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)

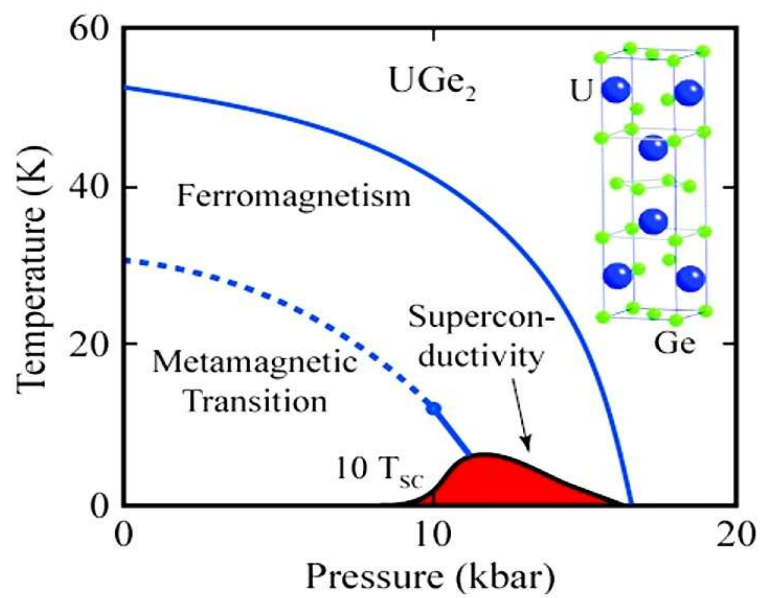
at low temperatures

$$F = E - TS$$

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

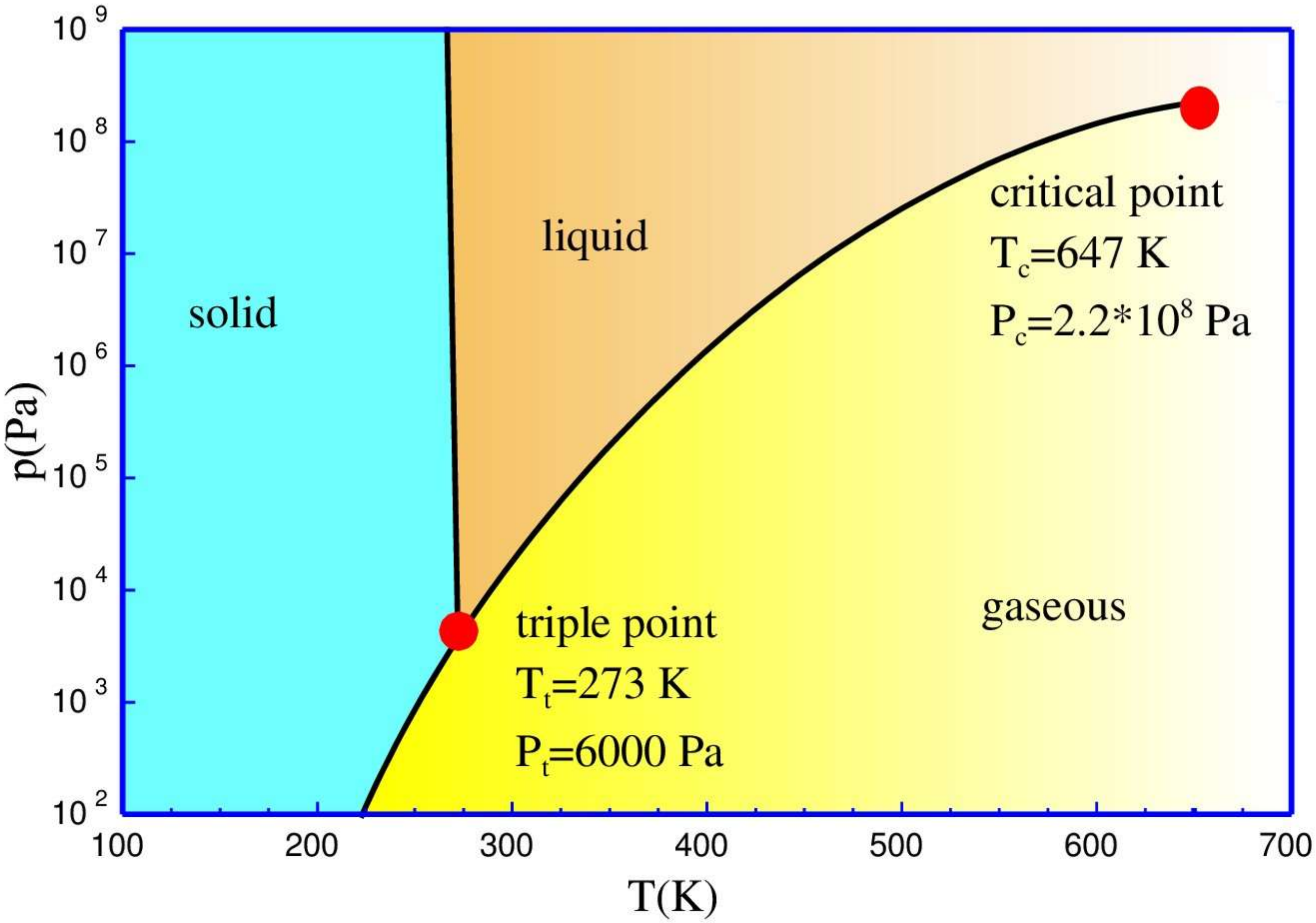
at boundaries of existing phases

- 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

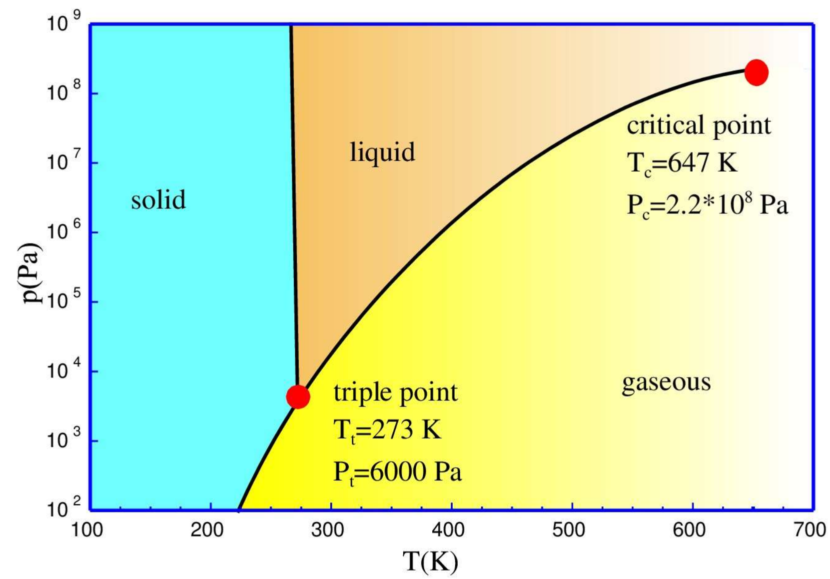
Phase diagram of water



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

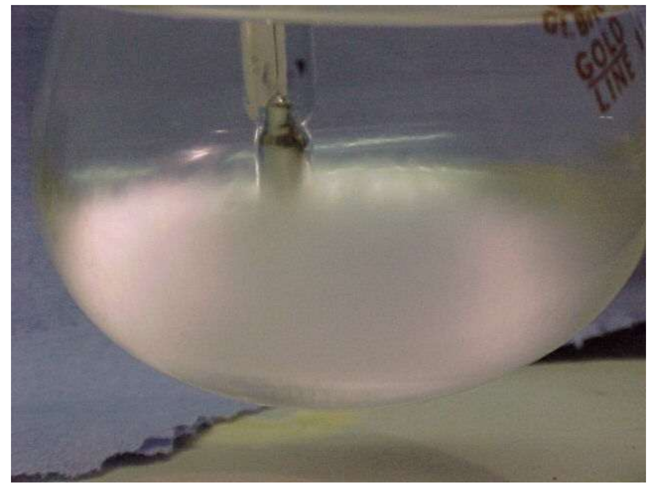
$T \to T_c$: length scale ξ of fluctuations grows

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

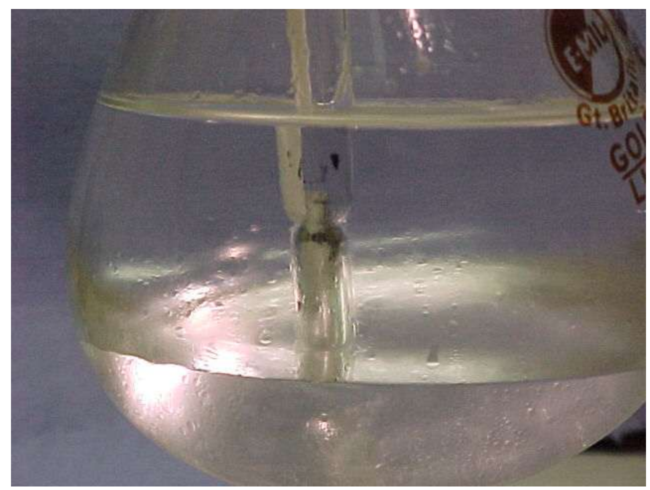
strong light scattering
fluid appears milky

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

46°C



39°C



18°C

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

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

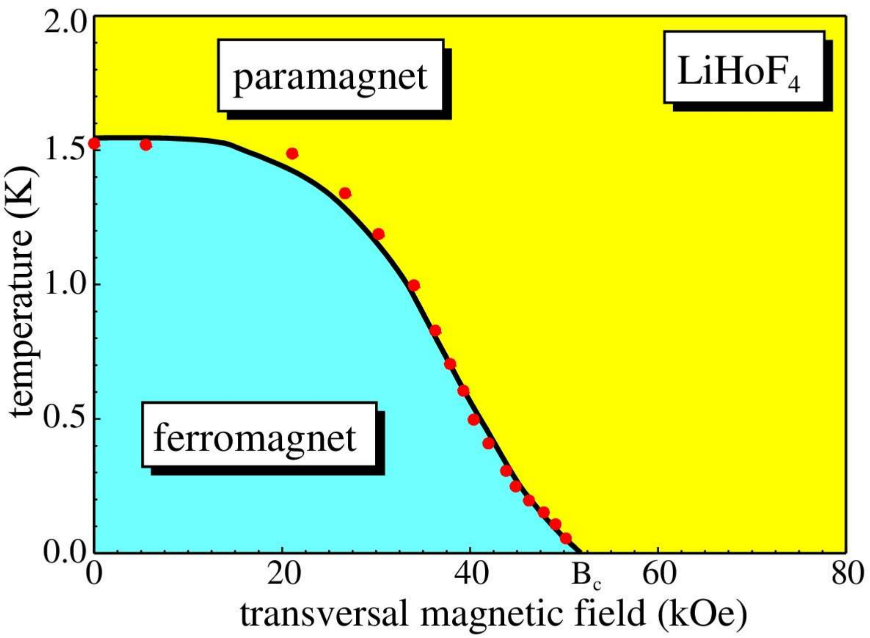
$\Rightarrow$ Quantum fluctuations **do** play a role a **zero** temperature

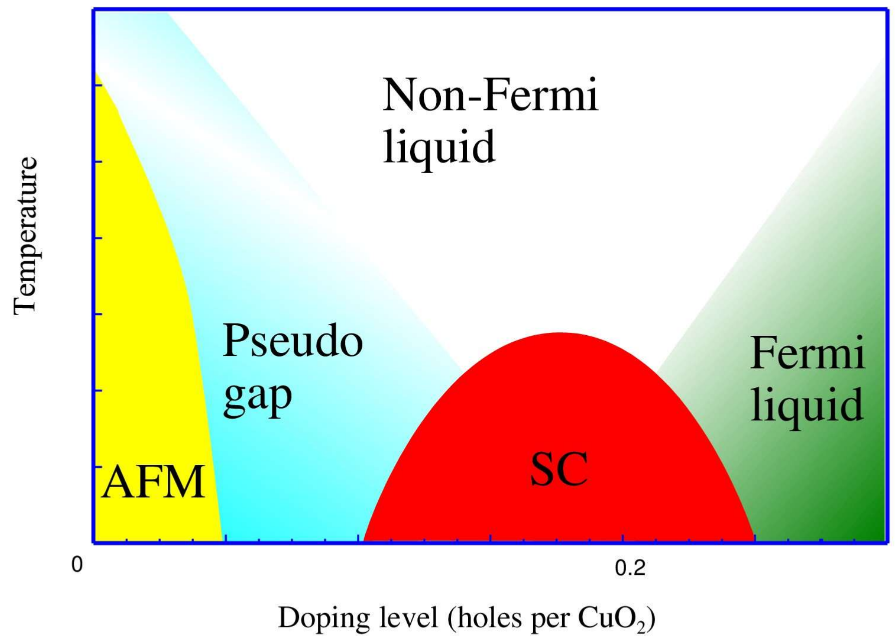
Zero-temperature continuous phase transitions constitute a special class of phase transitions, they are intrinsically quantum in nature

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



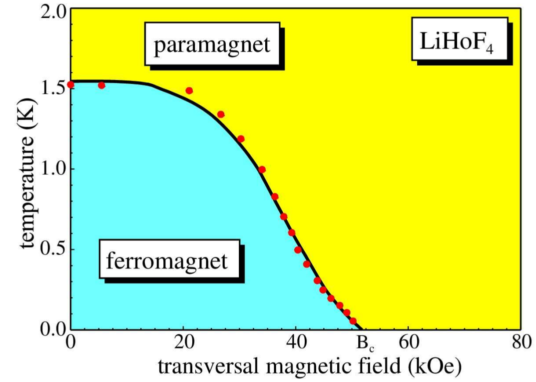


Phase diagrams of $LiHoF_4$ and a typical high-T_c superconductor such as $YBa_2Cu_3O_{6+x}$

Toy model: transverse field Ising model

Quantum spins S_i on a lattice: (c.f. $LiHoF_4$)

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



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:

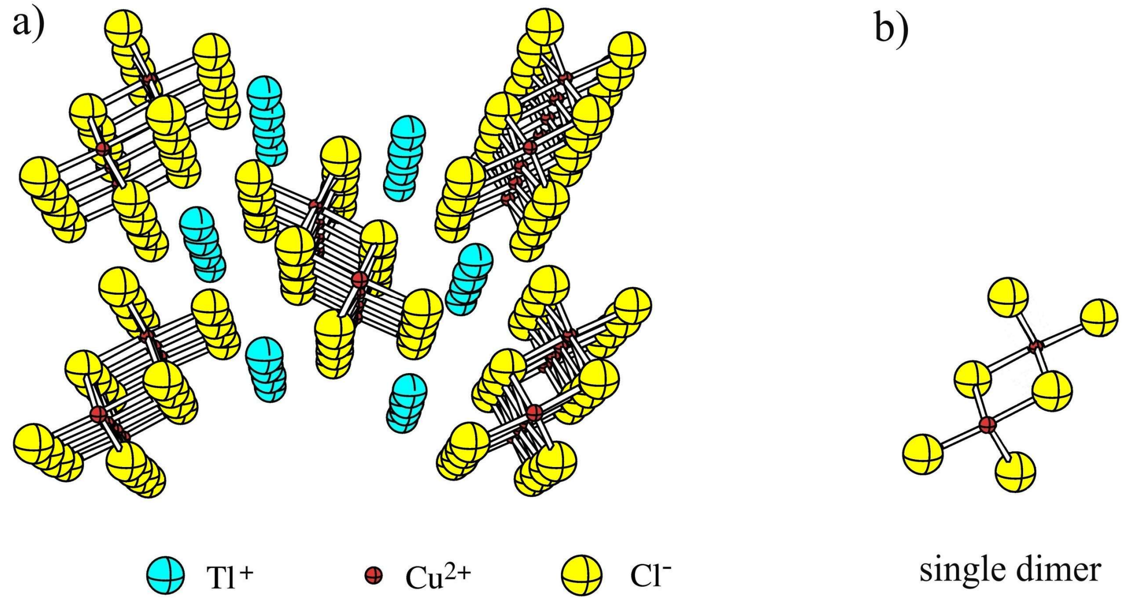
$|J| \gg |h|$ ferromagnetic ground state as in classical Ising magnet

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

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

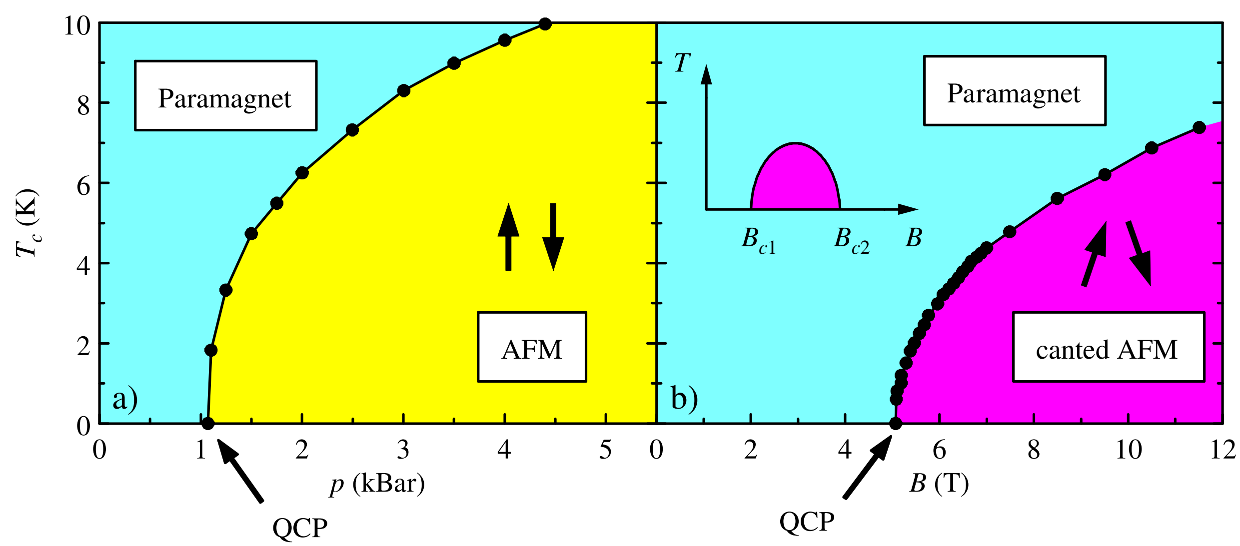
Magnetic quantum critical points of $TlCuCl_3$

- $TlCuCl_3$ 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

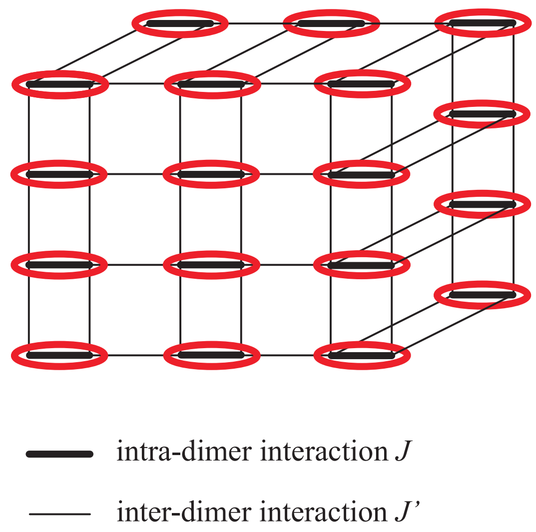


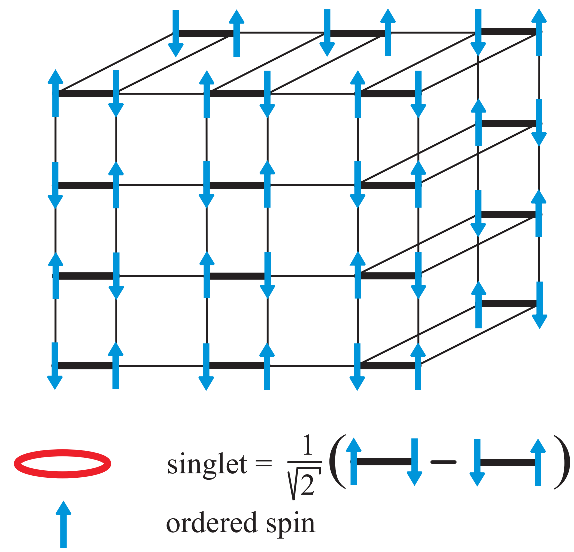
Pressure-driven quantum phase transition in $TlCuCl_3$

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)

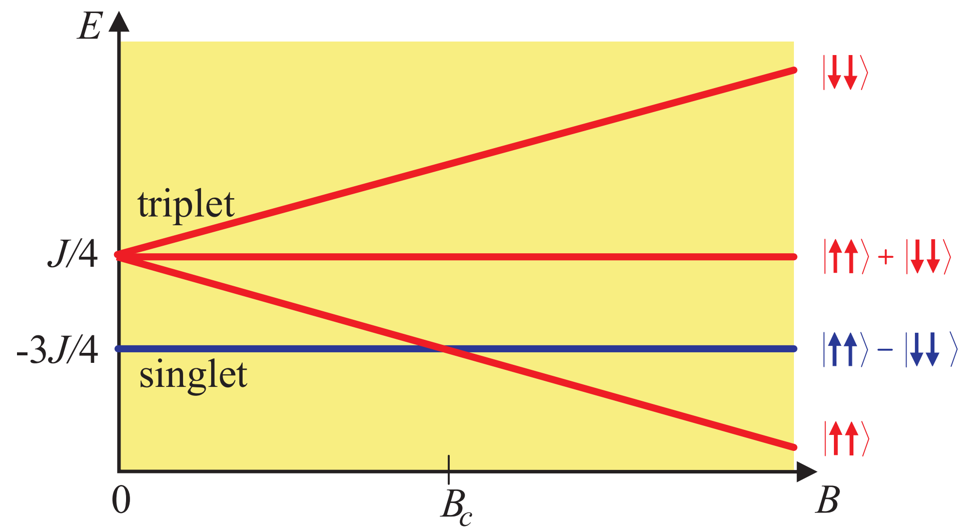
$|J| \approx |J'|$ long-range antiferromagnetic order (Néel order)
low-energy excitations are long-wavelength spin waves

$\Rightarrow$ 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 $B > B_c$

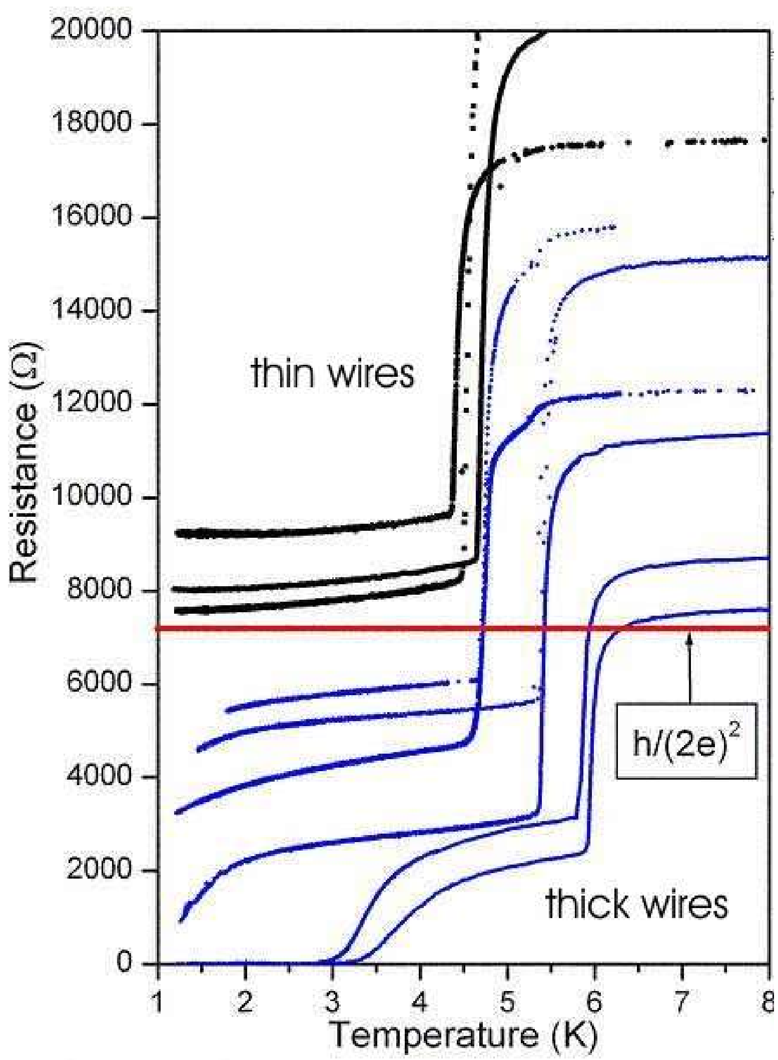


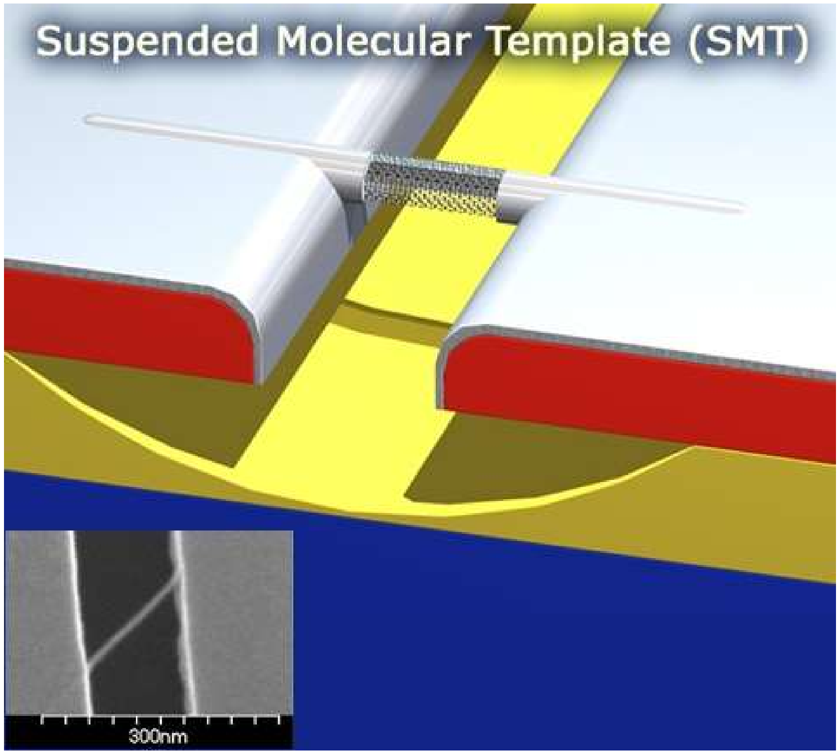
Full Hamiltonian:

- 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



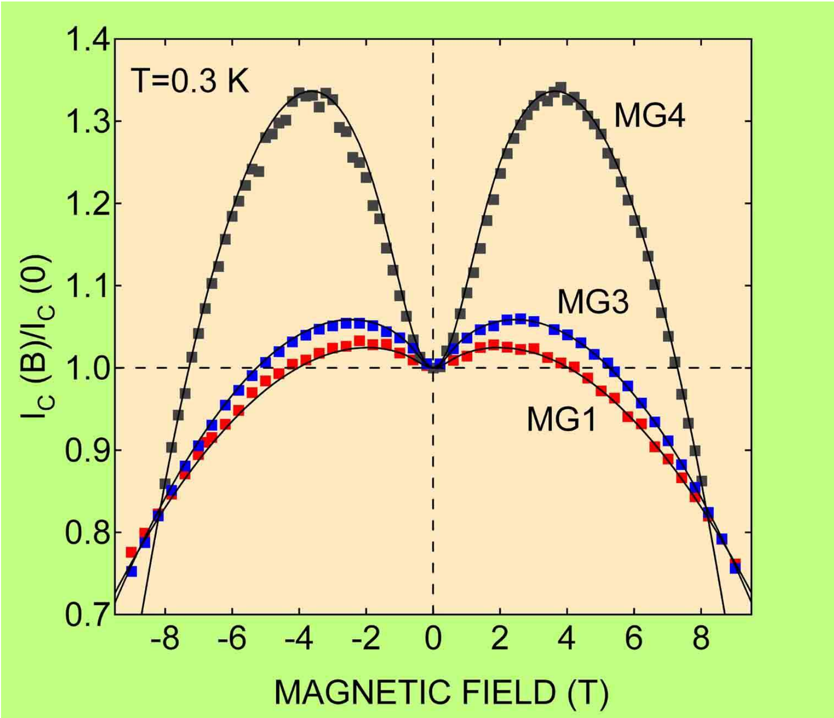


- thicker wires are superconducting at low temperatures
- thinner wires remain metallic

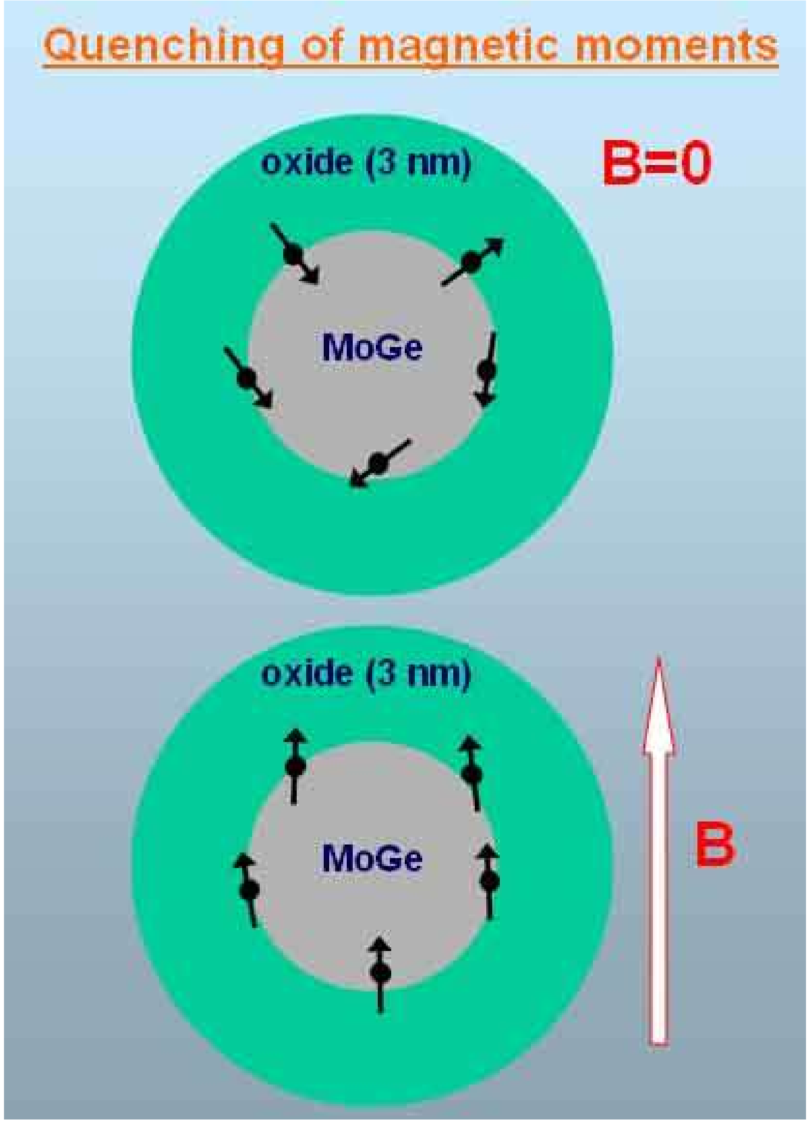
superconductor-metal QPT as function of wire thickness

Pairbreaking mechanism

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

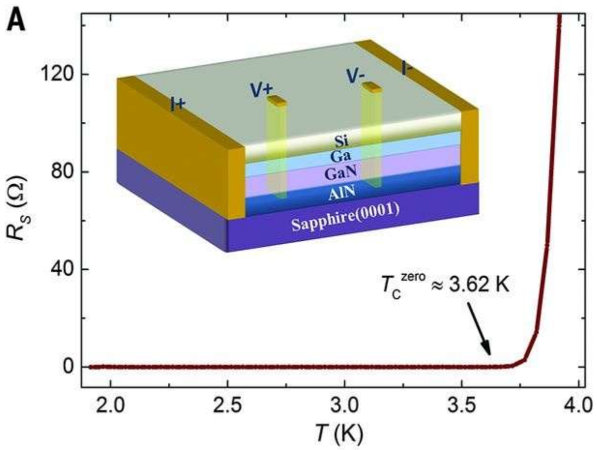


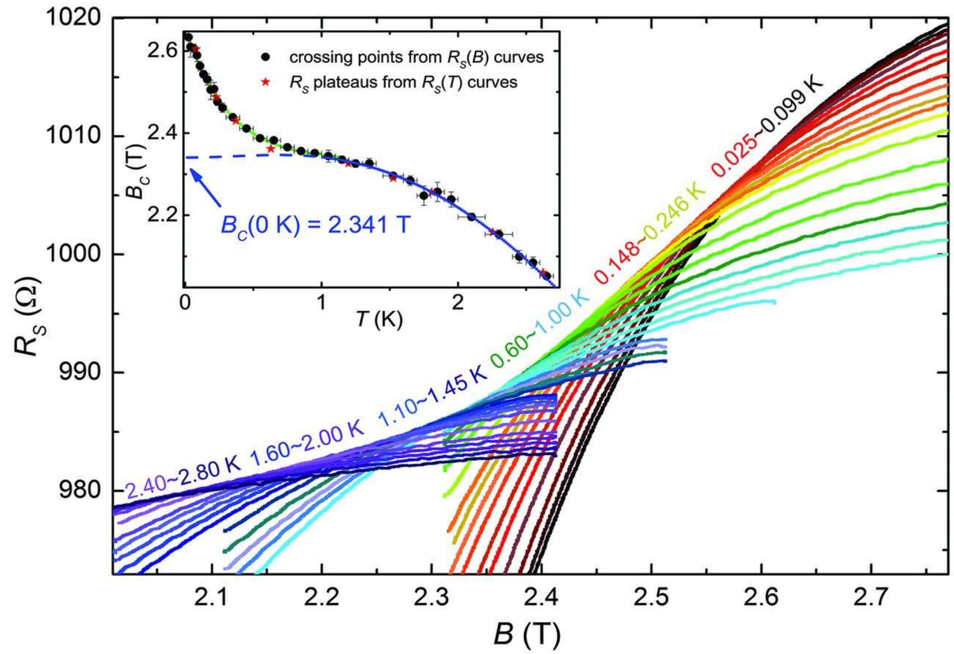
weak field enhances superconductivity



magnetic field aligns the impurities and reduces magnetic scattering

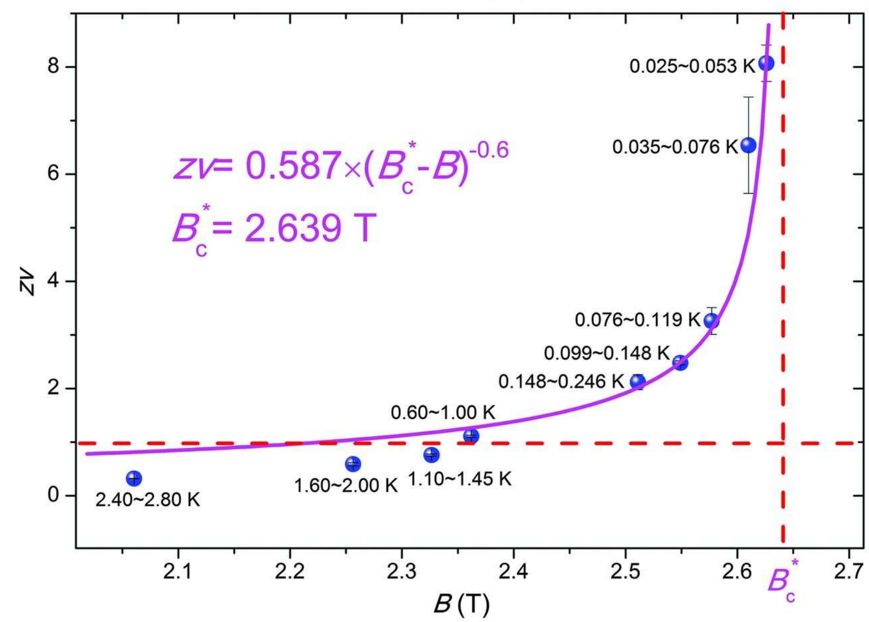
Experiment: Ga thin films



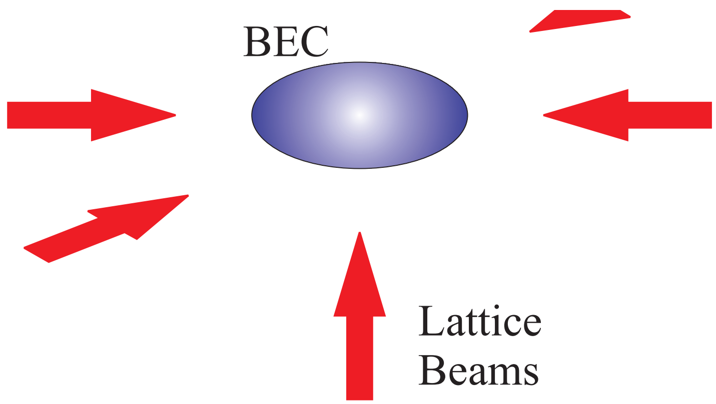


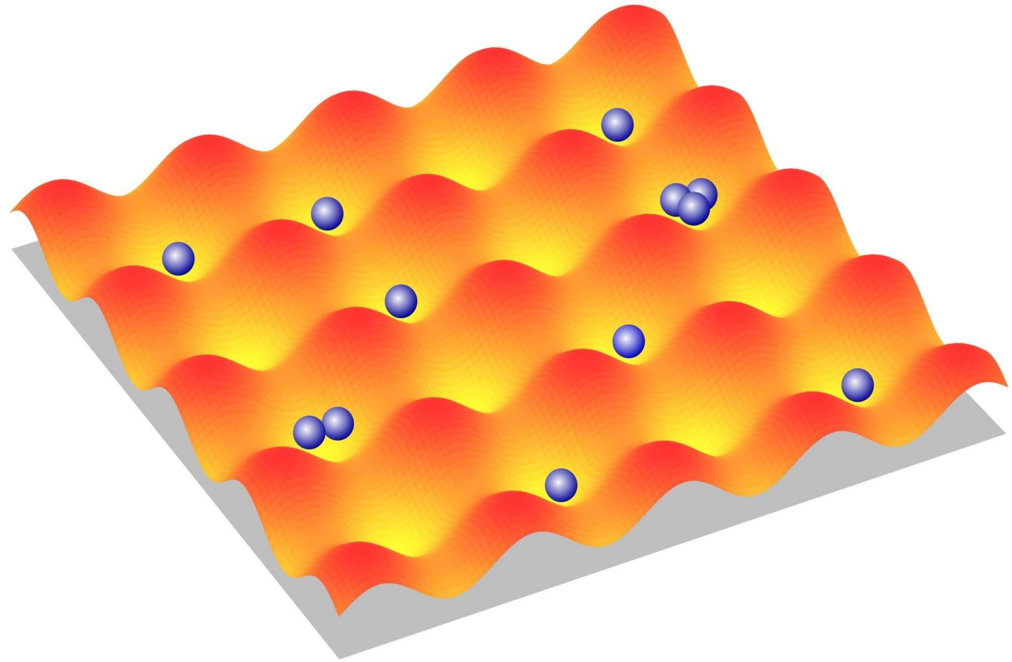
Xing et al., Science 350, 542 (2015)

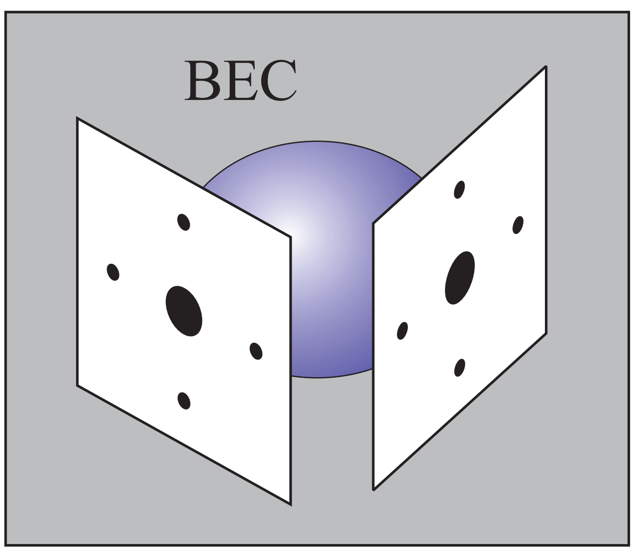
- three-monolayer Ga films
- superconductivity below $T_c \approx 3.62\text{K}$, suppressed by magnetic field
- field-driven QPT well described by **2D infinite-randomness critical point**
- dynamical exponent **diverges** as $z \sim |B - B_c|^{-\nu\psi}$ with $\nu \approx 1.2, \psi \approx 0.5$

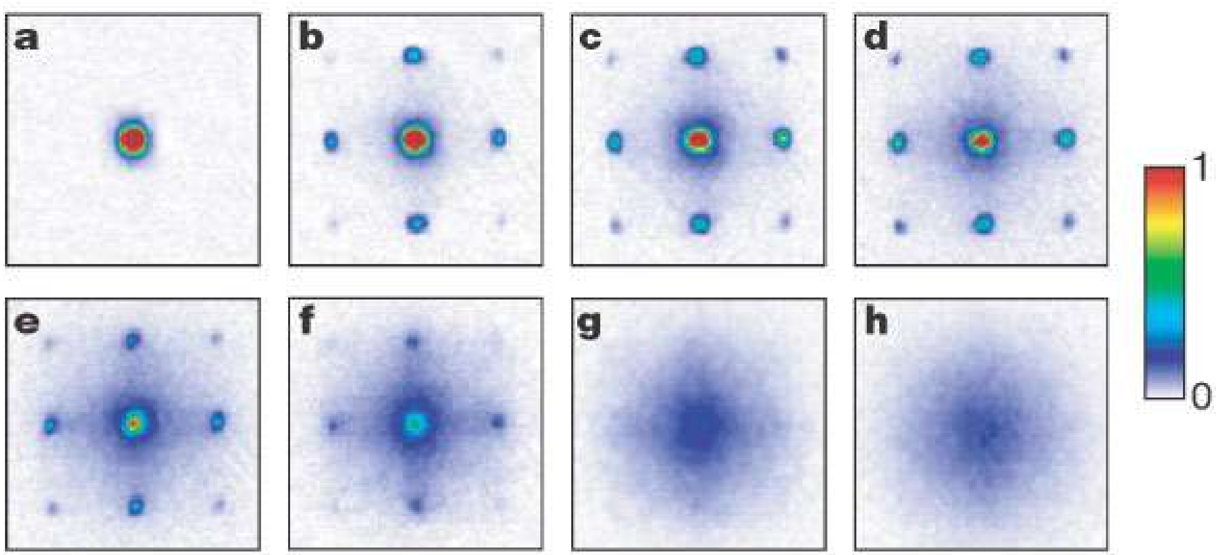


Mott transition in a Bose-Einstein condensate







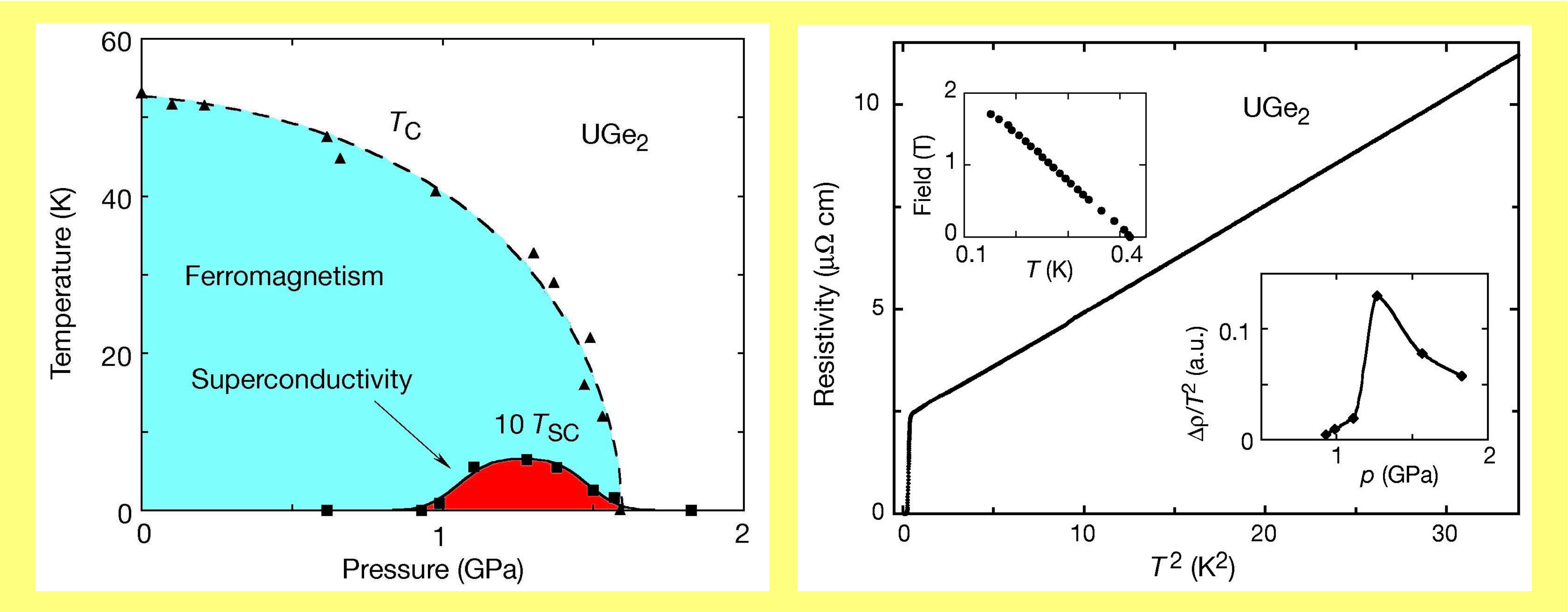


- Condensed matter physics: complexity and emerging phenomena
- Phase transitions and quantum phase transitions
- **Novel phases close to quantum critical points**

Exotic superconductivity in UGe_2

Phase diagram:

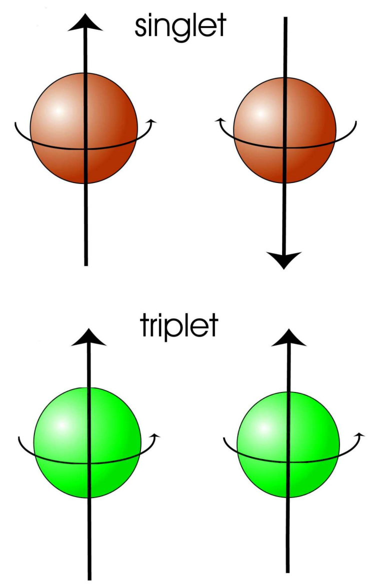
- phase diagram of UGe_2 has pocket of **superconductivity** close to ferromagnetic quantum phase transition (electrical resistivity **vanishes** below about 1K)
- in this pocket, UGe_2 is **ferromagnetic and superconducting** at the same time
- superconductivity appears only in superclean samples



Character of superconductivity in UGe_2

not compatible with conventional (BCS) superconductivity:

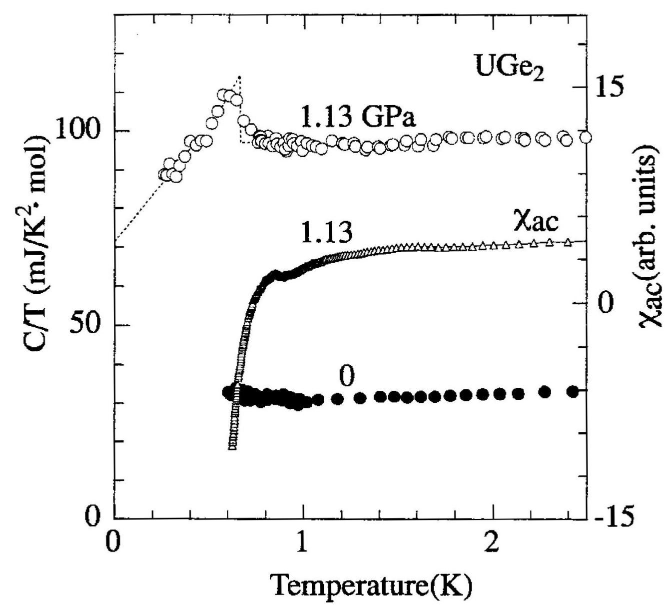
- in superconductor, electrons form (Cooper) pairs of spin-up and spin-down electrons
- ferromagnetism requires majority of spins to be in one direction



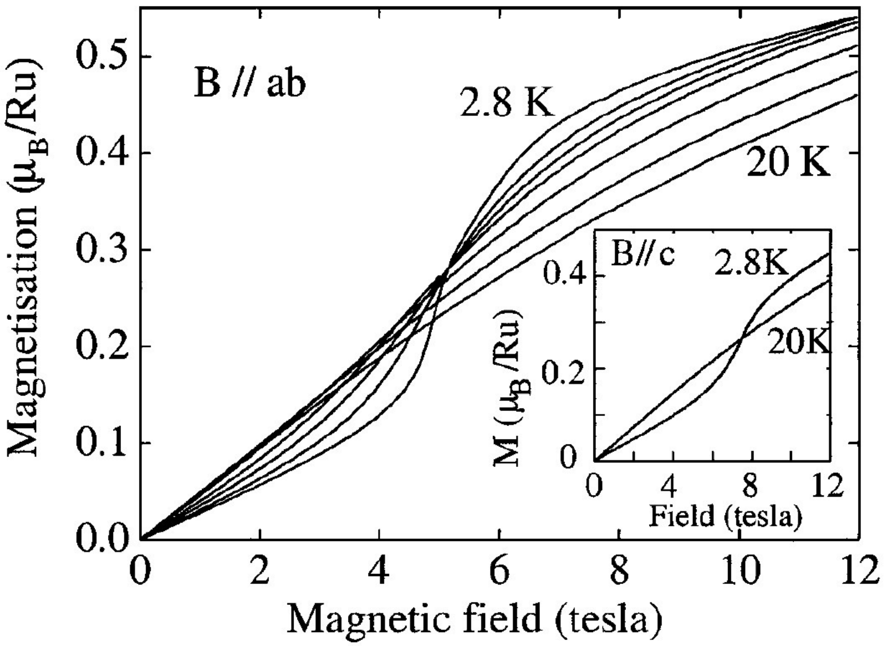
theoretical ideas:

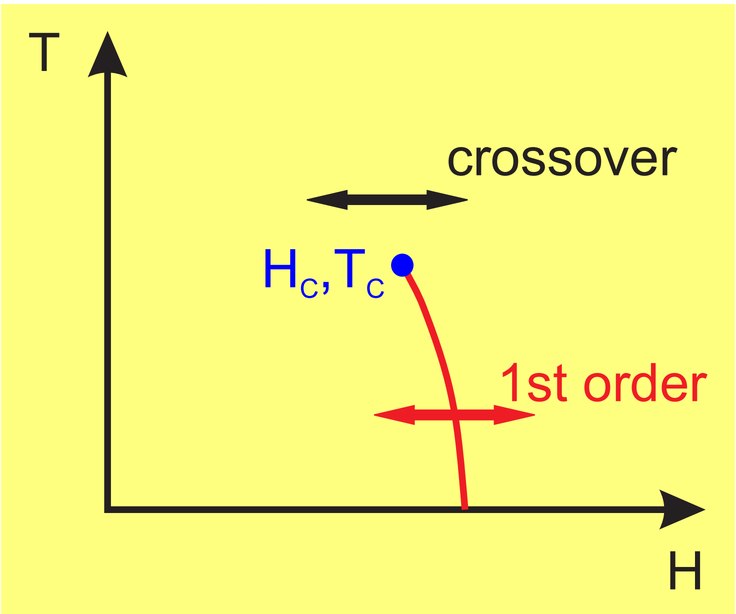
- phase separation (layering or disorder): **NO!**
- partially paired FFLO state: **NO!**
- spin triplet pairs with odd spatial symmetry, magnetic fluctuations promote this type of pairing

Magnetic quantum phase transition induces spin-triplet superconductivity



Metamagnetic transition in $Sr_3Ru_2O_7$

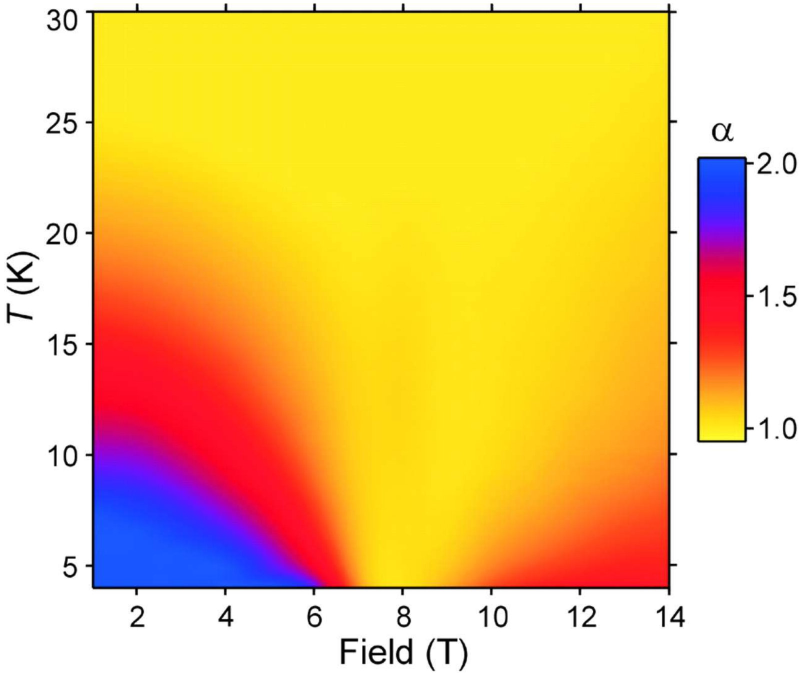




- $Sr_3Ru_2O_7$ undergoes metamagnetic transition as function of field
- critical endpoint can be tuned to $T = 0$ by tilting the field

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

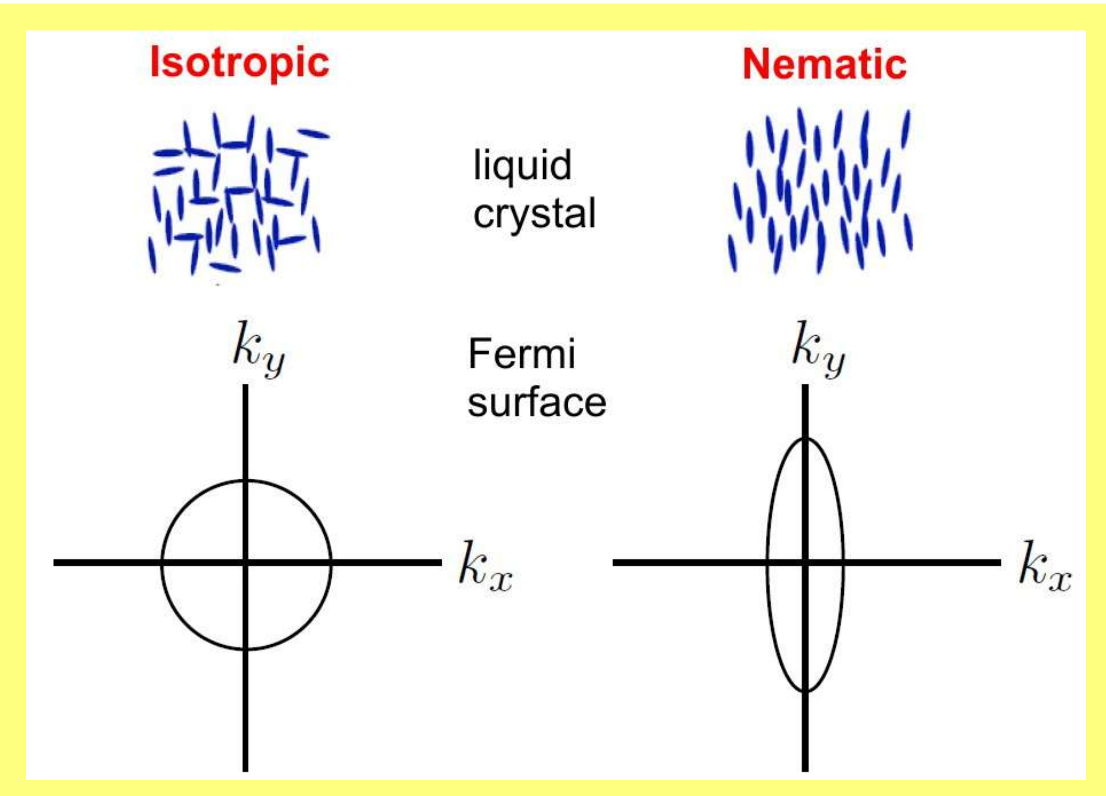
- seen in temperature dependence of resistivity $\rho = \rho_0 + AT^{\alpha}$

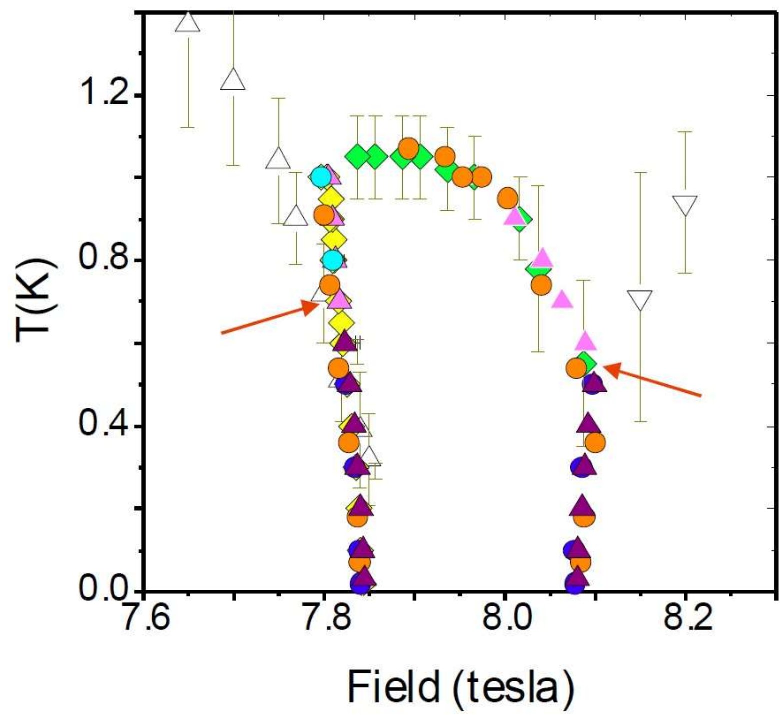


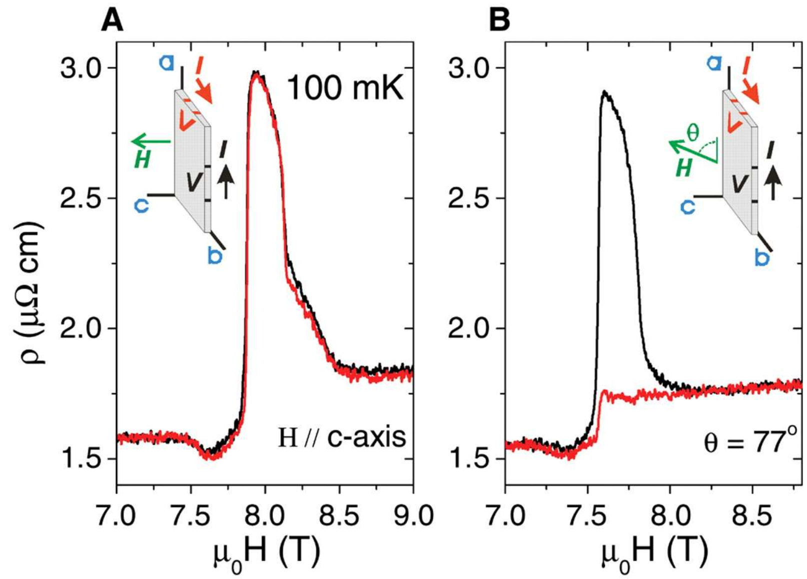
Electronic nematic phase in $Sr_3Ru_2O_7$

- 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)



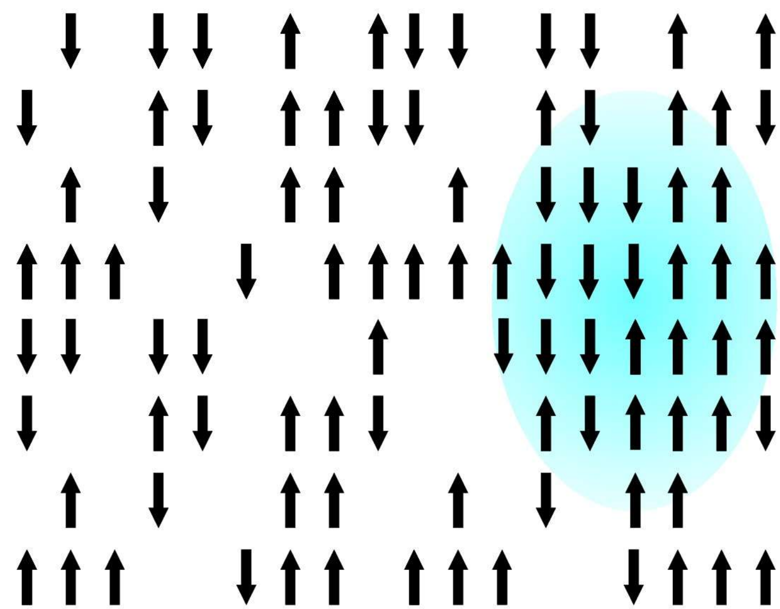


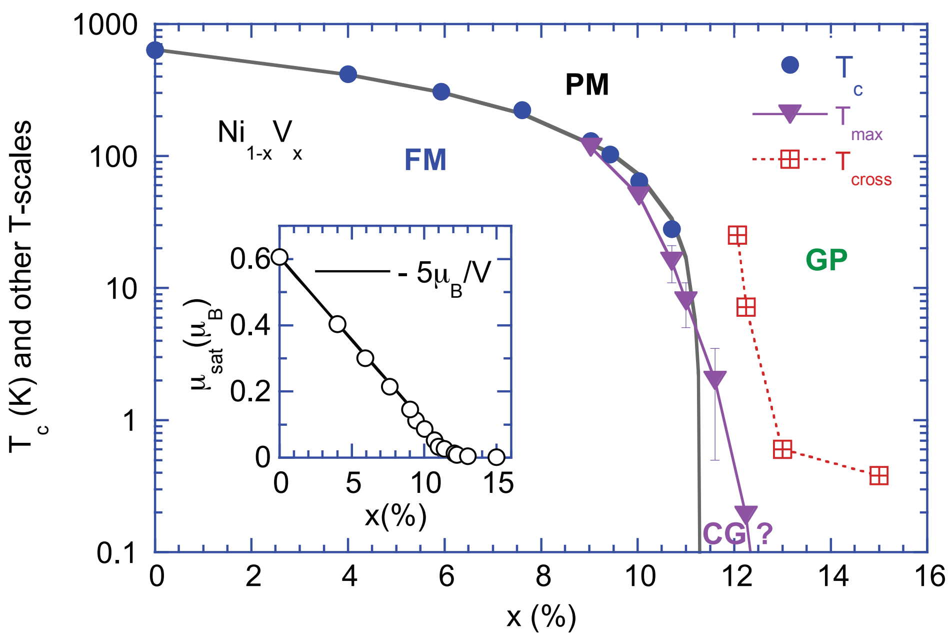


Disorder and Griffiths phases

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



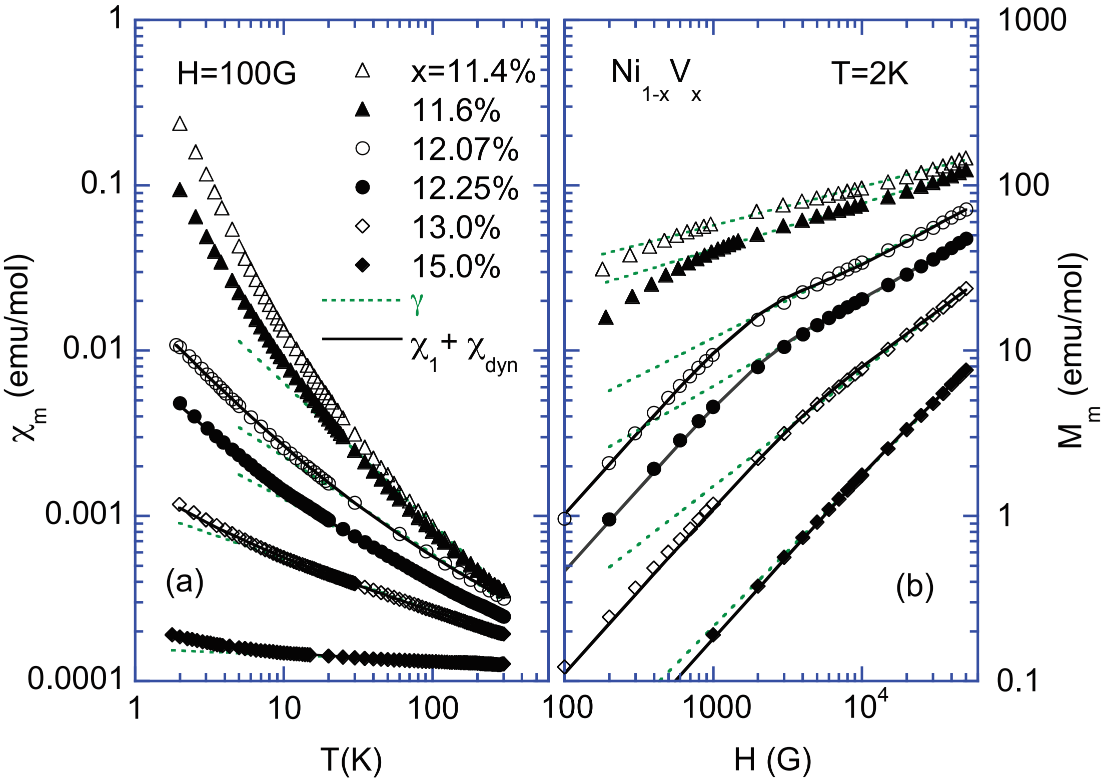


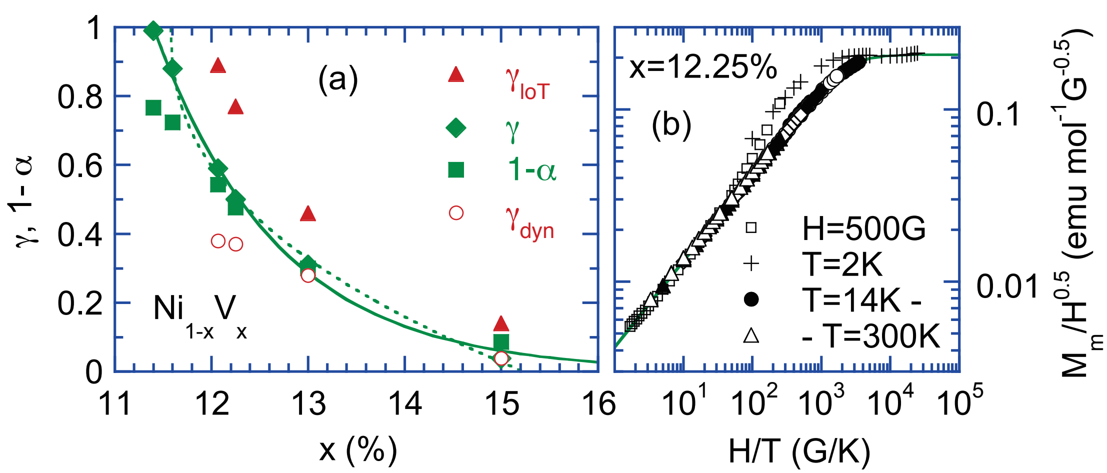
Can rare regions dominate the thermodynamic response?

$\Rightarrow$ **quantum Griffiths phase**

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

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



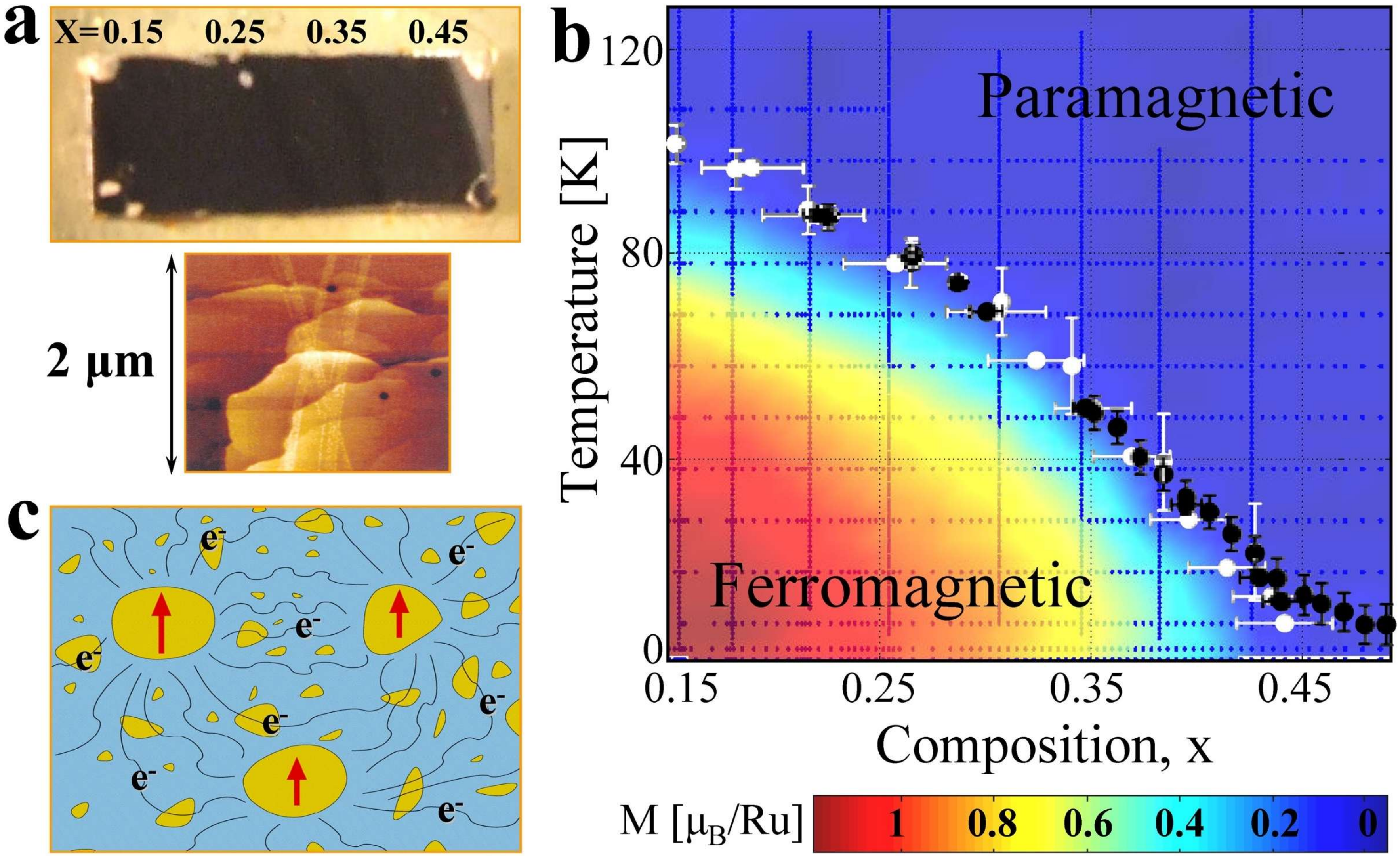


at concentrations above x_c:

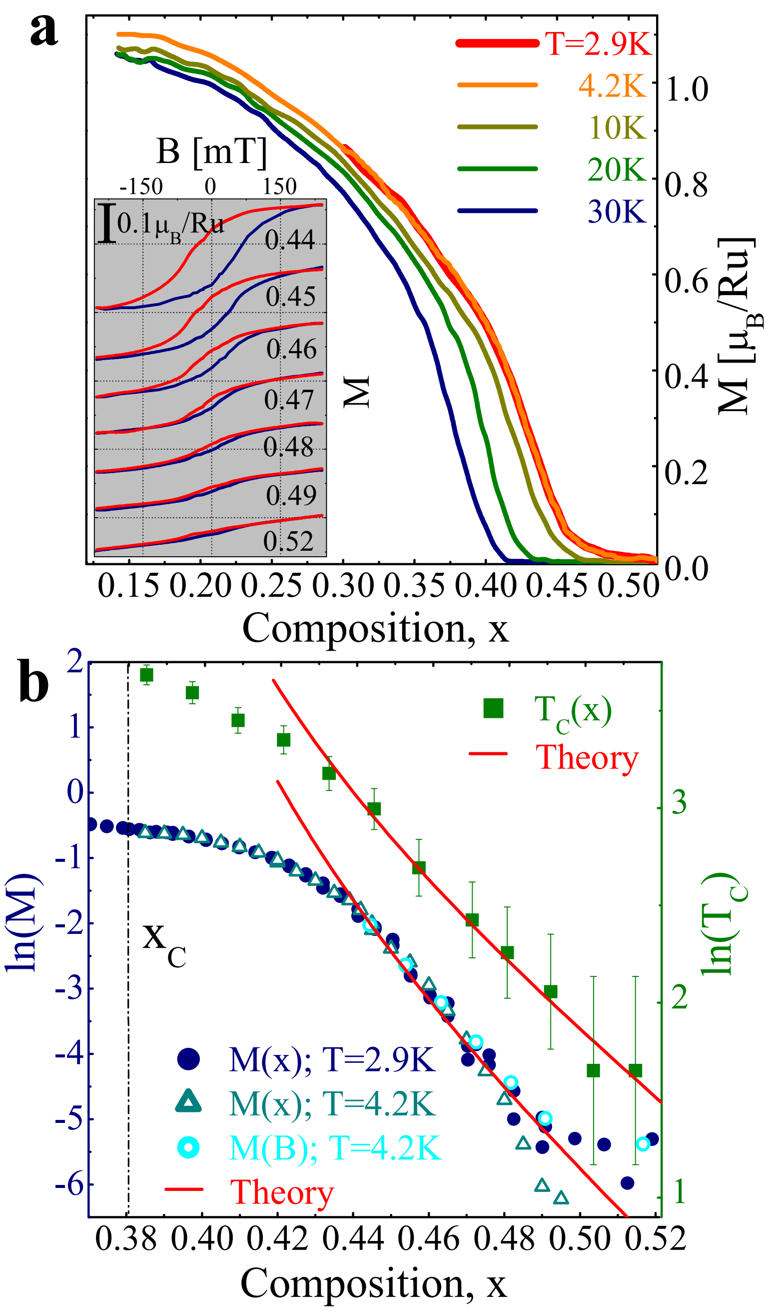
- strongly enhanced magnetic response
- susceptibility $\chi(T)$ diverges as $T \to 0$
- $\chi(T)$ and $m(H)$ follow nonuniversal power laws $\chi \sim T^{\lambda-1}, \qquad m \sim H^{\lambda}$ **(Griffiths singularities)**
- Griffiths exponent $\lambda = 1 - \gamma$ varies systematically with x
- experiments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

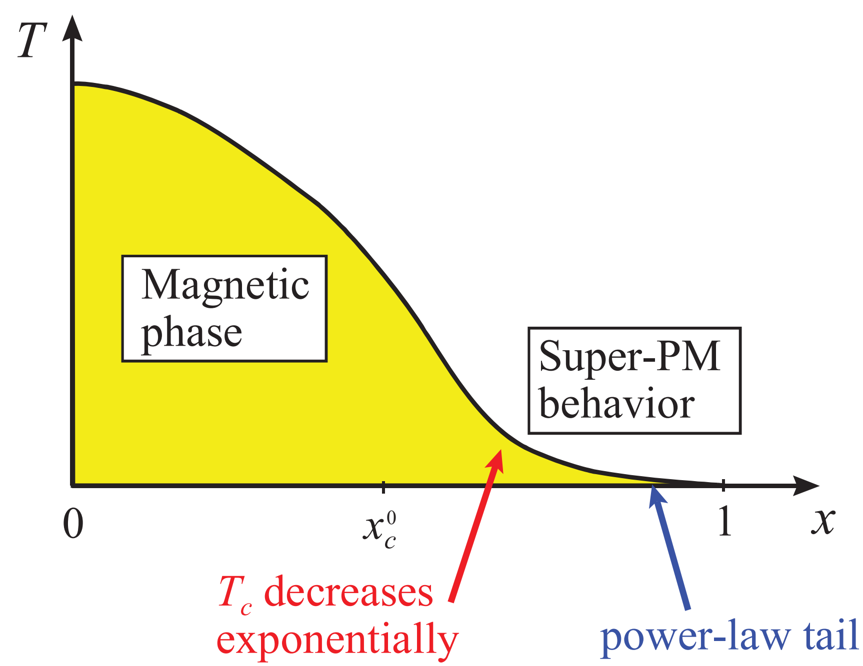


Magnetization and T_c in tail:

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

for $x \to 1$:

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

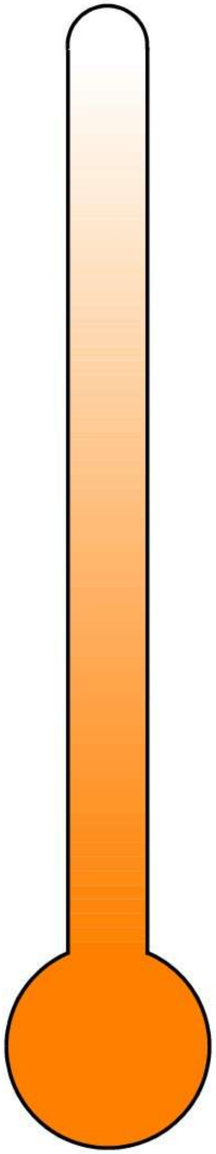


Conclusions

- **"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

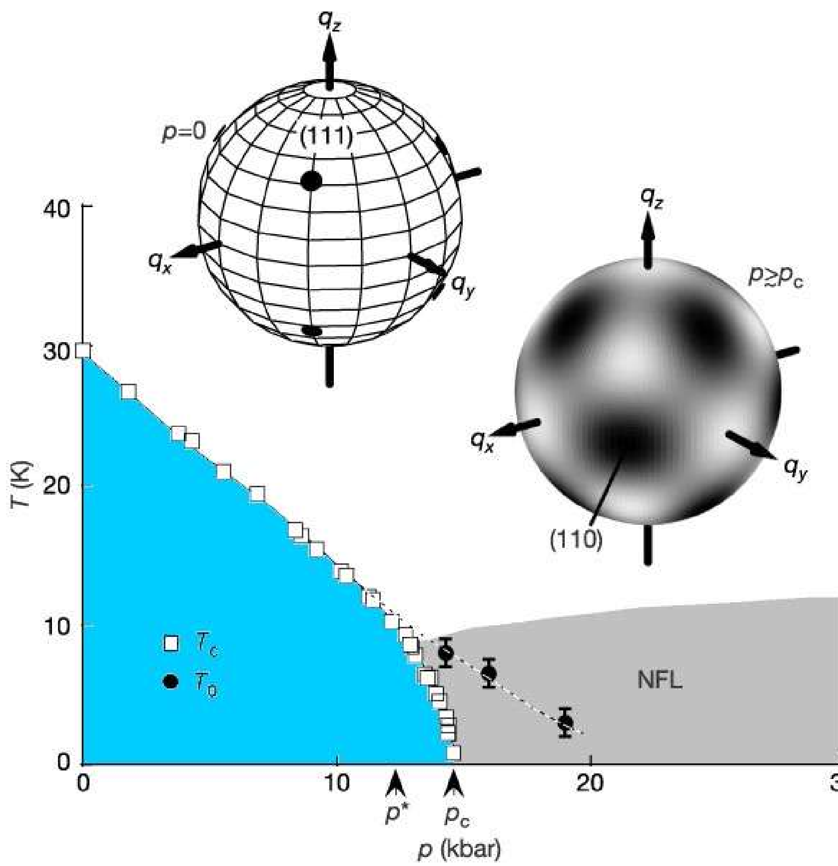


273K (0C)	water freezes
195K (-78C)	carbon dioxide sublimates (dry ice)
133K (-140C)	superconductivity in cuprate perovskites
77K (-196C)	nitrogen (air) liquefies
66K (-207C)	nitrogen (air) freezes
4.2K (-268.9C)	helium liquefies
2.2K (-270.9C)	helium becomes superfluid
170 nK	Bose-Einstein condensation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

Magnetic phases in MnSi

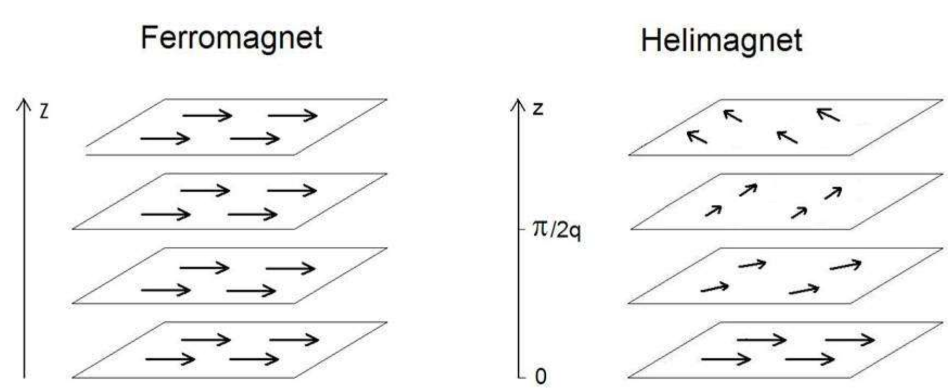
Phase diagram: (Pfleiderer et al, 2004)

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



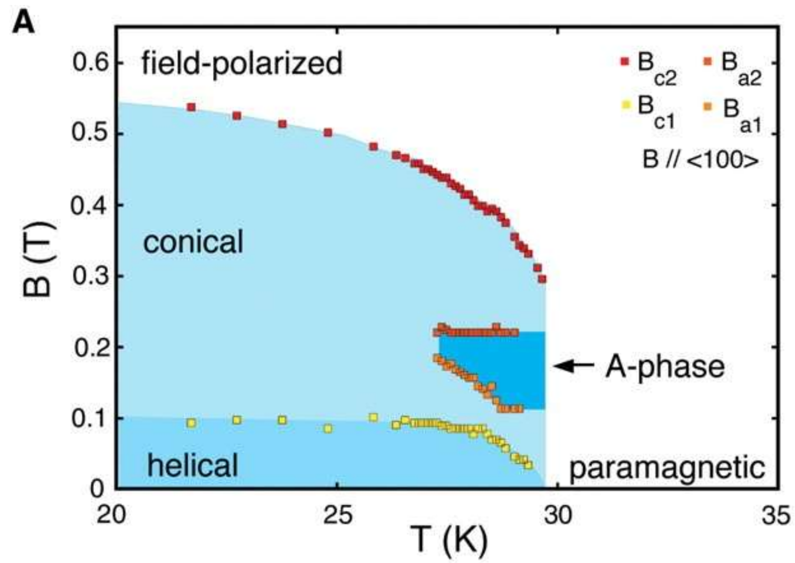
Magnetic state:

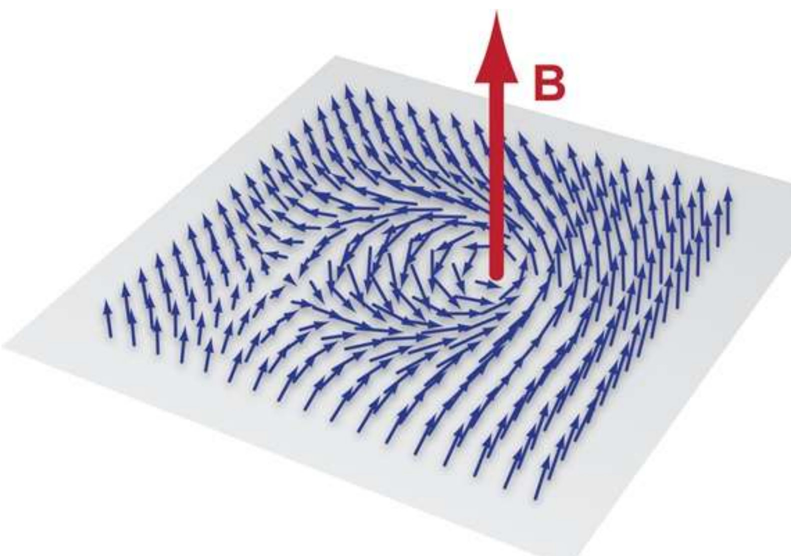
- ordered state is helimagnet with $q = 180$Å, pinned in (111) direction
- short-range order persists in para-magnetic phase, helical axis depinned

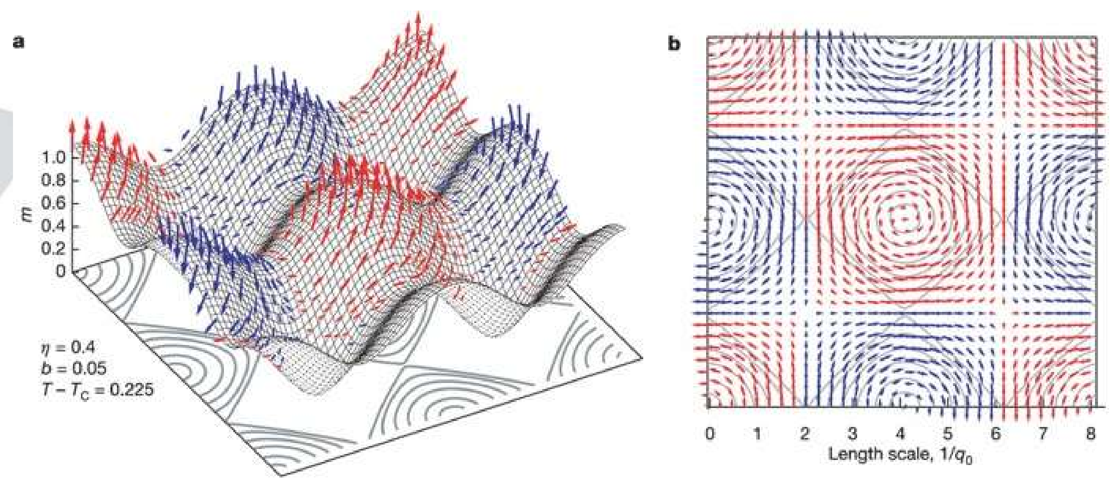


Skyrmions and skyrmion lattices

- 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