Exploring the dipolar XY model with arrays of single Rydberg atoms

Thierry Lahaye
Laboratoire Charles Fabry
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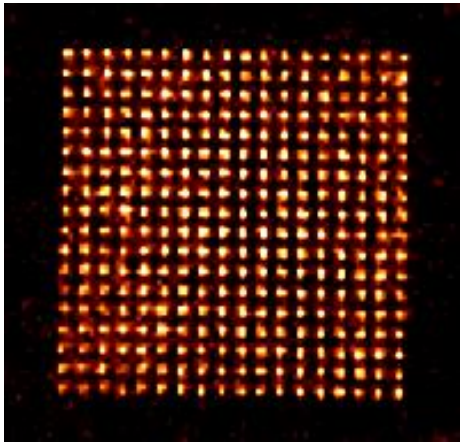
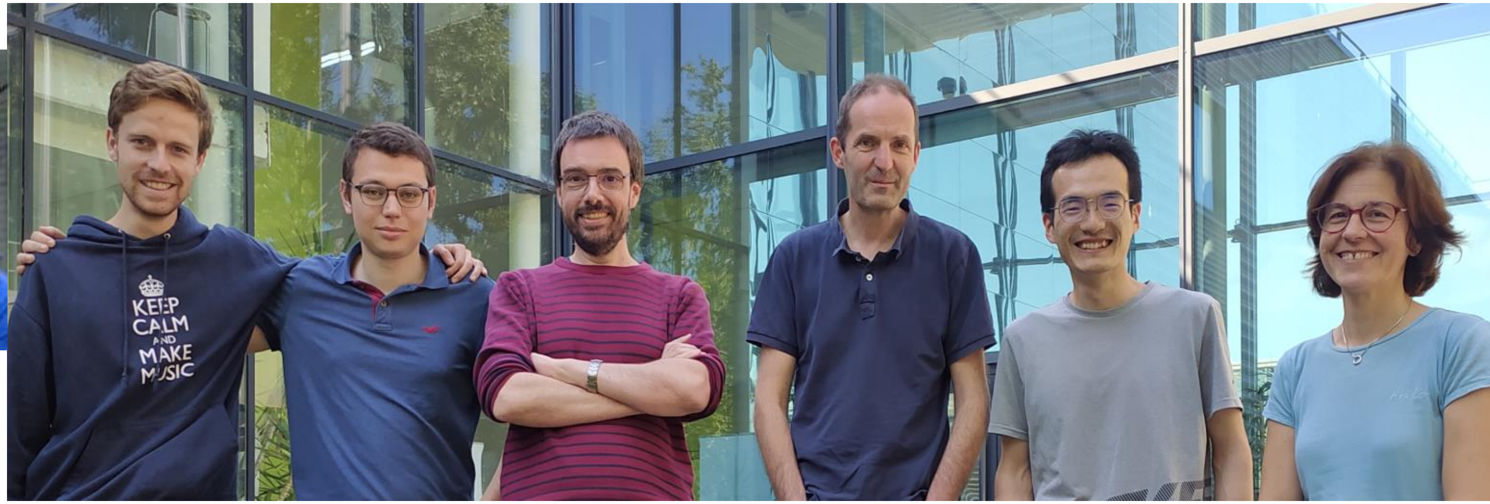


Precision Many-Body Physics 2023, Collège de France
June 14, 2023

The Rydberg team in Palaiseau

Jamie Boyd

Daniel Barredo



Gabriel Emperauger · *Guillaume Bornet* · *Thierry Lahaye* · *Antoine Browaeys* · *Cheng Chen* · *Florence Nogrette*

Bastien Gély

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

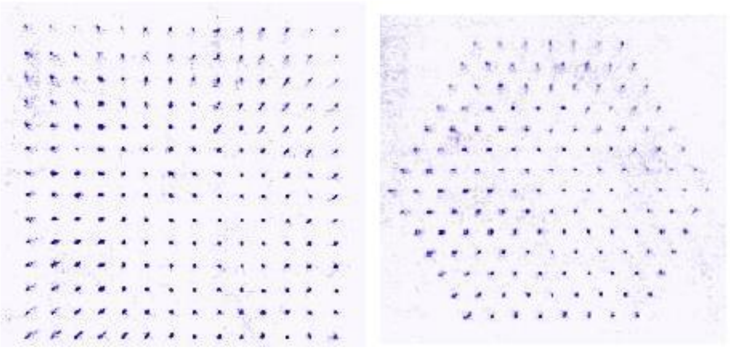
https://atom-tweezers-io.org/

Funding: SIRTEQ, îledeFrance, anr, erc, QUANTUM FLAGSHIP, PASQuanS

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)

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

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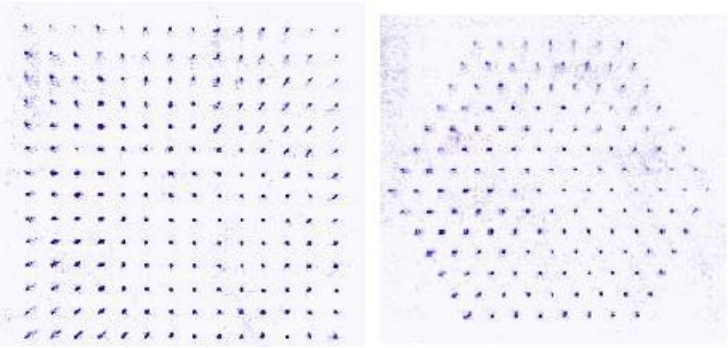

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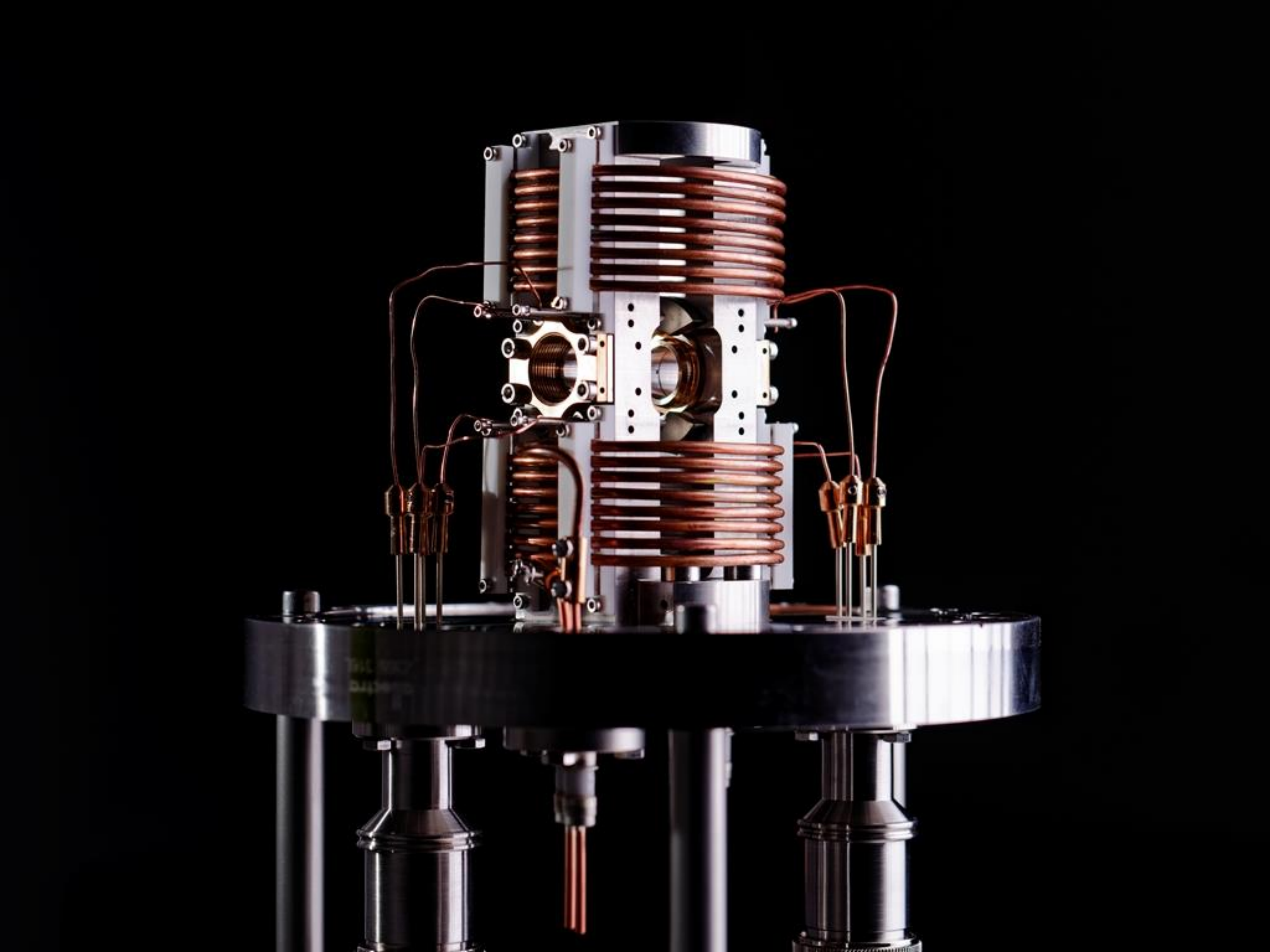
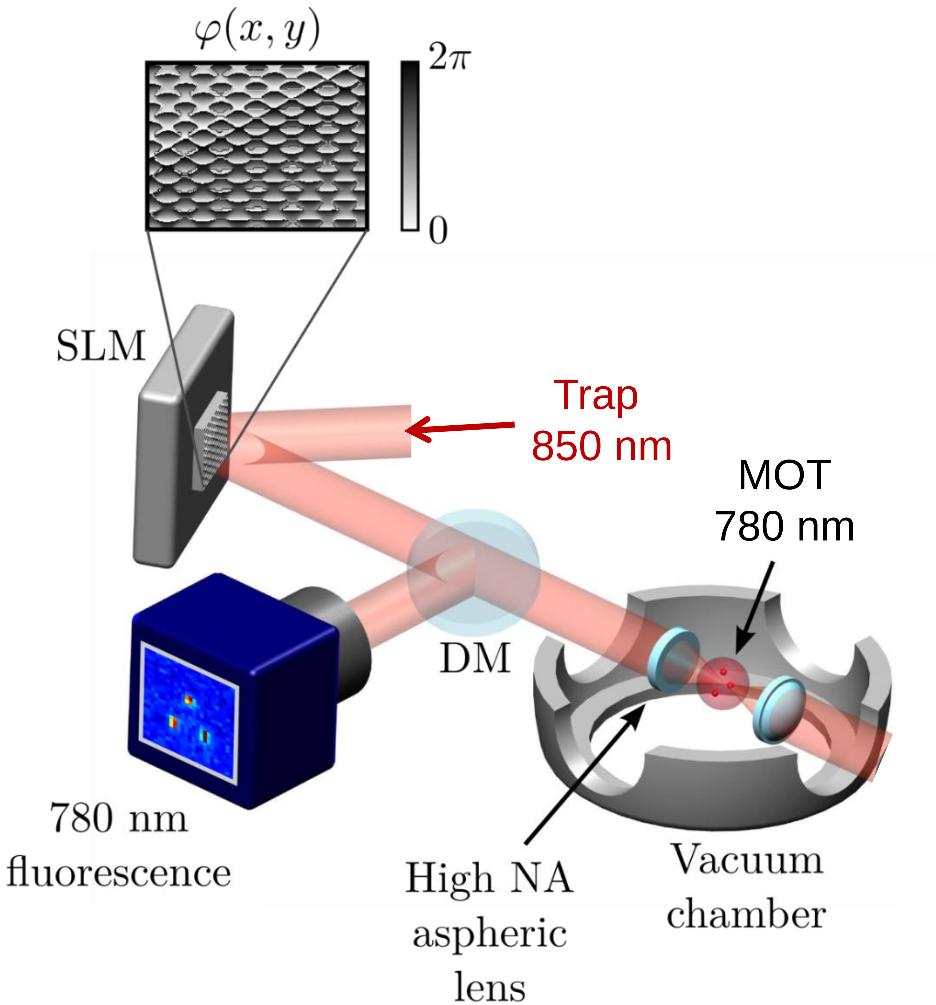
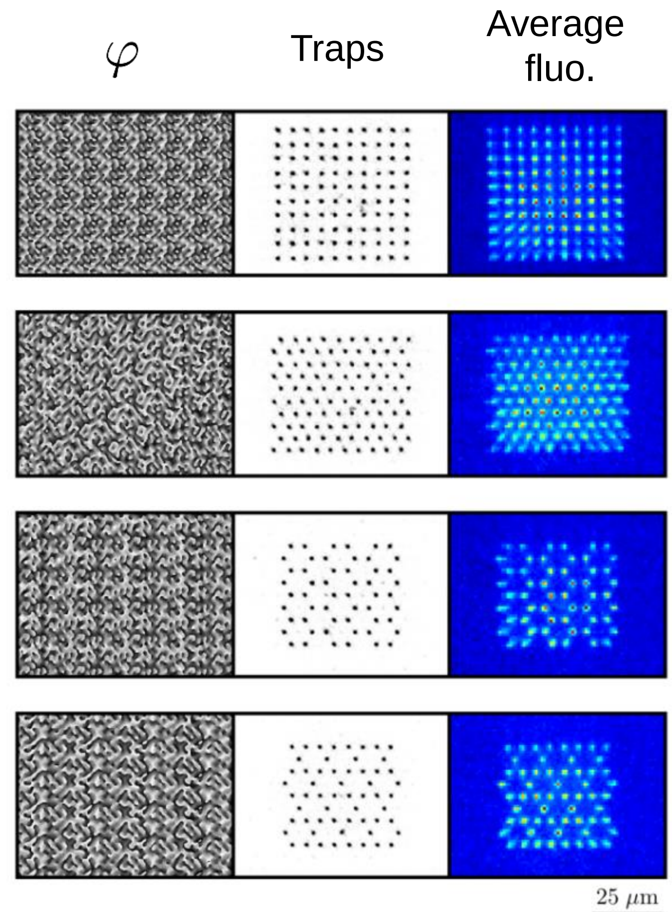
Experimental setup



Arrays of single atoms

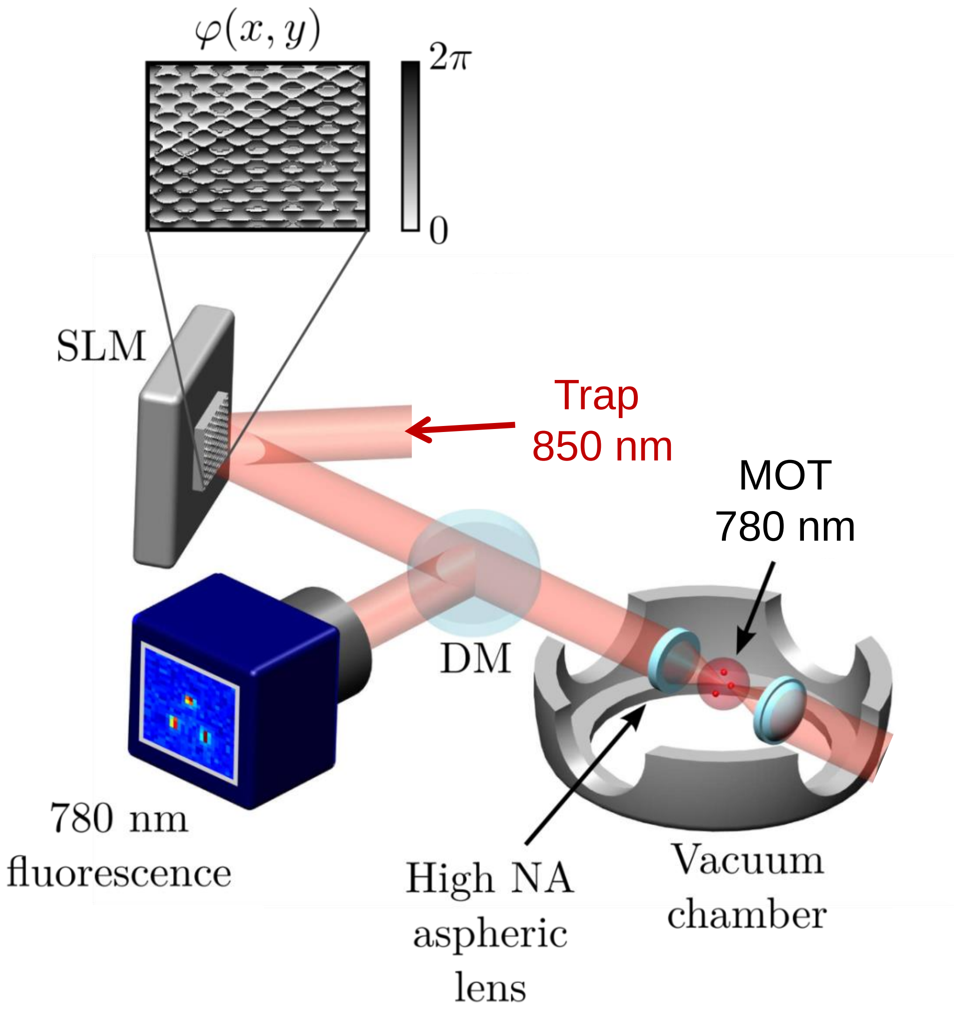


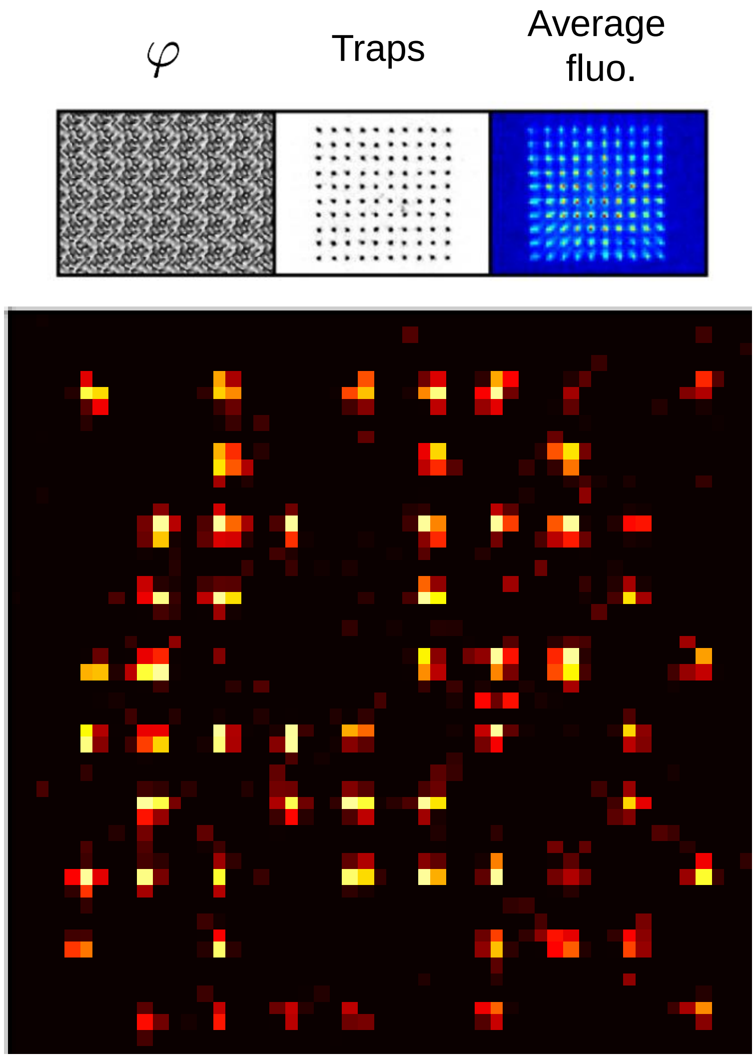


Single shot: 50% filling

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

Arrays of single atoms

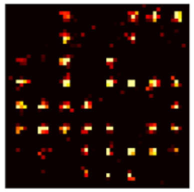




Nogrette *et al.*, PRX **4**, 021034 1021 (2014)

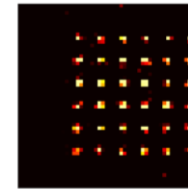
Atom-by-atom assembly

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

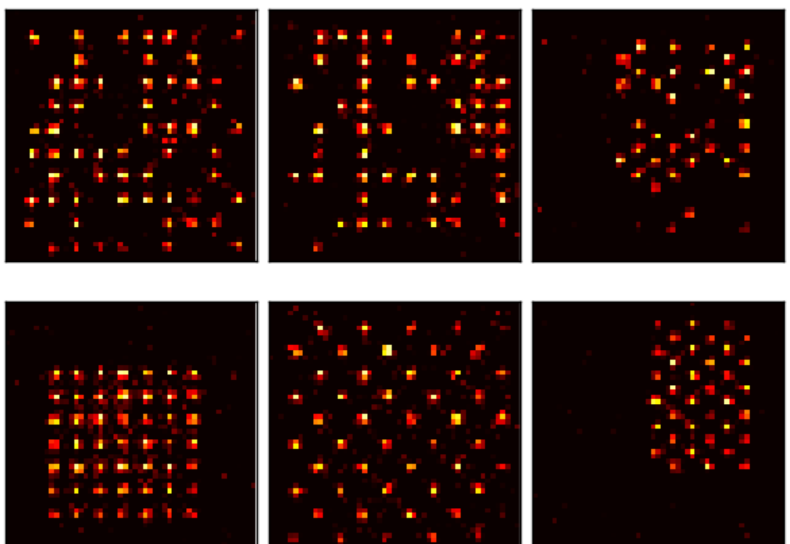


< 1 ms

~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

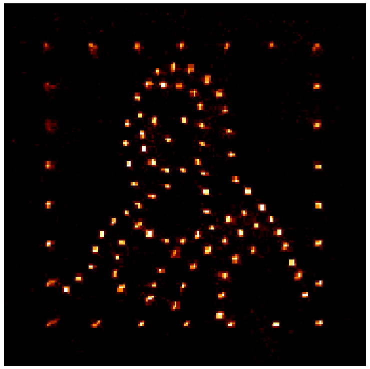
Barredo *et al.*, Science **354**, 1021 (2016)

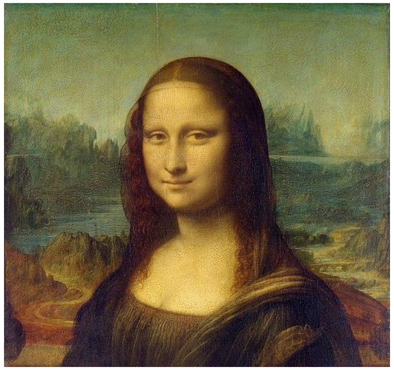
See also:
Endres *et al.*, Science **354**, 1024 (2016)
Kim *et al.*, Nature Comm. **7**, 13317 (2016)

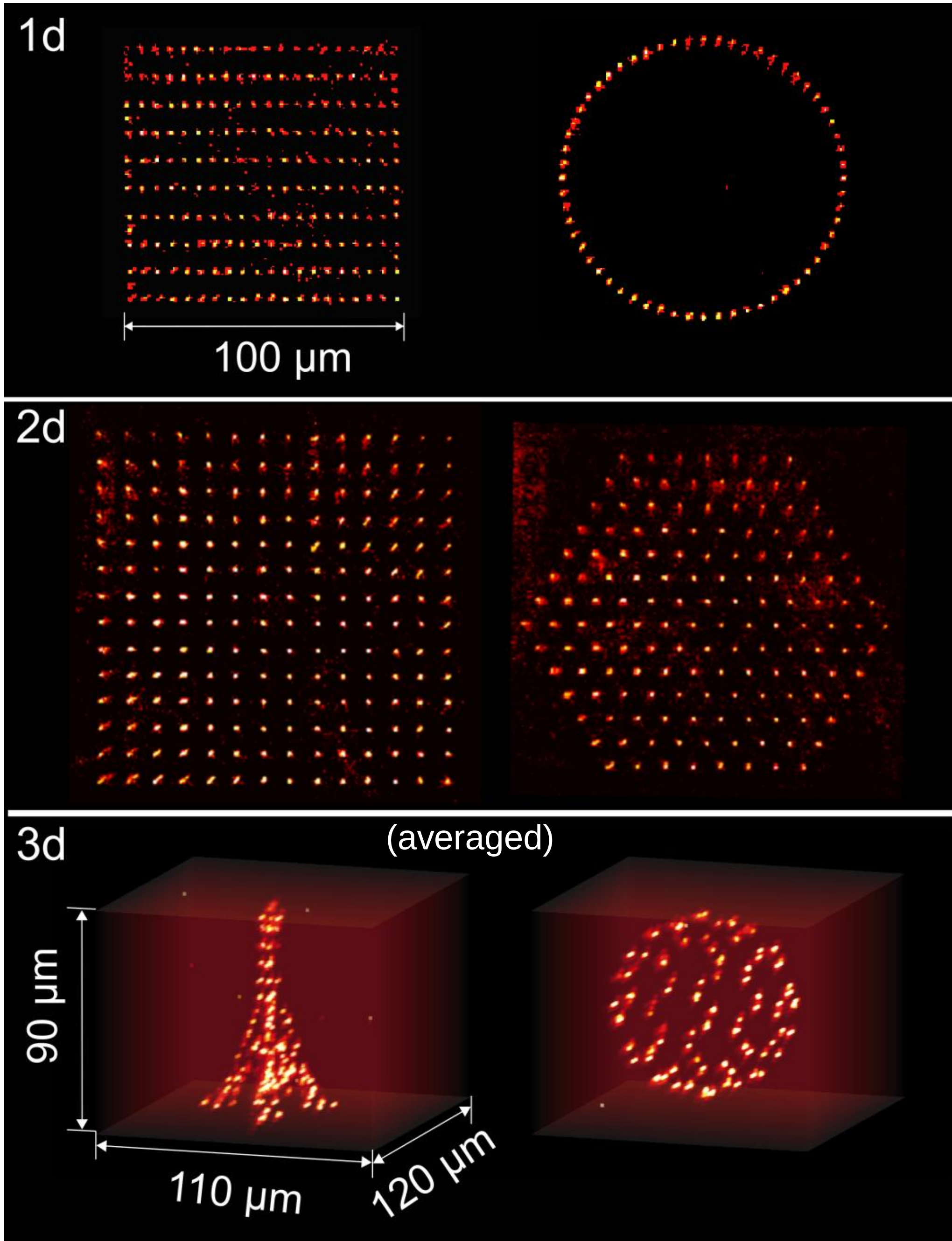
Flexible geometries

New assembler algorithms:

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





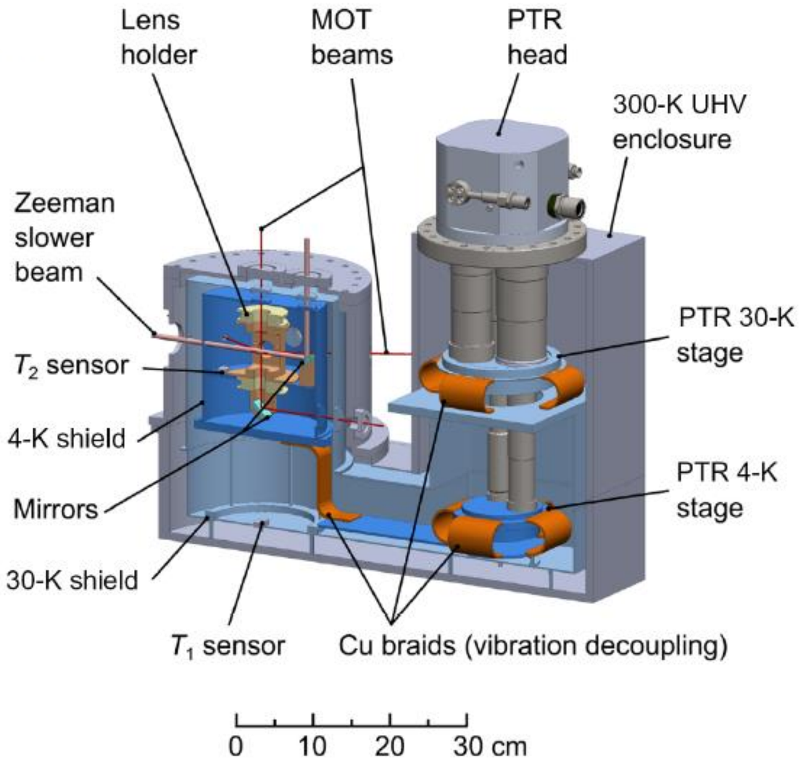


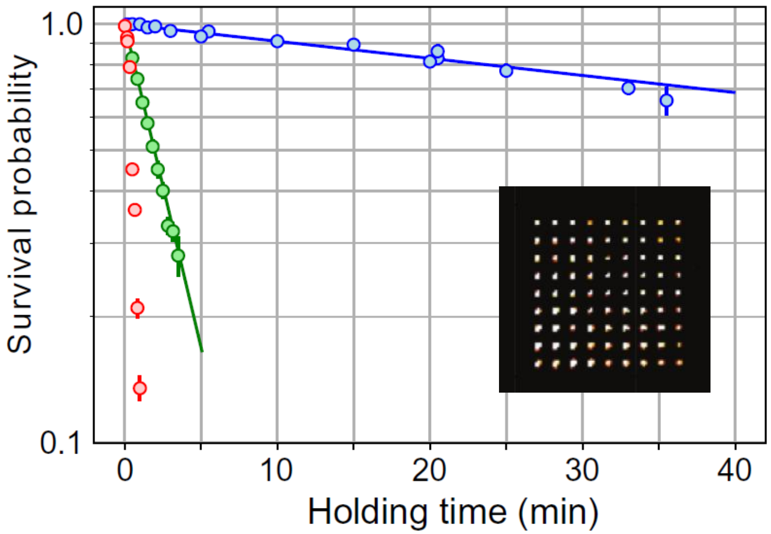
Up to N = 200 atoms:

Filling fraction > 99 %

Probability of defect-free shots ~ 20 %

A cryogenic setup

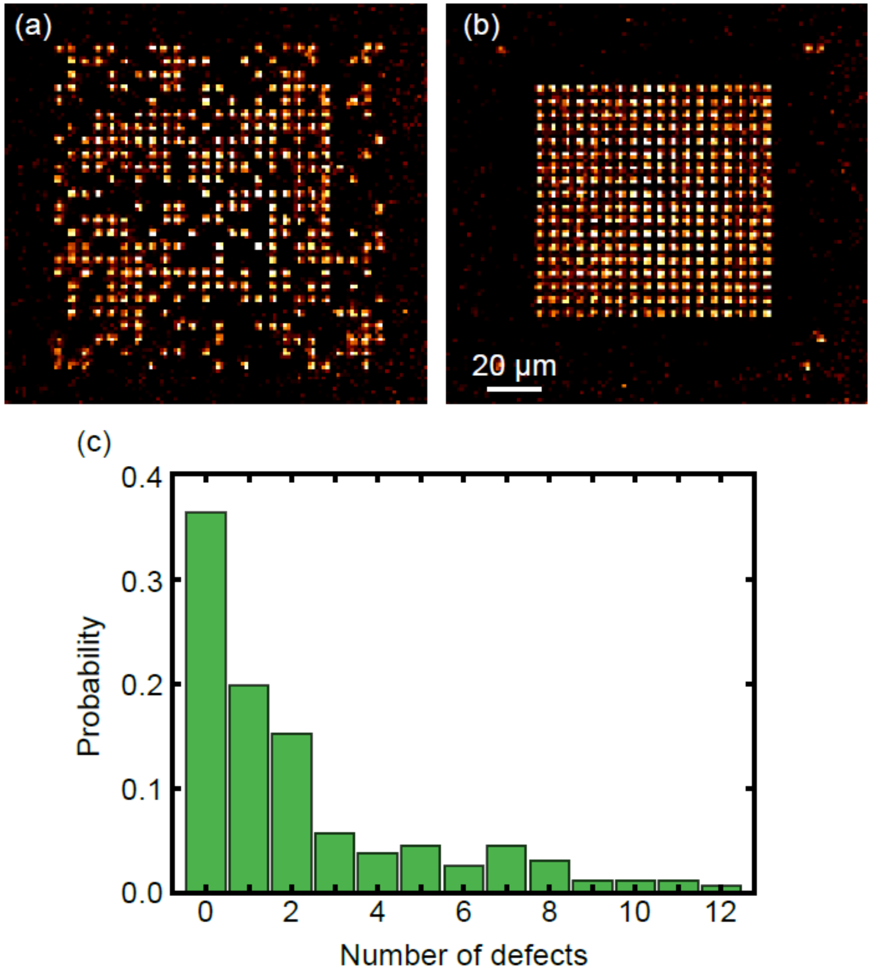




Trapping lifetime > 6000 s !

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

Defect-free arrays with 324 atoms



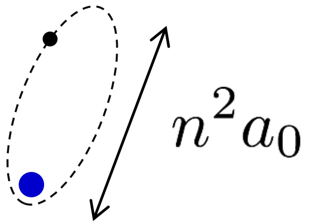
- New procedure to optimize trap loading
- Main limitation: field of view of objectives

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:

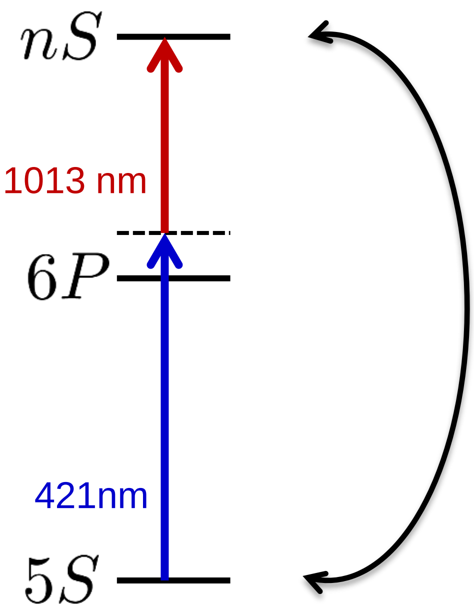
Electric dipole $\langle nS | \, d \, | nP \rangle \sim n^2$

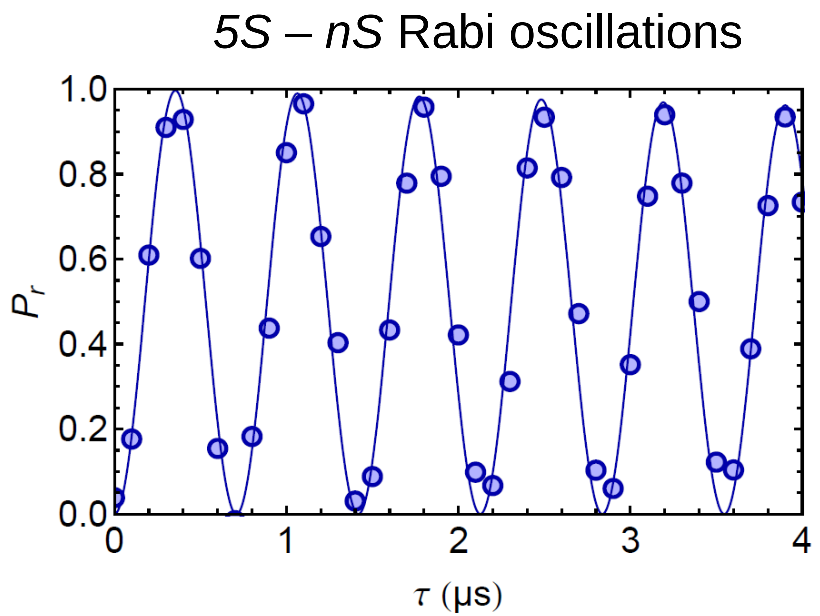
Lifetime $\tau \sim n^3$ (hundreds of µs)

Polarizability $\alpha \sim n^7$

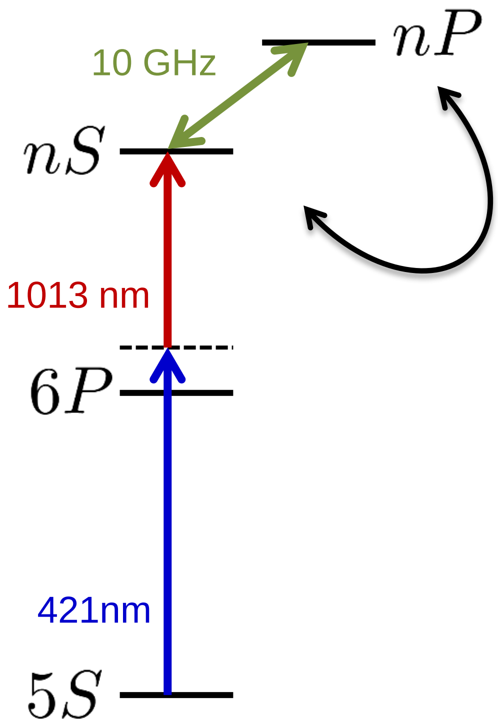
Interactions $V_{\mathrm{dd}} \sim n^4$ $V_{\mathrm{vdW}} \sim n^{11}$

Rydberg excitation

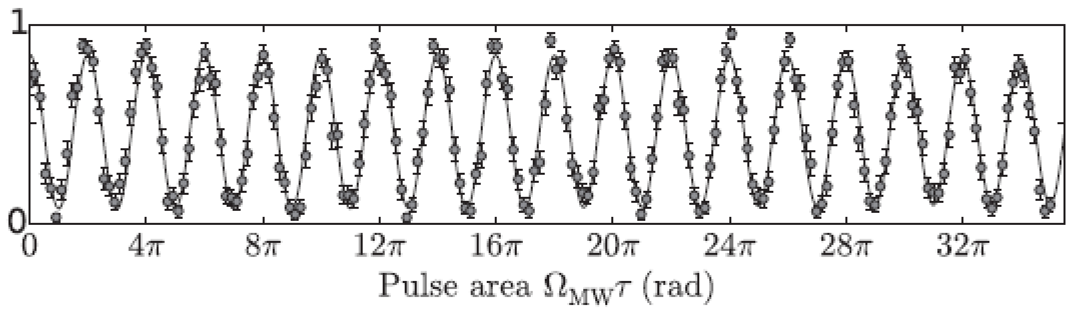




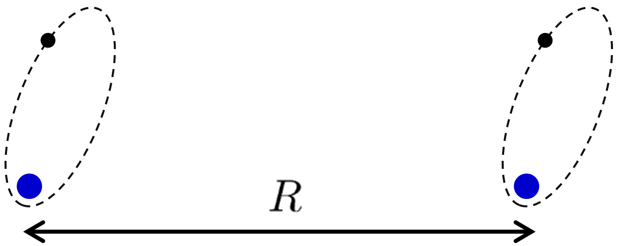
Rydberg atoms: microwave transitions



nS – *nP* Rabi oscillations

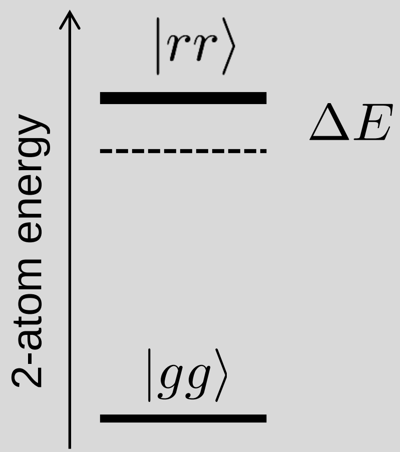


Interactions between Rydberg states



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

van der Waals

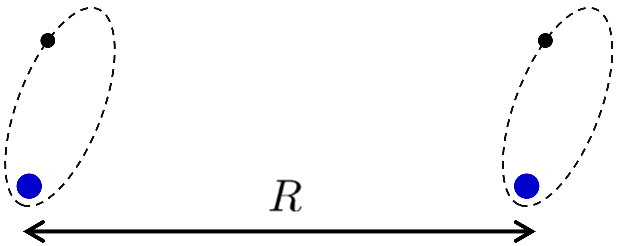


$$\Delta E \sim \frac{C_6}{R^6}$$

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

Ising-like interaction

Interactions between Rydberg states



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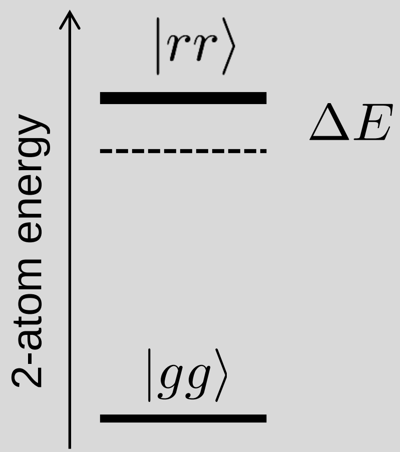
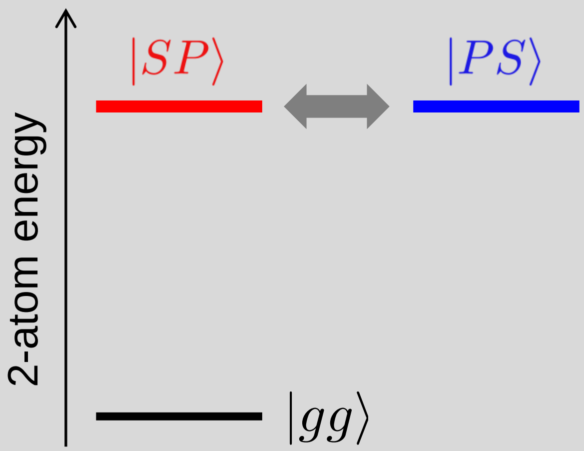


$$\Delta E \sim \frac{C_6}{R^6}$$

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

Ising-like interaction

Resonant DDI



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

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

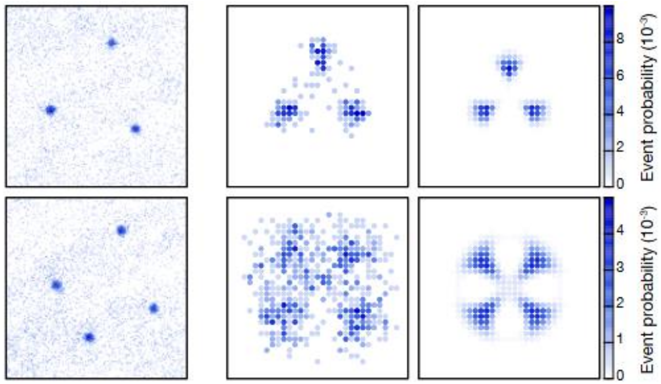
XY interaction (flip-flop)

Quantum simulation of the Ising model

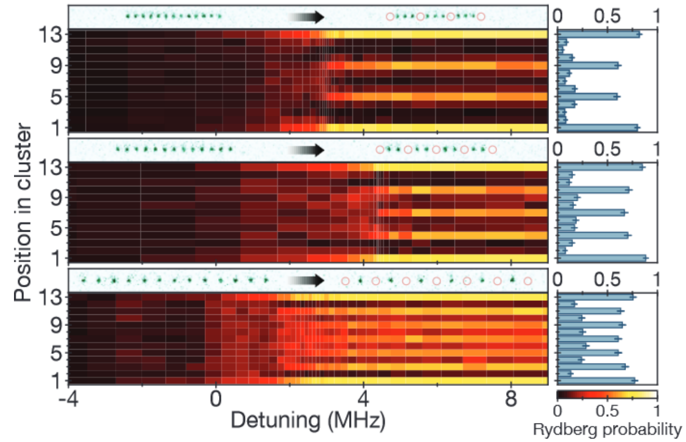
Andreas Läuchli
(PSI & EPFL)

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

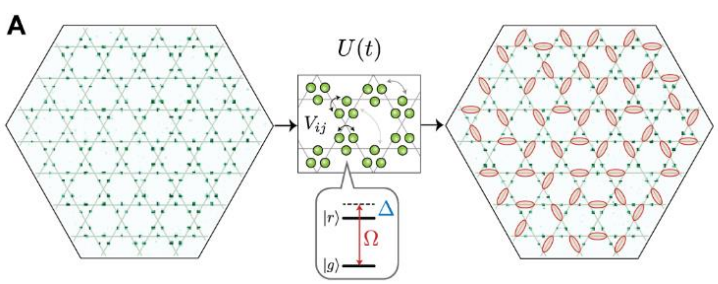
Many experiments using vdW interactions



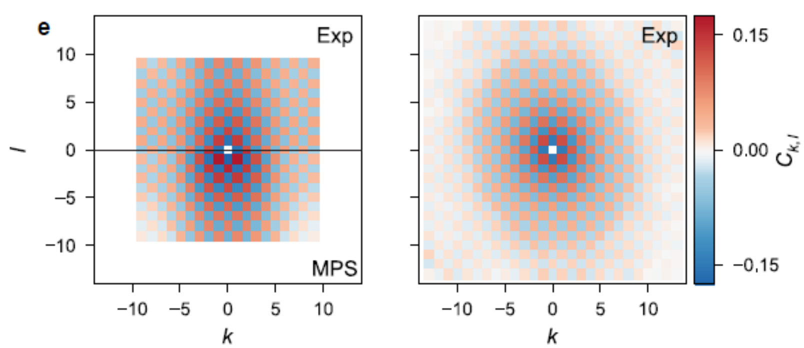
P. Schauss *et al.*, Nature **491**, 87 (2012)



Bernien *et al.*, Nature **551**, 579 (2017)



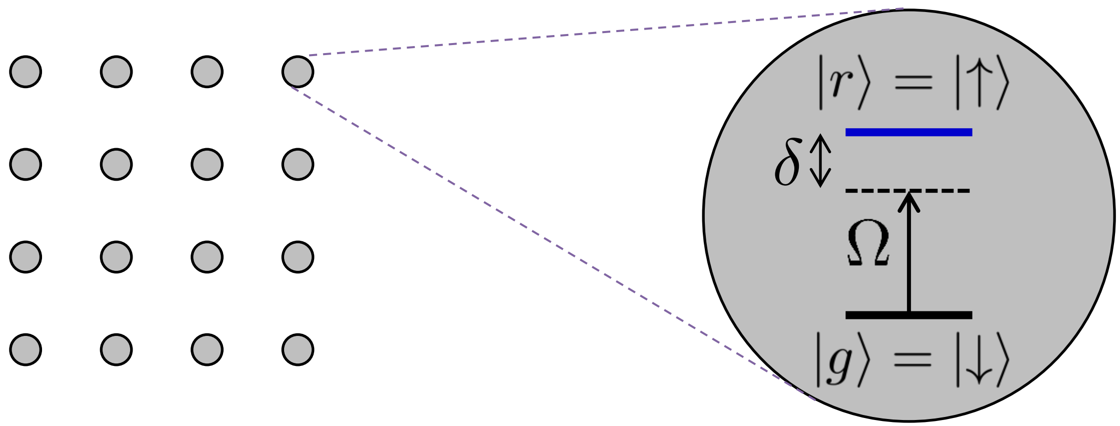
G. Semeghini *et al.*, Science **374**, 1242 (2021)



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

And many, many more examples!

Blockade: quantum Ising model

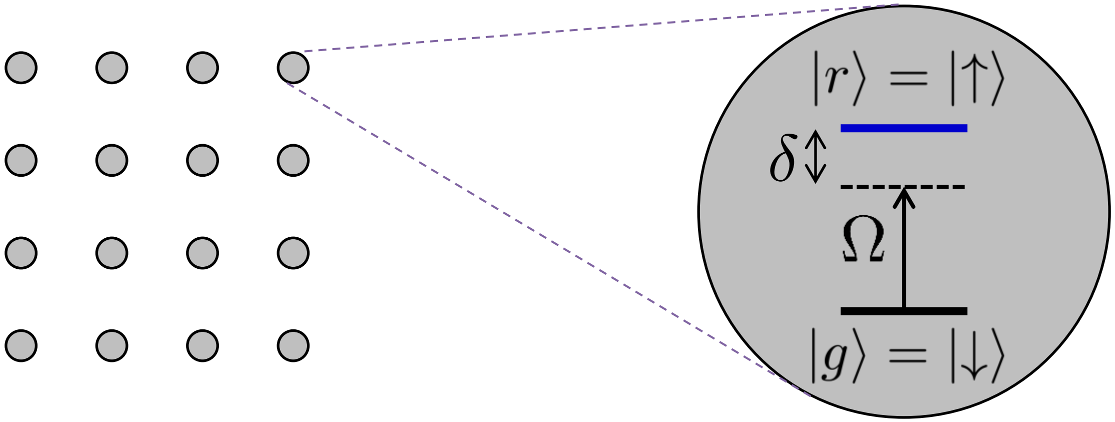


$$n^i = |r_i\rangle \langle r_i|$$

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

Rabi frequency   Laser detuning   van der Waals interactions

Blockade: quantum Ising model



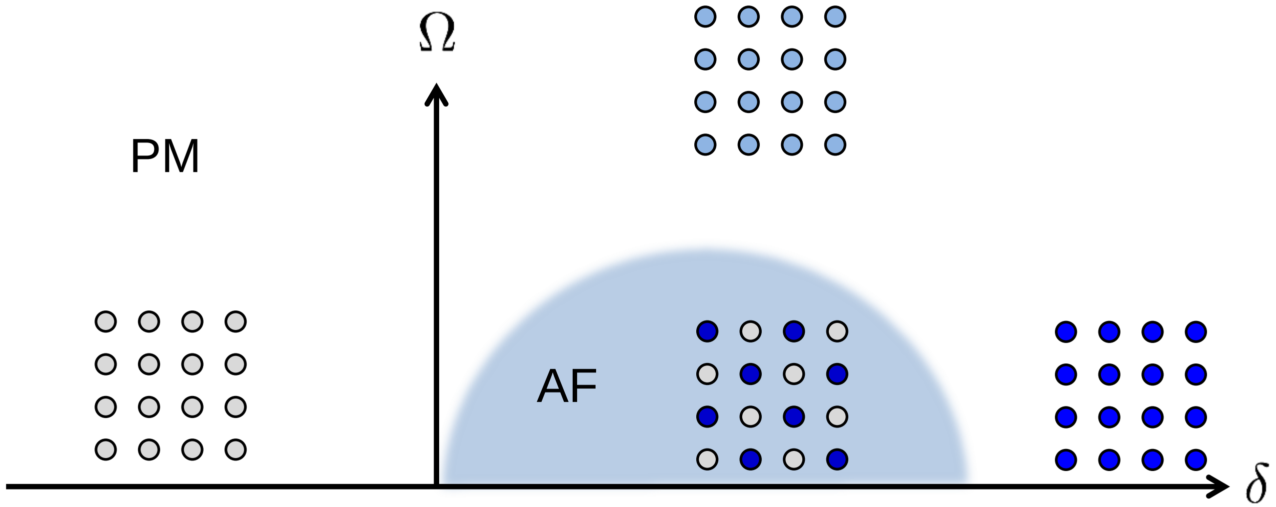
$$n^i = |r_i\rangle\langle r_i| = (1 + \sigma_z^i)/2$$

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

Transverse B   Longitudinal B   Ising couplings

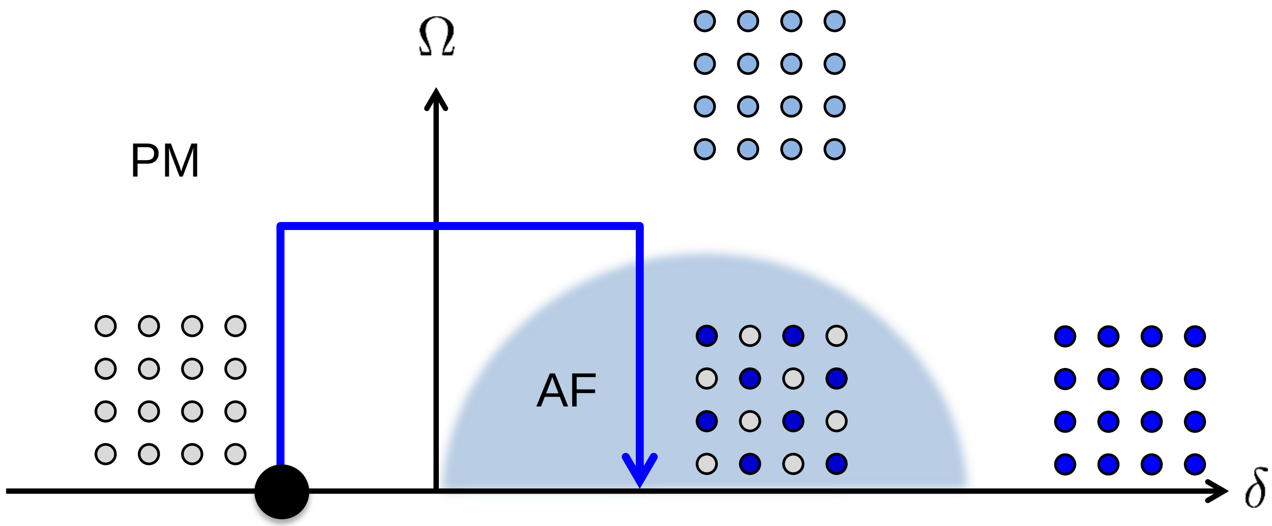
Ising model: adiabatic preparation

Ising AF phase diagram



Ising model: adiabatic preparation

Ising AF phase diagram

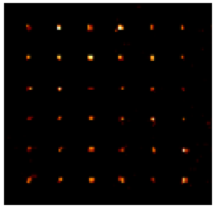


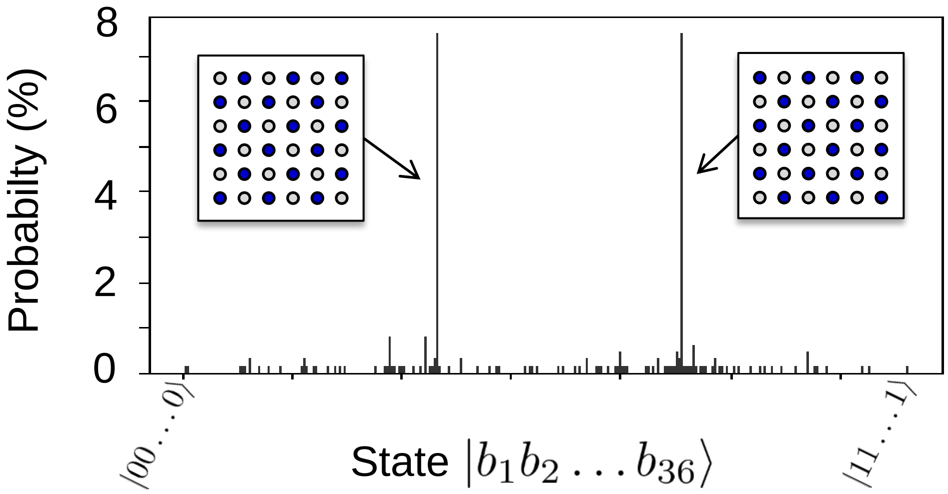
$$H = \sum_i \left(\frac{\hbar\Omega}{2}\sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Vary slowly Rabi frequency and detuning
to explore the phase diagram

‘Adiabatic’ preparation on a square array

6×6
square array





$2^{36} \approx 7.10^{10}$ states!

'Adiabatic' preparation on a square array

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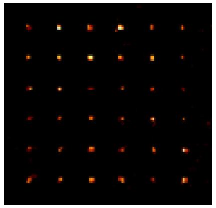
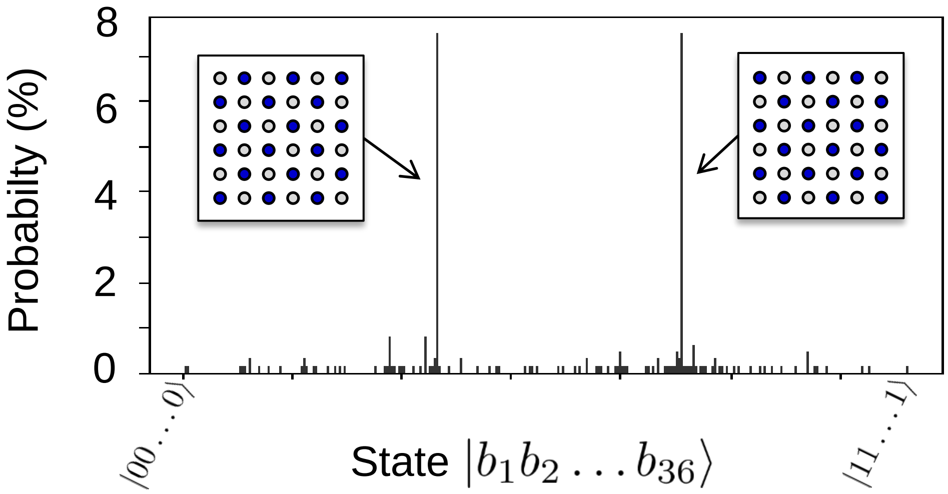
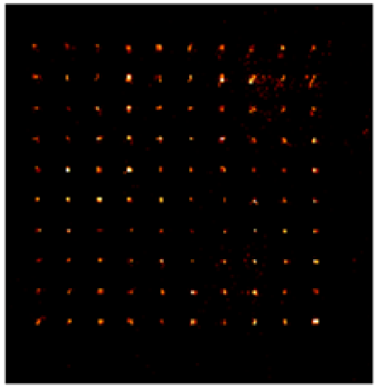


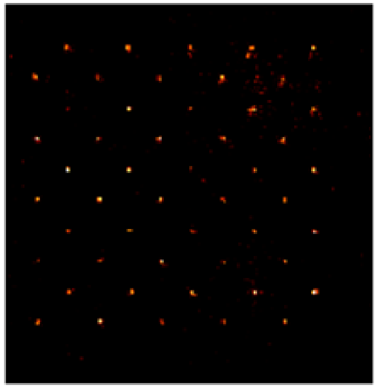


$2^{36} \approx 7.10^{10}$ states!

10×10



sweep



Perfect AF ordering!

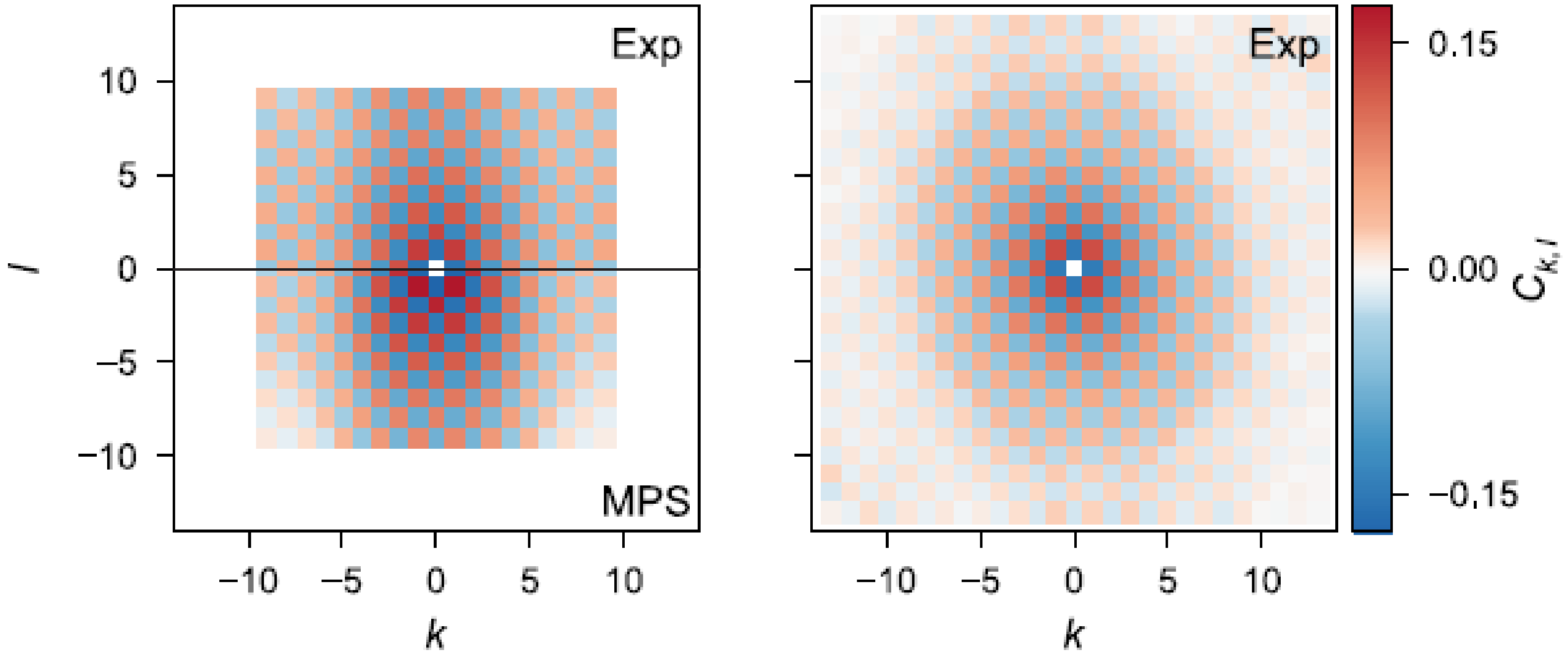
(1 shot in 500)

Correlation functions

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

10×10 array

14×14 array



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

Quantum simulation of the XY model

Quantum simulation of the XY model

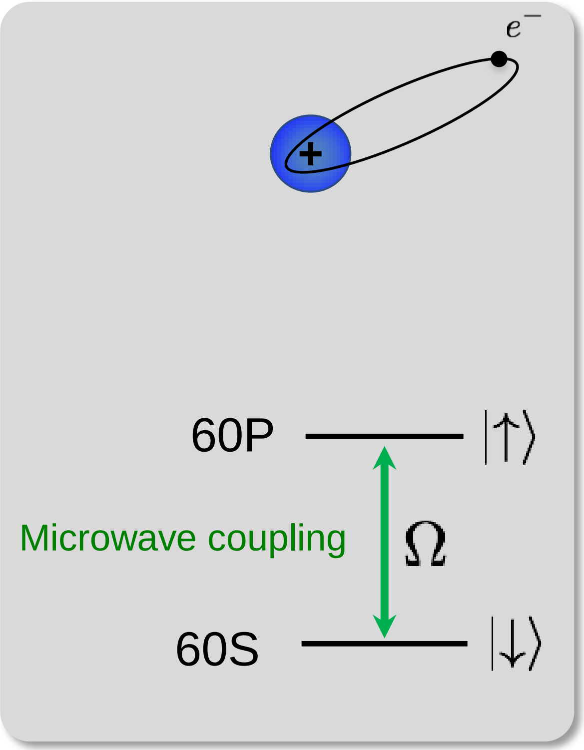
Theory support:

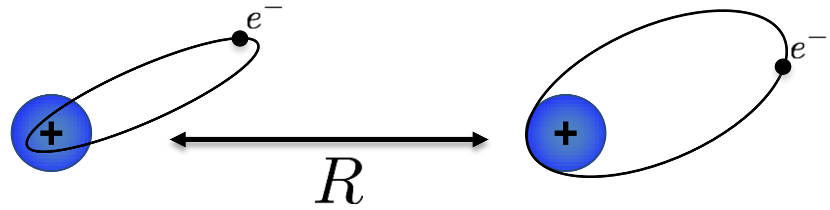
N. Yao
(Harvard)

M. Bintz
V. Liu
S. Chatterjee

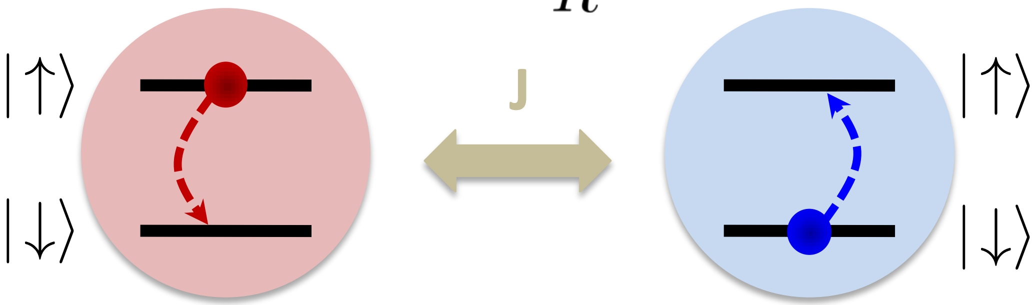
T. Roscilde F. Mezzacapo
(Lyon)

Resonant dipole-dipole interaction

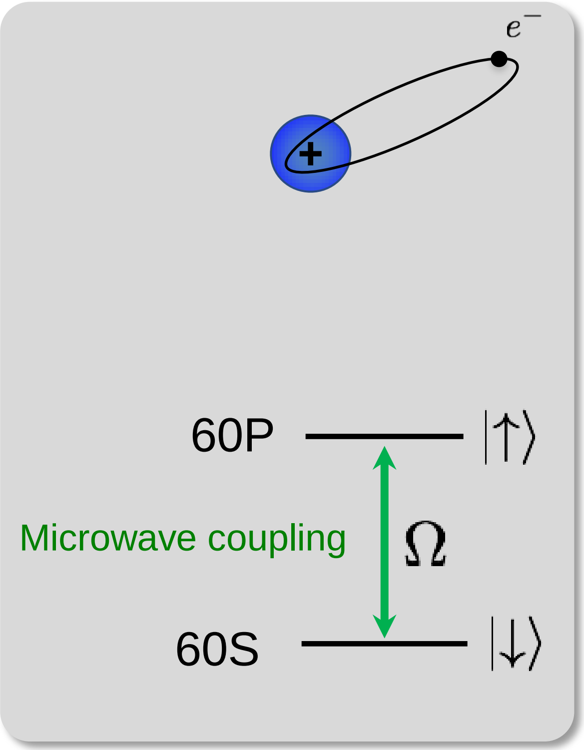


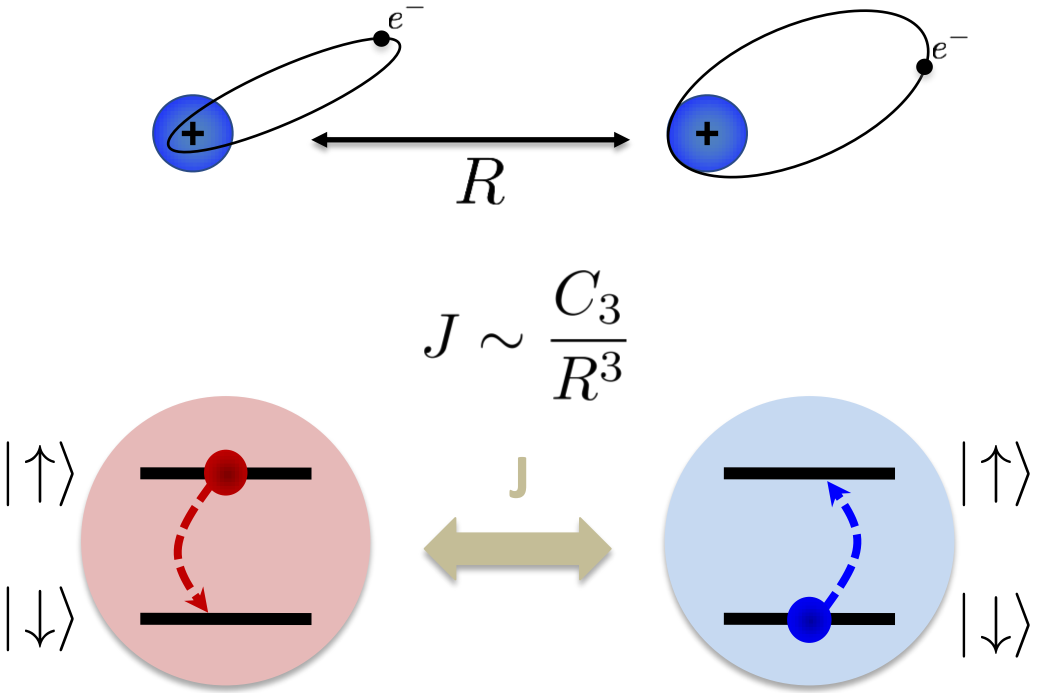


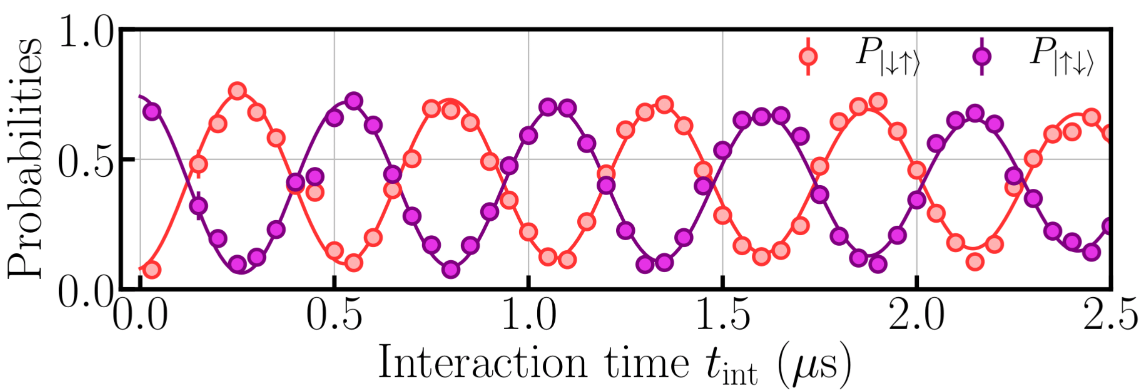
$$J \sim \frac{C_3}{R^3}$$



Resonant dipole-dipole interaction

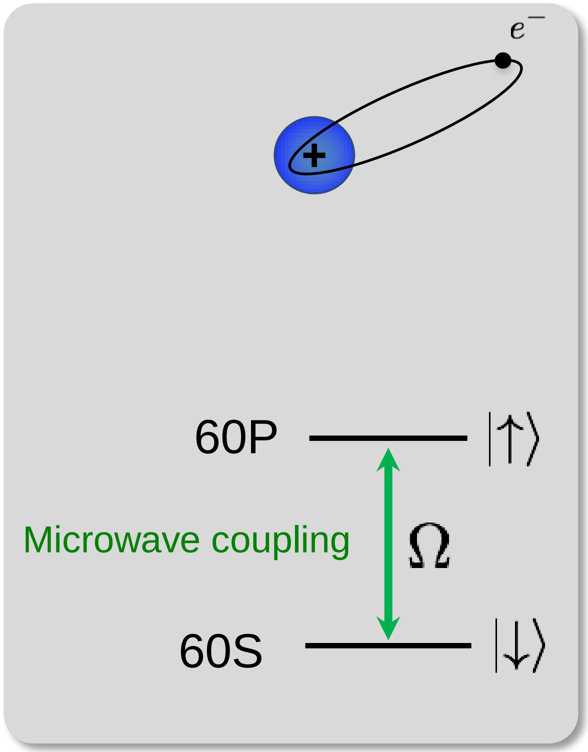


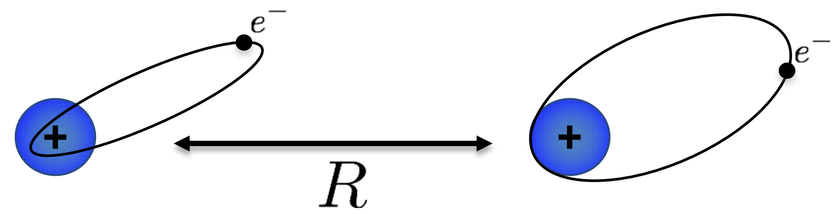




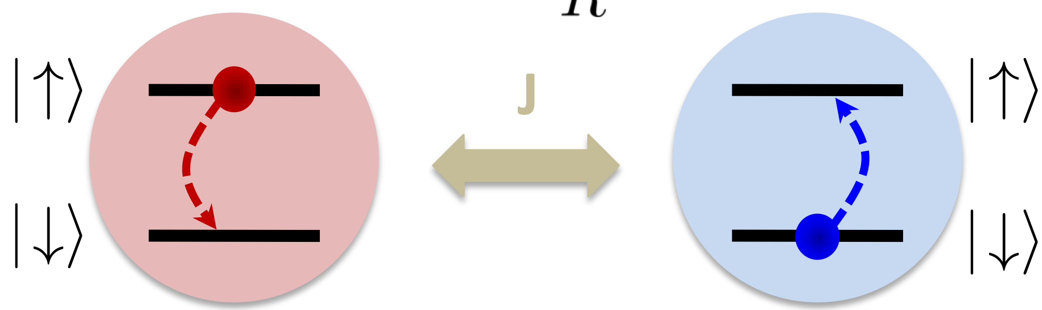
Barredo *et al.*, PRL **114**, 113002 (2015)

Resonant dipole-dipole interaction



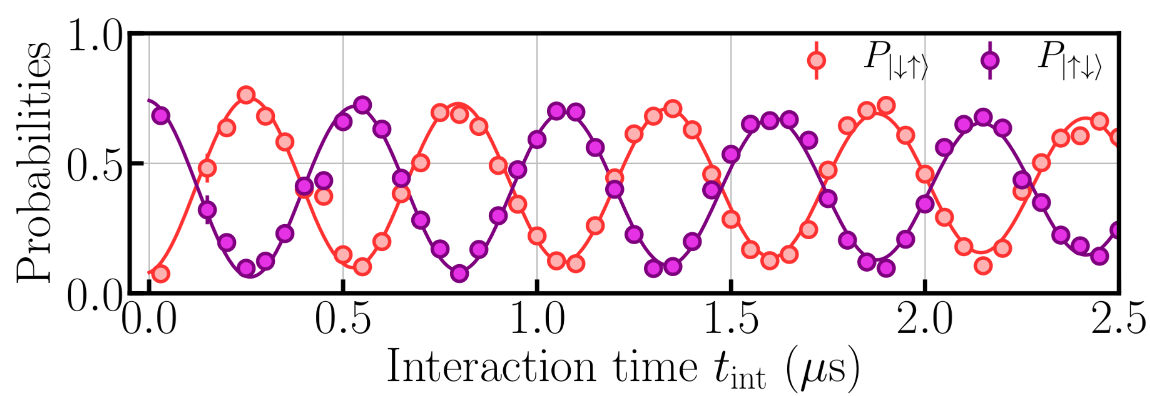


$$J \sim \frac{C_3}{R^3}$$



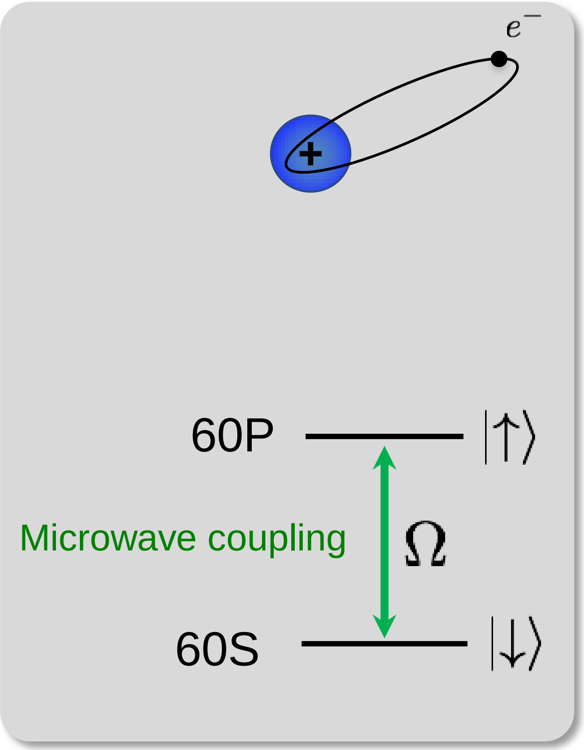
N atoms: XY model

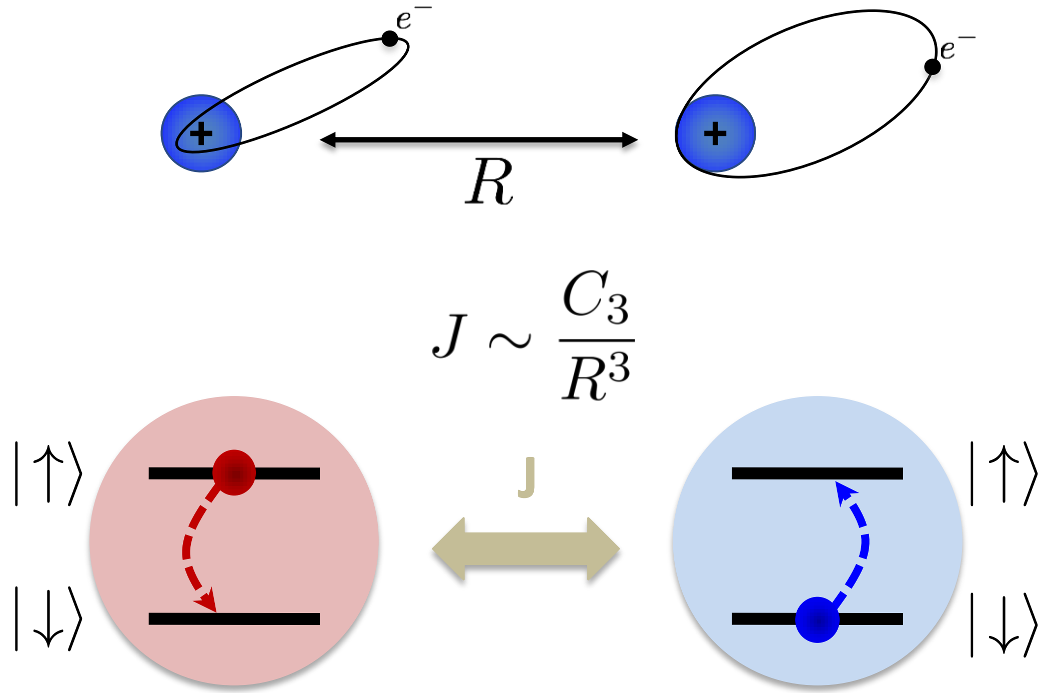
$$H = \sum_{i \neq j} \frac{C_3}{R_{ij}^3} \left(\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j \right)$$



Barredo *et al.*, PRL **114**, 113002 (2015)

Resonant dipole-dipole interaction





Studies conducted using the resonant dipole-dipole interaction:

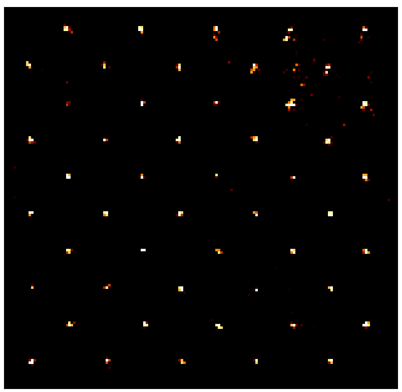
- Preparation of a many-body topological phase — de Léséleuc *et al.*, Science **365**, 775 (2019)
- Implementation of a density-dependent Peierls phase — Lienhard *et al.*, PRX **10**, 021031 (2020)
- Floquet engineering of XXZ Hamiltonians — Scholl *et al.*, PRX Quantum **3**, 02303 (2022)

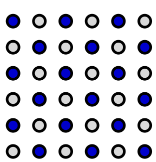
Ising vs. XY model

Ising model

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

AFM $\quad J_{ij} < 0$





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

Ground state =
classical Néel configurations

Ising vs. XY model

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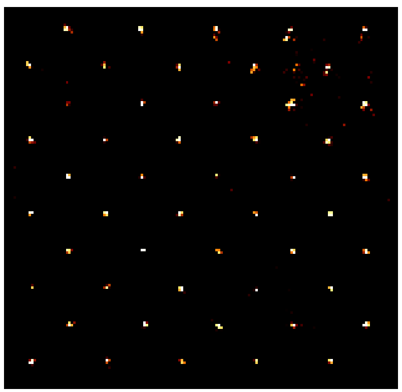

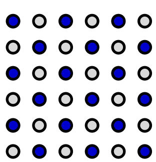

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Ground state =
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XY model

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

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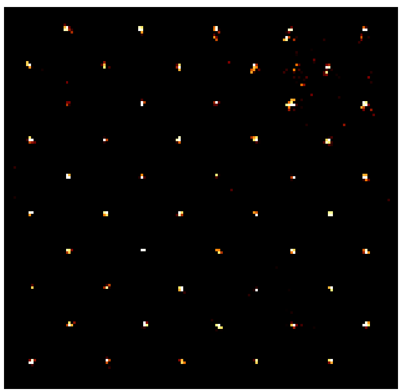

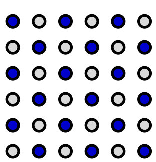

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XY model

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Competing order along *x* / along *y*

Ising vs. XY model

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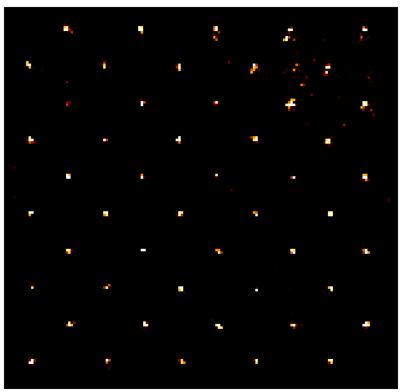

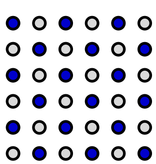

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Ground state =
classical Néel configurations

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

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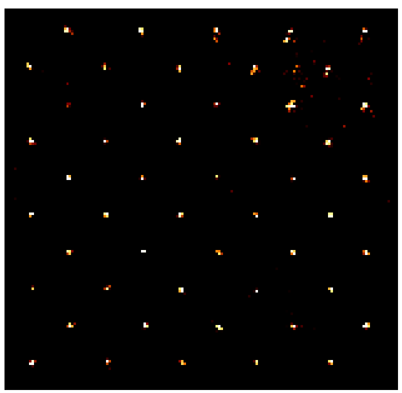

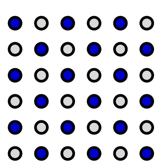

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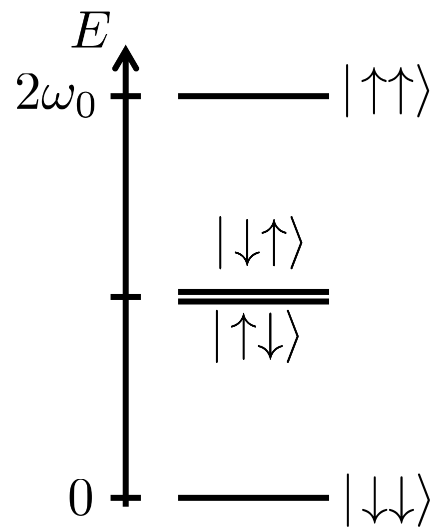

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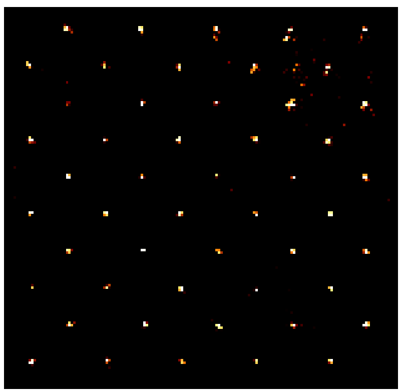

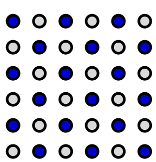

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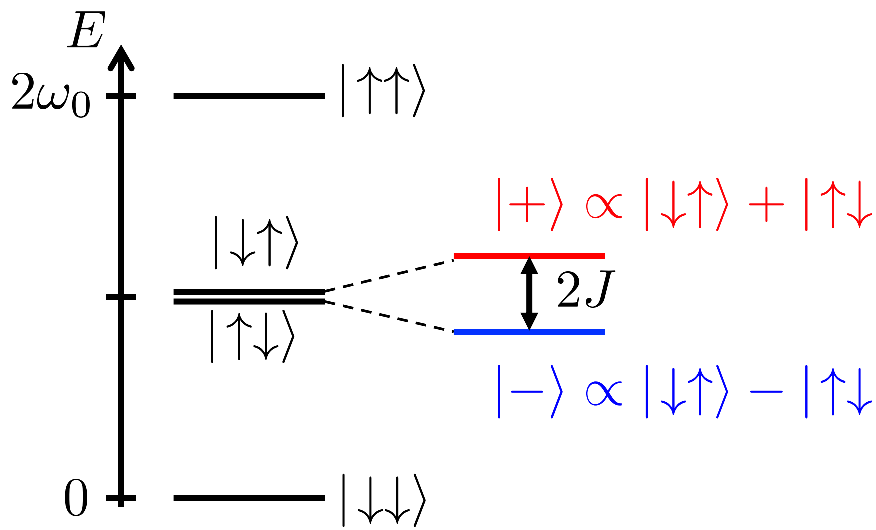
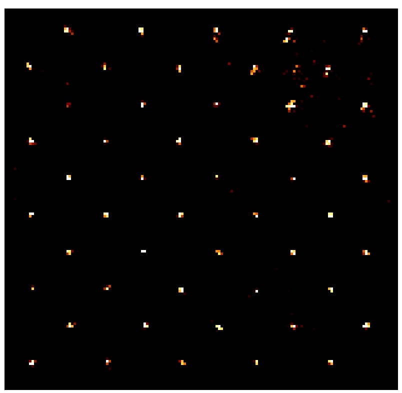


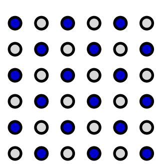
Ising vs. XY model

Ising model

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

AFM $\quad J_{ij} < 0$





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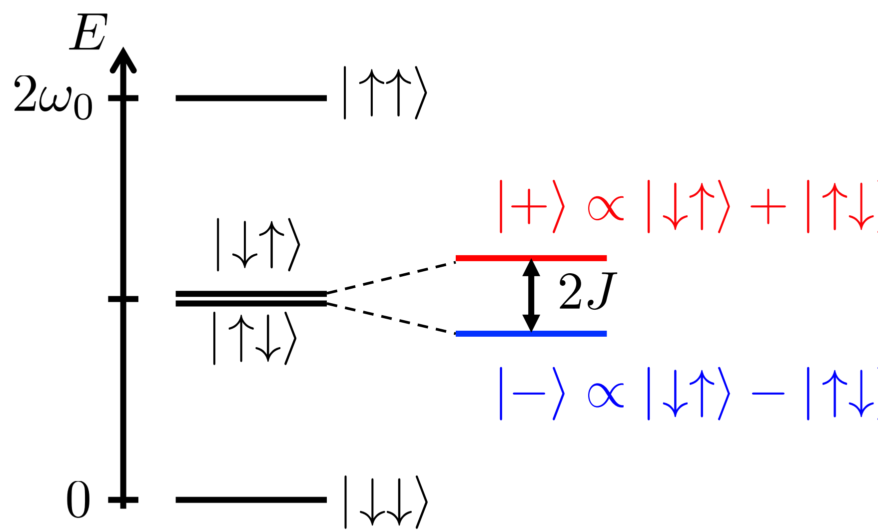
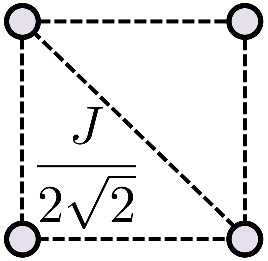


Ground state =
non-classical entangled state

XY on square lattice (1/2 filling)

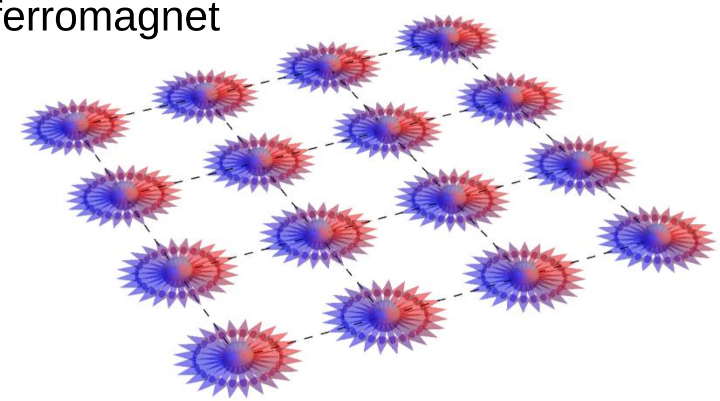


Ansätze wavefunctions

continuous $U(1)$ symmetry

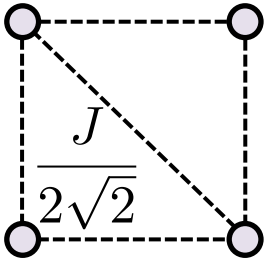
$M^z = \sum_i \sigma_i^z$ conserved

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)



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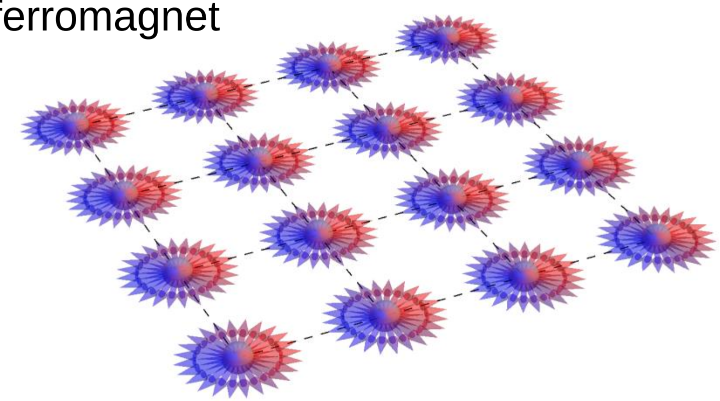


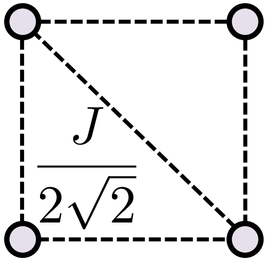
$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}}$$

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)

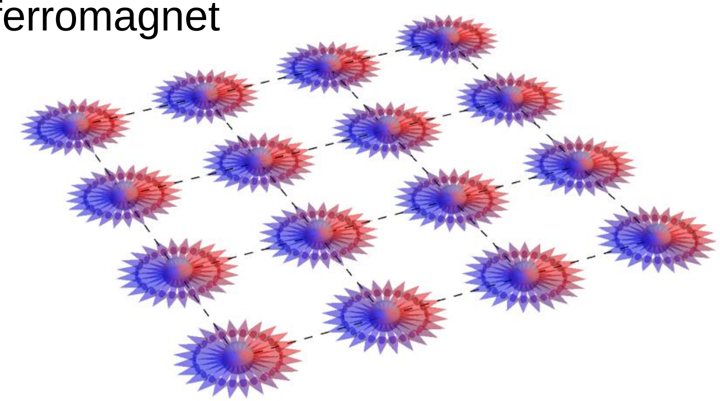


Ansätze wavefunctions

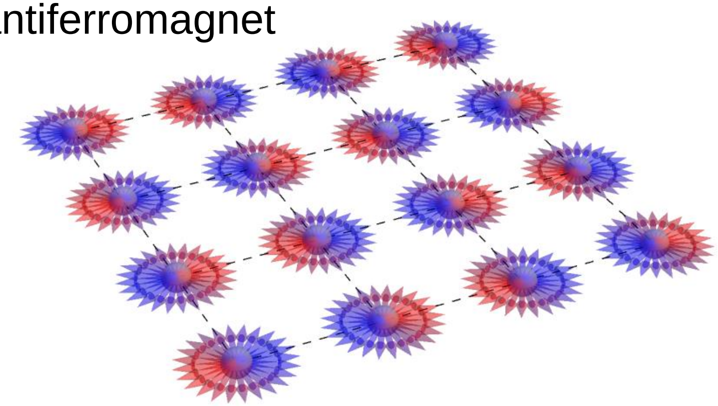
continuous $U(1)$ symmetry

$$M^z = \sum_i \sigma_i^z \quad \text{conserved}$$

XY ferromagnet



XY antiferromagnet



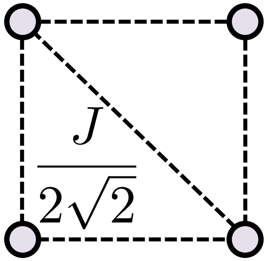
$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}} \qquad |\mathrm{AFM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{AFM}\rangle_{\mathrm{X}}$$

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)

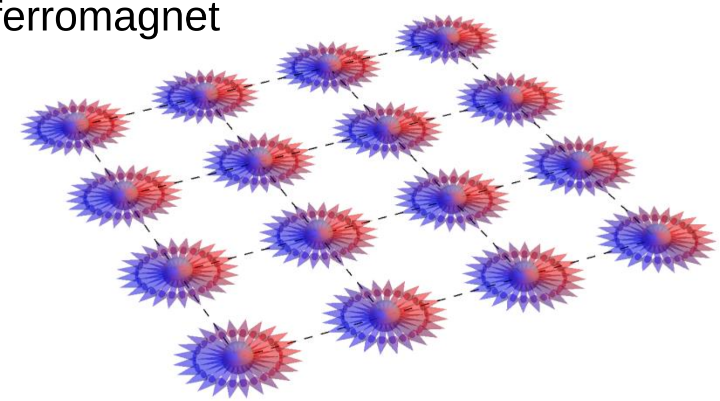


Ansätze wavefunctions

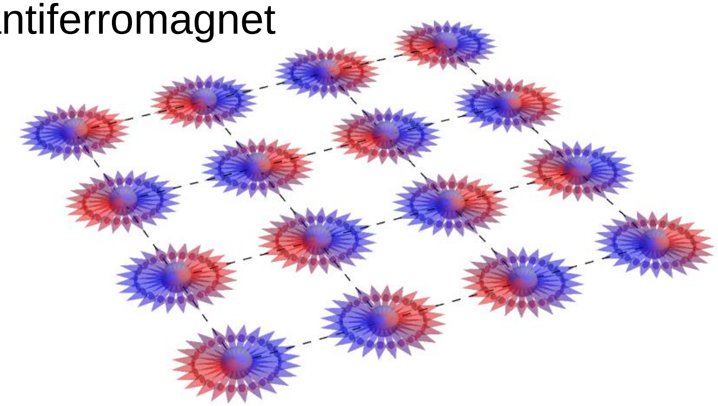
continuous $U(1)$ symmetry

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

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

$$\langle \hat{X} \rangle = 0$$
$$\langle \hat{X}\hat{X} \rangle_{NN}^{AF} < 0$$
$$\langle \hat{X}\hat{X} \rangle_{NNN}^{AF} > 0$$

Preparing FM and AFM XY magnets

C. Chen *et al*., Nature **616**, 691 (2023)

Preparing XY ferro- and antiferromagnets

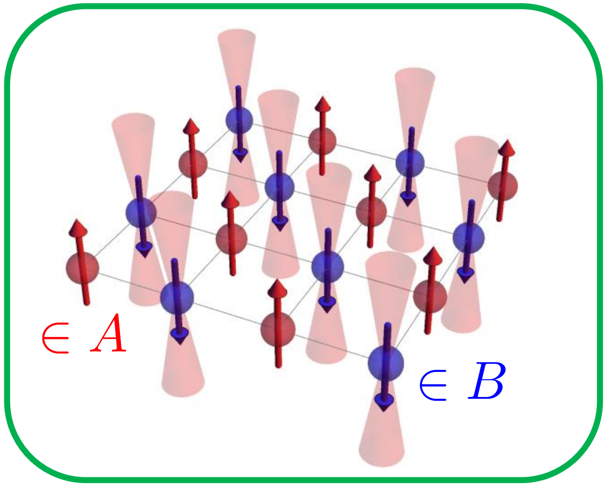
Start from: $$H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + \hbar \sum_i \delta_i \sigma_i^z$$

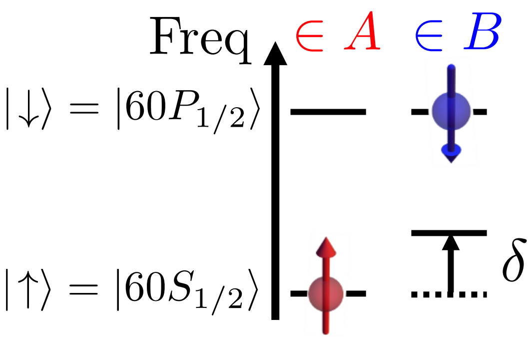
staggered

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





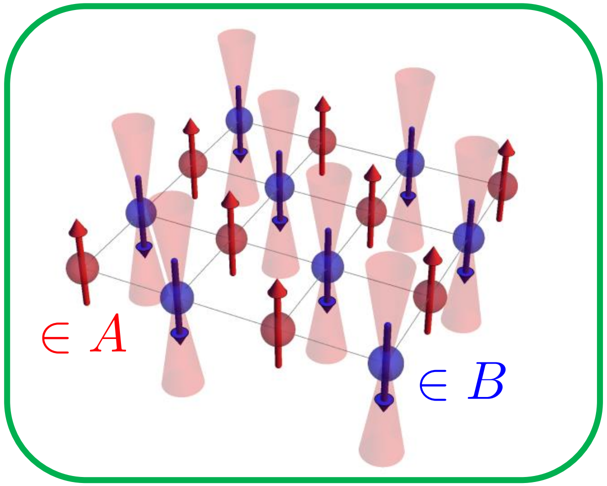
apply local light-shift
(2nd SLM)
+
microwaves

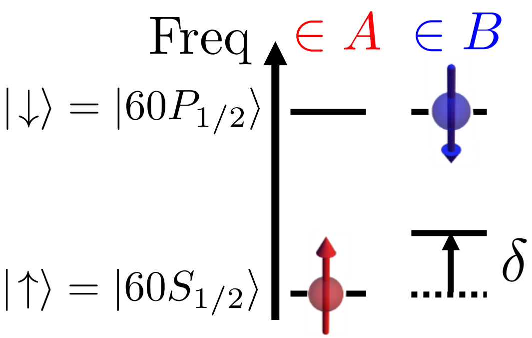
Sørensen *et al.*, PRA 81, 061603(R) (2010)

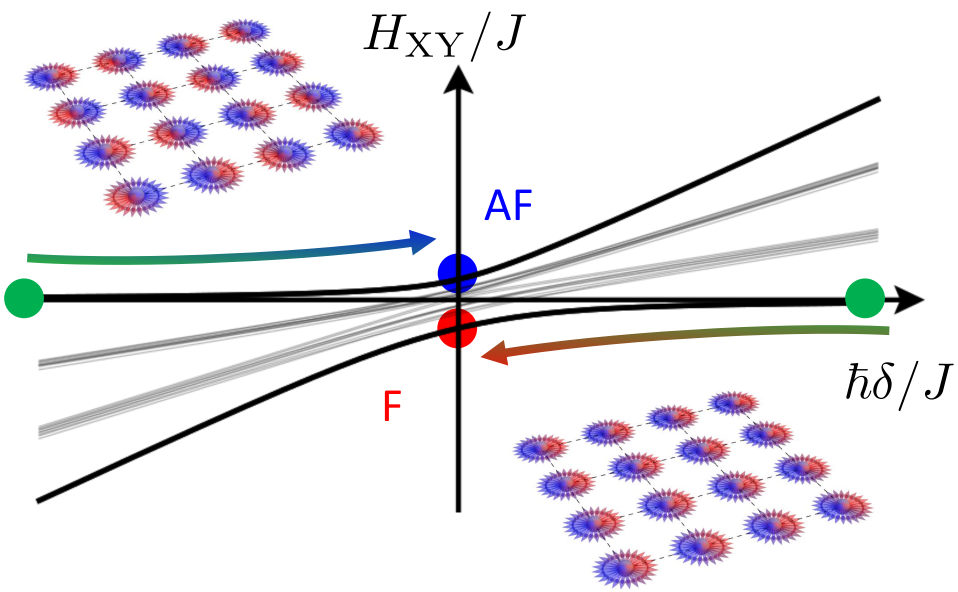
Preparing XY ferro- and antiferromagnets

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

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

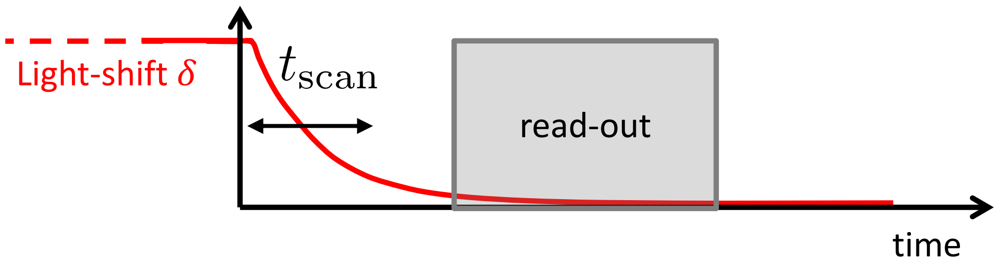






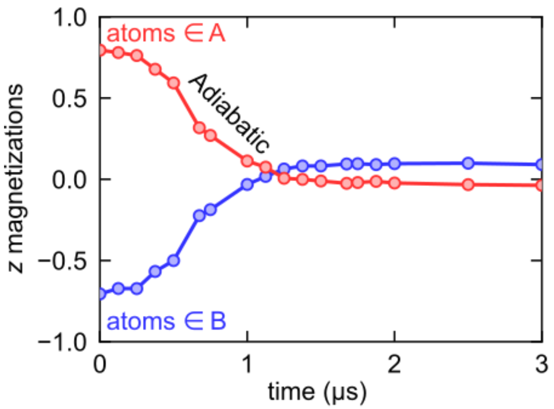
Sørensen *et al.*, PRA 81, 061603(R) (2010)

Preparing XY ferro- and antiferromagnets

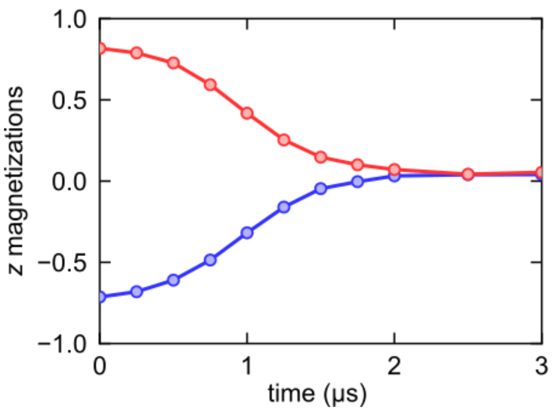


42 atoms

Ferromagnet

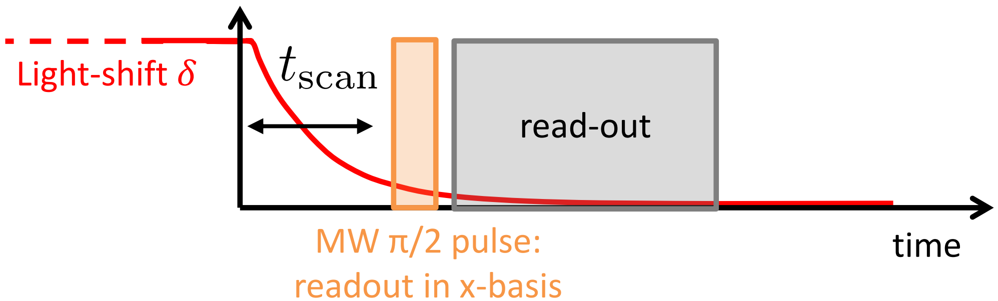


Antiferromagnet

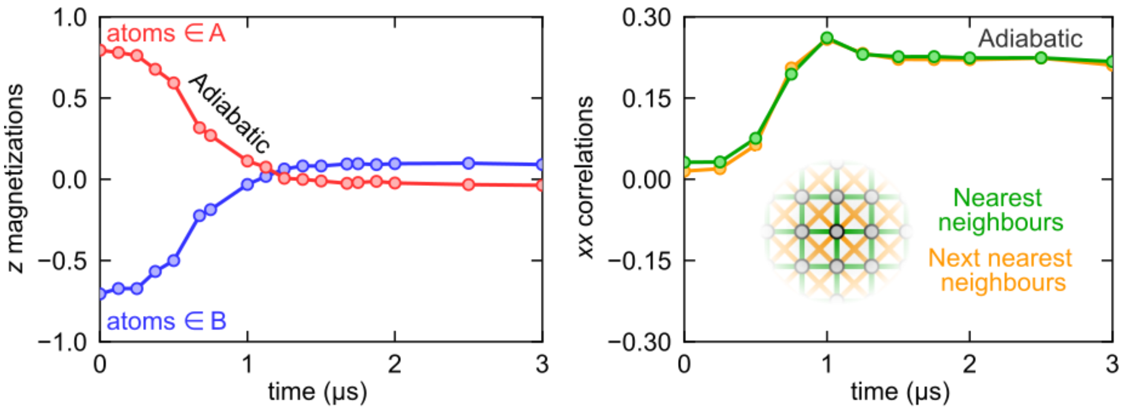


Preparing XY ferro- and antiferromagnets

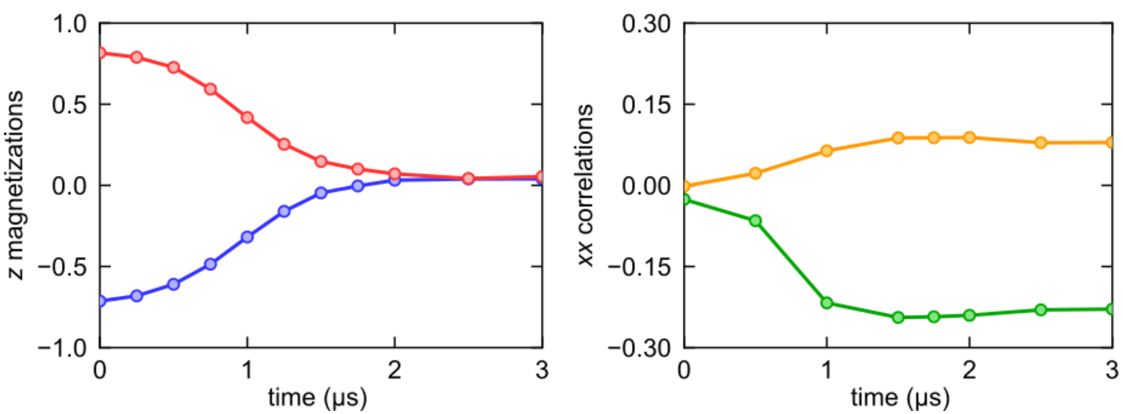
42 atoms



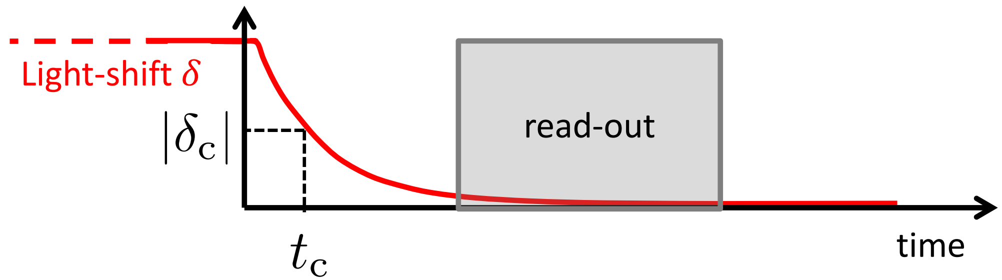
Ferromagnet



Antiferromagnet



Preparing XY ferro- and antiferromagnets



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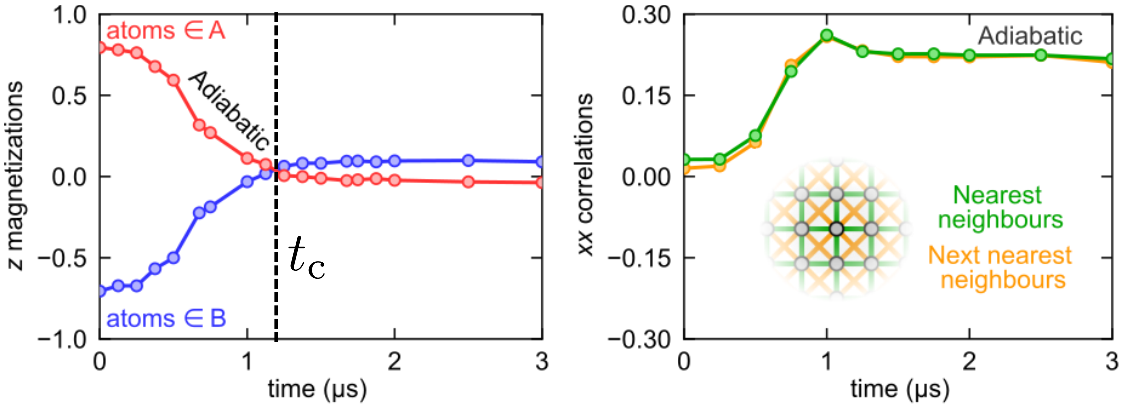
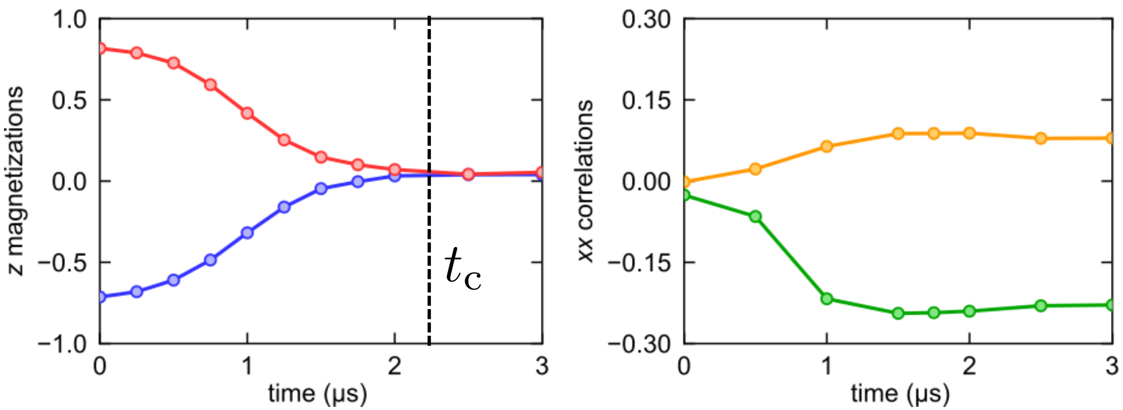


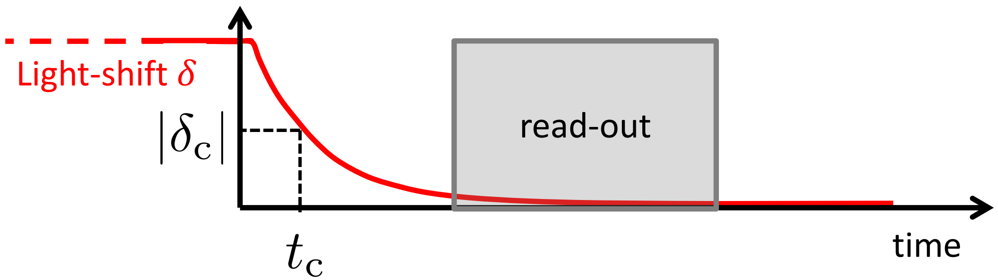
Antiferromagnet



If only NN interactions:

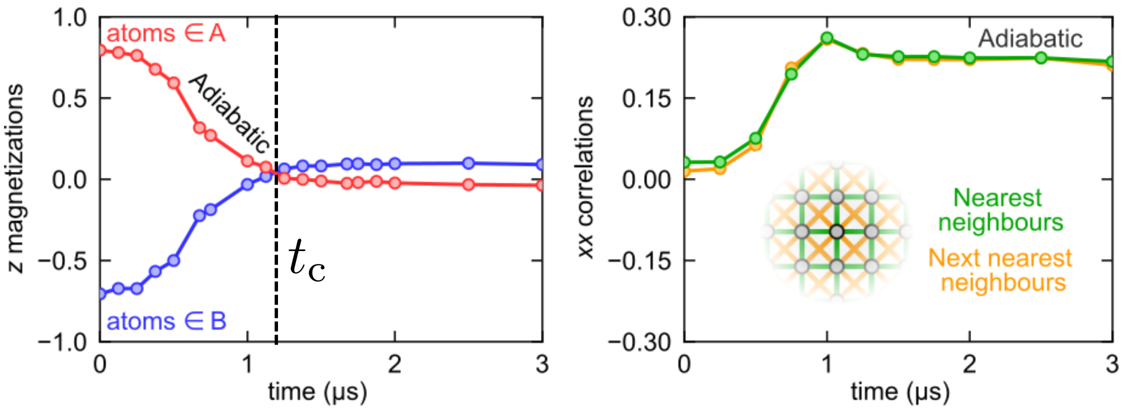
$$|\delta_c^{AFM}| = |\delta_c^{FM}|$$

Preparing XY ferro- and antiferromagnets

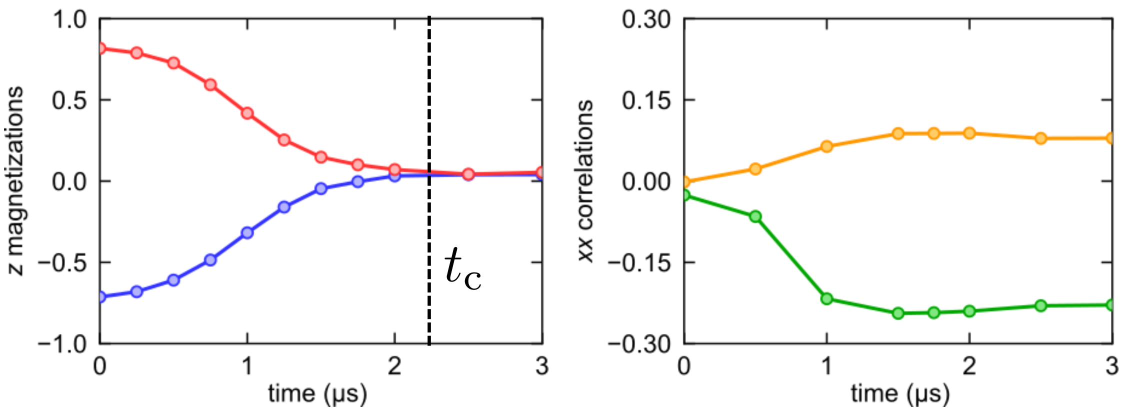


42 atoms

Ferromagnet



Antiferromagnet



If only NN interactions:

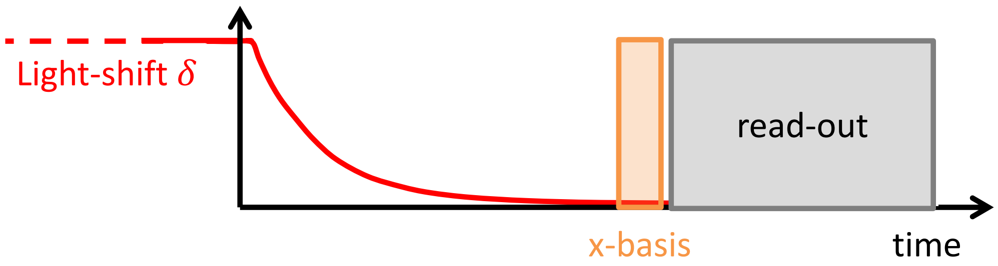
$$|\delta_c^{\mathrm{AFM}}| = |\delta_c^{\mathrm{FM}}|$$

Long-range dipolar interactions:

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

AFM weakly frustrated interactions

Preparing XY ferro- and antiferromagnets



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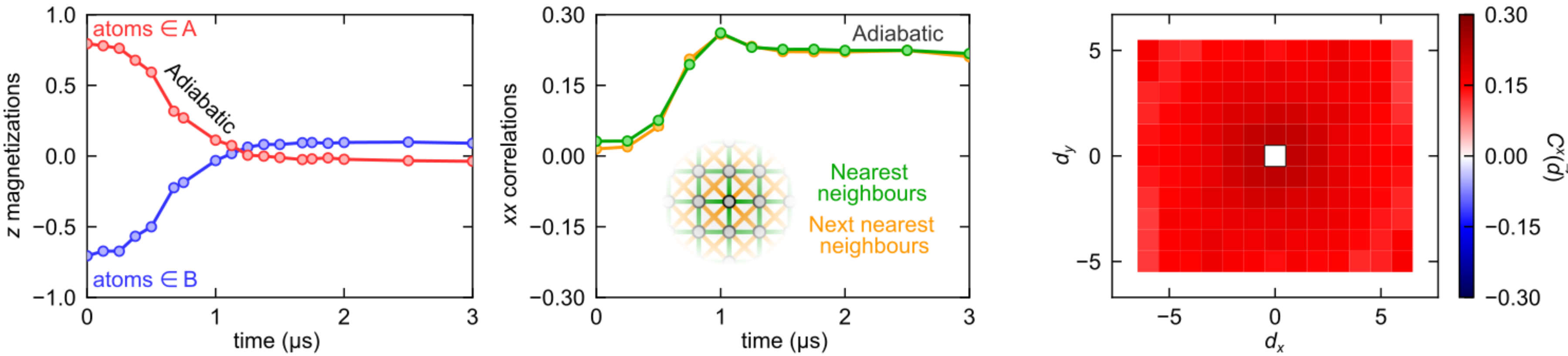
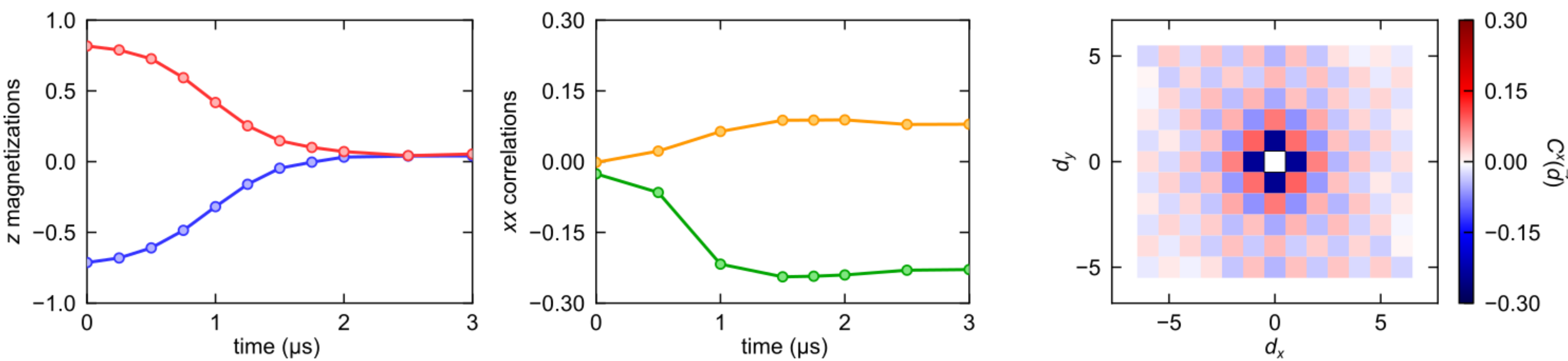
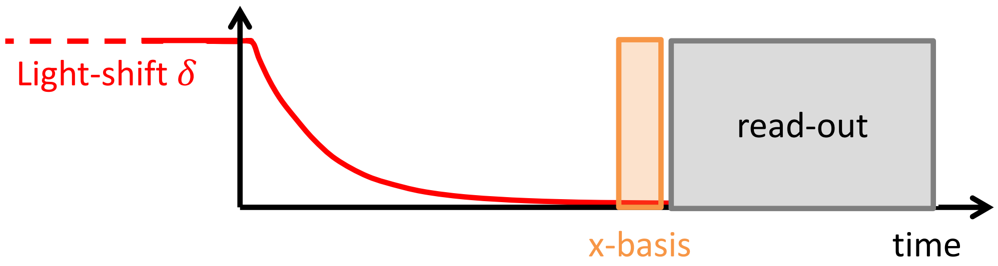
Ferromagnet



Antiferromagnet

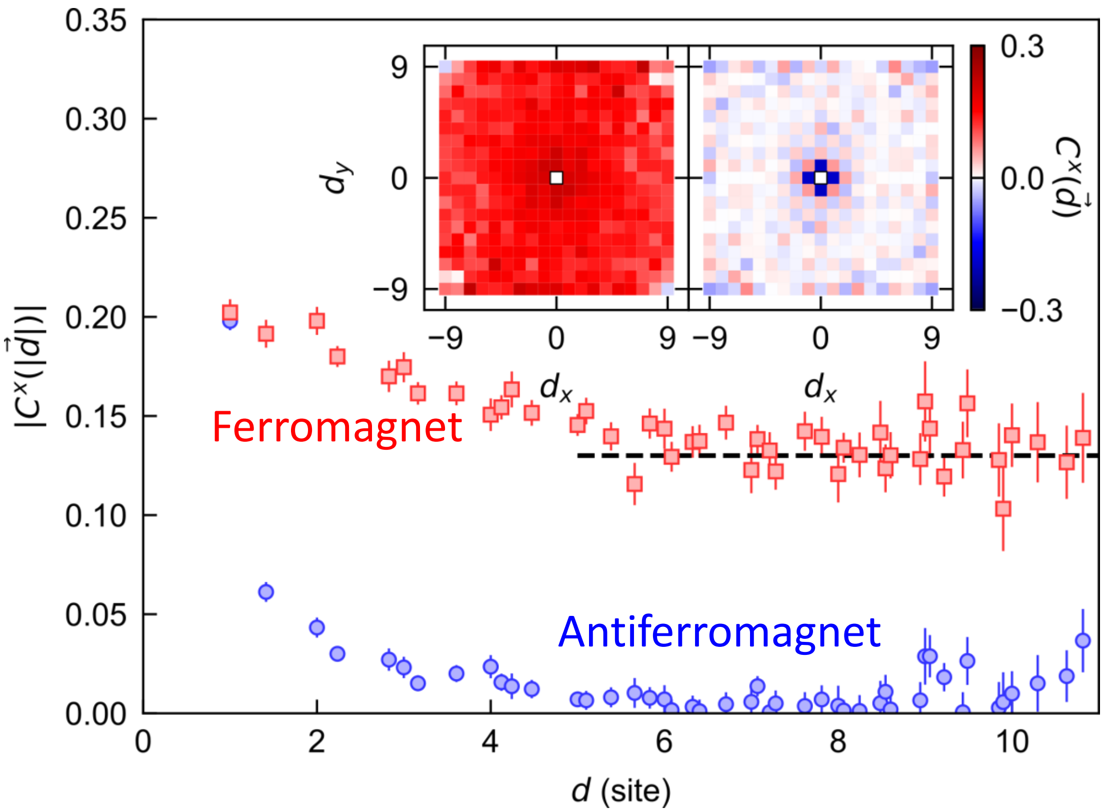


LRO for the FM case



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.*, Nature **616**, 691 (2023)

Scalable spin squeezing in the dipolar XY model

G. Bornet *et al*., arXiv:2303.08053

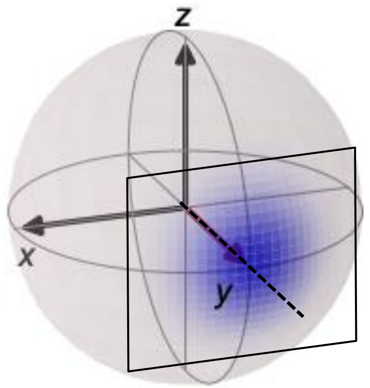
Scalable spin squeezing in the dipolar XY model

G. Bornet *et al*., arXiv:2303.08053

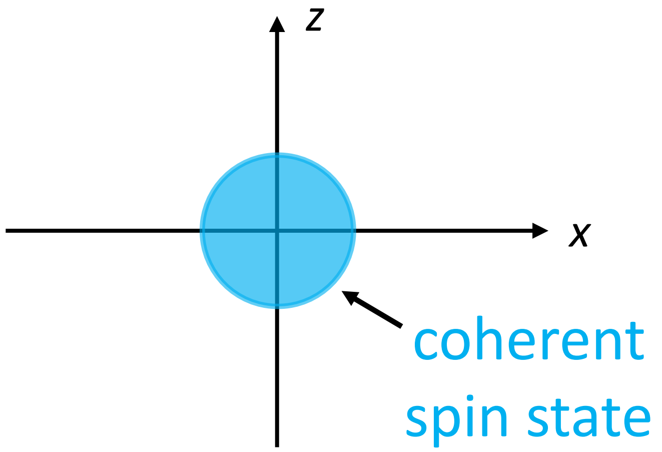
Similar results

- Trapped ions: arXiv:2303.10688 (C. Roos)
- Dressed Rydberg atoms: arXiv:2303.08078 (A. Kaufman), arXiv:2303.08805 (M. Schleier-Smith)

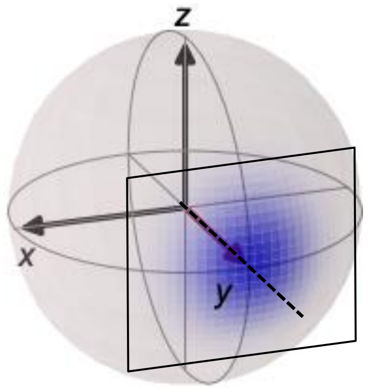
Spin squeezing



$$\Delta J_x \Delta J_z \geq \frac{|\langle J_y \rangle|}{2}$$



Spin squeezing



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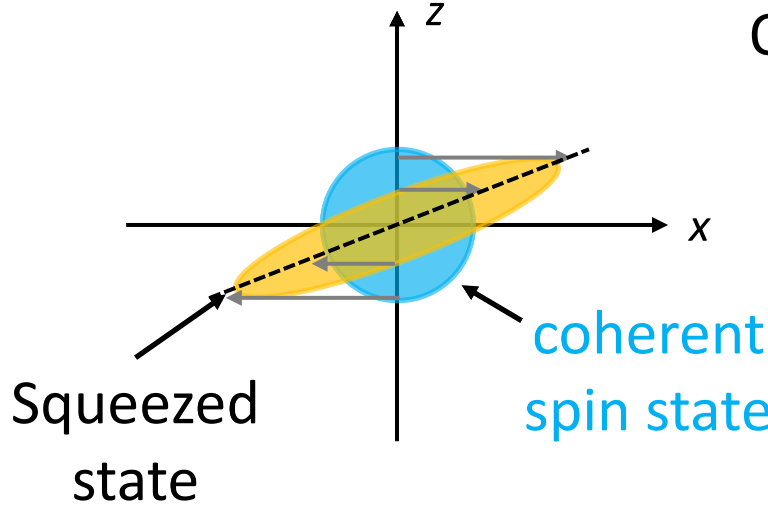
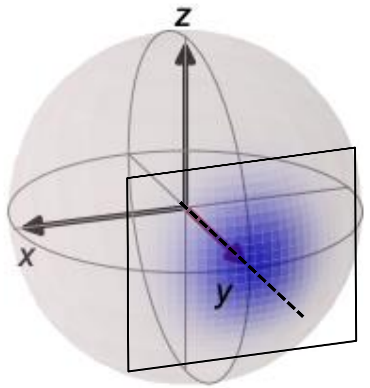


One-axis twisting model

$$H_{\mathrm{OAT}} = \chi J_z^2$$
$$= \chi \sum_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

Spin squeezing



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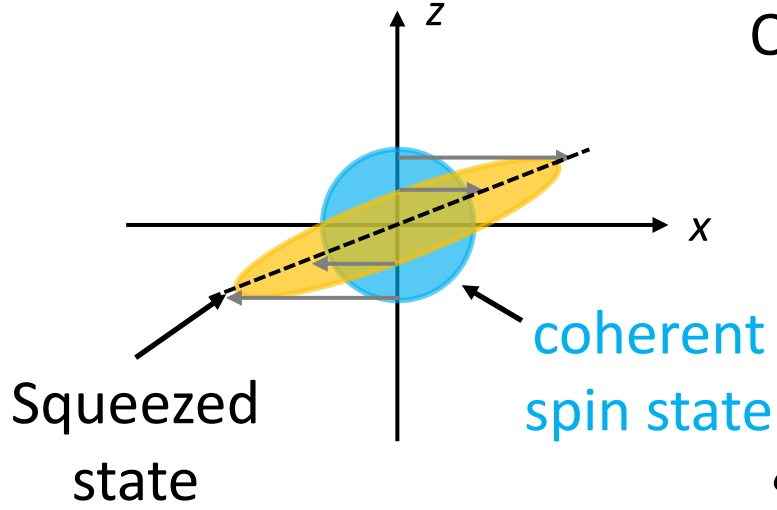
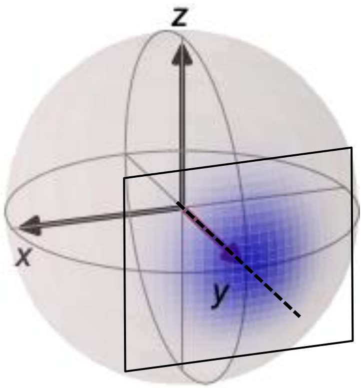


One-axis twisting model

$$H_{\text{OAT}} = \chi J_z^2 = \chi \sum_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

$$\xi_R^2 = N \frac{\min_\perp \left(\Delta J_\perp^2\right)}{\langle \mathbf{J} \rangle^2}$$

Spin squeezing



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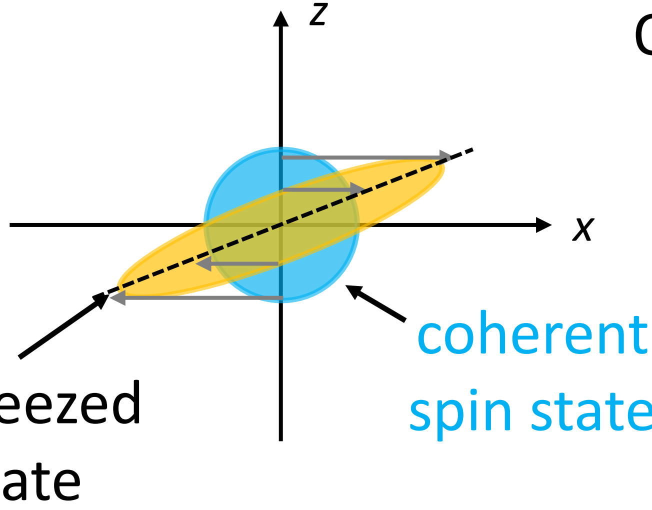

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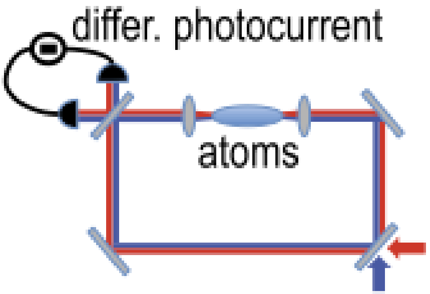
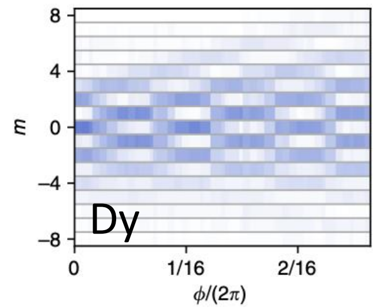
Metrological gain in Ramsey interf.: $\delta\theta_{\mathrm{sq}} = \xi_R^2 \, \delta\theta_{SQL}$ Wineland, PRA 1994

Experimental observations of spin squeezing

Pezzé *et al.*, RMP 2018

Hot / cold atomic vapors

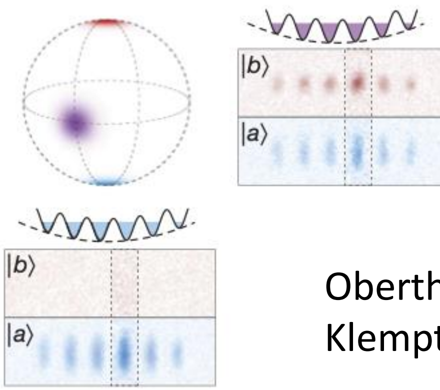




Nat Comm 2018

Polzik (1999), Giacobino, Mitchell, Nascimbene…

Bose-Einstein condensate (OAT)

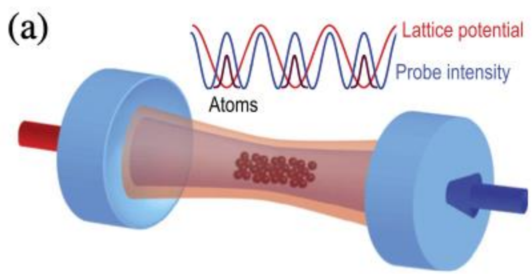


Nature 2010

Oberthaler, Treutlein, Klempt, Reichel, You…

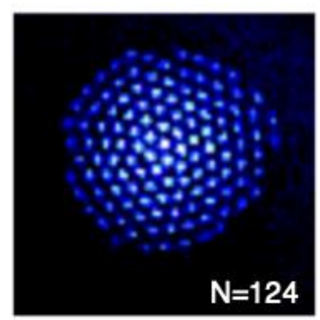
Cavity QED + cold atoms (OAT)

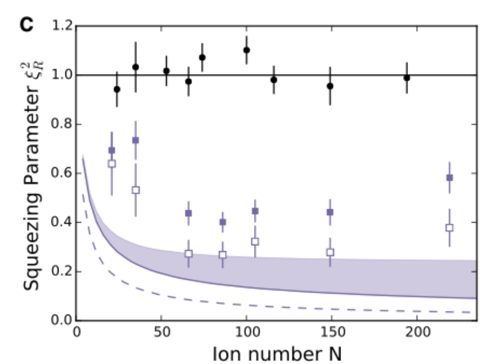
Kasevich, Nature 2016



Vuletic, Kasevich, Thompson (JILA), Je, Schleier-Smith…

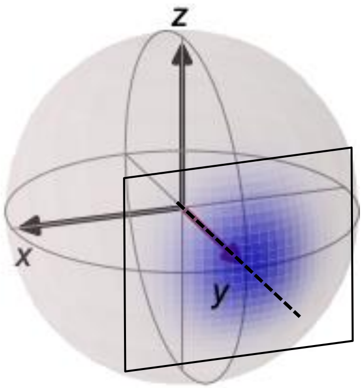
Ion crystal (~OAT)





Bollinger, Science 2016

Spin squeezing in OAT and dipolar XY



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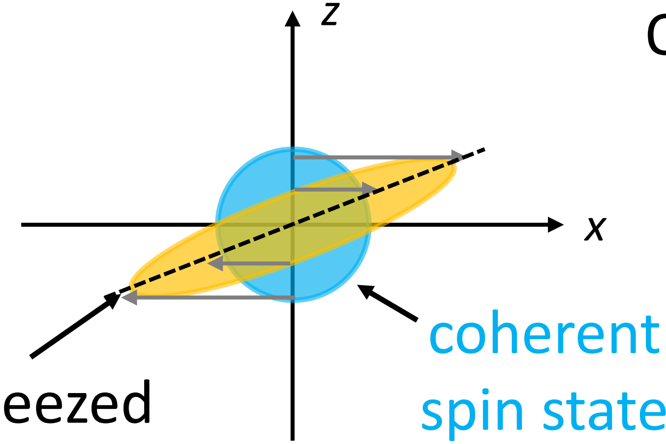

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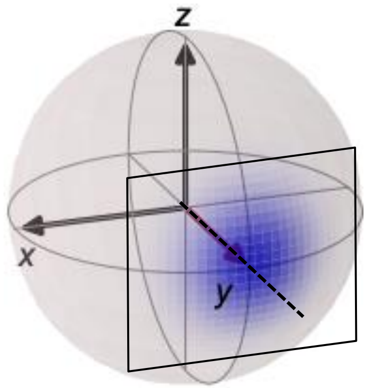
Dipolar XY: “same” structure $H_{\mathrm{XY}} = J \sum_{i<j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y)$

Is 1/*r*³ long-range enough to generate squeezing?

Spin squeezing in OAT and dipolar XY



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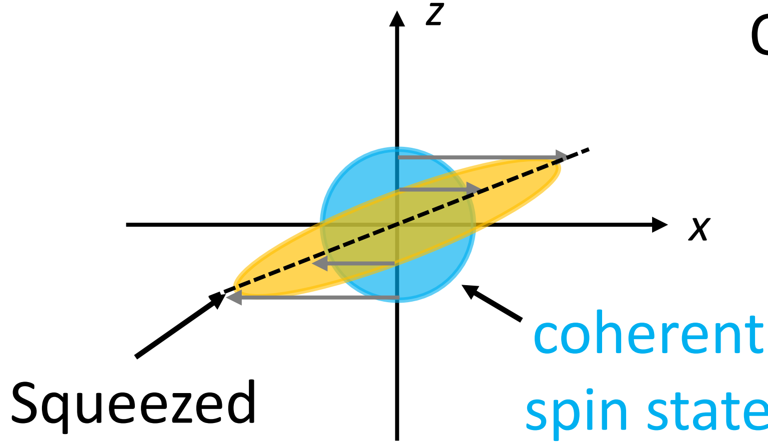

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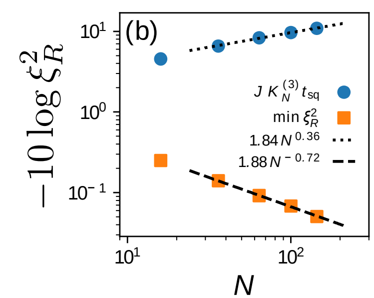
Is 1/*r*³ long-range enough to generate squeezing?

Prediction: yes!

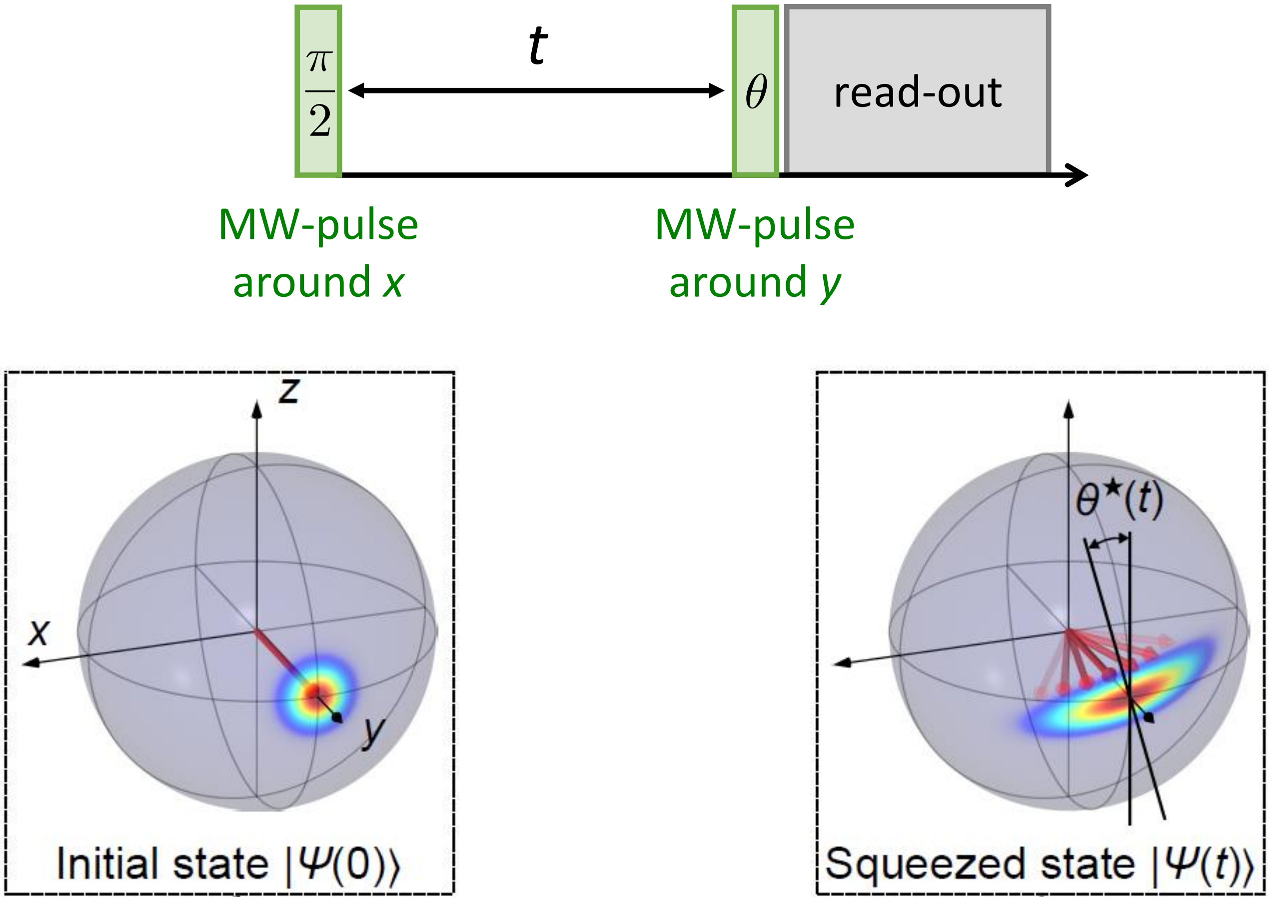
M.P.A Jones & T. Pohl, PRL (2014)
A-M. Rey, PRL (2020)
T. Roscilde, PRL **129**, 150503 (2022)
N. Yao, arXiv:2301.09636

And should scale:

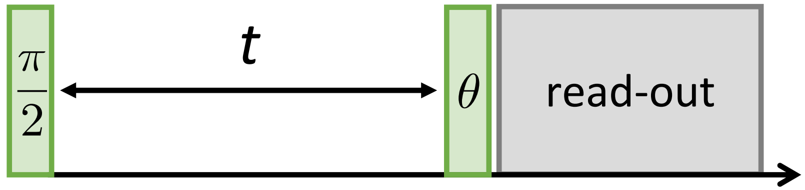
Roscilde
PRL (2022)



Dipolar spin squeezing with Rydberg atoms

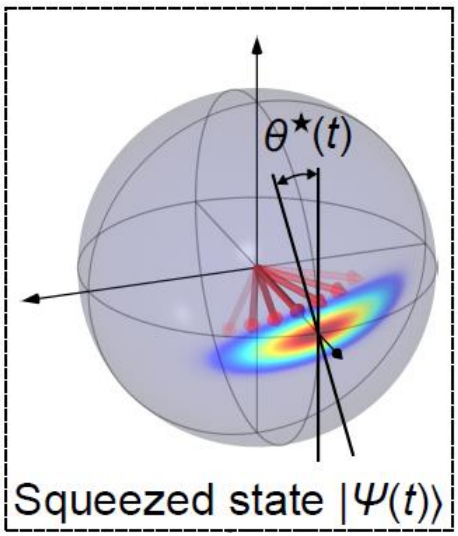


Dipolar spin squeezing with Rydberg atoms

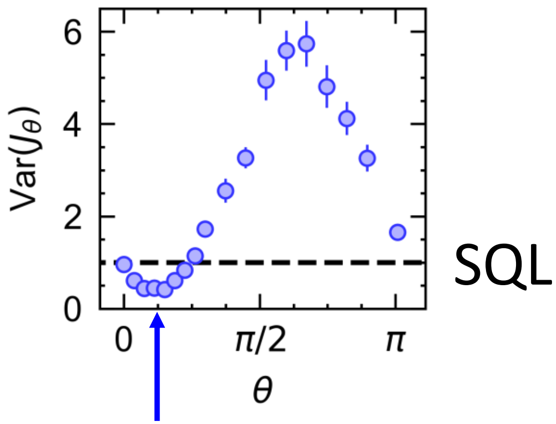


MW-pulse
around *x*

MW-pulse
around *y*

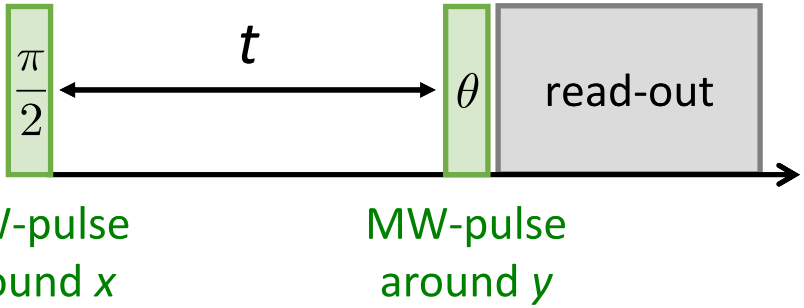


6 × 6 atoms
t = 300 ns



Squeezing !

Dipolar spin squeezing with Rydberg atoms



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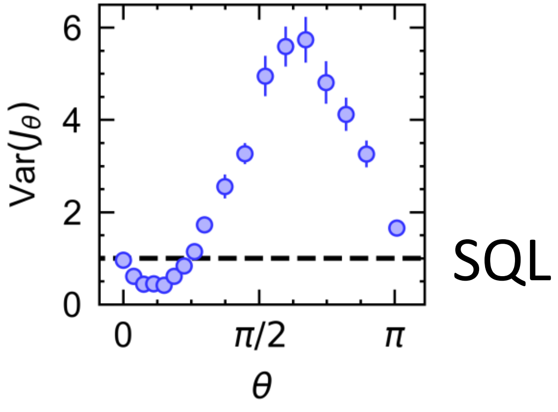
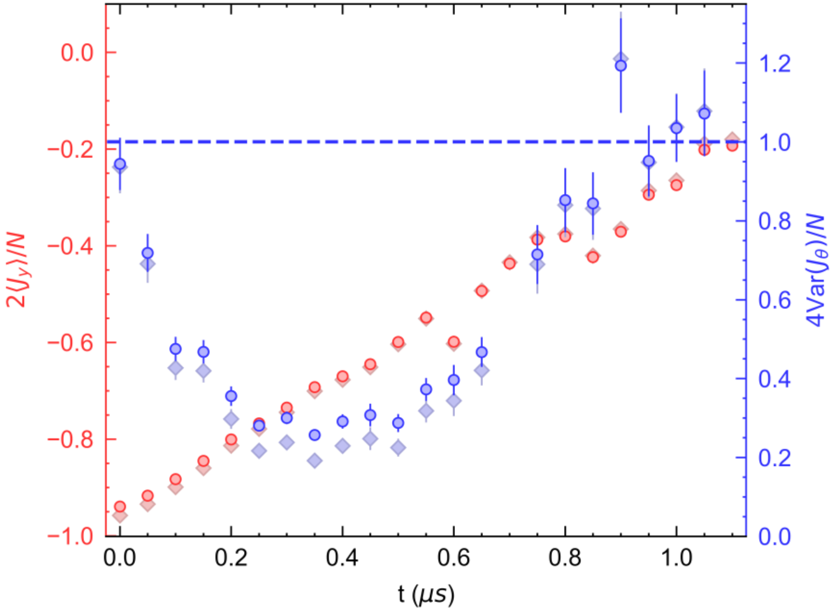
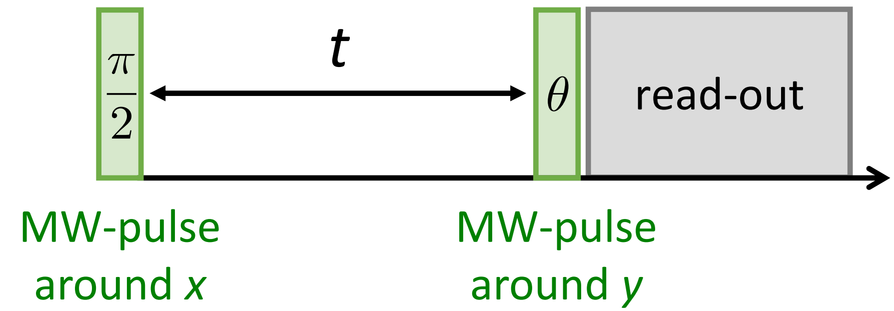




Dipolar spin squeezing with Rydberg atoms



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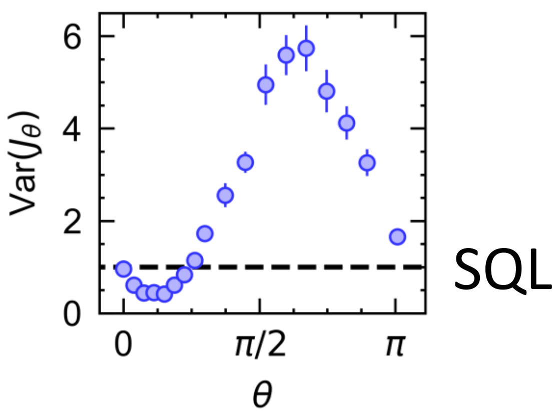

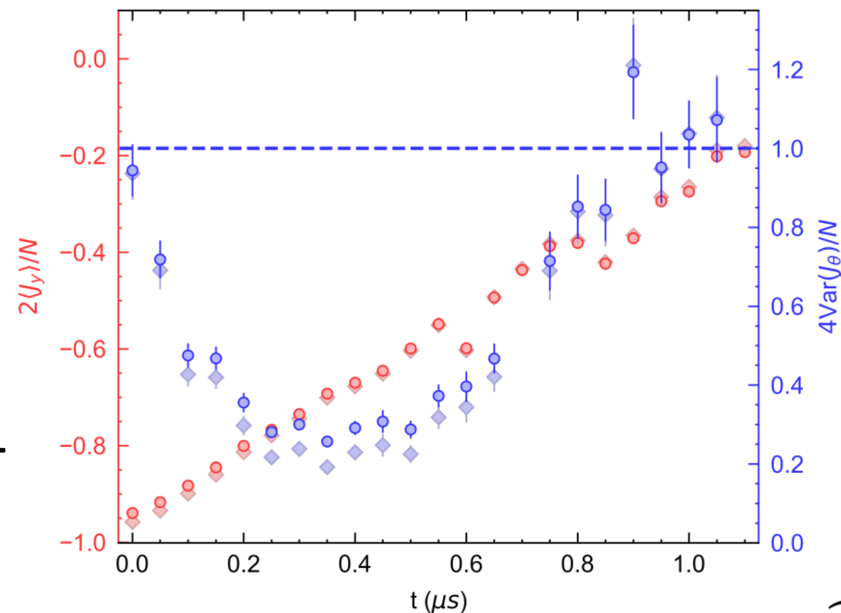

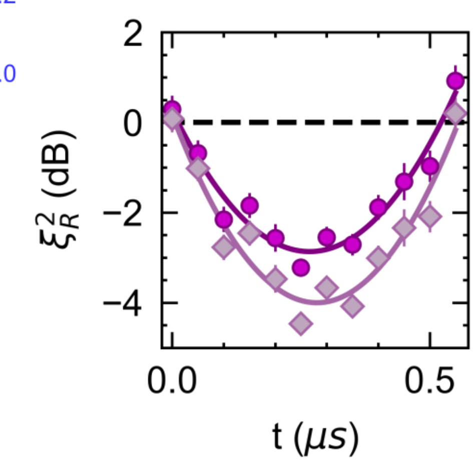

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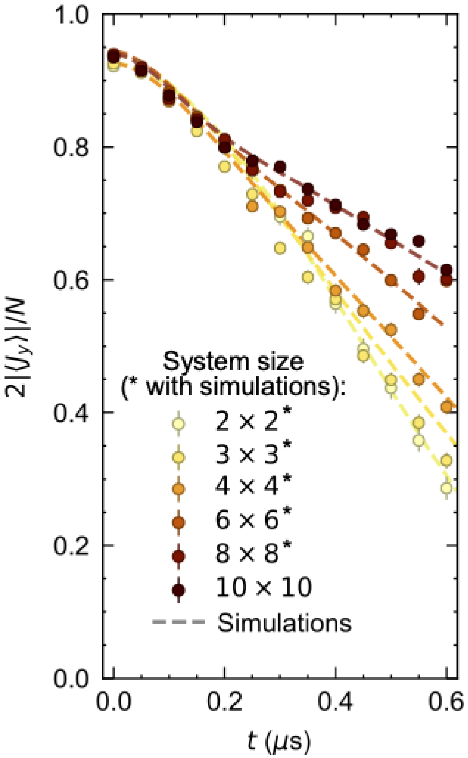
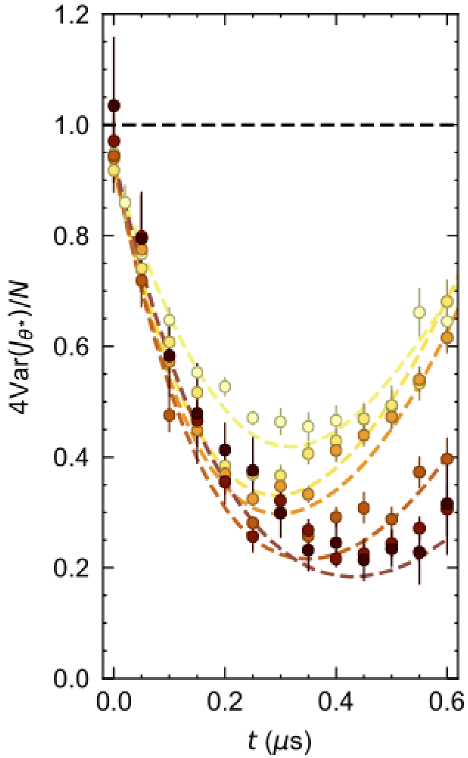
Scaling of the squeezing with the atom number





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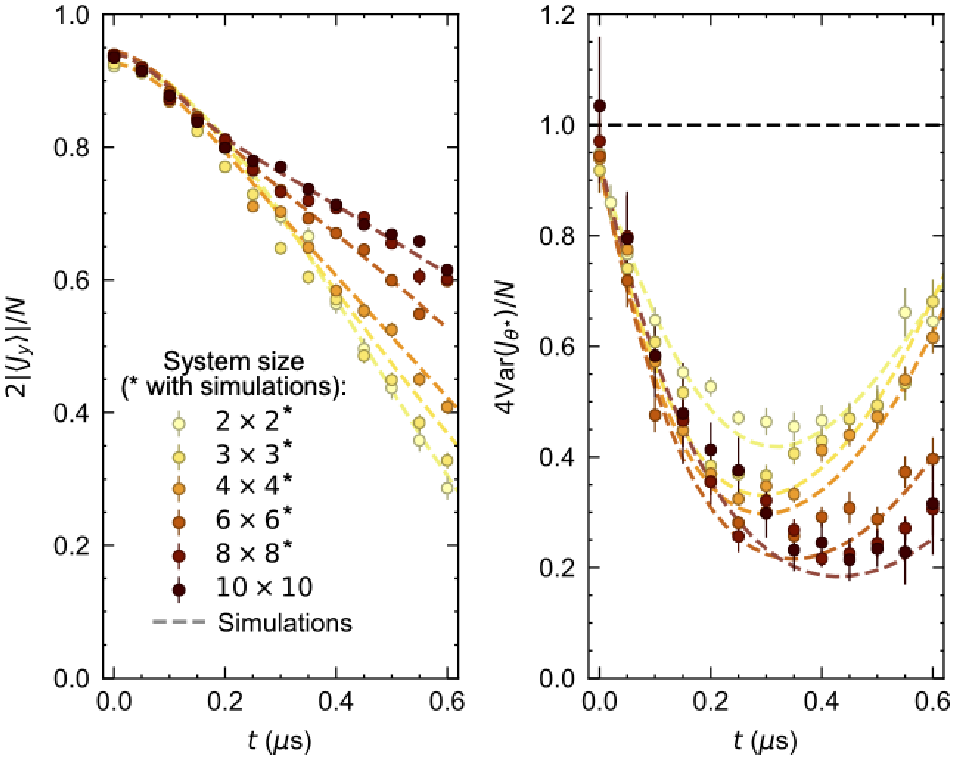
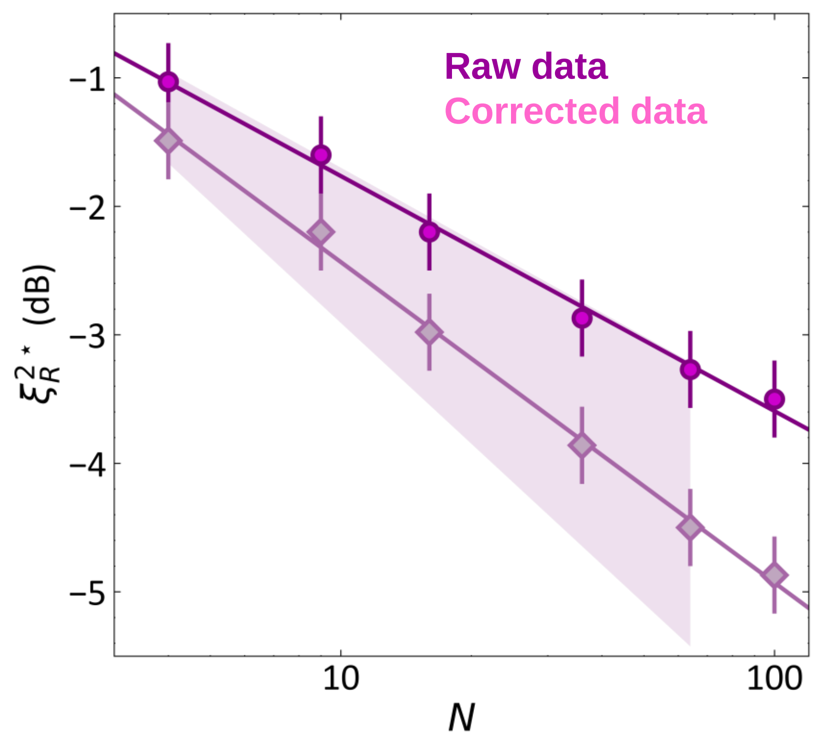


Comparin *et al.*, PRL **129**, 150503 (2022)
Block *et al.*, arXiv:2301.09636
Roscilde *et al.*, arXiv:2303.00380



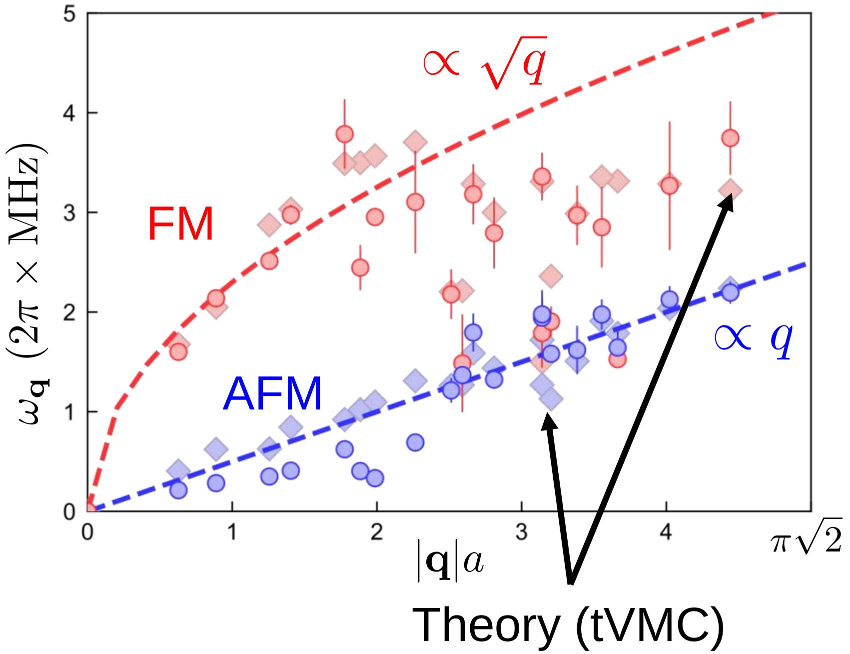
Scalable squeezing!!

Conclusion and future directions

Future directions with RDDI

XY models:

- “Quench spectroscopy”: elementary excitations of FM and AFM



WORK IN PROGRESS

Future directions with RDDI

XY models:

- "Quench spectroscopy": elementary excitations of FM and AFM
- 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…)

Thanks for your attention!