# Laboratory for Quantum Magnetism

## Quantum spins and correlated electrons

## Neutron Scattering and low-temperature physics

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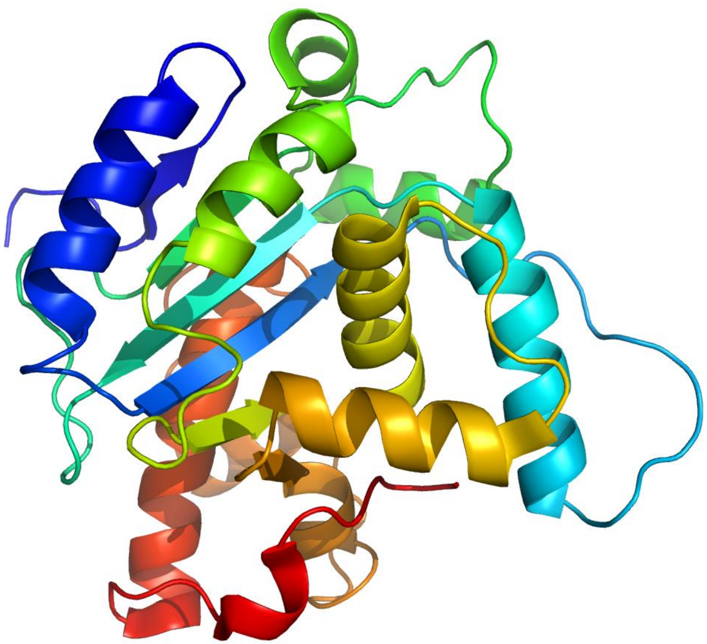
***EPFL, Switzerland***

# Complexity of many-body systems

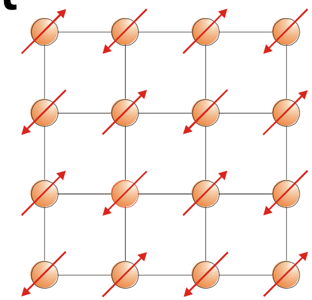
- Structure of a protein



- Pop2p-subunit Jonstrup et al (2007)
- Mega-Dalton:
  ~1’000’000 atoms (5 colors?)
  ~3’000’000 numbers needed
  to describe the structure

Ground state of a magnet

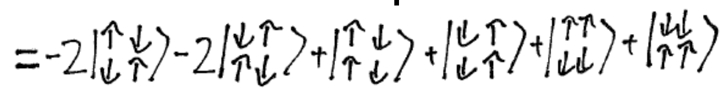
$$\mathcal{H} = J \sum \mathbf{S}_i \cdot \mathbf{S}_j$$



1 spin: trivial

2 spins: singlet state $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

4 spins: back-of-the-envelope calc.



16 spins: 10 seconds on computer (4GB)

40 spins: World record: 1’099’511’627’776 coefficients needed to describe a state

**Classical: 3N    Quantum: $2^N$**

$10^{23}$ spins:

1D: analytic solution (Bethe 1931)
2D: antiferromagnet (Néel 1932) or
fluctuating singlets? (Anderson 1973,1987)

$10^{23}$ ±some electrons: High-$T_c$ superconductivity – THE enigma of modern solid state physics

# Spin – the *drosophila* of quantum physics

Spin: an atomic scale magnetic moment

- Quantization: $S=0, 1/2, 1, 3/2, \ldots\ldots \infty$

$S = 1/2$ → $+1/2$ ↑ ; $-1/2$ ↓

- Superposition: $|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$

  likelihood of up: $\rho(\uparrow) = |\langle\uparrow|\psi\rangle|^2 = \alpha^2$

- Quantum fluctuations

  average moment $\langle S^z \rangle = 0$

  imagine that spins fluctuate in 'imaginary time'

- Quantum correlations

  $|\psi\rangle = ( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle ) / \sqrt{2}$

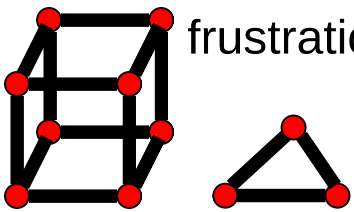
*e.g.* two spins 'entangled'

this is why $\propto 2^N$, not $\propto N$

# Quantum Magnetism – an arena for quantum phenomena

## 1) Model and Materials

Spin, interactions
dimension
frustration



The LEGO of many body physics

## 3) Experimental tools:

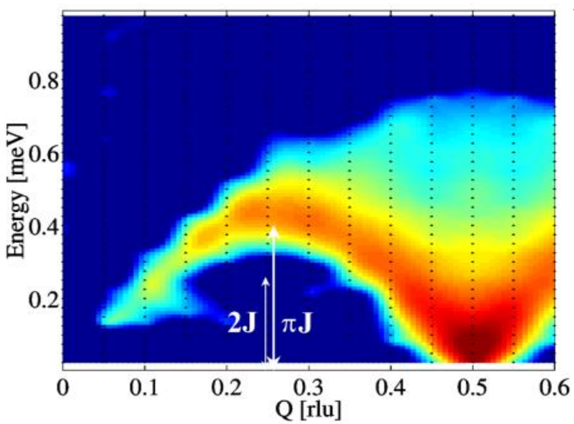
Bulk probes
Neutron scattering

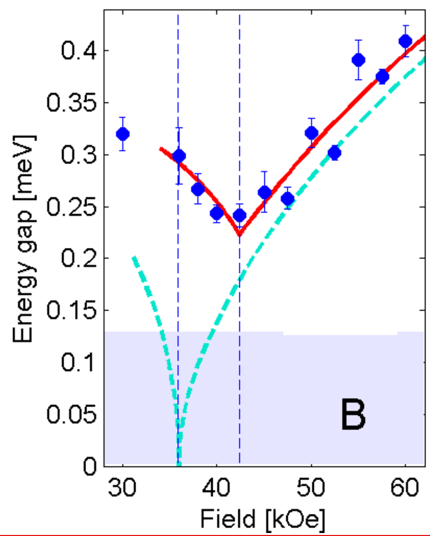
## Phenomena:

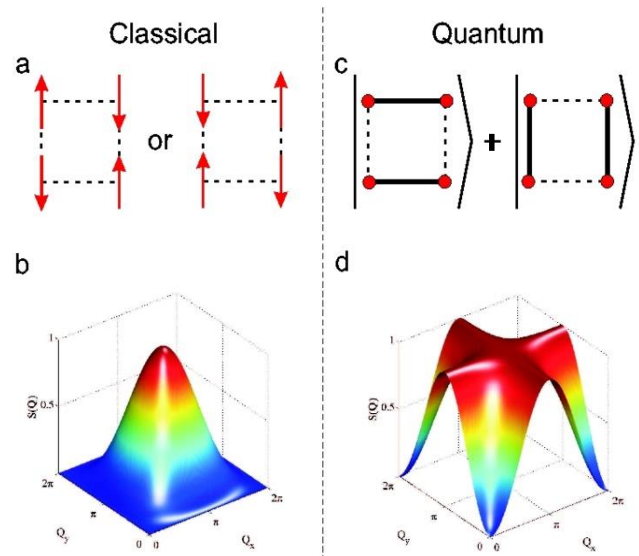
Order, phase transitions,
quantum fluctuations,
collective excitations,
entanglement …

## 2) Theoretical methods

analytic approximations
numerical simulations

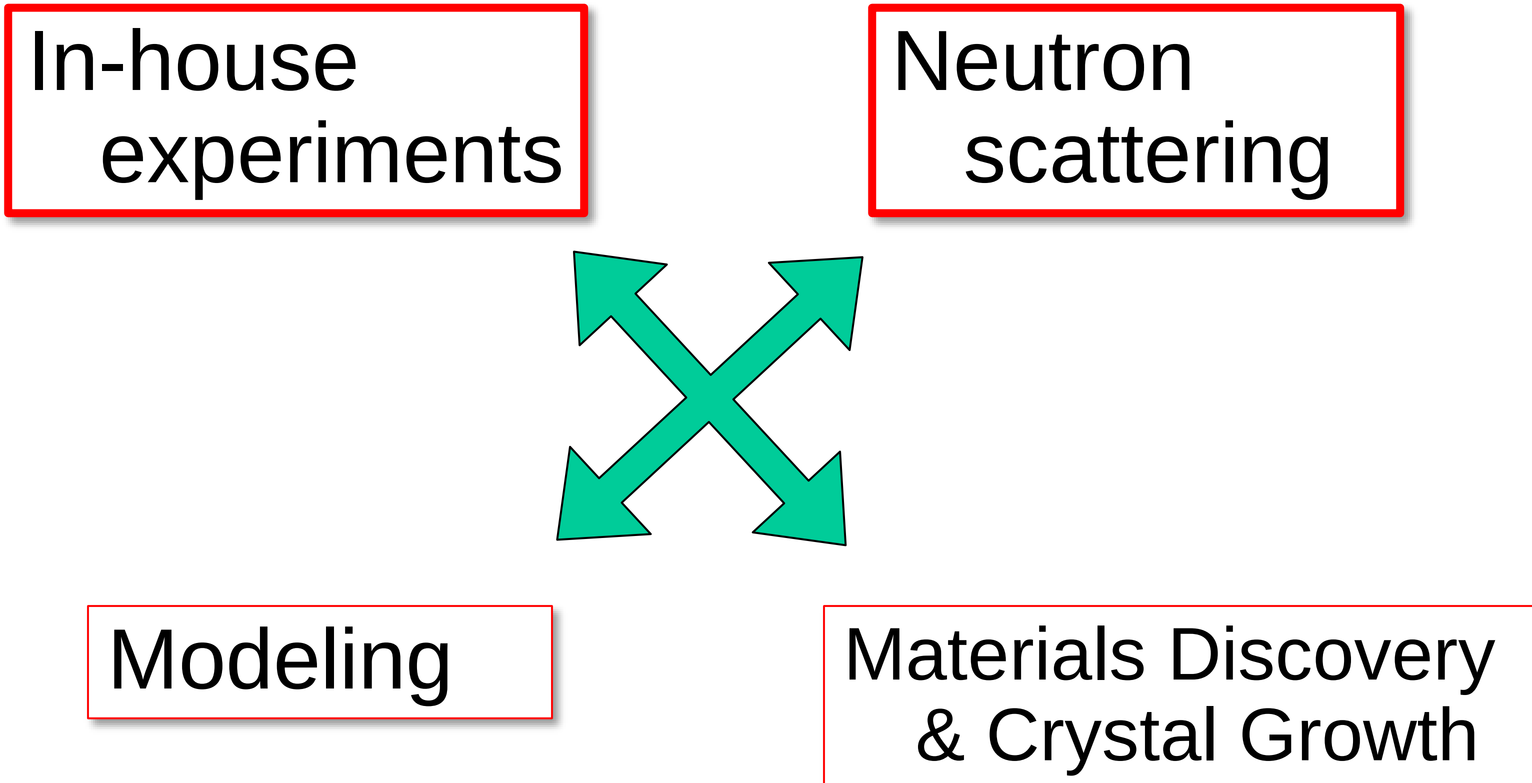


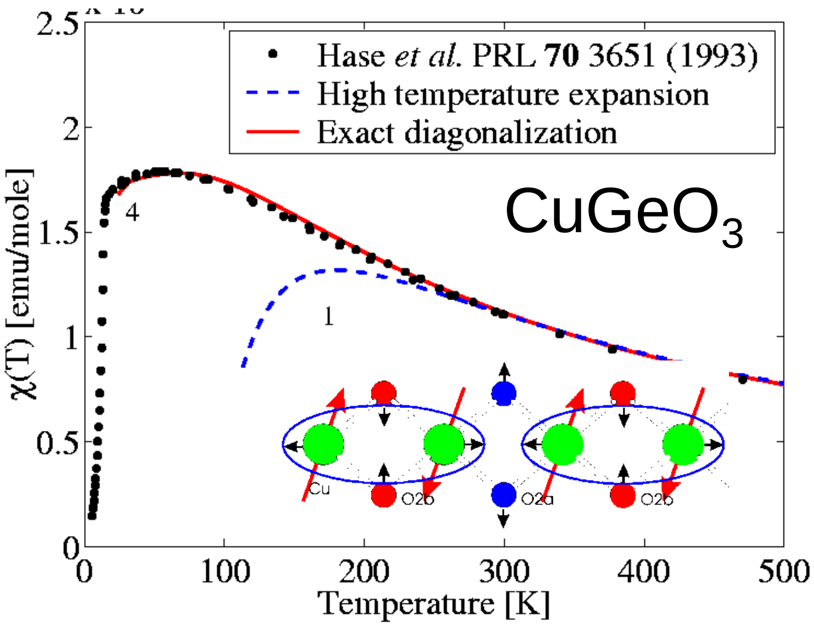
# Laboratory for Quantum Magnetism

- We do all parts in team:

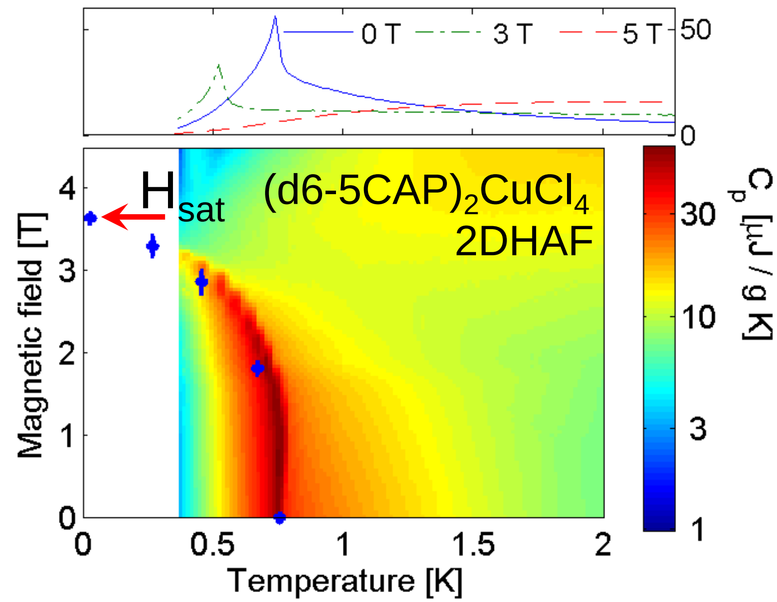


# In-house magnetic measurements

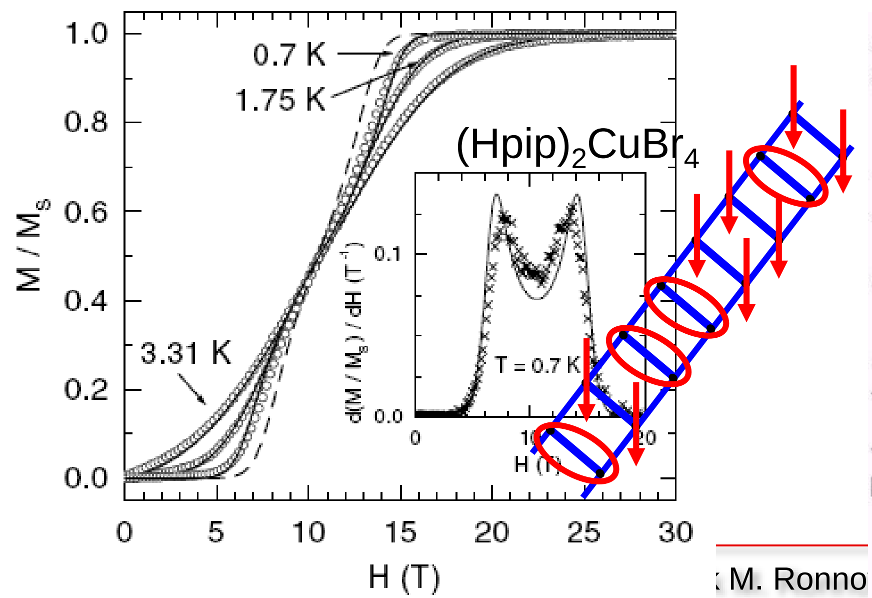
Susceptibility



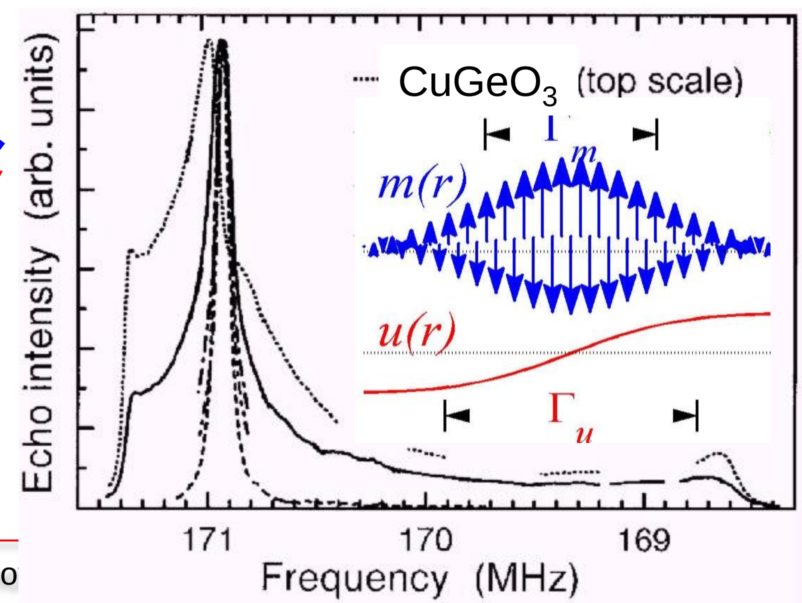

Specific heat




Magnetization



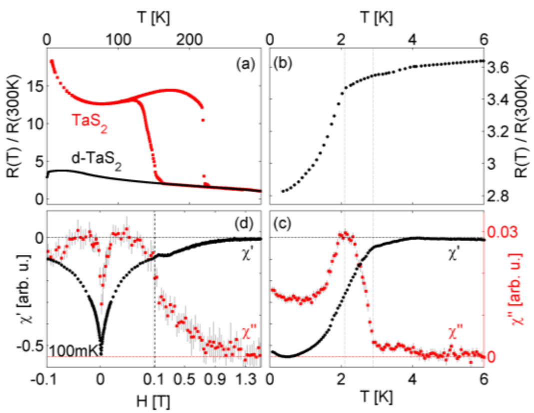

NMR, µSR etc.

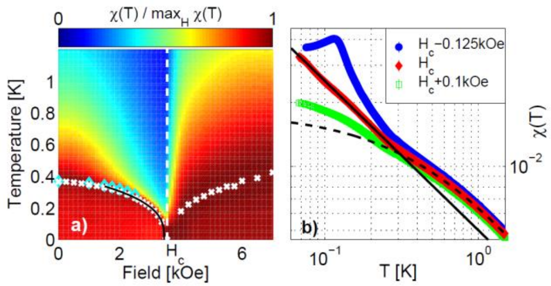


# LQM: Low temperature physics

## AC-susceptibility

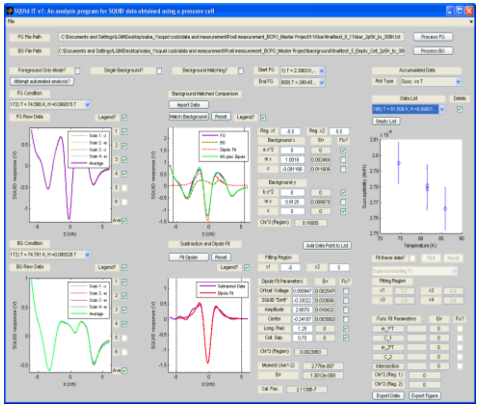
- Low-T→0.03K to 18T
- Macroscopic dynamics: spin-glass & domain-walls
- Superconductivity and vortex dynamics
- 0.03K squid setup

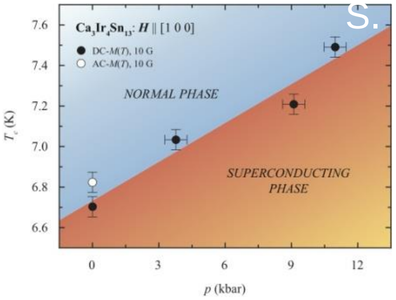



## DC-magnetization

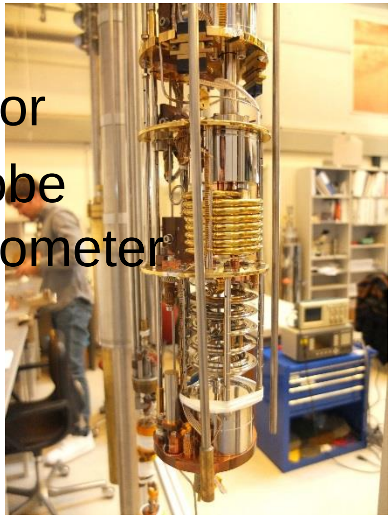
- Basic characterization
- In-situ E-field → 1keV/200μ = 5meV/nm
- low-T → 0.3K
- high-P → 1-5GPa

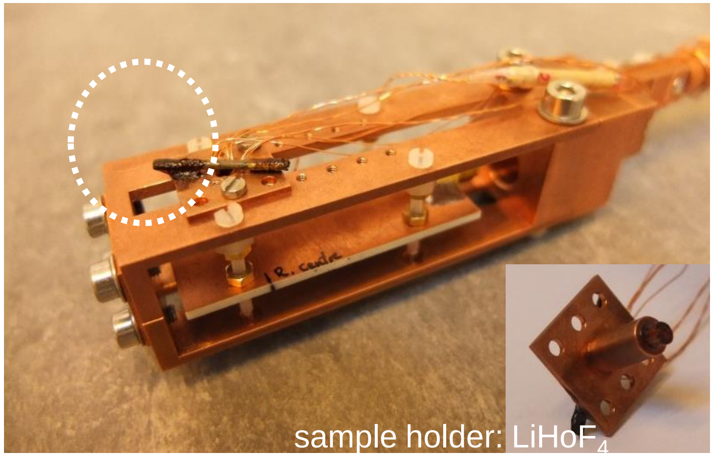





## GHz pumped quantum quench

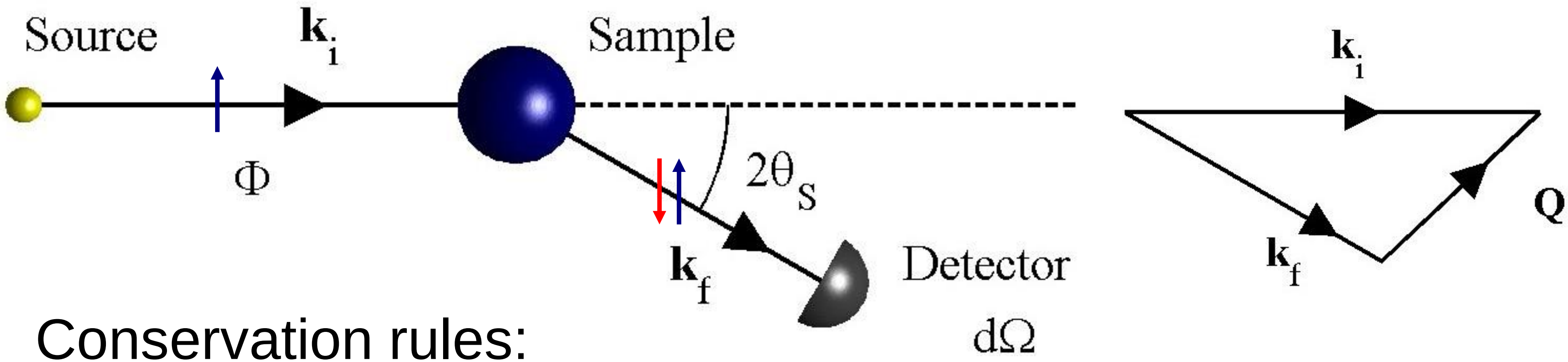
- Dilution fridge
- GHz resonator
- Hall-probe magnetometer





# A unique tool: Neutron scattering

scattering and conservation rules




Conservation rules:

| | Sample | | Neutron | |
|---|---|---|---|---|
| Momentum | $\hbar\mathbf{Q}$ | = | $\hbar\mathbf{k}_i - \hbar\mathbf{k}_f$ | |
| Energy | $\hbar\omega$ | = | $E_i - E_f$ | $= \hbar(k_i^2 - k_f^2)/2m_n$ |
| Spin | $\Delta S$ | = | $\sigma_i - \sigma_f$ | |

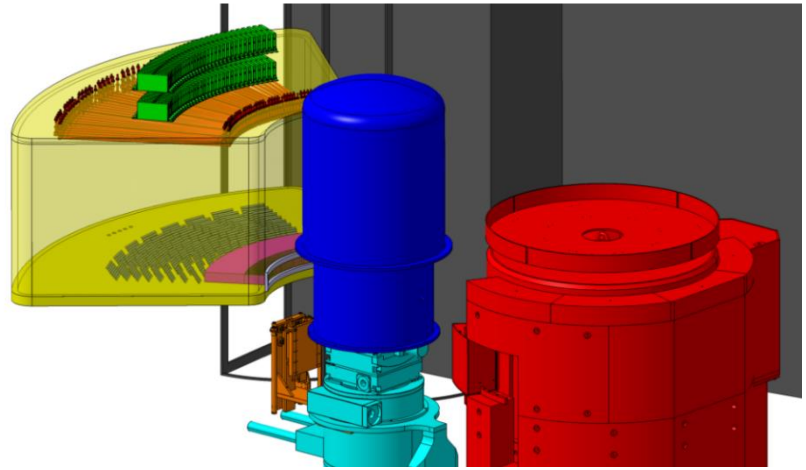
⇒ We can control and measure these quantities !

# LQM Neutron instrumentation @ PSI and ESS

- Designed: EIGER

EIGER: Thermal neutron triple-axis-spectrometer

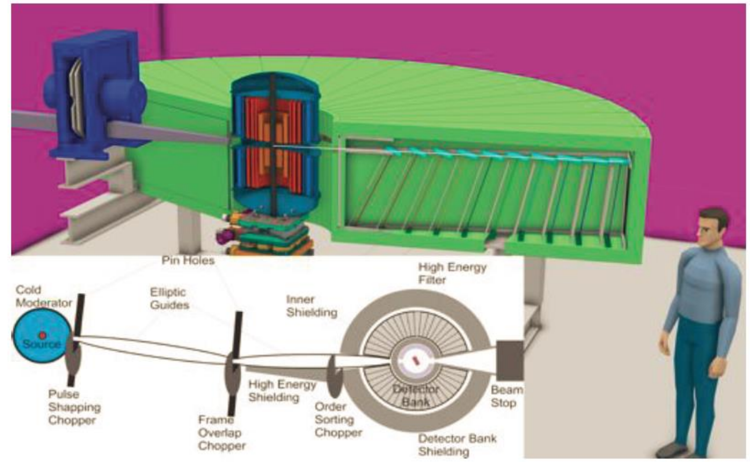
- Building: CAMEA-PSI



- Operate: TASP


TASP: Cold Neutron Triple-axis spectrometer

- Proposing: CAMEA-ESS



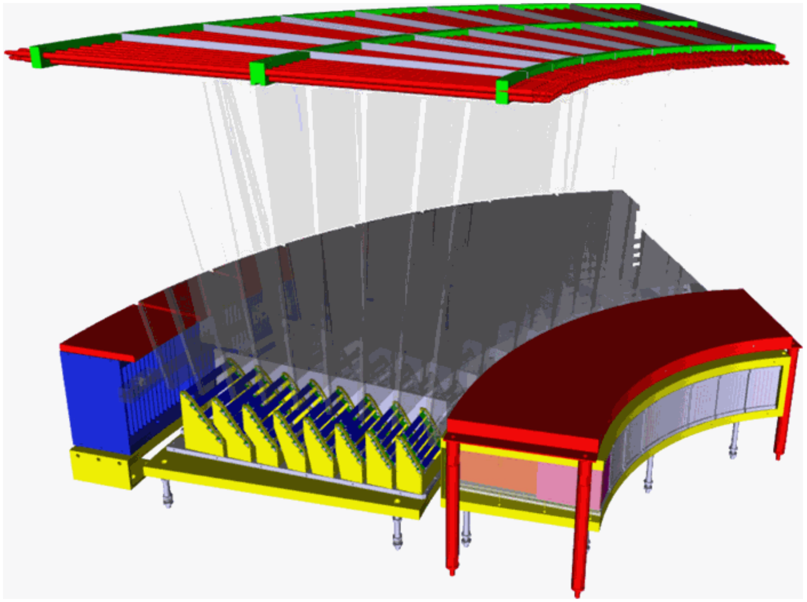
# CAMEA Continuous Angle Multiple Energy Analysis

- Large fields,
- High pressure

} Quantum Magnetism…

- Small samples <1mm$^3$
- 3-5 orders of magnitude gains

} Materials discovery



PSI-CAMEA ~2018
ESS-CAMEA ~2023
FRM2, ORNL, JR3, China?

100 kbar, 2 - 2000K

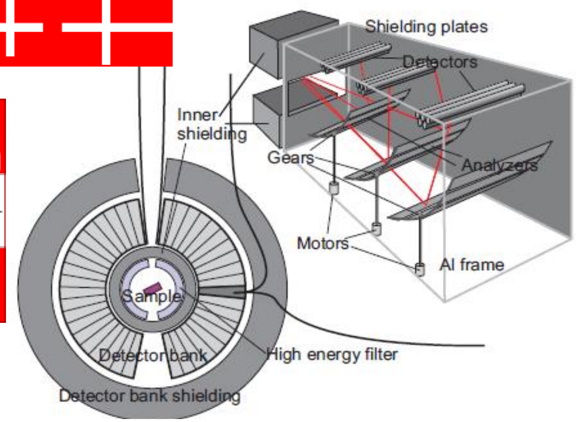

16 – 25? Tesla

# Neutron scattering – an intense future

- $1^{st}$ generation facilities:
  - General purpose research reactors
- $2^{nd}$ generation facilities:
  - Dedicated to neutron scattering:
  - ILL, France, FRM2 Munich, SINQ CH, ISIS, UK etc.
- $3^{rd}$ generation facilities:
  - SNS, US 1.4b$, commission 2006
  - J-Parc, Japan 150b¥, commission 2008
  - ESS, Sweden 1.5b€, start 2013, commission 2019
  - China Spallation, start 2011, commission 2018
- $2^{nd}$ to $3^{rd}$ generation gains of 10-1000 times !
  - Faster experiments, smaller samples, better data
  - Time resolved physics, new fields of science
  - New opportunities for EPFL life, mat-sci, chem

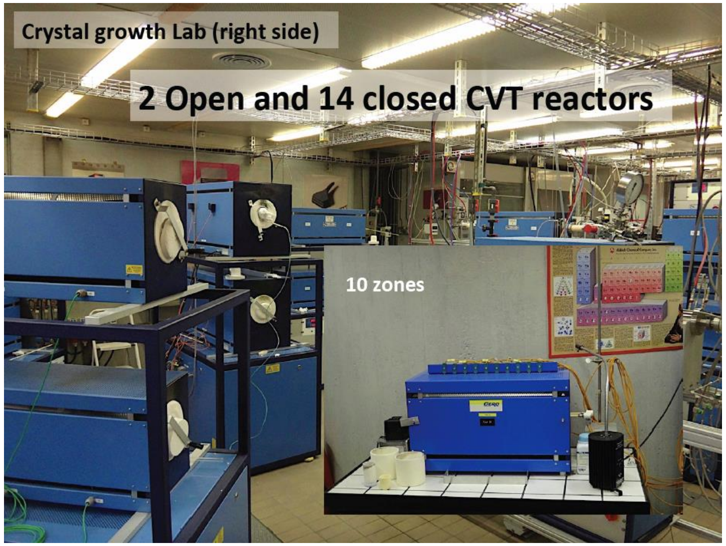
European Spallation Source (ESS)
1.8b€, almost certain to happen
(now: design update phase)
Switzerland will contribute 3-4%
⇒ Increased Swiss neutron scattering
⇒ CH-DK design 5 instruments and will bid for constructing and operating 2
⇒ CAMEA: $10^2$ -$10^4$ over swiss best now

ESS +

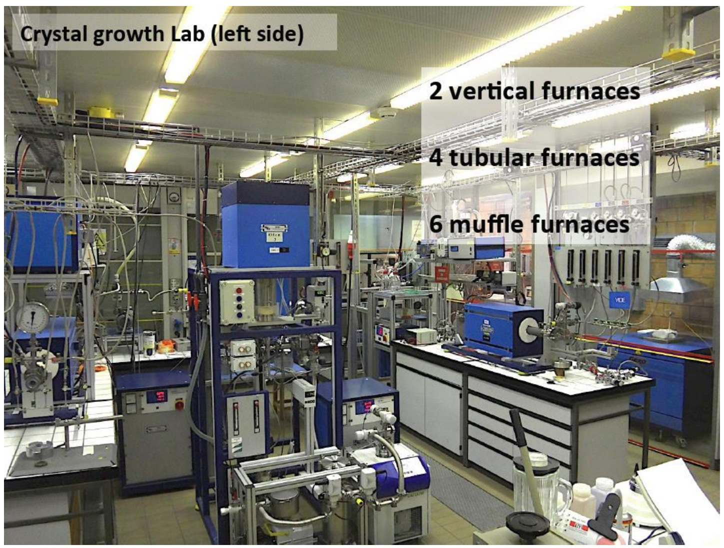


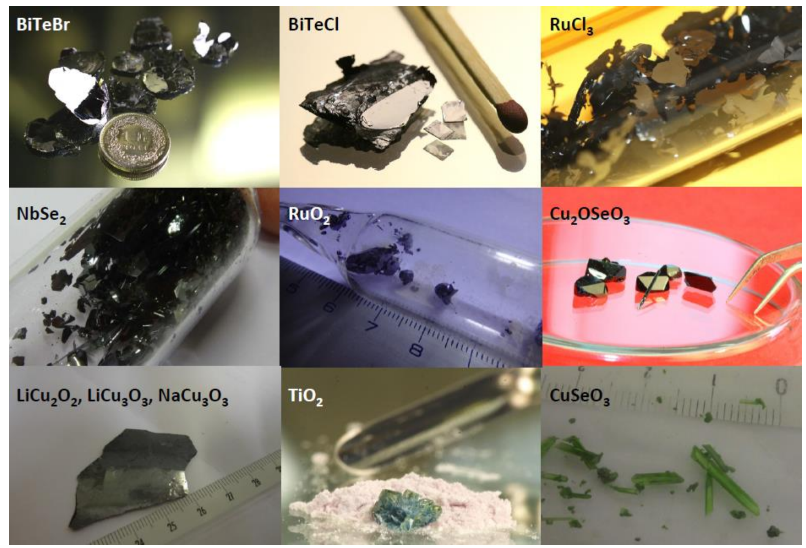



# Materials discovery at EPFL – collaborations welcome







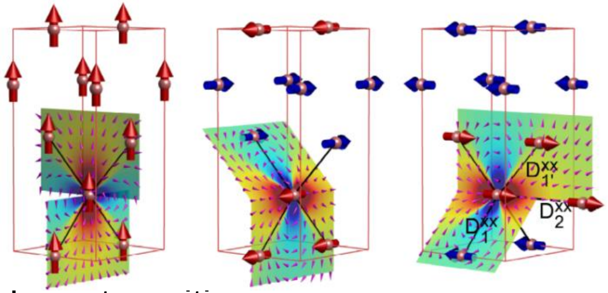

Crystal Growth Facility
*Nano to Macro*

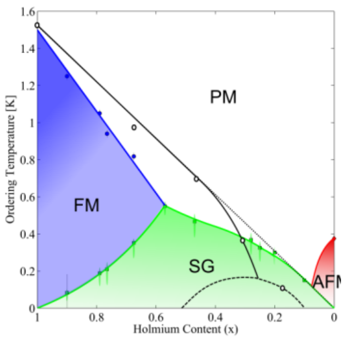
Arnaud Magrez, J. Karpinski et al.
Specialities: vapor transport, carbon-nano, high-P synth

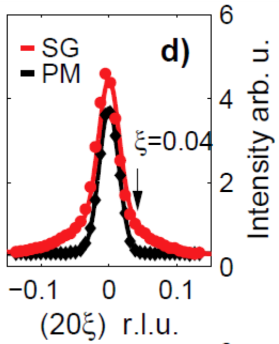
# LQM: Modeling

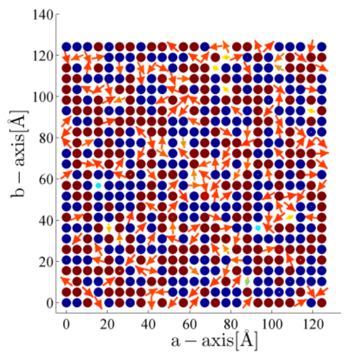
## $LiREF_4$:

- quantum dipoles
- Ising (Ho) and
- XY (Er)
- Nuclear spin order
- Quantum and classical phase transitions
- Re-entrant spin-glass in $LiHo_{1-x}Y_xF_4$ and $LiHo_{1-x}Er_xF_4$

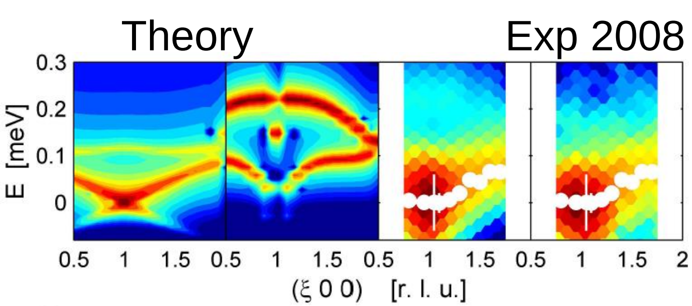


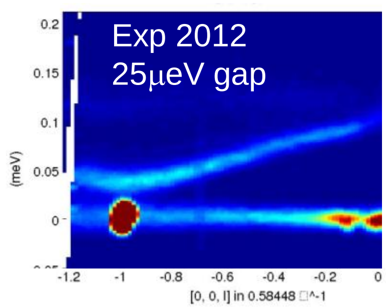




- Inhomogeneous meanfield: GPU simulation to $2 \times 10^6$ sites (needed because dipole coupling is 3D and long ranged)
- Dynamics: neutron spectroscopy and random phase approx

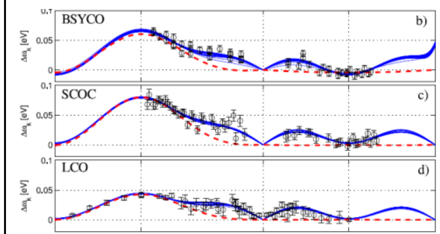



## Hubbard heritage

$$\hat{\mathcal{H}} = -\sum_{i,j,\sigma} t_{ij} c^\dagger_{i,\sigma} c_{j,\sigma} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

⇓ Project onto Mott insulator




$$\hat{\mathcal{H}}^{(4)} = \sum \left(\frac{4t_{12}^2}{U} - \frac{16t_{12}^4}{U^3}\right) \mathbf{S}_1\mathbf{S}_2 + \sum \frac{4t_{12}^2t_{23}^2}{U^3}\mathbf{S}_1\mathbf{S}_3 - \sum \frac{4t_{12}t_{23}t_{34}t_{41}}{U^3}\Big\{\sum_{\substack{i,j=1\\ i\neq j}}^{4} \mathbf{S}_i\mathbf{S}_j - 20\big[(\mathbf{S}_1\mathbf{S}_2)(\mathbf{S}_3\mathbf{S}_4) + (\mathbf{S}_1\mathbf{S}_4)(\mathbf{S}_2\mathbf{S}_3) - (\mathbf{S}_1\mathbf{S}_3)(\mathbf{S}_2\mathbf{S}_4)\big]\Big\} + E^{(4)}, \quad (2)$$

unified fit to neutron & RIXS spin wave data, achieve most accurate Hubbard parameters for cuprates

Consolidates: Neutron, RIXS, ARPES and Raman results

B. Dalla Piazza *et al* arxiv 1104.4224, collaboration w. Prof. Grioni

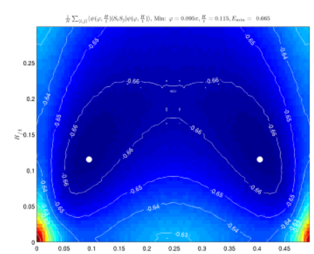
## Variational Neel + Valence-Bond states

(collaboration D. Ivanov)

$$\mathcal{H}_t = -t\sum_{i,\sigma}\sum_{\tau}\left[e^{i\varphi_\tau} c^{A\dagger}_{i,\sigma} c^{B}_{i+\tau,\sigma} + e^{-i\varphi_\tau} c^{B\dagger}_{i,\sigma} c^{A}_{i+\tau,\sigma}\right]$$

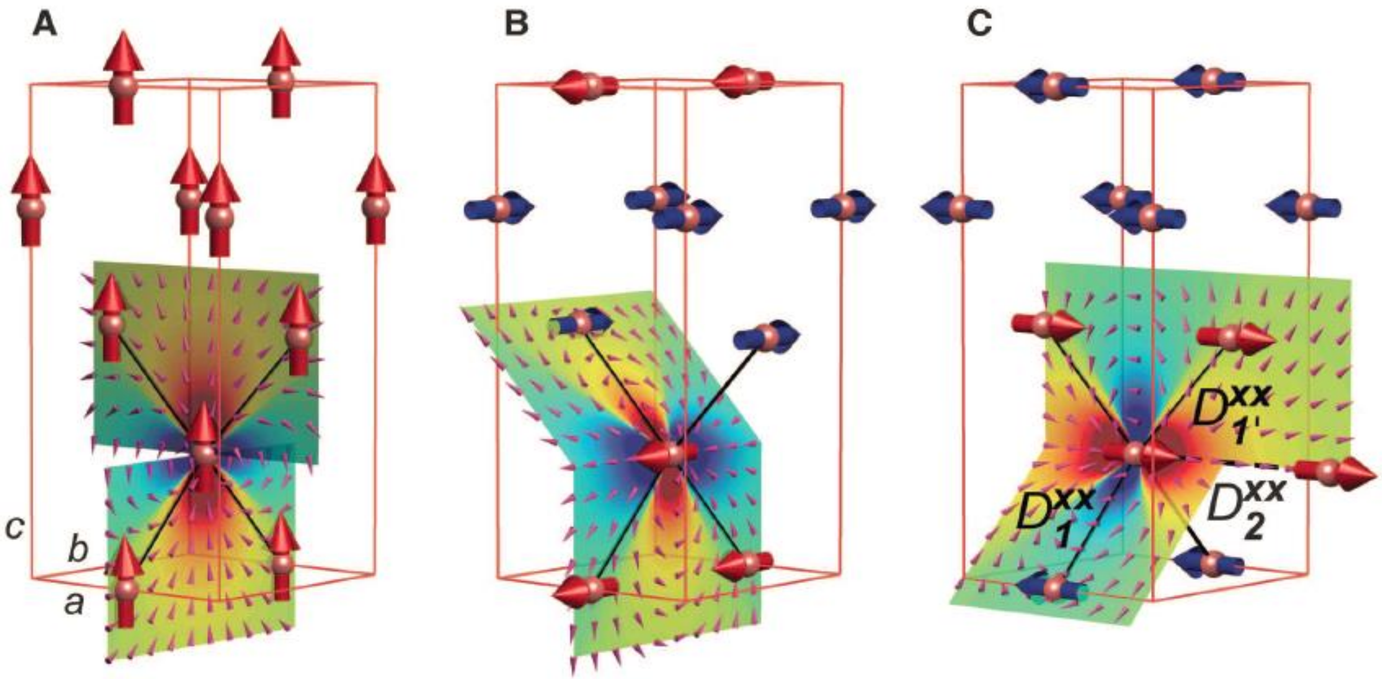
$$\mathcal{H}_N = -N\sum_{i,\sigma}\sigma\left[c^{A\dagger}_{i,\sigma}c^{A}_{i,\sigma} - c^{B\dagger}_{i,\sigma}c^{B}_{i,\sigma}\right] \quad \text{Néel field}$$

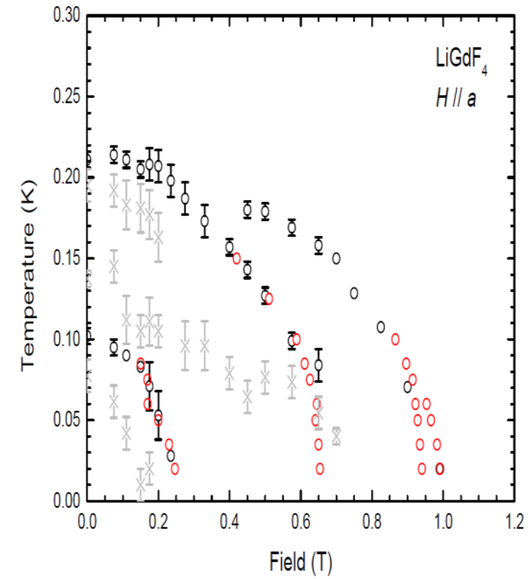
Get wave-function from mean-field Hamiltonian, minimize and excite with real Hamiltonain

# Exampe: dipolar coupled magnetism

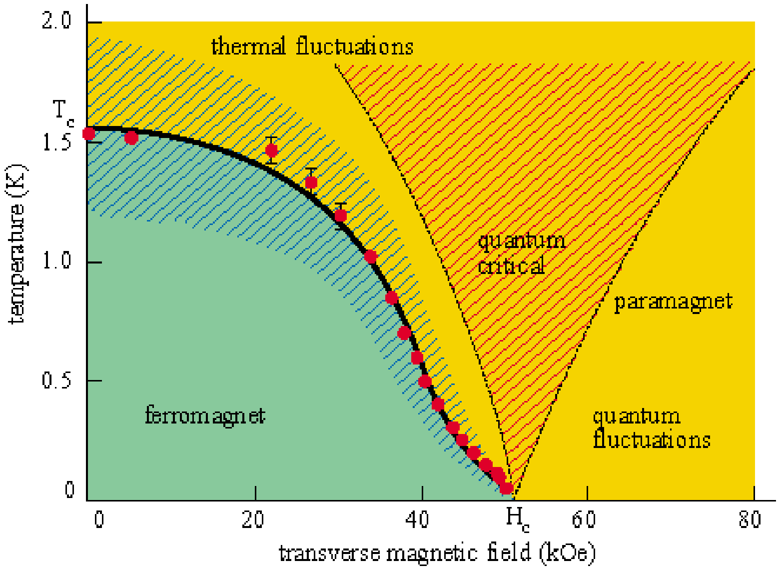
| $LiHoF_4$ | $LiErF_4$ and $LiYbF_4$ | $LiGdF_4$ … |
|---|---|---|
| Ising<br>ferromagnet | XY<br>anti-ferromagnet | Heisenberg<br>4 phases<br>No Bragg peaks |




| | | |
|---|---|---|
| QPT with<br>nuclear spin bath<br>Science **308**, 389 (2005) | Dimensional reduction<br>Science **336**, 1416 (2012)<br>PRL **116**, 197202 (2016) | Dipolar QSL?<br>to be published… ☺ |

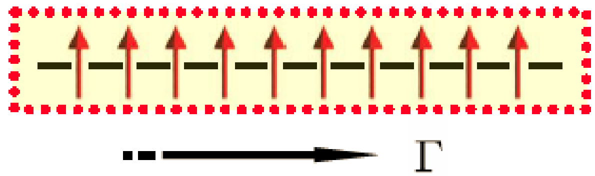
# $LiHoF_4$ - Ising ferromagnet in a transverse field

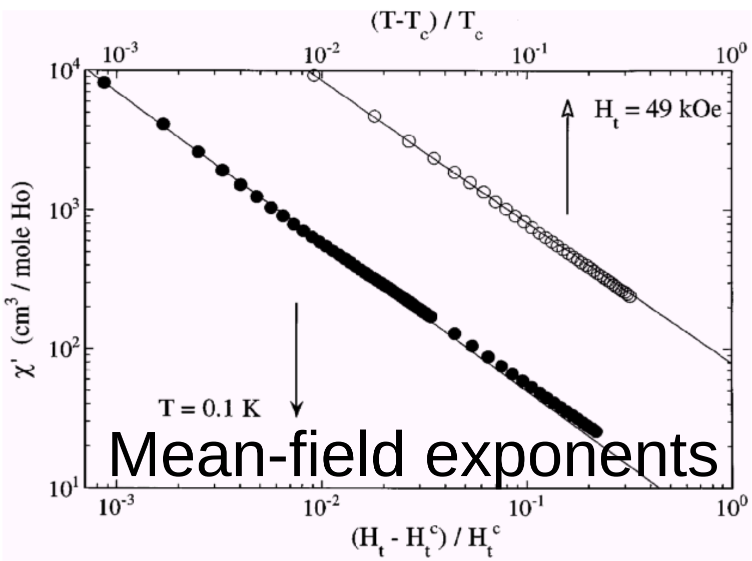



Subir Sachdev:

$\Leftarrow$ *world's simplest quantum critical point*

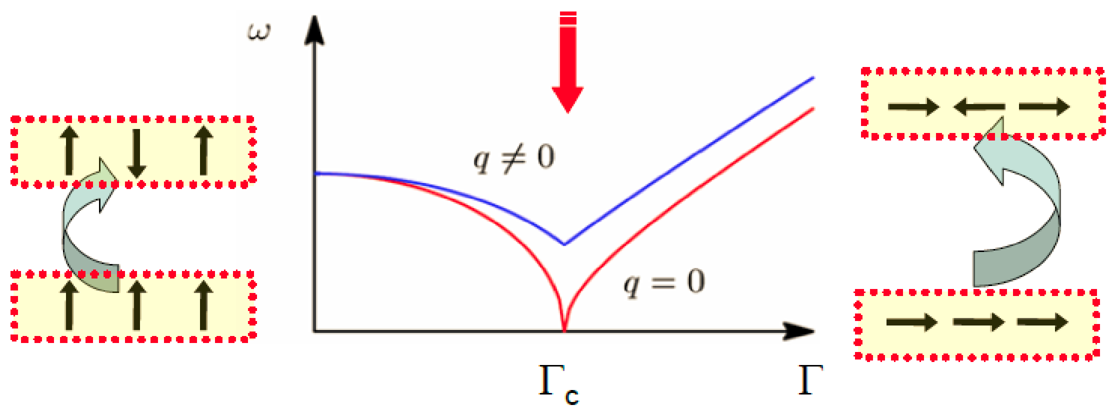
$$\mathcal{H} = -\frac{1}{2}\sum_{ij} J_{ij} S_i^z S_j^z - \Gamma \sum_i S_i^x$$



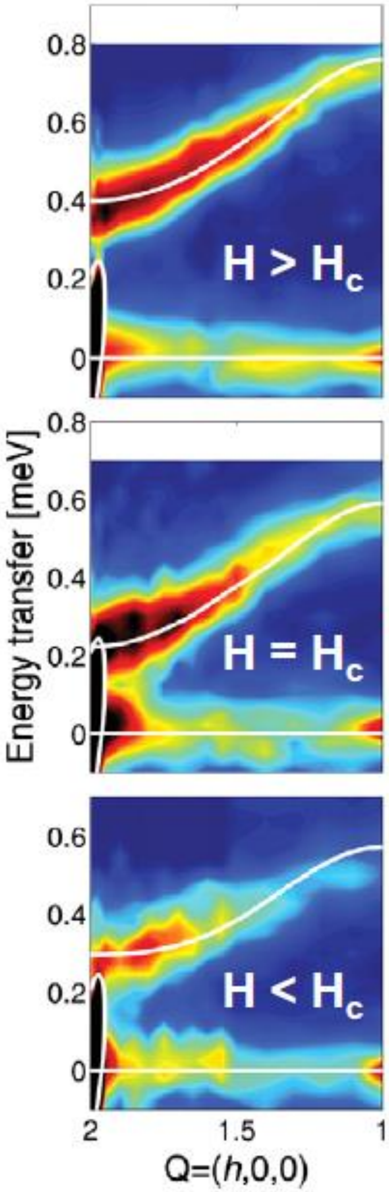



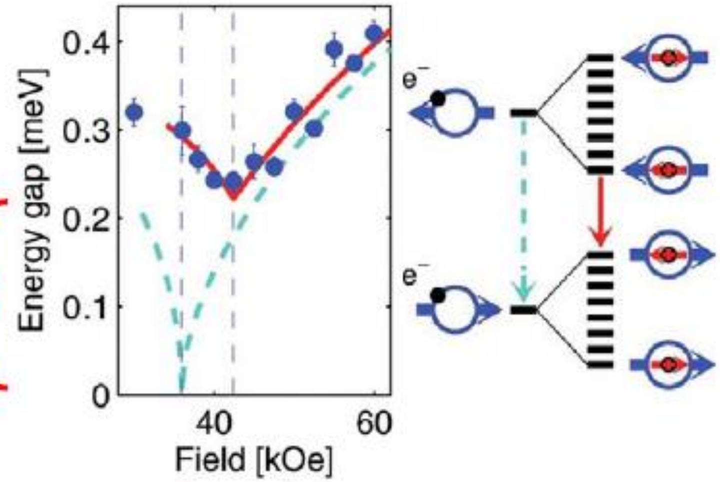

Expected fingerprint of quantum phase transition:

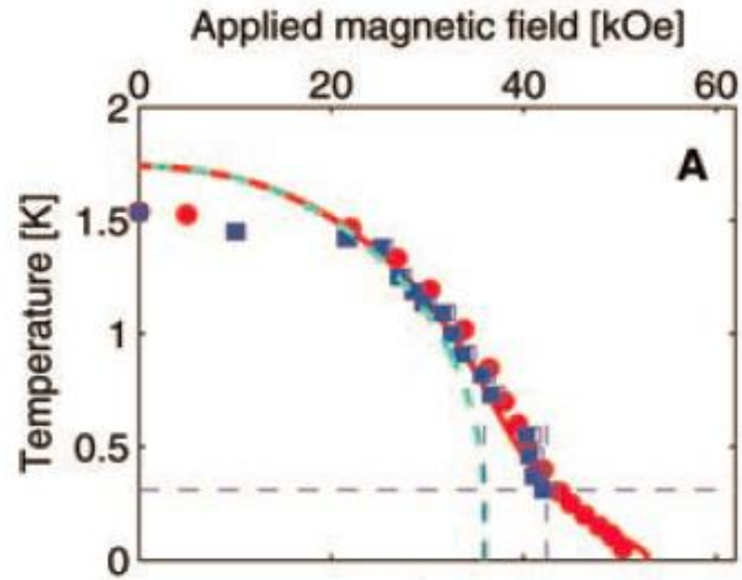
Dynamics: **Soft mode** in the characteristic excitations



# Surprise: incomplete softening – QPT in a spin bath



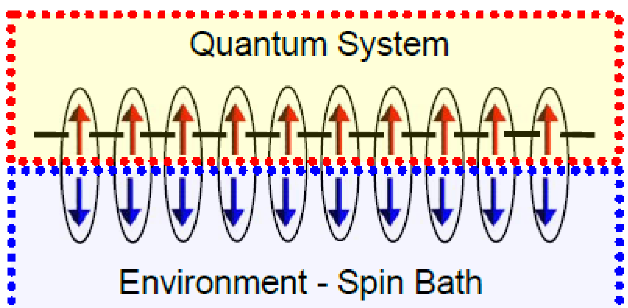




without, with hyperfine interaction

$$\mathcal{H} = \sum_i \left[\mathcal{H}_{CF} + A\boldsymbol{J}_i \cdot \boldsymbol{I}_i - g\mu_B \boldsymbol{J}_i \cdot H\right] + \frac{1}{2} \sum_{ij\,\alpha\beta} \mathcal{J}_{ij\,\alpha\beta} J_i^\alpha J_j^\beta$$

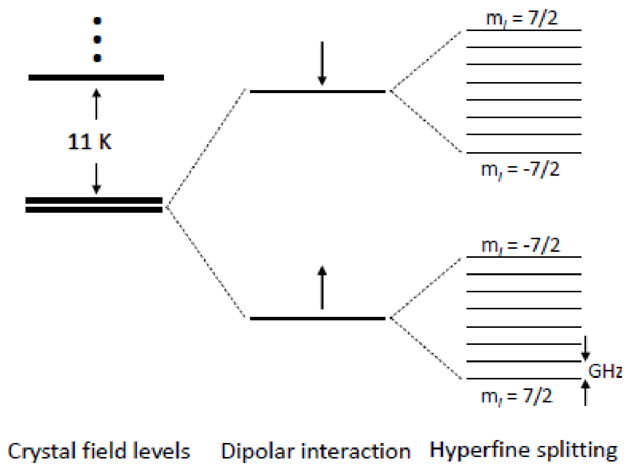
**Energy Gap** at QCP

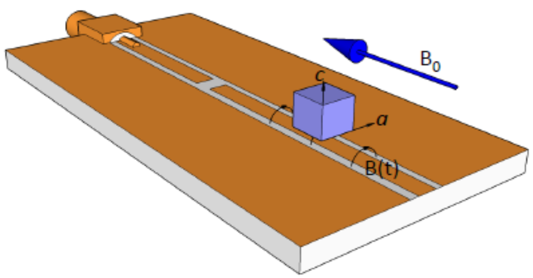
**Bath of Local Degrees of Freedom** – a '**Spin Bath**'

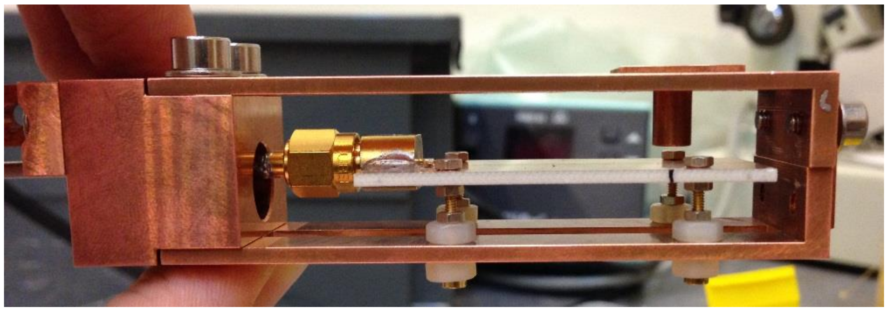


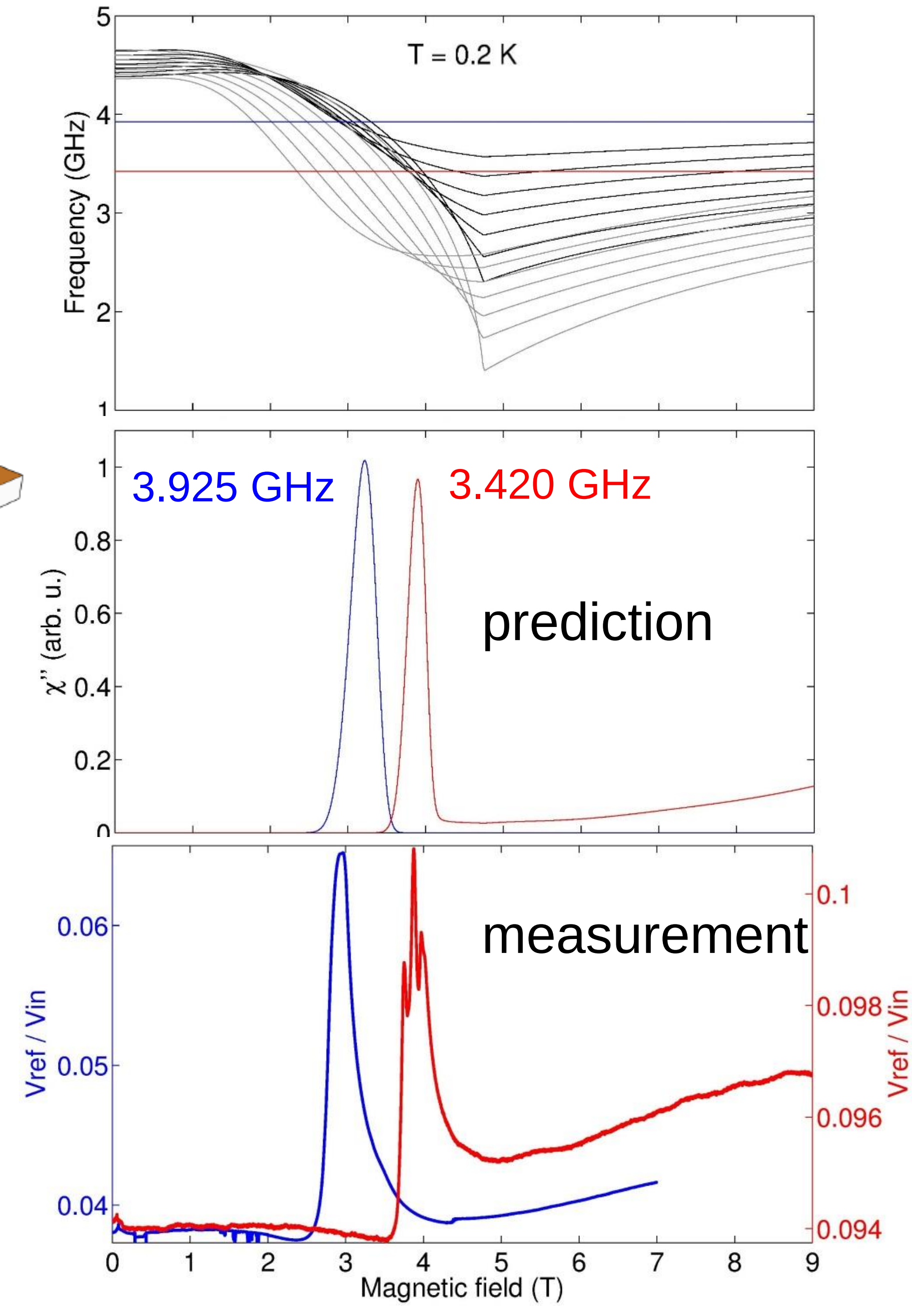

Ronnow et al.
Science **308**, 389 (2006)

# GHZ pumping to address entangled nuclear states






Kovacevic et al. PRB **94**, 214433 (2016)

# Example: spin-waves and fractional excitations

## Electronic states of matter:

Metal / Semiconductor / Insulator } Single particle picture

Superconductors: Cooper-pairs
fractional Quantum Hall effect: fractional charges } Correlated electron states

## Magnetic states and excitations:

Magnetic order
spin-wave magnon excitations } semiclassical single particle picture

Quantum 'disordered' states (quantum spin liquids)

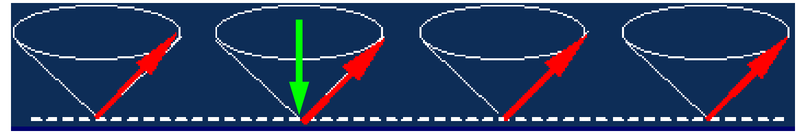
- Multi-magnon excitations
- Fractionalized excitations

} collective quantum states

Possibly simplest example: 1D Heisenberg chain

- Analytic solution by Bethe in 1931: 'domain wall quantum soup'

# Ferromagnets are simple (classical)



$H=-\sum_{rr'}J_{rr'}S_r\cdot S_{r'} = -J\sum_{<r,r'=r+d>} S^z_r S^z_{r'} + ½(S^+_r S^-_{r'} + S^-_r S^+_{r'})$

⇑ nearest neighbour ⇑

Ordered ground state, all spin up: $H|g\rangle = E_g|g\rangle$, $E_g=-zNS^2J$

Single spin flip not eigenstate: $|r\rangle = (2S)^{-½} S^-_r|g\rangle$, $S^-_r S^+_{r'}|r\rangle = 2S|r'\rangle$

$H|r\rangle=(-zNS^2J+2zSJ)|r\rangle - 2SJ\sum_d |r+d\rangle$ — flipped spin moves to neighbors

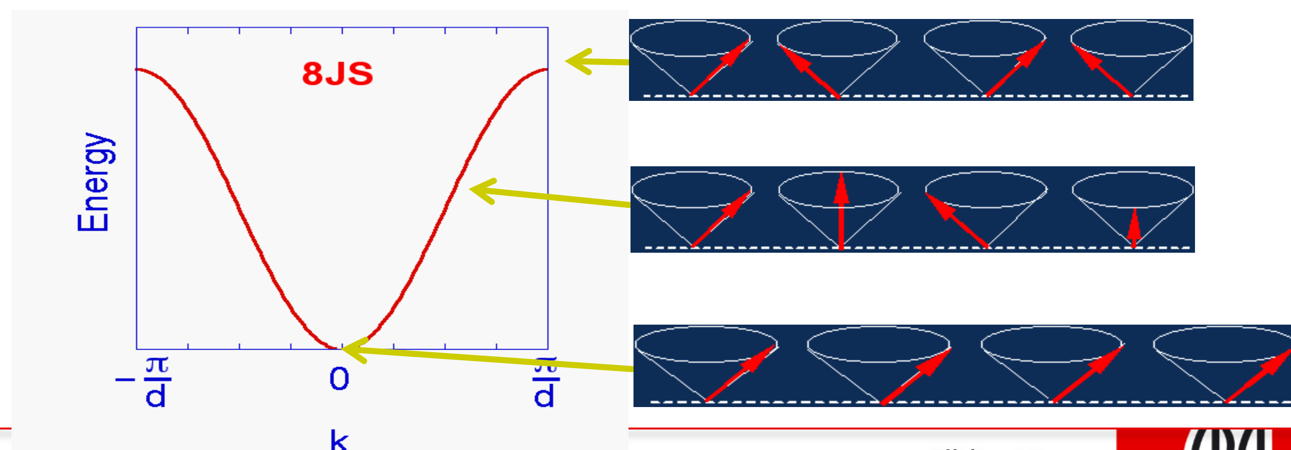
Periodic linear combination: $|k\rangle = N^{-½}\Sigma_r e^{ikr}|r\rangle$ — plane wave

Is eigenstate: $H|k\rangle = E_g+E_k|k\rangle$, $E_k=SJ\Sigma_d 1-e^{ikd}$ — dispersion = 2SJ (1-cos(kd)) in 1D

Time evolution: $|k(t)\rangle = e^{iHt}|k\rangle = e^{iE_k t}|k\rangle$ — sliding wave

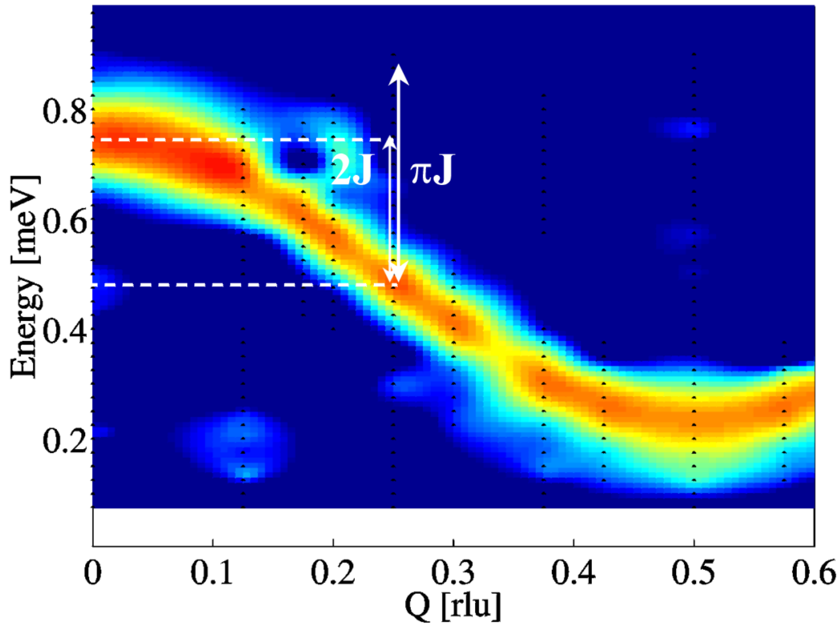
Dispersion:
relation between
time- and space-
modulation period

Same result in classical
calculation ⇒ precession:



# Spin waves in a "ferromagnet"

$CuSO_4 \cdot 5D_2O$

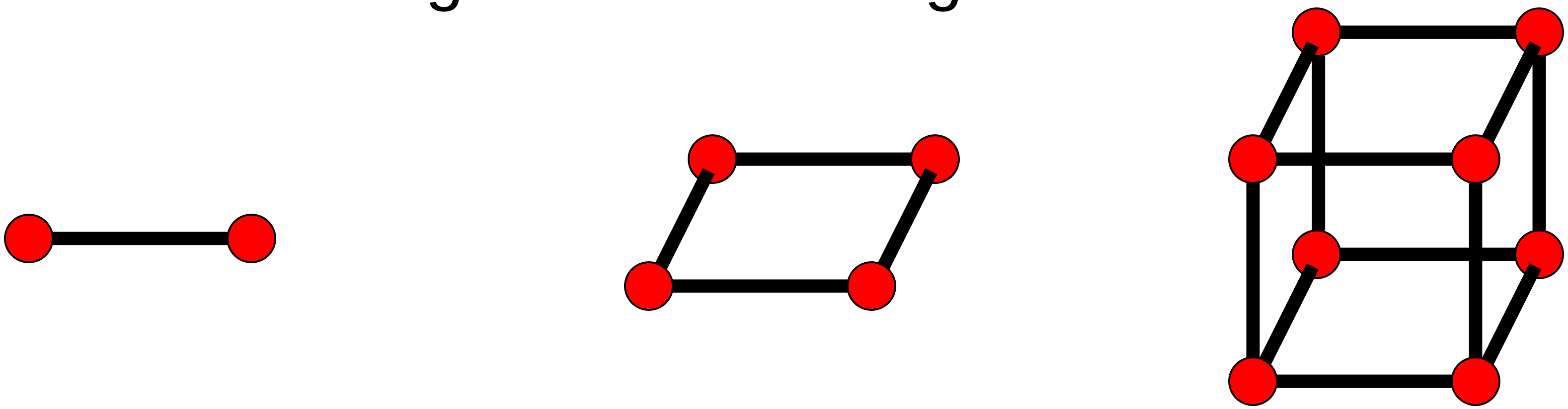



dispersion = 2SJ (1-cos(kd))

Actually it is an antiferromagnet polarized by 5T field

# Antiferromagnets are tricky

Fluctuations stronger for fewer neighbours



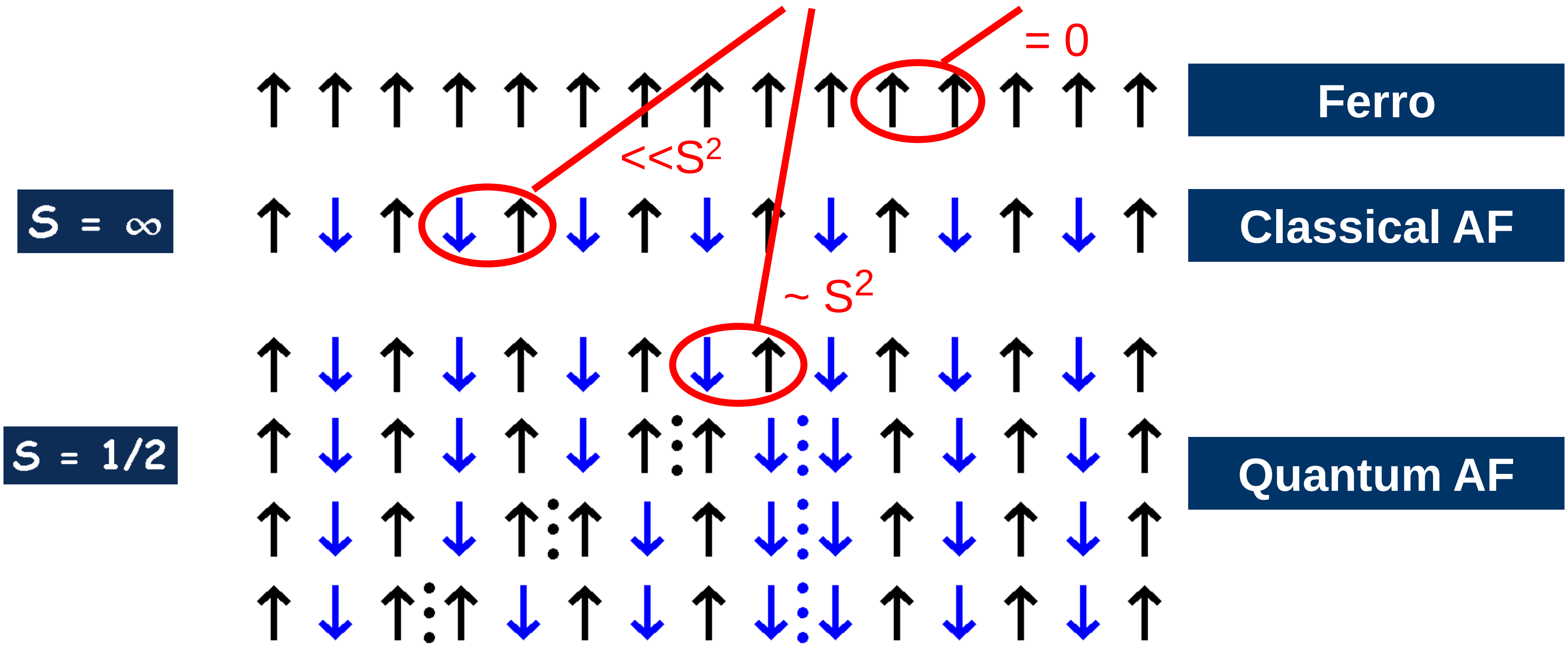
1D: Ground state ‘quantum disordered’ spin liquid of
S=1/2 spinons. Bethe ansatz ‘solves’ the model

2D: Ground state ordered at T=0 <S> = 60% of 1/2
(although not rigorously proven).

3D: Ground state long range ordered, weak quantum-effects

# antiferromagnetic spin chain

$$\mathcal{H} = J \sum S^z_n S^z_{n+1} + \frac{1}{2}\left(S^+_n S^-_{n+1} + S^-_n S^+_{n+1}\right)$$



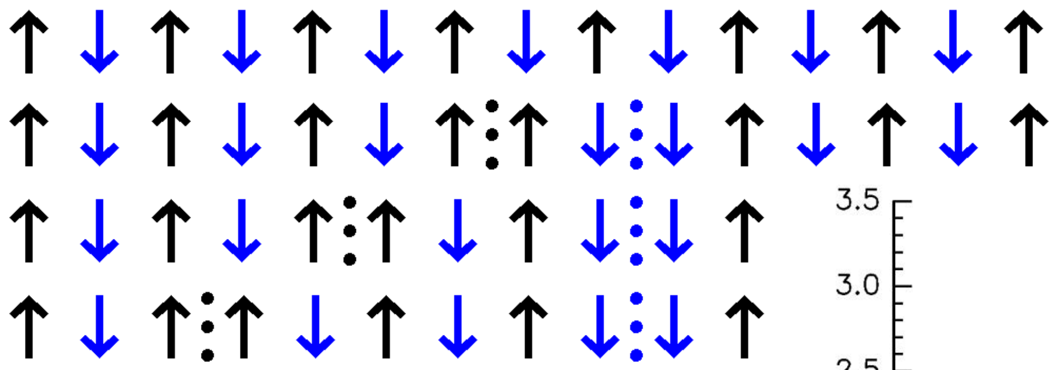

Ground state (Bethe 1931) – a soup of domain walls

# Spinon excitations

Elementary excitations:

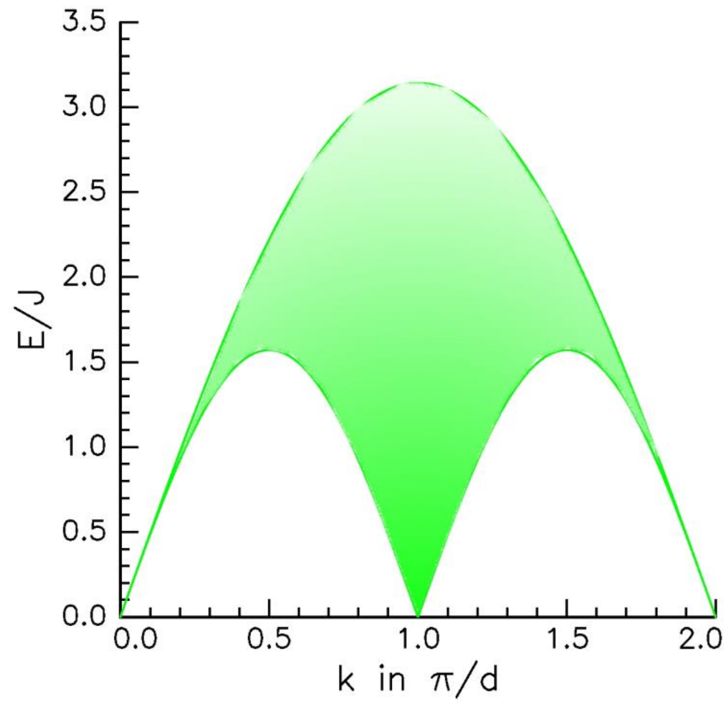
– "Spinons": spin S = ½ domain walls with respect to local AF 'order'

– Need 2 spinons to form S=1 excitation we can see with neutrons



| | | | |
|---|---|---|---|
| Energy: | $E(q) = E(k_1)$ | + | $E(k_2)$ |
| Momentum: | $q = k_1$ | + | $k_2$ |
| Spin: | $S = ½$ | ± | ½ |

Continuum of scattering ⇒



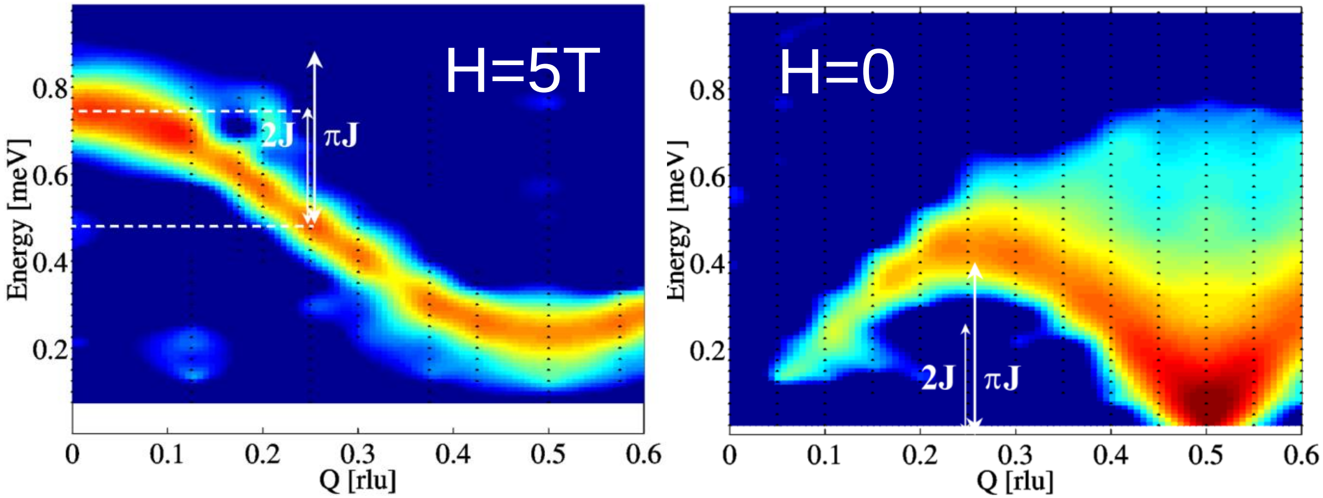
# The *antiferromagnetic* spin chain

FM: ordered ground state (in 5T mag. field)

- semiclassical spin-wave excitations

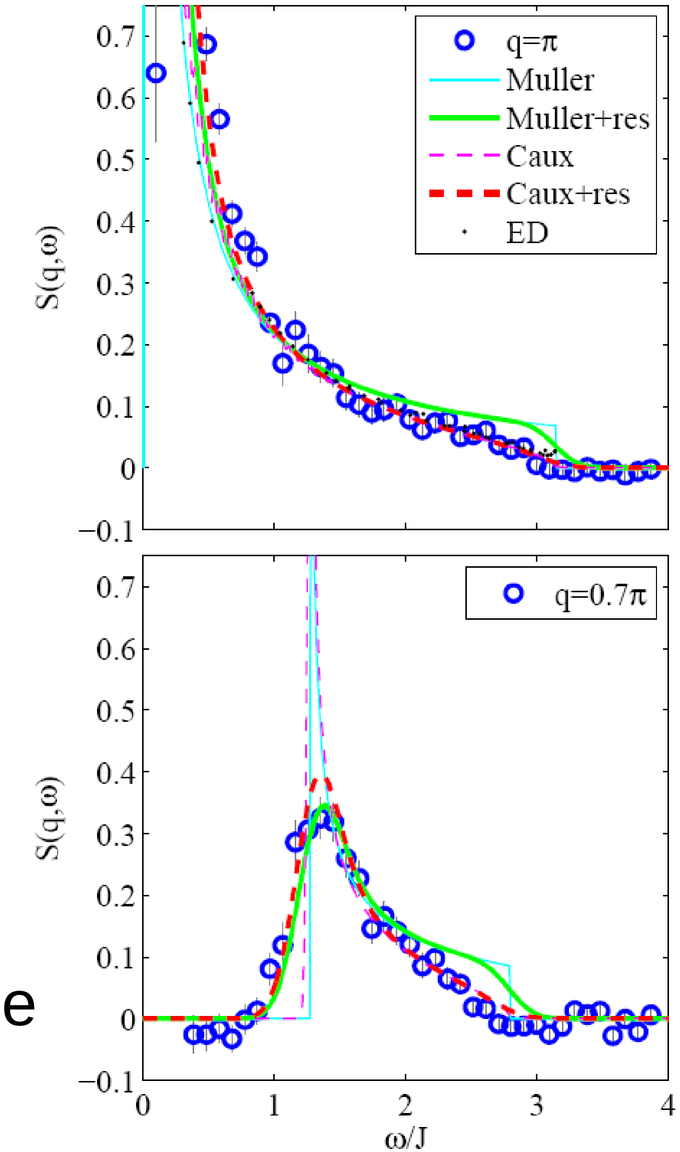
AFM: quantum disordered ground state

- Staggered and singlet correlations
- Spinon excitations




– Agebraic Bethe ansatz for inelastic lineshape

– Beyond Müller-conjecture ⇒



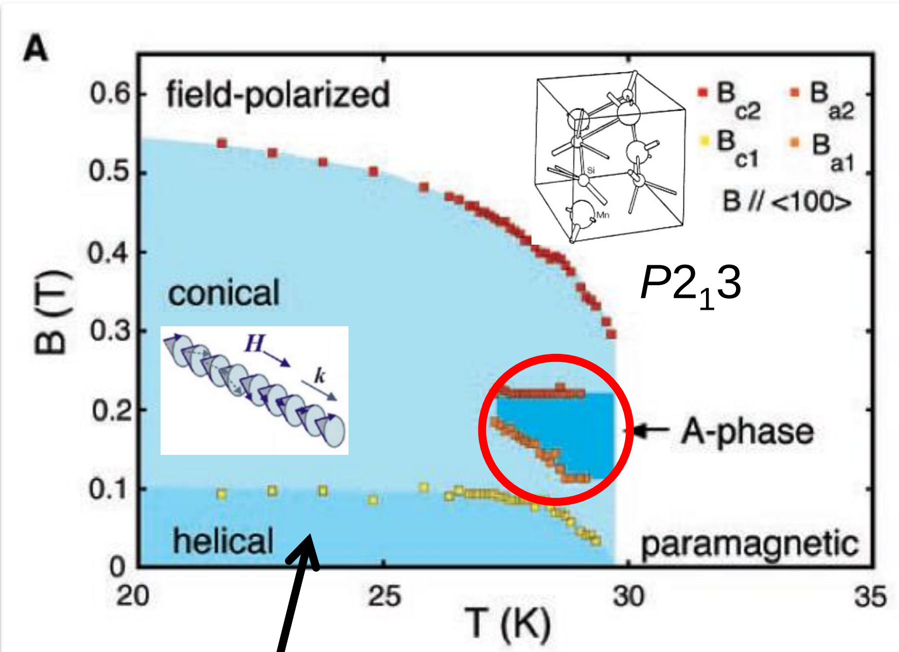

Mourigal, Enderle, HMR, Caux

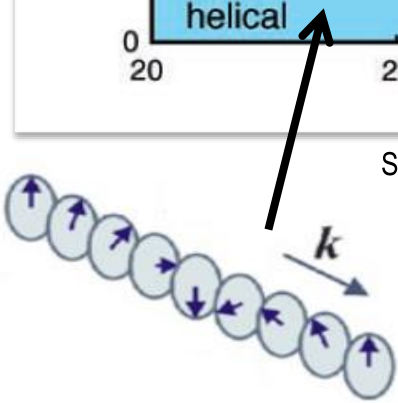
# Example: Skyrmions in chiral magnets

## Hamiltonian for helimagnetic groundstate

$$\mathcal{H} \propto J\,(S_1 \cdot S_2) + D\,(S_1 \times S_2)$$

## Weakly itinerant ferromagnet MnSi

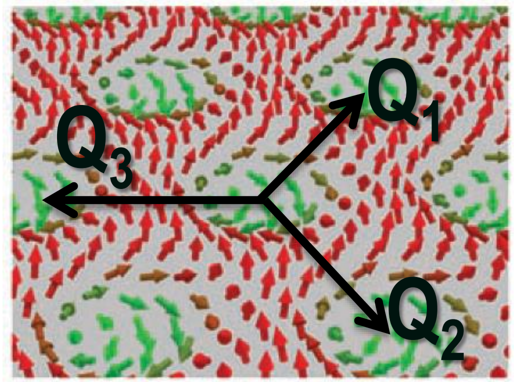


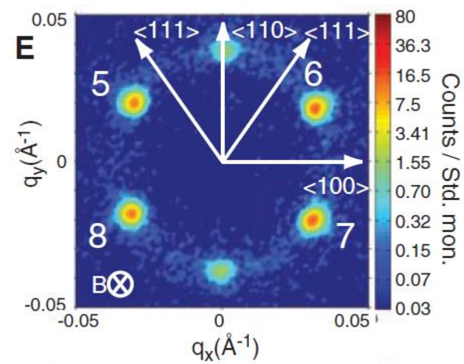




S. Mühlbauer *et al.*, Science **323**, 915 (2009)

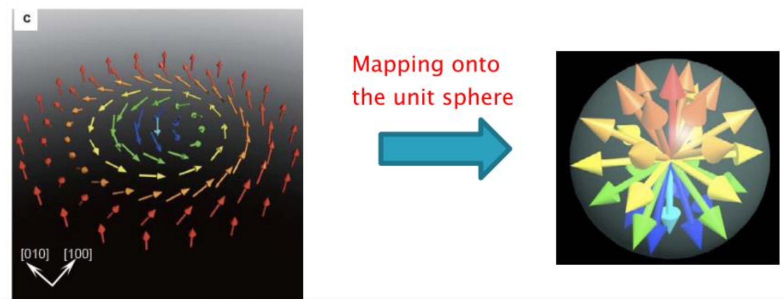
$$Q \sim D/J \sim \;180\ \text{Å}$$

## Topological skyrmion lattice in A-phase




## Hexagonal scattering pattern seen by SANS

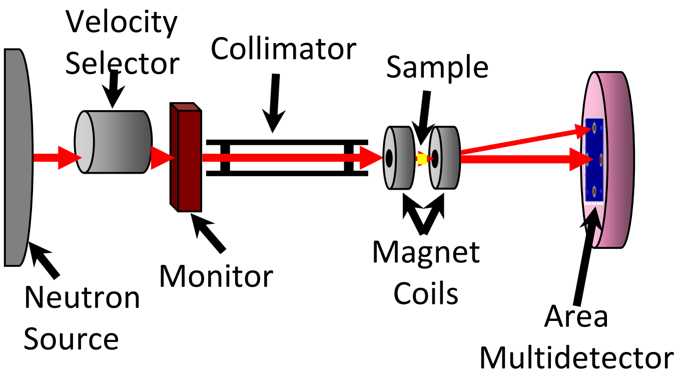



- **Topological stability**
- **Nanometric size (10-200nm)**
- **Found ~~close~~ to room temperature**
- **Fert and Tokura are interested…**

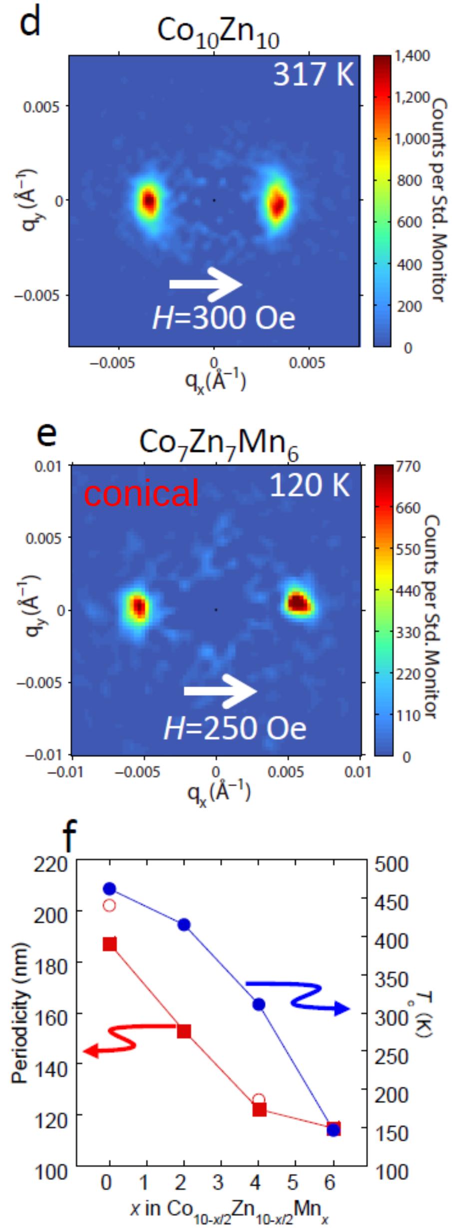
# Small-angle neutron scattering - and materials discovery

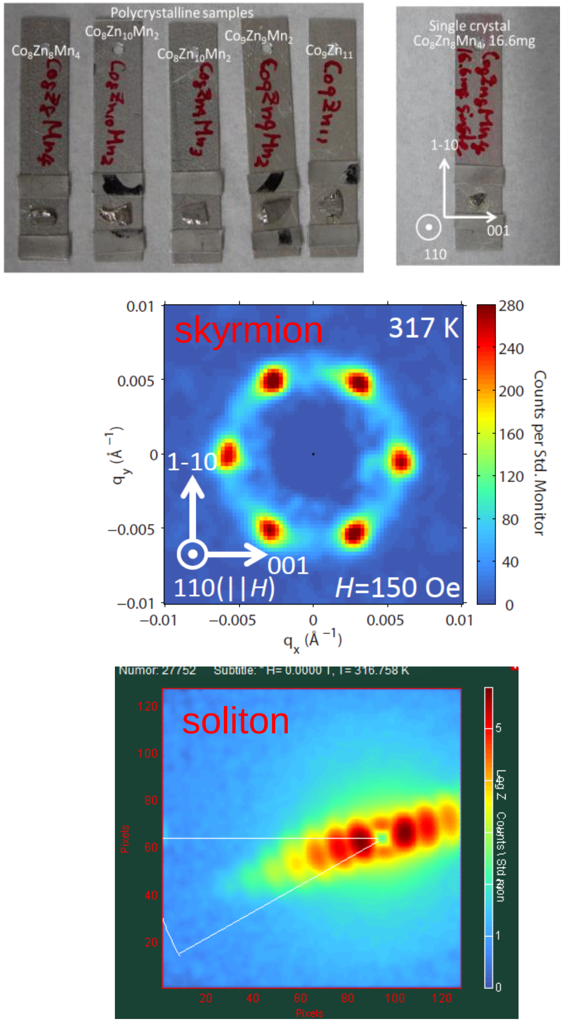
SANS-II beam line at SINQ

Large structures → low **q** SANS

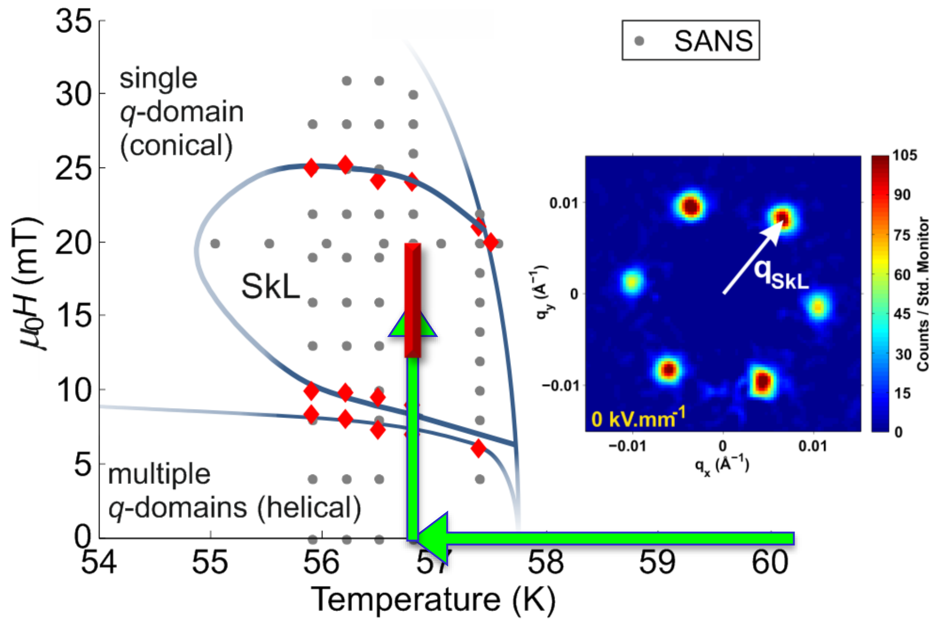



Length of instrument: 10-40 m, Scattering angle: ~1º
(mesoscopic length-scales up to 1μm)

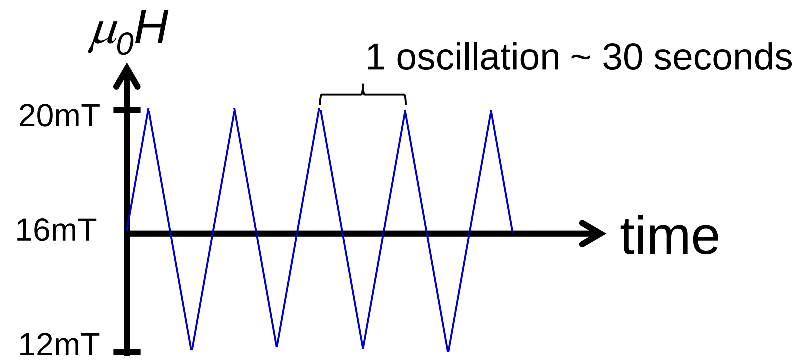


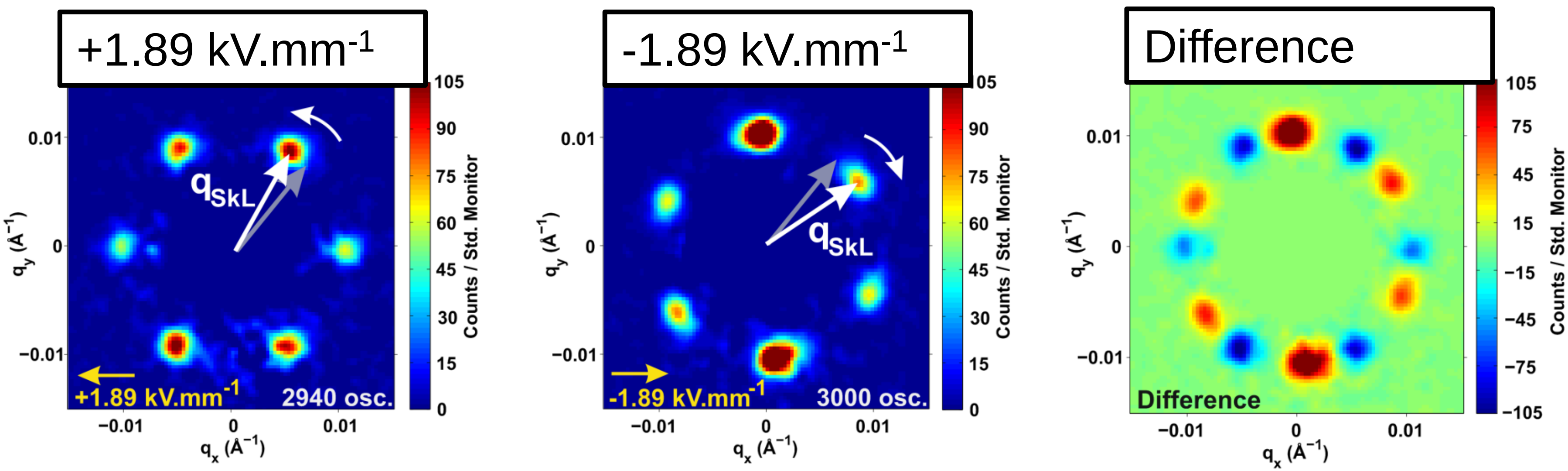



# Generating Skyrmion lattice rotations for $\mu_0 H$ || [1-10] and $E$ || [111]

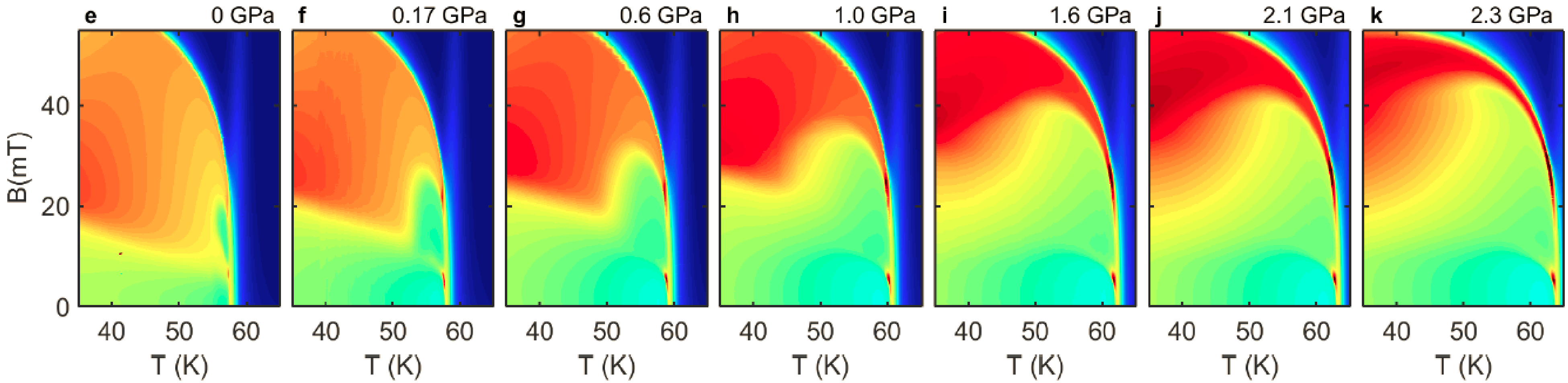



**Longitudinal magnetic field oscillations in the SkL phase to overcome pinning**



# Dramatic pressure enhancement of skyrmion pocket




- So far all bulk skyrmion hosts had universal small skyrmion pocket
  Some believed it could not be expanded in bulk materials

- These data show small tuning can enhance skyrmion phase stability

- Similar tuning can be sought in other existing and new compounds

# Where does stabilization come from?

0 GPa: $\Delta T_{SkL} \approx 2$ K

0.6 GPa: $\Delta T_{SkL} \approx 10$ K

- while parameters seemingly change little:

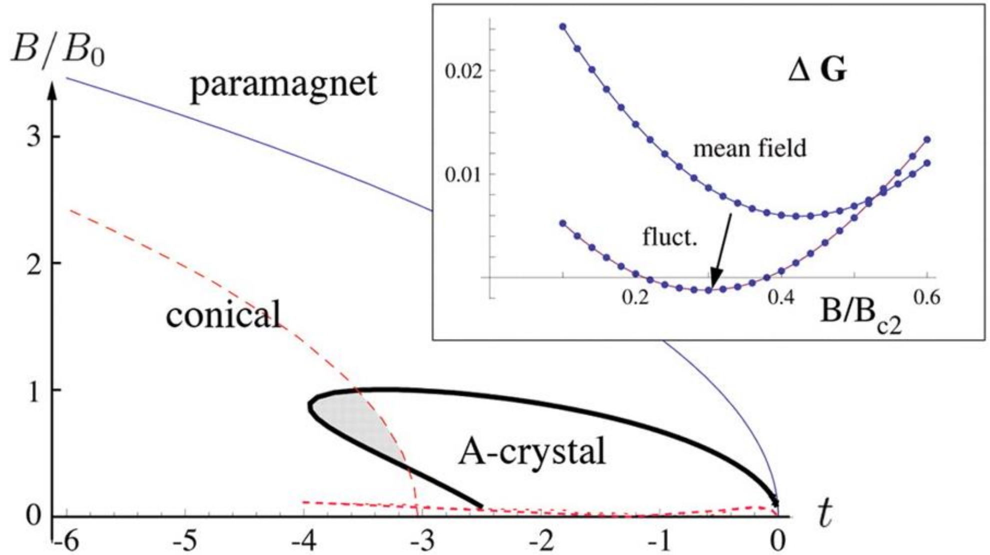
$$\Delta T_C / T_C = \Delta J / J = 2.5\ \%$$

$$\Delta B_{C1} / B_{C1} = \Delta K / K = 15\ \%$$

$$\Delta B_{C2} / B_{C2} = -9\ \%$$

translates to $\Delta D / D \approx -3.5\ \%$

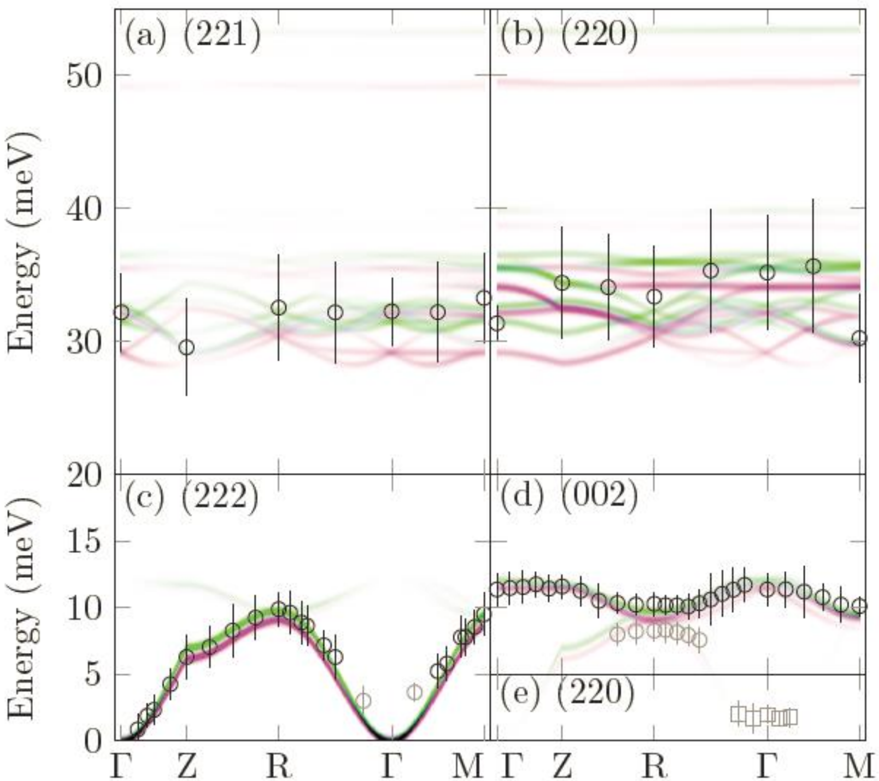
- Ginzburg-Landau approach Muhlbauer Science 323 915 (2009)

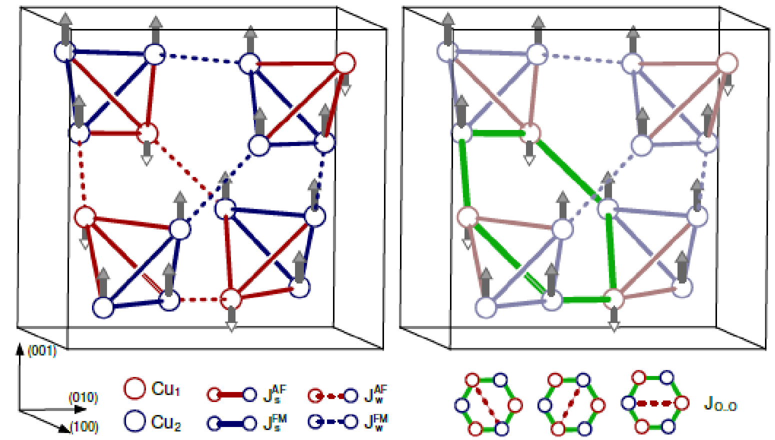


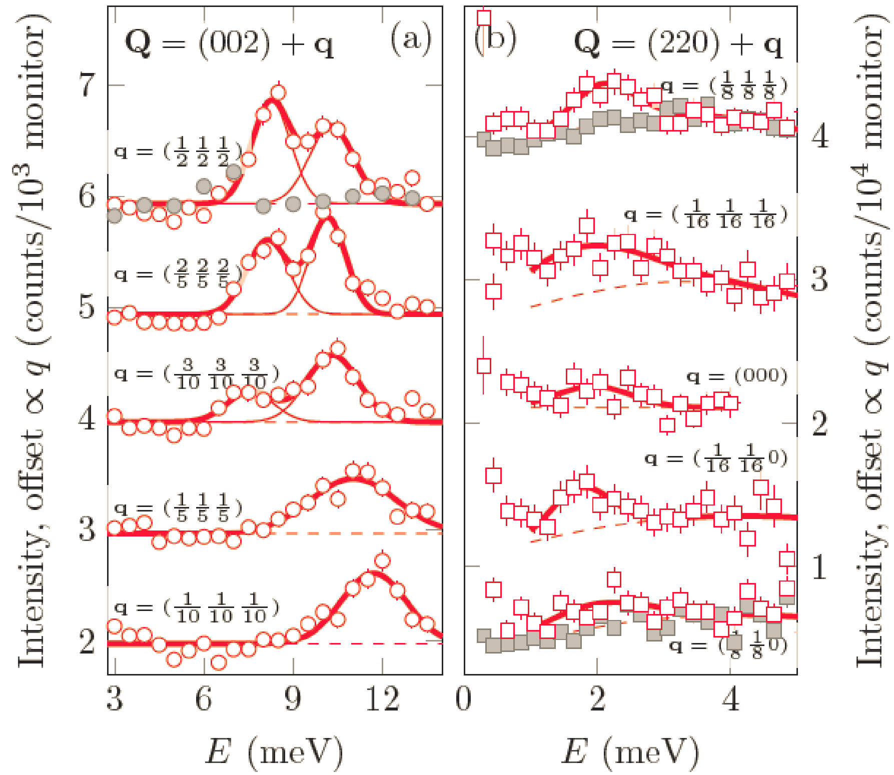

$$F[\mathbf{M}] = A\mathbf{M}^2 + J(\nabla\mathbf{M})^2 + D\mathbf{M}\cdot(\nabla\times\mathbf{M}) + K\mathbf{M}^4 - \mathbf{B}\cdot\mathbf{M}$$

$$\Delta G_{\text{fluct}} \approx \gamma \frac{\Lambda}{2\pi^2} \int \frac{dV}{V} \left(M_A^2(\mathbf{r}) - M_{con}^2(\mathbf{r})\right)$$

# Inelastic neutron scattering ⇒ Hamiltonian



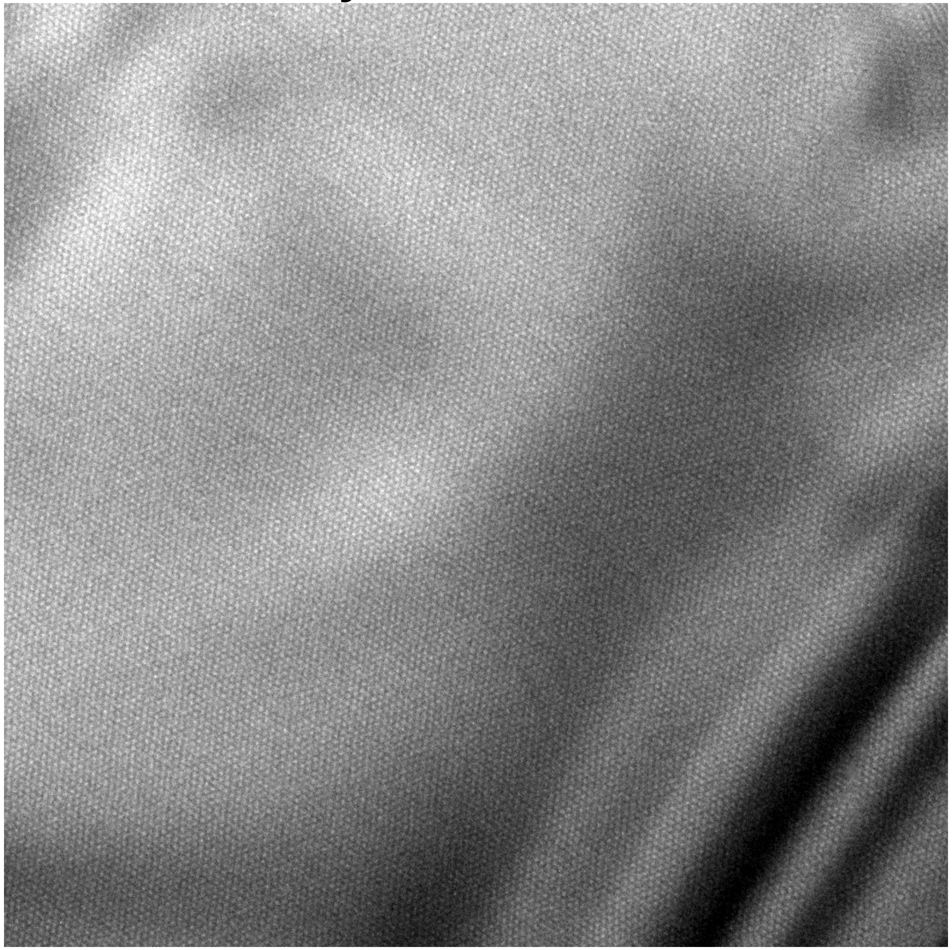

| $J_s^{AF}$/K | $J_s^{FM}$/K | $J_w^{AF}$/K | $J_w^{FM}$/K | $J_{o..o}$/K | Color | Reference |
|---|---|---|---|---|---|---|
| 145 | −140 | 28 | −50 | 45 | magenta | 22 |
| 135(5) | −157(7) | 4.8(5) | −42(5) | 91(8) | green | this work |

Gregory Tucker *et al.*, PRB in press

# Lorentz microscopy

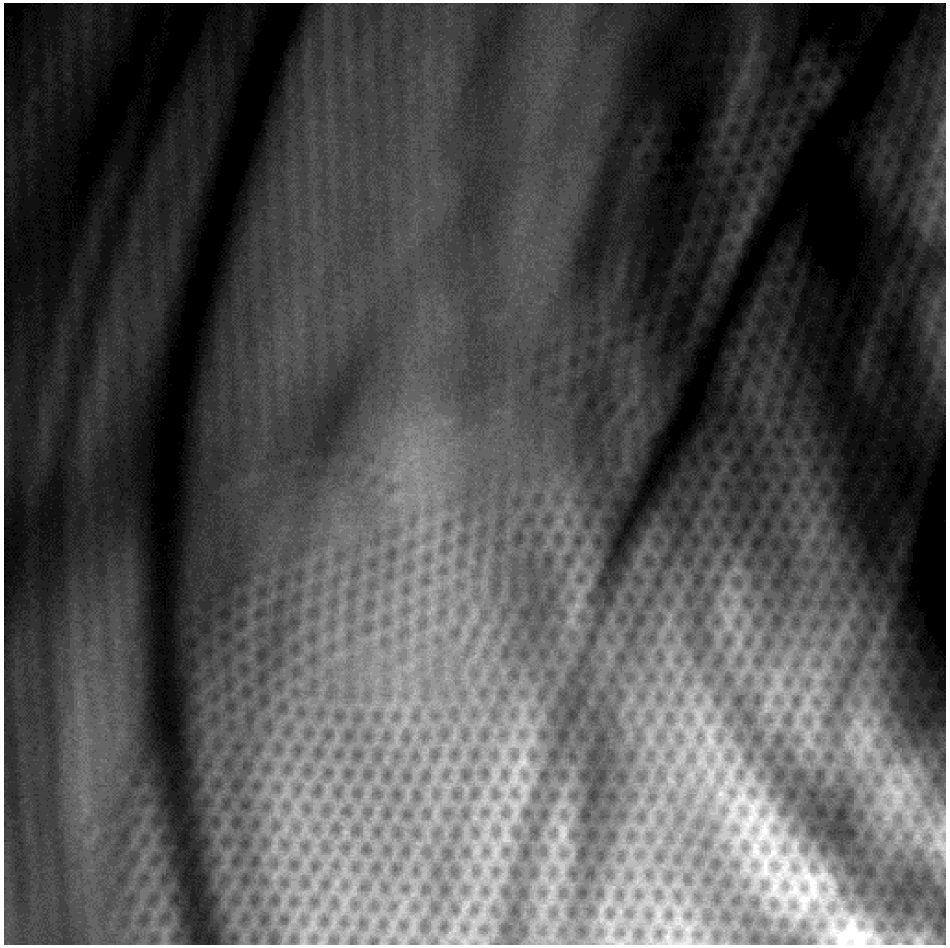
Ping Huang, Fabrizio Carbone et al.

- 10000 skyrmions resolved



Harmonics, domain structures, Bragg-glass etc.

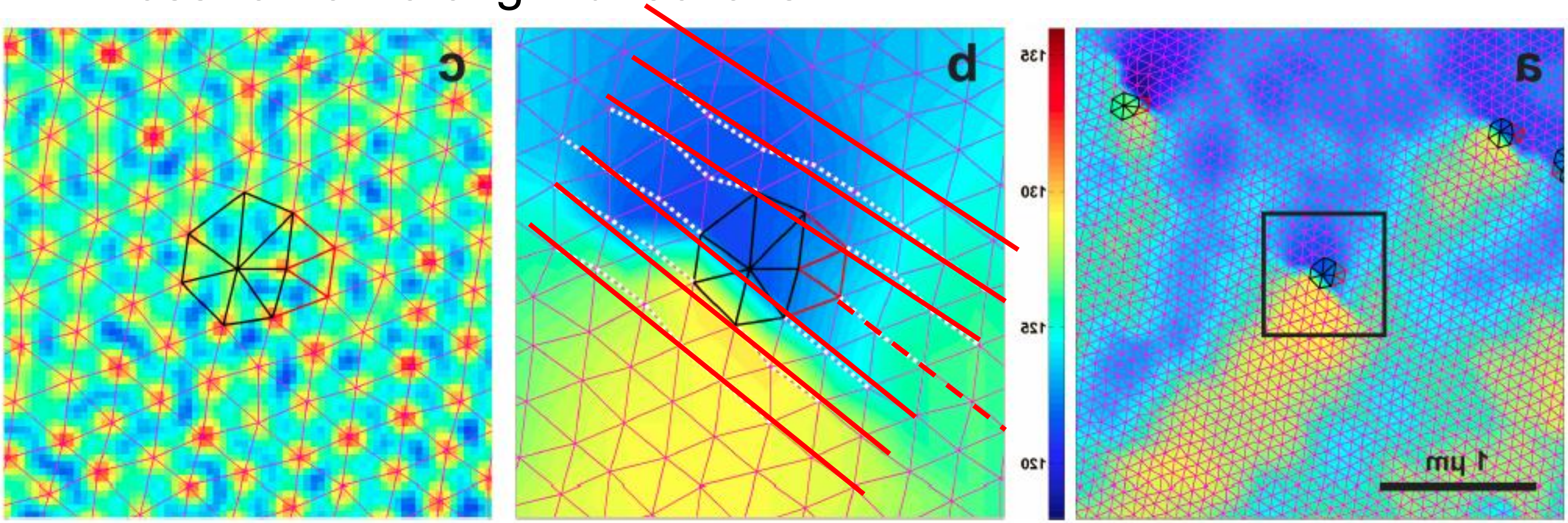
- Time resolution ns to minutes



EPFL center for electron microscopy
- Collaborations welcome

# Defects and angles

- Defects classifiable – eg a 5-7 or a 5-8-5 defect
  - “loss” of row along 2 directions

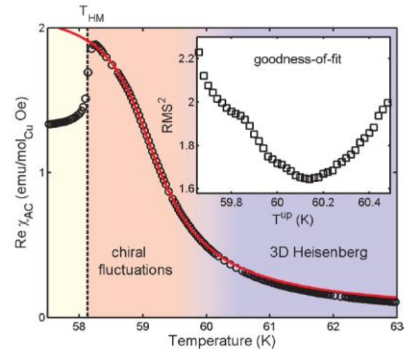


Map SkL angle: $\Psi_6(r_i) = \frac{1}{N_N^i} \sum_k^{n} e^{i6\theta(r_{ik})}$ or peak in “local Fourrier”

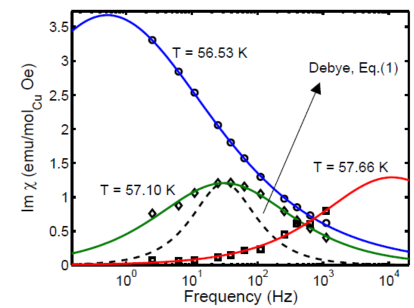
  - Defects creates far-stretching rotations

# Conclusions: $Cu_2OSeO_3$ offers fundamental insights

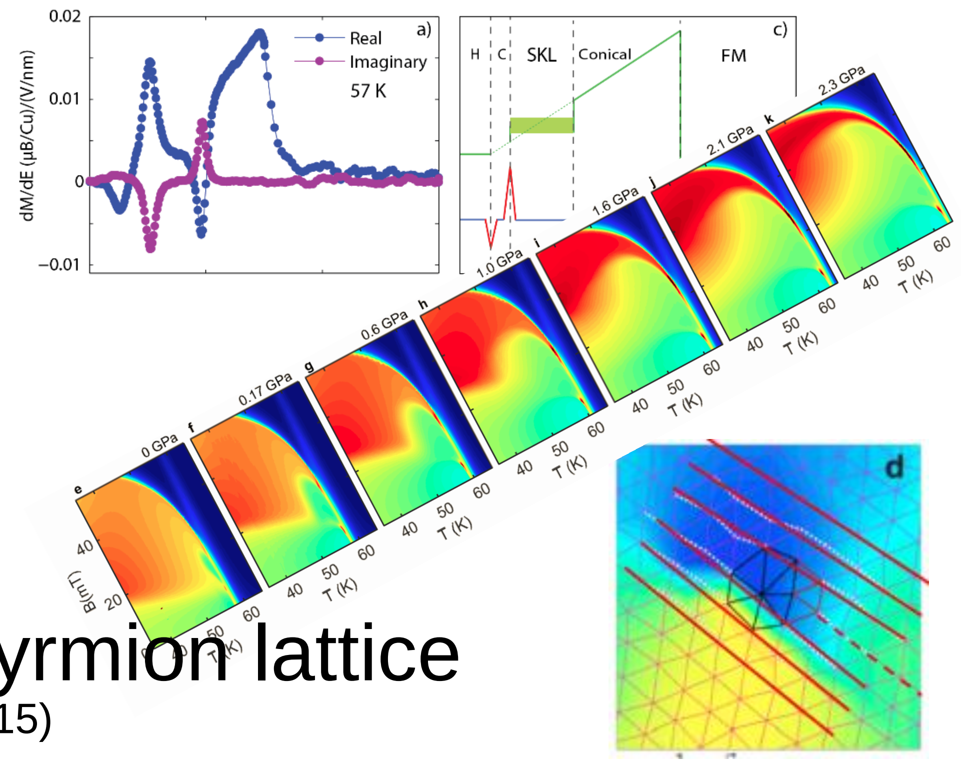
- Perfect PM-FM scaling
  I. Zivkovic *et al.* PRB **89** 060401 (2014)




- Relaxation phenomena
  I. Levatic *et al.* PRB **90** 224412 (2014)




- Magneto-electric coupling
  A. A. Omrani *et al.* PRB **89** 064406 (2014)




- Tuning of phase diagram, enhance skyrmion pocket
  I. Levatic *et al.* arxiv 1512.00633

- Order and defects in the skyrmion lattice
  J. Rajeswari, P. Huang *et al.* PNAS **112** 14212 (2015)

# Skyrmions:

Susceptibility

PHYSICAL REVIEW B **89**, 060401(R) (2014)

**Critical scaling in the cubic helimagnet $Cu_2OSeO_3$**

PHYSICAL REVIEW B **90**, 224412 (2014)

**Dissipation processes in the insulating skyrmion compound $Cu_2OSeO_3$**

PHYSICAL REVIEW B **89**, 064406 (2014)

**Exploration of the helimagnetic and skyrmion lattice phase diagram in $Cu_2OSeO_3$ using magnetoelectric susceptibility**

A. A. Omrani,[1] J. S. White,[1,2] K. Prša,[1] I. Živković,[3] H. Berger,[4] A. Magrez,[4] Ye-Hua Liu,[5] J. H. Han,[6,7] and H. M. Rønnow[1,*]

**Dramatic pressure-driven enhancement of bulk skyrmion stability**

I. Levatić[1], P. Popčević[1,2], V. Šurija[1], A. Kruchkov[3], H. Berger[4], A. Magrez[4], J. S. White[5], H. M. Rønnow[3] & I. Živković[1,3]

Neutron scattering

**Electric-Field-Induced Skyrmion Distortion and Giant Lattice Rotation in the Magnetoelectric Insulator $Cu_2OSeO_3$**

J. S. White,[1,2,*] K. Prša,[1] P. Huang,[1] A. A. Omrani,[1] I. Živković,[3] M. Bartkowiak,[4] H. Berger,[5] A. Magrez,[5]

**Spin excitations in the skyrmion host $Cu_2OSeO_3$**

G S Tucker,[1,2] J S White,[2] J Romhányi,[3] D Szaller,[4] I Kézsmárki,[4] B Roessli,[2] U Stuhr,[2] A Magrez,[5] F Groitl,[1,2] P Babkevich,[1] P Huang,[1] I Živković,[1] and H M Rønnow[1]

Electron microscopy

PNAS

**Filming the formation and fluctuation of skyrmion domains by cryo-Lorentz transmission electron microscopy**

Jayaraman Rajeswari[a,1], Ping Huang[b,1], Giulia Fulvia Mancini[a], Yoshie Murooka[a], Tatiana Latychevskaia[c], Damien McGrouther[d], Marco Cantoni[e], Edoardo Baldini[a], Jonathan Stuart White[f], Arnaud Magrez[g], Thierry Giamarchi[h], Henrik Moodysson Rønnow[b], and Fabrizio Carbone[a,2]

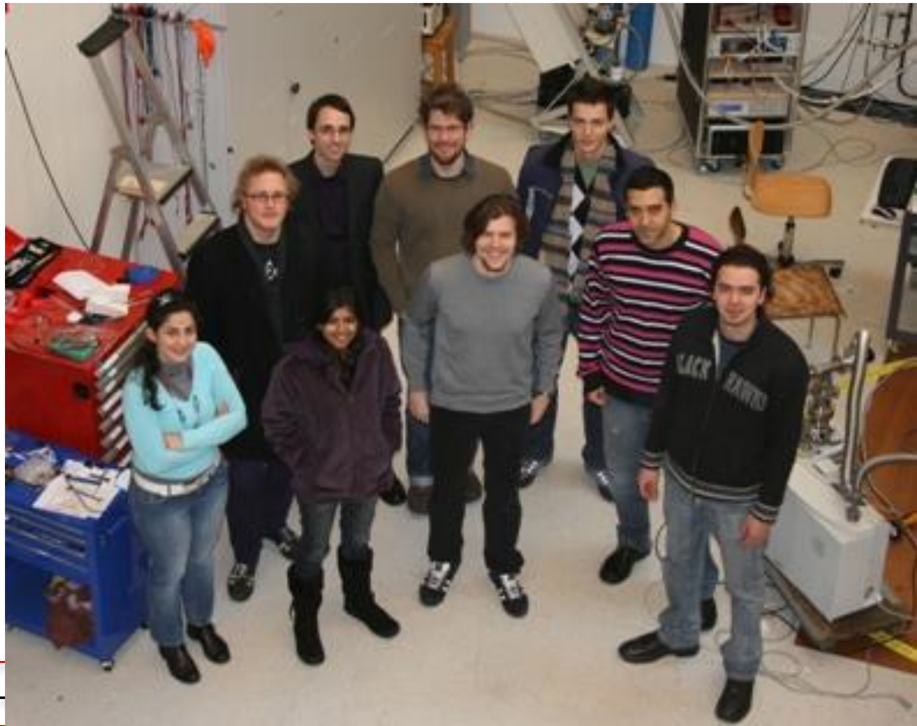
LQM

# TP4 and student projects in LQM

- General philosophy:
  - Foreseeable outcome in one semester
  - Related to real research (linked to ongoing projects)
  - Can be extended to Diploma/Master's project
  - Defined together with student:
    depend on preferences: experiment / instrumentation / numeric / theory

- More info:
  - Check lqm.epfl.ch
  - Under publications you can see old tp4 reports

- If interested,
  schedule a discussion
  - henrik.ronnow@epfl.ch



# Project opportunities:

- TP4, 1 or 2 semesters
- Semester projects (new Master system)
- Semester project at PSI or in Tokyo
- Possible master-internship in Tokyo (after 2 TP4)
- Master projects
- PhD positions

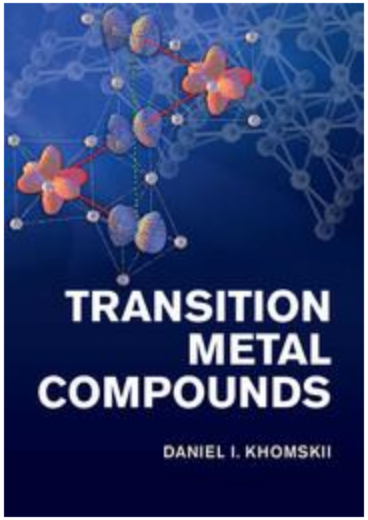
# What you will learn in LQM

- Magnetism in real materials
- Quantum many-body physics
- Instrumentation:
  - low-temperature methods
  - Building measurement setups
  - measurement electronics
- Measurements and analysis
- Coupling data to theory

Complementary:

Autumn: Solid State Physics 3 Prof Mila

Spring: Solid State Physics 4 Ronnow



# Examples of past TP4 and project students

- Julian Piatek: sub-K susceptometry $\Rightarrow$ Master $\Rightarrow$ PhD on Li(Ho/Er)F4

- Bastien Dalla Piazza: adiabatic cooling, spin-theory $\Rightarrow$ Master $\Rightarrow$ PhD
- Saba Zabihzadeh: high-P $\chi(T)$ and Cp $\Rightarrow$ Master LQM

- Laurent Cevey: high-P susceptometry $\Rightarrow$ Master in Beijing
- P-F Duc: commercial M(H) solution $\Rightarrow$ Master in Beijing
- Sarah Debler: Hall-probe susceptometer $\Rightarrow$ Master (Munich Centre for Advanced Photonics)

- Pau Jorba Cabre: Ultra-low temperature thermometry
- Visit lqm.epfl.ch→publications for examples of past reports

# Project examples

- Quantum critical scaling of magnetization in spin ladder
- Scaling analysis of susceptibility in dipolar magnet
- Magneto-electric susceptibility and skyrmion creation/annihilation
- Resistivity and dielectric measurements of novel materials
- Magnetic characterization of new spin-compounds
- Refinement of neutron diffraction data to solve crystal and magnetic structures
- Permanent magnet R&D in collaboration with a company (details confidential)

# PhD positions in LQM

If interested, let me know
Please forward to friends

1. Neutron scattering@LQM&PSI
   - New spectrometer CAMEA
   - Novel correlated spin systems
   - Advanced data-analysis
2. Neutron scattering @ILL Grenoble
   - Polarised neutrons
   - Quantum spin systems (square lattice)
   - Successor to Mourigal => now faculty position
3. Novel quantum magnets
   - Investigate new materials with magnetic, electronic and scattering methods
4. Electronic materials discovery
   - Synthesis and characterization of new correlated electron materials
   - Crystal growth using unique laser-based floating zone furnace
5. Magnetic electron microscopy and skyrmionics
   - Topologically protected spin textures. Control with E-fields and currents, observe with electron microscope
   - Microfabricate devices, image in-situ control
6. Nuclear-electronic entanglement in LiREF4
   - GHz milli-Kelvin experiments
7. Random field Ising model (joint LQM PSI)
   - Many-body localization, (d-wave quantum computer)
   - From susceptibility to free electron laser experiments

# Interested

- Please send an email: Henrik.ronnow@epfl.ch to schedule a discussion

- You can find this presentation here:

http://lqm.epfl.ch