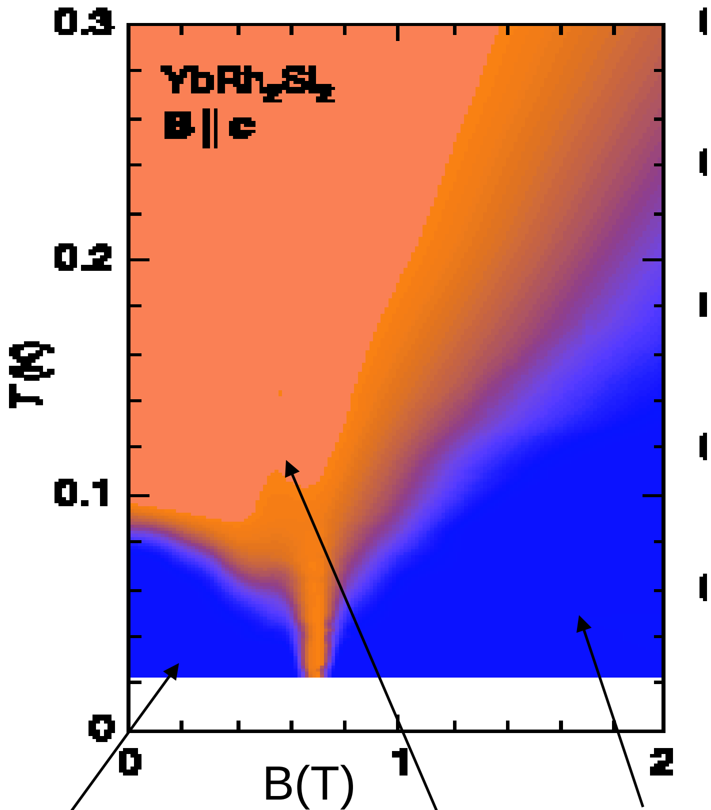
$CePd_2Si_2$, $CeCu_{6-x}Au_x$, $YbRh_2Si_2$,……



Model as lattice of localized magnetic moments coupled to conduction electrons by spin exchange (the Kondo lattice)

Representative data on $YbRh_2Si_2$

Custers et al, Nature, 2003

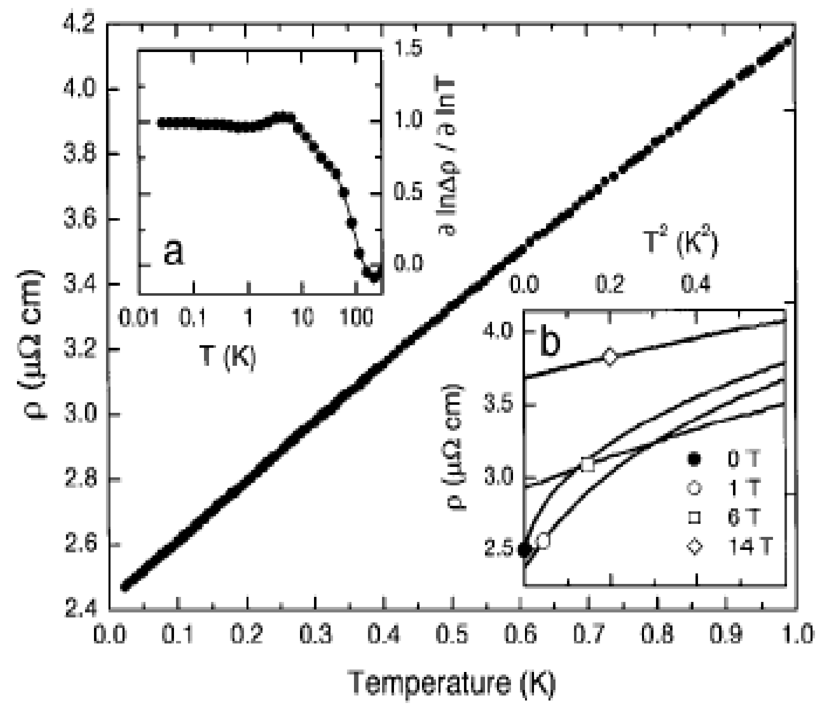


Magnetic metal

Non fermi liquid

Fermi liquid

Trovarelli et al, PRL 2000



T-dependence of resistivity at critical point: ρ(T) ~ T for three decades in temperature!

``Classical'' assumptions

1. NFL: Universal physics associated with quantum critical point between phases A and B.

2. Landau: Universal critical singularities ~ fluctuations of order parameter for transition between phases A and B.

Try to play Landau versus Landau.

- However ``classical'' assumptions have difficulty with producing NFL at quantum critical points!!

Eg: Landauesque theory of magnetic ordering

in metallic environment (``Moriya-Hertz-Millis theory'') spectacularly inconsistent with NFL near heavy fermion critical points.

Reexamine ``classical'' assumptions

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KEEP!

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KEEP!

2. Landau: Universal critical singularities ~ fluctuations of order parameter for transition between phases A and B.

??IS THIS REALLY CORRECT??

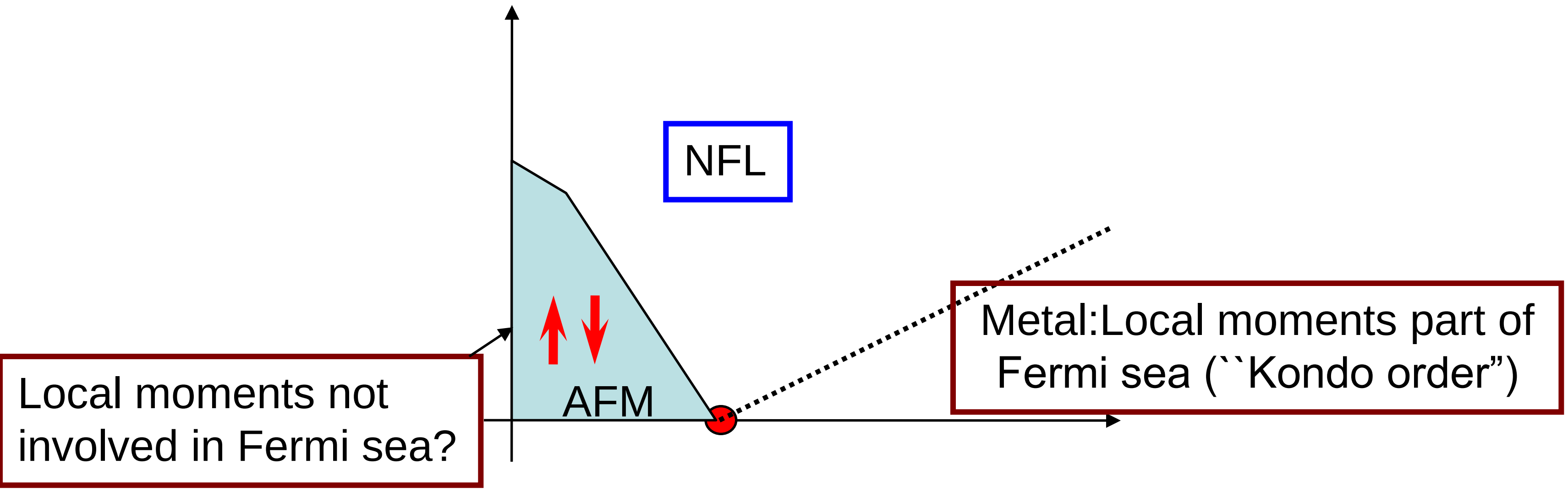
(Radical) alternate to classical assumptions

- Universal singularity at some quantum critical points: Not due to fluctuations of natural order parameter but due to some other competing effects.

- Order parameters/broken symmetries of phases A and B mask this basic competition.

=> Physics beyond Landau-Ginzburg-Wilson paradigm of phase transitions.

NFL in heavy electron systems

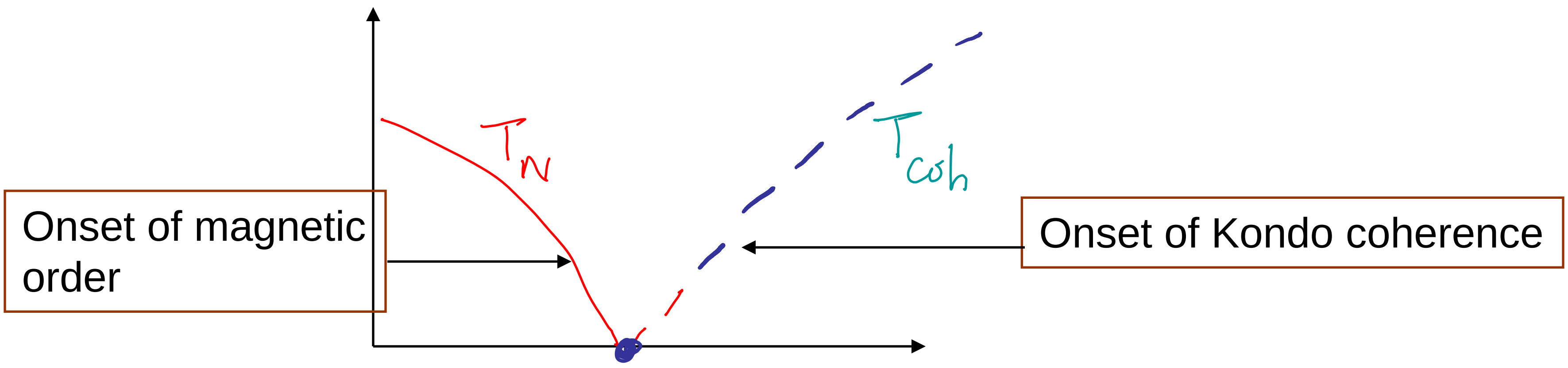


Critical NFL physics: are fluctuations of loss of local moments from Fermi sea important? (Si, Coleman,……)

Is magnetic ordering itself a distraction?? (TS, Vojta,Sachdev)

Perhaps NFL only due to fluctuations of ``Kondo order” ??

Questions



1. Is such a second order transition generically possible?
(Loss of magnetic order happens at same point as onset of ``Kondo'' order)

2. Theoretical description?

3. Will it reproduce observed non-fermi liquid behaviour?

Answers not known!!

General observations

- f-moments drop out of Fermi surface (⇔ change of electronic structure)

Associated time scale t_e.

- Onset of magnetic order

Associated time scale t_m.

Both time scales diverge if there is a critical point.

General observations

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Associated time scale t_e.

- Onset of magnetic order

Associated time scale t_m.

Both time scales diverge if there is a critical point.

Suggestion: t_m diverges faster than t_e.

(electronic structure change first, magnetic order comes later)

Separation between two competing orders as a function of scale (rather than tuning parameter) might make second order transition possible.

Some implications

- ``Underlying'' transition: loss of participation of the f-electrons in forming the heavy fermi liquid.

(View as a Mott ``metal-insulator'' transition of f-band).

- Magnetic order: ``secondary'' effect – a low energy

complication once Kondo effect is suppressed.

- Non-fermi liquid due to fluctuations associated with change of electronic structure rather than those of magnetic order parameter.

$\Rightarrow$ PHYSICS BEYOND LANDAU-GINZBURG-WILSON PARADIGM FOR PHASE TRANSITIONS.

(Natural magnetic order parameter is a distraction).

This talk – more modest goal

- Are there any clearly demonstrable theoretical instances of such strong breakdown of Landau-Ginzburg-Wilson ideas at quantum phase transitions?

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- Are there any clearly demonstrable theoretical instances of such strong breakdown of Landau-Ginzburg-Wilson ideas at quantum phase transitions?

Study phase transitions in insulating quantum magnets

- Good theoretical laboratory for physics of phase transitions/competing orders.

Highlights

- Failure of Landau paradigm at (certain) quantum transitions

- Emergence of `fractional' charge and gauge fields near quantum critical points between two CONVENTIONAL phases.

- ``Deconfined quantum criticality'' (made more precise later).

- Many lessons for competing order physics in correlated electron systems.

Phase transitions in quantum magnetism

$$H = J \sum_{\langle r r' \rangle} \vec{S}_r \cdot \vec{S}_{r'} + \ldots\ldots$$

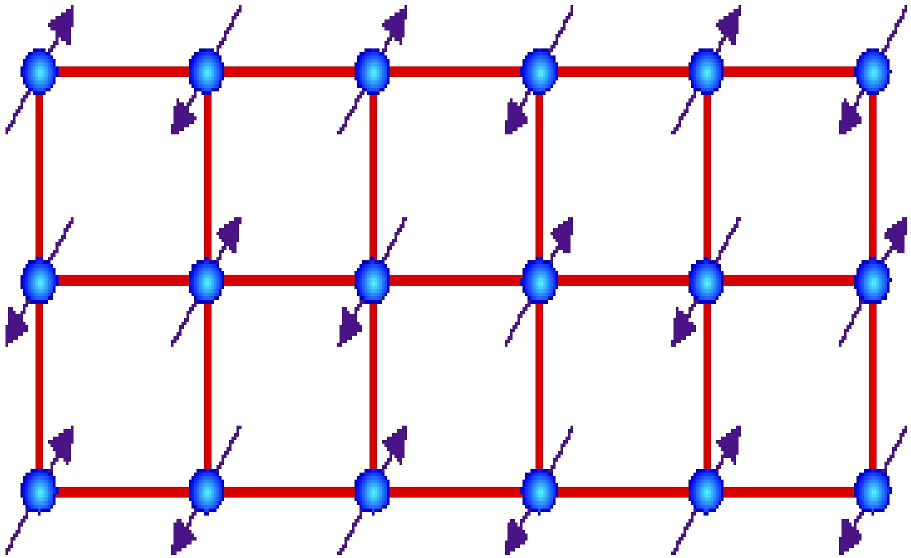
- Spin-1/2 quantum antiferromagnets on a square lattice.

- ``……” represent frustrating interactions that can be tuned to drive phase transitions.

(Eg: Next near neighbour exchange, ring exchange,…..).

Possible quantum phases

- Neel ordered state



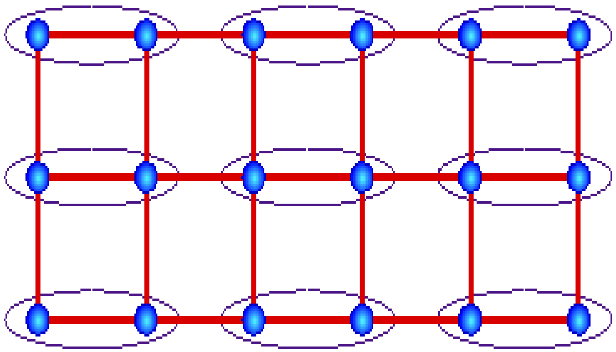
Possible quantum phases (contd)

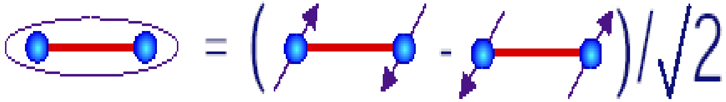
<u>QUANTUM PARAMAGNETS</u>

- Simplest: Valence bond solids.

- Ordered pattern of valence bonds breaks lattice translation symmetry.

- Elementary spinful excitations have S = 1 above spin gap.

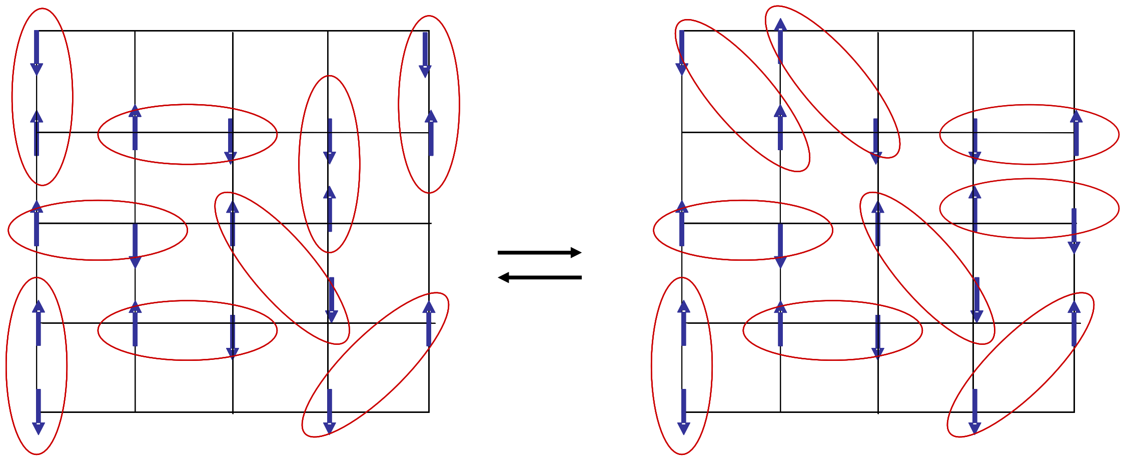




Possible phases (contd)

- Exotic quantum paramagnets – ``resonating valence bond liquids''.

- Fractional spin excitations, interesting topological structure.



Neel-valence bond solid(VBS) transition

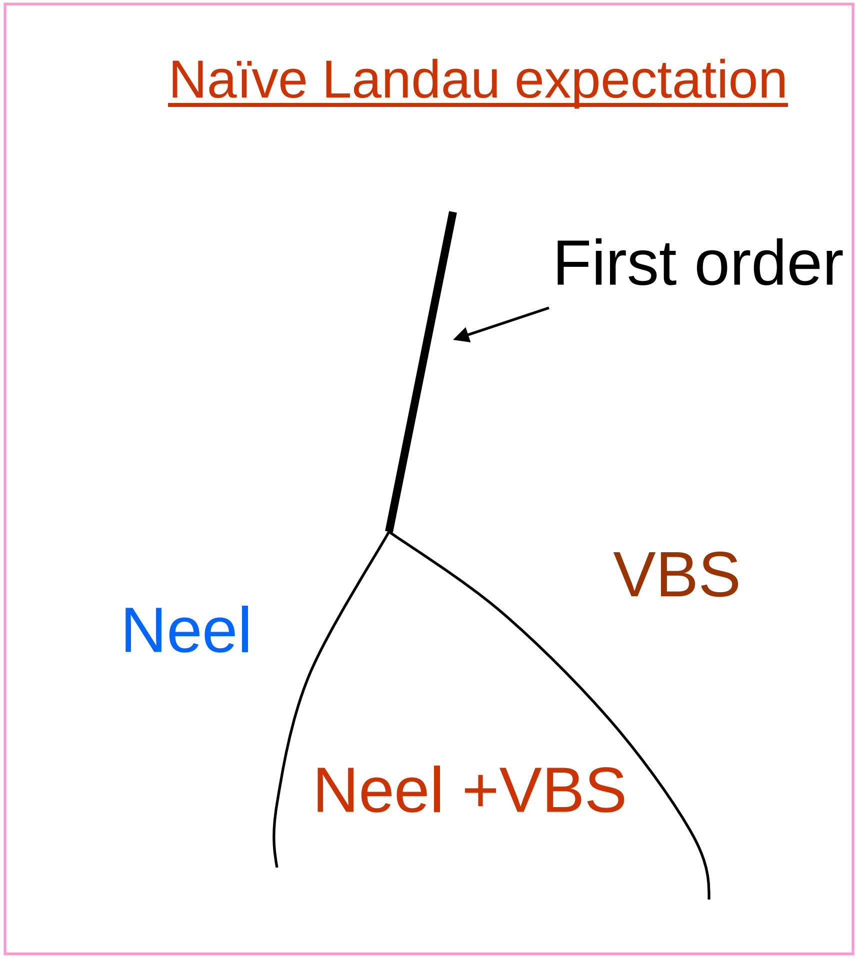
- Neel: Broken spin symmetry
- VBS: Broken lattice symmetry.

- Landau – Two independent order parameters.

- no generic direct second order transition.

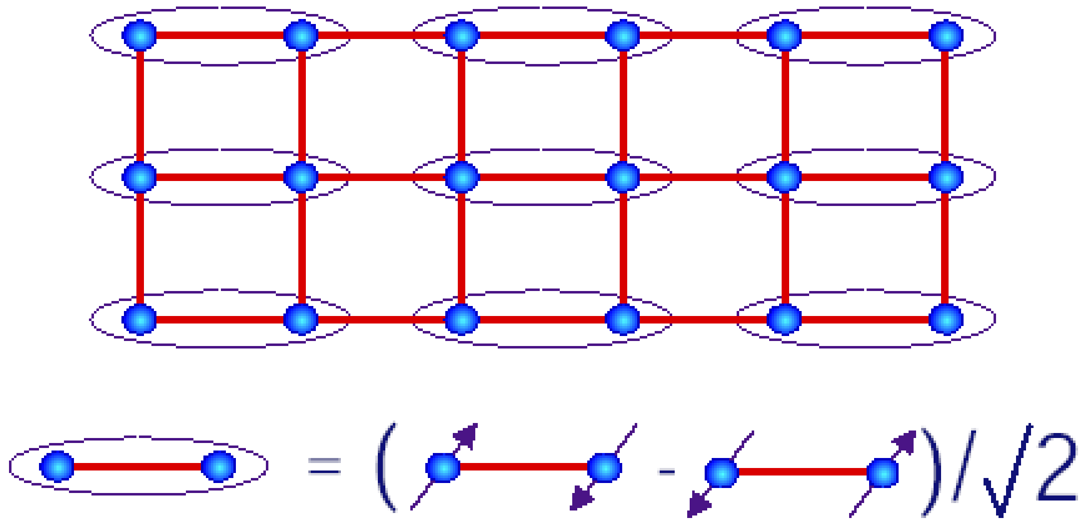
- either first order or phase coexistence.

This talk: Direct second order transition but with description not in terms of natural order parameter fields.

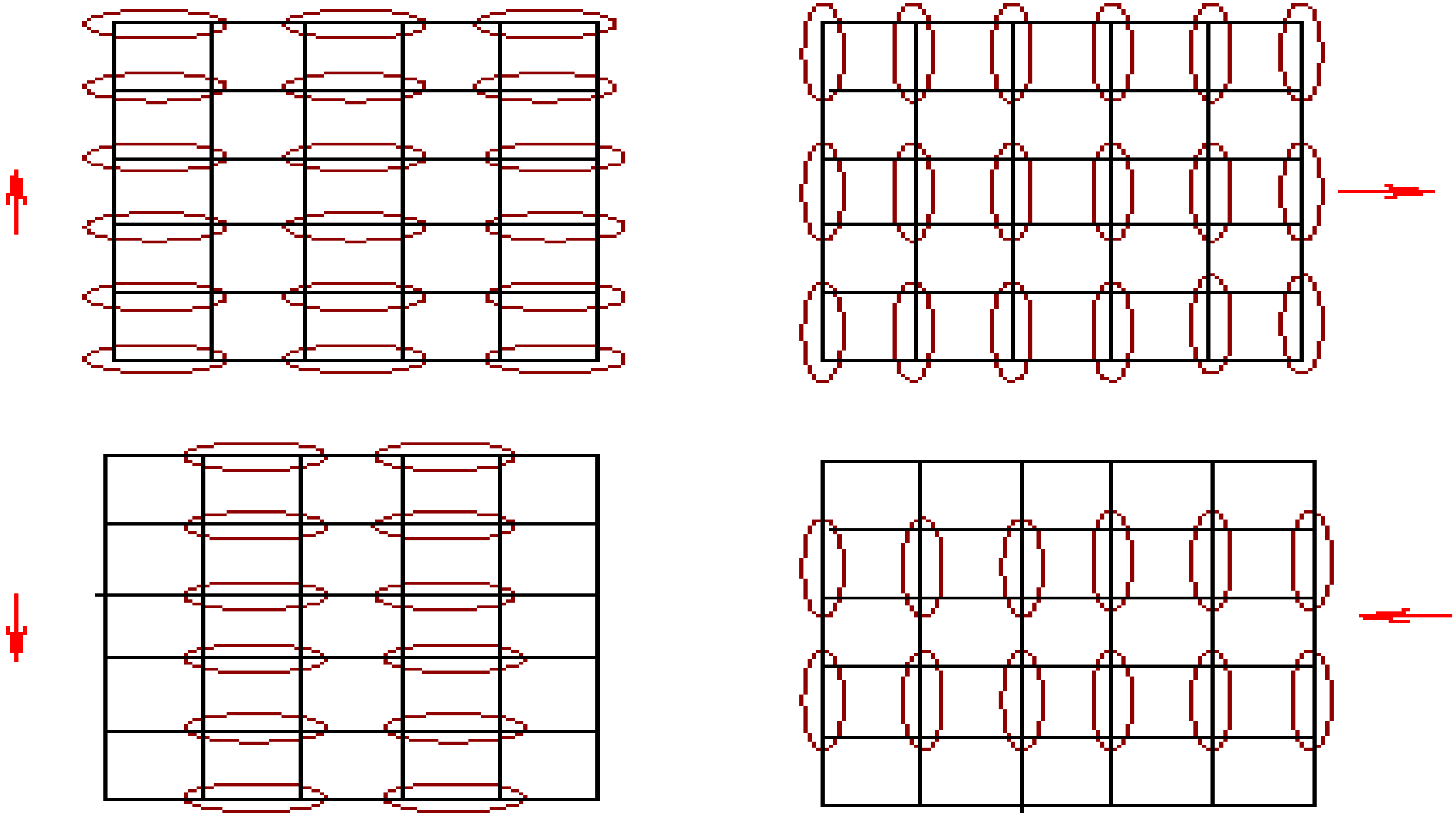


Broken symmetry in the valence bond solid(VBS) phase

Valence bond solid with spin gap.



Discrete Z_4 order parameter



Neel-Valence Bond Solid transition

- Naïve approaches fail

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

Attack from VBS ≠ Usual Z_4 transition in D = 3

(= XY universality class).

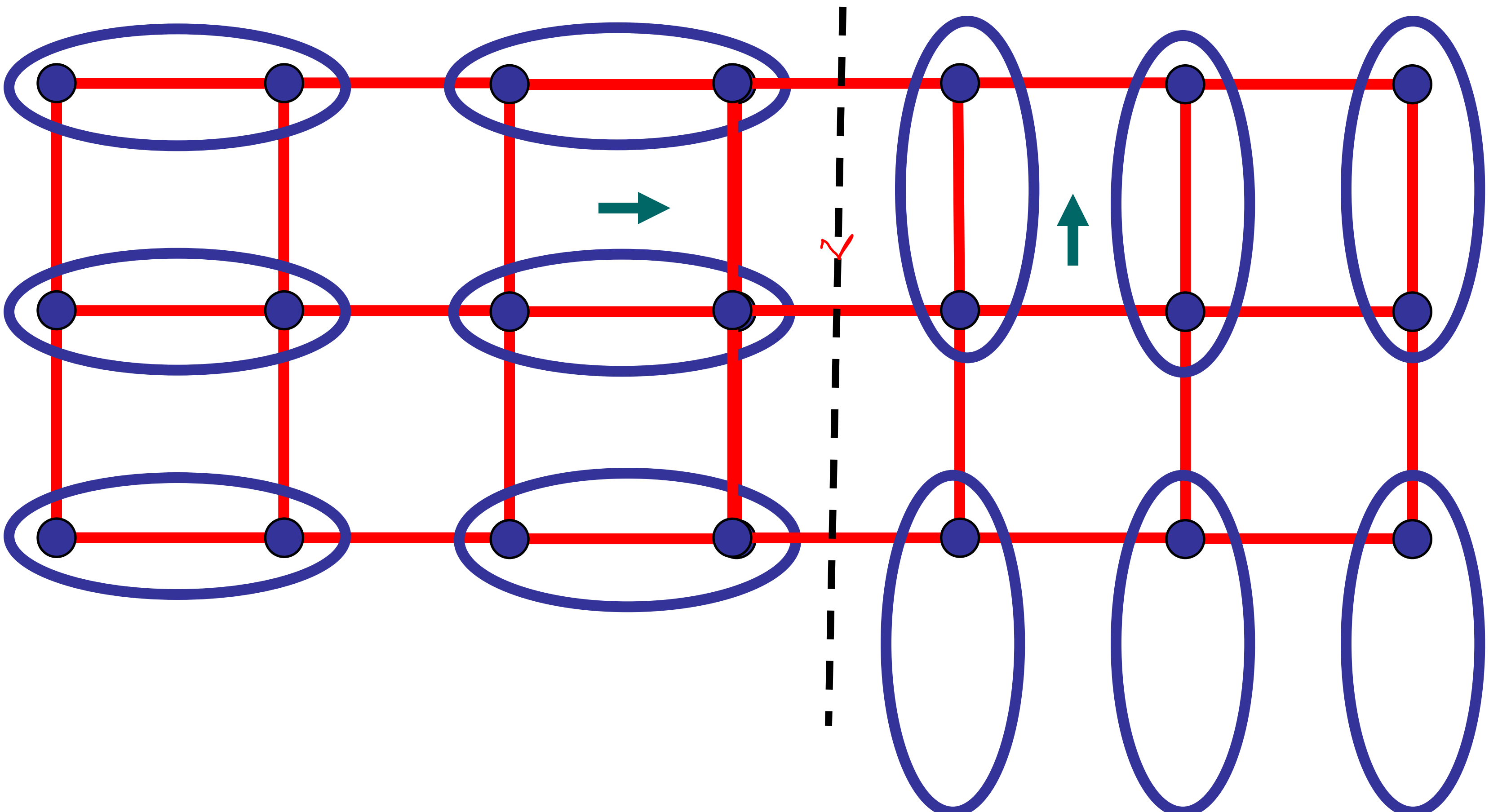
Why do these fail?

Topological defects carry non-trivial quantum numbers!

Attack from VBS (Levin, TS, ‘04)

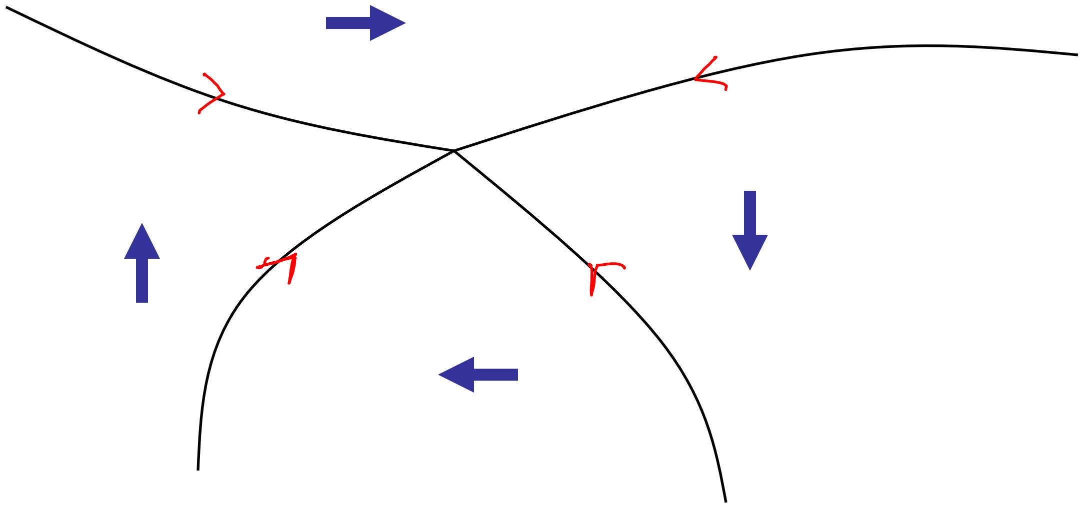
Topological defects in Z_4 order parameter

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

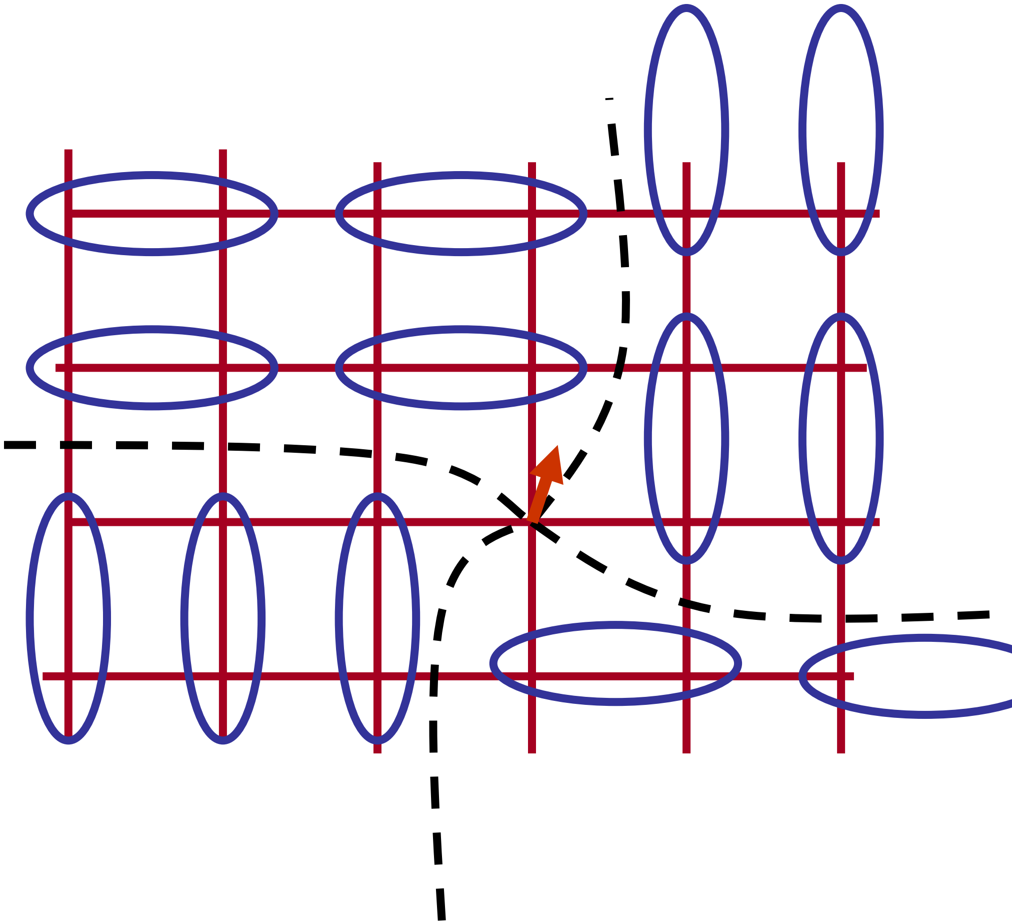


Z_4 domain walls and vortices

- 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 U(1) gauge field*.

*non-compact

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

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

$$+ (\varepsilon_{\mu\nu\lambda} \partial_\nu a_\lambda)^2$$

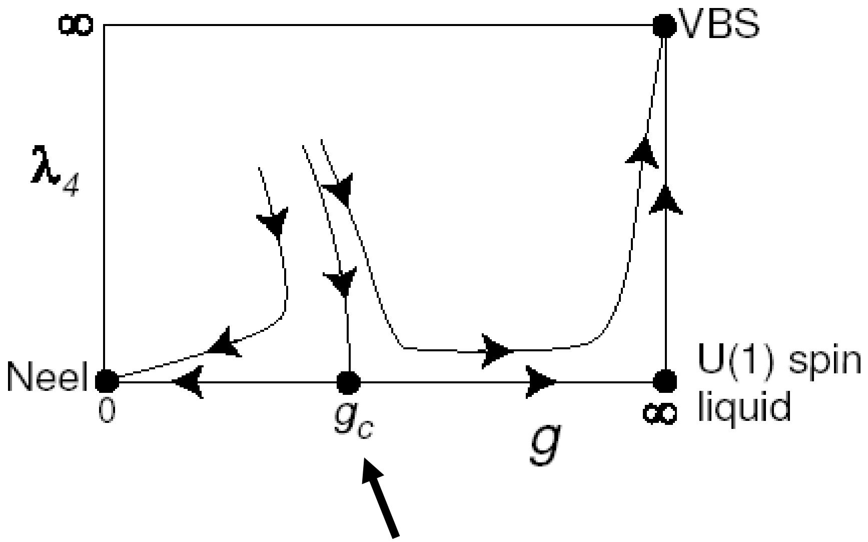
z = two-component spin-1/2 spinon field
a_μ = non-compact U(1) gauge field.
Distinct from usual O(3) or Z_4 critical theories*.

Theory not in terms of usual order parameter fields but involve spinons and gauge fields.

*Distinction with usual O(3) fixed point definitively established by detailed numerics (Motrunich,Vishwanath, '03)

Renormalization group flows

Clock anisotropy

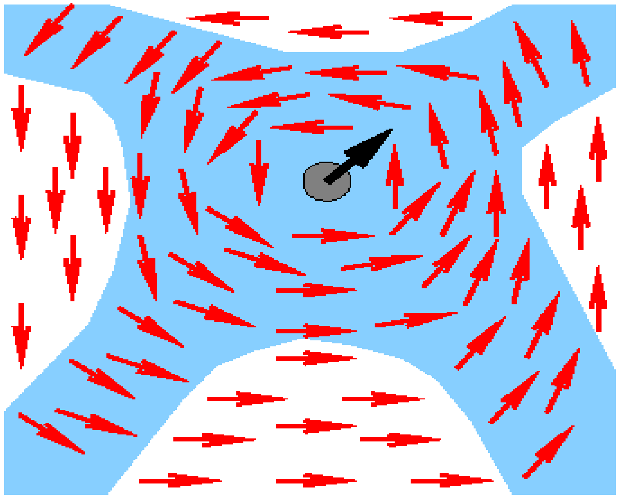


Deconfined critical fixed point

Clock anisotropy is ``dangerously irrelevant''.

Precise meaning of deconfinement

- Z_4 symmetry gets enlarged to XY



⇒ Domain walls get very thick and very cheap near the transition.

=> Domain wall energy not effective in confining Z_4 vortices (= spinons)

.

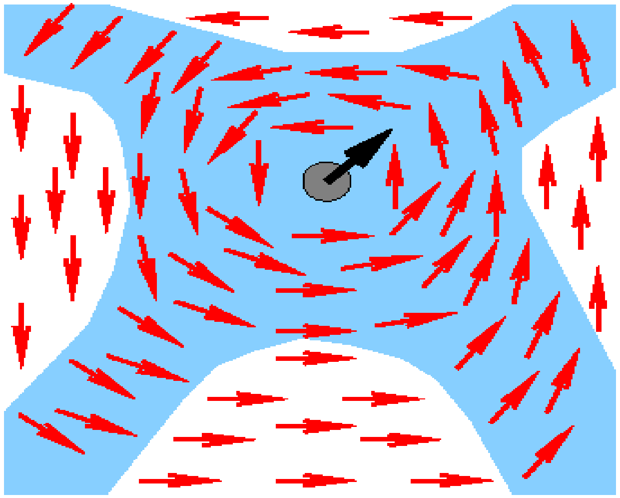
Formal: Extra global U(1) symmetry not present in microscopic model :

Two diverging length scales in paramagnet

ξ: spin correlation length
ξ_{VBS} : Domain wall thickness.

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

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



Extensions/generalizations

- Similar phenomena at other quantum transitions of spin-1/2 moments in d = 2

1. VBS- spin liquid (Senthil, Balents, Sachdev, Vishwanath, Fisher, '03)
2. Neel –spin liquid (Ghaemi, Senthil)
3. Certain VBS-VBS (Vishwanath, Balents, Senthil, '03; Fradkin, Huse, Moessner, Oganesyan, Sondhi, '03)

Apparently fairly common!

- Deconfined critical <u>phases</u> with gapless fermions coupled to gauge fields also exist in 2d quantum magnets (Hermele, Senthil, Fisher, Lee, Nagaosa, Wen, '04)

- interesting applications to cuprate theory.

Numerical/experimental sightings of Landau-forbidden transitions

Weak first order/second order transitions between two phases with very different broken symmetry surprisingly common….

Numerics (more in the next 2 talks)

Antiferromagnet – superconductor (Assaad et al 1996)

Superfluid – some kinds of charge density wave (Sandvik et al 2002)

J1-J2 spin-1/2 quantum AF on square lattice:

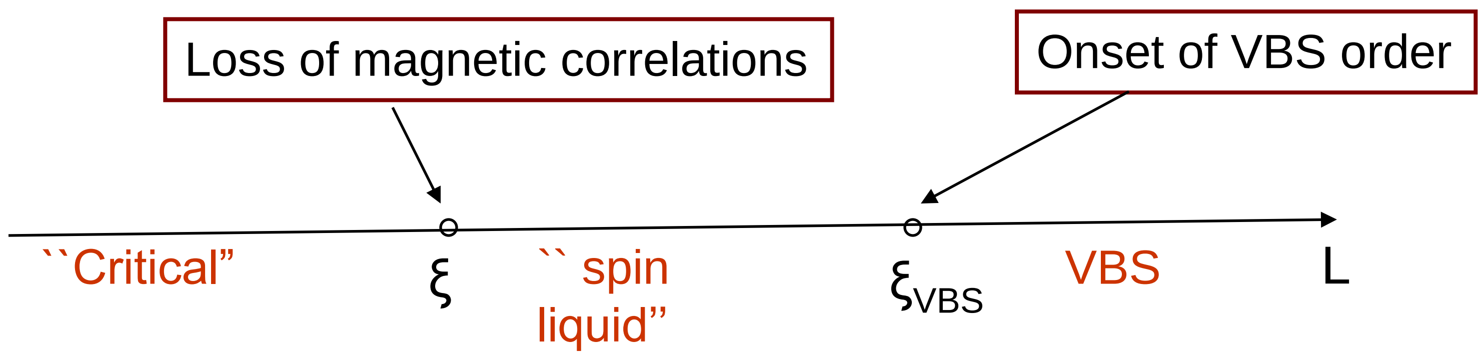
Second order Neel -VBS ? (Singh, Sushkov,…………….)

Experiments:

$UPt_{3-x}Pd_x$ SC – AF with increasing x. (Graf et al 2001)

Some lessons-I

Separation between the two competing orders
not as a function of tuning parameter but as a function of (length or time) scale (exactly as suggested near heavy fermion critical point)



Some lessons-II

- Striking ``non-fermi liquid'' (morally) physics at critical point between two competing orders.

Eg: At Neel-VBS, magnon spectral function is anamolously broad (roughly due to decay into spinons) as compared to usual critical points.

Most important lesson:

Failure of Landau paradigm – order parameter fluctuations do not capture true critical physics.

Caricature of phenomena suggested near heavy fermion critical points.

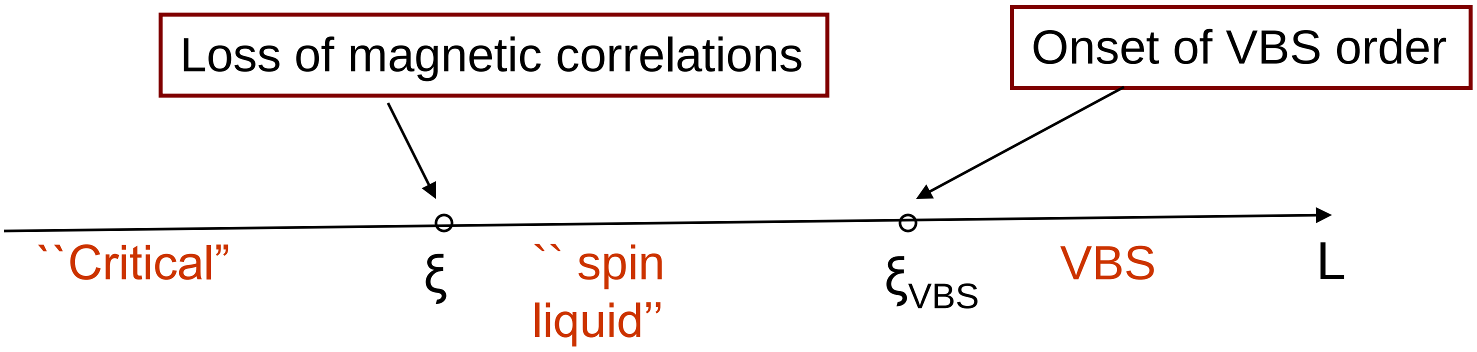
Experiments: Are there really two distinct time/length scales at heavy fermion critical points?

Summary and some lessons-I

- Direct 2nd order quantum transition between two phases with different competing orders possible

- Separation between the two competing orders

not as a function of tuning parameter but as a function of (length or time) scale



Summary and some lessons-II

- Striking ``non-fermi liquid'' (morally) physics at critical point between two competing orders.

Eg: At Neel-VBS, magnon spectral function is anamolously broad ($\eta \sim 0.6$)- roughly due to decay into spinons- as compared to usual critical points.