Magnetization plateaux of frustrated antiferromagnets



Oleg Starykh, University of Utah

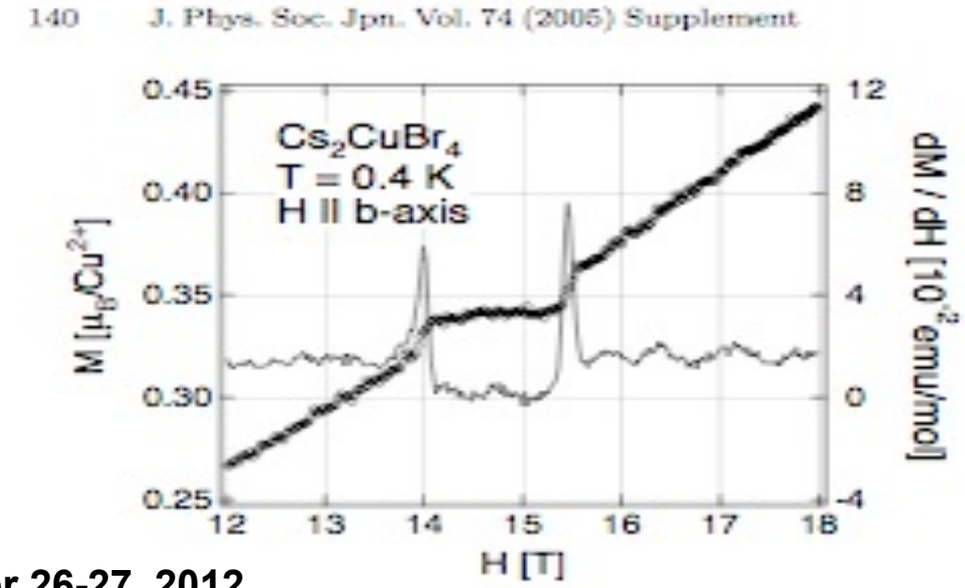


Fig. 8. The magnetization curve and dM/dH versus H for $H \parallel b$ measured at $T = 0.4$ K in magnetic fields up to 20 T.

APS2012 - Four Corners Meeting, October 26-27, 2012

Outline

- Context: new materials and promise of spin liquid
- Magnetization curve
- classical antiferromagnet in a field: entropic selection
  - spatial anisotropy - high-T stabilization of the plateau
- Quantum spins - plateau due to quantum fluctuations
- Kagome

★ Conclusions

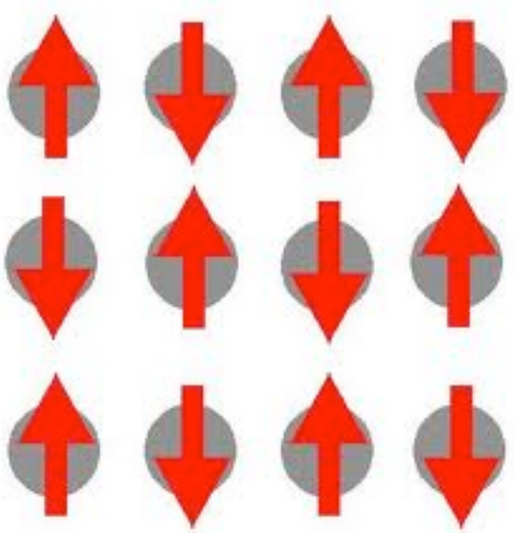
Frustrated magnetism is growing...
Statistics from APS March 2012 Meeting

- Graphene (combined topics) 466
- Topics in topological insulators (combined topics) 206
- Pnictides (9.1.1) 163
- Frustrated magnetism (10.1.6) 145

number of abstracts

Anti-ferromagnet

$$H = |J| \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$



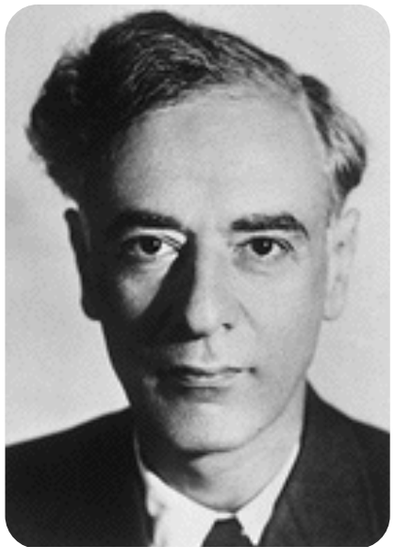
spins should be antiparallel locally

A debate



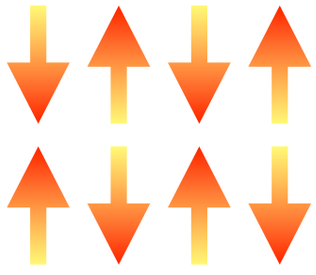
$$H = |J| \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

spins should be antiparallel locally

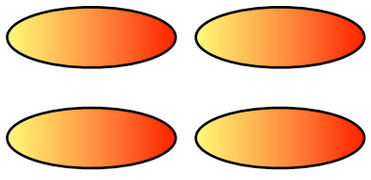


Landau
(and Pomeranchuk)

Néel



classical
antiferromagnet



$$= \frac{1}{\sqrt{2}} \left(\uparrow\downarrow - \downarrow\uparrow \right)$$

singlets

Amusing bit of history: I. Pomeranchuk, JETP vol. 4, pp. 357-374 (1941)

THE THERMAL CONDUCTIVITY OF THE PARAMAGNETIC DIELECTRICS AT LOW TEMPERATURES

By I. POMERANCHUK

(Received October 25, 1940)

In the paramagnetic dielectrics the paramagnetic spectrum can take part in the heat transfer. Besides the mutual collision (as in the ordinary dielectrics) the free path of the phonons essentially depends on this spectrum. At low temperatures the main part in the conduction of heat is played in some cases by the phonons, in the others by the paramagnetic spectrum. The run of the curve of termal conductivity as function of temperature has a complicated character with a number of maxima and minima, and is quite different as compared with the corresponding situation in ordinary dielectrics. An experimental check of the theory could give opportunity to find out the character of the paramagnetic exchange spectrum.

Spin liquid with spinon Fermi surface

Regarding the nature of excitations:

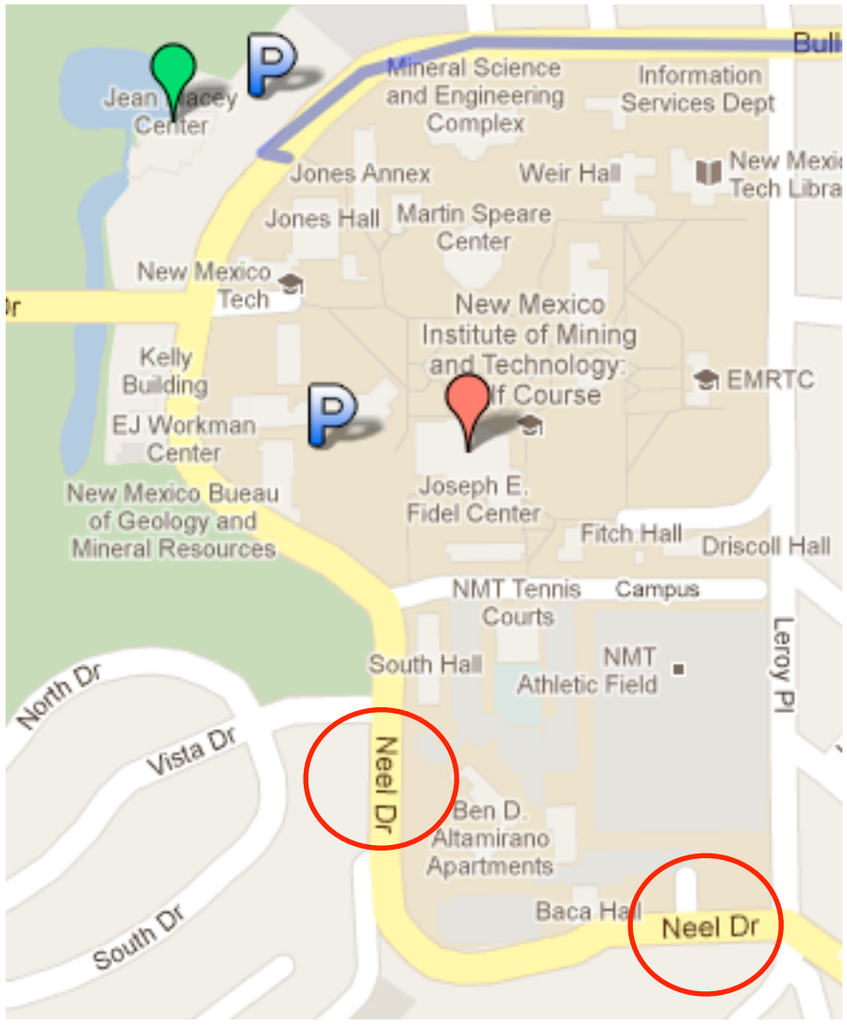
...the magnetic excitations levels correspond to the deviations from the normal distribution of the magnetic moments which are propagating through the whole crystal and are not localized in a definite place of the lattice. Such magnetic excitations will be called in the following "**magnons**"
(**this name was suggested by L. Landau**).

Regarding statistics of spin excitations:

"The experimental facts available suggest that the magnons are submitted to the Fermi statistics; namely, when $T << T_{CW}$ the susceptibility tends to a constant limit, which is of the order of $const/T_{CW}$ (5) [for $T > T_{CW}$, $\chi = const/(T + T_{CW})$]. Evidently we have here to deal with the Pauli paramagnetism which can be directly obtained from the Fermi distribution. Therefore, we shall assume the Fermi statistics for the magnons."

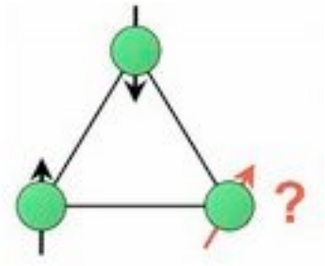
Ref. (5) A. Perrier and Kamerlingh Onnes, Leiden Comm. No.139 (1914)

It seems that Neel point of view has prevailed in Socorro...(and everywhere)

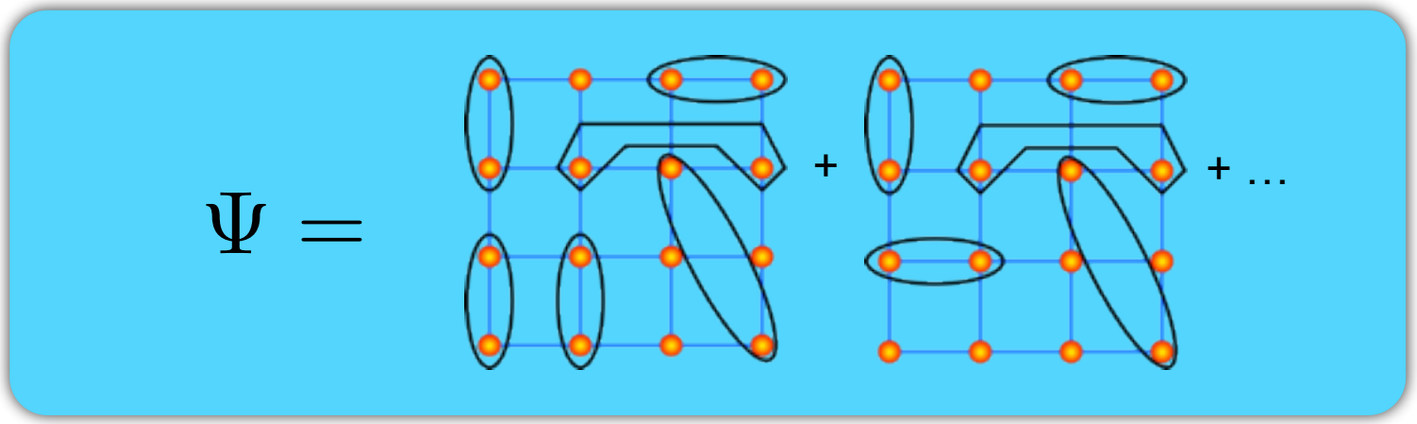


Singlets are back

frustrated geometry is the key



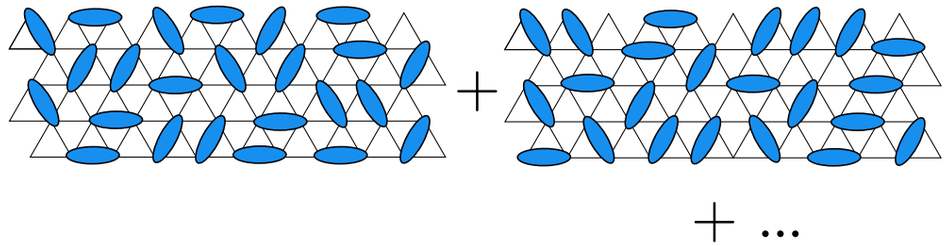
- Anderson (1973): revived the idea of singlets in the "Resonating Valence Bond" state *for triangular lattice AFM*



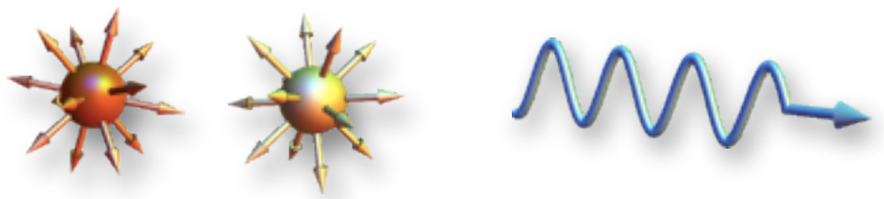
- prototype of modern Quantum Spin Liquid

Classes of Quantum Spin Liquids

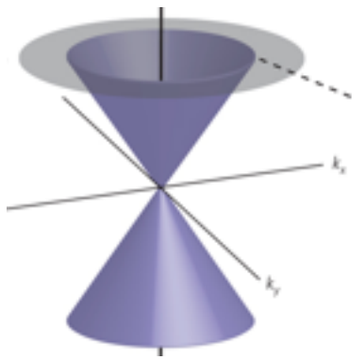
- Topological QSLs
  - full gap



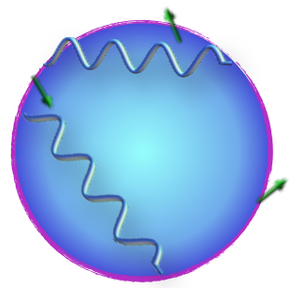
- U(1) QSL
  - gapless emergent "photon"



- Algebraic QSLs
  - Relativistic CFT (power-laws)

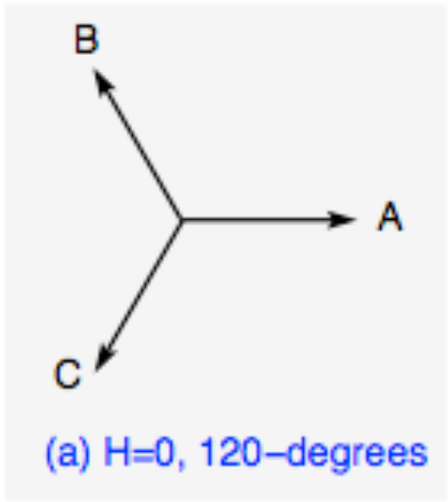


- Spinon Fermi surface QSL

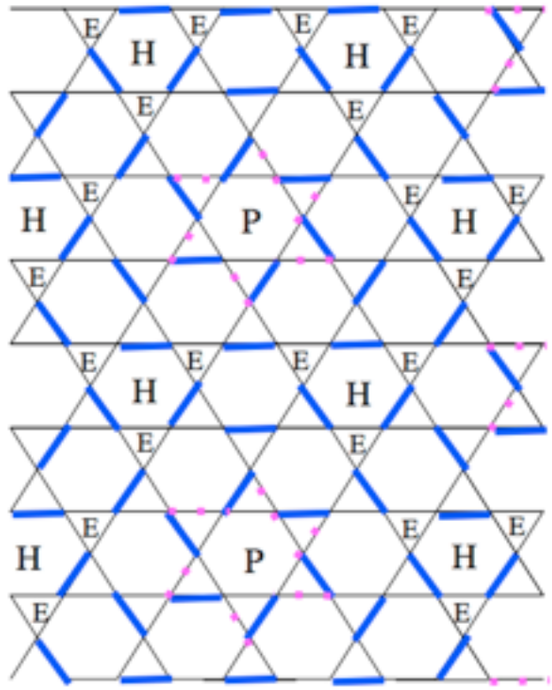


Simple models: state of affairs

- Triangular lattice AFM: ordered in a semi-classical 120° pattern, albeit with strongly reduced ordered moment (Bernu et al 1994; Capriotti et al 1999 ...)



(a) H=0, 120–degrees



- kagome:
  - exact diagonalization - spin liquid with very small gap to singlet excitations (Leung, Elser 1993; Lecheminant et al 1997 ...)
  - series expansions - ordered into Valence Bond Solid (no ordered moment but crystal-like order in bond variables) (Huse, Singh 2007)
  - DMRG - Z_2 topological spin liquid ! (2011...)

Topological Z_2 spin liquid in s=1/2 kagome

Spin-Liquid Ground State of the $S = 1/2$ Kagome Heisenberg Antiferromagnet

Simeng Yan,[1] David A. Huse,[2,3] Steven R. White[1]*

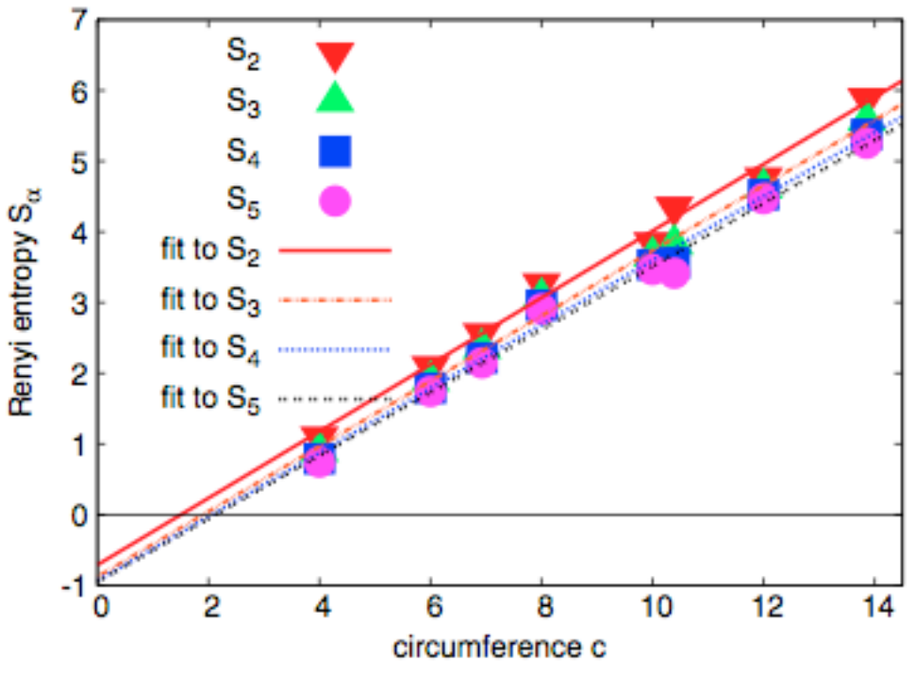
Science 2011

Identifying Topological Order by Entanglement Entropy

arXiv:1205.4289

Hong-Chen Jiang[1,2], Zhenghan Wang[3], and Leon Balents[1,*]

[1]Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA, 93106, U
[2]Center for Quantum Information, IIIS, Tsinghua University, Beijing, 100084, China
[3]Microsoft Station Q, University of California, Santa Barbara, CA, 93106, U.S.A.



PRL 109, 067201 (2012) PHYSICAL REVIEW LETTERS week ending 10 AUGUST 2012

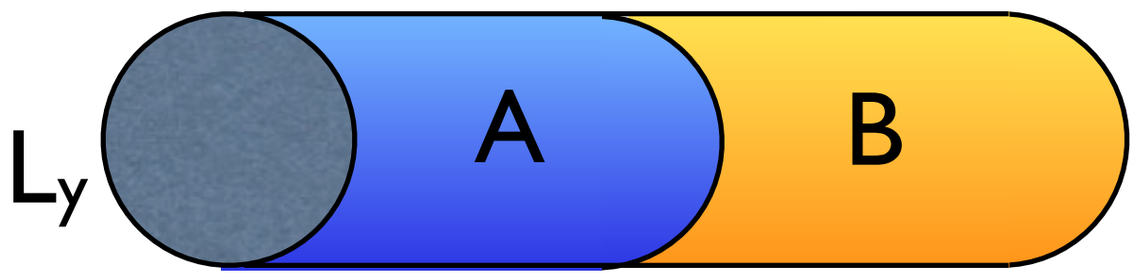
Nature of the Spin-Liquid Ground State of the $S = 1/2$ Heisenberg Model on the Kagome Lattice

Stefan Depenbrock,[1,*] Ian P. McCulloch,[2] and Ulrich Schollwöck[1]

Topological Entanglement Entropy

- For gapped QSLs, can define a quantitative measure of long-range entanglement

$$S(L) \sim \alpha L - \gamma$$

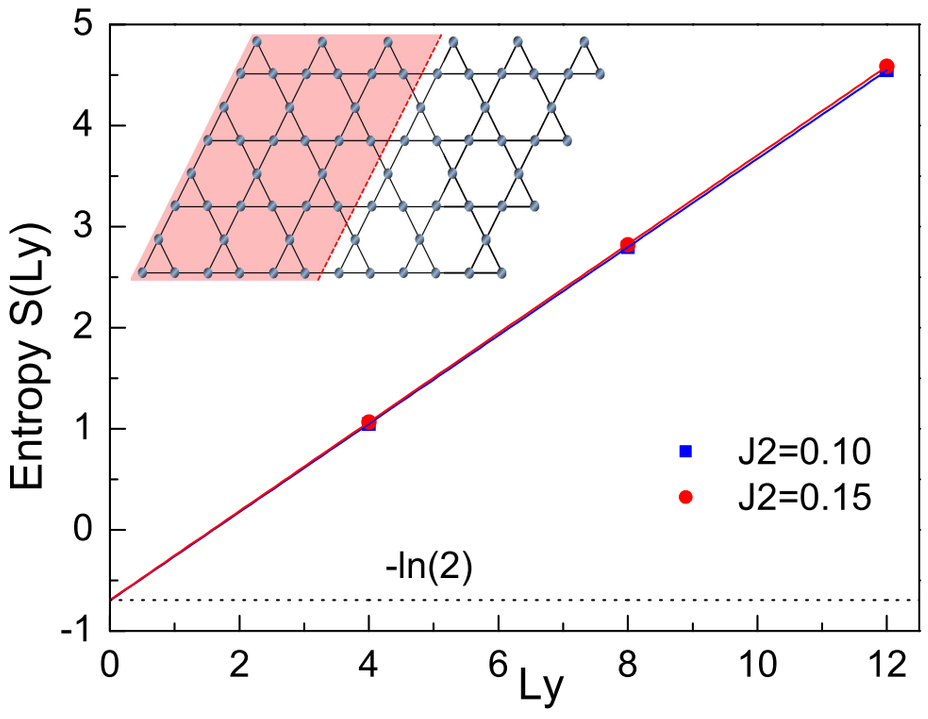


$$\rho_A = \mathrm{Tr}_B |\psi\rangle\langle\psi|$$

$$S = -\mathrm{Tr}_A[\rho_A \ln \rho_A]$$

short-ranged spin correlations

but long-range entangled state



γ_{DMRG}=0.698(8)

γ_{th}=ln(2)=0.693

H.C. Jiang, Z. Wang, L. Balents
arXiv:1205.4289

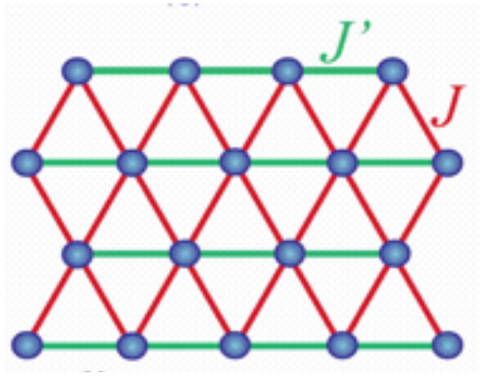
Promising spin 1/2 materials

Cs_2CuBr_4

κ-$(ET)_2Cu_2(CN)_3$

$EtMe_3Sb[Pd(dmit)_2]_2$

$Ba_3CuSb_2O_9$

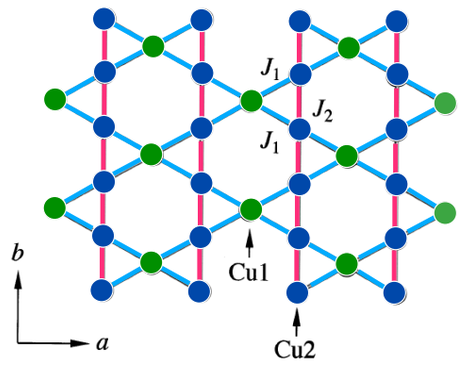


triangular

$ZnCu_3(OH)_6Cl_2$

$Cu_3V_2O_7(OH)_2 \cdot 2H_2O$

$BaCu_3V_2O_3(OH)_2$



kagome

Outline

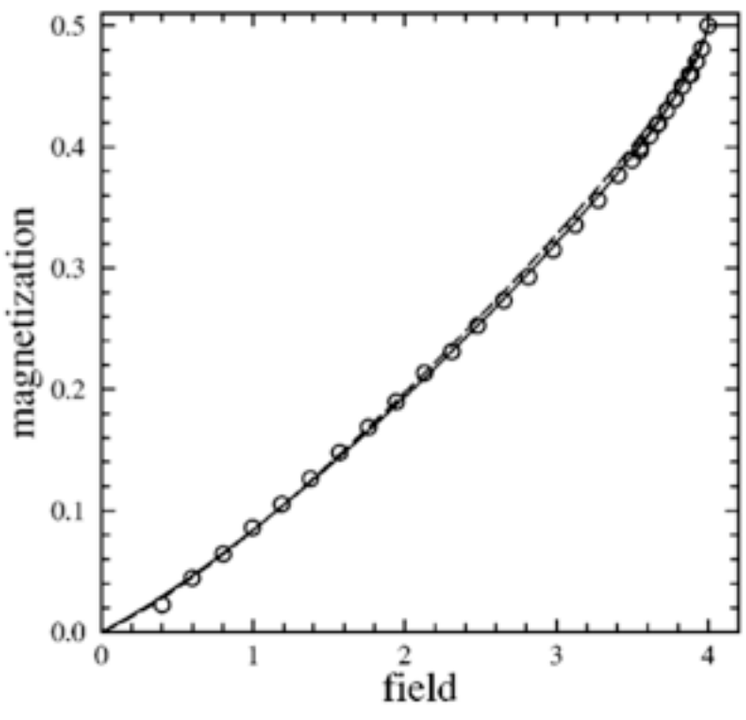
- Context: new materials and spin liquids
- Magnetization curve
- classical antiferromagnet in a field: entropic selection
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★ Conclusions

Magnetization studies of frustrated antiferromagnets



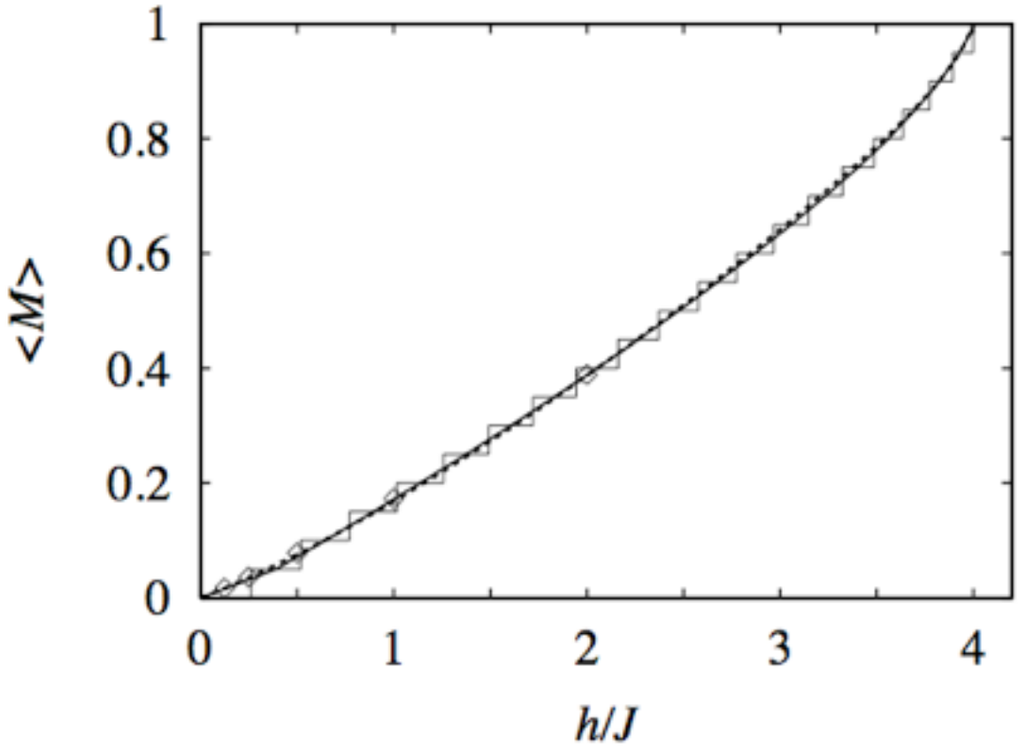
square lattice AFM



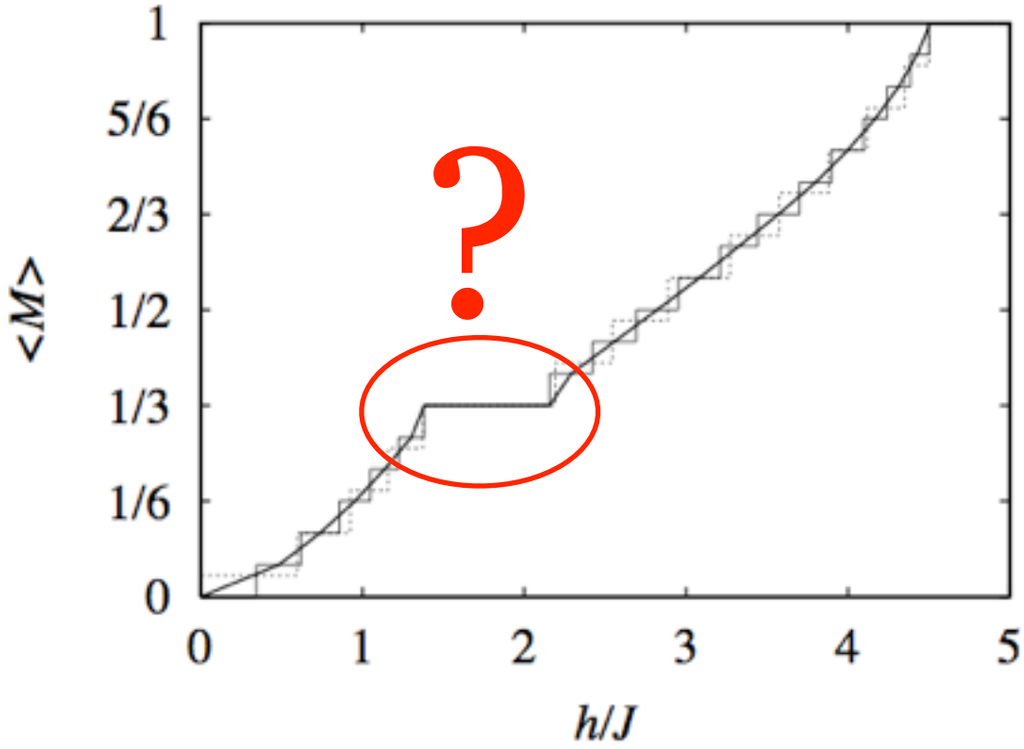
nothing interesting in magnetically ordered systems? :-(

Magnetization plateau

square



triangular



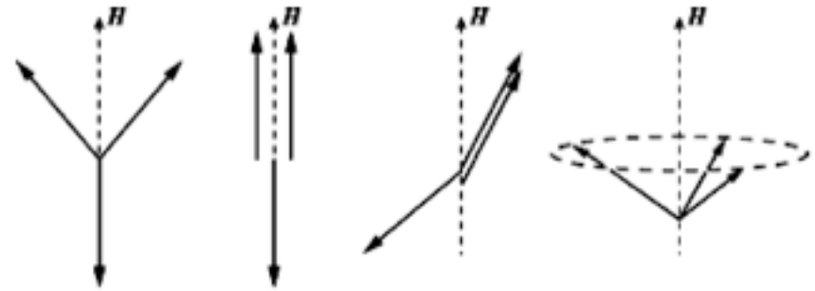
A. Honecker , J. Schulenburg and J. Richter (2004)

Classical isotropic triangular AFM in magnetic field

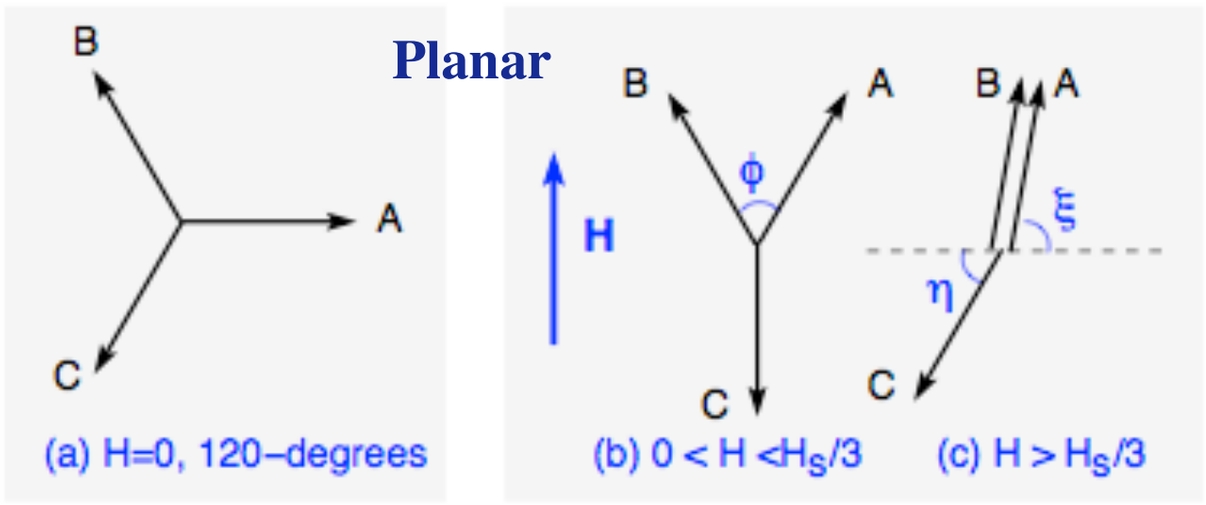
- No field: spiral (120 degree) state
- Magnetic field: **accidental degeneracy**

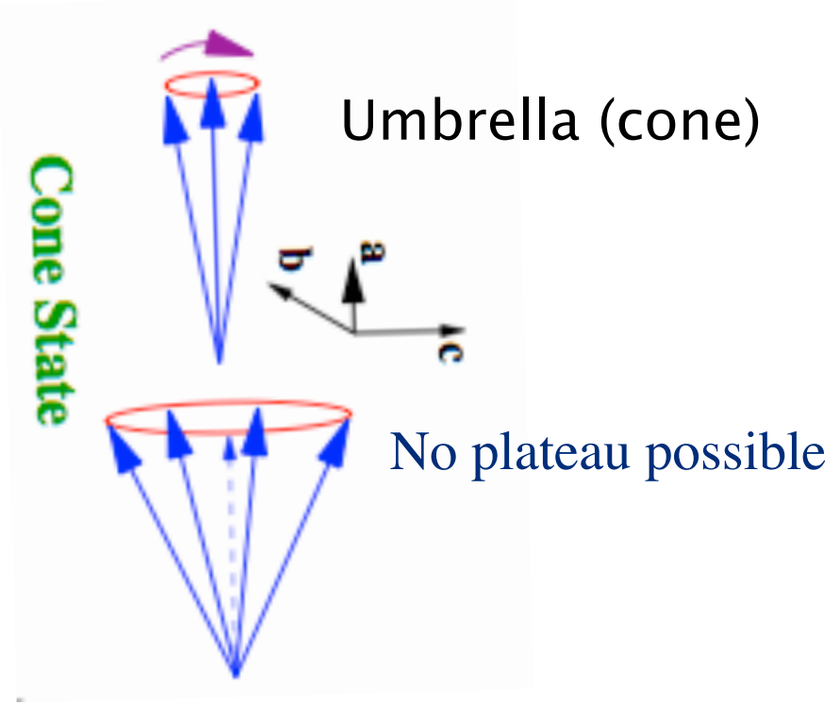
$$H = J\sum_{i,j}\vec{S}_i\cdot\vec{S}_j - \sum_i \vec{h}\cdot\vec{S}_i$$

$$H = \frac{1}{2}J\sum_{\triangle}\Big(\sum_{i\in\triangle}\vec{S}_i - \frac{\vec{h}}{3J}\Big)^2$$

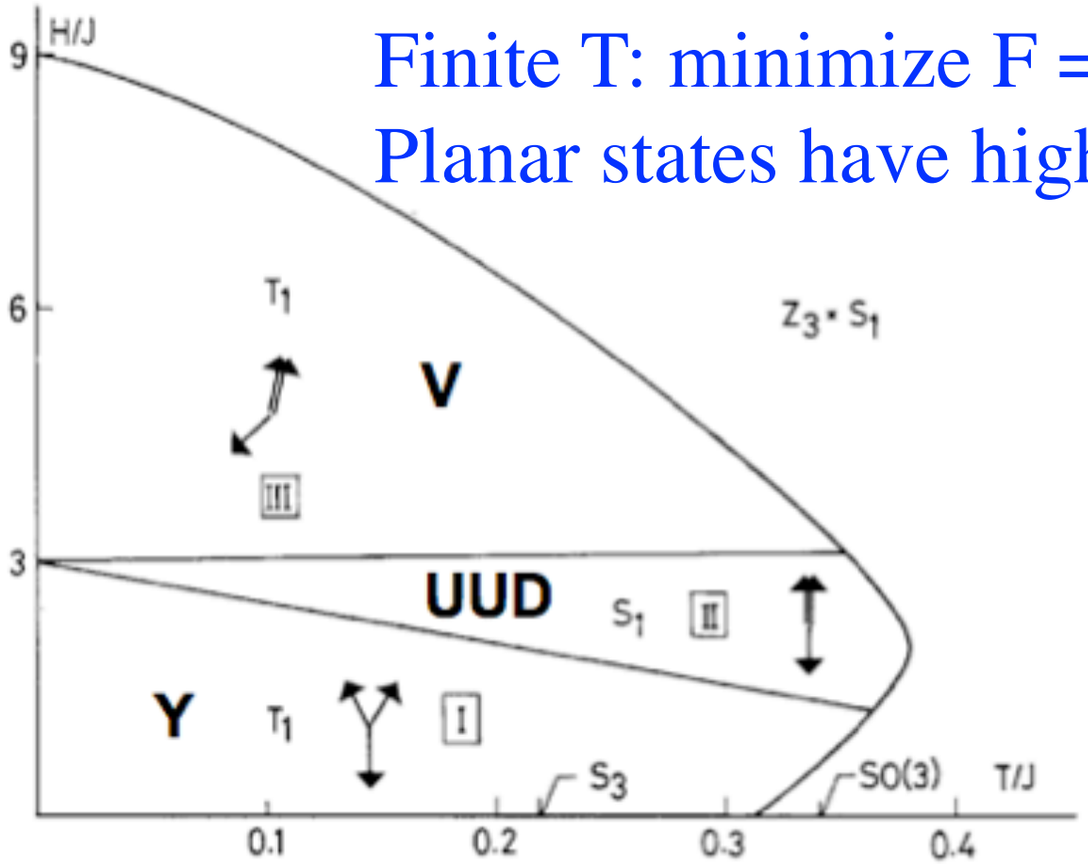


- all states with $\vec{S}_{i1}+\vec{S}_{i2}+\vec{S}_{i3} = \dfrac{h}{3J}$ form the lowest-energy manifold
  - 6 angles, 3 equations => **2 continuous angles** (upto global U(1) rotation about **h**)





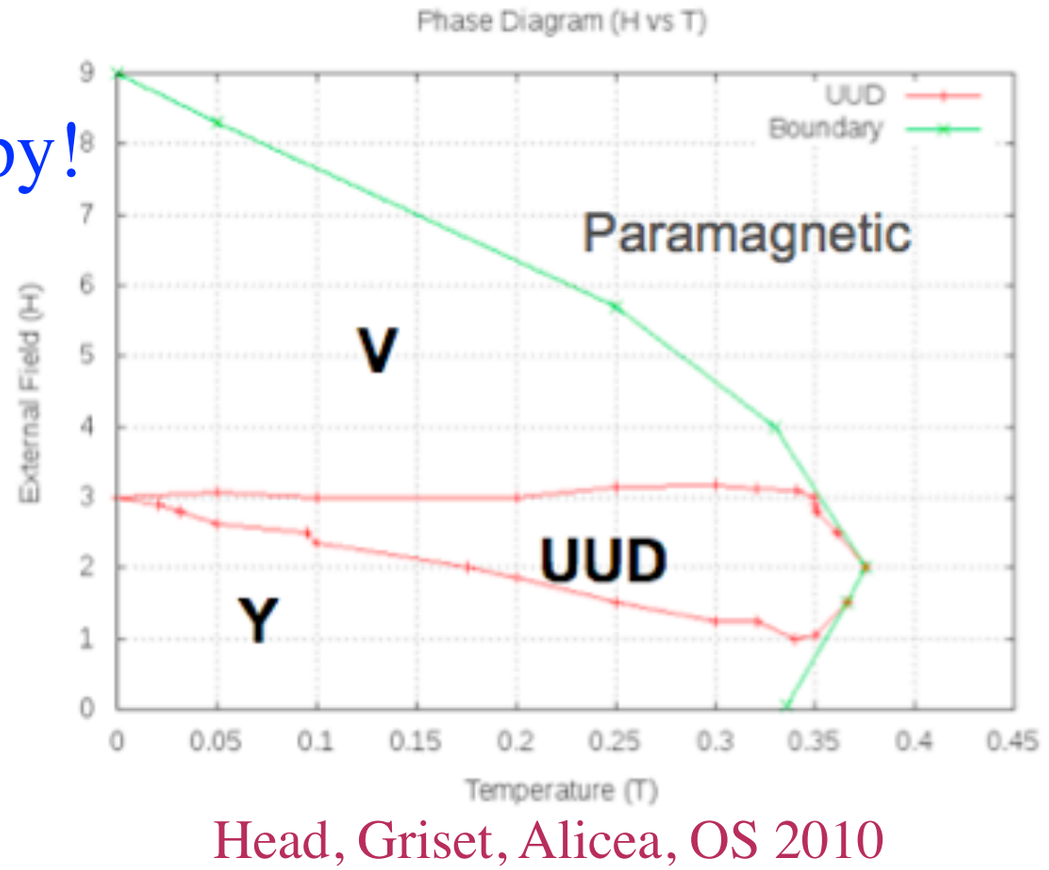
Phase diagram



H. Kawamura, S. Miyashita:
JPSJ (1985)

Finite T: minimize F = E - T S

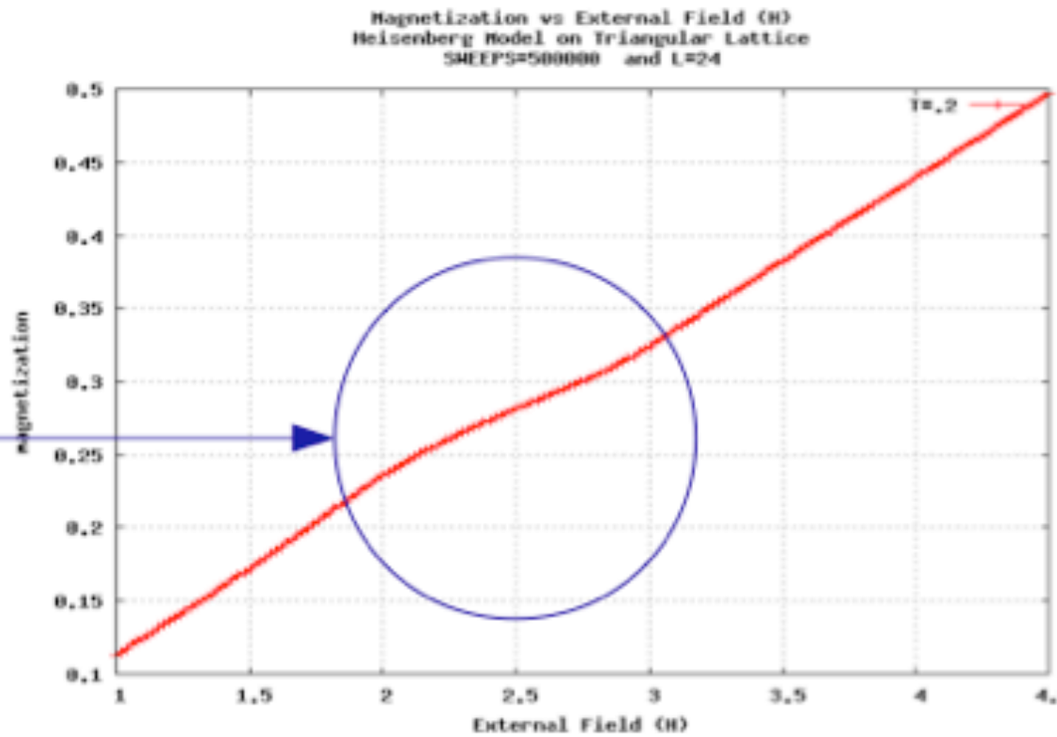
Planar states have higher entropy!



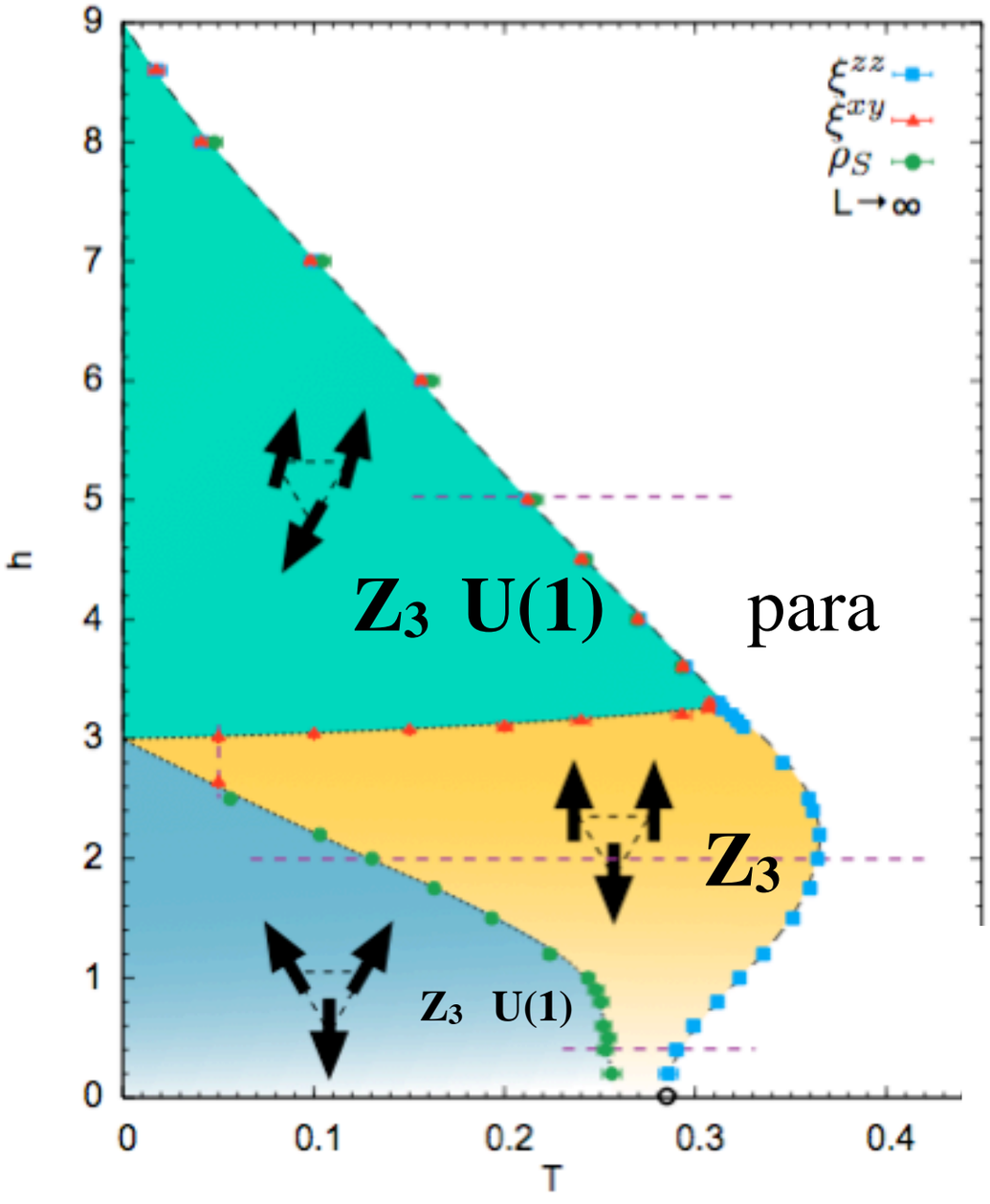
Head, Griset, Alicea, OS 2010

Entropic Selection:

- Planar states favored by thermal fluctuations
- UUD state around m=1/3 resulting in quasi-plateau



Phase diagram of the classical model



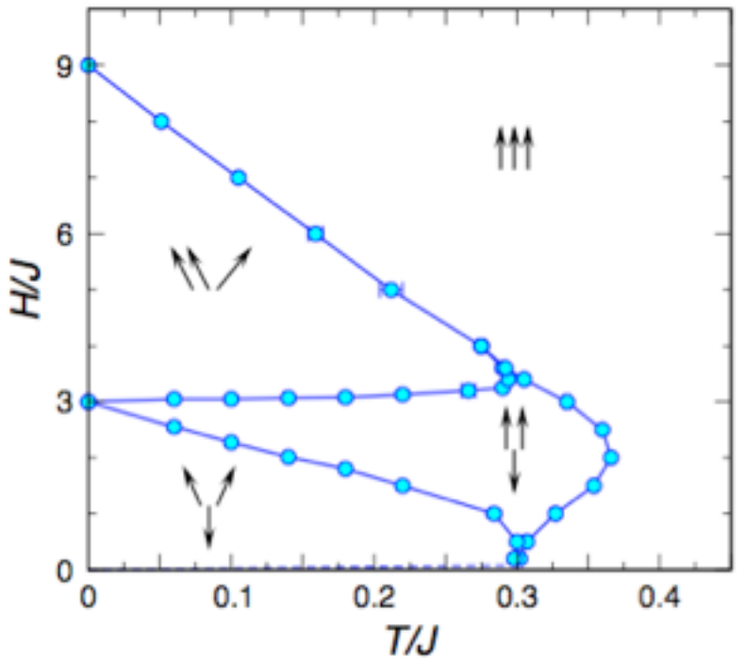
Seabra, Momoi, Sindzingre, Shannon 2011

why so stable?

Collinear UUD state does not break U(1) symmetry (rotations about field axis).

Hence, no gapless Goldstone modes.

All spin excitations are gapped.

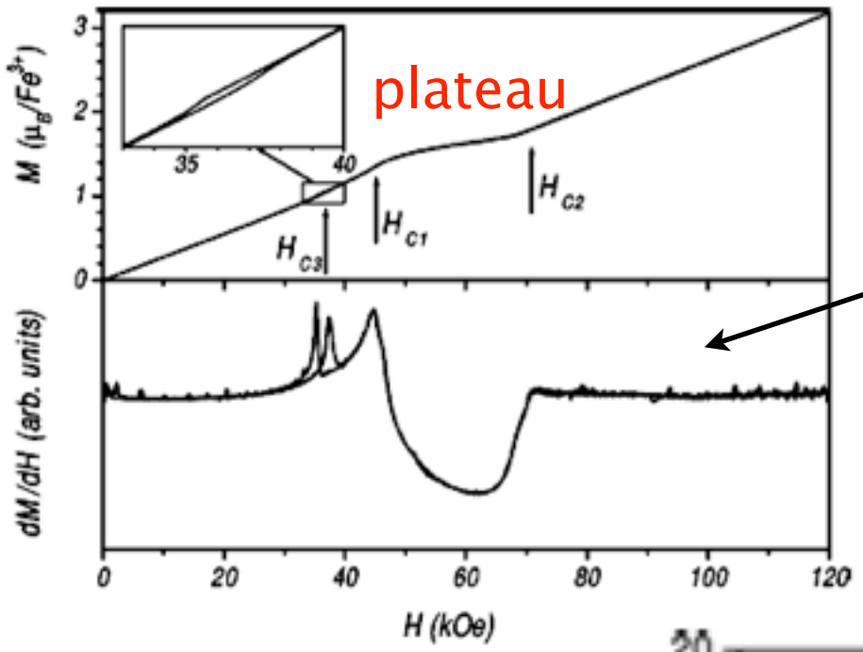


Gvozdikova, Melchy, Zhitomirsky 2010

Experimental realizations

$RbFe(MoO_4)_2$: $S=5/2$ Fe^{3+}

Svistov et al PRB (2003)
Smirnov et al PRB (2007)

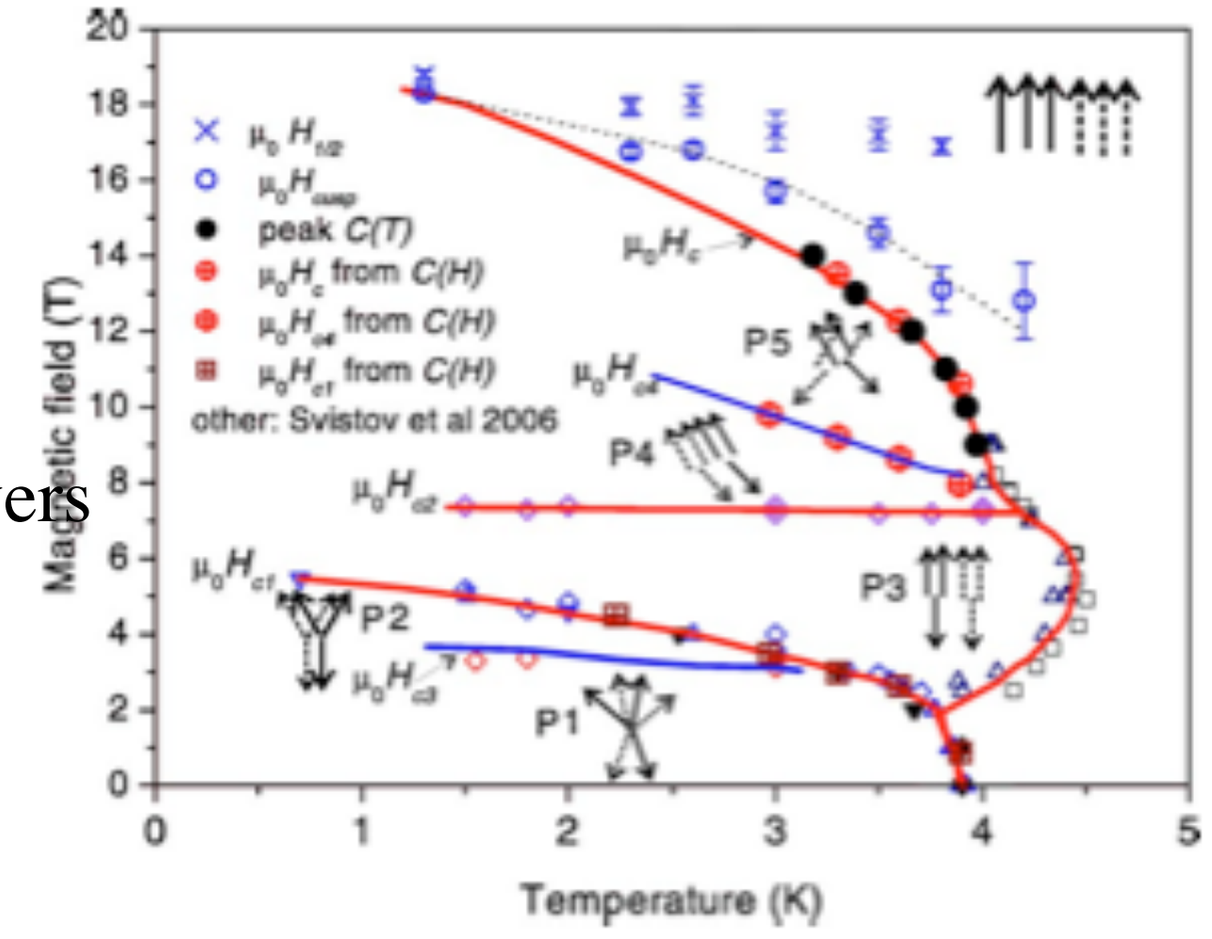


plateau is signaled by depression in dM/dH

Phase diagram contains only co-planar states (while classically - only non-planar cone state!)

Two antiferromagnetically coupled layers

Plateau width increases with T



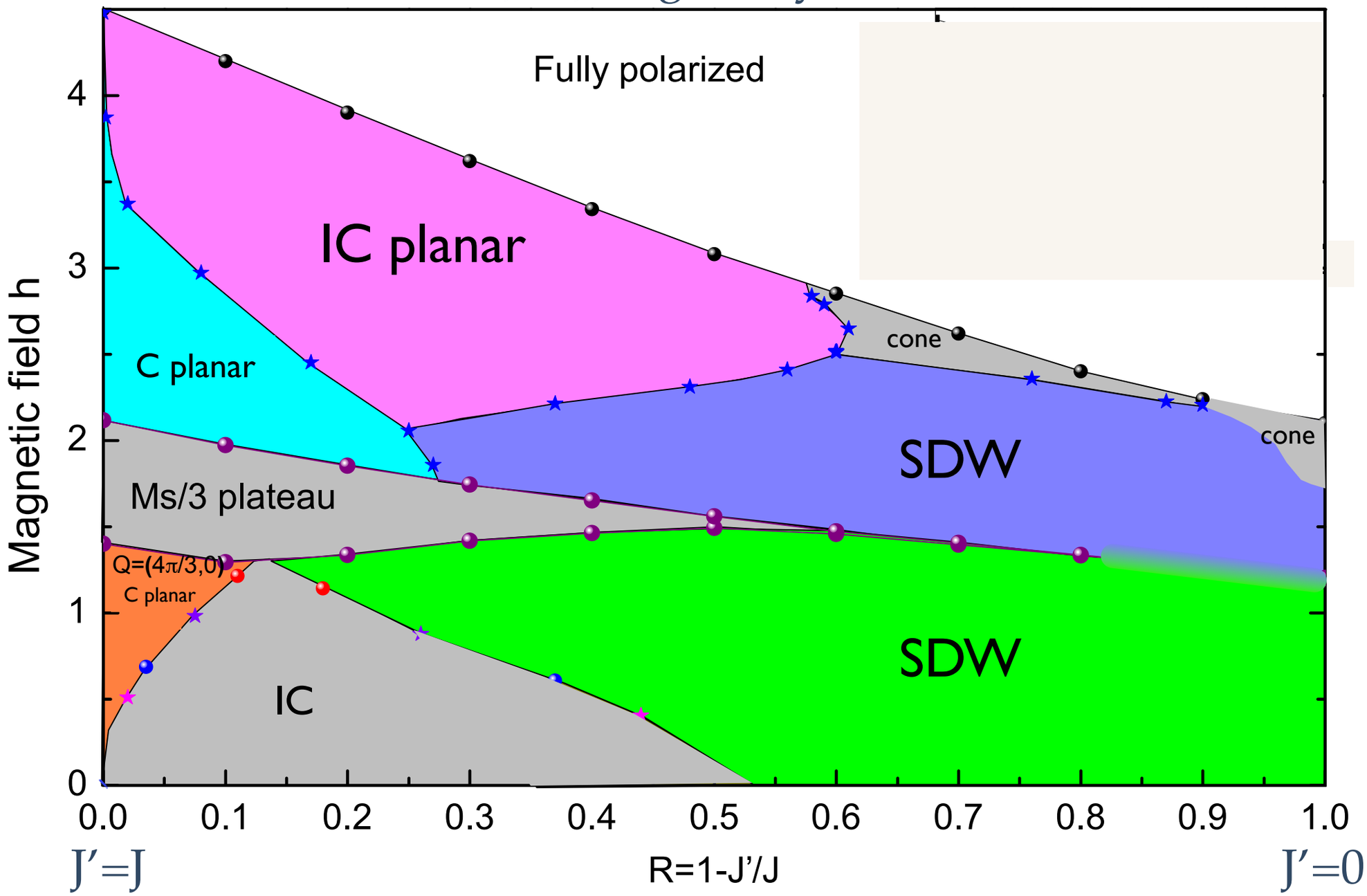
Outline

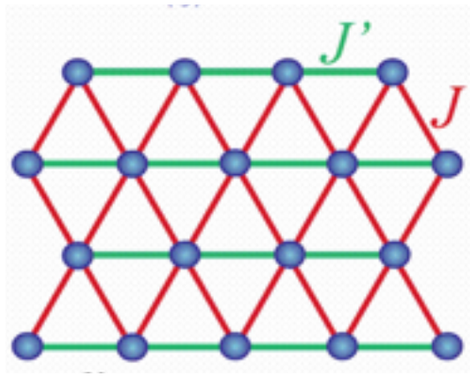
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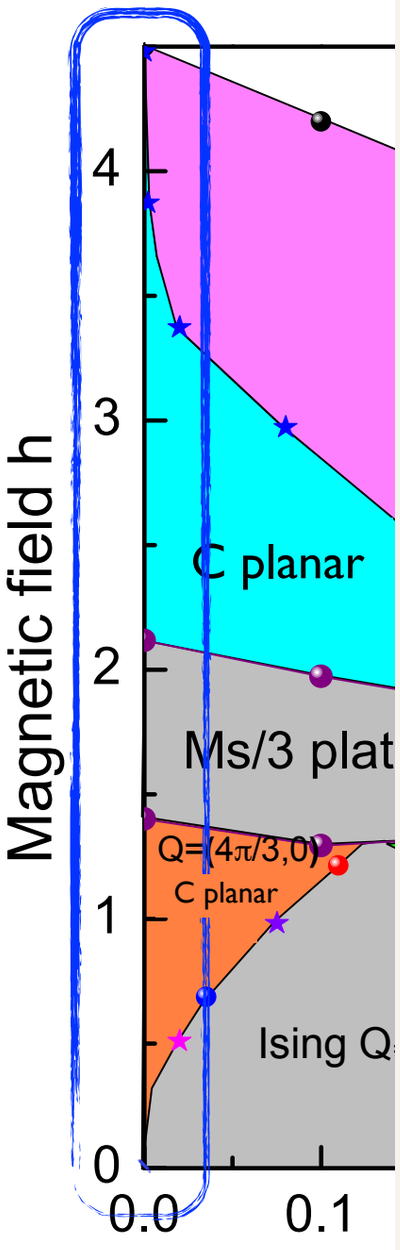
DMRG studies: phase diagram of 3 leg ladder

Chen, Ju, Jiang, Starykh, Balents 2012

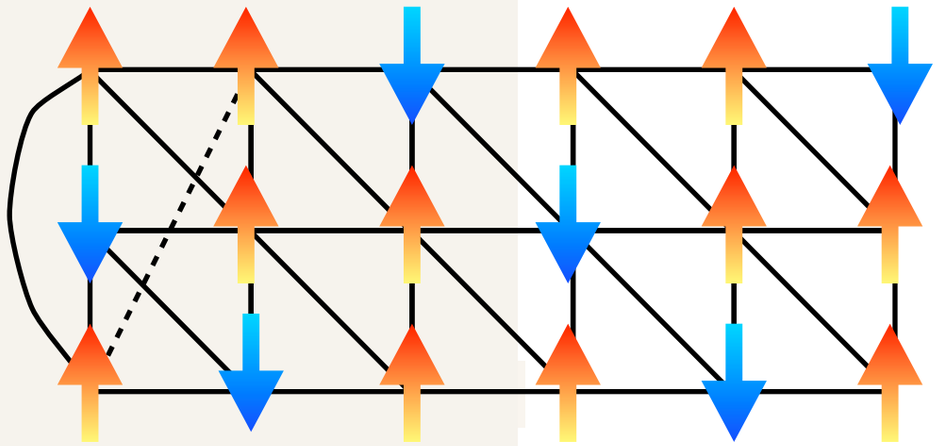


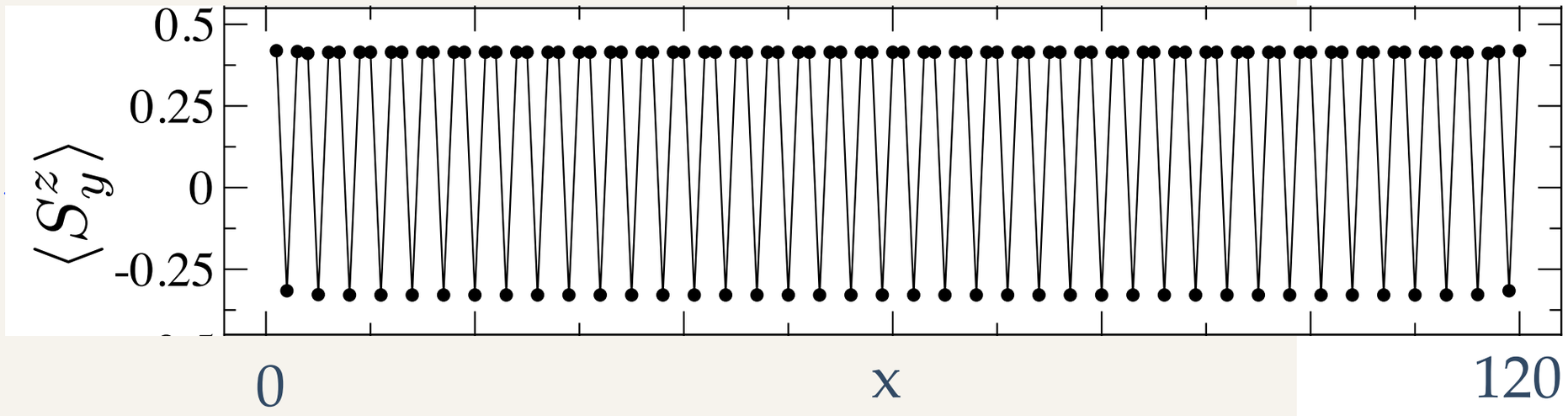


Plateau phase



$M/M_s=1/3$ plateau:
uud state

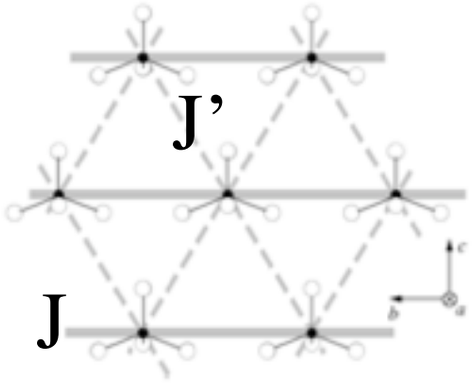


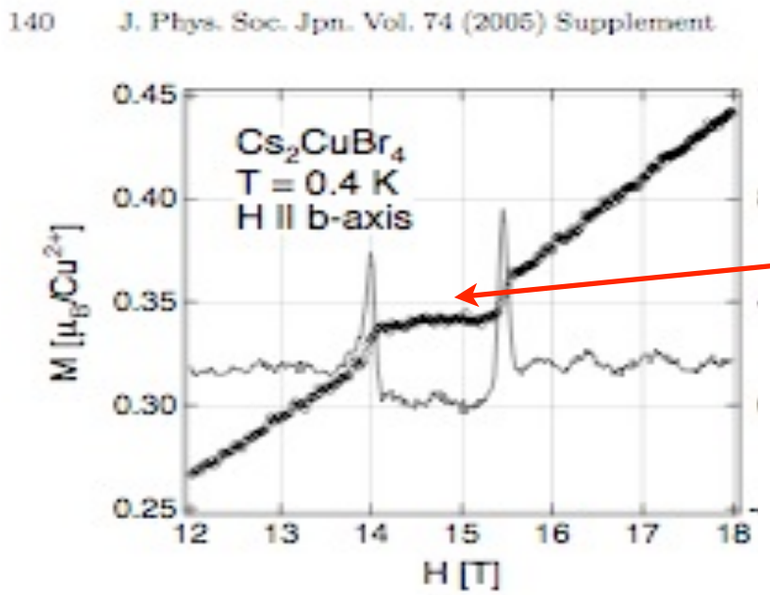


M=1/3 magnetization plateau in Cs_2CuBr_4

★ Observed in Cs_2CuBr_4 (Ono 2004, Tsuji 2007) **J'/J = 0.75**

S=1/2





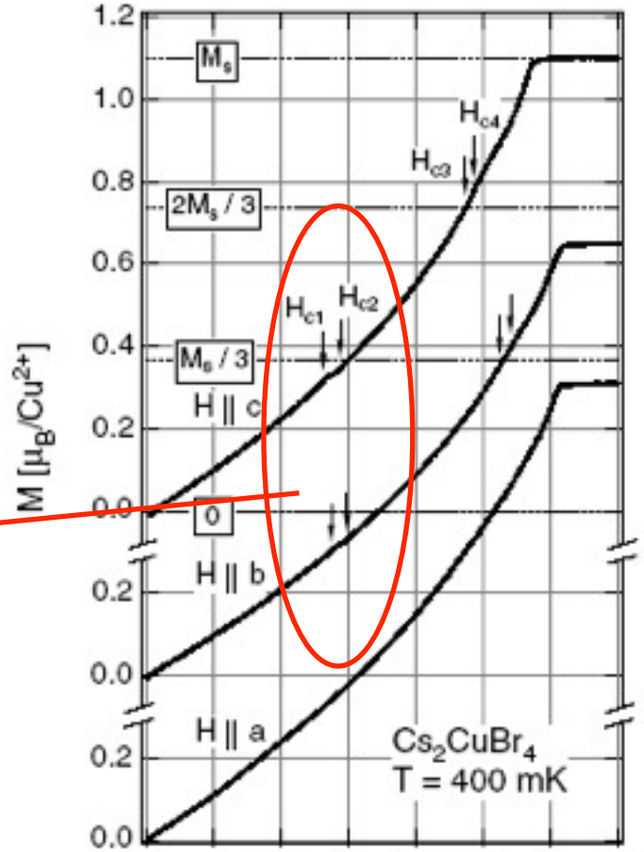
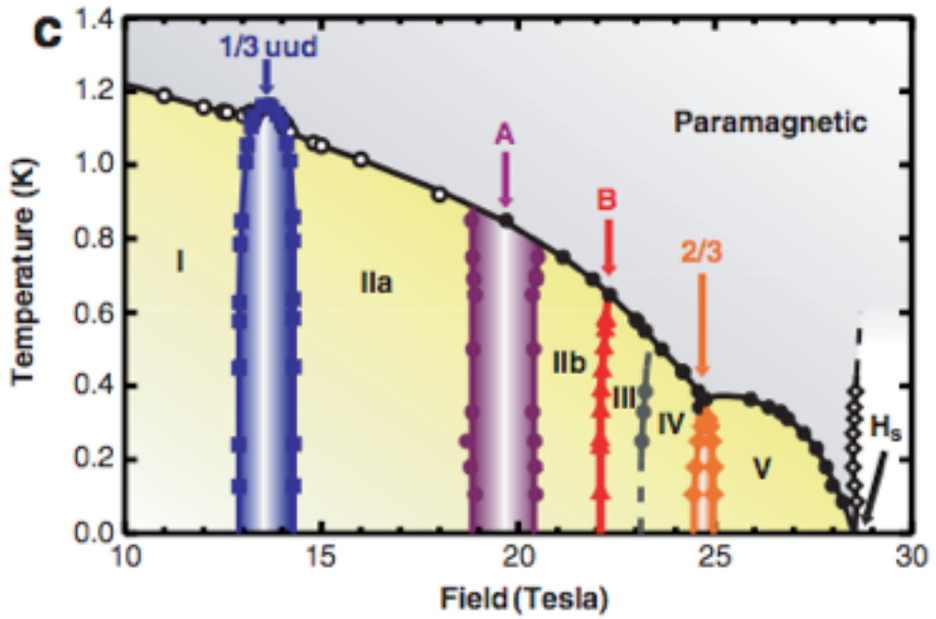


Fig. 8. The magn
measured at T =

★ first observation of "**up-up-down**" state
in spin-1/2 triangular lattice antiferromagnet

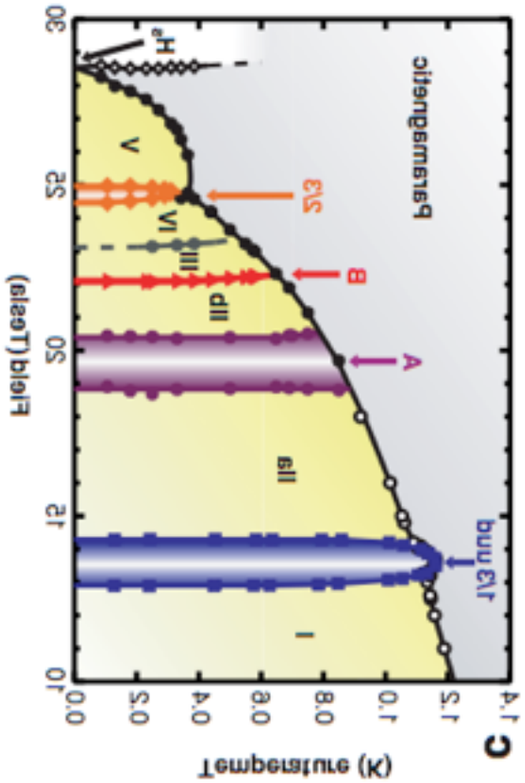
★ and **8** more **phases** (instead of 2 expected)!

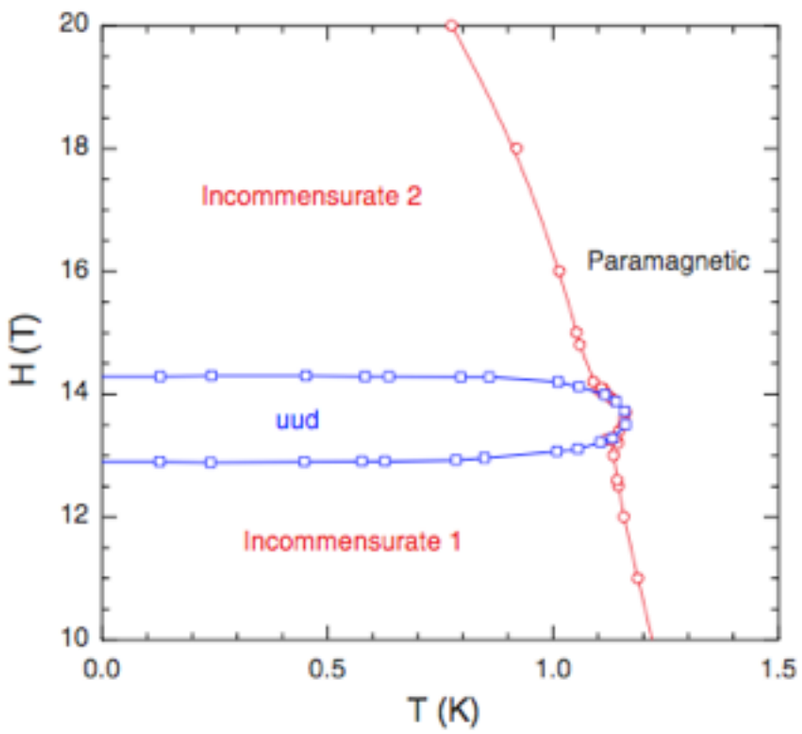


Quantum fluctuations stabilize 1/3 plateau already at T=0

T-independent plateau width

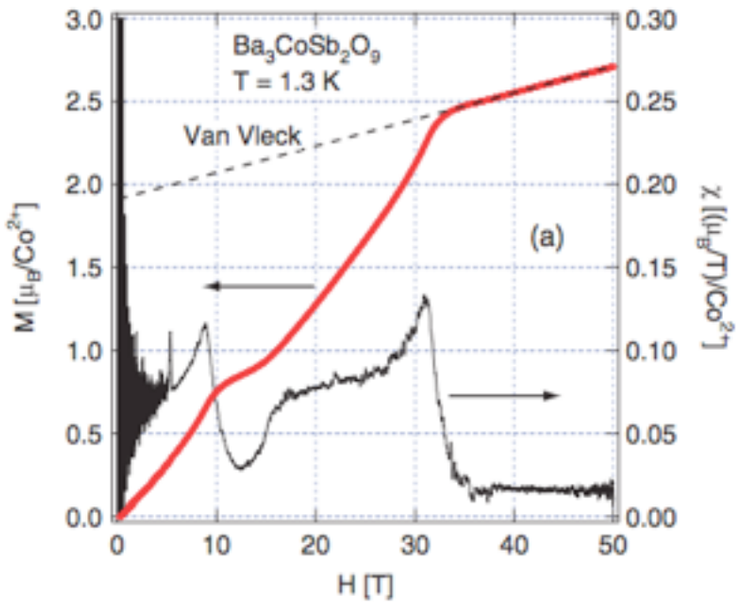
UUD spin structure

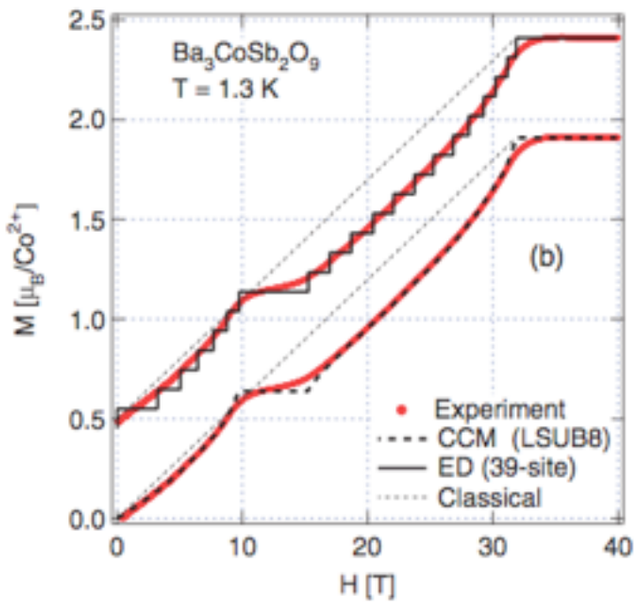




Tsujii 2007

PRL 108, 057205 (2012) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2012





Shirata et al 2012

Schematic phase diagram for spin-1/2 triangular lattice AFM

h/J

fully polarized

C planar

IC planar

1/3

SDW

cone

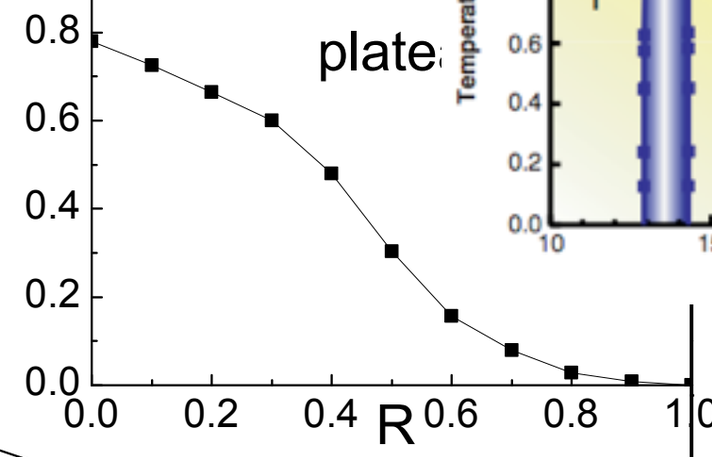
C planar

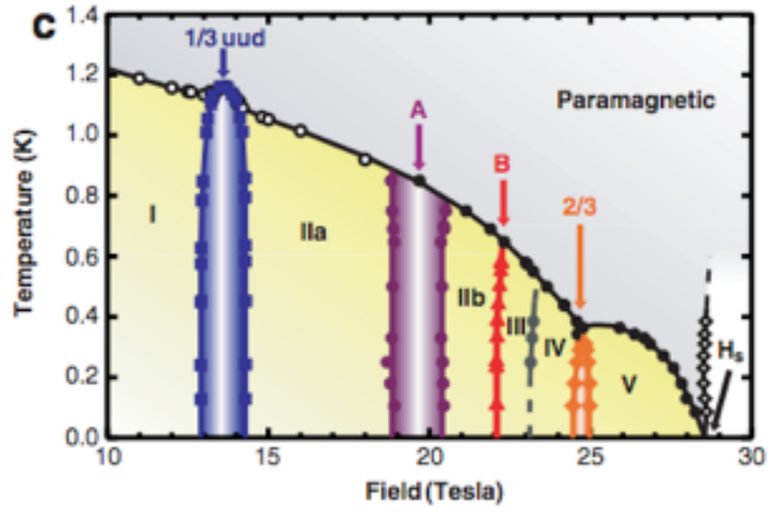
IC planar

SDW

quasi-collinear

R=1-J'/J





many more interesting phases in addition to the plateau

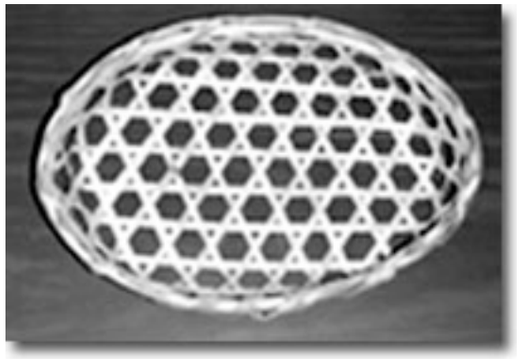
Outline

- Context: new materials and spin liquids
- Magnetization curve
- classical antiferromagnet in a field: entropic selection
  - spatial anisotropy - high-T stabilization of the plateau
- Quantum spins - plateau due to quantum fluctuations
- Kagome

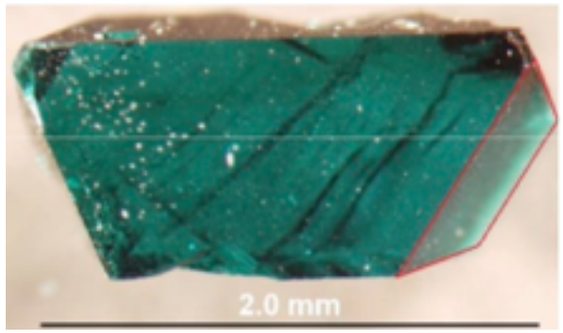
★ Conclusions

Herbertsmithite

$ZnCu_3(OH)_6Cl_2$

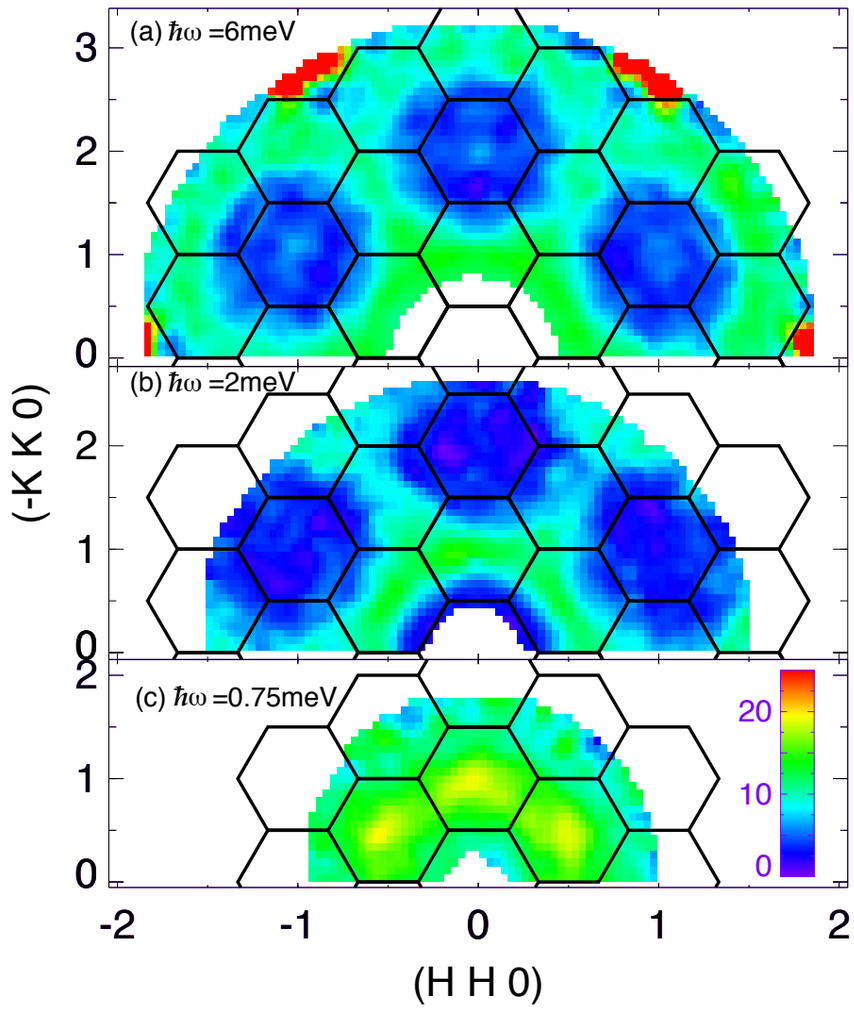


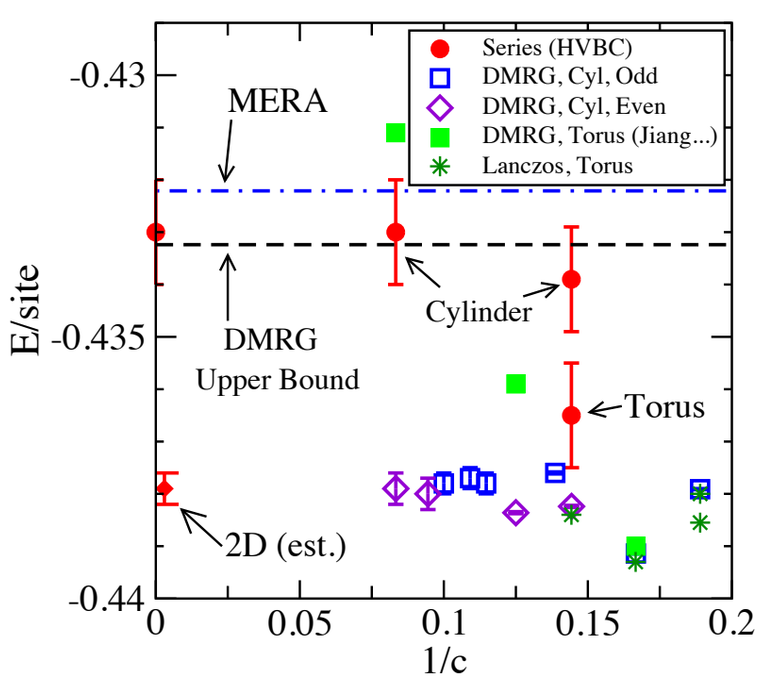
- S=1/2 kagome material does not order to 50mK with exchange J ~ 200K



Neutron scattering on single crystal Y S Lee (2011...)

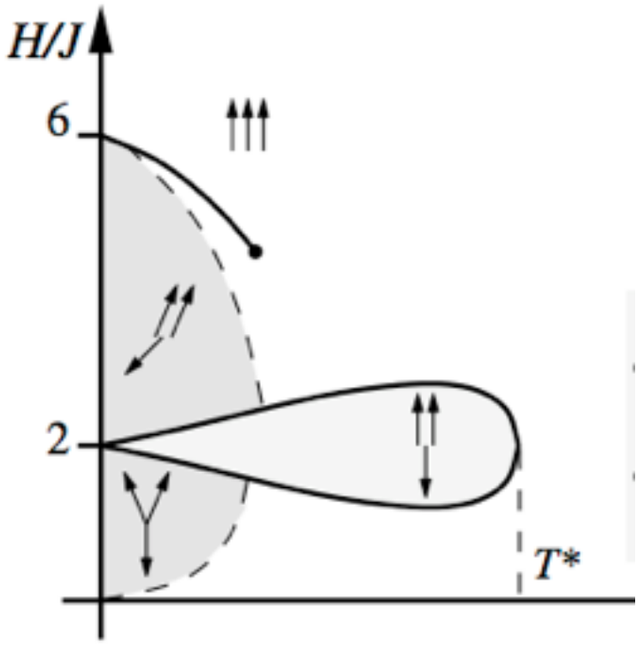
T-H Han *et al*, 2012





S. Yan, D. Huse, S. White , 2010

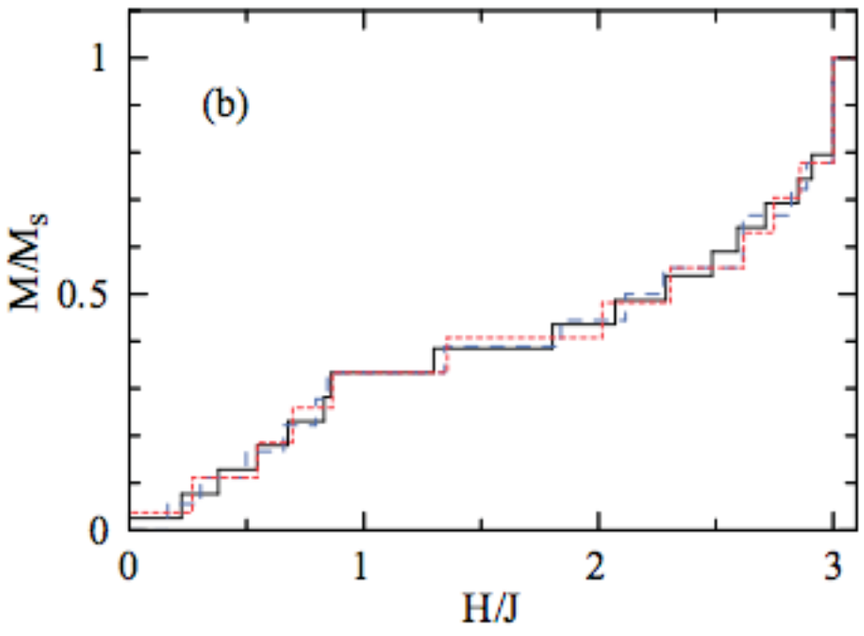
Magnetization curve

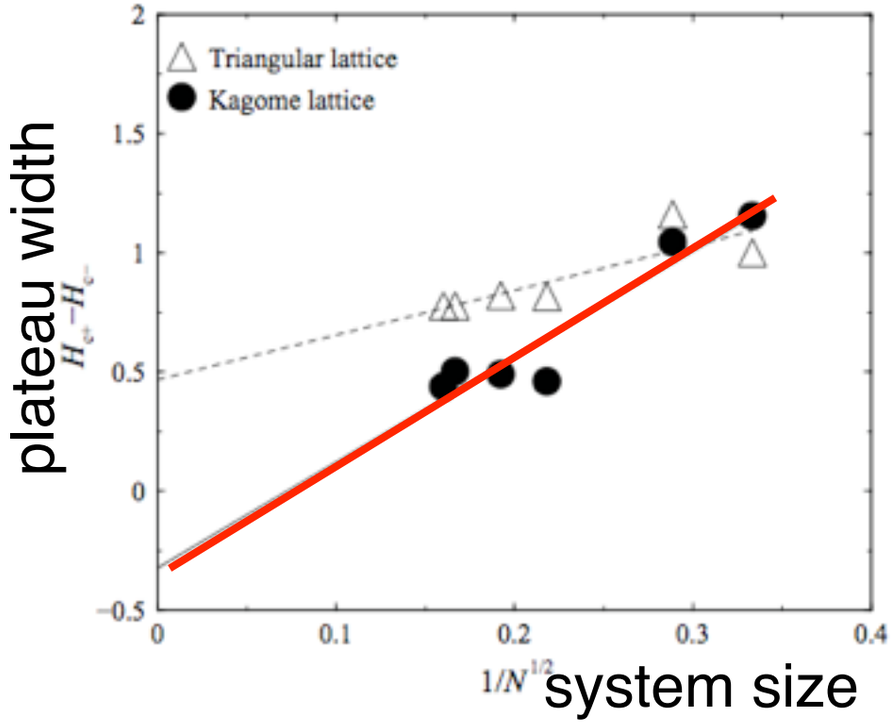


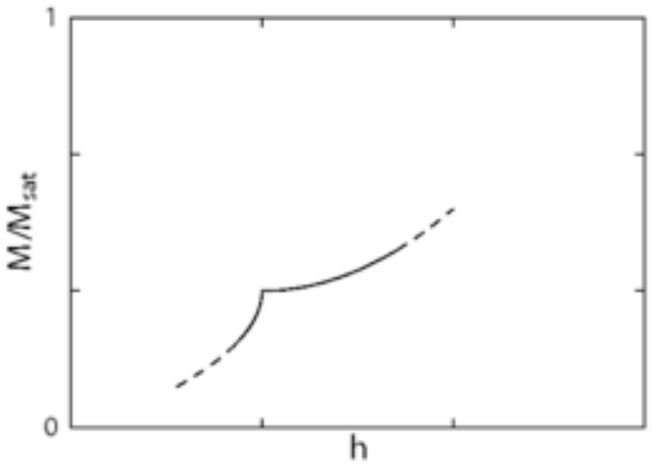
classical spins: UUD plateau at 1/3 M_{sat}
Zhitomirsky 2002

classical - yes
quantum - maybe not

s=1/2: plateau-like feature disappears in thermodynamic limit; ramp-up behavior instead

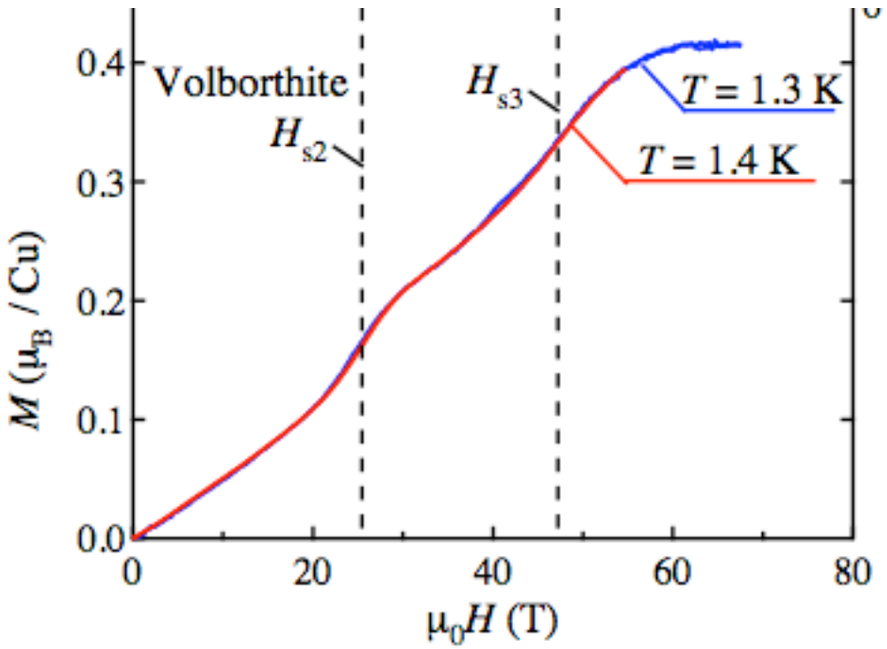


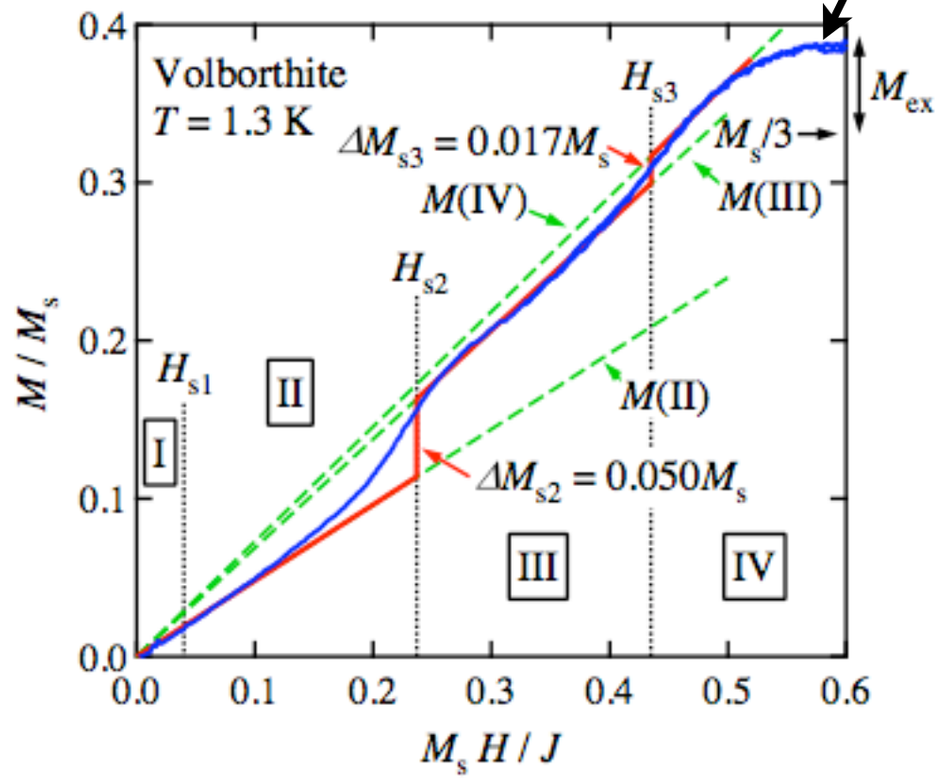




Nakano, Sakai 2011

Experiments





Okamoto et al 2011

plateau at M = 0.4 M_{sat} ?!

Conclusions

- This is good time for frustrated magnetism
- Spin liquids found in simple exchange spin-1/2 kagome antiferromagnet
- Magnetization plateau in spin-1/2 triangular lattice antiferromagnet: persists for **all** J'/J
- Many open theoretical questions (kagome...)
- Even more challenges for experimentalists