Quantum phase transitions out of the heavy fermi liquid

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Collaborators on related issues: Levin, Motrunich, Vishwanath, Balents, Fisher.

Luttinger's theorem for Fermi liquids

In a Fermi liquid, volume V_F of Fermi surface is set by electron density n independent of interaction strength.

$V_F = (2\pi)^d n/2$ (mod Brillouin zone volume).

Perturbative proof: Luttinger
Non-perturbative topological arguments:
Yamanaka, Oshikawa, Affleck (d = 1), Oshikawa (d > 1).

Oshikawa: Regard as ``topological quantization''.

Heavy fermion liquids

- Heavy fermion materials: Typically rare earth intermetallic compounds with strongly correlated half-filled

f-band weakly hybridized with conduction electron band.

- Describe by Anderson model

$$H = \sum_k \varepsilon_k c_k^+ c_k + \sum_k (\varepsilon_k^f - \mu_f) f_k^+ f_k$$

$$+ V \sum_r (c_r^+ f_r + f_r^+ c_r) + U \sum_r (f_r^+ f_r)^2$$

or in large - U limit by Kondo lattice model

$$H = \sum_k \varepsilon_k c_k^+ c_k + \frac{J_K}{2} \sum_r \vec{S}_r . c_r^+ \vec{\sigma} c_r$$

Luttinger's theorem in Kondo lattices

- Kondo lattice model admits a Fermi liquid phase.

(Denote ``Kondo liquid'').

- To satisfy Luttinger's theorem must include local moments in the count of conduction electron density

  ``Large'' Fermi surface

- Fermi liquid adiabatically connected to small U Anderson model.

- Understand through (i) slave particle mean field calculation

(Read et al, Millis et al)

(ii) Oshikawa topological argument.

Other known metallic states of Kondo lattice

- Magnetically ordered (typically antiferromagnetic) metal due to RKKY

Favored at small J_K (Doniach).

There are actually two distinct kinds of antiferromagnetic metals.

- Other broken symmetry states (SC, …..)

Two kinds of antiferromagnetic metals in Kondo lattices

(A): ``Local moment magnetic metal''

Ordering of local moments (due to intermoment exchange).

c-electrons ≈ decoupled from local moments.

Typically large (staggered) moment.

``f-electrons do not participate in Fermi surface''.

(B): ``Spin density wave metal''

SDW instability of heavy fermi liquid with large fermi surface.

c- and f-electrons strongly coupled.

Typically weak moment.

``f-electrons participate in Fermi surface''.

- Two kinds of magnetic metals often sharply distinct!!

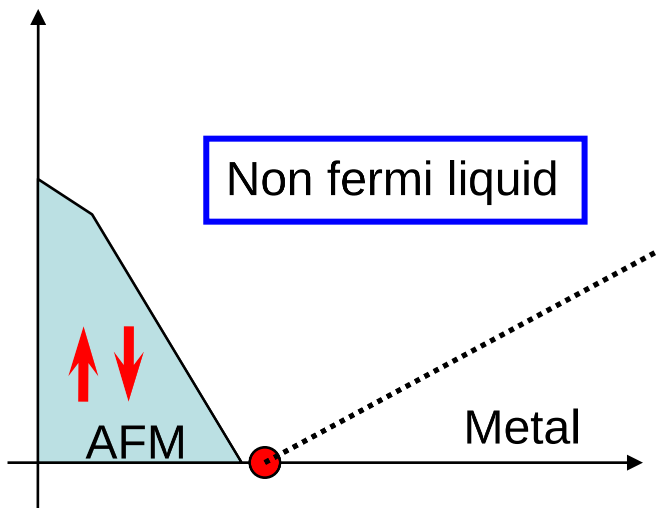
- Distinction in topology of Fermi surface –

Evolution from one to other occurs through a quantum phase transition where the Fermi surface topology changes

(Lifshitz transition)

Magnetic ordering in heavy electron systems

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



Non fermi liquid: diverging γ coefficient, T dependence of resistivity, scaling of spin fluctuation spectrum with ω/T, ………….

``Classical'' assumption

1. NFL: Universal physics associated with quantum critical point between heavy fermi liquid and magnetic metal

2. Landau: Universal critical singularities ~ fluctuations of natural magnetic order parameter for transition

Try to play Landau versus Landau.

Which magnetic metal?

1. Heavy fermi liquid – SDW metal:

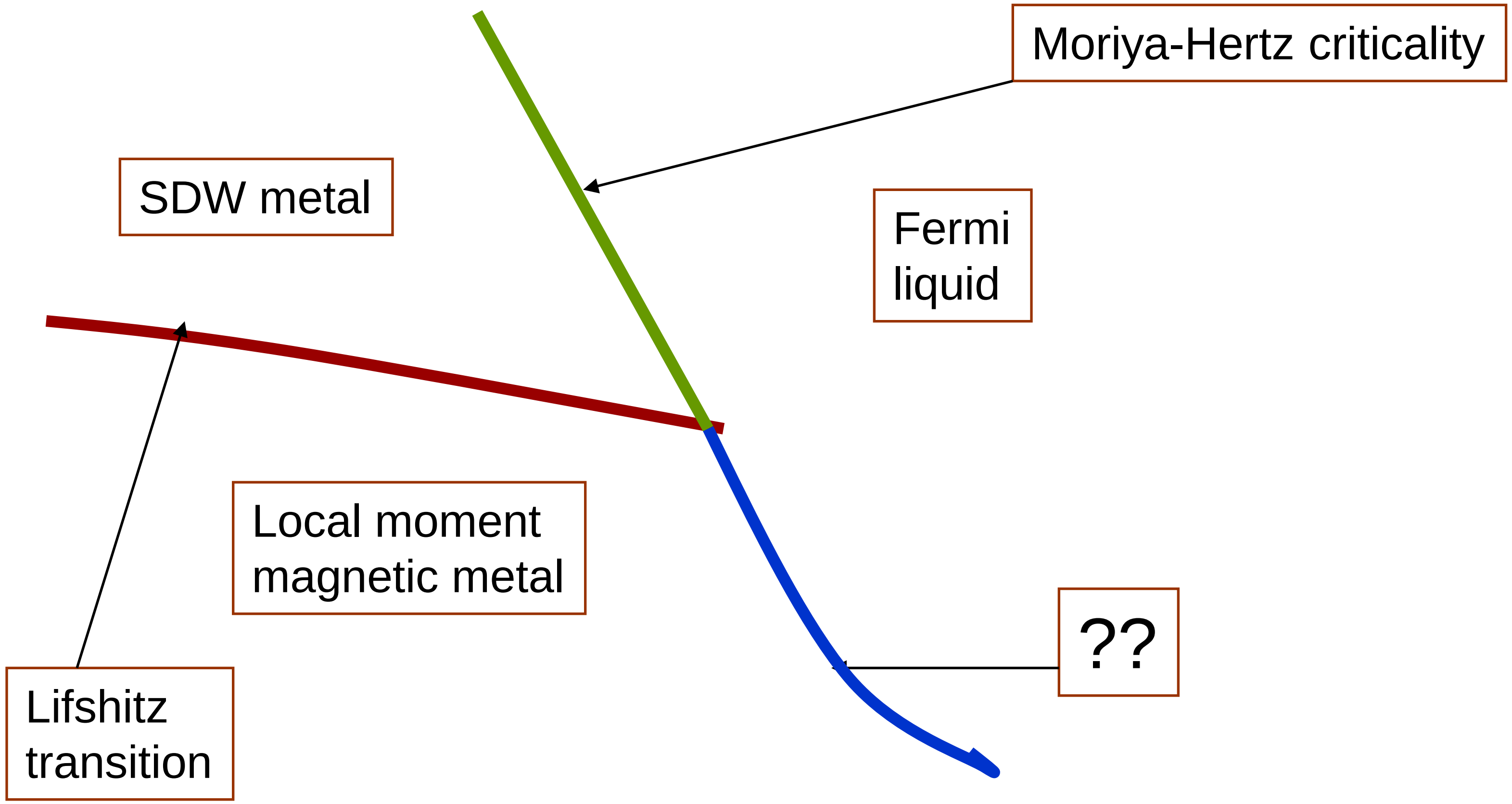
Fluctuations of magnetic order parameter with damping due to fermionic quasiparticles (Moriya-Hertz-Millis)

- Fail to reproduce observed NFL physics.

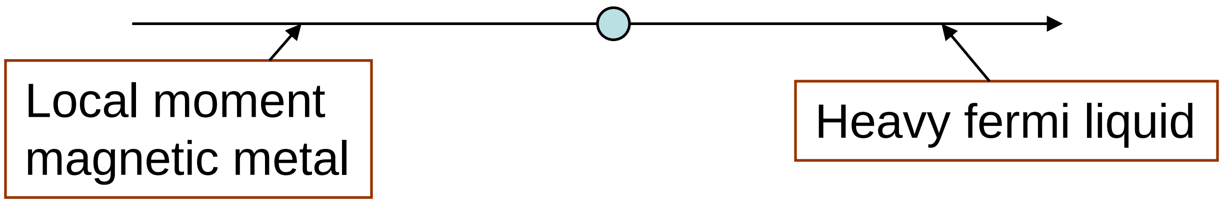
2. Explore alternate possibility:

Transition between heavy fermi liquid and local moment magnetic metal.

Schematic phase structure



Questions



1. Is there a generic second order quantum phase transition between the two phases?
(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!!

This talk: describe some ideas I am pursuing with various collaborators.

Other ideas/points of view: Q. Si et al, ,
Coleman, Pepin, ………

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).

Intermediate time scale physics

- f-moments drop put of Fermi surface but continue to form singlet bonds with each other

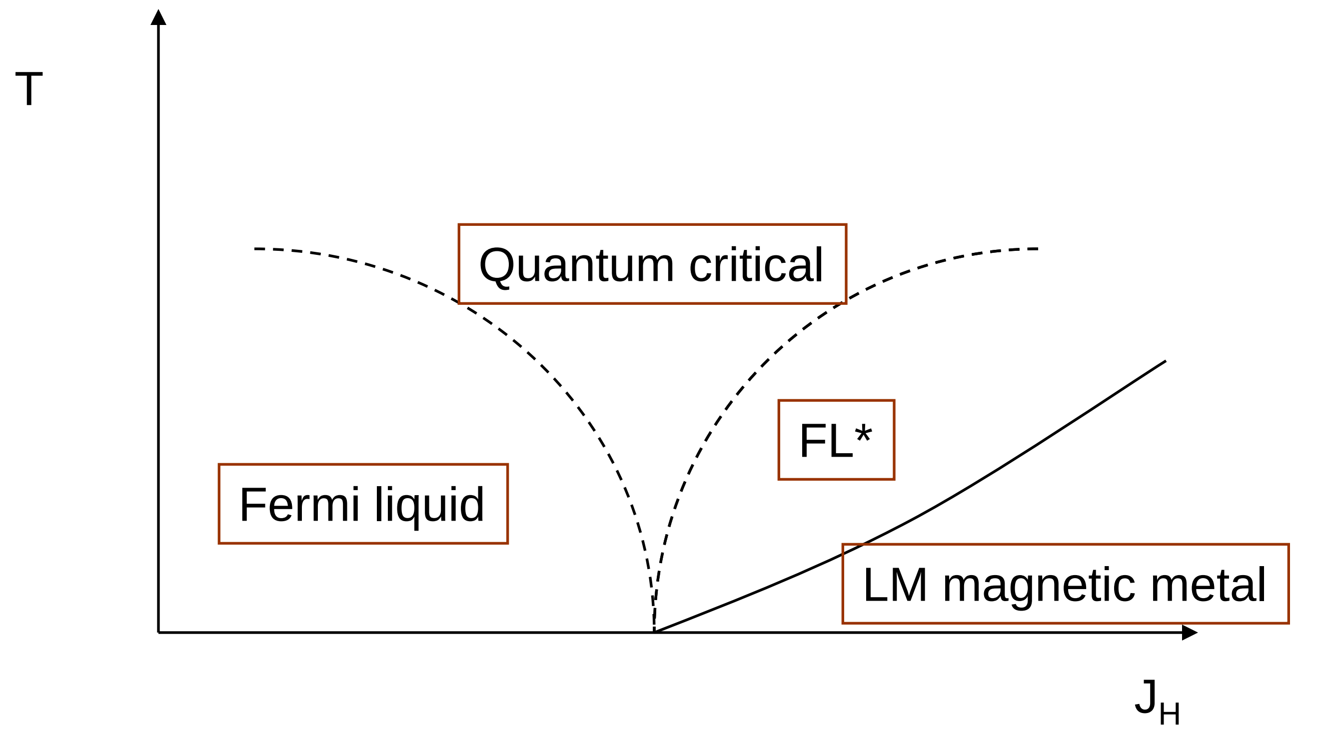
Resulting state: spin liquid of f-moments coexisting with small Fermi surface of conduction electrons

(a ``fractionalized Fermi liquid'')

Magnetism: low energy instability of

such a small Fermi surface state.

Suggested phase diagram and crossovers



? HOW TO PUT MEAT INTO THIS PICTURE ?

Study tractable simpler questions

1. Effects of loss of ``Kondo'' order?

Study second order quantum transitions associated with loss of Kondo screening. [TS,Vojta, Sachdev;

Related precursor: Burdin, Grempel, Georges]

Worry about magnetism later

2. Do similar theoretical phenomena (eg: breakdown of Landau paradigm) happen in other contexts?

Yes! (study quantum phase transitions in insulating magnets)

(TS, Vishwanath, Balents, Sachdev, M. Fisher)

Kondo Heisenberg models

$$H = \sum_k \varepsilon_k c_k^+ c_k + \frac{J_K}{2} \sum_r \vec{S}_r . c_r^+ \vec{\sigma} c_r + \sum_{rr'} J_H(r,r') \vec{S}_r . \vec{S}_{r'}$$

- $J_K = 0$: Conduction electrons are decoupled from local moments and have small Fermi surface.

- Non-magnetic ground states of spin system

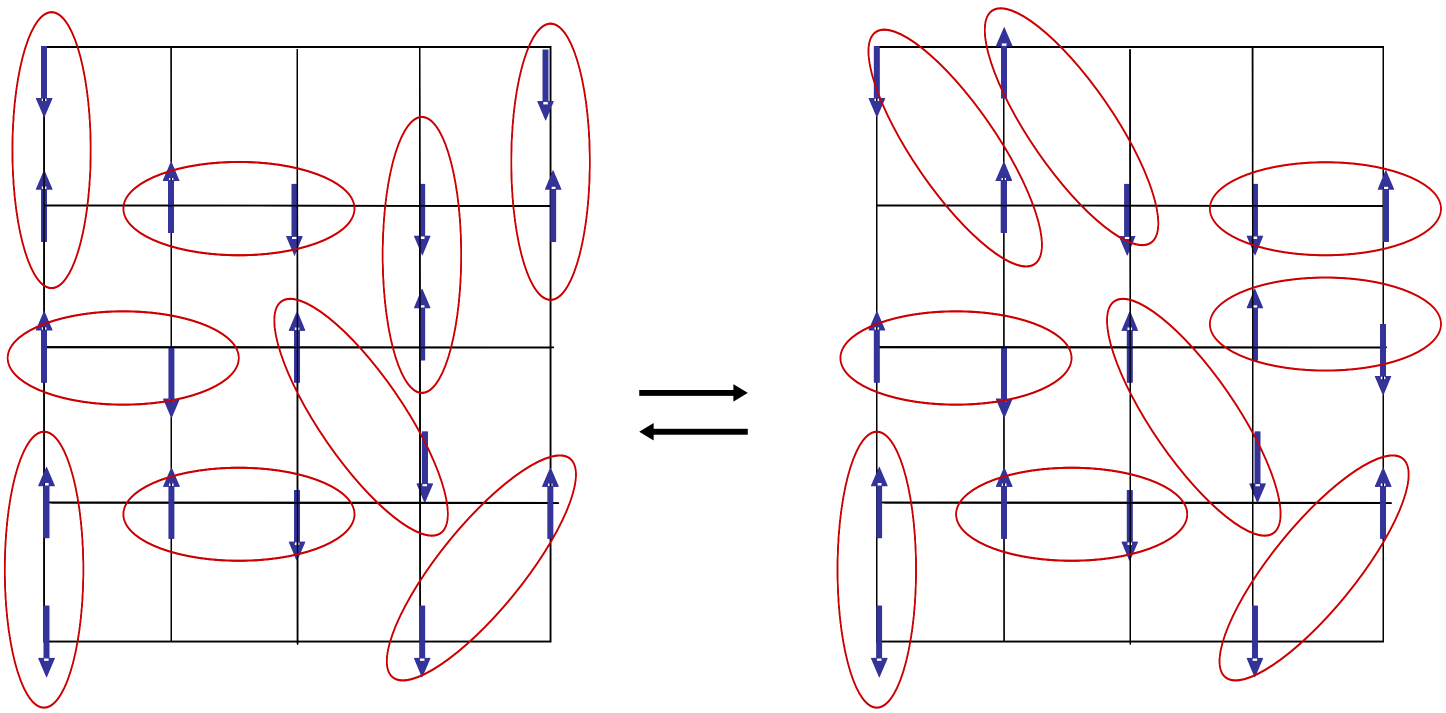
(i) Spin –Peierls: break translational symmetry

(ii) Fractionalized: can preserve translational symmetry

Focus on (ii) to discuss small Fermi surface state.

Fractionalization in d > 1

- Anderson: RVB spin liquid state for quantum spin models.



Couple spin liquids to conduction electrons

- Small non-zero J_K: Perturb in J_K

- Emergent gauge structure of local moment system survives; conduction electrons stay sharp on a small Fermi surface*.

 - advertised small fermi surface state.

- A fermi liquid in peaceful coexistence with fractionalization

  ``Fractionalized fermi liquid'' (denote FL*)

- Large J_K: Recover large Fermi surface Kondo liquid.

(* Possible pairing instability at low T).

Physics of fractionalized fermi liquid (FL*) state

- Each local moment forms singlet with another local moment.

- Weak Kondo coupling can’t break singlets:

Local moments and conduction electrons essentially stay decoupled.

Mean field theory

Kondo-Heisenberg model

$$H = -t\sum_{<rr'>} c_r^+ c_{r'} - \mu \sum_r c_r^+ c_r + J_K \sum \vec{S}_r . c_r^+ \tfrac{\vec{\sigma}}{2} c_r + J_H \sum_{<rr'>} \vec{S}_r . \vec{S}_{r'}$$

$$\vec{S}_r = f_r^+ \tfrac{\vec{\sigma}}{2} f_r \text{ with } f_r^+ f_r = 1.$$

Decouple Kondo with $b \sim c^\dagger f$; Heisenberg with $\chi \sim f^\dagger{}_r f_{r'}$

Treat b and χ in mean field.

Direct fermi volume changing transition

- Condensation of hybridization amplitude b drives direct Fermi volume changing transition.

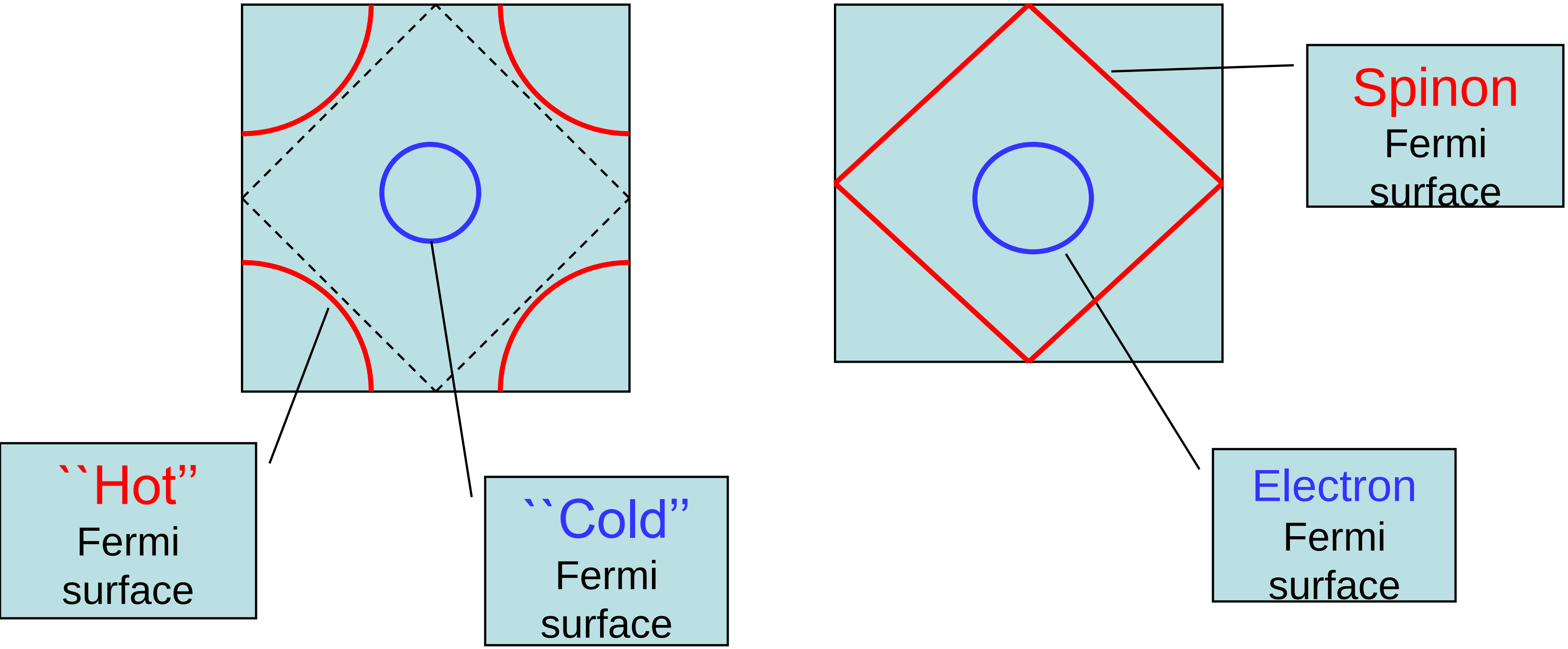
- Transition can be second order despite jump in fermi surface volume!
  (Z goes to zero).

- Critical point is clearly a non fermi liquid.

Mean field fermi surface evolution

Fermi liquid

Fractionalized fermi liquid



At transition $Z \sim b^2 \rightarrow 0$ on hot Fermi surface.

Fluctuations

FL*: spinons coupled to gapless U(1) gauge field[+]

- Near critical point: (slave) bosons and spinons coupled to a gapless U(1) gauge field

Transition driven by condensation of slave boson.

Non-fermi liquid critical point:
Eg: Specific heat C ≈TlnT (d = 3), $T^{2/3}$ (d = 2),
singular `$2k_f$' spin susceptibility along lines in k-space (d = 2),
conductivity ≈ ln(1/T),……………

(Similar to gauge theories of optimally doped cuprates but bosons are at fixed chemical potential rather than fixed density).

+other possibilites such as a Z_2 gauge field also exist.

How to get magnetism?

- Gauge field can confine spinons leading to magnetic long range order (particularly in d = 2) – low energy instability of FL* to local moment magnetic metal.

- Interesting possibility: confinement effective only in FL* phase but not at critical point

$\Rightarrow$ Direct second order transition between heavy Fermi liquid and local moment magnetic metal but with interesting `deconfined' critical point described in terms of spinons and gauge fields.

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Admittedly speculative but……………………….

Evidence from a simpler context – insulating quantum magnets

- Highlights: Clear demonstration of

such theoretical phenomena 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

$$H = J \sum_{<rr'>} \vec{S}_r . \vec{S}_{r'} + ...$$

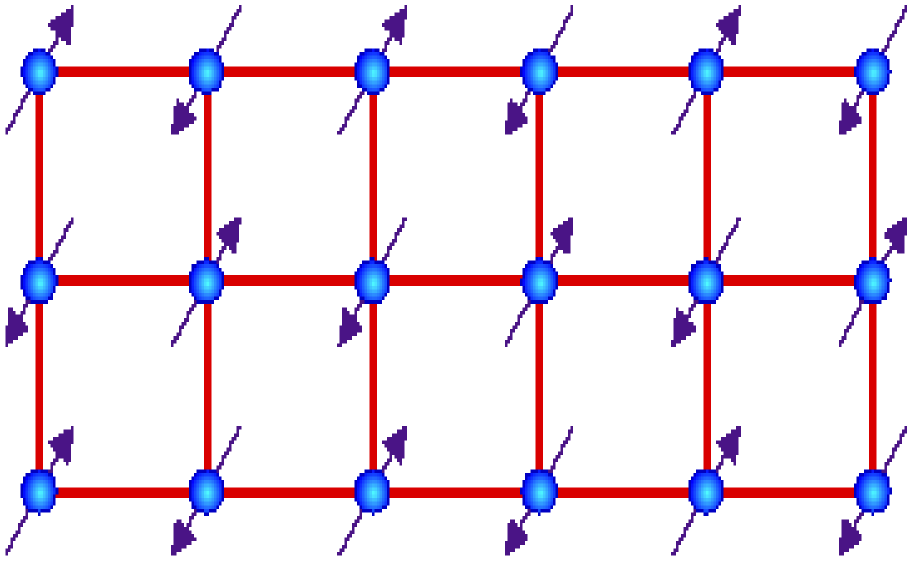
- Spin-1/2 quantum antiferromagnets on a square lattice.

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

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

Possible quantum phases

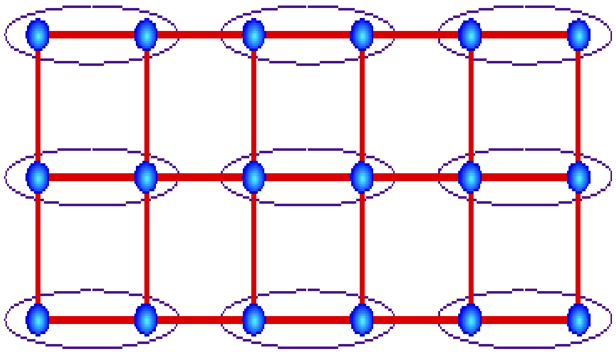
- Neel ordered state



Possible quantum phases (contd)

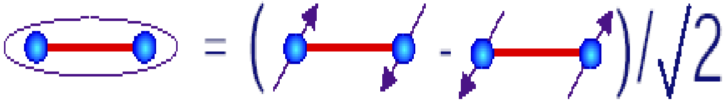
QUANTUM PARAMAGNETS

- Simplest: Valence bond solids.



- Ordered pattern of valence bonds breaks lattice translation symmetry.

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



Neel-valence bond solid(VBS) transition

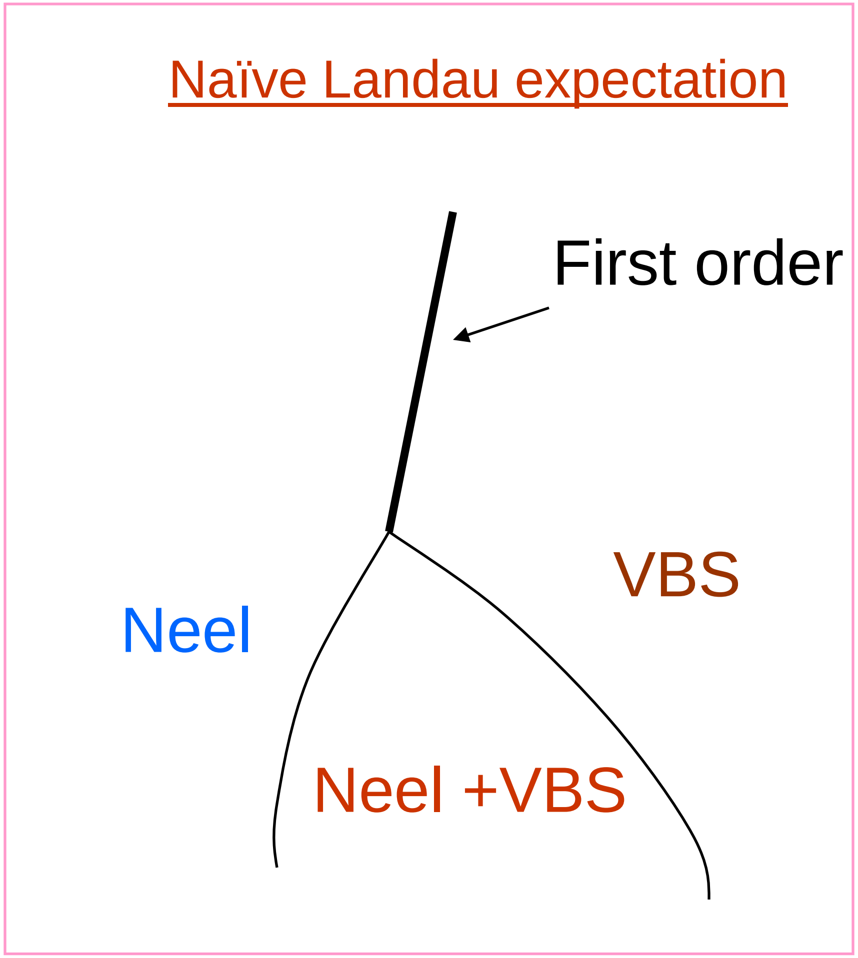
- Neel: Broken spin symmetry
- VBS: Broken lattice symmetry.

- Landau – Two independent order parameters.

- no generic direct second order transition.

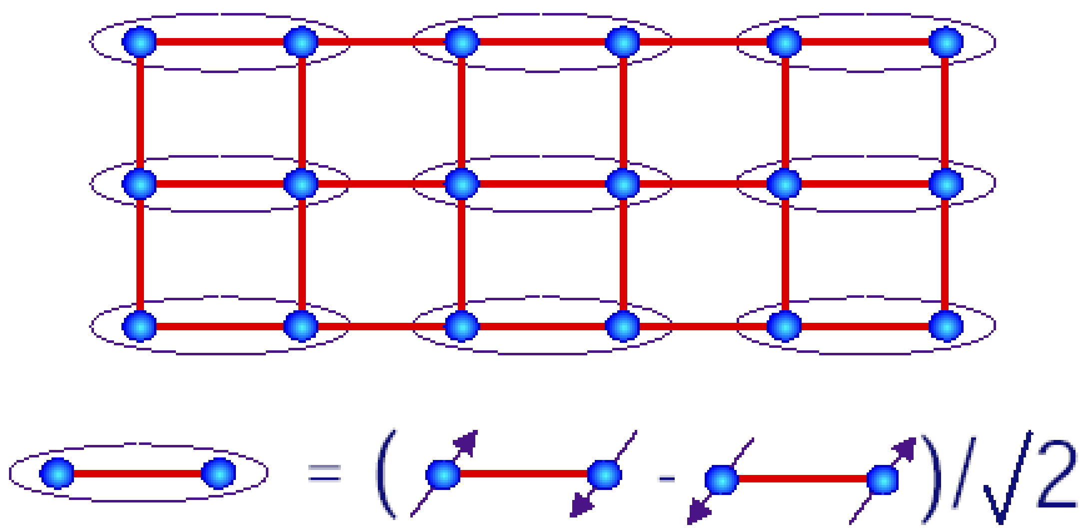
- either first order or phase coexistence.

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

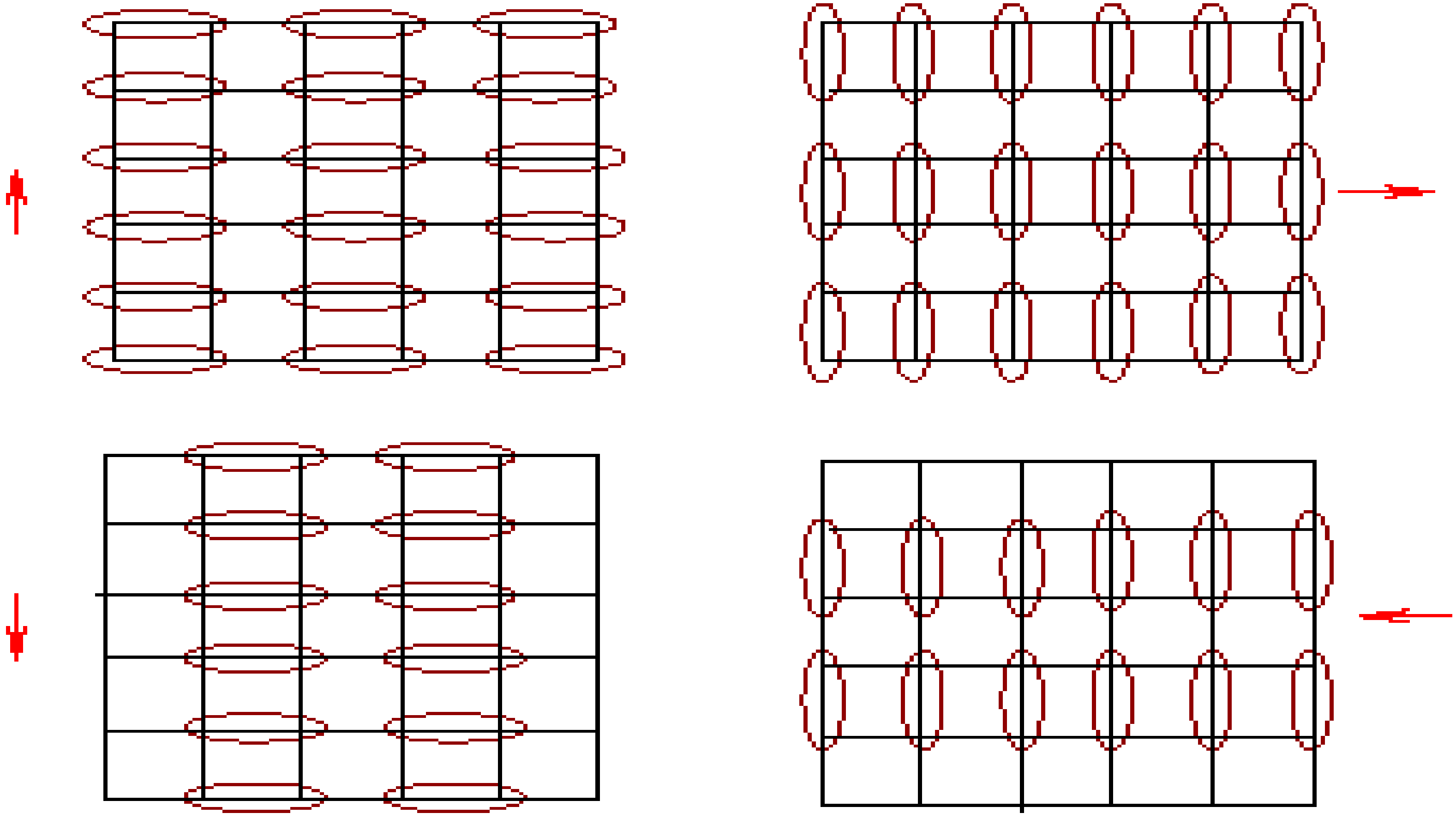


Broken symmetry in the valence bond solid(VBS) phase

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).

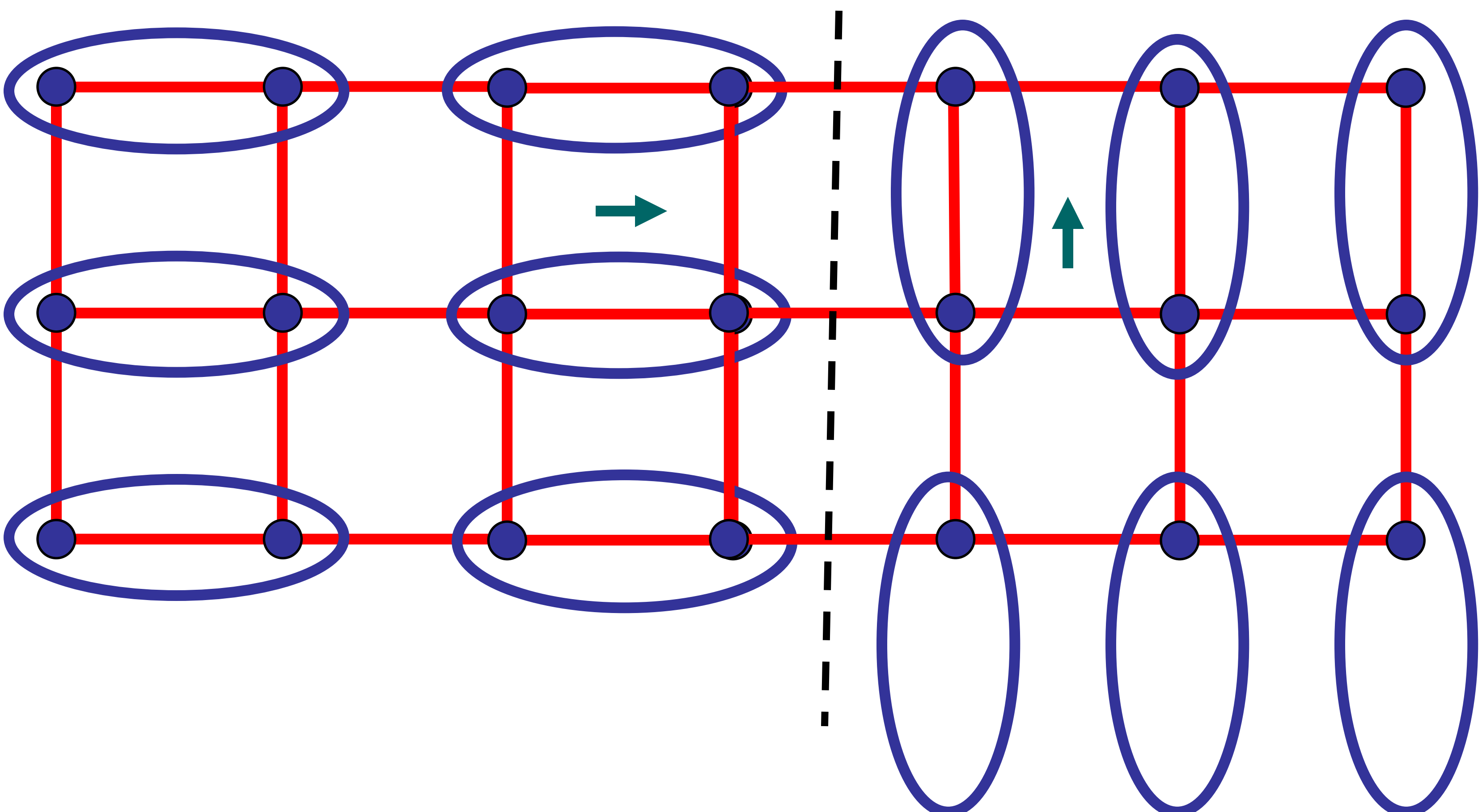
Why do these fail?

Topological defects carry non-trivial quantum numbers!

This talk: attack from VBS (Levin, TS, cond-mat/0405702)

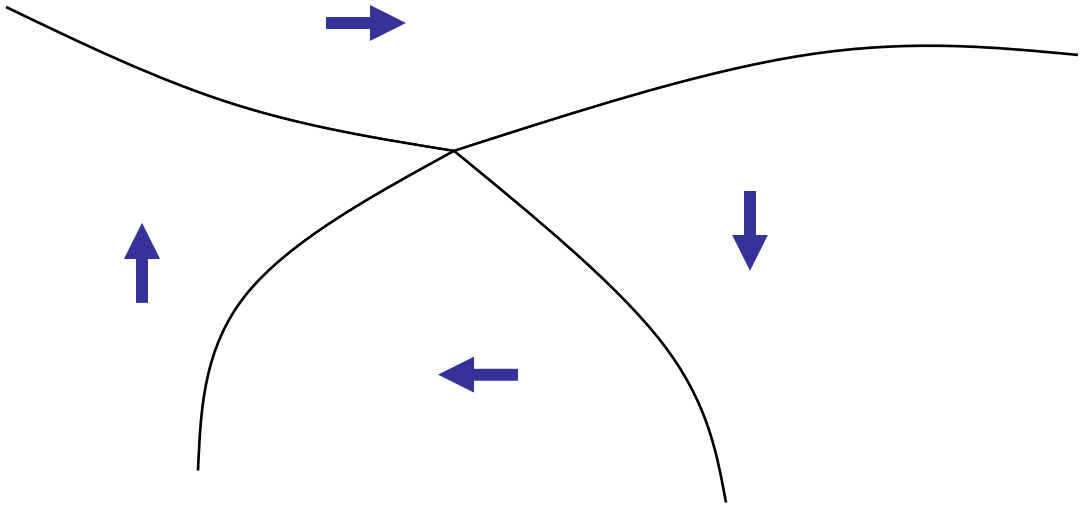
Topological defects in Z_4 order parameter

- 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.

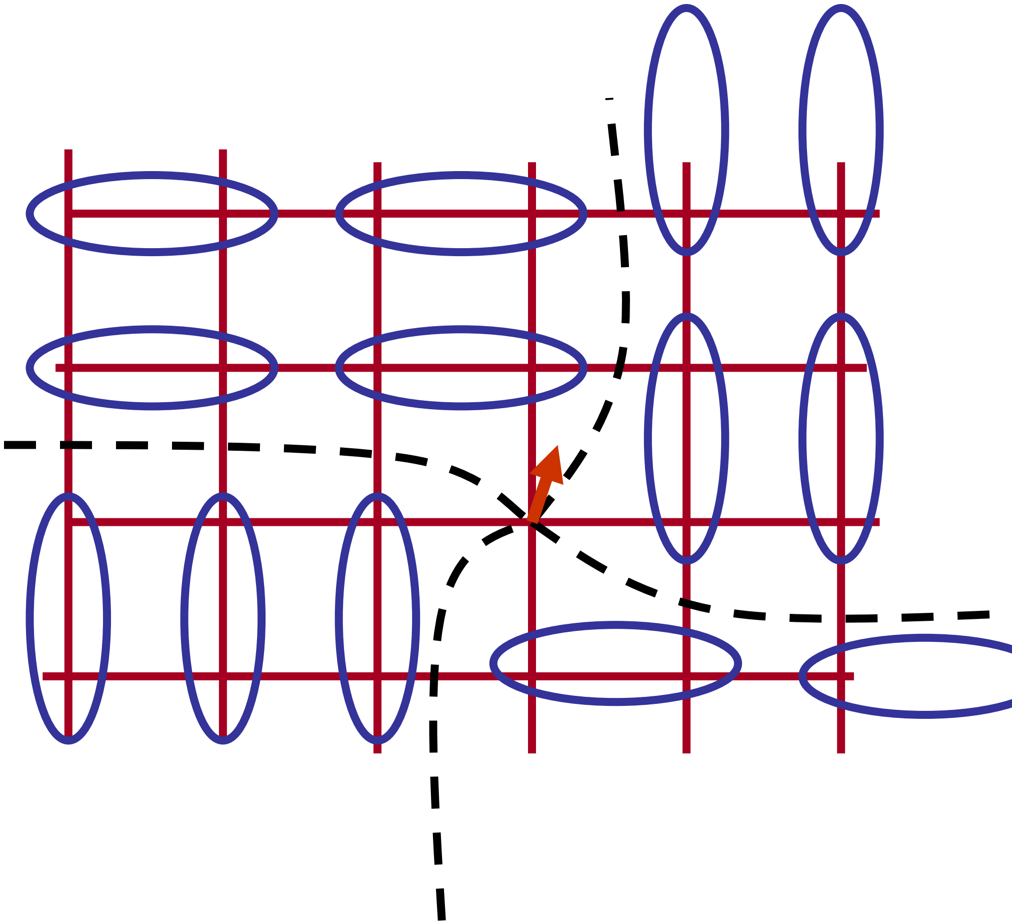


Z_4 vortices in VBS phase

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''

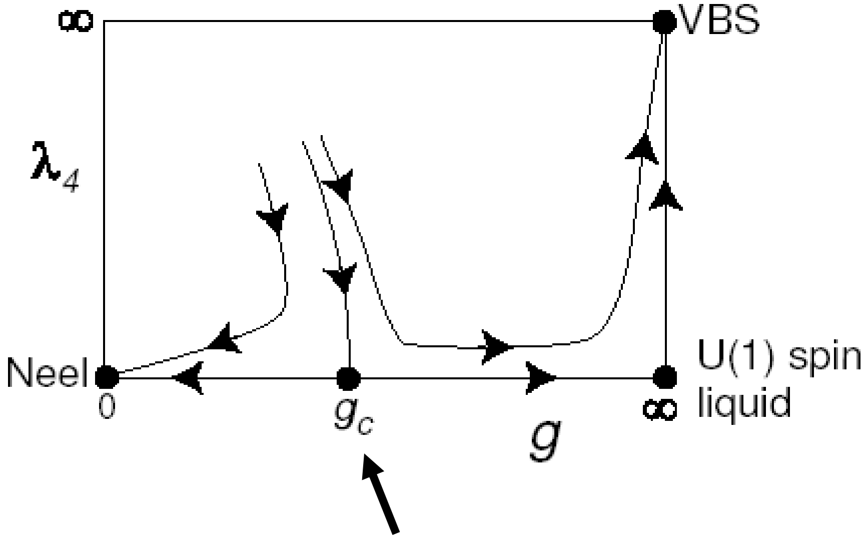
$$S = \int d^2x d\tau \, |(\partial_\mu - i a_\mu) z|^2 + r|z|^2 + u|z|^4 + (\varepsilon_{\mu\nu\lambda}\partial_\nu a_\lambda)^2$$

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.

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

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)

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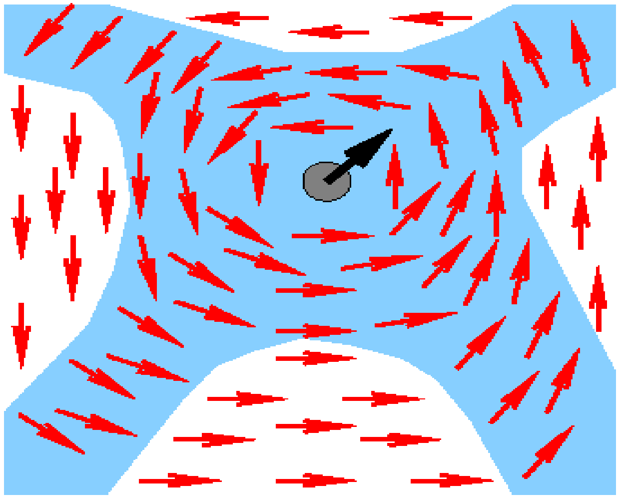


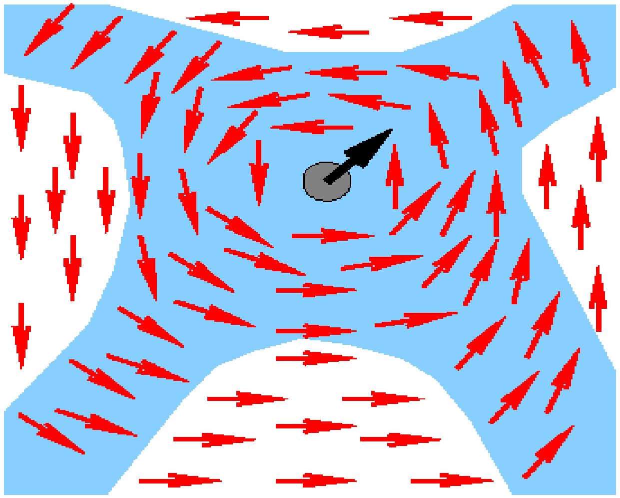
Formal: Extra global U(1) symmetry not present in microscopic model :

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.



Other examples

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

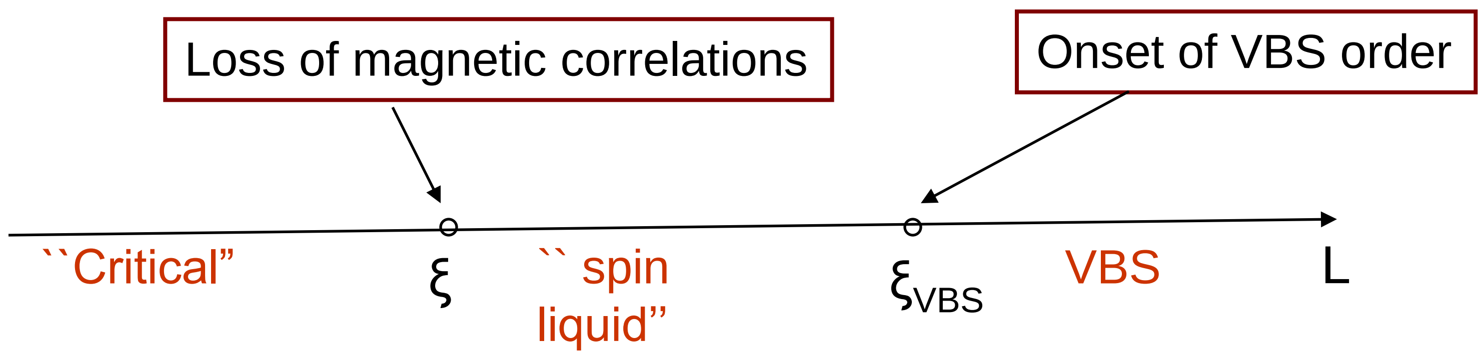
(VBS- spin liquid, VBS-VBS, Neel – spin liquid, …)

Apparently fairly common

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?