Two spins $\frac{1}{2}$ and an antiferromagnetic spring

$S = \frac{1}{2}$ at each site

strong antiferromagnetic	coupling between	next-neighbours
no	coupling between	pairs

Dimer: Pair spin 0 $\qquad \frac{1}{\sqrt{2}} \left[\, |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \, \right]$

Local singlet-triplet excitations

$S = \frac{1}{2}$ at each site

strong antiferromagnetic	coupling between	next-neighbours
no	coupling between	pairs

Triplon: Pair spin 1

$$\begin{cases} \quad |\uparrow\uparrow\rangle \\ \frac{1}{\sqrt{2}} \left[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \right] \\ \quad |\downarrow\downarrow\rangle \end{cases}$$

Triplons – Signature Zeeman splitting

$S = \frac{1}{2}$ at each site

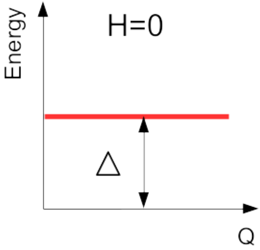
strong antiferromagnetic coupling between next-neighbours

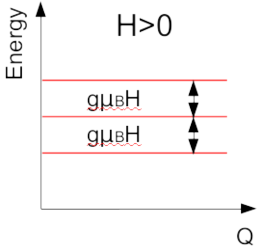
no coupling between pairs

$$|\uparrow\uparrow\rangle$$

$$\frac{1}{\sqrt{2}} \left[\, |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \, \right]$$

$$|\downarrow\downarrow\rangle$$





Triplons – Signature Zeeman splitting

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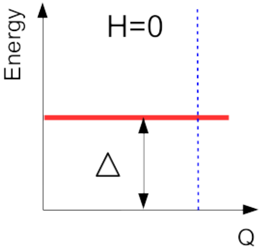
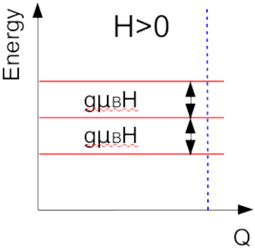
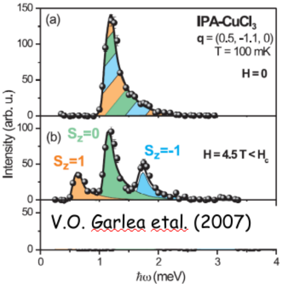




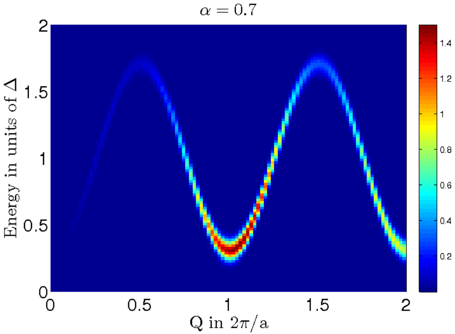


Interacting triplons – propagation – dispersion

$S = \frac{1}{2}$ at each site

strong antiferromagnetic coupling between next-neighbours

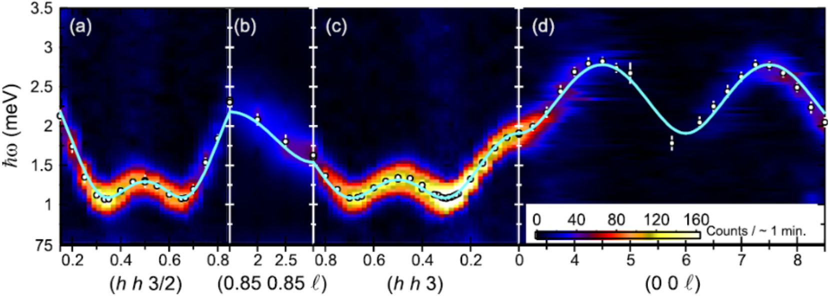
increasing coupling between pairs



Interacting triplons – propagation – dispersion

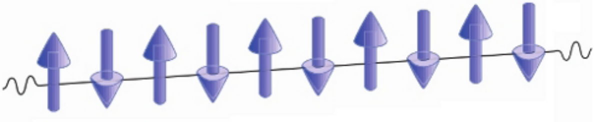
$S = \frac{1}{2}$ at each site

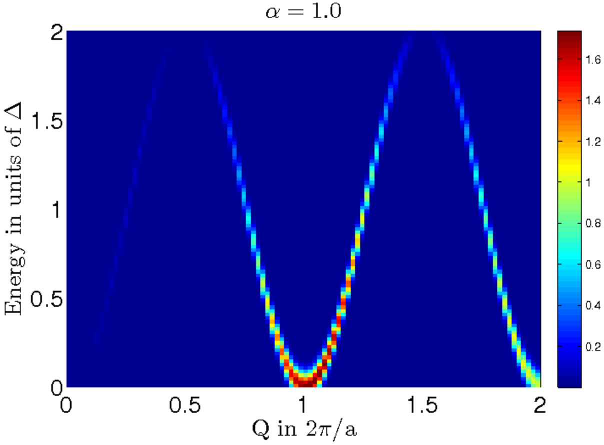
strong antiferromagnetic	coupling between	next-neighbours
increasing	coupling between	pairs



M.B. Stone *et al.* PRL **100** 237201 (2008)

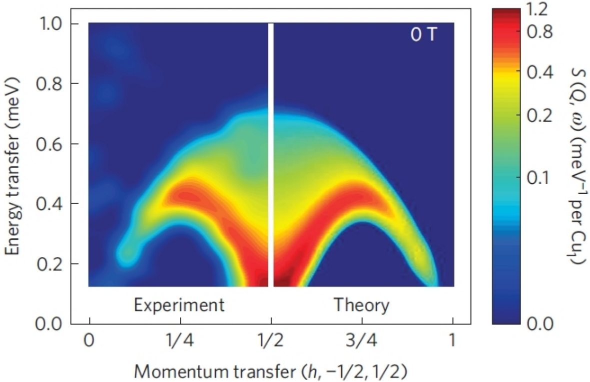
1D array – Limit of uniform coupling between $S = \frac{1}{2}$





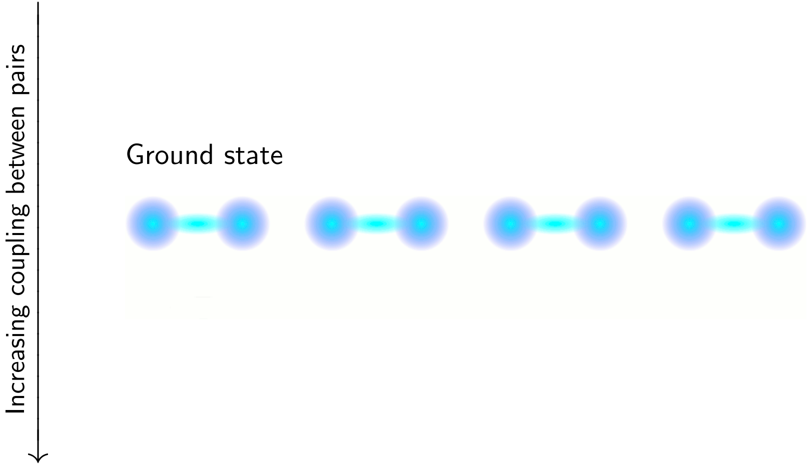
1D array – Limit of uniform coupling between $S = \frac{1}{2}$

$H = 0$

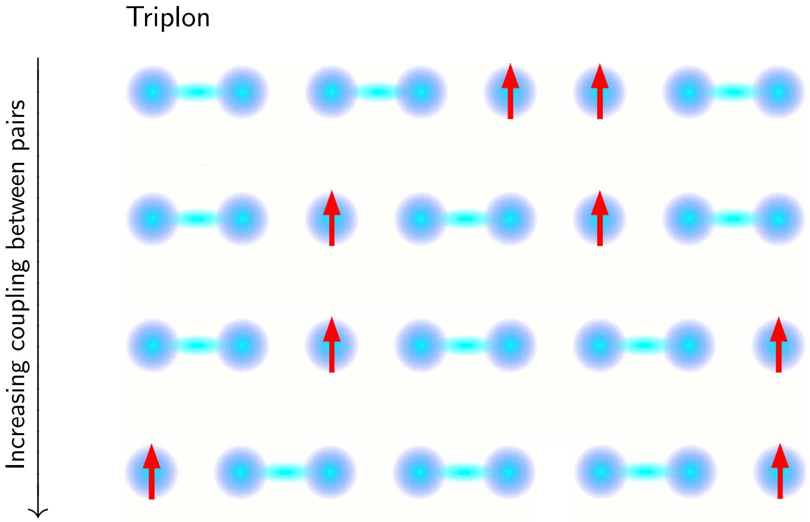


M. Mourigal, M.E. *et al.* Nat.Phys. **9** 435 (2013)

1D array – Limit of uniform coupling between $S = \frac{1}{2}$



1D array – Limit of uniform coupling between $S = \frac{1}{2}$

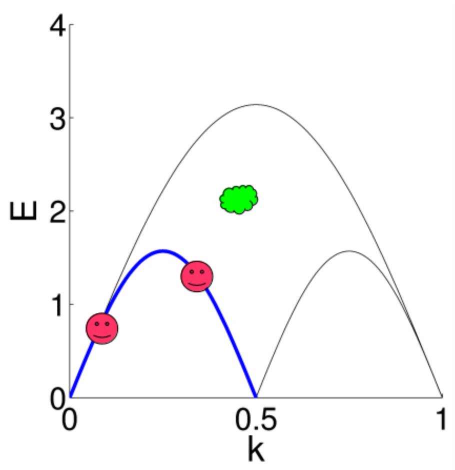


1D array – Limit of uniform coupling between $S = \frac{1}{2}$

freely propagating spin $\frac{1}{2}$ particles: spinons

Two-particle excitation: Signature continuous scattering

Neutron excites **pairs** of freely propagating spin $\frac{1}{2}$ particles



1-particle   dispersion

$E(k)$

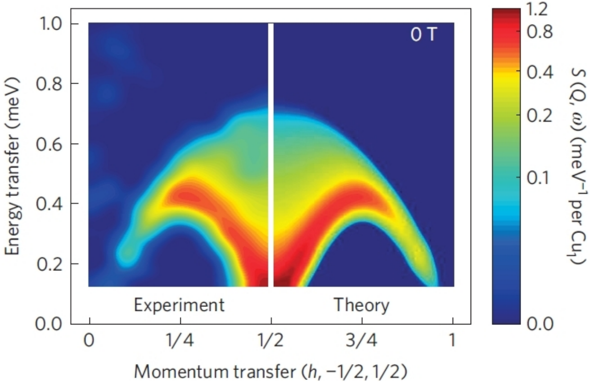
neutron excites pair

= +

$$Q = k_1 + k_2$$
$$E = E(k_1) + E(k_2)$$

Spinon continuum in $CuSO_4.5D_2O$

$H = 0$



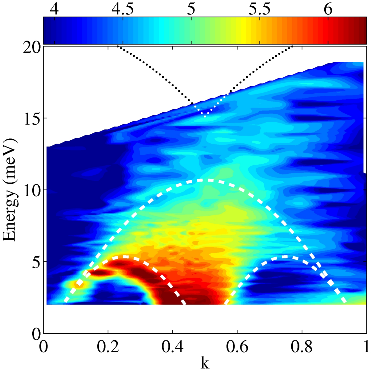
M. Mourigal, M.E. *et al.* Nat.Phys. **9** 435 (2013)

New many-particle states and excitations

2 zig-zag coupled 1D spin $\frac{1}{2}$ arrays

Continuum:
pairs of free particles

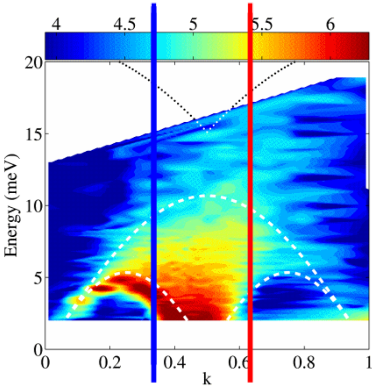
discrete branch:
bound particle-pairs

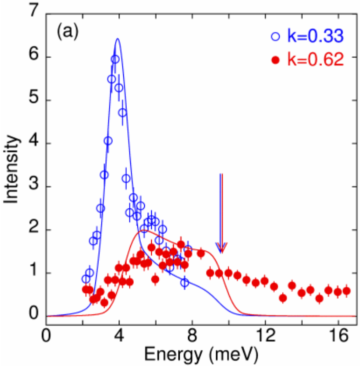


M.E. *et al.* PRL **104** 237207 (2010)

New many-particle states and excitations

2 zig-zag coupled 1D spin $\frac{1}{2}$ arrays



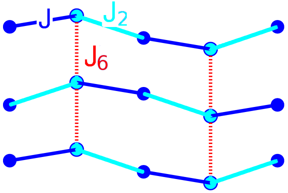


M.E. *et al.* PRL **104** 237207 (2010)

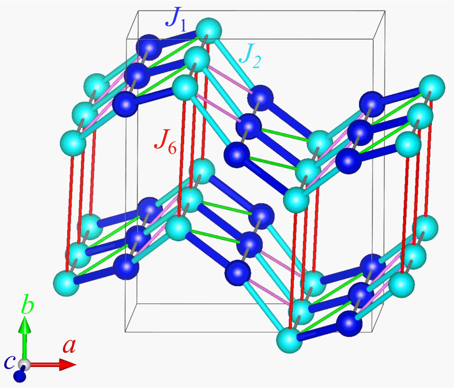
Correlated Excitations – How do we measure them ?

- powder on TOF – valuable info
- single crystal TOF – large overview of Q-E-space
- Questions at specific Q/H,p,T: TAS
- Small single crystal: TAS
- inelastic polarized: TAS (today !)

Powder on TOF: 2D strongly coupled dimers Malachite



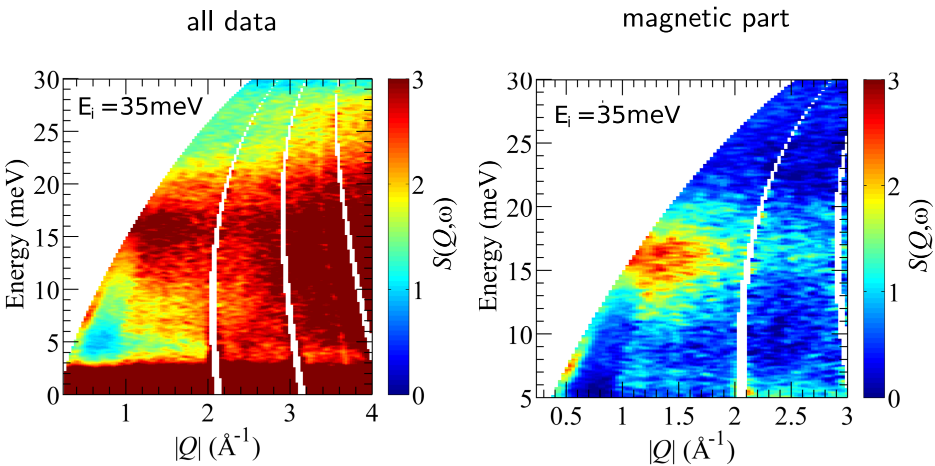
Malachite



E. Canevet *et al.* PRB **91** 060402(R) (2015).

Malachite Inelastic neutron scattering on deuterated powder

TOF: MARI/ISIS



If possible: subtract phonons via non-magnetic "blank"

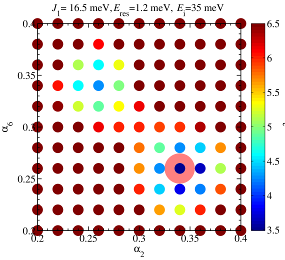
E. Canevet *et al.* PRB **91** 060402(R) (2015).

Malachite magnetic DOS from inelastic neutron scattering

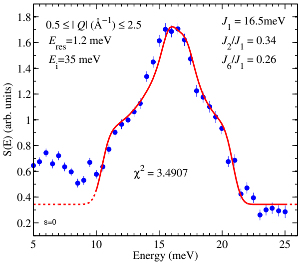
$$S(E) \equiv \int_Q dQ\ S(Q,E)$$

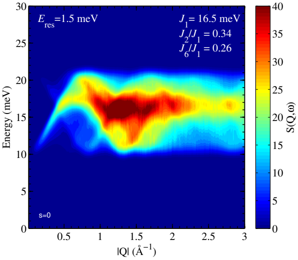
χ^2 $S(E)$ $S(Q,E)$

$\frac{J_6}{J}$



$\frac{J_2}{J}$



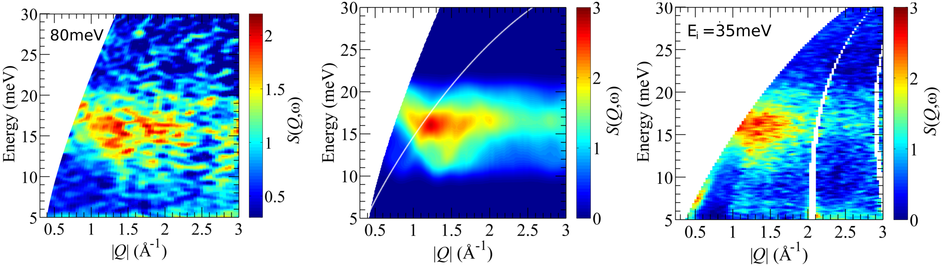


E. Canevet *et al.* PRB **91** 060402(R) (2015).

Malachite Inelastic neutron scattering on D-powder

TOF: MARI

magnetic $E_i = 35$meV model magnetic $E_i = 80$meV



best fit: $J_1 = 16.5$meV, $J_2 = 5.6$meV, $J_6 = 4.3$meV

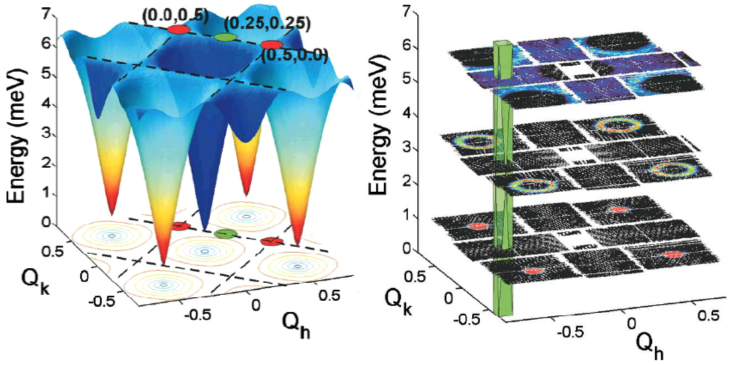
$$J_2/J_1 = 0.34,\ J_6/J_1 = 0.26$$

E. Canevet *et al.* PRB **91** 060402(R) (2015).

Single crystal TOF: Large overview over (**Q**, E)-space

3D: large single crystal + rotation

2D/1D: gain by Q-integration



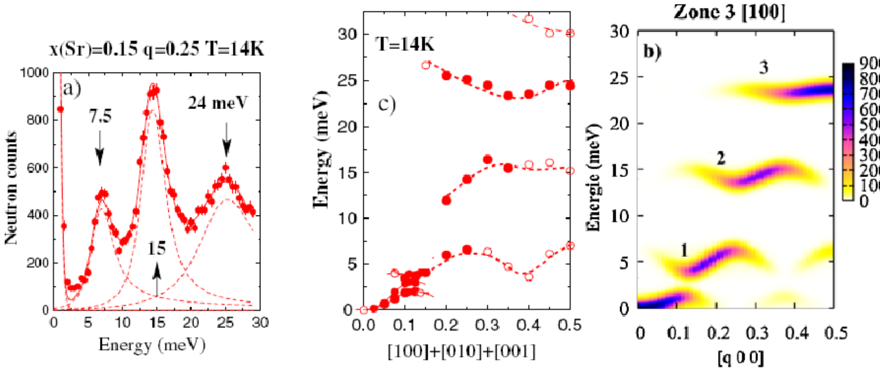
Rb_2MnF_4 R. Hubermann *et al.*PRB **72** 014413 (2005)

Single crystal TAS: details/specific regions of **Q**-space

Quantized spin waves

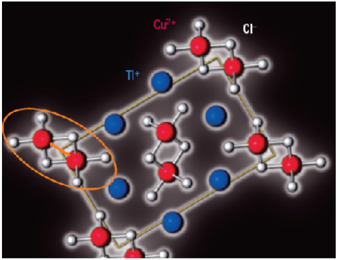
Metallic magnetoresistive $La_{0.85}Sr_{0.15}MnO_3$

S. Petit et al. (2009
PRL 102, 207201



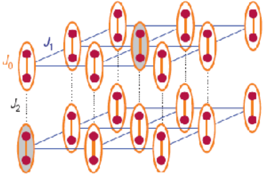
Single crystal TAS: specific **Q** as function of **H**

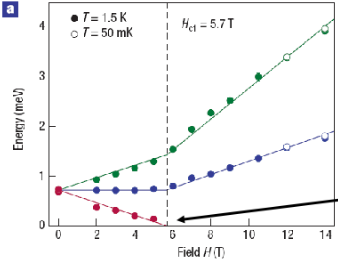
Bose-Einstein Condensation of triplons



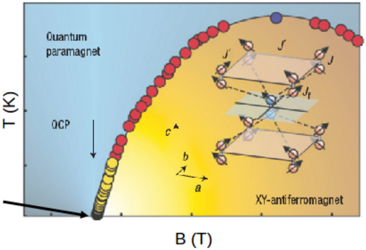
$TlCuCl_3$

T. Giamarchi et al. (2008)
Nature phys. 4, 198





BEC



Single crystal TAS: specific **Q** as function of T

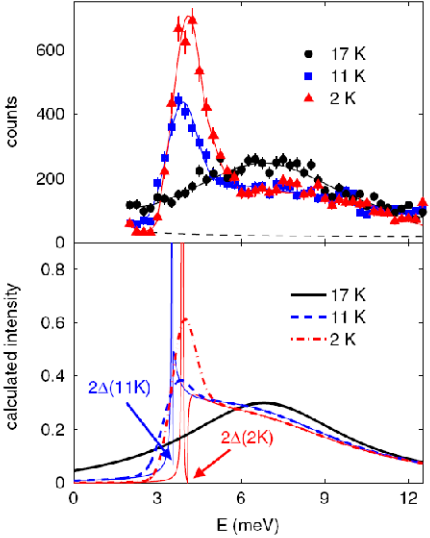
Superconductivity $\Rightarrow$ phonon lineshape

YNi_2B_2C

Q = (0.5 0 8)

F. Weber et al (2008)
PRL 101, 237002

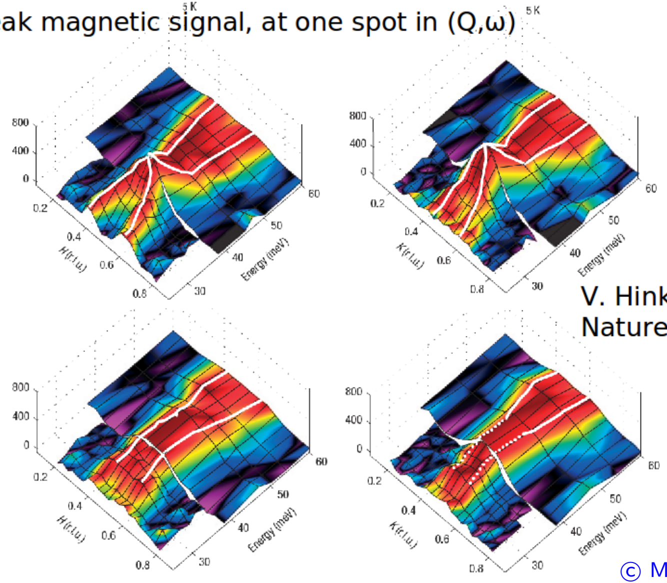
1T, PUMA



Single crystal TAS: weak signals

superconducting resonance peak YBaCuO

Weak magnetic signal, at one spot in (Q,ω)



V. Hinkov et al. (2007
Nature phys 3, 780

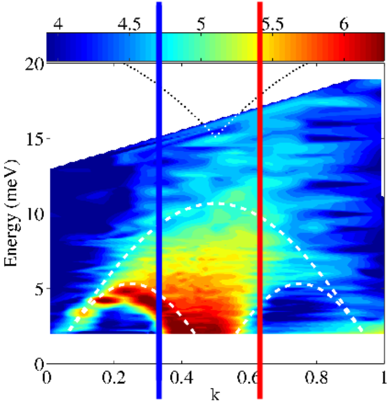
2T, IN8

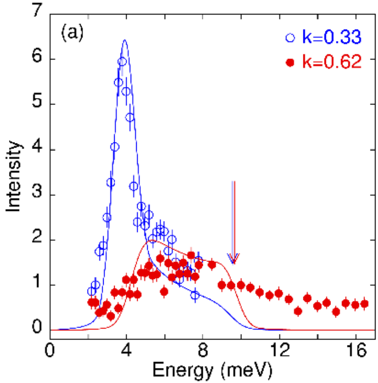
Single crystal TAS: small single crystals

$50\mathrm{mm}^3$

Quantum spiral magnet $LiCuVO_4$

M.E. etal (2010) PRL 104, 237207





Excitations

Localized

- powder on TOF – works for many purposes
- single crystal on TOF – Q-dependence of "eigenvector"
- single crystal polarized: TAS – direction of the "eigenvector"

Correlated/collective

- powder on TOF – valuable info
- single crystal TOF – large overview of Q-E-space
- Questions at specific Q/H,p,T: TAS
- Small single crystal: TAS
- inelastic polarized: TAS – separation from phonons ...