Frustrated Magnets (2)
Materials Survey

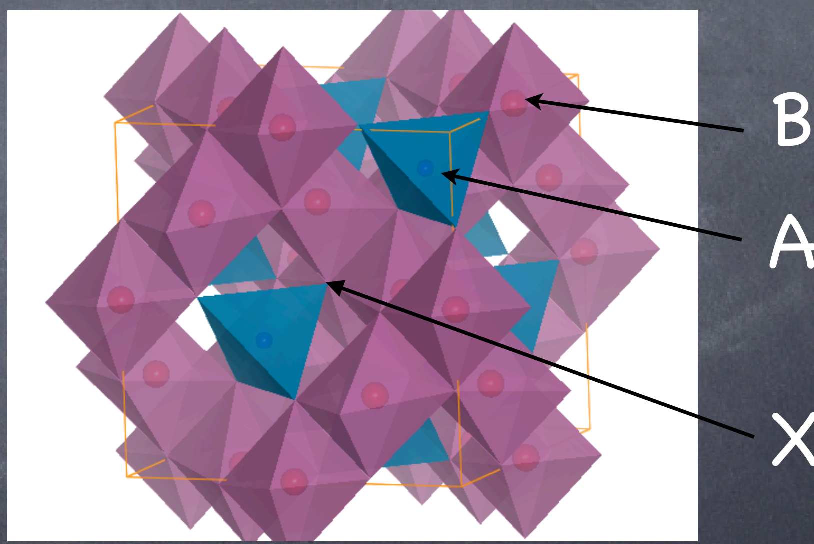
Leon Balents

Boulder summer school, 2008

AB_2X_4 spinels

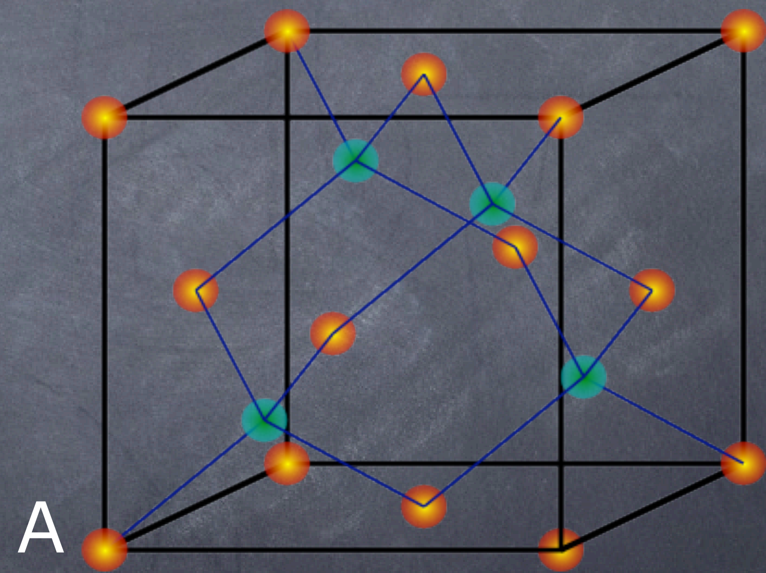
- One of the most common mineral structures
- Common valence:
  - A^{2+}, B^{3+}, X^{2-}
  - X=O,S,Se

cubic $Fd\bar{3}m$

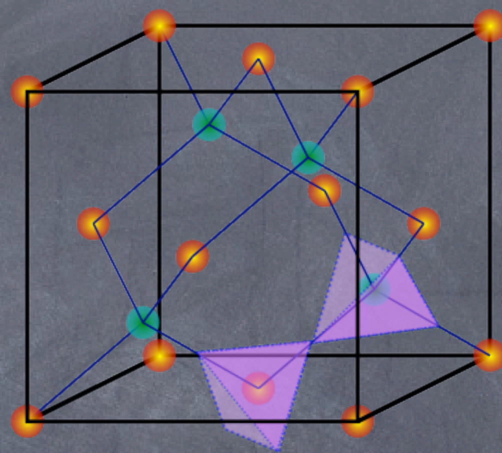


Deconstructing the spinel

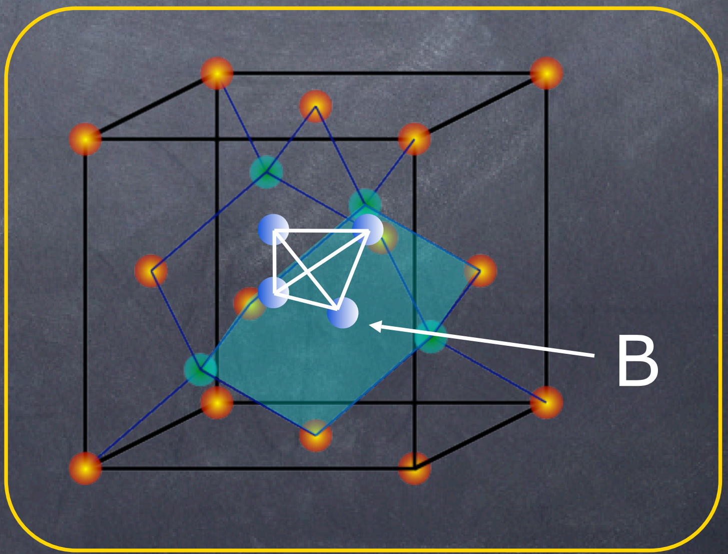
- A atoms: diamond lattice
  - Bipartite: not *geometrically* frustrated



Deconstructing the spinel

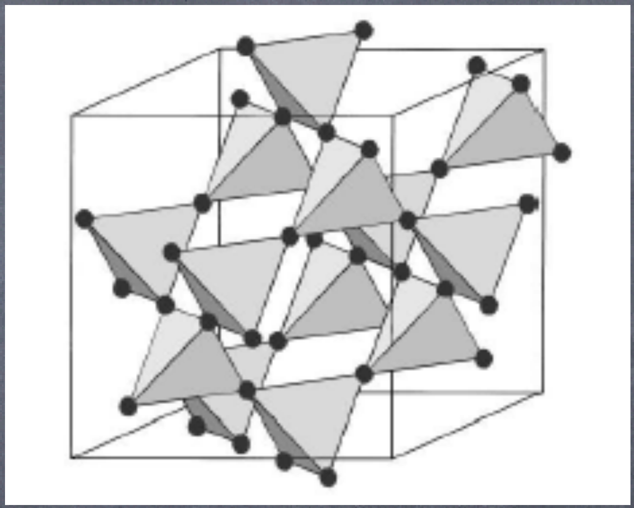


- B atoms: pyrochlore
  - decorate the plaquettes of the diamond lattice



ACr_2O_4 spinels

- pyrochlore lattice
- S=3/2 Isotropic moment
- X=O spinels: B-B distance close enough for direct overlap
  - dominant AF nearest-neighbor exchange

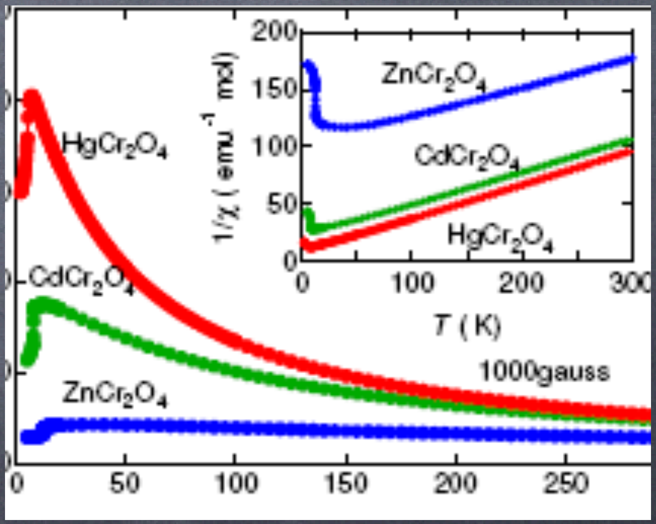


H=0 Susceptibility

- Frustration:

	Zn	Cd	Hg
Θ_{CW} (K)	-390	-70	-32
T_N (K)	12	7.8	5.8
f	33	9	6

χ



T

Degeneracy

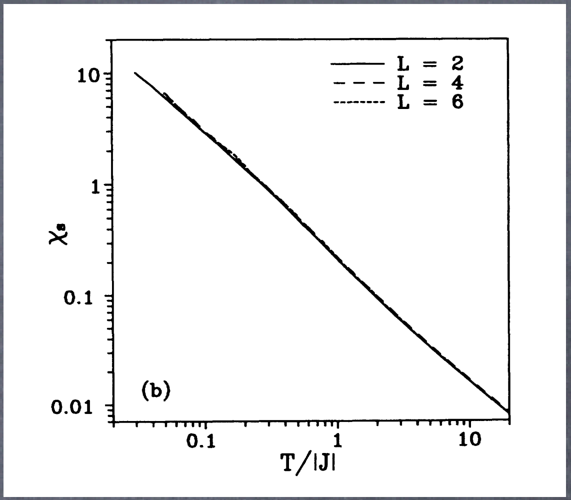
- Heisenberg model

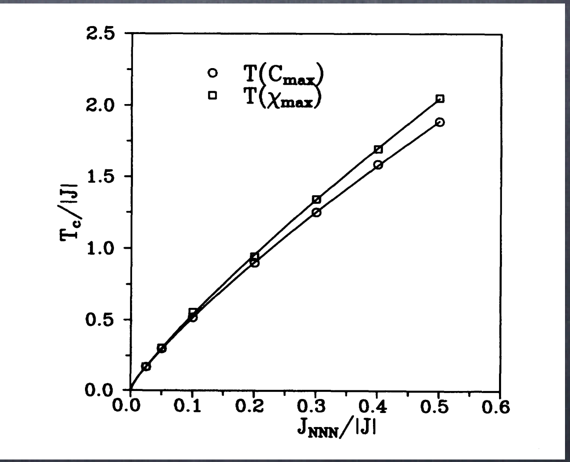
$$H = \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j = \frac{1}{2} \sum_t \left(\sum_{i \in t} \vec{S}_i \right)^2 + \text{const.}$$

- Ground state constraint: total spin 0 per tetrahedron
  - Quantum mechanically: not possible

Classical spin liquid

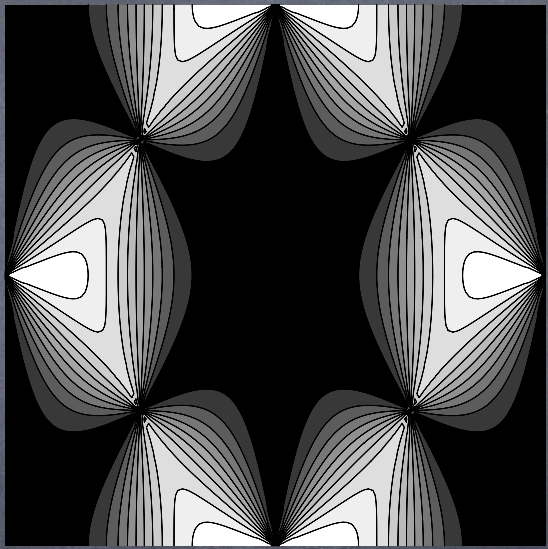
- No LRO (Reimers)





Classical spin liquid

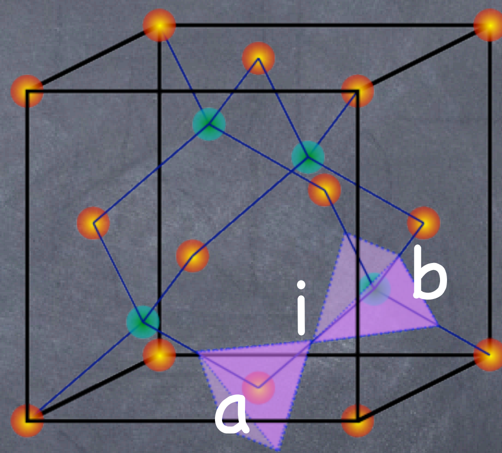
- No LRO (Reimers)
- Dipolar correlations



$$S_i^\mu = b_{ab}^\mu$$

Classical spin liquid

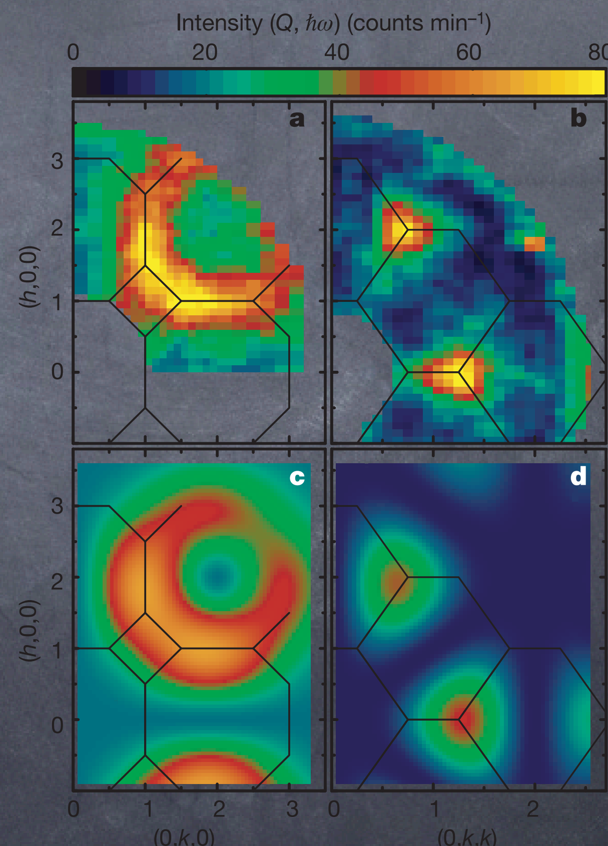
- No LRO (Reimers)
- Dipolar correlations



$$S_i^\mu = b_{ab}^\mu$$

Classical spin liquid

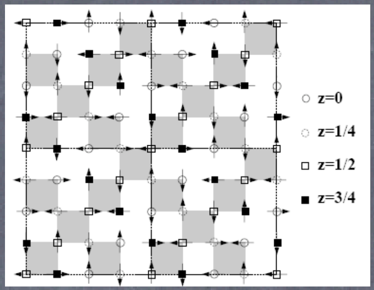
- Unusual "ring" correlations seen in $CdCr_2O_4$ related
- $Y_2Ru_2O_7$: J. van Duijn et al, 2007



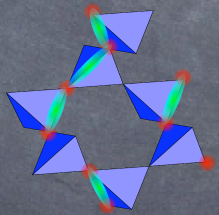
Broholm et al

Ordering

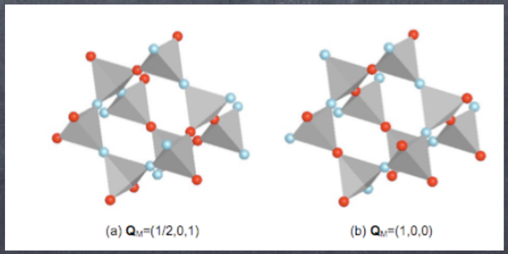
- Many perturbations important for ordering:
  - Spin-lattice coupling
  - Further exchange
  - Spin-orbit effects
  - Quantum corrections



$ZnCr_2O_4$



$CdCr_2O_4$

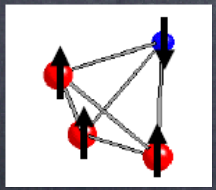


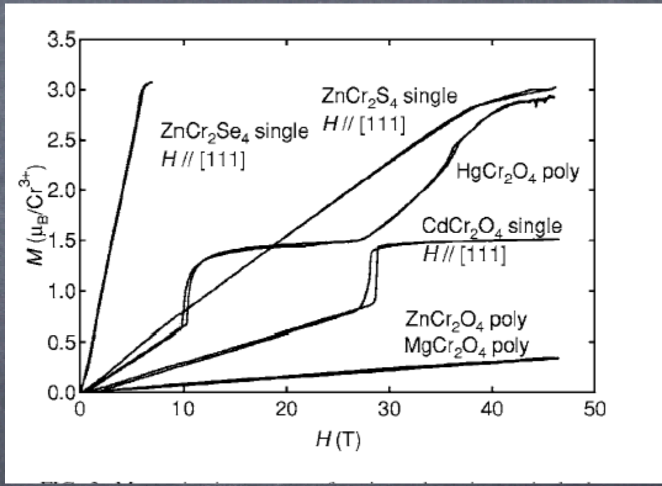
$HgCr_2O_4$

S.H. Lee + many others

Magnetization Plateaus

- Classically: $M = M_s H/H_s$
- Plateau indicates 3:1 structure

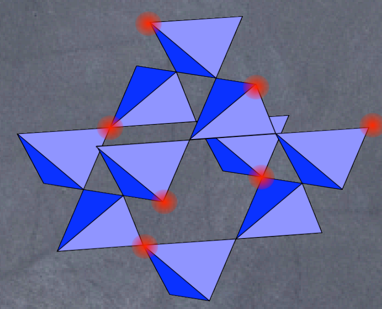




H. Ueda at al, 2005/6

Magnetization Plateaus

- Plateau mechanism:
  - spin-lattice coupling favors collinearity
- Order on plateau may be selected by
  - spin-lattice
  - quantum effects

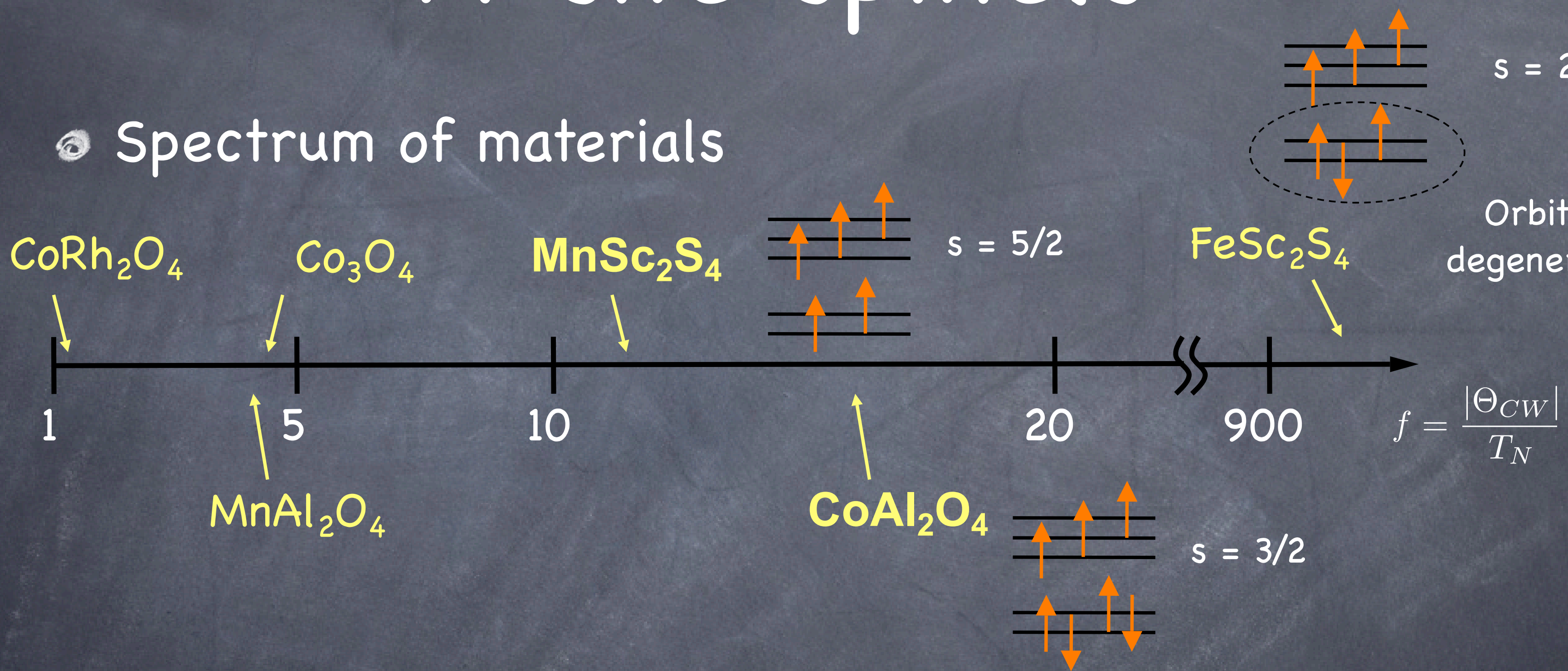


"R" state observed in neutrons

Matsuda et al

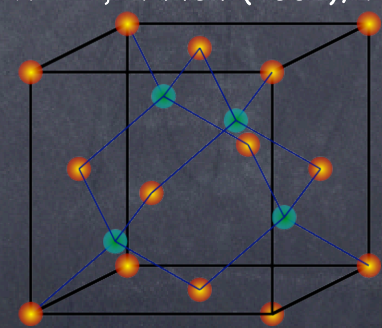
A-site spinels

- Spectrum of materials



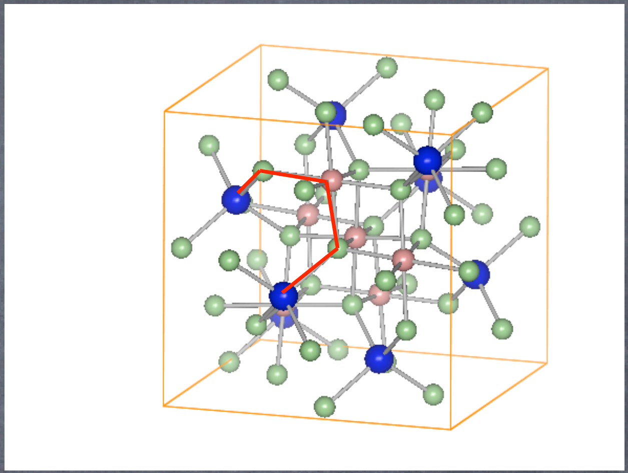
V. Fritsch et al. PRL **92**, 116401 (2004); N. Tristan et al. PRB **72**, 174404 (2005); T. Suzuki *et al.* (2006)

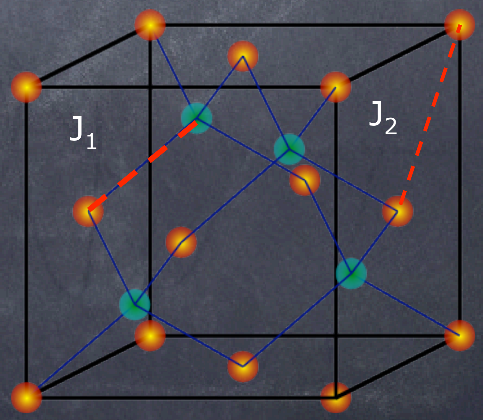
- Naively unfrustrated



Why frustration?

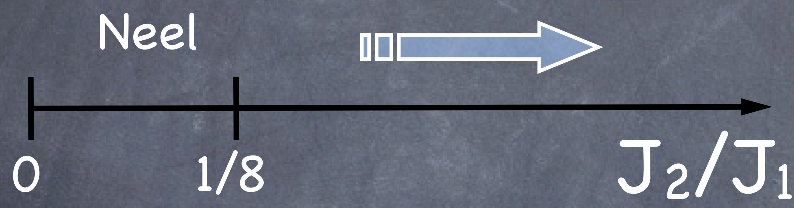
- Roth, 1964: 2nd and 3rd neighbor exchange not necessarily small
  - Exchange paths: A-X-B-X-B comparable
- Minimal model
  - J_1-J_2 exchange

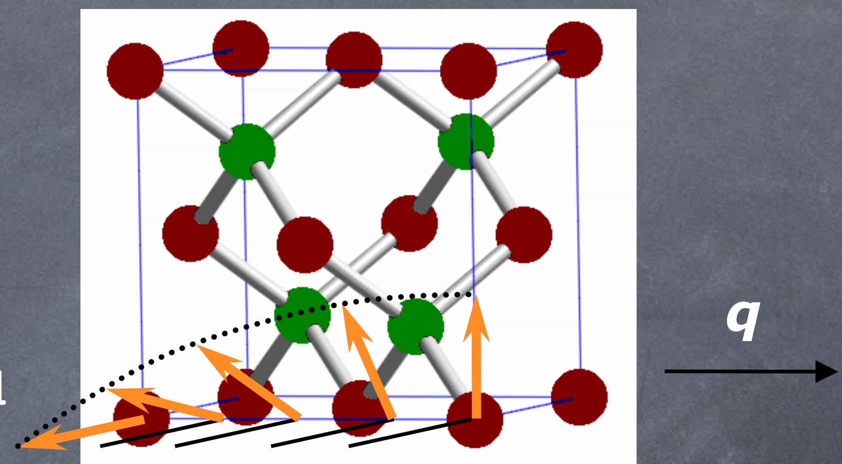




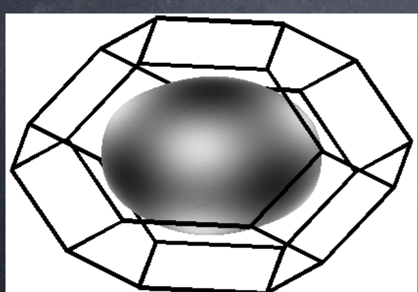
Ground state evolution

- Coplanar spirals

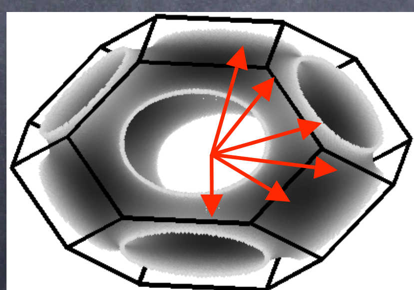




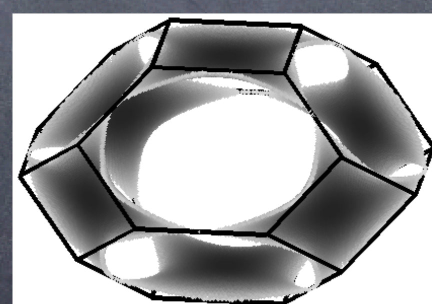
- Spiral surfaces:



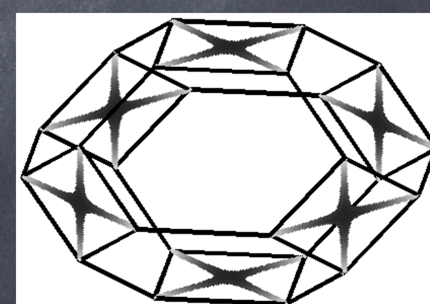
$J_2/J_1 = 0.2$



$J_2/J_1 = 0.4$



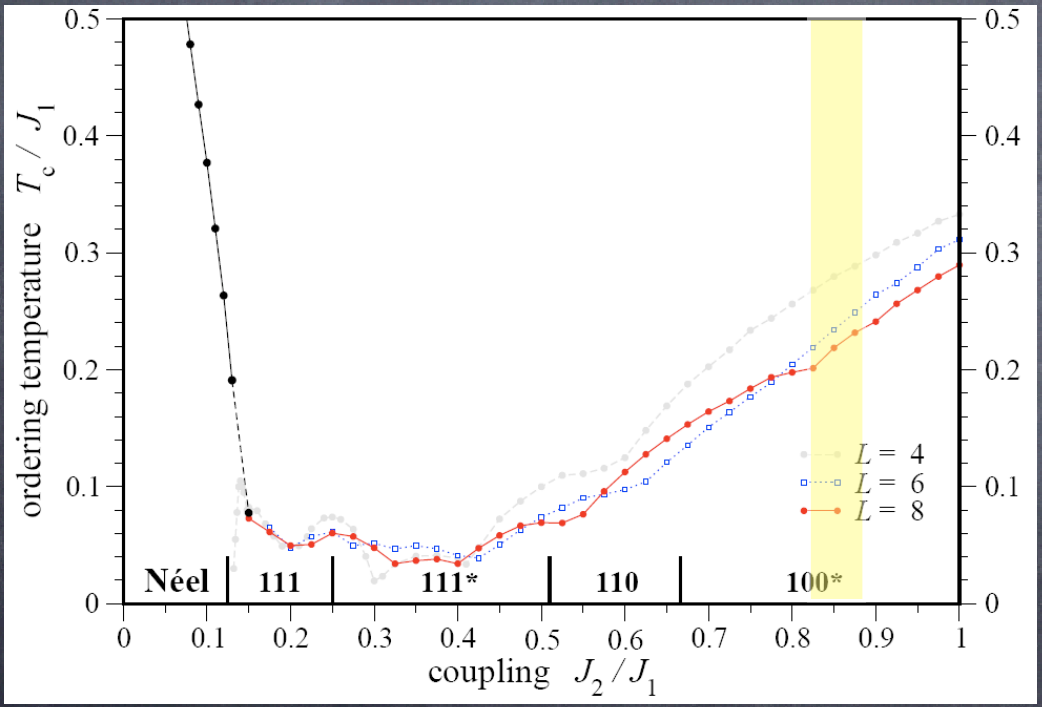
$J_2/J_1 = 0.85$



$J_2/J_1 = 20$

Monte Carlo

$MnSc_2S_4$

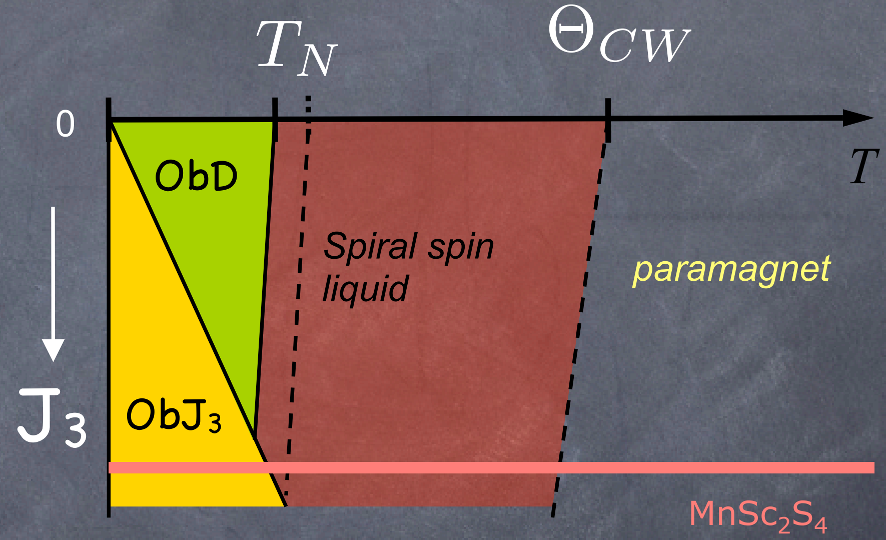


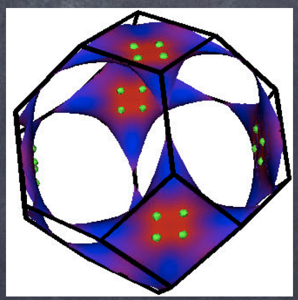
f = 11 at

$J_2/J_1 = 0.85$

Phase Diagram

- Entropy and J_3 compete to determine ordered state
- Spiral spin liquid regime has intensity over entire spiral surface



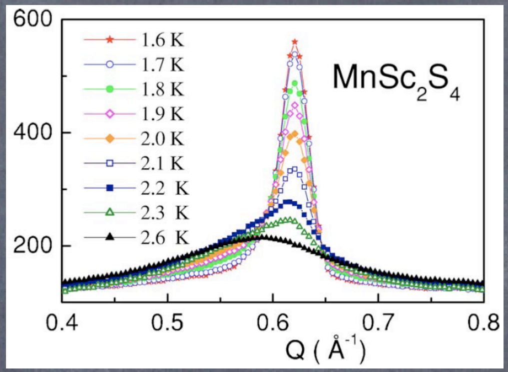


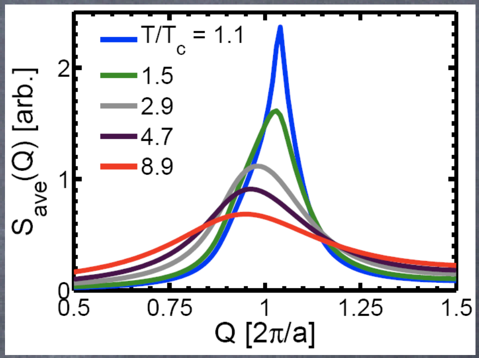
Comparison to Expt.

Expt.

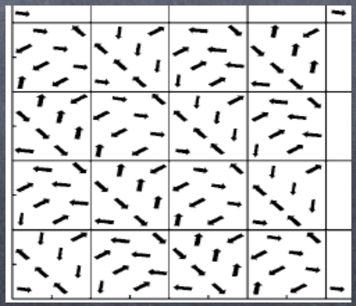
Theory

- Diffuse scattering





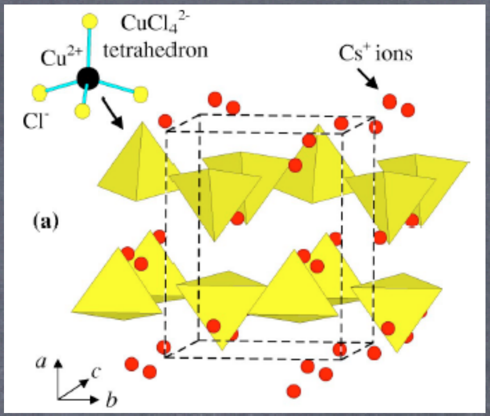
- Ordered state
  - (qq0) spiral
- Specific heat?



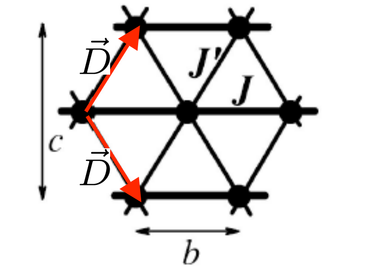
agrees with theory for FM J_1

Cs_2CuCl_4

- Spatially anisotropic triangular lattice
  - Cu^{2+} spin-1/2 spins



$$H = \frac{1}{2}\sum_{ij}\left[J_{ij}\vec{S}_i \cdot \vec{S}_j - \vec{D}_{ij} \cdot \vec{S}_i \times \vec{S}_j\right]$$



$$\vec{D} = D\hat{a}$$

- couplings:

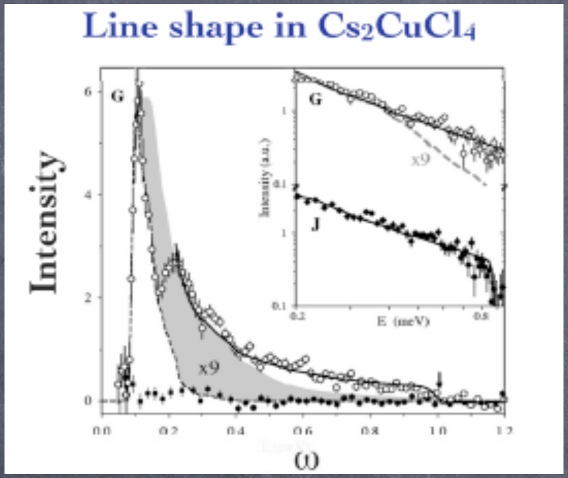
J=0.37meV

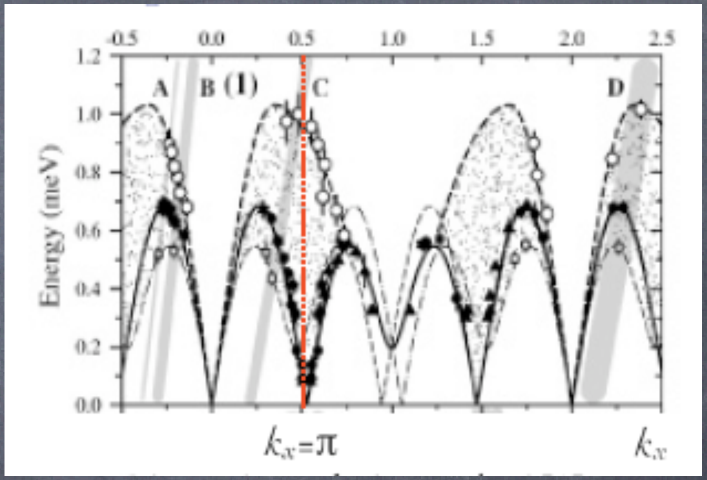
J'=0.3J

D=0.05J

Neutron scattering

- Coldea et al, 2001/03: a 2d spin liquid?



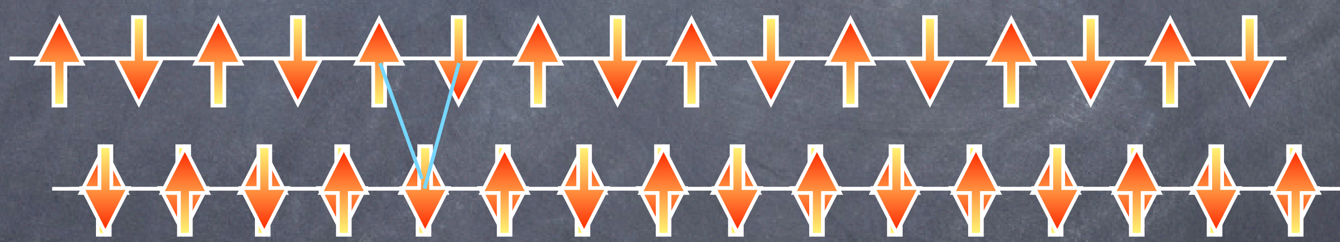


Very broad spectrum similar to 1d (in some directions of k space). Roughly fits power law.

Fit of "peak" dispersion to spin wave theory requires adjustment of J,J′ by 40% – in opposite directions!

Dimensional reduction?

- Frustration of interchain coupling makes it less "relevant"
  - First order energy correction vanishes

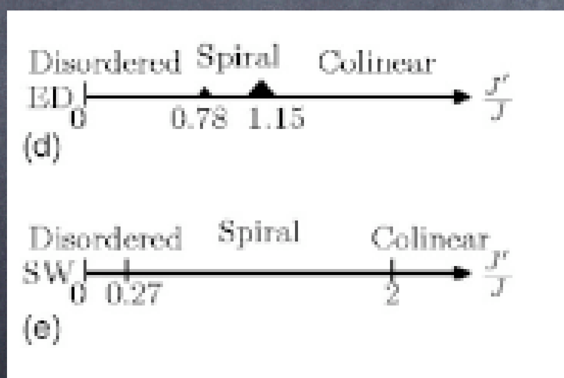


  - Leading effects are in fact $O[(J')^4/J^3]$!

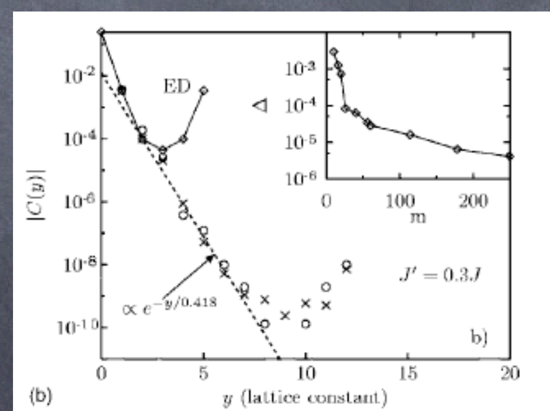
Dimensional reduction?

- Frustration of interchain coupling makes it less "relevant"
  - First order energy correction vanishes.
  - Numerics: J'/J < 0.7 is "weak"

Weng et al, 2006



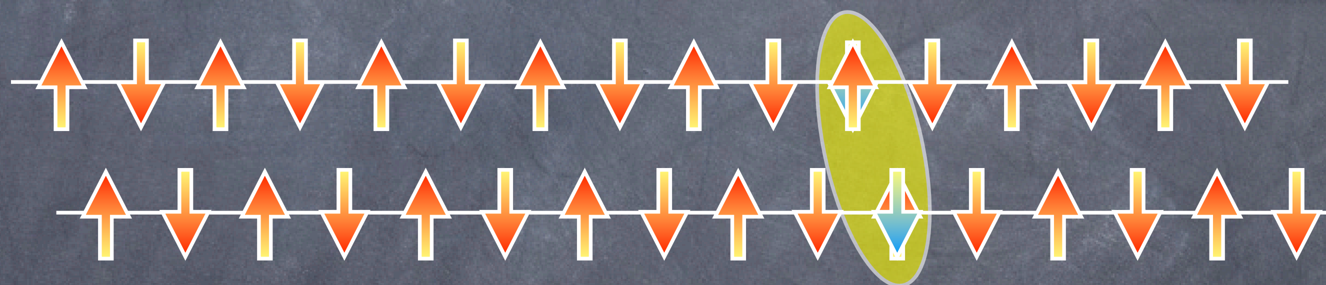
Very different from spin wave theory



Very weak inter-chain correlations

Excitations

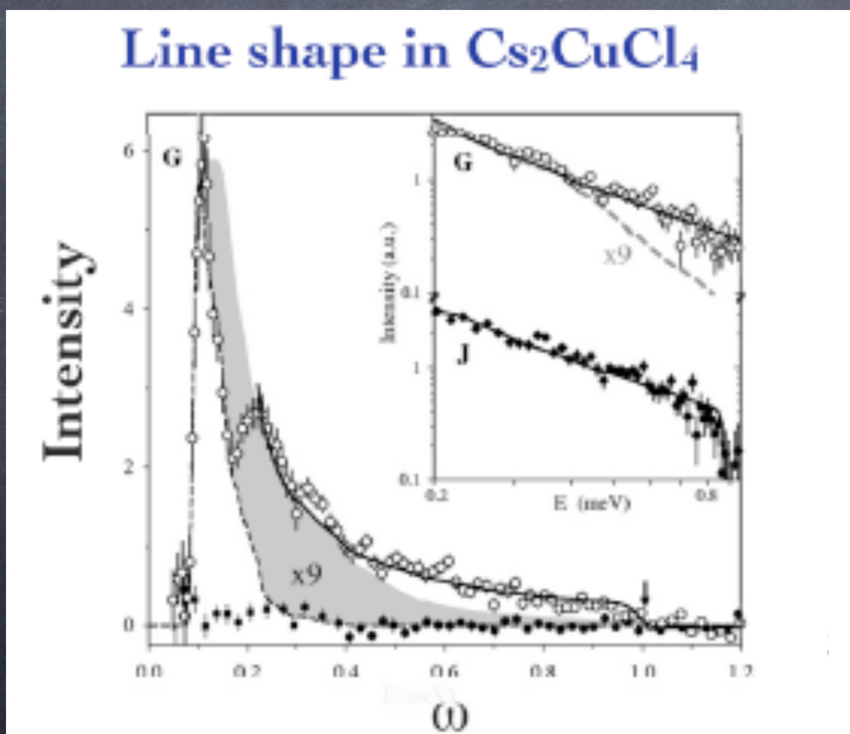
- Build 2d excitations from 1d spinons
  - Exchange: $\frac{J'}{2}\left(S_i^+ S_j^- + S_i^- S_j^+\right)$

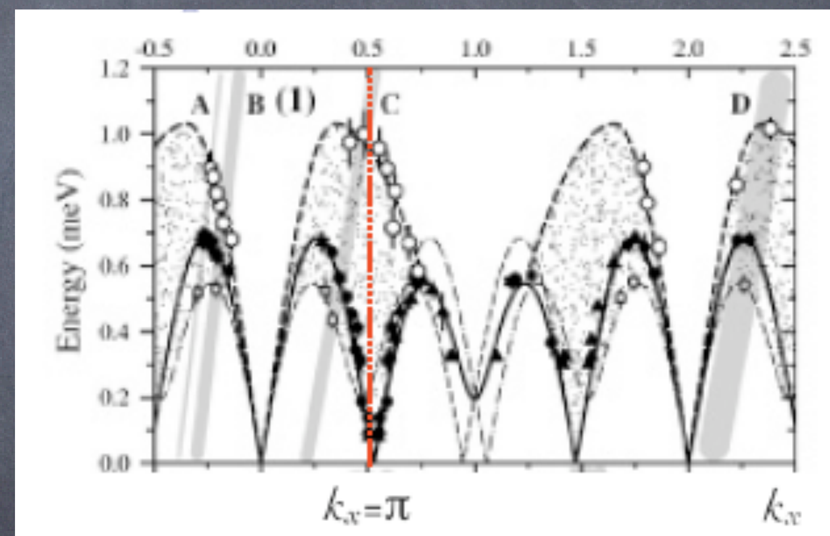


- Expect spinon binding to lower inter-chain kinetic energy
  - Use 2-spinon Schroedinger equation

Broad lineshape: "free spinons"

- "Power law" fits well to free spinon result
  - Fit determines normalization

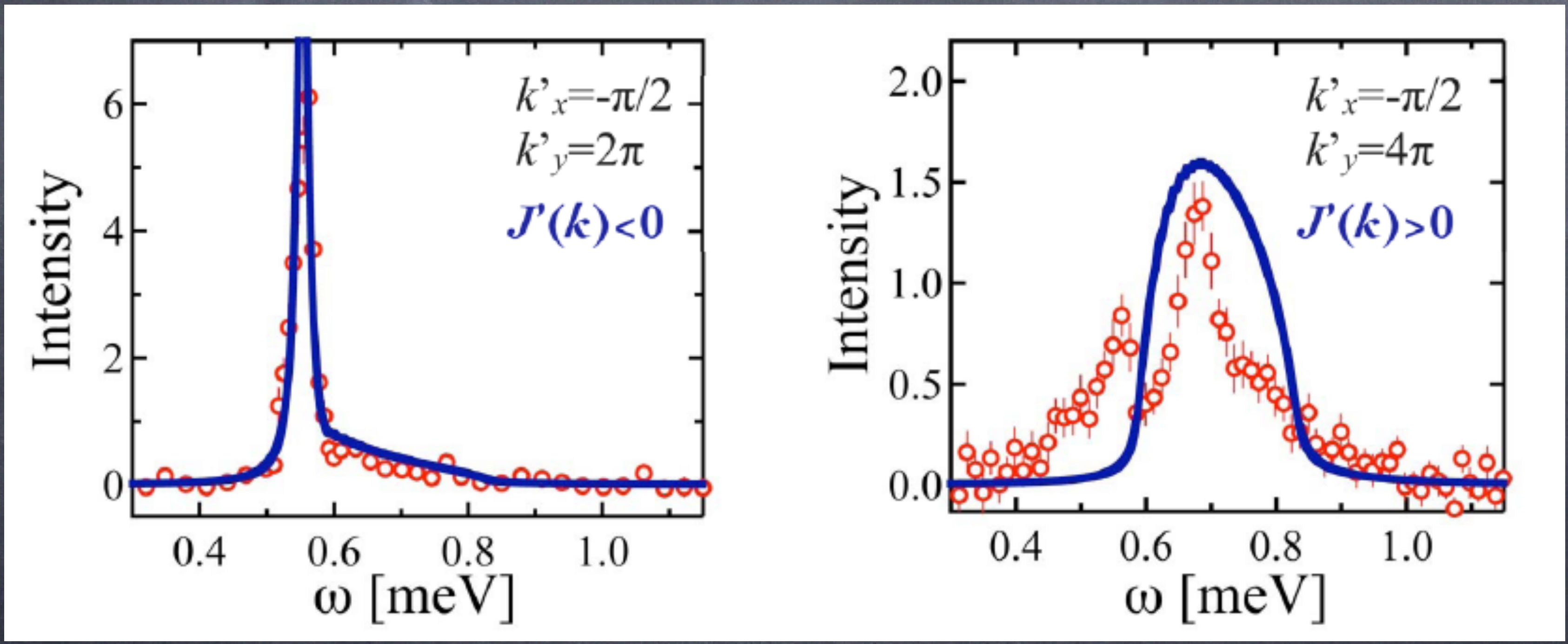




J'(k)=0 here

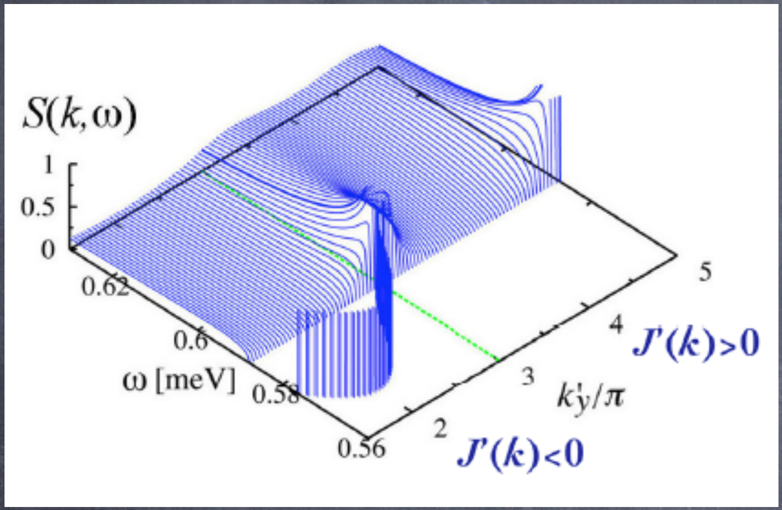
Bound state

- Compare spectra at J'(k)<0 and J'(k)>0:

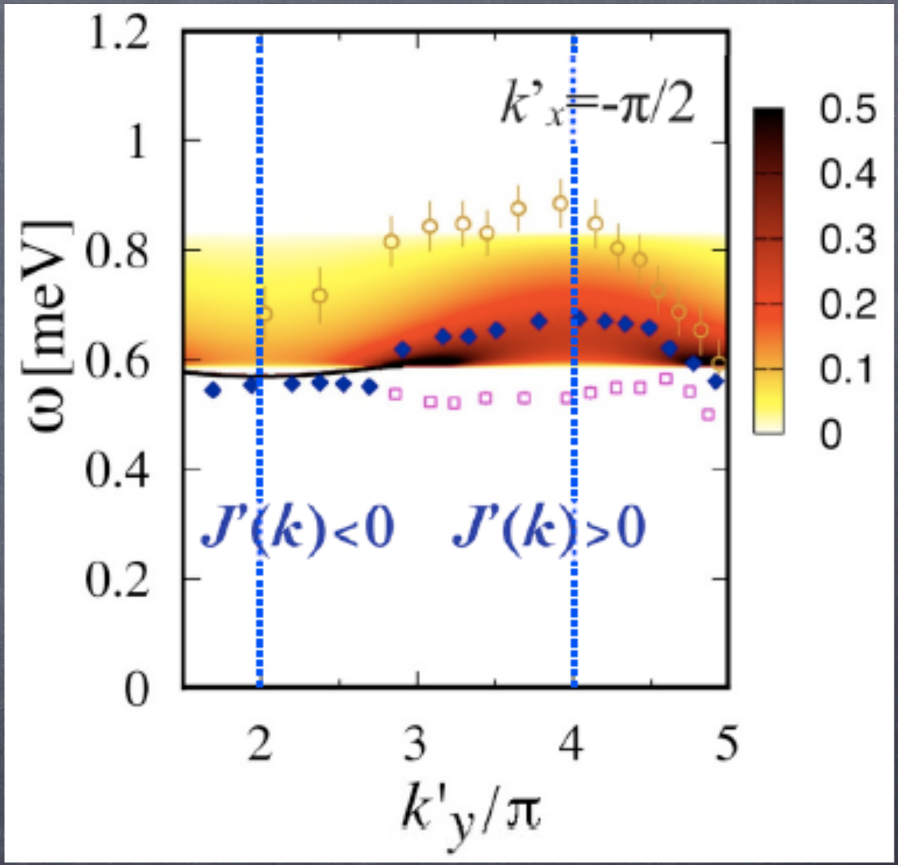


- Curves: 2-spinon theory w/ experimental resolution
- Curves: RPA w/ experimental resolution

Transverse dispersion

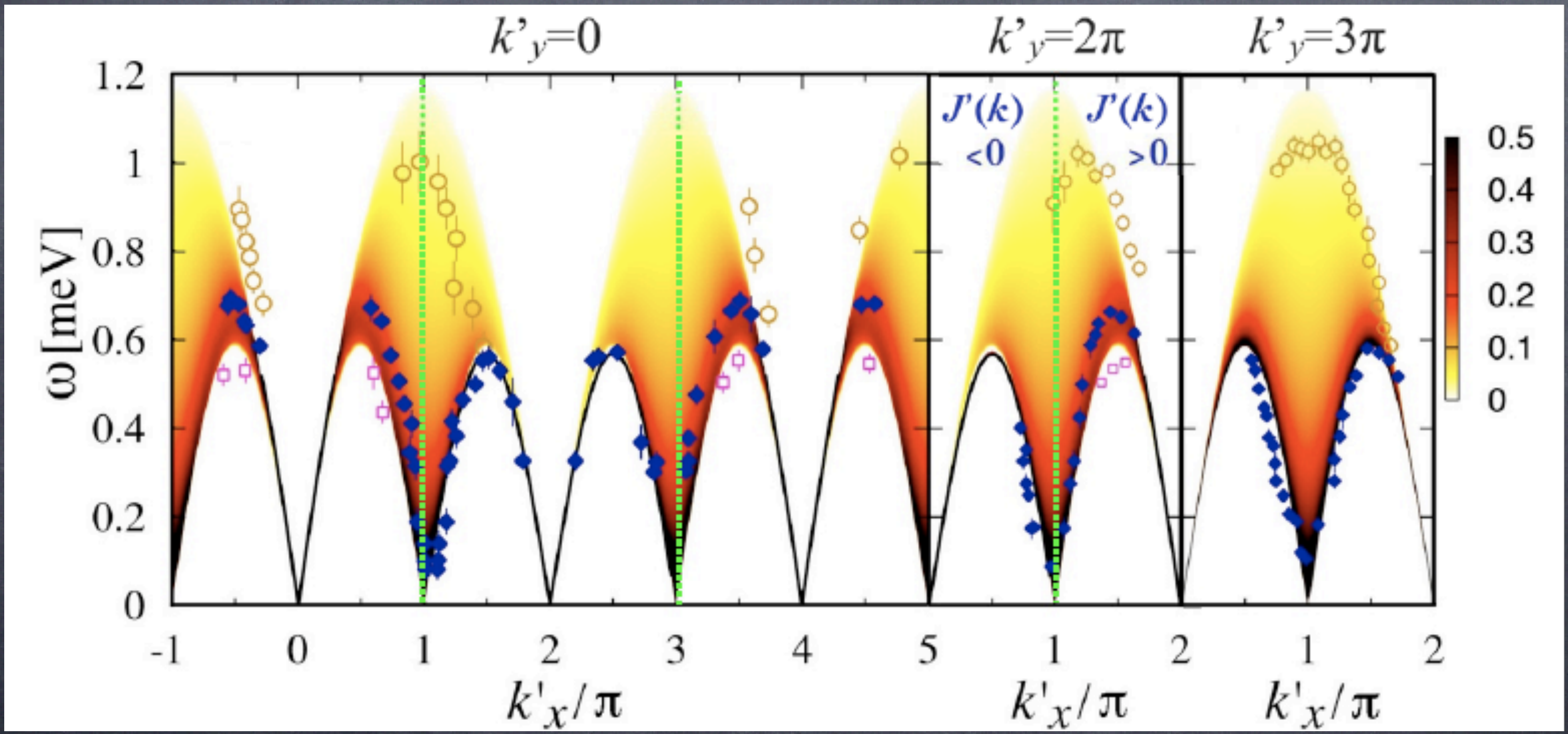


Bound state and resonance



Solid symbols: experiment
Note peak (blue diamonds) coincides with bottom edge only for J'(k)<0

Spectral asymmetry



- Vertical lines: J’(k)=0.