Designing
Frustrated Magnets in a 2D Ion Crystal

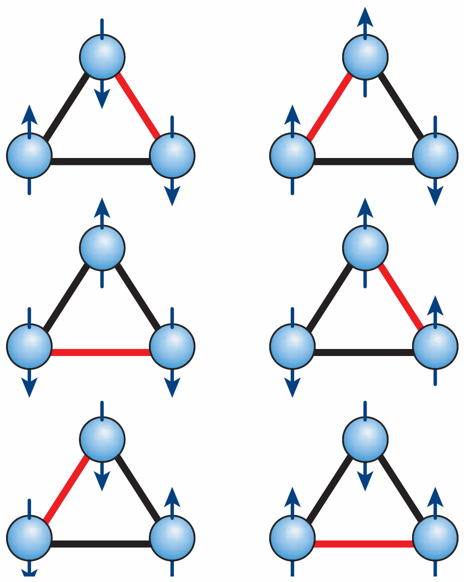
Rejish Nath
IISER Pune

Delhi, 12th Feb

Geometric Frustration

No unique ground state !

Examples: triangle of anti-ferromagnetically interacting Ising spins



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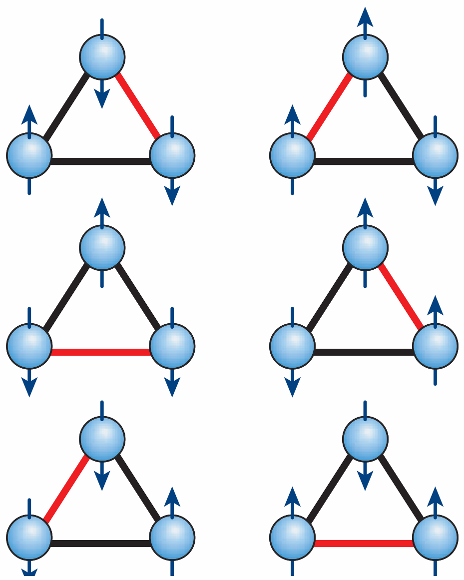
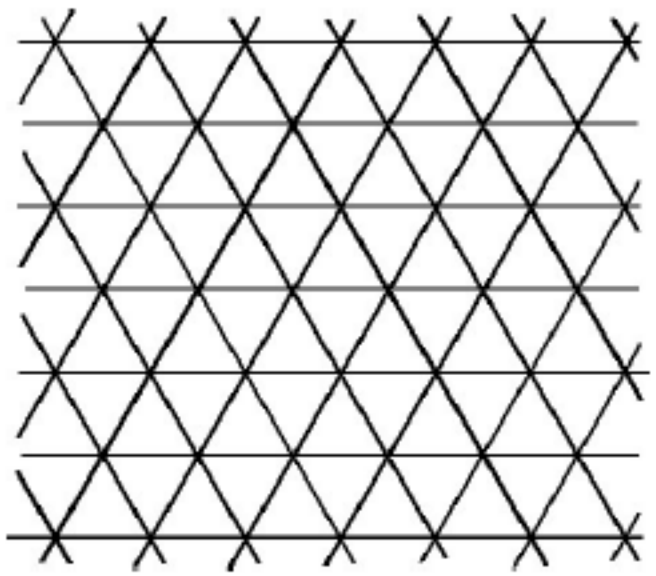


Infinite number of degenerate ground states



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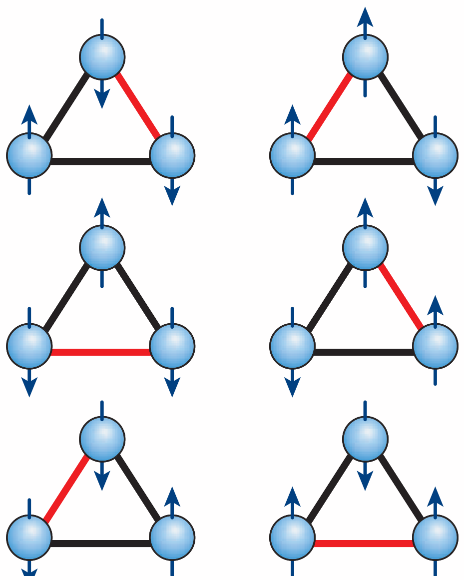

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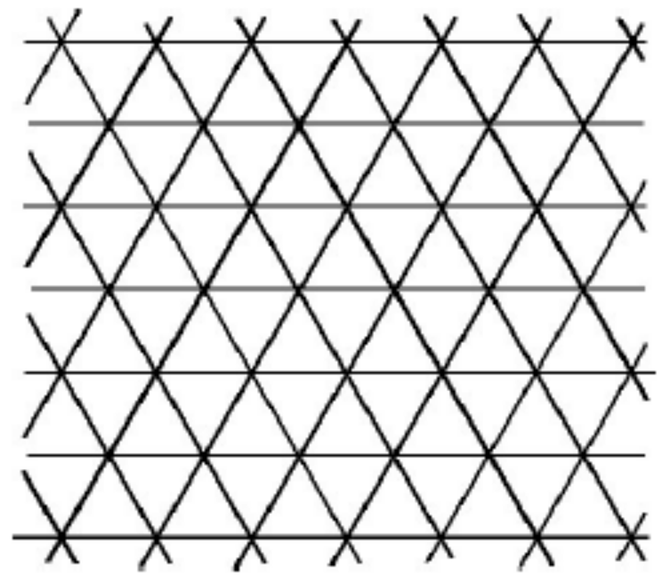
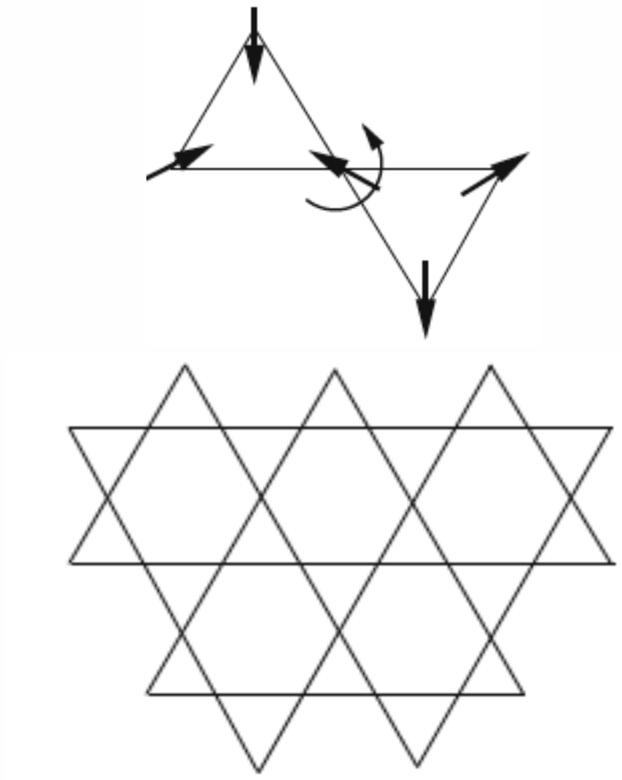


Corner-sharing triangles : Kagome lattice



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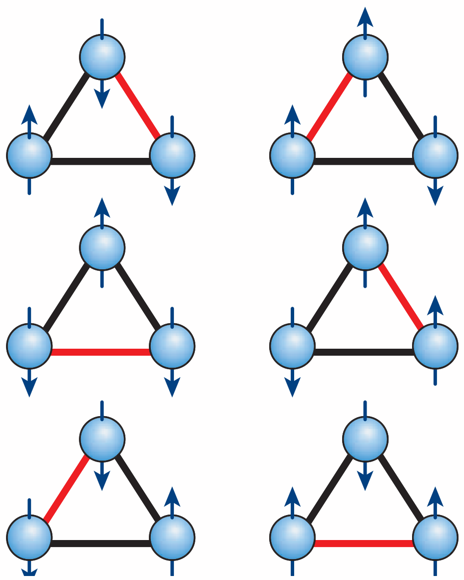

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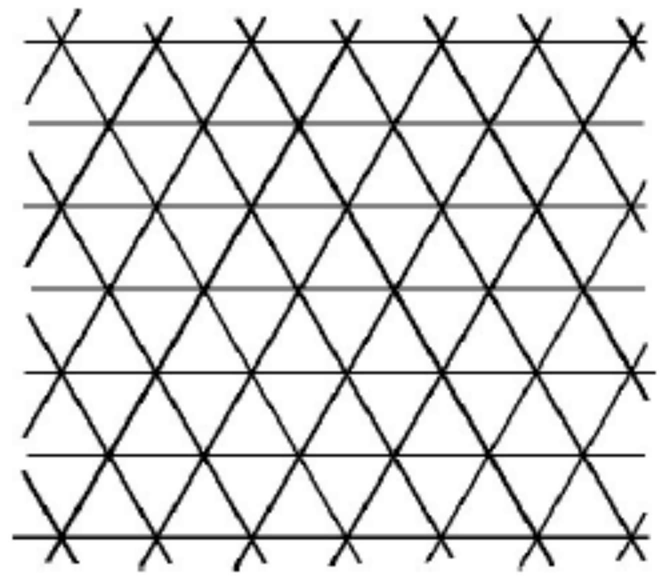

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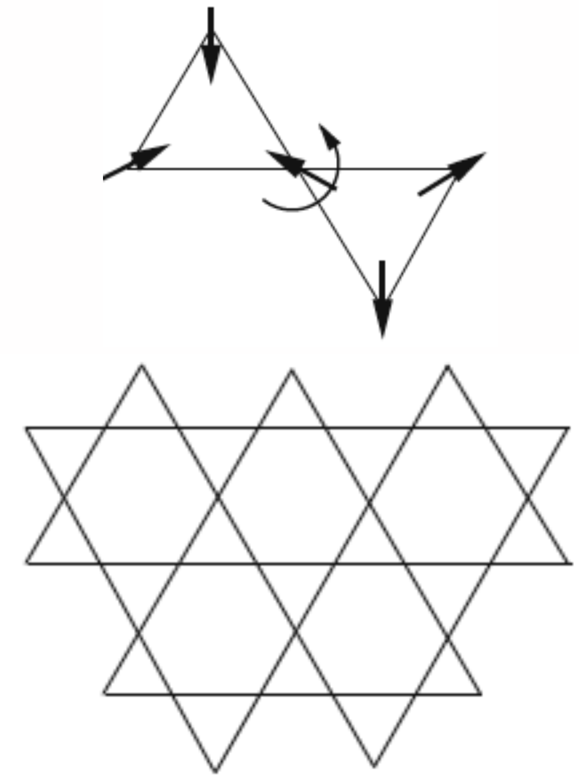
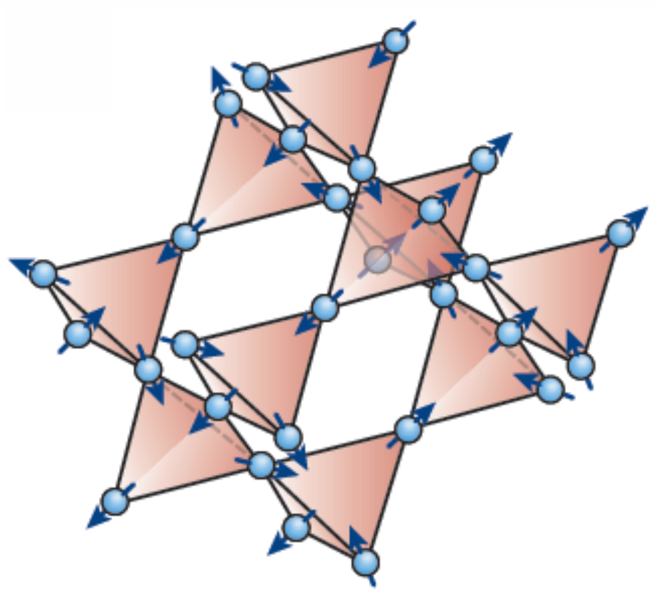


Pyrochlore lattice: **Spin ice**



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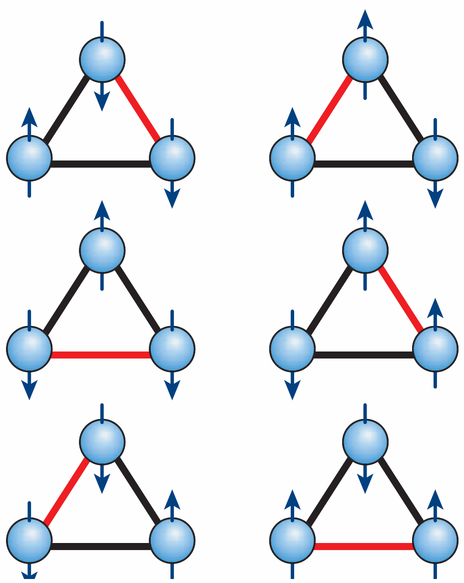

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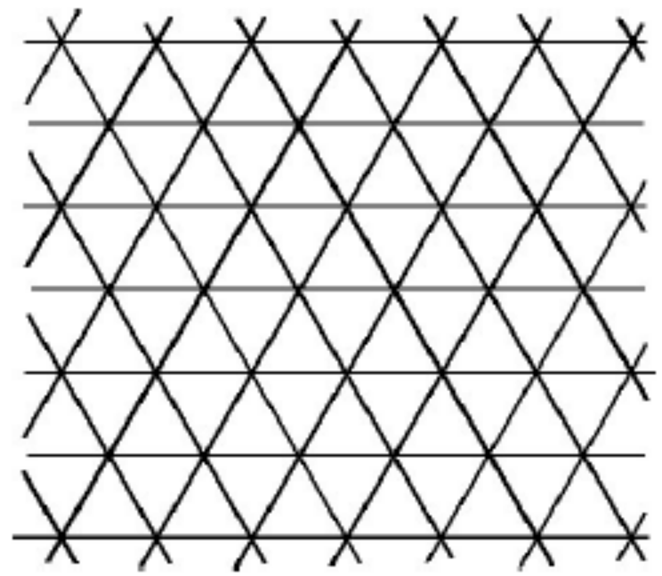

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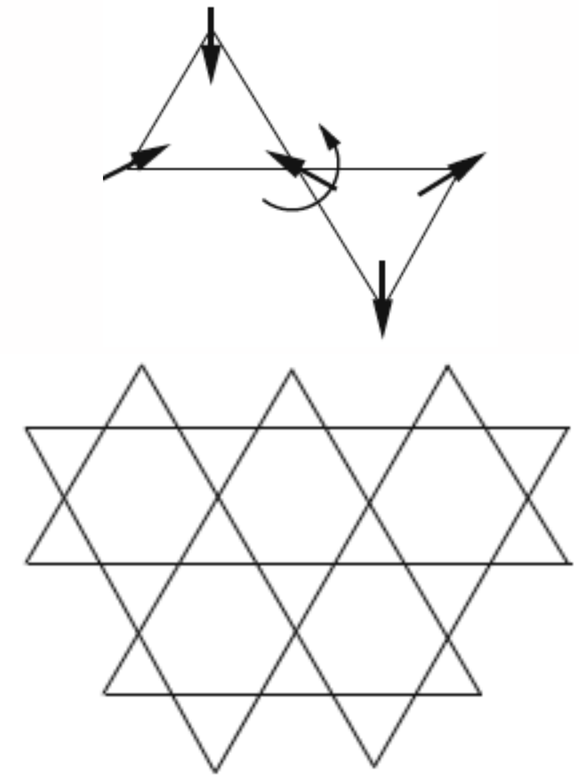

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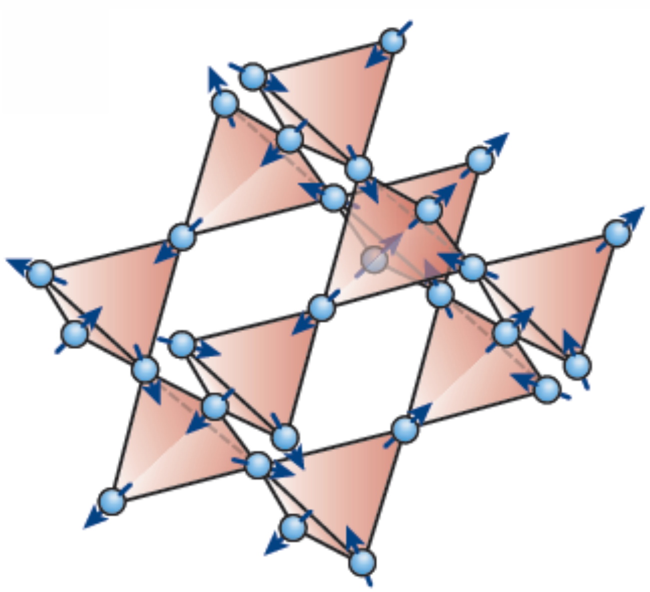

<u>Features</u>:

- large degeneracy of ground state
- non-zero ground state entropy. (ice entropy, Pauling 1935)
- fluctuations can be classical (thermal) and quantum (T=0).

order by disorder

Quantum spin liquids
(fractional excitations, artificial gauge field)

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Frustrated magnets with emergent gauge fields

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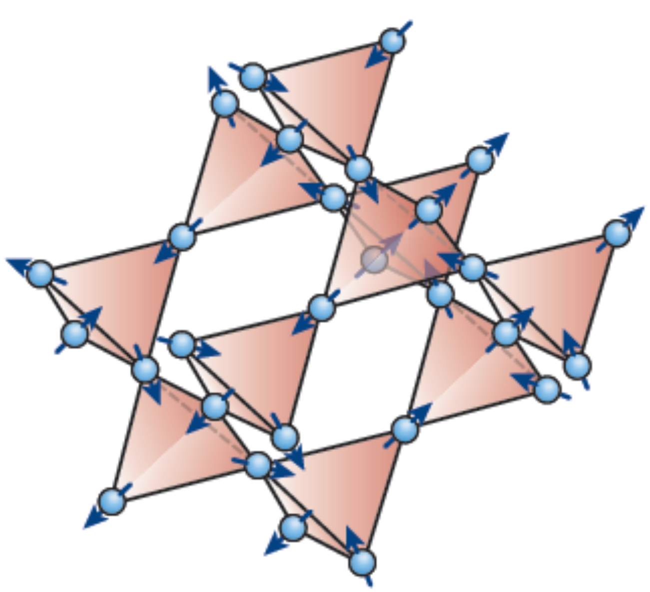

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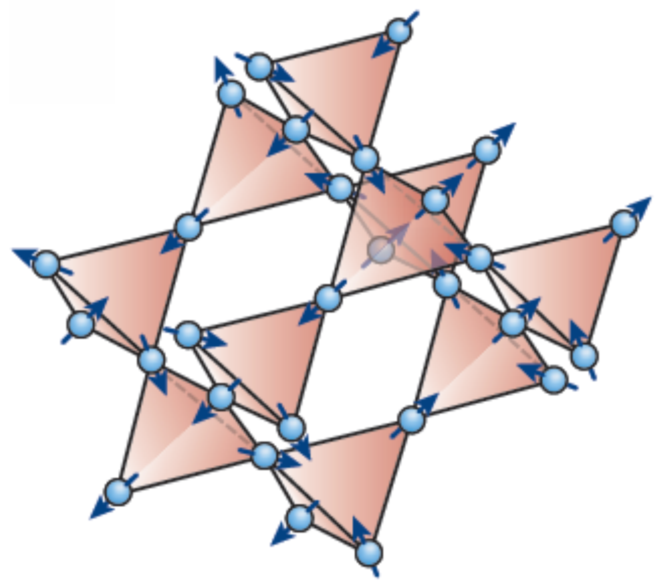

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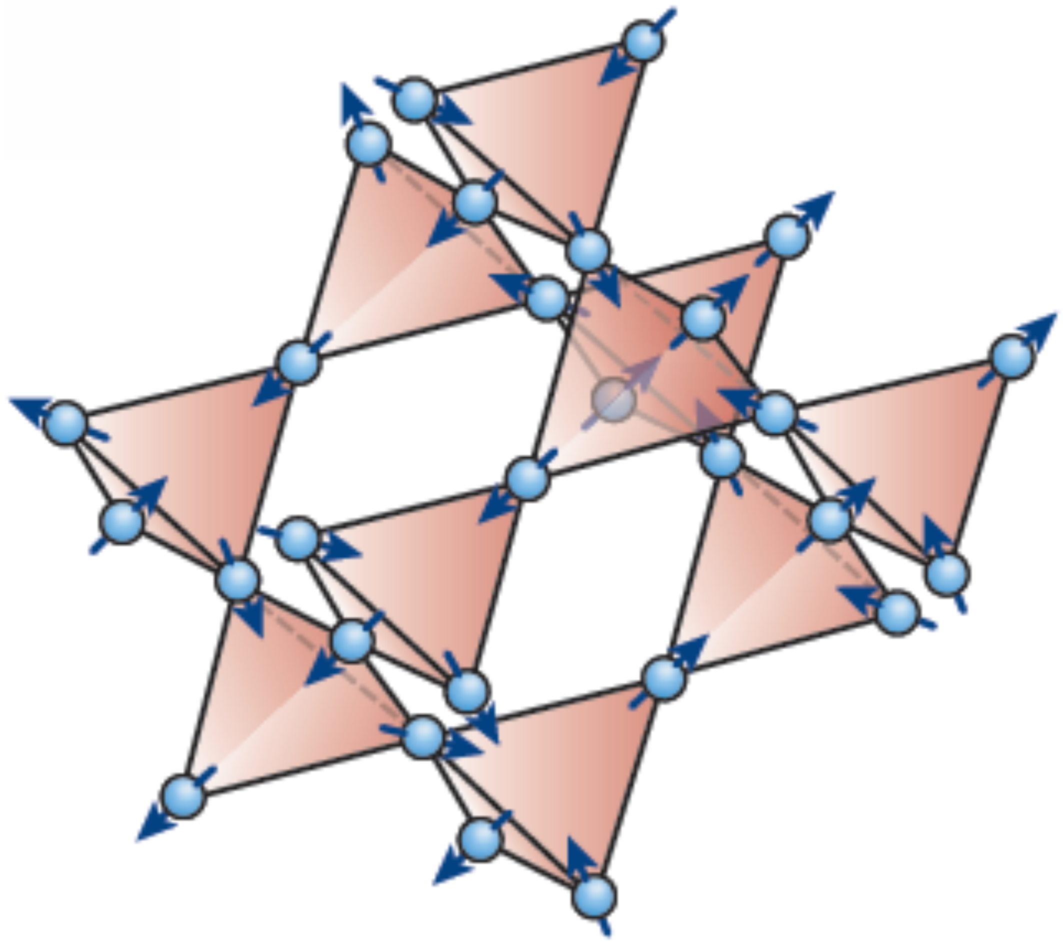

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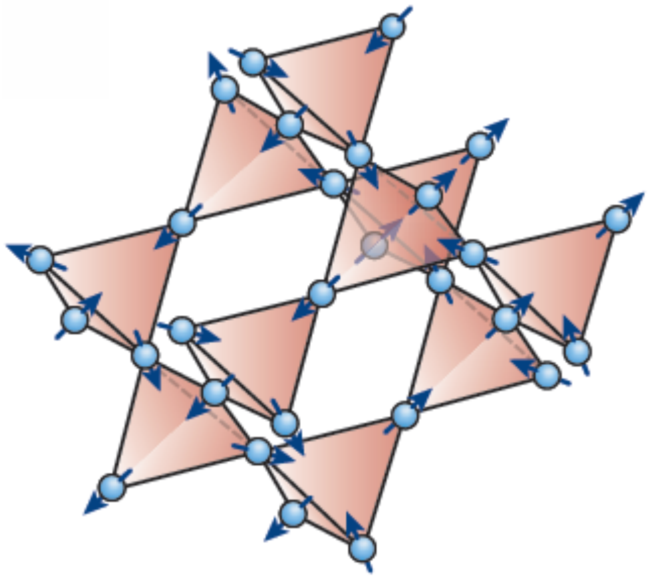

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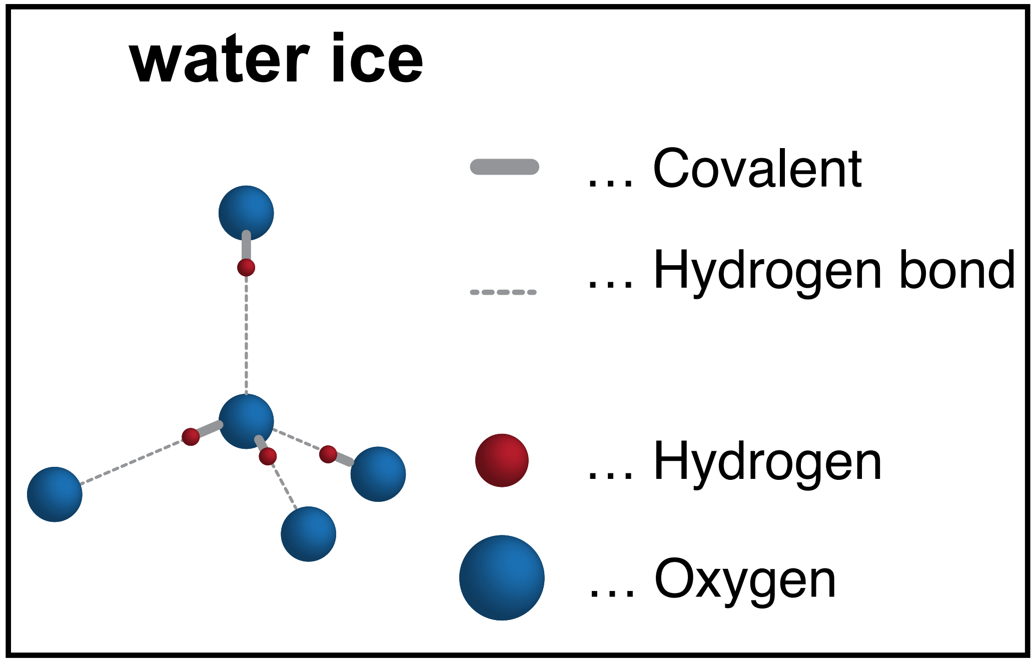

Around each oxygen atom, two hydrogen atoms are closer, two are far.

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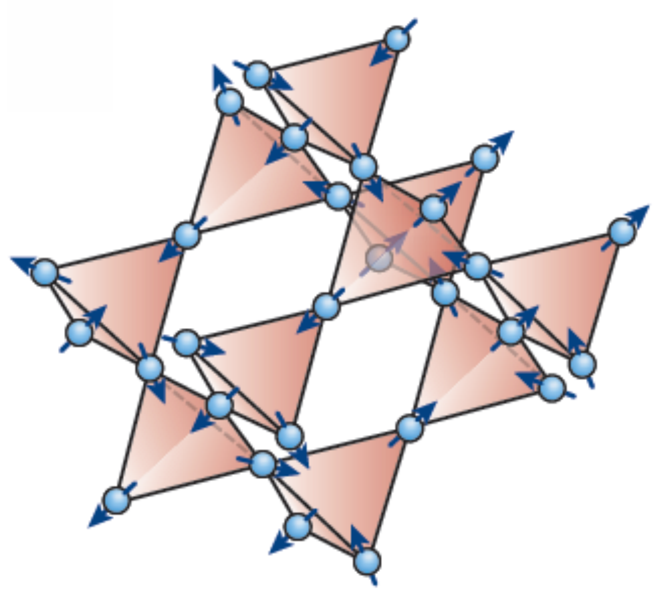

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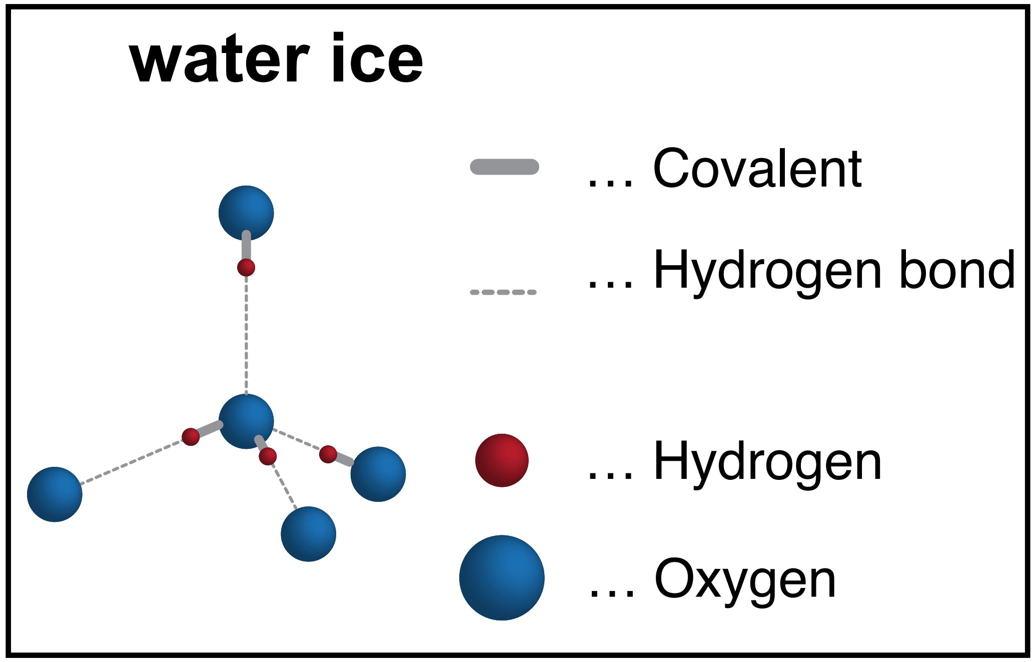

Around each oxygen atom, two hydrogen atoms are closer, two are far.

The Structure and Entropy of Ice and of Other Crystals with Some Randomness of Atomic Arrangement

BY LINUS PAULING

many possibilities!

(1) In ice each oxygen atom has two hydrogen atoms attached to it at distances of about 0.95 Å., forming a water molecule, the HOH angle being about 105° as in the gas molecule.

(2) Each water molecule is oriented so that its two hydrogen atoms are directed approximately toward two of the four oxygen atoms which surround it tetrahedrally, forming hydrogen bonds.

(3) The orientations of adjacent water molecules are such that only one hydrogen atom lies approximately along each oxygen–oxygen axis.

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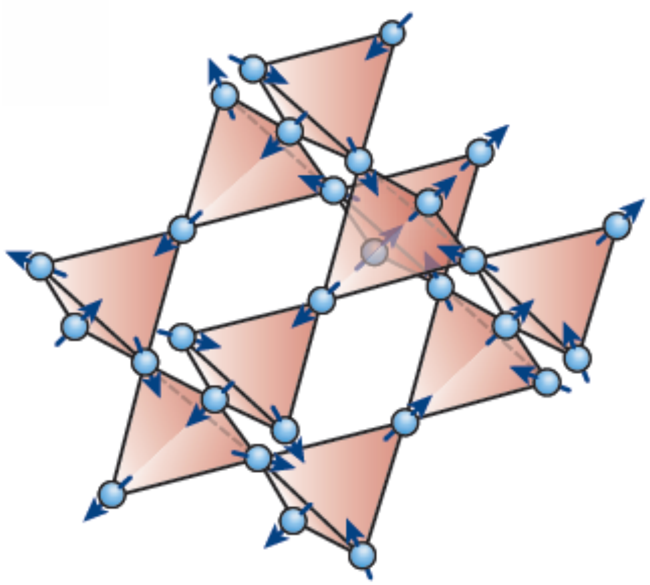
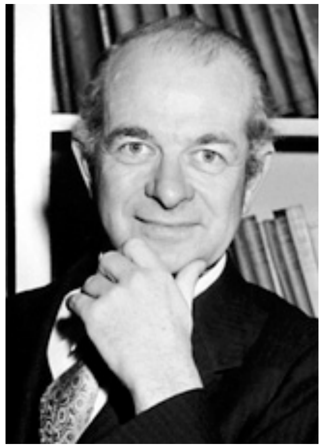


1935… **Linus Pauling**

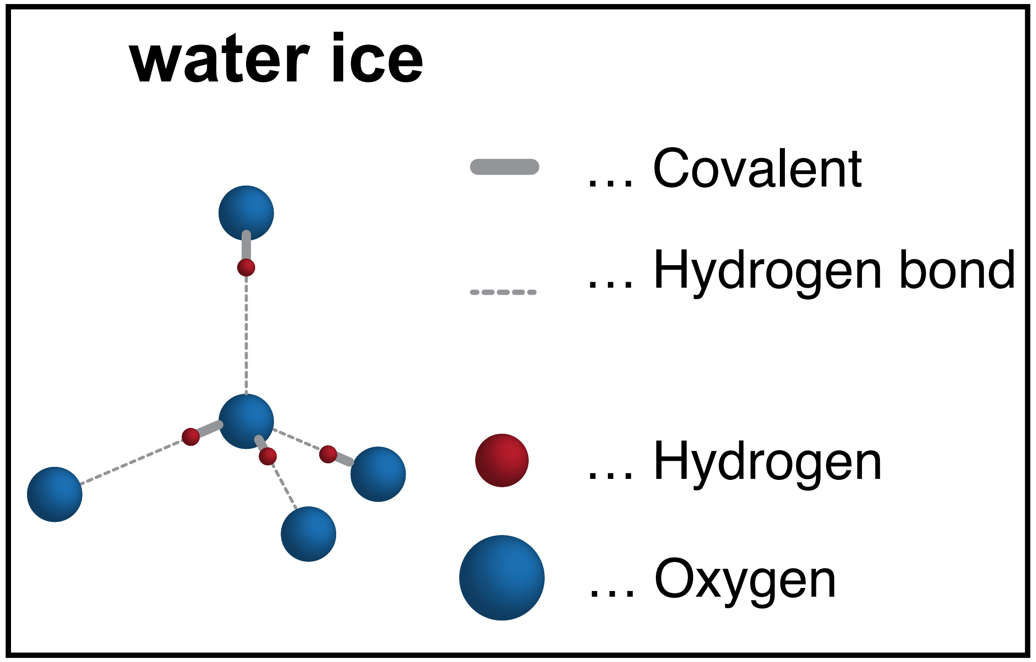


Nobel Prize 1954 (Chemistry)
"for his research into the nature of the chemical bond and its application to the elucidation of the structure of complex substances"

Nobel Prize 1962 (Peace)

(ice entropy, Pauling 1935)

Why "ice"?



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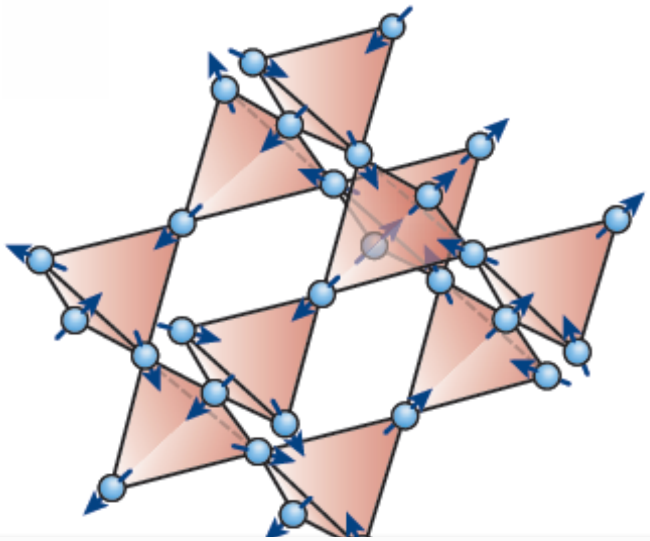
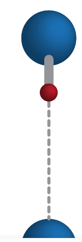


Why "ice"?

water ice

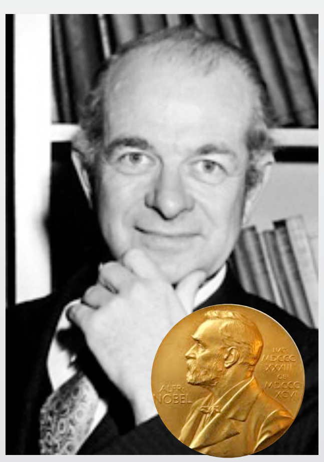


... Covalent

... Hydrogen bond

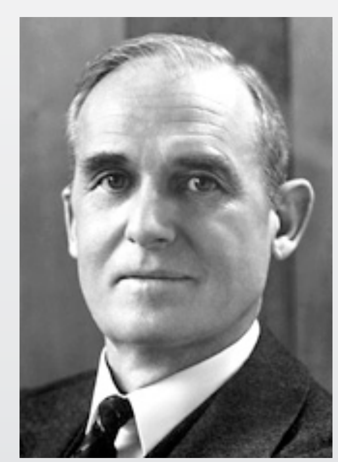
1935...

Linus Pauling (1935):



1933...

Theory:
$S_0 = 0.806$ Cal/deg mol



William F. Giauque

Experiment:
$S_0 = 0.82 \pm 0.05$ Cal/deg mol

Geometric Frustration: Spin ice

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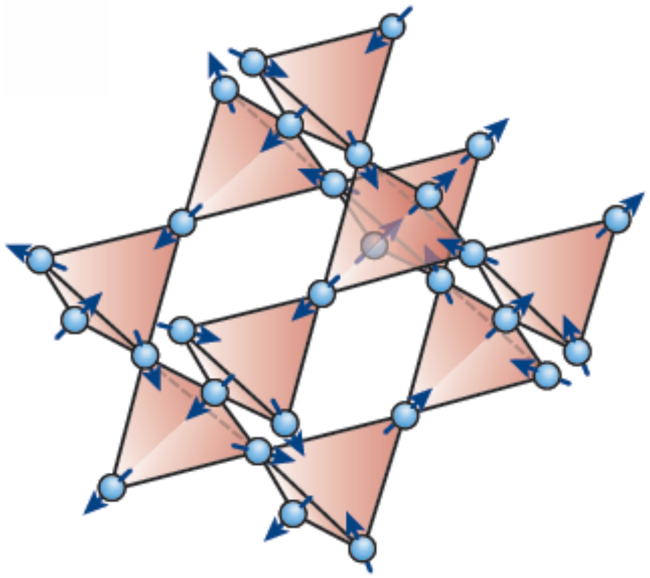

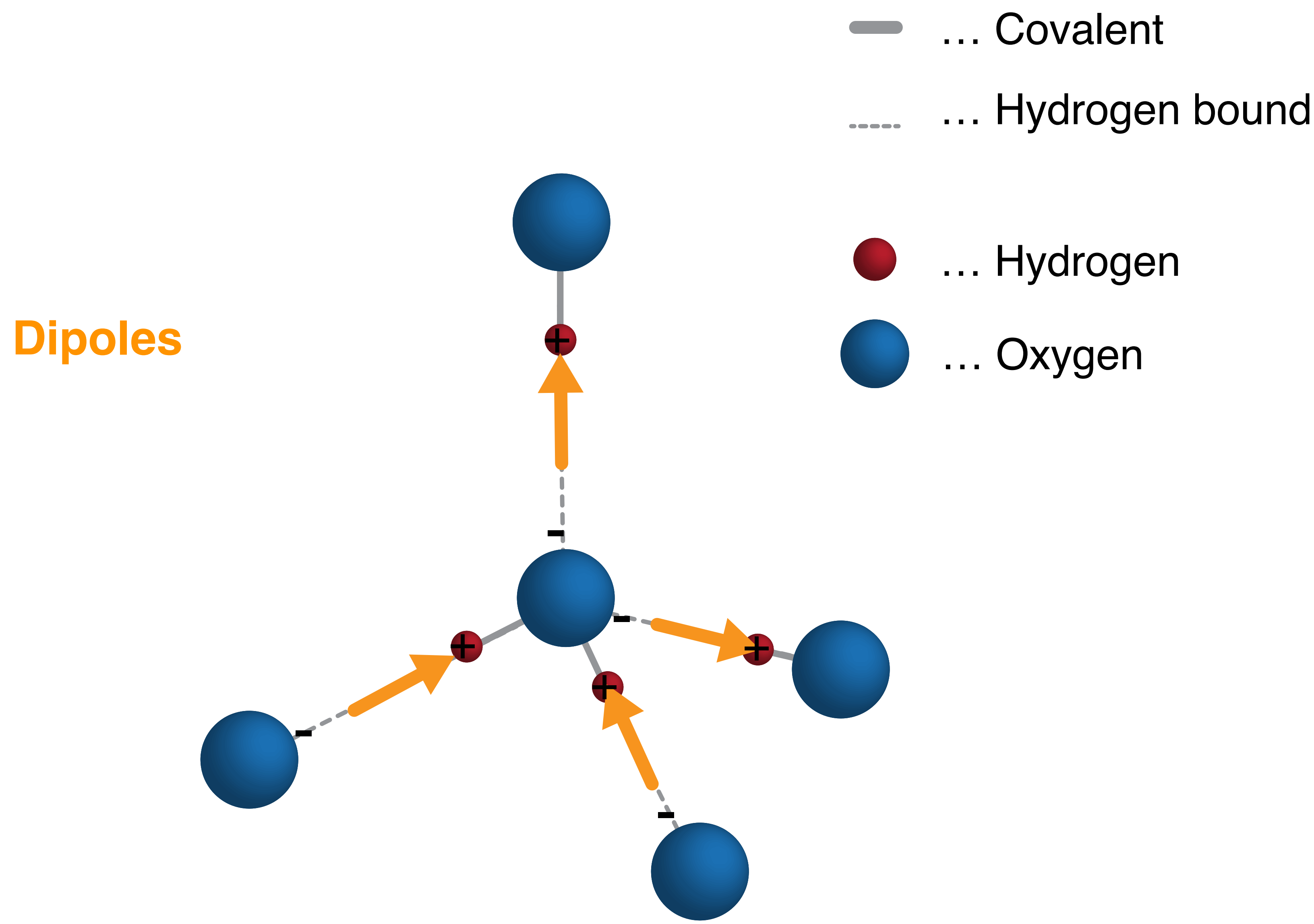

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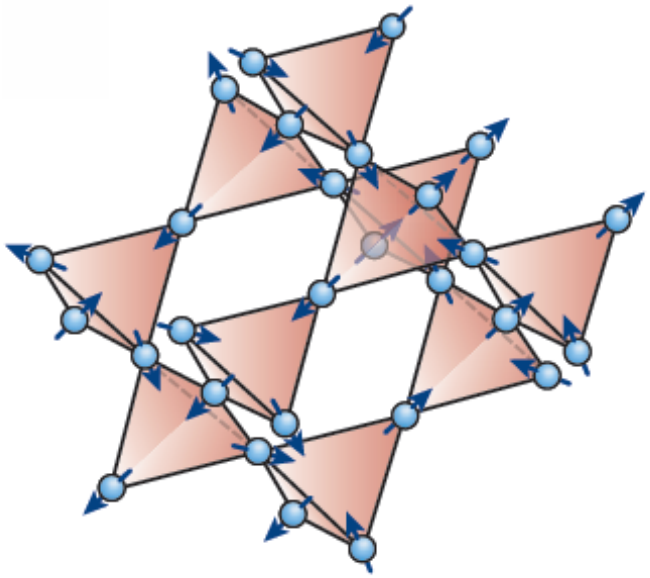
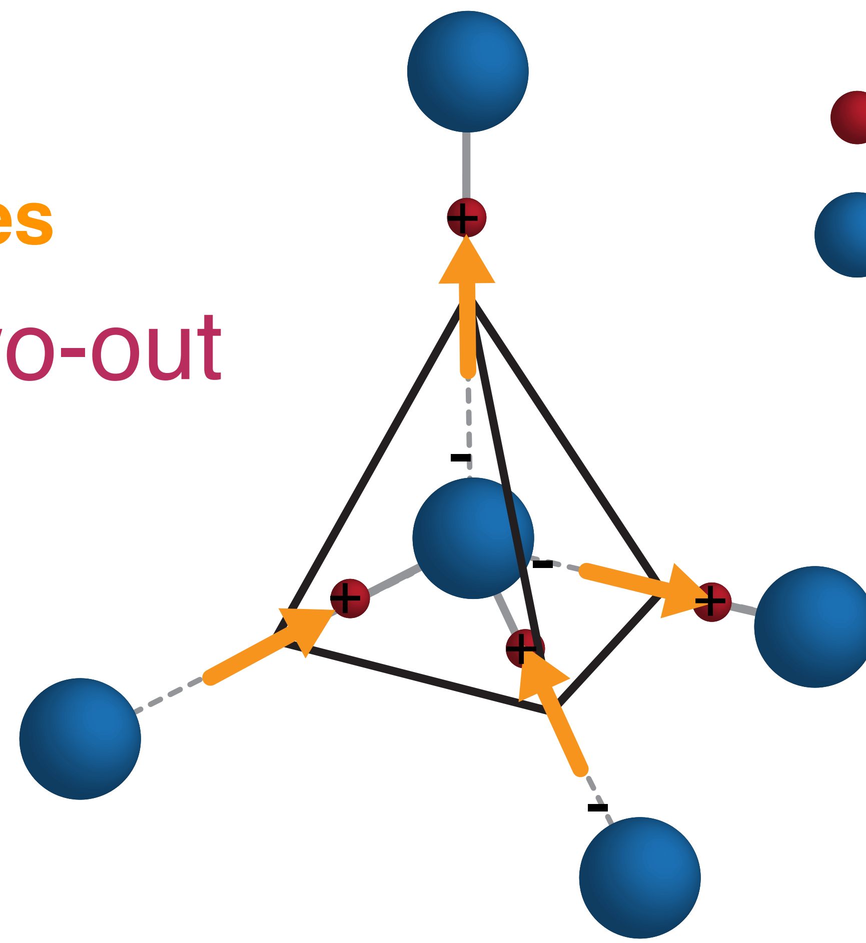
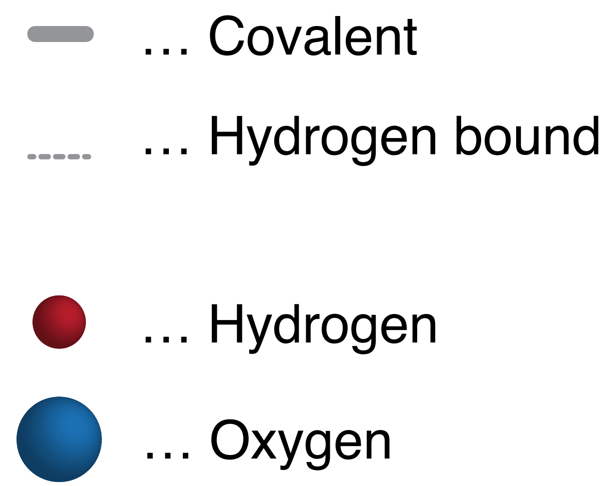


Dipoles

two-in / two-out





Geometric Frustration: Spin ice

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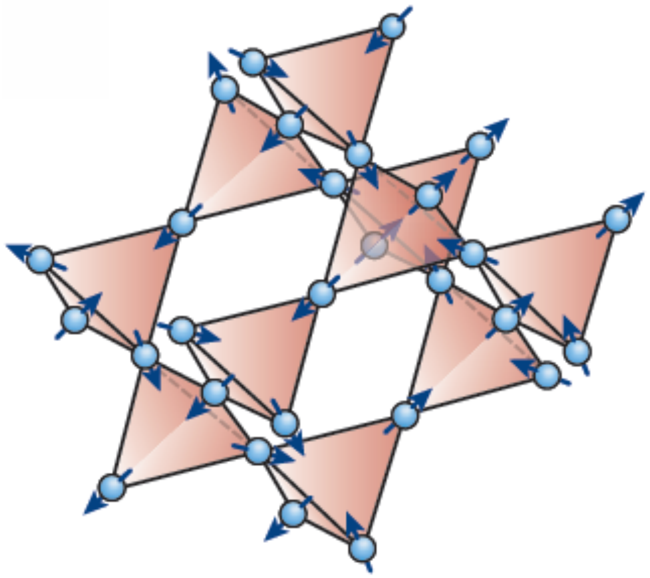
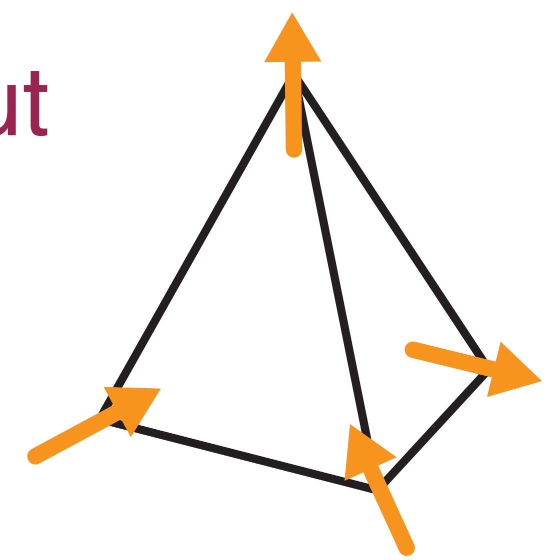
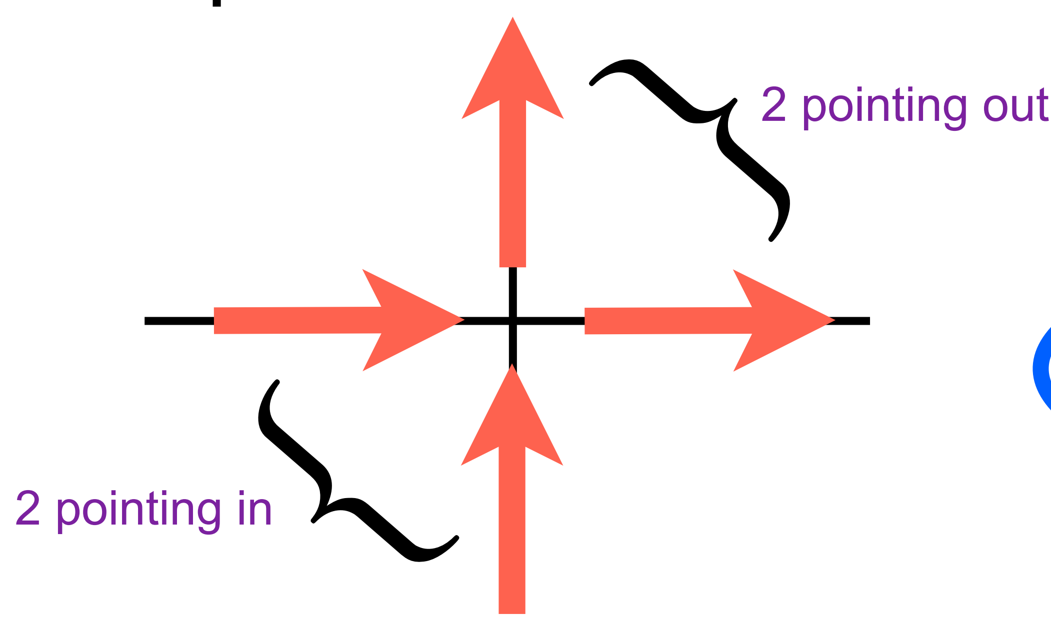


“Spin-Ice”

two-in / two-out



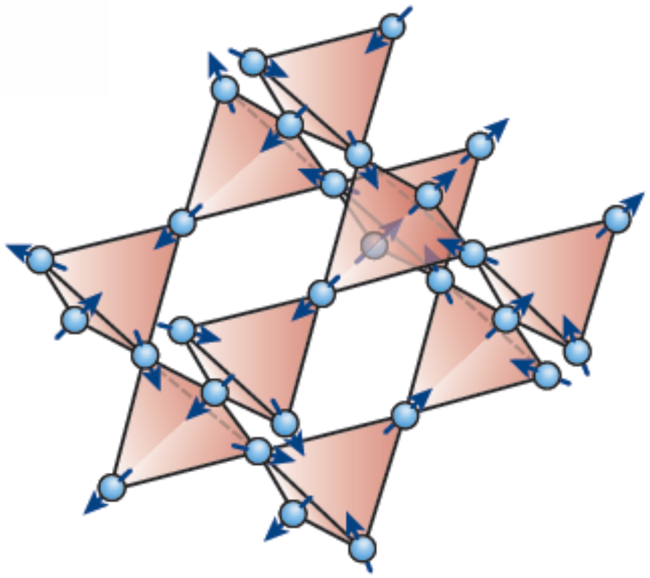
This can be modelled in a **square lattice**



Ice Rule : Two in Two out

Geometric Frustration: Spin ice

Pyrochlore lattice: **Spin ice**

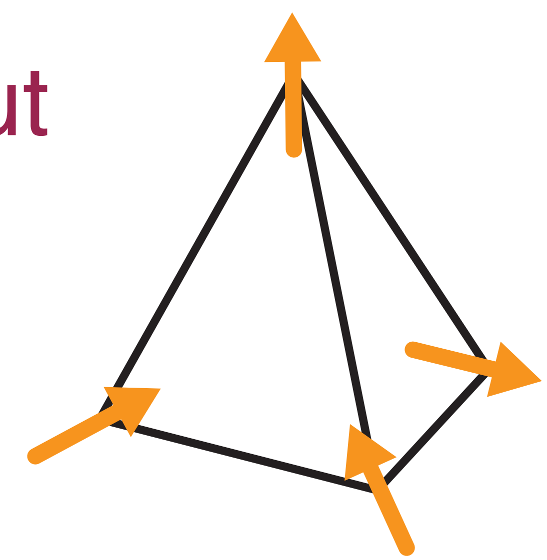


Spin-Ice materials:

$Ho_2Ti_2O_7$
$Dy_2Ti_2O_7$
$Ho_2Sn_2O_7$

"Spin-Ice"

two-in / two-out



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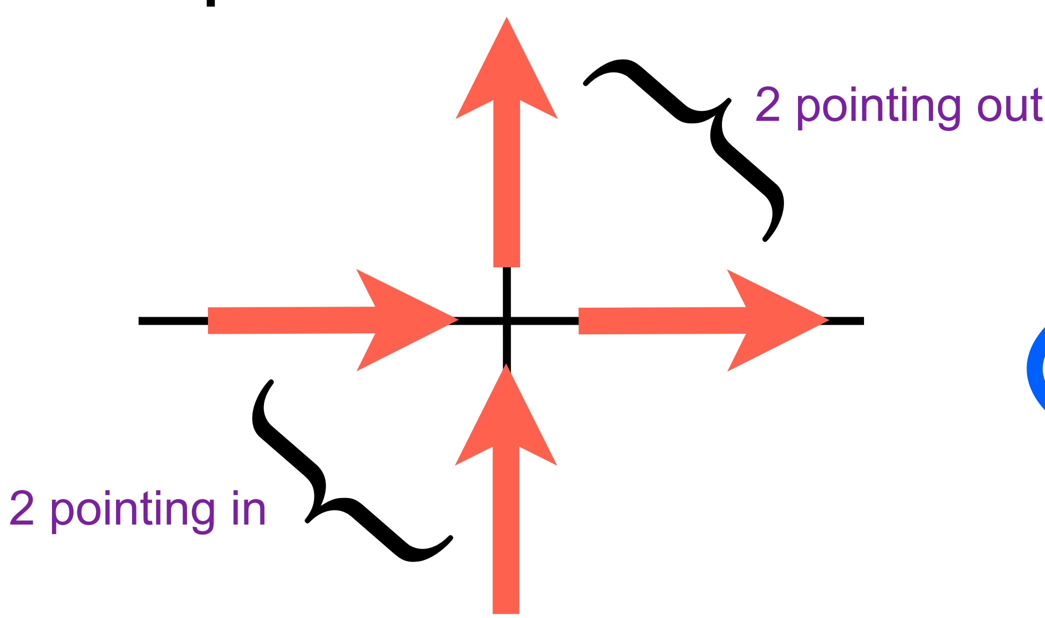

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Spin ice : Six vertex model

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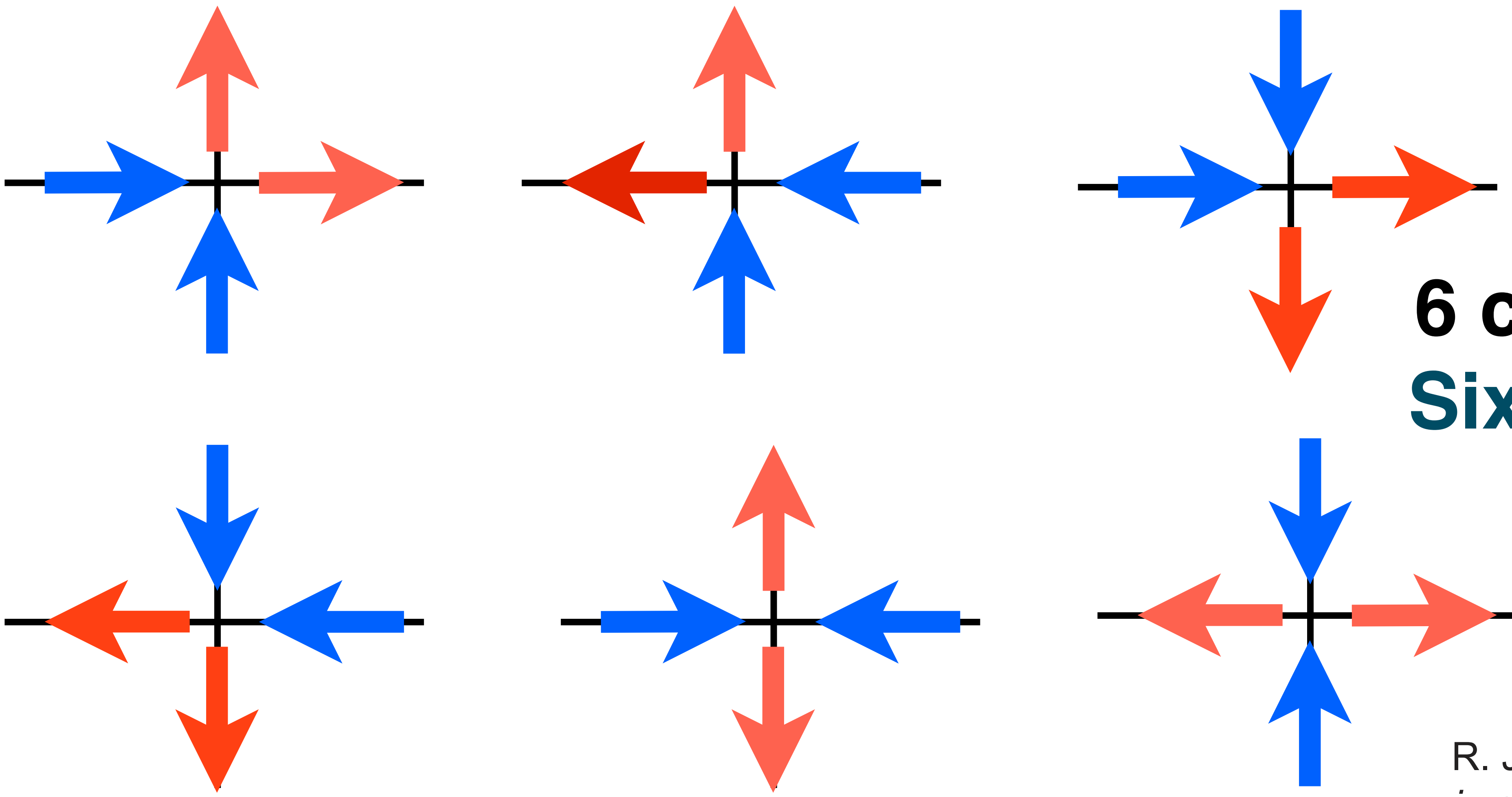


6 configurations

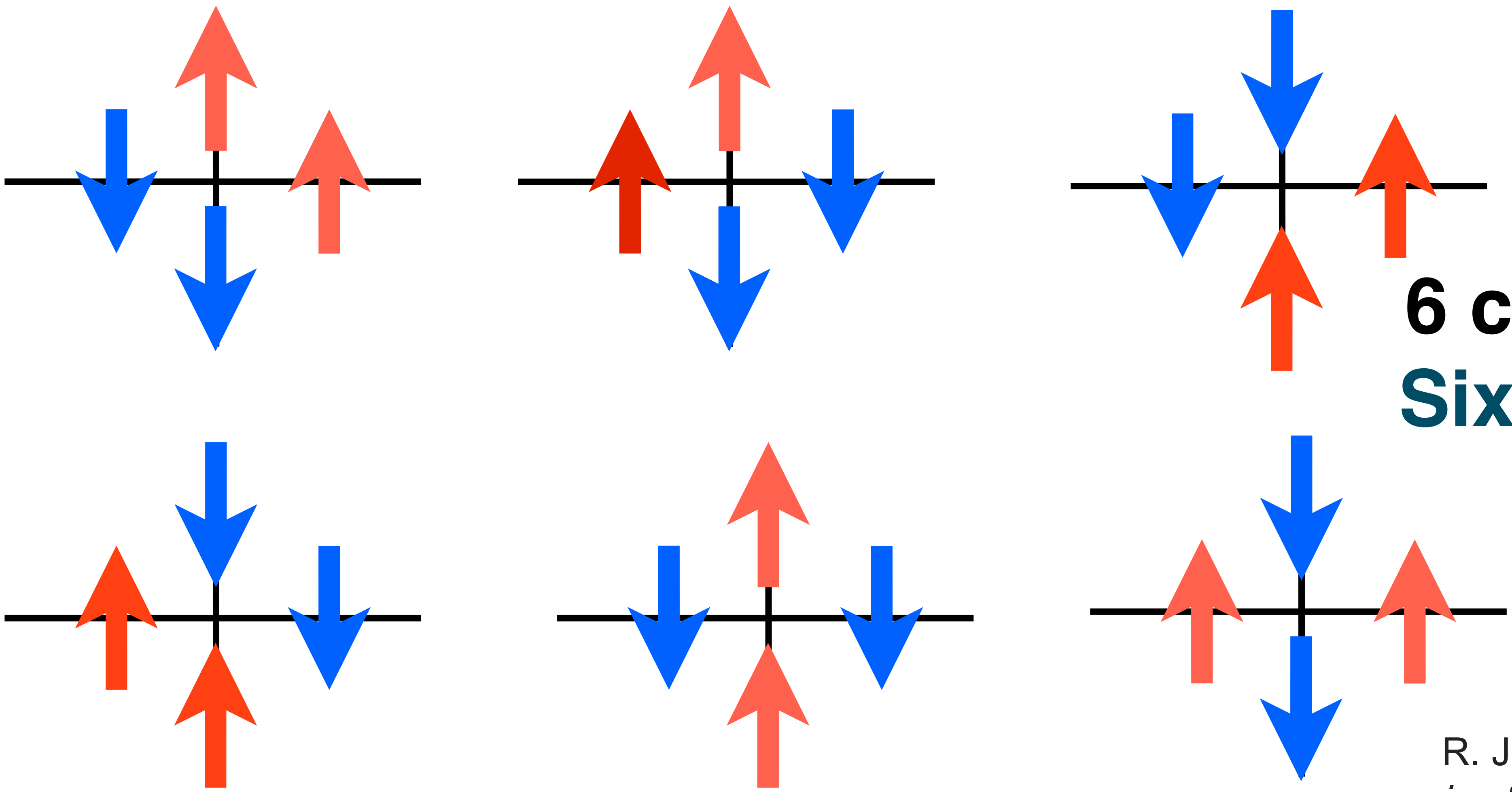
Six-vertex Model

R. J. Baxter, *Exactly solved models in statistical mechanics*

Spin ice : Six vertex model

Ice Rule : Two in Two out

Spin-1/2 Ising system



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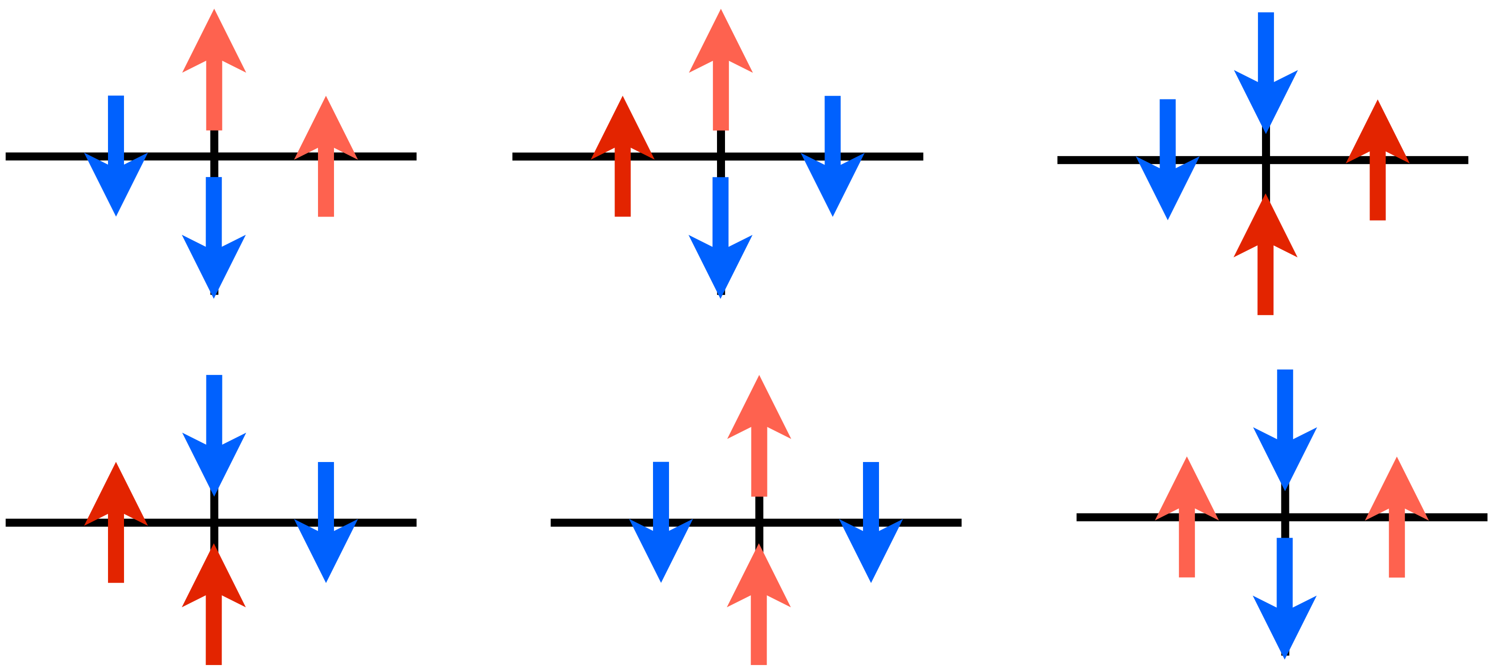


6 configurations
Six-vertex Model

$$H_0 = J_z(\sigma_z^1 + \sigma_z^2 + \sigma_z^3 + \sigma_z^4)^2$$

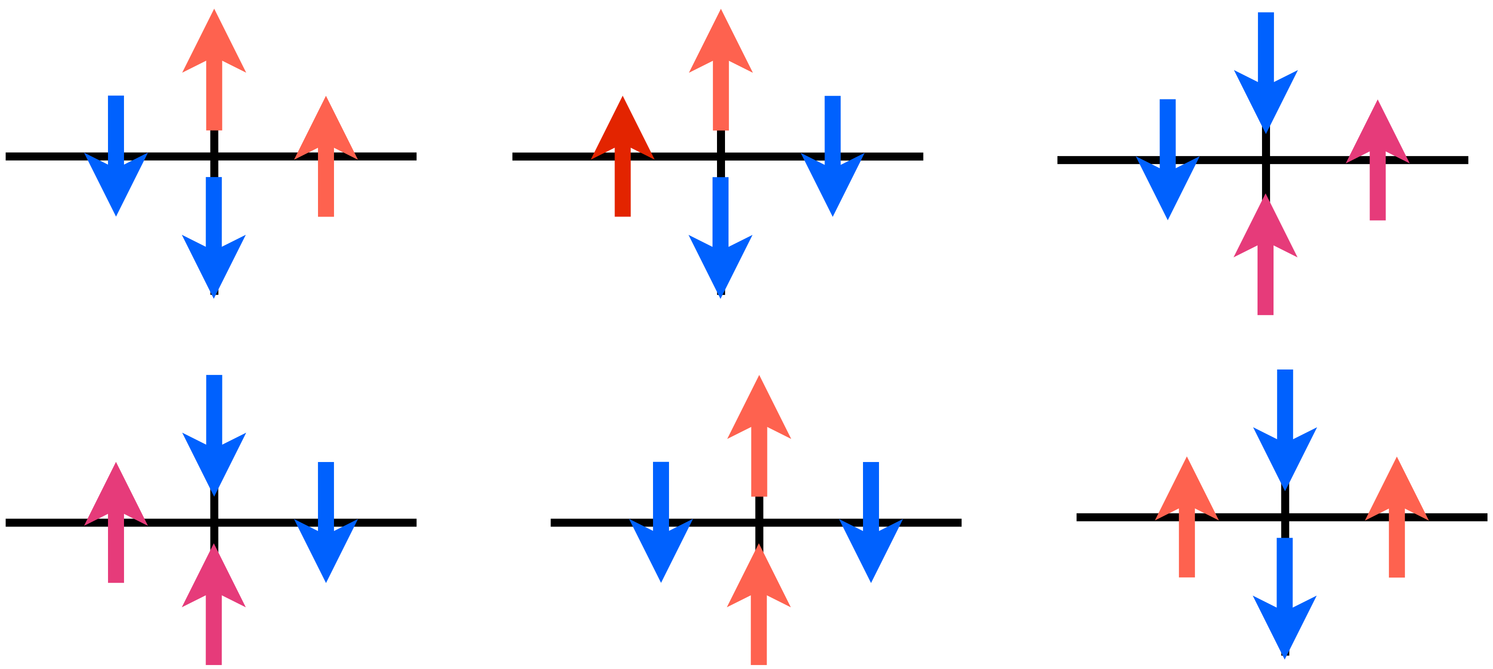
(Classical spin ice)

Every pair-interaction has the same strength
(Independent of inter-particle separation)

Ground state constraint: $$\sum_{i \in +} \sigma_z^i = 0$$

Equivalent to Gauss's law (flux free fields)

Spin ice : Six vertex model



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+

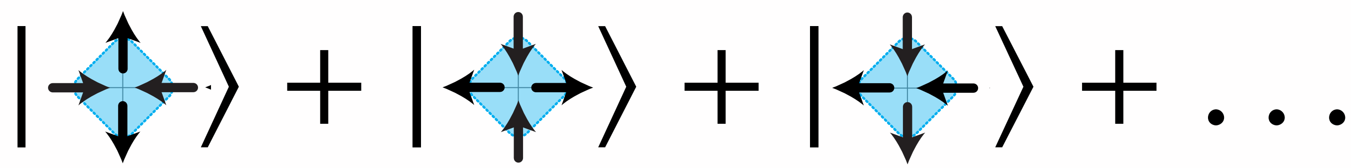
quantum fluctuations
(Hopping dynamics)

(Quantum spin ice)

Quantum Spin Ice

From Water Ice to Spin Ice

tunneling between Ice-rule configurations



spin fluctuations even at T=0.

… to **Quantum** Spin Ice

Quantum Spin Liquids (3D)
Resonating Valence bonds solid (2D)

Ice-type Models: Spin Ice

From Water Ice to Spin Ice

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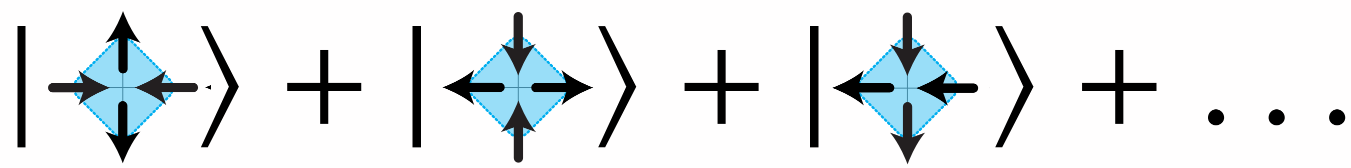

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Non-trivial dynamics of Quantum Spin Ice models

Non-trivial dynamics has to
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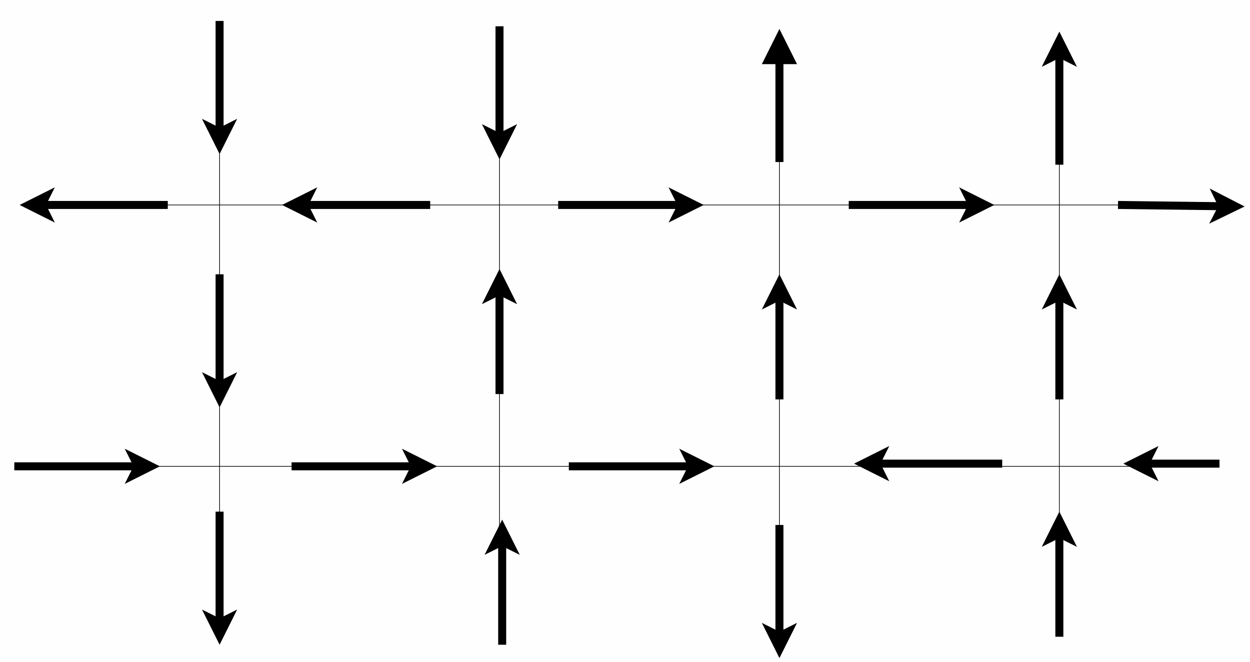

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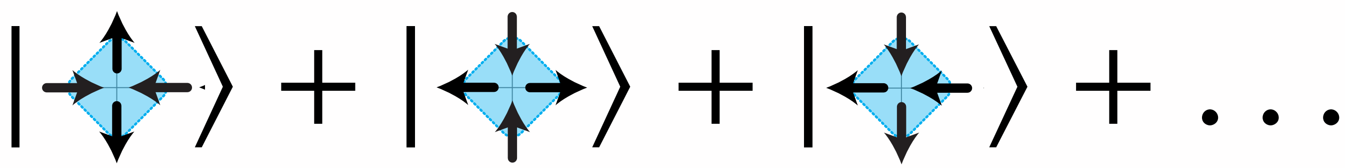

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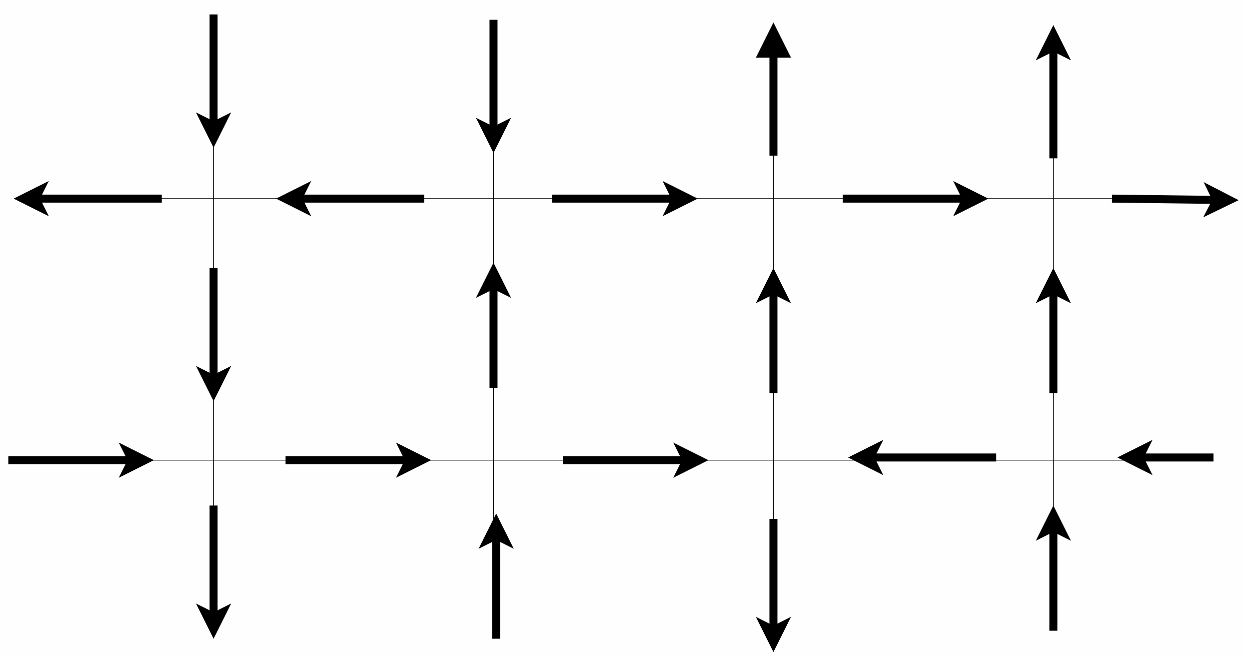

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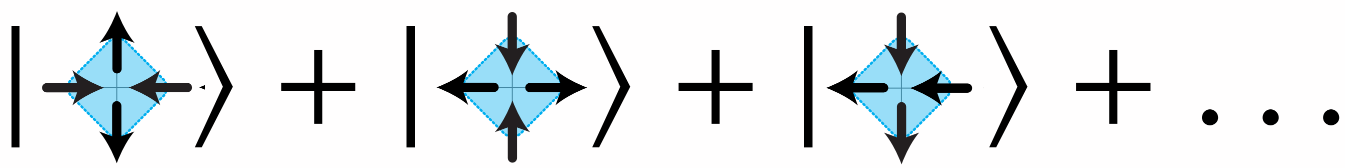

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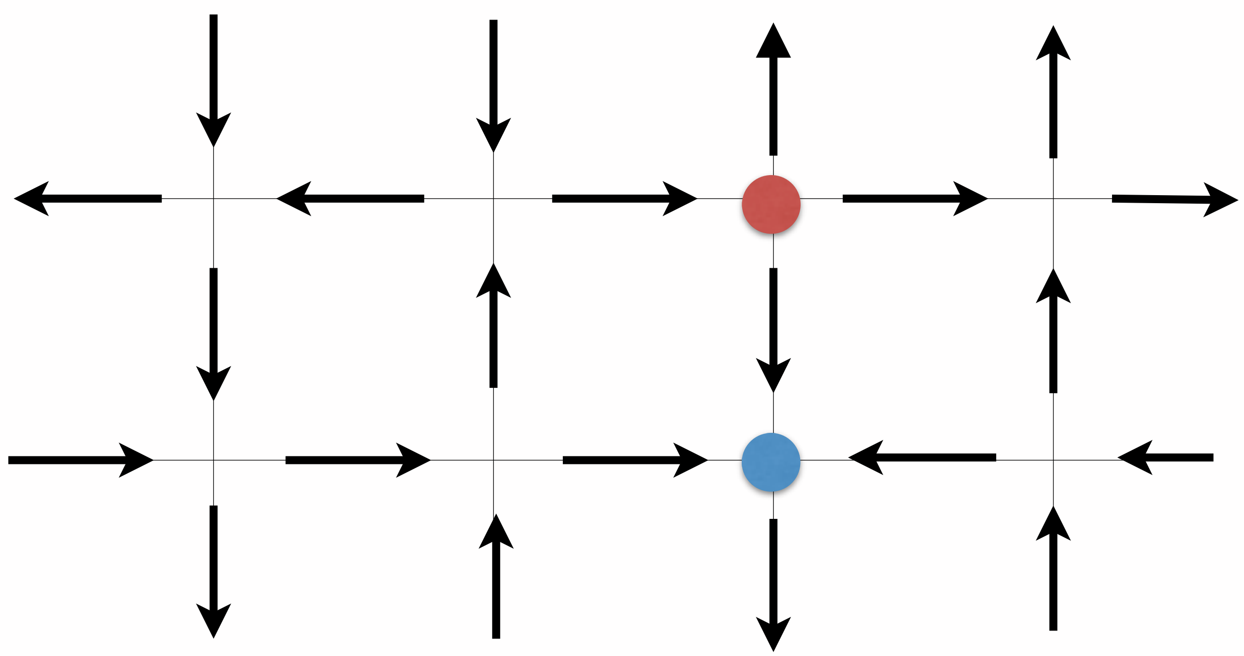

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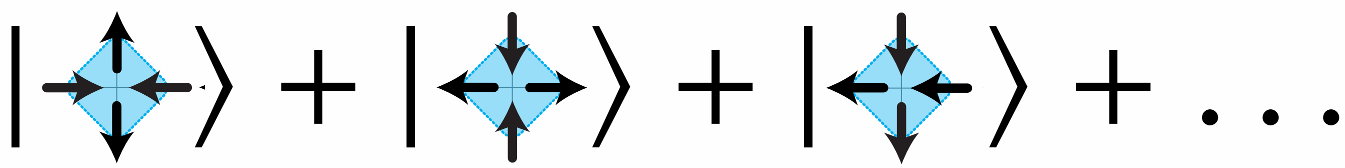

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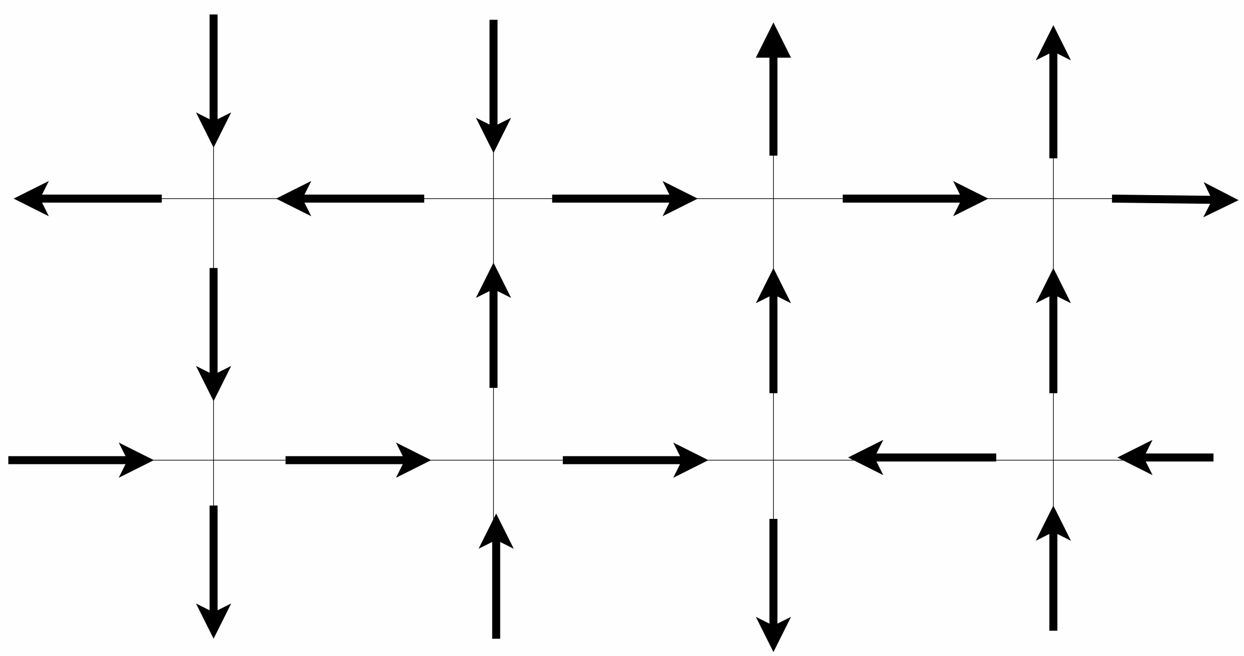

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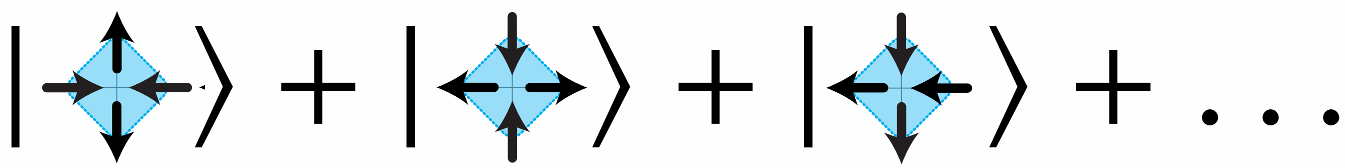


spin fluctuations even at T=0.

… to **Quantum** Spin Ice

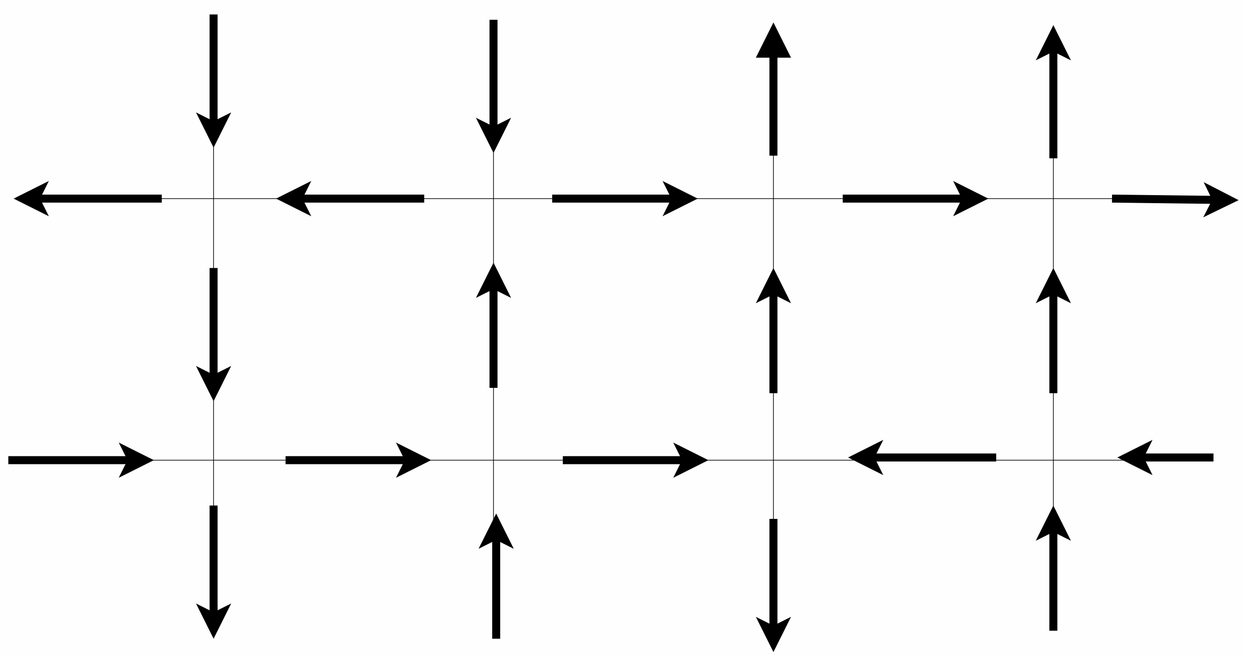
Quantum Spin Liquids (3D)
Resonating Valence bonds solid (2D)

Non-trivial dynamics of Quantum Spin Ice models

Non-trivial dynamics has to satisfy Ice rules

Flips of 1, 2 or 3 spins are not allowed!

4-spin (plaquette moves / ring exchange) are allowed!



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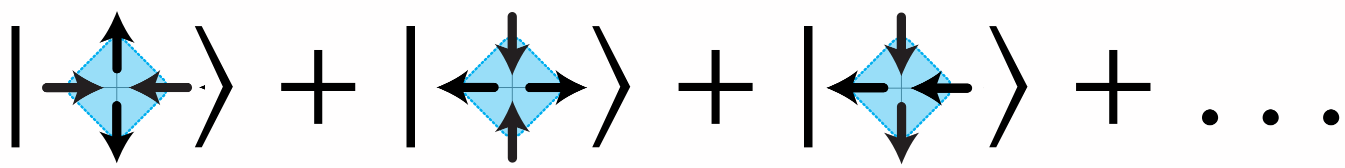

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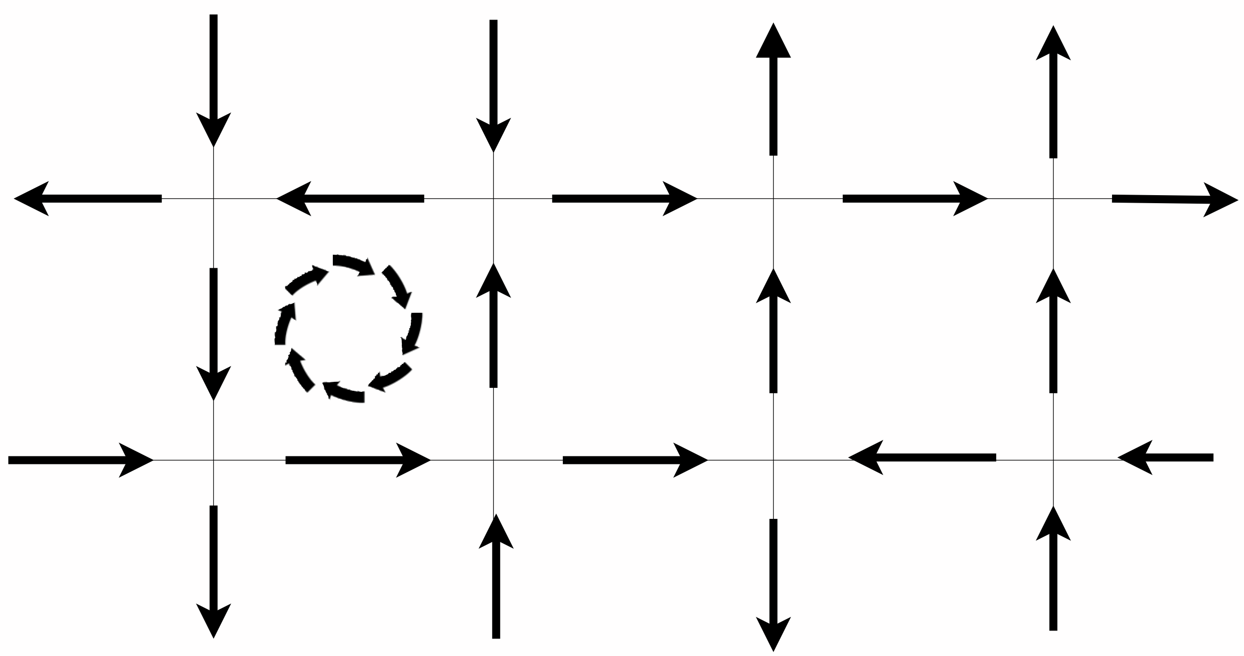

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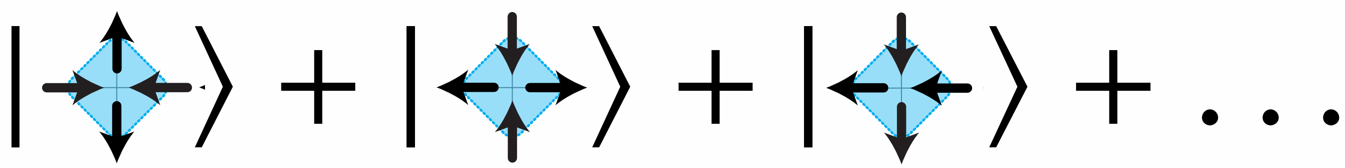

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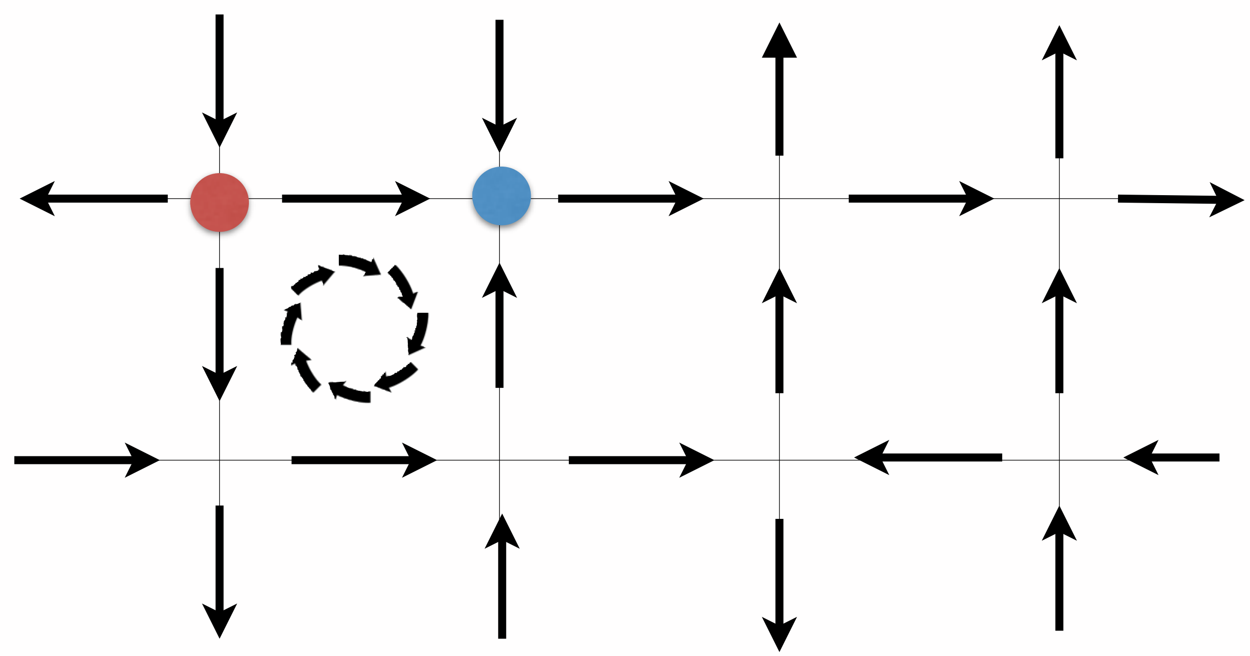

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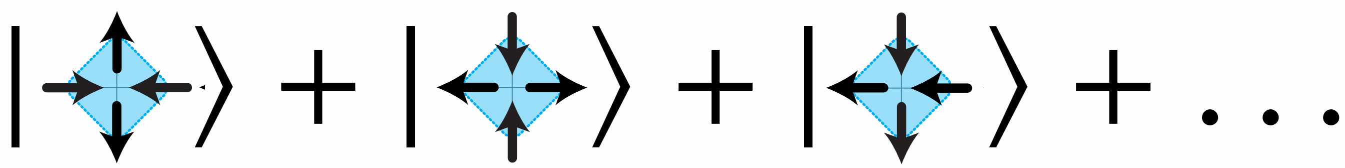

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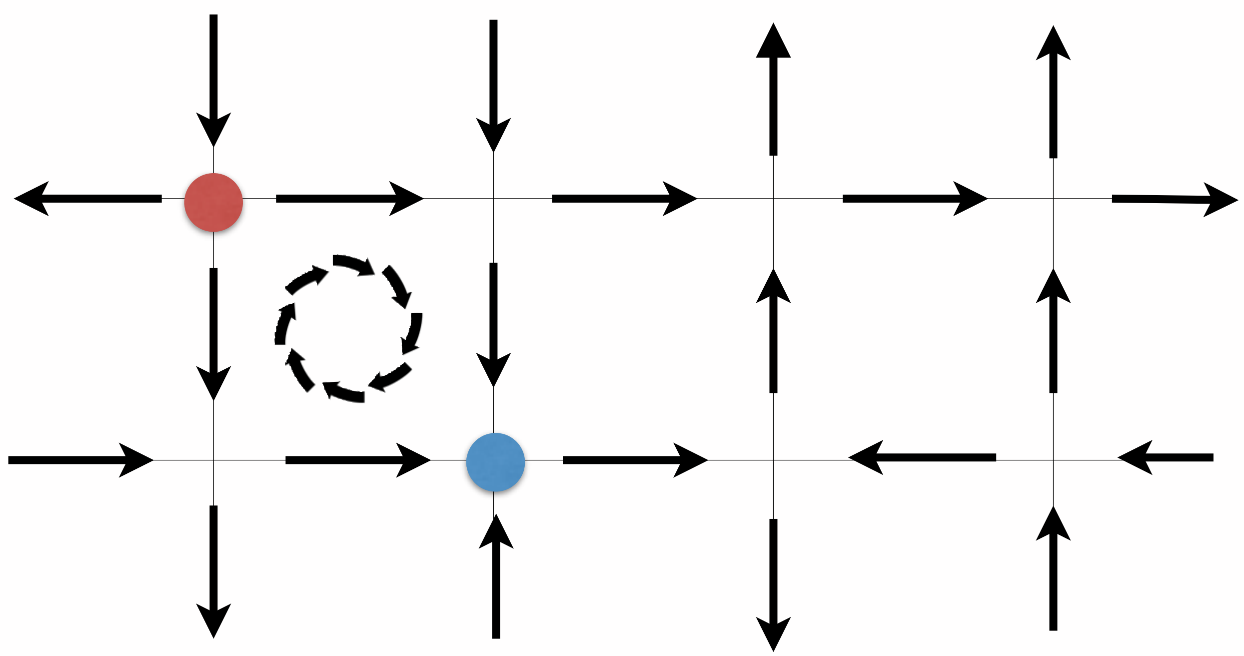

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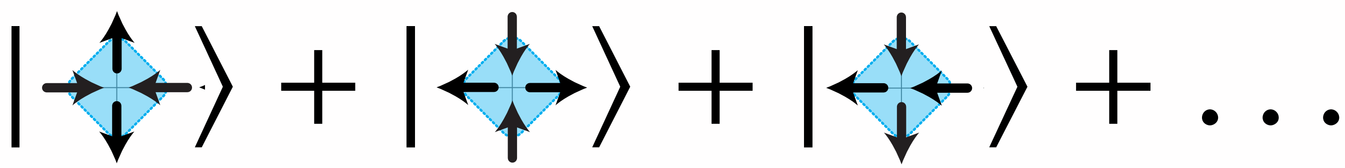

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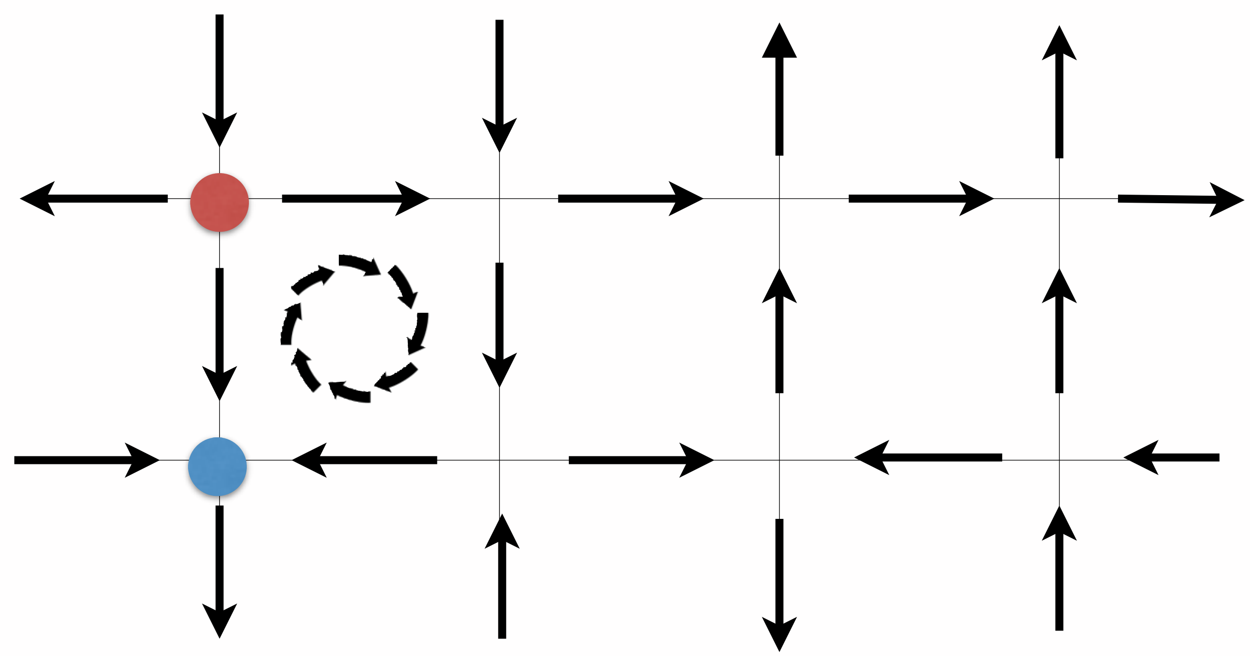

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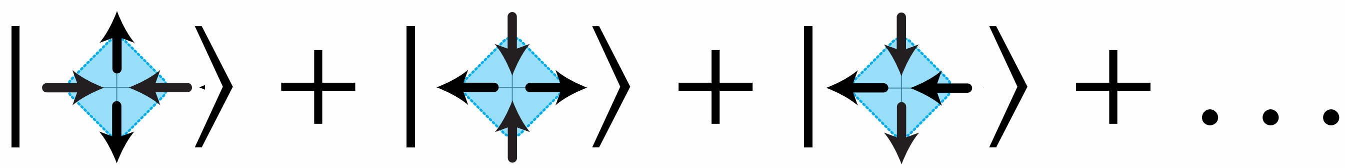

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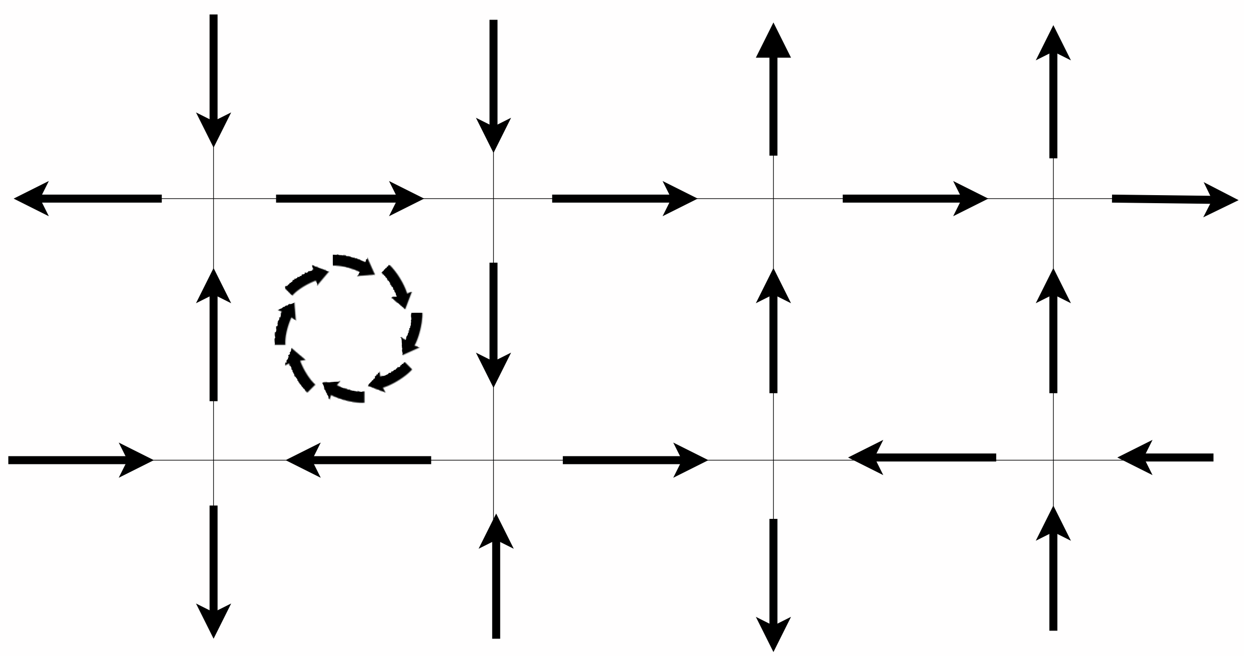

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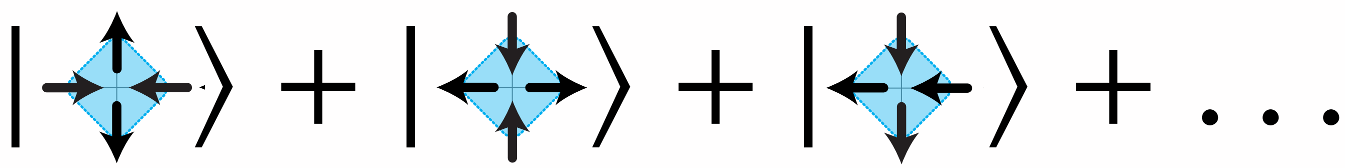

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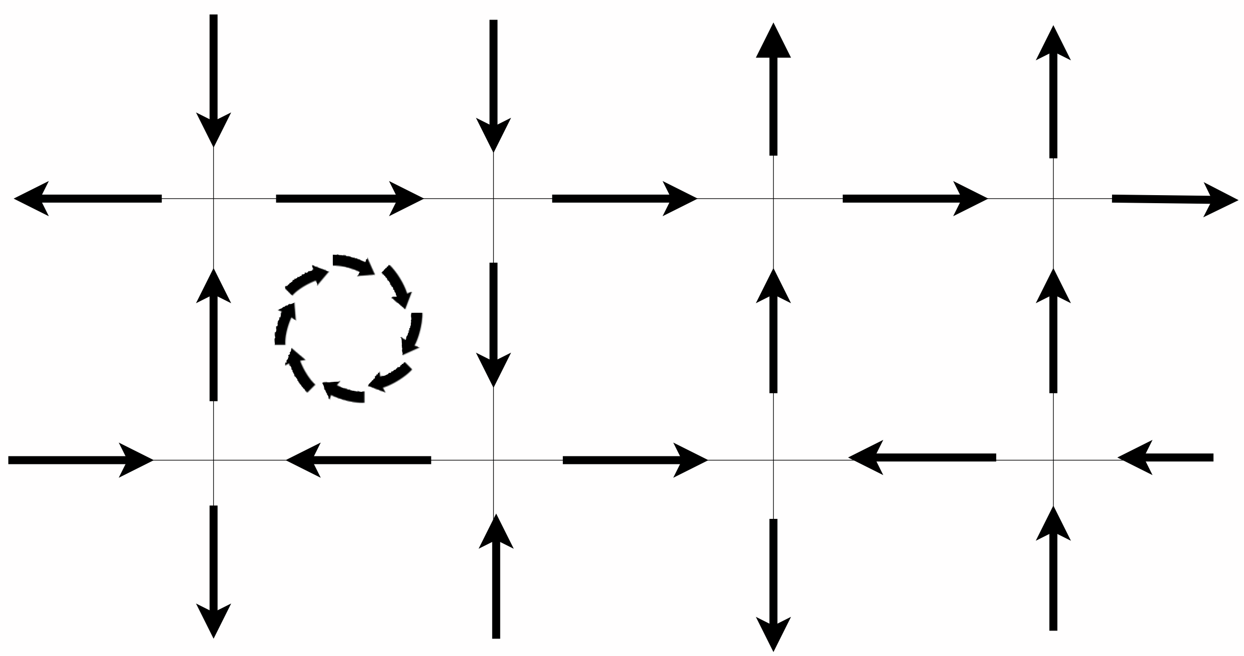
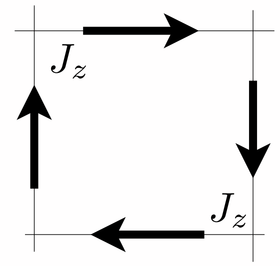


Minimal Hamiltonian for quantum Ice

$$H = J \sum_{j,i,k,\ell \in \square} S_j^+ S_i^- S_k^+ S_\ell^-$$

Implementation using Rydberg Atoms

Step 1: impose **gauge invariance via energy punishment - Ising interactions**



PRX **4** 041037 (2014)

$$H_0 = J_z \left(\sum_{j \in +} S_j^z \right)^2$$

Step 2: generate **dynamics in perturbation theory**

$$H_1 = J_\perp \sum_{<i,j>} S_j^+ S_i^-$$

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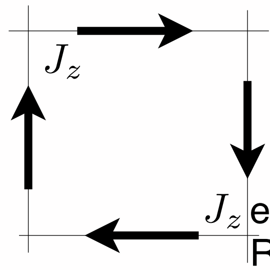
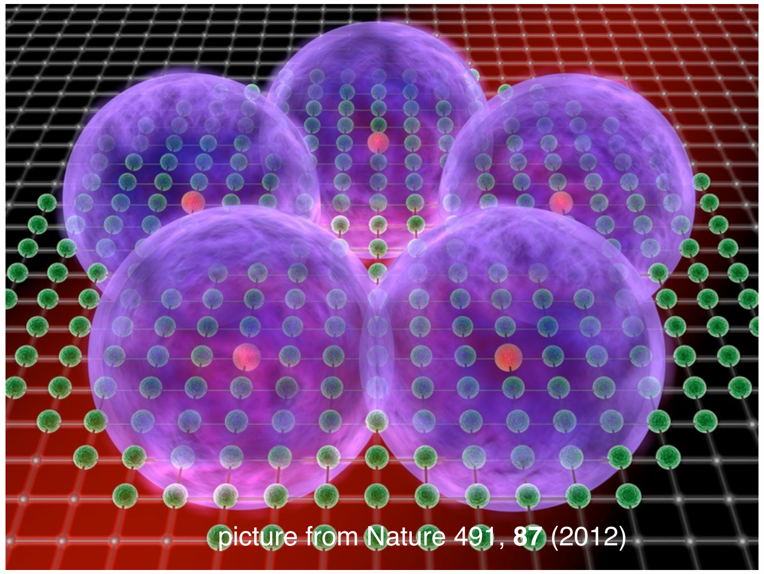


engineer with
Rydberg atoms

PRX **4** 041037 (2014)



picture from Nature 491, **87** (2012)

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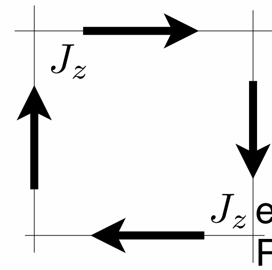
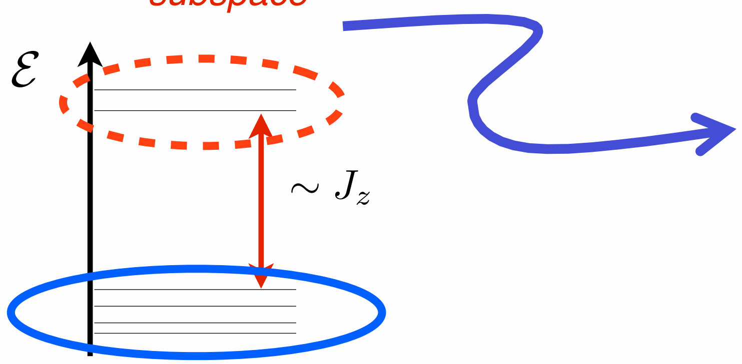
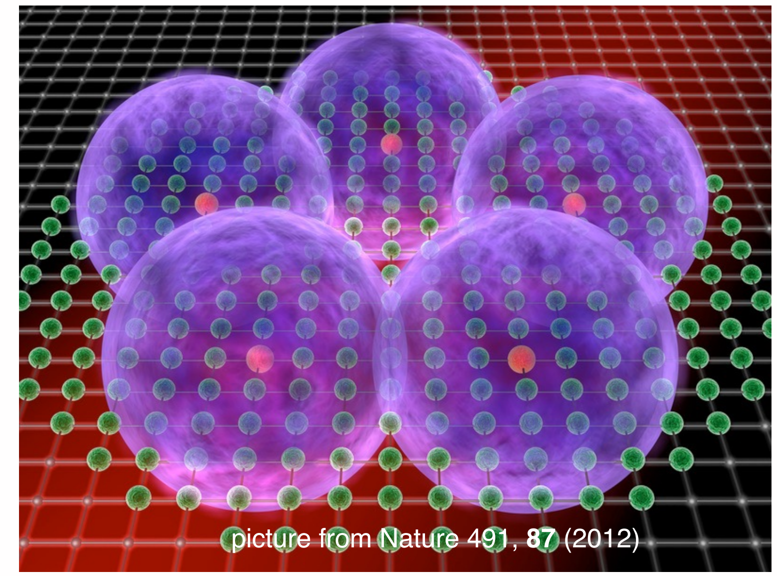


engineer with Rydberg atoms

Unphysical subspace



Physical Hilbert subspace we are interested in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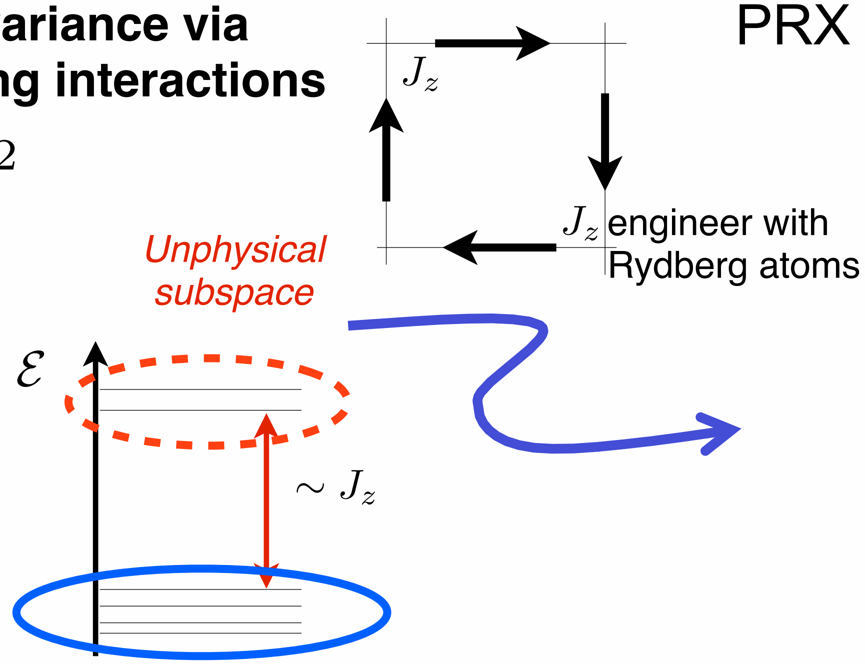

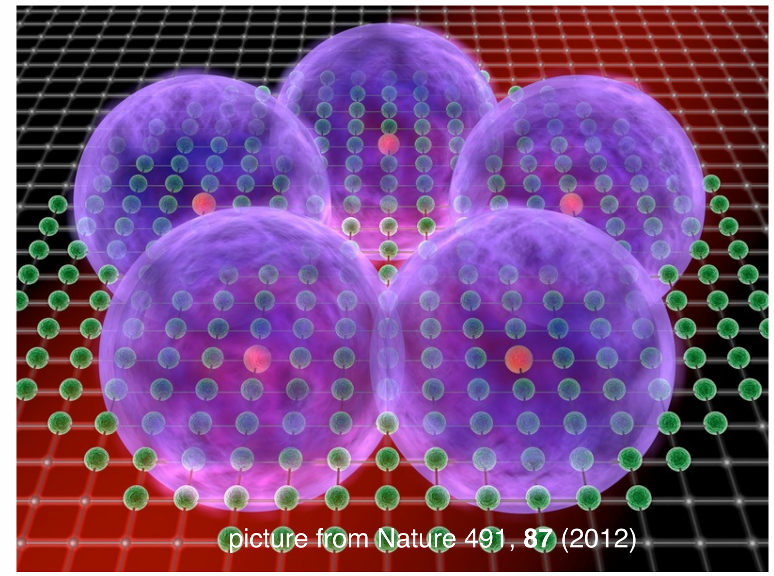

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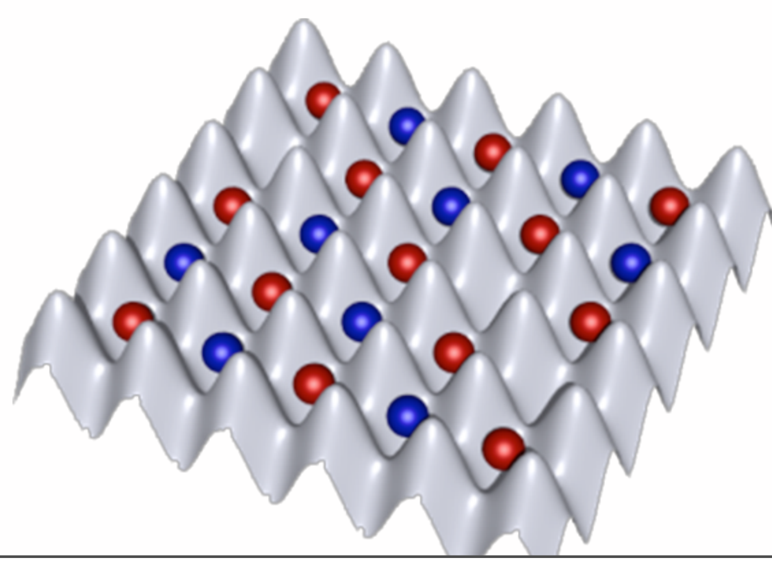
e.g. tunneling in optical lattices



Implementation using Rydberg Atoms

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PRX **4** 041037 (2014)

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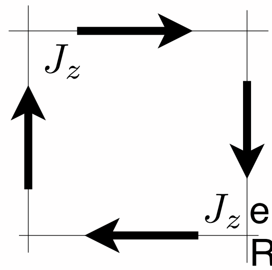

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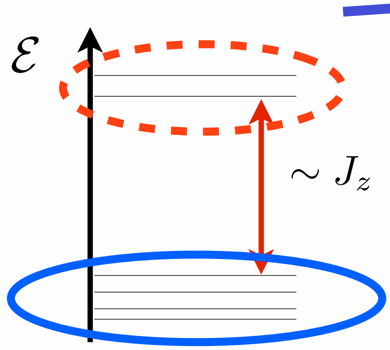

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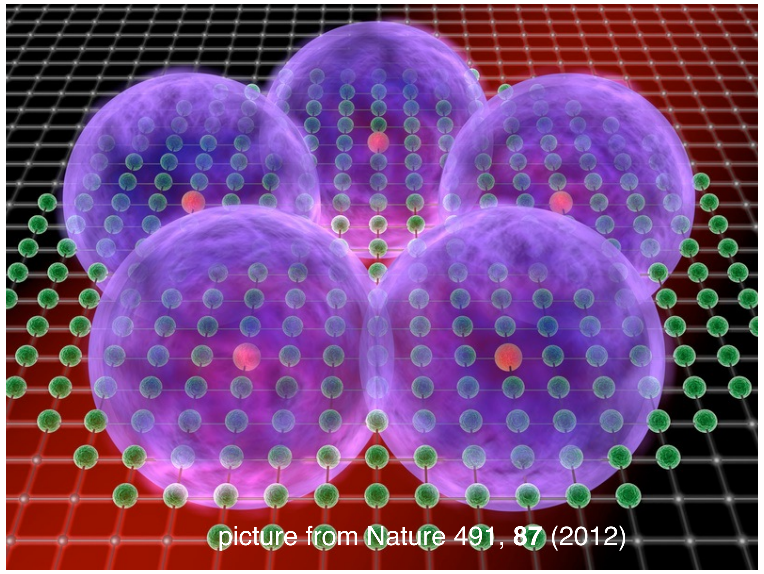

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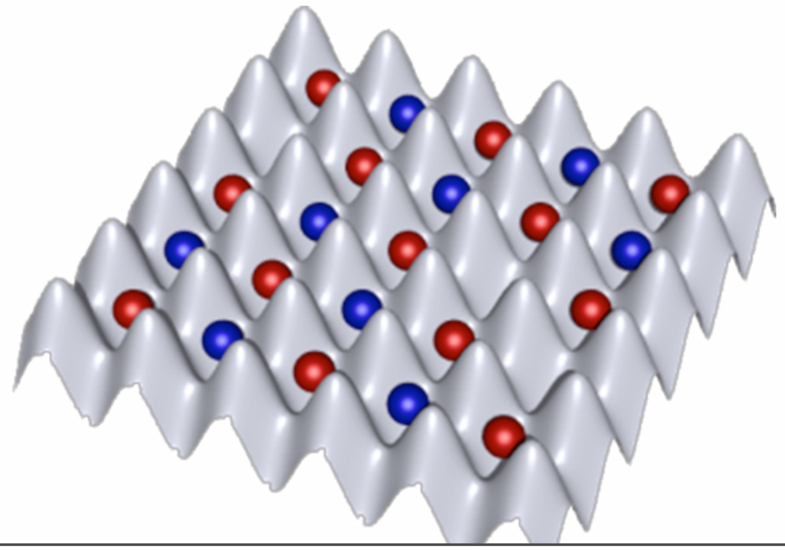
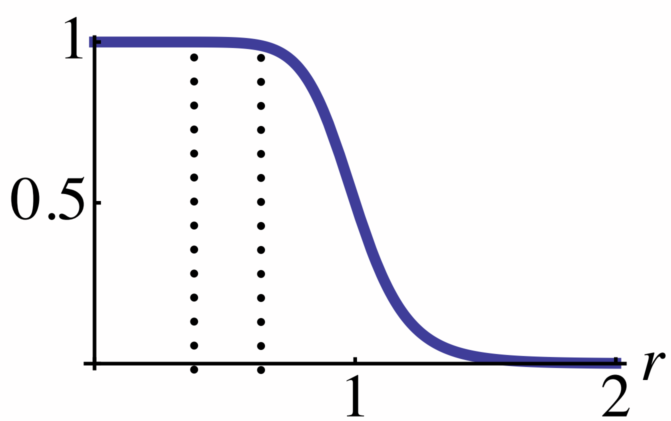


$$H_{ef} = J \sum_{j,i,k,\ell\in\square} S^+_i S^-_j S^+_k S^-_\ell\,, \quad J \simeq \frac{J^2_\perp}{J_z}$$

Recipe for Rydberg-Spin ice

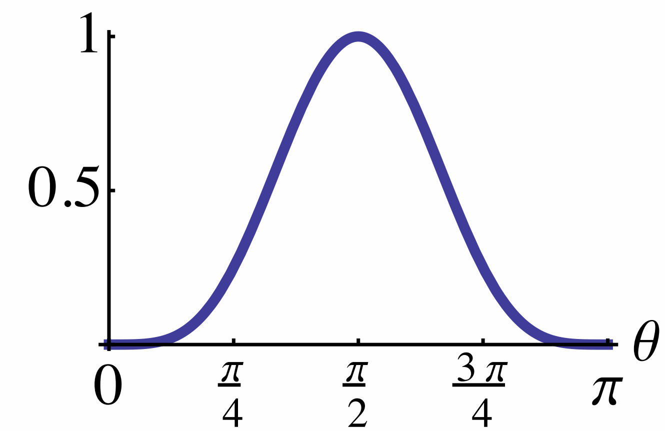
1) step-like potentials (radial)

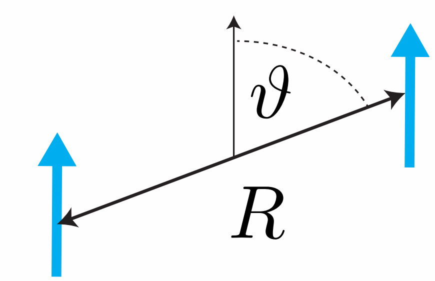
Rydberg dressing



2) anisotropic interaction (angle)

p-states





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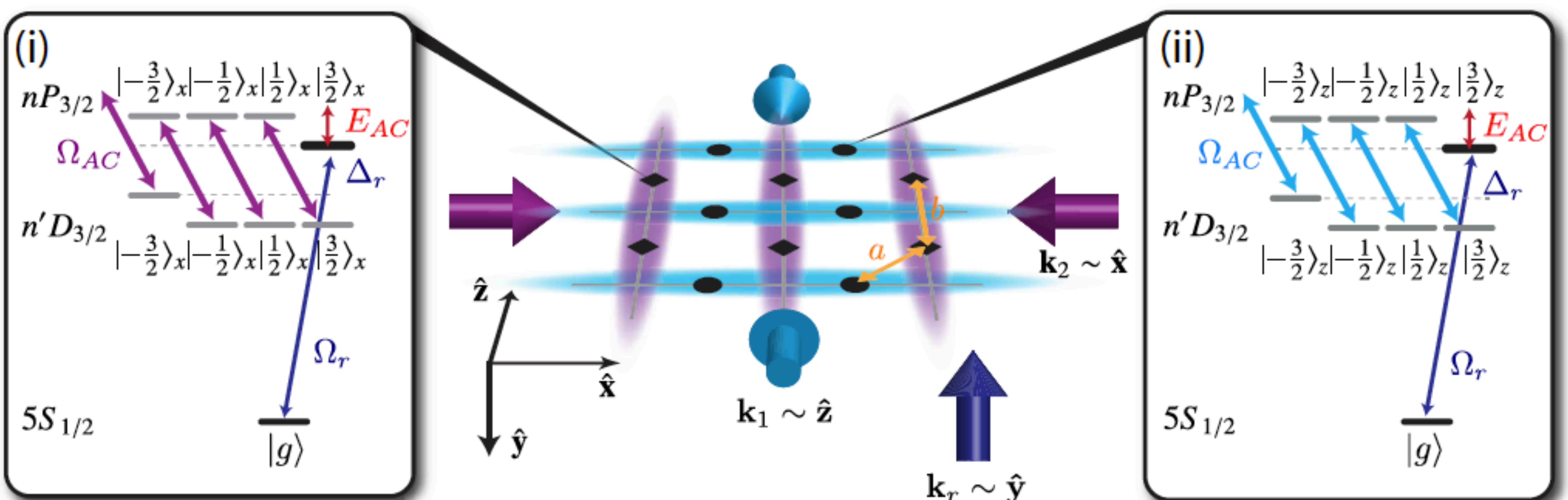
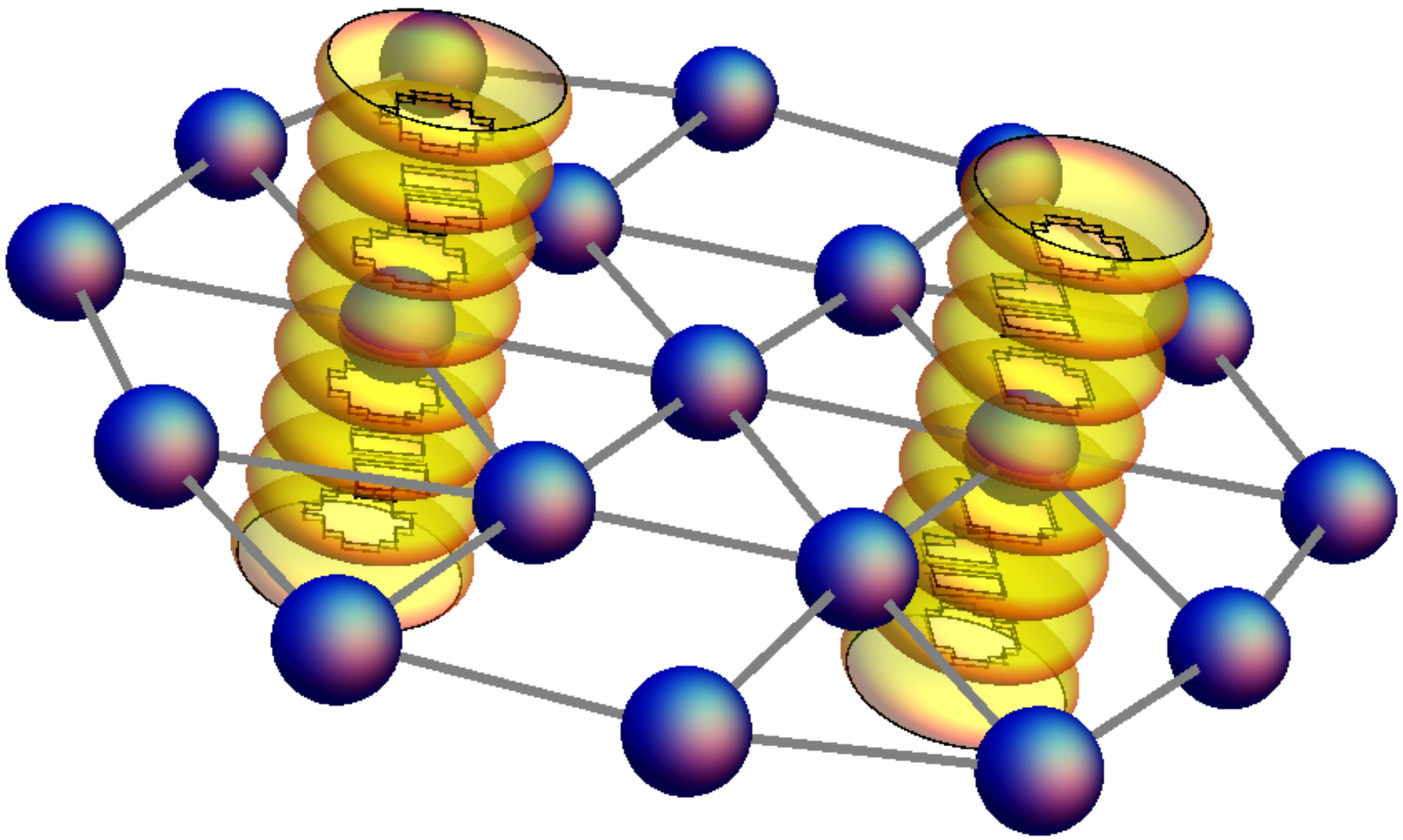


global Rydberg excitation laser

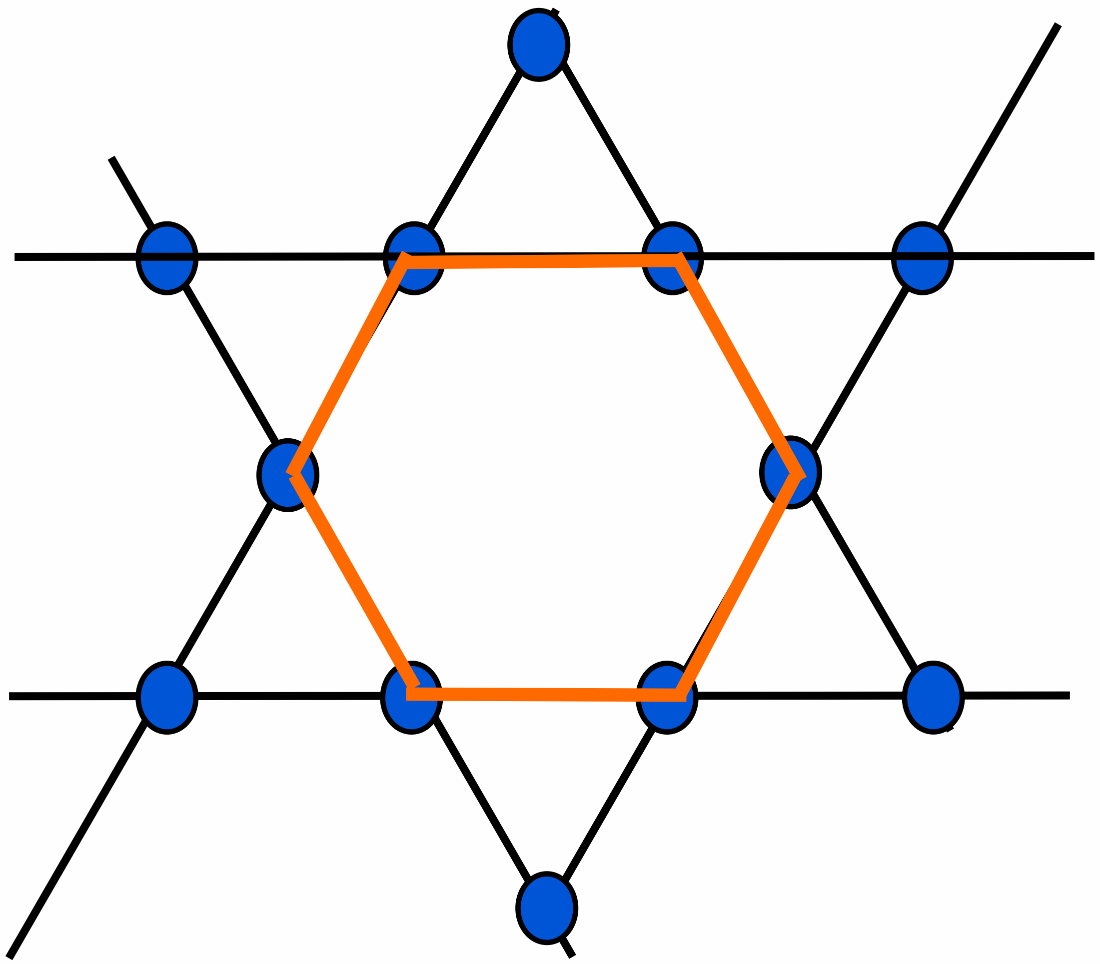
This talk: Frustrated magnetism in an ion crystal



Motivation: From square to Kagome lattice

Balents Fisher Girvin model:

Kagome lattice



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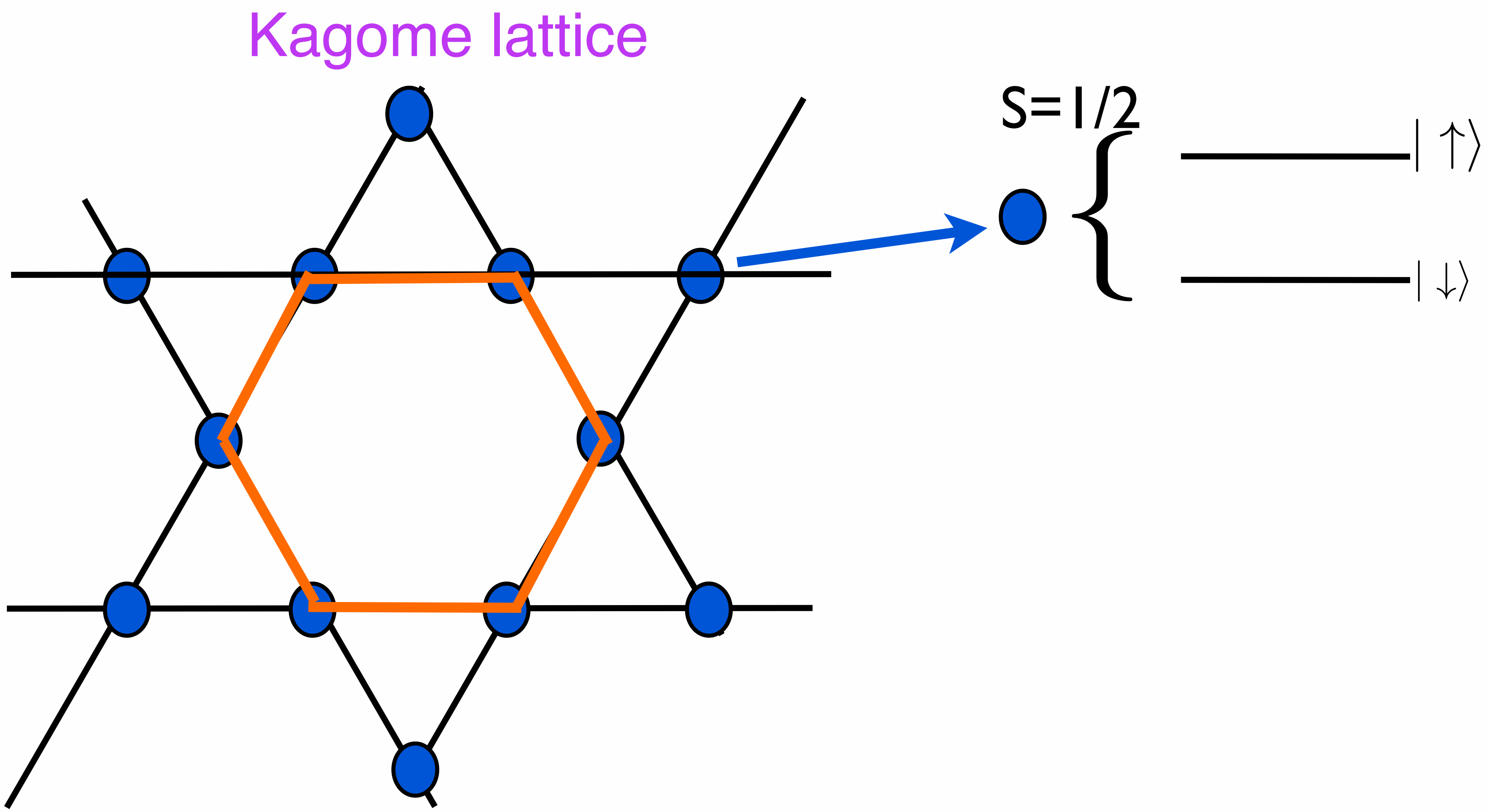

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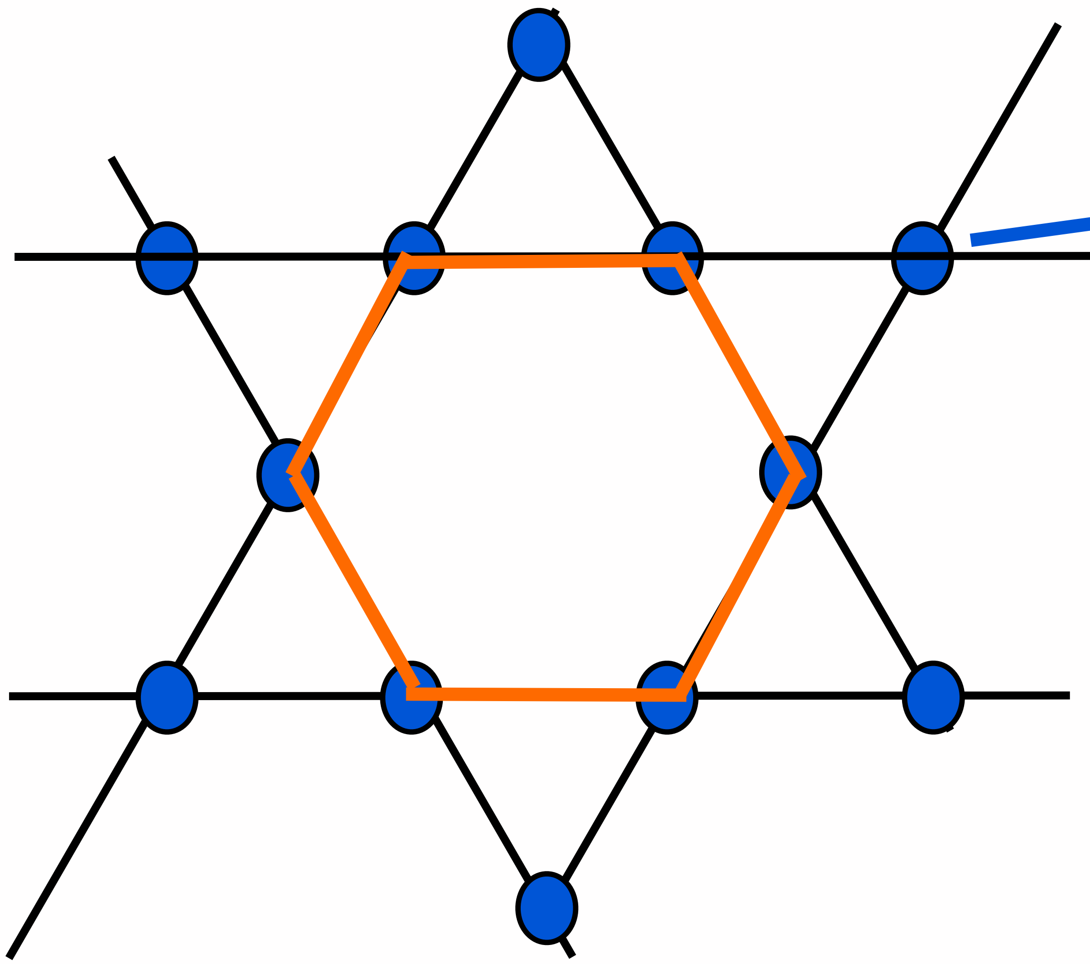

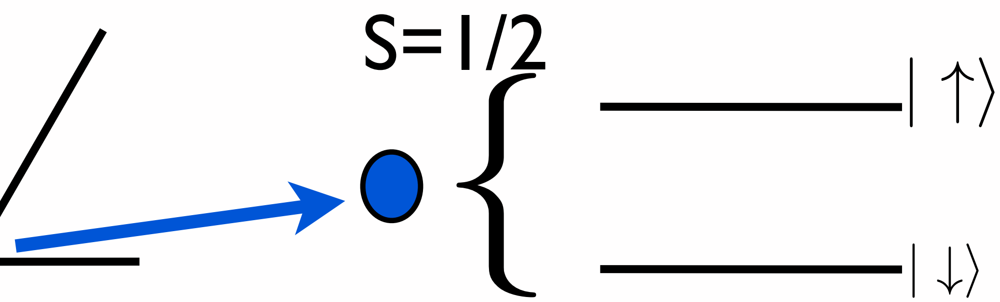

PRB, **65**, 224412 (2002).

Hamiltonian

$$H_{\hexagon}^{BFG} = J_z \left(\sum_{i \in \hexagon} S_i^z \right)^2 + J_\perp \sum_{<ij> \in \hexagon} \left(S_i^+ S_j^- + h.c. \right)$$

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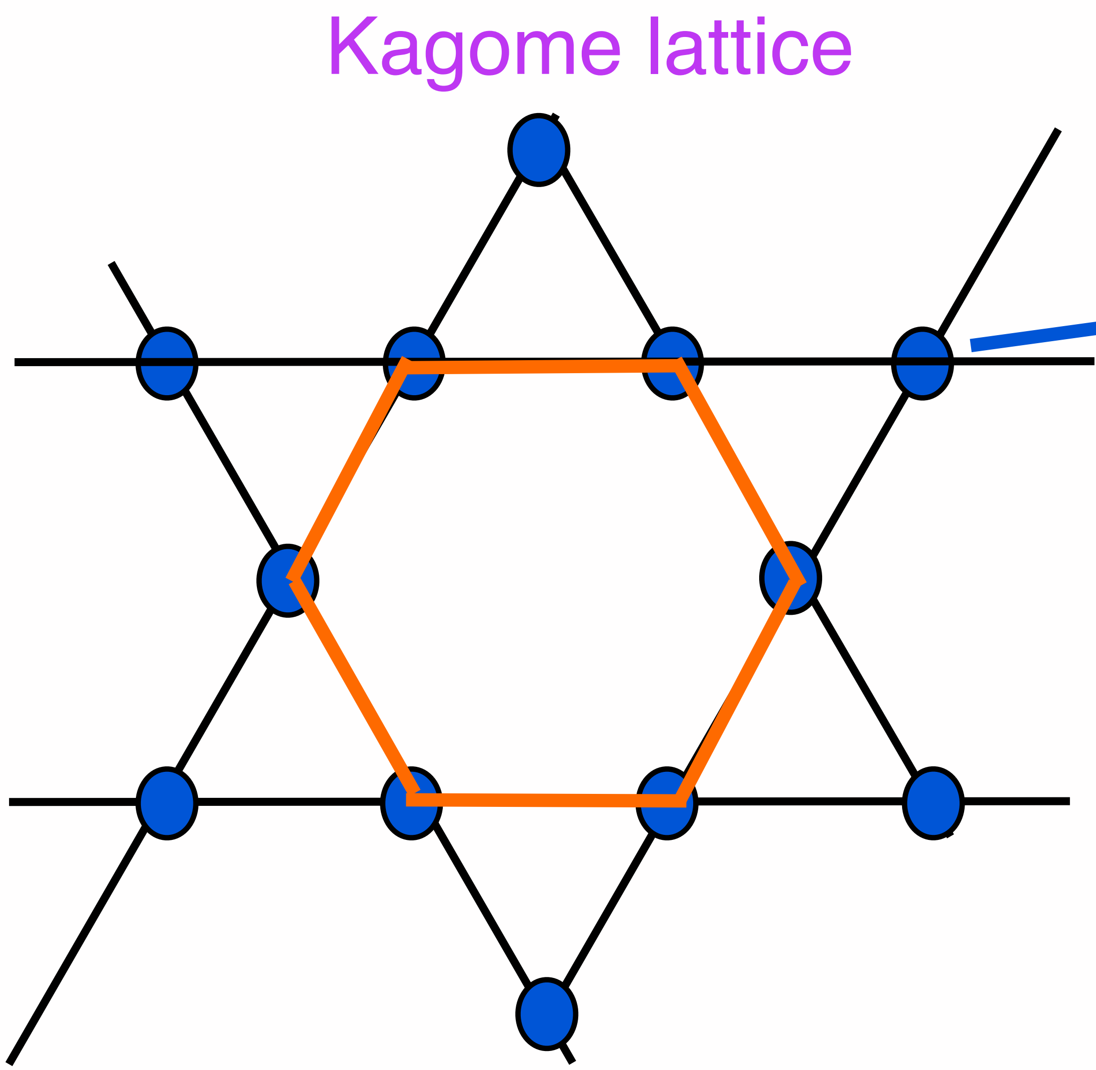

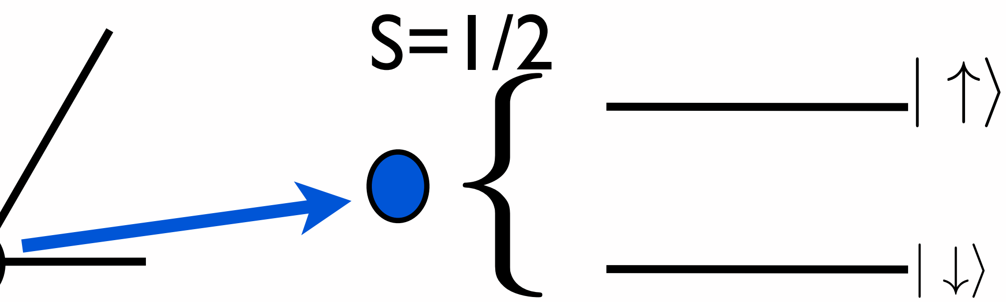

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Classical Ground states

$$\sum_{i \in \hexagon} S_i^z = 0$$

- **Similar to ice rule!**

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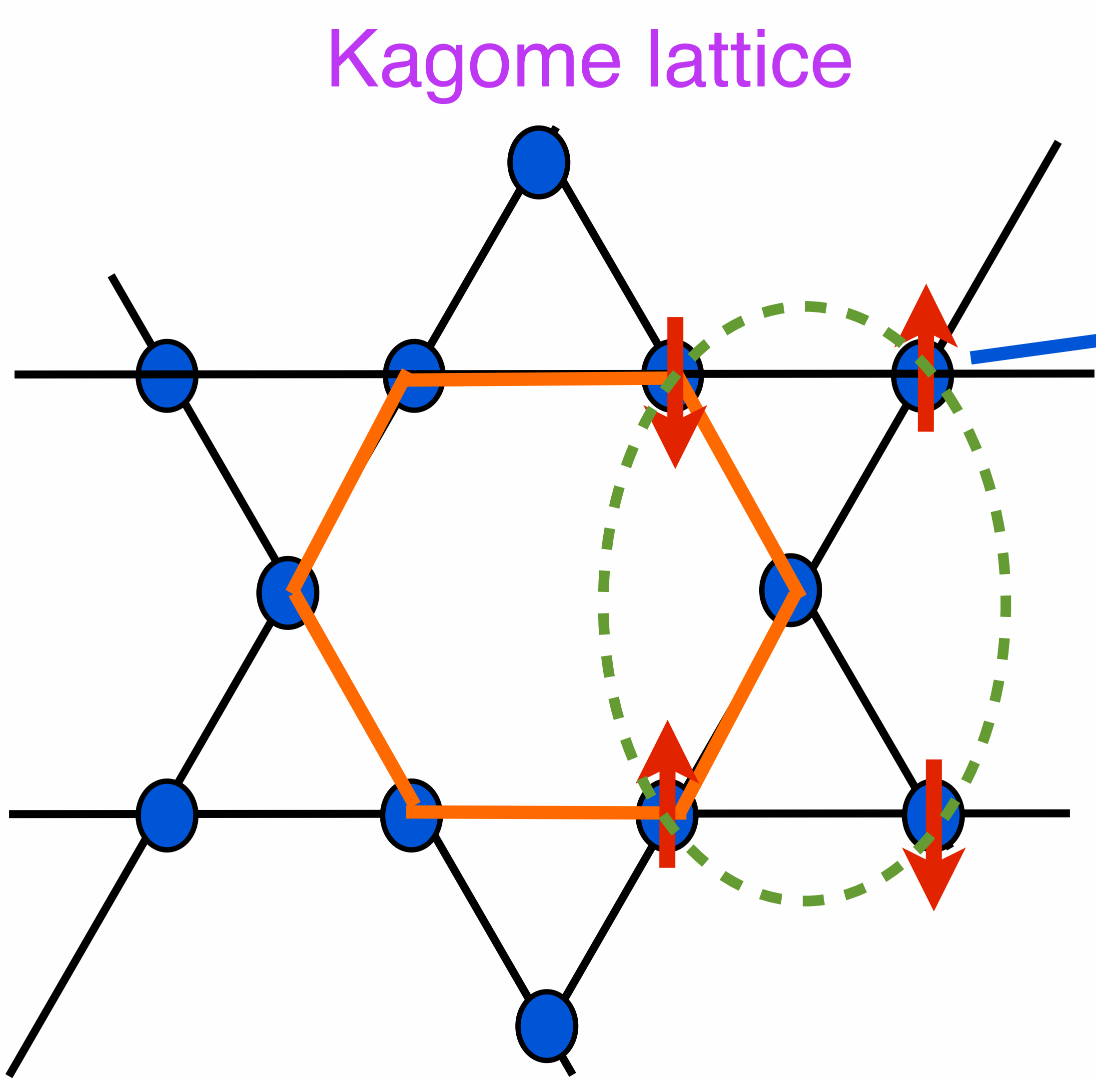

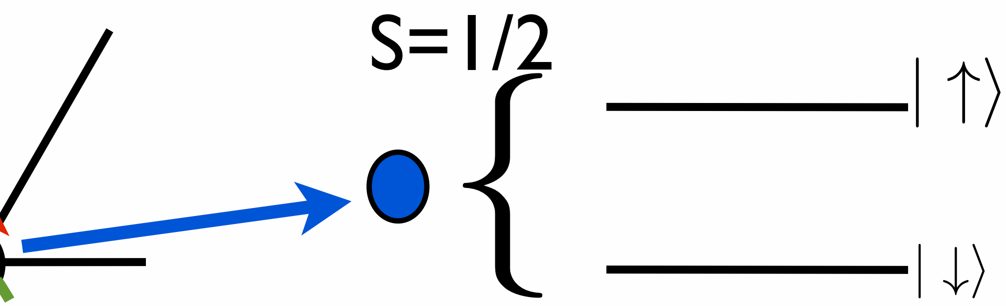

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$$J_\perp << J_z$$

Ring exchange

$$H_{ring} = J_{\rm ring}(S_1^+ S_2^- S_3^+ S_4^- + \rm{h.c})$$

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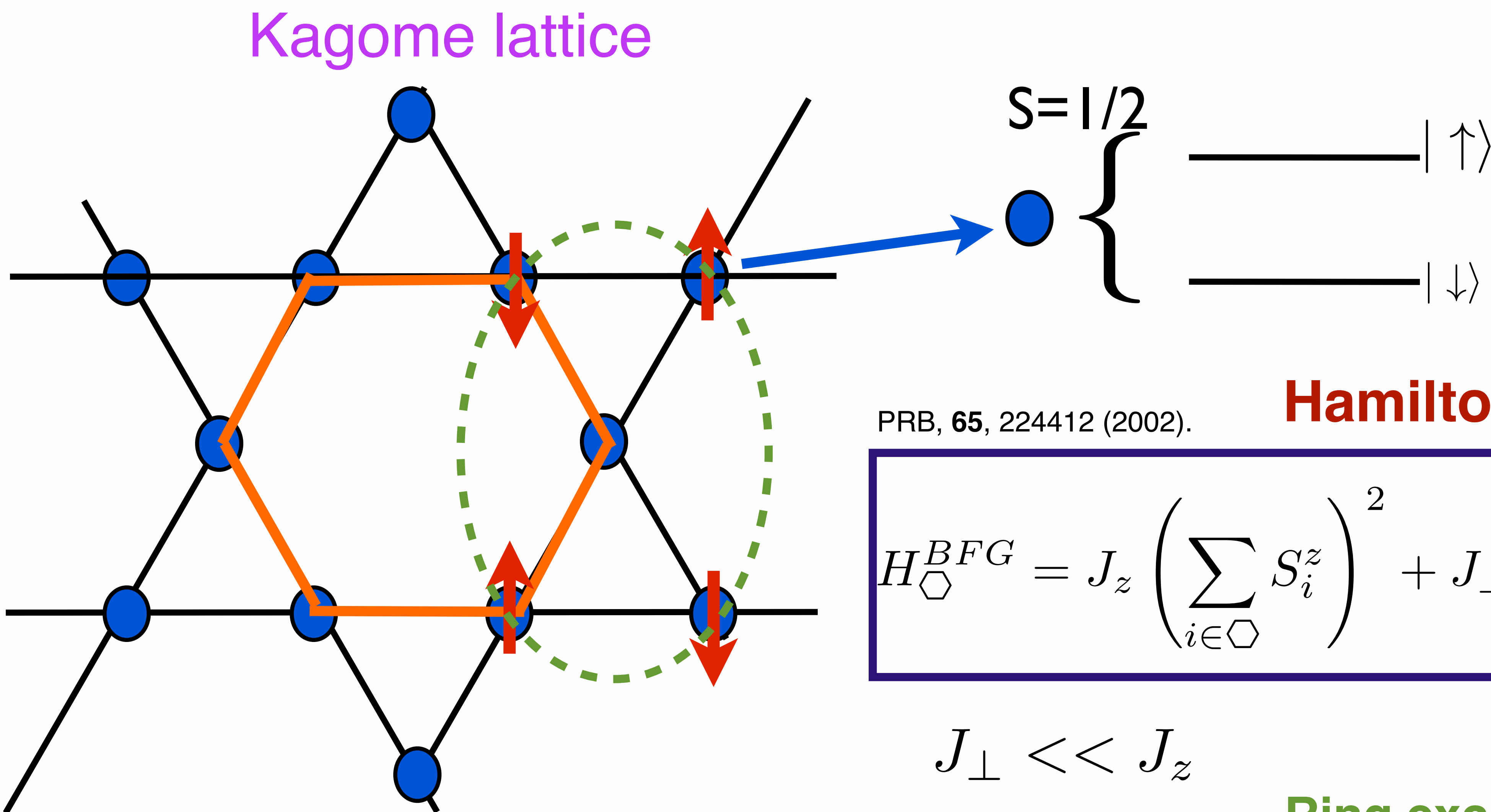

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- **Spin Liquid phase**
- **Fractionalized Excitations**
- **Visons (Vortex-like excitations)**
- **Gauge Theory**

Nat. Phys, **7**, 772 (20011).

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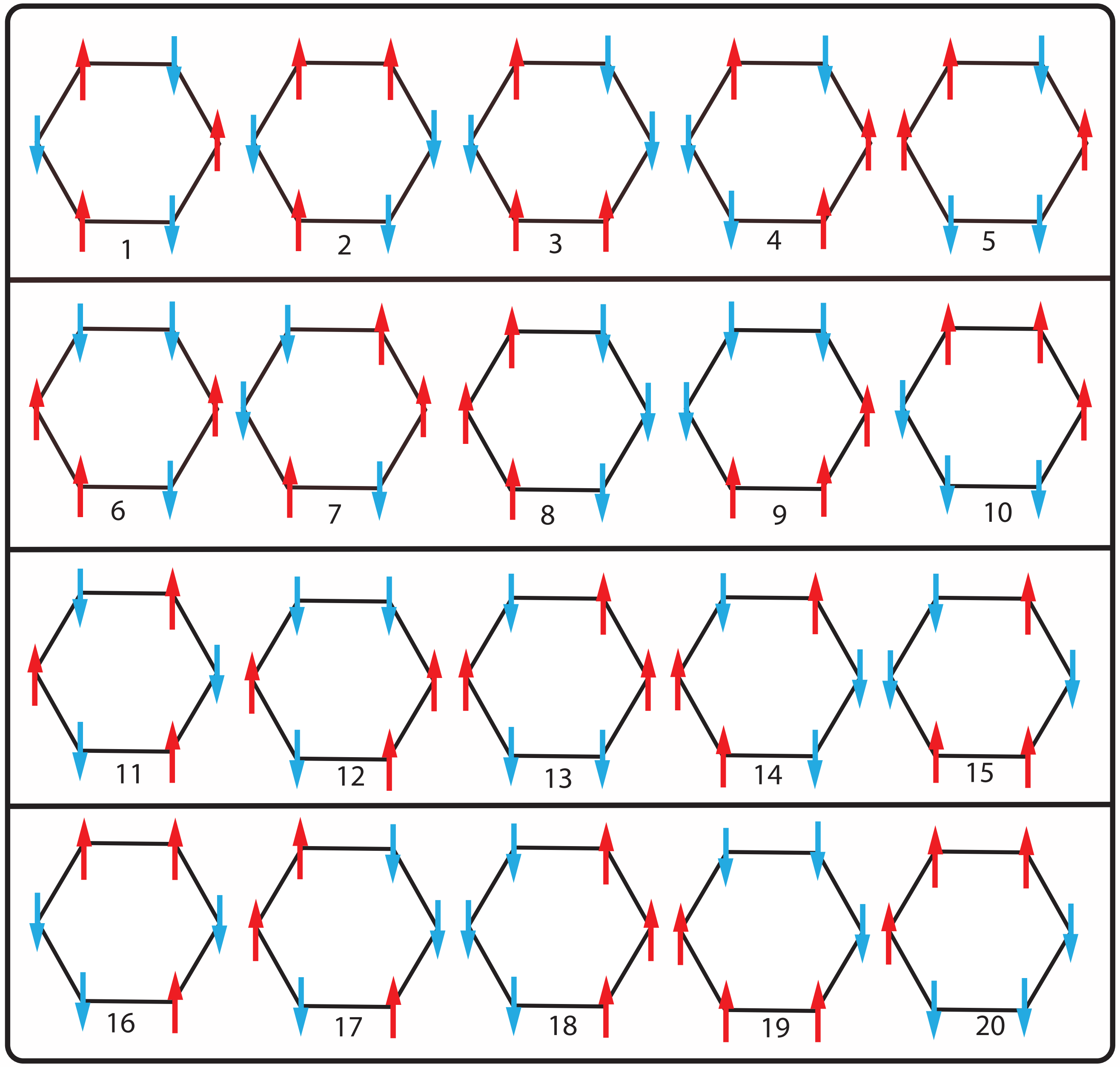
(Kagome lattice)



20 classical degenerate ground states

Classical Ground states

$$\sum_{i \in \hexagon} S_i^z = 0$$

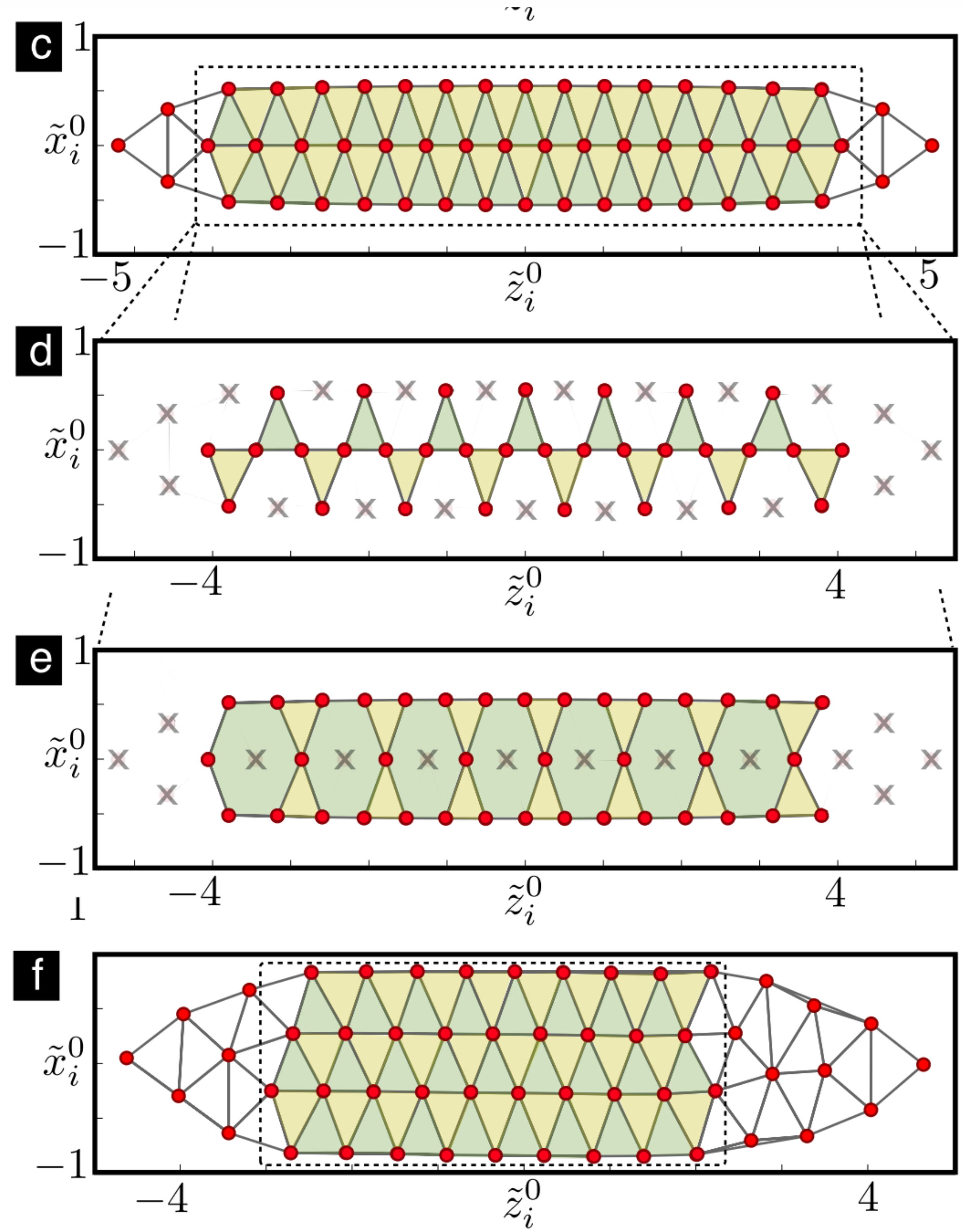
•**Similar to ice rule!**

Trapped ions: 2D planar crystal

- Start out with planar crystal

- Hide out ions from
  spin interaction to $D_{5/2}$ state

- Corner-sharing triangles (d)
- Hexagons (e)
- Kagome geometry
- Multiple ladders (f)
- Random hiding
  for spin glass experiments



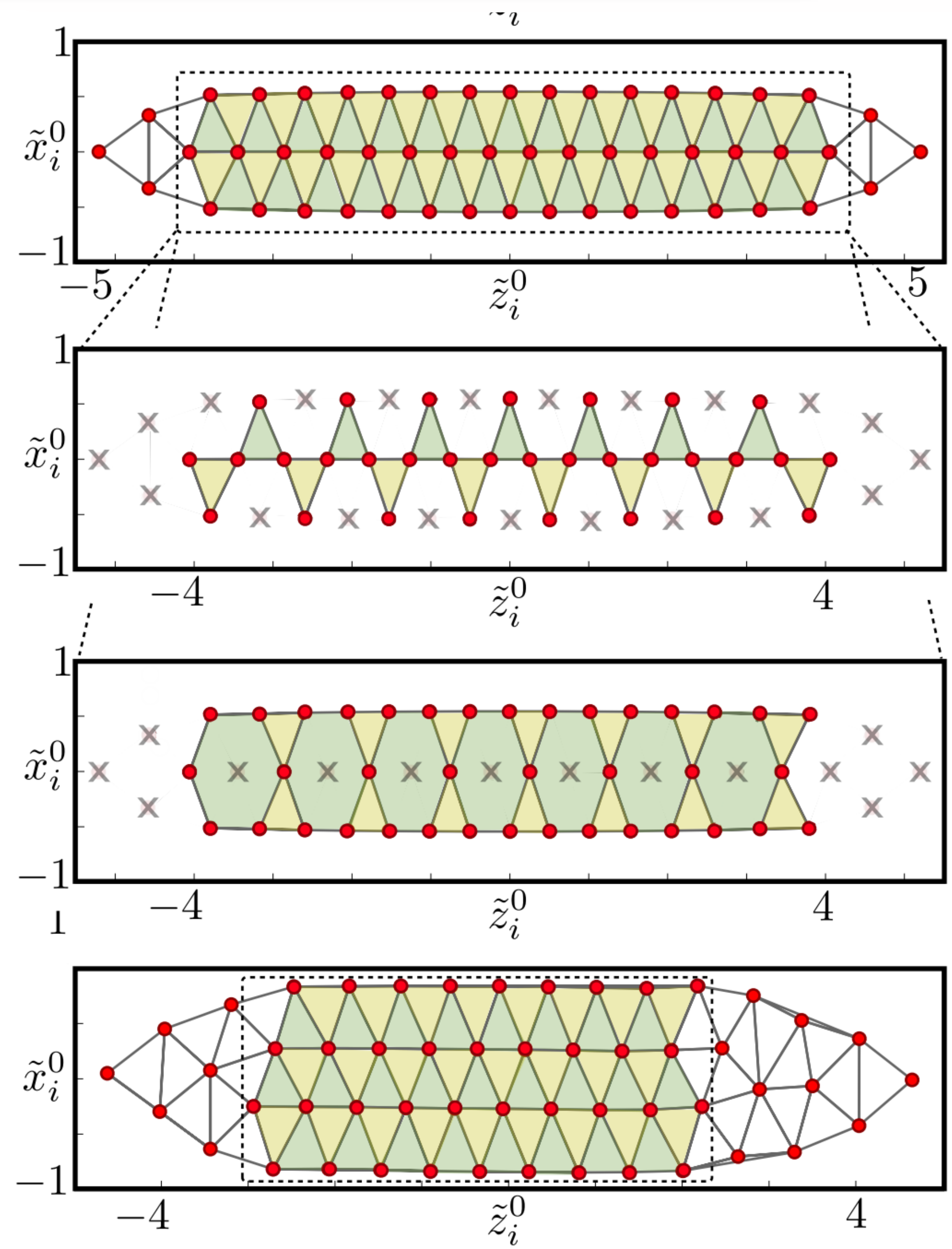
Bermudez, et al, NJP 14 093042 (2012)

Trapped ions: 2D planar crystal

Trap

Coulomb Potential

$$V=\sum_{i=1}^{N}\frac{1}{2}M\left(\nu_x^2x_i(t)^2+\nu_y^2y_i(t)^2+\nu_z^2z_i(t)^2\right)+\sum_{i,j=1,i\neq j}^{N}\frac{Ze^2}{8\pi\epsilon_0}\frac{1}{|\mathbf{r}_i(t)-\mathbf{r}_j(t)|}$$



Normal Mode spectrum: Lattice vibrations

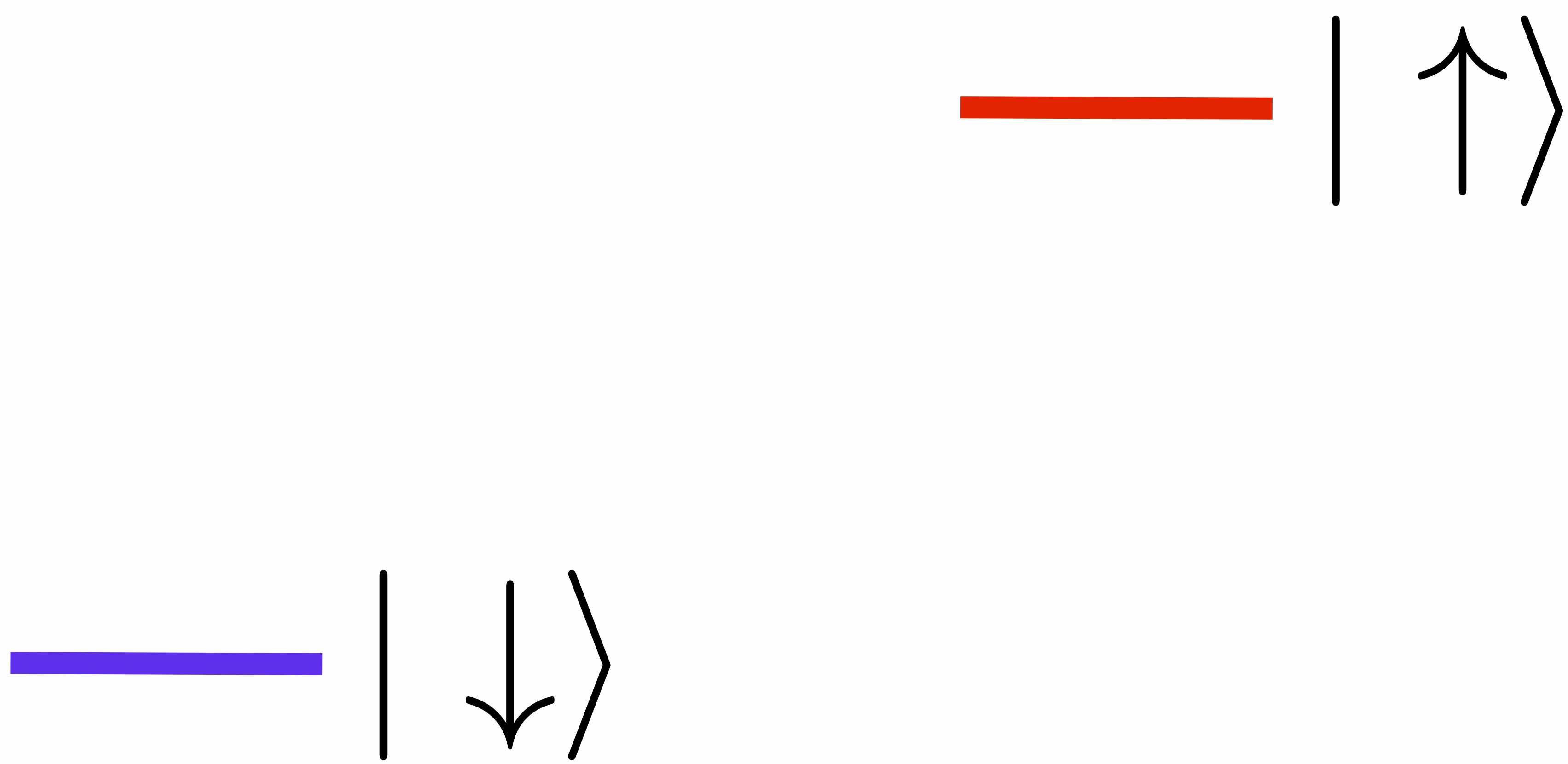
$$H_v=\sum_{n=1}\hbar\omega_n(a_n^\dagger a_n+1/2)$$

Longitudinal and transversal modes

Recipe for Quantum simulation in an ion crystal

☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)



Recipe for Quantum simulation in an ion crystal

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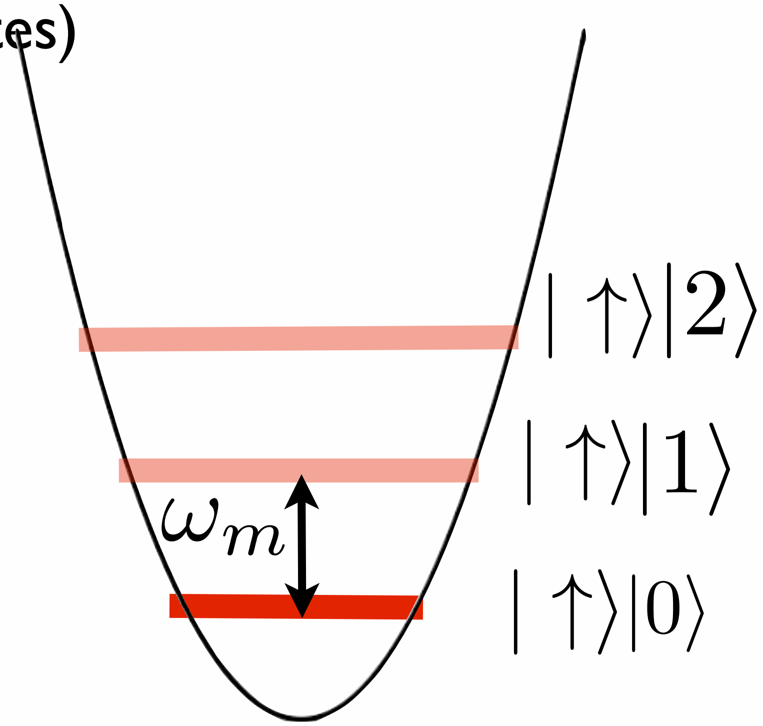
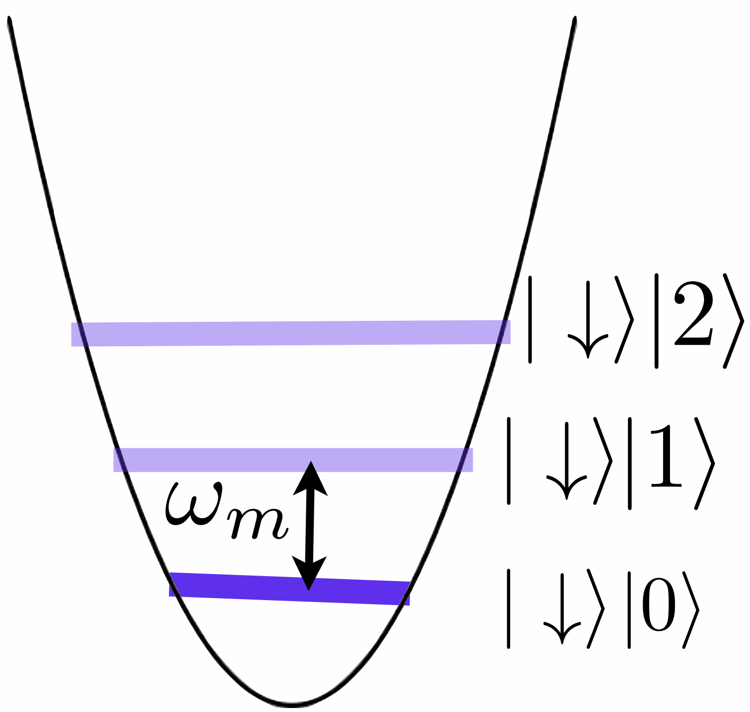
ω_m Phonon mode frequency of *m*th mode





☑ Phonons as mediator of interactions (shared among all ions)

Recipe for Quantum simulation in an ion crystal

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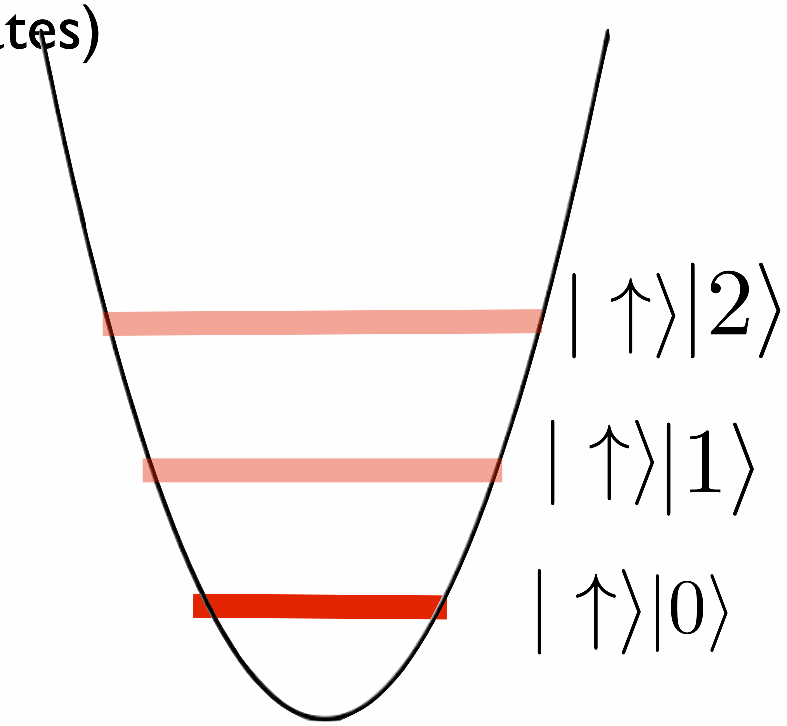

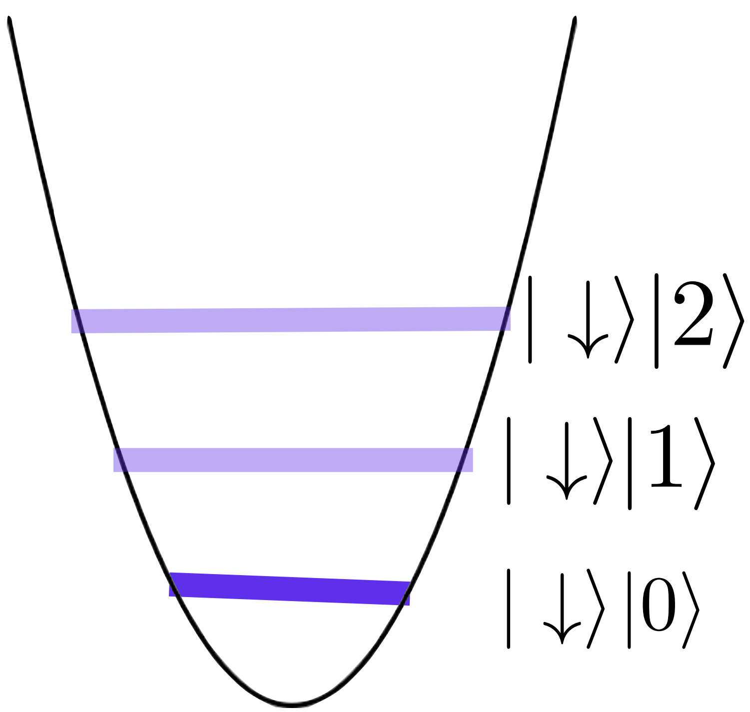

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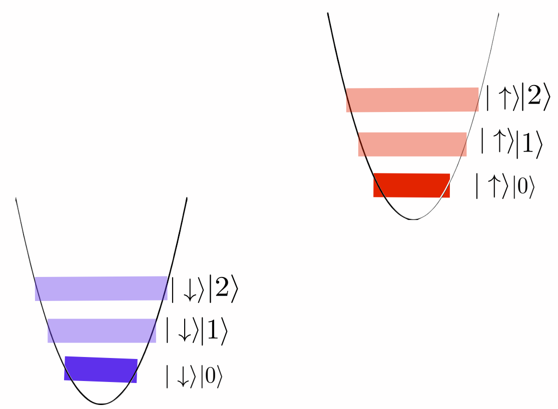
☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)



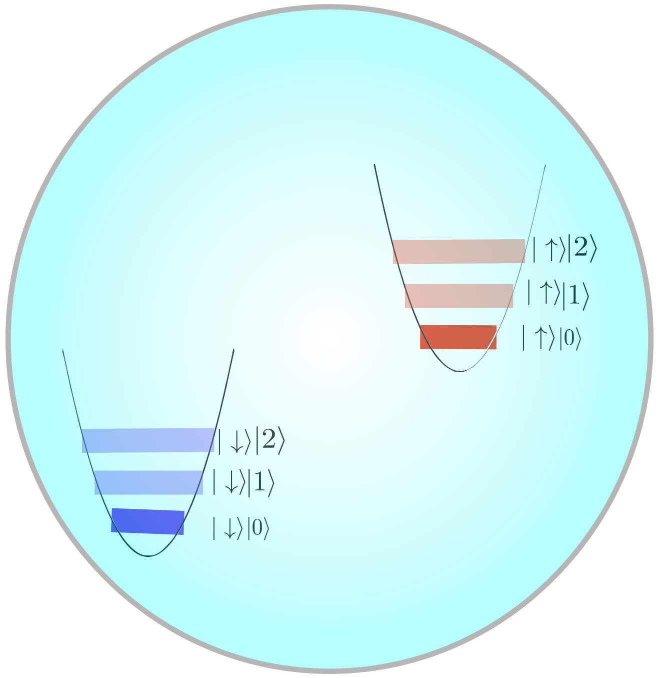
☑ Phonons as mediator of interactions

(shared among all ions)

Recipe for Quantum simulation in an ion crystal

☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)



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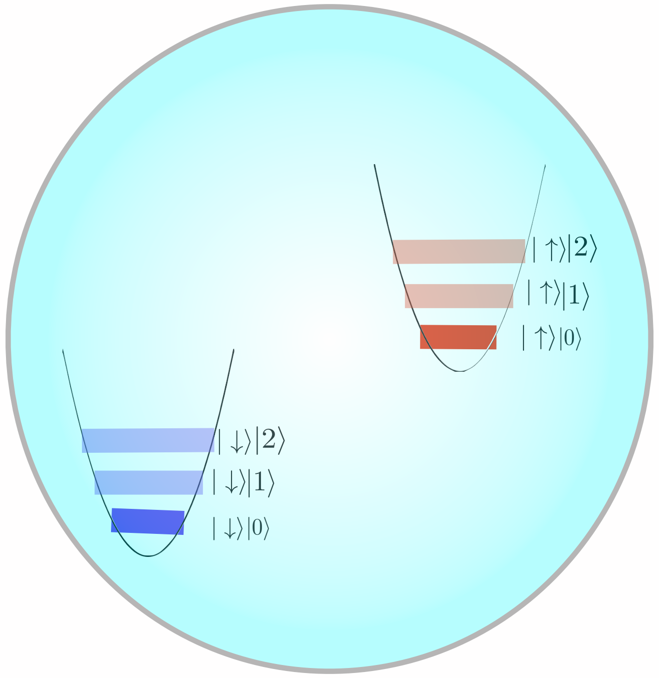
(shared among all ions)

Recipe for Quantum simulation in an ion crystal

☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)

single ion qubit (spin-1/2)



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Recipe for Quantum simulation in an ion crystal

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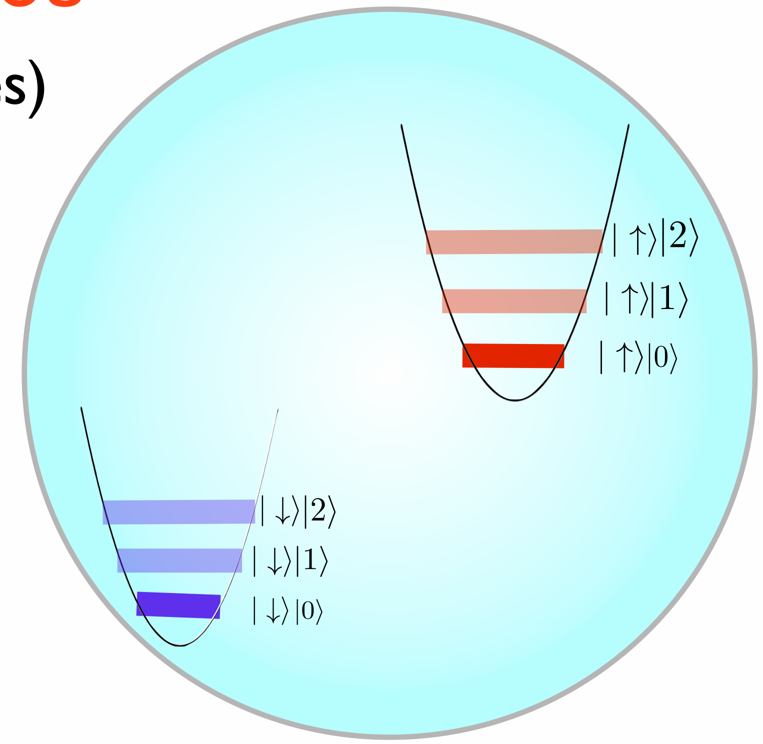
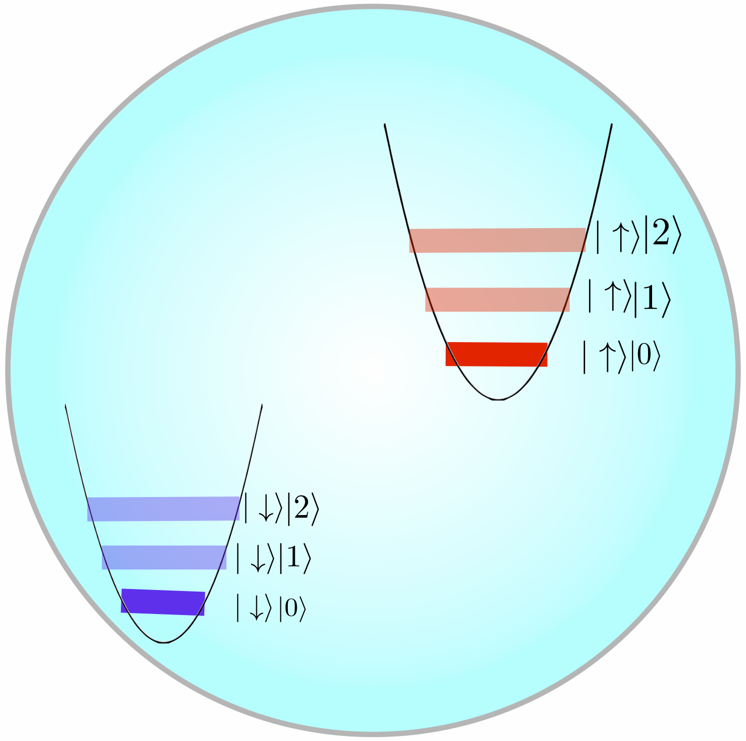




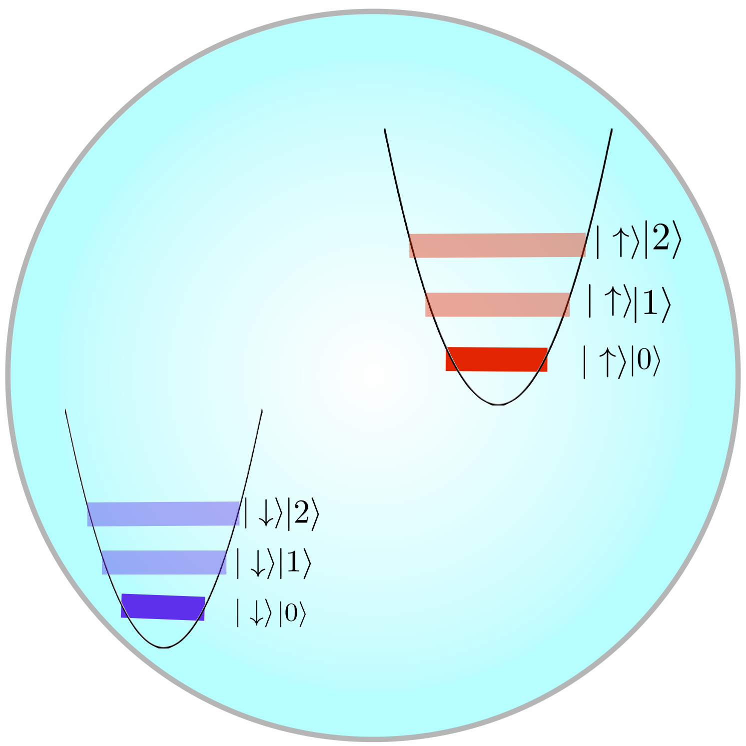
☑ Phonons as mediator of interactions

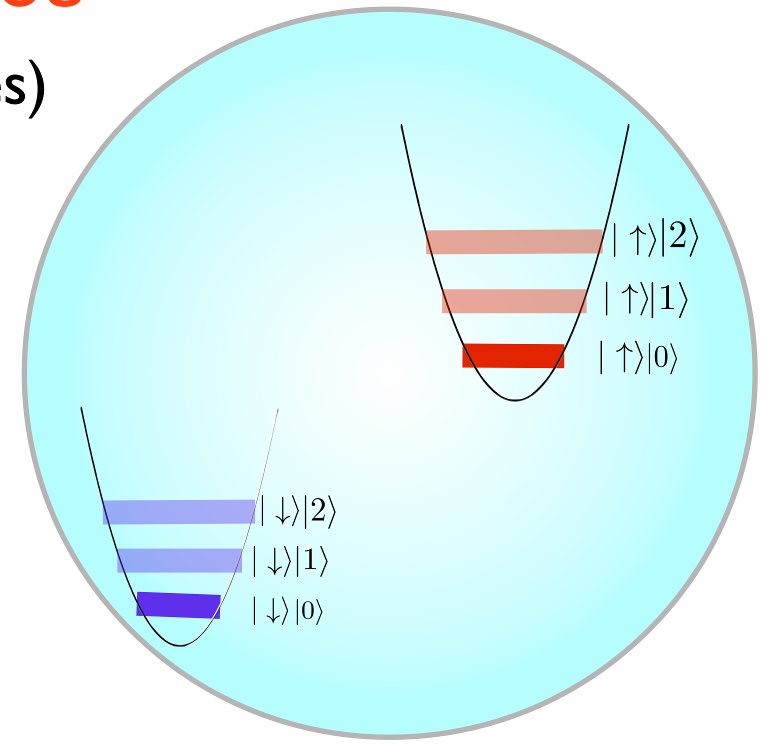
Recipe for Quantum simulation in an ion crystal

☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)

ion 1





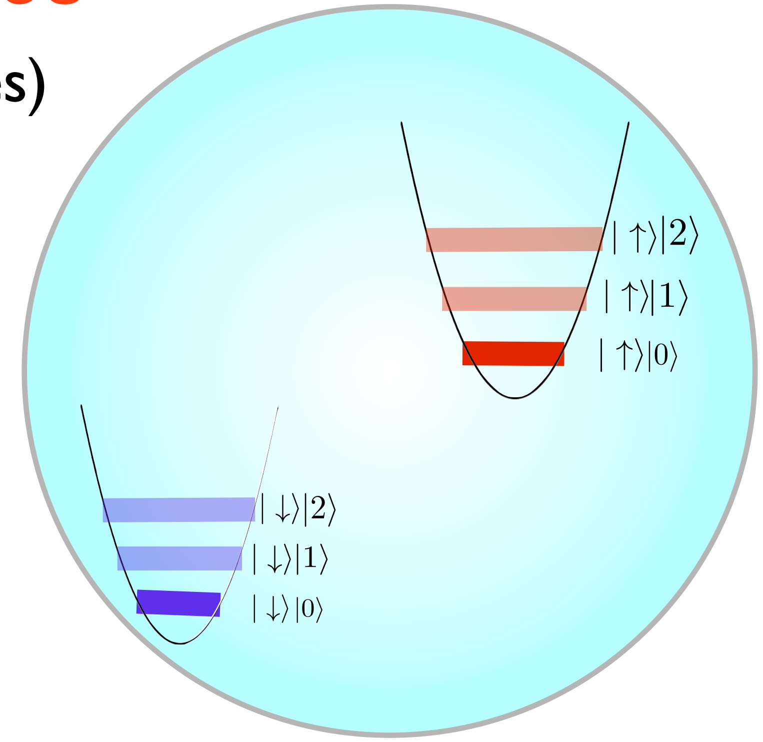
☑ Phonons as mediator of interactions

Recipe for Quantum simulation in an ion crystal

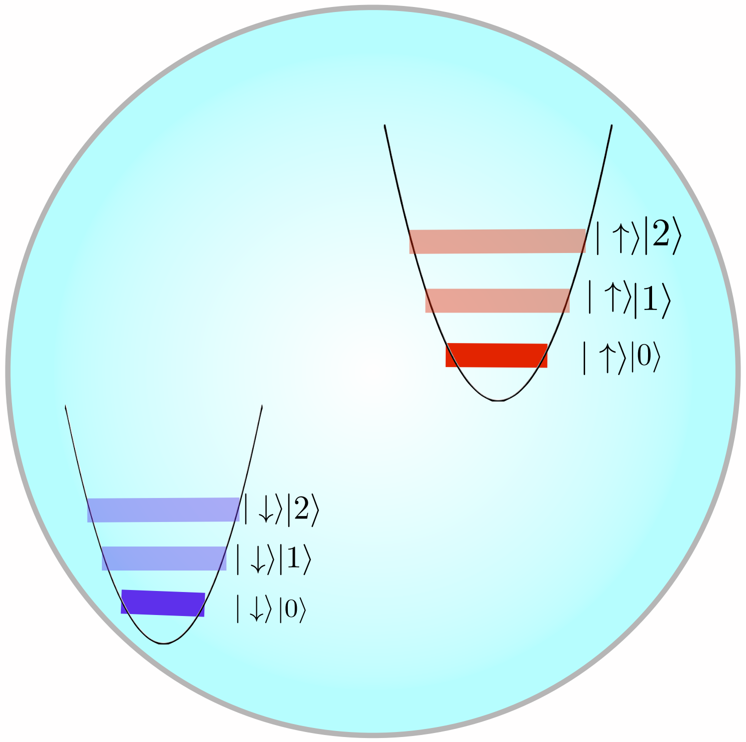
☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)

ion 2



ion 1



☑ Phonons as mediator of interactions

Recipe for Quantum simulation in an ion crystal

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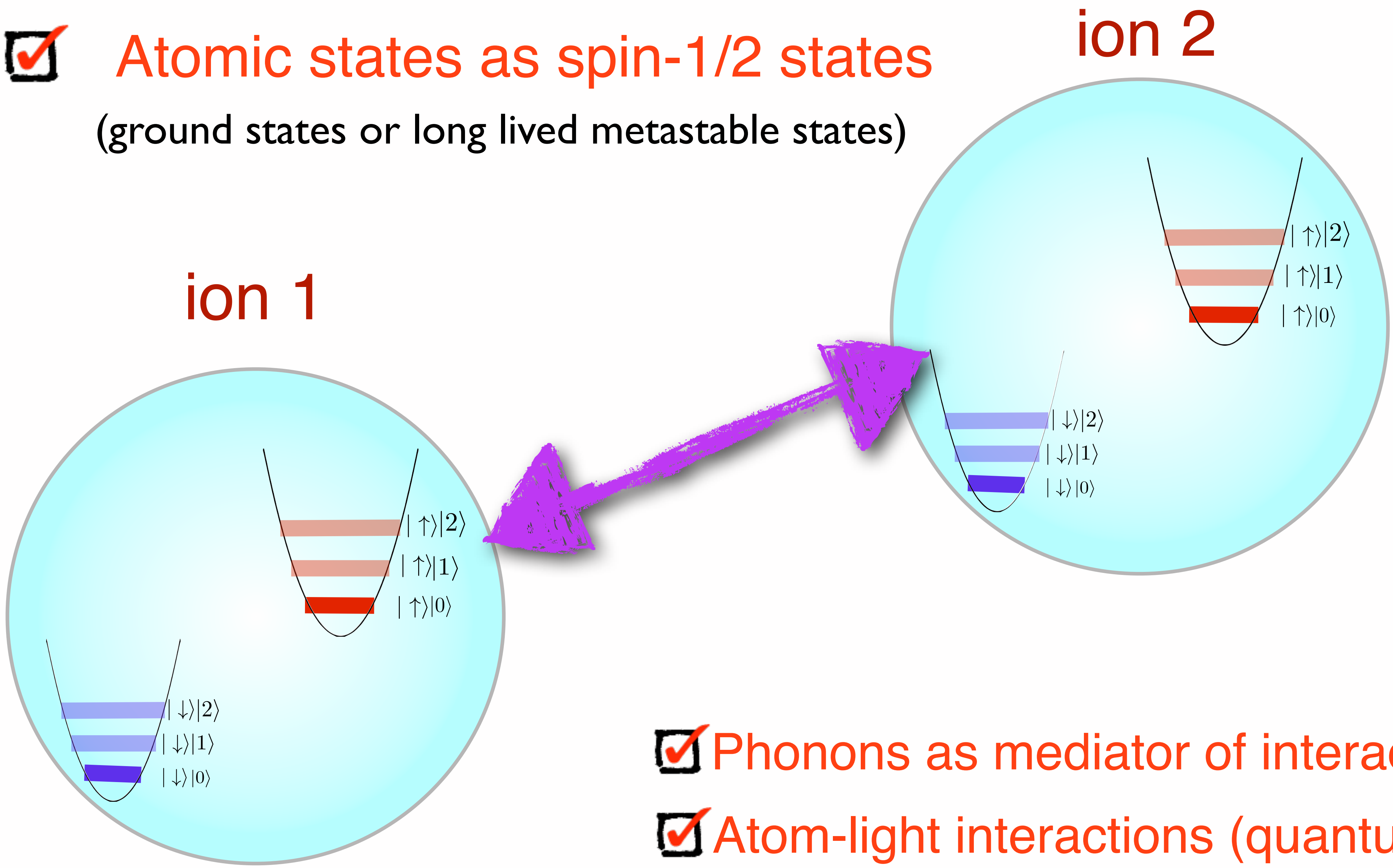


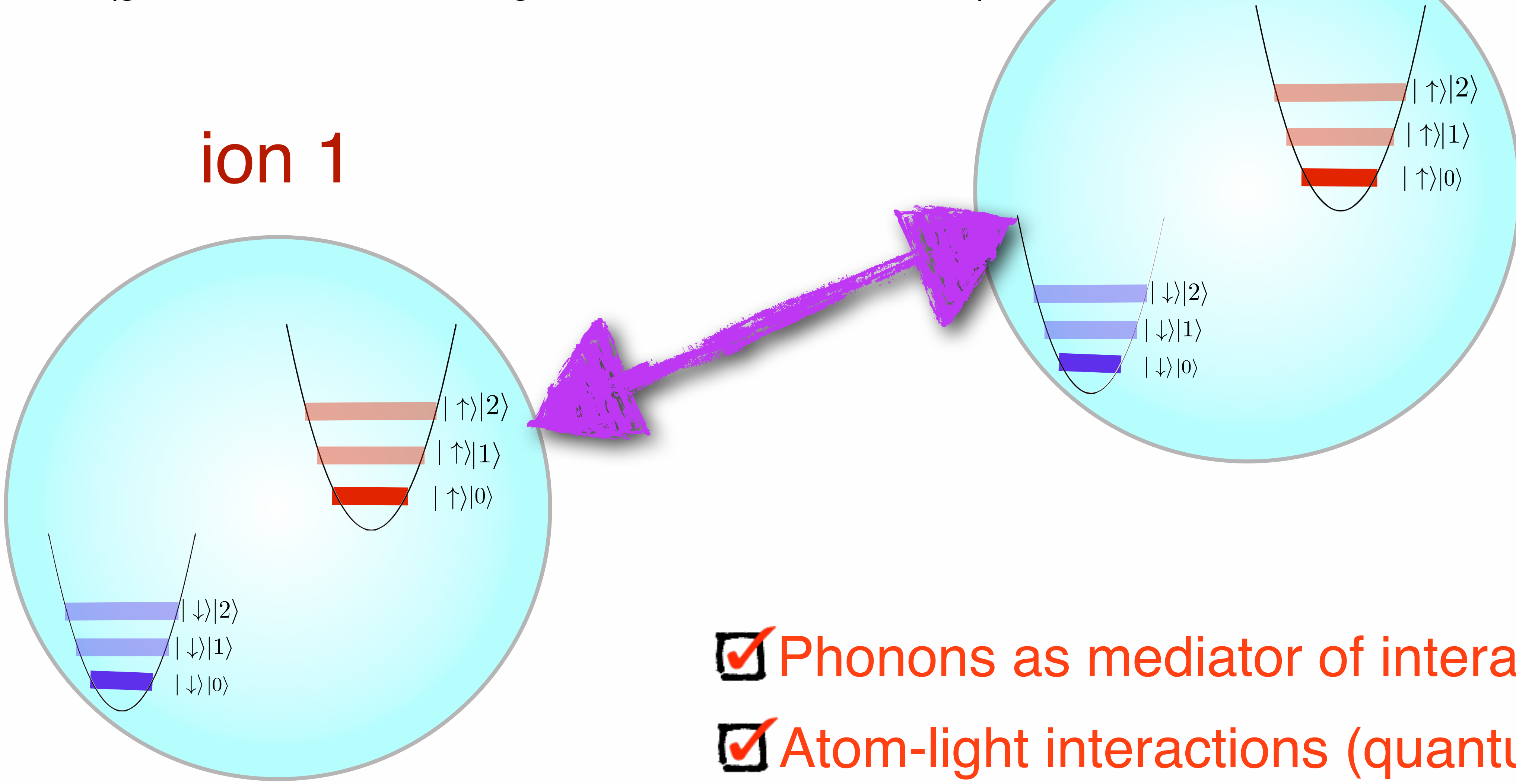
☑ Phonons as mediator of interactions

☑ Atom-light interactions (quantum gates)
(selective population of modes)

Recipe for Quantum simulation in an ion crystal

- ☑ Atomic states as spin-1/2 states

  (ground states or long lived metastable states)



- ☑ Phonons as mediator of interactions
- ☑ Atom-light interactions (quantum gates)

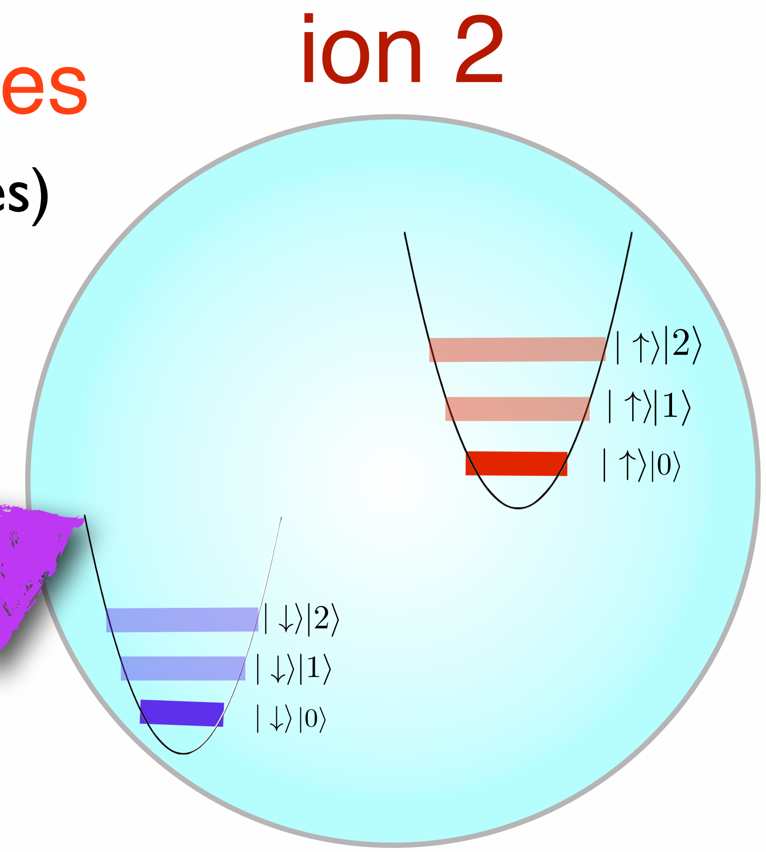
  (selective population of modes)

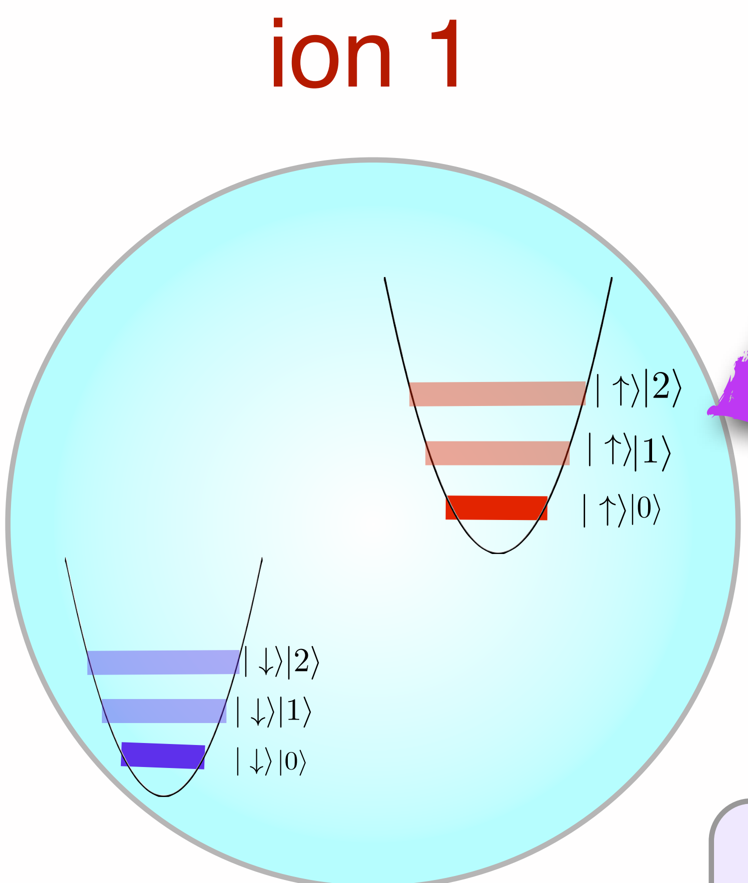
- ☑ Mode-structure determines the nature of spin-spin interactions

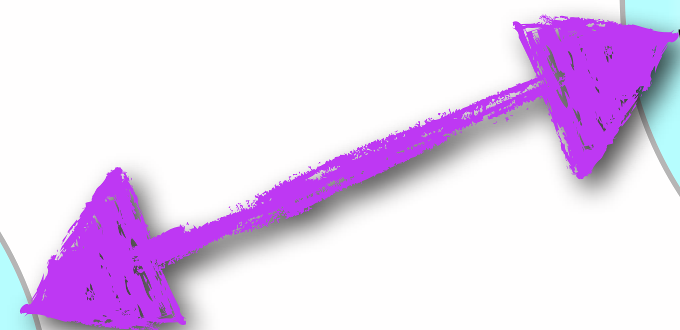
Recipe for Quantum simulation in an ion crystal

☑ Atomic states as spin-1/2 states

(ground states or long lived metastable states)







Phonon mediated spin-spin couplings

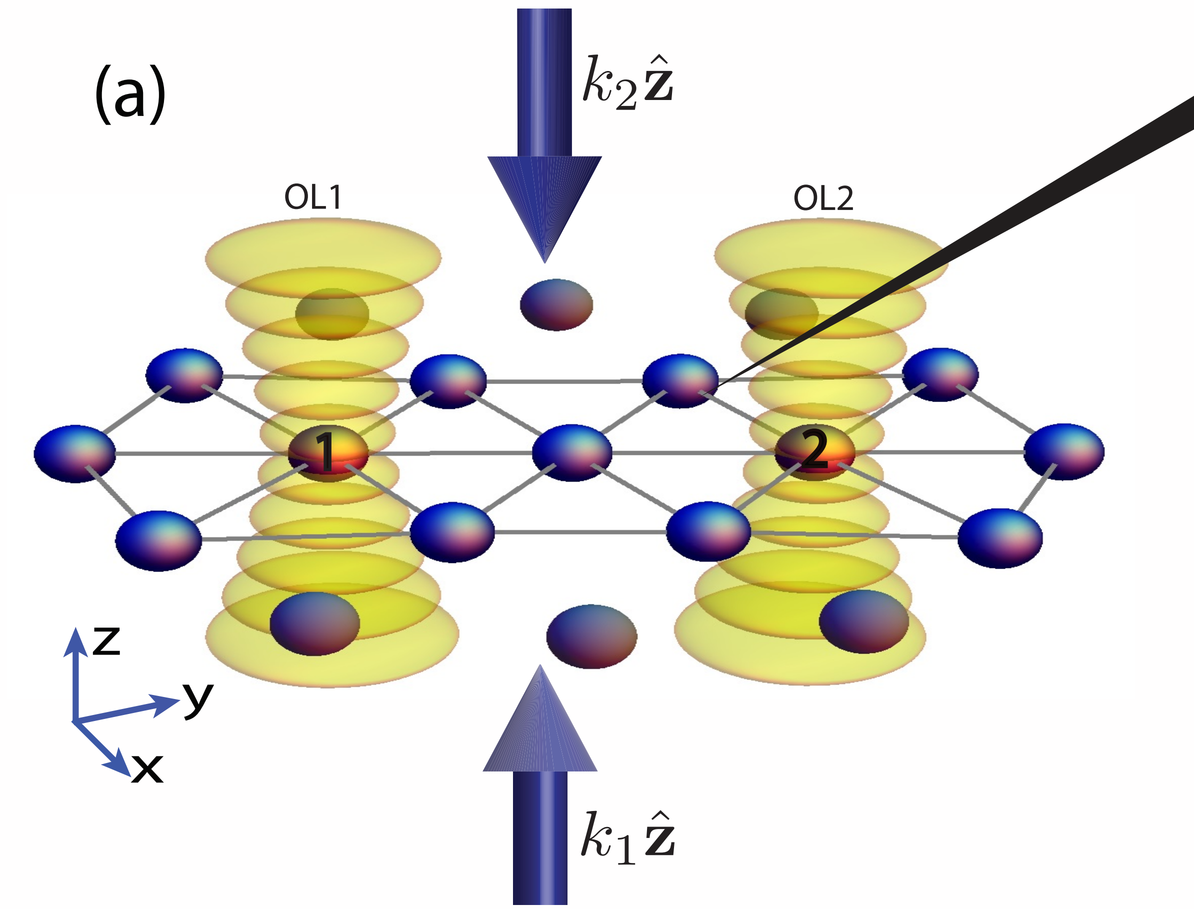
$$H = \sum_{i<j} J^z_{ij} \sigma^i_z \otimes \sigma^j_z$$

$$J^z_{ij} = \sum_{m=1}^{N} \frac{\Omega^i_I \Omega^j_I \eta^i_m \eta^j_m}{\delta_m}$$

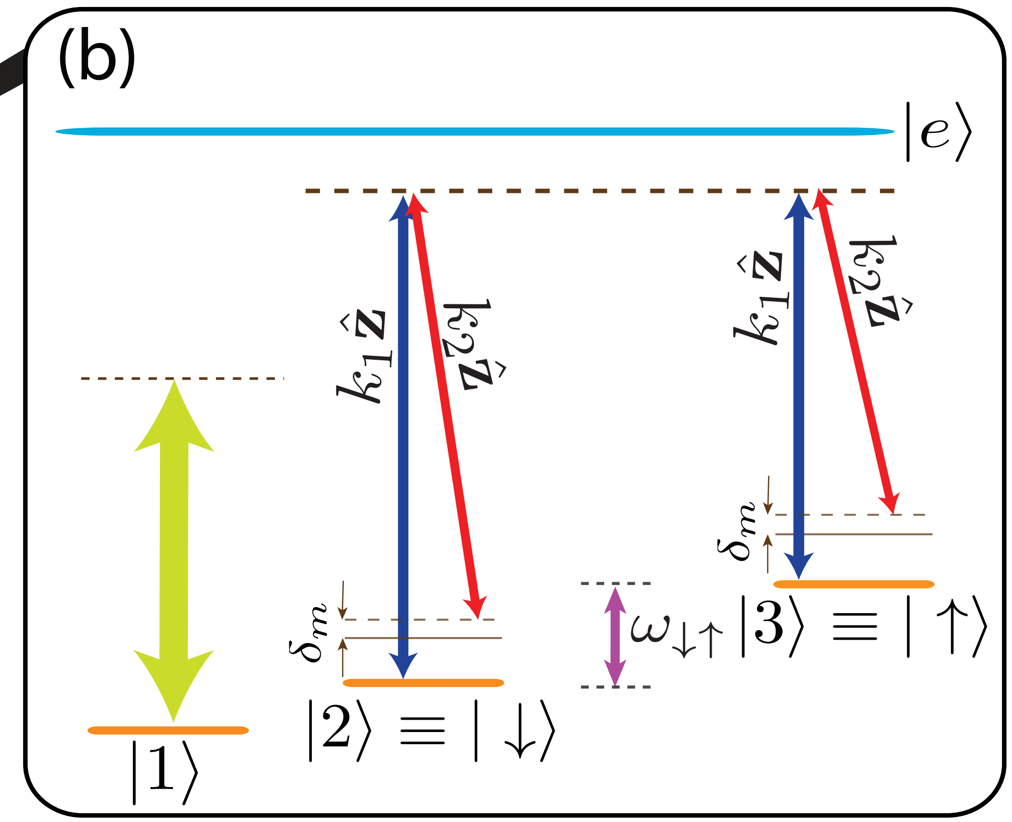
Lamb-Dicke params **(depends on phonon eigen-vector)**

Detuning from mode m

Our Setup: 2D planar crystal



Raman scheme for generating spin-spin interaction between ions



(in preparation)

Phonon mediated spin-spin interactions

$$H = \sum_{i<j} J^z_{ij}\sigma^i_z \otimes \sigma^j_z$$

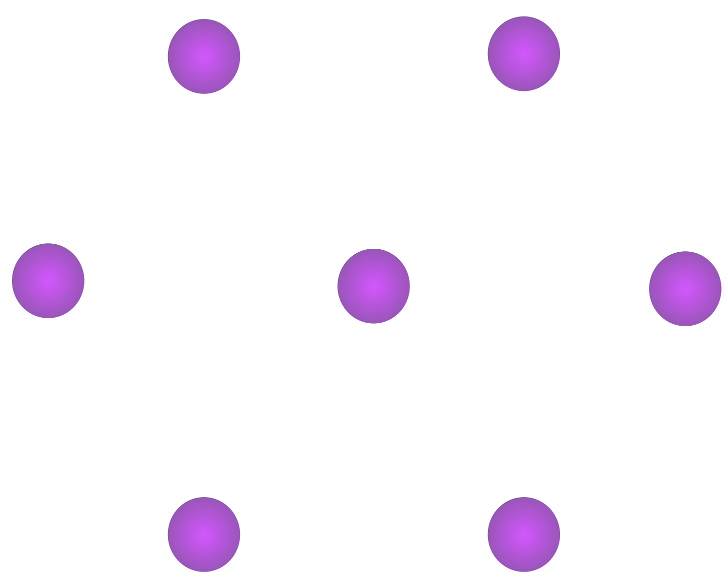
$$J^z_{ij} = \sum_{m=1}^{N} \frac{\Omega^i_I \Omega^j_I \eta^i_m \eta^j_m}{\delta_m}$$

Lamb-Dicke params

Detuning from mode m

Spin-spin interactions depends crucially on the nature of phonon modes!!! (We use transversal modes)

Single Plaquette: 7-ion crystal

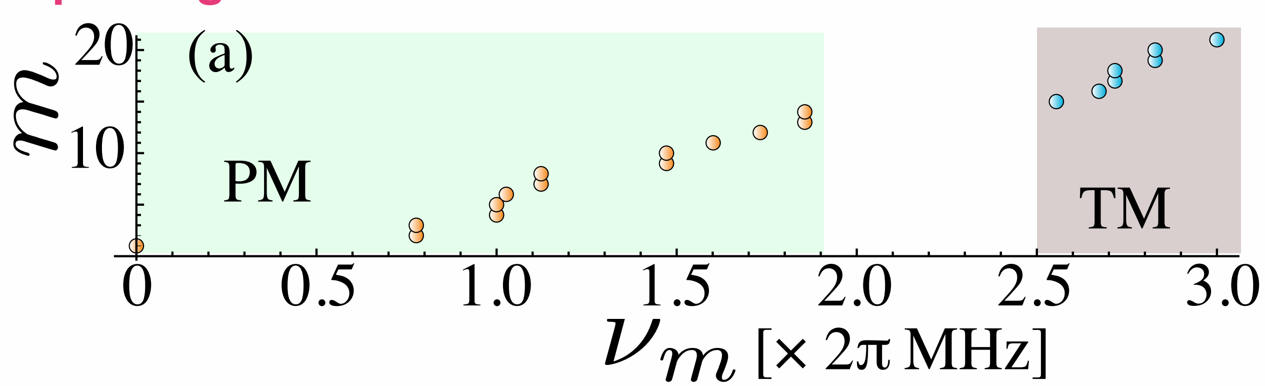


ions in the qubit states

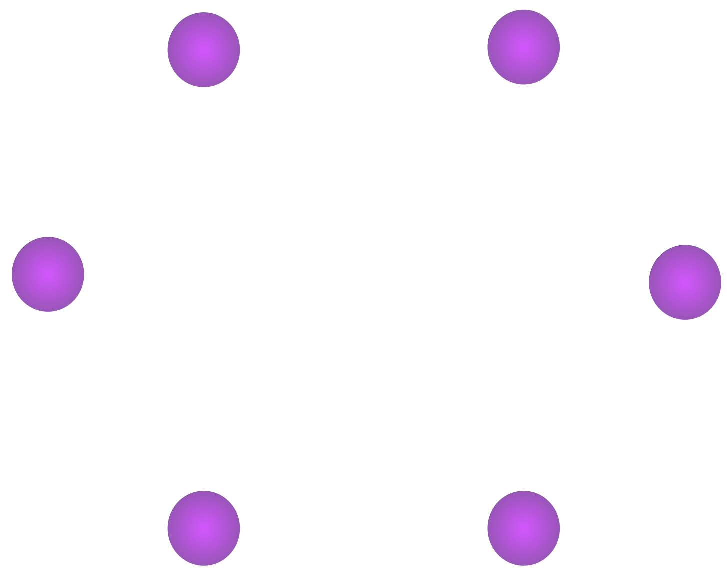
(in preparation)

Phonon mode spectrum (21 modes)

without pinning



Single Plaquette: 7-ion crystal



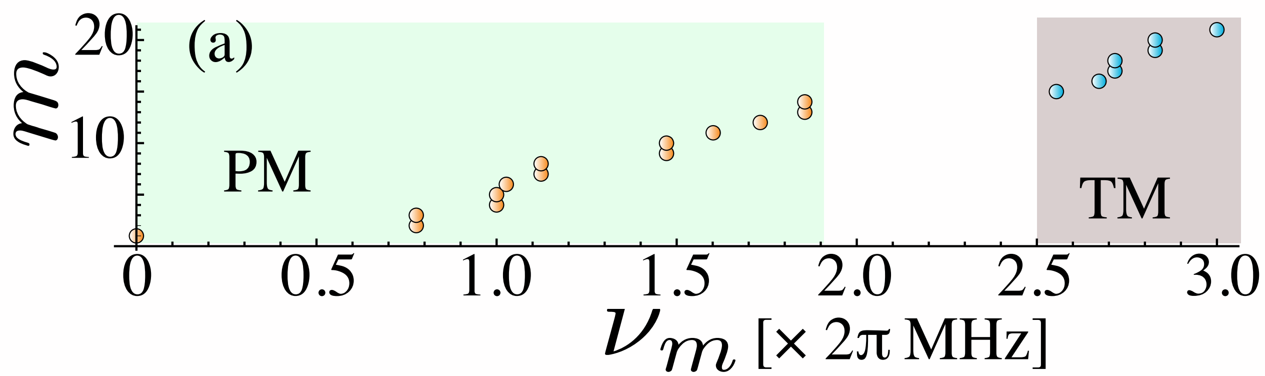
ions in the qubit states

move the central ion to state $|1\rangle$ (pinning ion)

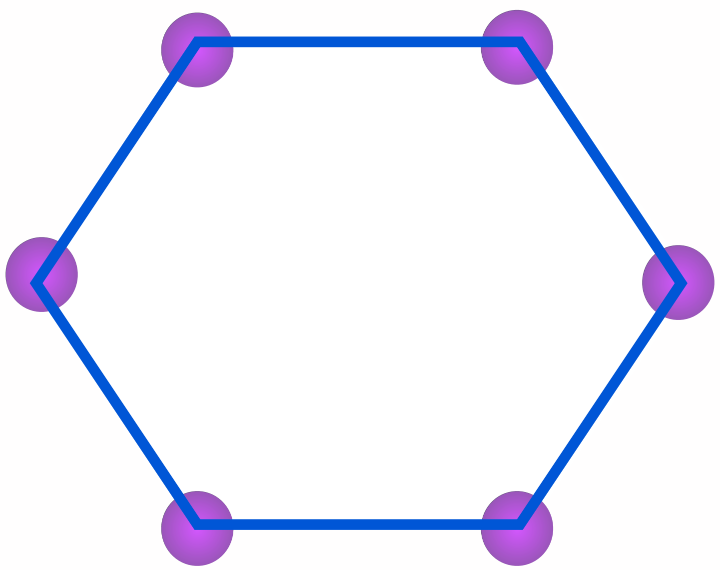
(in preparation)

Phonon mode spectrum (21 modes)

without pinning



Single Plaquette: 7-ion crystal



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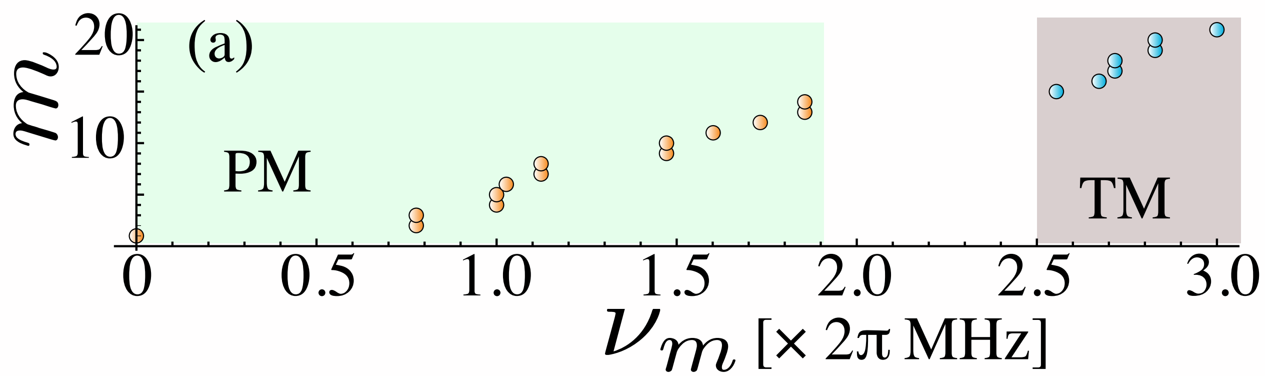
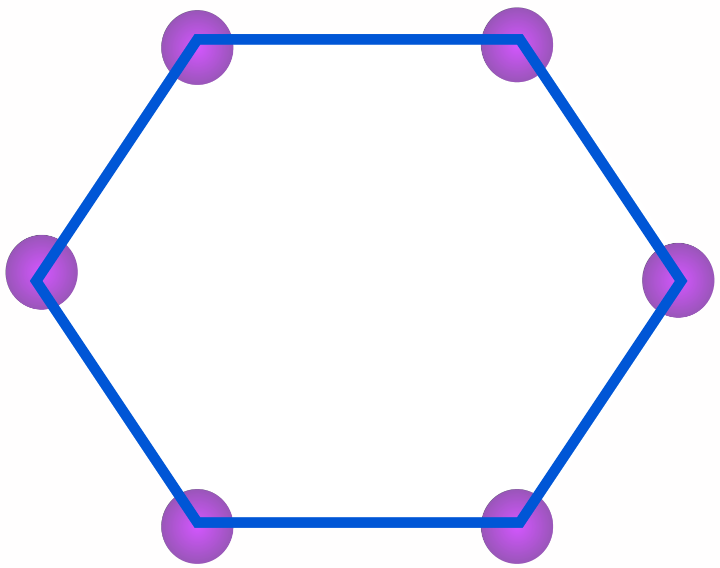


Single Plaquette: 7-ion crystal

Hexagonal plaquette



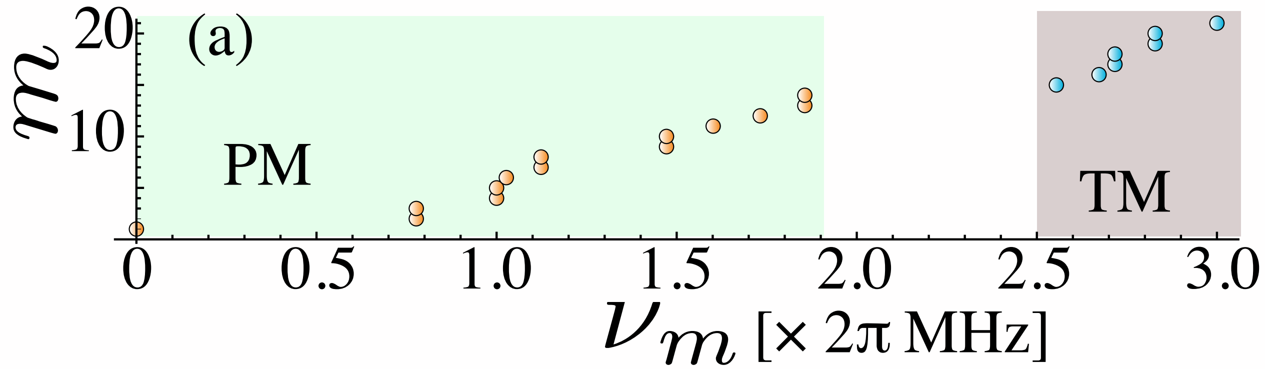
ions in the qubit states

move the central ion to state $|1\rangle$ (pinning ion)

(in preparation)

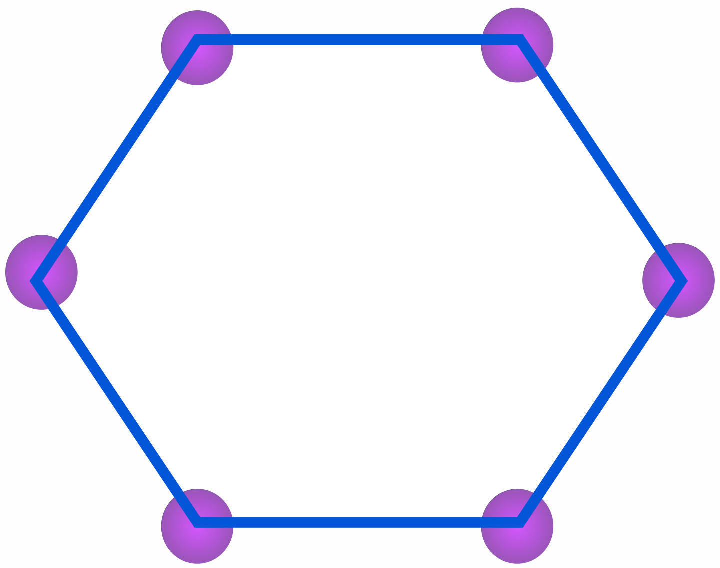
Phonon mode spectrum (21 modes)

without pinning



Single Plaquette: 7-ion crystal

Hexagonal plaquette



ions in the qubit states

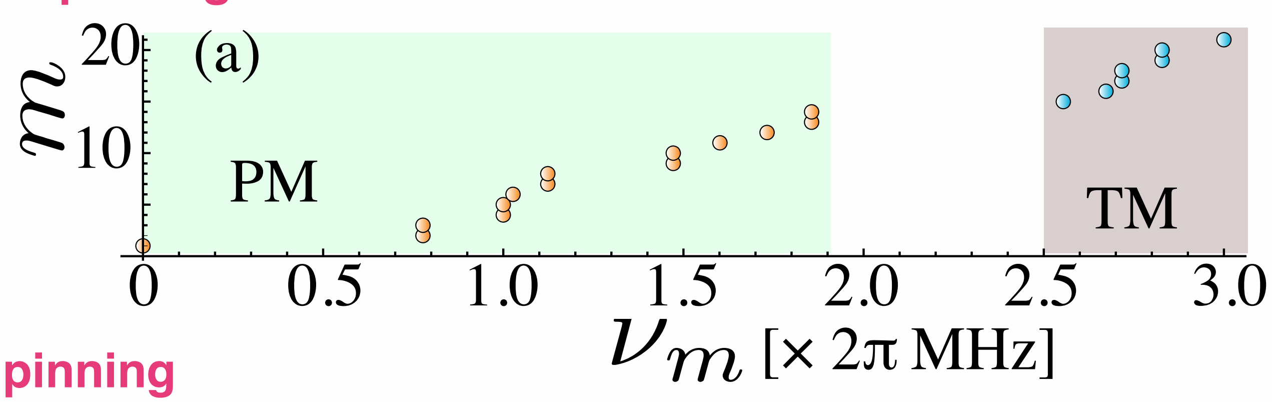
move the central ion to state $|1\rangle$ (pinning ion)

(in preparation)

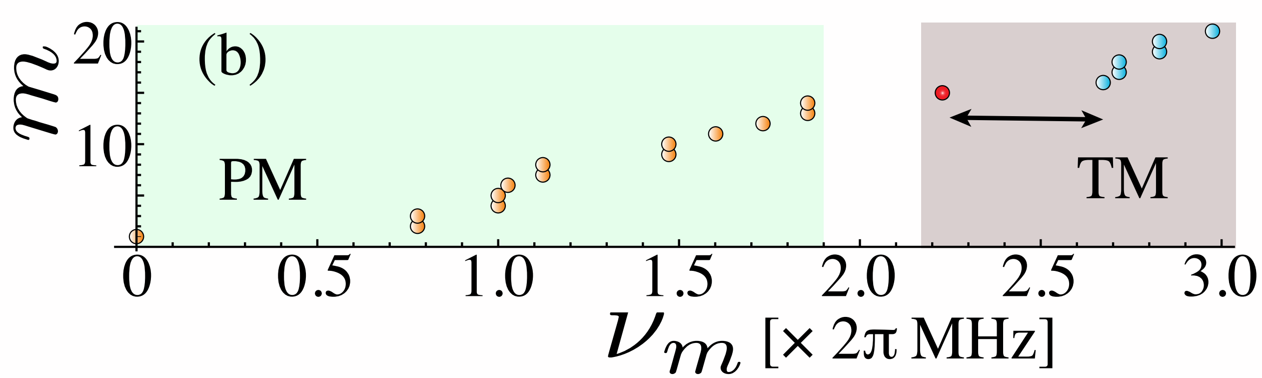
Spin-spin interactions depends crucially on the nature of phonon modes!!! (We use transversal modes)

Phonon mode spectrum (21 modes)

without pinning

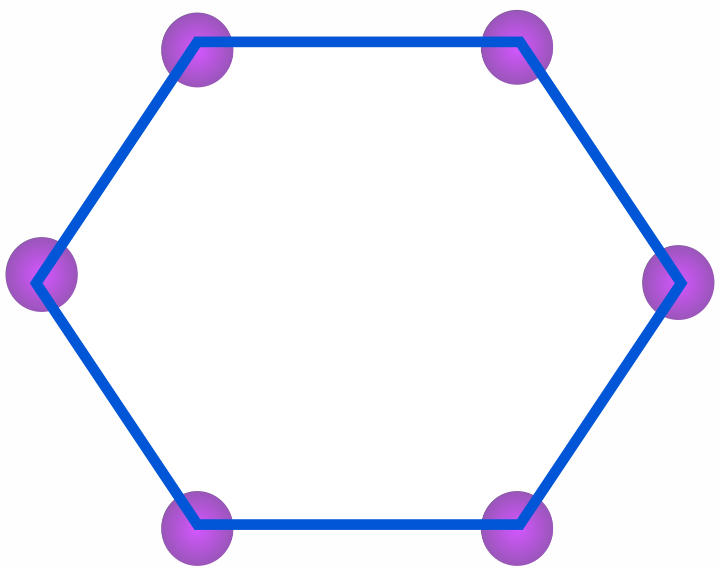


with pinning



Single Plaquette: 7-ion crystal

Hexagonal plaquette



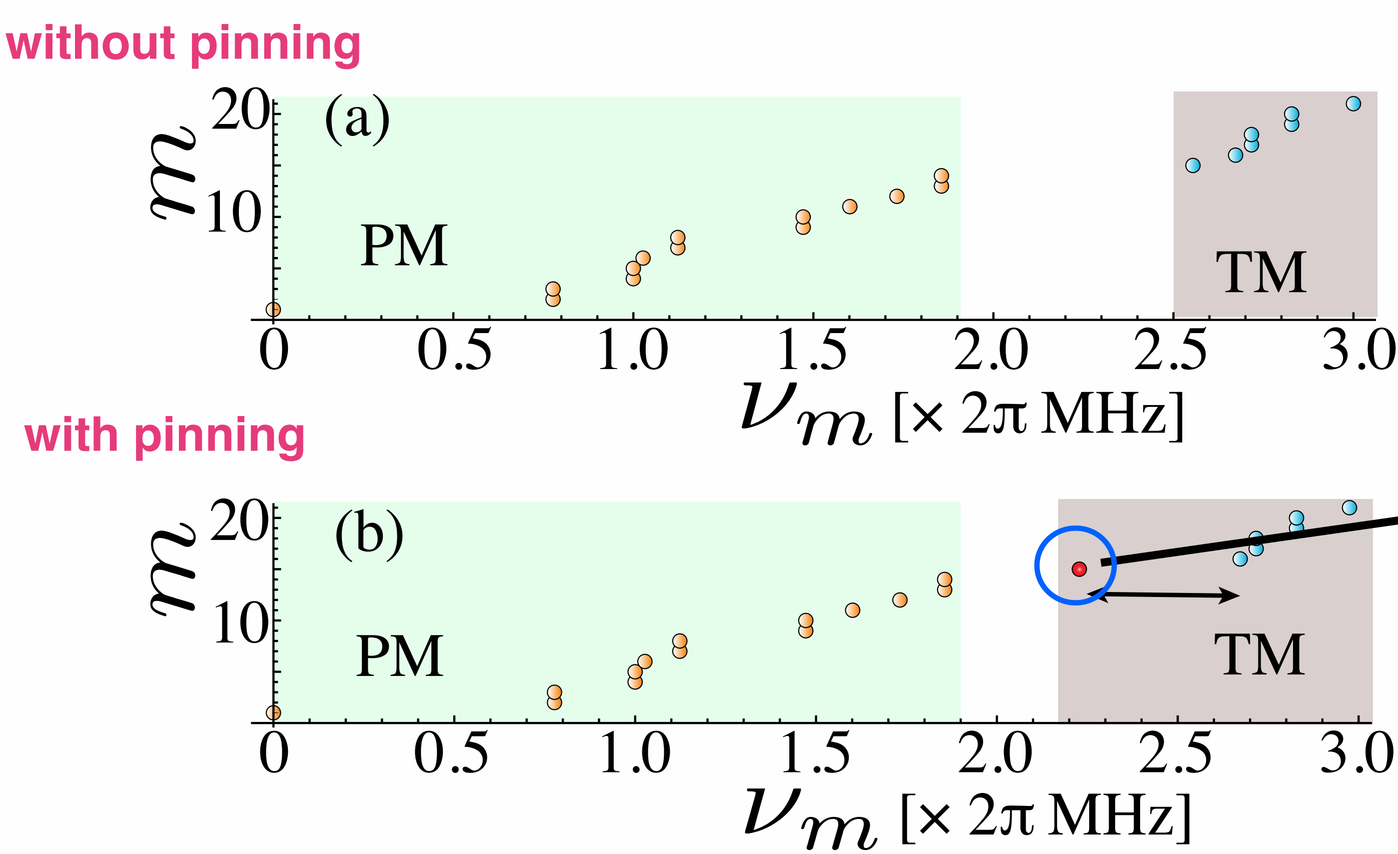
ions in the qubit states

move the central ion to state $|1\rangle$ (pinning ion)

(in preparation)

Spin-spin interactions depends crucially on the nature of phonon modes!!! (We use transversal modes)

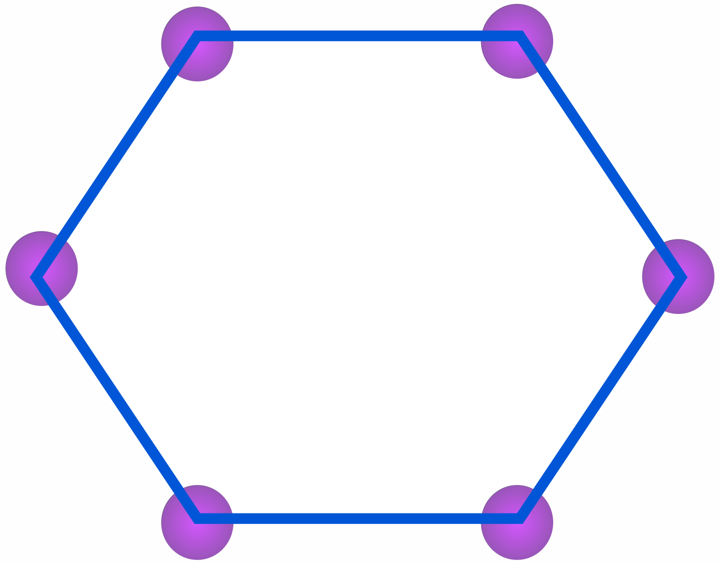
Phonon mode spectrum (21 modes)



Appearance of an isolated mode in the lowest part (transversal modes) of the spectrum when the pinning relaxes the trapping frequency of the central ion

Single Plaquette: 7-ion crystal

Hexagonal plaquette



ions in the qubit states

move the central ion to state $|1\rangle$ (pinning ion)

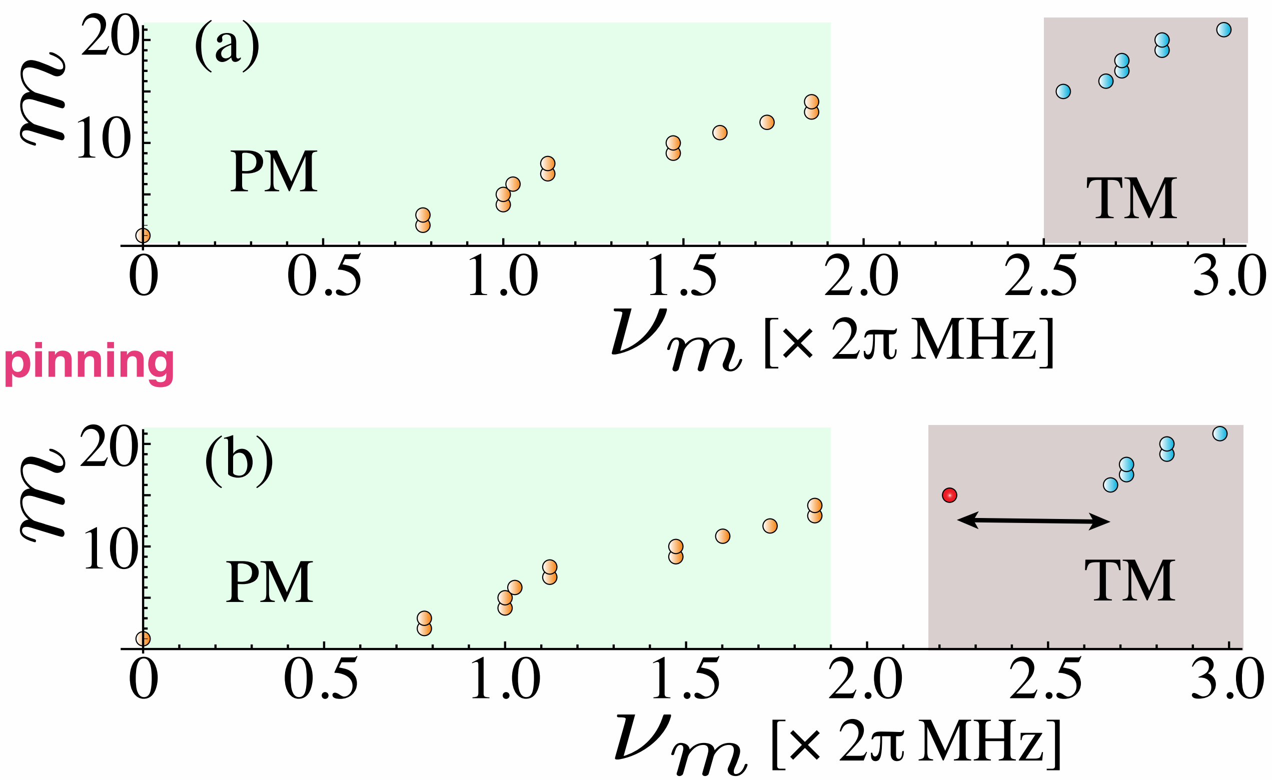
(in preparation)

Spin-spin interactions depends crucially on the nature of phonon modes!!! (We use transversal modes)

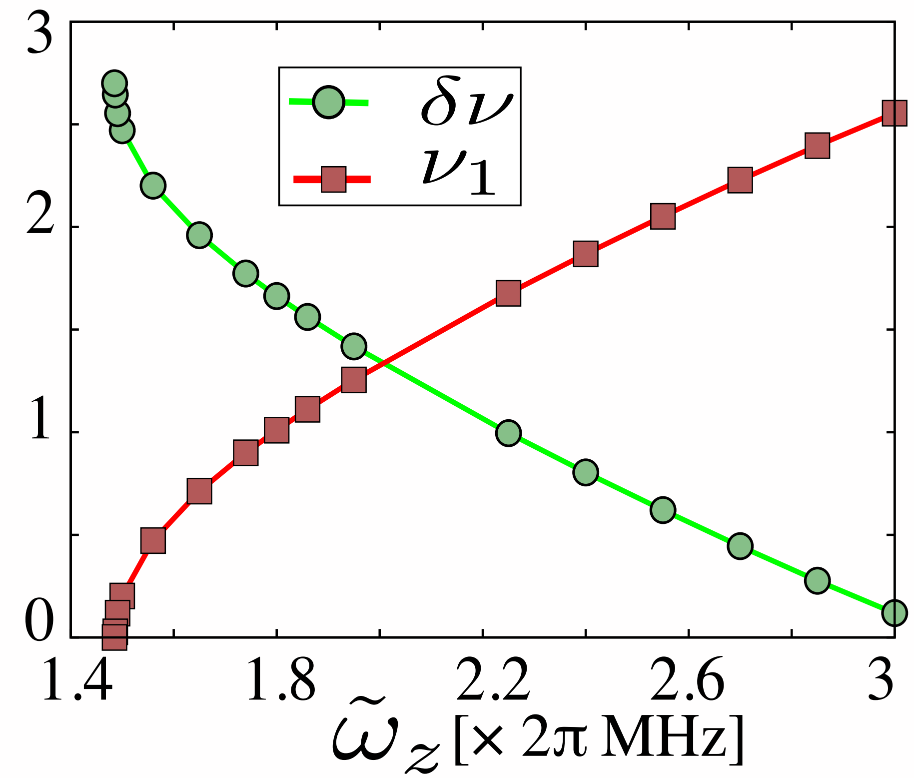
Phonon mode spectrum (21 modes)

without pinning

with pinning



$$\delta\nu = \nu_2 - \nu_1$$



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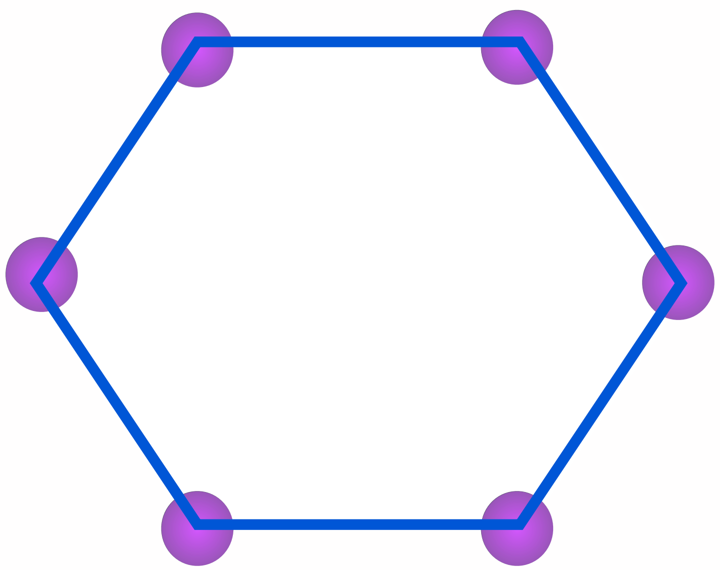
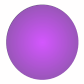




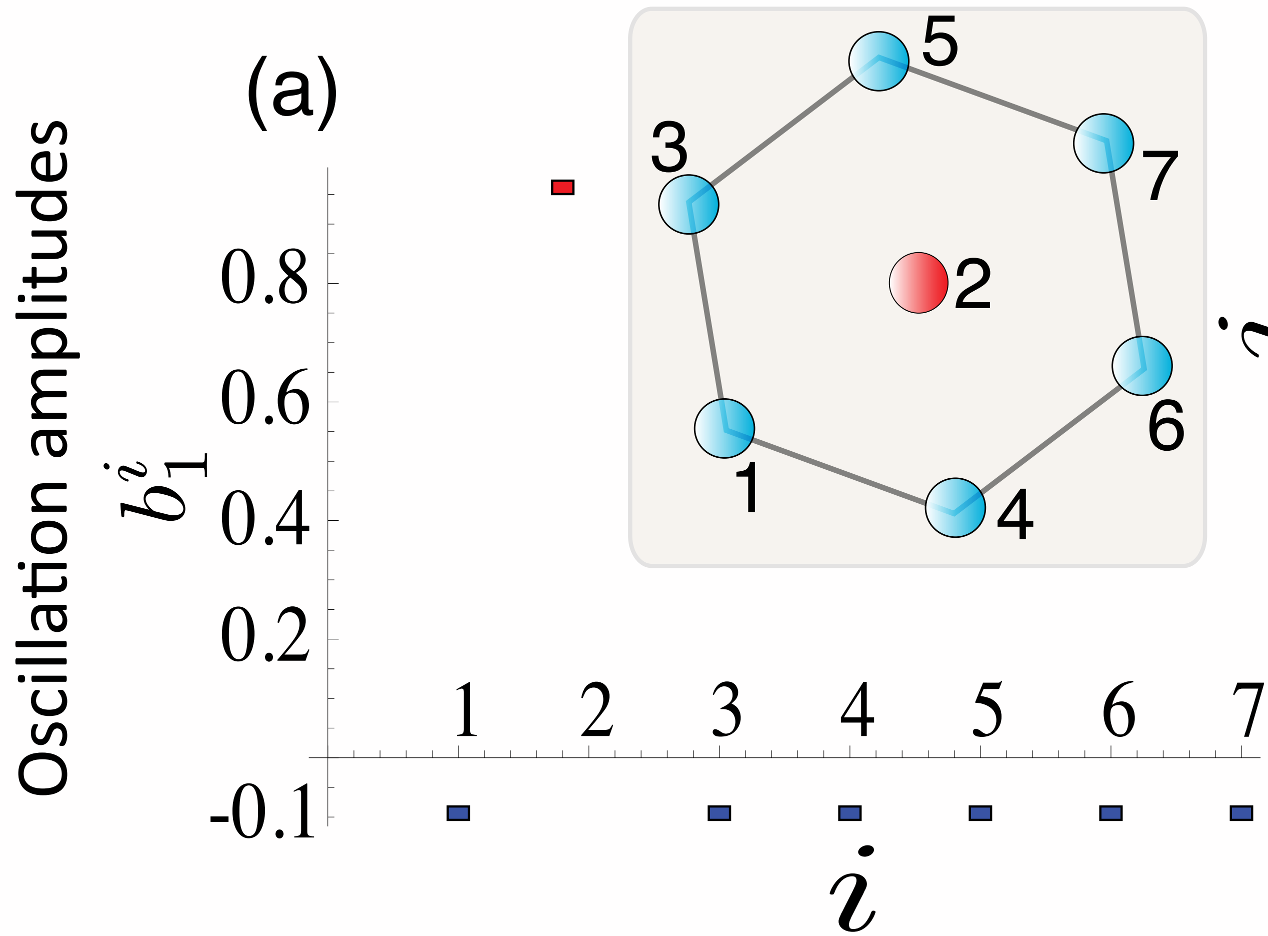
move the central ion to state $|1\rangle$ (pinning ion)

(in preparation)

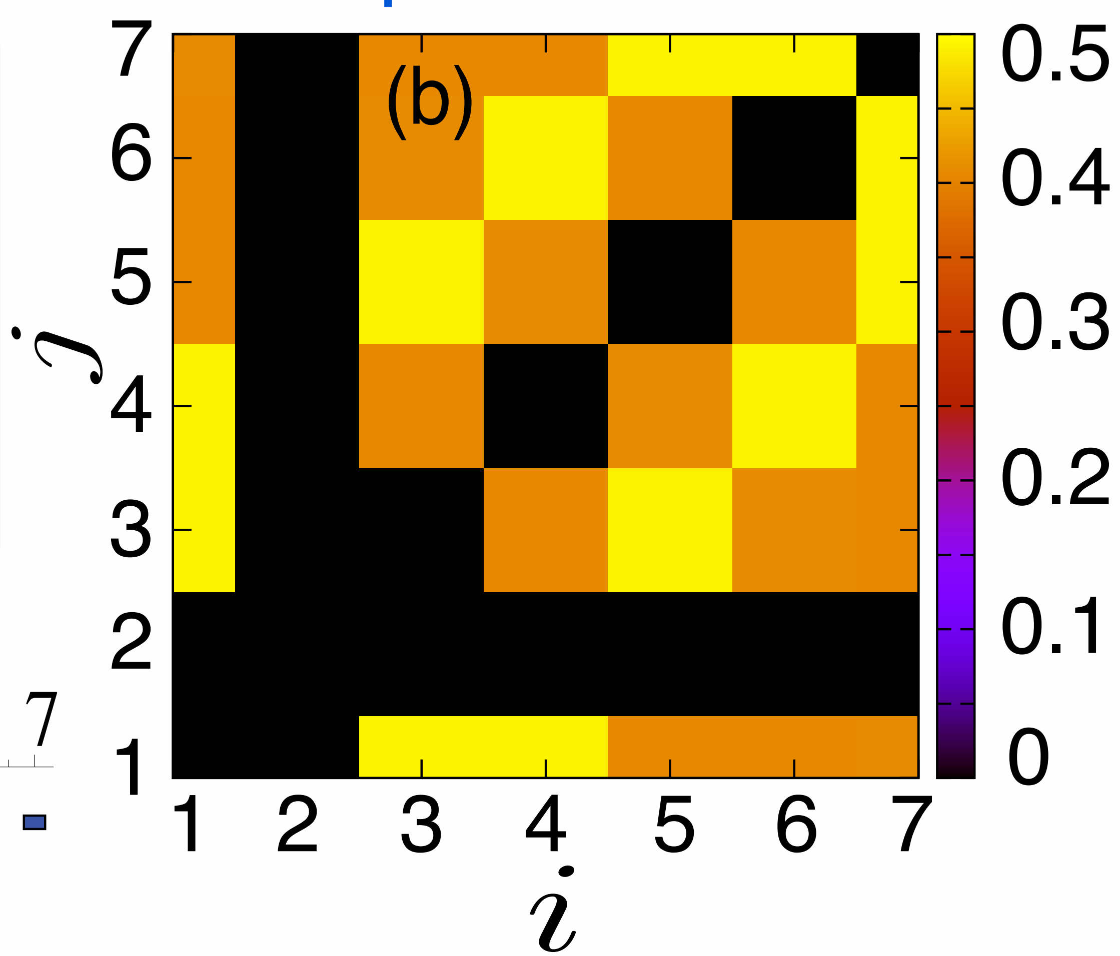
Spin-spin interactions depends crucially on the nature of phonon modes!!! (We use transversal modes)

$$\omega_{x,y} = 2\pi \times 1 \text{ MHz}$$
$$\omega_z = 2\pi \times 3 \text{ MHz}$$
$$\omega_z^R = 2\pi \times 2.7 \text{ MHz}$$
$$\delta_{m=1} = 10 \text{ kHz}$$

→ Admixture with other modes causes imperfections

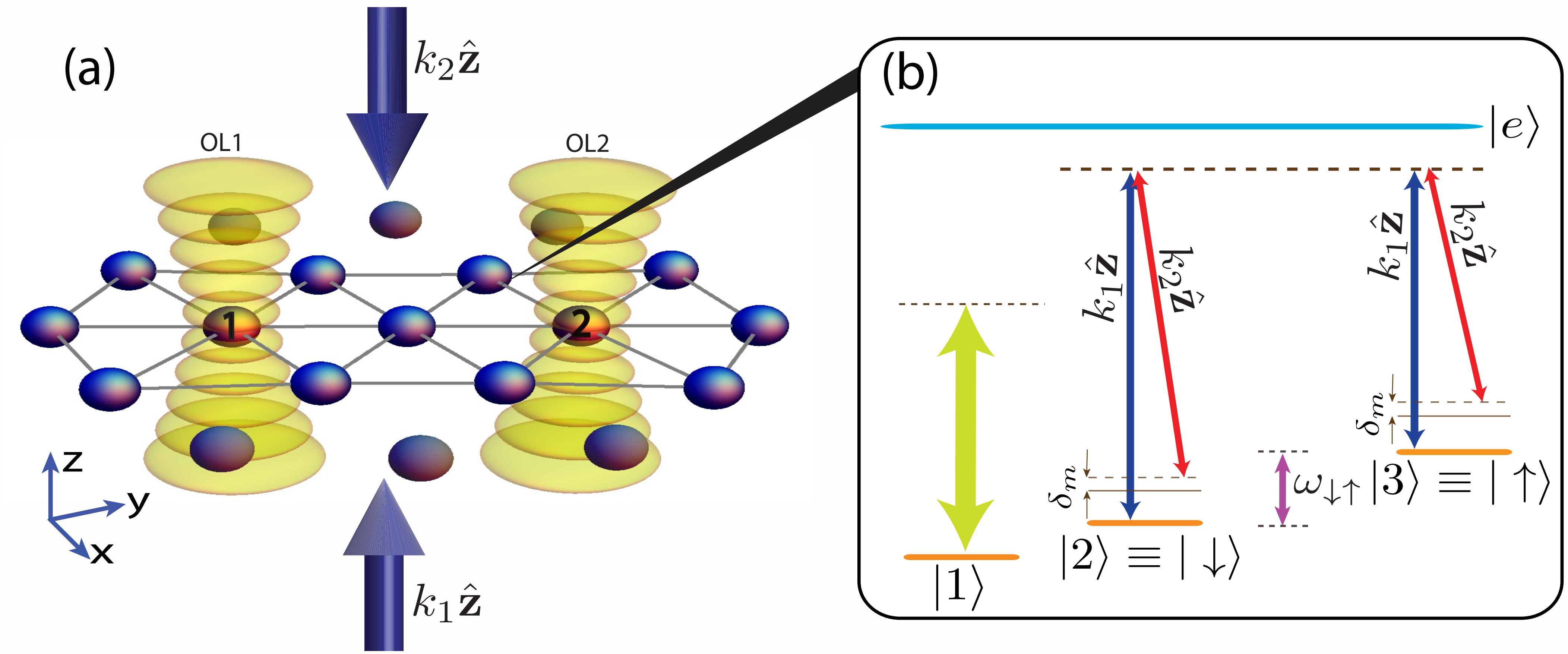


Plaquette interactions



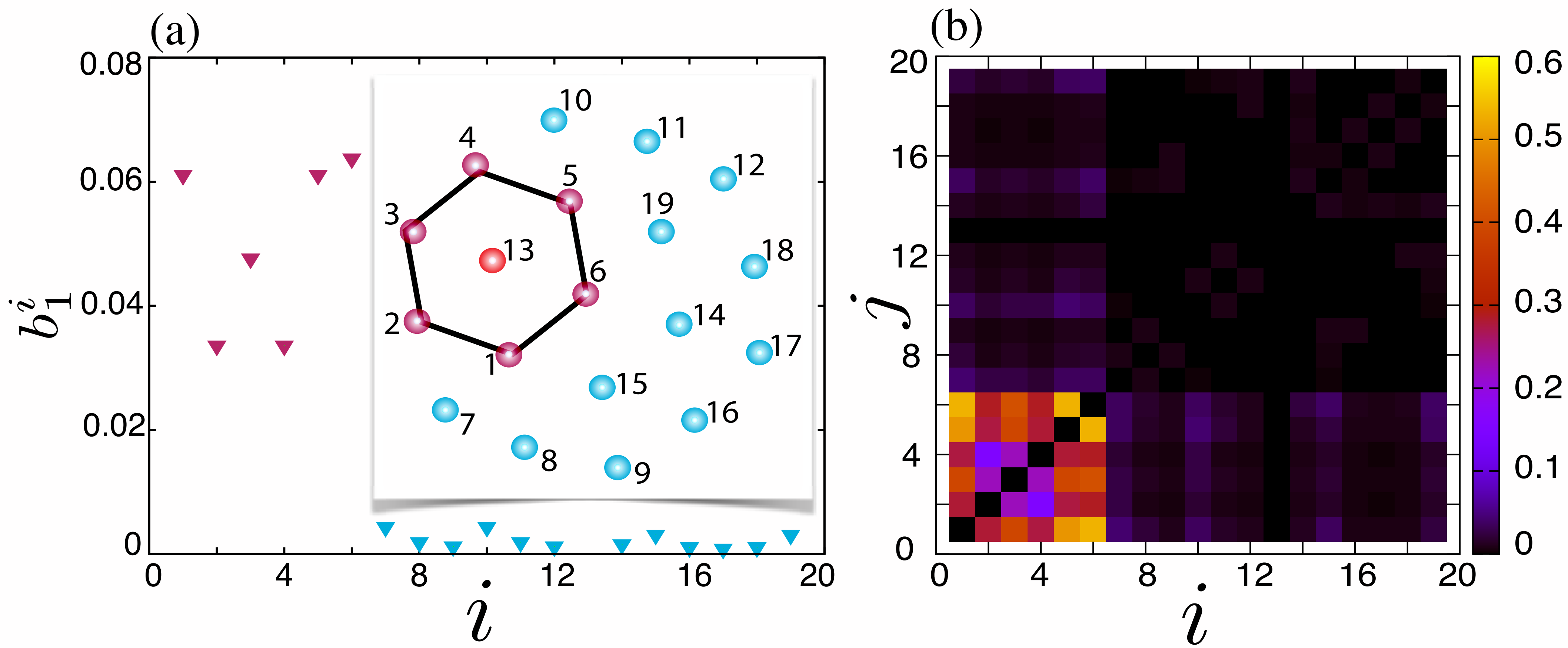
Two Plaquettes: 19-ion crystal

(in preparation)



Single plaquette in a 19-ion crystal

(in preparation)

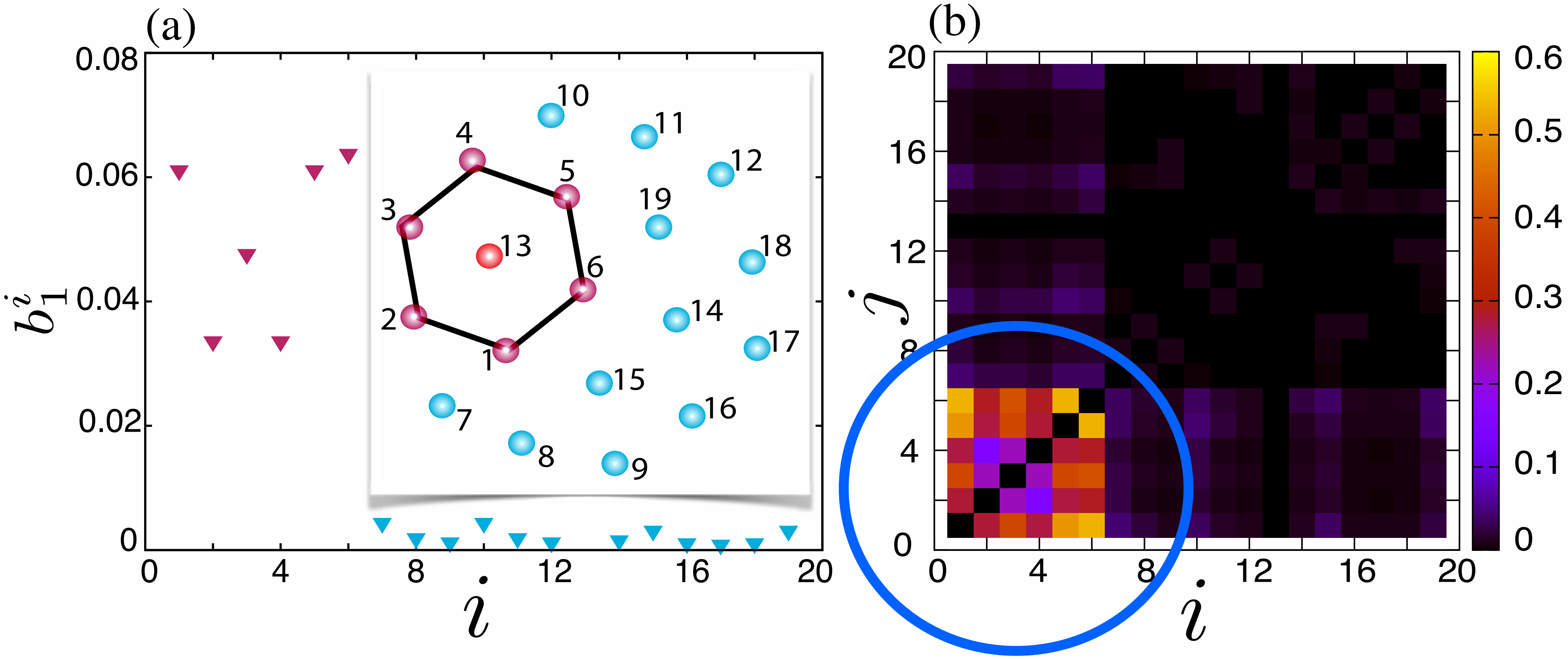


→ Admixture with other modes causes imperfections

but can be controlled

Single plaquette in a 19-ion crystal

(in preparation)



→ Admixture with other modes causes imperfections

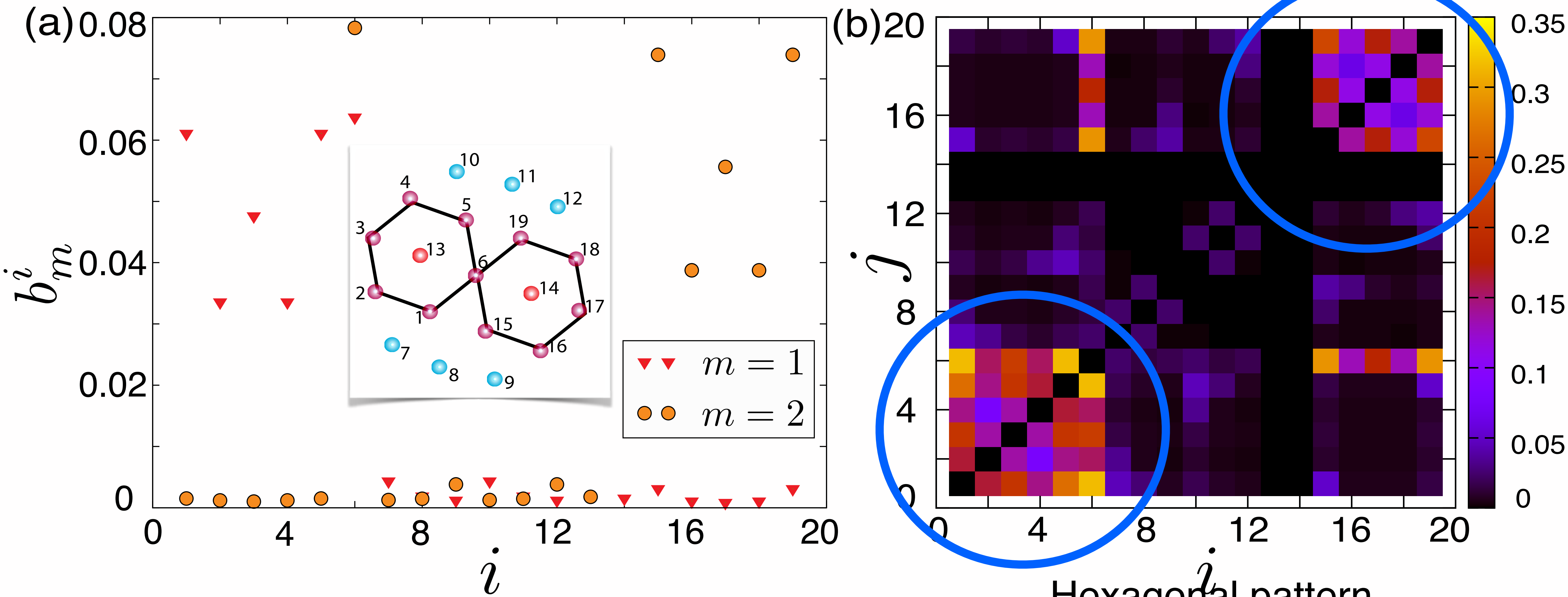
but can be controlled

Hexagonal pattern

(interactions localized among the six ions)

Double plaquette in a 19-ion crystal

(in preparation)



Hexagonal pattern

(interactions localized among the six ions)

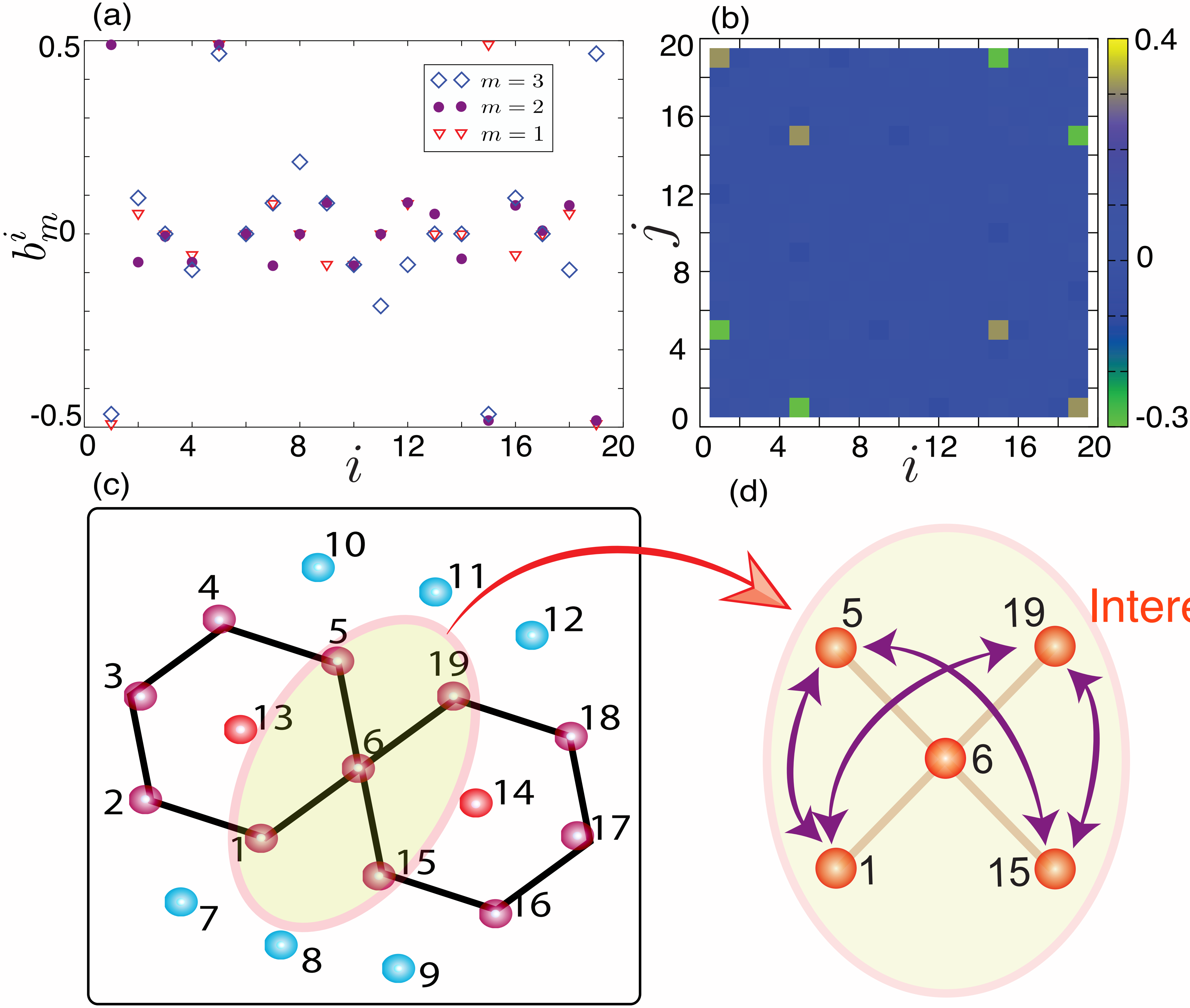
- Two different pinning lattices
- Two modes with hexagonal plaquette character
- Two set of Raman fields

No (or negligible) inter-plaquette interactions

→ Admixture with other modes causes imperfections

Double plaquette in a 19-ion crystal

☑ Quantum dynamics



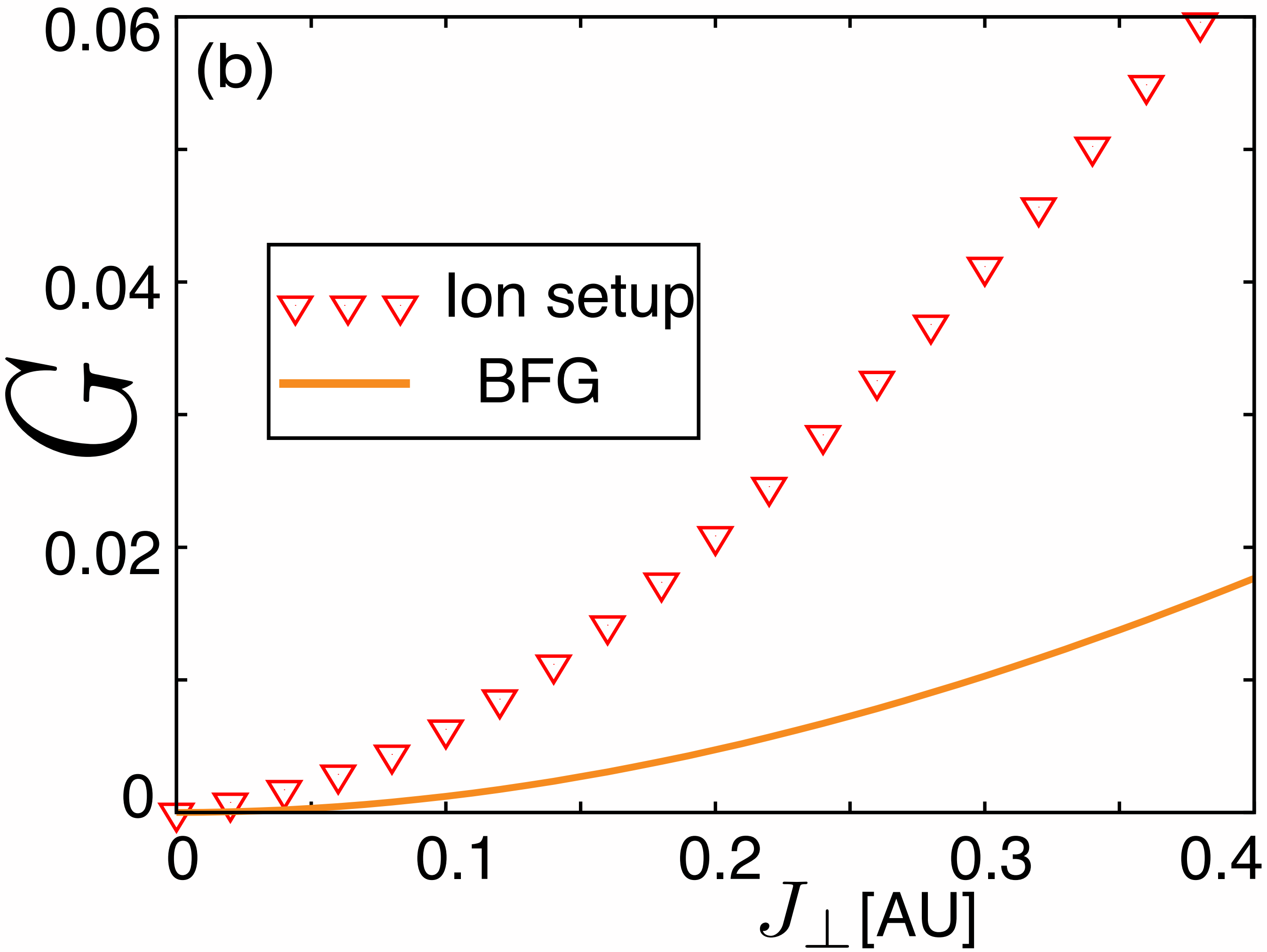
Ring-exchange

Interesting inter-plaquette dynamics

Double plaquette in a 19-ion crystal

(in preparation)

Gauss's law



- Sufficiently strong quantum fluctuations mix those levels

$$G = \frac{1}{N_{\hexagon}} \left\langle \sum_{\hexagon} \left(\sum_{i \in \hexagon} S_z^i \right)^2 \right\rangle$$

- G gives us the measure of states outside the ground state manifold

Double plaquette in a 19-ion crystal

Some trivial dynamics

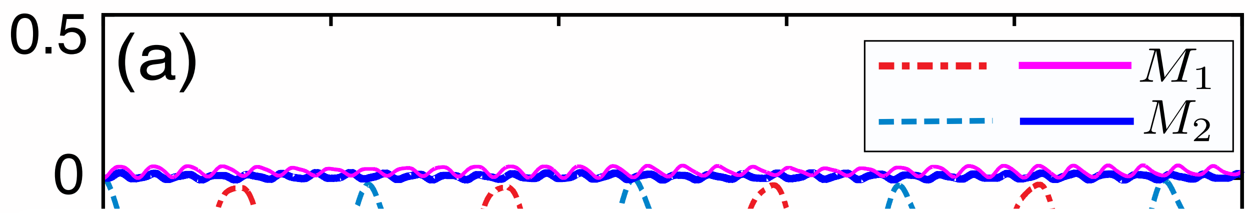
$$M_1 = \sum_{i \in \hexagon^1} S_z^i$$
$$M_2 = \sum_{i \in \hexagon^2} S_z^i$$

PRB, **65**, 224412 (2002).

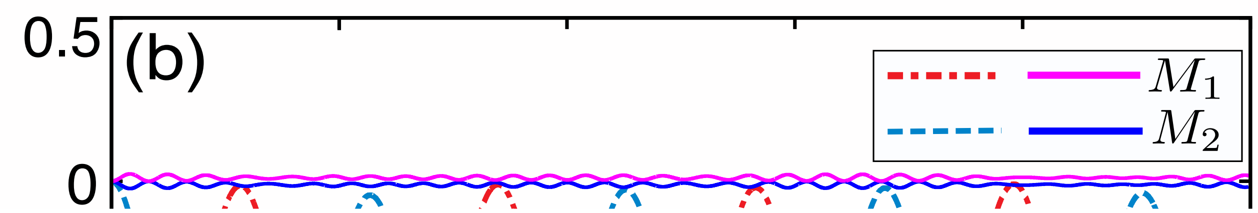
Hamiltonian

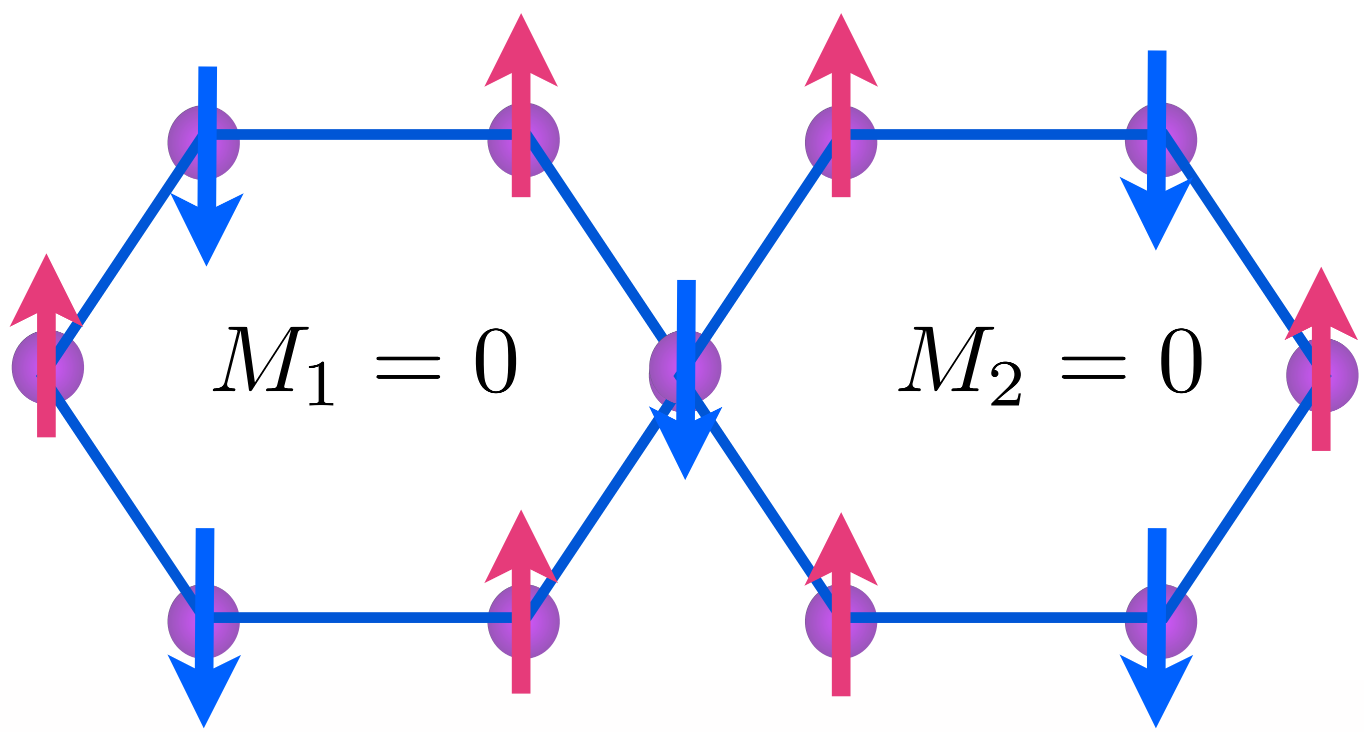
$$H_{\hexagon}^{BFG} = J_z \left(\sum_{i \in \hexagon} S_i^z \right)^2 + J_\perp \sum_{<ij> \in \hexagon} (S_i^+ S_j^- + h.c.)$$

BFG model (Ideal case)



BFG model (ion setup)





Double plaquette in a 19-ion crystal

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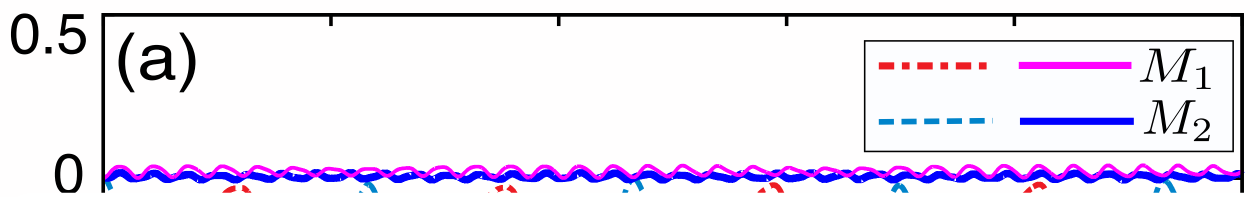

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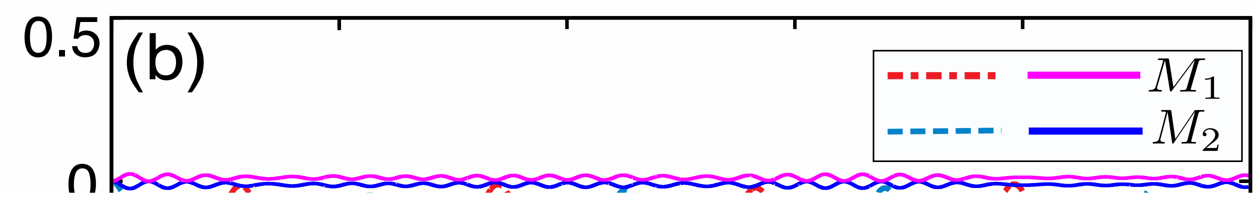

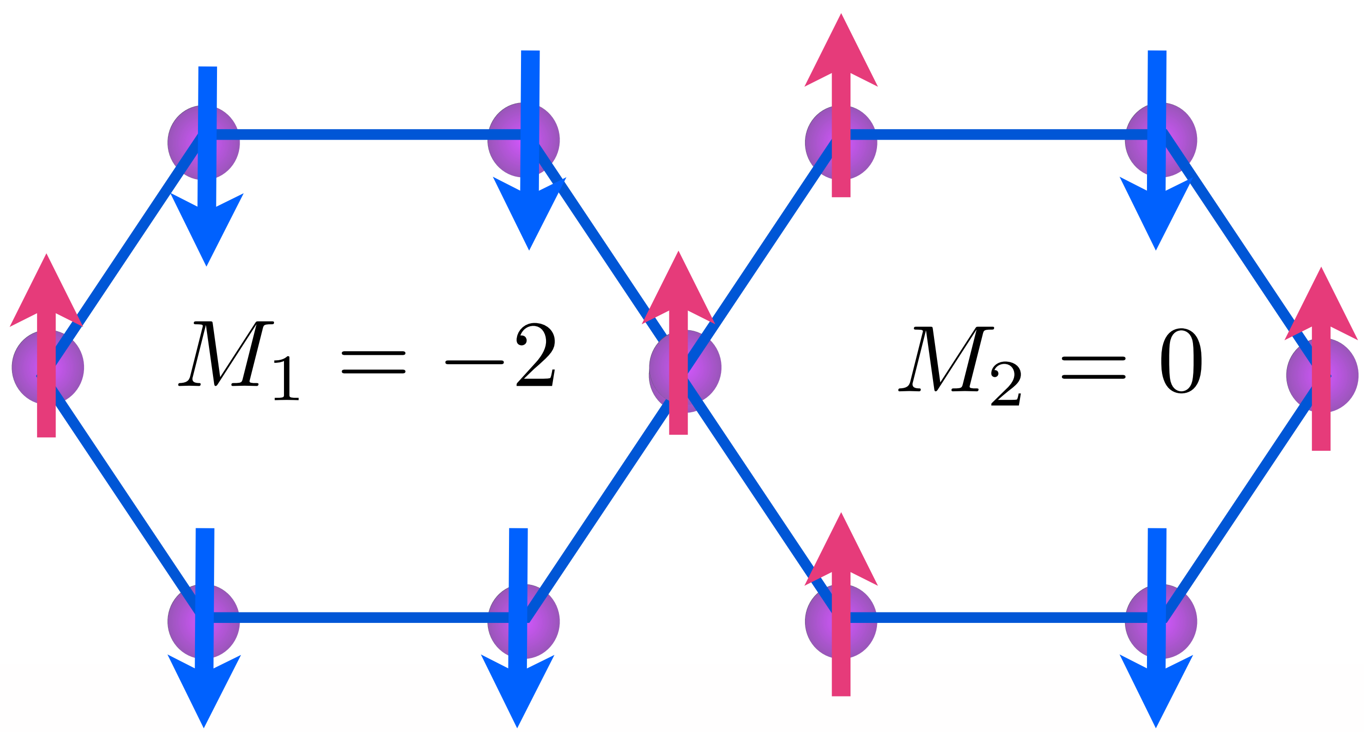

Double plaquette in a 19-ion crystal

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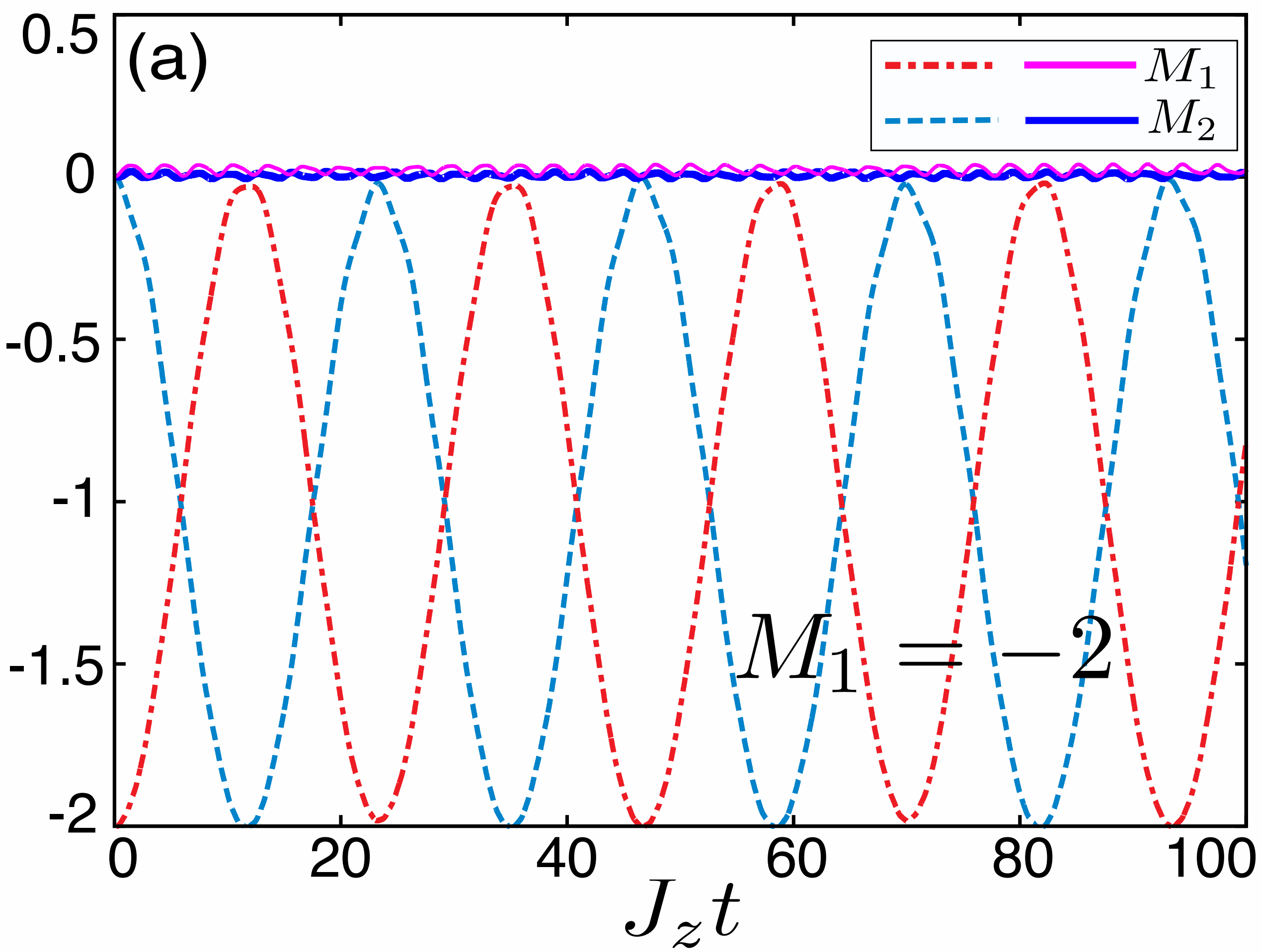
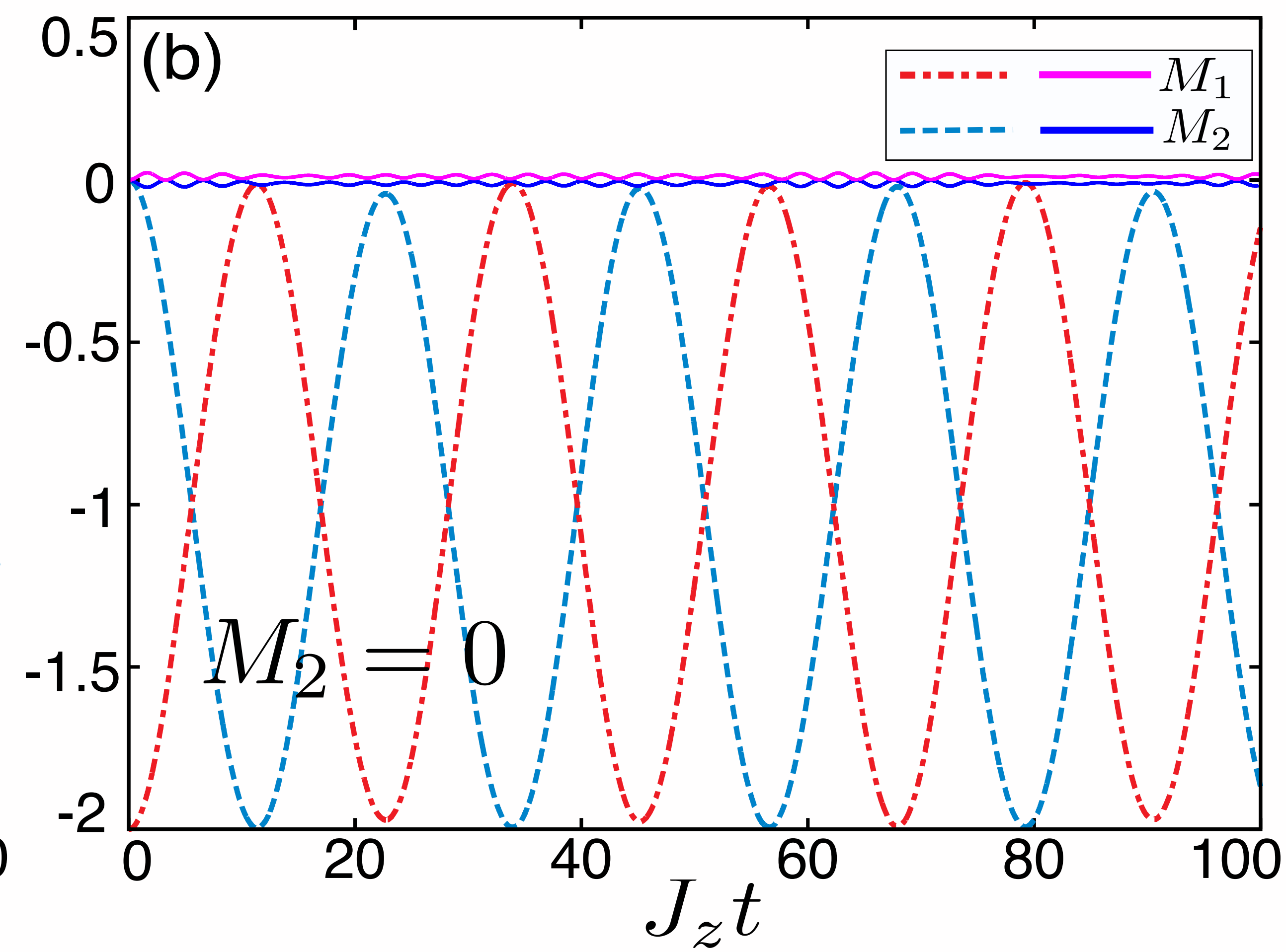
BFG model (Ideal case)



BFG model (ion setup)



Charge oscillates between the two plaquettes

Double plaquette in a 19-ion crystal

Some trivial dynamics

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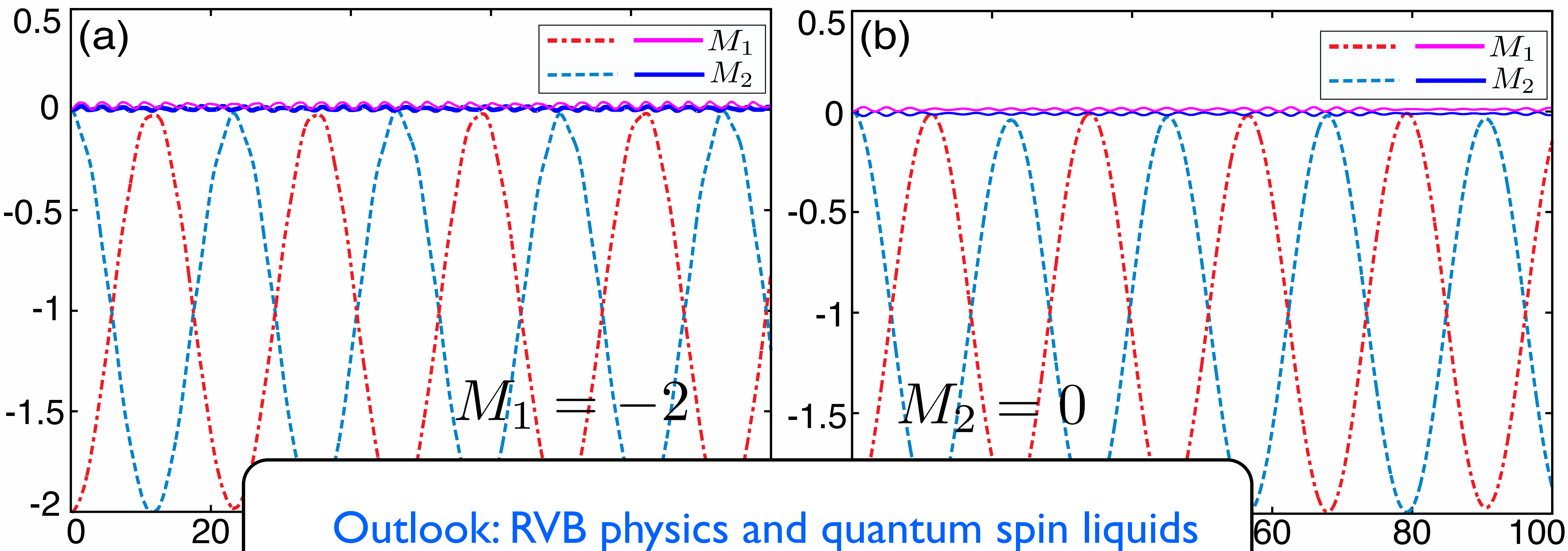
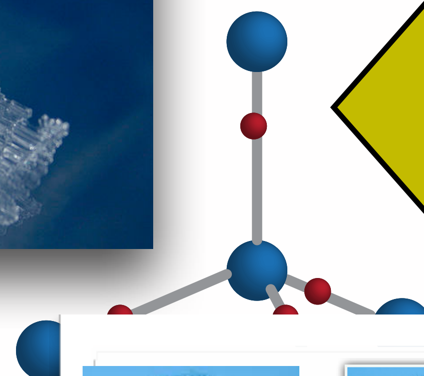
BFG model (Ideal case) BFG model (ion setup)

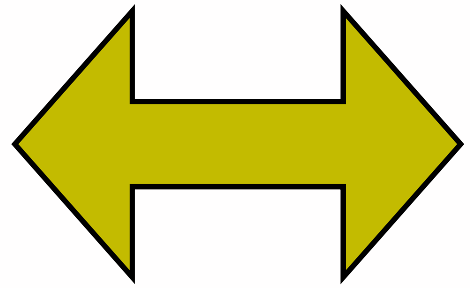


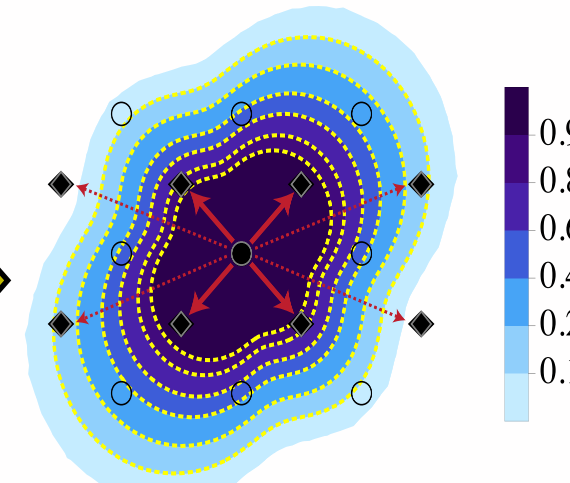
Outlook: RVB physics and quantum spin liquids

tes

Spin Ice





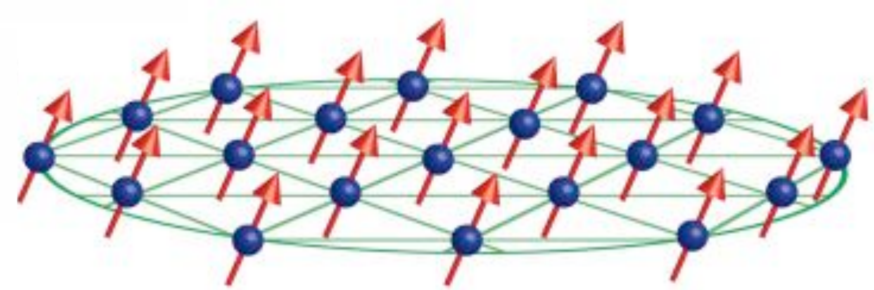


PRX **4** 041037 (2014)

A Glätzle M Dalmonte I. Rousochatzakis R Mössner P Zoller

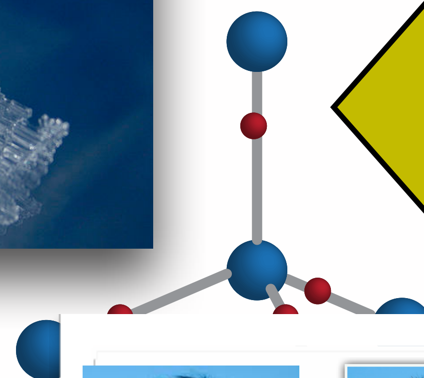
Ion Crystal

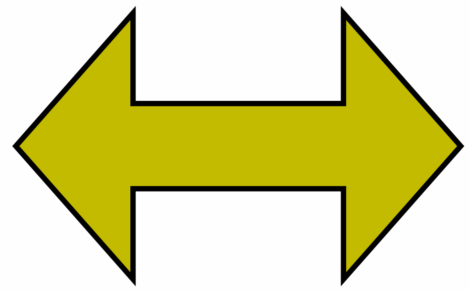
Mode shapping,
Spin Models
in a
2D Ion Crystal

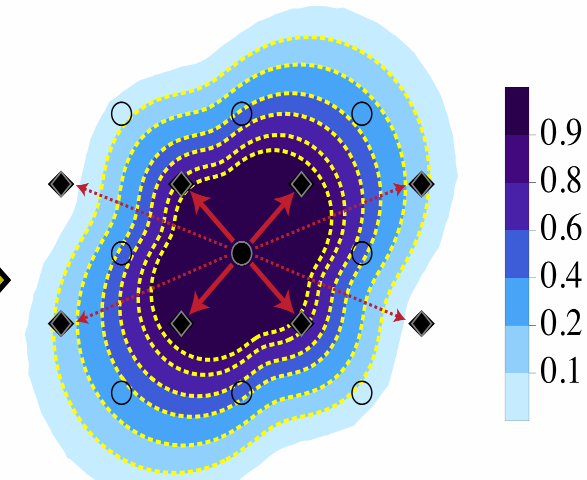


(in preparation)

Spin Ice







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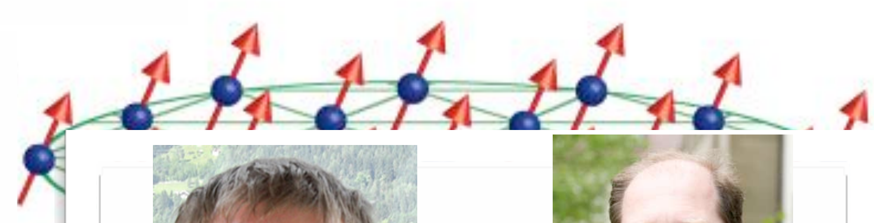
A Glätzle | M Dalmonte | I. Rousochatzakis | R Mössner | P Zoller

Ion Crystal

Mode shapping,
Spin Models
in a
2D Ion Crystal



R. Gerritsma | Schmidt Kaler

(in preparation)