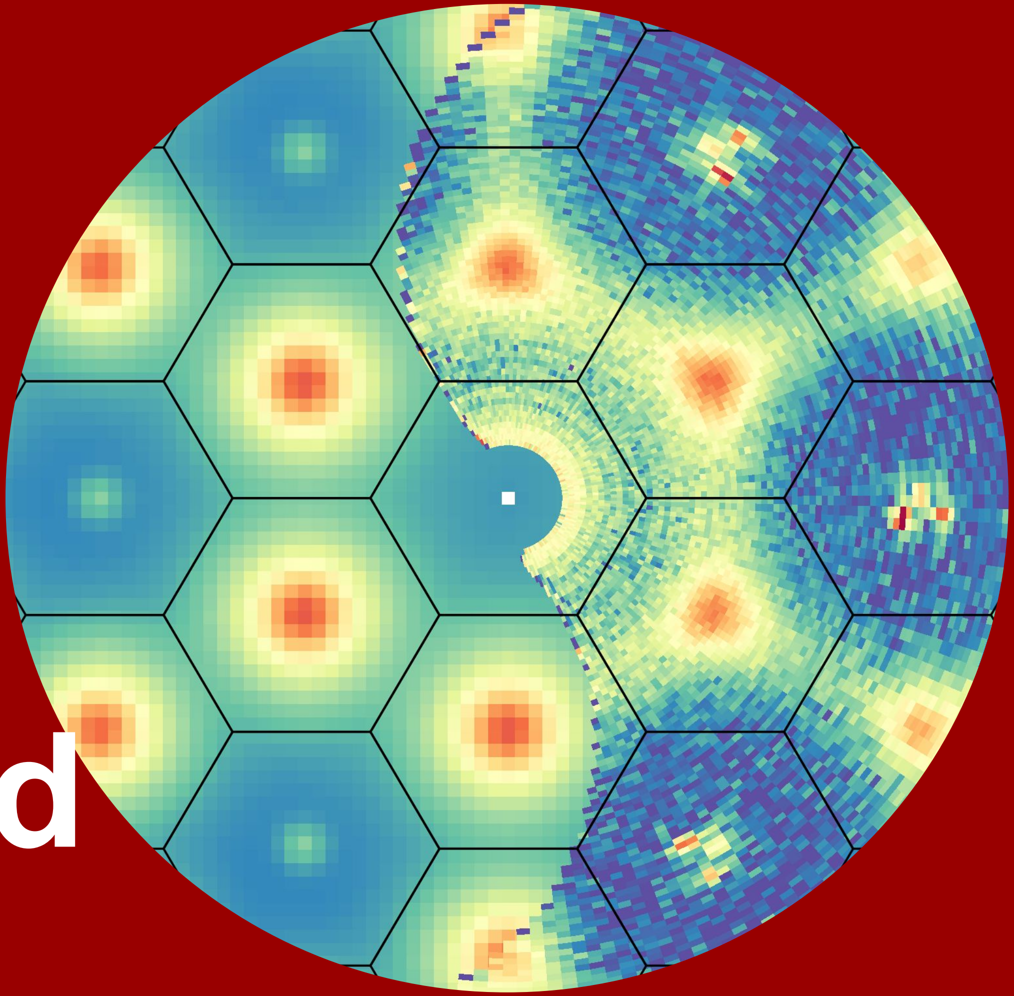
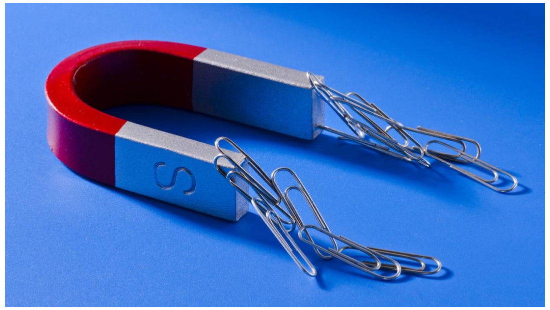
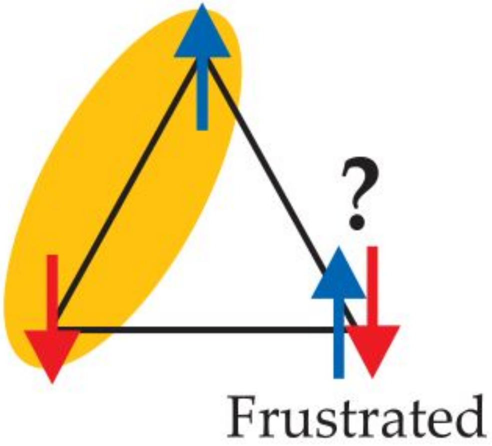


Sofie Janas
Postdoc

Classical spin liquid phase in frustrated magnet $YMnO_3$

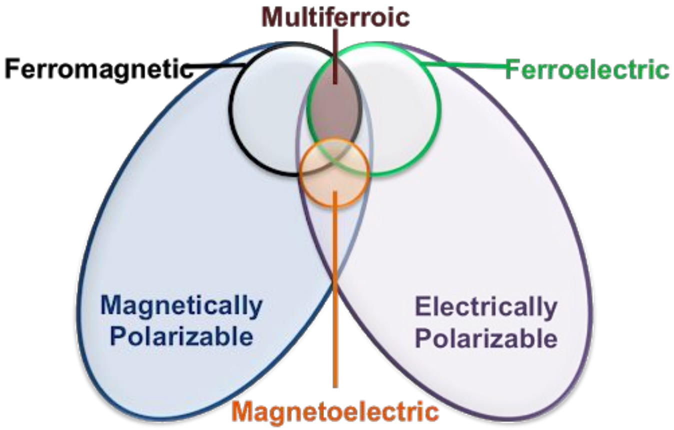
My background





- PhD in Physics from Niels Bohr Institute
  - Supervisor: Kim Lefmann
  - Neutron spectroscopy
  - Frustrated magnets: triangular and kagome geometries

- Now: Postdoc at Technical University of Denmark
  - With Rasmus Toft-Petersen (BIFROST lead)
  - Project: magnetoelectric materials & time-resolved neutron diffraction

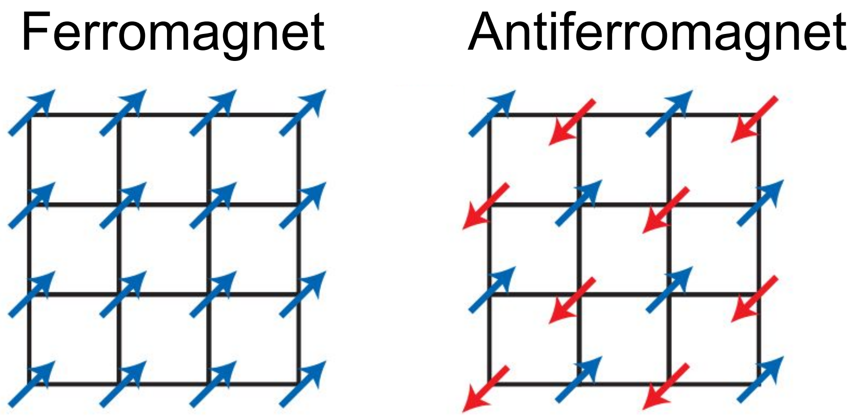


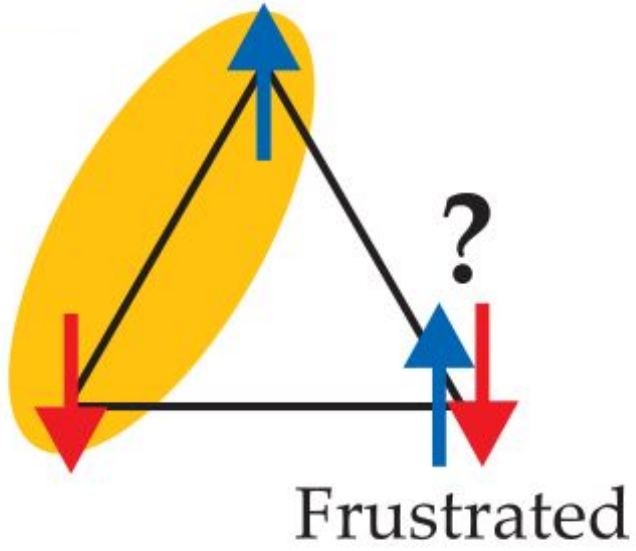
Geometrically frustrated magnets: The Triangular lattice Ising magnet

$$\mathcal{H} = -J \sum_{ij} S_i^z S_j^z$$

Frustration suppresses magnetic ordering

Competing interactions give degenerate ground states

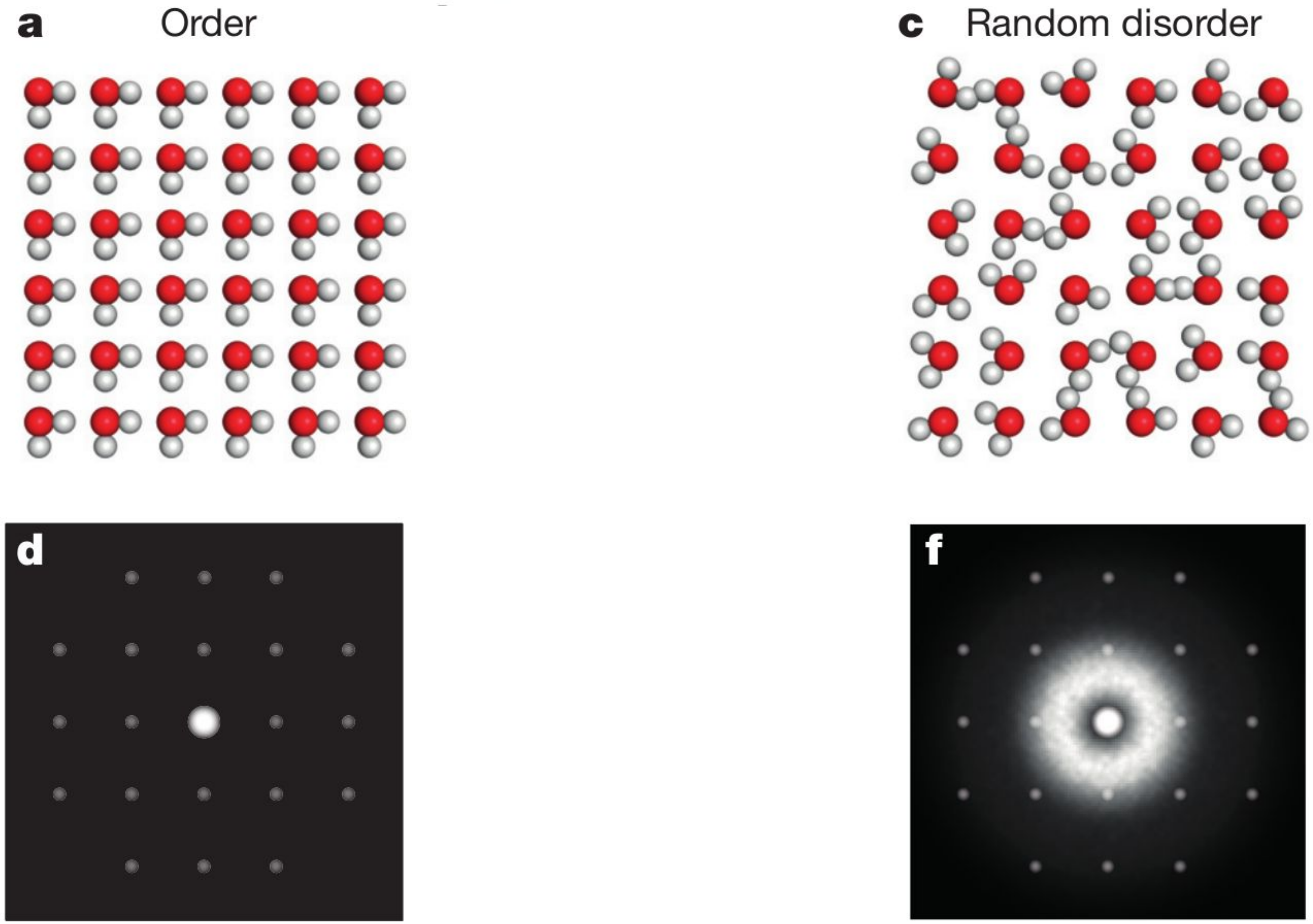




Imai, T., & Lee, Y. S. (2016). *Physics Today*, *69*(8), 30–36.

Correlated disorder in square ice

Reciprocal space, 1/Å



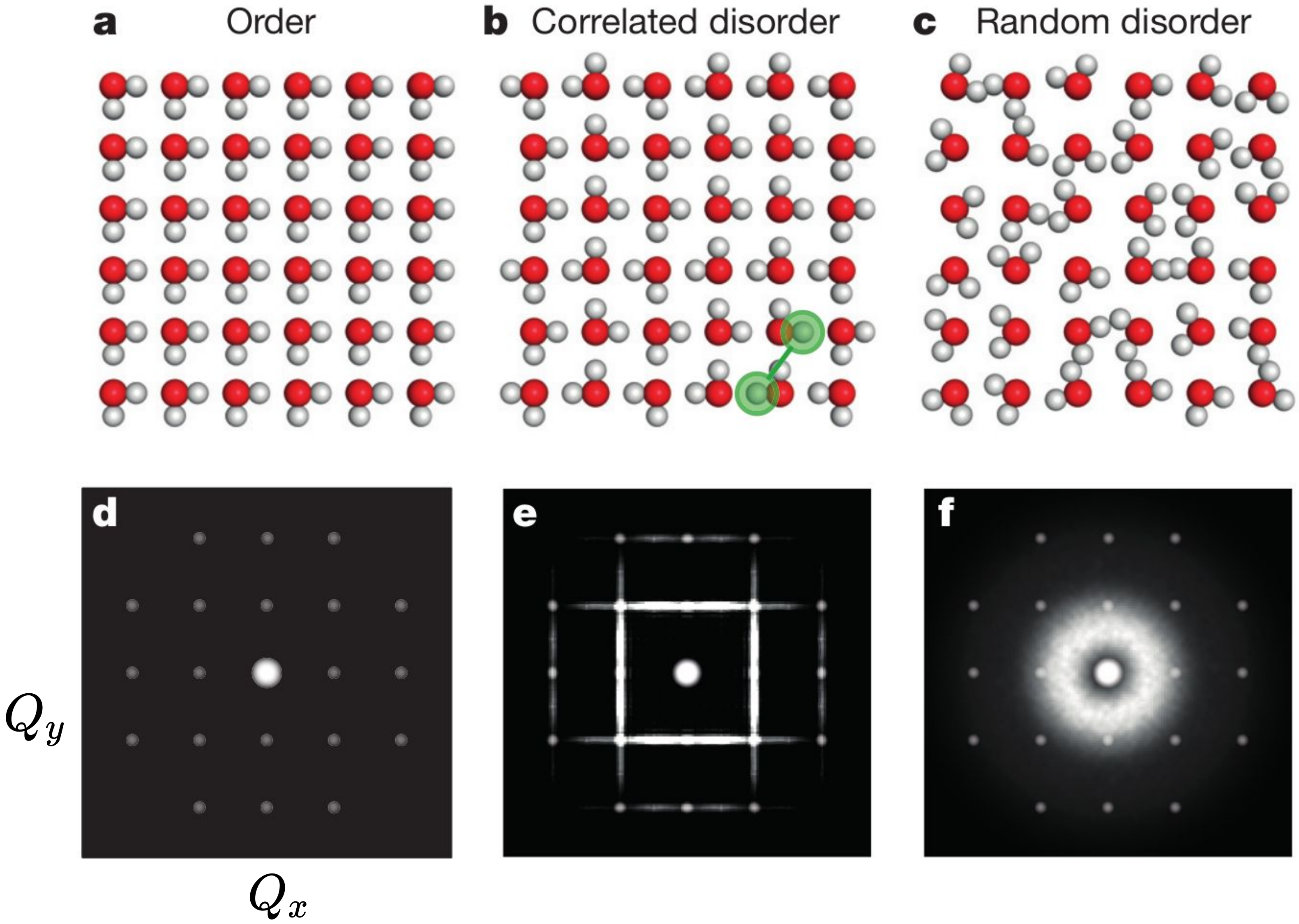
Q_y

Q_x

Keen, D. A., & Goodwin, A. L. (2015). *Nature*, *521*(7552), 303–309.

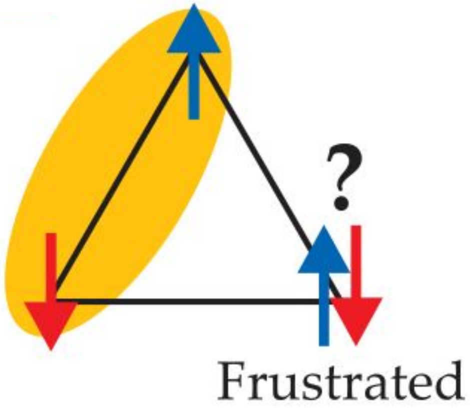
Correlated disorder in square ice

Reciprocal space, 1/Å



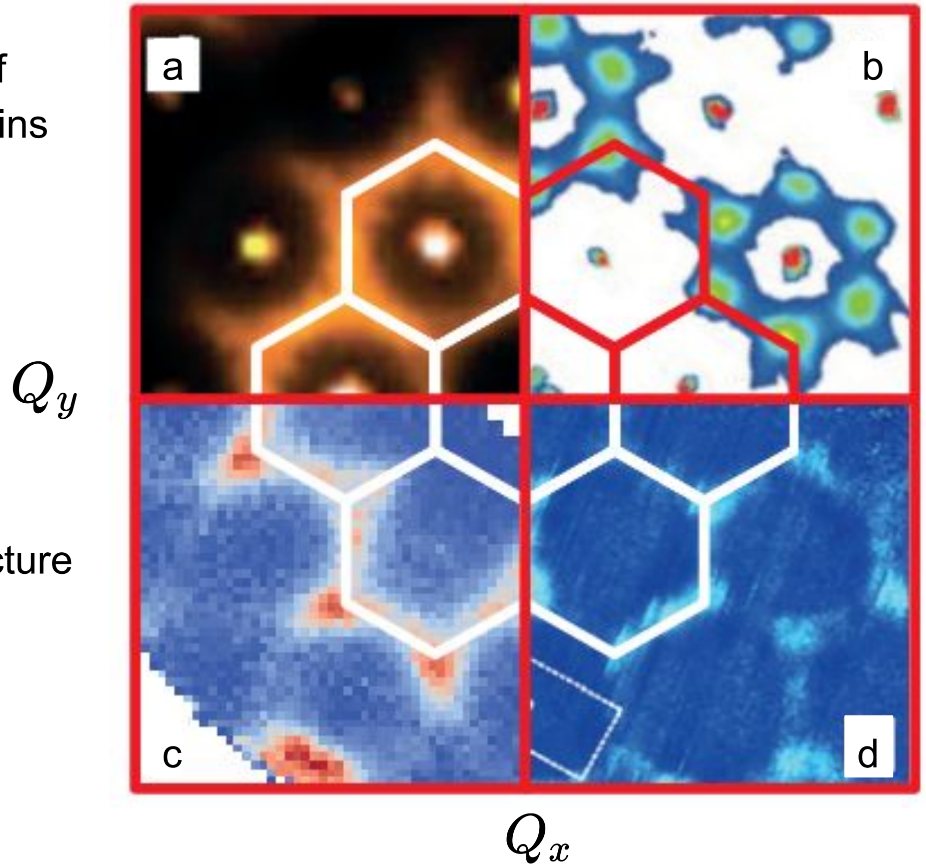
Geometrically frustrated magnets:
The Triangular lattice Ising magnet

$$\mathcal{H} = -J\sum_{ij} S_i^z S_j^z$$



Packing of Gag proteins

Orbital orientation in frustrated magnet $Ba_3CuSb_2O_9$



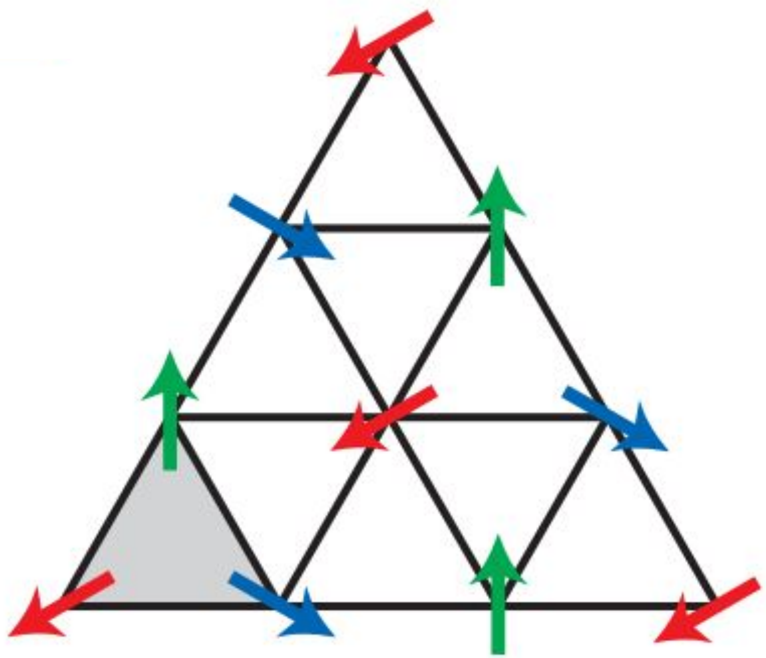
Spin structure in β-Mn

Electronic structure in graphene

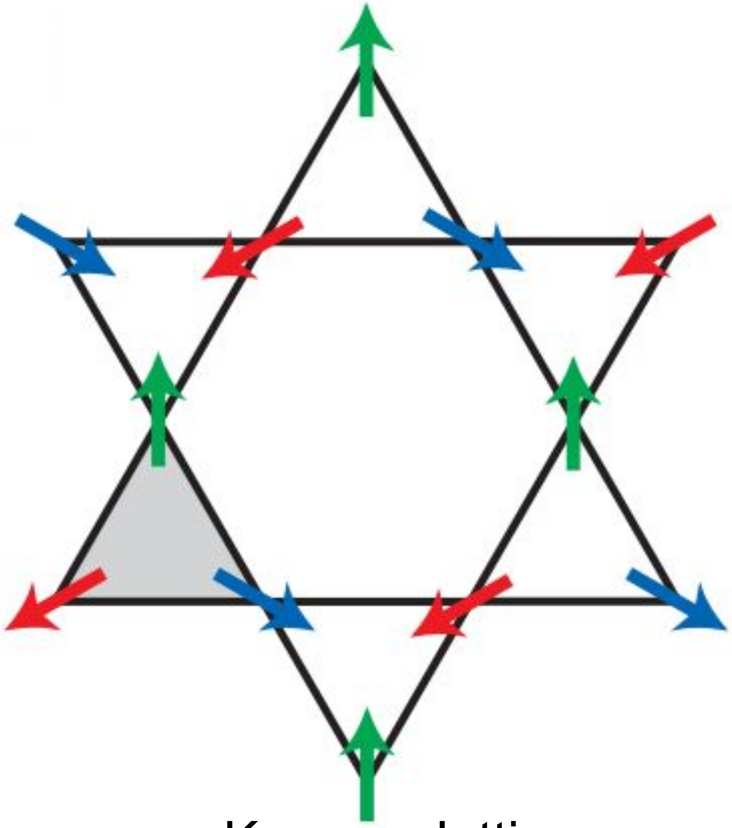
Keen, D. A., & Goodwin, A. L. (2015). *Nature*, *521*(7552), 303–309.

Geometrically frustrated magnets: The Heisenberg magnet

$$\mathcal{H} = -J\sum_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$



Triangular lattice



Kagome lattice

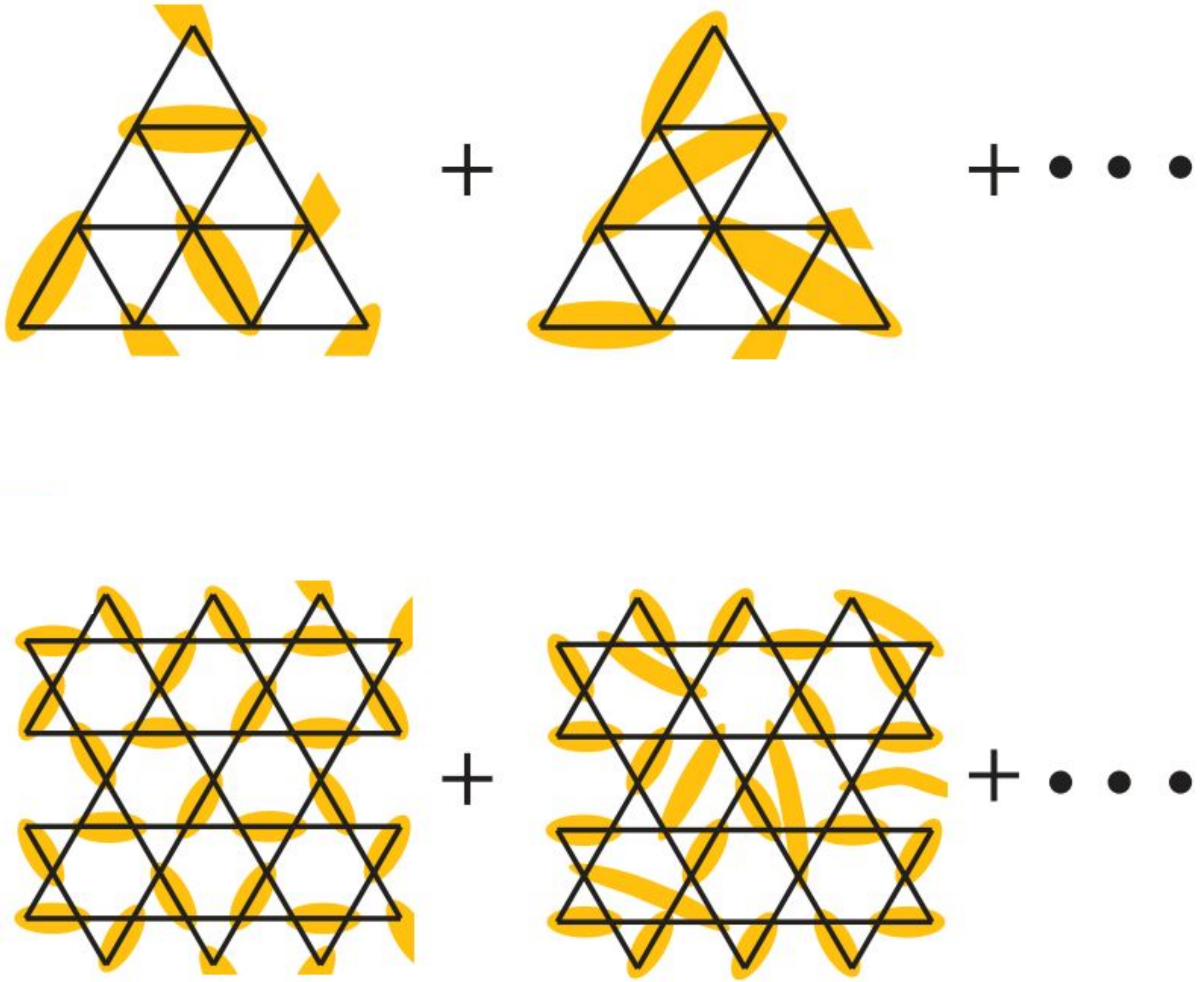
Imai, T., & Lee, Y. S. (2016). *Physics Today*, *69*(8), 30–36.

Quantum spin liquids

Properties:

- No magnetic order, even at T = 0
- Liquid-like fluctuations at all T
- Long range entanglement
- Fractionalized excitations

Quantum spin: S = ½
→ Spin singlets

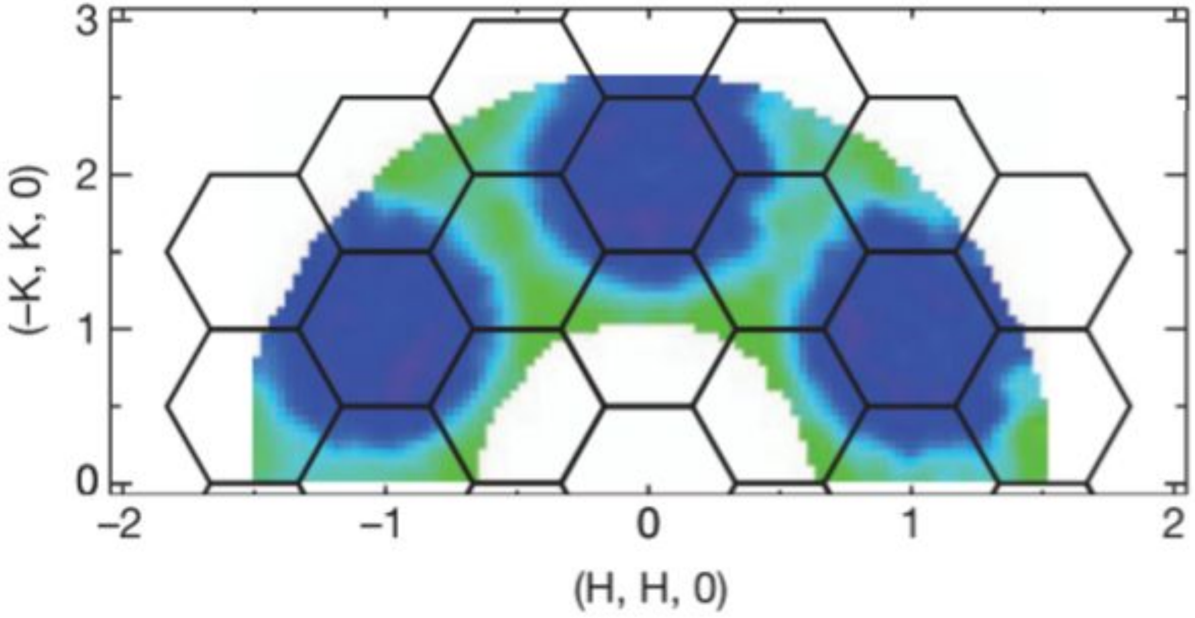


Imai, T., & Lee, Y. S. (2016). *Physics Today*, *69*(8), 30–36.

Quantum spin liquids

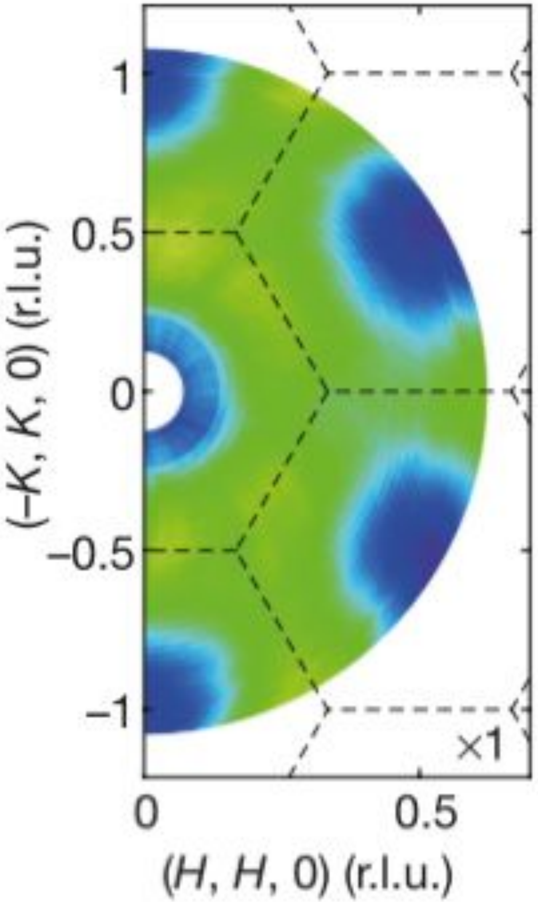
Herbertsmithite: spin-½ kagome

$$\hbar\omega = 1 - 9\,\mathrm{meV},\ \mathrm{T} = 1.5\,\mathrm{K}$$



YbMgGaO$_4$: spin-½ Triangular lattice

$$\hbar\omega = 0.6\,\mathrm{meV},\ \mathrm{T} = 70\,\mathrm{mK}$$



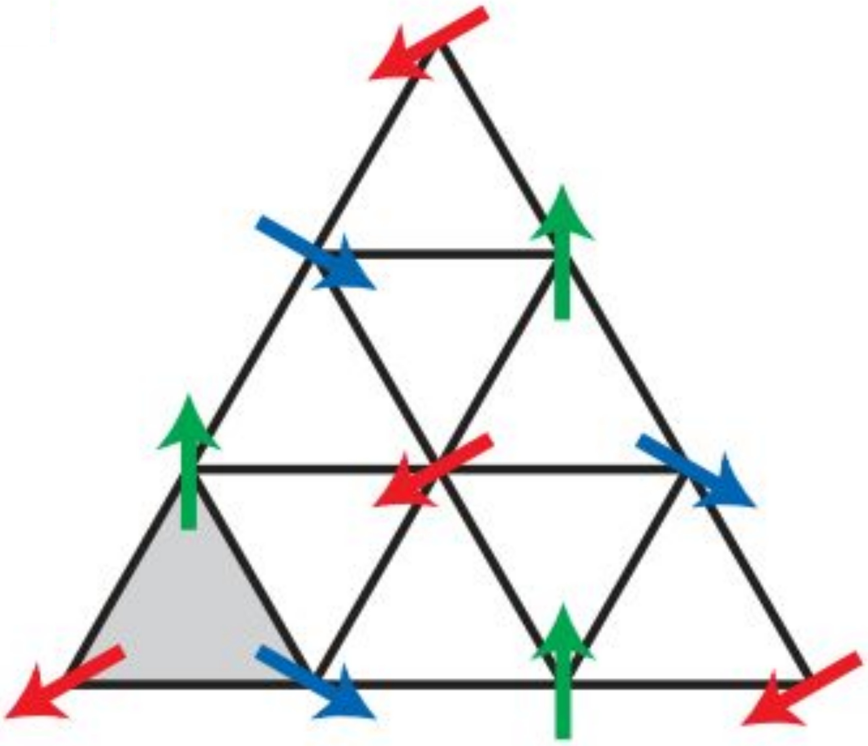
Imai, T., & Lee, Y. S. (2016). *Physics Today*, *69*(8), 30–36.
Shen, Y., et al (2016). *Nature*, *540*(7634), 559–562.
Han, T. H., et al (2012). *Nature*, *492*(7429), 406–410.

Classical spin liquids

- Frustrated magnets
- Classical spin (S > ½)
- Finite ordering temperature

Above T_N:
- Broad excitations: short-ranged and finite lifetimes
- Low-energy excitations

However:
Definition not agreed upon!



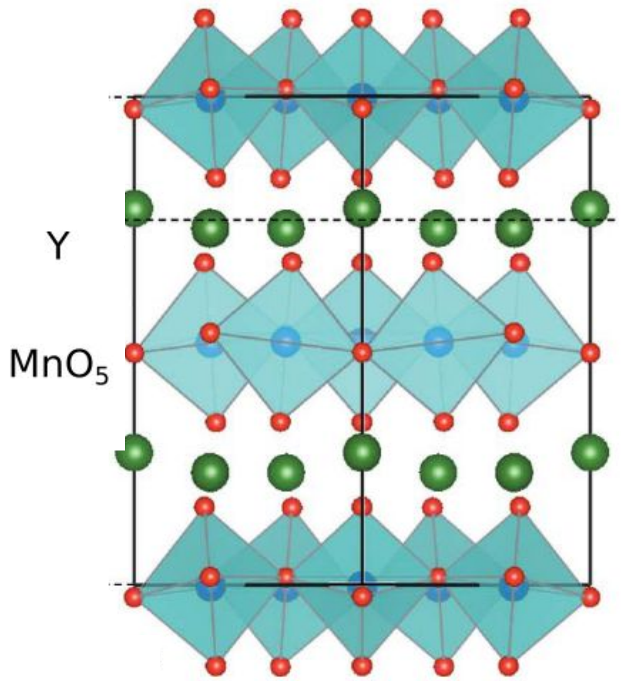
Classical spin liquid phase in $YMnO_3$

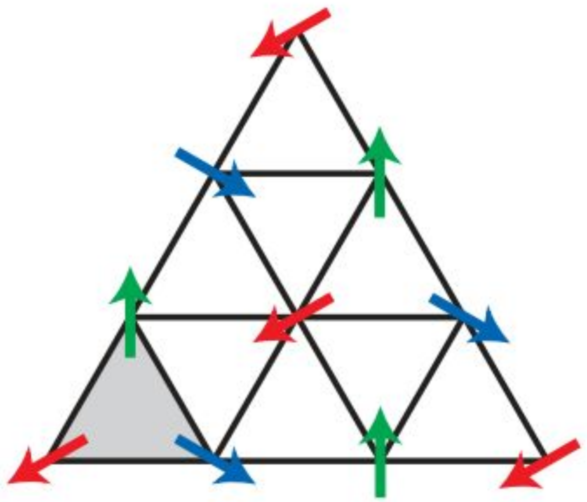
Hexagonal $YMnO_3$

Frustrated, triangular lattice Heisenberg AFM
Magnetic Mn^{3+} : S = 2

Ferroelectric transition: T_C = 1259 K ≈ 1000 °C

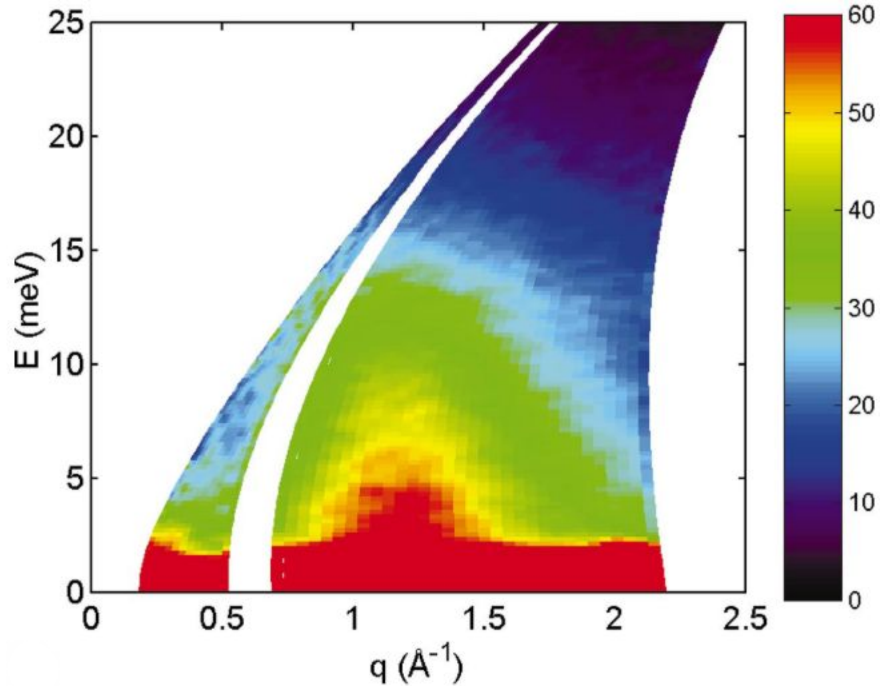
Antiferromagnetic ordering: T_N = 72 K ≈ -200 °C

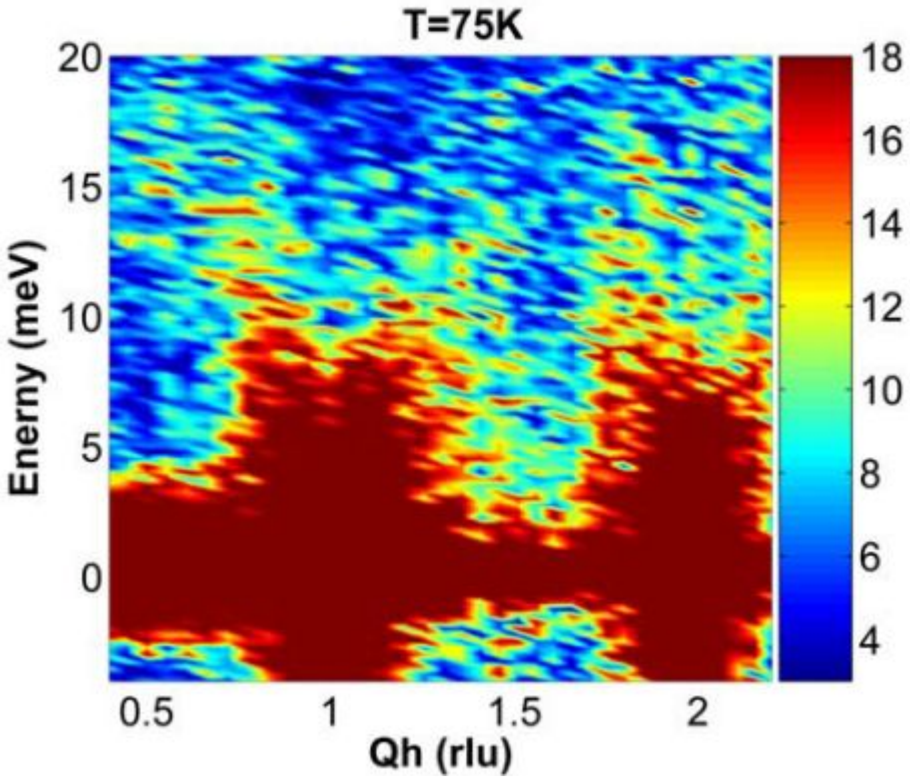




Diffuse scattering in $YMnO_3$

T = 280 K



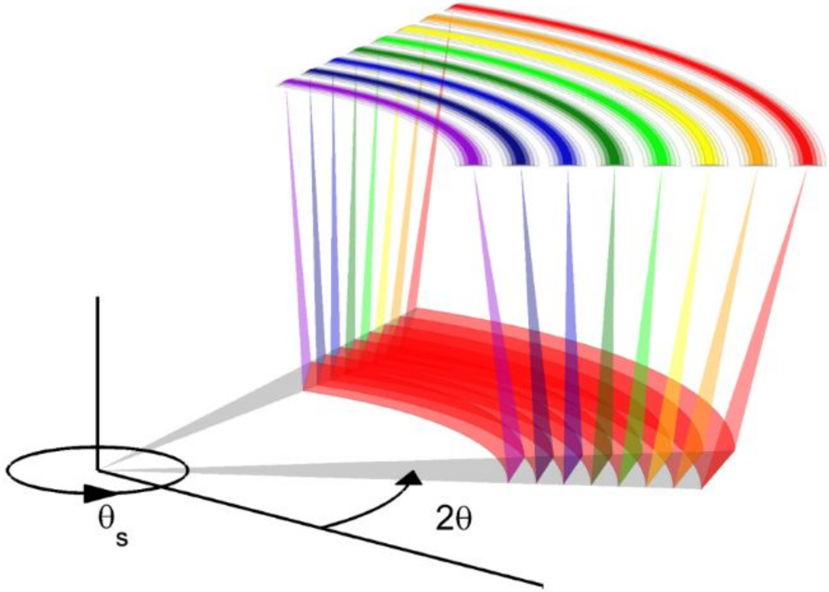


Park, J., et al (2003). *Physical Review B*, *68*, 104426.
Demmel, F., & Chatterji, T. (2007). P *Physical Review B*, *76*(21), 212402.

Experimental

CAMEA - multiplexing spectrometer, newly commissioned
Paul Scherrer Institute, Switzerland

Similar to BIFROST @ ESS:
Multiple analysers & detectors

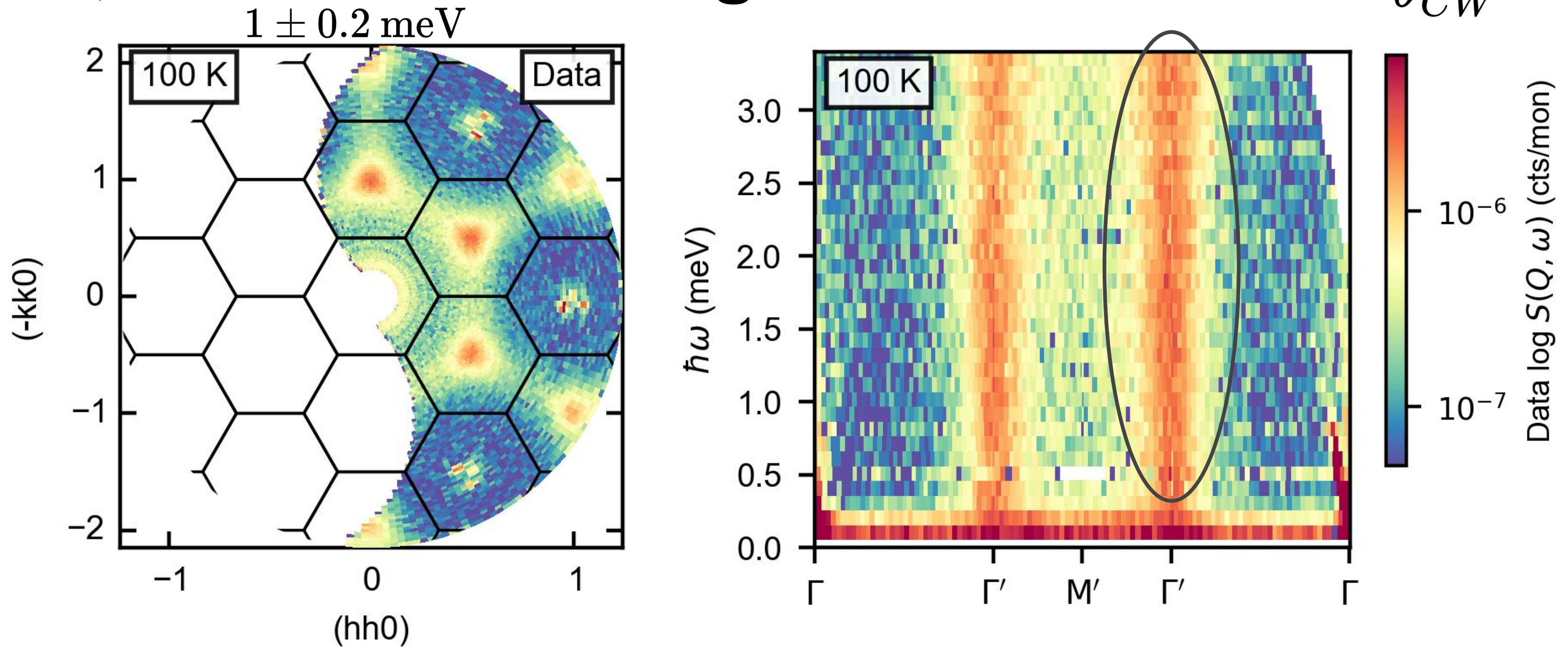


Dynamic, diffuse scattering

$T_N = 72\ K$

$\theta_{CW} = -550\ K$

$T > T_N$

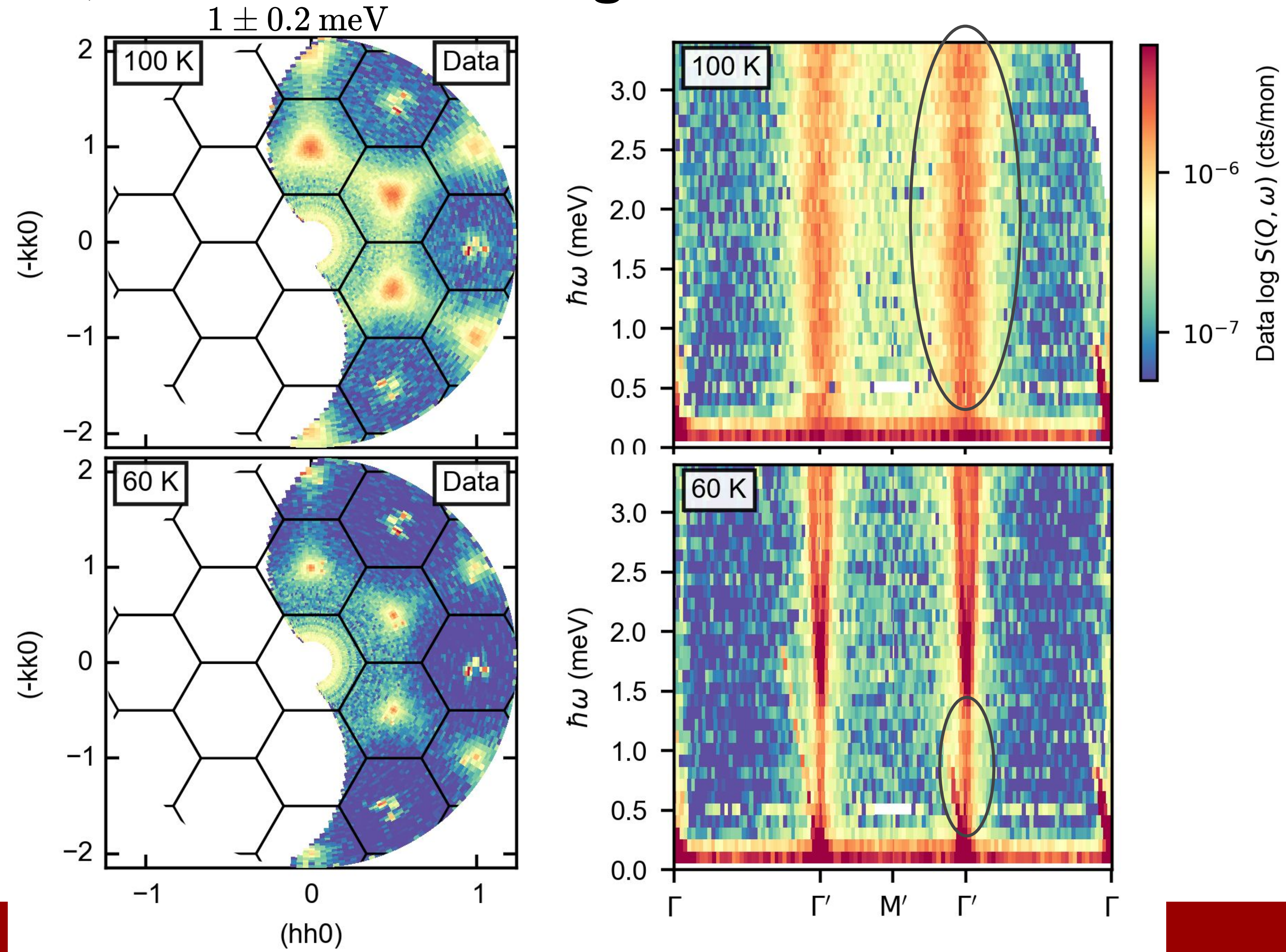


Dynamic, diffuse scattering

$T_N = 72\ K$

$T > T_N$

$T < T_N$



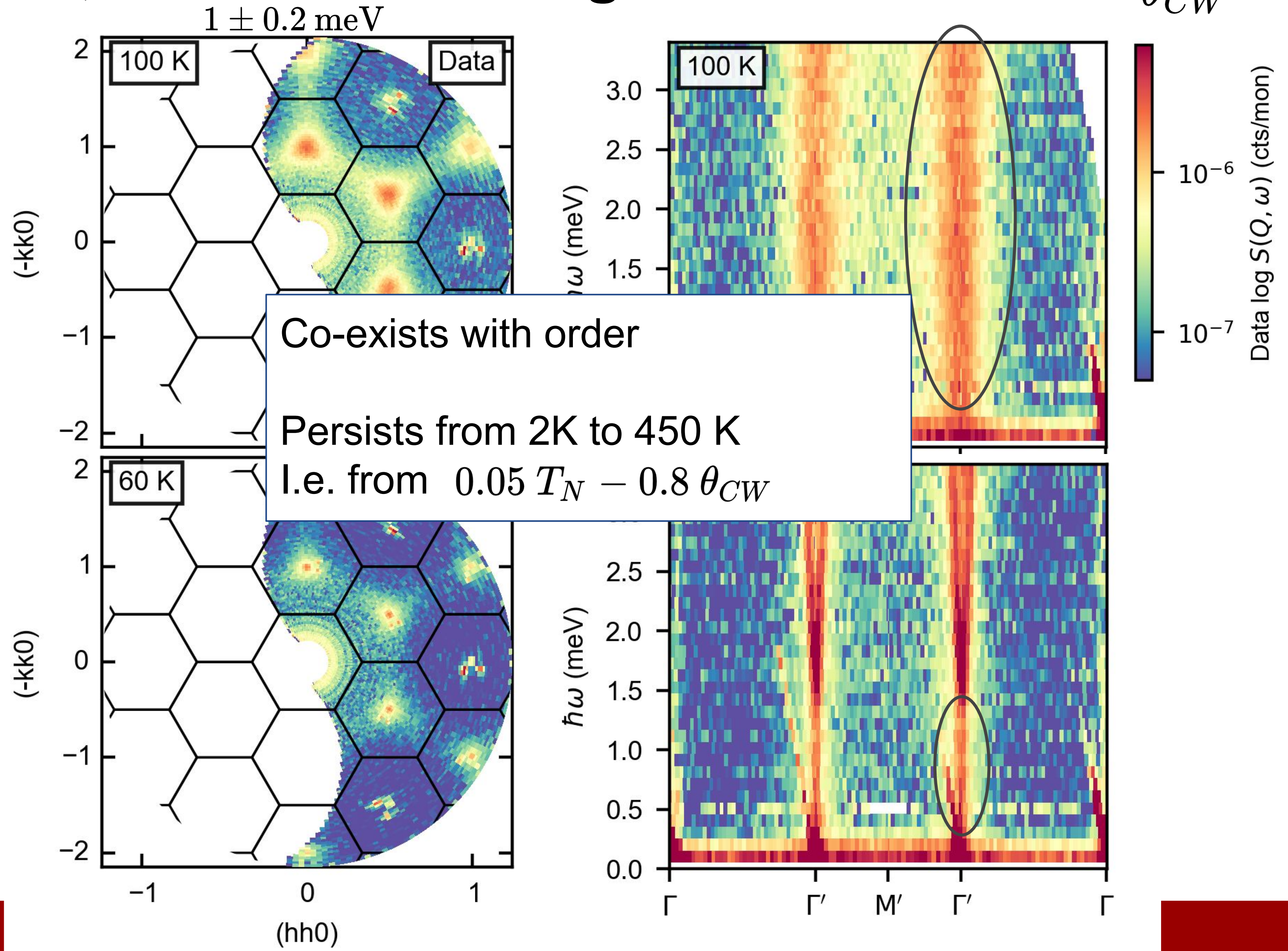
Dynamic, diffuse scattering

$$T_N = 72\ K$$

$$\theta_{CW} = -550\ K$$

$T > T_N$

$T < T_N$



Co-exists with order

Persists from 2K to 450 K

I.e. from $0.05\,T_N - 0.8\,\theta_{CW}$

Critical scattering near phase transitions

Fluctuations on all length and time scales

→ Diffuse scattering:

Short-ranged correlations

Quasielastic profile

Critical spin-spin correlation

$$\langle S_0 S_l \rangle \propto \exp(-|\mathbf{r}_{0l}|/\xi)$$

Critical scattering near phase transitions

Fluctuations on all length and time scales

→ Diffuse scattering:

Short-ranged correlations

Quasielastic profile

Critical spin-spin correlation

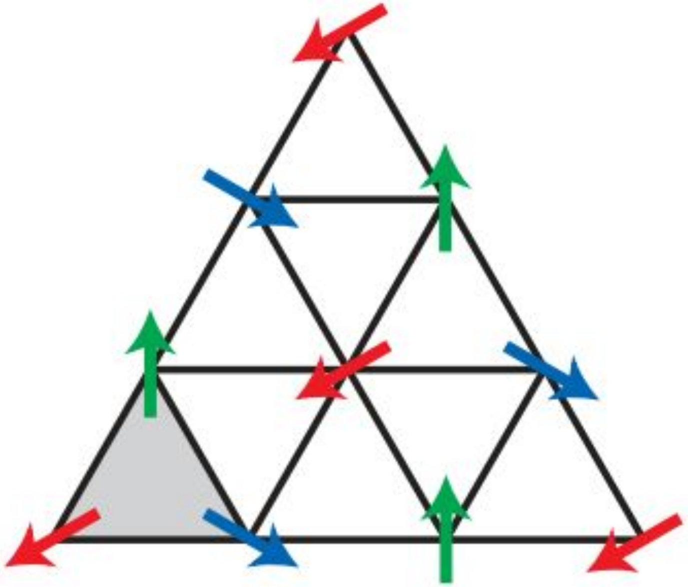
$$\langle S_0 S_l \rangle \propto \exp(-|\mathbf{r}_{0l}|/\xi)$$

Correlation length:
Measurable quantity!

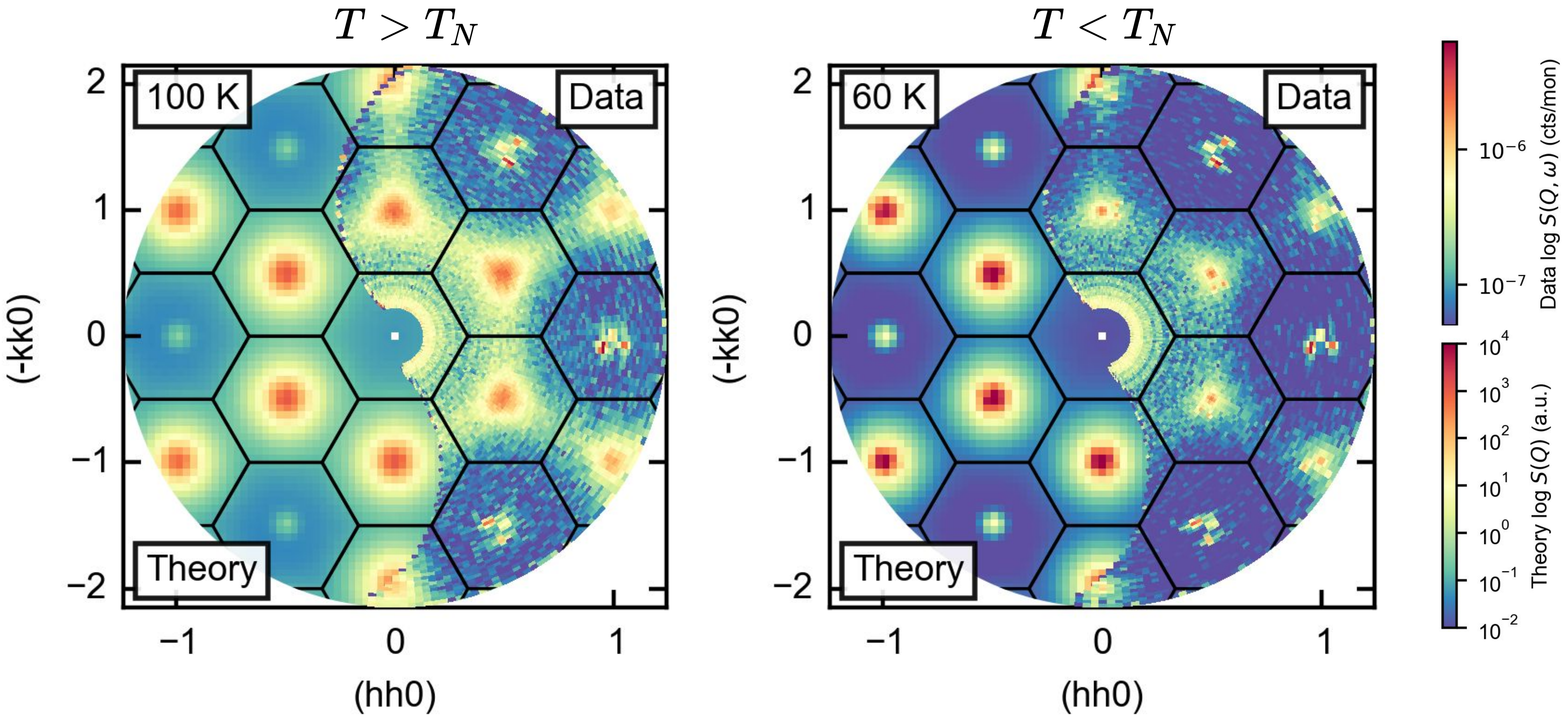
Modelling: structure factor of spin clusters

$$S(\mathbf{Q}) = f(Q)^2 \sum_{l=0}^{N} e^{i\mathbf{Q}\cdot\mathbf{r}_l} \sum_{\substack{\{\alpha,\beta \\ \in\{x,y,z\}}} \left(\delta_{\alpha,\beta} - \hat{Q}_\alpha \hat{Q}_\beta\right) \left\langle S_0^\alpha S_l^\beta \right\rangle_{\mathrm{Rot}}$$

$$\langle S_0 S_l \rangle \propto \exp(-|\mathbf{r}_{0l}|/\xi)$$



Dynamic, diffuse scattering



PHYSICAL REVIEW LETTERS **126,** 107203 (2021)

Classical Spin Liquid or Extended Critical Range in *h*-$YMnO_3$?

Sofie Janas,[1,2] Jakob Lass,[1,3] Ana-Elena Ţuţueanu,[1,4] Morten L. Haubro,[1] Christof Niedermayer,[3] Uwe Stuhr,[3] Guangyong Xu,[5] Dharmalingam Prabhakaran,[6] Pascale P. Deen,[7,1] Sonja Holm-Dahlin,[1,8] and Kim Lefmann[1,*]

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[2]*Institute of Physics, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*
[3]*Laboratory for Neutron Scattering, Paul Scherrer Institute (PSI), 5232 Villigen, Switzerland*
[4]*Institut Laue-Langevin (ILL), Grenoble Cedex 9 38042, France*
[5]*NIST Center for Neutron Research, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*
[6]*Clarendon Laboratory, Department of Physics, University of Oxford, Oxford OX1 3PU, United Kingdom*
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Neutron spectroscopy on the classical triangular-lattice frustrated antiferromagnet *h*-$YMnO_3$ reveals diffuse, gapless magnetic excitations present both far below and above the ordering temperature. The correlation length of the excitations increases as the temperature approaches zero, bearing a strong resemblance to critical scattering. We model the dynamics in the ordered and correlated disordered phase as critical spin correlations in a two-dimensional magnetic state. We propose that our findings may provide a general framework to understand features often attributed to classical spin liquids.

DOI: 10.1103/PhysRevLett.126.107203

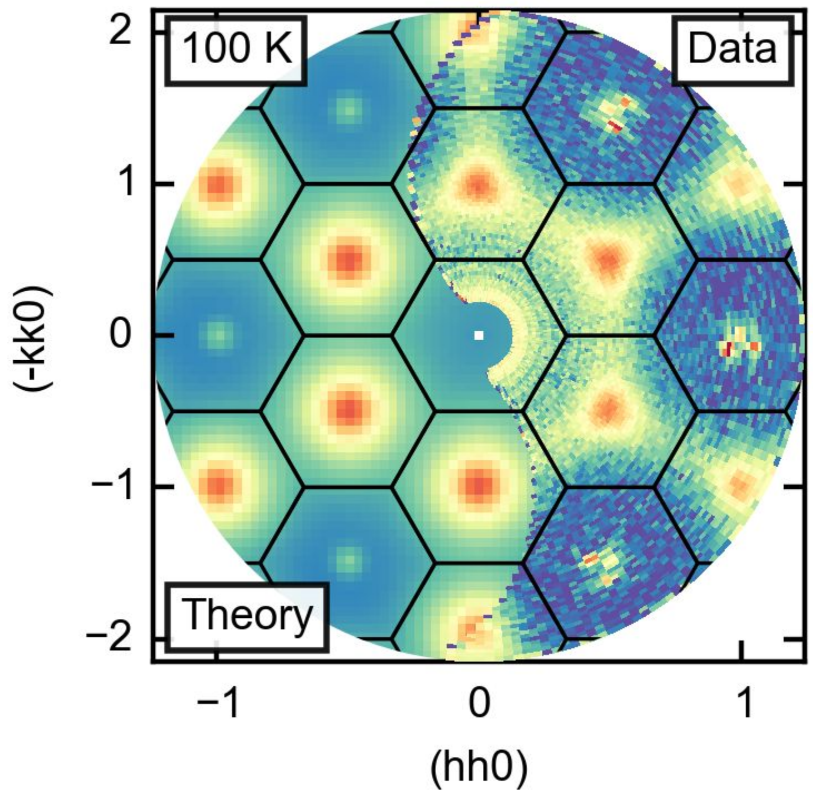
Link:
https://doi.org/10.1103/PhysRevLett.126.107203

So what are classical spin liquids really?

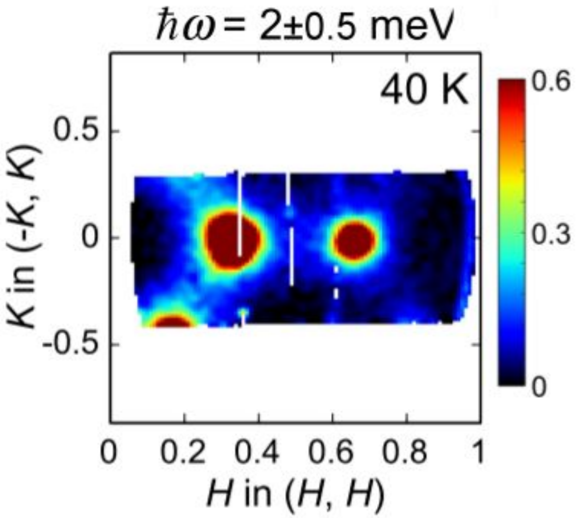
Classical spin liquids and critical scattering

Model: Critical scattering in vastly extended critical region due to frustration

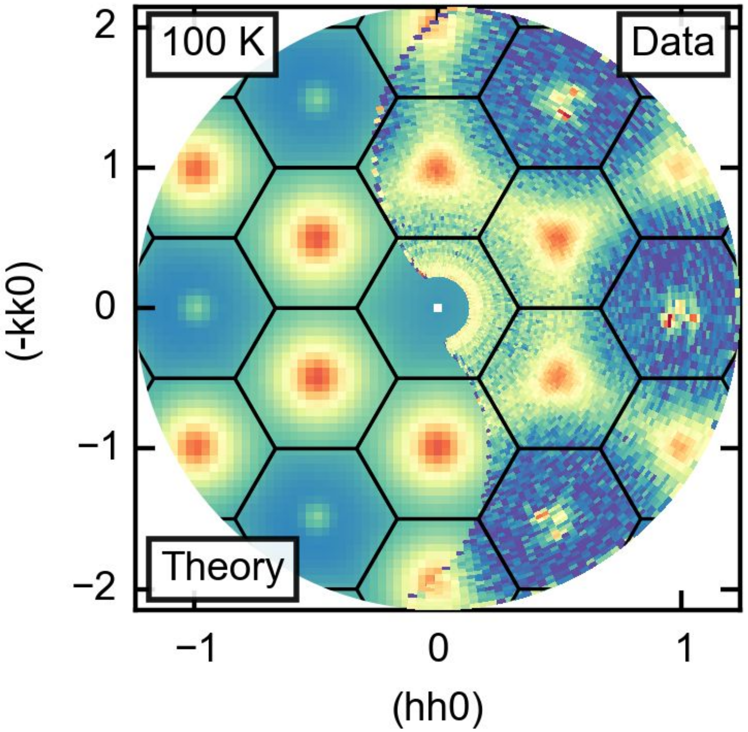
$YMnO_3$
S = 2
Triangular lattice



$CuCrO_2$:
S = 3/2
Triangular lattice

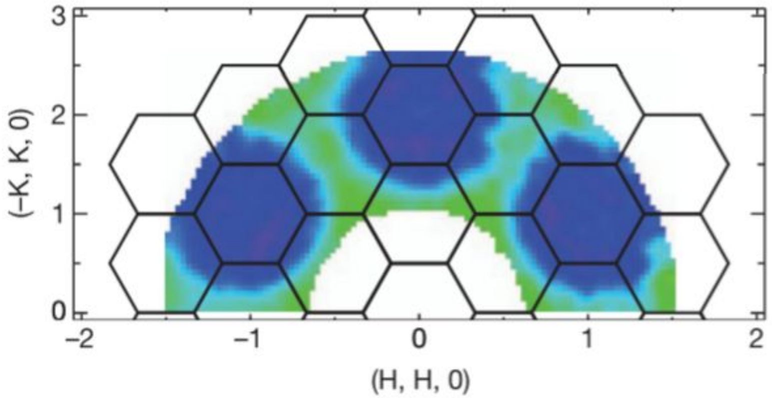


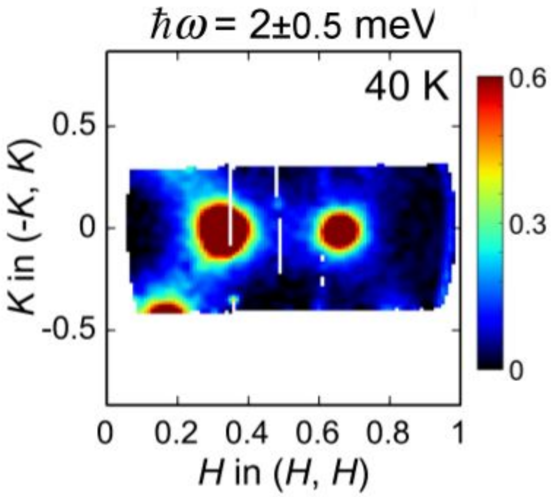
Telling classical and quantum spin liquids apart



$YMnO_3$
S = 2
Triangular lattice

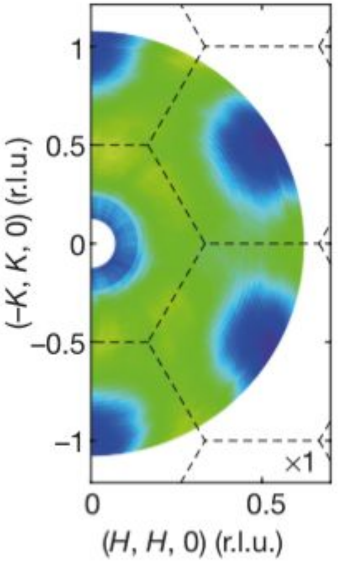
Herbertsmithite: S = ½, kagome lattice





$CuCrO_2$:
S = 3/2
Triangular lattice

$YbMgGaO_4$:
S = 1/2
Triangular lattice



Thanks!

PhD Supervisor
Kim Lefmann

Collaborator
Pascale P. Deen