Title: Understanding the Emergence of Chiral Spin Liquids in Mott Insulators

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Abstract: In recent years, there has been a resurgence of interest in the study of chiral spin liquids (CSLs), topologically ordered states of matter that are closely related to the celebrated fractional quantum Hall states. This resurgence has been driven by the introduction of exact parent Hamiltonians and a number of numerical studies that have identified CSLs in local spin models. However, our understanding of how and why these states emerge is still lacking. I will discuss evidence supporting one particularly intuitive mechanism in which they arise as "quantum-disordered" descendants of certain non-coplanar magnetic parent states, uniting many of the CSLs found so far under a common framework.

Understanding the Emergence of Chiral Spin Liquids in Mott Insulators

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Collaborators

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CH, L. Cincio, Z. Papic, A. Paramekanti, PRL **116**, 137202 (2016)
CH, L. Cincio, Z. Papic, A. Paramekanti, arXiv:1705.05381

Outline

- Introduction
  - Quantum Spin Liquids
  - Chiral Spin Liquids (CSLs)
  - Regular Magnetic Orders (RMOs)
- RMOs as CSL Parent States
  - Honeycomb Lattice
  - Triangular Lattice
  - Square Lattice
  - ~~Kagome Lattice~~
- Conclusions

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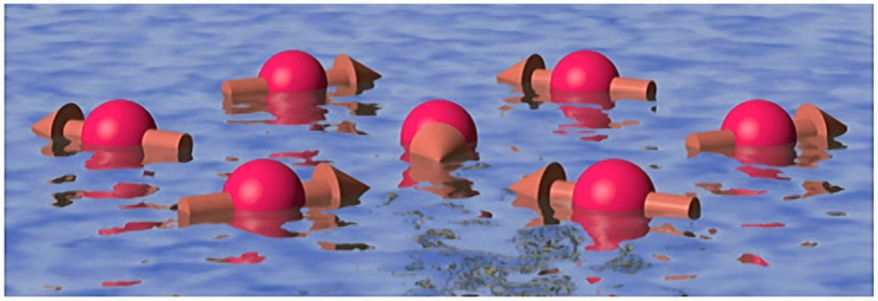

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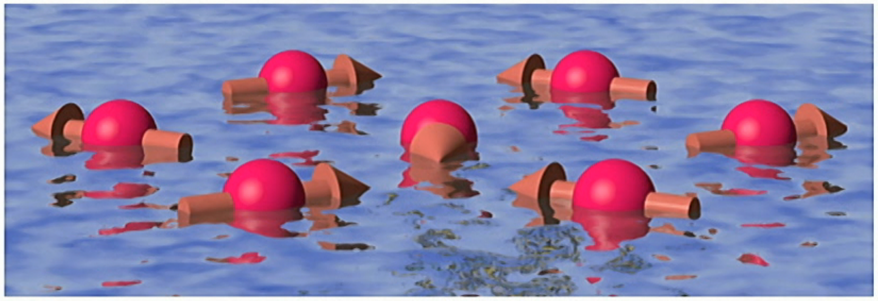


High-T_c Cuprates

Frustrated Magnets

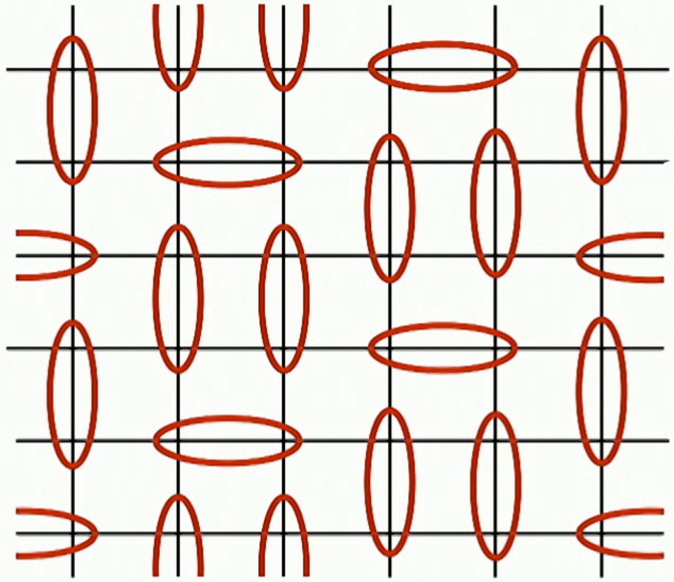
Quantum Dimer Models

Lattice Gauge Theory

Topological Quantum Computing

Spin Liquids as Resonating Valence Bond States

- Resonating Valence Bond (RVB) idea proposed by Anderson envisions the wavefunction as a superposition of different singlet pairings



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

P. W. Anderson, Mater. Res. Bull. **8**, 153 (1973)

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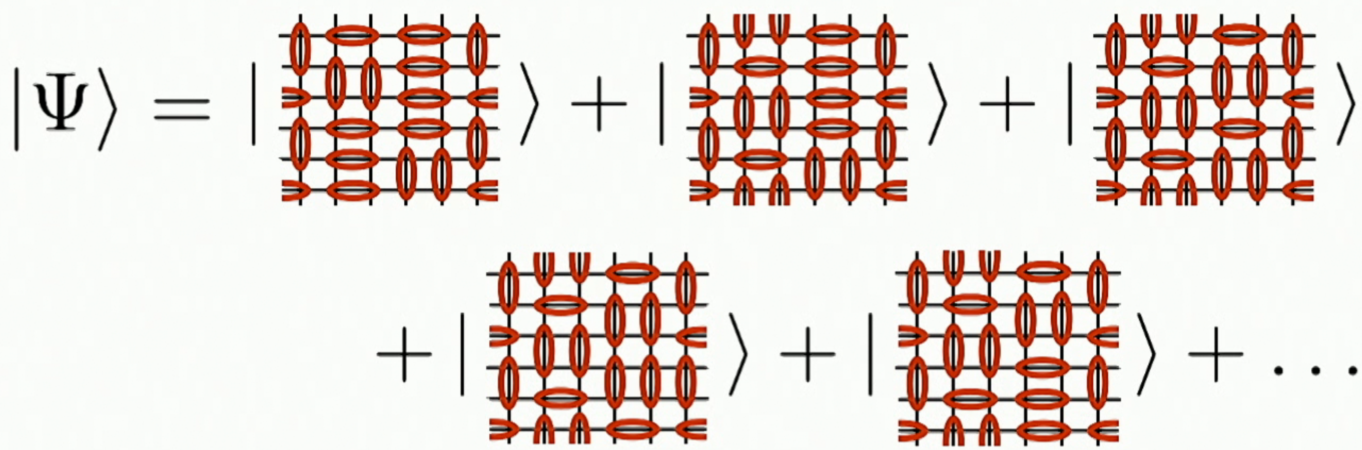


P. W. Anderson, Mater. Res. Bull. **8**, 153 (1973)

Spin Liquids as “Quantum-Disordered” States

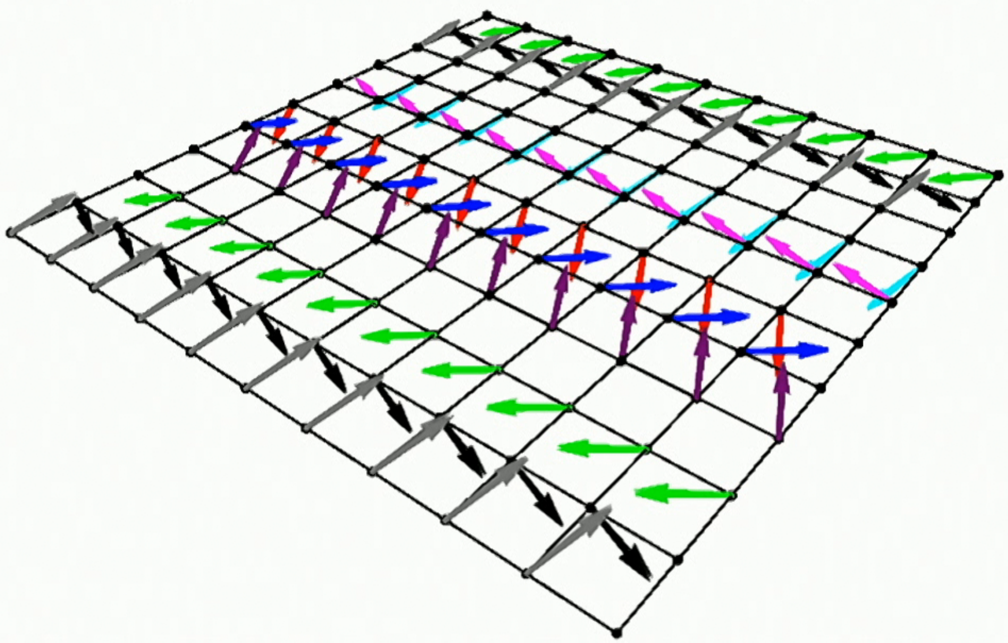
Start with an ordered magnetic/valence bond “parent” state

↓

Frustrate that order by tuning the Hamiltonian

↓

Quantum fluctuations may be strong enough
to melt the magnetic/valence bond order and produce a QSL



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Chiral Spin Liquids

- Spin liquids with broken time-reversal symmetry, non-zero scalar spin chirality $\mathbf{S}_i \cdot \mathbf{S}_j \times \mathbf{S}_k \neq 0$

V. Kalmeyer, R. B. Laughlin, PRL **59**, 2095 (1987)

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Spin-1/2	$\longleftrightarrow$	Hardcore Bosons
$\vert\uparrow\rangle$		$\vert 1\rangle$
$\vert\downarrow\rangle$		$\vert 0\rangle$

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  - Two-fold GS degeneracy on a torus (each with specific quantum numbers)

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How do such phases emerge? Is there a common mechanism that unites the various CSLs that have been found so far?

V. Kalmeyer, R. B. Laughlin, PRL **59**, 2095 (1987)

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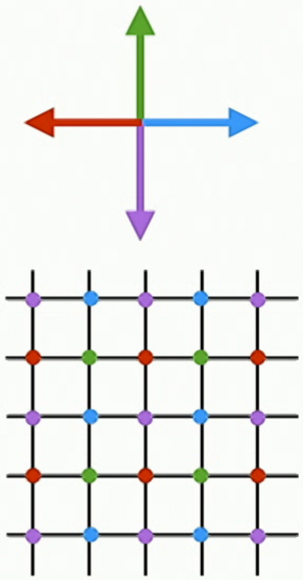
Example: Square Lattice Coplanar Spiral



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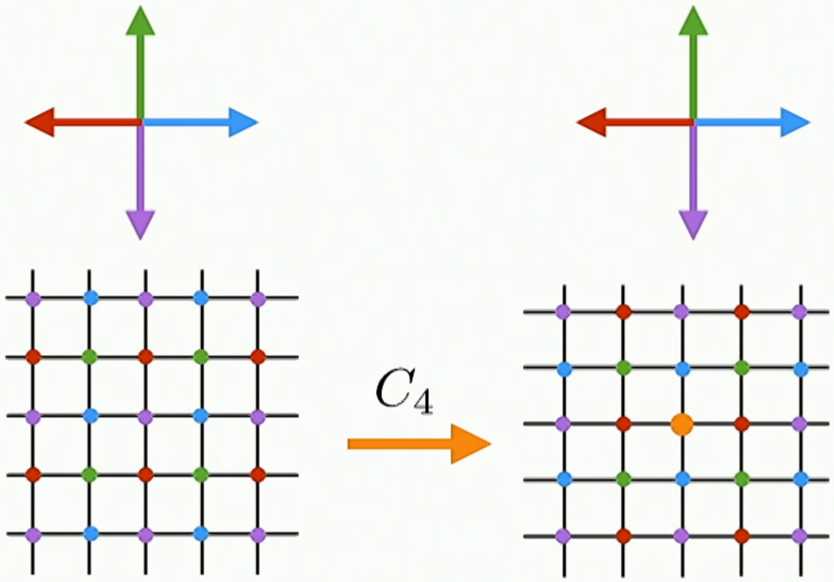

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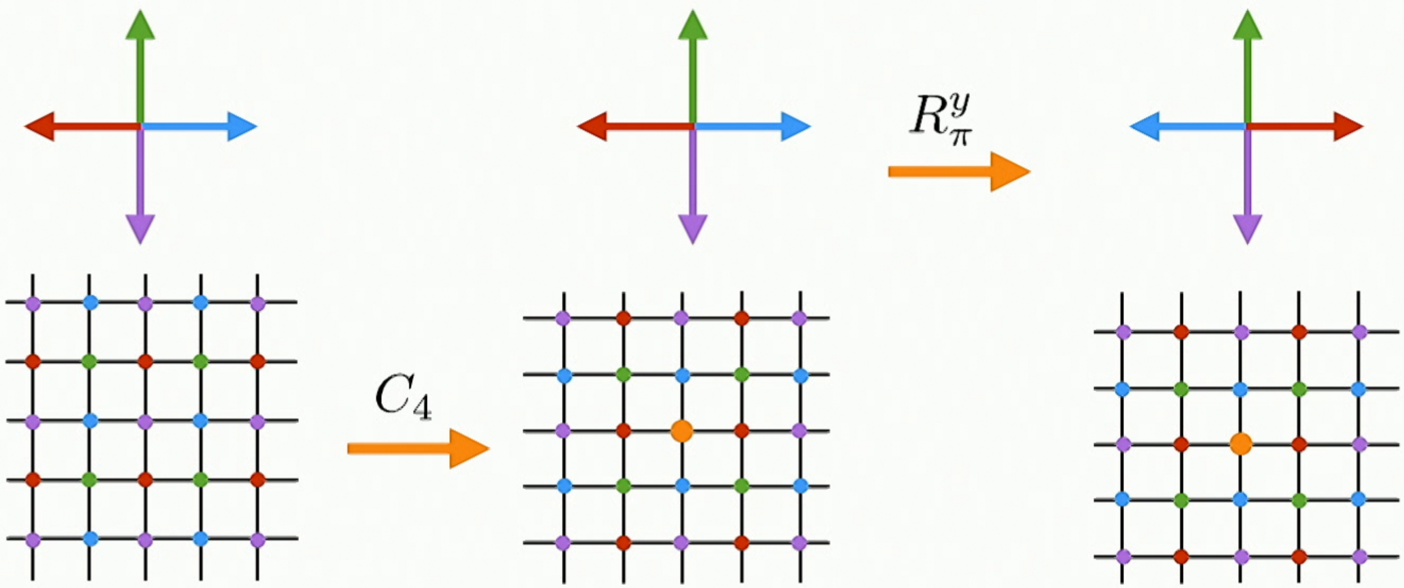
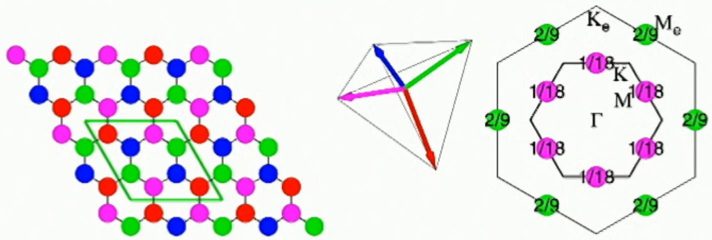


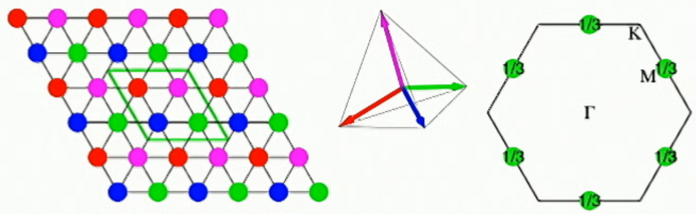
Regular Magnetic Orders

Honeycomb



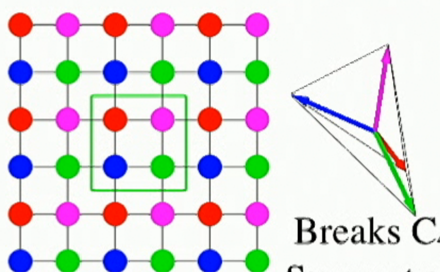
(d) Tetrahedral state. $E = -J_1 - 2J_2 + 3J_3$.

Triangular



(b) Tetrahedral state. $E = -2J_1 - 2J_2 + 6J_3 - 34K/3$.

Square



Breaks C_4 Symmetry!

(e) Tetrahedral umbrella states (*AF umbrellas*)

Kagome

(will not discuss here)

L. Messio, C. Lhuillier, G. Misguich, PRB **83**, 184401 (2011)

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RMOs as CSL Parent States

1. The regular magnetic orders (RMOs) for the honeycomb, triangular, square and kagome lattices have all been constructed.

2. In recent years SU(2) invariant spin models with CSL ground states have also been found for all of these lattices.

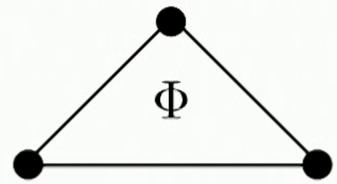
Can these CSL states be understood
as quantum-disordered RMOs?

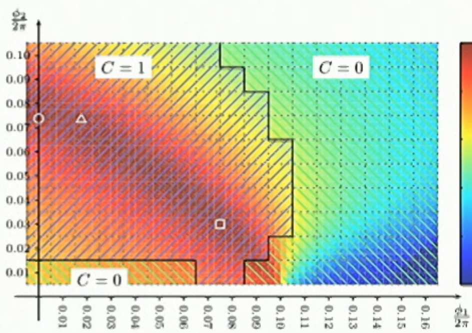
Model Hamiltonians

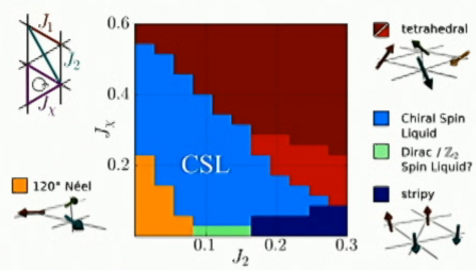
$$H = \sum_{i,j} J_{ij}\, \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ijk} J_\chi\, \mathbf{S}_i \cdot \mathbf{S}_j \times \mathbf{S}_k$$

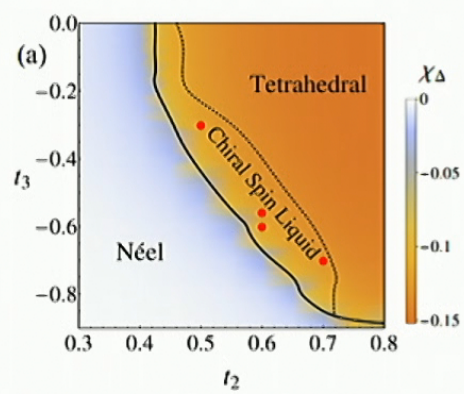
- From a Hubbard model, the coefficients are:

$$J_{ij} = \frac{4t_{ij}^2}{U} \quad , \quad J_\chi = \frac{24t^3}{U^2} \sin\Phi$$









A.B. Nielsen, G. Sierra, J.I. Cirac, Nature Comm **4** (2013)
CH, L. Cincio, Z. Papic, A. Paramekanti, PRL **116**, 137202 (2016)
A. Wietek, A. Läuchli, PRB **95**, 035141 (2017)

Numerical Signatures

- Static Spin Structure Factor

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- Ground State Manifold Fidelity:

$$F_n(g) = \frac{1}{n}\sum_{i=1}^{n} |\langle \Psi_i(g)|\Psi_i(g+\delta g)\rangle|$$

and its numerical second derivative χ_n^F

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Exact Diagonalization

A. Sandvik, AIP Conf. Proc. 1297:135 (2010) / arXiv:1101.3281

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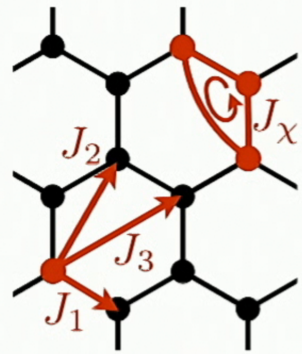
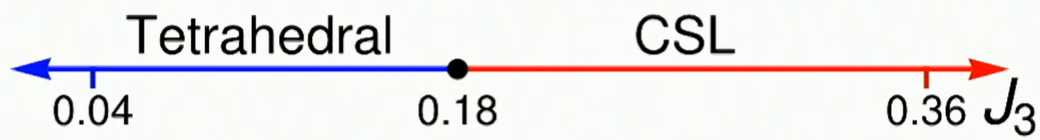
Honeycomb Lattice





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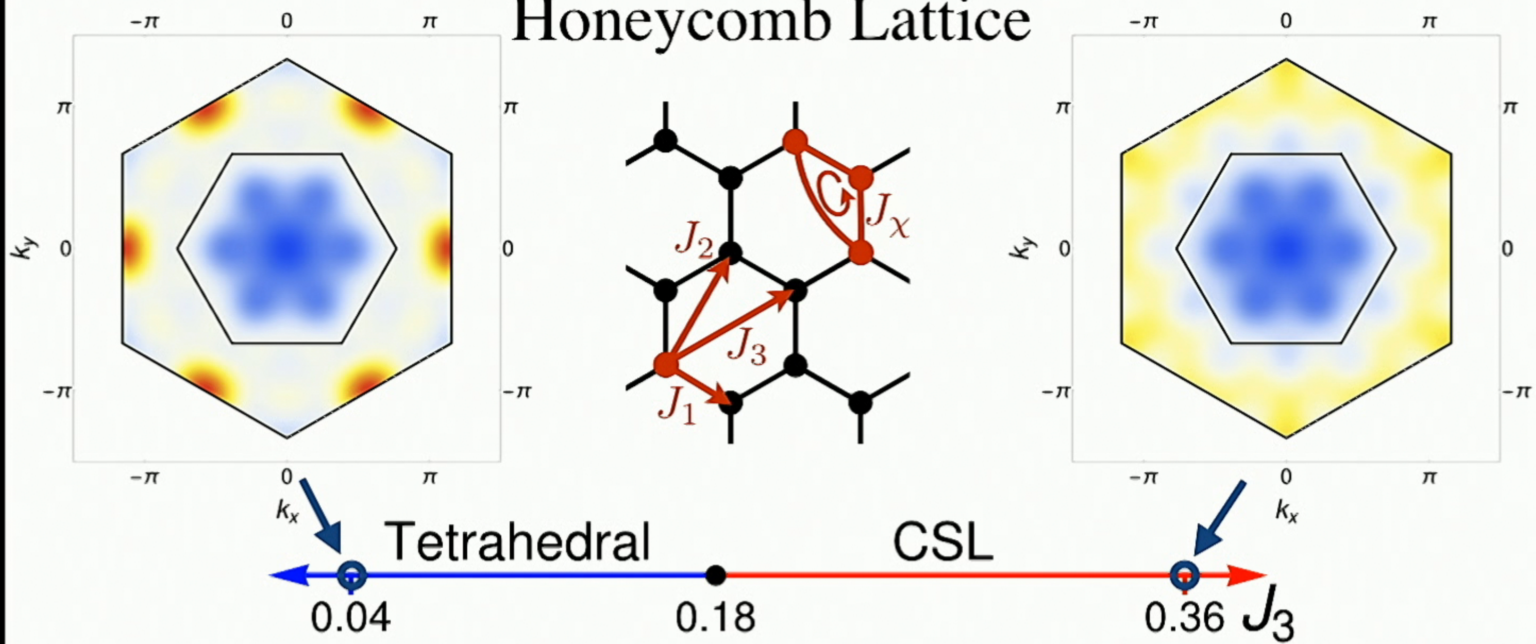
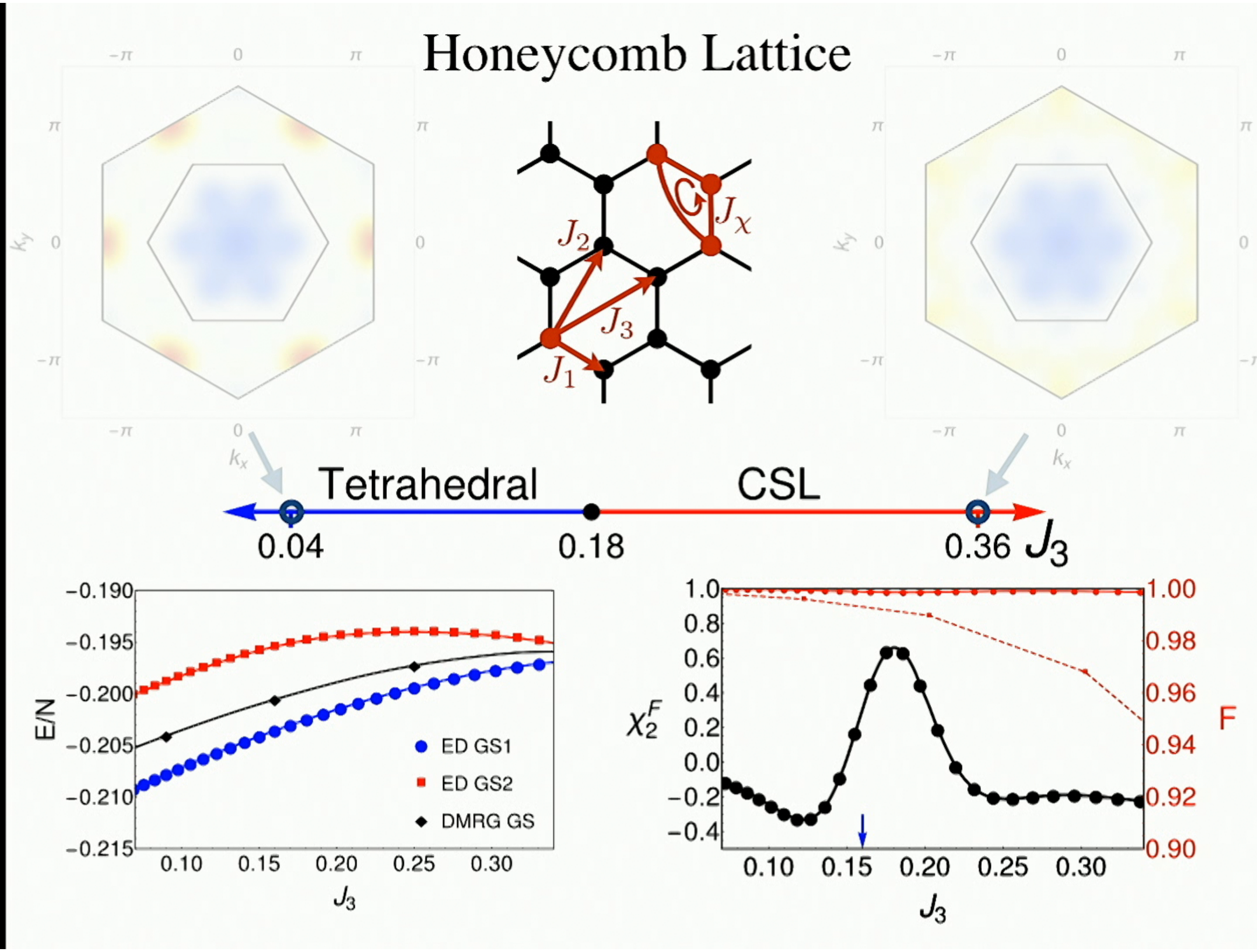
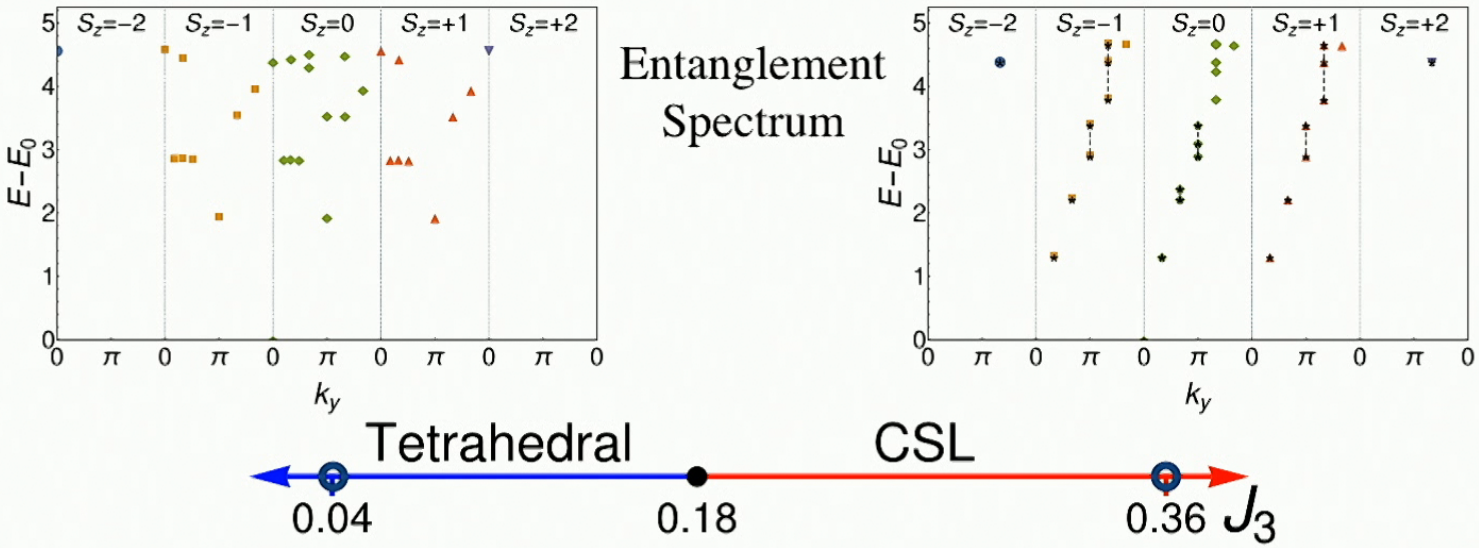


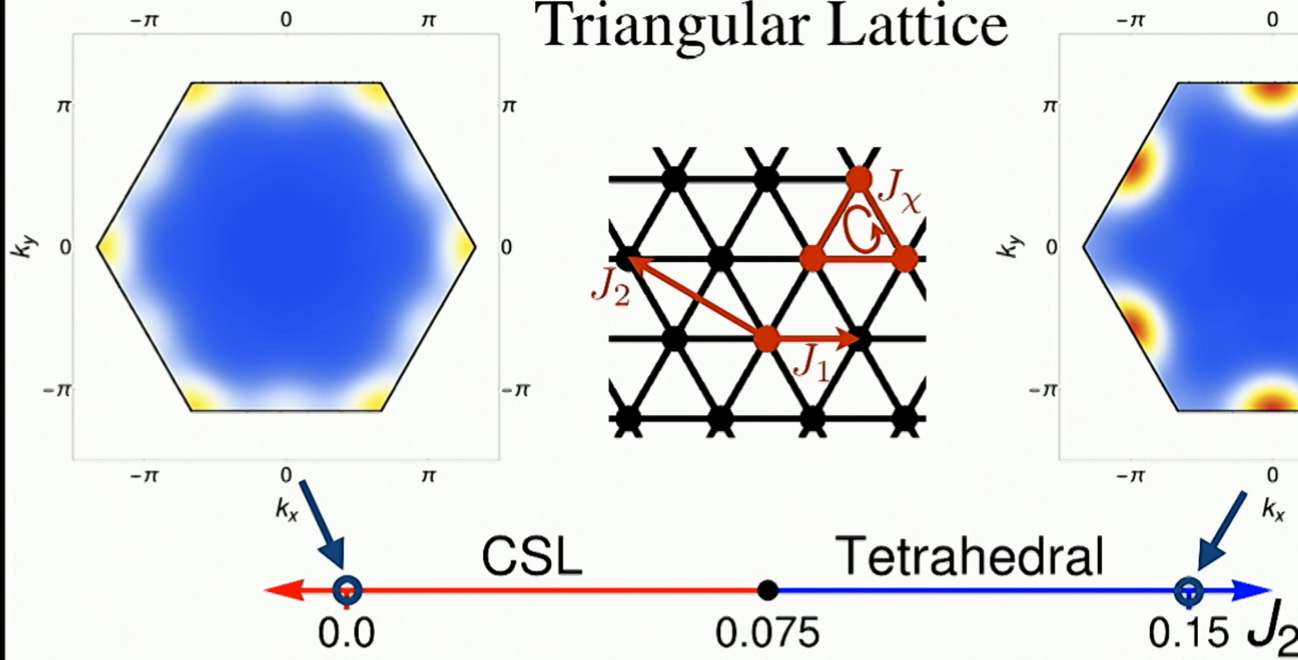

Honeycomb Lattice
Tetrahedral
CSL
0.04
0.18
0.36 J3
E/N
ED GS1
ED GS2
DMRG GS
J3
F

Honeycomb Lattice

Entanglement Spectrum



Triangular Lattice



A. Wietek, A. Läuchli, PRB **95**, 035141 (2017)

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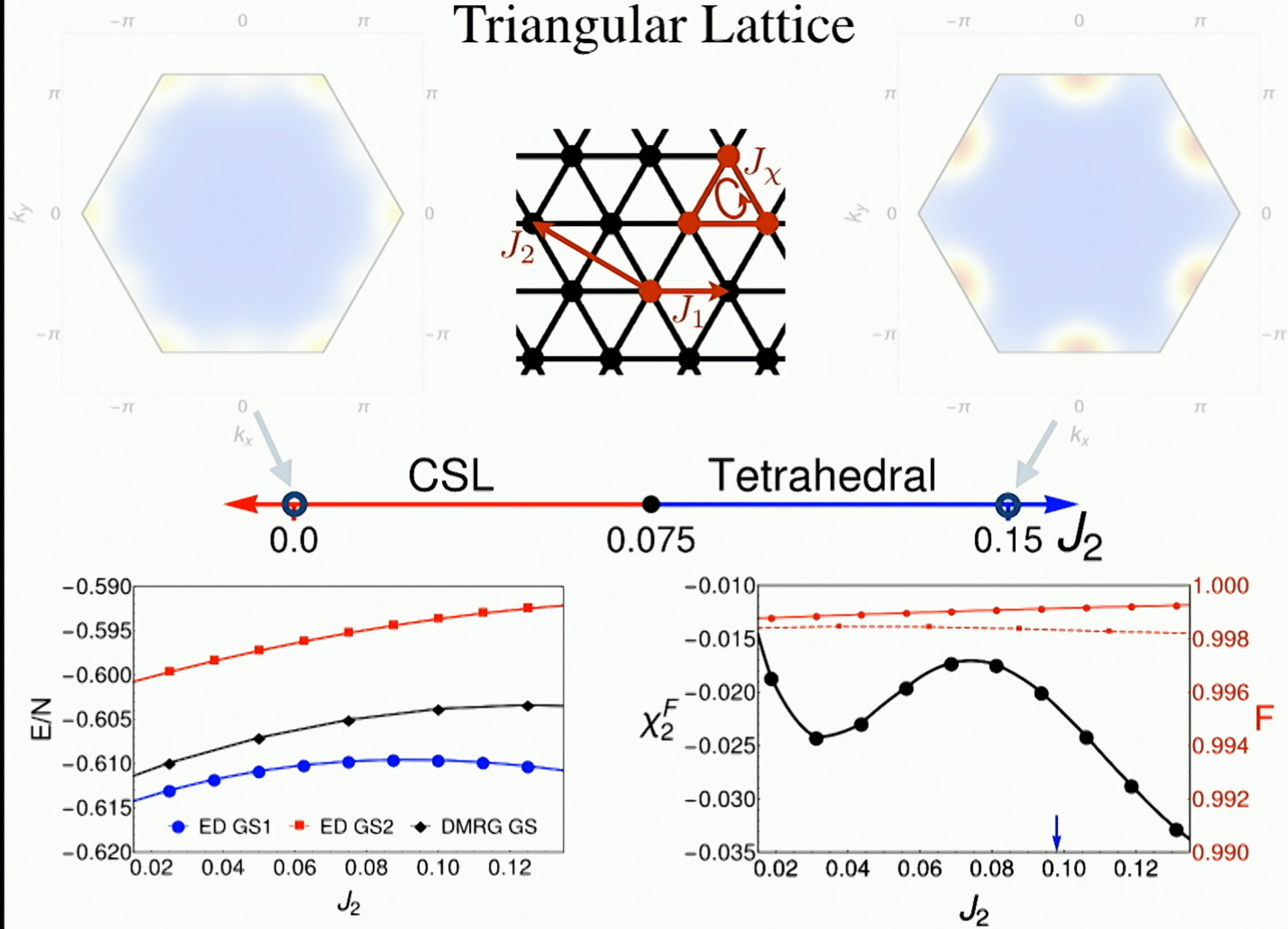
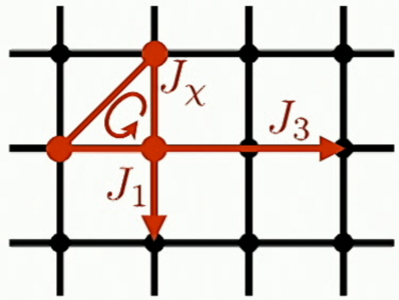
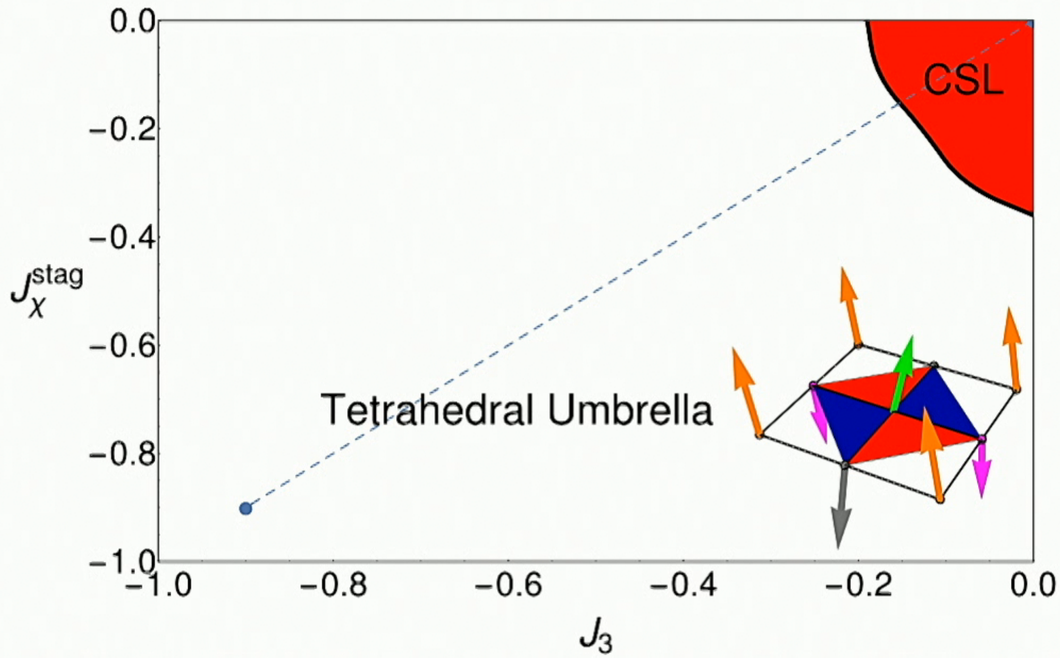


Square Lattice





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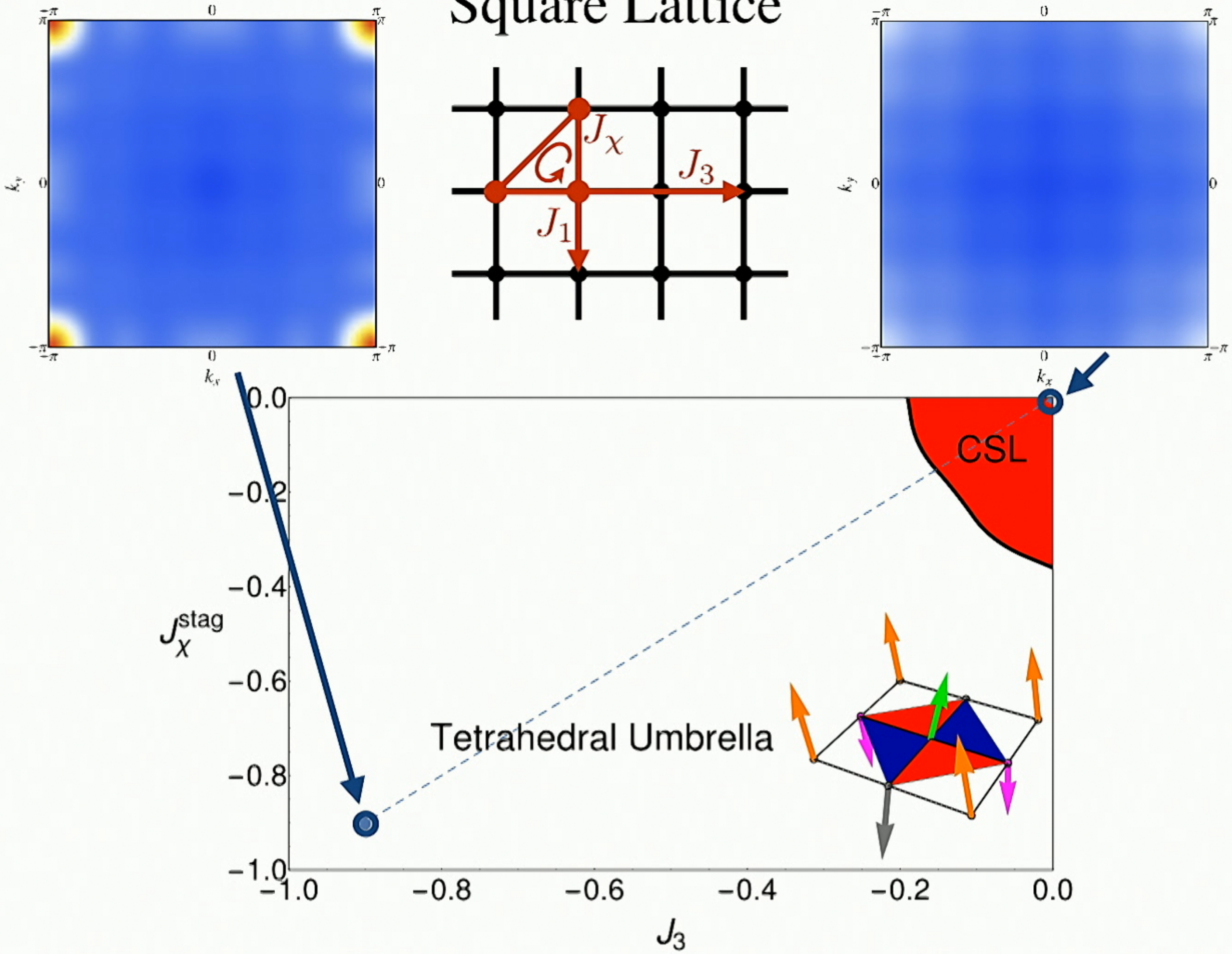

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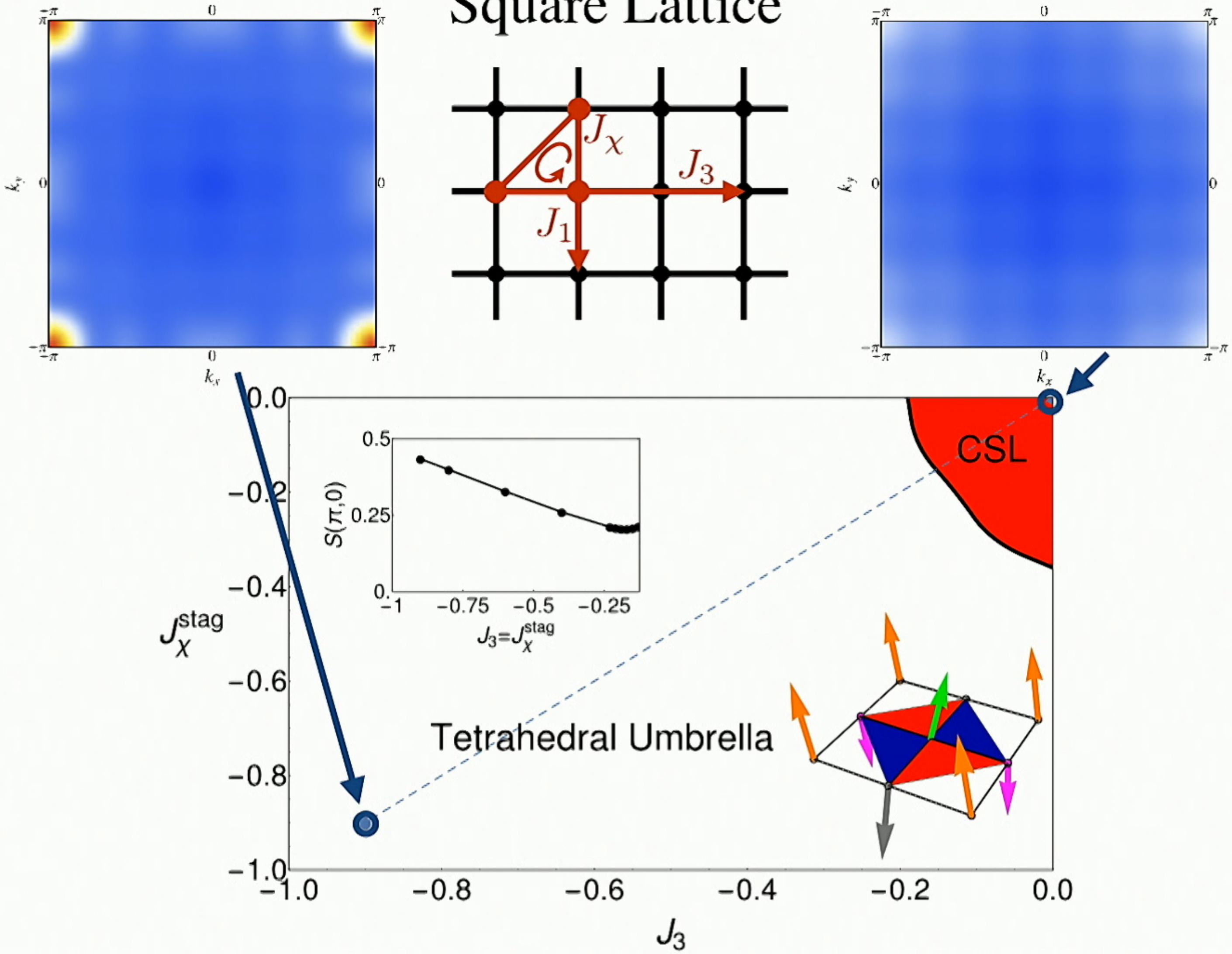

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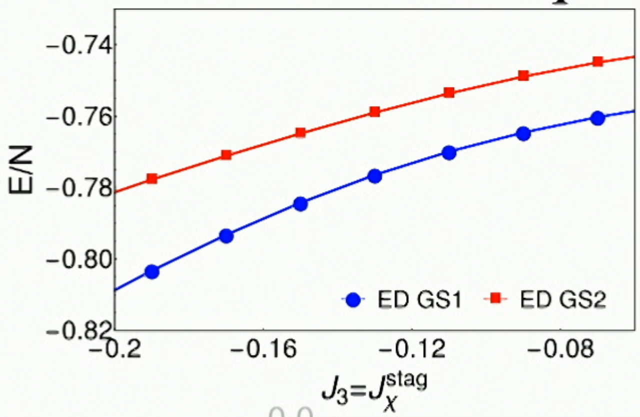

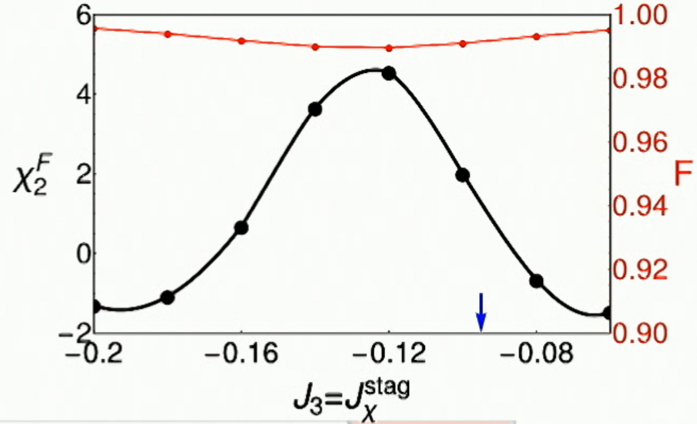

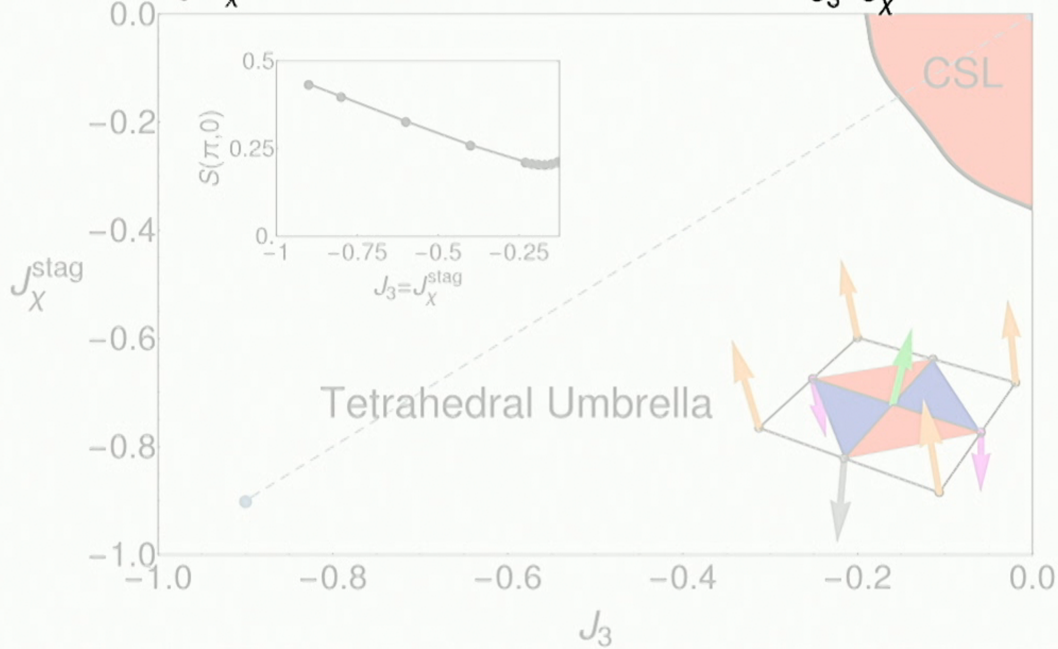

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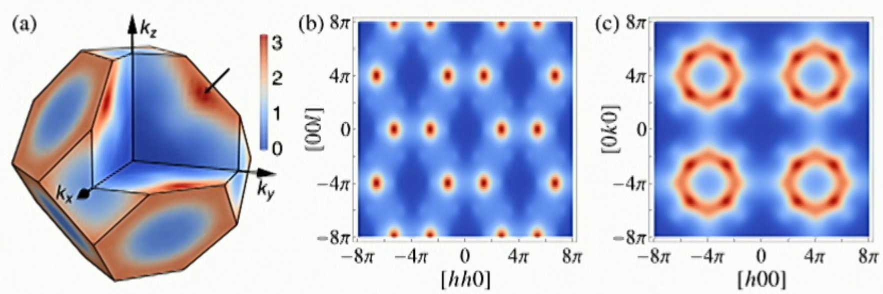
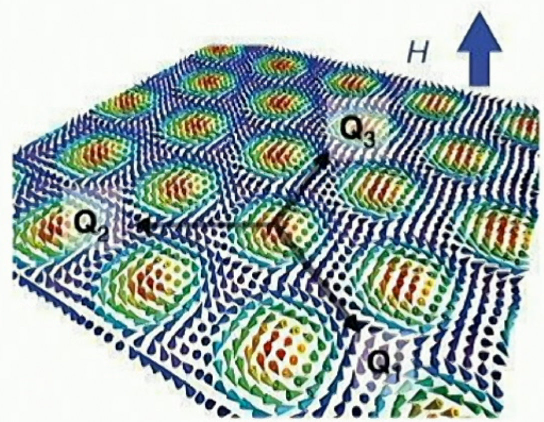
- Future Work
  - 3-d generalisation?
  - Higher-spin (e.g. spin-1) generalisation?
  - Relation to skyrmion crystals?
  - Natural field theory of the transition?





Y. Iqbal et al., arXiv:1705:05291


Thank you!