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ICTP 40th Anniversary

SMR.1572 - 27

Workshop on Novel States and Phase Transitions in Highly Correlated Matter

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Deconfined Quantum Criticality

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Deconfined quantum criticality

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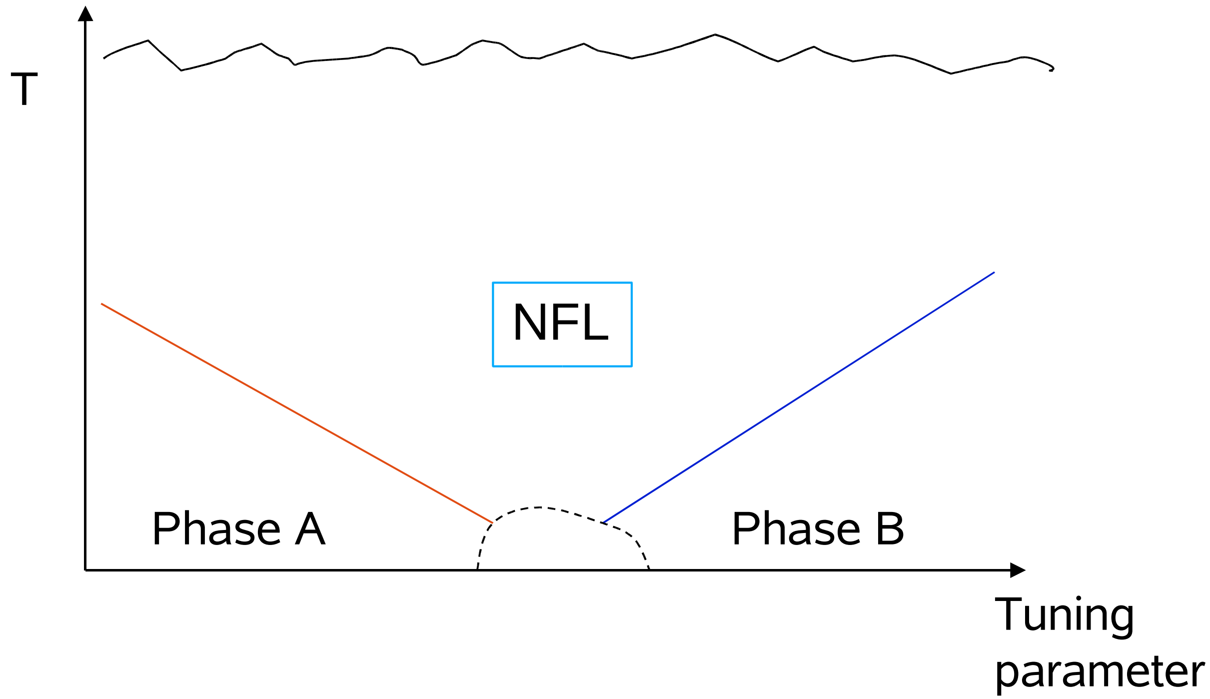
Competing orders and non-fermi liquids in correlated systems



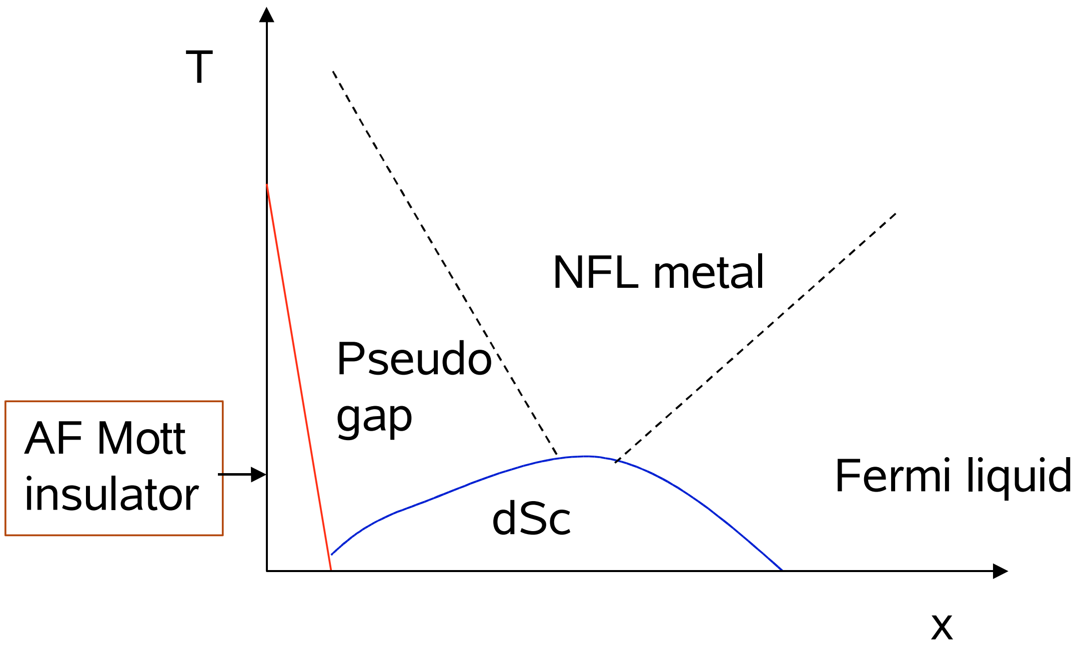
``Classical" assumptions

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

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

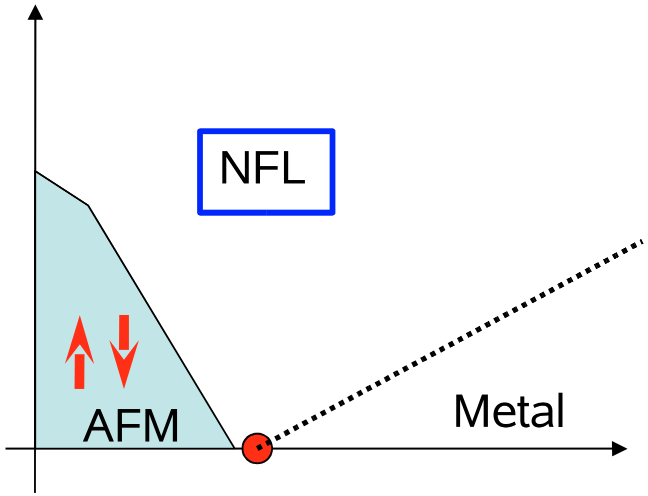
Try to play Landau versus Landau.

Example 1: Cuprates



Example 2: Magnetic ordering in heavy electron systems

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



``Classical'' assumptions have difficulty with producing NFL at quantum critical points

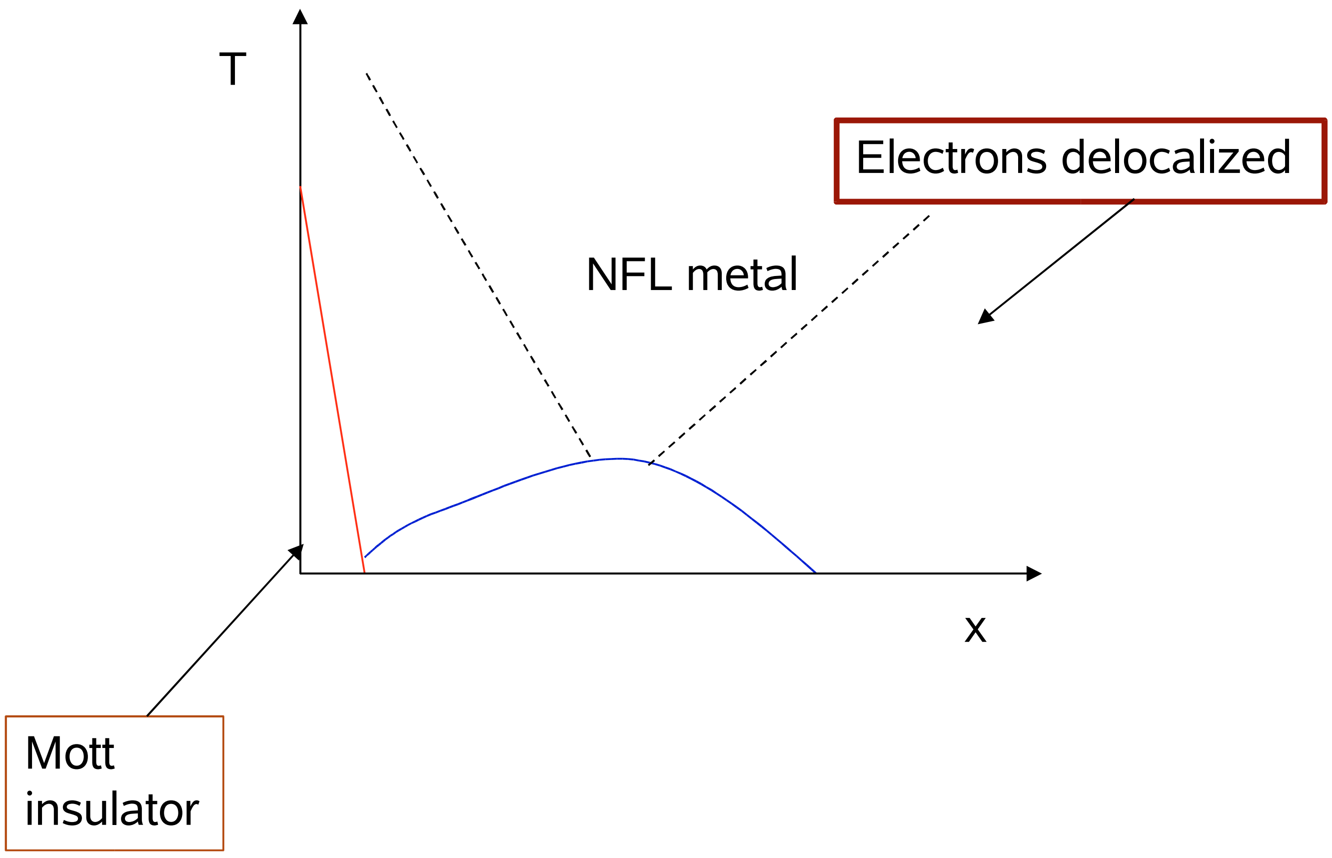
(Radical) alternate to classical assumptions

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

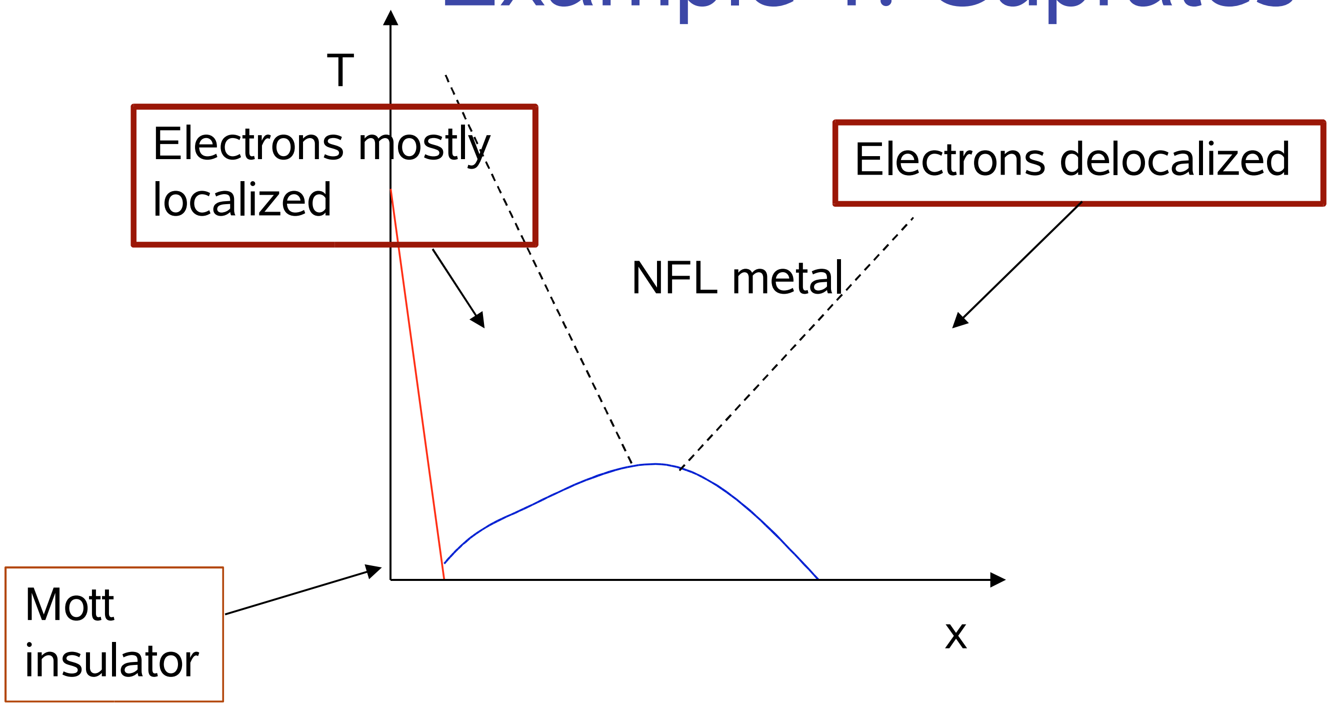
- Order parameters/broken symmetries of phases A and B mask this basic competition.

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

Example 1: Cuprates

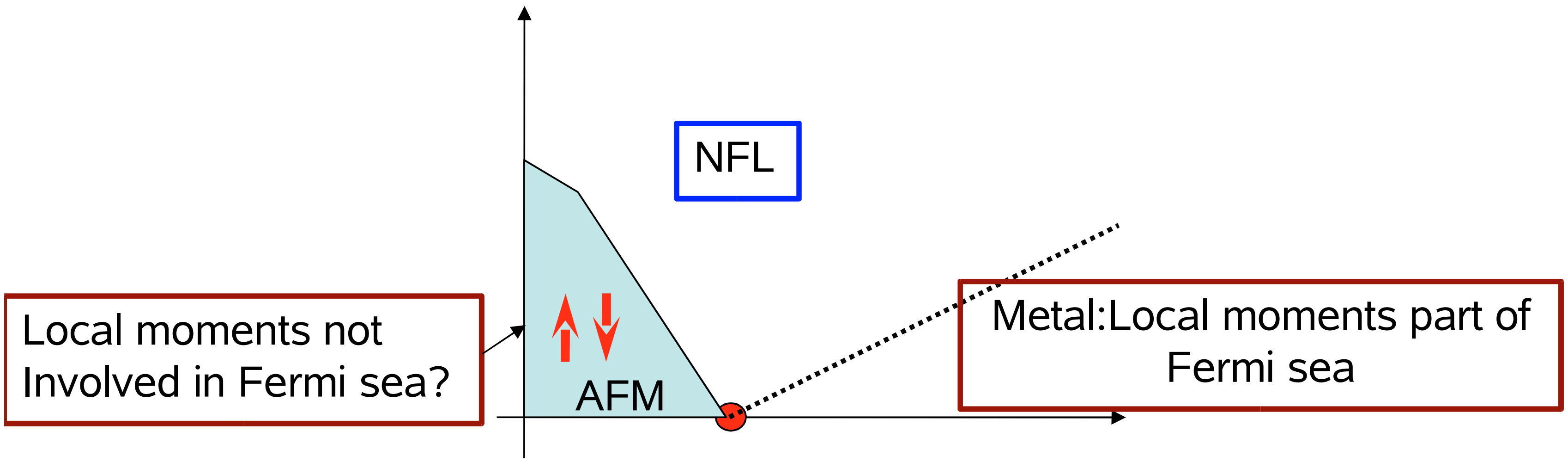


Example 1: Cuprates



- Competition between Fermi liquid and Mott insulator
- Low energy order parameters (AF, SC, …) mask this competition.

Similar possibility in heavy electron systems



Critical NFL physics: fluctuations of loss of local moments from Fermi sea?
Magnetic order – a distraction??

This talk – more modest goal

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

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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

$$H = J \sum_{<rr'>} S_r . S_{r'} + \ldots\ldots$$

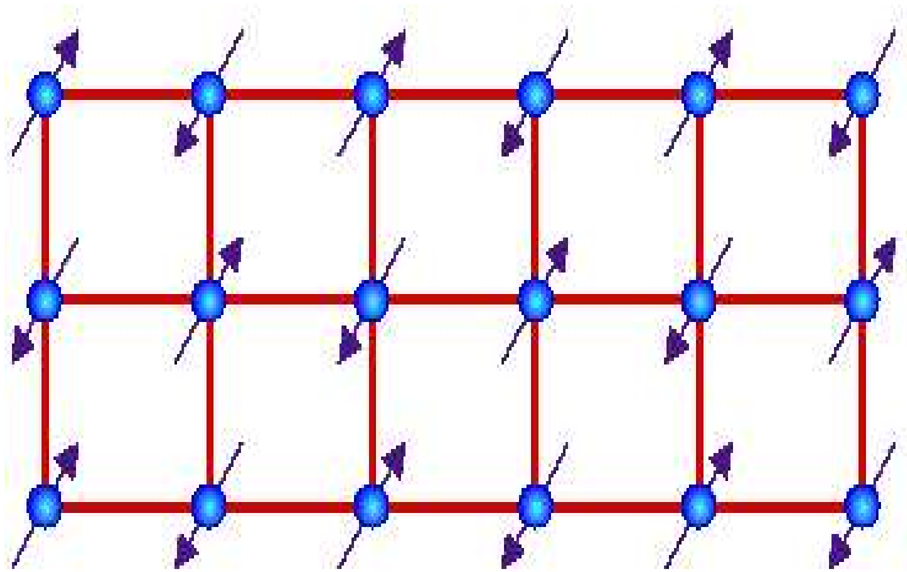
- Spin-1/2 quantum antiferromagnets on a square lattice.

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

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

Possible quantum phases

- Neel ordered state



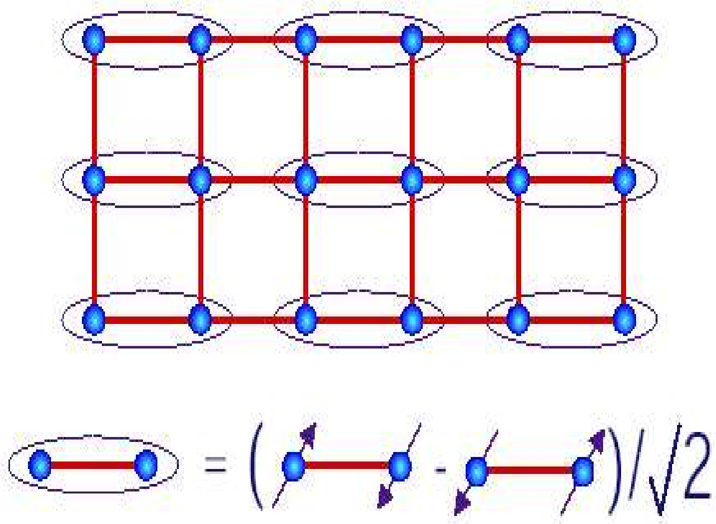
Possible quantum phases (contd)

QUANTUM PARAMAGNETS

- Simplest: Valence bond solids.

- Ordered pattern of valence bonds breaks lattice translation symmetry.

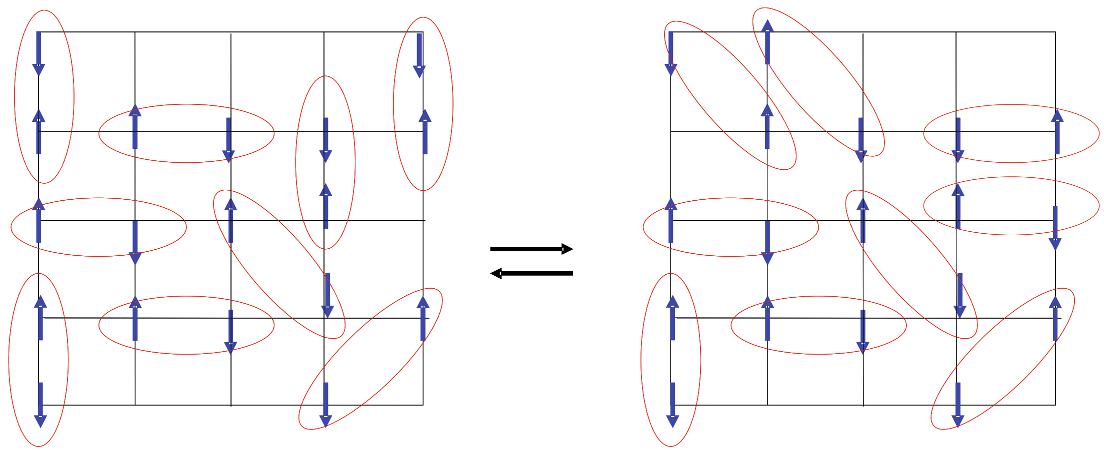
- Elementary spinful excitations have S = 1 above spin gap.



Possible phases (contd)

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

- Fractional spin excitations, interesting topological structure.



Neel-valence bond solid(VBS) transition

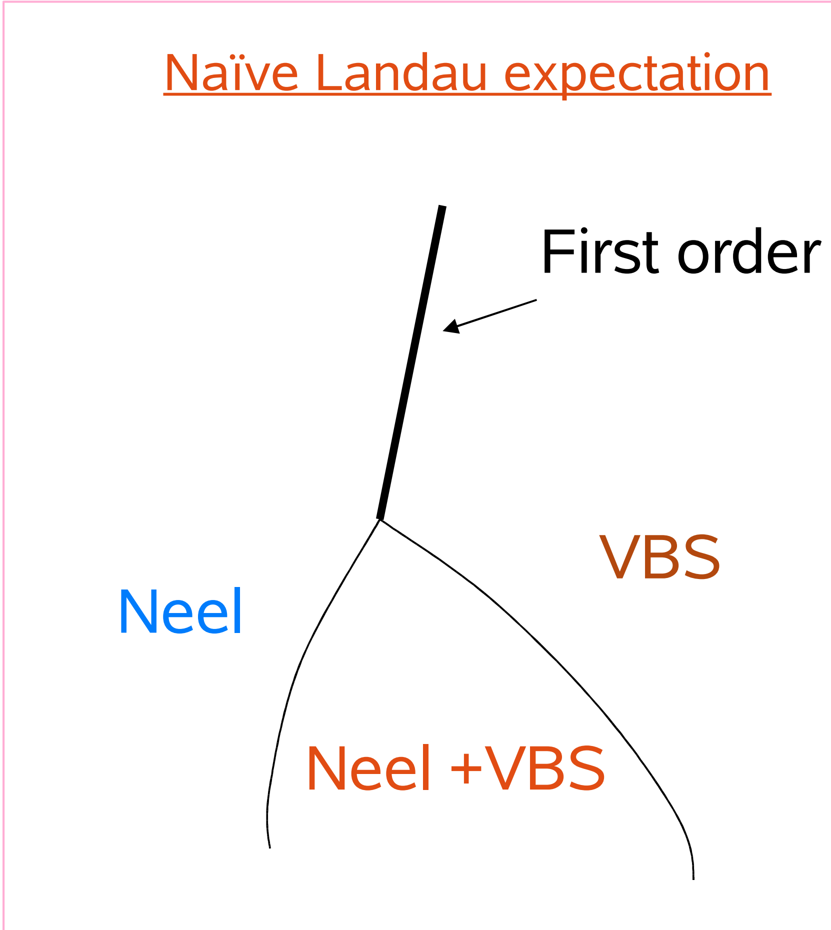
- Neel: Broken spin symmetry
- VBS: Broken lattice symmetry.

- Landau – Two independent order parameters.

- no generic direct second order transition.

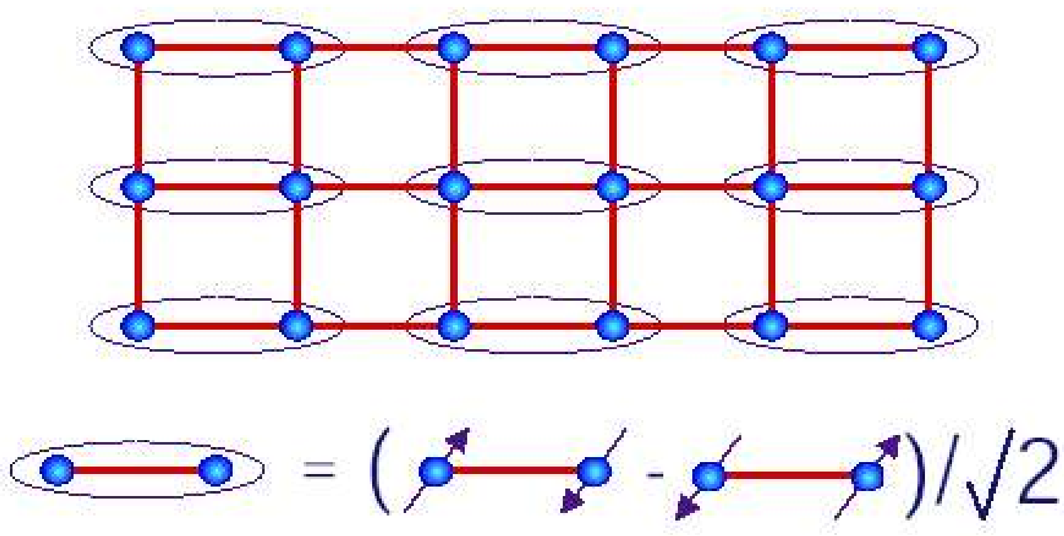
- either first order or phase coexistence.

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

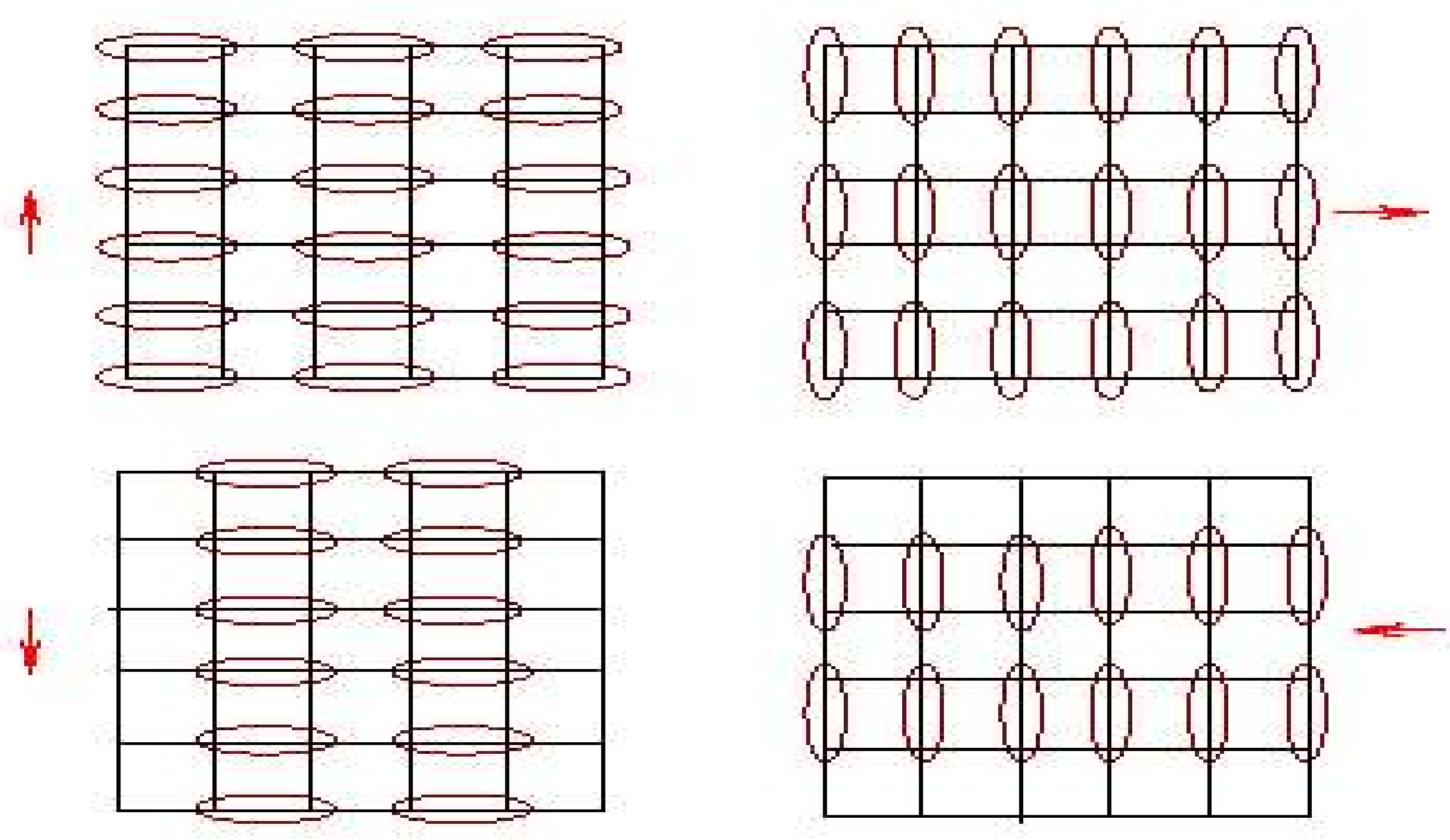


Broken symmetry in the valence bond solid(VBS) phase

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).

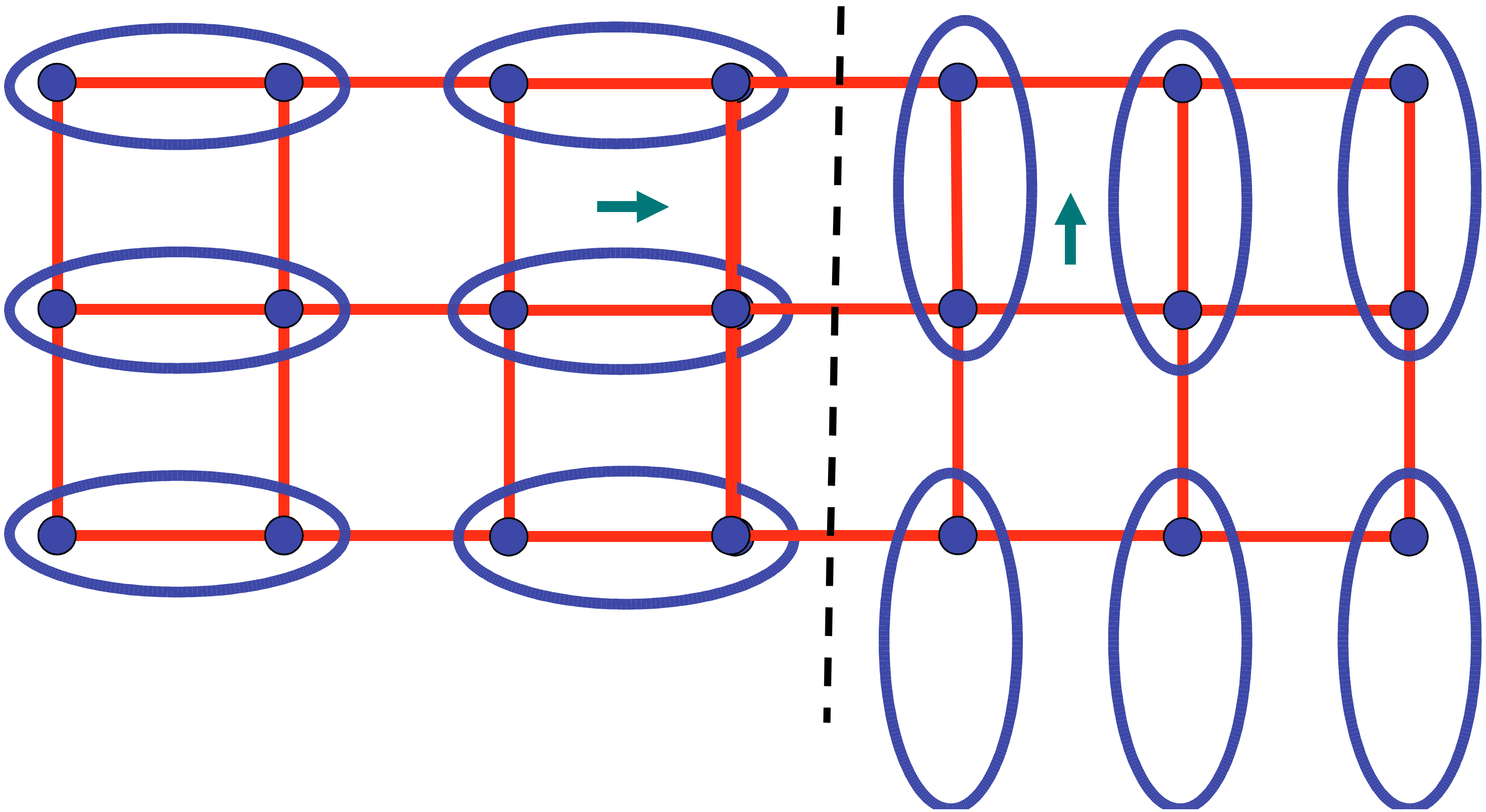
Why do these fail?

Topological defects carry non-trivial quantum numbers!

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

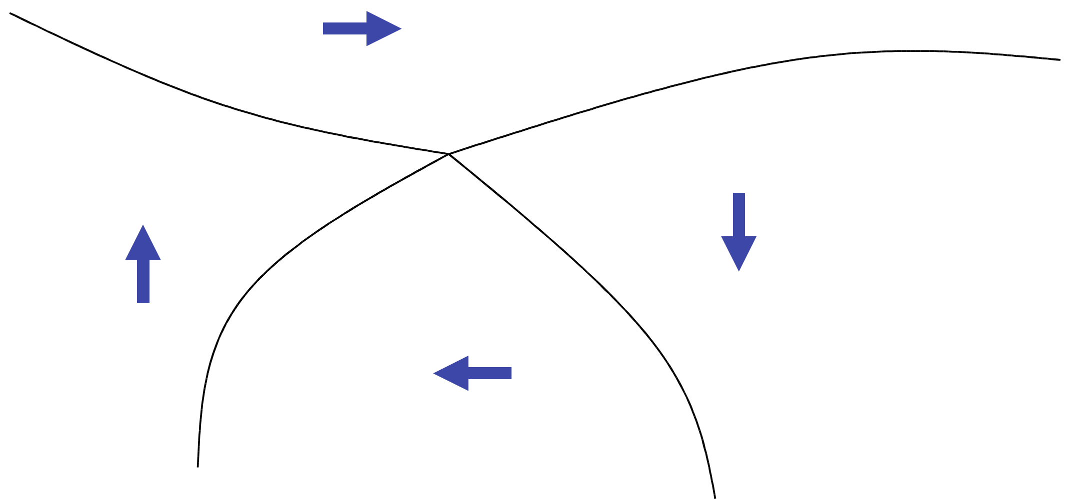
Topological defects in Z_4 order parameter

- 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.

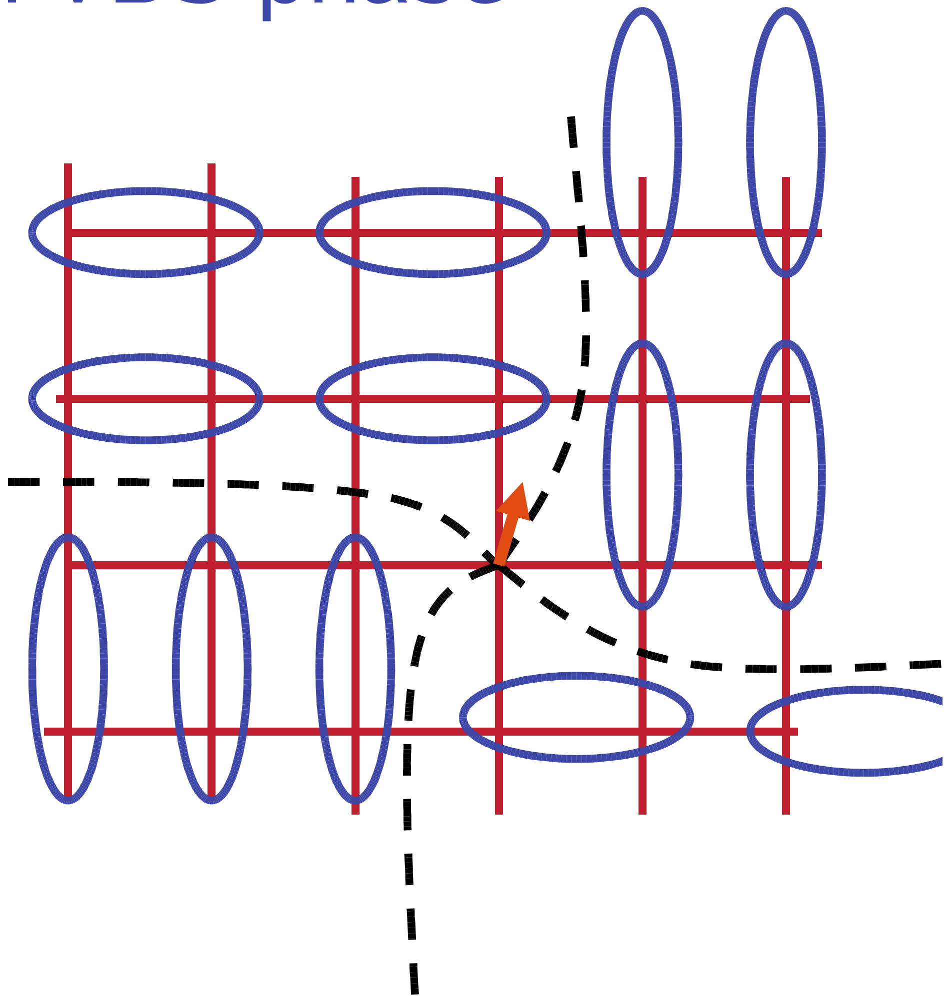


Z_4 vortices in VBS phase

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''

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

$$+ (\varepsilon_\mu \quad \partial_\nu a_\lambda)^2 \qquad\qquad\qquad \nu$$

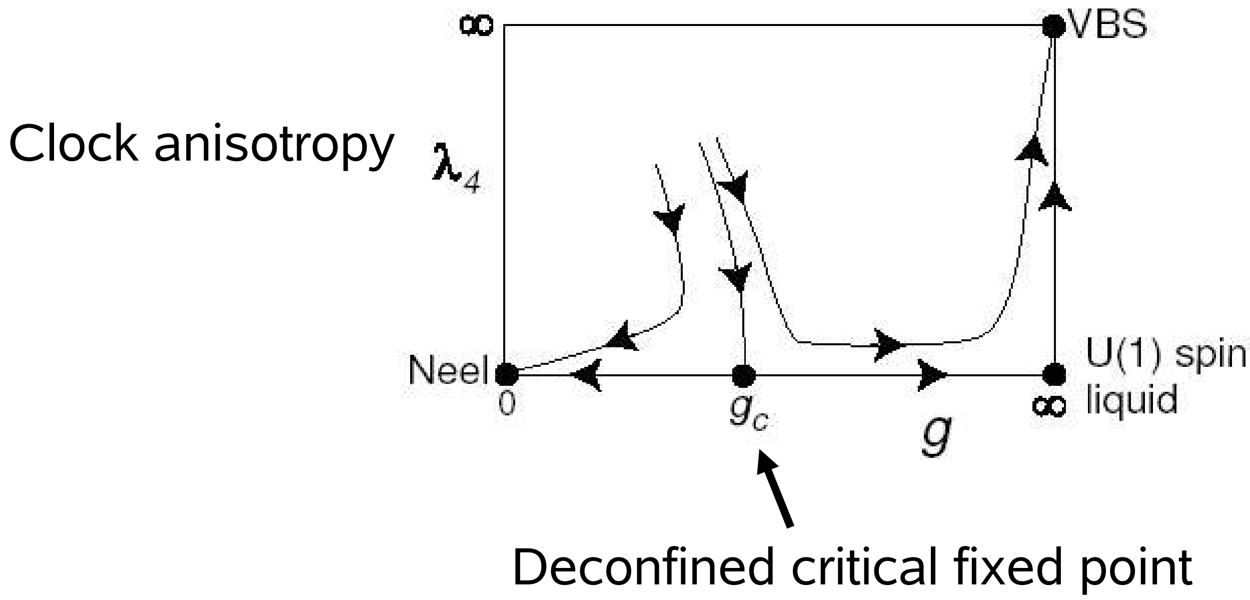
z = two-component spin-1/2 spinon field

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



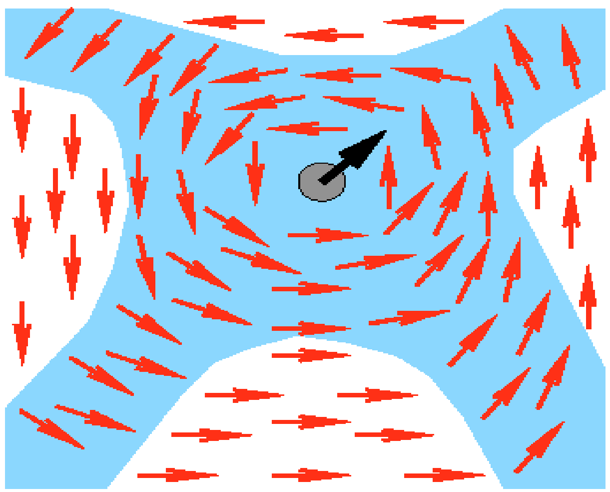
Clock anisotropy is ``dangerously irrelevant''.

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 :

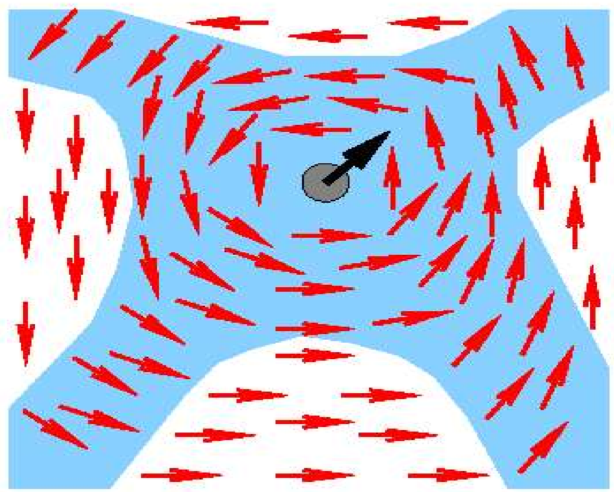
Two diverging length scales in paramagnet

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

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

Apparently fairly common

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

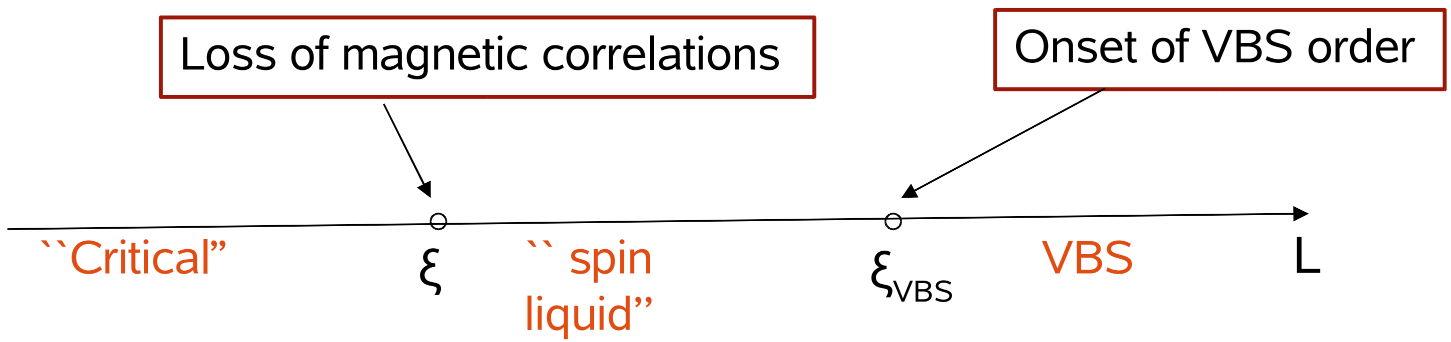
- interesting applications to cuprate theory.

Summary and some lessons-I

- Direct 2nd order quantum transition between two phases with different broken symmetries 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 (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.

Strong impetus to radical approaches to NFL physics at heavy electron critical points (and to optimally doped cuprates).