Fracton conservation laws in hole-doped antiferromagnets

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JS & M. Pretko

npj Quantum Mater. **5**, 1 (2020) and PRB **102** 214437 (2020)

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

2021 GGI workshop
"Topological properties of gauge theories and their applications to high-energy and condensed-matter physics"

What are fractons

- Quasiparticles with restricted mobility to a subdimensional space of the system
- GS degeneracy is extensive in the system size

<u>This talk</u>*:* Realization of subdimensional mobility constraints in simple models

Take-home message

- *Fracton conservation laws emerge in hole-doped antiferromagnets*
- *Quasiparticles reminiscent of fractons and dipoles*
  - **Fracton** = one hole dressed by magnetic background
  - **Dipole** = two holes on neighboring sites dressed by magnetic background
- *Robust fracton behavior (relatively stable to certain small perturbations)*
  - Approximate in 2D and 3D AFMs
  - Exact in “mixed-dimensional” 1D limit
  - Lattice geometry enables tunability of conservation laws

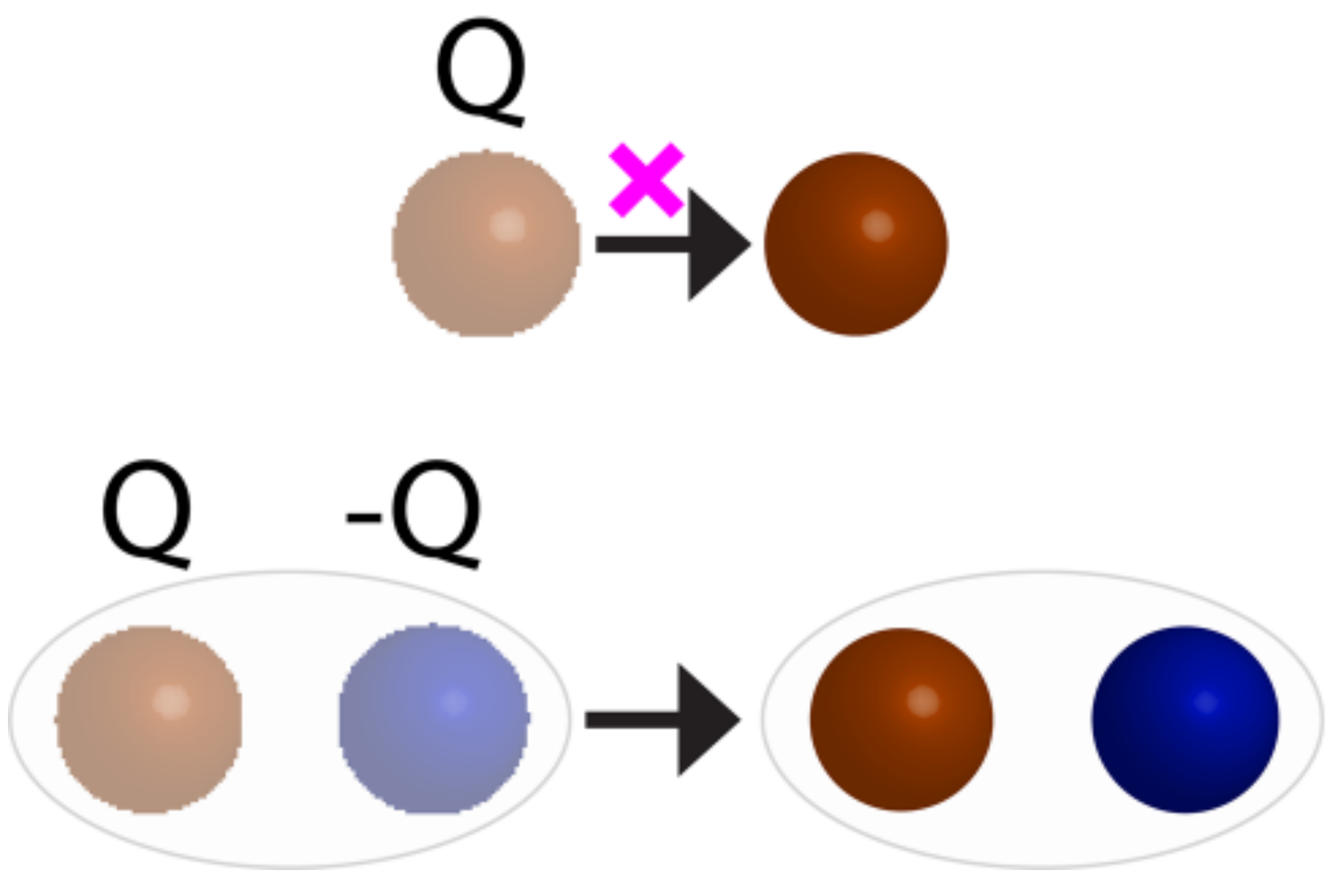
Objective: Realization of fracton conservation laws in realistic systems

Physics of fractons

- *Rank-2 symmetric tensor gauge theory:* $\partial_i \partial_j E_{i,j} = \rho$

Pretko, PRB (2017)

Dipole is conserved $\int d^d x (\rho \vec{x}) = \text{const}$



- *Severe restrictions on charge dynamics*
    - **Fracton** cannot move in isolation
    - **Dipole** = bound state of two oppositely charged fractons can move together

Objective: Realization of fracton conservation laws in realistic systems

- Large external $\vec{E}$ fields? Khemani et al., PRB (2020), Guardado-Sanchez et al., PRX (2020)
- `Intrinsic' mechanism (e.g. interactions)
  - Many:
    - Bond algebraic liquid Xu and Fisher, PRB (2007)
    - Thin-torus limit of the QHE Moudgalya et al., arXiv (2019)
    - Z_2 gauge theory Borla et al., arXiv (2020)
    - Bose-Hubbard + ring-exchange Giergiel et al., arXiv (2021)
  - This talk: *holes doped into AFMs*
    - Single hole = fracton
    - Two holes = dipole

Motivation: Realize fracton phenonemonlogy

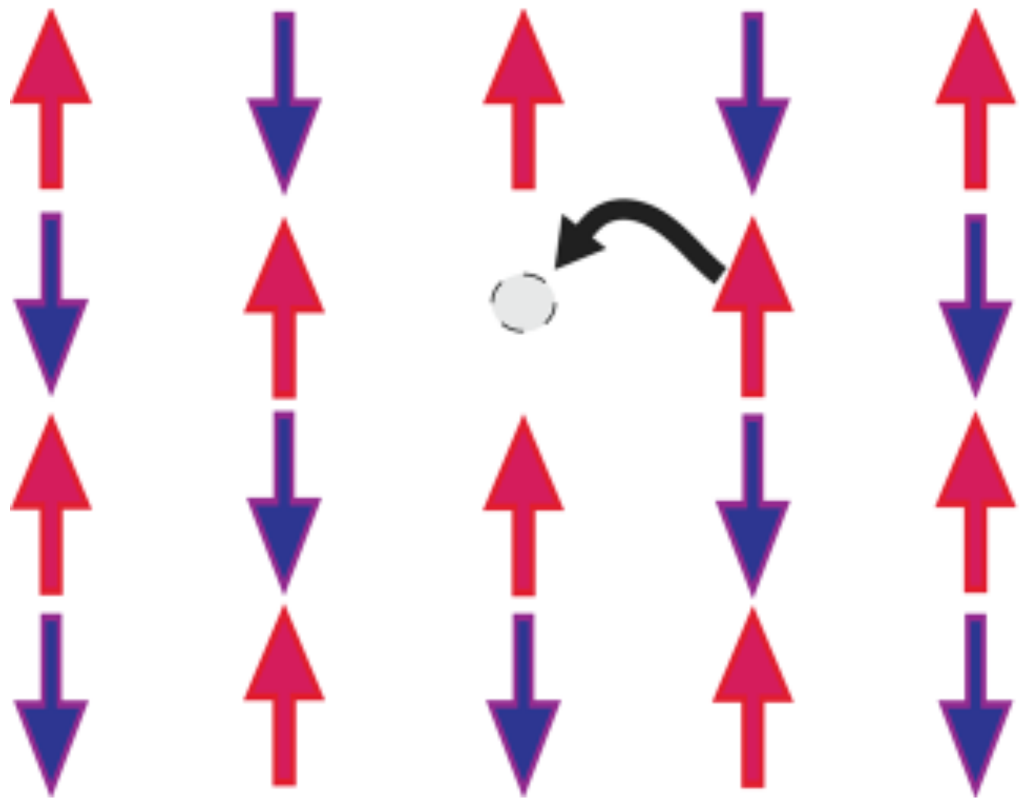
Manifestations of dipole conservation in

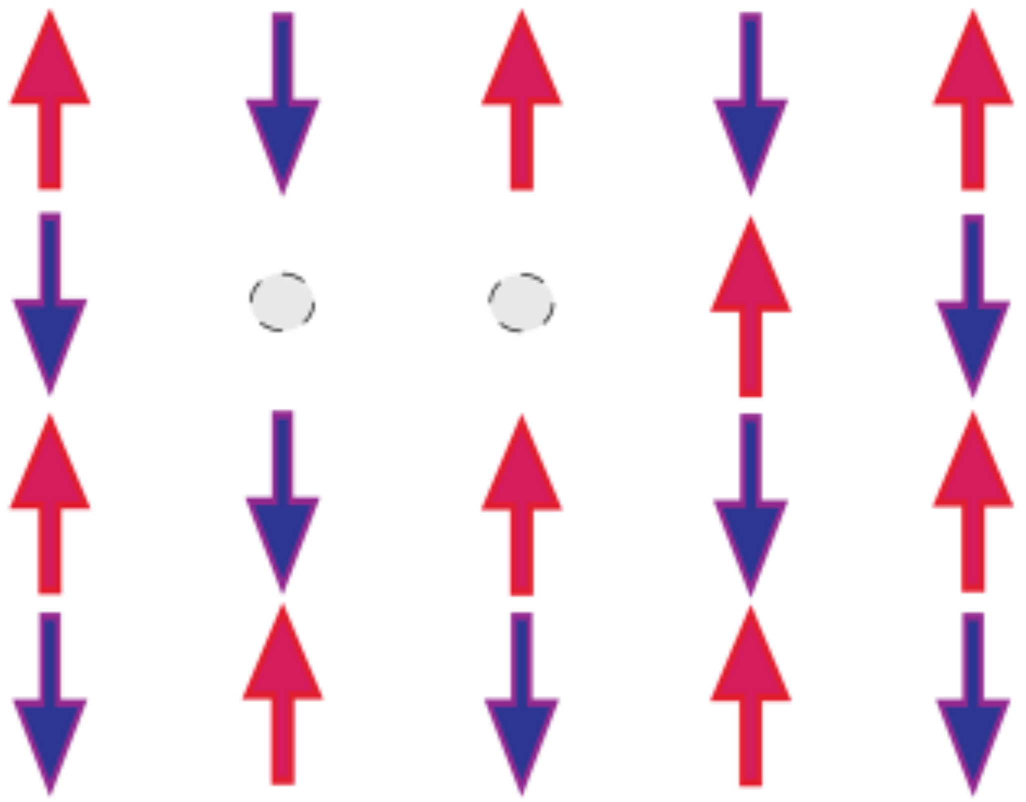
- static thermodynamic quantities
  - Phase separation   Prem et al., PRB (2017)
- in dynamics
  - Hilbert space fragmentation   Pai et al., PRX (2019), Sala et al. PRX (2019), Khemani et al. PRB (2019)

Physical setup: Hole-doped AFMs

Study one and two hole states in

- 2D square AFMs
- “Mixed-dimensional”1D AFMs
- Honeycomb collinear AFMs

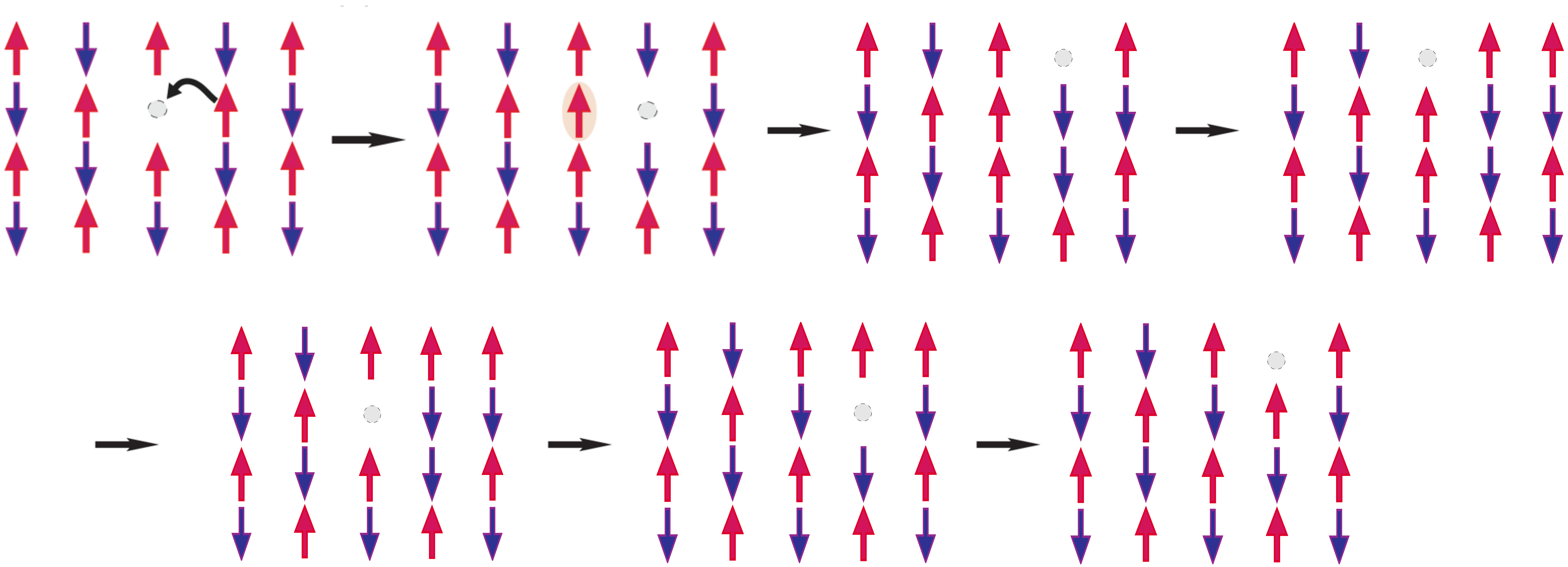




★ Consider Ising spin interactions + treat spin-exchange perturbatively

- **2D square AFM**
- Mixed-dimensional 1D AFM
- Honeycomb collinear AFM

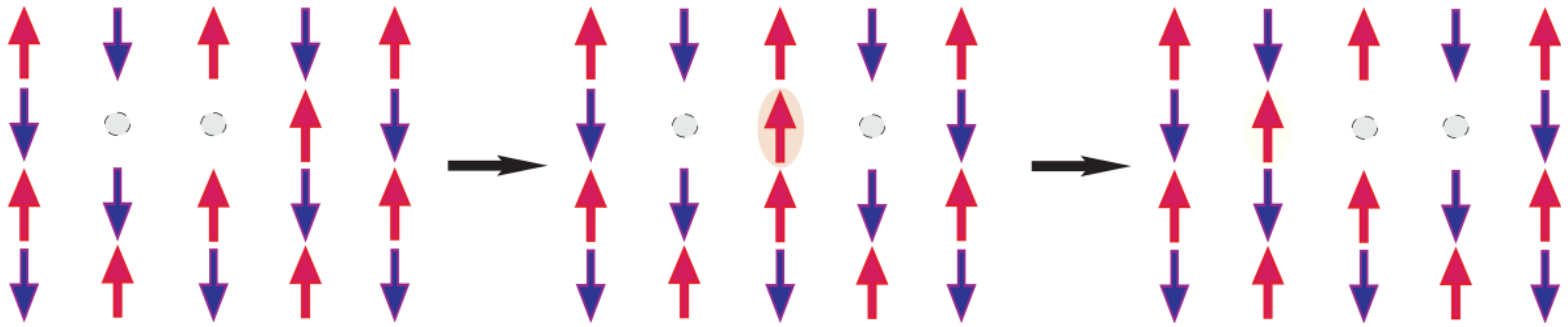
Single hole in a 2D square AFM



<u>Fracton</u>-like constraints on single particles up to 6th-order   Trugman, PRB (1988)

Single-particle dynamics restricted to a single sublattice   Burnell, discussions

Two holes in a 2D square AFM



- Two nearest-neighbor holes on different sublatttices are connected by a `string’ → bound state

- Relative separation of holes in bound state is conserved

- Two holes (with opposite spins) = <u>dipole</u>

Approximate fracton behavior in 2D square AFM

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- 2D square AFM
- **Mixed-dimensional 1D AFM**
- Honeycomb collinear AFM

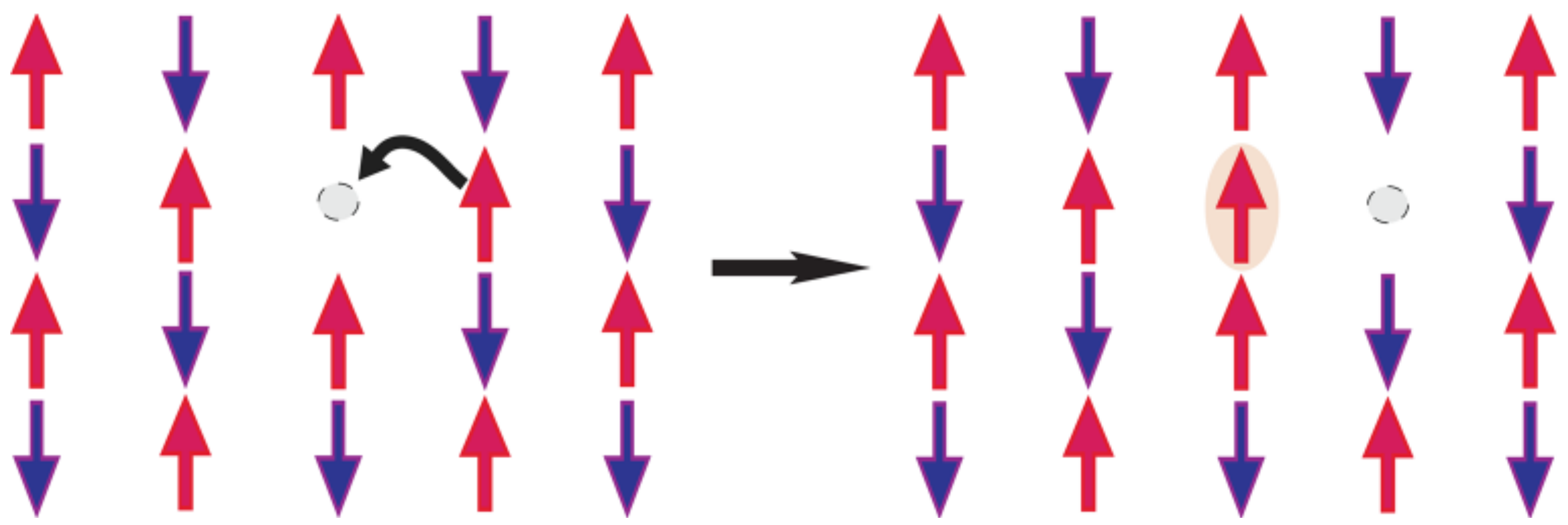
Single hole in a 1D chain

- Only leading-order contribution leads to frustration of AFM correlations
- Hole moves freely after first hop - manifestation of spin-charge separation
  $\rightarrow$ no fractons
- We need true AFM order to obtain fracton behavior

Single hole in mixed-dimensional AFM

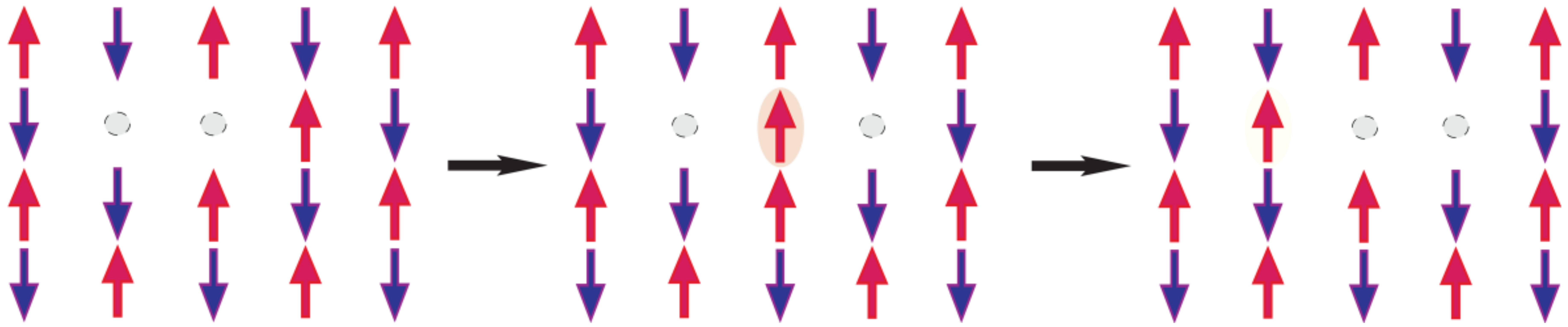
Constrain hole motion along a line in an otherwise 2D square AFM

Apply gentle external fields aligned along one of the system's principal axes



Completely localized single hole = fracton

Two holes in mixed-dimensional AFM



Mechanism from 2D square AFM carries over:

- Two holes on different sublatttices connected by a string → <u>dipole</u>
- Relative separation of holes in bound state is conserved

Exact fracton behavior in mixed-dimensional 1D AFM

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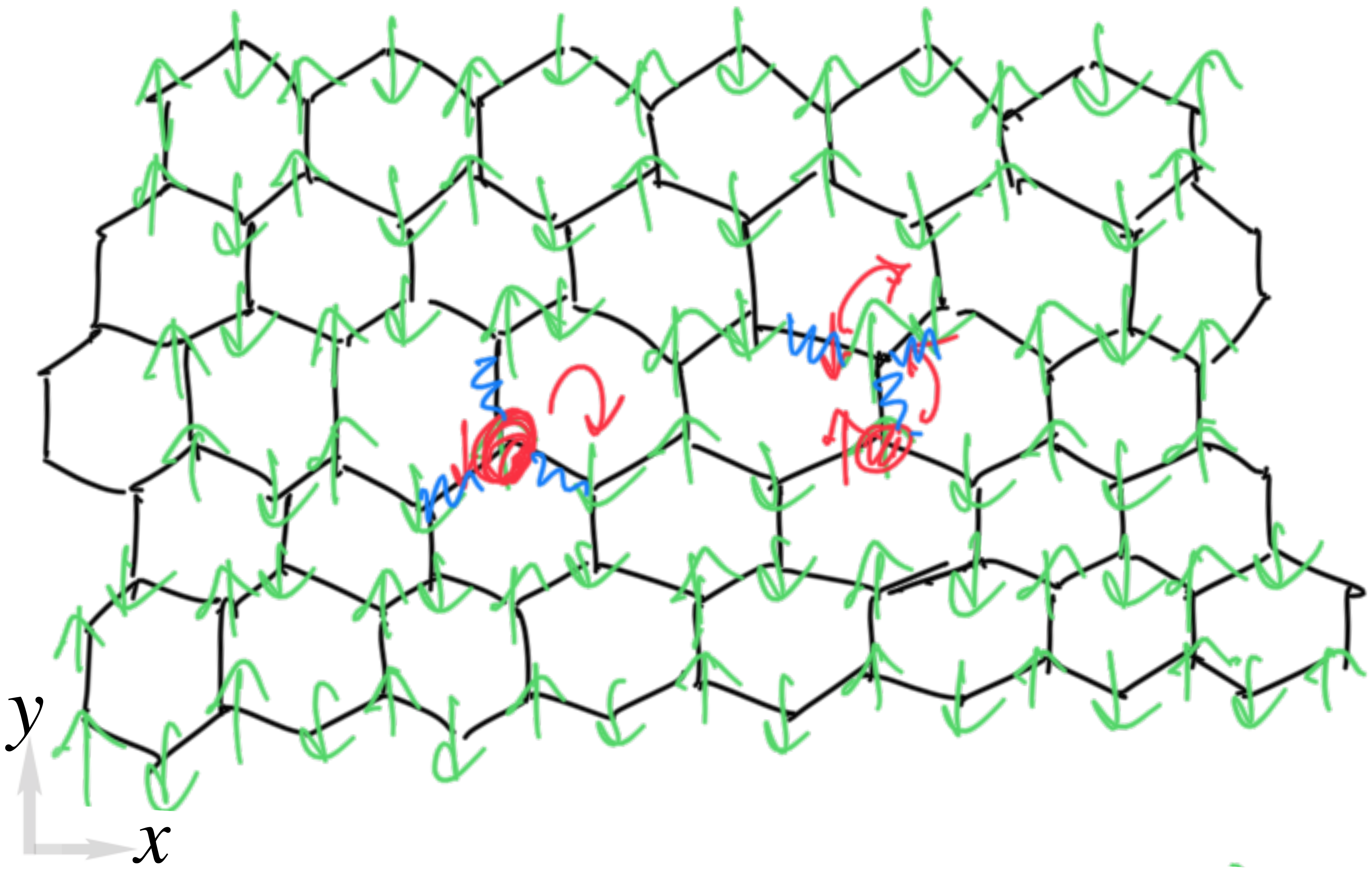
more details in **JS** & M. Pretko, PRB **102** 214437 (2020)

- 2D square AFM
- Mixed-dimensional 1D AFM
- **Honeycomb collinear AFM**

Single hole in a honeycomb collinear AFM



AFM ordering in x-direction

FM ordering in y-direction

Original position of spin

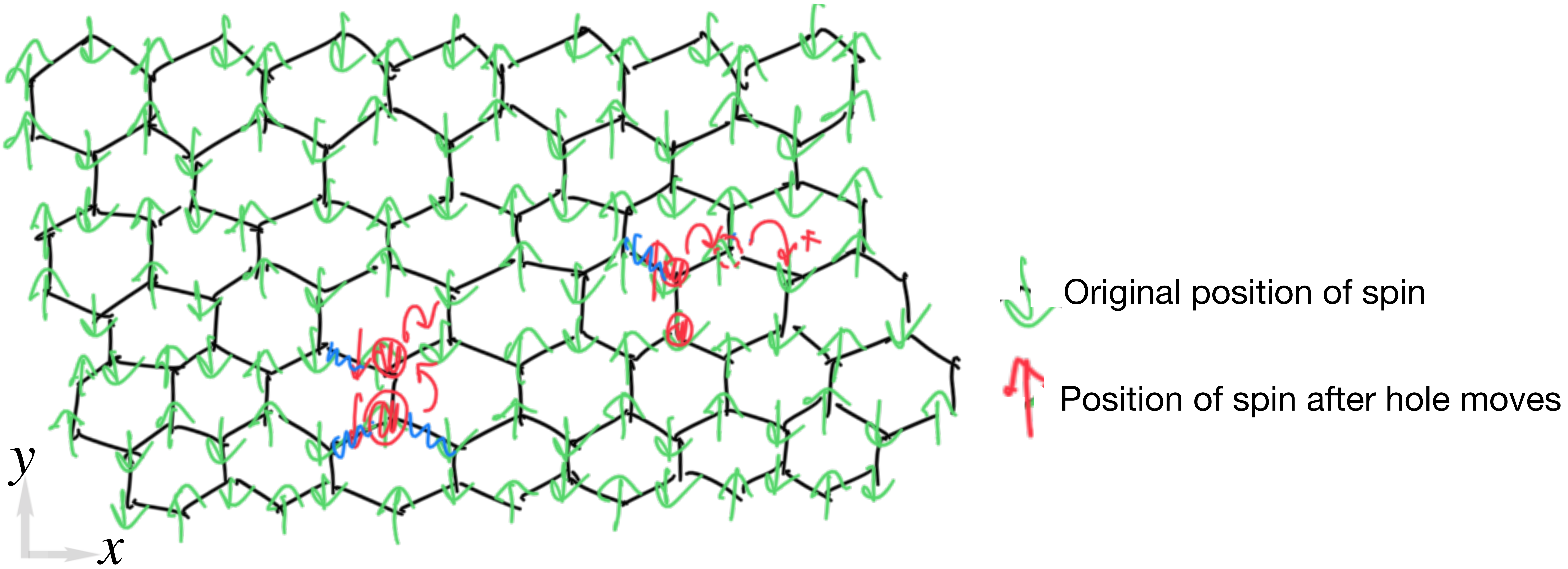
Position of spin after hole moves

Single hole cannot move in the AFM x-direction

Single hole can move only by one site in the FM y-direction

S. Sanyal, A. Wietek & **JS**, in preparation

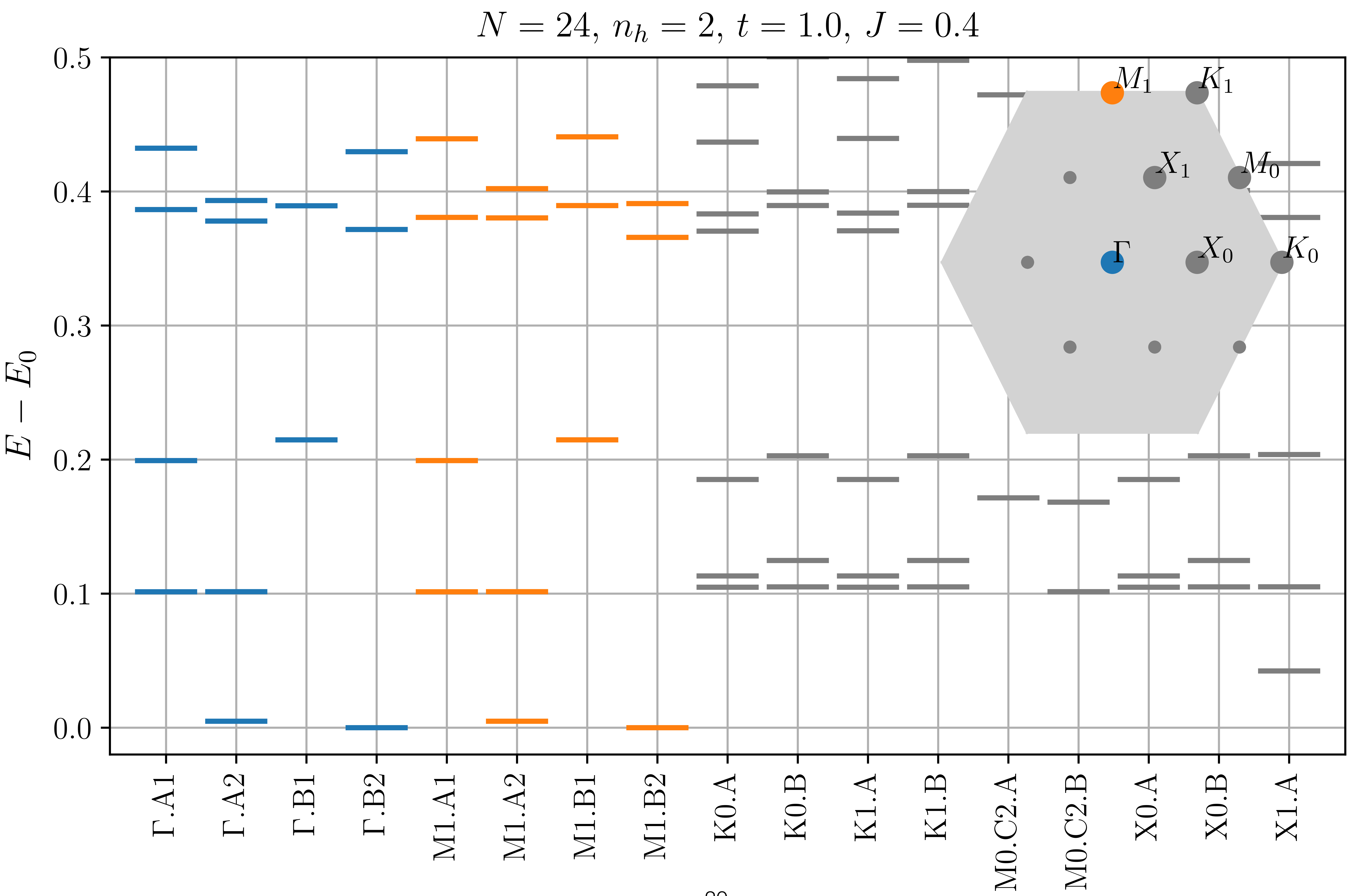
Two holes in a honeycomb collinear AFM



Pairs can move in the AFM x-direction (as before)

Pairs now cannot move in the FM y-direction

S. Sanyal, A. Wietek & **JS**, in preparation


$N = 24,\ n_h = 2,\ t = 1.0,\ J = 0.4$
$E - E_0$
0.0
0.1
0.2
0.3
0.4
0.5
Γ.A1
Γ.A2
Γ.B1
Γ.B2
M1.A1
M1.A2
M1.B1
M1.B2
K0.A
K0.B
K1.A
K1.B
M0.C2.A
M0.C2.B
X0.A
X0.B
X1.A
M_1
K_1
X_1
M_0
Γ
X_0
K_0

- Single holes are localized = fractons

- Pairs of holes move only along the AFM direction = dipoles restricted to a subdimensional manifold (line)

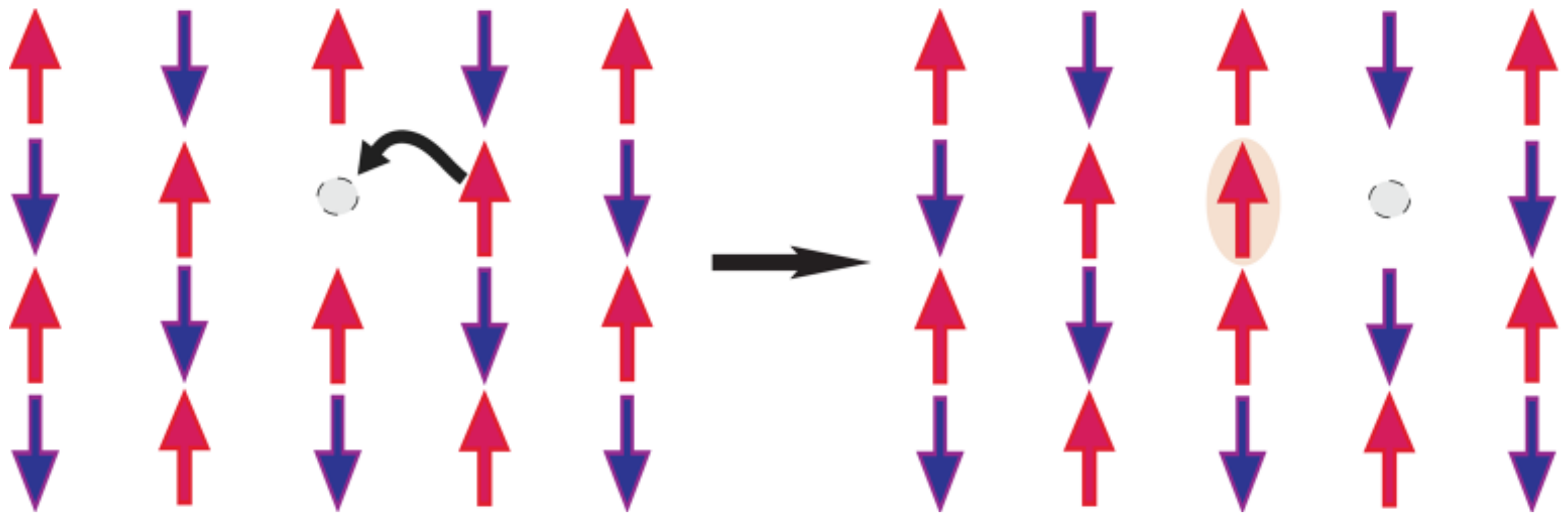
Dipolar lineons in honeycomb collinear AFMs

S. Sanyal, A. Wietek & **JS**, in preparation

Fast recap

- Square AFM:
  - Single hole = fracton (approximate)
  - Two holes = dipole
- Mixed-dimensional AFM:
  - Single hole = fracton
  - Two holes = dipole
- Honeycomb collinear AFM:
  - Single hole = fracton
  - Two holes = dipolar lineon

Fracton physics in AFM



- Stable against $J_\perp$ leading order in t/J_z
- Readily realizable in materials
- May be possible to probe fracton phenomenology in experiment
  - Emulsion at finite densities   Prem et al., PRB (2018)
  - Slow thermalization   Pai et al., PRX (2019), Sala et al. PRX (2019), Khemani et al. PRB (2019)

Summary

- *Quasiparticles reminiscent of fractons and dipoles*
  - **Fracton** = one hole dressed by magnetic background
  - **Dipole** = two holes on neighboring sites coupled to magnetic background
- *Robust fracton behavior*
  - Exact in mixed-dimensional 1D limit + Approximate in 2D square lattice + Extra mobility constraints from collinear order on different geometries
  - relatively stable to small $J_\perp$
- Future directions?
  - Symmetry-based theory   Discussions with Burnell and Prem