Designing Light in an Artificial Universe

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Nat. Phys. 14, 711–715 (2018) R Sibille, N Gauthier, **HY** *et al*

npj Quantum Materials 7 (1), 51 A Bhardwaj, S Zhang, **HY** *et al*

PRB 106 (9), 094425, B Gao, T Chen, **HY** *et al*

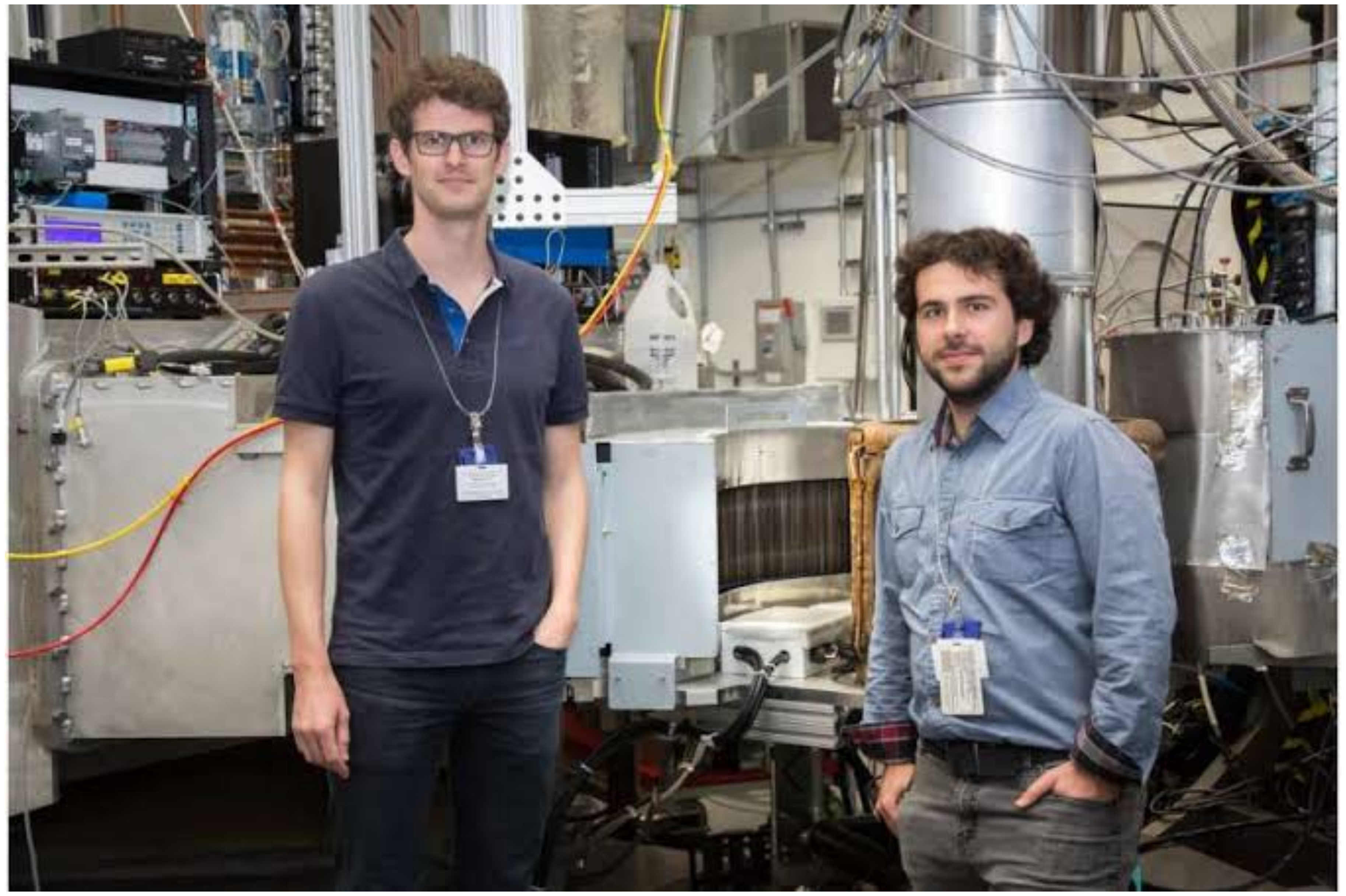
Nat. Phys. 21, 83-88 (2025) V Porée, **HY** *et al*

arXiv:2312.11641 A Sanders, **HY**, C Castelnovo, AH Nevidomskyy

arXiv:2402.08723, arXiv:2305.08261

Quantum Geometry and Transport of Collective Excitations in (Non-)Magnetic Insulators

Ingelheim, May 7 2025



Romain Sibille Nicolas Gauthier
Paul Scherrer Institute

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Rice

Pengcheng Dai
Rice

Andriy Nevidomskyy
Rice

Victor Porée
Paul Scherrer Institute

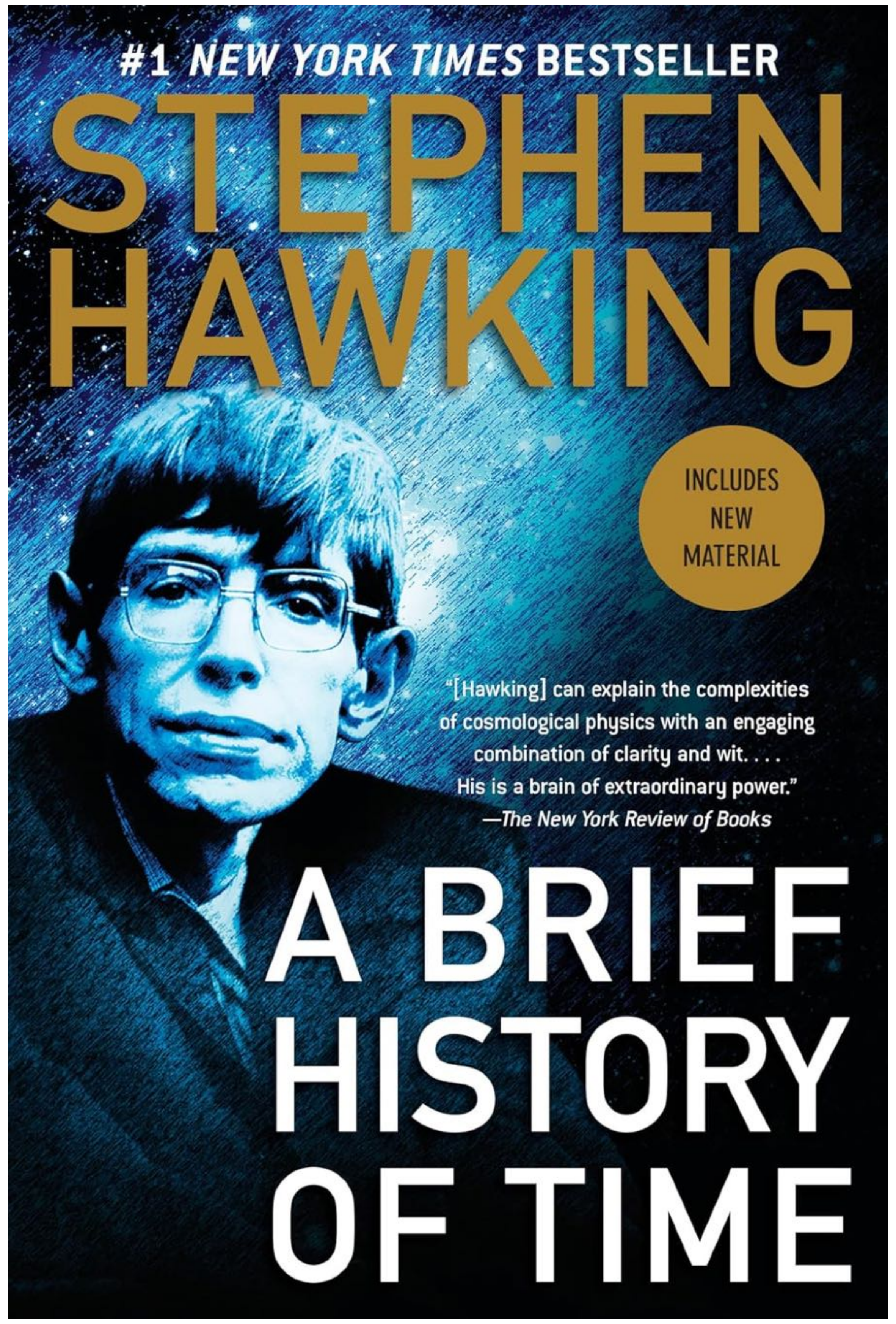
Alaric Sanders
Cambridge

Claudio Castelnovo
Cambridge

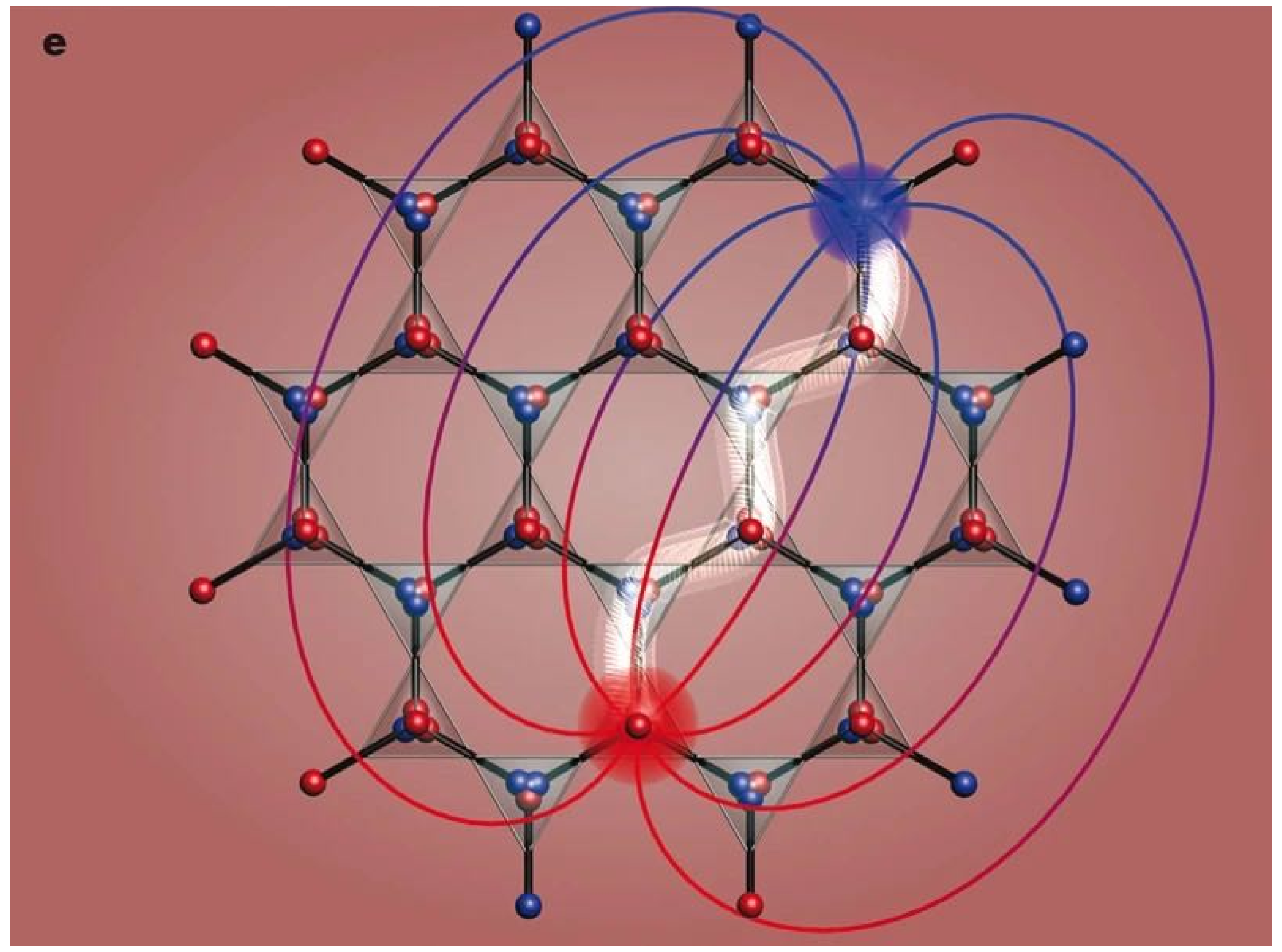
What if we can change the law of nature?

The laws of science, as we know them at present, contain **many fundamental numbers**, like the size of the electric charge of the electron and the ratio of the masses of the proton and the electron. ... The remarkable fact is that **the values of these numbers seem to have been very finely adjusted** to make possible the development of life.

A Brief History of Time, Stephen Hawking



Quantum Spin Ice: A universe in a grain of sand



Effective theory: **3D U(1) Quantum Electrodynamics (QED)**

1. Ground state: gapless topological quantum liquid state
2. Gapless excitations: **photons**
3. Gapped excitations: electric **charges** and magnetic **monopoles**

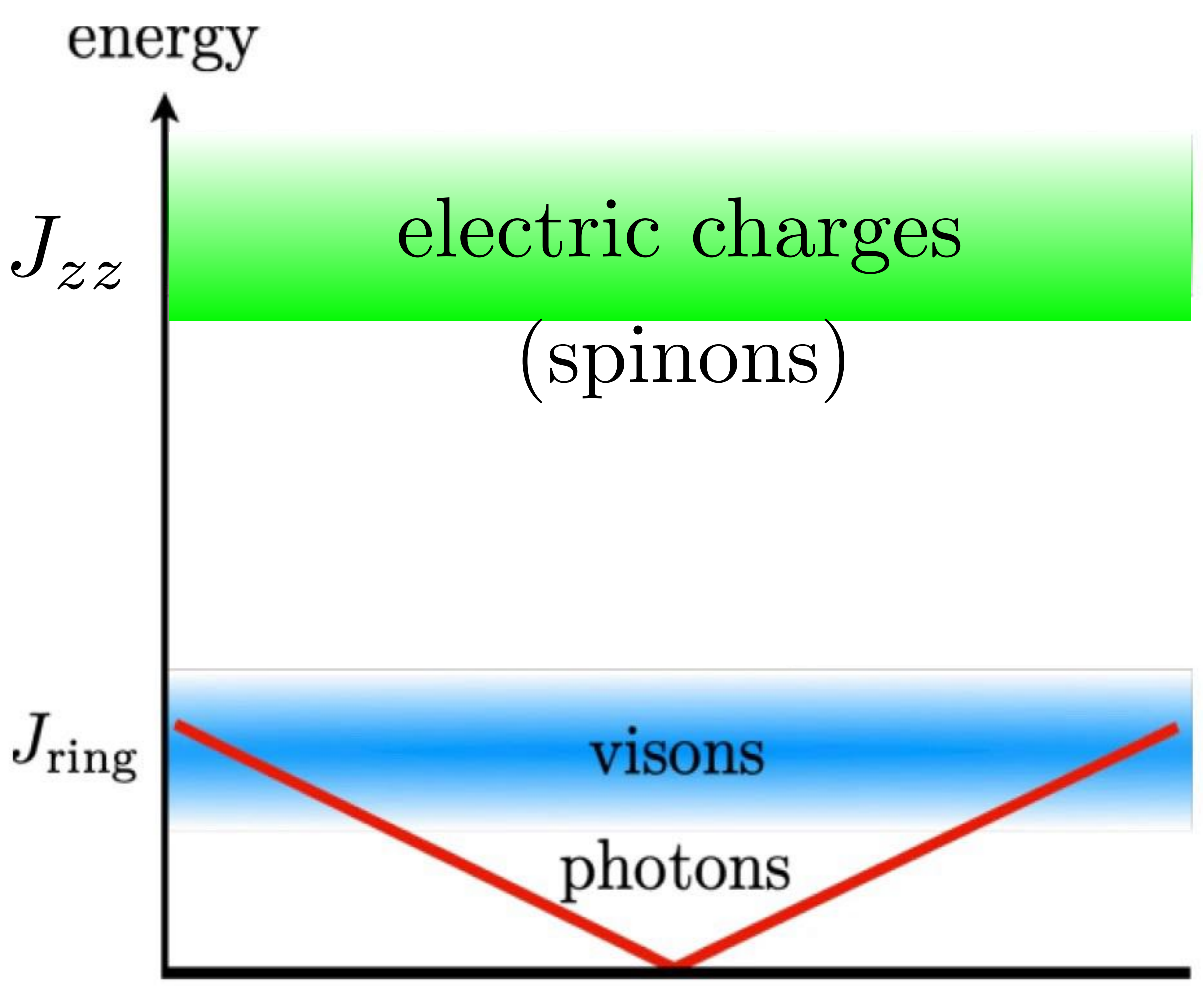
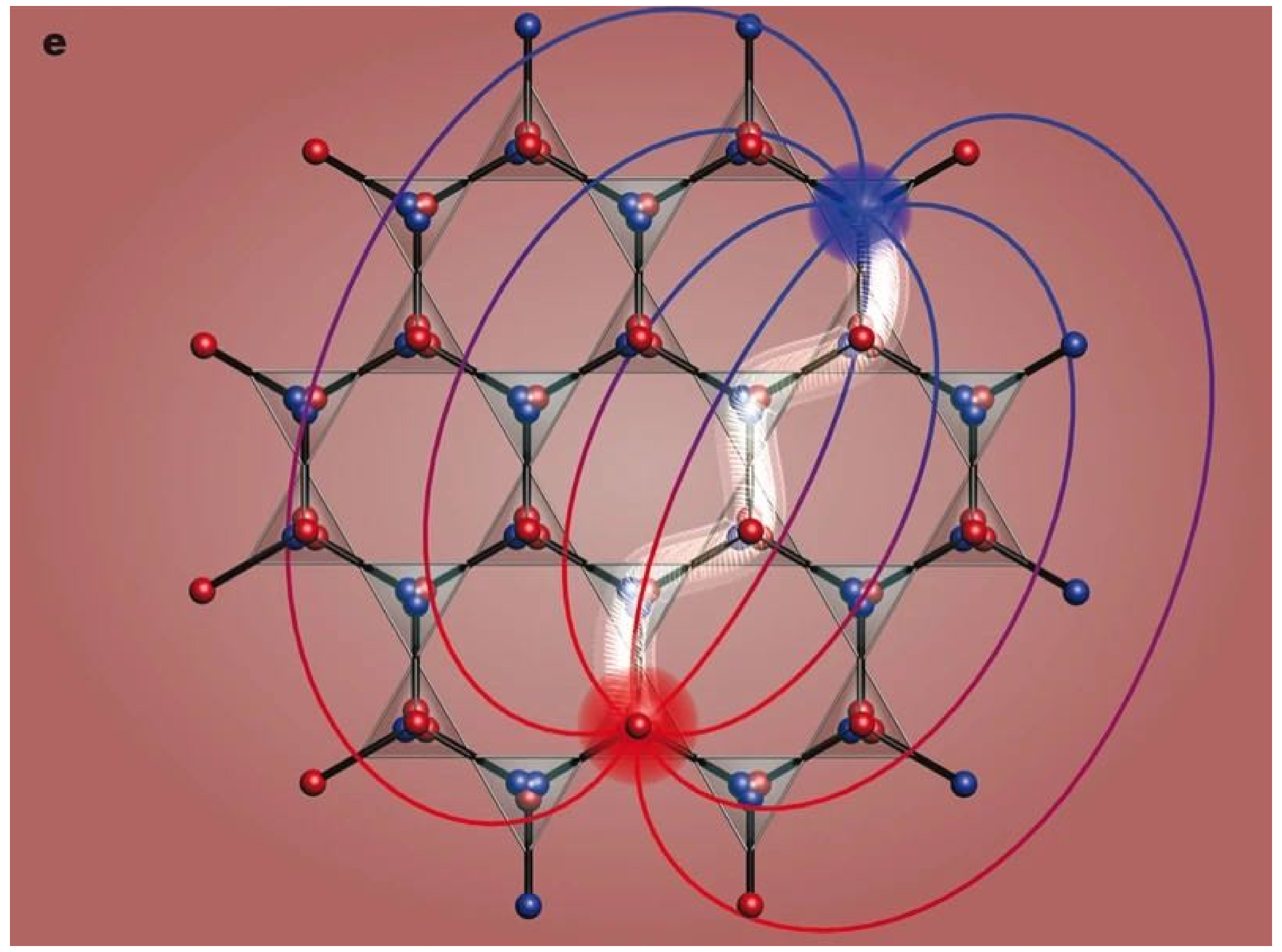


figure credit: Nature 451, 42–45 (2008)

Quantum Spin Ice: A universe in a grain of sand



Effective theory: **3D U(1) Quantum Electrodynamics (QED)**

1. Ground state: gapless topological quantum liquid state
2. Gapless excitations: **photons**
3. Gapped excitations: electric **charges** and magnetic **monopoles**

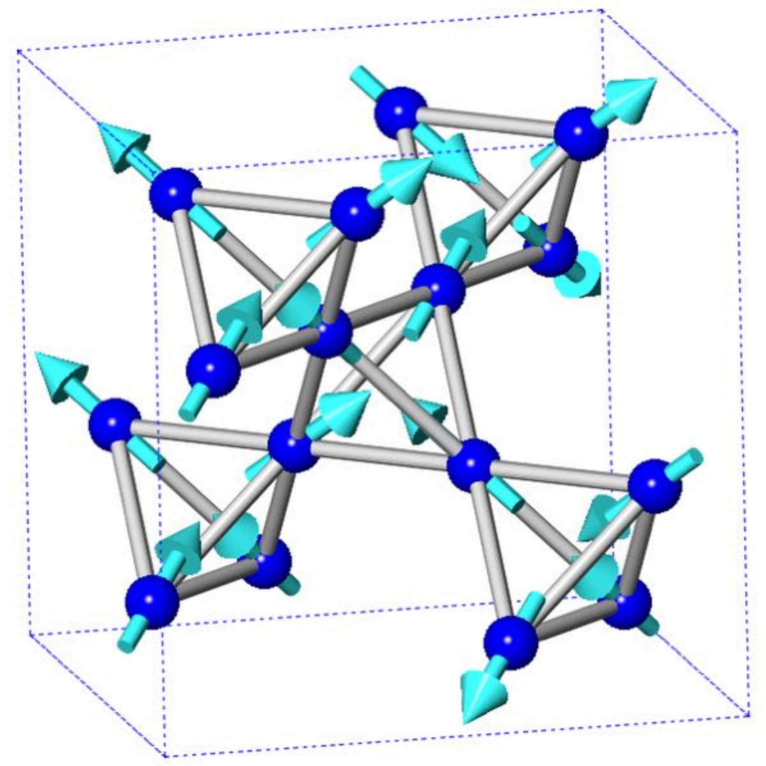
Our result: proposal to **experimentally tune the quantum dynamics** of lattice QED of dipolar-octupolar quantum spin ice

1. New lattice QED **phases** and **phase transitions**.
2. Photon dynamics: tune the emergent **speed of light**, **birefringence**, **non-linear photon coupling.**

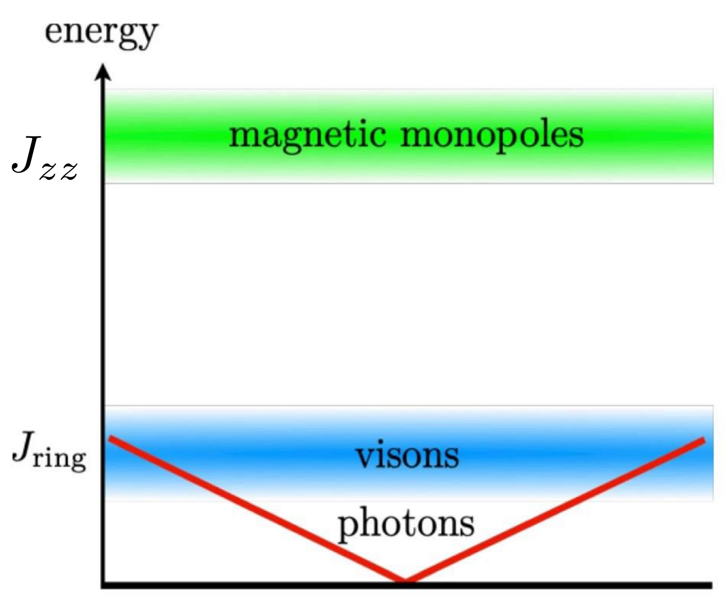
figure credit: Nature 451, 42–45 (2008)

Outline

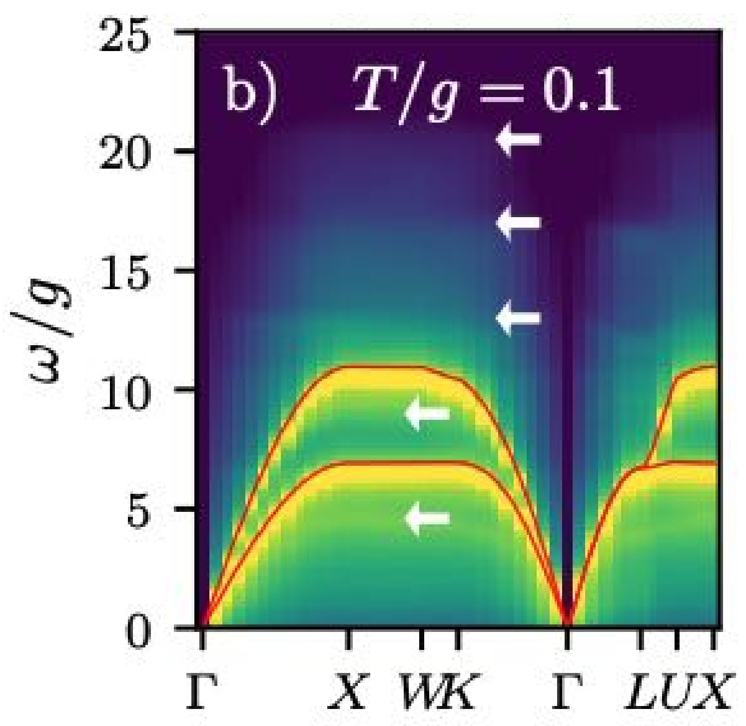
1. Classical spin ice as electrostatics



2. Quantum spin ice as emergent Quantum Electrodynamics (eQED)

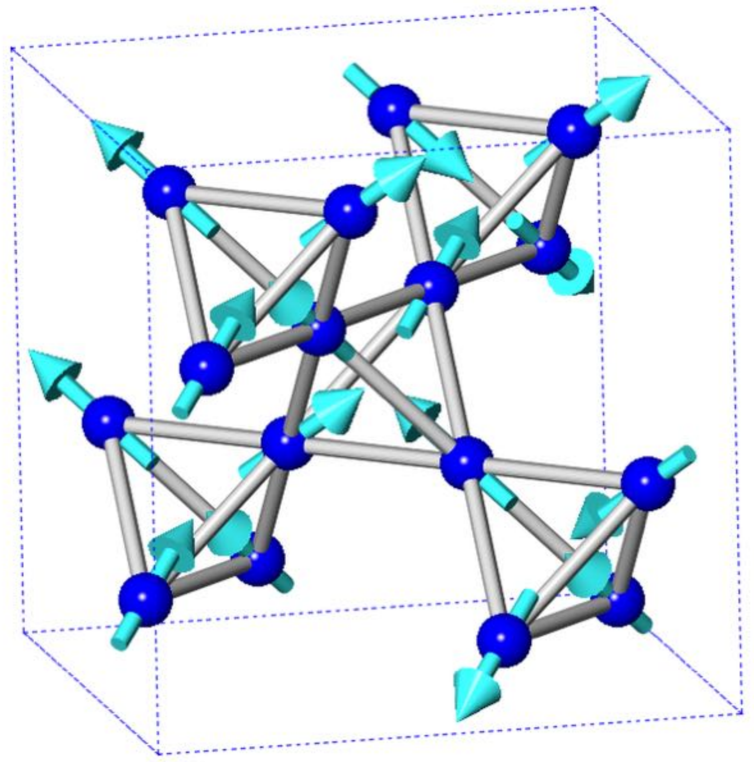


3. Controlling eQED dynamics in dipolar-octupolar quantum spin ice



Classical Spin Ice

Classical Spin Ice
on the pyrochlore lattice



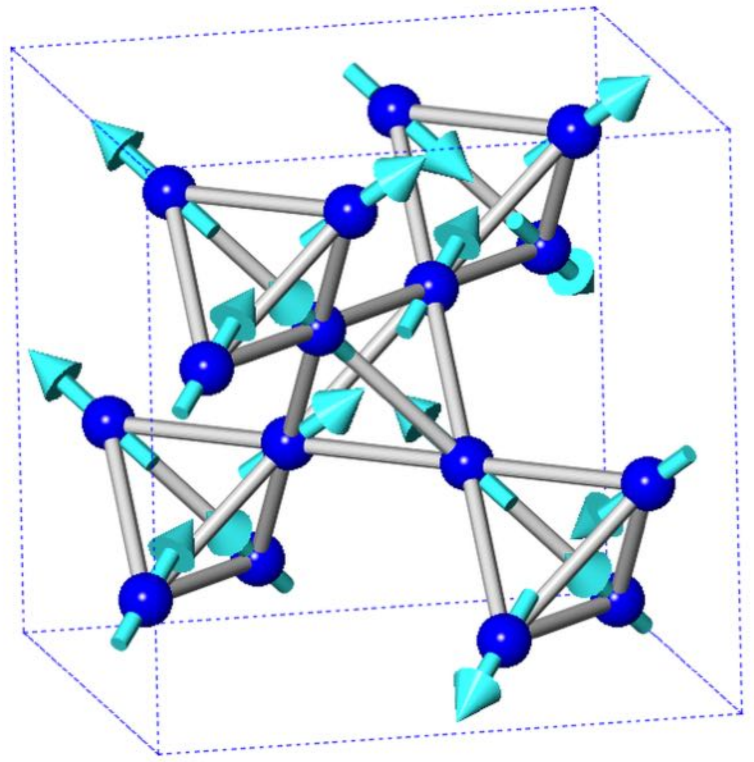
$$\mathcal{H} = \sum_{ij} S_i^z S_j^z$$

$\boldsymbol{z}$ is local basis of in/out tetrahedron

M. Hermele, M. P. A. Fisher, and L. Balents, Phys. Rev. B 69, 064404 (2004)

Classical Spin Ice

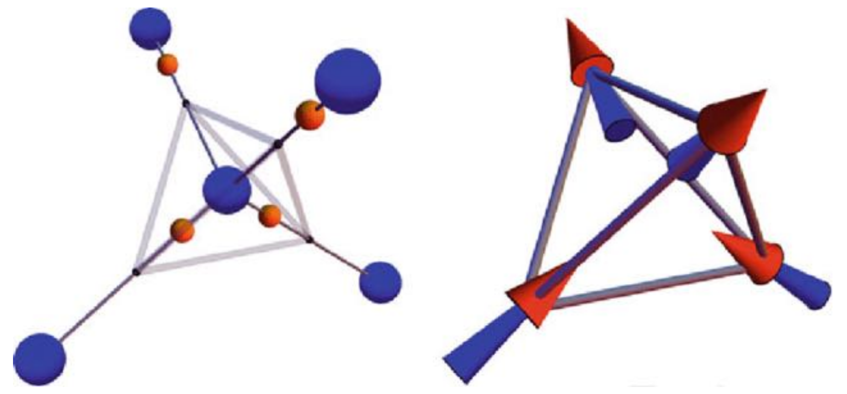
Classical Spin Ice
on the pyrochlore lattice

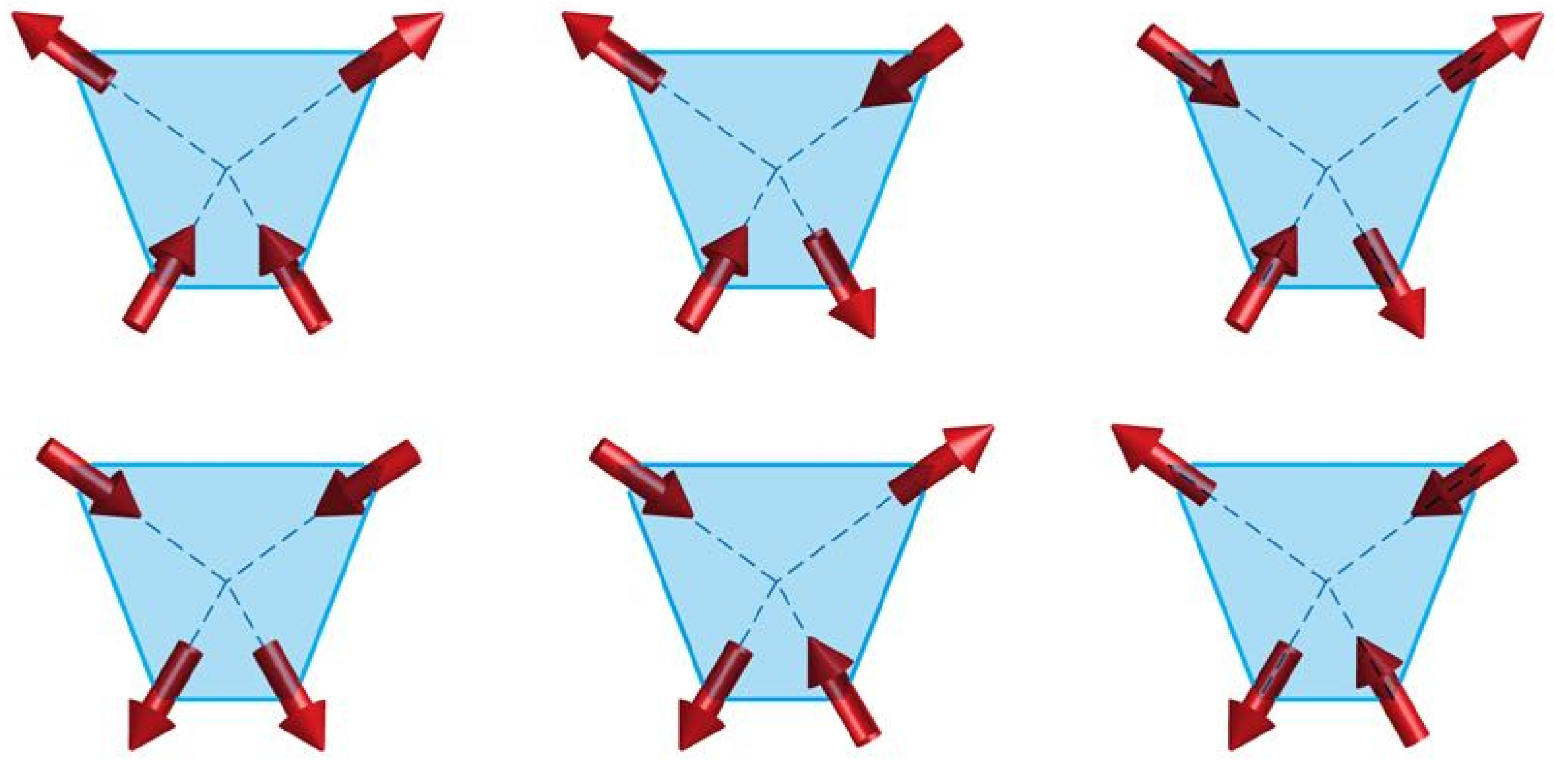


$$\mathcal{H} = \sum_{ij} S_i^z S_j^z$$

$\boldsymbol{z}$ is local basis of in/out tetrahedron

single tetrahedron
ground state:
2-in-2-out (**ice-rule**)



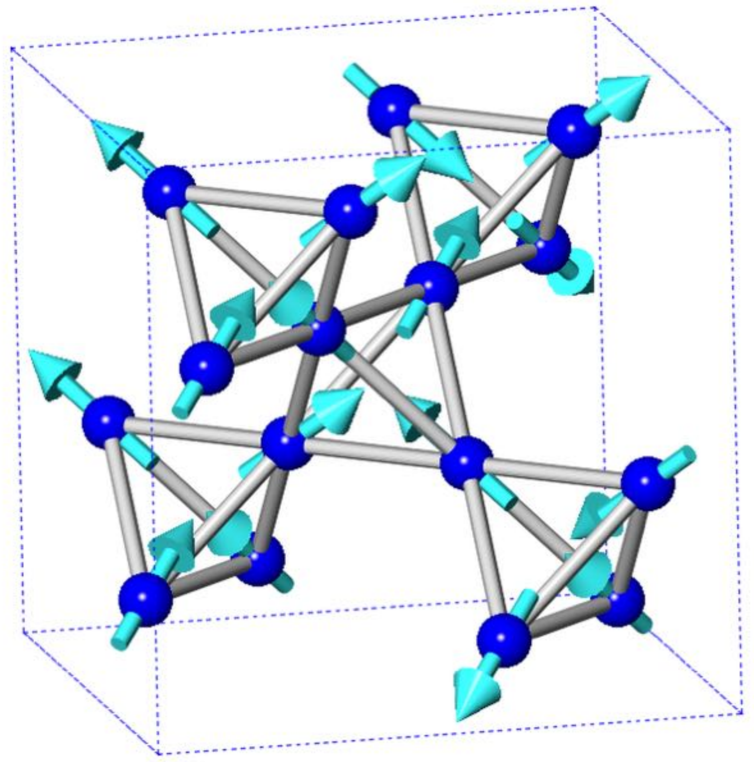


similar hydrogen
arrangement in ice

$$\nabla \cdot \boldsymbol{E} = 0$$

Classical Spin Ice

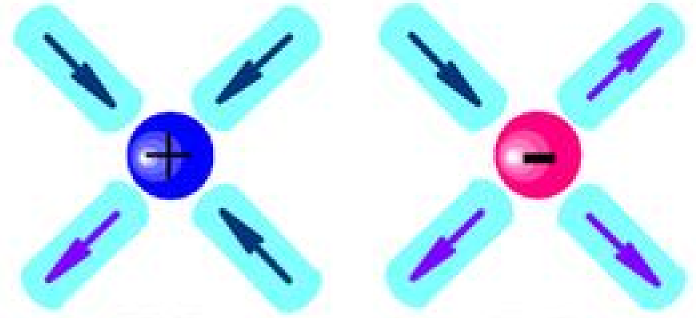
Classical Spin Ice
on the pyrochlore lattice



$$\mathcal{H} = \sum_{ij} S_i^z S_j^z$$

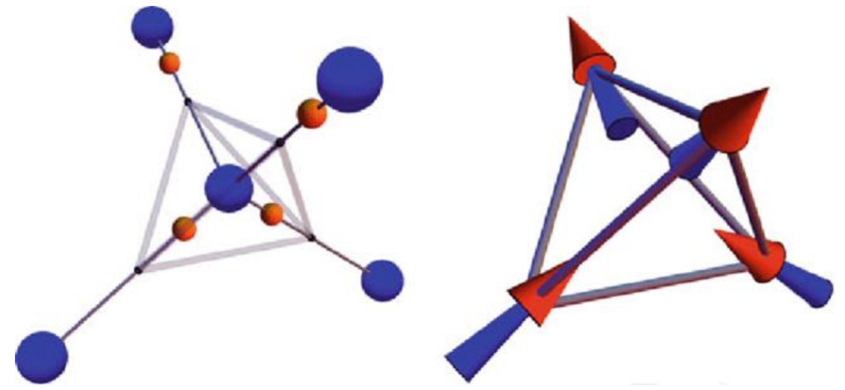
$\boldsymbol{z}$ is local basis of in/out tetrahedron

single tetrahedron
excited state:
3-in-1-out / 3-out-1-in



$$\nabla \cdot \boldsymbol{E} = \pm 1$$

single tetrahedron
ground state:
2-in-2-out (**ice-rule**)



similar hydrogen
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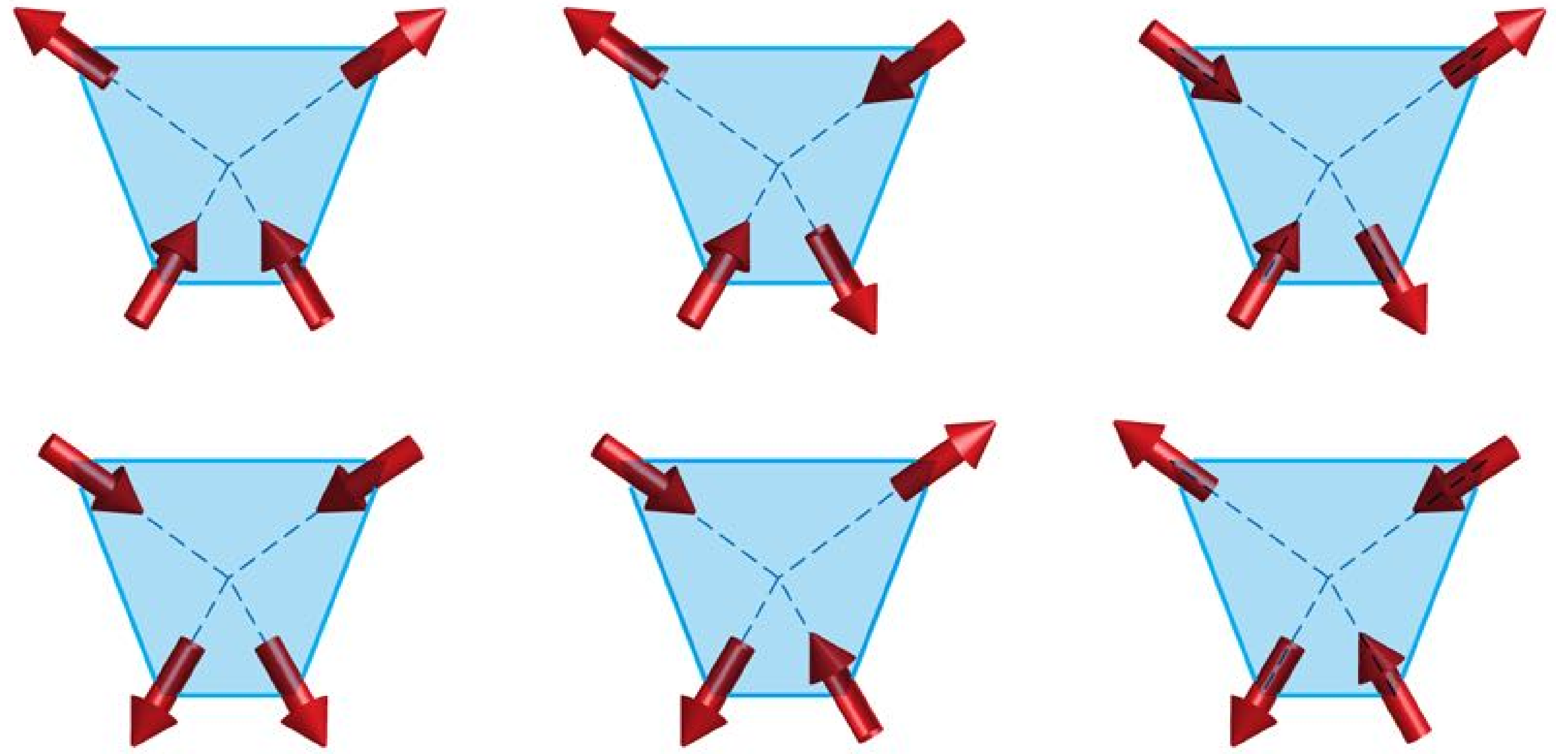
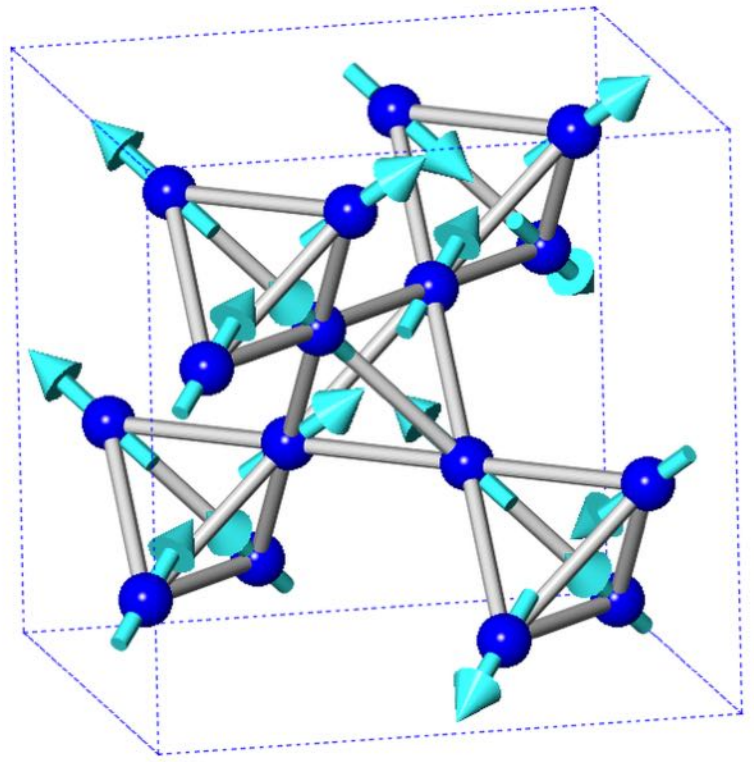


$$\nabla \cdot \boldsymbol{E} = 0$$

Classical Spin Ice

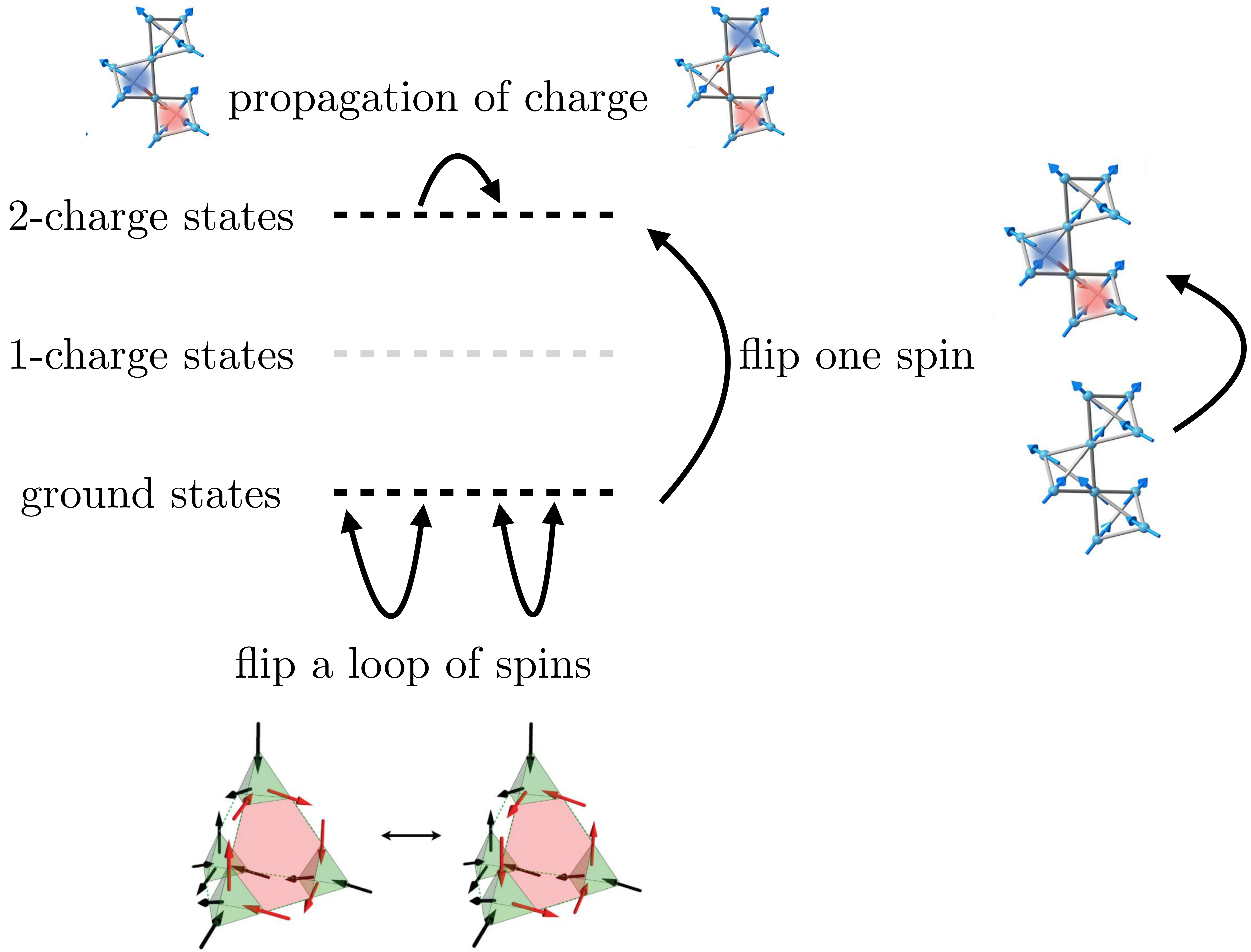
Classical Spin Ice



$$\mathcal{H} = \sum_{ij} S_i^z S_j^z$$

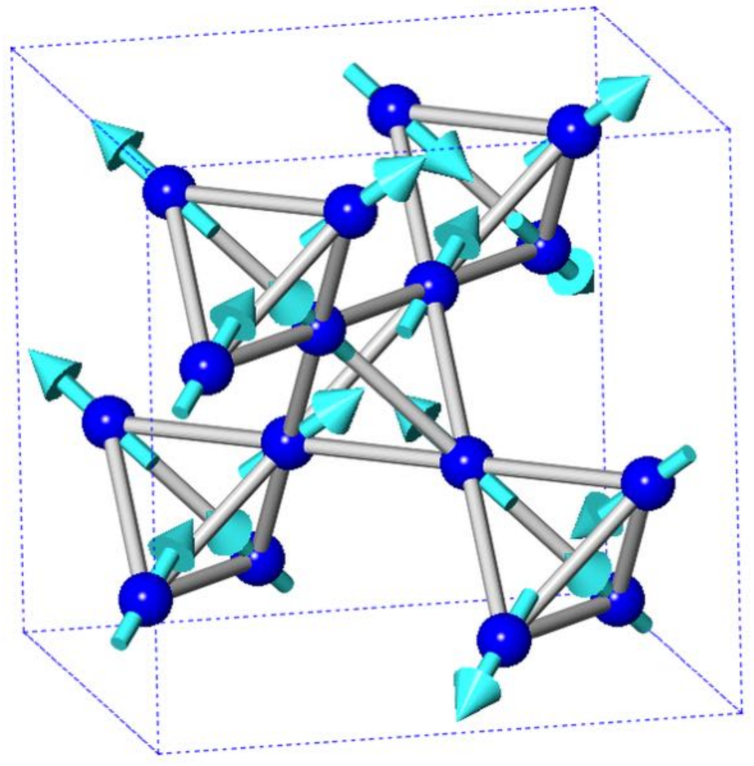
Ground state: 2-in-2-out

$$\nabla \cdot \boldsymbol{E} = 0$$



Classical Spin Ice

Classical Spin Ice



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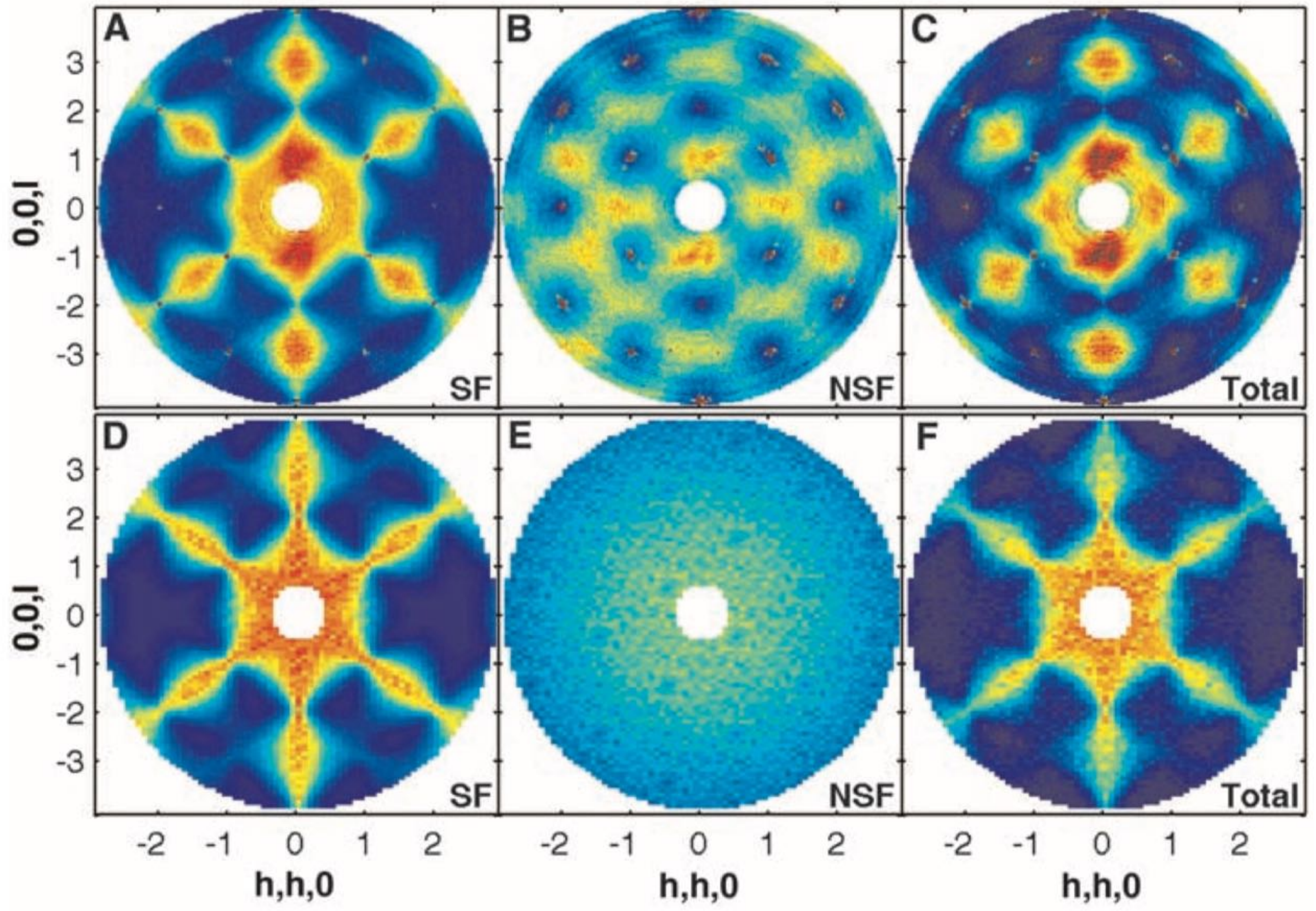


Magnetic Coulomb Phase in the Spin Ice $Ho_2Ti_2O_7$

T. Fennell,[1*] P. P. Deen,[1] A. R. Wildes,[1] K. Schmalzl,[2] D. Prabhakaran,[3] A. T. Boothroyd,[3] R. J. Aldus,[4] D. F. McMorrow,[4] S. T. Bramwell[4]

Holmium Titanium

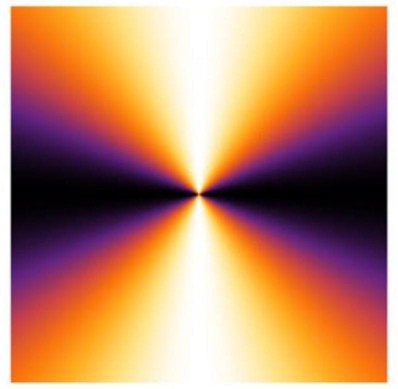
Science ***326***, *415 (2009)*

neutron scattering measures spin-spin correlation in momentum space

$$\nabla \cdot \boldsymbol{E} = 0 \rightarrow \boldsymbol{q} \cdot \boldsymbol{E} = 0$$

$$\langle E_i(\boldsymbol{q}) E_j(-\boldsymbol{q}) \rangle \propto \delta_{ij} - q_i q_j / q^2$$

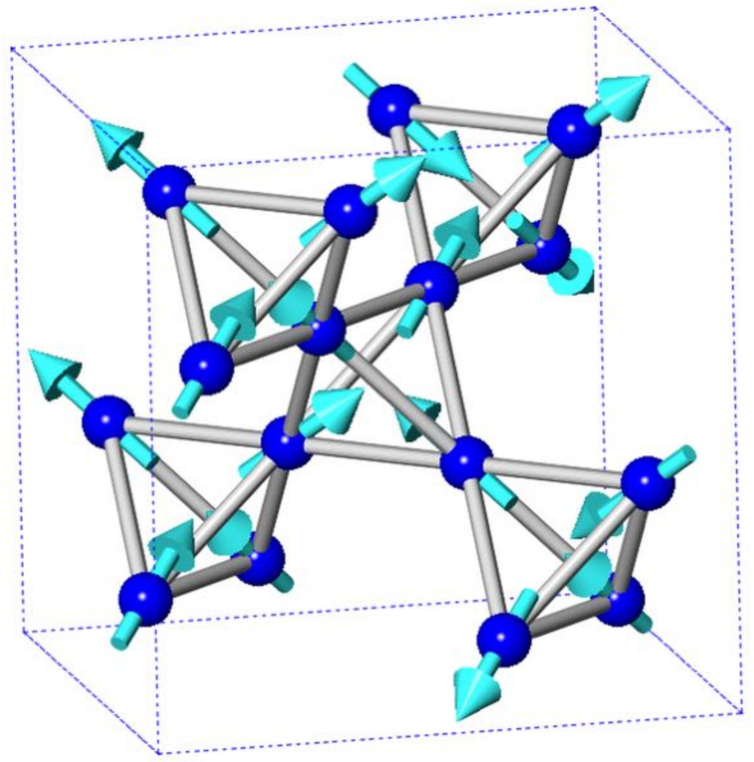
$$\langle E_x(\boldsymbol{q}) E_x(-\boldsymbol{q}) \rangle \sim q_y^2 / q^2$$



“pinch point”

Classical Spin Ice

Classical Spin Ice



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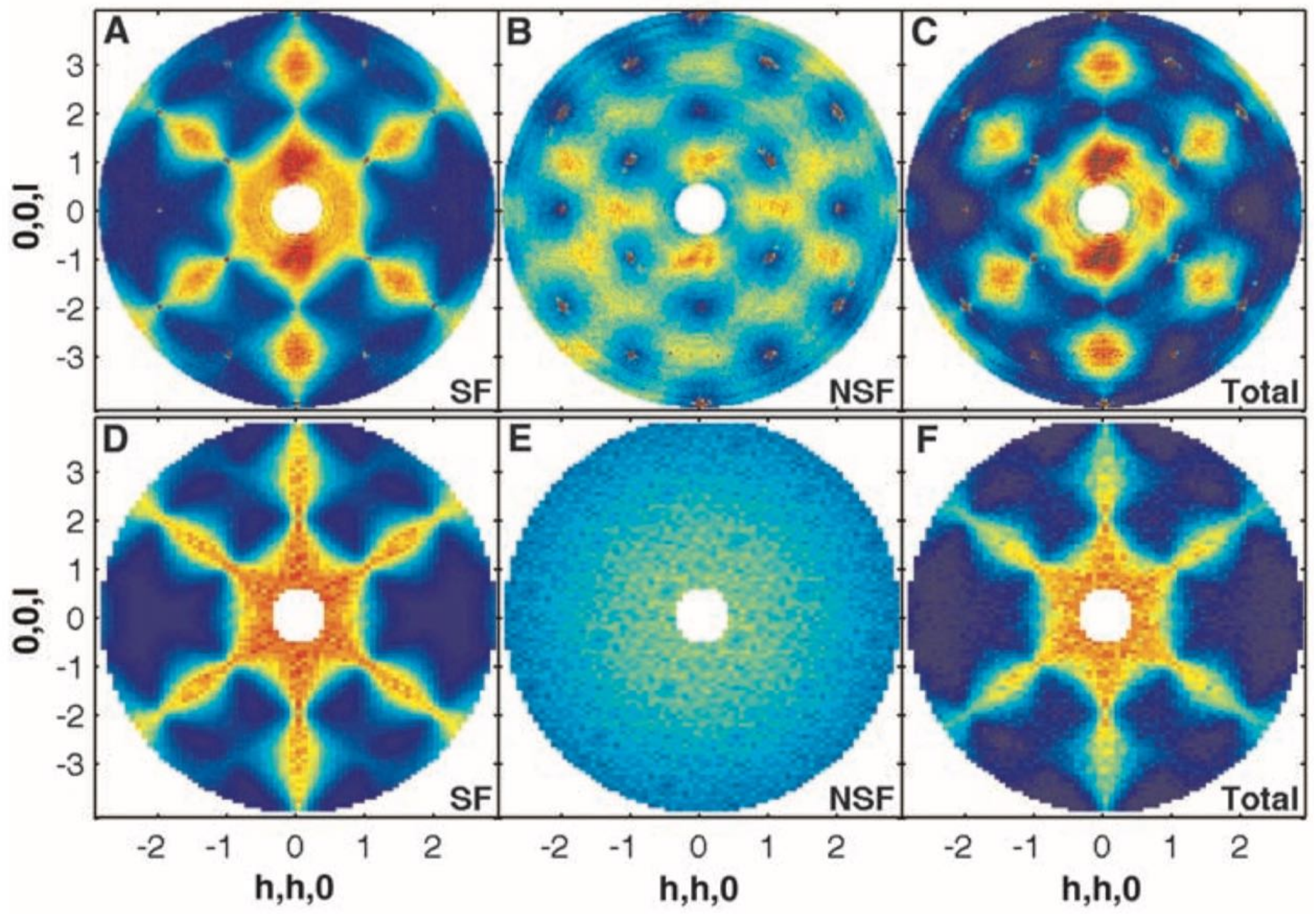

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Holmium Titanium

Science ***326***, *415 (2009)*

"artificial magnetic monopoles"

Outline

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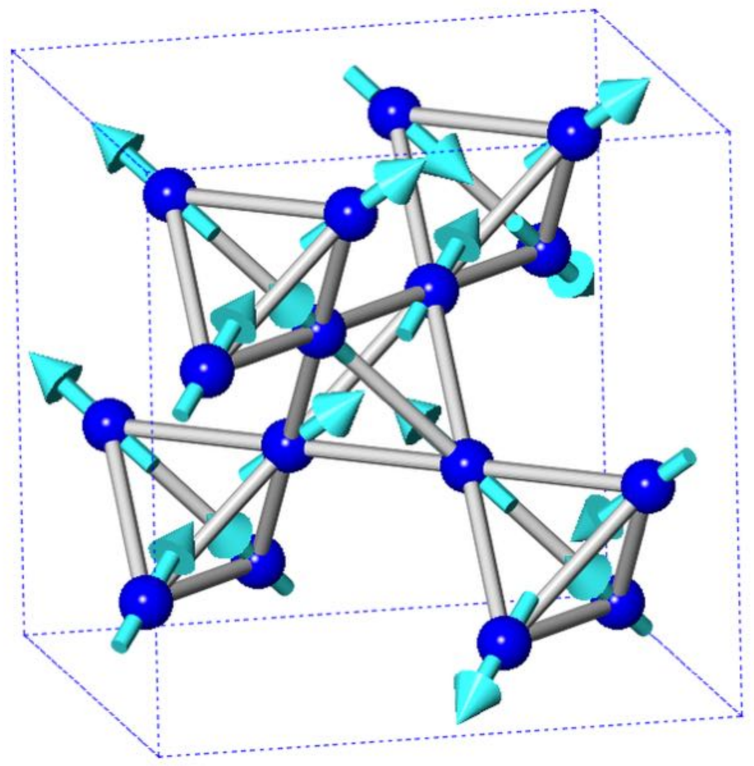

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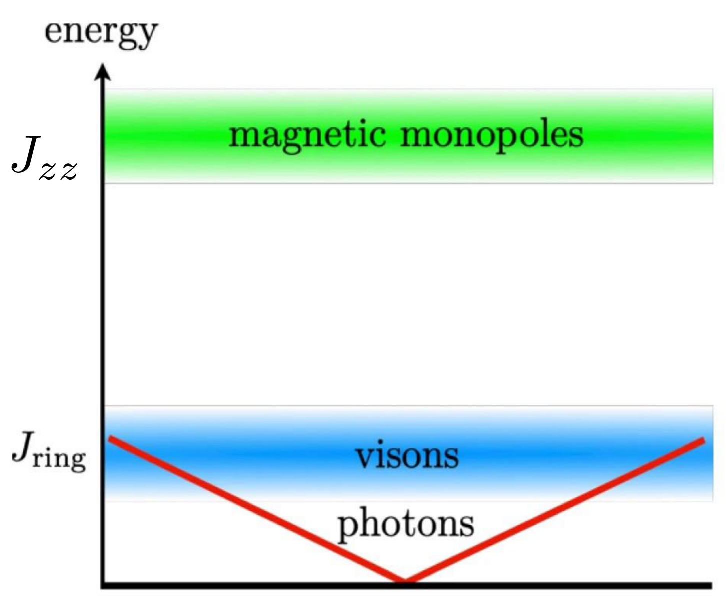

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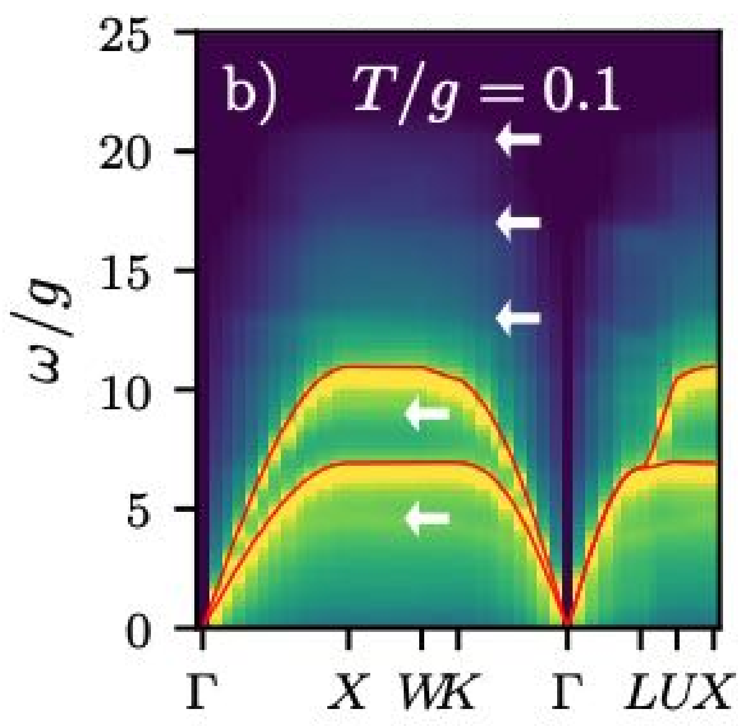
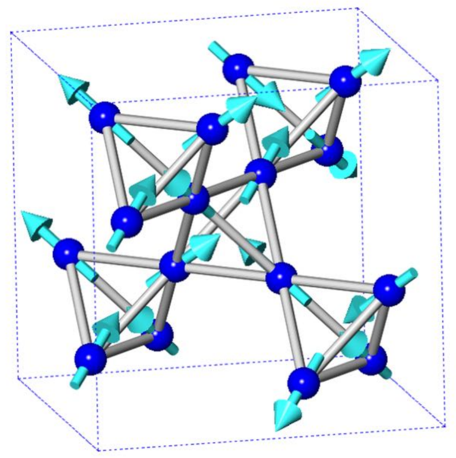


Emergent QED in Quantum Spin Ice

Classical Spin Ice



$$\mathcal{H} = \sum_{ij} S_i^z S_j^z$$

Ground state: 2-in-2-out $\nabla \cdot \boldsymbol{E} = 0$

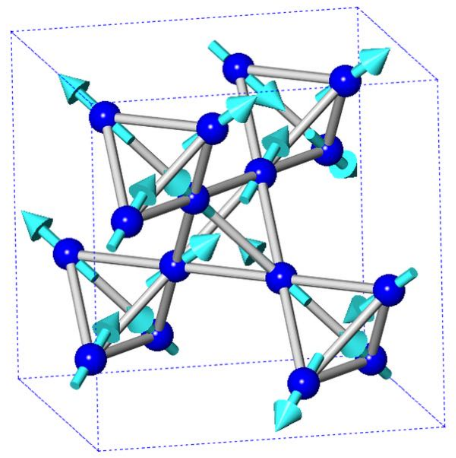
$$H = (\nabla \cdot \boldsymbol{E})^2 \text{ or } |\phi|^2$$

2 charge states

1 charge states

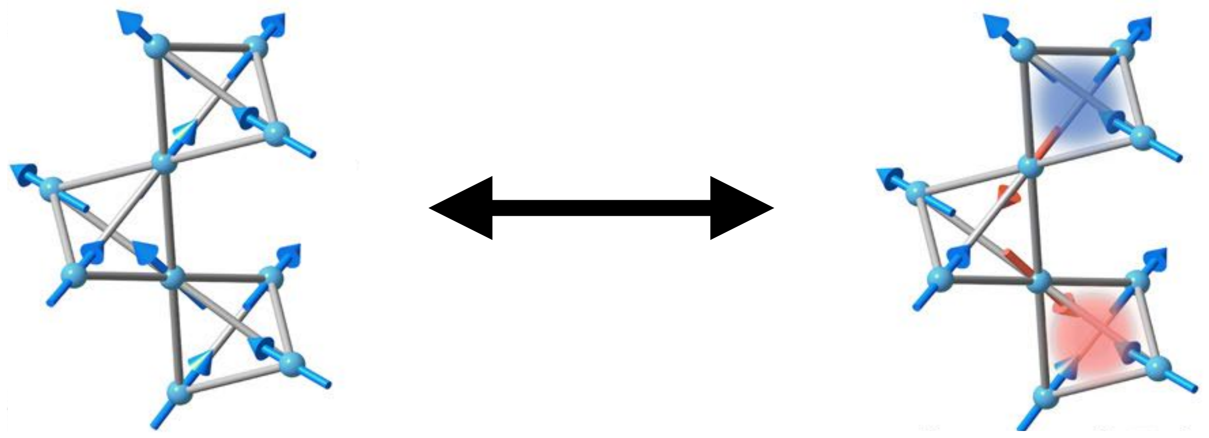
ground states

Quantum Spin Ice



quantum dynamics

$$H = \sum_{\langle ij \rangle} \{ J_{zz} S_i^z S_j^z - J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+)$$

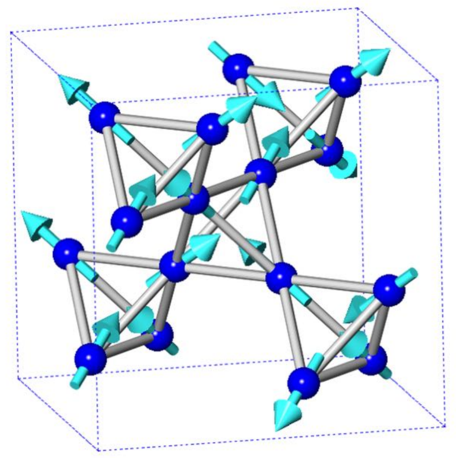


Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}} \phi_j^\dagger + \text{h.c.}$$

Emergent QED in Quantum Spin Ice

Classical Spin Ice



$$\mathcal{H} = \sum_{ij} S_i^z S_j^z$$

Ground state: 2-in-2-out $\nabla \cdot \boldsymbol{E} = 0$

$$H = (\nabla \cdot \boldsymbol{E})^2 \text{ or } |\phi|^2$$

2 charge states - - - - - - - - - - - -

1 charge states - - - - - - - - - - - -

ground states - - - - - - - - - - - -

Quantum Spin Ice

quantum dynamics

$$H = \sum_{\langle ij \rangle} \{ J_{zz} \mathsf{S}_i^z \mathsf{S}_j^z - J_\pm (\mathsf{S}_i^+ \mathsf{S}_j^- + \mathsf{S}_i^- \mathsf{S}_j^+)$$

Effective model (roughly speaking)

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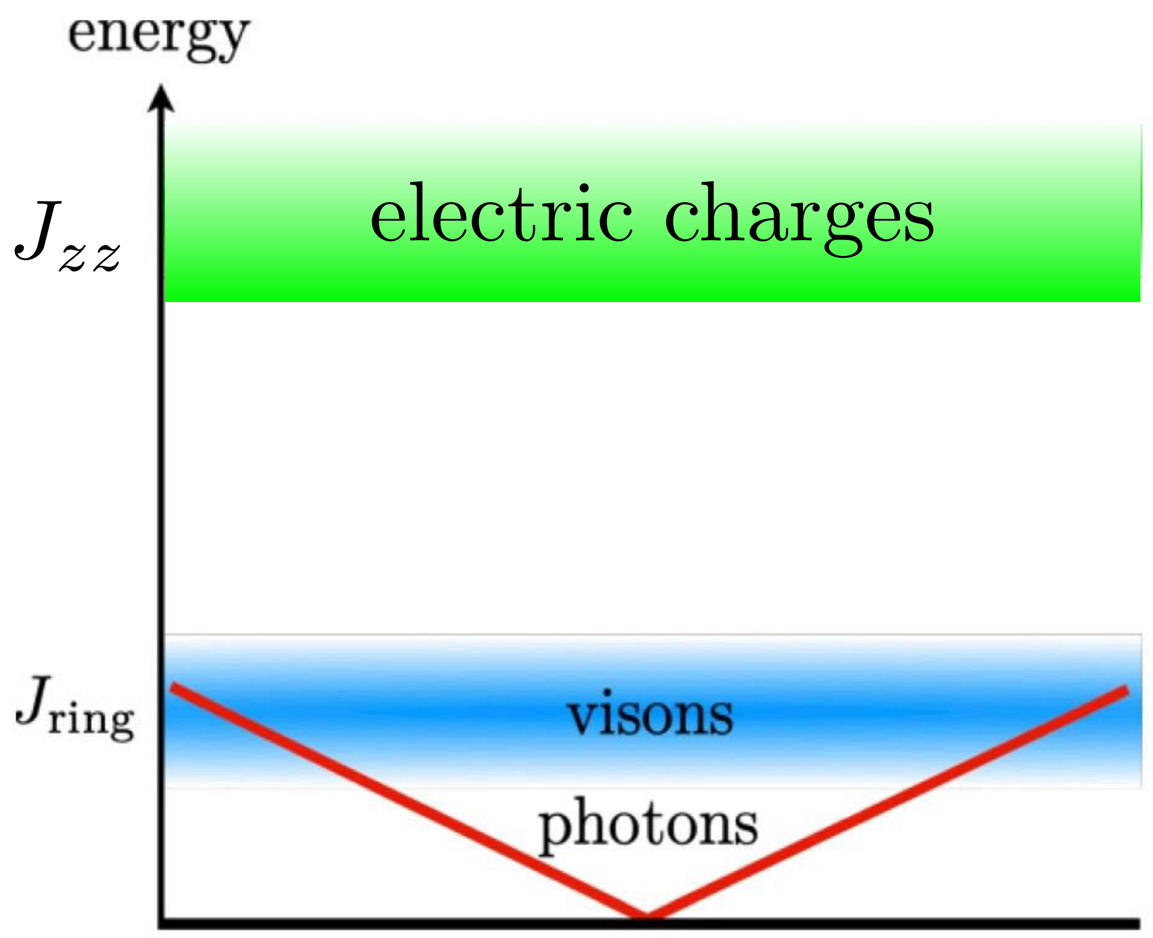
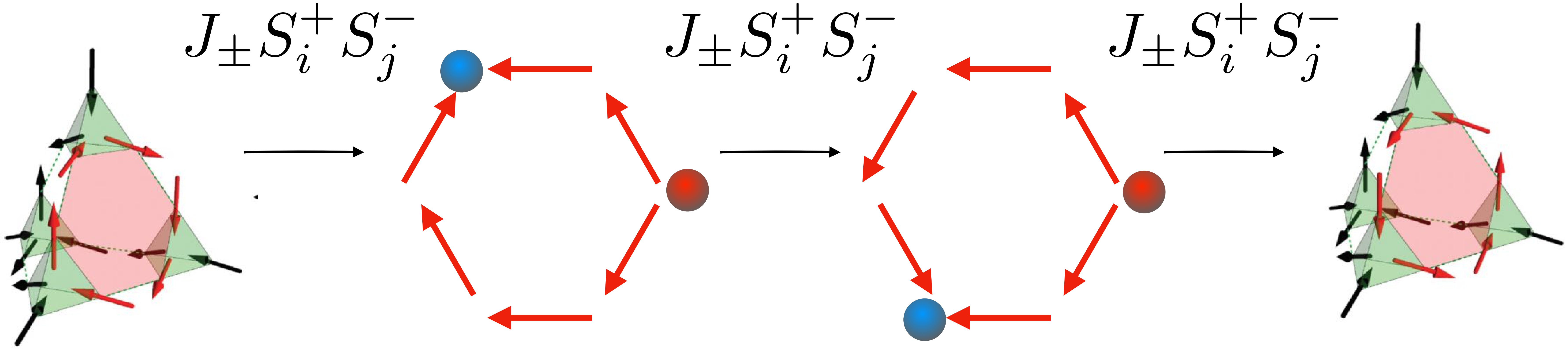


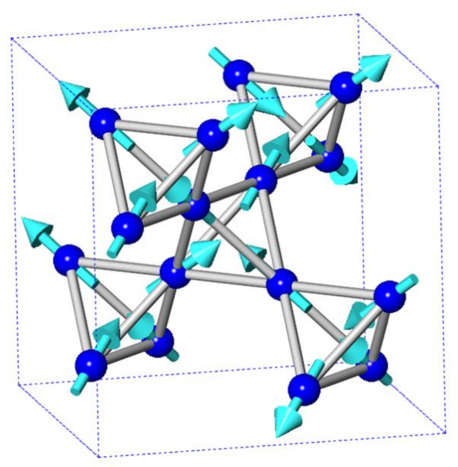
SungBin Lee, Shigeki Onoda, and Leon Balents Phys. Rev. B 86, 104412

Emergent QED in Quantum Spin Ice



$$J_{ring} \sum_{\hexagon} (S_1^+ S_2^- S_3^+ S_4^- S_5^+ S_6^- + \mathrm{H.c.}) \sim J_{\rm ring} \cos(b) \qquad J_{\rm ring} = 3J_\pm^3/(2J_{zz}^2)$$

Emergent QED in Quantum Spin Ice



$H = (\nabla \cdot \boldsymbol{E})^2$ or $|\phi|^2$

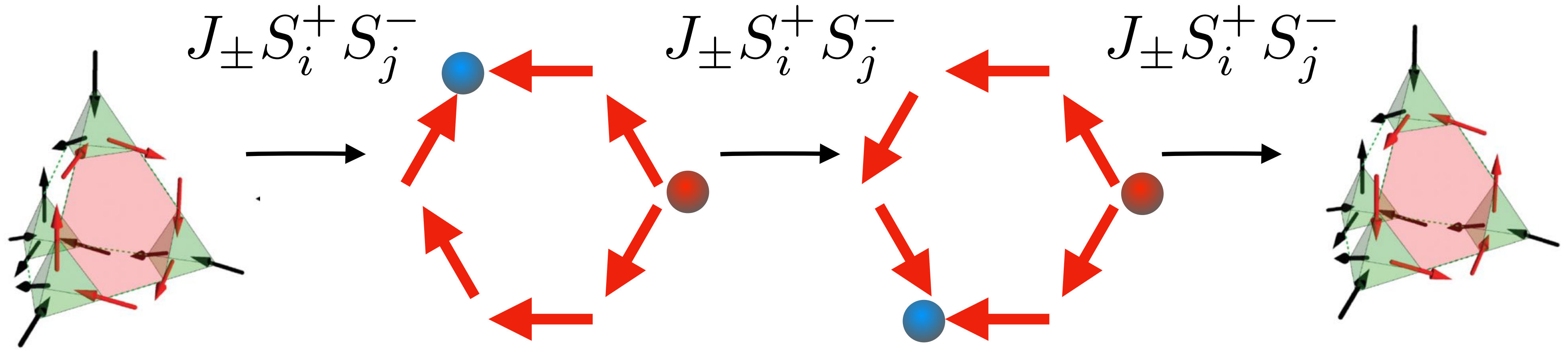
2 charge states

1 charge states

ground states

$\cos(b) \sim b^2 + \dots$

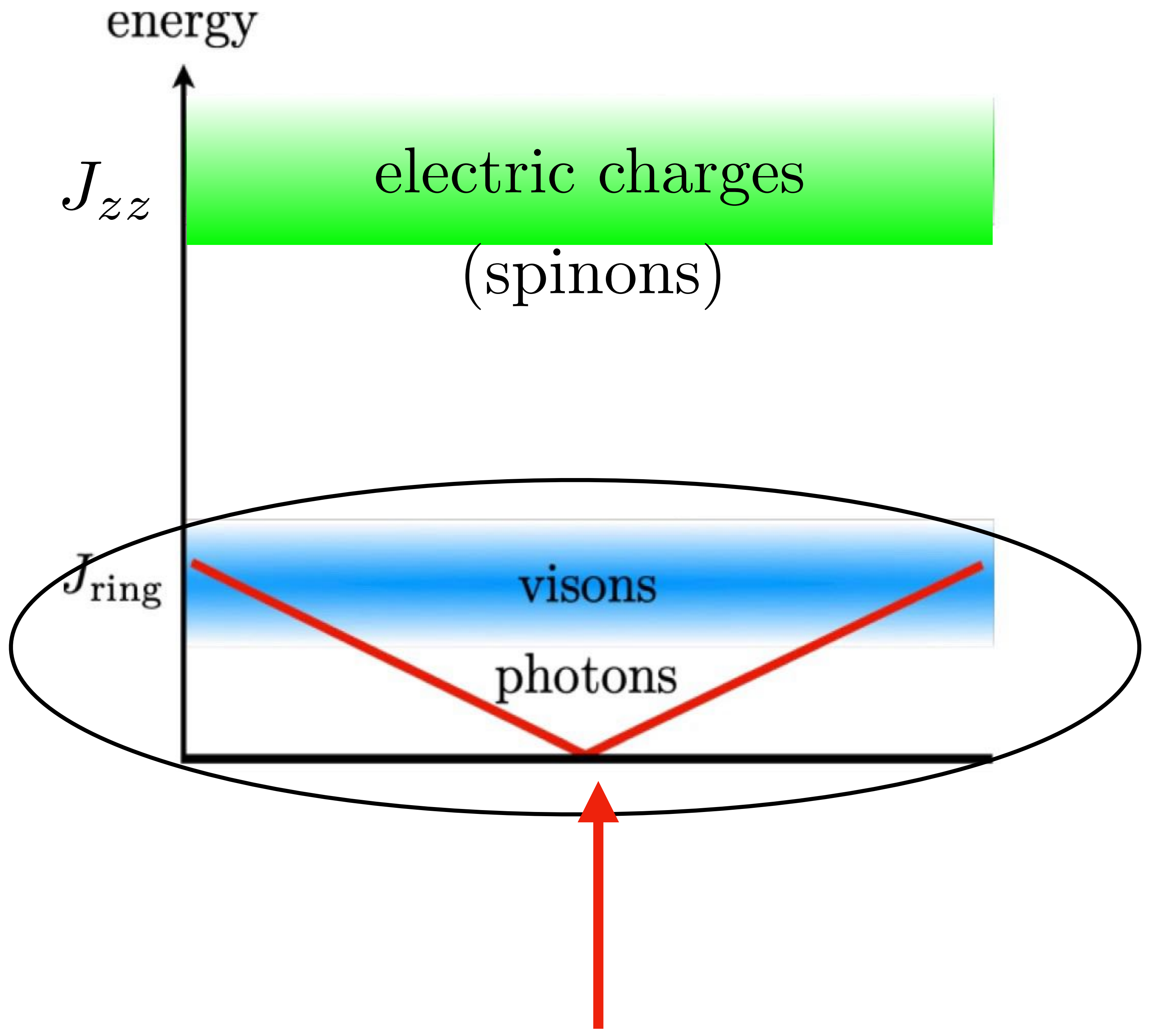
$H \sim E^2 + b^2$



$J_{ring} \sum_{\hexagon} (S_1^+ S_2^- S_3^+ S_4^- S_5^+ S_6^- + \text{H.c.}) \sim J_{\text{ring}} \cos(b)$

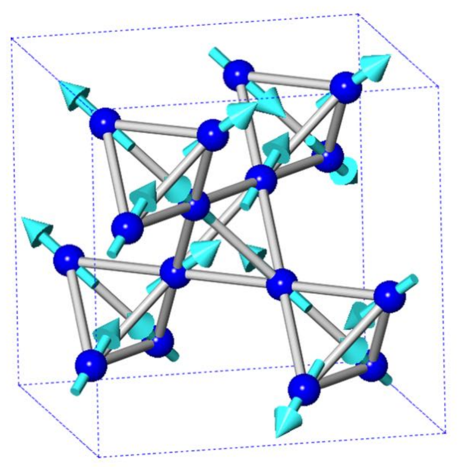
Effective model (roughly speaking)

$H = J_{zz}|\phi|^2 + J_\pm \phi_i e^{iA_{ij}} \phi_j^\dagger + \text{h.c.}$



QSI g.s.: superposition of ice-states

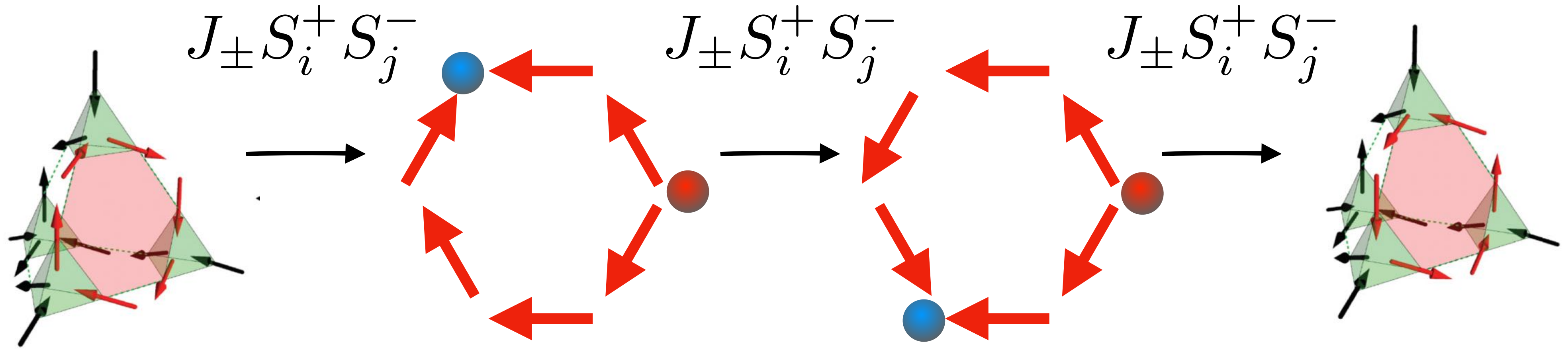
Emergent QED in Quantum Spin Ice



$H = (\nabla \cdot \boldsymbol{E})^2$ or $|\phi|^2$

$\cos(b) \sim b^2 + \dots$

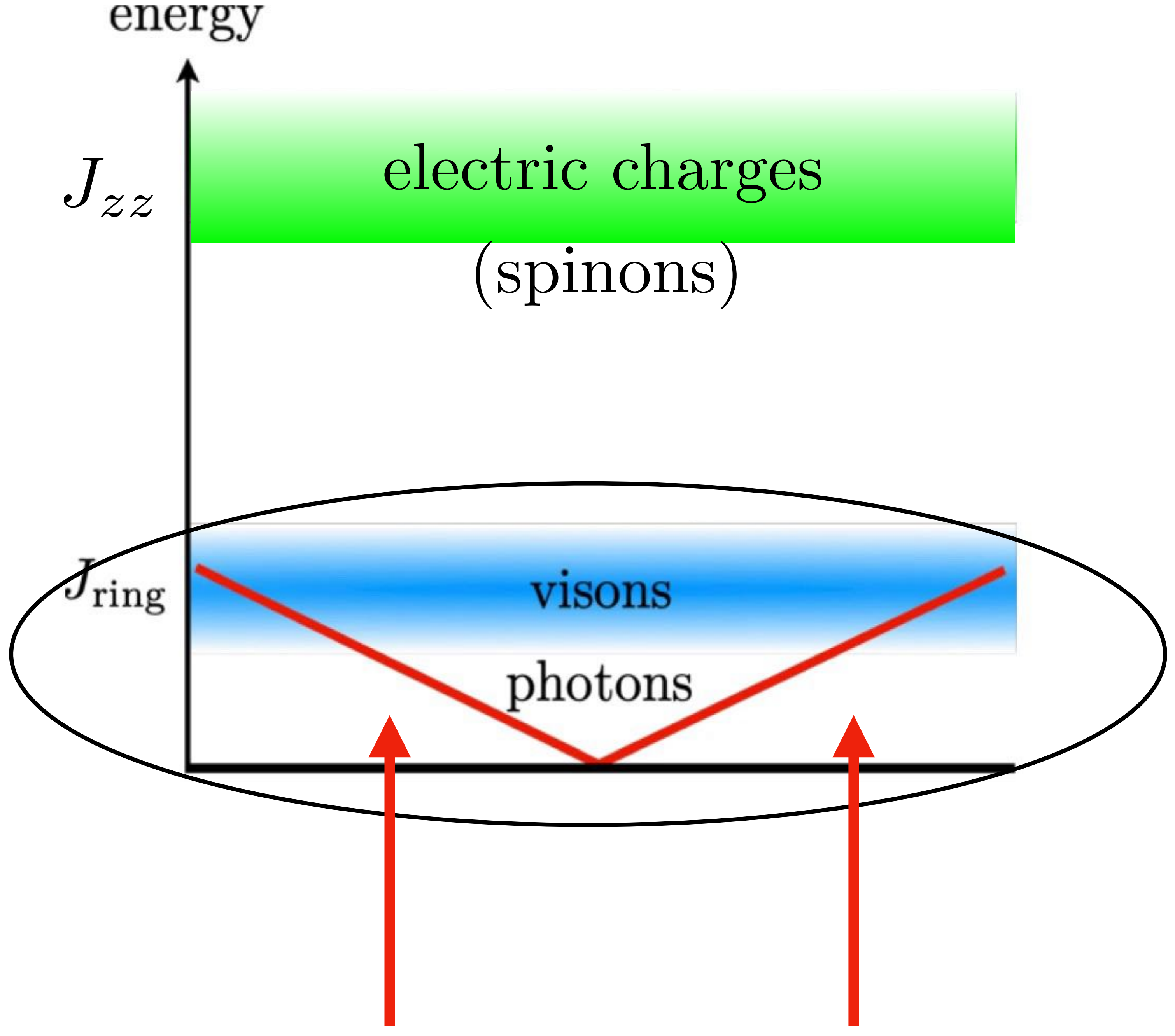
$H \sim E^2 + b^2$



$J_{ring} \sum_{\hexagon} (S_1^+ S_2^- S_3^+ S_4^- S_5^+ S_6^- + \text{H.c.}) \sim J_{\text{ring}} \cos(b)$

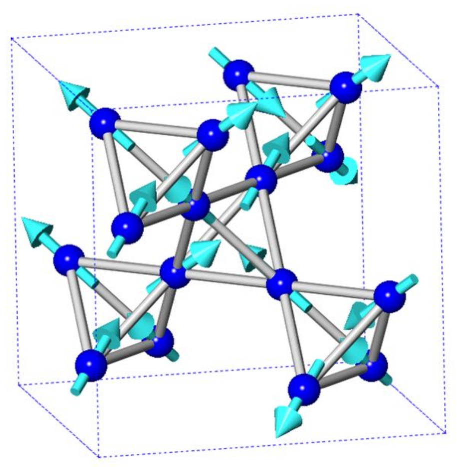
Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_\pm \phi_i e^{iA_{ij}} \phi_j^\dagger + \text{h.c.}$$



photons: also superposition of ice-states, with finite momentum

Emergent QED in Quantum Spin Ice



$H = (\nabla \cdot \boldsymbol{E})^2$ or $|\phi|^2$

2 charge states

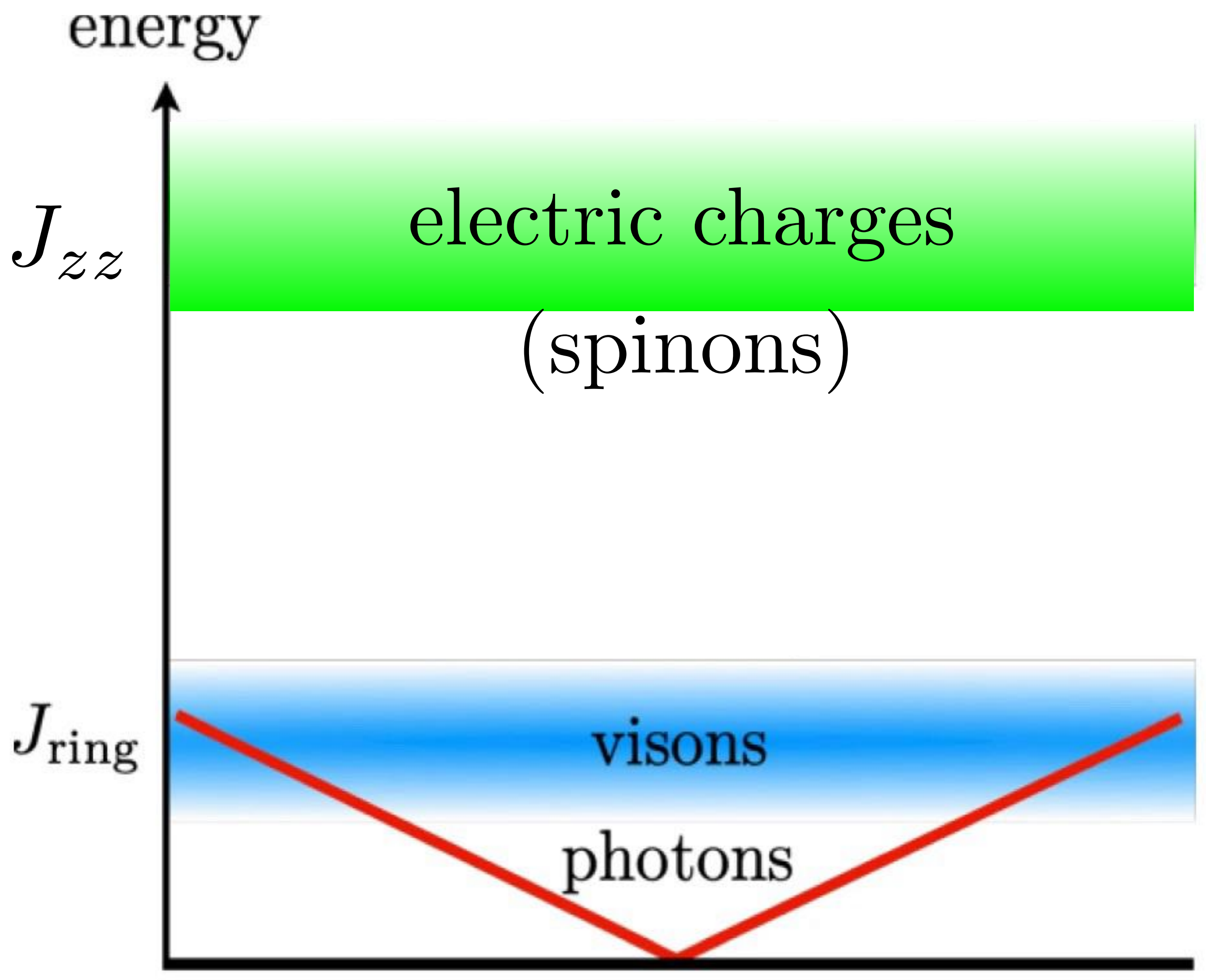
1 charge states

ground states

$J_\pm \phi_i e^{iA_{ij}} \phi_j^\dagger + \text{h.c.}$

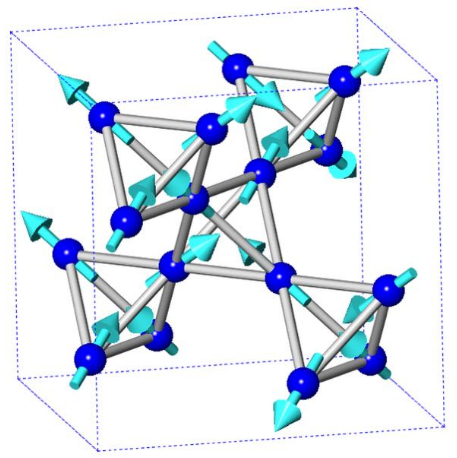
Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_\pm \phi_i e^{iA_{ij}} \phi_j^\dagger + \text{h.c.}$$



hopping of charges on a gauge field background

Emergent QED in Quantum Spin Ice



$H = (\nabla \cdot \boldsymbol{E})^2$ or $|\phi|^2$

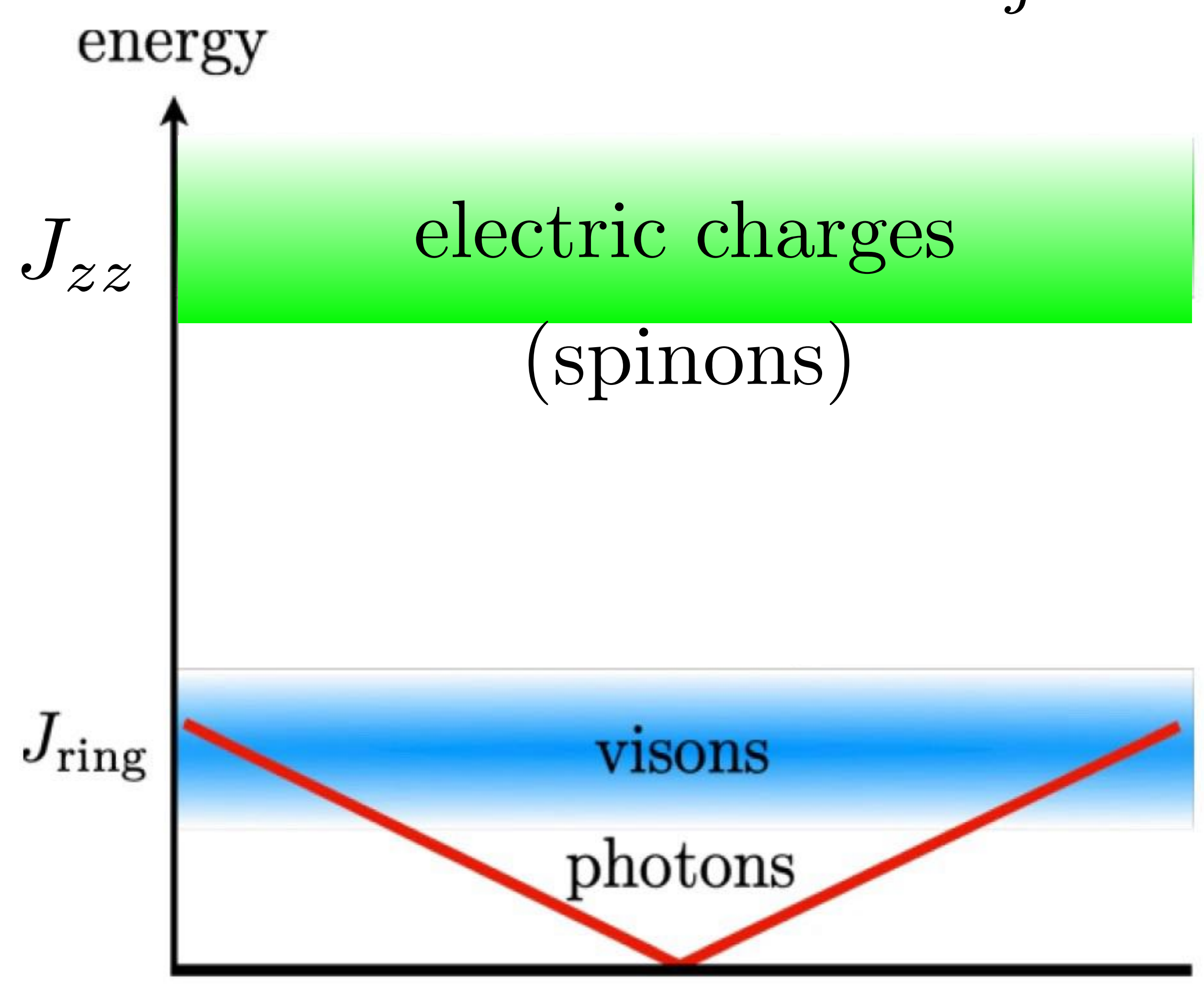
2 charge states

1 charge states

ground states

Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^{\dagger} + \text{h.c.}$$



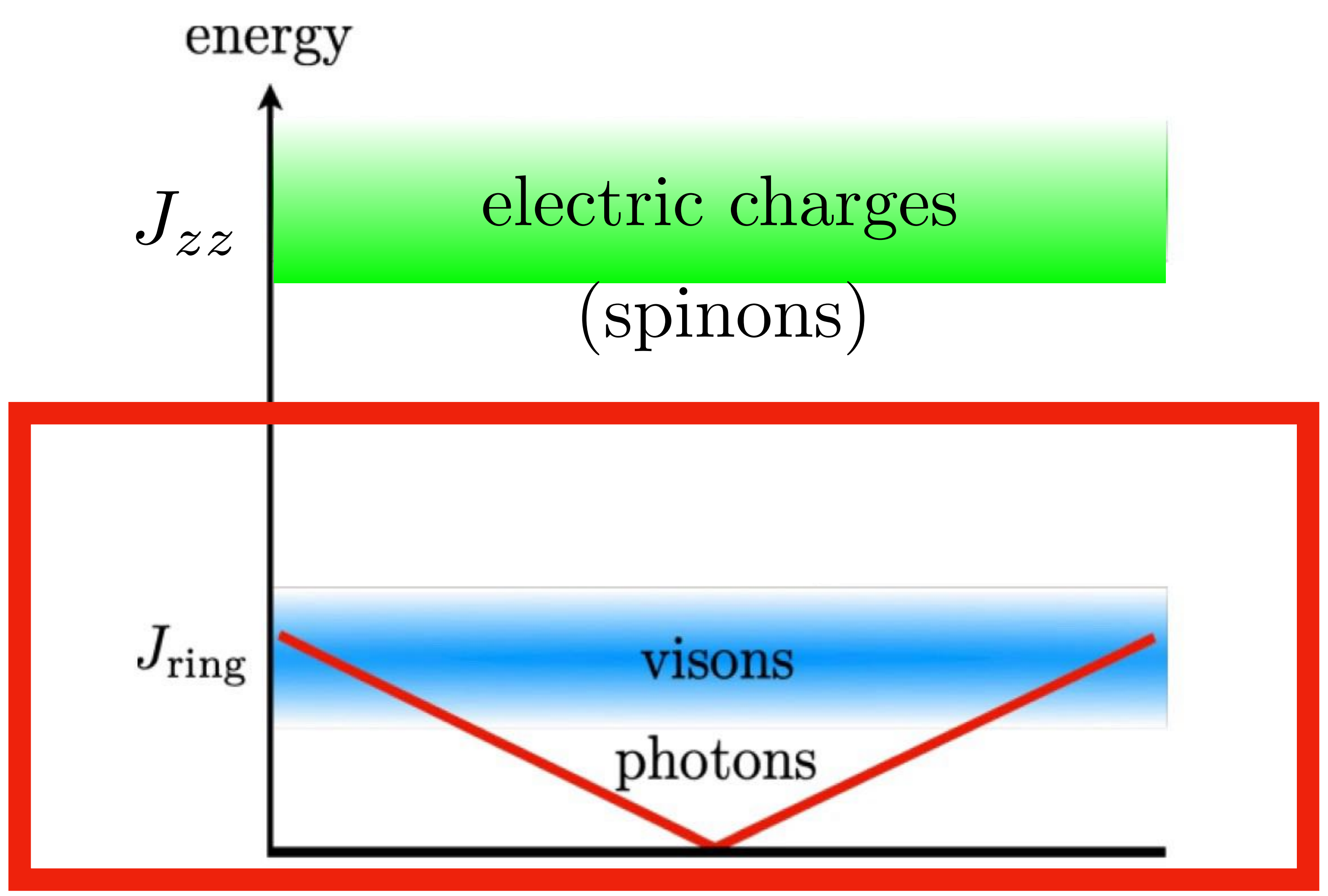
overall picture: **QSI is a lattice emergent QED** (eQED) with photons, electric charges, and magnetic monopoles. All these components have their dynamics and interactions.

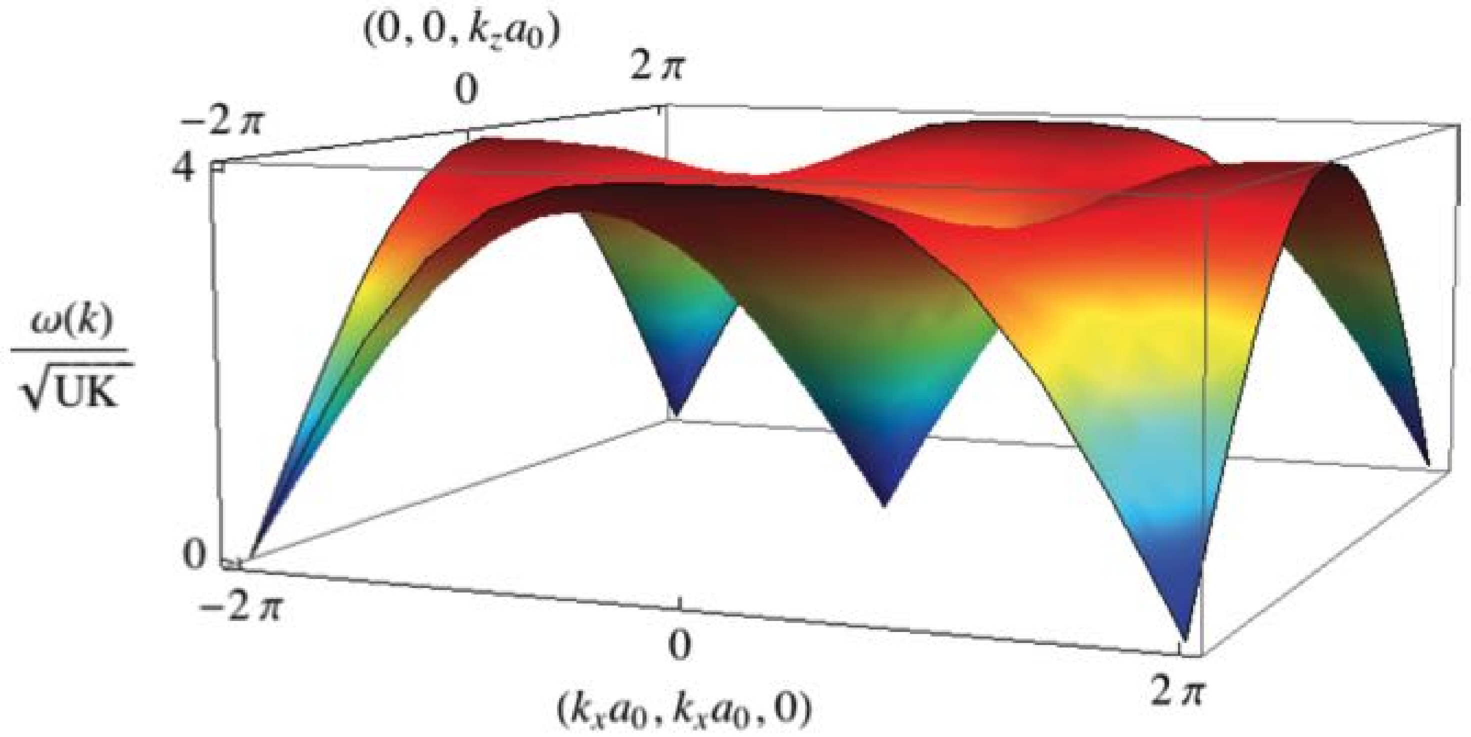
Emergent QED in Quantum Spin Ice

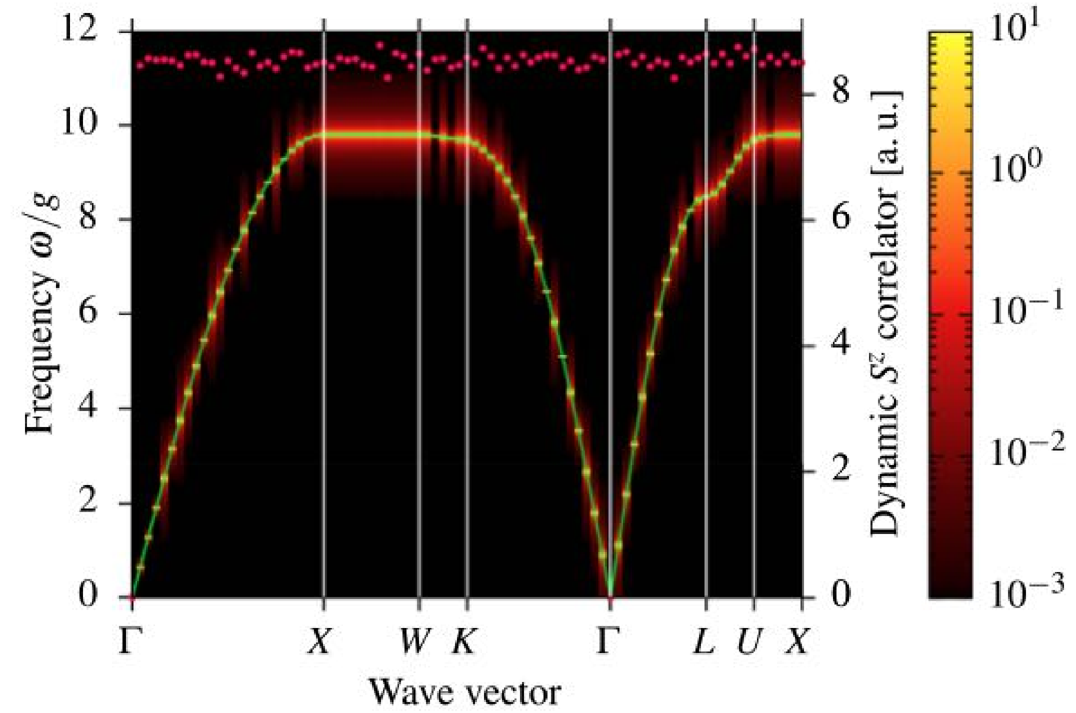
It is generally impossible to solve this model exactly. So mean-field theory and numerics are used to identify the spectrum.

Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^\dagger + \text{h.c.}$$







Seeing the light: Experimental signatures of emergent electromagnetism in a quantum spin ice

Owen Benton,[1] Olga Sikora,[1,2] and Nic Shannon[1,2,3]
[1]*H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, United Kingdom*
[2]*Okinawa Institute of Science and Technology, 12-22 Suzaki, Uruma, Okinawa, 904-2234, Japan*
[3]*Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
(Received 5 April 2012; published 30 August 2012)

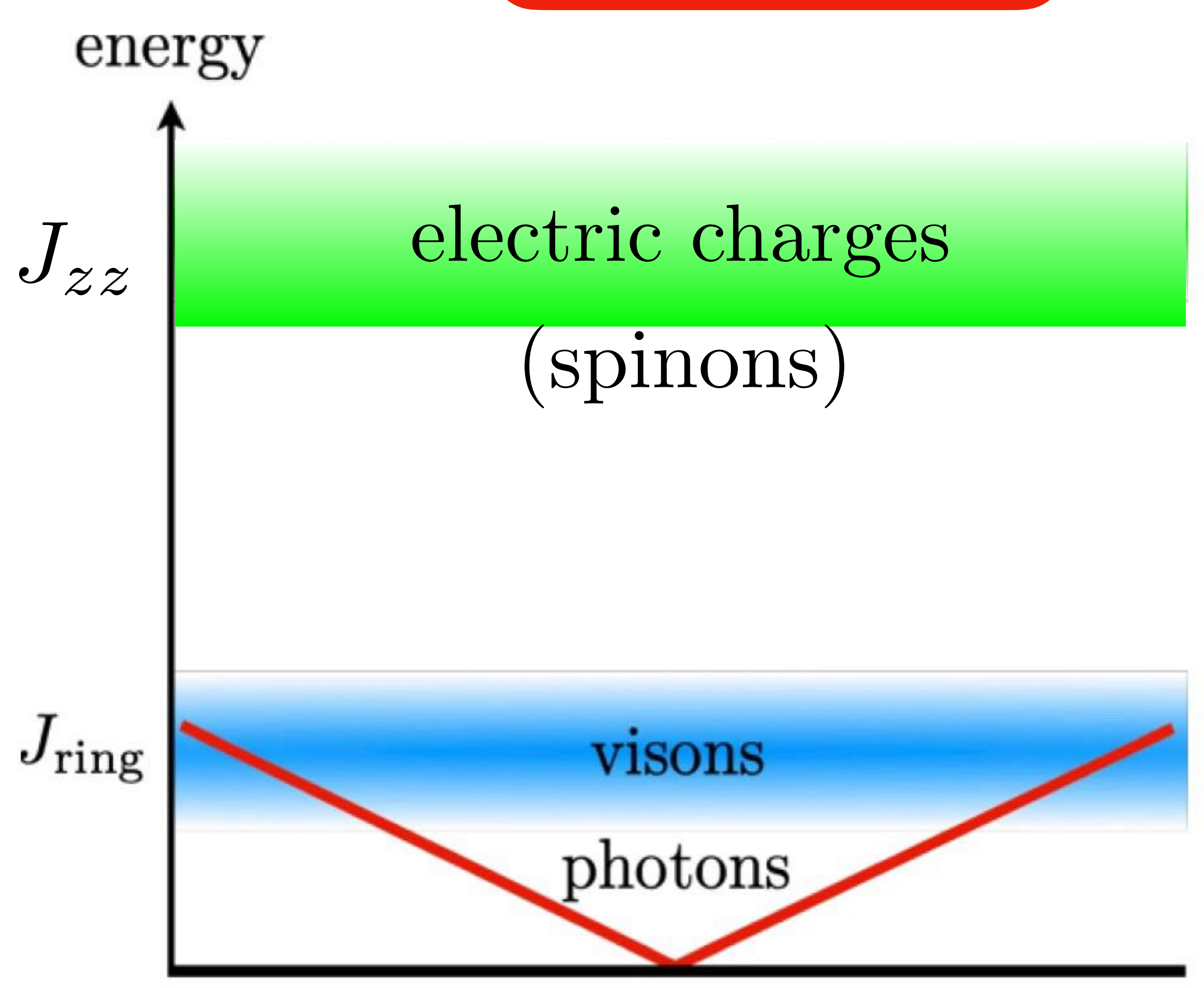
Seeing beyond the light: Vison and photon electrodynamics in quantum spin ice

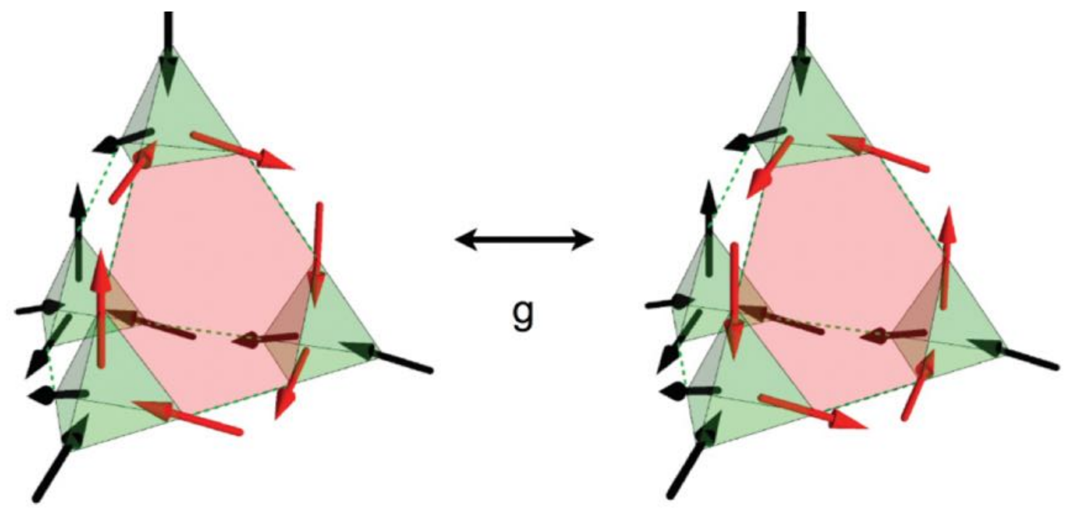
Attila Szabó and Claudio Castelnovo
TCM Group, Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

Emergent QED in Quantum Spin Ice

Effective model (roughly speaking)

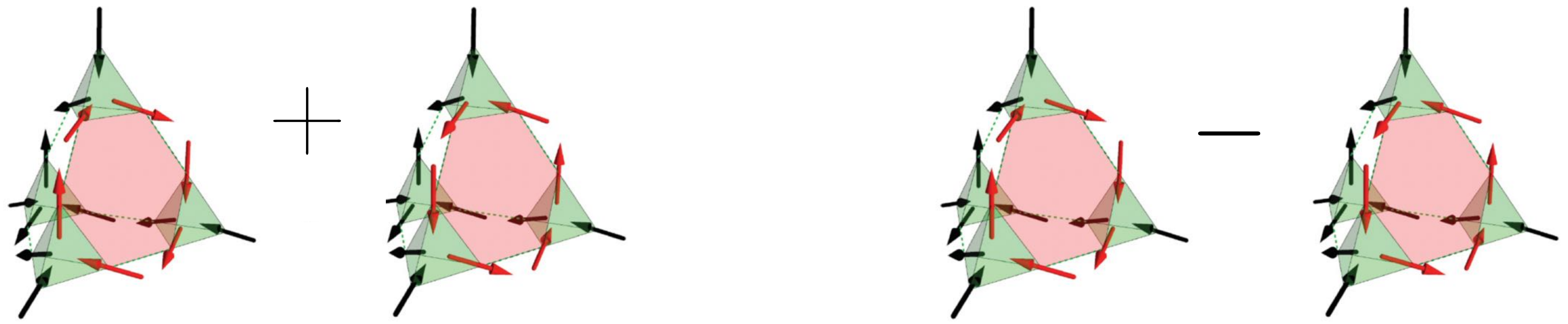
$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^{\dagger} + \text{h.c.}$$





$g\cos(b)$

It is generally impossible to solve this model exactly. So mean-field theory and numerics are used to identify the spectrum.



$H \sim -\cos(b)$
background $b = 0$

$H \sim +\cos(b)$
background $b = \pi$

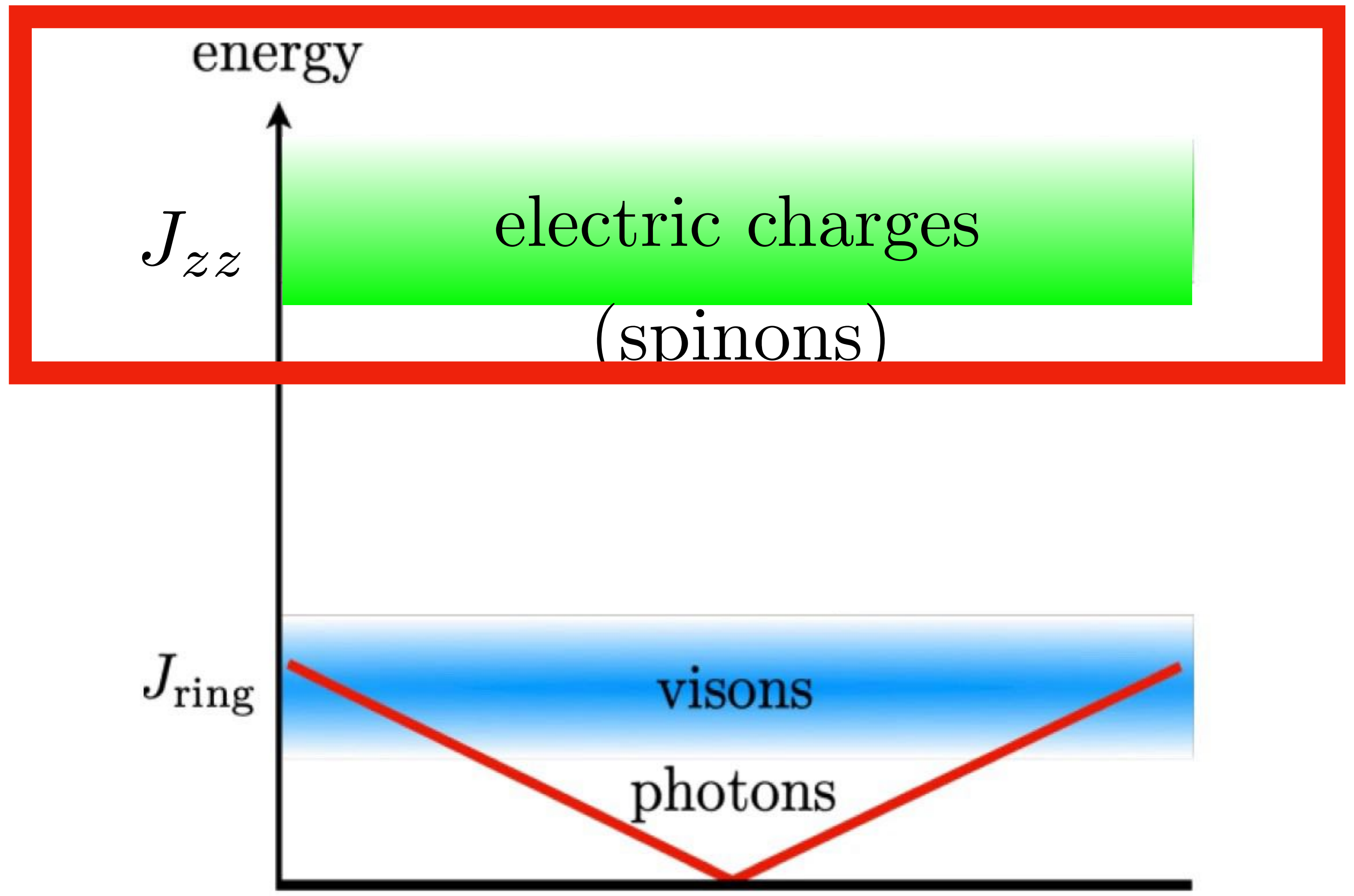
2 different phases of lattice eQED

SungBin Lee, Shigeki Onoda, and Leon Balents Phys. Rev. B 86, 104412

Emergent QED in Quantum Spin Ice

Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^\dagger + \text{h.c.}$$



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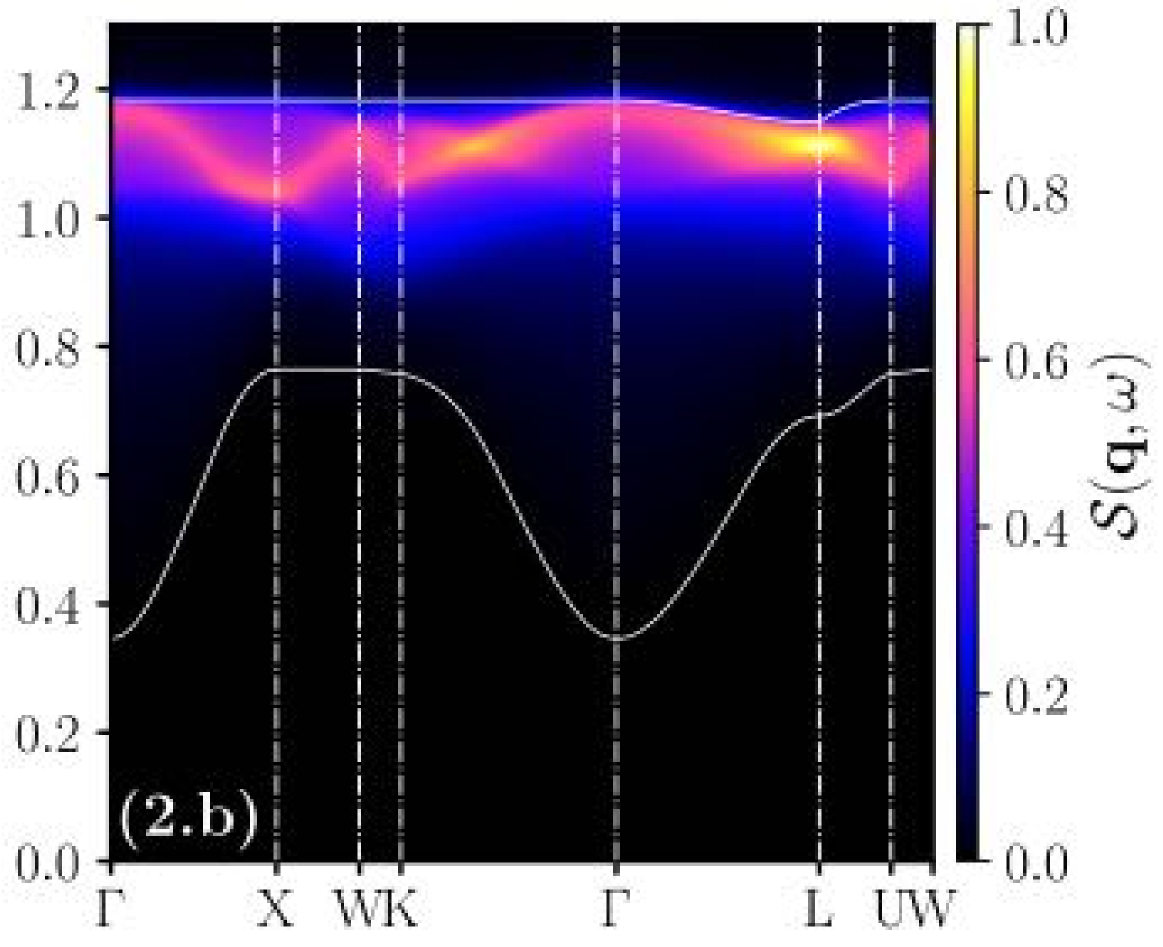
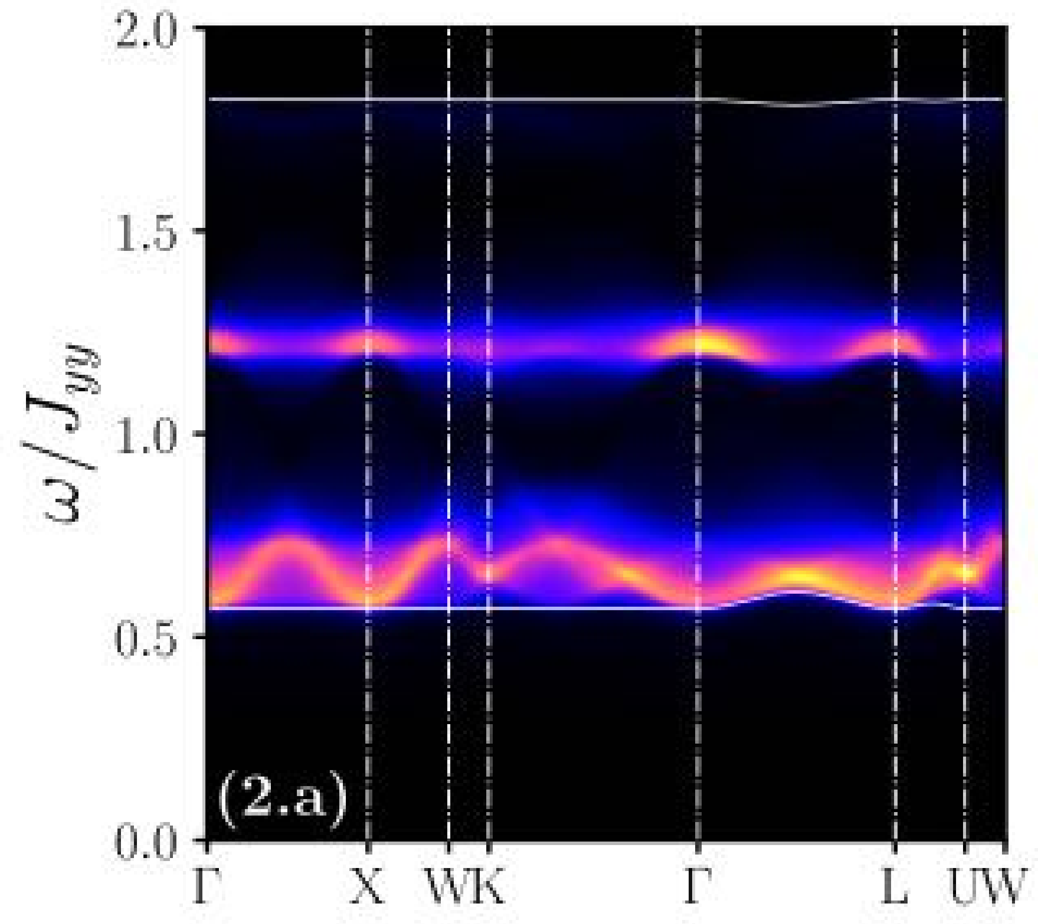


$H \sim -\cos(b)$

background b = 0



$H \sim +\cos(b)$

background $b = \pi$

Gang Chen & collaborators:
PRR 5, 033169 PRR 2, 013066 PRB 96, 195127
PRB 96, 085136 PRB 95, 041106 PRL 112, 167203

Spectroscopic signatures of fractionalization in octupolar quantum spin ice

Félix Desrochers[1,*] and Yong Baek Kim[1,†]
[1] *Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada*

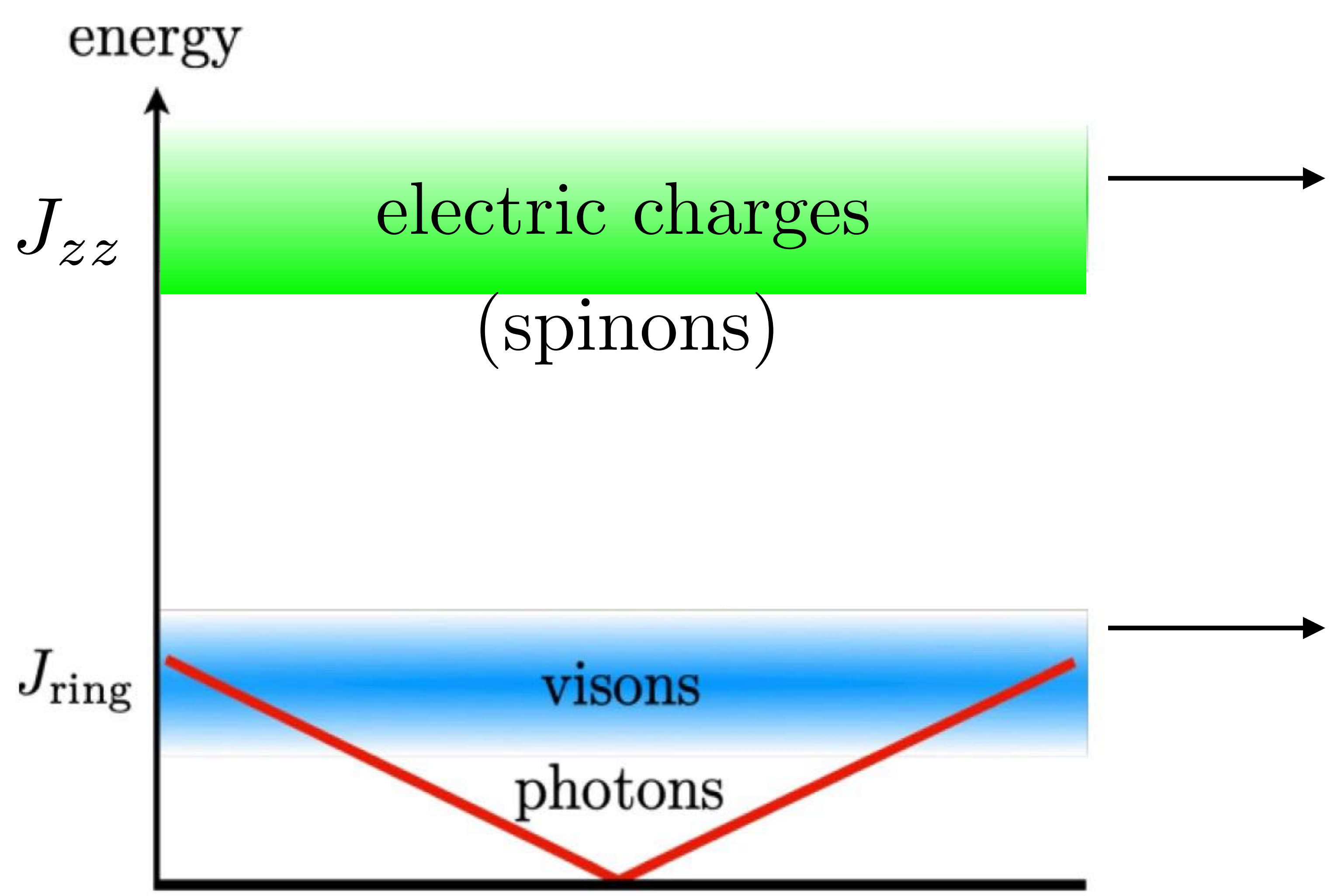
(Dated: January 16, 2023)

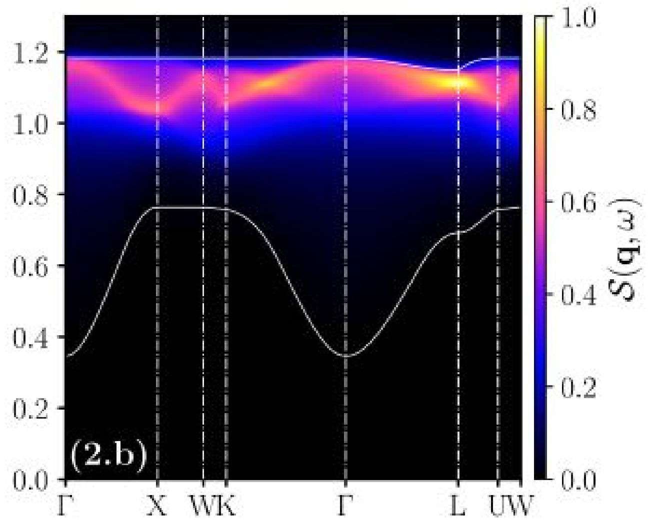
Emergent QED in Quantum Spin Ice

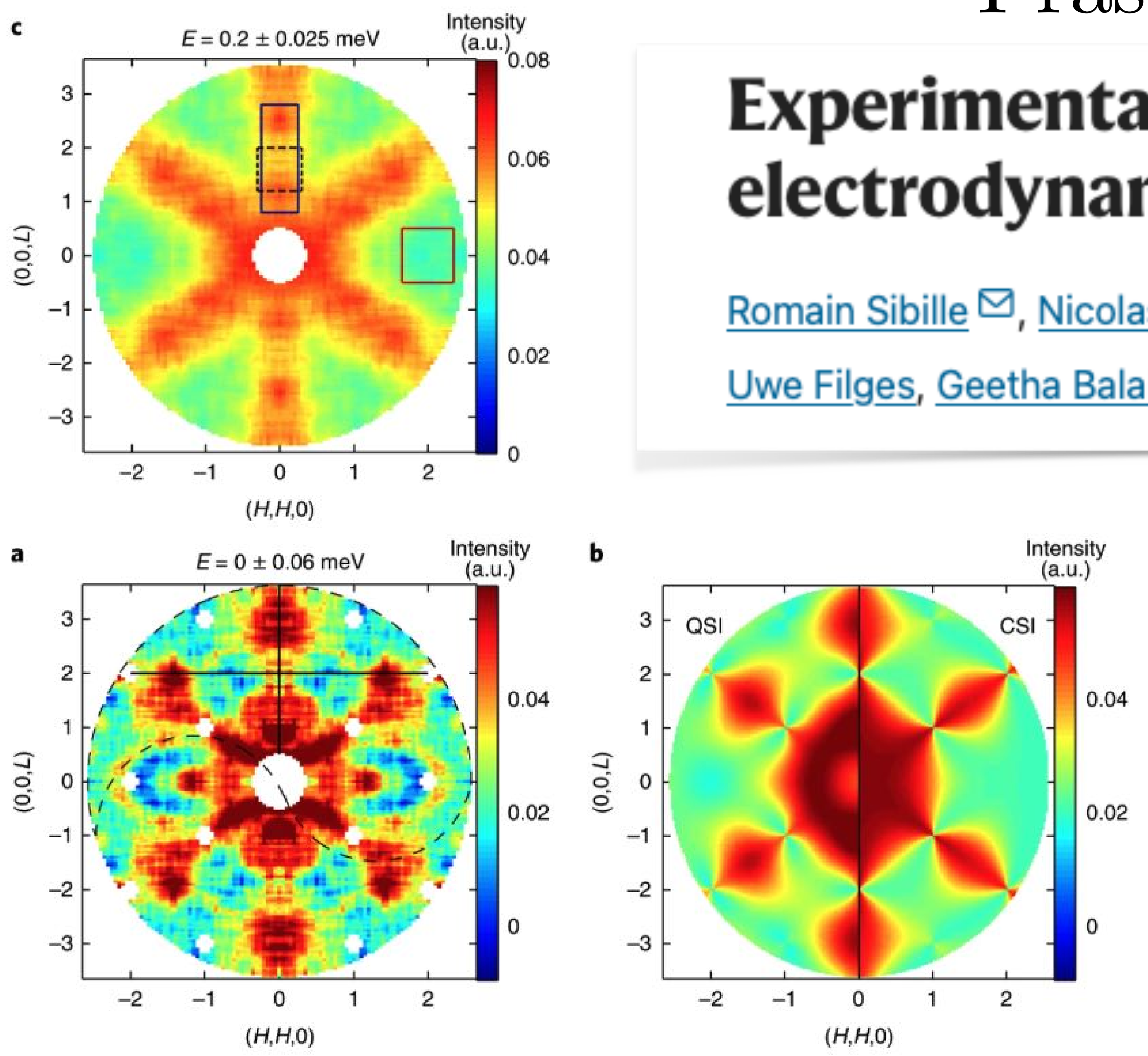
The spectrum can be measured by neutron scattering expriments.

Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^\dagger + \text{h.c.}$$

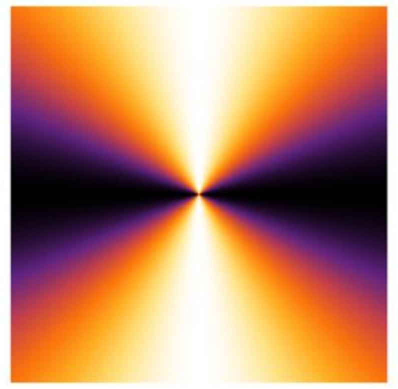






exp theory

$$\langle E_x(\boldsymbol{q})E_x(-\boldsymbol{q})\rangle \sim q_y^2/q^2$$

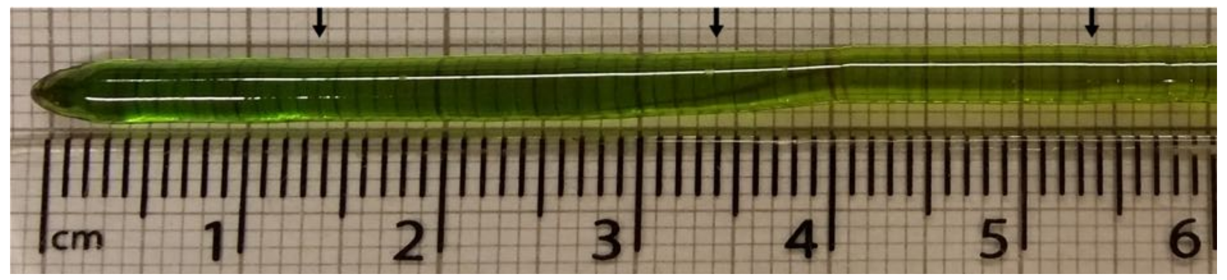


Praseodymium-Hafnium

Experimental signatures of emergent quantum electrodynamics in $Pr_2Hf_2O_7$

Romain Sibille, Nicolas Gauthier, Han Yan, Monica Ciomaga Hatnean, Jacques Ollivier, Barry Winn, Uwe Filges, Geetha Balakrishnan, Michel Kenzelmann, Nic Shannon & Tom Fennell

Nature Physics 14, 711–715



Emergent QED in Quantum Spin Ice

Effective model (roughly speaking)

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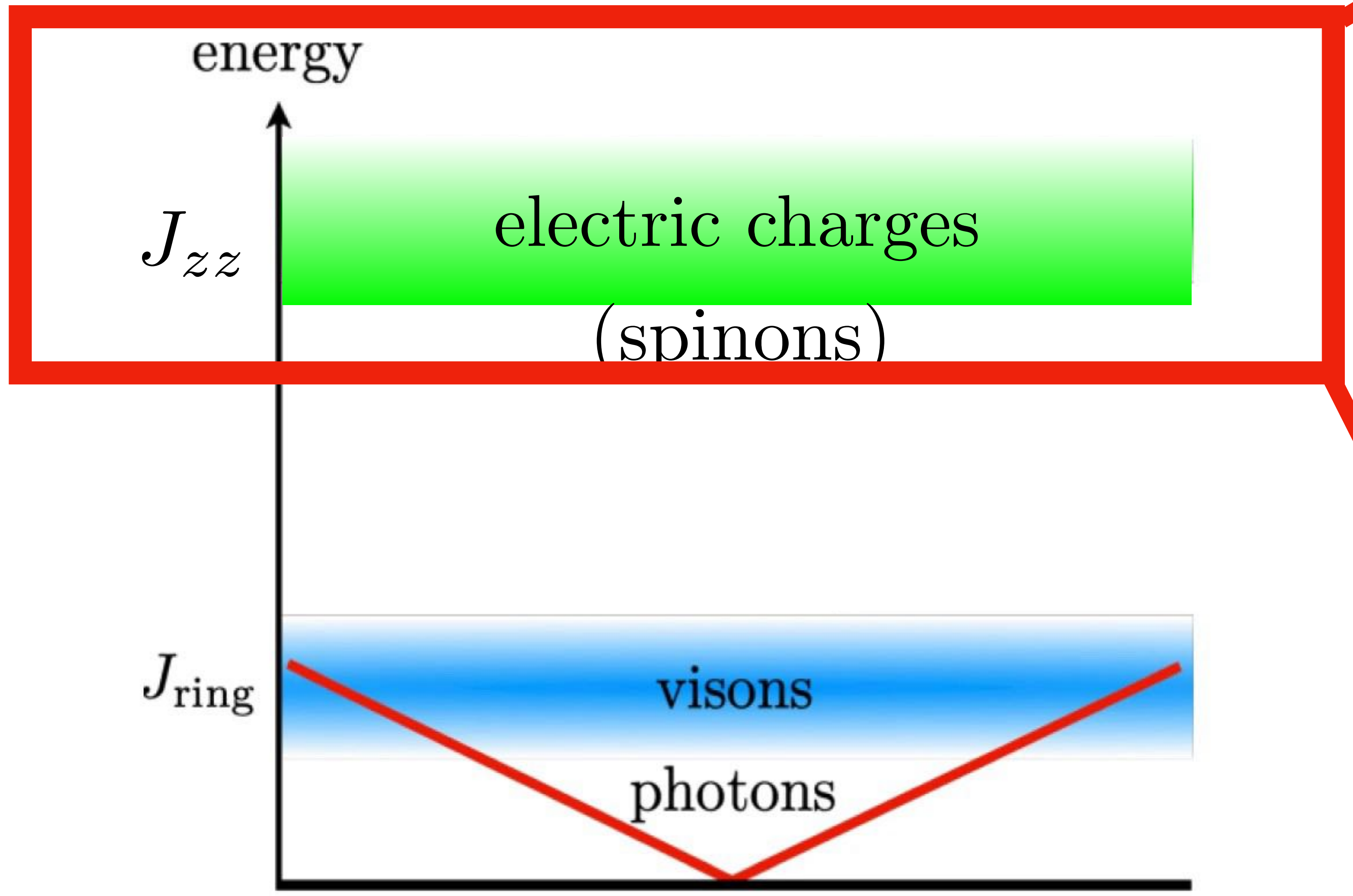
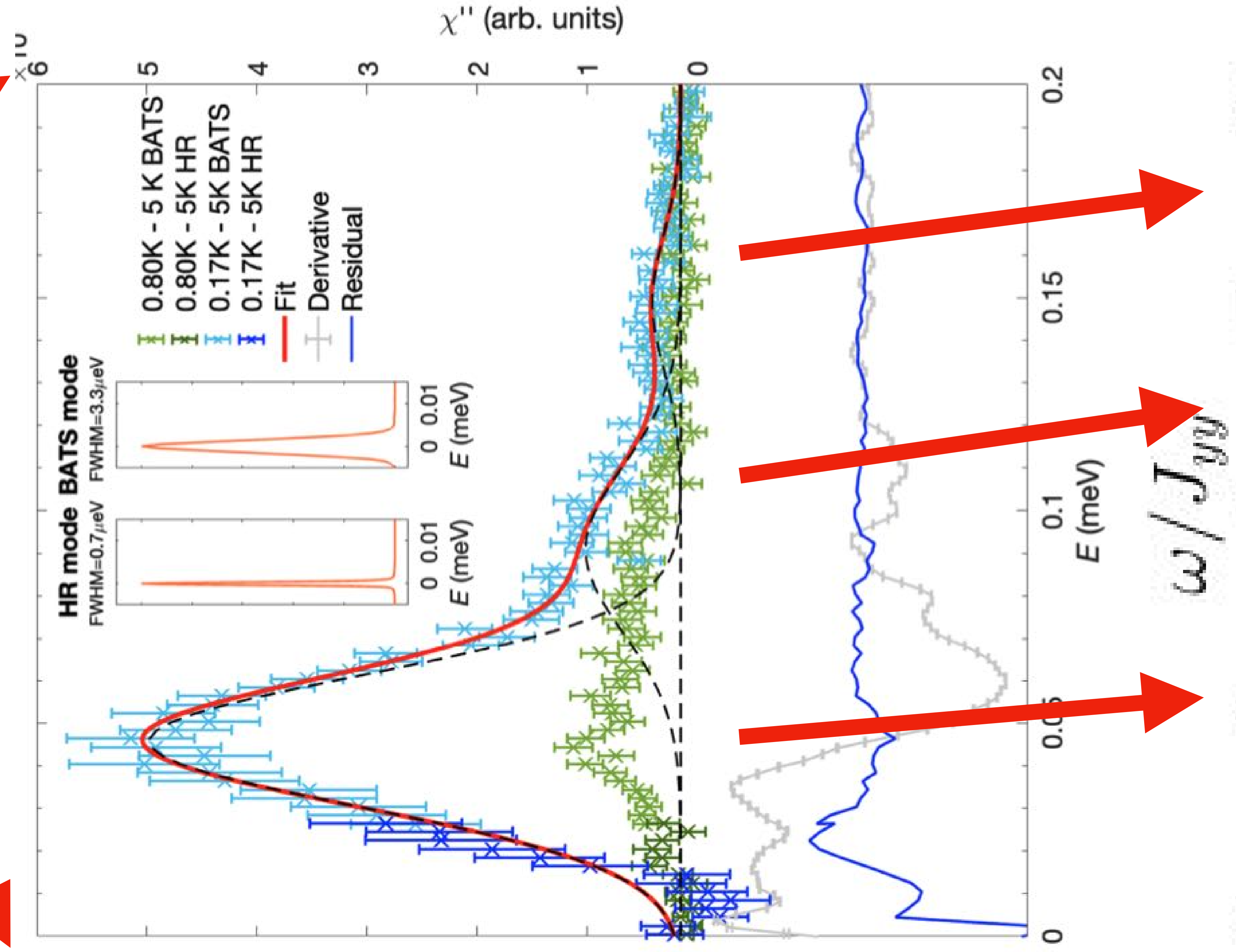
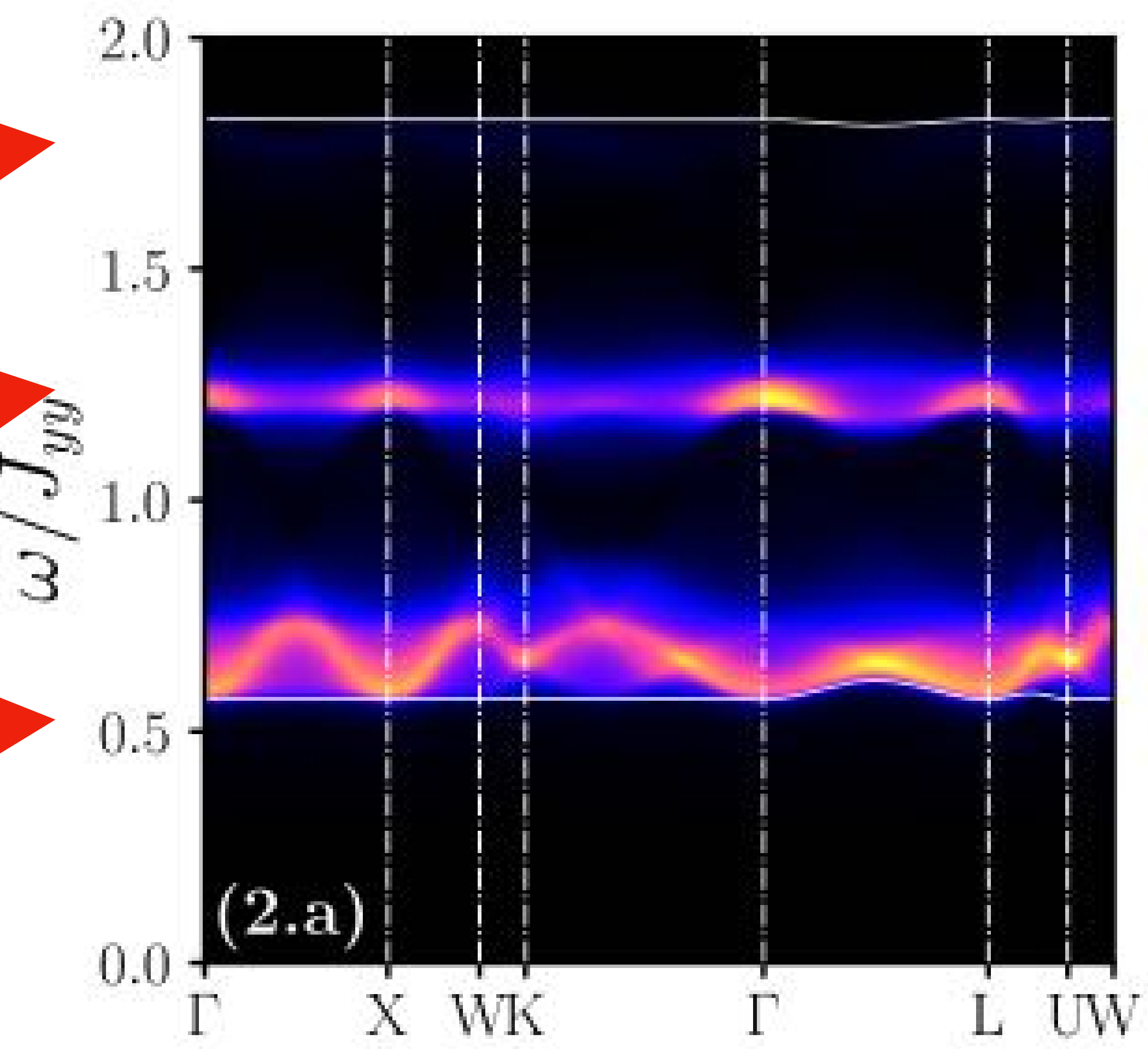


The spectrum can be measured by neutron scattering experiments. $Ce_2Sn_2O_7$ Cerium Stannum



q-integrated DOS



$$H \sim +\cos(b)$$

background $b = \text{Pi}$

arXiv:2304.05452, to appear on Nat. Phys.

V Porée, **HY** , ..., Romain Sibille

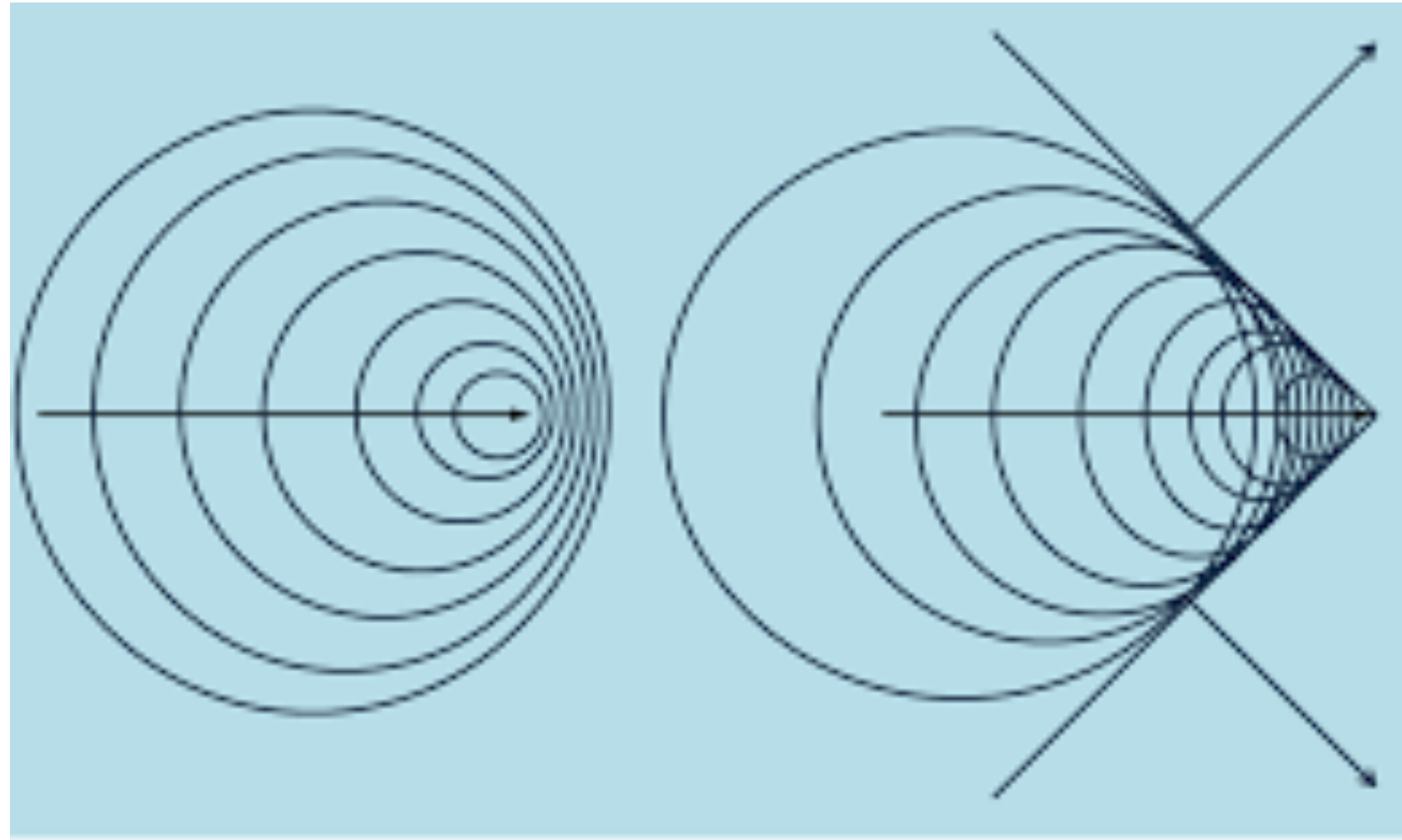
Emergent QED in Quantum Spin Ice

As a lattice QED, it is interesting for probing QED physics not accessible from fundamental particles

superluminal Cherenkov radiation effect:
charges propagating faster than light!

Spectroscopy of Spinons in Coulomb Quantum Spin Liquids

Siddhardh C. Morampudi,[1] Frank Wilczek,[2,3,4,5,6] and Chris R. Laumann[1]
[1]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
[2]*Center for Theoretical Physics, MIT, Cambridge Massachusetts 02139, USA*
[3]*T. D. Lee Institute, Shanghai 200240, China*
[4]*Wilczek Quantum Center, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[5]*Department of Physics, Stockholm University, Stockholm 114 19, Sweden*
[6]*Department of Physics and Origins Project, Arizona State University, Tempe Arizona 25287, USA*



large fine-structure constant

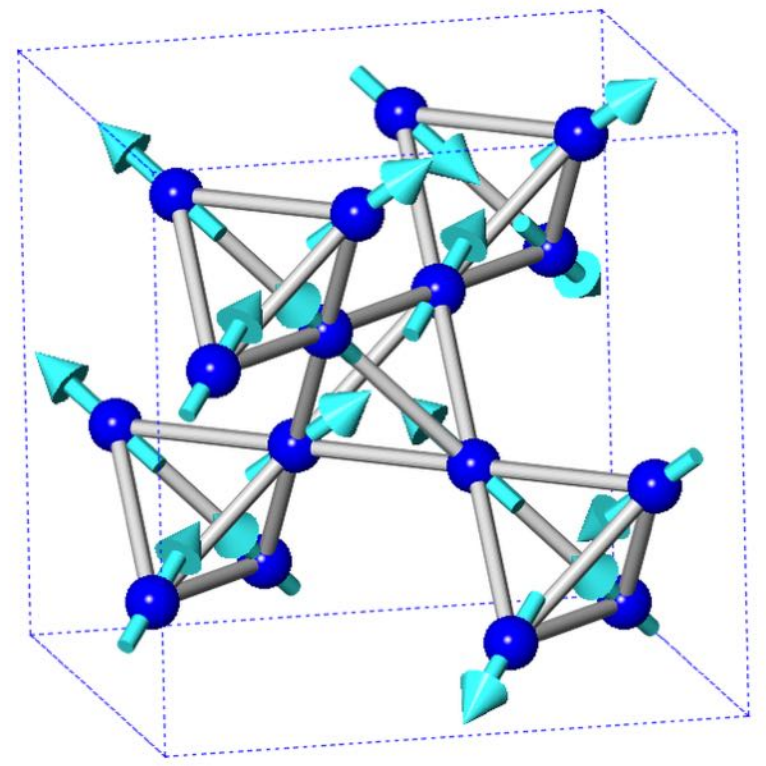
Emergent Fine Structure Constant of Quantum Spin Ice Is Large

Salvatore D. Pace,[1,2] Siddhardh C. Morampudi,[3] Roderich Moessner,[4] and Chris R. Laumann[2]
[1]*TCM Group, Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom*
[2]*Department of Physics, Boston University, Boston, Massachusetts 02215, USA*
[3]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[4]*Max-Planck-Institut für Physik komplexer Systeme, 01187 Dresden, Germany*

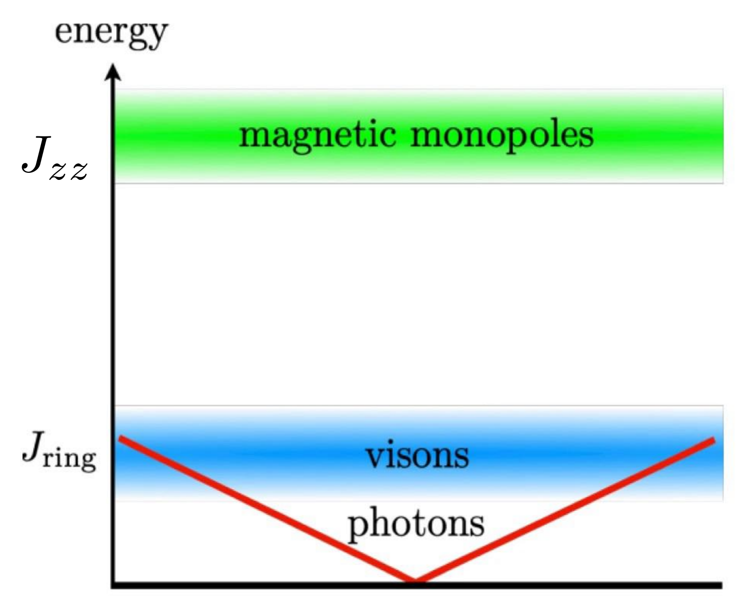
	Candidate QSI material	Vacuum QED
α	$1/10$	$1/137$
c	$1\ \mathrm{ms}^{-1}$	$3.0\times10^{8}\ \mathrm{ms}^{-1}$
e	$10^{-4}\ \sqrt{\mathrm{eV\,nm}}$	$1.2\ \sqrt{\mathrm{eV\,nm}}$
m	$10^{-3}\ \sqrt{\mathrm{eV\,nm}}$	$82.2\ \sqrt{\mathrm{eV\,nm}}$

Outline

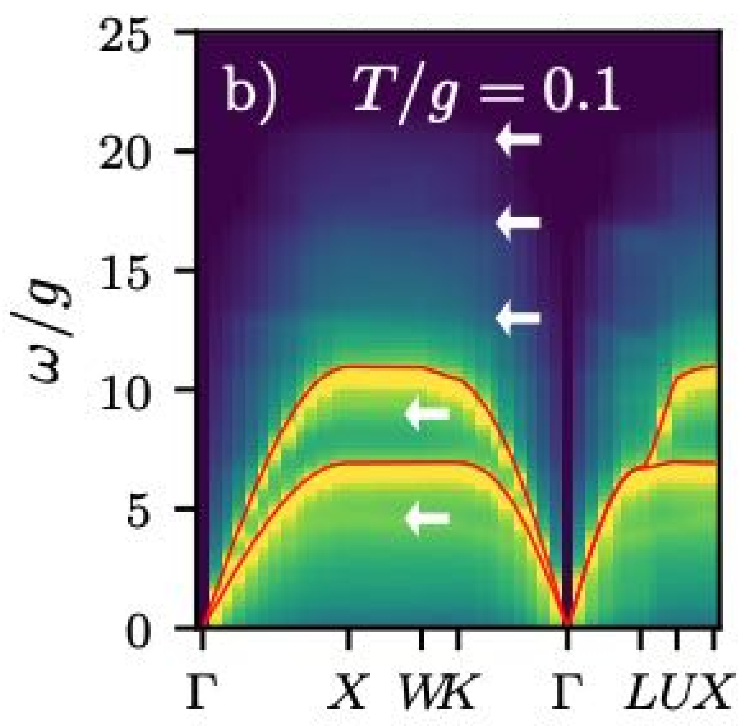
1. Classical spin ice as electrostatics



2. Quantum spin ice as emergent Quantum Electrodynamics (eQED)



3. Controlling eQED dynamics in dipolar-octupolar quantum spin ice



Control the dynamics of eQED?

Alaric Sanders
Cambridge

Claudio Castelnovo
Cambridge

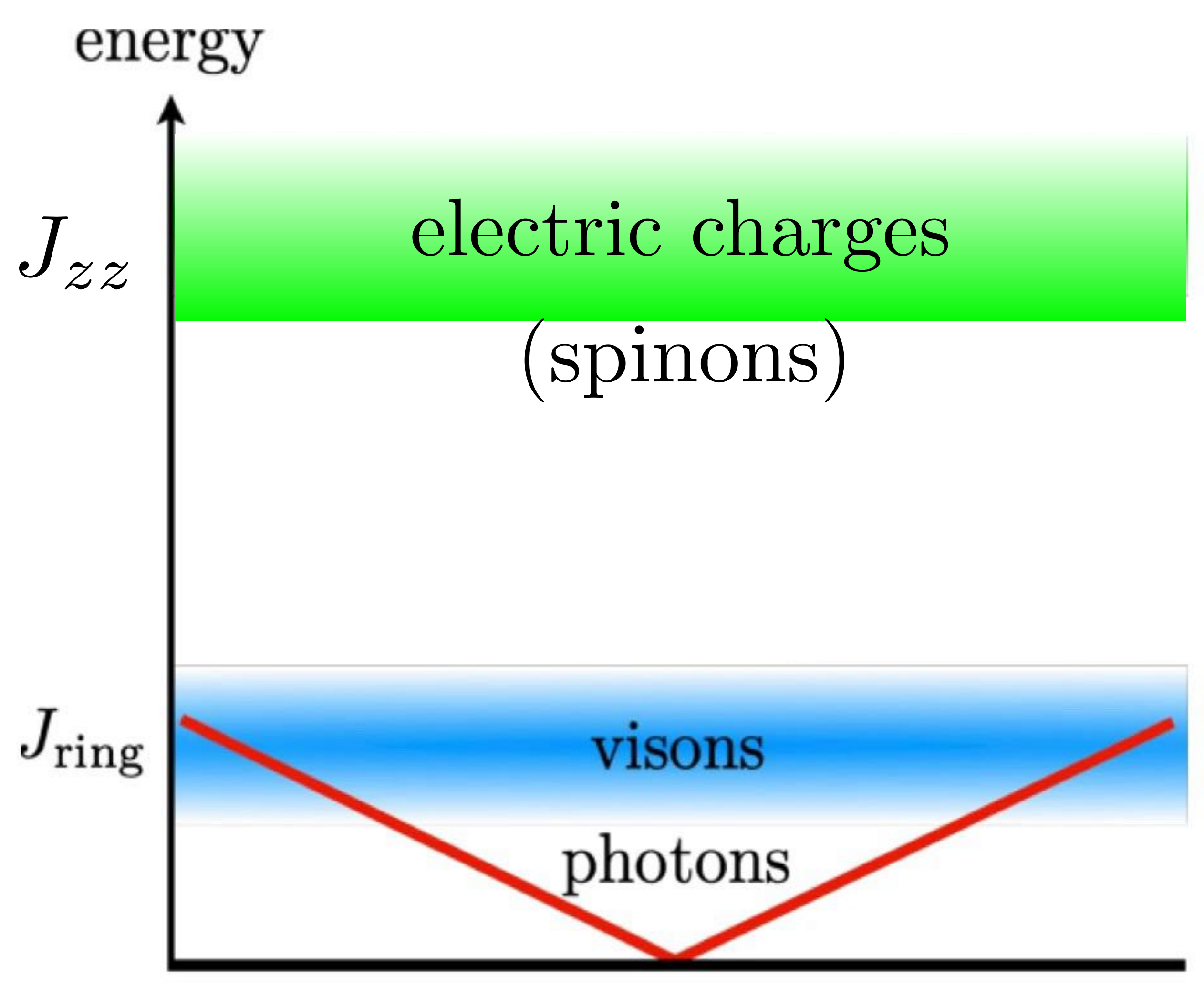
Andriy H. Nevidomskyy
Rice

arXiv:2312.11641, *Experimentally tunable QED in dipolar-octupolar quantum spin ice*

Control the dynamics of eQED?

Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^\dagger + \text{h.c.}$$



One material, one version of eQED

Generally very difficult to have accurate control of its dynamics!

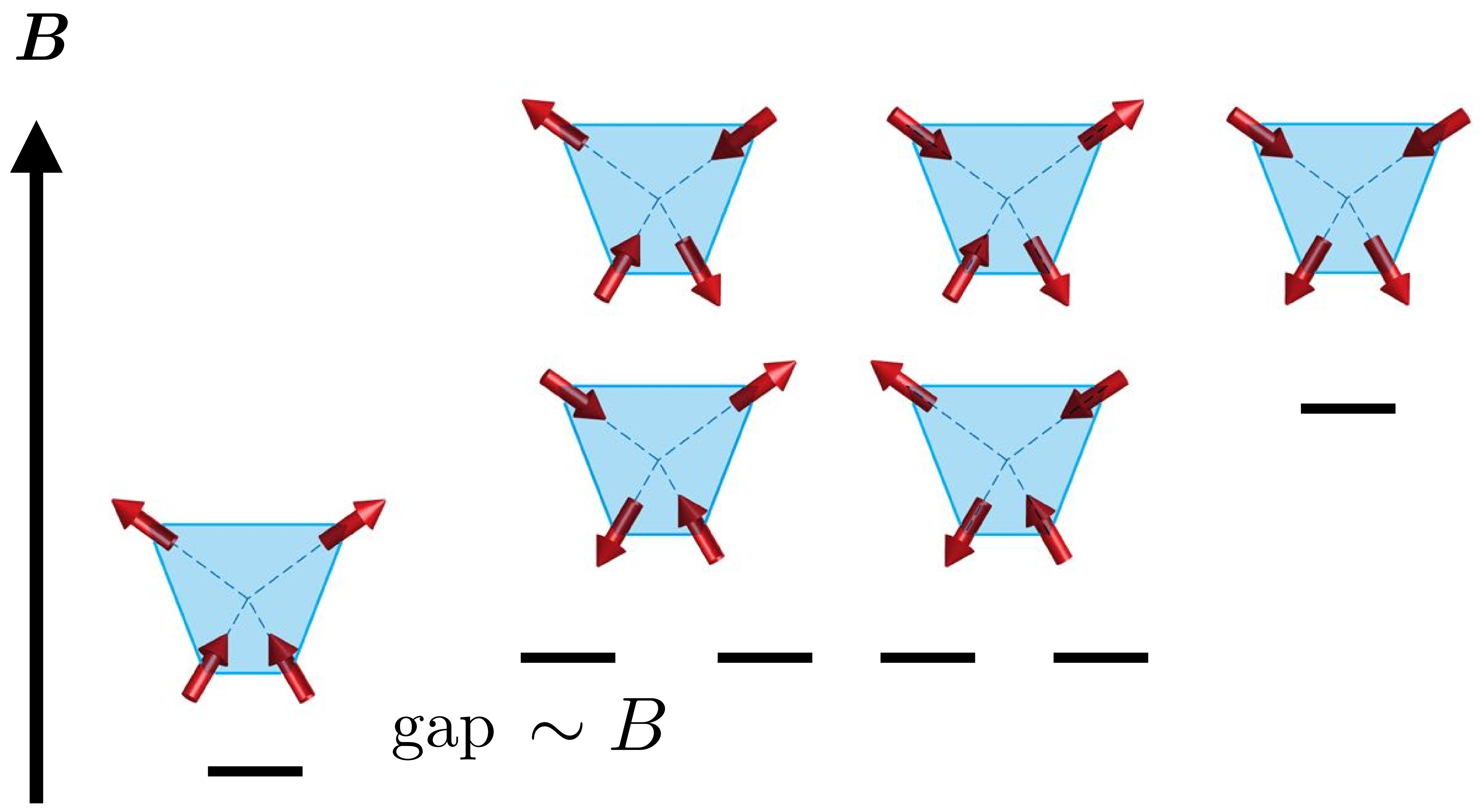
Control the dynamics of eQED?

Conventional spin 1/2s on pyrochlore lattice:

$$H = \sum_{\langle ij \rangle} \{ J_{zz} S_i^z S_j^z - J_{\pm} (S_i^+ S_j^- + S_i^- S_j^+)$$

$$-g \sum_i \boldsymbol{B} \cdot \boldsymbol{S}_i \ + \text{(other spin-spin terms)}$$

classical limit $H \sim \sum J_z S_i^z S_j^z$



apply magnetic field

Control the dynamics of eQED?

Conventional spin 1/2s on pyrochlore lattice:

$$H = \sum_{\langle ij \rangle} \{ J_{zz} S_i^z S_j^z - J_{\pm} (S_i^+ S_j^- + S_i^- S_j^+)$$

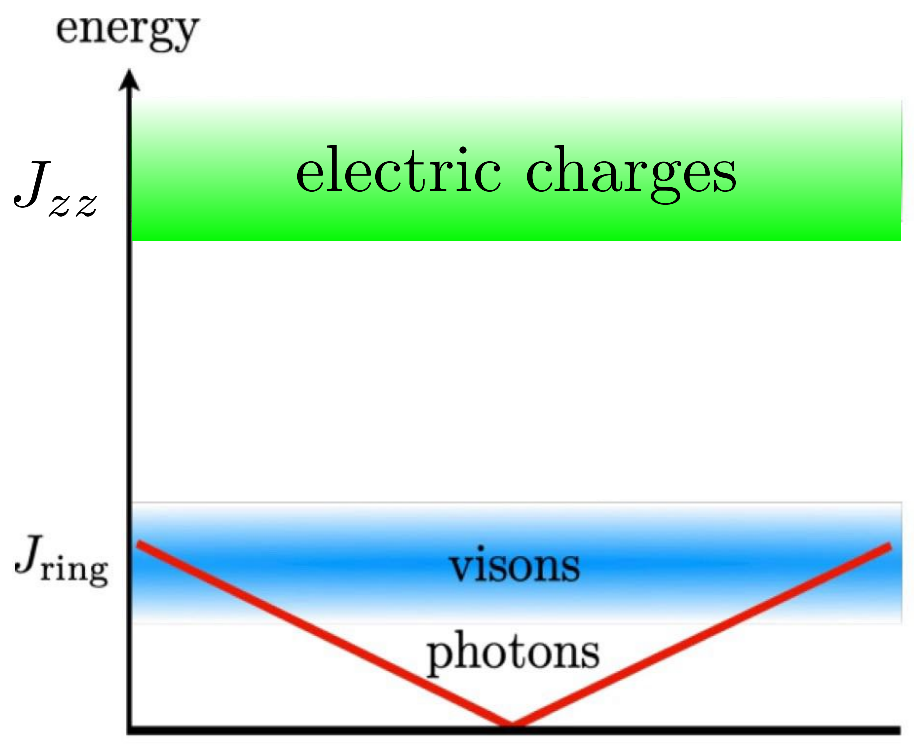
$$-g \sum_i \boldsymbol{B} \cdot \boldsymbol{S}_i + \text{(other spin-spin terms)}$$

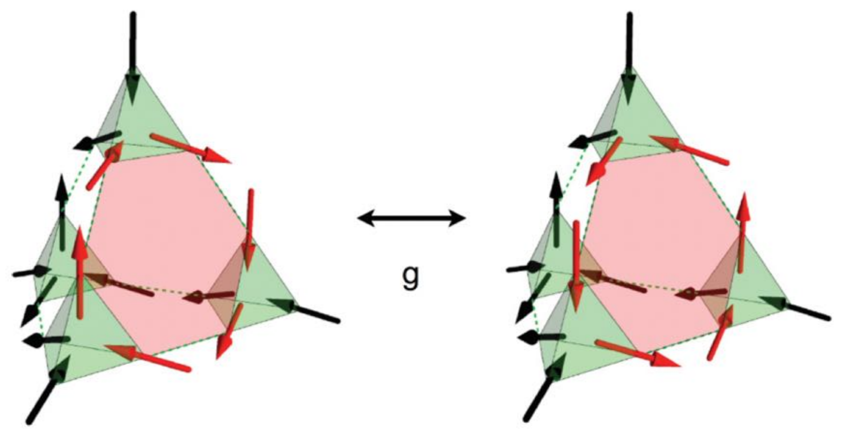
2 charge states

1 charge states

ground states

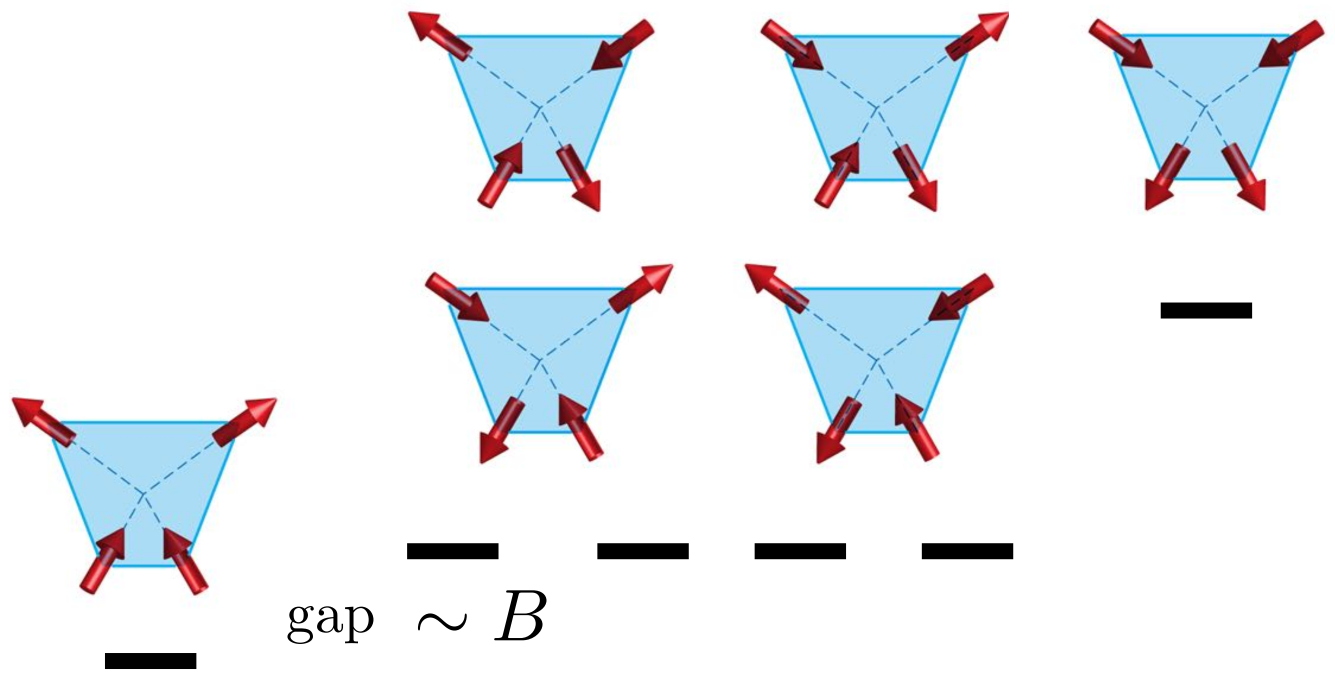
classical limit $H \sim \sum J_z S_i^z S_j^z$





$J_{\text{ring}} = 3J_{\pm}^3/(2J_{zz}^2)$

drives system to QSI



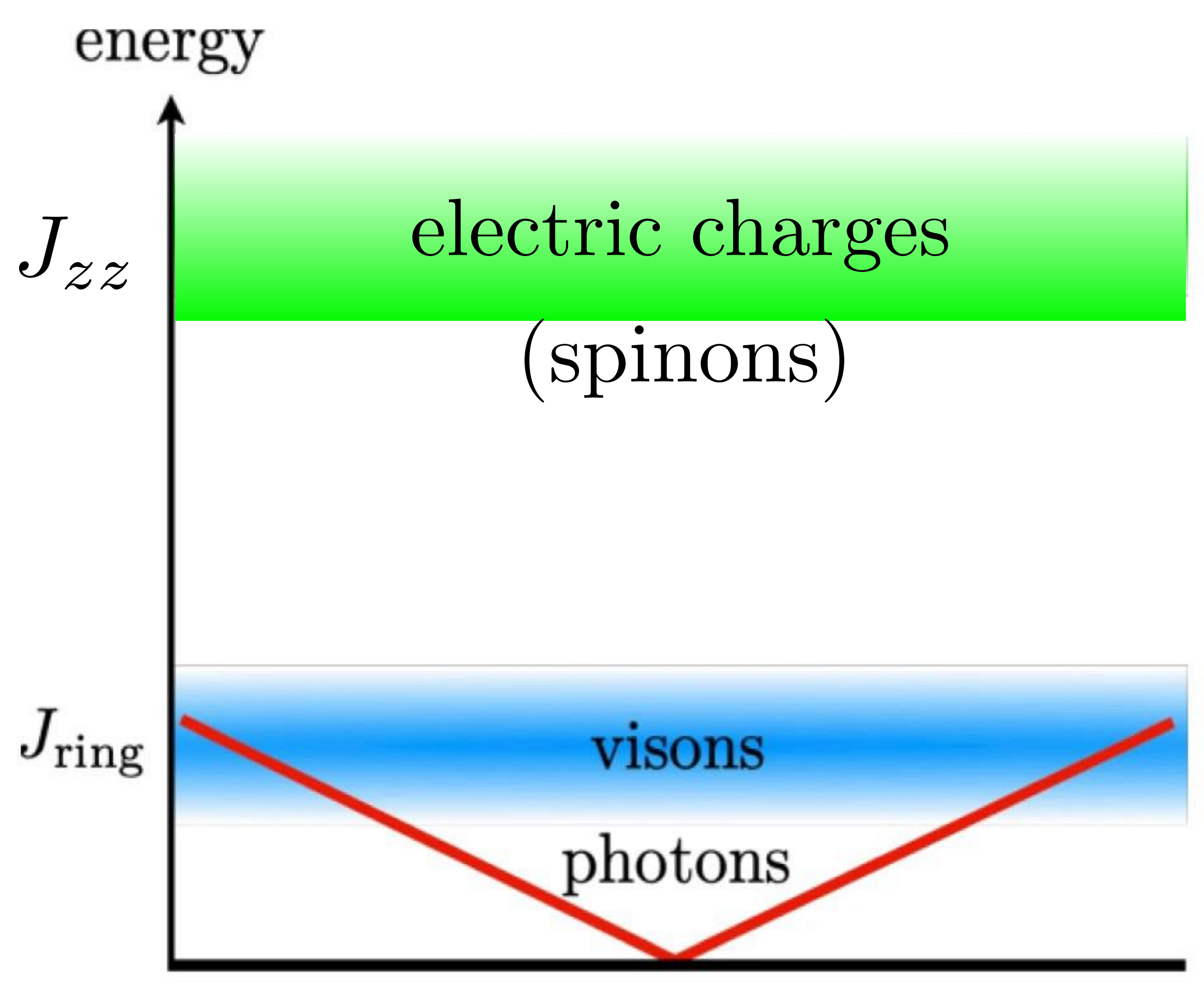
apply magnetic field

drives system to magnetic order

Control the dynamics of eQED?

Effective model (roughly speaking)

$$H = J_{zz}|\phi|^2 + J_{\pm}\phi_i e^{iA_{ij}}\phi_j^\dagger + \text{h.c.}$$



Given a material, the interactions are fixed: one material, one eQED

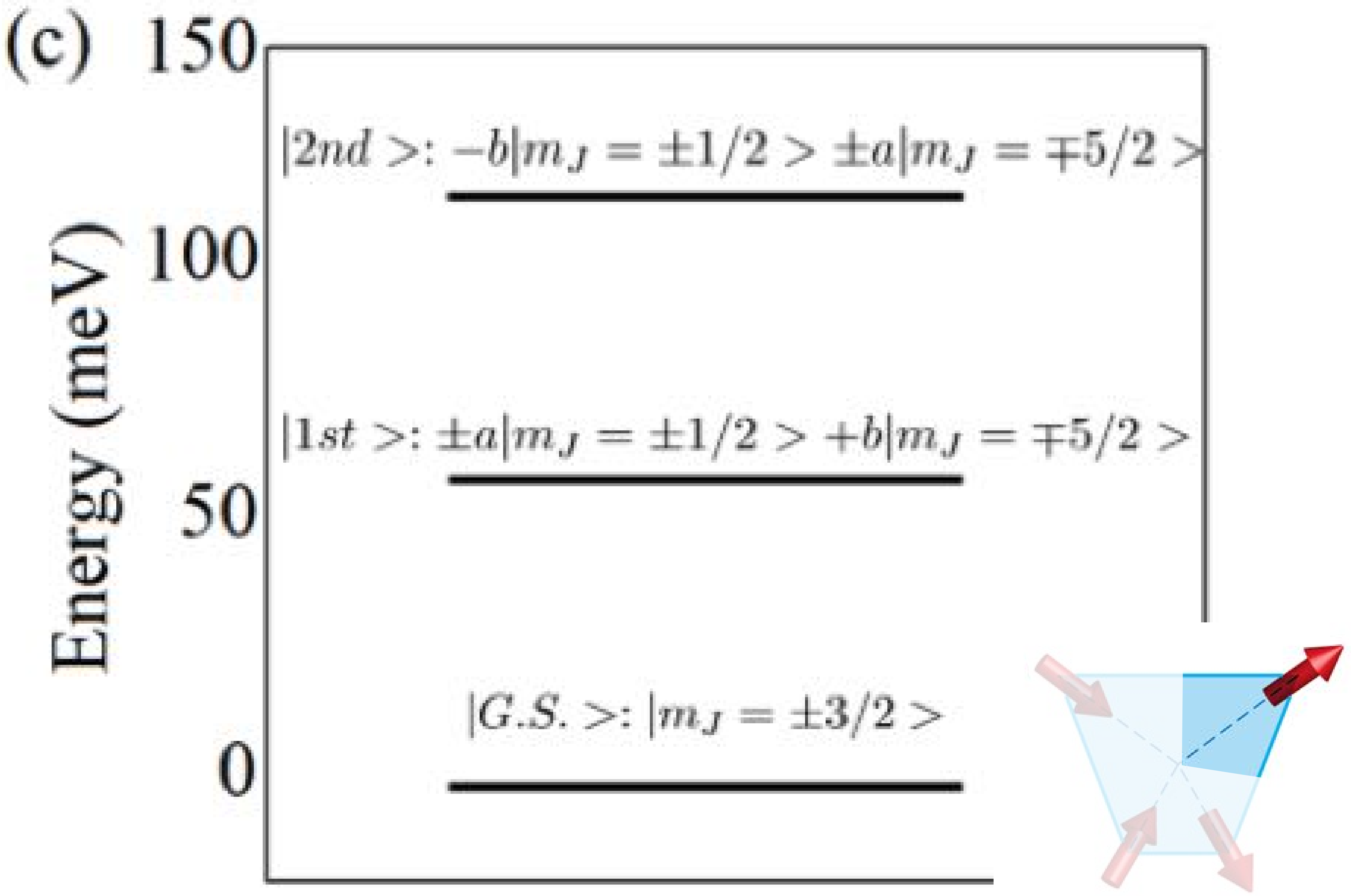
Our work: can we also control the dynamics of the eQED in QSI, so we can probe different regimes of QED in one compound?

It is possible in a class of materials called Dipolar-Octupolar QSI!

arXiv:2312.11641 A Sanders, **HY**, C Castelnovo, AH Nevidomskyy

Dipolar-Octuplar QSI

electron orbitals on each single site



Quantum Spin Ices and Topological Phases from Dipolar-Octupolar Doublets on the Pyrochlore Lattice

Yi-Ping Huang, Gang Chen, and Michael Hermele
Phys. Rev. Lett. **112**, 167203 – Published 25 April 2014

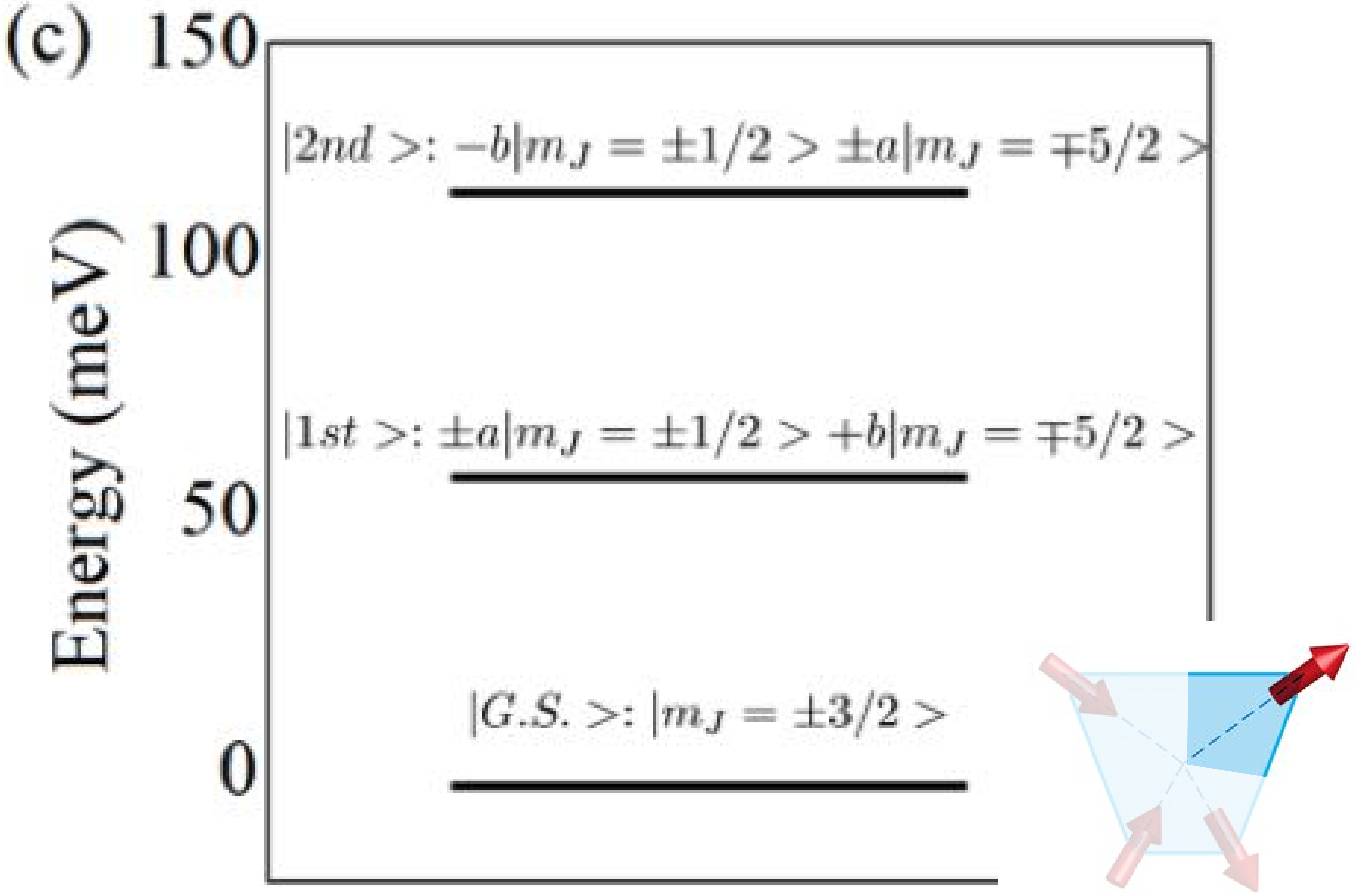
sketch of the idea: spin comes from the d electron orbitals.

lowest two states are two of the $j_z = 3/2$ states instead of $1/2$

the pseudo spin-$1/2$ operators act differently under symmetry

Dipolar-Octuplar QSI

electron orbitals on each single site



Quantum Spin Ices and Topological Phases from Dipolar-Octupolar Doublets on the Pyrochlore Lattice

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S^y has the symmetry of an octupole

S^y does not couple to applied magnetic field

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Dipolar-Octuplar QSI

S^y has the symmetry of an octupole

S^y does not couple to applied magnetic field

DO-pyrochlore lattice spin Hamiltonian

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[\sum_{\alpha = x,y,z} J_\alpha S_i^\alpha S_j^\alpha + J_{xz}(S_i^x S_j^z + S_i^y S_j^x) \right]$$

$$- \sum_i (S_i^z g_z + S_i^x g_x) \hat{\boldsymbol{z}}_i \cdot \boldsymbol{B}$$

conventional pyrochlore lattice spin Hamiltonian

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[\sum_{\alpha = x,y,z} J_\alpha S_i^\alpha S_j^\alpha + J_{xz}(S_i^x S_j^z + S_i^y S_j^x) \right]$$

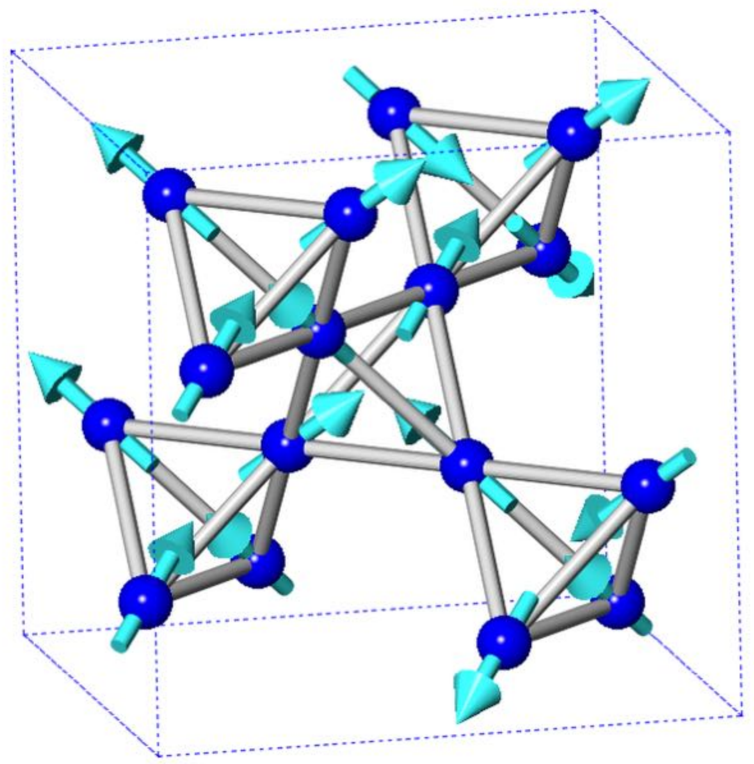
$$-g \sum_i \boldsymbol{B} \cdot \boldsymbol{S}_i + \text{(other spin-spin terms)}$$

2 charge states

1 charge states

ground states

classical limit $H \sim \sum J_y S_i^y S_j^y$



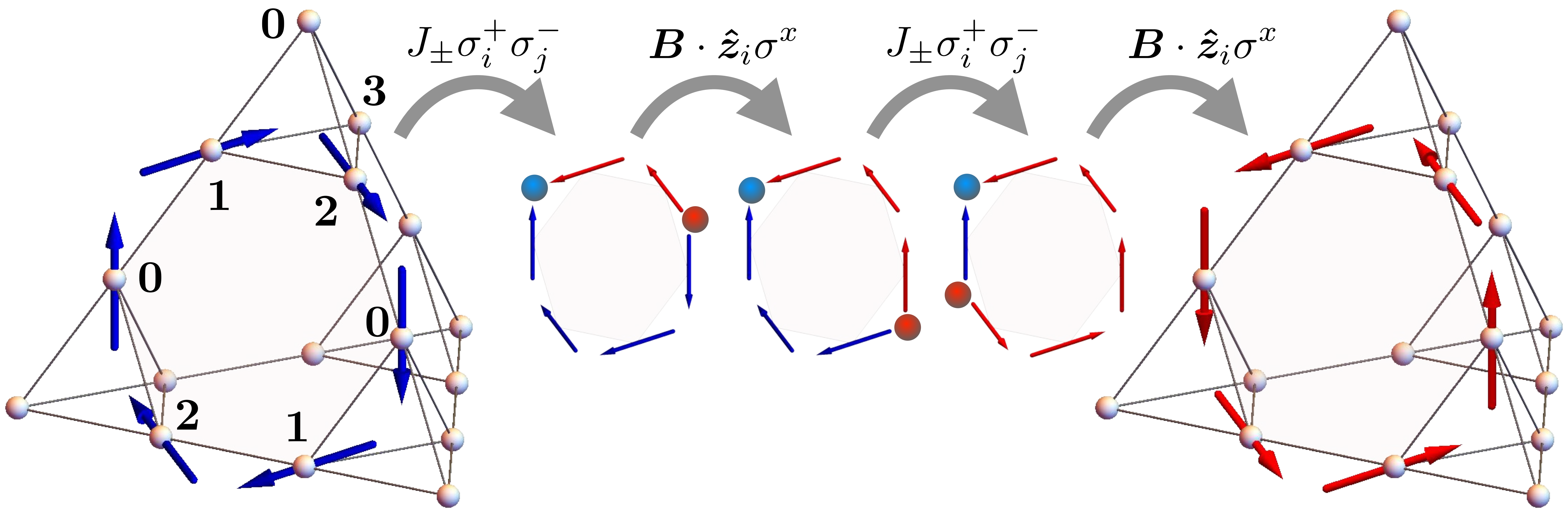
Emergent QED in DO-QSI

DO-pyrochlore lattice spin Hamiltonian

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[\sum_{\alpha=x,y,z} J_\alpha S_i^\alpha S_j^\alpha + J_{xz}(S_i^x S_j^z + S_i^y S_j^x) \right] - \sum_i (S_i^z g_z + S_i^x g_x) \hat{\boldsymbol{z}}_i \cdot \boldsymbol{B}$$

$$\mathcal{H}_I = \sum_{\langle ij \rangle} J_y \sigma_i^z \sigma_j^z, \tag{2}$$

$$\mathcal{H}' = \sum_{\langle ij \rangle} \frac{J_\pm}{2}(\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+) - \sum_i \frac{\hat{\boldsymbol{z}}_i \cdot \boldsymbol{B}}{2}(\sigma_i^+ + \sigma_i^-). \tag{3}$$



Emergent QED in DO-QSI

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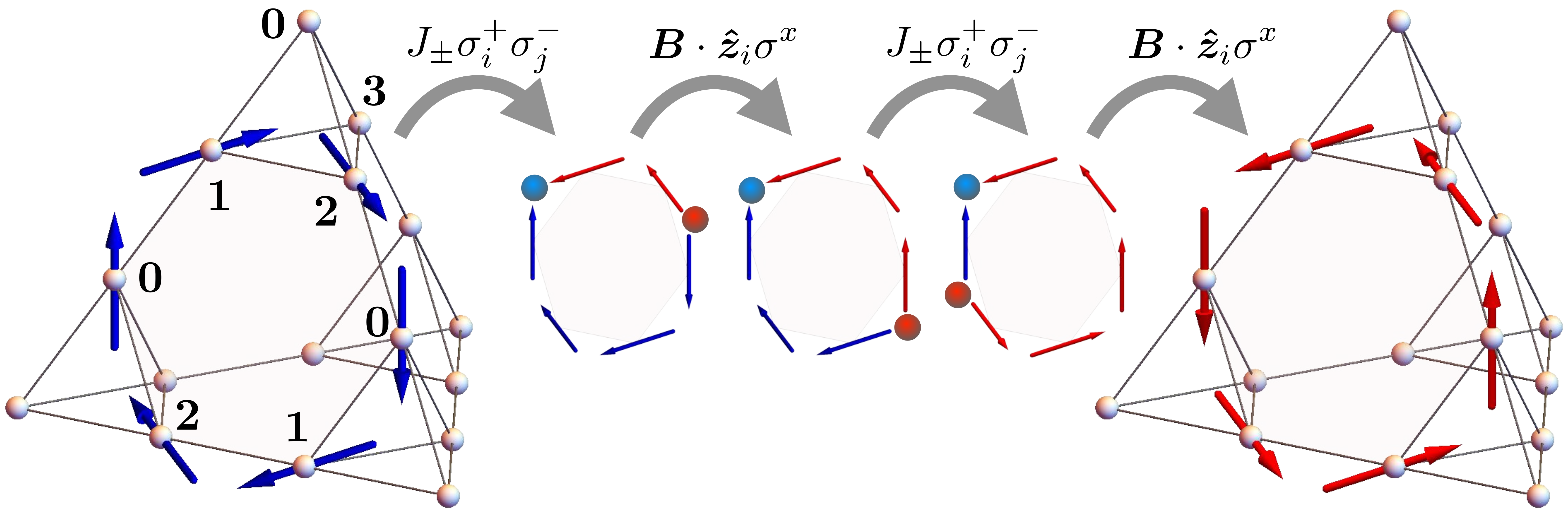

$$\mathcal{H}_{\text{eff}} = (1 - \mathcal{P}) \left[-\mathcal{H}' \frac{\mathcal{P}}{\mathcal{H}_I} \mathcal{H}' + \mathcal{H}' \frac{\mathcal{P}}{\mathcal{H}_I} \mathcal{H}' \frac{\mathcal{P}}{\mathcal{H}_I} \mathcal{H}' + \dots \right] (1 - \mathcal{P}),$$

$$= \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

Emergent QED in DO-QSI

DO-pyrochlore lattice spin Hamiltonian

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[\sum_{\alpha = x,y,z} J_\alpha S_i^\alpha S_j^\alpha + J_{xz}(S_i^x S_j^z + S_i^y S_j^x) \right] - \sum_i (S_i^z g_z + S_i^x g_x) \hat{\boldsymbol{z}}_i \cdot \boldsymbol{B}$$

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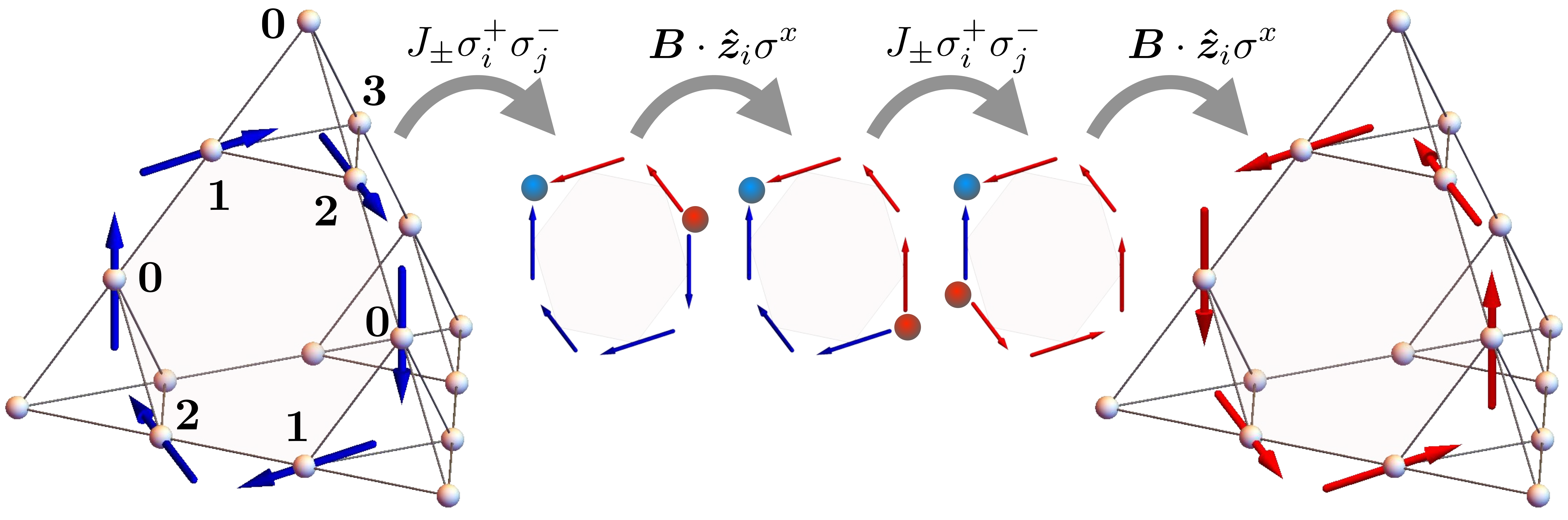


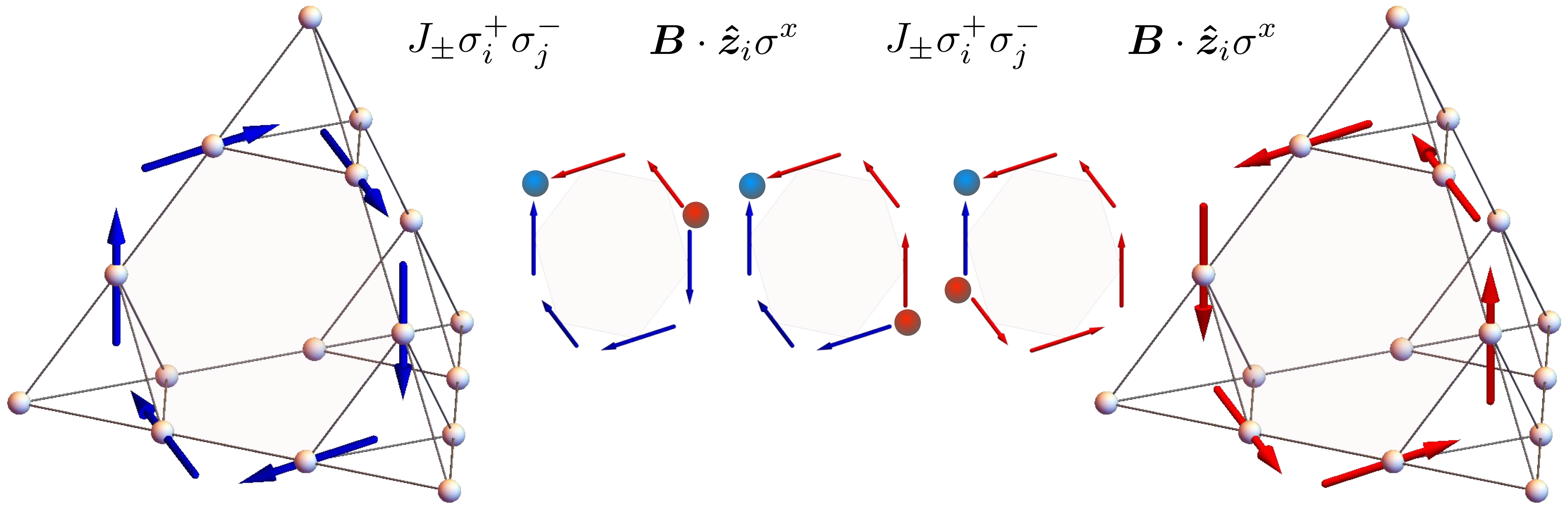
$$\mathcal{H}_{\text{eff}} = (1 - \mathcal{P}) \left[-\mathcal{H}' \frac{\mathcal{P}}{\mathcal{H}_I} \mathcal{H}' + \mathcal{H}' \frac{\mathcal{P}}{\mathcal{H}_I} \mathcal{H}' \frac{\mathcal{P}}{\mathcal{H}_I} \mathcal{H}' + \dots \right] (1 - \mathcal{P}),$$

$$= \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

$$g_p = \frac{3 J_\pm^3}{2 J_y^2} + \frac{5\sqrt{3} J_\pm^2}{12 J_y^3} (\hat{\boldsymbol{z}}_p \cdot \boldsymbol{B})^2.$$

p=0,1,2,3 for 4 types of rings

Emergent QED in DO-QSI



$$\mathcal{H}_{\text{eff}} = \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

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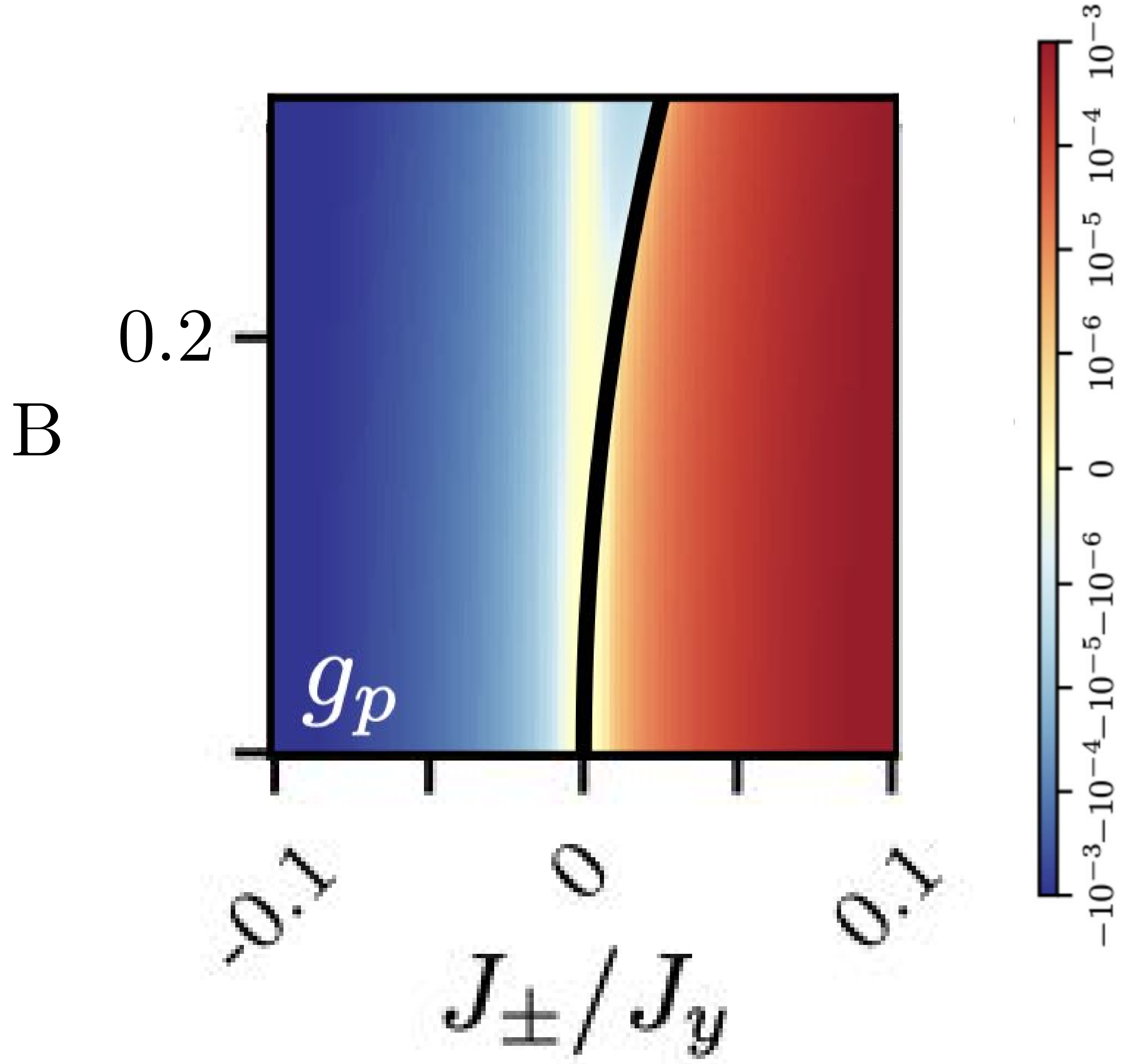
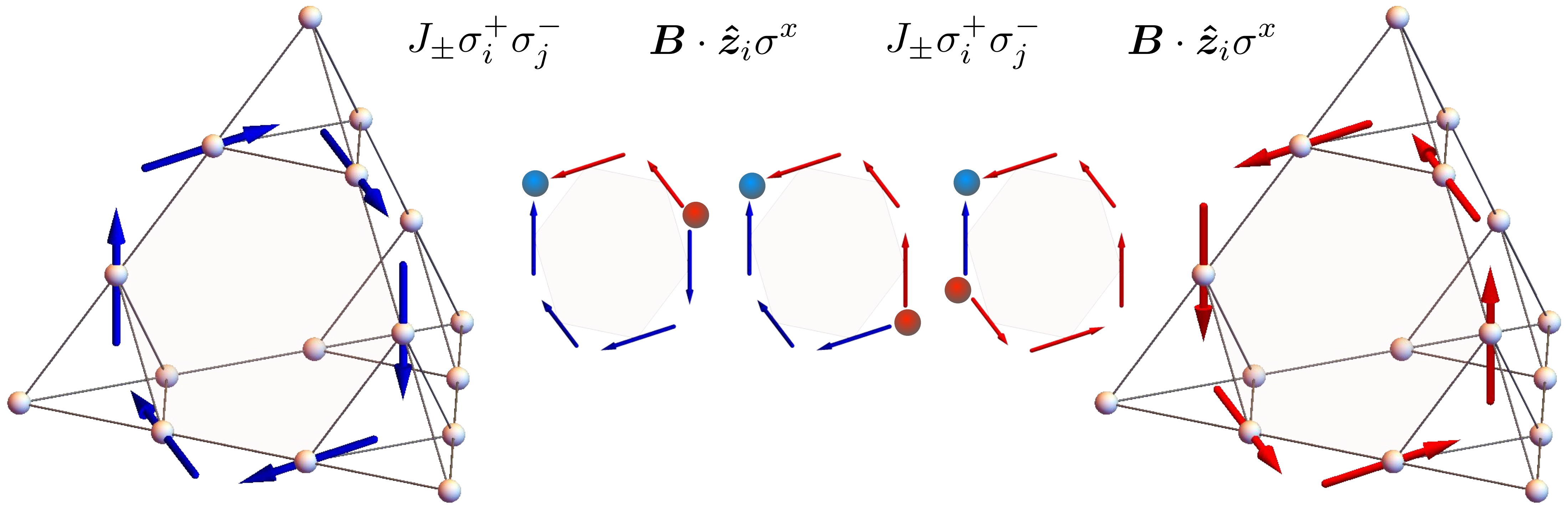
$$\boldsymbol{B} \parallel [100]: \quad g_p = \frac{3J_\pm^3}{2J_y^2} + \frac{5B^2J_\pm^2}{12J_y^3}.$$

four rings have the same dynamics



also see: Zhou, Desrochers, Kim arXiv:2406.18650

Emergent QED in DO-QSI



$$\mathcal{H}_{\rm eff} = \sum_{\boldsymbol{R}\in\{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

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1. We can tune the speed of light!

$$\boldsymbol{B} \parallel [100]: \quad g_p = \frac{3J_\pm^3}{2J_y^2} + \frac{5B^2J_\pm^2}{12J_y^3}.$$

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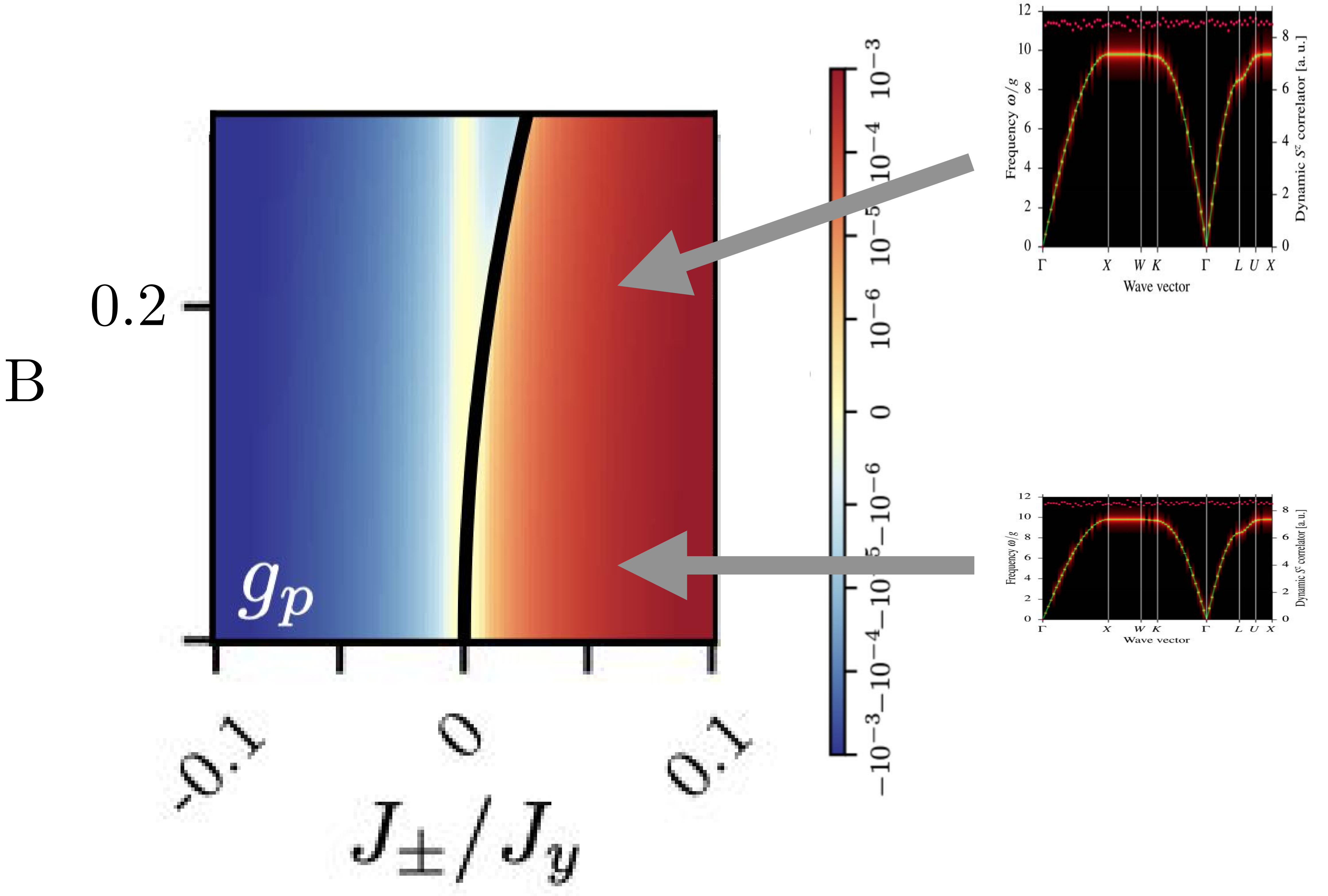
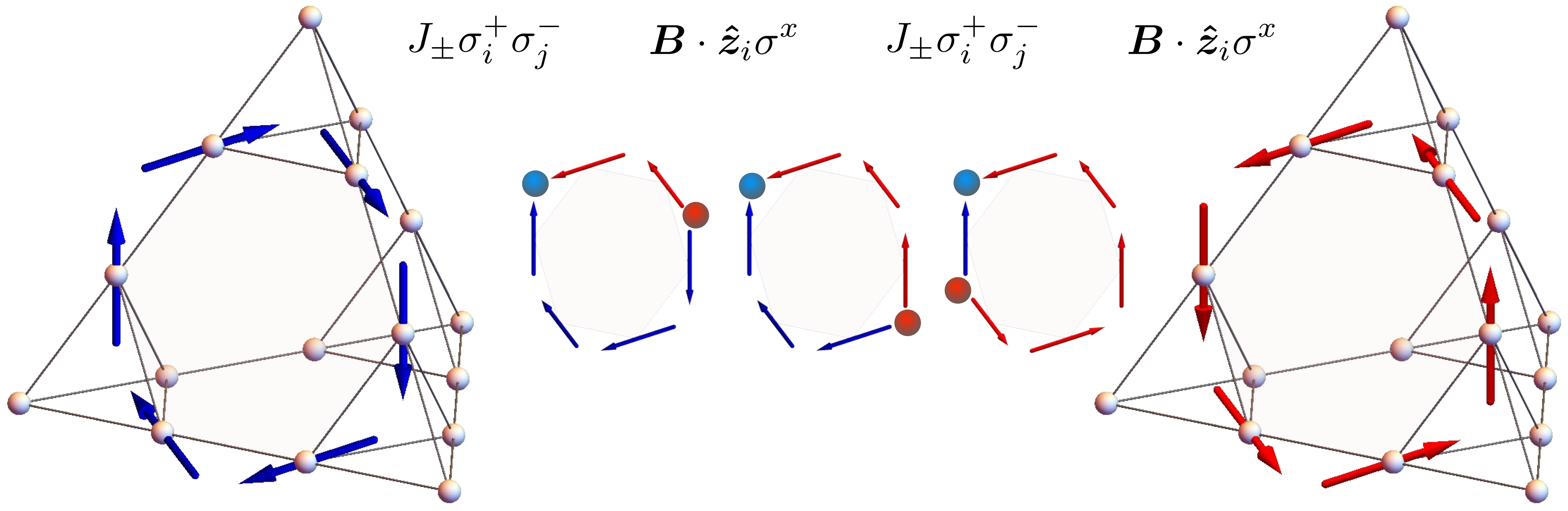


Emergent QED in DO-QSI



$$\mathcal{H}_{\text{eff}} = \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

$$g_p = \frac{3J_\pm^3}{2J_y^2} + \frac{5\sqrt{3}J_\pm^2}{12J_y^3}(\hat{\boldsymbol{z}}_p \cdot \boldsymbol{B})^2.$$

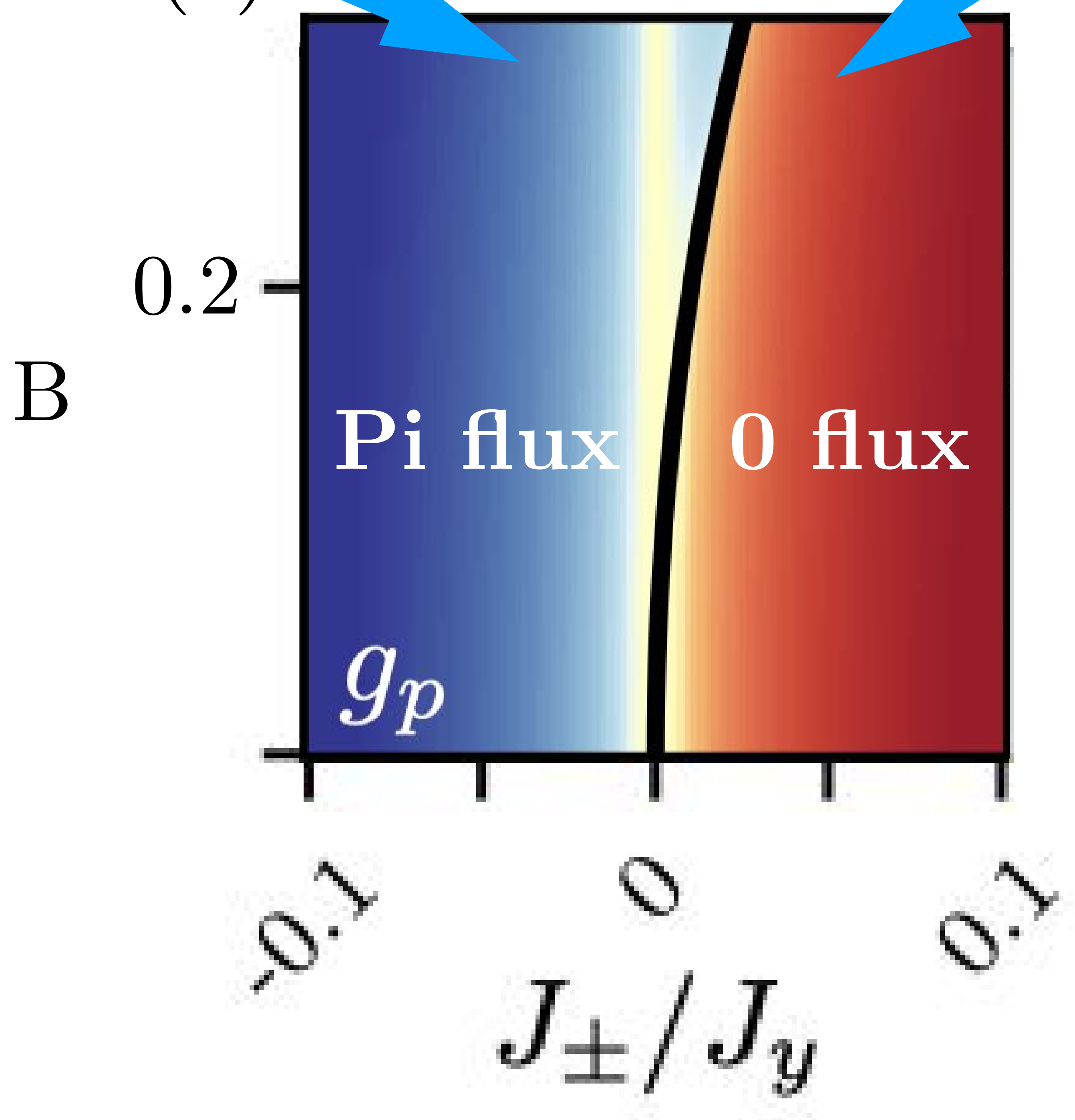
1. We can tune the speed of light.
2. We can also induce quantum phase transition.

$$\boldsymbol{B} \parallel [100]: \quad g_p = \frac{3J_\pm^3}{2J_y^2} + \frac{5B^2J_\pm^2}{12J_y^3}.$$

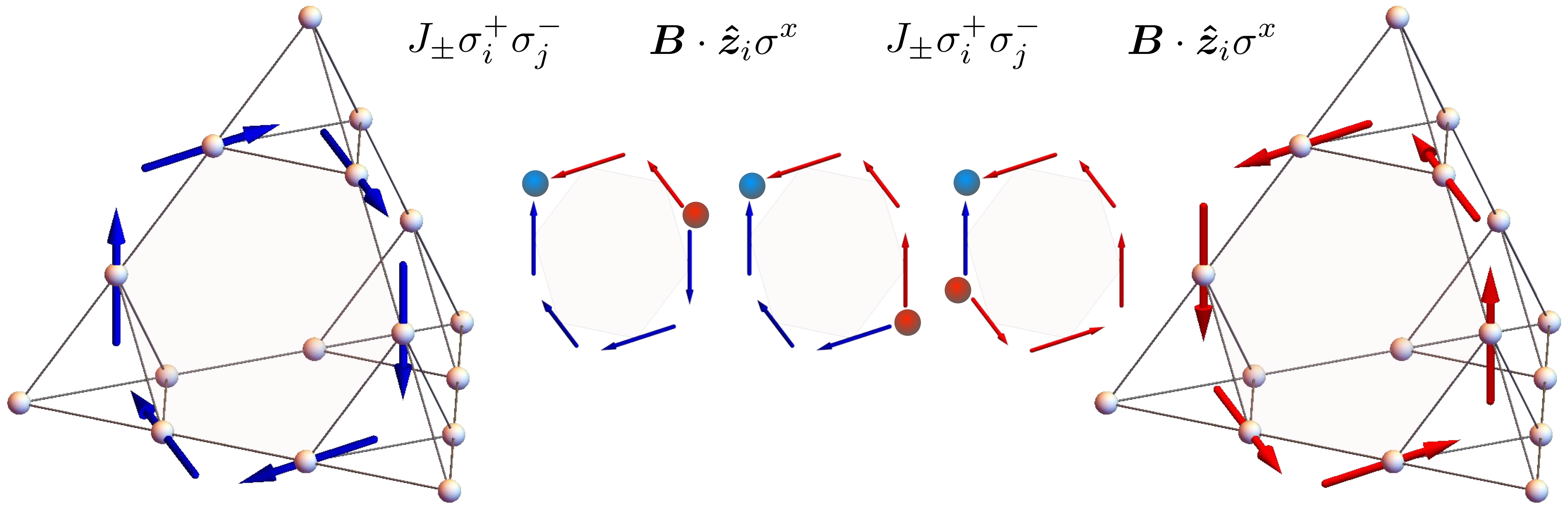
four rings have the same dynamics

$H \sim -\cos(b)$

$H \sim +\cos(b)$

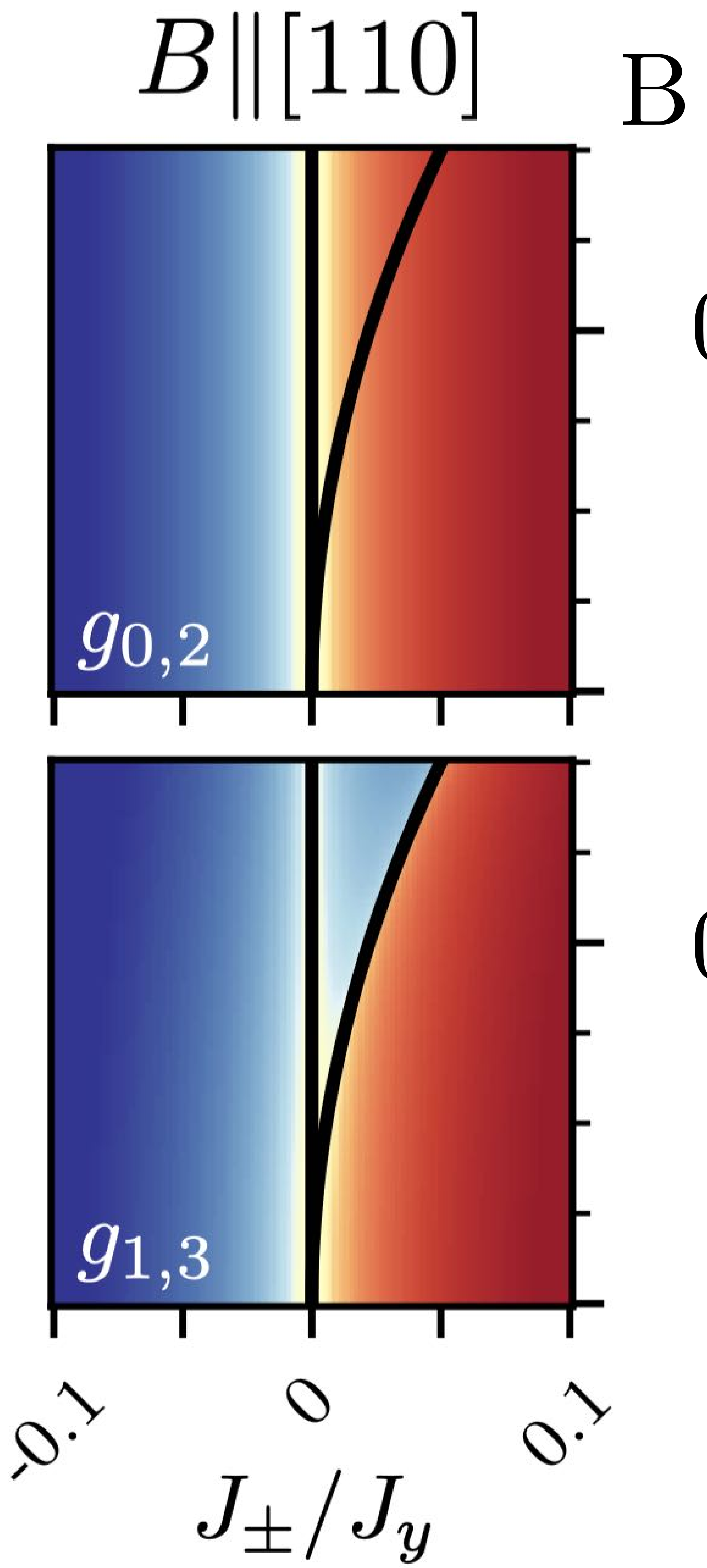


Emergent QED in DO-QSI

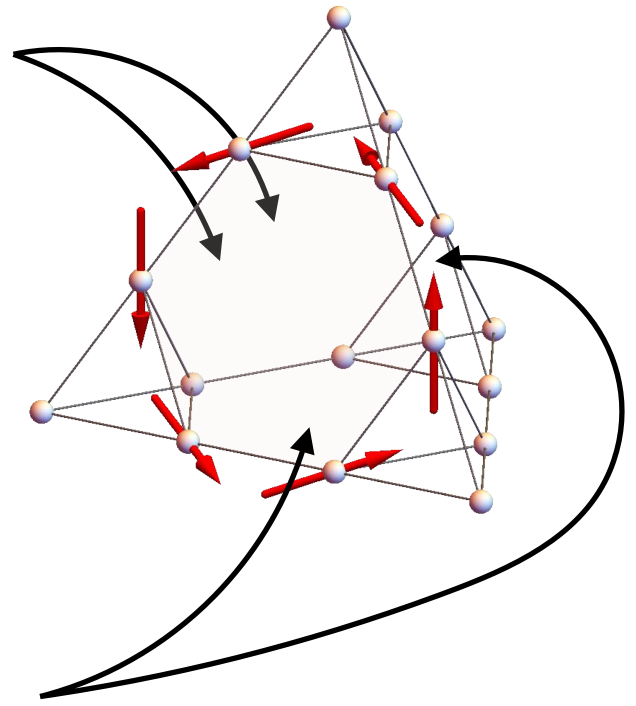


$$\mathcal{H}_{\text{eff}} = \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

$$g_p = \frac{3J_\pm^3}{2J_y^2} + \frac{5\sqrt{3}J_\pm^2}{12J_y^3}(\hat{\boldsymbol{z}}_p \cdot \boldsymbol{B})^2.$$



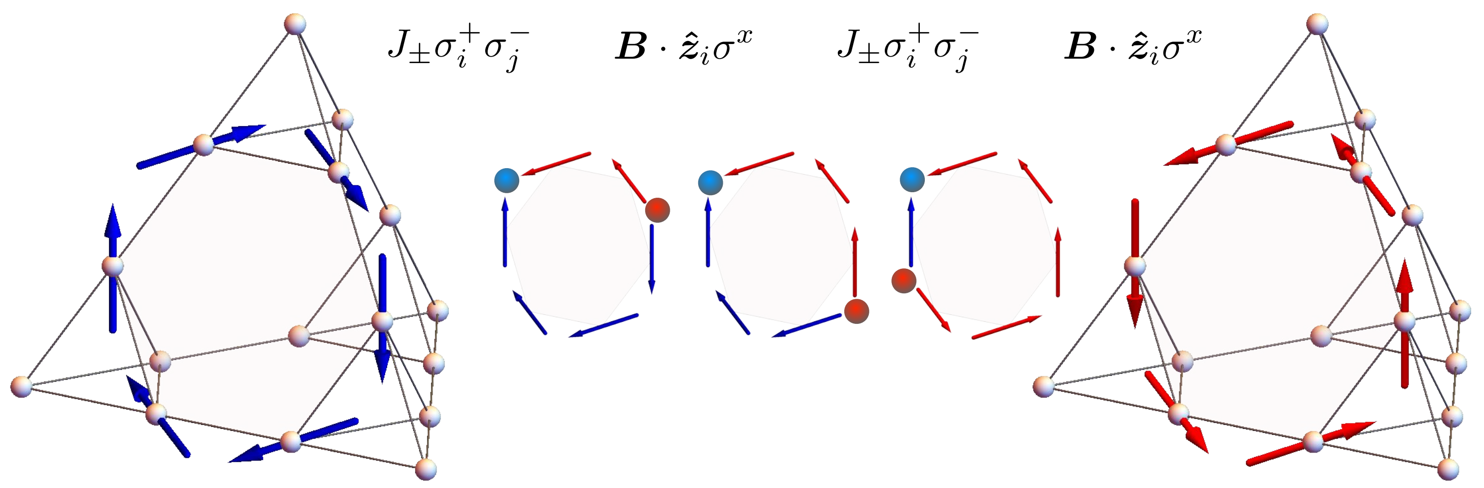
$$\frac{3J_\pm^3}{2J_y^2}$$



$$\frac{3J_\pm^3}{2J_y^2} + \frac{5B^2J_\pm^2}{6J_y^3},$$

also see: Zhou, Desrochers, Kim arXiv:2406.18650

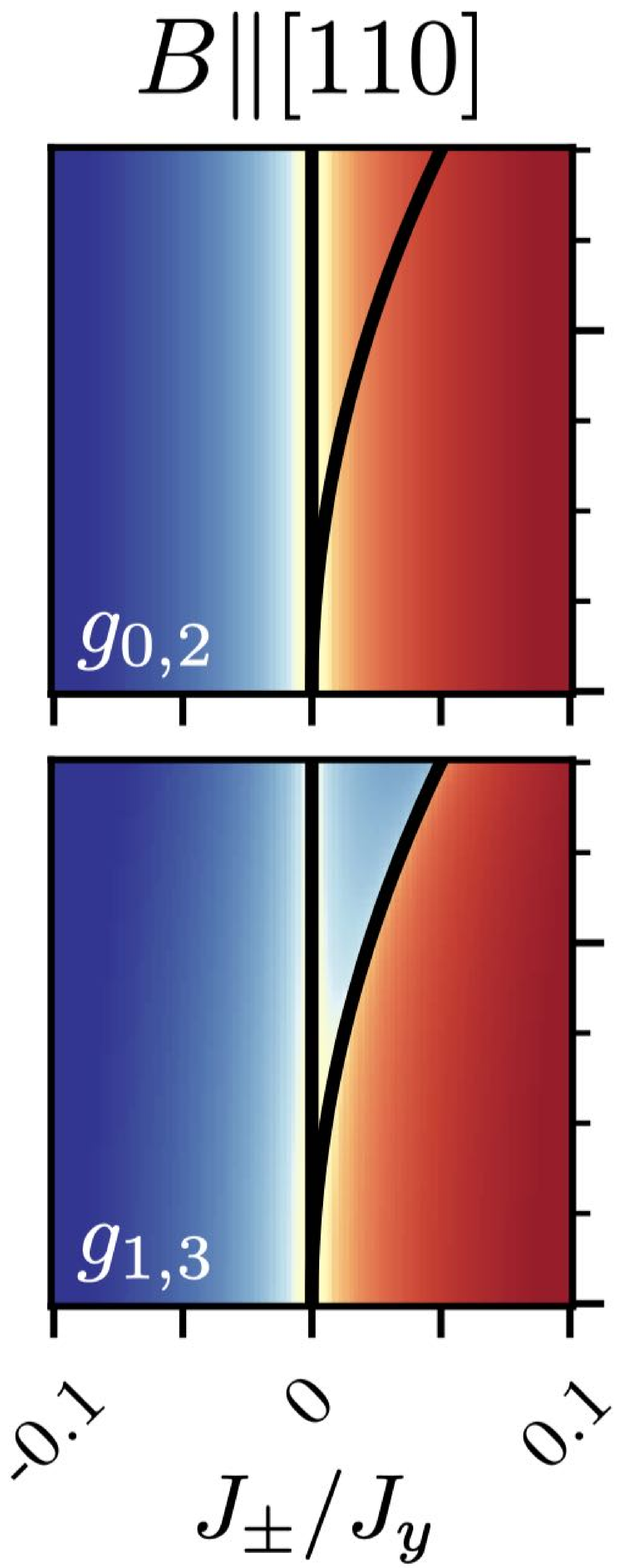
Emergent QED in DO-QSI

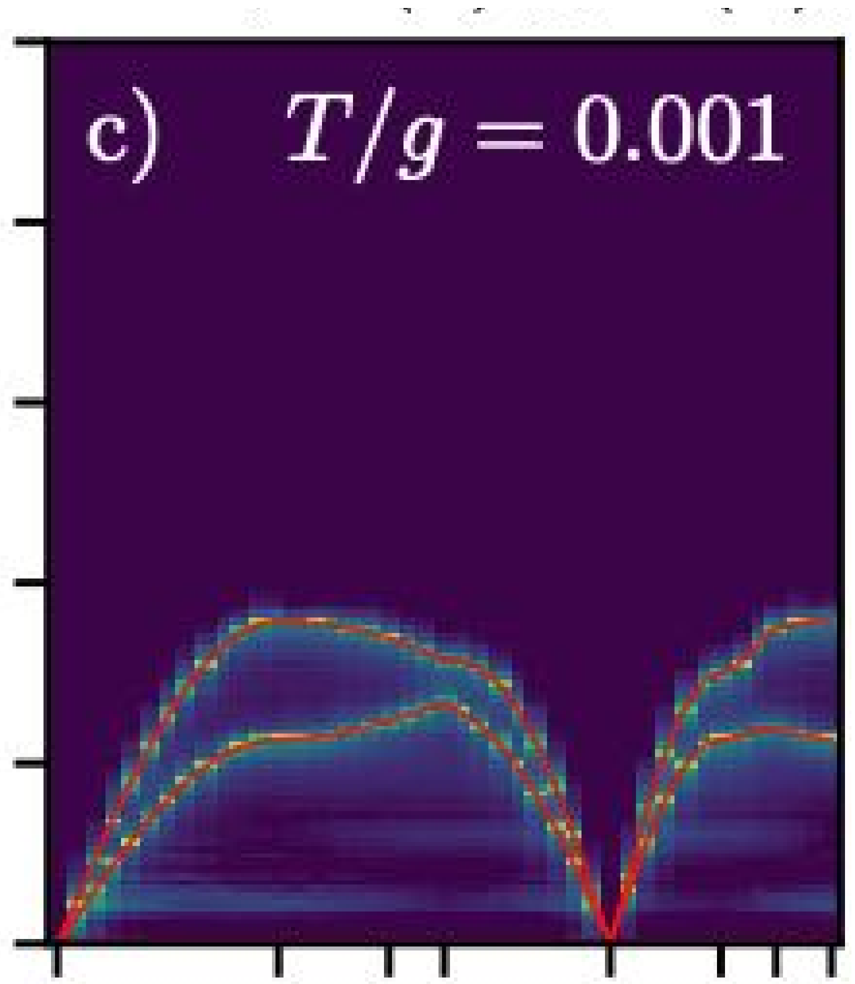


$$\mathcal{H}_{\text{eff}} = \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

$$g_p = \frac{3J_\pm^3}{2J_y^2} + \frac{5\sqrt{3}J_\pm^2}{12J_y^3}(\hat{\boldsymbol{z}}_p \cdot \boldsymbol{B})^2.$$

3. We can realize new emergent birefringence.

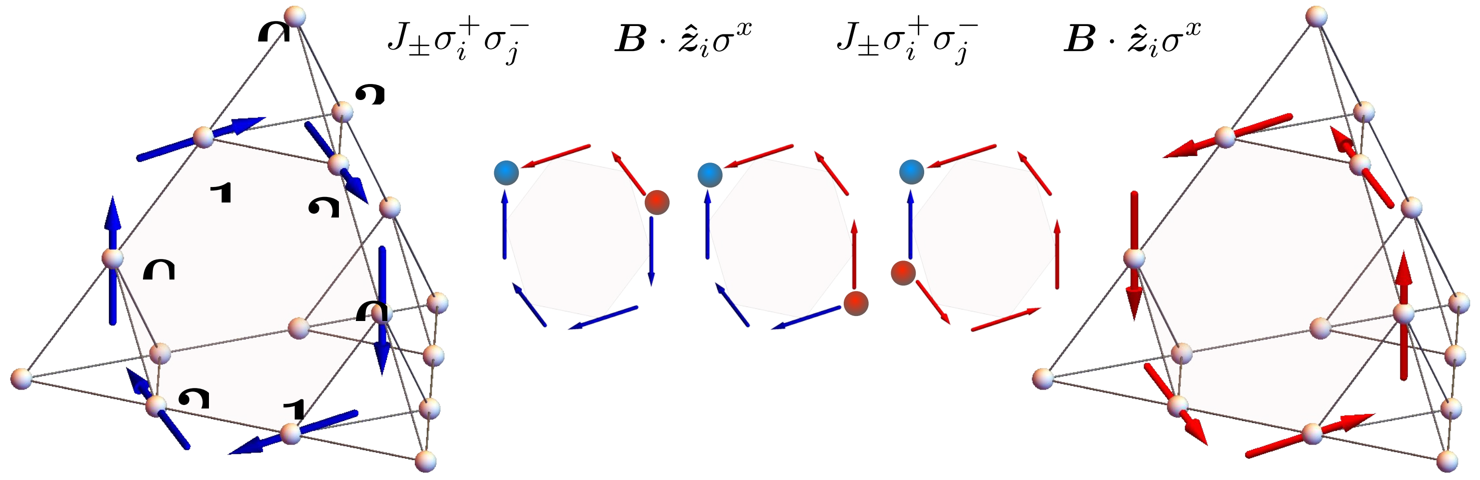




photon dispersion:

birefringence: two photon polarizations have different speeds of light and refraction rates.

Emergent QED in DO-QSI



$$\mathcal{H}_{\text{eff}} = \sum_{\boldsymbol{R}\in\{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

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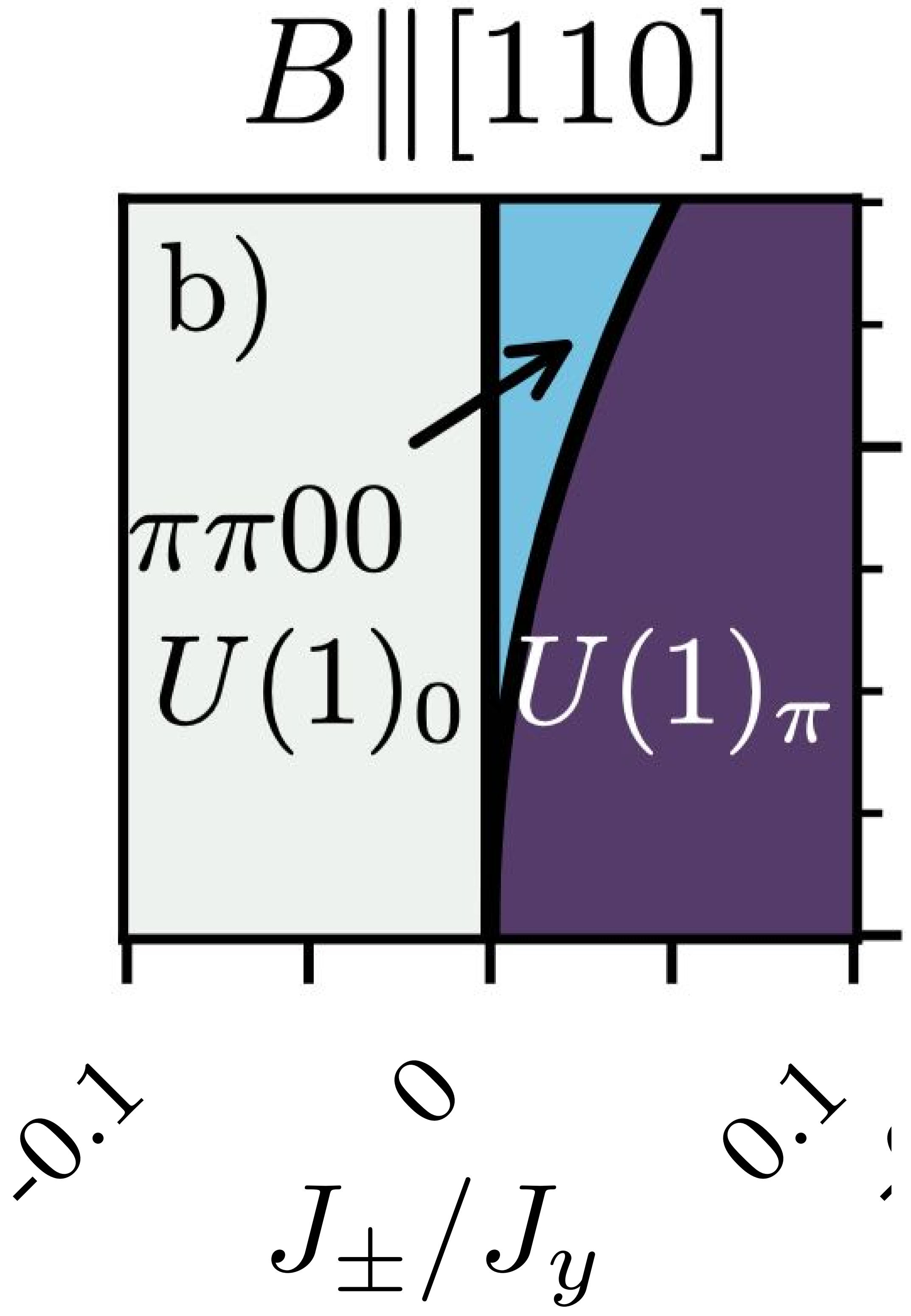
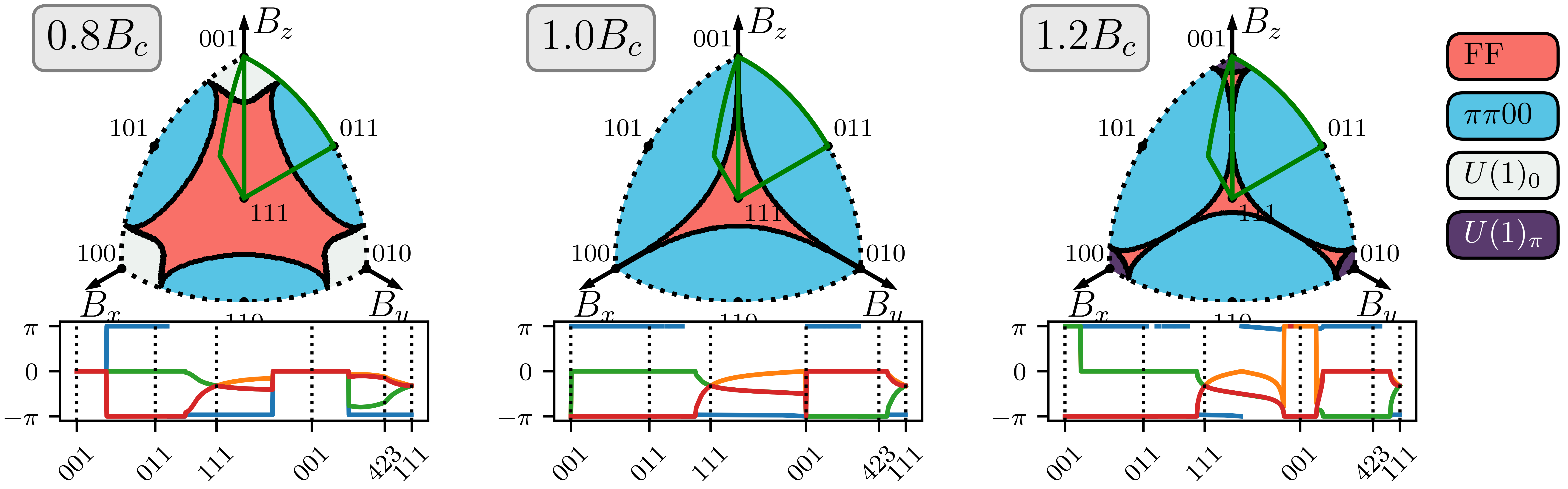
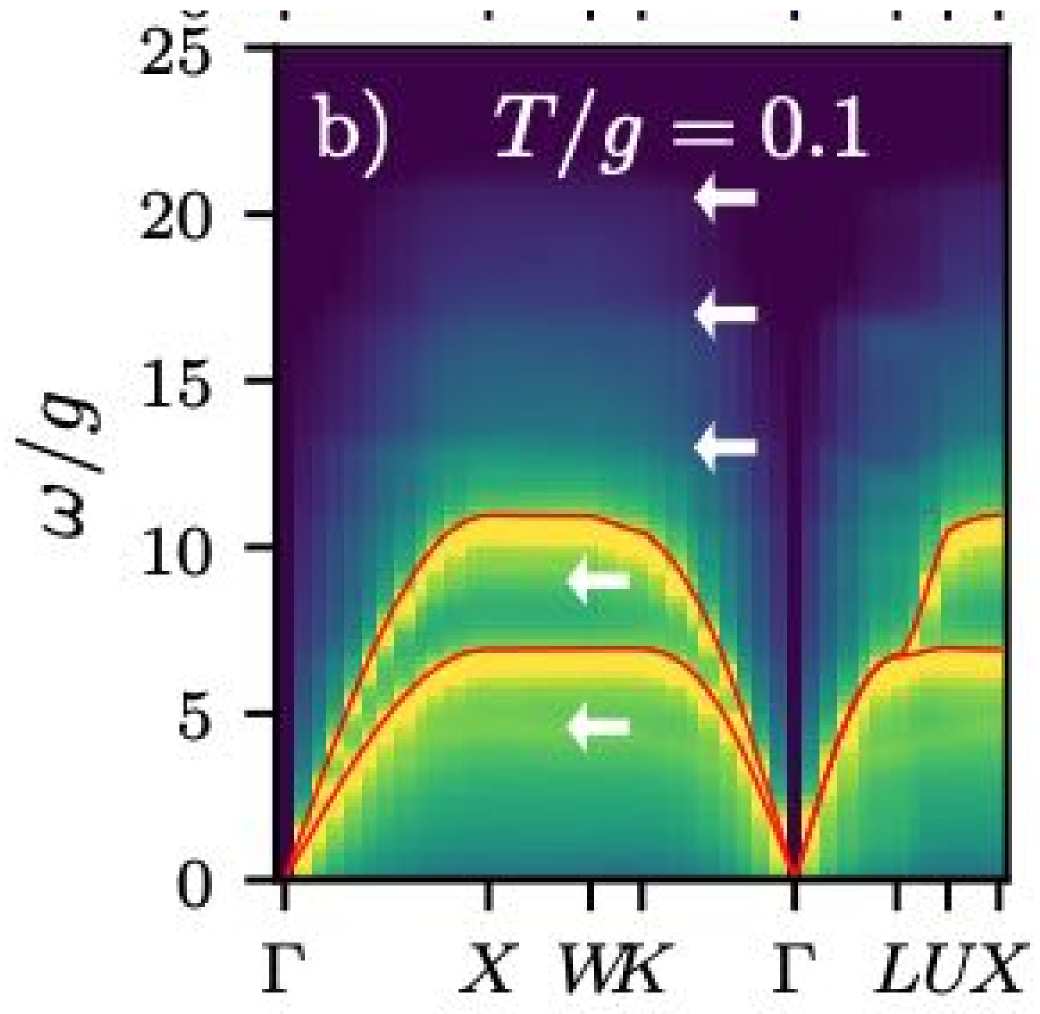
3. We can realize new emergent birefringence.
4. We have new quantum liquid phase(s)



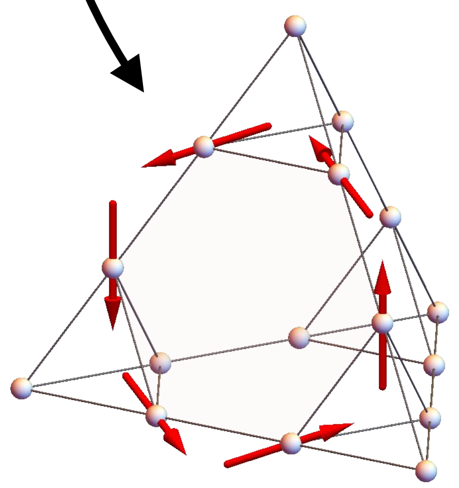
A new eQED phase of different gauge background

Emergent QED in DO-QSI





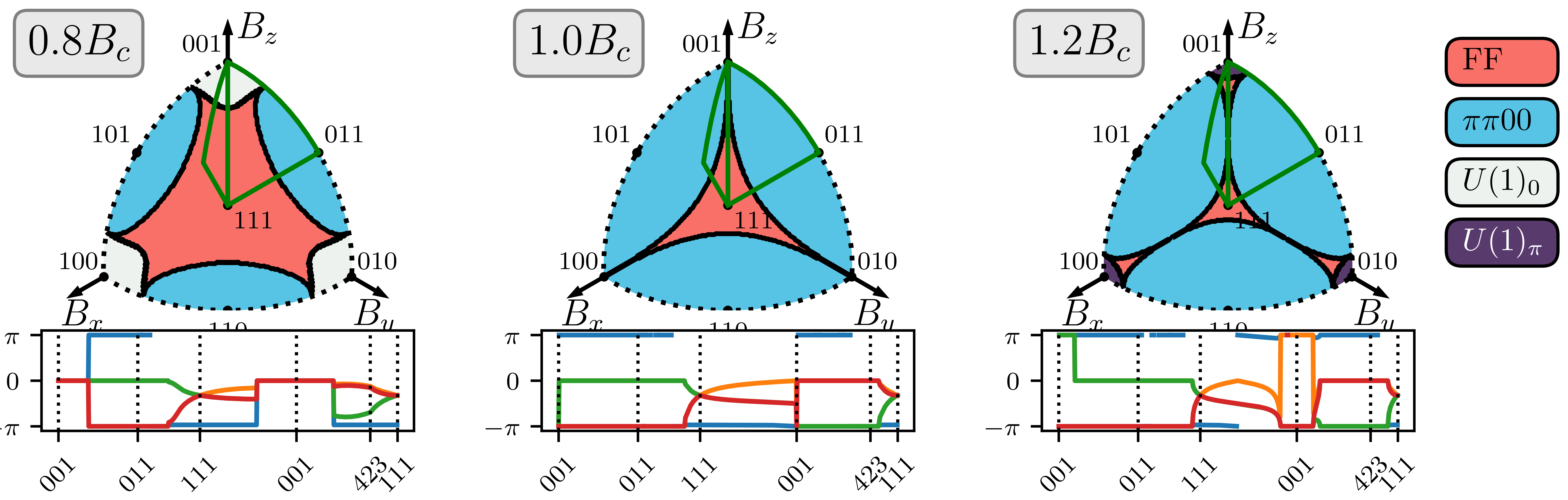
background b-flux on different hexagons

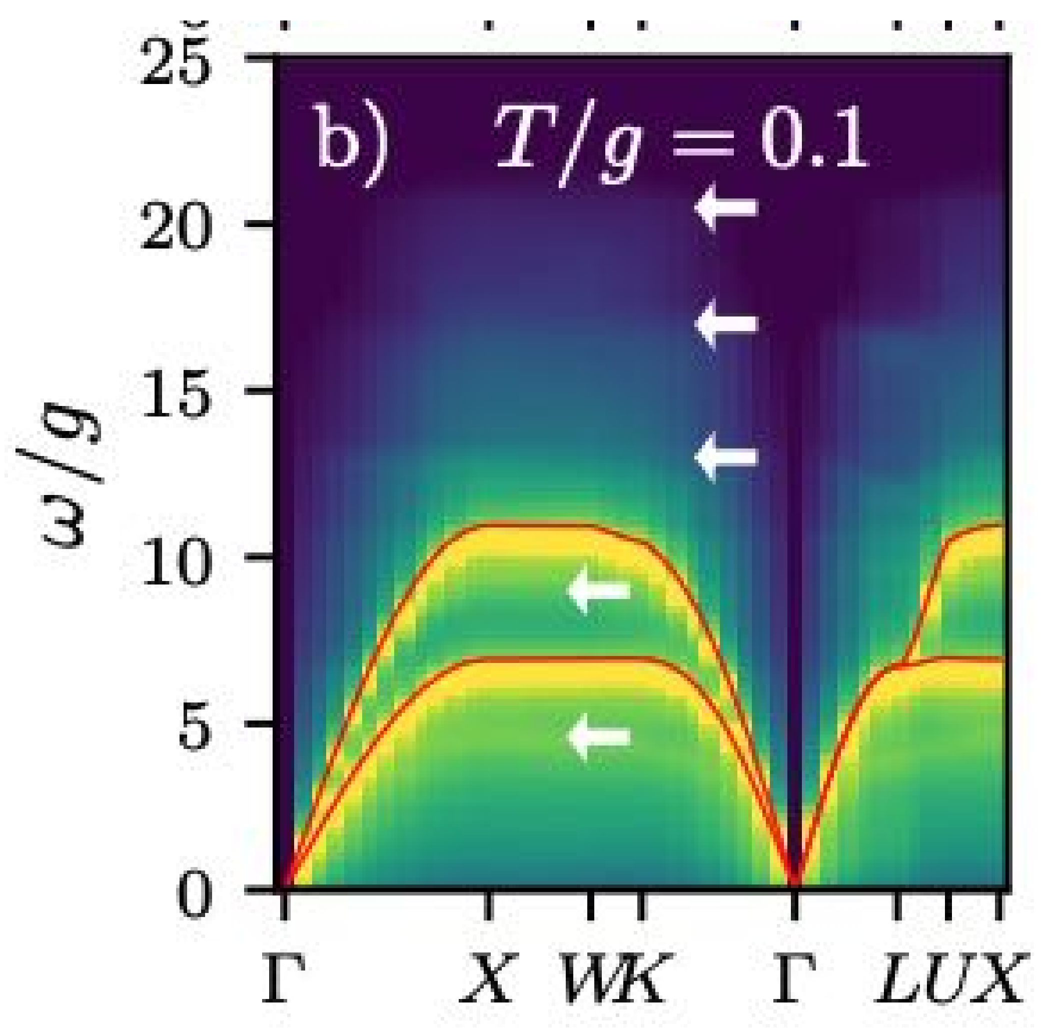


Possible three-photon couplings

C. L. Basham and P. K. Kabir
Phys. Rev. D **15**, 3388 – Published 1 June 1977

Emergent QED in DO-QSI





1. We can tune the speed of light.
2. We can also induce quantum phase transition.
3. We have new quantum liquid phase(s)
4. We can realize new emergent birefringence.
5. We can realize non-linear photon coupling of b^3 in frustrated flux phase.

Possible three-photon couplings

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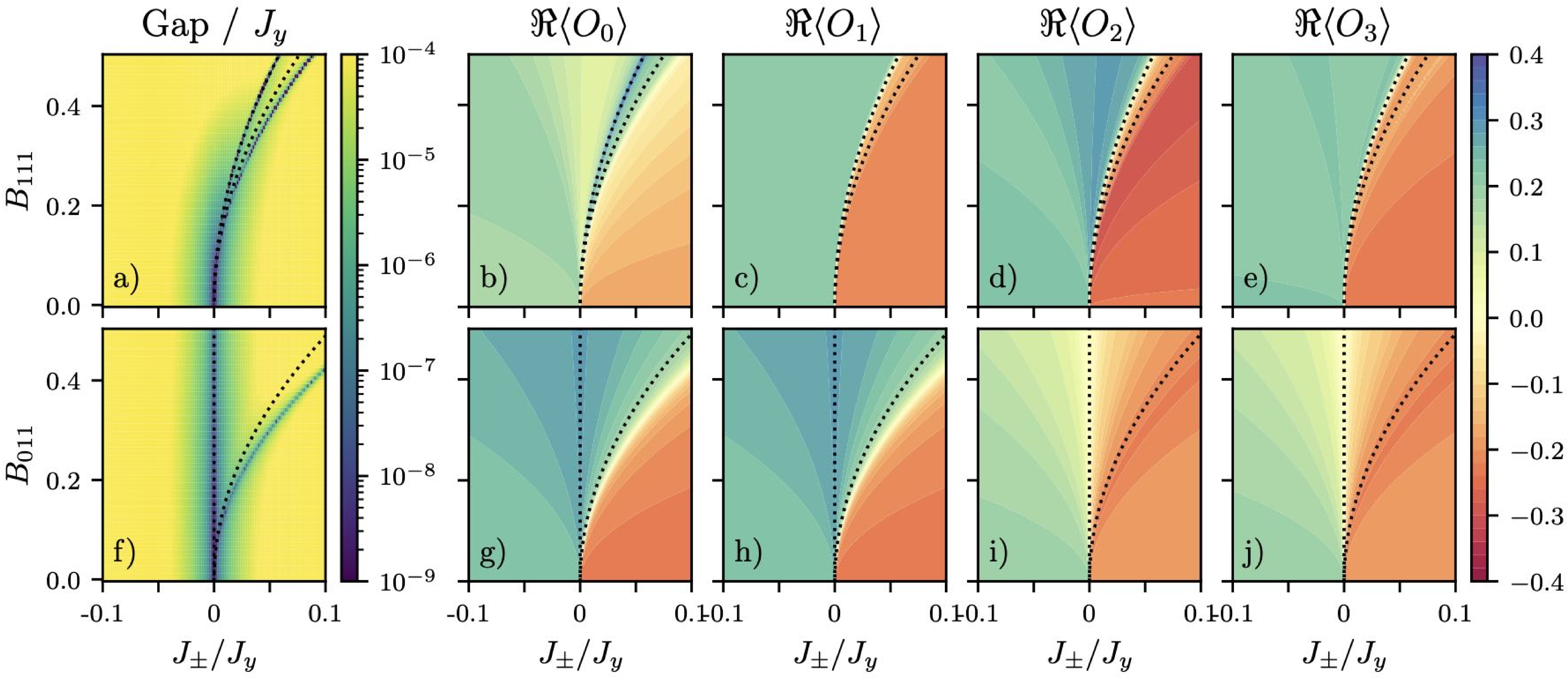
Exact diagonlizations



ED Expectation values of ring-flip operators on a 72-site cluster subject to (a-e) 111 and (f-j) 011 magnetic fields.

Black dotted lines indicate the semiclassical phase boundaries

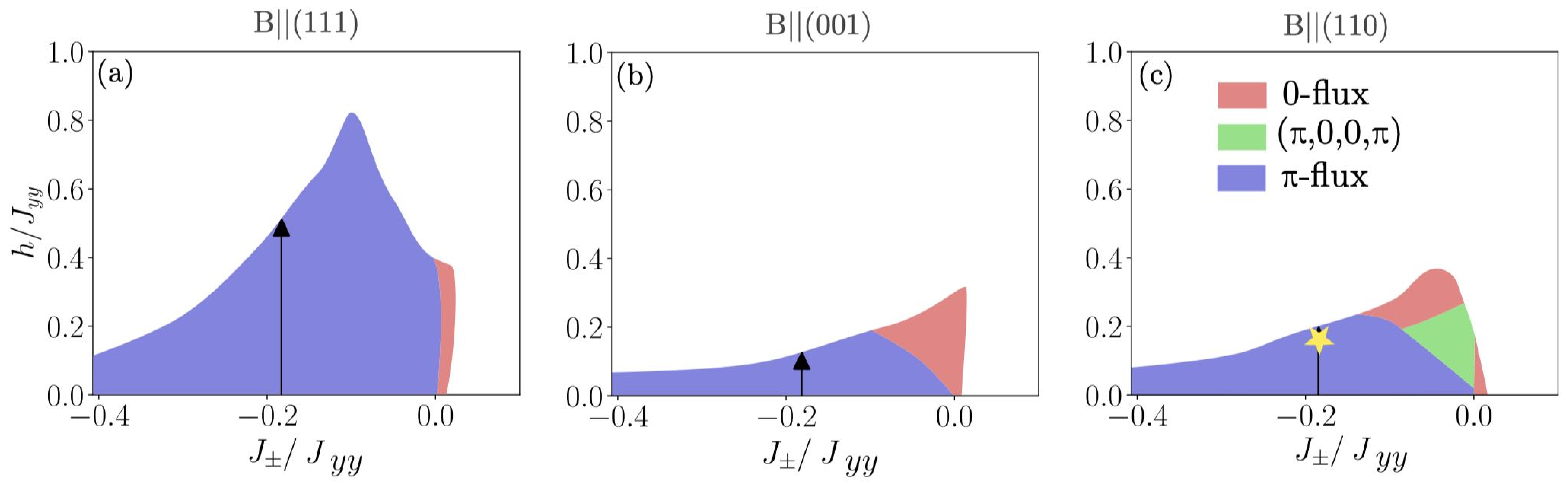
Emergent QED in DO-QSI

$$\mathcal{H} = \sum_{\langle ij \rangle} \left[\sum_{\alpha=x,y,z} J_\alpha S_i^\alpha S_j^\alpha + J_{xz}(S_i^x S_j^z + S_i^y S_j^x) \right] - \sum_i (S_i^z g_z + S_i^x g_x) \hat{\boldsymbol{z}}_i \cdot \boldsymbol{B}$$

	J_y	J_x	J_z	J_{xz}
$Ce_2Sn_2O_7$	0.069	0.001	0.001	0
$Ce_2Hf_2O_7$	0.044	0.011	0.016	-0.002
$Ce_2Zr_2O_7$	0.062	0.063	0.011	0

Cerium Tin/Stannum Hafnium Zirconium

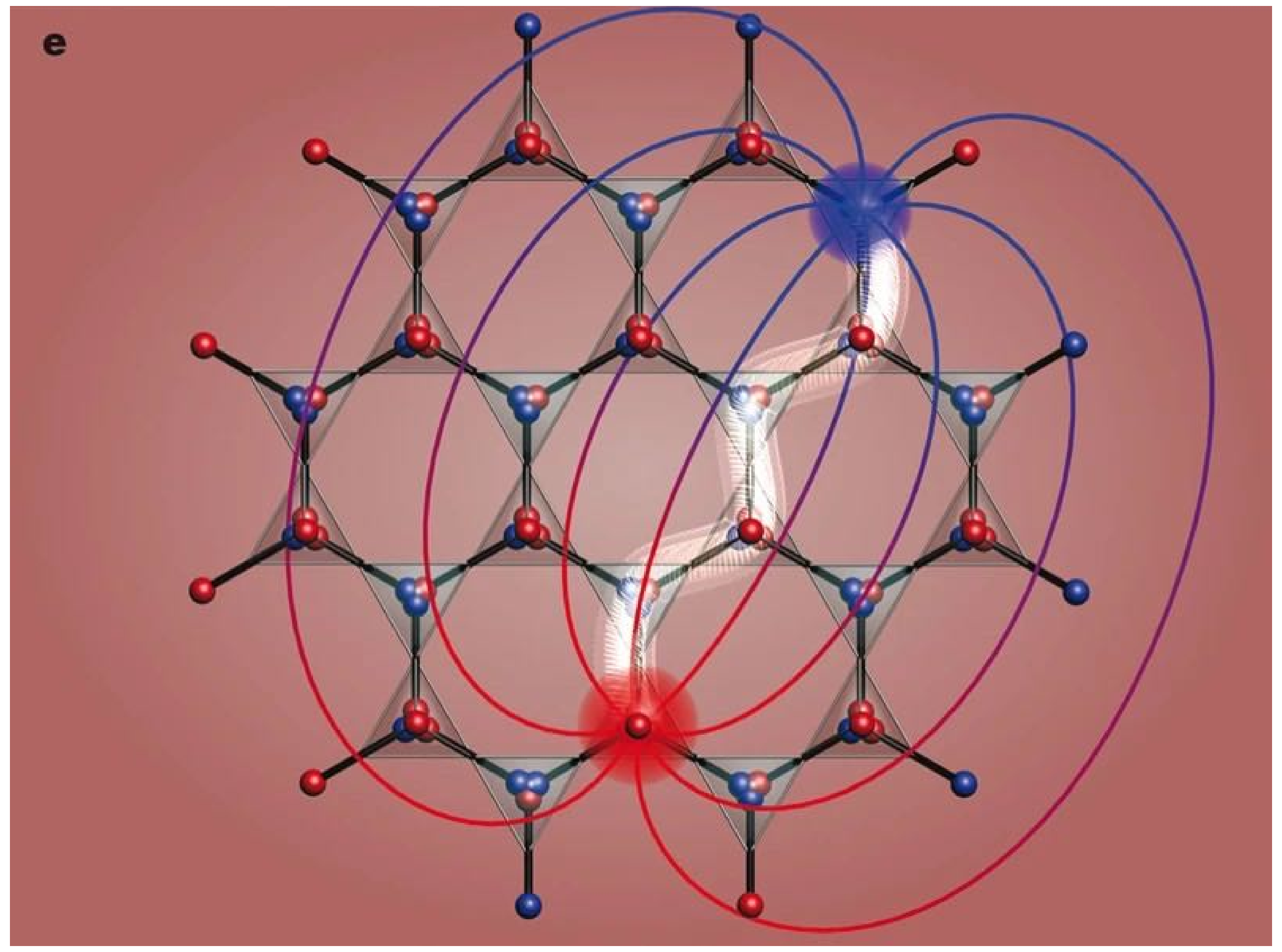
Various works by Romain Sibille, Bruce Gaulin, Pengcheng Dai



arXiv: 2502.14067, Z Zhou, Y-B Kim

According to GMFT, such exotic phase transitions may not happen to current materials.

Quantum Spin Ice: A universe in a grain of sand



Effective theory: **3D U(1) Quantum Electrodynamics**

1. Ground state: gapless topological quantum liquid state
2. Gapless excitations: **photons**
3. Gapped excitations: electric **charges** and magnetic **monopoles**

Our result: proposal to **experimentally tune the quantum dynamics** of lattice QED of dipolar-octupolar quantum spin ice

1. New lattice QED **phases** and **phase transitions**.
2. Photon dynamics: tune the emergent **speed of light**, **birefringence**, **non-linear photon coupling.**

[OIST Symposium] Generalized Symmetries in Quantum Matter - Registration

Registration for the symposium (ONLY necessary if you have not previously been contacted by OIST/TSVP)

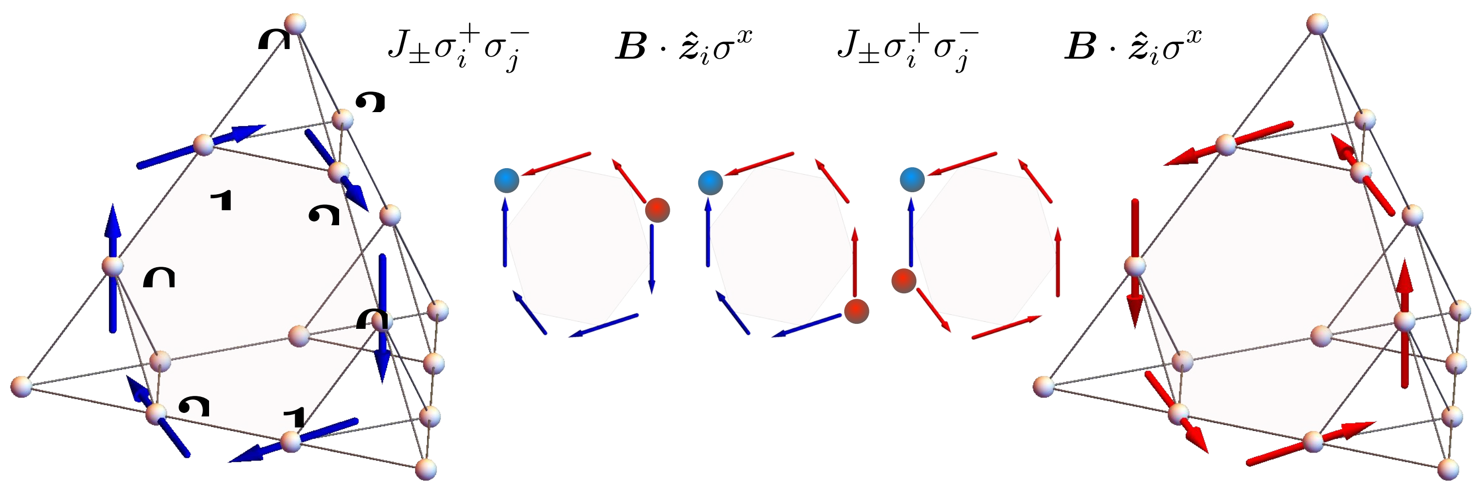
"**Generalized Symmetries in Quantum Matter**" organized by Daniel Bulmash, Abhinav Prem, Masahito Yamazaki, Han Yan. The **symposium is scheduled to take place from June 16-21** at the Okinawa Institute of Science and Technology Graduate University (OIST).
Symposium website: https://www.oist.jp/events/tsvp-symposium-aspects-generalized-symmetries

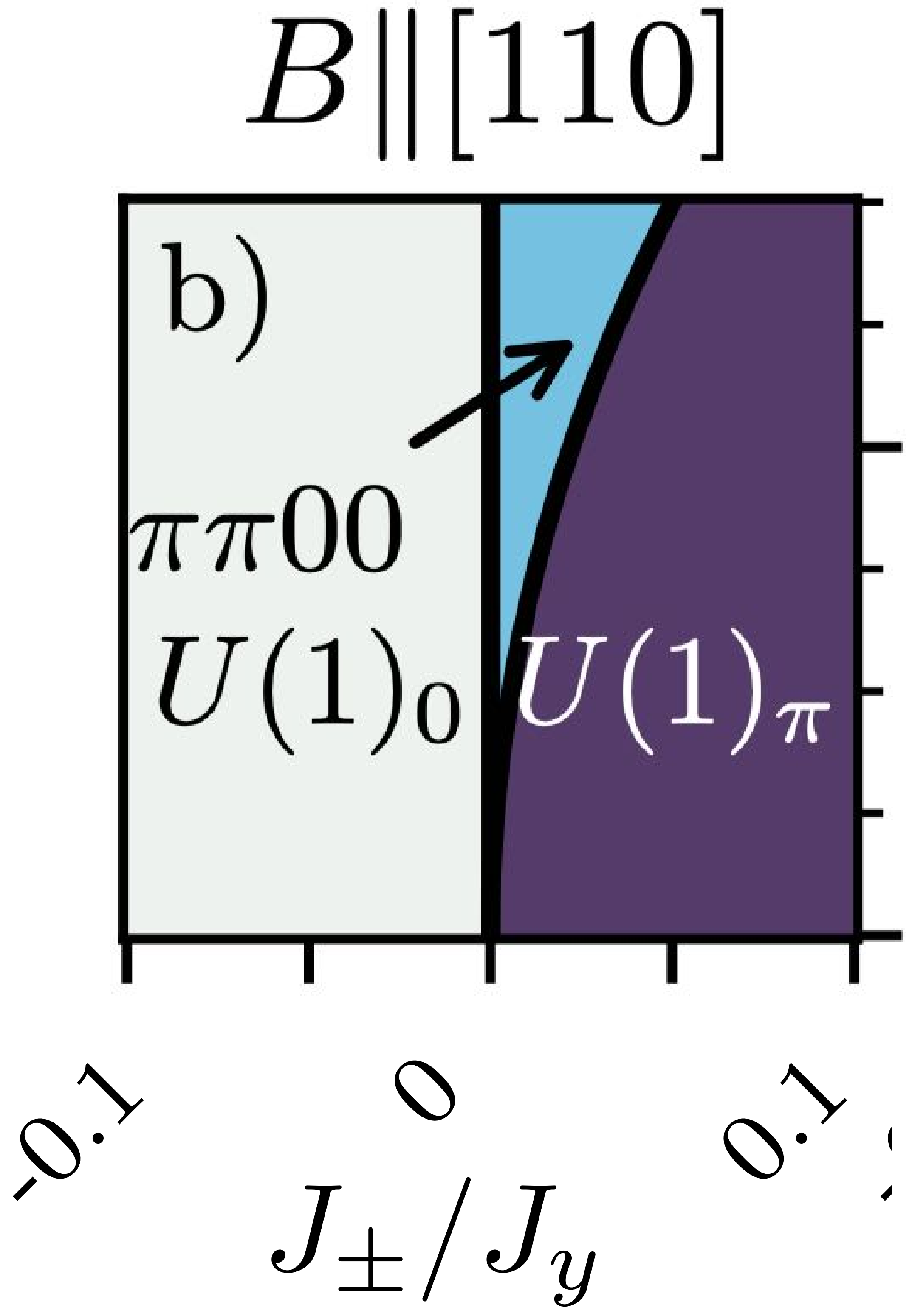
This symposium is part of the **TSVP Thematic Program** "Generalized Symmetries in Quantum Matter". The program will run from May 12 to July 5, 2025.
Thematic Program website: https://www.oist.jp/visiting-program/tp25qm

https://groups.oist.jp/tsvp/tp25qm

Back-up slides

Emergent QED in DO-QSI





B

A new eQED phase of different gauge background

$$\mathcal{H}_{\text{eff}} = \sum_{\boldsymbol{R} \in \{\text{all } \hexagon\}} g(\boldsymbol{R}) \cos(b)$$

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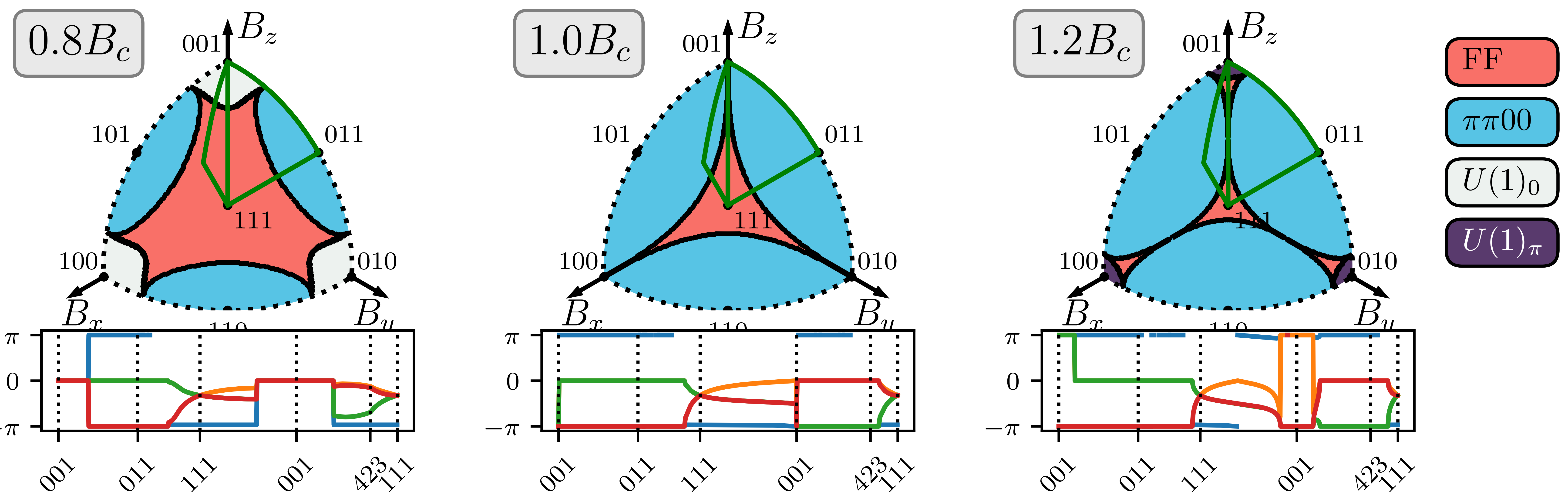

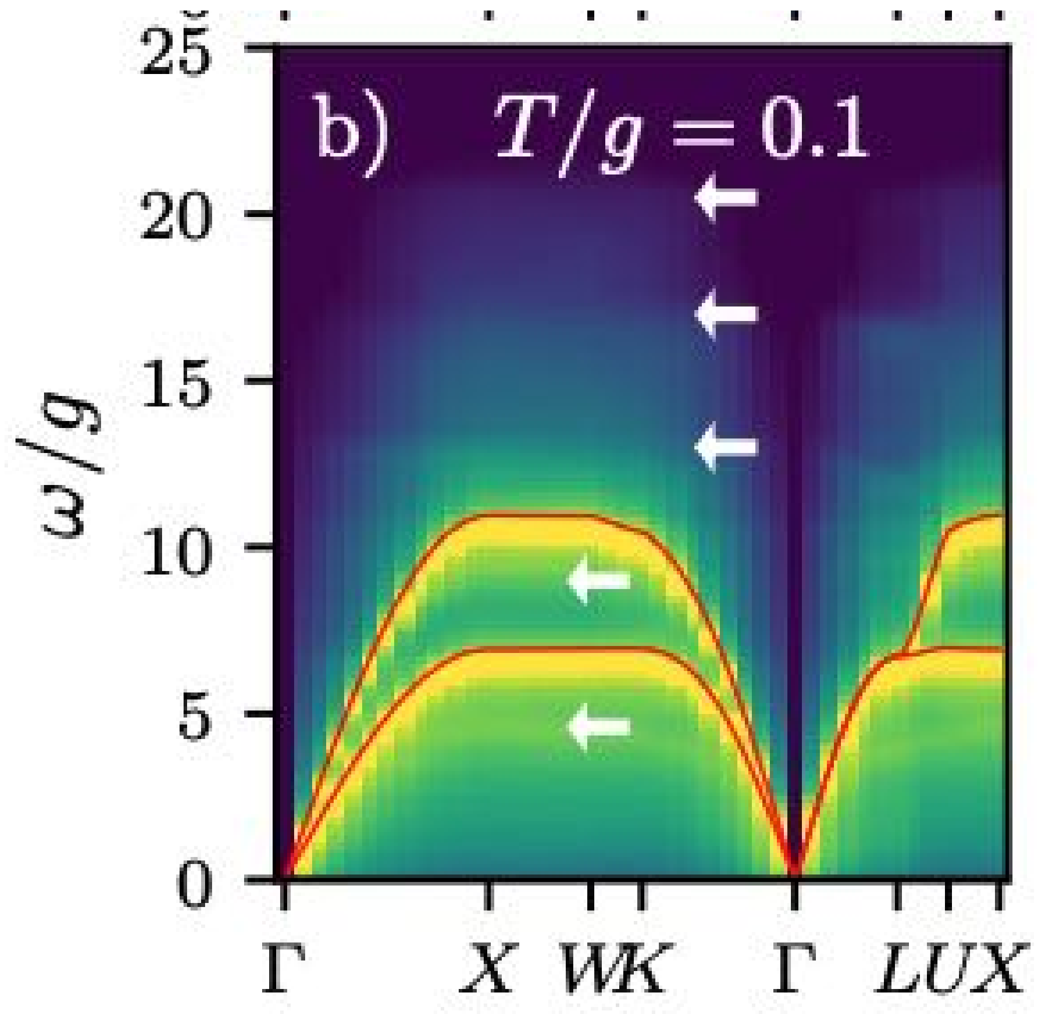

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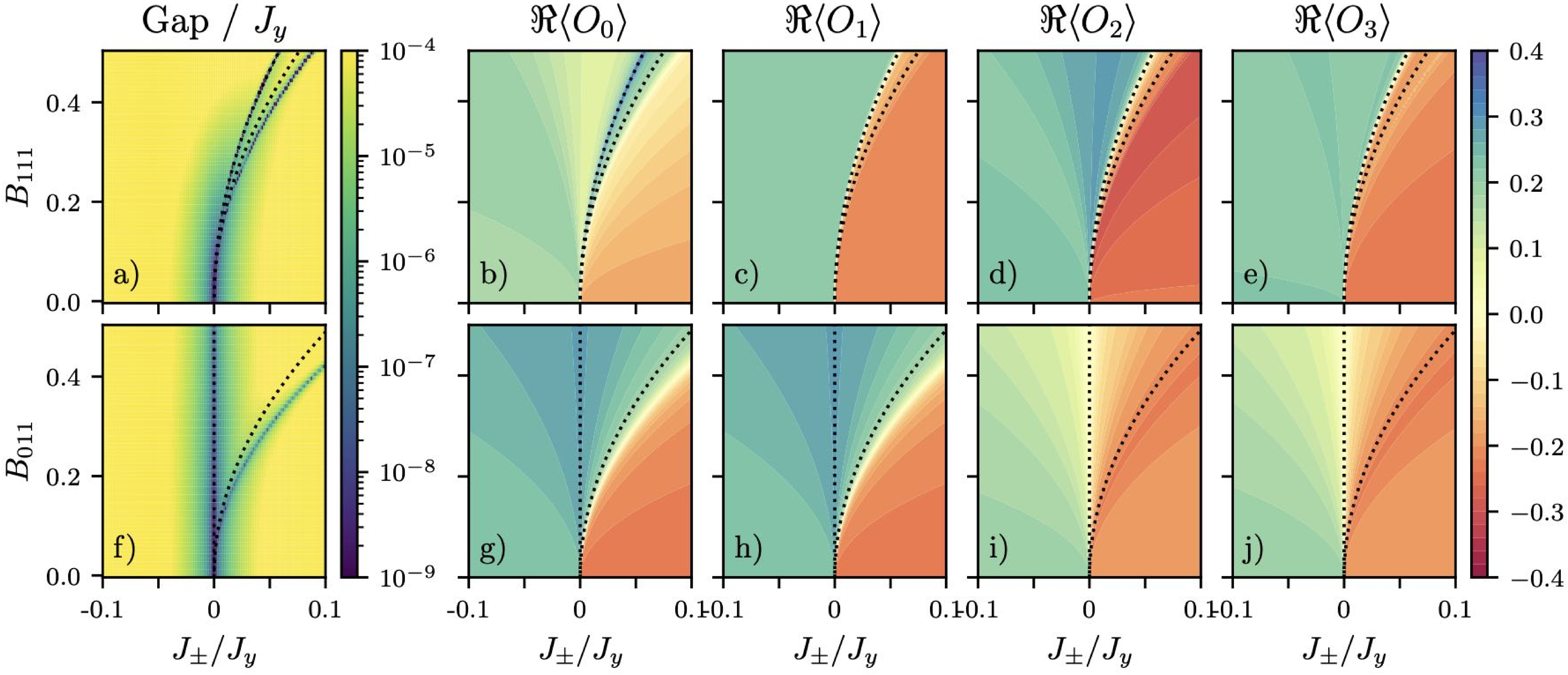
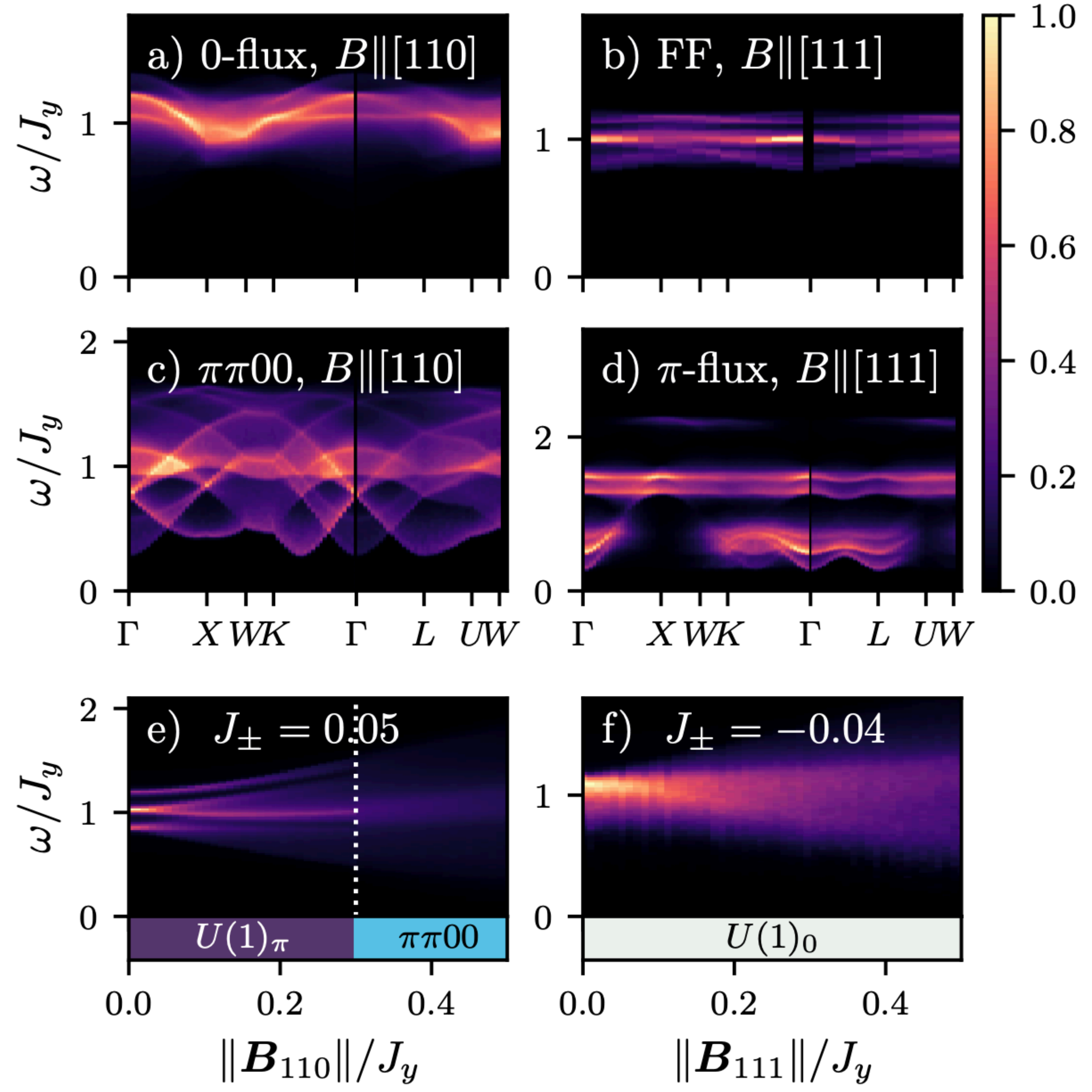


ED Expectation values of ring-flip operators on a 72-site cluster subject to (a-e) 111 and (f-j) 011 magnetic fields.

Black dotted lines indicate the semiclassical phase boundaries

Spinon Signatures



The spinon spectrum is much easier to be measured in current neutron scattering experiments.

Different phases have very different features.

Also ref. F Desrochers, Y-B Kim PRL, 132(6), 066502 (2024)
Z Zhou, F Desrochers, Y-B Kim PhysRevB.110.174441