Heavy Fermion Physics – Perspectives from look-alikes

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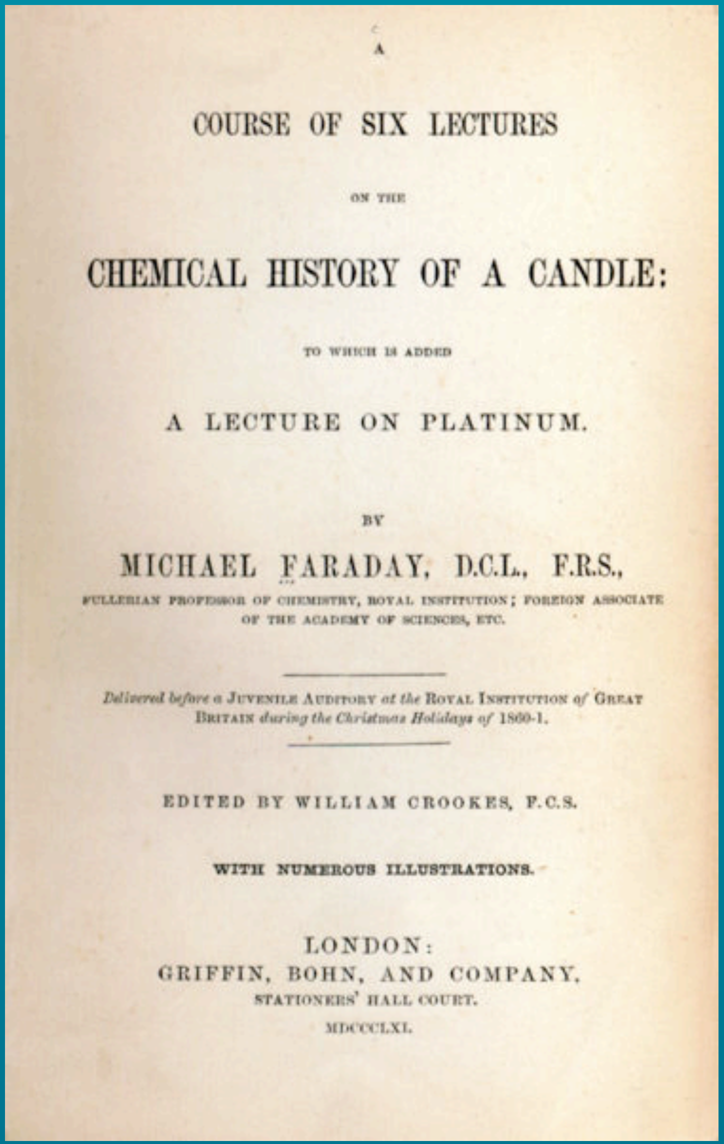
EPSRC
Engineering and Physical Sciences Research Council
The Leverhulme Trust

The chemical history of a candle



A

COURSE OF SIX LECTURES

ON THE

CHEMICAL HISTORY OF A CANDLE:

TO WHICH IS ADDED

A LECTURE ON PLATINUM.

BY

MICHAEL FARADAY, D.C.L., F.R.S.,

FULLERIAN PROFESSOR OF CHEMISTRY, ROYAL INSTITUTION; FOREIGN ASSOCIATE OF THE ACADEMY OF SCIENCES, ETC.

Delivered before a JUVENILE AUDITORY *at the* ROYAL INSTITUTION *of* GREAT BRITAIN *during the Christmas Holidays of* 1860-1.

EDITED BY WILLIAM CROOKES, F.C.S.

WITH NUMEROUS ILLUSTRATIONS.

LONDON:
GRIFFIN, BOHN, AND COMPANY,
STATIONERS' HALL COURT.
MDCCCLXI.

"There is no better, there is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomena of a candle."

Michael Faraday 1860

Heavy fermions – a universe of correlated electron physics

"There is no better, there is no more open door by which you can enter into the study of correlated electrons than by considering the physical phenomena of the heavy fermions."

- Fermi liquids
- Novel Superconductors
- Quantum critical metals – conventional and unconventional
- "Hidden order" phases
- Significant challenges
- Insights from look-alikes – can we build simple analogues?
- Future Trends:
  - Analogue heavy fermion systems
  - Semiconductors; cold atoms
  - New experimental techniques

The basic Hamiltonian

- The Anderson lattice model:

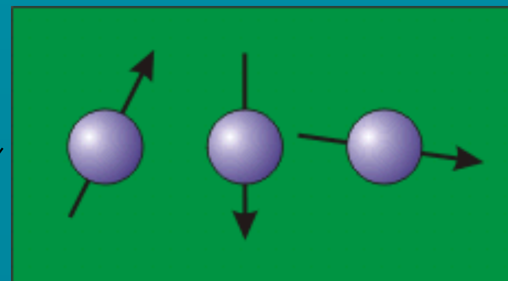
$$H = \sum_{ij\sigma} \epsilon_{ij} c^\dagger_{i\sigma} c_{j\sigma} - \sum_{ij\sigma} \left[V_{ij} c^\dagger_{i\sigma} f_{j\sigma} + V^*_{ij} f^\dagger_{i\sigma} c_{j\sigma} \right] - \Delta \sum_{i\sigma} f^\dagger_{i\sigma} f_{i\sigma} + U \sum_i f^\dagger_{i\sigma} f_{i\sigma} f^\dagger_{i\bar{\sigma}} f_{i\bar{\sigma}}$$

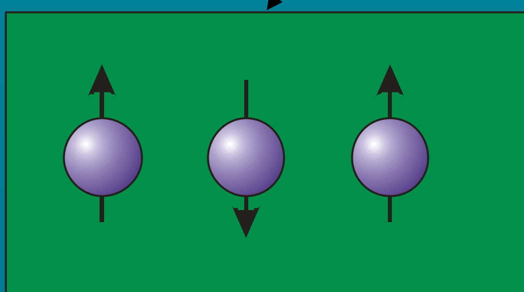
- Essential ingredients
  - Non-interacting conduction electrons (c)
  - Strongly interacting f electrons – usually considered in the limit of large U and Δ (so valence fluctuations small) with no direct f-f hybridization
  - Weak hybridization between f and c.
- Reduces to:
  - Local moments with spin degrees of freedom interacting via magnetic exchange with the conduction electrons

How is the spin entropy of the f moments lost as T->0?

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

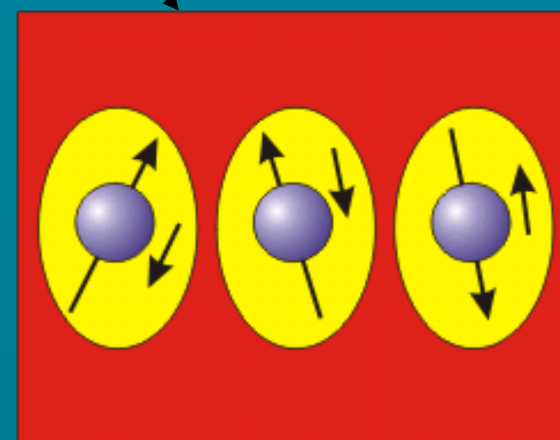
High temperature
free magnetic moments
+ conduction electrons
$N_e=N_c$





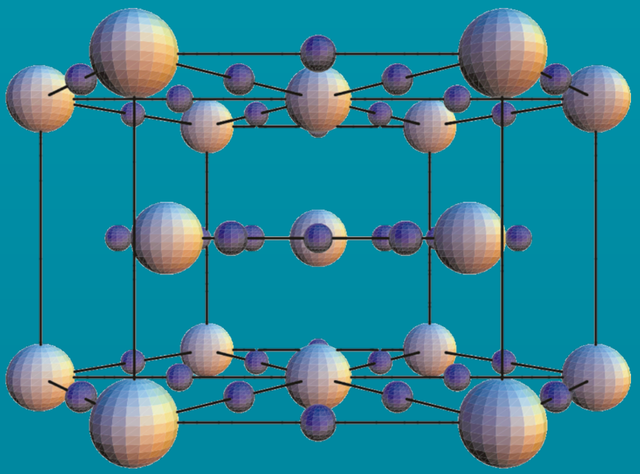
Low temperatures
Free spins order, and
$N_c=N_c$ (small Fermi volume)

OR



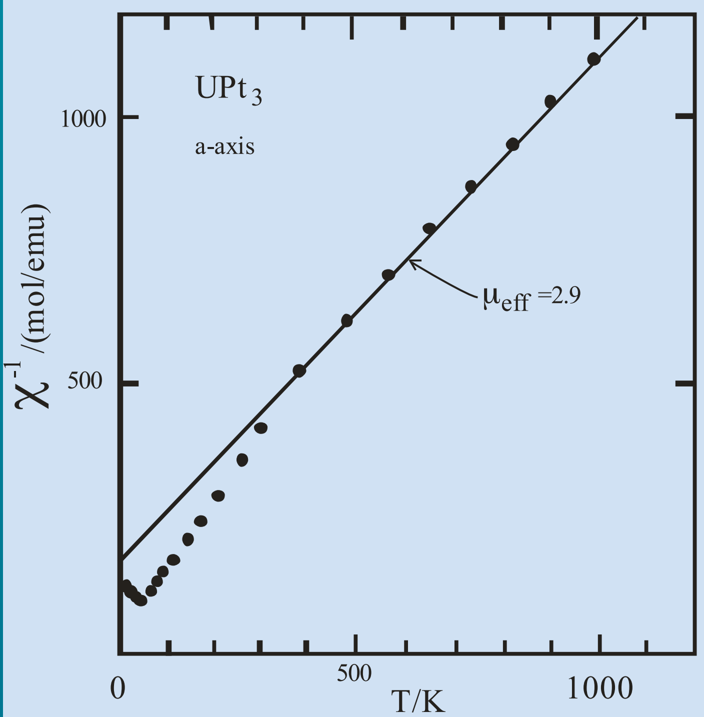
Low temperatures
No free spins but very heavy electrons ($m\sim 10^3\ m_e$) and
$N_e=N_c+N_f$ (large Fermi volume)

The remarkable Fermi liquid: UPt_3



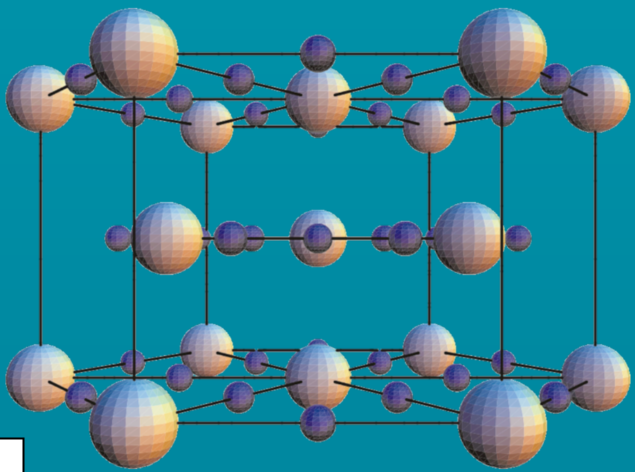
A heavy Fermi liquid: $U \sim 5f^3$

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



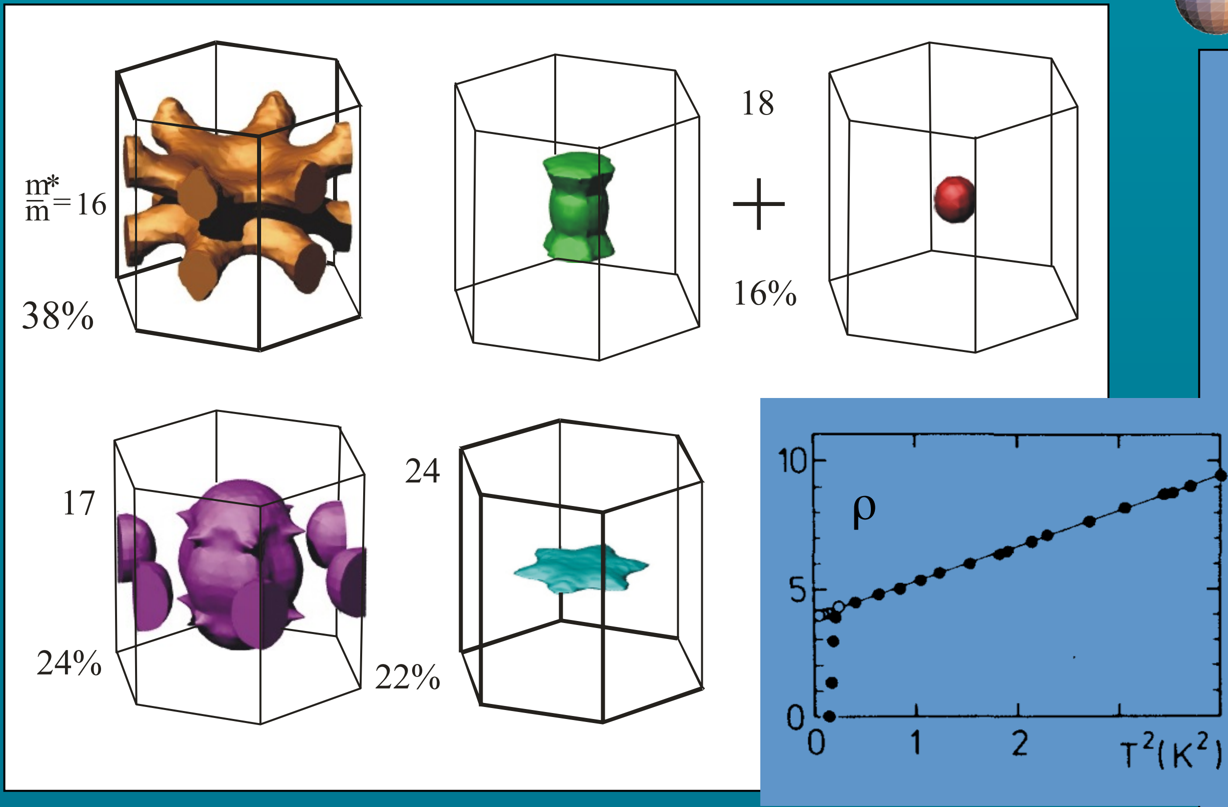
Frings *et al.*,
JMMM 31-34, 240 (1983).

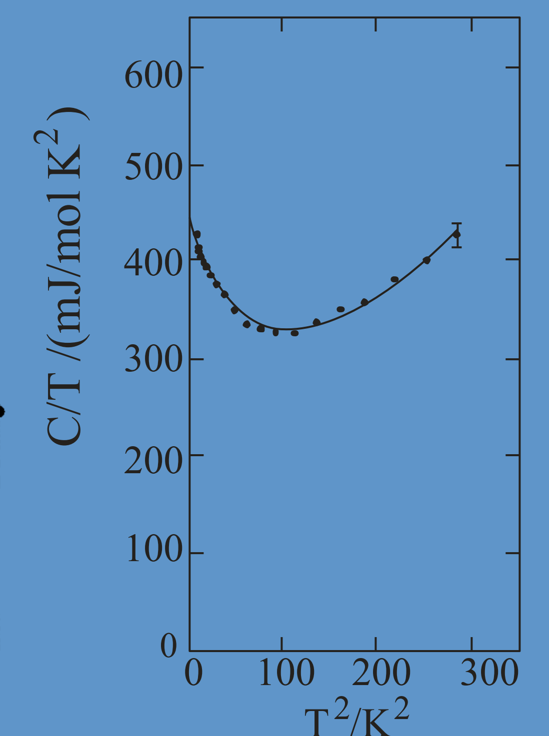
The remarkable Fermi liquid: UPt_3



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

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

A Fermi liquid susceptible to superconductivity

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich

Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz

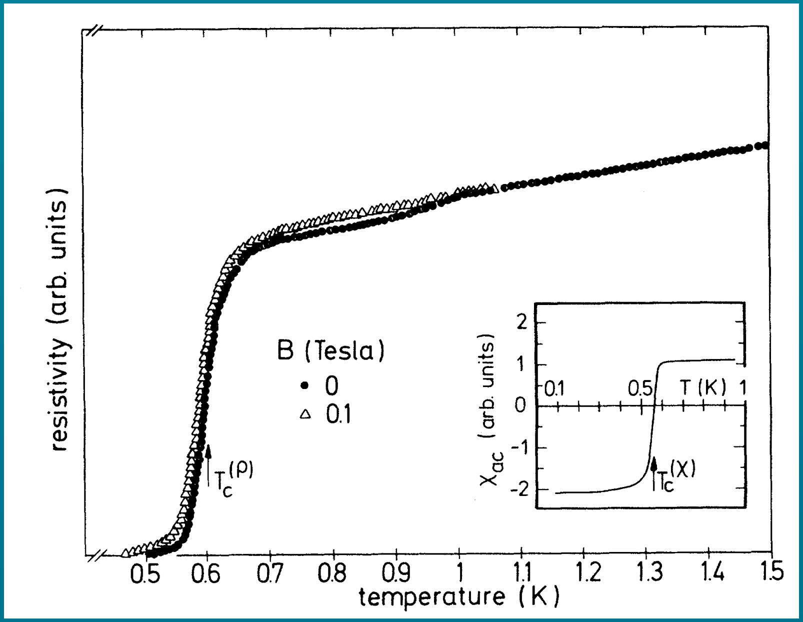
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

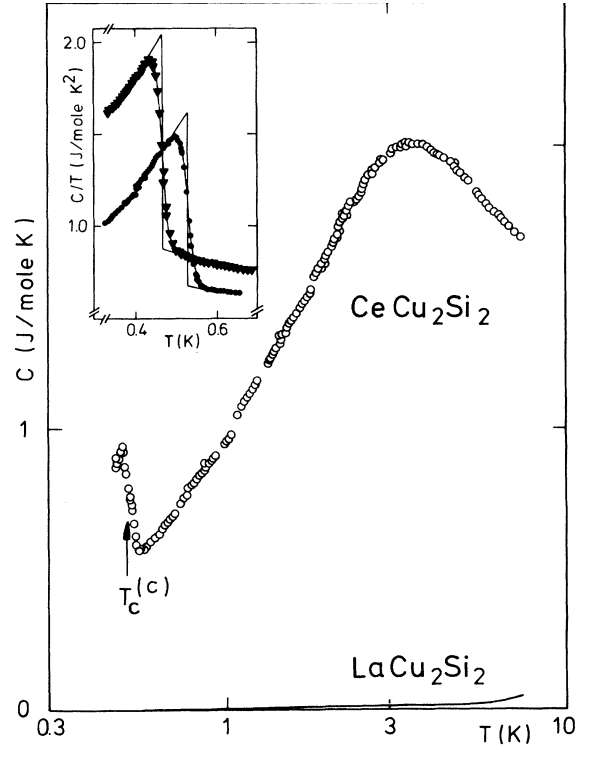
and

H. Schäfer

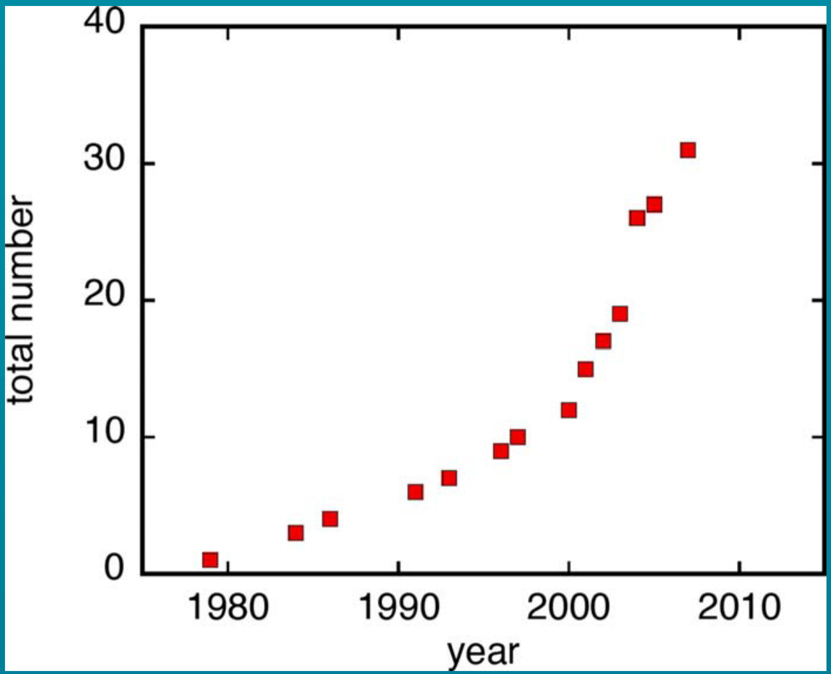
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 10 August 1979; revised manuscript received 7 November 1979)





A universe of new superconductors



Christian Pfleiderer
Rev. Mod. Phys. 81, #4, 1551-1624 (2009).

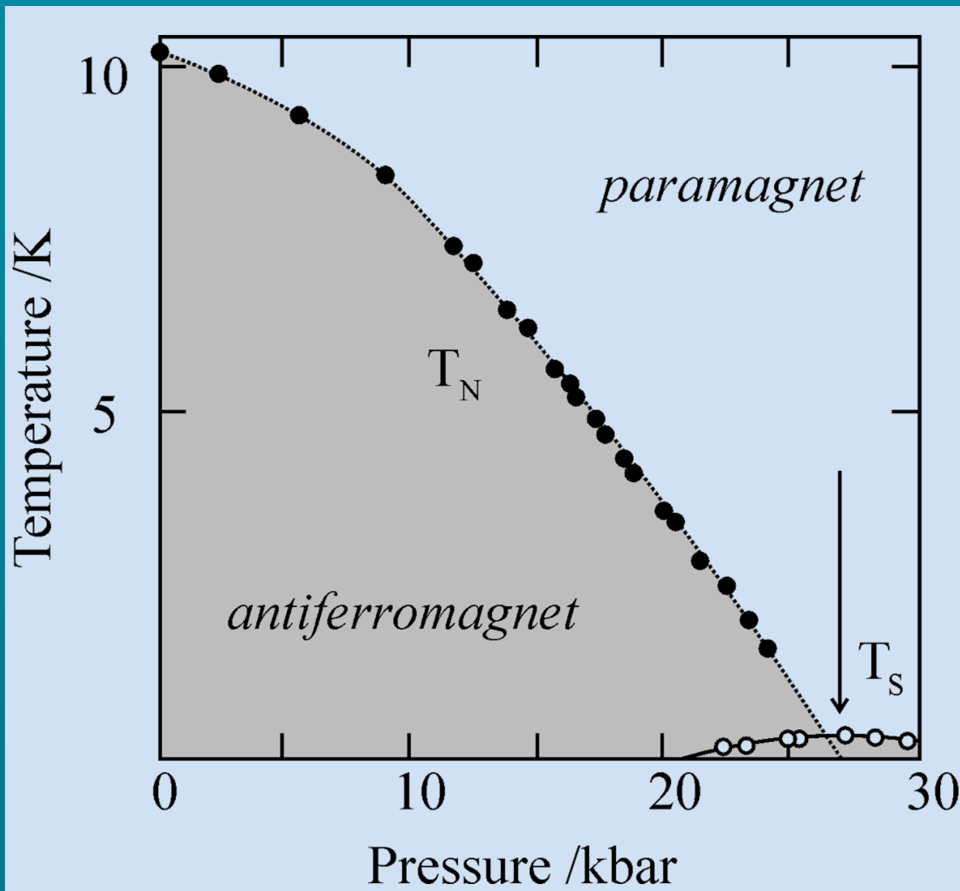
Superconductors that require new rules:

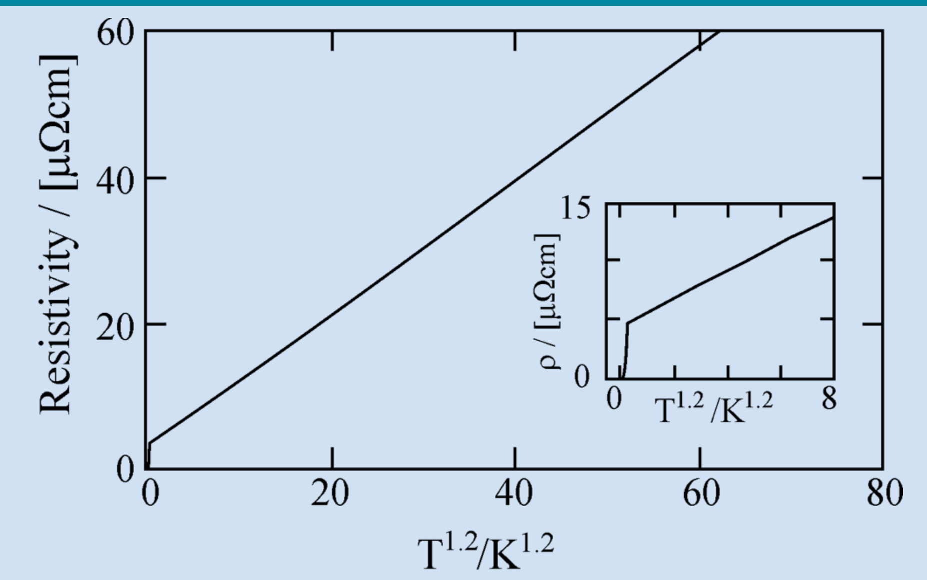
- On the border of magnetism
  - AFM: $CePd_2Si_2$
  - FM: UCoGe
- Coexisting with magnetism
  - AFM: UPt_3
  - FM: UGe_2
- Non-centrosymmetric
  - $CePt_3Si$
- "High temperature" superconductors
  - $PuCoGa_5$

Exemplars of 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 $CePd_2Si_2$





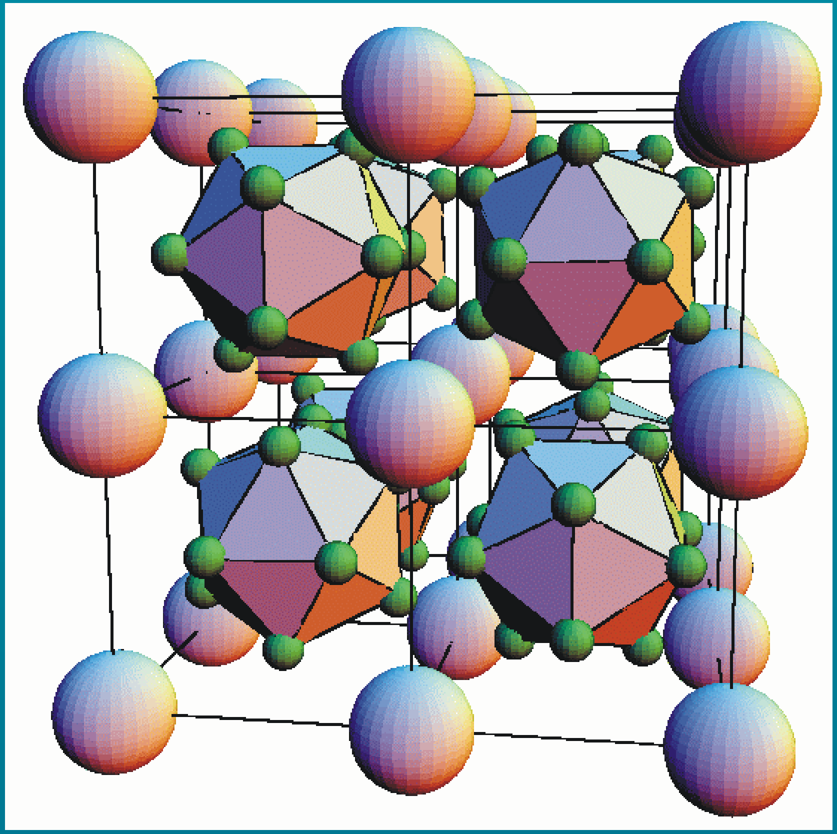
$$\rho \sim T^{1+\epsilon}$$

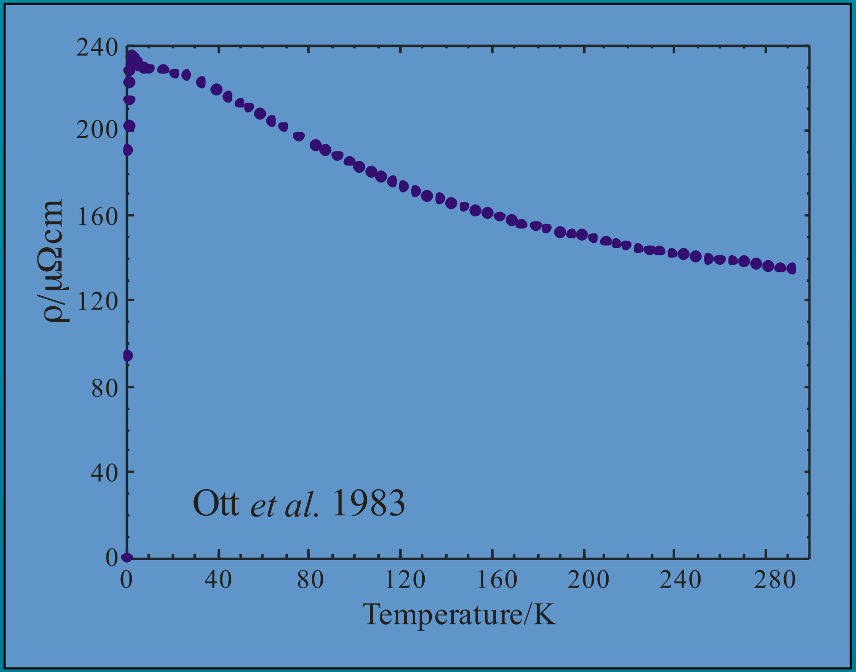
Subtlety: need to include disorder
A. Rosch, Phys Rev Lett **82**, 4280 (1999)

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

Are heavy fermion materials simply metals with small E_F?

- Many outstanding puzzles – like UBe_{13}

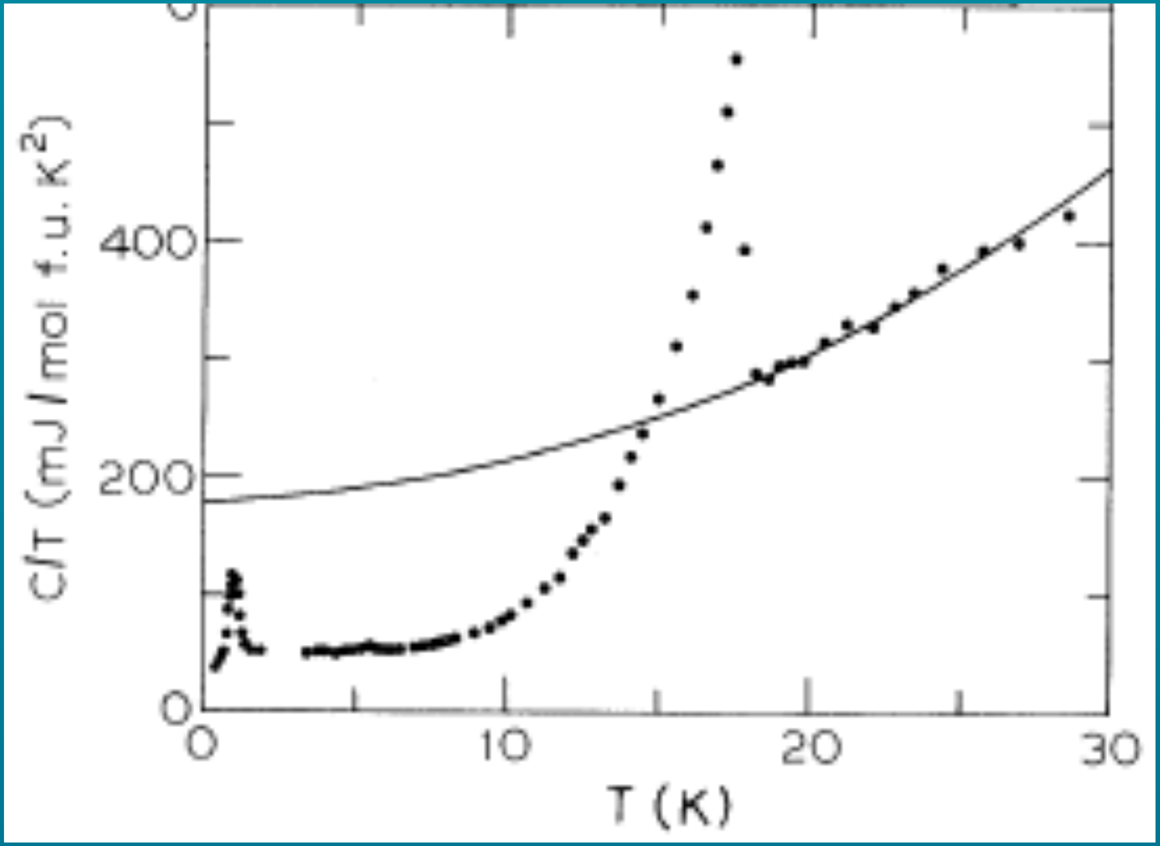




Superconductivity without a Fermi surface?

Are heavy fermion materials simply metals with small E_F?

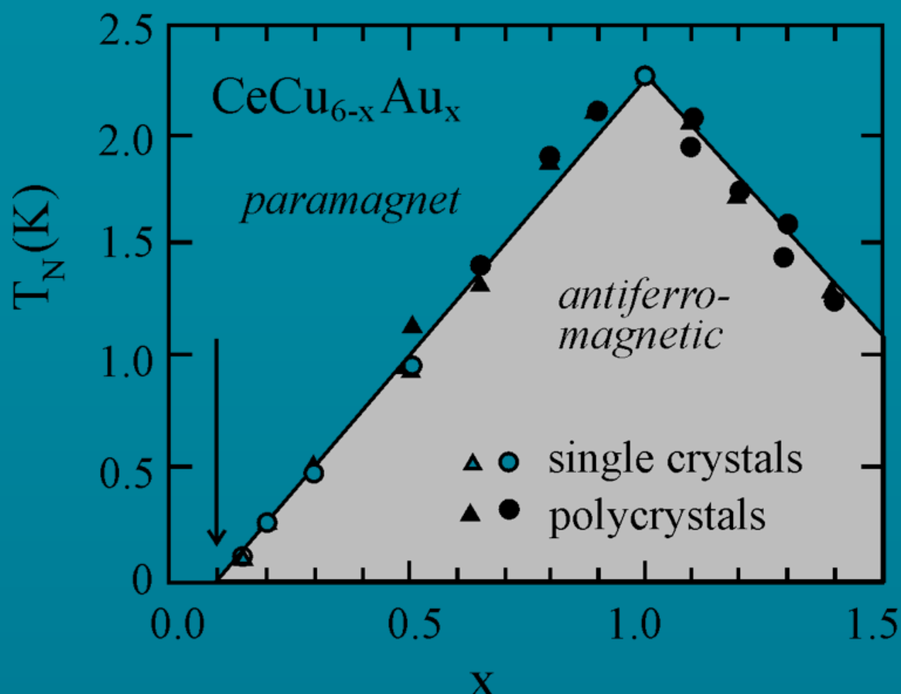
- Many outstanding puzzles – like the mysterious order in URu_2Si_2

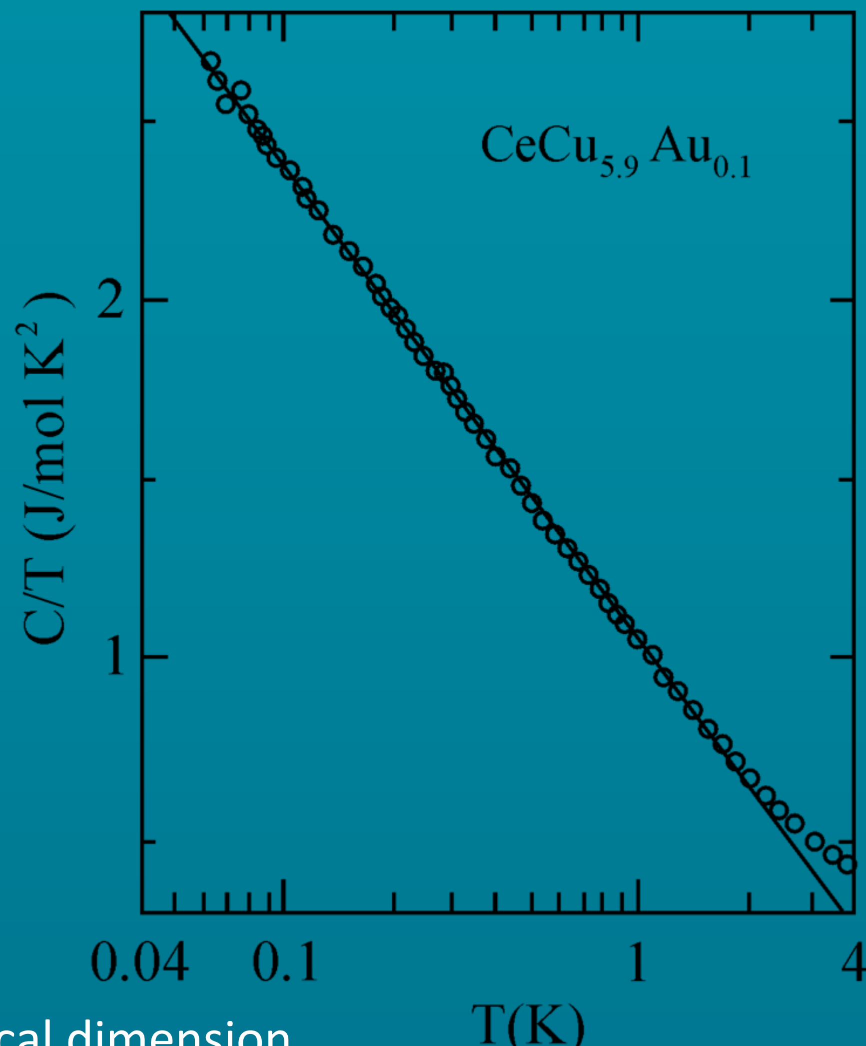


URu_2Si_2: T. T. M. Palstra, A. A. Menovsky, J. van den Berg, A. J. Dirkmaat, P. H. Kes, G. J. Nieuwenhuys and J. A. Mydosh Physical Review Letters **55**, 2727 (1985)

LGWH: Failure in heavy fermion AFM

Is this above or below the upper critical dimension?





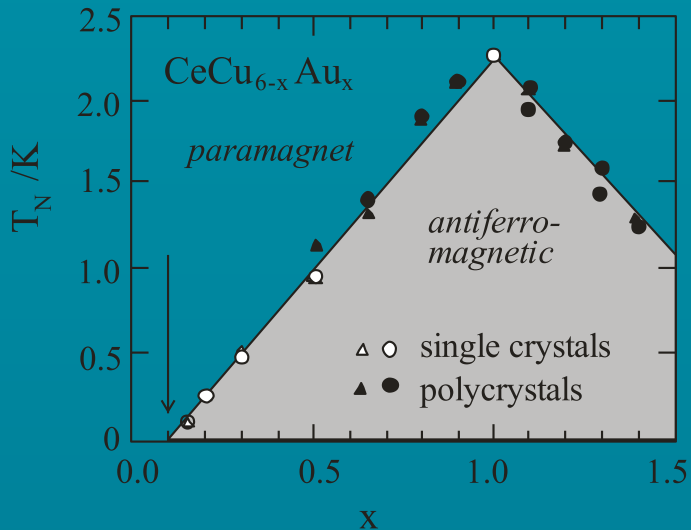
Control parameter is chemical doping:

- Fluctuations at Q=AFM vector
- D=3 (perhaps 2), *z*=2 so above upper-critical dimension

Von Löhneysen *et al.* J. Phys: Condens. Matt. **8**, 9689 (1996)

… yet E/T scaling seen

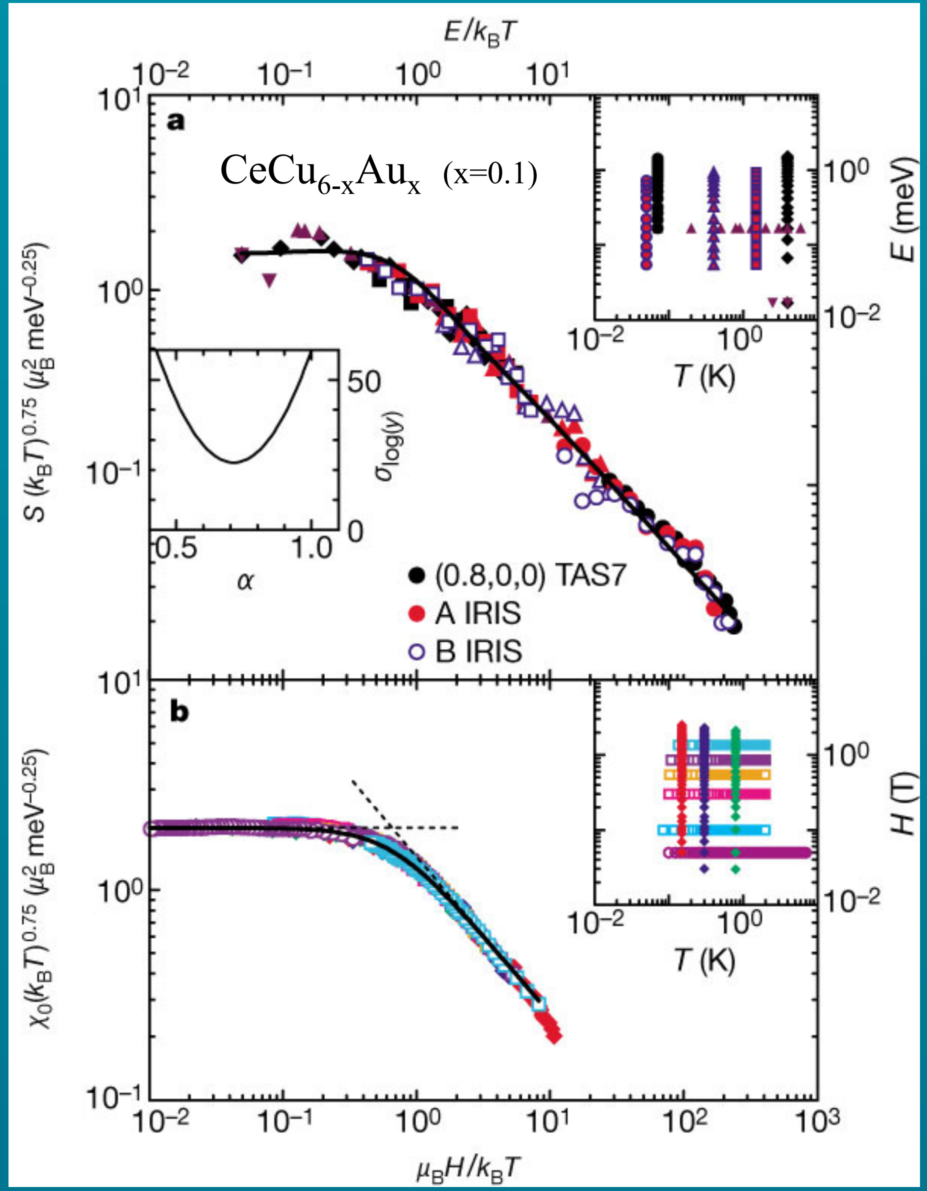
Schröder et al, Nature 407,351 (2000).



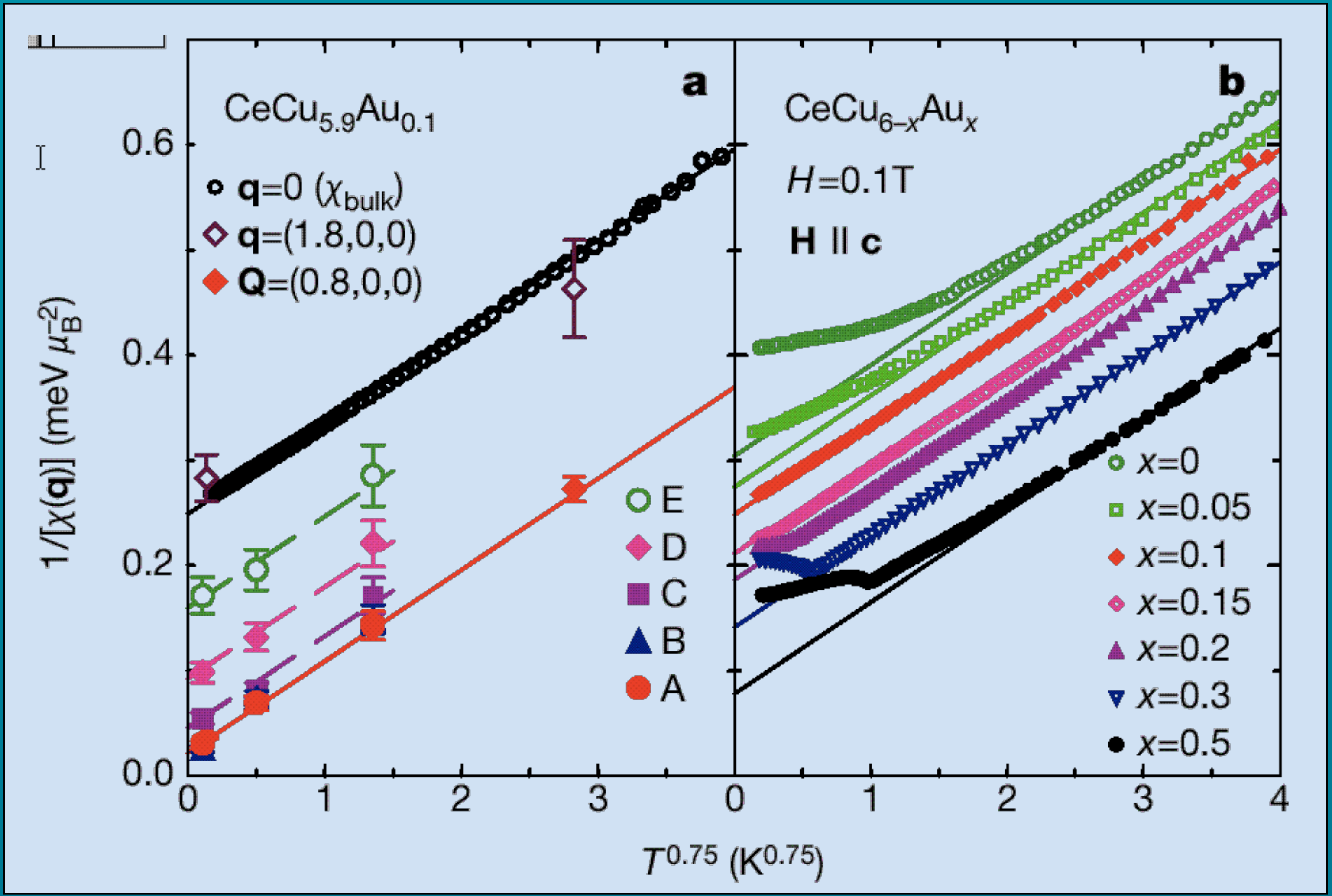
von Löhneysen et al (1994).

$$\chi''(E) = \frac{1}{E^{1-\alpha}} G\left(\frac{E}{T}\right)$$

Physics <u>below</u> the upper critical dimension.



… and seems show criticality everywhere in k-space

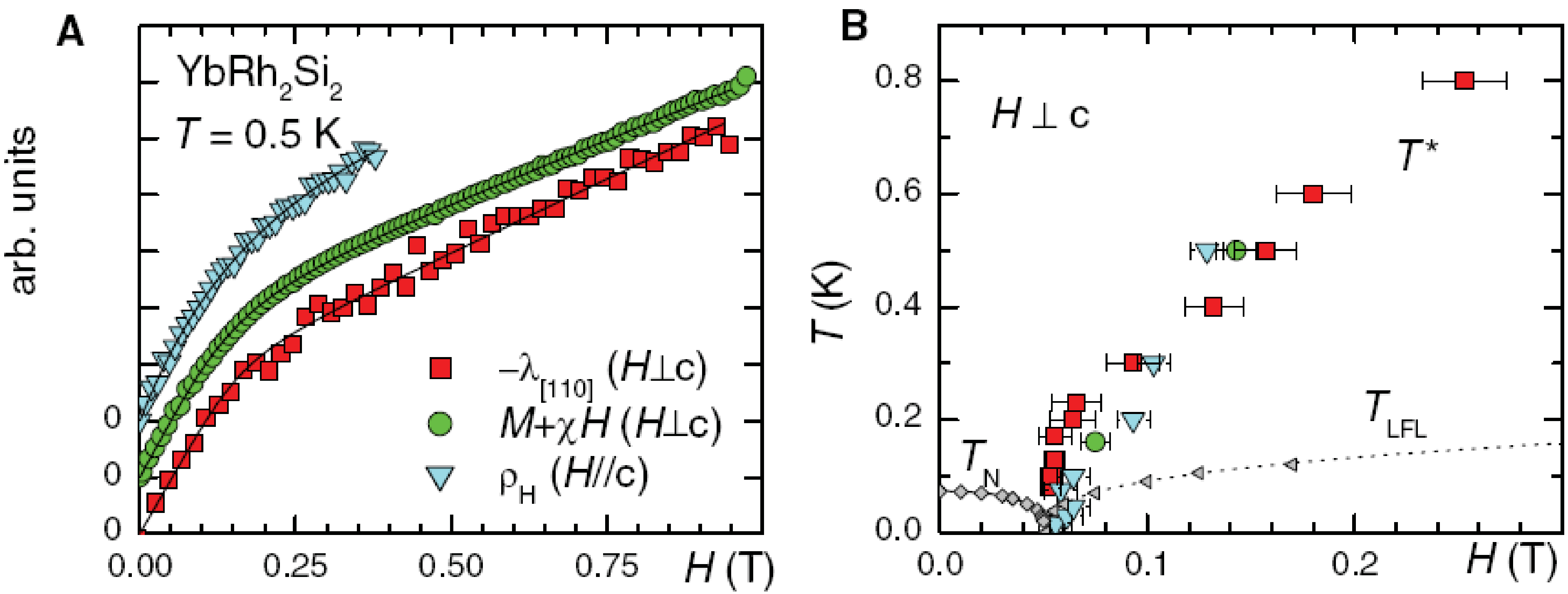


$$\chi^{-1}(\mathbf{q}, E, T) = \left[\left(\left[T^2 + \left(\frac{g\mu_B}{k_B}\right)^2 H^2\right]^{1/2} - iE/a\right)^\alpha + \theta(\mathbf{q})^\alpha\right] C^{-1}$$

A. Schröder *et al.* Nature, **407**, 351 (2000)

Evidence for new physics at a heavy fermion quantum critical point

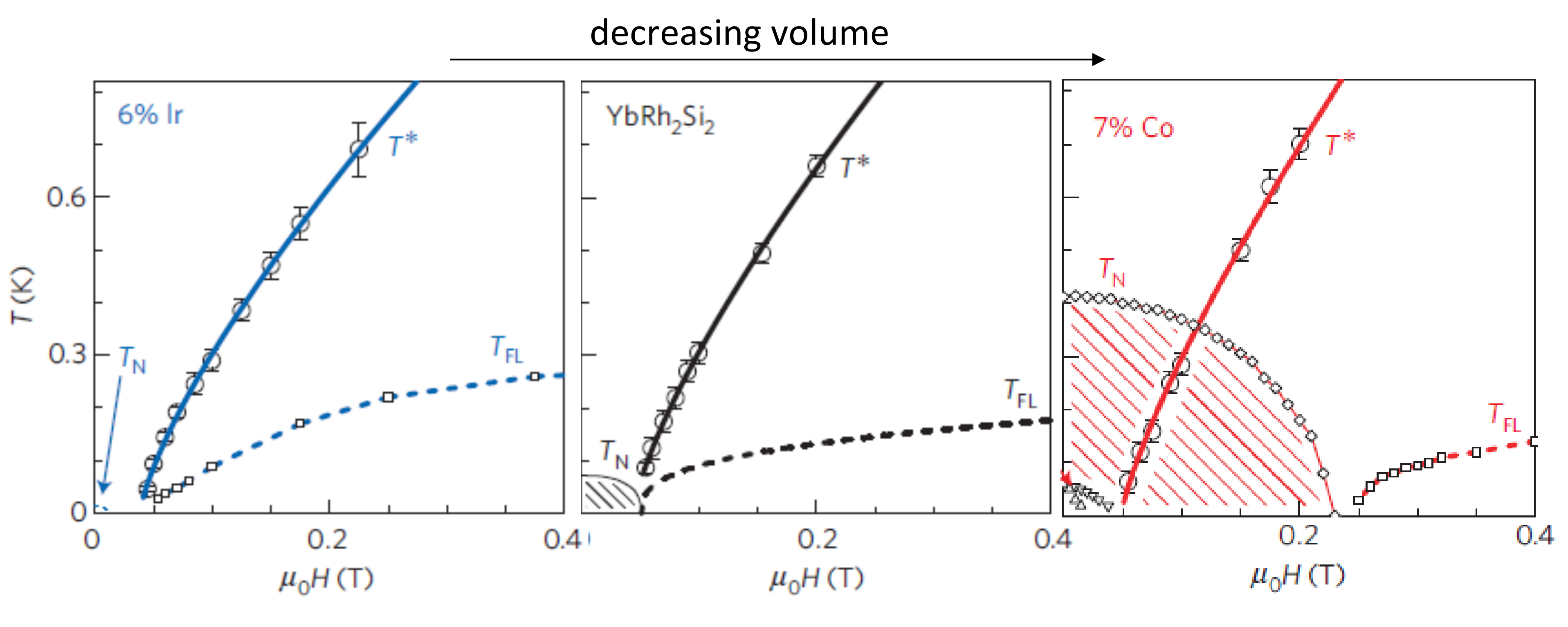
P. Gegenwart, T. Westerkamp, C. Krellner, Y. Tokiwa, S. Paschen, C. Geibel, F. Steglich, E. Abrahams, Q. Si Science **315**, *#5814*, 969-971 (2007).



An additional energy scale appears to converge on the quantum phase transition: Failure of the Landau assumption of a single order parameter controlling criticality

Phase diagram appears even richer

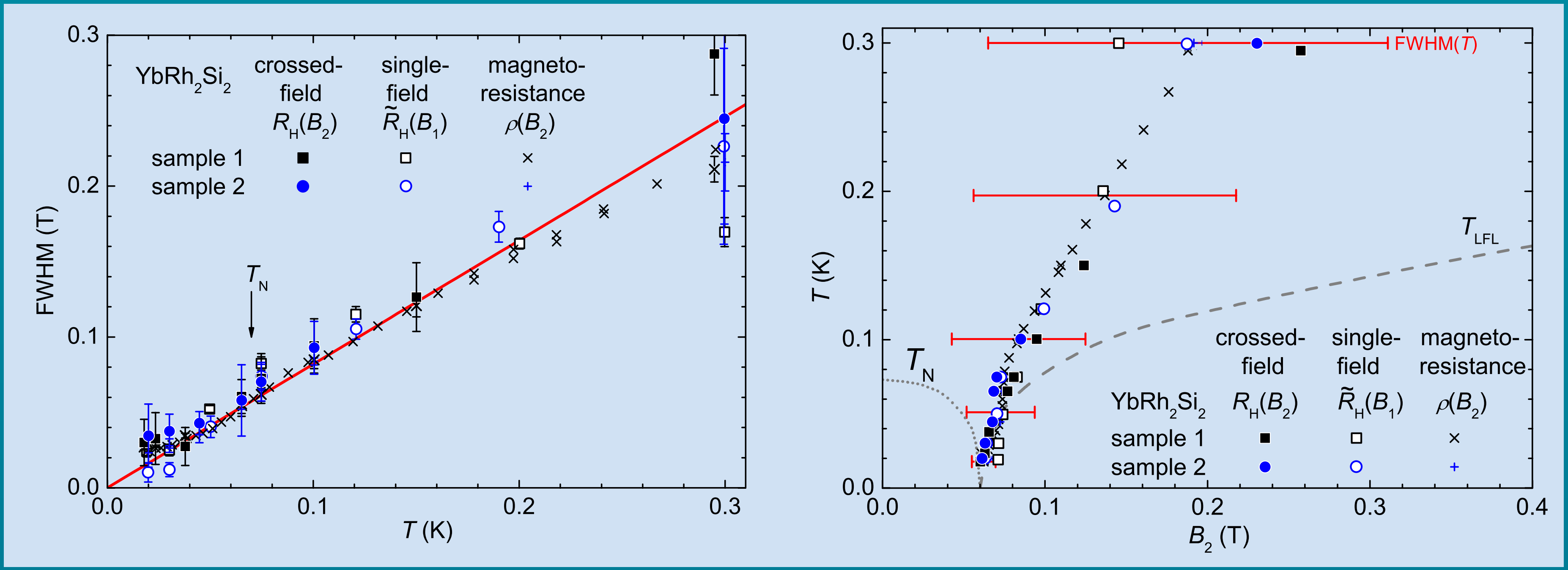
It looks like you can control the two scales independently



S. Friedemann, T. Westerkamp, M. Brando, N. Oeschler, S. Wirth, P. Gegenwart, C. Krellner, C. Geibel and F. Steglich

Nature Physics **5**, *#7*, 465-469 (2009).

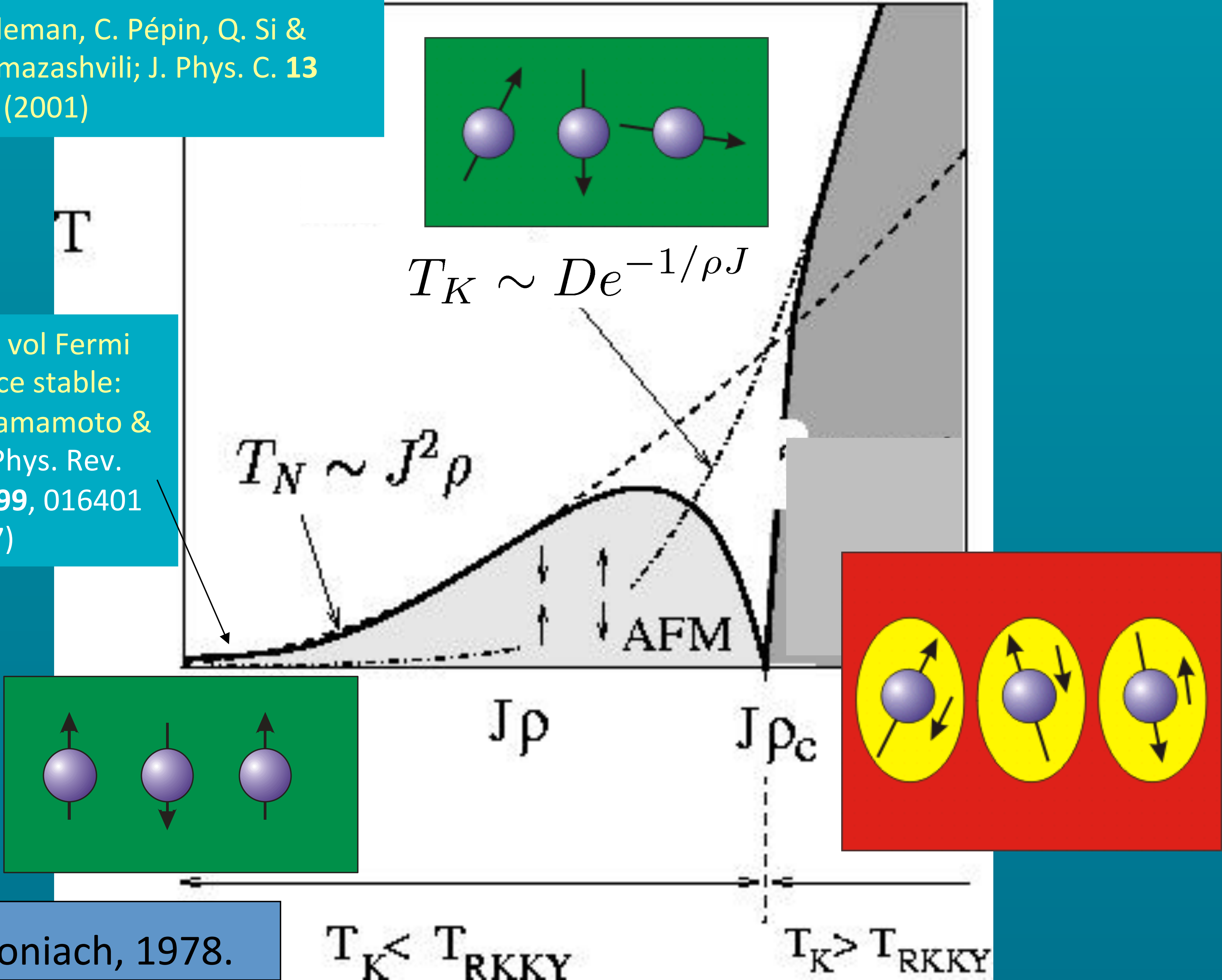
Moreover – evidence of E/T scaling



Sven Friedemann et al. PNAS, **107**, 14547 (2010)

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.

Using analogues to understand the physics

- Are the anomalies seen in quantum critical heavy fermion metals a consequence of Kondo physics OR a generic failure of our understanding of quantum criticality?
- Is there a "look – alike" for quantum criticality without the Kondo physics?
  - *d*–metals near a magnetic instability
  - AFM?
  - FM? (issues of non-analyticity)
- Is there a "look–alike" for the Kondo lattice which illustrates the same physics?
  - ^{3}He bilayers

Quantum criticality in metallic systems

- Paramagnon theory (1960s onward):
  - metals on the border of ferromagnetism.
  - Pd, Ni_3Al, Ni_3Ga, YNi_3, $ZrZn_2$
  - Puzzles: neither Stoner nor Heisenberg-like
    - Stoner: B=a M + b M^3 with a$\sim$ a_0-λ(T/TF)2
    - T_c small, χ Curie-Weiss like, yet μ_{eff}/μ_0 large
  - Resolution: include spin-fluctuations
    - Berk, Schrieffer, Doniach, Engelsberg, Rice, Moriya, Yamada, Beal-Monod, Misawa, Lonzarich, Continentino … and more
    - B=(a+ b $\langle m\rangle^2$) M + b M^3
  - Modern incarnation: Hertz-Millis (RG) approach

$$S = \int \sum_{\omega} d^D q \left[\left((x - x_c) + q^2 + \frac{i\omega}{q^{z-2}} \right) |\psi|^2 + u|\psi|^4 + \cdots) \right]$$

LGWH: Landau-Ginzburg-Wilson-Hertz (…)

Itinerant antiferromagnetic quantum criticality ($Q \neq 0$)

Hilbert v. Löhneysen, Achim Rosch, Matthias Vojta, Peter Wölfle
Rev. Mod. Phys. **79**, 1015-1075 (2007).

Interplay between spin-fluctuations and the electron fluid

- LGWH: Upper critical dimension should formally be 2
- At d=2:
  - Long range interactions induced by fluid, LGWH expansion breaks down (infinite number of marginal operators)
    - Abanov and Chubukov, Phys Rev Lett 93, 255702 (2004)
- At d=3:
  - Breakdown of Fermi liquid at hot spots – need to treat fully self-consistently
- At Q=2k_F:
  - d=2 First order:
    - Ioffe, Millis Phys. Rev. B 51, 16151 (1995).

Ferromagnetic quantum critical points (Q=0)

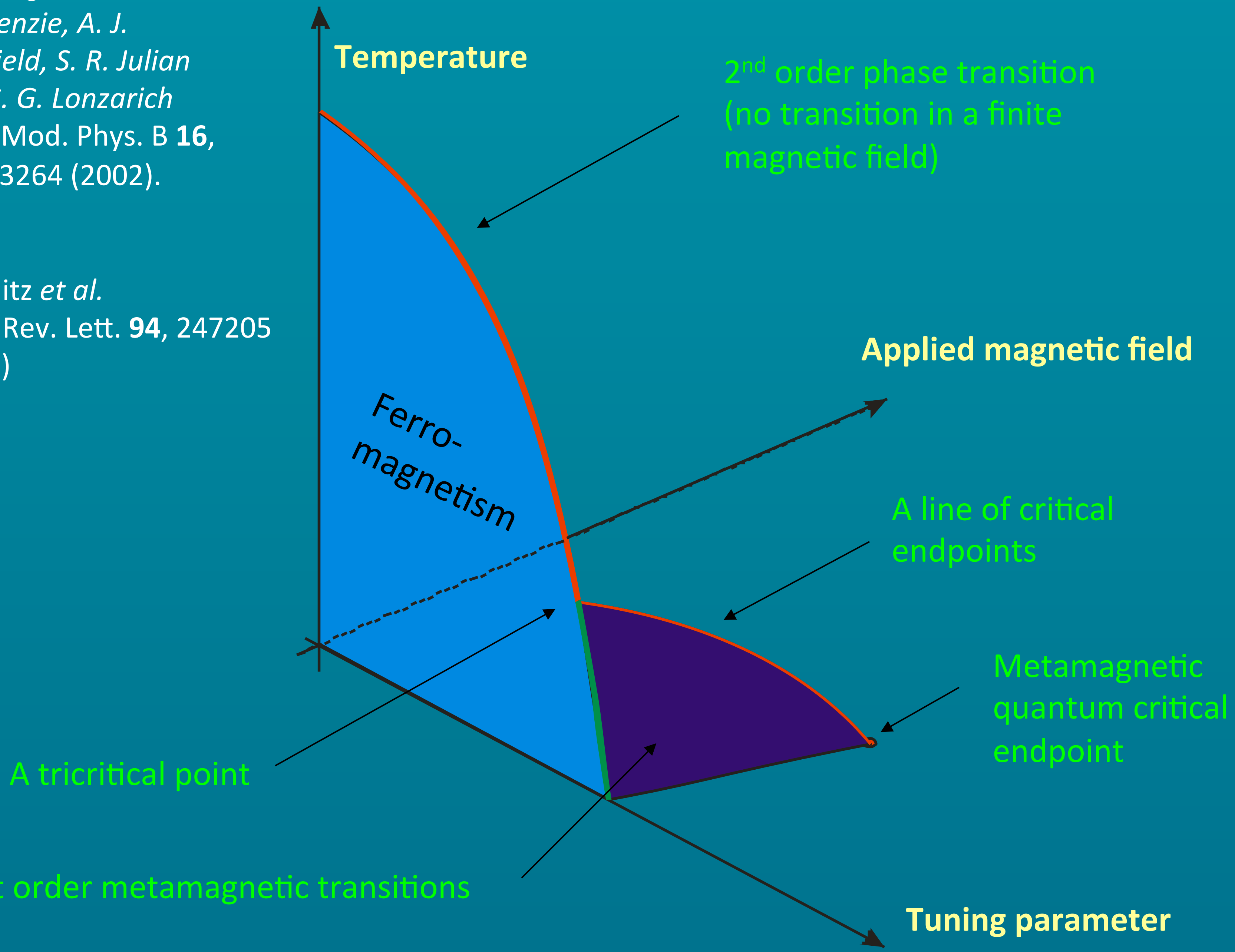
- Coupling to soft modes: particle-hole excitations in the spin channel:
  - $F \to F_{\text{conventional}} + w\, m^4 \ln(m^2/m_0^2 + T^2/T_0^2)$
    - D. Belitz, T.R. Kirkpatrick, Jorg Röllbühler, PRL **94**, 247205 (2005) and references therein.
      Reminiscent of other fluctuation induced first order transitions.
  - Non-analytic action in q: *e.g.* d=3 $\to q^2 \ln q$
    d=2 $\to -|q|^{3/2}\, m_q^{\ 2}$ at QCP. $|q|$ near QCP.
    - A. V. Chubukov, C. Pépin, J. Rech, PRL **92**, 147003 (2004).
      D. Belitz, T. R. Kirkpatrick, and T. Vojta, Phys. Rev. B **55**, 9452 (1997).
  - Over counting? No – observe corrections in Fermi liquid theory.
    - G.Y.Chitov and A. J. Millis, PRB **64**, 054414 (2001).
- Special pleading: Negative curvature of the density of states

Conclusion: generically driven first order, or order parameter must “curl up”.
But you can find a true LGWH quantum critical point at finite magnetic field.

Generic phase diagram

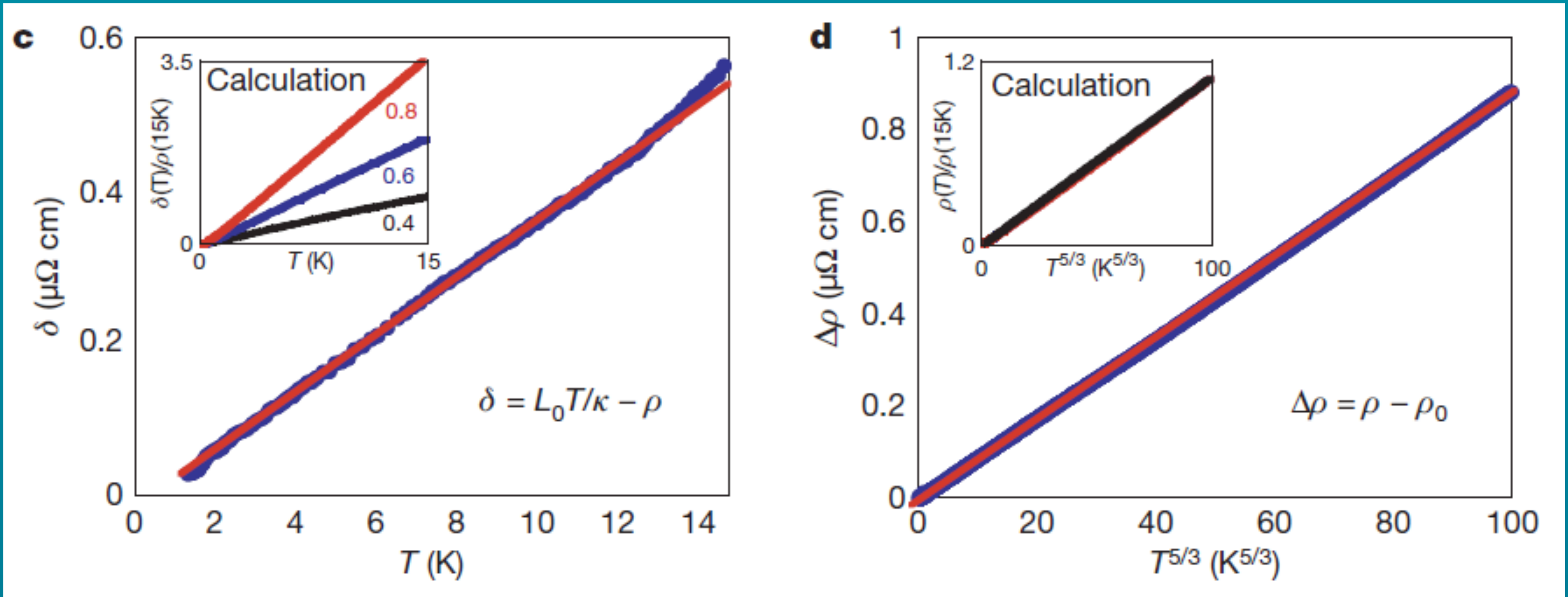
S. A. Grigera, A. P. Mackenzie, A. J. Schofield, S. R. Julian and G. G. Lonzarich
Int. J. Mod. Phys. B **16**, 3258-3264 (2002).

D. Belitz *et al.*
Phys. Rev. Lett. **94**, 247205 (2005)



LGWH: successes – $ZrZn_2$ a clean itinerant FM (>1K)

A Marginal Fermi Liquid

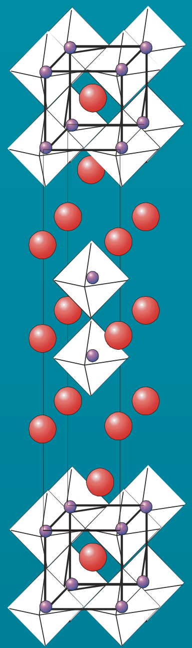


R. P. Smith, M. Sutherland, G. G. Lonzarich, S. S. Saxena, N. Kimura, S. Takashima, M. Nohara and H. Takagi
Nature **455**, *#7217*, 1220-1223 (2008).

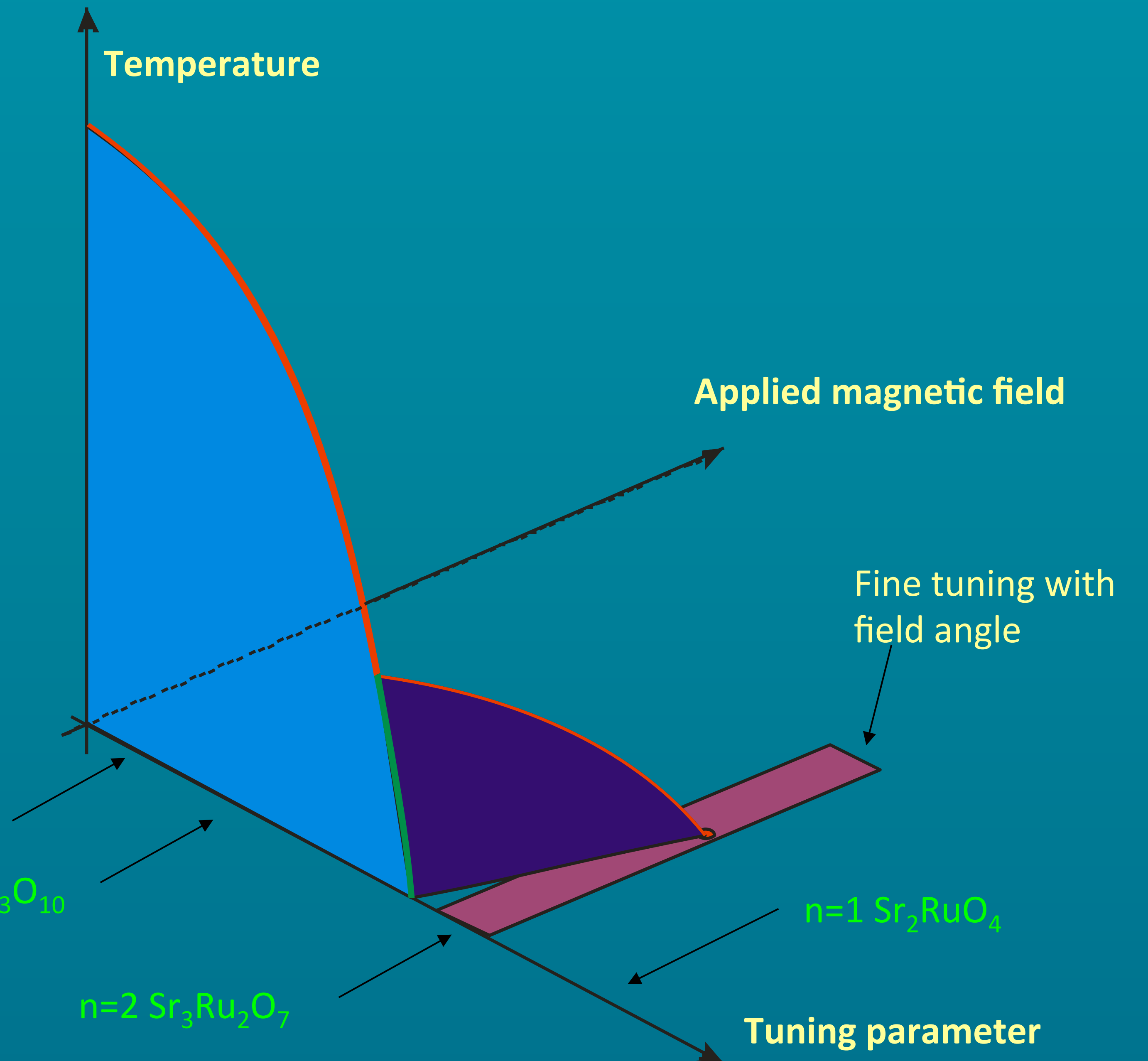
Exposing physics normally too weak to see: e.g. Michael Reizer (1989)

See: **Non-Fermi liquids** *A. J. Schofield* Contemp. Phys. **40**, *#2*, 95-115 (1999).

The Ruddlesden-Popper Series: $Sr_{1+n}Ru_nO_{1+3n}$

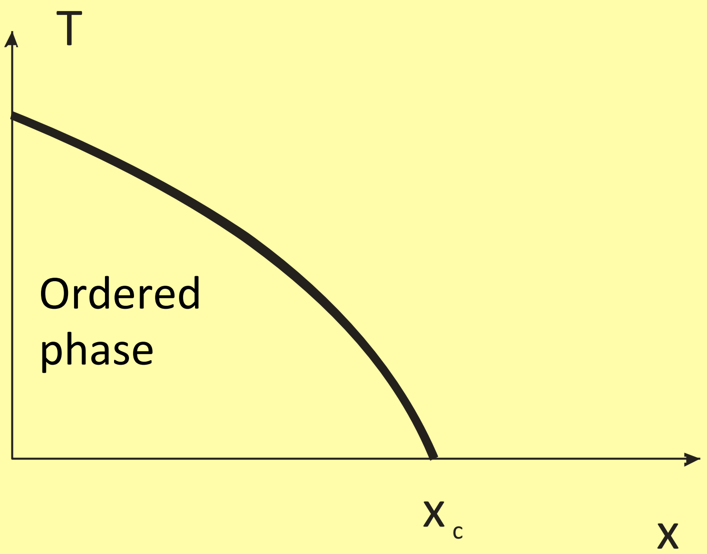


n=2
bilayer



Generating quantum criticality

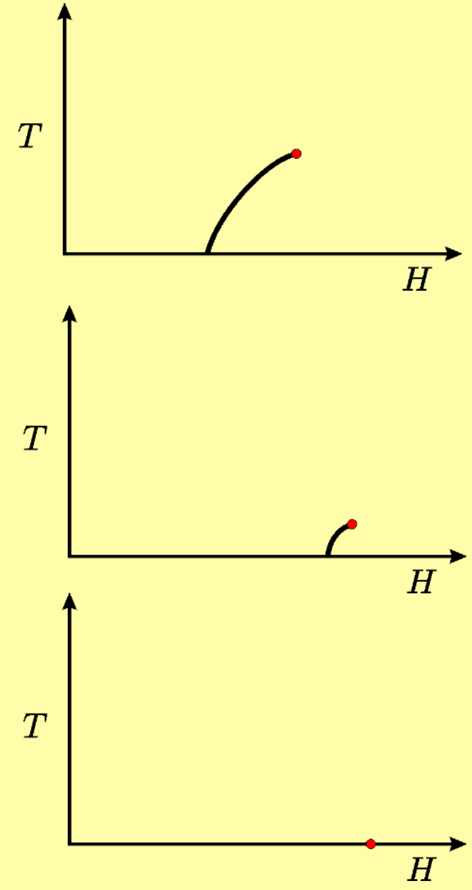
Continuous phase transition driven to *T*=0



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

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

Critical end-point driven to *T*=0

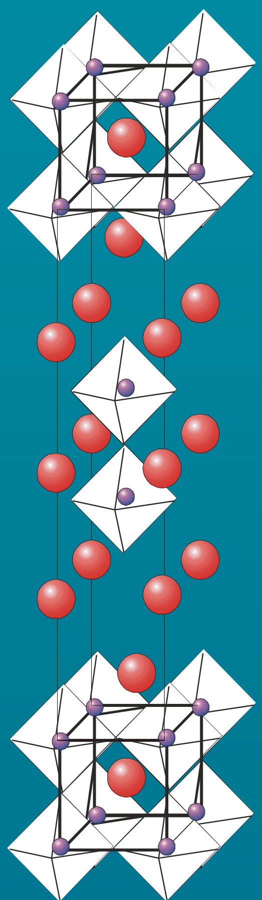


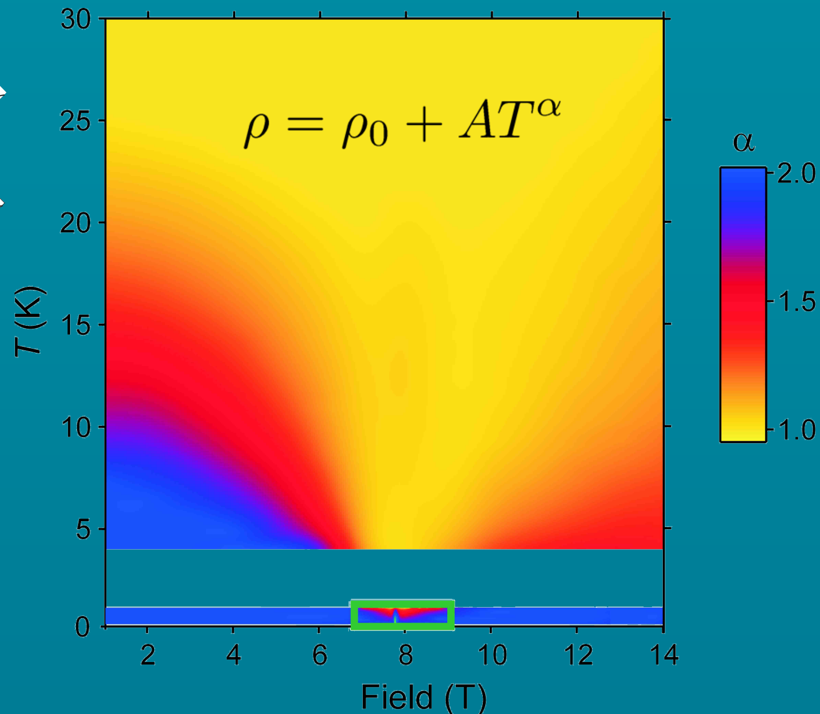
Example: **$Sr_3Ru_2O_7$** Metamagnetism tuned by magnetic field angle

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

The metamagnetic quantum critical end-point (QCEP)

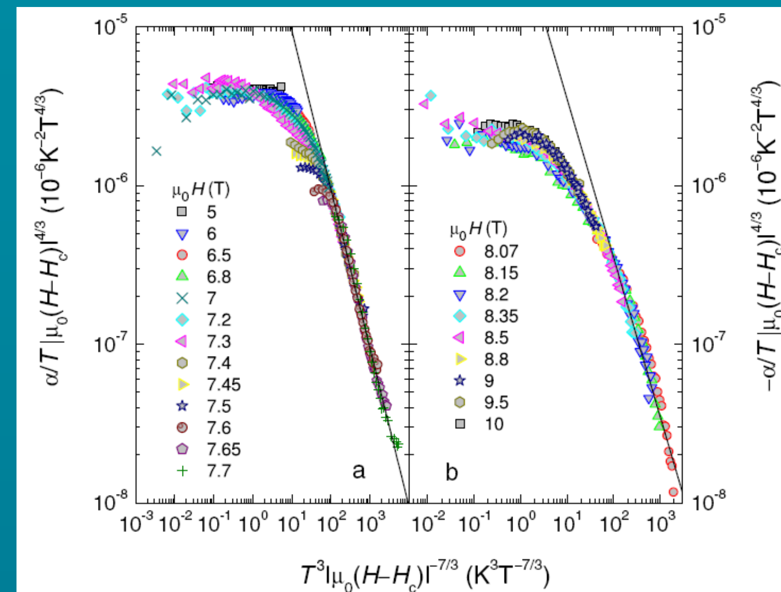
Theory of the metamagnetic quantum critical endpoint:
A.J. Millis, A. J. Schofield, G.G. Lonzarich and S.A. Grigera, Phys. Rev. Lett. **88**, 217204 (2002)





S.A.Grigera, R.S.Perry, A.J.Schofield, M.Chiao, S.R.Julian, G.G.Lonzarich, S.I.Ikeda, Y.Maeno, A.J.Millis, A.P.Mackenzie,

Science, **294**, 329 (2001).



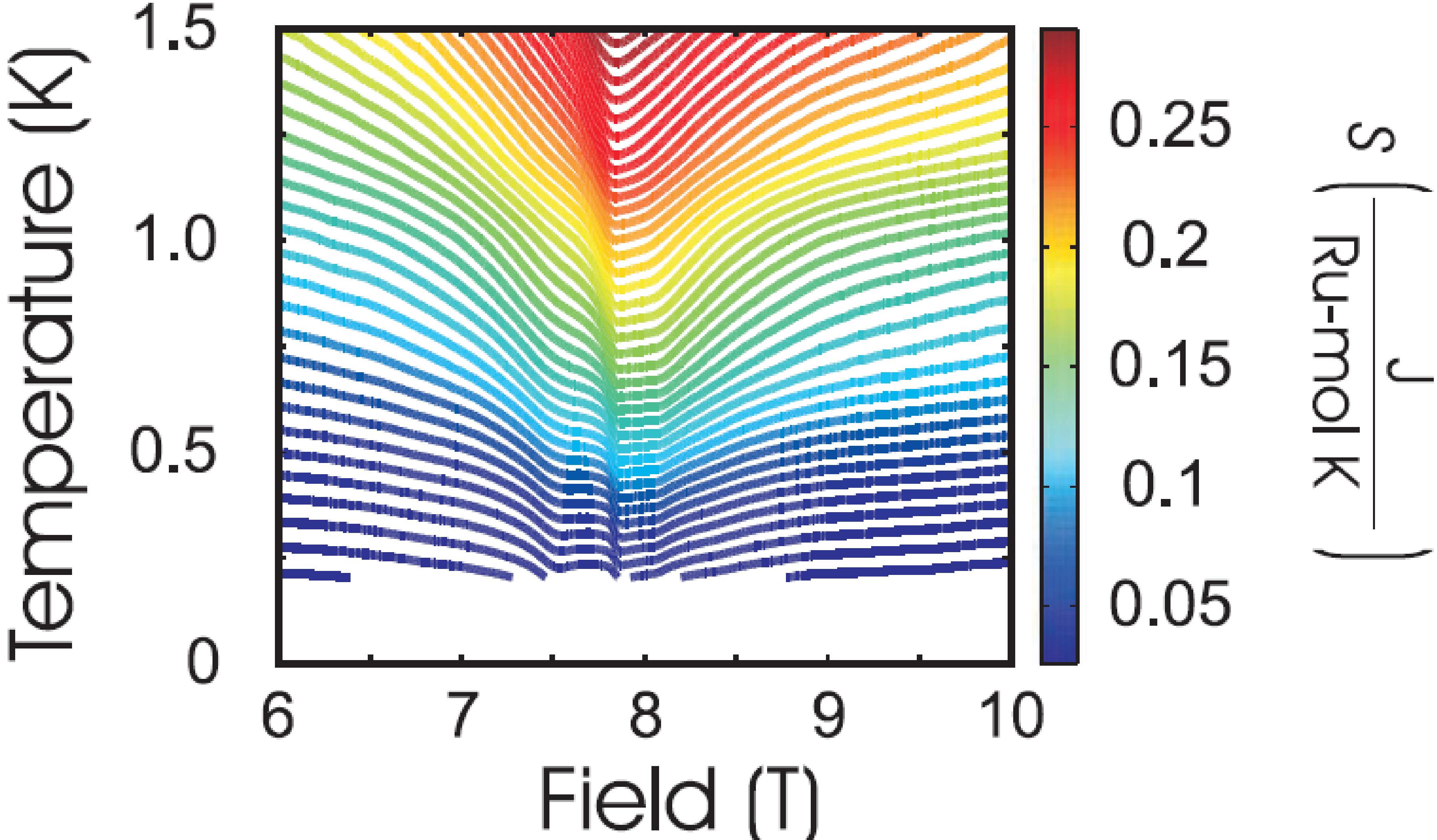
P. Gegenwart, F. Weickert, M. Garst, R.S. Perry and Y. Maeno,

Phys. Rev. Lett. **96**, 136402 (2006).

QCEP scenario consistent with thermal conductivity: F. Ronning, et al. PRL 97, 067005 (2006)

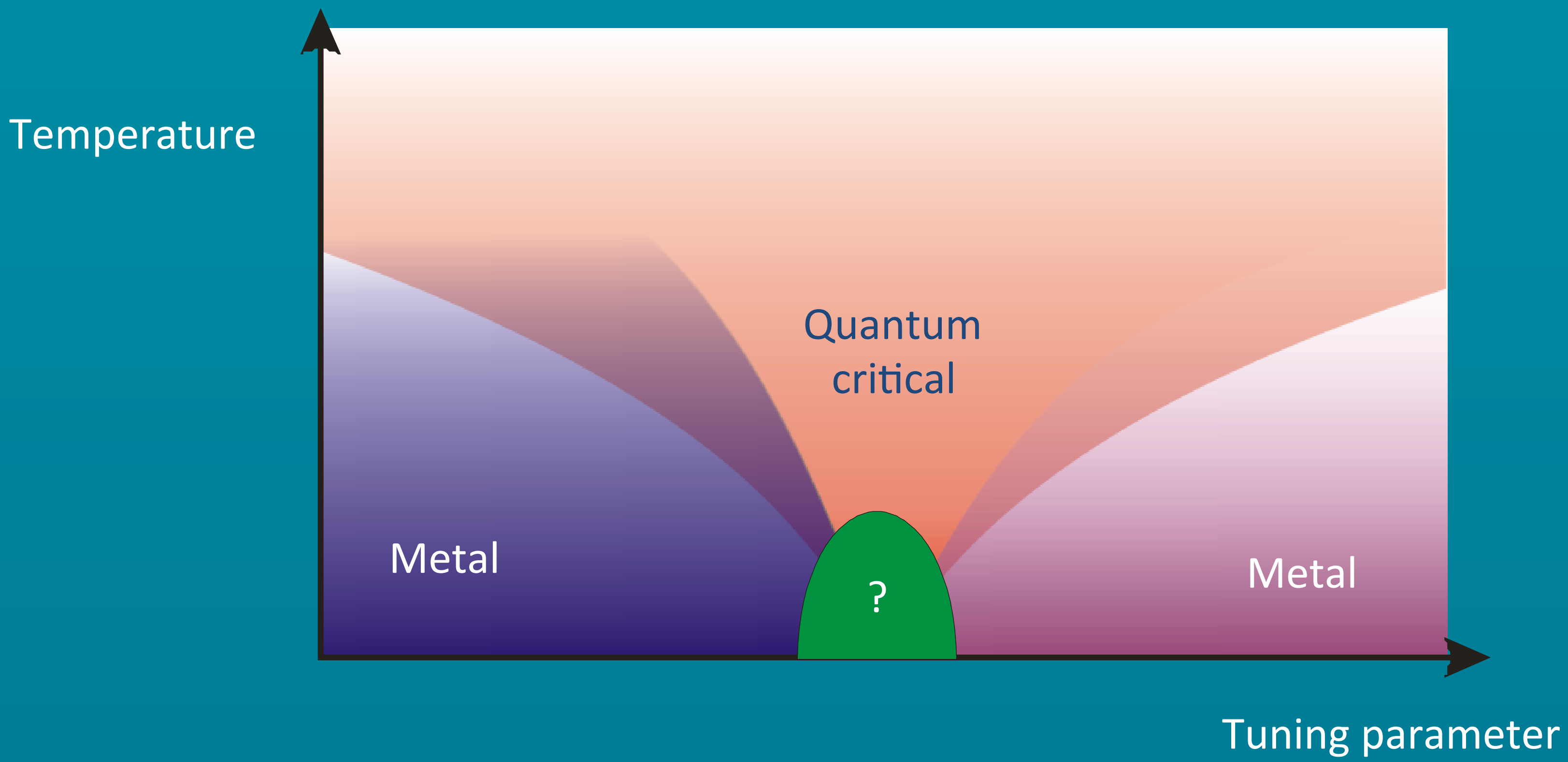
Quantum criticality – a playground for new phases

Quantum criticality concentrates the entropy: devices???



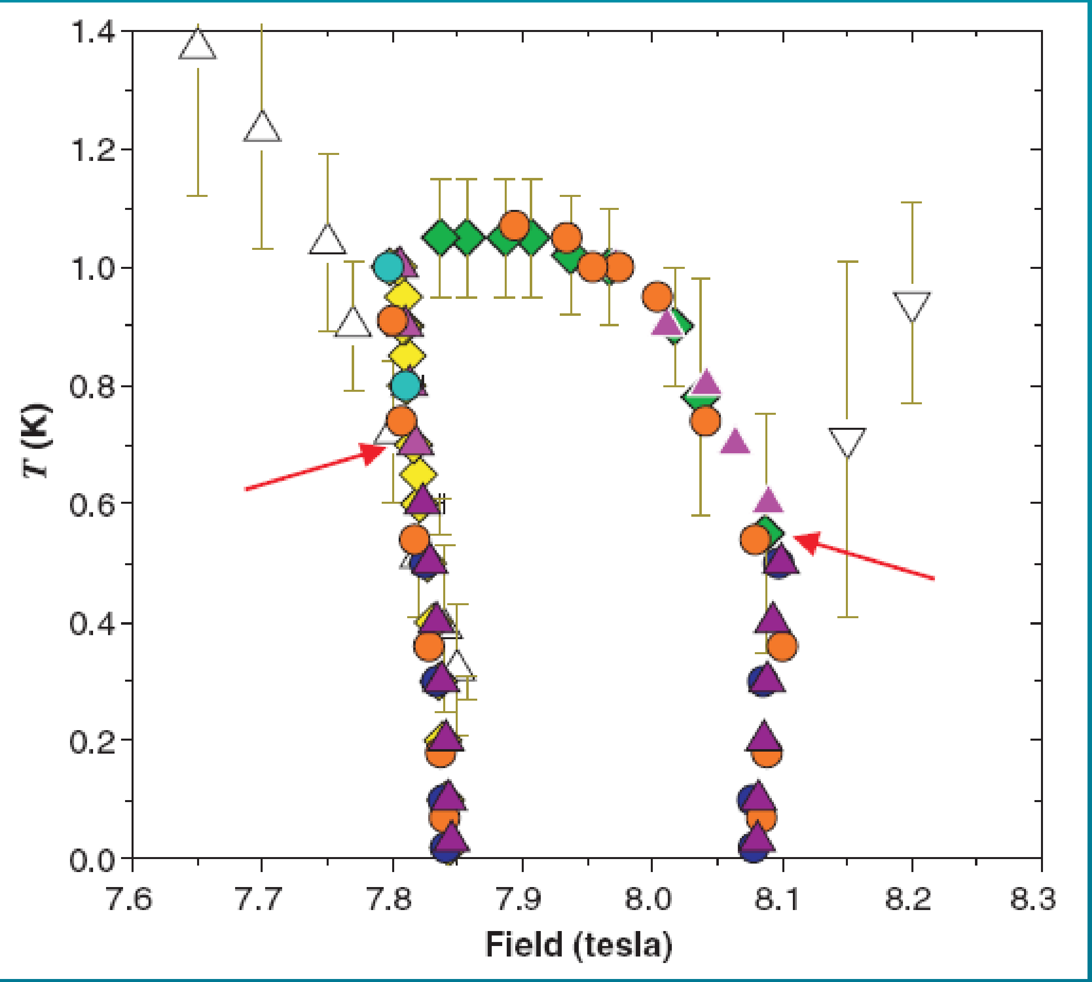
A. W. Rost, R. S. Perry, J.-F. Mercure, A. P. Mackenzie and S. A. Grigera
Science **325**, #*5946*, 1360-1363 (2009).

Quantum criticality driving new order in the vicinity of the QCP



Often superconductivity…but what if superconductivity cannot form?

Quantum "dark matter"



$Sr_3Ru_2O_7$

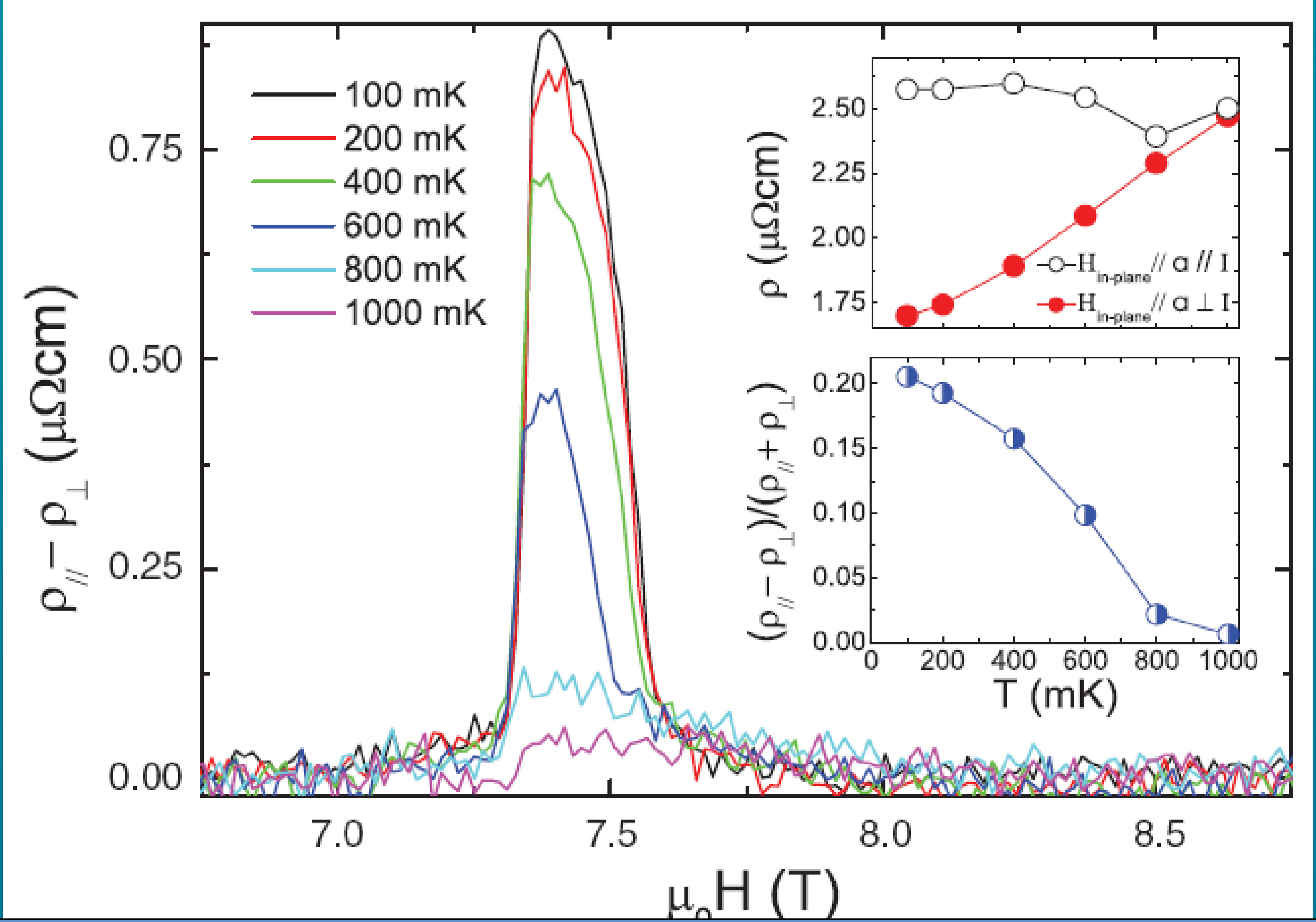
"Disorder sensitive phase formation linked to metamagnetic quantum criticality":
S. A. Grigera, P. Gegenwart, R. A. Borzi, F. Weickert, A. J. Schofield, R. S. Perry, T. Tayama, T. Sakakibara, Y. Maeno, A. G. Green, A. P. Mackenzie, Science **306**, 1154 (2004)

Metal-to-Metal transition seen in susceptibility, dc magnetization, resistivity, magnetostriction.

- URu_2Si_2 , $Sr_3Ru_2O_7$, Cuprates, …

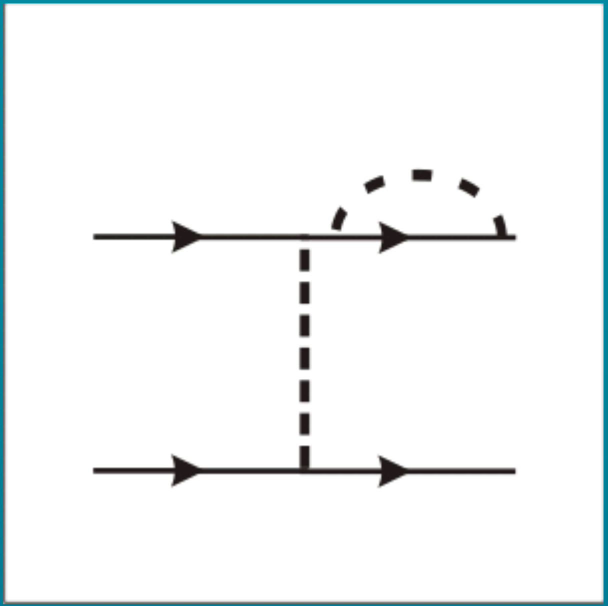
Condensed dark matter: matter that has a thermodynamic effect but whose order parameter is transparent to current probes.

Resistivity anisotropy appears… as if magnetic field aligns domains



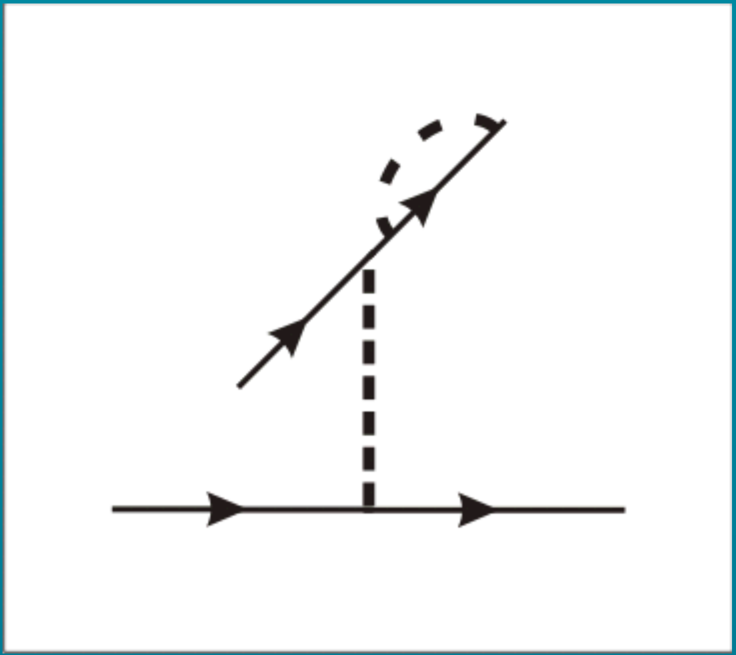
R.A. Borzi, S. A. Grigera, J. Farell, R.S.Parry, S. J. S. Lister, S. L. Lee, D. A. Tennant, Y. Maeno, A. P. Mackenzie, Science, **315**, 214 (2007).

From particle-particle pairing to particle-hole pairing



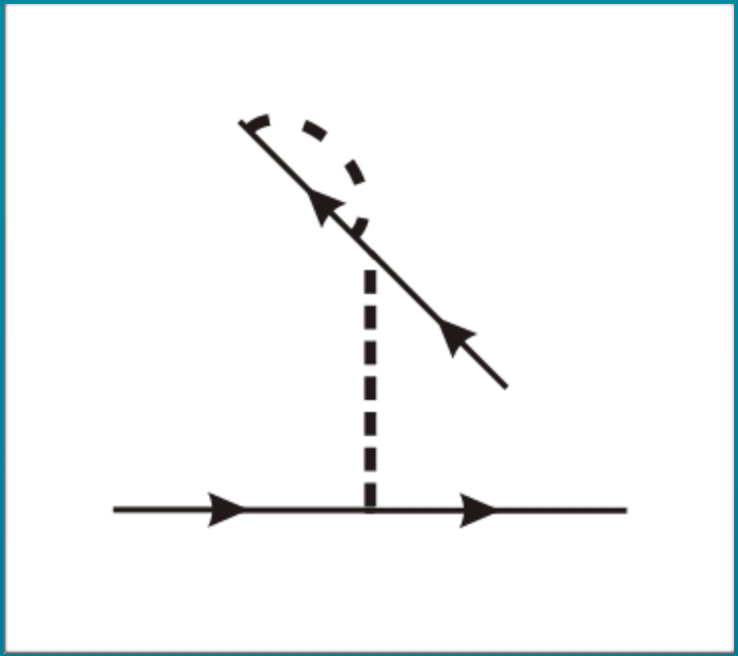
A. J. Schofield phys. stat. sol. (b) **247**, *#3*, 563-569 (2010).

From particle-particle pairing to particle-hole pairing



A. J. Schofield phys. stat. sol. (b) **247**, *#3*, 563-569 (2010).

From particle-particle pairing to particle-hole pairing



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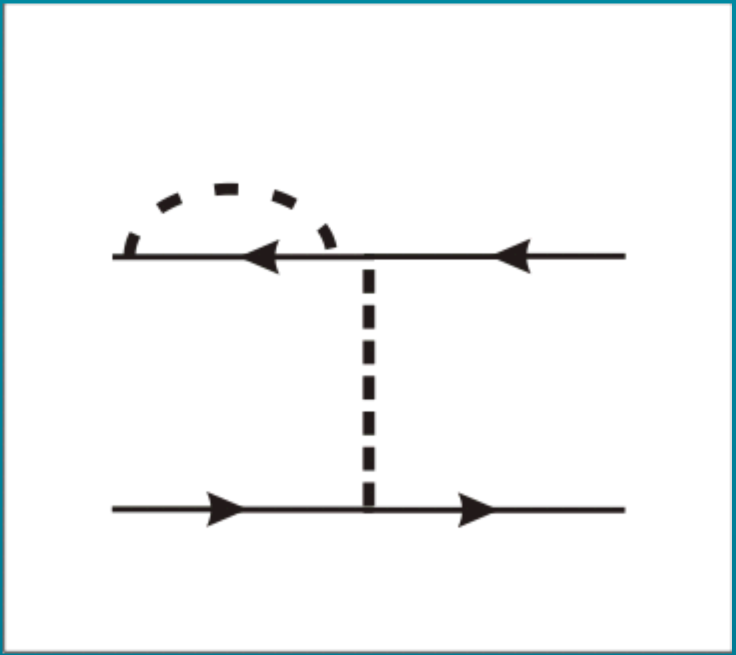


A. J. Schofield phys. stat. sol. (b) **247**, *#3*, 563-569 (2010).

Dark order states as magnetic analogues of unconventional superconductors

A. J. Schofield phys. stat. sol. (b) **247**, #*3*, 563-569 (2010).

Superconductors: part-part

Conventional: *s*-wave

$$\Delta = \sum_{k,k',\sigma} V_{k,k'} \langle c^\dagger_{k'\sigma} c^\dagger_{-k'\bar{\sigma}} \rangle$$

Unconventional: *p*-wave, *d*-wave,…

$$\Delta(k) = \sum_{k,k',\sigma} V_{k,k'} \langle c^\dagger_{k'\sigma} c^\dagger_{-k'\bar{\sigma}} \rangle$$

Inhomogeneous: FFLO

$$\Delta(q) = \sum_{k,k',\sigma} V_{k,k'} \langle c^\dagger_{k'+q/2,\sigma} c^\dagger_{-k'+q/2,\bar{\sigma}} \rangle$$

Mixed State

Magnets: part-hole

Conventional: Stoner ferromagnetism

$$M = \sum_{k,\sigma,\sigma'} g_{\sigma,\sigma'} \langle c^\dagger_{k\sigma} c_{k\sigma'} \rangle$$

“Pomeranchuk”: *p*-wave, *d*-wave,…

$$M(k) = \sum_{k,\sigma,\sigma'} g_{k,k';\sigma,\sigma'} \langle c^\dagger_{k'\sigma} c_{k'\sigma'} \rangle$$

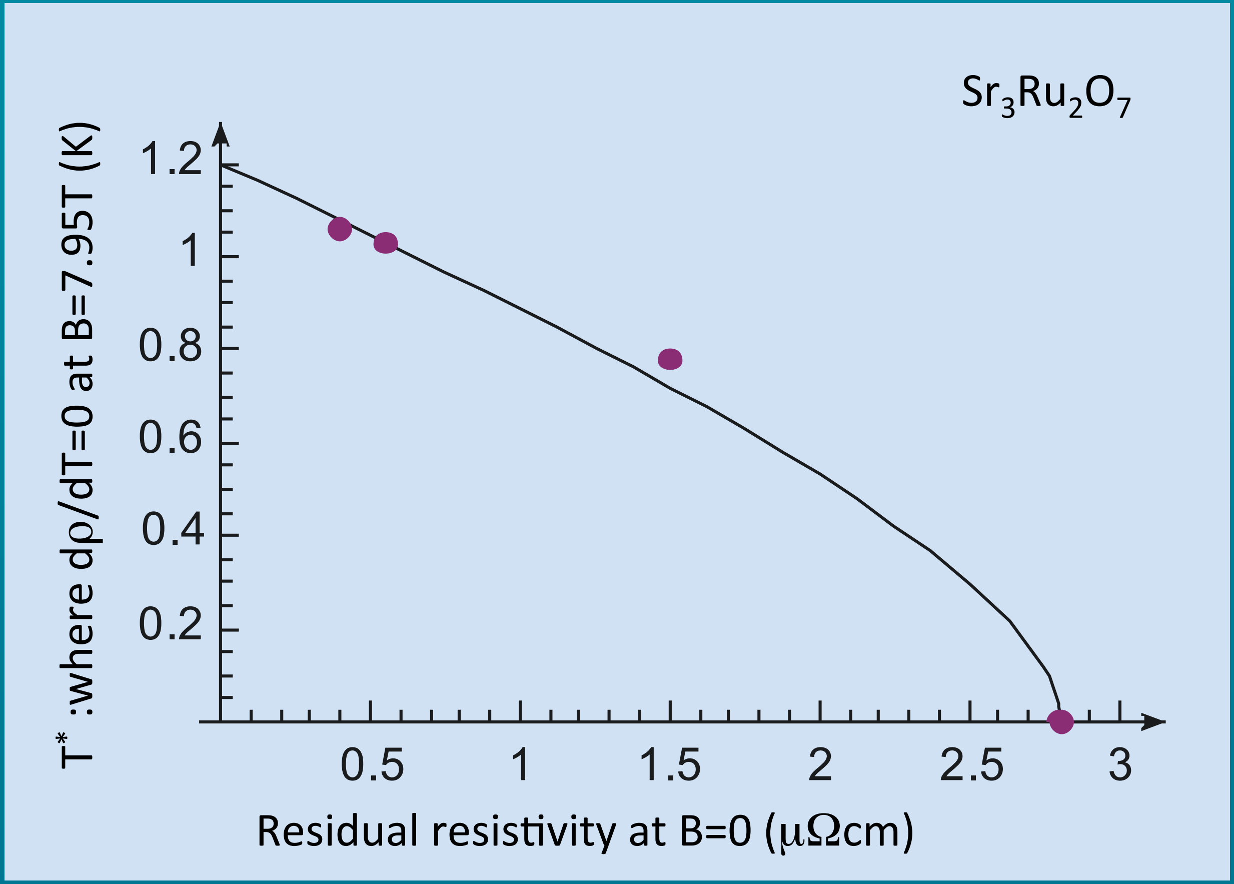
Inhomogeneous: “spirals”, density waves

$$M(q) = \sum_{k,\sigma} g_{k,k';\sigma,\sigma'} \langle c^\dagger_{k'+q/2,\sigma} c_{k'-q/2,\sigma'} \rangle$$

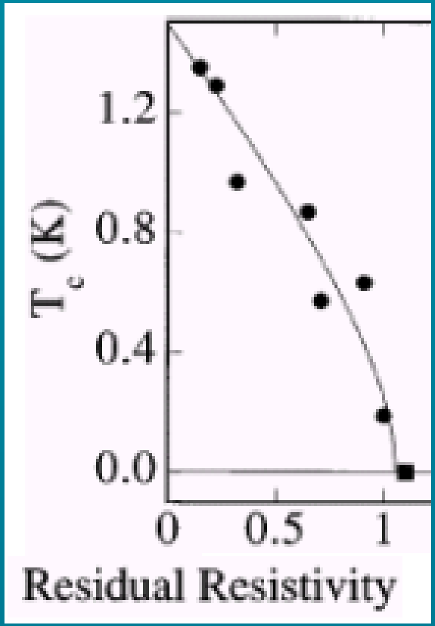
Spin textured state

Predictions: magnetic analogues of unconventional superconductors should show strong disorder dependence

A. F. Ho and A. J. Schofield EPL **84**, #2, 27007 (2008).



c.f. Sr_2RuO_4



A. P. Mackenzie *et al.* Phys. Rev. Lett. **80**, 161 (1998)

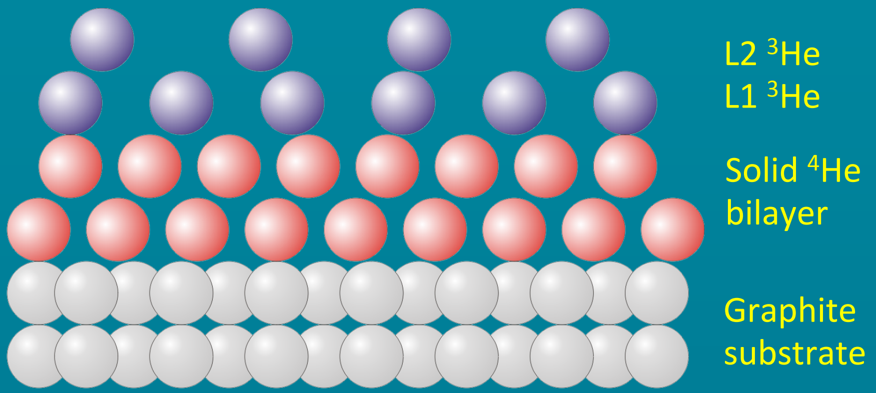
- No systematic studies. Existing data from S. A. Grigera

Can we make Kondo lattice look-alike?

- Evidence from d-metals of some resonance with the Landau-Ginzburg-Wilson-Hertz view of quantum criticality
- Can we create quantum criticalty in a Kondo lattice "look-alike"?

Kondo breakdown in a look-alike?

- Bilayers of ^3He:
  Michael Neumann, Ján Nyéki, Brian Cowan and John Saunders
  Science **317**, #*5843*, 1356-1359 (2007).



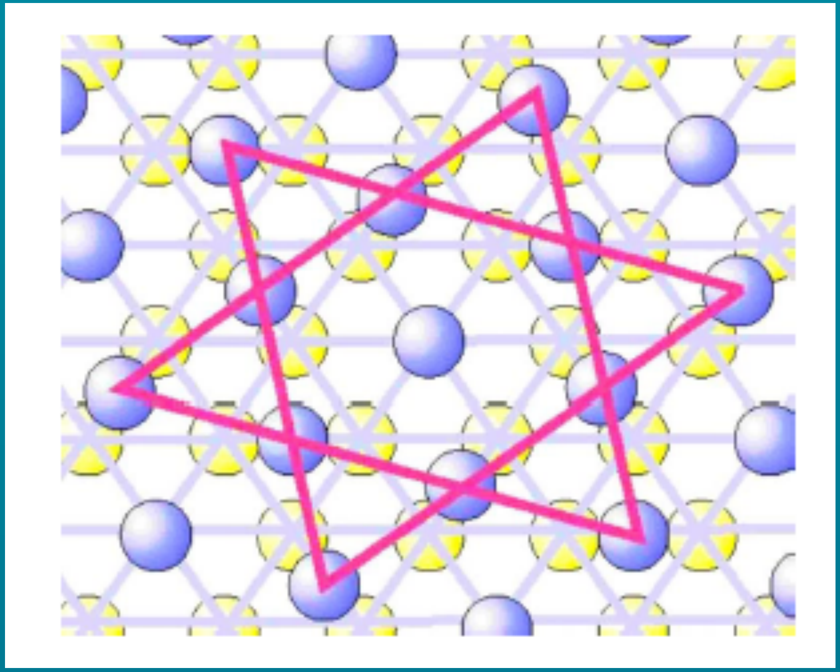


Figure from A. Benlagra and C. Pepin, PRB, 79, 045112 (2009)

Kondo breakdown in a look-alike?

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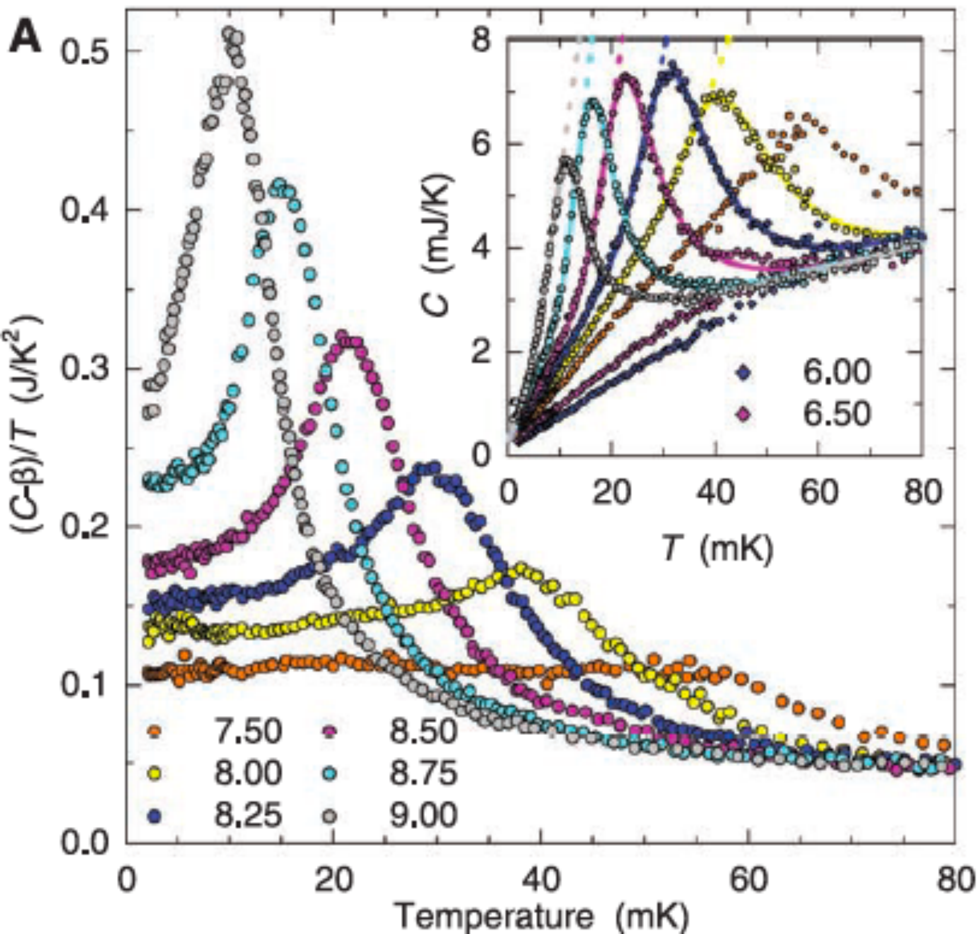

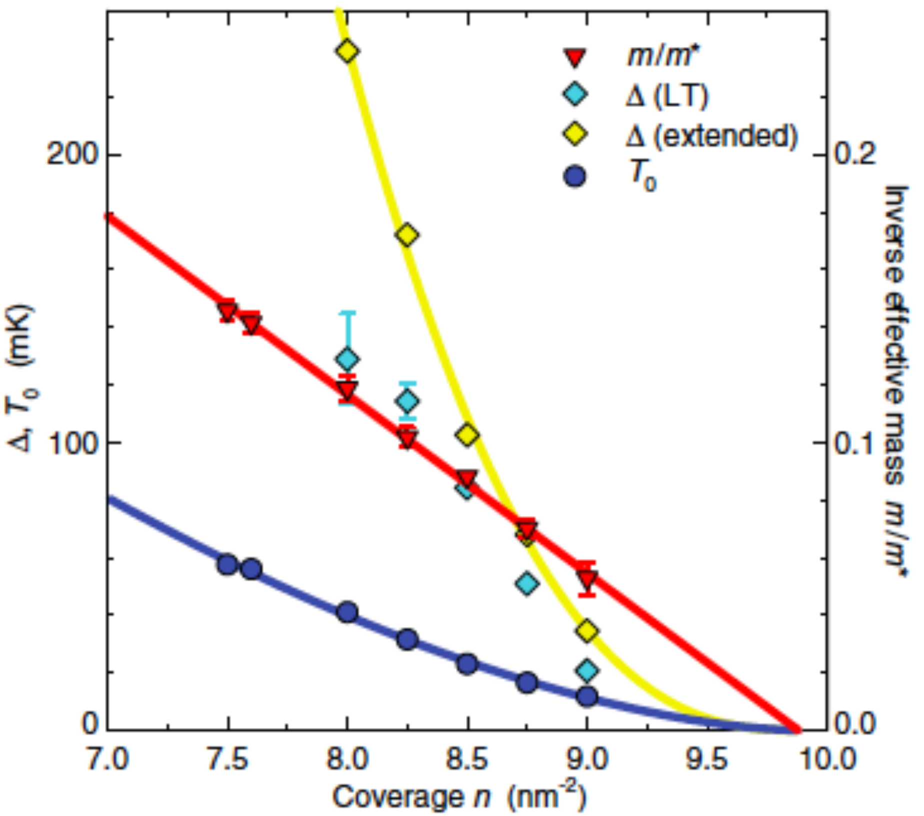

Kondo breakdown in a look-alike?

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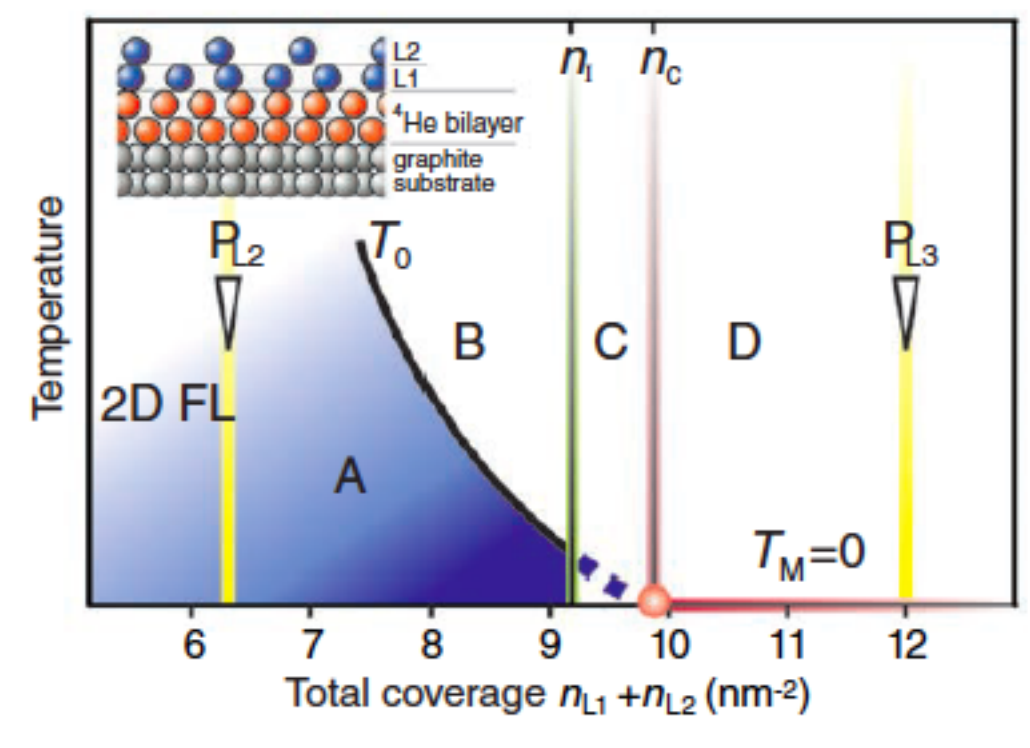


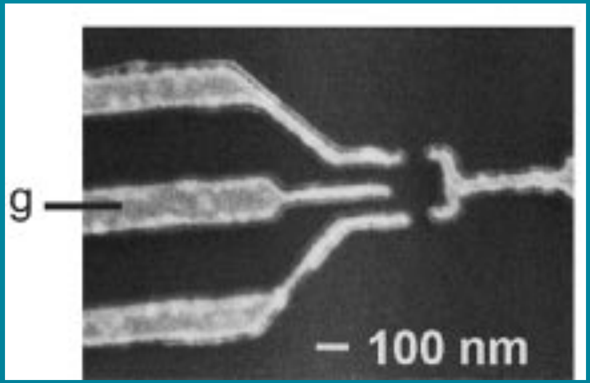
Evidence of quantum criticality in a Kondo like system: does it resemble heavy fermion anomalous quantum critical points?

Future Trends and Perspectives

- Developments in materials:
  - Epitaxial growth [c.f. *H. Shishido et al.* Science **327**, #*5968*, 980-983 (2010).]
- Developments in look-alikes:
  - Quantum critical d-metals, oxides, organics…
  - Realizing an Anderson lattice in a semiconductor
  - Realizing an Anderson lattice in a cold atomic gas
- Developments in experiments:
  - ARPES, tunnelling, high field facilities
  - How could we use the new field of quantum metrology?

Realizing an Anderson lattice in semiconductors

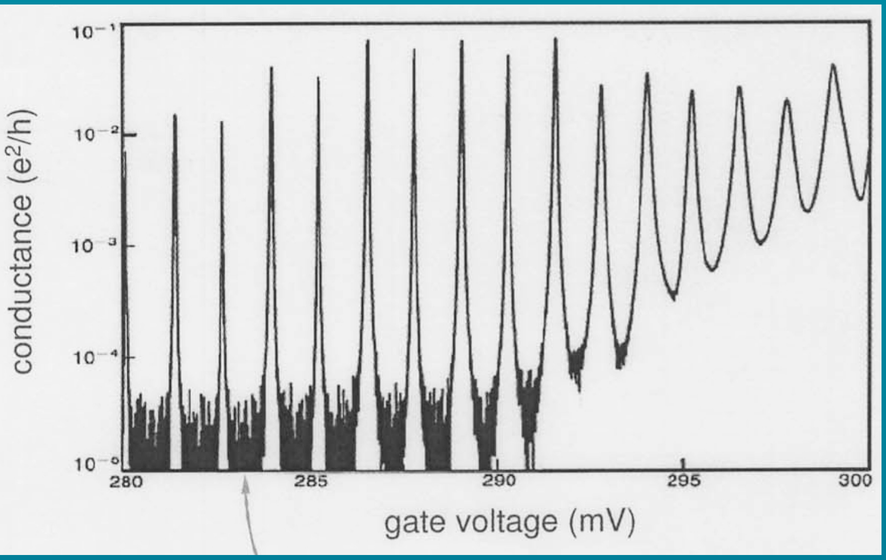
- Inspiration 1: Kondo dots

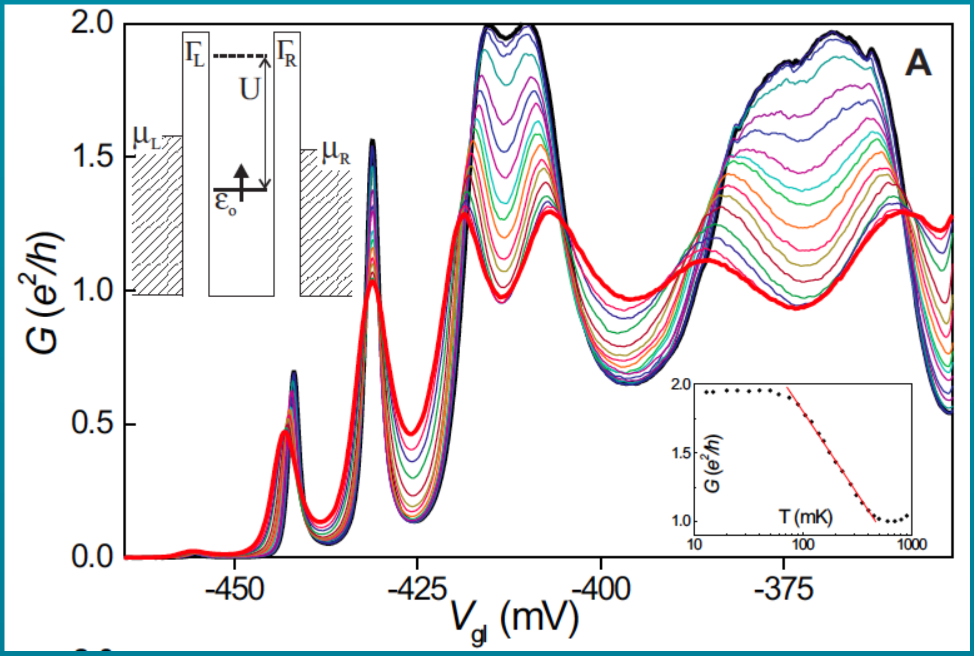


Andrei Kogan, Sami Amasha, M. A. Kastner
Science **304**, *#5675*, 1293-1295 (2004).

Realizing an Anderson lattice in semiconductors

- Inspiration 1: Kondo dots





M. Kastner (1993)

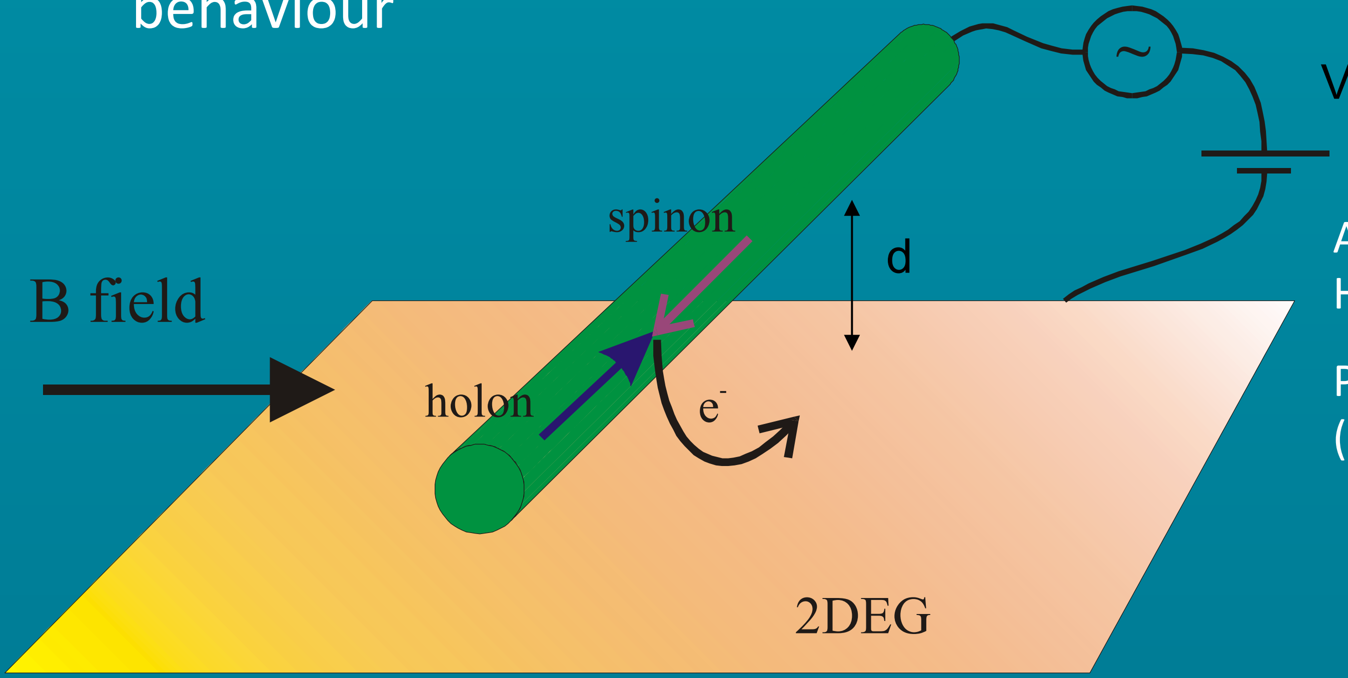
Van der Wiel et al. Science 289, 2105 (2004)

For a review, see M. Pustilnik and L. I. Glasman: cond-mat/0501007.

Could you make a lattice of Coulomb blockaded dots?

Realizing an Anderson lattice in semiconductors

- Inspiration 2: Bilayer 2DEGs used to probe Luttinger liquid behaviour



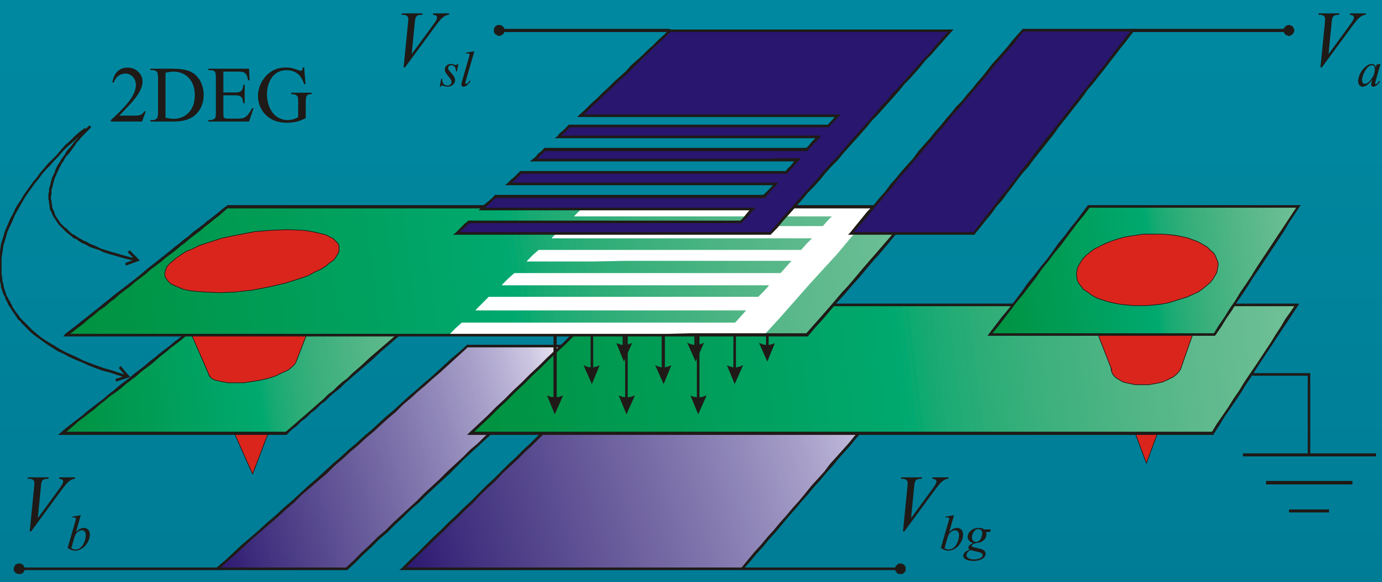
A Altland, CW Barnes, F Hekking & AJ Schofield,

Phys Rev Lett, **83**, 1203 (1999).

- Tunnelling between a 2D system (known probe) and a 1D wire (unknown subject).
- Smooth interface: momentum conserved along wire
- Transverse magnetic field tunes relative momentum

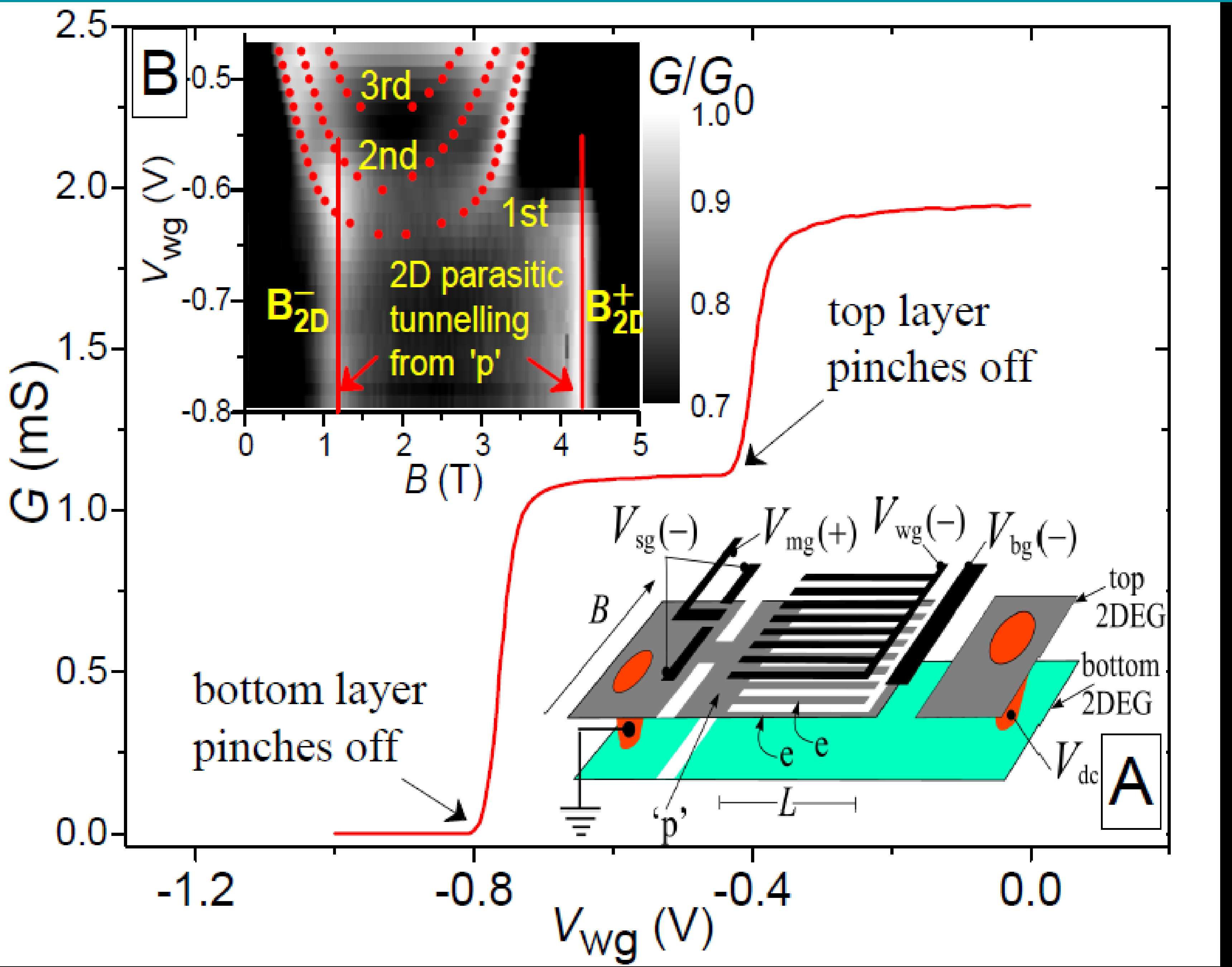
Realizing an Anderson lattice in semiconductors

- Inspiration 2: Bilayer 2DEGs used to probe Luttinger liquid behaviour

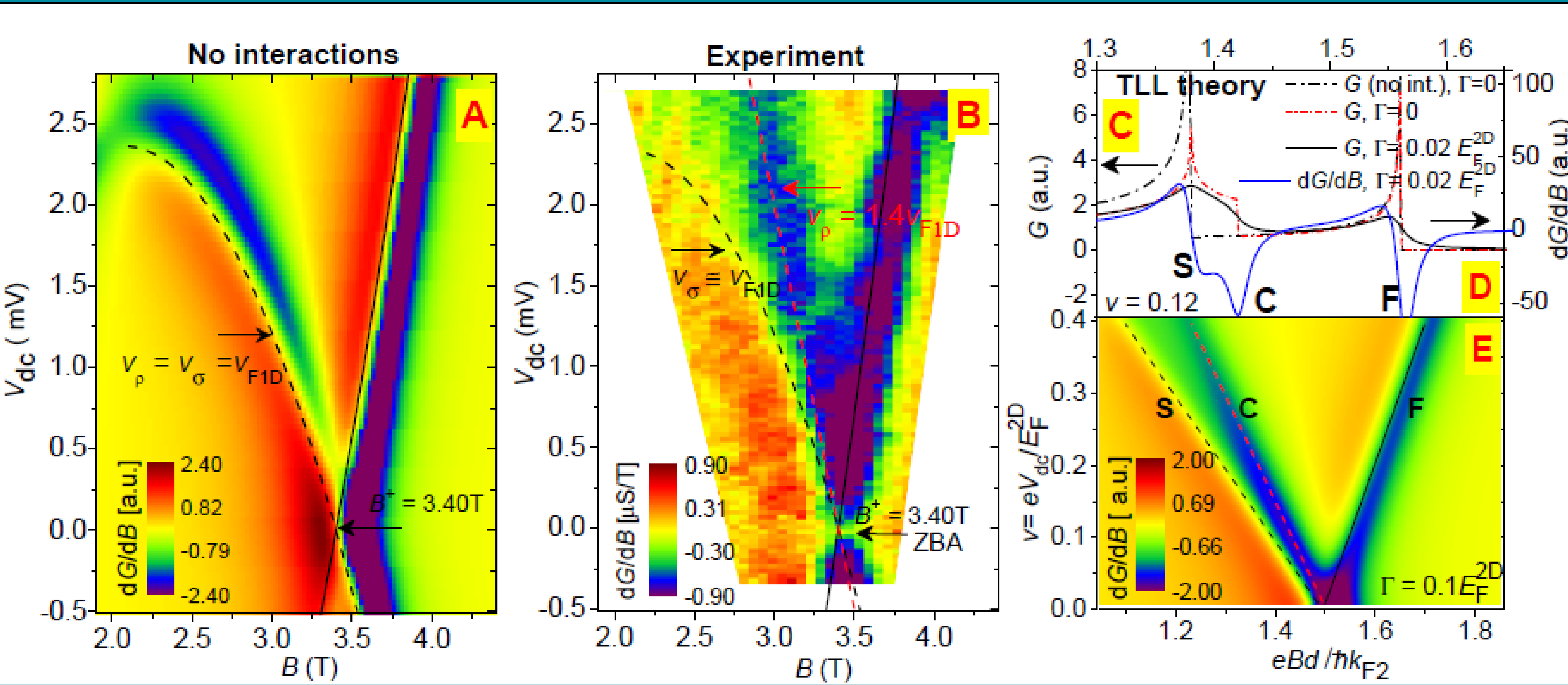


Y. Jompol, C. J. B. Ford, J. P. Griffiths, I. Farrer, G. A. C. Jones, D. Anderson, D. A. Ritchie, T. W. Silk and A. J. Schofield
Science **325**, #*5940*, 597-601 (2009).

Achieving a single channel wire:



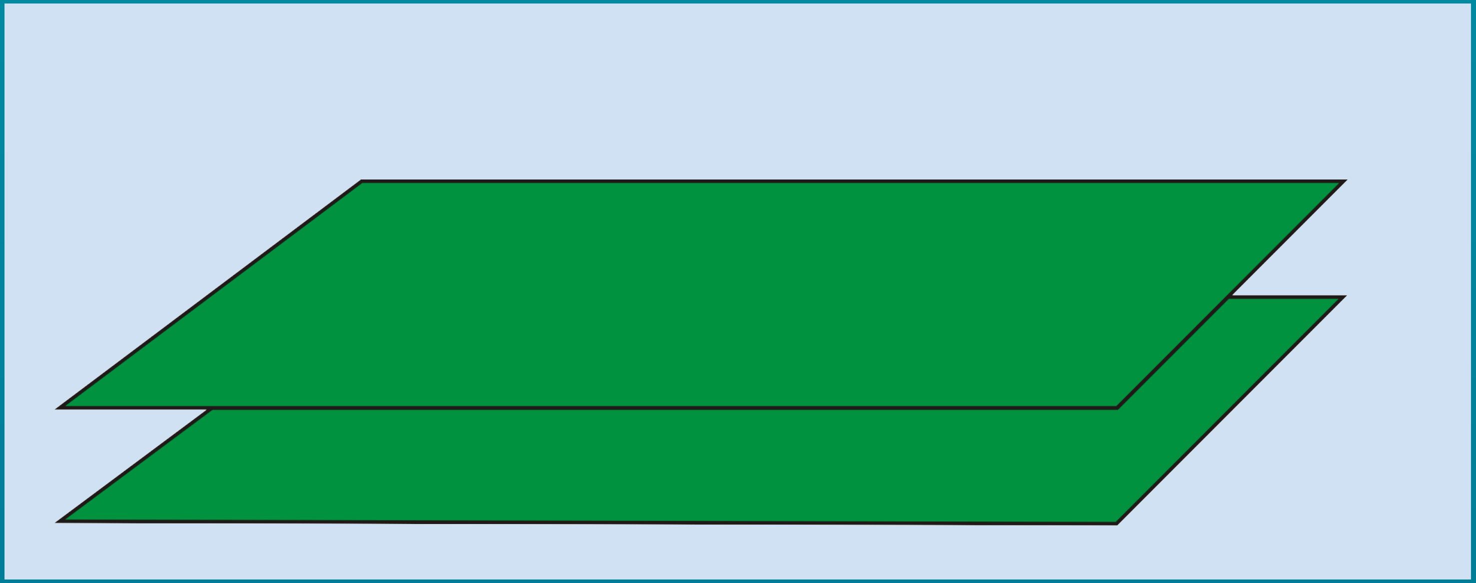
Finally – dispersing spinons and holons



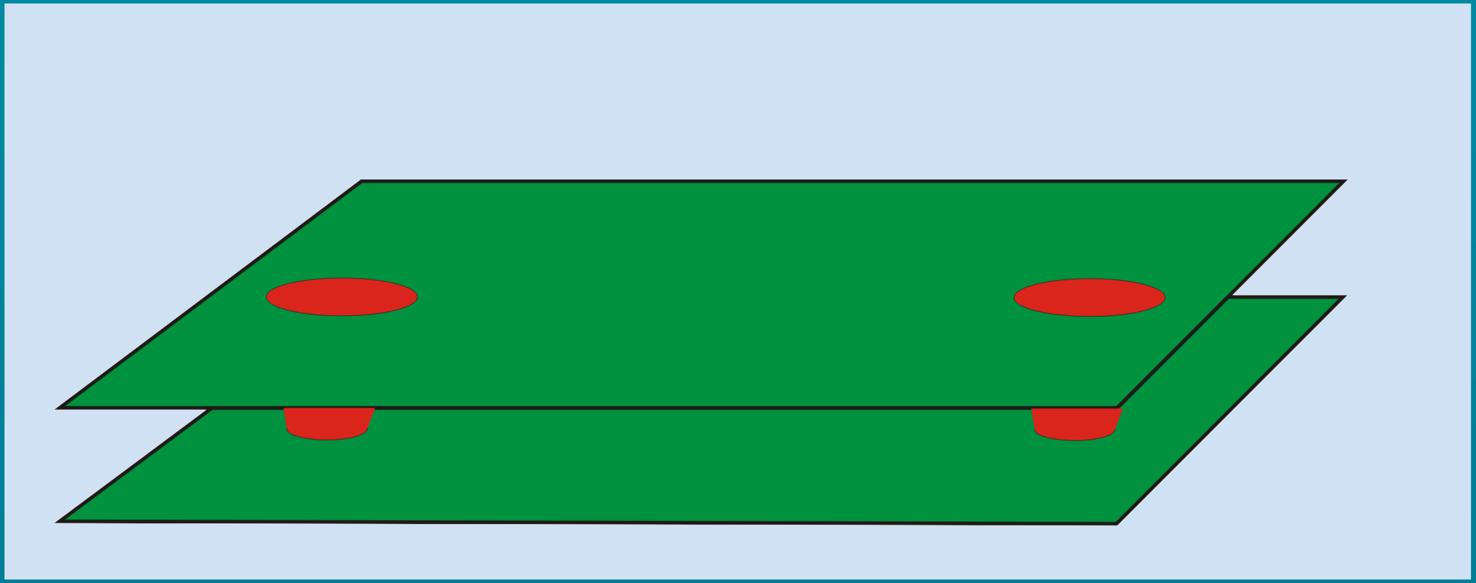
- See spinon and holon beyond the universal region.

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).

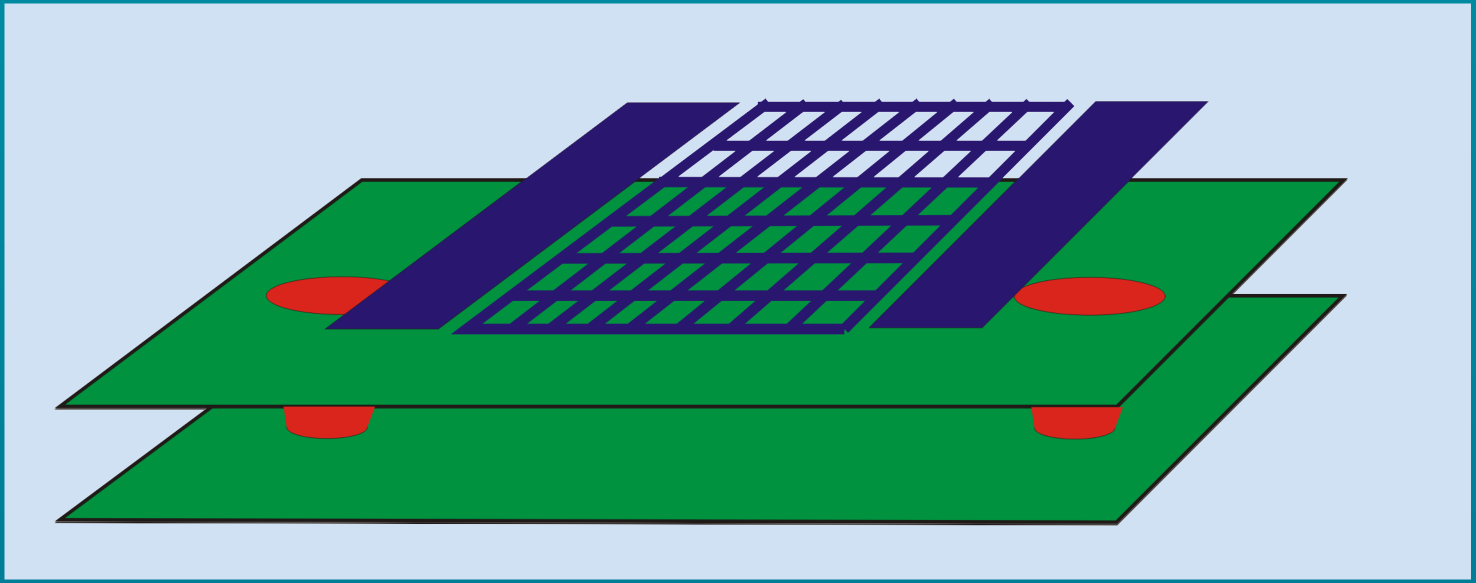
Realizing an Anderson lattice in a bilayer system



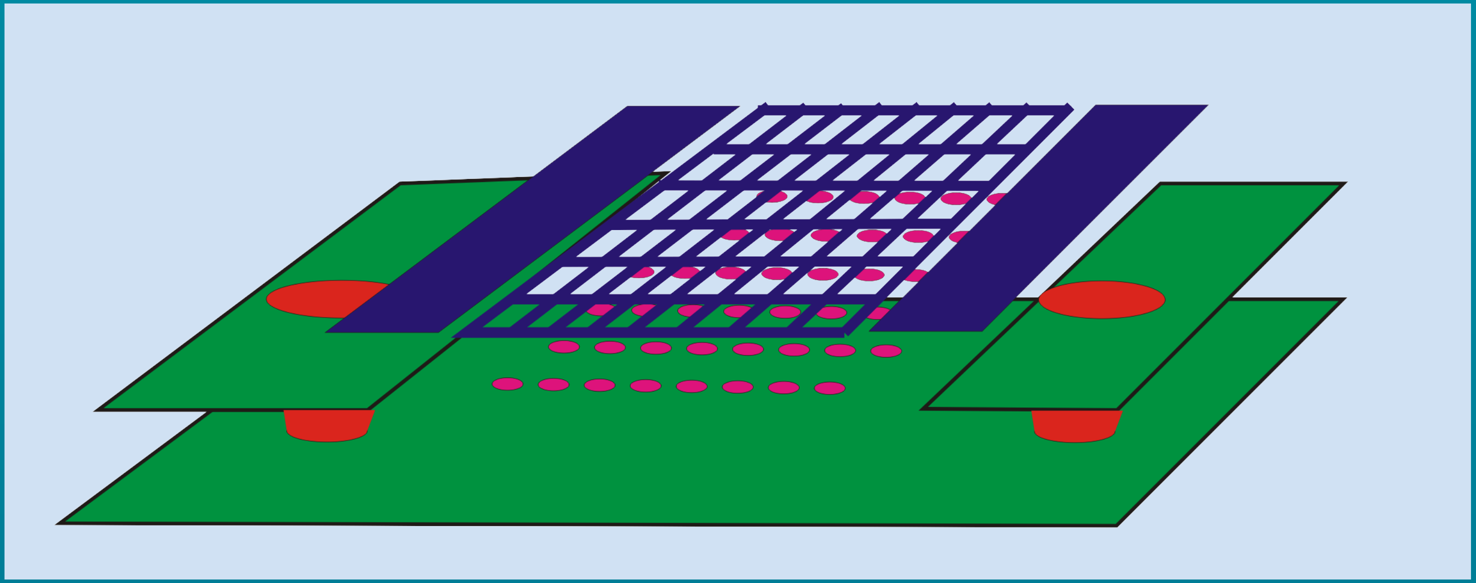
Realizing an Anderson lattice in a bilayer system



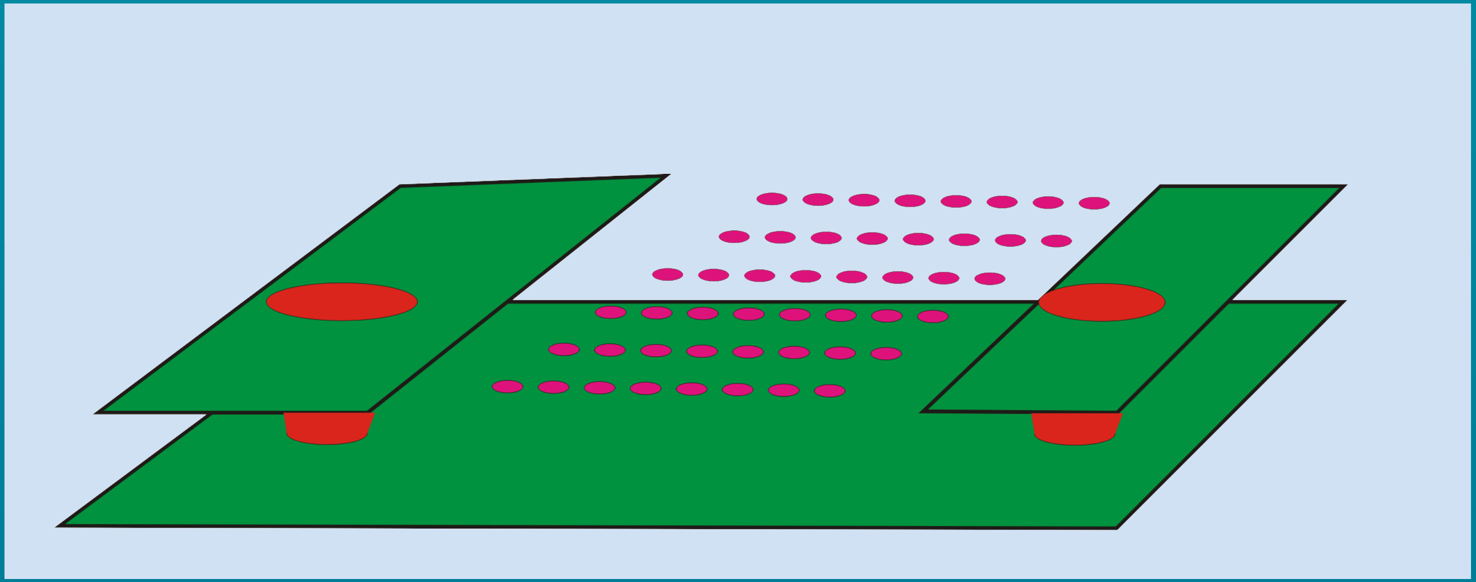
Realizing an Anderson lattice in a bilayer system



Realizing an Anderson lattice in a bilayer system



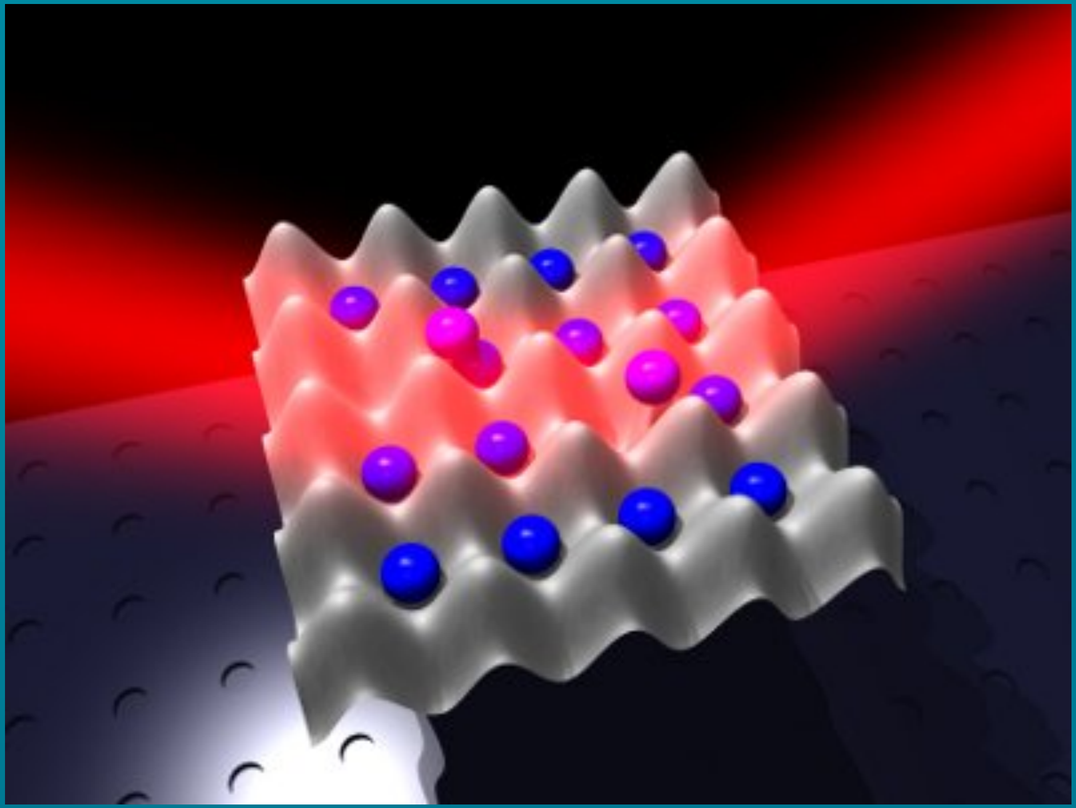
Realizing an Anderson lattice in a bilayer system



Would be a very dilute Anderson/Kondo lattice – can we improve this?

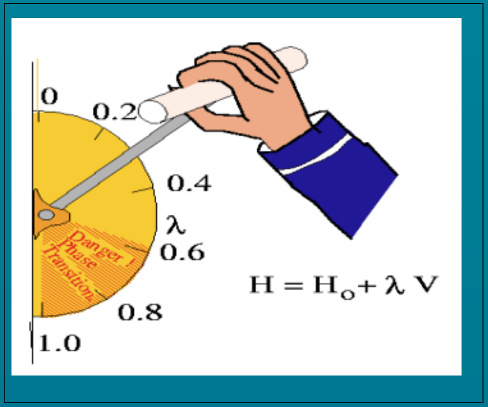
Cold quantum gases as quantum simulators

- Remarkable developments in cold quantum gases



- Ultimate control of the Hamiltonian – lattice shape, interactions etc.

The hand of Landau…

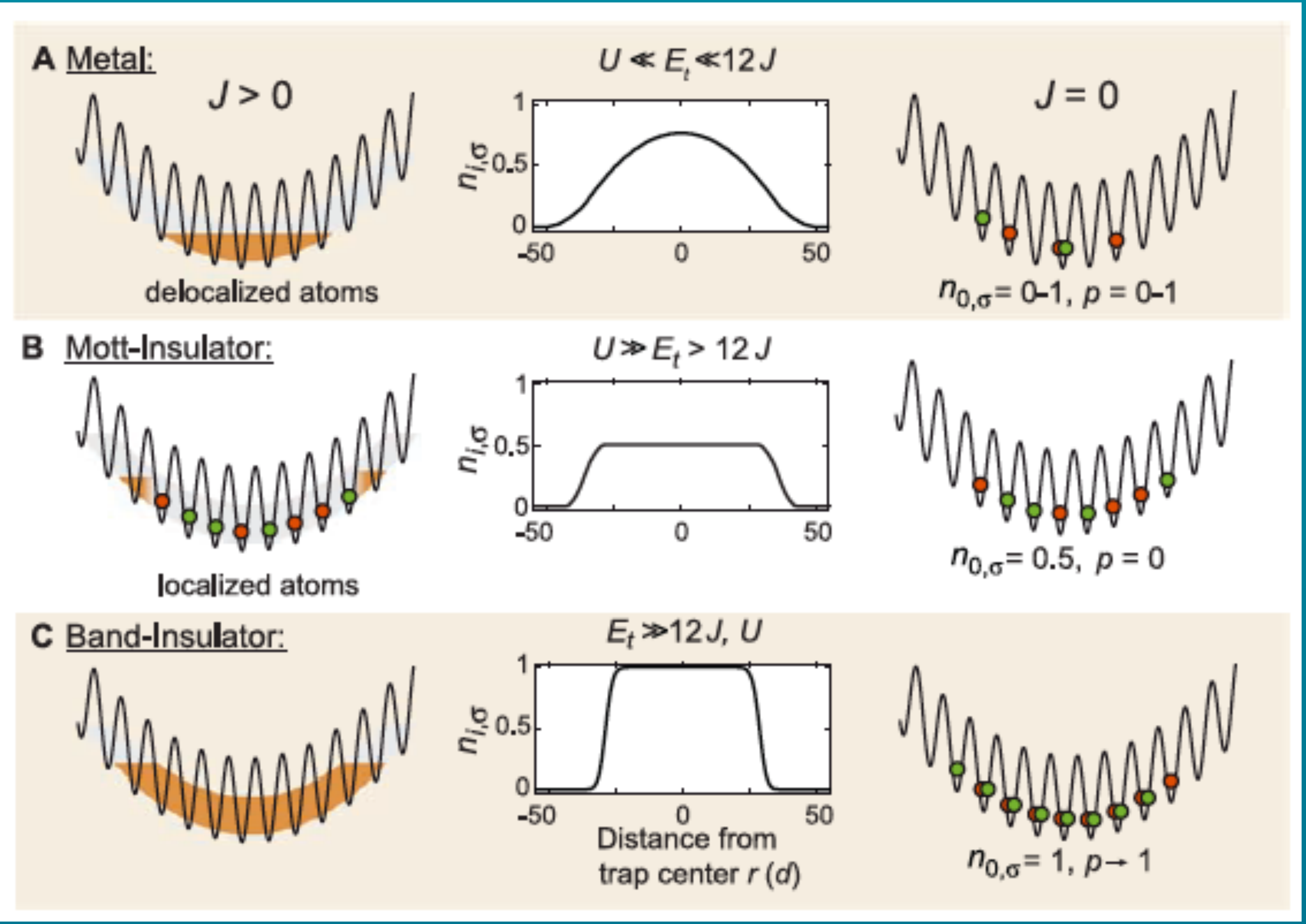


…becomes the hand of the experimentalist (changes are adiabatic).

Image: http://www.lens.unifi.it

Realizing an Anderson Lattice in an optical lattice

- Inspiration: the (Fermi) Hubbard model in cold atomic gases



U. Schneider, L. Hackermüller, S. Will, Th. Best, I. Bloch, T. A. Costi, R. W. Helmes, D. Rasch and A. Rosch Science **322**, *#5907*, 1520-1525 (2008).

Realizing an Anderson Lattice in an optical lattice

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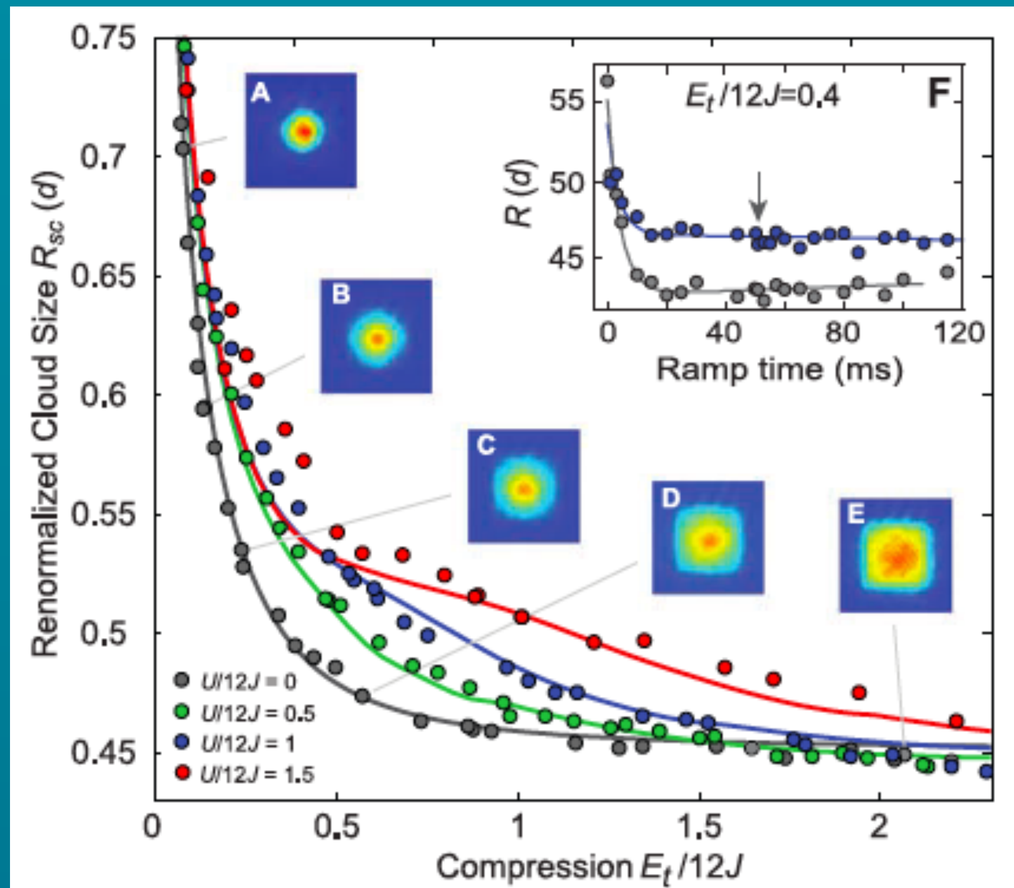
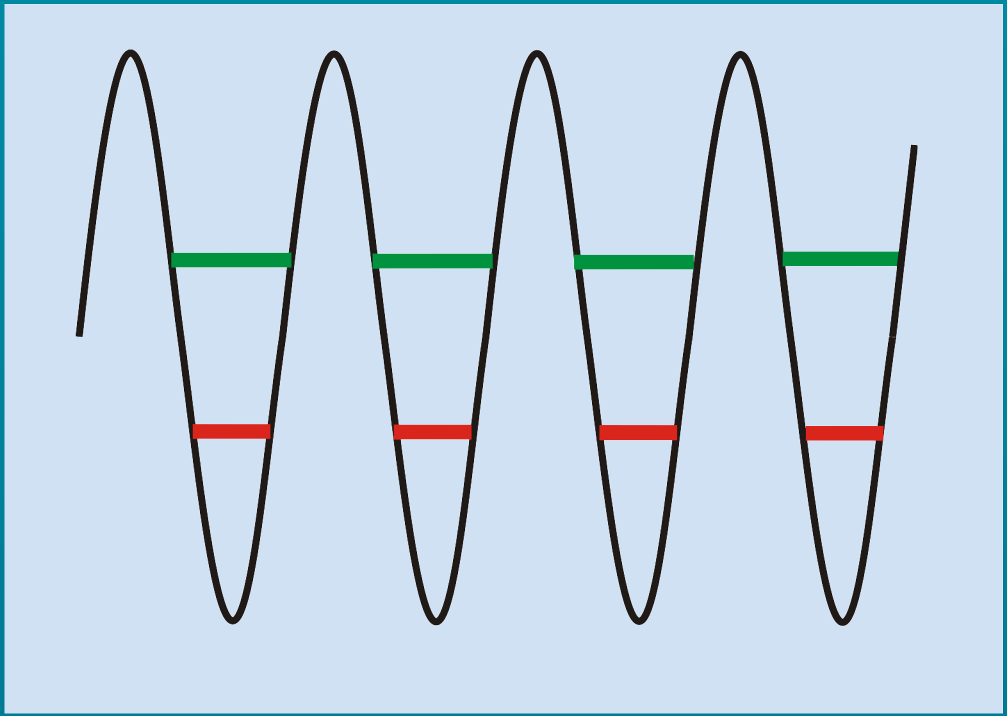


U. Schneider, L. Hackermüller, S. Will, Th. Best, I. Bloch, T. A. Costi, R. W. Helmes, D. Rasch and A. Rosch Science **322**, #*5907*, 1520-1525 (2008).

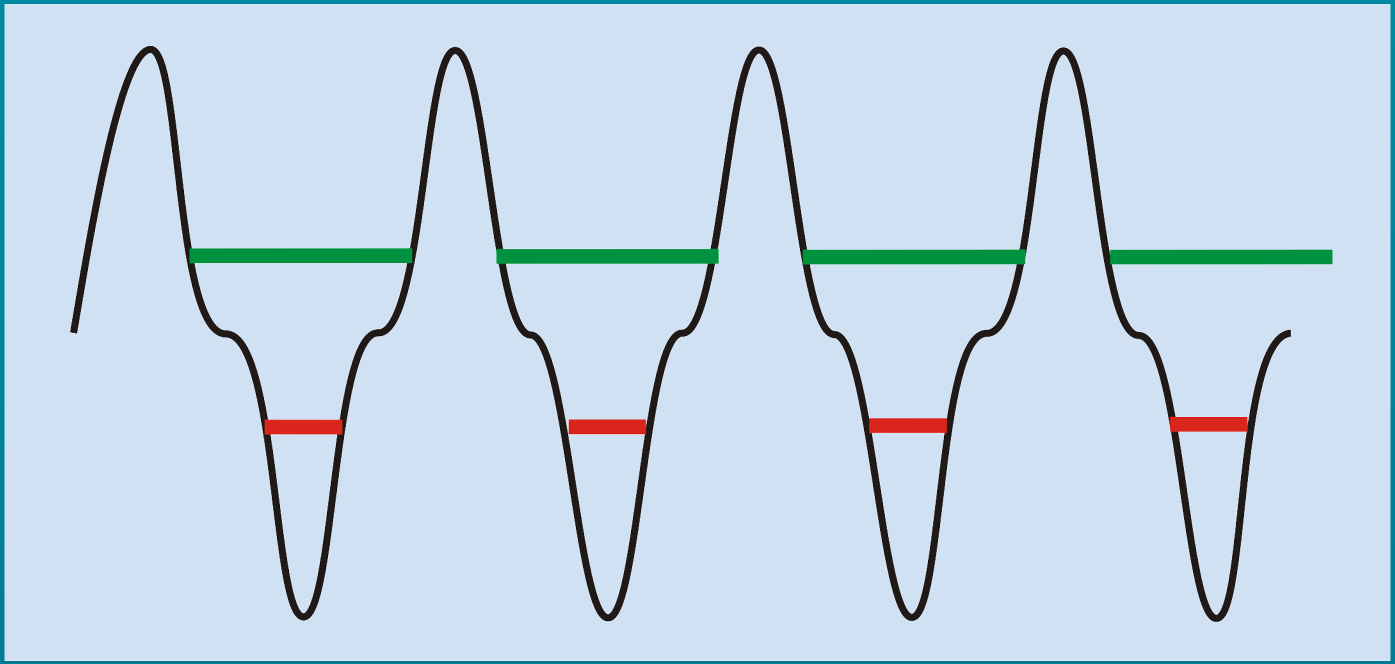
Realizing an Anderson Lattice in an optical lattice

- Idea 1: a tuned optical lattice



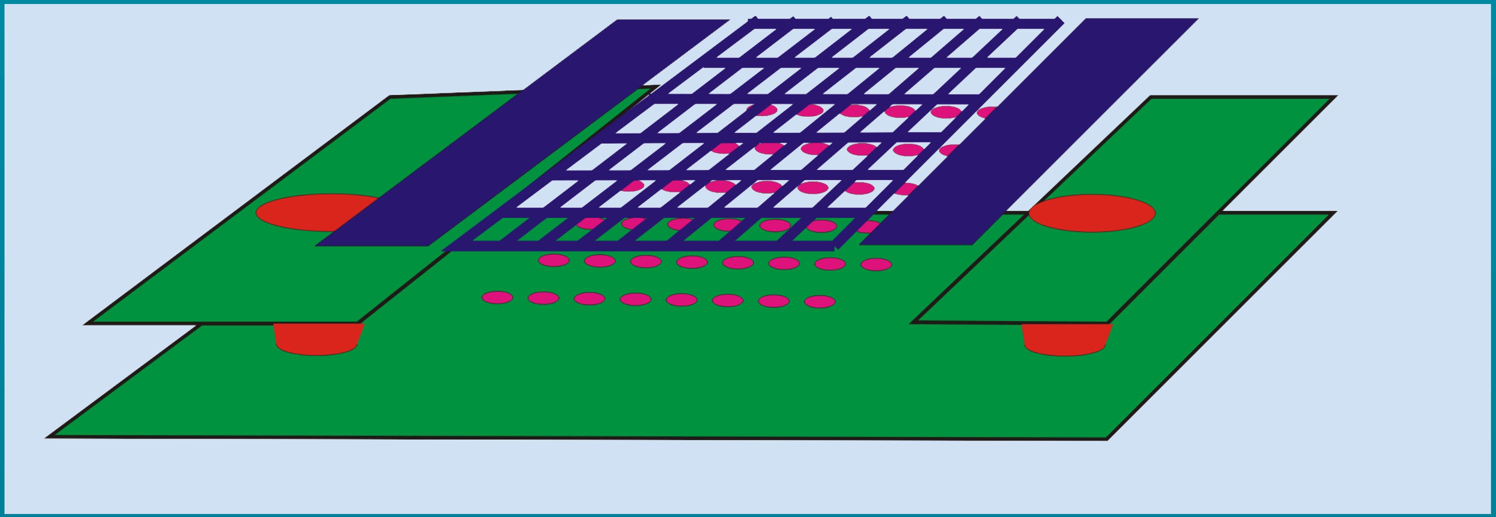
Realizing an Anderson Lattice in an optical lattice

- Idea 1: a shaped optical lattice (multi-chroic lasers)



Realizing an Anderson Lattice in an optical lattice

- Idea 2: A bilayer – with K. Bongs



Like the semiconductor bilayer but created with standing waves of light and an imaging system on the top layer.

Developments in experiments

- Can we make use of high precision optical frequencies?
  - Hansch and Hall – Nobel prize in 2005

VOLUME 85, NUMBER 11 PHYSICAL REVIEW LETTERS 11 SEPTEMBER 2000

Optical Frequency Synthesizer for Precision Spectroscopy

R. Holzwarth, Th. Udem, and T. W. Hänsch
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

J. C. Knight, W. J. Wadsworth, and P. St. J. Russell
Optoelectronics Group, Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom
(Received 4 May 2000)

We have used the frequency comb generated by a femtosecond mode-locked laser and broadened to more than an optical octave in a photonic crystal fiber to realize a frequency chain that links a 10 MHz radio frequency reference phase-coherently in one step to the optical region. By comparison with a similar frequency chain we set an upper limit for the uncertainty of this new approach to 5.1×10^{-16}. This opens the door for measurement and synthesis of virtually any optical frequency and is ready to revolutionize frequency metrology.

Summary and conclusions

- All the world of strong correlation physics seems to be contained in the Heavy Fermions
- Many open puzzles still remain
- Can some be solved by understanding heavy fermion look-alikes?
- Future trends:
  - Dilute Kondo lattices in semiconductors
  - Kondo lattices in cold atoms
  - New experiments