Emerging phases and phase transitions in quantum matter

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- Condensed matter physics: complexity and emerging phenomena
- Phase transitions and quantum phase transitions
- Emerging phases close to quantum critical points

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What is condensed matter physics?

Condensed Matter Physics (Wikipedia):

> *deals with the macroscopic properties of matter; in particular ... the "condensed" phases that appear whenever the number of constituents in a system is large and their interactions ... are strong*

Traditionally: Physics of solids and liquids

- What is the structure of crystals?
- How do solids melt or liquids evaporate?
- Why do some materials conduct an electric current and others do not?

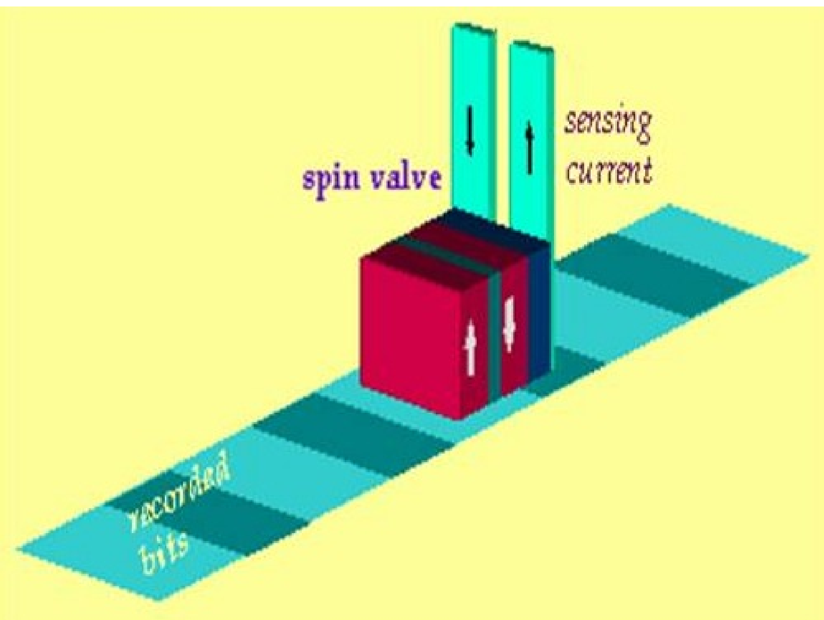
Today: all systems consisting of a large number of interacting constituents

- biological systems: biomolecules, DNA, membranes, cells
- geological systems: earthquakes
- economical systems: fluctuations of stock markets, currencies

Why condensed matter physics?

Applications: **"Helps you to make stuff."**

- semiconductors, transistors, microchips
- magnetic recording devices
- liquid crystal displays
- to come: qbits for quantum computers



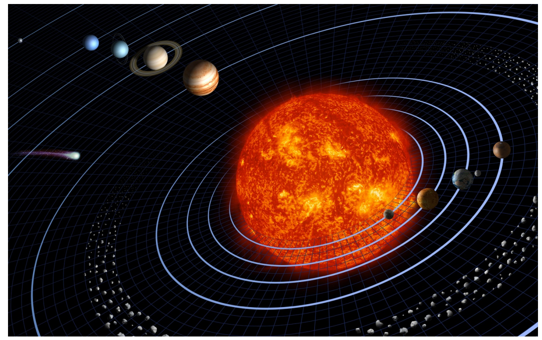
Read head, based on Giant Magnetoresistance effect
(A. Fert + P. Grünberg, Physics Nobel Prize 2007)

Maglev train using levitation by superconducting magnets, can go faster than 350 mph

Why condensed matter physics II

Directions of fundamental physics research :

Astrophysics and cosmology:
increasing length and time scales
"physics of the very large"



Atomic, nuclear and elementary particle physics:
decreasing length and time scales
"physics of the very small"

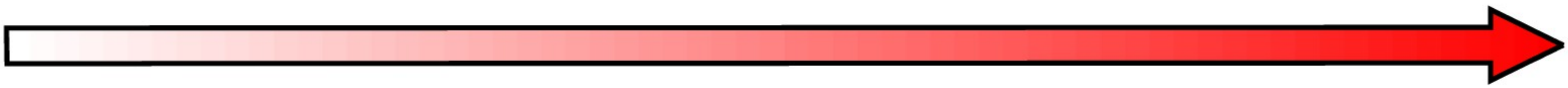
Particle accelerator at Fermilab

What fundamental direction does condensed matter research explore?
"physics of the very complex"

Emerging phenomena and the axis of complexity

"More is different!"

number of particles



10^0	10^1 - 10^2	10^3 - 10^5	$\sim 10^{12}$	10^{23}
elementary particles	atoms, molecules	cluster	mesoscopic systems	macroscopic solid or liquid
	chemical prop. (periodic table) optical prop. (e.g., color)	mechanical properties (rigidity, solid vs. liquid)	transport properties (conductivity)	phases and phase transitions (ferromagnetism) ... biology, life

Emerging phenomena:

When **large numbers** of particles strongly **interact**, qualitatively new properties of matter **emerge** at every level of complexity

New states of quantum matter and where to find them

Quantum matter:

- matter with emerging **macroscopic** properties that are intrinsically **quantum** (superconductors, superfluids, fractional quantum Hall states, spin liquids)

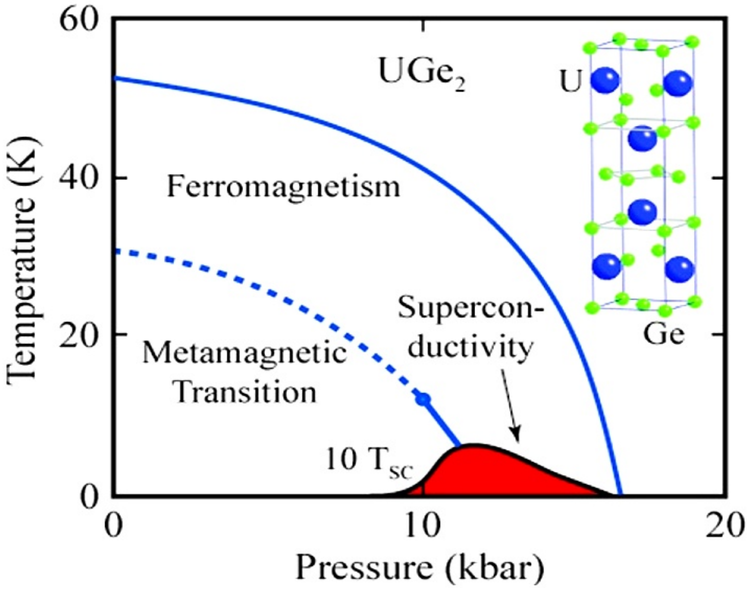
at low temperatures

$$F = E - TS$$

- thermal motion is suppressed
- new types of order can form

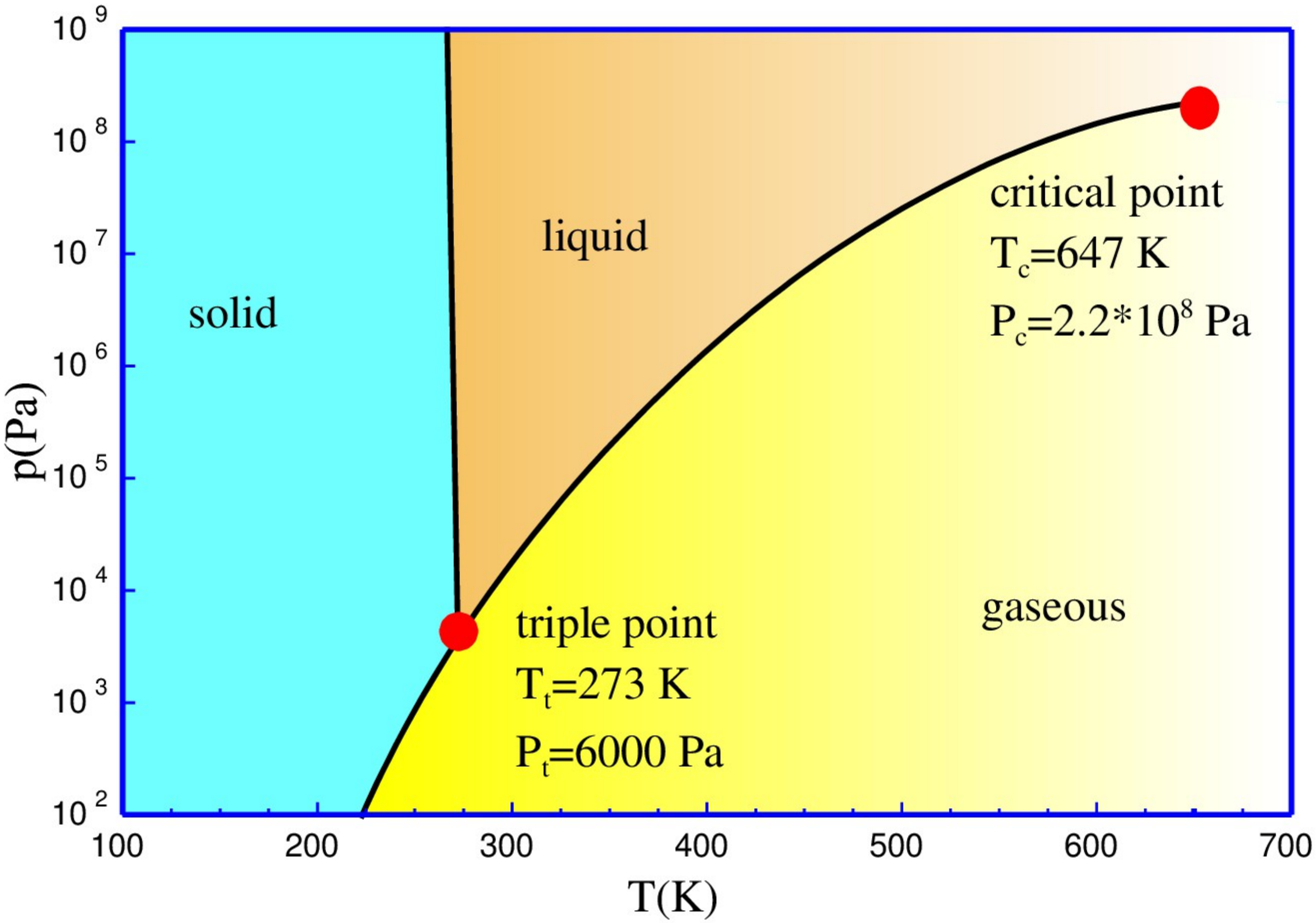
at boundaries of existing phases

- two types of order compete, suppress each other
- novel type of order may appear



- Condensed matter physics: complexity and emerging phenomena
- **Phase transitions and quantum phase transitions**
  - Novel phases close to quantum critical points

Phase diagram of water



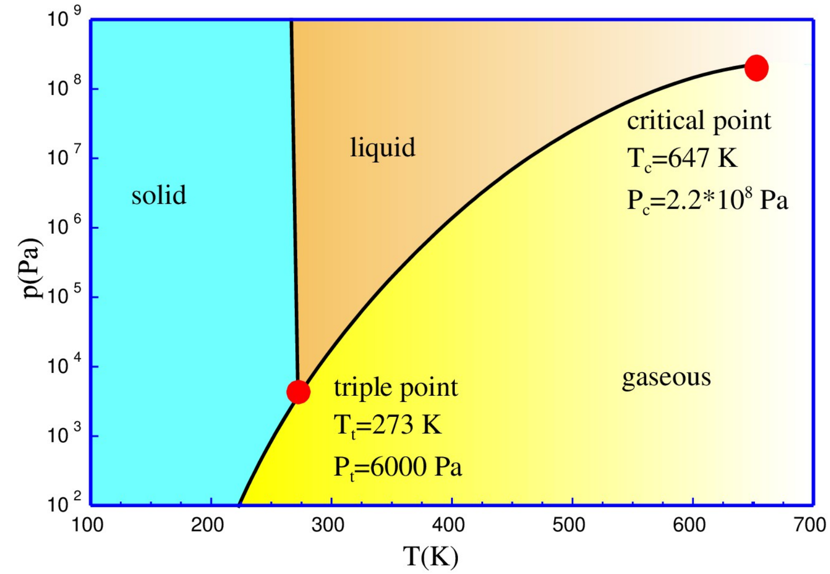
Phase transition:

singularity in thermodynamic quantities as functions of external parameters

Phase transitions: 1st order vs. continuous

1st order phase transition:

phase coexistence, latent heat,
short range spatial and time correlations



Continuous transition (critical point):

no phase coexistence, no latent heat,
infinite range correlations of fluctuations

Critical behavior at continuous transitions:

diverging correlation length $\xi \sim |T - T_c|^{-\nu}$ and time $\xi_\tau \sim \xi^z \sim |T - T_c|^{-\nu z}$

- Manifestation: critical opalescence (Andrews 1869)

Universality: critical exponents are independent of microscopic details

Critical opalescence

Binary liquid system:

e.g. hexane and methanol

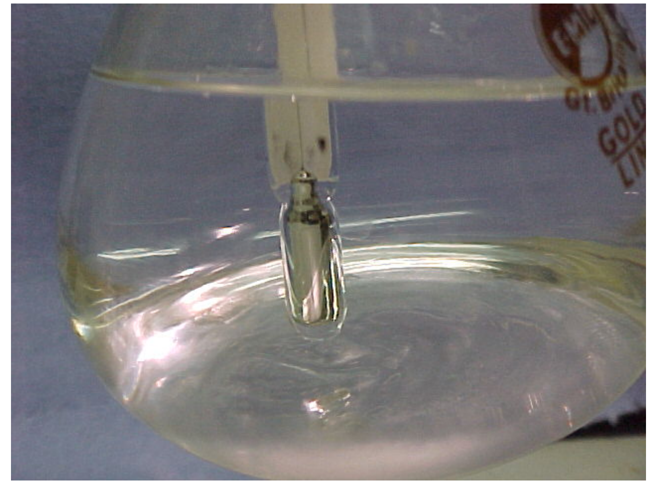
$T > T_c \approx 36°$C: fluids are miscible

$T < T_c$: fluids separate into two phases

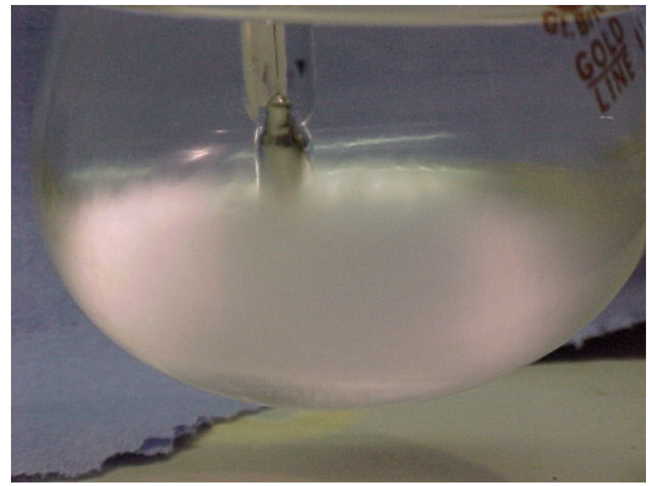
$T \to T_c$: length scale ξ of fluctuations grows

When ξ reaches the scale of a fraction of a micron (wavelength of light):

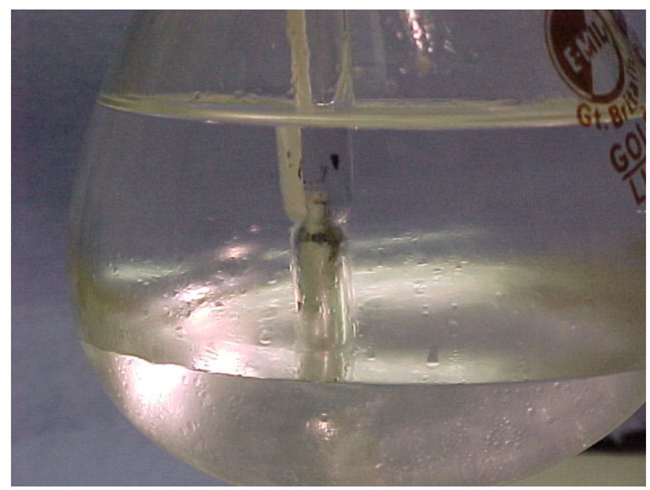
strong light scattering
fluid appears milky



46°C



39°C



18°C

Pictures taken from http://www.physicsofmatter.com

How important is quantum mechanics close to a critical point?

Two types of fluctuations:

thermal fluctuations (**thermal motion**), energy scale $k_B T$
quantum fluctuations (**quantum zero-point motion**), energy scale $\hbar\omega_c$

Quantum effects **unimportant** if $\hbar\omega_c \ll k_B T$.

Critical slowing down:

$\omega_c \sim 1/\xi_\tau \sim |T - T_c|^{\nu z} \to 0$ at the critical point

⇒ For any **nonzero** temperature, quantum fluctuations do **not** play a role close to the critical point

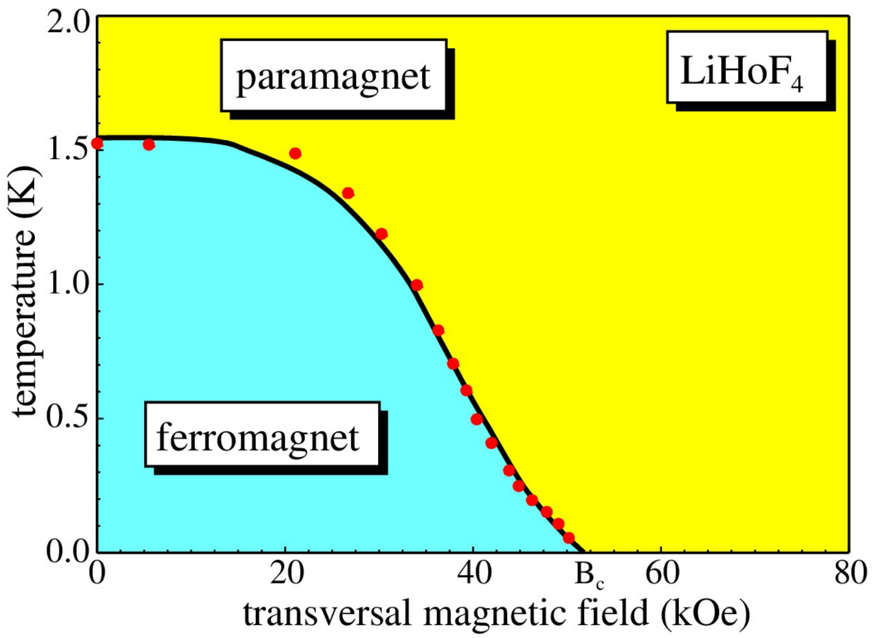
⇒ Quantum fluctuations **do** play a role a **zero** temperature

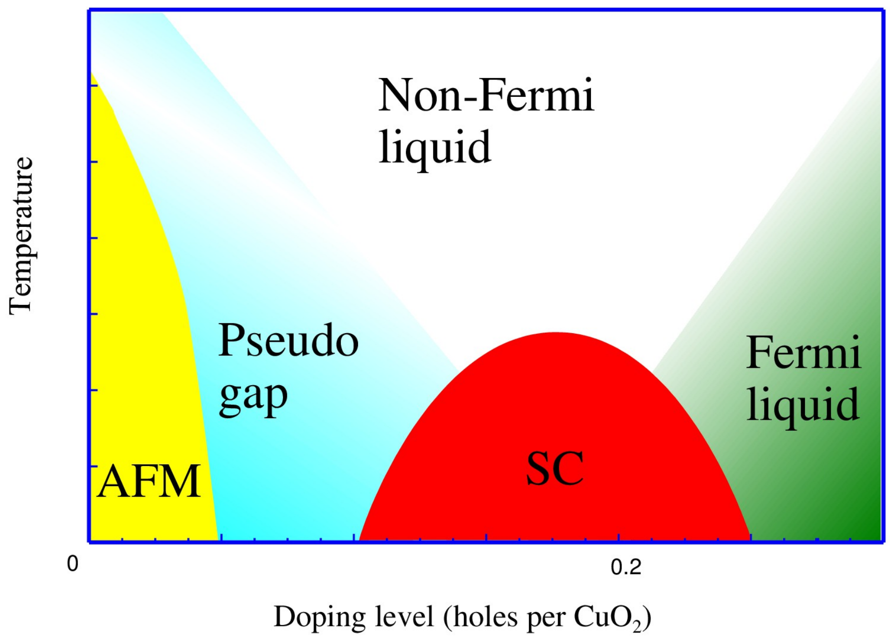
Zero-temperature continuous phase transitions constitute a special class of phase transitions, they are intrinsically quantum in nature

Quantum phase transitions

occur at **zero temperature** as function of pressure, magnetic field, chemical composition, ...

driven by **quantum zero-point motion** rather than thermal fluctuations

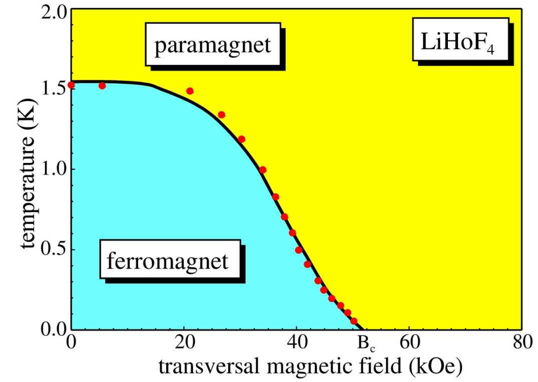




Phase diagrams of $LiHoF_4$ and a typical high-T_c superconductor such as $YBa_2Cu_3O_{6+x}$

Toy model: transverse field Ising model

Quantum spins S_i on a lattice: (c.f. LiHoF$_4$)



$$
\begin{aligned}
H &= -J\sum_i \mathbf{S}_i^z\mathbf{S}_{i+1}^z - h\sum_i \mathbf{S}_i^x \\
&= -J\sum_i \mathbf{S}_i^z\mathbf{S}_{i+1}^z - \frac{h}{2}\sum_i (\mathbf{S}_i^+ + \mathbf{S}_i^-)
\end{aligned}
$$

J: exchange energy, favors parallel spins, i.e., ferromagnetic state

h: transverse magnetic field, induces quantum fluctuations between up and down states, favors paramagnetic state

Limiting cases:

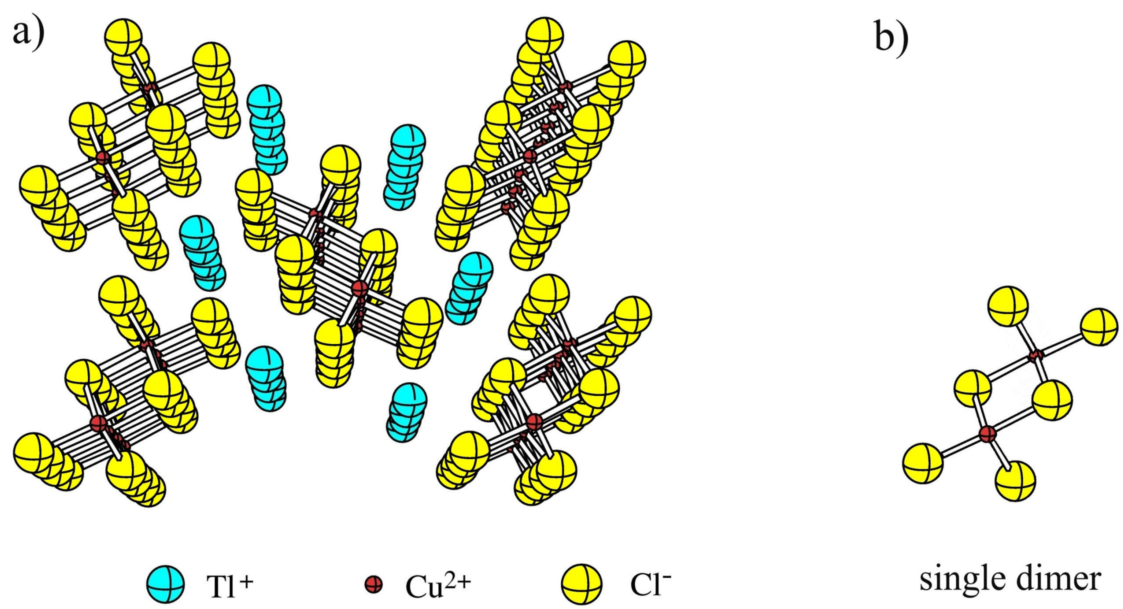
$|J| \gg |h|$ ferromagnetic ground state as in classical Ising magnet

$|J| \ll |h|$ paramagnetic ground state as for independent spins in a field

$\Rightarrow$ **Quantum phase transition** at $|J| \sim |h|$ (in 1D, transition is at $|J| = |h|$)

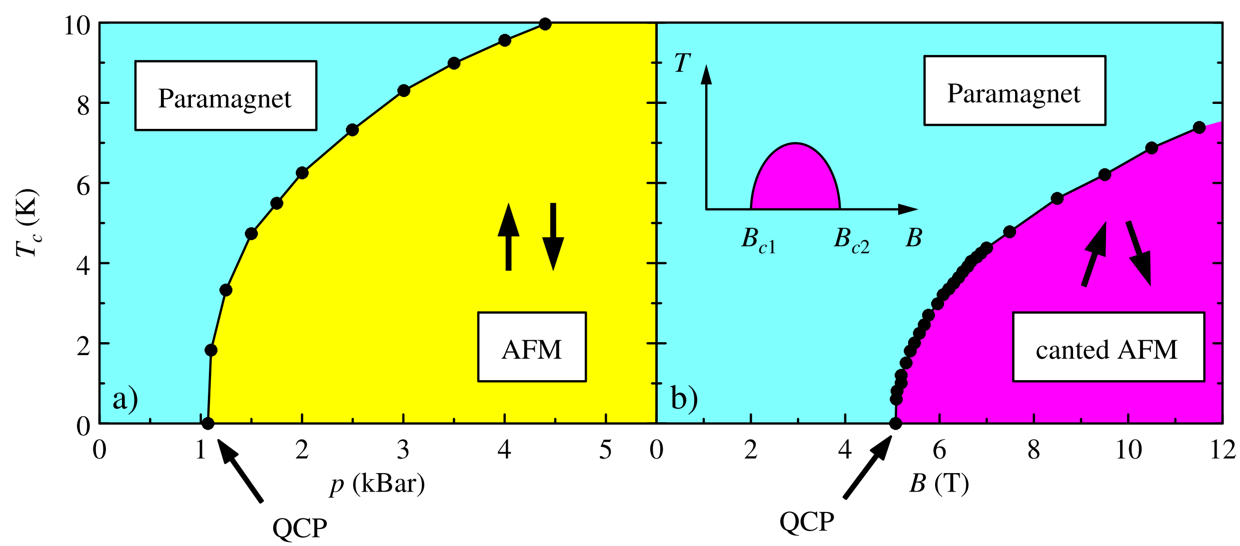
Magnetic quantum critical points of $TlCuCl_3$

- $TlCuCl_3$ is magnetic insulator
- planar Cu_2Cl_6 dimers form infinite double chains
- Cu^{2+} ions carry spin-1/2 moment



antiferromagnetic order can be induced by

- applying pressure
- applying a magnetic field

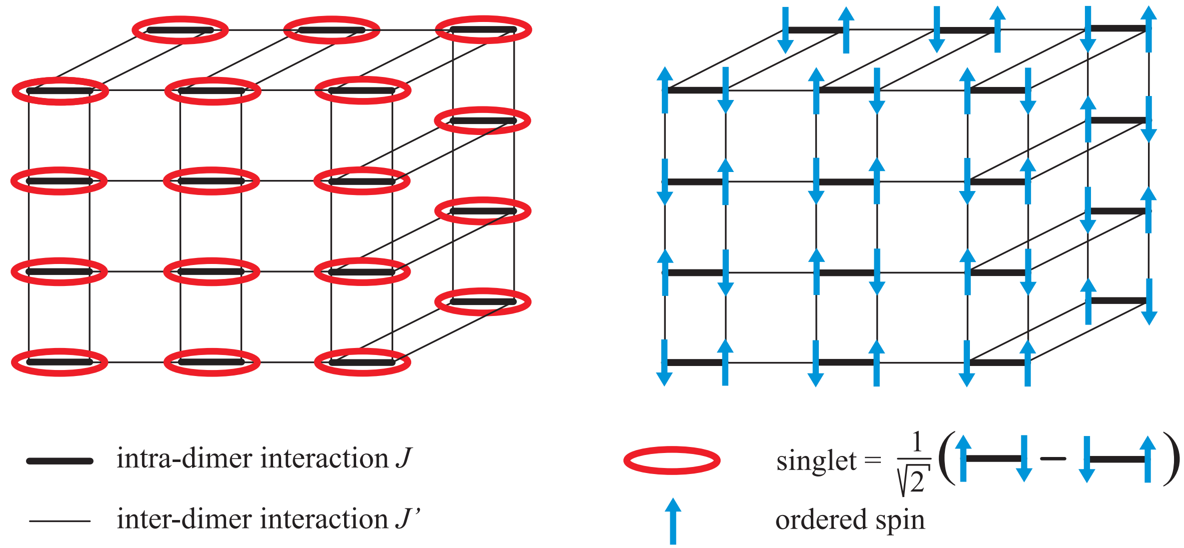


Pressure-driven quantum phase transition in $\mathrm{TlCuCl_3}$

quantum Heisenberg model

$$H = \sum_{\langle ij \rangle} J_{ij}\, \vec{S}_i \cdot \vec{S}_j - \vec{h} \cdot \sum_i \vec{S}_i$$

$$J_{ij} = \begin{cases} J & \text{intra-dimer} \\ J' & \text{between dimers} \end{cases}$$



pressure changes ratio J/J'

Limiting cases:

$|J| \gg |J'|$ spins on each dimer form singlet $\Rightarrow$ no magnetic order
low-energy excitations are "triplons" (single dimers in the triplet state)

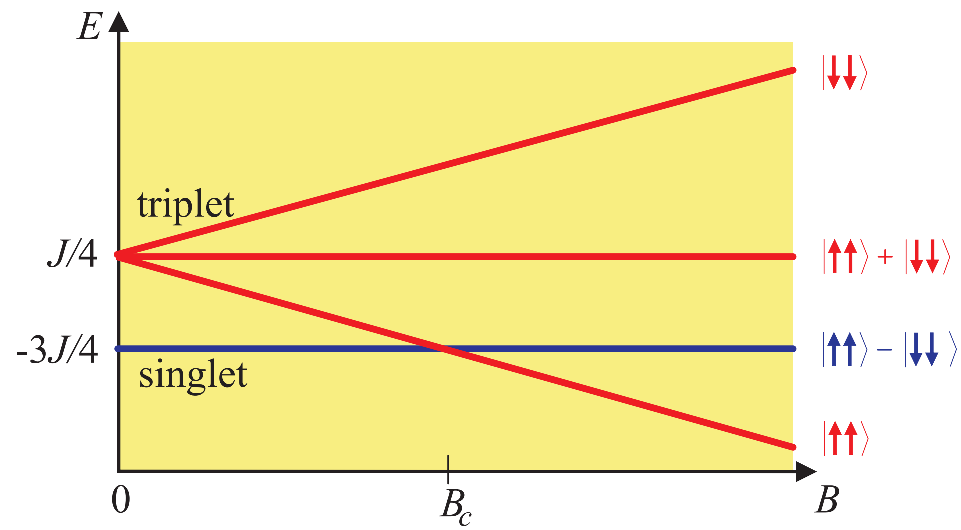
$|J| \approx |J'|$ long-range antiferromagnetic order (Néel order)
low-energy excitations are long-wavelength spin waves

$\Rightarrow$ quantum phase transition at some critical value of the ratio J/J'

Field-driven quantum phase transition in $TlCuCl_3$

Single dimer in field:

- field does not affect singlet ground state but splits the triplet states
- ground state: singlet for $B < B_c$ and (fully polarized) triplet for $B > B_c$

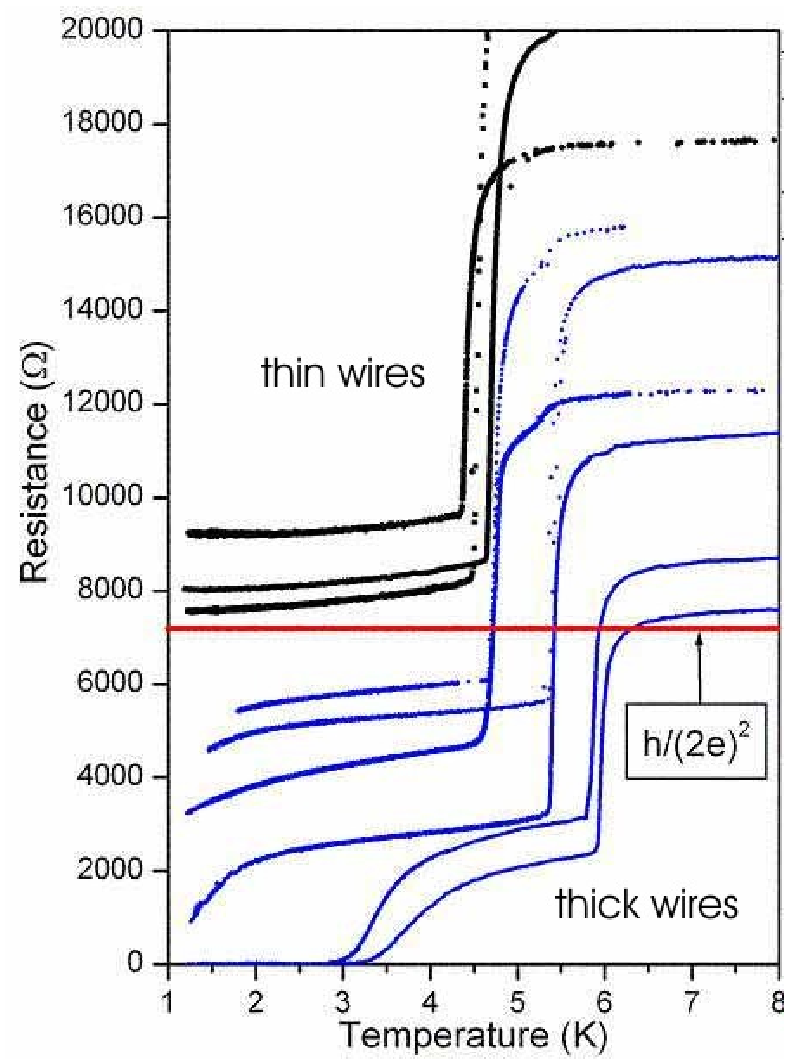


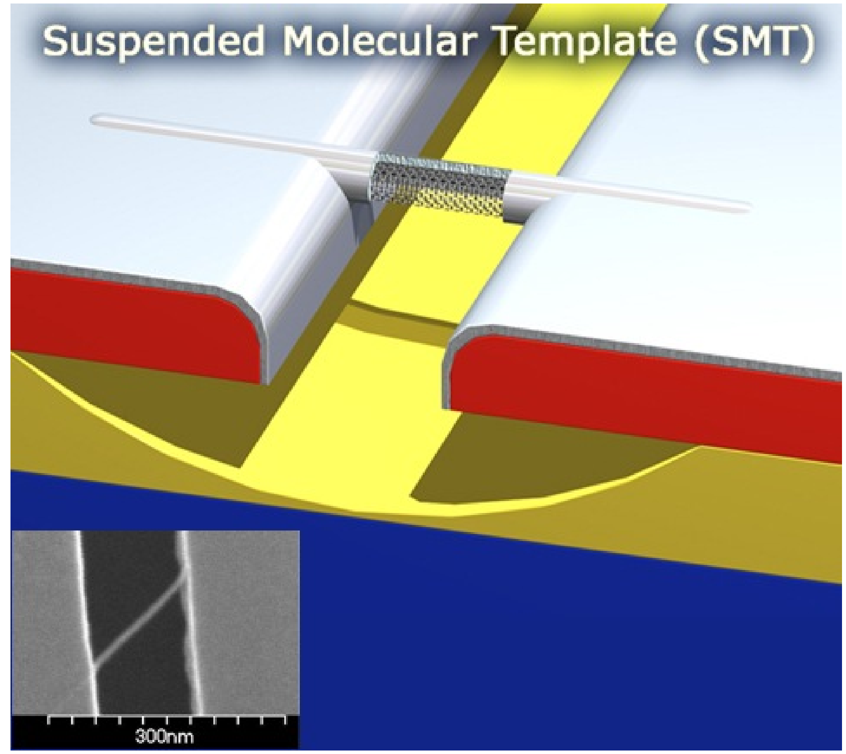
Full Hamiltonian:

- singlet-triplet transition of isolated dimer splits into two transitions
- at B_{c1}, triplon gap closes, system is driven into ordered state (uniform magnetization $||$ to field and antiferromagnetic order $\perp$ to field)
- "canted" antiferromagnet is Bose-Einstein condensate of triplons
- at B_{c2} system enters fully polarized state

Superconductor-metal QPT in ultrathin nanowires

- ultrathin MoGe wires (width $\sim$ 10 nm)
- produced by molecular templating using a single carbon nanotube



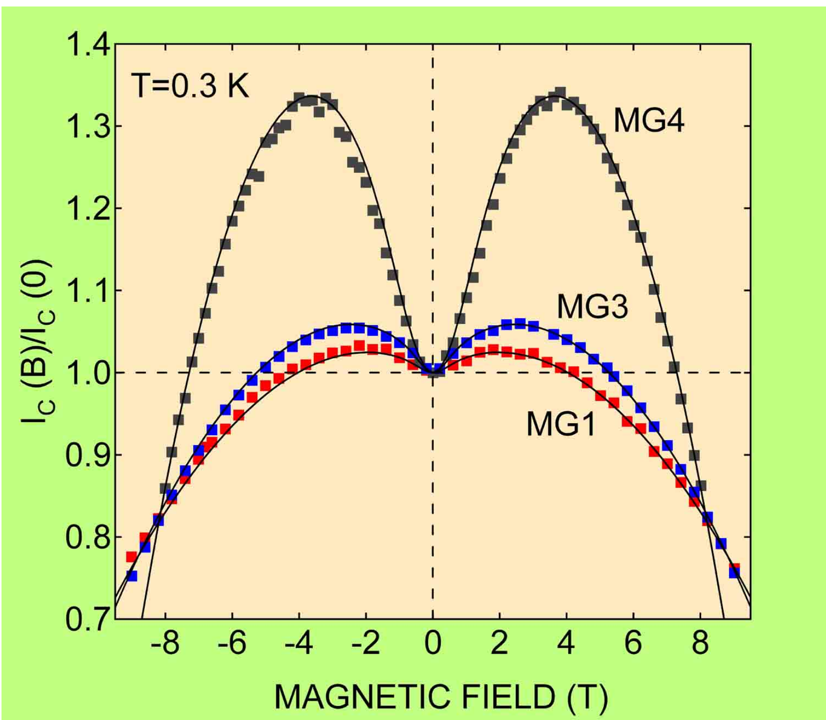


- thicker wires are superconducting at low temperatures
- thinner wires remain metallic

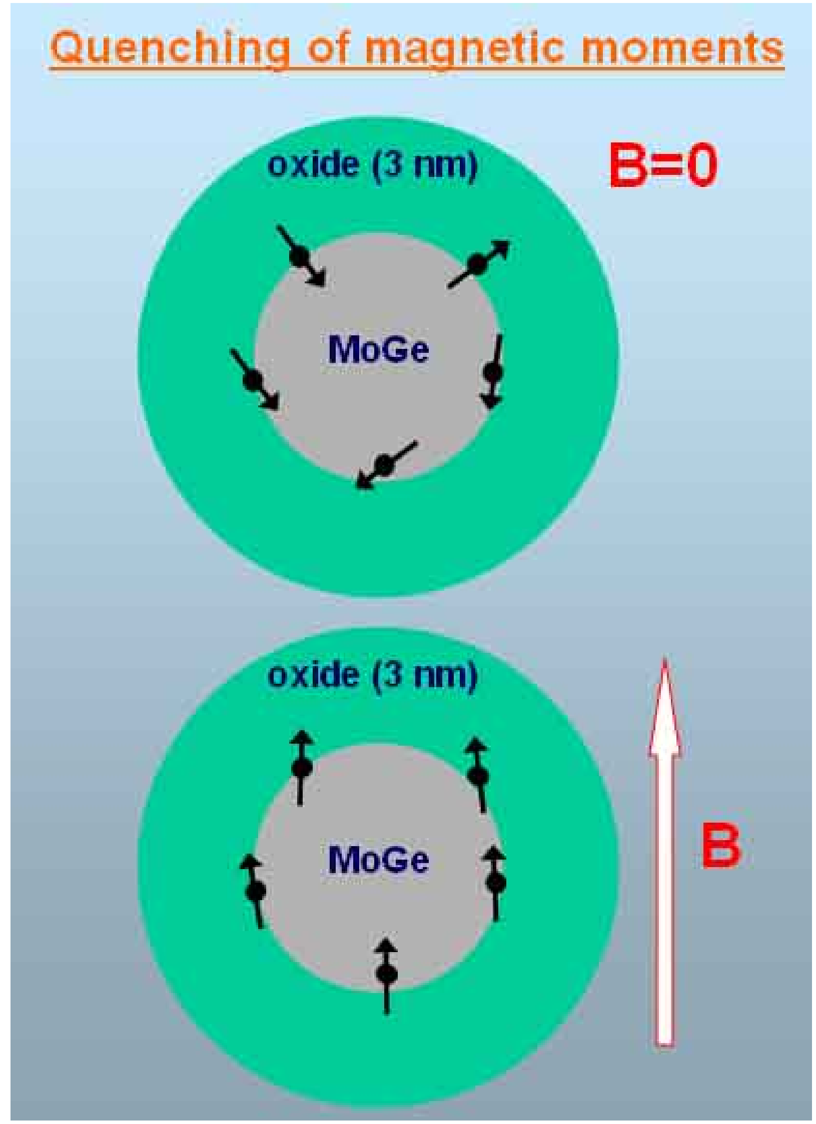
superconductor-metal QPT as function of wire thickness

Pairbreaking mechanism

- pair breaking by surface magnetic impurities
- random impurity positions
  $\Rightarrow$ quenched **disorder**
- gapless excitations in metal phase
  $\Rightarrow$ Ohmic **dissipation**

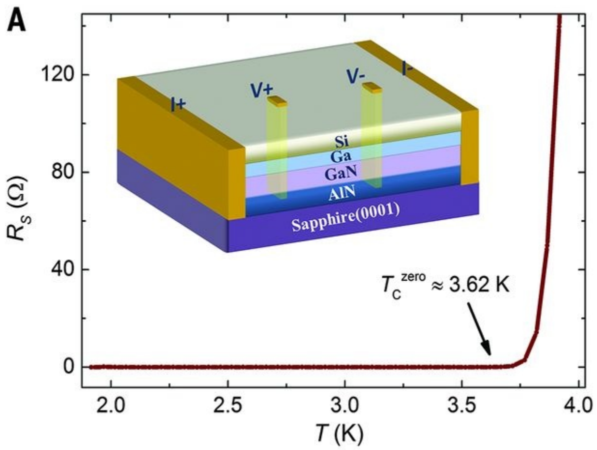


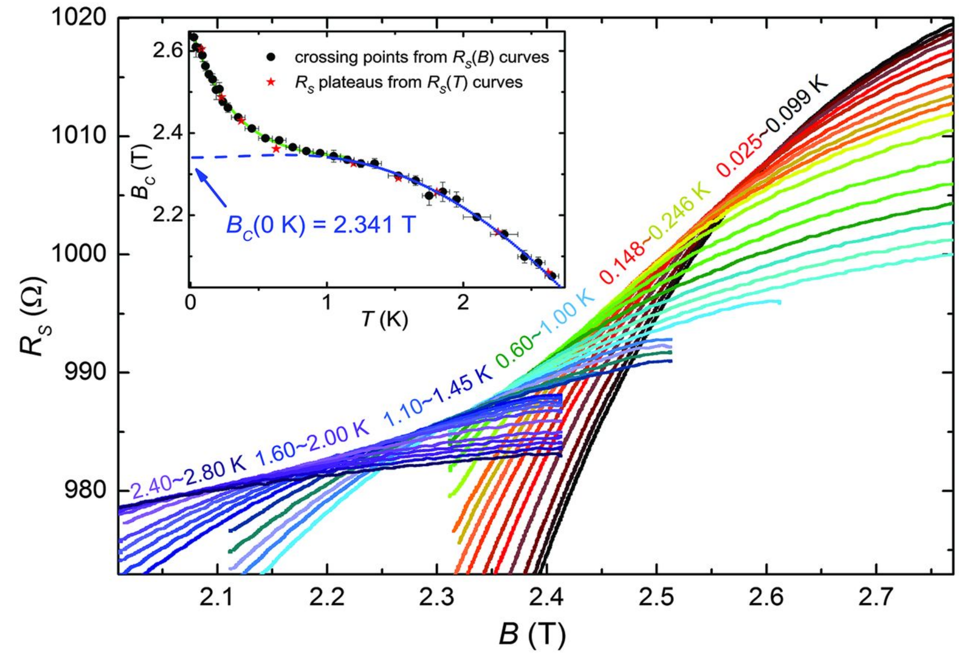
weak field enhances superconductivity

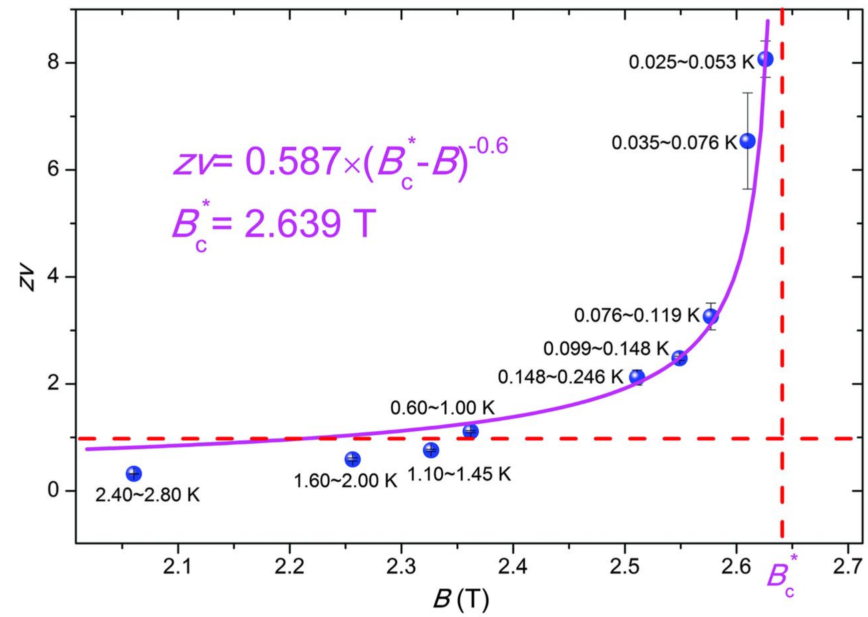


magnetic field aligns the impurities and reduces magnetic scattering

Experiment: Ga thin films



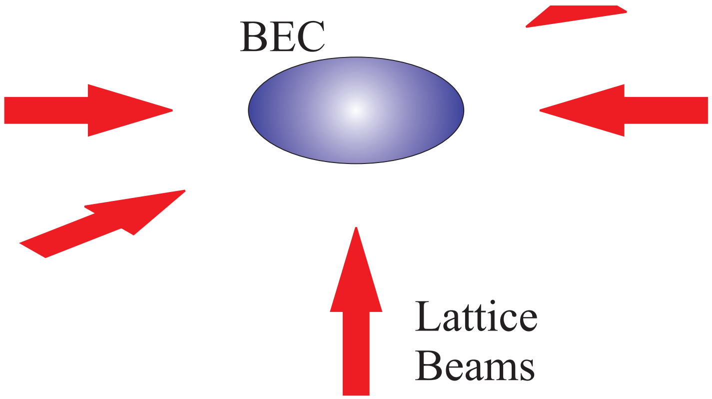


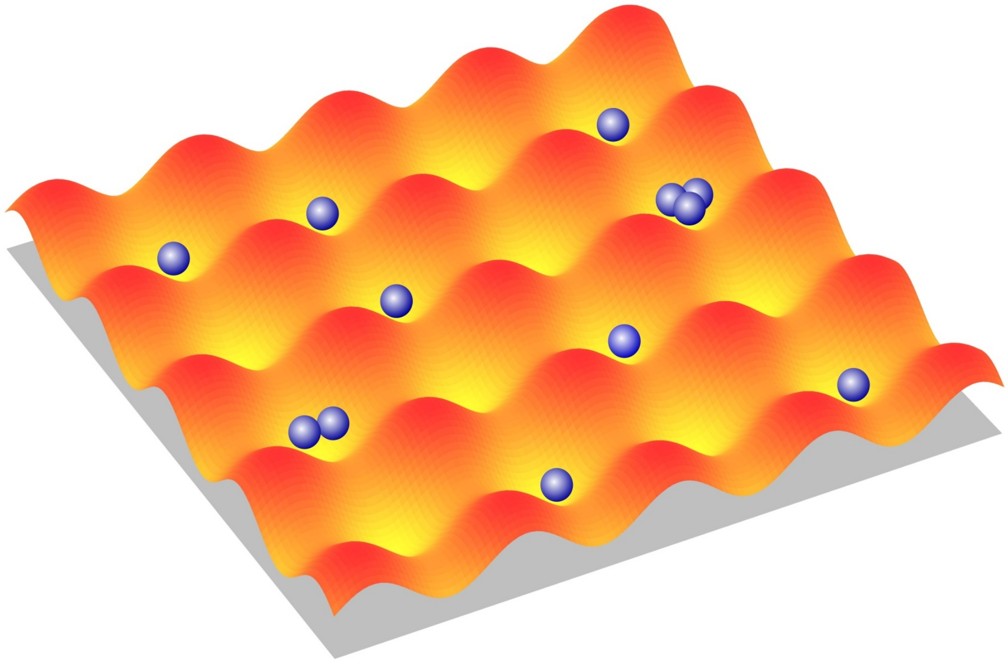


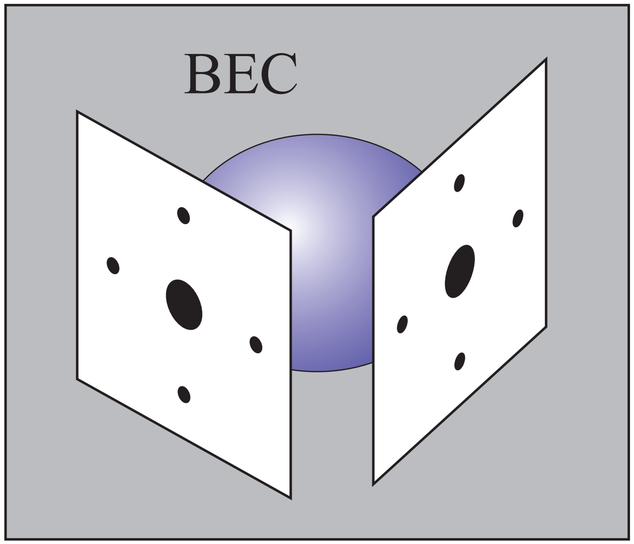
Xing et al., Science 350, 542 (2015)

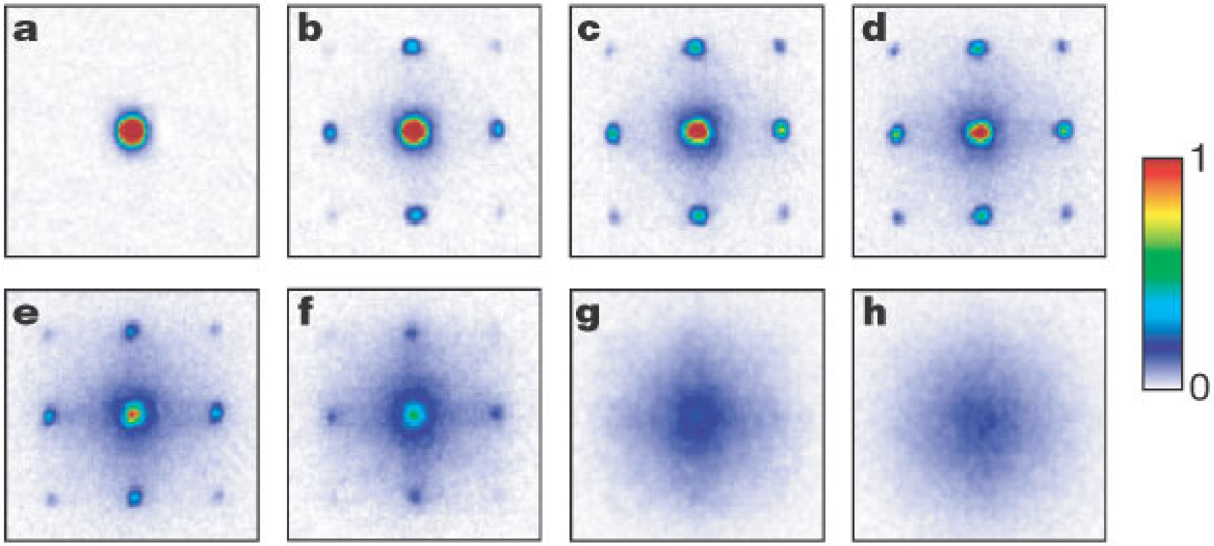
- three-monolayer Ga films
- superconductivity below $T_c \approx 3.62$K, suppressed by magnetic field
- field-driven QPT well described by **2D infinite-randomness critical point**
- dynamical exponent **diverges** as $z \sim |B - B_c|^{-\nu\psi}$ with $\nu \approx 1.2, \psi \approx 0.5$

Mott transition in a Bose-Einstein condensate







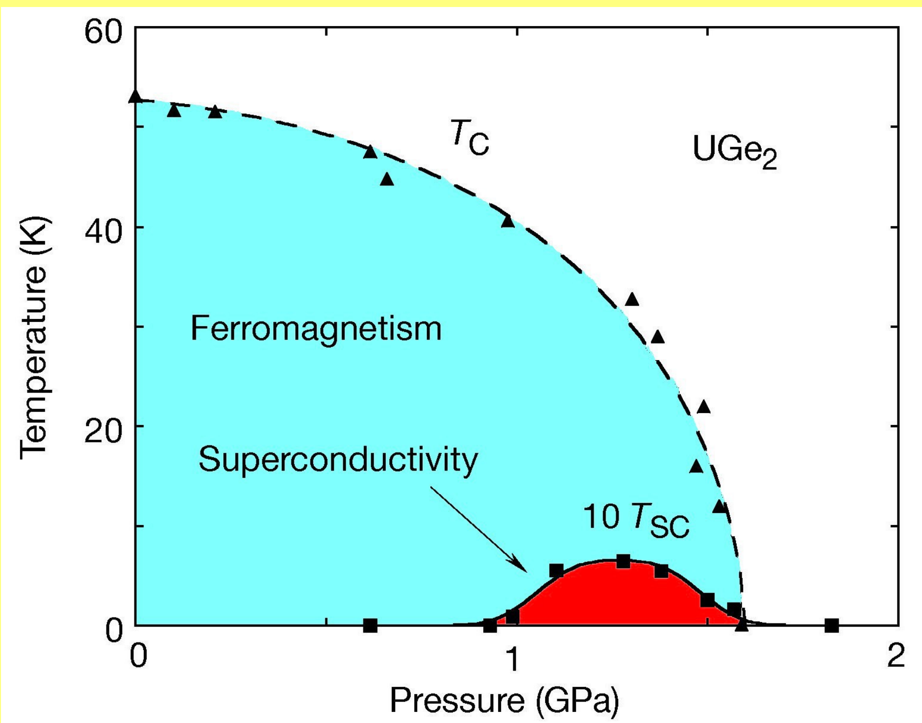


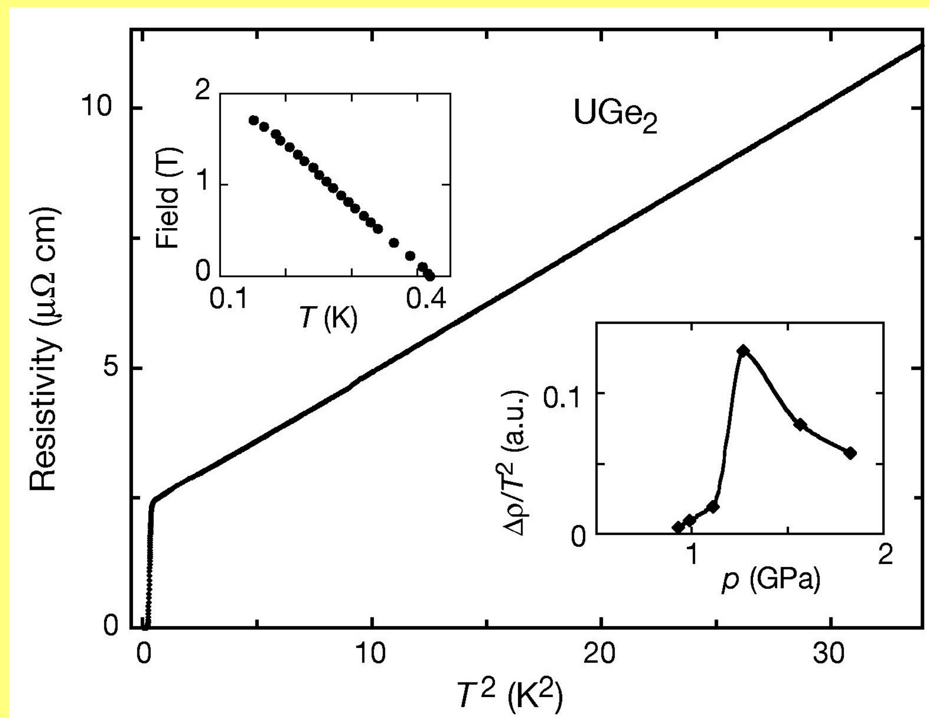
- Condensed matter physics: complexity and emerging phenomena
- Phase transitions and quantum phase transitions
- **Novel phases close to quantum critical points**

Exotic superconductivity in UGe_2

Phase diagram:

- phase diagram of UGe_2 has pocket of **superconductivity** close to ferromagnetic quantum phase transition (electrical resistivity **vanishes** below about 1K)
- in this pocket, UGe_2 is **ferromagnetic and superconducting** at the same time
- superconductivity appears only in superclean samples

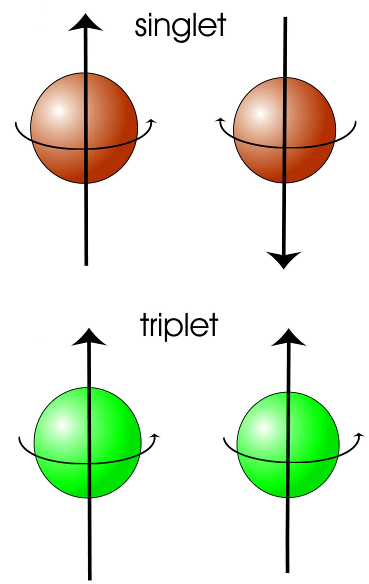




Character of superconductivity in UGe_2

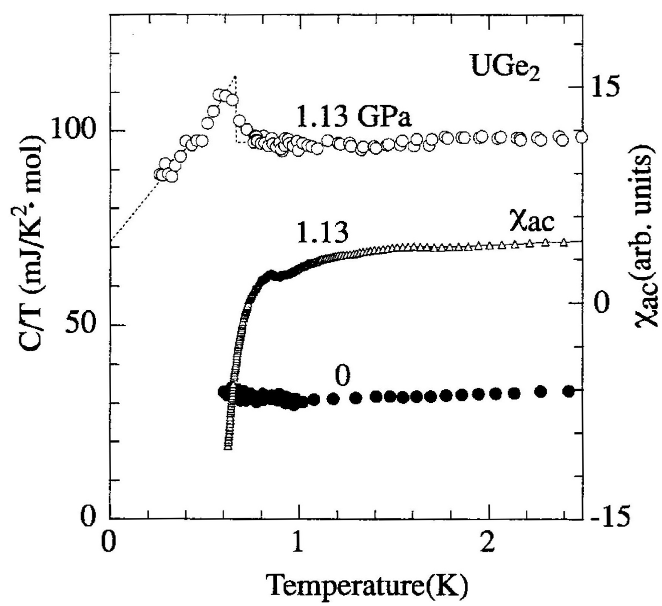
not compatible with conventional (BCS) superconductivity:

- in superconductor, electrons form (Cooper) pairs of spin-up and spin-down electrons
- ferromagnetism requires majority of spins to be in one direction



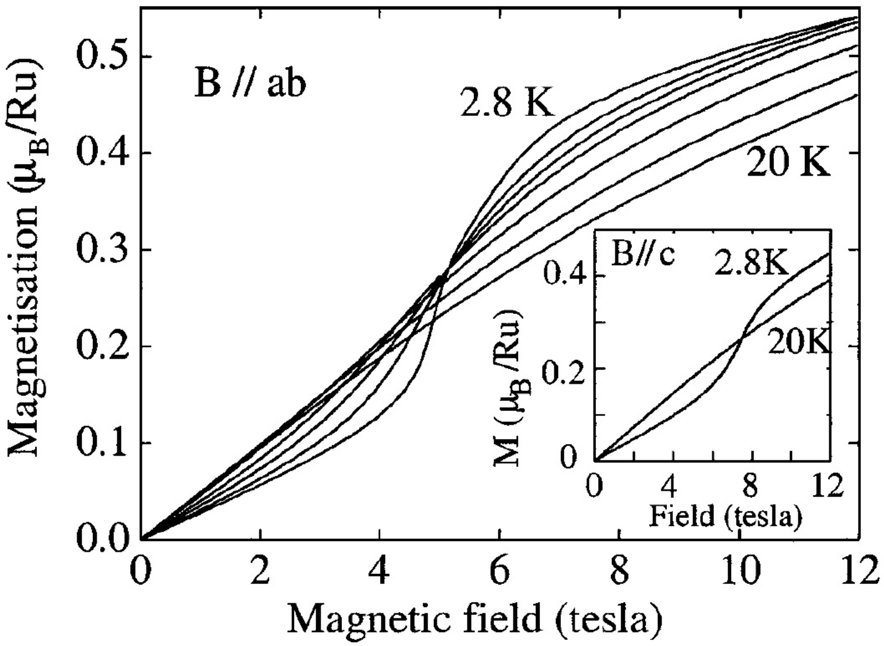
theoretical ideas:

- phase separation (layering or disorder): **NO!**
- partially paired FFLO state: **NO!**
- spin triplet pairs with odd spatial symmetry, magnetic fluctuations promote this type of pairing



Magnetic quantum phase transition induces spin-triplet superconductivity

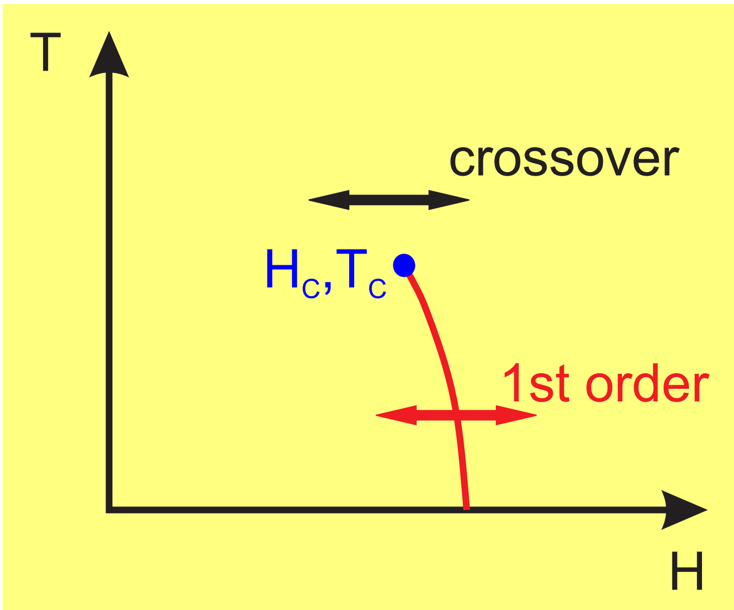
Metamagnetic transition in $Sr_3Ru_2O_7$

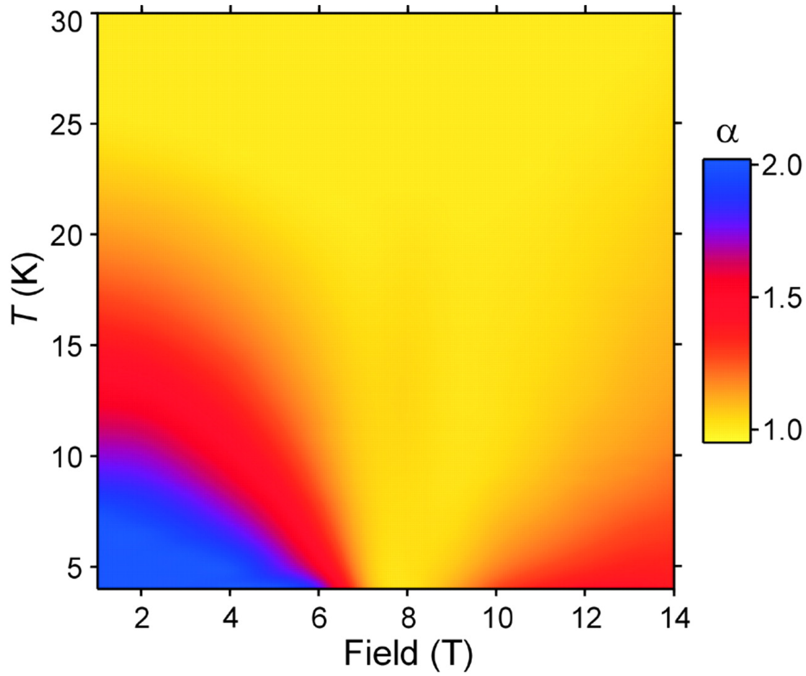


- $Sr_3Ru_2O_7$ undergoes metamagnetic transition as function of field
- critical endpoint can be tuned to $T = 0$ by tilting the field

$\Rightarrow$ **metamagnetic quantum critical point**

- seen in temperature dependence of resistivity $\rho = \rho_0 + AT^{\alpha}$

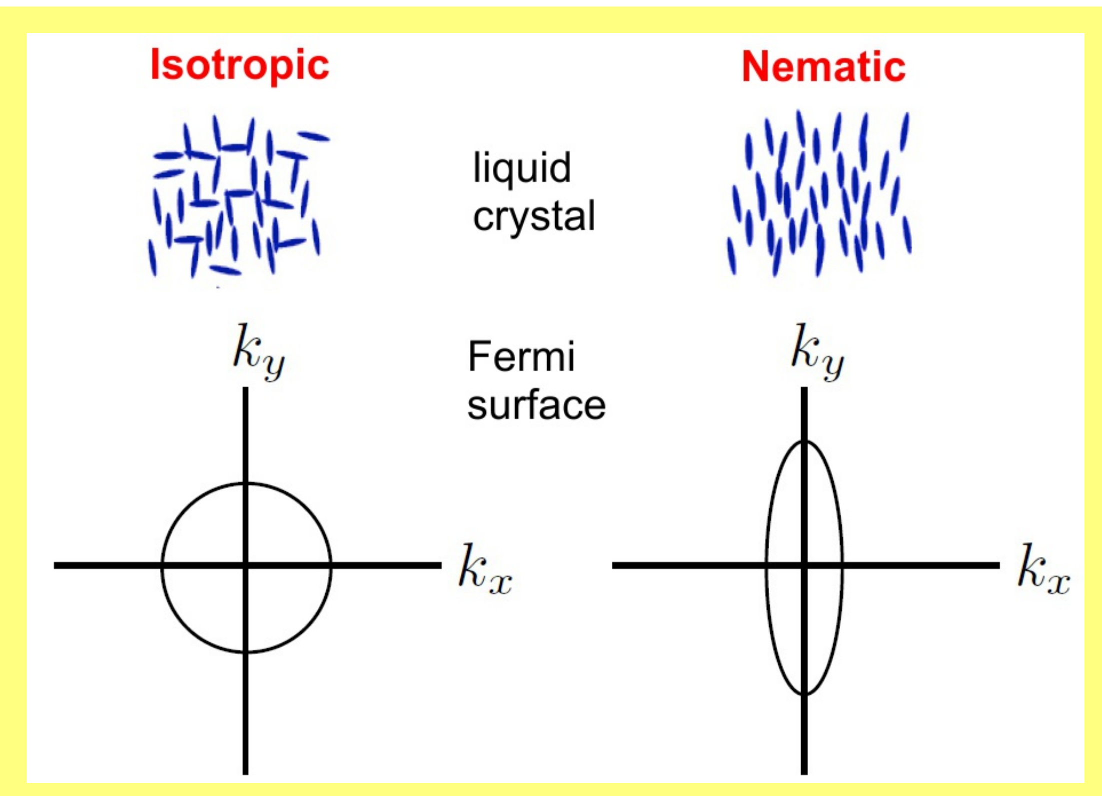


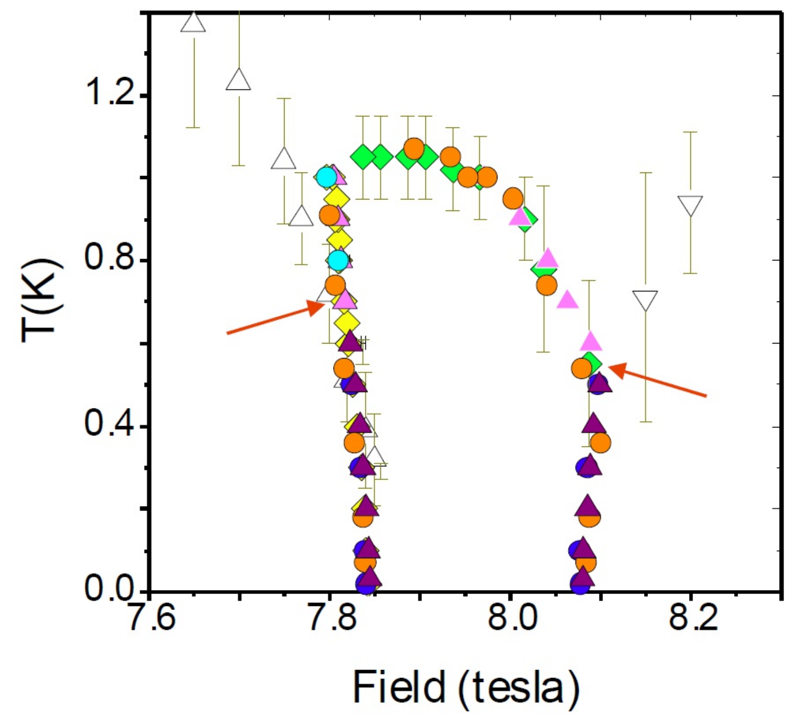


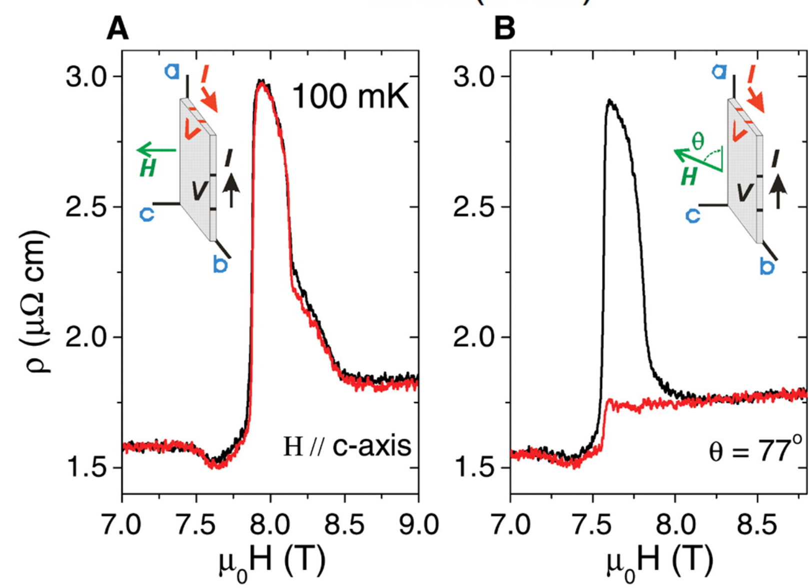
Electronic nematic phase in $Sr_3Ru_2O_7$

- in pure samples at low temperatures, QCP **preempted by novel phase**
- resistivity highly anisotropic (C4 $\rightarrow$ C2)

$\Rightarrow$ new phase is **electronic nematic** (translational invariant but rotational symmetry spontaneously broken)



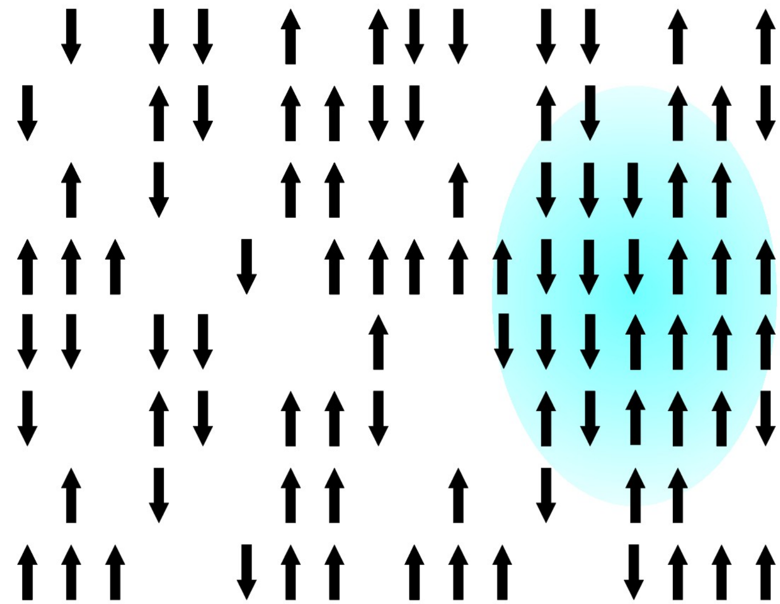


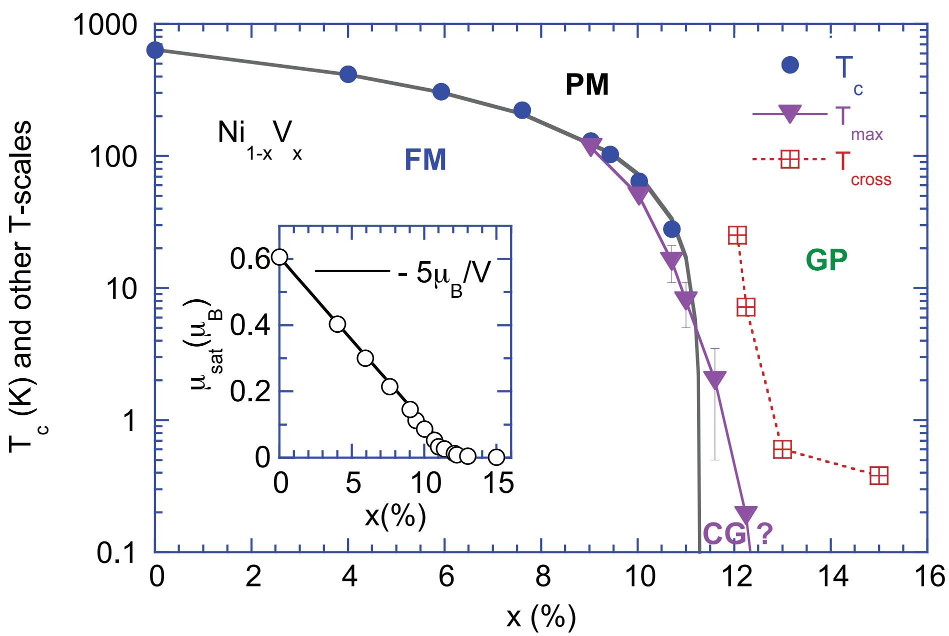


Disorder and Griffiths phases

QPT in a disordered system:

- **rare region** can be locally in ordered phase even if bulk system is in disordered phase
- probability of rare region exponentially small $p(L) \sim \exp(-cL^d)$:
- rare regions act as large **superspins**
  $\Rightarrow$ slow dynamics, large contribution to TD



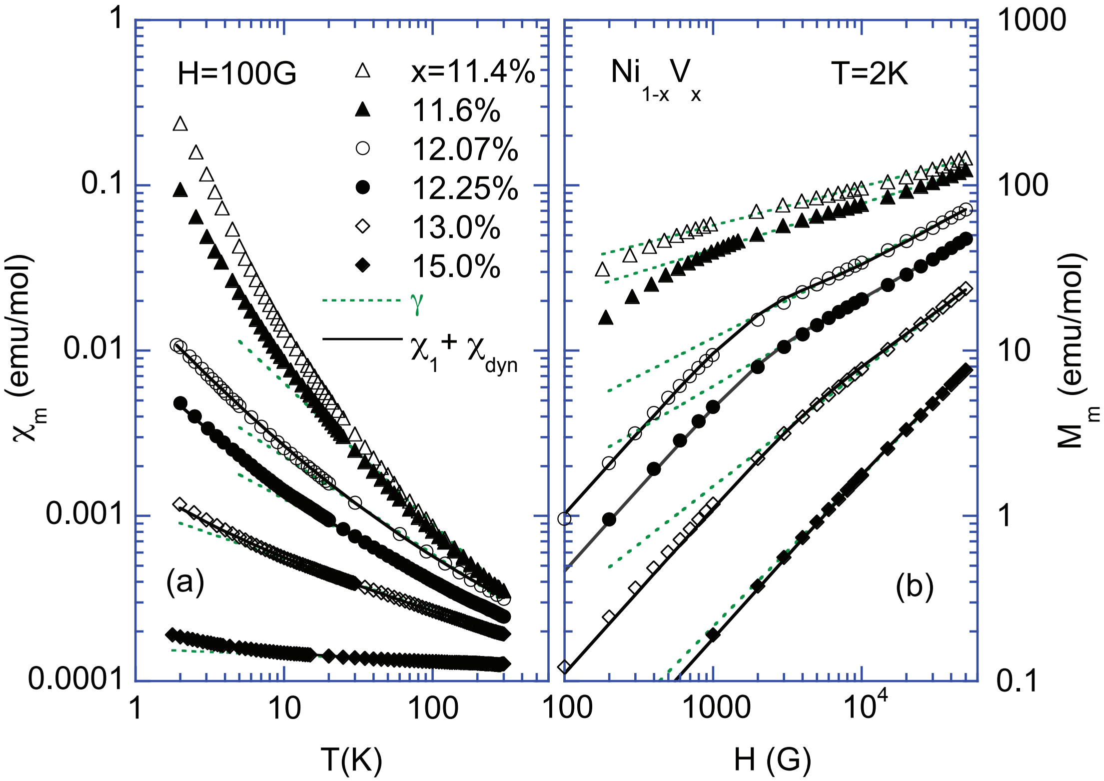


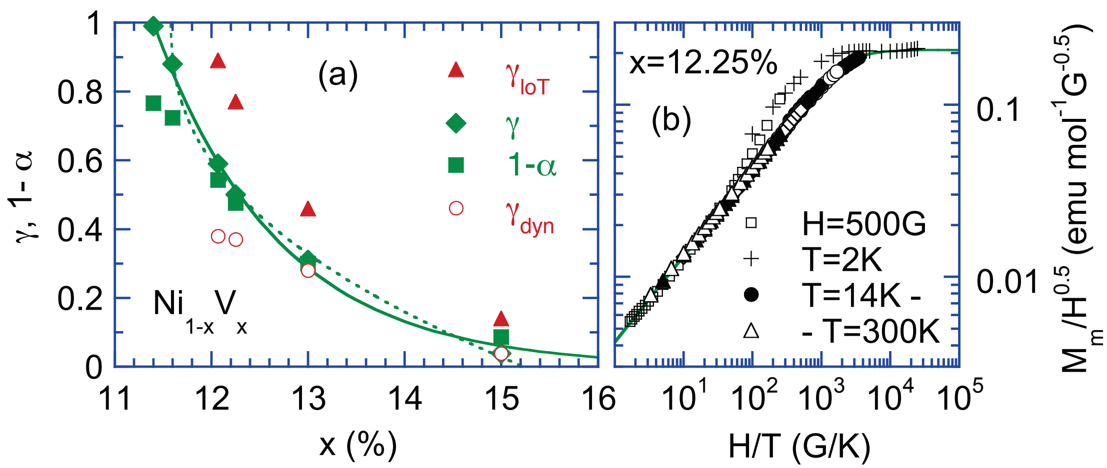
Can rare regions dominate the thermodynamic response?

$\Rightarrow$ **quantum Griffiths phase**

- example:
  diluted ferromagnet $Ni_{1-x}V_x$

Quantum Griffiths phase in $Ni_{1-x}V_x$



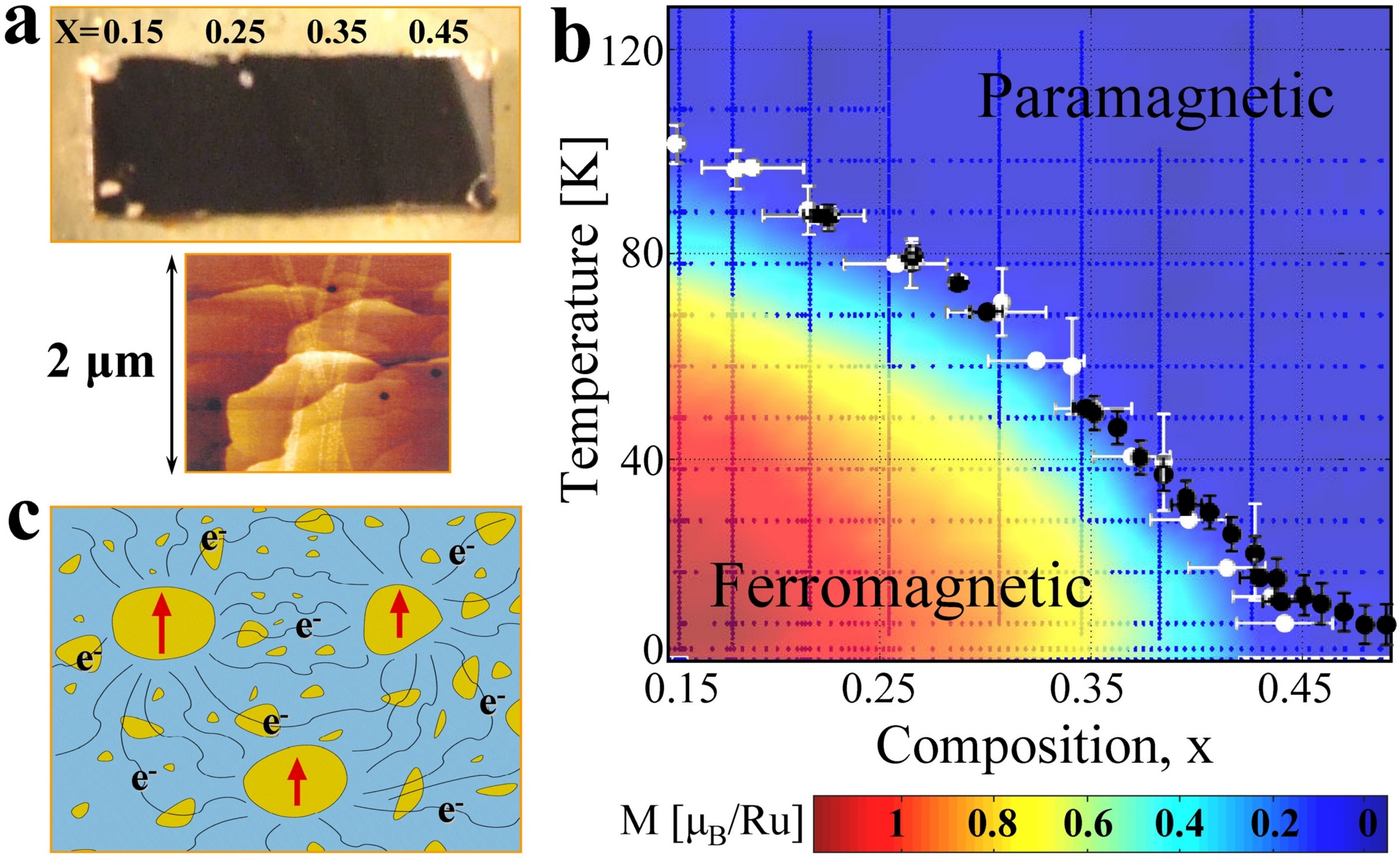


at concentrations above x_c:

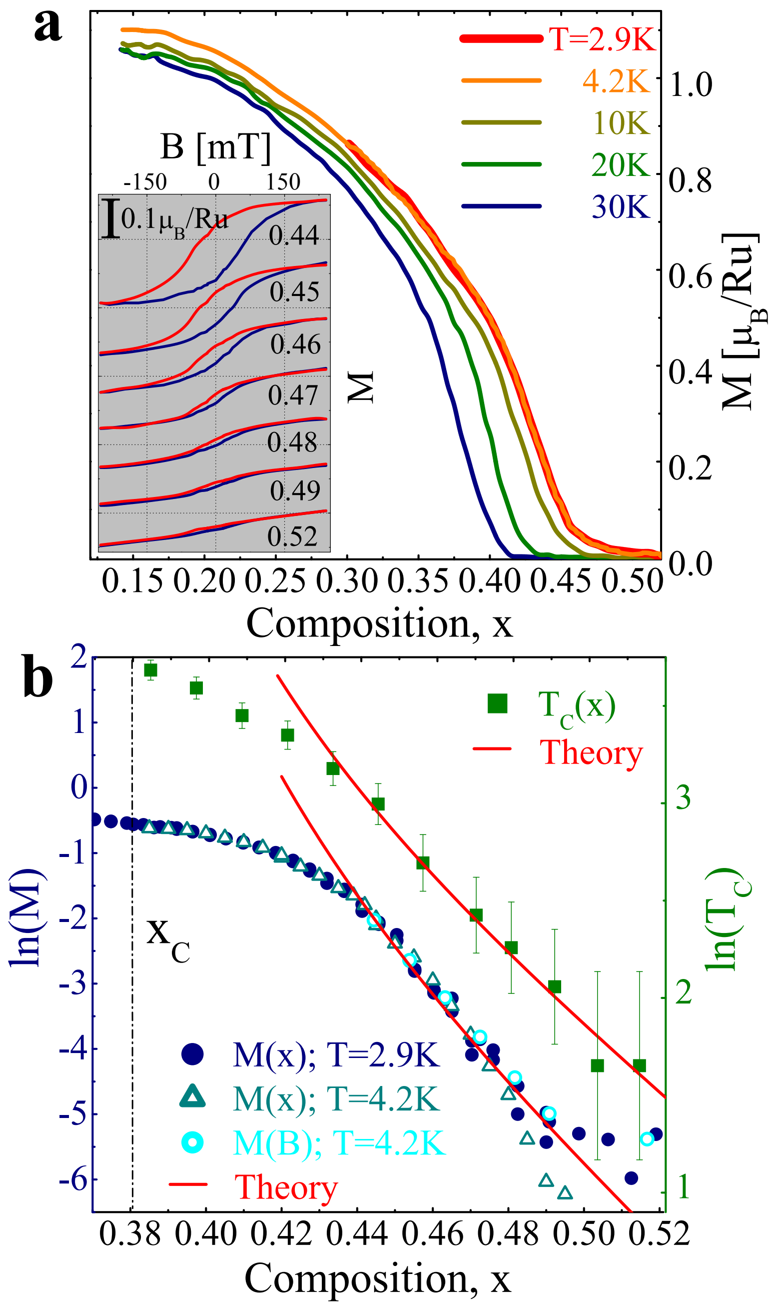
- strongly enhanced magnetic response
- susceptibility $\chi(T)$ diverges as $T \to 0$
- $\chi(T)$ and $m(H)$ follow nonuniversal power laws $\chi \sim T^{\lambda-1}, \qquad m \sim H^{\lambda}$ **(Griffiths singularities)**
- Griffiths exponent $\lambda = 1 - \gamma$ varies systematically with x
- experiments agree with **infinite-randomness** critical point scenario

quantum Griffiths phase for $x \approx 11.5$ to 15%.

Rare regions and smeared phase transition in $Sr_{1-x}Ca_xRuO_3$



Composition-tuned smeared phase transitions

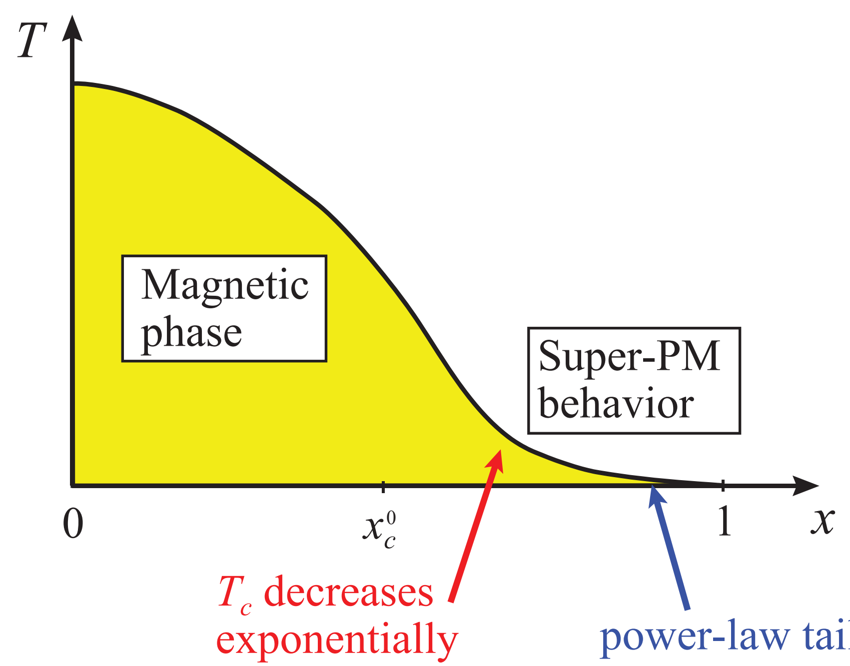


Magnetization and T_c in tail:

$$M, T_c \sim \exp\left[-C\frac{(x - x_c^0)^{2-d/\phi}}{x(1-x)}\right]$$

for $x \to 1$:

$$M, T_c \sim (1-x)^{L_{\min}^d}$$

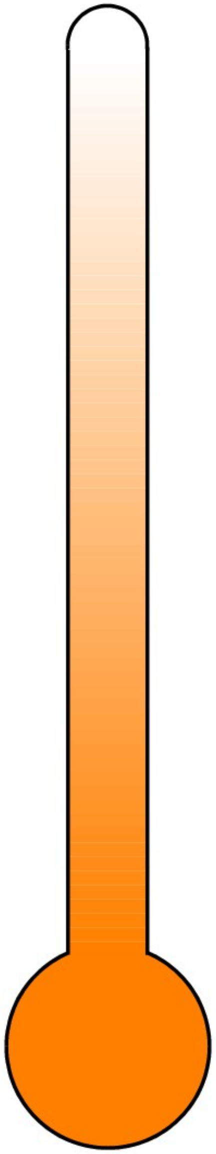


Conclusions

- **"More is different:"** condensed matter physics explores **emerging phenomena** caused by the interplay of many constituent particles
- new states of quantum matter can be found at **low temperatures** and at **boundaries** between existing phases
- quantum phase transitions occur at **zero temperature** as a function of a parameter like pressure, chemical composition, disorder, magnetic field
- quantum phase transitions are caused by **quantum fluctuations** (i.e, Heisenberg's uncertainty principle) rather than thermal fluctuations
- quantum phase transitions can have fascinating consequences including the genesis of **new phases of matter**

Quantum phase transitions provide a novel ordering principle in condensed matter physics

Wonderland at low temperatures

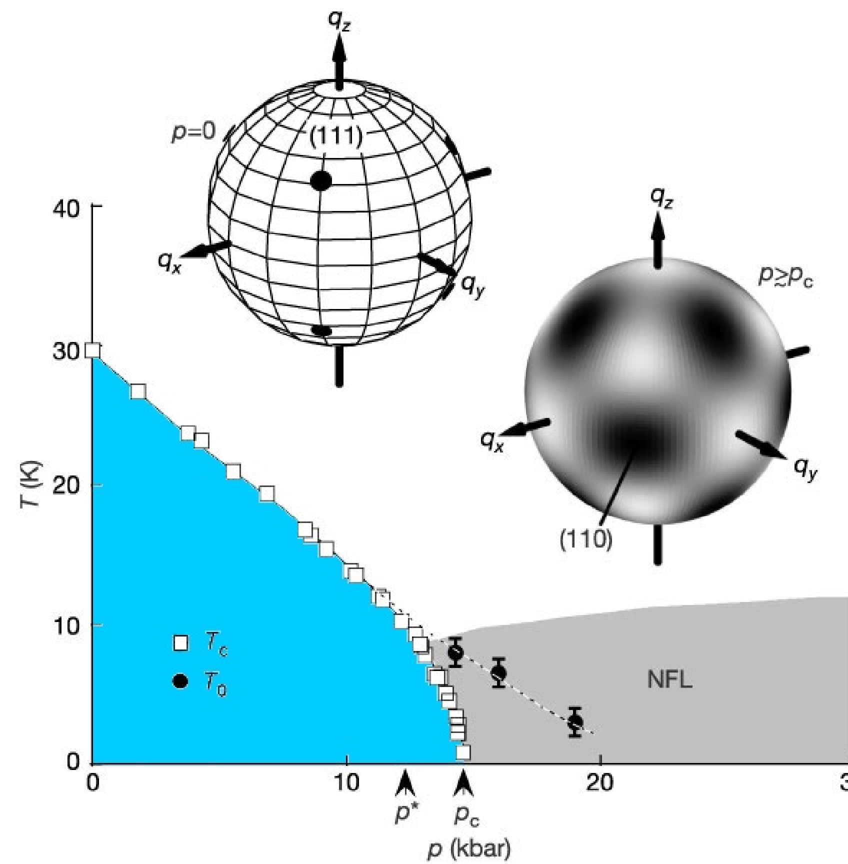


273K (0C)	water freezes
195K (-78C)	carbon dioxide sublimates (dry ice)
133K (-140C)	superconductivity in cuprate perovskites
77K (-196C)	nitrogen (air) liquefies
66K (-207C)	nitrogen (air) freezes
4.2K (-268.9C)	helium liquefies
2.2K (-270.9C)	helium becomes superfluid
170 nK	Bose-Einstein condensation of rubidium
0K (-273.1C)	***absolute zero of temperature***

Magnetic phases in MnSi

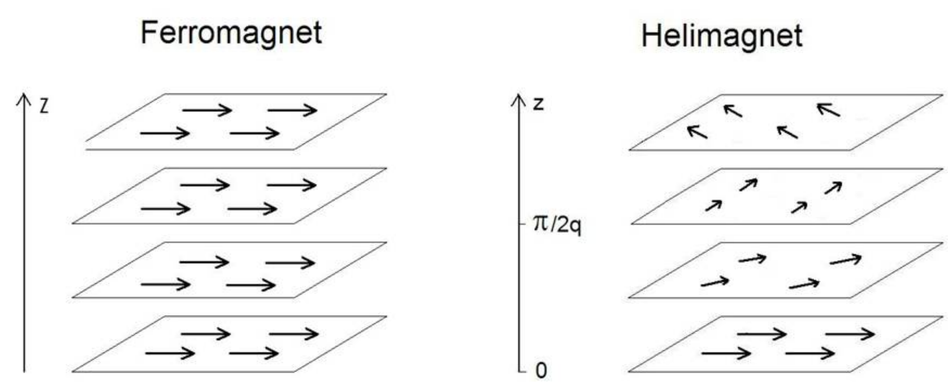
Phase diagram: (Pfleiderer et al, 2004)

- magnetic transition at 30 K at ambient pressure
- transition tunable by hydrostatic pressure
- quantum phase transition at $p_c = 14$ kbar



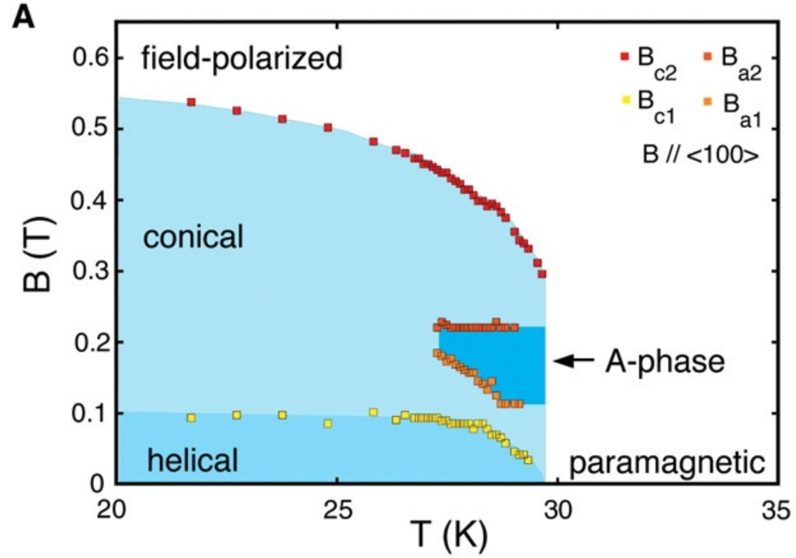
Magnetic state:

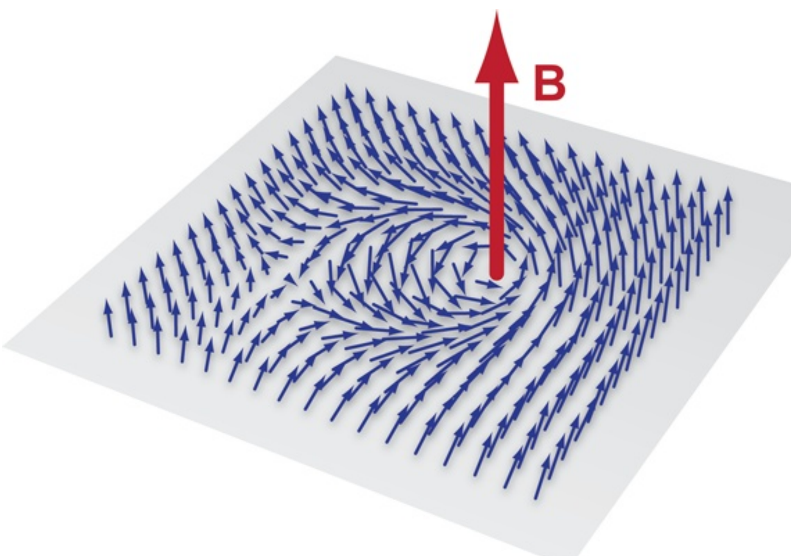
- ordered state is helimagnet with $q = 180\text{Å}$, pinned in (111) direction
- short-range order persists in paramagnetic phase, helical axis depinned

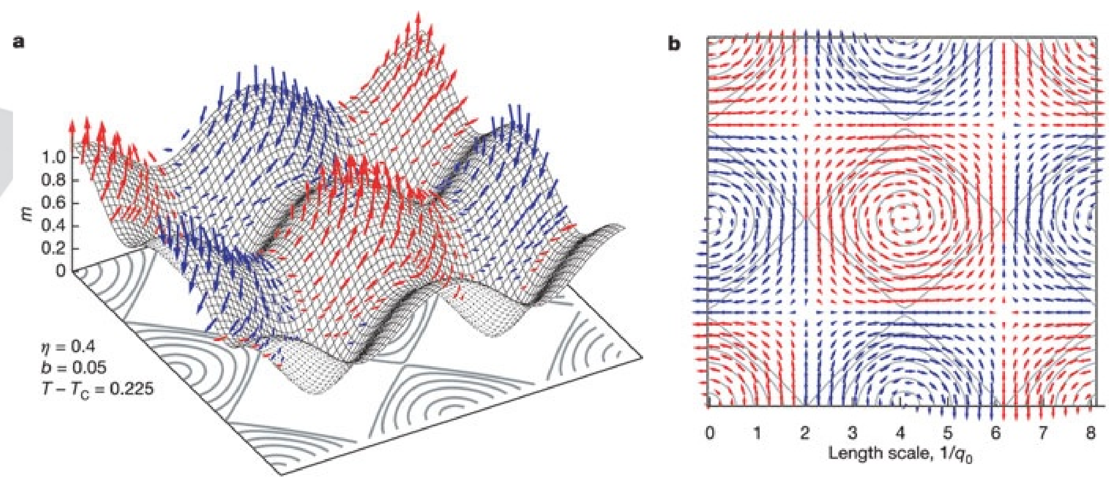


Skyrmions and skyrmion lattices

- even more exotic magnetic states occur in magnetic field B
- in "A" phase, magnetization vector forms knots, called **skyrmions**, by twisting in two directions
- these skyrmions arrange themselves into regular **skyrmion lattice**







If the critical behavior is classical at any nonzero temperature, why are quantum phase transitions more than an academic problem?

Phase diagrams close to quantum phase transition

Quantum critical point controls **nonzero-temperature** behavior in its vicinity:

Path (a): crossover between classical and quantum critical behavior

Path (b): temperature scaling of quantum critical point