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INSTITUT FÜR LASERPHYSIK

Simulating classical frustrated magnetism with ultra-cold atoms

NewSpins 2011

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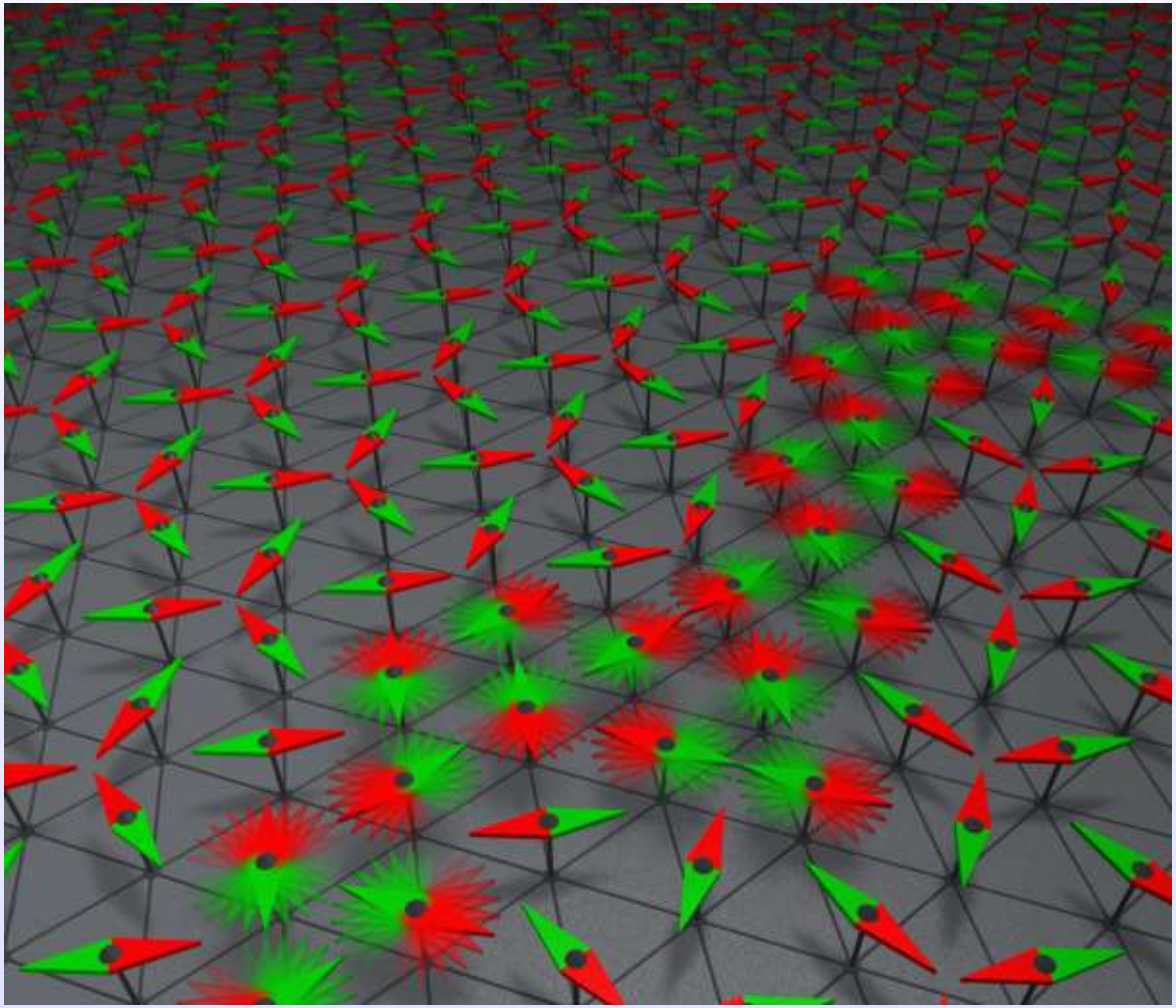
DFG FOR 801 Strong correlations in multiflavor ultracold quantum gases

LEXI LANDESEXZELLENZINITIATIVE HAMBURG

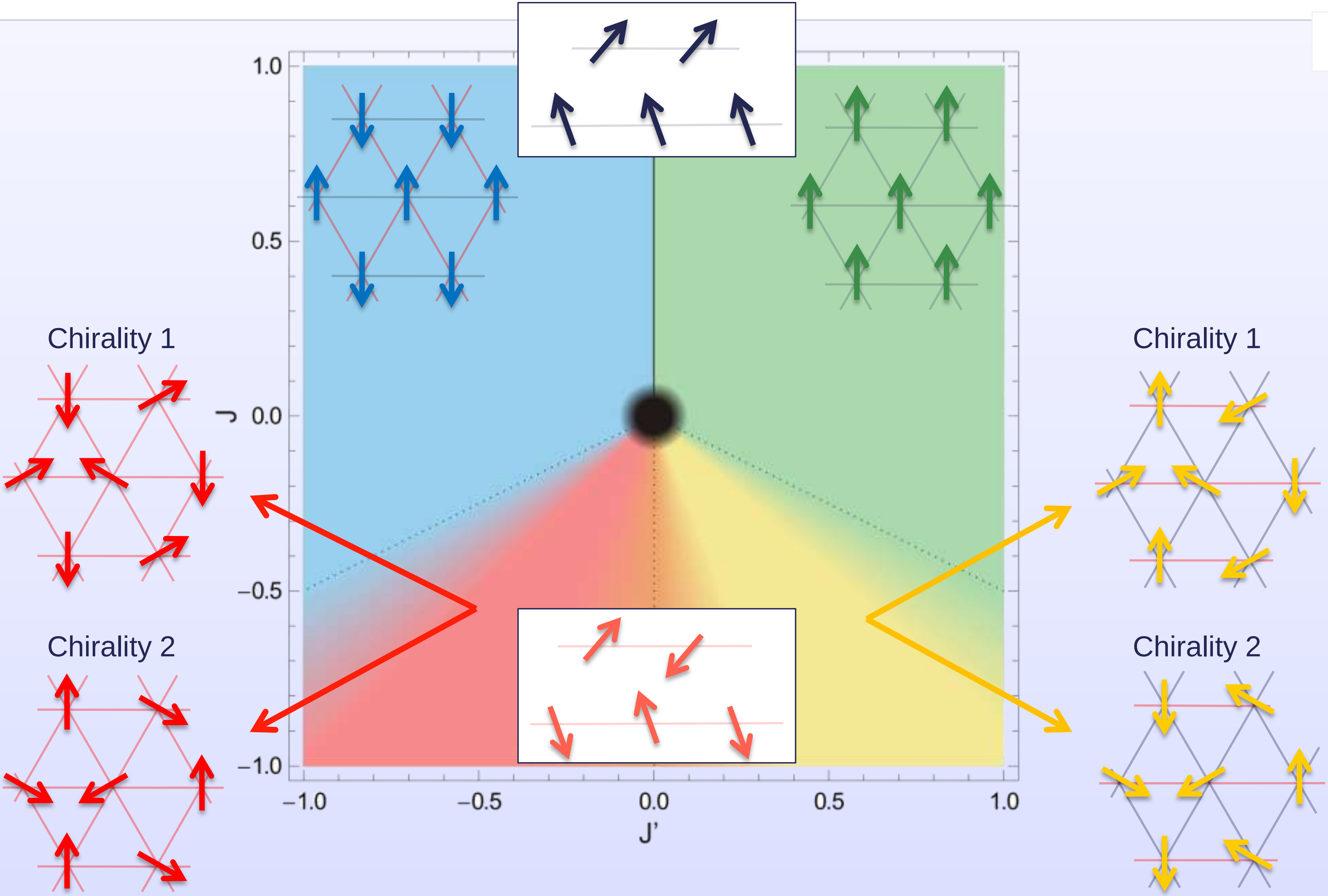
JOACHIM HERZ STIFTUNG

Classical magnetism on a triangular lattice

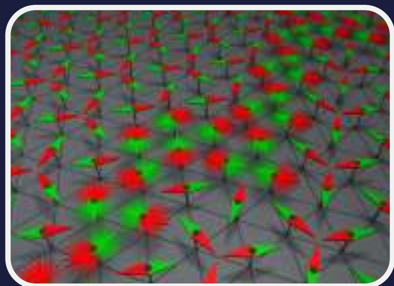


Related work on simulation of magnetism:
J. Simon et al., Nature 472, 307 (2011) ; K. Kim et al., Nature 465, 590 (2010); S. Trotzky et al., Science 319, 295 (2008)

Phase diagram



Key ingredients to simulation

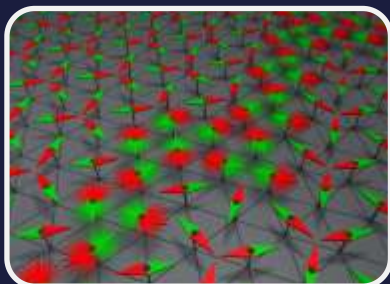


Classical vector spin system

Control of spin interactions

Readout of spin configuration,
Verification of the phase diagram

Key ingredients to simulation



Classical vector spin system

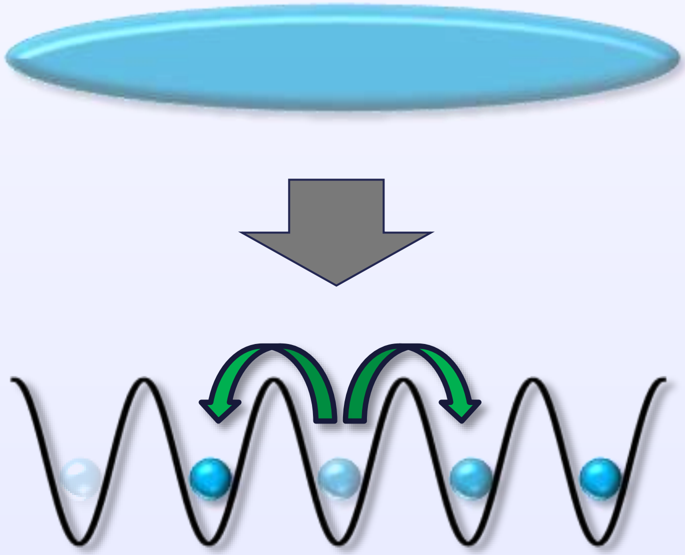
Control of spin interactions

Readout of spin configuration,
Verification of the phase diagram

Using spinless bosons to simulate magnetism

BEC: macroscopic wave function
with uniform global phase

$$\Psi = \Psi_0 e^{-i\phi}$$



*load BEC into **shallow** optical lattice*

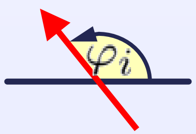
$$\boxed{\hat{H}_{BH} = -J \sum_{\langle i,j \rangle} \hat{a}_i^{+} \hat{a}_j + \cancel{\frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)}} \quad J > 0$$

tunneling ➡ well defined relative phases between neighboring sites

Using spinless bosons to simulate magnetism

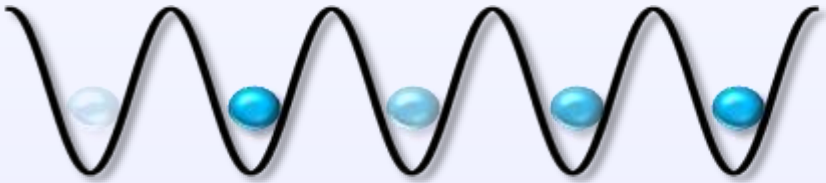
$$|\Psi\rangle = \prod_i \exp(\psi_i \hat{b}_i^\dagger)\,|\text{vacuum}\rangle$$

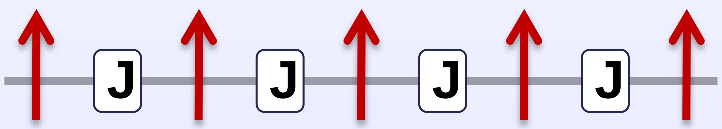
Assign a local phase to each lattice site



$$\psi_i = \sqrt{n_i}\,\exp(i\varphi_i)$$

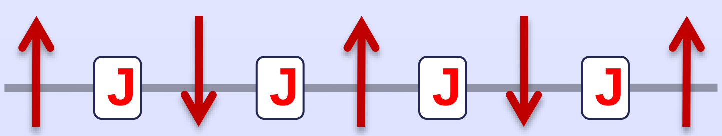
Controlling the tunneling
=
Simulating magnetism



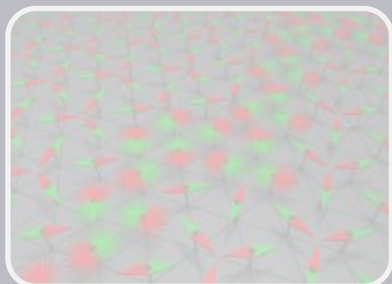


Ferromagnetic coupling

Antiferromagnetic coupling



Key ingredients to simulation



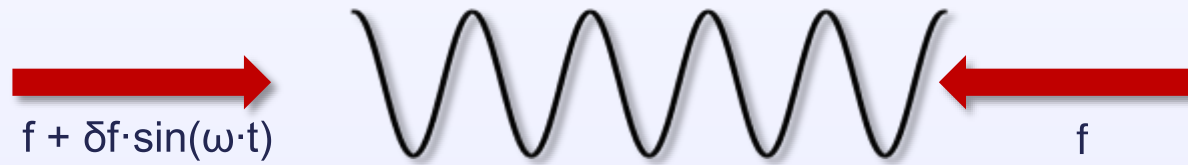
Classical vector spin system

Control of spin interactions

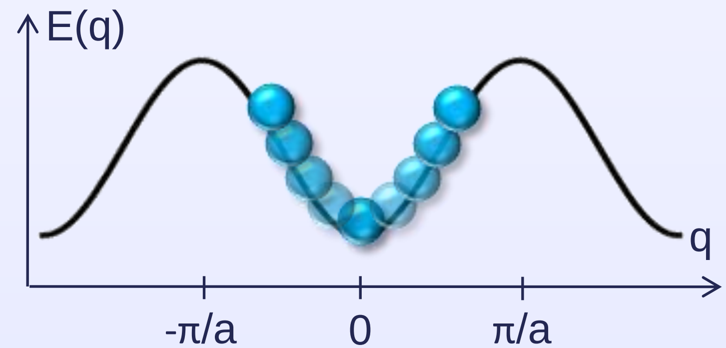
Readout of spin configuration,
Verification of the phase diagram

Tune coupling with lattice modulation

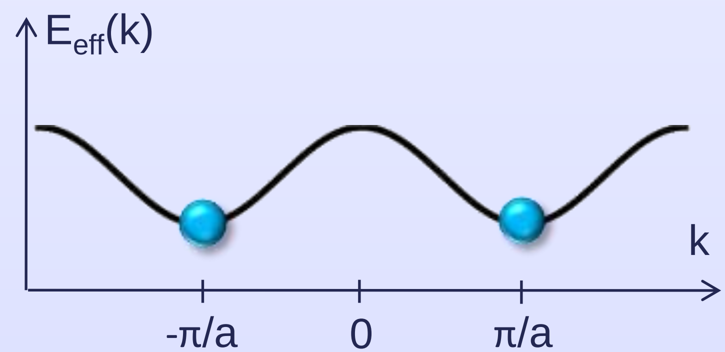
induce lattice shaking by frequency modulation of a lattice beam:



atoms experience time dependent momentum



time averaging

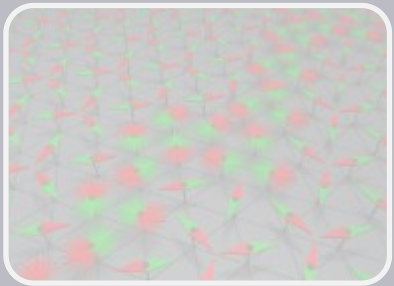


inversion of band structure possible!

$$\boxed{J \to J_{eff}}$$

Theory: *André Eckardt, Christoph Weiss, and Martin Holthaus PRL 95,260404 (2005)*

Key ingredients to simulation

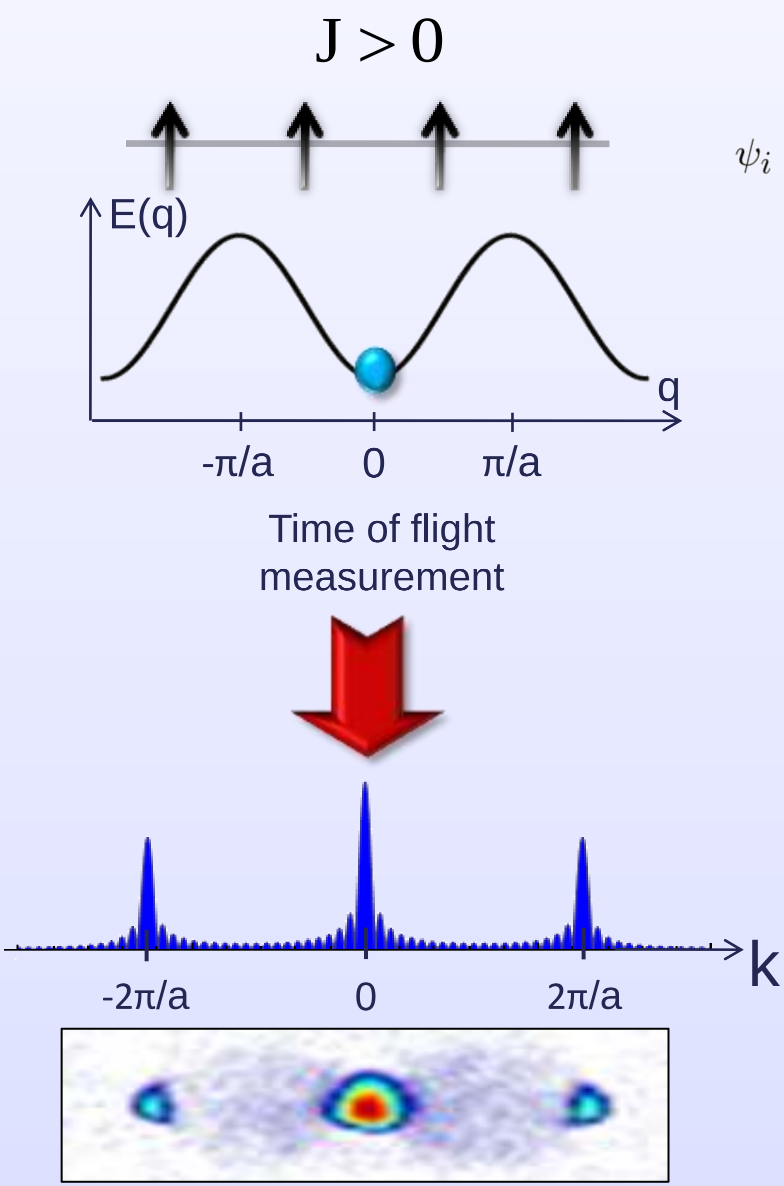


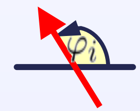
Classical vector spin system

Control of spin interactions

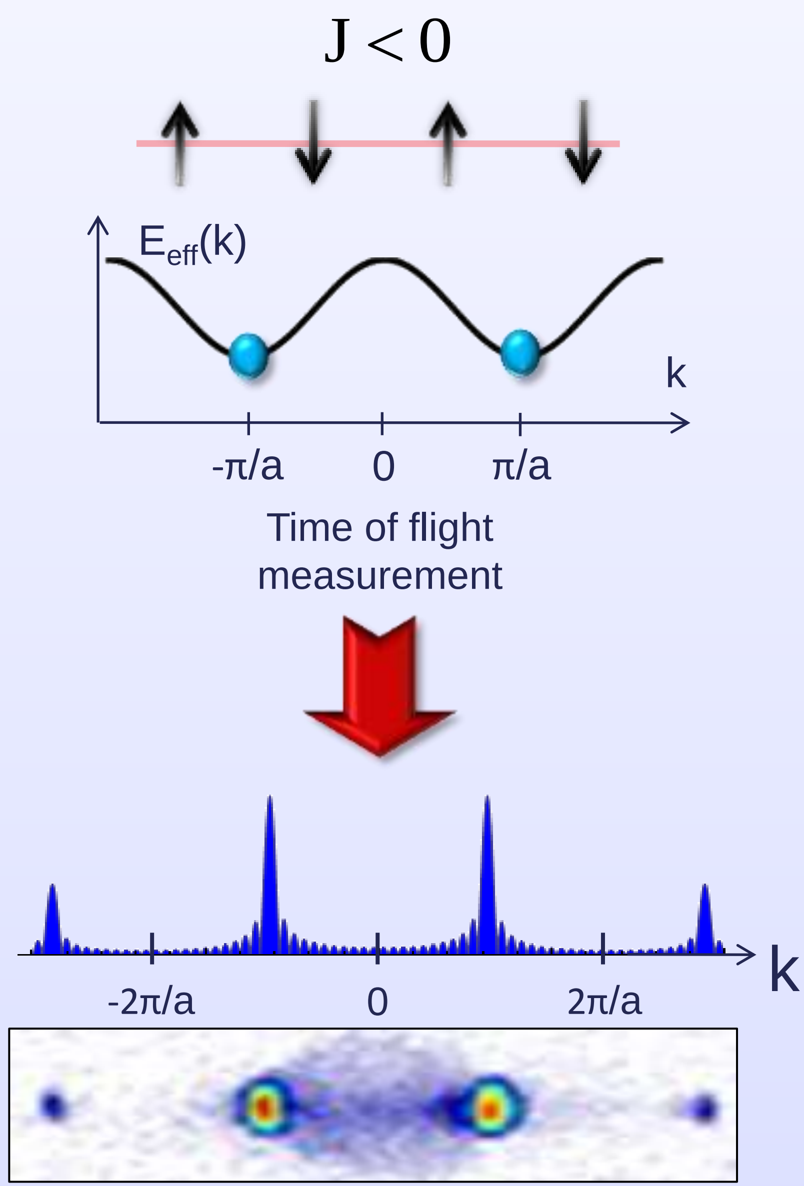
Readout of spin configuration,
Verification of the phase diagram

Measurement of spin configuration



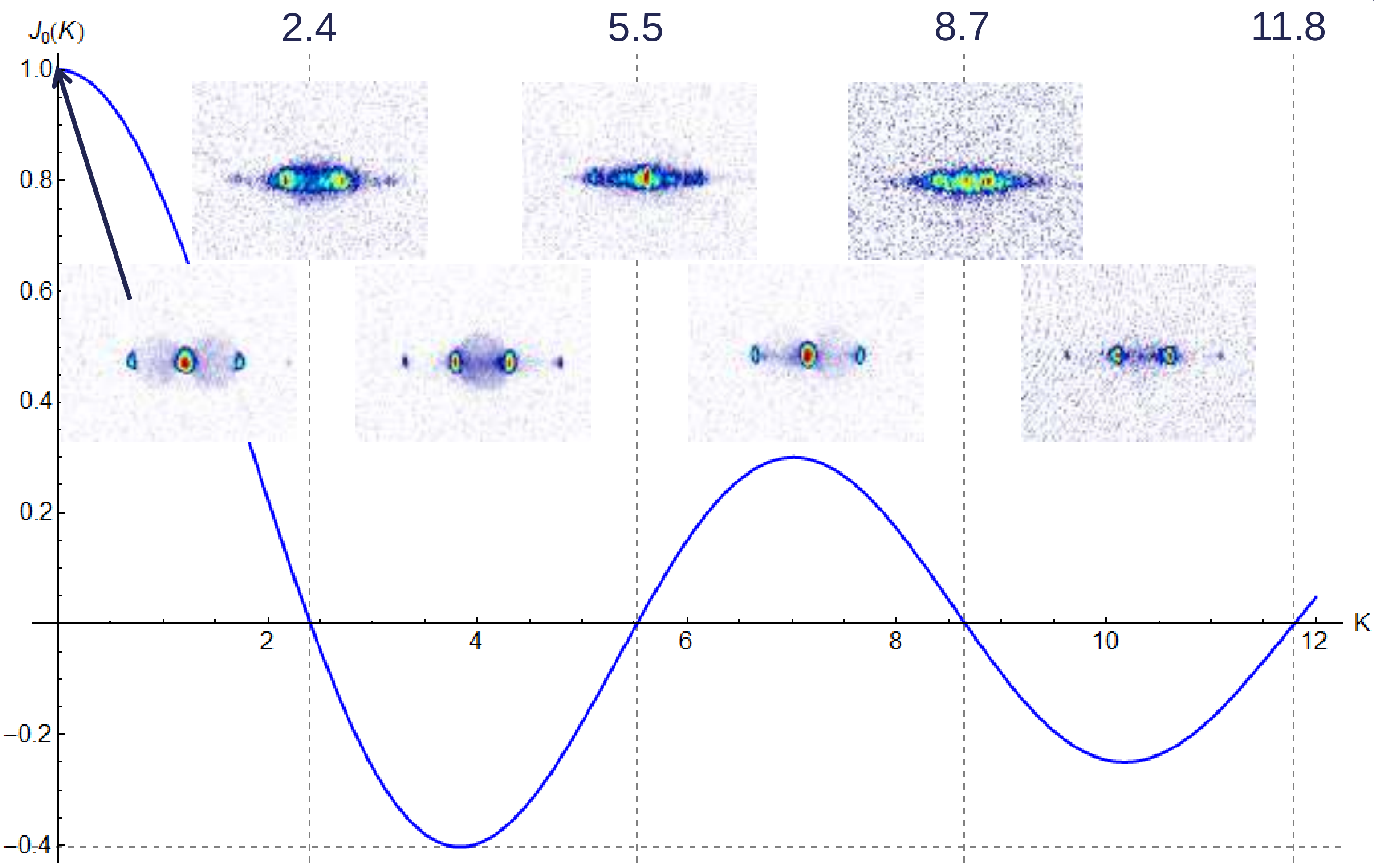


$$\psi_i = \sqrt{n_i}\,\exp(i\varphi_i)$$



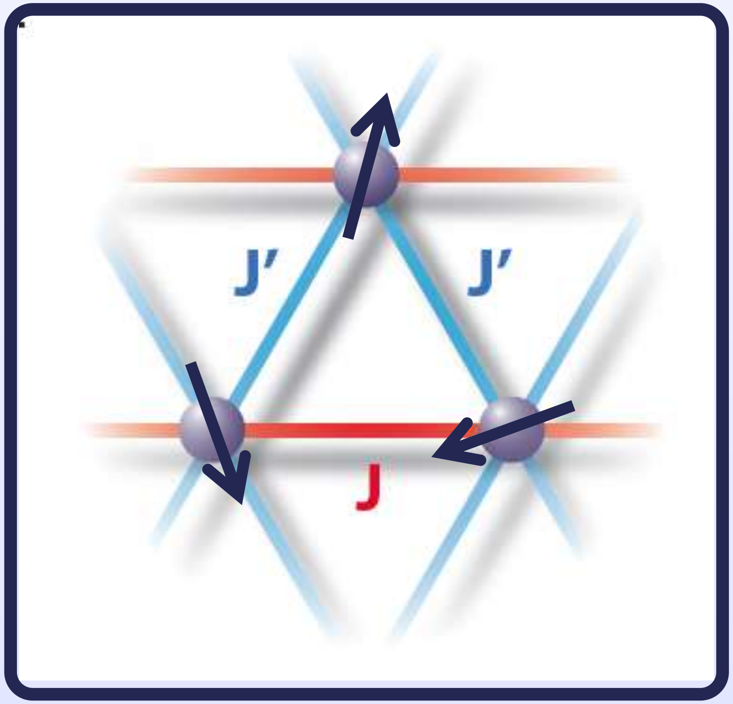
First experiments: *H. Lignier et al, Phys. Rev. Lett. 99, 220403 (2007)*

Design of tunneling parameters

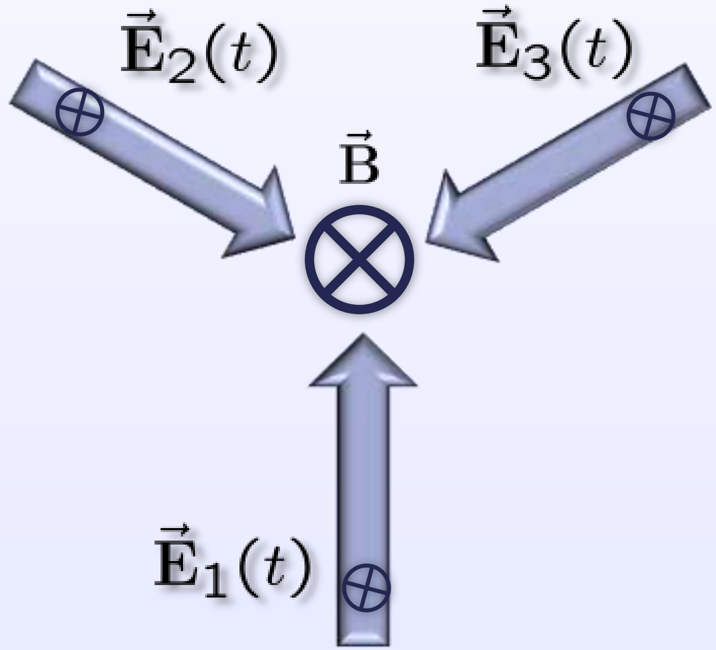


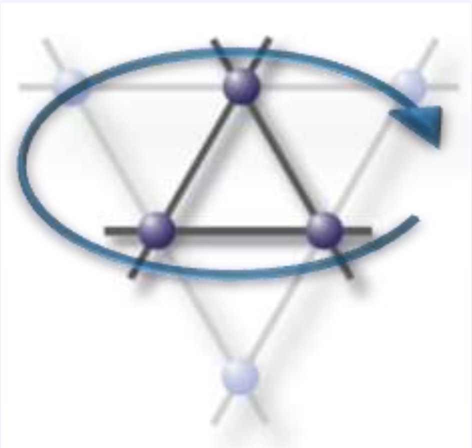
Modulation frequency: ~1.5kHz; Lattice depth: ~8E_{rec}

How about the trinagular lattice?



Experimental realization





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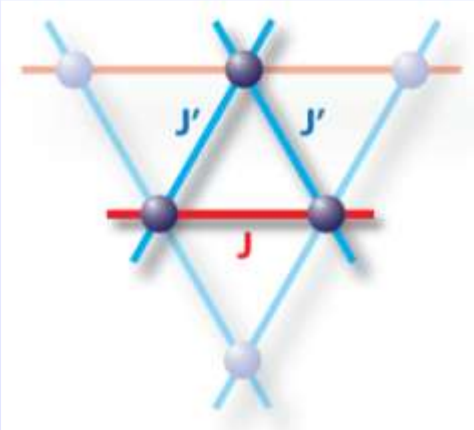


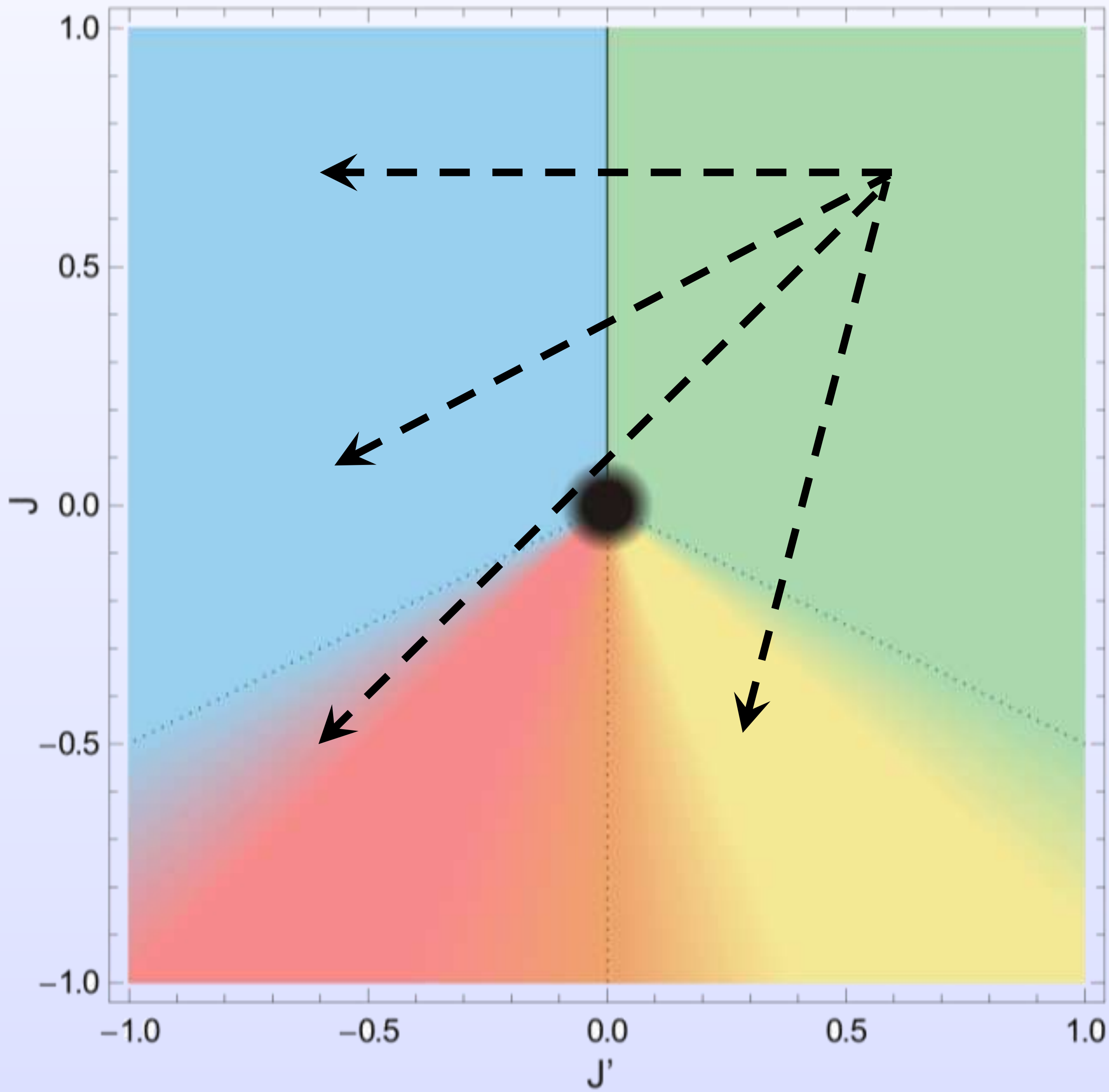
$$\vec{\mathbf{E}}_i(t) \,||\, \vec{\mathrm{B}} = B\vec{\mathbf{e}}_z$$

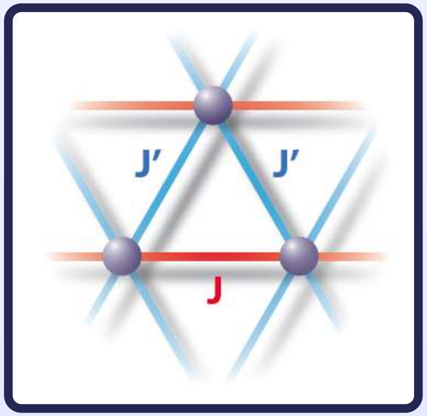
- Interference of 3 beams under 120° creates 2D lattice of 1D tubes

- Shaking the lattice = global elliptical forcing => Independent tuning of the coupling parameters

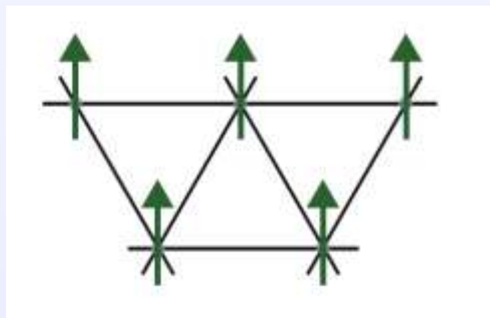
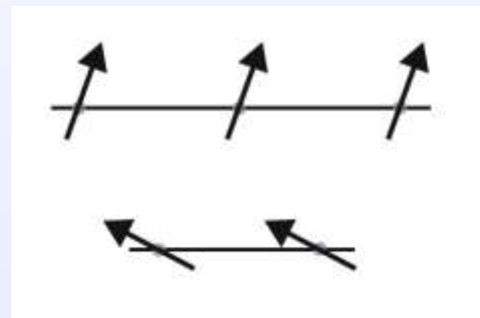
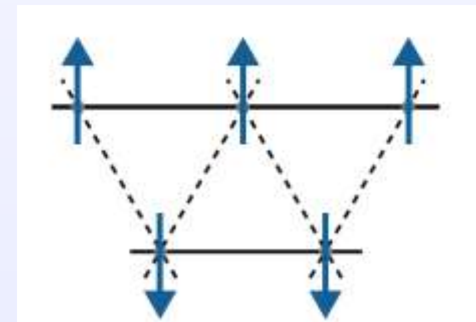
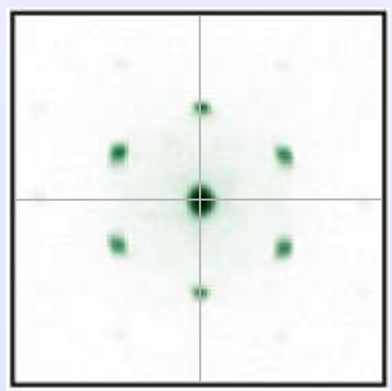
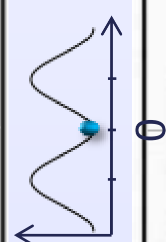
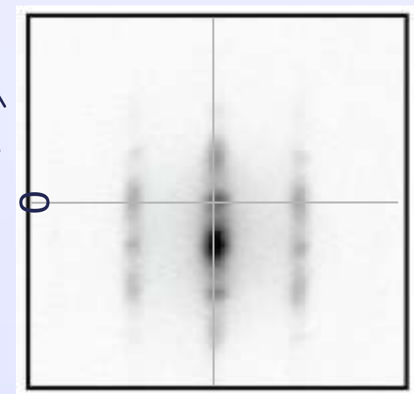
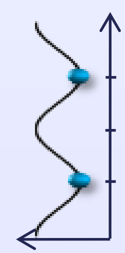
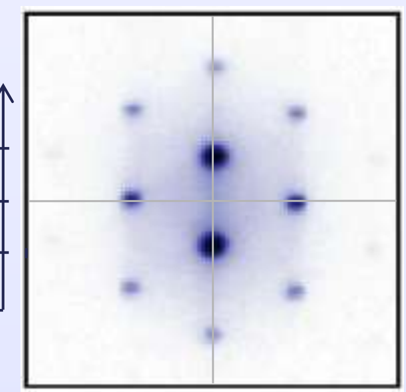
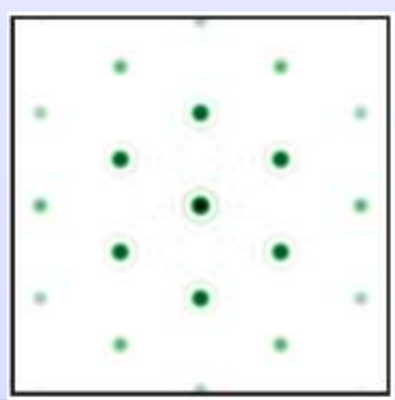
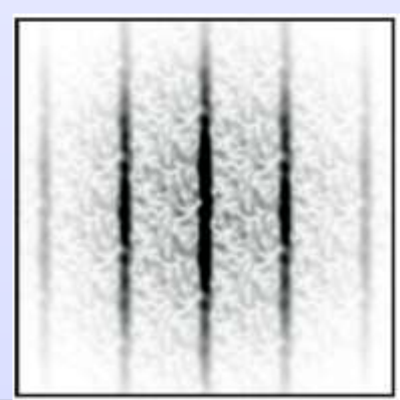
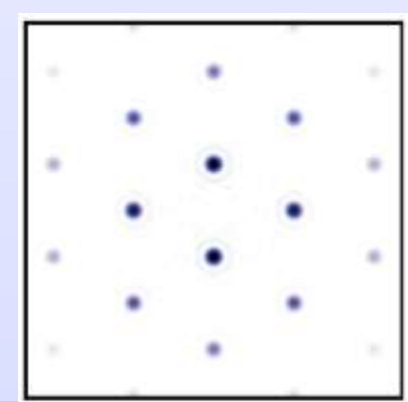
Proposal: A. Eckardt et al. EPL 89 10010 (2010)

Let‘s run the simulator

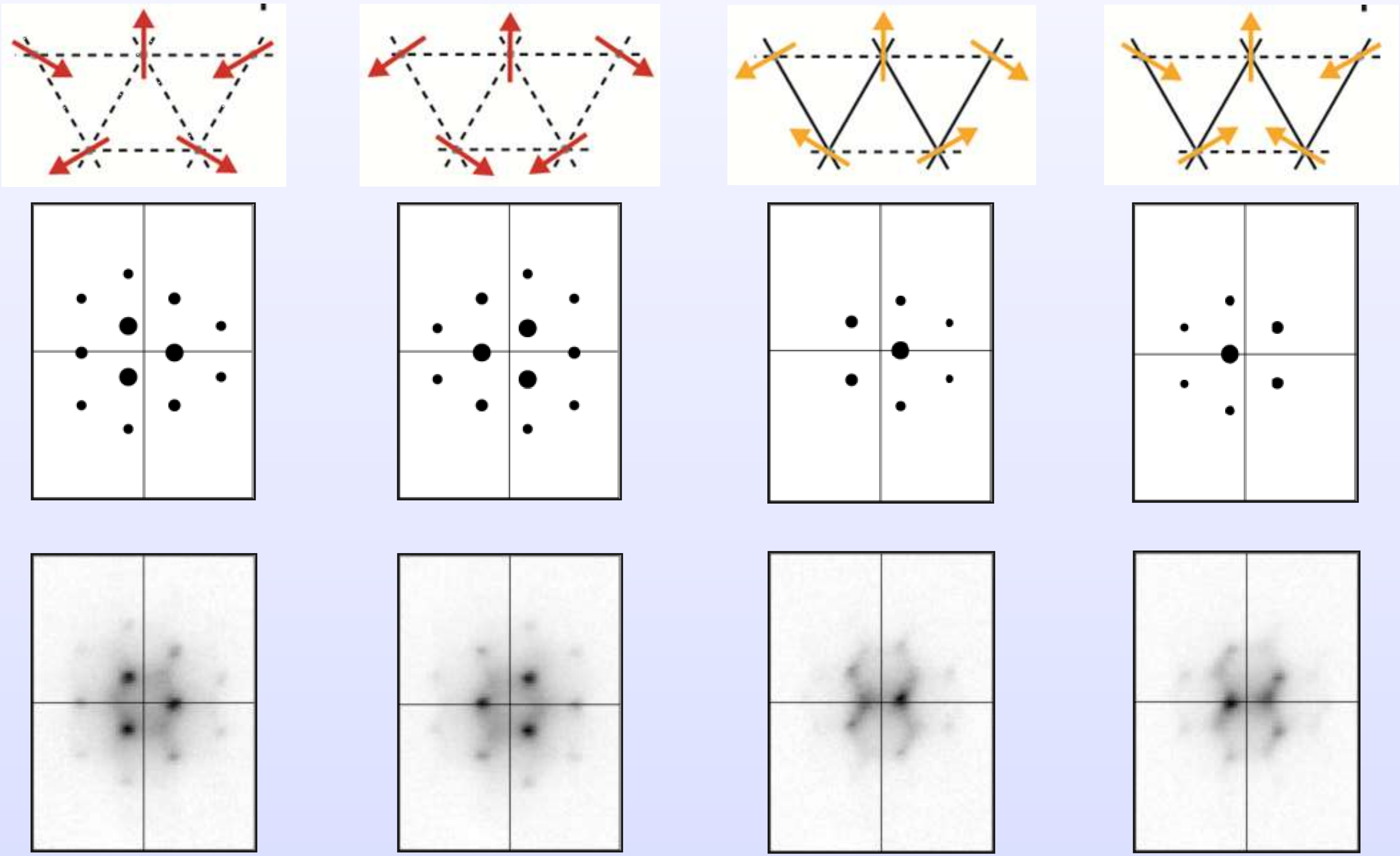




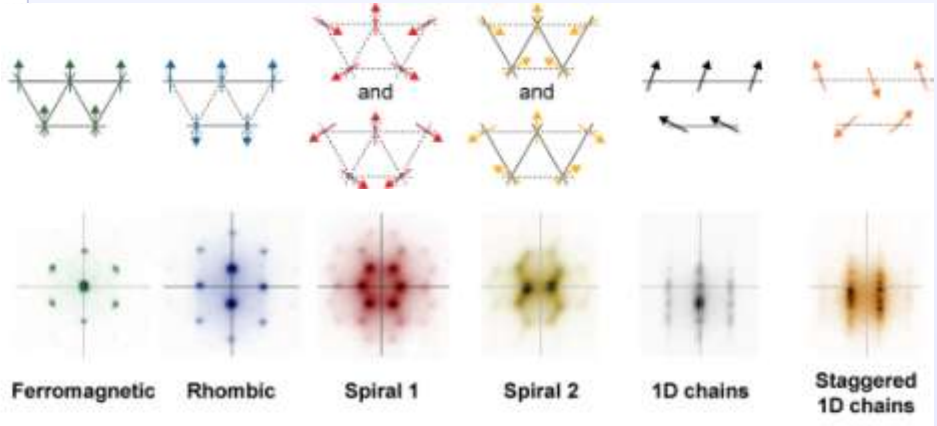
Magnetic phases

	Fully ferromagnetic coupling (J,J'>0)		1D chains		Mixed coupling : Rhombic order (J>0, J'<0)
Spin configuration					
TOF picture					
Minima of the calculated band structure					

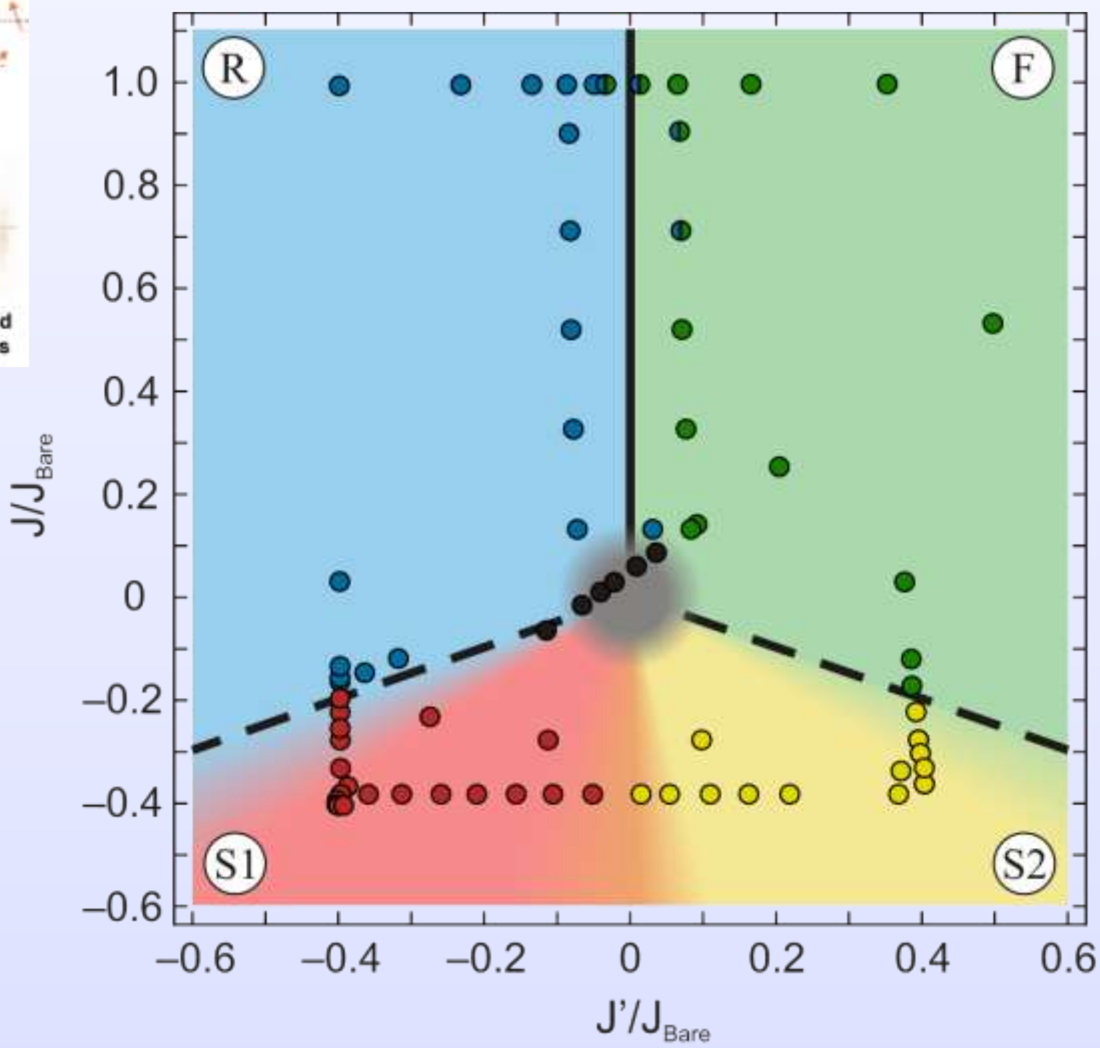
Magnetic phases



Distinguishing experimental signatures

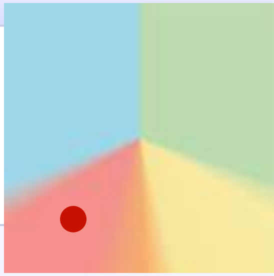


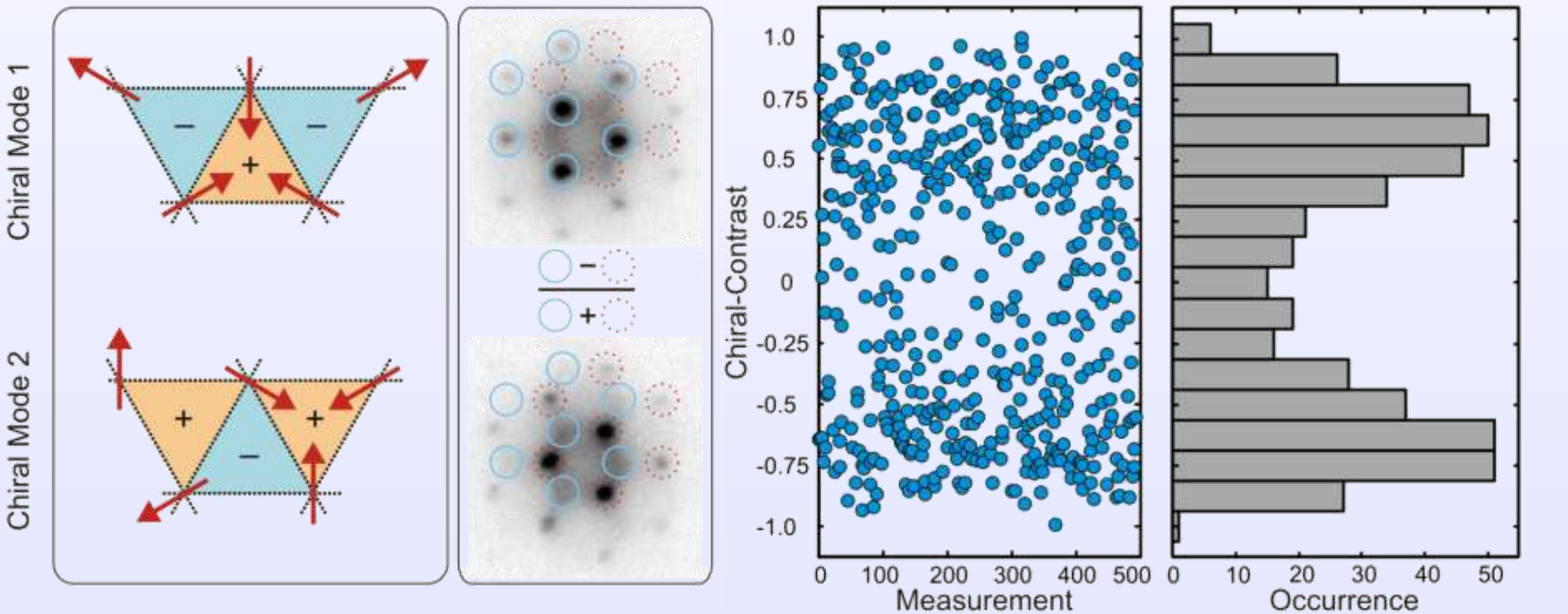
Measurements confirm the phase diagram



J. Struck et al. Science 333, 996 (2011)

Spontaneous symmetry breaking in the spiral phase

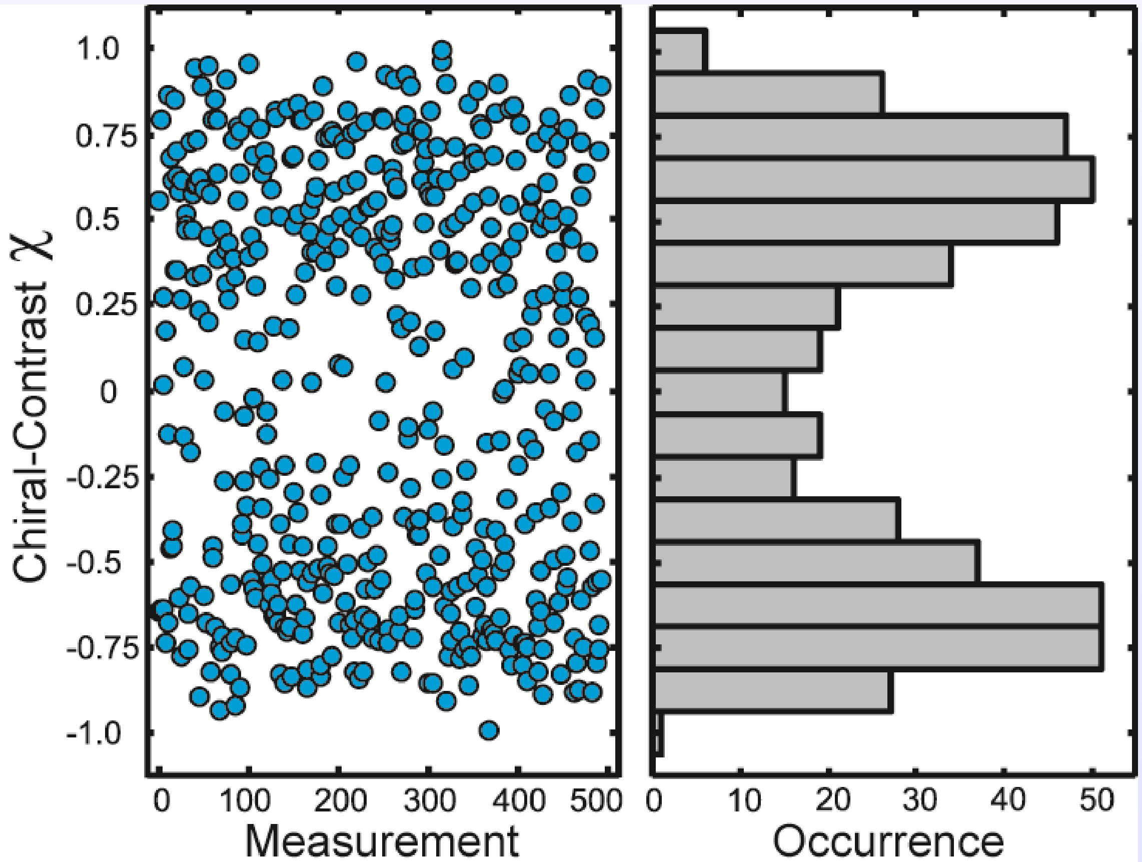




Degenerate ground state

Spontaneous symmetry breaking

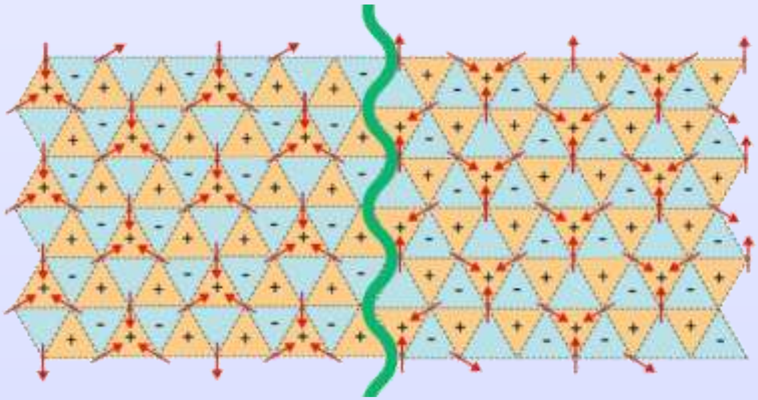
Spontaneous symmetry breaking



- Most of the time, one mode clearly predominates

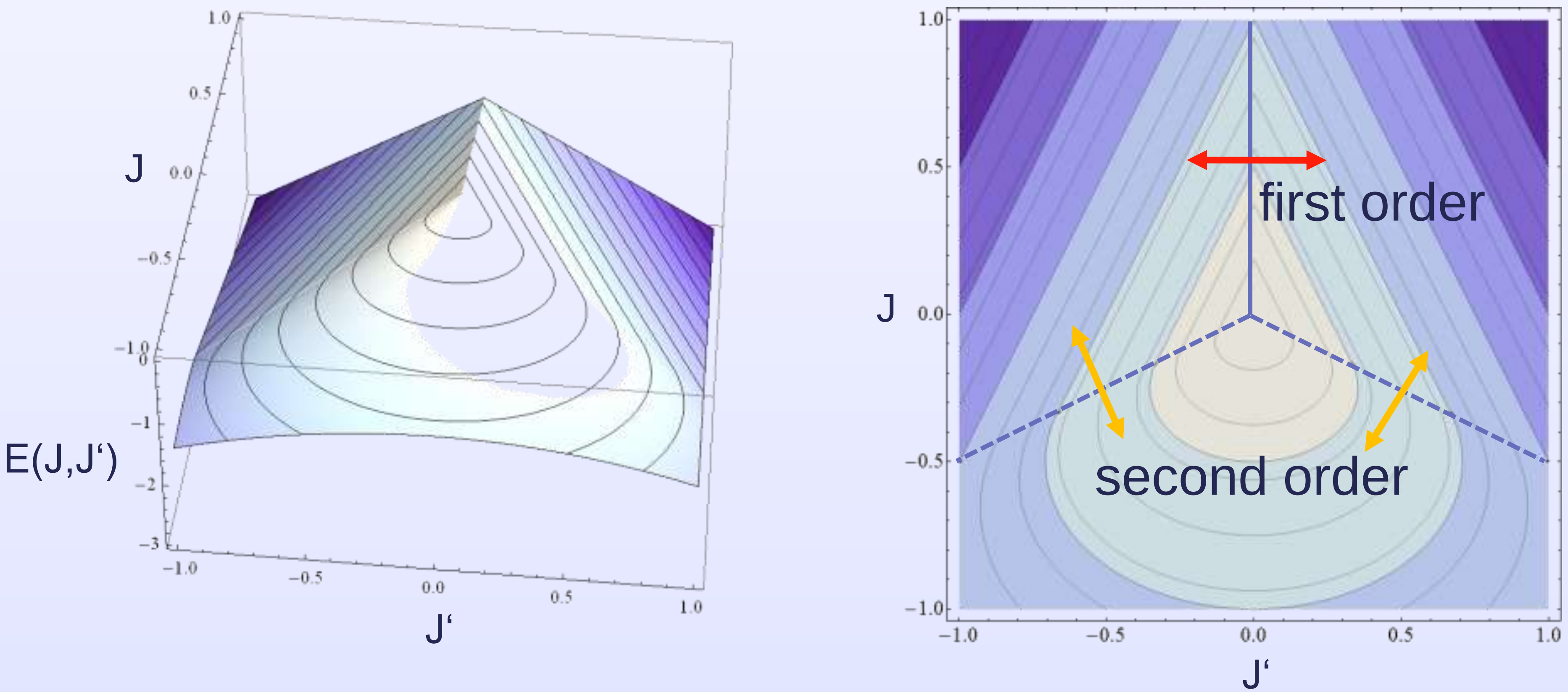
- Almost half/half and random repartition ⇨ **spontaneous symmetry breaking**

- Sometimes, both modes are mixed ⇨ **excitation of the system (domains ?)**



Characterization of phase transitions

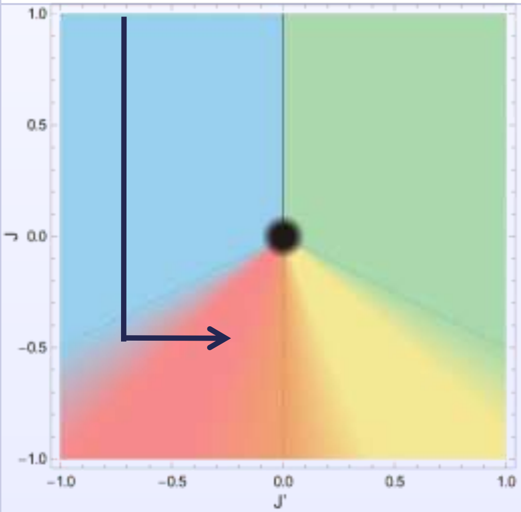
$$E(\{\theta_i\}) = -\sum_{\langle i,j\rangle} J_{ij}\cos(\theta_i - \theta_j) = -\sum_{\langle i,j\rangle} J_{ij}\, S_i \cdot S_j$$



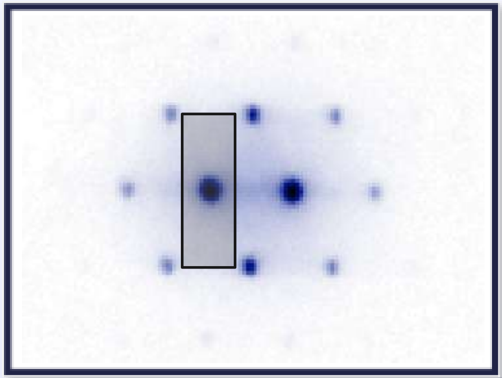
Three distinct phases with six classes of different spin configurations

First order and second order phase transitions!!

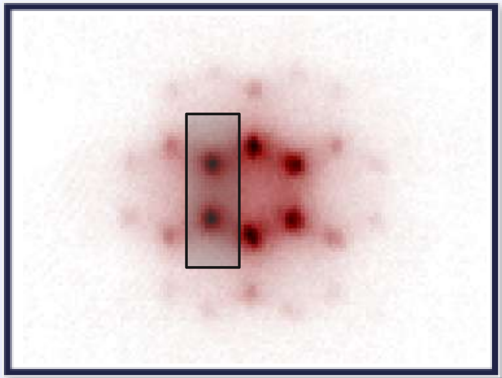
Map out phase transition



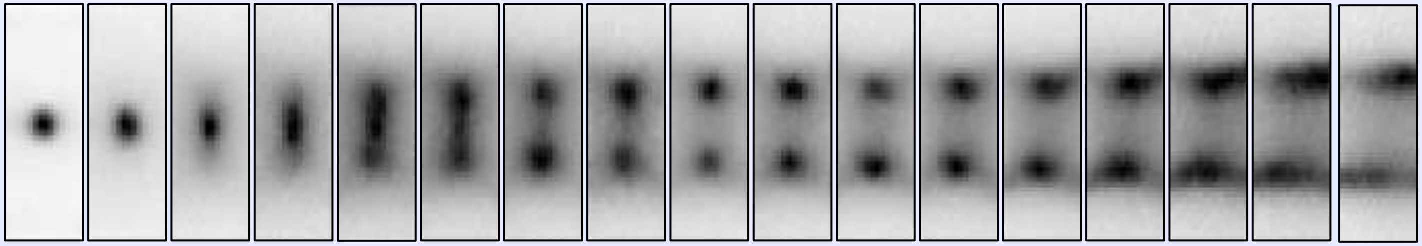
rhombic



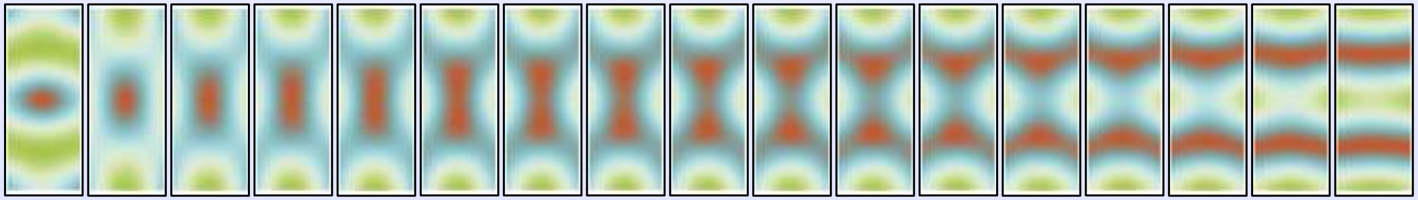
spiral I



TOF images



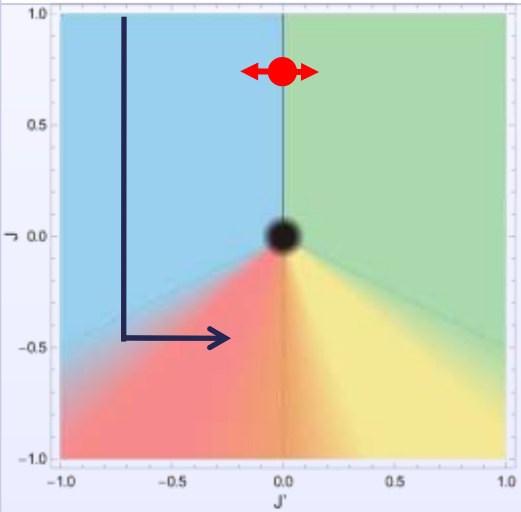
band structure



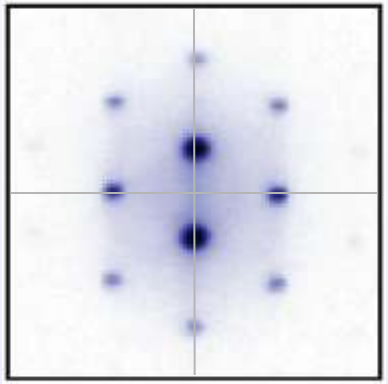
rhombic

spiral I

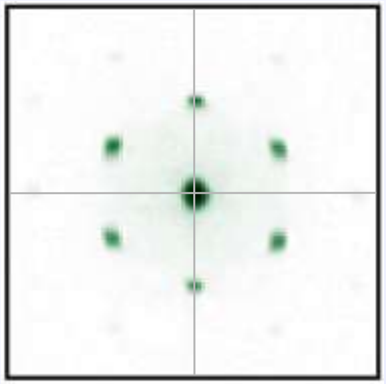
Map out phase transition

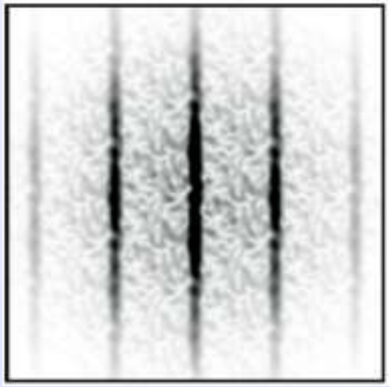


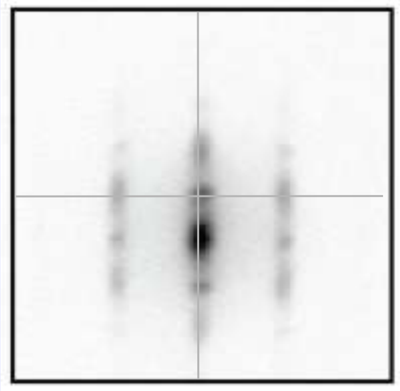
rhombic



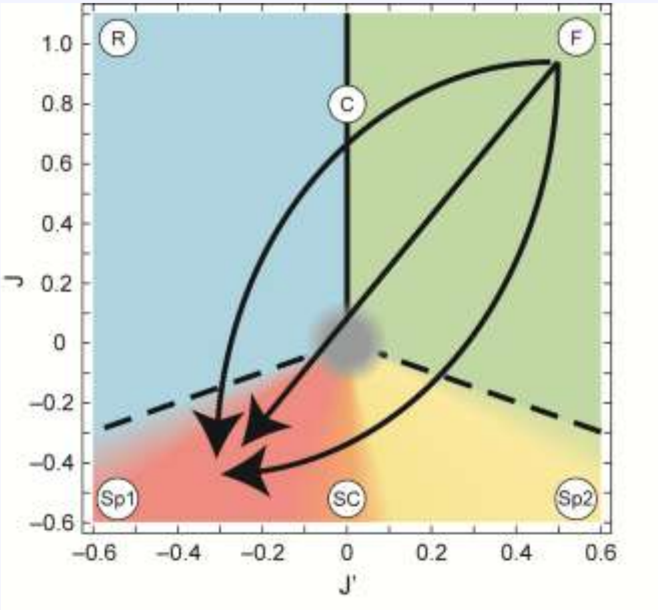
ferromagnetic

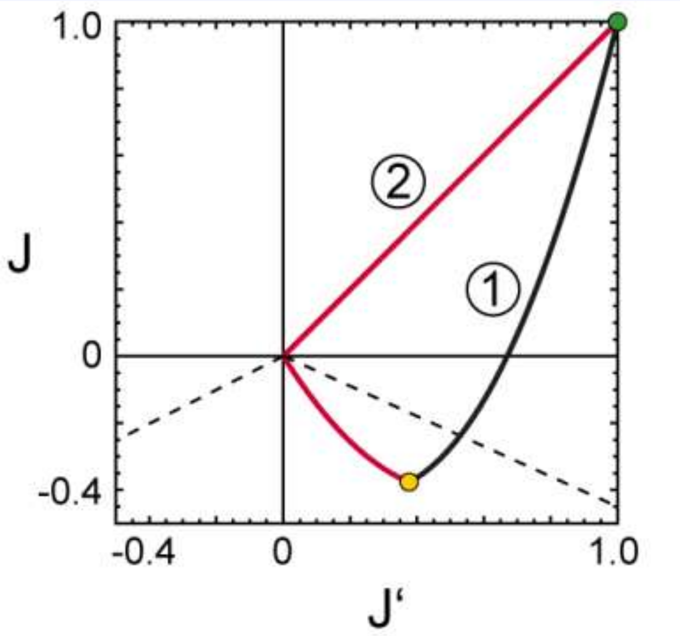






Outlook I: Non-equilibrium dynamics





Different trajectories in phase space ?

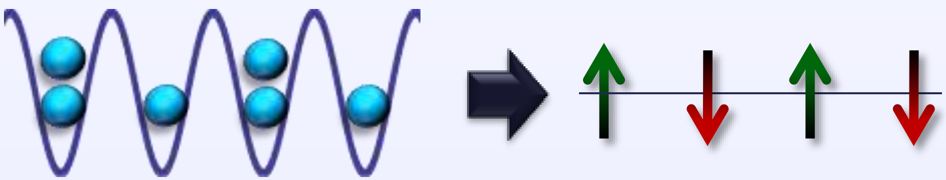
⟹ time dependence ?

Fast quenches across phase boundaries ?

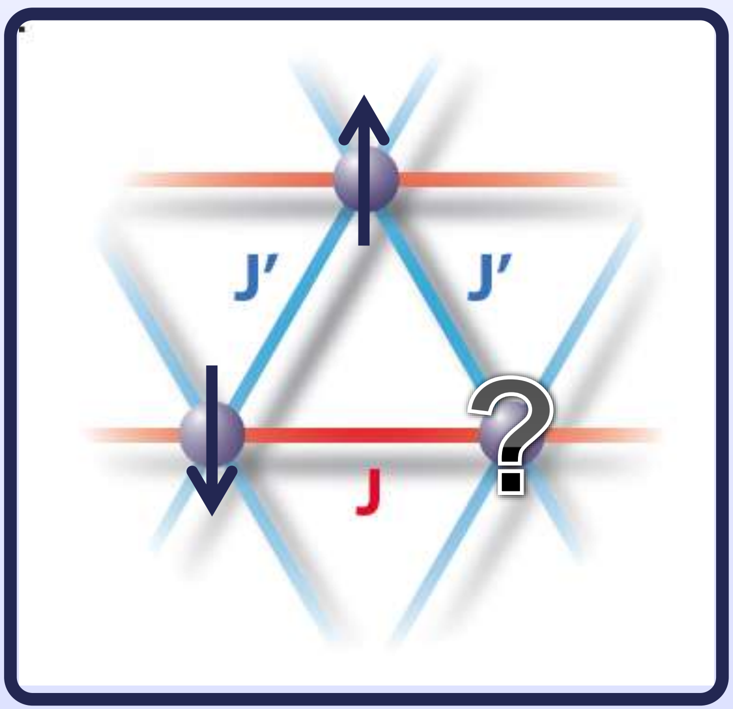
⟹ Excitations ?

⟹ Relaxation dynamics ?

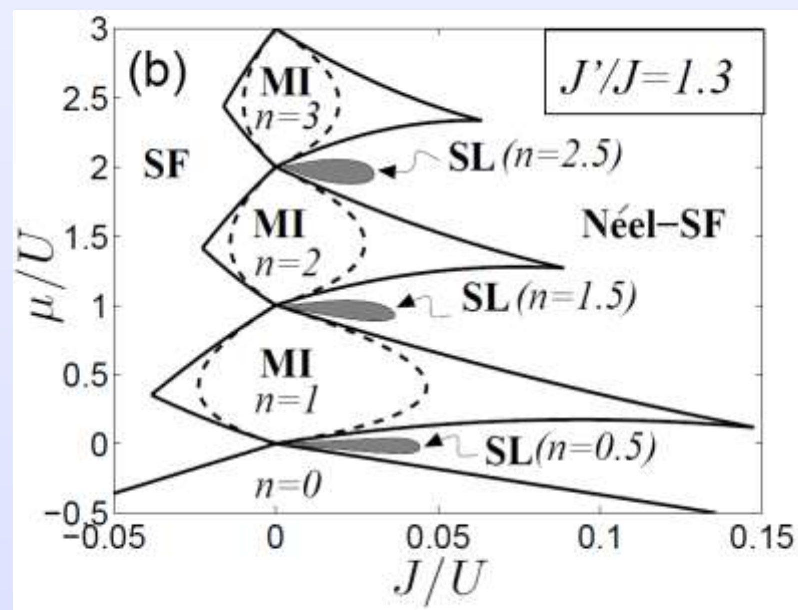
Outlook II: Quantum XY-Model Strongly correlated regime



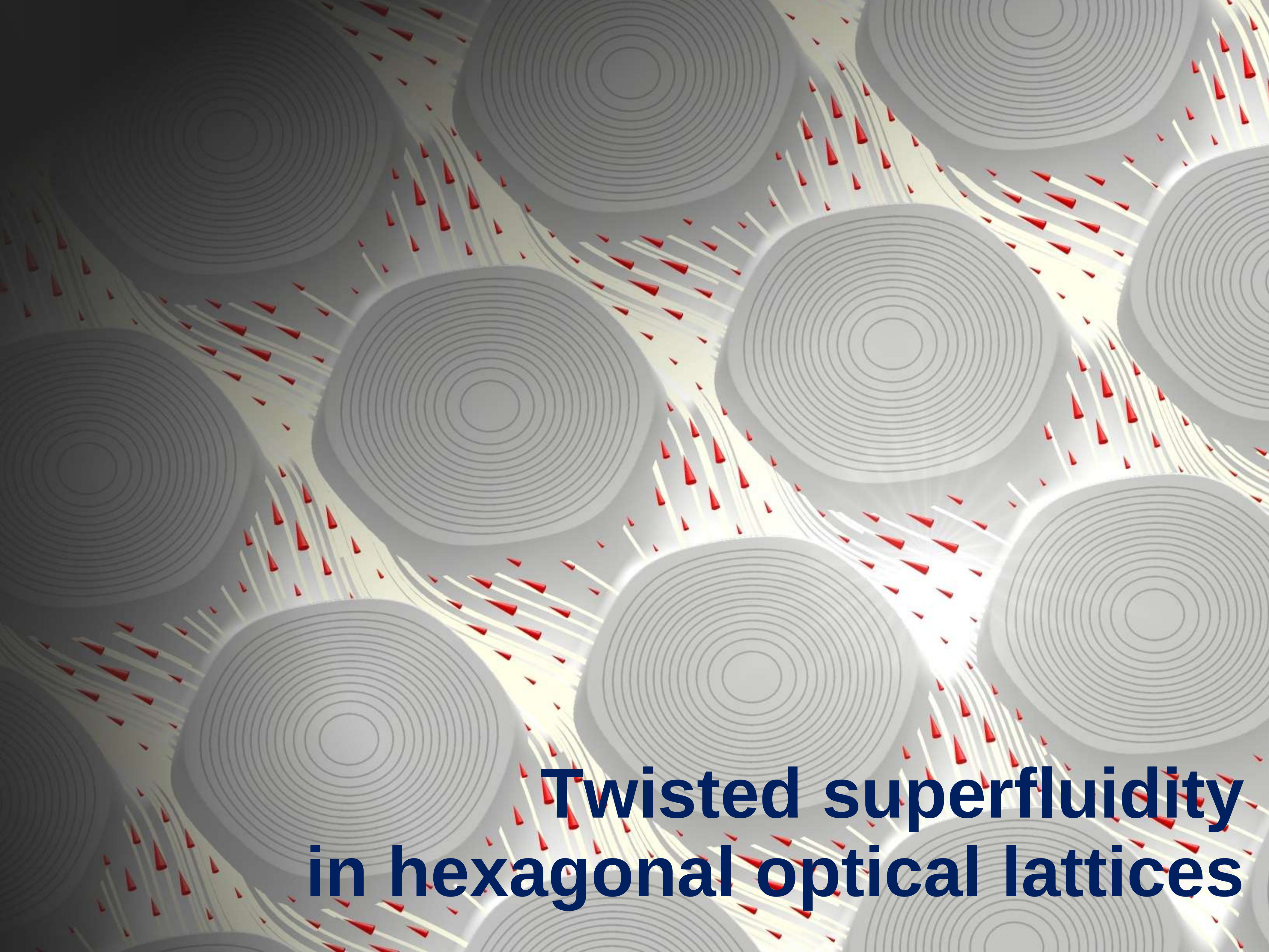
Mapping occupation numbers onto spins



Frustration: Spin-liquid ?

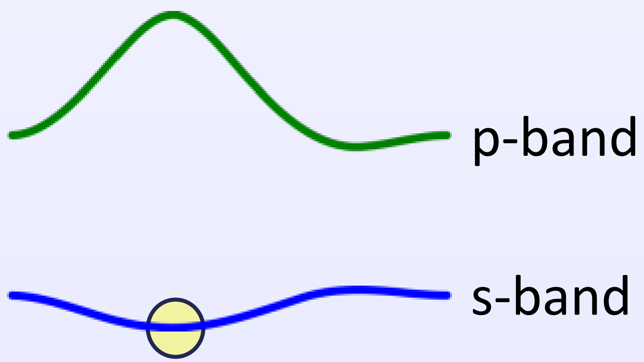


A. Eckardt et al.; EPL 89 10010 (2010)


Twisted superfluidity
in hexagonal optical lattices

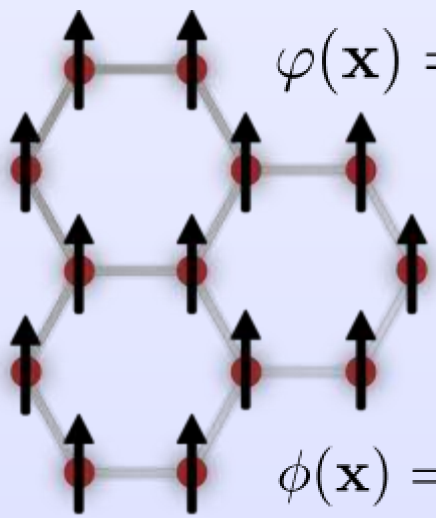
Orbital hybridization in superfluids

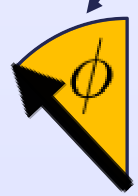
Normal superfluid



Superfluid order parameter:

$$\varphi(\mathbf{x}) = \sqrt{n(\mathbf{x})}e^{i\boxed{\phi(\mathbf{x})}}$$

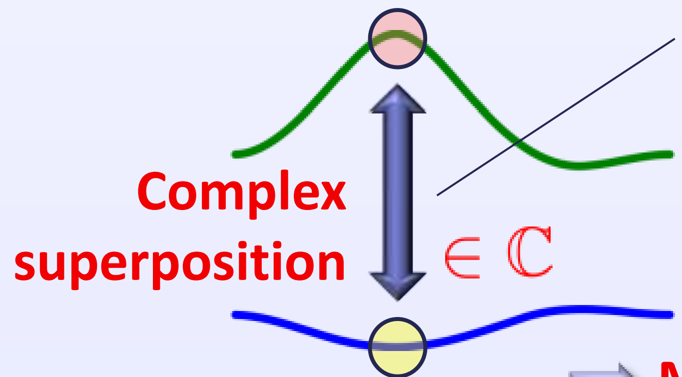




$\phi(\mathbf{x}) = \text{const}$

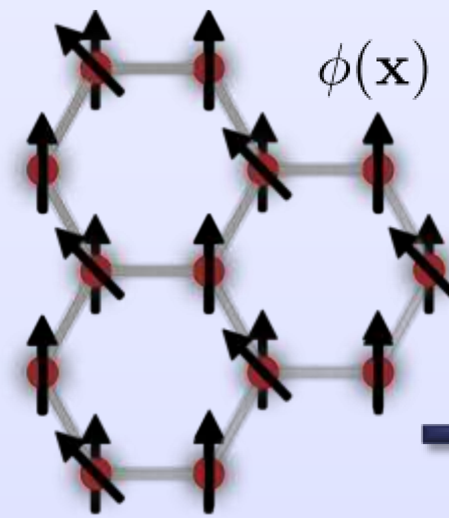
➡ **Real** order parameter

Hybridized orbital superfluid



Interaction-induced hybridization of s- and p-band

➡ **Multi-band** state

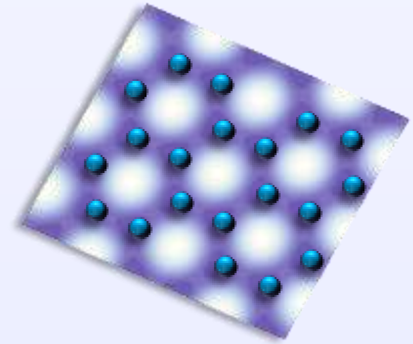


$\phi(\mathbf{x}) \neq \text{const}$

➡ **Complex** order parameter

➡ **Twisted superfluid phase**

Hexagonal optical lattices



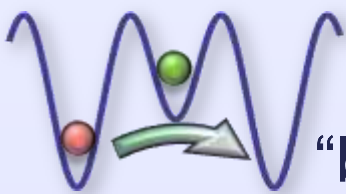
- **Studies of spin-dependent lattices**

  Becker *et al*., **NJP 12, 065025 (2010)**

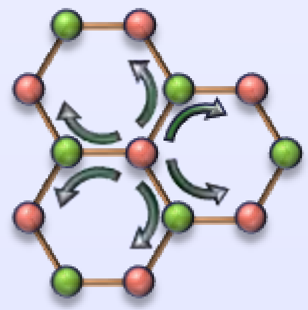
- **State-dependent Mott-insulator transition**

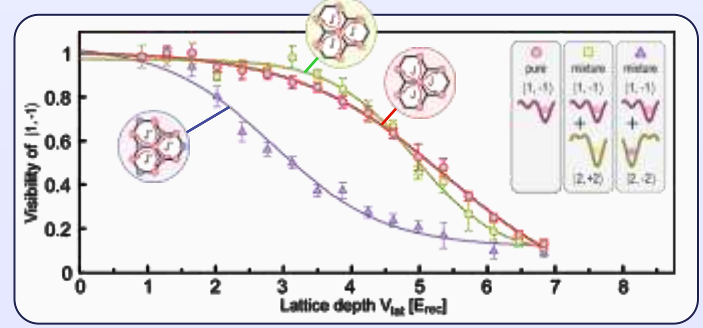
  P. Soltan-Panahi *et al.* ***Nature Physics*** **7, 434 (2011)**

- **Tunneling blockade**



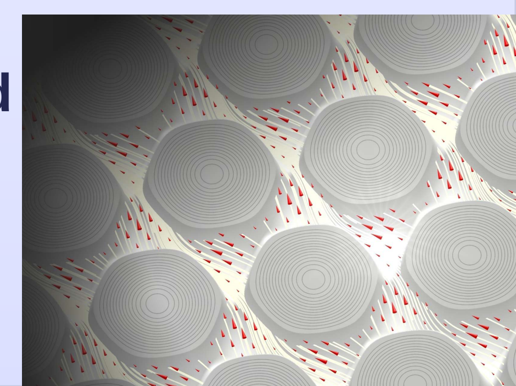
"blocked"





- **Orbital physics**
  - Interaction-induced *p*-band admixture
  - Unconventional superfluid → ***complex*** **order parameter**
  - **Quantum phase transition: normal ↔ *twisted* superfluid**

  P. Soltan-Panahi *et al.*, ***arXiv***:**1104.3456, Nature Physics, doi:10.1038/nphys2128 (2011)**



Summary

- Simulation of classical magnetism in a triangular lattice with bosons

➡ all possible phases realized

➡ spontaneous symmetry breaking observed

➡ phase transitions mapped