Title: Chiral Magnetic and Topological Order in Mott Insulators

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Abstract: <p>Experimentalists have recently been able to engineer non-trivial topological band structures using ultracold atoms in optical lattices.</p>

<p>Motivated by ongoing experimental efforts to tune interactions, we explore the interplay between strong correlations and topology in these systems. Focusing on the Haldane-Hubbard honeycomb model as an example, we show that its strongly interacting Mott limit exhibits various chiral magnetic orders, including a wide regime of triple-Q tetrahedral order. Incorporating an additional third-neighbour hopping frustrates and ultimately "quantum-melts" the tetrahedral magnetic order. From analysing low energy spectra, many-body Chern numbers, entanglement spectra, and modular matrices, we identify the molten state as a chiral spin liquid with gapped semion excitations. Our numerical results suggest that this frustration induced melting may be realised as an exotic continuous quantum phase transition. Finally, we discuss recent results which point toward a common mechanism of realising chiral spin liquids through the continuous melting of non-coplanar magnetic "parent" states.</p>

Chiral Magnetic and Topological Order in Mott Insulators

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Collaborators

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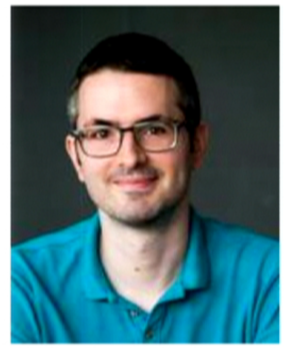

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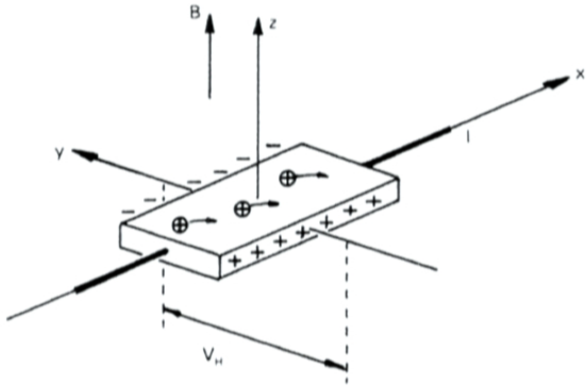
CH, L. Cincio, Z. Papic, A. Paramekanti, PRL **116**, 137202 (2016)
CH, P. Rath, A. Paramekanti, PRB **91**, 134414 (2015)

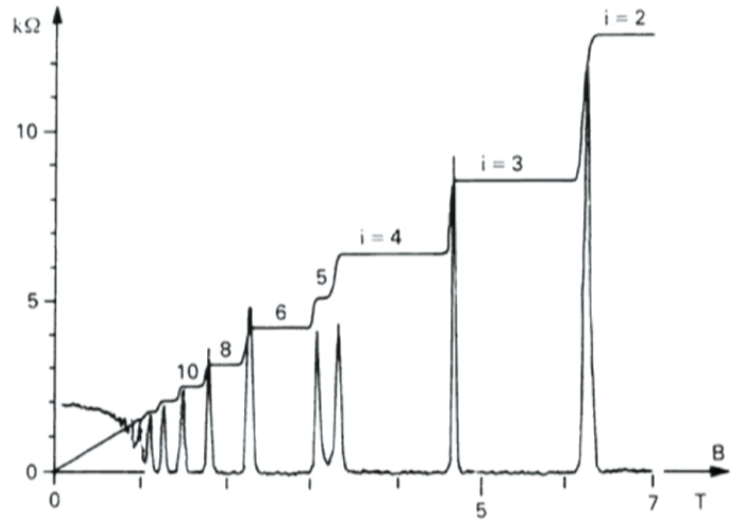
Outline

- Motivation
  - Integer and Fractional Quantum Hall Physics
  - Ultracold Atoms and the Haldane Model
- Haldane-Hubbard Model
  - Effective Spin Hamiltonian
  - Classical/Quantum Phase Diagrams
- Disordering the Tetrahedral
  - Quantum Spin Liquids
  - Numerical Signatures of Chiral Spin Liquids
- RMOs as Chiral Spin Liquid “Parent States”
- Conclusions

Integer Quantum Hall Effect (IQHE)

2-D electron gas in uniform magnetic field





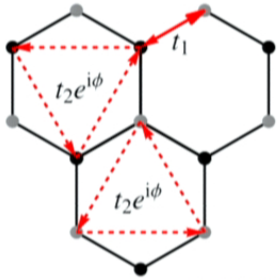
- Plateaus with quantized Hall conductivity: $\sigma_{xy} = ne^2/h$
- Quantized to better than one part in 10^9
- Can be understood in terms of non-interacting electrons in Landau levels

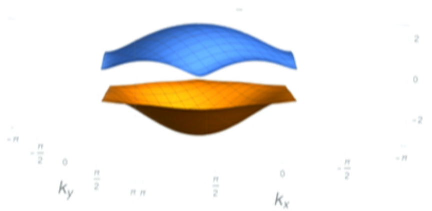
K. v. Klitzing, G. Dorda, M. Pepper, PRL **45**, 494 (1980)

IQHE without Landau Levels

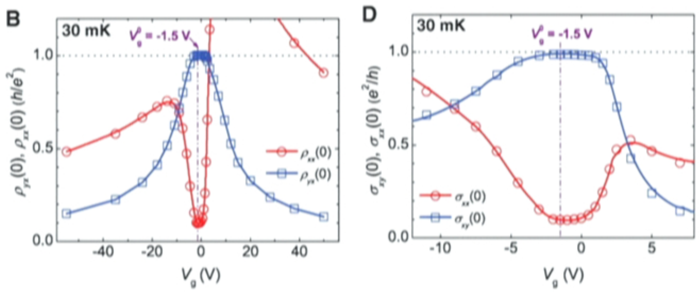
- Band insulators can also exhibit IQH physics

Haldane's Honeycomb Model
(Chern Insulator)





Quantum Anomalous Hall Effect

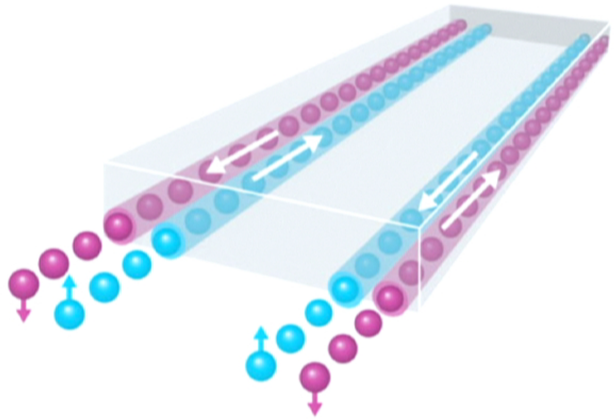


C.-Z. Chang, Science **340**, 167 (2013)

Hall conductivity related to topological property of band structure

$$\sigma_{xy} \propto \int_{BZ} F\ d^2k$$

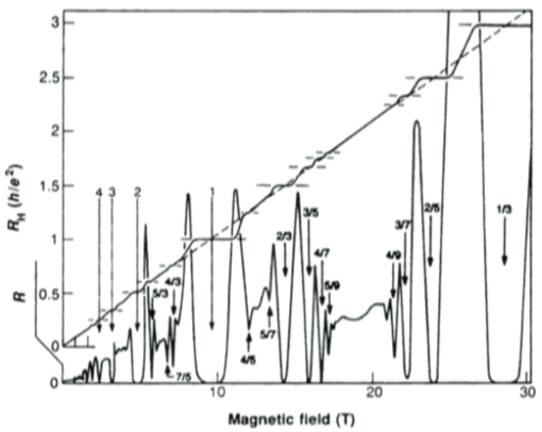
Quantum Spin Hall Effect



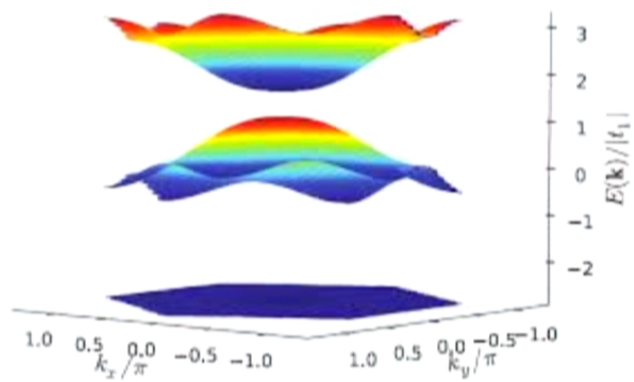
Interacting Quantum Hall Systems

KE quenched due to

Landau level physics or Flat band physics



Fractional Quantum Hall Effect

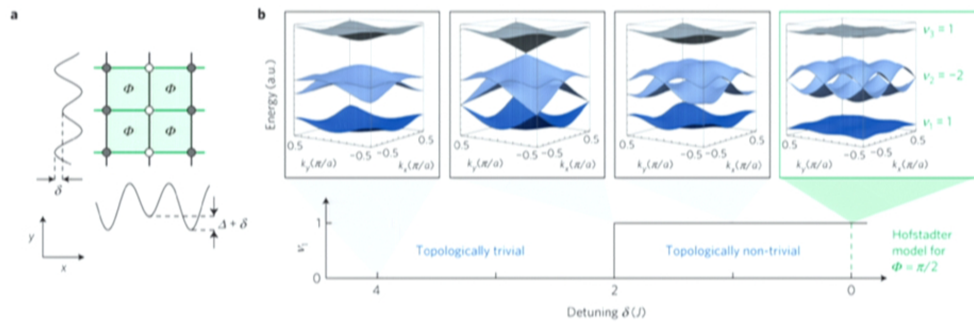


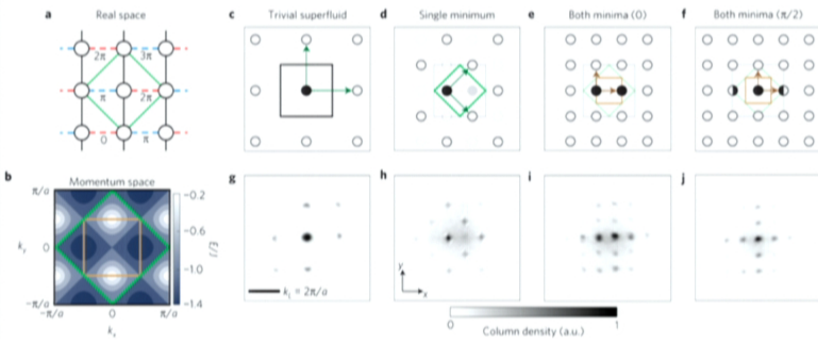
Fractional Chern Insulators

- At fractional filling, interactions lead to fractionalization of fermions and a new type of "topological order"
  - Topology-dependent GS degeneracy
  - Bulk anyonic excitations
  - Robust against *any* local perturbation

Cold Atoms and Artificial Magnetic Fields

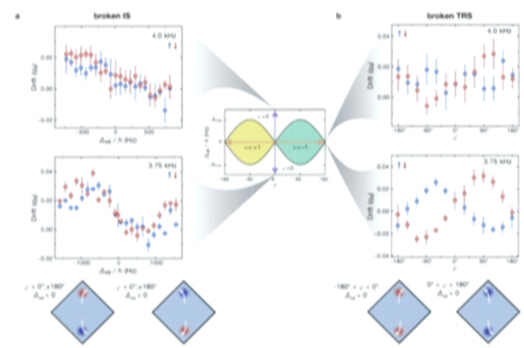
Hofstadter Model
(M Aidelsburger et al, Nature Physics, 2015)





BEC in strong B-field
(CJ Kennedy et al, Nature Physics 2015)

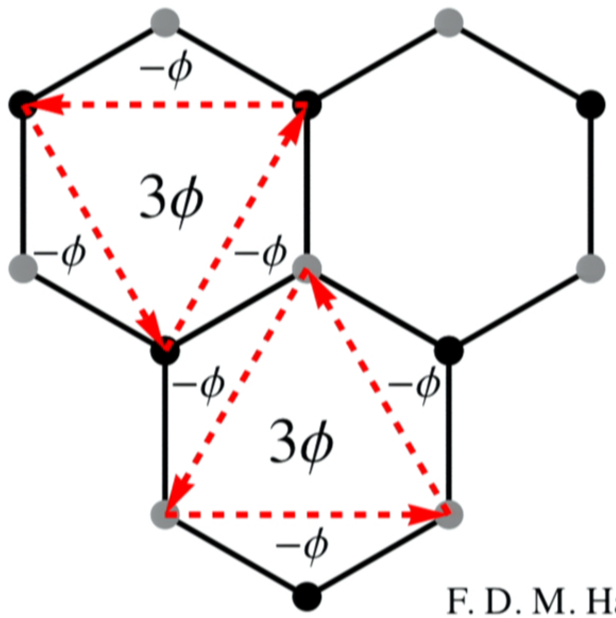
Haldane Model
(G. Jotzu et al, Nature 2014)



Haldane Model:
Quantized σ_{xy} without Landau levels

$$H_{\mathrm{Hal}} = -t_1 \sum_{\langle i,j \rangle} (c_i^\dagger c_j + h.c.) - t_2 \sum_{\langle\langle i,j \rangle\rangle} (e^{i\nu_{ij}\phi} c_i^\dagger c_j + h.c.) + \Delta_{AB} \sum_{i \in A} c_i^\dagger c_i$$

Broken Time-Reversal Symmetry (Chern insulator)



F. D. M. Haldane, PRL **61**, 2015 (1988)

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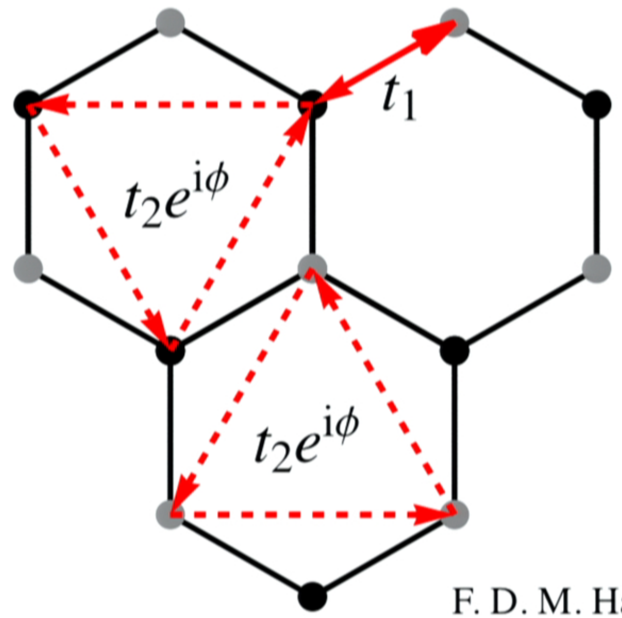

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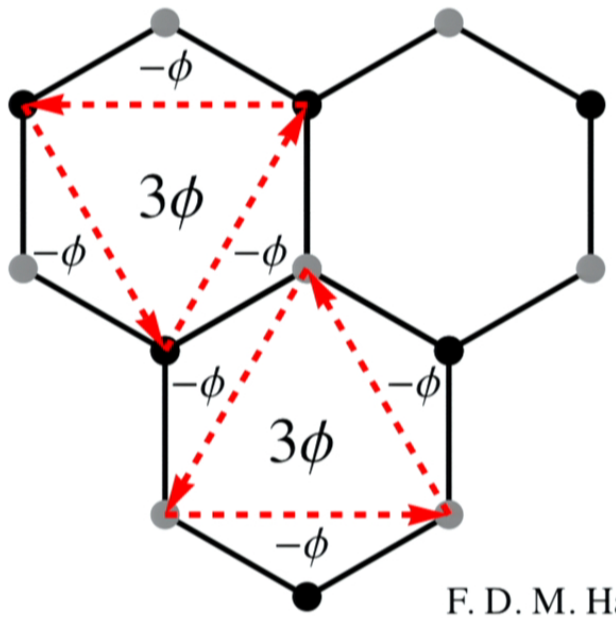
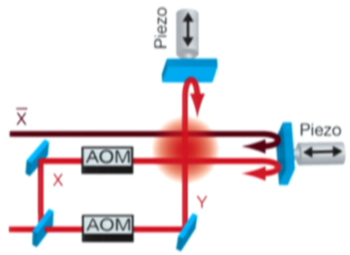
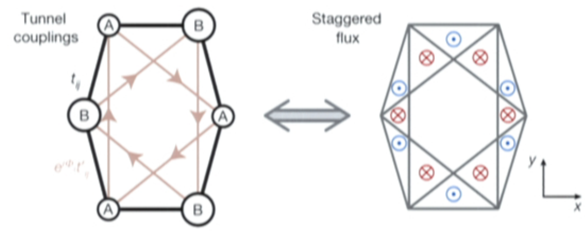


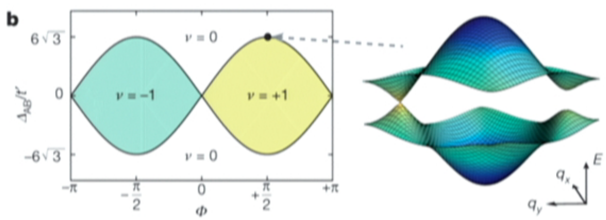
F. D. M. Haldane, PRL **61**, 2015 (1988)

Experimental Realisation of the Haldane Model

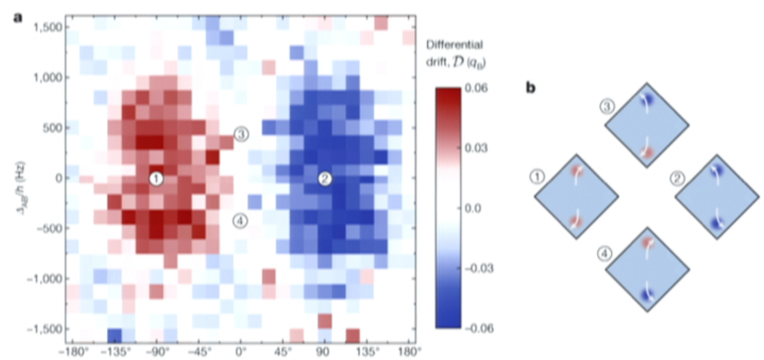




Periodic Lattice Shaking ⟷ Effective Staggered Flux Pattern



Location of gap closing points measured using Bloch oscillations



Berry curvature at Dirac points measured using differential drift

G. Jotzu et al., Nature **515**, 237 (2014)

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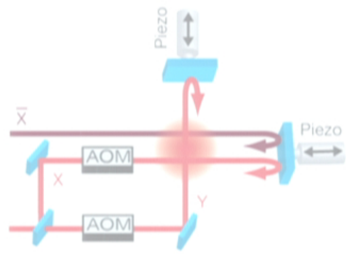
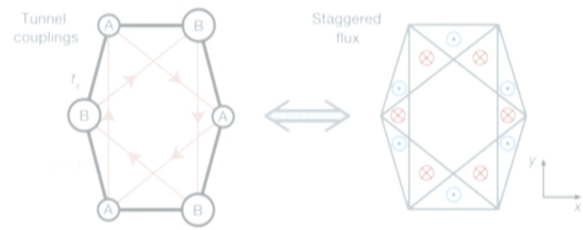
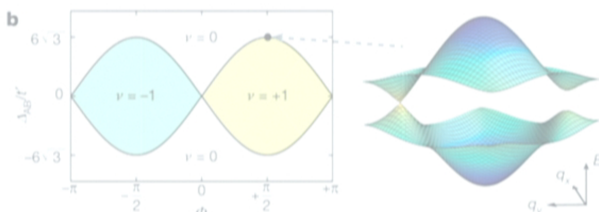




Periodic Lattice Shaking ⟷ Effective Staggered Flux Pattern

What about adding interactions?



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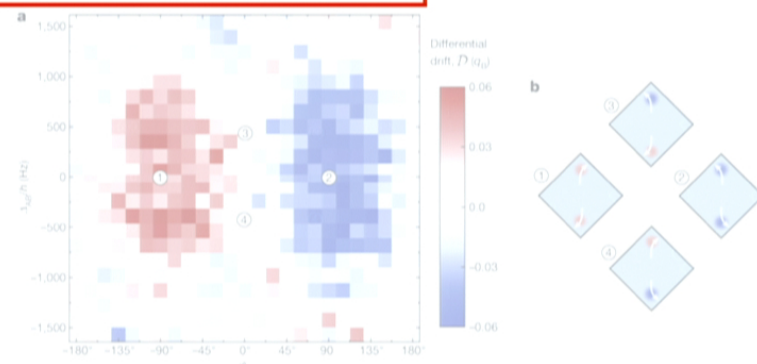

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G. Jotzu et al., Nature **515**, 237 (2014)

$$V(x, y)$$

$$V(x + \delta x(t),\ y + \delta y(t))$$

$$\vec{p} \to \vec{p} + \vec{A}(t)$$

$$V(\tilde{x}, \tilde{y})$$

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Quantized σ_{xy} without Landau levels

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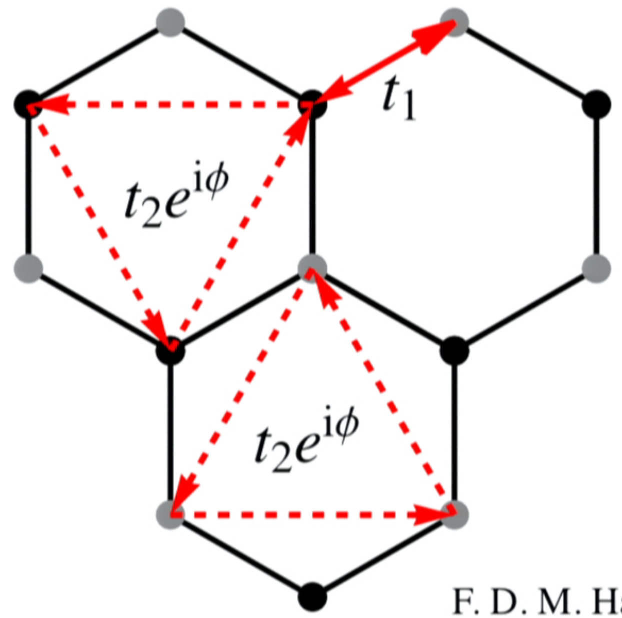
Broken Time-Reversal Symmetry (Chern insulator)



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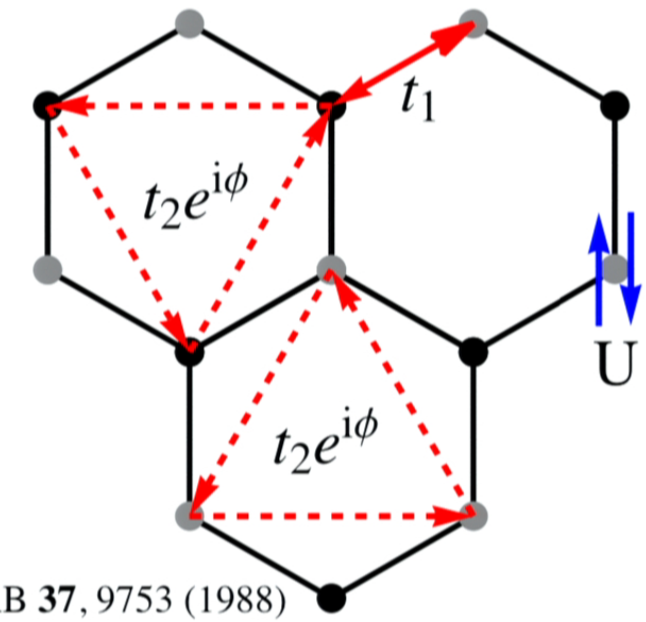
Haldane-Hubbard Model

$$H_{\rm HH} = -t_1 \sum_{\langle ij \rangle \sigma} (c^\dagger_{i\sigma} c_{j\sigma} + h.c.) - t_2 \sum_{\langle\langle ij \rangle\rangle \sigma} (e^{i\nu_{ij}\phi} c^\dagger_{i\sigma} c_{j\sigma} + h.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

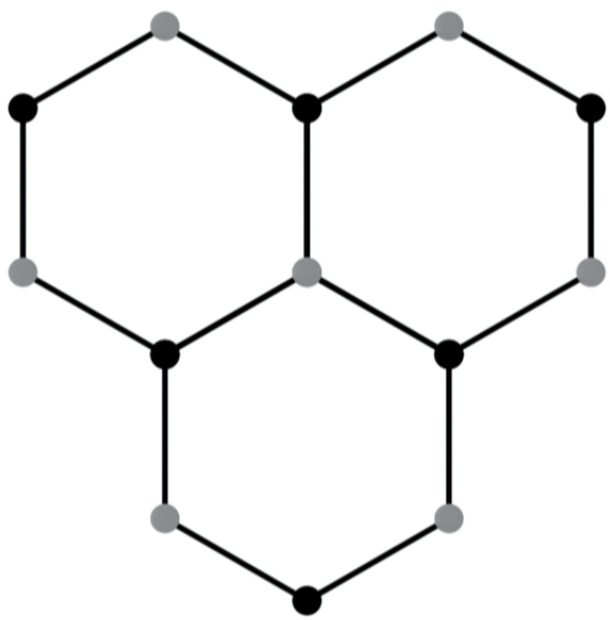
At half-filling, for U >> t_1, t_2, we can derive an *effective spin Hamiltonian*



A. H. MacDonald et al., PRB **37**, 9753 (1988)

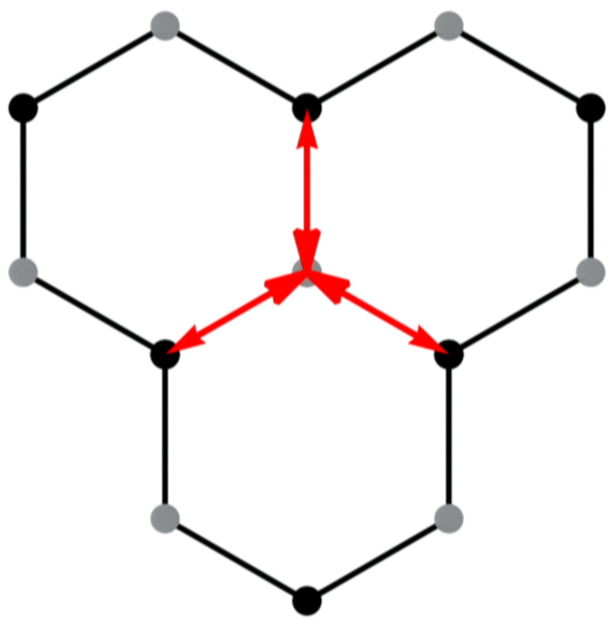
Effective Spin Hamiltonian

$$H_{\rm spin} = \frac{4t_1^2}{U} \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + \frac{4t_2^2}{U} \sum_{\langle\langle ij \rangle\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$



Effective Spin Hamiltonian

$$H_{\text{spin}} = \boxed{\frac{4t_1^2}{U} \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j} + \frac{4t_2^2}{U} \sum_{\langle\langle ij \rangle\rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$



Effective Spin Hamiltonian

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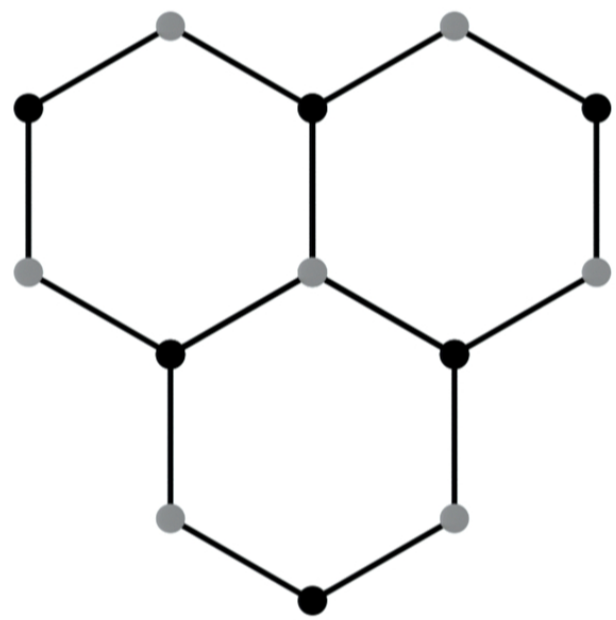
At this order the flux does not appear!



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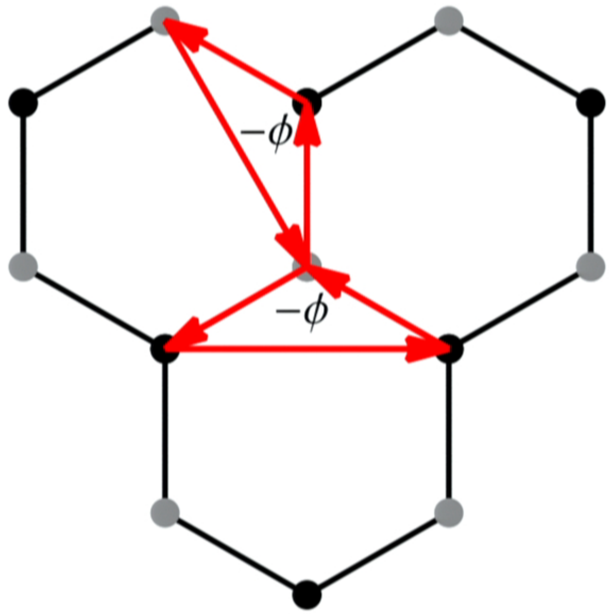
$$+ \frac{24 t_1^2 t_2}{U^2} \sum_{\text{small}-\triangle} \hat{\chi}_\triangle \sin \Phi_\triangle$$

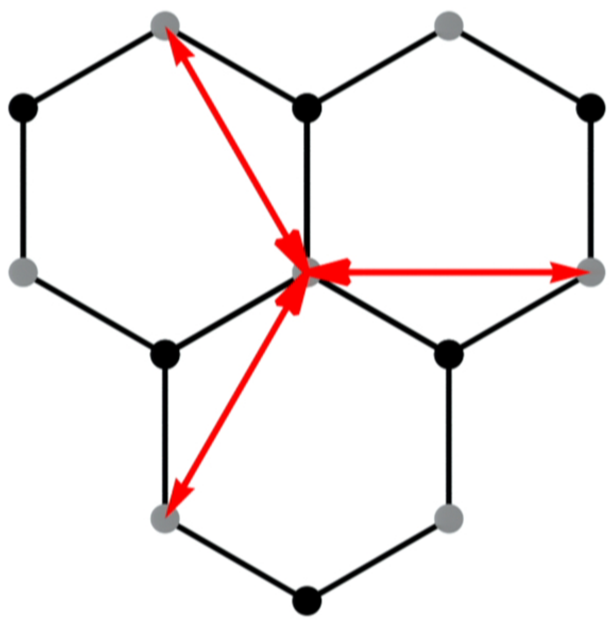


$$\hat{\chi}_\triangle = \mathbf{S}_i \cdot \mathbf{S}_j \times \mathbf{S}_k$$

$$\Phi_\triangle = \text{Enclosed flux}$$

Effective Spin Hamiltonian

$$H_{\text{spin}} = \frac{4t_1^2}{U}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + \boxed{\frac{4t_2^2}{U}\sum_{\langle\langle ij\rangle\rangle}\mathbf{S}_i\cdot\mathbf{S}_j}$$



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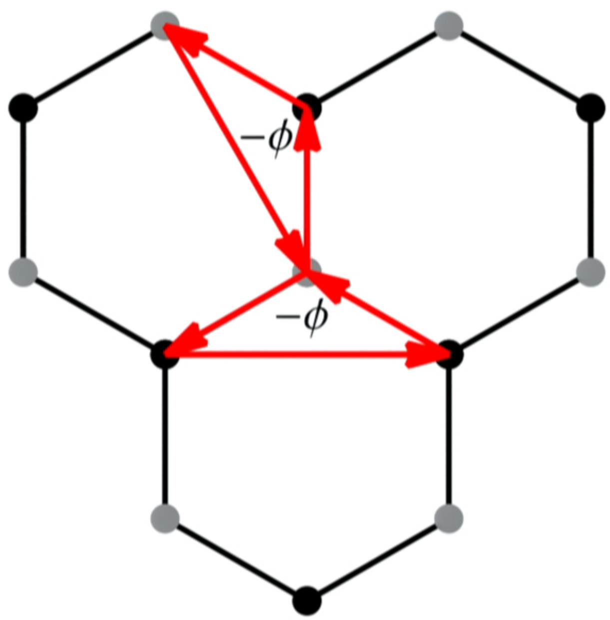

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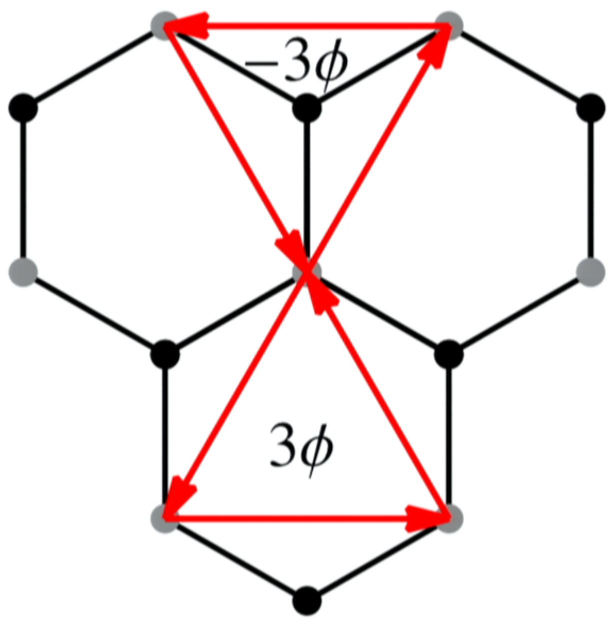
$$+\frac{24t_1^2t_2}{U^2}\sum_{\text{small}-\triangle}\hat{\chi}_\triangle\sin\Phi_\triangle + \boxed{\frac{24t_2^3}{U^2}\sum_{\text{big}-\triangle}\hat{\chi}_\triangle\sin\Phi_\triangle}$$



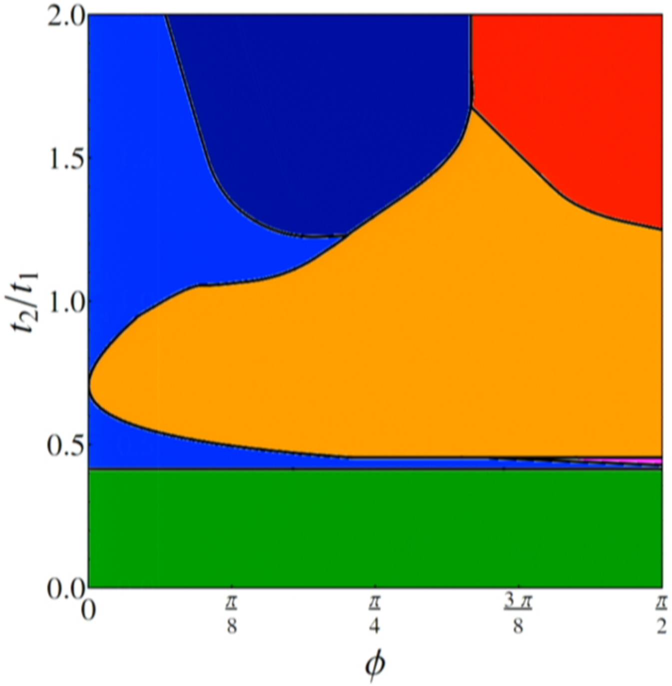
$$\hat{\chi}_\triangle = \mathbf{S}_i\cdot\mathbf{S}_j\times\mathbf{S}_k$$

$$\Phi_\triangle = \text{Enclosed flux}$$

Classical Magnetic Orders

Treat spins as classical vectors

Determine ground states using simulated annealing and variational spin configurations



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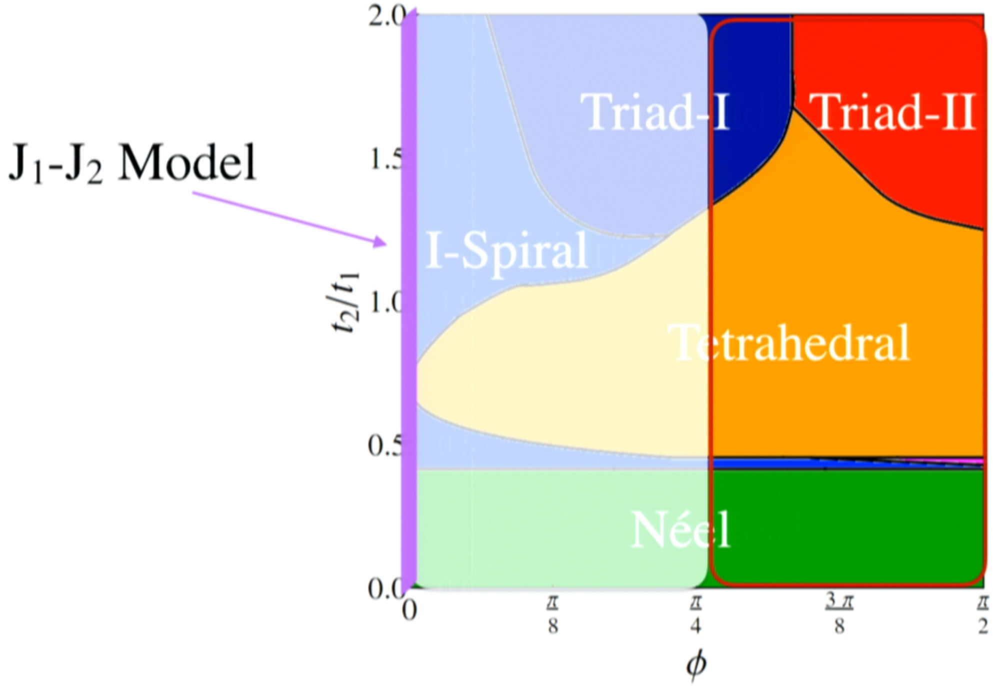

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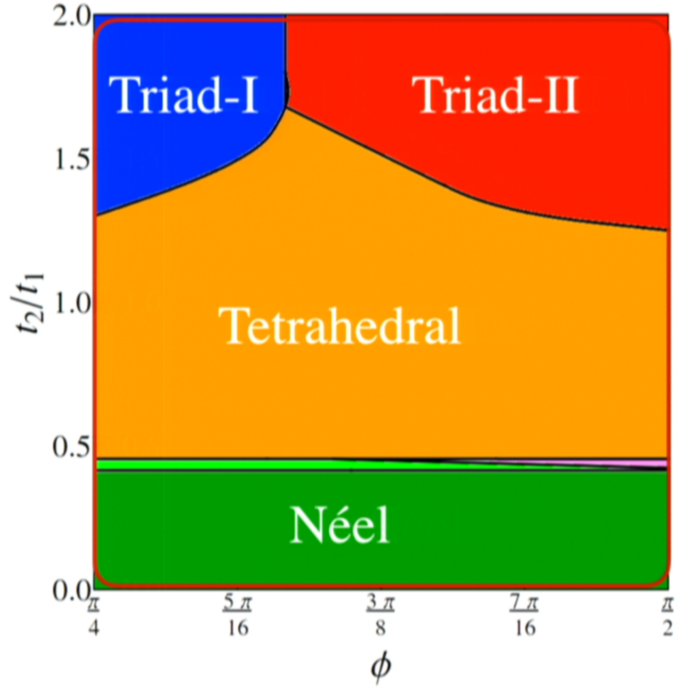

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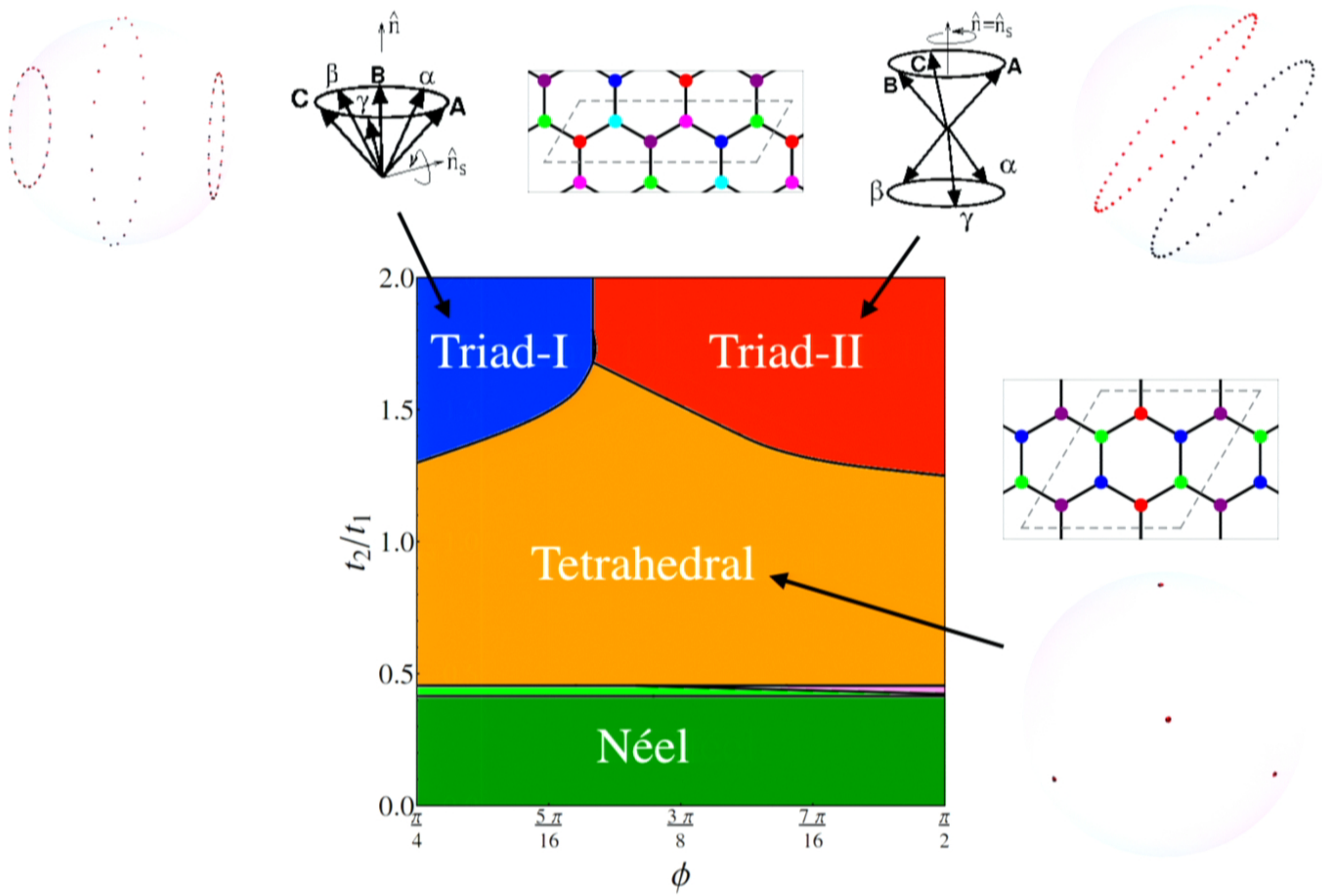
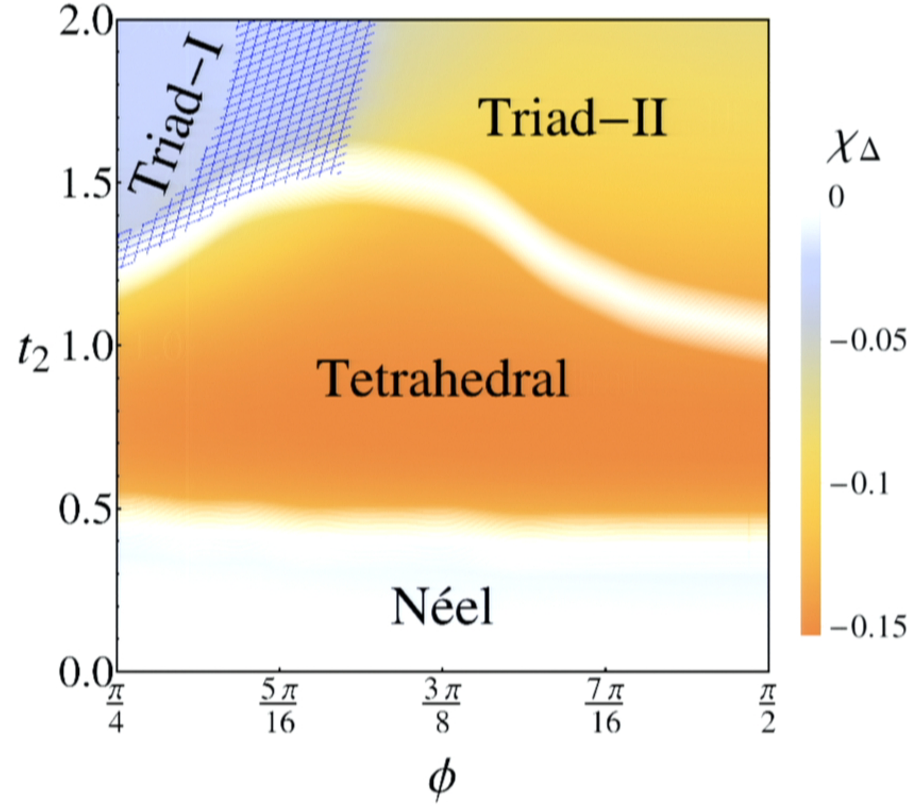
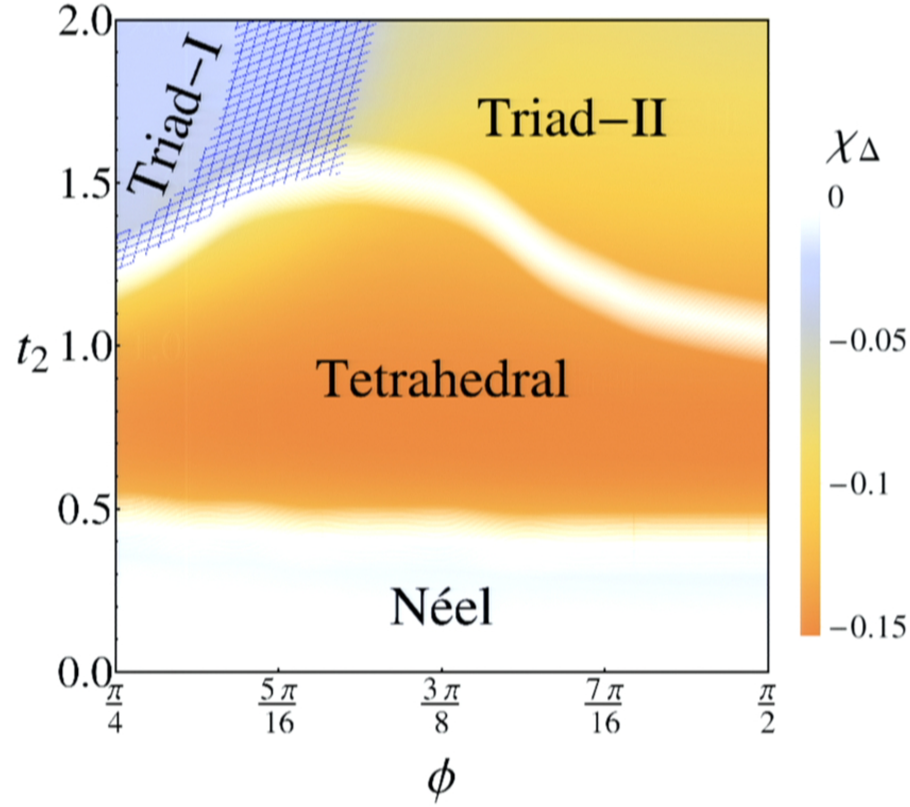


Quantum Phase Diagram

- Exact diagonalisation on 18, 24 and 32-site clusters
- Phase diagram mapped out using energy spectra, spin gap, GS fidelity, scalar spin chirality and spin structure factor



Quantum Phase Diagram



"Regular magnetic order" = Respects all lattice symmetries modulo global spin transformations

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Quantum Spin Liquids

- Spin liquids provide another example of "topological order"
- Quantum paramagnets with $\langle \mathbf{S}_i \cdot \mathbf{S}_j \rangle \propto e^{-R/\xi}$
- Despite many promising candidates, conclusive experimental proof is currently lacking

High-T_c Cuprates

Frustrated Magnets

Quantum Dimer Models

Lattice Gauge Theory

Topological Quantum Computing

Quantum Spin Liquids

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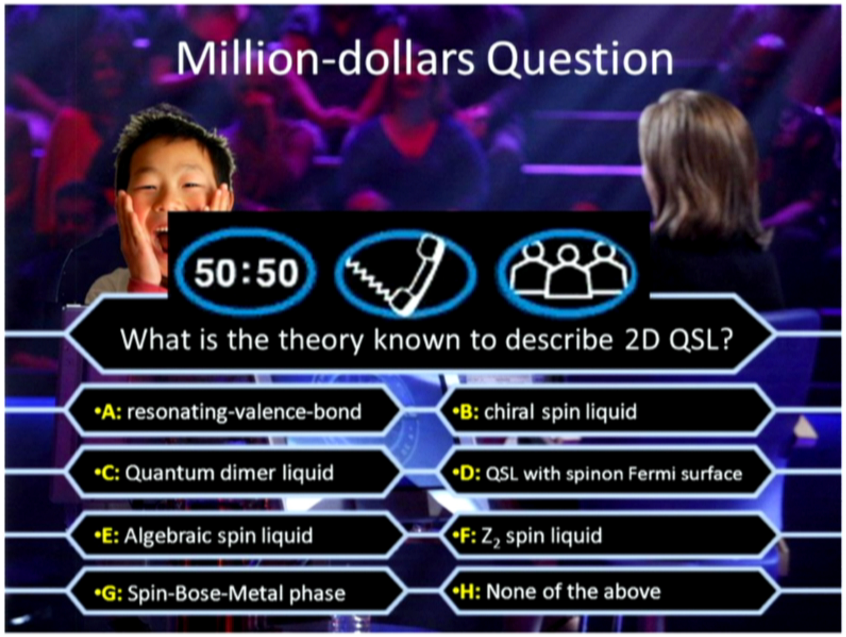
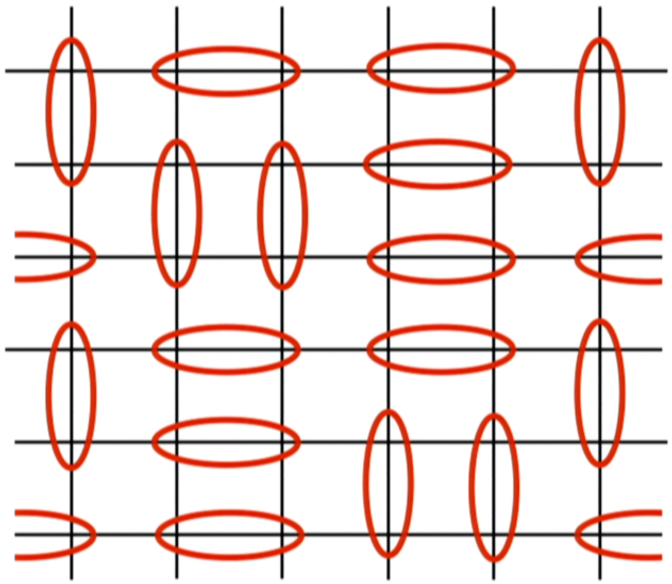


Spin Liquids as Resonating Valence Bond States

- 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)

Spin Liquids as “Quantum-Disordered” States

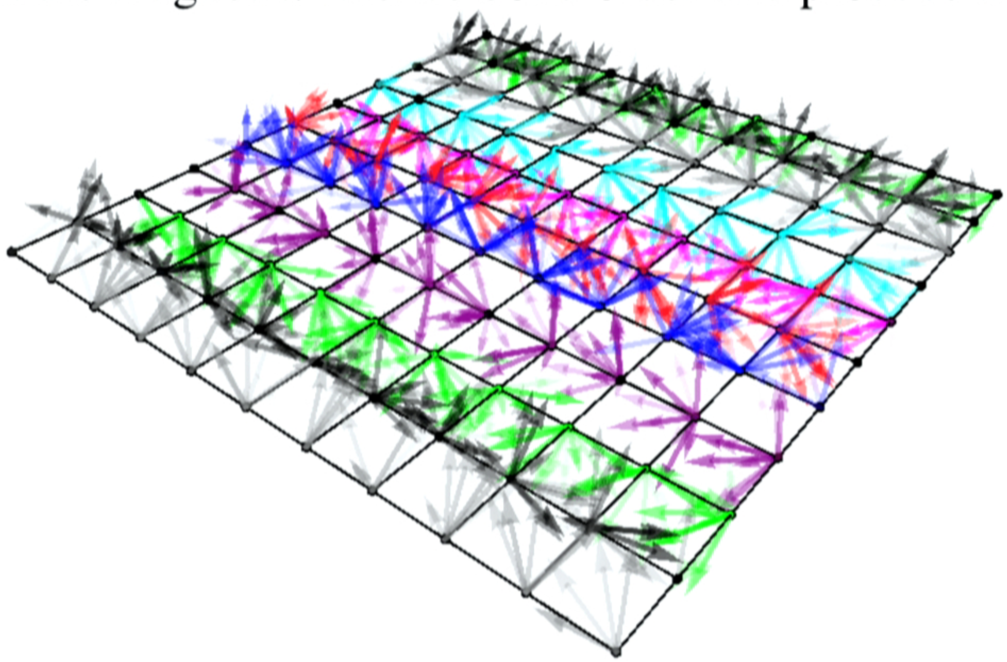
Start with an ordered magnetic/valence bond “parent” state

↓

Frustrate that order by tuning the Hamiltonian

↓

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



Chiral Spin Liquids

- Spin liquids with broken time-reversal symmetry, non-zero scalar spin chirality $\mathbf{S}_i \cdot \mathbf{S}_j \times \mathbf{S}_k \neq 0$
- Universal properties described by $\nu = 1/2$ bosonic Laughlin state, such as:
  - Two-fold GS degeneracy on a torus (each with total momentum $\mathbf{k} = (0,0)$)
  - Total many-body Chern number:

$$C_{Tot} = C_1 + C_2 = -\frac{1}{\pi} \sum_{i=1,2} \int d\theta_1 d\theta_2 \mathrm{Im} \langle \partial_{\theta_1} \Psi_i \,|\, \partial_{\theta_2} \Psi_i \rangle = 1$$

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

Chiral Spin Liquids

- Spin liquids with broken time-reversal symmetry, non-zero scalar spin chirality $\mathbf{S}_i \cdot \mathbf{S}_j \times \mathbf{S}_k \neq 0$
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  - Two-fold GS degeneracy on a torus (each with total momentum $\mathbf{k} = (0,0)$)
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$$C_{Tot} = C_1 + C_2 = -\frac{1}{\pi} \sum_{i=1,2} \int d\theta_1 d\theta_2 \mathrm{Im} \langle \partial_{\theta_1} \Psi_i \,|\, \partial_{\theta_2} \Psi_i \rangle = 1$$

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

Chiral Spin Liquids

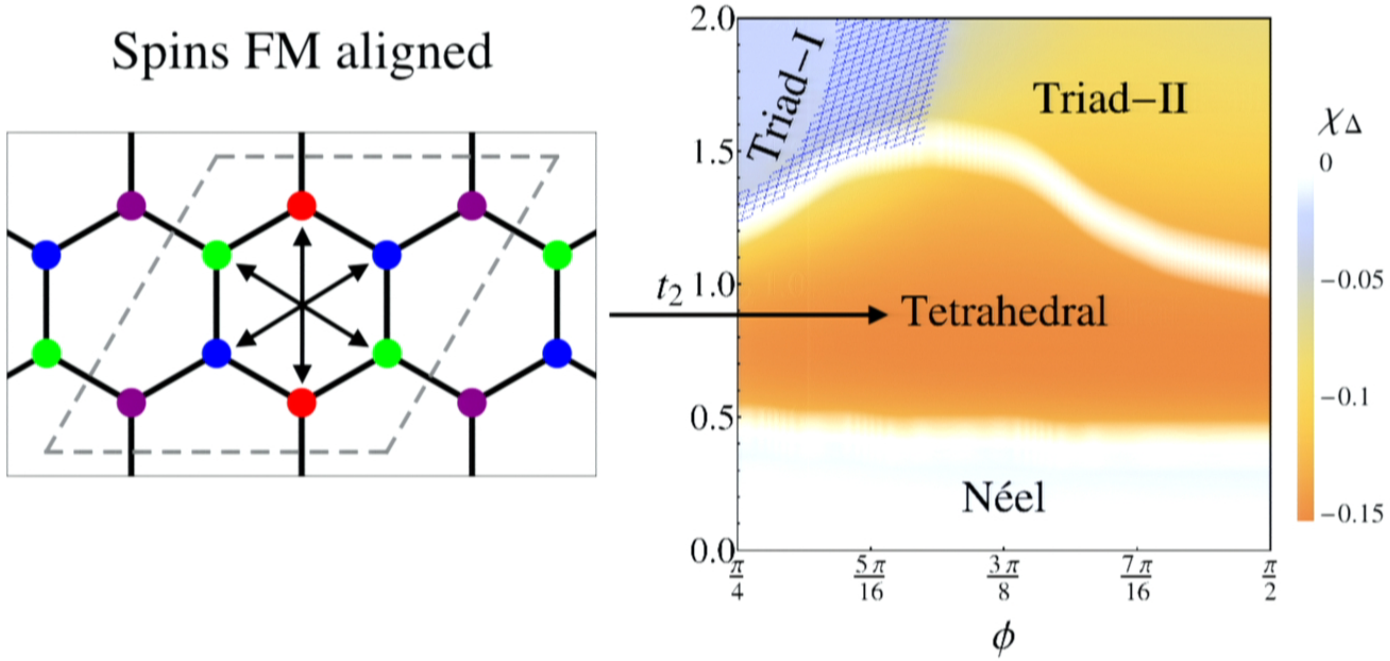
- Spin liquids with broken time-reversal symmetry, non-zero scalar spin chirality $\mathbf{S}_i \cdot \mathbf{S}_j \times \mathbf{S}_k \neq 0$
- Universal properties described by $\nu = 1/2$ bosonic Laughlin state, such as:
  - Two-fold GS degeneracy on a torus (each with total momentum $\mathbf{k} = (0,0)$)
  - Total many-body Chern number:

$$C_{Tot} = C_1 + C_2 = -\frac{1}{\pi} \sum_{i=1,2} \int d\theta_1 d\theta_2 \mathrm{Im} \langle \partial_{\theta_1} \Psi_i \,|\, \partial_{\theta_2} \Psi_i \rangle = 1$$

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)

Quantum Phase Diagram



Adding a 3rd nearest neighbour hopping will result in a frustrating AF exchange interaction in the Mott limit

Disordering the Tetrahedral

$$H_{\text{spin}} = \frac{4t_1^2}{U}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + \frac{4t_2^2}{U}\sum_{\langle\langle ij\rangle\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + \frac{4t_3^2}{U}\sum_{\langle\langle\langle ij\rangle\rangle\rangle}\mathbf{S}_i\cdot\mathbf{S}_j$$

$$+ \frac{24t_1^2t_2}{U^2}\sum_{\text{small}-\triangle}\hat{\chi}_\triangle \sin\Phi_\triangle + \frac{24t_2^3}{U^2}\sum_{\text{big}-\triangle}\hat{\chi}_\triangle \sin\Phi_\triangle$$

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Set $\phi = \pi/3$

$\Rightarrow \sin 3\phi = 0$

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Set $\phi = \pi/3$

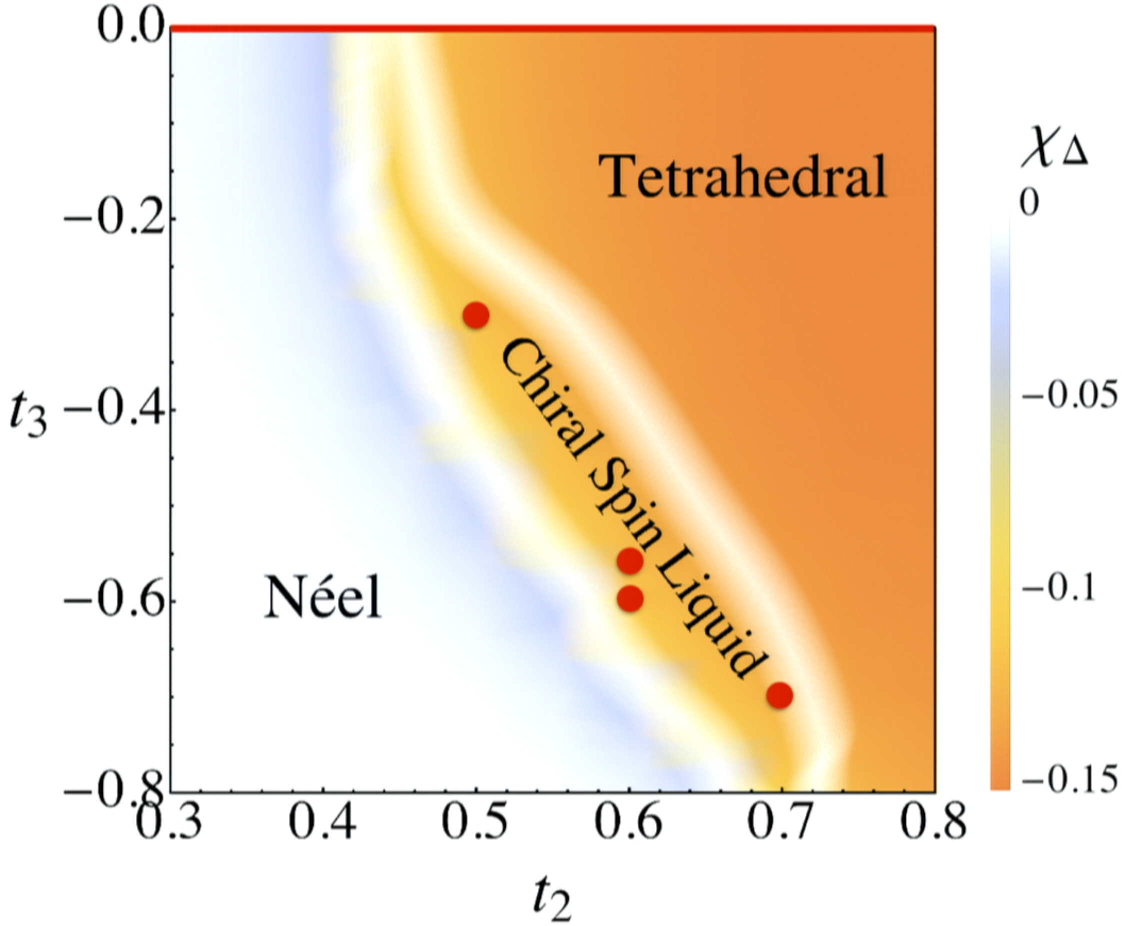
$\Rightarrow \sin 3\phi = 0$

Doesn't affect physics much

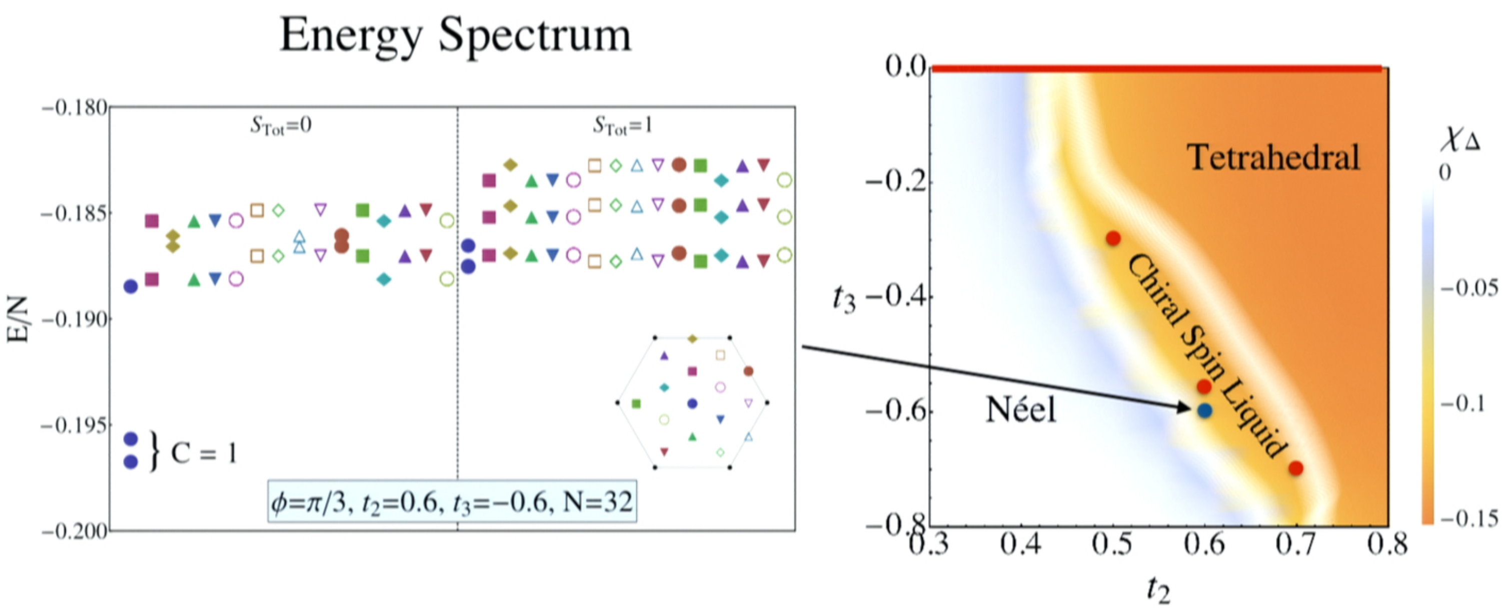
Disordering the Tetrahedral

$$H_{\rm spin} = \frac{4t_1^2}{U}\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + \frac{4t_2^2}{U}\sum_{\langle\langle ij\rangle\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + \frac{4t_3^2}{U}\sum_{\langle\langle\langle ij\rangle\rangle\rangle}\mathbf{S}_i\cdot\mathbf{S}_j + \frac{24t_1^2t_2}{U^2}\sum_{\rm small-\triangle}\hat{\chi}_\triangle\sin\Phi_\triangle$$

Disordering the Tetrahedral

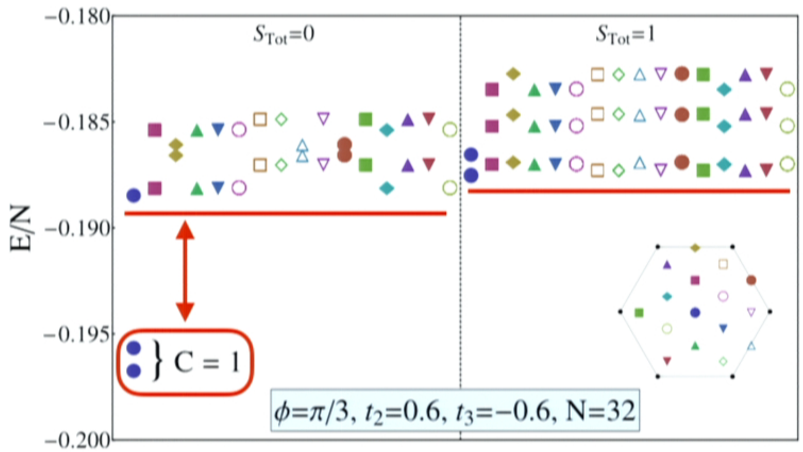


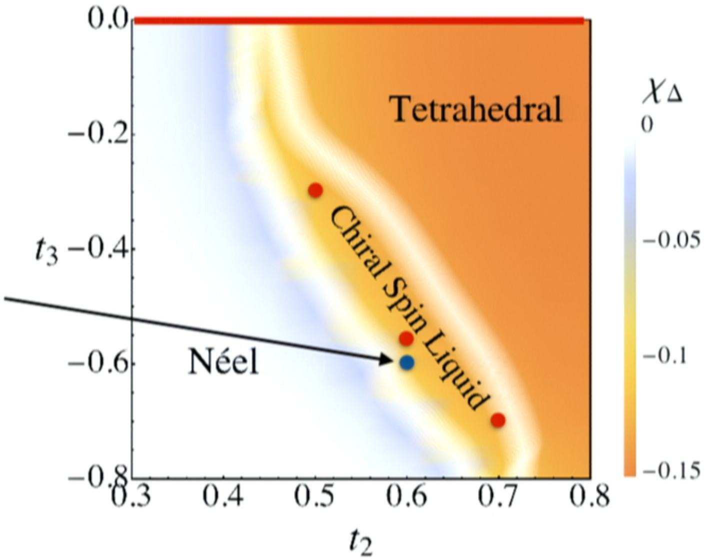
Disordering the Tetrahedral



Disordering the Tetrahedral

Energy Spectrum

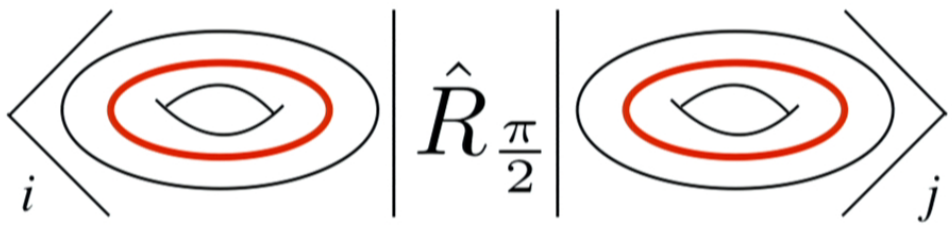




2-fold quasi-degenerate GS with $C_{Tot} = 1$

Chiral Spin Liquids and $SU(2)_1$ Chern-Simons Theory

- Topological S and T matrices encode the braiding properties of quasiparticles, e.g.
  - S_{ij} is the phase acquired by quasiparticle i when encircling quasiparticle j



- Can be extracted using DMRG

L. Cincio, G. Vidal, PRL **110**, 067208 (2013)

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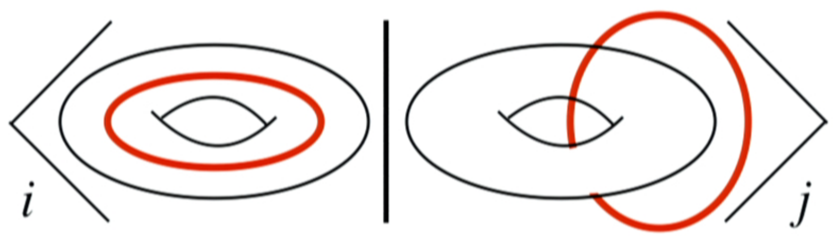

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L. Cincio, G. Vidal, PRL **110**, 067208 (2013)

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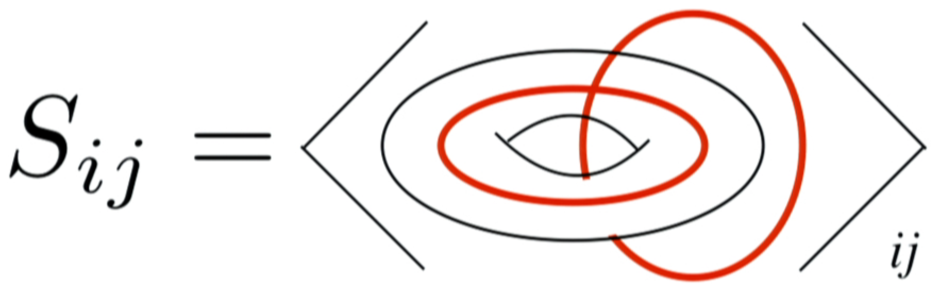

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L. Cincio, G. Vidal, PRL **110**, 067208 (2013)

Chiral Spin Liquids and SU(2)$_1$ Chern-Simons Theory

- Topological S and T matrices encode the braiding properties of quasiparticles, e.g.
  - S_{ij} is the phase acquired by quasiparticle i when encircling quasiparticle j

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

$$T = e^{i\frac{2\pi}{24}} \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix}$$

Exact Result

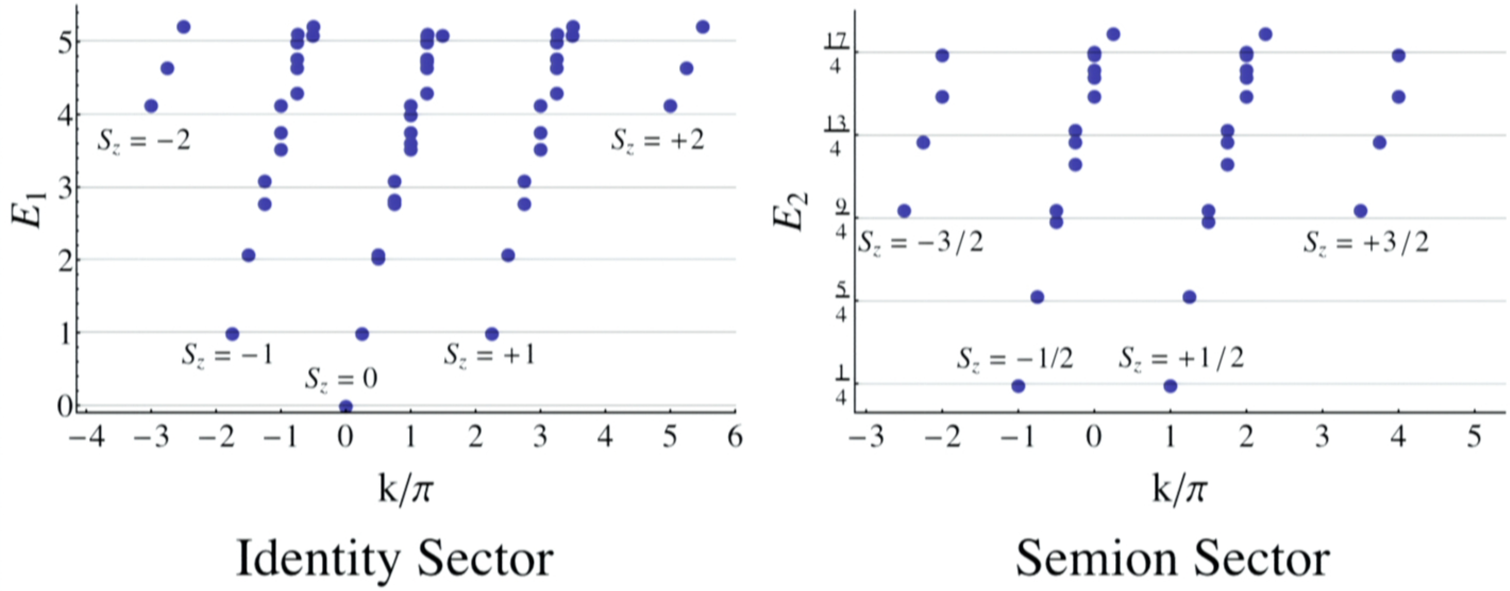
$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} 0.99 & 0.97 \\ 0.96 & -0.97 \cdot e^{i\pi \cdot 0.01} \end{pmatrix}$$

$$T = e^{i\frac{2\pi}{24} \cdot 0.96} \begin{pmatrix} 1 & 0 \\ 0 & -i \cdot e^{i\pi \cdot 0.01} \end{pmatrix}$$

Numerical Result

Entanglement Spectrum

- Conjectured that the entanglement spectrum of a CSL should reflect its physical edge spectrum
- This is a chiral $SU(2)_1$ Wess-Zumino-Witten conformal field theory



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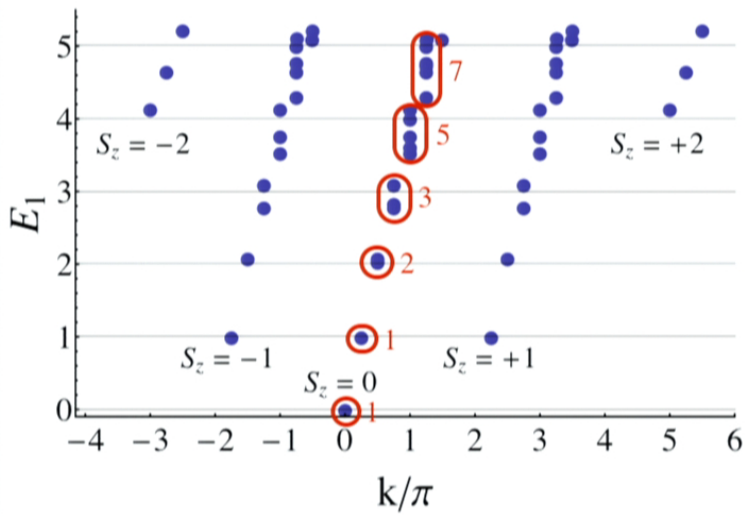
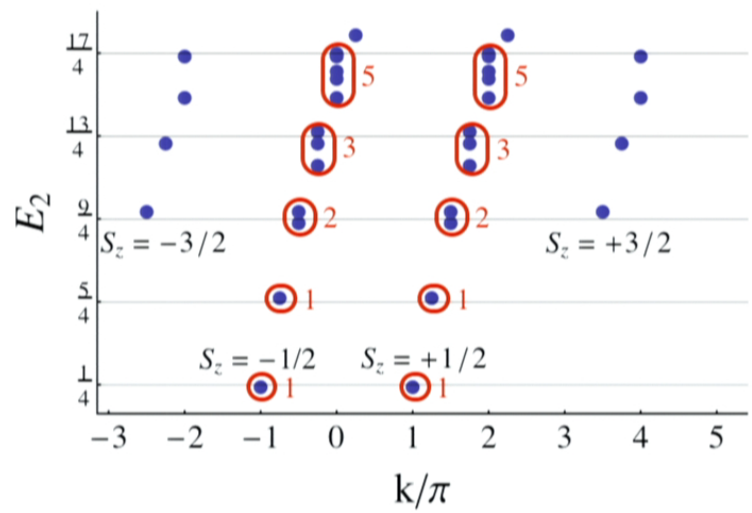
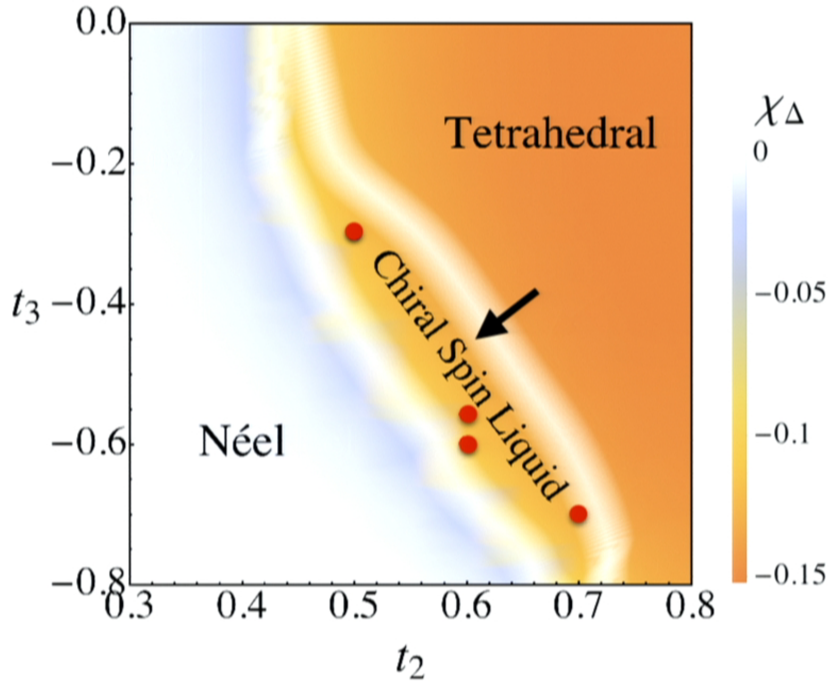


Identity Sector



Semion Sector

Disordering the Tetrahedral



- Transition is an excellent candidate for exotic continuous quantum phase transition
- Can be captured by Chern-Simons-Higgs field theory of bosonic spinons

Outline

- Motivation
  - Integer and Fractional Quantum Hall Physics
  - Ultracold Atoms and the Haldane Model
- Haldane-Hubbard Model
  - Effective Spin Hamiltonian
  - Classical/Quantum Phase Diagrams
- Disordering the Tetrahedral
  - Quantum Spin Liquids
  - Numerical Signatures of Chiral Spin Liquids
- RMOs as Chiral Spin Liquid "Parent States"
- Conclusions

RMOs as CSL Parent States

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

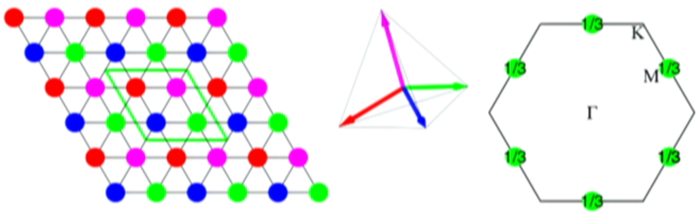
2. In recent years SU(2) invariant spin models with CSL ground states have also been found for all of these lattices.

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

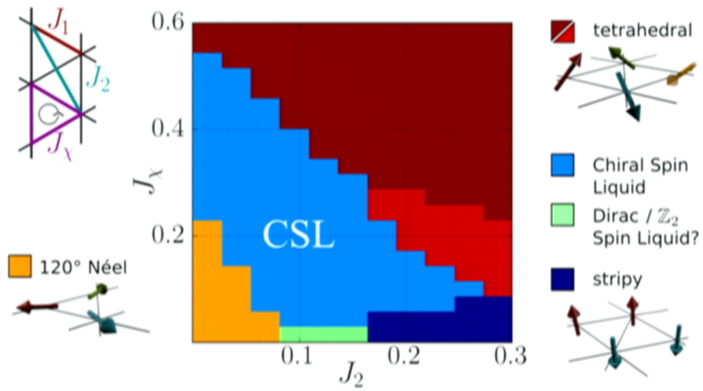
L. Messio, C. Lhuillier, G. Misguich, PRB **83**, 184401 (2011)

RMOs as CSL Parent States

Triangular Lattice

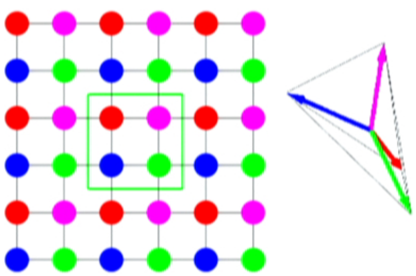


(b) Tetrahedral state. $E = -2J_1 - 2J_2 + 6J_3 - 34K/3$.

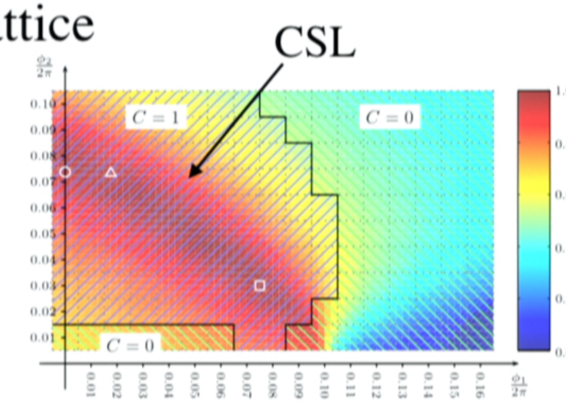


A. Wietek, A. Läuchli, arXiv:1604.07829

Square Lattice



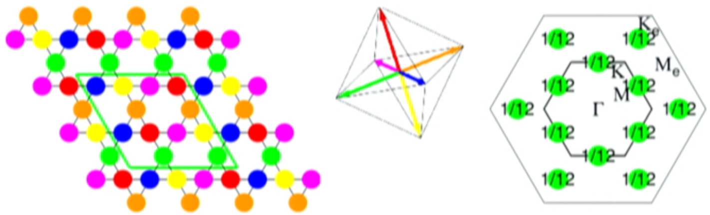
(e) Tetrahedral umbrella states (*AF umbrellas*)



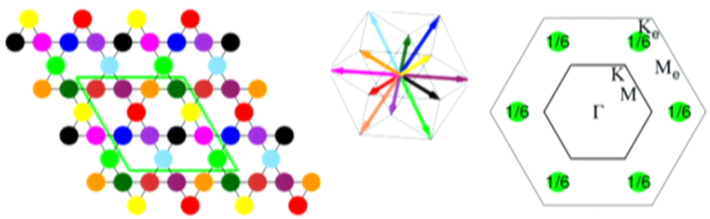
A.E.B. Nielsen, G. Sierra, J.I. Cirac, Nat. Comm. **4**, 2864 (2013)

RMOs as CSL Parent States

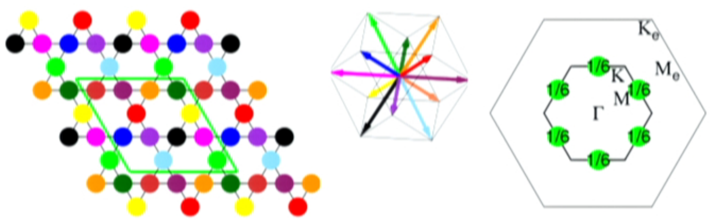
Kagome Lattice



(d) Octahedral state. $E = 2J_3' - 4J_3$.

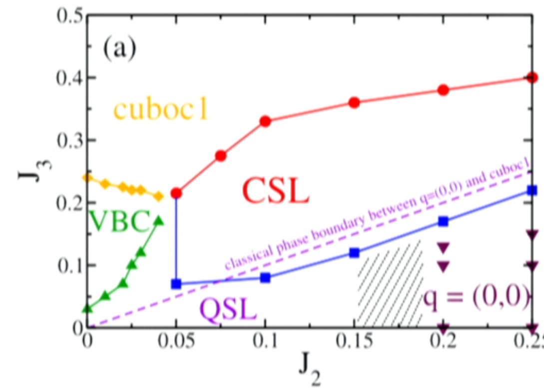


(e) Cuboc1 state. $E = -2J_1 + 2J_2 - 2J_3'$.



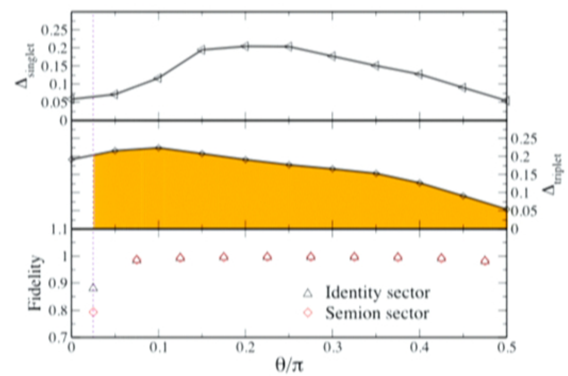
(f) Cuboc2 state. $E = 2J_1 - 2J_2 - 2J_3'$.

$J_1 - J_2 - J_3$



S.S. Gong et al., PRB **91**, 075112 (2015)

$J_1 - J_\chi$



B. Bauer et al., Nat. Comm. **5**, 5137 (2014).

Conclusions

- Mott limit of Haldane-Hubbard model exhibits a variety of chiral magnetic orders.
- Adding 3rd-NN hopping frustrates and ultimately melts the tetrahedral order, leading to the emergence of a chiral spin liquid.
- Ongoing work on other lattices suggests that the emergence of CSL states can naturally be understood through quantum disordering RMOs.
- Still work needed to understand Floquet aspects of the experiment, nature of the CSL, and the field theory of the transition.


Thank you!