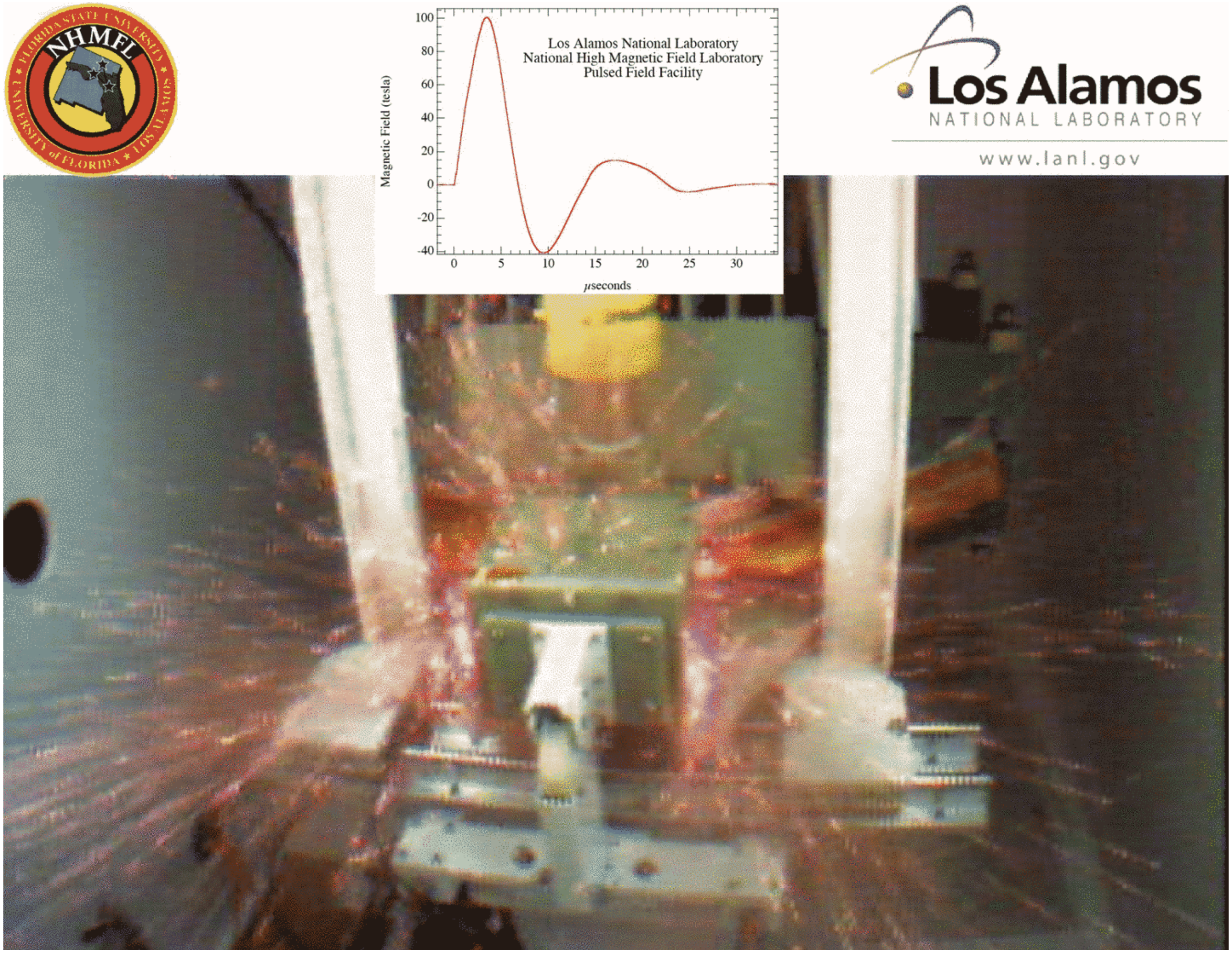
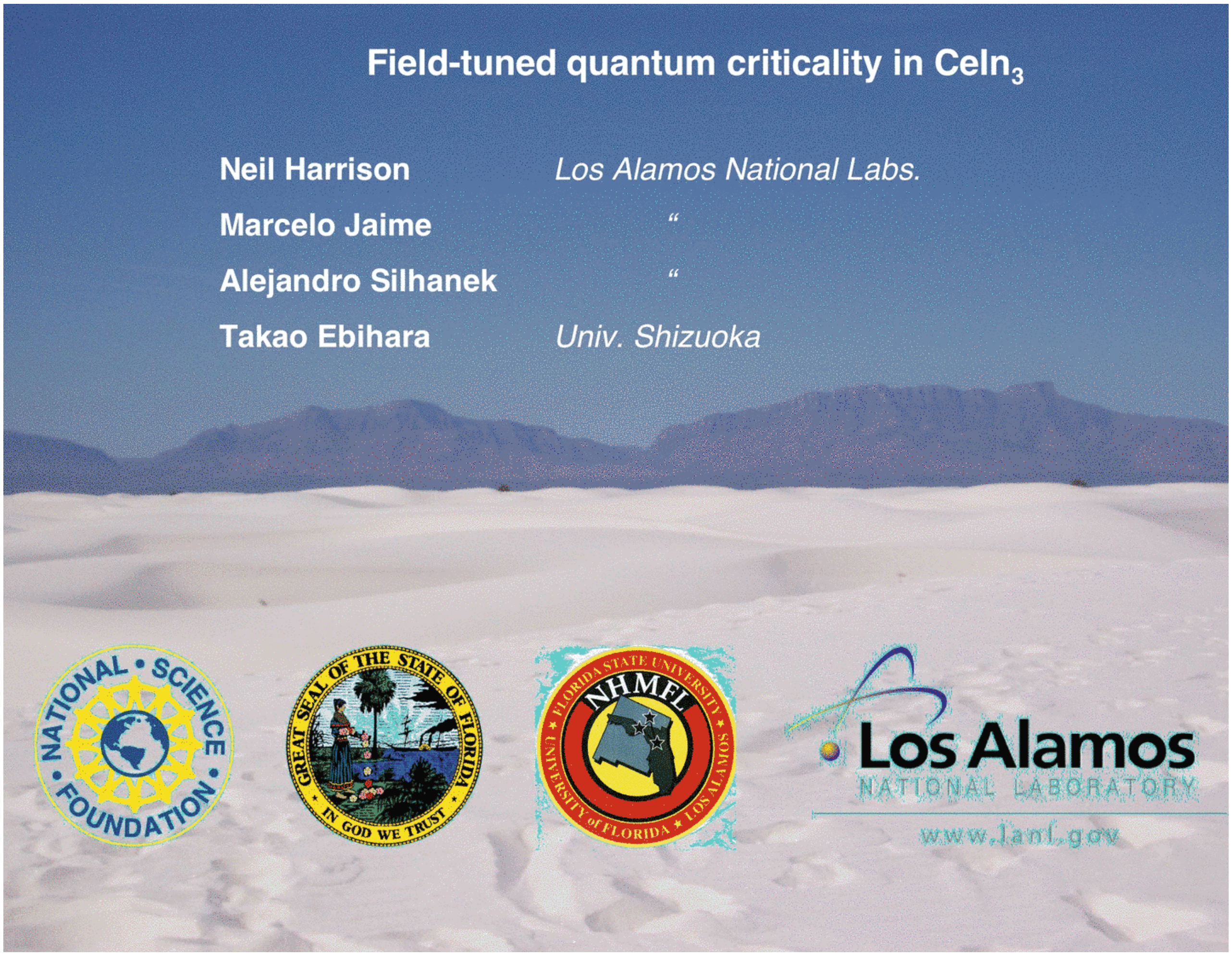




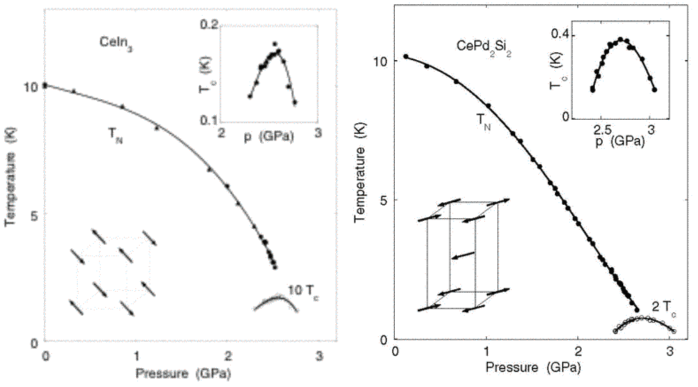
Field-tuned quantum criticality in $CeIn_3$

Neil Harrison	*Los Alamos National Labs.*
Marcelo Jaime	"
Alejandro Silhanek	"
Takao Ebihara	*Univ. Shizuoka*

Antiferromagnetic quantum criticality in heavy fermions

Pressure-induced antiferromagnetic quantum criticality: perhaps generic property of strongly correlated *f*-electron materials

One goal: understand link between Antiferromagnetic quantum criticality and phase formation (e.g. unconventional forms of superconductivity)



Grosche et al. JPCM 13,(2001)

Requires microscopic model of quantum critical point itself

Generalizations: Quantum Criticality Basic Observables

Transport:

$\rho = \rho_0 + AT^n$

$A \propto 1/\varepsilon_F^2$ (provided $n = 2$)

$kT^* \approx \varepsilon_F$ (crossover from $n = 2$ to < 1)

$\varepsilon_F \propto |g - g_{QCP}|^\alpha$ $(\alpha <= 1)$

Thermodynamics:

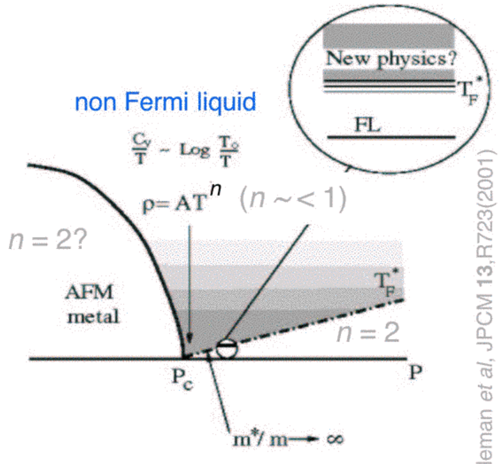
$C = \gamma T + \beta T^3$

$\gamma(T) \propto -\ln T$

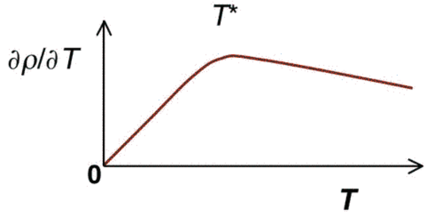
$\gamma(g) \propto m^* \propto 1/\varepsilon_F$

$\chi(T) \propto 1/(a+T^q)$

Inside AFM phase? spin waves may cause problems



Coleman *et al*, JPCM 13,R723(2001)

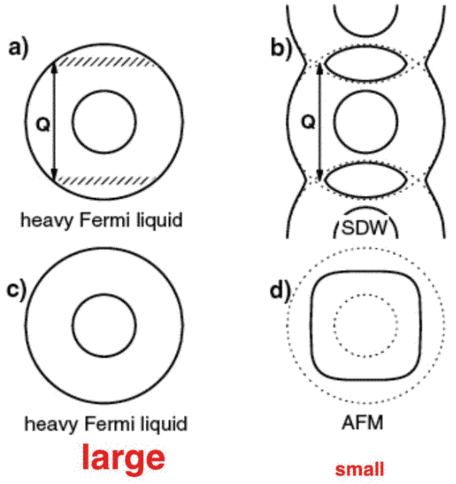


What is the antiferromagnetic order parameter?

State formed from heavy Fermi liquid: “Kondo” screening of a lattice of *f*-moments leads to composite-quasiparticles and Fermi surface that appears to accommodate *f*-electrons (large Fermi surface)

Antiferromagnetism in the weak coupling limit: modification of Fermi surface as for spin-density wave (SDW), with its translation with respect to ordering vector **Q**

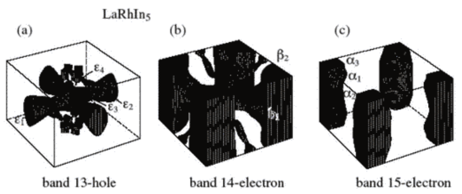
Antiferromagnetism in the strong coupling limit: composite quasiparticles break into their constituent components, leading to radically modified Fermi surface that does not accommodate *f*-electrons (small Fermi surface)



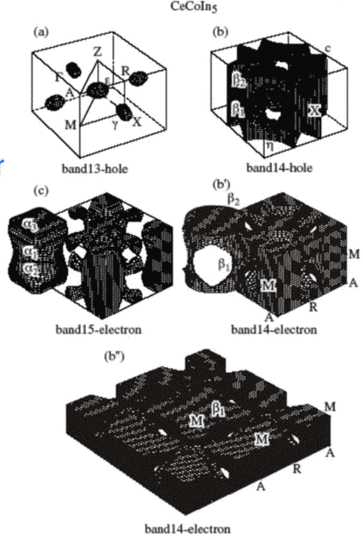
Quantum oscillations (de Haas-van Alphen): absolute measure of Fermi surface as $T \rightarrow 0$

Fermi surface topology determined precisely from frequencies in $1/B$

$$F = \left(\frac{h}{2\pi e}\right) A_k$$



$p > p_c > 16$ kbar



Shishido et al, JPSJ 71,162(2002)

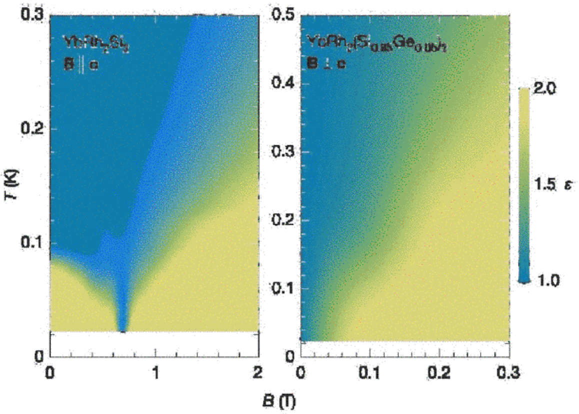
dHvA on antiferromagnetic CeRhIn$_5$ under pressure yields radical Fermi surface change consistent with formation of heavy Fermi liquid (like that of CeCoIn$_5$) [Onuki et al (to be published)]

Issue 1: T_N nor staggered moment observed to drop continuously as $p \rightarrow p_c$ (yet only measured to 16 kbar) [Llobet et al PRB 69,024403(2004)]

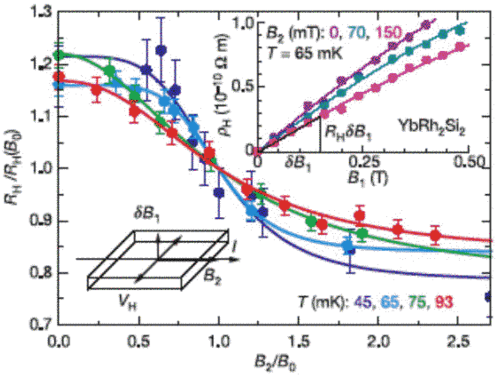
Issue 2: magnetic fields (~10 T) implicit to dHvA measurements. What is magnetic field effect on putative quantum critical point?

Indeed: magnetic field can itself be used to tune quantum criticality

YbRh$_2$Si$_2$ for example: so it is quite likely that $p_c(B=0) \neq p_c\ (B\sim10\ T)$



Custers *et al*, Nature **424**,524(2003)



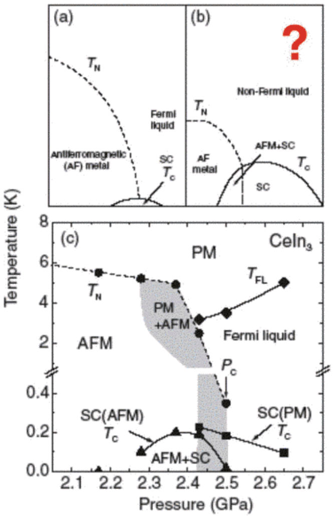
Change in Hall coefficient (though indirect) yields evidence for change in Fermi surface topology [Paschen et al,Nature 432,881(2004)].

Advantage: magnetic fields more controllable and reversible than pressure, enabling very precise measurements

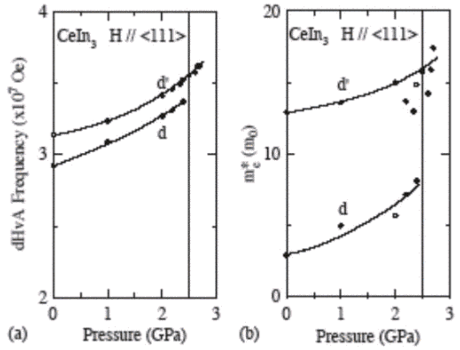
Closer look at the classic case: CeIn$_3$

CeIn$_3$ recently shown to appear more complicated under pressure, with possible phase coexistence

p_c first order transition or sub-phases product of quantum criticality?



[Kawasaki et al,JPSJ 73,1647(2004)].

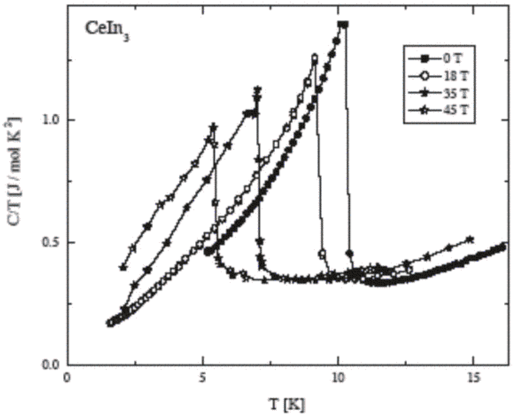


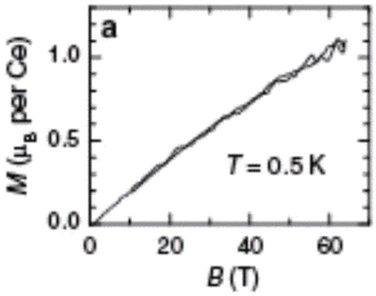
dHvA measurements under p alone have not yielded clear evidence for Fermi surface change at p_c [Settai et al,JMMM 272,223(2004)].

Effect of magnetic field? (implicit to dHvA measurements) once again neglected

Magnetic field-dependence of CeIn$_3$

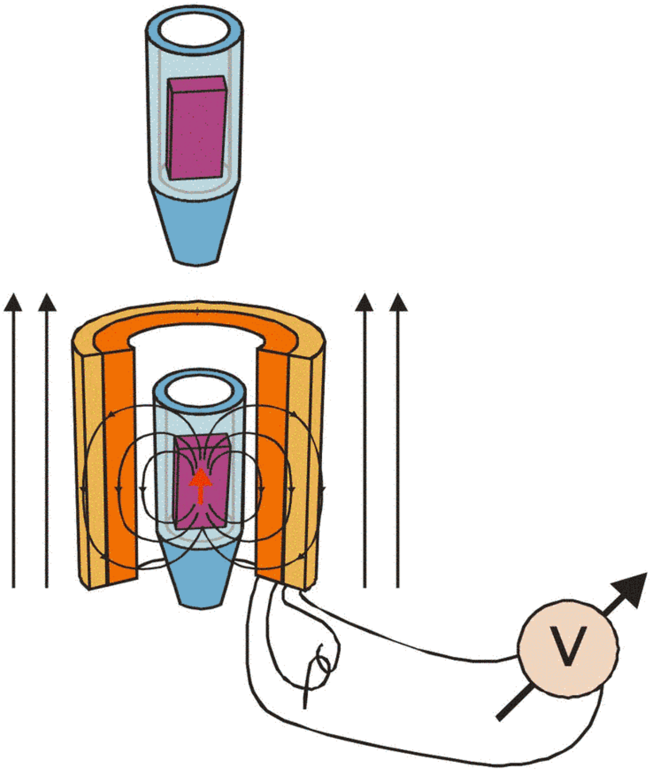
Magnetic fields suppress T_N in CeIn$_3$ as in YbRh$_2$Si$_2$: except ~ 100 times larger fields required since T_N is ~ 100 times larger



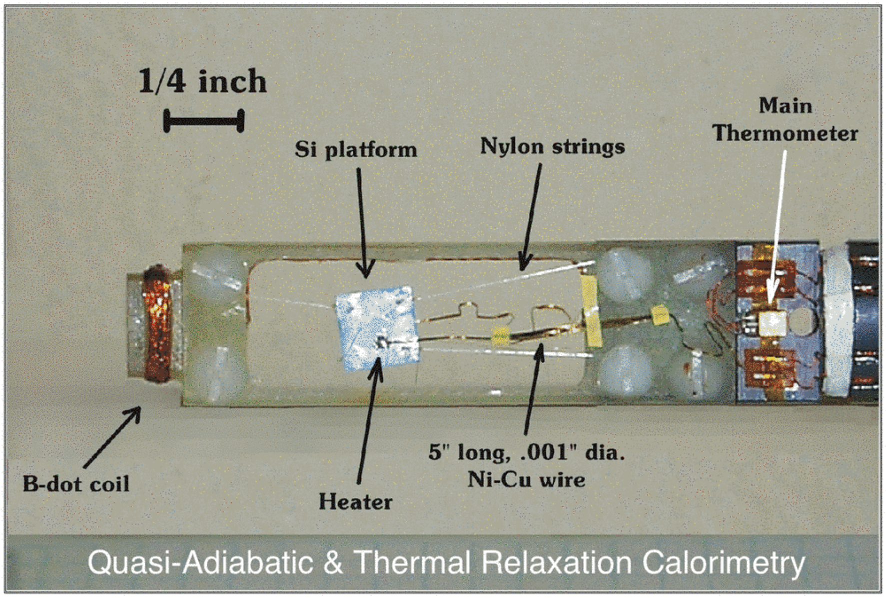


Magnetization can be measured in very strong magnetic fields ($B > 45$ T), while specific heat is more of a challenge/impossibility

Extraction magnetometer

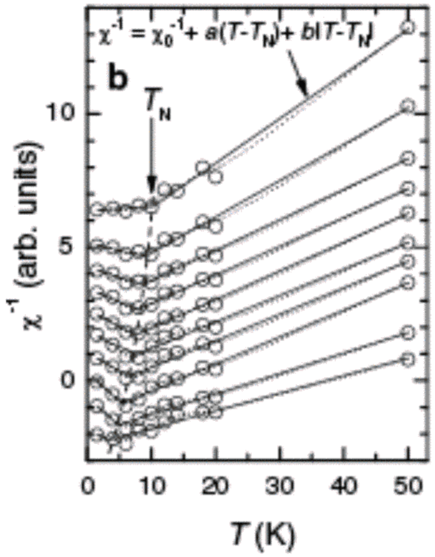


Specific heat in large fields

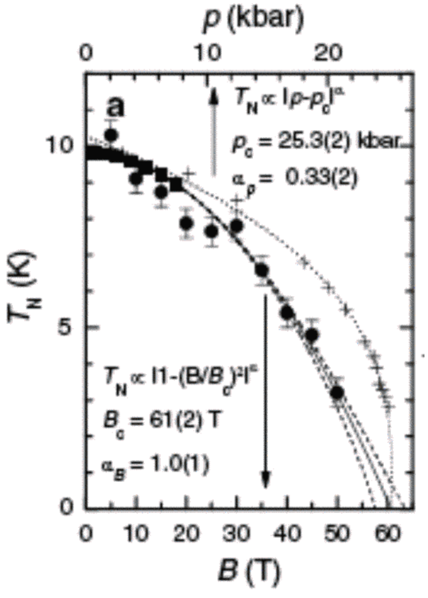


Quasi-Adiabatic & Thermal Relaxation Calorimetry

Magnetic field-dependence of CeIn$_3$

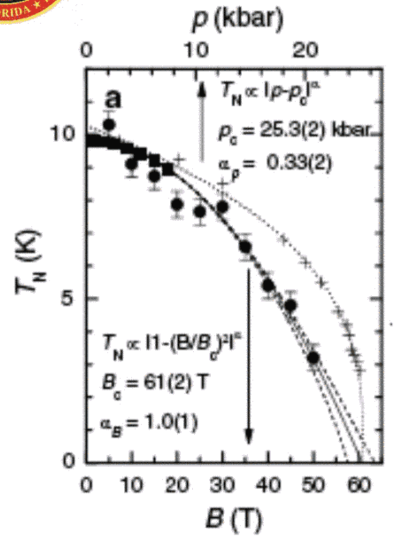


Kink in 1/χ observed to be consistent with T_N from specific heat (lines drawn at 5 T intervals in magnetic field)

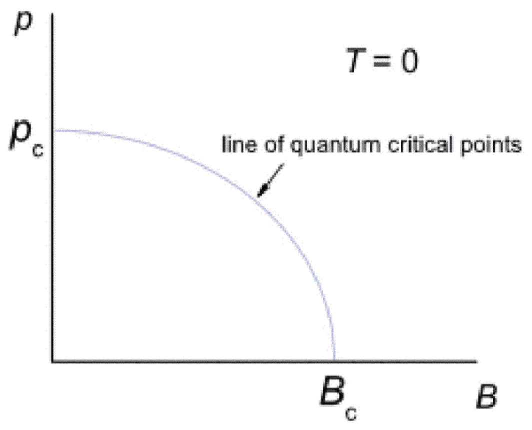


Specific heat anomaly reveals that T_N versus B is approximately quadratic, and 1/χ supports continuation of trend to $B_c \sim 61$ T

Magnetic field-dependence of $CeIn_3$

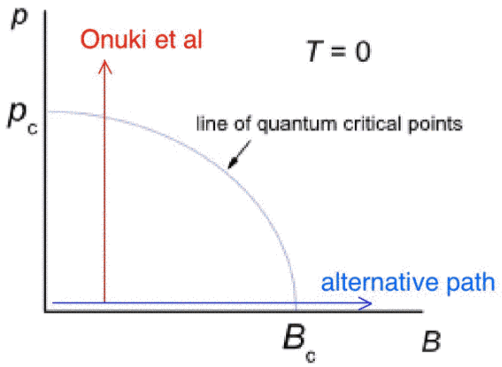


Data consistent with notional line of quantum critical points with considerably different p and B exponents

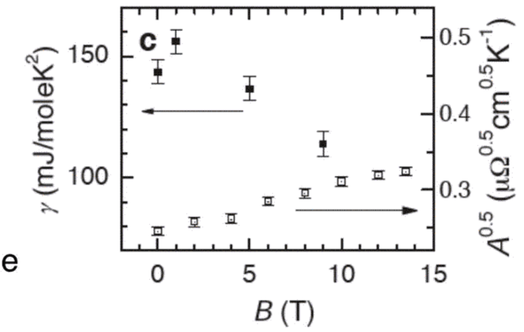


Function for p versus B ?

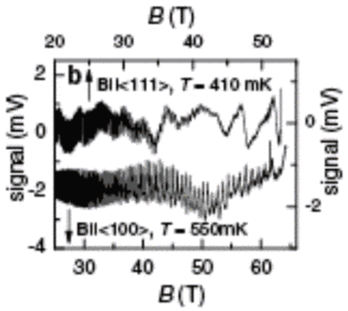
Line of quantum criticality of $CeIn_3$



Magnetic field-tuning enables access to quantum criticality in different part of phase diagram

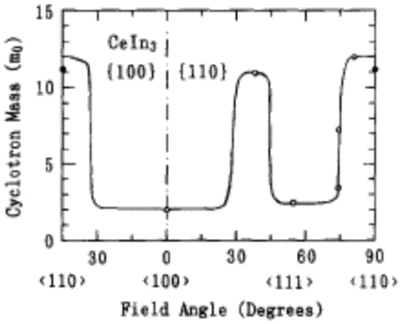


Measurements of a and γ inconclusive (large spin-wave component inside AFM phase)



dHvA through quantum critical point? m^* enhanced directly by fluctuations: possibly reveal influence of increasing fluctuations as $B \rightarrow B_c$

dHvA effect provides unique access to distribution of fluctuations

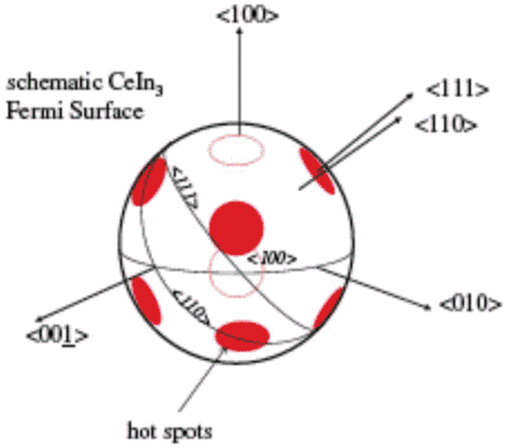


Ebihara et al, Physica B 186,123(1993)

***m** varies with orientation** but not *F* (Fermi surface cross-section), provides direct evidence for many body mass enhancement

i.e. *m ∝ *F* in one-electron picture**

Symmetry of angular dependence implies existence of `hot spots' of fluctuations on nea spherical Fermi surface sheet: each orientatic corresponds to an orbital average

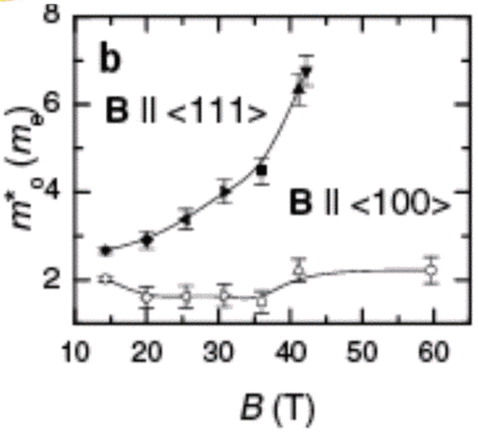


$$m_o^* = \frac{1}{2\pi}\oint (m^*(\mathbf{k})/k_F)dk$$

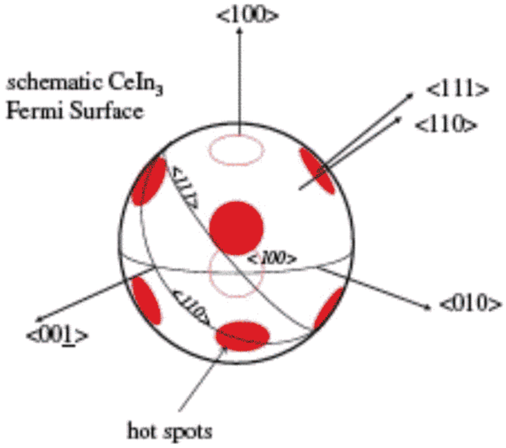
m^* (hot spot) ~ 30 m_e

m^* (cold regions) ~ 2 m_e

Magnetic field-dependent effective masses



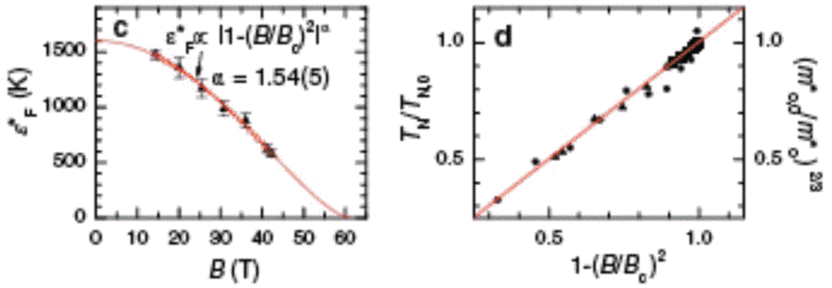
***m** exhibits increase only** for orbits that pass through hot spots: i.e. only mass at hot spot increases (corresponding to *m** (hot spot) ~ 270 ± 50 m_e at 42 T)



***m** for *B* II <110> too heavy** to be observed in pulsed magnetic fields at temperatures above 450 mK !

Other very small but heavy bits of FS (m^* = 20-50 m_e) unobservable in pulsed field experiments (and at high pressures)

Apparent scaling behavior



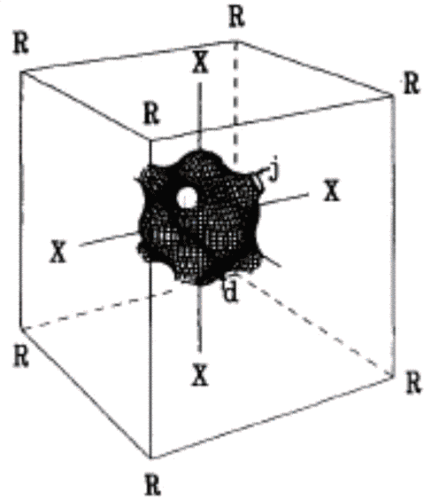
$$\varepsilon^*_F \equiv \frac{\hbar eF}{m^*_o} = \varepsilon^*_{F,0}g^{\alpha'} \qquad \frac{\varepsilon^*_F}{\varepsilon^*_{F,0}} = \frac{m^*_{o,0}}{m^*_o} = \left(\frac{T_N}{T_{N,0}}\right)^{\alpha'/\alpha_B}$$

↑ \`orbital'

$g = (1-B^2)$

Empirical scaling behavior although cannot be continued to B_c, it does show that m^* seems to follow simple power law

Origin of \`hot spots' ?

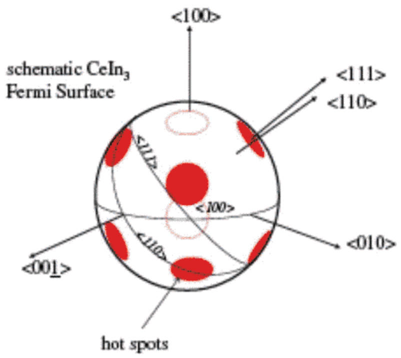


Ebihara et al, Physica B 186,123(1993)

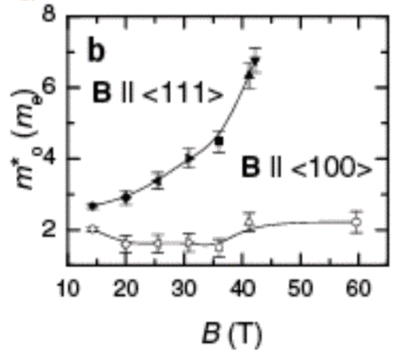
Spherical Fermi surface similar to d-sheet of $LaIn_3$, since the 4*f*-electrons are mostly localized within AFM phase

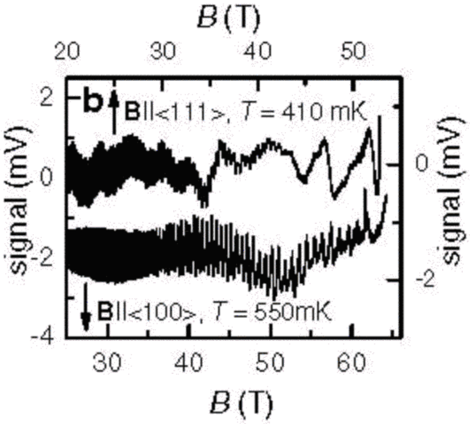
Bragg reflection of conduction electrons off ordered *f*-moments with respect to **Q** = [1/2,1/2,1/2] will nevertheless open gaps which can \`truncate' necks of d-sheet (larger sheets get completely fragmented)

Fluctuations of AFM order parameter leads to fluctuations at necks, hence the \`hot spots' situated at precisely the same location in *k*-space



Some sections of Fermi surface insensitive to impending quantum critical point ?



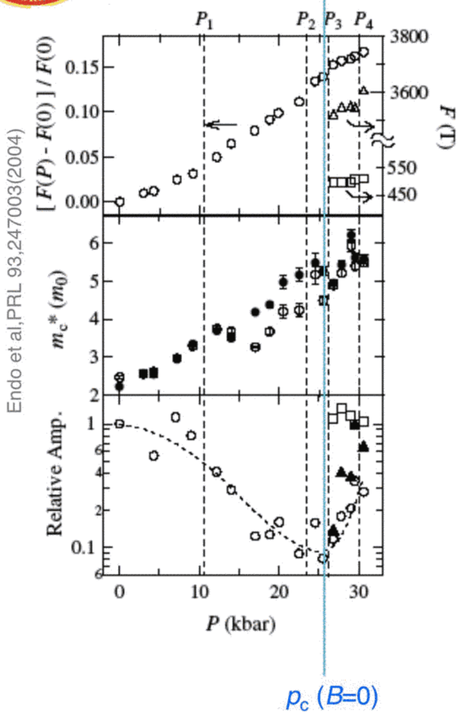


For B||<111> signal vanishes due to heavy mass long before B_c: should not survive outside AFM phase once necks reappear

For B||<100> signal unperturbed to 65 T: suggesting this orbit might survive B_c. Since it seems unlikely that B_c is 1st order, we would expect to see some precursor damping/mass enhancement.

***f*-electrons** remain localized for $B > B_c$?

p-dependent behavior appears to be different:

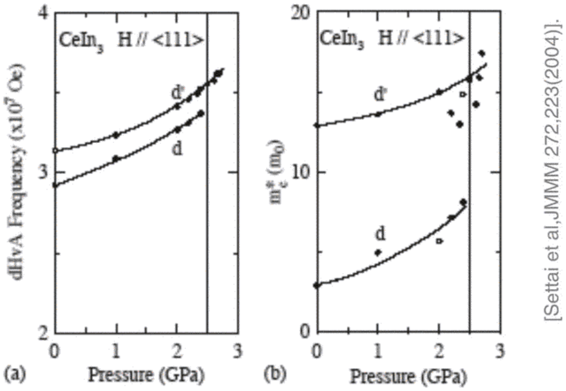


Endo et al,PRL 93,247003(2004)

For both B||<100> and B||<111> mass increases with *p*

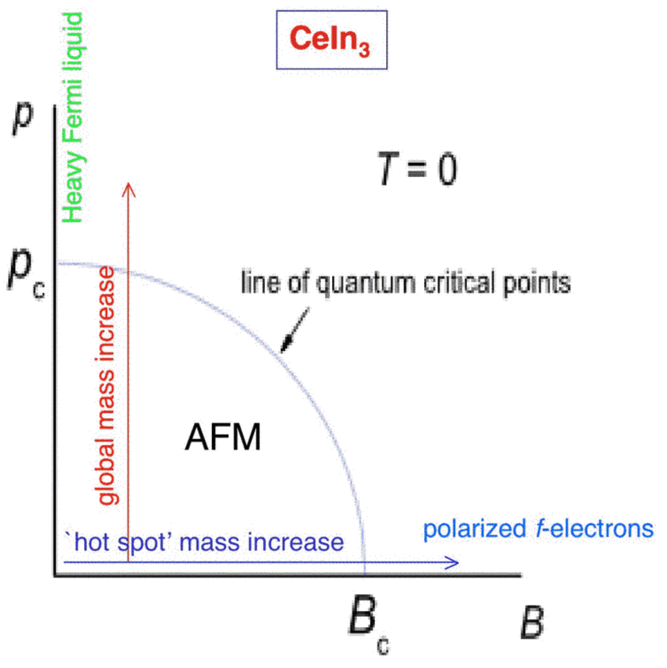
Mass enhancement therefore global over Fermi surface for increasing *p*

New Fermi surface sheets at high pressures?



[Settai et al,JMMM 272,223(2004)].

Implications for phase diagram

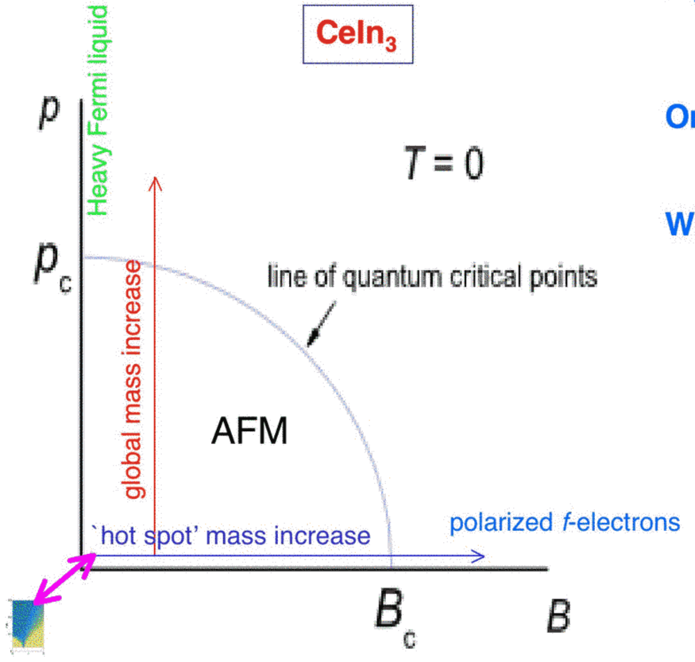


Global mass increase implies fluctuations over entire Fermi surface: consistent with radical Fermi surface change

`hot spot' mass increase implies fluctuations associated with AFM **Q**-vector: consistent with **q**-dependent Fermi surface change

How does Fermi liquid evolve from itinerant to localized f-electrons between large p and large B regimes?

Does CeIn3 scale with YbRh$_2$Si$_2$?

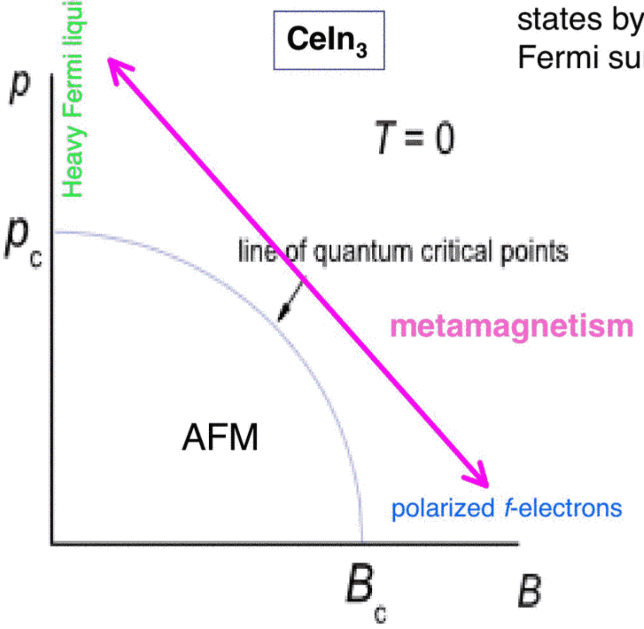


~ factor of 100 scale in B and T

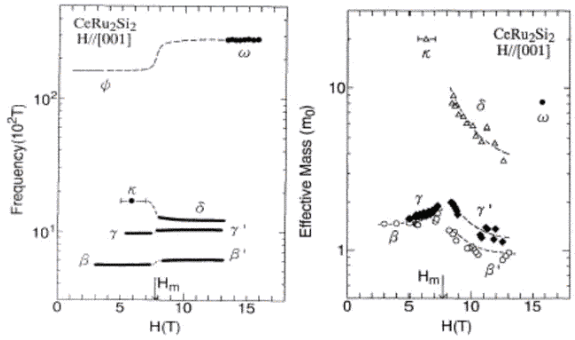
Or is the physics different?

What role does symmetry play?

Cubic versus tetragonal ?



Anisotropic materials can undergo transformation between localized and itinerant f-states by way of metamagnetism: e.g. CeRu$_2$Si$_2$ Fermi surface change

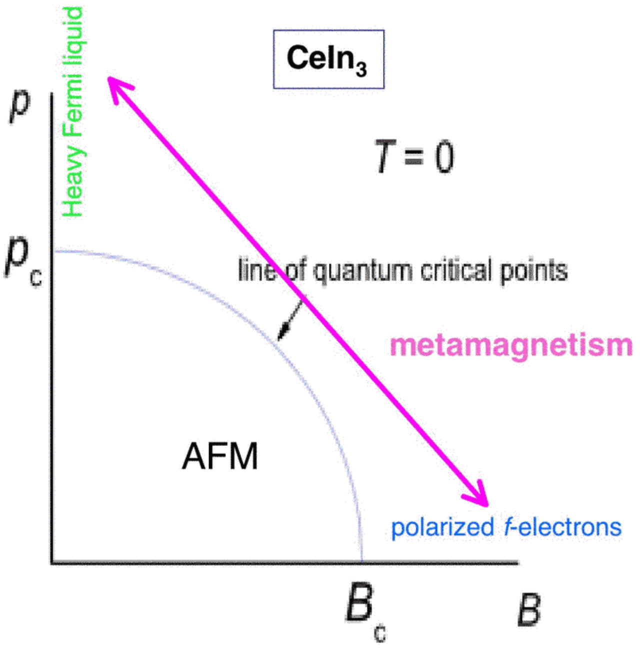


Aoki et al, PRL 71,2110(1993)

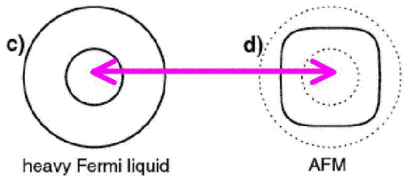
But metamagnetism unexpected in cubic material (i.e. CeIn$_3$) !

How does the Fermi surface transform continuously at $T = 0$ while maintaining Luttinger's theorem?

Riddles of the Fermi surface



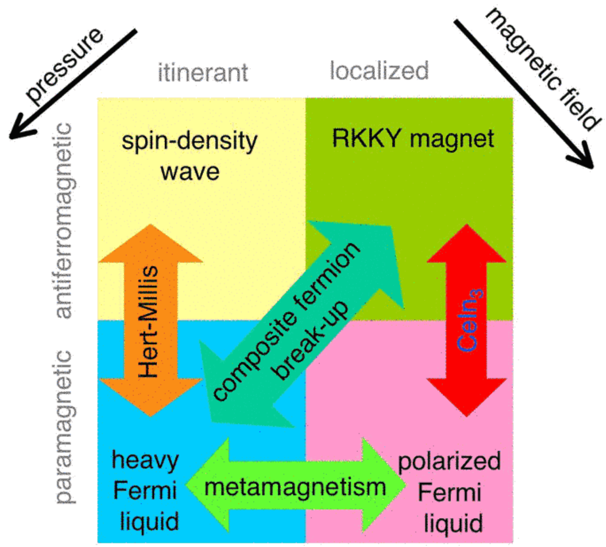
Can transformation from itinerant to localized take place continuously? Obeying Luttinger's theorem throughout



i.e. in CeRu$_2$Si$_2$ it take places abruptly, at metamagnetic cross-over/transition accompanied by large magnetization change

What would be the equivalent process in CeIn$_3$?

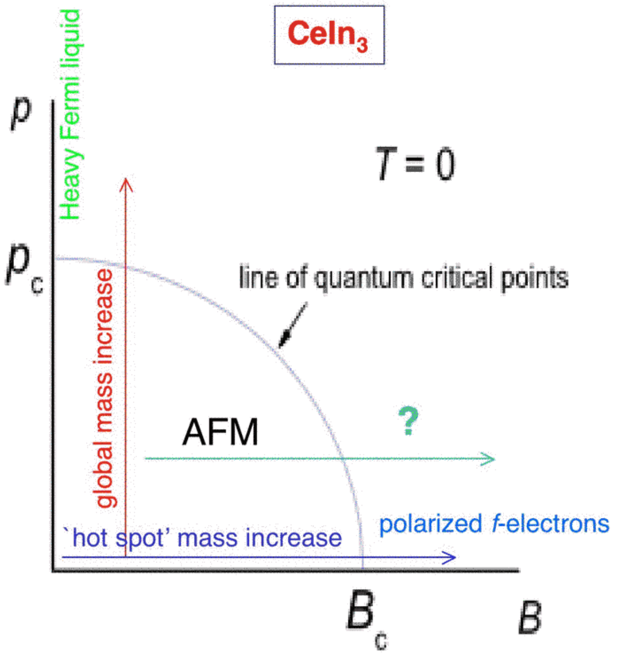
$CeIn_3$ quantum critical points



Perhaps $CeIn_3$ in a magnetic field is localized *f*-electron equivalent of Hertz-Millis type QCP?

AFM order parameter causes Bragg reflection of conduction electrons, but due to RKKY-mediated AFM ordered *f*-moments rather than a SDW.

Future directions: large areas of unexplored phase space



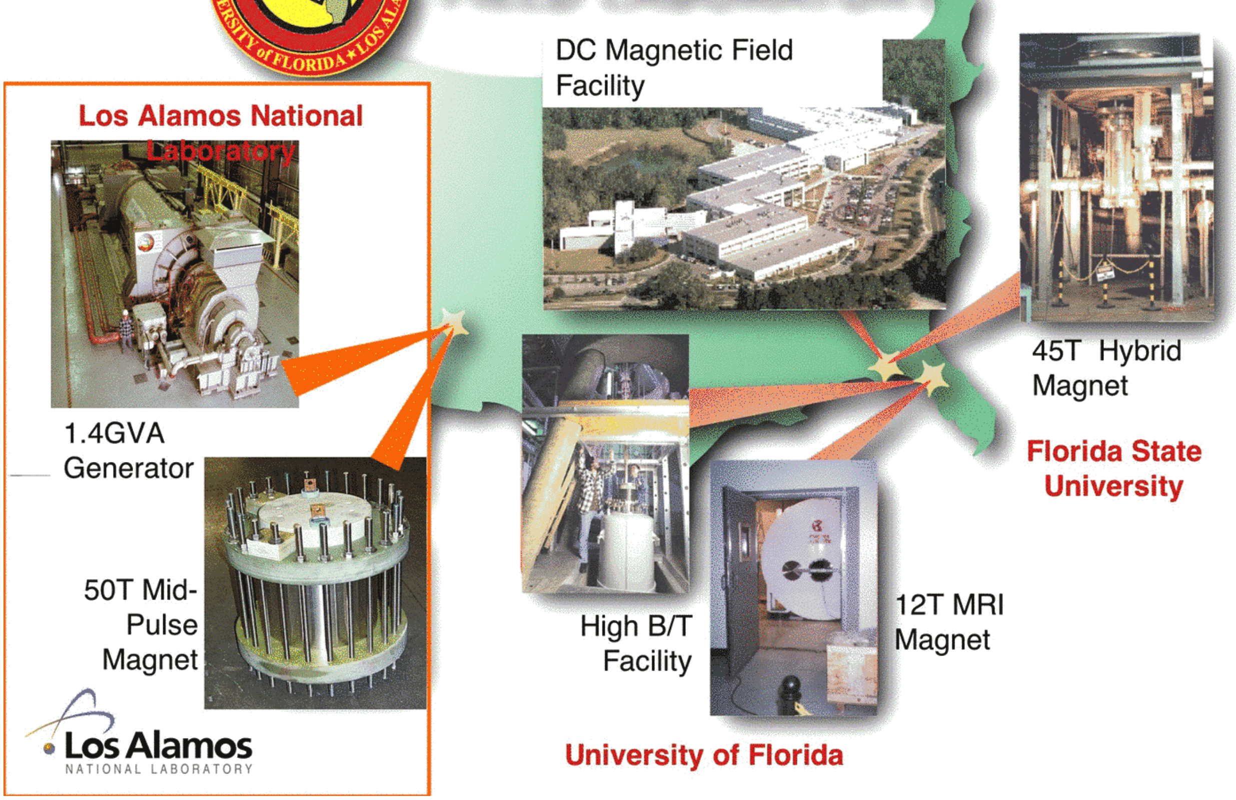
1) Electrical transport under pressure in strong magnetic fields (turquoise line) or observed dHvA and *T*-dependent transport at $B >> 65$ T

2) Electrical transport versus pressure in a constant field $B < 45$ T

3) Field-dependence of γ and AT^2 requiring use of dil. fridge because of big C_p anomaly

4) Sn-doping study to reduce B_c to more manageable fields so that electrical resistivity can be measured in 45 T hybrid

NATIONAL HIGH MAGNETIC FIELD LABORATORY



Los Alamos National Laboratory

1.4GVA Generator

50T Mid-Pulse Magnet

Los Alamos NATIONAL LABORATORY

DC Magnetic Field Facility

High B/T Facility

12T MRI Magnet

University of Florida

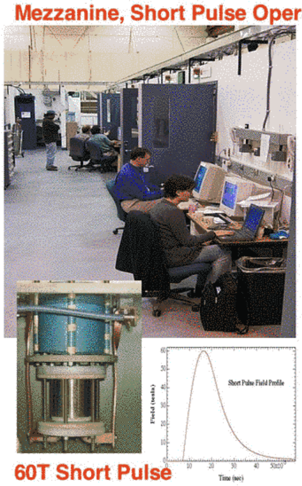
45T Hybrid Magnet

Florida State University

NHMFL - Pulsed Field Facility

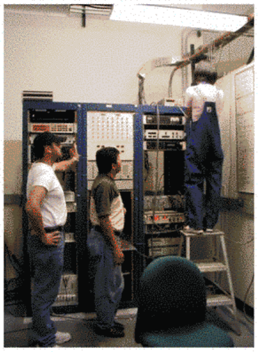
Alex H. Lacerda, Director

Mezzanine, Short Pulse Operations



60T Short Pulse

20T Control Room



In-house Scientists:

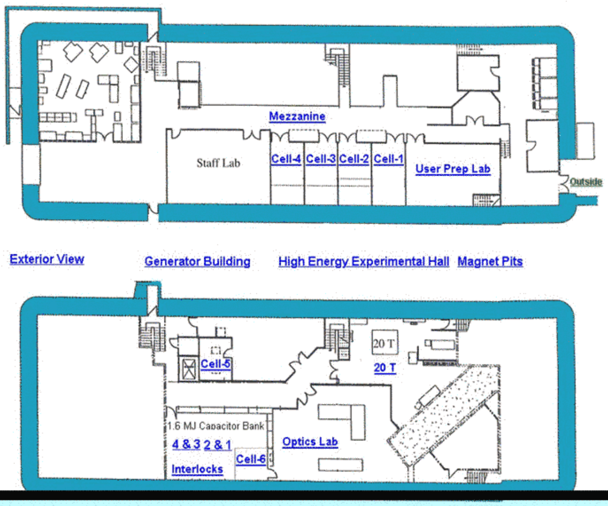
Scott Crooker (*Spectroscopy,Optics*)
Marcelo Jaime (*Thermodynamics*)
Neil Harrison (*Magnetization*)
Fedor Balakirev (*Transport*)
John Singleton (*Magnetization*)
Charles Mielke (*Transport & Head Users Program*)
Albert Migliori (*Spectroscopy,Ultrasound*)
Dwight Rickel (*Spectroscopy,Optics*)
Jason Lashley (*Thermodynamics*)
7 Postdoctoral Fellows, 4 graduate students

Instrumentation & Magnets Highlights

50T-SP (400ms), 65T-SP (25ms), 20T-SC, (2) 15T-SC and 14T-SC
–μΩ magnetotransport measurements
-THz, RUS and GHz spectroscopy
-Magnetization

User Program:
- 150 groups of users per year
- 20% from abroad
- 50% from US Universities

2003 Highlights: (4) PRLs, (2) Nature, (1) Science



High Energy Experimental Hall: 60T-LP & 100T-MS