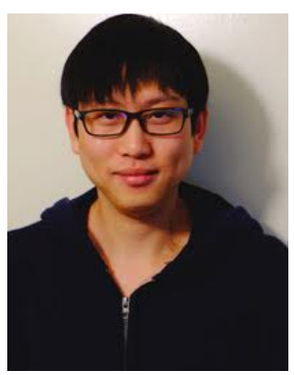
Landau ordering transitions beyond the Landau paradigm

T. Senthil (MIT)



Zhen Bi (MIT postdoc)

Ethan Lake (MIT student)

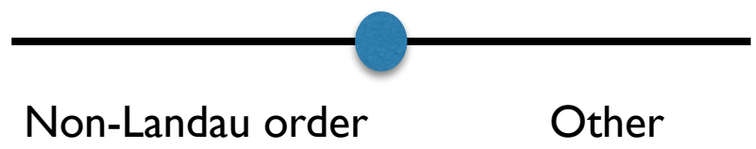
Bi, Lake, TS, forthcoming

Previous pertinent work:
Bi, TS, PR X 2019 (arXiv:1808.07465)

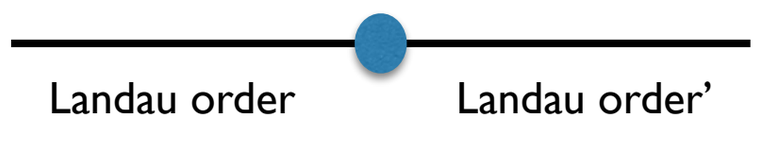
Simons Foundation

Quantum criticality beyond the Landau paradigm

Eg: 1. One or both phases have non-Landau order

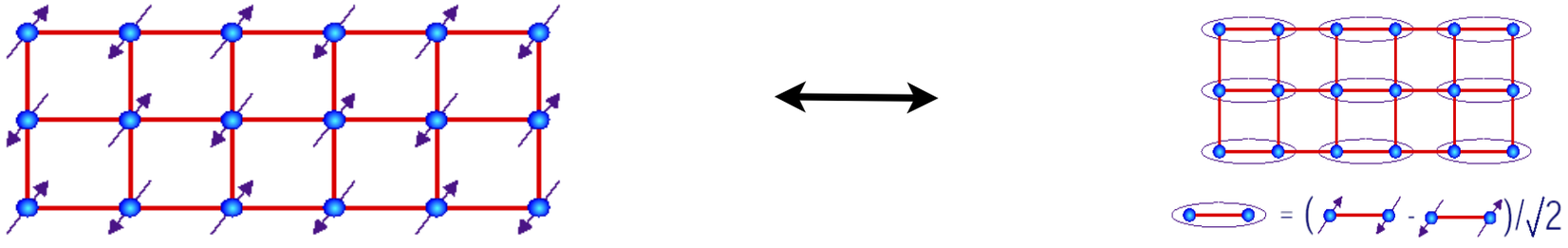


2. Landau-forbidden continuous transitions between Landau allowed phases



TS, Vishwanath, Balents, Fisher, Sachdev, 2004

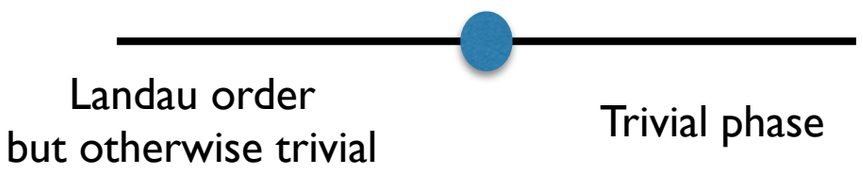
Eg: Neel - valence bond solid state in square lattice antiferromagnets.



This talk

(Bi, Lake, TS, to appear)

Focus instead on the textbook example



The transition can of course be in the conventional universality class described by a Landau-Ginzburg-Wilson (LGW) theory of the fluctuating order parameter.

Could there be another universality class for the same transition which is beyond the LGW paradigm?

Outline

1. Some old fantasies about quantum critical points (mainly in metals)

- can a focus on order parameter fluctuations distract from the true physics at some Landau ordering phase transitions?

2. A concrete example in a simpler (but more esoteric) setting

3. Comparison with other somewhat related critical points

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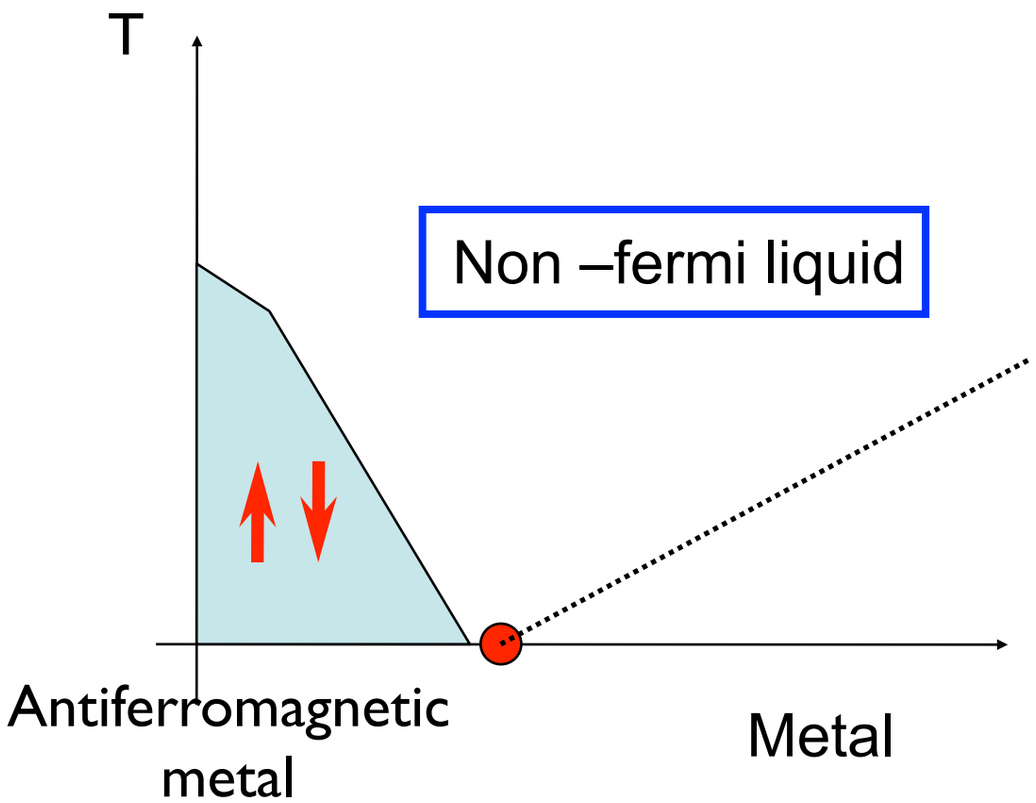
Onset of magnetism in Kondo lattice systems

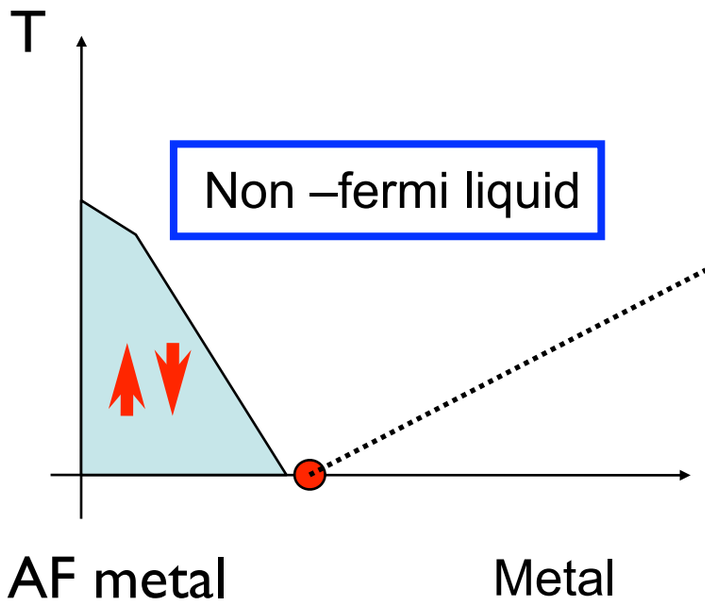
$CePd_2Si_2$, $CeCu_{6-x}Au_x$, $YbRh_2Si_2$, $CeRhIn_5$,….

Microscopics: Local f-moments + separate band of conduction electrons coupled by Kondo exchange



Non-fermi liquid associated with quantum critical fluctuations of the T = 0 critical point.

Onset of magnetism in Kondo lattices (cont'd)



Landauesque theory (``Moriya-Hertz-Millis")

Start in paramagnetic metal phase - couple critical order parameter fluctuations to electrons near the fermi surface of this metal (see, eg, Shamit Kachru's talk)

However this theory has many problems with the observed phenomenology - particularly the non-fermi liquid physics.

Onset of magnetism in Kondo lattices (cont'd)

Old idea: Perhaps other things are changing across the phase transition that are not captured by the natural Landau order parameter

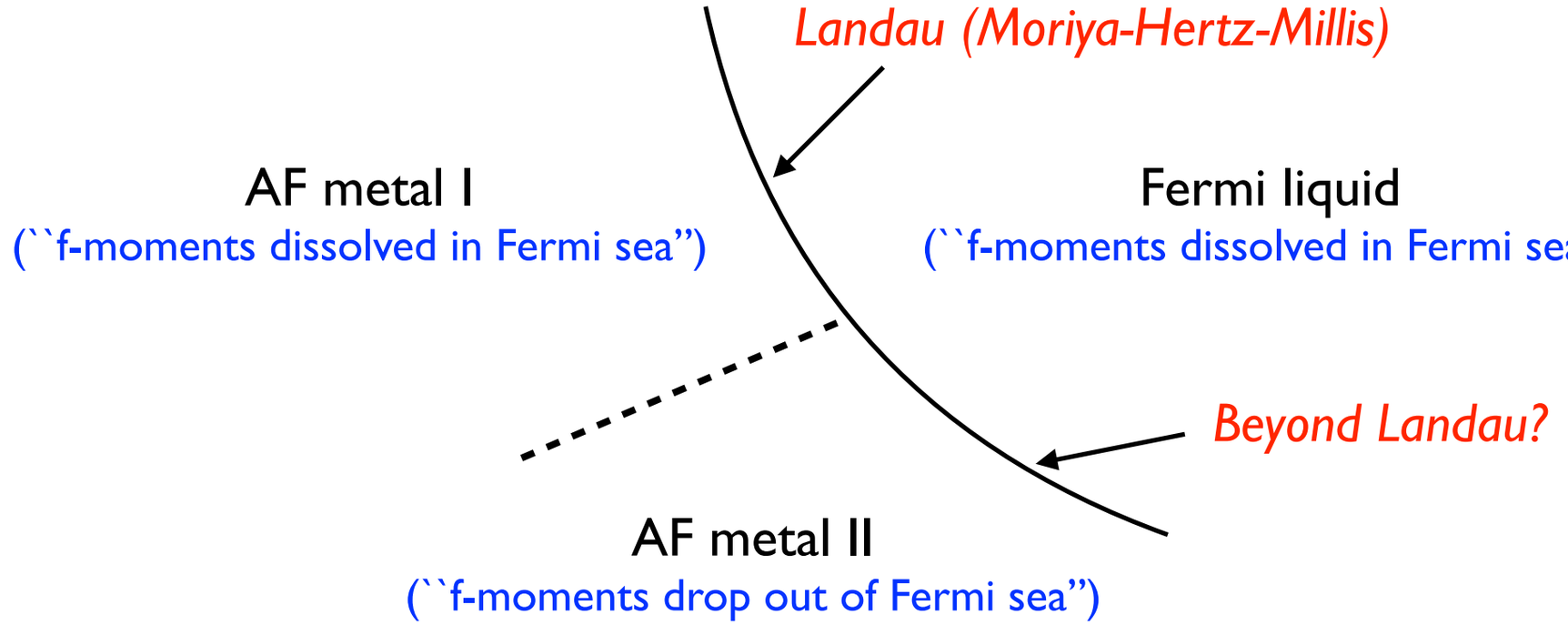
A natural candidate: a jump of Fermi surface associated with ``Kondo breakdown"

(Coleman, Si, TS, Vojta, Sachdev, …… 2001-05)

Many of the most basic questions about such quantum critical points remain wide open still.

Fantasized phase diagrams

TS, Vojta, Sachdev, 04
Q. Si, 06
Nevidomskii, Coleman, 10



AF metal I and AF metal II: are they sharply distinct?
If not are there multiple universality classes for the same Landau ordering transition in these metals?

Remarks

A basic possibility suggested by these systems is that Landau ordering transitions may occur through novel quantum critical points where focusing on order parameter fluctuations may be a distraction.

Perhaps the fundamental transition is something else and the Landau ordering is a low energy after-thought. TS, Vojta, Sachdev 04

However it has been hard to make theoretical progress on these problems, at least in part due to the complications of dealing with mobile electrons with a Fermi surface.

Are there any examples at all of Landau ordering transitions that are beyond the Landau paradigm?

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Strategy

Construct examples of novel criticality by interpreting known CFTs as quantum critical points

SU(2) gauge theory with fundamental matter

$$\mathcal{L} = \bar{\psi}\left(-i\gamma^{\mu}(\partial_{\mu} - ia_{\mu}) + m\right)\psi + \frac{1}{2g^2}tr\left(f_{\mu\nu}^2\right)$$

Dynamical SU(2) gauge field

Despite appearances, this is a theory of bosons!

All local operators (baryons, mesons,….) are bosonic.

N_f flavors: can show theory has global symmetry $\frac{Sp(N_f)}{Z_2} \times T$.

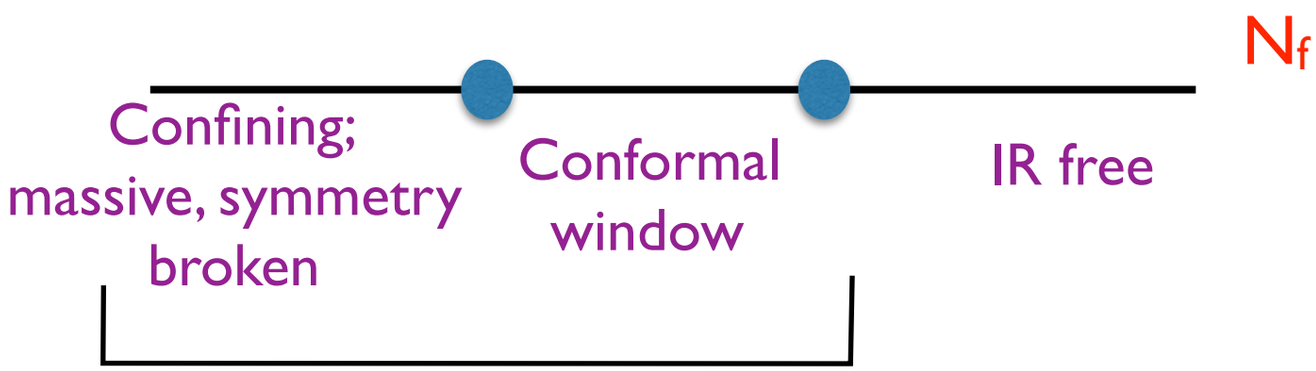
View this gauge theory as the IR description of some UV system of interacting gauge-invariant bosons with this global symmetry.

UV theory of bosons

Intermediate energy:
SU(2) gauge theory

IR phase diagram

Some well known properties of the SU(2) gauge theory



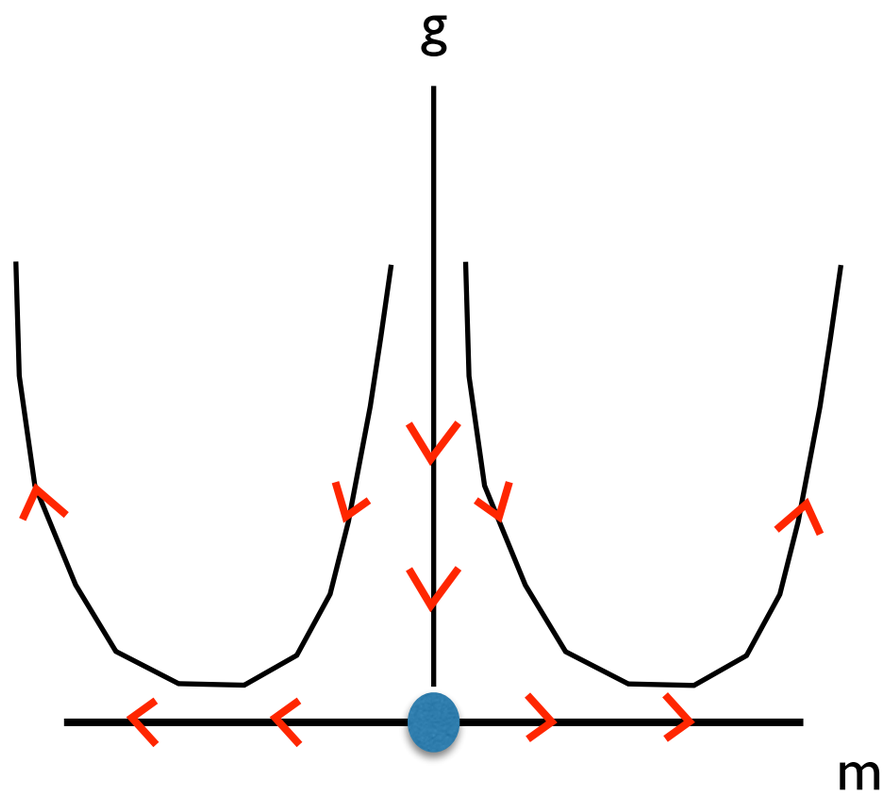
Asymptotically free (in ``UV" limit
of continuum field theory)

Upper boundary of conformal window known from perturbative RG.
Lower boundary: many numerical studies, controversial.

Though the theories in the conformal window are interesting,
to keep things simple I will mostly focus on the IR-free theories in this talk.

Q: What kind of criticality do these theories describe??

RG flow structure for large N_f



Massless (weakly coupled) fixed point separates two strongly coupled phases

Massless point is deconfined though both phases are confined (deconfined quantum criticality)

Nature of the two massive phases

m < 0: Trivial symmetric gapped phase.

m > 0: Dynamical SU(2) gauge field has a theta response at $\theta = N_f \pi$.

N_f even - standard SU(2) gauge theory => trivial symmetric gapped phase but could be in a different SPT phase.

Interesting example of continuous phase transition between trivial and SPT phases of bosons in 3+1-D (Bi, TS, 19) - not focus of this talk.

Focus here on N_f odd - m > 0 phase depends on fate of SU(2) gauge theory at $\theta = \pi$

SU(2) (and other non-abelian) gauge theories at $\theta = \pi$

A natural possibility: theory spontaneously breaks T

(believed to be true for high Nc and likely also for Nc = 2)

A modern point of view (Gaiotto, Kapustin, Komorgodski, Seiberg 2017)

Pure gauge theory has time reversal symmetry, and a 1-form Z_2 symmetry but there is a mixed anomaly between these

=> a trivial symmetry preserving ground state is not allowed.

Nature of T-broken phase

T-broken phase is confined - excitations are bosons.

Preserves global $Sp(N_f)/Z_2$ symmetry, and has no topological order.

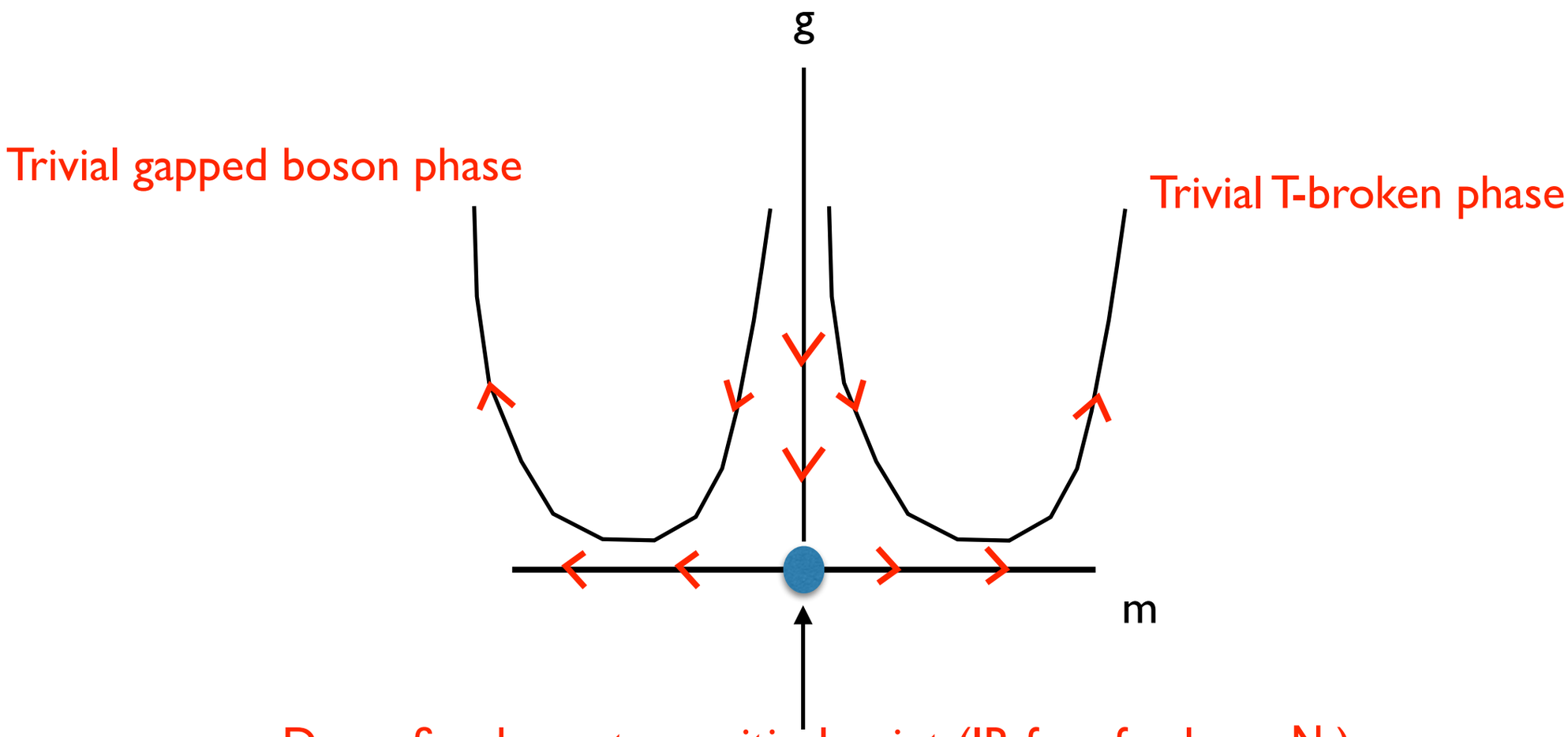
Response to background $Sp(N_f)/Z_2$ gauge fields:
Only possible theta term is $\propto Tr(F \wedge F)$

Once T is broken, the corresponding coefficient is not quantized.

=> no SPT order for unbroken $Sp(N_f)/Z_2$ symmetry.

T-broken phase has Landau order but is otherwise trivial

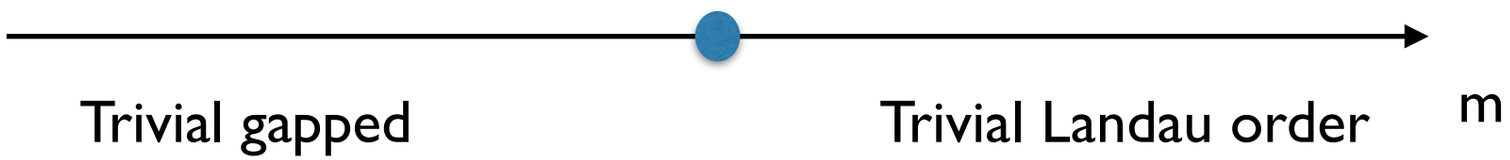
Interpretation of phase transition



Deconfined quantum critical point (IR free for large N_f);
definitely distinct from theory from standard 3+1-D Ising universality class

Landau ordering transition beyond the Landau paradigm

T = 0 phase diagram/crossovers

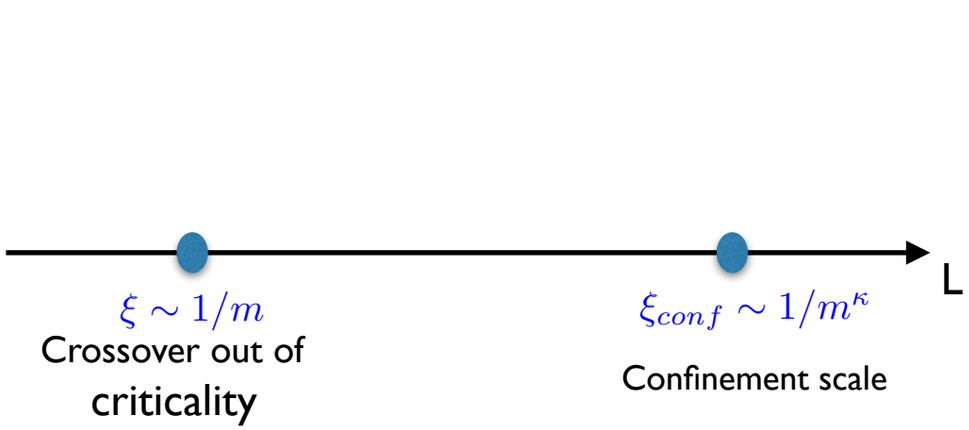


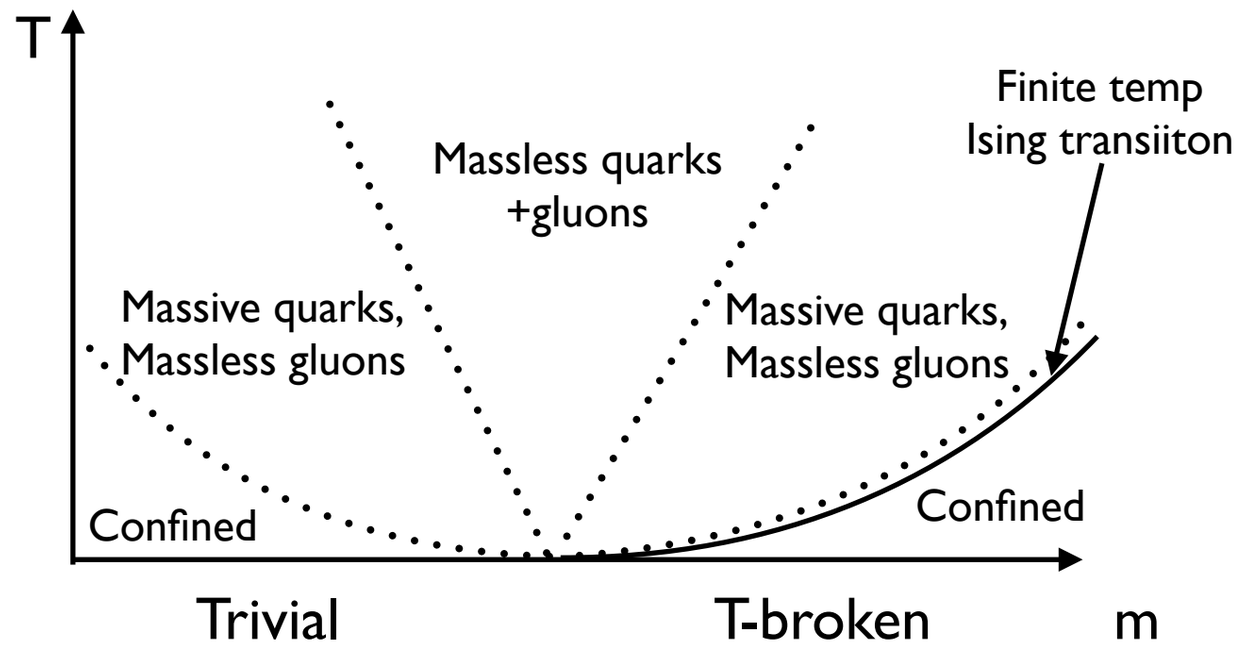
The transition could have been in the usual Ising universality class
but, here, happens in a different universality class with emergent fermions, etc.

In a putative microscopic lattice model, both these possibilities will be realized upon varying parameters.

Multiple universality classes for a Landau ordering transition.

Crossovers





Theory has two diverging length/time scales:

The true nature of the phases (including the Ising ordering) is only established at the second, longer, confinement length scale.

The essential physics of the transition is controlled by the crossovers at the first length scale: a topological transition of emergent fermions.

Comments

1. Despite being a Landau ordering transition, focusing on order parameter fluctuations alone is a distraction.

2. Can generalize to other gauge groups, eg $Sp(N_c)$ gauge theories with Nf fundamental fermions: also describe UV bosonic systems with same global symmetry, and the same phase transition.

3. New universality class is protected by the global $Sp(N_f)/Z_2$ symmetry even though this symmetry acts trivially in both phases.

   Breaking this symmetry is a relevant perturbation at this deconfined quantum critical point. (Similar phenomena also in 1+1-D (Jiang, Motrunich 2019)

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Other interesting Landau ordering transitions

1. 3-state Potts model in 1+1-D

Landau mean field - first order but fluctuations allow for a second order transition

2. CP^N models in 2+1-D at large enough N (and other similar large-N gauge theories)

Landau mean field for gauge invariant order parameter: first order transition

But the transition is second order with a deconfined quantum critical point

Both of these are presumably (?) describable within the LGW framework but the resulting theories are strongly coupled

Contrast with the example in this talk: second order in standard Landau theory but also admits a new universality class protected by a global symmetry.

Quantum criticality in condensed matter

Our intuition for what kinds of continuous quantum phase transitions are possible and their description is very poor.

Textbook example:

Landau order Trivial phase

Even here a quantum Landau-Ginzburg-Wilson (LGW) theory of fluctuating order parameter may fail !

Perhaps the mechanism in the example discussed in this talk suggests some new route to the Landau ordering transition in metals.