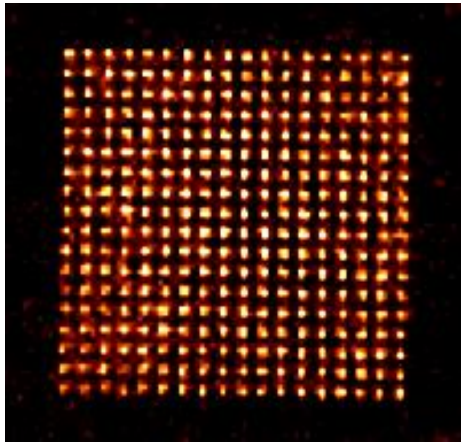
Exploring the properties of the dipolar XY model using arrays of Rydberg atoms

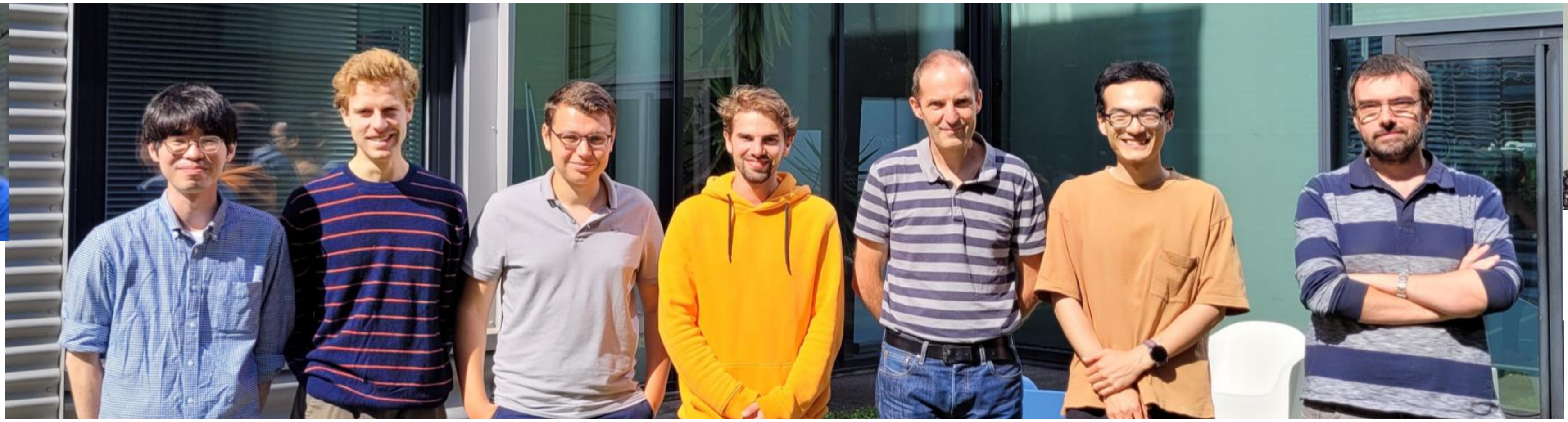
Thierry Lahaye
Laboratoire Charles Fabry, CNRS & Institut d'Optique, Palaiseau, France



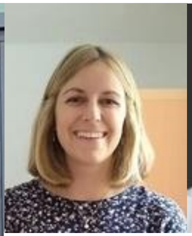
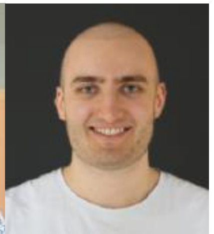
Workshop on Rydberg quantum simulators
Collège de France, April 5th, 2024

The Rydberg team in Palaiseau


Mu Qiao *Daniel Barredo*



Yeelai Chew *Gabriel Emperauger* *Guillaume Bornet* *Bastien Gély* *Antoine Browaeys* *Cheng Chen* *Thierry Lahaye*

Jamie Boyd *Lukas Klein*

Collaborators (theory):
N. Yao (Harvard), T. Roscilde (ENS Lyon)…

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

Funding:

PROGRAMME ET EQUIPEMENTS PRIORITAIRES DE RECHERCHE QUANTIQUE

anr

erc

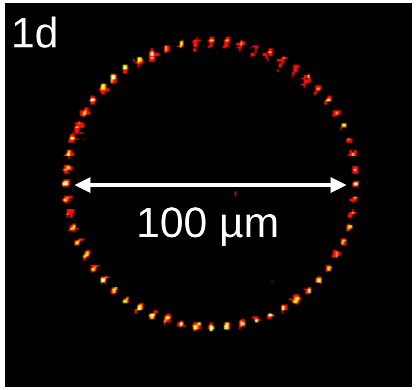
QUANTUM FLAGSHIP

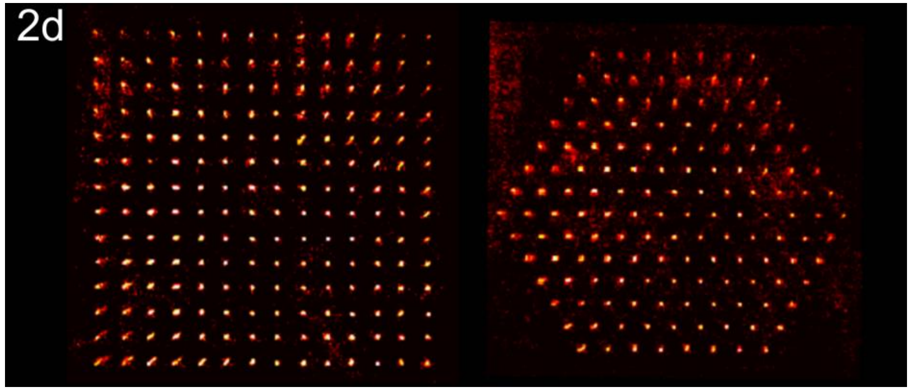
PASQuanS2

Rydberg atom arrays

- **Arrays of single atoms**

Up to 200 atoms
Spacing: a few microns
Full control of geometry in 2D

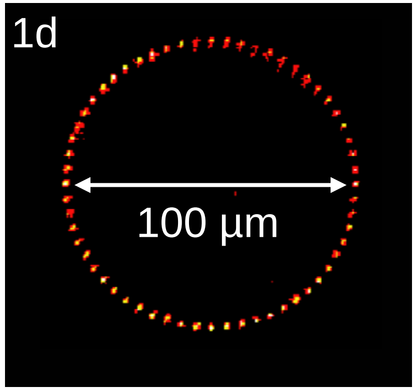


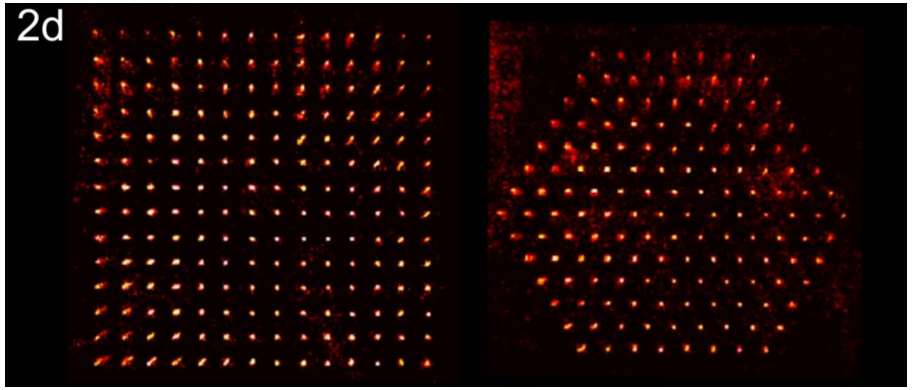


Rydberg atom arrays

- **Arrays of single atoms**

Up to 200 atoms
Spacing: a few microns
Full control of geometry in 2D



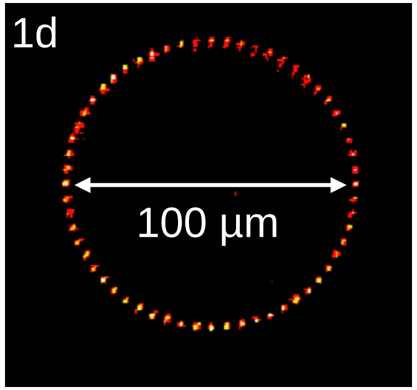


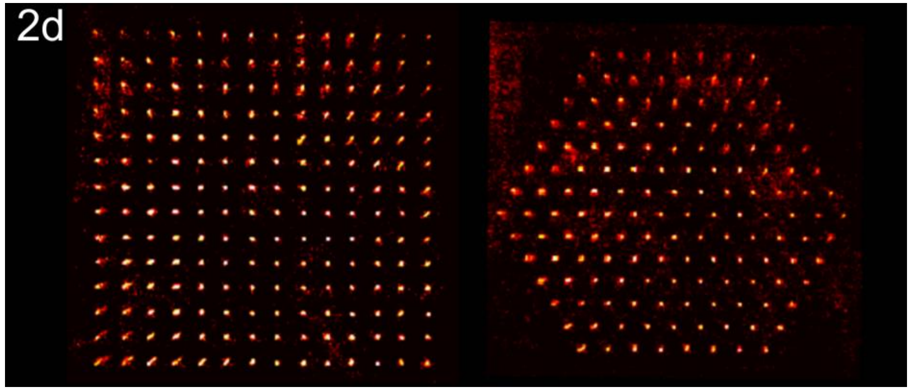
- **Strong interactions via Rydberg excitation**

Interaction strength: 1 to 10 MHz for R ~ 5 µm
Lifetime > 100 µs

Rydberg atom arrays

- **Arrays of single atoms**





Up to 200 atoms
Spacing: a few microns
Full control of geometry in 2D

- **Strong interactions via Rydberg excitation**

Interaction strength: 1 to 10 MHz for $R \sim 5$ µm
Lifetime > 100 µs

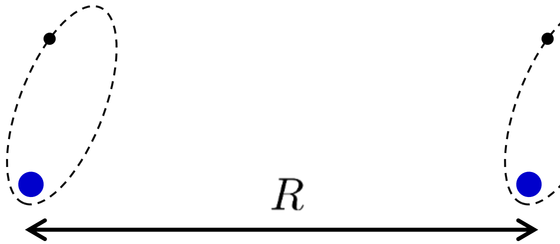
- ***Implement quantum gates***

- ***Quantum simulation of spin models***

Ising (van der Waals interactions)

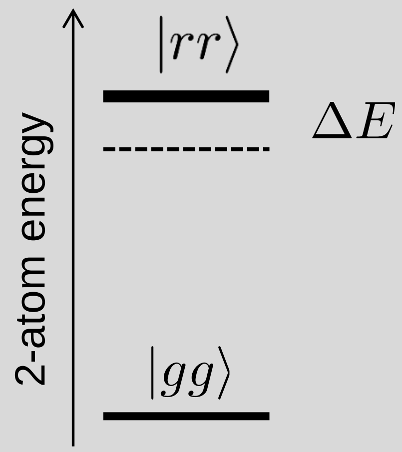
XY (resonant dipole-dipole interaction)

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

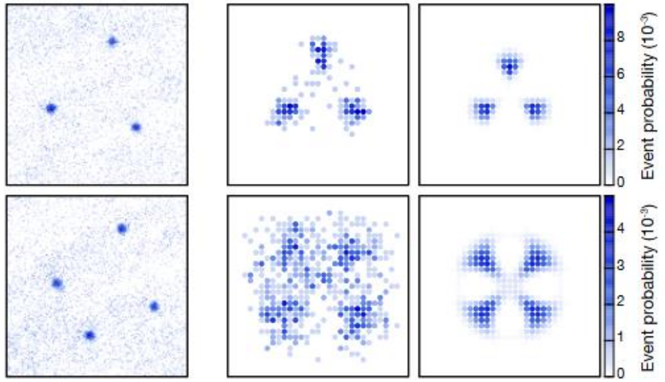


$$\Delta E \sim \frac{C_6}{R^6}$$

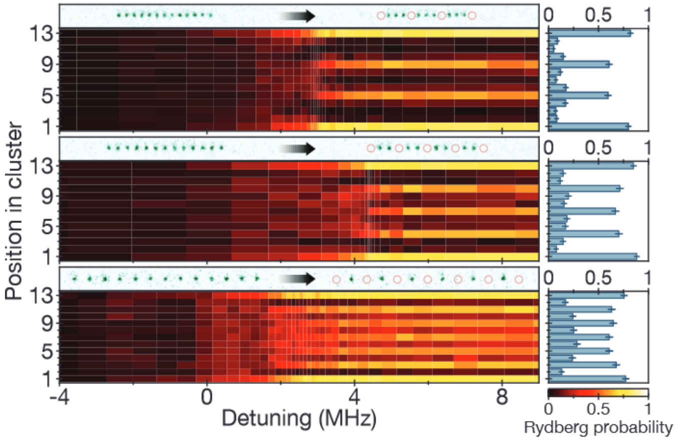
$$\begin{cases} |g\rangle \rightarrow |\downarrow\rangle \\ |r\rangle \rightarrow |\uparrow\rangle \end{cases}$$

Ising-like interaction

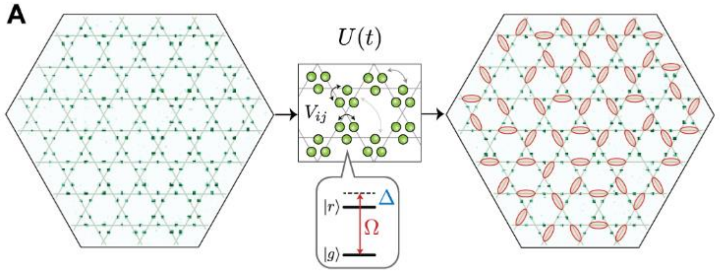
Many experiments on the Ising model



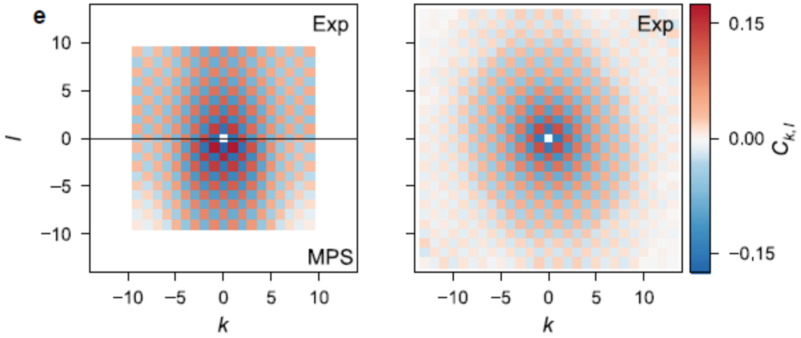
P. Schauss *et al.*, Nature **491**, 87 (2012)



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



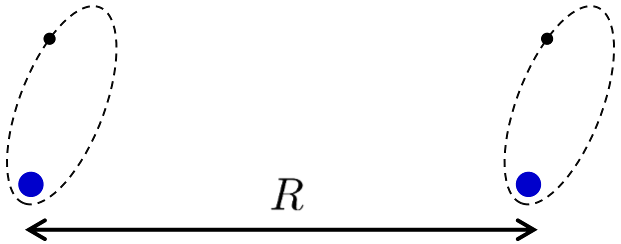
G. Semeghini *et al*., Science **374**, 1242 (2021)



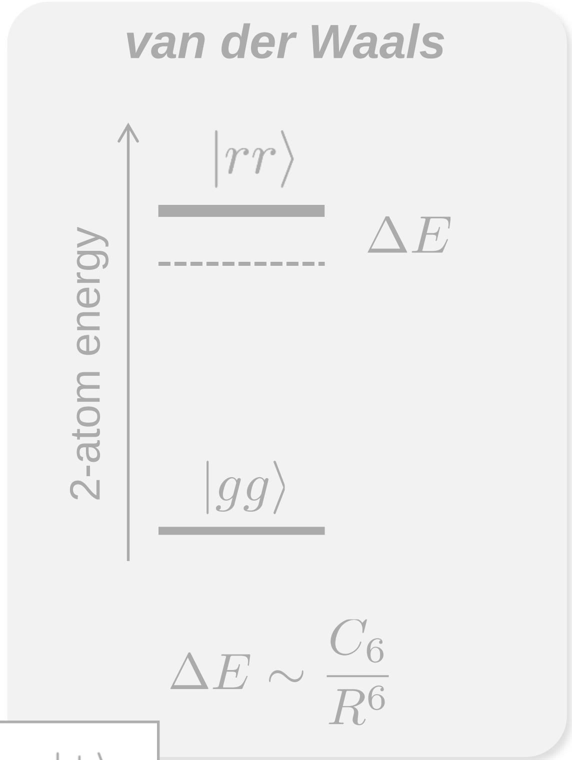
P. Scholl *et al.*, Nature **595**, 233 (2021).

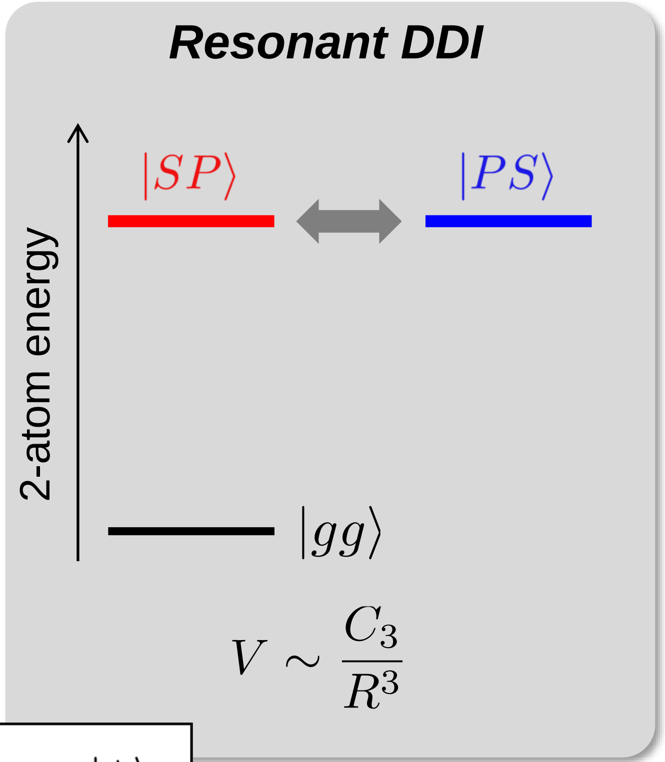
And many, many more examples!

Interactions between Rydberg states



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





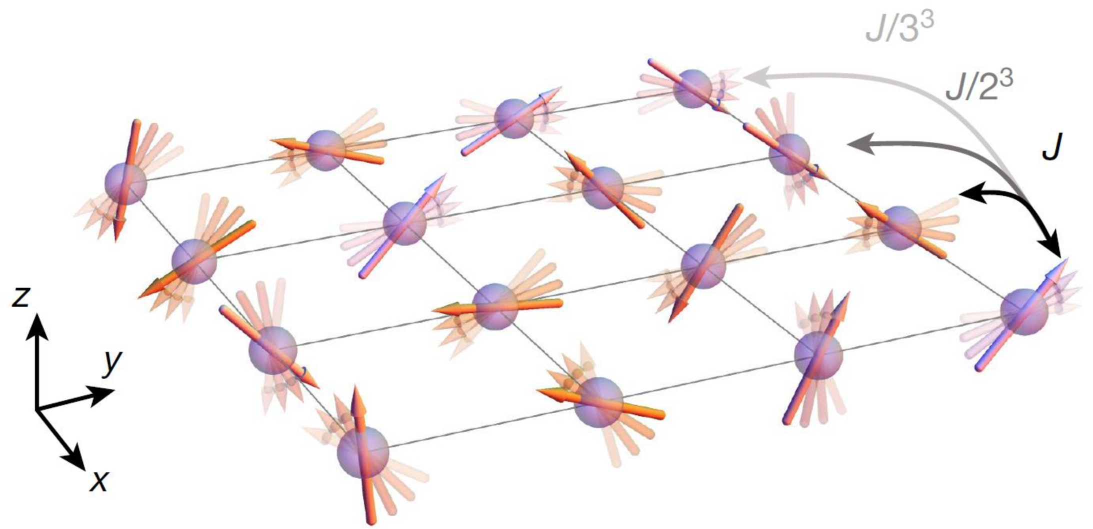
$$\begin{cases} |g\rangle \rightarrow |{\downarrow}\rangle \\ |r\rangle \rightarrow |{\uparrow}\rangle \end{cases}$$

Ising-like interaction

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

XY interaction (flip-flop)

The resonant dipole-dipole interaction: dipolar XY model



$$H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3} \left(\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y \right)$$

- ***Ground-state properties?***
- ***Effect of "long-range" couplings?***
- ***Elementary excitations?***

Outline

1. ***Our tools***

2. ***Quasi-adiabatic preparation of the ground state***

3. ***Quench dynamics: spin squeezing and spectroscopy of spin waves***

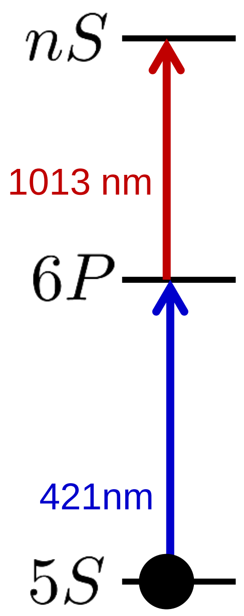
Outline

1. ***Our tools***

2. ***Quasi-adiabatic preparation of the ground state***

3. ***Quench dynamics: spin squeezing and spectroscopy of spin waves***

Encoding a spin in two Rydberg levels



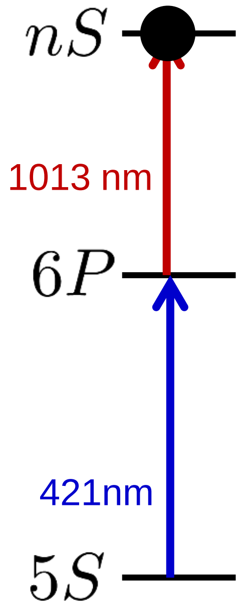
First step: excite all the atoms to *n*S

STIRAP at high Rabi frequencies to overcome the Rydberg blockade

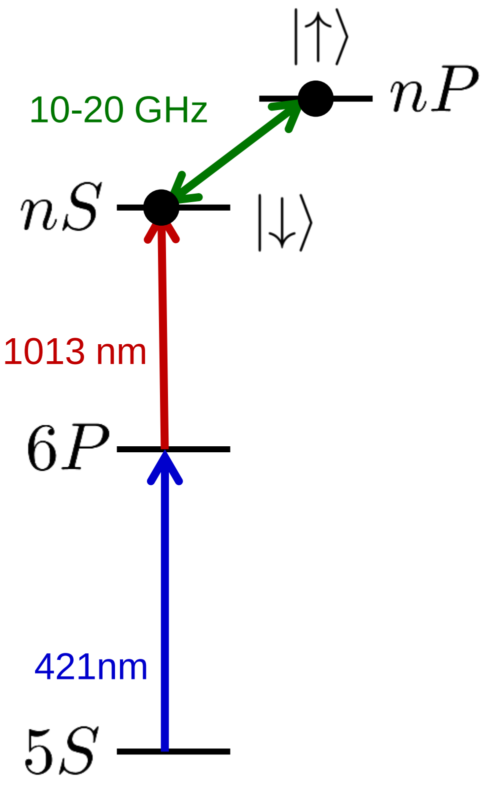
Encoding a spin in two Rydberg levels

First step: excite all the atoms to *n*S

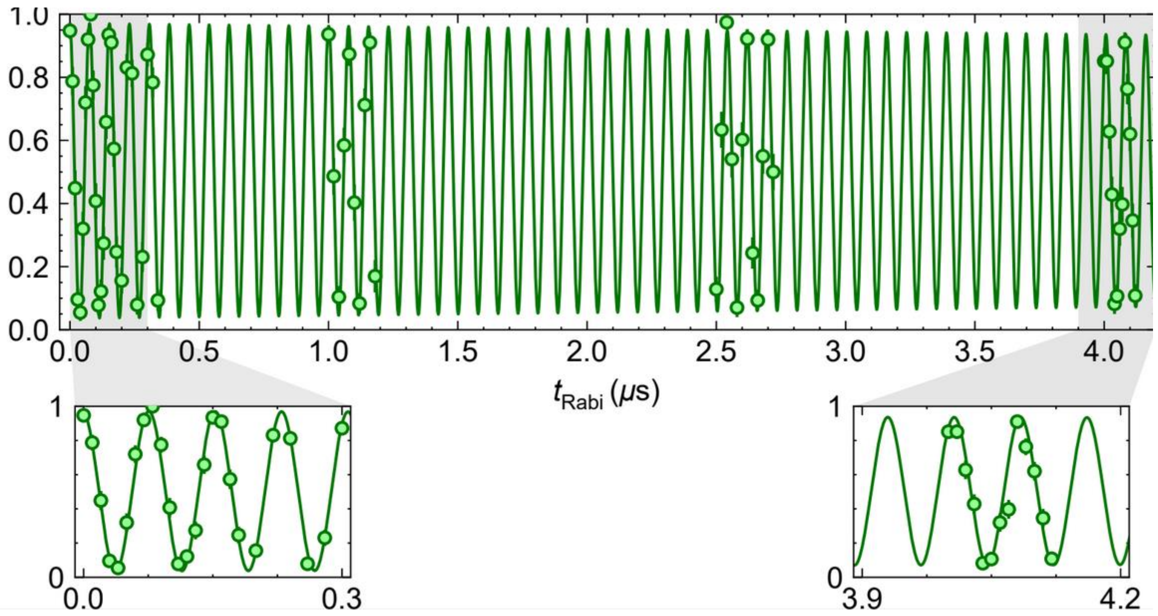
STIRAP at high Rabi frequencies to overcome the Rydberg blockade



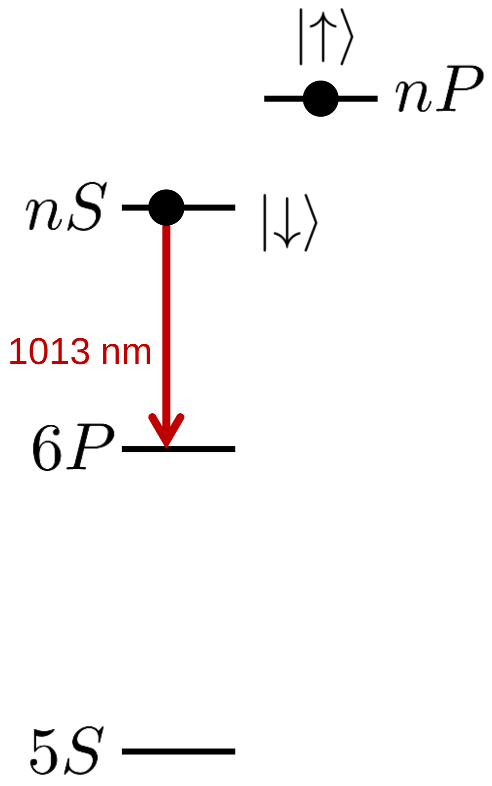
Encoding a spin in two Rydberg levels



60S – 60P Rabi oscillations

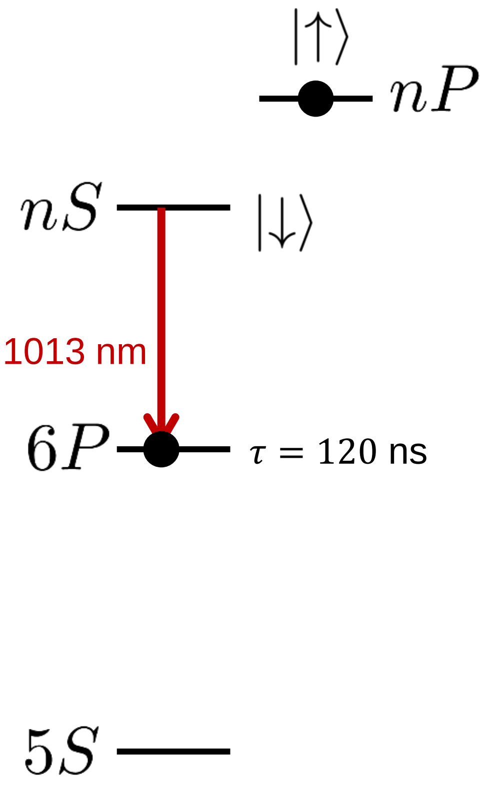


Encoding a spin in two Rydberg levels



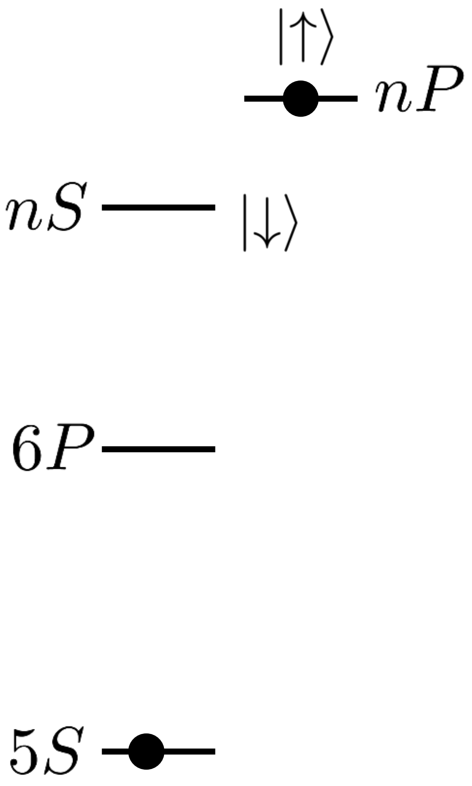
Last step: de-excite selectively the nS atoms to $5S$ for imaging

Encoding a spin in two Rydberg levels

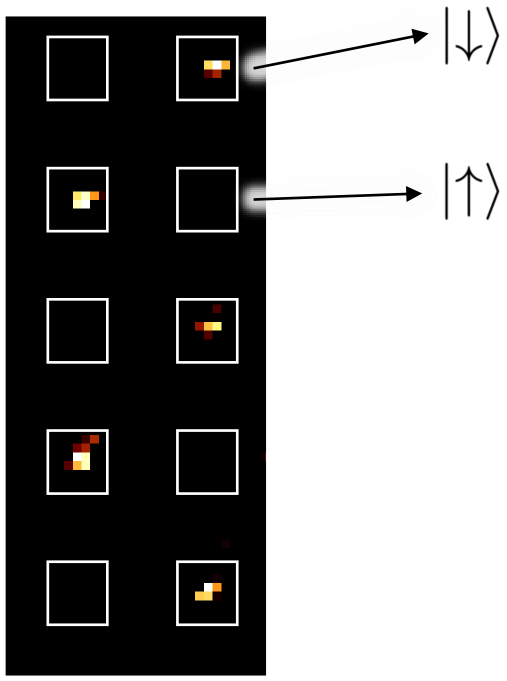


Last step: de-excite selectively the nS atoms to $5S$ for imaging

Encoding a spin in two Rydberg levels



Last step: de-excite selectively the nS atoms to $5S$ for imaging

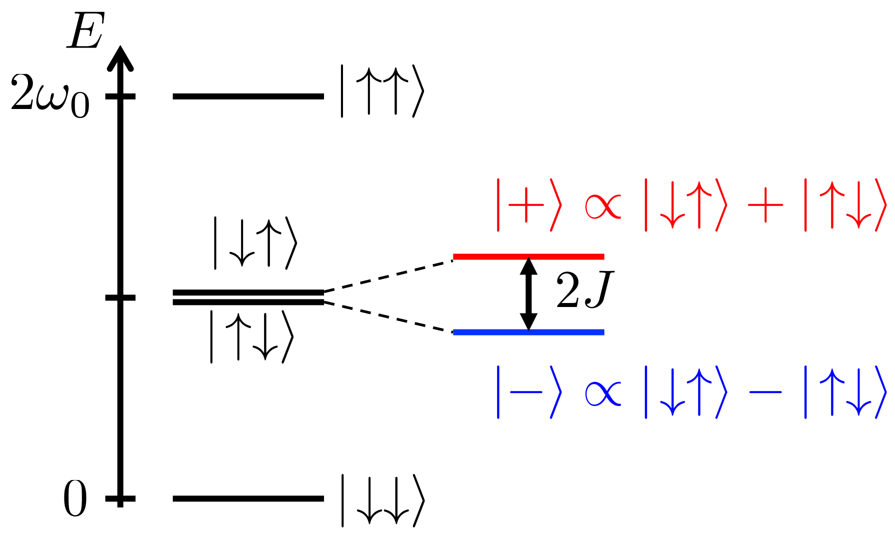


Detection errors (false positives and false negatives) *at the percent level*

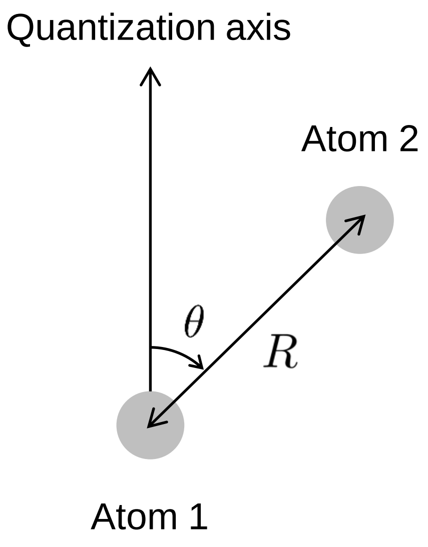
The resonant dipole-dipole interaction: spin exchange

Consider just two atoms:

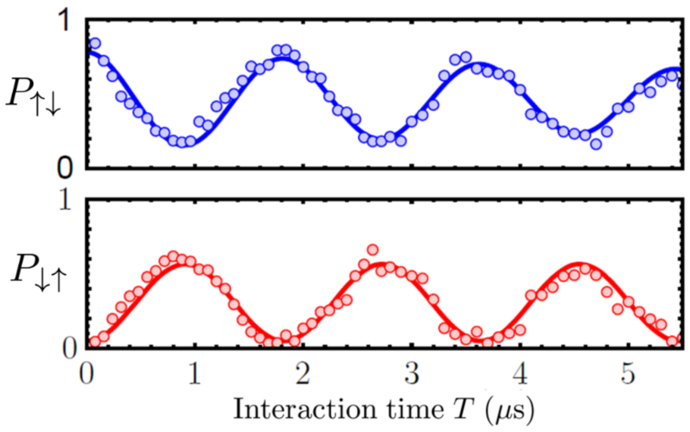
$$H = J\left(\sigma_1^x \sigma_2^x + \sigma_1^y \sigma_2^y\right)$$



Scaling with distance and angular dependence

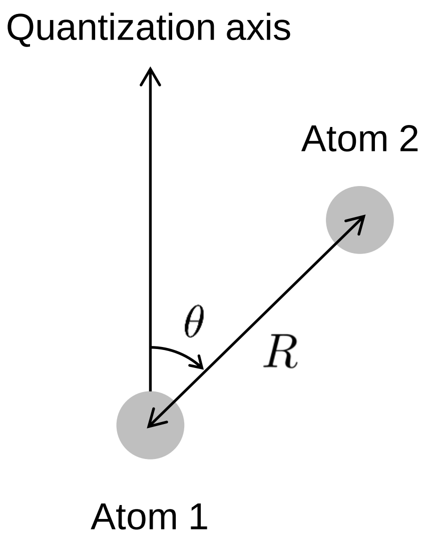


- ***Prepare*** $|\uparrow\downarrow\rangle$ ***and let the two atoms evolve***

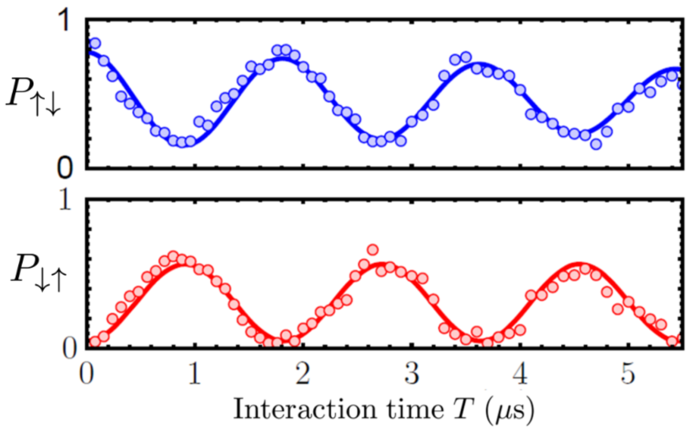


Coherent flip-flops over $R = 30\ \mu\text{m}$ (!)

Scaling with distance and angular dependence

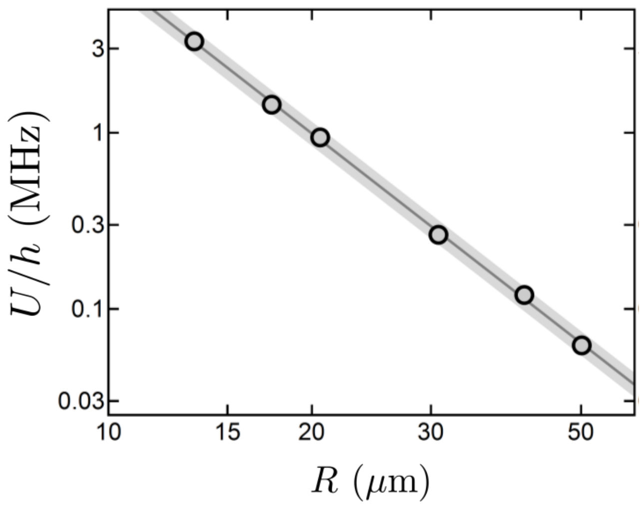


- ***Prepare*** $|\uparrow\downarrow\rangle$ ***and let the two atoms evolve***



Coherent flip-flops over $R = 30$ μm (!)

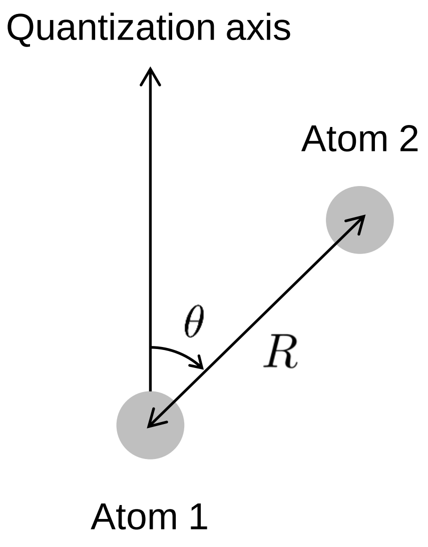
- ***Vary the distance***



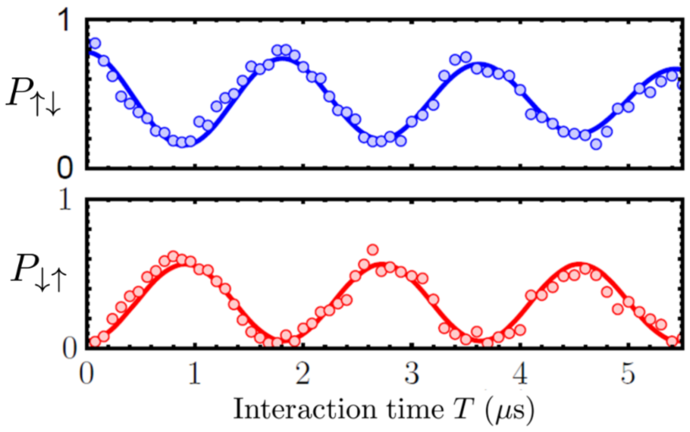
$1/R^3$ interaction

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

Scaling with distance and angular dependence



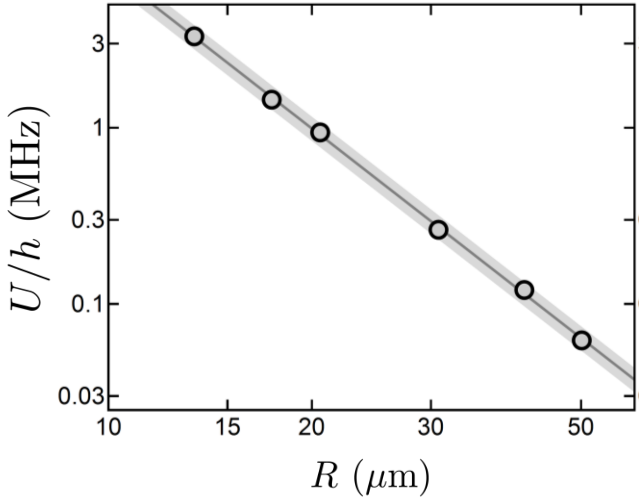
- ***Prepare*** $|\uparrow\downarrow\rangle$ ***and let the two atoms evolve***



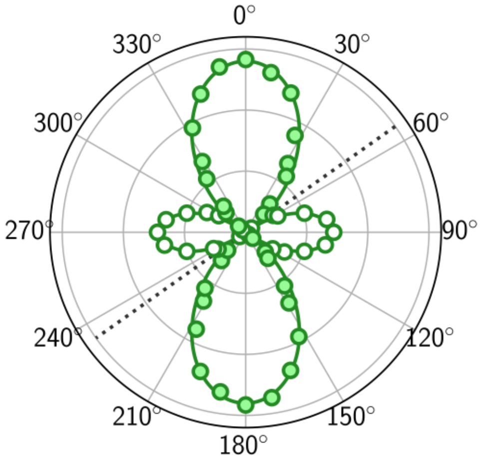
Coherent flip-flops over $R = 30\ \mu\mathrm{m}$ (!)

- ***Vary the distance***

$1/R^3$ interaction



- ***Vary the angle***



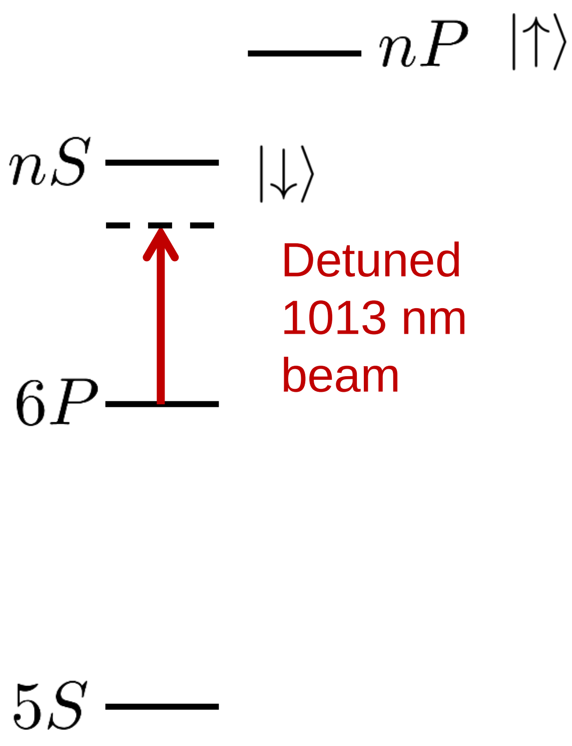
$$V_{\mathrm{dd}} \propto \left(1 - 3\cos^2\theta\right)$$

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

Optical addressing

Microwave manipulations are ***global*** $(\lambda \sim \mathrm{cm})$

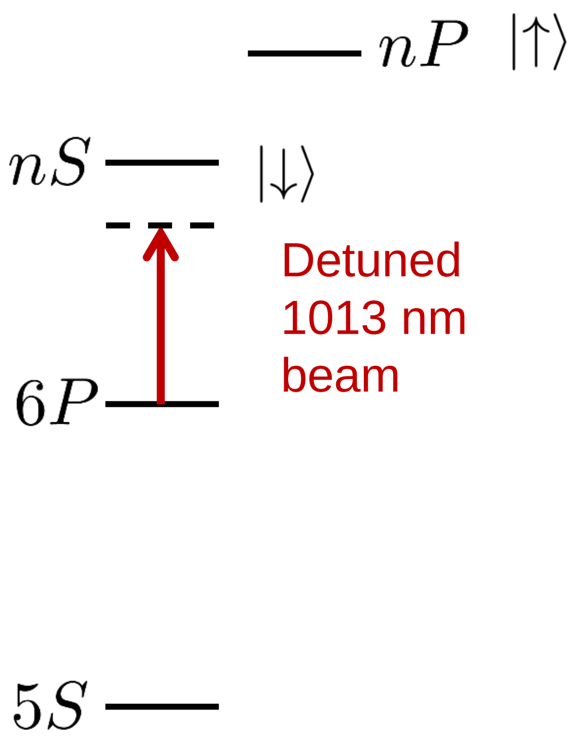
$\Longrightarrow$ ***use local light shifts to address atoms with an array***



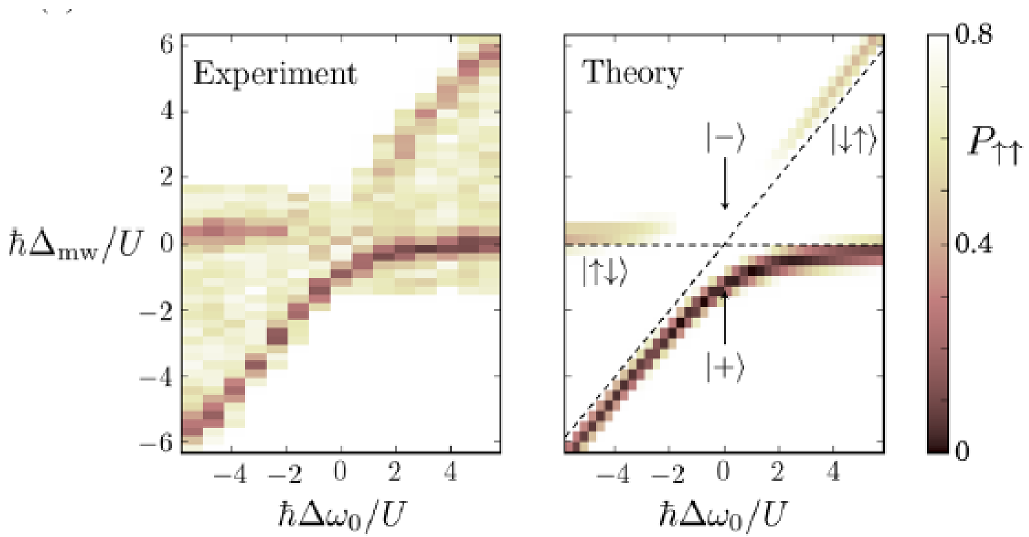
Optical addressing

Microwave manipulations are ***global*** ($\lambda \sim \mathrm{cm}$)

$\Longrightarrow$ ***use local light shifts to address atoms with an array***



First experiments with a *single beam:*
S. de Léséleuc *et al.*,
PRL **119**, 053202 (2017)

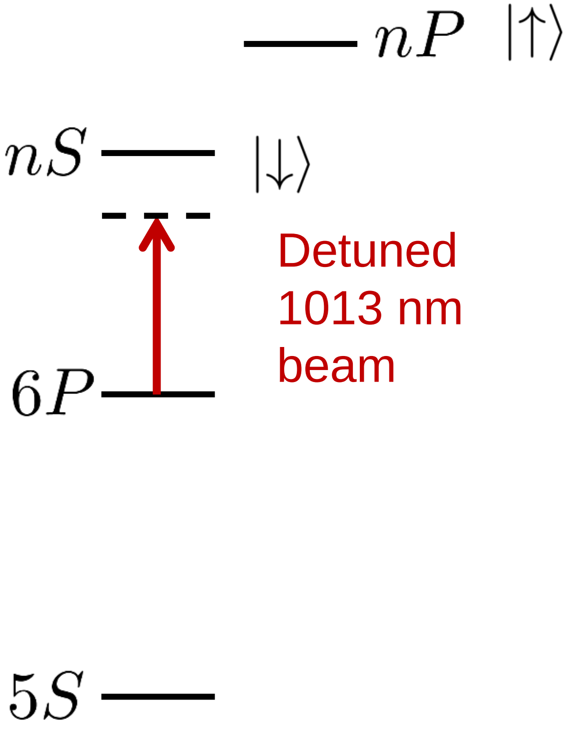


Optical addressing

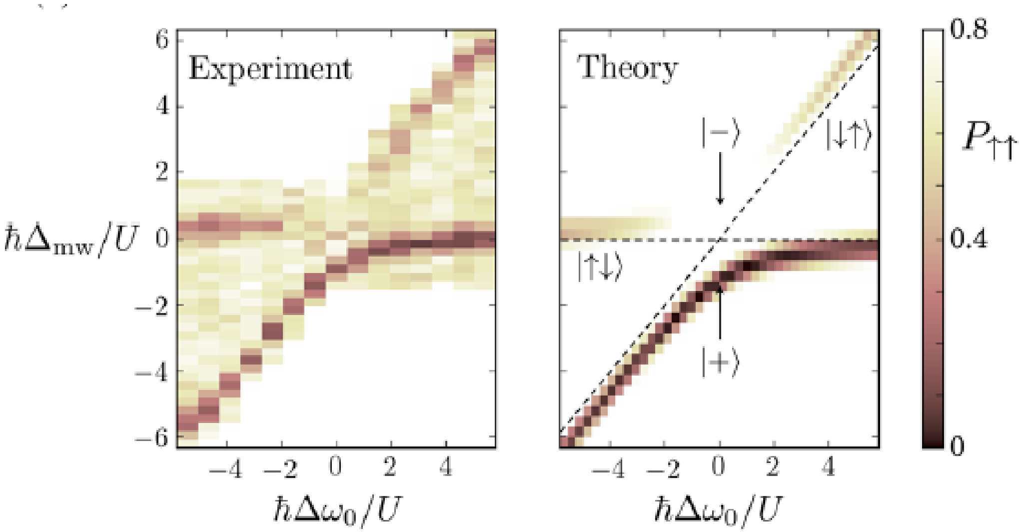
Microwave manipulations are ***global*** ($\lambda \sim \mathrm{cm}$)

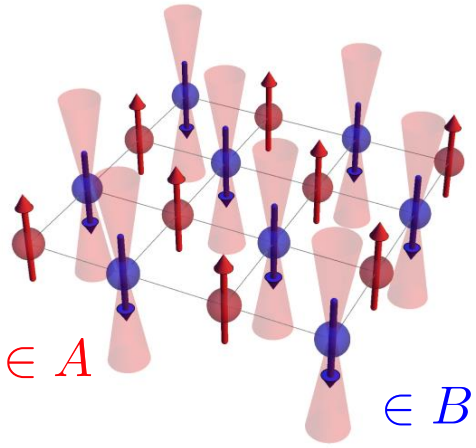
$\Longrightarrow$ ***use local light shifts to address atoms with an array***

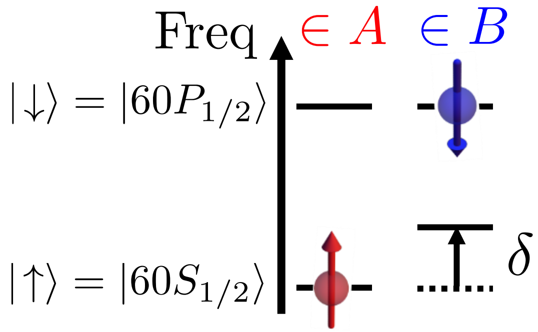
Adding an SLM: spatial control
(but time dependence is global)



First experiments with a *single beam:*
S. de Léséleuc *et al.*,
PRL **119**, 053202 (2017)



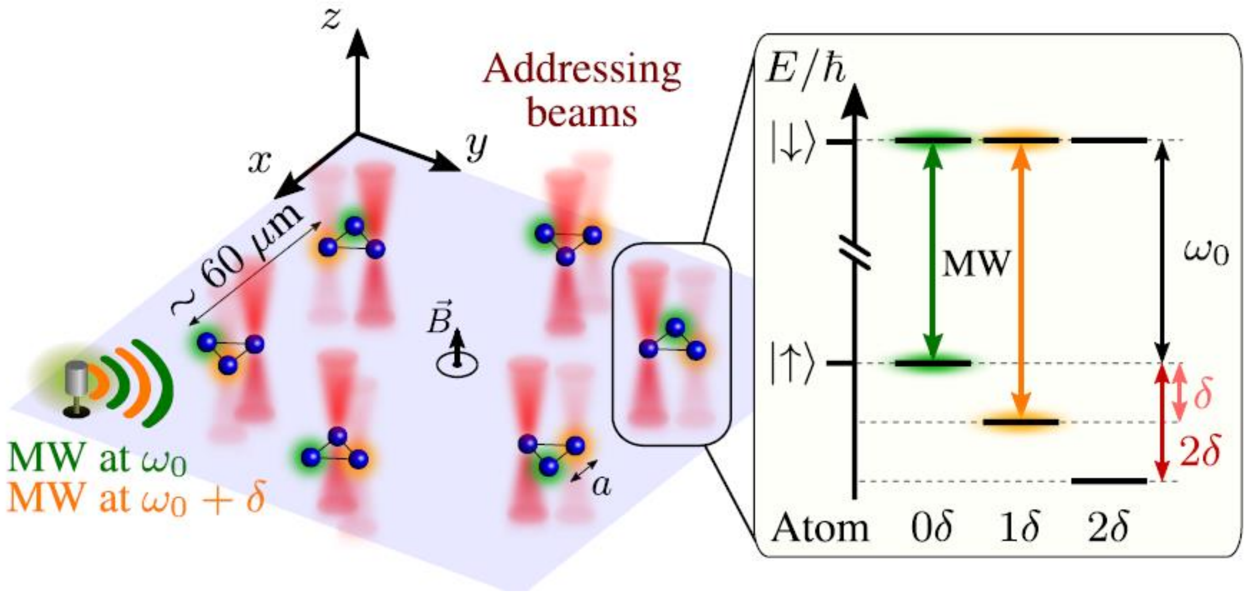




Multi-basis rotations

Use several values of light-shift and multi-tone microwaves:

Measure different atoms in different bases: $X, Y, Z\ldots$
Access to crossed-basis correlation functions, e.g., $\langle X_1 Z_2 Y_3 X_4 \rangle$



G. Bornet *et al.*, arXiv:2402.11056

Similar results in quantum gas microscopes: A. Impertro *et al.*, arXiv:2312.13268

Preparing and measuring a 3-spin chiral state

Chirality for three spins

$$\hat{\chi} = \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$$

Takes up a maximum value of $2\sqrt{3}$ for the state

$$|\chi_+\rangle = \frac{|\uparrow\downarrow\downarrow\rangle + \omega|\downarrow\uparrow\downarrow\rangle + \omega^2|\downarrow\downarrow\uparrow\rangle}{\sqrt{3}} \qquad (\omega = e^{\frac{2i\pi}{3}})$$

G. Bornet *et al.*, arXiv:2402.11056

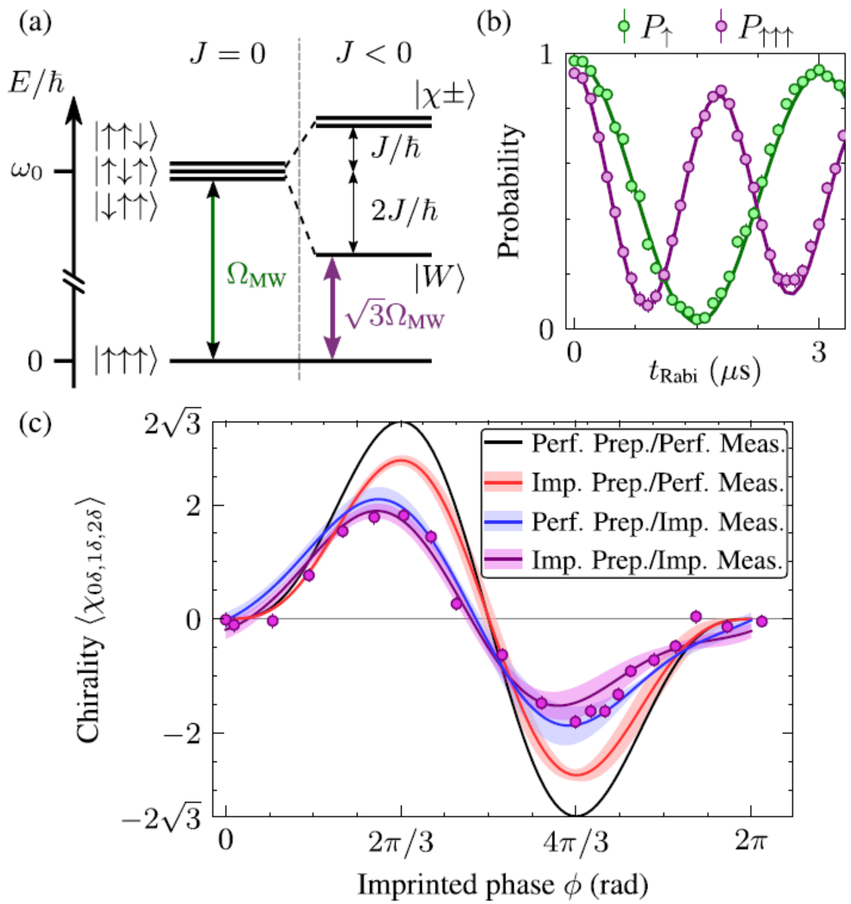
Preparing and measuring a 3-spin chiral state

Chirality for three spins

$$\hat{\chi} = \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$$

Takes up a maximum value of $2\sqrt{3}$ for the state

$$|\chi_+\rangle = \frac{|\uparrow\downarrow\downarrow\rangle + \omega|\downarrow\uparrow\downarrow\rangle + \omega^2|\downarrow\downarrow\uparrow\rangle}{\sqrt{3}} \qquad (\omega = e^{\frac{2i\pi}{3}})$$



(i) Prepare $|W\rangle = (|\uparrow\downarrow\downarrow\rangle + |\downarrow\uparrow\downarrow\rangle + |\downarrow\downarrow\uparrow\rangle)/\sqrt{3}$ with global MW

(ii) Apply local light-shifts to imprint phases ϕ and 2ϕ

(iii) For $\phi = 2\pi/3$ we get $|\chi_+\rangle$!

G. Bornet *et al.*, arXiv:2402.11056

Preparing and measuring a 3-spin chiral state

Chirality for three spins

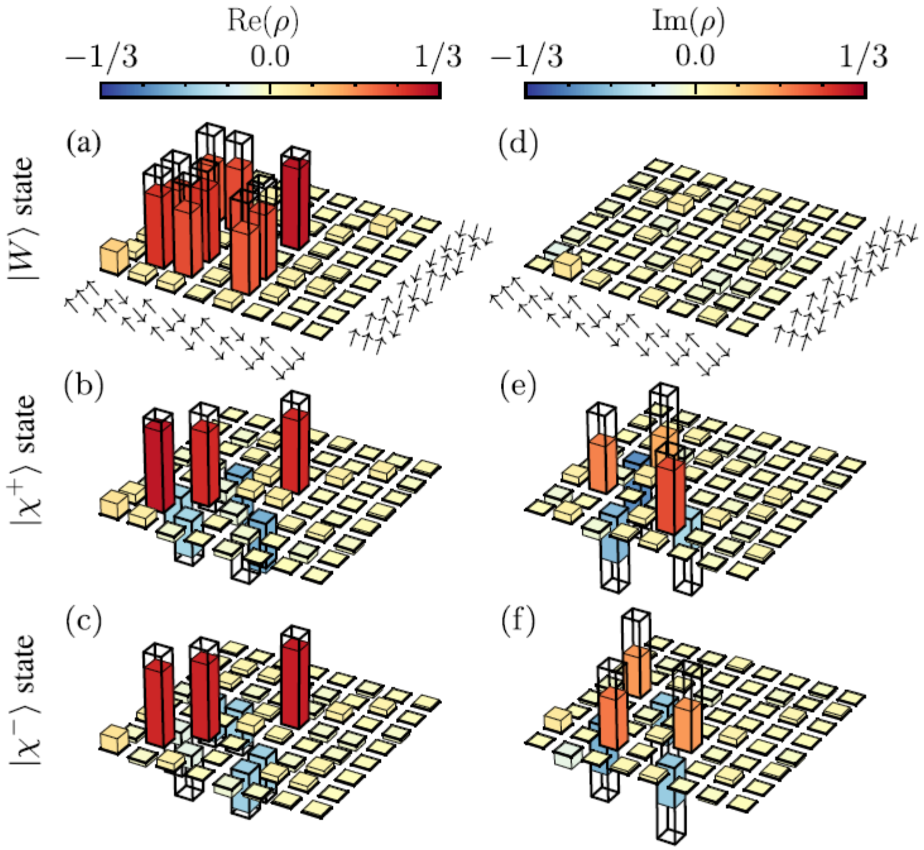
$$\hat{\chi} = \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$$

Takes up a maximum value of $2\sqrt{3}$ for the state

$$|\chi_+\rangle = \frac{|\uparrow\downarrow\downarrow\rangle + \omega|\downarrow\uparrow\downarrow\rangle + \omega^2|\downarrow\downarrow\uparrow\rangle}{\sqrt{3}} \qquad (\omega = e^{\frac{2i\pi}{3}})$$

Measure the states
$|W\rangle$ and $|\chi_\pm\rangle$
by quantum tomography

$$F \simeq 0.75$$

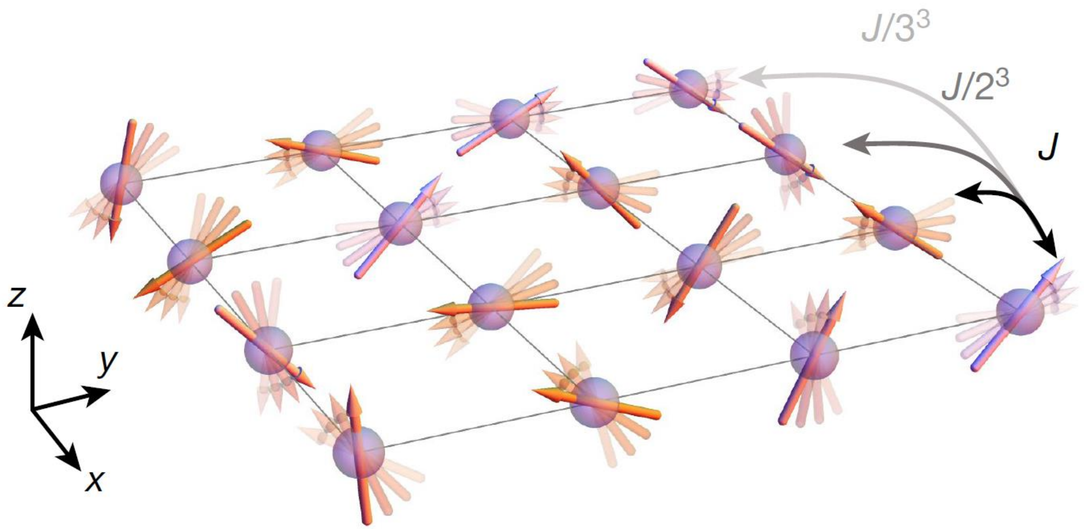


Bornet *et al.*, arXiv:2402.11056

Outline

1. *Our tools*
2. ***Quasi-adiabatic preparation of the ground state***
3. *Quench dynamics: spin squeezing and spectroscopy of spin waves*

The resonant dipole-dipole interaction: dipolar XY model

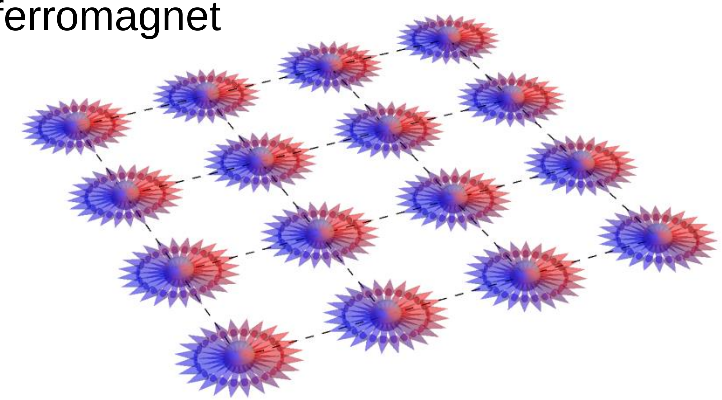


$$H_{\mathrm{XY}} = -J \sum_{i<j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y)$$

- ***Ground-state properties?***
- ***Effect of “long-range” couplings?***
- ***Elementary excitations?***

XY on square lattice (1/2 filling)

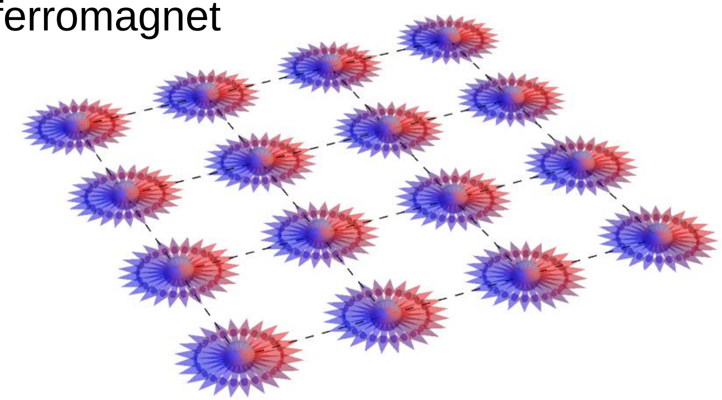
XY ferromagnet



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

XY on square lattice (1/2 filling)

XY ferromagnet



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

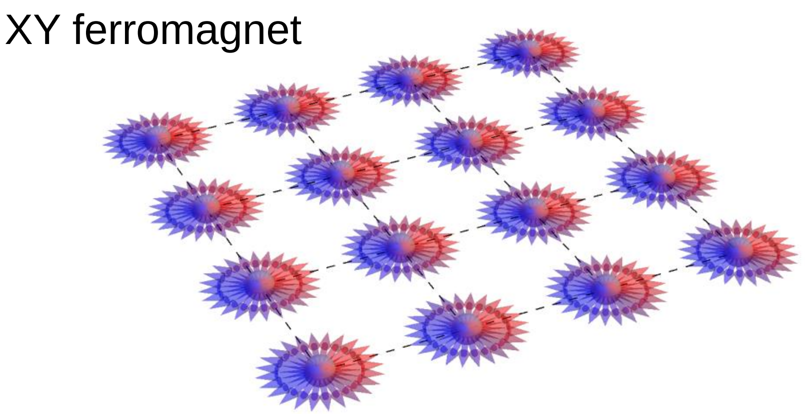
Expect:

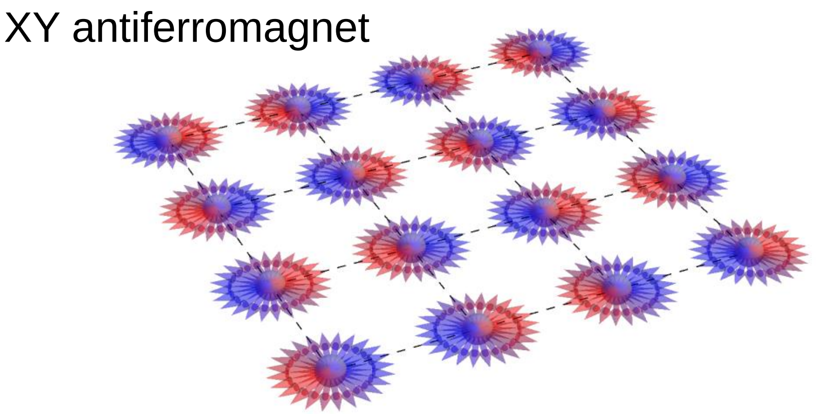
$$\langle \hat{X} \rangle = 0$$

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

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

XY on square lattice (1/2 filling)





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

Expect:

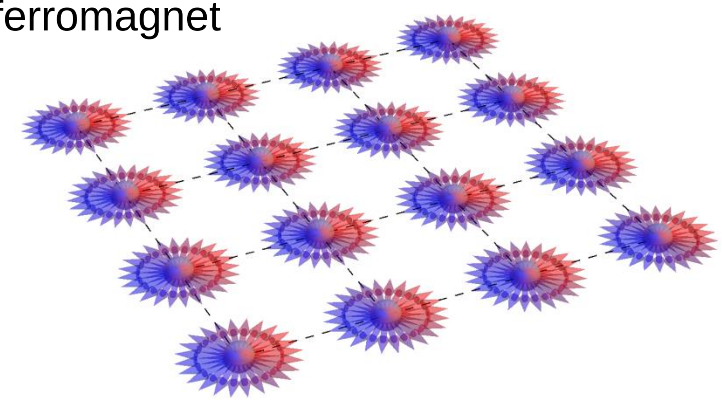
$$\langle \hat{X} \rangle = 0$$

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

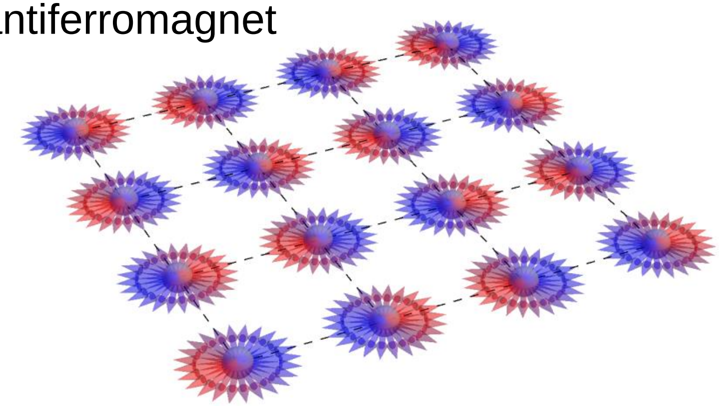
$$\langle \hat{X}\hat{X} \rangle^{F}_{NNN} > 0$$

XY on square lattice (1/2 filling)

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:

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

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

Preparing XY ferro- and antiferromagnets

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

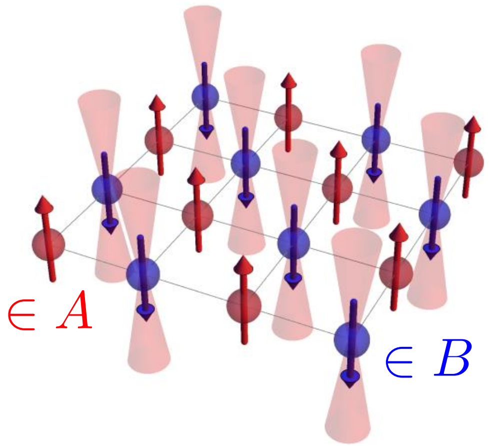
Staggered *z*-field

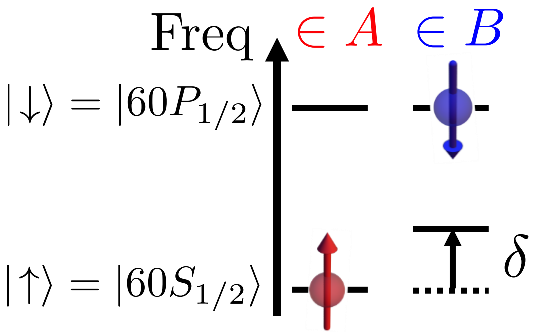
Preparing XY ferro- and antiferromagnets

Start from:

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

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



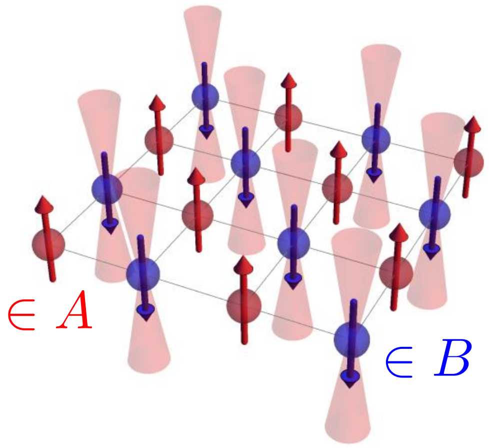


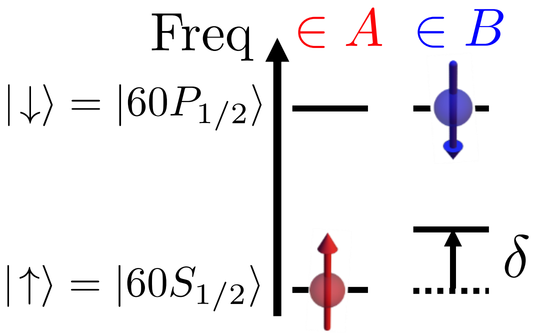
- Apply local light-shift on atoms on sublattice B
- Apply microwave pulse

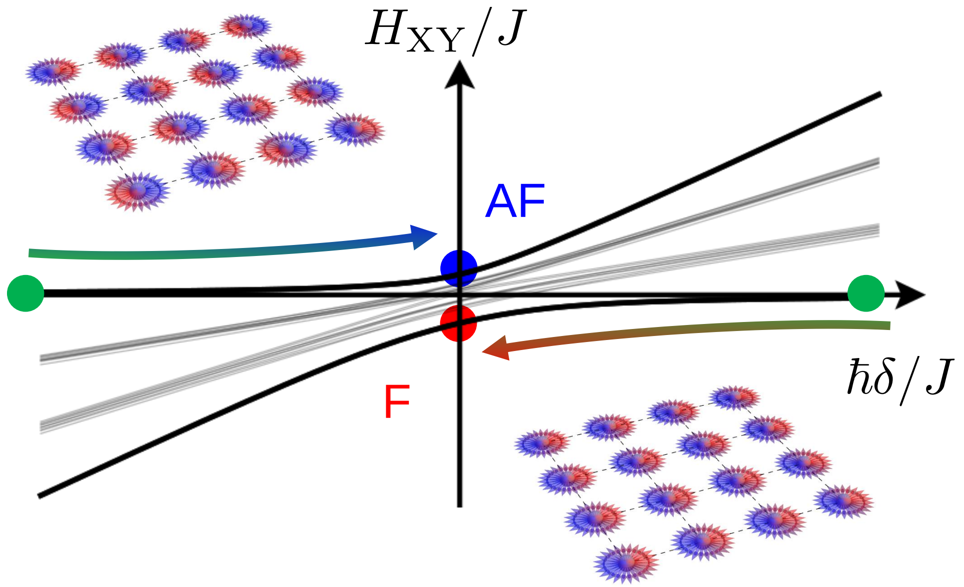
Preparing XY ferro- and antiferromagnets

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

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

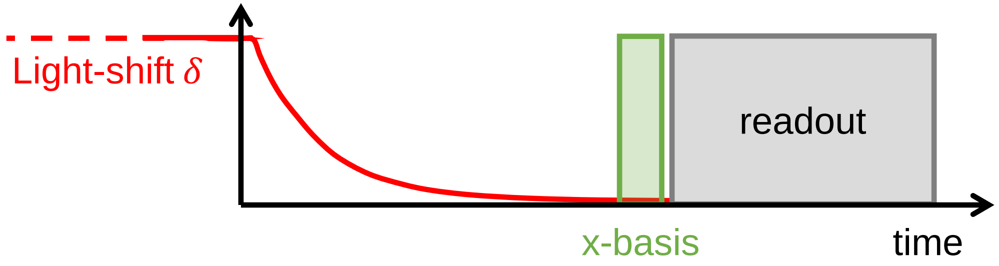




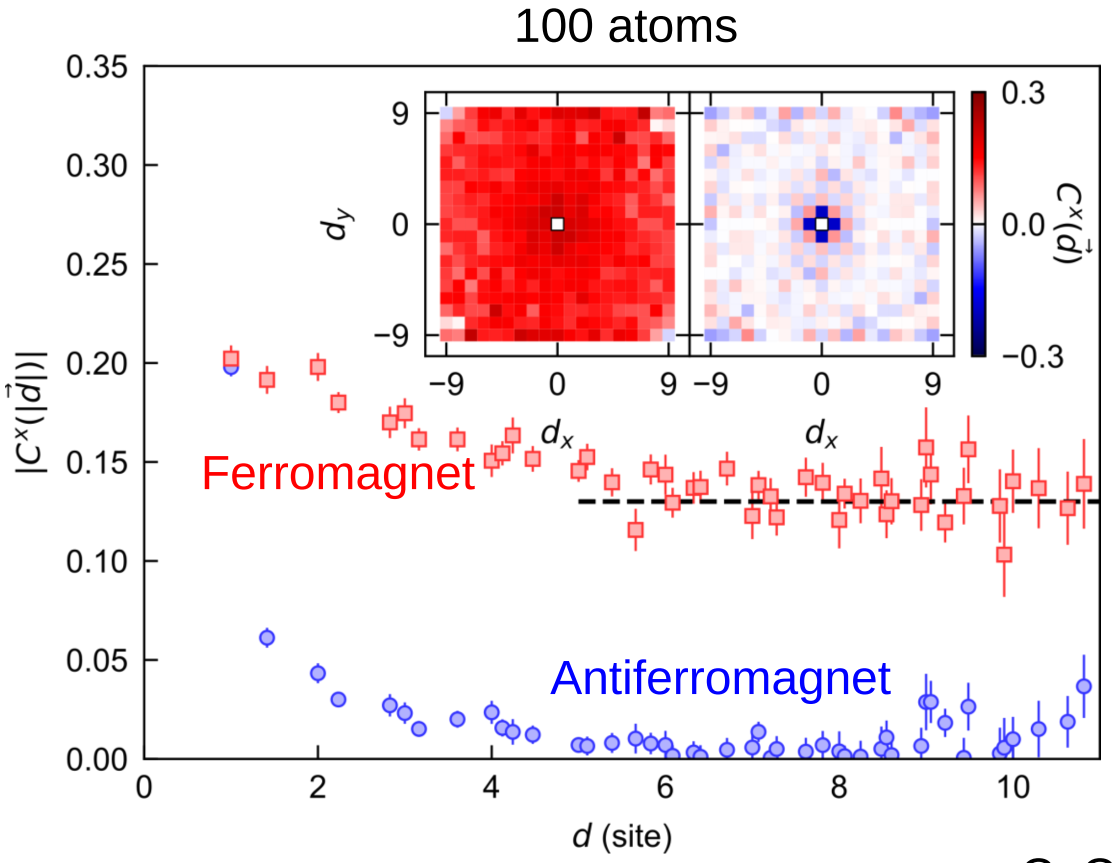


Sørensen *et al.*, PRA **81**, 061603(R) (2010)

Long-range order for the FM case



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



Ferromagnet:
Long-range order

Antiferromagnet:
Correlations decay to 0

Crucial role of
dipolar couplings
(*cf*. Mermin- Wagner)

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

Outline

1. Our tools
2. Quasi-adiabatic preparation of the ground state
3. Quench dynamics: spin squeezing and spectroscopy of spin waves

Quantum quench from the mean-field ground state

- ***Ferromagnet:***

Prepare $|\psi_0\rangle = |\rightarrow_x \cdots \rightarrow_x\rangle$ at $t = 0$ and let the system evolve

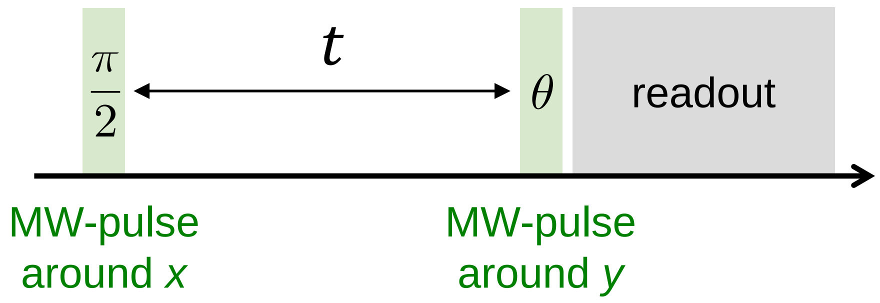
- ***Antiferromagnet:***

Prepare $|\psi_0\rangle = |\rightarrow_x, \leftarrow_x, \cdots, \rightarrow_x\rangle$ at $t = 0$ and let the system evolve

Dipolar spin squeezing with Rydberg atoms

Ferromagnetic case

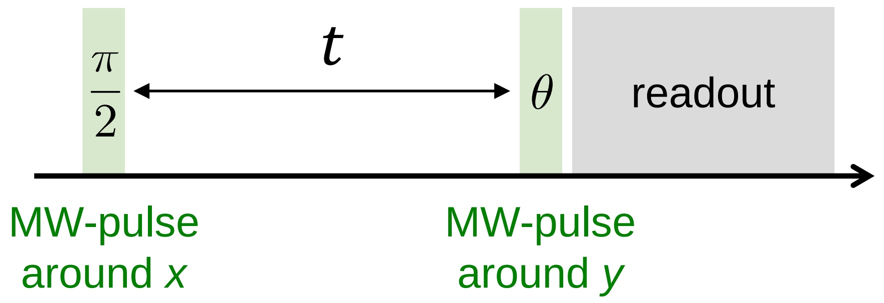
Prepare $|\psi_0\rangle = |\rightarrow_x \cdots \rightarrow_x\rangle$ at $t = 0$ and let the system evolve



Dipolar spin squeezing with Rydberg atoms

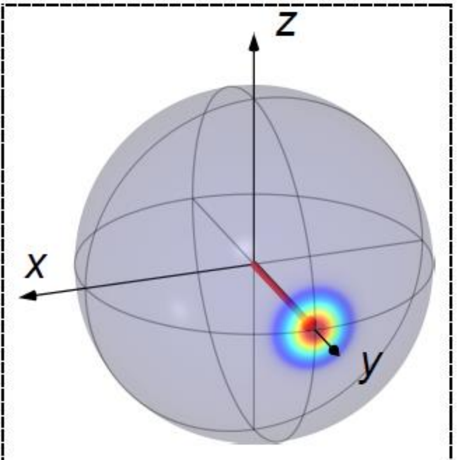
Ferromagnetic case

Prepare $|\psi_0\rangle = |\rightarrow_x \cdots \rightarrow_x\rangle$ at $t = 0$ and let the system evolve



Collective spin

$$\vec{J} = \sum_i \vec{\sigma}_i$$

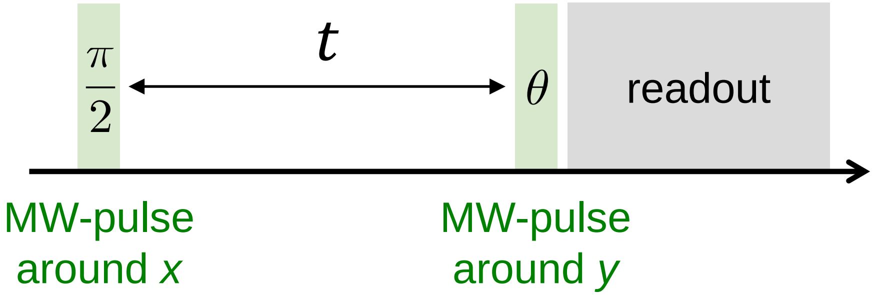


Initial state $|\Psi(0)\rangle$

Dipolar spin squeezing with Rydberg atoms

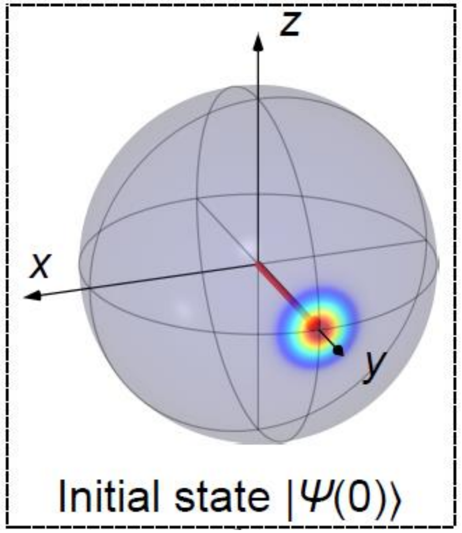
Ferromagnetic case

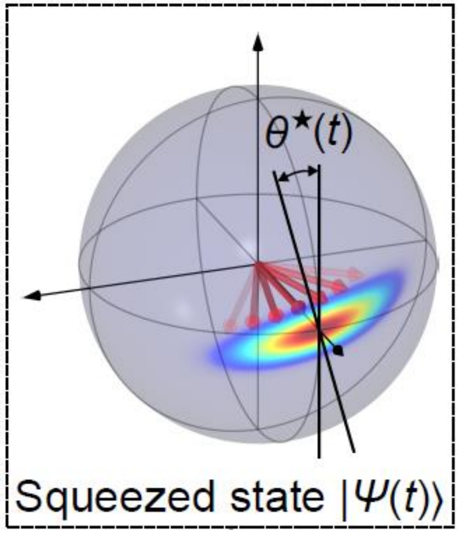
Prepare $|\psi_0\rangle = |\rightarrow_x \cdots \rightarrow_x\rangle$ at $t = 0$ and let the system evolve



Collective spin

$$\vec{J} = \sum_i \vec{\sigma}_i$$

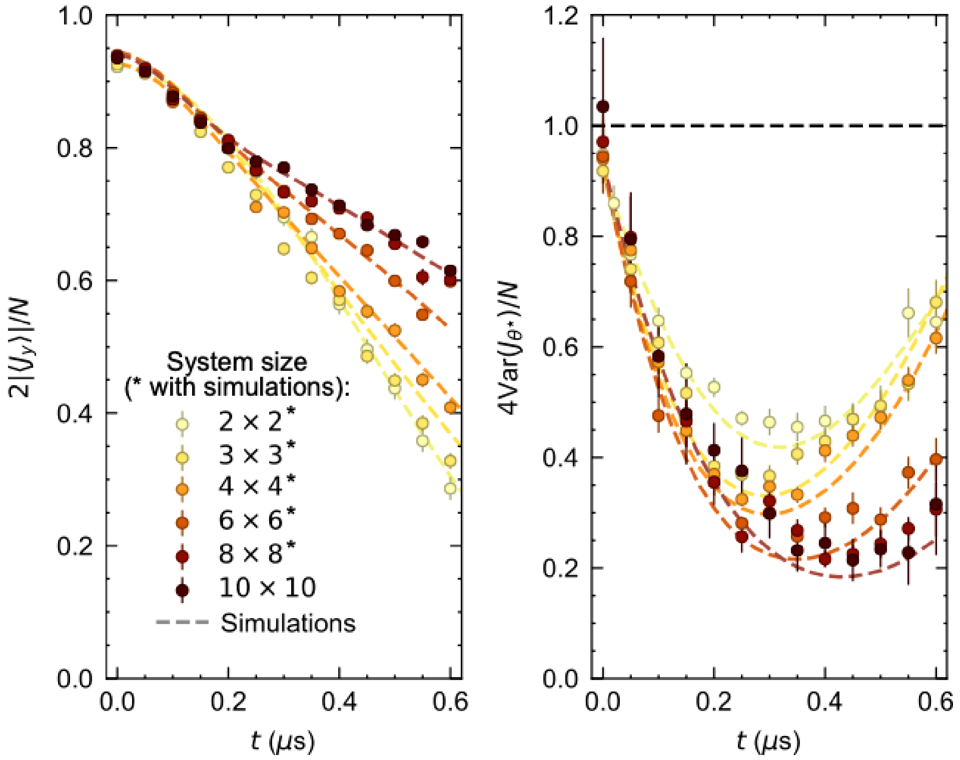




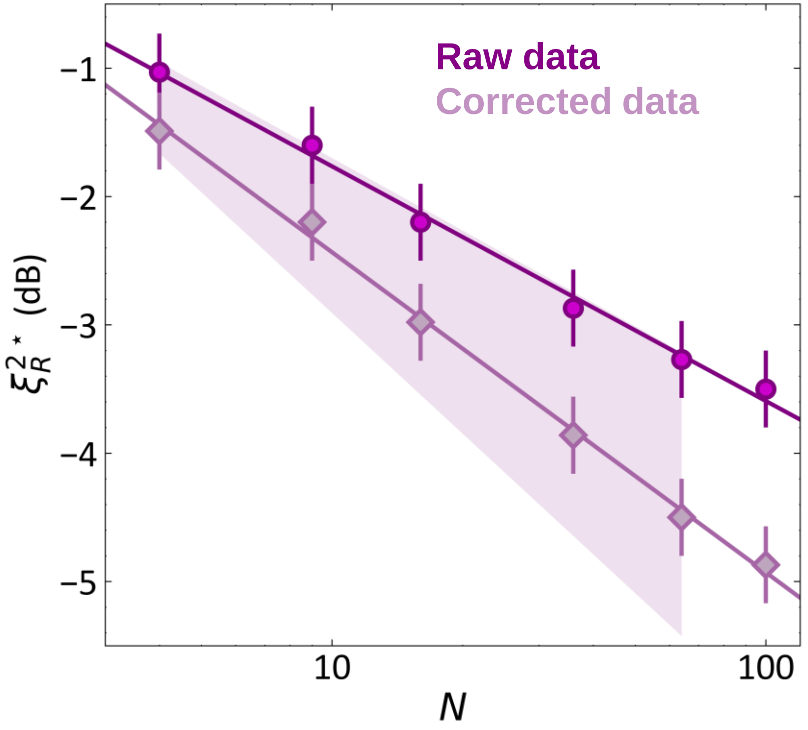
Squeezing parameter:

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

Scaling of the squeezing parameter with N



T. Comparin *et al.*, PRL **129**, 150503 (2022)
M. Block *et al.*, arXiv:2301.09636
T. Roscilde *et al.*, Phys. Rev. B **108**, 155130 (2023)



Scalable squeezing!!

G. Bornet *et al.*, Nature **621**, 728 (2023)

Quench spectroscopy

Spin squeezing: global observables $\langle\vec{J}\rangle, \Delta\vec{J}$

But we also have access to *local* observables:

→ correlation functions $C^{zz}(d,t)$

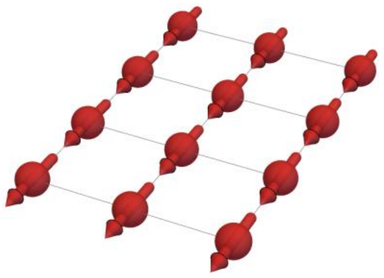
Quench spectroscopy

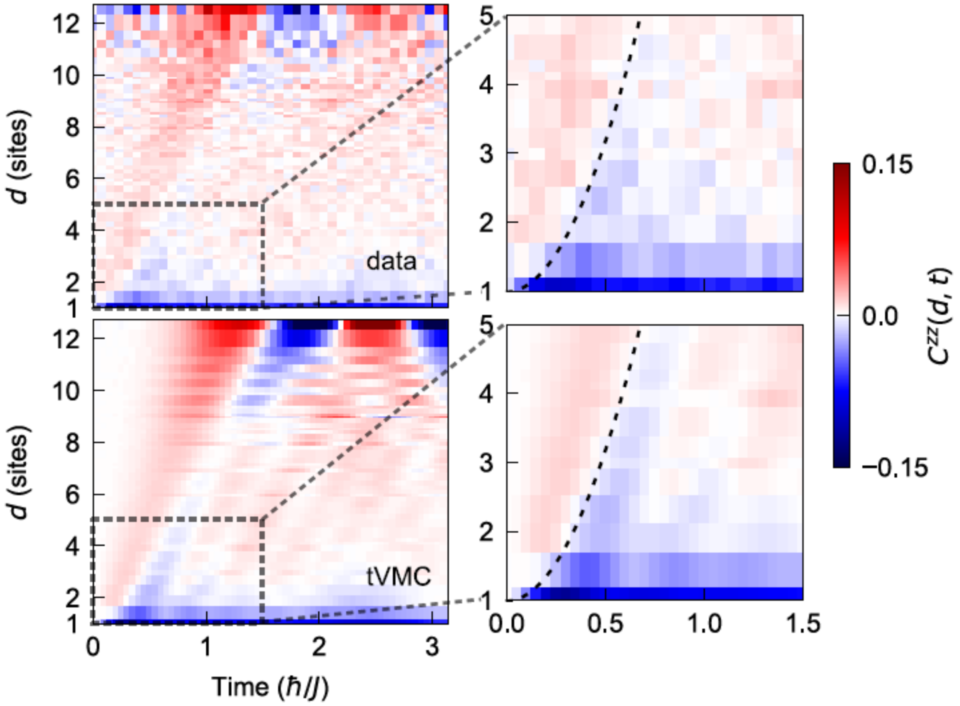
Spin squeezing: global observables $\langle \vec{J} \rangle, \Delta \vec{J}$

But we also have access to *local* observables:

→ correlation functions $C^{zz}(d,t)$

Ferromagnet:





Quench spectroscopy

Spin squeezing: global observables $\langle\vec{J}\rangle, \Delta\vec{J}$

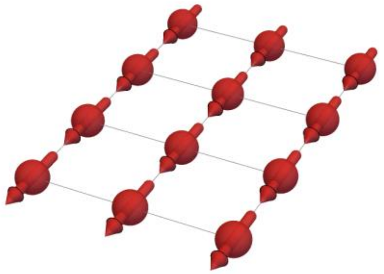
But we also have access to *local* observables:

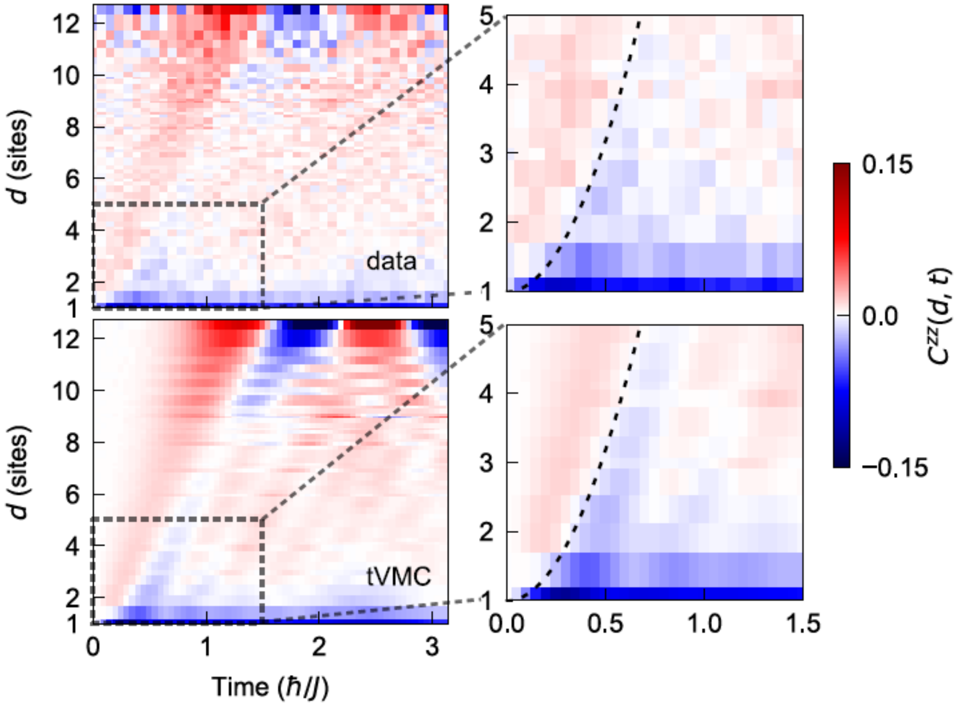
→ correlation functions $C^{zz}(d,t)$

Quench spectroscopy: dispersion relation of spin waves

Sanchez-Palencia, PRA (2019)
Roscilde PRL (2023), PRB (2023)

Ferromagnet:

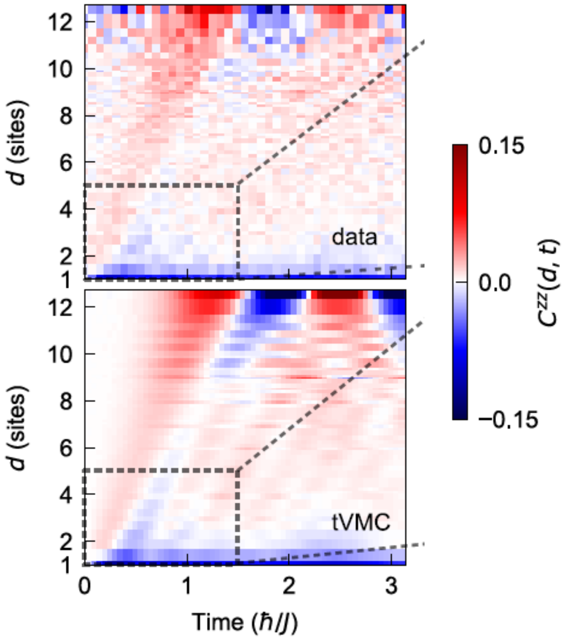




From correlations to the dispersion relation of spin waves

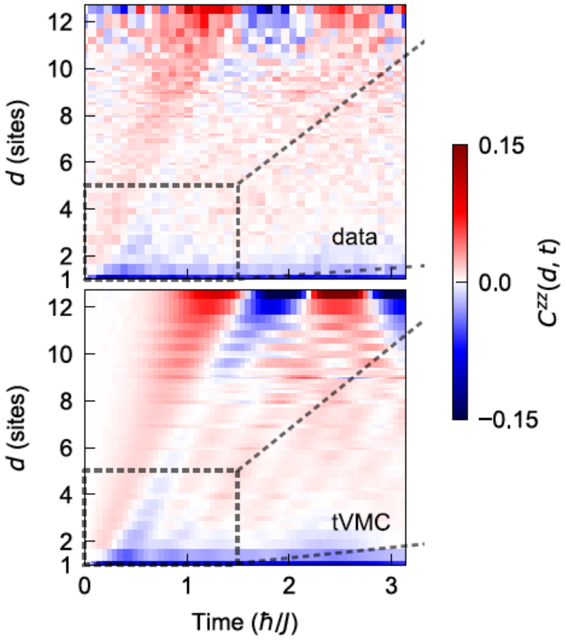
Correlation function

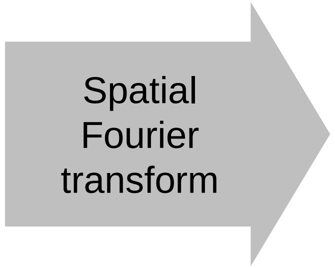
$C^{zz}(i, j, t)$



From correlations to the dispersion relation of spin waves

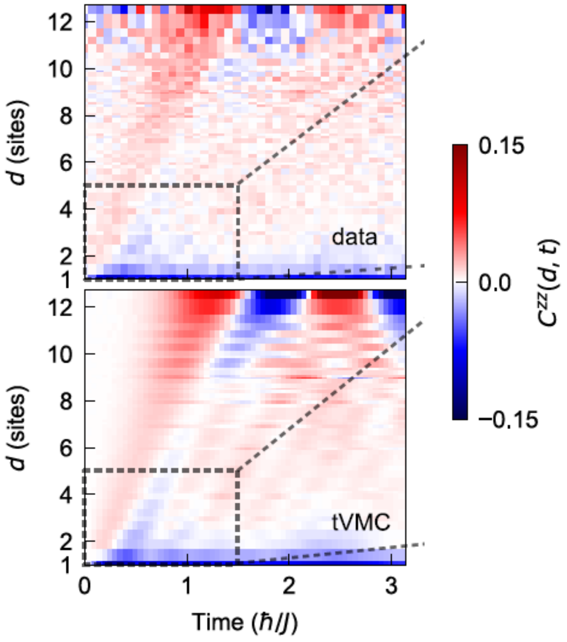
Correlation function
$C^{zz}\ (i, j, t)$





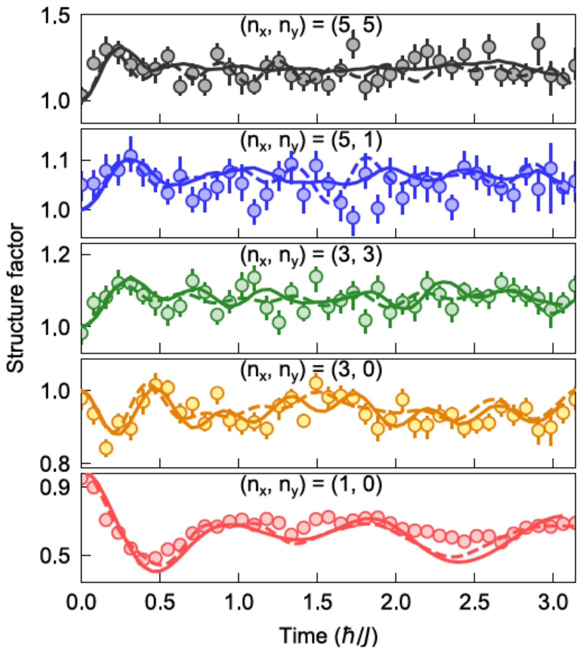
From correlations to the dispersion relation of spin waves

Correlation function
$C^{zz}\,(i,j,t)$



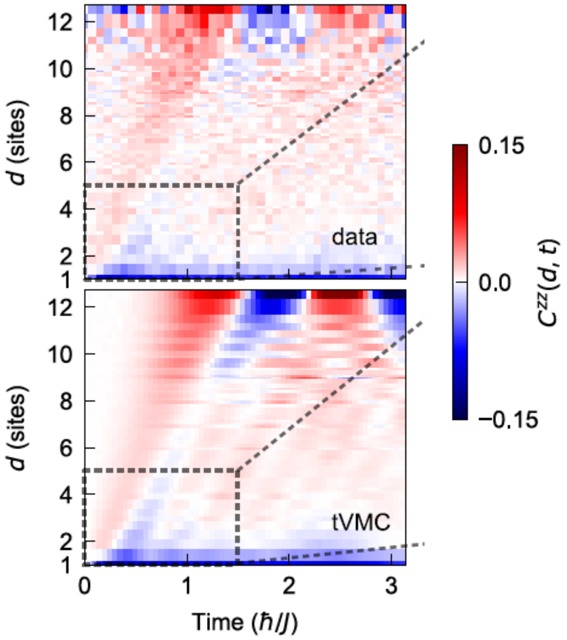
Spatial Fourier transform

Time-dependent structure factor
$S^{zz}\,(k_x,k_y,t)$



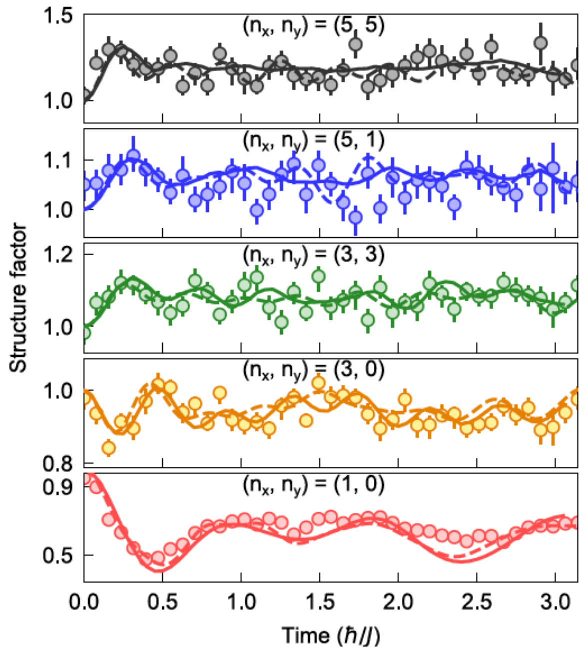
From correlations to the dispersion relation of spin waves

Correlation function
$C^{zz}(i,j,t)$



Spatial Fourier transform

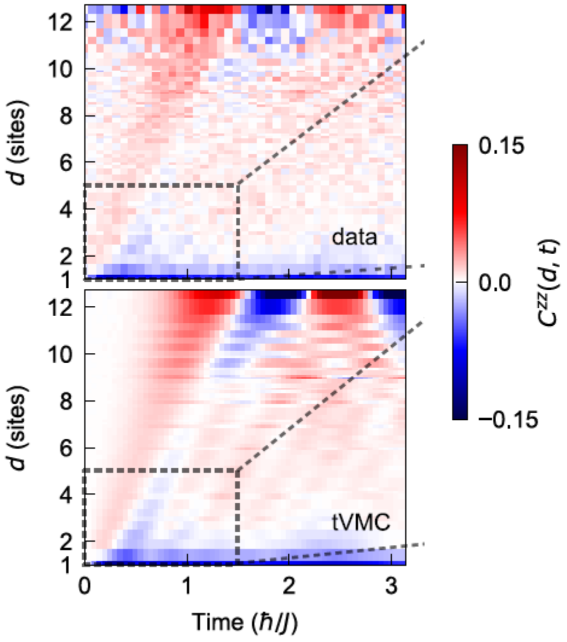
Time-dependent structure factor
$S^{zz}(k_x,k_y,t)$



Fit offset for
$t \to \infty$

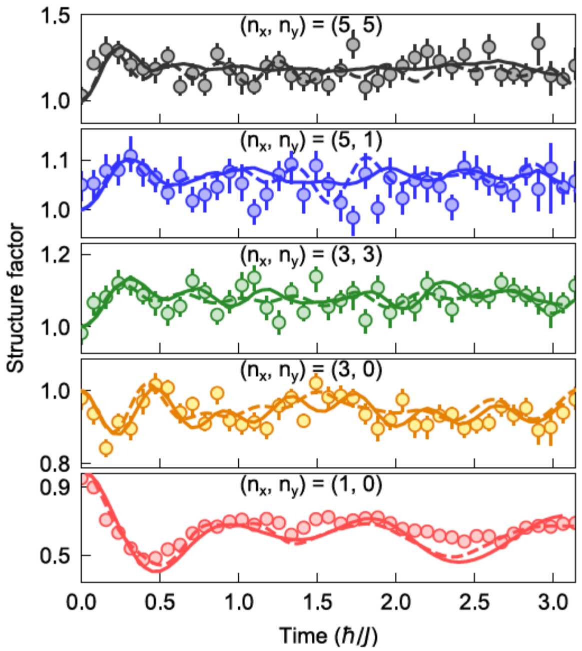
From correlations to the dispersion relation of spin waves

Correlation function
$C^{zz}(i,j,t)$



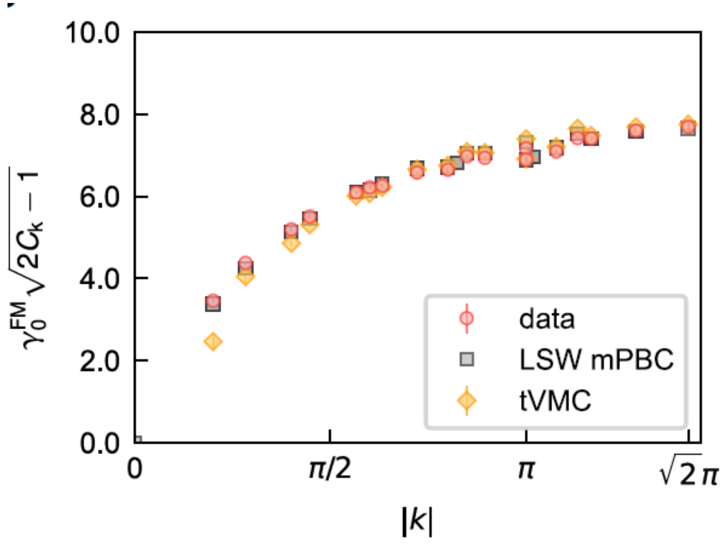
Spatial Fourier transform

Time-dependent structure factor
$S^{zz}(k_x,k_y,t)$



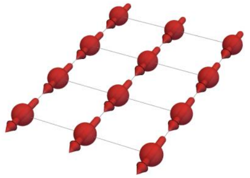
Fit offset for $t \to \infty$

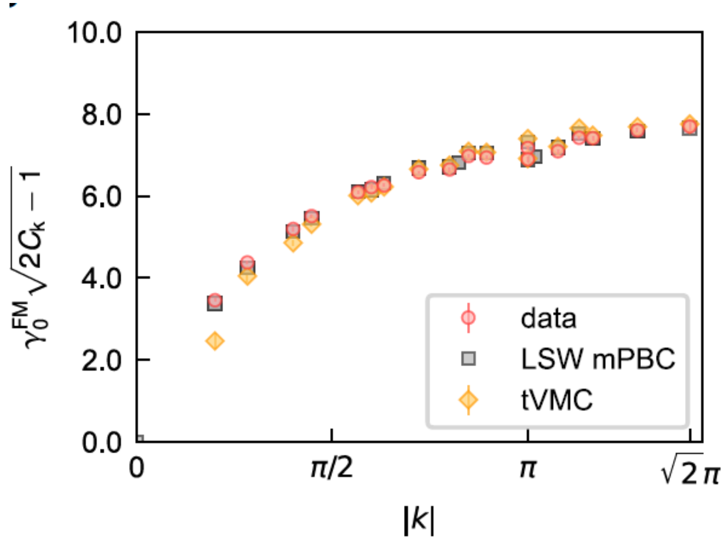
Spin-waves dispersion
$\omega_k(k_x,k_y)$



Dispersion relation: FM vs AFM

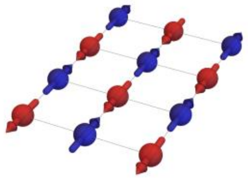
Ferromagnet:

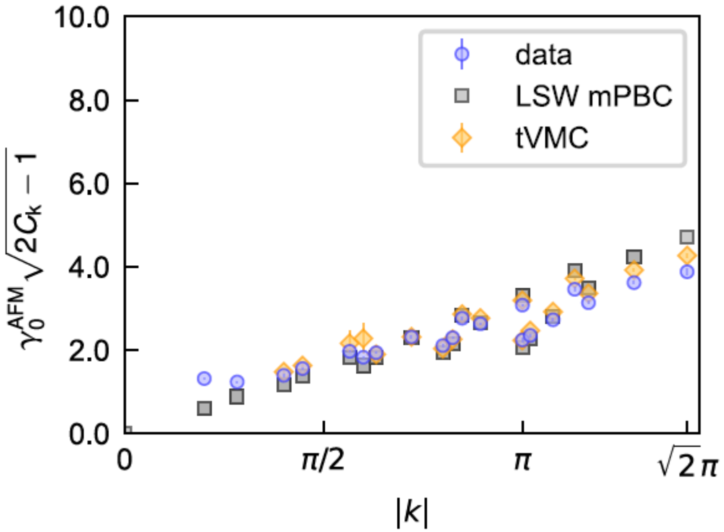




$\omega_k \sim \sqrt{k}$ for $k \to 0$

Antiferromagnet:





$\omega_k \sim k$ for $k \to 0$

Anomalous dispersion relation of spin waves for the FM dipolar XY model!

See D. Peter, S. Müller, S. Wessel, and H. P. Büchler, PRL **109**, 025303 (2012).

C. Chen *et al.*, arXiv:2311.11726

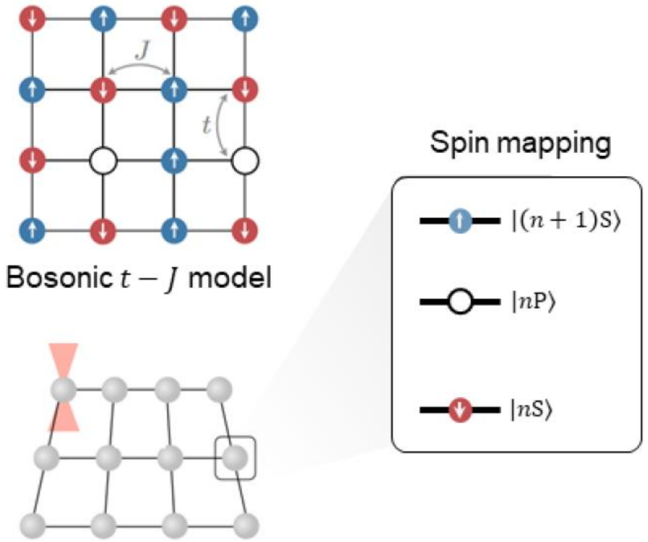
Conclusion and outlook

- ***Better and better control*** on the simulation of the dipolar XY model

- ***Quench spectroscopy in 1D XY magnets***

- ***Towards chiral spin liquids on Kagome arrays?***

- ***Beyond pure spin models:*** doped magnets (bosonic $t - J$ model)
  L. Homeier *et al.*, arXiv:2305.02322



Thanks for your attention!