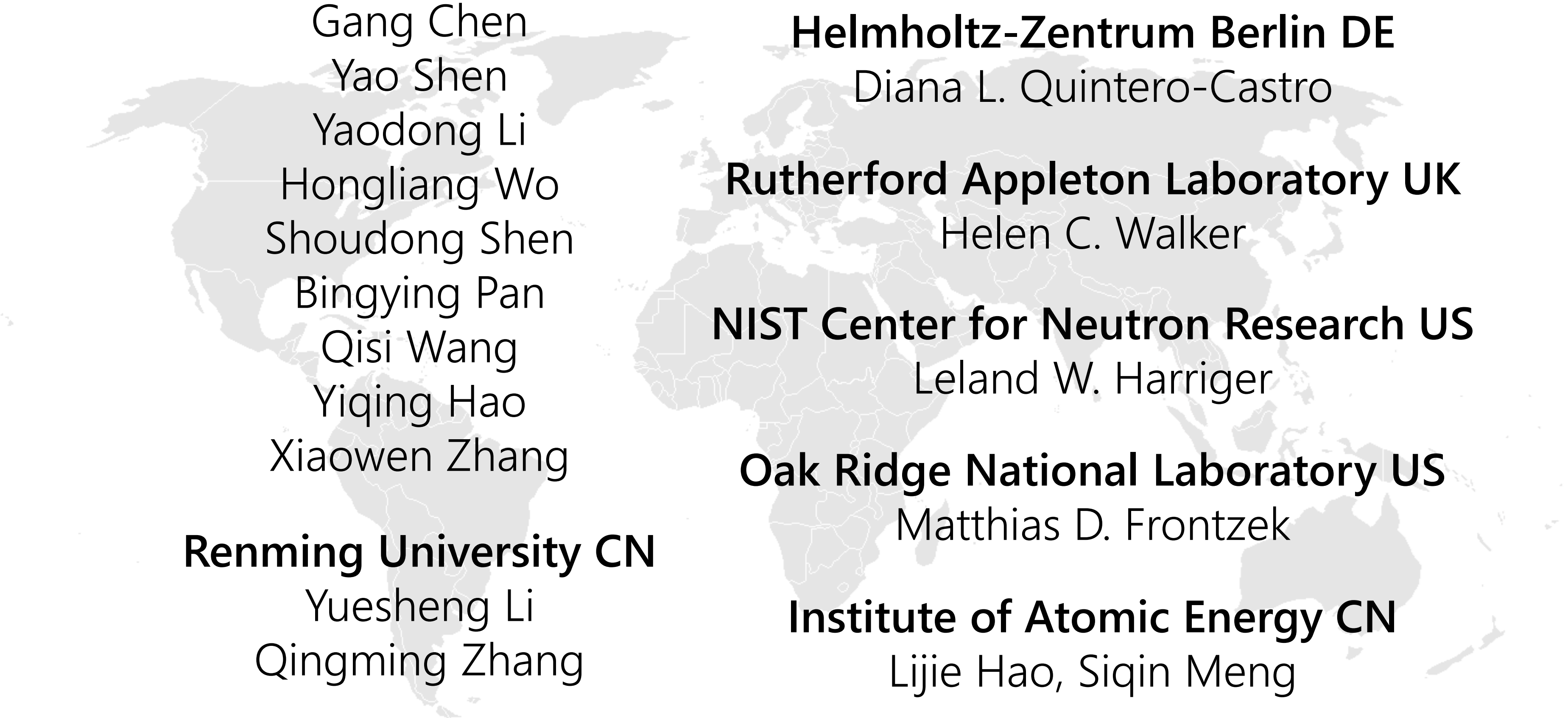
Spinon Excitations in $YbMgGaO_4$

Speaker: **Yao SHEN**
Advisor: Prof. **Jun ZHAO**
Fudan University
July 10th 2017

Topological States and Phase Transitions in Strongly Correlated Systems



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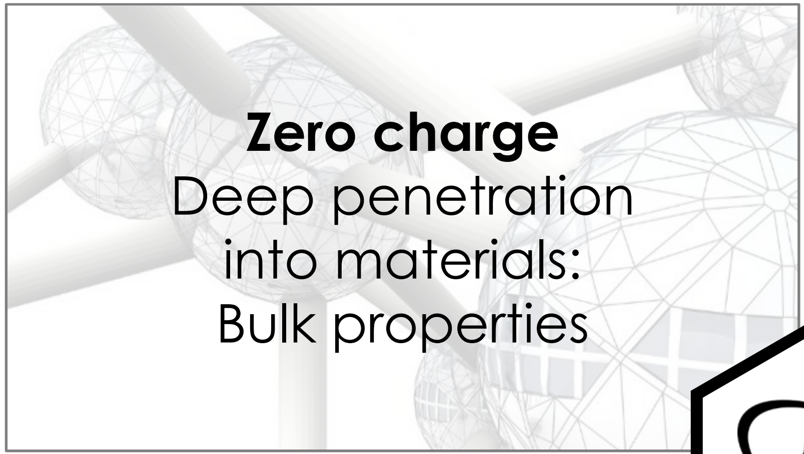
Topological States and Phase Transitions
in Strongly Correlated Systems:
Spinon Excitation in $YbMgGaO_4$

CHAPTER A **Neutron Scattering in QSL Research**

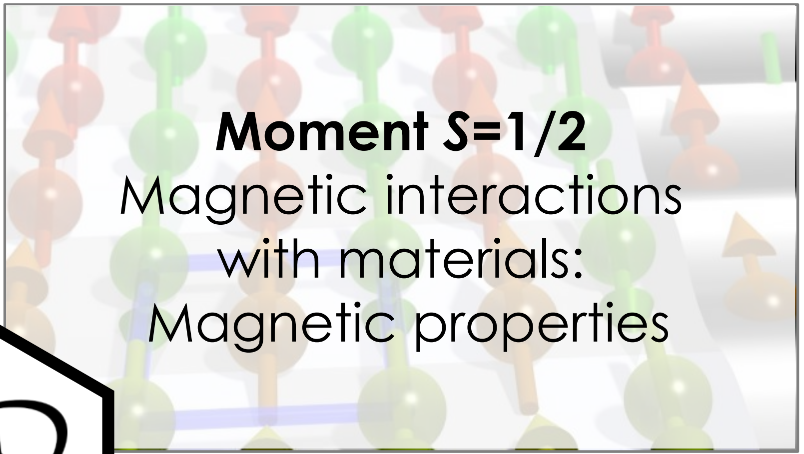
CHAPTER B **Spin Excitations in $YbMgGaO_4$ with zero field**

CHAPTER D **Conclusions**

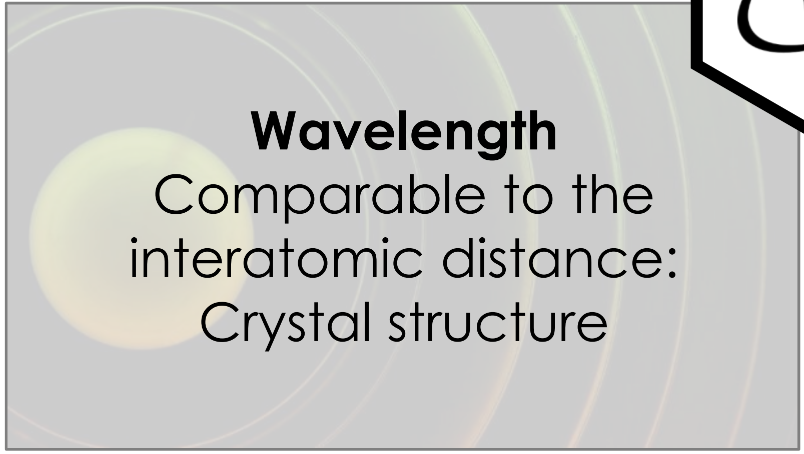
Neutron scattering: Unique advantages for neutron



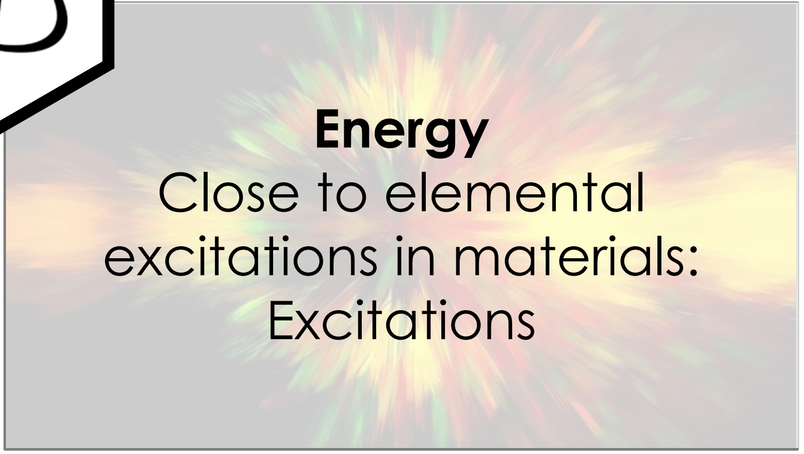
Zero charge
Deep penetration
into materials:
Bulk properties



Moment *S*=1/2
Magnetic interactions
with materials:
Magnetic properties



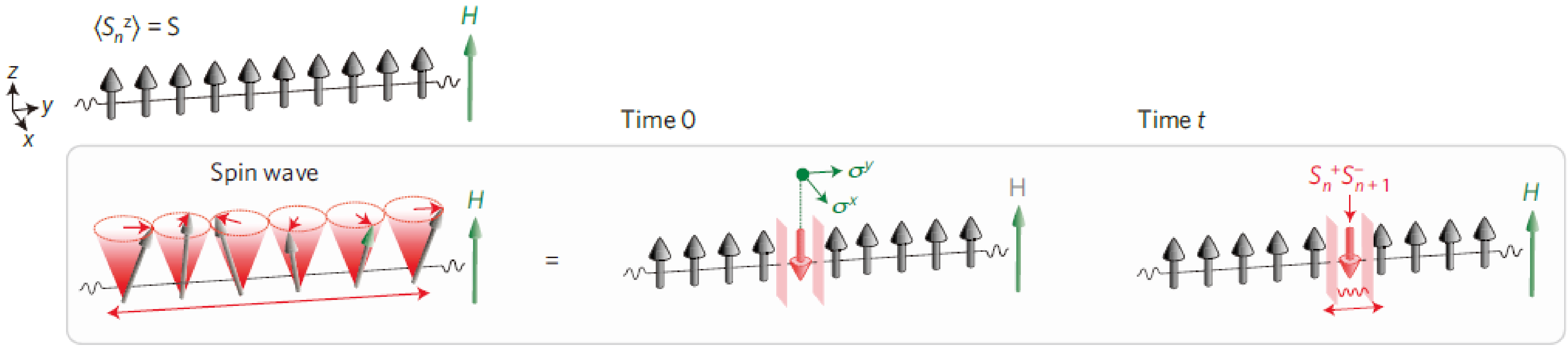
Wavelength
Comparable to the
interatomic distance:
Crystal structure



Energy
Close to elemental
excitations in materials:
Excitations

Neutron scattering: Magnon and spinon

EXAMPLE: **Neutron scattering in 1 dimensional systems**



Classical picture: **Spin Wave**
A coherent precession of the local spin expectations value around the field caused by incident neutron.

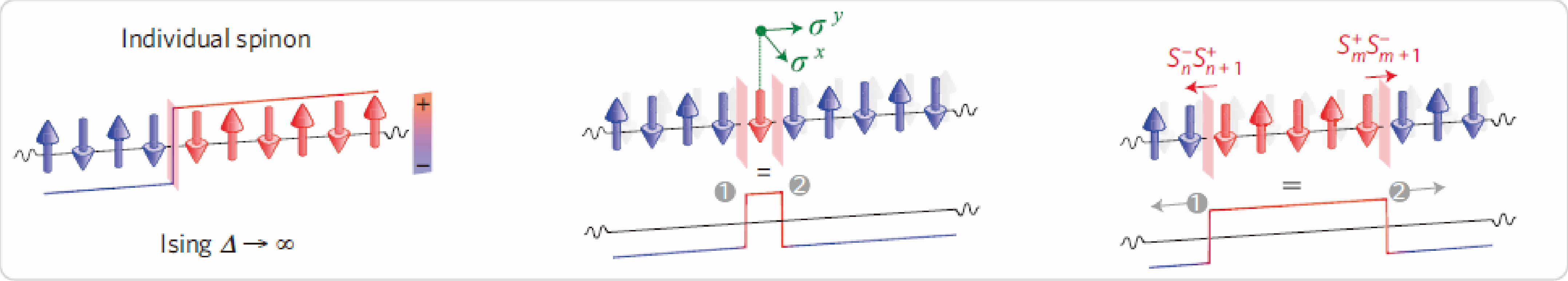
Quasiparticle: **Magnon (*S*=1, charge free)**
Neutron (*S*=1/2) → Neutron scattering: neutron flip (*S*=1 process)
Single spin flip → two domain walls bound together:

$$E(\mathbf{p}) = \omega_m(\mathbf{k})$$

M. Mourigal *et al.*, *Nat. Phys.* **9**, 435 (2013).

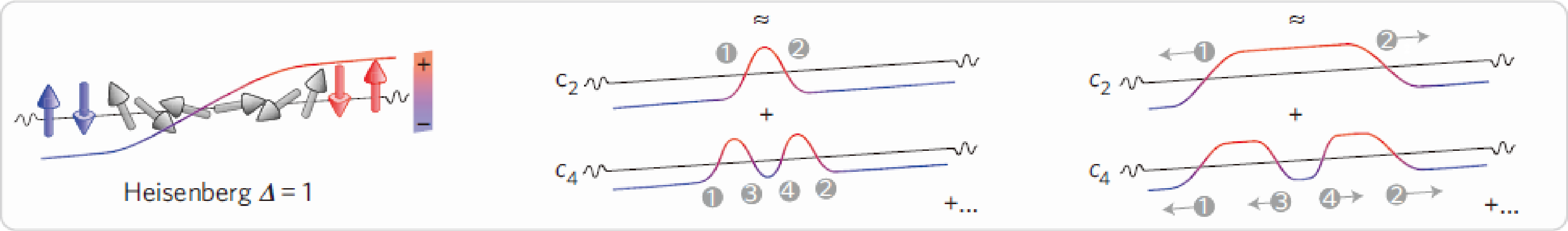
Neutron scattering: Magnon and spinon

EXAMPLE: **Neutron scattering in 1 dimensional systems**



Quasiparticle: **Spinon (*S*=1/2, charge free)**
Two domain walls propagating separately (spinon excitations)
Spinons have to be created by pairs → Confined spinon pairs

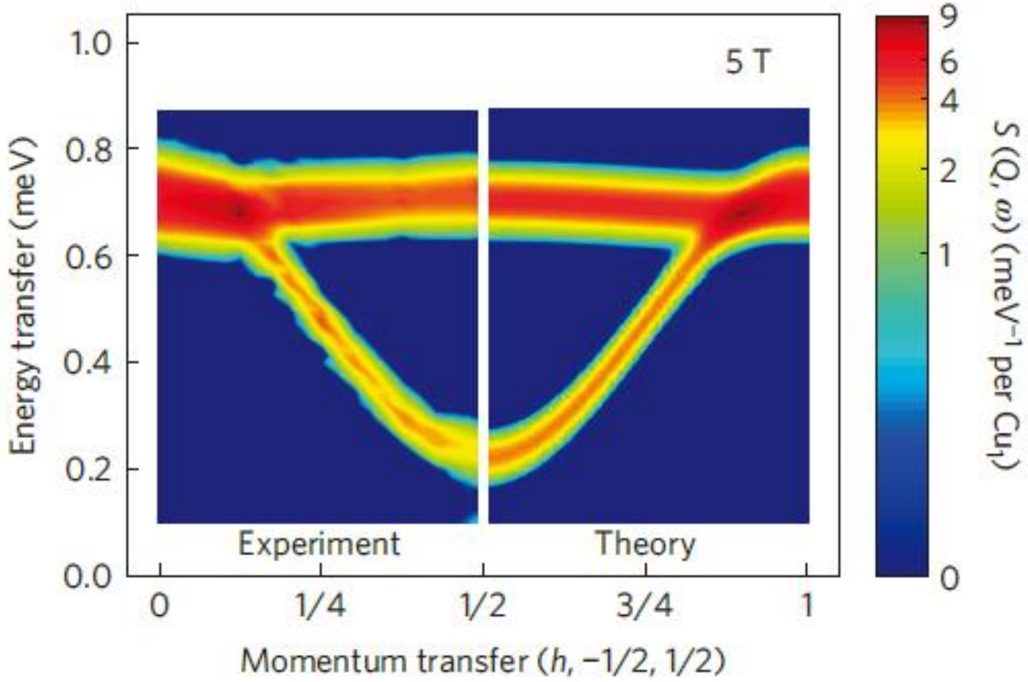
$$E(\mathbf{p}) = \omega_s(\mathbf{k}) + \omega_s(\mathbf{p}-\mathbf{k})$$

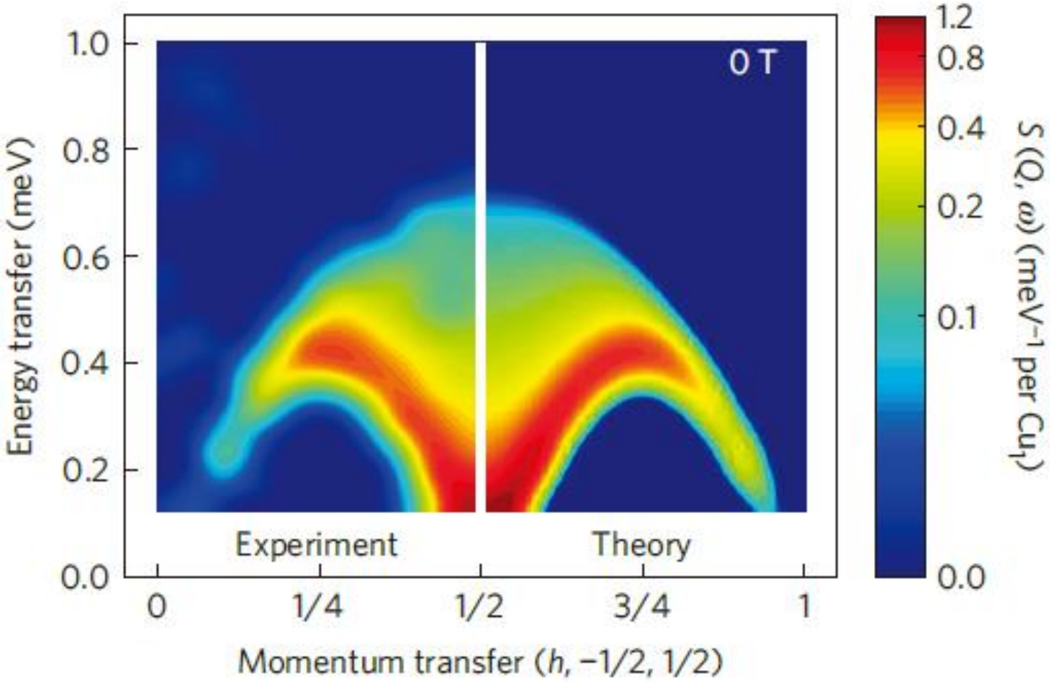


M. Mourigal *et al.*, *Nat. Phys.* **9**, 435 (2013).

Neutron scattering: Magnon and spinon

EXAMPLE: **Neutron scattering in 1 dimensional systems**





Magnon (S=1):

$$E(\mathbf{p}) = \omega_m(\mathbf{k})$$

Sharp dispersive excitations

Peaked at specific wave vectors

Spinon (S=1/2) :

$$E(\mathbf{p}) = \omega_s(\mathbf{k}) + \omega_s(\mathbf{p}-\mathbf{k})$$

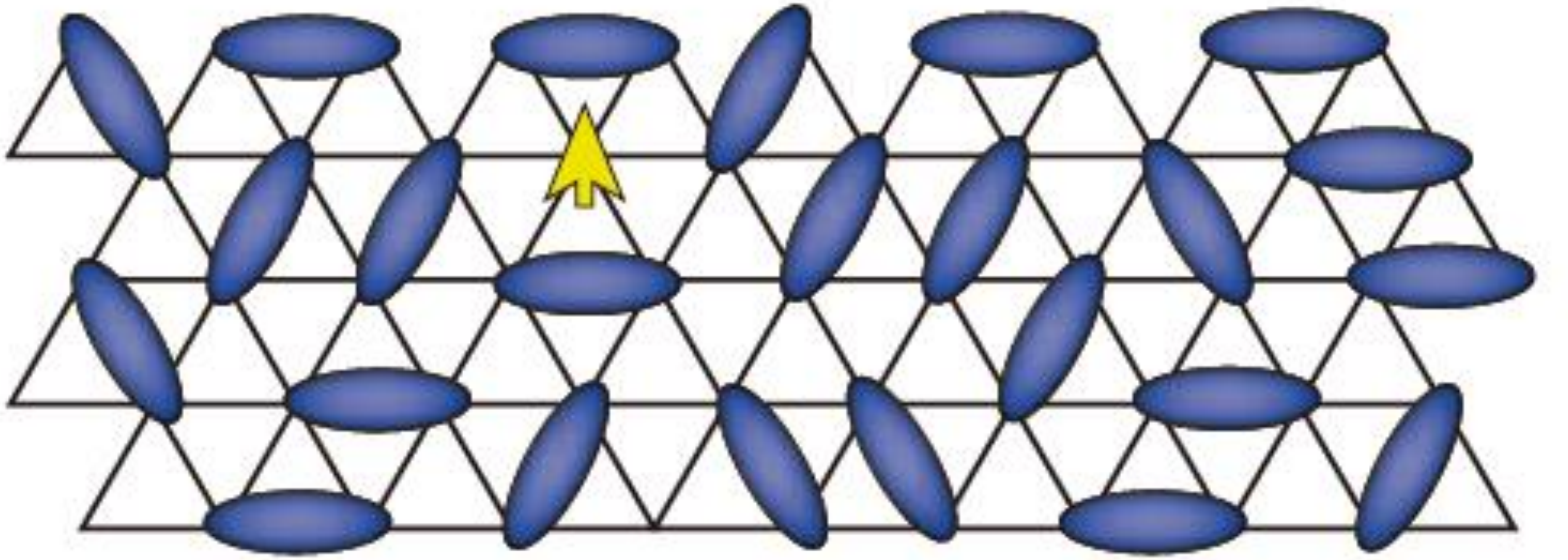
Continuum along **k** and *E*

Covering a large range of Brillouin zone

M. Mourigal *et al.*, *Nat. Phys.* **9**, 435 (2013).

Neutron scattering: Magnon and spinon

EXAMPLE: **Neutron scattering in 2 dimensional systems**



Different kind of models including RVB

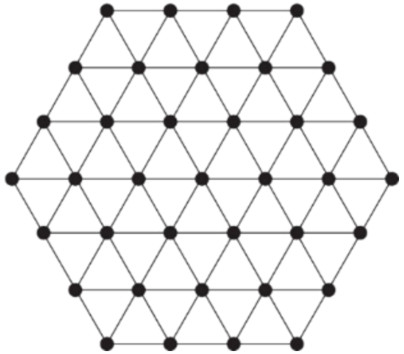
RULE A: Spinons have to be created in pairs.

RULE B: Two spinons can propagate separately.

→ **Continuum**

L. Balents, *Nature* **464**, 199 (2010).

QSL candidates: Looking for high-dimensional QSL

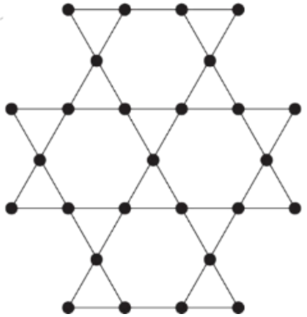


Triangle

κ-(BEDT-TTF)$_2$-Cu$_2$(CN)$_3$

EtMe$_3$Sb[Pd-(dmit)$_2$]$_2$

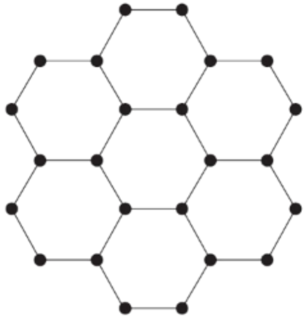
et al.



Kagome

ZnCu$_3$(OH)$_6$Cl$_2$

et al.

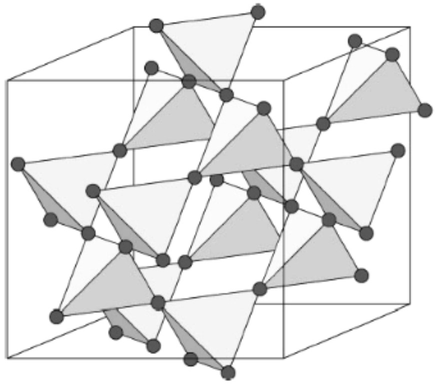


Honeycomb

α-RuCl$_3$

Na$_2$IrO$_3$

et al.



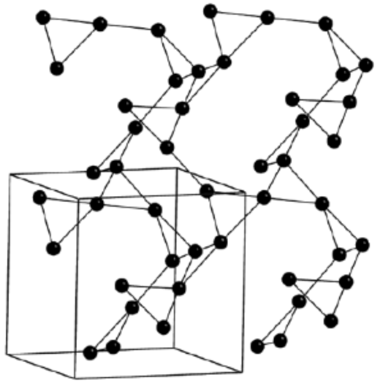
Pyrochlore

Ce$_2$Sn$_2$O$_7$

Pr$_2$Zr$_2$O$_7$

Yb$_2$Ti$_2$O$_7$

et al.



Hyperkagome

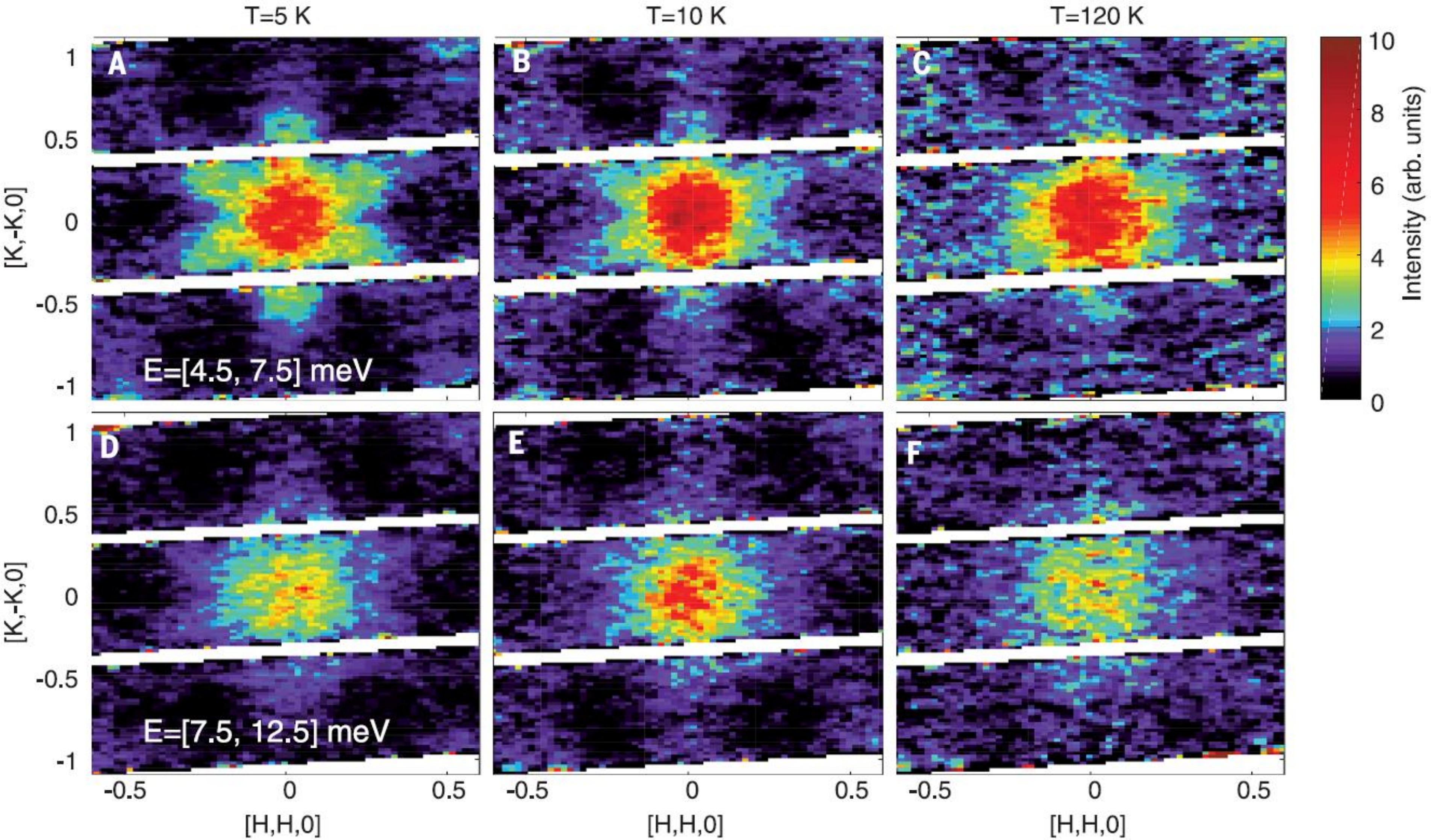
Na$_4$Ir$_3$O$_8$

PbCuTe$_2$O$_6$

et al.

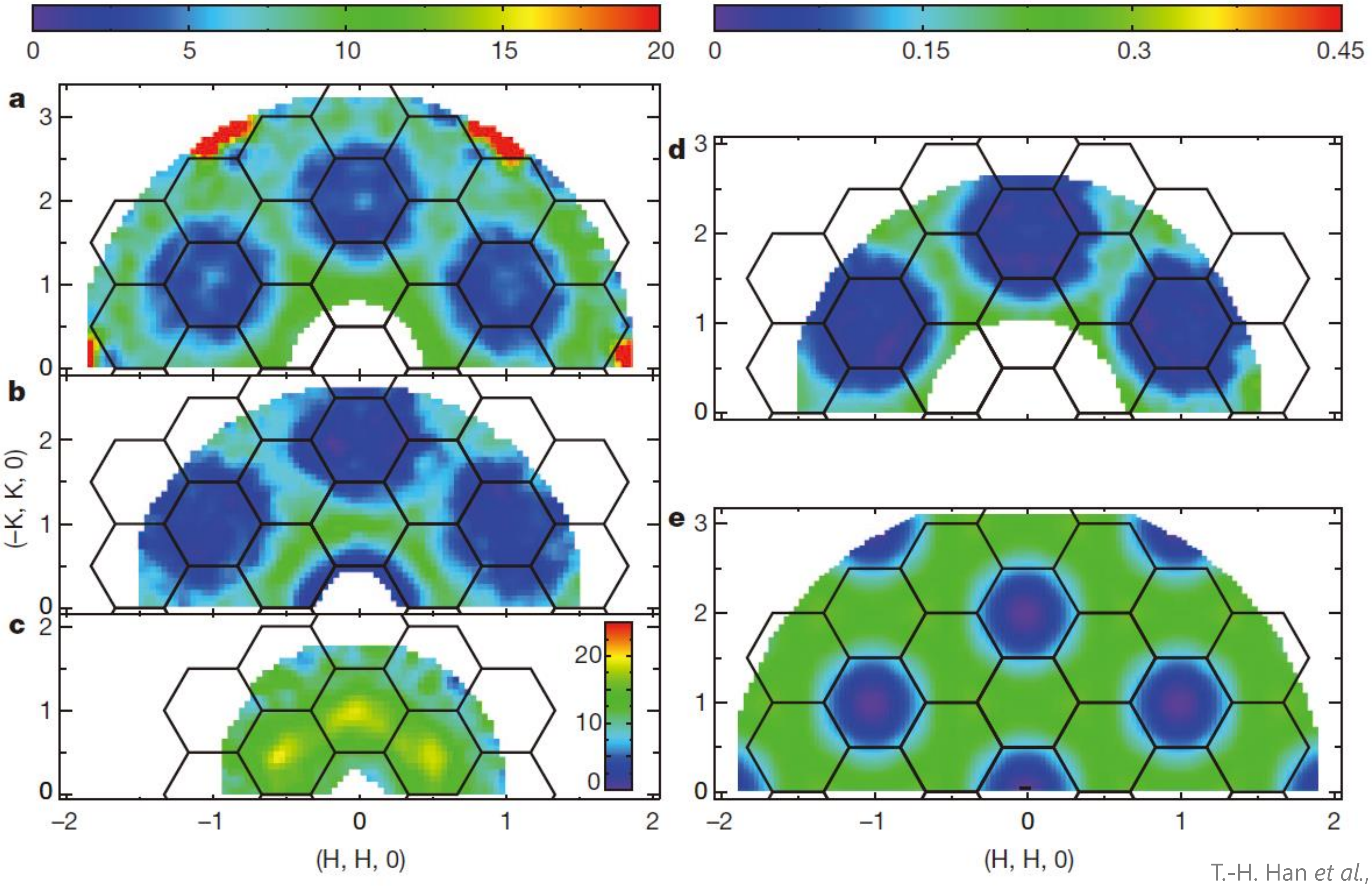
Lack of promising QSL candidate. Lack of sizable crystals for neutron scattering.

Honeycomb lattice: α-RuCl$_3$



A. Banerjee *et al.*, *Science* **356**, 1055 (2017).

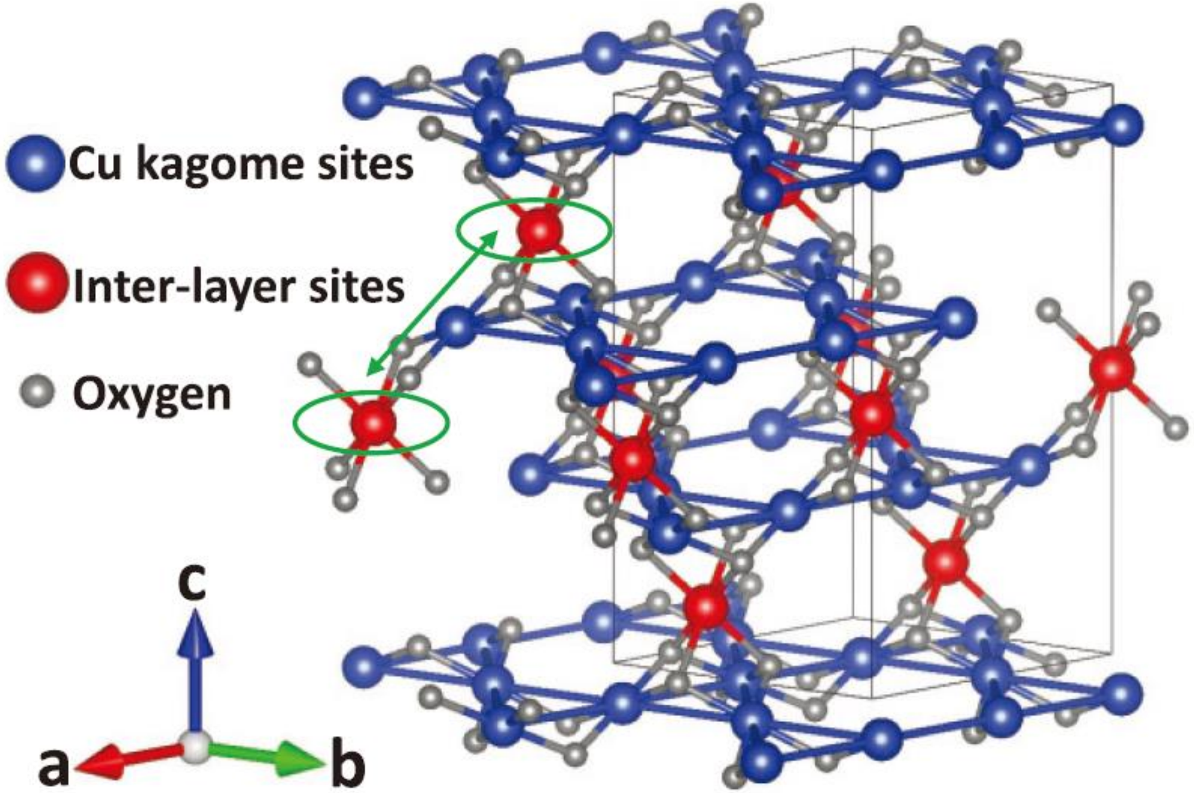
Kagome lattice: Herbertsmithite- $ZnCu_3(OH)_6Cl_2$



T.-H. Han *et al.*, *Nature* **492**, 406 (2012).

Kagome lattice: Herbertsmithite- $ZnCu_3(OH)_6Cl_2$

DISADVANTAGES: **Site-mixing of Cu^{2+} and Zn^{2+}**



→ **Site-mixing up to 15%**

Comparable ion size of Cu^{2+} and Zn^{2+}:

Cu^{2+} (6-coordinate, octahedral): 87 pm

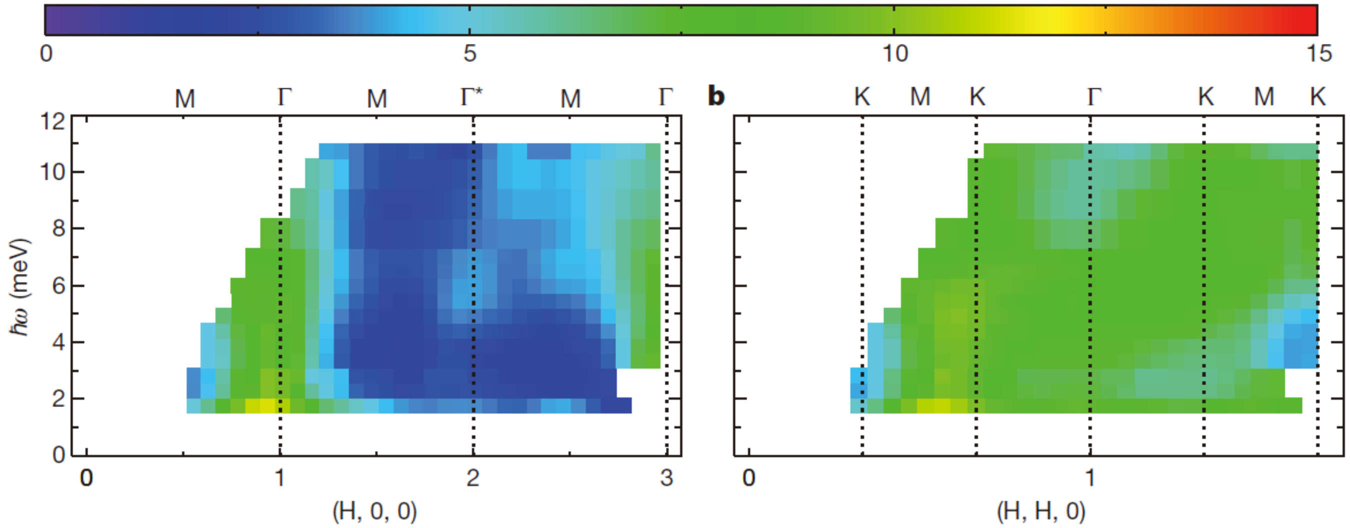
Zn^{2+} (6-coordinate, octahedral): 88 pm

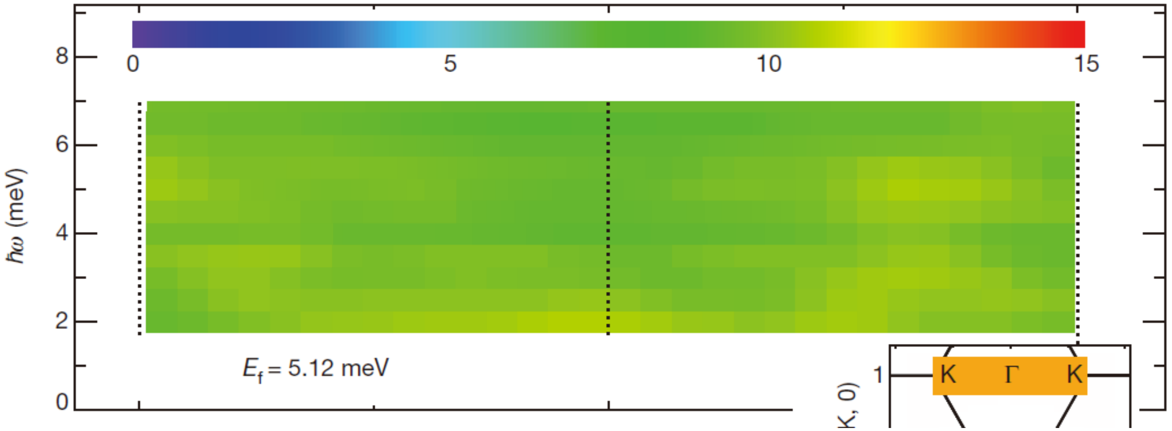
→ **Small DM interaction and easy-axis exchange anisotropy**

T.-H. Han *et al.*, *Phys. Rev. B* **94**, 060409(R) (2016).

Kagome lattice: Herbertsmithite- $ZnCu_3(OH)_6Cl_2$

DISADVANTAGES: **complete E-K relationship undecided**

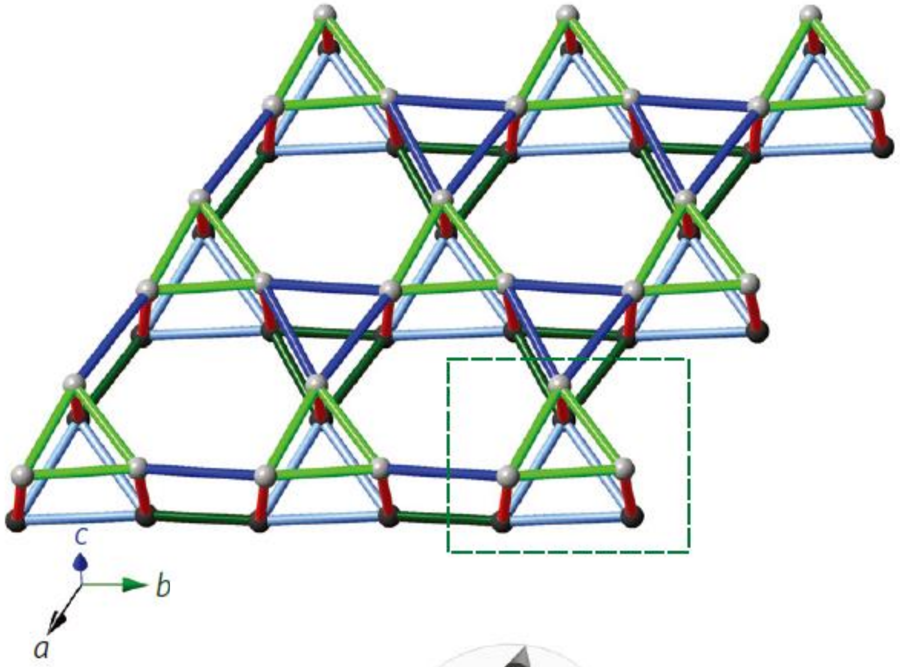


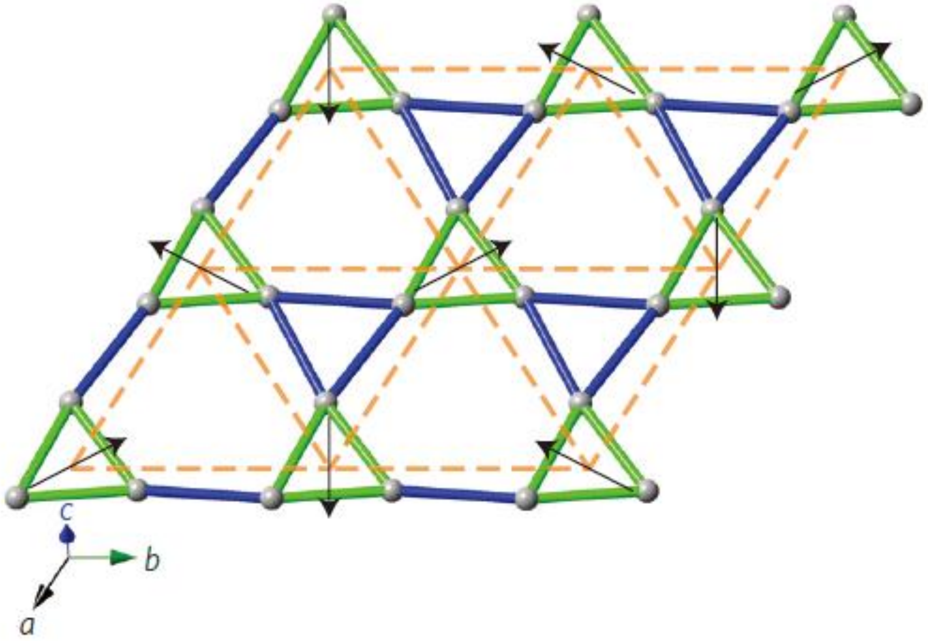


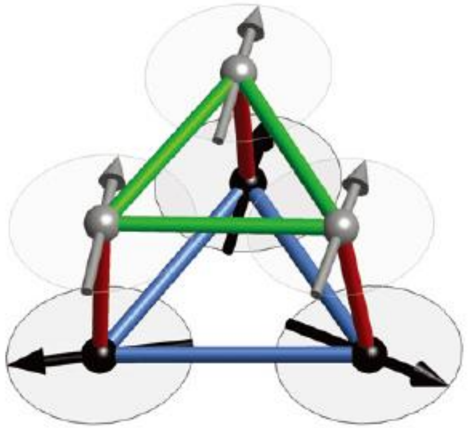
***J*~17 meV. However, high energy data lacked.**

T.-H. Han *et al.*, *Nature* **492**, 406 (2012).

Quasi-triangular lattice: $Ca_{10}Cr_7O_{28}$



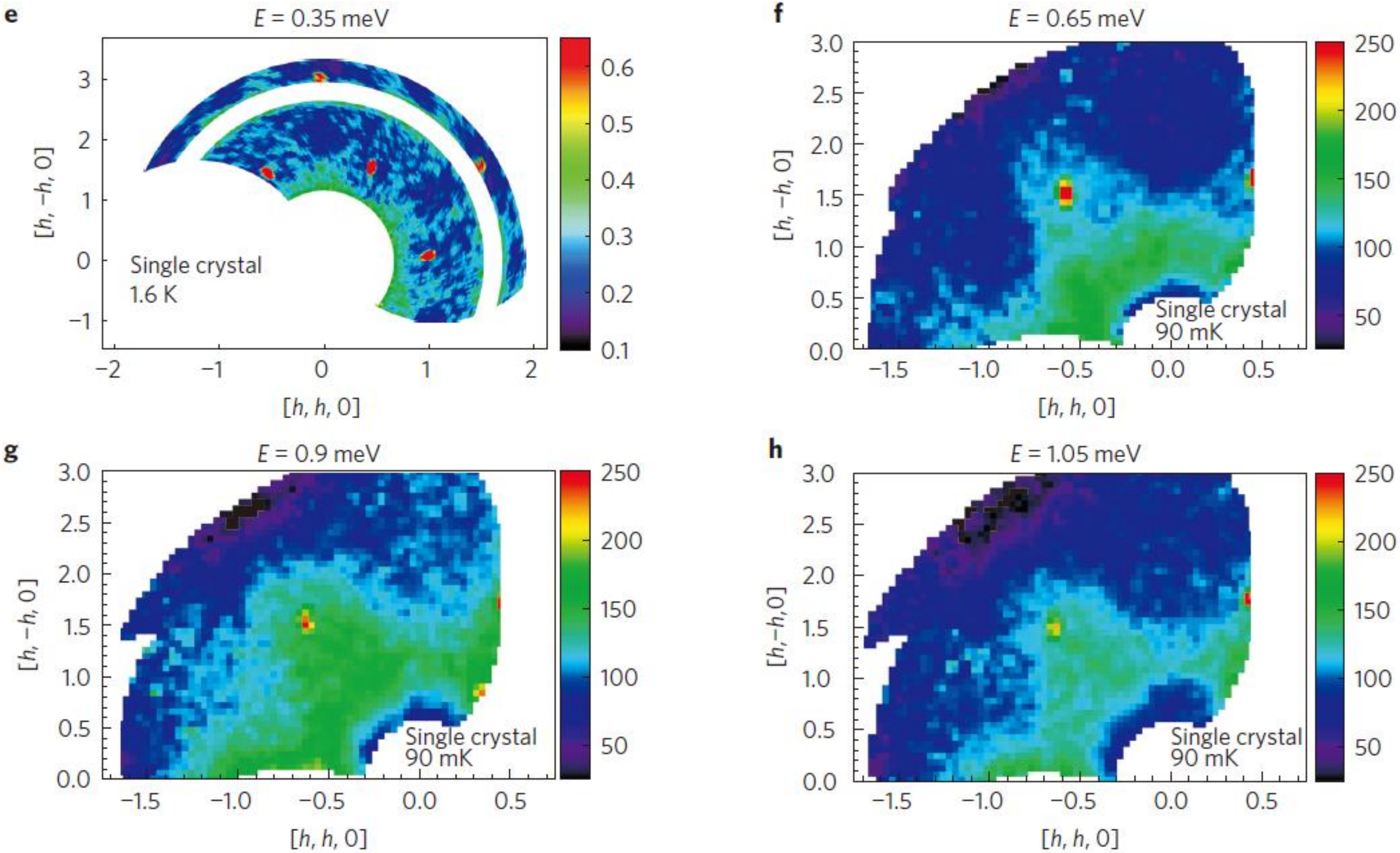




→ Distorted Kagome lattice
→ Strong FM interaction but dominant AFM correlations
→ FM layer coupled with AFM layer: Frustrated unit

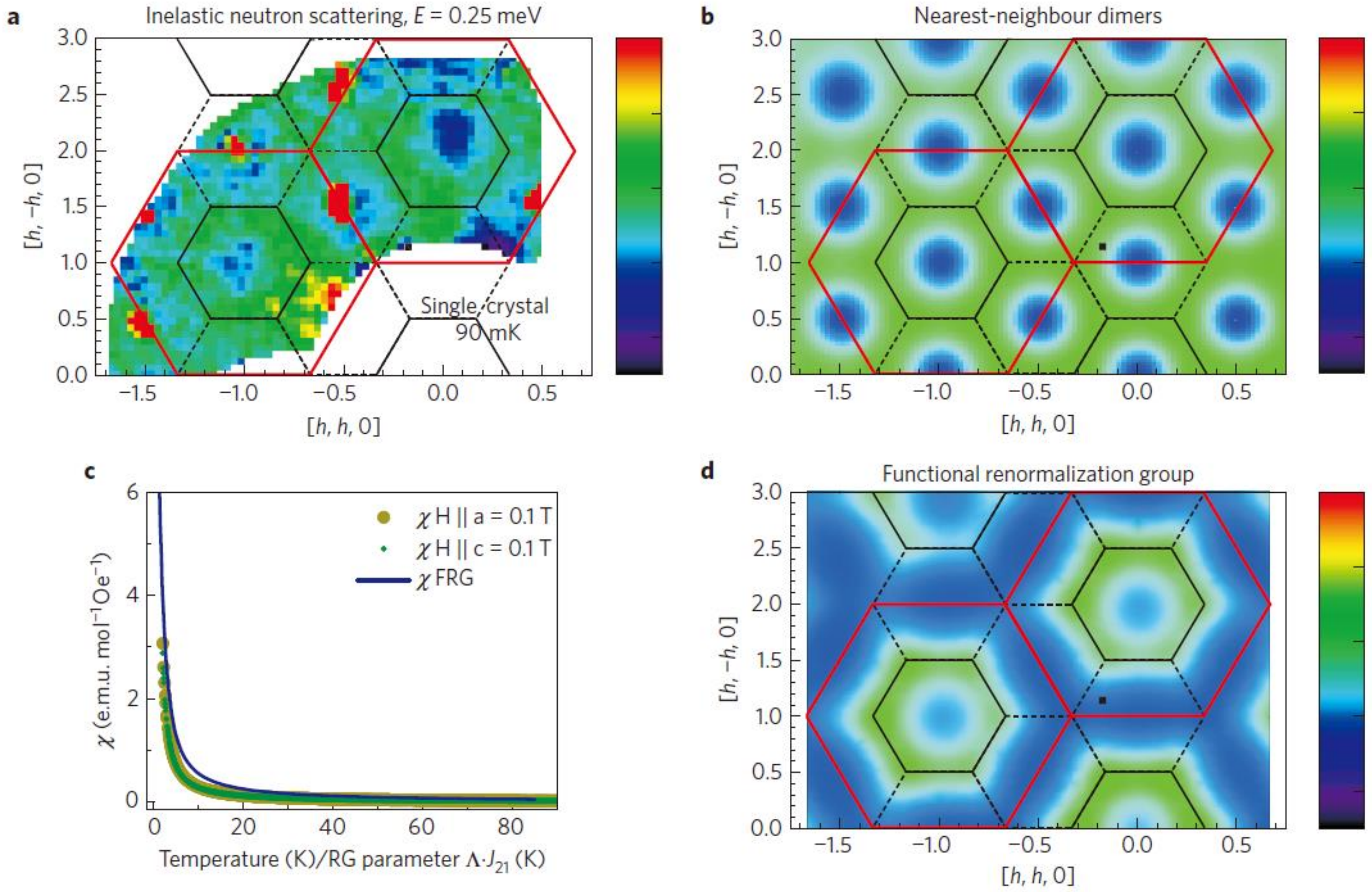
C. Balz *et al.*, *Nat. Phys.* **12**, 942 (2016).

Quasi-triangular lattice: $Ca_{10}Cr_7O_{28}$



C. Balz *et al.*, *Nat. Phys.* **12**, 942 (2016).

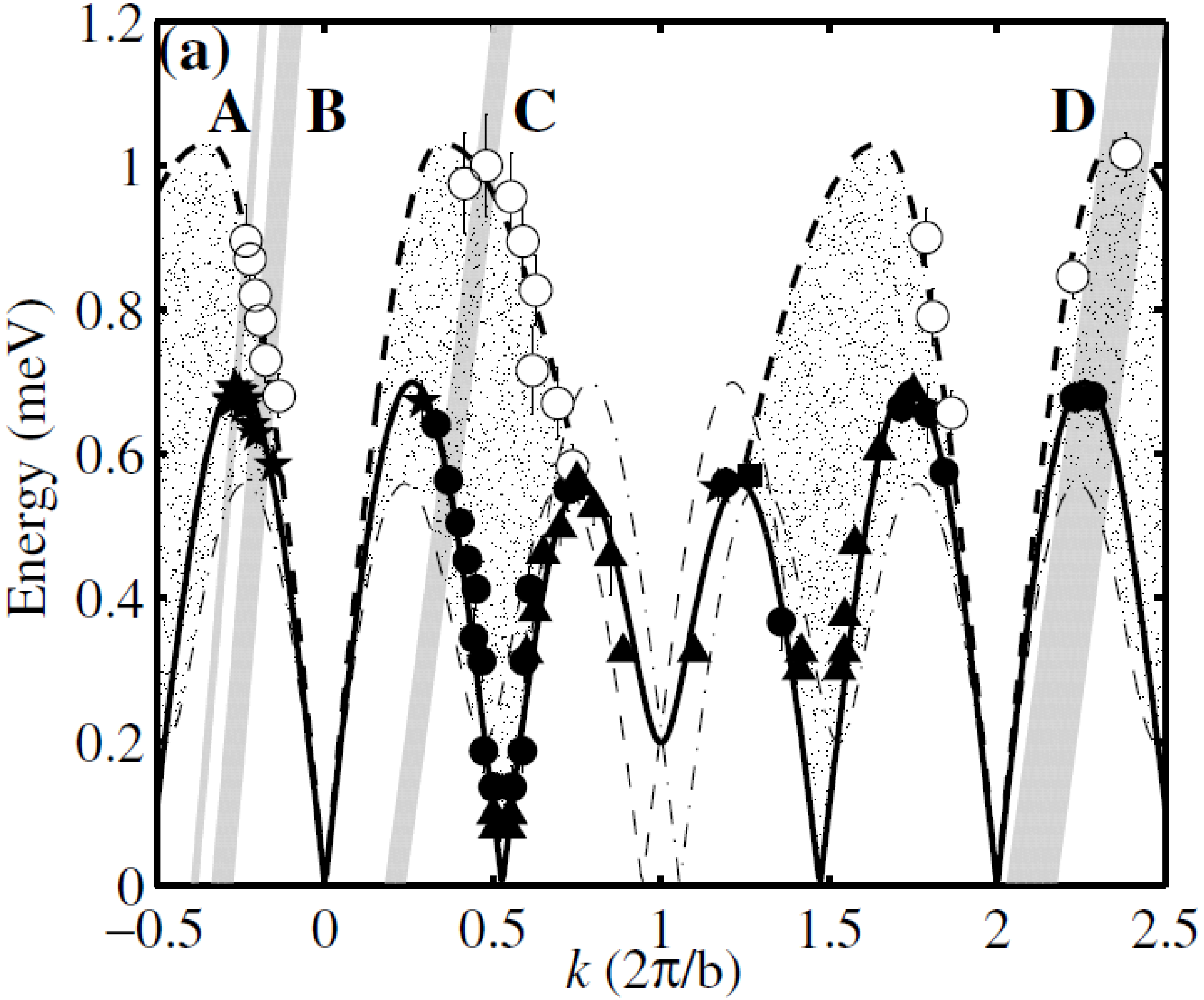
Quasi-triangular lattice: $Ca_{10}Cr_7O_{28}$

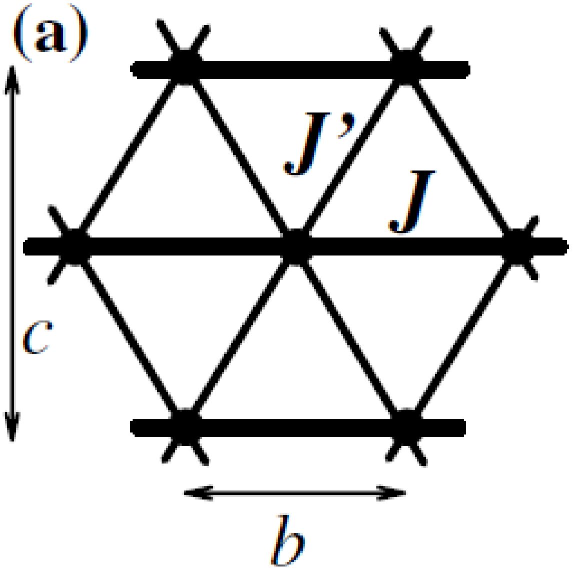


Complete E-K relationship lacked.
Complex magnetism need more research.

C. Balz *et al.*, *Nat. Phys.* **12**, 942 (2016).

Distorted triangular lattice: Cs_2CuCl_4





Spinon detected, but turns to be 1 dimensional behavior afterwards.

R. Coldea *et al.*, *Phys. Rev. B* **86**, 1335 (2001).

Triangular lattice: YbMgGaO$_4$

PRL 115, 167203 (2015) PHYSICAL REVIEW LETTERS week ending 16 OCTOBER 2015

Rare-Earth Triangular Lattice Spin Liquid: A Single-Crystal Study of YbMgGaO$_4$

Yuesheng Li,[1] Gang Chen,[2,3,*] Wei Tong,[4] Li Pi,[4] Juanjuan Liu,[1] Zhaorong Yang,[5]
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[6]*Department of Physics and Astronomy, Shanghai Jiao Tong*
and Collaborative Innovative Center
Nanjing 210093, People's
(Received 19 August 2015; pu

YbMgGaO$_4$, a structurally perfect two-dimensional
per unit cell and spin-orbit entangled effective spin 1/
experimentally realize the quantum spin liquid ground
zation of single-crystal YbMgGaO$_4$ samples. Becaus
between the neighboring Yb^{3+} moments depends on the
spin space. We carry out thermodynamic and the elec
anisotropic nature of the spin interaction as well as to qu
first step towards the theoretical understanding of the
system and sheds new light on the search for quantum s

DOI: 10.1103/PhysRevLett.115.167203

Introduction.—Recent theoretical advances have extended the Hastings-Oshikawa-Lieb-Schultz-Mattis theorem to the spin-orbit coupled insulators [1–4]. It is shown that as long as the time reversal symmetry is preserved, the ground state of a spin-orbit coupled insulator with an odd number of electrons per unit cell must be exotic [1]. This important result indicates that the ground state of strong spin-orbit coupled insulators can be a quantum spin liquid (QSL). QSLs, as used here, are new phases of matter that are characterized by properties such as quantum number fractionalization, intrinsic topological order, and gapless excitations without symmetry breaking [5,6]. Among the existing QSL candidate materials [7–33], the majority have a relatively weak spin-orbit coupling (SOC), which only slightly modifies the usual SU(2) invariant Heisenberg interaction by introducing weak anisotropic spin interactions such as the Dzyaloshinskii-Moriya interaction [34–36]. It is likely that the QSL physics in many of these systems mainly originates from the Heisenberg part of the Hamiltonian rather than from the anisotropic interactions due to the weak SOC. The exceptions are the hyperkagome Na$_4$Ir$_3$O$_8$ and the pyrochlore quantum spin ice materials where the non-Heisenberg spin interaction due to the strong SOC plays a crucial role in determining the ground state properties [16,17,37–48],

0031-9007/15/115(16)/167203(6) 167203

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Gapless quantum spin liquid ground state in the two-dimensional spin-1/2 triangular antiferromagnet YbMgGaO$_4$

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Yuesheng Li[1], Haijun Liao[2], Zhen Zhang[3], Shiyan Li[3], Feng Jin[1], Langsheng Ling[4], Lei Zhang[4], Youming Zou[4], Li Pi[4], Zhaorong Yang[5], Junfeng Wang[6], Zhonghua Wu[7] & Qingming Zhang[1,8]

Quantum spin liquid (QSL) is a novel state of matter which refuses the conventional spin freezing even at 0 K. Experimentally searching for the structurally perfect candidates is a big challenge in condensed matter physics. Here we report the successful synthesis of a new spin-1/2 triangular antiferromagnet YbMgGaO$_4$ with $R\bar{3}m$ symmetry. The compound with an ideal two-dimensional and spatial isotropic magnetic triangular-lattice has no site-mixing magnetic defects and no antisymmetric Dzyaloshinsky-Moriya (DM) interactions. No spin freezing down to 60 mK (despite $\theta_w \sim -4$ K), the power-law temperature dependence of heat capacity and nonzero susceptibility at low temperatures suggest that YbMgGaO$_4$ is a promising gapless ($\leq|\theta_w|/100$) QSL candidate. The residual spin entropy, which is accurately determined with a non-magnetic reference LuMgGaO$_4$, approaches zero (<0.6%). This indicates that the possible QSL ground state (GS) of the frustrated spin system has been experimentally achieved at the lowest measurement temperatures.

Low spin geometrically frustrated systems in two dimensional (2D) lattices have received significant interest in condensed-matter physics. The two most studied frustrated spin systems are spin-1/2 triangular and kagomé antiferromagnets, in which strong quantum fluctuations prevent spin freezing even at very low temperatures[1]. With respect to theoretical studies, Anderson first proposed that the triangular Heisenberg antiferromagnet (THAF) has a resonating valence bond GS, which is a type of spin liquid[2,3]. However, recent numerical studies have consistently indicated a long-range Néel GS for spin-1/2 THAF. The calculated order parameter is much smaller than the classical value, indicating that it is very close to a quantum critical point between magnetic ordered and disordered GSs[4,5]. On the experimental side, "structurally perfect" triangular or kagomé antiferromagnets (AFs) are still extremely rare, although many spin-1/2 geometrically frustrated triangular and kagomé AFs have been proposed[6–17]. Most of the existing candidates suffer from spatially anisotropic intralayer exchange interactions[6,7,8,12], site mixing between magnetic and nonmagnetic ions[12–14], interlayer exchange interactions[8–12], and/or antisymmetric Dzyaloshinsky-Moriya (DM) interactions[15]. These factors are critical to the GSs of the frustrated spin

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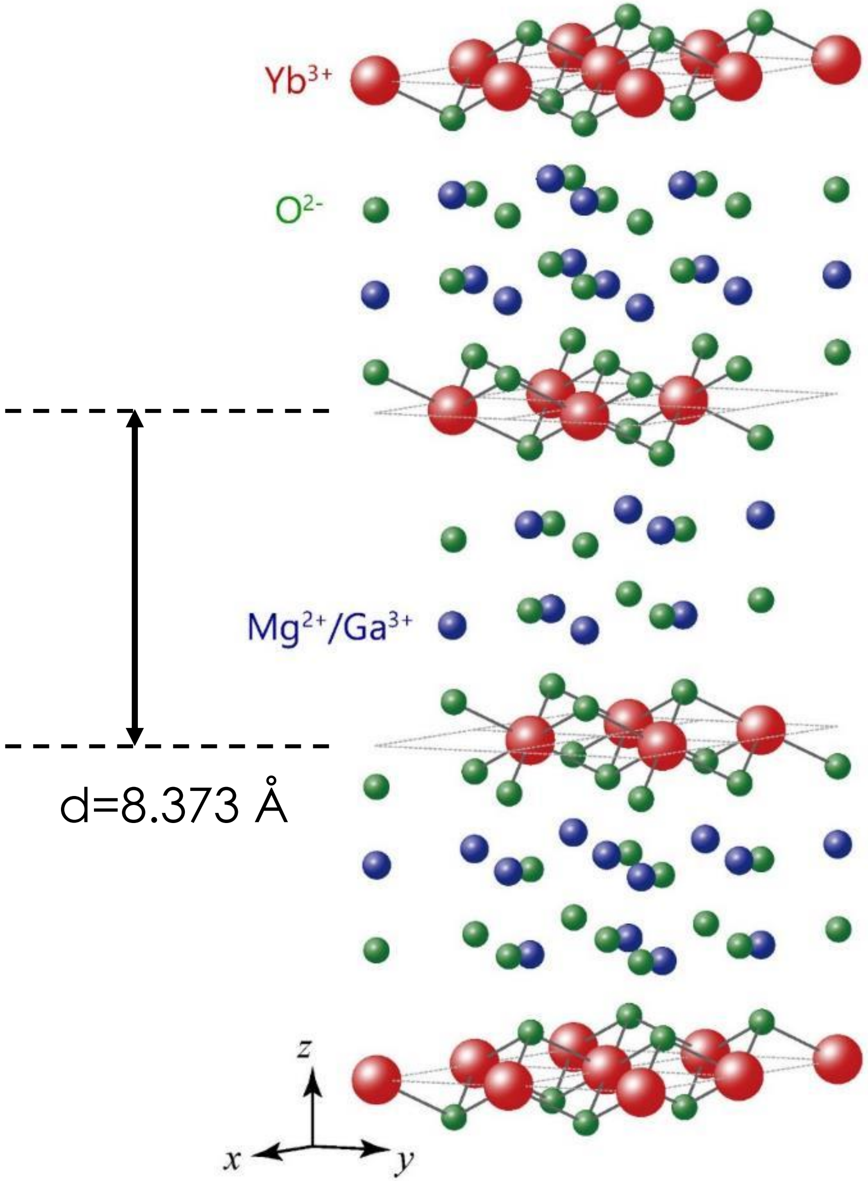
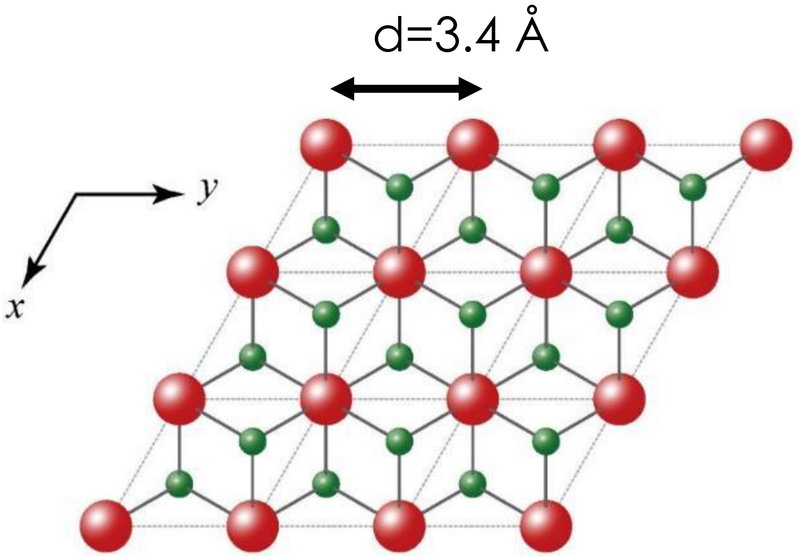
SCIENTIFIC REPORTS | 5:16419 | DOI: 10.1038/srep16419 1

Prof. Qingming Zhang Group from Renming University

Y. Li *et al.*, *Sci. Rep.* **5**, 16419 (2015).
Y. Li *et al.*, *Phys. Rev. Lett.* **115**, 167203 (2015).

Triangular lattice: $YbMgGaO_4$

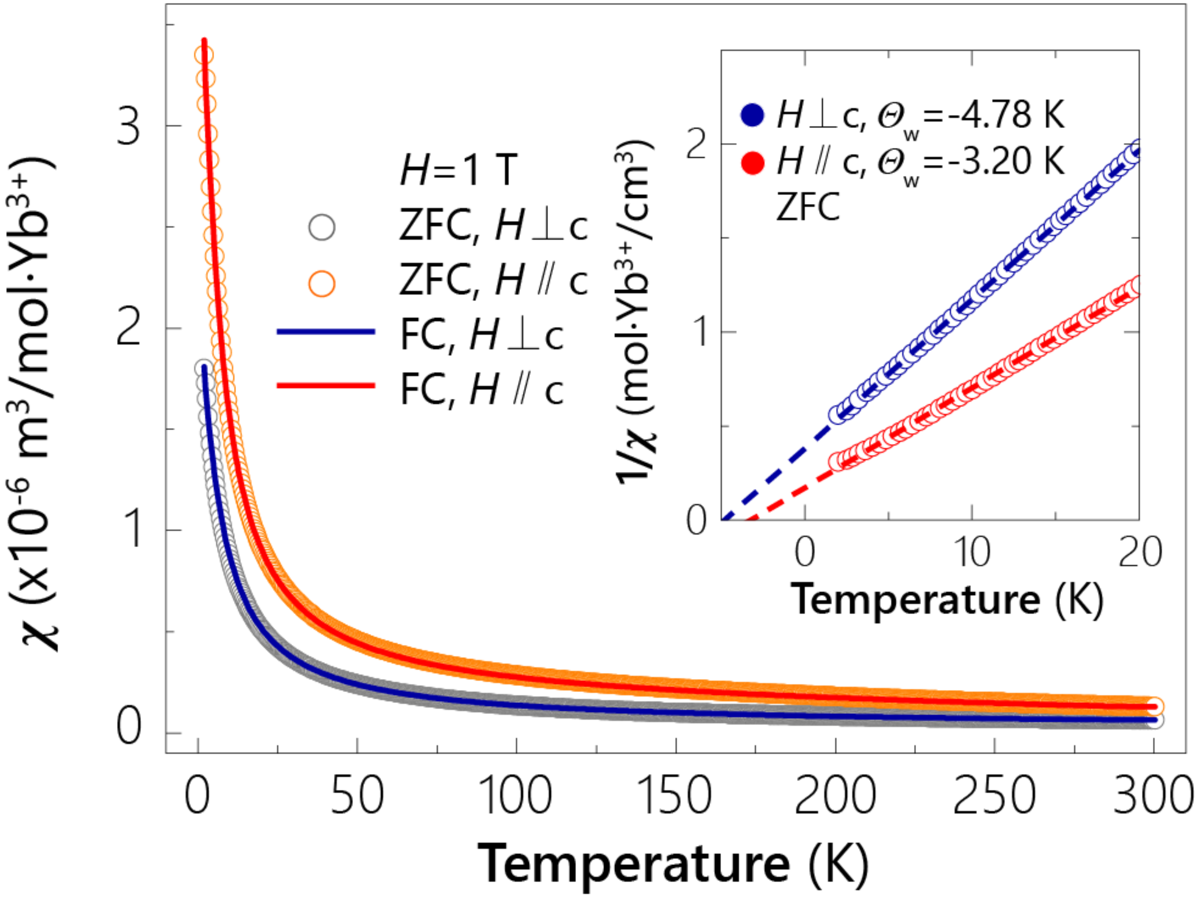




- $S_{eff}=1/2$ for Yb^{3+} under crystal field.
- Trigonal lattice without distortion.
- Two-dimensionality.
- Absence of DM interaction.
- Site-mixing forbidden for difference of radiuses of Yb^{3+} and Mg^{2+}/Ga^{3+}.

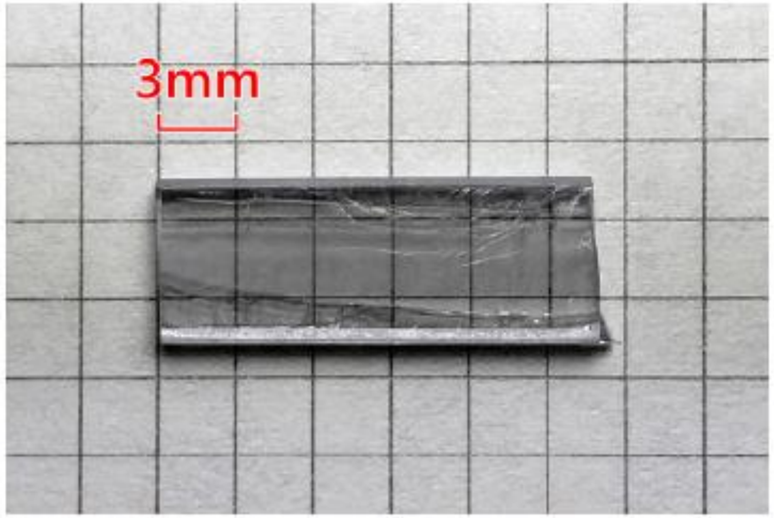
Triangular lattice: $YbMgGaO_4$

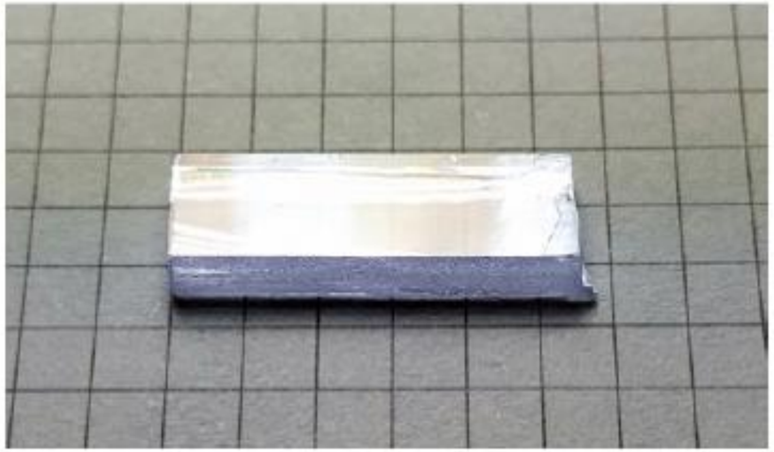
PLOTS: **Magnetic susceptibility**



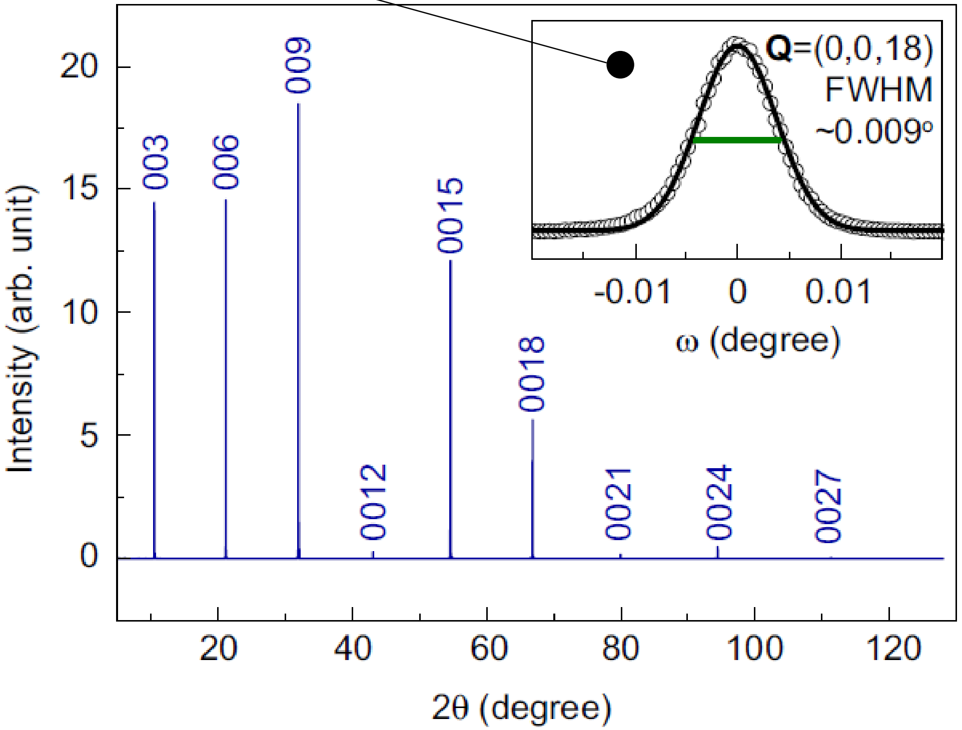
No ordering down to 40 mK in susceptibility, NMR, μSR, heat capacity measurements.

Triangular lattice: $YbMgGaO_4$





Resolution limited Bragg peak



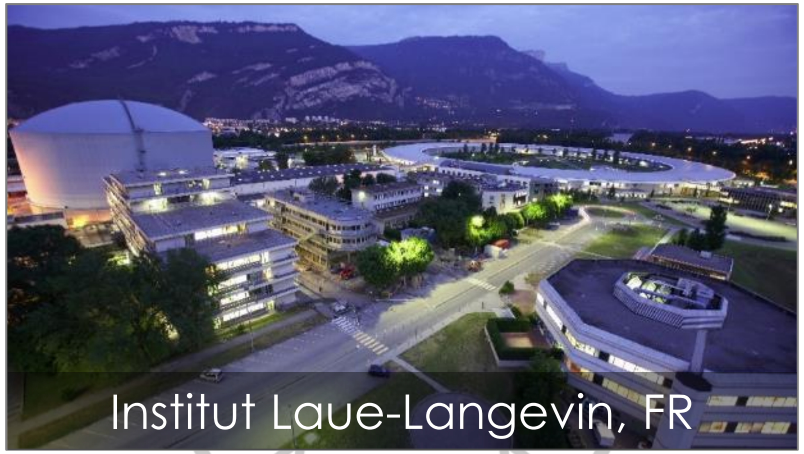
Single crystal X-ray diffraction

CHAPTER A **Neutron Scattering in QSL Research**

CHAPTER B **Spin Excitations in $YbMgGaO_4$ with zero field**

CHAPTER D **Conclusions**

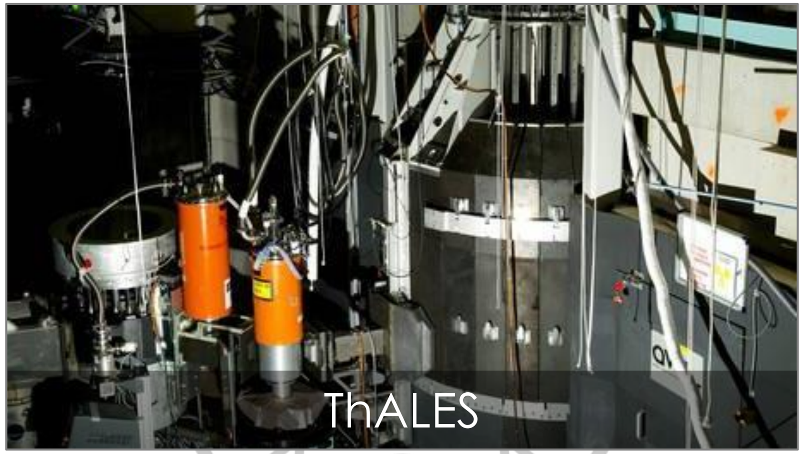
Neutron source: International collaboration


Institut Laue-Langevin, FR


Helmholtz-Zentrum Berlin, DE


Oak Ridge National Lab, US

Neutron source: International collaboration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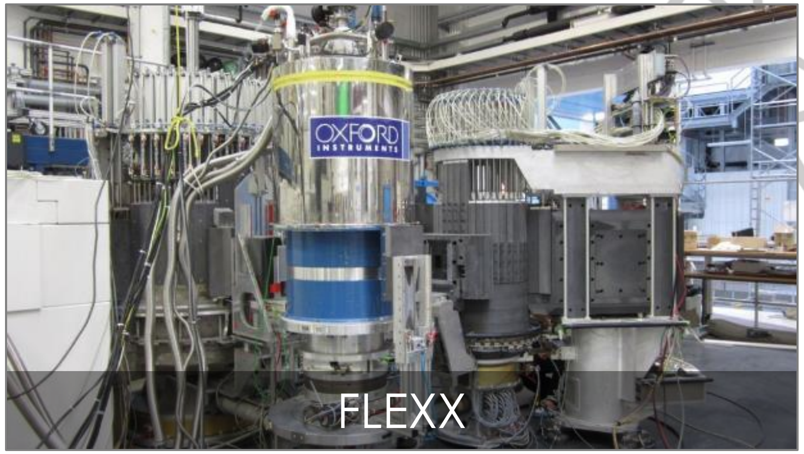
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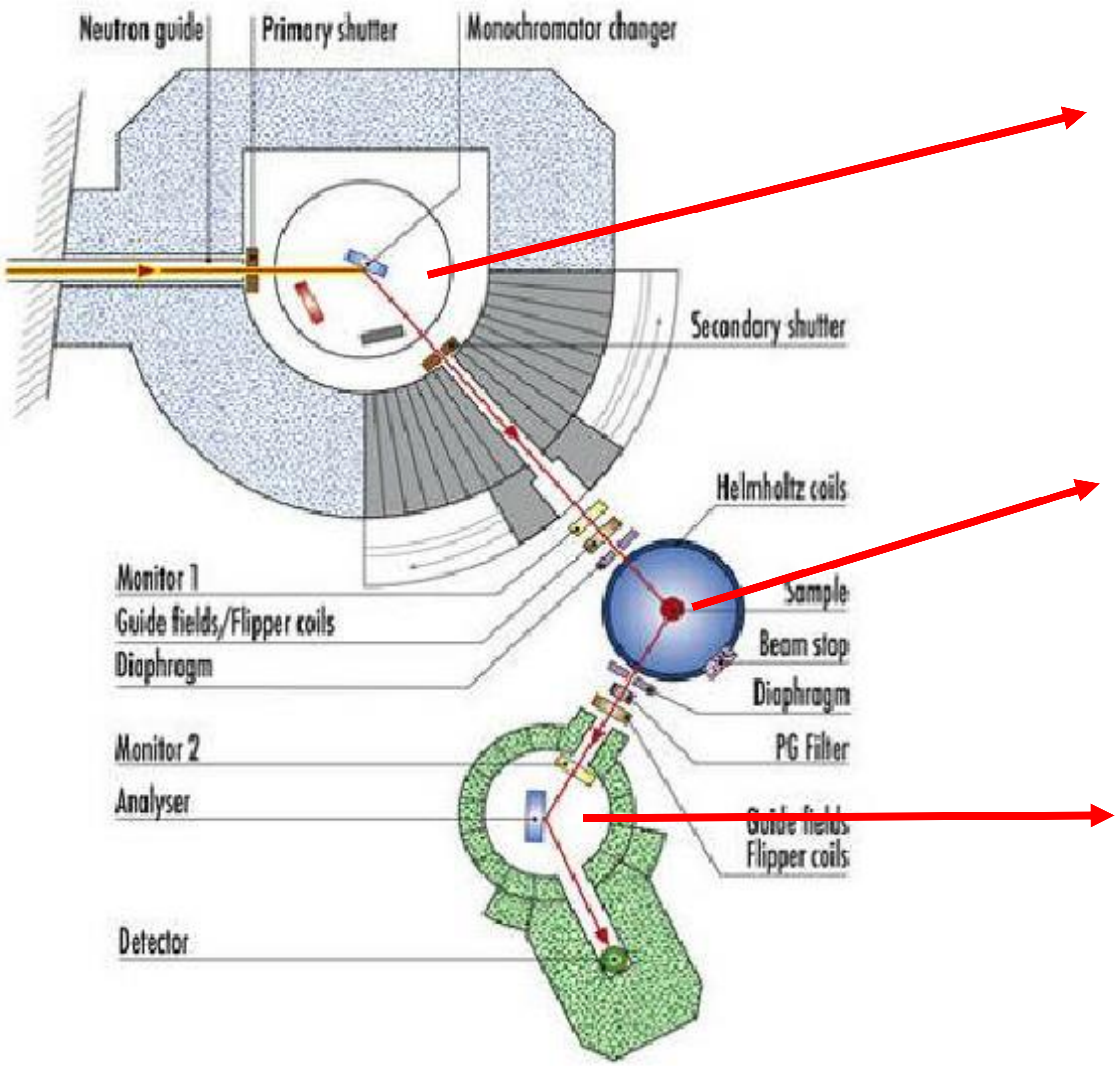
WAND

Triple axis spectrometer: Example IN22

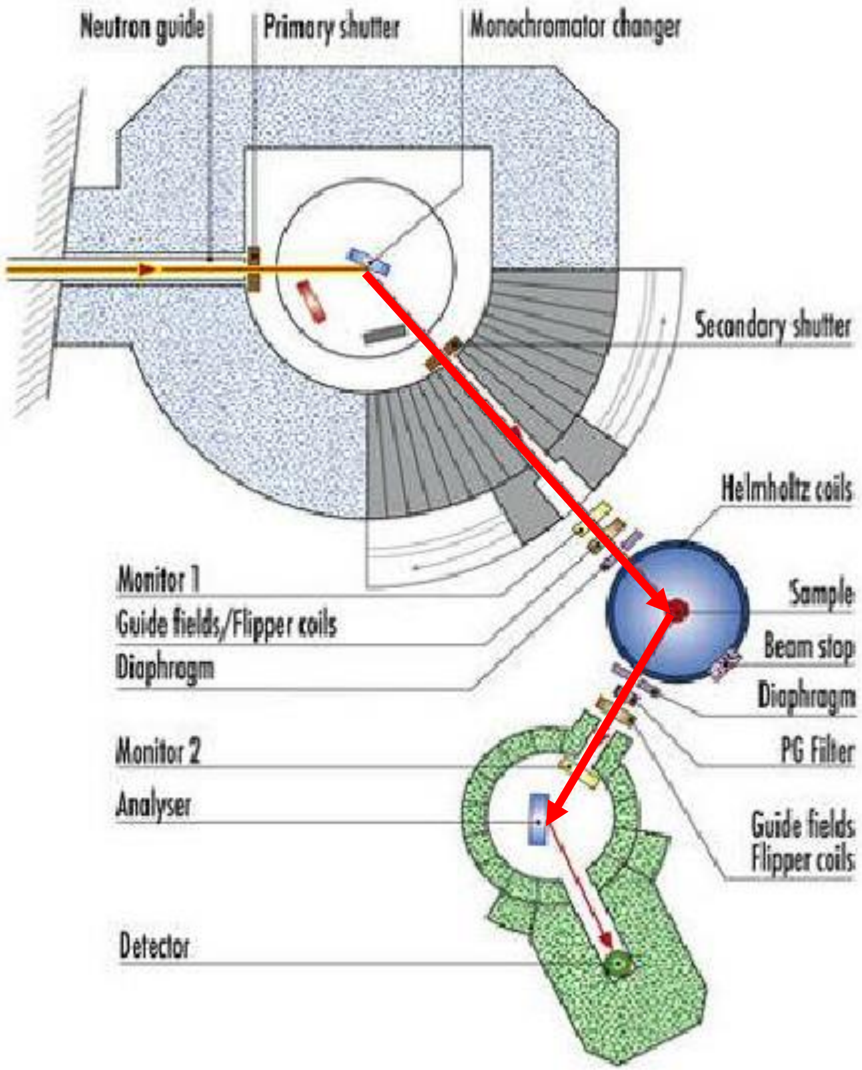


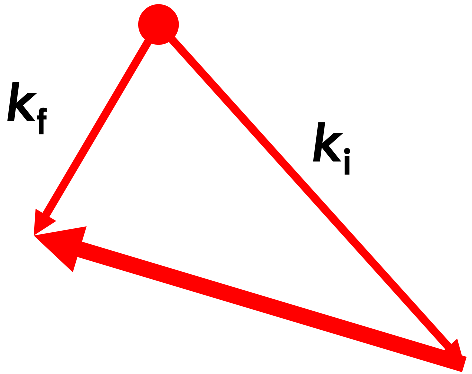
Monochromator:
Use Bragg peak of material to choose a specific energy

Sample:
Co-aligned in the scattering plane with varied environment

Analyzer:
Use Bragg peak of material to choose a specific energy

Triple axis spectrometer: Example IN22

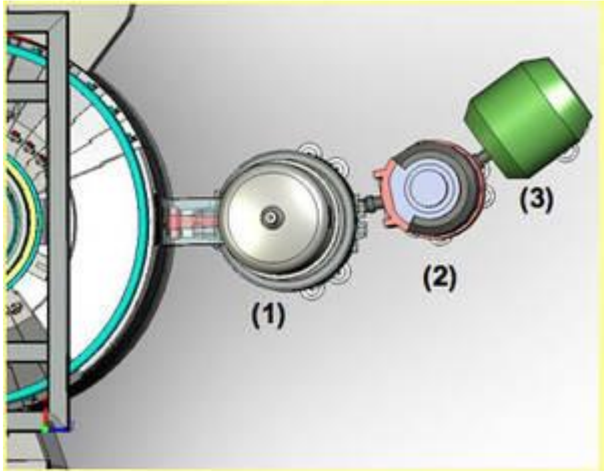




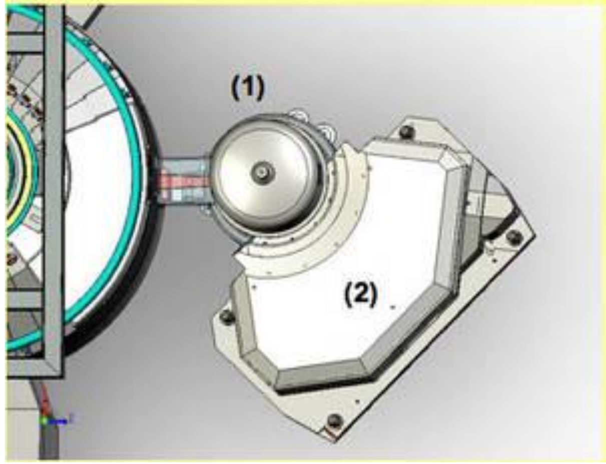
$$\mathbf{Q} = k_f - k_i$$
$$E = E_i - E_f$$

Specific position in the Hilbert space **(Q, E)** with different environment **(H, T)**

Triple axis spectrometer: Example ThALES

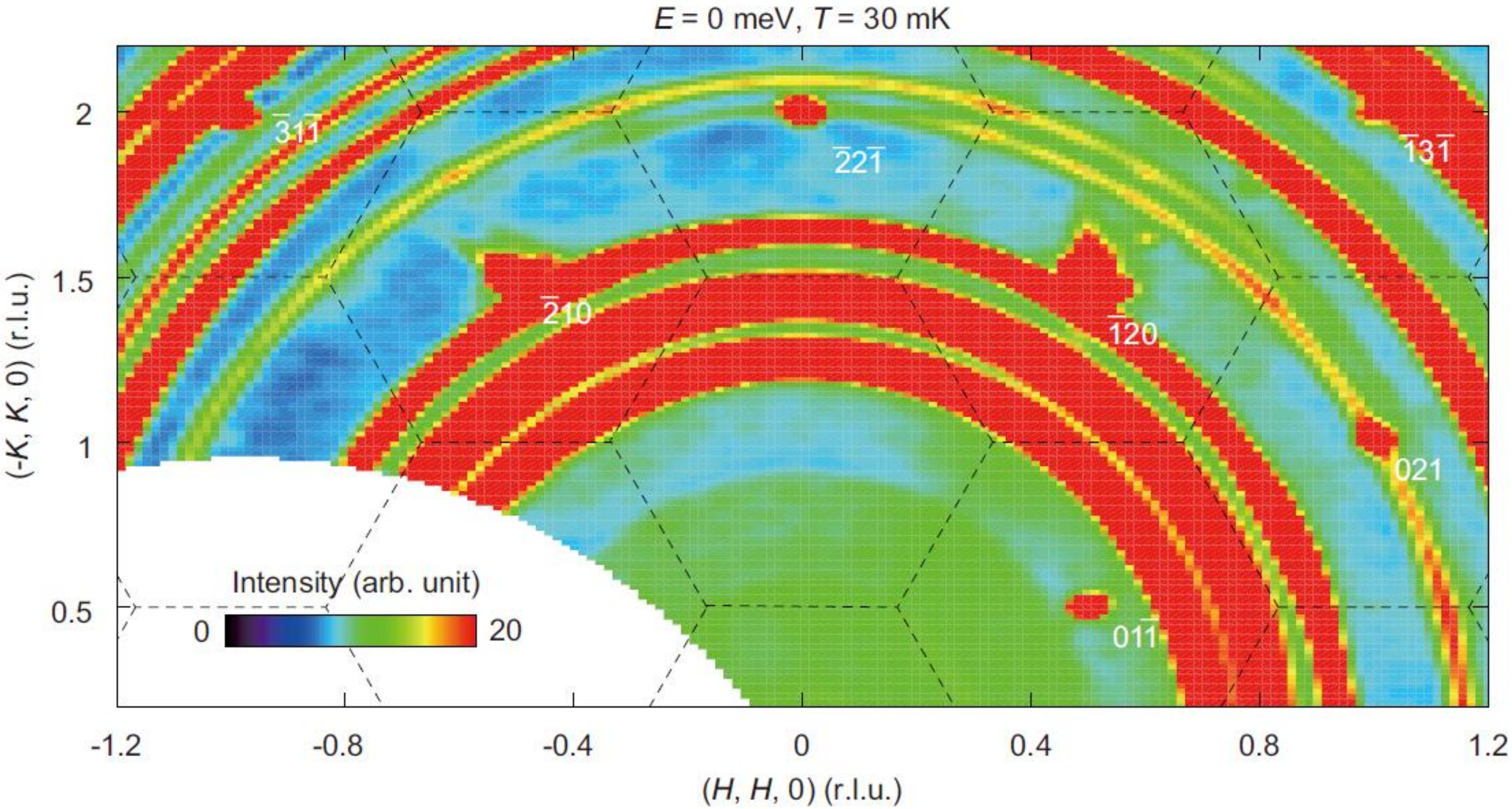


Standard mode:
Single detector, measure one position in the Hilbert space every time
ADVANTAGE: high flux, tunable resolution



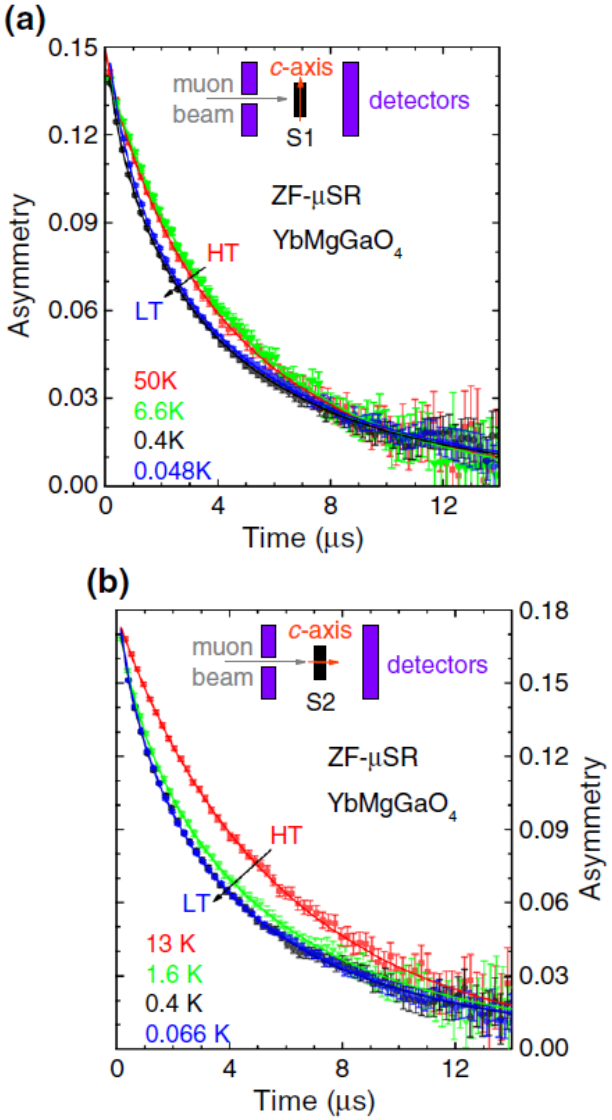
Flatcone mode:
Multi-channel analyzer-detector system, measure 31 Q-position with the same energy transfer at the same time
ADVANTAGE: high measuring efficiency, large covering range in Q-space

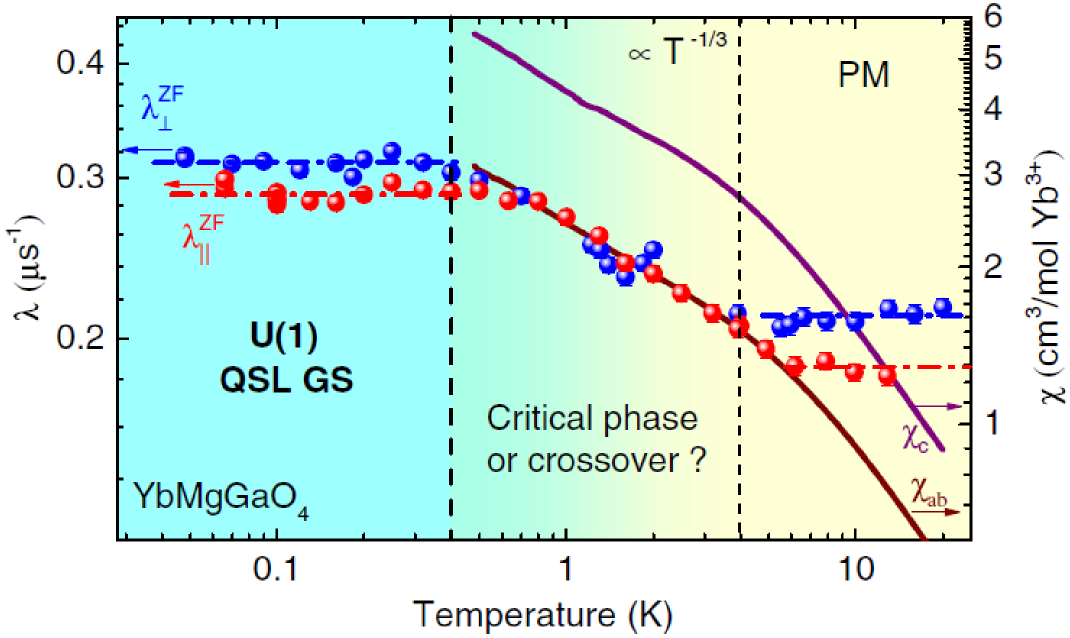
Neutron diffraction : Absence of ordering



No Magnetic peak observed down to 30 mK.

Neutron diffraction : Absence of ordering



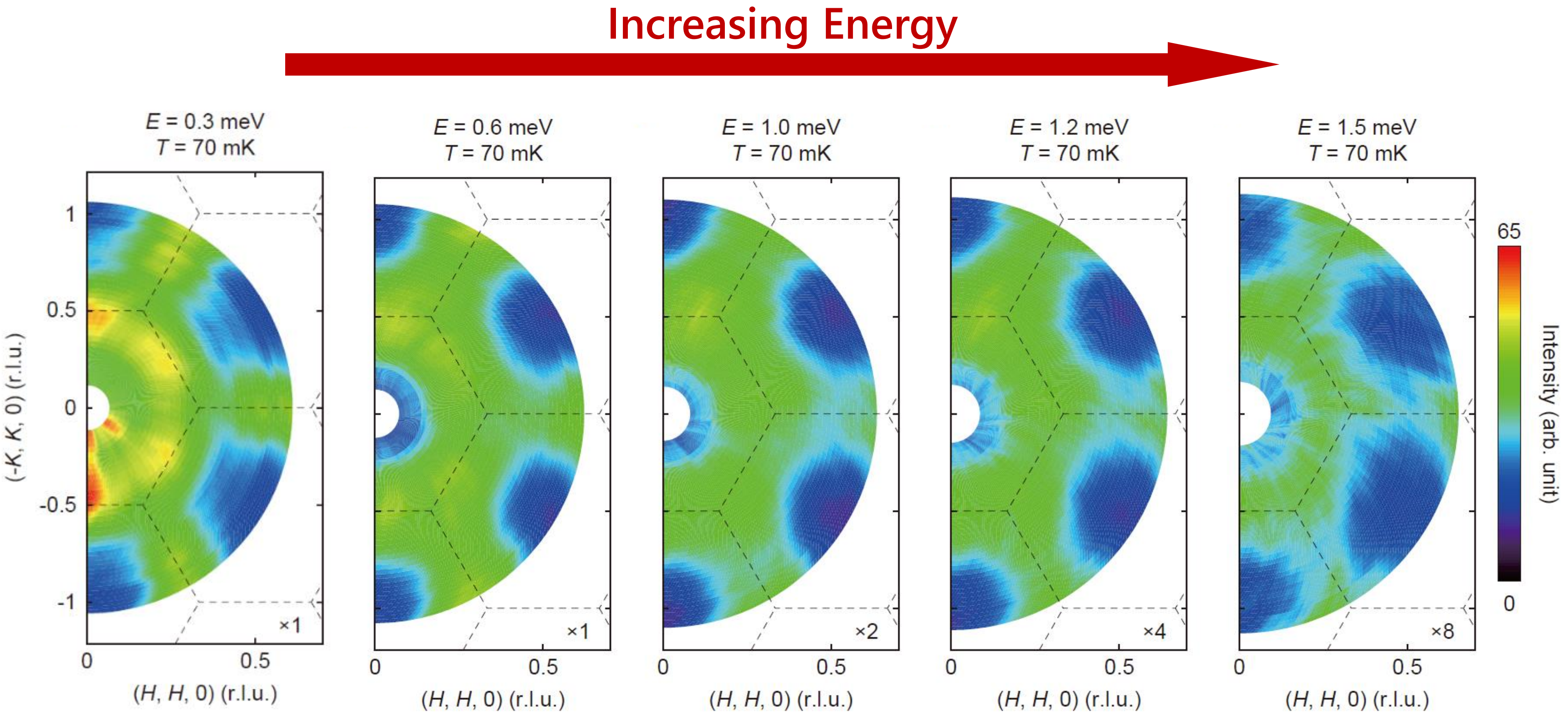


No spin freezing observed down to 40 mK in μSR measurement

Y. Li *et al.*, *Phys. Rev. Lett.* **117**, 097201 (2016).

Inelastic neutron scattering: Continuum

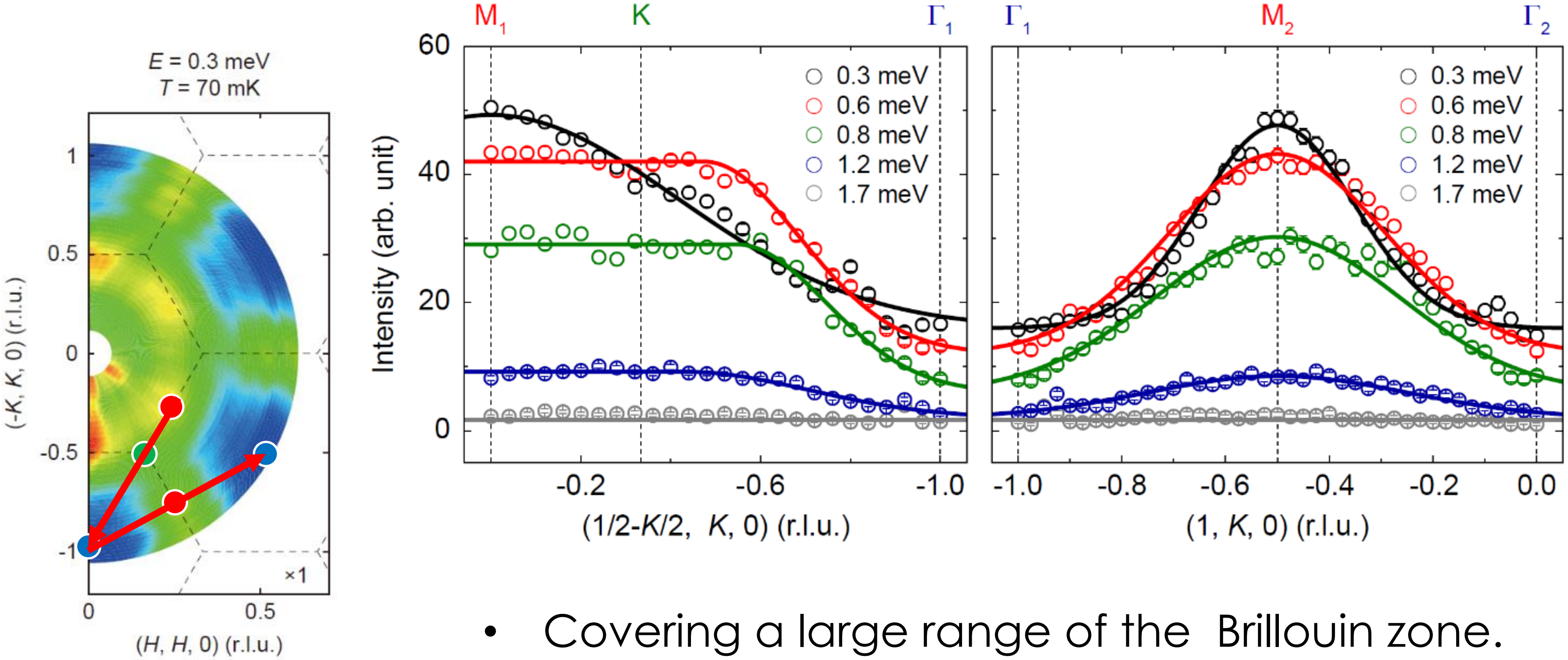
PLOTS: **Constant energy slices**



Continuum at different energies: SPINON excitations

Inelastic neutron scattering: Continuum

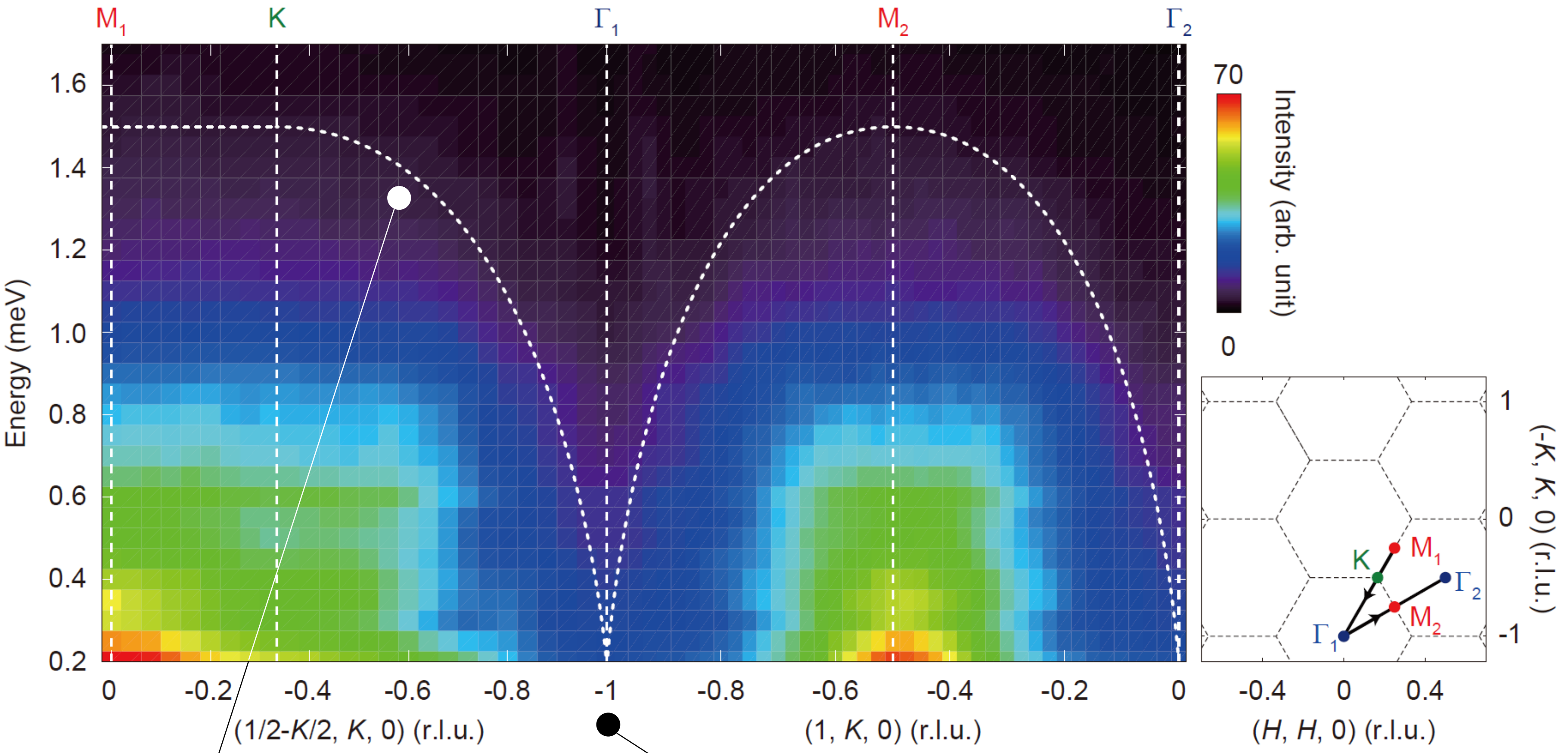
PLOTS: **Constant energy cuts**



- Covering a large range of the Brillouin zone.
- Decreasing with increasing energy.
- Similar shape up to 1.7 meV.

Inelastic neutron scattering: Continuum

PLOTS: **Energy-momenta relationship**

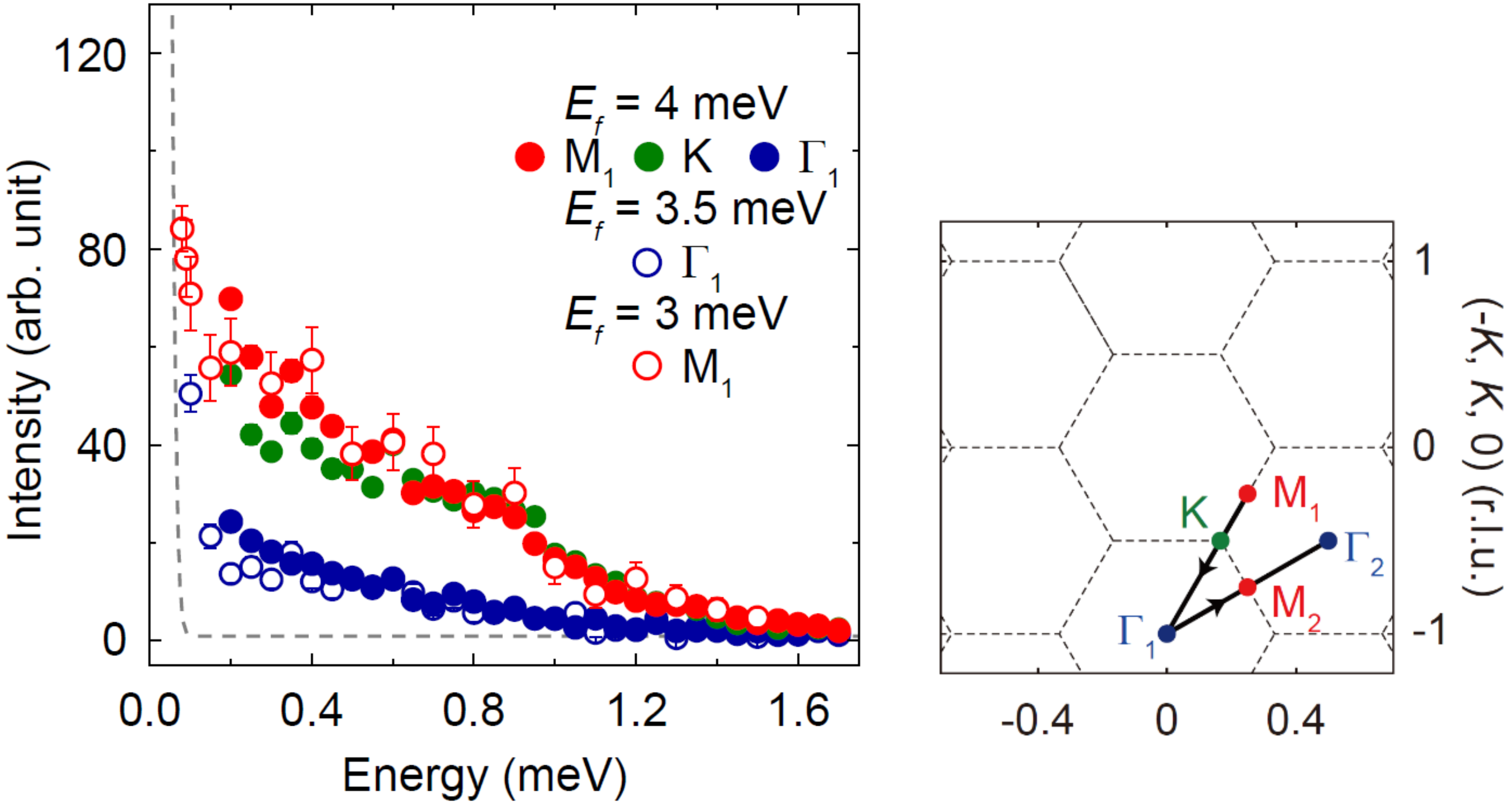


Suppressed signal around Γ point.

Upper boundary.

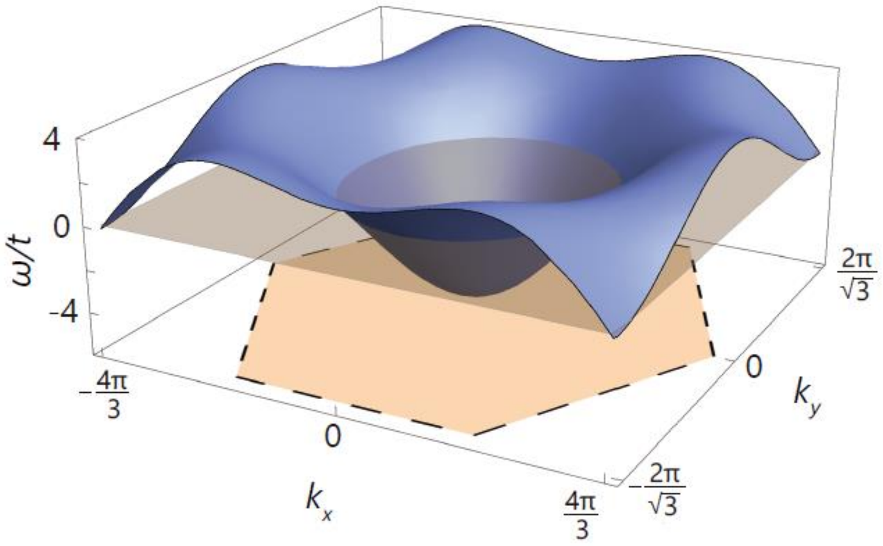
Inelastic neutron scattering: Continuum

PLOTS: **Energy cuts**

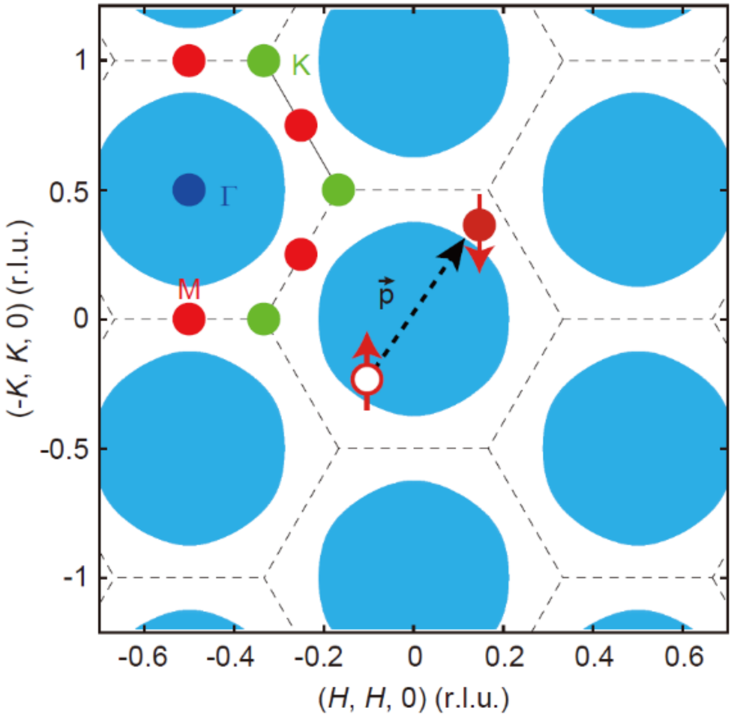


- No observable gap within instrument resolution.
- Decreasing with increasing energy gradually.

Theoretical proposal: Spinon Fermi surface



Band structure



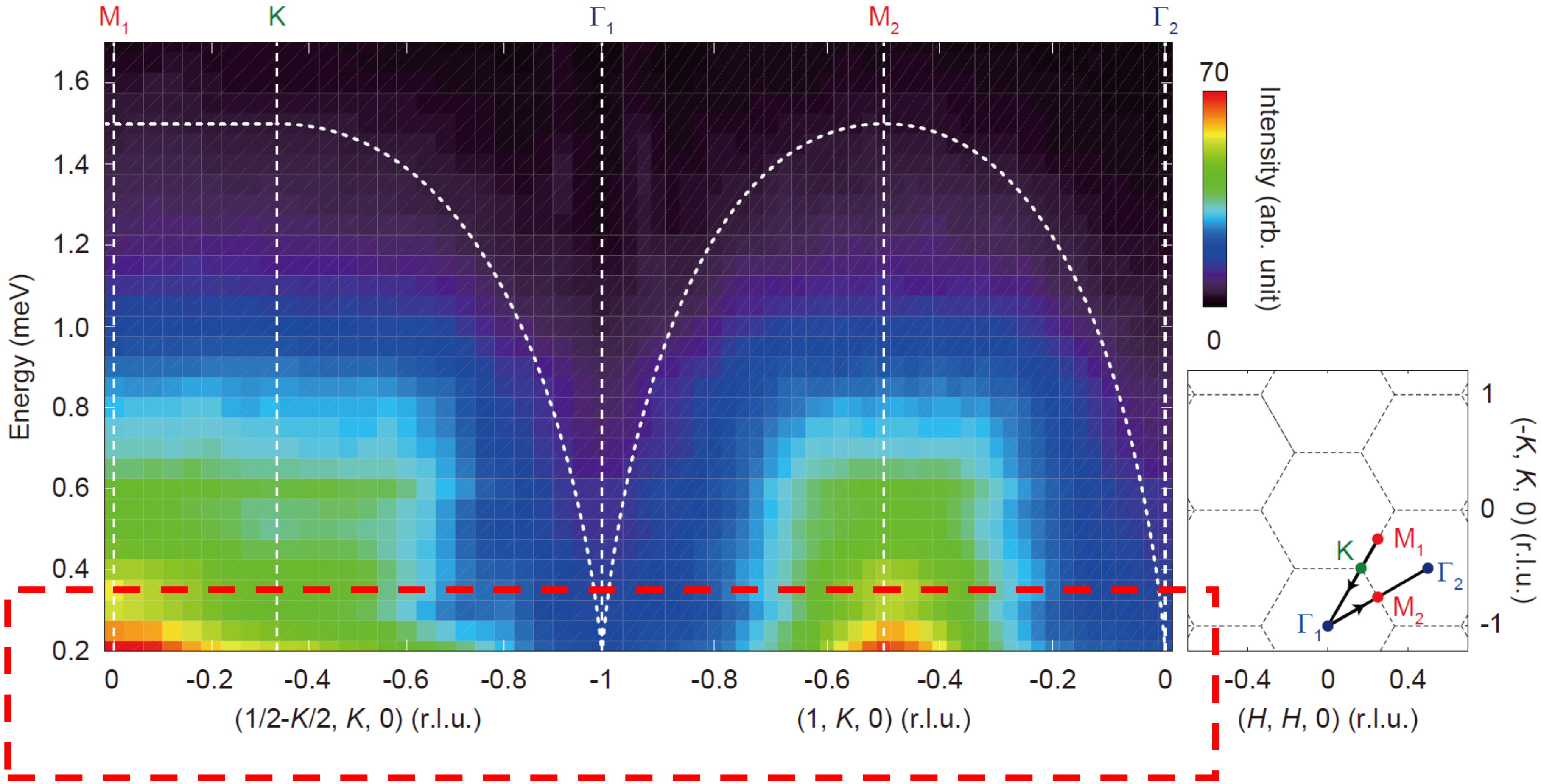
Fermi surface

Neutron Scattering → ΔS=1 process → particle-hole pair

Large Fermi surface → large density of states at low energy

Theoretical proposal: Spinon Fermi surface

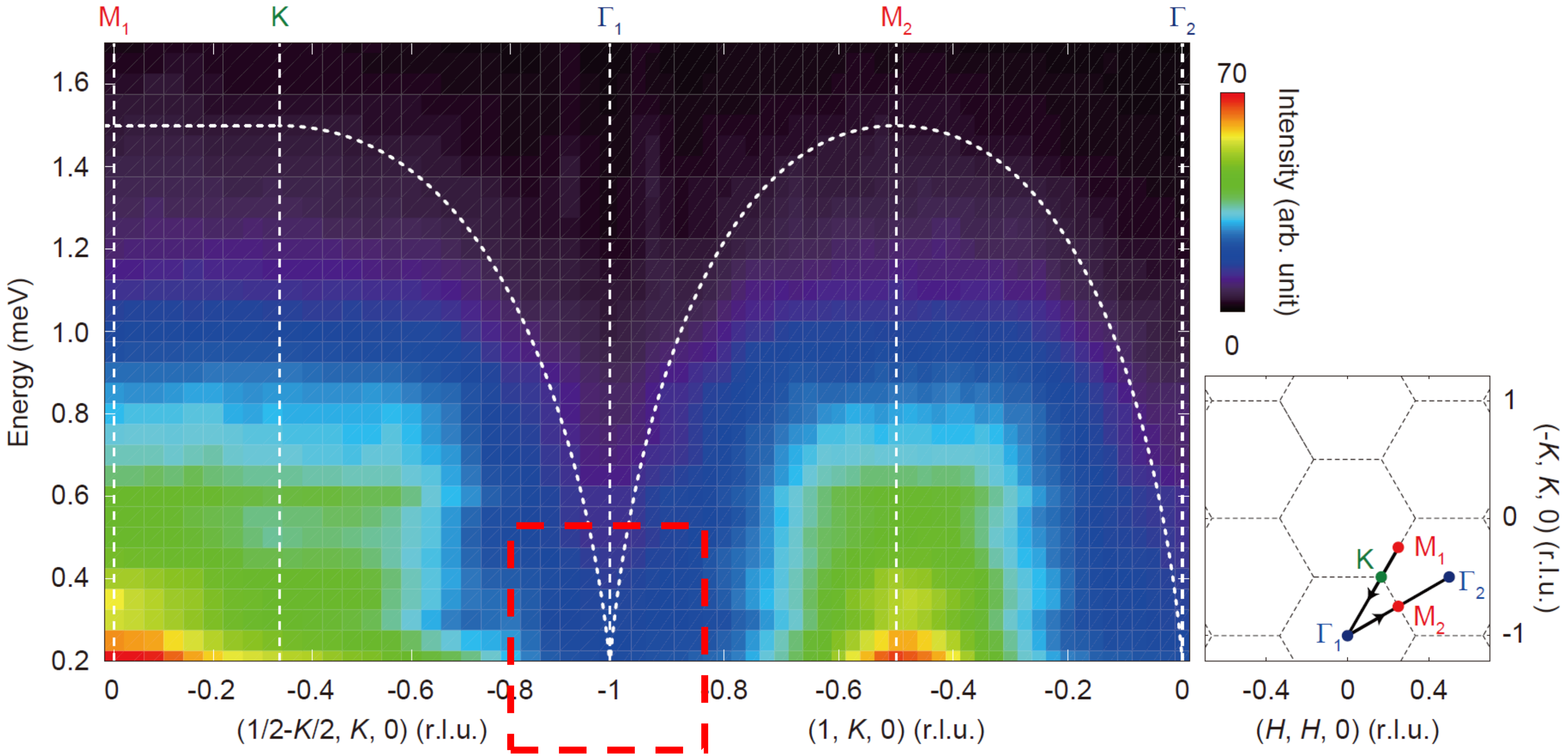
PLOTS: **Energy-momenta relationship**



Large Fermi surface → large density of states at low energy

Theoretical proposal: Spinon Fermi surface

PLOTS: **Energy-momenta relationship**

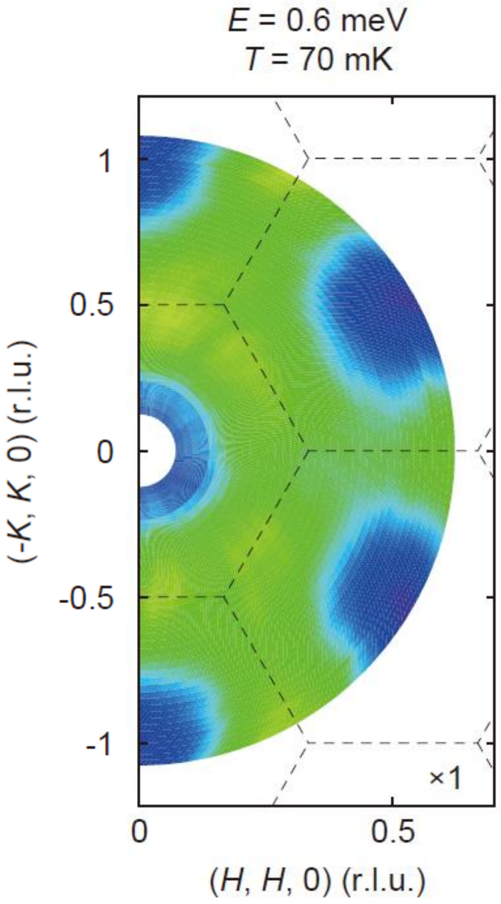


$\boldsymbol{p_{min} \sim E/v_F}$ (p: momentum, v_F: Fermi velocity)

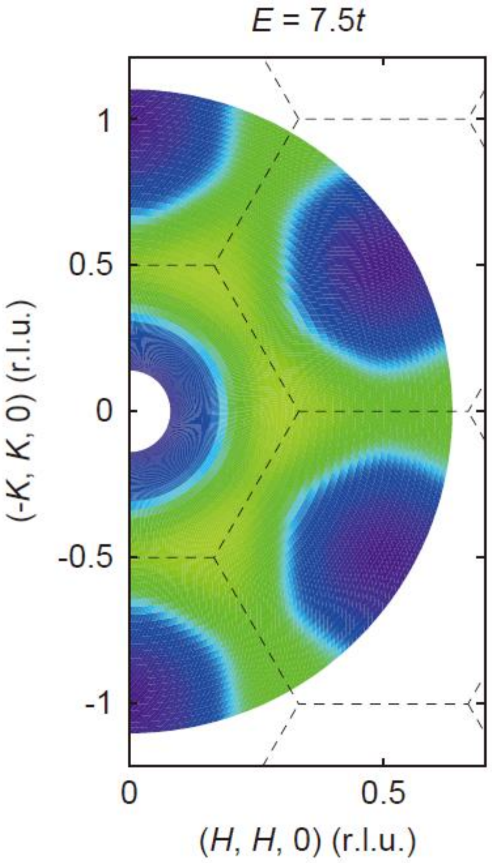
→ Suppressed signal around Γ point

Theoretical proposal: Spinon Fermi surface

PLOTS: **Constant energy slices**



Data



Calculation

Topological States and Phase Transitions
in Strongly Correlated Systems:
Spinon Excitation in $YbMgGaO_4$

CHAPTER A **Neutron Scattering in QSL Research**

CHAPTER B **Spin Excitations in $YbMgGaO_4$ with zero field**

CHAPTER D **Conclusions**

CONCLUSIONS

Continuum covering a wide range of Brillouin zone is revealed in the whole measured energy range.

A clear upper excitation edge is presented at zero field which can be accounted by the particle-hole excitation of a spinon Fermi surface.

Our results therefore identify a QSL with spinon Fermi surface in a spin-1/2 triangular lattice.

Y. Shen *et al.*, *Nature* **540**, 559-562 (2016).

Thank you for your attention!

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Fudan University
July 10th 2017