Beyond LGW

- Driven partly by experiment and partly by theory, recent research in quantum criticality mostly focuses on situations *beyond* the Landau-Ginzburg-Wilson paradigm
- That is, situations in which an approach based on an order parameter alone is inadequate

When do we go beyond?

1. When a neighboring phase has lots of gapless excitations (like in metals!)
2. When a neighboring phase is not described by an order parameter
3. Sometimes even if both the neighboring phases and their excitations are ordinary, unconventional behavior can emerge at the QCP

When do we go beyond?

1. **When a neighboring phase has lots of gapless excitations (like in metals!)**
   1. Failure of Hertz theory for most such QCPs motivates other approaches
   2. Conservation approach: strongly-coupled fermion-boson criticality
   3. Radical approach: "Kondo breakdown"

Kondo effect

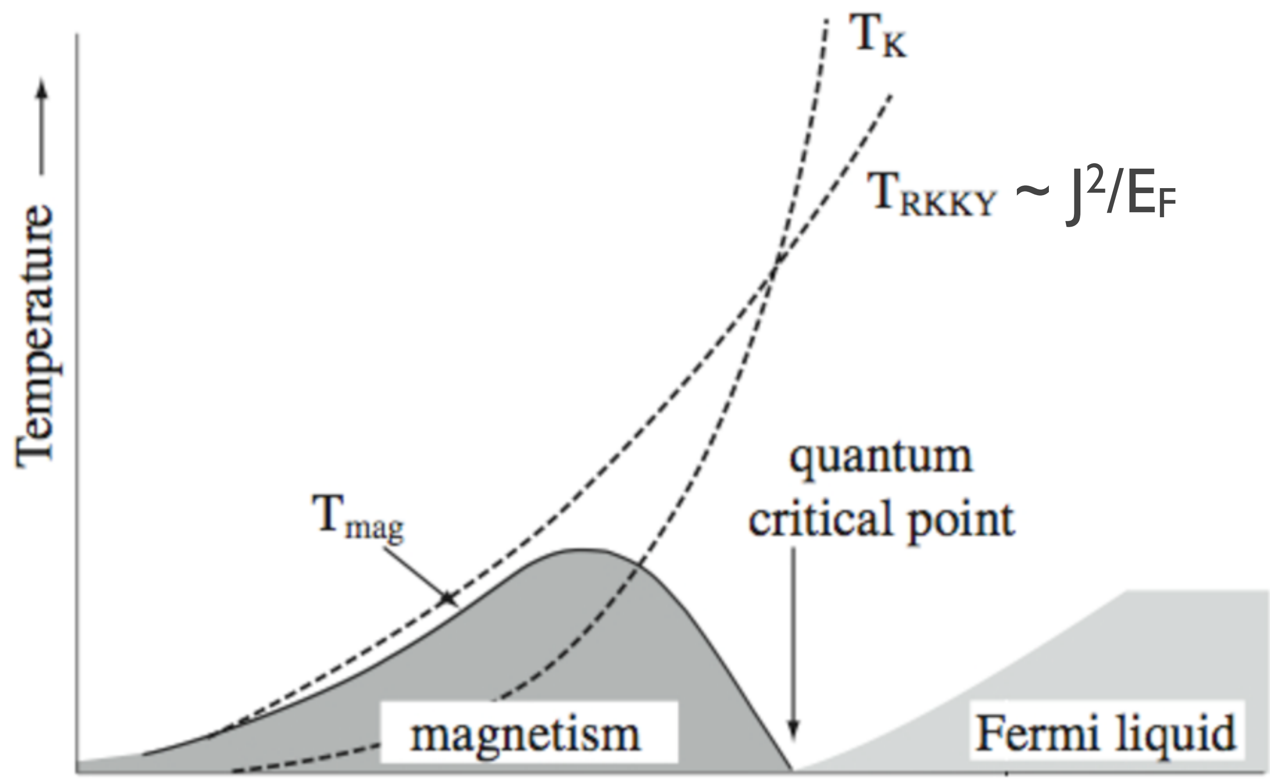
- Kondo effect:
  - a spin can be *screened* by coupling to conduction electrons
  - this happens with a "binding energy" which is exponentially small

$$k_B T_K \sim \epsilon_F e^{-\epsilon_F / J_K}$$

  - When there are many spins, the Kondo effect competes with the tendency of spins to order - RKKY interaction

Doniach diagram

?? Is the QCP a Kondo breakdown transition ??



"light" carriers

J/E_F

"heavy fermion": spins included in the carriers

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Phases without order parameters

- Phases are more fundamental - and more important - than phase transitions
- Usually, they are distinguished by symmetry
- But phases may differ even with the same symmetry
  - Excitations or other properties may be qualitatively different in two phases

Phases without order parameters

- Example: metal versus insulator
  - both are possible with the same symmetry, but excitations differ qualitatively, as does conductivity
  - but at T>0, they are the same phase
  - one can still have a T>0 *first order* "Mott transition", e.g. VO_2, V_2O_3,...
- There are other types of "quantum order" that can distinguish a phase

Mott transitions

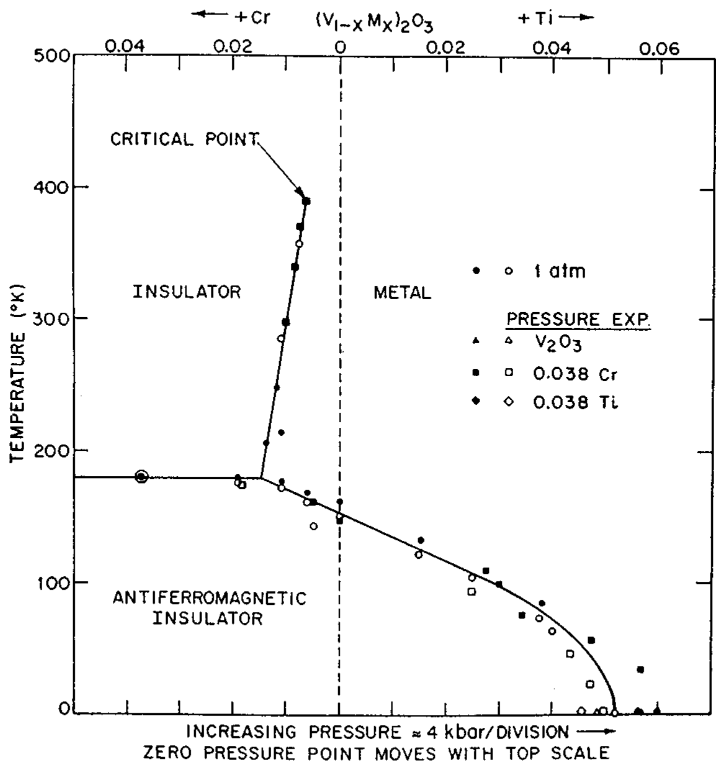
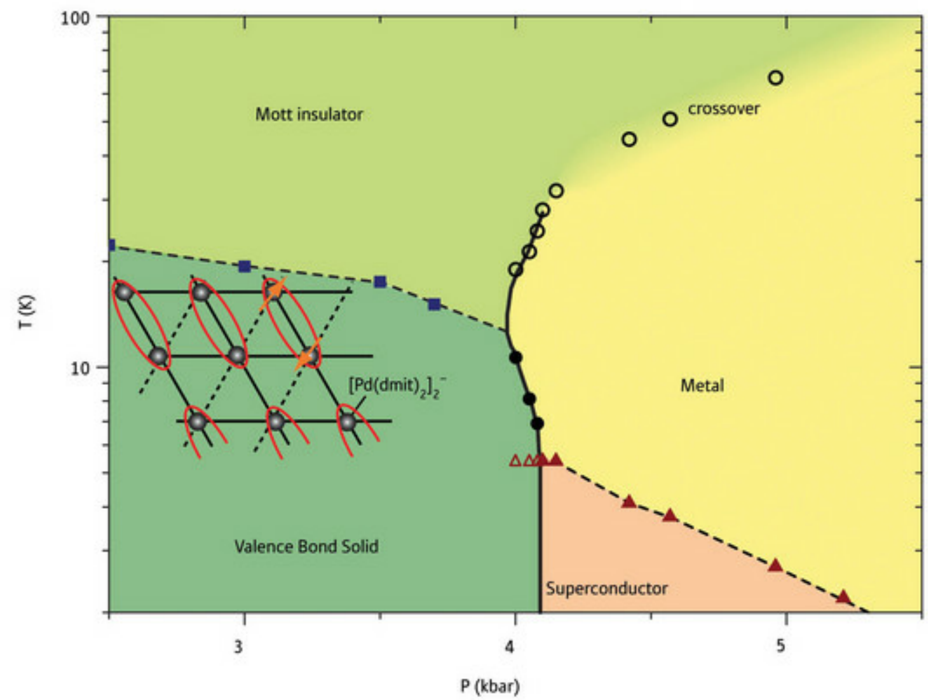


FIG. 70. Phase diagram for doped V_2O_3 systems, $(V_{1-x}Cr_x)_2O_3$ and $(V_{1-x}Ti_x)_2O_3$. From McWhan *et al.*, 1971, 1973.



Quantum orders

- Simplest cases are quantum phases in which there is a gap to all (bulk) excitations
- In this situation, there are "topological orders"
  - e.g. "Topological Insulators" : just non-interacting band insulators which are distinct from usual ones by "twisting" of wavefunctions of occupied bands
  - more interesting are "topological phases" : ground states of interacting electrons that host exotic excitations with fractional (or nonabelian) statistics (Q)

Examples?

- quantum Hall state (TI)
- toric code
- quantum spin liquid (RVB)
- entanglement entropy
- deconfined quantum critical points