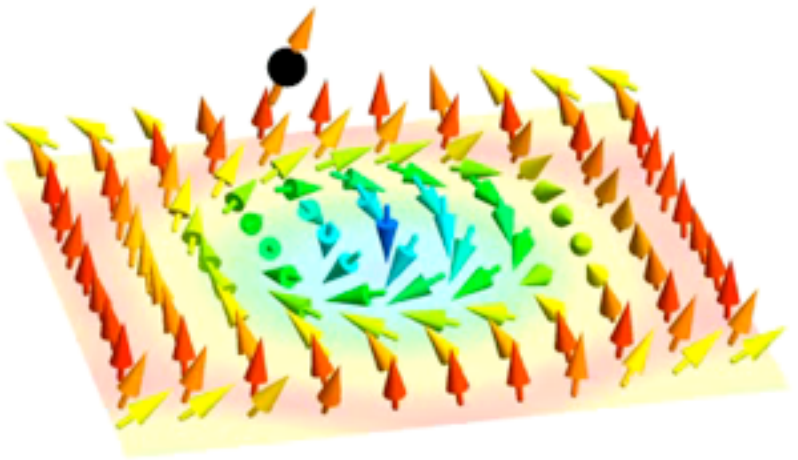
Emergence and Non-Equilibrium in Strongly Correlated Electron Systems



Christian Pfleiderer

Physik-Department
Technische Universität München

erc TOPFIT bmb+f DFG

Instructions

- Main scientific goals of our research area
- Key challenges 20 years ago
    - ➢ What progress has been made?
    - ➢ What challenges have been overcome?
- Key challenges 20 years from now
    - ➢ What methods will be used?
    - ➢ What problems will have been solved?
    - ➢ What will the field look like?

Main Scientific Goals of our Research Area

P.W. Anderson

More Is Different

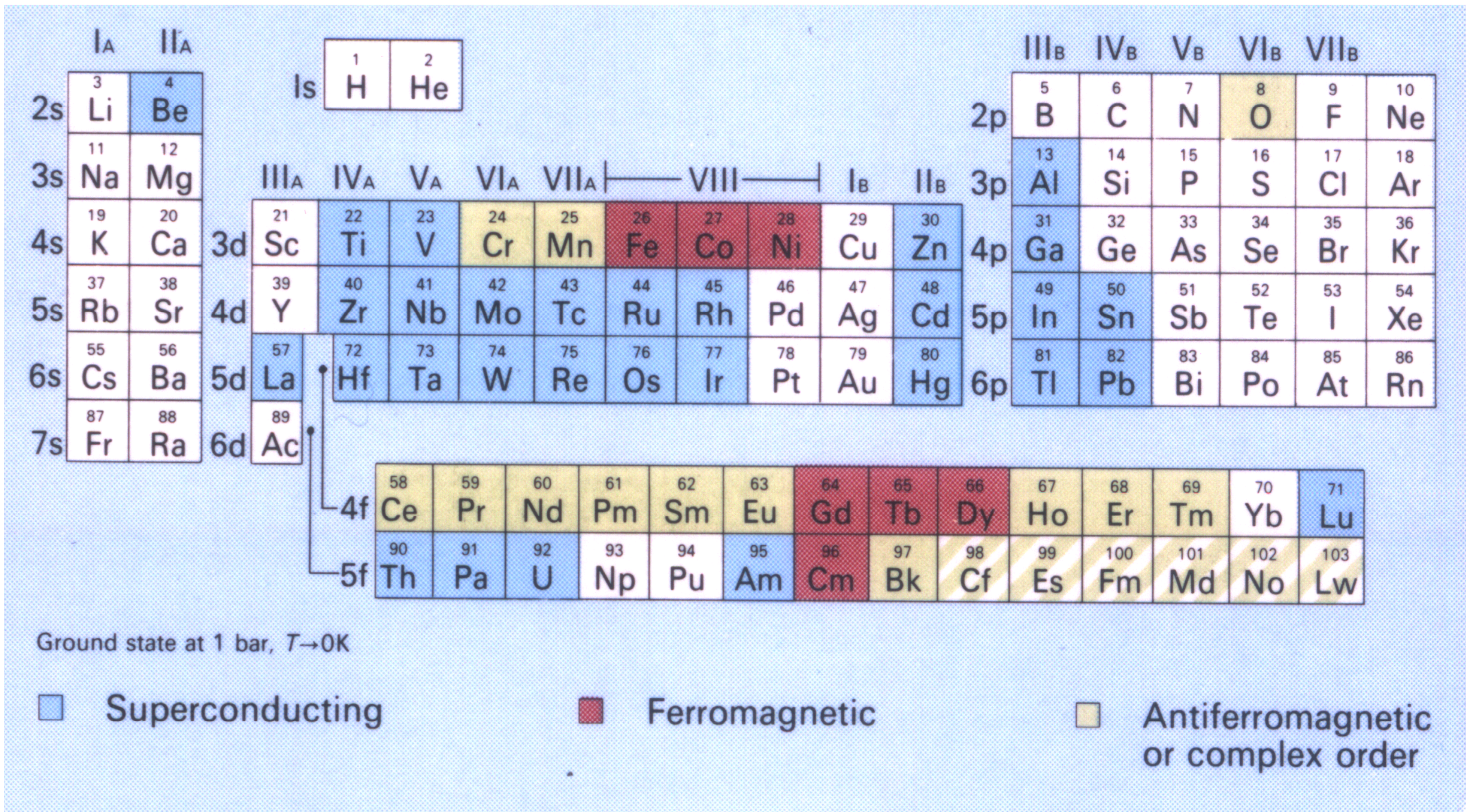
Broken symmetry and the nature of the hierarchical structure of science.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

Science **177**, 393 (1972)

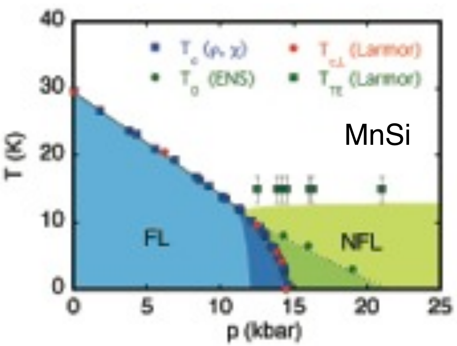
Do we know all the basic forms of order?

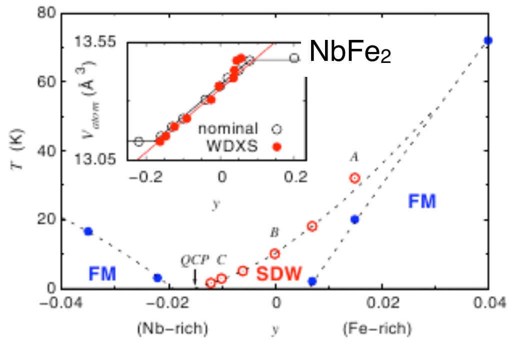
(in simple condensed matter systems)

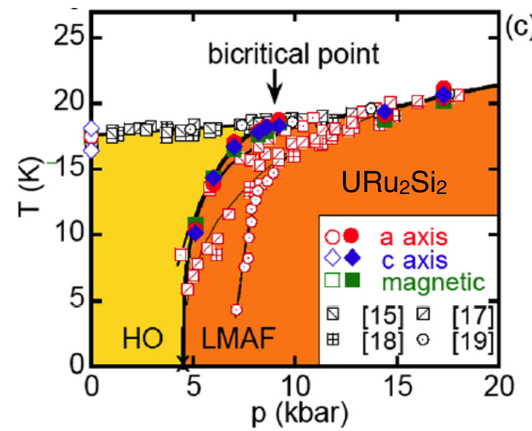


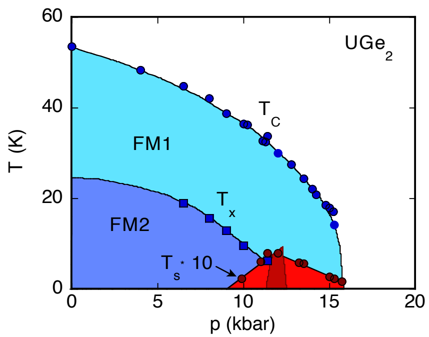
Exploratory Search for New Materials Properties

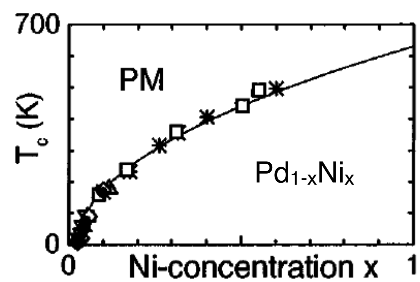
(in metallic d- and f-electron systems)

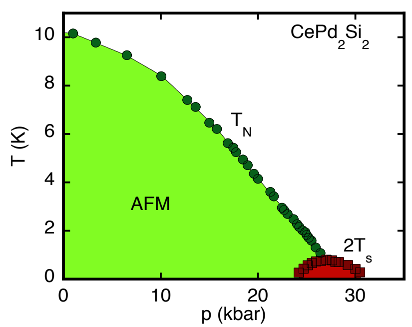


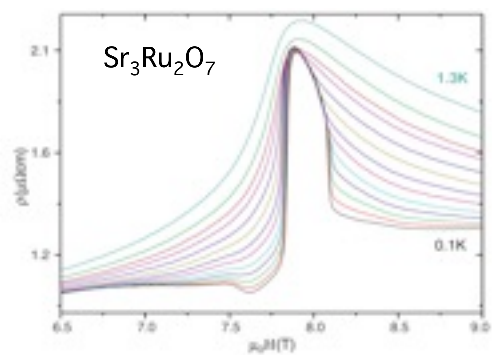


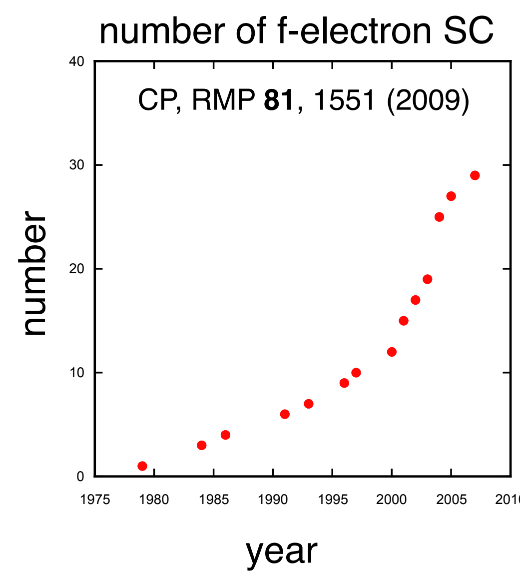






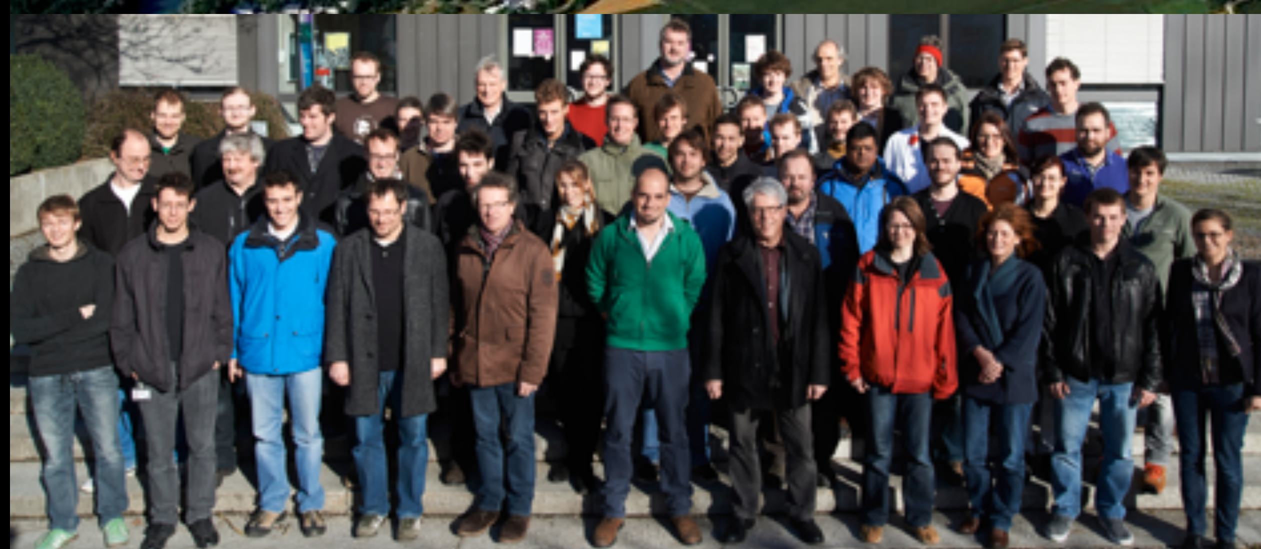







Nürnberg
A9
A92
Airport
11
388
Stuttgart
Garching
A8
471
A99
Passau
A94
2
Lindau
A96
304
München
(Munich)
A95
11
A8
Salzburg





Key challenges 20 years ago

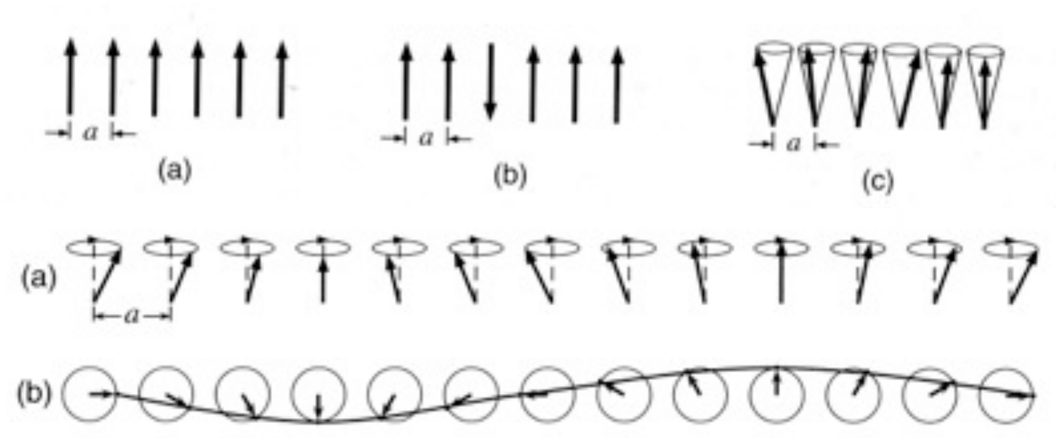
- ➢ What progress has been made?
- ➢ What challenges have been overcome?

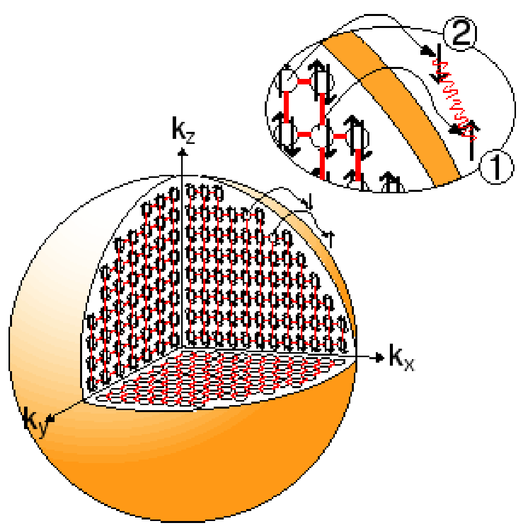
Elementary Excitations

(1) the low lying excitations **determine the physical properties**
(the absolute value of the ground state energy is not important)

(2) the low lying excitations (in most cases) can be viewed as
non-interacting particles
(this corresponds to linearizing the response functions)

Landau, J. Phys. USSR **5**, 71 (1941) Lee & Pines, Phys. Rev. **88**, 960 (1952) cf Anderson in Concepts in Solids

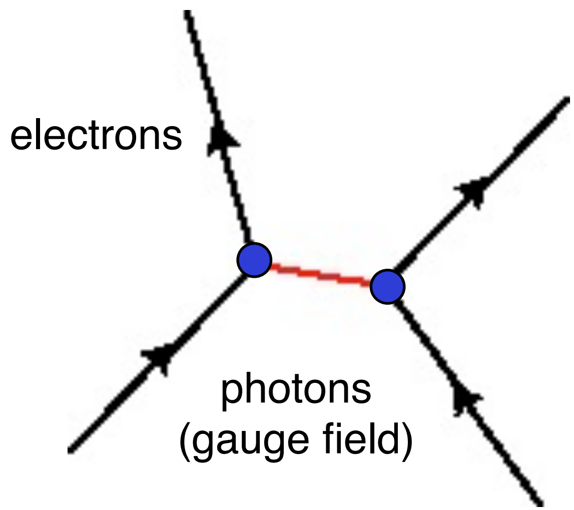




collective single-particle

On the Nature of Elementary Excitations in Many-Body Systems

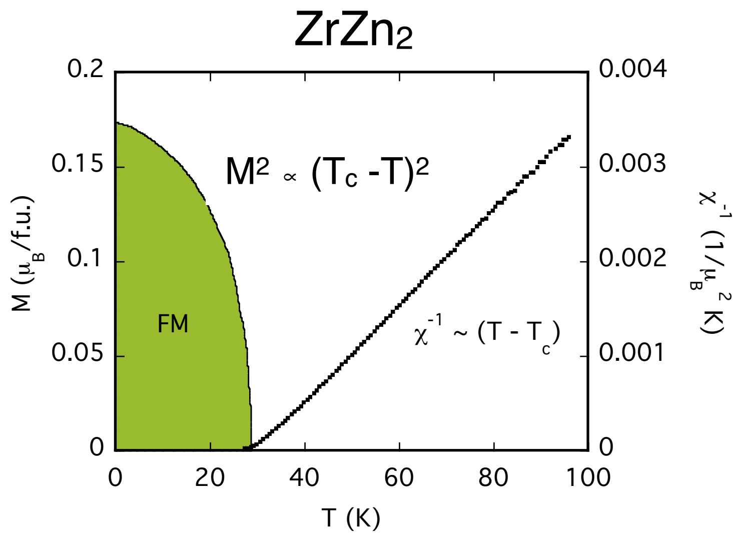
consider QED

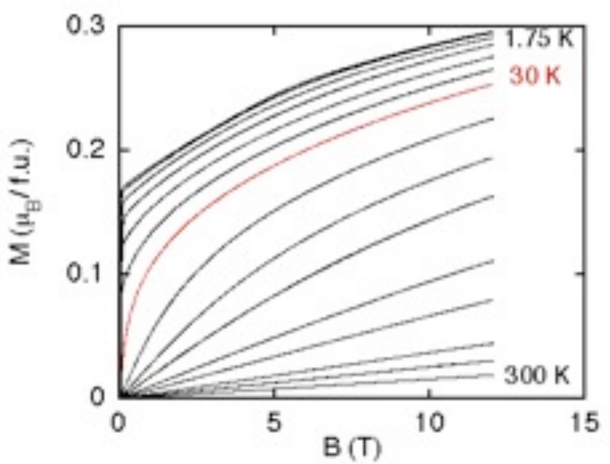


integrate out photons:
„see“ electrons with
retarded interaction

integrate out electrons:
„see“ interacting photons
(gauge fields)

Nature of „Weak" Magnetism in Metals





material	T_c (K) Expt.	T_c (K) Stoner
MnSi	28	50-150
Ni_3Al	41	150-300
$ZrZn_2$	29	300-500
Ni	627	-
Fe	1043	-

challenge:

- large Curie-Weiss moment
- small ordered moment
- T-dependence of M
- unsaturated M

Self-Consistent Ginzburg-Landau Theory

(includes stochastic order parameter fluctuations)

based on four parameters
(material specific)

$$B = \frac{\partial F(M)}{V \partial M} = AM + bM^3 + \ldots$$

↑ mode-coupling

$$A = a + b[3\langle m_{\parallel}^2 \rangle + 2\langle m_{\perp}^2 \rangle]$$

↑ initial susceptibility

$$\Gamma(\mathbf{q}) = \gamma q \, (\chi^{-1} + cq^2)$$

↑ damping ↑ spin wave stiffness

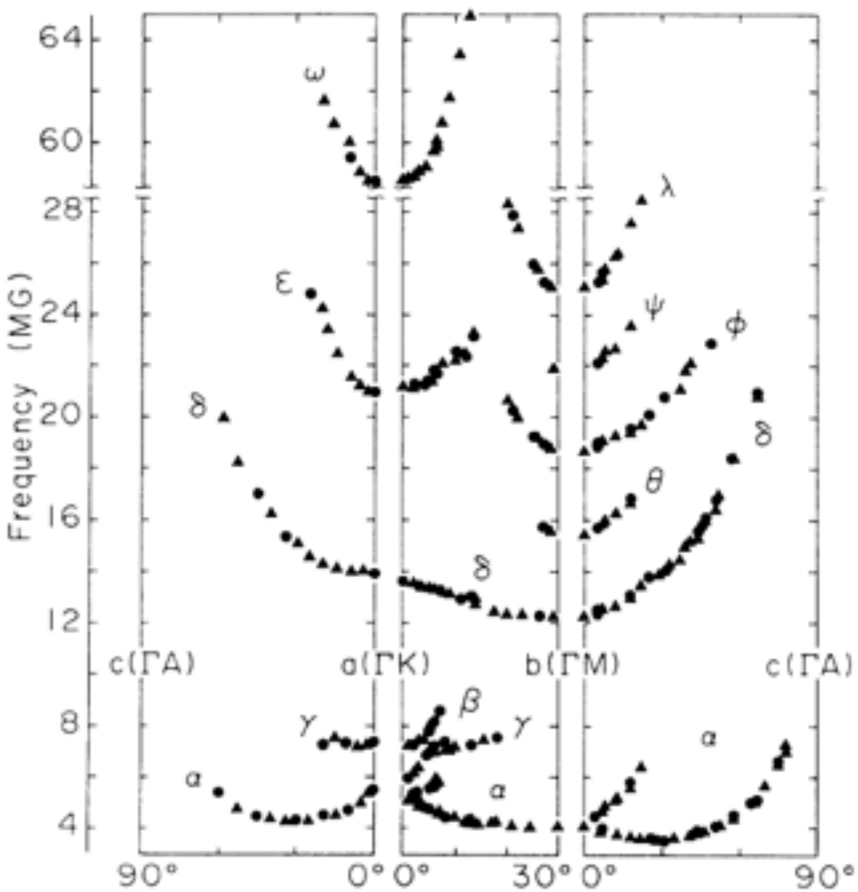
material	T_C (K) Expt.	T_C (K) Stoner	T_C (K) Spin Fluct.
MnSi	28	50-150	29
Ni_3Al	41	150-300	40
$ZrZn_2$	29	300-500	31
Ni	627	-	560-680
Fe	1043	-	920-1100

accounts for:

- large Curie-Weiss moment
- small ordered moment
- T-dependence of M
- unsaturated M

PhD thesis G.J. McMullan

Electronic Structure & Correlations Effects
in the heavy fermion superconductor UPt_3



Branch:*FS* orbit	*F* (MG) Expt.	*F* (MG) Calc.	m^*/m_e Expt.	m^*/m_e Calc.
	a axis (ΓK)			
α:*ML*4	5.4(3)	10.4	25(3)	2.2
β:*L*4	6.0(4)	5.2	···	1.0
γ:Γ1	7.3(3)	8.2	40(7)	2.0
δ:*A*5	14.0(3)	9.1	50(8)	1.9
ϵ:Γ2	21.0(3)	24.0	60(8)	4.6
ω:Γ3	58.5(5)	52.8	90(15)	5.3
	b axis (Γ*M*)			
α:*ML*4	4.1(2)		15(5)	
δ:*A*5	12.3(2)		30(3)	
θ:*A*4,5	15.5(2)		35(7)	
ϕ:*A*4,5	18.7(3)		40(8)	
ψ:*A*4,5	21.9(4)		···	
λ:*A*4	25.1(5)		(50)	

Nature of mass enhancement?

Taileffer & Lonzarich, PRL **60**, 1570 (1988)

Fermion-Quasiparticles in Real Materials

material	type of system	nature of dressing cloud	mass enhancement
MnSi	weak itinerant FM	magnetic polarons of conduction electrons	all with similar mass
Pr	paramagnet localised f-electrons	conduction electron induces polarisation of f-electrons	all with similar mass
UPt_3	heavy-fermion SC	magnetic polarons; stronger spatial localisation; strong spin and orbital character	wide range of masses
$CeRu_2Si_2$	heavy fermion PM	magnetic polarons; stronger spatial localisation; strong spin and orbital character	light & heavy masses
$CeAl_2$	heavy fermion PM	conduction electron induces polarisation of f-electrons	wide range of masses

Lonzarich, J. Mag. Mag. Mat. **76**, 1 (1988)

tune QP interactions with pressure, field, ...

What is a Quantum Phase Transition?

equivalent definitions:

(-) Phase transition driven by **quantum fluctuations**.

(-) Phase transition at **zero temperature**.

(-) Phase transition between **quantum phases**.

(-) Phase transition characterized by change of **quantum entanglement**.

$d \to d_{\text{eff}} = d + z$

many systems:

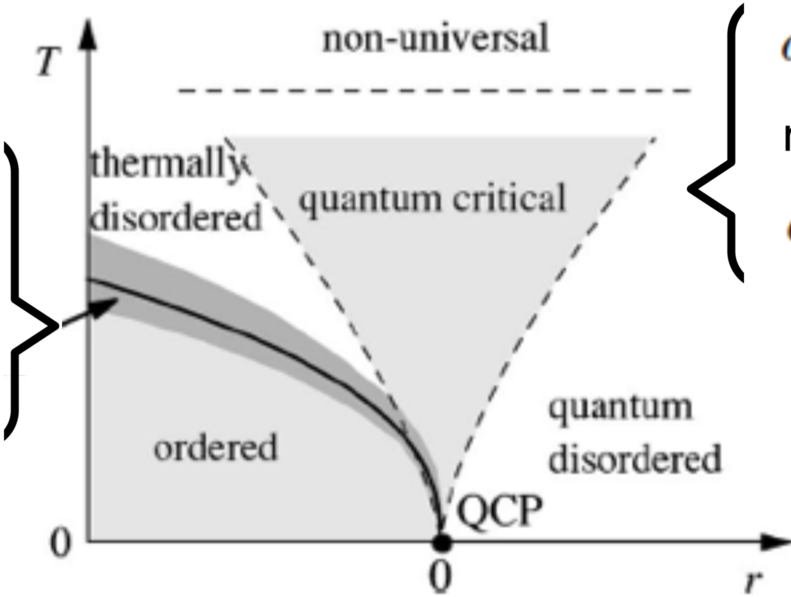
$d_{\text{eff}} \geq 4$

entropy driven

for $T \to T_c$

$\hbar\Gamma_q \ll k_B T$

classical fluct.



change of U

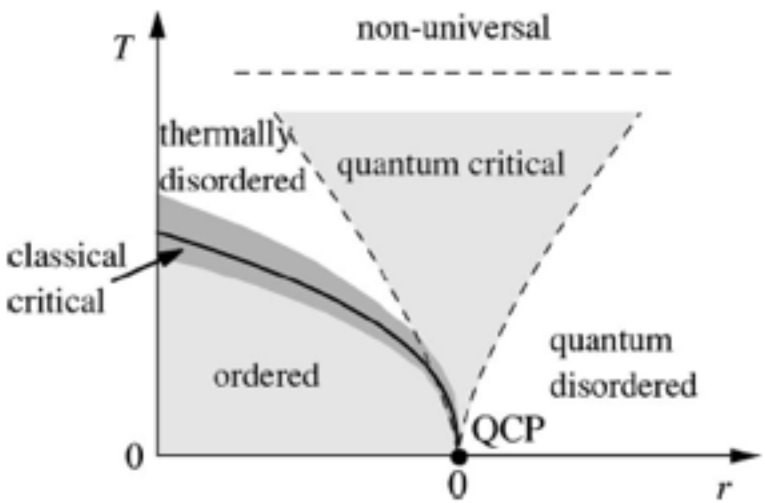
for $T_c \to 0$

$\hbar\Gamma_q \gg k_B T$

quantum fluctuations

system in quantum-mechanical ground state

Hertz-Millis Analysis of Quantum Criticality



some predictions

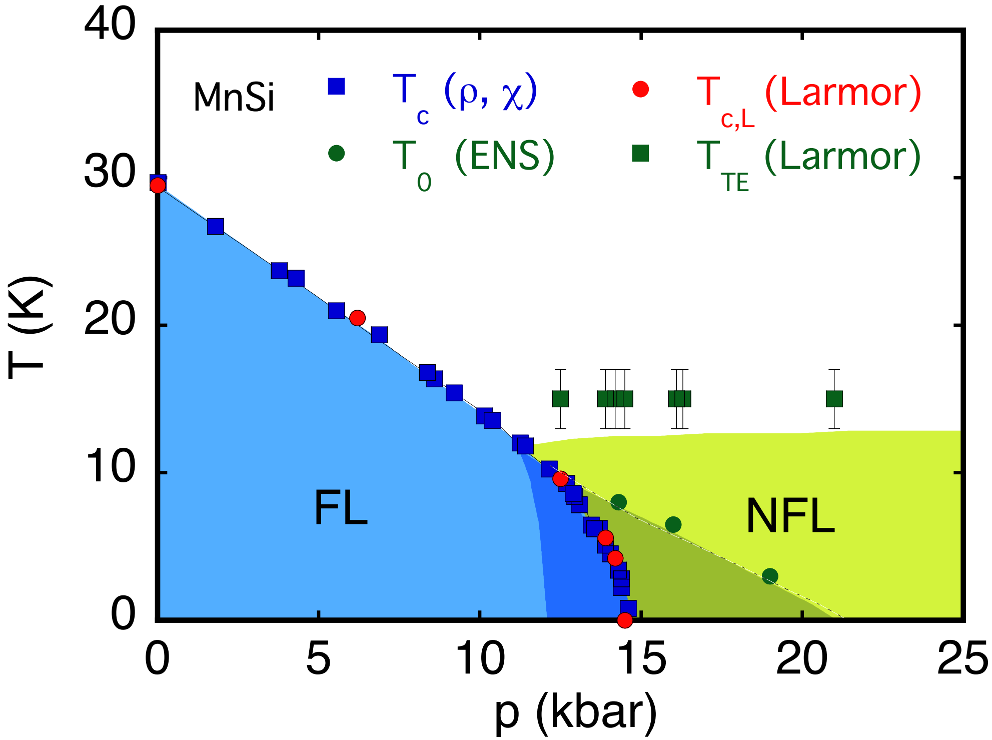
	$d=2$ $z=2$	$d=3$ $z=2$	$d=2$ $z=3$	$d=3$ $z=3$
$\alpha_{cr}\sim$	$\ln\ln\frac{1}{T}$	$T^{1/2}$	$\ln\frac{1}{T}$	$T^{1/3}$
$C_{cr}\sim$	$T\ln\frac{1}{T}$	$-T^{3/2}$	$T^{2/3}$	$T\ln\frac{1}{T}$
$\Gamma_{r,cr}\sim$	$\dfrac{\ln\ln\frac{1}{T}}{T\ln\frac{1}{T}}$	$-T^{-1}$	$T^{-2/3}\ln\frac{1}{T}$	$\left(T^{2/3}\ln\frac{1}{T}\right)^{-1}$

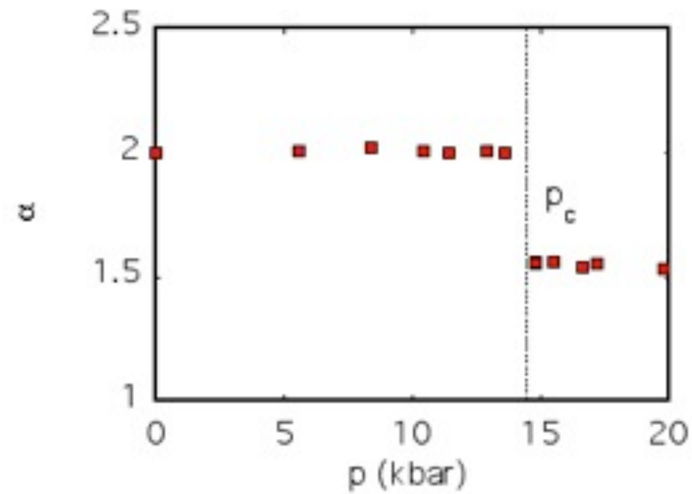
imply ill-defined (singular)
Fermi quasiparticles

Hertz, PRB **14**, 1165 (1976)
Millis, PRB **48**, 7183 (1993)

von Löhneysen, et al. RMP **79**, 1015 (2007)

NFL-Resistivity without Quantum Criticality

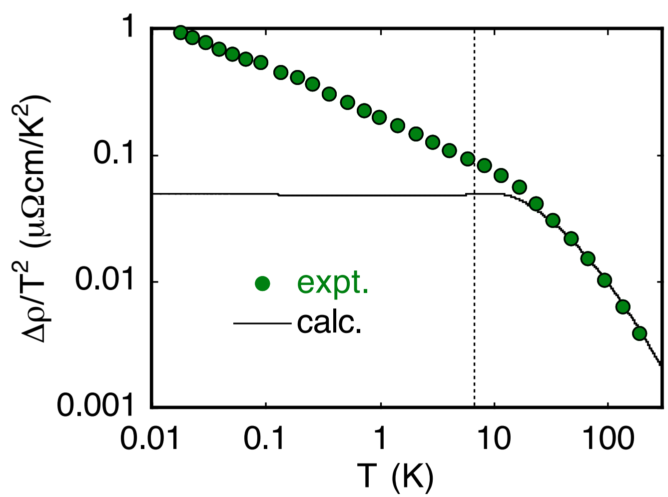




$$\rho(T) = \rho_0 + AT^\alpha + \ldots$$

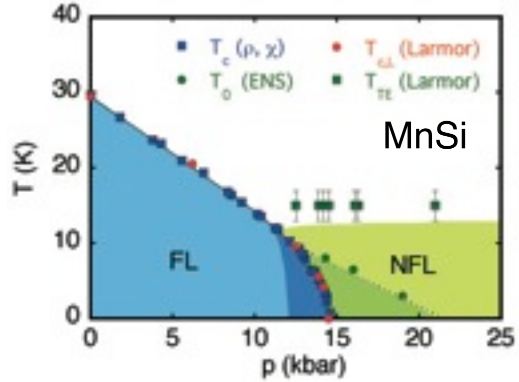
↑

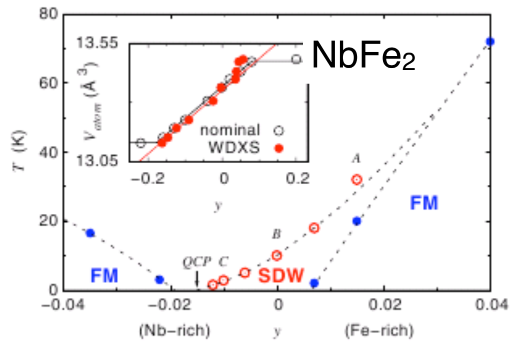
singular für T→0

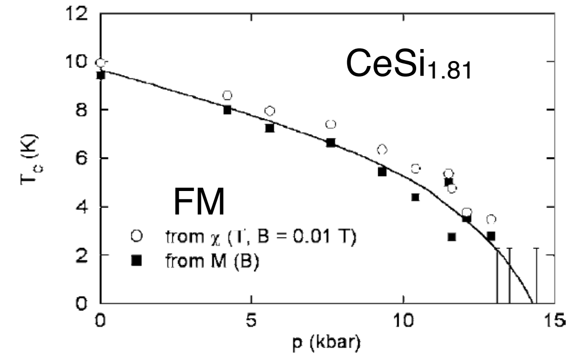


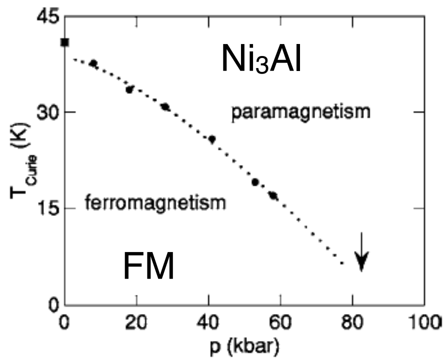
CP et al. Physica B **199-200**, 634 (1994)
CP et al. PRB **55**, 8330 (1997)
Thessieu et al., JPCM **9**, 6677 (1997)
CP et al. Nature **414**, 427 (2001)
CP et al. Nature **427**, 227 (2004)
CP et al., PRL **99**, 156406 (2007)
CP et al. Science **318**, 1871 (2007)
Uemura et al. Nature Physics **3**, 34 (2007)

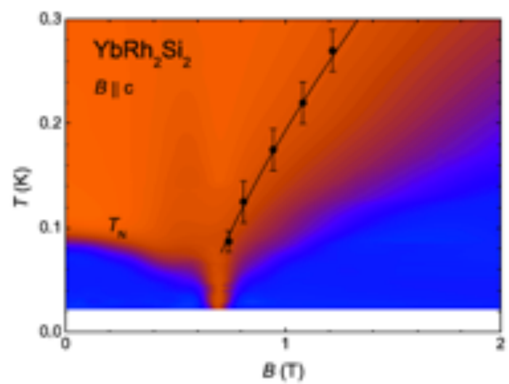
more Non-Fermi Liquid Puzzles

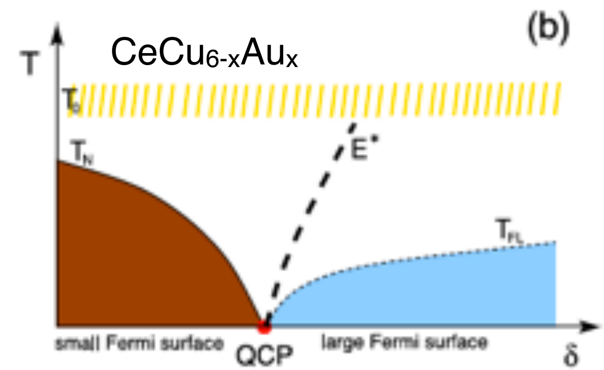


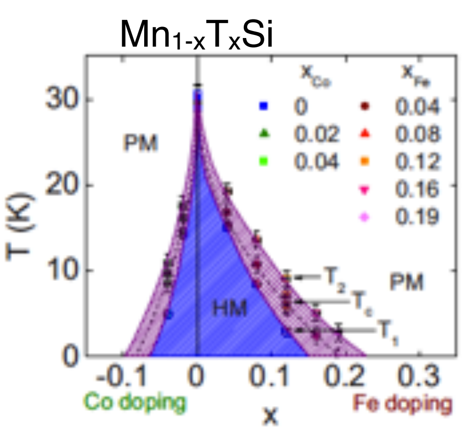


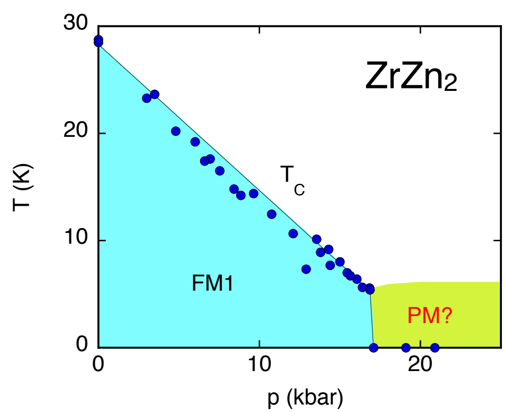


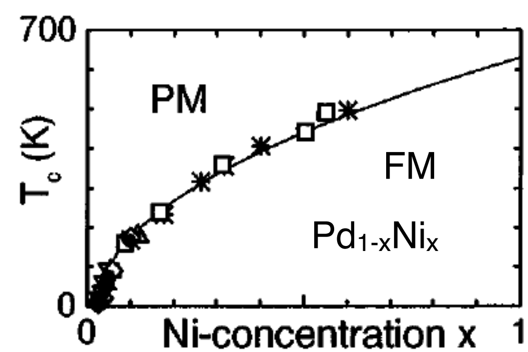




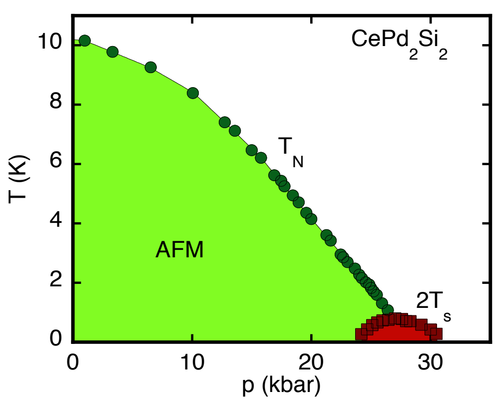


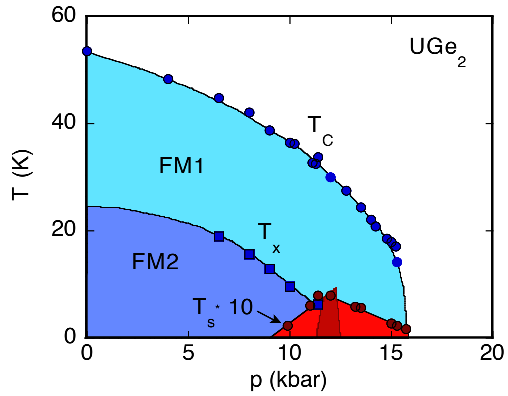


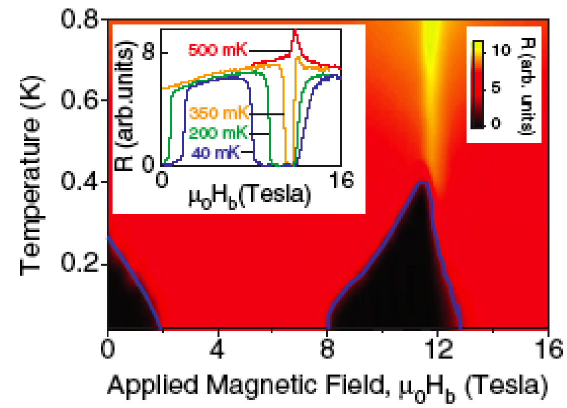


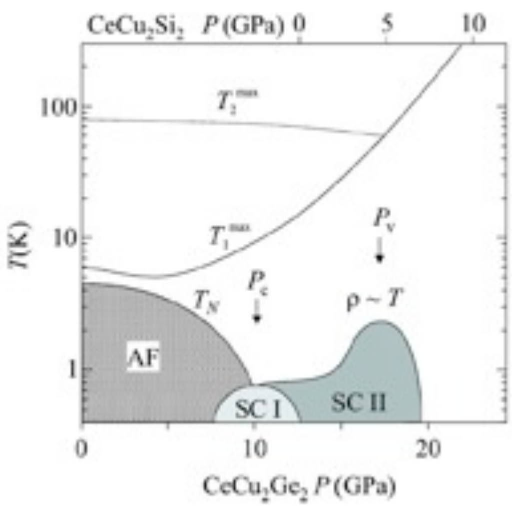


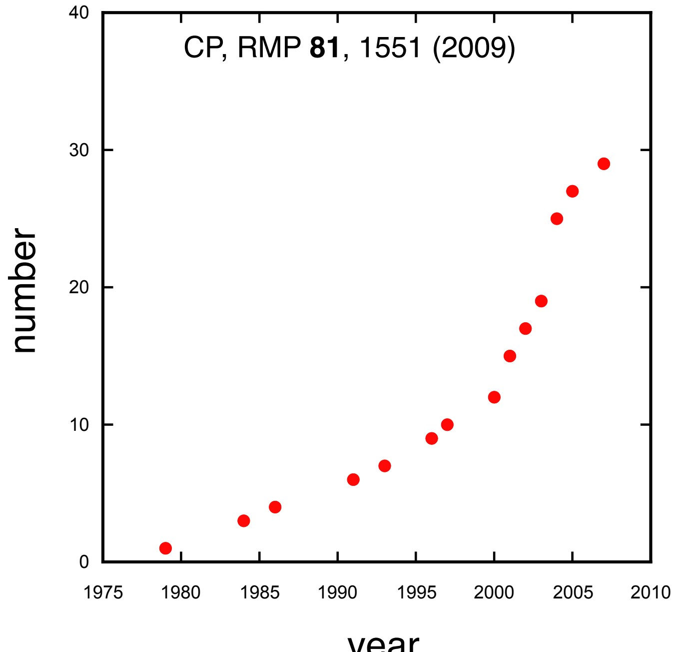
More Superconducting Phases in f-Electron Systems



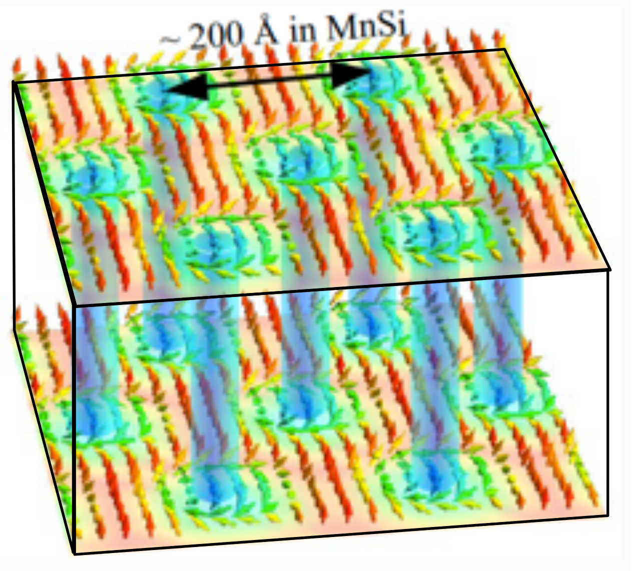




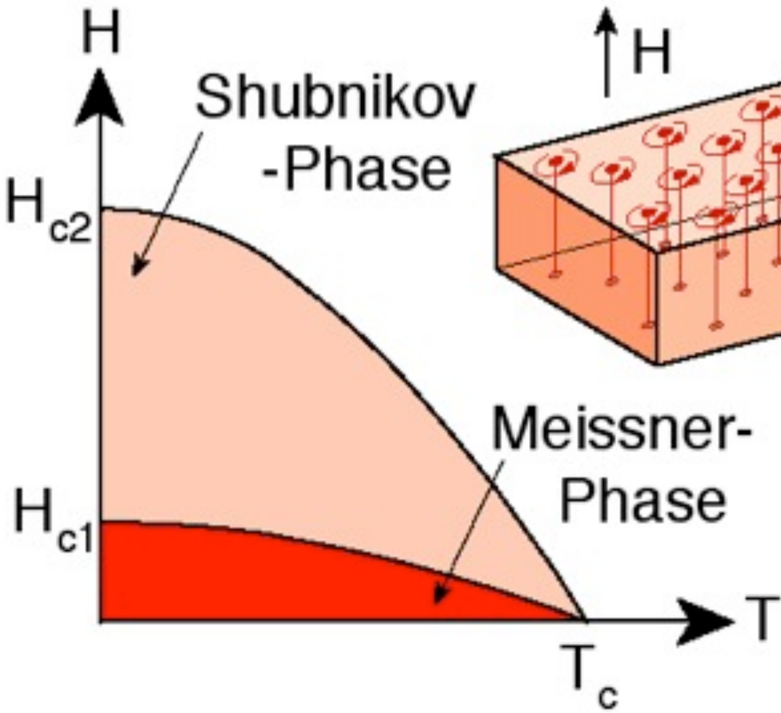




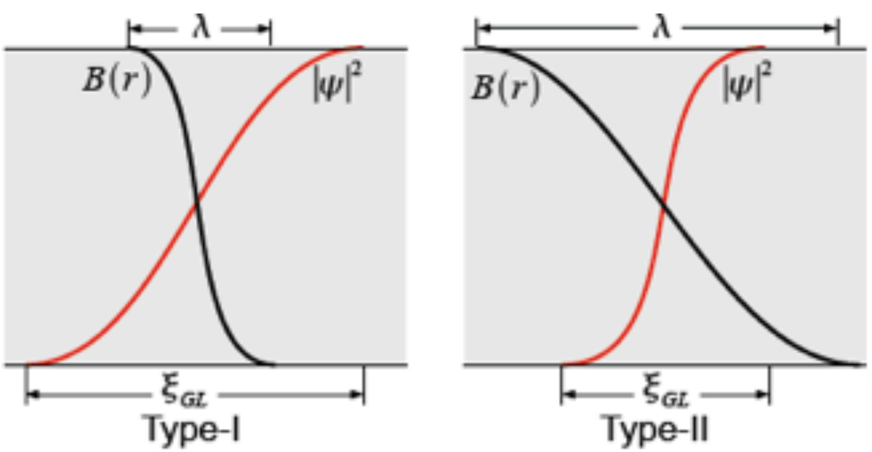
Beyond subtle details:
a ‚new‘ form of magnetic order



Type 2 Superconductivity Revisited



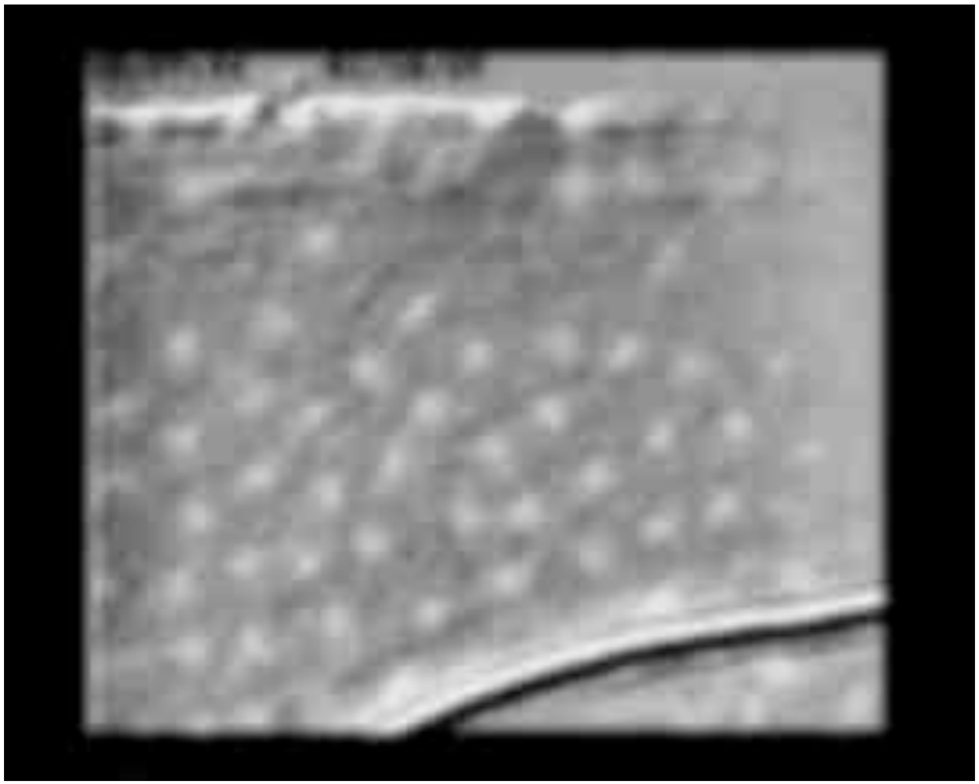
A. Abrikosov



superconducting rigidity
vs field penetration depth

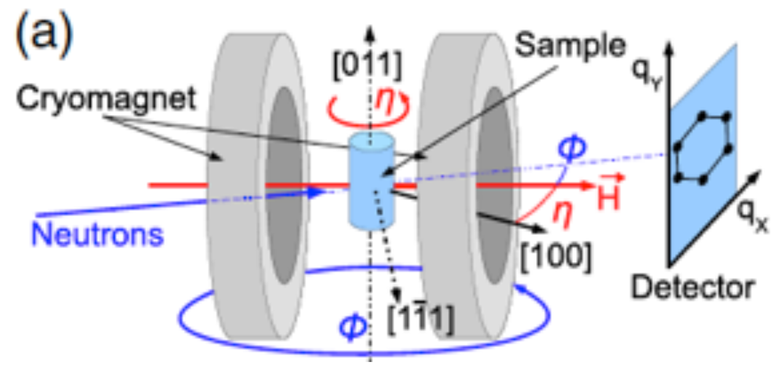
Fluxlines in Type 2 Superconductors

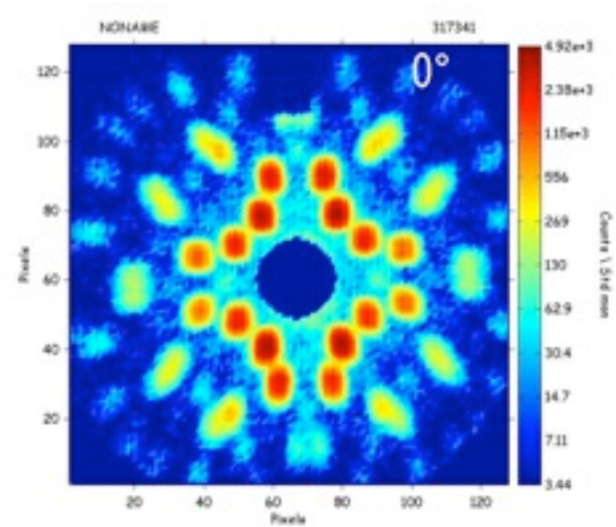
Magneto-Optical Imaging in $NbSe_2$



http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/sv/index.html

Neutron Scattering in Nb





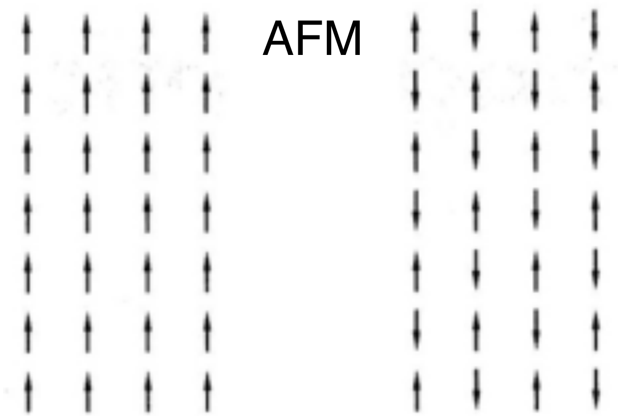
Mühlbauer et al., PRL **102** 136408 (2009)

Is there „Type 2" Magnetic Order?

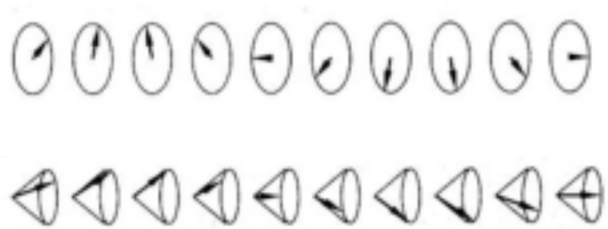
Text Book Forms of Magnetic Order

FM

AFM

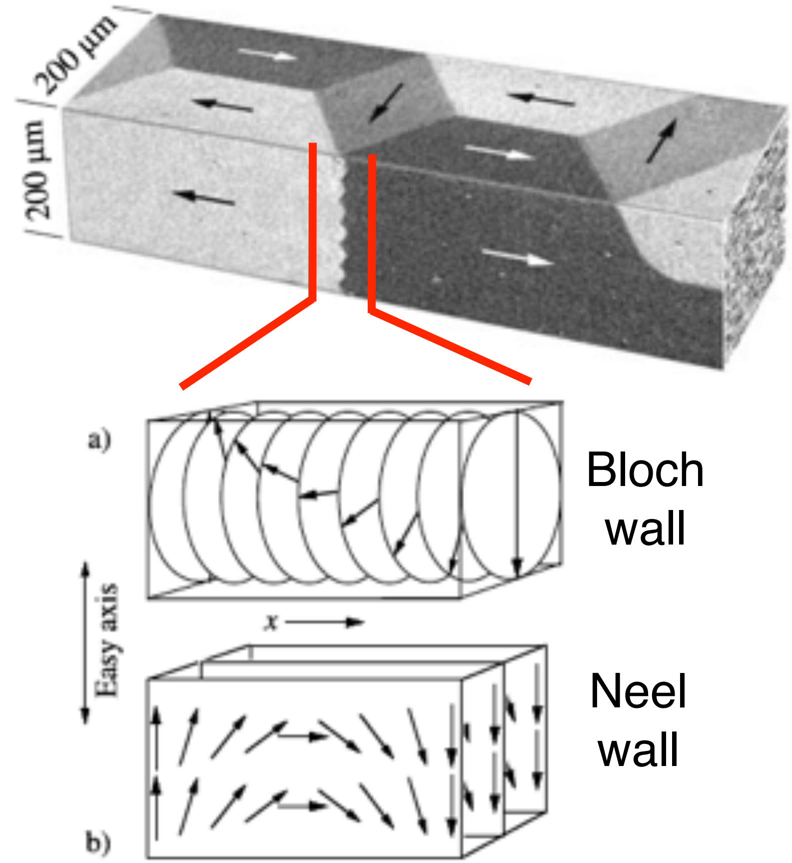


spin spirals



„twisting" versus exchange

Text Book Forms of Domains



Bloch wall

Neel wall

anisotropy versus exchange

from Huber & Schäfer, Springer

Bogdanov, Yablonskii, JETP **68** 101 (1989)

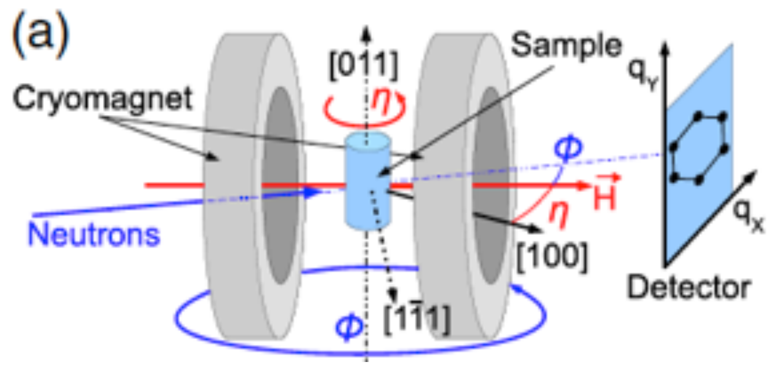
Skyrmion Lattice in Chiral Magnets

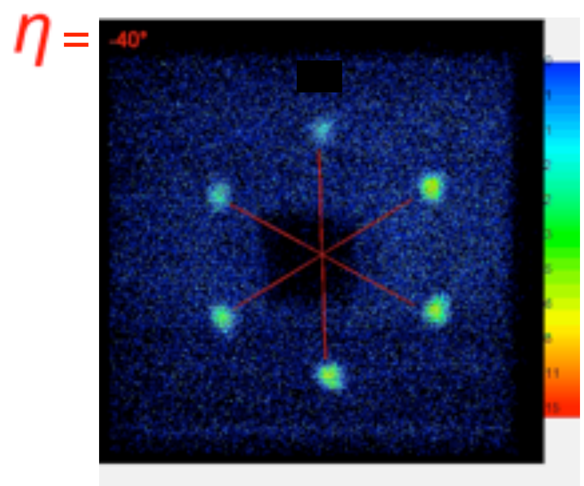
TEM Imaging in FeGe

TEM data by Xiuzhen Yu (RIKEN)

Yu et al., Nature Materials **10**, 106 (2010)

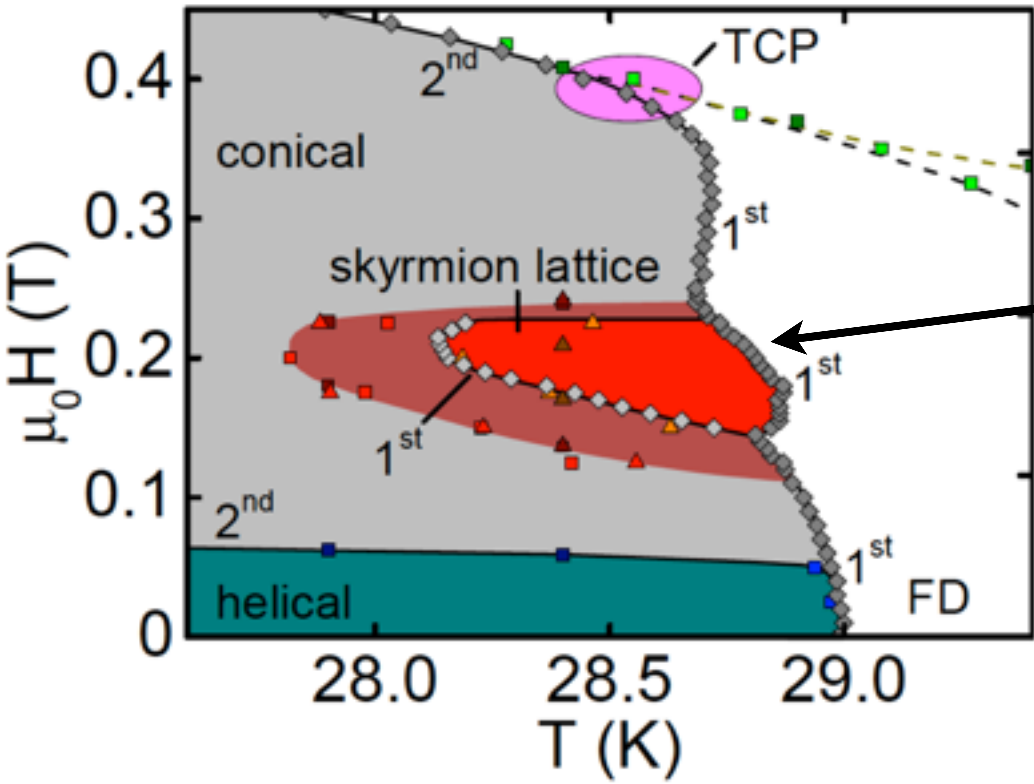
Neutron Scattering in MnSi



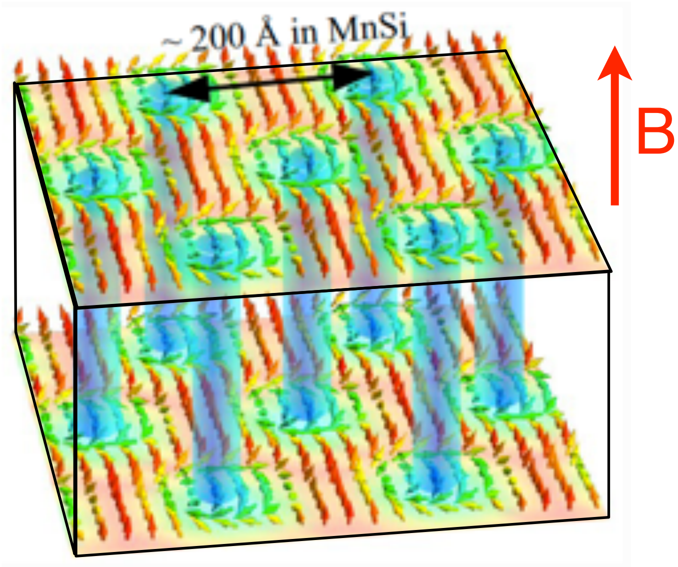


Mühlbauer, et al. Science **323**, 915 (2009)

Magnetic Phase Diagram of MnSi



Bauer, Garst, CP, PRL **110**, 177207 (2013)



Mühlbauer et al, Science **323**, 915 (2009)

$$\phi = \frac{1}{4\pi}\vec{n}\cdot\frac{\partial\vec{n}}{\partial x}\times\frac{\partial\vec{n}}{\partial y}$$

winding number per unit cell:

$$\Phi = -1$$

lattice of topological knots

stabilized by thermal fluctuations

➡ skyrmions ⬅

Adams et al., PRL **107**, 217206 (2011)

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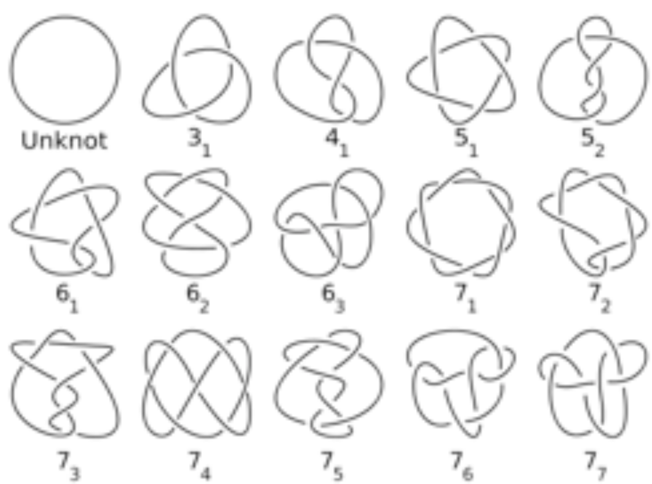
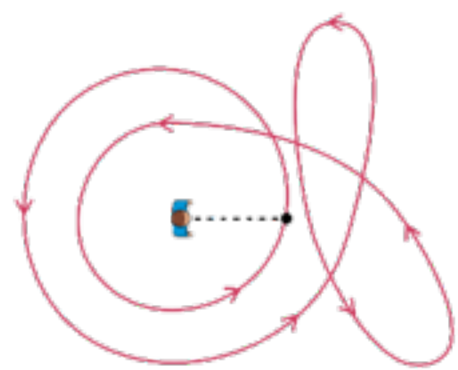
Main Entry: **to·pol·o·gy**
Pronunciation: \tə-ˈpä-lə-jē, tä-\

2 a (1) : a branch of mathematics concerned with those properties of geometric configurations (as point sets) which are unaltered by elastic deformations (as a stretching or a twisting) that are homeomorphisms (2) : the set of all open subsets of a topological space **b** : CONFIGURATION <topology of a molecule> <topology of a magnetic field>
— **to·pol·o·gist** \-jist\ *noun*

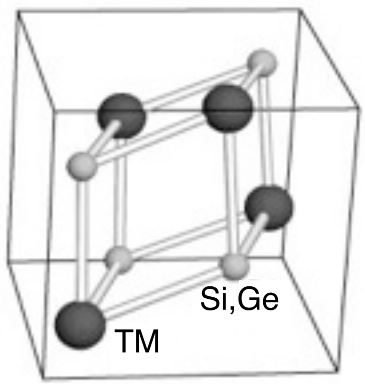




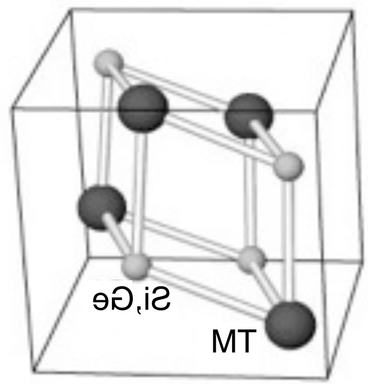
winding number: +2

Hierarchical Energy Scales in B20 compounds

Landau-Lifshitz vol. 8, §52



B20: no inversion center



B20: no inversion center

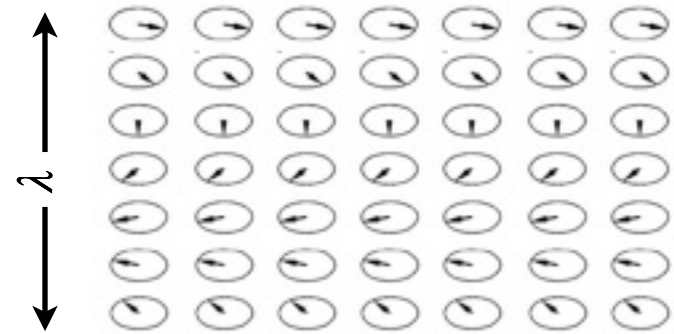
left-handed

right-handed

(1) ferromagnetism

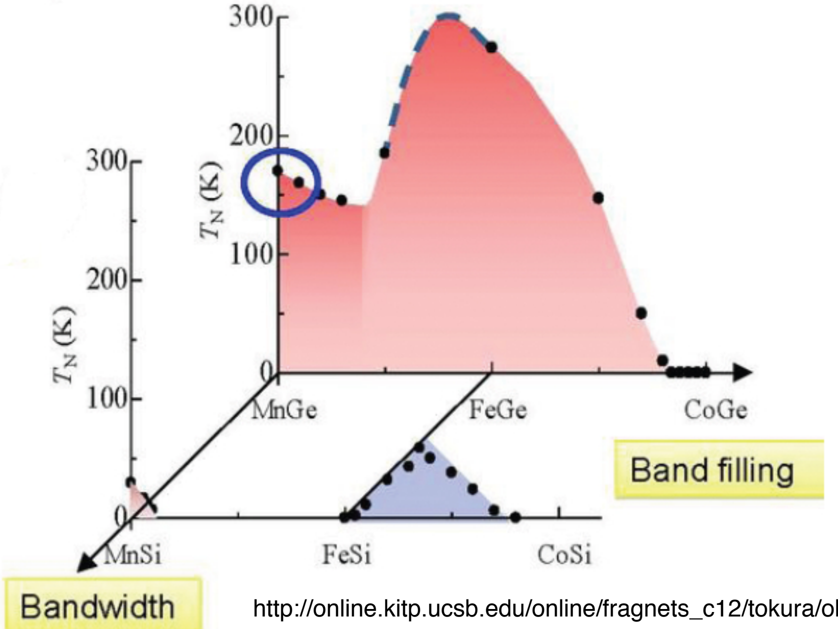
(2) Dzyaloshinsky-Moriya

(3) crystal field ($P2_13$):
locked to <111> or <100>



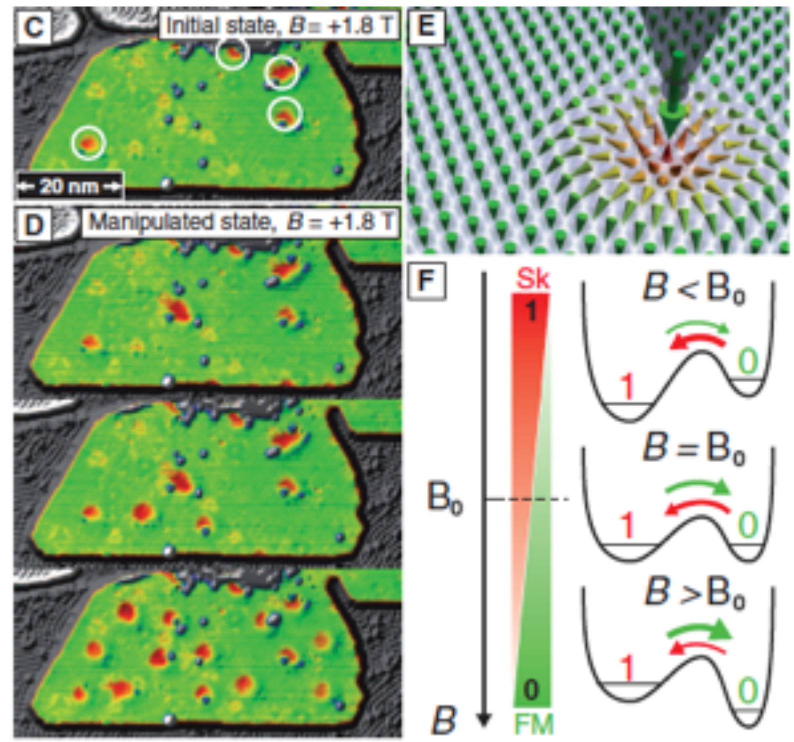
	T_N (K)	λ (Å)
MnGe	170	30 to 60
$Mn_{1-x}Fe_xSi$	< 28	180 to 120
$Fe_{1-x}Co_xSi$	< 45	> 300
FeGe	280	700
Cu_2OSeO_3	54	620

Skyrmions in Non-Centrosymmetric Materials



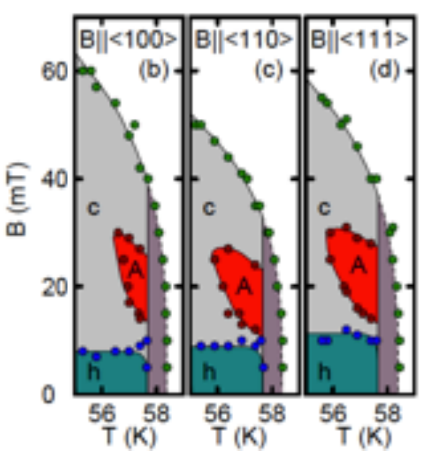
http://online.kitp.ucsb.edu/online/fragnets_c12/tokura/oh/11.html

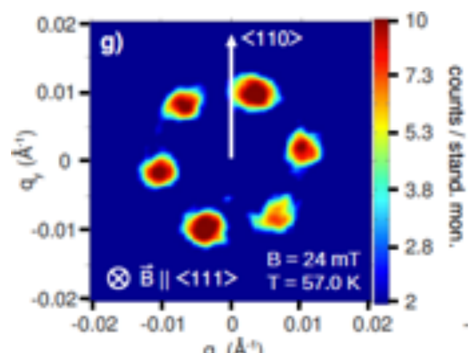
PdFe-layer on Ir (111)



(stochastic) reading & writing

P2$_1$3 insulator: Cu_2OSeO_3



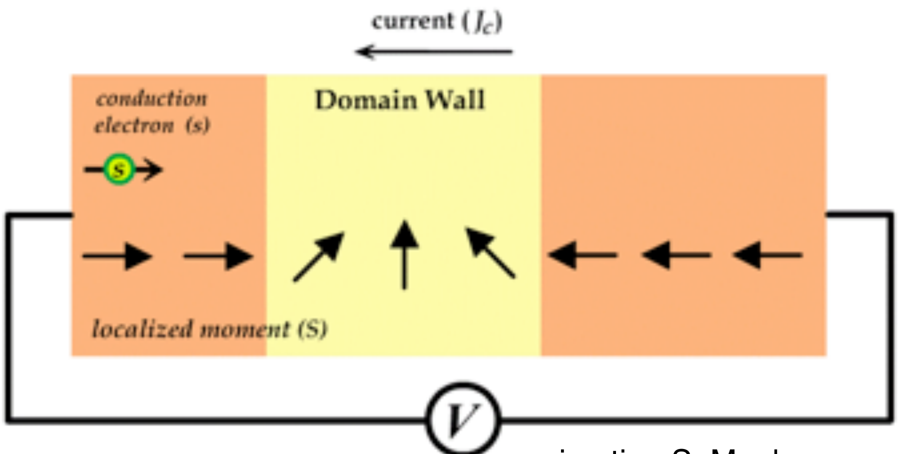


Seki al., Science **336** 198 (2012)
Adams et al., PRL, **108** 237204 (2012)

Romming et al. Science **341**, 636 (2013)
CP, Physik Journal **12**, 20 (2013)

What about Spin Transfer Torques in Helimagnets?

A. Rosch, R. Duine et al. (November 2006)



animation S. Maekawa

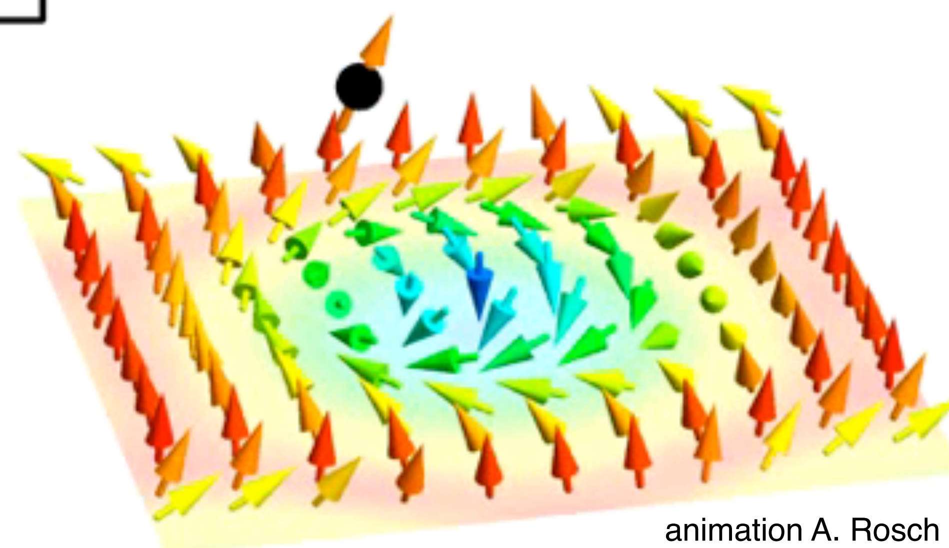
typical current density

10^{12} A/m^2

current density: 10^6 A/m^2

$$B_i^e = \frac{\hbar}{2}\epsilon_{ijk}\hat{n}\cdot(\partial_j\hat{n}\times\partial_k\hat{n})$$

$$E_i^e = \hbar\,\hat{n}\cdot(\partial_i\hat{n}\times\partial_t\hat{n})$$



animation A. Rosch

Jonietz et al., Science, **330** 1648 (2010)

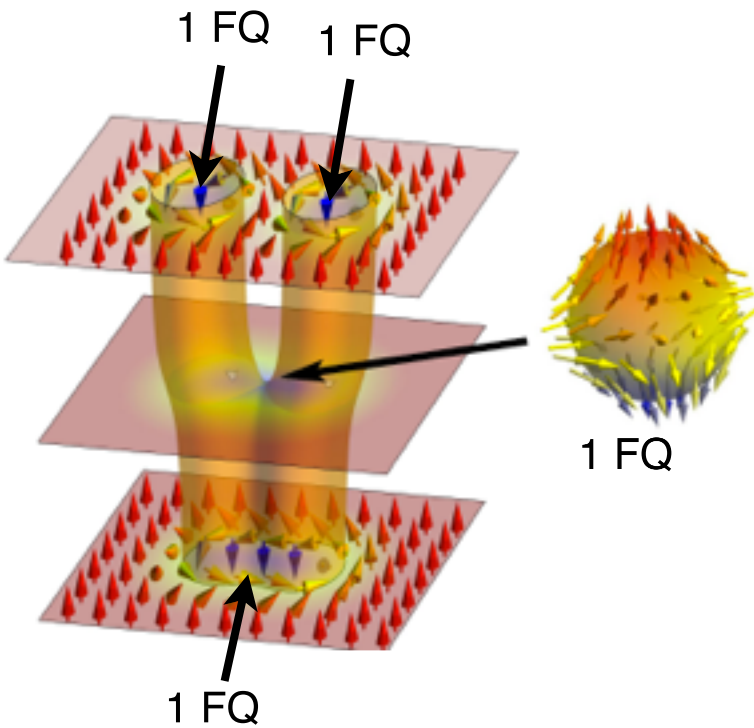
Schulz et al. Nat. Phys., **8** 301 (2012)

see also Goto, et al. condmat/0807.2907

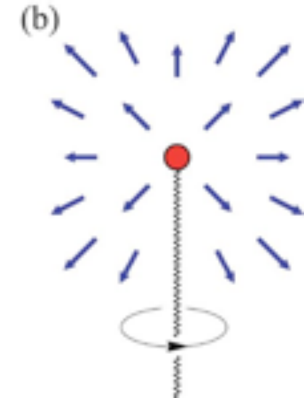
Wessely et al., PRL **96**, 256601 (2006)

both consider j ≈ 10^{12} Am^{-2}

Nature of the Topological Unwinding of Skyrmions: Emergent Magnetic Monopoles



Paul Dirac



cf. prediction of magnetic monopoles to explain **quantized** electric charge

$$\oint_{\partial\Omega} \mathrm{B}^e d\sigma = \int_{\Omega} \nabla \mathrm{B}^e d\mathrm{r}$$

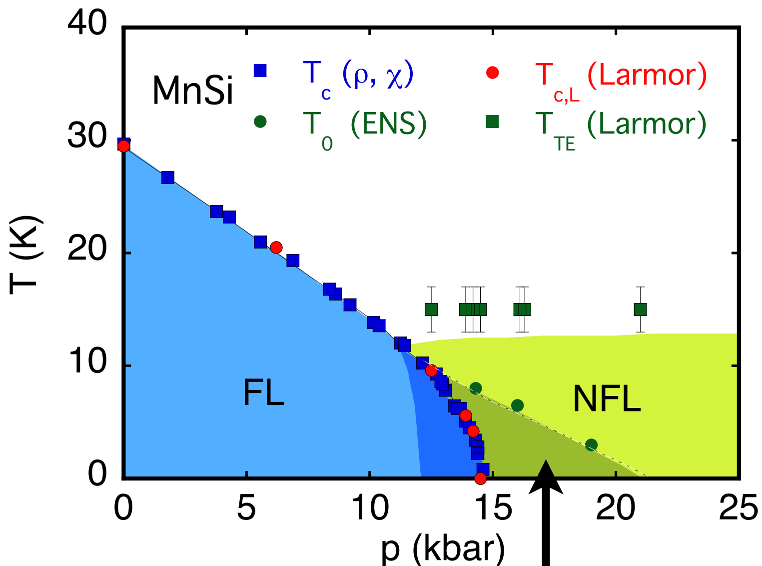
$$= -\frac{2\pi}{|q^e|}(N^s_{\mathrm{out}} - N^s_{\mathrm{in}}) = \mp\Phi_0$$

$$\mathbf{q_m} = n\frac{2\pi\hbar}{\mathbf{e}} \qquad \mathbf{e} = n\frac{2\pi\hbar}{\mathbf{q_m}}$$

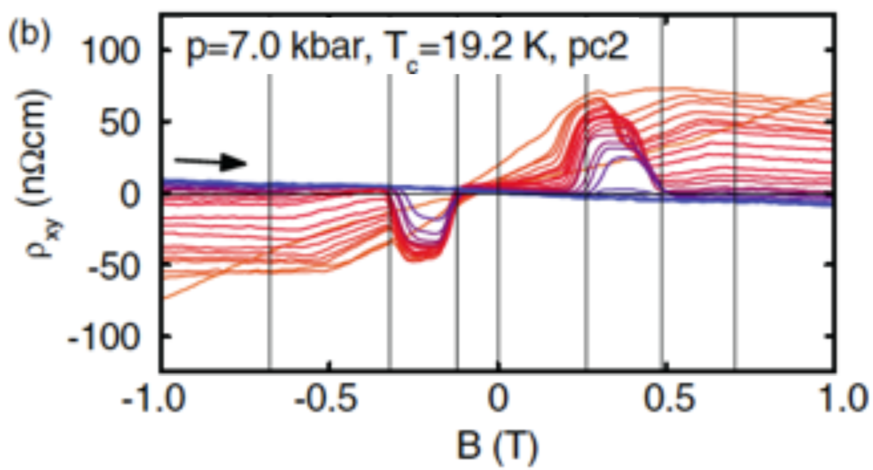
defects in (emergent) B-field with **quantized** charge

Milde et al., Science, **340** 1076 (2013)

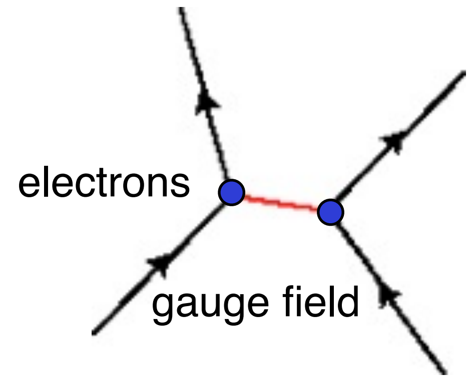
Formation of a Topological Non-Fermi Liquid in MnSi



topological Hall signal



Nature of emergent gauge field?



Topological charge?
Spontaneous skyrmions?
Deconfined monopoles?
...

Ritz, et al. PRB **87**, 134424 (2013)
Ritz, et al. Nature **497**, 231 (2013)

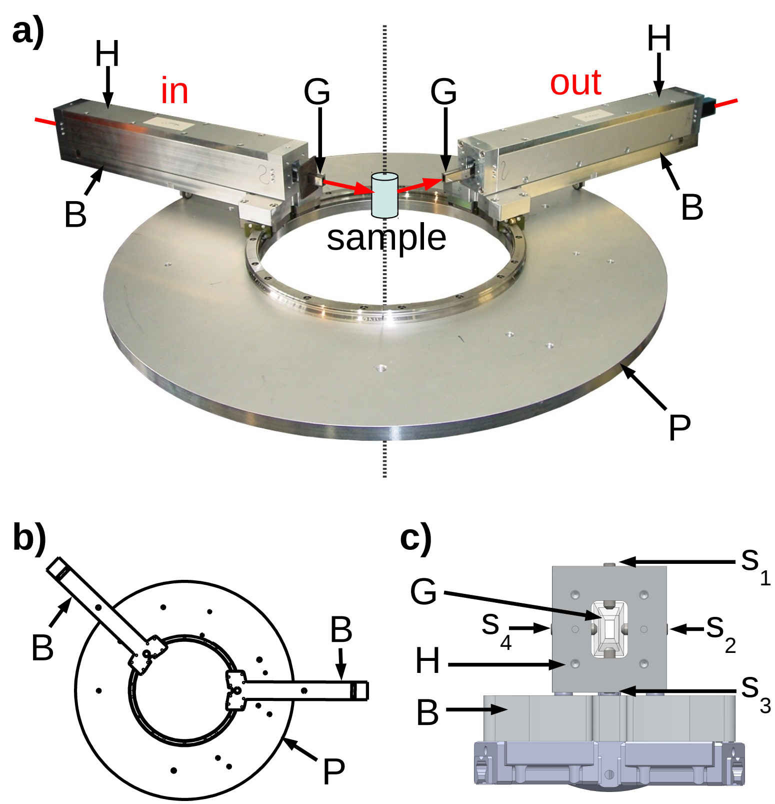
Key challenges 20 years from now

- What methods will be used?
- What problems will have been solved?
- What will the field look like?

What methods will be used?

- Materials
  - ➢ advanced preparation
  - ➢ heterogeneous systems
  - ➢ custom-taylored systems
- Experimental Methods
  - ➢ **small samples**
  - ➢ extended range
  - ➢ combined parameters
  - ➢ pump-probe techniques
  - ➢ tracking complexity

Focussing Neutron Guides



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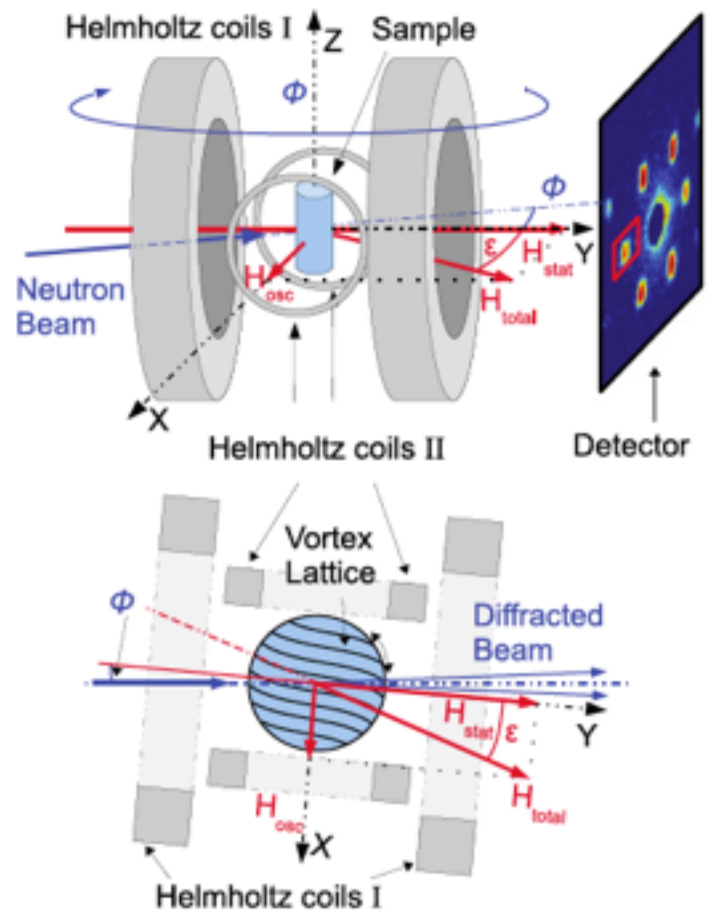
Time-Resolved Processes



Mühlbauer et al., PRB **83**, 184502 (2011)

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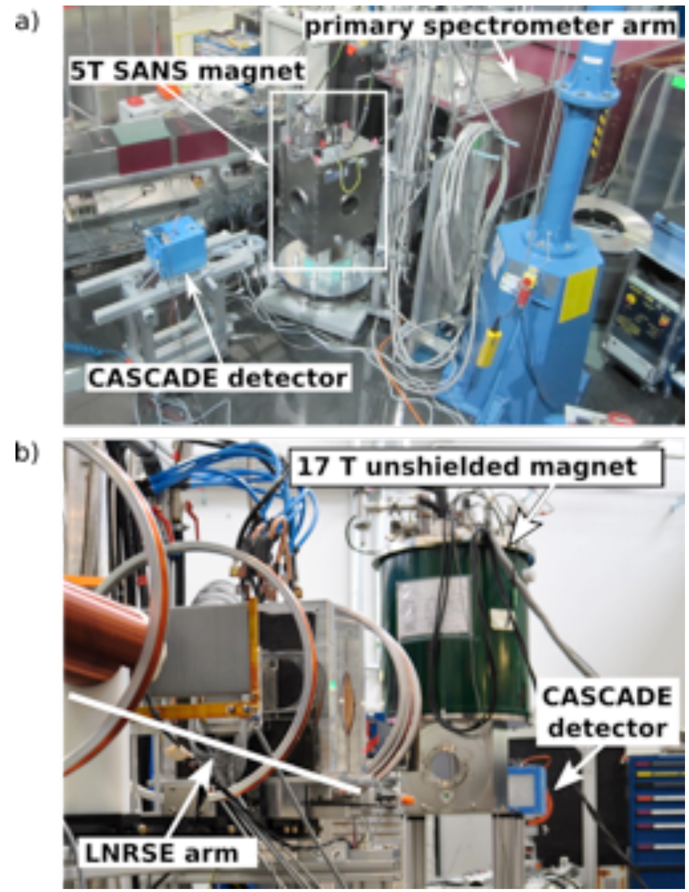
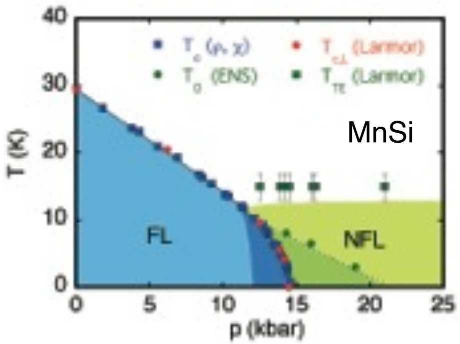
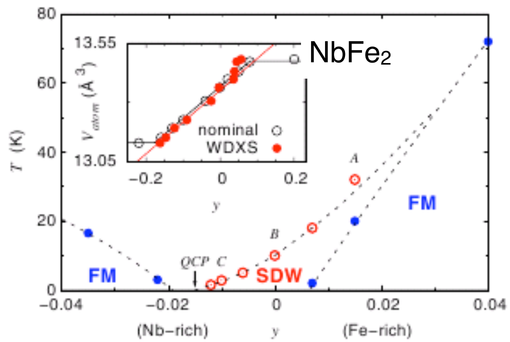
Spin-Echo Spectroscopy &
Depolarising Conditions

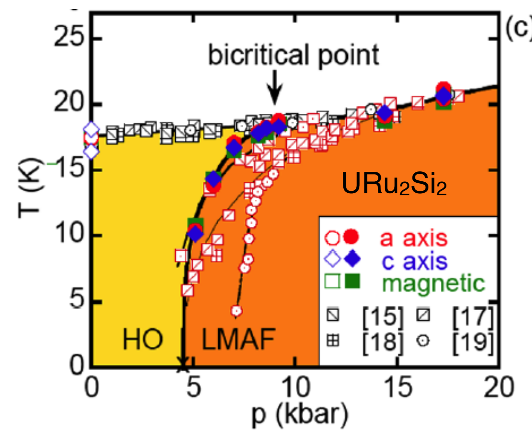


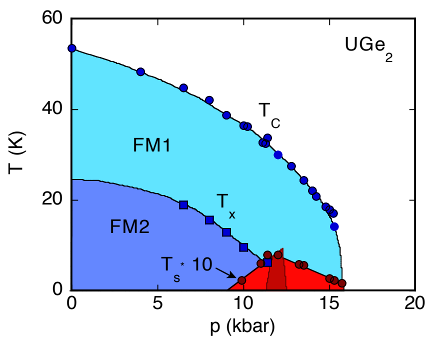
Kindervater et al., arxiv/1406.0405

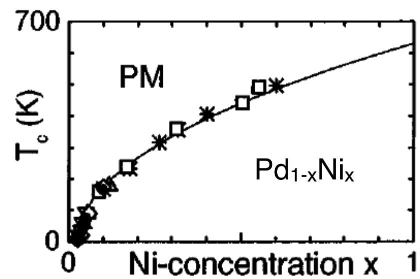
What problems will have been solved?

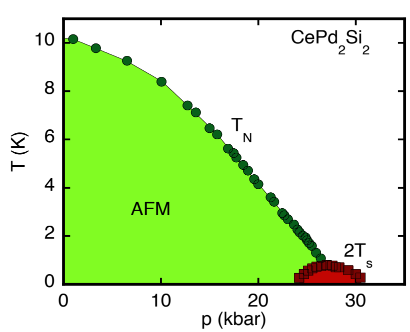


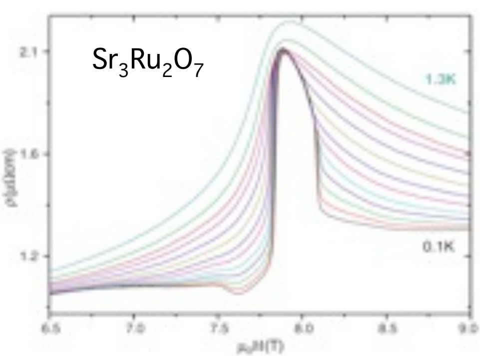




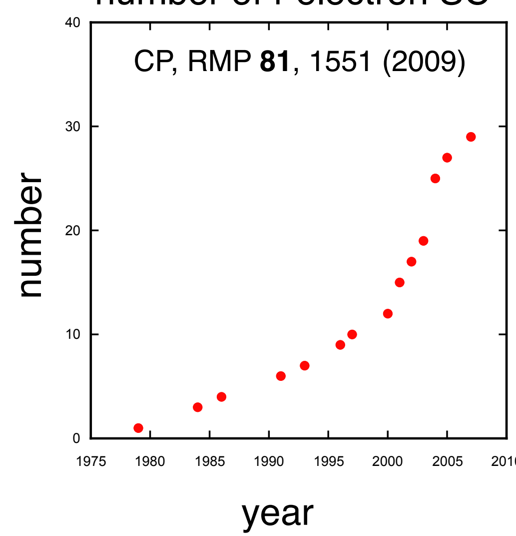








number of f-electron SC



What will the field look like?

Towards Changes of Paradigm

Characterisation of ordered phases

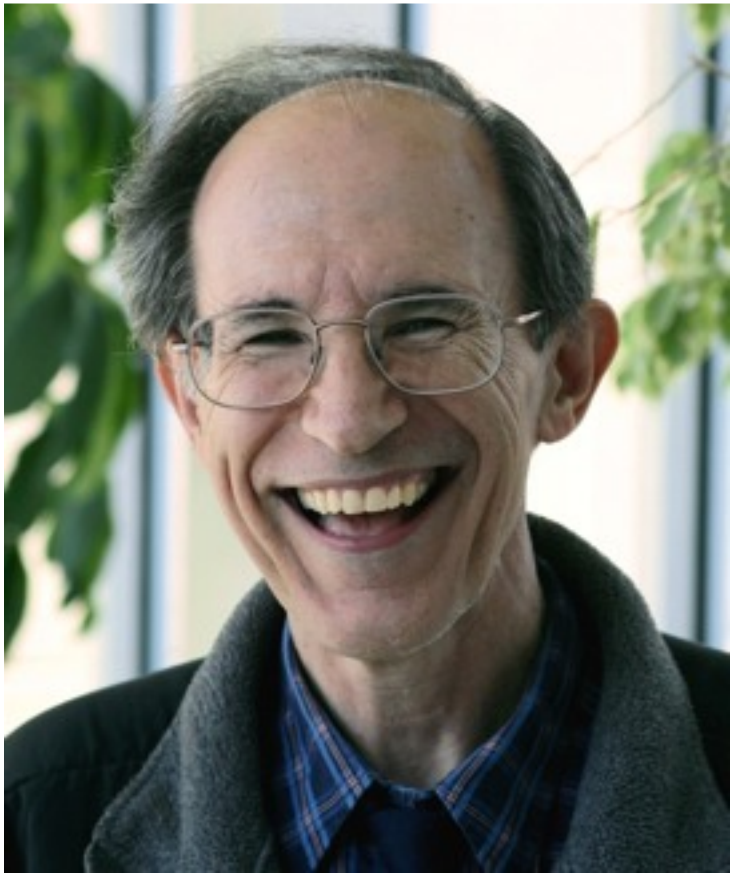
	fluid	nematic	smectic-A	crystal	Heisenberg magnet	superfluid	Ising magnet
new order	none	orientational	1D periodic	3D periodic	spin	condensate wave function	spin
rigidity	none	rotational elastic constant	layer modulus	shear modulus	spin-wave stiffness	phase of condensate	
broken symmetry	none	rotational	1D translation	3D translation	rotational	none	up/down
new mode	none	diffusive orientational	second. snd. undulation	shear sound	spin wave	second sound	
defect	none	disclinations, hedgehops	dislocations	dislocations	hedgehog	vortices	domain walls

Everything is stochastic?

Fluctuation stabilized order?

Stochastic topology?

What will the field look like?



Gilbert Lonzarich

Great discoveries are completely unexpected.

Chance favours the prepared mind.

Taming Serendipity.