Quantum Ice

nic shannon

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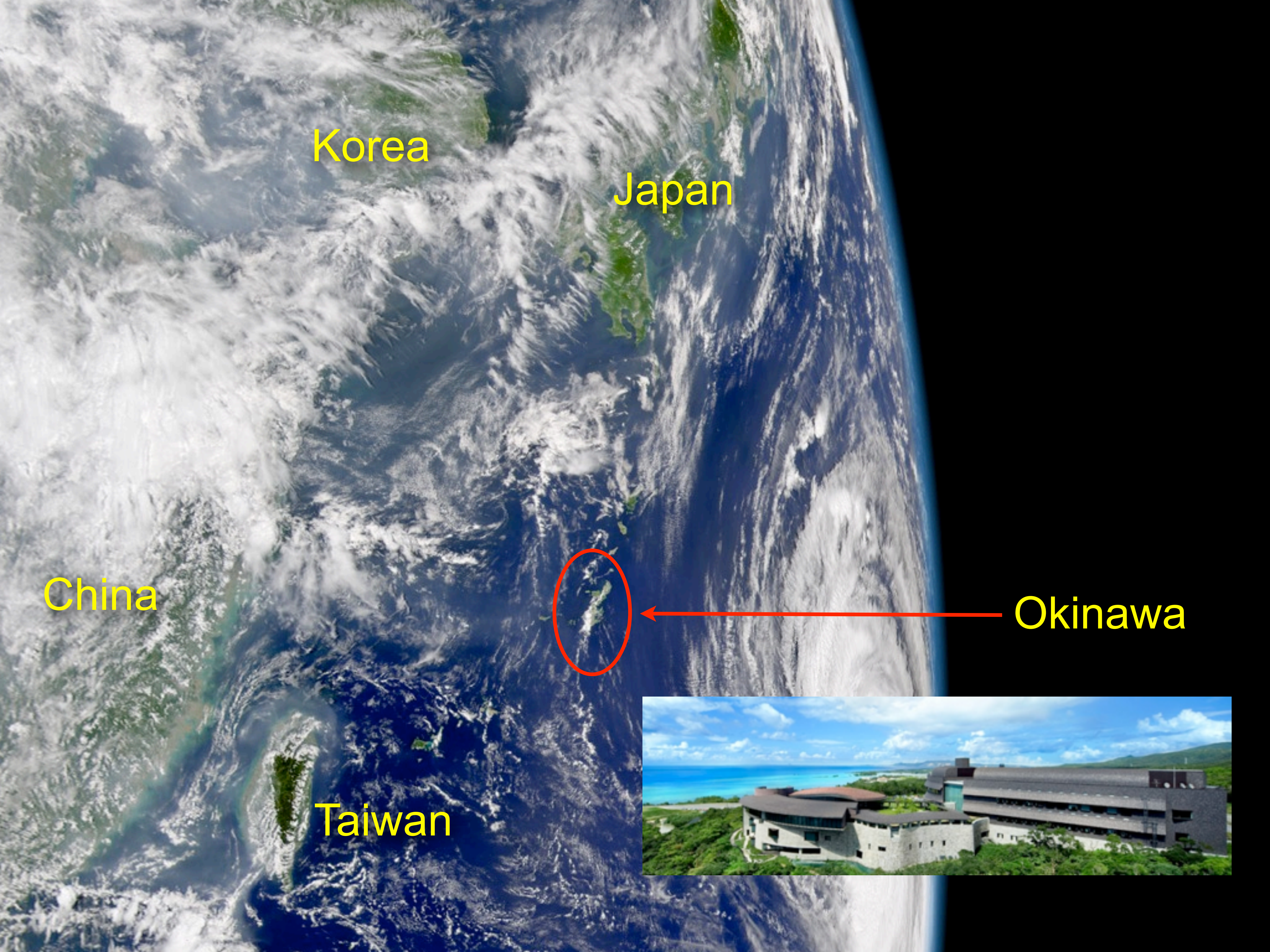
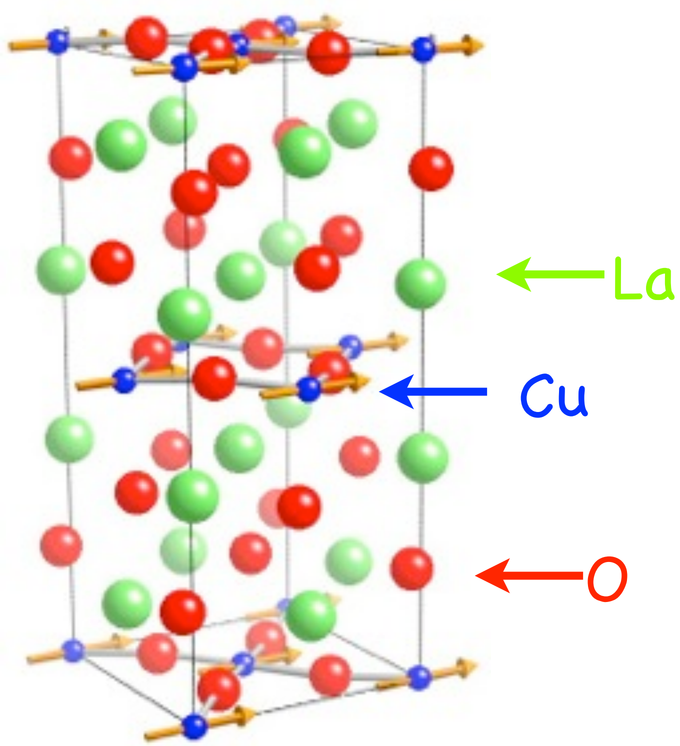
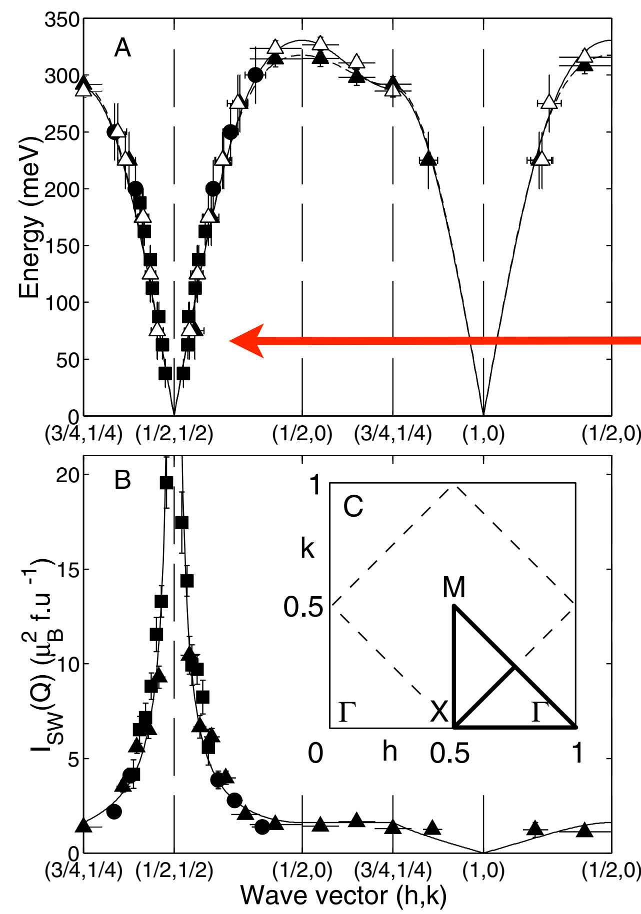

Korea
Japan
China
Okinawa
Taiwan

spin liquids are boring...

...because there's nothing to measure

La_2CuO_4 - everybody's favourite Néel AF :





spin wave excitation dispersing out of ordering vector

R. Coldea *et al.*, Phys. Rev. Lett. **86**, 5377 (2001).

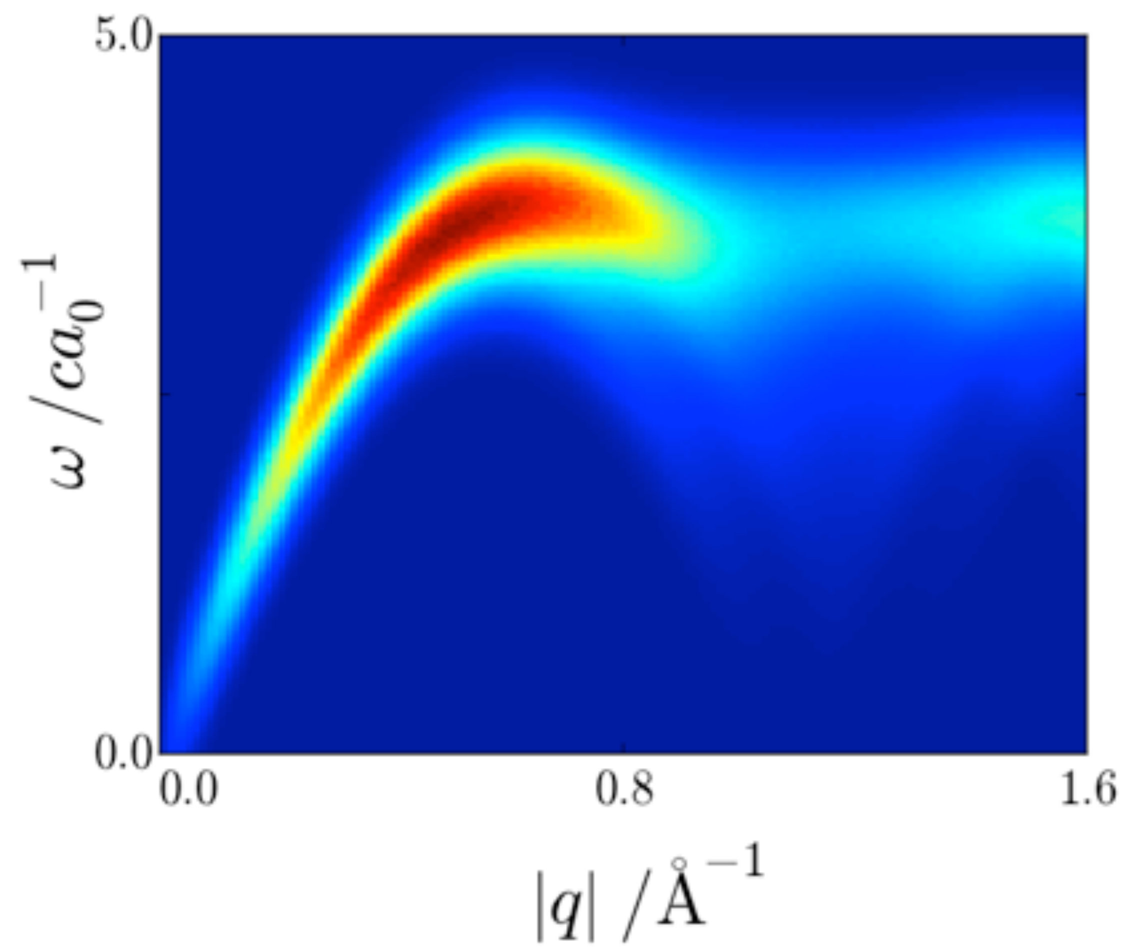
spin wave excitations which control all properties of La_2CuO_4 for $T < T_N = 250$ K follow directly from broken spin-rotation symmetry...

...but not everything works like this


just because there's no
broken symmetry...
FIAT LUX
...doesn't mean
there's no physical effect !

a quantum spin liquid with artificial light ?

$S(|\mathbf{q}|, \omega)$



...prediction for inelastic neutron scattering taken from microscopic model of a quantum spin ice

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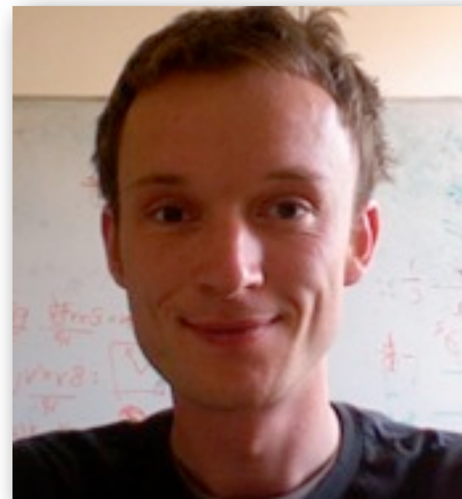
wouldn't have happened without

Karlo Penc
Budapest

Peter Fulde
APCTP



Frank Pollmann
MPI-PKS

Olga Sikora
NTU

Owen Benton
Bristol/OIST

MAX-PLANCK-GESELLSCHAFT

EPSRC Engineering and Physical Sciences Research Council

OTKA

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THE JOURNAL OF CHEMICAL PHYSICS

VOLUME 1 AUGUST, 1933 NUMBER 8

A Theory of Water and Ionic Solution, with Particular Reference to Hydrogen and Hydroxyl Ions

J. D. BERNAL AND R. H. FOWLER, *University of Cambridge, England*

(Received April 29, 1933)

SHORT SUMMARY

ON the basis of the model of the water molecule derived from spectral and x-ray data and a proposed internal structure for water, the following properties of water and ionic solutions have been deduced quantitatively in good agreement with experiment.

(1) The crystal structure of ice.
(2) The x-ray diffraction curve for water.
(3) The total energy of water and ice.
(4) The degree of hydration of positive and negative ions in water.

ice, and of the density of water, leads to the proposing of an irregular four-coordinated structure for water. This structure is tested and found to account for the positions of the maxima of x-ray diffraction by water, and for the change in these positions with temperature, which are quite different from those of a simple liquid such as mercury. Three different intermolecular arrangements are postulated for water at different temperatures.

(1) Ice-tridymite-like (four-coordinated) at low temperatures below 4°C.

how does water ice work ?

water molecules link up through hydrogen bonds...

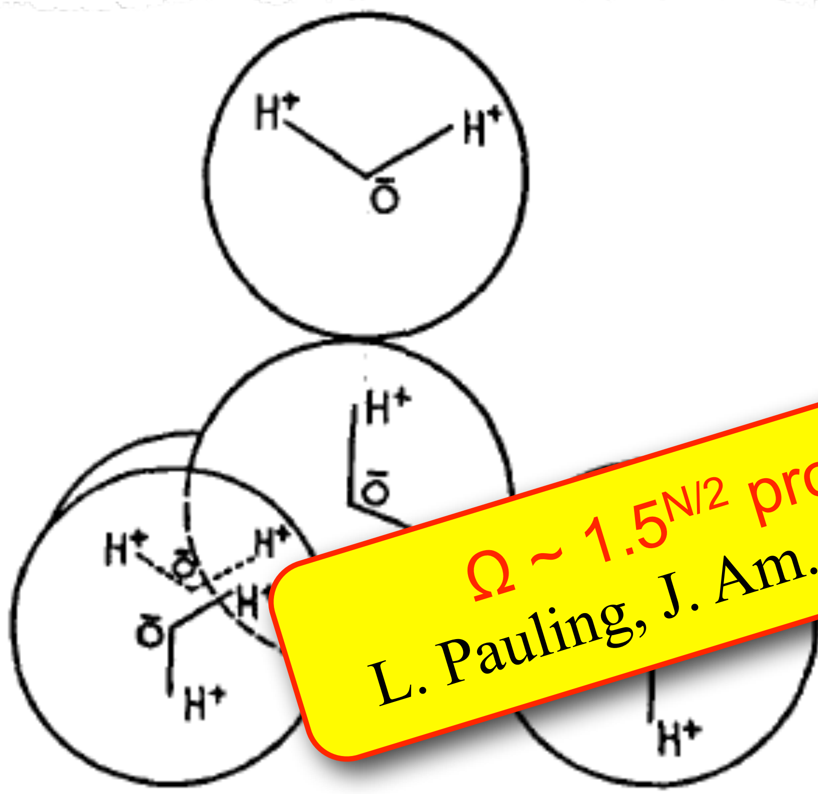
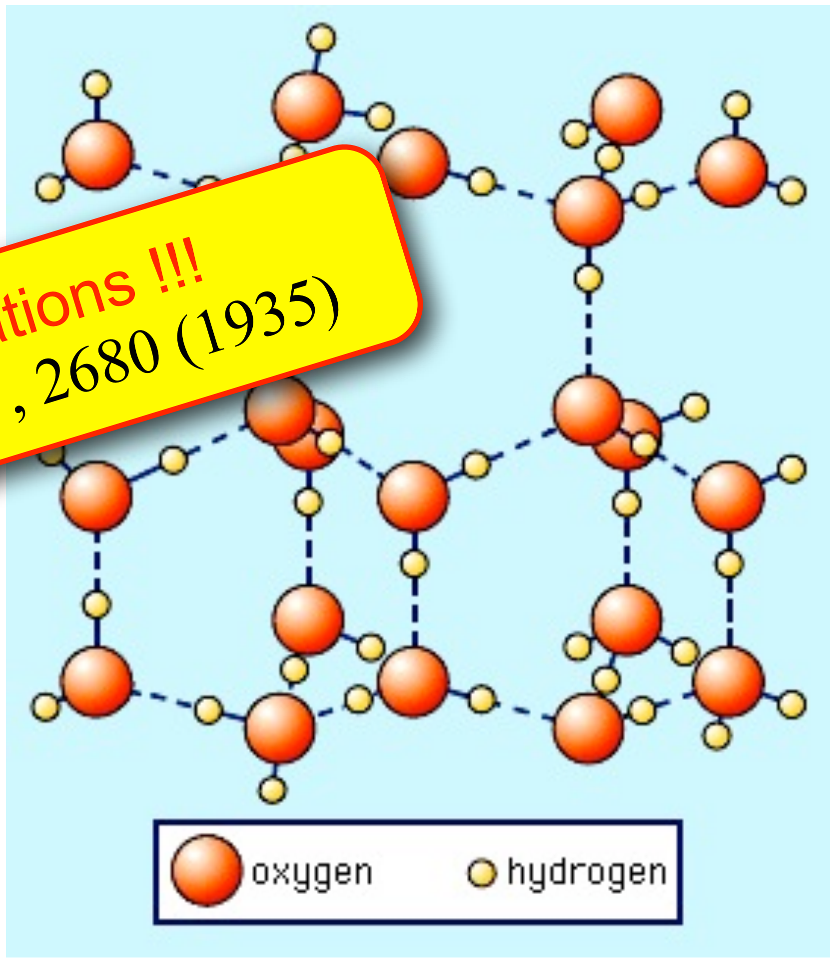


FIG. 4. Tetrahedral coordination of water molecules. The four molecules surrounding one water molecule are shown. Of these, two are in the plane of the paper, one above and one below it.

...to form a tetrahedrally co-ordinated lattice :



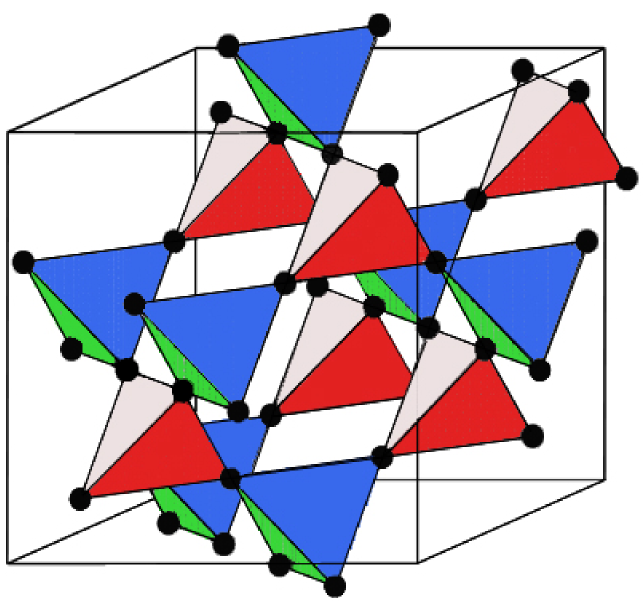
$\Omega \sim 1.5^{N/2}$ proton configurations !!!

L. Pauling, J. Am. Chem. Soc. **27**, 2680 (1935)

J. D. Bernal and R. H. Fowler, J. Chem. Phys. **1**, 515 (1933).

the fashionable form of ice...

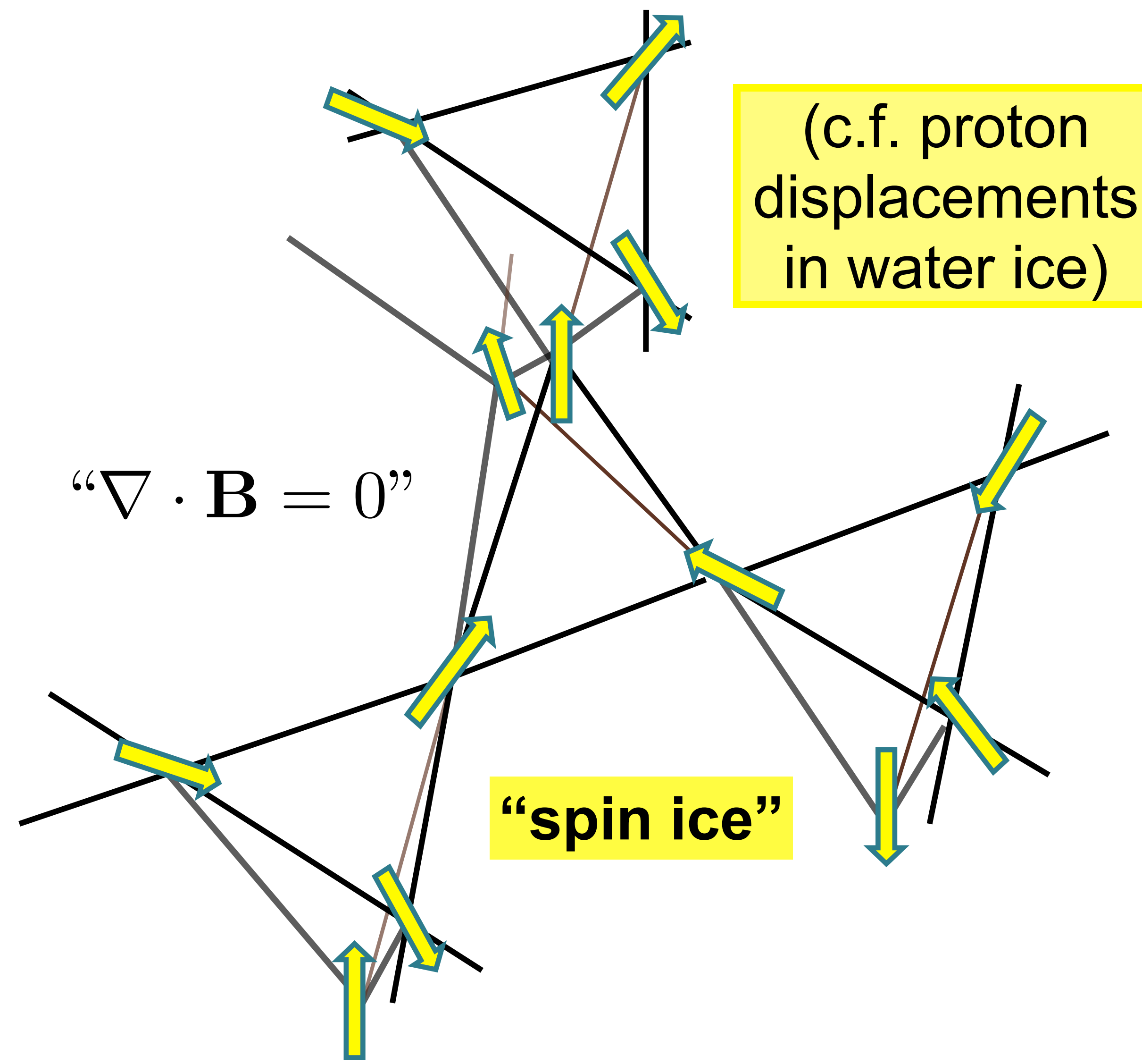
$Ho_2Ti_2O_7$
$Dy_2Ti_2O_7$



magnetic
Ho^{8+} or
Dy^{8+} ions
live on a
pyrochlore
lattice

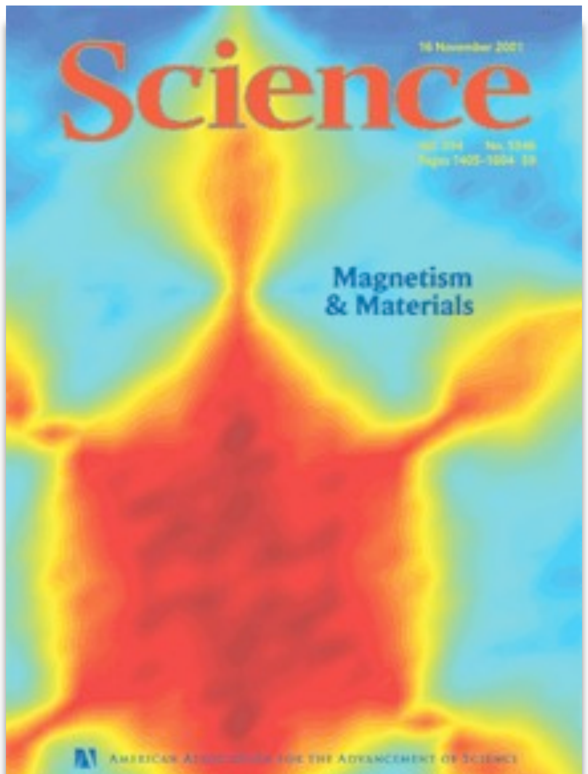
strong easy axis anisotropy forces spins to point in or out of tetrahedron

ferromagnetic interactions select states with two in and two out spins per tetrahedron



M.J. Harris et al., Phys. Rev. Lett. **79**, 2554 (1997)
A.P. Ramirez et al., Nature **399**, 333 (1999)

spin ice and its monopoles...



...discussed in all the most reputable sources of scientific information !

PRL 106, 187202 (2011) PHYSICAL REVIEW LETTERS 6 MAY 2011

Rods of Neutron Scattering Intensity in $Yb_2Ti_2O_7$: Compelling Evidence for Significant Anisotropic Exchange in a Magnetic Pyrochlore Oxide

Jordan D. Thompson,[1] Paul A. McClarty,[1] Henrik M. Rønnow,[2] Louis P. Regnault,[3] Andreas Sorge,[4,5] and Michel J. P. Gingras[1,5,6]

PHYSICAL REVIEW X 1, 021002 (2011)

Quantum Excitations in Quantum Spin Ice

Kate A. Ross,[1] Lucile Savary,[2] Bruce D. Gaulin,[1,3,4] and Leon Balents[5,*]

ARTICLE

Received 27 Jan 2012 | Accepted 5 Jul 2012 | Published 7 Aug 2012

DOI: 10.1038/ncomms1989

Higgs transition from a magnetic Coulomb liquid to a ferromagnet in $Yb_2Ti_2O_7$

Lieh-Jeng Chang[1,2], Shigeki Onoda[3], Yixi Su[4], Ying-Jer Kao[5], Ku-Ding Tsuei[6], Yukio Yasui[7,8], Kazuhisa Kakurai[2] & Martin Richard Lees[9]

PRL 109, 097205 (2012) PHYSICAL REVIEW LETTERS week ending 31 AUGUST 2012

Vindication of $Yb_2Ti_2O_7$ as a Model Exchange Quantum Spin Ice

R. Applegate,[1] N. R. Hayre,[1] R. R. P. Singh,[1] T. Lin,[2] A. G. R. Day,[2,3] and M. J. P. Gingras[1,2,4]

PRL 109, 017201 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

Power-Law Spin Correlations in the Pyrochlore Antiferromagnet $Tb_2Ti_2O_7$

T. Fennell,[1,*] M. Kenzelmann,[2] B. Roessli,[1] M. K. Haas,[3] and R. J. Cava[3]

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PRL **106,** 187202 (2011) PHYSICAL REVIEW LETTERS week ending 6 MAY 2011

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PHYSICAL REVIEW X **1,** 021002 (2011)

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ARTICLE

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Received 27 Jan 2012 | Accepted 5 Jul 2012 | Publis

Higgs transition fro
to a ferromagnet in

Lieh-Jeng Chang[1,2], Shigeki Onoda[3], Yixi
Kazuhisa Kakurai[2] & Martin Richard Lees

spin ice goes quantum...

TTERS week ending 31 AUGUST 2012

ge Quantum Spin Ice

R. Applegate,[1] N. R. Hayre,[1] R. R. P. Singh,[1] T. Lin,[2] A. G. R. Day,[2,3] and M. J. P. Gingras[1,2,4]

PRL **109,** 017201 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

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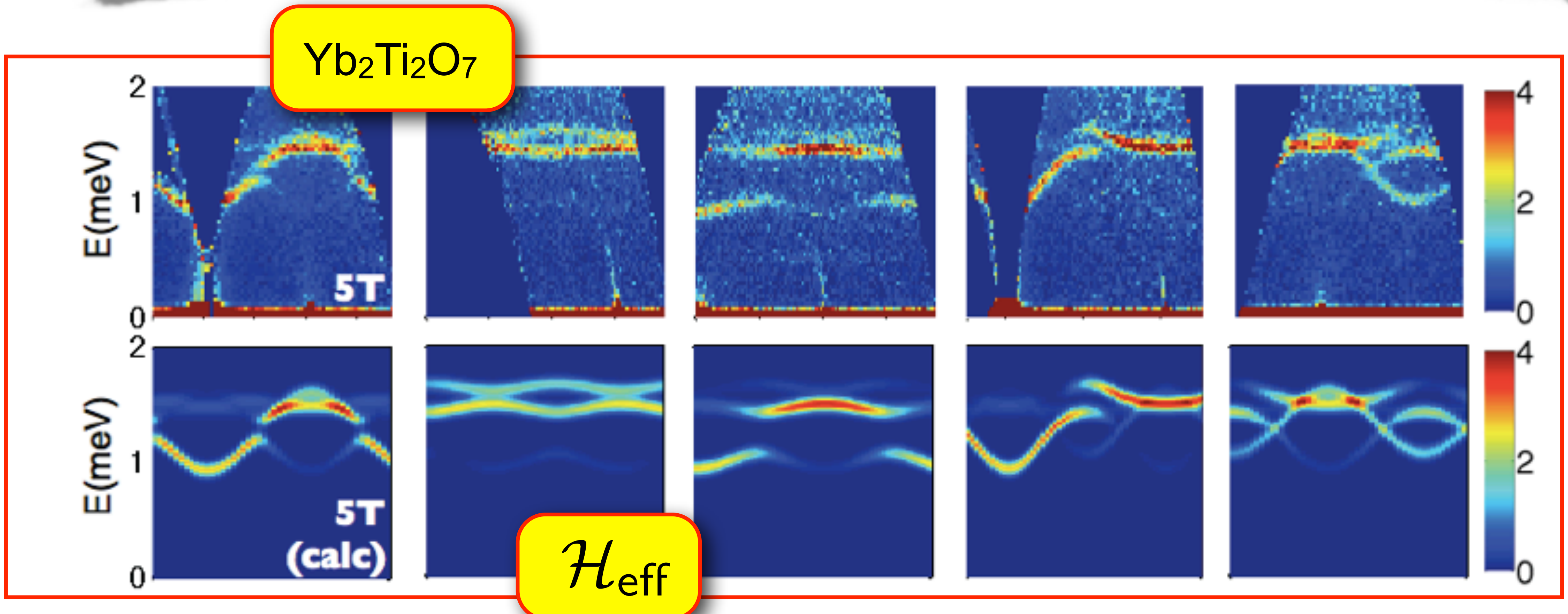
PHYSICAL REVIEW X **1**, 021002 (2011)

Quantum Excitations in Quantum Spin Ice

Kate A. Ross,[1] Lucile Savary,[2] Bruce D. Gaulin,[1,3,4] and Leon Balents[5,*]



$$\mathcal{H}_{\text{eff}} = \sum_{\langle ij\rangle}\Big\{J_{zz}\mathsf{S}_i^z\mathsf{S}_j^z - J_\pm(\mathsf{S}_i^+\mathsf{S}_j^- + \mathsf{S}_i^-\mathsf{S}_j^+)$$
$$+J_{\pm\pm}\left[\gamma_{ij}\mathsf{S}_i^+\mathsf{S}_j^+ + \gamma_{ij}^*\mathsf{S}_i^-\mathsf{S}_j^-\right]$$
$$+J_{z\pm}\left[\mathsf{S}_i^z(\zeta_{ij}\mathsf{S}_j^+ + \zeta_{ij}^*\mathsf{S}_j^-) + i \leftrightarrow j\right]\Big\}$$

fit to spin wave spectrum in saturated state

$$J_{zz} = 0.17 \pm 0.04\ meV$$
$$J_\pm = 0.05 \pm 0.01\ meV$$
$$J_{z\pm} = 0.14 \pm 0.01\ meV$$
$$J_{\pm\pm} = 0.05 \pm 0.01\ meV$$

Ising term ⇒ ice

transverse term ⇒ dynamics

PRL **108,** 037202 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

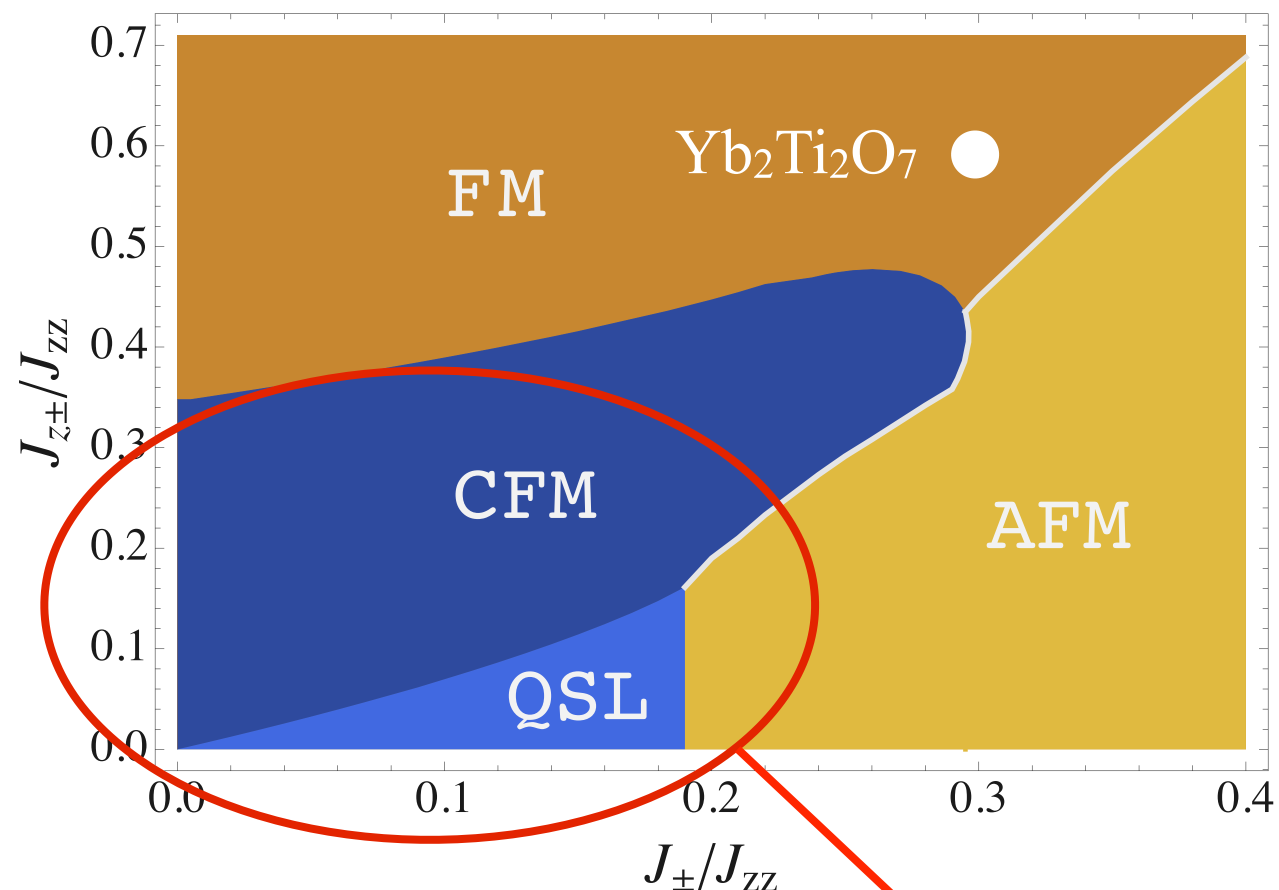
Coulombic Quantum Liquids in Spin-1/2 Pyrochlores

Lucile Savary[1,2] and Leon Balents[3]

most general nearest-neighbour exchange Hamiltonian :

$$H = \sum_{\langle ij \rangle} \Big[J_{zz} \mathsf{S}_i^z \mathsf{S}_j^z - J_{\pm} (\mathsf{S}_i^+ \mathsf{S}_j^- + \mathsf{S}_i^- \mathsf{S}_j^+) + J_{\pm\pm} \left[\gamma_{ij} \mathsf{S}_i^+ \mathsf{S}_j^+ + \gamma_{ij}^* \mathsf{S}_i^- \mathsf{S}_j^- \right] + J_{z\pm} \left[\mathsf{S}_i^z (\zeta_{ij} \mathsf{S}_j^+ + \zeta_{ij}^* \mathsf{S}_j^-) + i \leftrightarrow j \right] \Big],$$

phase diagram within Gauge mean field theory :



quantum spin liquids derived from spin ice

N.B. see also :
S. Onoda *et al.*, Phys. Rev. B **83**, 094411 (2011)
S-B. Lee *et al.*, arXiv:1204.2262

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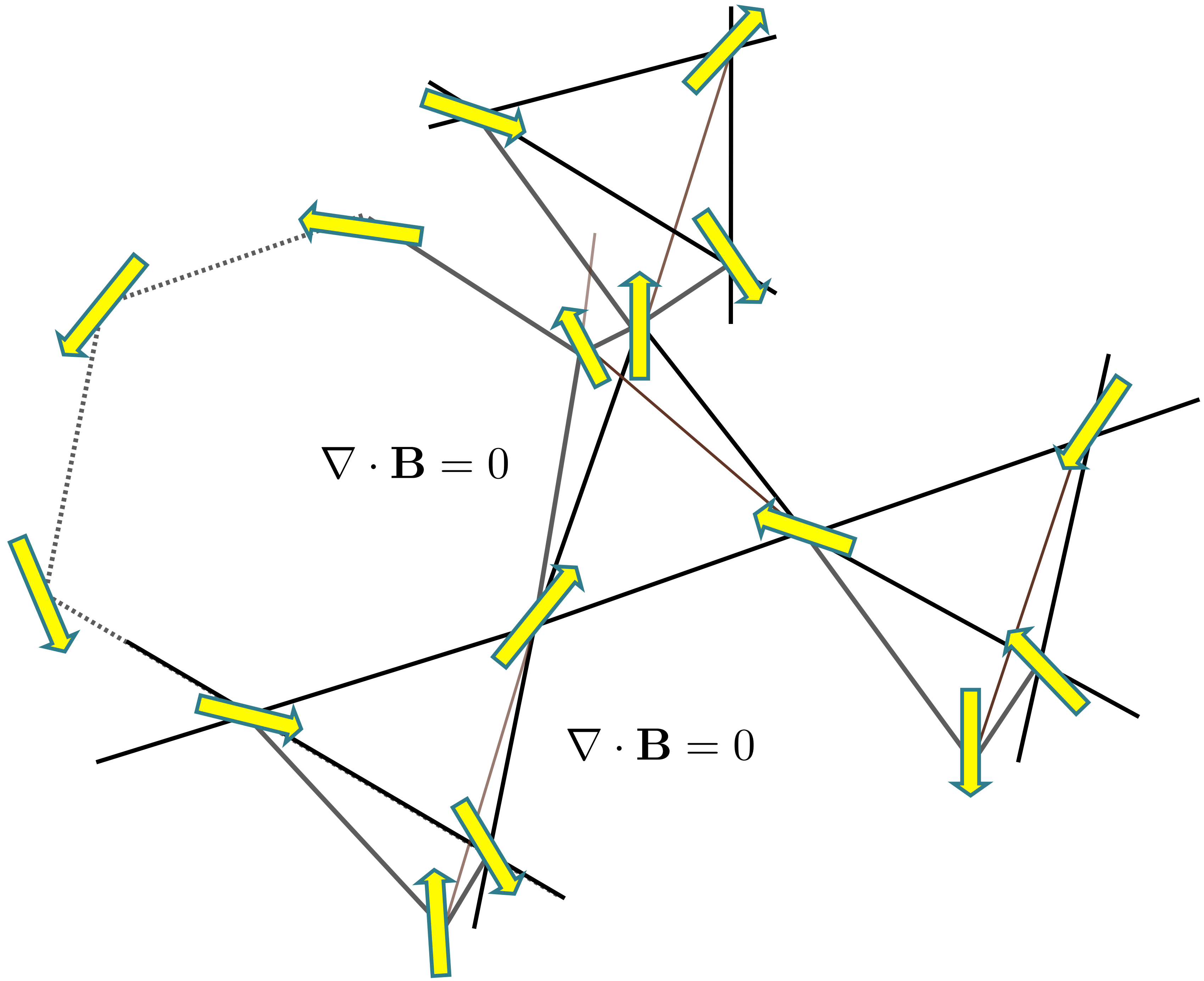
how might things change in
a quantum ice ?

$$\hbar \neq 0$$

$\Rightarrow$ tunnelling between ice states

what kind of dynamics are there in ice ?



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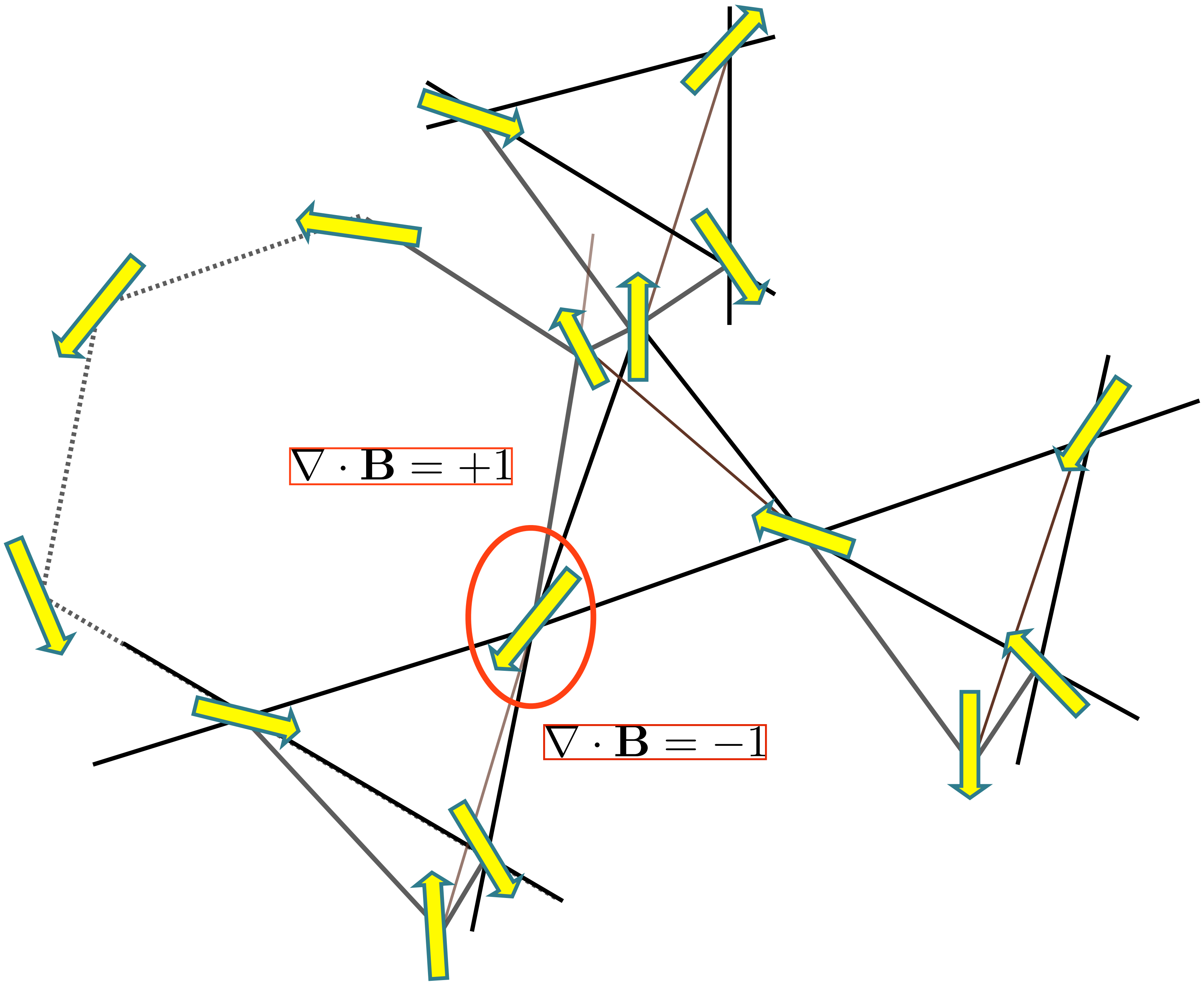

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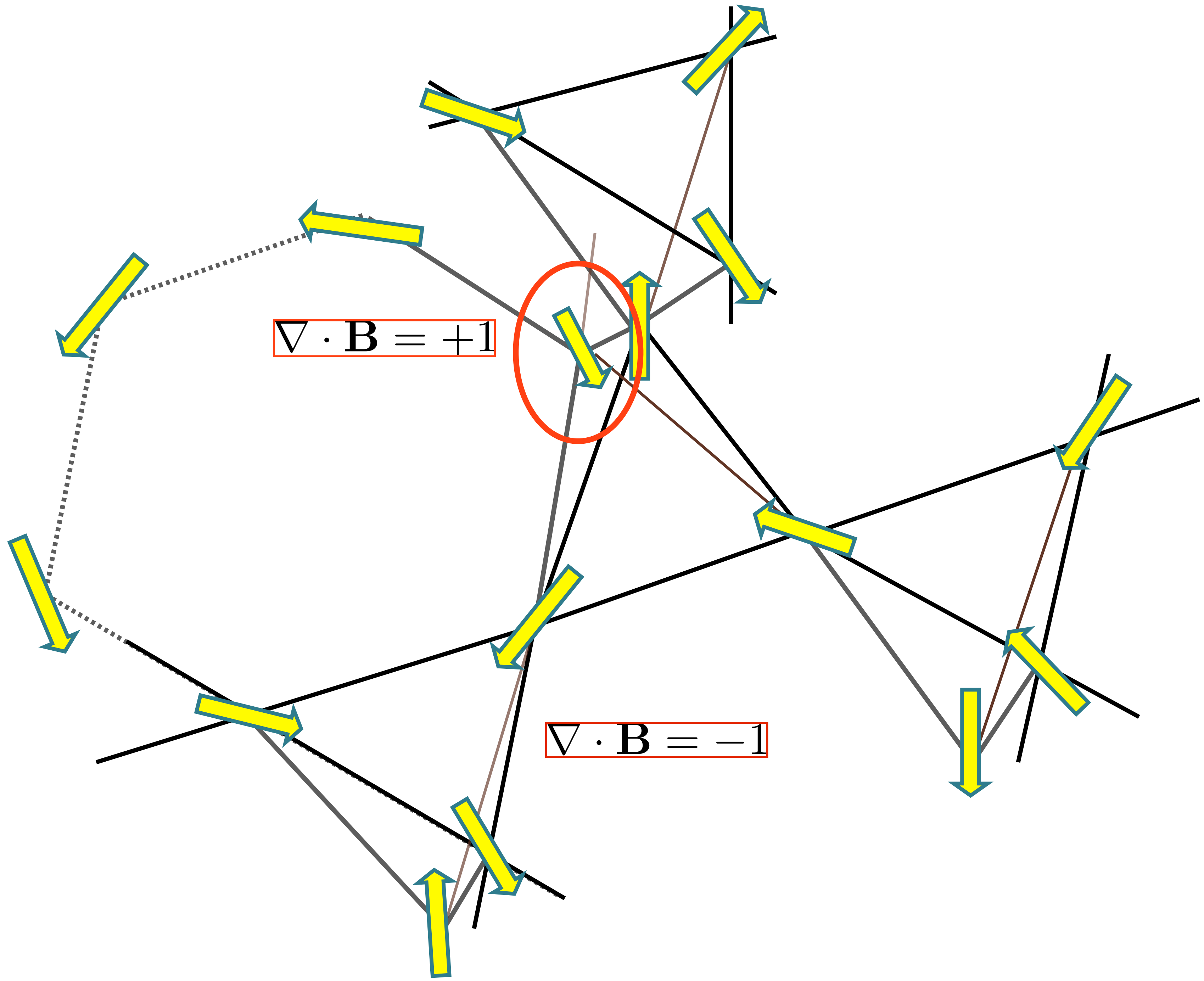

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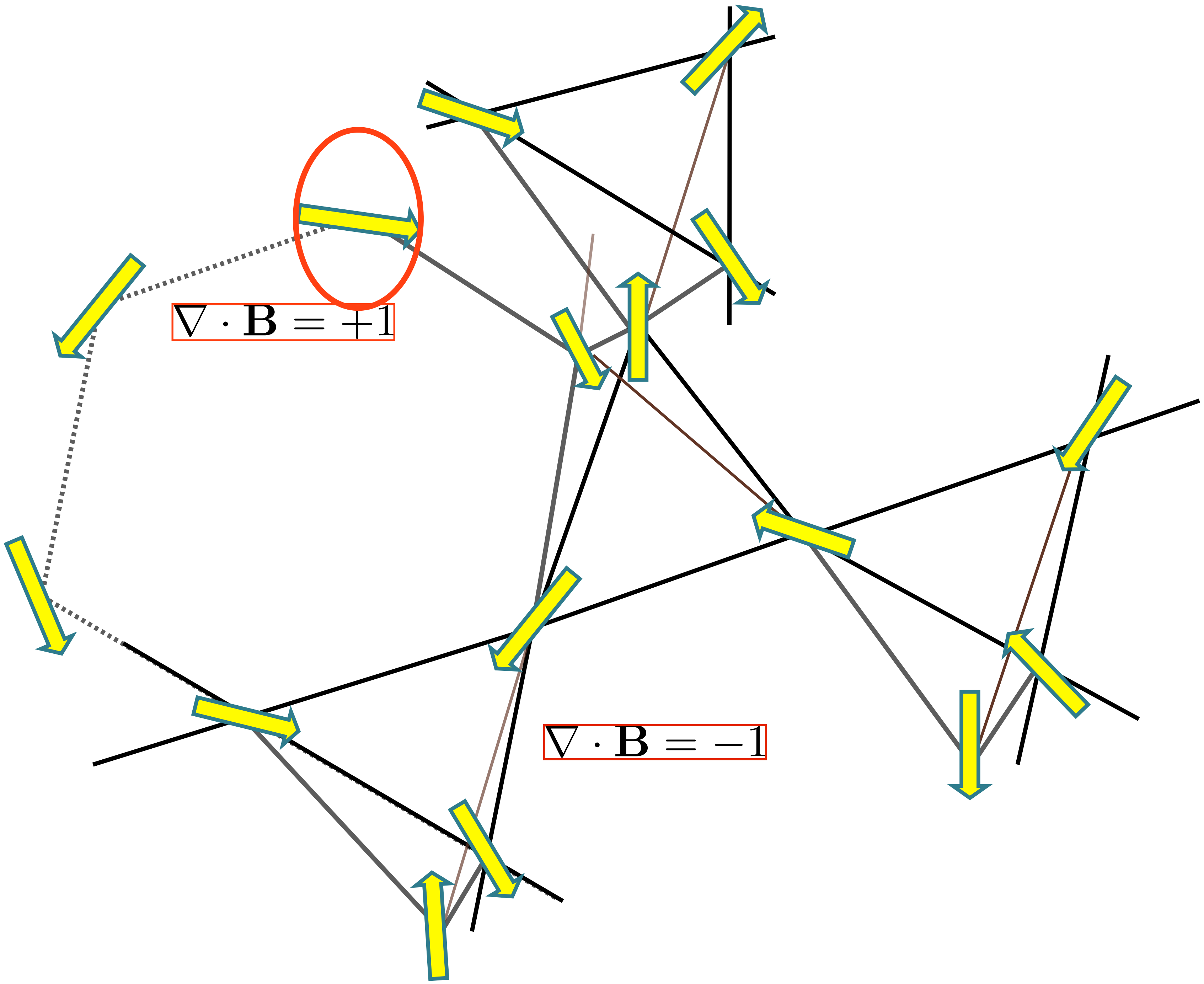

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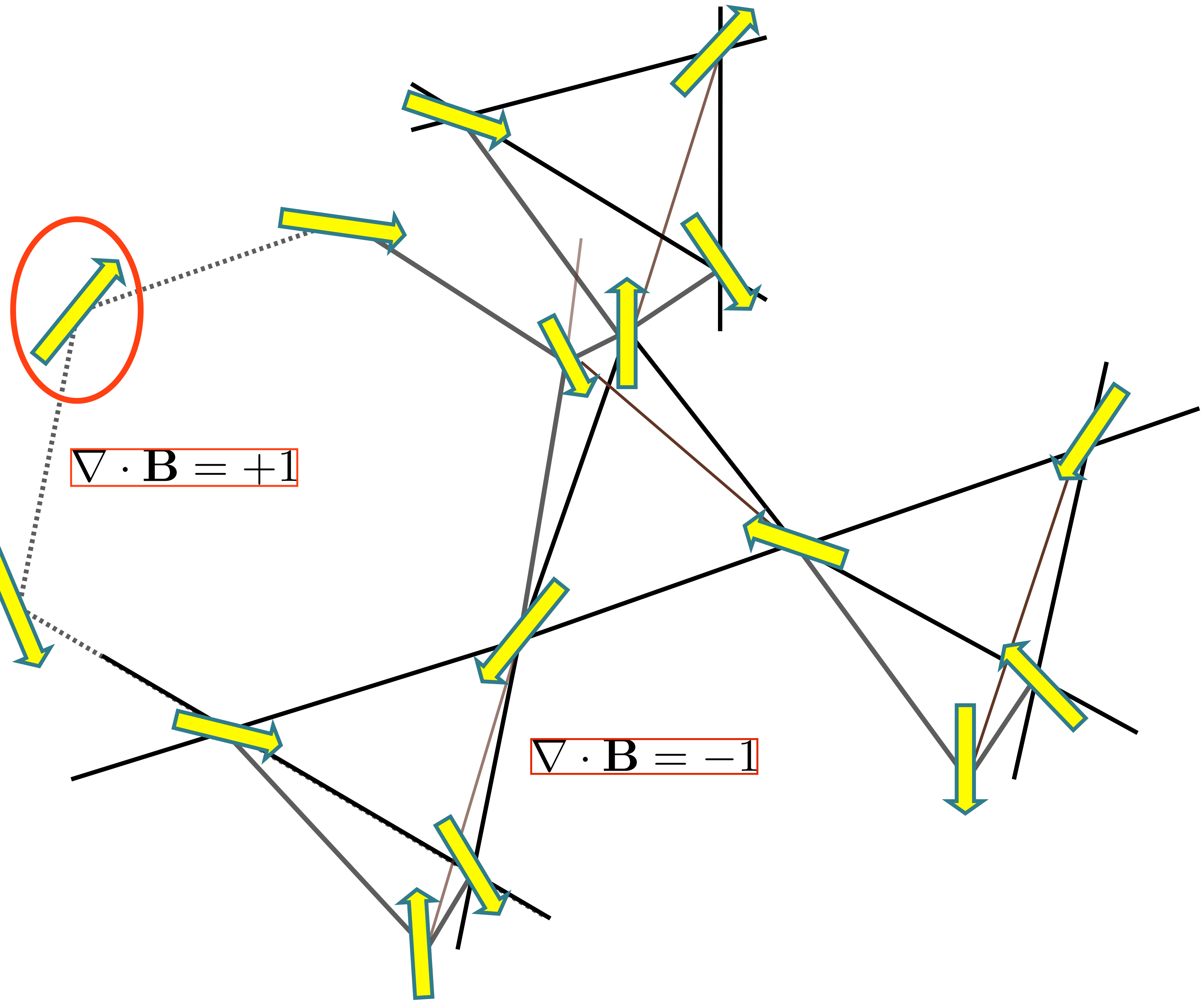

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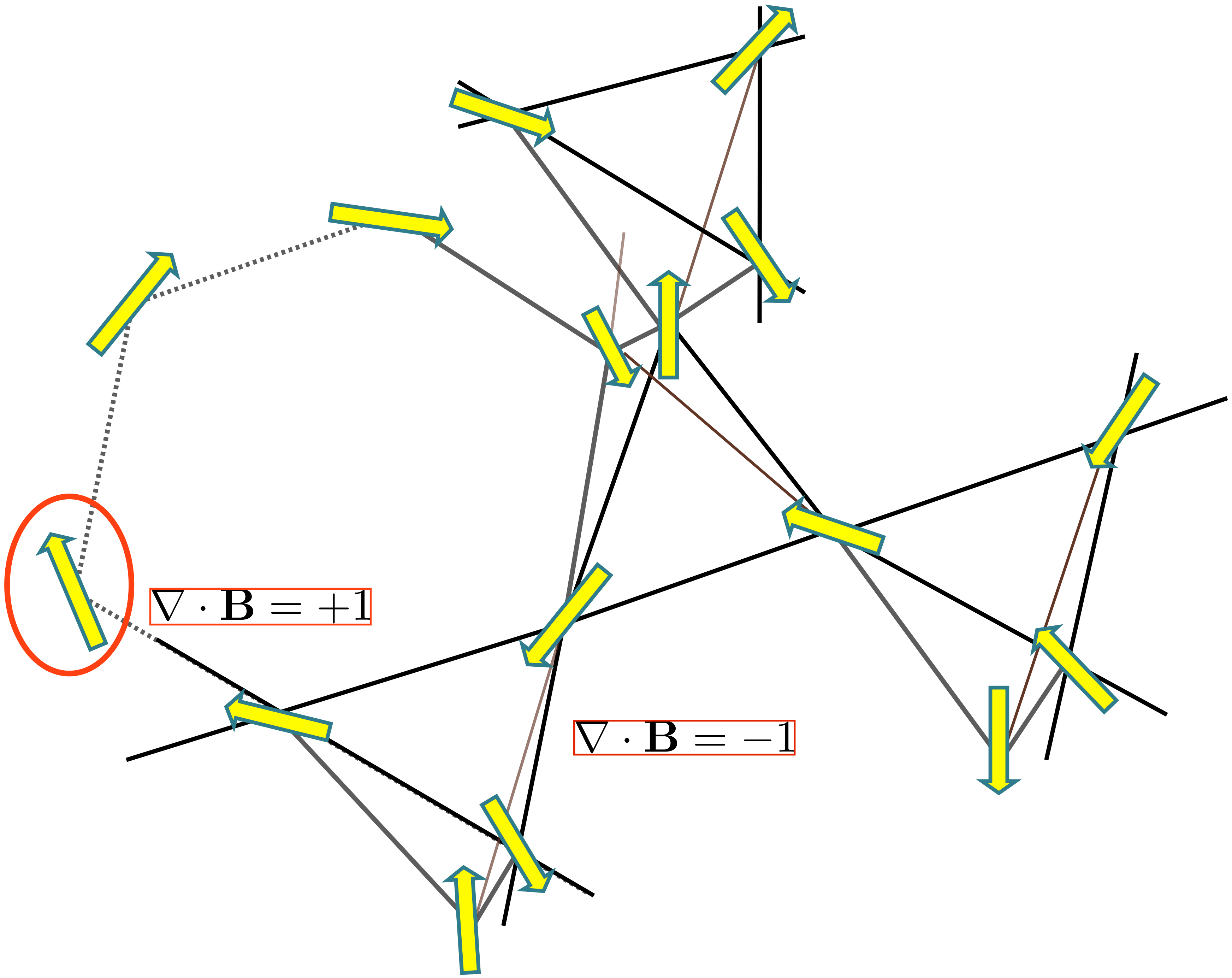

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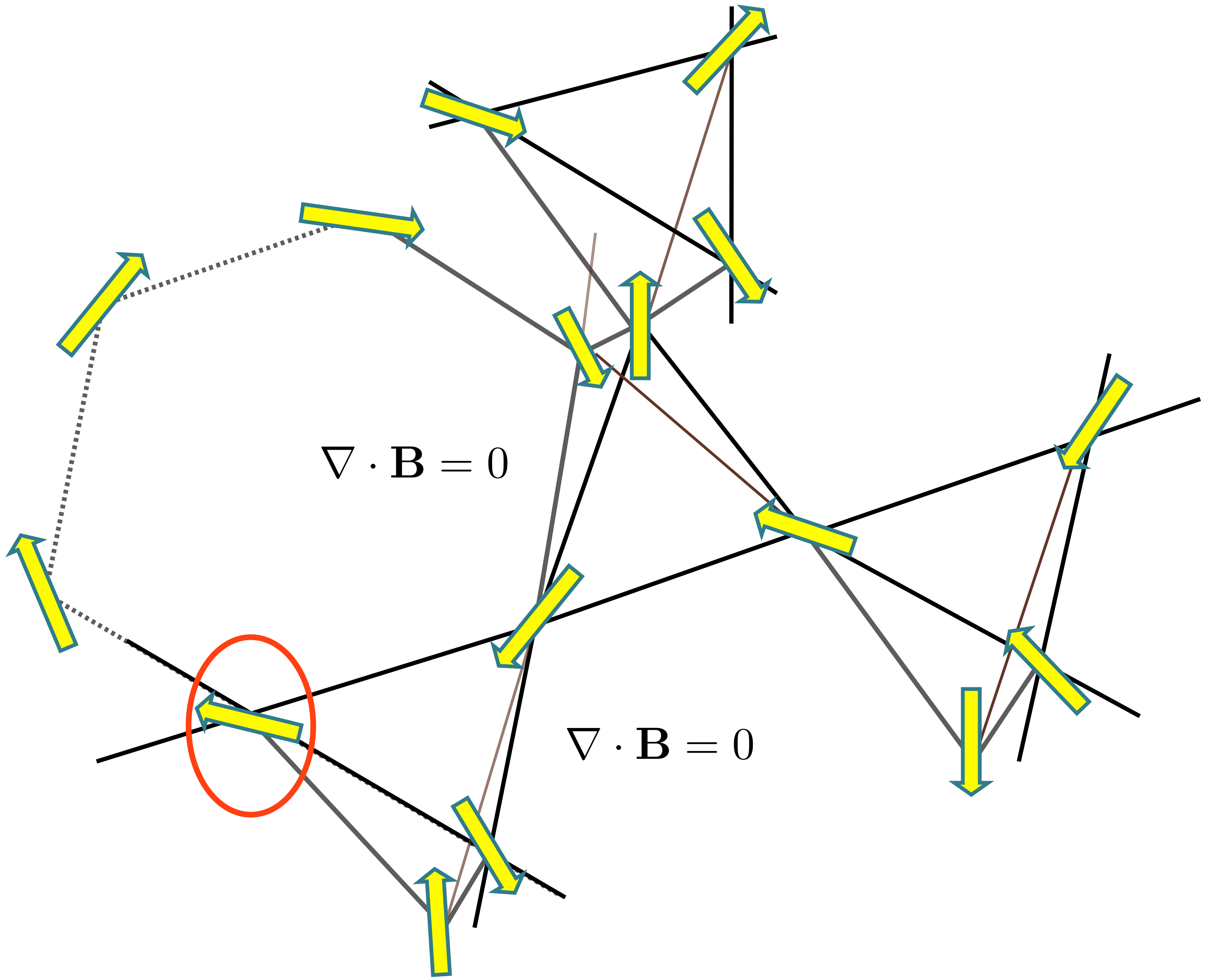
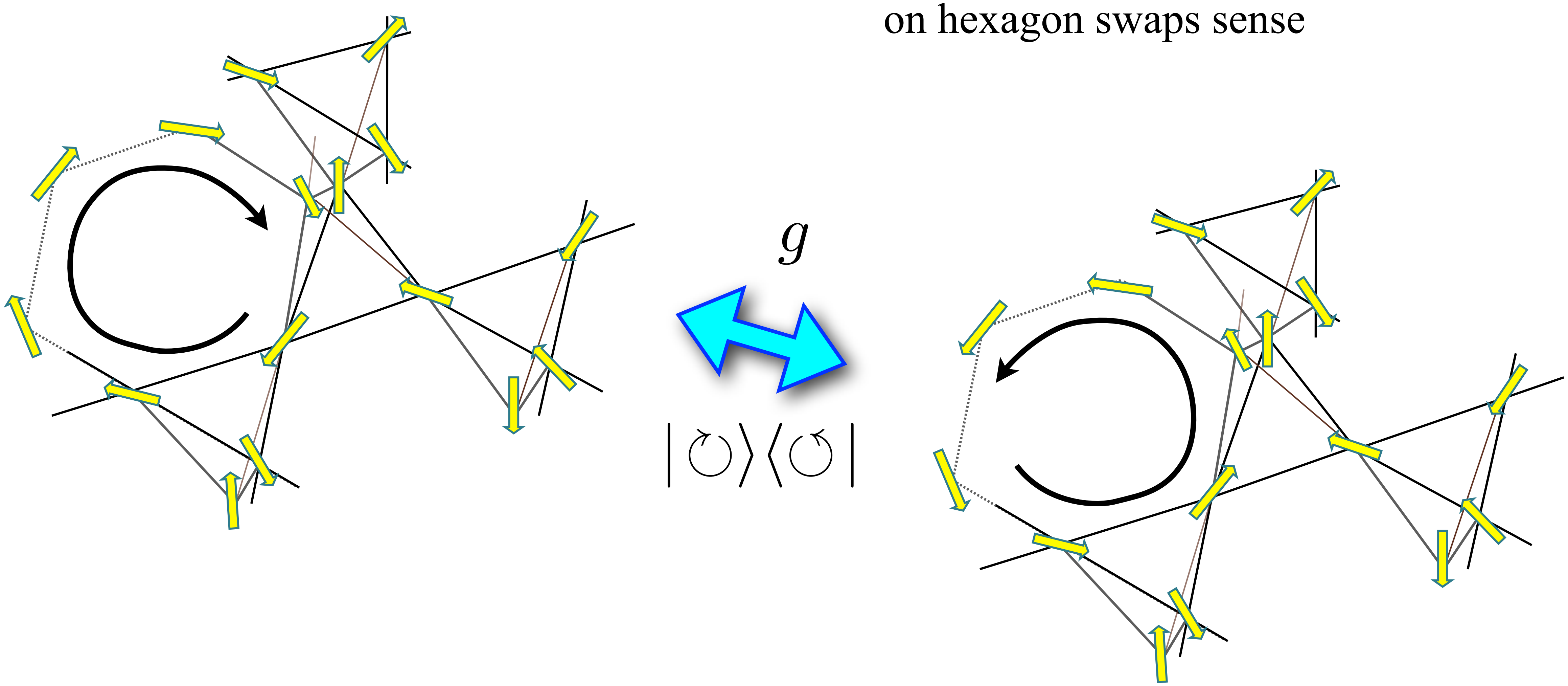


what kind of dynamics are there in ice ?

circulation of “magnetic” field
on hexagon swaps sense



what does this kind of quantum tunneling do to (spin) ice ?

PHYSICAL REVIEW B **69**, 220403(R) (2004)

Cyclic exchange, isolated states, and spinon deconfinement in an *XXZ* Heisenberg model on the checkerboard lattice

Nic Shannon,[1,2] Grégoire Misguich,[3] and Karlo Penc[4]

S=1/2 easy-axis magnet on a checkerboard lattice...

$$\mathcal{H}_{xxz} = J_z \sum_{\langle ij \rangle} S_i^z S_j^z + J_{xy} \sum_{\langle ij \rangle} S_i^x S_j^x + S_i^y S_j^y$$

strong anisotropy

$$J_z \gg J_{xy}$$

selects ice manifold

Hamiltonian acting on ice states...

$$\mathcal{H} = -g \sum_{\square} |\circlearrowright\rangle\langle\circlearrowleft| + |\circlearrowleft\rangle\langle\circlearrowright| \quad +\mu \sum_{\square} |\circlearrowright\rangle\langle\circlearrowright| + |\circlearrowleft\rangle\langle\circlearrowleft|$$

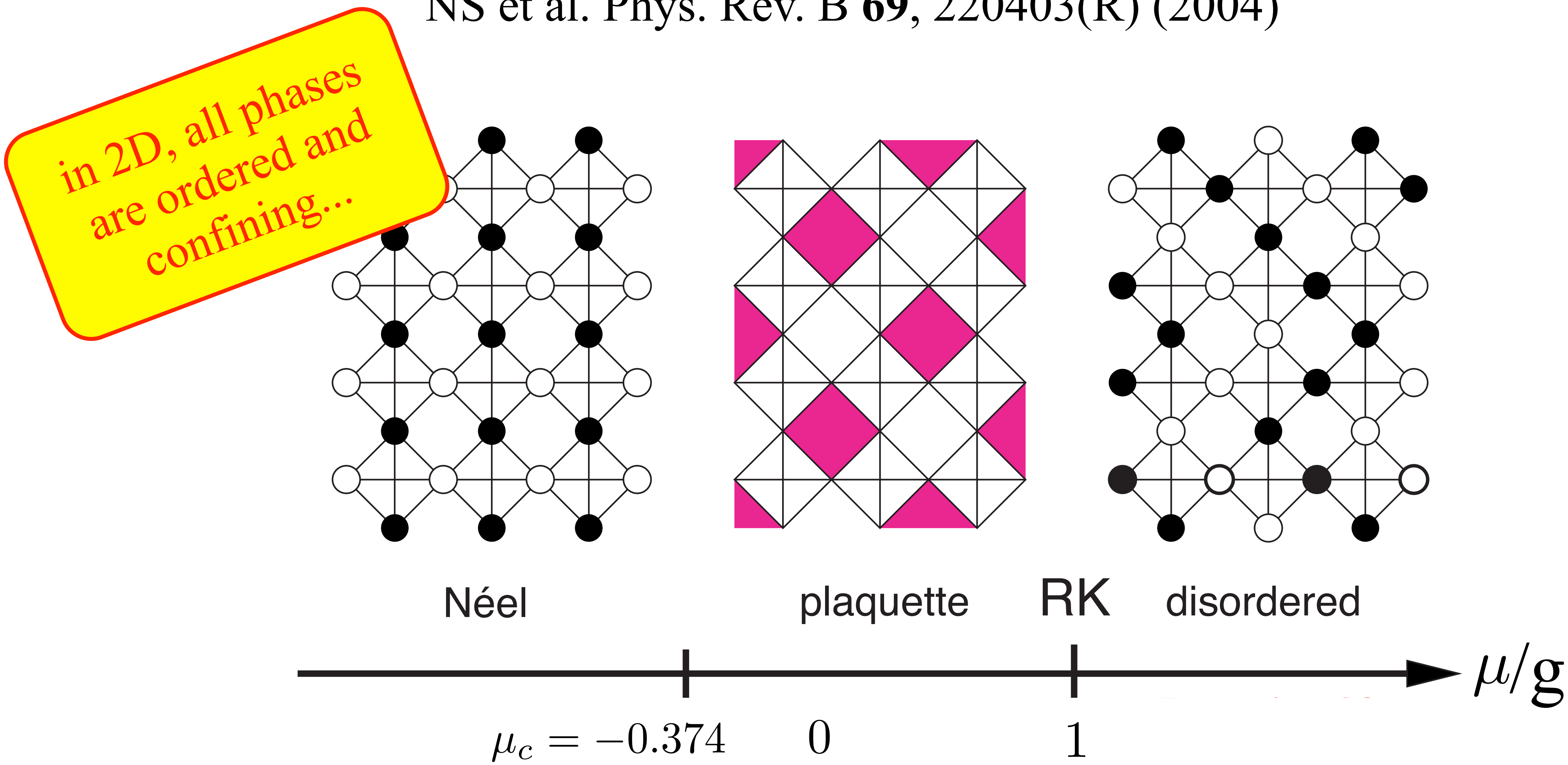
degenerate perturbation theory $\quad g = \frac{2J_{xy}^2}{J^z}$

...makes model exactly soluble for μ=g

...2D quantum ice, *aka* the quantum six vertex model

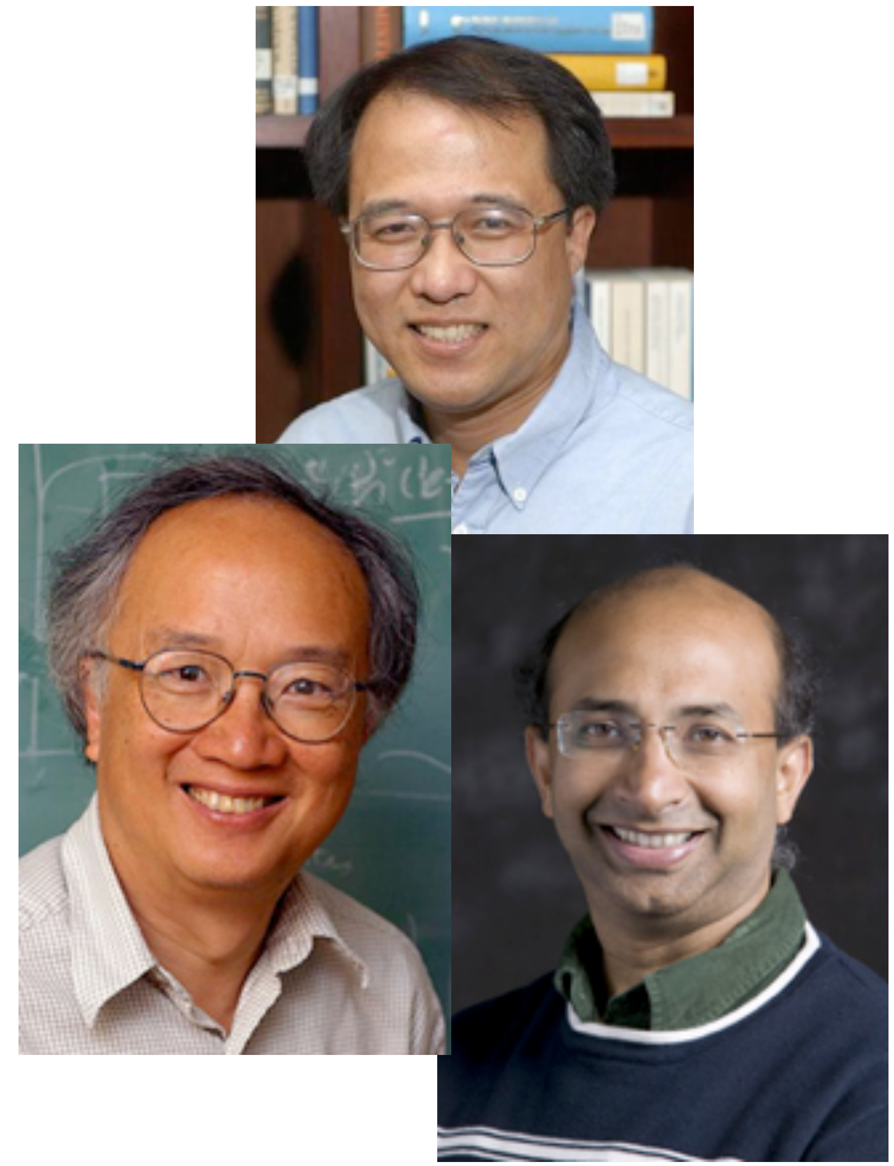
what happens happens at T=0 ?

ground state phase diagram from exact diagonalisation :
NS et al. Phys. Rev. B **69**, 220403(R) (2004)



cf. O. F. Syljusen and S. Chakravarty, Phys. Rev. Lett. **96**, 147004 (2006).
S. Chakravarty, Phys. Rev. B **66**, 224505 (2002).

V.



et al.

PHYSICAL REVIEW B **69**, 064404 (2004)

Pyrochlore photons: The $U(1)$ spin liquid in a $S=\frac{1}{2}$ three-dimensional frustrated magnet

Michael Hermele,[1] Matthew P. A. Fisher,[2] and Leon Balents[1]

S=1/2 easy-axis magnet on a pyrochlore lattice...

$$\mathcal{H}_{xxz} = J_z \sum_{\langle ij \rangle} S_i^z S_j^z + J_{xy} \sum_{\langle ij \rangle} S_i^x S_j^x + S_i^y S_j^y$$

strong anisotropy

$$J_z \gg J_{xy}$$

selects ice manifold

Hamiltonian acting on ice states...

$$\mathcal{H} = -g \sum_{\hexagon} |\circlearrowright\rangle\langle\circlearrowleft| + |\circlearrowleft\rangle\langle\circlearrowright| + \mu \sum_{\hexagon} |\circlearrowright\rangle\langle\circlearrowright| + |\circlearrowleft\rangle\langle\circlearrowleft|$$

degenerate perturbation theory

$$g = \frac{12 J_{xy}^3}{J_z^2}$$

...extra term makes model exactly soluble for μ=g

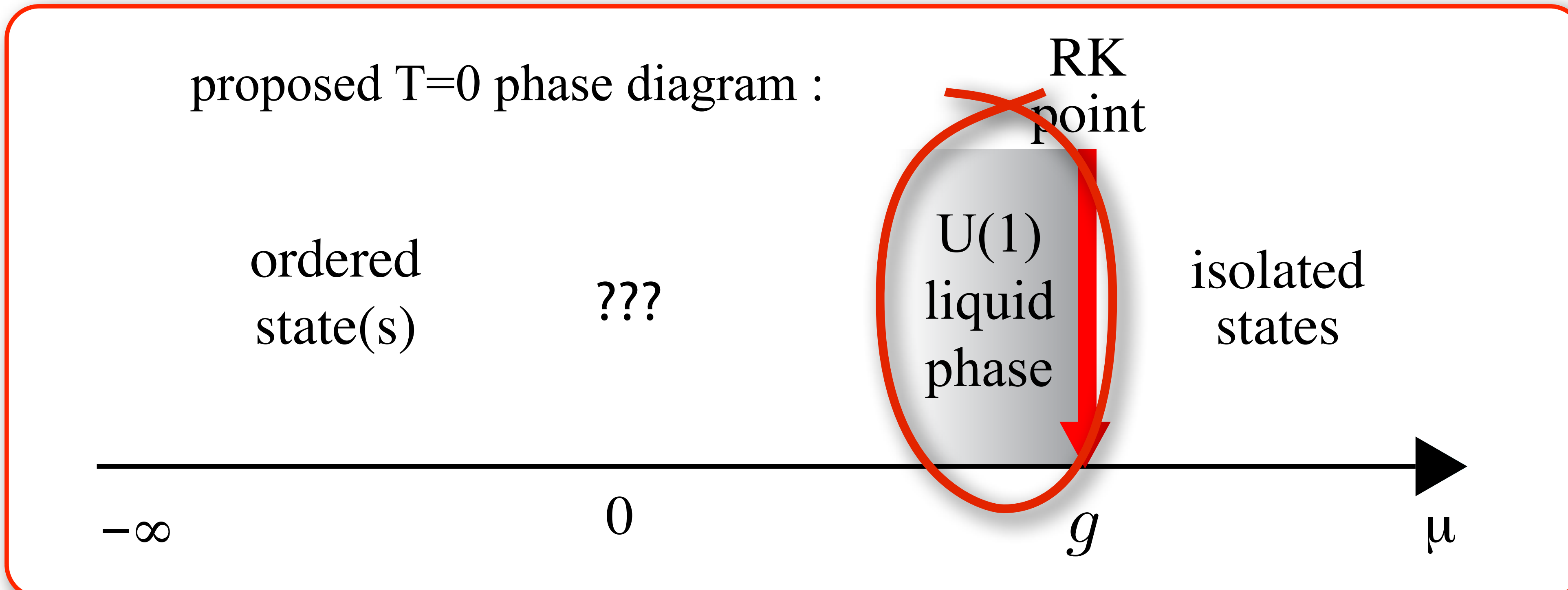
$$\mathcal{H}_\mu = -g \sum_{\hexagon} |\circlearrowleft\rangle\langle\circlearrowright| + |\circlearrowright\rangle\langle\circlearrowleft| + \mu \sum_{\hexagon} |\circlearrowleft\rangle\langle\circlearrowleft| + |\circlearrowright\rangle\langle\circlearrowright|$$

PHYSICAL REVIEW B **69**, 064404 (2004)

Pyrochlore photons: The $U(1)$ spin liquid in a $S=\frac{1}{2}$ three-dimensional frustrated magnet

Michael Hermele,[1] Matthew P. A. Fisher,[2] and Leon Balents[1]

...microscopic model is equivalent to compact, frustrated, lattice U(1) gauge theory



...equivalent proposal for 3D Quantum Dimer Model :
R. Moessner and S Sondhi, Phys. Rev. B **68**, 184512 (2003)

does this idea work ?

PRL 100, 047208 (2008) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2008

Unusual Liquid State of Hard-Core Bosons on the Pyrochlore Lattice

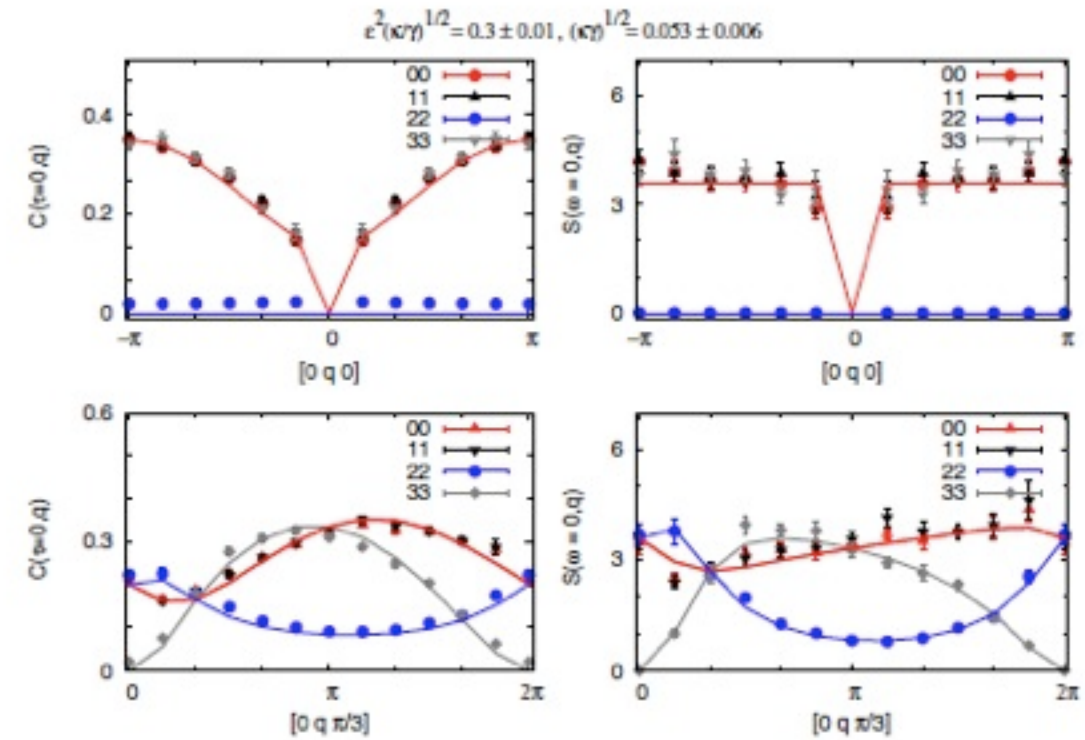
Argha Banerjee,[1] Sergei V. Isakov,[2] Kedar Damle,[1] and Yong Baek Kim[2]

consider hard-core Bosons with
strong nearest neighbour
interactions V >> t
on a pyrochlore lattice

$$\mathcal{H}_{\text{charge-ice}} = -t\sum_{\langle ij\rangle}\left(b_i^\dagger b_j + b_j^\dagger b_i\right) + V\sum_{\langle ij\rangle}\left(n_i - \frac{1}{2}\right)\left(n_j - \frac{1}{2}\right)$$

quantum charge ice with tunneling

$$g = 12t^3/V^2$$



finite temperature correlation functions, calculated using QMC, and compared to the predictions of a U(1) gauge theory

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...suppose it orders at a lower temperature

effective Hamiltonian in ice manifold

$$\mathcal{H} = -g \sum_{\square} |\circlearrowright\rangle\langle\circlearrowleft| + |\circlearrowleft\rangle\langle\circlearrowright| + \mu \sum_{\square} |\circlearrowright\rangle\langle\circlearrowright| + |\circlearrowleft\rangle\langle\circlearrowleft|$$

all off-diagonal matrix elements have definite (negative) sign

suitable for T=0 GFMC simulation as no sign problems
(but simulation doesn't need to converge in finite time !)

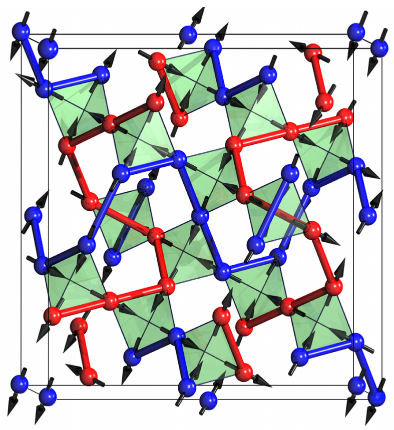
...some CPU-centuries later

PRL **108,** 067204 (2012) PHYSICAL REVIEW LETTERS 10 FEBRUARY 2012

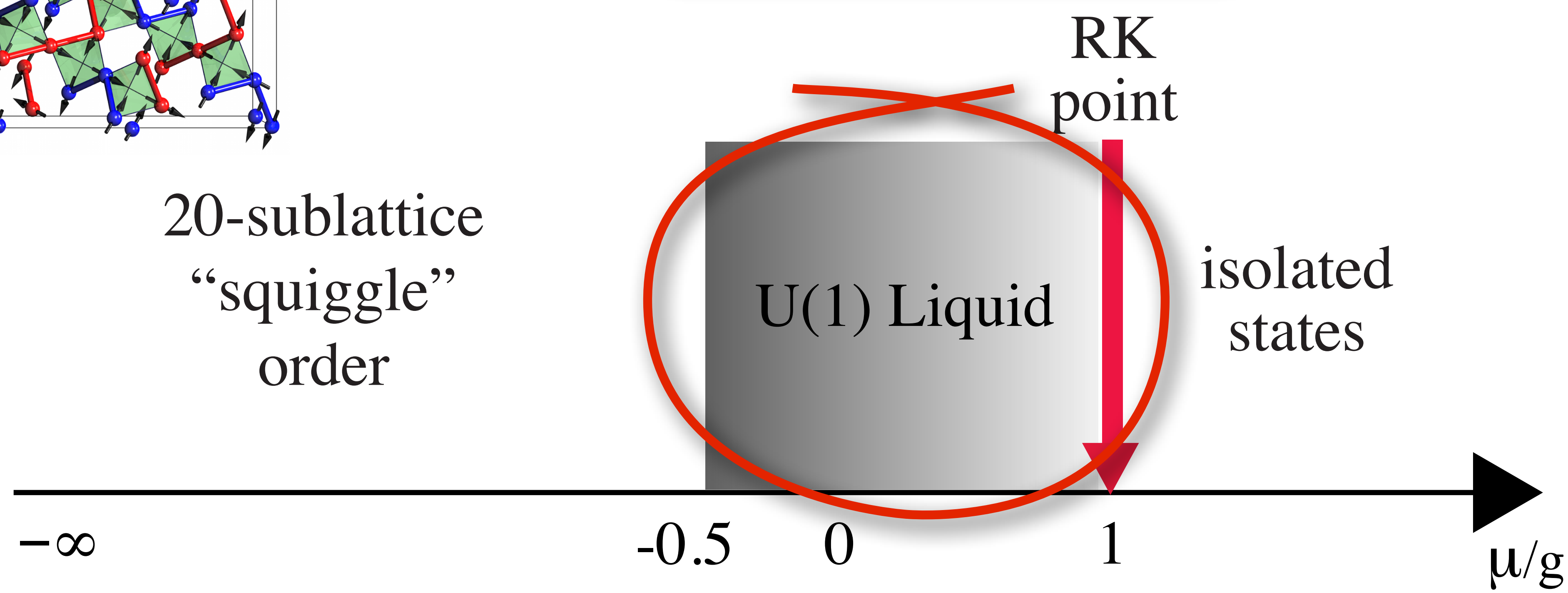
Quantum Ice: A Quantum Monte Carlo Study

Nic Shannon,[1] Olga Sikora,[1] Frank Pollmann,[2] Karlo Penc,[3] and Peter Fulde[2,4]

$$\mathcal{H}_\mu = -g\sum_{\hexagon}\left(|\circlearrowleft\rangle\langle\circlearrowright| + |\circlearrowright\rangle\langle\circlearrowleft|\right) + \mu\sum_{\hexagon}\left(|\circlearrowleft\rangle\langle\circlearrowleft| + |\circlearrowright\rangle\langle\circlearrowright|\right)$$



extended T=0 quantum spin liquid phase !



ground state phase diagram from Quantum Monte Carlo simulation

so what's a quantum U(1) liquid ?

- **quantum (spin) liquid** with excitations described by the Maxwell action of classical electromagnetism
- supports both electric and magnetic charges (**magnetic monopoles**)
- electric and magnetic fields couple to give **photons**

$$S = \int d^3x dt \left[\mathbf{E}^2 - c^2 \mathbf{B}^2 \right]$$

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so what's a quantum U(1) liquid ?

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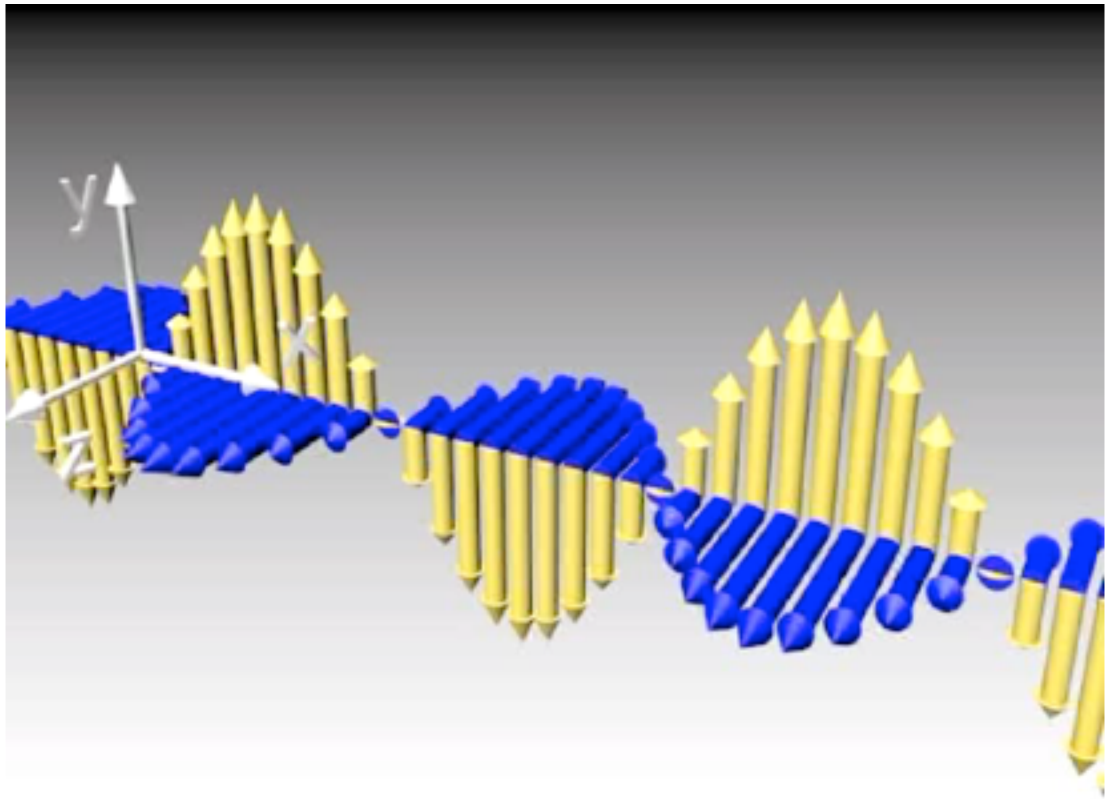
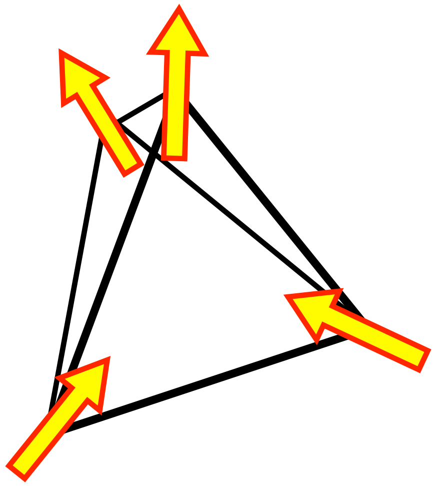


$$S = \int d^3x dt \left[\mathbf{E}^2 - c^2 \mathbf{B}^2 \right]$$

how does this happen ?



$\nabla.\mathbf{B} = 0$ ...by **explicit construction**

solve as : $\mathbf{B} = \nabla \times \mathbf{A}$ and chose Coulomb gauge : $\nabla.\mathbf{A} = 0$

quantum ice has **local dynamics** :

$$\mathcal{H} = -g \sum_{\hexagon} |\circlearrowright\rangle\langle\circlearrowleft| + |\circlearrowleft\rangle\langle\circlearrowright|$$

tunneling between ice states ⇒ gauge field varies in time

simplest guess for effective field theory in a liquid phase is **Maxwell** action :

$$S = \int d^3x dt \left[\mathbf{E}^2 - c^2\mathbf{B}^2\right]$$

$$\mathbf{E} = \partial_t \mathbf{A} - \nabla A_0$$

same story, longer equations...

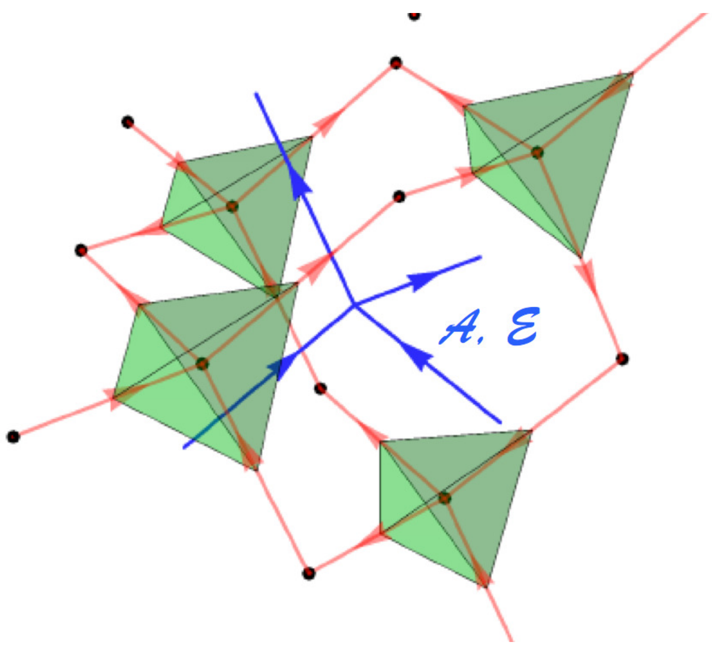
compact U(1) lattice gauge theory...

$$\mathcal{H}'_{\mathsf{U(1)}} = \frac{\mathcal{U}}{2} \sum_{\mathbf{r}\in A,n} \left[(\nabla_{\circ} \times \mathcal{A})_{(\mathbf{r},n)}\right]^2 + \frac{1}{2\mathcal{K}} \sum_{\mathbf{s}\in A',m} \left[\frac{\partial \mathcal{A}_{(\mathbf{s},m)}}{\partial t}\right]^2 + \frac{\mathcal{W}}{2} \sum_{\mathbf{s}\in A',m} \left[(\nabla_{\circ} \times \nabla_{\circ} \times \mathcal{A})_{(\mathbf{s},m)}\right]^2$$

"ice" term

tunnelling term

"μ" term (relevant at RK point)



...theory is quadratic in gauge field

can diagonalise problem by introducing suitable photon basis :

$$\mathcal{A}_{(\mathbf{s},m)} = \sqrt{\frac{2}{N}} \sum_{\mathbf{k}} \sum_{\lambda=1}^{4} \sqrt{\frac{\mathcal{K}}{\omega_\lambda(\mathbf{k})}} \times \Big(\exp\left[-i\mathbf{k}\cdot(\mathbf{s}+\mathbf{e}_m/2)\right] \eta_{m\lambda}(\mathbf{k}) a_\lambda(\mathbf{k}) + \exp\left[i\mathbf{k}\cdot(\mathbf{s}+\mathbf{e}_m/2)\right] \eta^*_{\lambda m}(\mathbf{k}) a^\dagger_\lambda(\mathbf{k})\Big)$$

DYNAMICAL STABILITY OF LOCAL GAUGE SYMMETRY

Creation of Light From Chaos

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Received 14 May 1980

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

Origin of Gauge Bosons from Strong Quantum Correlations

Xiao-Gang Wen*

VOLUME 89, NUMBER 27 PHYSICAL REVIEW LETTERS 30 DECEMBER 2002

Exotic Order in Simple Models of Bosonic Systems

O. I. Motrunich and T. Senthil

a spin liquid with many advocates...

X.-G. Wen, Phys. Rev. B **68**, 115413 (2003).
R. Moessner and S. Sondhi, Phys. Rev. B **68**, 184512 (2003)
M. Hermele, L. Balents and M. Fisher, Phys. Rev. B **69**, 064404 (2004)
O. I. Motrunich and A. Vishwanath, Phys. Rev. B **70**, 075104 (2004)
O. I. Motrunich and T. Senthil, Phys. Rev. B **71**, 125102 (2005)
M. Levin and X.-G. Wen, Rev. Mod. Phys. **77**, 871 (2005)
(and many more...)

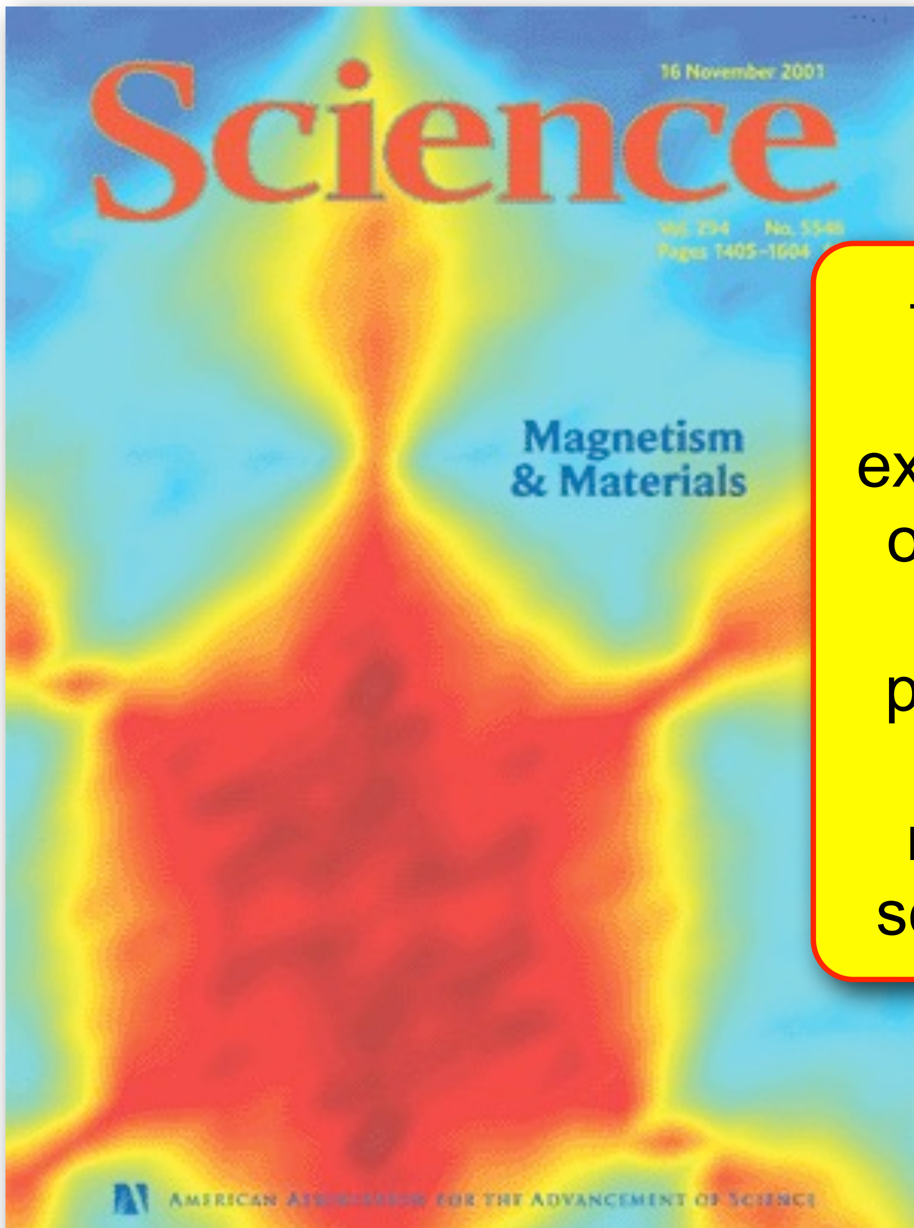
the story so far...

classical ice = magnetostatics

quantum ice = electromagnetism

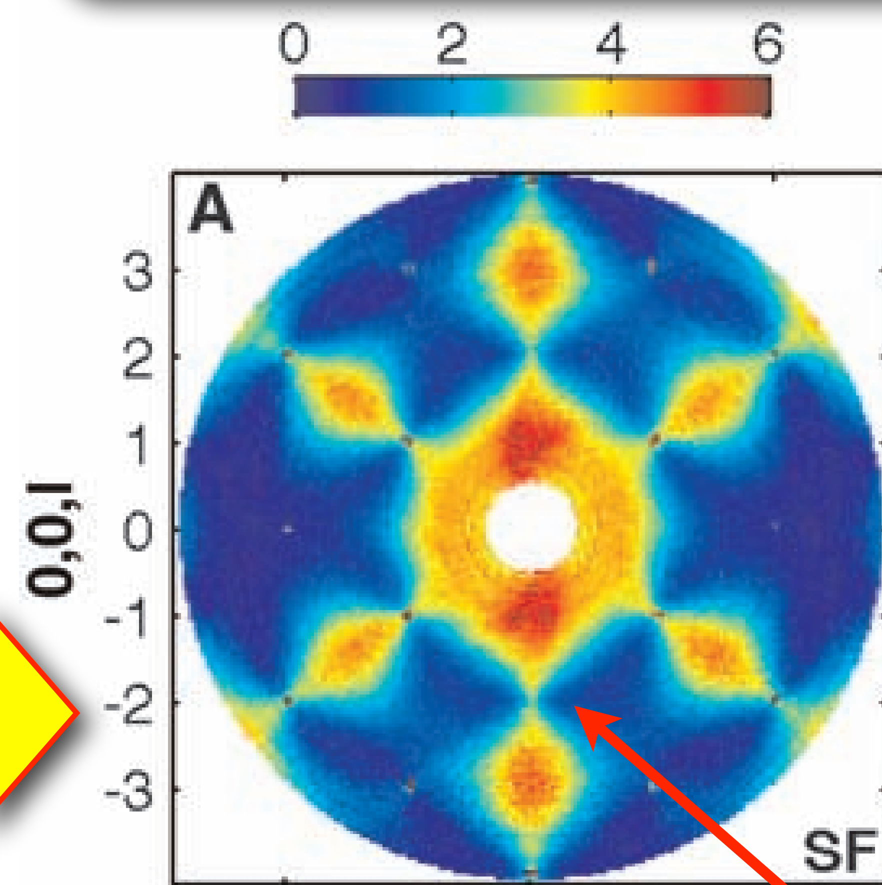
...so what ?

how can we “see” the ice rules ?



for spin ices, experiment of choice is spin-polarised elastic neutron scattering

experimental results for $Ho_2Ti_2O_7$ in spin-flip channel



pinch point

T. Fennell et al, Science **326**, 415 (2009).

what does a quantum ice look like ?

quantum fluctuations in the quantum U(1) liquid supress pinch points

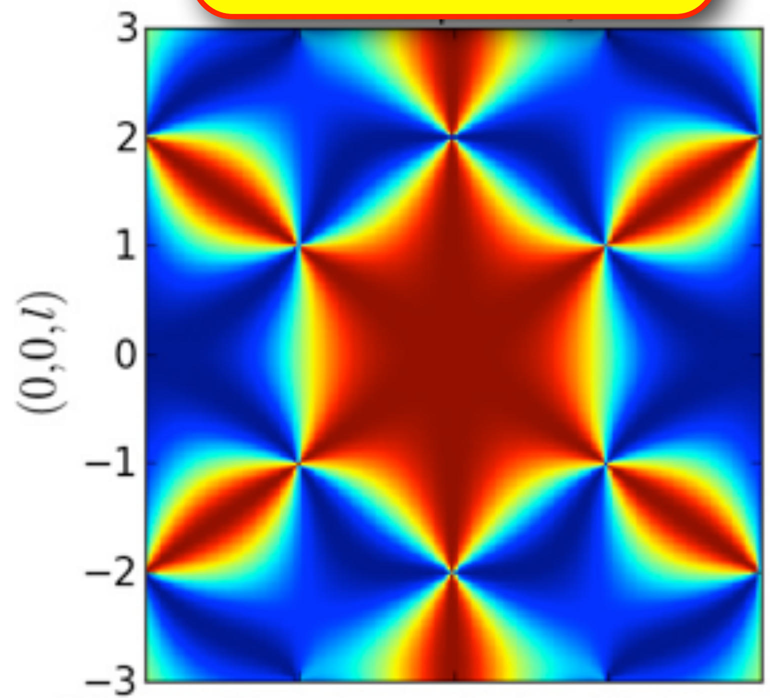
$$S^{\alpha\beta}(\mathbf{q}) \propto \langle \mathcal{B}_\alpha(-\mathbf{q})\mathcal{B}_\beta(\mathbf{q})\rangle = \frac{8\pi^4 q}{c}\left[\delta_{\alpha\beta} - \frac{q_\alpha q_\beta}{q^2}\right]\coth\left(\frac{cq}{2T}\right)$$

what would this look like in a quantum spin ice ?

predictions for quasi-elastic structure factor at T=0

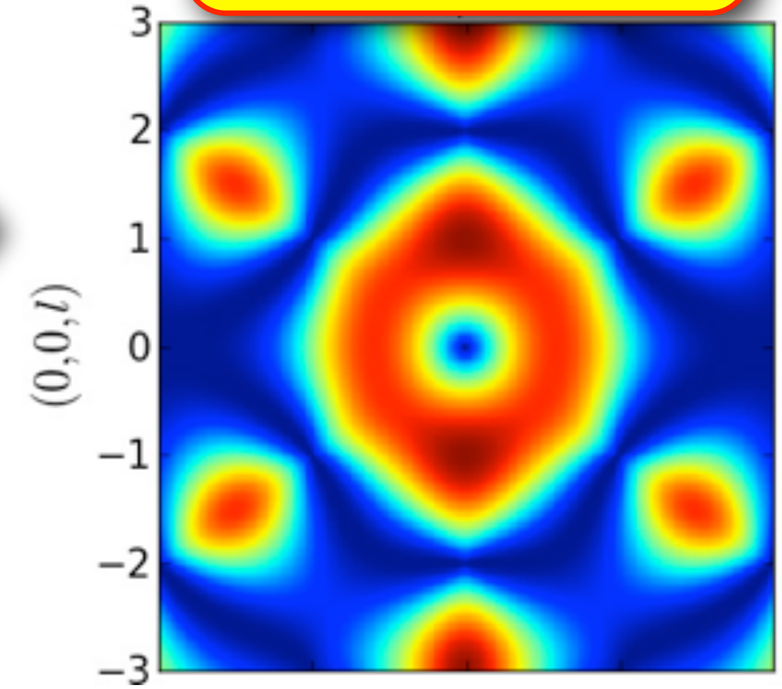
Owen Benton

classical ice



finite speed of light

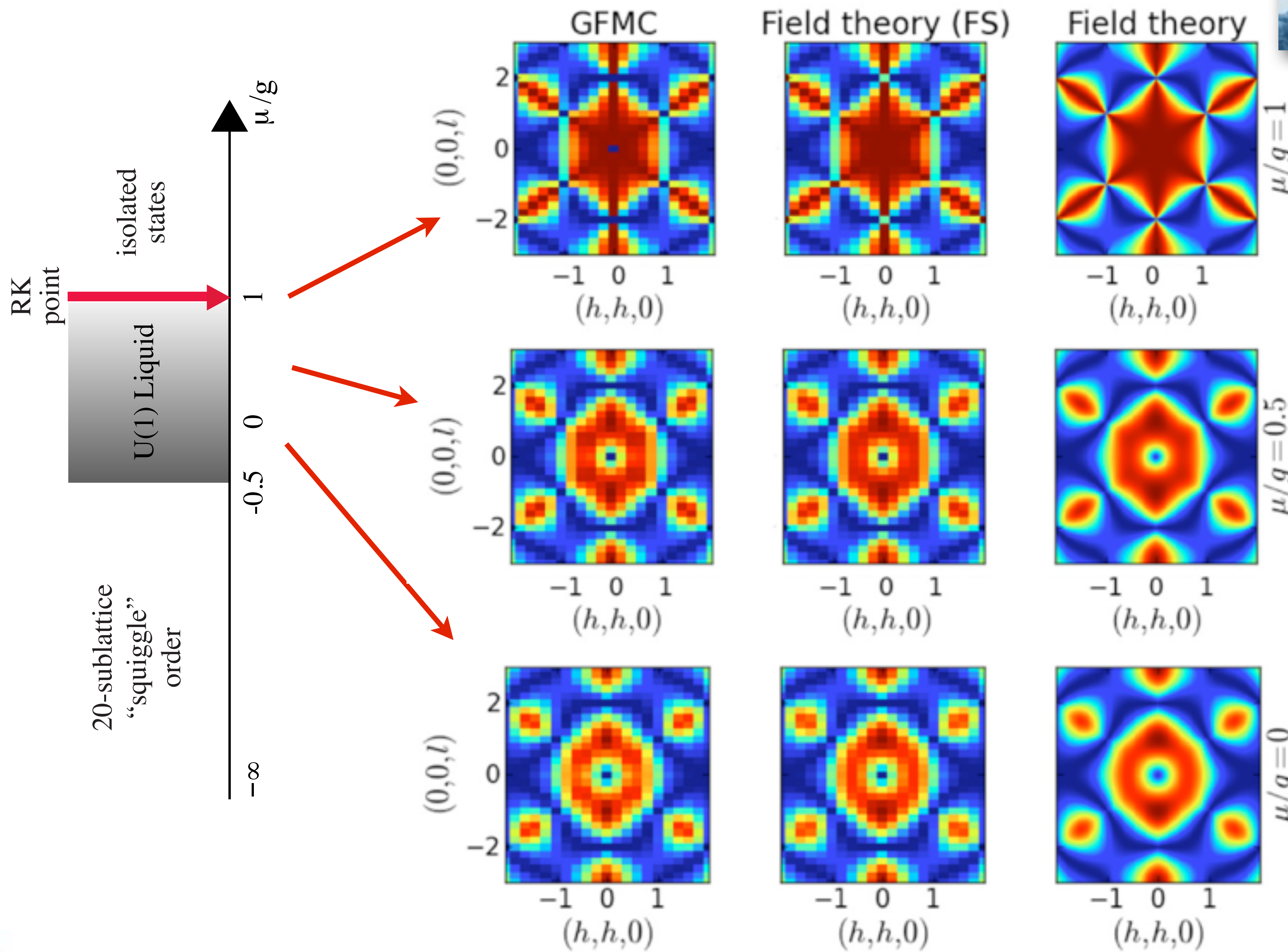
quantum ice



...no pinch points !

is this what we see in simulation ?

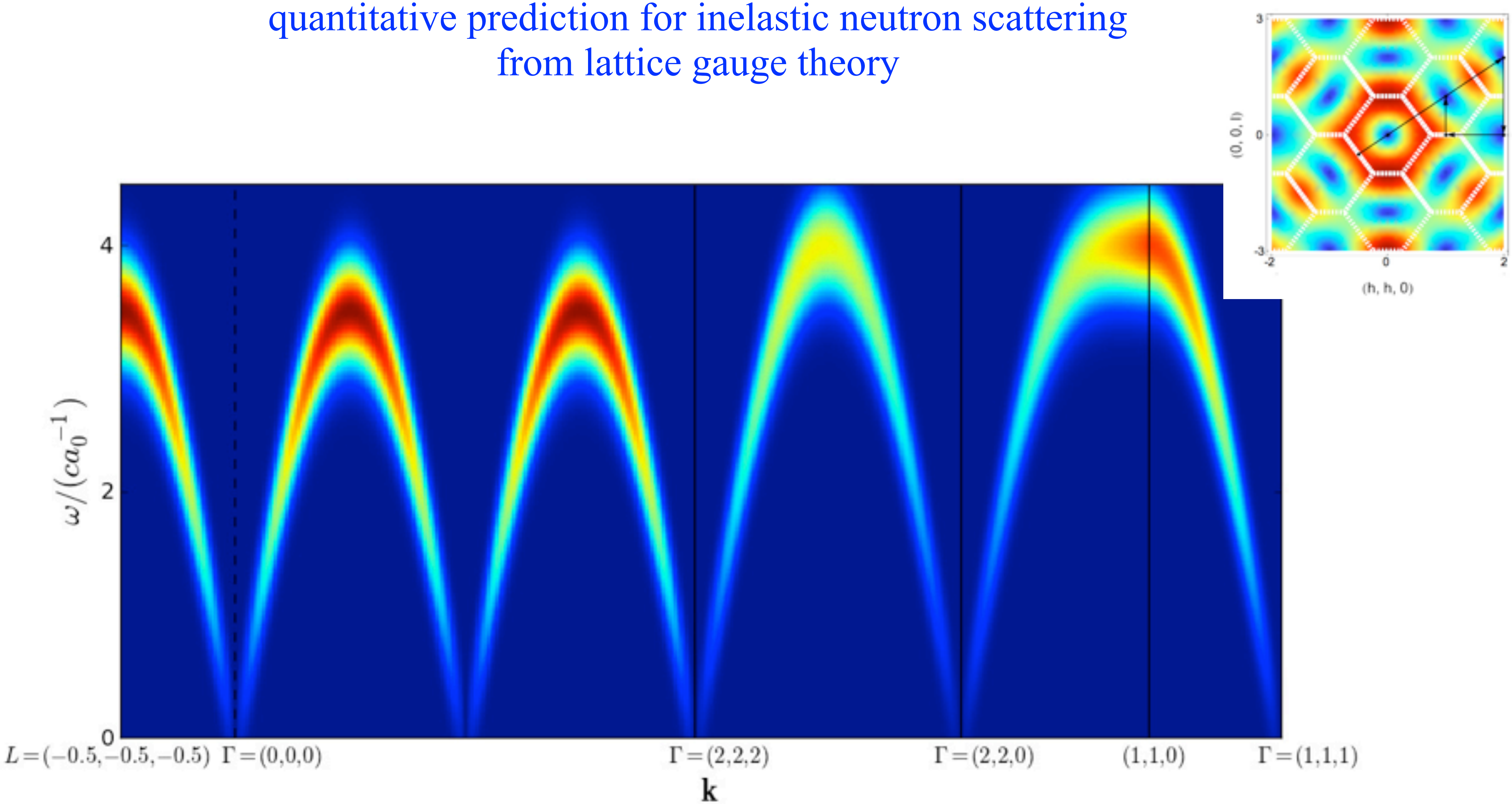
$$\mathcal{H}_\mu = -g \sum_{\hexagon} |\circlearrowright\rangle\langle\circlearrowleft| + |\circlearrowleft\rangle\langle\circlearrowright| + \mu \sum_{\hexagon} |\circlearrowright\rangle\langle\circlearrowright| + |\circlearrowleft\rangle\langle\circlearrowleft|$$



O. Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012)

seeing the light ?

quantitative prediction for inelastic neutron scattering
from lattice gauge theory



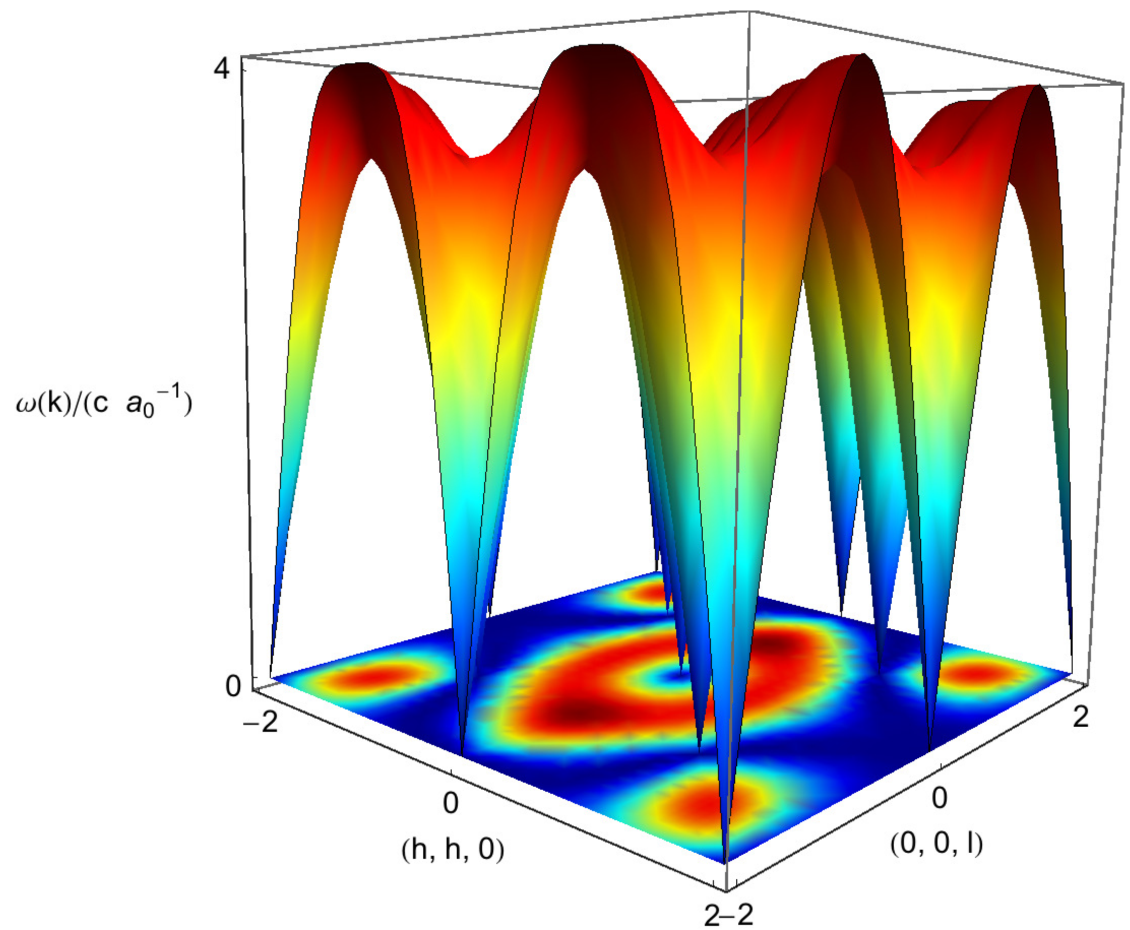
O. Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012) ❦

where did the pinch-points go ?

quasi-elastic scattering
given by energy-intergral of
dynamical structure factor

$$S^{\alpha\beta}(\mathbf{q}) = \int d\omega\, S^{\alpha\beta}(\mathbf{q},\omega)$$

vanishing spectral weight in
photons at low energies
$\Rightarrow$ loss of pinch-points



cf. M. Hermele, L. Balents and M. Fisher, Phys. Rev. B **69**, 064404 (2004)
L. Savary and L. Balents. Phys. Rev. Lett. **108**, 037202 (2012)

what happens at finite temperature ?

photons can be thermally excited, just like phonons...

$$S^{\alpha\beta}(\mathbf{q}) \propto \langle \mathcal{B}_\alpha(-\mathbf{q})\mathcal{B}_\beta(\mathbf{q})\rangle = \frac{8\pi^4 q}{c}\left[\delta_{\alpha\beta} - \frac{q_\alpha q_\beta}{q^2}\right] \coth\left(\frac{cq}{2T}\right)$$

...how does this change the scattering ?

Owen Benton

$$\lim_{q\to 0} \coth\left(\frac{cq}{2T}\right) \propto \frac{T}{q} \quad \Rightarrow$$

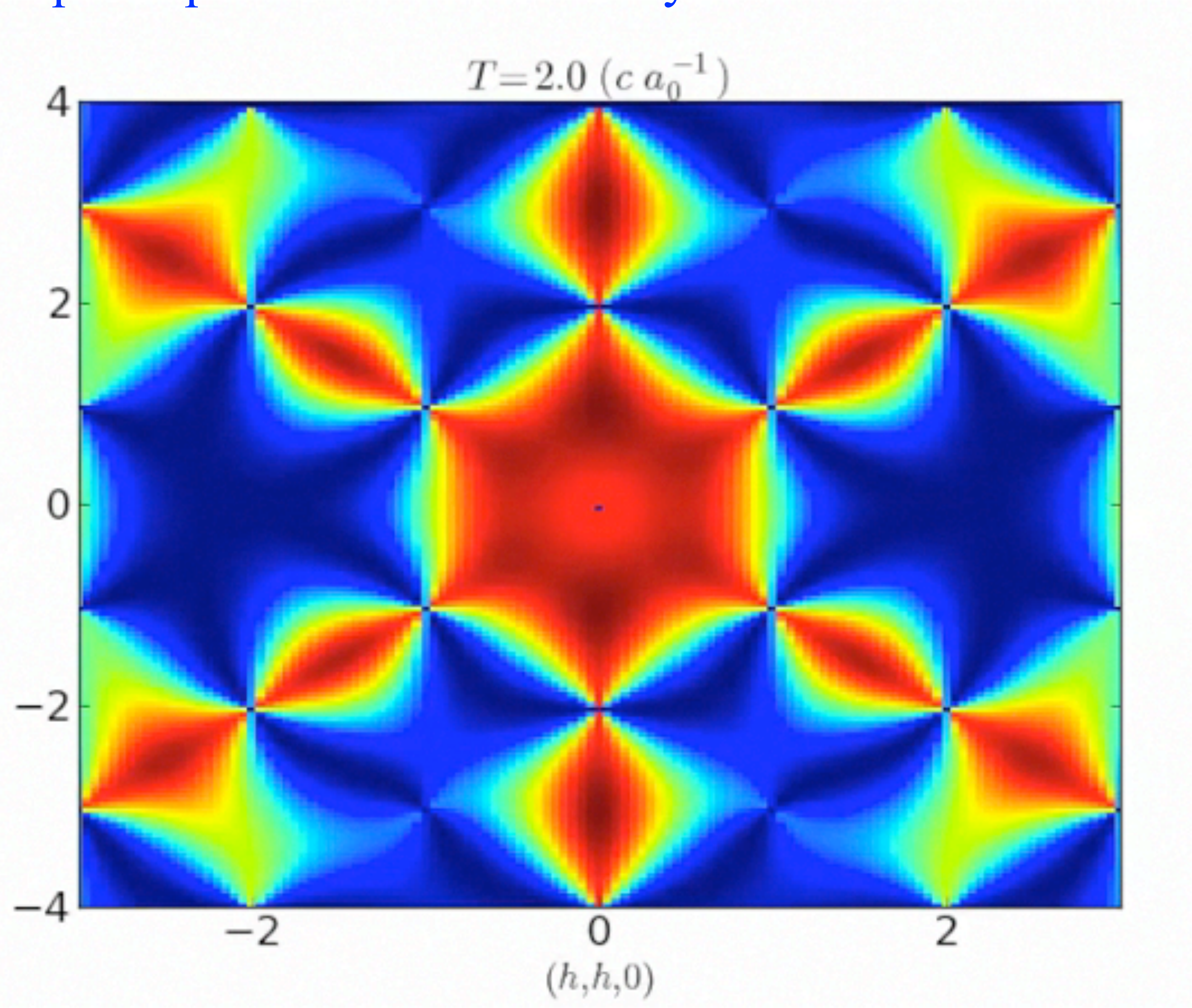
$$S^{\alpha\beta}(\mathbf{q}\approx 0) \propto T\left[\delta_{\alpha\beta} - \frac{q_\alpha q_\beta}{q^2}\right]$$

...i.e. pinch points vanish linearly with T

O. Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012) ❦

what happens at finite temperature ?

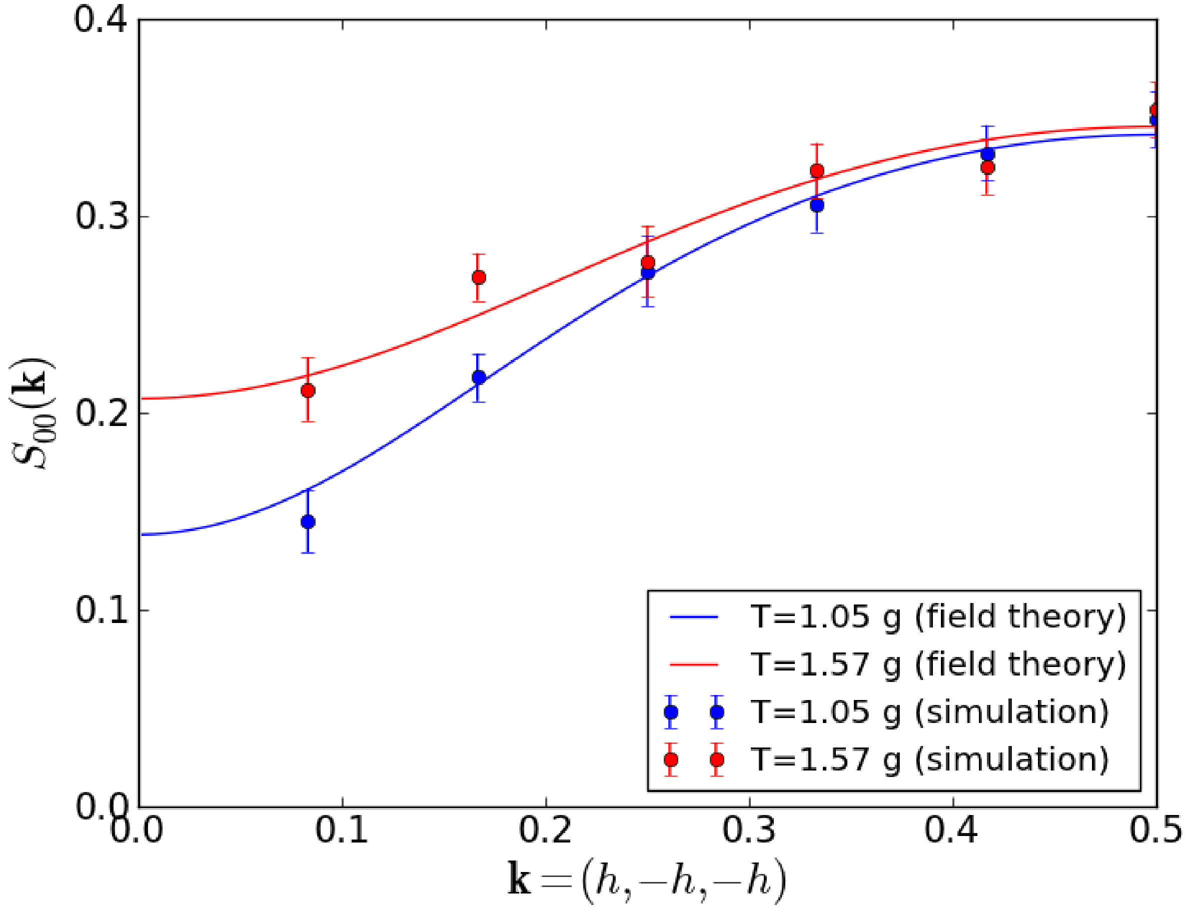
pinch points "wash out" as system is cooled to T=0



...predictions of lattice gauge theory

O. Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012) ❦

what about simulation ?



points : finite temperature QMC simulation

A. Banerjee *et al.*, Phys. Rev. Lett. **100**, 047208 (2008)

lines : U(1) lattice gauge theory at finite temperature

O. Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012) ❦

does this have anything to do with real materials ?

can we hope to see photons in $Yb_2Ti_2O_7$?

estimate of tunnelling matrix element between ice states in Yb2Ti2O7 from parameters obtained by Ross et al.

$$g_{\mathrm{Yb_2Ti_2O_7}} \approx 0.05\ \mathrm{meV}.$$

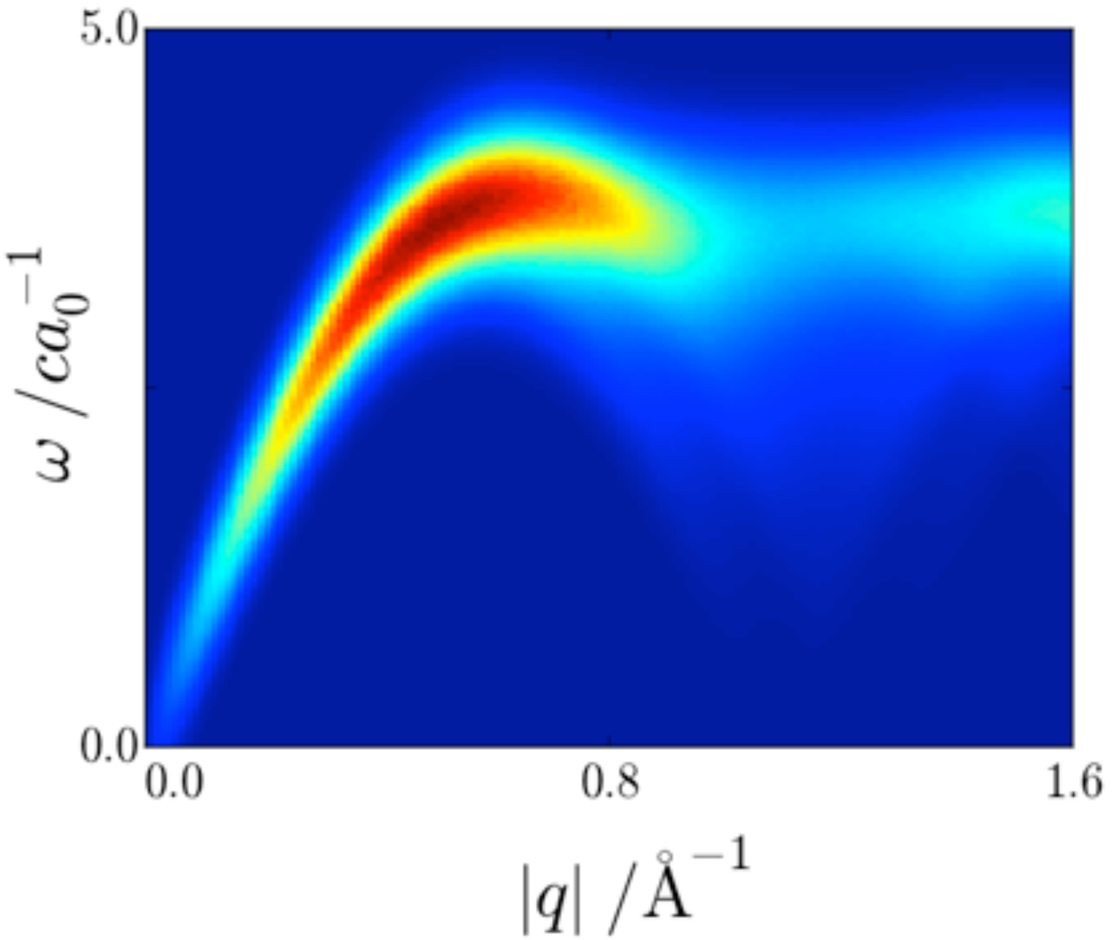
corresponding speed of light

$$c \sim 0.3\ \mathrm{meV}\ \mathrm{Å} \sim 50\ \mathrm{ms}^{-1}$$

photon bandwidth

$$\Delta\omega \sim 0.1\ \mathrm{meV}$$

this can be resolved !



predictions for inelastic neutron scattering on a powder sample of $Yb_2Ti_2O_7$

O. Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012) ❦

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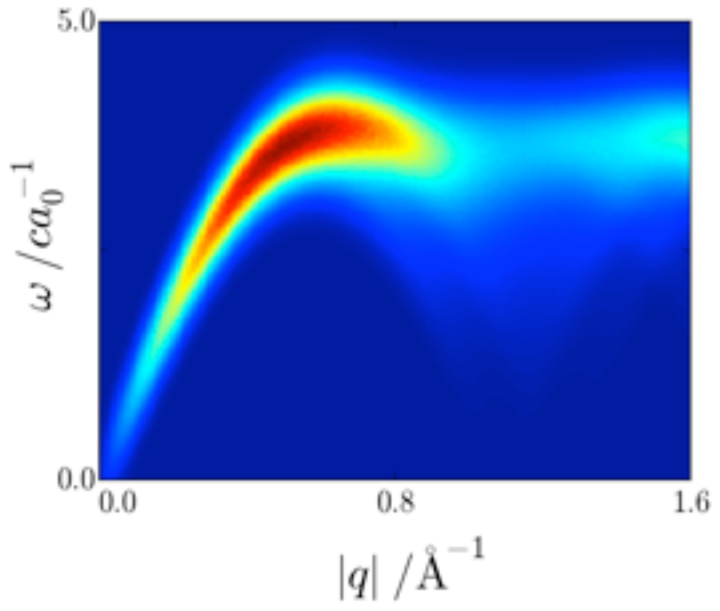
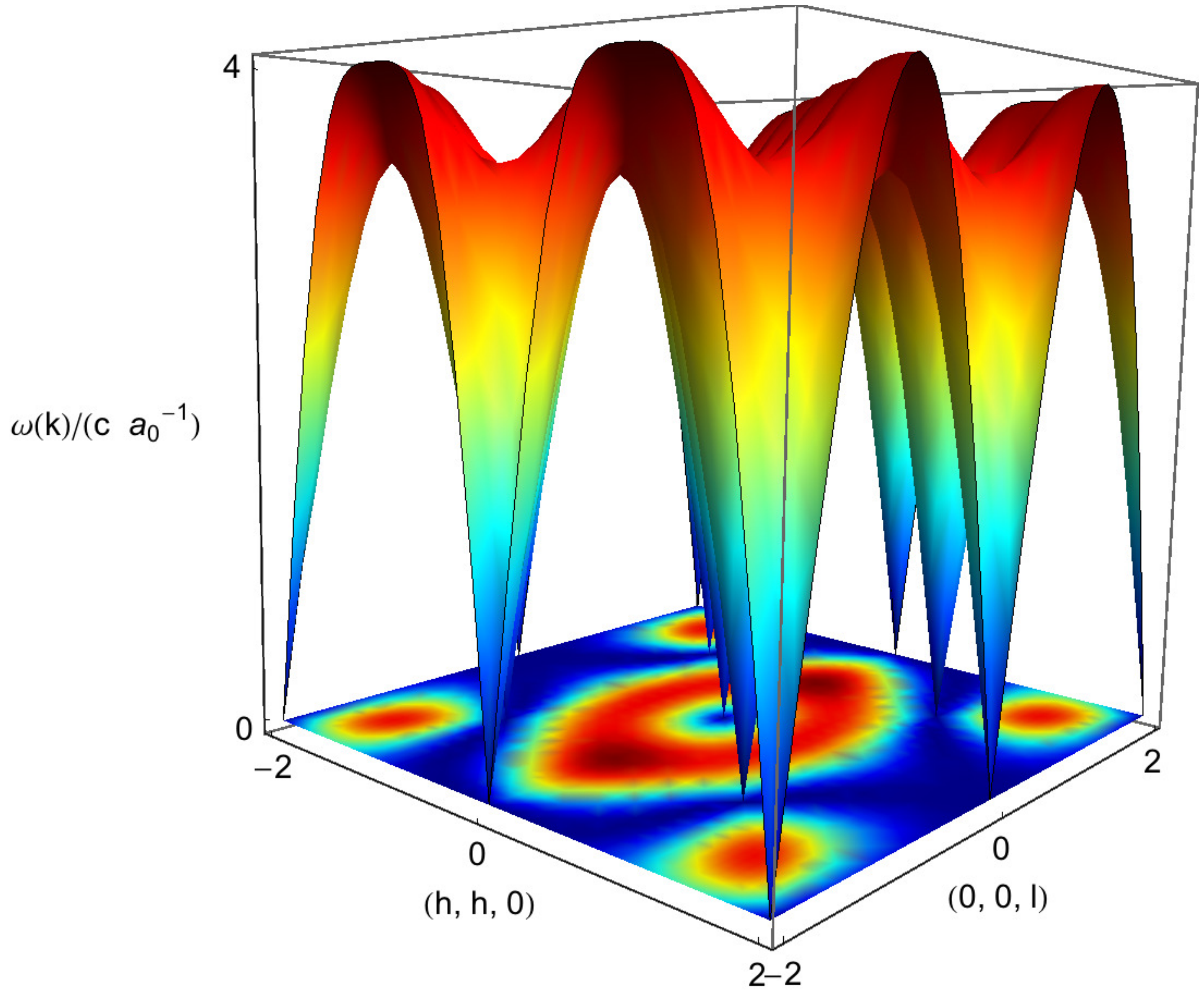
where does this leave us ?

- **quantum ice** has a (spin) liquid ground state with excitations described by the Maxwell action of classical electromagnetism
- this state support **photons** which should be visible in neutron scattering experiments
- a number candidate **‘quantum spin ice’** materials are now being intensively investigated...
- lots of interesting open questions !



thanks for listening !



Owen Benton *et al.*, Phys. Rev. B. **83**, 075174 (2012) ❦
N.S. *et al.*, Phys. Rev. Lett. **108**, 067204 (2012)