New Quantum States of Matter

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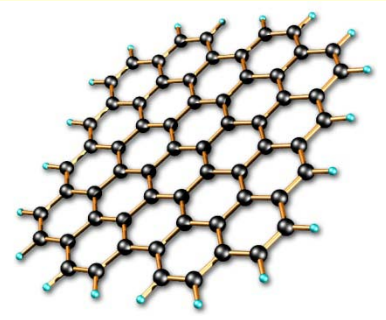
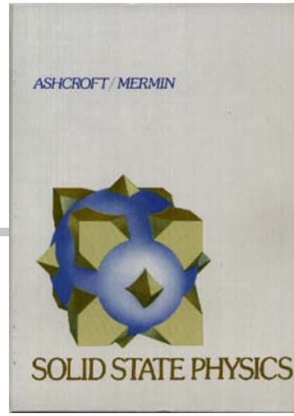
- ***new states at Quantum Phase Transitions***
    - ***Superconductors, superinsulators, nematics, BEC's***
- ***Fermi surface reconstruction and high temperature superconductivity***

A brief history of new states in condensed matter:

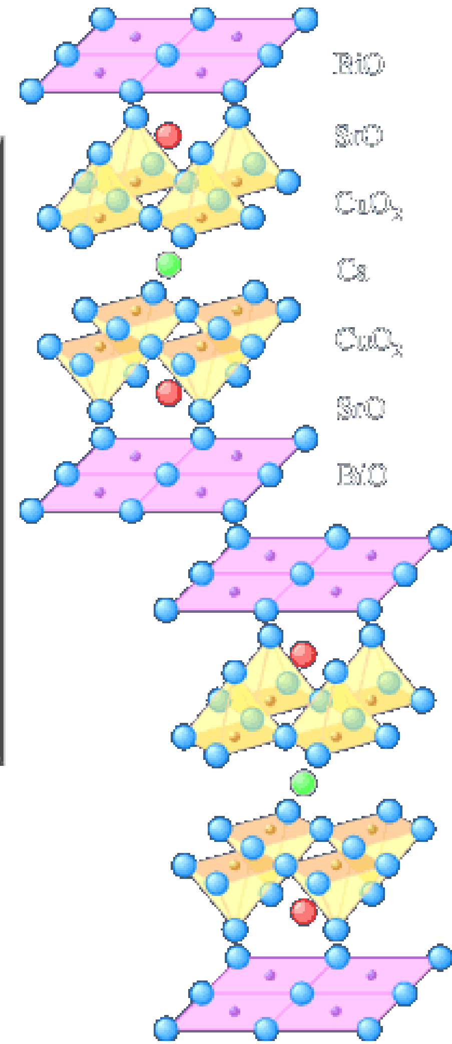
- Crystalline order (Von Laue 1914)
- Superconductivity (Kammerlingh Onnes 1913)
- Superfluidity (4He) (Kapitza 1978)
- Antiferromagnetism (Neel 1970)
- Superfluidity (3He) (Lee, Richardson, Osheroff 1996)
- Fractional quantum Hall state (Laughlin, Stormer, Tsui 1998)
- High Tc superconductivity (Bednorz, Mueller 1987)
- Bose-condensates (Cornell, Ketterle, Weiman 2001)
- (graphene) (Geim, Novosolov, 2010)





1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub	113 113	114 Uuq	115 115	116 Uuh	117 117	118 Uuo

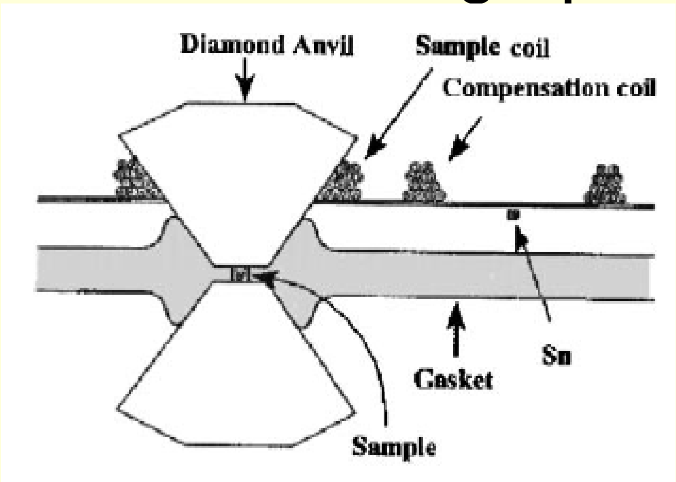
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

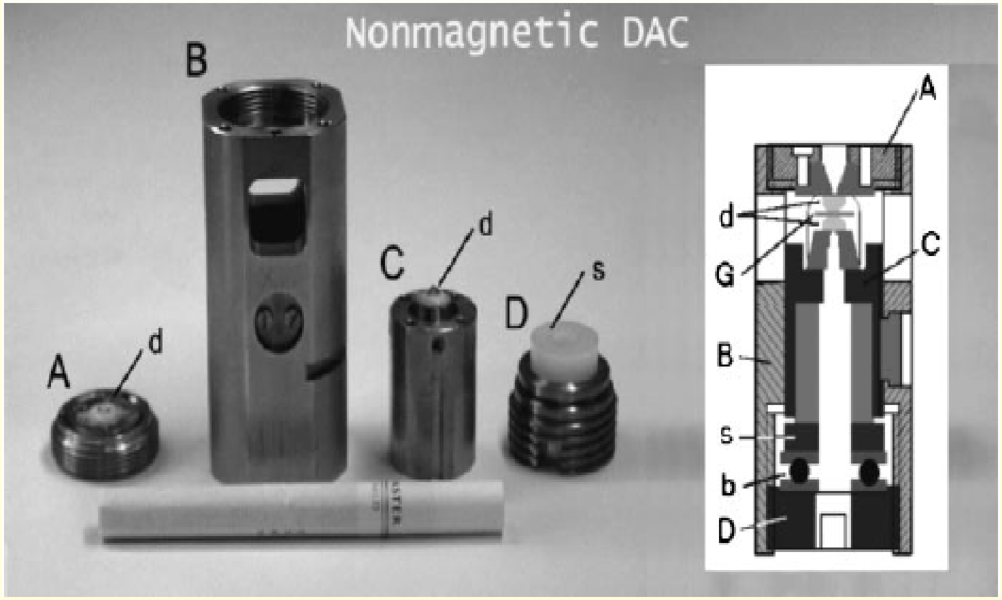


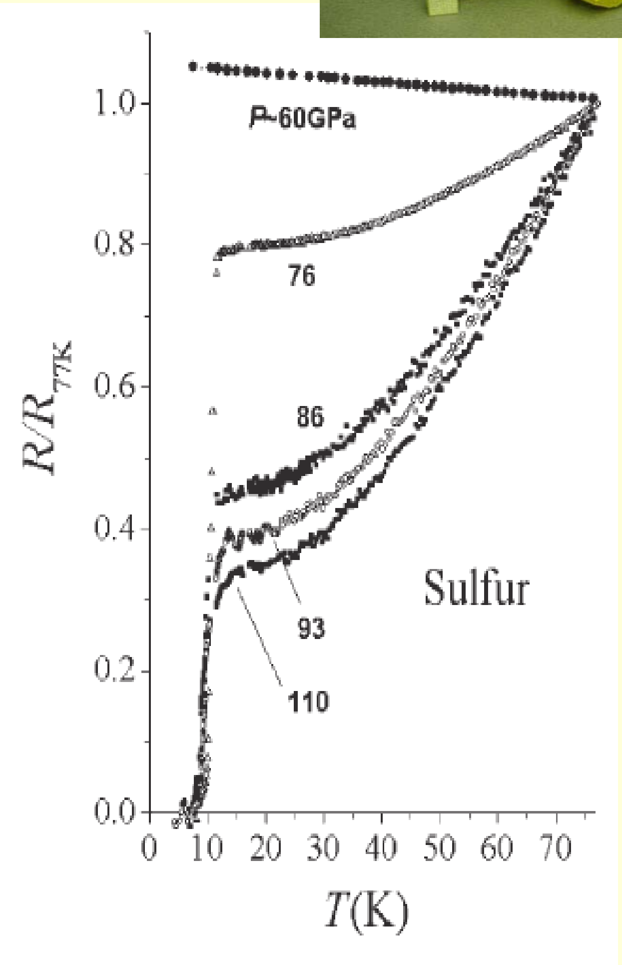
New Materials

- Compared to biology, materials preparation in quantum condensed matter is
  - Small-scale
  - Slow
  - comparatively unsophisticated (very little automation)
- Greater use of electronic structure calculations?
- Automation?
- Pressure?

Superconducting elements under very high pressure

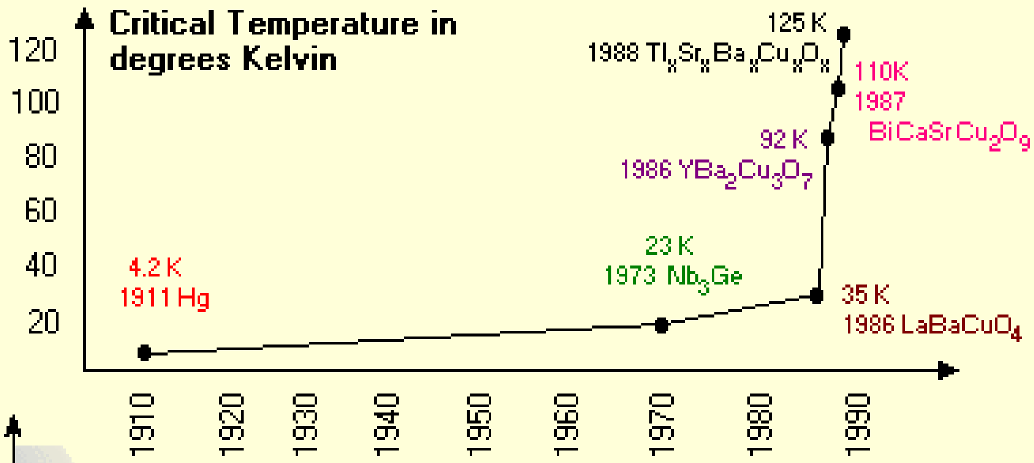


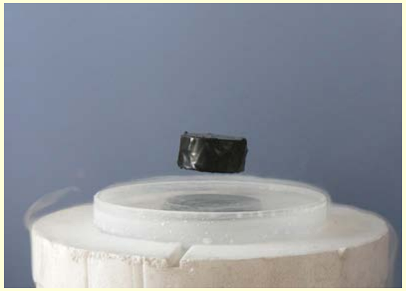


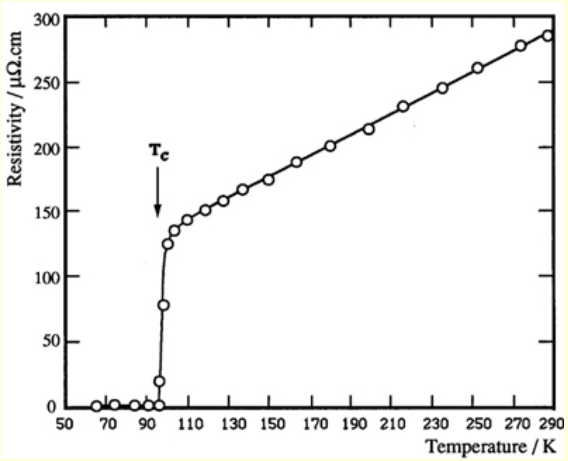


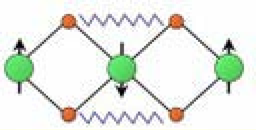
Shimizu et al., JPSJ **74** (2005) 1345.

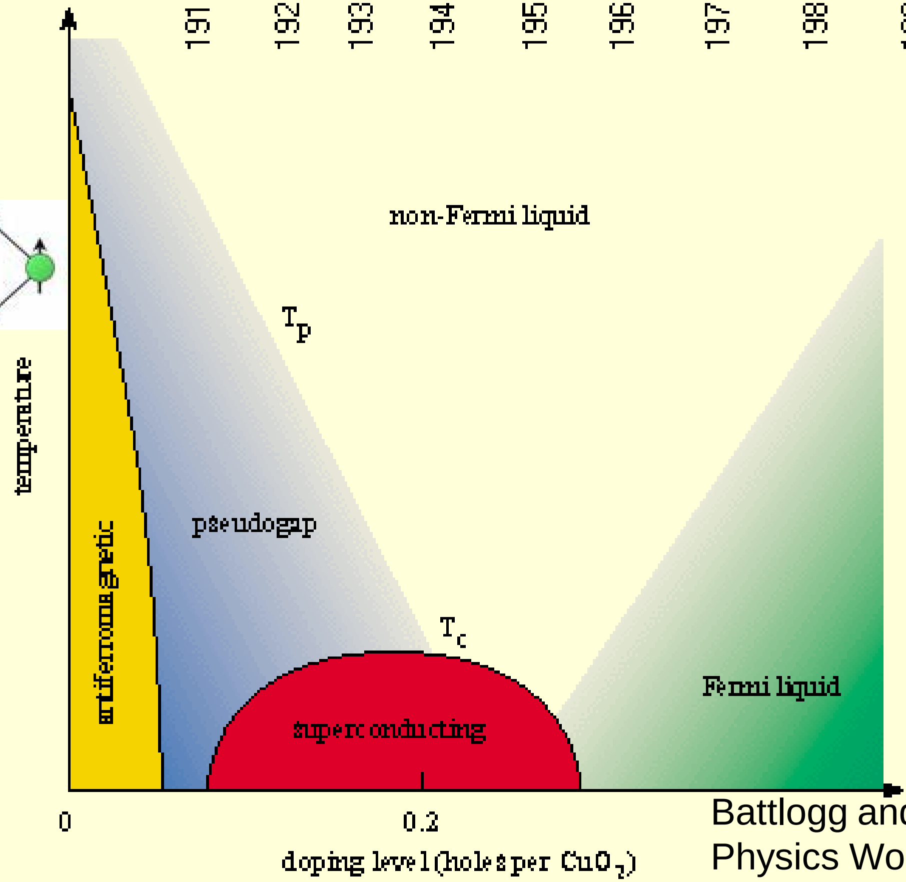
high temperature superconductivity



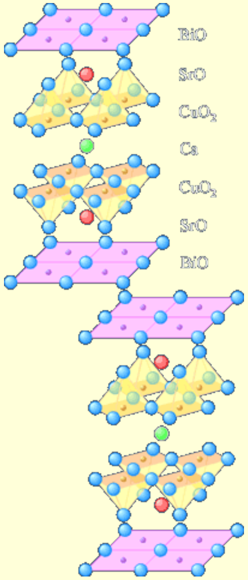








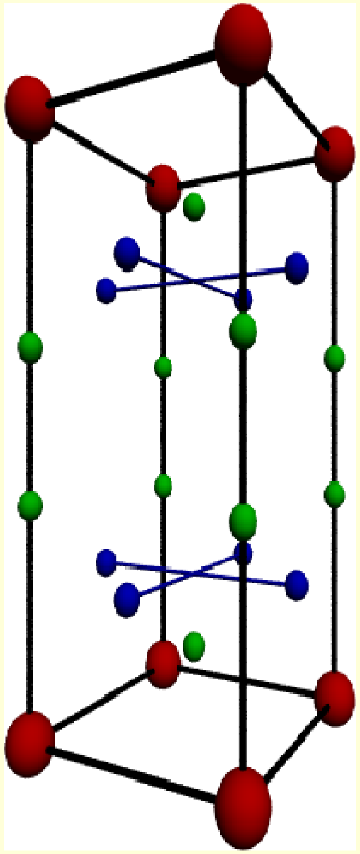
Battlogg and Varma, Physics World, Feb. 2000



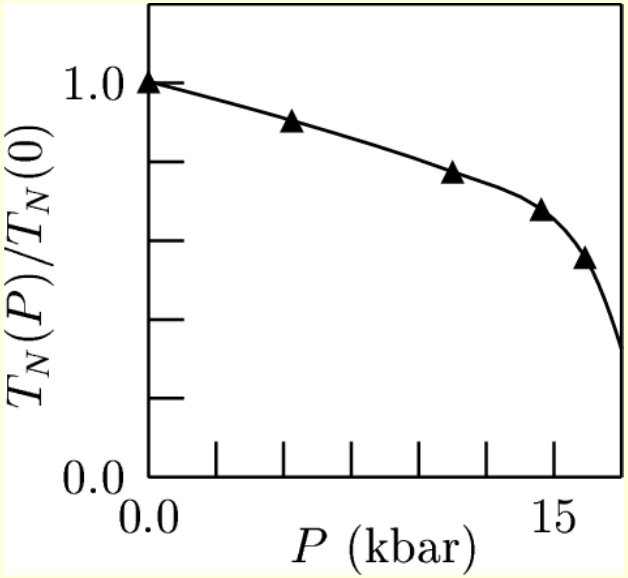
JC Davis web site

American Superconductor Corporation (NASDAQ: AMSC), a global power technologies company, today announced that it has received the world's largest order for high temperature superconductor (HTS) wire. LS Cable Ltd. (LS Cable), the world's third largest power cable manufacturer, has placed an order for 3 million meters (nearly 10 million feet) of Amperium wire - AMSC's proprietary second generation (2G) HTS wire. (6 Oct 2010)

$CePd_2Si_2$

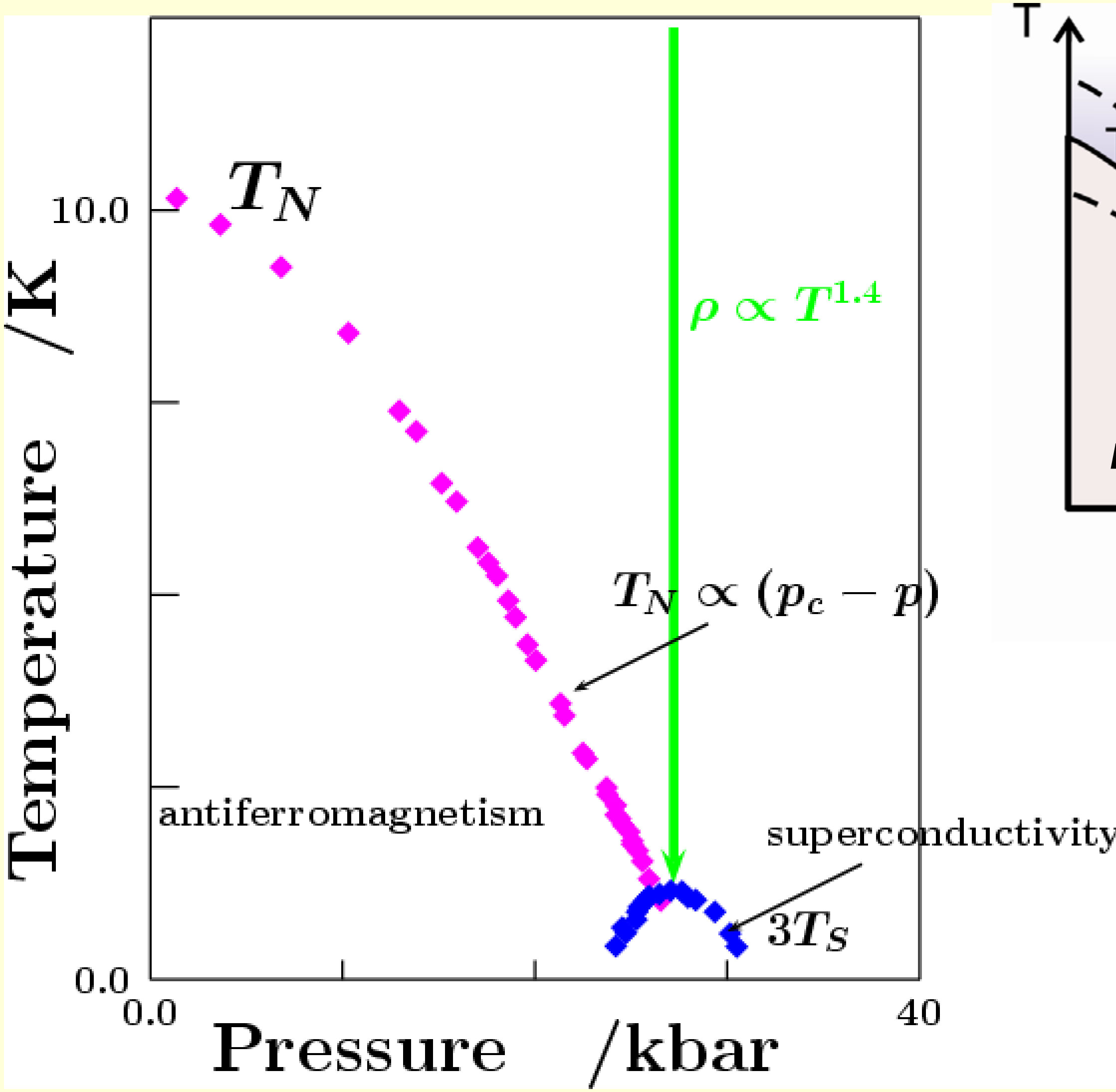


-Crystal structure common to many heavy fermion alloys
-Antiferromagnetic below T_N=10K, with an ordered moment of 0.7μ_B
- Pressure suppresses magnetic order

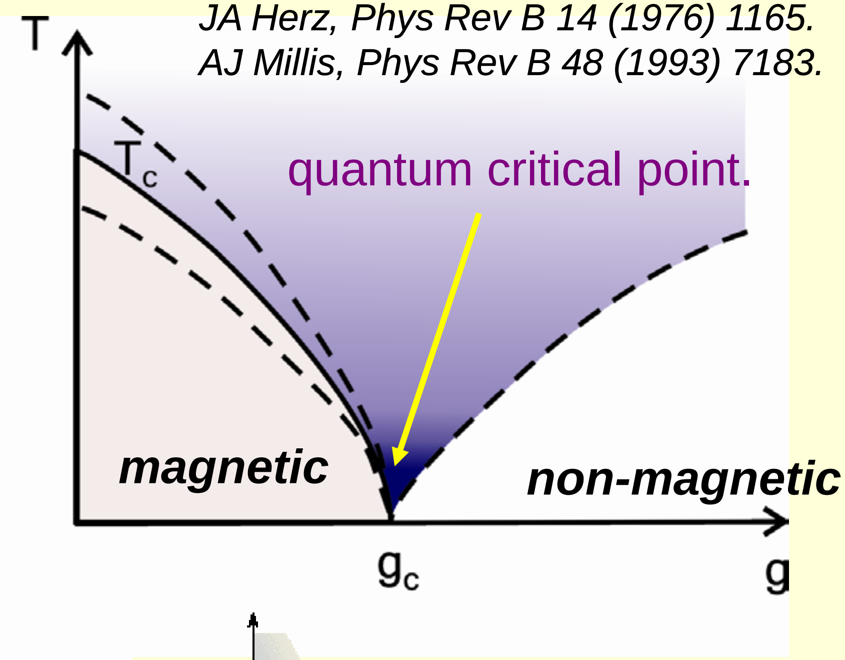


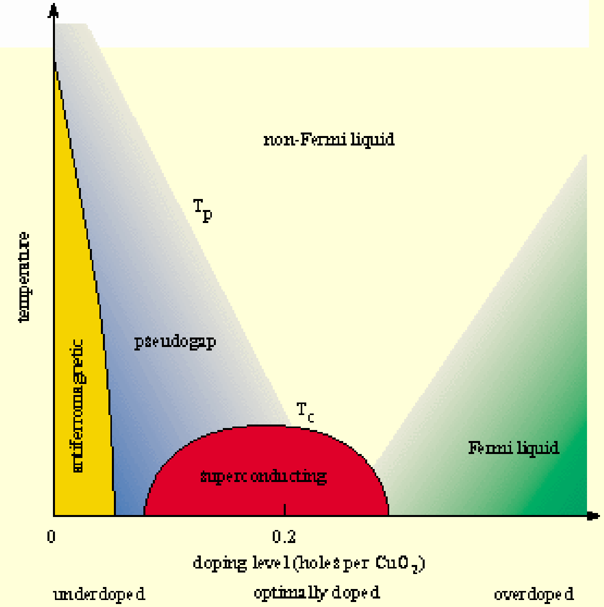
Thompson et al., JMMM 54-57 (1986) 377.

$CePd_2Si_2$ phase diagram



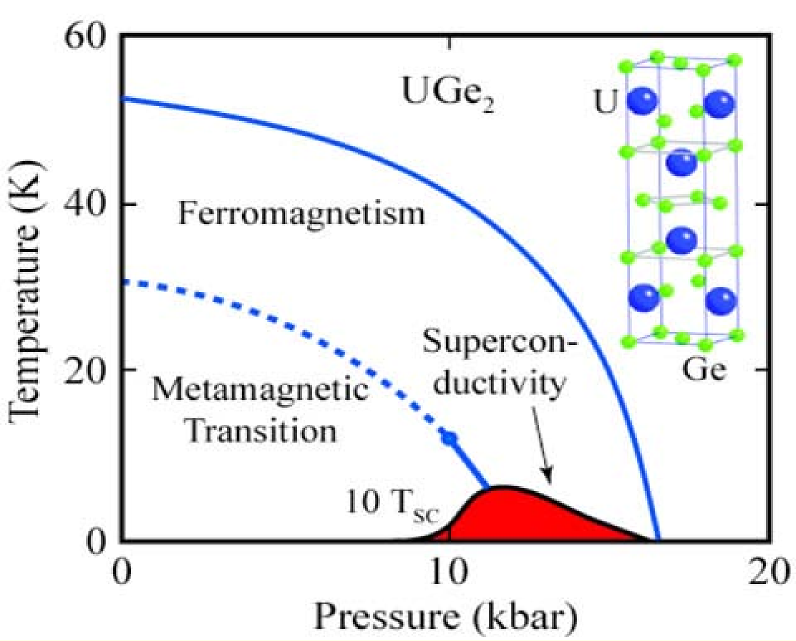
JA Herz, Phys Rev B 14 (1976) 1165.
AJ Millis, Phys Rev B 48 (1993) 7183.

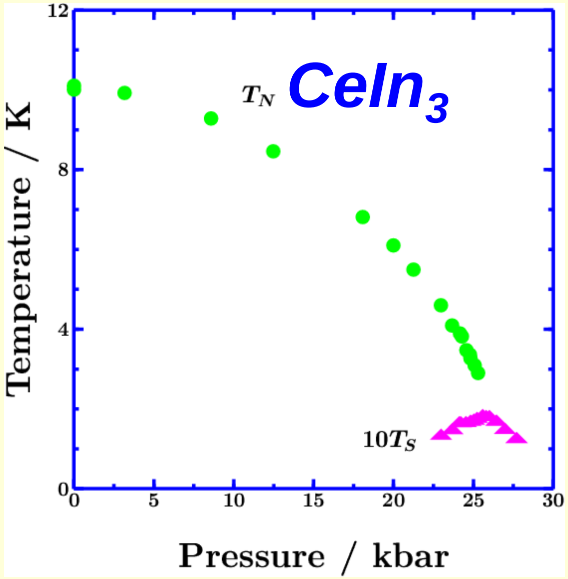




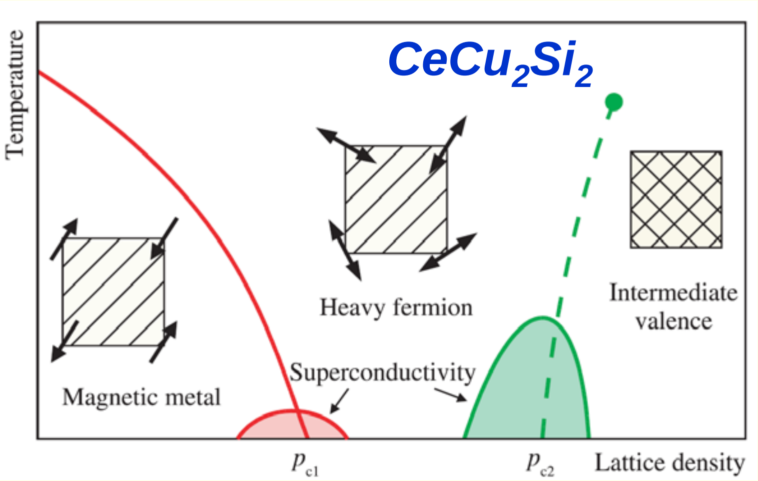
Other quantum critical superconductors

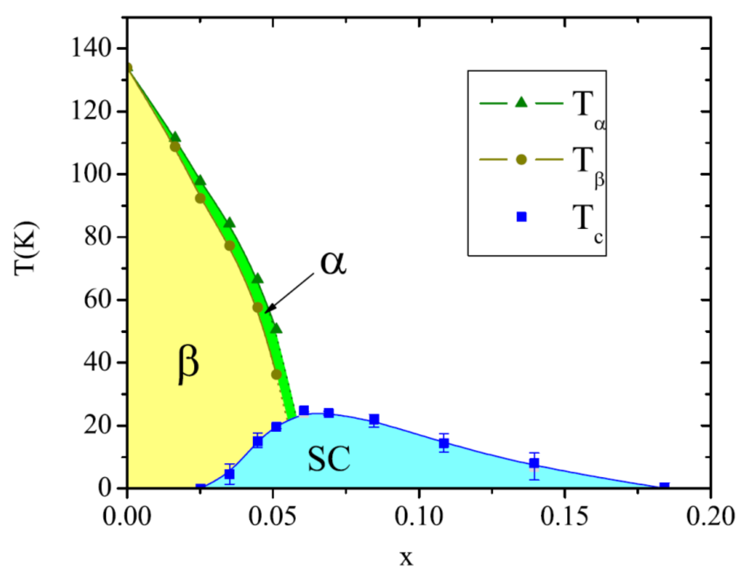
Saxena et al., Nature 2002





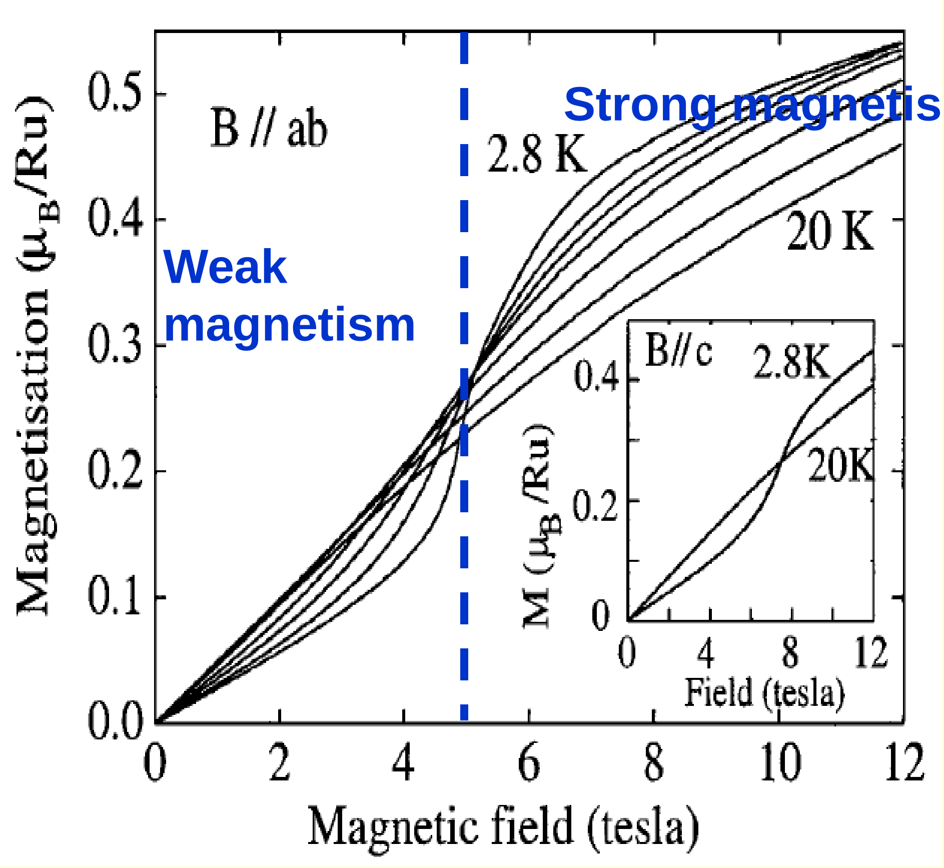
$BaFe_2As_2$
Chu et al. 2009



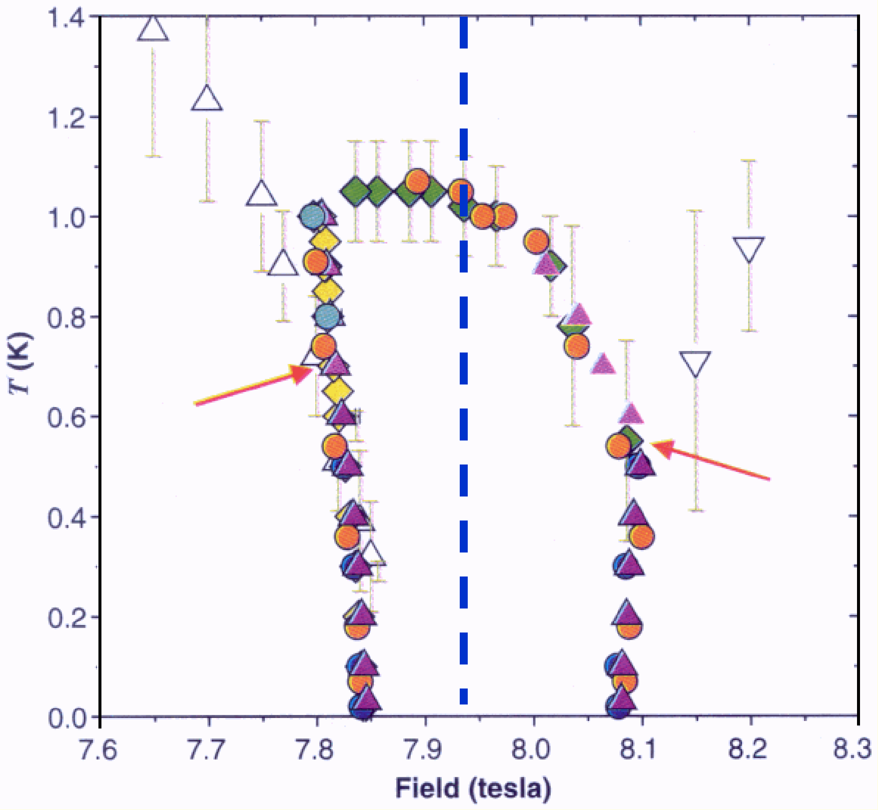


Yuan et al., Science 2003

Metamagnetic quantum phase transition

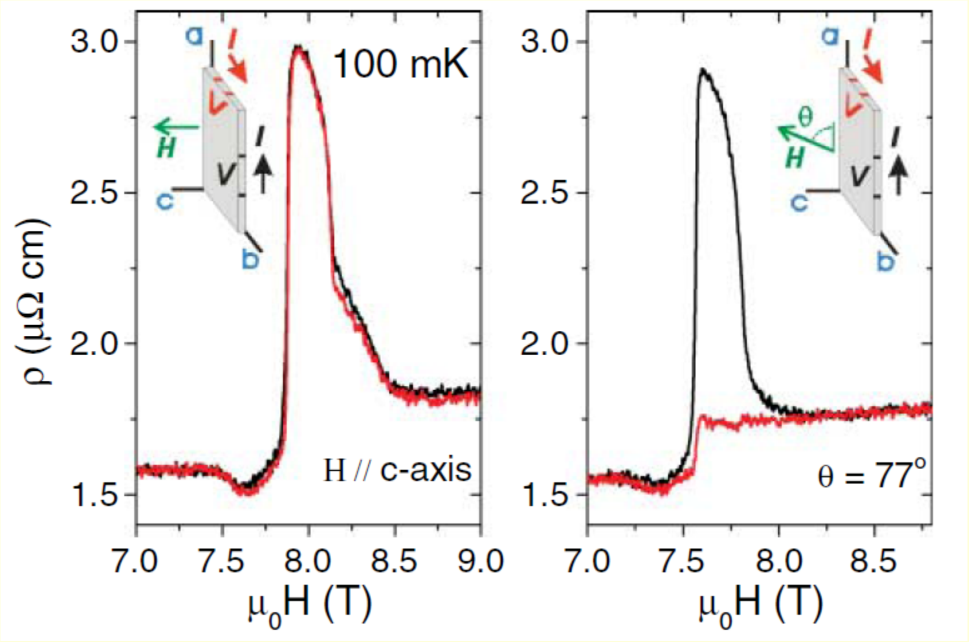


$Sr_3Ru_2O_7$



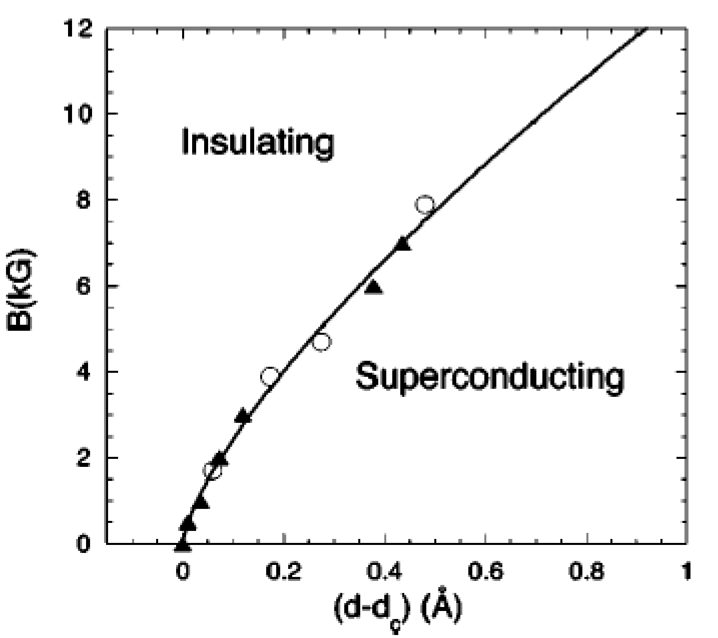
Grigera et al., Science 306 (2004) 1154; Science 2006; Perry et al. PRL 84 (2001) 2661; Harrison et al., PRL 91 (2003) 269902.

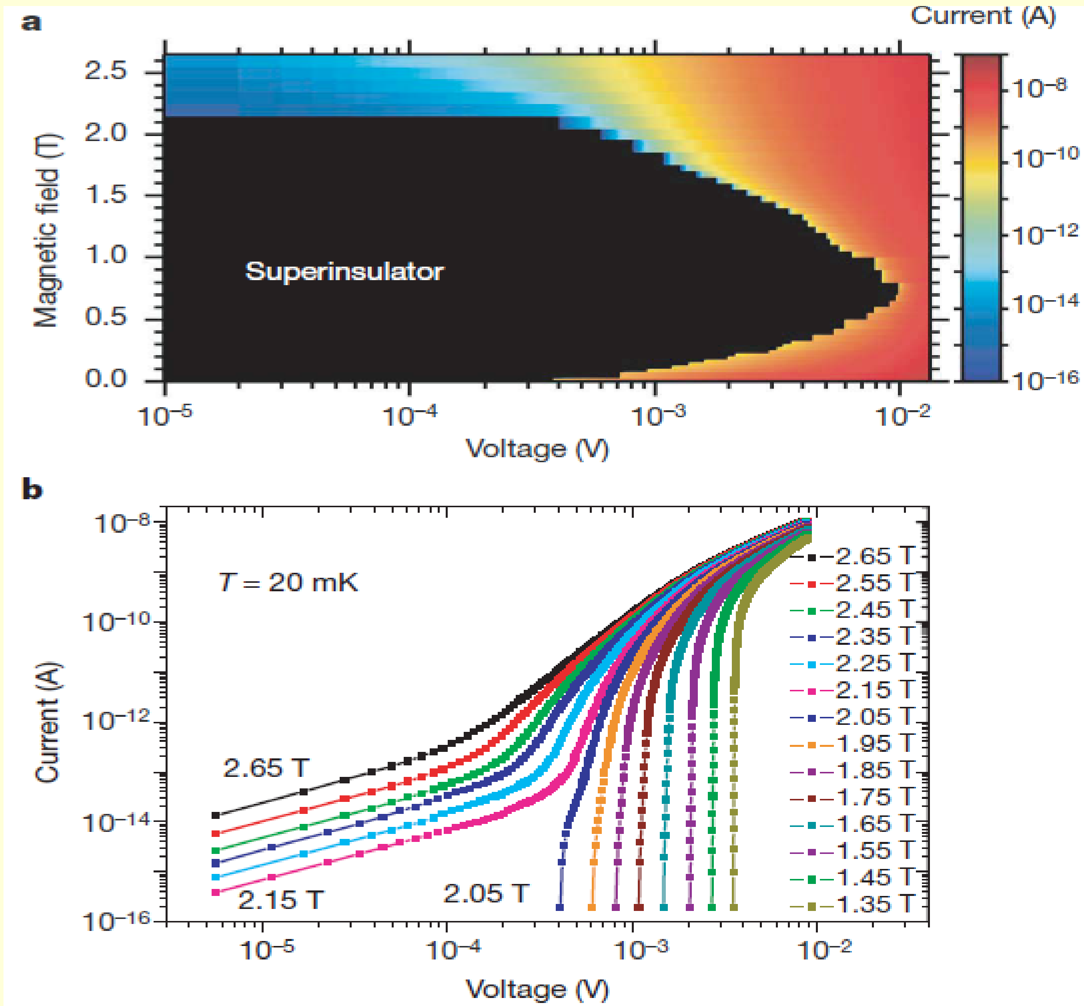
Electron nematic at a metamagnetic instability

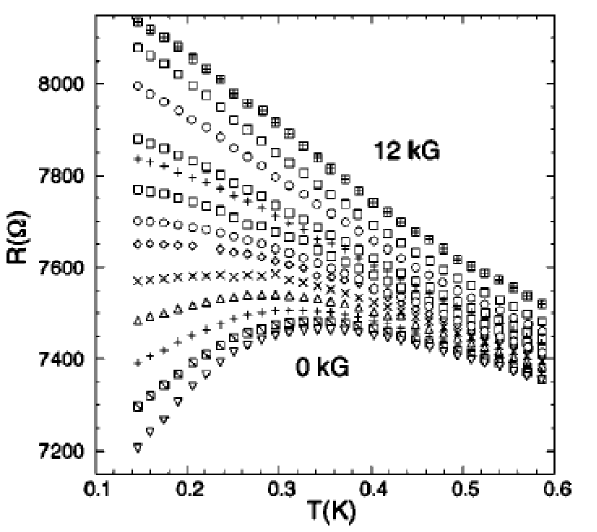


Grigera et al. Science 2003
Borzi et al. Science 2006
Rost et al. Science 2009

Superinsulator at the superconductor-insulator boundary



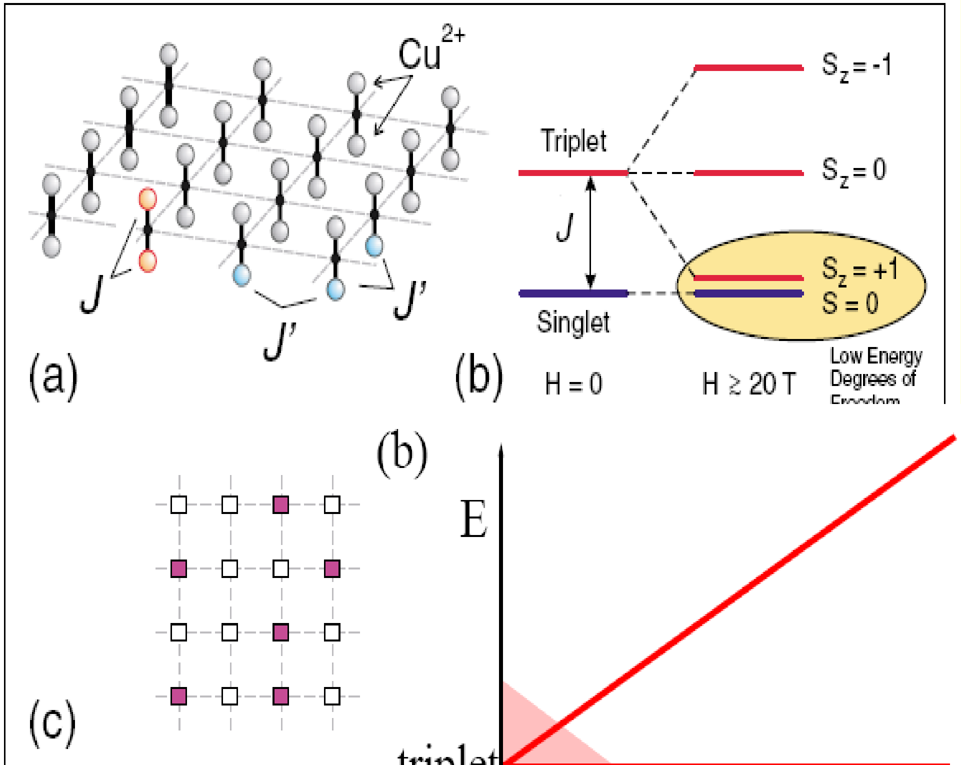


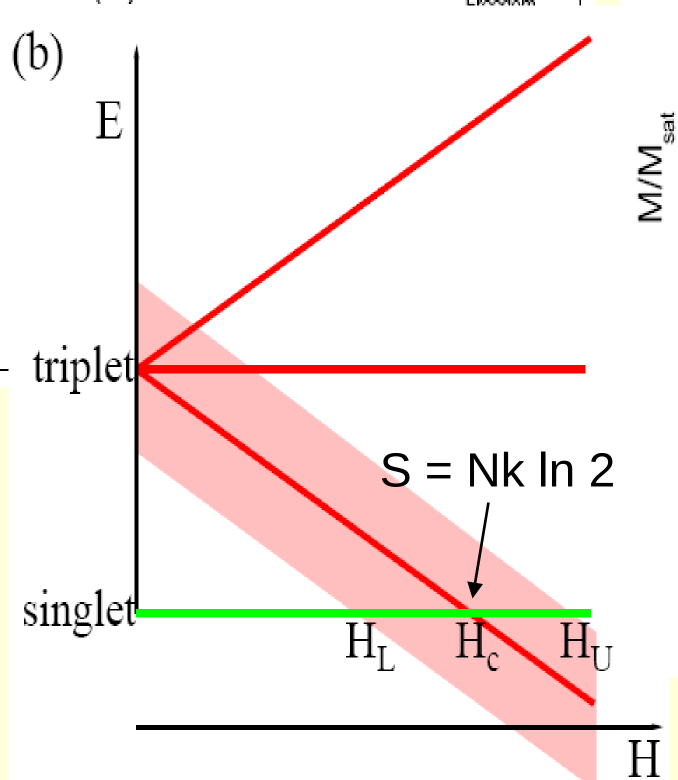


Vinokur et al., Nature 2008

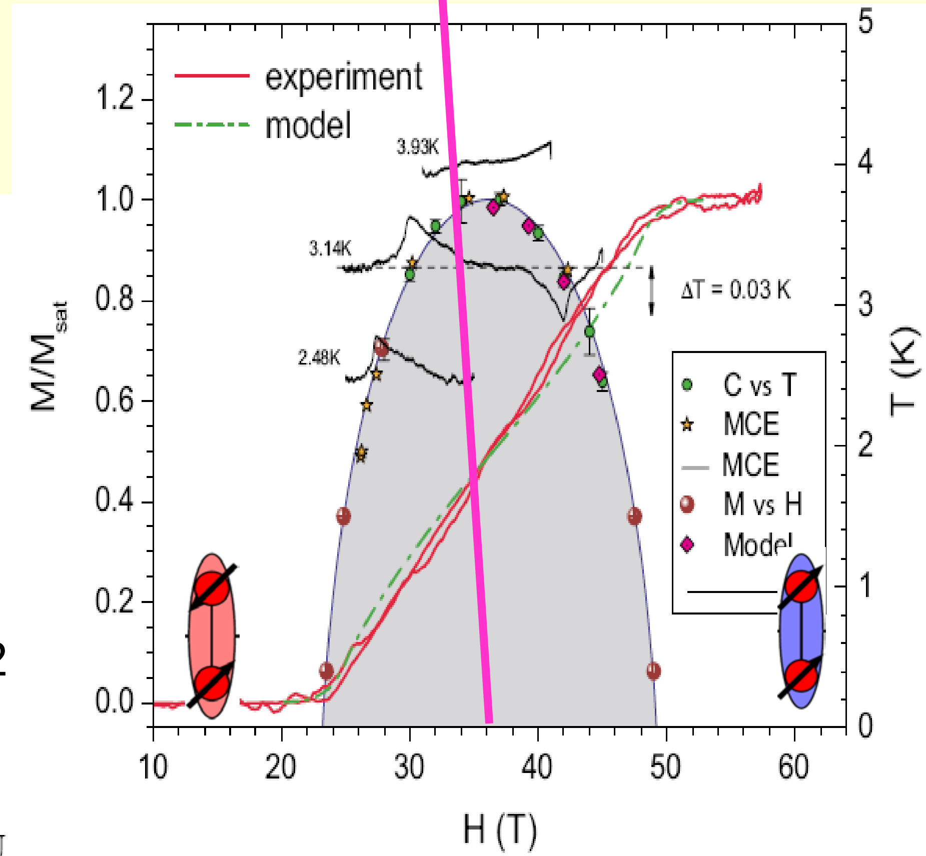
BEC of triplons

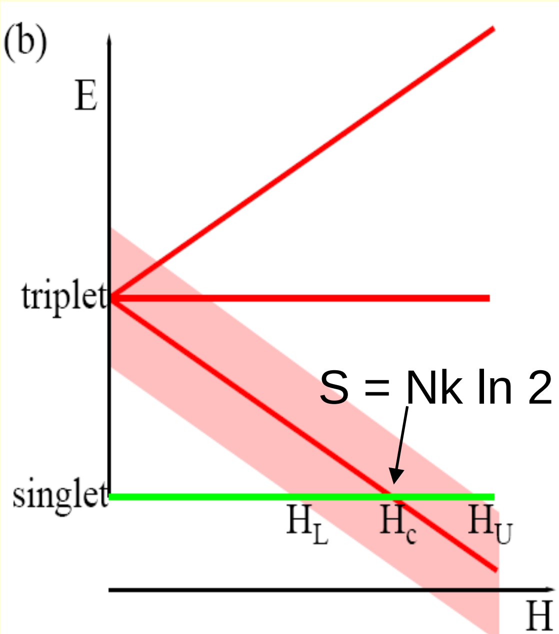
M. Jaime et al., Phys. Rev. Lett. 93 (2004) 087203

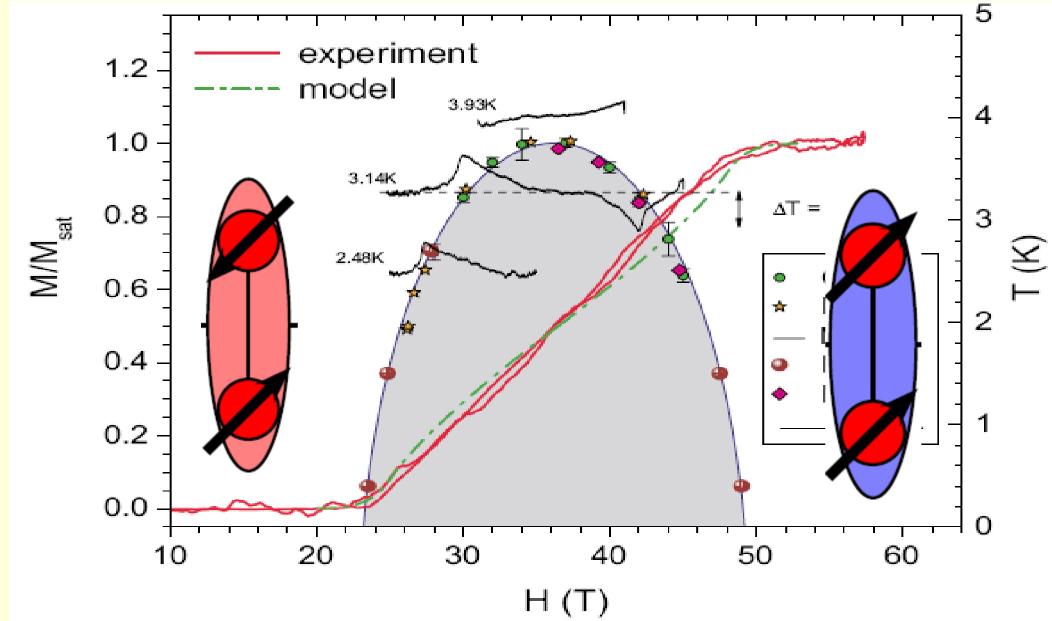




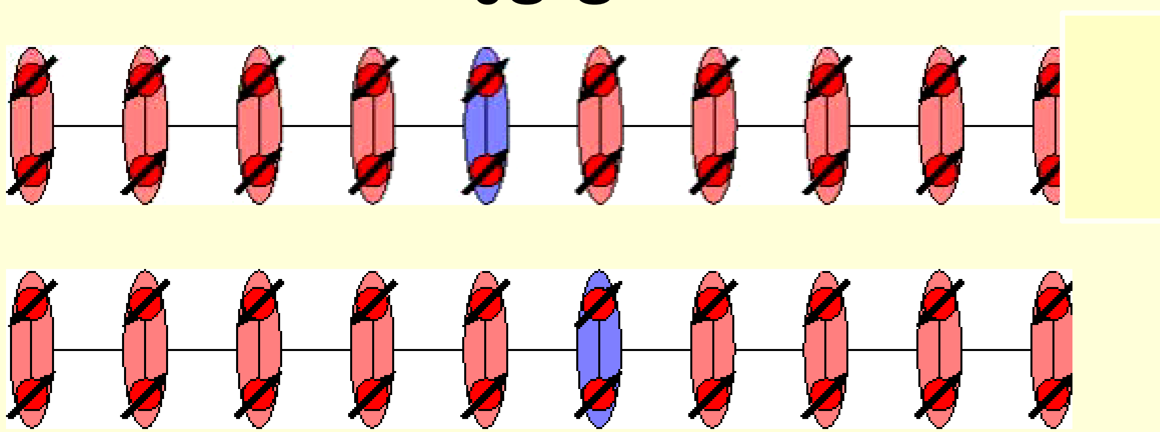
triplet-singlet
energy




(b)
E
triplet
singlet
S = Nk ln 2
H_L
H_c
H_U
H


experiment
model
3.93K
3.14K
2.48K
ΔT =
M/M_{sat}
T (K)
H (T)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
10
20
30
40
50
60
0
1
2
3
4
5

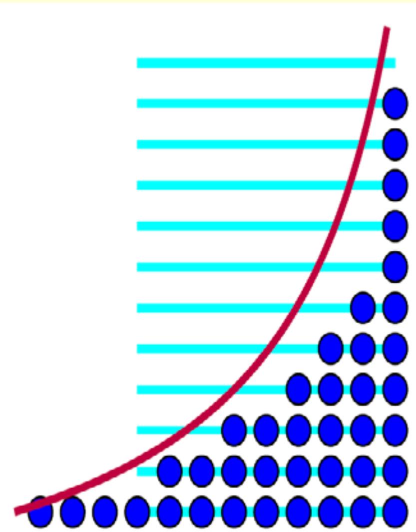
JS^+S^-



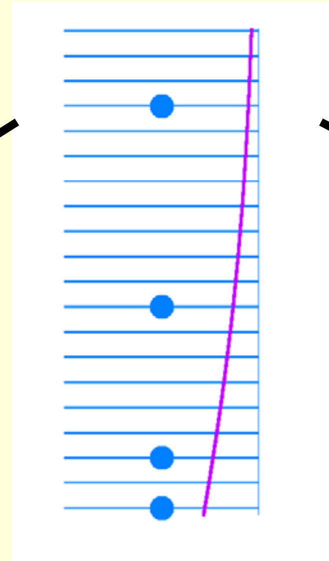
"Algorithm" for discovering a new state of condensed matter:

- Take a very pure material with some kind of order (e.g. magnetic)
- Apply pressure or magnetic field etc. to suppress the order (produce a highly degenerate state with strong interactions to mediate new order)
- Cool to low temperature (to get rid of thermal noise, allow fragile quantum states to emerge)

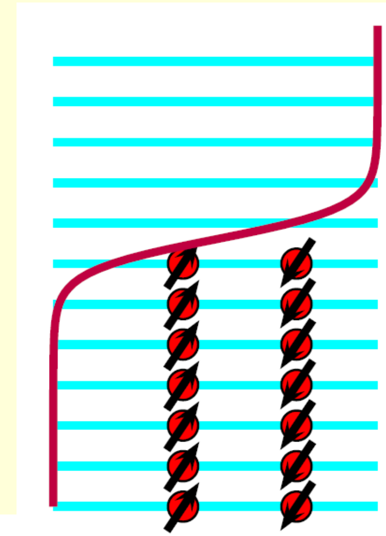
Why "Quantum" Phases?

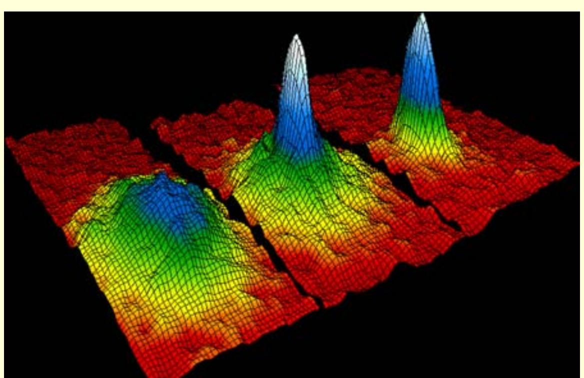


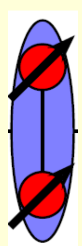
bosons

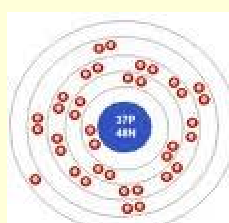


fermions

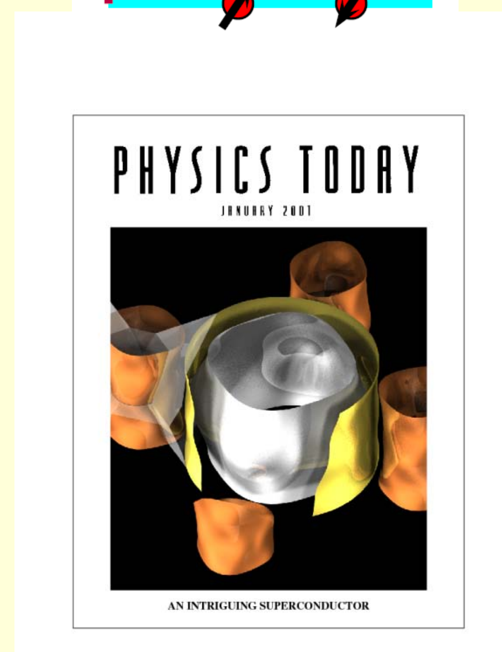




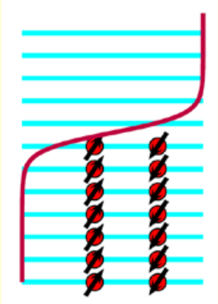


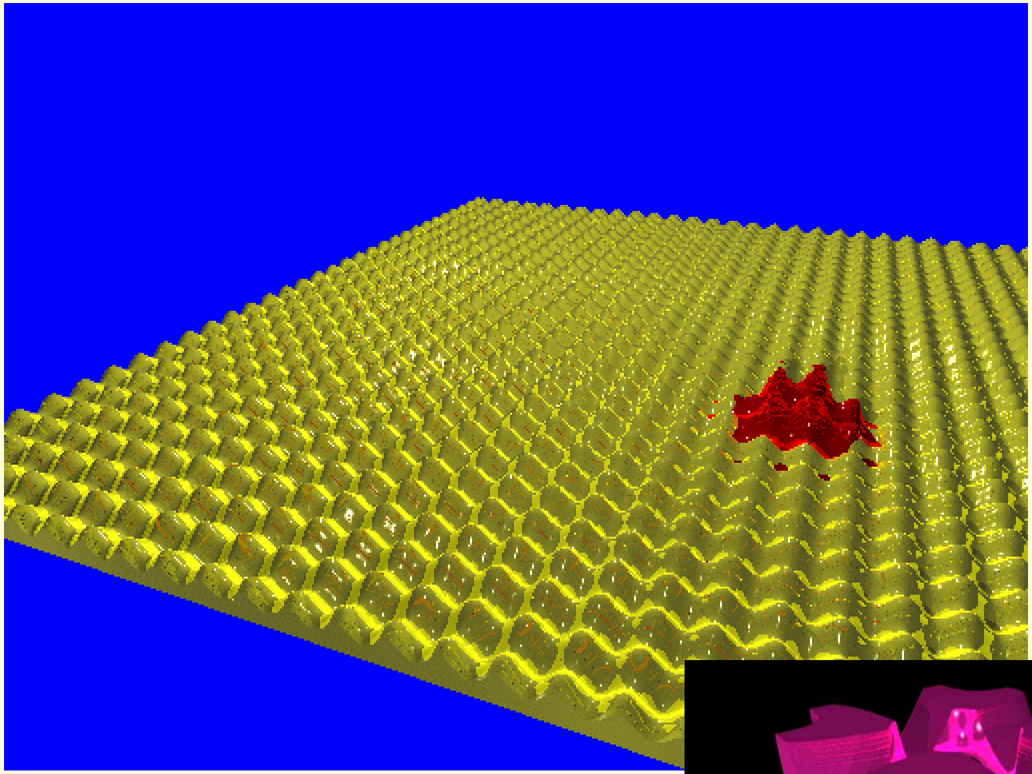


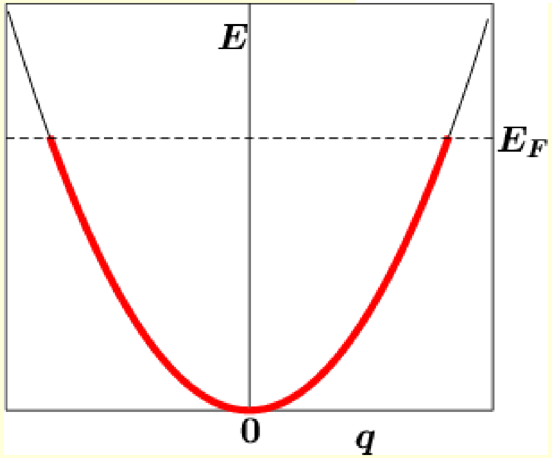
pairing

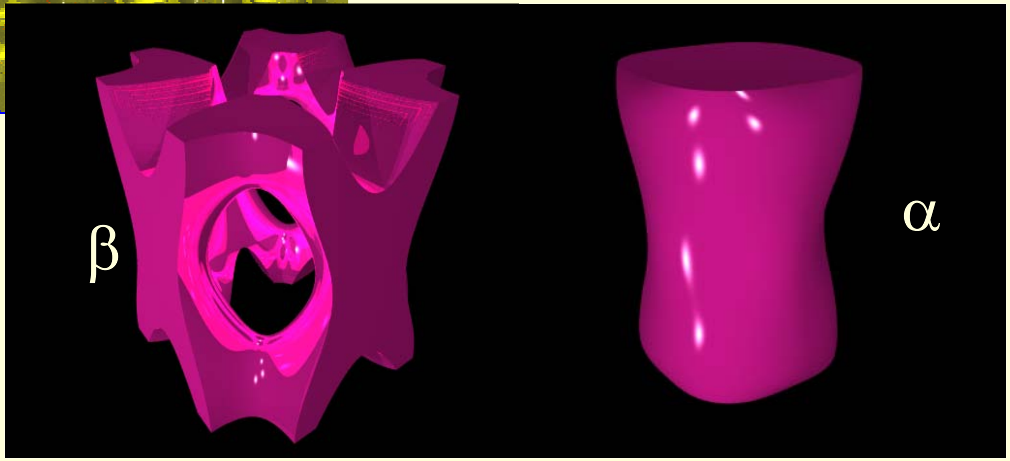


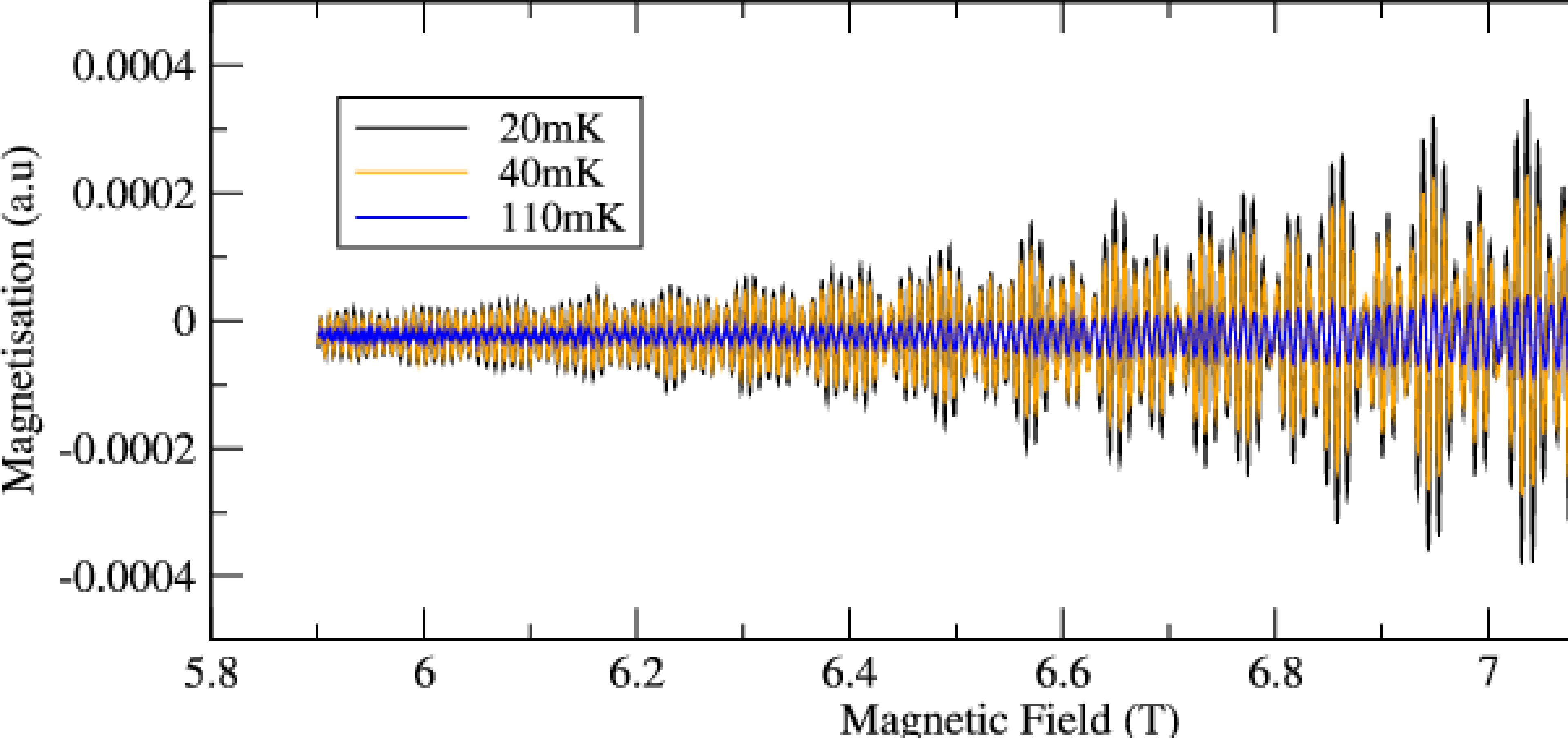
Electron quasiparticle in a magnetic field



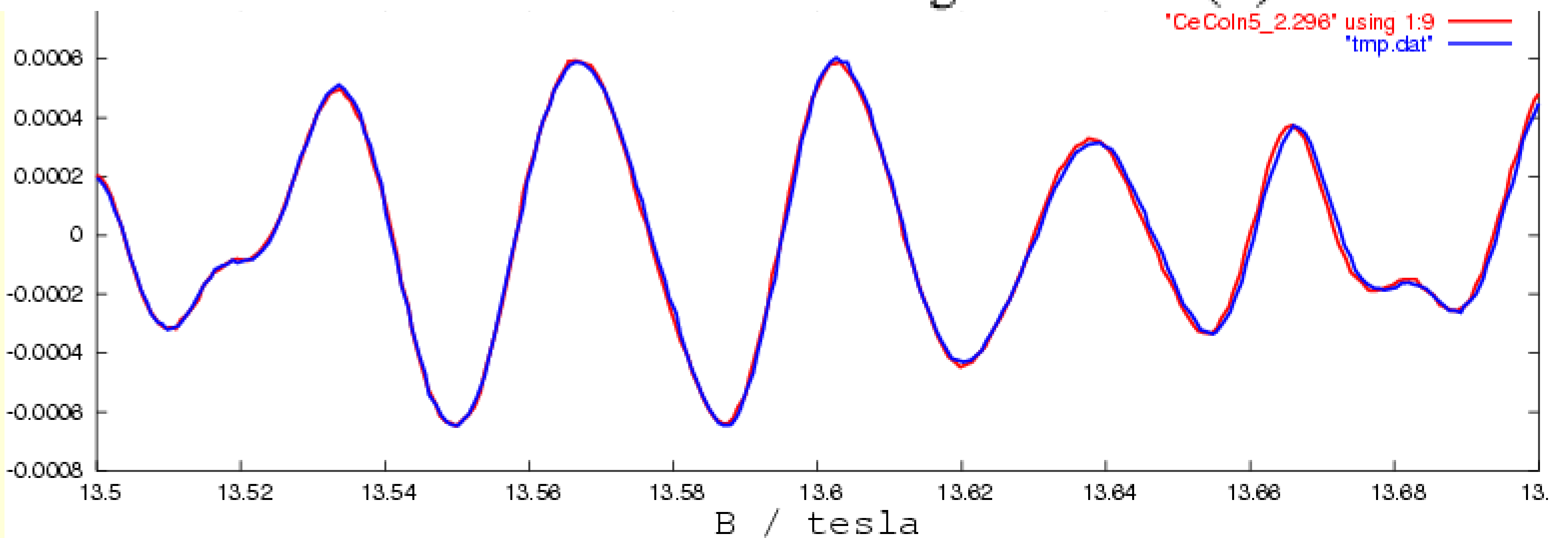




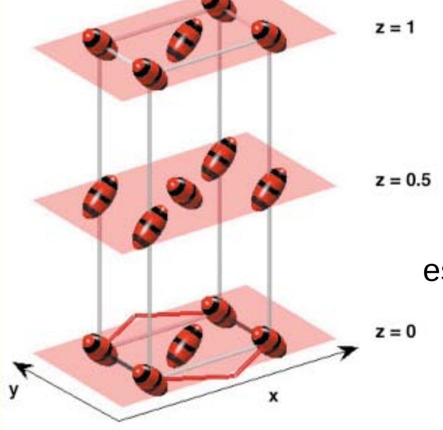




Magnetisation (a.u)
0.0004
0.0002
0
-0.0002
-0.0004
20mK
40mK
110mK
5.8
6
6.2
6.4
6.6
6.8
7
Magnetic Field (T)



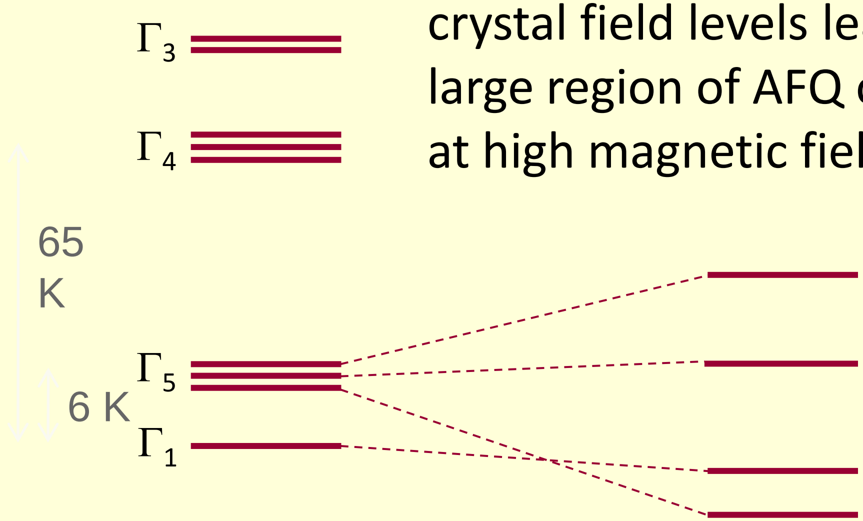
"CeCoIn5_2.296" using 1:9
"tmp.dat"
0.0006
0.0004
0.0002
0
-0.0002
-0.0004
-0.0006
-0.0008
13.5
13.52
13.54
13.56
13.58
13.6
13.62
13.64
13.66
13.68
13.7
B / tesla

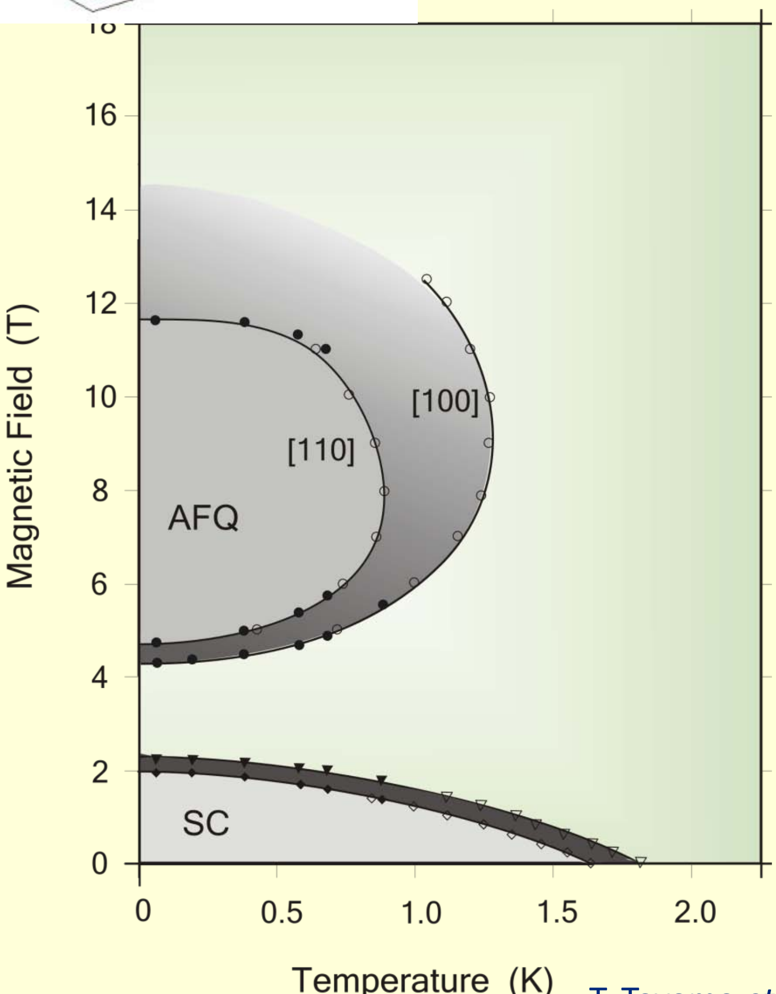


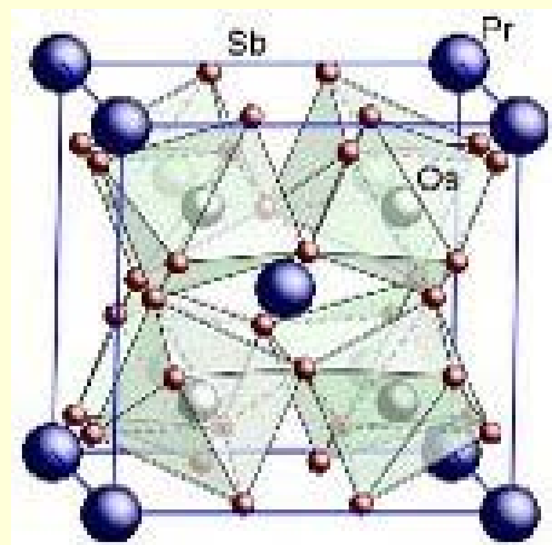
esrf.edu

$PrOs_4Sb_{12}$

Crossing of Zeeman-split crystal field levels leads to large region of AFQ order at high magnetic field.



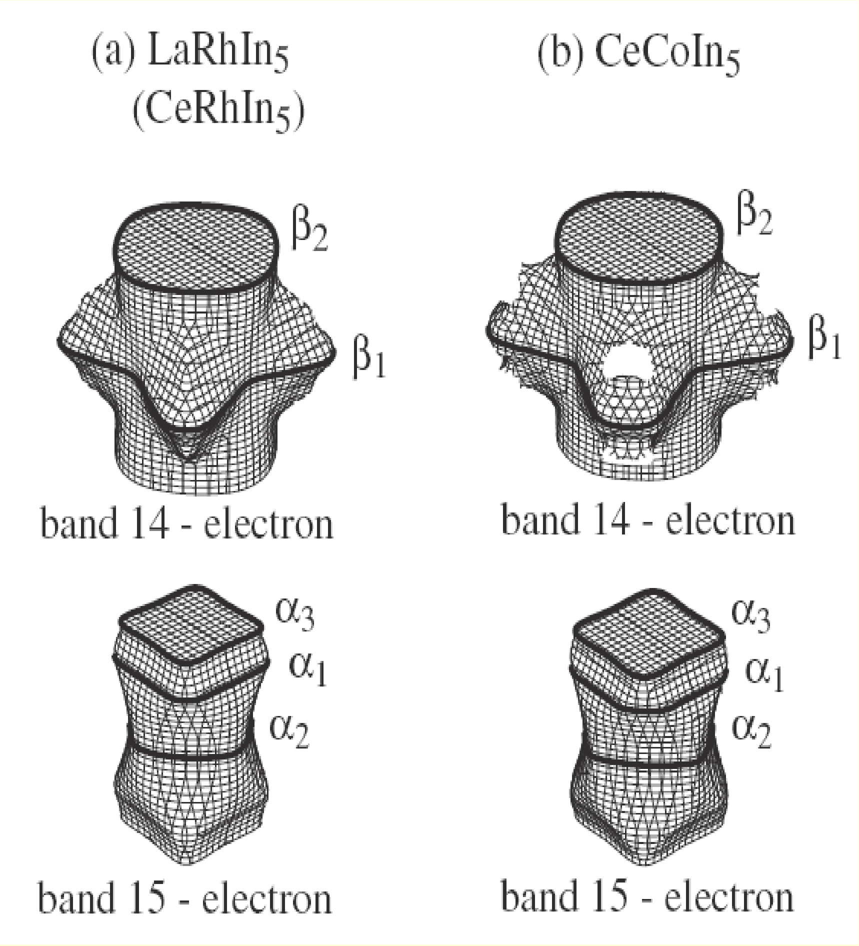


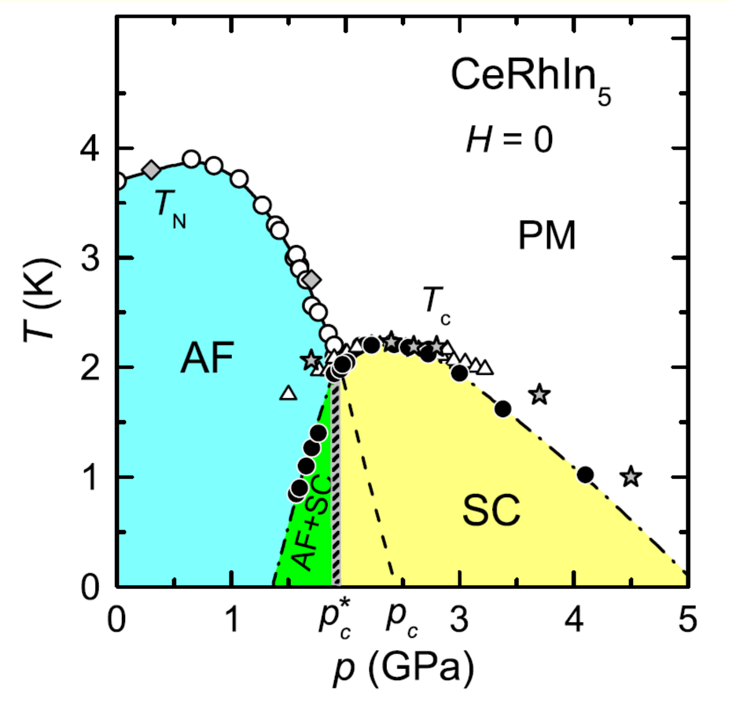


mblab.ucsd.edu

T. Tayama *et al.*, J. Phys. Soc. Jpn. **72**, 1516 (2003)

Small to Large Fermi surface transition

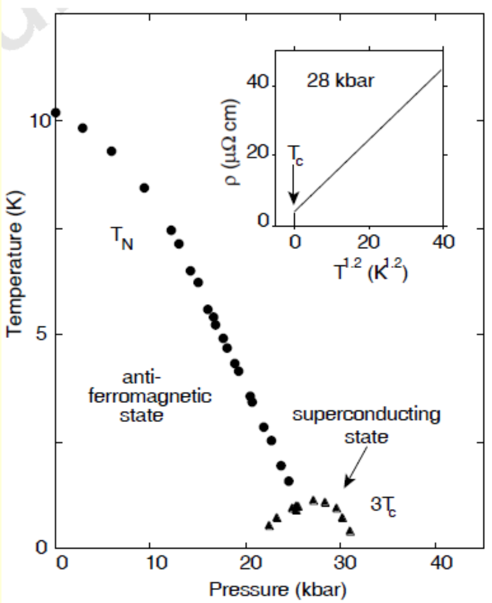


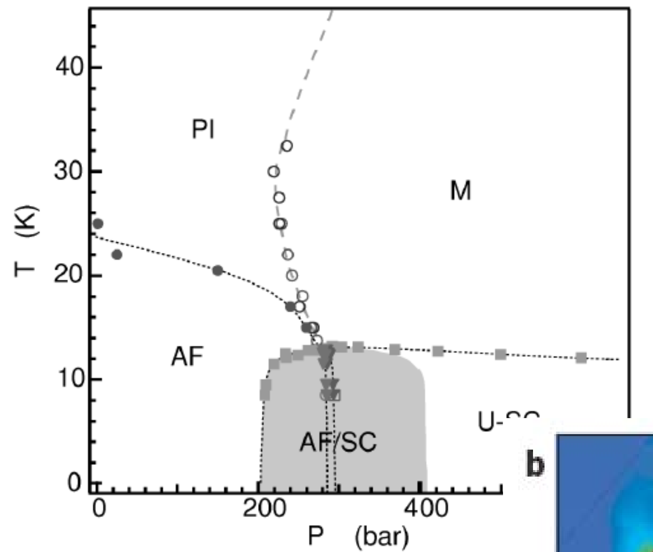


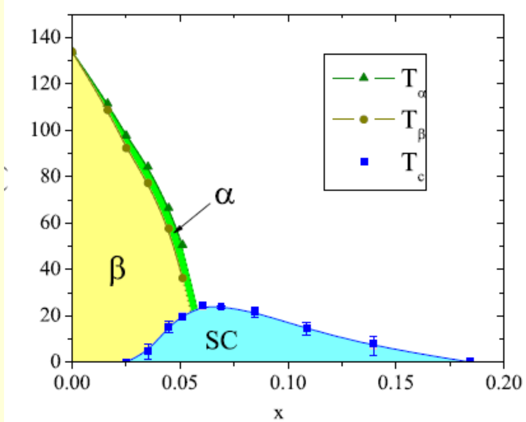
Knebel, JPSJ 2008

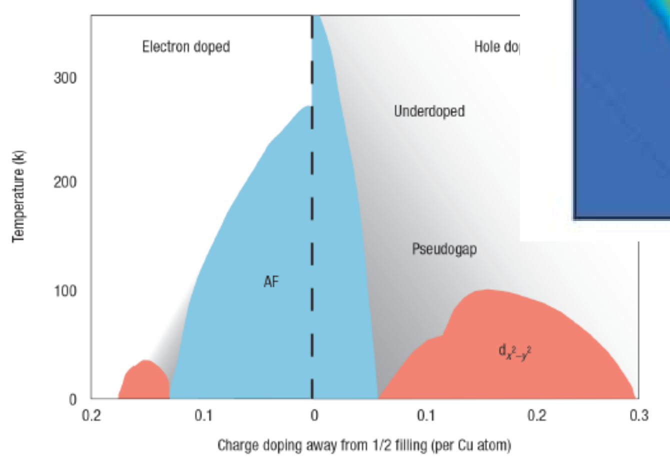
Harima et al., JPSJ 74 (2005) 1103.

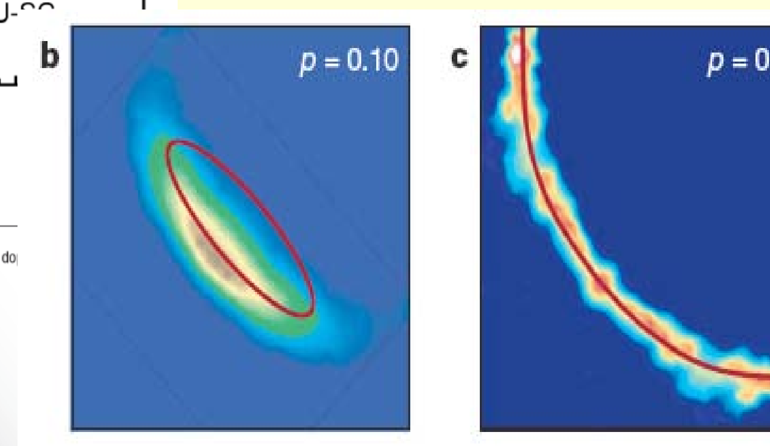
Is high temperature superconductivity the response of a metal when it doesn't know what it's Fermi surface should be?











Taillefer, 2010

Conclusions

- Quantum phase transitions offer a natural place to look for new quantum states of matter
- Exotic superconductivity is not rare, but it is usually fragile
- Quantum magnetism has emerged as a field of central importance
- Fermi surface instabilities may be the key to finding new high temperature superconductors