Studying XY spin models with arrays of single Rydberg atoms

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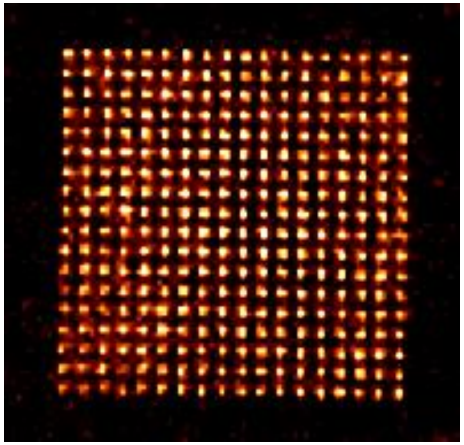
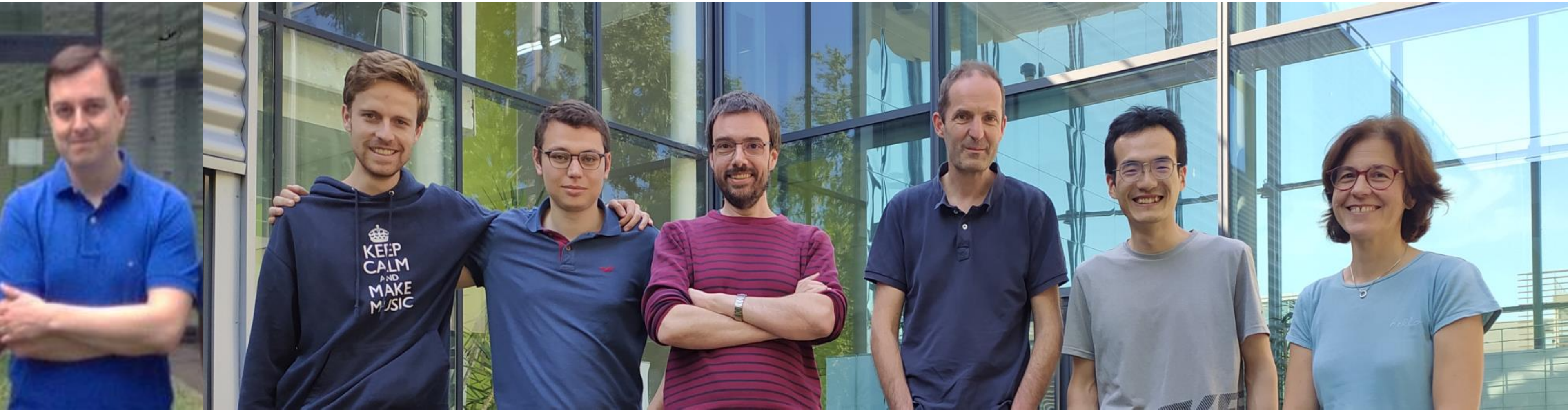


JMC2022 – Mini-colloque MC22
Lyon, 25th of August 2022

The Rydberg team in Palaiseau



Daniel Barredo | *Gabriel Emperauger* | *Guillaume Bornet* | *Thierry Lahaye* | *Antoine Browaeys* | *Cheng Chen* | *Florence Nogrette*

Collaborators (theory):
H.-P. Büchler (Stuttgart), A. Läuchli (Innsbruck), N. Yao (Harvard)

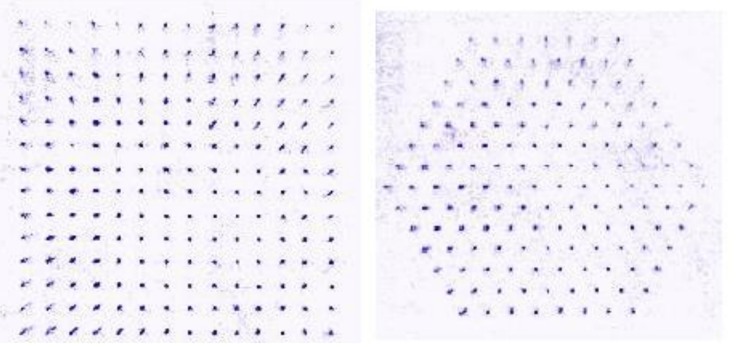
https://atom-tweezers-io.org/

Funding:

Arrays of single Rydberg atoms

- **Arrays of single atoms with arbitrary geometries**

Up to 300 atoms
Spacing: a few microns



- **Strong interactions via Rydberg excitation**

Interaction strength 1 to 10 MHz for *R* ~ 5 µm
Lifetime 100s of µs

Implement spin models

Ising (vdW interactions)

$$\hat{H} \sim \sum_{i,j} J_{ij} \sigma_z^{(i)} \sigma_z^{(j)}$$

XY (resonant dipole-dipole interaction)

$$\hat{H} \sim \sum_{i,j} J_{ij} \sigma_+^{(i)} \sigma_-^{(j)}$$

Outline

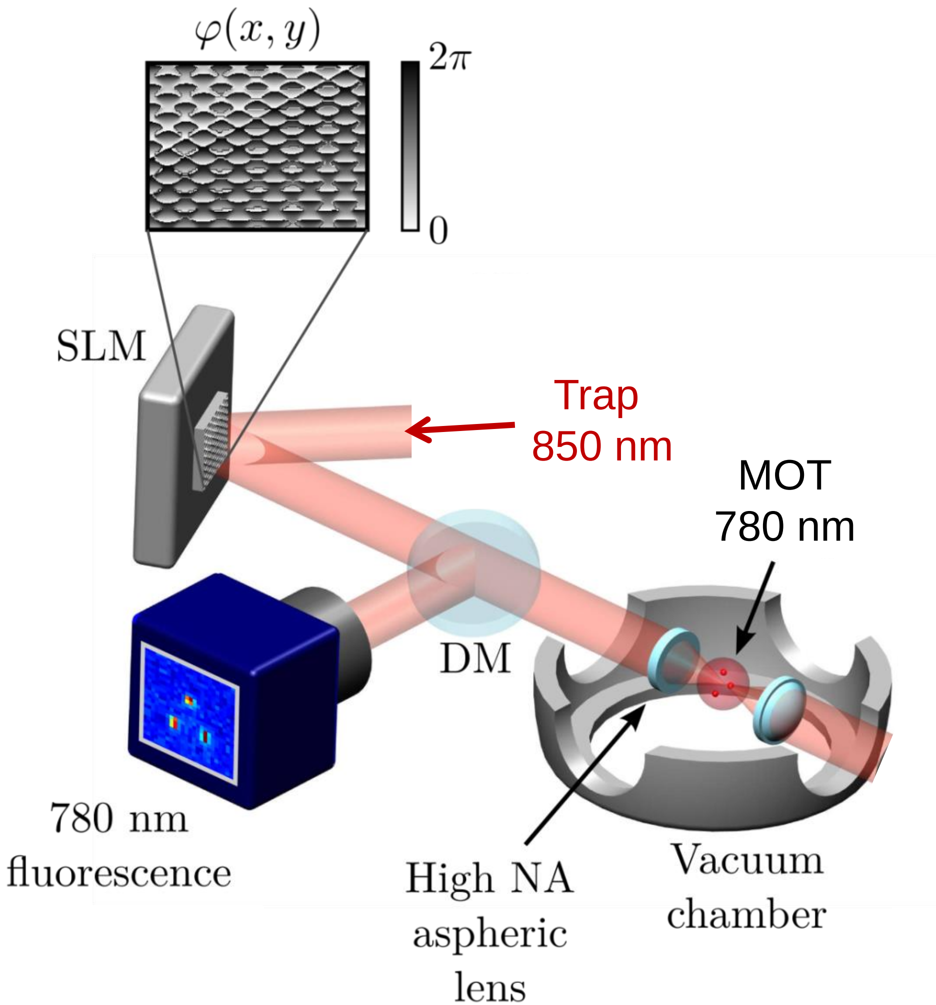
1. ***Experimental setup***

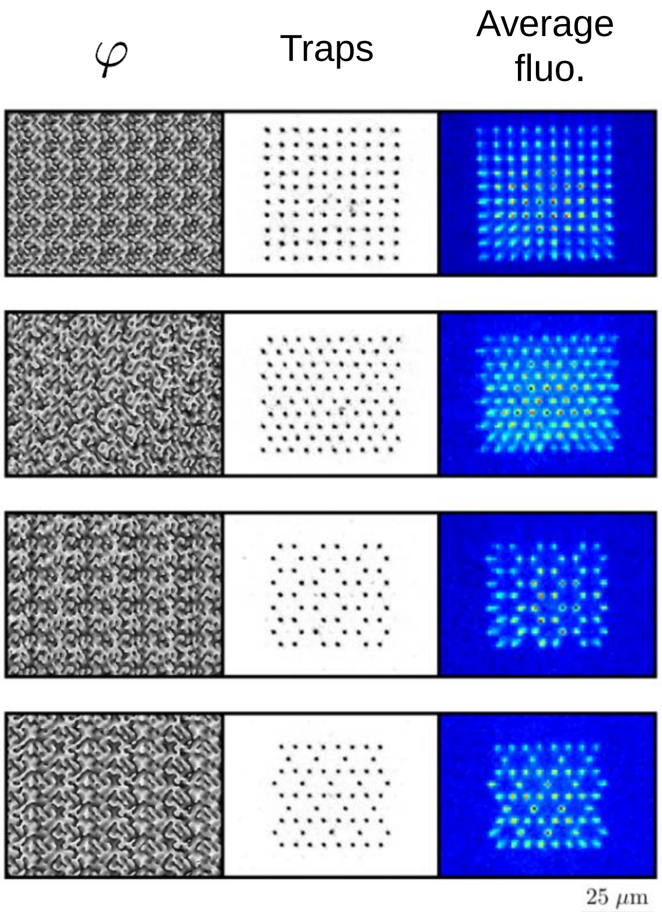
2. ***Ising model***

3. ***Dipolar XY model***

1. Experimental setup

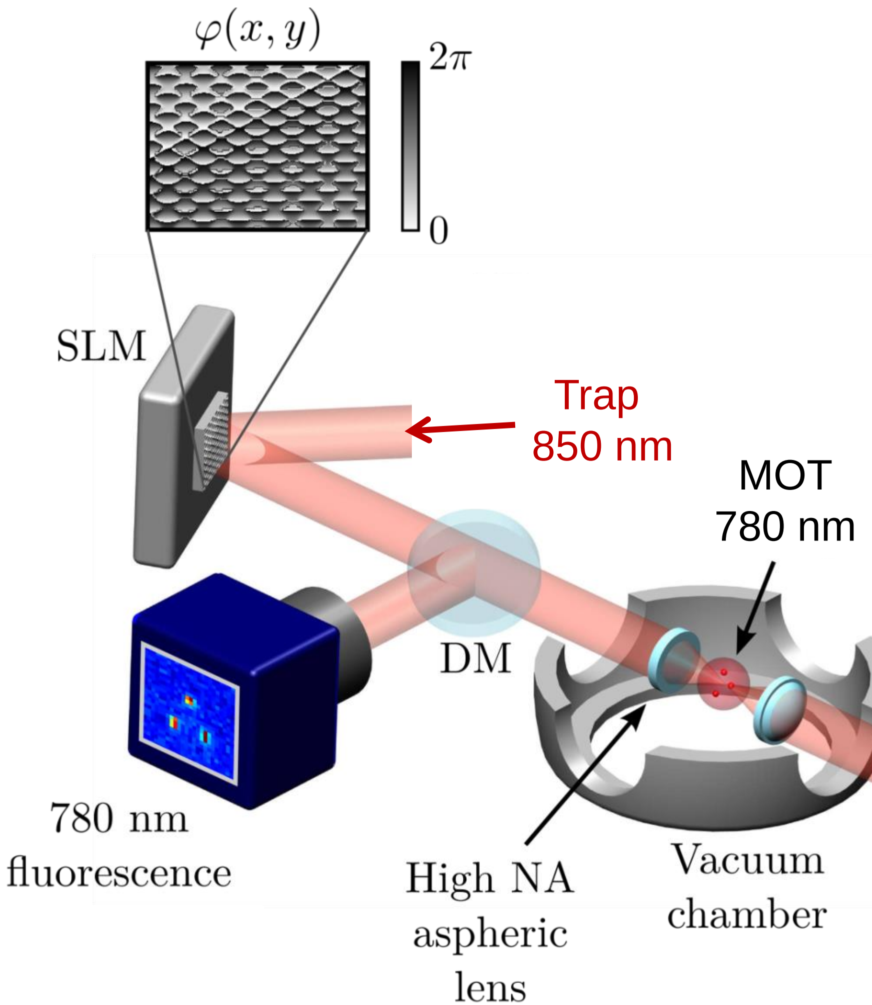
Arrays of single atoms

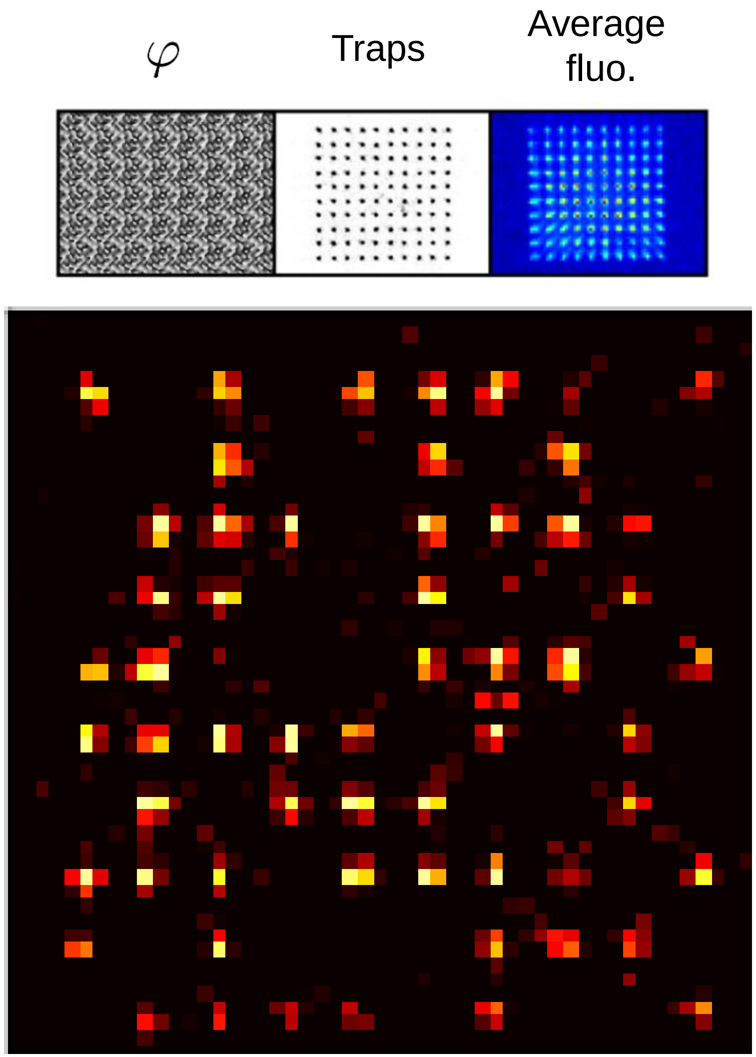




Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

Arrays of single atoms

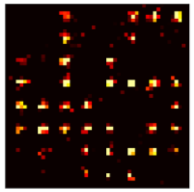




Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

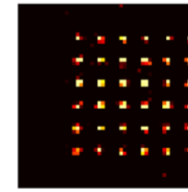
Atom-by-atom assembly

Load 2*N* traps with ~ *N* atoms ➡ Initial image ➡ Compute moves ➡ Move atoms with 2d AOD ➡ Check image

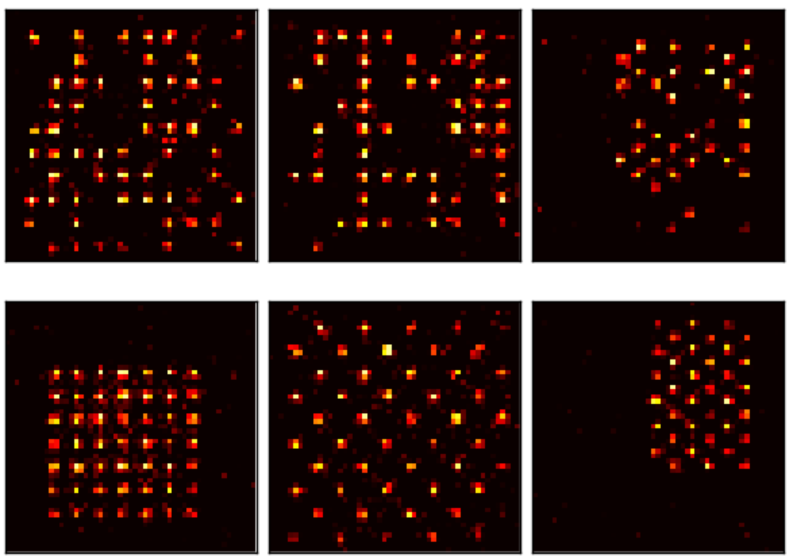


< 1 ms

~1 ms
per move



Total assembly time ~ 50 ms



- Fully loaded arrays up to 50 atoms
- 98% filling fraction
- Rep. rate up to ~ 4 Hz

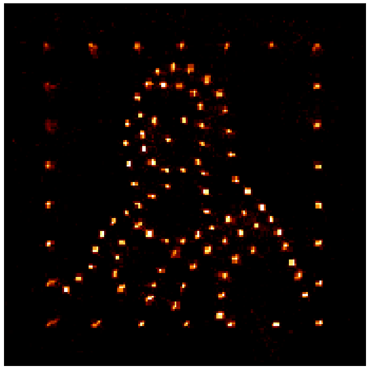
Barredo *et al.*, Science **354**, 1021 (2016)

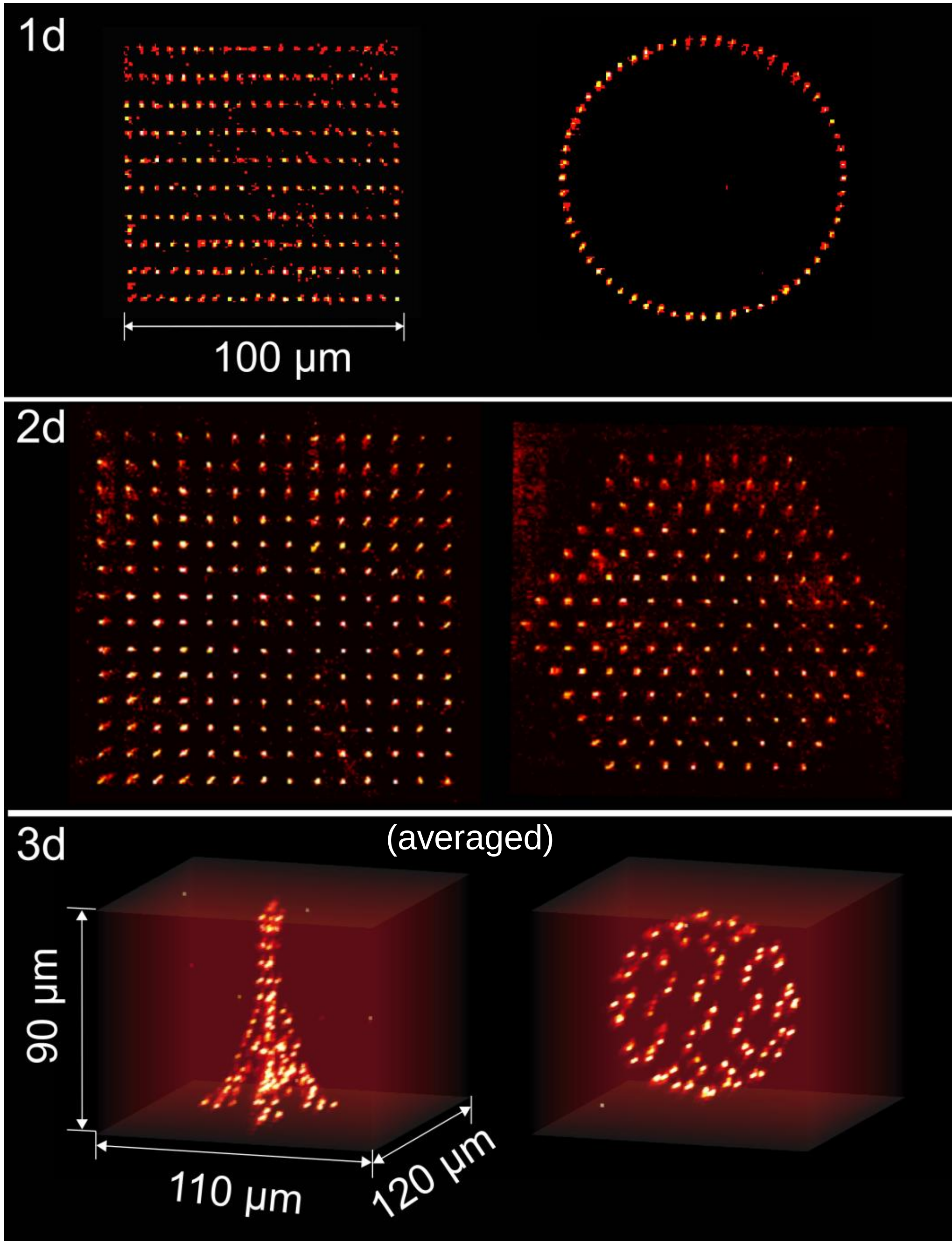
See also:
Endres *et al.*, Science **354**, 1024 (2016)
Kim *et al.*, Nature Comm. **7**, 13317 (2016)

Flexible geometries

New assembler algorithms:

Schymik *et al*., PRA **102**, 063107 (2020)



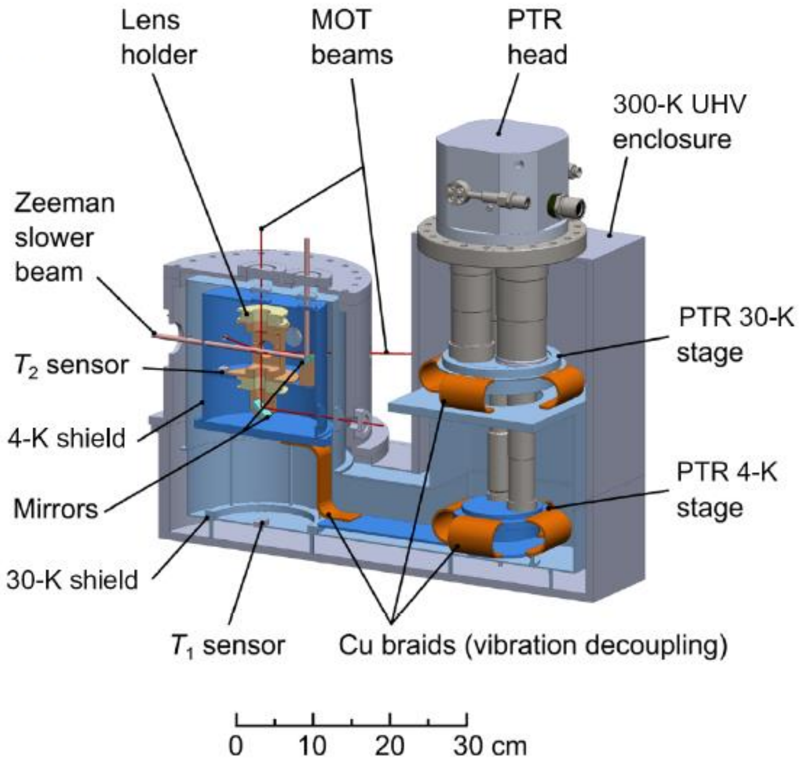


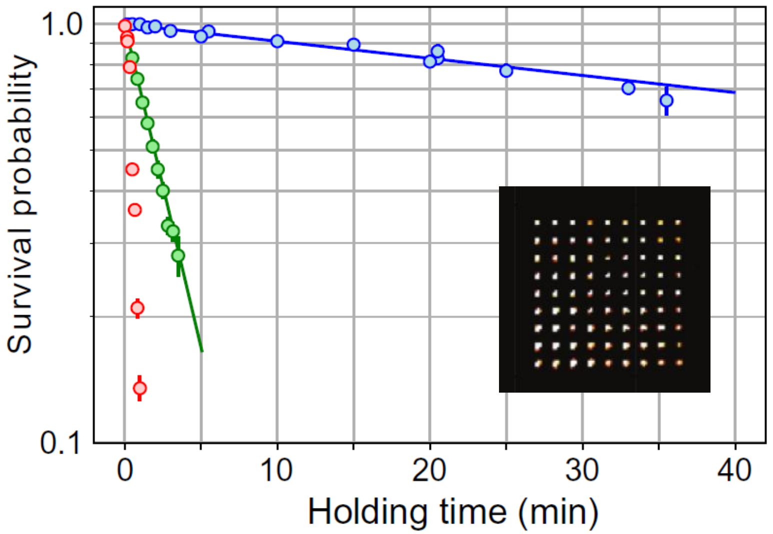
For N = 100 atoms:

Filling fraction > 99 %

Probability of defect free shots ~ 40 %

A cryogenic setup

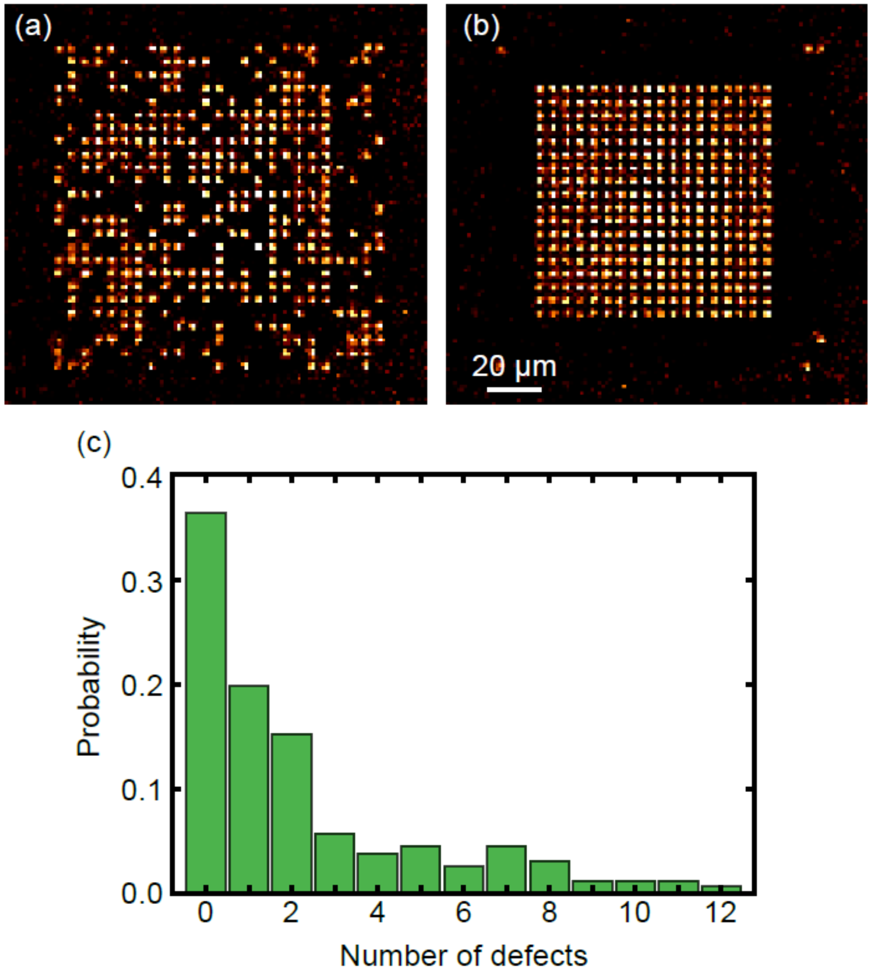




Trapping lifetime > 6000 s !

K.N. Schymik *et al*, Phys. Rev. Applied **16** 034013 (2021)

Defect-free arrays with 324 atoms!



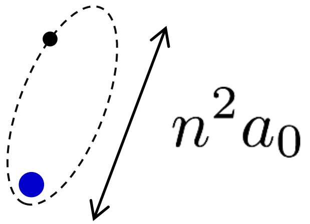
- New procedure to optimize trap loading
- Main limitation: field of view of objectives

K.-N. Schymik *et al.*, Phys. Rev. A **106**, 022611 (2022).

Rydberg atoms

Large principal quantum number: $n \gg 1$

$n \sim 50 - 100$



Exaggerated properties:

Electric dipole $\langle nS| \, d \, |nP\rangle \sim n^2$

Lifetime $\tau \sim n^3$ (100s of μs)

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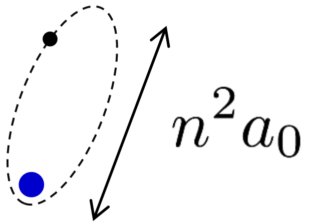

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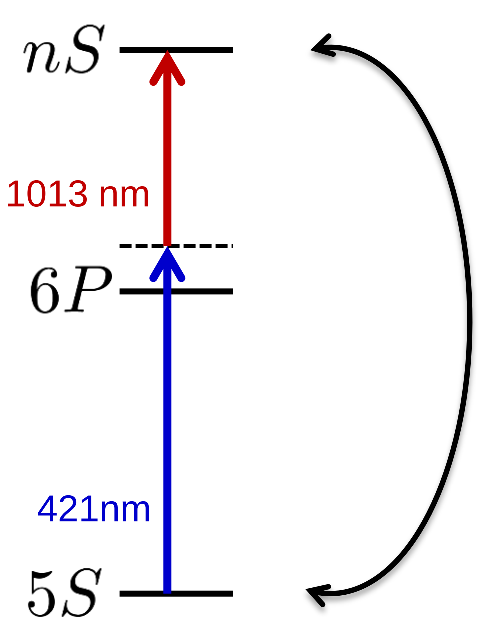
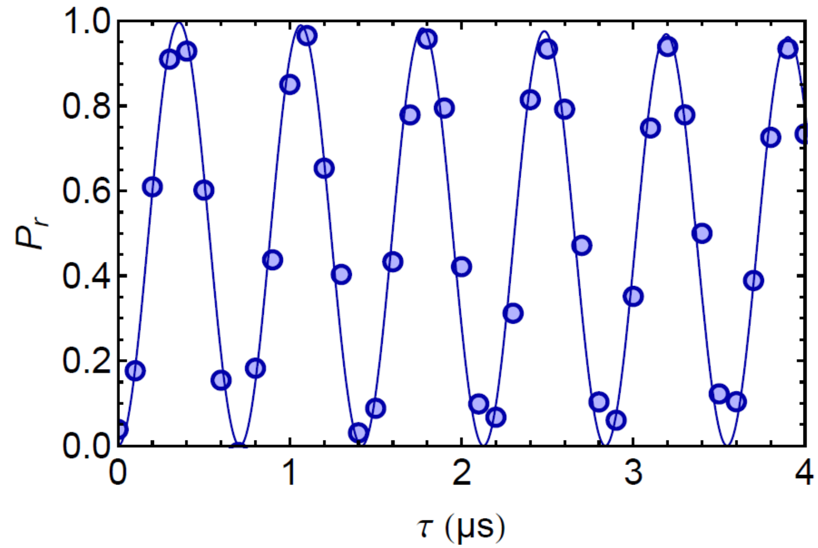


5S – *nS* Rabi oscillations



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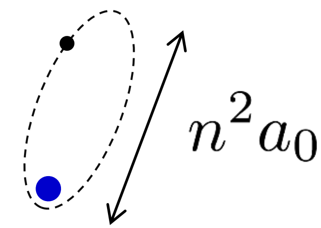

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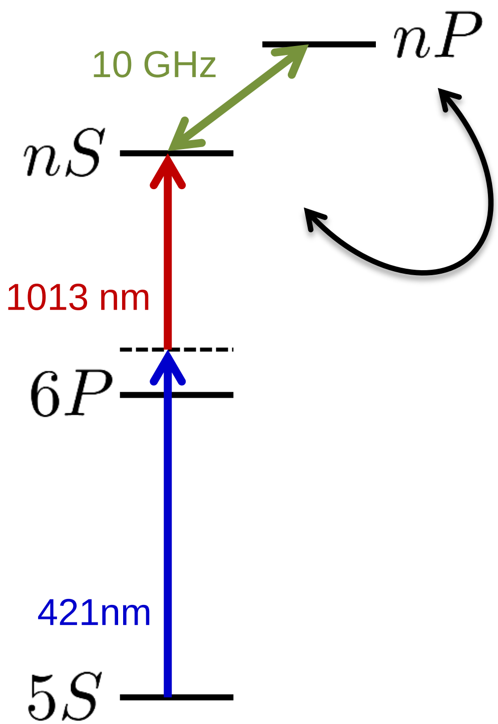

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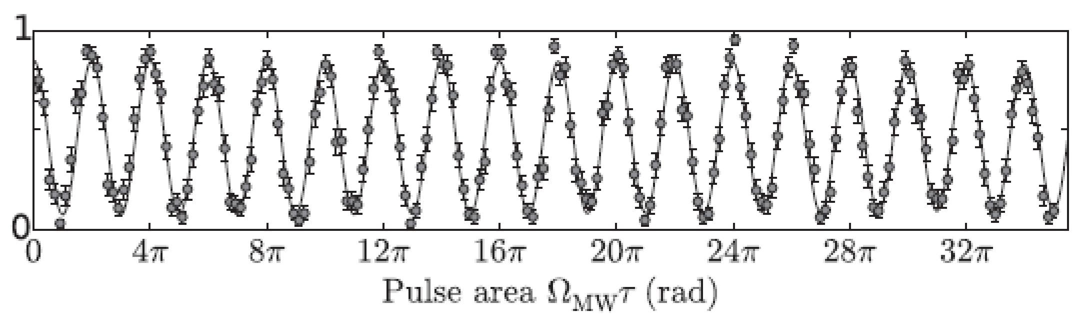
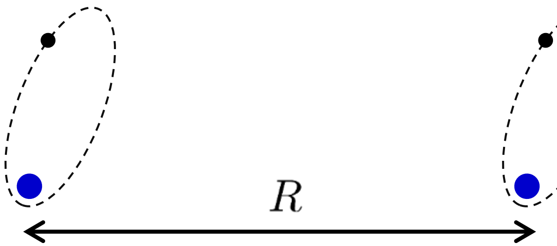
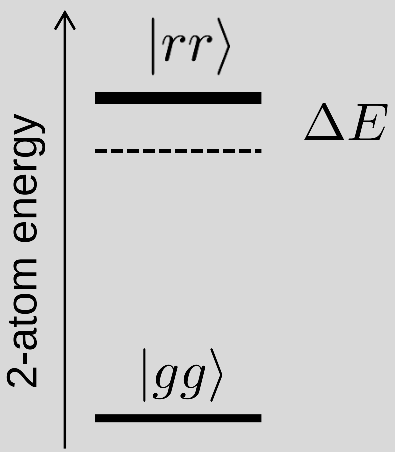


Interactions between Rydberg states



$$\hat{V}_{\mathrm{ddi}} = \frac{1}{4\pi\varepsilon_0}\frac{\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{d}}_2 - 3(\hat{\boldsymbol{d}}_1\cdot\hat{\boldsymbol{n}})(\hat{\boldsymbol{d}}_2\cdot\hat{\boldsymbol{n}})}{R^3}$$

van der Waals

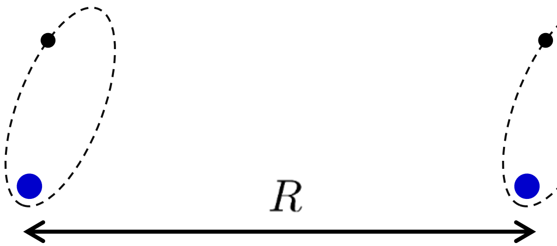


$$\Delta E \sim \frac{C_6}{R^6}$$

$$\left\{\begin{array}{l} |g\rangle \rightarrow |{\downarrow}\rangle \\ |r\rangle \rightarrow |{\uparrow}\rangle \end{array}\right.$$

Ising-like interaction

Interactions between Rydberg states



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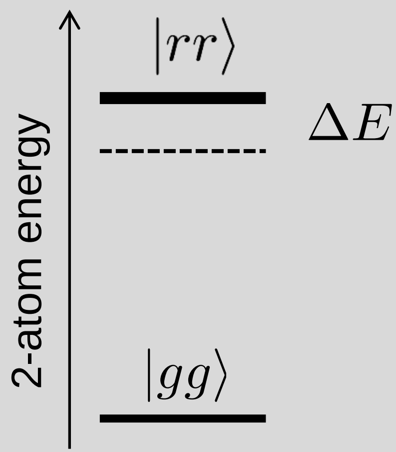
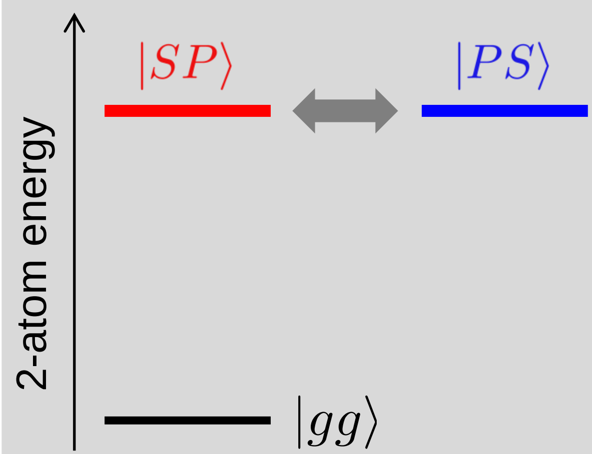


$$\Delta E \sim \frac{C_6}{R^6}$$

$$\begin{cases} |g\rangle \rightarrow |\downarrow\rangle \\ |r\rangle \rightarrow |\uparrow\rangle \end{cases}$$

Ising-like interaction

Resonant DDI



$$V \sim \frac{C_3}{R^3}$$

$$\begin{cases} |S\rangle \rightarrow |\downarrow\rangle \\ |P\rangle \rightarrow |\uparrow\rangle \end{cases}$$

XY interaction (flip-flop)

2. Quantum simulation of the Ising model

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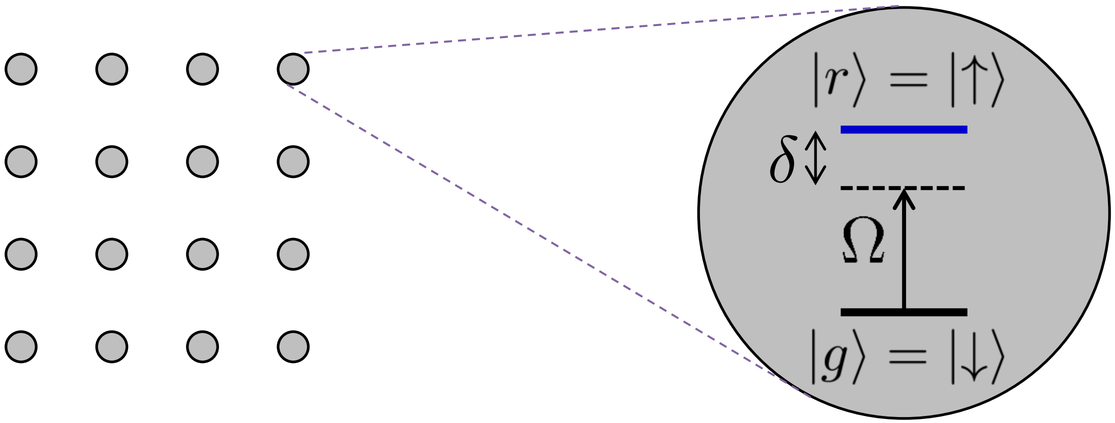
Theory support: Andreas Läuchli (Innsbruck, now PSI)

van der Waals interaction: Ising model

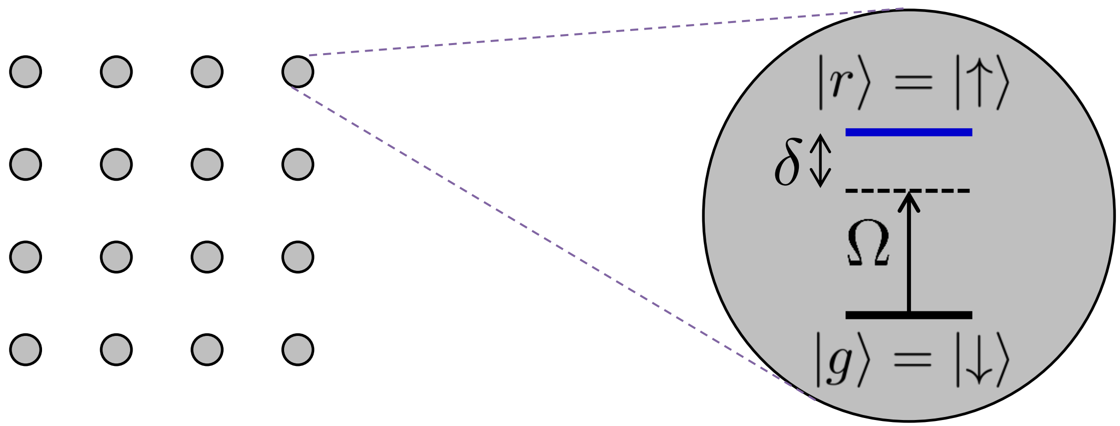


$$n^i = |r_i\rangle \langle r_i|$$

$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Rabi frequency   Laser detuning   van der Waals interactions

van der Waals interaction: Ising model



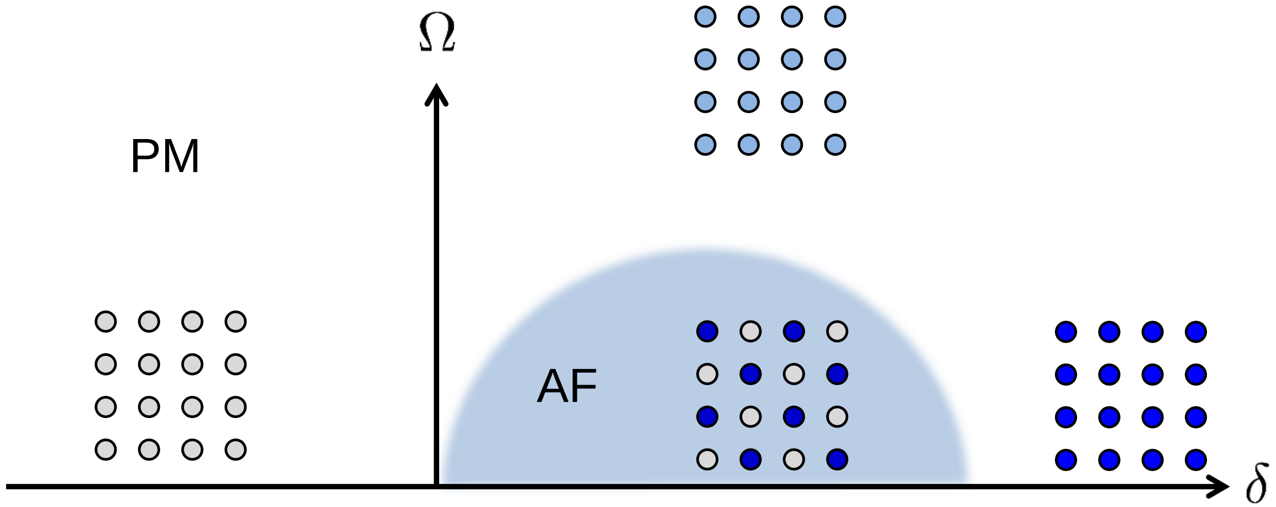
$$n^i = |r_i\rangle\langle r_i| = \left(1 + \sigma_z^i\right)/2$$

$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Transverse B   Longitudinal B   Ising couplings

Ising model: adiabatic preparation

Ising AF phase diagram



Ising model: adiabatic preparation

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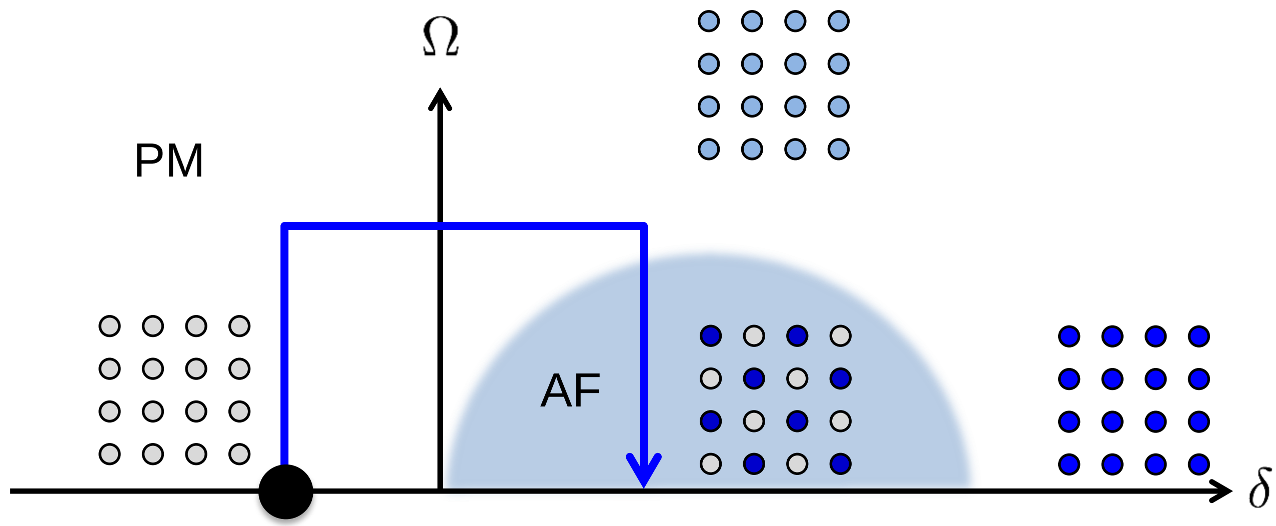
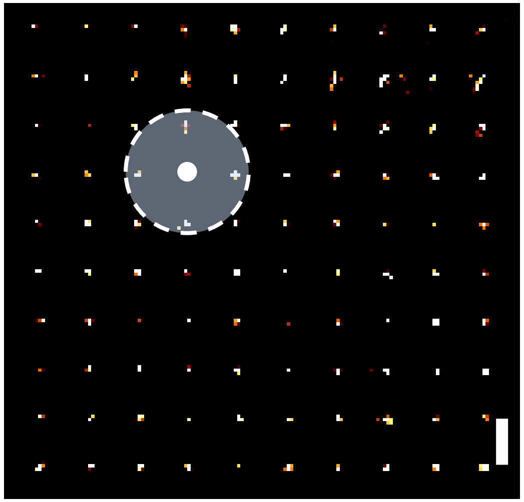


$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Vary slowly Rabi frequency and detuning
to explore the phase diagram

Adiabatic preparation of 2D Ising AF

10×10 square array



a=10 µm

1D: Pohl **PRL** 2010; Bloch **Science** 2015; Lukin **Nature** 2017, 2019;
2D: Lienhard **PRX** 2018, Bakr **PRX** 2018; Lukin **Nature** 2021

Adiabatic preparation of 2D Ising AF

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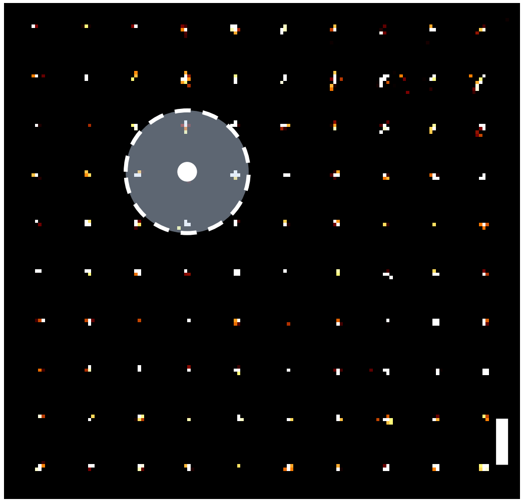
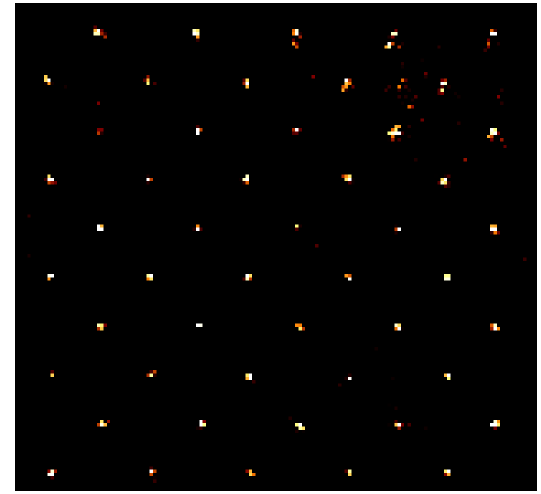


a=10 µm

sweep

n=75S

Perfect AF (Néel) ordering!



Missing atoms = Rydberg

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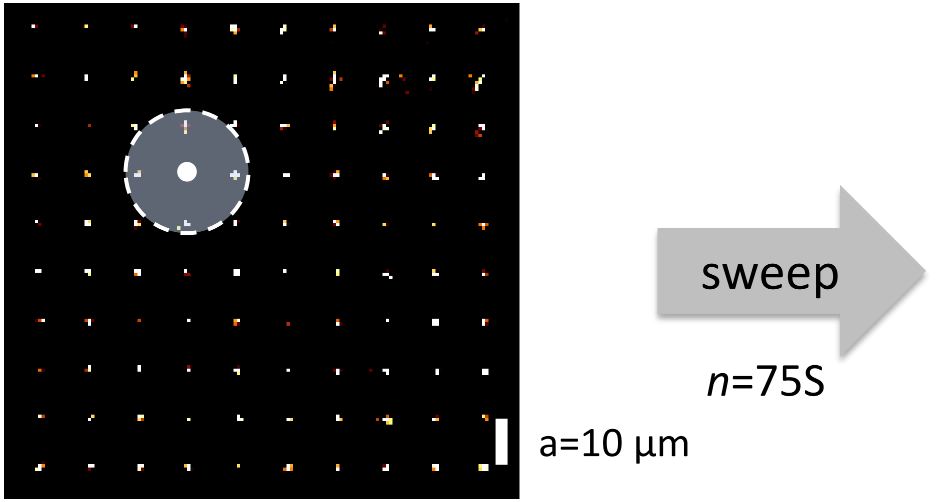
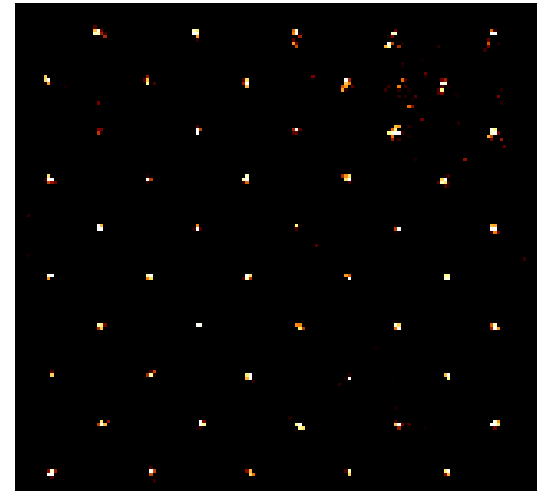
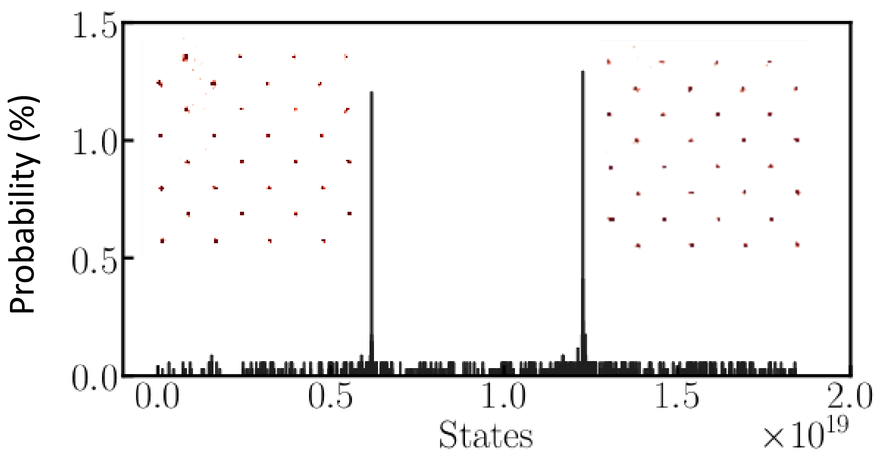




Missing atoms = Rydberg

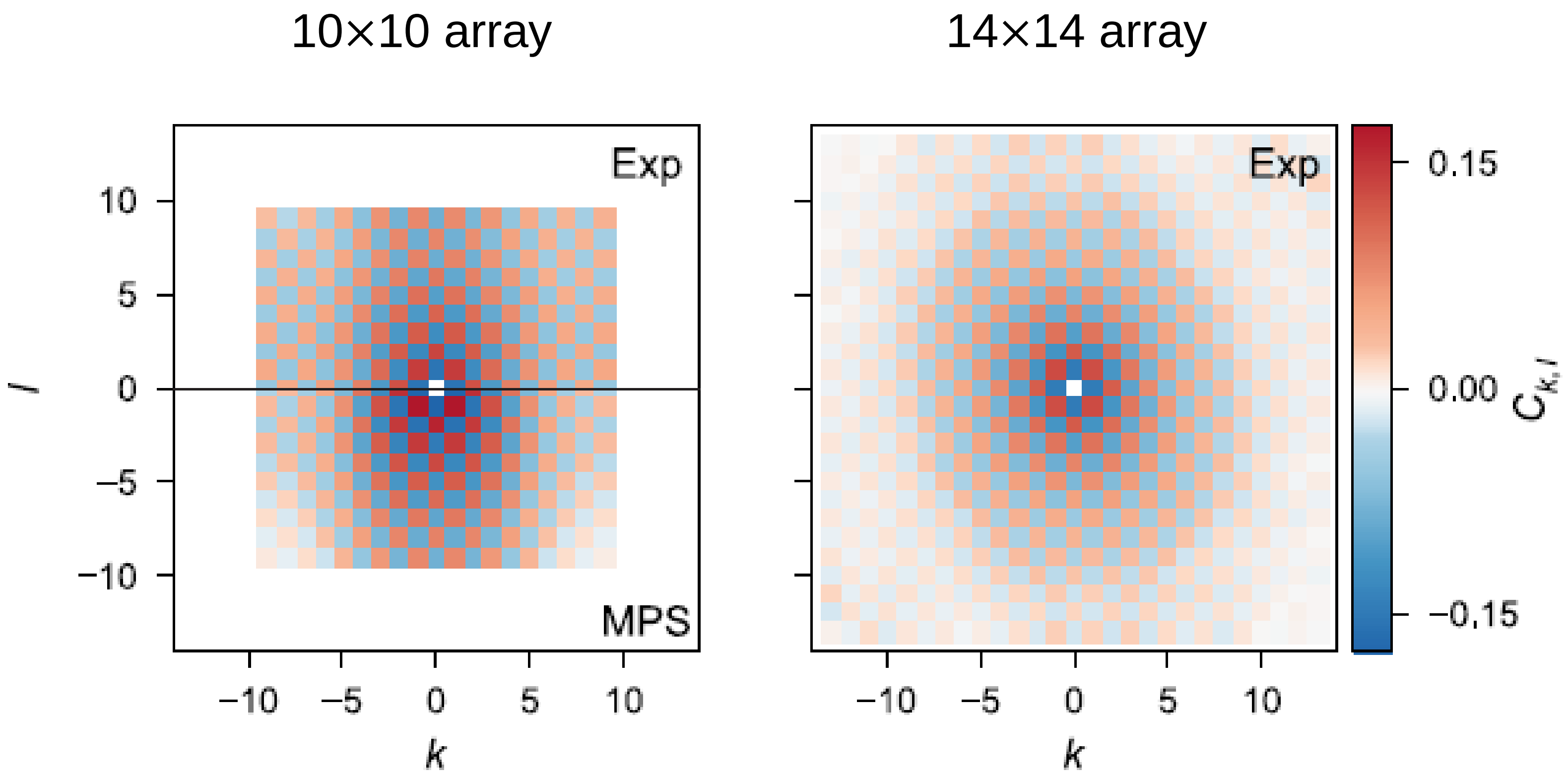
(8x8)



1D: Pohl **PRL** 2010; Bloch **Science** 2015; Lukin **Nature** 2017, 2019;
2D: Lienhard **PRX** 2018, Bakr **PRX** 2018; Lukin **Nature** 2021

Correlation functions

$$C_{k,l} = \frac{1}{N_{k,l}} \sum_{i,j} \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle$$



P. Scholl *et al.*, Nature **595**, 233 (2021).

3. Quantum simulation of XY models

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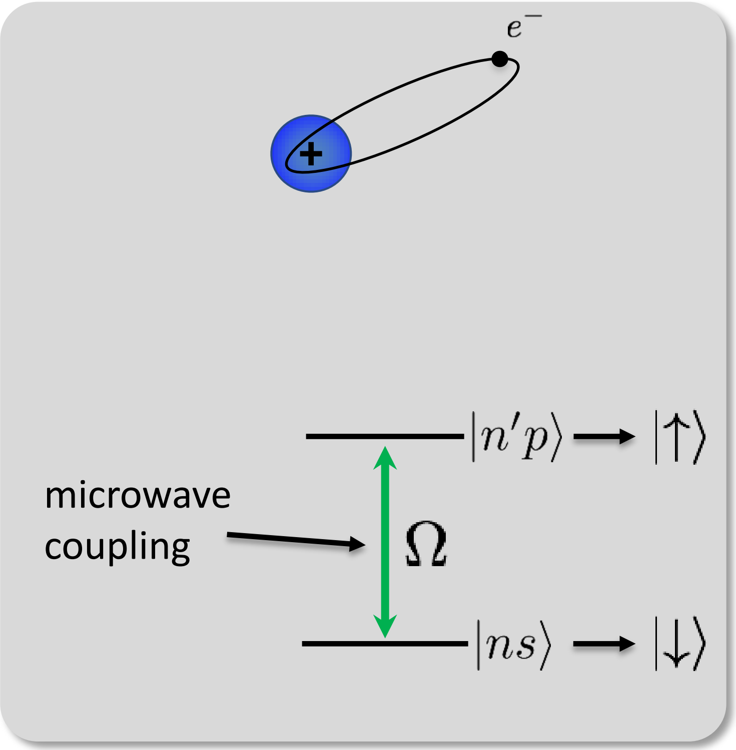
Theory support: Norm Yao (Berkeley)

Resonant dipole-dipole interaction



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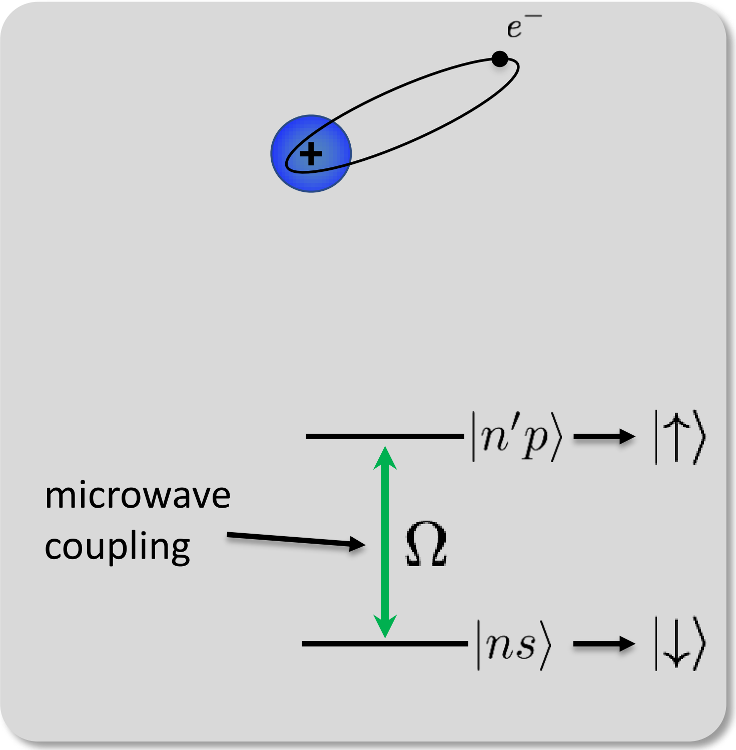
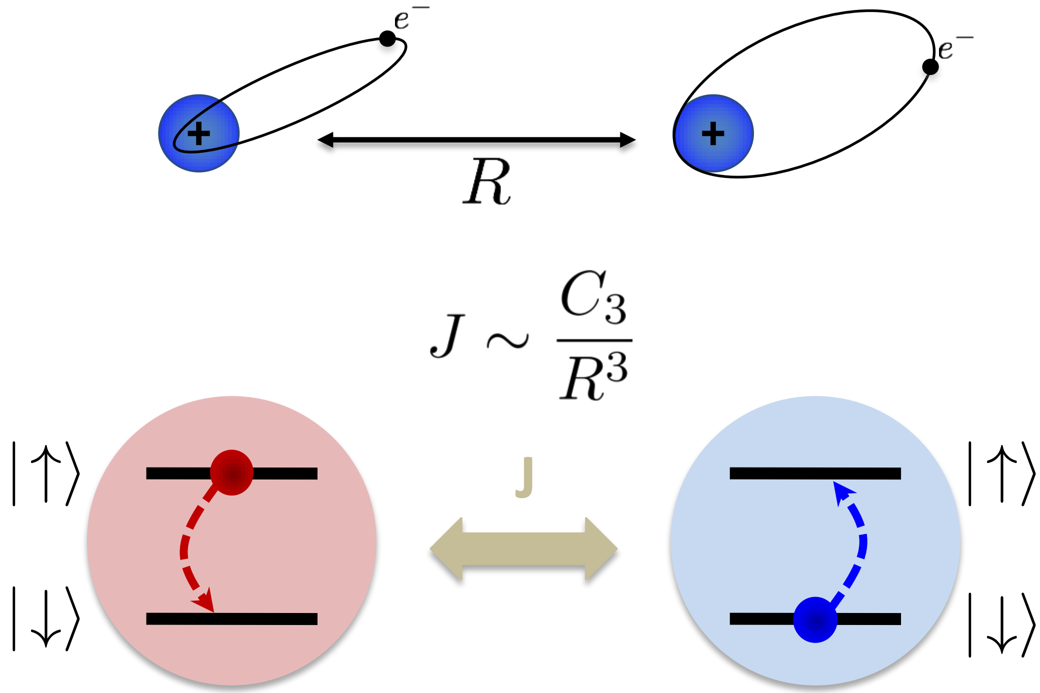
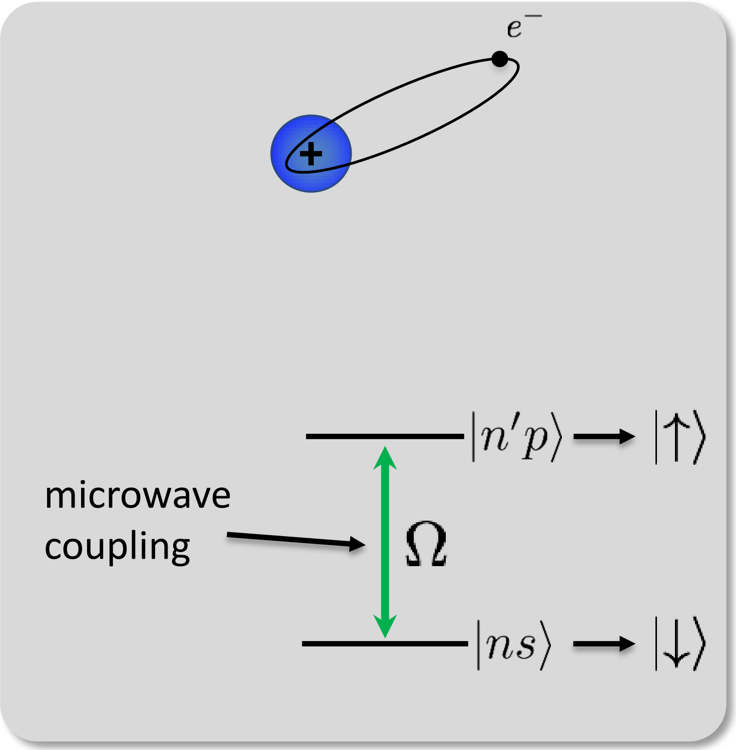


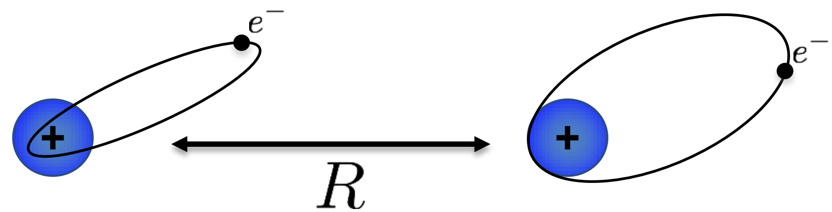


XY model:

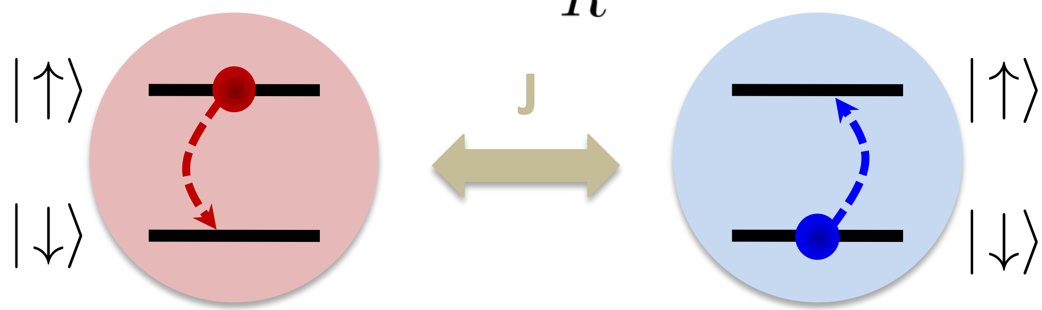
$$H = \sum_{i \neq j} \frac{C_3}{R_{ij}^3} (\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j)$$

Resonant dipole-dipole interaction





$$J \sim \frac{C_3}{R^3}$$



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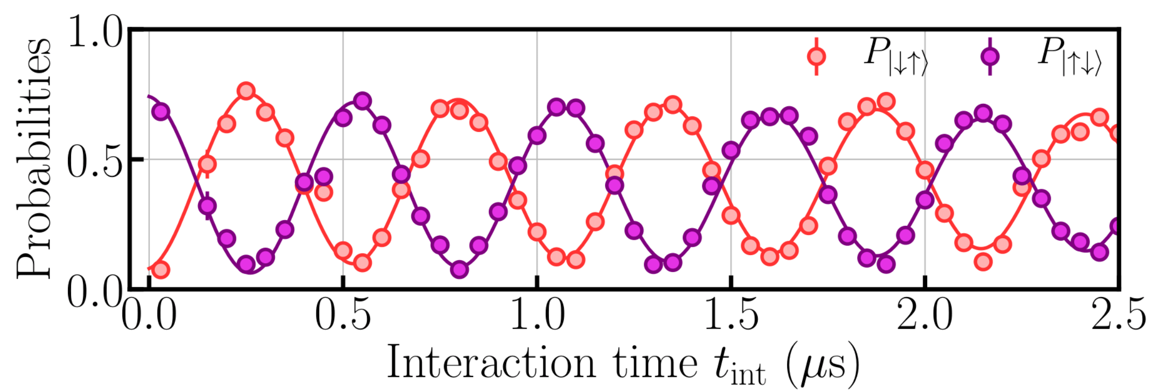
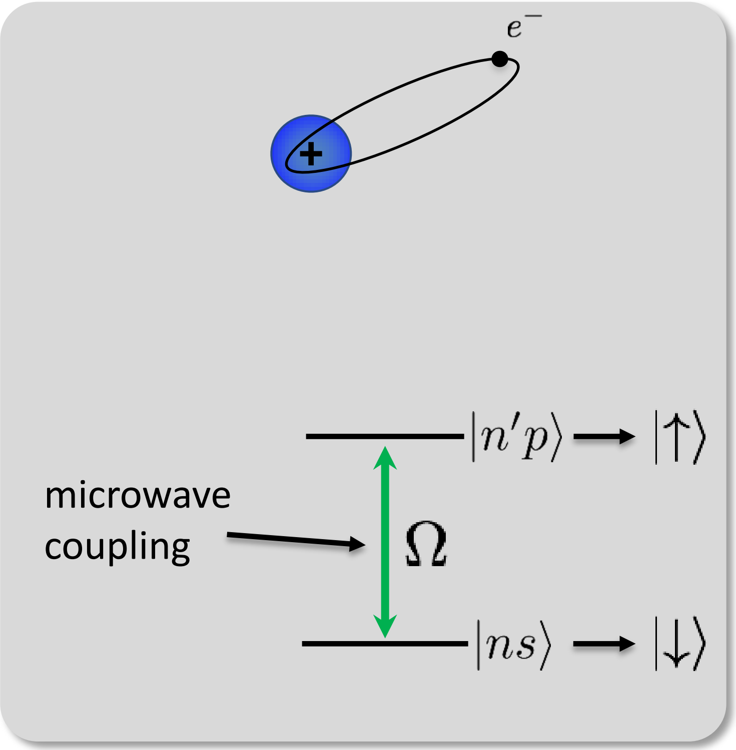
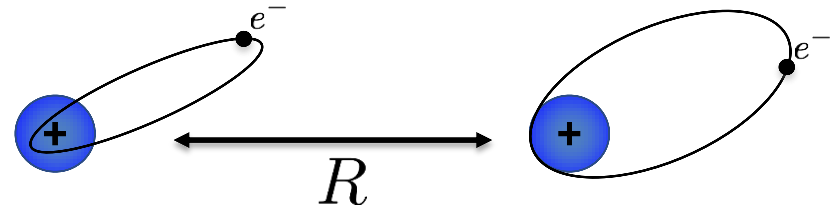


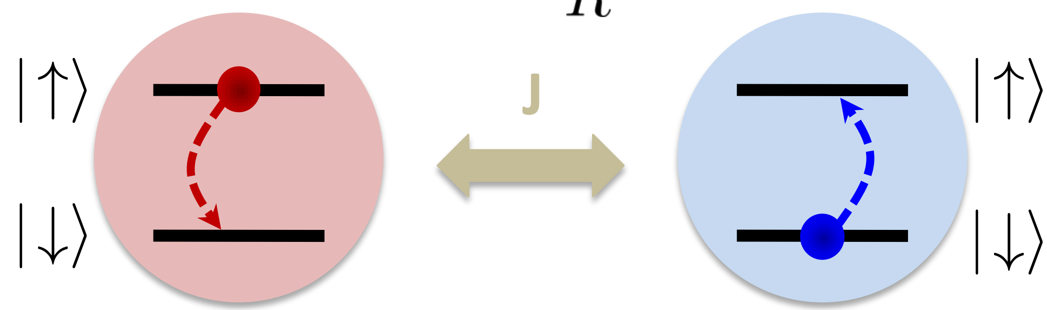
Barredo *et al.*, PRL, **124**, 023201 (2020)

Resonant dipole-dipole interaction





$$J \sim \frac{C_3}{R^3}$$



Studies conducted using the resonant dipole-dipole interaction:

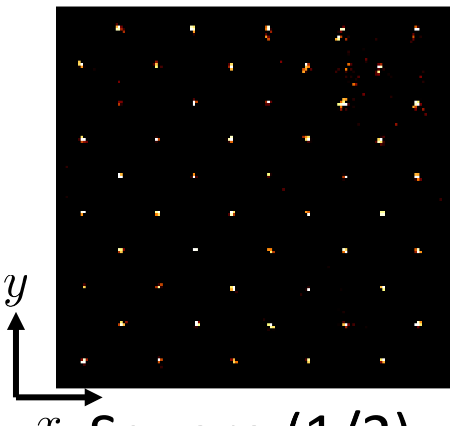
- Preparation of a many-body topological phase — de Léséleuc *et al.*, Science **365**, 775 (2019)
- Implementation of a density-dependent Peierls phase — Lienhard *et al.*, PRX **10**, 021031 (2020)
- Floquet engineering of XXZ Hamiltonians — Scholl *et al.*, PRX Quantum **3**, 02303 (2022)

Ising vs. XY model

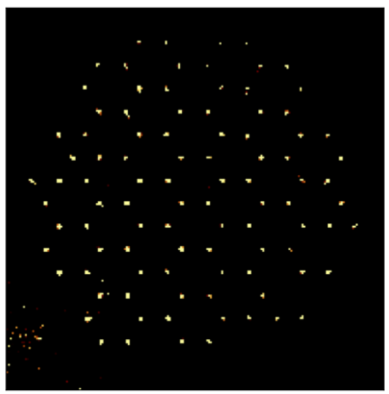
Ising model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

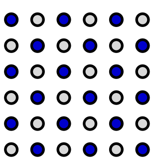
Antiferro $J_{ij} < 0$



Square (1/2)



Triangle (1/3)



$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$
$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$
$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

Ground state (1/2, 1/3…) =
classical Néel configurations

Ising vs. XY model

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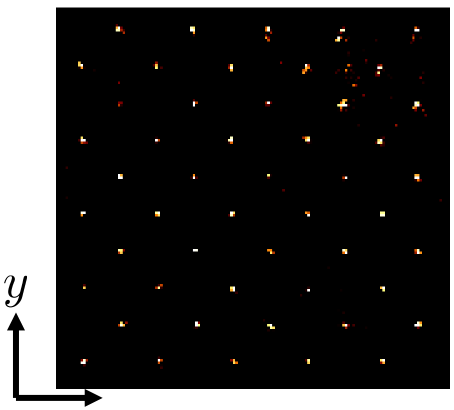
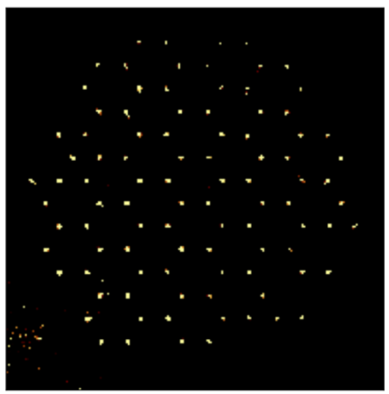
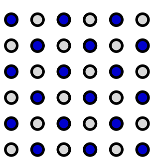


Square (1/2)



Triangle (1/3)



$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$

$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

Ground state (1/2, 1/3…) =
classical Néel configurations

XY model

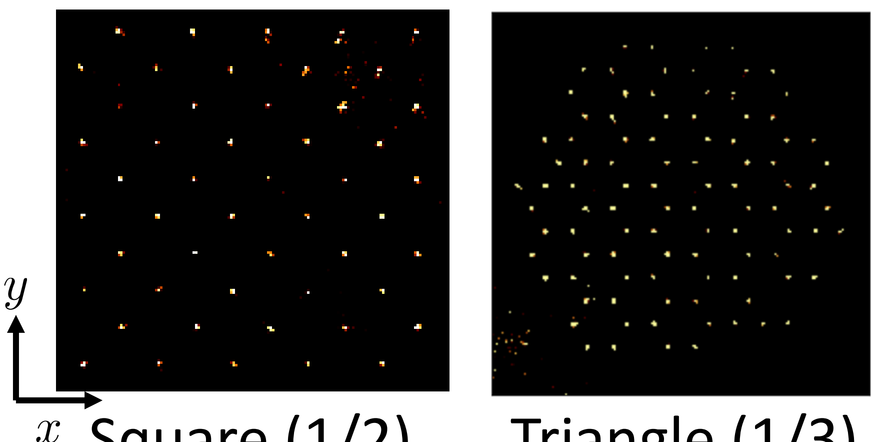
$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

Ising vs. XY model

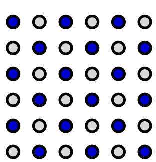
Ising model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

Antiferro $J_{ij} < 0$



Square (1/2) Triangle (1/3)



$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$

$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

Ground state (1/2, 1/3…) =
classical Néel configurations

XY model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

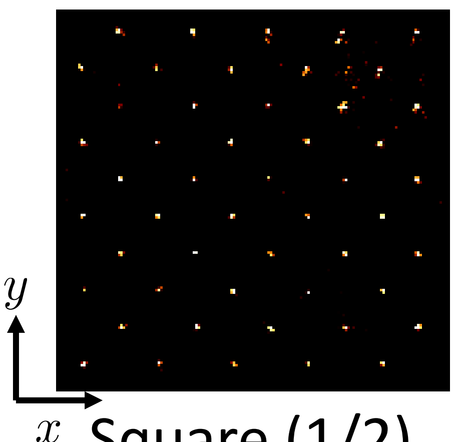
Competing order along *x* / along *y*

Ising vs. XY model

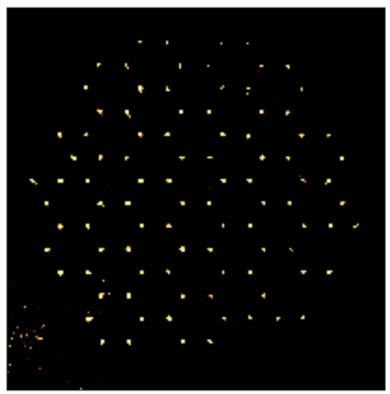
Ising model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

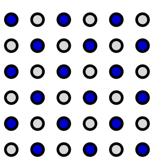
Antiferro $J_{ij} < 0$



Square (1/2)



Triangle (1/3)



$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$

$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

Ground state (1/2, 1/3…) =
classical Néel configurations

XY model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

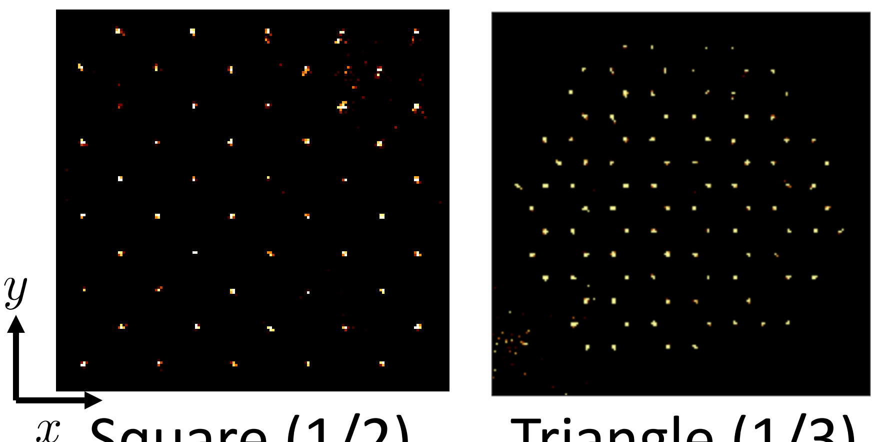
$$= \sum_{\langle i,j \rangle} \frac{J_{ij}}{2} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

Ising vs. XY model

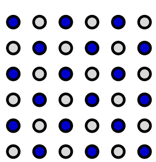
Ising model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

Antiferro $J_{ij} < 0$



Square (1/2) Triangle (1/3)



$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$

$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

Ground state (1/2, 1/3…) =
classical Néel configurations

XY model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

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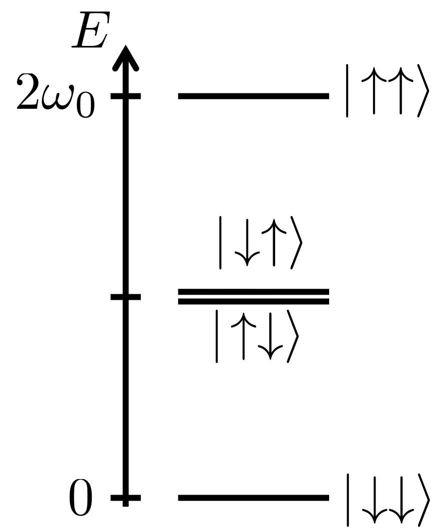
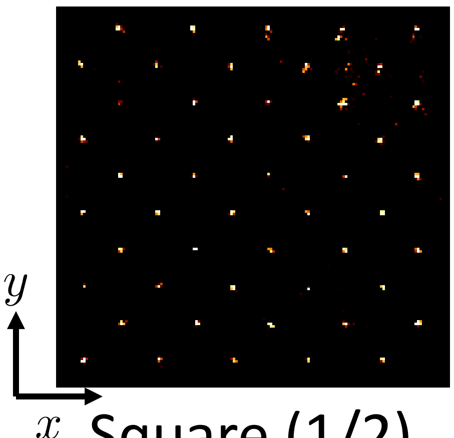


Ising vs. XY model

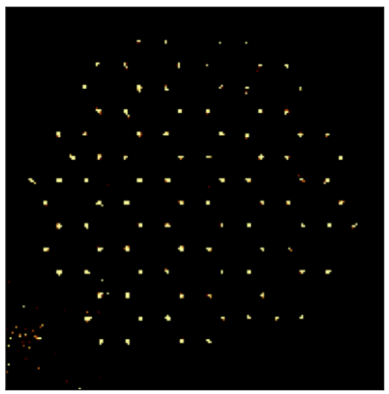
Ising model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

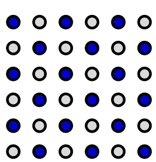
Antiferro $J_{ij} < 0$



Square (1/2)



Triangle (1/3)



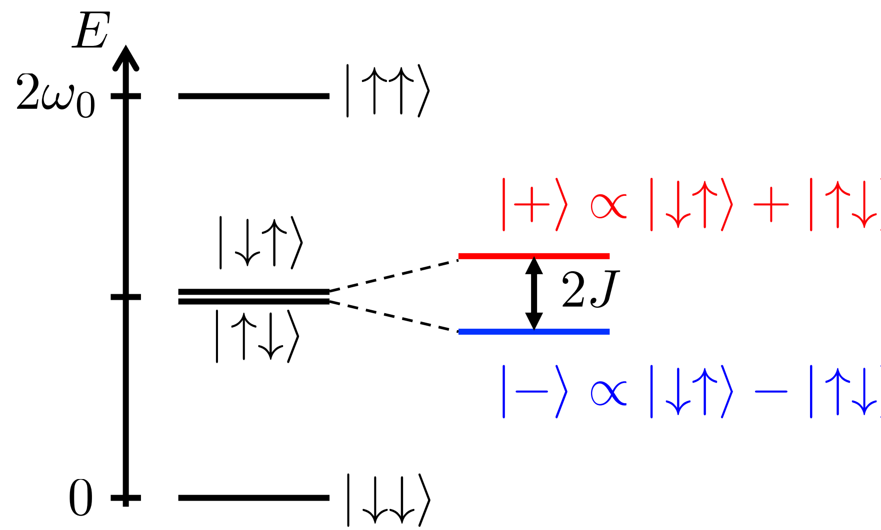
$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$
$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$
$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

Ground state (1/2, 1/3…) =
classical Néel configurations

XY model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

$$= \sum_{\langle i,j \rangle} \frac{J_{ij}}{2} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

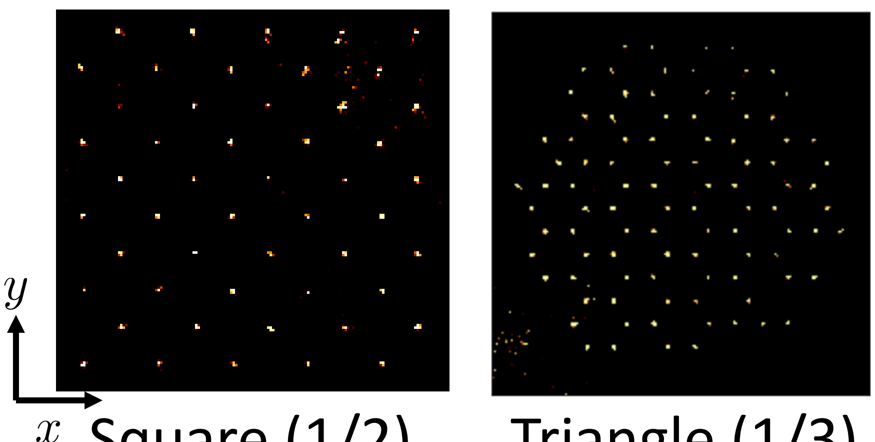


Ising vs. XY model

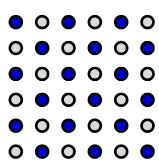
Ising model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

Antiferro $J_{ij} < 0$



Square (1/2)   Triangle (1/3)



$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$

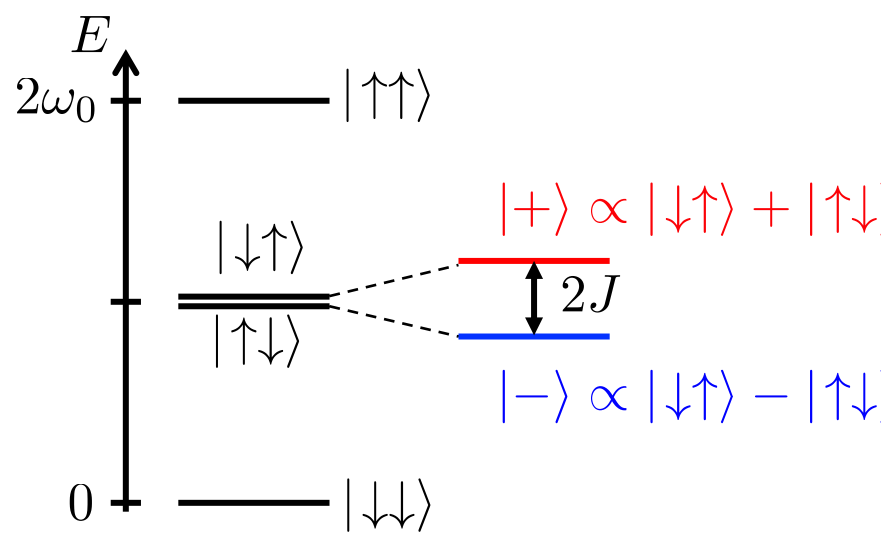
$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

Ground state (1/2, 1/3…) =
classical Néel configurations

XY model

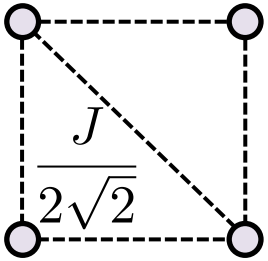
$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

$$= \sum_{\langle i,j \rangle} \frac{J_{ij}}{2} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$



Ground state (1/2) =
non-classical entangled state

XY on square lattice (1/2 filling)

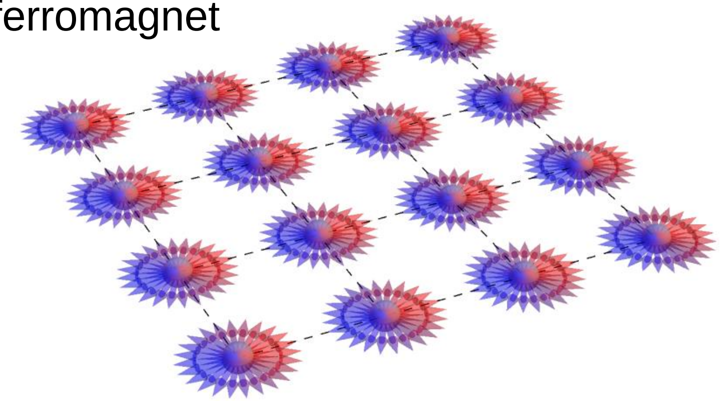


Ansätze wavefunctions

continuous $U(1)$ symmetry

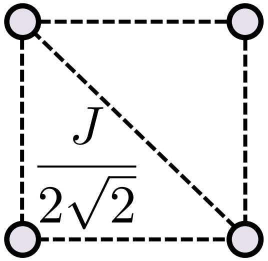
$M^z = \sum_i \sigma_i^z$ conserved

XY ferromagnet



$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}}$$

XY on square lattice (1/2 filling)



Ansätze wavefunctions

continuous $U(1)$ symmetry

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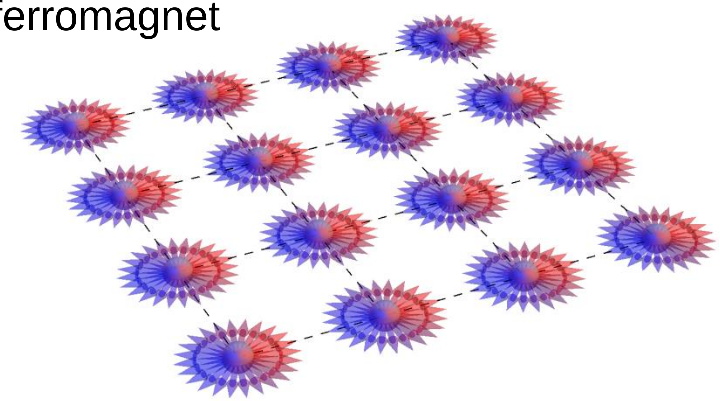
XY ferromagnet



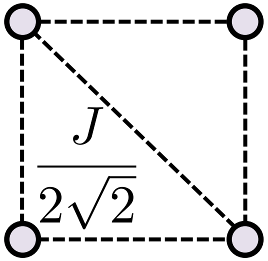
$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}}$$

Expect: $\langle \hat{X} \rangle = 0$

$$\langle \hat{X}\hat{X} \rangle_{NN}^{F} > 0$$

$$\langle \hat{X}\hat{X} \rangle_{NNN}^{F} > 0$$

XY on square lattice (1/2 filling)

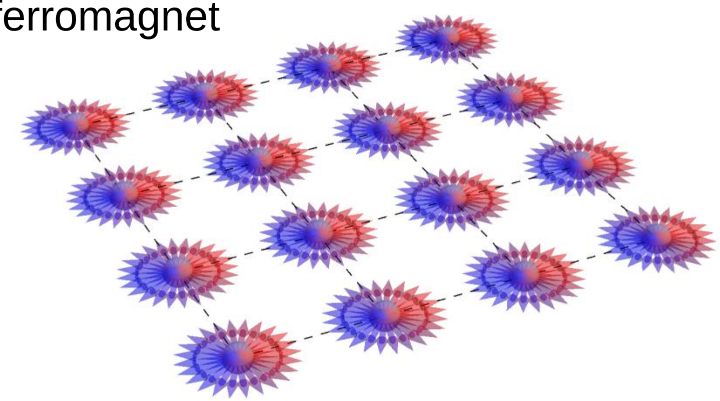


Ansätze wavefunctions

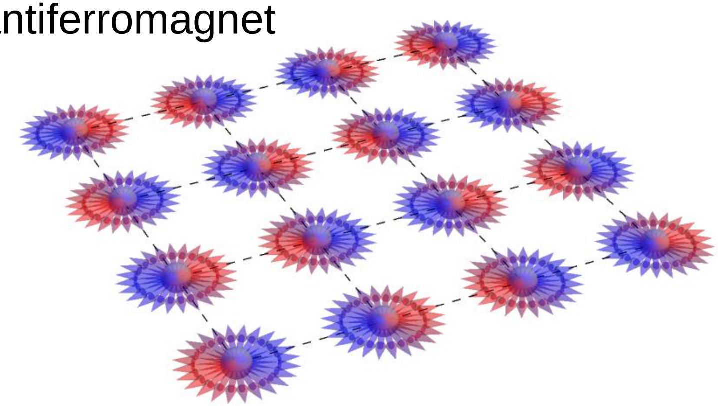
continuous $U(1)$ symmetry

$M^z = \sum_i \sigma_i^z$ conserved

XY ferromagnet



XY antiferromagnet



$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}}$$

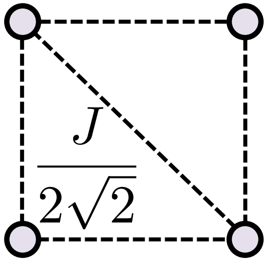
$$|\mathrm{AFM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{AFM}\rangle_{\mathrm{X}}$$

Expect: $\langle \hat{X} \rangle = 0$

$$\langle \hat{X}\hat{X} \rangle^F_{NN} > 0$$

$$\langle \hat{X}\hat{X} \rangle^F_{NNN} > 0$$

XY on square lattice (1/2 filling)

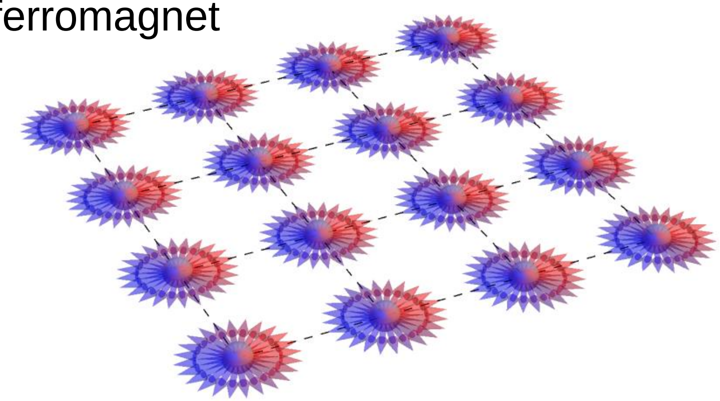


Ansätze wavefunctions

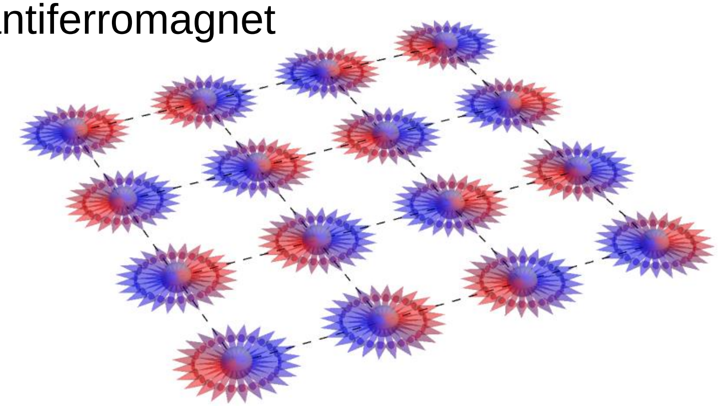
continuous $U(1)$ symmetry

$M^z = \sum_i \sigma_i^z$ conserved

XY ferromagnet



XY antiferromagnet



$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}}$$

$$|\mathrm{AFM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{AFM}\rangle_{\mathrm{X}}$$

Expect:

$$\langle \hat{X} \rangle = 0 \qquad \langle \hat{X} \rangle = 0$$

$$\langle \hat{X}\hat{X} \rangle^{F}_{NN} > 0 \qquad \langle \hat{X}\hat{X} \rangle^{AF}_{NN} < 0$$

$$\langle \hat{X}\hat{X} \rangle^{F}_{NNN} > 0 \qquad \langle \hat{X}\hat{X} \rangle^{AF}_{NNN} > 0$$

Preparing XY ferro- and antiferromagnets

Start from: $$H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3}(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \hbar \sum_i \delta_i \sigma_i^z$$

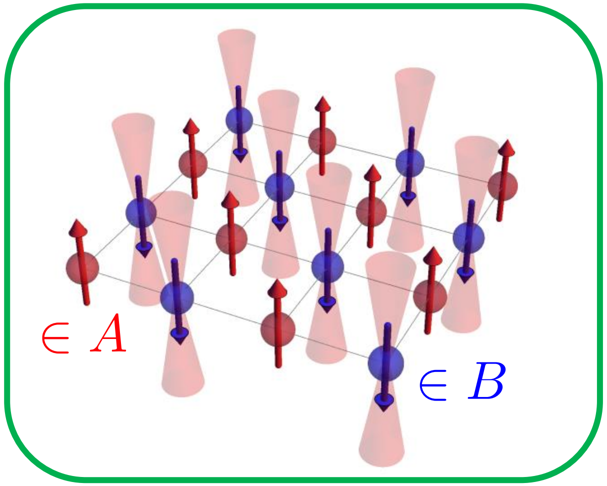
staggered

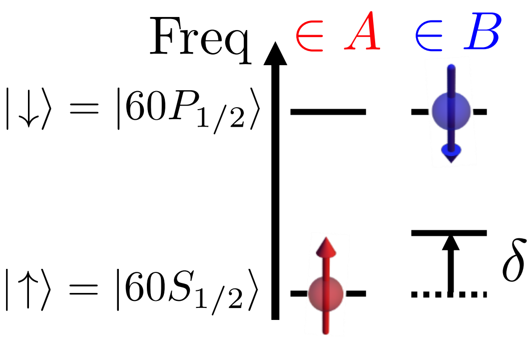
Preparing XY ferro- and antiferromagnets

Start from: $H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \hbar \sum_i \delta_i \sigma_i^z$

staggered

1. Prepare a classical Néel state along *z*: checkerboard pattern





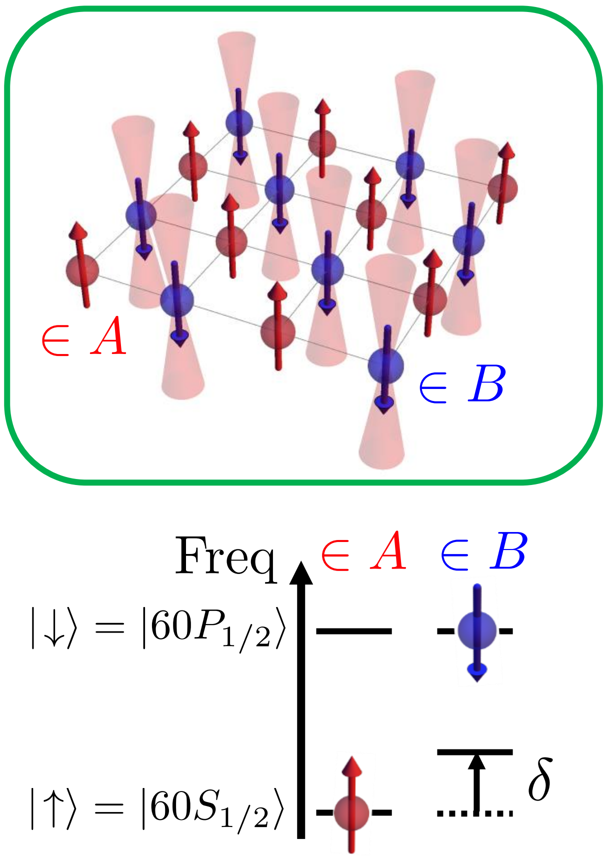
apply local light-shift
(2nd SLM)
+
microwaves

Sørensen *et al.*, PRA 81, 061603(R) (2010)

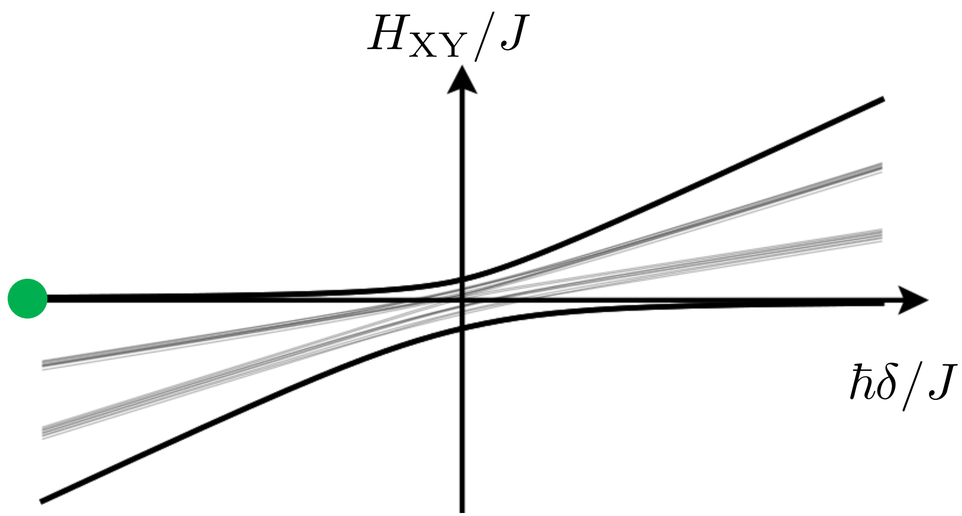
Preparing XY ferro- and antiferromagnets

Start from: $H_{\mathrm{XY}} = -J\sum_{i<j}\frac{a^3}{r_{ij}^3}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y) + \hbar\sum_i \delta_i\sigma_i^z$ staggered

2. Adiabatically decrease δ to "melt" into XY AF



Q. Phase transition

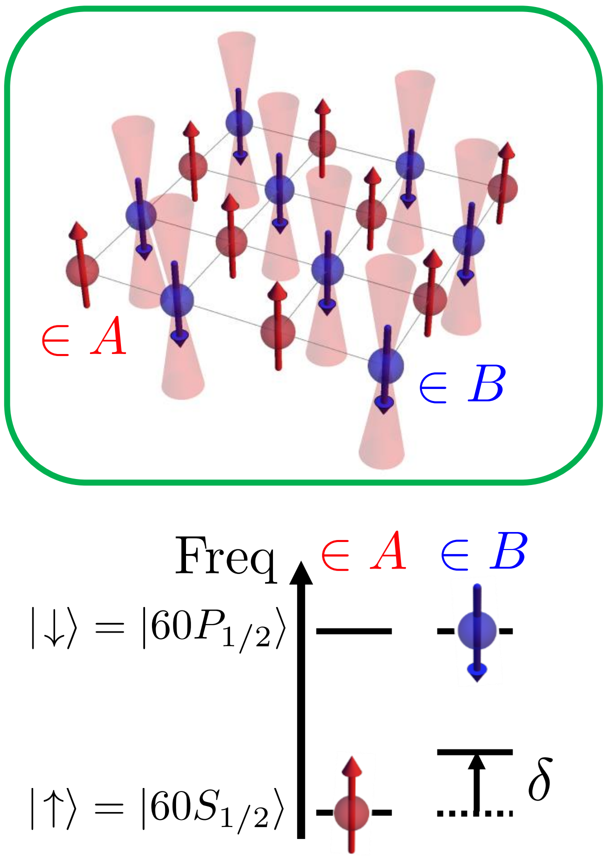


Sørensen *et al.*, PRA 81, 061603(R) (2010)

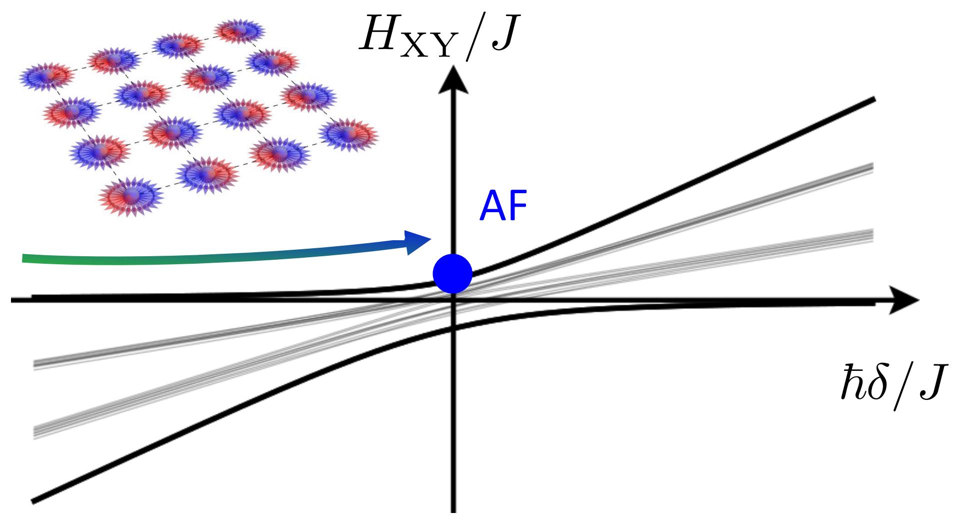
Preparing XY ferro- and antiferromagnets

Start from: $$H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \hbar \sum_i \delta_i \sigma_i^z$$ staggered

2. Adiabatically decrease δ to "melt" into XY AF



Q. Phase transition

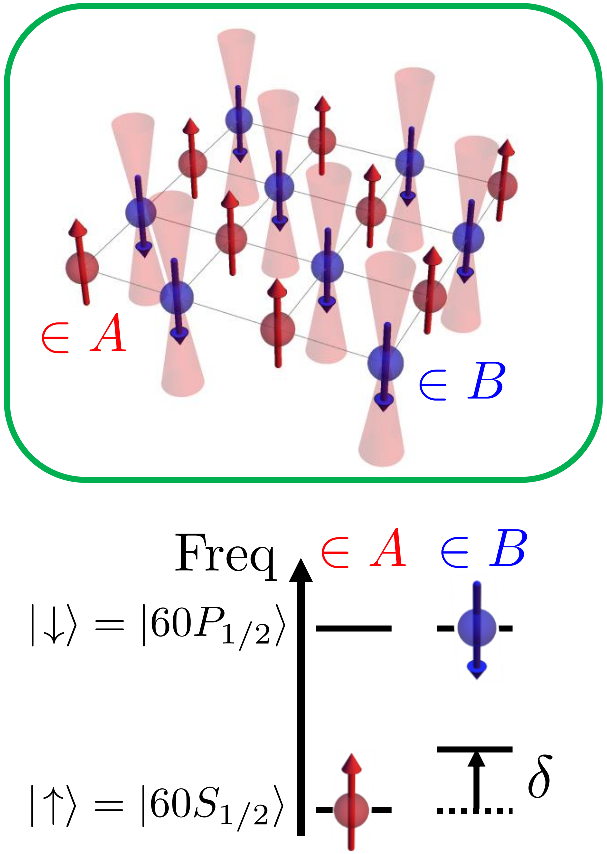


Sørensen *et al.*, PRA 81, 061603(R) (2010)

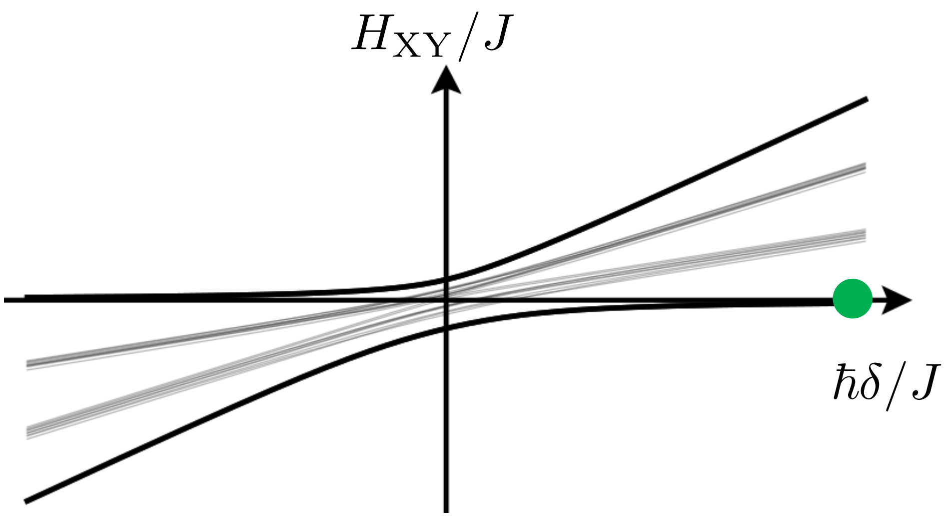
Preparing XY ferro- and antiferromagnets

Start from: $H_{\mathrm{XY}} = -J\sum_{i<j}\frac{a^3}{r_{ij}^3}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y) + \hbar\sum_i \delta_i\sigma_i^z$ staggered

2. Adiabatically decrease δ to “melt” into XY F



Q. Phase transition

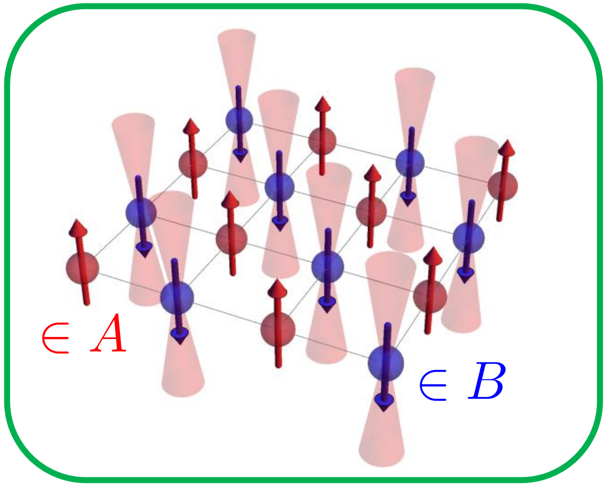


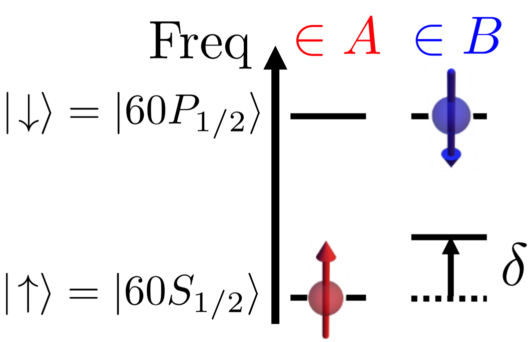
Sørensen *et al.*, PRA 81, 061603(R) (2010)

Preparing XY ferro- and antiferromagnets

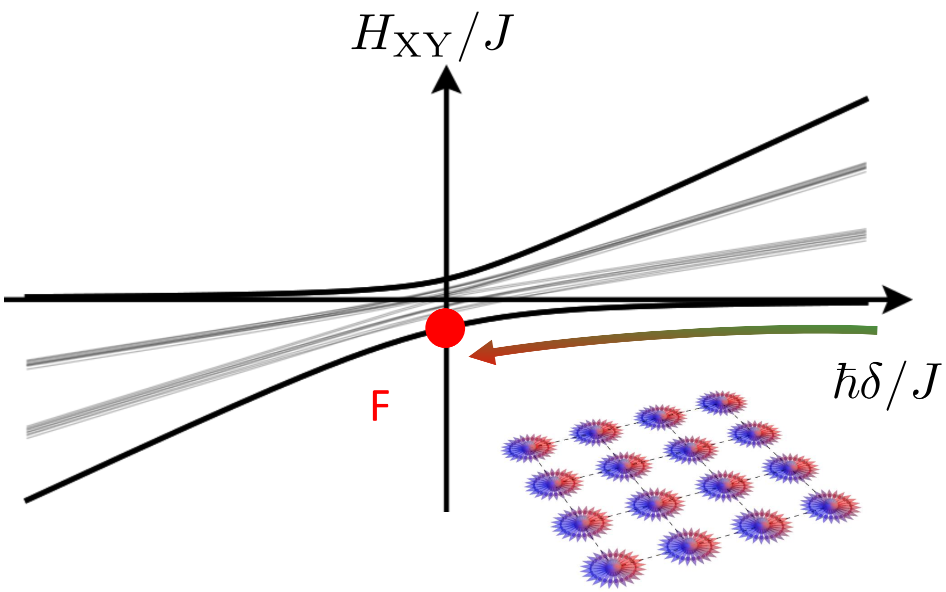
Start from: $H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3}(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \hbar \sum_i \delta_i \sigma_i^z$ staggered

2. Adiabatically decrease δ to "melt" into XY F





Q. Phase transition

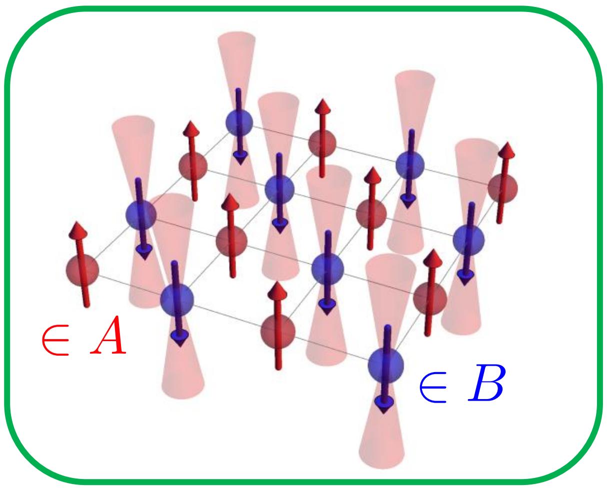


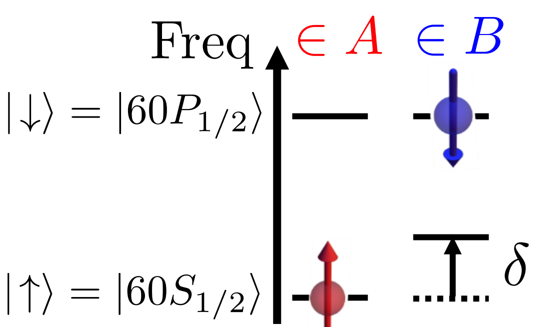
Sørensen *et al.*, PRA 81, 061603(R) (2010)

Preparing XY ferro- and antiferromagnets

Start from: $H_{\rm XY} = -J\sum_{i<j}\frac{a^3}{r_{ij}^3}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y) + \hbar\sum_i \delta_i\sigma_i^z$ staggered

2. Adiabatically decrease δ to "melt" into XY AF/F





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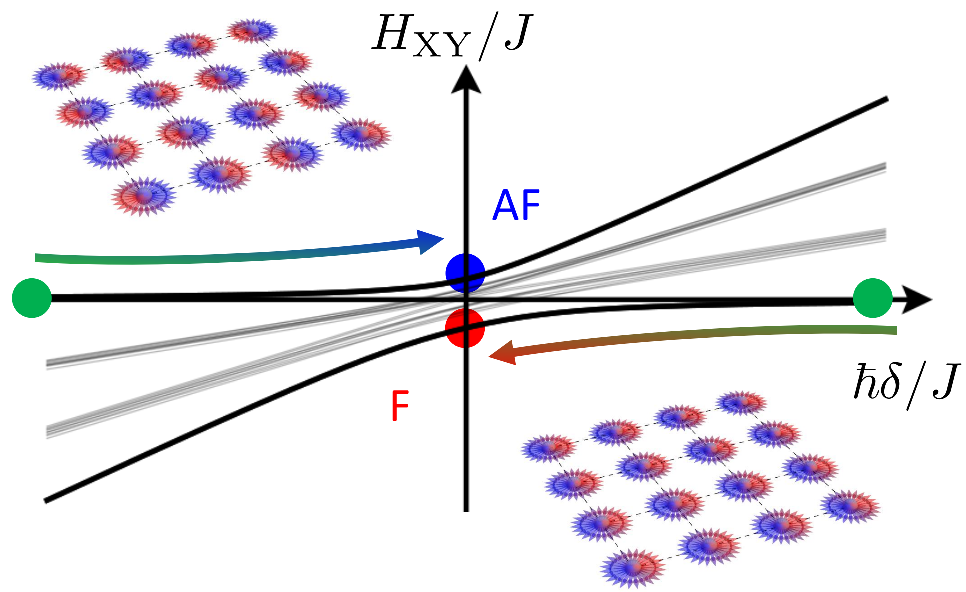
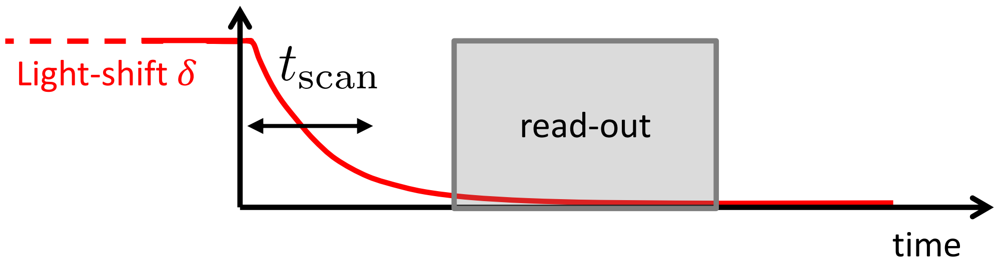


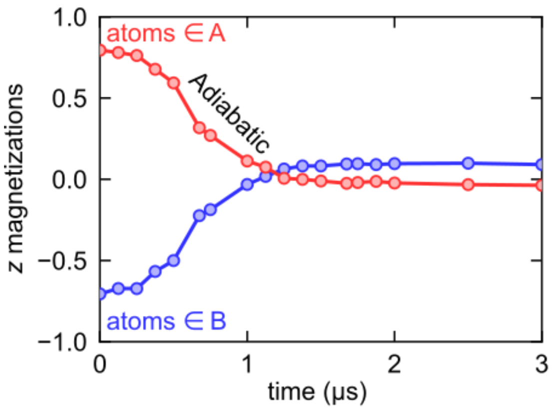
Sørensen *et al.*, PRA 81, 061603(R) (2010)

Preparing XY ferro- and antiferromagnets

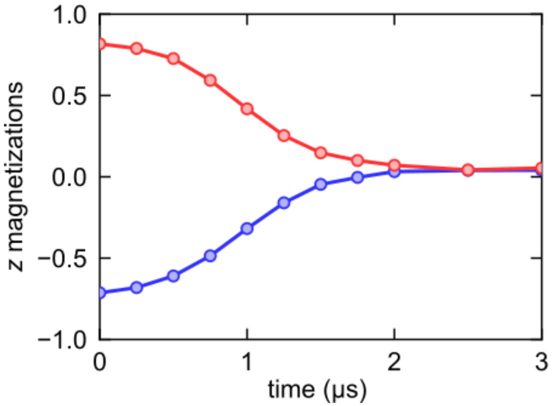


42 atoms

Ferromagnet

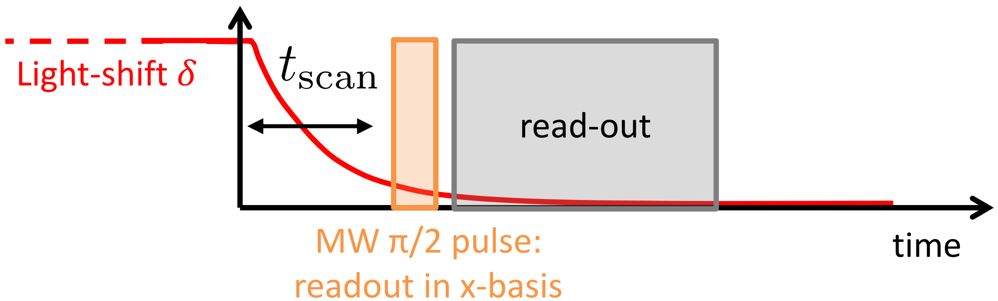


Antiferromagnet

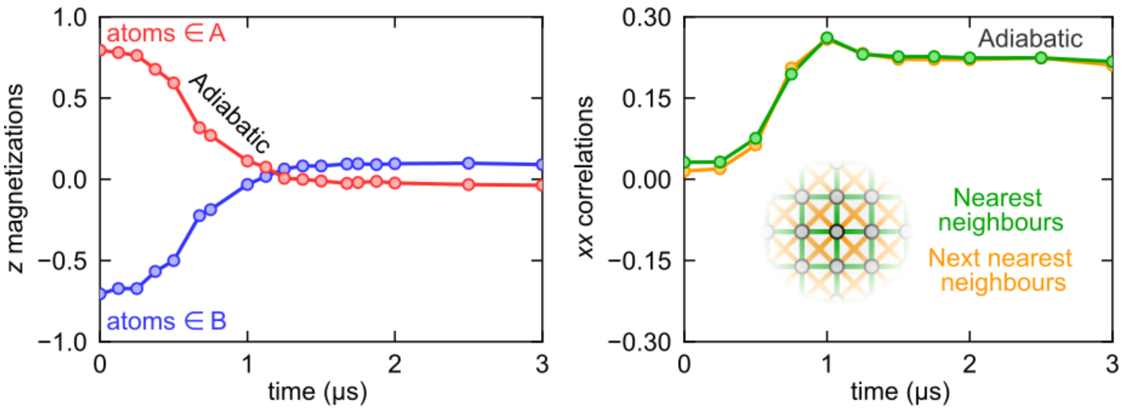


Preparing XY ferro- and antiferromagnets

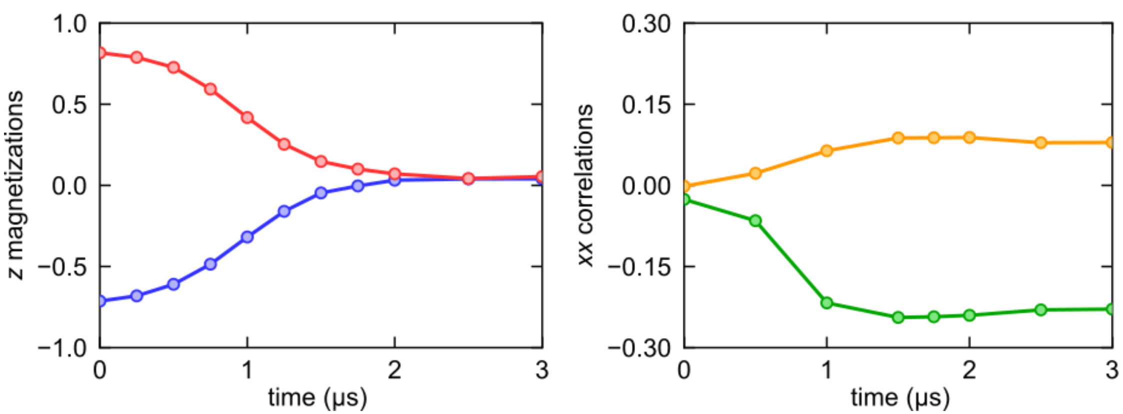
42 atoms



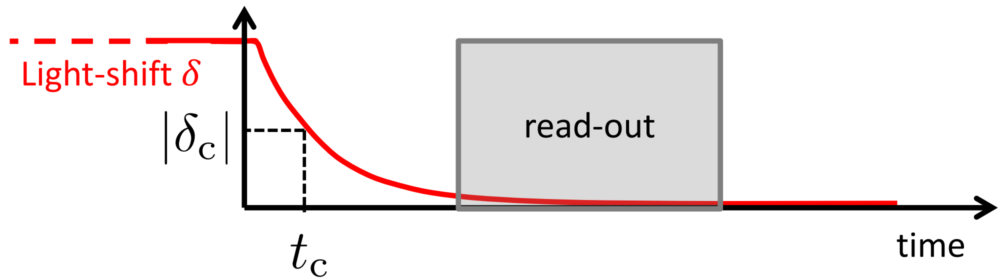
Ferromagnet



Antiferromagnet

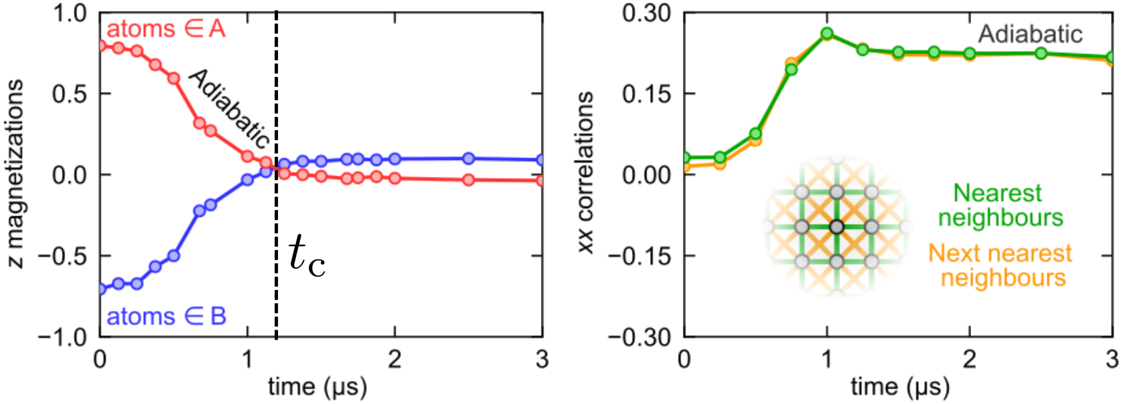


Preparing XY ferro- and antiferromagnets



42 atoms

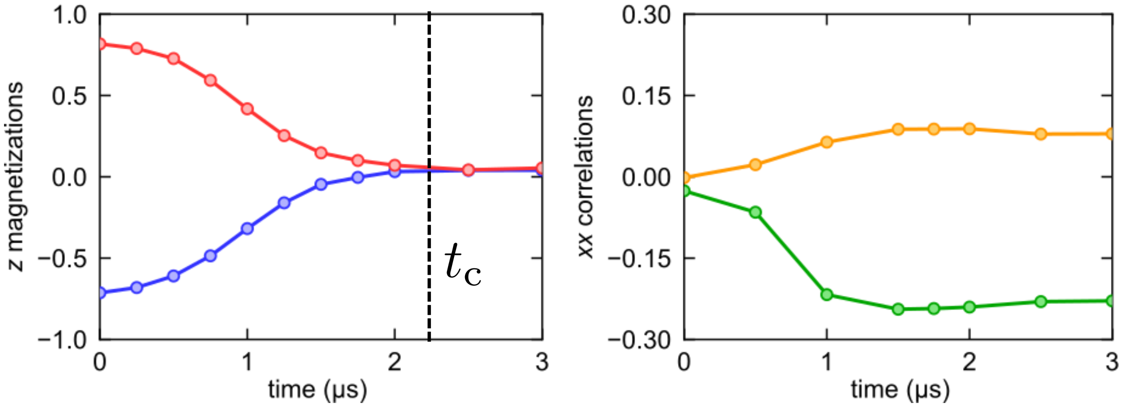
Ferromagnet



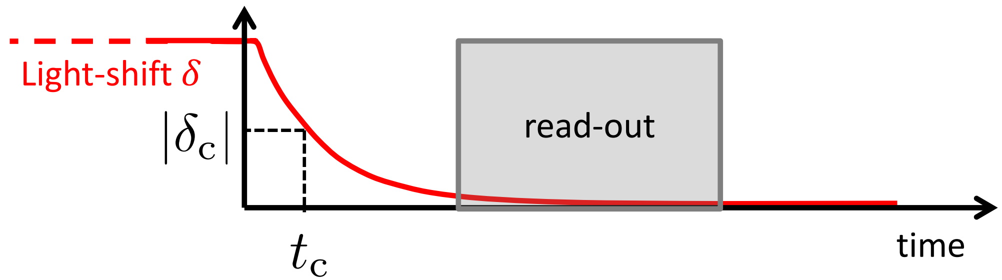
If only NN interactions:

$$|\delta_c^{AFM}| = |\delta_c^{FM}|$$

Antiferromagnet

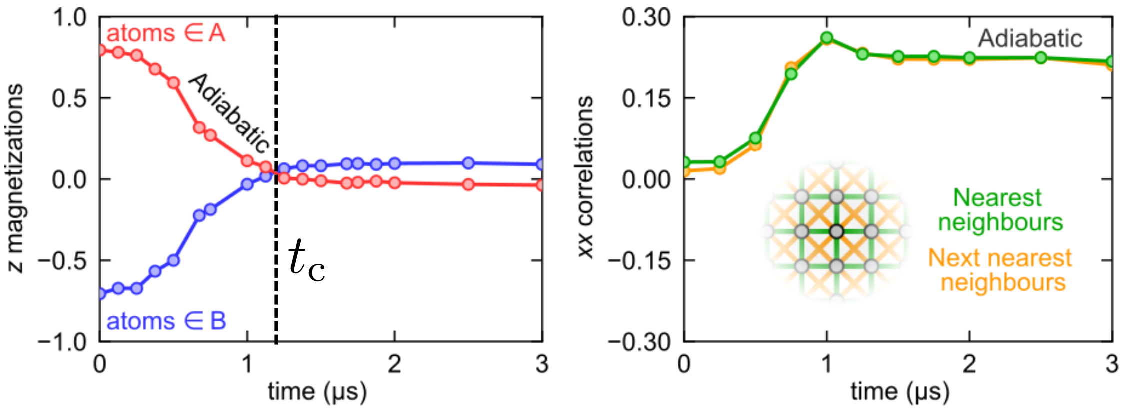


Preparing XY ferro- and antiferromagnets

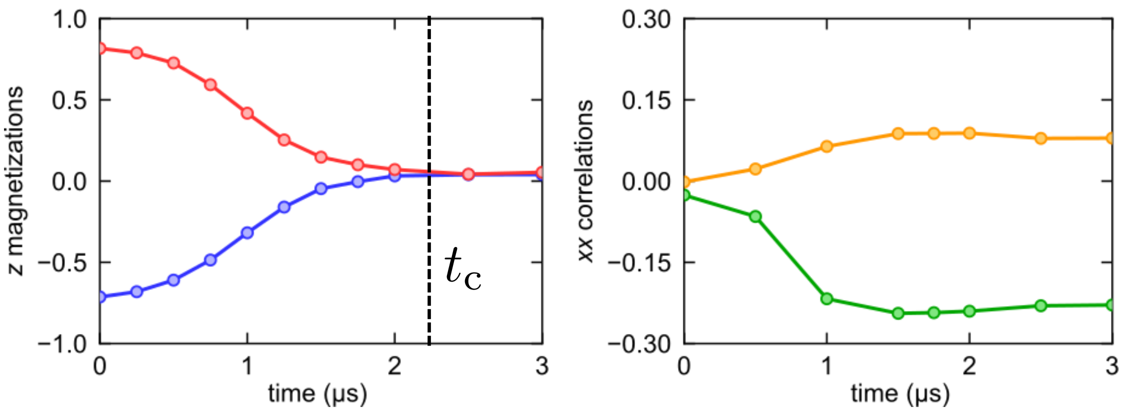


42 atoms

Ferromagnet



Antiferromagnet



If only NN interactions:

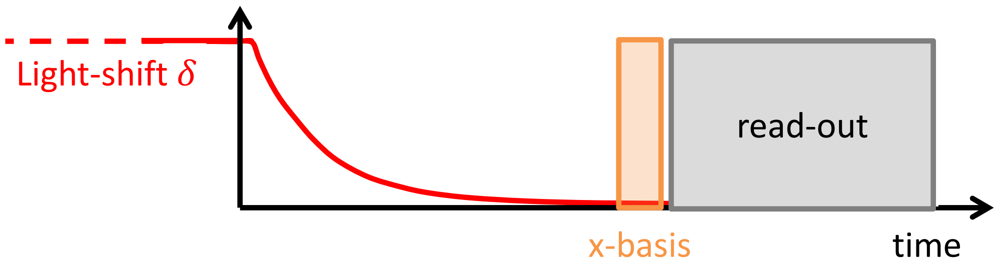
$$|\delta_c^{\mathrm{AFM}}| = |\delta_c^{\mathrm{FM}}|$$

Long-range dipolar interactions:

$$|\delta_c^{\mathrm{AFM}}| < |\delta_c^{\mathrm{FM}}|$$

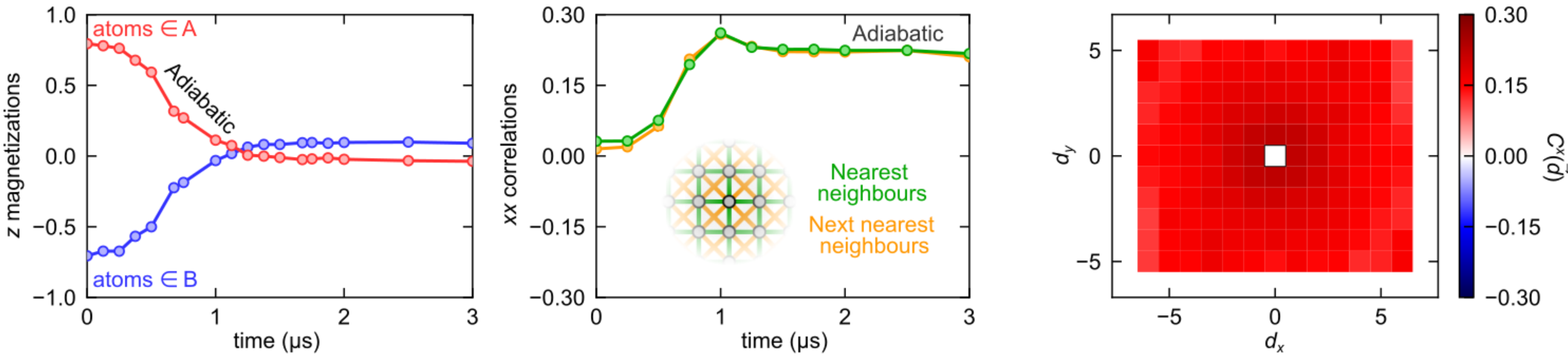
AFM weakly frustrated interactions

Preparing XY ferro- and antiferromagnets

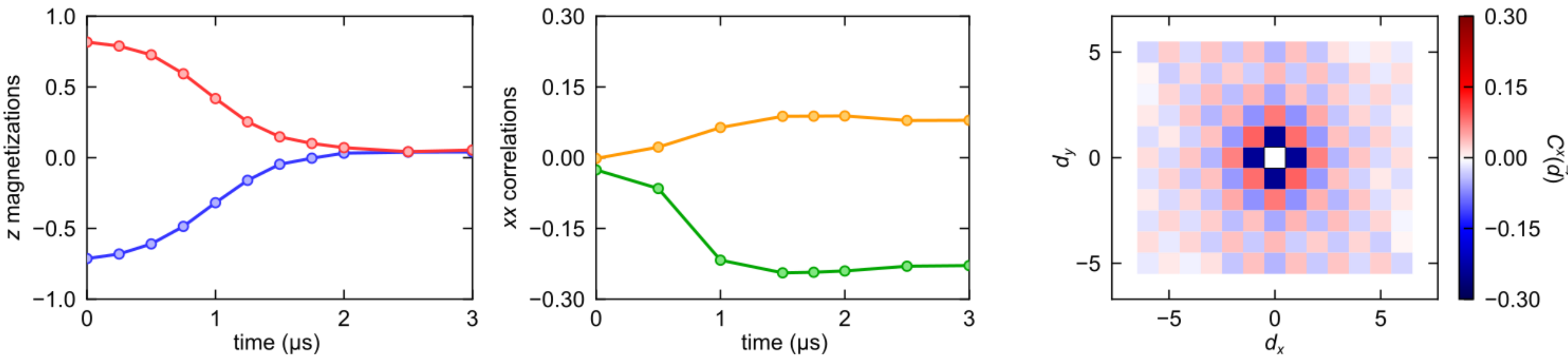


42 atoms

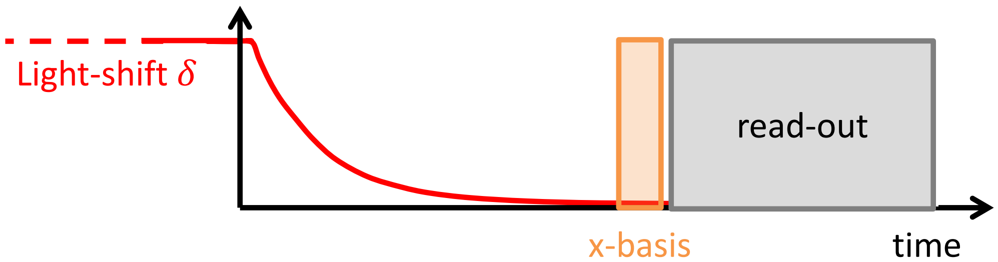
Ferromagnet



Antiferromagnet

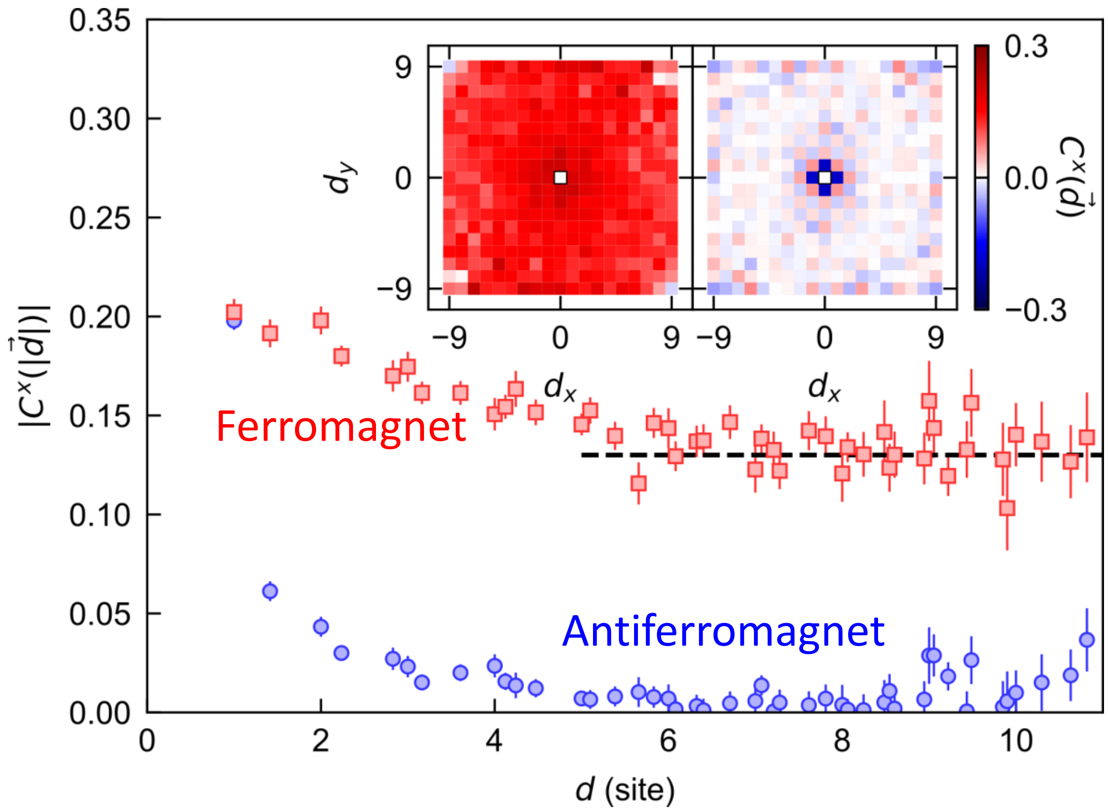


LRO for the FM case



100 atoms

$$C^x(\vec{d}) \equiv \langle C^x_{\vec{r},\vec{r}+\vec{d}} \rangle_{\vec{r}}$$



Ferromagnet:
Long-range order

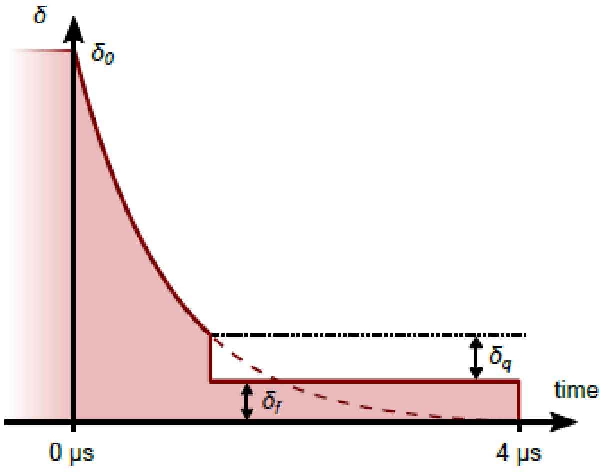
Antiferromagnet:
Correlations decay to 0

Crucial role of
$1/r^3$ interactions

C. Chen *et al.*, arXiv:2207.12930

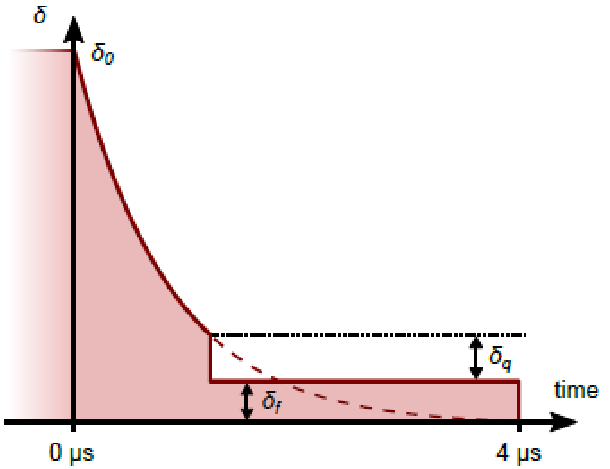
Finite-T phase diagram?

Partial quench during the ramp,
of amplitude δ_q and equilibration time
“Proxy” for the temperature

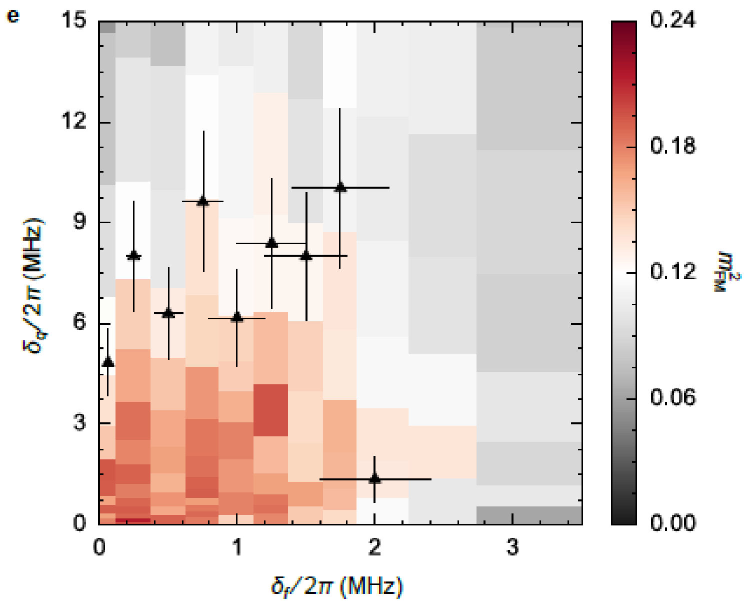


Finite-T phase diagram?

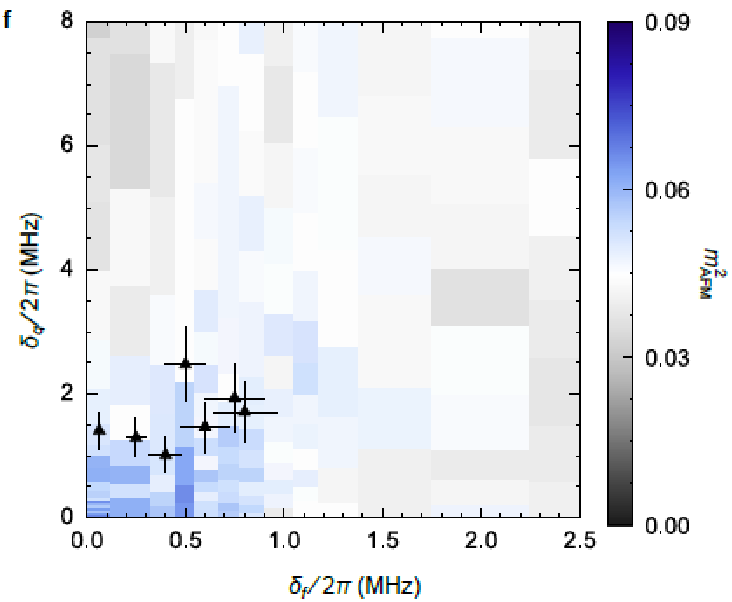
Partial quench during the ramp,
of amplitude δ_q and equilibration time
"Proxy" for the temperature



FM



AFM



Future directions with RDDI

XY models:

- Scalable spin squeezing in dipolar XY arrays
  Comparin *et al*., arXiv:2202.08607

- On Kagome arrays: Spin liquids (Dirac, Chiral)

- Spin transport

Beyond XY:

- Topological matter with RDDI
  Weber *et al*., PRX Quantum **3**, 030302 (2022)

- Floquet engineering of exotic spin models (DM interaction…)

Conclusion

- ✓ Rydberg arrays: ideal platform for ***quantum simulation of spin models***

- ✓ ***Quantum computing:*** fidelities steadily improving
(Harvard, Caltech, Wisconsin, etc.)

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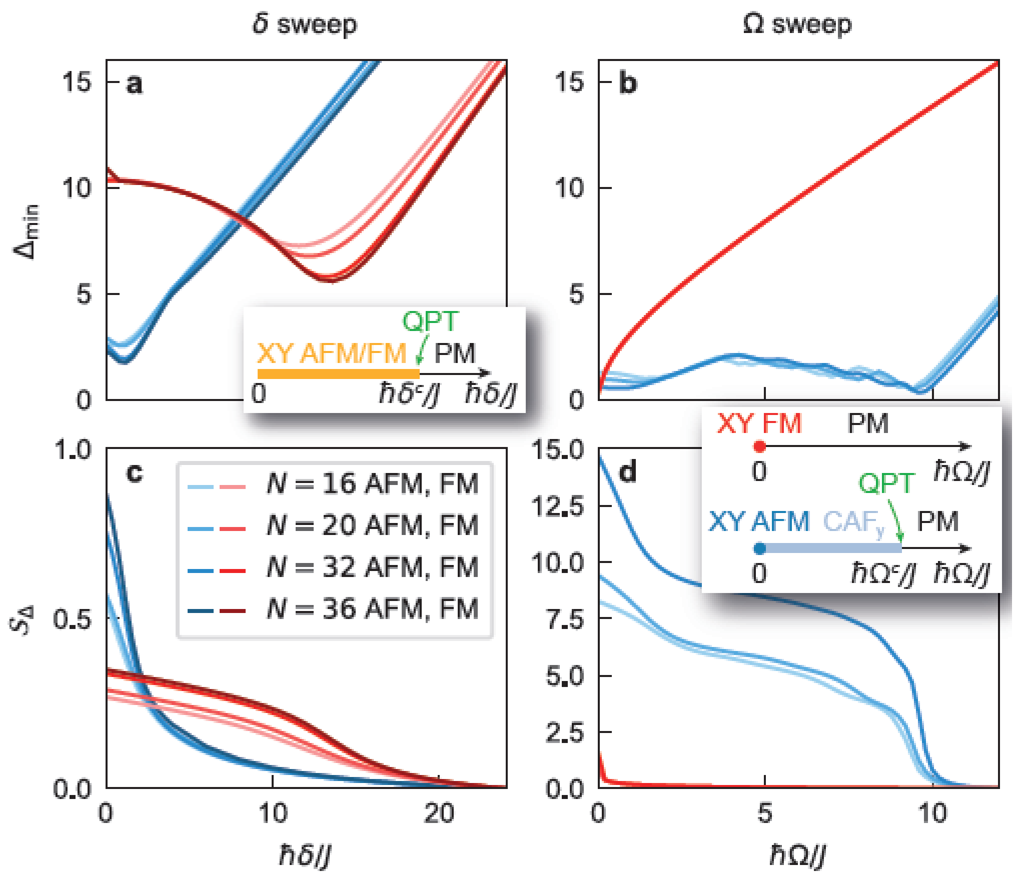
Thanks for your attention!


δ sweep
Ω sweep
a
b
c
d
Δ_{min}
S_Δ
XY AFM/FM
QPT
PM
0
ħδ^c/J
ħδ/J
XY FM
PM
0
ħΩ/J
QPT
XY AFM
CAF_y
PM
0
ħΩ^c/J
ħΩ/J
N = 16 AFM, FM
N = 20 AFM, FM
N = 32 AFM, FM
N = 36 AFM, FM
ħδ/J
ħΩ/J