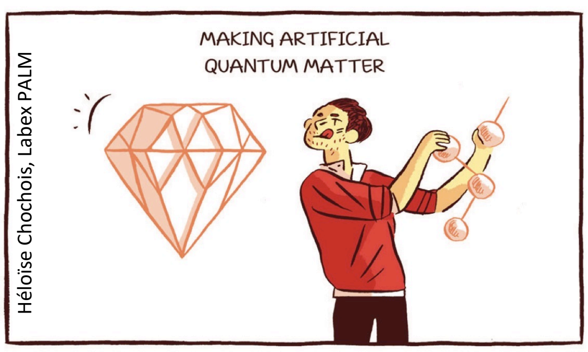
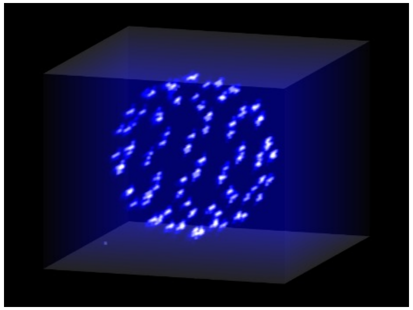
Magnetism and spin squeezing with arrays of Rydberg atoms

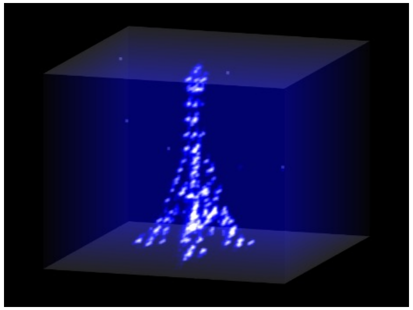


Antoine Browaeys

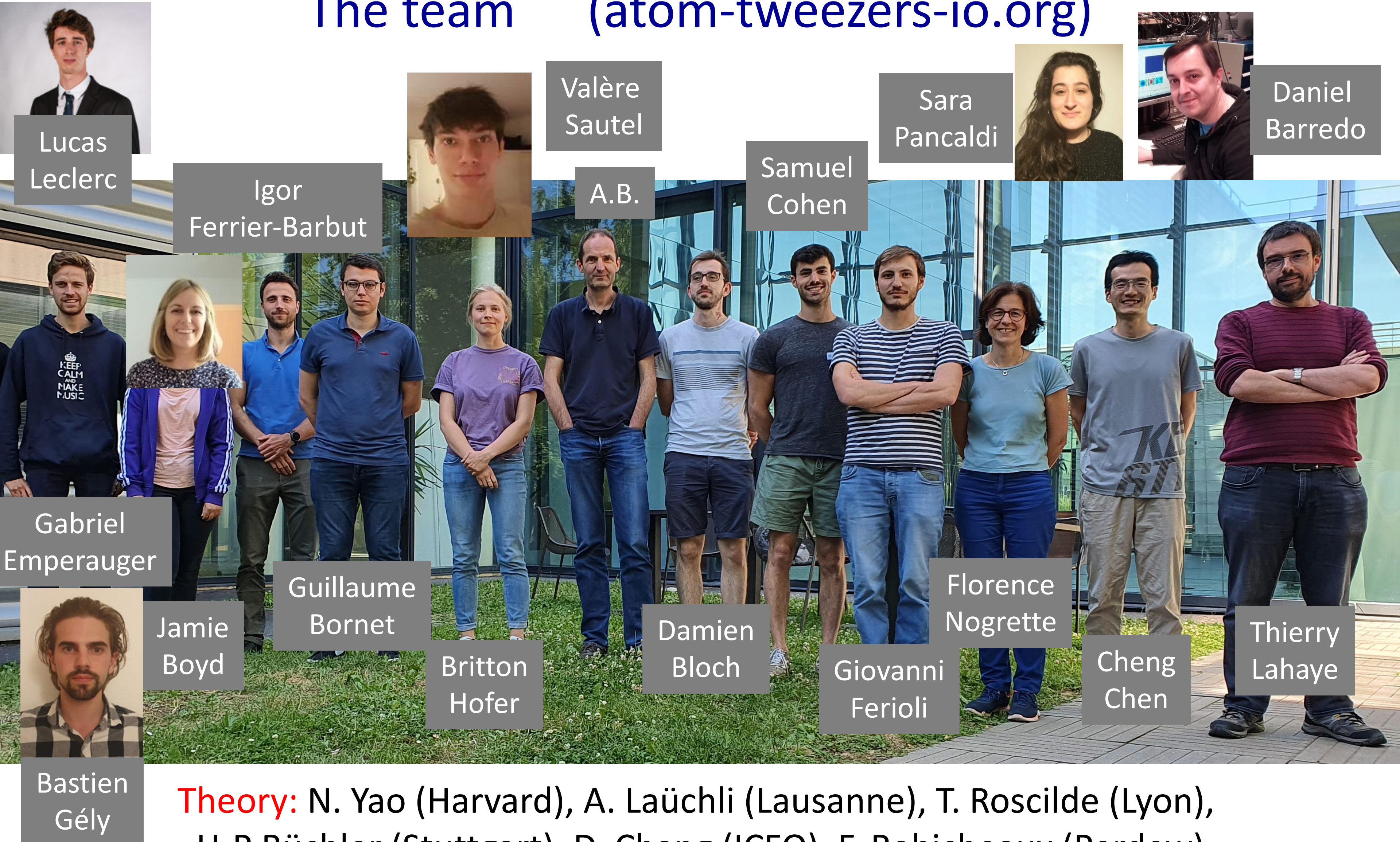
Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE

Congrès SFP, july 6th 2023





The team (atom-tweezers-io.org)



Theory: N. Yao (Harvard), A. Laüchli (Lausanne), T. Roscilde (Lyon), H-P Büchler (Stuttgart), D. Chang (ICFO), F. Robicheaux (Perdew)

AGENCE INNOVATION DÉFENSE · SIRTEQ · îledeFrance · anr · PASQuanS · erc

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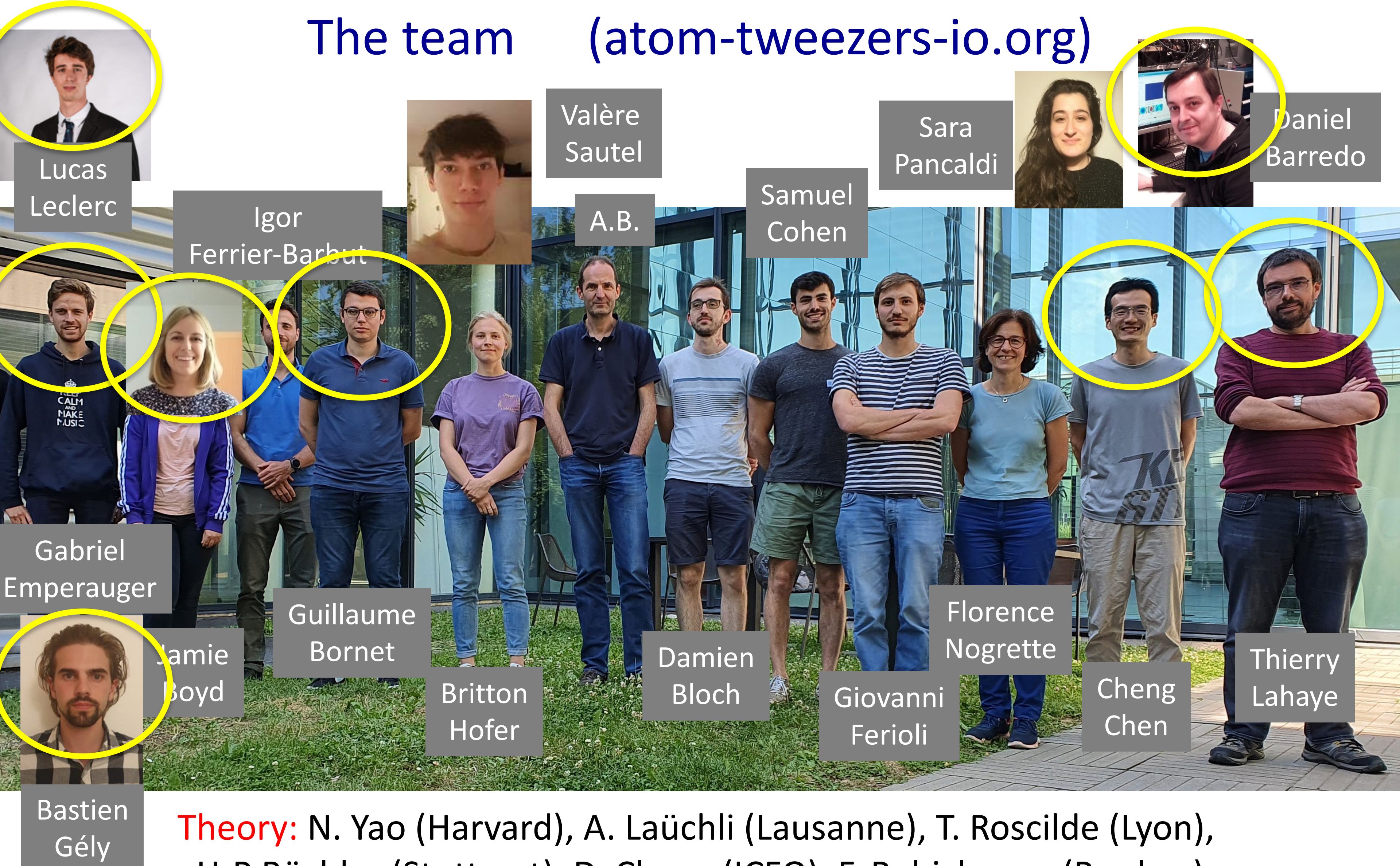

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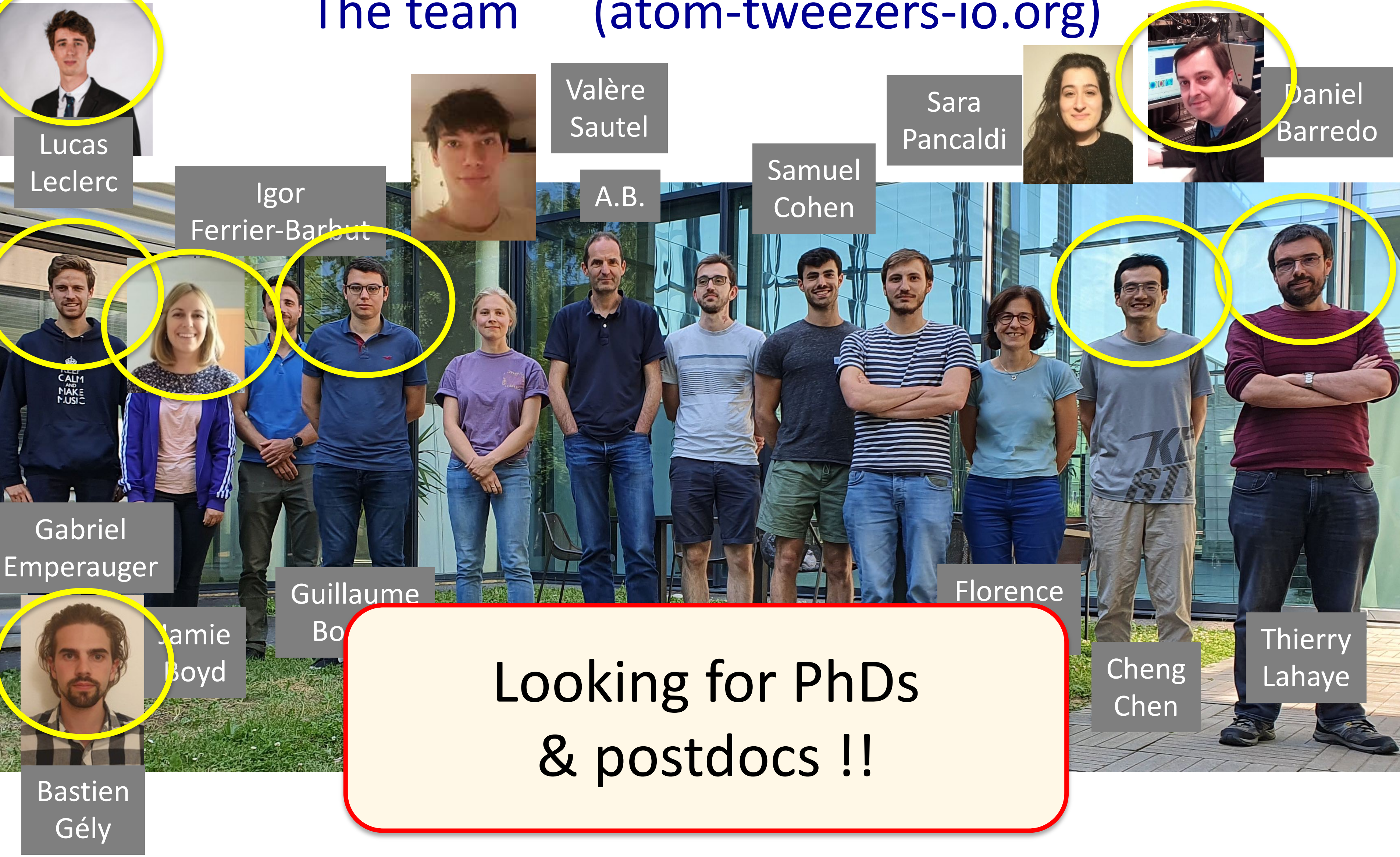
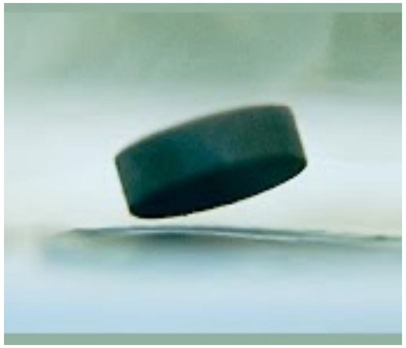


Looking for PhDs
& postdocs !!

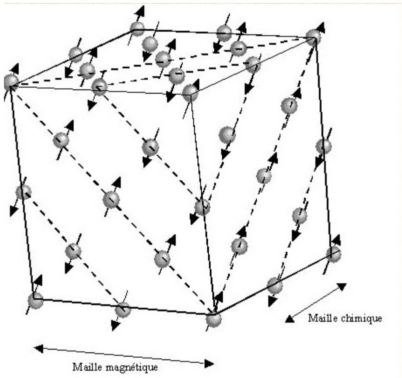
Many-body physics with synthetic matter

Goal: Understand ensembles of interacting quantum particles

superfluidity



superconductivity



magnetism

neutron star

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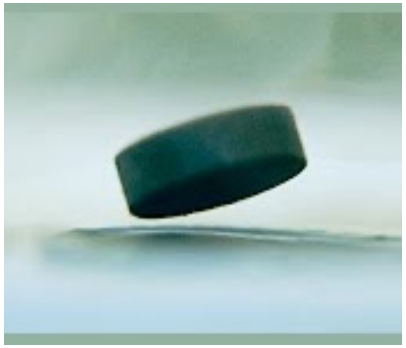
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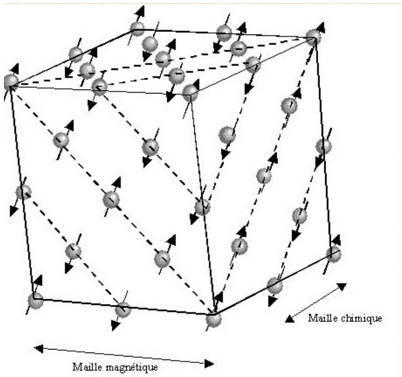

magnetism


neutron star

Open questions: Phase diagram, dynamics (hard for N>40…)
Topology, disorder, entanglement,…

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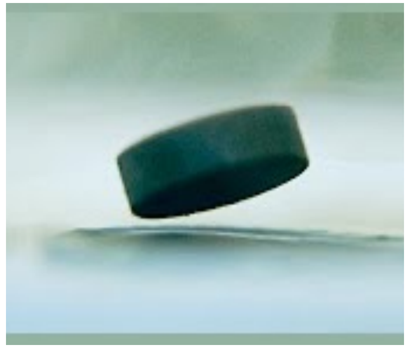
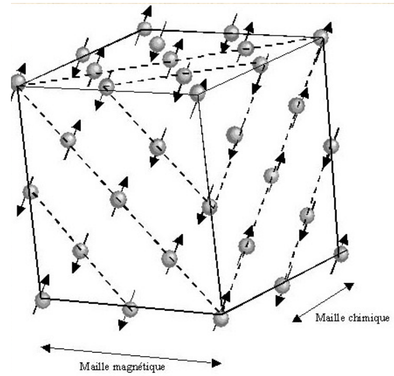


superconductivity



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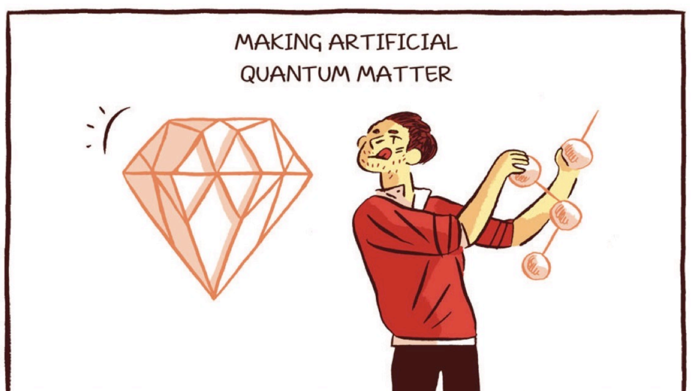


Héloïse Chochois, Labex PALM

R.P. Feynman

Use experimental control to

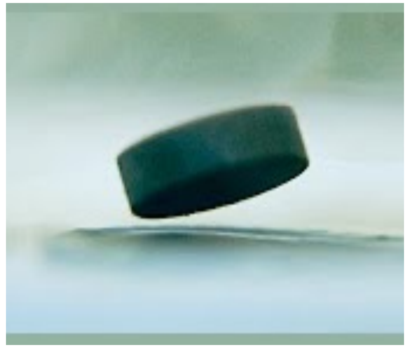
Implement **many-body Hamiltonians**
(including "mathematical" ones…)

Larger **tunability** than « real » systems

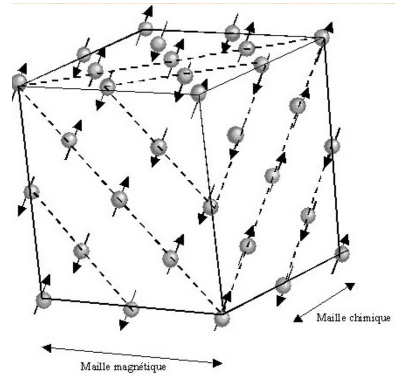
Many-body physics with synthetic matter

Goal: Understand ensembles of interacting quantum particles

superfluidity



superconductivity



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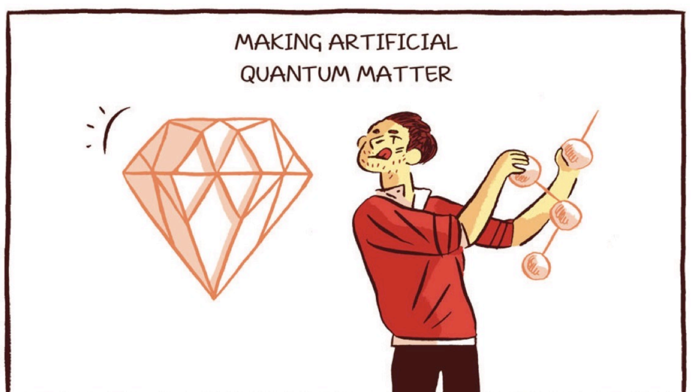

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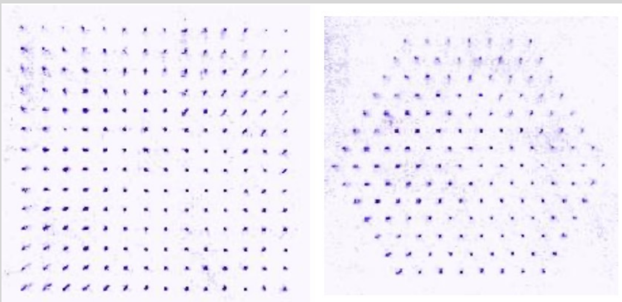
Quantum Simulation

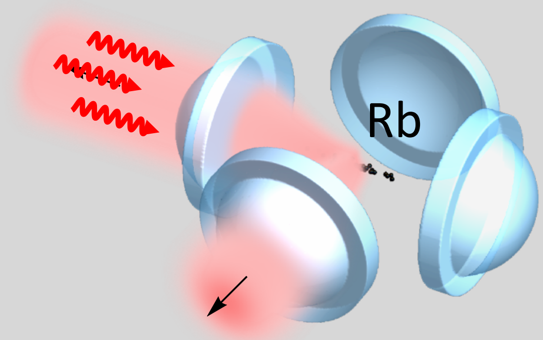
Many-body physics with synthetic quantum systems

Tunable arrays of individual Rydberg atoms



$r \sim 10\,\mu\mathrm{m}$

Light-induced interactions in atomic ensembles



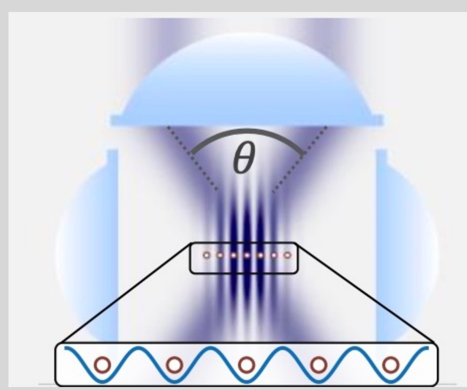
$r \sim \lambda$ arXiv:2207.10361 (Nat. Phys. 2023)

INSTITUT d'OPTIQUE GRADUATE SCHOOL

I. Ferrier-Barbut

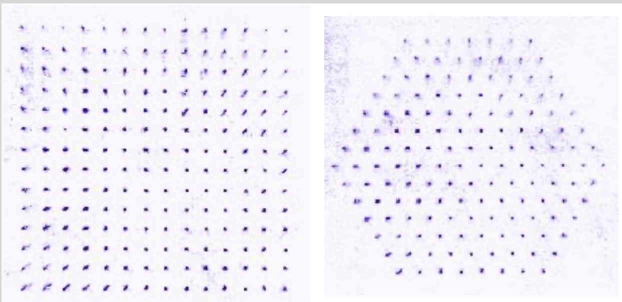
$r \sim \lambda$

Light-induced interactions in arrays of Dy atoms



Many-body physics with synthetic quantum systems

Tunable arrays of individual Rydberg atoms



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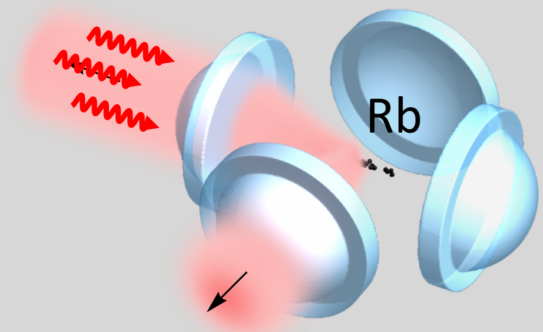

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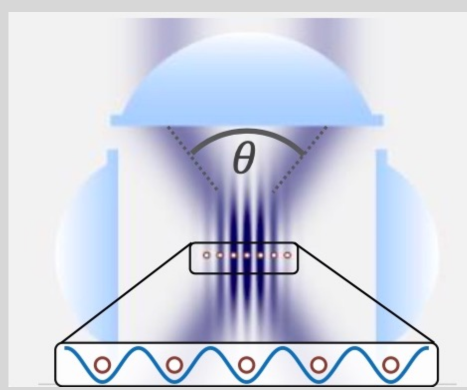
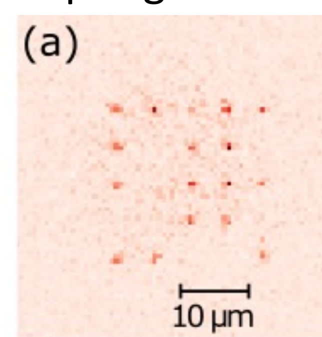


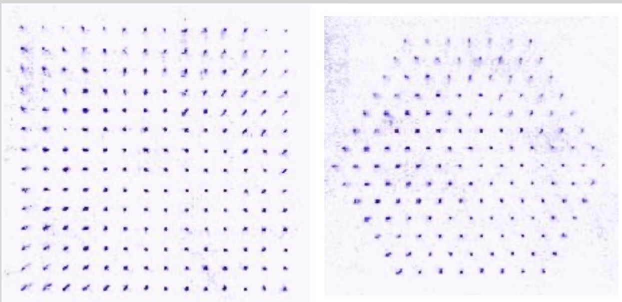
Spring 2023!!



Single Dy atoms in tweezers

Many-body physics with synthetic quantum systems

Tunable arrays of individual Rydberg atoms



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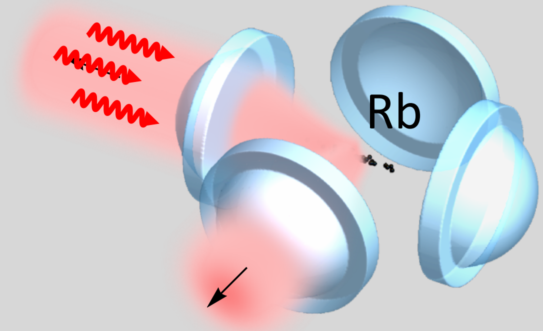

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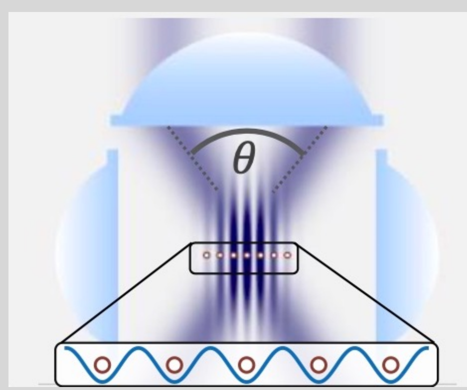

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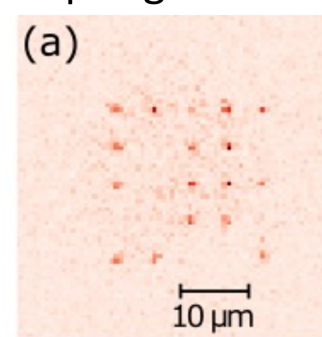
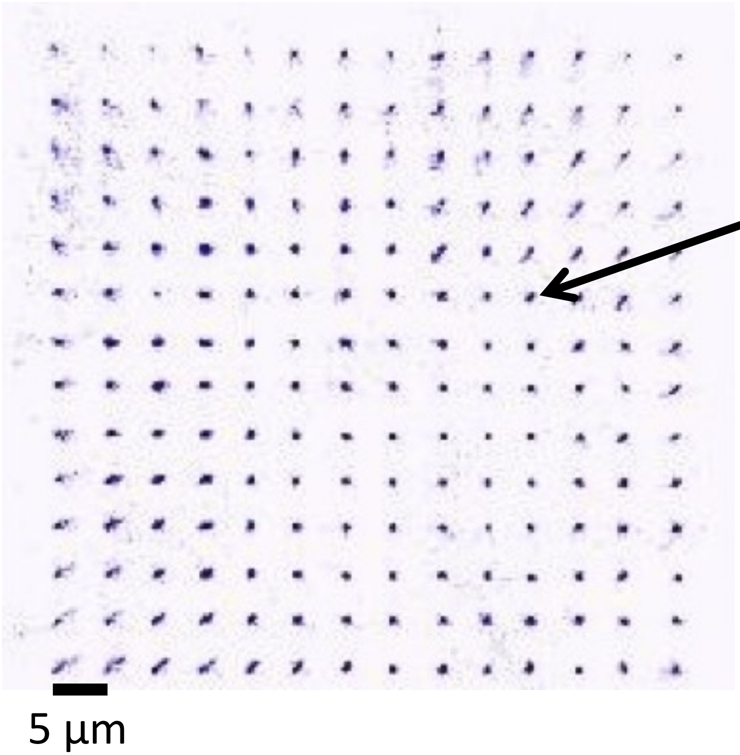
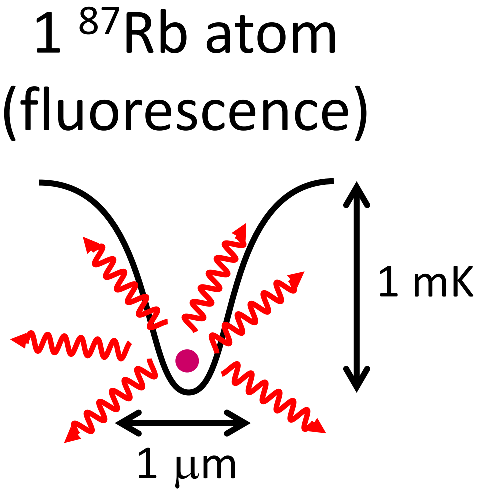


Single Dy atoms in tweezers

Arrays of interacting Rydberg atoms

Assembled arrays of tweezers (~200 at.)



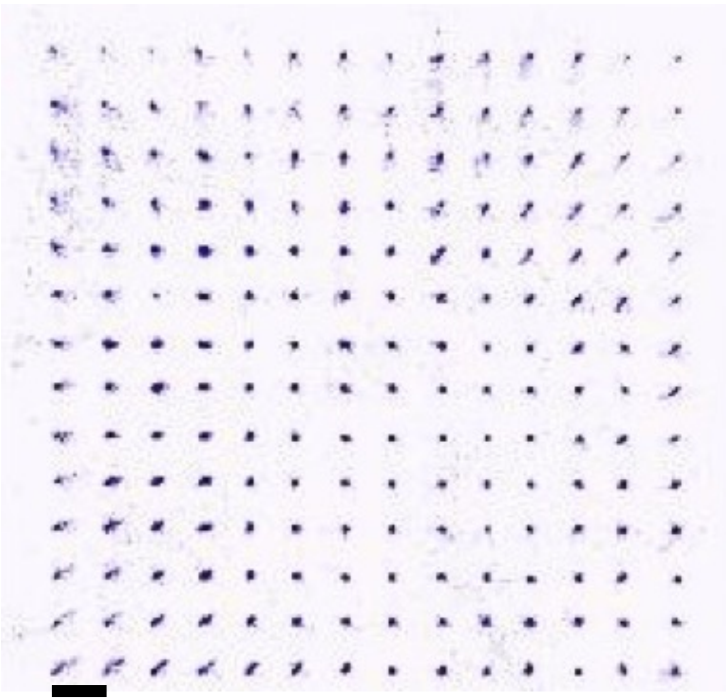


Grangier (2001)
Sortais (2007)

Fluorescence: single shot!!

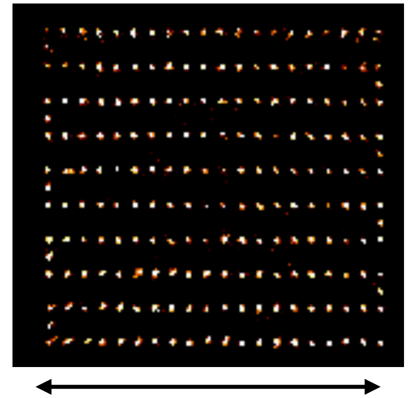
Arrays of interacting Rydberg atoms

Assembled arrays of tweezers
(~200 at.)



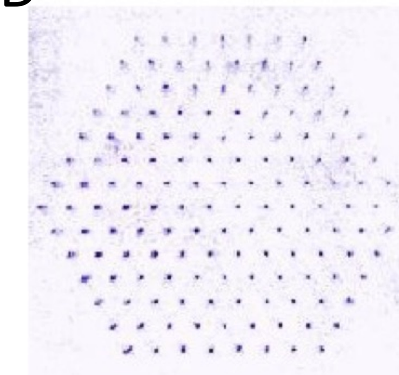
5 μm

1D



~100 μm

2D



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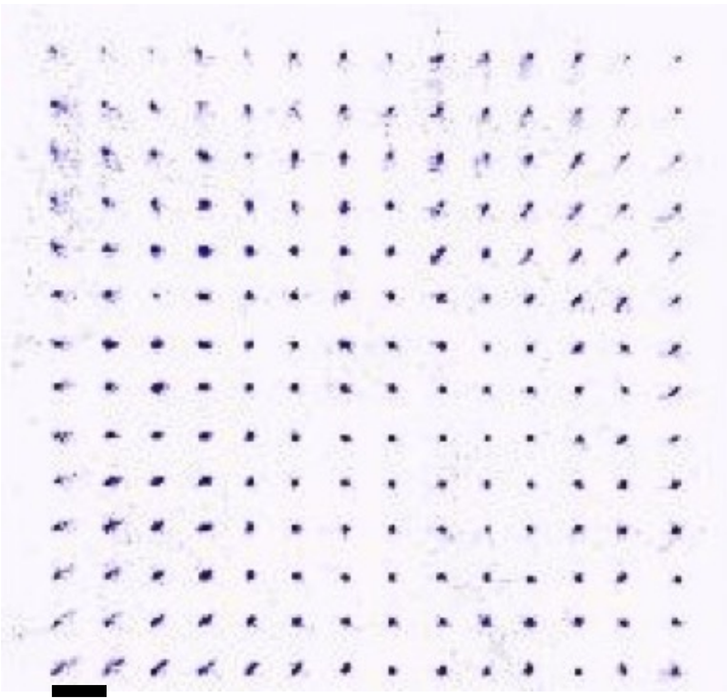

5 µm

Fluorescence: single shot!!

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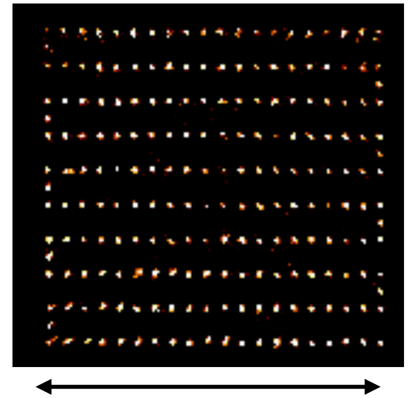
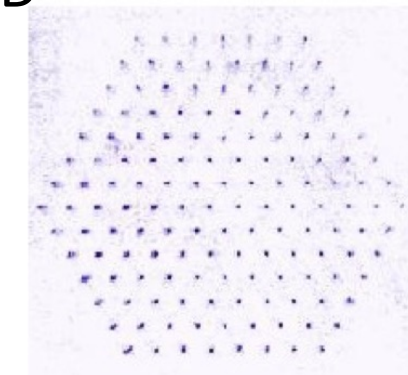
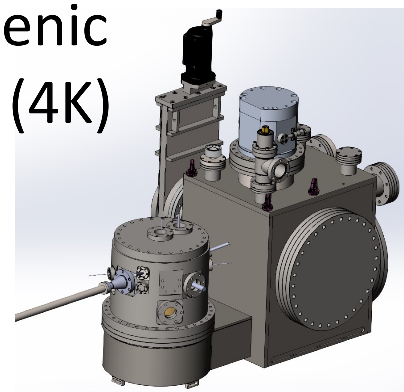


~100 µm

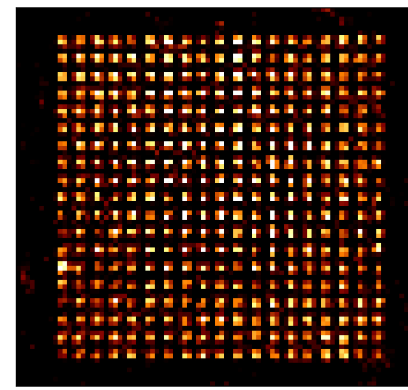
2D



Cryogenic setup (4K)



Schymik, PRApplied 2021

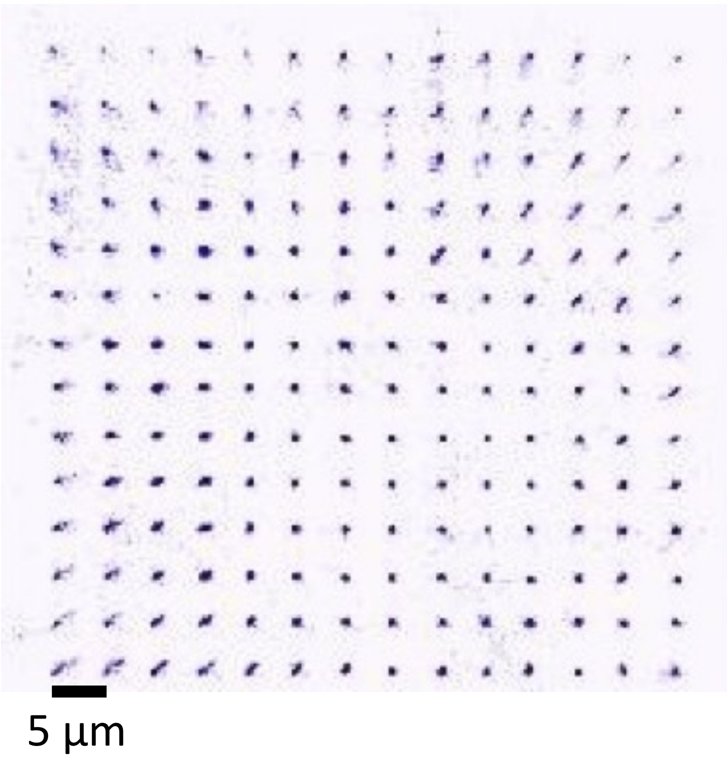


Schymik, PRA 2022

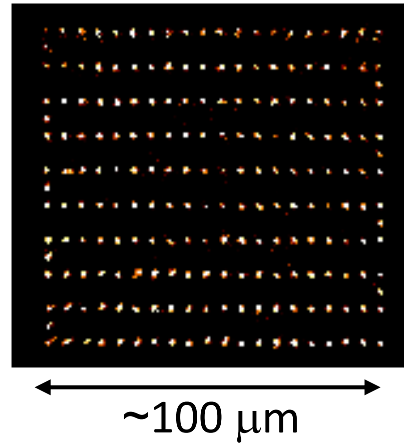
> 320 atoms assembled
> 35% probability

Arrays of interacting Rydberg atoms

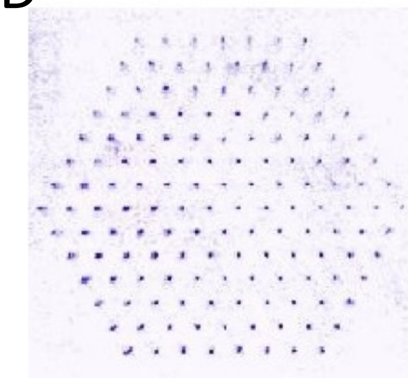
Assembled arrays of tweezers (~200 at.)



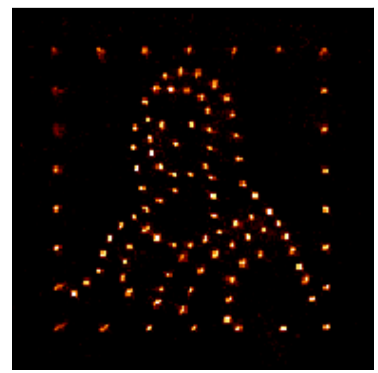
1D



2D



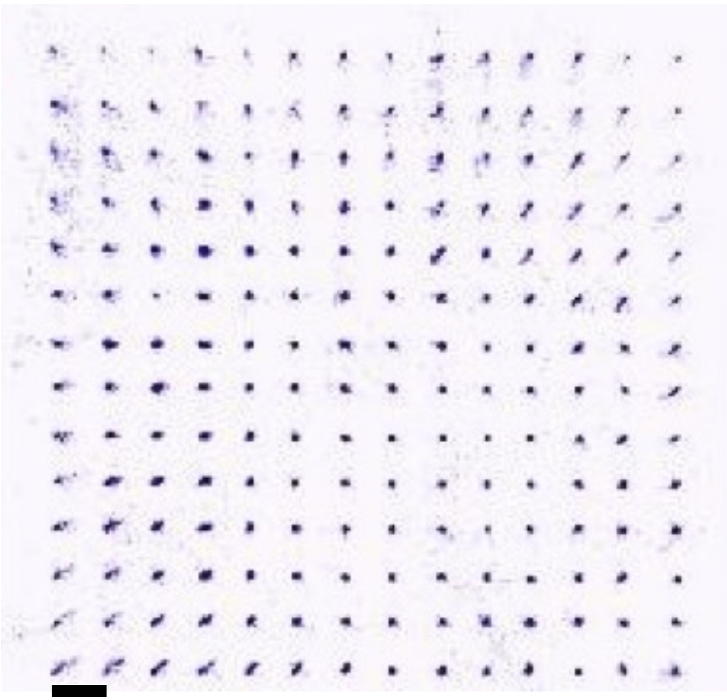
Schymik, PRA 2021



Fluorescence: single shot!!

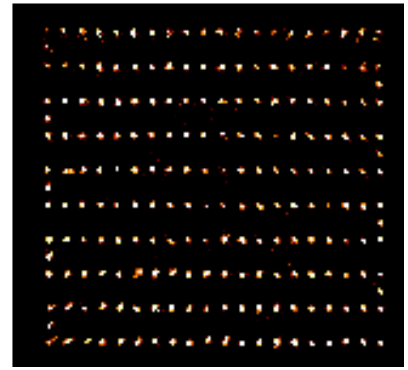
Arrays of interacting Rydberg atoms

Assembled arrays of tweezers (~200 at.)



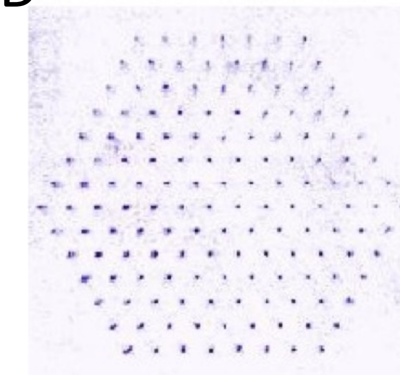
5 µm

1D

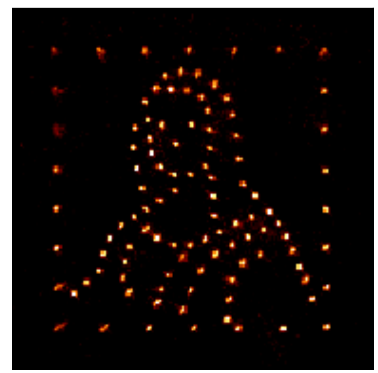


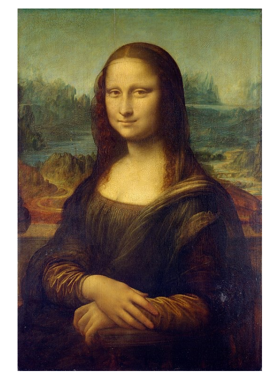
~100 µm

2D



Schymik, PRA 2021





L. da Vinci

Fluorescence: single shot!!

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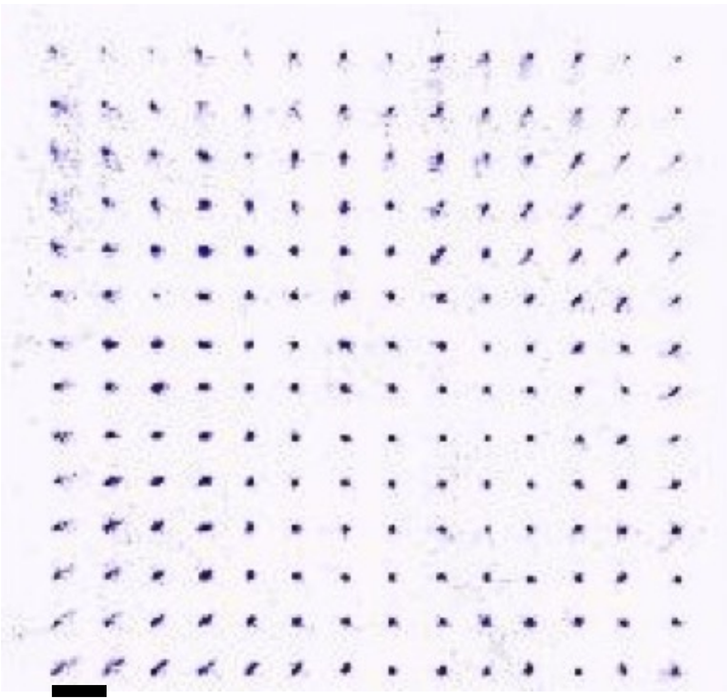

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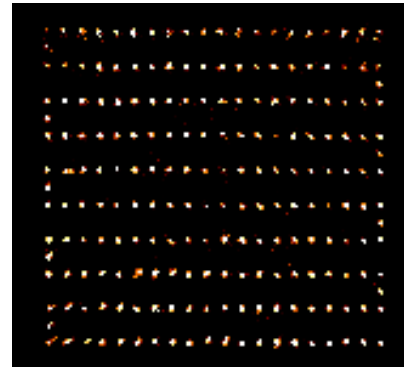
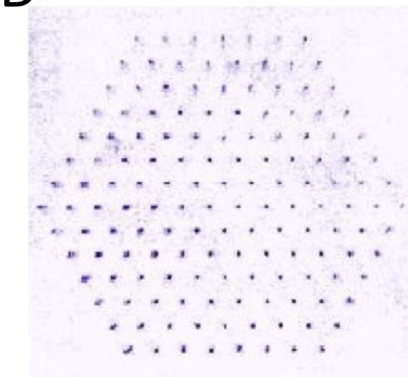
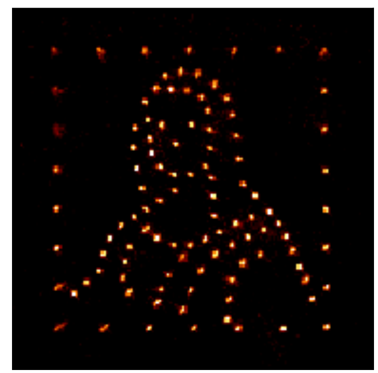


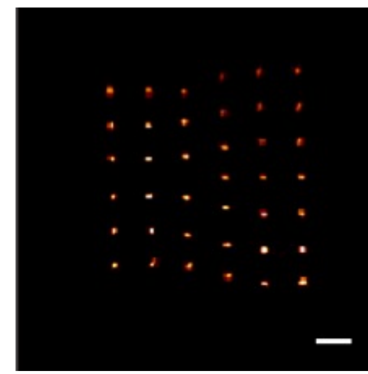
~100 µm

2D



Schymik, PRA 2021





Fluorescence: single shot!!

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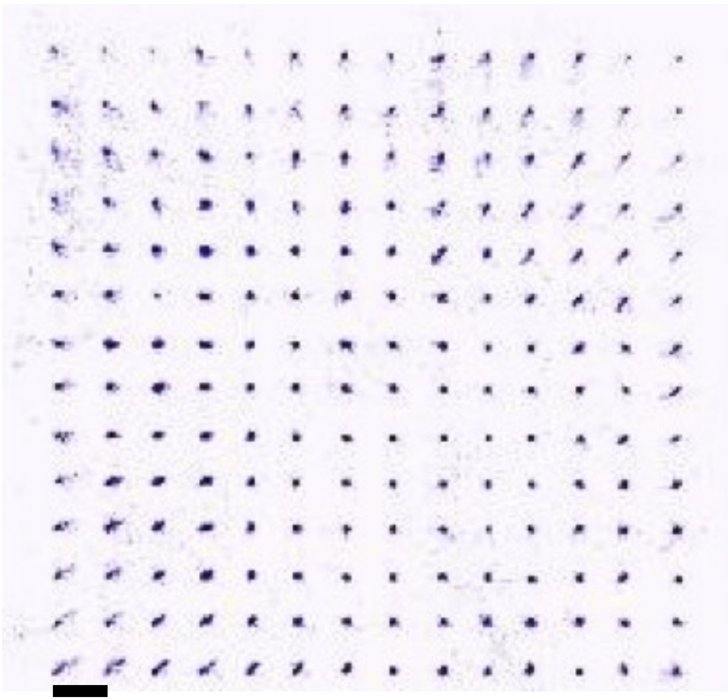
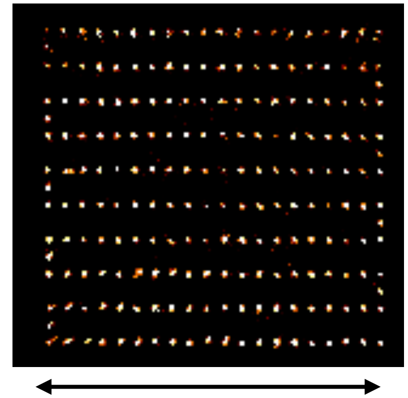


5 μm

1D



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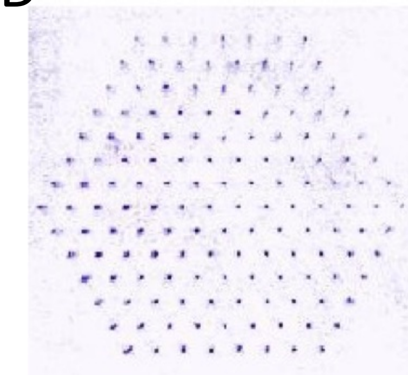
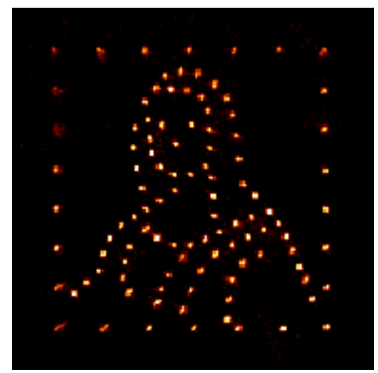
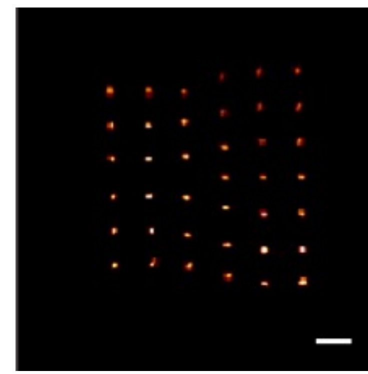
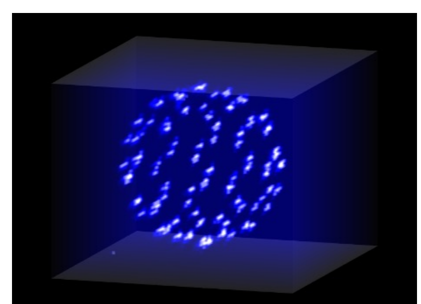


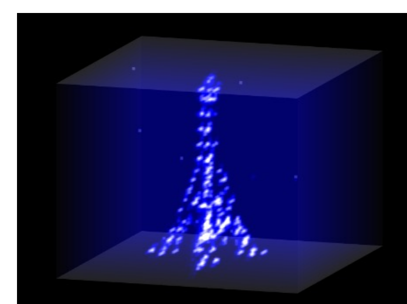
Schymik,
PRA 2021





3D



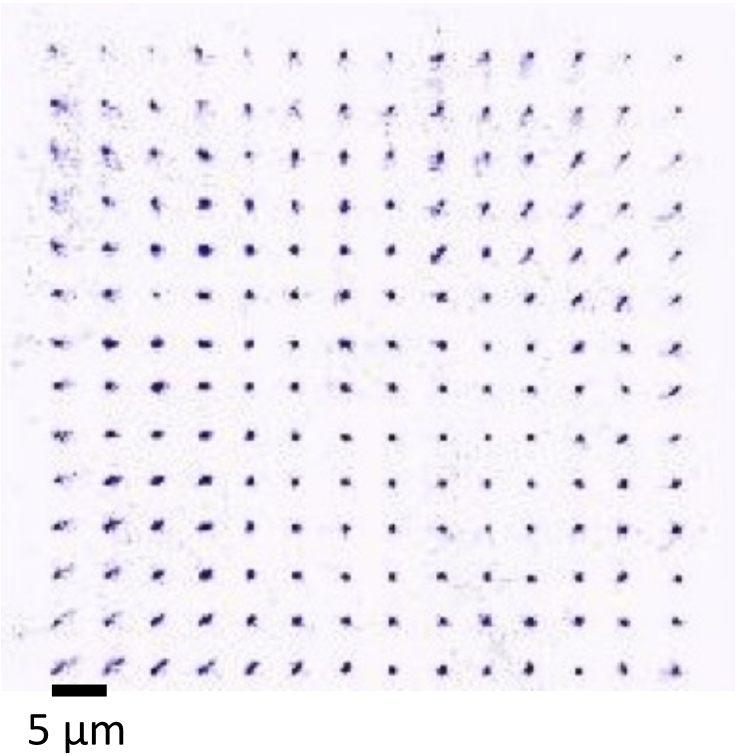


(Averaged)

Fluorescence: single shot!!

Arrays of interacting Rydberg atoms

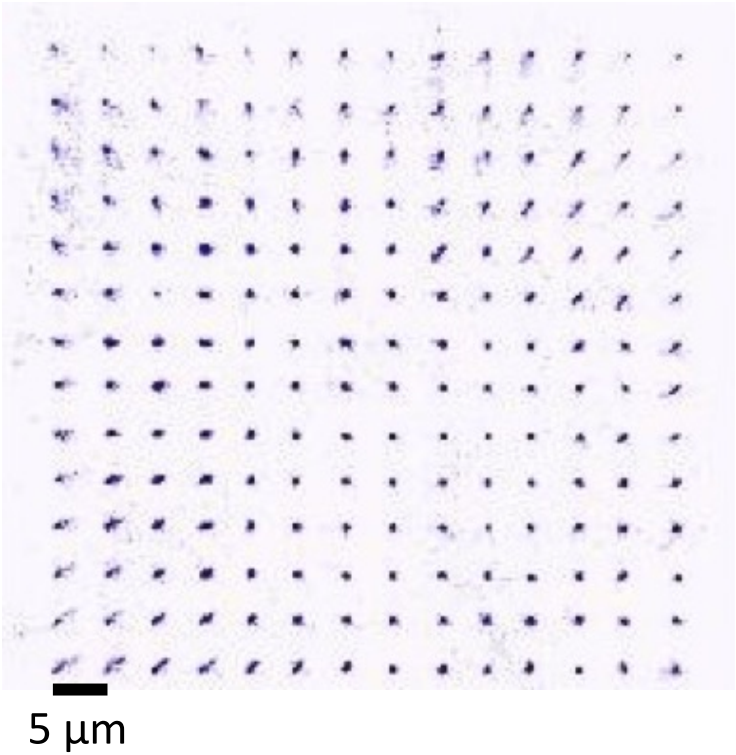
Assembled arrays of tweezers
(~200 at.)



Addressable!!

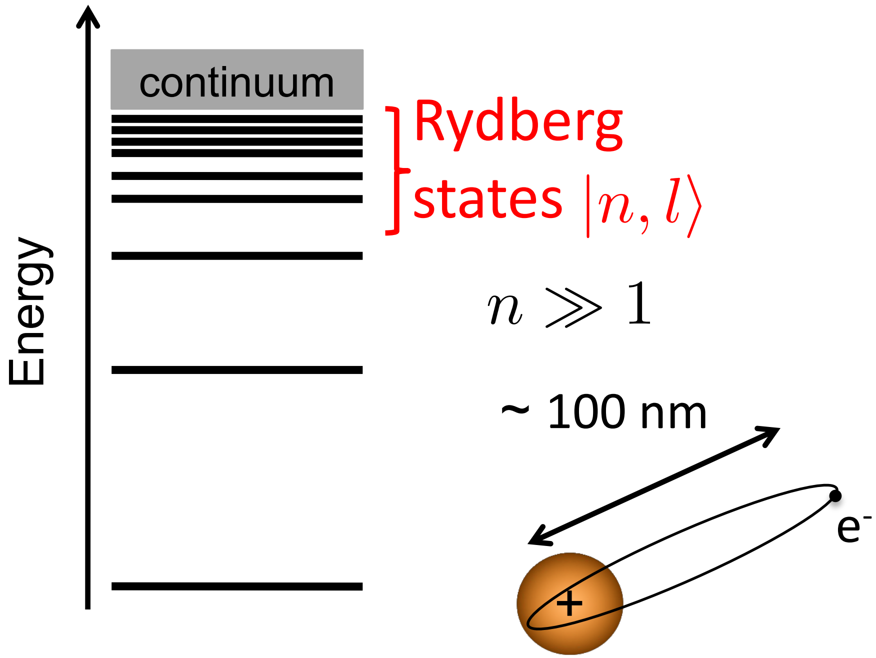
Arrays of interacting Rydberg atoms

Assembled arrays of tweezers (~200 at.)



Addressable!!

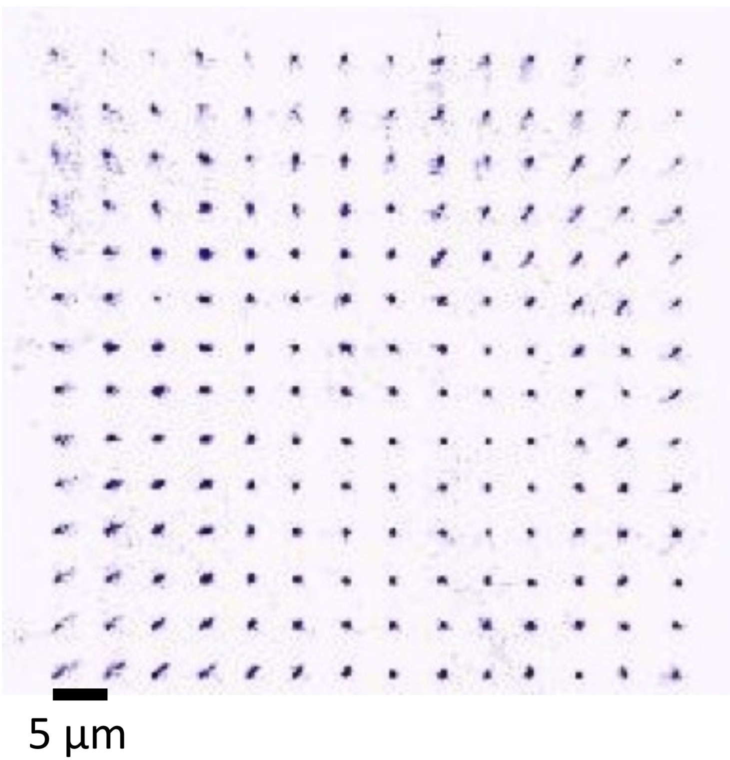
Rydberg atoms



Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

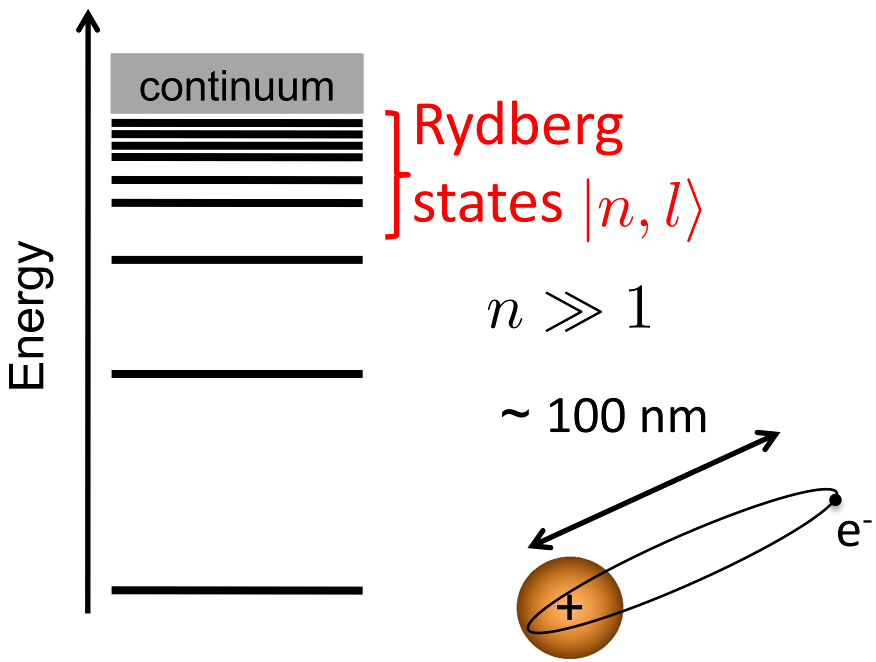
Arrays of interacting Rydberg atoms

Assembled arrays of tweezers (~200 at.)



Addressable!!

Rydberg atoms



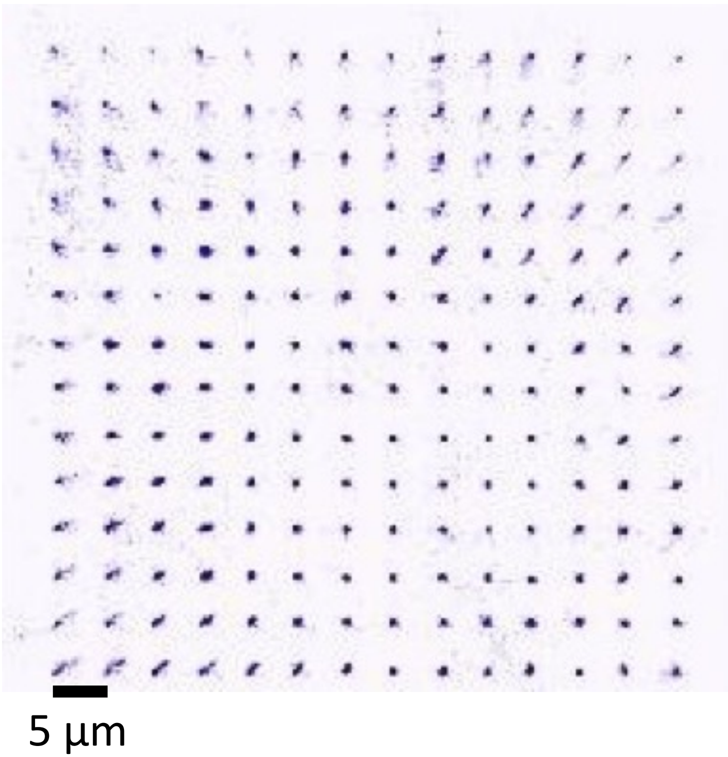
Lifetime > 100 µs

Transition dipole: $d_{n,n\pm1} \sim n^2 e a_0$

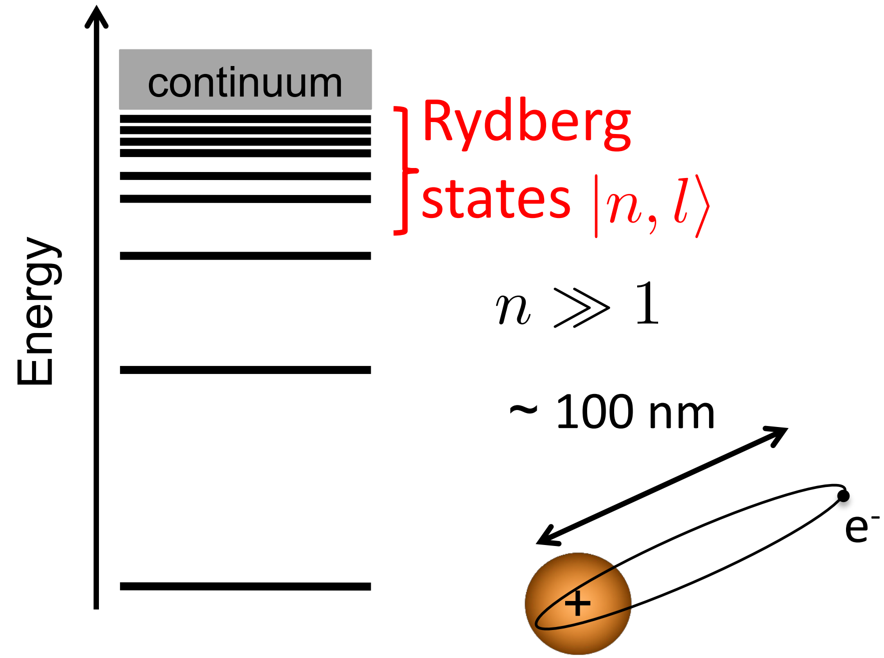
Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

Arrays of interacting Rydberg atoms

Assembled arrays of tweezers (~200 at.)



Rydberg atoms



Lifetime > 100 µs

Transition dipole: $d_{n,n\pm1} \sim n^2 e a_0$

$\Rightarrow$ **Large dipole-dipole interactions**

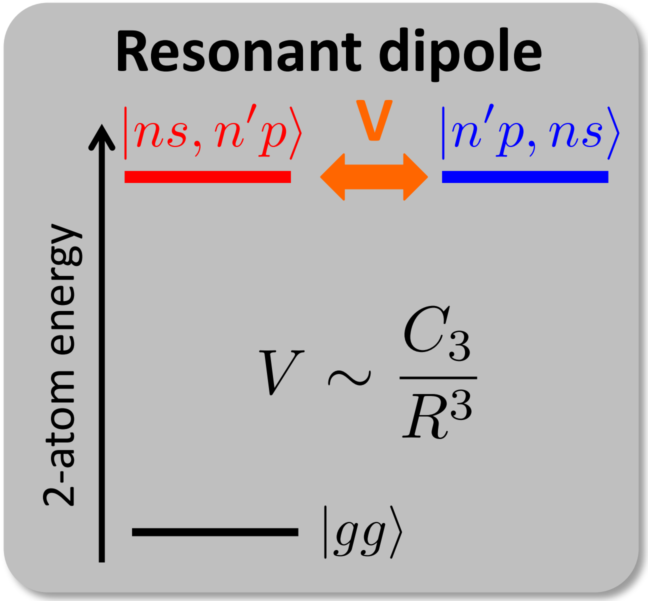
$R = 10\ \mu\mathrm{m} \Rightarrow V_{\mathrm{int}}/h \sim 1 - 10\ \mathrm{MHz}$

$\Rightarrow$ **timescales < µsec**

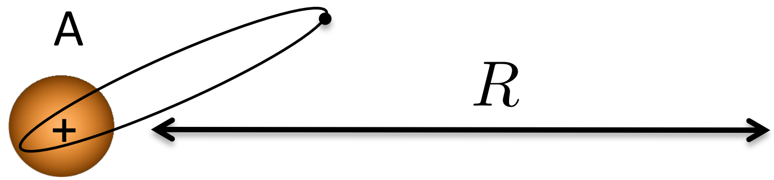
Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

Interactions between Rydberg atoms and spin models

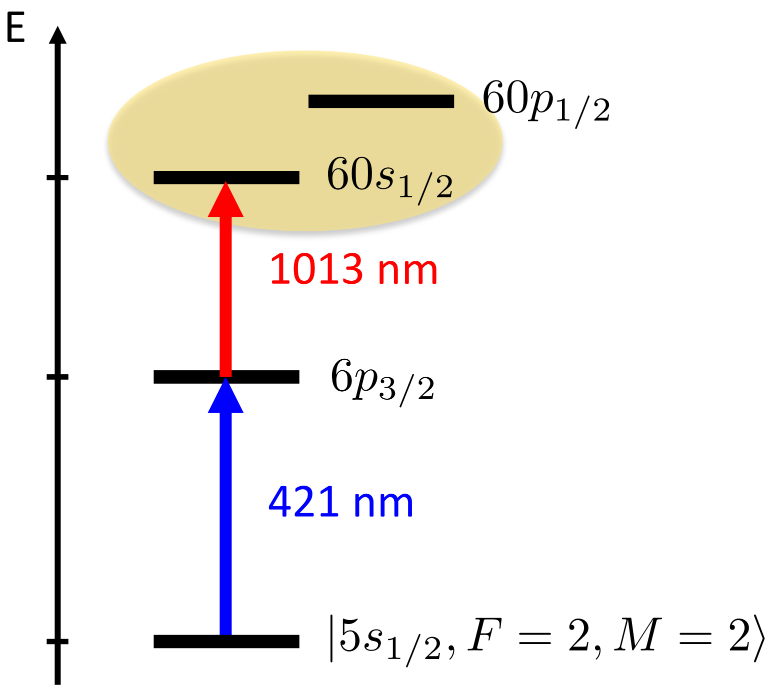
Browaeys & Lahaye, Nat.Phys. (2020)

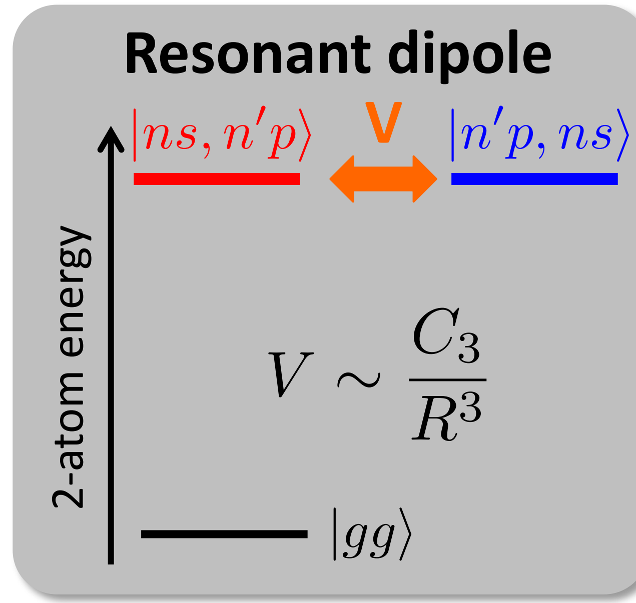


Interactions between Rydberg atoms and spin models



Browaeys & Lahaye, Nat.Phys. (2020)





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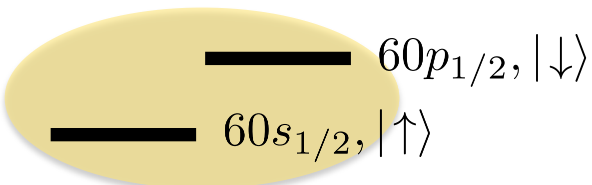

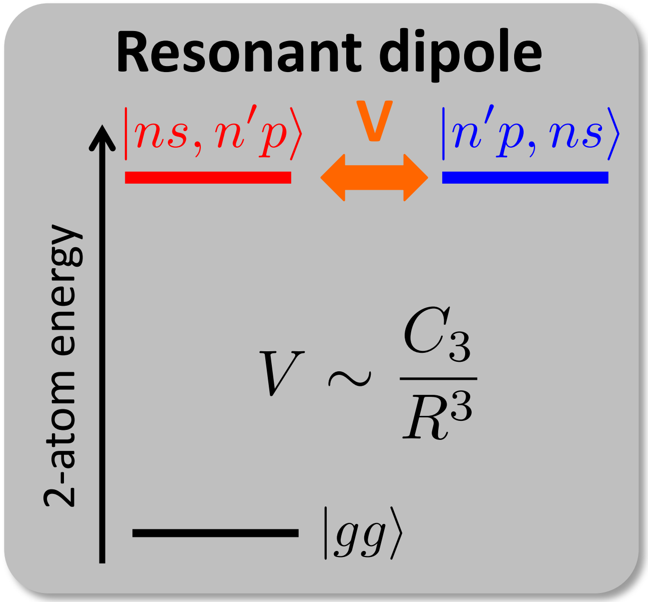

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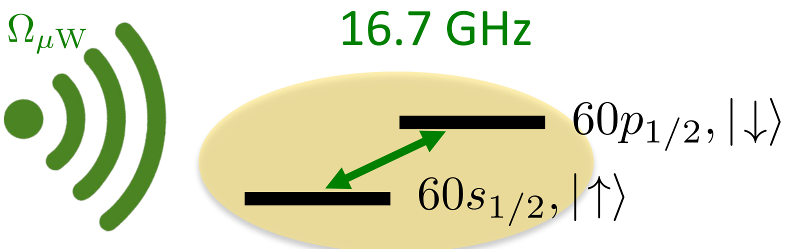

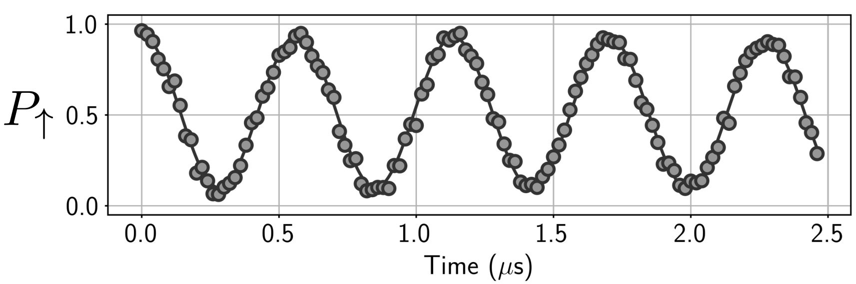

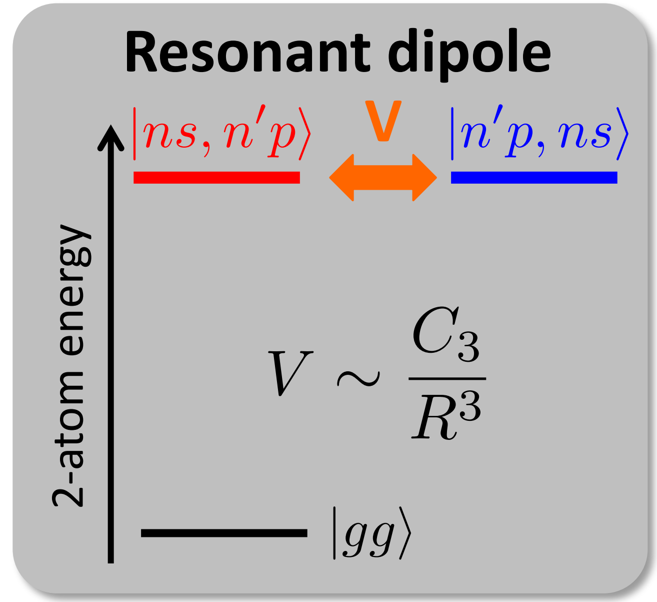

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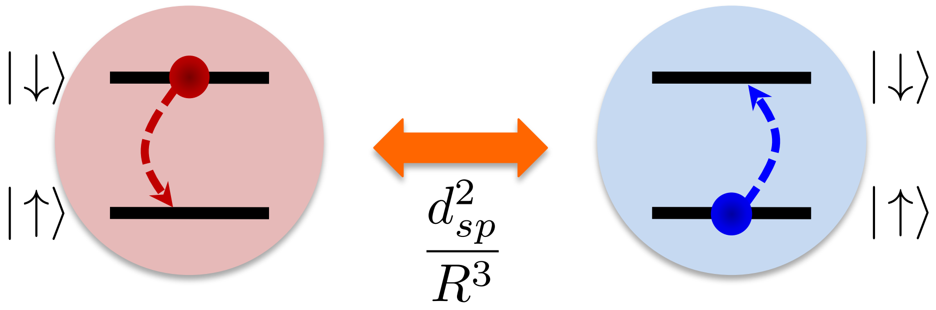

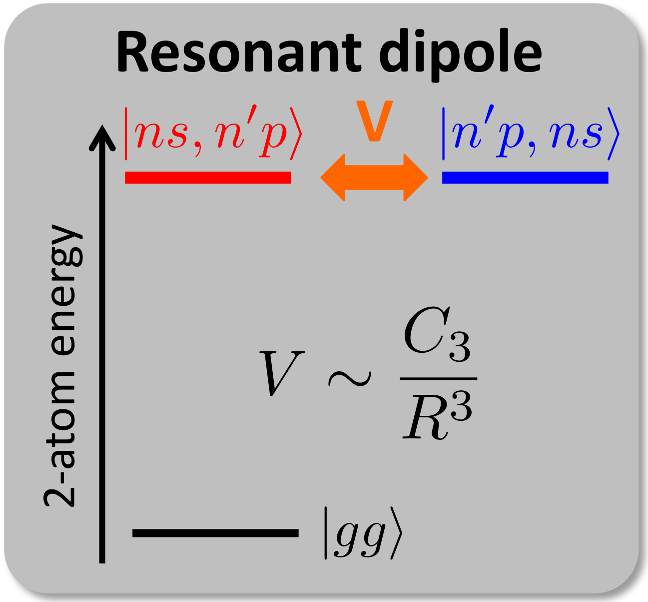

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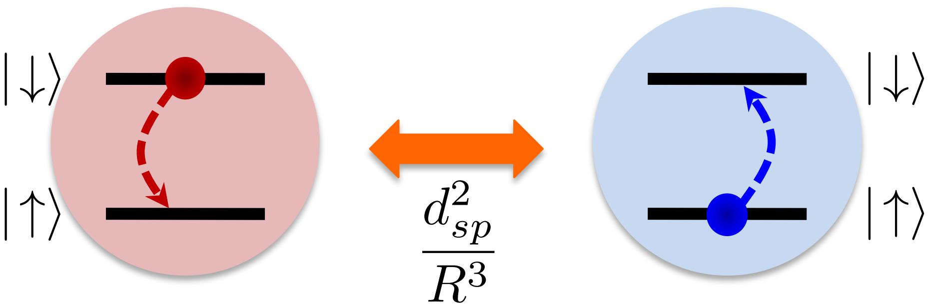
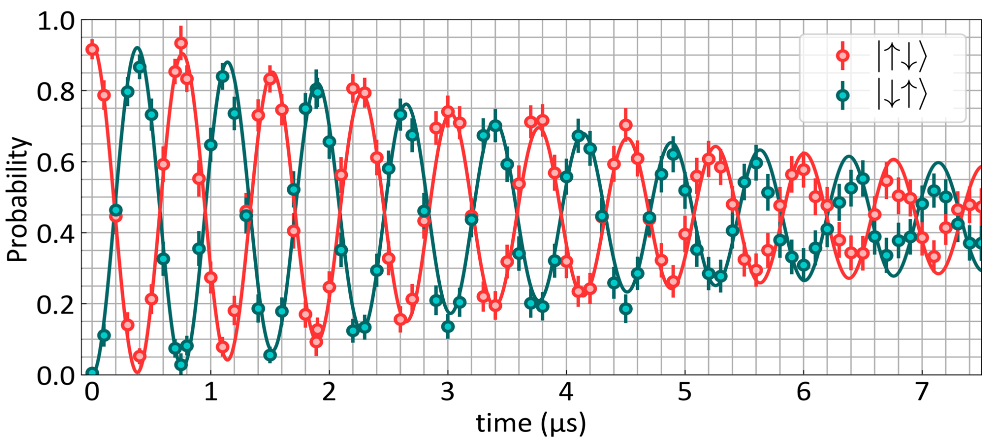
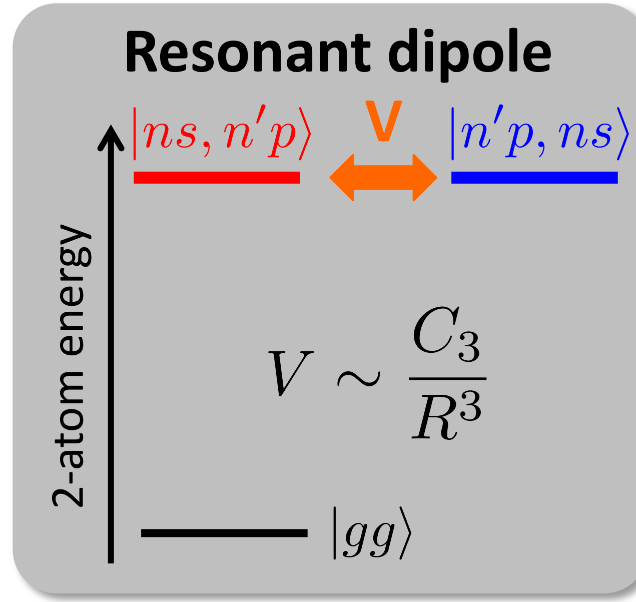




Barredo PRL (2015), de Léséleuc, PRL (2017)



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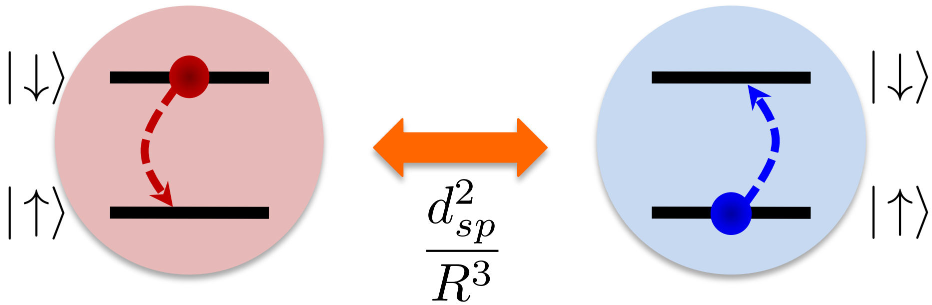

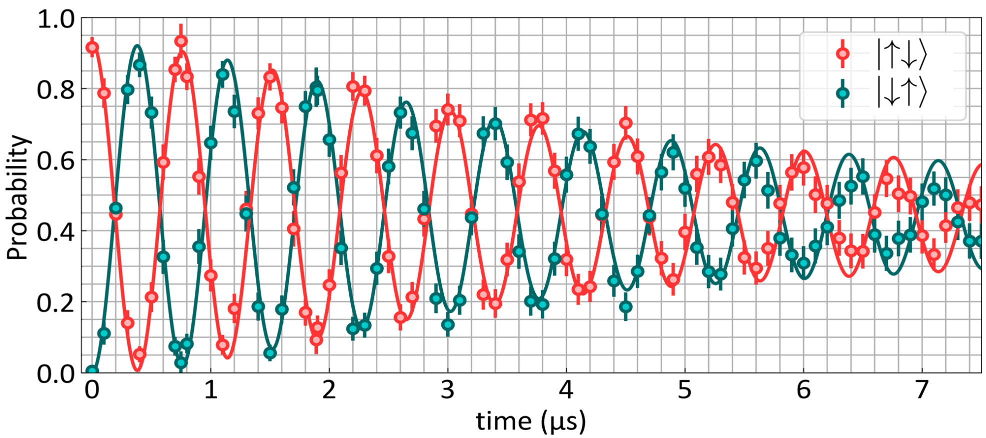

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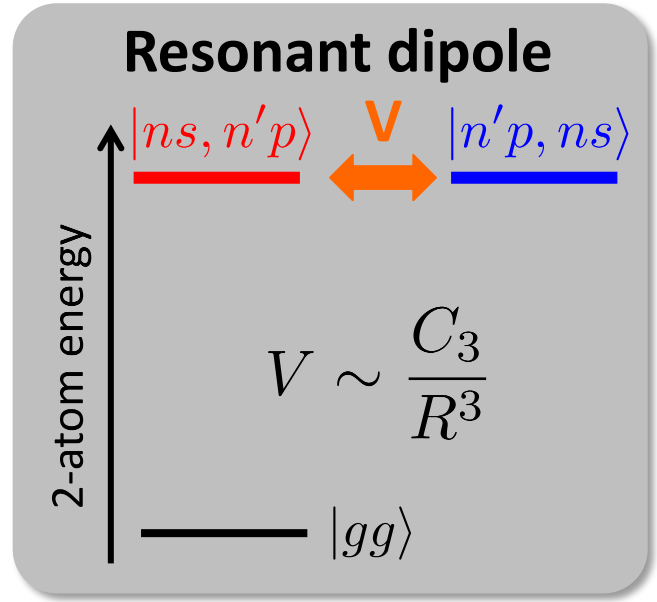


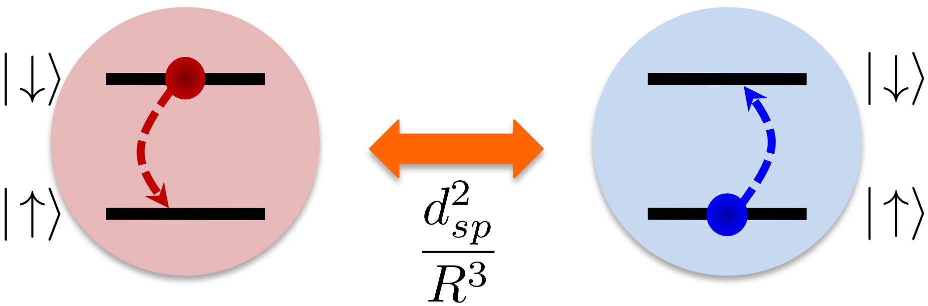
XY model

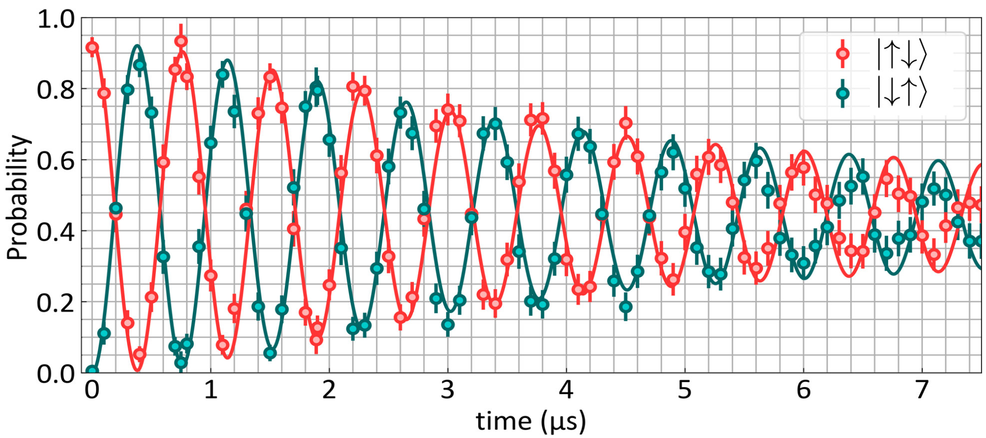
$$\hat{H} = \sum_{i \neq j} J_{ij} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

$$J_{ij} = C_3 / R_{ij}^3$$

Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)





Barredo PRL (2015), de Léséleuc, PRL (2017)

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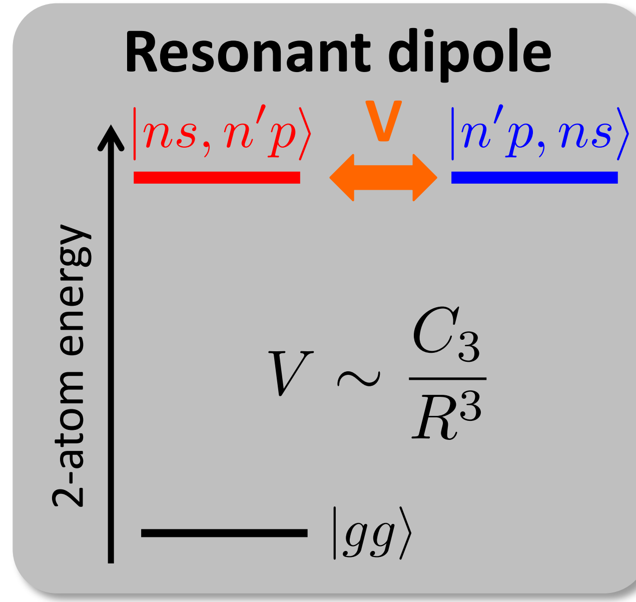

XY model

$$\hat{H} = \sum_{i \neq j} J_{ij}(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

$$= \sum_{i \neq j} 2J_{ij}(\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

Outline

1. Dipolar XY magnet with resonant dipole interactions

2. Spin squeezing using dipolar interaction

Outline

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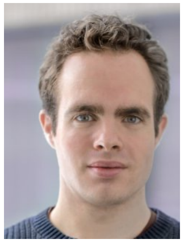
C. Chen *et al.*, Nature 2023

2. Spin squeezing using dipolar interaction

N. Yao +



M. Zaletel

M. Bintz

V. Liu
J. Hauschild
S. Chatterjee
(Berkeley)

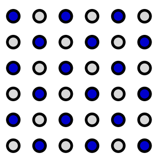
A. Läuchli + M. Schuler
(Innsbruck)

Ising versus XY model = classical versus quantum…

Ising model

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

Antiferro $J_{ij} < 0$



=

$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$
$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$
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Ground state (1/2, 1/3…) =
classical Néel configurations

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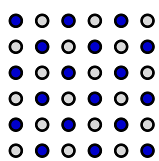

$$= \begin{matrix} \rightarrow_x \leftarrow_x \rightarrow_x \cdots \\ \leftarrow_x \rightarrow_x \leftarrow_x \cdots \\ \rightarrow_x \leftarrow_x \rightarrow_x \cdots \end{matrix}$$

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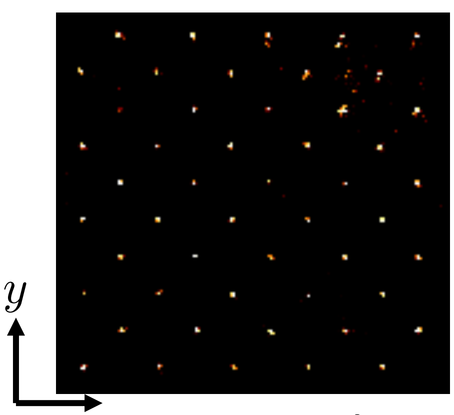
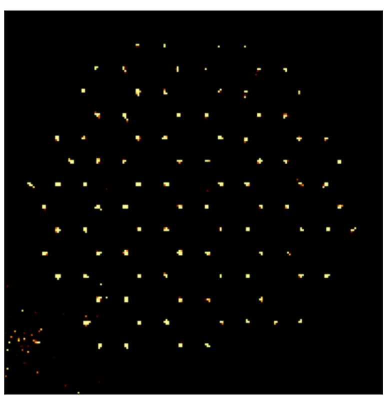


x Square (1/2)



Triangle (1/3)

Schauss *et al.*, Nature 2013
Scholl *et al.*, Nature 2021
Ebadi *et al.*, Nature 2021
Choi *et al.*, Nature 2023…

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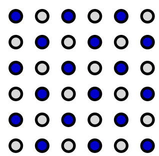

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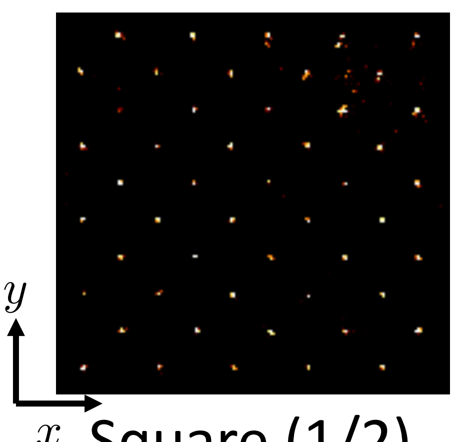
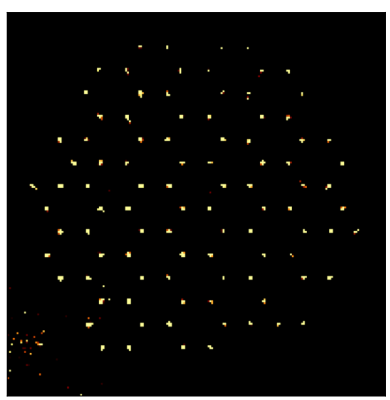


Square (1/2)



Triangle (1/3)

XY model

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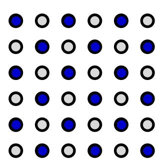

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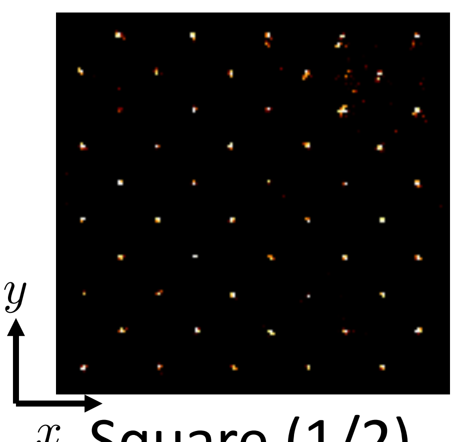
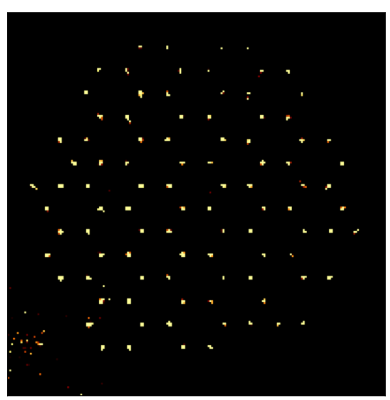


Square (1/2)



Triangle (1/3)

XY model

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Competing order along *x* / along *y*

$$“\left| \begin{matrix} \rightarrow_x \leftarrow_x \\ \leftarrow_x \rightarrow_x \end{matrix} \right\rangle + \left| \begin{matrix} \uparrow_y \downarrow_y \\ \downarrow_y \uparrow_y \end{matrix} \right\rangle”$$

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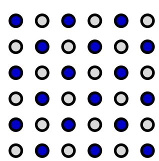

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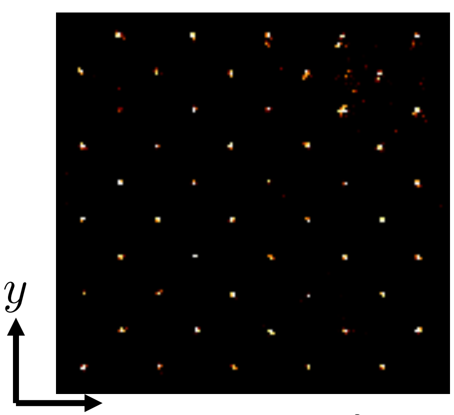
Ground state (1/2, 1/3…) = ***classical*** Néel configurations



Square (1/2)

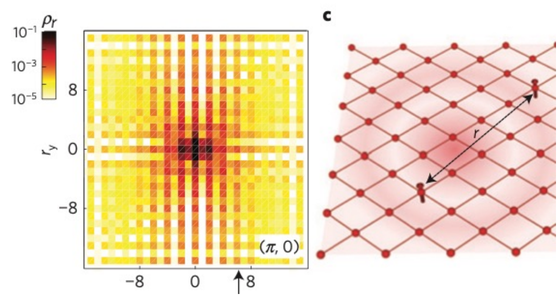
Triangle (1/3)

XY model

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

Metal organic compound

$Cu(DCOO)_2 4D_2O$



Dalla Piazza, Nat. Phys. 2017

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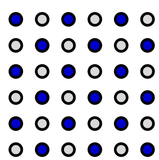

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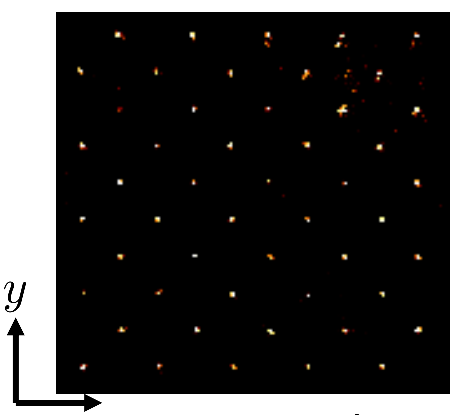

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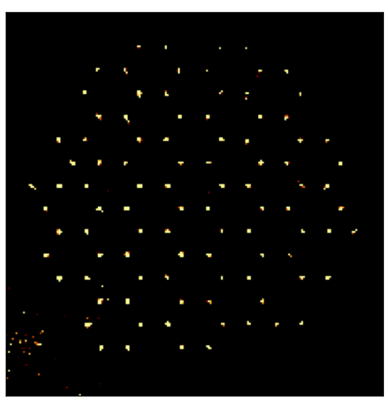

Triangle (1/3)

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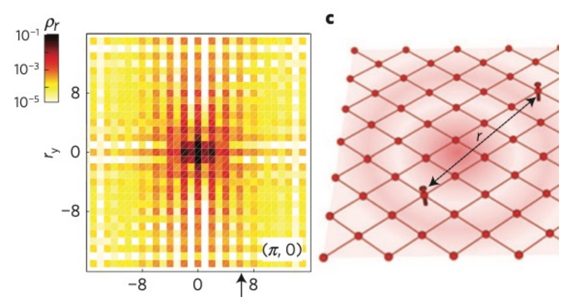
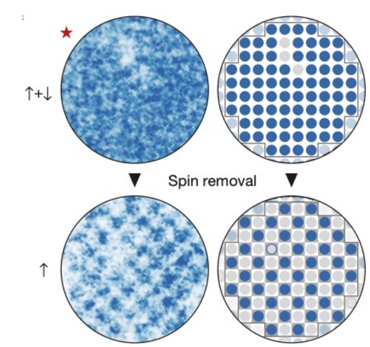


Dalla Piazza, Nat. Phys. 2017

Atoms in lattices



Greiner, Bloch, Esslinger, Kuhr…

Ising versus XY model = classical versus quantum…

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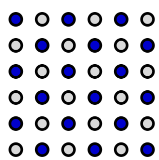

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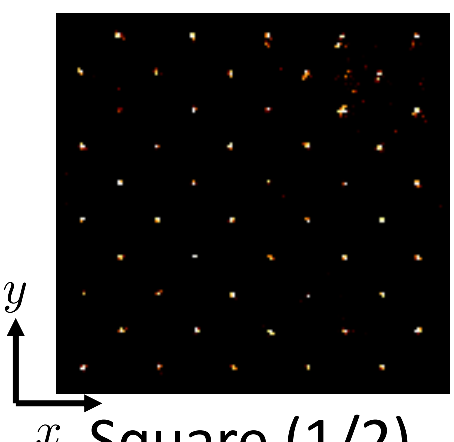
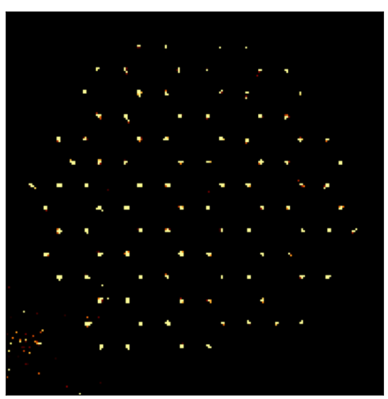


Square (1/2)



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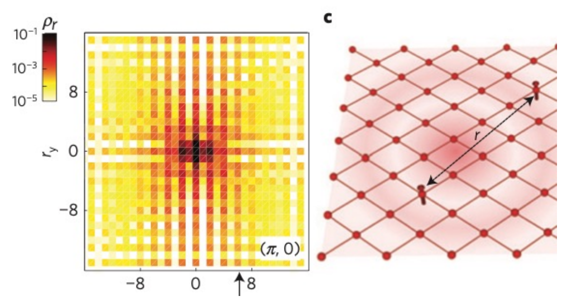
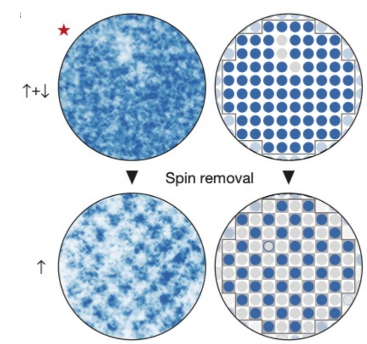


Dalla Piazza, Nat. Phys. 2017

Atoms in lattices



Greiner, Bloch, Esslinger, Kuhr…

Heisenberg: $\hat{H} = \sum_{i \neq j} J_{ij} \, \mathbf{S}_i \cdot \mathbf{S}_j$

Ising versus XY model = classical versus quantum…

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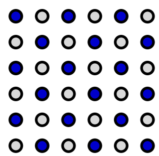

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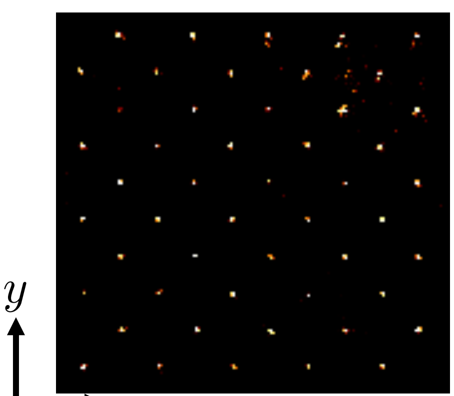

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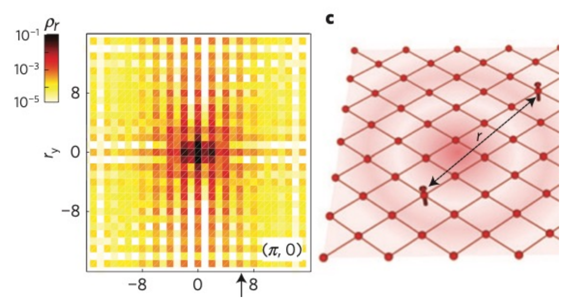
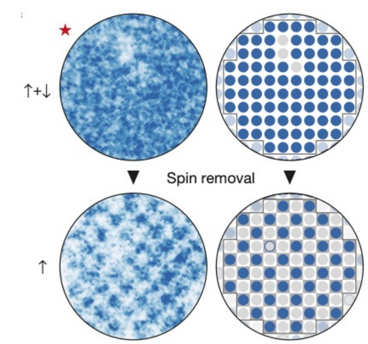


Dalla Piazza, Nat. Phys. 2017

Atoms in lattices



Greiner, Bloch, Esslinger, Kuhr…

Heisenberg: $\hat{H} = \sum_{i \neq j} J_{ij} \, \mathbf{S}_i \cdot \mathbf{S}_j$

Short-range interactions

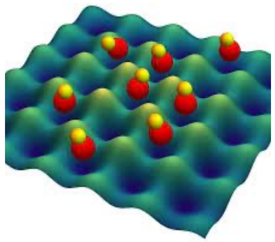
Dipolar XY magnets: possibility of Long-Range Order

Dipolar interactions $\Rightarrow 1/R^3$

Polar molecules

KRb, NaRb

Bakr, Ye, Ni…



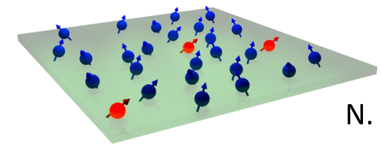
Hannover

Magnetic atoms

Cr, Er, Dy

Laburthe, Ferlaino, Pfau, Ketterle, Modugno…

Defects in solid



N. Yao

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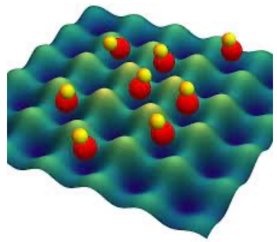

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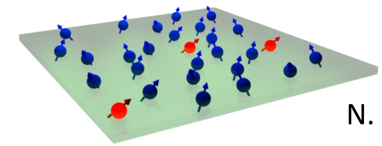
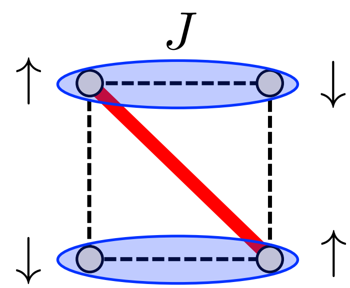


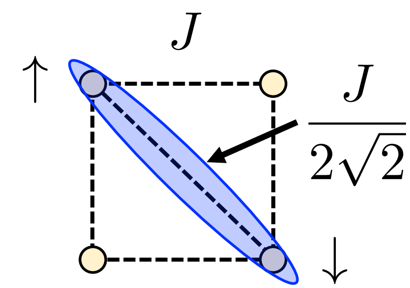
N. Yao

Introduces frustration!!

AFM: $J < 0$



vs.



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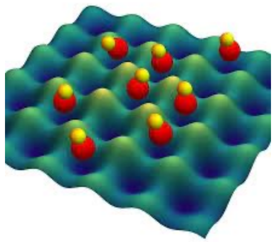

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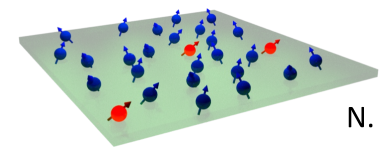

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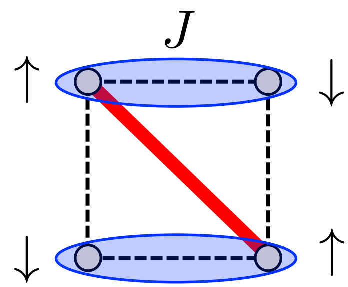

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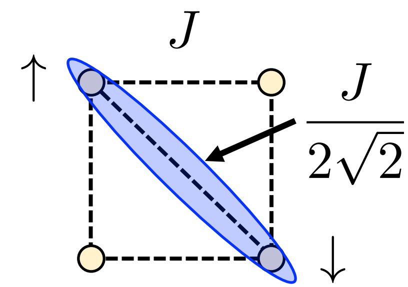

Expectations for ground state:

$T = 0 \Rightarrow$ Long Range order for FM & AFM   Bruno, PRL 2001

$$\langle \sigma_i^x \sigma_j^x \rangle \neq 0, |i-j| \to \infty$$

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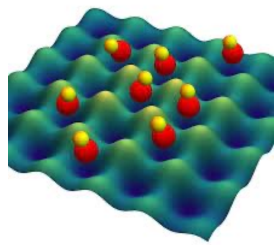

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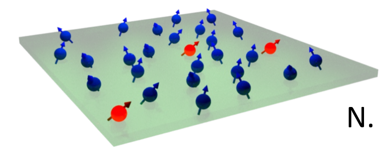

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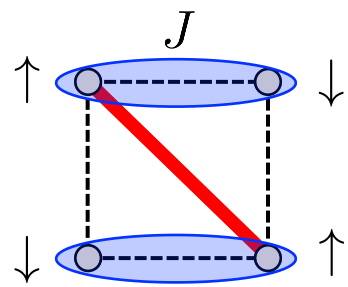

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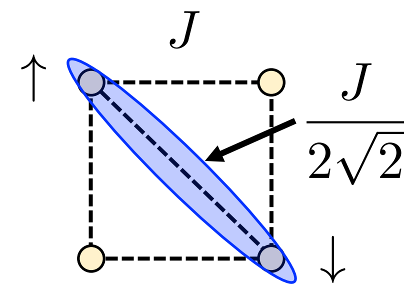

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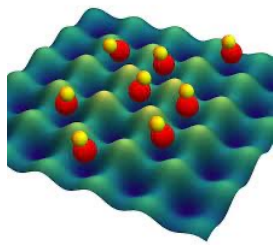

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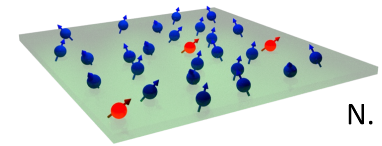

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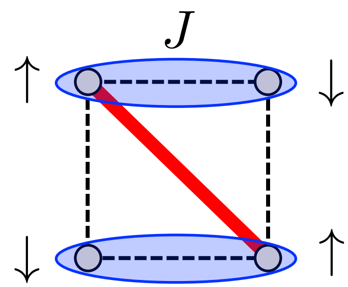

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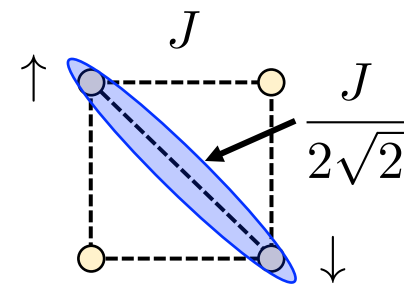

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Long-range order in 2D - XY magnets never observed…

Experimental preparation of XY ferro- & anti-ferromagnets

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

$(J/h \approx 0.8\,\mathrm{MHz})$

staggered

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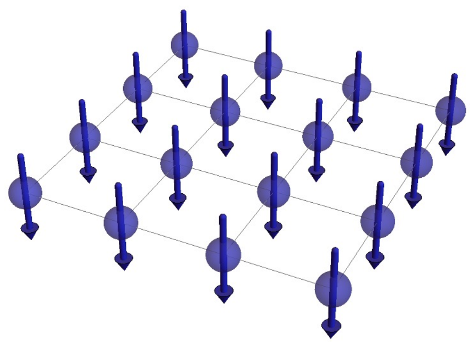

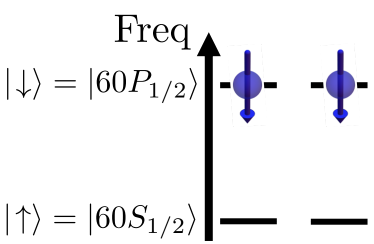

Sørensen *et al.*, PRA 81, 061603(R) (2010)

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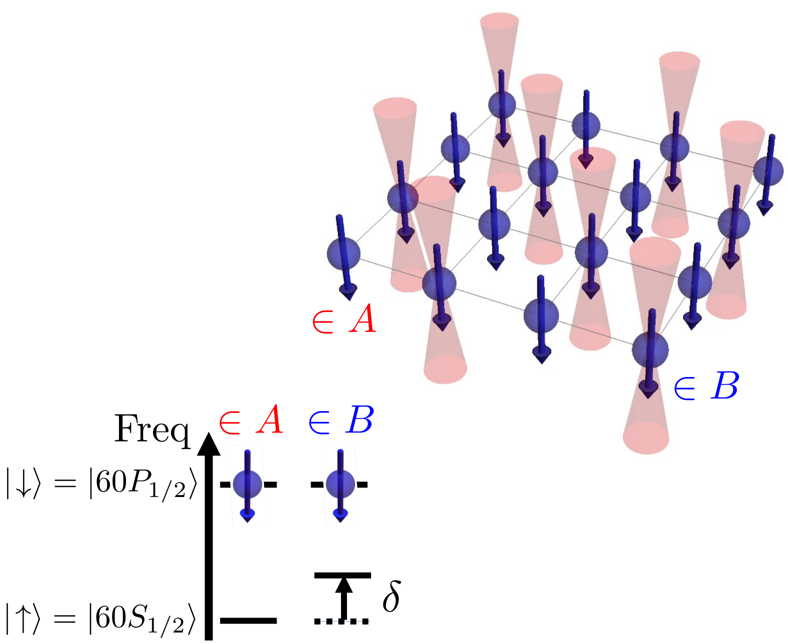

apply local light-shifts

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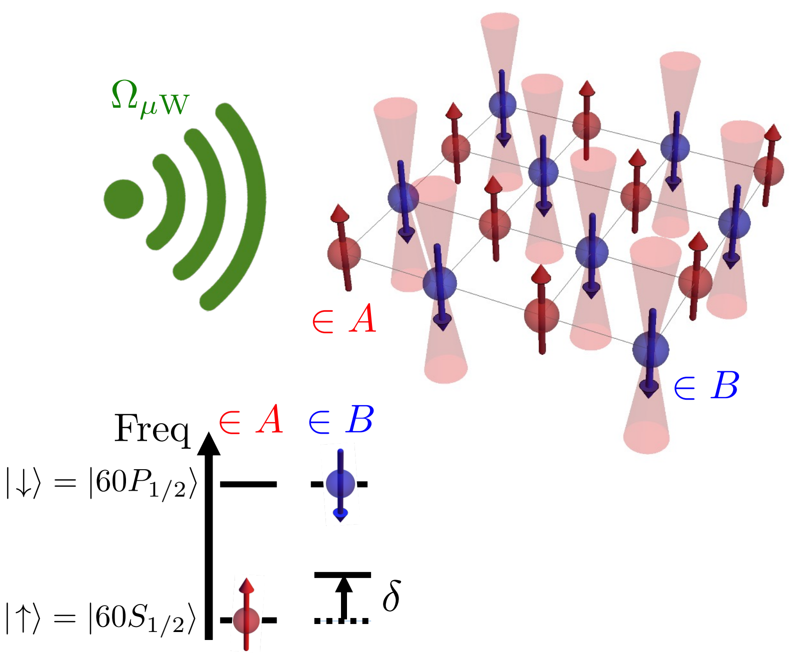

$$M_z = 0$$

apply local light-shifts

+

microwaves

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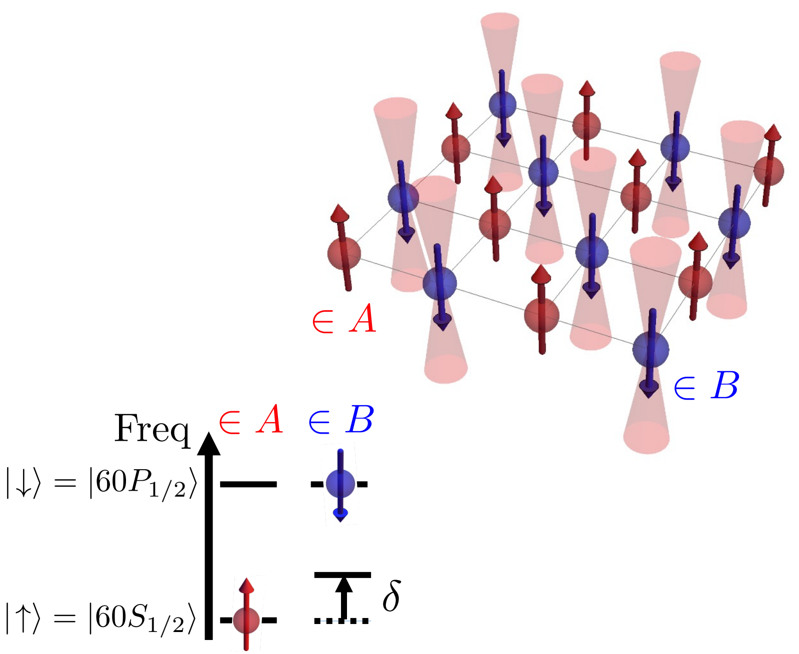
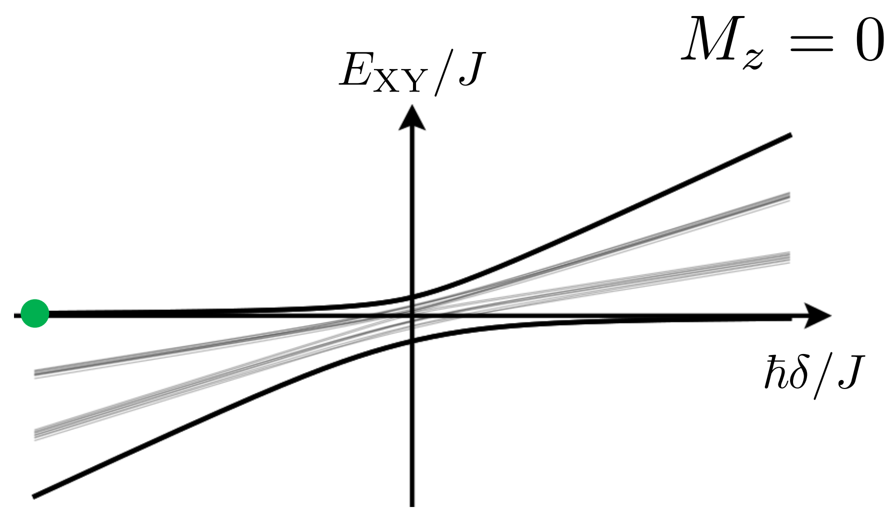
2. Adiabatically decrease δ to "melt" into XY AFM





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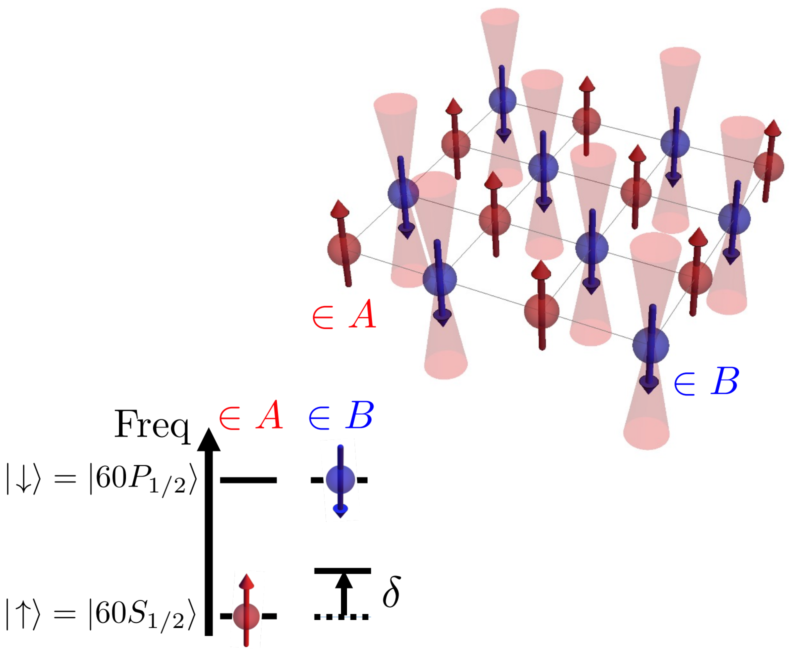

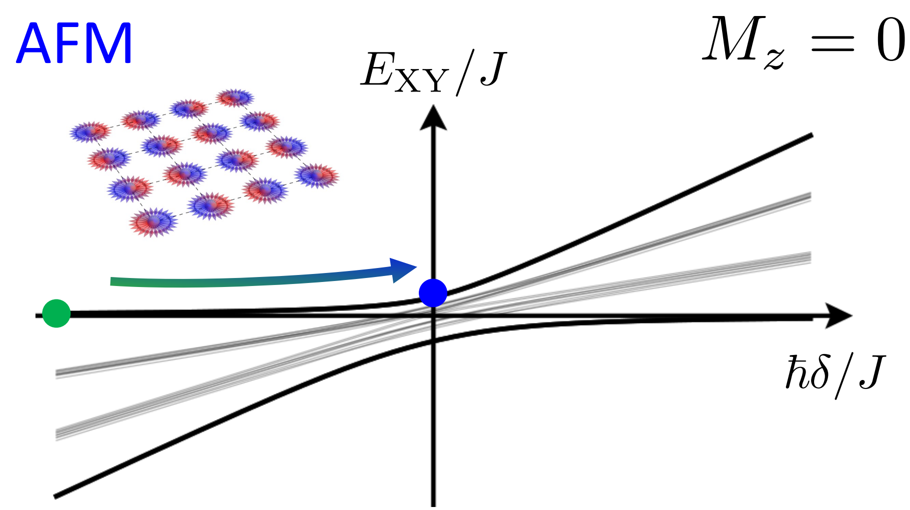

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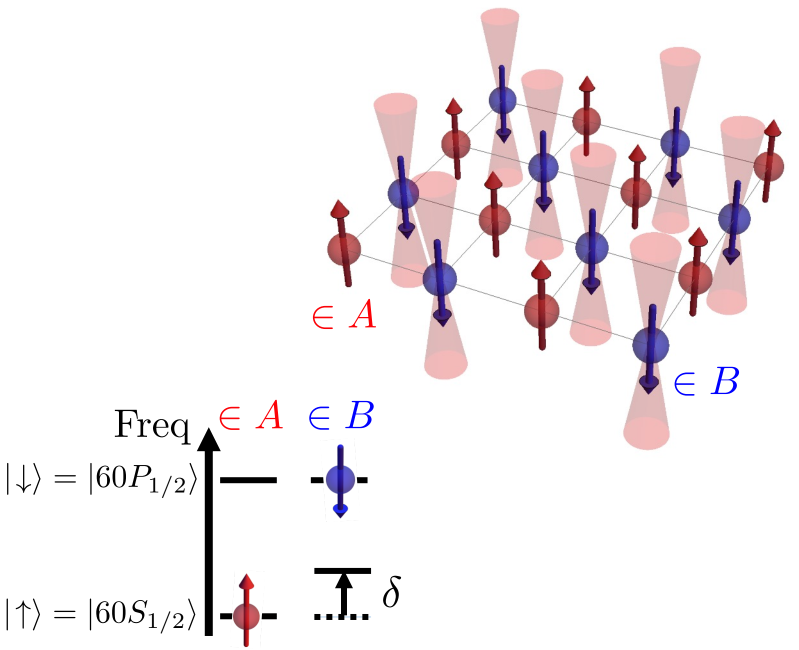

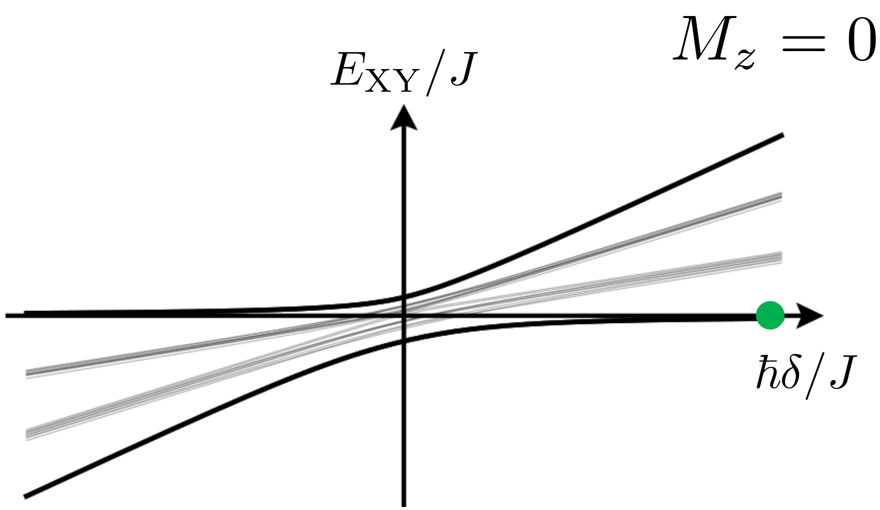

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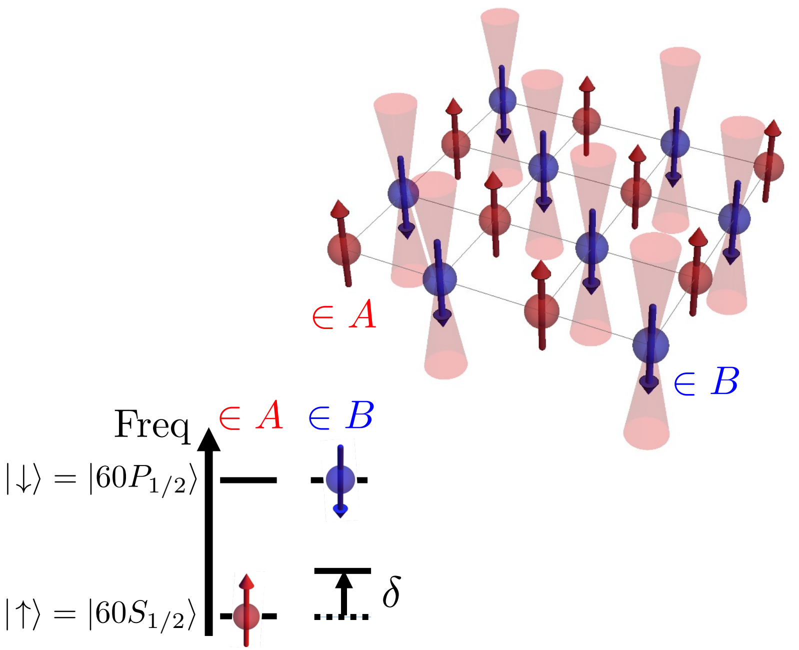

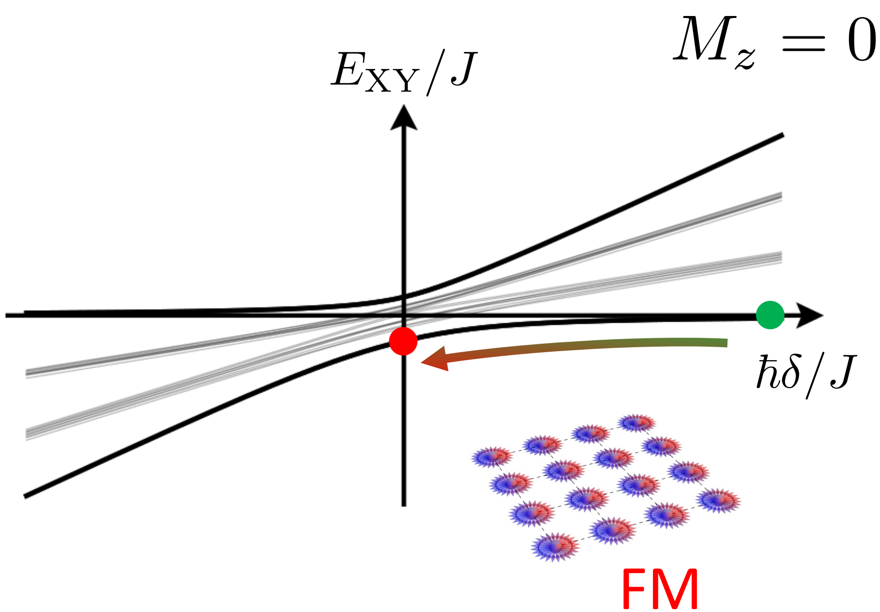

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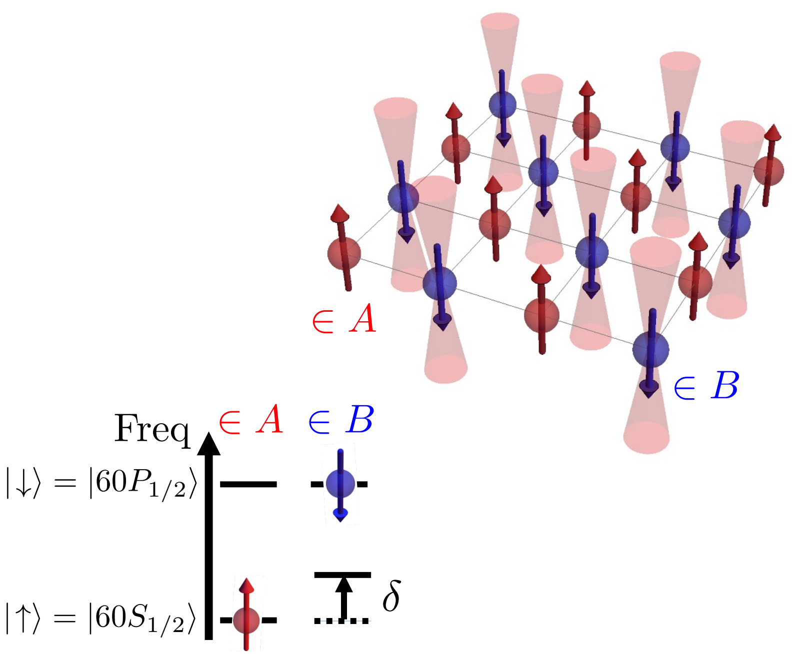
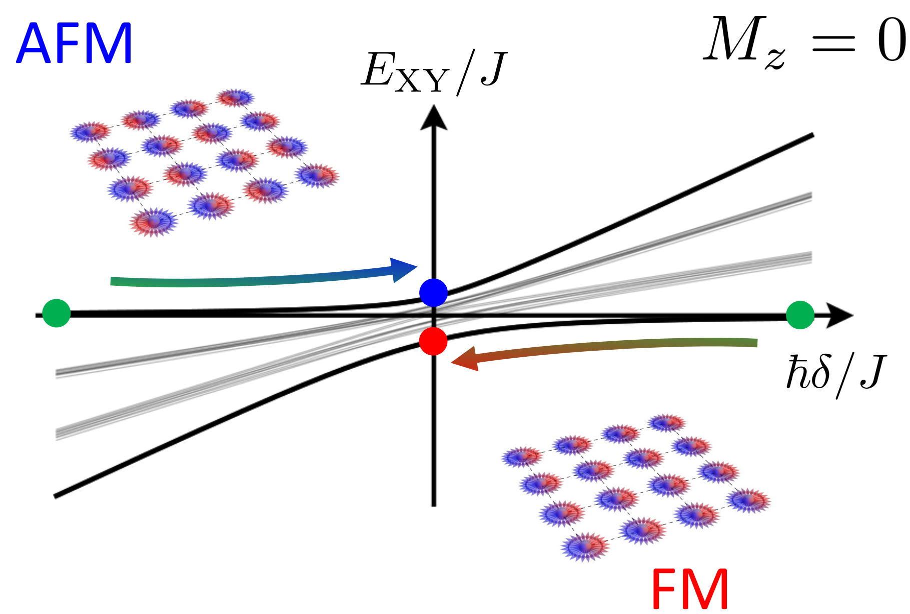
$(J/h \approx 0.8\,\mathrm{MHz})$

← staggered

2. Adiabatically decrease δ to “melt” into XY AFM / FM





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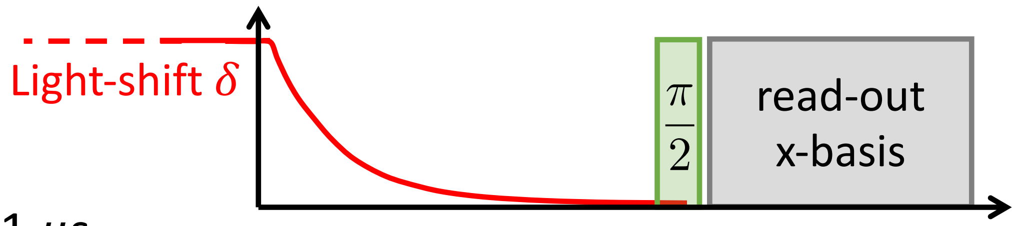
Observation of Long-Range FM order



t = 1 μs

10 x 10 = 100 atoms

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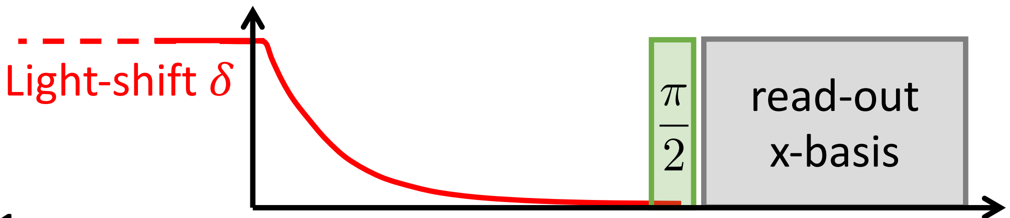

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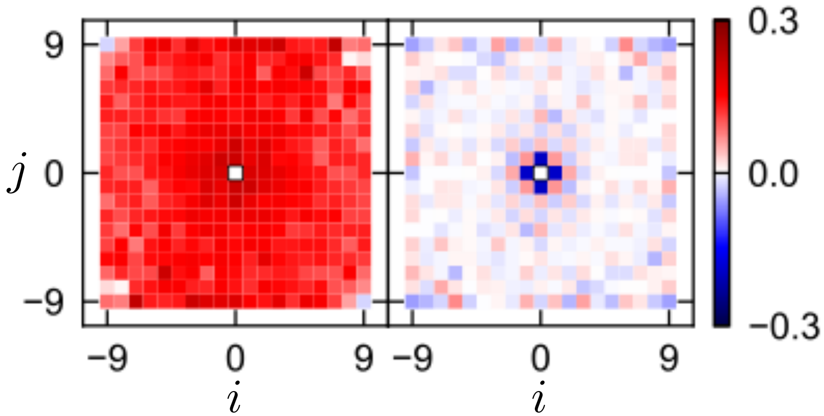
$$C_{ij}^x = \langle \sigma_i^x \sigma_j^x \rangle - \langle \sigma_i^x \rangle \langle \sigma_j^x \rangle$$



FM AFM

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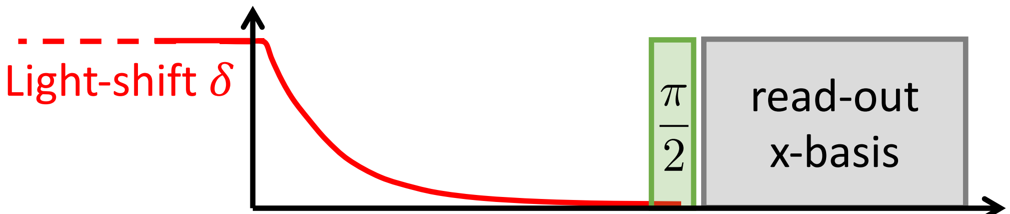

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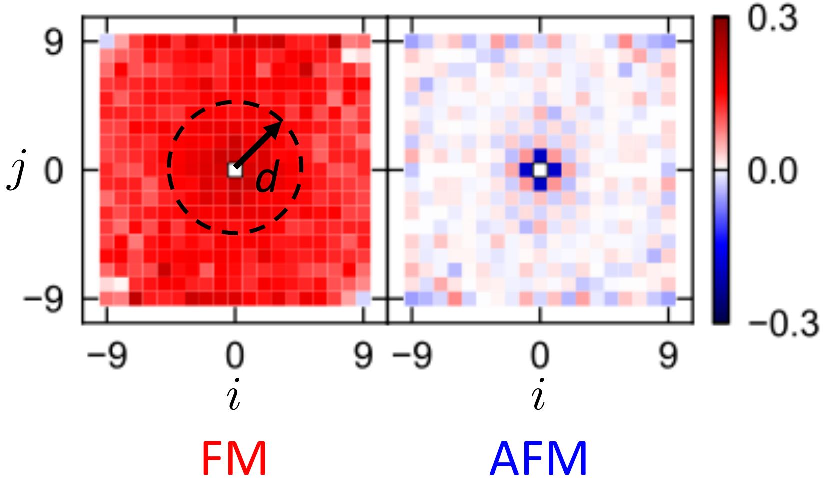

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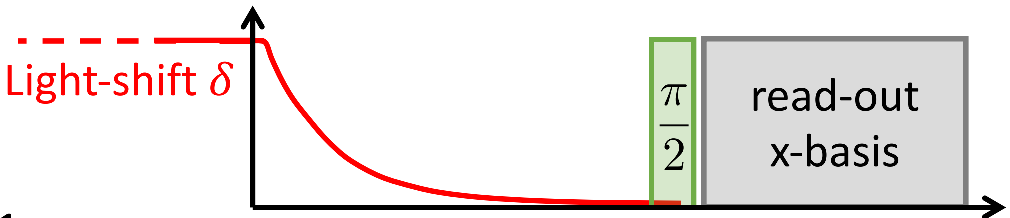

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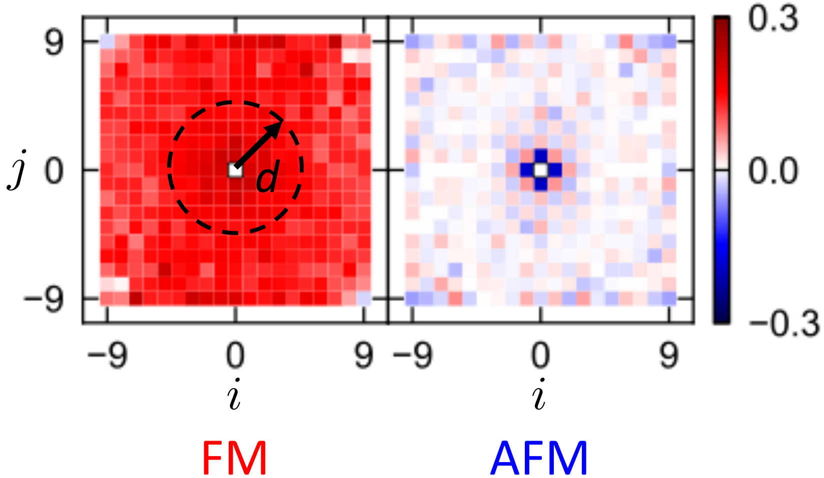

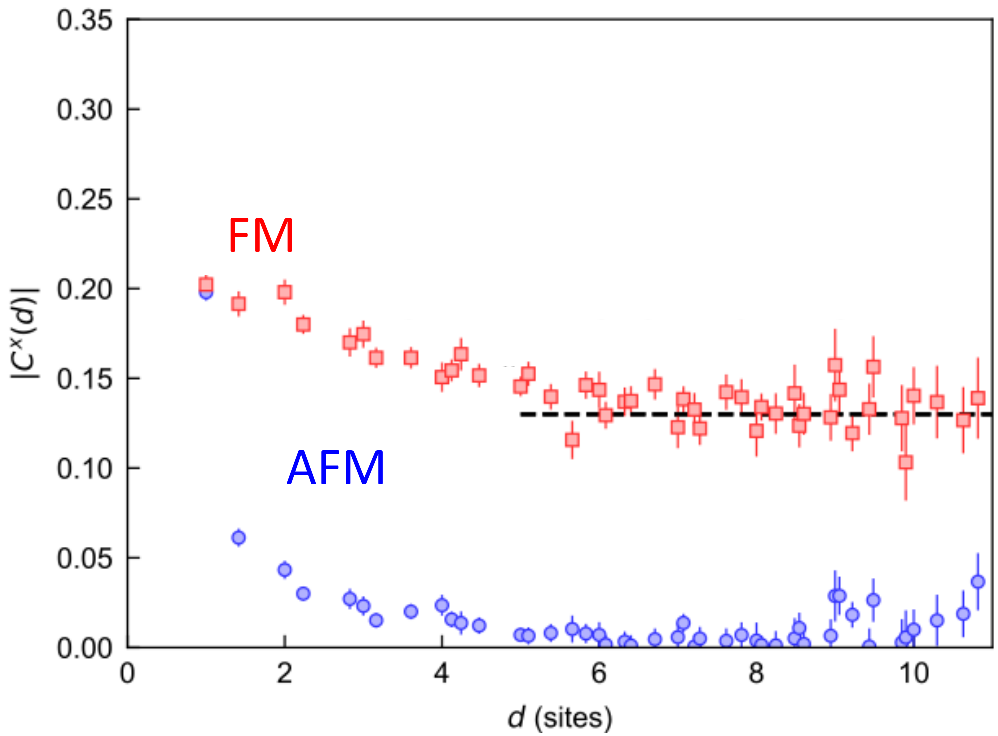

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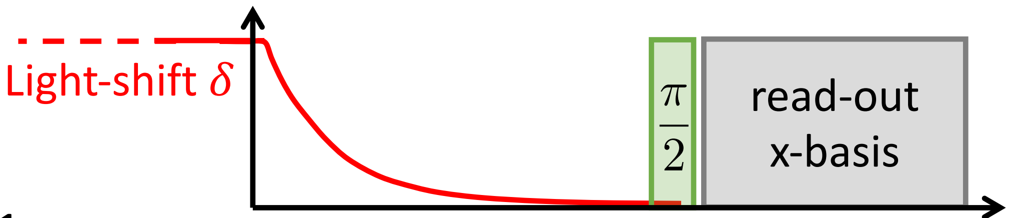

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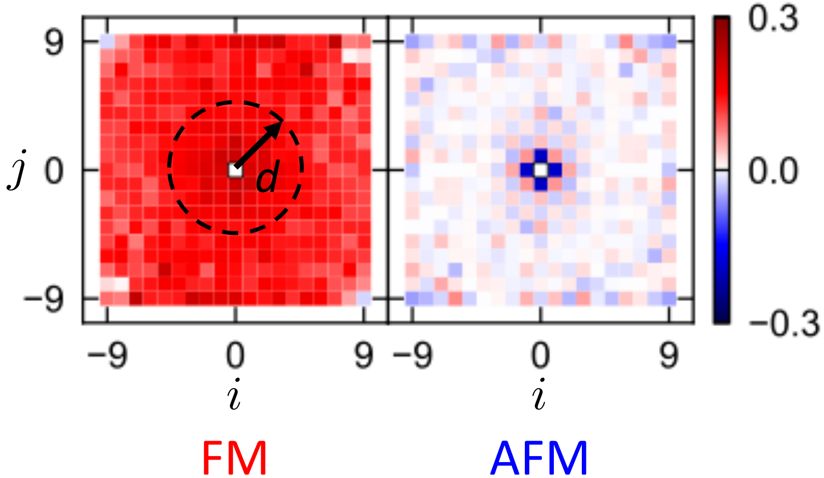

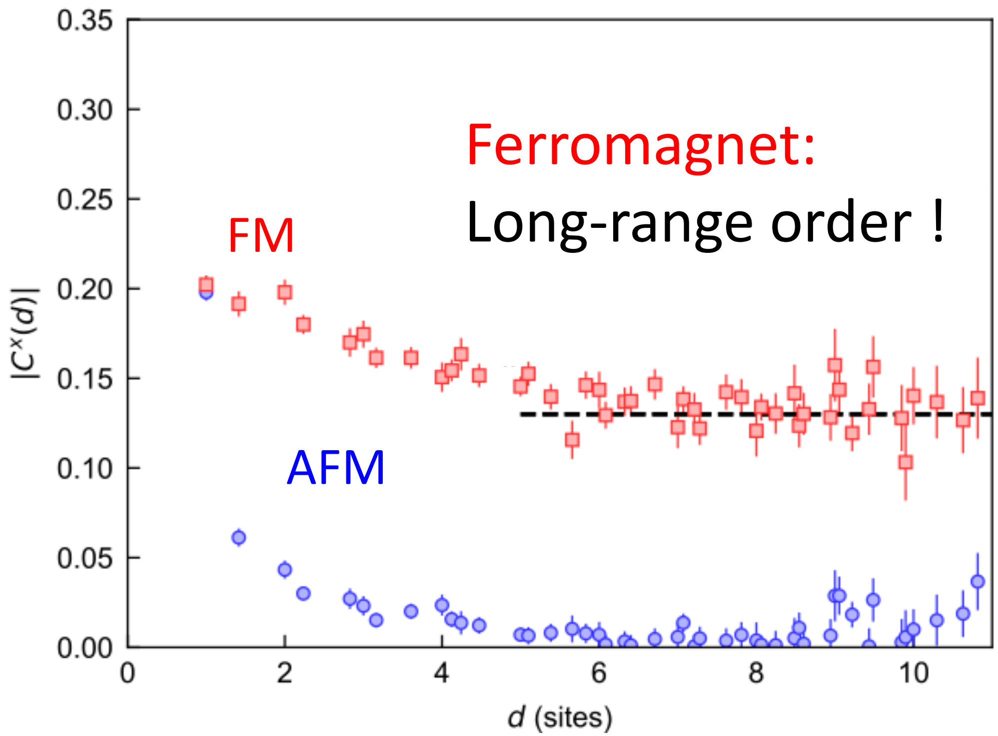

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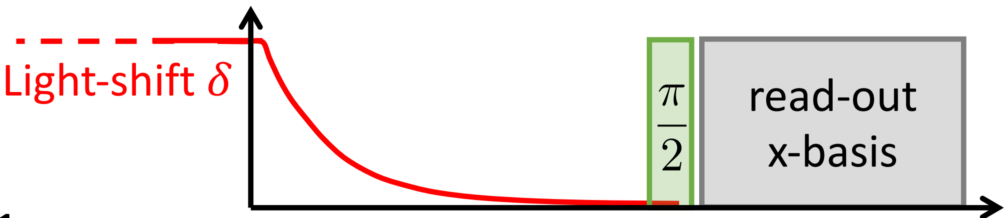

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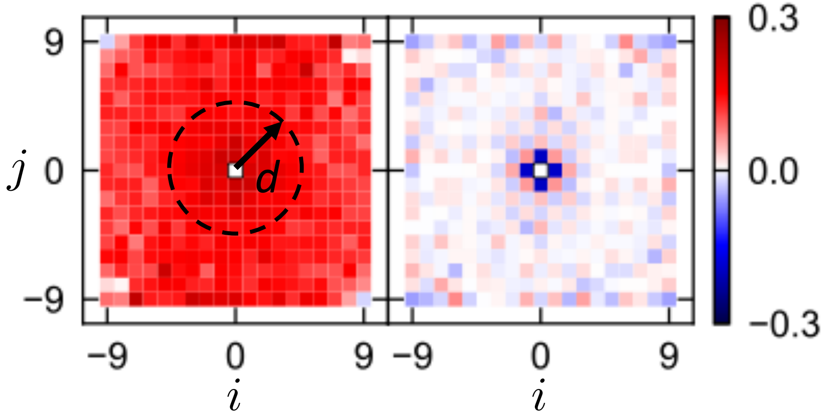
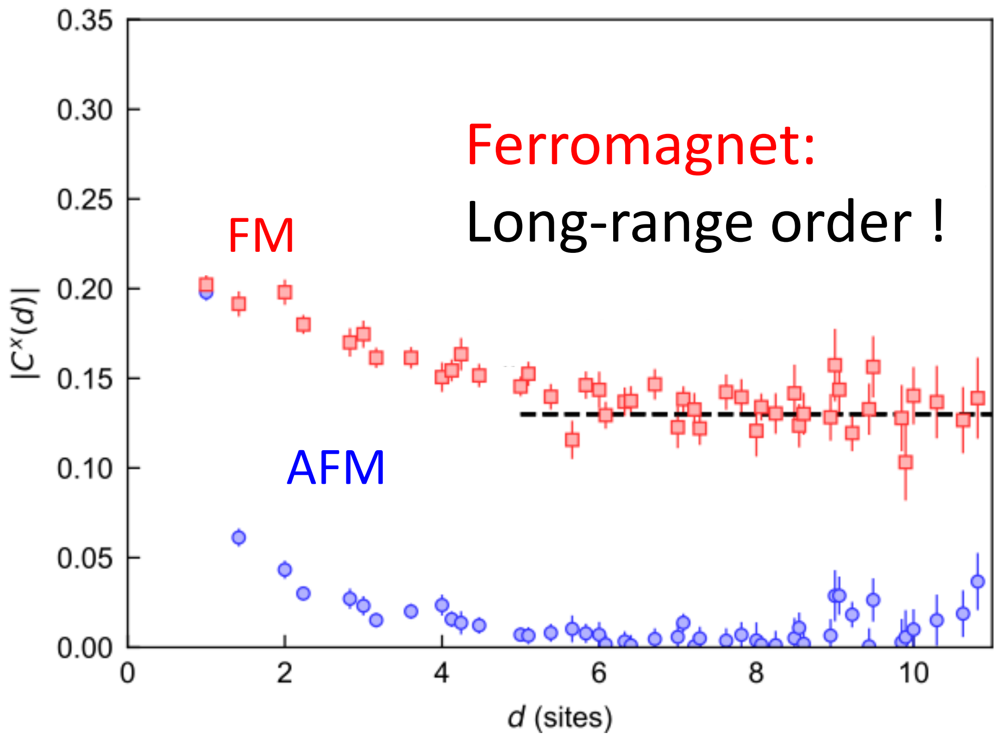
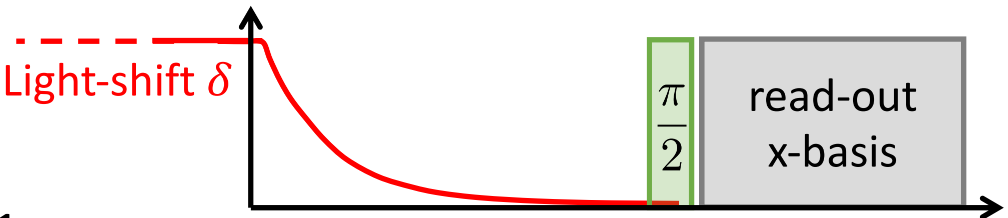




Antiferromagnet: LRO destabilized by imperfections

Observation of Long-Range FM order



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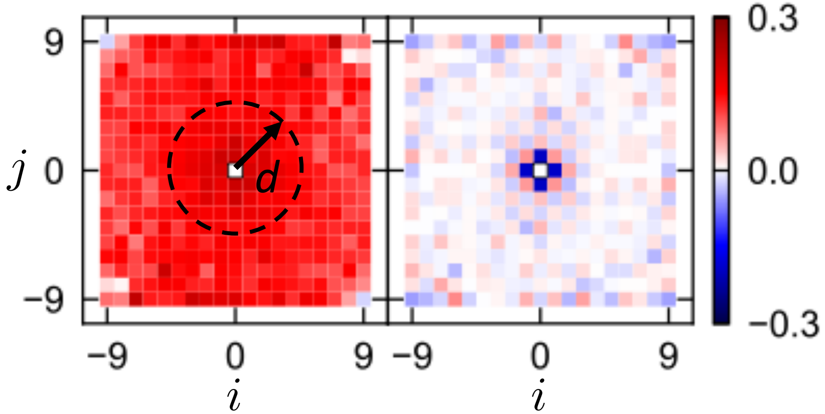
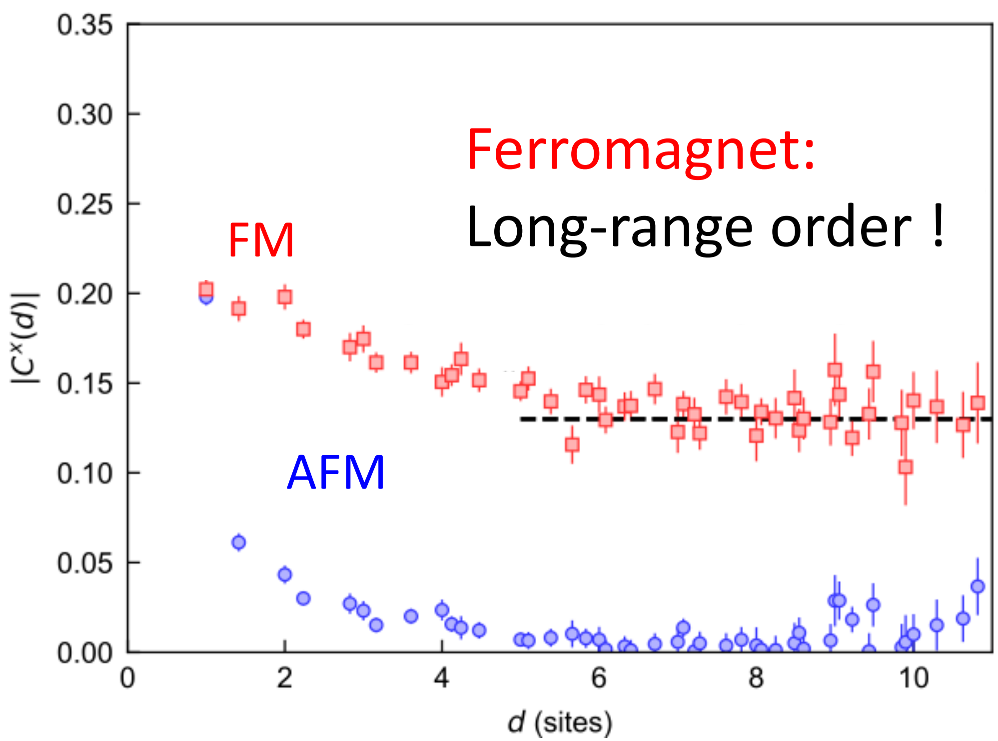
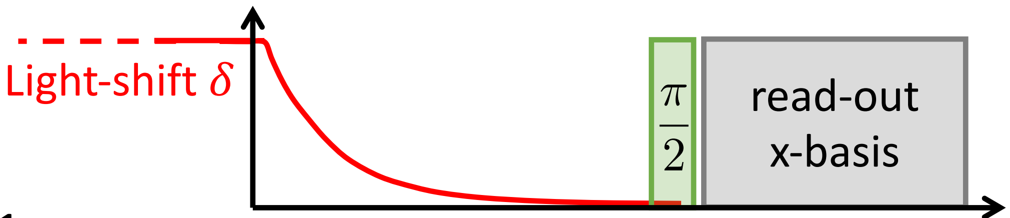




Antiferromagnet: LRO destabilized by imperfections

Important role $1/r^3$ of interaction

Observation of Long-Range FM order



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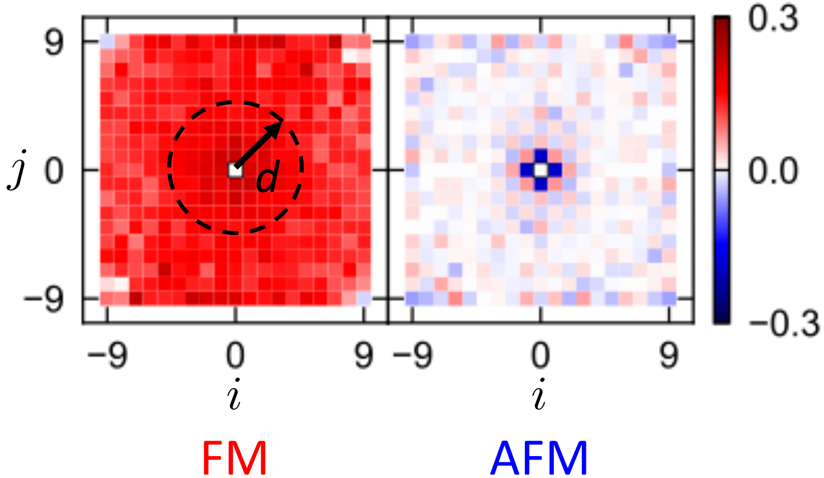
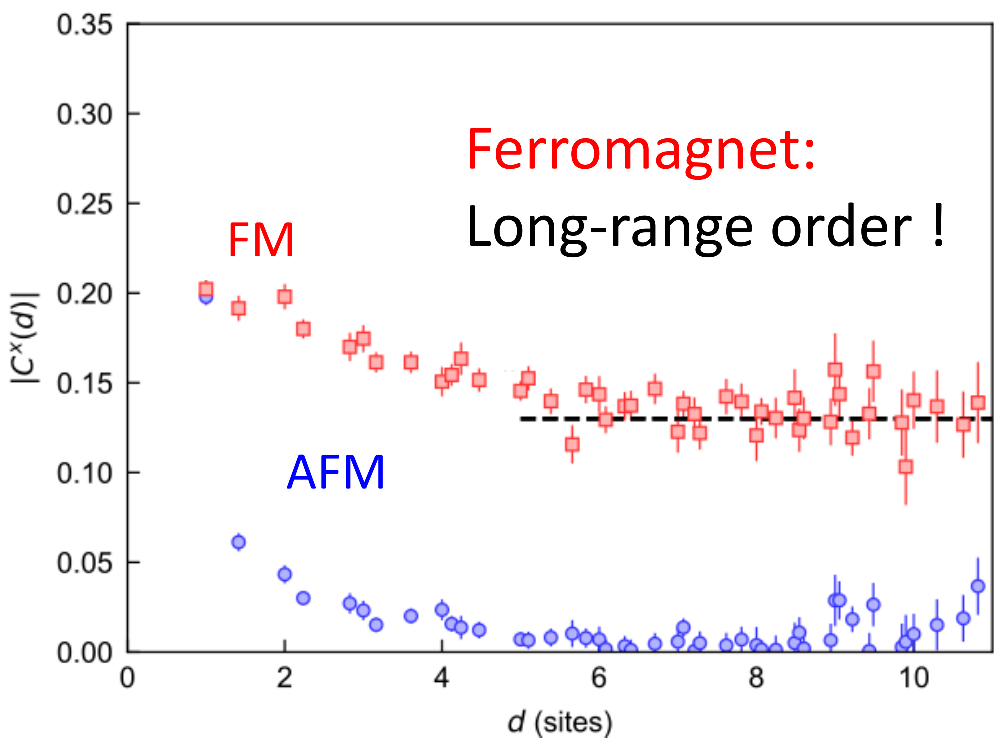
t = 1 μs

$$C^x_{ij} = \langle \sigma^x_i \sigma^x_j \rangle - \langle \sigma^x_i \rangle \langle \sigma^x_j \rangle$$





Antiferromagnet: LRO destabilized by imperfections

Also: ions 1D
arXiv:2211.01275

Important role $1/r^3$ of interaction

Sbierski *et al.*,
arXiv:2305.03673

Outline

1. Dipolar XY magnet with resonant dipole interactions

2. Spin squeezing using dipolar interaction

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

N. Yao
M. Block
B. Ye
(Harvard)

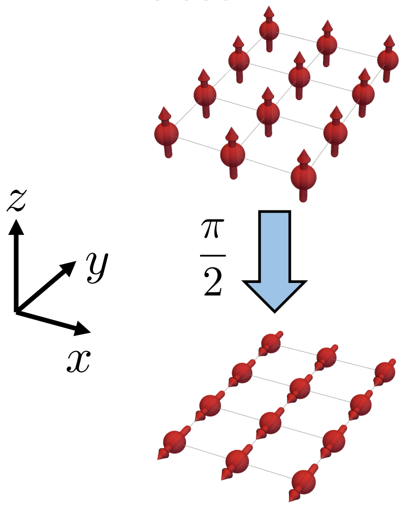
T. Roscilde

F. Mezzacapo

(Lyon)

Dynamics under XY Hamiltonian

FM

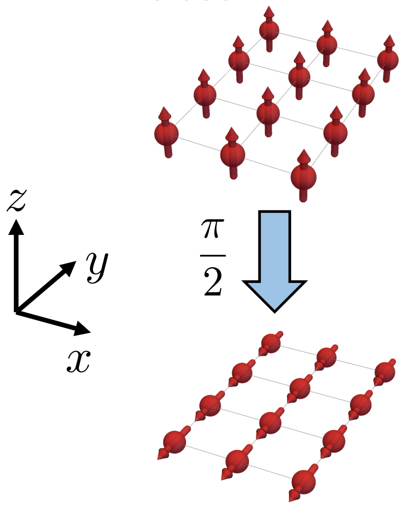


Initialize: $|\rightarrow, \rightarrow \ldots\rangle_y = (|\uparrow\rangle + i|\downarrow\rangle)^{\otimes N}$

"Coherent spin state"

Dynamics under XY Hamiltonian

FM



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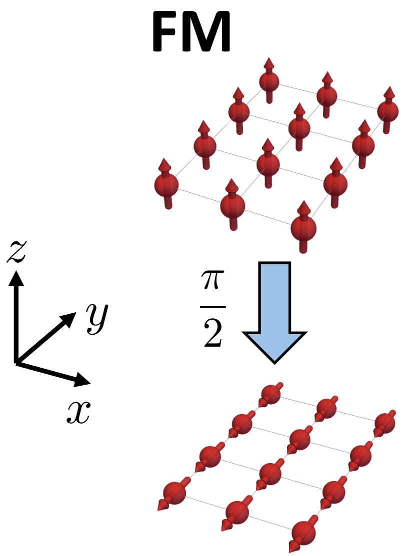
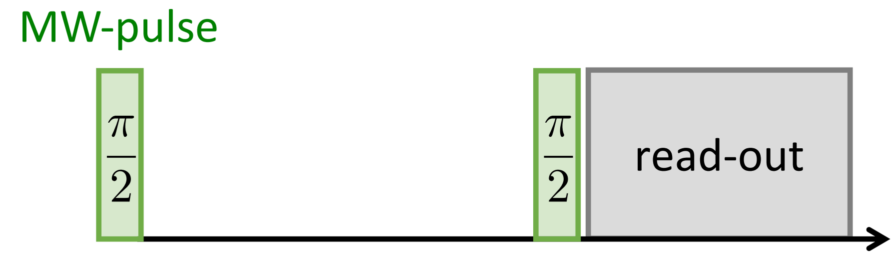
Evolve:

$$|\psi(t)\rangle = e^{-iH_{\mathrm{XY}}t/\hbar}|\psi(0)\rangle$$

Dynamics under XY Hamiltonian





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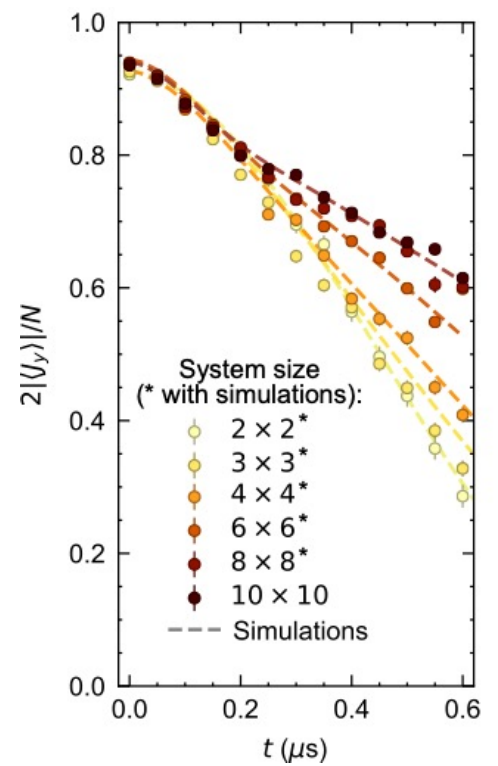
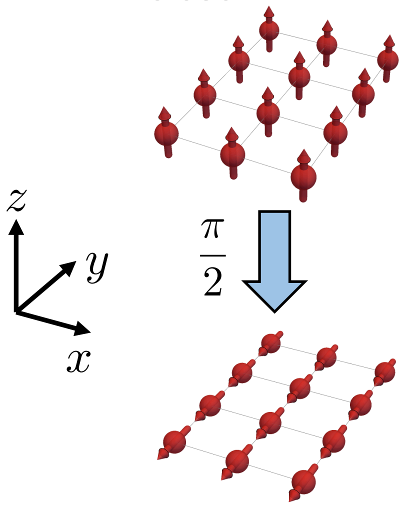
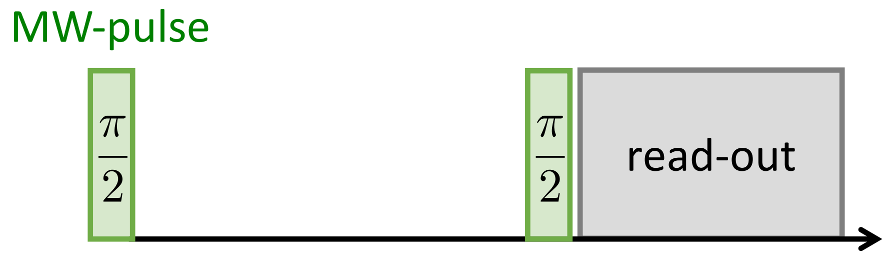
Interactions depolarize...



Dynamics under XY Hamiltonian

FM





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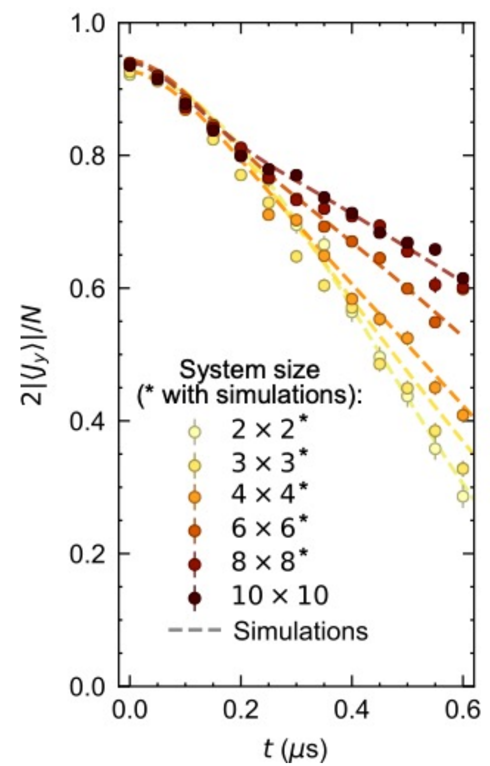
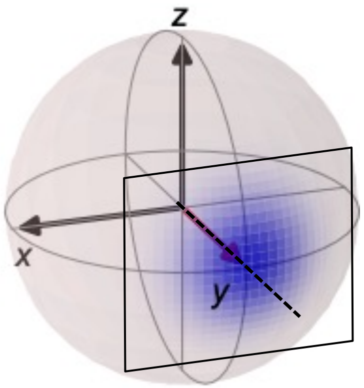
Interactions depolarize…

Generation entanglement?



A detour: spin squeezing in OAT versus dipolar model



Collective spin: $\hat{J}_\alpha = \sum_{i=1}^{N} \hat{\sigma}_i^\alpha$

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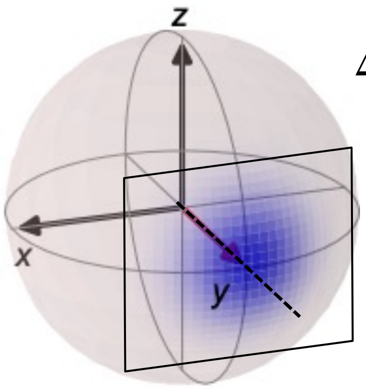
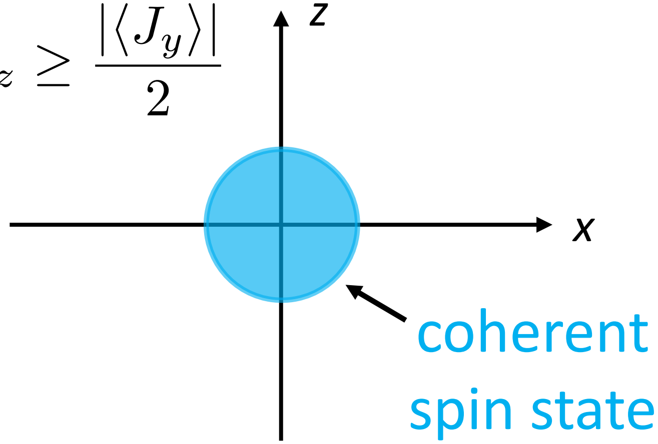


$$\Delta J_x \Delta J_z \geq \frac{|\langle J_y \rangle|}{2}$$



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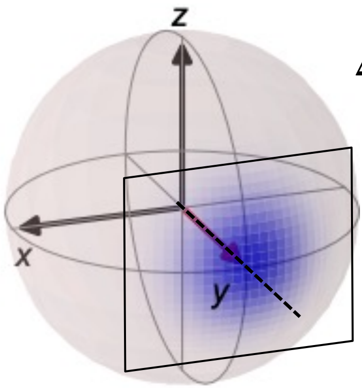

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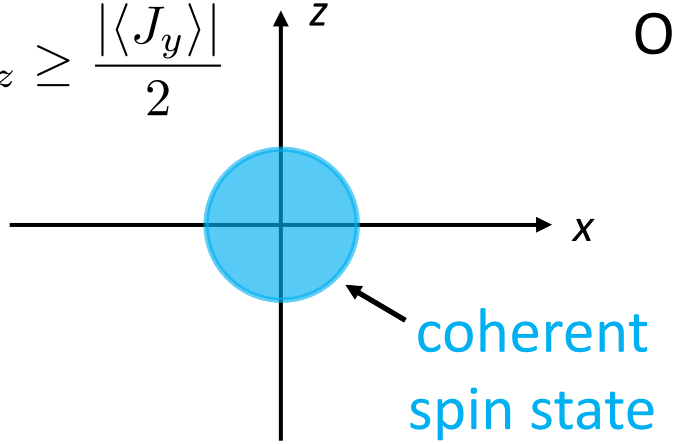

One-axis twisted model

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

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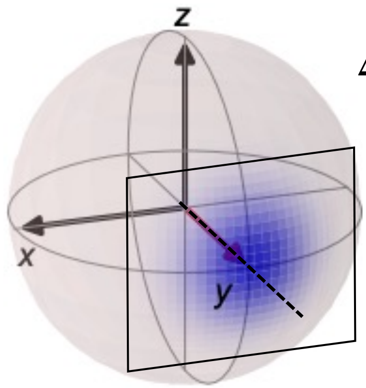

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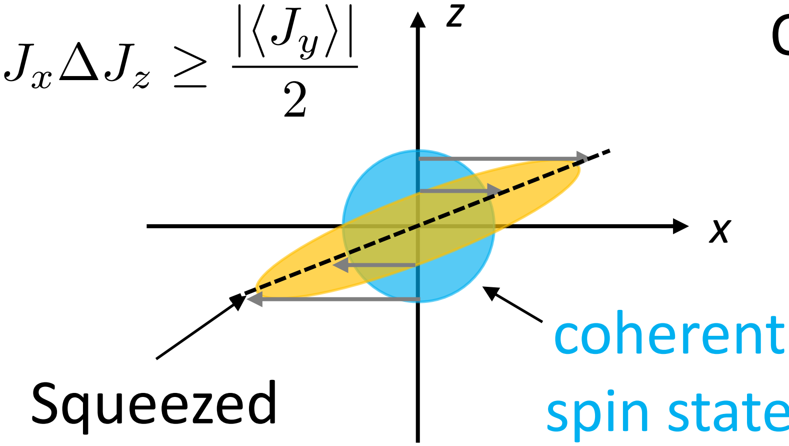

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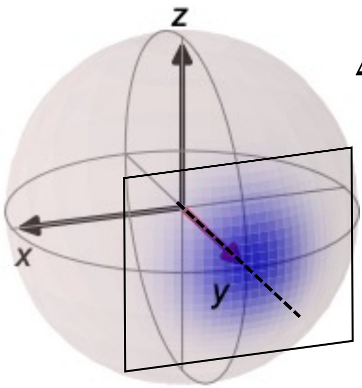

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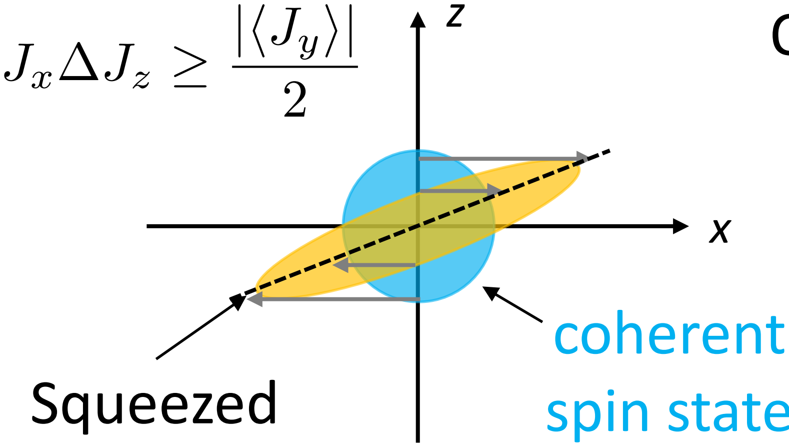

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Metrological gain in Ramsey interf.: $\delta\theta_{\mathrm{sq}} = \xi_R^2 \, \delta\theta_{SQL}$ Wineland, PRA 1994

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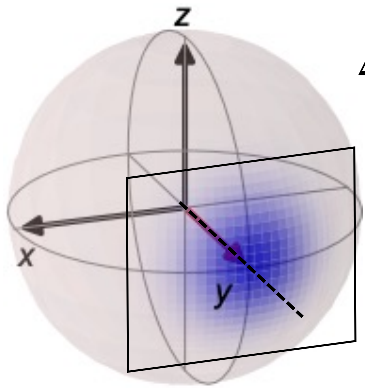

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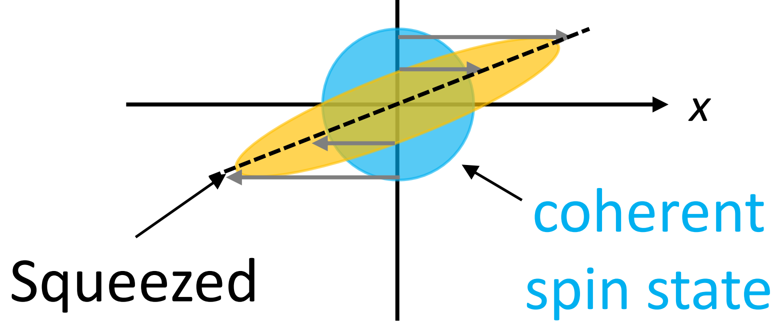

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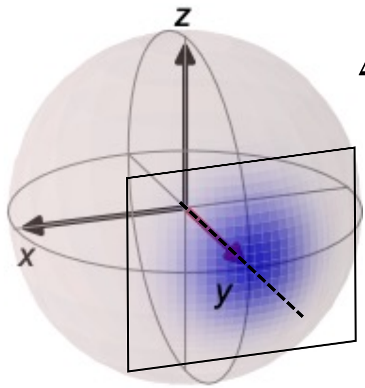

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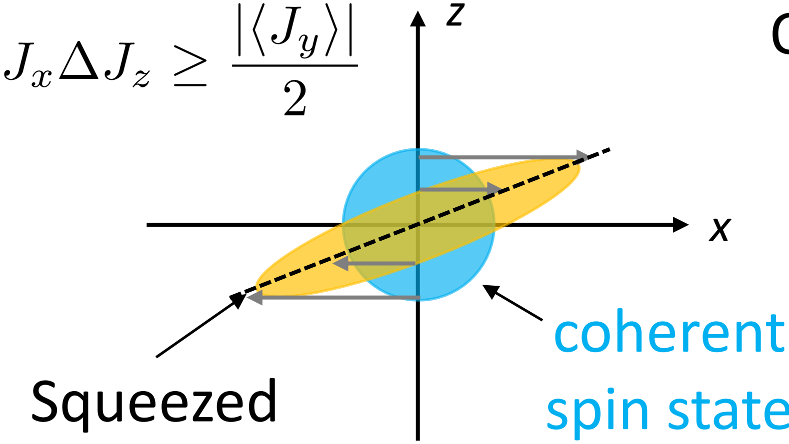

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Is $1/r^3$ long-range enough to generate squeezing?

If yes, does it scale with N?

From dipolar XY to one-axis twisting model…

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

$$H_{\mathrm{XY}} \sim \sum_{i<j} \frac{1}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) \sim \hat{\mathbf{J}}^2 - \hat{J}_z^2$$

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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

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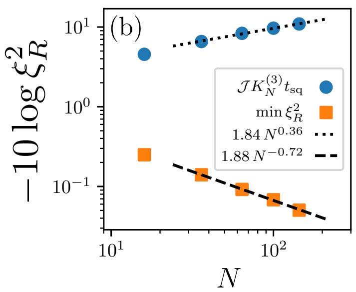
And should scale:



Roscilde
PRL (2022)

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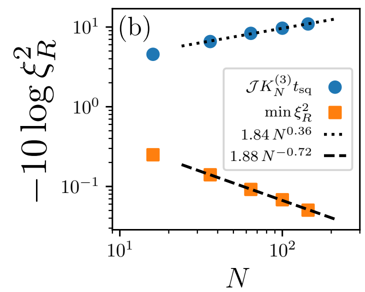

Rotor / spin wave theory

Roscilde *et al.*, arXiv:2302.0927, 2303.00380

$$H_{\mathrm{XY}} \approx E_0 + \frac{(\hat{J}_z)^2}{2 I_N} + \sum_{\mathbf{q} \neq 0} \hbar \omega_{\mathbf{q}}\, a_{\mathbf{q}}^\dagger a_{\mathbf{q}}$$

Collective spin:

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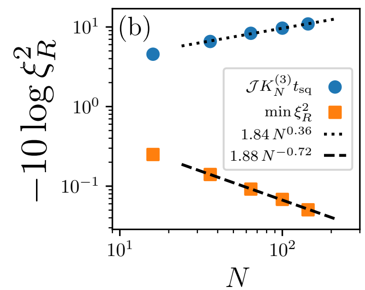

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"Rotor", **q** = 0

$$I_N \sim \frac{N}{J_0}$$

Collective spin:

$$\hat{J}_\alpha = \sum_{i=1}^{N} \hat{\sigma}_i^\alpha$$

$$J_0 = \frac{Ja^\alpha}{N}\sum_{i\neq j}(\pm 1)^{|i-j|}\frac{1}{r_{ij}^\alpha}$$

FM

AFM

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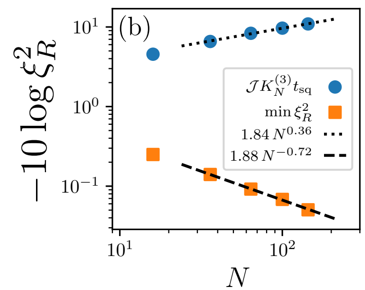
PRL (2022)



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Spin wave

"Rotor", **q** = 0

Collective spin:

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$$I_N \sim \frac{N}{J_0}$$

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FM

AFM

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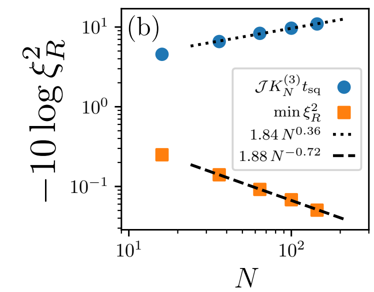

Roscilde
PRL (2022)

Rotor / spin wav

arXiv:2302.0927, 2303.00380

pin wave

Collective spi

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$$\sum_{i\neq j} (\pm 1)^{|i-j|} \frac{1}{r_{ij}^\alpha}$$

FM

AFM

N. Yao's conjecture:

H with LRO at T$\neq 0 \Rightarrow$ squeezing

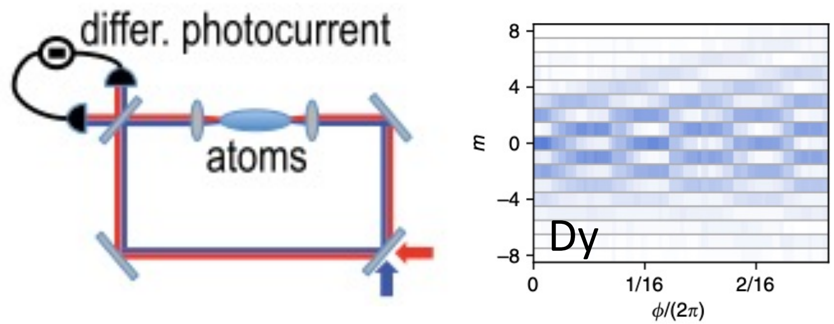
arXiv:2301.09636

Here: dipolar FM has LRO

Experimental observations of spin squeezing

Pezzé *et al.*, RMP 2018

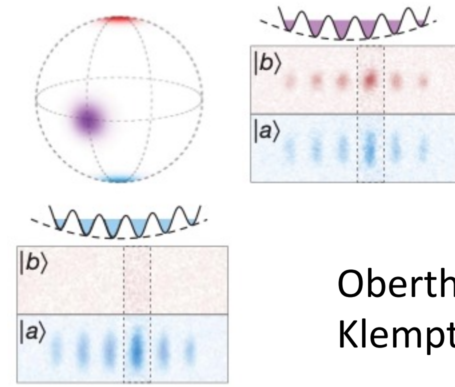
Hot / cold atomic vapors



Nat Comm 2018

Polzik (1999), Giacobino, Mitchell, Nascimbene…

Bose-Einstein condensate (OAT)

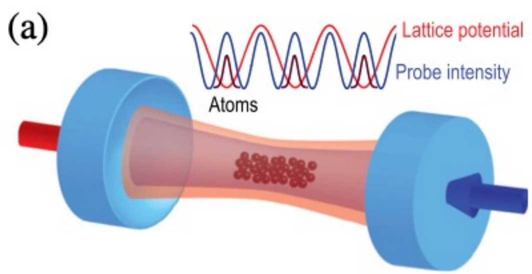


Nature 2010

Oberthaler, Treutlein, Klempt, Reichel, You…

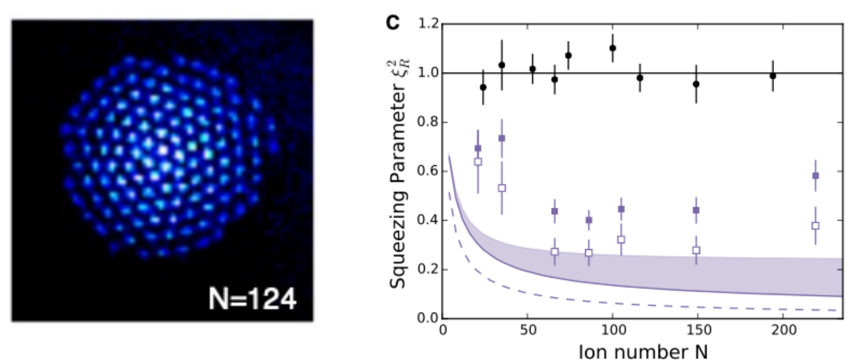
Cavity QED + cold atoms (OAT)

Kasevich, Nature 2016



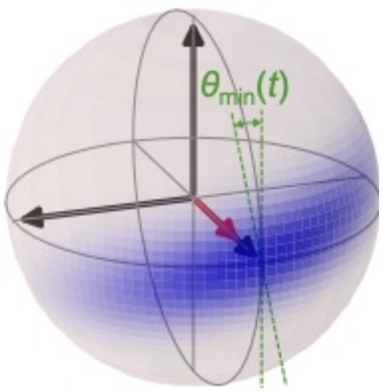
Vuletic, Kasevich, Thompson (JILA), Je, Schleier-Smith…

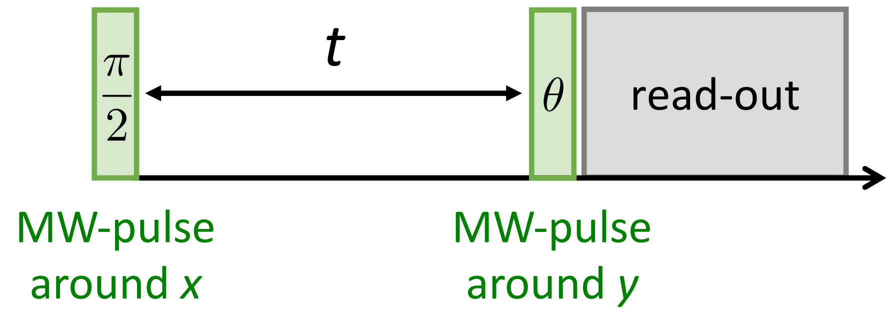
Ion crystal (~OAT)



Bollinger, Science 2016

Dipolar squeezing with Rydberg atoms: the recipe





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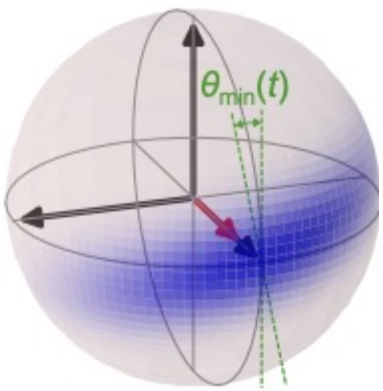
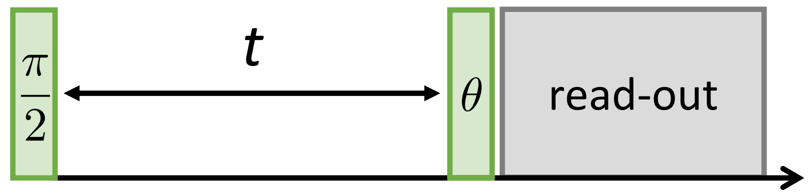
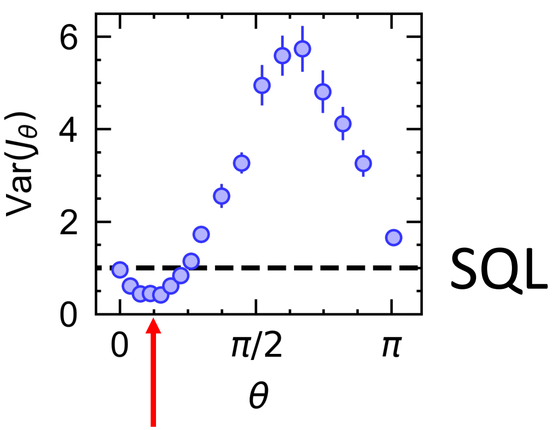




MW-pulse around *x*

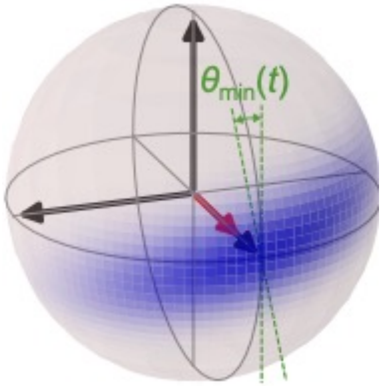
MW-pulse around *y*

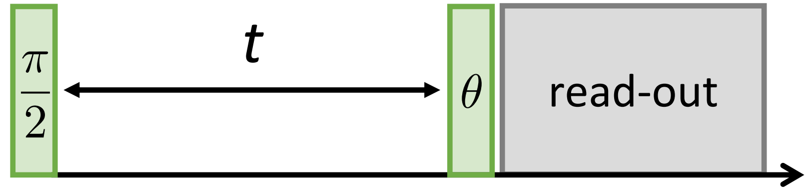
6 x 6 atoms
t = 300 ns



Squeezing !

Dipolar squeezing with Rydberg atoms: the recipe





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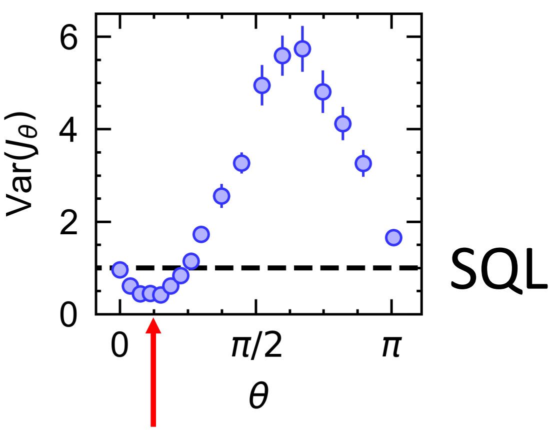

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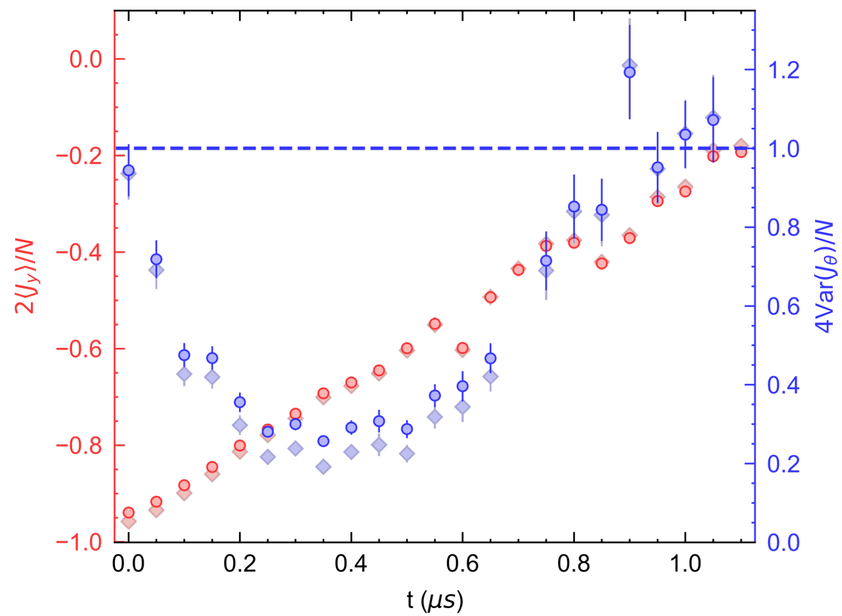
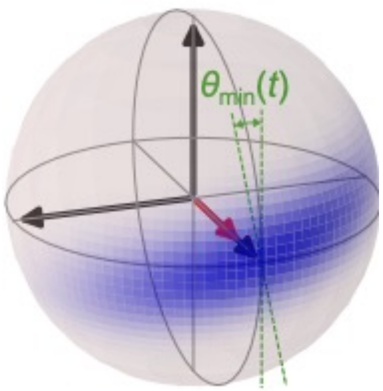
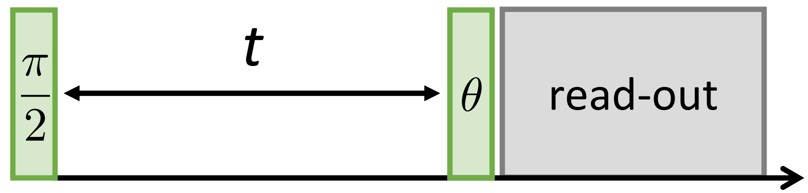


Dipolar squeezing with Rydberg atoms: the recipe

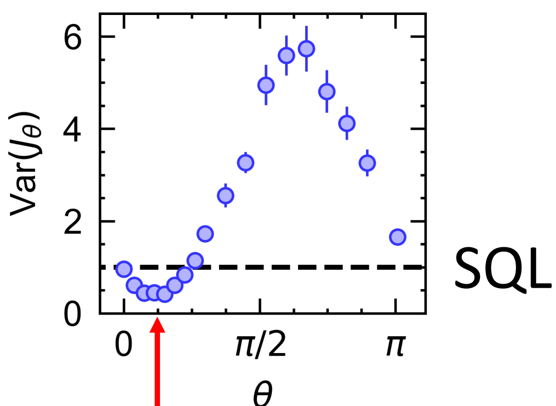




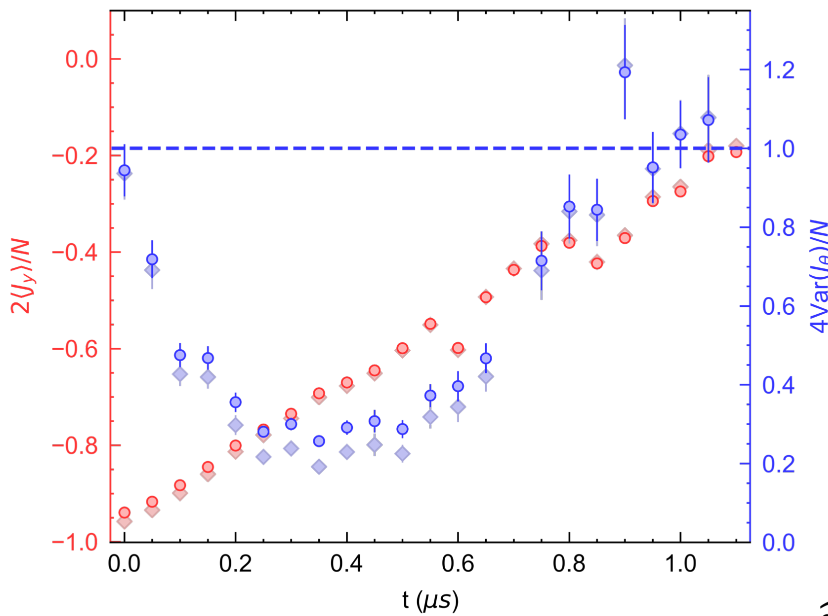
MW-pulse around *x*

MW-pulse around *y*

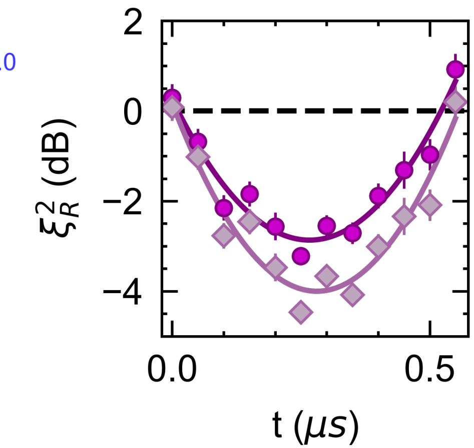
6 x 6 atoms
t = 300 ns



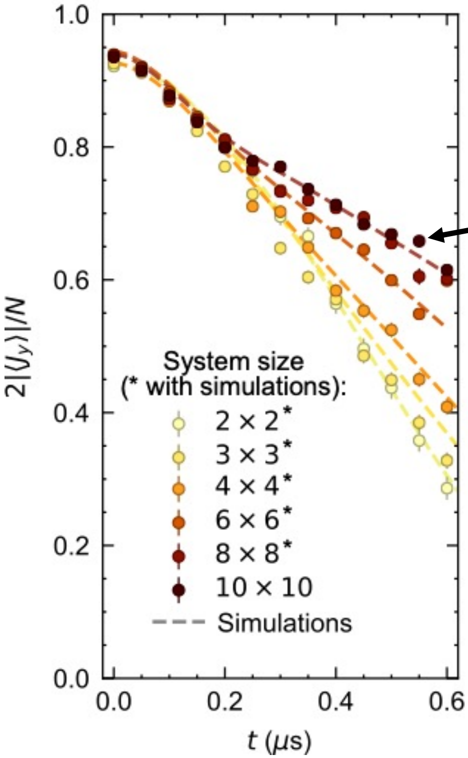
Squeezing !



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



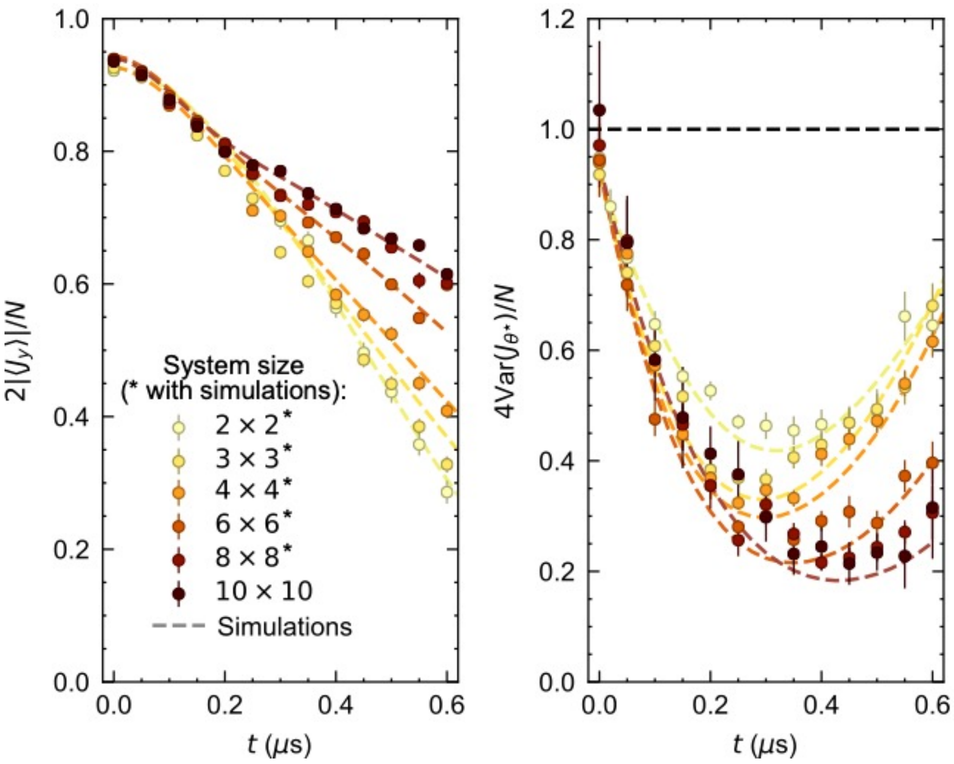
Scaling of squeezing with atom number



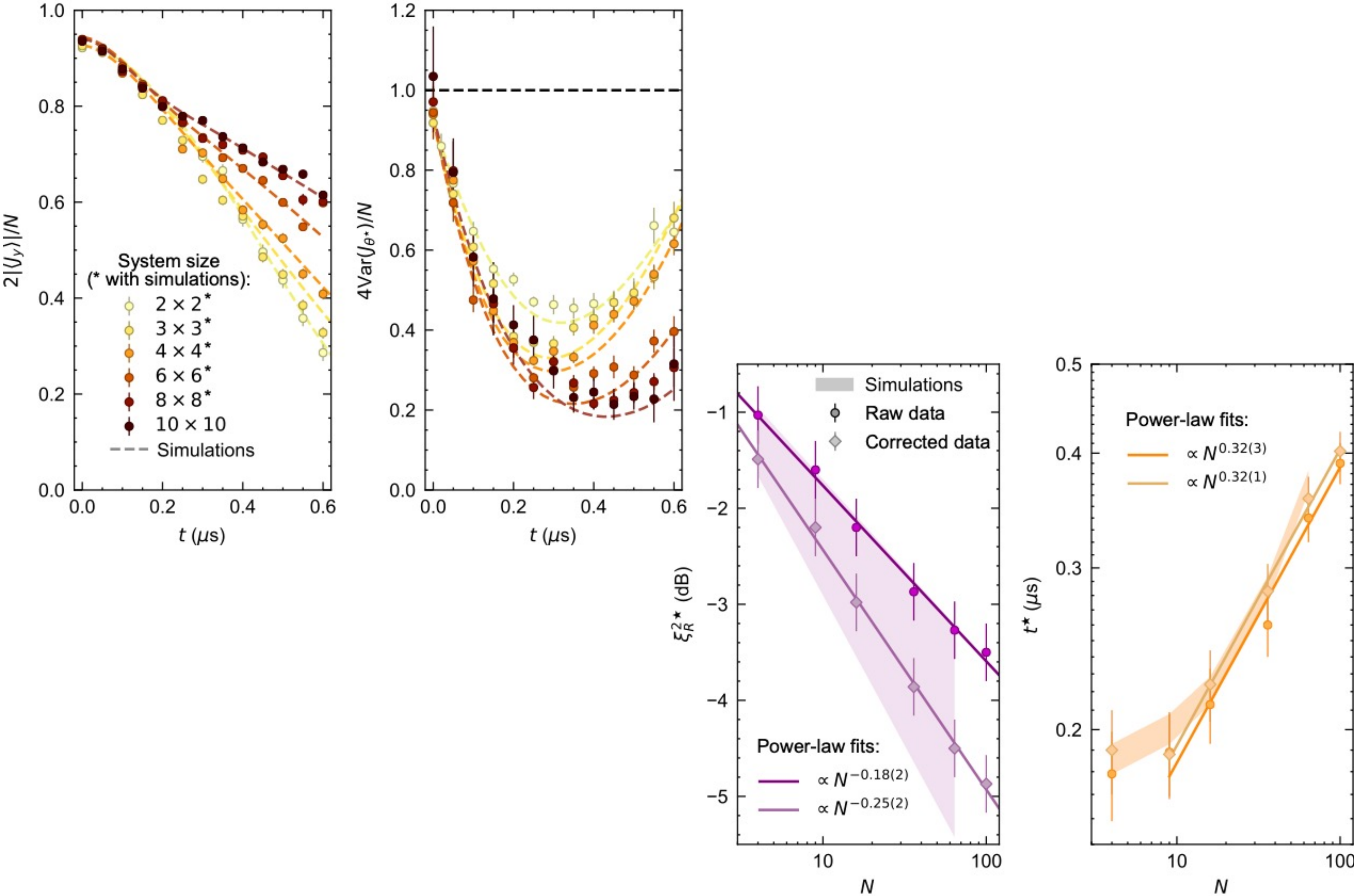
Dynamics of the Rotor

$$H \sim \frac{(J_z)^2}{2I_N} \quad \text{with} \quad I_N \sim \frac{N}{J_0}$$

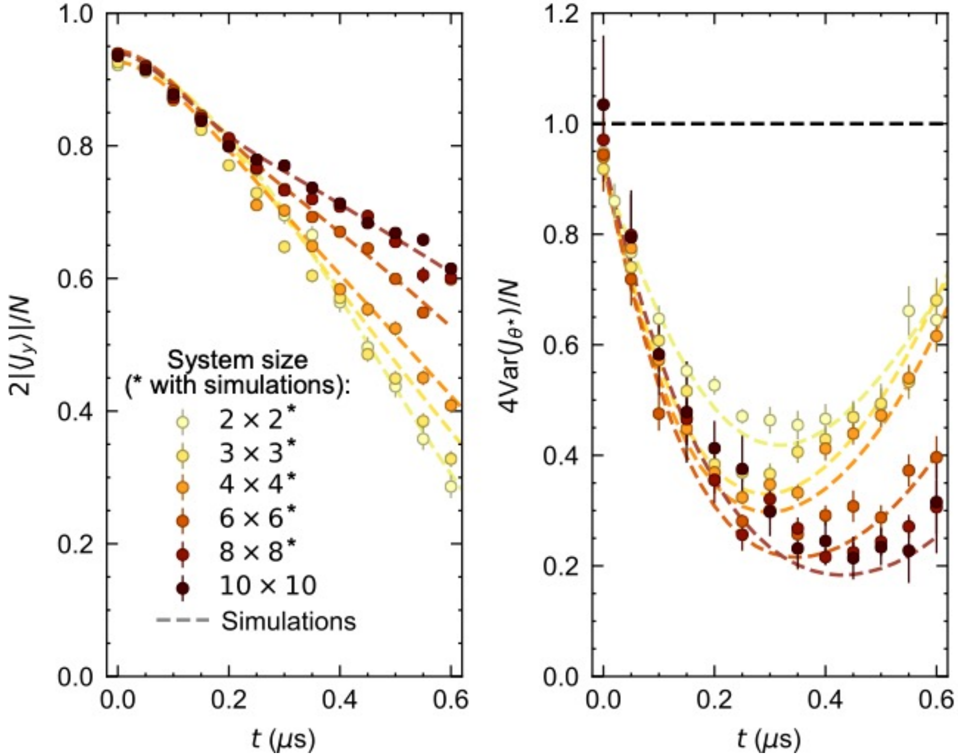
Scaling of squeezing with atom number



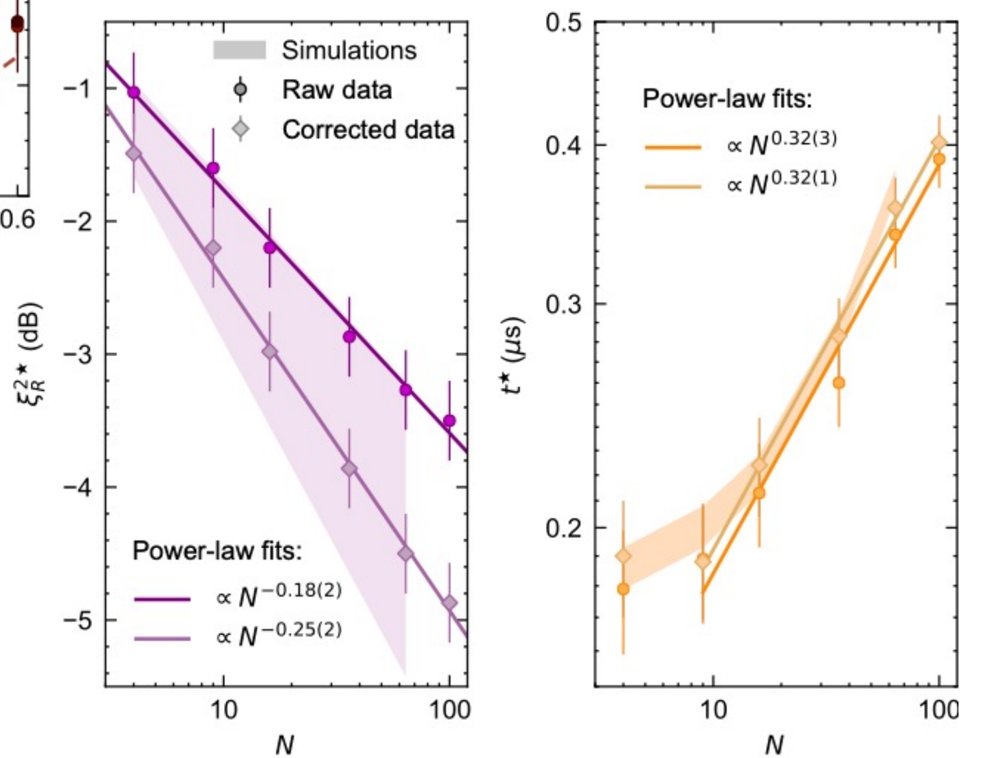
Scaling of squeezing with atom number



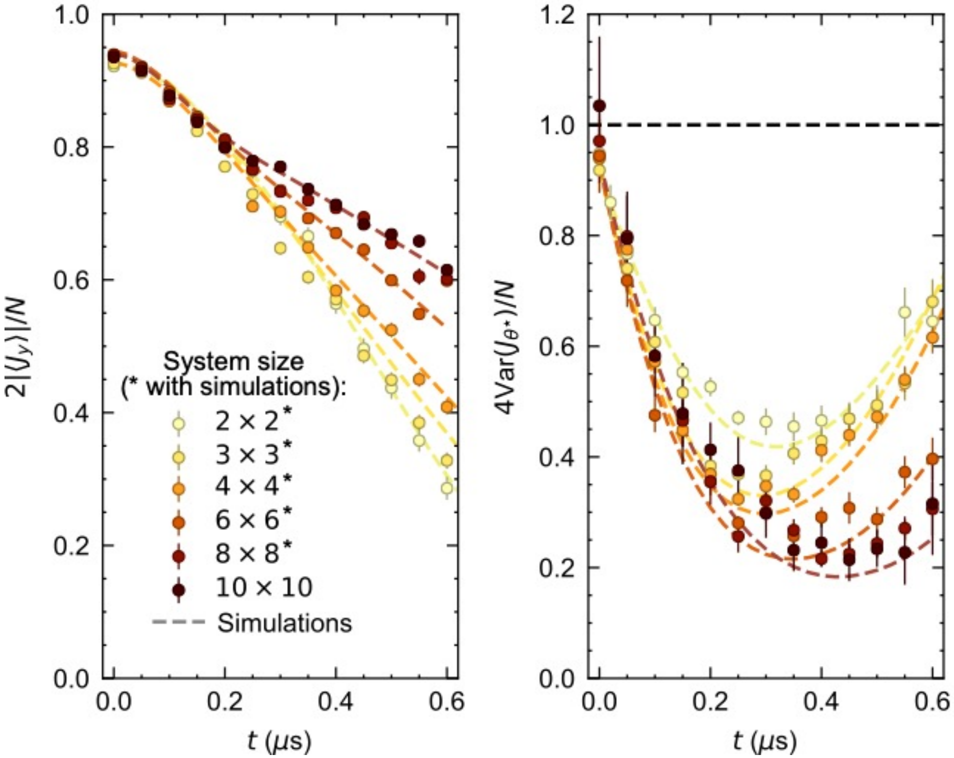
Scaling of squeezing with atom number

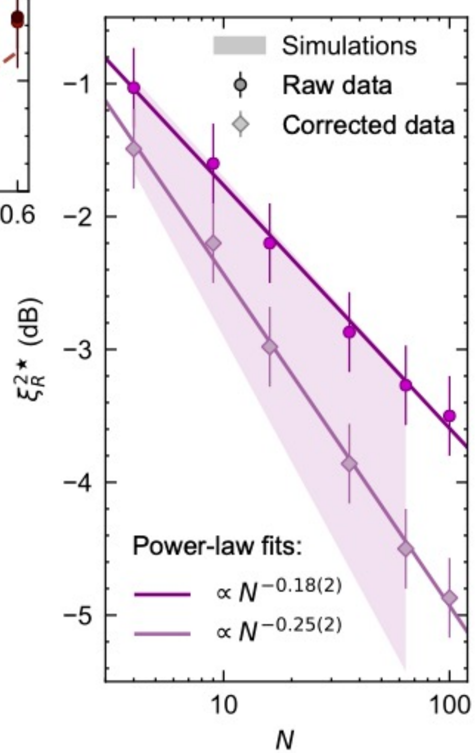


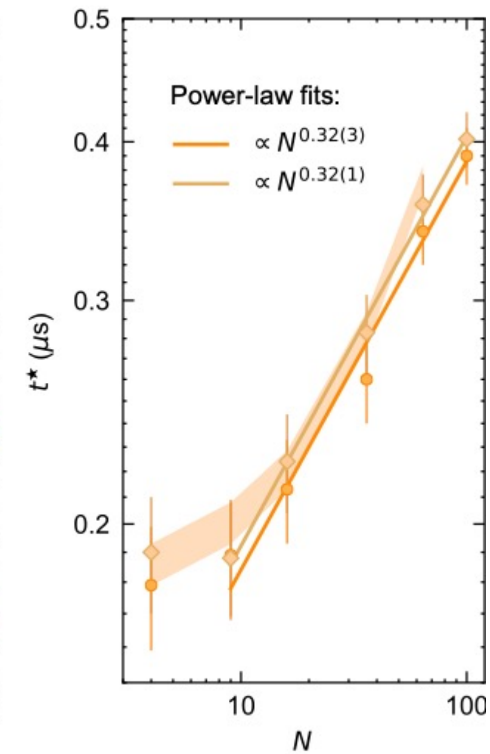
Conclusion: dipolar squeezing *is* scalable!!



Scaling of squeezing with atom number







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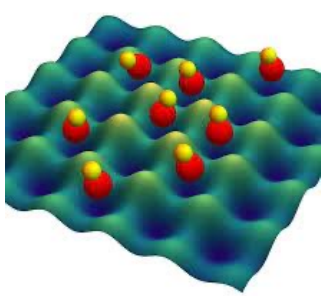
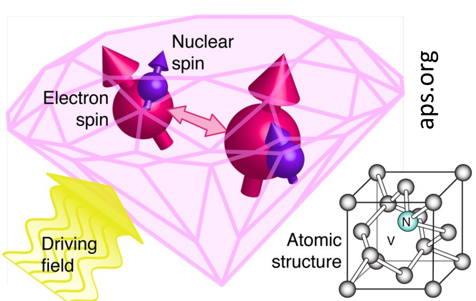
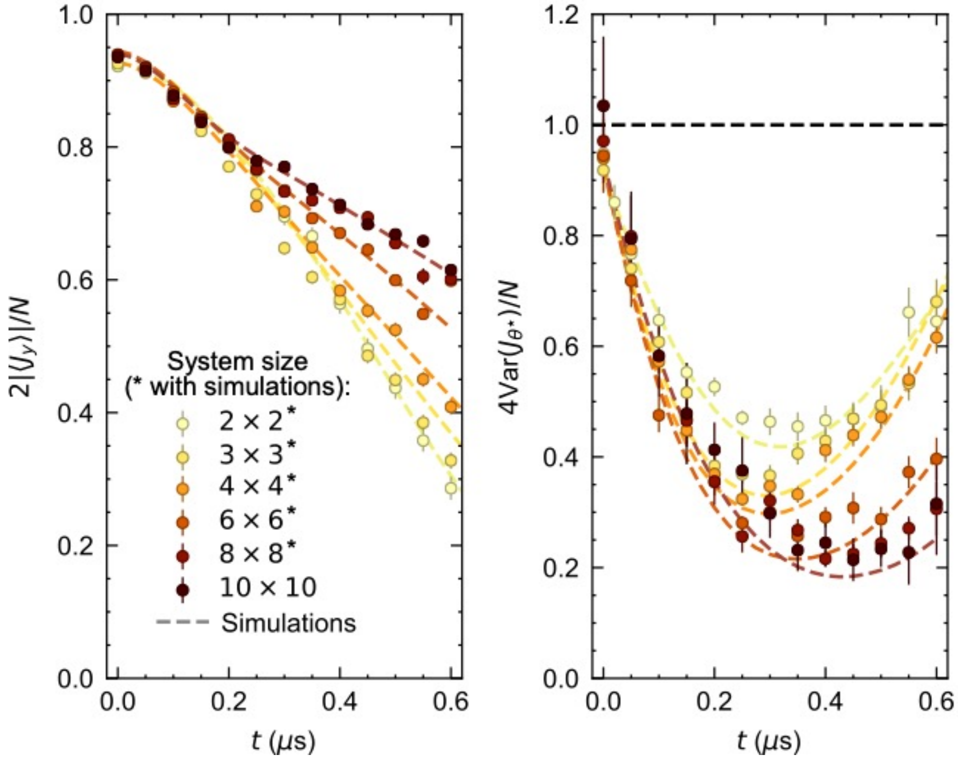




Scaling of squeezing with atom number



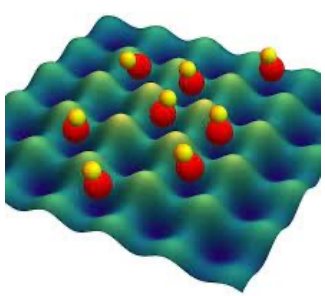
Trapped ions: C. Roos arXiv:2303.10668

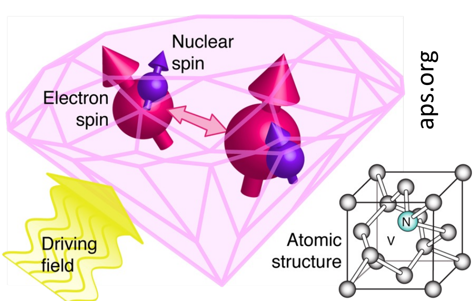
Dressed Rydberg atoms:

A. Kaufman arXiv:2303.10668

M. Schleier-Smith arXiv:2303.08805

Conclusion: dipolar squeezing *is* scalable!!





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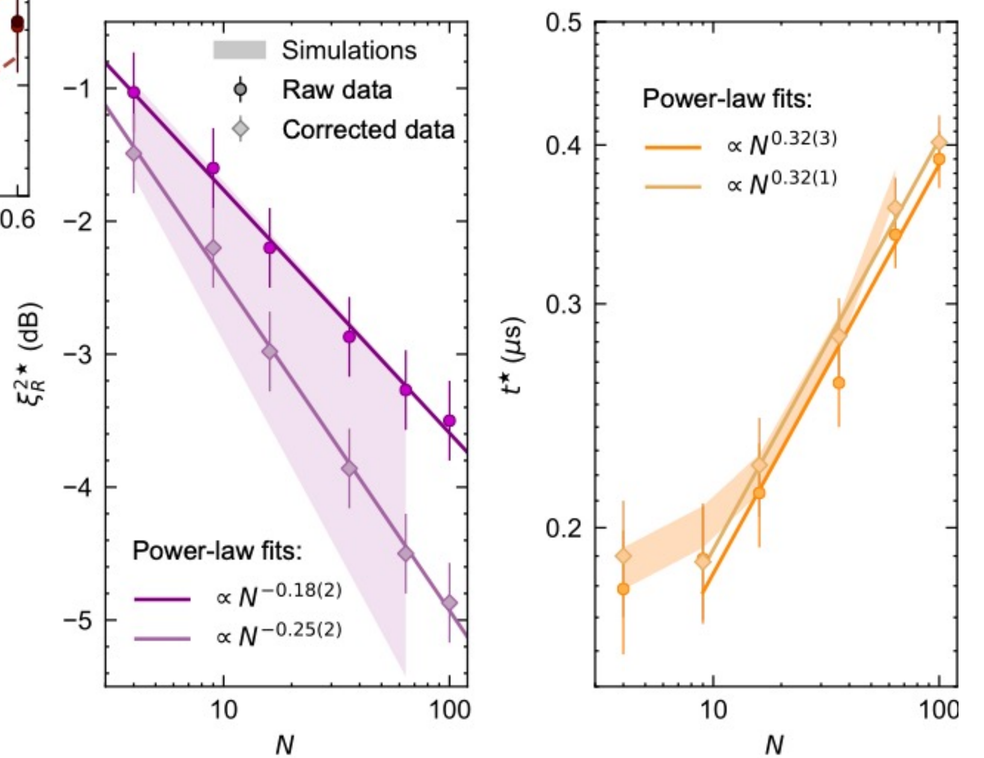

Conclusion and outlook: XY and beyond…

Measuring the dispersion relation

FM: $\omega(\mathbf{q}) \propto \sqrt{\mathbf{q}}$

AFM: $\omega(\mathbf{q}) \propto \mathbf{q}$

H. P. Büchler PRL 2012

Conclusion and outlook: XY and beyond…

Preliminary

Measuring the dispersion relation

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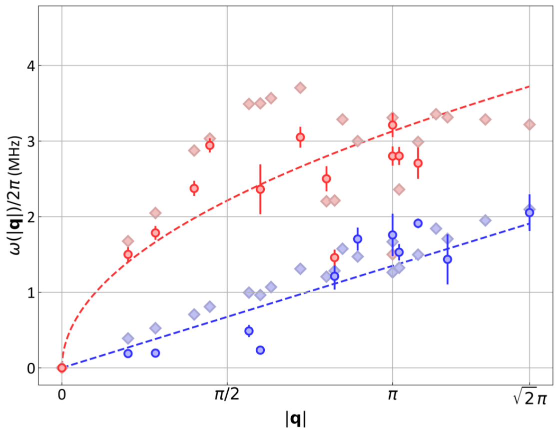
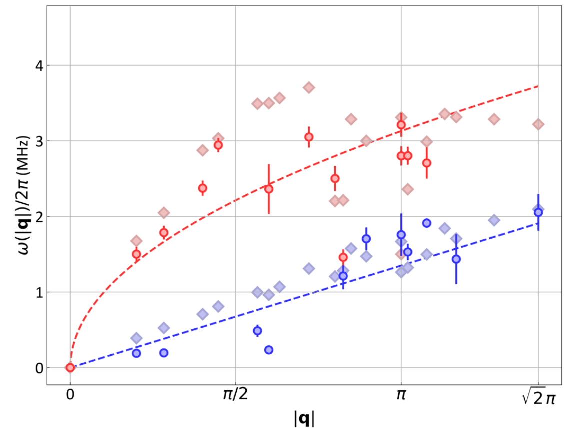
H. P. Büchler PRL 2012



Conclusion and outlook: XY and beyond…

Measuring the dispersion relation

Preliminary



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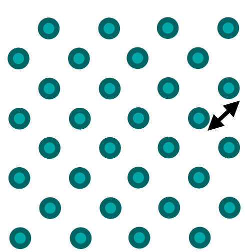
H. P. Büchler PRL 2012

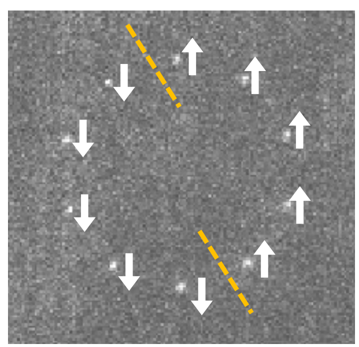
Floquet engineering

XYZ model: MW + XY

$$\hat{H}_{\mathrm{XYZ}} = \sum_{i \neq j} J^x_{ij}\, \sigma^x_i \sigma^x_j + J^y_{ij}\, \sigma^y_i \sigma^y_j + J^z_{ij}\, \sigma^z_i \sigma^z_j$$



$$\hat{H}_{\mathrm{Heis.}} = \sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$



Scholl *et al.*, PRXQ (2022)

Conclusion and outlook: XY and beyond…

Preliminary

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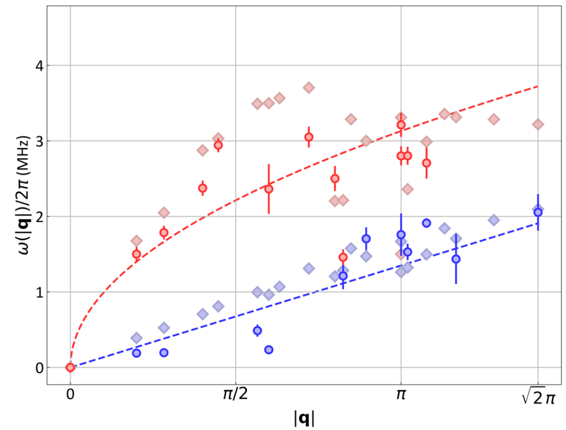
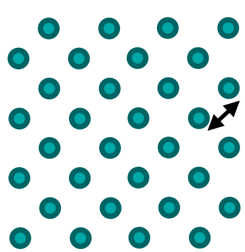
H. P. Büchler PRL 2012



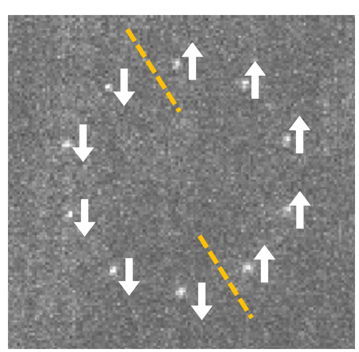
Floquet engineering

XYZ model: MW + XY

$$\hat{H}_{\mathrm{XYZ}} = \sum_{i\neq j} J_{ij}^x\, \sigma_i^x \sigma_j^x + J_{ij}^y\, \sigma_i^y \sigma_j^y + J_{ij}^z\, \sigma_i^z \sigma_j^z$$

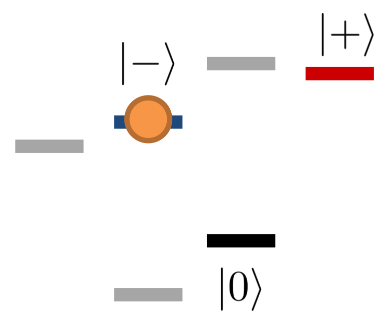


$$\hat{H}_{\mathrm{Heis.}} = \sum_{i\neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

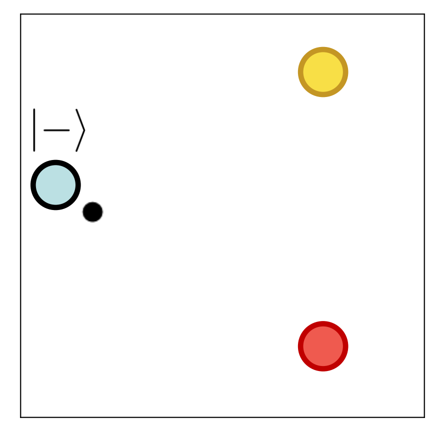


Scholl *et al.*, PRXQ (2022)

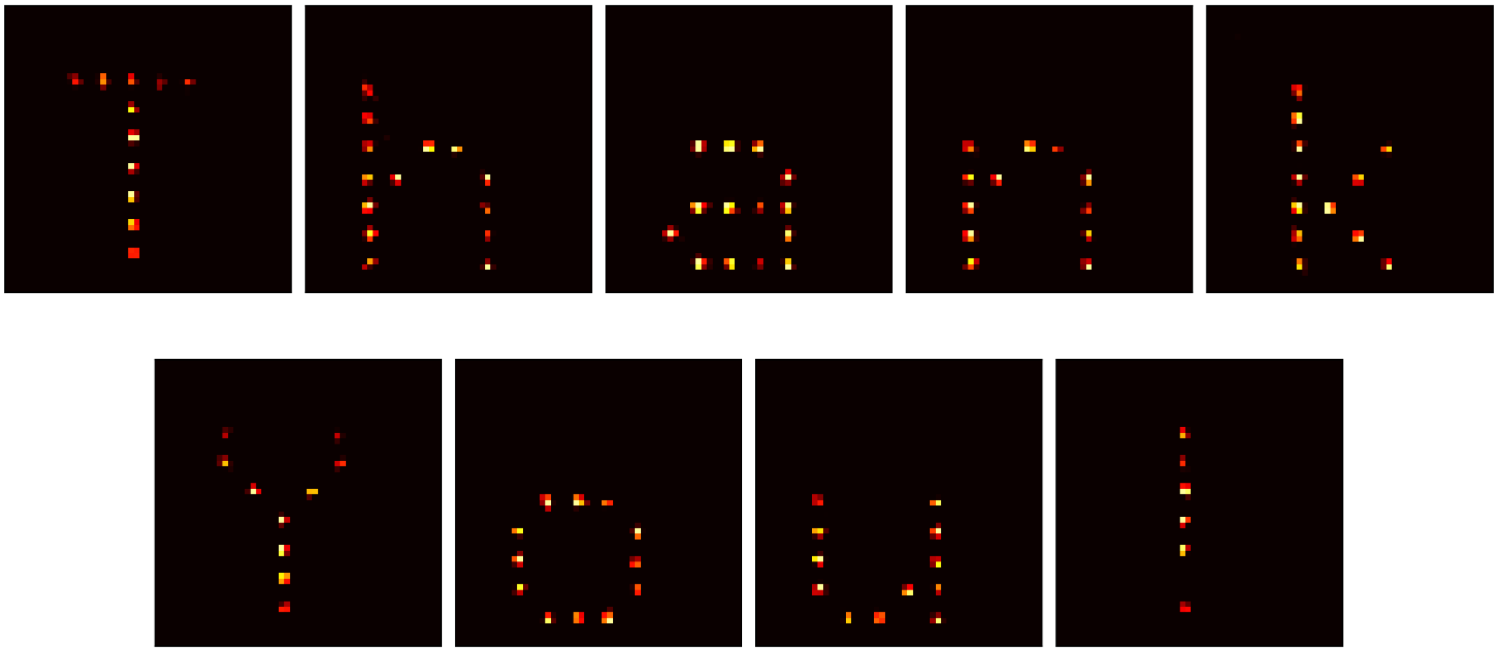
Spin-orbit coupling



Lienhard, PRX 2021



Frac. Chern ins. Weber, *et al.* PRXQ 2022


Thank
You!