Jamming in a spin liquid

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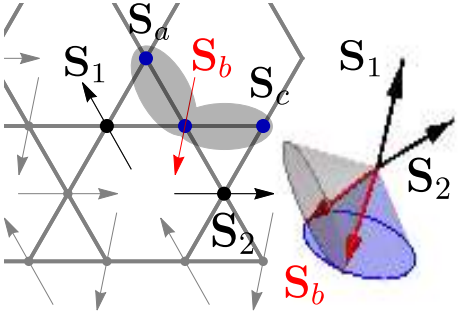

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Ingredients/Protagonists

Frustration & classical spin liquids

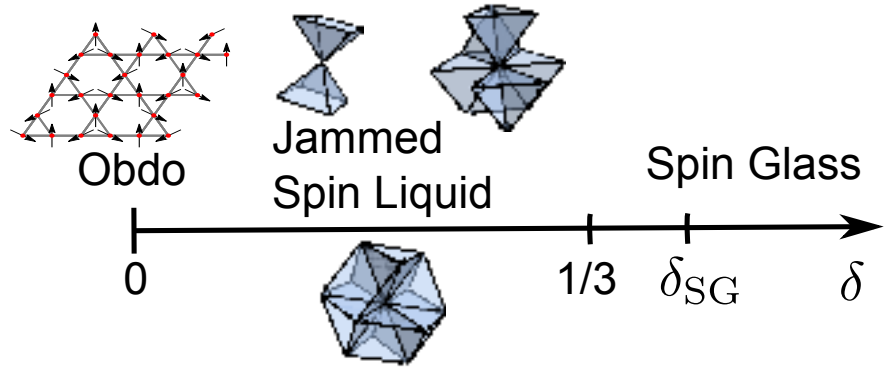
- recent additions Rehn at al., Benton et al.

Disorder in magnetism

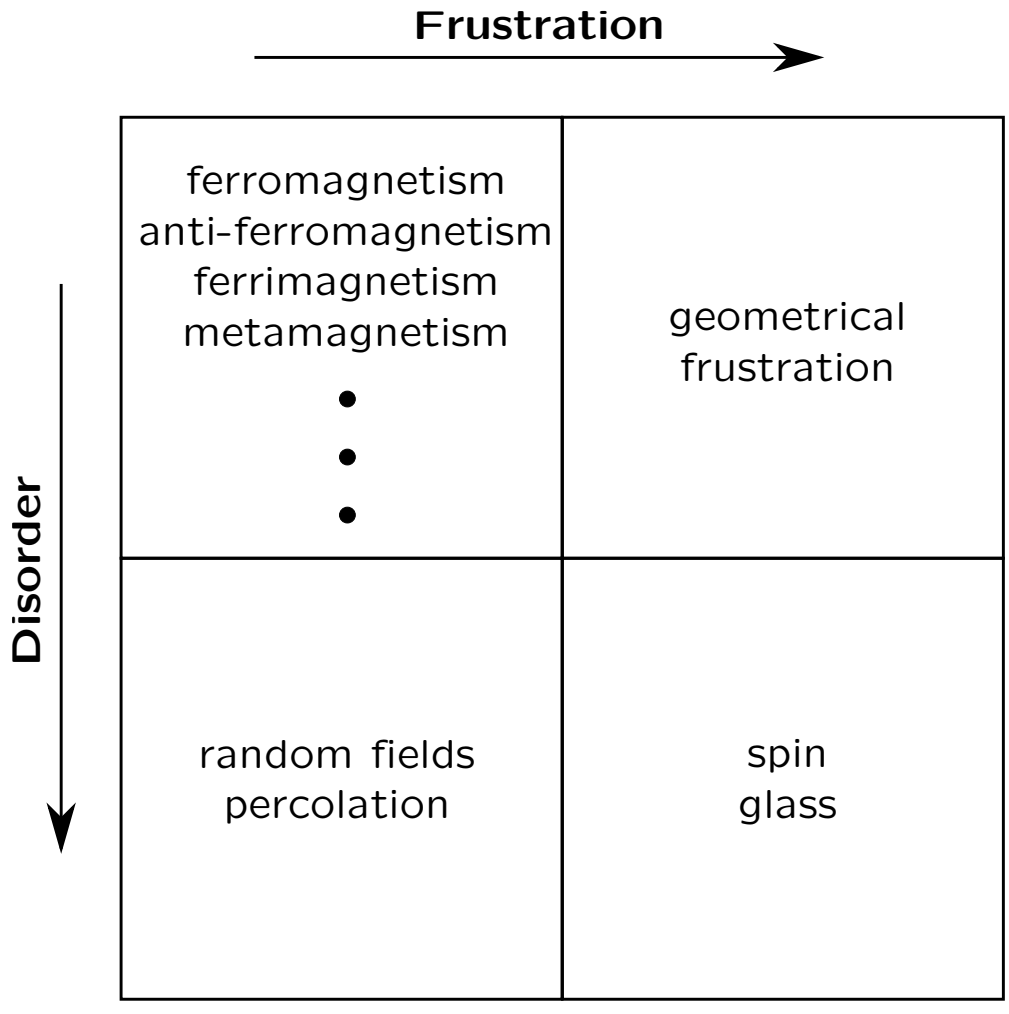
- distraction, probe, source of new physics
- with frustration: disorder-free glassiness?

Bond-disordered kagome

- marginal constraint
  - no order by disorder
  - discrete degeneracy
- unusual excitation spectrum
- termination by spin glass



Disorder and frustration



Ramirez, 1994

Bond disorder in frustrated magnets

Ancient subject

- spin glass physics:
  Sherrington-Kirkpatrick model

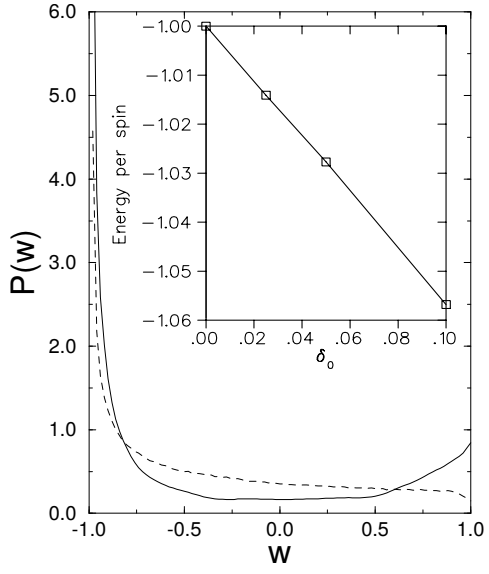
Highly frustrated magnets: pyrochlore

- lifts huge ground-state degeneracy

  Bellier-Castella et al., Can. J. Phys. 2001

- leeds to conventional spin freezing

  Saunders + Chalker, PRL 2007



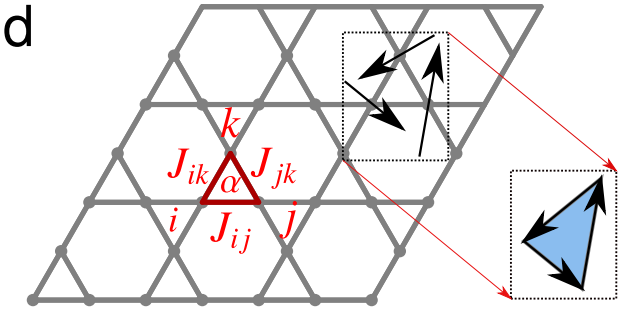
How general?

- Consider classical kagome magnet

Bond-disordered kagome magnet

Exchange strength J_{ij} random for each bond

$$\mathcal{H} = \sum_{\langle ij \rangle} J_{ij} \mathbf{S}_i \mathbf{S}_j$$



can be rewritten using $\gamma_{i\alpha} = \sqrt{J_{ij} J_{ik} / J_{jk}}$ as 'perfect square'

$$\mathcal{H} = \sum_{\alpha} \left(\sum_{i \in \alpha} \gamma_{i\alpha} \mathbf{S}_i \right)^2 = \sum_{\alpha} \mathbf{L}_{\alpha}^2$$

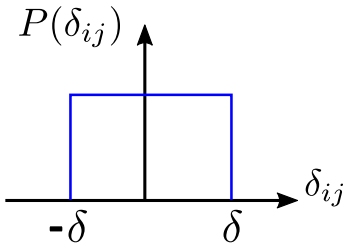
Ground-state constraint: $\mathbf{L}_{\alpha} = \sum_{i \in \alpha} \gamma_{i\alpha} \mathbf{S}_i = 0$ for each triangle α

- degrees of freedom per unit cell: $F = 3(n-1)$
- constraints for unit cell: $K = 2n$
  - marginal constraint for Heisenberg, n = 3: $D = F - K = 0$

Ground state construction and entropy

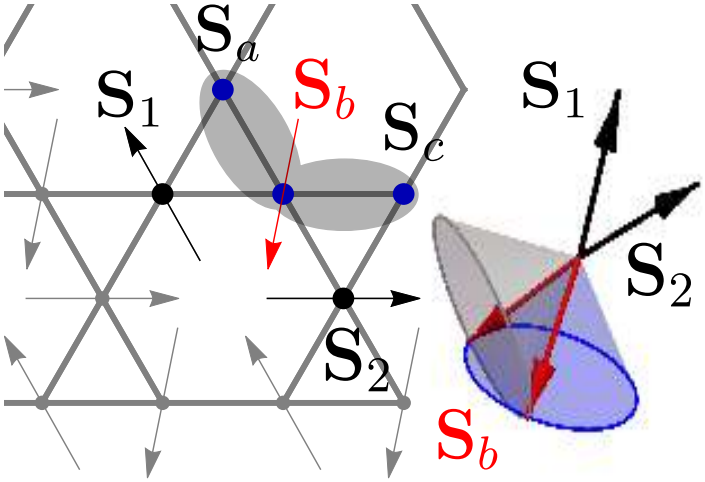
Box distribution for $J_{ij} = 1 + \delta_{ij}$

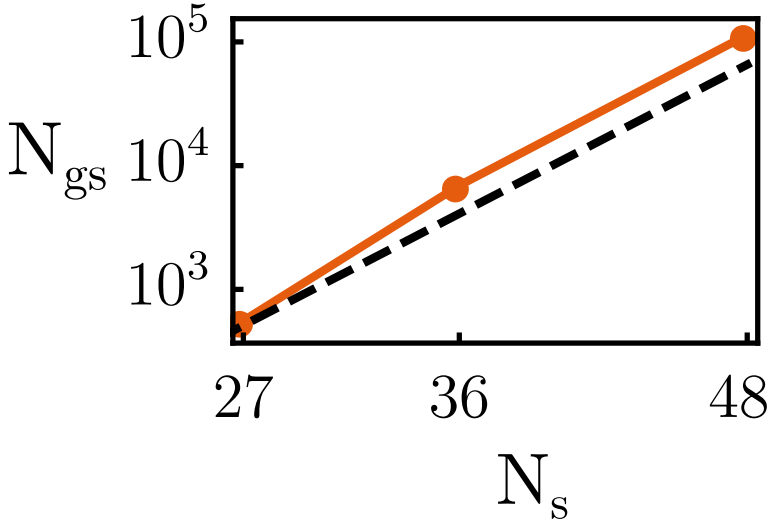
- boundedness useful



Ground-state construction by transfer matrix

- two choices at each step
- entropy $S \sim (\ln 2)/3$ per spin

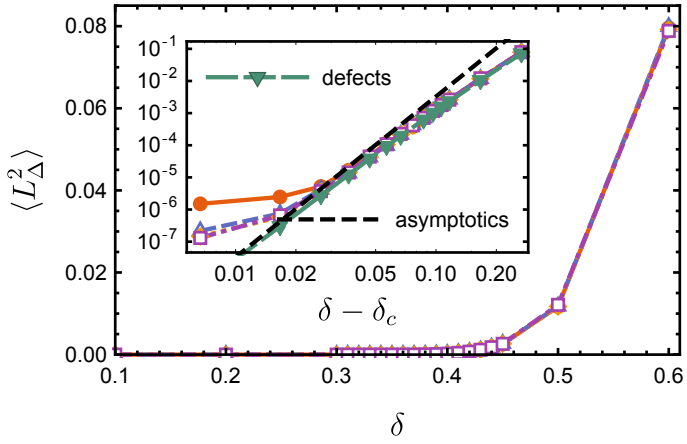




Ground state & correlations

Constraint satisfaction $(E = 0)$ until $\delta = 1/3$

- $E \sim (\delta - \delta_c)^5$

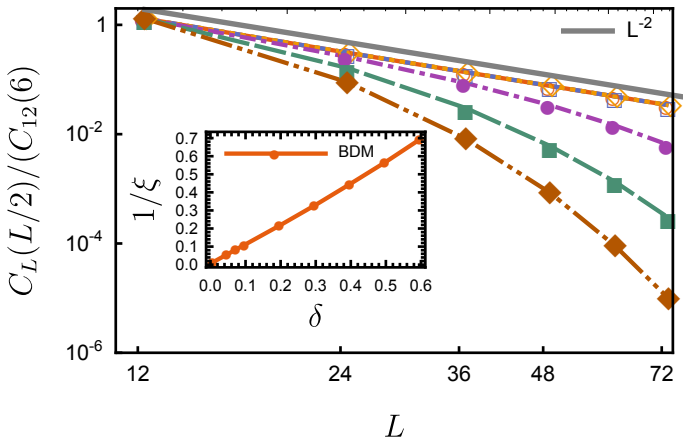


Bond-disordered model (BDM)

- "screened" with $\xi \sim 1/\delta$

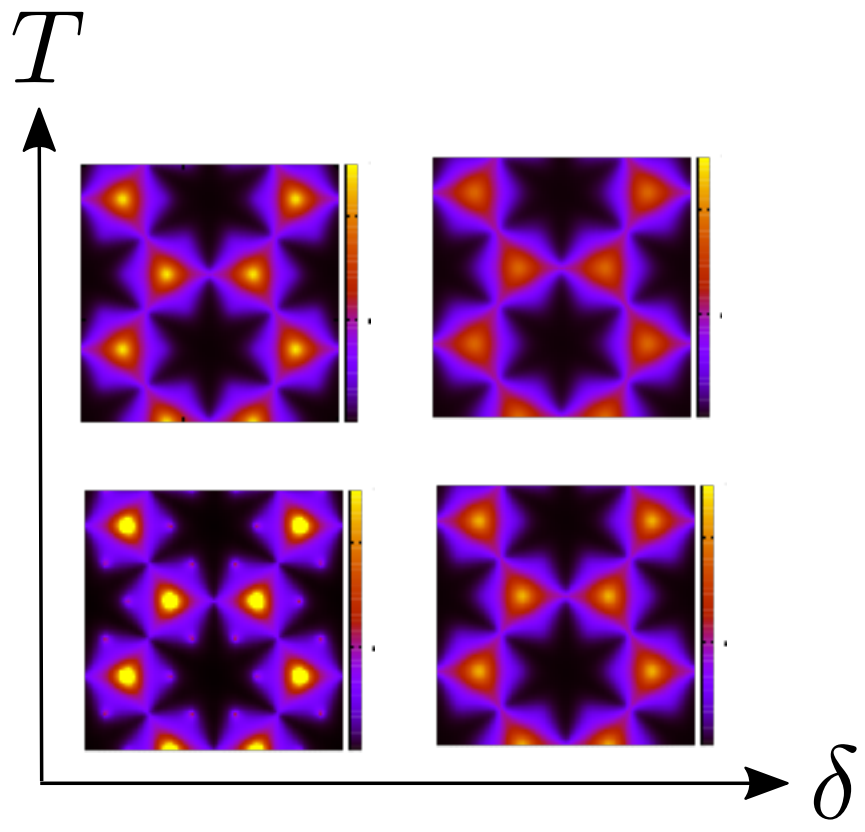
Restricted maximal Coulomb model

- $\gamma_{i\alpha} = \gamma_i \gamma_\alpha$
  (5 d.o.f. per unit cell)
- algebraic "Coulomb" correlations



No coplanar order by disorder Chalker et al., Ritchey et al.

- Peaks in structure factor disappear
- coplanar states higher in energy



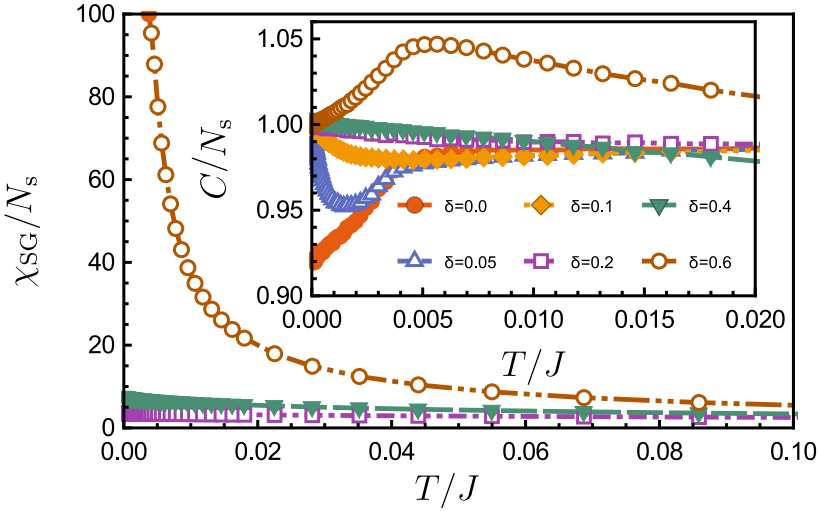
New non-coplanar ground states

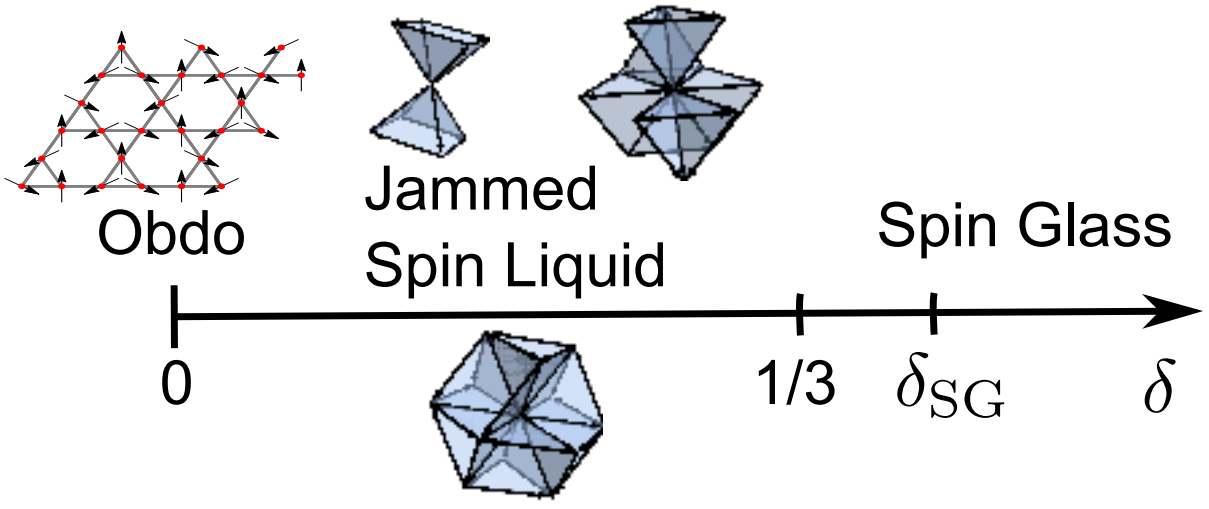
cf. Roychowdhury et al., arxiv:1705.00015

Phase diagram with disorder strength δ

Terminated by order-by-disorder $(\delta = 0)$ and spin glass $(\delta \geqslant \delta_{SG})$

- $\delta_{SG} > 1/3$
- new liquid regime?





Jammed spin liquid

Jamming: critical constraint density

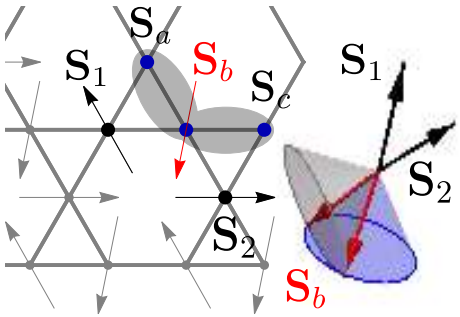
- e.g. transition in granular materials
  - exponential degeneracy

Marginally constrained, fully SAT Hamiltonian

- continuous SAT Parisi et al. 2017
- cf. Maxwellian lattices Kane+Lubensky

Open questions

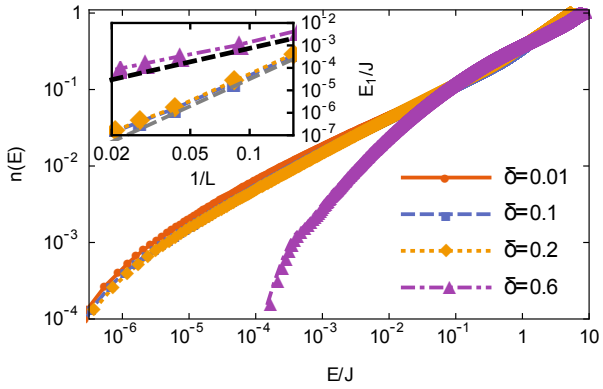
- exact ground-state entropy
- theory of soft excitations
- nature of (jamming?) transition
- existence of intermediate phase
- ...
- materials/realisations?
- dynamics (in prep.)



Local minima, soft excitations and continuity

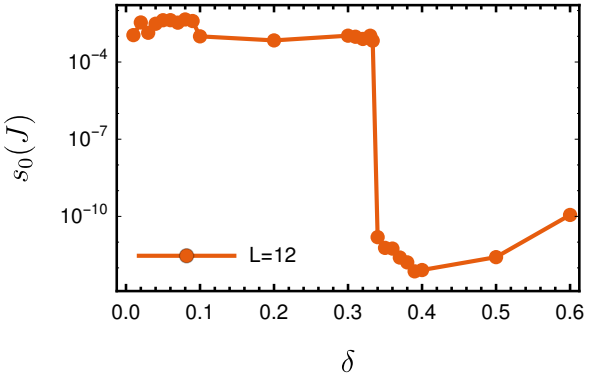
Spectrum of fluctuations (Hessian)

- gapped
  - minima rather than saddles
  - unlike conventional SLs
- anomalously soft



Ground states vary continously with δ

- limit $\delta \to 0$ appears non-singular

New set of states

- beyond spin origami