Chiral Spin Liquid from Dzyaloshinskii-Moriya Interactions

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Introduction to spin liquids

- Spin Liquids
  - Retains rotational and translational symmetries down to the lowest temperatures
  - No magnetic long range order
  - Chiral spin liquids (chiral order present)
    - Scalar chiral spin liquid (sCSL) breaks time-reversal symmetry

      → $\langle S_i \cdot S_j \times S_k \rangle \neq 0$
    - Vector chiral spin liquid (vCSL) breaks inversion symmetry

      → $\langle z \cdot S_i \times S_j \rangle \neq 0$
  - Chirality arises due to frustration from geometry or competing interactions
    - Triangular, kagome, pyrochlore, J_1–J_2, *etc.*

Studies on spin liquids

- Major research topic for past couple of decades
  - Search for spin liquid states usually starts with Heisenberg Hamiltonian on various frustrated lattices
    - Kalmeyer & Laughlin, PRL **59**, 2095 (87)
    - Wen, Wilczek, & Zee, PRB **39**, 11413 (89)
  - Systems with larger atomic numbers and complex lattices with less symmetry becoming more important
    - → Spotlight on Dzyaloshinskii–Moriya (DM) interaction effects
    - **$Na_3Ir_3O_8$ (Hyper-Kagome spin liquid)**
      Okamato, Nohara, Aruga-Katori, & Takagi, PRL **99**,137207 (07)
      Chen & Balents, PRB **78**, 094403 (08)
      Zhou, Lee, Ng, & Zhang, PRL **101**, 197201 (08)
  - **What effect does DM have on spin liquid physics?**

Method of approach

- J_1–J_2 spin model without DM

1. Begin with fermionic mean field theory (fMFT) on the J_1-J_2 Heisenberg Hamiltonian
2. Map out phase diagram w.r.t. J_2/J_1 (degree of frustration)
3. Compare the energies of the mean field states using variational Monte Carlo (VMC)
4. What are the (low-lying) excitations?
5. Order parameter (chirality: scalar or vector?)
6. Add DM interactions and repeat steps 1. through 5.

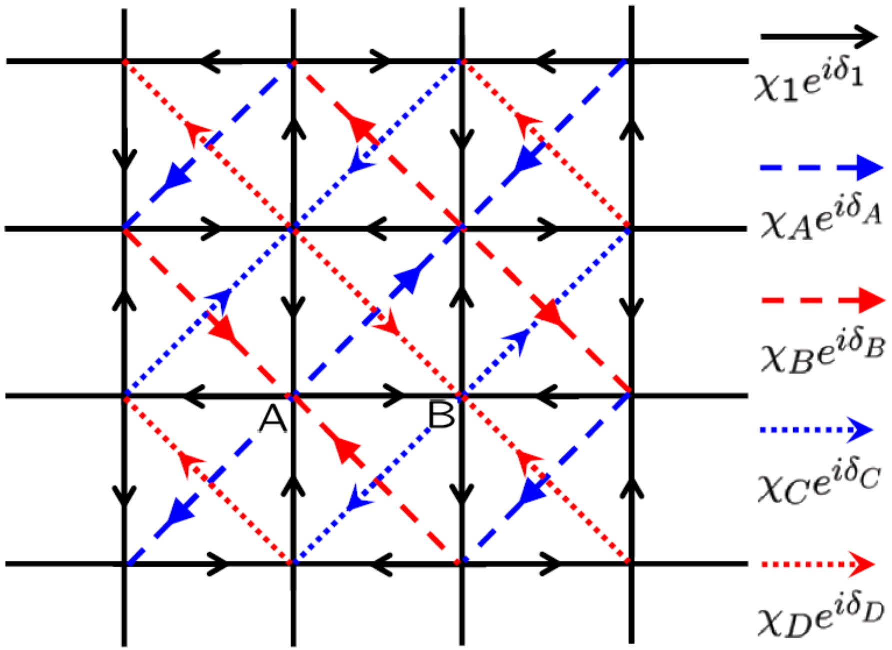
+ DM ⇒ New Phase?

Fermionic mean field theory (fMFT)

- J_1–J_2 spin model on a square lattice

$$H = J_1 \sum_{\langle ij \rangle} S_i \cdot S_j + J_2 \sum_{\langle ik \rangle} S_i \cdot S_k$$

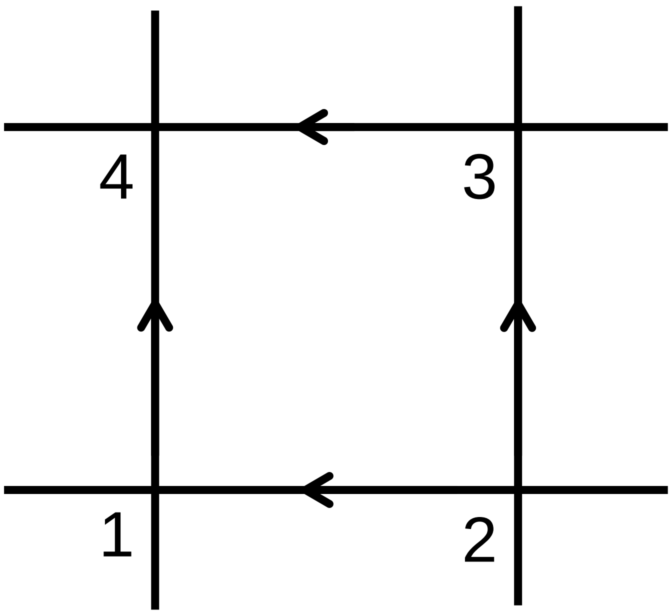
- Constraint : no charge fluctuations, n_i=1
- Rewrite spins as fermionic bilinears
- Define $\chi_{ij,\sigma}$: hopping between sites
- Apply mean field theory



$$S_i = \frac{1}{2} f^\dagger_{i\alpha} \boldsymbol{\sigma}_{\alpha\beta} f_{i\beta} \qquad \chi_{ij,\sigma} = f^+_{i\sigma} f_{j\sigma}$$

$$H = -J_1 \sum_{\langle ij,\sigma \rangle} \langle \chi_{ij} \rangle f^+_{j,\sigma} f_{i,\sigma} - J_2 \sum_{\langle ik,\sigma \rangle} \langle \chi_{ik} \rangle f^+_{k,\sigma} f_{i,\sigma} + h.c.$$

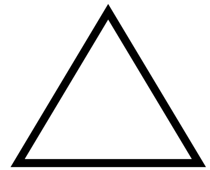
Flux States – Rokshar's Rule



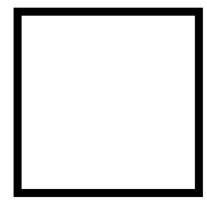
$$\prod \chi_{ij} = \chi_{12}\chi_{23}\chi_{34}\chi_{41} = \chi e^{i\Phi}$$

Φ : (physical) flux

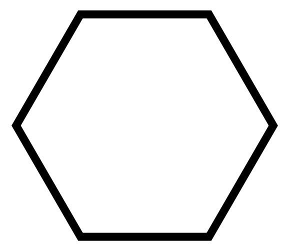
Rokhsar PRL 65, 1506 (1990)



$\Phi = \frac{\pi}{2}$

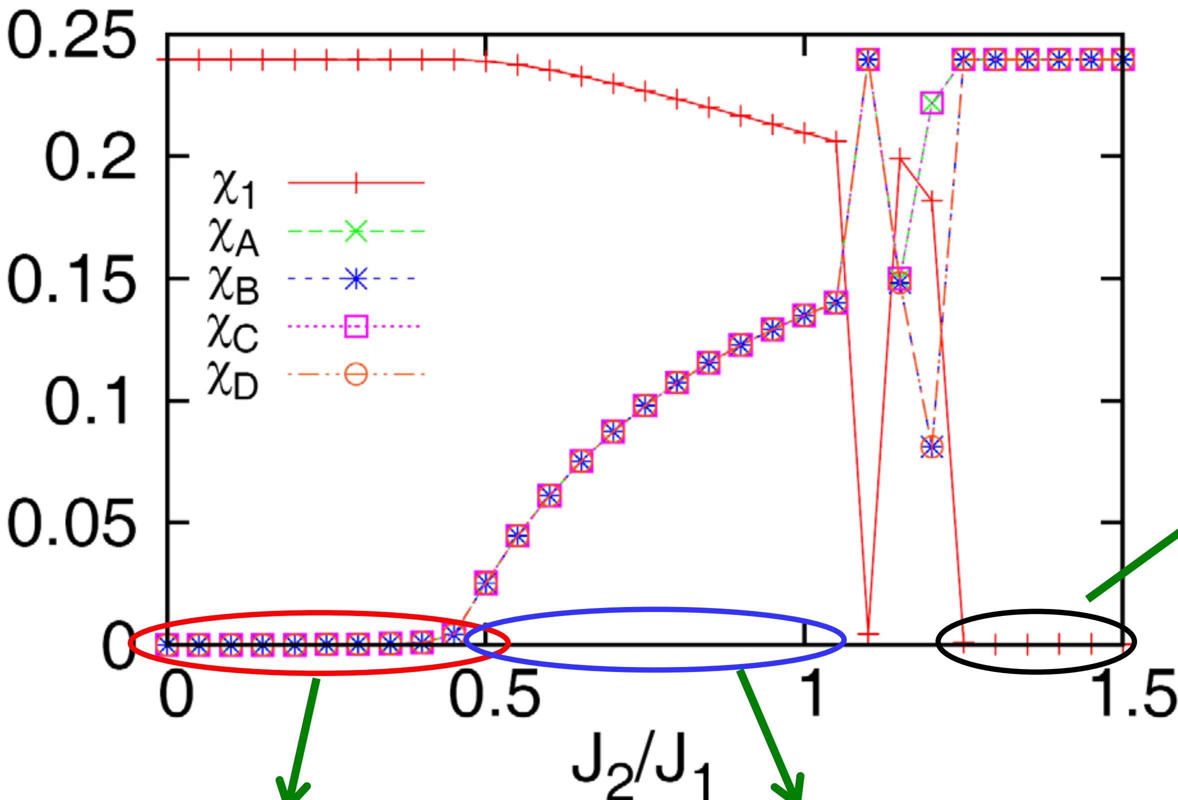


$\Phi = \pi$



$\Phi = 0$

Phase diagram of J_1–J_2 without DM



See also :
Wen, Wilczek, & Zee
PRB 39, 11413 (89)

Bipartite π–flux

$\chi_A=\chi_B=\chi_C=\chi_D\neq 0,$
$\chi_1=0$

π–flux

$\chi_A=\chi_B=\chi_C=\chi_D=0,$
$\chi_1\neq 0,\ \delta_1=\pi/4$

(s)CSL

$\chi_A=\chi_B=\chi_C=\chi_D\neq 0,$
$\delta_A=\delta_D=0,\ \delta_B=\delta_C=\pi,$
$\delta_1=\pi/4$

π–flux phases

π–flux

$\chi_A=\chi_B=\chi_C=\chi_D=0,$

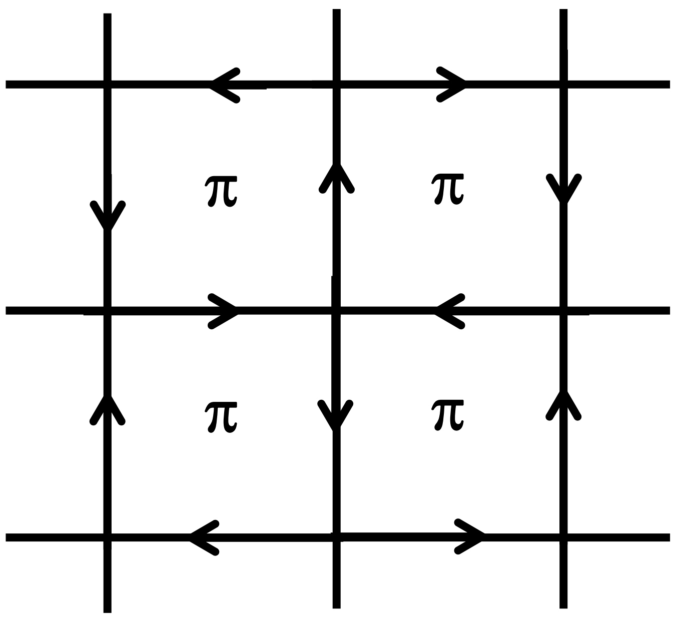
$\chi_1\neq0,\ \delta_1=\pi/4$

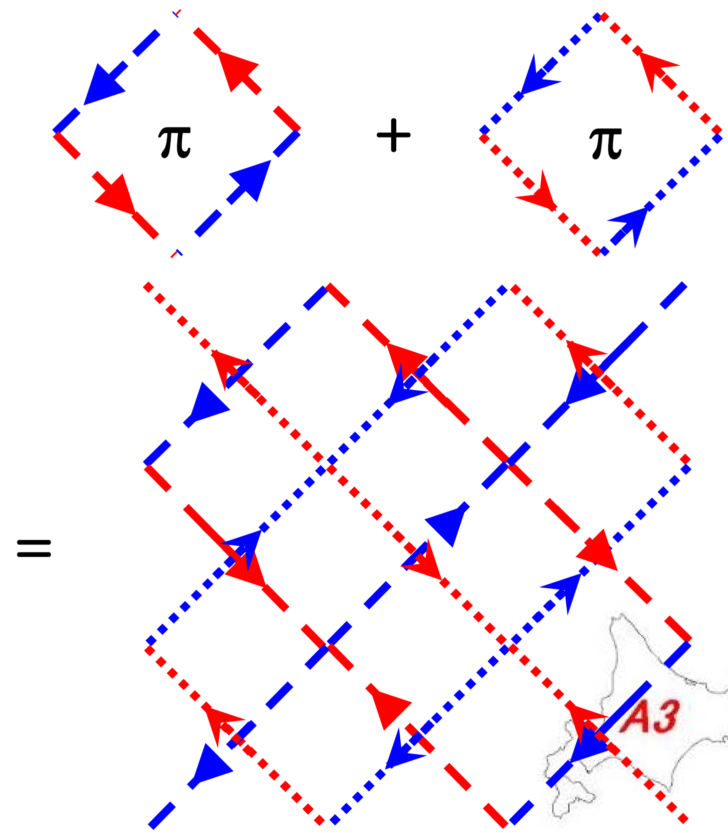
$\longrightarrow$ $\chi_1 e^{i\delta_1}$

Bipartite π–flux

$\chi_A=\chi_B=\chi_C=\chi_D\neq0,$

$\chi_1=0$





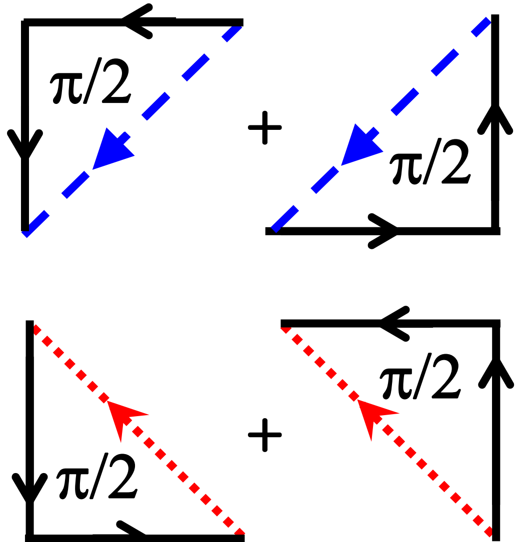
Chiral spin liquid phase

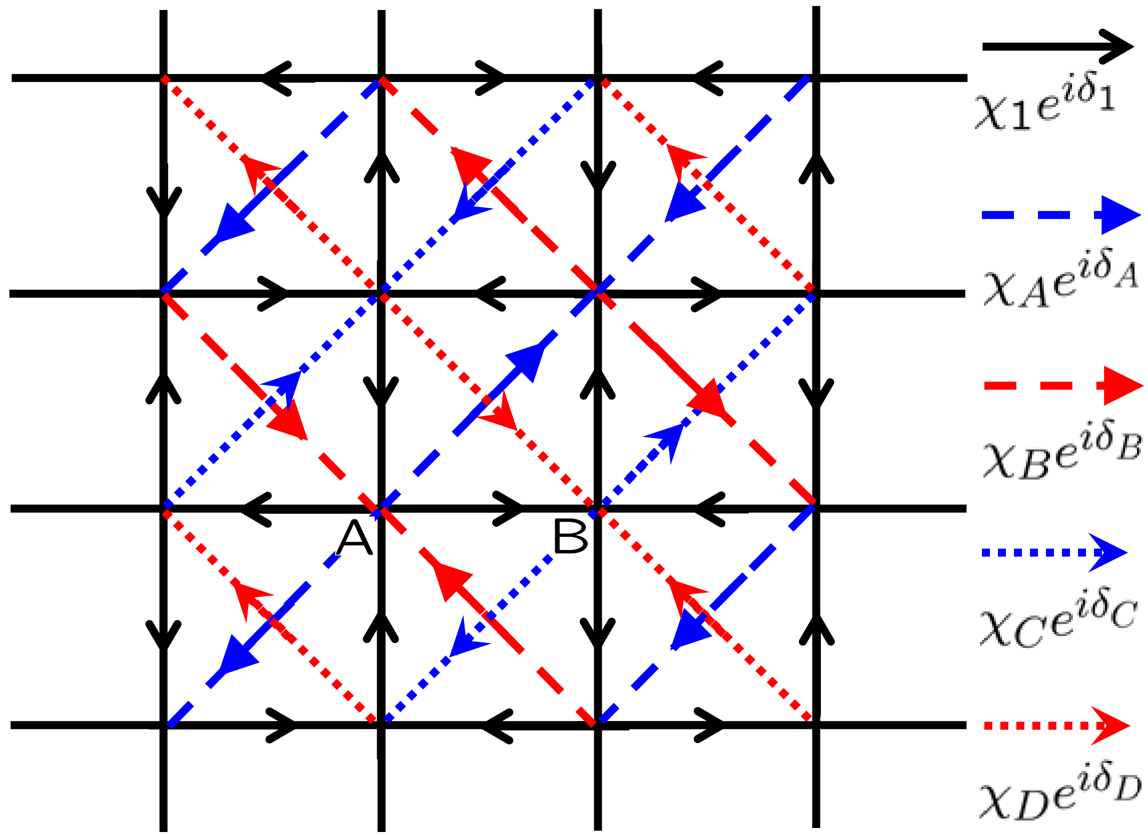
Chiral Spin Liquid

$\chi_A=\chi_B=\chi_C=\chi_D\neq 0,$

$\delta_A=\delta_D=0,\ \delta_B=\delta_C=\pi,$

$\delta_1=\pi/4$

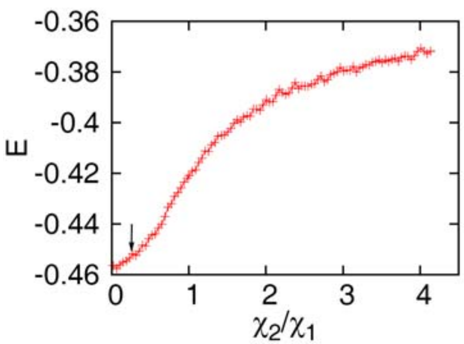




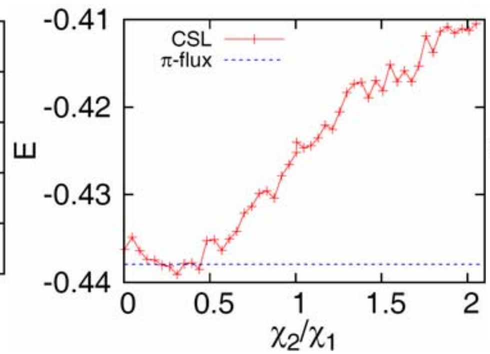
Both up and down spin species "feels" a flux of $\pi/2$ for each triangle

Variational Monte Carlo (VMC) results

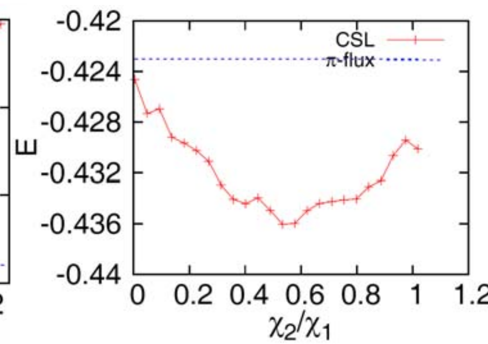
J_2/J_1=0.6



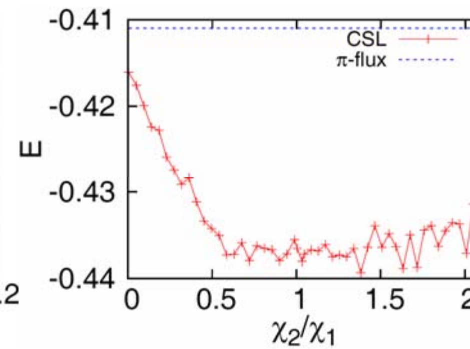
J_2/J_1=0.7

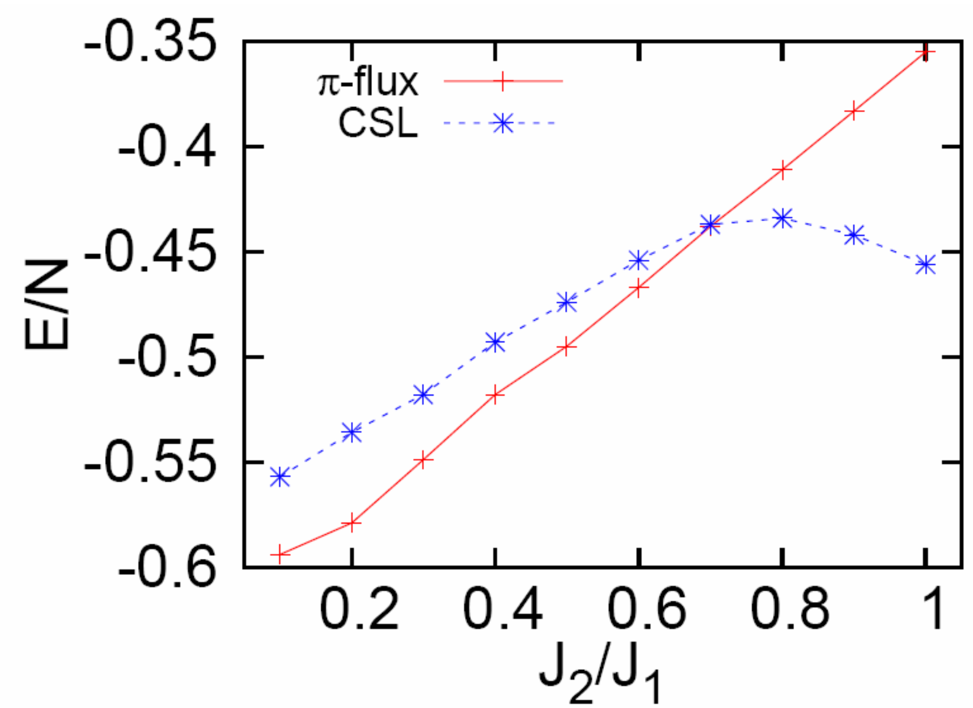


J_2/J_1=0.75



J_2/J_1=0.8





J_2/J_1	π-flux	CSL	χ_2/χ_1
0.70	-0.438	-0.439	0.31
0.75	-0.423	-0.436	0.53
0.80	-0.411	-0.438	1.03*

Heisenberg + DM (HDM model)

- DM interaction in fermion representation

$$(S_i \times S_j)^z = -\frac{i}{2}(\chi_{ij\uparrow}\chi_{ji\downarrow} - \chi_{ij\downarrow}\chi_{ji\uparrow})$$

- H_{HDM} model has the following form

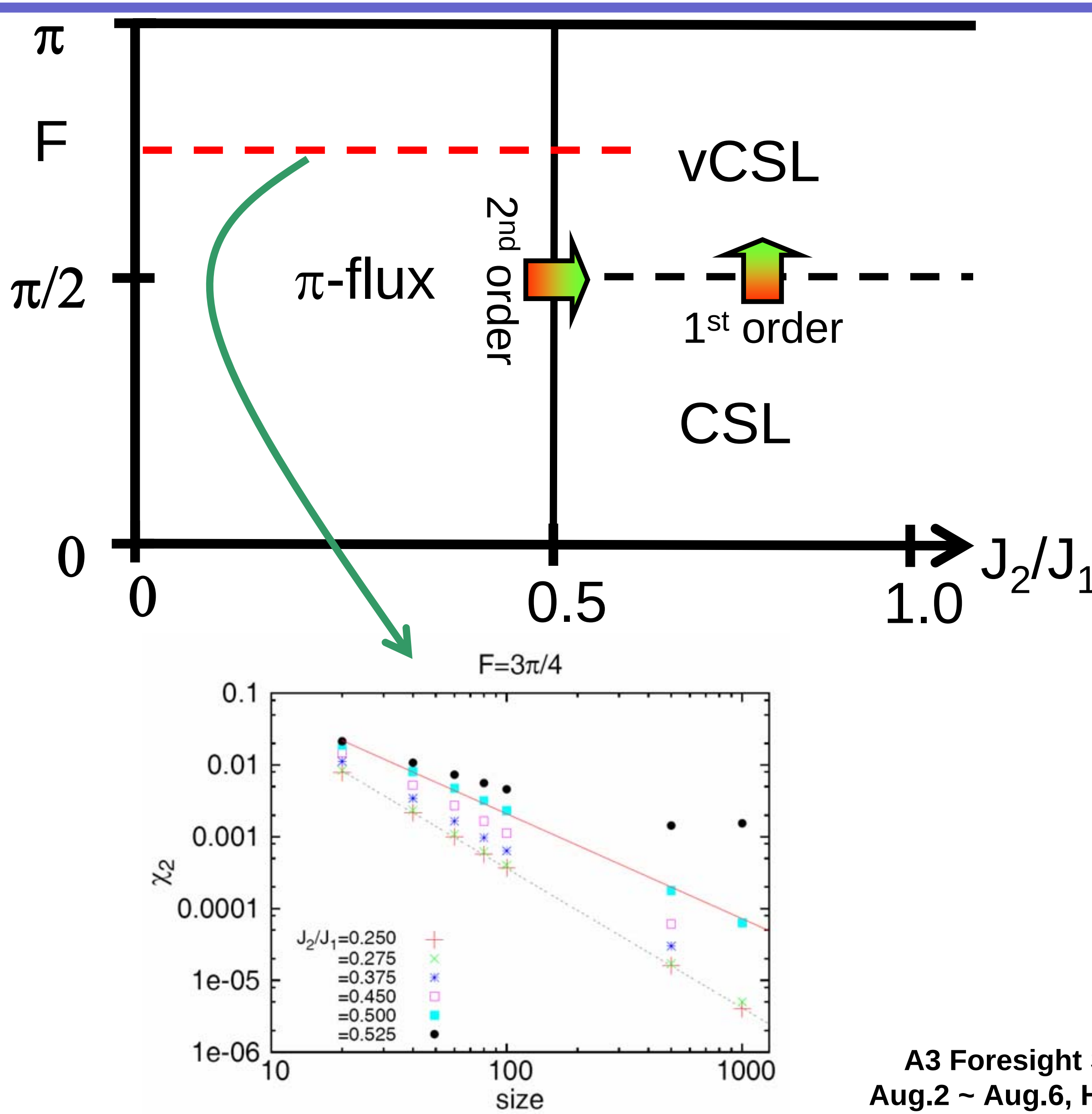
$$\Rightarrow \quad JS_i \cdot S_j + K(S_i \times S_j)^z \sim -J\sum_\sigma \chi_{ij\sigma}\chi_{ji\sigma} - J'\sum_\sigma e^{iF\sigma}\chi_{ij\sigma}\chi_{ji\bar{\sigma}}$$

- F can be thought of as the strength of the DM interaction
  - tan(F)=K/J
  - Decouple spin dependent gauge flux $e^{iF\sigma}$ by

$$f_{i,\sigma} \rightarrow e^{iF(x_i+y_i)\sigma/2} f_{i,\sigma}$$

  - Introduce NNN coupling to stabilize DM effects

Phase diagram of H_{HDM}



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Vector chiral spin liquid (vCSL) phase

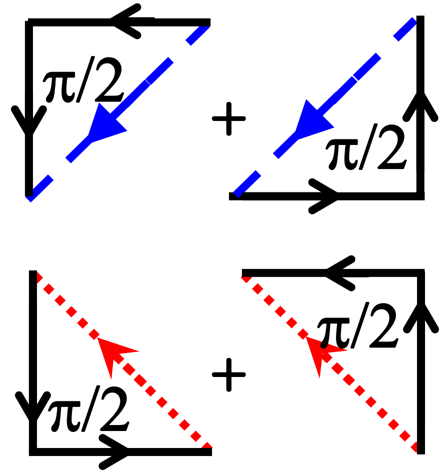
vCSL

$\delta_1=\pi/4,\ \chi_2\neq 0,$

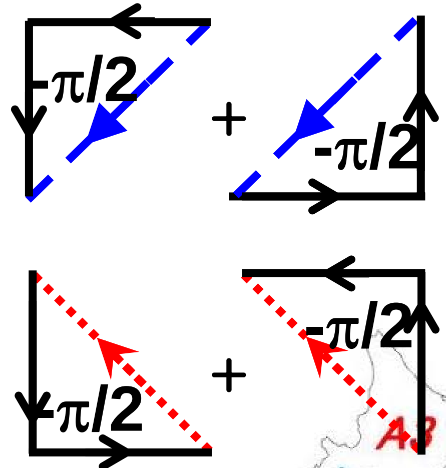
$\delta_{A,\sigma}=\delta_{B,\bar{\sigma}}=\delta_{C,\bar{\sigma}}=\delta_{D,\sigma}=\pi,$

$\delta_{A,\bar{\sigma}}=\delta_{B,\sigma}=\delta_{C,\sigma}=\delta_{D,\bar{\sigma}}=0,$

Up spins :



Down spins :



up spins : flux of $\pi/2$ per triangle

down spins : flux of $-\pi/2$ per triangle

Conclusions & future work

- The introduction of DM leads to a new phase, a vector chiral spin phase.
- vCSL phase can be reached from a CSL phase by increasing the DM strength past a certain critical value (first order phase transition).
- In the vCSL phase, the transverse spin Hall conductivity is no longer zero.
- Ground state of H_{HDM} has been established. What about spinon excitations?
- Through VMC, can calculate the vector chirality of vCSL phase. Is it really non-zero?