Title: Reaching Experimentally Quantum Criticality: A Playground to Explore Novel Correlated Quantum States of Matter

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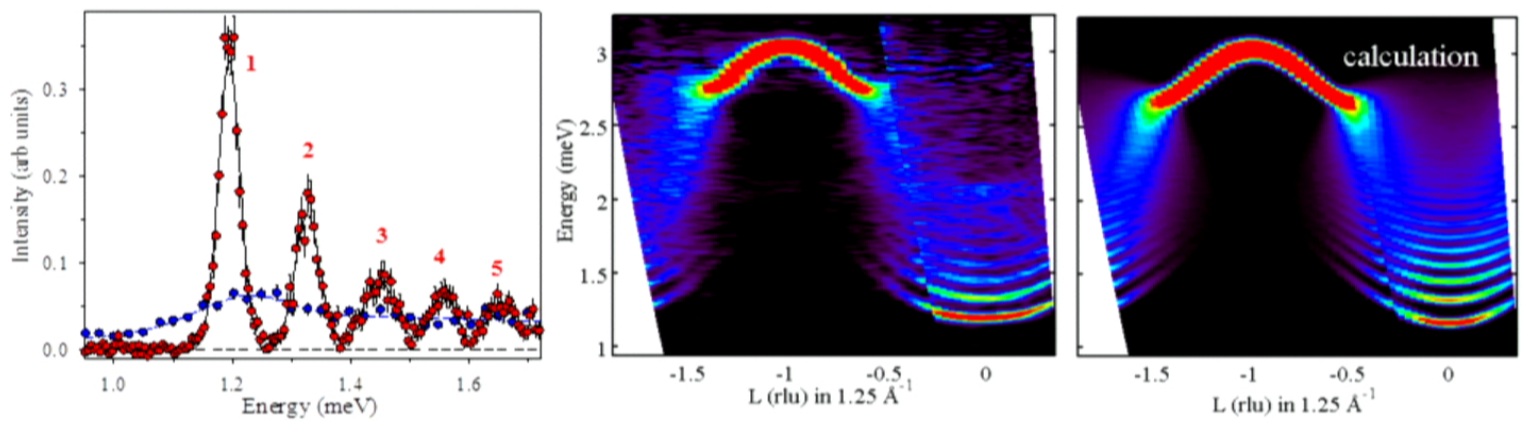
Abstract: <span>Realizing experimentally continuous phase transitions in the electronic ground state of materials near zero temperature as a function of tuning some external parameter (magnetic field, pressure etc.) offers a unique opportunity to probe the extreme regime (near the transition point) where strong quantum correlations encompass the macroscopic sample as a whole, so called â€œquantum criticalityâ€• [1]. In this regime of strong correlations small perturbations/interactions can stabilize novel forms order or collective fluctuations that otherwise do not exist. One of the theoretically most studied paradigms for quantum criticality is a chain of Ising spins driven by a transverse field to a critical point separating spontaneous magnetic order and paramagnetic phases. We have realized this system experimentally by applying strong magnetic fields to the quasi-one-dimensional Ising ferromagnet CoNb2O6 and have probed via single-crystal inelastic neutron scattering the evolution of the magnetic order and spin excitation spectrum as a function of applied field at mili-Kelvin temperatures [2]. Near the critical point the spin excitations were theoretically predicted nearly two decades ago to have a set of quantum resonances (collective modes of vibration of the interacting spins) with universal ratios between their frequencies reflecting an exceptional mathematical structure of the quantum many-body eigenstates with a â€œhiddenâ€• E8 symmetry governing the physics in the scaling limit. Experiments indeed observed evidence for a spectrum of resonances and the ratio between the frequencies of the two lowest modes approached the "golden ratio" near the critical point, as predicted by field theory. As a second example of novel physics near quantum criticality I will discuss how an amplitude-modulated incommensurate spin-density wave (SDW) order appears near the field-induced critical point in the quasi-1D spin-1/2 XY antiferromagnet Cs2CoCl4. Incommensurate SDWs are very uncommon in magnetic insulators and are not stable zero-temperature ground states at the classical mean-field level, we propose that here such a state is stabilized by the strong quantum fluctuations associated with the proximity to the critical point and the weak frustrated inter-chain couplings.

Reaching experimentally quantum criticality: a playground to explore novel correlated quantum states of matter

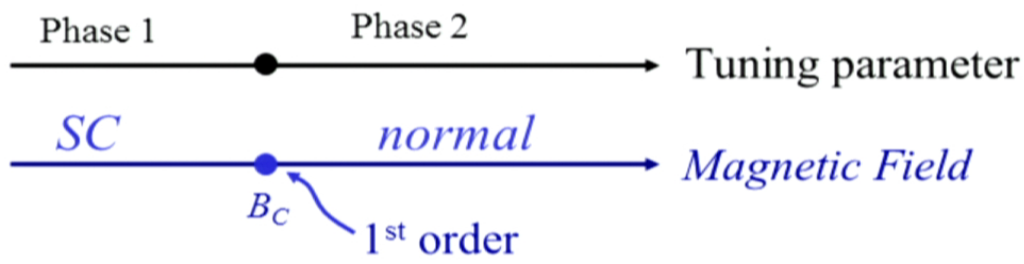
Radu Coldea (Oxford)



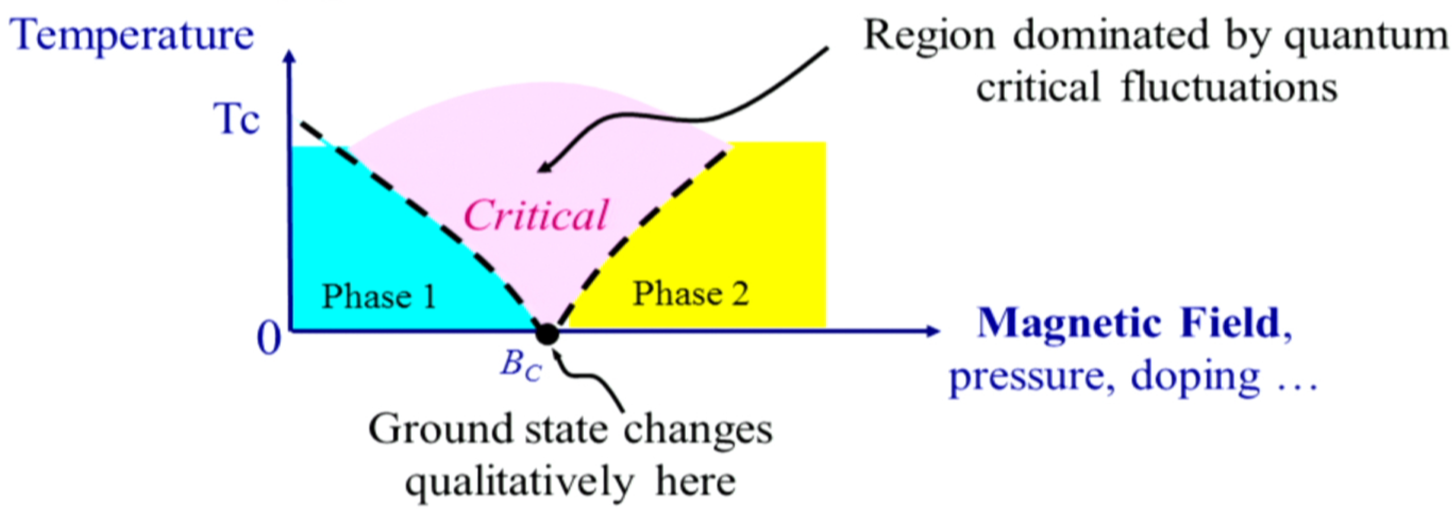
Quantum Phase Transitions

- any T=0 transition

Example:
Type I superconductors



- richer physics if transition is **continuous**
- transition driven by **quantum** fluctuations



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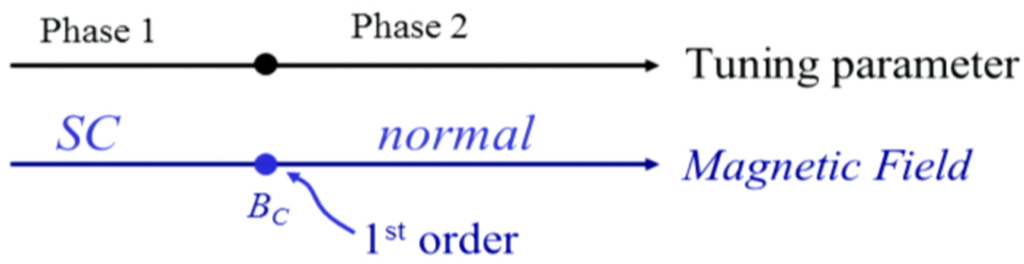

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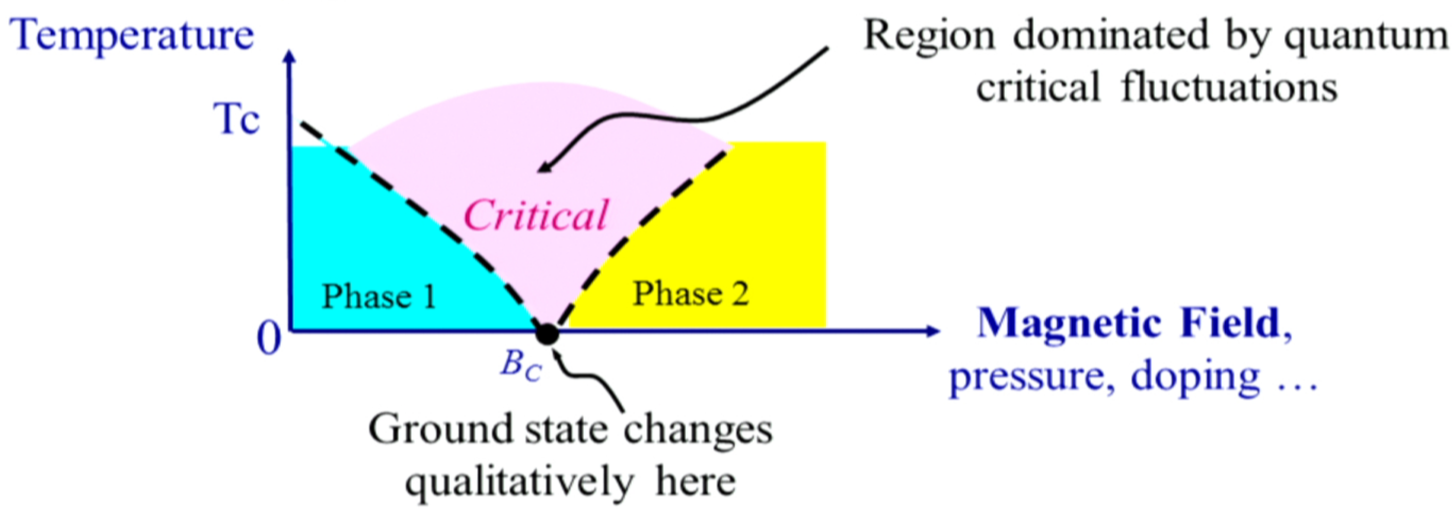
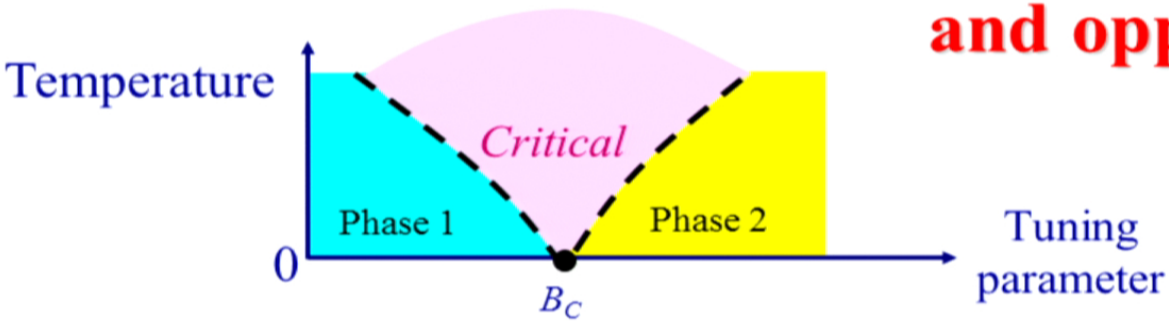


Quantum criticality: experimental challenges and opportunities



-what is **microscopic mechanism of transition,** can one observe the quantum fluctuations that drive transition ?

- how **quasiparticles evolve near critical point** ?

- what are the **fundamental symmetries** that govern physics of QCP ?

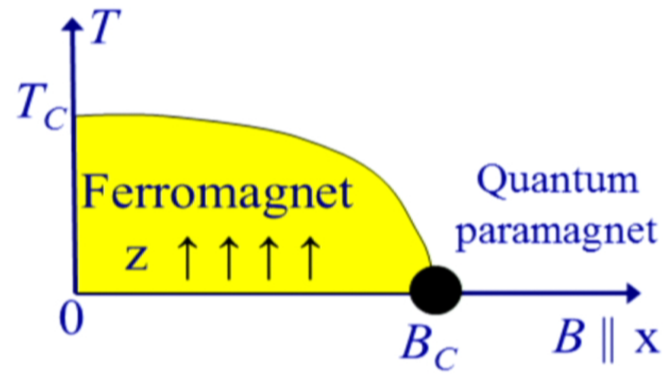
- what are **finite-T properties** (interplay of thermal and quantum fluctuations, under what conditions universal scaling ?

Ising magnets in transverse field

$H = -\sum_i J\, S_i^z S_{i+1}^z$ ↑↑↑↑↑↑ ⟶ B_x

$- B\, S^x = - B\, (S^+ + S^-)\, /\, 2$

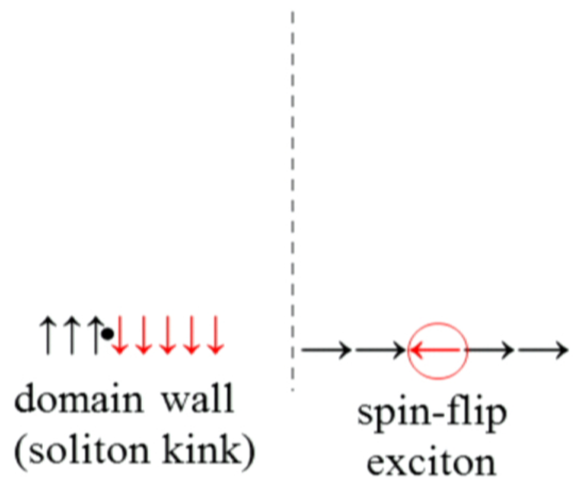
quantum fluctuations suppress order at $B_C \sim J$



3D ($LiHoF_4$) – dipolar, mean-field behaviour, spin flips both below&above B_C *Ronnow (06)*

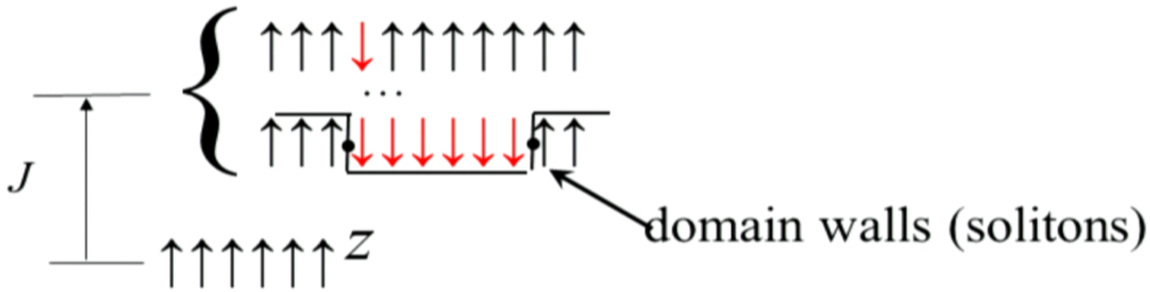
1D richer physics expected:

- excitations change character at B_C
- conformal E/T scaling at B_C in pure 1D
- effects of perturbations, bound states ?

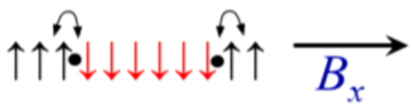


1D Ising chain in transverse field

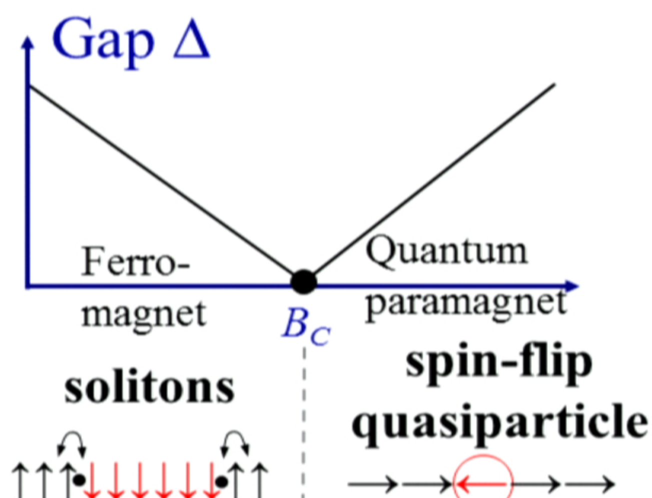
$H = -\sum_i J\ S_i^z S_{i+1}^z$ 2 ground states: ↑↑↑↑↑↑ or ↓↓↓↓↓↓



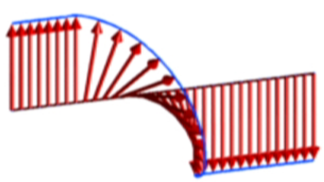
- transverse field $B\,S^x \sim -B\,(S^+ + S^-)$
flips spins



=> **propagating solitons**
(Jordan Wigner fermions)

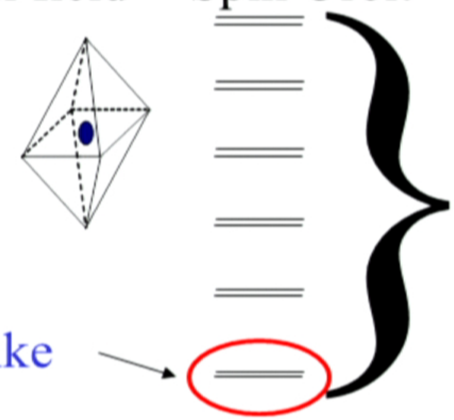


classical soliton
(large-*S* limit)



Experimental requirements

1) good **1D character** to see solitons
2) **low-exchange** $J \sim 1$ meV to access critical field $B_C \sim J/2 < 10$ T
3) strong uniaxial anisotropy (**Ising character**) but not perfect to still have transverse g-factor



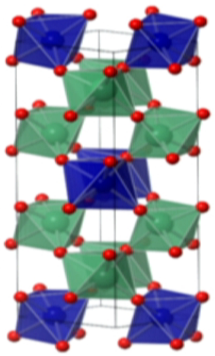
- depending on crystal environment Co^{2+} $3d^7$ can have strong easy-axis

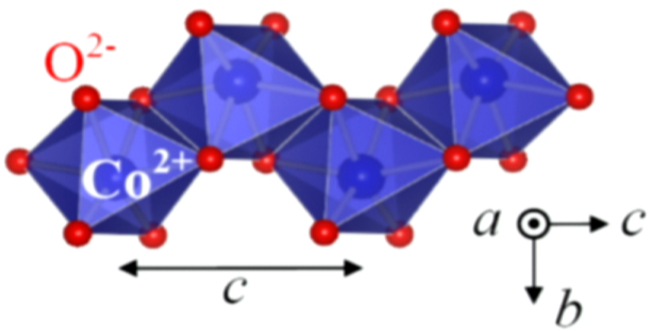
lowest Kramers doublet effective spin-1/2 Ising-like

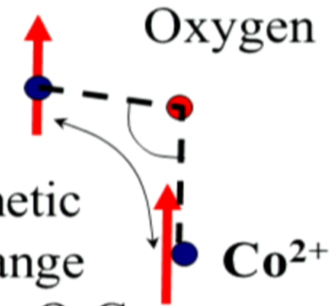
2D Ising AF K_2CoF_4 (*Birgeneau '73, Cowley '84*)
1D Ising AF $CsCoCl_3$ (*Goff '95*) *also* $CsCoBr_3$ (*Nagler*)
$J \sim 12$ meV $B_C > 50$ T not accessible

Quasi-1D Ising ferromagnet $CoNb_2O_6$

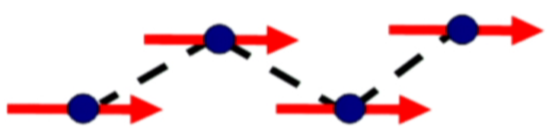
zig-zag Co^{2+} spin chain along c





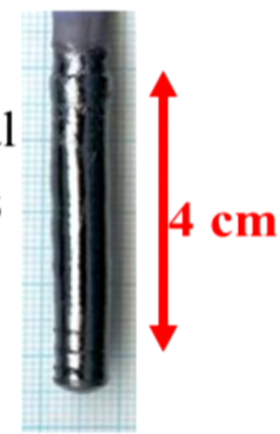


Ferromagnetic superexchange
~ 90° bond Co-O-Co
~ 20K ~ 2meV

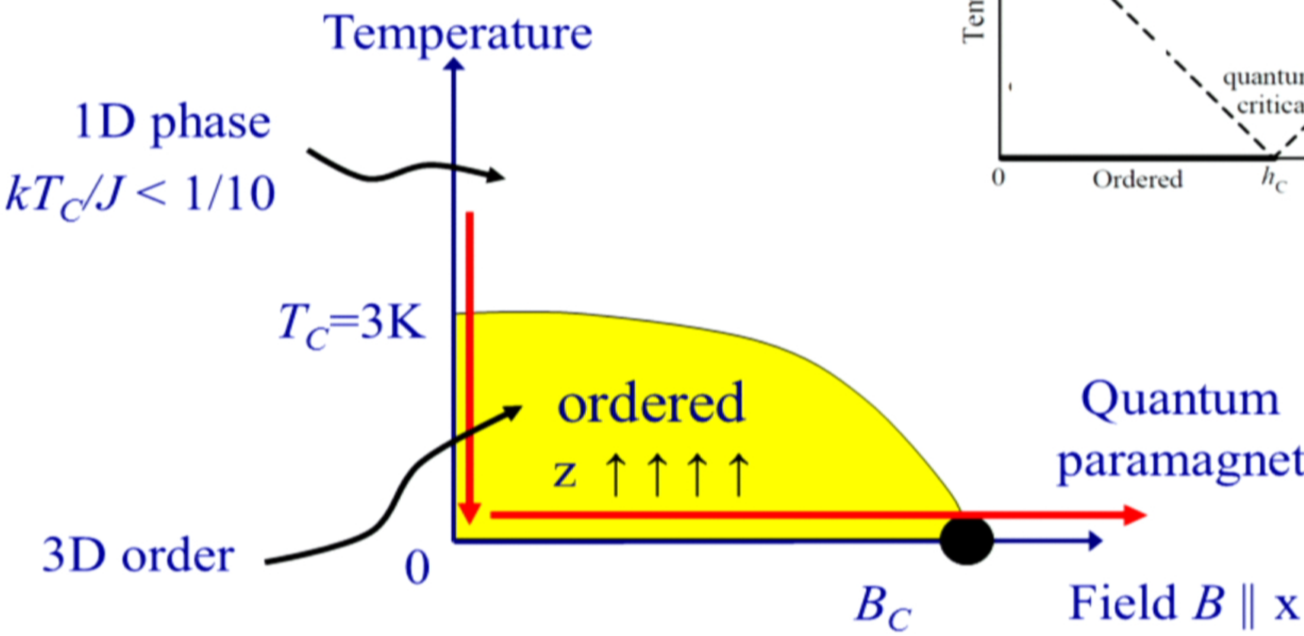


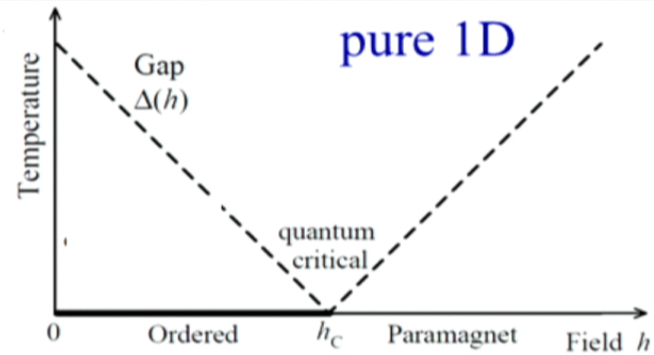
Ferromagnetic order along chain
Strong easy-axis (Ising) in *ac* plane

Single crystal of $CoNb_2O_6$ (Oxford image furnace)



Schematic phase diagram

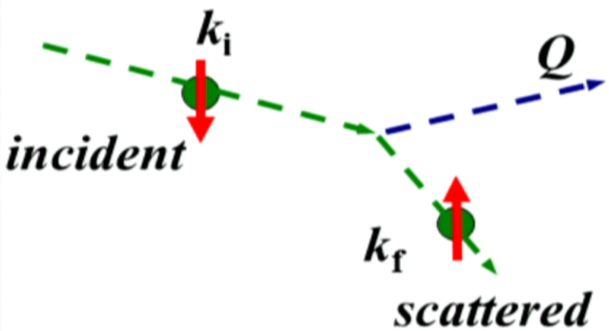




1. Excitations in zero field in "1D phase"
2. Excitations in 3D ordered phase at mK temperatures
3. Transverse field effects

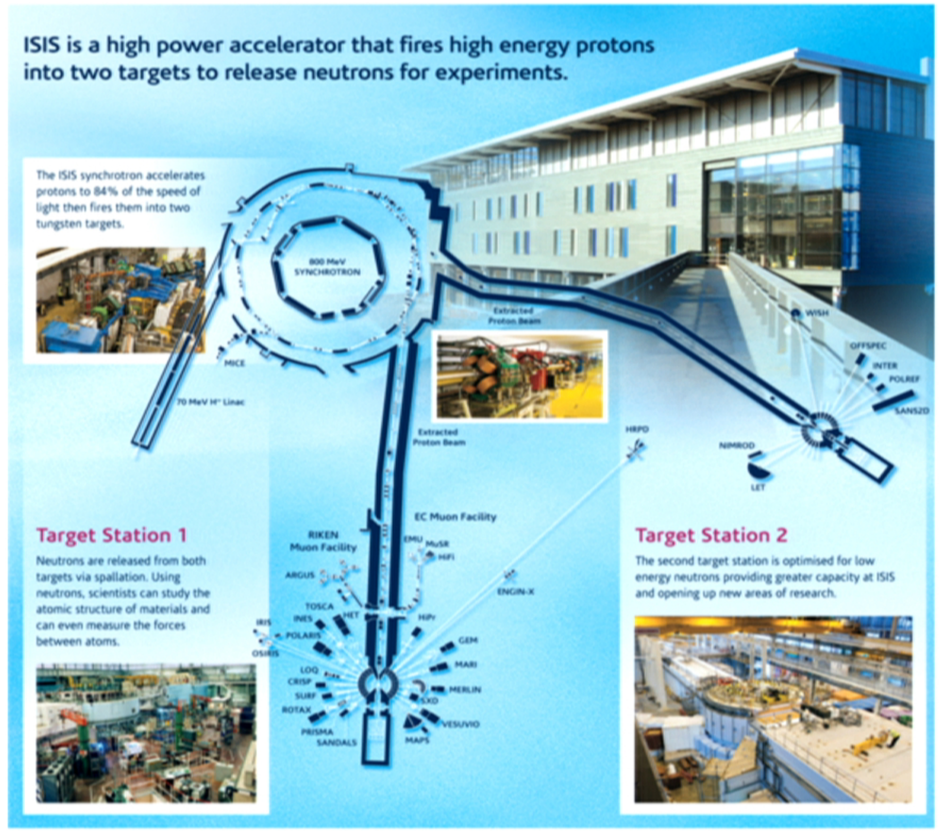
Neutron Scattering

- ideal probe of magnetic order & dynamics



Scattering conserves energy, momentum & spin

$$\boldsymbol{k}_i - \boldsymbol{k}_f = \boldsymbol{Q}$$
$$E_i - E_f = E$$



ISIS pulsed neutron source

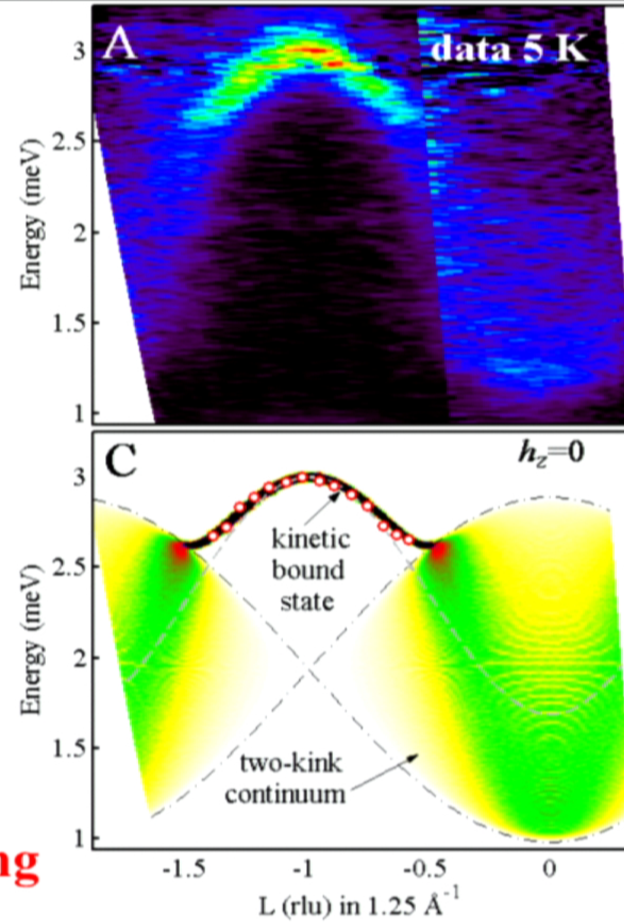
Phenomenological model of soliton gas

- work perturbatively around the Ising limit

(spin clusters)

J — ↑↑↑•↓↓↓•↑↑ 2-soliton states

↑↑↑↑↑↑



H |↑↑↑↓↓↓↓↓↓↑↑⟩ a 2 soliton state

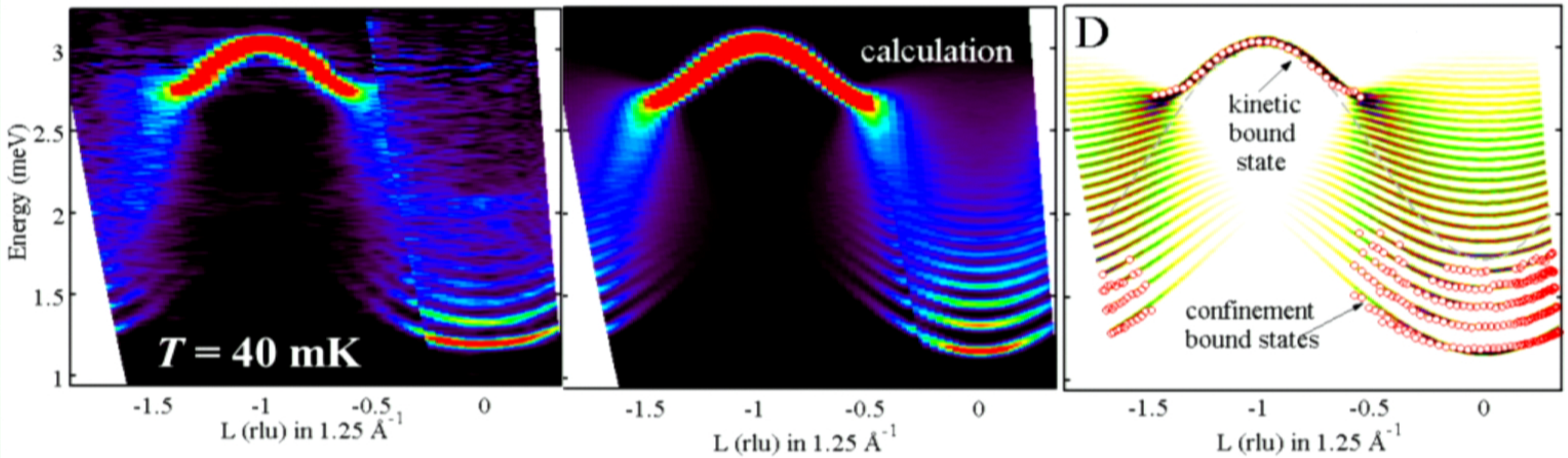
$= J$ |↑↑↑↓↓↓↓↓↓↑↑⟩ from Ising $J\, S^z_i\, S^z_{i+1}$ **gap**

$-\alpha$ |↑↑↑↓↓↓↓↓↓↓↑⟩ + . . . **soliton hopping**

$-\beta\, \delta_{n,1}$ (|↑↑↓↑↑⟩$_{i+1}$ + |↑↑↓↑↑⟩$_{i-1}$) from XY term **kinetic bound state**

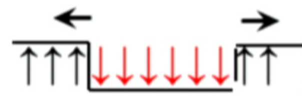
$- J_{xy}\, (\, S^x_i\, S^x_{i+1} + S^y_i\, S^y_{i+1}\,) \sim S^+_i\, S^-_{i+1} + S^-_i\, S^+_{i+1}$

Phenomenological model of soliton gas describes full spectrum

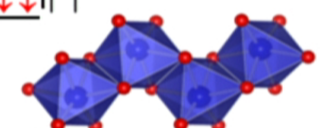


Gap: $J \sim 1.94$ meV from Ising *zz* exchange

Bandwidth $\alpha = 0.12\,J$ domain-wall hopping term



[microscopic origin S^zS^x … ?]



Kinetic bound state : transverse couplings for nn bond $S^xS^x + S^yS^y$, $J^{\perp}/J^{z} = 0.24$

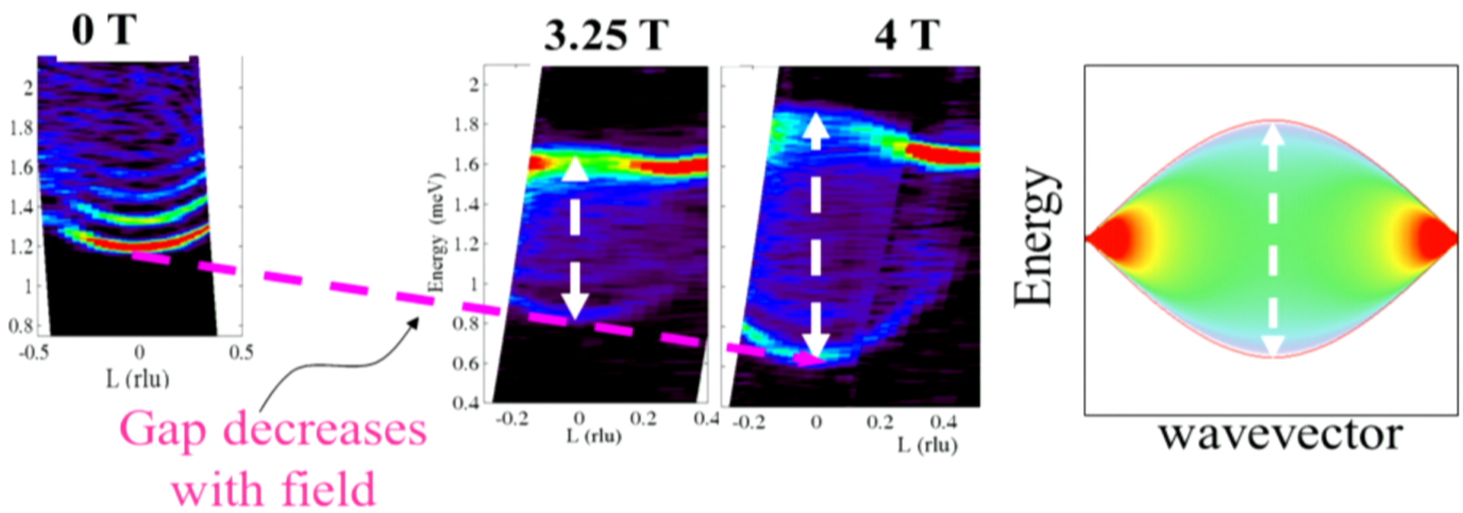
and 2-nd neighbour AFM along chain $J^{z\prime} = -\,0.15\,J^{z}$

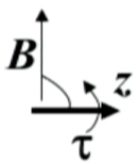
***Weak** confinement term:* $h_z \sim 0.02\,J$ longitudinal field includes interchain mean-field

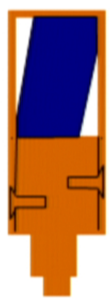
numerical calculation agrees with exact analytic solution of effective Hamiltonian

S.B. Rutkevich, J. Stat. Phys (2010)

Experiments in applied transverse field







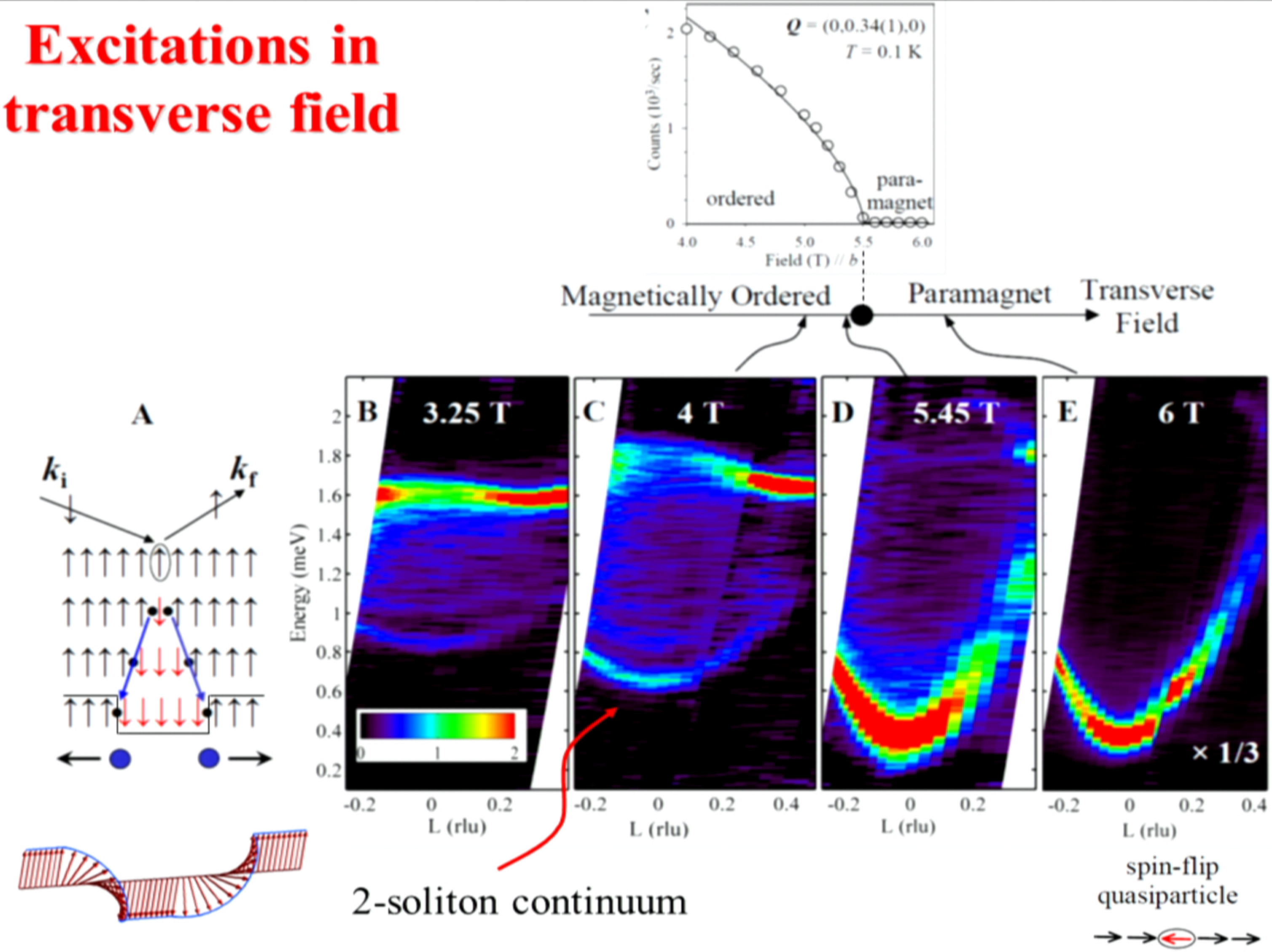
Place crystal in metallic cage to prevent movement under high torque

- field tunes quasiparticle dispersion

Field ~ kinetic energy

$B_x S^x = (S^+ + S^-)/2$

Excitations in transverse field



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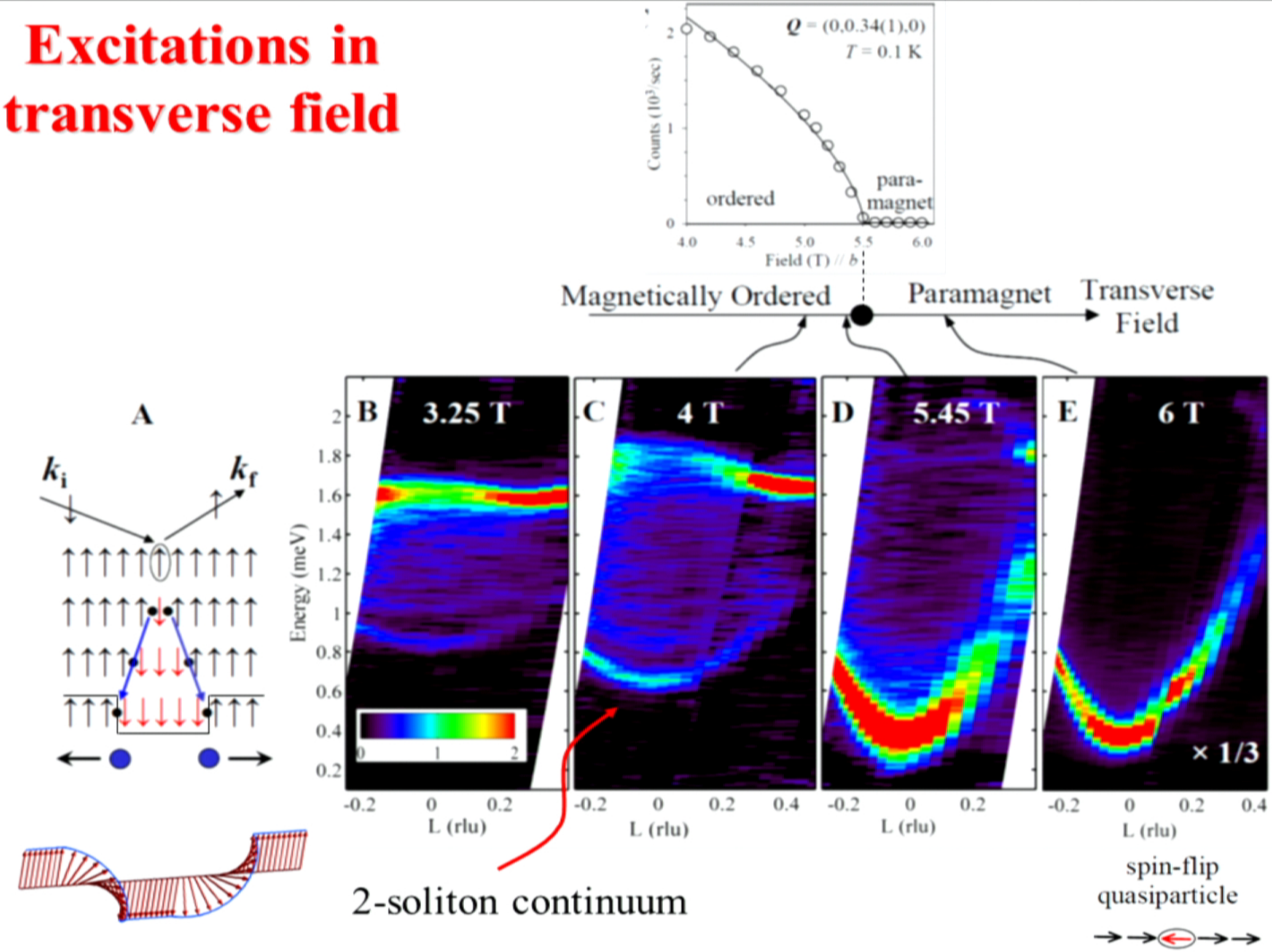
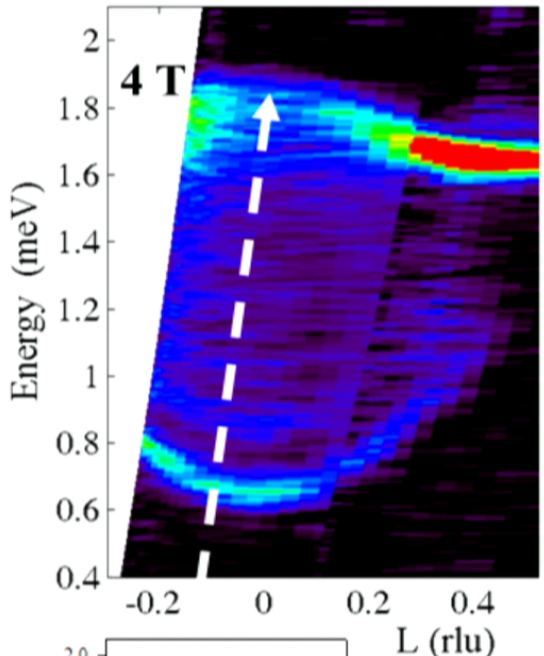
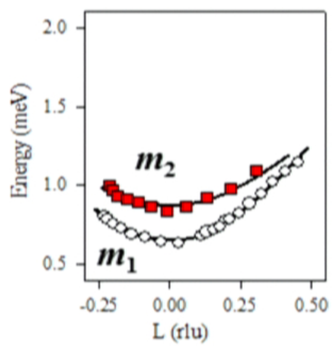
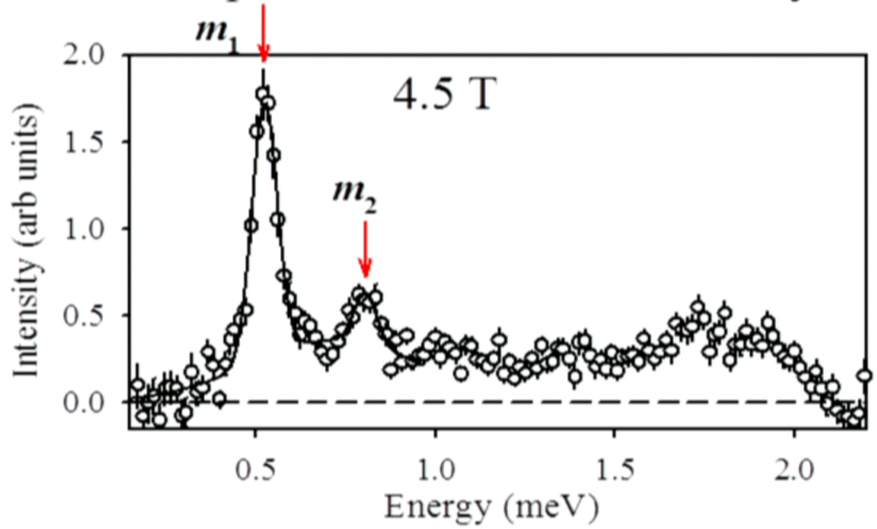


Structure of excitations just below B_C

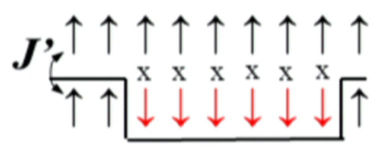




see 2 sharp modes at lower boundary



- confinement due to longitudinal field h (mean field of 3D interchain couplings)

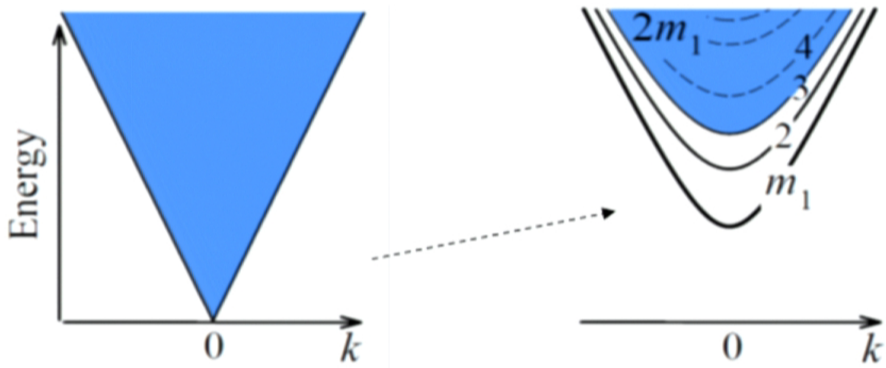


$V(x) = \lambda\, x$

$\lambda \sim J' \langle S^z \rangle$

Longitudinal mean-field $-hS^z$, $\lambda = 2h \langle S^z \rangle$

Perturb the QCP: add longitudinal field –h S^z



critical solitons
= quarks

h S^z opens gap and confines solitons

integrable model in scaling limit Zamolodchikov (1988)

no of particles 8 = C/η
(conjecture G. Mussardo)

conformal charge C =1/2
anomalous dimension of h, η = 1/16

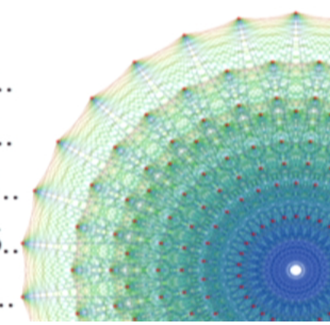
"Universal" spectrum with 8 "meson" particles

- integrable but no "conventional" symmetry rotational invariance broken by $B_\perp$ and h, but "hidden dynamical symmetry"

-no decay (even when overlapping with continuum - matrix elements cancel)

- exceptional mathematical structure E8

$$m_1 = Ch^{8/15} \equiv 1$$
$$m_2 = 2m_1 \cos(\pi/5) = 1.618..$$
$$m_3 = 2m_1 \cos(\pi/30) = 1.989..$$
$$m_4 = 2m_2 \cos(7\pi/30) = 2.405..$$
$$m_5 = 2m_2 \cos(2\pi/15) = 2.956..$$
$$m_6 = 2m_2 \cos(\pi/30) = 3.218..$$



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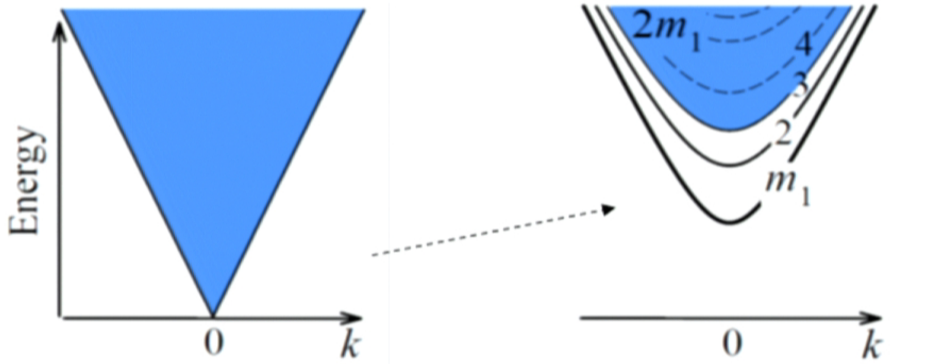

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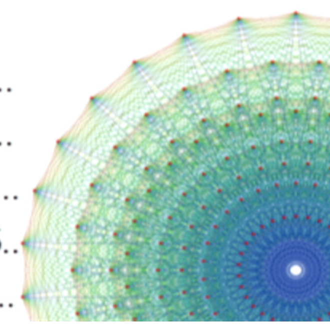
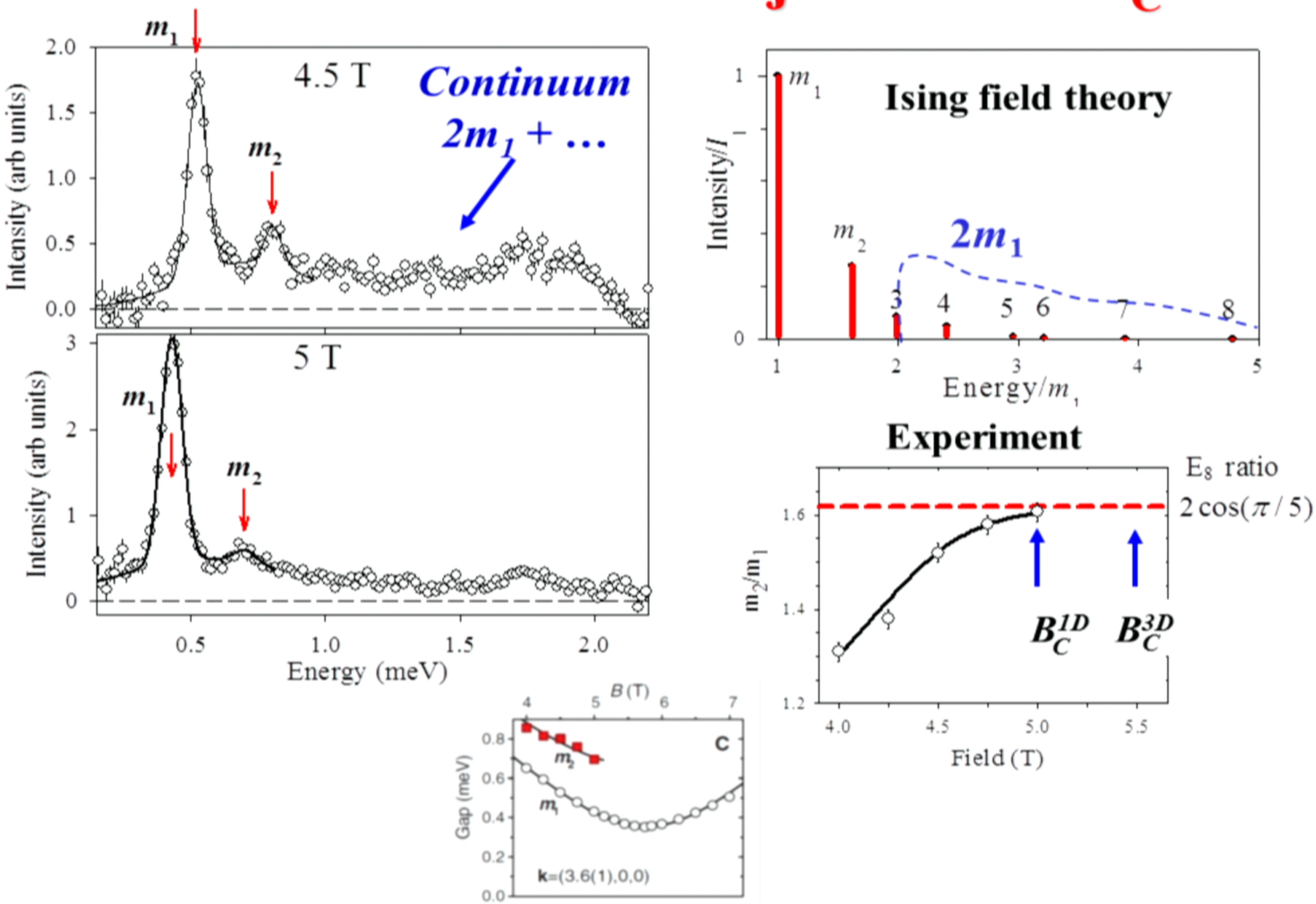


Structure of excitations just below B_C



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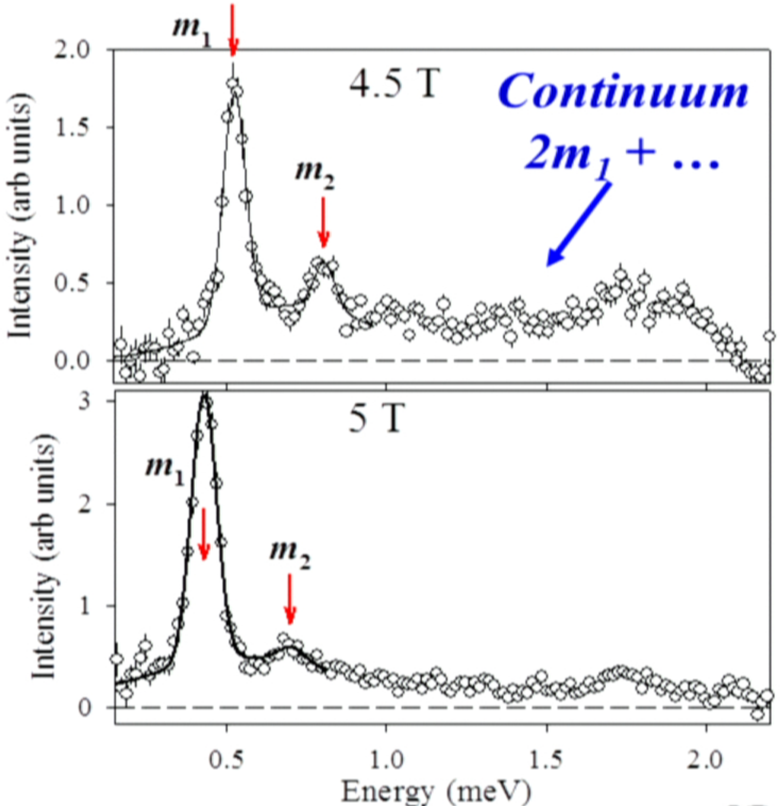
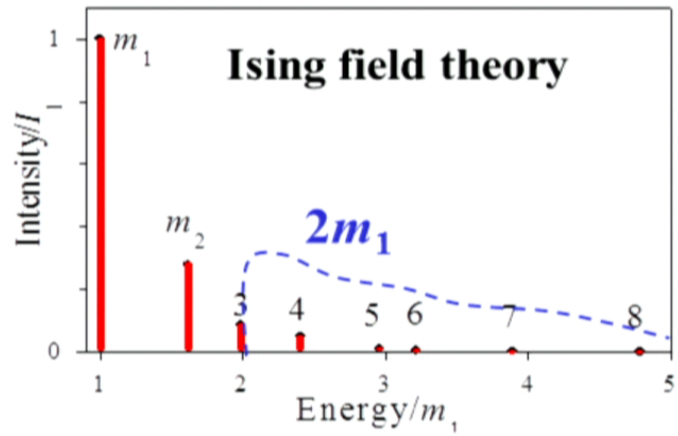
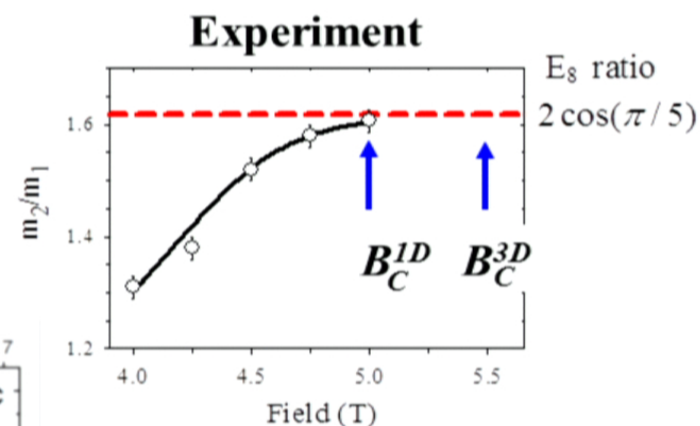
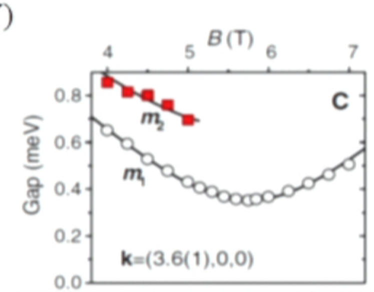
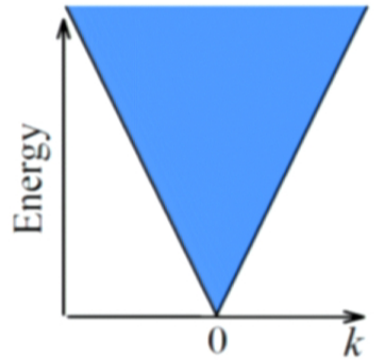




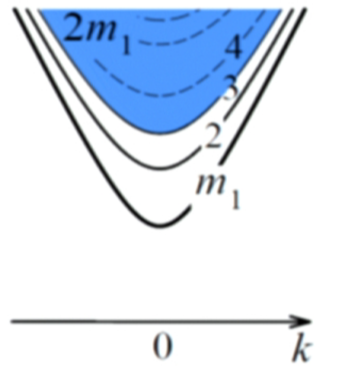




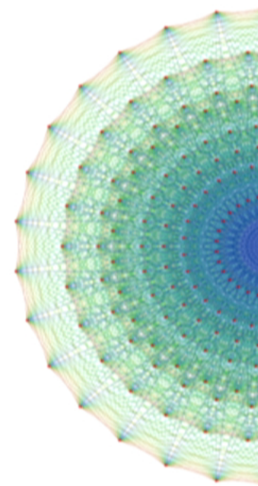
Zamolodchikov's E8 spectrum



tune 1D chain exactly at criticality



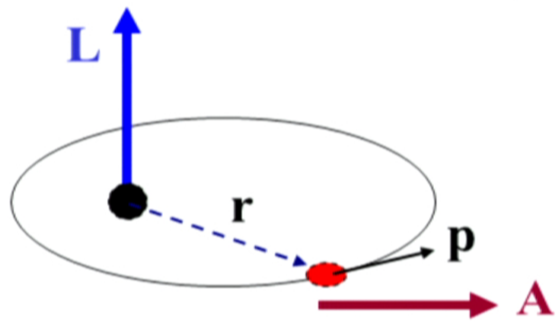
add confinement term (longitudinal field $h\ S^z$)



- E8 spectrum expected when the 1D chain is tuned to criticality, only then h is perturbation around QCP
- Zamolodchikov found several "conserved integrals of motion" ⇔ generalized "rotations" have an E8 group structure
- abstract "symmetry", no simple geometric analogue

1D off-critical Ising chain is 1st concrete realization of E8 in nature

Simple case of hidden (dynamical) symmetry



- continuous symmetries ⇔ conservation laws (Noether)

(if Hamiltonian symmetric under spatial rotations -> conserved **L**)

Motion under central forces - conserved Energy, **L**

if force $\mathbf{F}(\mathbf{r}) = -k/r^2\, \hat{\mathbf{r}}$ then

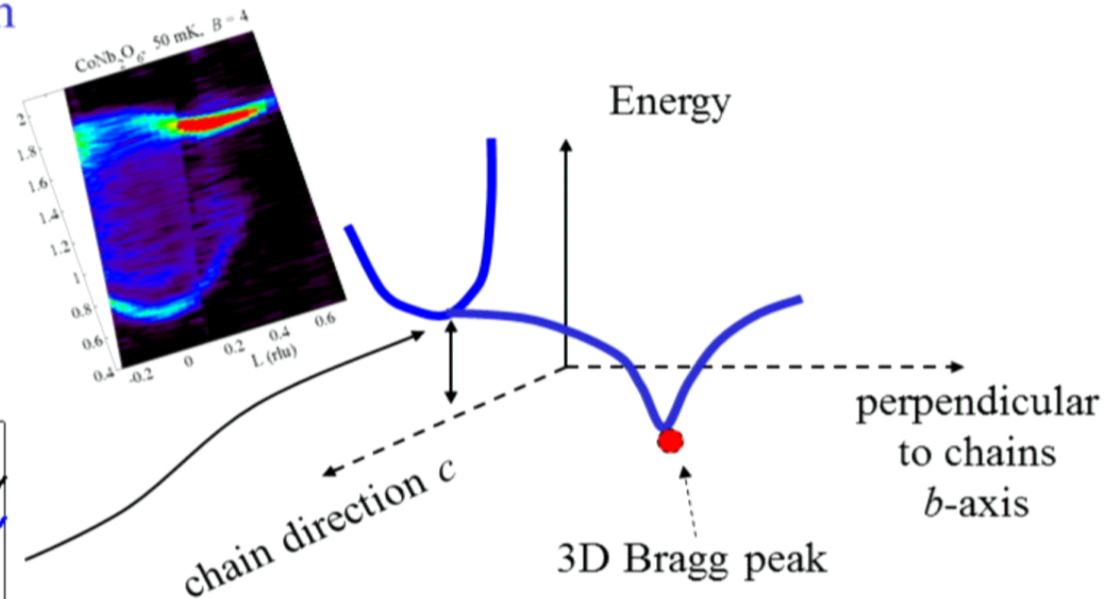
$\mathbf{A} = \mathbf{p} \times \mathbf{L} - m\,k\,\hat{\mathbf{r}}$ Lenz vector *also conserved*

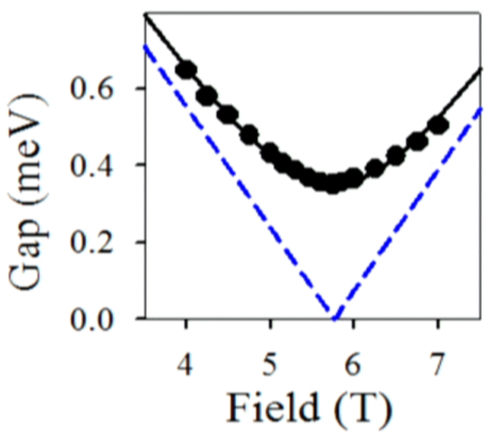
conservation of **A** not due to any conventional "rotation" in spacetime, but is due to a "hidden" symmetry, SO(4) group

Cross-over 1D to 3D physics at low energies at Bc

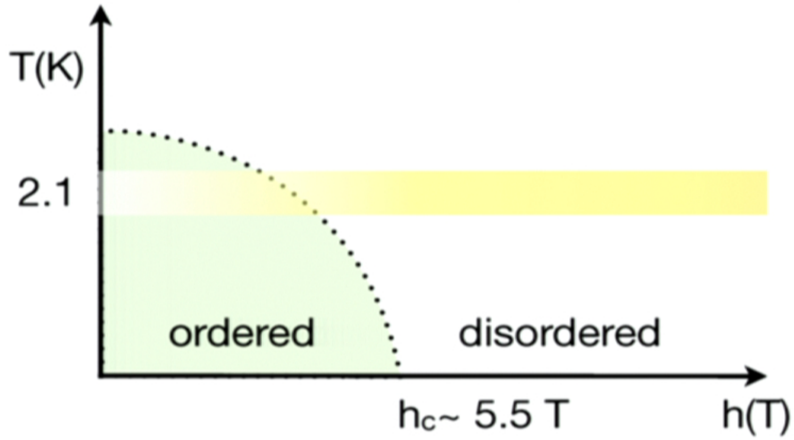
- at critical field expect low-energy physics is 3D with significant interchain dispersion

- see partial gap softening away from 3D Bragg peak

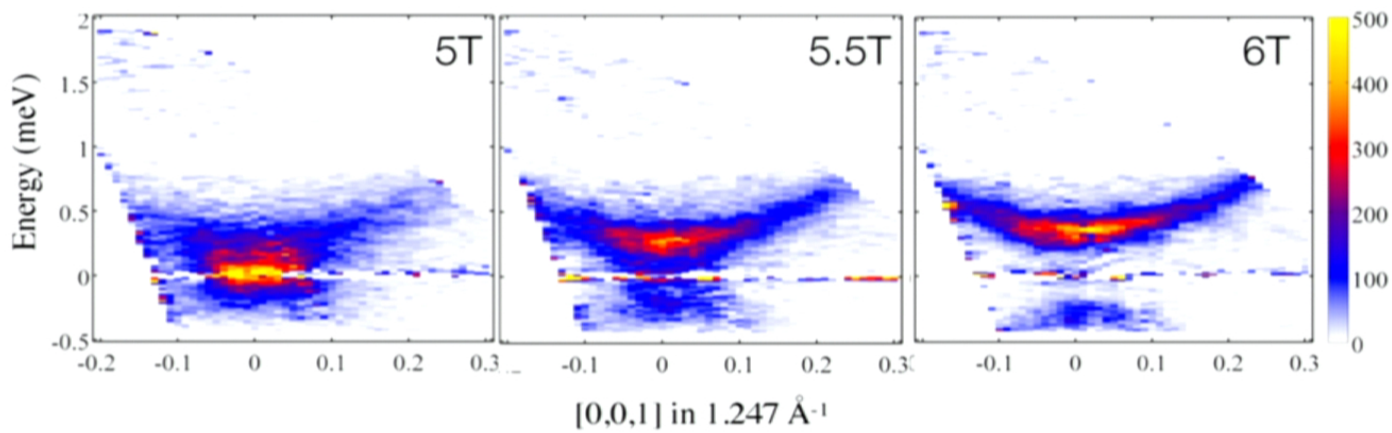




Towards reaching the quantum critical point



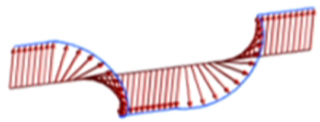
data (B) – data (9T)

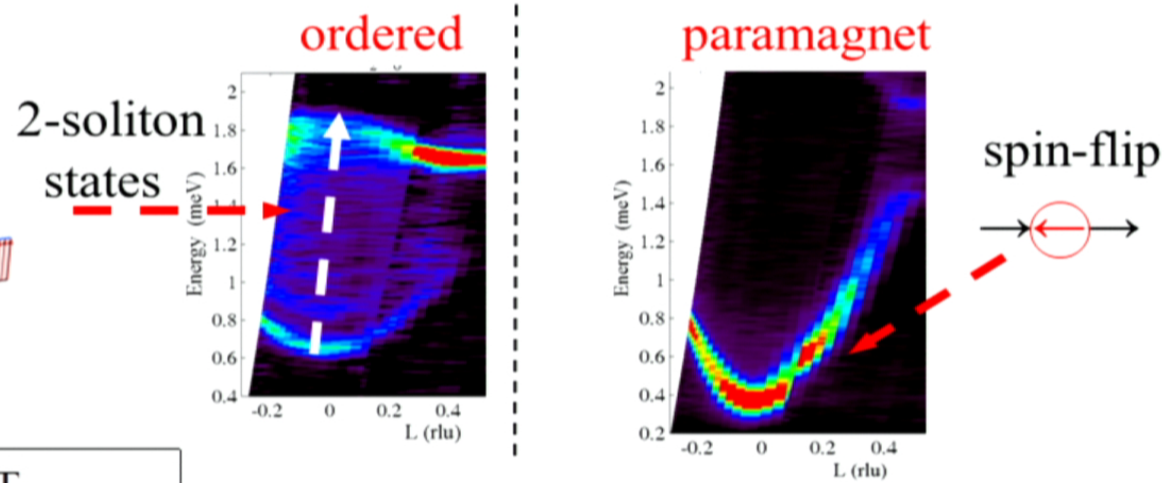


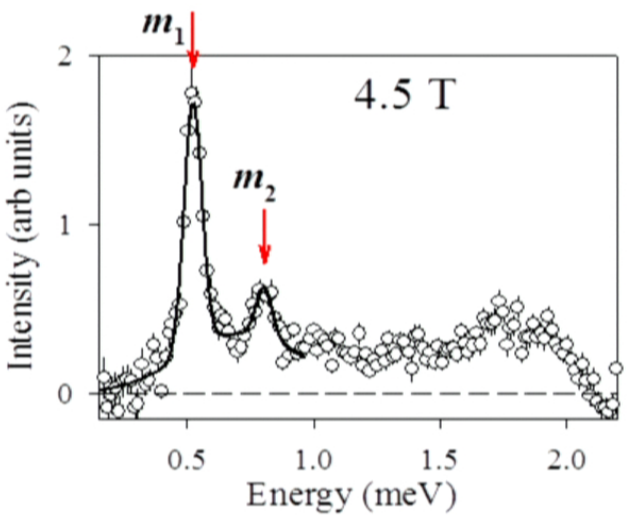
- no gap can be detected at 2.1 K at 5 T

Summary

- created quantum phase transition in quasi 1D Ising magnet $CoNb_2O_6$
- observed transmutation of quasiparticles at critical point



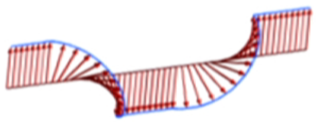


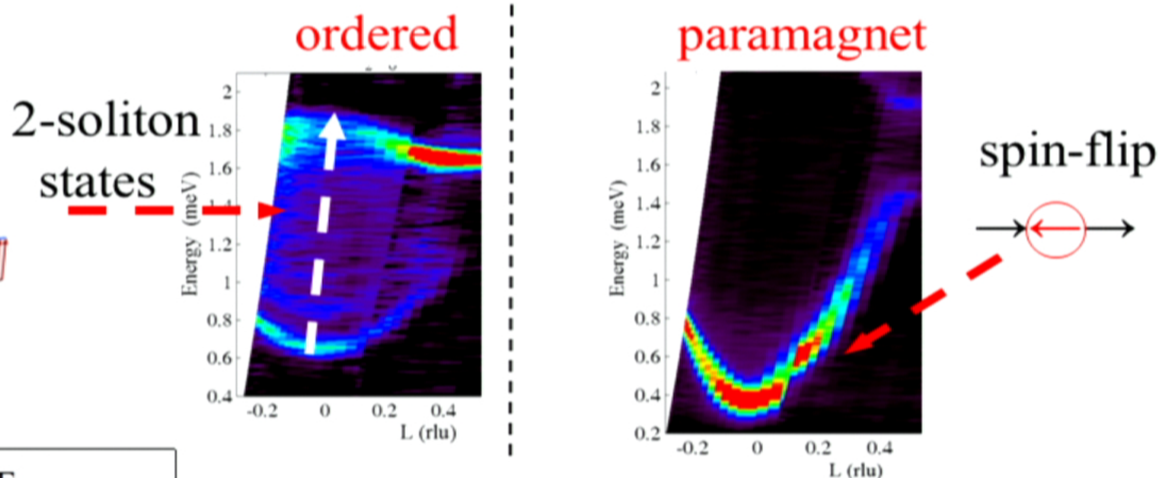


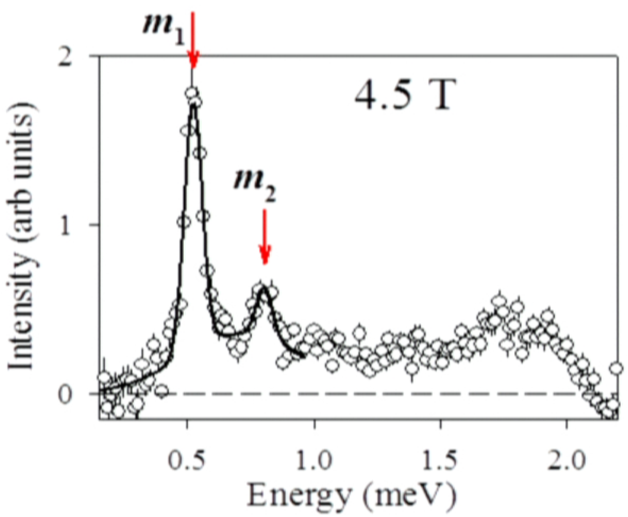
-2 lowest peaks associated with $\mathbf{m_1}$, $\mathbf{m_2}$ of the E8-particle spectrum in the off-critical Ising chain in longitudinal field

Summary

- created quantum phase transition in quasi 1D Ising magnet $CoNb_2O_6$
- observed transmutation of quasiparticles at critical point

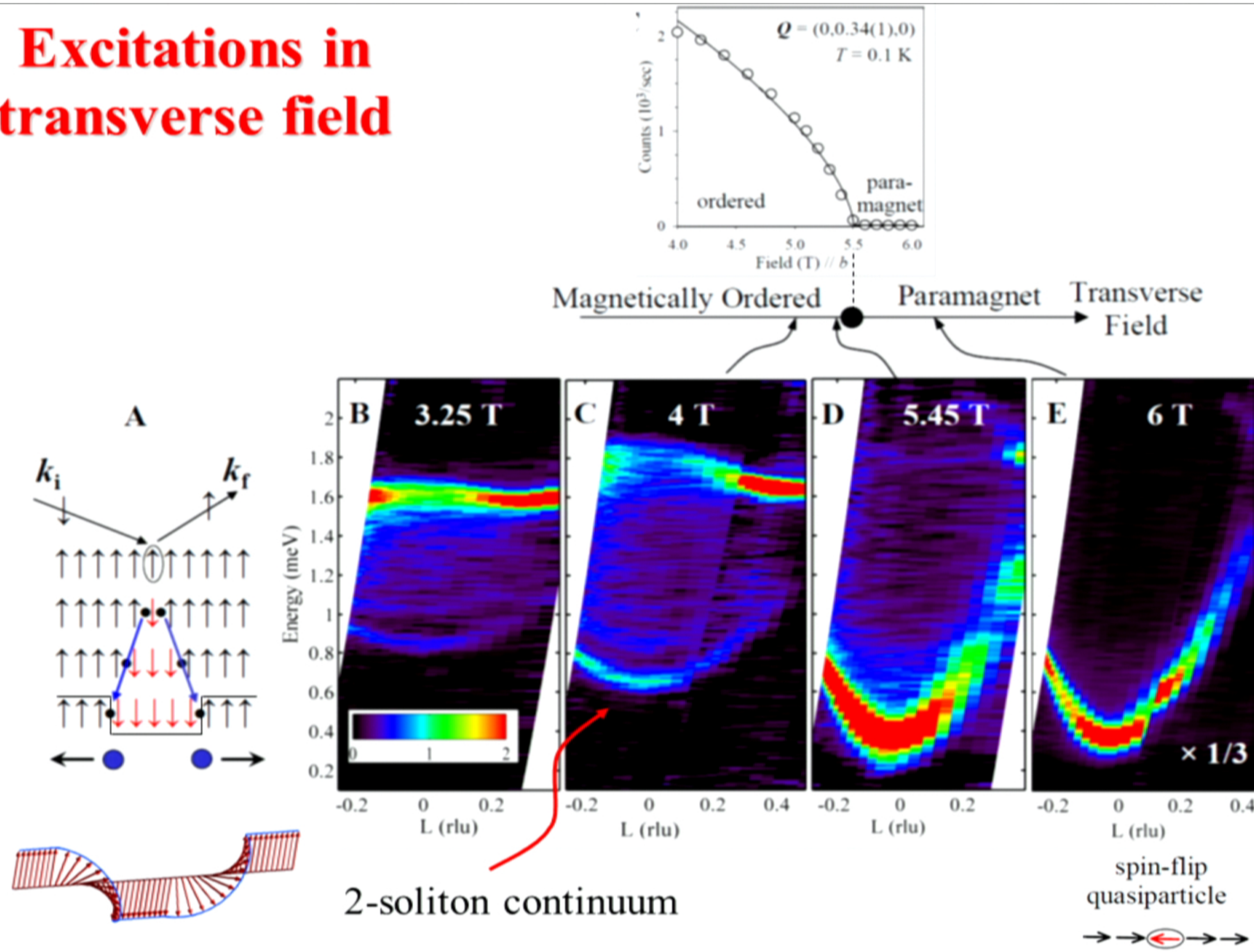






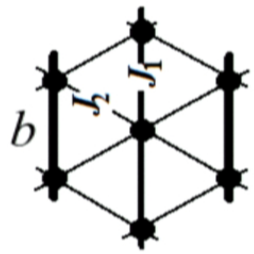
-2 lowest peaks associated with $\mathbf{m_1}$, $\mathbf{m_2}$ of the E8-particle spectrum in the off-critical Ising chain in longitudinal field

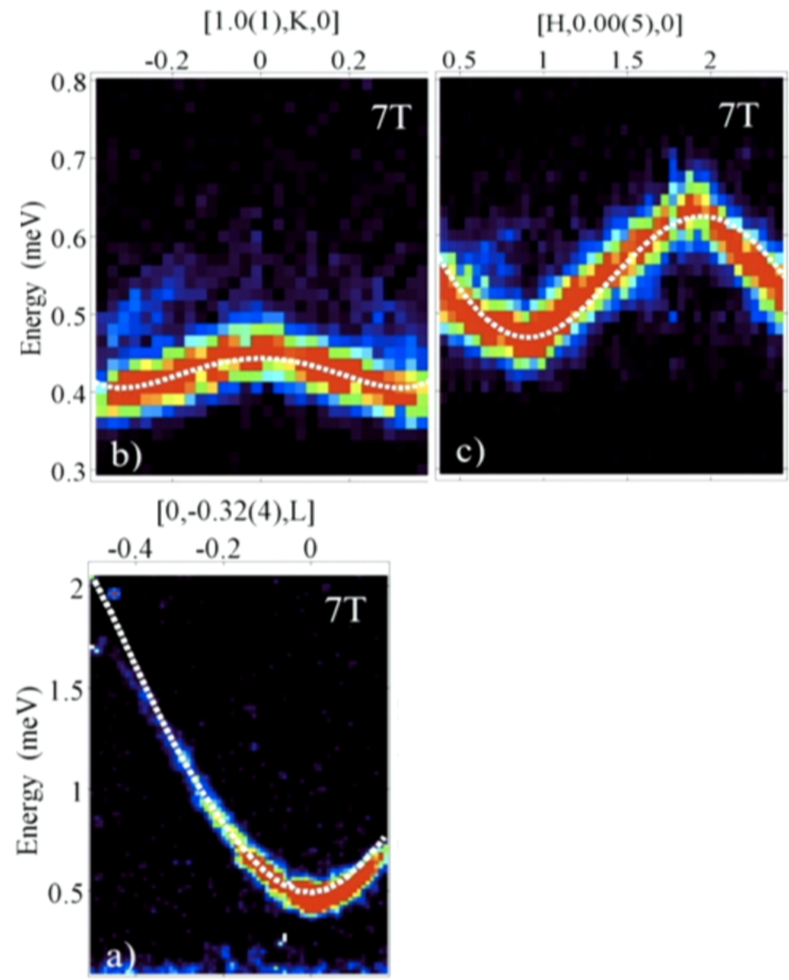
Excitations in transverse field



Interchain dispersions at 7 T

- confirm 2D dispersion in transverse plane is consistent with triangular lattice





Phase Diagram in Field along *a*

2.1 T AFM -> INC (1st order)
2.36 T INC -> paramagnetic (continuous)