Quantum Criticality and Fermi Surface Topology Transitions

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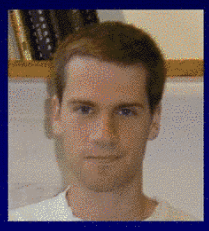
In Collaboration With…


Ramzy Daou

Peter Mann

Stephen Julian

(Cambridge/Toronto)

$CeRu_2Si_2$ samples by Stefan Tautz, now at IU Bremen

In Collaboration With…

Naoki Kikugawa

Andy Mackenzie

Chufo Borzi

Santiago Grigera
(St. Andrews)

Yoshi Maeno
(Kyoto)

Critical Behaviour & FS Topology

Empirical Observations:

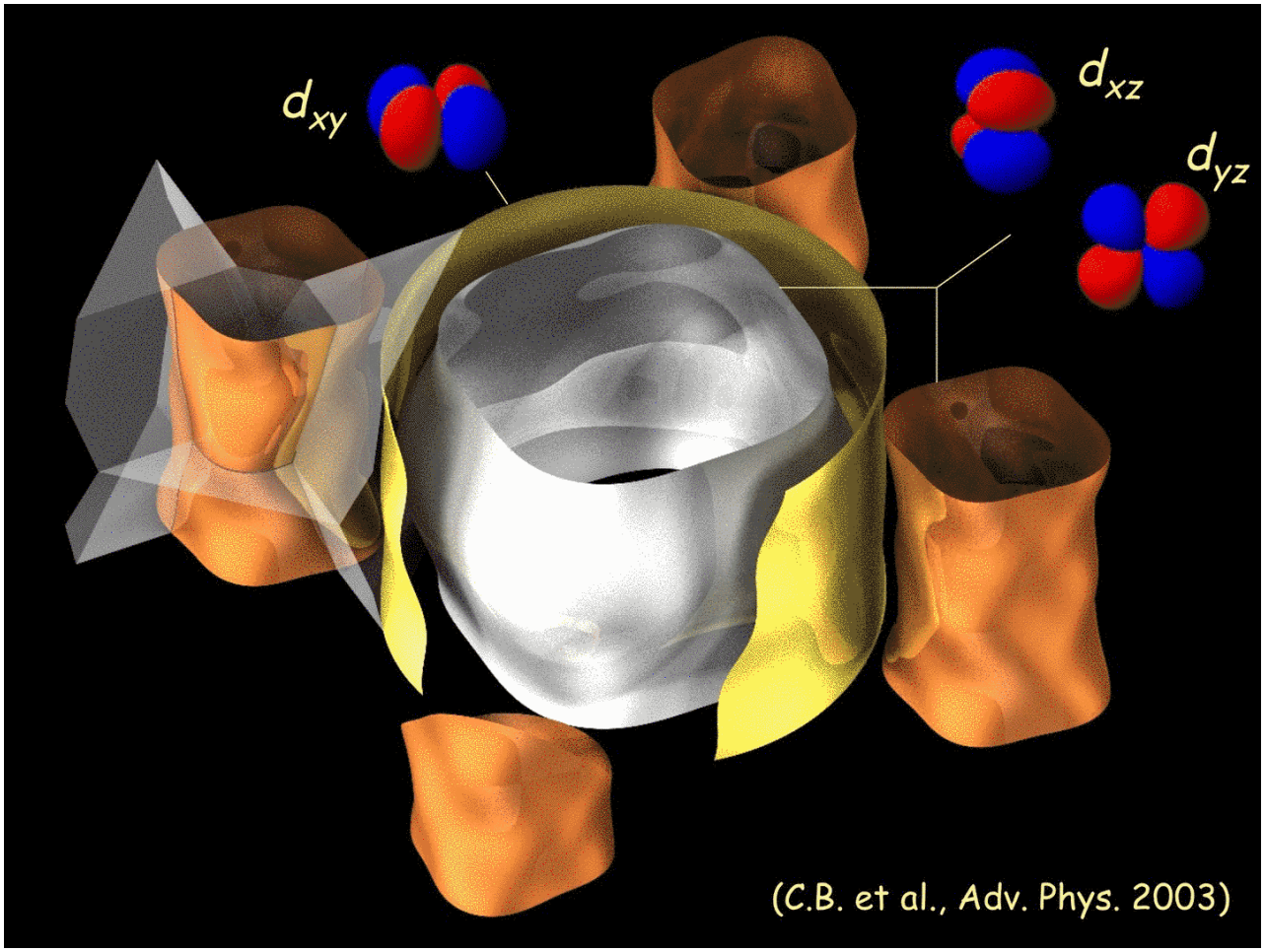
Electron-doped Sr_2RuO_4: NFL behaviour near van Hove e->h transition

$CeRu_2Si_2$ revisited: sudden f-localisation vs. "kinky" spin sheet disappearance

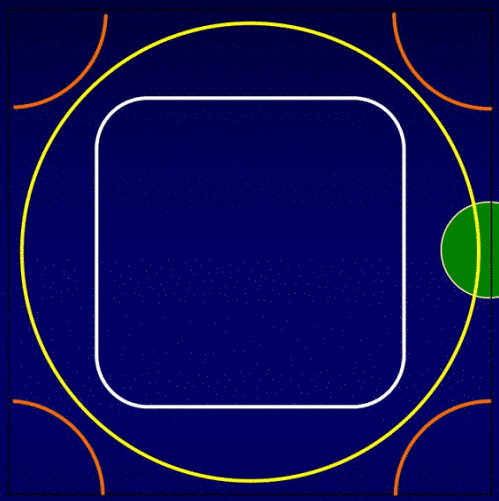
Resistivity anomaly in $Sr_3Ru_2O_7$ (Grigera et al. 2004): Pomeranchuk-driven e->open->h transition?

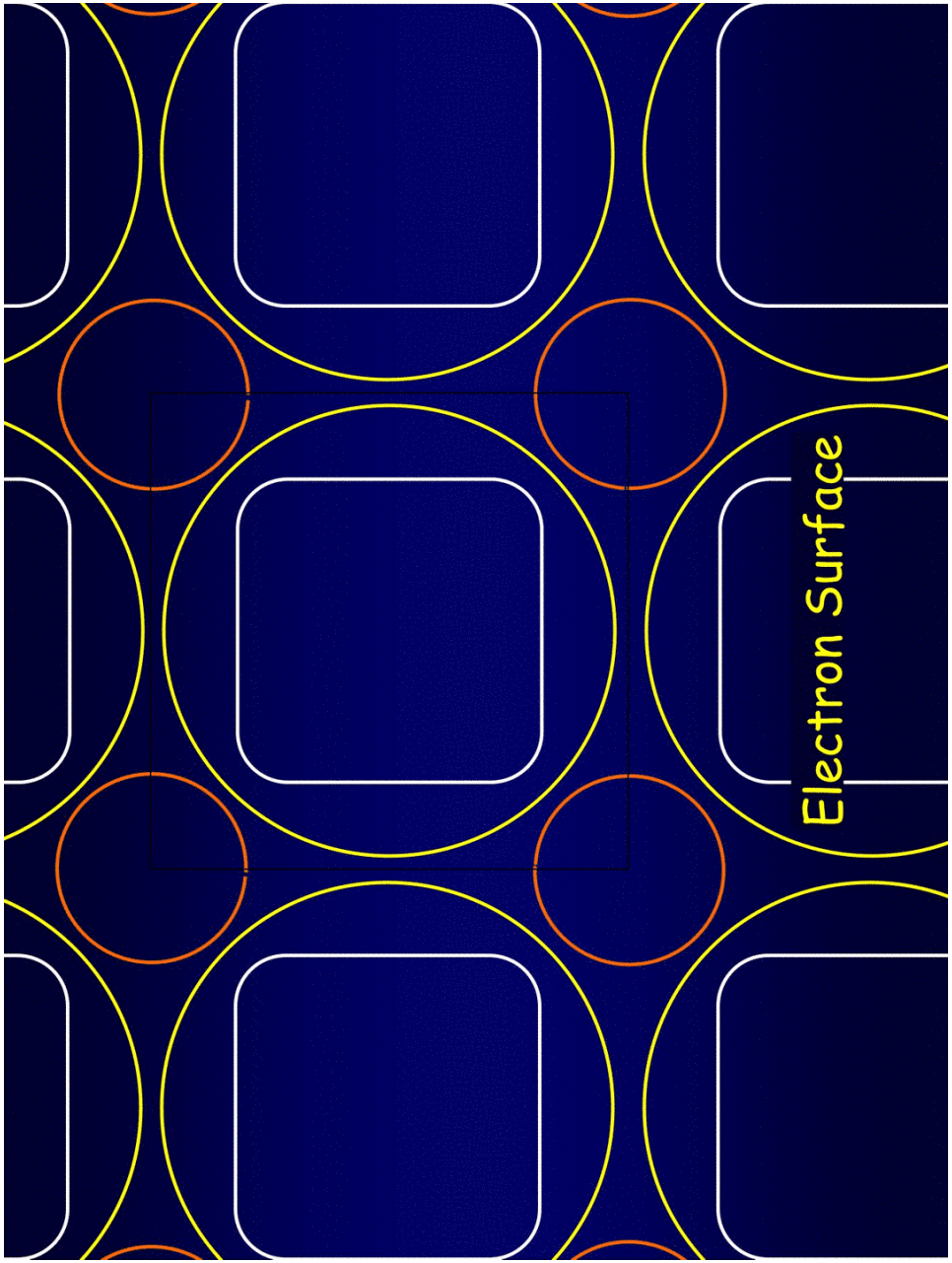
FS "Webbing" and Rare Earth Magnetism (Crowe et al. 2004): Do nesting and disk->donut transition drive AFM vs. FM?

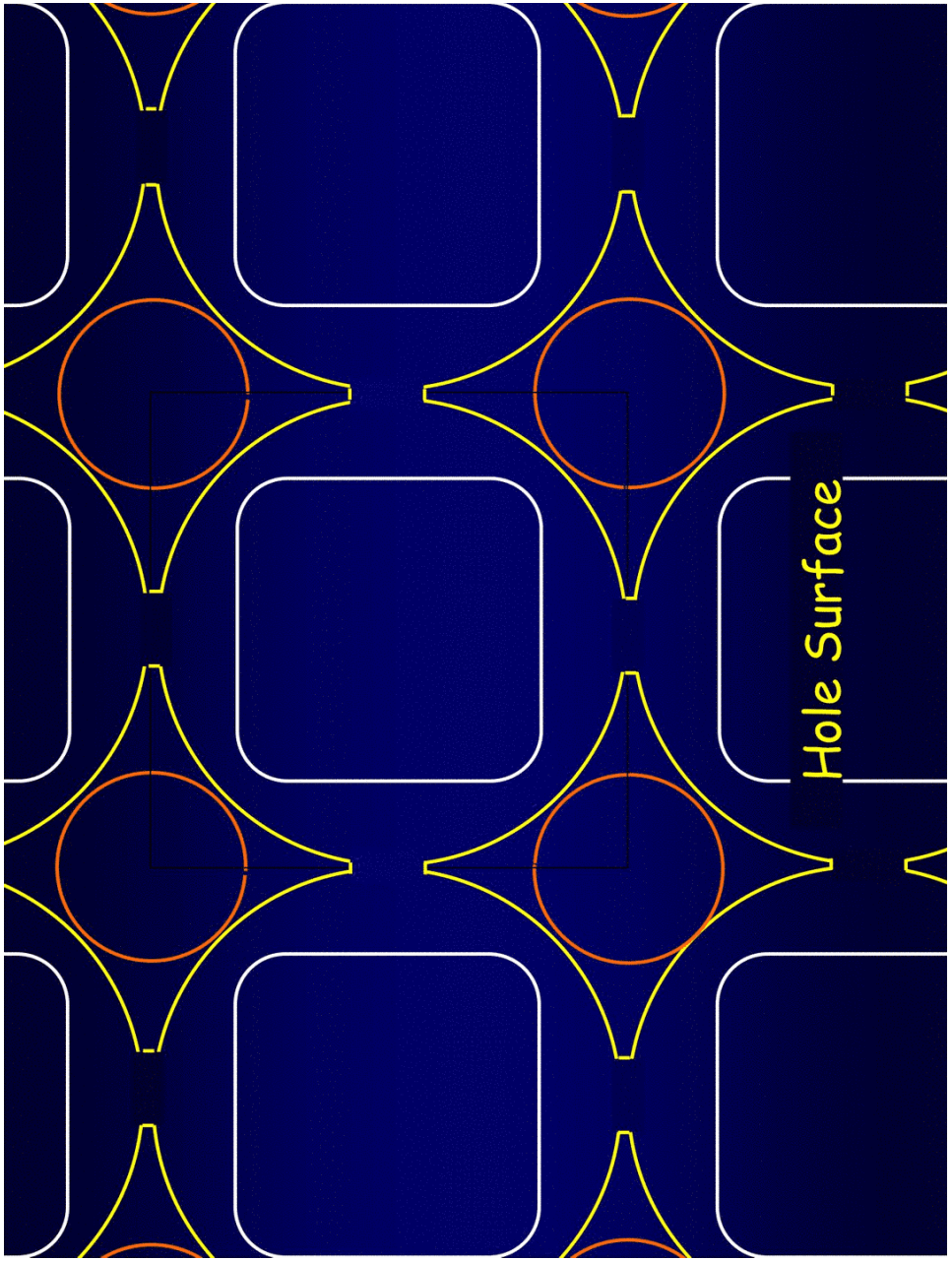
Hall effect in $YbRh_2Si_2$ (Paschen et al. 2004):



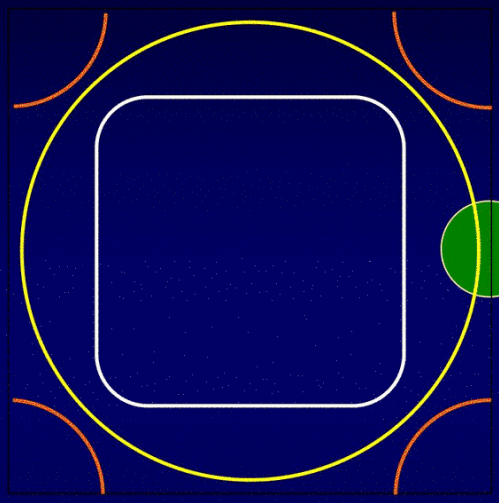
Tuning the Band Structure?




Electron Surface


Hole Surface

Tuning the Band Structure?



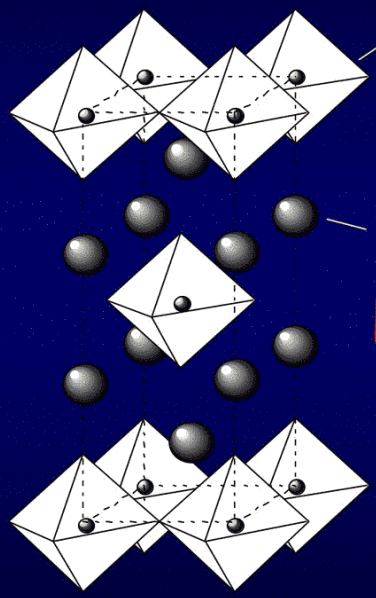
Temperature: wipes out quantum oscillations (Shen et al.)

Magnetic Field: simple, but energy scale only meV

Pressure: hard to try, difficult to predict effect

Doping: expect large effect, but impurity problem!

Electron Doping in Sr_2RuO_4

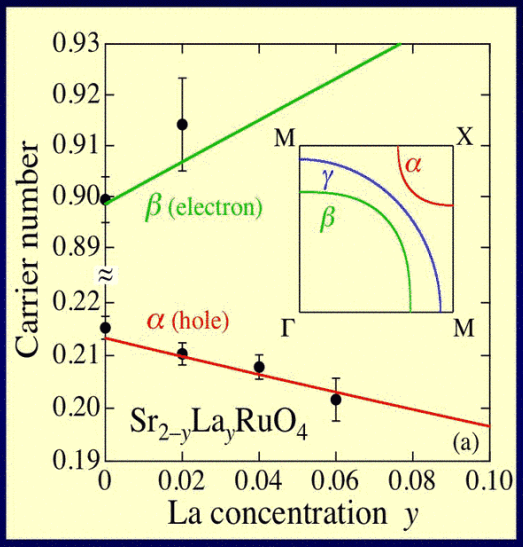


- Adds one electron per La^{3+}
- Out-of-plane substitution
- Similar size ion – little distortion

Relatively gentle electron doping

DHvA visible up to 10% (!)

Rigid Band Shift

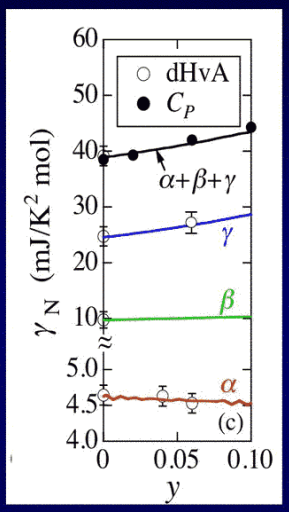


Lines are not fits but rigorous predictions from tight binding model

(Kikugawa, Mackenzie, C.B. et al. 2004)

Non-trivial statement – d_{xy} can shift with respect to $d_{xz/yz}$ (like in $Ca_xSr_{2-x}RuO_4$), or correlations can change Fermi surface (Hamacher et al. 2002)

Masses and Specific Heat

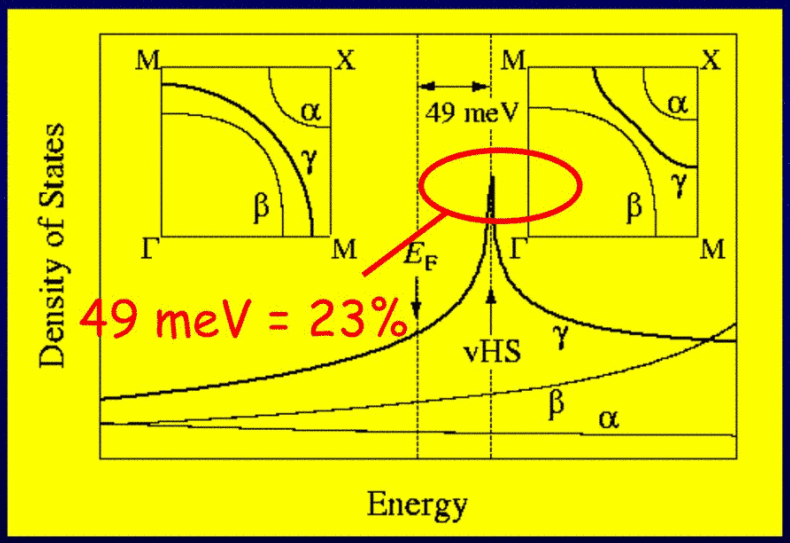


Lines are not fits but rigorous predictions from tight binding model

Renormalisation factor m_{dHvA}/m_{band} set to be independent of y -> no free parameters in calculation

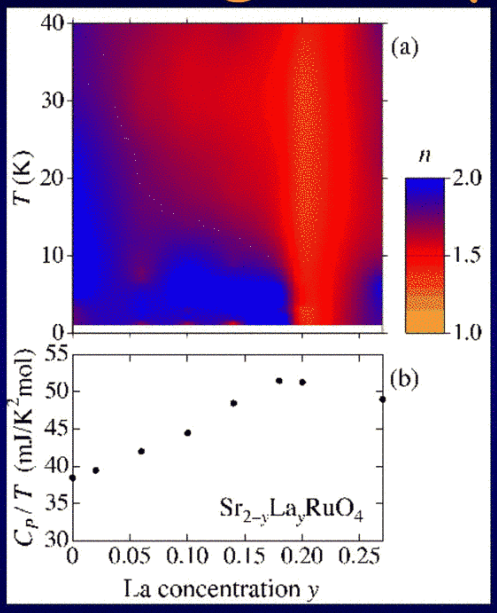
Towards the van Hove Singularity

Tight binding fit to dHvA predicts van Hove singularity in density of states at y = 23% La doping



Towards the van Hove Singularity

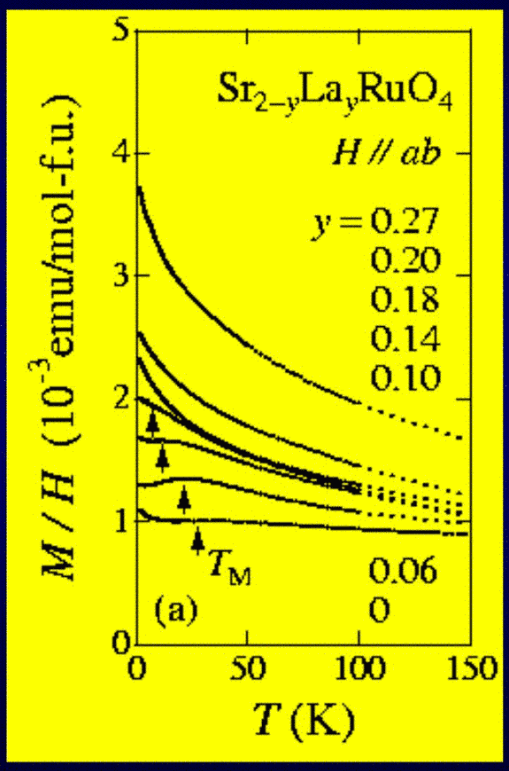
- Resistivity sees *A*-coefficient peak towards 20%, with non-Fermi liquid $T^{1.4}$ power law at that point
- *C*/*T* peaks at 20%

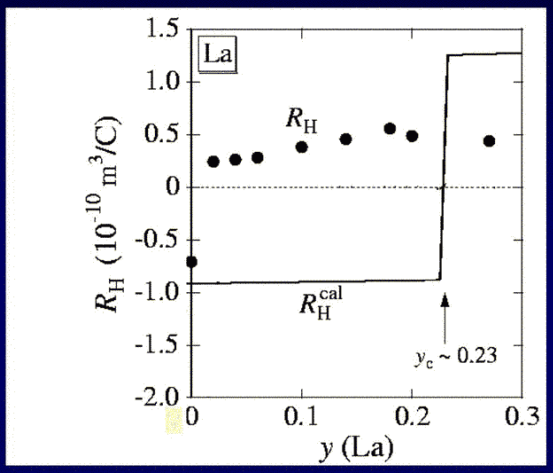


- However, bulk χ continues to rise up to 27%
- … and Hall effect is weird

(Kikugawa, C.B. et al. 2004)

$La_xSr_{2-x}RuO_4$ - Bulk χ and R_H





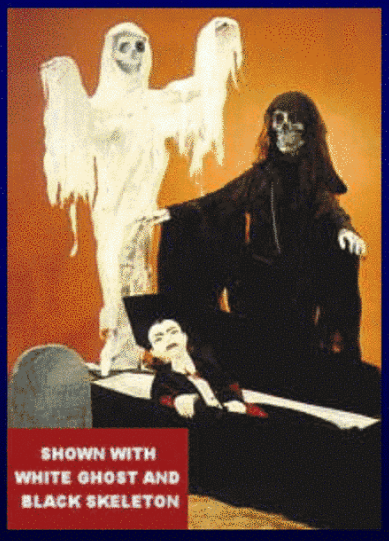
Hall effect changes sign at entirely the wrong place

Susceptibility changes enhanced beyond tight binding (on α, β, γ)

$CeRu_2Si_2$ Key Facts

Itinerant metamagnetism of $CeRu_2Si_2$: bringing out the dead. Comparison with the new $Sr_3Ru_2O_7$ case

J. Flouquet[a,*], P. Haen[b], S. Raymond[a], D. Aoki[b], G. Knebel[a]



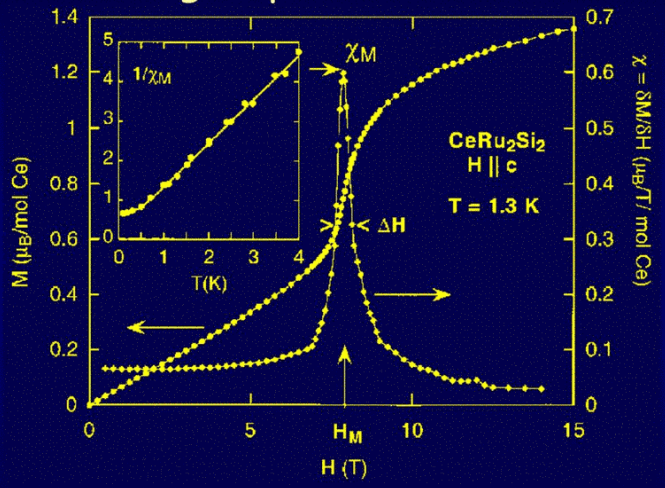
Nice review article, actually!

Picture credits: christmas-depot.com

$CeRu_2Si_2$ Key Facts

Previous work by Grenoble & Osaka groups and others:

- Ising-like metamagnet
- steep crossover rather than real transition
- strong lattice coupling
- Fermi liquid across whole field region
- γ = 350 mJ/mol K^2
- no magnetic or SC order in zero field
- strong AFM & FM fluctuations
- 4f spins: $J = m = 5/2$, Kondo temperature $T_K \sim 20$ K

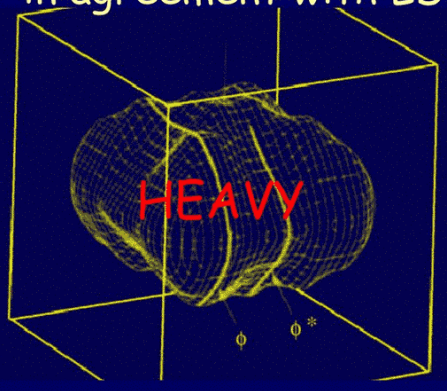


(Flouquet et al. 1995)

f-Localisation at Transition?

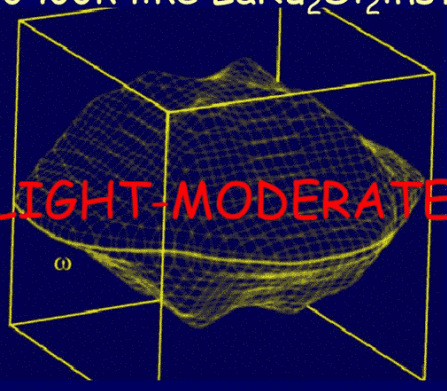
DHvA on $CeRu_2Si_2$:

Low-field state looks like this – in agreement with LDA:



+ 3 small surfaces
+ 1 open surface

...but high-field state appears to look like $LaRu_2Si_2$ instead:



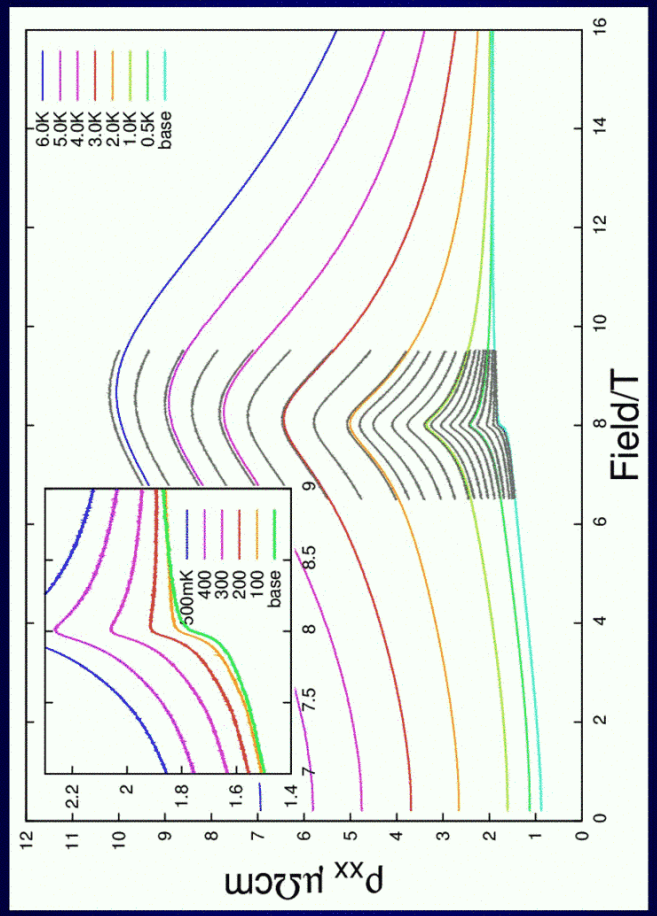
+ several small surfaces

(Onuki, Aoki and coworkers, 1990s)

Continuous localisation?

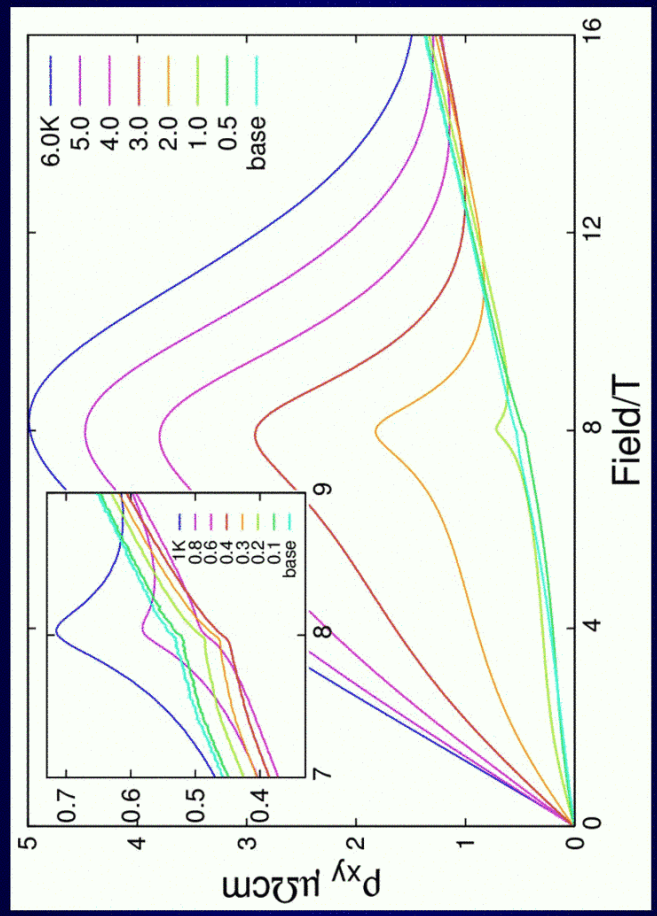
Missing mass!

$CeRu_2Si_2$ Magnetoresistance



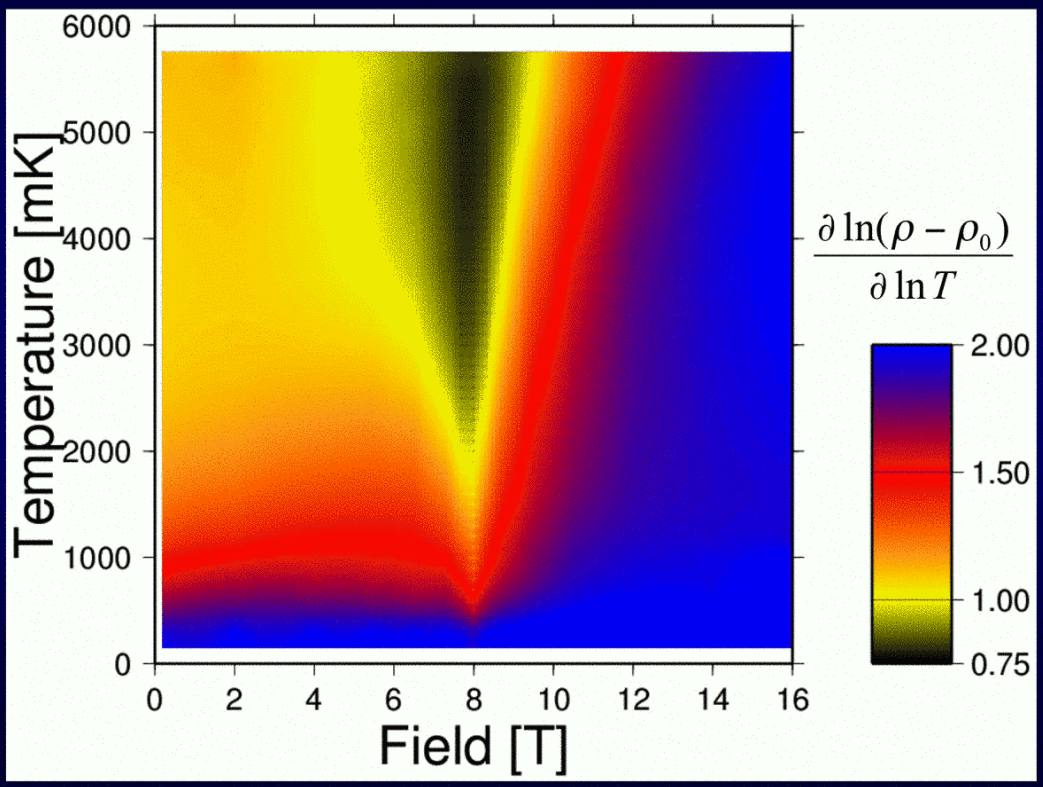
Similar to previous work by Kambe et al. (1995), but better sample (0.2 μΩcm ||c), higher fields, lower T, some quantitative differences

$CeRu_2Si_2$ Hall Effect

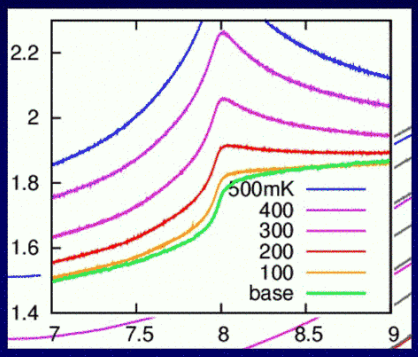


Similar to previous work by Kambe et al. (1996), but better sample (0.2 μΩcm ||c), higher fields, lower T, some qualitative differences

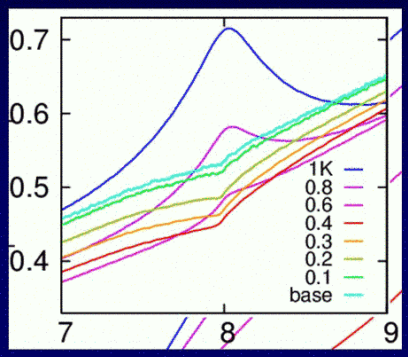
$CeRu_2Si_2$ Exponent Plot



Close-Up on the Transition



Magnetoresistance



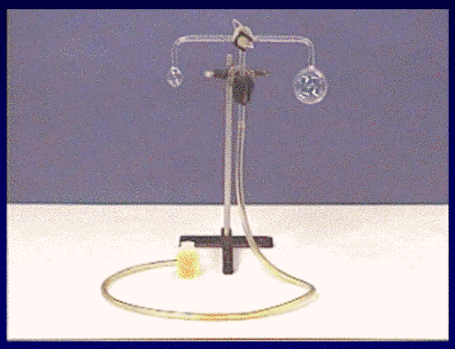
Hall resistivity

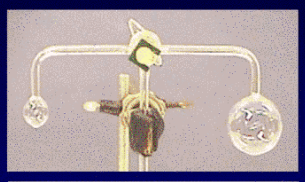
Kink – but no discontinuity!

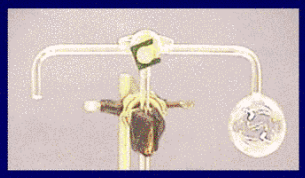
How to reconcile with f-localisation idea?

Cannot have "partial localisation"!

Saturated Spin-Splitting?

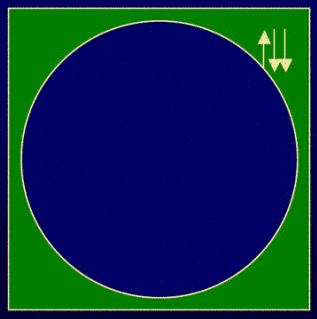






- same volume
- less area
  - ➢ less σ
  - ➢ kink if linear energy shift in B

Picture credits: Univ. Maryland

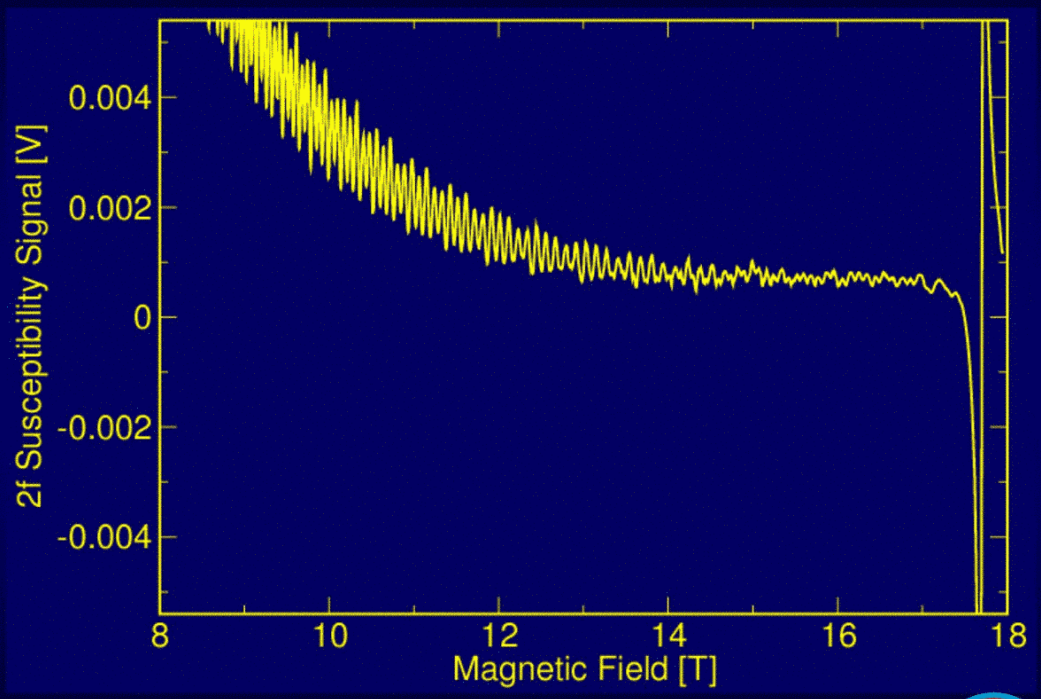


+ localised ↑

Does this make sense energetically?

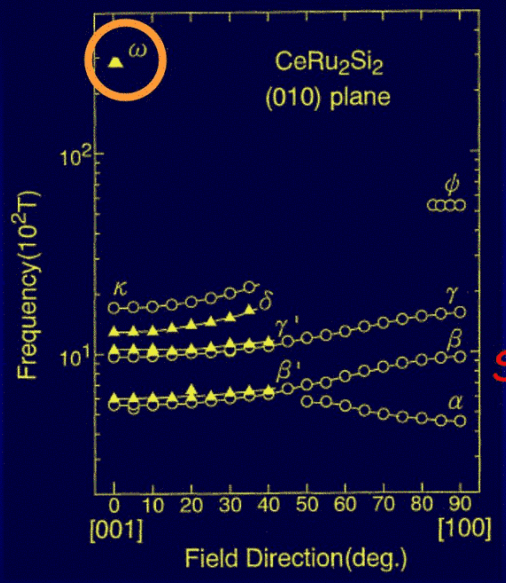
- LDA Fermi energy: ~100 meV
- Factor-of-20 mass enhancement over LDA
- Wilson ratio approx. 2
- Ising anisotropy of magnetic response

Can dHvA Observe "Mini-Sheet"?

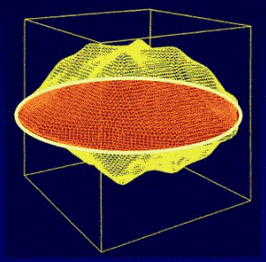


θ = 63°, MM transition at 17.6 T – but dHvA is cut out, presumably due to extra scattering

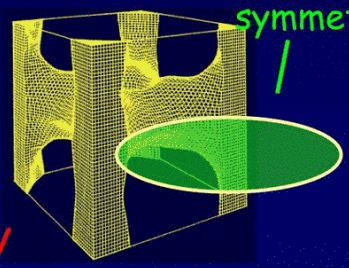
DHvA Is Surprisingly Ambiguous



(Aoki et al. 1993)



28 kT
Should be HEAVY
but isn't

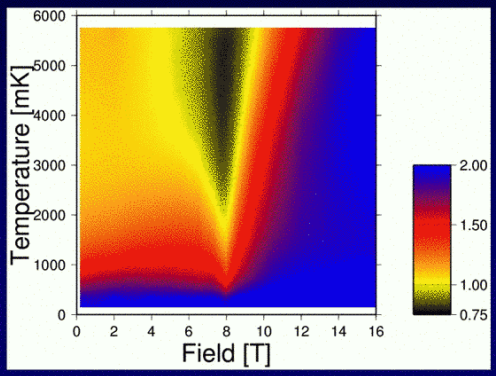


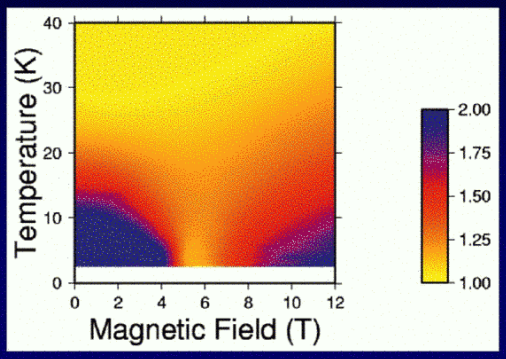
NB: b.c.t. symmetry

28 kT
Should be LIGHT-MODERATE … and is!

This could explain missing mass –
heavy 28 kT orbit simply not seen yet

Comparison with $Sr_3Ru_2O_7$



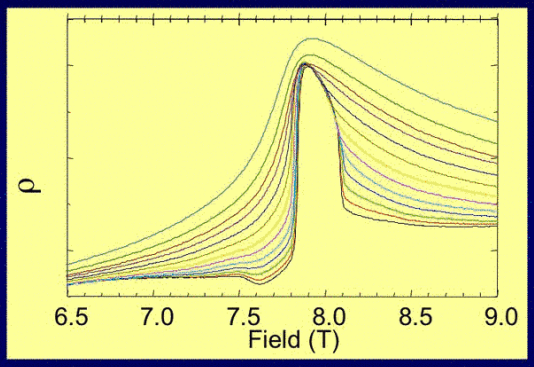


Chiao & Pfleiderer, in Perry et al. 2001;
follow-up work by Grigera et al.

- Same field scale but different temperatures
- $CeRu_2Si_2$: Kondo f-bands with Ising $1/\cos\theta$ behaviour
- $Sr_3Ru_2O_7$: DoS metamagnet with more isotropic response
- $CeRu_2Si_2$ less correlated beyond MMT, $Sr_3Ru_2O_7$ more so

$Sr_3Ru_2O_7$: Pomeranchuk Scenario

Resistivity Anomaly:

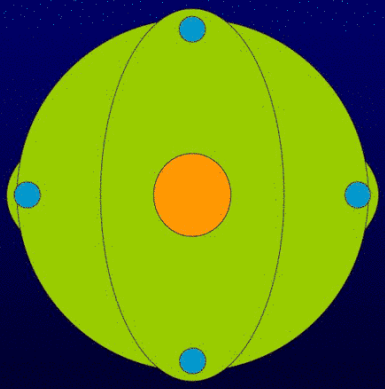


Grigera et al. (2004)

Spin up FS

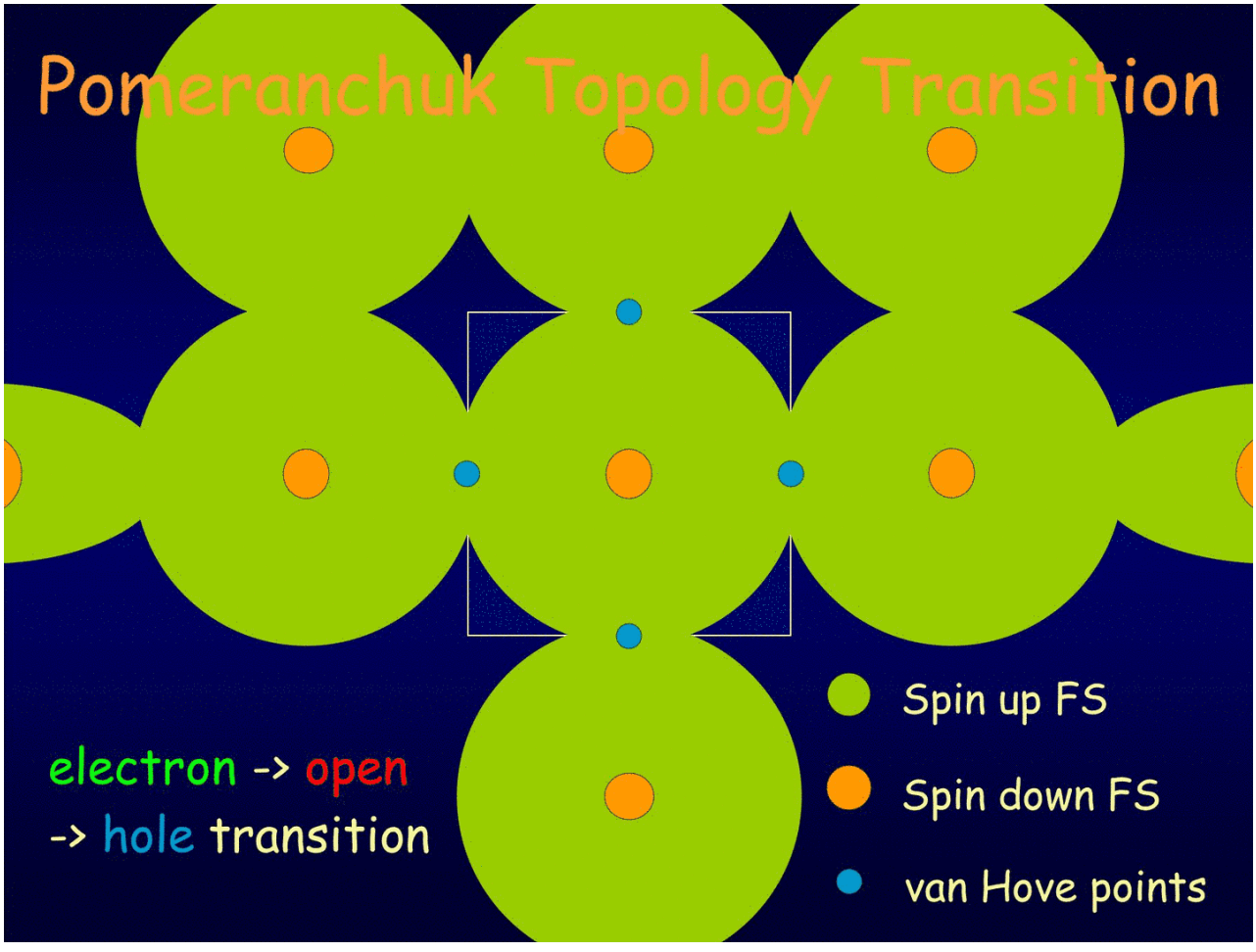
Spin down FS

van Hove points

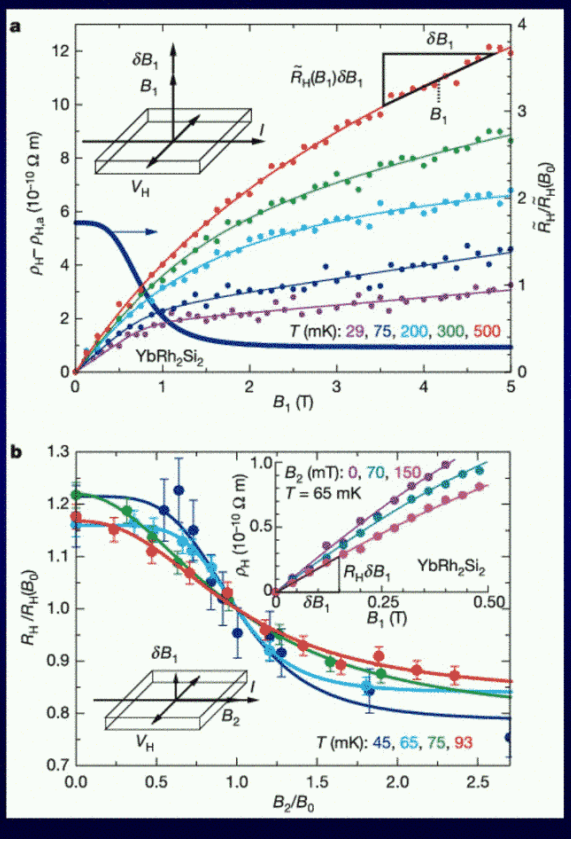


Domains in *k*-space responsible for high resistivity?

Pomeranchuk Topology Transition



FS Discontinuity in $YbRh_2Si_2$

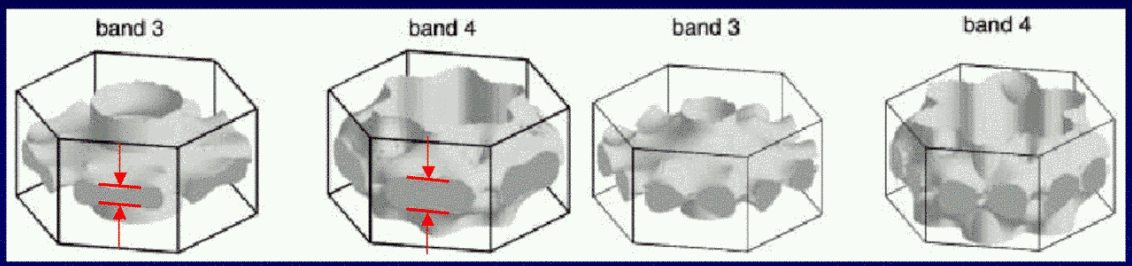


- Kink (?) in ρ_H for one field direction (|| c)
- Step in ρ_H for the other field direction (|| ab)
- Fermi surface reconstruction on leaving the AFM state
- NFL/QCP ρ–behaviour (Trovarelli et al., Custers et al.)

(Paschen et al. 2004)

FS "Webbing" in the Rare Earths

Magnetism and nesting in Y and heavy RE: Gd-Tm



Webbing feature – incommensurate ordering
(Dy, Er, Lu – Evenson & Liu 1968)

No webbing feature – ferromagnetism
(Gd)

Alloying (e.g. $Gd_{1-x}Y_x$) can tune the Fermi surface, and the magnetism (Crowe et al. 2004) – what about critical resistivity?