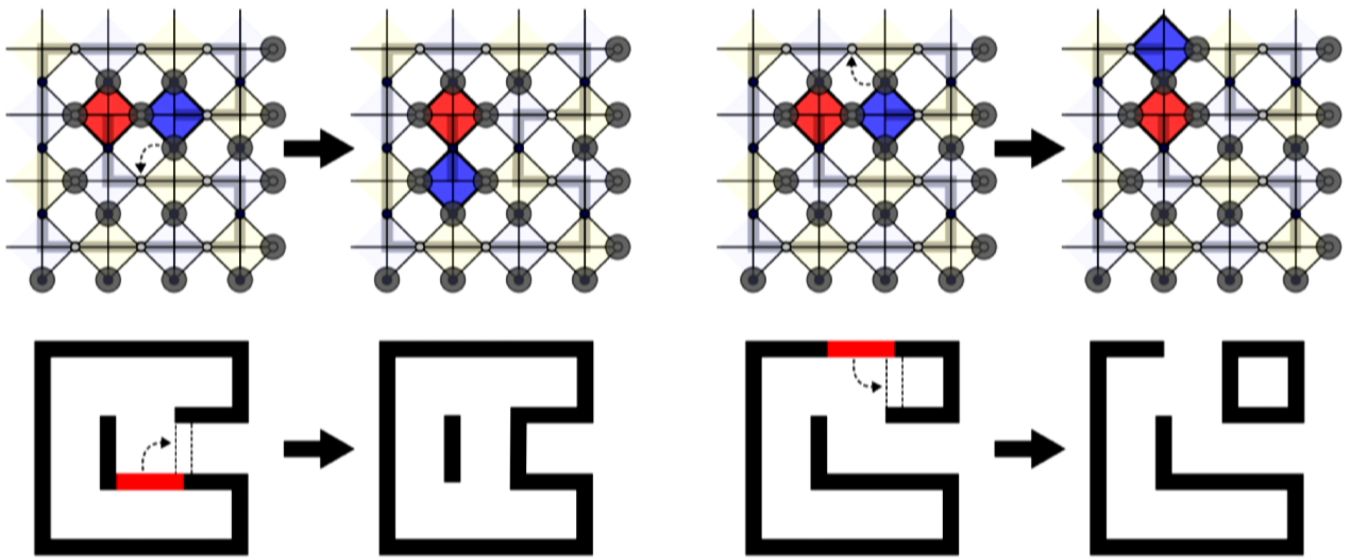
Title: Spinon freedom in quantum square ice

Date: Apr 15, 2016 01:00 PM

URL: http://pirsa.org/16040099

Abstract: <p>Recent theoretical and experimental efforts have been focused on the identification of excitations in quantum spin ice. Due to their relation to the magnetic monopoles of classical spin ice, their quantum counterparts, called spinons, are a highly sought-after manifestation of fractionalization in frustrated quantum magnets like Yb2Ti2O7. Of particular current interest is the quantum dynamics of spinons, namely, their modes of propagation and interaction with the strongly correlated spin background. To investigate this dynamics, we study excited quantum square ice, as captured by the spin-1/2 checkerboard-lattice XXZ model. We formulate effective free-spinon theories in the strong Ising coupling limit, with spinons either deconfined or artificially confined to nearest-neighbor distance, and calculate the corresponding approximate dynamic spin-structure factors (DSFs). We then evaluate the DSF of the fully interacting model exactly for clusters of up to 72 sites. The resulting spectra allow us to identify dispersive fingerprints of coherent spinon propagation in the correlated ``vacuum" of quantum square ice within an extended low-energy regime. We thus provide unbiased evidence for the formation of coherent quasiparticles in quantum spin ice above the Ising gap.</p>



Spinon freedom in quantum square ice

Stefanos Kourtis and Claudio Castelnovo, arXiv:1604.03951

April 15th 2016 – Perimeter Institute

ICAM-I2CAM Institute for Complex Adaptive Matter

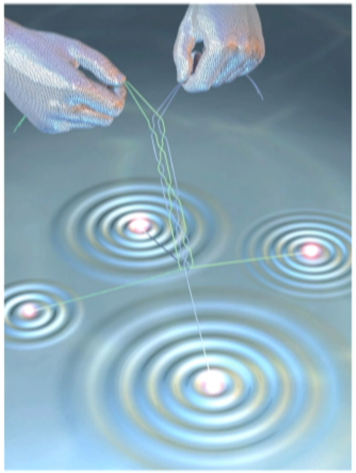
TCM

UNIVERSITY OF CAMBRIDGE

PRINCETON UNIVERSITY

Dynamics in strongly correlated **quantum** matter

or in this case: what happens when I flip a spin in a quantum magnet?



What are they? Can we do anything with them?

In particular:

~ what happens if there is **no Landau order**?

~ what **observables** to look at?

→ Dynamic responses:

~ $$\mathcal{S}(\mathbf{k},\omega) = \sum_m |\langle m|S^+_{\mathbf{k}}|0\rangle|^2 \delta(E_m - E_0 - \hbar\omega)$$

~ sharp bands → free excitations

~ free excitations → sharp bands**?**

Fractionalization of spin flips

PROC. PHYS. SOC., 1966, VOL. 87

Spin waves in $RbMnF_3$

C. G. WINDSOR† and R. W. H. STEVENSON‡

† Solid State Physics Division, Atomic Energy Research Establishment, Harwell, Didcot, Berks.

‡ Department of Natural Philosophy, Aberdeen University, Aberdeen

MS. received 12*th October* 1965

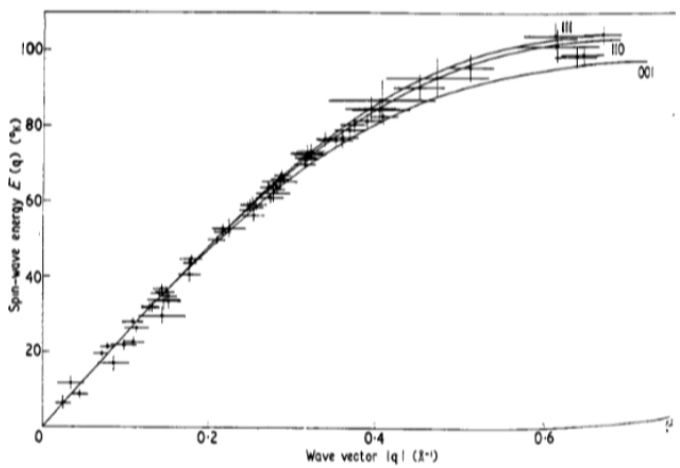


Figure 2. Spin waves in $RbMnF_3$ at 4·2 °K with **q** vectors distributed over a 110 plane. The smooth curves show the calculated dispersion along particular directions with $J_1 = 3·4$ °K, $J_2 = J_3 = 0·0$ °K. These values were found from a least-squares analysis, the exact direction of all the **q** vectors being taken into account. The fact that the linear part of the curve extends so close to the origin reflects the very small anisotropy field.

ARTICLES
nature physics
PUBLISHED ONLINE: 29 NOVEMBER 2009 | DOI: 10.1038/NPHYS1462

Confinement of fractional quantum number particles in a condensed-matter system

Bella Lake[1,2]*, Alexei M. Tsvelik[3]*, Susanne Notbohm[1,4], D. Alan Tennant[1,2], Toby G. Perring[5,6], Manfred Reehuis[1], Chinnathambi Sekar[7,8], Gernot Krabbes[7] and Bernd Büchner[7]

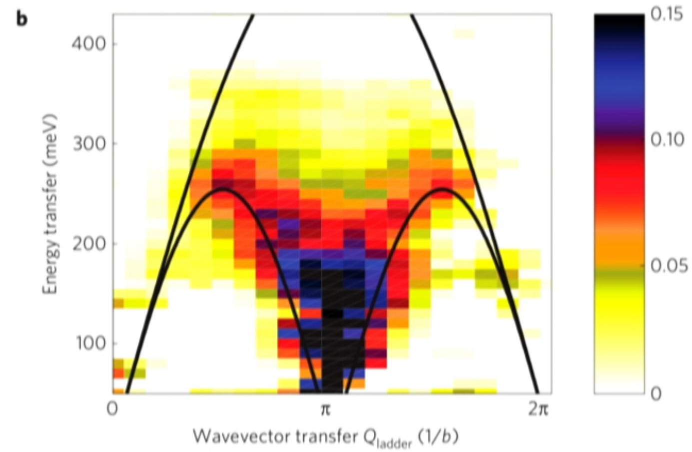
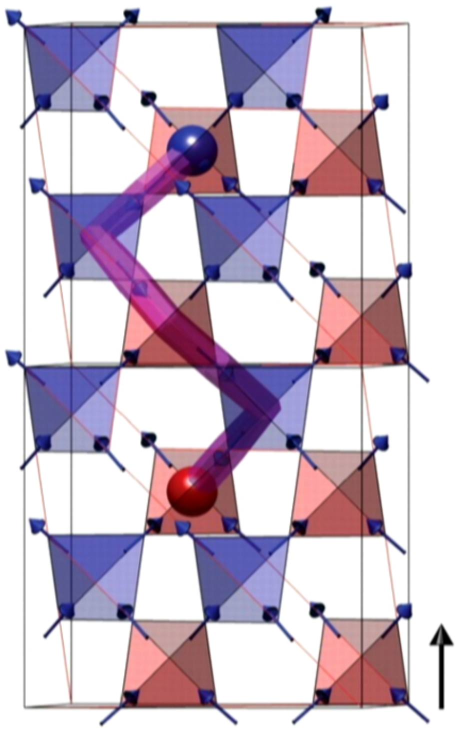


Figure 2 | High-energy inelastic neutron scattering data for $CaCu_2O_3$.

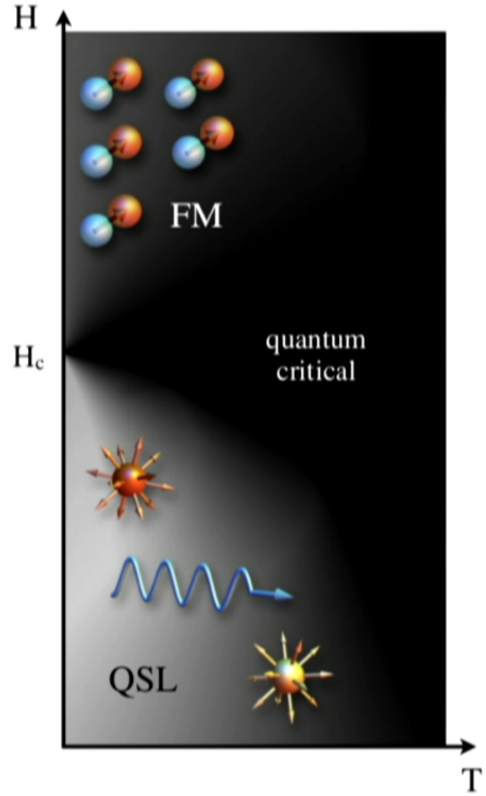
Spinons in 3D: spin ice → quantum spin ice

Gingras and McClarty, Rep. Prog. Phys. (2014)

Morris *et al.*, Science (2009)



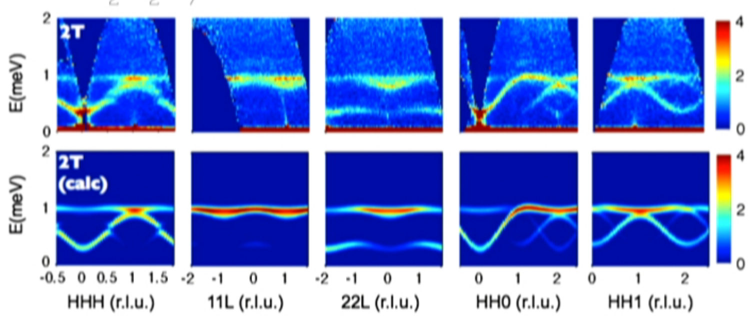
Ross *et al.*, PRX (2011)



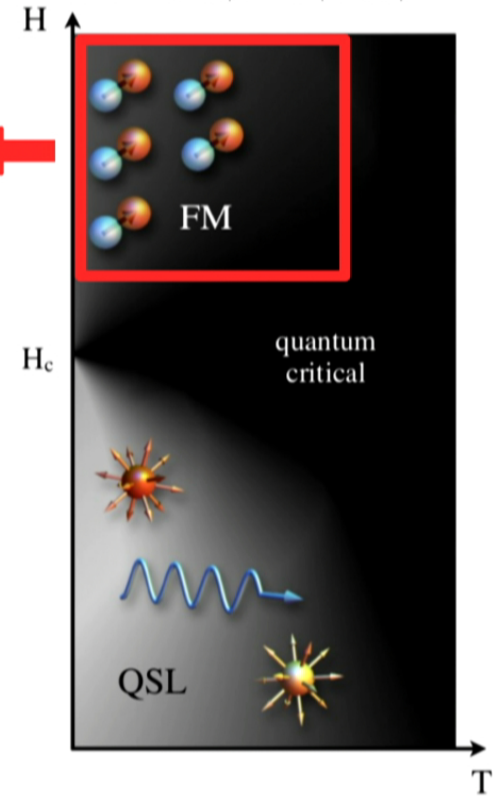
Spinons in 3D: spin ice → quantum spin ice

Gingras and McClarty, Rep. Prog. Phys. (2014)

$Yb_2Ti_2O_7$:



Ross *et al.*, PRX (2011)



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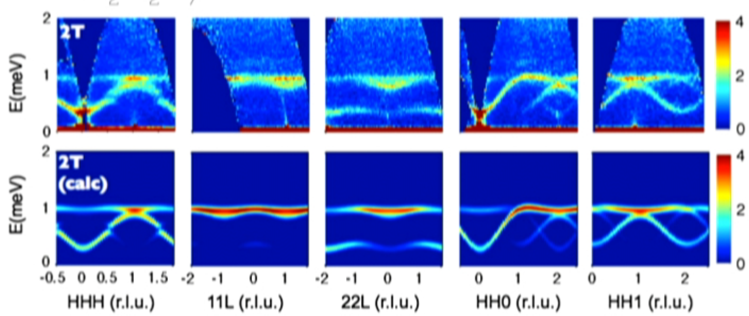
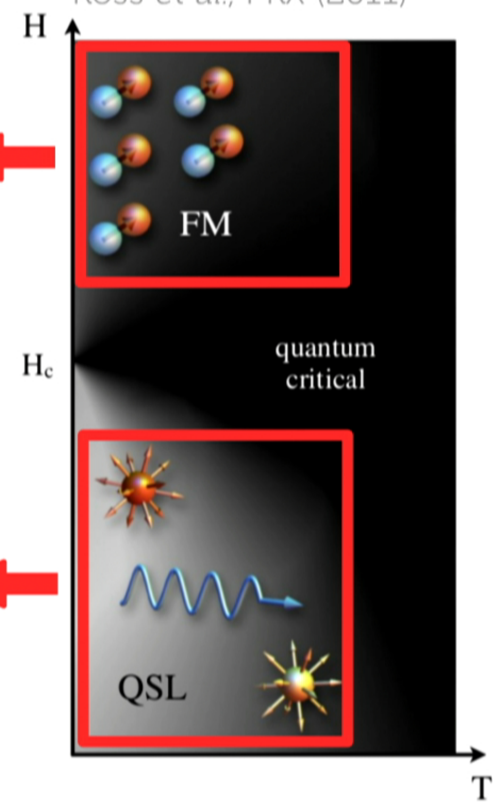


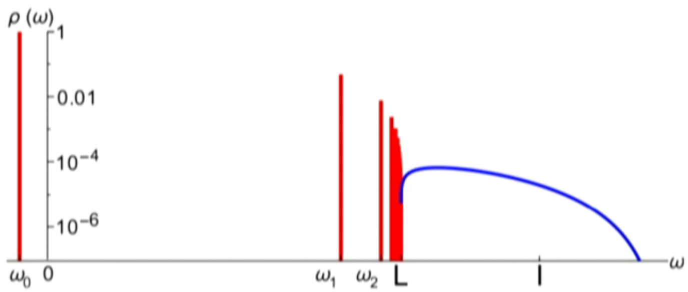
?

Ross *et al.*, PRX (2011)

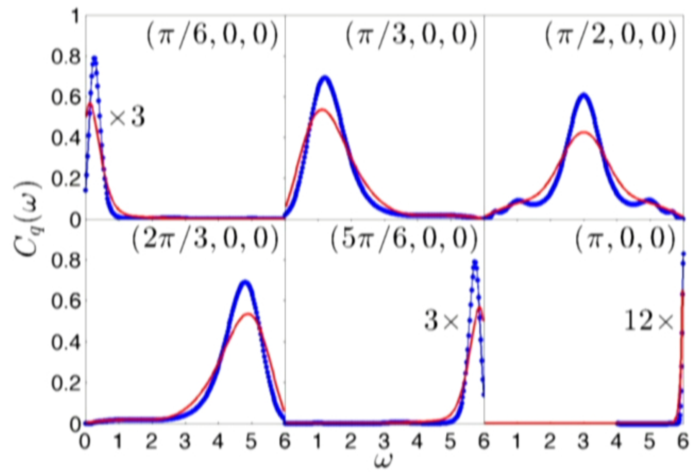


Spinon dynamics in quantum spin ice

Petrova *et al.*, PRB (2015)



Wan *et al.*, soon in PRL (2016)



Experiments:

A measure of monopole inertia in the quantum spin ice $Yb_2Ti_2O_7$

LiDong Pan, N. J. Laurita, Kate A. Ross, Bruce D. Gaulin & N. P. Armitage
Nature Physics **12**, 361–366 (2016) | doi:10.1038/nphys3608
Received 24 April 2015 | Accepted 19 November 2015 | Published online 21 December 2015

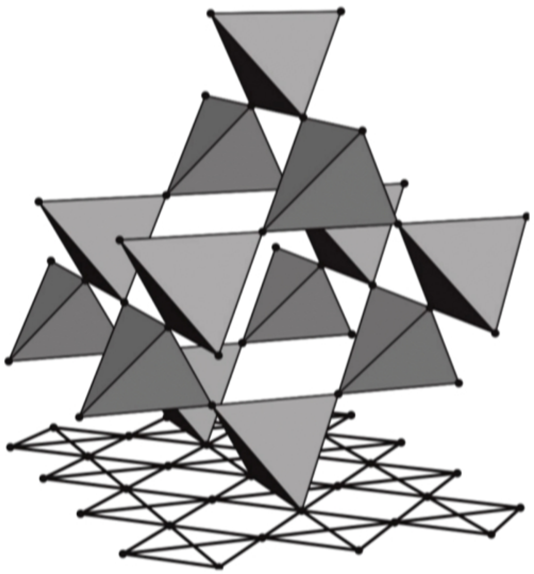
Possible observation of highly itinerant quantum magnetic monopoles in the frustrated pyrochlore $Yb_2Ti_2O_7$

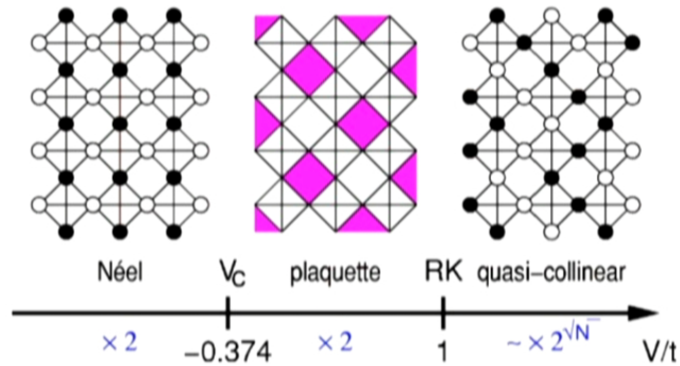
Y. Tokiwa, T. Yamashita, M. Udagawa, S. Kittaka, T Sakakibara, D. Terazawa, Y. Shimoyama, T. Terashima, Y. Yasui, T. Shibauchi & Y. Matsuda
Nature Communications **7**, Article number: 10807 | doi:10.1038/ncomms10807
Received 26 May 2015 | Accepted 22 January 2016 | Published 25 February 2016

Spinons are deconfined but are they **free**?

Down to 2D: quantum square ice

Moessner *et al.*, J. Stat. Phys. (2004) ; Shannon *et al.*, PRB Rapid (2004)





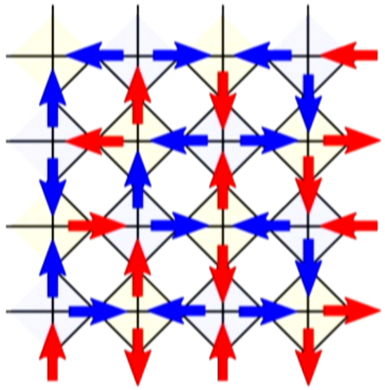
$$\mathcal{H} = J_z \sum_{\langle ij \rangle} S_i^z S_j^z + \frac{J_{xy}}{2} \sum_{\langle ij \rangle} (S_i^+ S_j^- + S_i^- S_j^+)$$

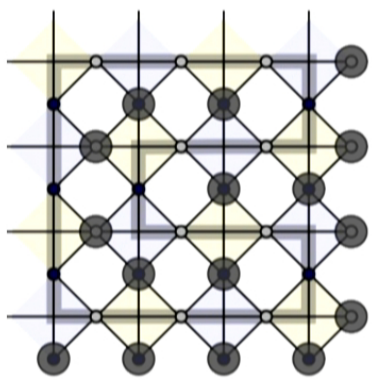
$J_z, J_{xy} > 0$, in the limit $J_z \gg J_{xy}$

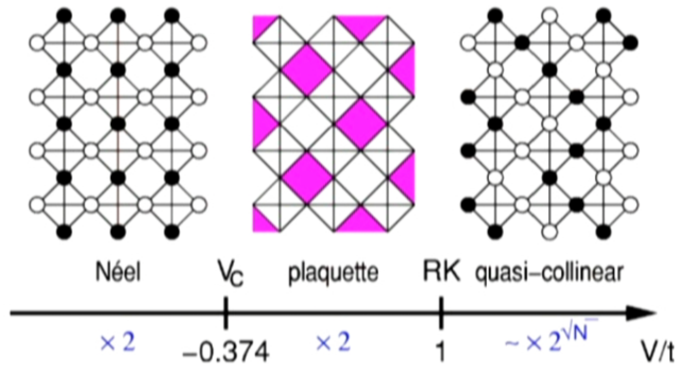
$$\mathcal{H} = \sum_{\square} [V(|\circlearrowleft\rangle\langle\circlearrowleft| + |\circlearrowright\rangle\langle\circlearrowright|) - t(|\circlearrowleft\rangle\langle\circlearrowright| + |\circlearrowright\rangle\langle\circlearrowleft|)]$$

Down to 2D: quantum square ice

Moessner *et al.*, J. Stat. Phys. (2004) ; Shannon *et al.*, PRB Rapid (2004)







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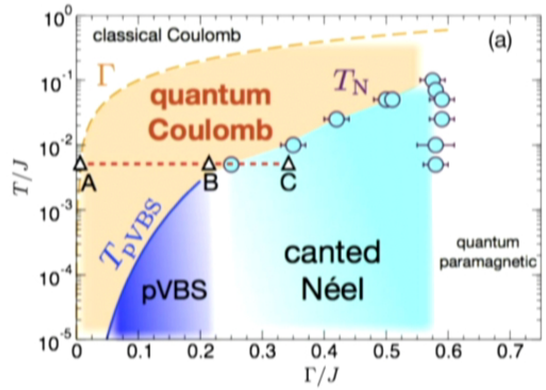
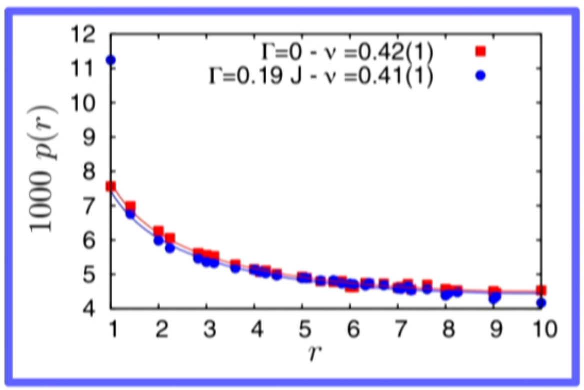
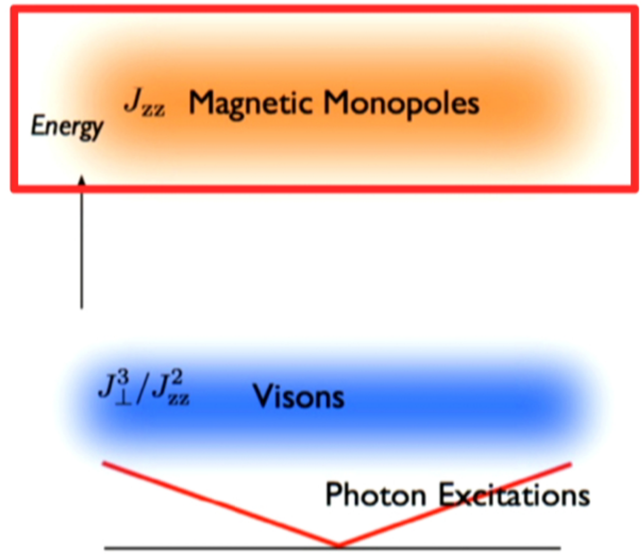
Excited quantum square ice

Henry and Roscilde, PRL (2014)



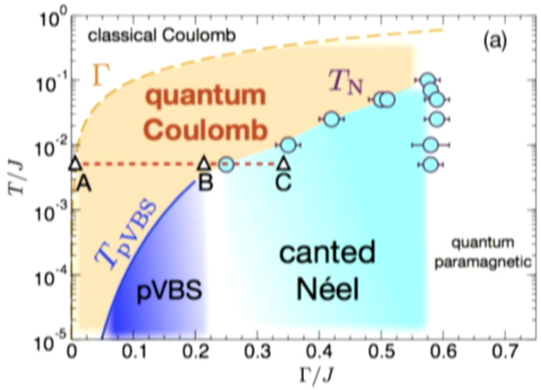


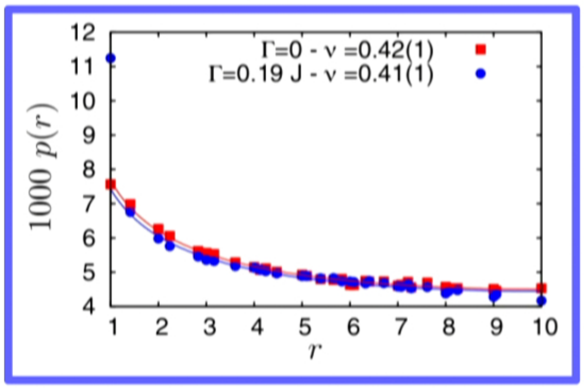


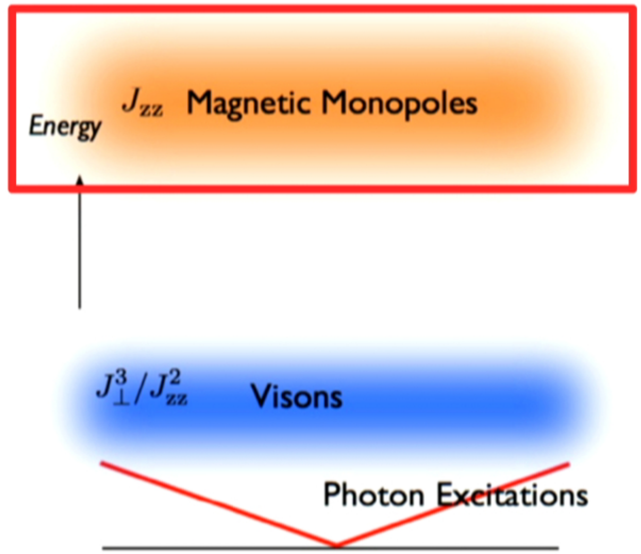
Spinons are deconfined but are they **free**?

Excited quantum square ice

Henry and Roscilde, PRL (2014)

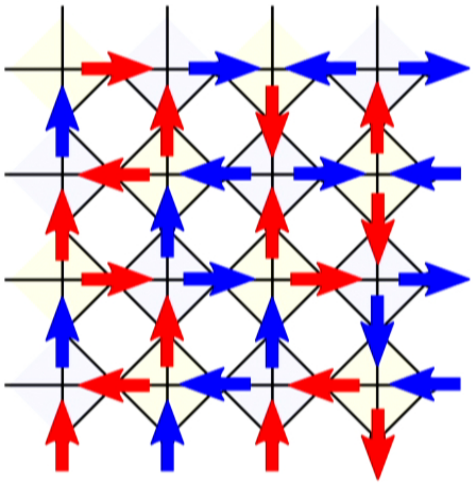


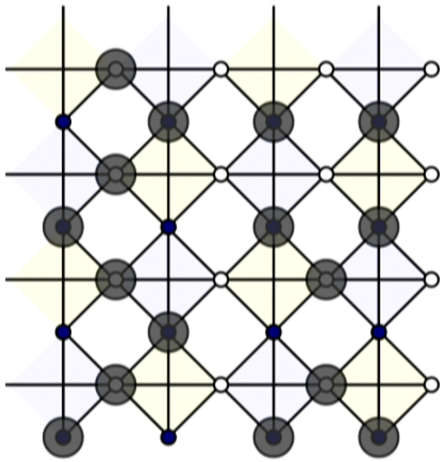




Spinons are deconfined but are they **free**?

The checkerboard-lattice XXZ model

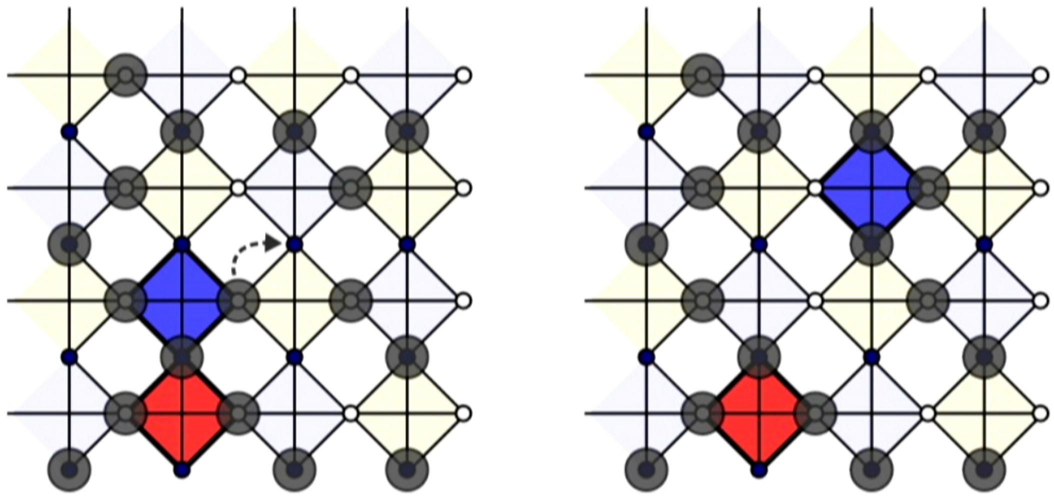




$$\mathcal{H}_{\mathrm{XXZ}} = \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} J_z S^z_{\boldsymbol{i}} S^z_{\boldsymbol{j}} - \frac{J_\pm}{2}(S^+_{\boldsymbol{i}} S^-_{\boldsymbol{j}} + S^-_{\boldsymbol{i}} S^+_{\boldsymbol{j}})$$

$$\mathcal{H} = \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} J_z \left(n_{\boldsymbol{i}} - \frac{1}{2}\right)\left(n_{\boldsymbol{j}} - \frac{1}{2}\right) - \frac{J_\pm}{2}(a^\dagger_{\boldsymbol{i}} a_{\boldsymbol{j}} + a^\dagger_{\boldsymbol{j}} a_{\boldsymbol{i}})$$

Single spin flip in the strong Ising limit



$$\mathcal{H} = -J_{\pm} \sum_{\langle \boldsymbol{i}, \boldsymbol{j} \rangle} (a_{\boldsymbol{i}}^{\dagger} F_{\boldsymbol{ij}} a_{\boldsymbol{j}} + \text{h.c.}) \,,$$

where

$$F_{\boldsymbol{ij}} = (2 - \sum_{\boldsymbol{m} \in \langle \boldsymbol{i} \rangle} n_{\boldsymbol{m}})(2 - \sum_{\boldsymbol{l} \in \langle \boldsymbol{j} \rangle} n_{\boldsymbol{l}}) \,.$$

Exact solution at RK point

$$\mathcal{H} = -J_{\pm} \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} (a_{\boldsymbol{i}}^{\dagger} F_{\boldsymbol{ij}} a_{\boldsymbol{j}} + \text{h.c.})\,,$$

where

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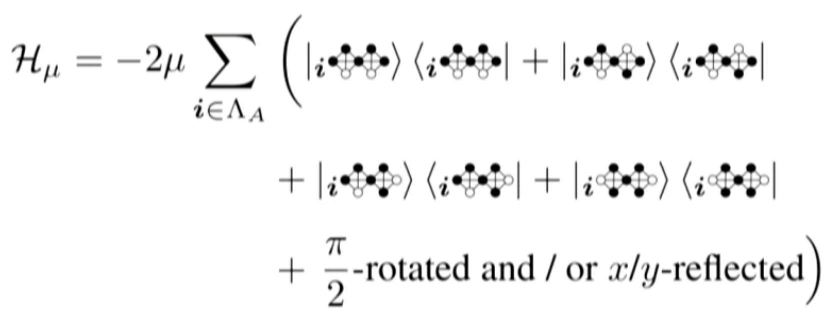
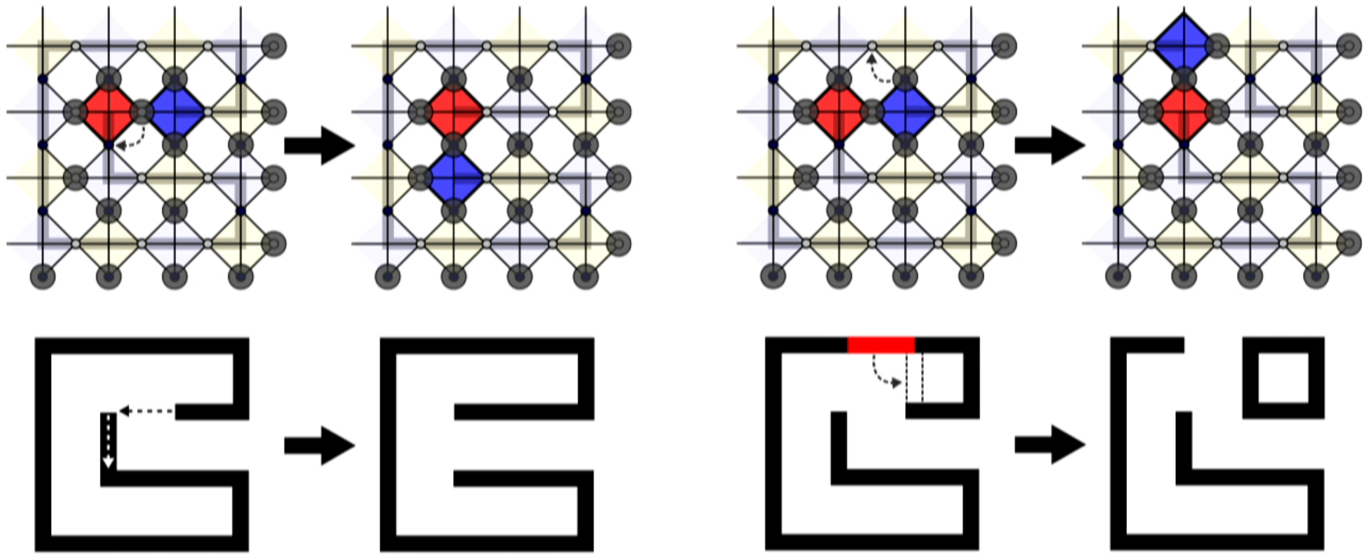


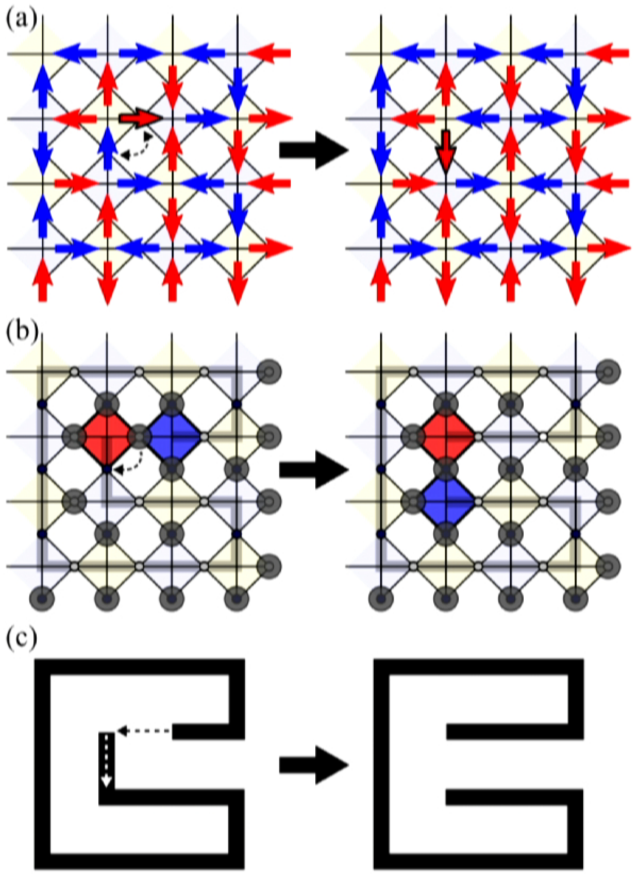
Confined propagation – two processes



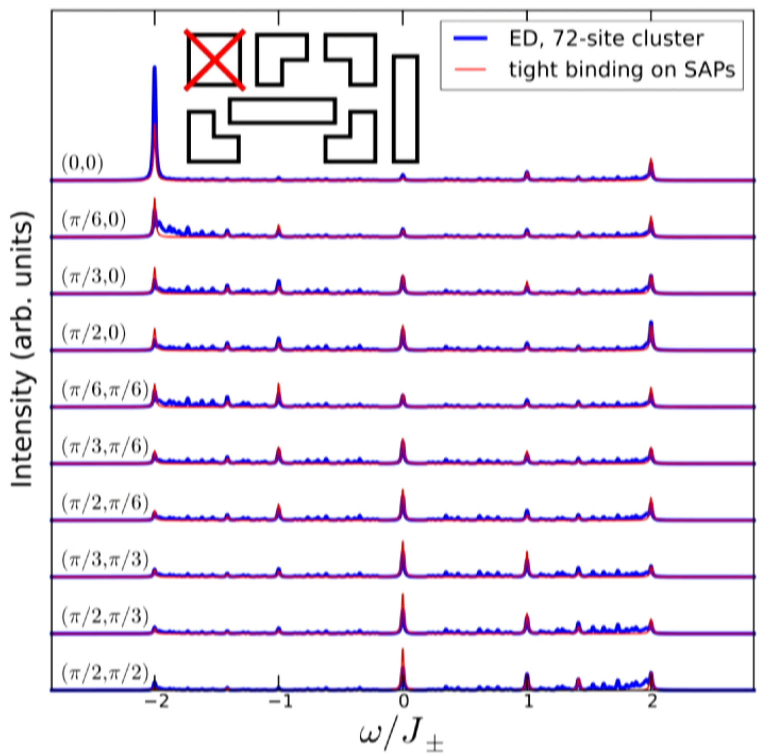
Confined dynamics → effective “averaged” **dipole** tight binding on the checkerboard lattice with

$$t_1/J_\pm \simeq 0.8069 \text{ and } t_2/J_\pm \simeq 0.3257$$

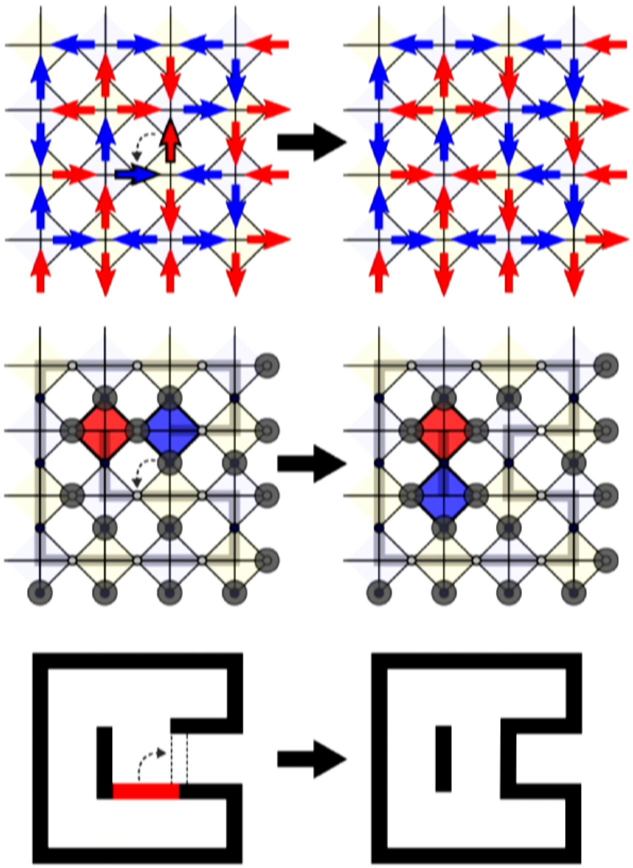
Confined process #1: "leapfrog"



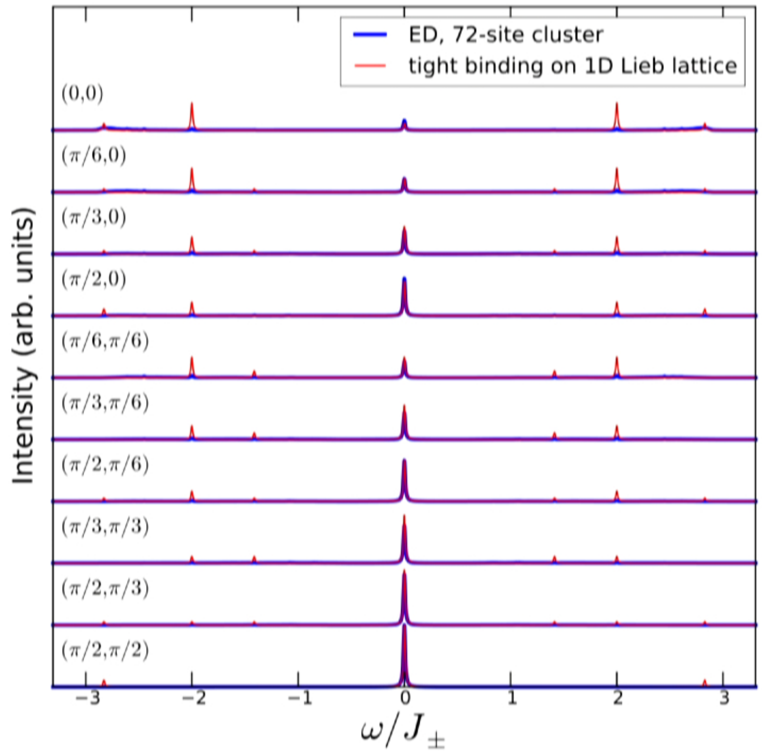
Equivalent to hopping on **self-avoiding polygons**



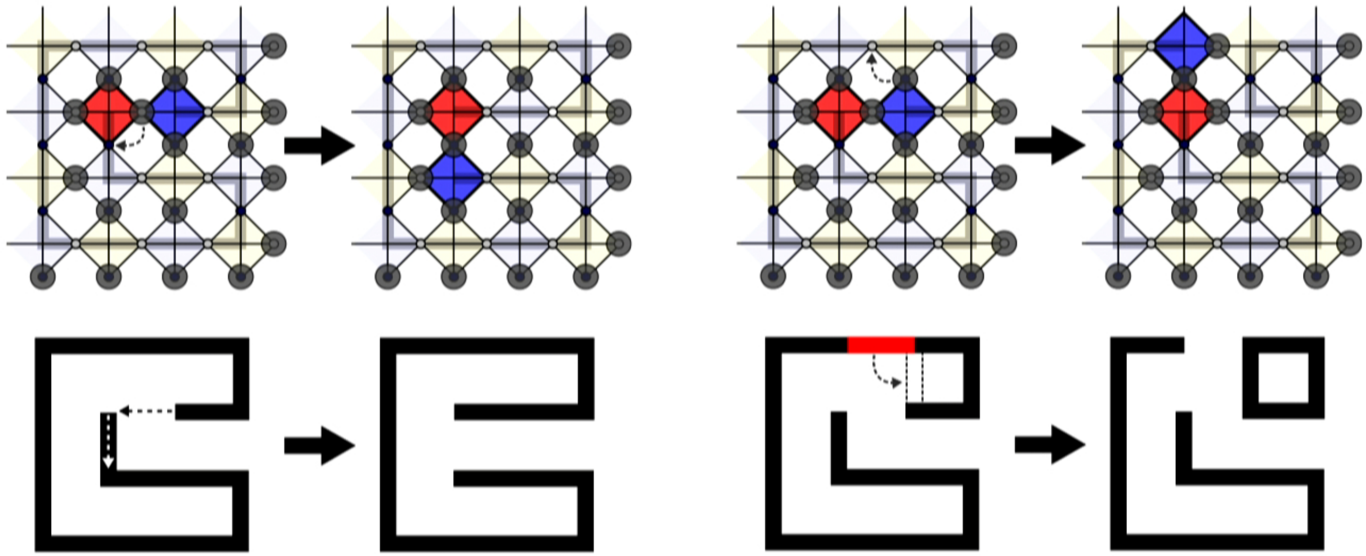
Confined process #2: “reconnection”



Mostly equivalent to hopping on **1D Lieb lattices**



Confined propagation – two processes



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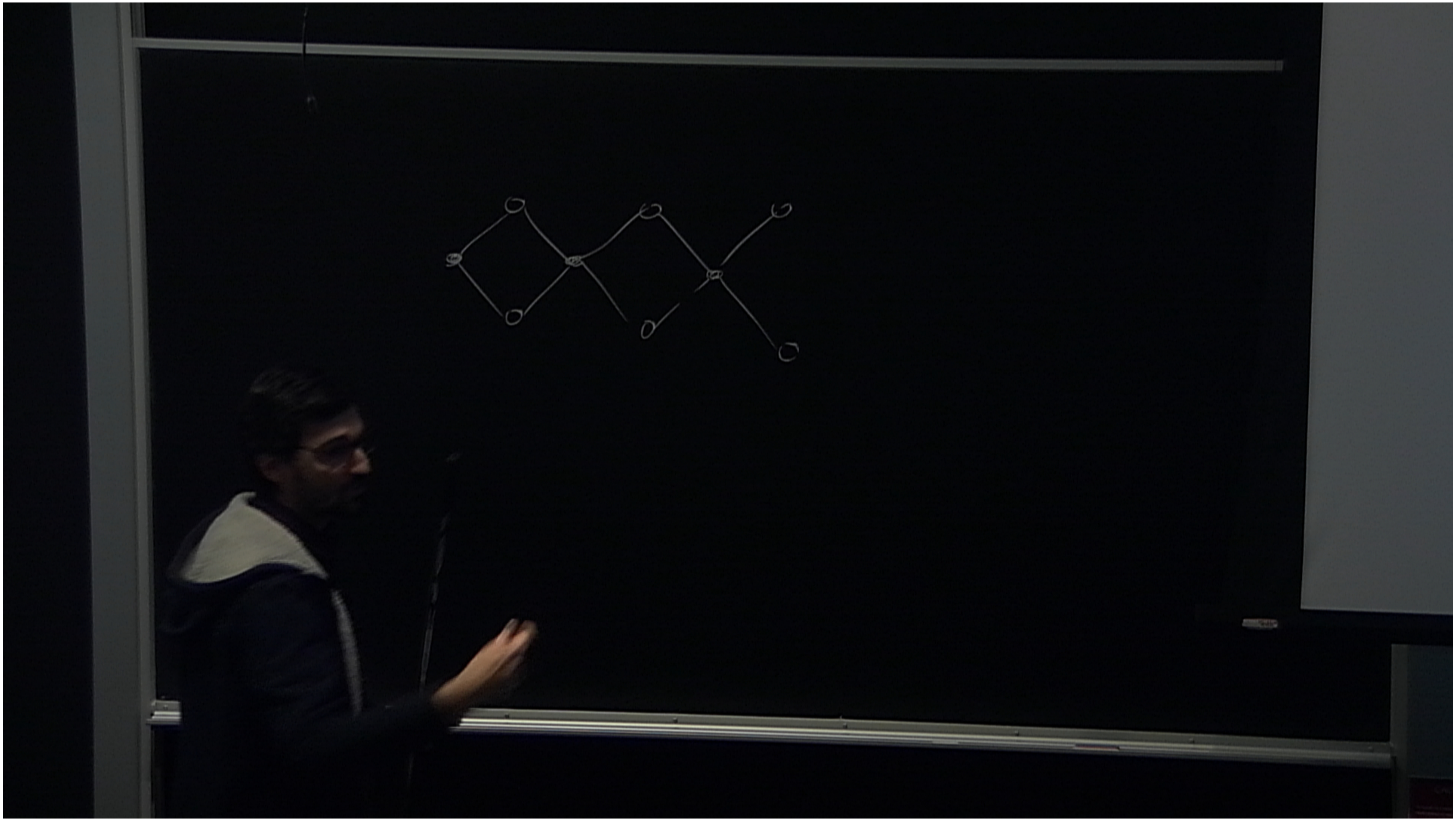

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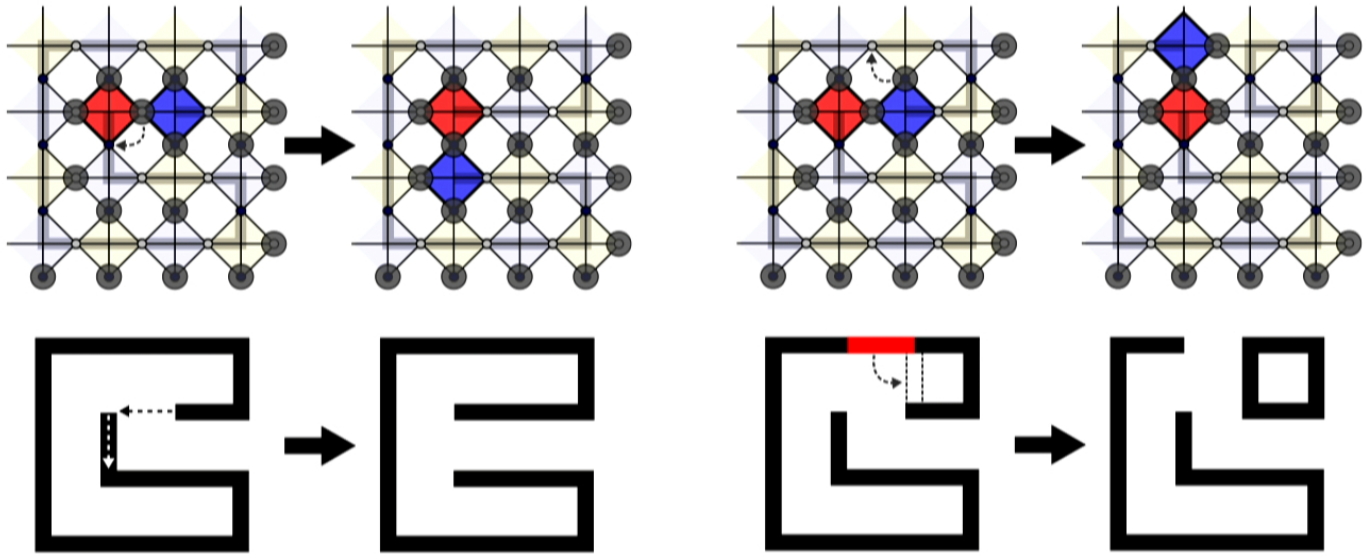

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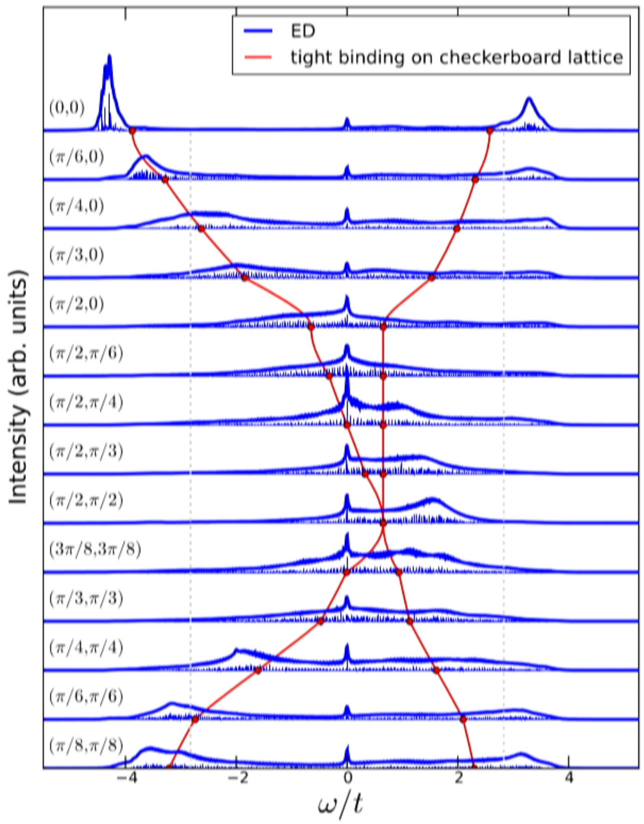
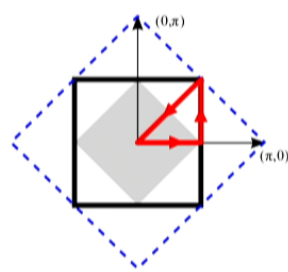
Confined propagation – structure factor



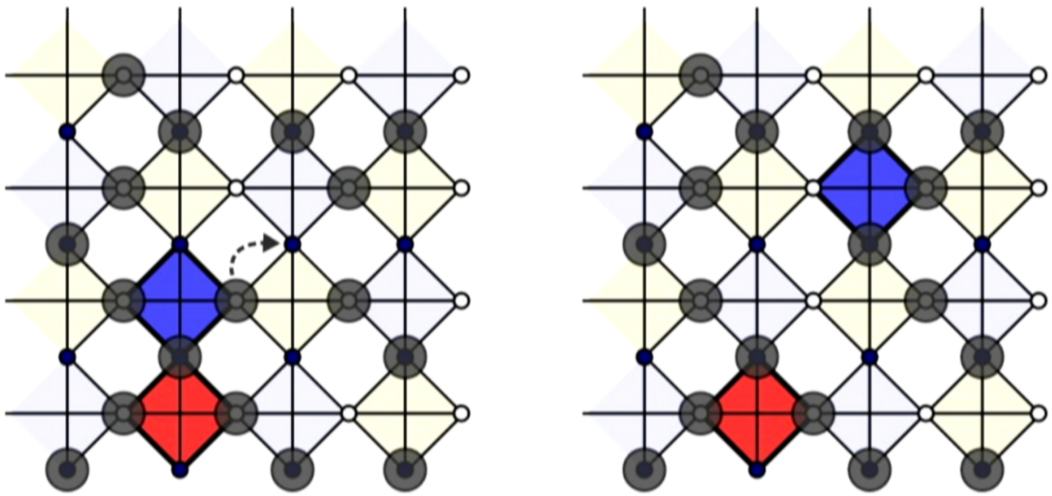
$$\mathcal{S}(\boldsymbol{k},\omega) = \sum_{s=A,B}\sum_{m} |\langle m|S^{+}_{s,\boldsymbol{k}}|\mathrm{RK}\rangle|^2 \delta(\omega - E_m + E_{\mathrm{RK}})$$

$$= \sum_{s=A,B}\sum_{m} |\langle m|a^{\dagger}_{s,\boldsymbol{k}}|\mathrm{RK}\rangle|^2 \delta(\omega - E_m + E_{\mathrm{RK}})$$

- Lower energies:
  sharp peaks → **coherence**
  dipole → free **bispinon**
- Higher energies:
  broadening → restricted kinetics

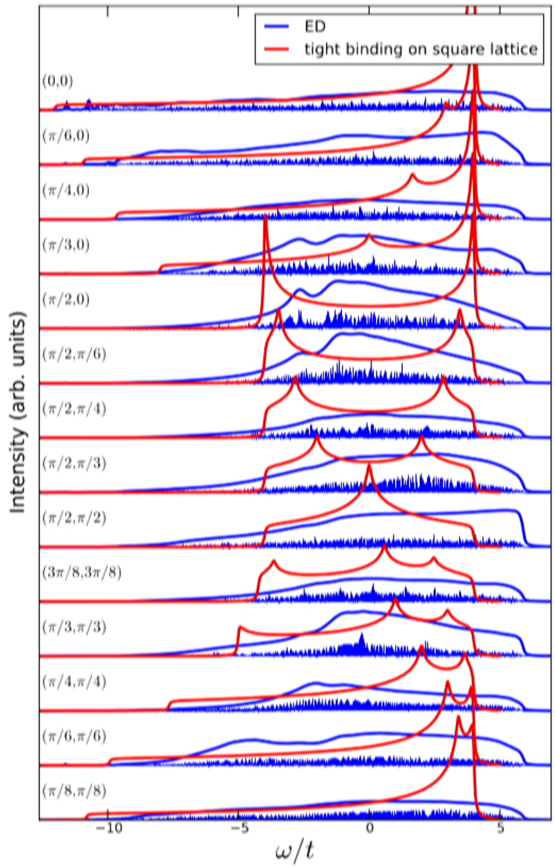


Deconfined dynamics

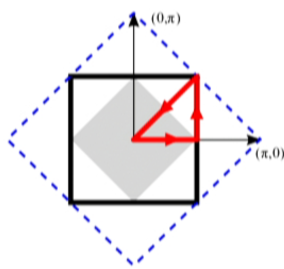


At long distances → 2 x **monopole** tight binding on square lattice

Deconfined propagation – structure factor

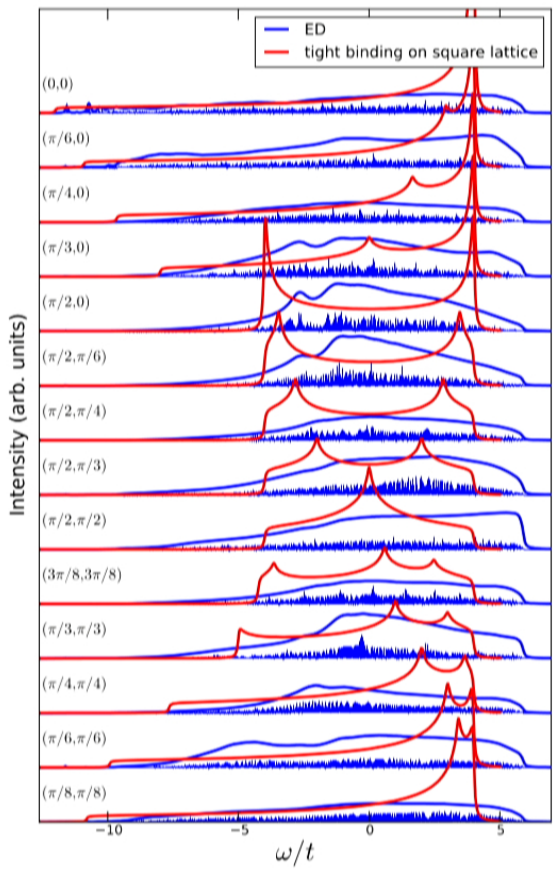


- free 2-particle dynamics → **broad** spectra
- lower bound of 2-spinon continuum captured by square-lattice tight binding
- evidence for **free spinons** at low energies



Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

Deconfined propagation – structure factor



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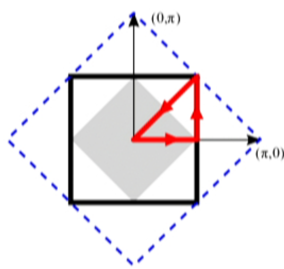

Conclusions

- confined case: two (almost) free processes
  → combined: **effectively free** "bispinon"
- deconfined case: dispersive lower bound of 2-spinon continuum → **spinon freedom** at low energies

Outlook: defects? 3D? $J_{z\pm}$?

Thanks!

Stefanos Kourtis and Claudio Castelnovo, arXiv:1604.03951