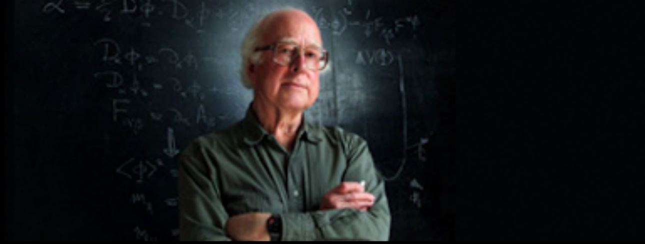
The Higgs Centre
For Theoretical Physics



New Directions In Theoretical Physics: Edinburgh 8th – 10th Jan 2014

Condensed Matter: Plenty of Places To Go…
…but which direction to get there?

Andy Schofield

School of Physics & Astronomy

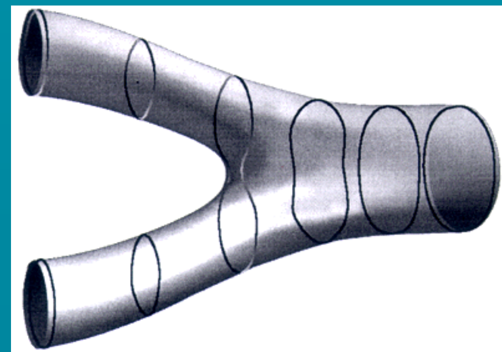
University of Birmingham

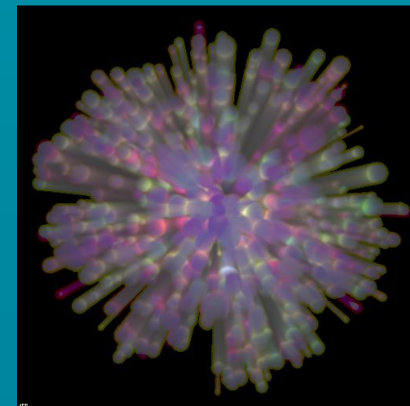
O. Tsyplyatyev and A. J. Schofield, Phys Rev B 88, 115142 (2013):
How much of the low energy quasiparticle is left to influence the higher energy physics?

Supported by EPSRC grant EP/J016888/1

High energy challenge: unravelling emergence

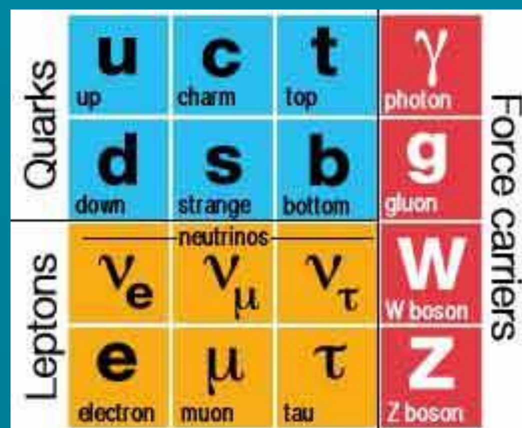
Unification?

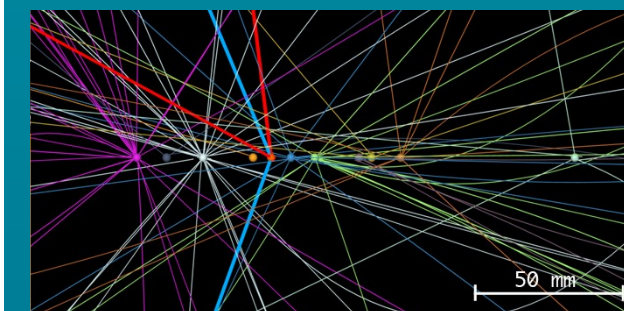




Big bang

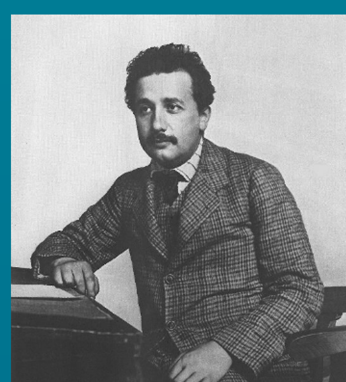
"Standard Model"
+ Einstein's GR

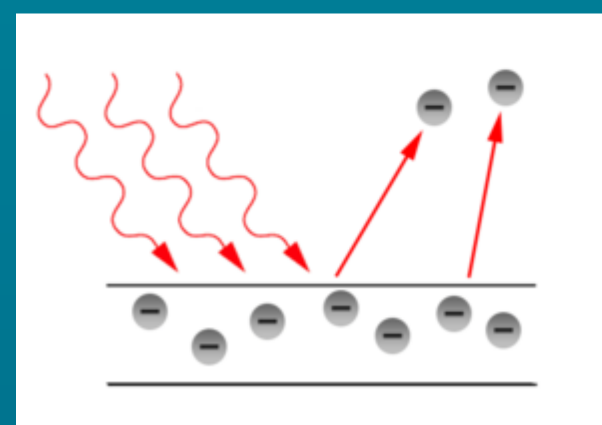




7TeV

Quantum
theory

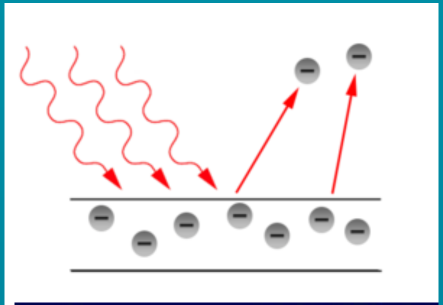




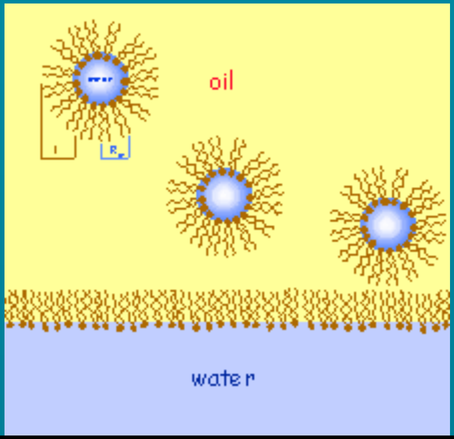
10eV

Condensed matter challenge: understanding emergence

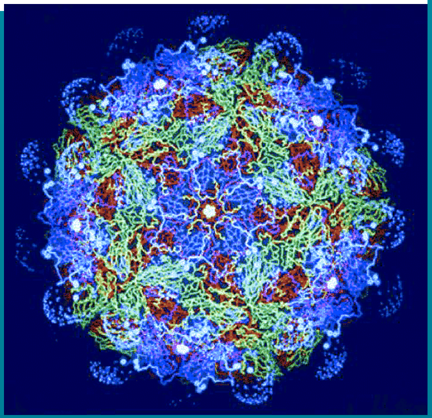
Schrödinger equation



$10eV \sim 10^5 K$



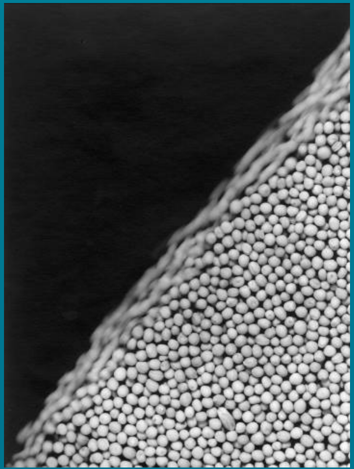
Soft matter
k_B, ($\hbar$=0)



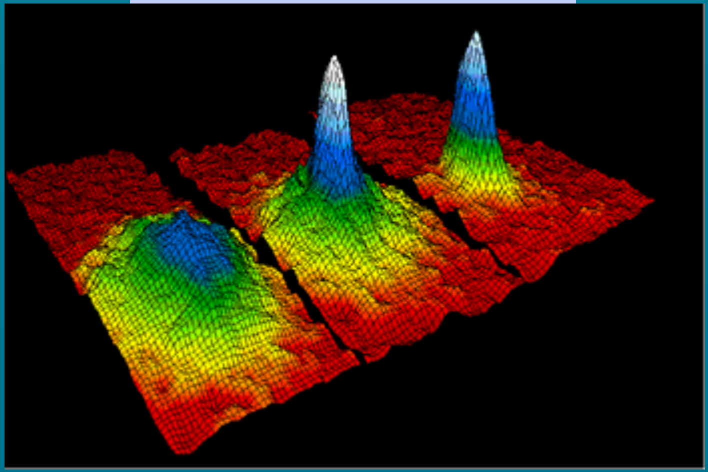
Biological Matter ($\hbar$=0?)

10^2 K

1 K

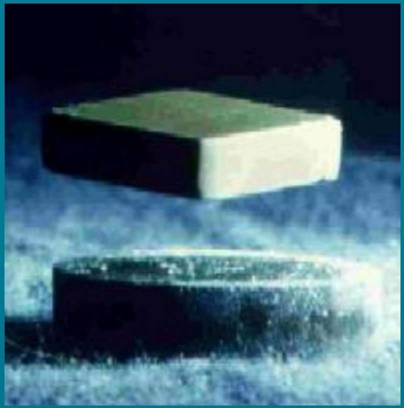


Non-equilibrium



Atom traps (k_B, $\hbar$)

10^{-9} K



“hard” condensed matter (k_B, $\hbar$)

Synergy: condensed matter and high energy theory

1940/50' s	**Many Body Physics** (imaginary time)	←	**QED** (Field Theory, Feynman diagrams)
50/60' s	Broken Symmetry, **Superconductivity**	→	Revival of Field Theory **Higgs**, Standard Model
60/70' s	**Critical phenomena** (stat mech/expt)	↔	**Renormalization**, Field Theory
	Nucleation	→	Inflation
70-90' s	Kondo, Heavy Electrons 1D conductors Edge states	←	QCD, Gross Neveu, Large N conformal field theory
2010' s	Quantum Critical Matter	←	Higher dimensional classical gravity in novel spaces

Challenges in quantum matter:
Our "Standard Model" can be shown to fail in some experiments

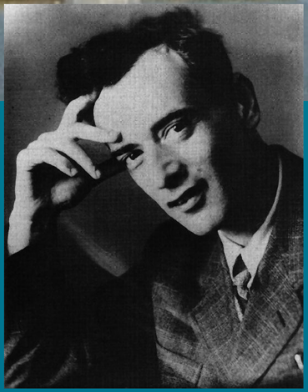
Two key ideas of emergence in correlated quantum matter are under siege

The electron quasiparticle
Fermi liquid theory

Critical fluctuations
(Quantum criticality)

Fermionic excitations

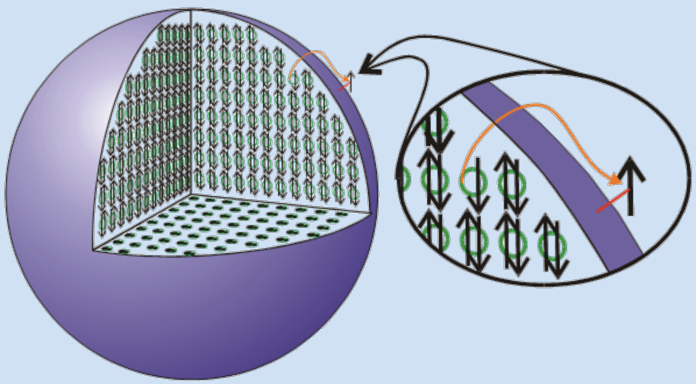
Bosonic excitations



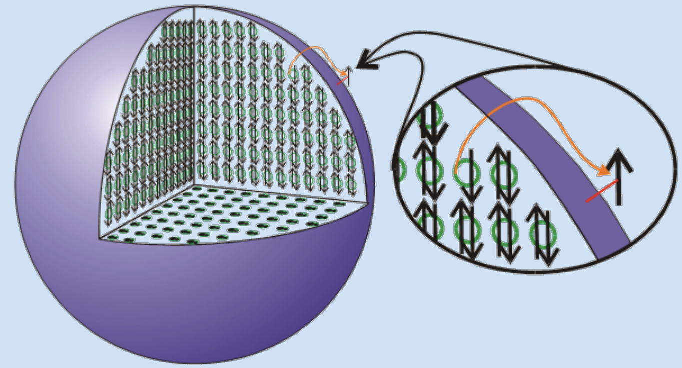
Landau

Slide Idea: Ashvin Vishwanath

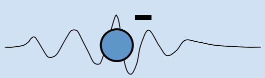
Landau's Fermi liquid – the "Standard Model" of metals



Interactions
adiabatically

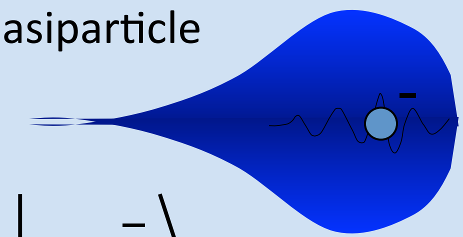


Free electrons



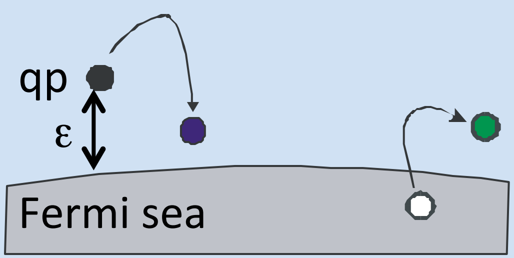
$$\left| e^- \right\rangle$$

Quasiparticle



$$\left| qp^- \right\rangle$$

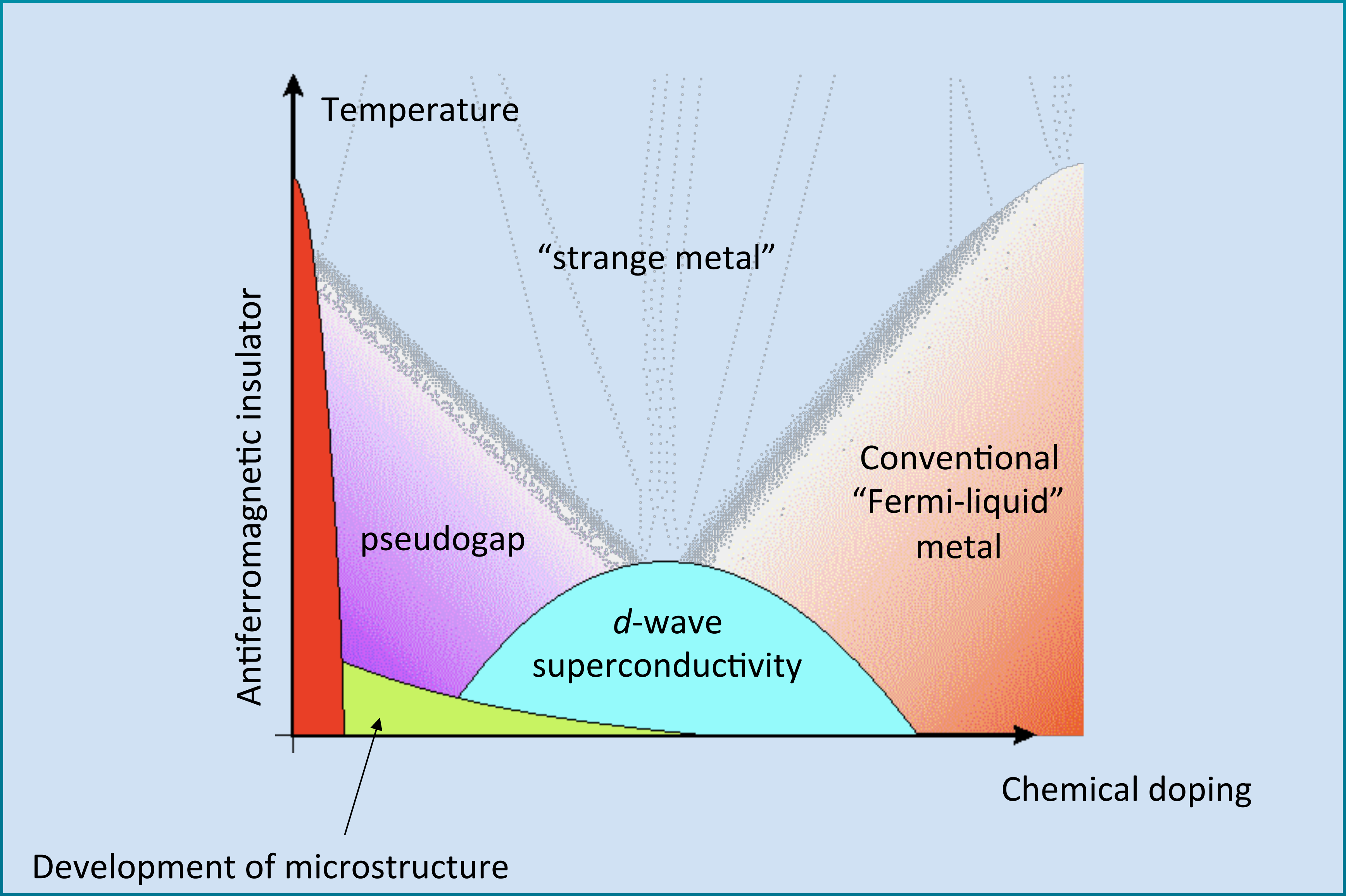
Phase space provides self-consistency: consider the decay rate of a quasiparticle



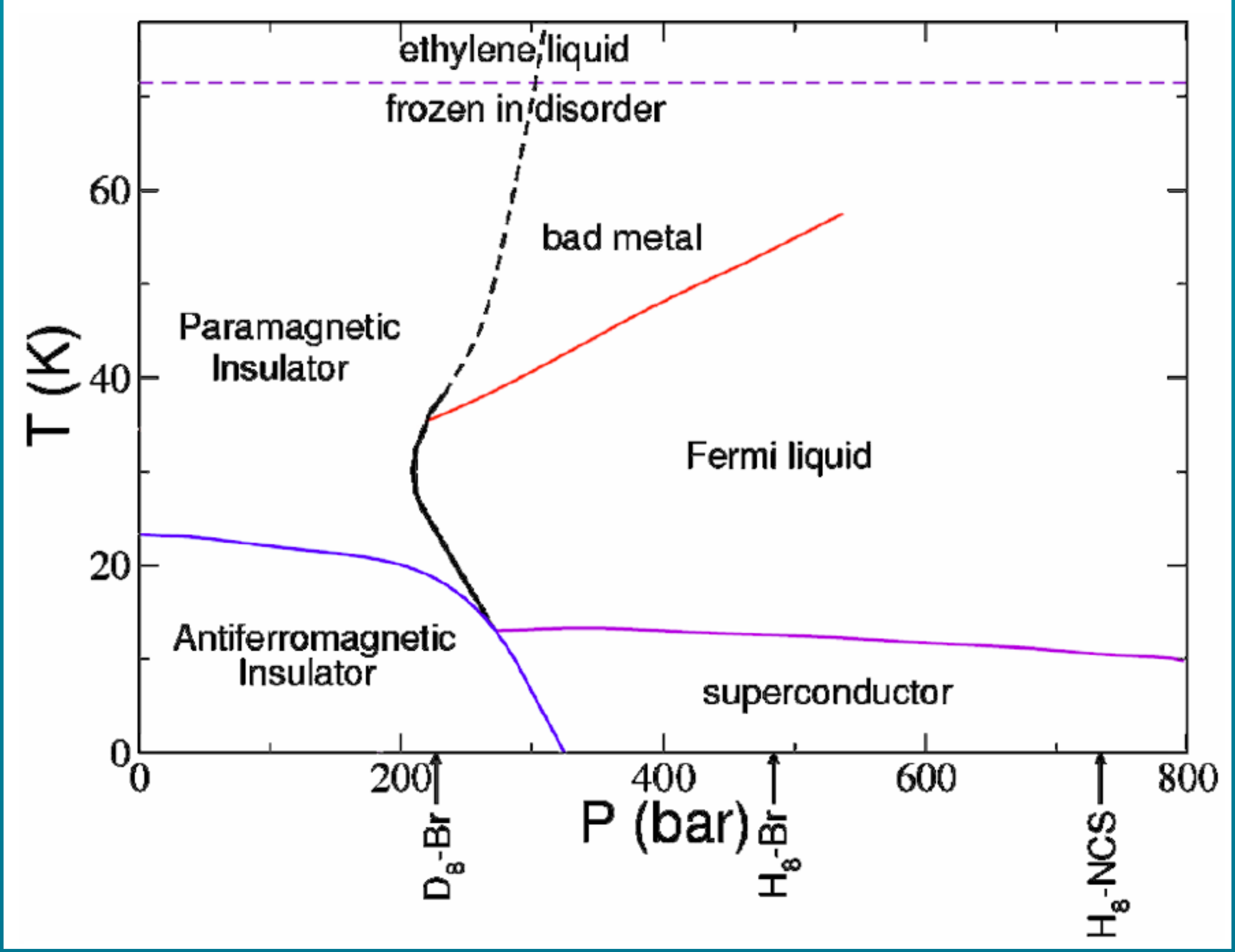
$$\frac{1}{\tau_\epsilon} = \frac{2\pi}{\hbar} \sum_f |V_{if}|^2 \delta(\epsilon - \epsilon_f) \sim \frac{\pi}{\hbar} |V|^2 g_F^3 \epsilon^2$$

$$\Longrightarrow \rho \sim T^2$$

The legacy of cuprate "Hi-T_c" superconductors



…and now seems to be more general

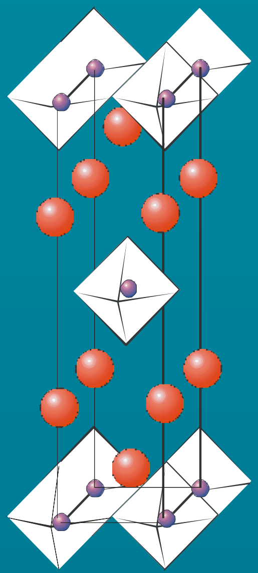


Phase diagram for a set of organic salts under pressure: κ-$(ET)_2X$
taken from Powell and Mckenzie, PRL (2005).

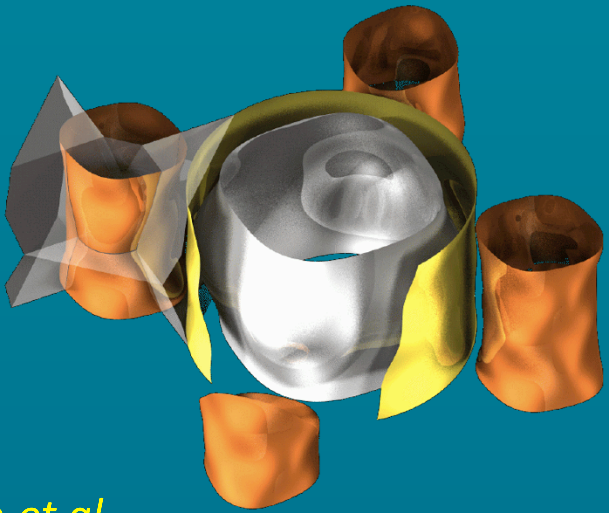
Sr_2RuO_4: an exemplar of Fermi liquid theory

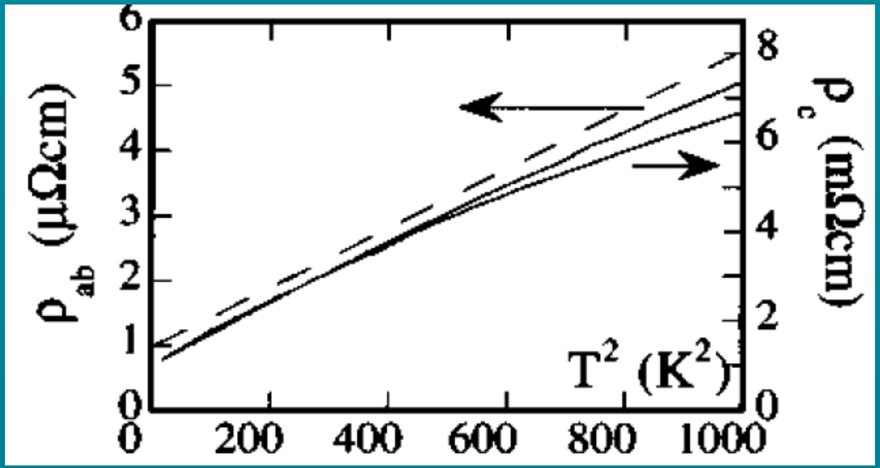
- c1990 High T_c cuprates: Do 2D Fermi liquids exist?
  - e.g. P W Anderson; PRL **64**, 1839 (1990),

Sr_2RuO_4: the control experiment



- Isostructural to the cuprates
- Allowed high precision tests of Fermi liquid theory





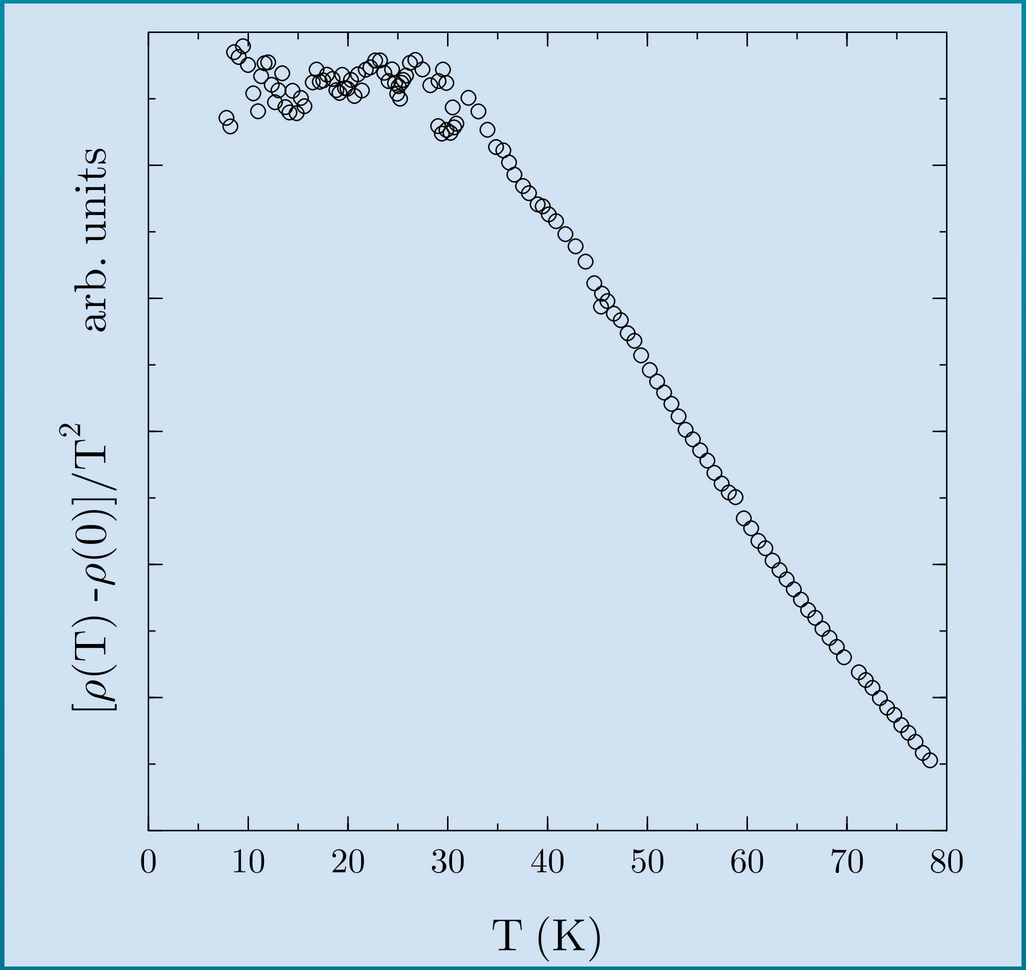
N.E. Hussey et al. PRB (1998).

C. Bergemann *et al.*,
Adv. Phys. 52, 639 (2004).

Sr_2RuO_4: a scale between low energy FL quasiparticles and ?

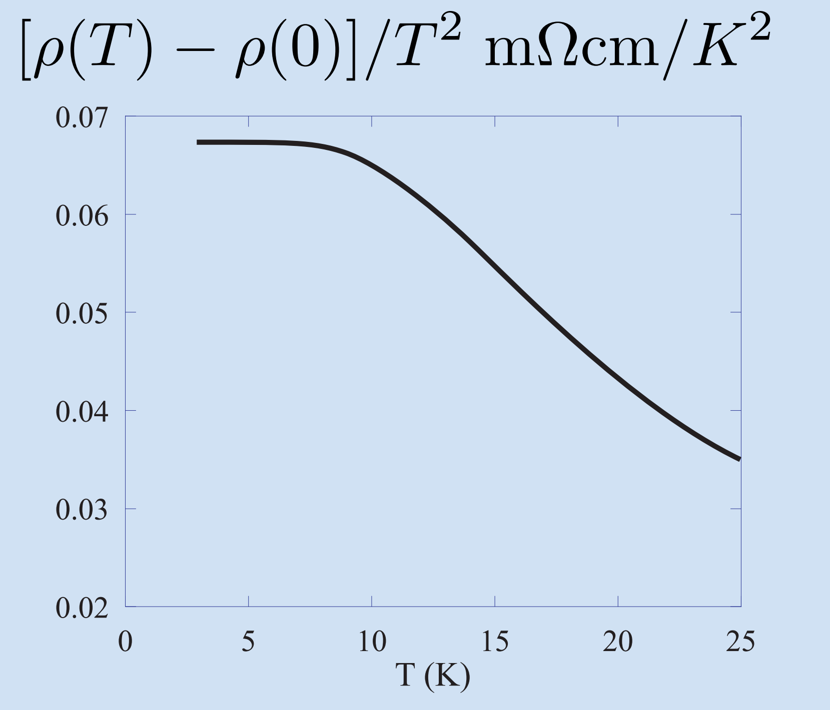
- The "Emery Plot"

$$\frac{\rho(T) - \rho(0)}{T^2}$$

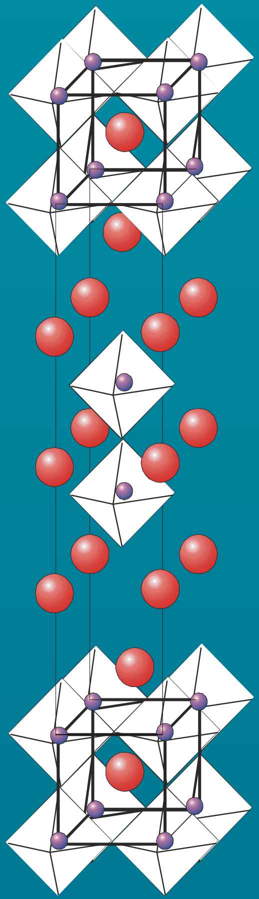


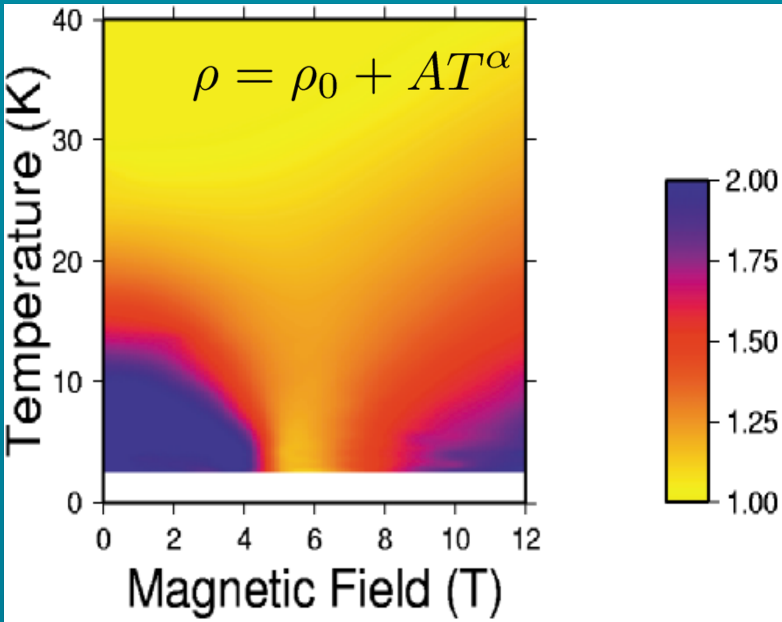
A. P. Mackenzie et al. circa 1999 (unpublished)

Quantum criticality: driving that scale to zero
e.g. $Sr_3Ru_2O_7$



A. P. Mackenzie et al circa 1999 unpublished

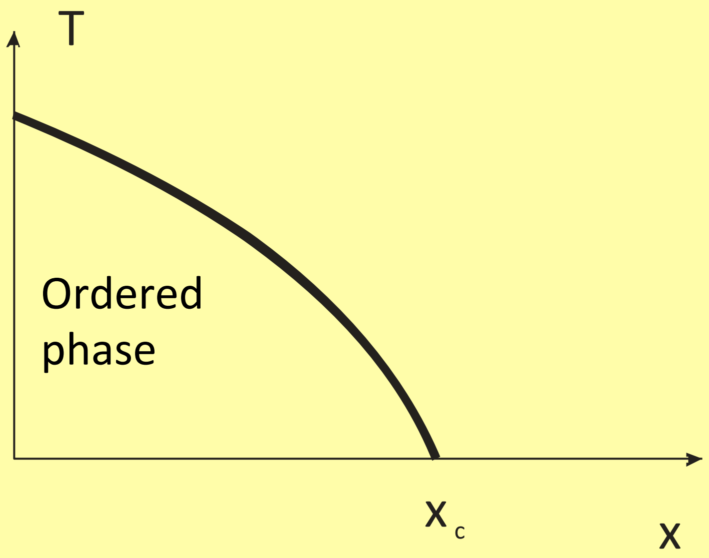




R. S. Perry, L. M. Galvin, S. A. Grigera, L. Capogna, A. J. Schofield, and A. P. Mackenzie, M. Chiao and S. R. Julian, S. I. Ikeda, S. Nakatsuji, and Y. Maeno, C. Pfleiderer Phys. Rev. Lett. **86**, 2661 (2001)

Generating quantum criticality

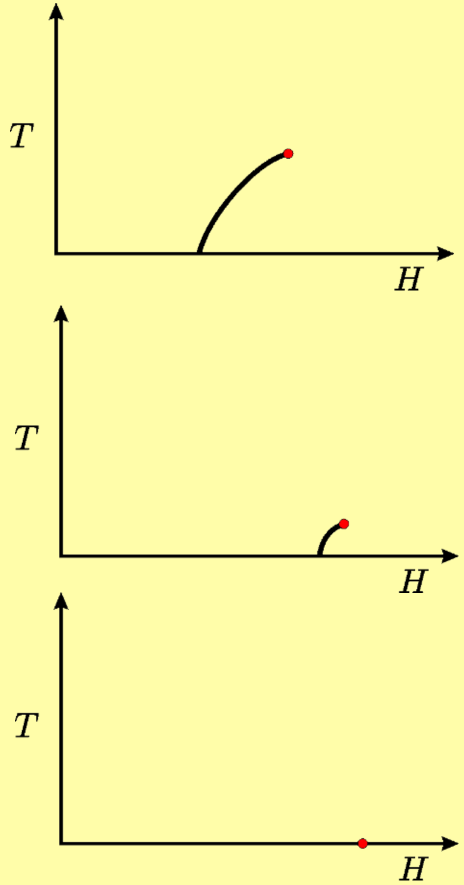
Continuous phase transition driven to T=0



Example: **$CePd_2Si_2$** Antiferromagnetism tuned by pressure.

[S. R. Julian *et. al.* J. Phys. C. (1996)]

Critical end-point driven to T=0

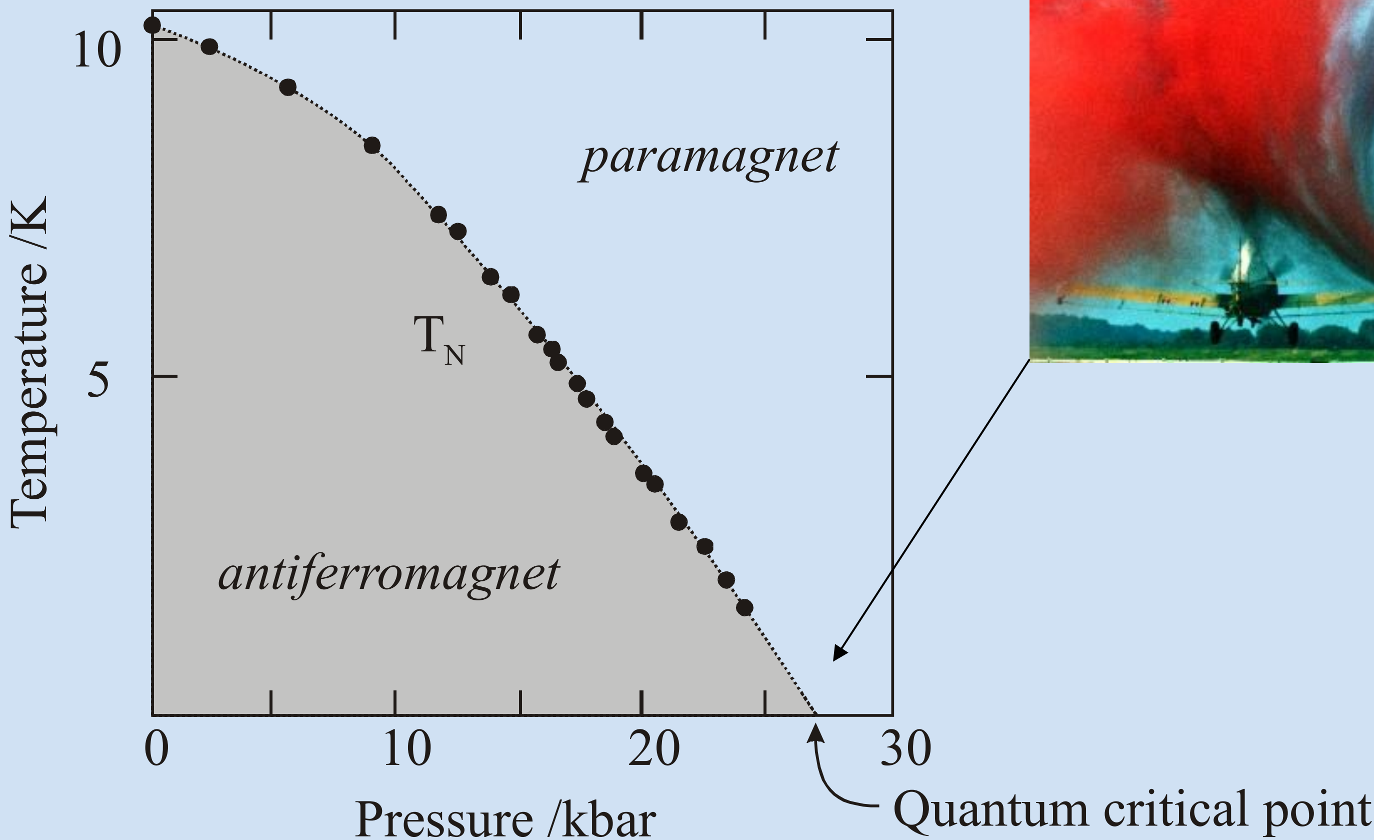


Example: **$Sr_3Ru_2O_7$** Metamagnetism tuned by magnetic field angle

[S.A. Grigera *et al.*, Science (2001)]

Quantum criticality – a route to a non Fermi liquid

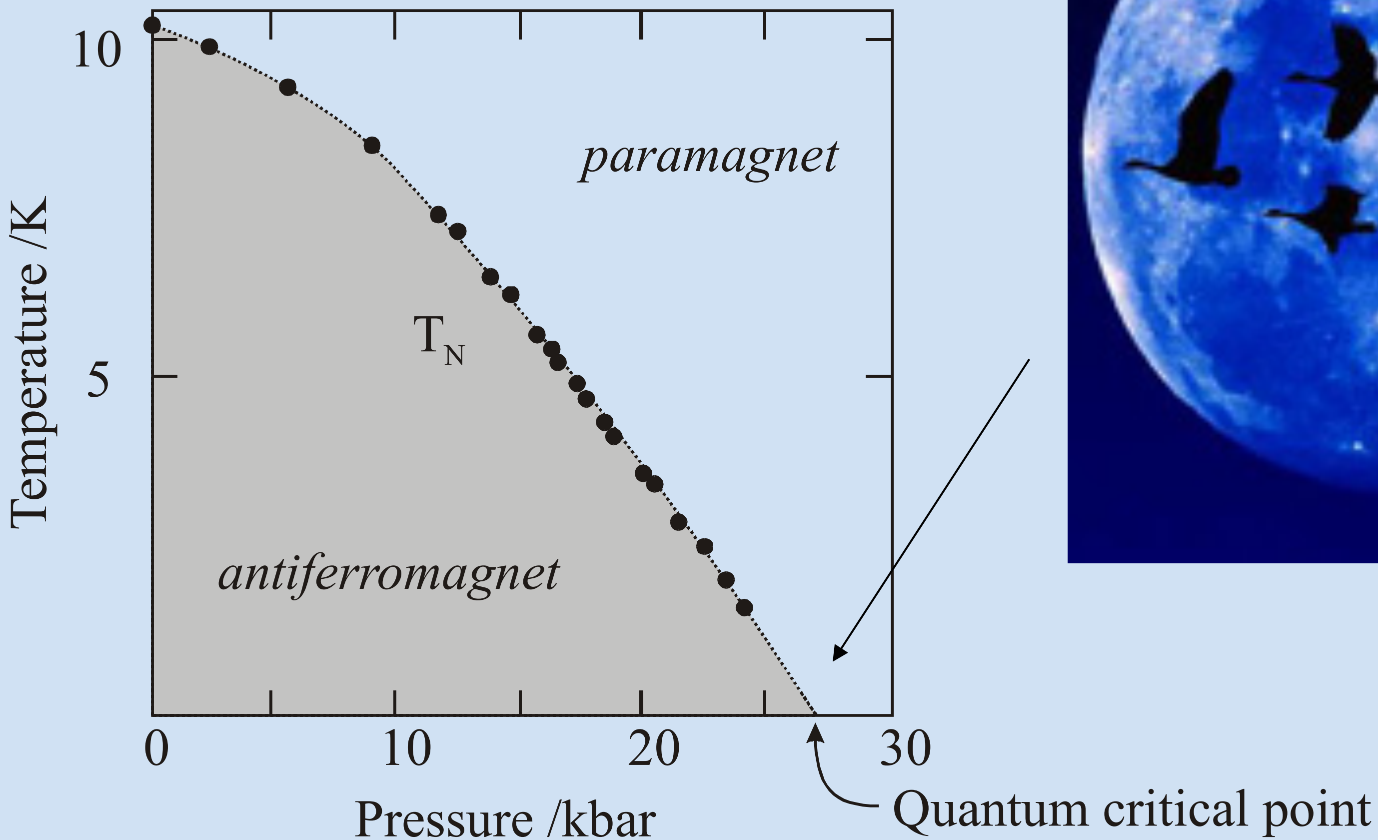
e.g. $CePd_2Si_2$ under pressure



S. R. Julian *et al.* J. Phys: Condens. Matt., **8**, 9675 (1996)

Quantum criticality – a route to new correlated states

e.g. $CePd_2Si_2$ under pressure

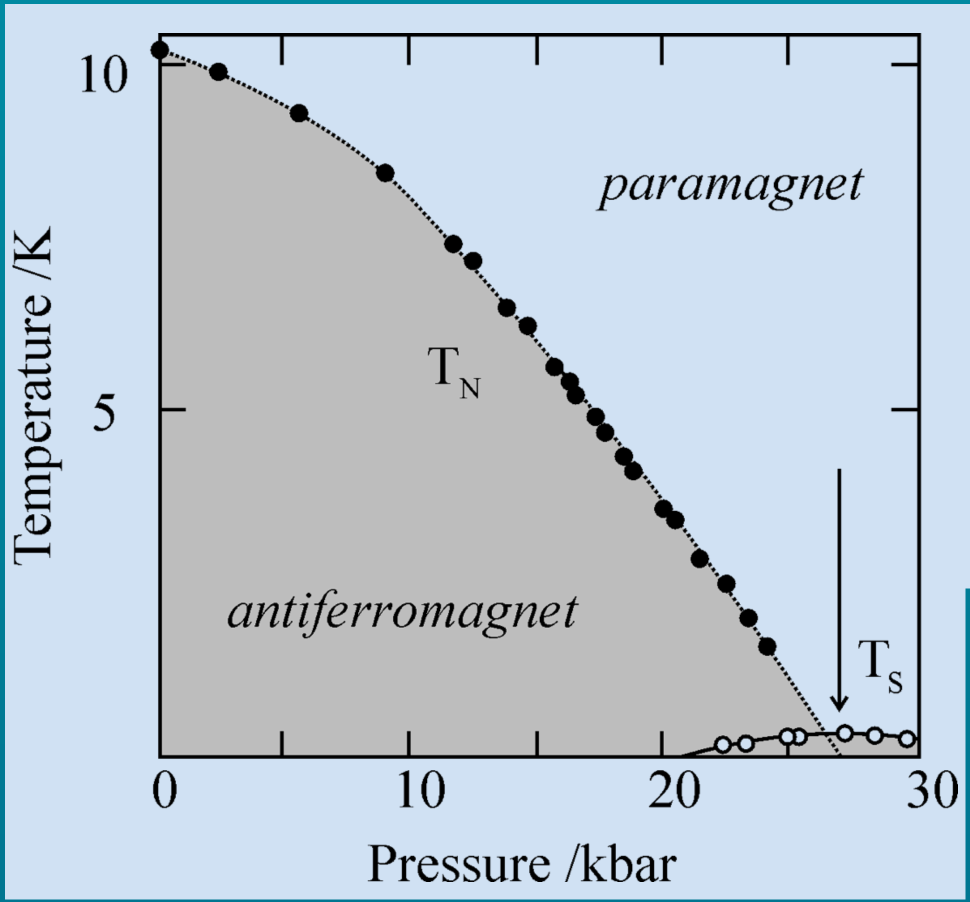


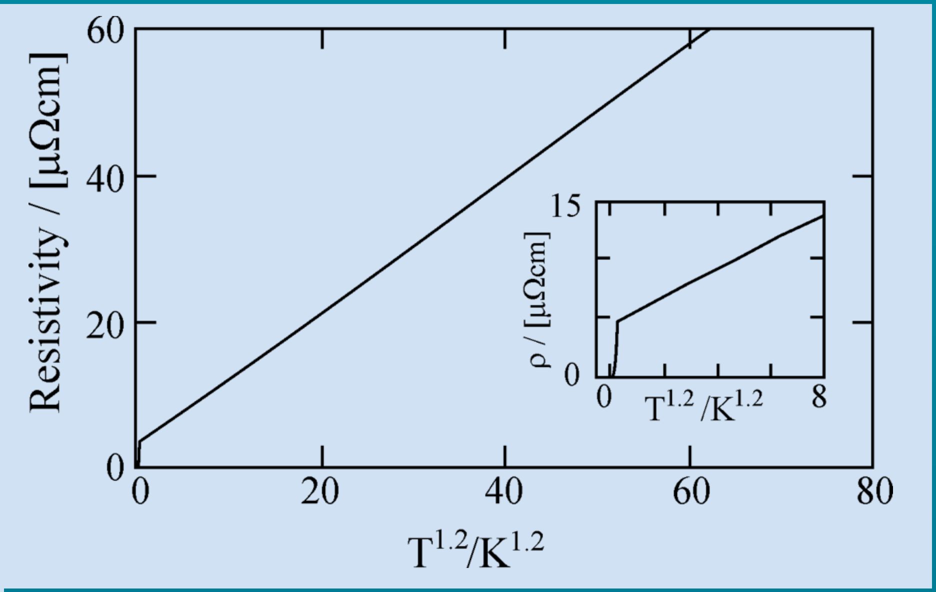
S. R. Julian *et al.* J. Phys: Condens. Matt., **8**, 9675 (1996)

Fresh impetus – tuning a material to quantum criticality

H. v. Löhneysen, T. Pietrus, G. Portisch, H. G. Schlager, A. Schröder, M. Sieck and T. Trappmann Phys. Rev. Lett. **72**, *#20*, 3262-3265 (1994).

e.g. pressure tuned $CePd_2Si_2$





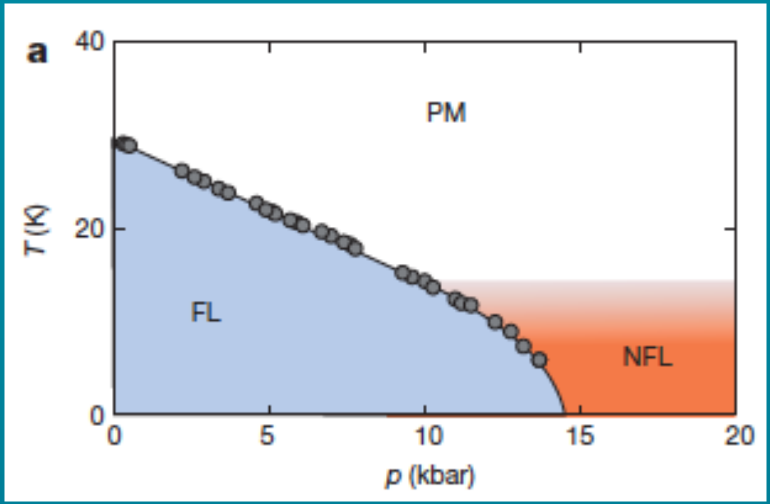
$$\rho \sim T^{1+\epsilon}$$

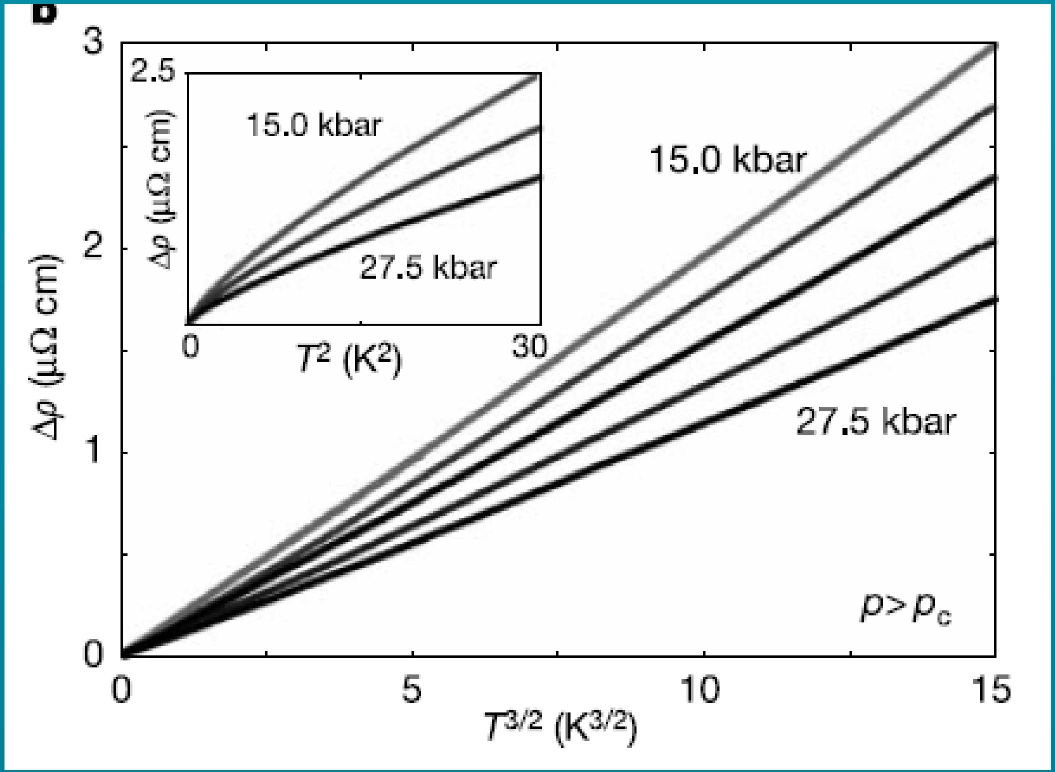
Subtlety: need to include disorder
A. Rosch, Phys Rev Lett **82**, 4280 (1999)

S.R.Julian et al. J. Phys.:cond. matt. **8**, 9675 (1996).

Puzzle 1: A non-Fermi liquid phase?

MnSi: a helical magnet tuned with pressure



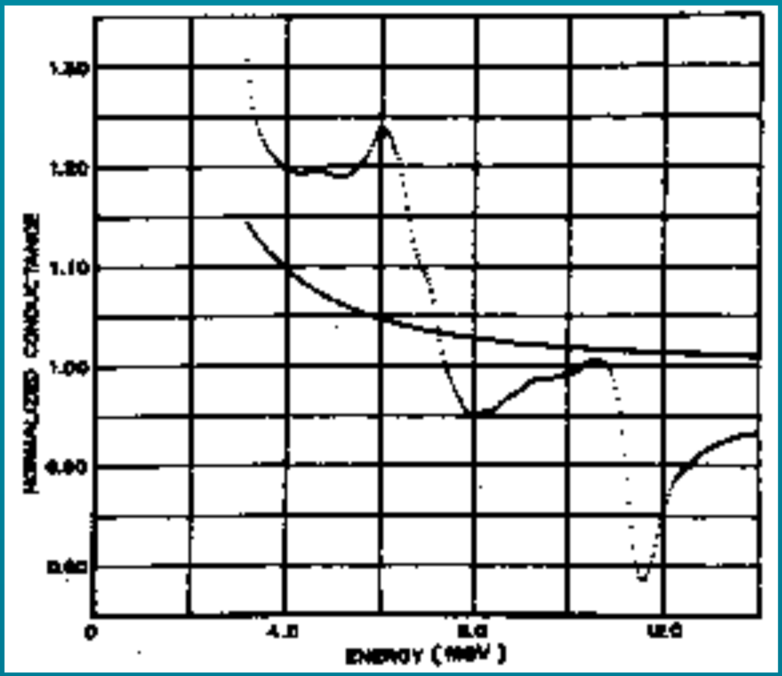


- A line of quantum criticality points?
- Not the only example: also seen in:
  - $ZrZn_2$ [Smith et al. Nature (2008)]
  - $PrNiO_3$ [Zhou, PRL (2005)]

N. Doiron-leyraud et al. Nature (2003);
R. Ritz et al. Nature (2013).

Puzzle 2: The origin of pairing in novel superconductors

- Conventional: retarded electron-phonon interaction

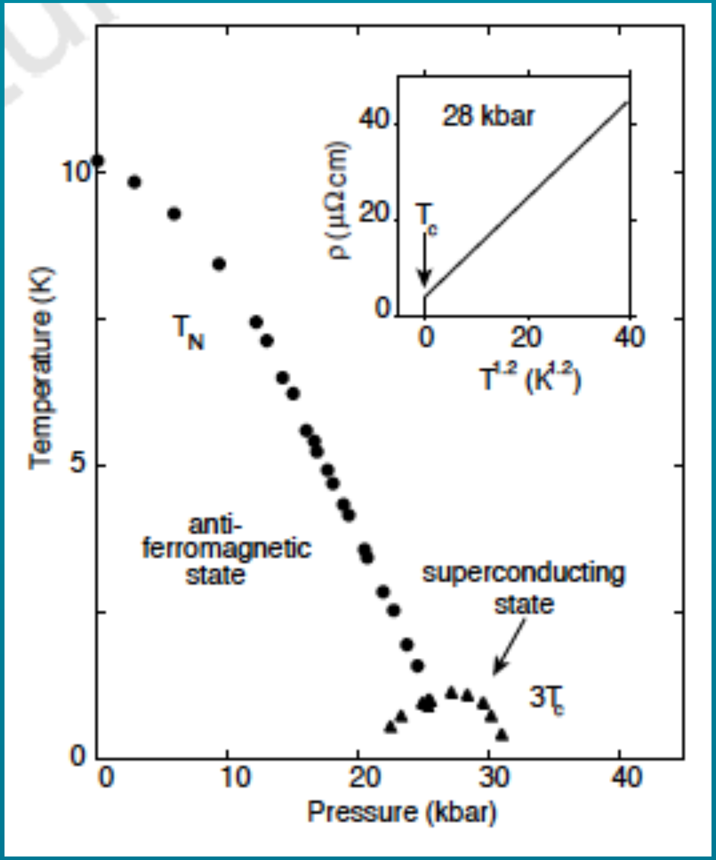


"Proof": from energy structure in the superconducting gap (tunnelling density of states). Can be quantitatively related to the phonon spectrum.

McMillan & Rowell (1969).

Puzzle 2: The origin of pairing in novel superconductors

- Unconventional: widely believed to be magnetic "glue"



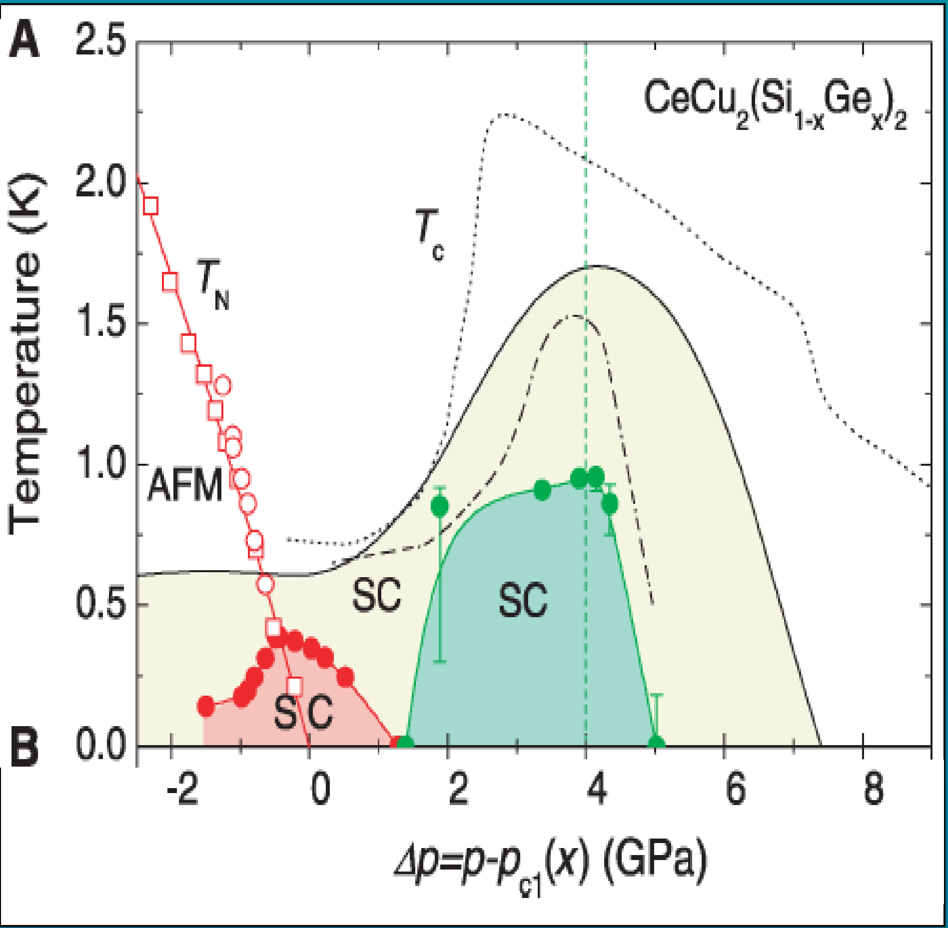
"Proof":
(1) Prediction of *d*-wave pairing – later seen in the cuprates: Scalapino et al. (1986)

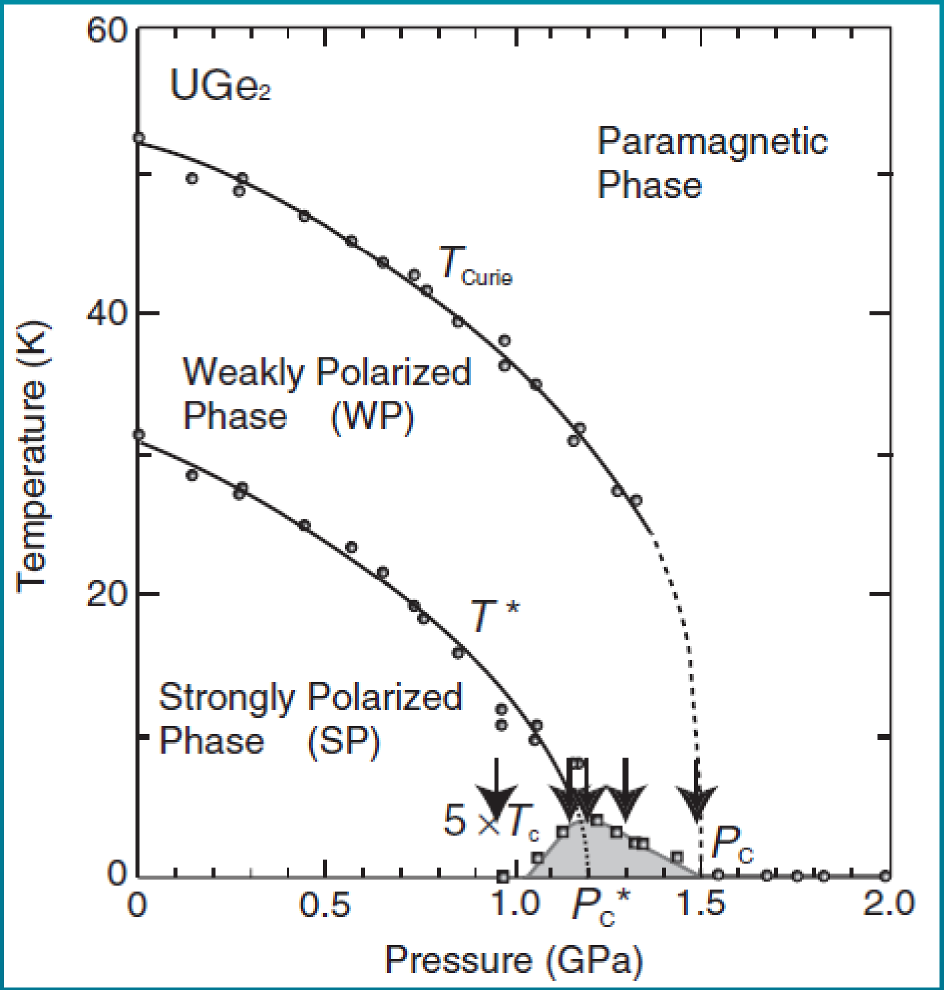
(2) Frequent proximity of superconductivity to magnetic instabilities – a reliable route to new superconductors.

N. Mathur et al., Nature (1998).

Puzzle 2: The origin of pairing in novel superconductors

- Yet proximity could be misleading…



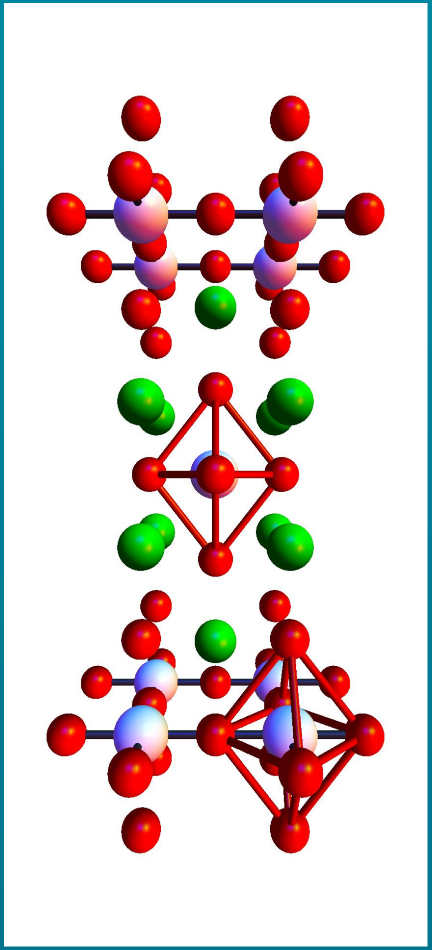


H. Q. Yuan, F. M. Grosche, M. Deppe, C. Geibel, G. Sparn, F. Steglich
Science **302**, *#5653*, 2104-2107 (2003).

Y Kitaoka *et al* 2005 *J. Phys.: Condens. Matter* **17** S975-S986

Puzzle 2: The origin of pairing in novel superconductors

- A good theory should be falsifiable:
  e.g. interlayer tunnelling mechanism:
  J. M. Wheatley, T. C. Hsu and P. W. Anderson, (1988)



Mechanism:

- Novel excitations made up the normal metal and were confined to the CuO_2 planes.
- Superconducting state was made of normal Cooper pairs which could move between planes.

Prediction:

- Condensation energy for pairing comes from the KE gain of liberated Cooper pairs

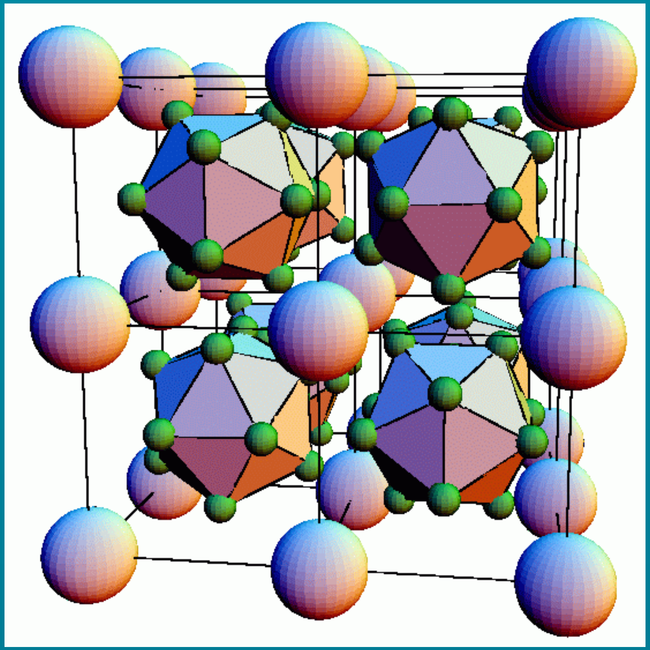
Experiment:

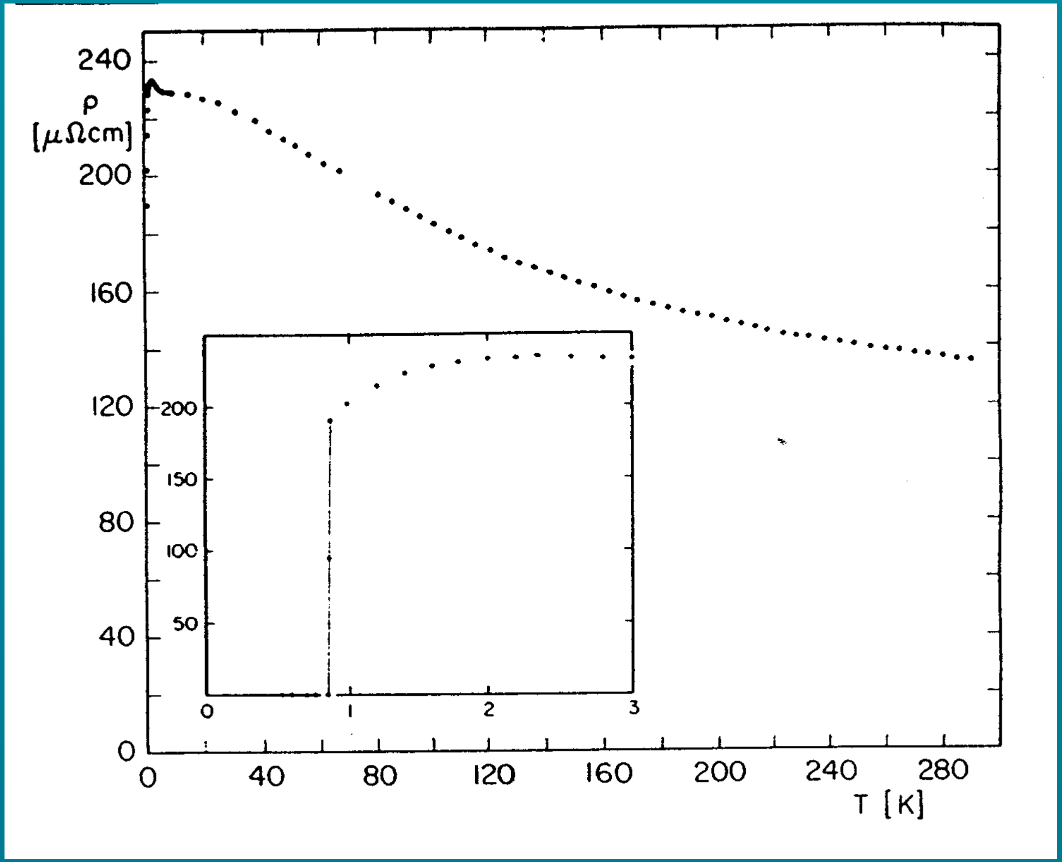
- Measure condensation energy (specific heat)
- Compare to KE of pairs in c-axis from their pair oscillations (plasma frequency) in optical cond.

Result: this mechanism provides < 5% of the energy (Tsvetkov et al., 1998)

Puzzle 2: The origin of pairing in novel superconductors

- Yet we are missing something – how can superconductivity arise in UBe_{13}?



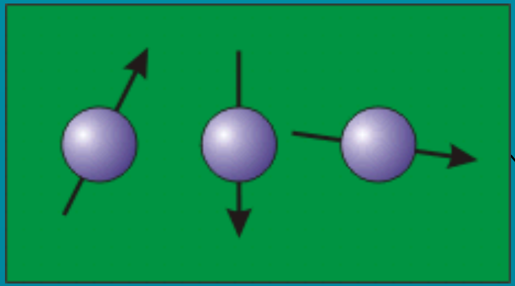


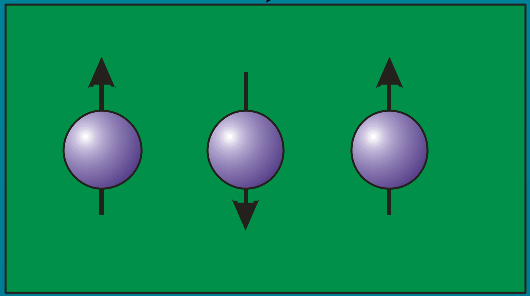
Ott et al. PRL (1983).

Puzzle 3: The fate of the spins in Kondo lattices

P. Coleman, C. Pépin, Q. Si & R. Ramazashvili; J. Phys. C. **13** R723 (2001)

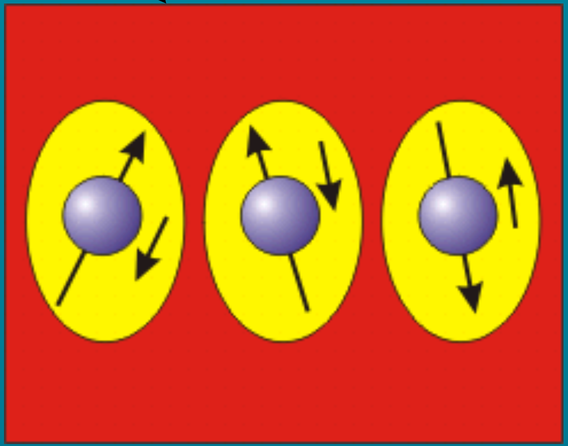
High temperature
free magnetic moments
+ conduction electrons
$N_e=N_c$





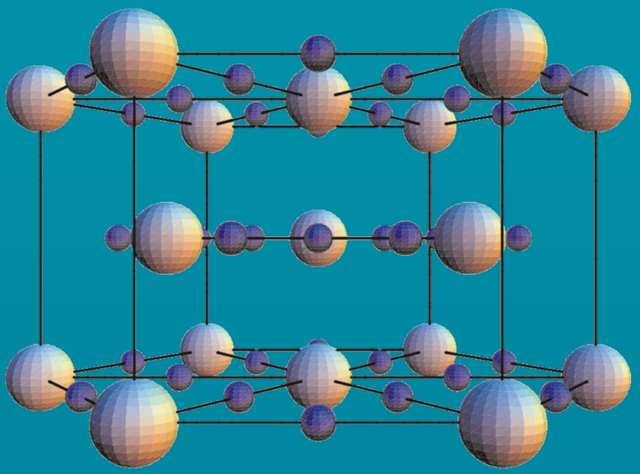
Low temperatures
Free spins order, and
$N_c=N_c$ (small Fermi volume)

OR



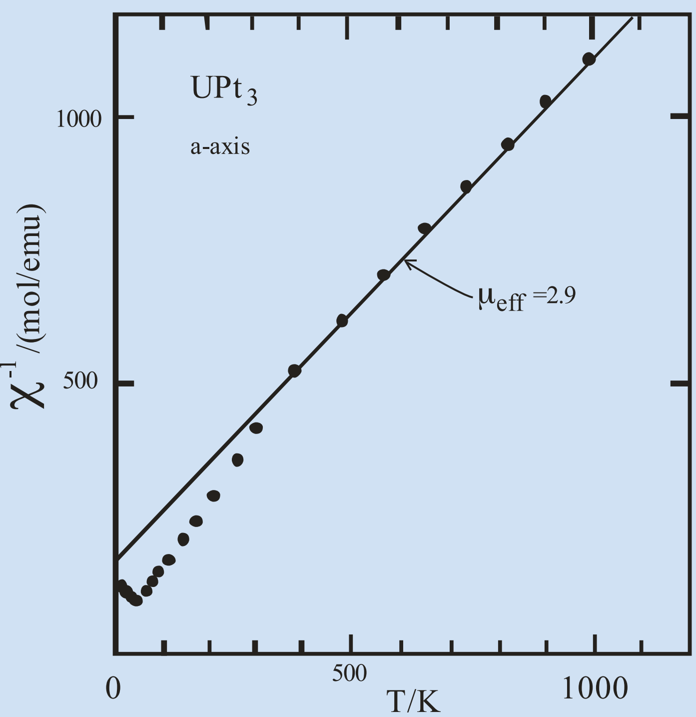
Low temperatures
No free spins but very heavy electrons ($m\sim 10^3\ m_e$) and
$N_e=N_c+N_f$ (large Fermi volume)

Experimental example: UPt_3



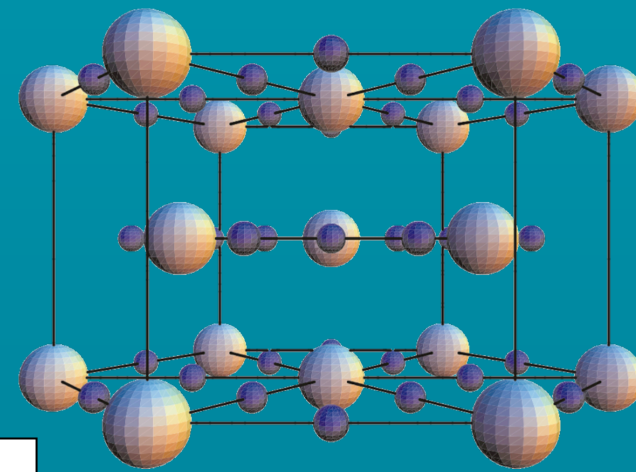
A heavy Fermi liquid: $U \sim 5f^3$

High temp: f electrons bound to form a local moment via Hund's rule (~ 1eV):



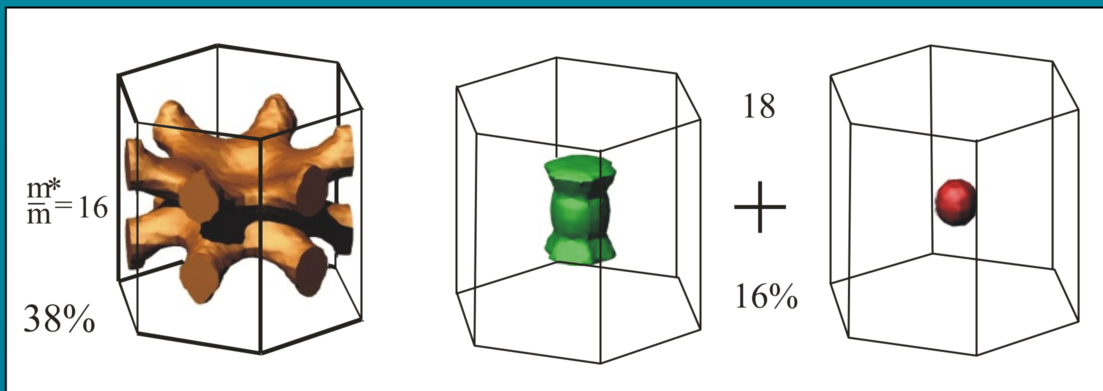
Frings *et al.*,
JMMM 31-34, 240 (1983).

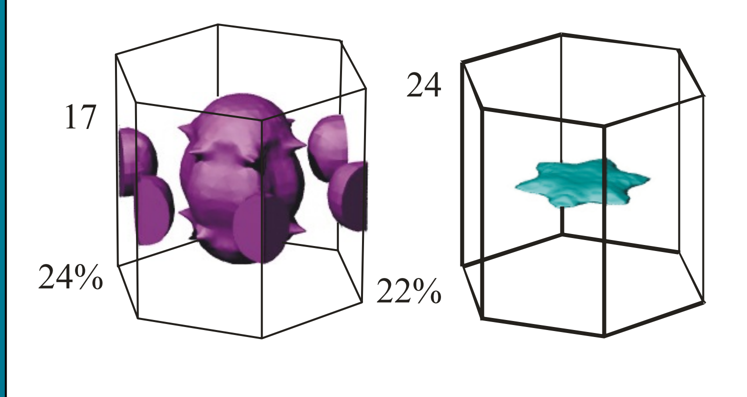
Experimental example: UPt_3

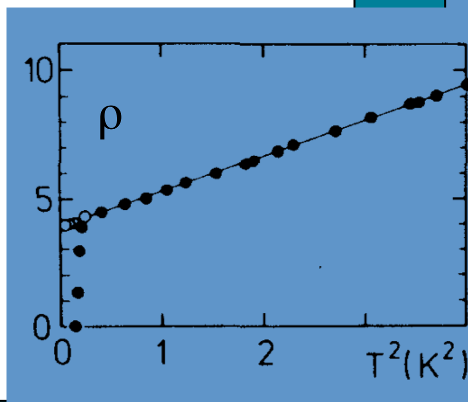


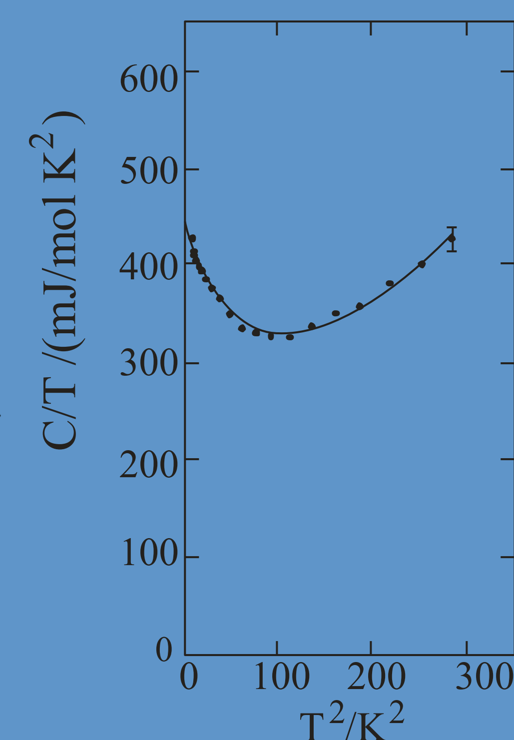
A heavy Fermi liquid: U ~ $5f^3$

S.R. Julian and G. McMullan, unpublished (1998)







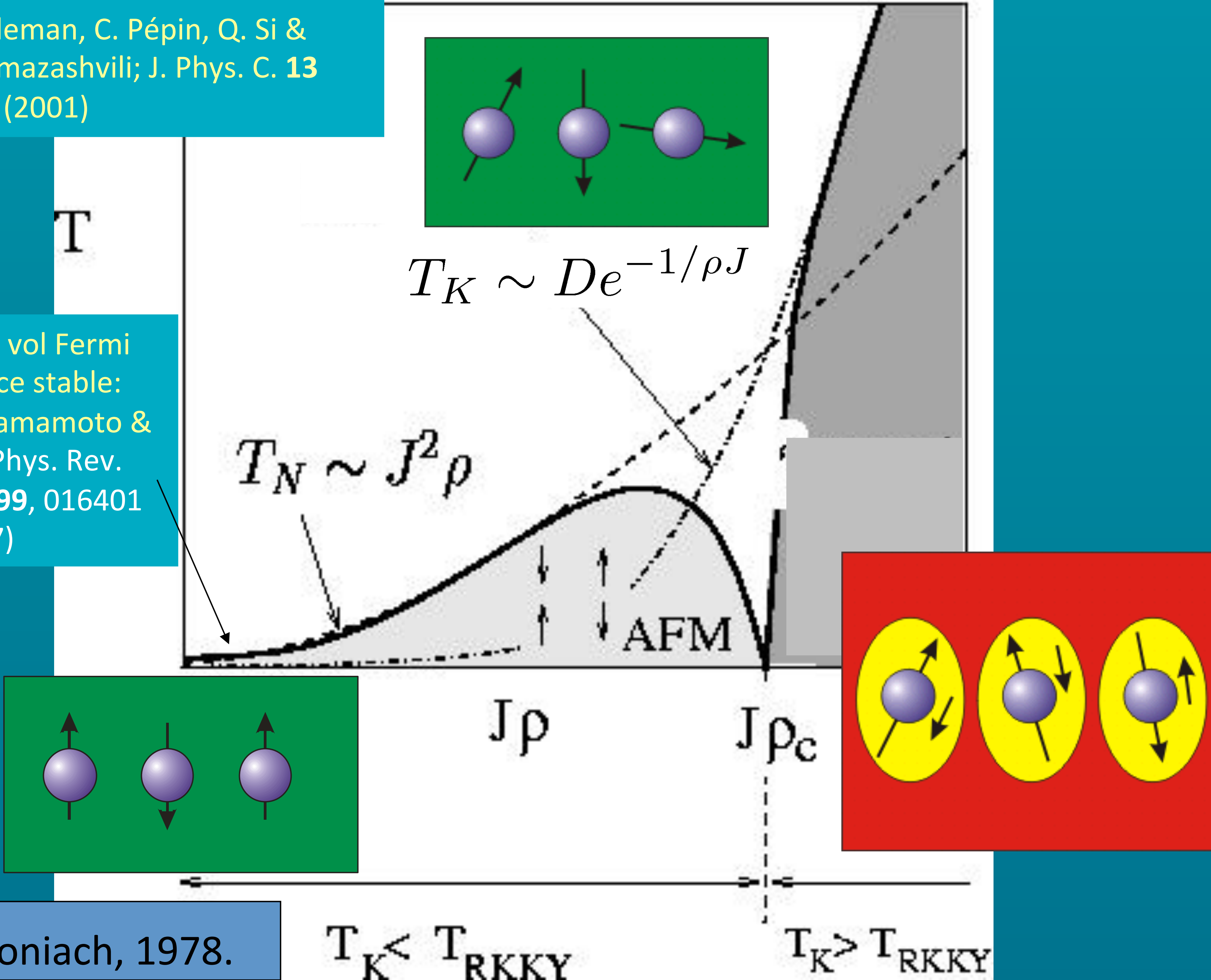


G.R. Stewart *et al.*, PRL, 52, 679 (1984)

Low temp: f electrons delocalize to make up a heavy Fermi liquid

P. Coleman, C. Pépin, Q. Si & R. Ramazashvili; J. Phys. C. **13** R723 (2001)

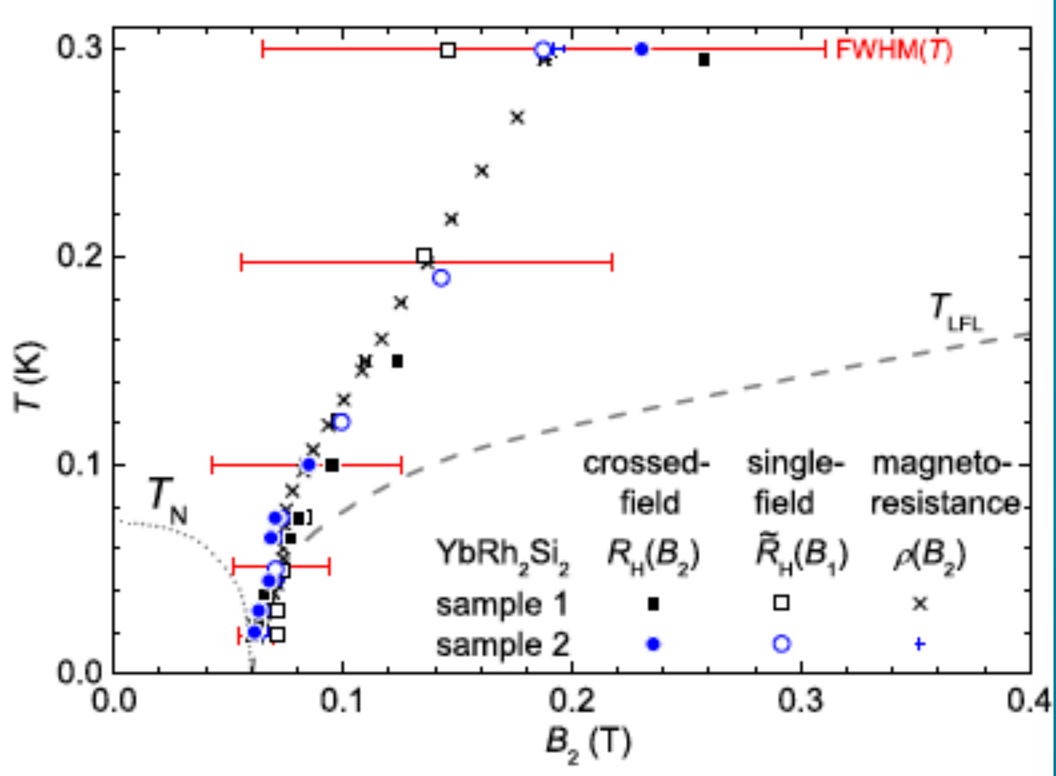
Small vol Fermi surface stable: S.J. Yamamoto & Q.Si Phys. Rev. Lett. **99**, 016401 (2007)



S. Doniach, 1978.

Puzzle 3: The fate of the spins in Kondo lattices

- Multiple energy scales at the quantum critical point in $YbRh_2Si_2$



- Magnetic energy scale collapses ($T_N \rightarrow 0$)
- Could the other scale be the collapse of the Fermi surface?

Friedemann et al PNAS (2010)

Could we find an emergent supersymmetry in this kind of system?

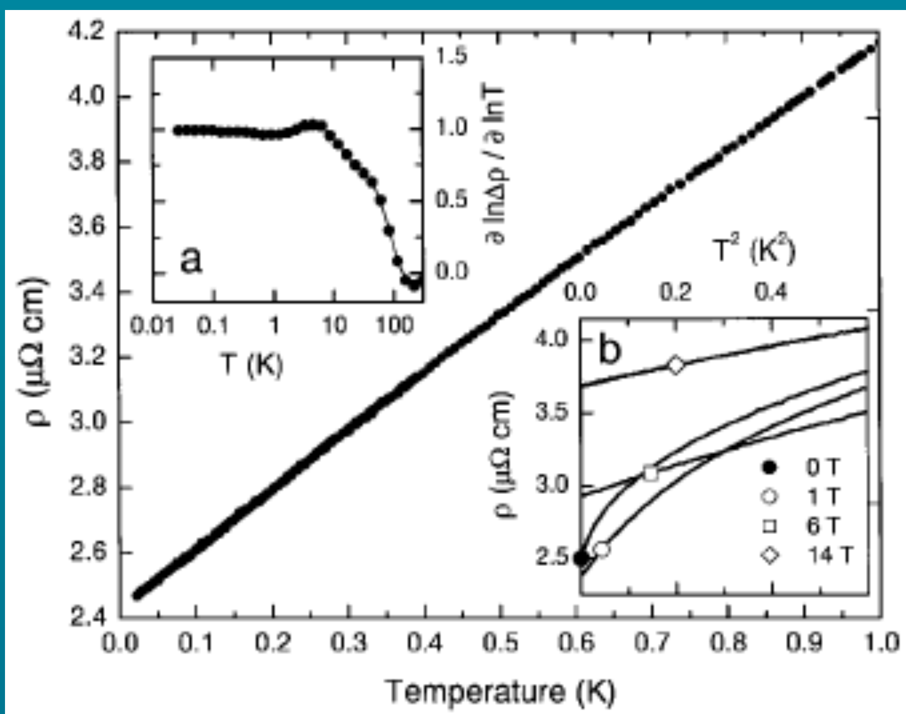
Puzzle 4: low energy physics controlling high energy

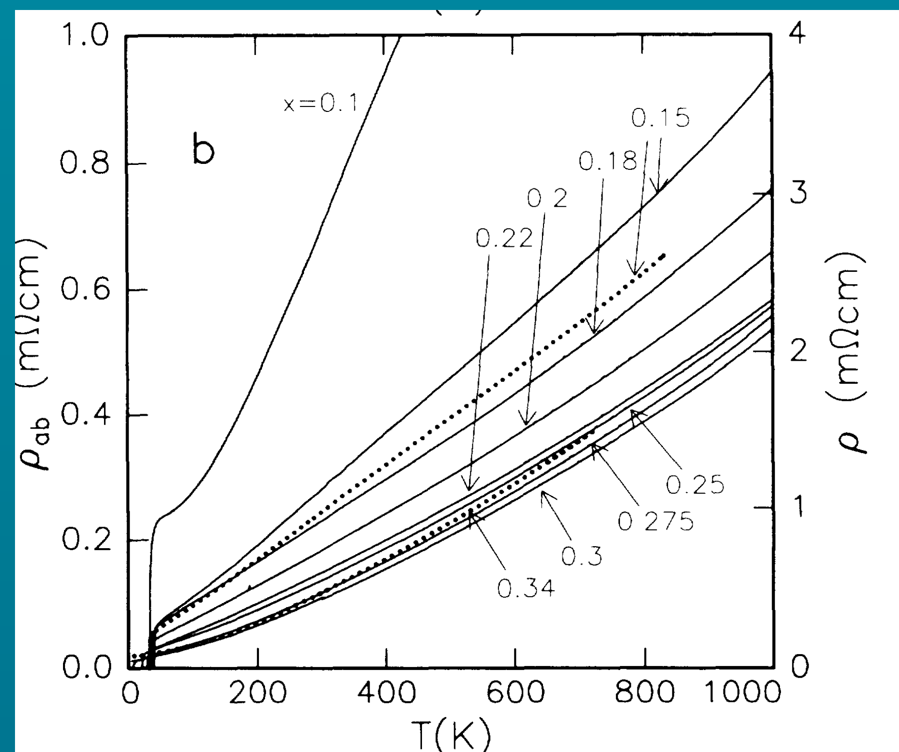
- Quantum critical system: $YbRh_2Si_2$

Trovarelli *et.al.,* PRL 85, 626 (2000)

- Optimally doped cuprates $La_{2-x}Sr_xCuO_4$

H. Takagi *et.al.,* PRL **69**, 2975 (1992)





Can we find a state where some of the properties of the low energy quasiparticle control high energy physics?

- Ingredients needed:
  - Can't rely on an RG type process to throw away high energy physics
  - Need potentially to keep everything
- Simplest testing ground for this:
  - Need to understand the low energy physics

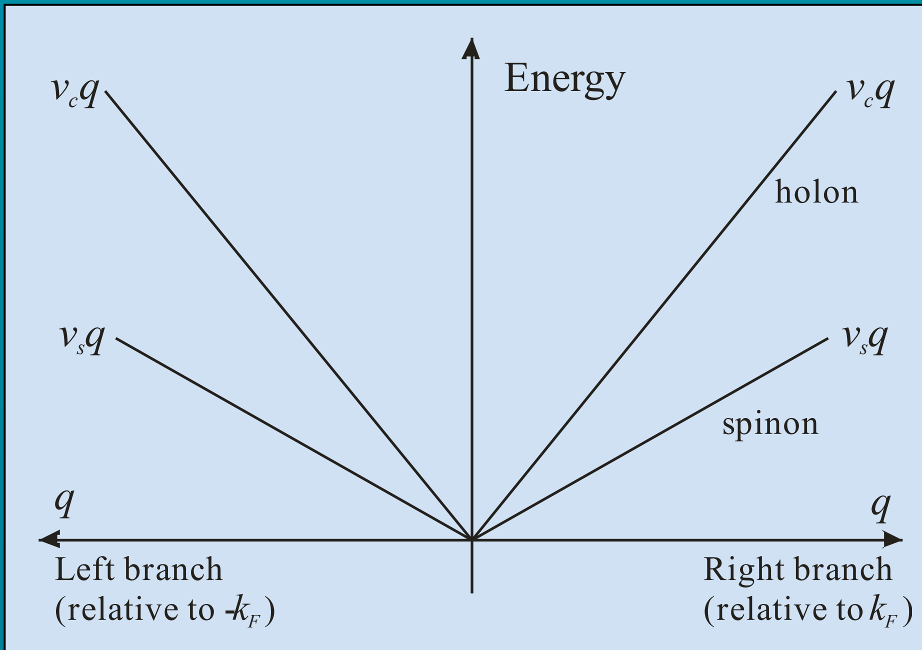
    Luttinger Liquid theory
  - Need to be able to test in experiment to high energy

    Momentum conserving tunnelling
  - Need to understand by solving exactly

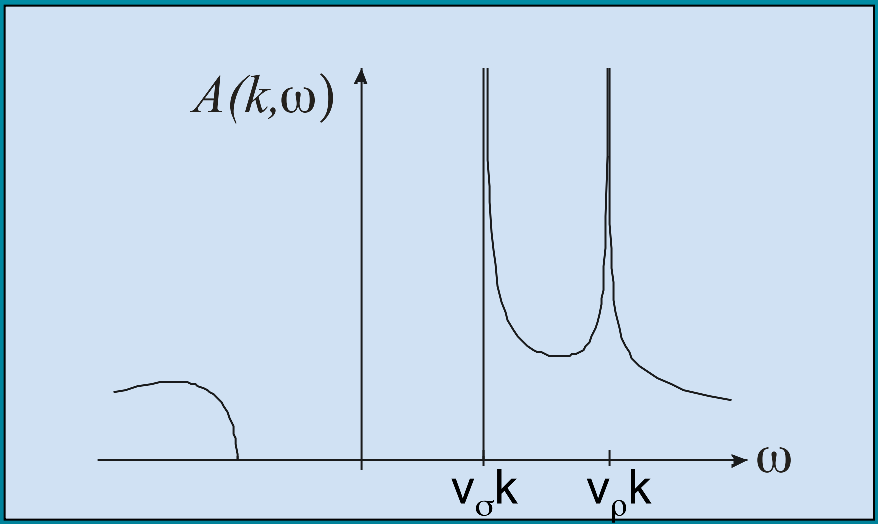
    Bethe Ansatz solvable models
- ➔The physics of one dimension

Consequences:

Excitation spectrum

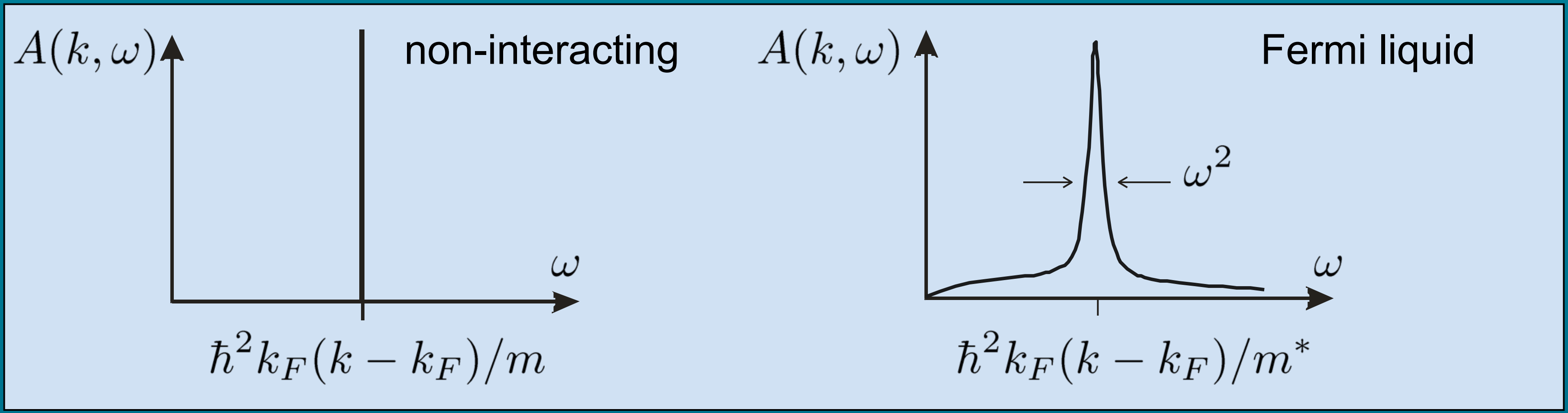


Luttinger Liquid spectral function

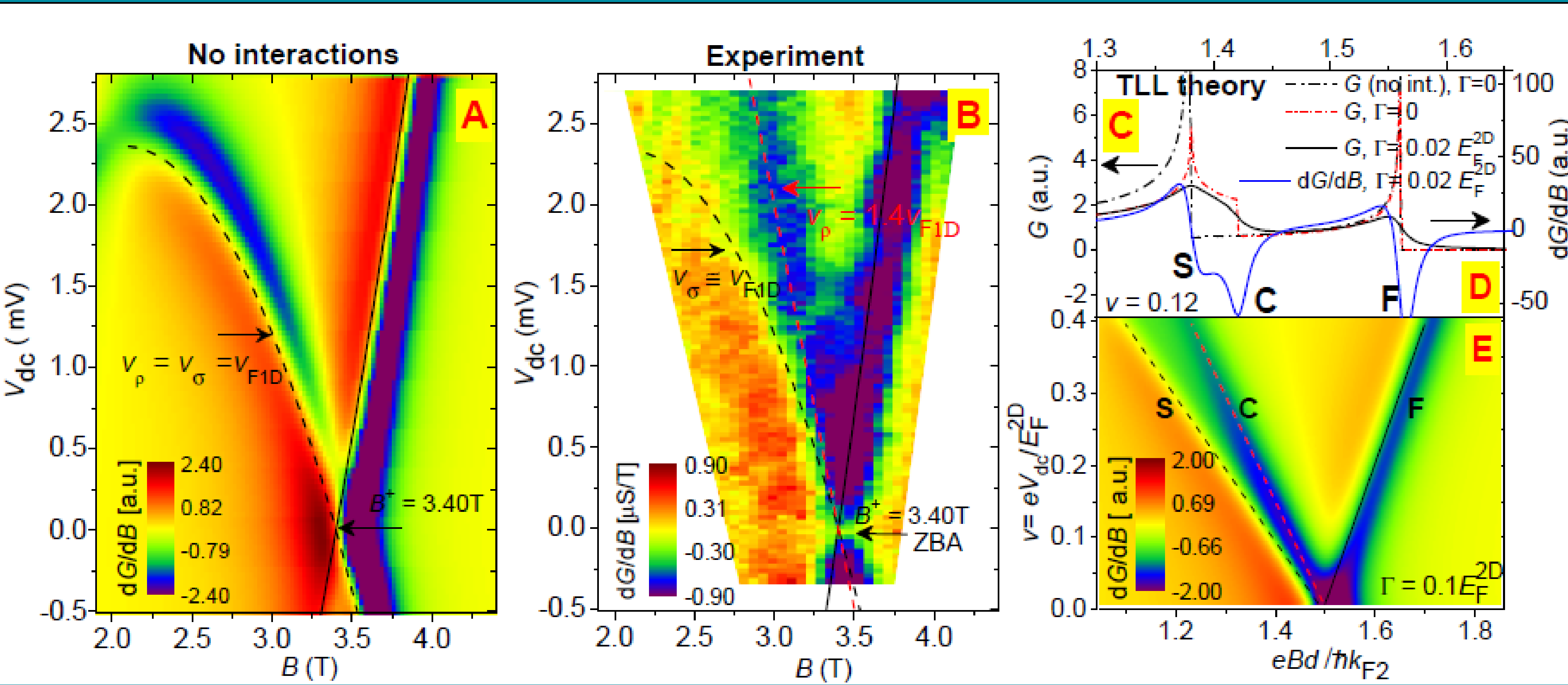


J. Voit, Phys Rev B **47**, 6740 (1993)

<u>The spectral function</u>: probability of finding an electron with specific momentum



Finally – dispersing spinons and holons



- See spinon and holon beyond the universal region.

Y. Jompol, C. J. B. Ford, J. P. Griffiths, I. Farrer, G. A. C. Jones, D. Anderson, D. A. Ritchie, T. W. Silk and A. J. Schofield
Science 325, #5940, 597-601 (2009).

Following the Luttinger quasiparticle to higher energy

- Finite range interaction between spinless fermions

$$H=-t\sum_{j=1}^{L}\left(c_j^\dagger c_{j+1}+c_j^\dagger c_{j-1}\right)+\sum_{j=1,i}^{L}V_i c_j^\dagger c_j c_{j+i}^\dagger c_{j+i}$$

t- tunneling amplitude, V_i- interaction potential

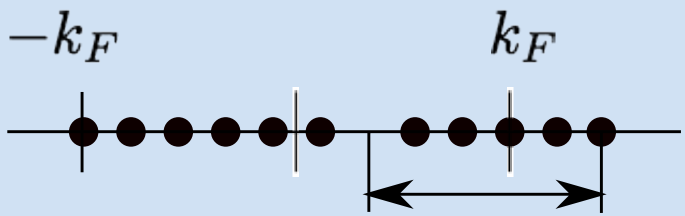
- Probability of adding (removing) a particle: spectral function

$$A\left(k,\varepsilon\right)=L\sum_f\left|\left\langle f\left|c_1^\dagger\right|0\right\rangle\right|^2\delta\left(k-P_f\right)\delta\left(\varepsilon+E_0-E_f\right)$$

$|0\rangle$ is the ground state with n particle, $|f\rangle$ is an eigenstate with n+1 particles

High energies

- States on the edge

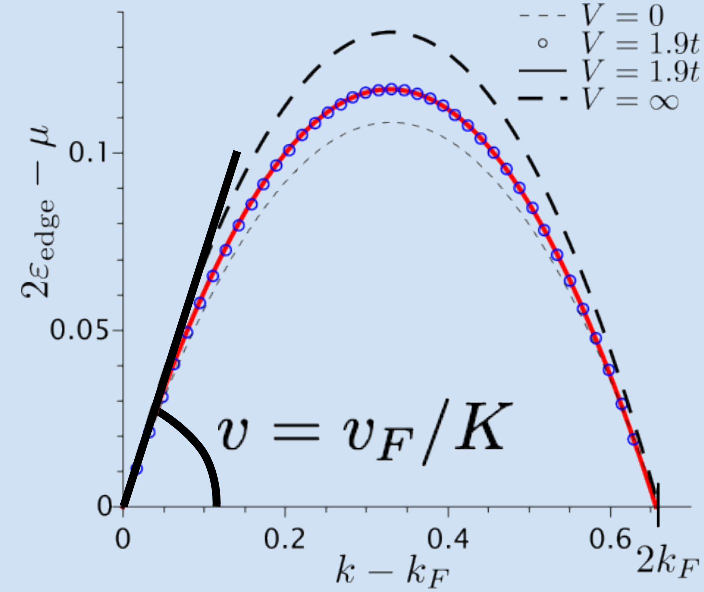


$$\Delta P = k_F + 2\pi/L - k$$

- Chemical potential

$$\mu = mv_F^2/(2K)$$

- Arbitrary momentum and interactions



- Position of the edge on the energy-momentum plane in the continuum limit

$$\varepsilon_{\mathrm{edge}}(k) = \frac{mv_F^2}{K} - \frac{(k - 2mv_F)^2}{2mK}$$

Summary

- Synergy between condensed matter and high energy physics.
- Every new material is like a new universe with its own low energy (emergent) theory
- In some of those "universes" the standard model of metals is seen to fail.
- Identified some key puzzles/challenges for future directions:
  1. Understanding a non-Fermi liquid "phase"
  2. Pinning down the pairing glue in novel superconductors?
  3. Understanding the fate of the spin in Kondo lattice quantum critical points
  4. Following excitations/properties from low to high energies.