Magnetism of spinor BEC in an optical lattice

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Outline

- Introduction. Magnetism in condensed matter systems
- Engineering magnetic systems using cold atoms in an optical lattice
- New phenomena with spinor systems in optical lattices

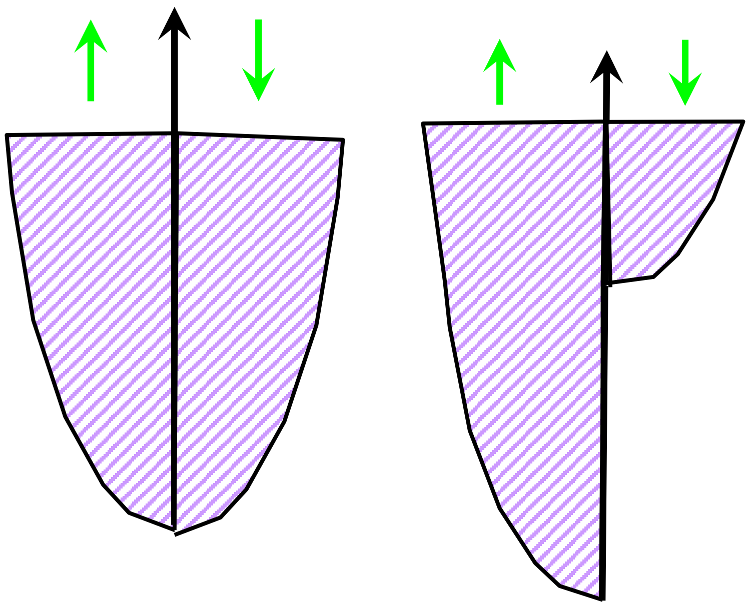
Magnetism in condensed matter systems

Ferromagnetism

Magnetic needle in a compass

Magnetic memory in hard drives.
Storage density of hundreds of billions bits per square inch.

Stoner model of ferromagnetism



Spontaneous spin polarization decreases interaction energy but increases kinetic energy of electrons

Mean-field criterion

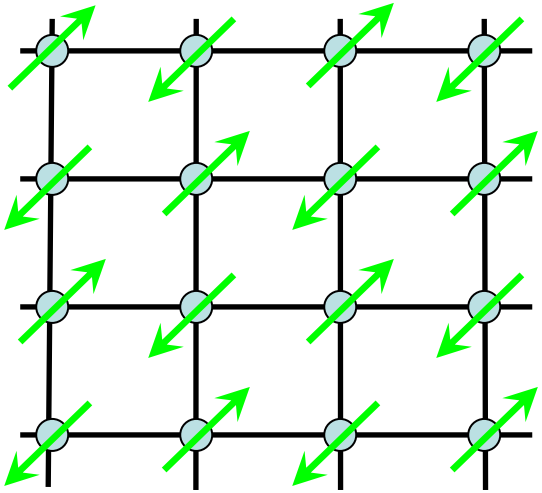
$$I\,N(0) = 1$$

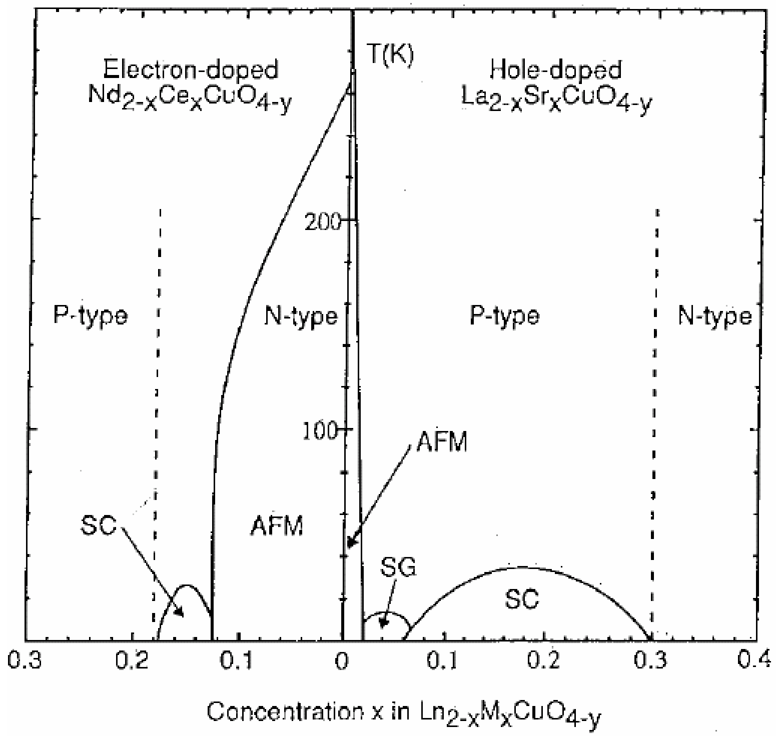
I – interaction strength

$N(0)$ – density of states at the Fermi level

Antiferromagnetism

Maple, JMMM 177:18 (1998)





High temperature superconductivity in cuprates is always found near an antiferromagnetic insulating state

Antiferromagnetism

Antiferromagnetic Heisenberg model $\mathcal{H} = J \sum_{\langle ij \rangle} \vec{S}_i \vec{S}_j$

$$|AF\rangle = |\uparrow \downarrow\rangle$$

$$|s\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow \downarrow\rangle - |\downarrow \uparrow\rangle \right)$$

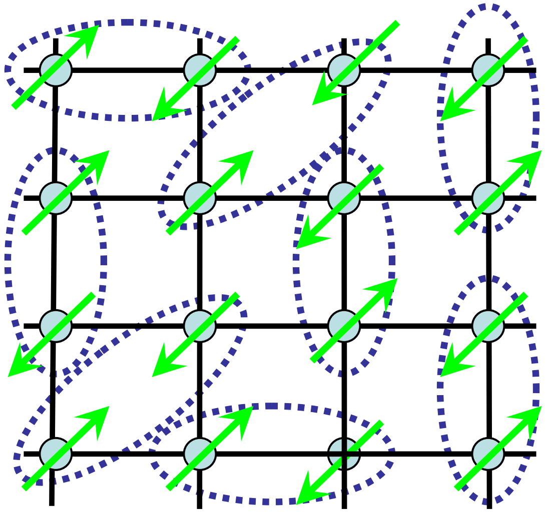
$$|t\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow \downarrow\rangle + |\downarrow \uparrow\rangle \right)$$

$$\boxed{|AF\rangle = \frac{1}{\sqrt{2}} \left(|s\rangle + |t\rangle \right)}$$

Antiferromagnetic state breaks spin symmetry.
It does not have a well defined spin

Spin liquid states

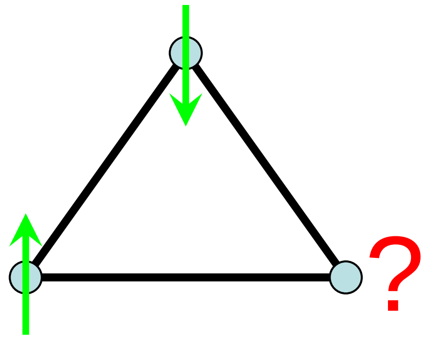
Alternative to classical antiferromagnetic state: spin liquid states



Properties of spin liquid states:

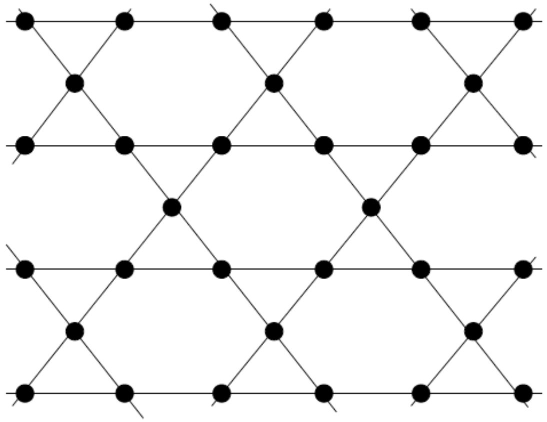
- fractionalized excitations
- topological order
- gauge theory description

Systems with geometric frustration



Spin liquid behavior in systems with geometric frustration

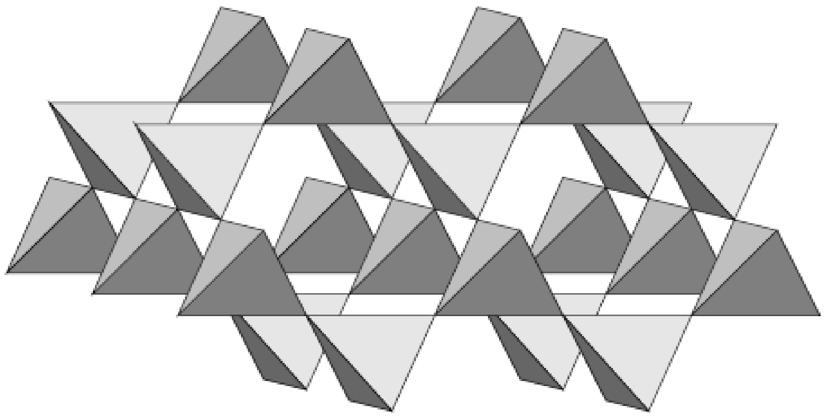
Kagome lattice



$SrCr_{9-x}Ga_{3+x}O_{19}$

Ramirez et al. PRL (90)
Broholm et al. PRL (90)
Uemura et al. PRL (94)

Pyrochlore lattice



$ZnCr_2O_4$
$A_2Ti_2O_7$

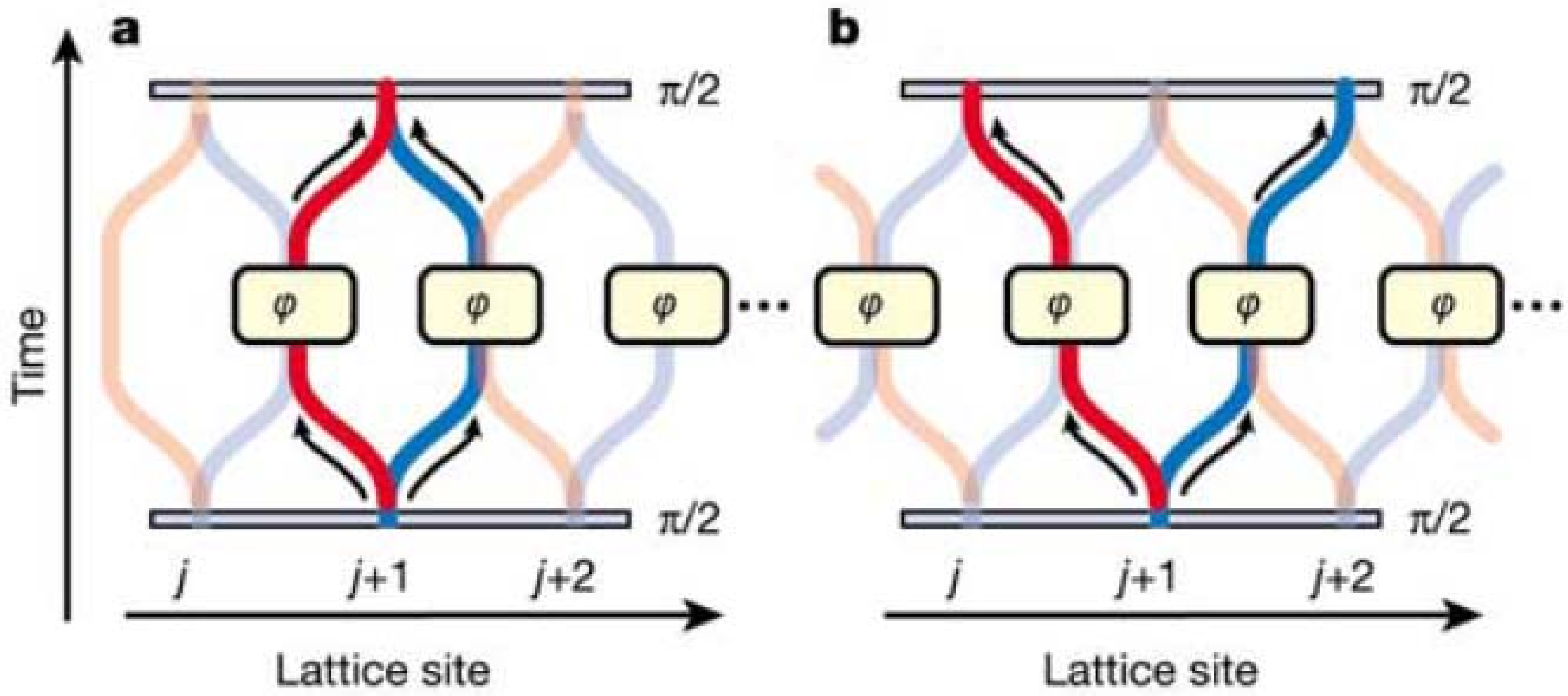
Ramirez et al. PRL (02)

Engineering magnetic systems using cold atoms in an optical lattice

Spin interactions using controlled collisions

Experiment: Mandel et al., Nature 425:937(2003)

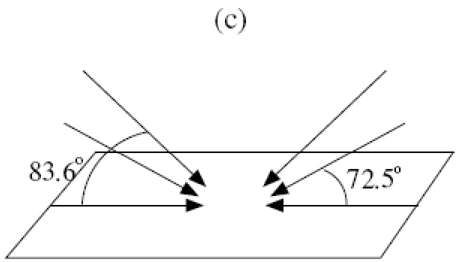
Theory: Jaksch et al., PRL 82:1975 (1999)

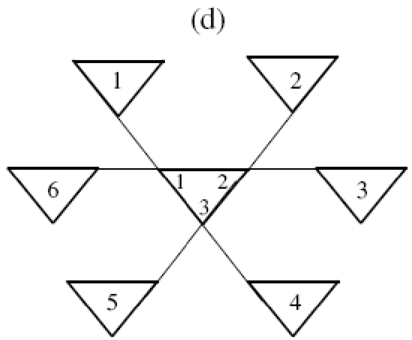


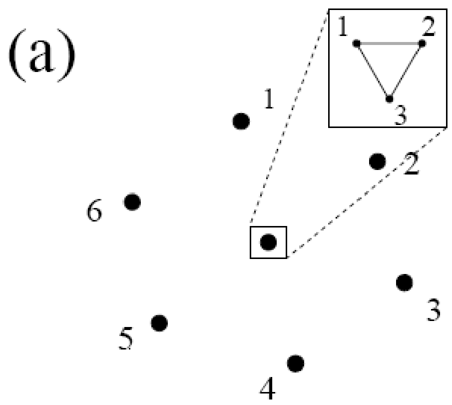
Effective spin interaction from the orbital motion. Cold atoms in Kagome lattices

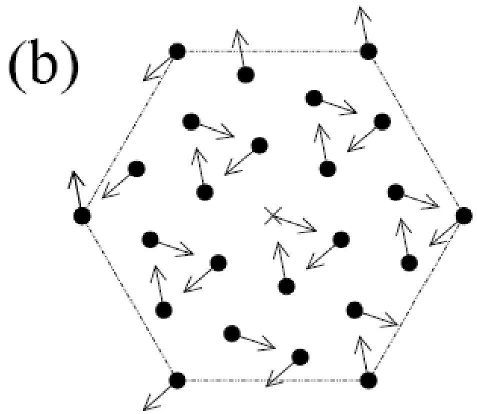
Santos et al., PRL 93:30601 (2004)

Damski et al., PRL 95:60403 (2005)





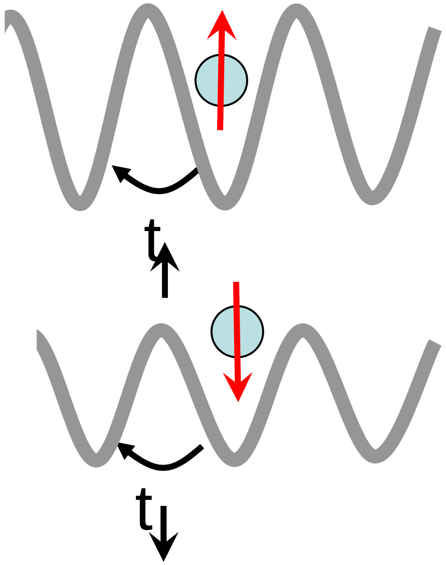




$$H_{trimer} = \frac{J}{2} \sum_{i=1}^{N} \sum_{j=1}^{6} s_i(\phi_{i \to j}) s_j(\tilde{\phi}_{j \to i}),$$

Two component Bose mixture in optical lattice

Example: $^{87}\mathrm{Rb}$. Mandel et al., Nature 425:937 (2003)



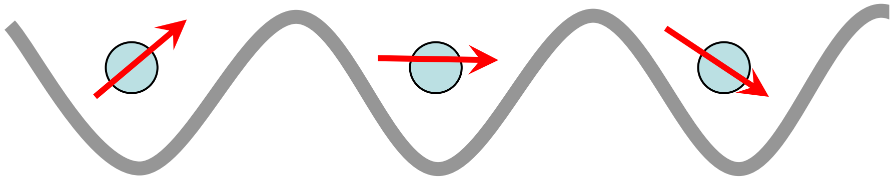
$$|\uparrow\rangle = |F=1, m_F=-1\rangle$$

$$|\downarrow\rangle = |F=2, m_F=-2\rangle$$

Two component Bose Hubbard model

$$\mathcal{H} = -t_\uparrow \sum_{\langle ij \rangle} b^\dagger_{i\uparrow} b_{j\uparrow} - t_\downarrow \sum_{\langle ij \rangle} b^\dagger_{i\downarrow} b_{j\downarrow} + U_{\uparrow\uparrow} \sum_i n_{i\uparrow}(n_\uparrow - 1) + U_{\downarrow\downarrow} \sum_i n_{i\downarrow}(n_\downarrow - 1) + U_{\uparrow\downarrow} \sum_i n_{i\uparrow} n_\downarrow$$

Quantum magnetism of bosons in optical lattices



Kuklov and Svistunov, PRL (2003)

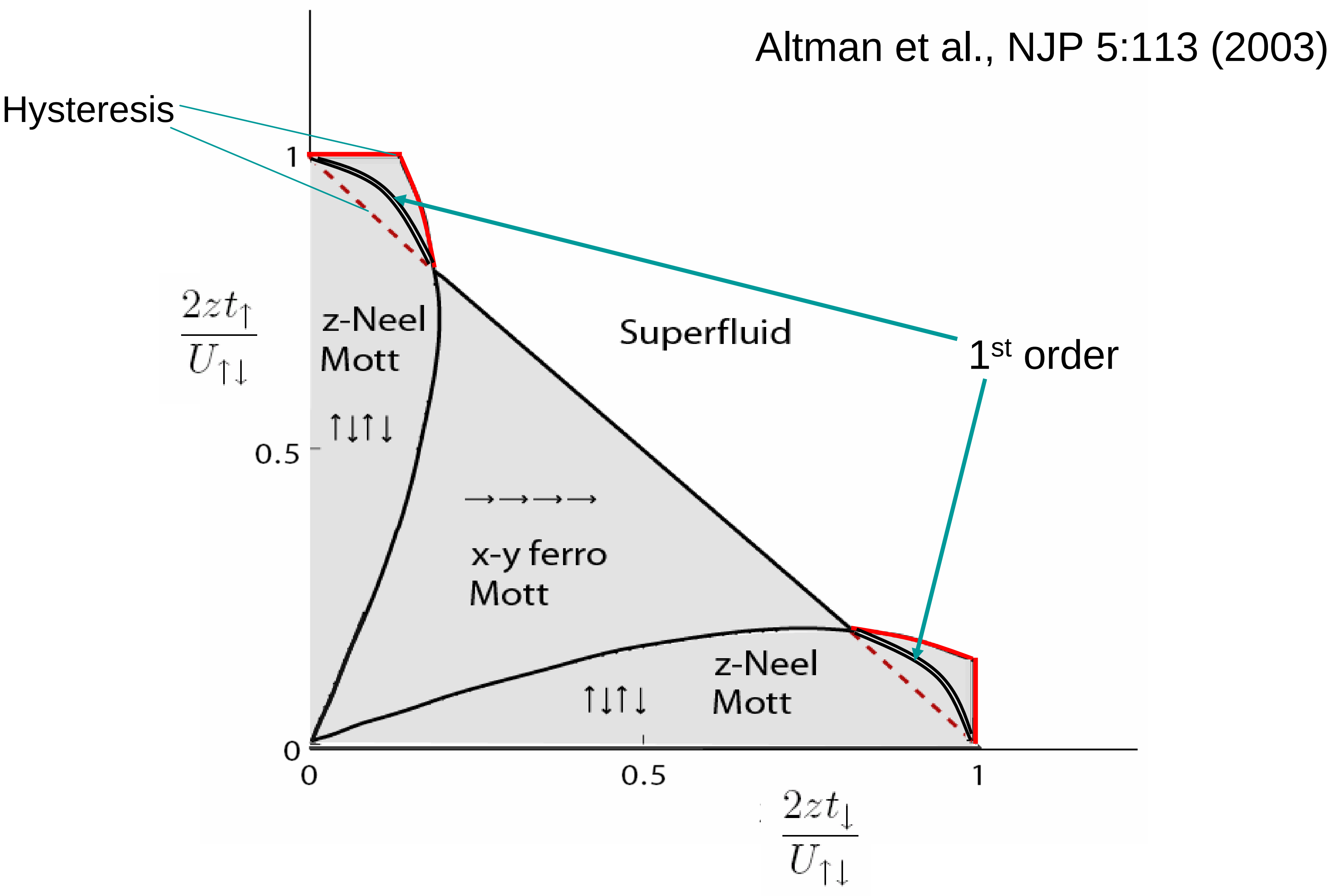
Duan et al., PRL (2003)

$$\mathcal{H} = J_z \sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z + J_\perp \sum_{\langle ij \rangle} \left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y \right)$$

$$J_z = \frac{t_\uparrow^2 + t_\downarrow^2}{2U_{\uparrow\downarrow}} - \frac{t_\uparrow^2}{U_{\uparrow\uparrow}} - \frac{t_\downarrow^2}{U_{\downarrow\downarrow}} \qquad J_\perp = -\frac{t_\uparrow t_\downarrow}{U_{\uparrow\downarrow}}$$

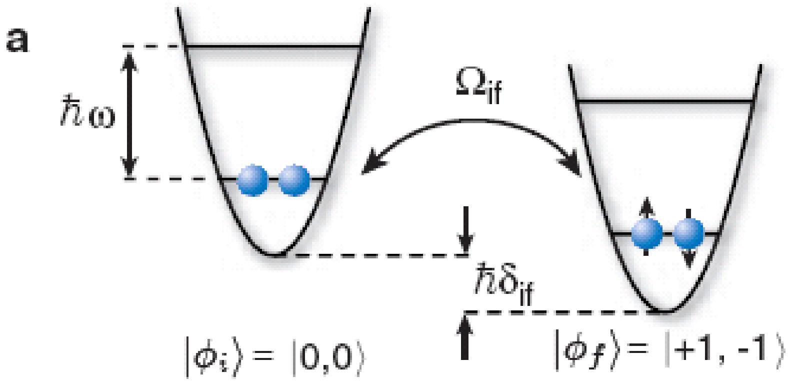
- Ferromagnetic $\quad U_{\uparrow\downarrow} >> U_{\uparrow\uparrow},\ U_{\downarrow\downarrow}$
- Antiferromagnetic $\quad U_{\uparrow\downarrow} << U_{\uparrow\uparrow},\ U_{\downarrow\downarrow}$

Two component Bose mixture in optical lattice.
Mean field theory + Quantum fluctuations

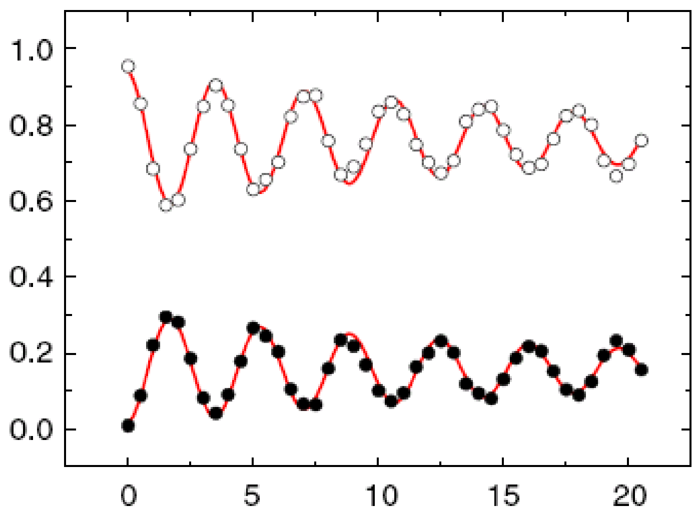


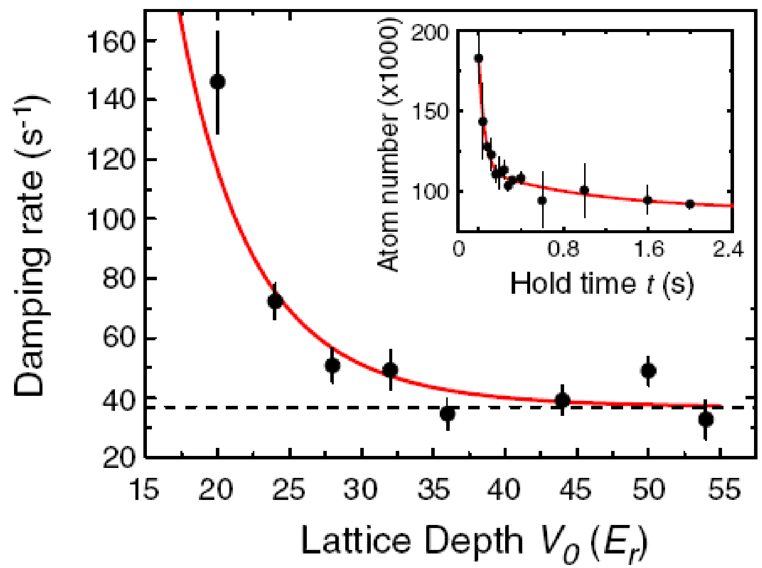
Coherent spin dynamics in optical lattices

Widera et al., cond-mat/0505492

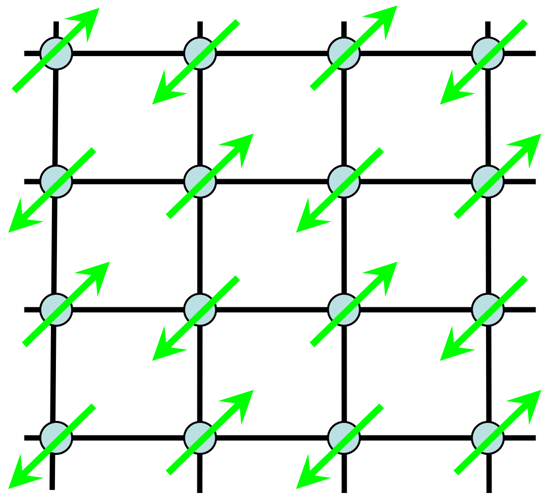


$^{87}\mathrm{Rb}$ **atoms in the F=2 state**





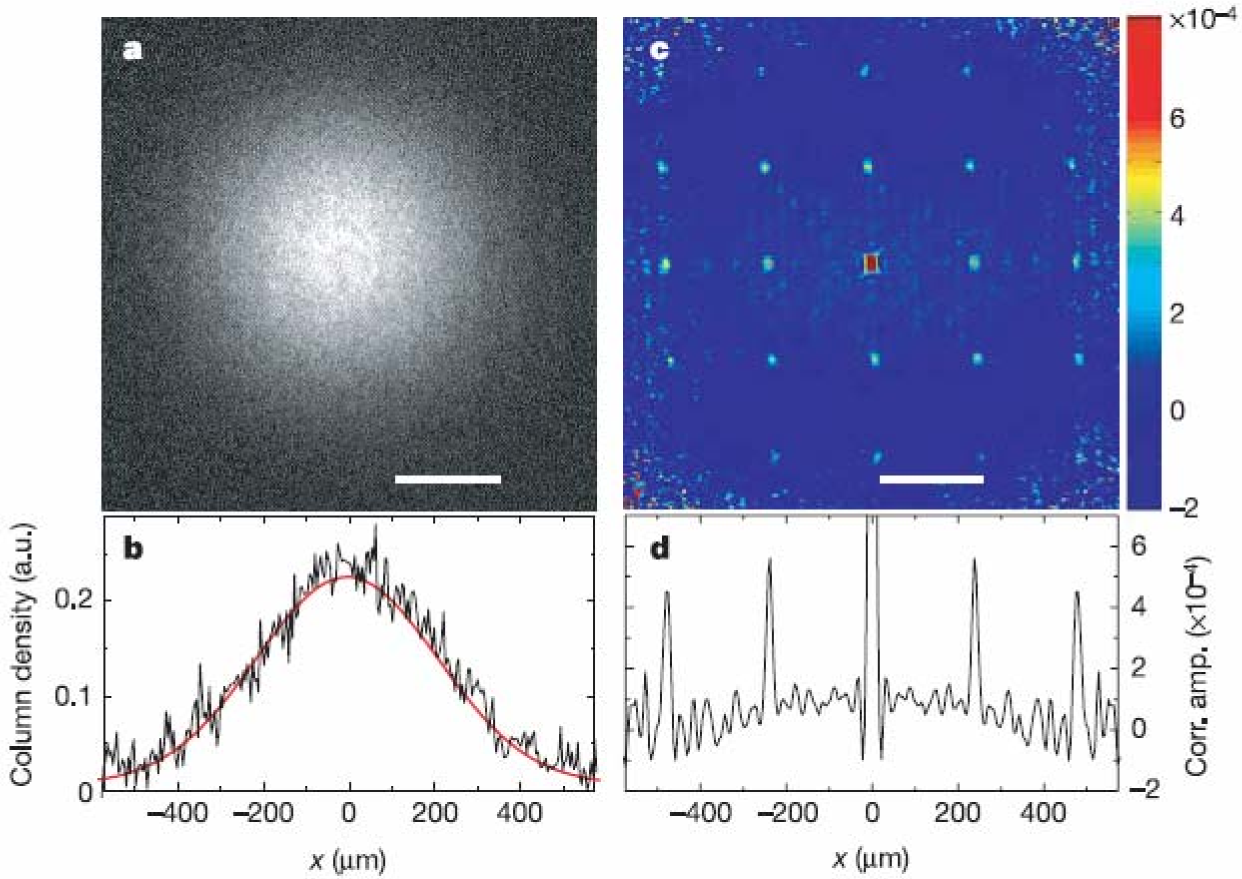
How to observe antiferromagnetic order of cold atoms in an optical lattice?



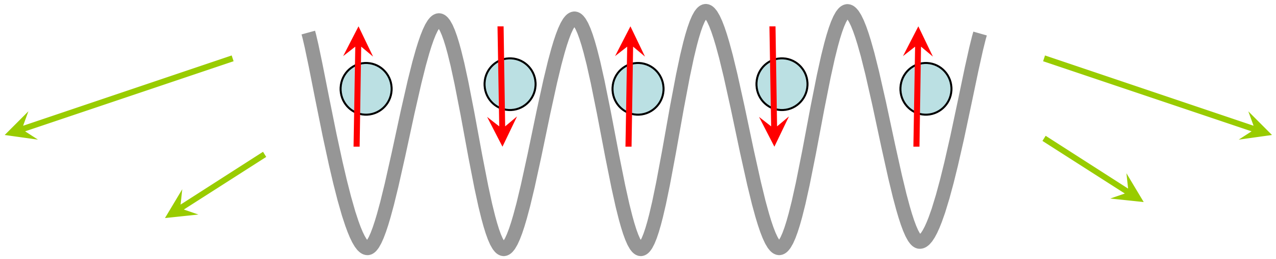
Second order coherence in the insulating state of bosons. Hanburry-Brown-Twiss experiment

Theory: Altman et al., PRA 70:13603 (2004)
See also Bach, Rzazewski, PRL 92:200401 (2004)

Experiment: Folling et al., Nature 434:481 (2005)
See also Hadzibabic et al., PRL 93:180403 (2004)



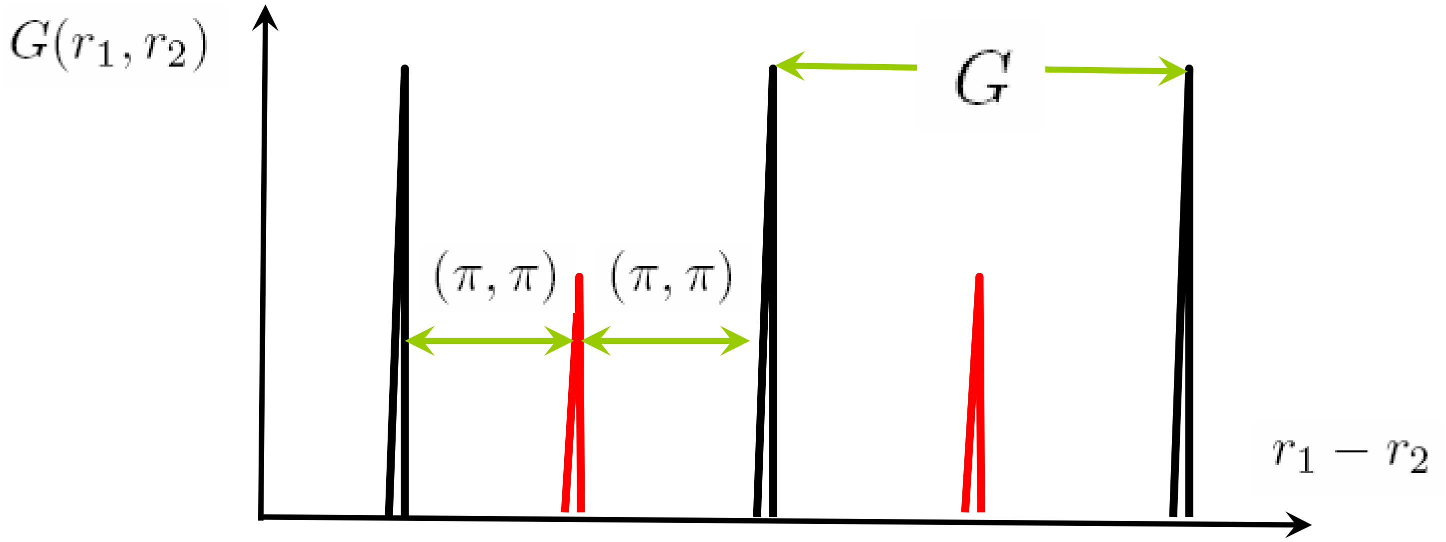
Probing spin order of bosons



$$r = \frac{\hbar\, k\, t}{m}$$

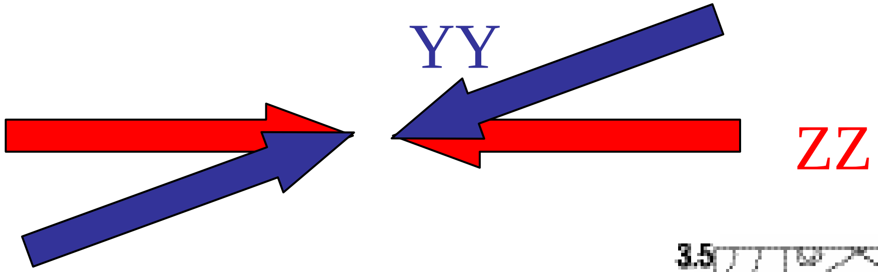
Correlation Function Measurements

$$\begin{aligned} G(r_1, r_2) &= \langle\, n(r_1)\; n(r_2)\, \rangle_{\mathrm{TOF}} - \langle\, n(r_1)\, \rangle_{\mathrm{TOF}} \; \langle\, n(r_2)\, \rangle_{\mathrm{TOF}} \\ &\sim \langle\, n(k_1)\; n(k_2)\, \rangle_{\mathrm{LAT}} - \langle\, n(k_1)\, \rangle_{\mathrm{LAT}} \; \langle\, n(k_2)\, \rangle_{\mathrm{LAT}} \end{aligned}$$



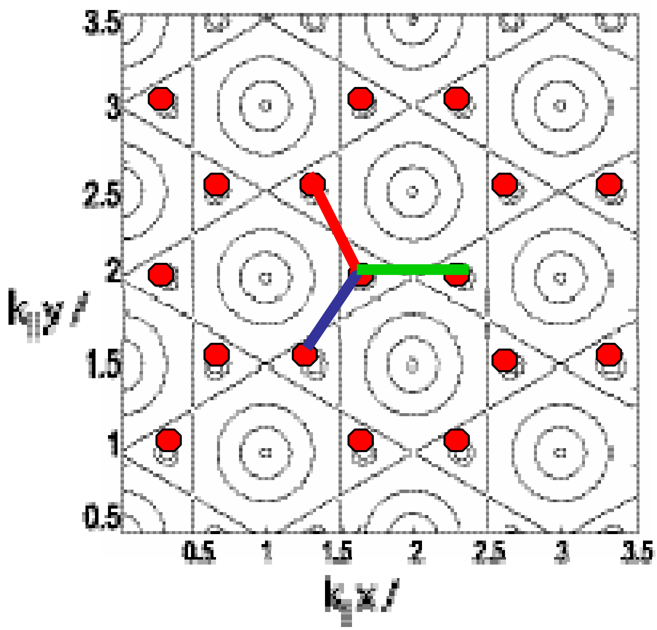
Engineering exotic phases

• Optical lattice in 2 or 3 dimensions: polarizations & frequencies of standing waves can be different for different directions



• Example: exactly solvable model Kitaev (2002), honeycomb lattice with

$$H = J_x \sum_{<i,j>\in x} \sigma_i^x \sigma_j^x + J_y \sum_{<i,j>\in y} \sigma_i^y \sigma_j^y + J_z \sum_{<i,j>\in z} \sigma_i^z \sigma_j^z$$



• Can be created with 3 sets of standing wave light beams !

• Non-trivial topological order, “spin liquid” + non-abelian anyons …those has not been seen in controlled experiments

Other multicomponent systems in optical systems:

Spin 1 bosons

Ho;
Ohmi, Machida;
Imambekov et al.;
Zhou et al.;
Cirac et al.;
Tsuchiya, Kurihara, Kimura;
Zhang, Yu;
Rizzi et al.; …

Spin 2 bosons

Koashi, Saito, Ueda;
Jin, Hao, et al.;
Hou, Ge; …

High spin fermions

Wu, Hu, Zhang;
Honerkamp, Hofstetter; …

Systems with three spin interactions, ring exchange terms, …

Pachos et al.;
Buchler et al.;
Trebst et al.; …

Boson-Fermion mixtures

Cazalilla, Ho;
Vignolo et al.;
Illuminati et al.;
Buchler, Blatter;
Lewenstein et al;
Burnett et al.;
Mathey et al.;
Wang et al.; …

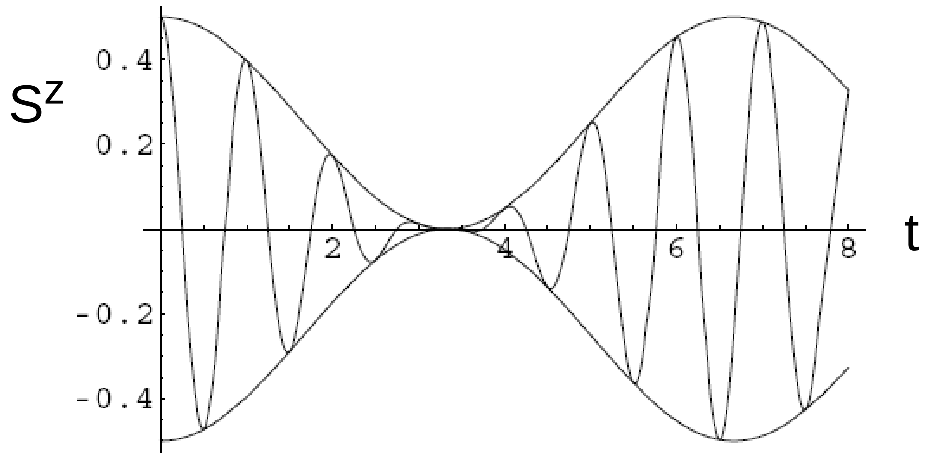
New phenomena with spinor systems in optical lattices

Coherent far from equilibrium dynamics of spin systems. Collapse and revival

Exactly solvable longitudinal field Ising model $\mathcal{H} = J_x \sum_{\langle ij \rangle} S_i^x S_j^x - h \sum_i S_i^x$

At t=0 $|\Psi\rangle = \prod_i |\uparrow\rangle$

$$S^z(t) = \frac{1}{4}(1 + \cos Jt)\cos ht$$



Fast Rabi oscillations $\omega = h$

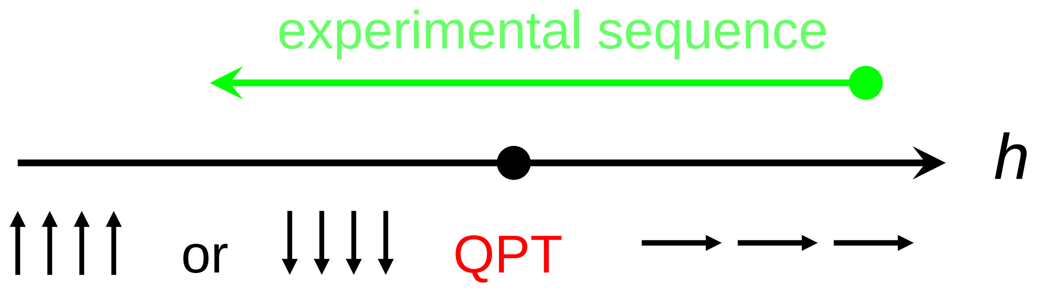
Collapse and revival $\omega = J$

Do we have collapse and revival for more generic Hamiltonians?

Crossing a quantum phase transition

Transverse field Ising model
$$\mathcal{H} = -J\sum_{\langle ij\rangle} S_i^z S_j^z - h(t)\sum_i S_i^x$$

Ground state



Density of kinks excited by crossing the QPT $\quad n_{\text{kinks}} \sim (\dot{h})^{-1/2}$

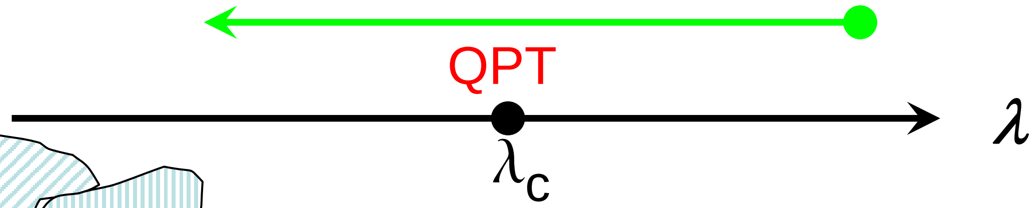
Zurek et al., cond-mat/0503511
Cherng, Levitov, preprint

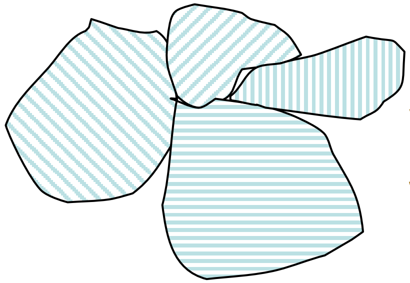
Crossing a general QPT. Quantum critical point is characterized by critical exponents ν and *z.* Density of created excitations

$$n_{\text{excit}} \sim (\dot{\lambda})^{\frac{\nu z}{\nu z+1}}$$

Polkovnikov, cond-mat/0312144

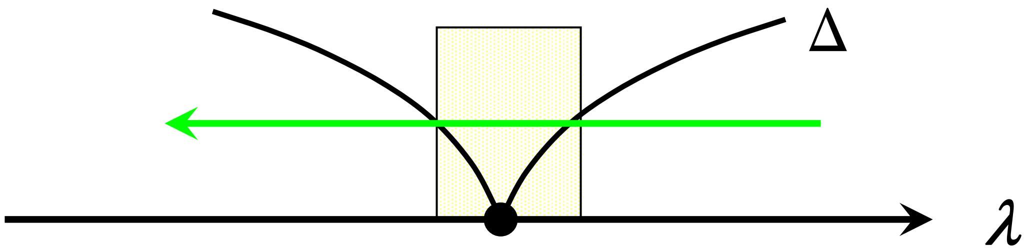
Crossing a quantum phase transition





What determines the lengthscale of domains which appear after crossing QPT?

Critical exponents ν and z: $\xi \sim (\lambda - \lambda_c)^{-\nu}$ $\quad \Delta \sim \xi^{-z} \sim (\lambda - \lambda_c)^{z\nu}$



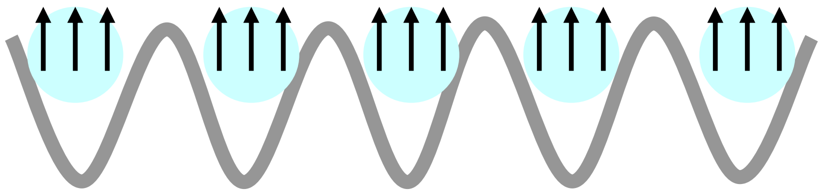
When $d \log \Delta / dt \sim \Delta$ we change from adiabatic to antiadiabatic evolution. The lengthscale of domains is determined by the correlation length at this point

$$\boxed{L \sim (\dot{\lambda})^{-\frac{\nu}{(z\nu+1)}}}$$

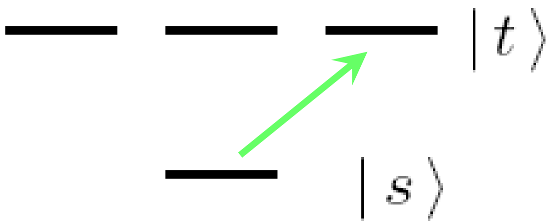
Spin systems with long range interactions

Magnetic dipolar interactions

Meystre et al.

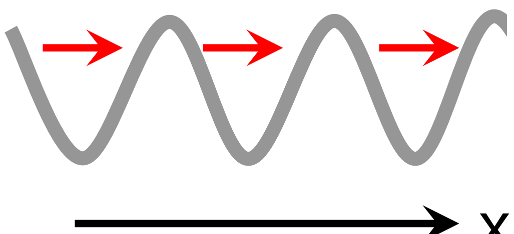


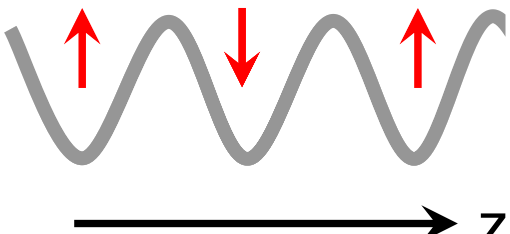
Electric dipolar interactions. Heteronuclear molecules.
Mixture of $l=0$ and $l=0$, $l_z=+1$ states.



$$d^x = d_0\,(\,s^\dagger\,t + t^\dagger\,s\,)$$

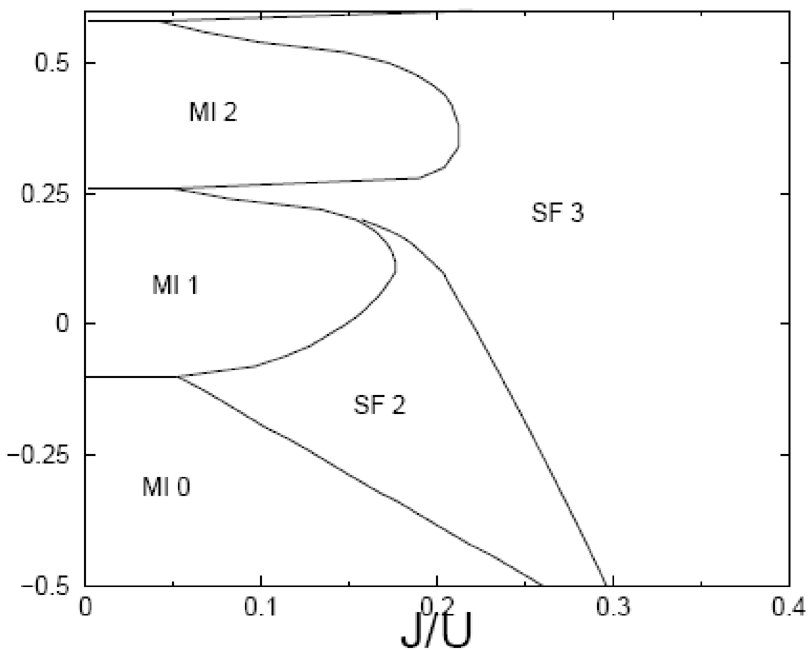
$$d^y = \frac{d_0}{i}\,(\,s^\dagger\,t - t^\dagger\,s\,)$$

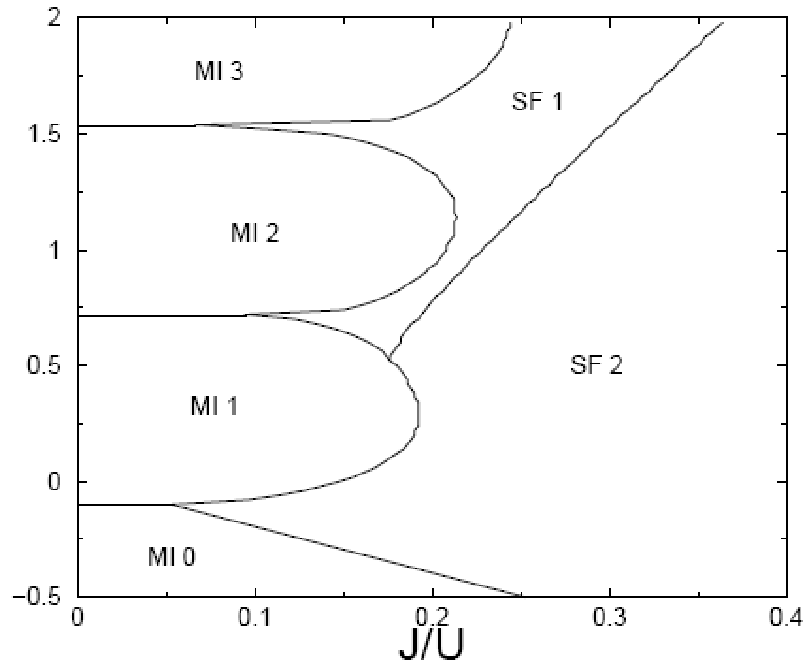




Mixture of *l=0* and *l=0*, $l_z=+1$ molecules in an optical lattice

Barnett, Petrov, Lukin, Demler





SF3 – superfluid phase. Spin order has a continuouslly varying wavevector

SF1 – superfluid phase with partial phase separation of *s* and *t* components

SF2 – superfluid phase with phase separation

Conclusions

- Quantum magnetism is an important many-body phenomenon that is not yet fully understood

- Many kinds of magnetic Hamiltonians can be realized using cold atoms in optical lattices

- Magnetic systems created of cold atoms can be used to address new kinds of questions:
  coherent far from equilibrium dynamics,
  crossing quantum phase transitions,
  magnetic systems with long range interactions, …