Title: Exploring quantum spin models with tunable arrays of Rydberg atoms

Speakers: Daniel Barredo

Collection: Cold Atom Molecule Interactions (CATMIN)

Date: July 15, 2022 - 9:40 AM

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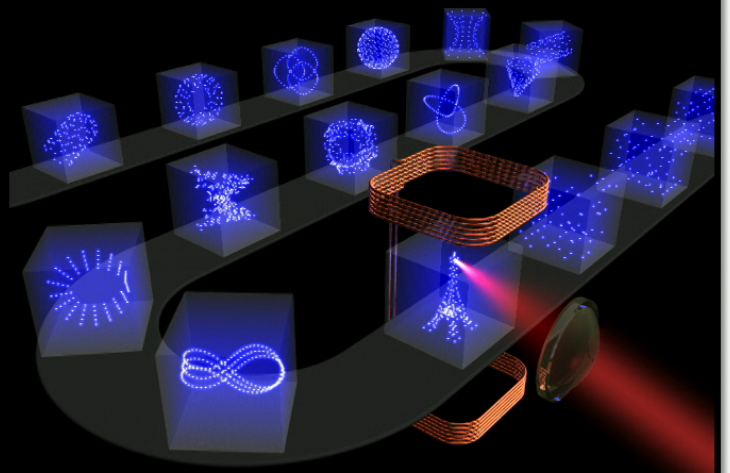
Abstract: "Rydberg atoms in arrays of optical tweezers offer a new perspective for the quantum simulation of many body systems. In this talk, I will give a brief overview about this platform and describe our efforts to control Rydberg interactions to explore different types of Hamiltonians. Through recent experimental results, I will illustrate the implementation of the Ising [1] and XXZ [2] Hamiltonians to study quantum magnetism. Finally, I will show our first steps to scale up the atom numbers in our platform by using a cryogenic environment [3].
References:
[1] P. Scholl et al., Nature 595, 233 (2021).
[2] P. Scholl et al., PRX Quantum 3, 020303 (2022).
[3] K.N. Schymik et al., Phys. Rev. Applied 16, 034013 (2021)."

Exploring quantum spin models with tunable arrays of Rydberg atoms

Daniel Barredo

Laboratoire Charles Fabry
Institut d'Optique, CNRS
Palaiseau (France)
&
CINN, CSIC
El Entrego (Spain)



Cold Atom Molecule Interactions - CATMIN

Perimeter Institute for Theoretical Physics

July 15th, 2022

The team

Gabriel Emperauger | Pascal Scholl | Vincent Lienhard | Daniel Barredo | Antoine Browaeys | Thierry Lahaye | Kai-Niklas Schymik | Hannah Williams | Guillaume Bornet

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

Lucas Leclerc

Theory:

A. Läuchli (Innsbruck)

N. Yao (Berkeley/ Harvard)

M. Zaletel (Berkeley)

Cheng Chen

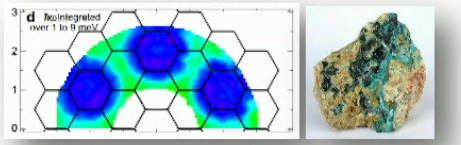
DGA | SIR TEQ | îledeFrance | erc European Research Council Established by the European Commission | PASQuanS

Many-body quantum systems: challenges

Goal: Understand ensembles of interacting quantum particles

Quantum magnetism

Nature **492**, 406 (2012)

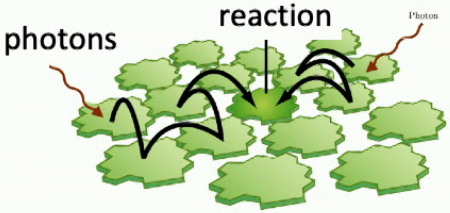


Herbertsmithite

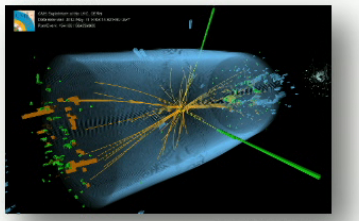
Superconductivity

Charles O'Rear Getty Images

Biology



High energy physics

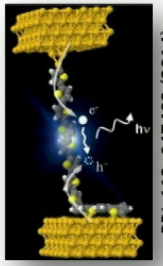


home.cern/

Cosmology

Juric.P/Depositphotos

Transport



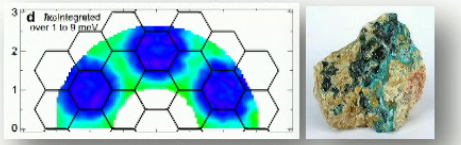
PRL 112, 047403 (2014)

Many-body quantum systems: challenges

Goal: Understand ensembles of interacting quantum particles

Quantum magnetism

Nature **492**, 406 (2012)



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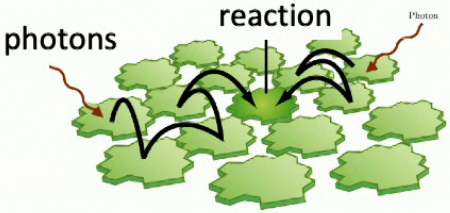

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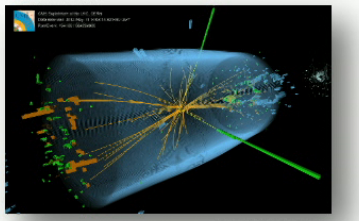

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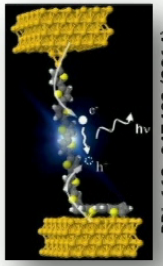

PRL 112, 047403 (2014)

Description by many-body Hamiltonians

(Ising, XY, Heisenberg, Bose–Hubbard, …)

Many-body quantum systems: challenges

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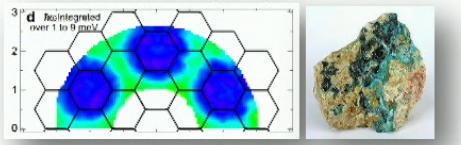

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Superconductivity

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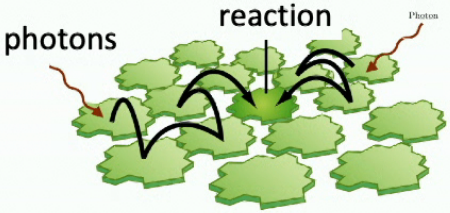
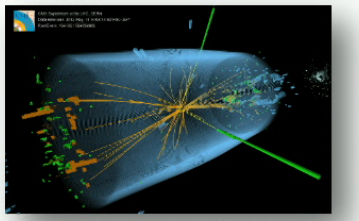


High energy physics



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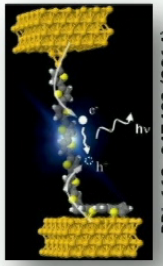


PRL 112, 047403 (2014)

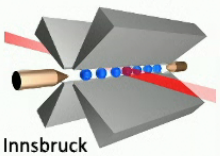
Description by many-body Hamiltonians

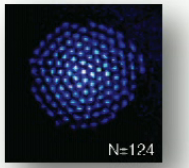
(Ising, XY, Heisenberg, Bose–Hubbard, …)

Open questions: Phase diagrams, dynamics (hard for N>50), topology, role of disorder, entanglement…

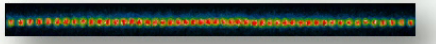
Many-body synthetic quantum systems: platforms

Trapped ions



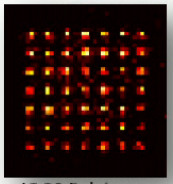


NIST

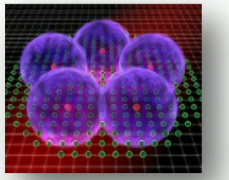


JQI

Rydberg atoms

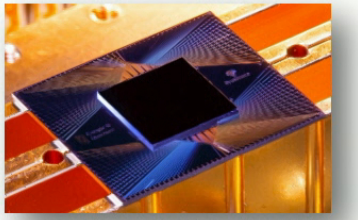


IOGS Palaiseau



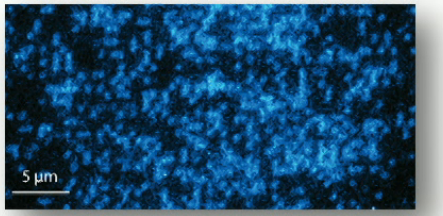
MPQ Garching

Supercond. circuits



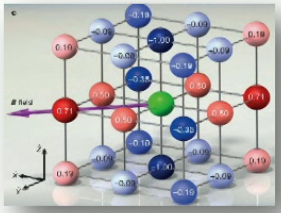
Sycamore processor, Google Inc.

Ultracold atoms



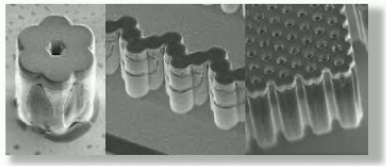
Harvard

Polar molecules



JILA

Polaritons



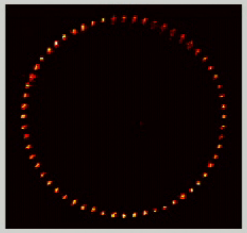
C2N

…And many others!

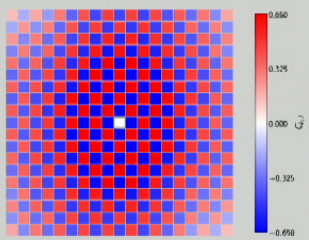
See e.g. Hazzard *et al.*, PRA **90**, 063622 (2014)

Outline

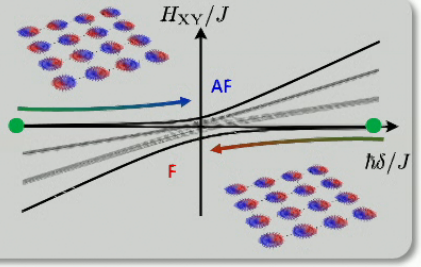
1. Assembled arrays of atoms



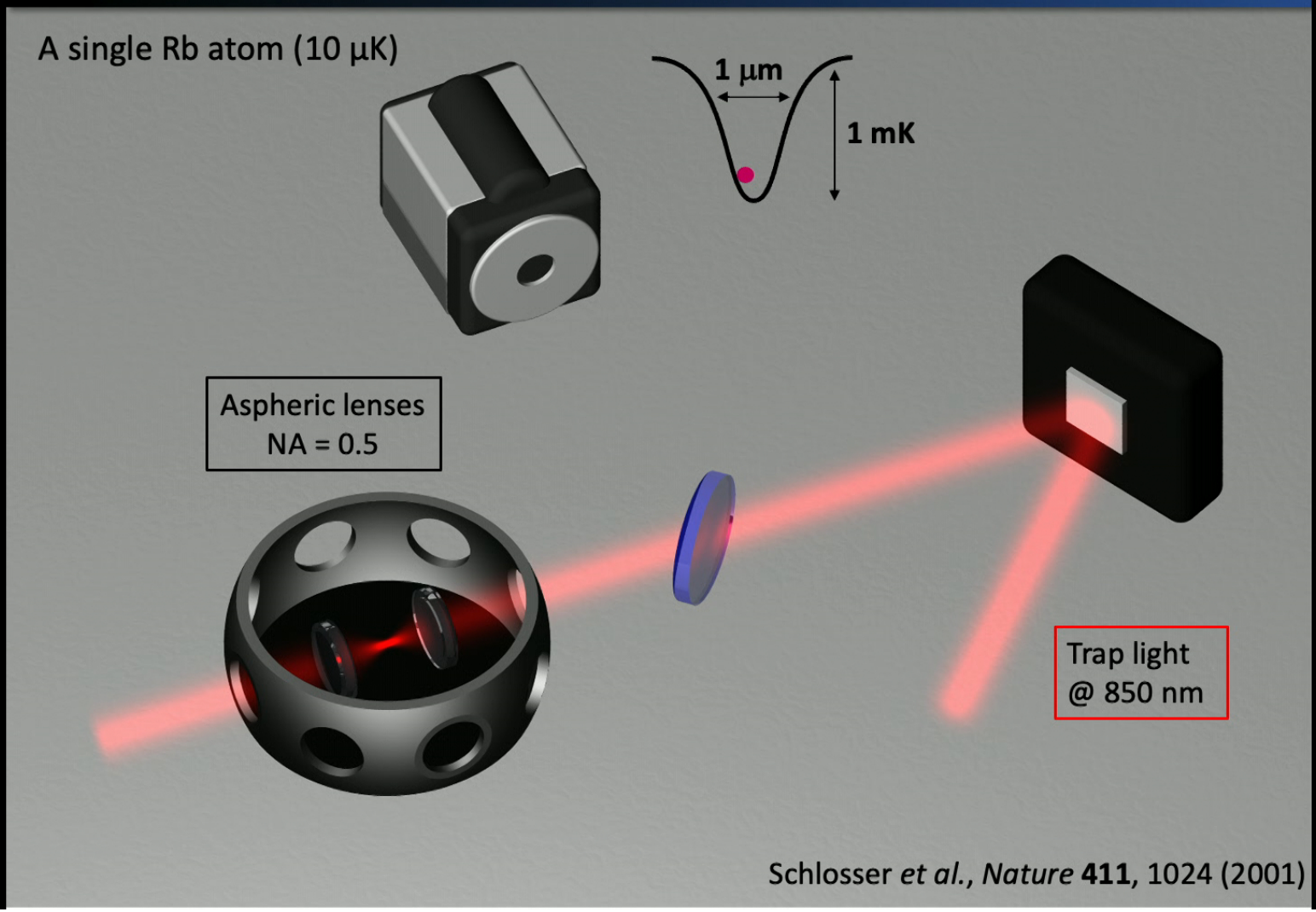
2. Ising model on square and triangular lattices



3. XY ferro- & anti-ferromagnets

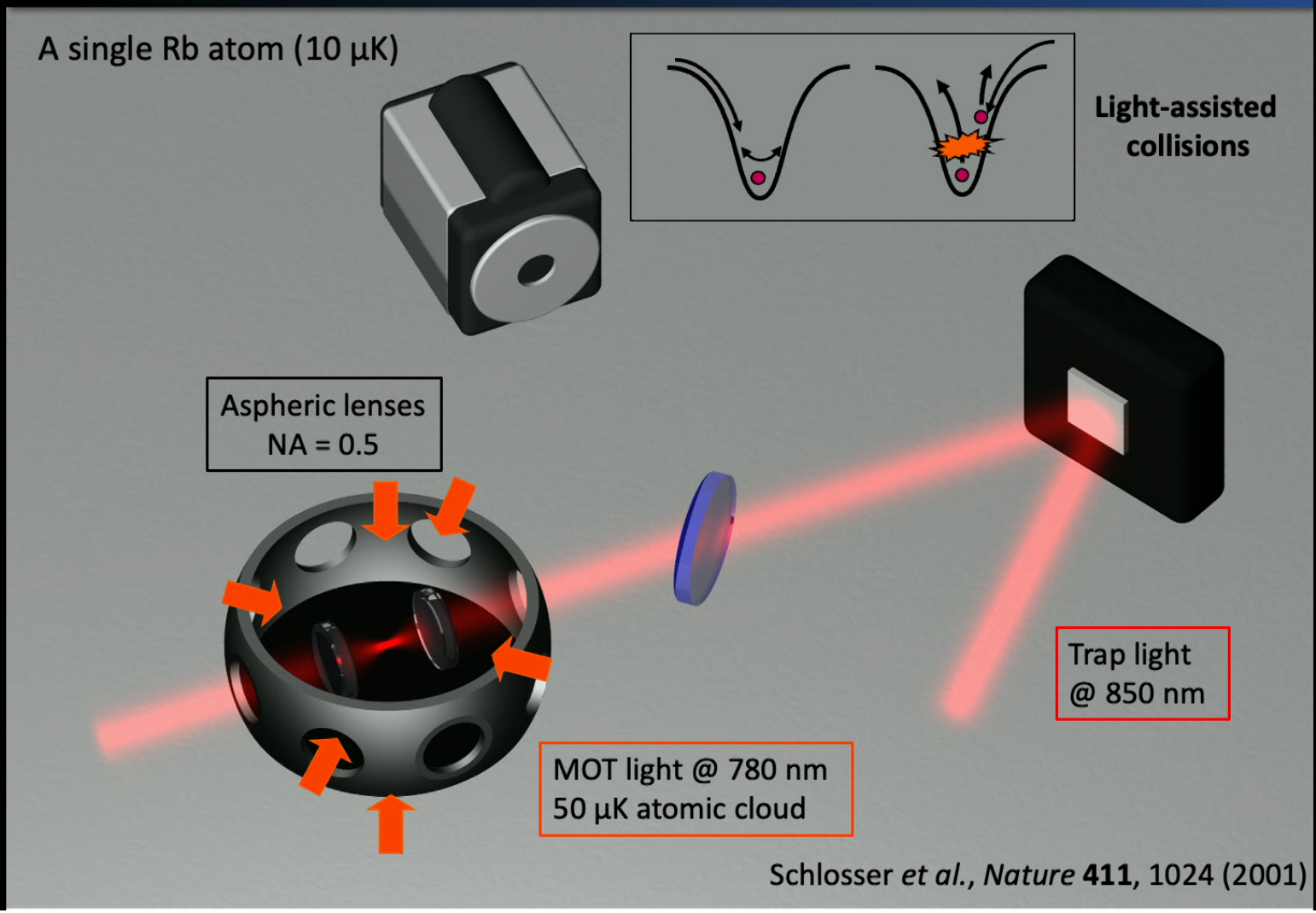


Individual atoms in optical tweezers

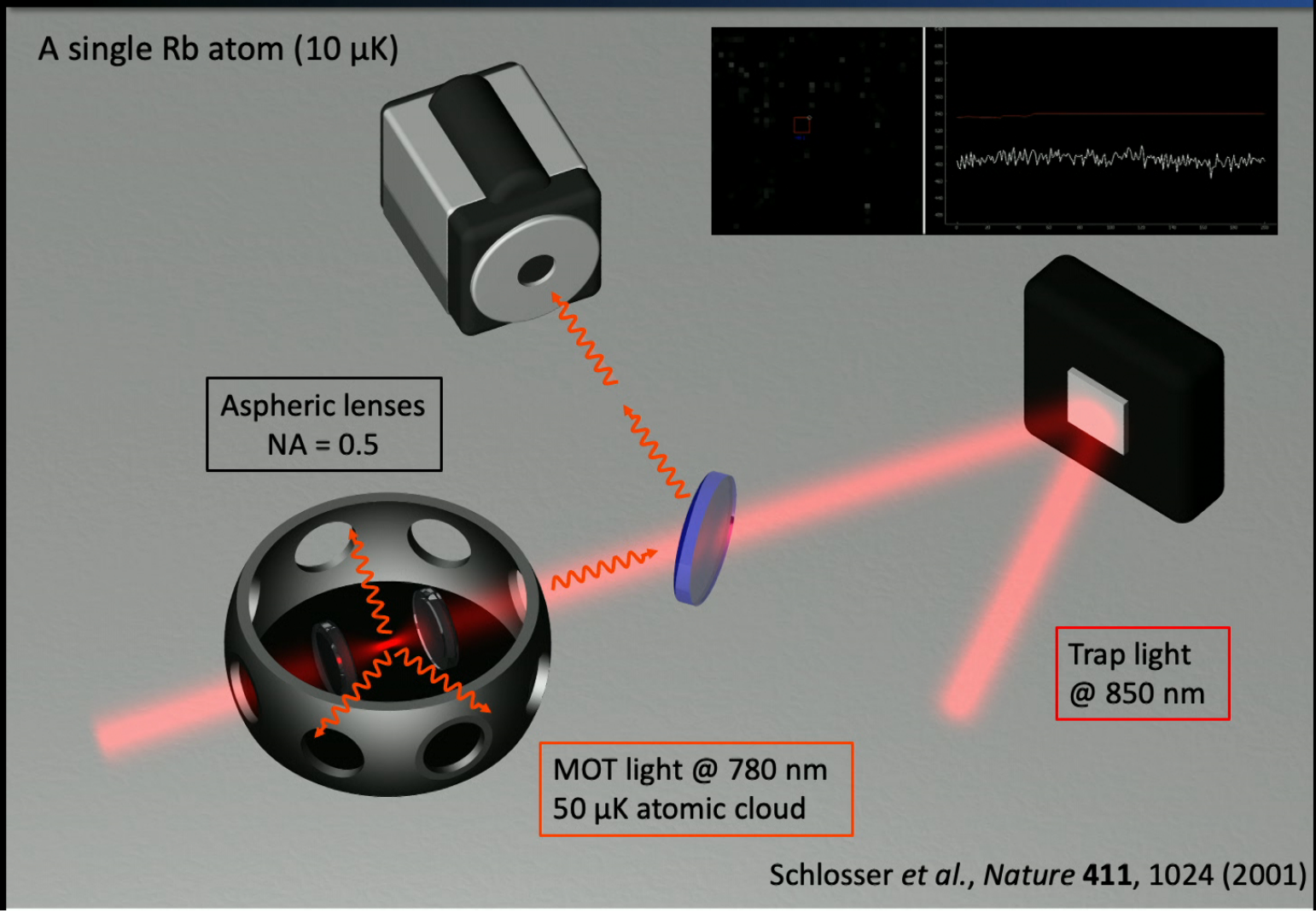


Schlosser *et al.*, *Nature* **411**, 1024 (2001)

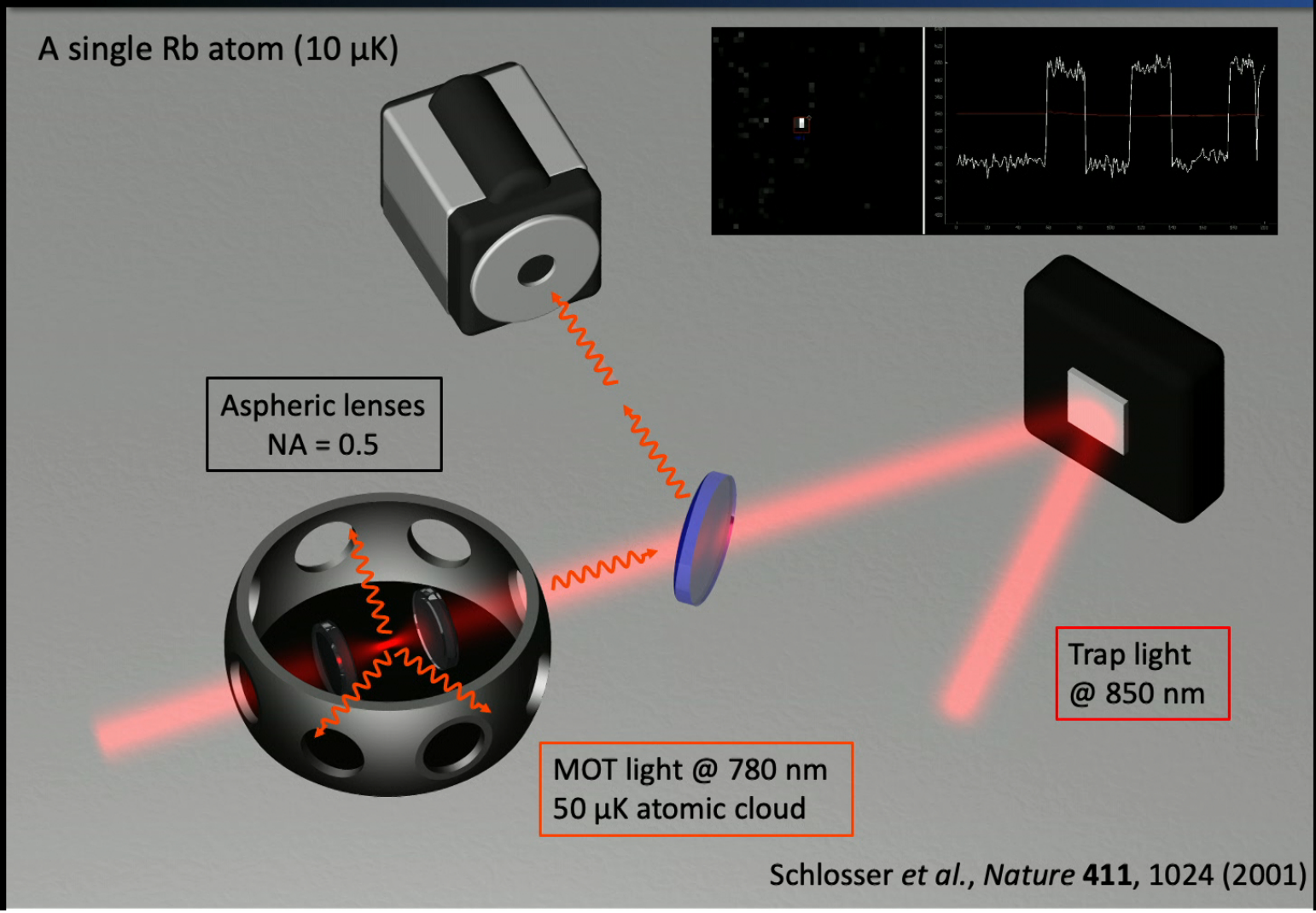
Individual atoms in optical tweezers



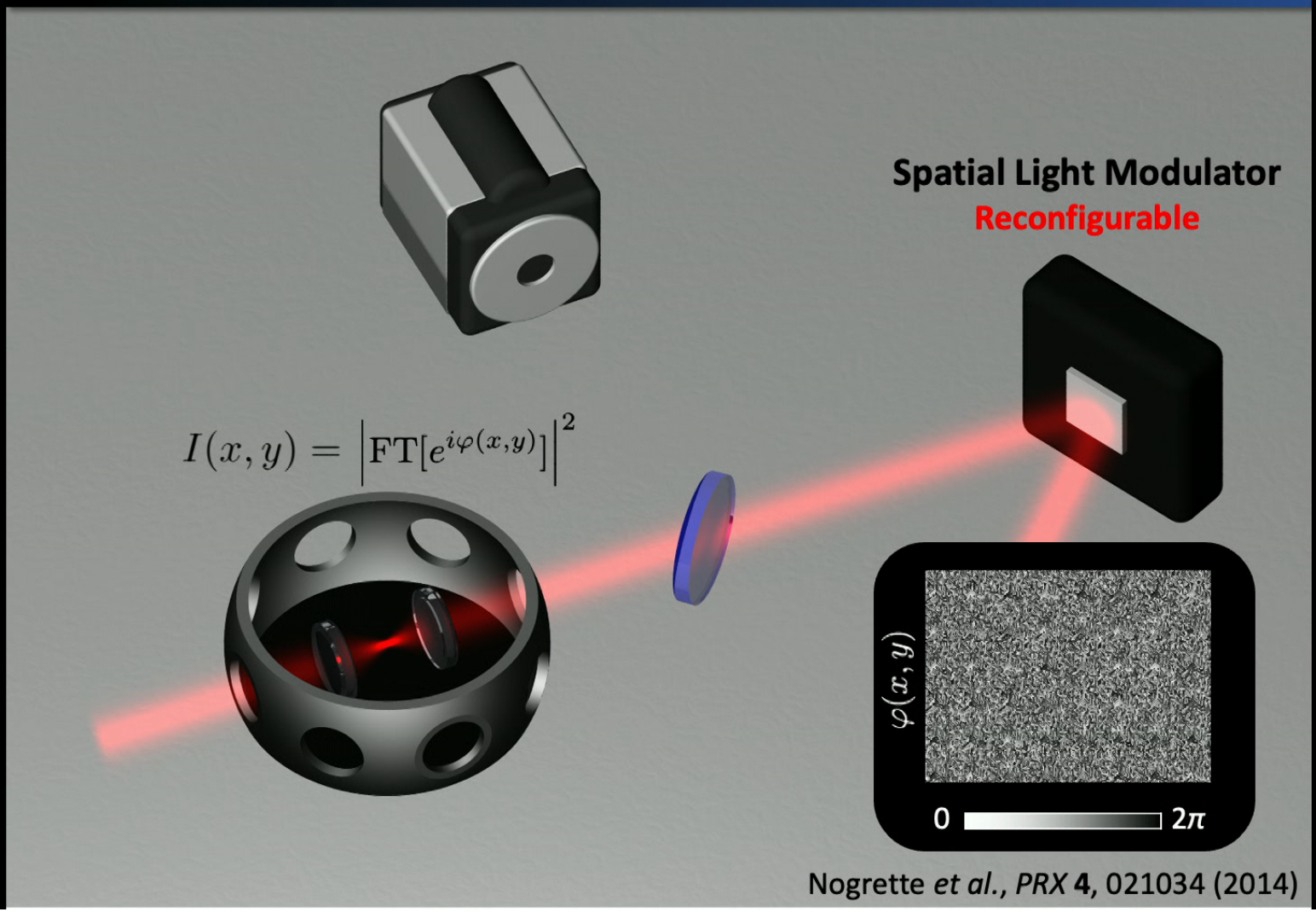
Individual atoms in optical tweezers



Individual atoms in optical tweezers



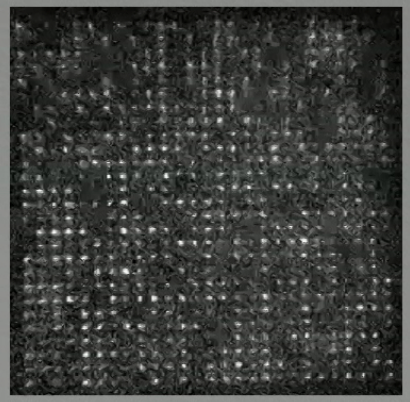
Individual atoms in optical tweezers

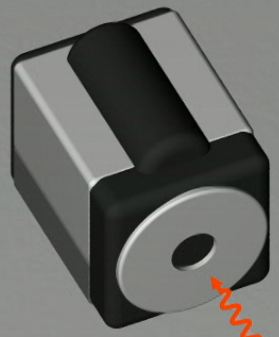


Nogrette *et al.*, *PRX* **4**, 021034 (2014)

Individual atoms in optical tweezers

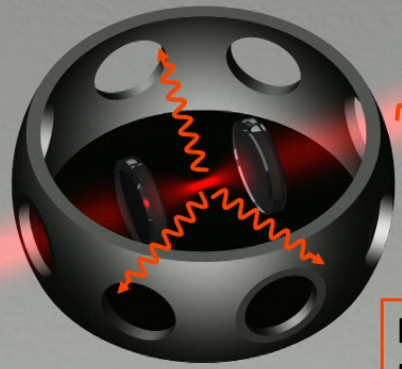
Avg. Fluorescence

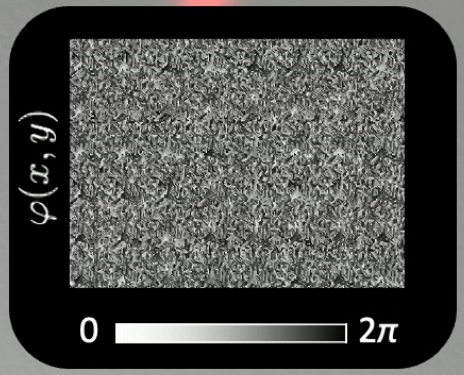




$$I(x,y) = \left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

Spatial Light Modulator
Reconfigurable

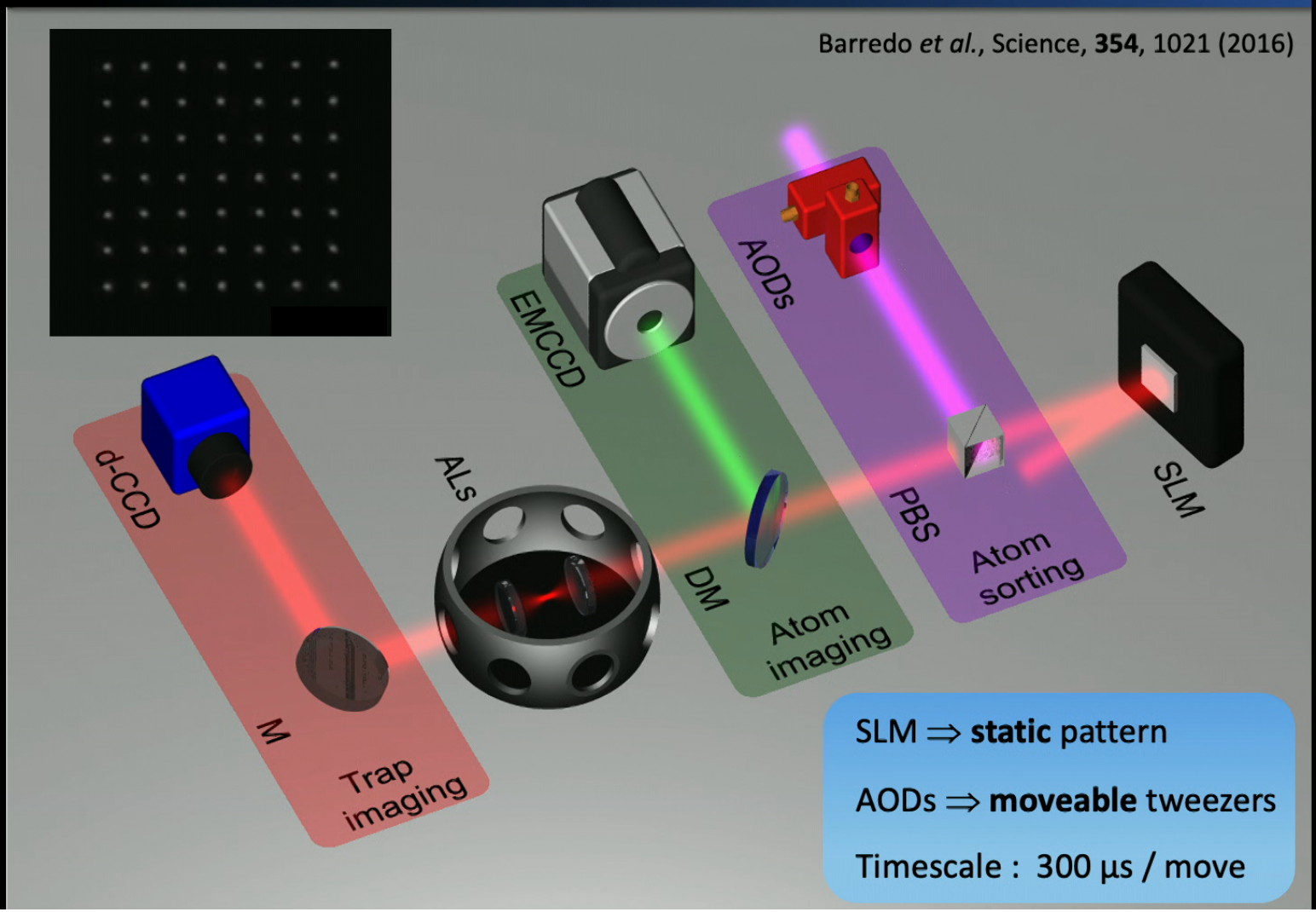




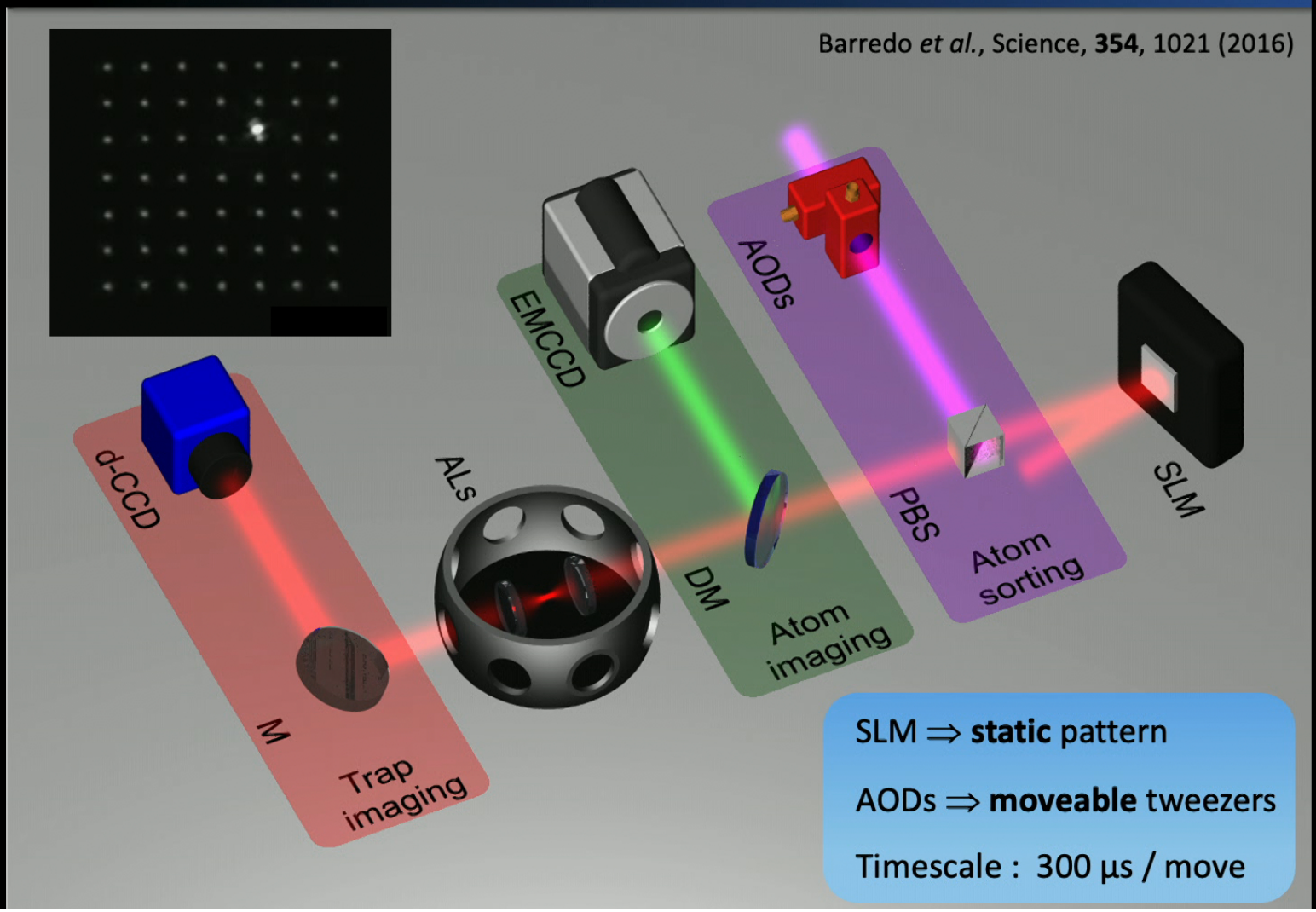
MOT light @ 780 nm
50 μK atomic cloud

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

Assembled arrays of individual atoms

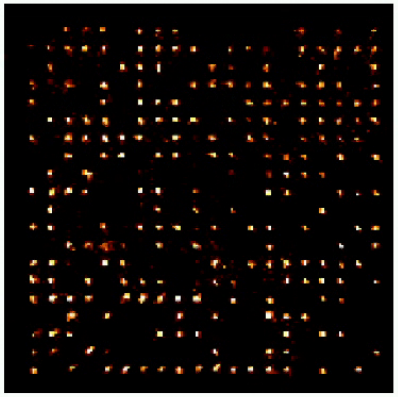


Assembled arrays of individual atoms

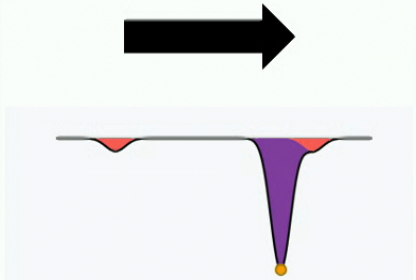


Assembled arrays of individual atoms

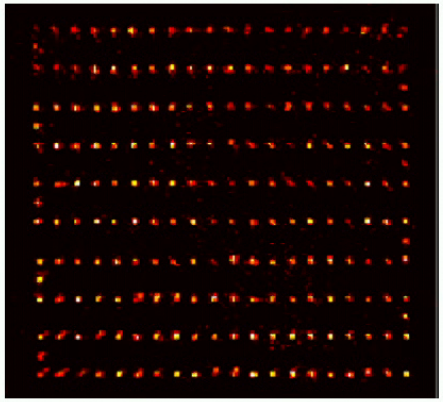
Initial configuration



Assembling process



Assembled configuration



~100 μm

Related: Endres *et al.*, Science **354**,1024 (2016)
Kim *et al.*, Nat. Comm. **7**, 13317 (2016)

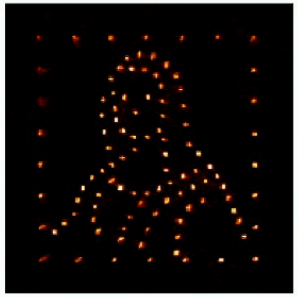
Barredo *et al.*, Science, **354**, 1021 (2016)

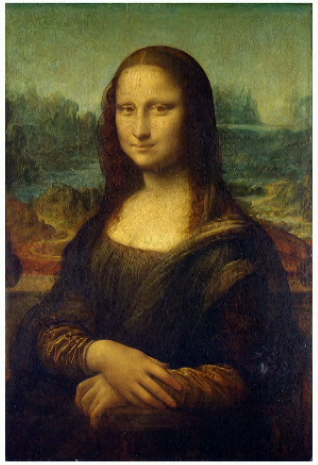
Assembled arrays of individual atoms

New assembler algorithms:

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

L. da Vinci

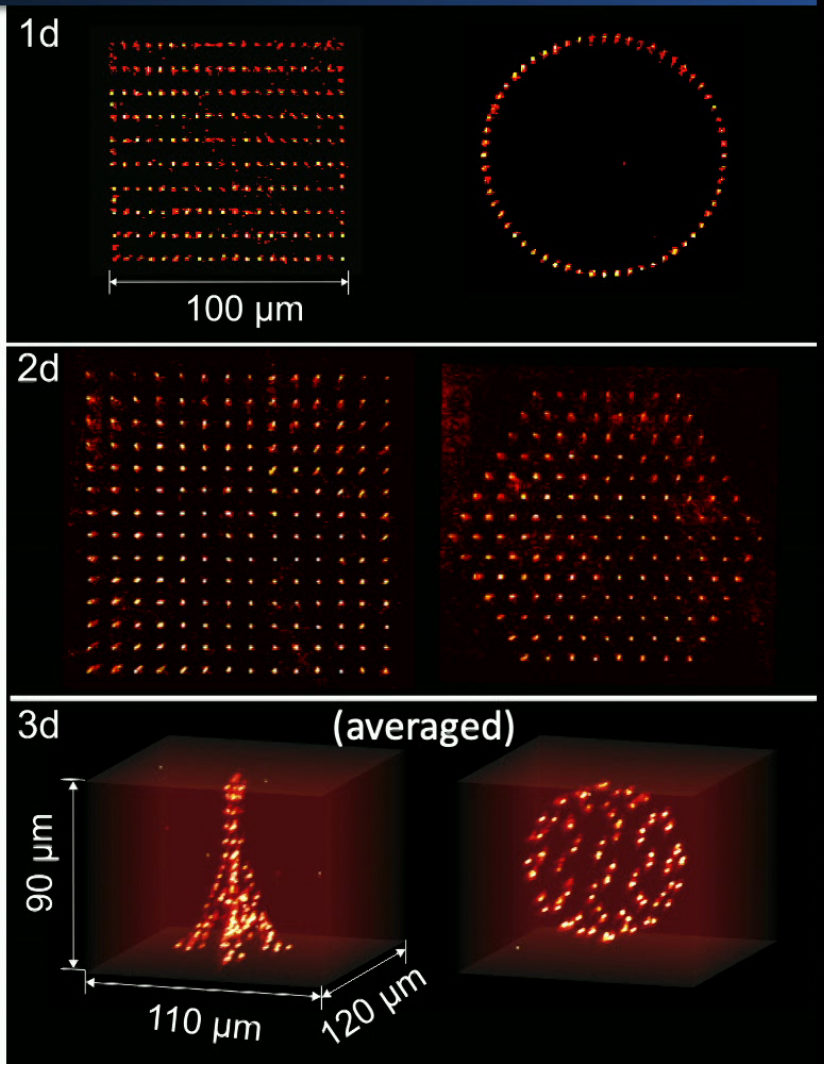




For N = 100 atoms:

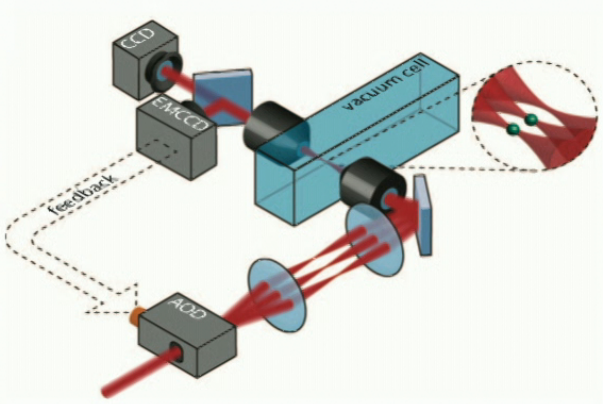
Filling fraction > 99 %

Probability of defect free shots ~ 40 %

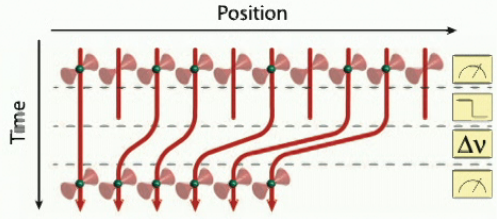


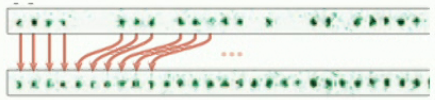
Assembled arrays in the world

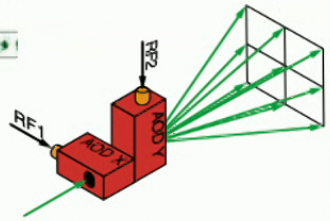
Lukin (Harvard), 2016



Rb

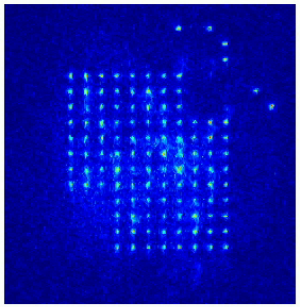






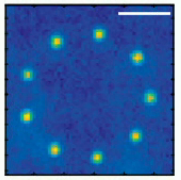
Birkl (Germany)

2D

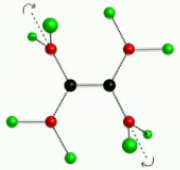


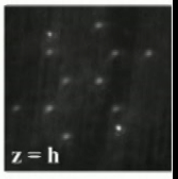
Ahn (Korea)

2D

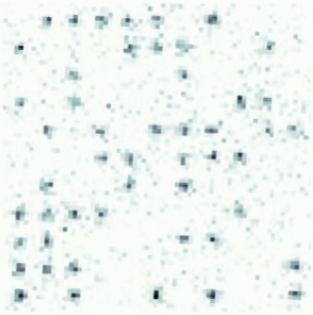


3D

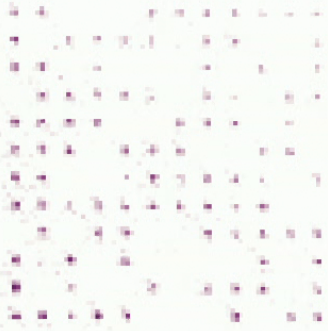




Sr



Yb



Endres (Caltech)
Kauffman (JILA)
2018

Thompson (Princeton)
2018

Towards more atoms: arrays in a cryostat

Why larger arrays?

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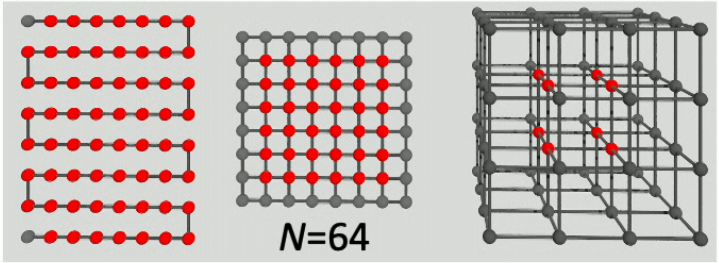
Why larger arrays?

Avoid edge effects…



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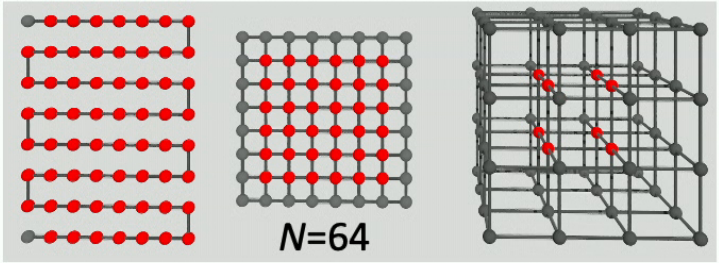
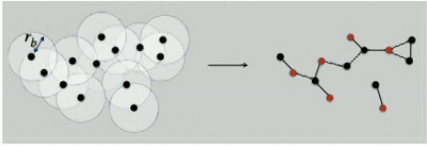


Optimization problems $N > 1000$

Graph problems (MIS)

Lukin & Pichler ,
Ahn, Pasqal, Ayral…



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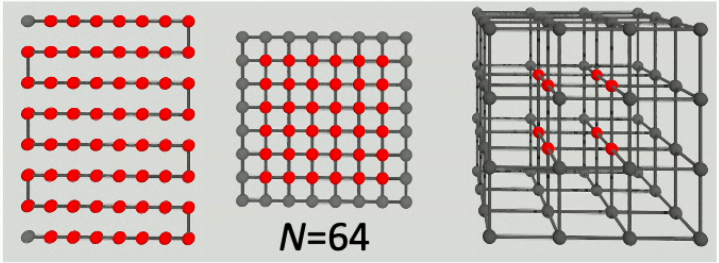

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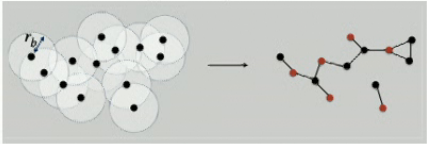

Quantum error correction

~ 100 phys. qbits for 1 logical qbit

Lifetime: $\tau_1 \rightarrow \tau_N = \tau_1/N$ $\Rightarrow$ atom losses + detection errors

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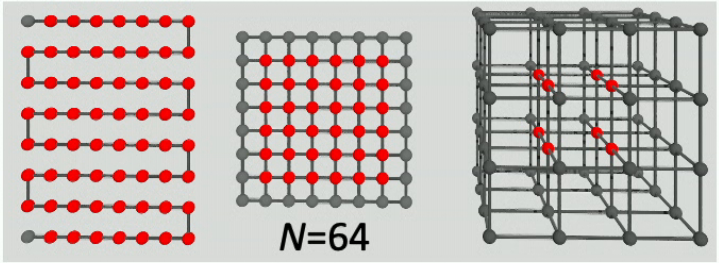

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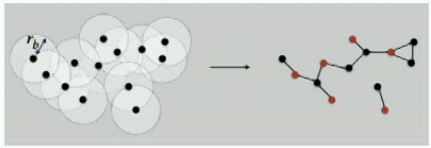

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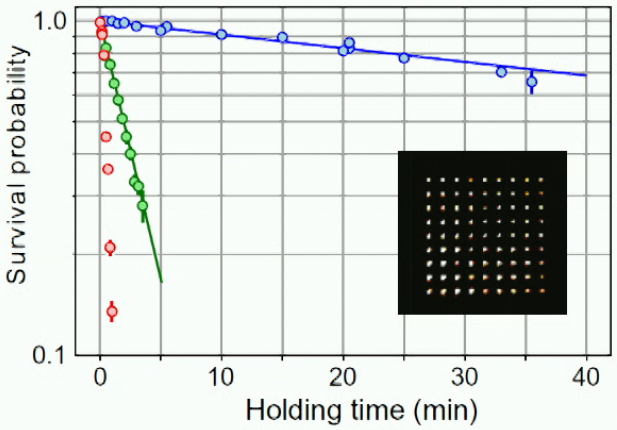
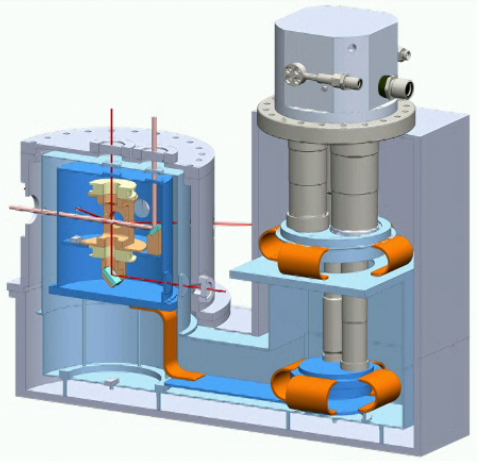
MYCRYOFIRM
CRYOGENIC SOLUTIONS

Development of a 4K,
UHV compatible closed-cycle
cryostat $\Rightarrow$ "vacuum ~ 0"

K.N. Schymik, Phys. Rev. Applied (2021)

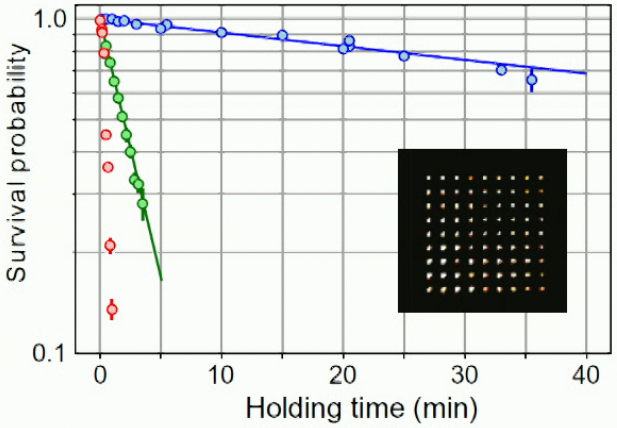
Towards more atoms: arrays in a cryostat

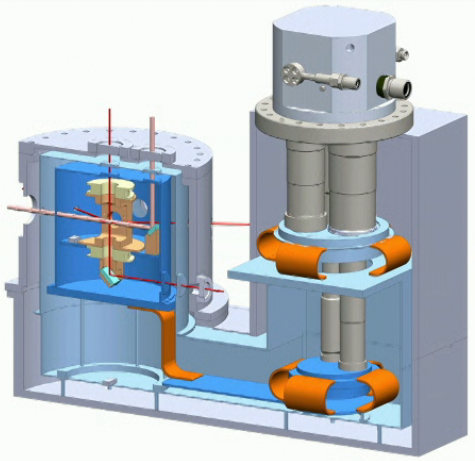




Trapping lifetime > 6000 s !

Towards more atoms: arrays in a cryostat





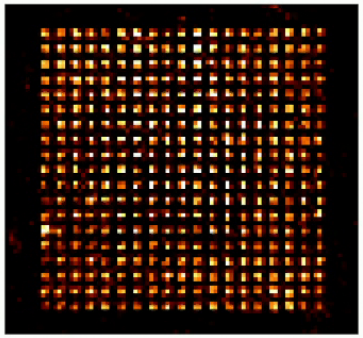
Trapping lifetime > 6000 s !

Now:

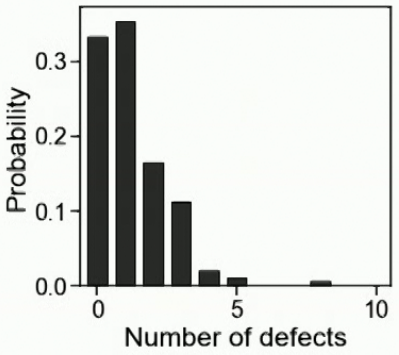
>300 atoms assembled
> 30% probability

K.N. Schymik *et al.*, arXiv:2207.06500

19 x 19

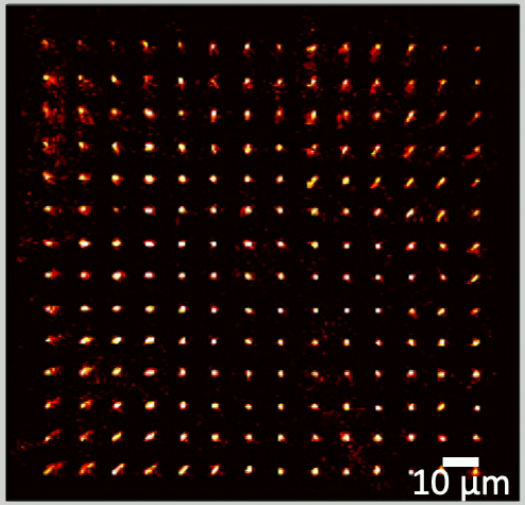


17 x 18



Arrays of interacting Rydberg atoms

Arrays of atoms



Addressable

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

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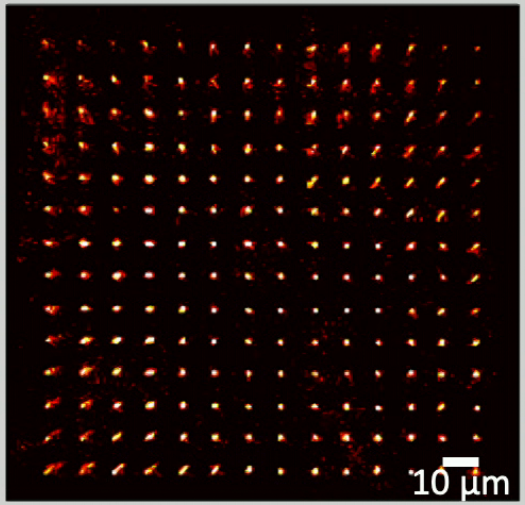
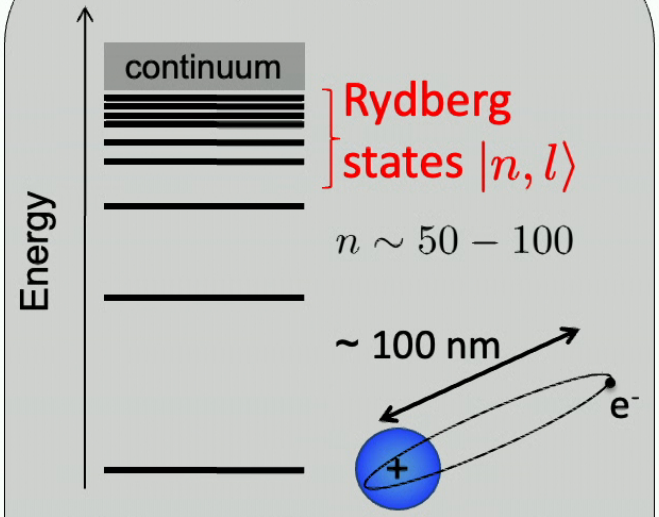


Addressable

+

Rydberg atoms



Lifetime > 100 µs $\tau \sim n^3$

Transition dipole: $d \sim n^2$

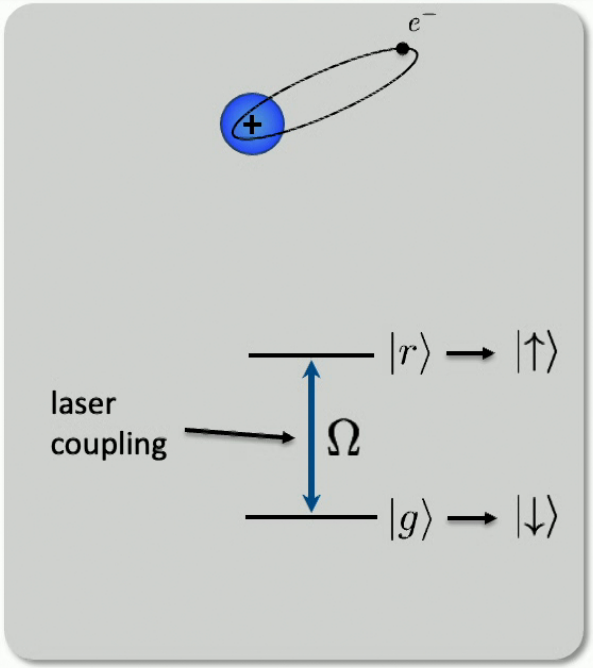
Large dipole-dipole interactions

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

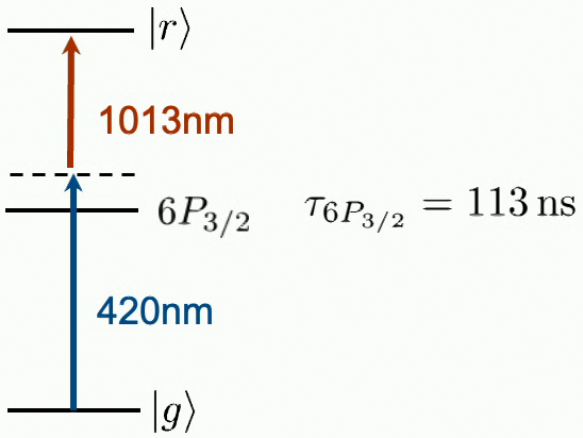
$T_{\mathrm{int}} \approx \mu\mathrm{s} \ll T_{\mathrm{lifetime}}$

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

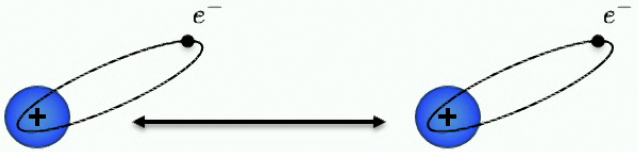
Coherent excitation to the Rydberg states

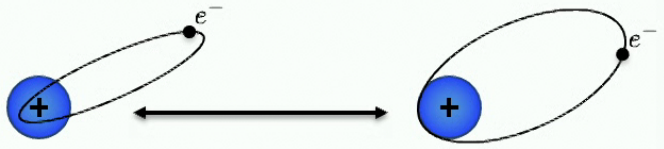


Bernien 2017, Levine 2019

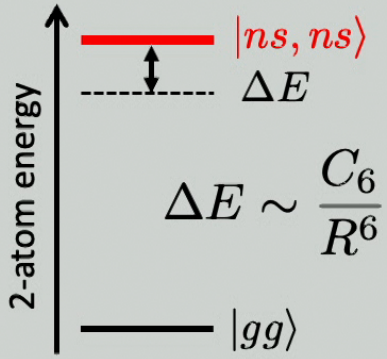


Interactions between Rydberg atoms and spin models



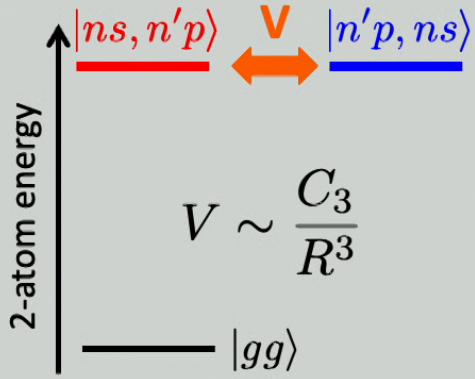


van der Waals



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

Resonant dipole



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

Quantum Ising

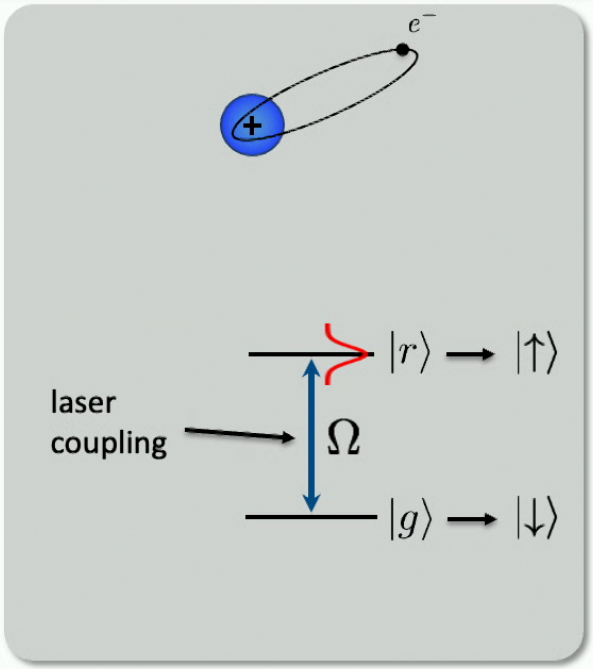
$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

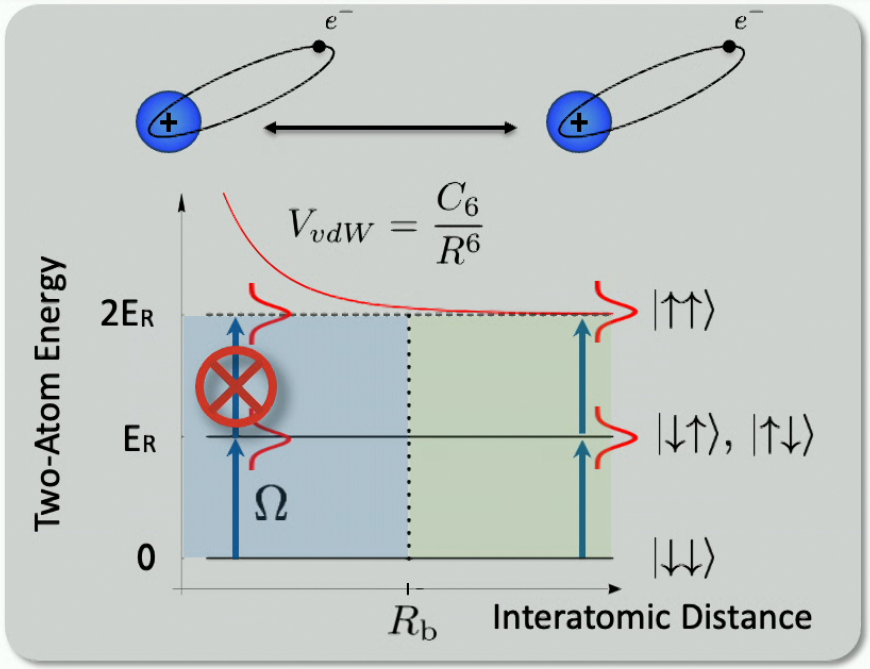
XY model

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

Browaeys, Nat.Phys. (2020)

From van der Waals to Ising

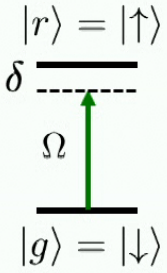




Quantum Ising model:

$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i + \hbar\delta\sum_i \hat{n}_i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

Transverse B *Longitudinal B* *Spin-spin interaction*

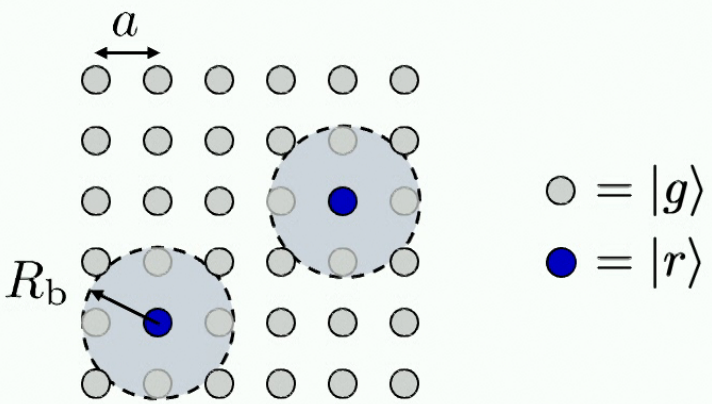


Rydberg occupation number $n^i = |r_i\rangle\langle r_i| = (1+\sigma_z^i)/2$

Rydberg blockade and anti-ferromagnetic order

$$R_\mathrm{b} \sim a \qquad \frac{C_6}{a^6} \sim \Omega$$

Nearest-neighbor blockade



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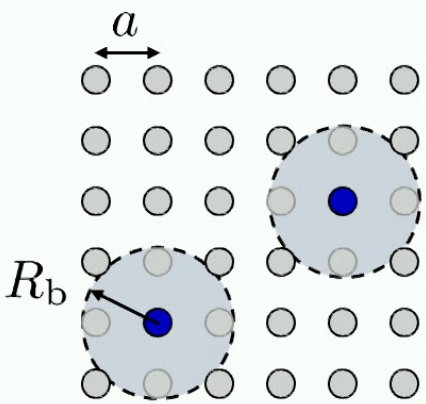
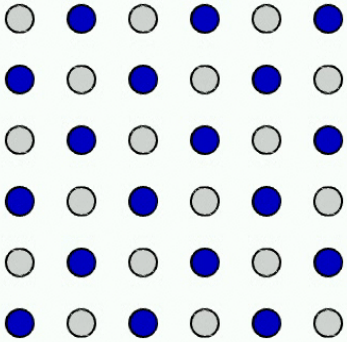


$\circ = |g\rangle$

$\bullet = |r\rangle$

Antiferromagnetic ground state

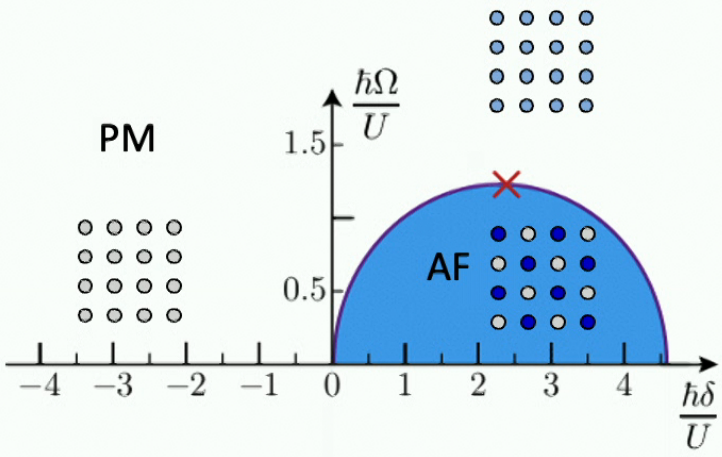


Phase diagram on a square lattice

$\bigcirc = |g\rangle$

$\bullet = |r\rangle$

Ising AF phase diagram



$R_b \sim a$

$U = C_6/a^6$

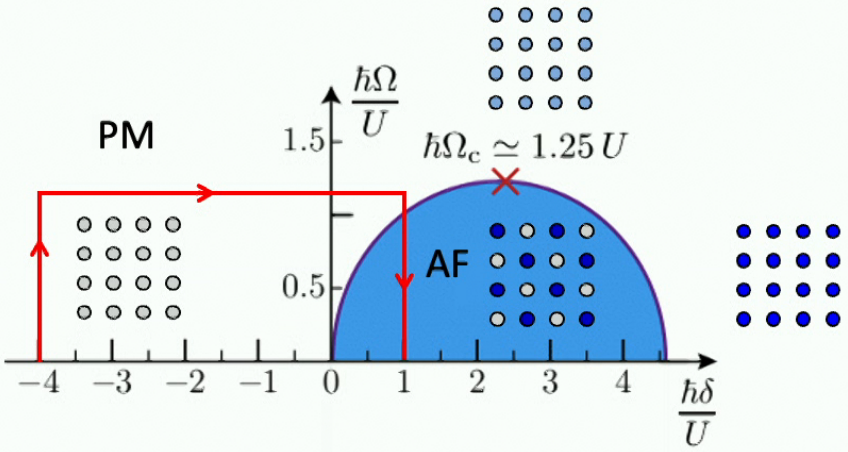
Probing anti-ferromagnetic order on a square lattice

$\bigcirc = |g\rangle$

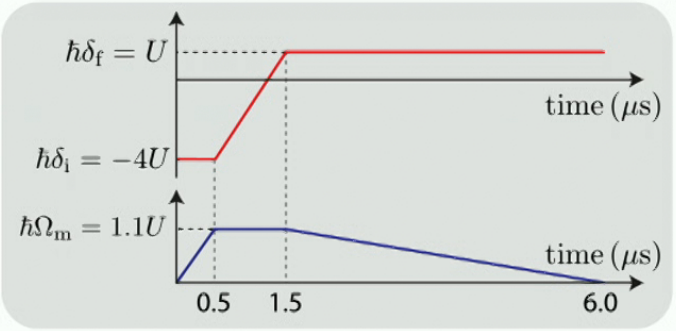
$\bullet = |r\rangle$

$R_\mathrm{b} \sim a$

Ising AF phase diagram



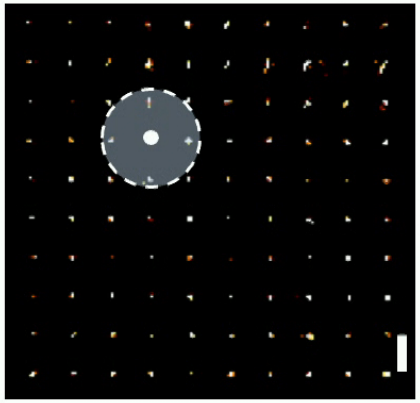
$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$



Vary Rabi frequency and detuning
to explore the phase diagram

Preparation of a 2D Ising anti-ferromagnet on a square

10×10 square array



1D: Pohl **PRL** 2010; Bloch **Science** 2015; Lukin **Nature** 2017, 2019;
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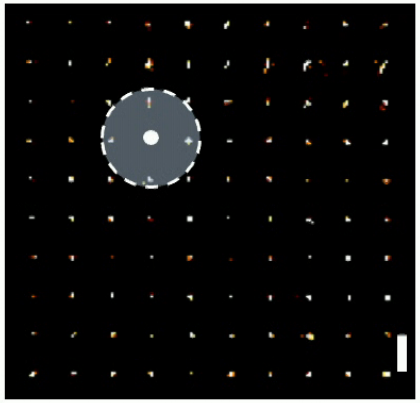
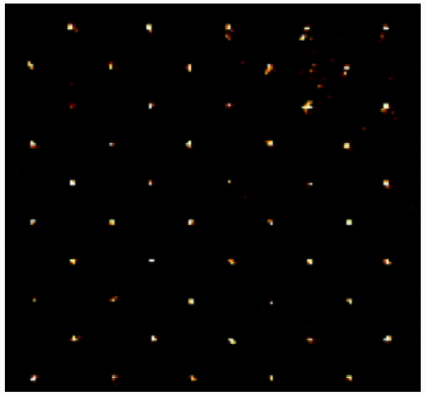


sweep

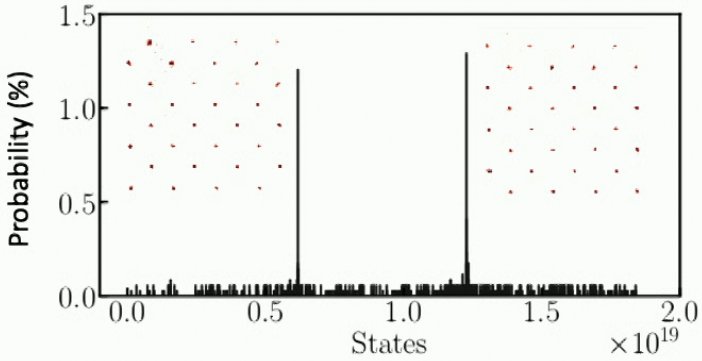
n=75S

Perfect AF (Néel) ordering!



Missing atoms = Rydberg

(8x8)



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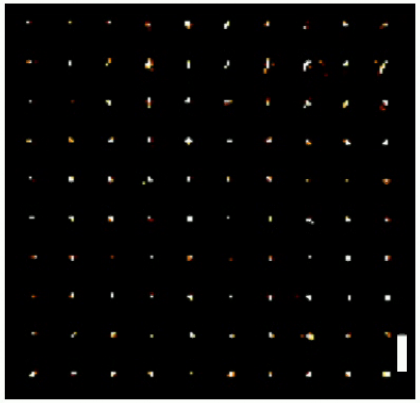
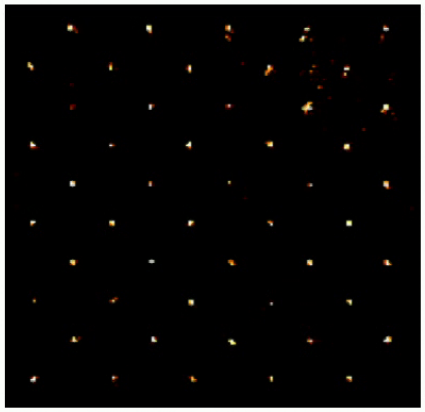


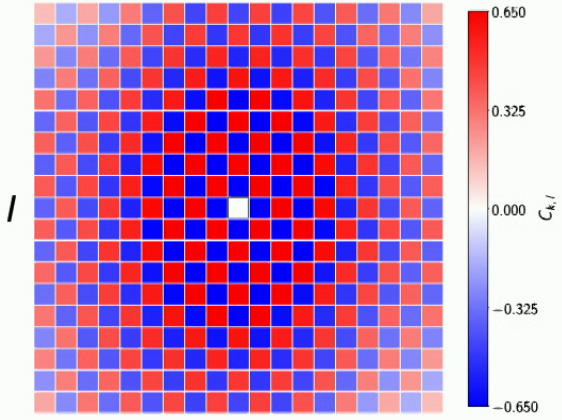
a=10 µm

sweep

n=75S



$$C_{kl} \sim \langle n_k n_l \rangle - \langle n_k \rangle \langle n_l \rangle$$

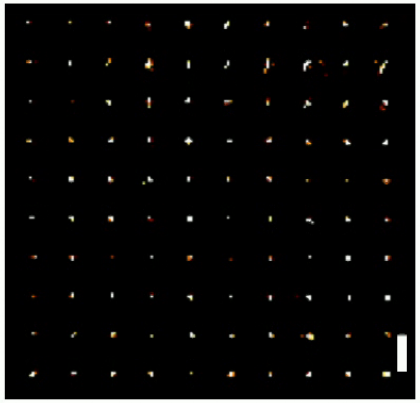


Scholl *et al.,* Nature **595**, 233 (2021)

Also: Ebadi *et al.,* Nature **595**, 227 (2021)

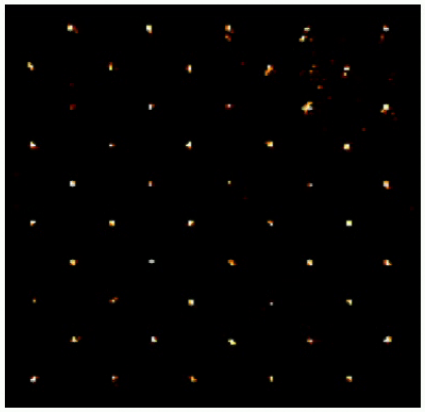
Preparation of a 2D Ising anti-ferromagnet on a square

10×10 square array



sweep

n=75S



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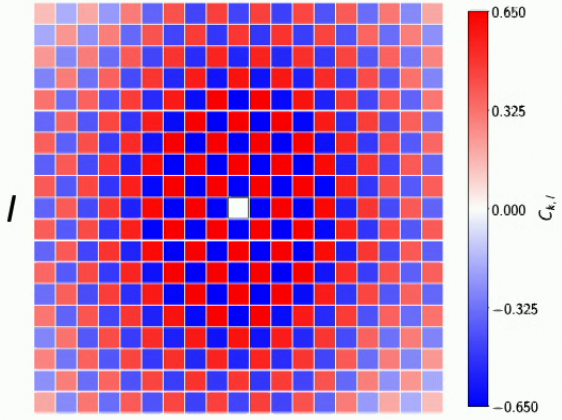
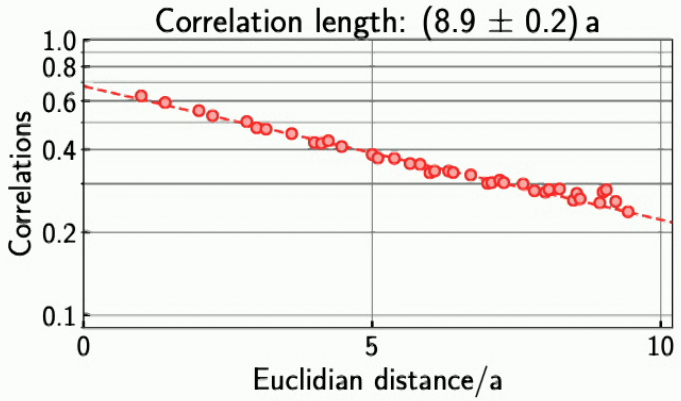


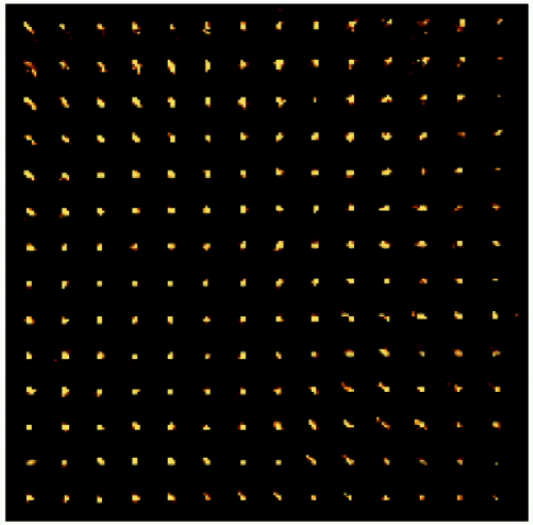


Scholl *et al.*, Nature **595**, 233 (2021)

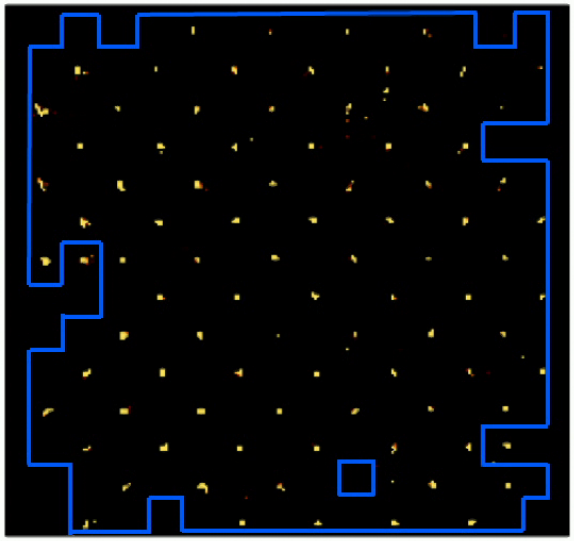
Also: Ebadi *et al.*, Nature **595**, 227 (2021)

Preparation of a 2D Ising anti-ferromagnet on a square

14x14 square array



sweep

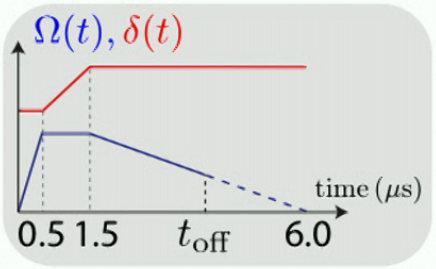


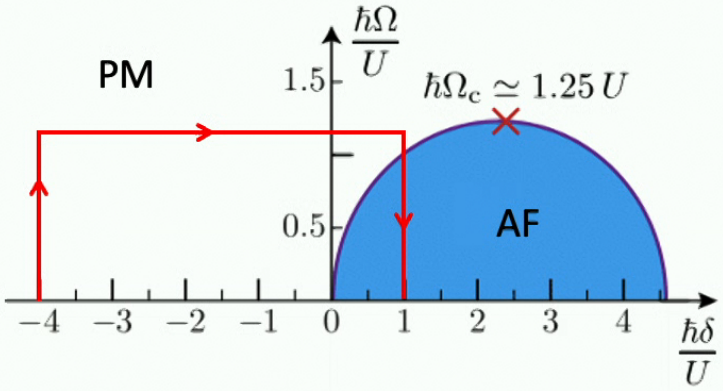
182-atom antiferromagnetic cluster!

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

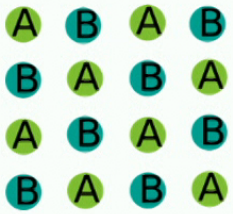
Also: Ebadi *et al.,* Nature **595**, 227 (2021)

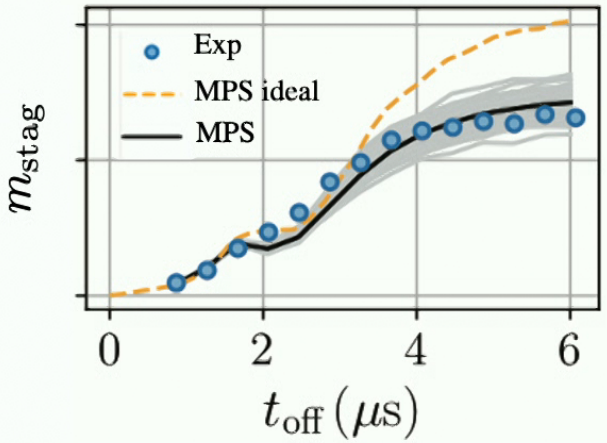
Benchmarking the dynamics on a square





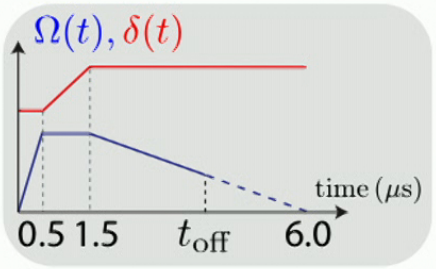
Staggered magnetisation: $m_{\rm stag} = \langle |n_A - n_B| \rangle$

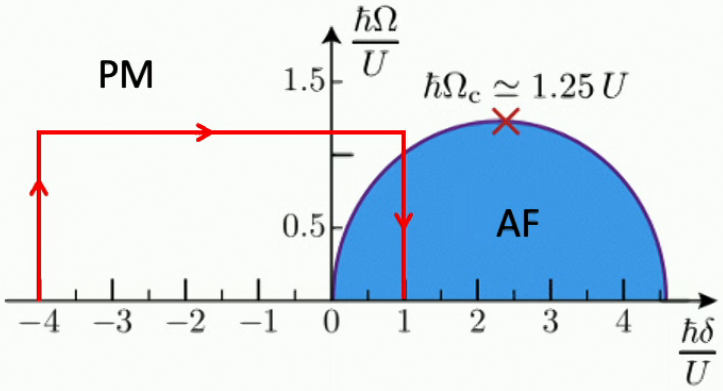




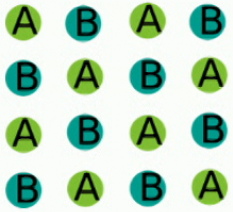
Including experimental imperfections: $U_{ij}, \Omega_i, \delta_i$, real ramp…

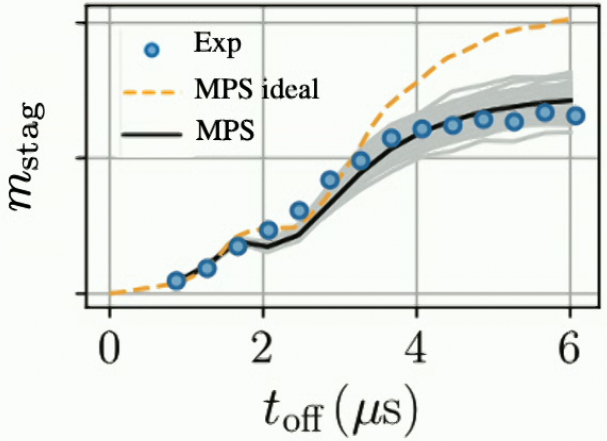
Benchmarking the dynamics on a square





Staggered magnetisation: $m_{\rm stag} = \langle |n_A - n_B| \rangle$





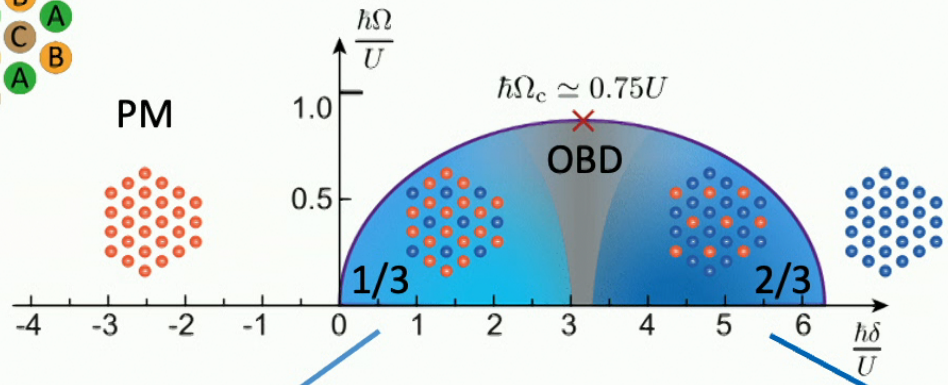
Accurate MPS limited to 10 x 10 (14 days!!)

Including experimental imperfections: $U_{ij}, \Omega_i, \delta_i$, real ramp…

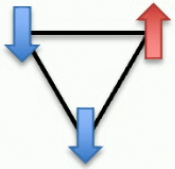
2D Ising anti-ferromagnet on triangular lattices

Ising AF phase diagram on triangle

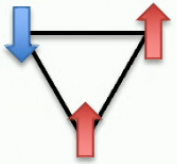
$R_{\mathrm{b}} \sim a$



1/3 phase:

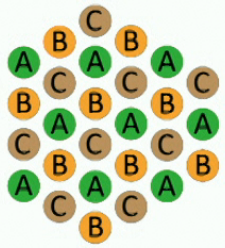


2/3 phase:



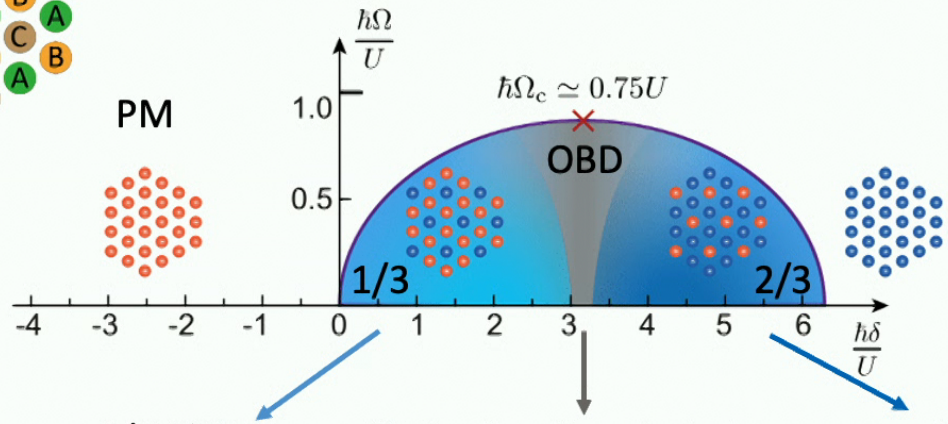
Classical phases

2D Ising anti-ferromagnet on triangular lattices

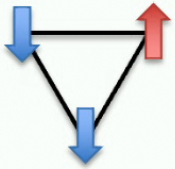


Ising AF phase diagram on triangle

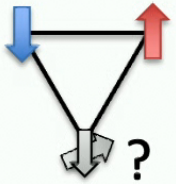
$R_{\mathrm{b}} \sim a$



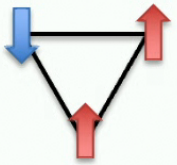
1/3 phase:



'Order-by-disorder' phase:

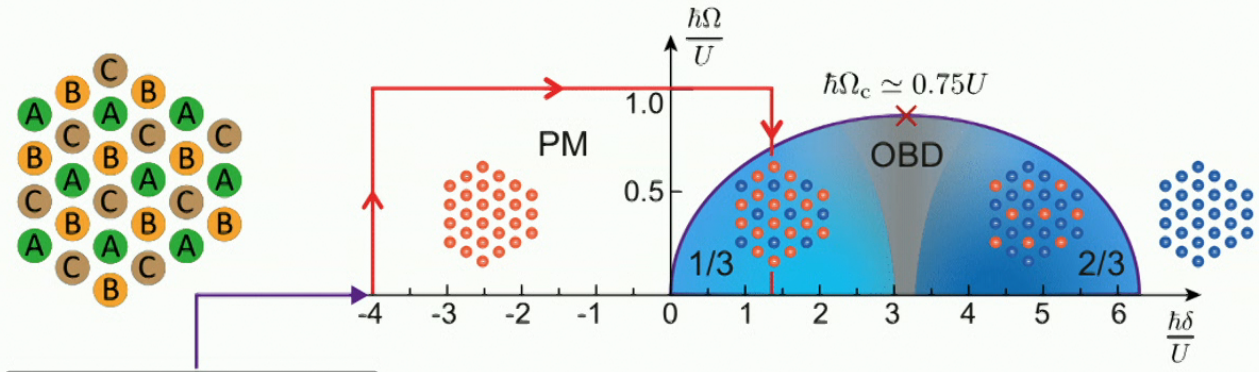


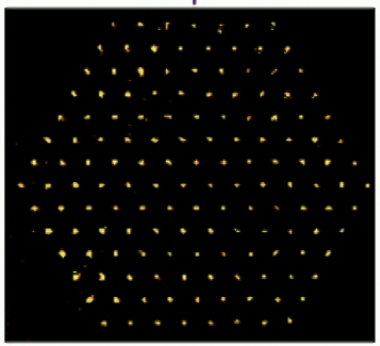
2/3 phase:



Geometrical frustration

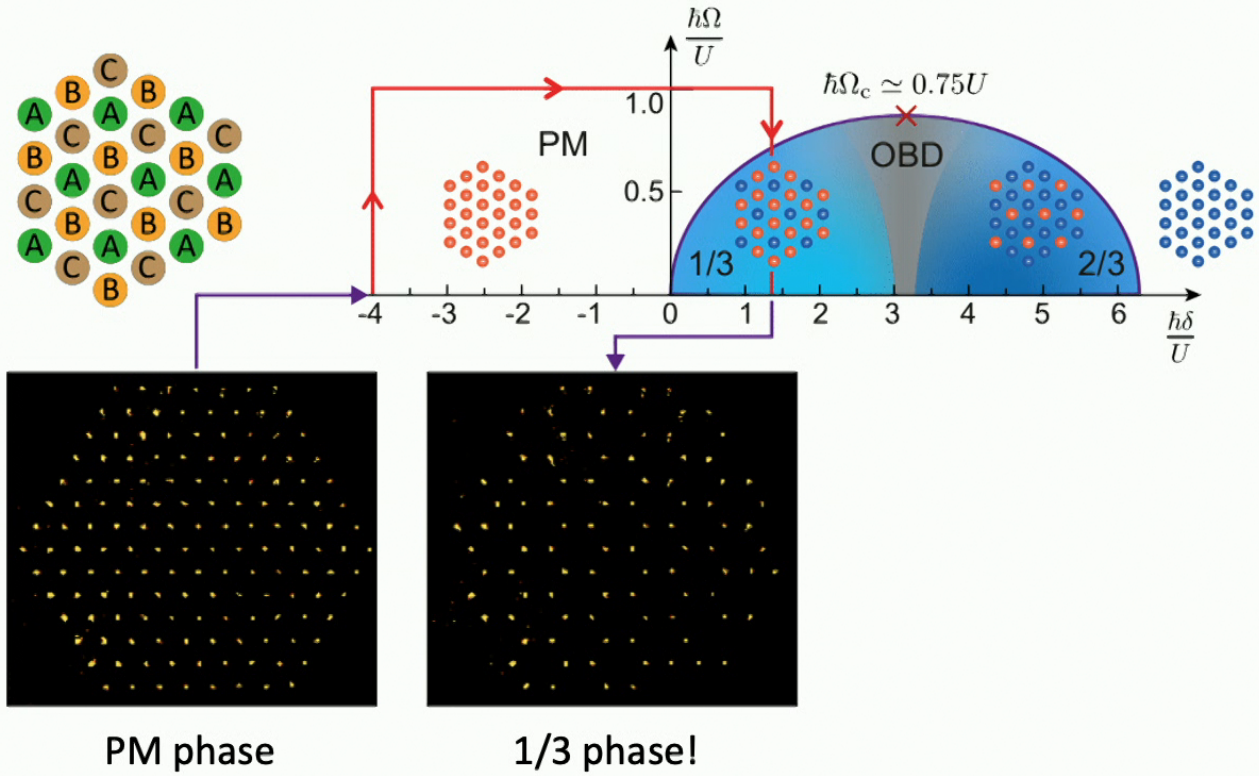
Probing the 1/3 phase





PM phase

Probing the 1/3 phase

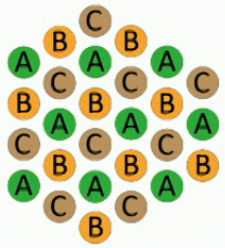


PM phase

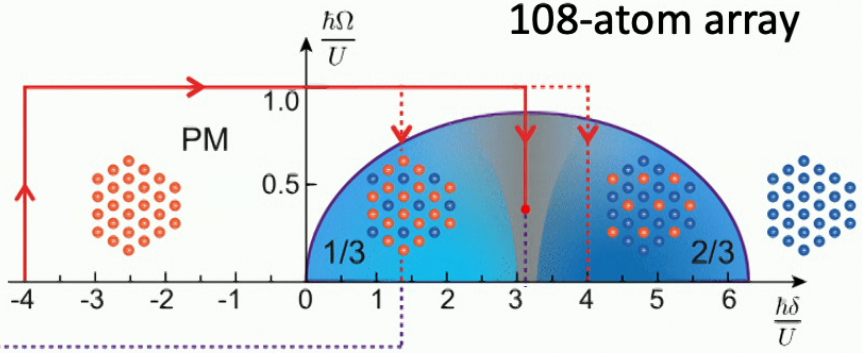
1/3 phase!

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

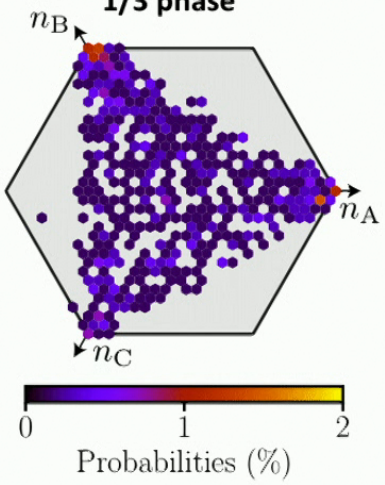
2D Ising anti-ferromagnet on a triangle



108-atom array

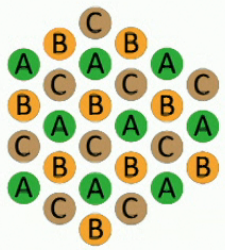


1/3 phase

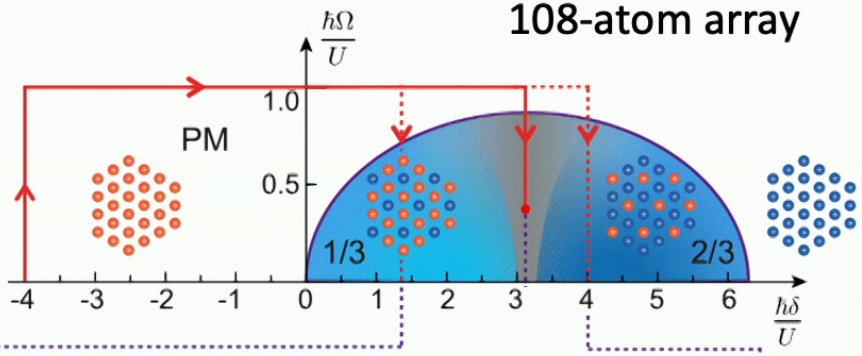


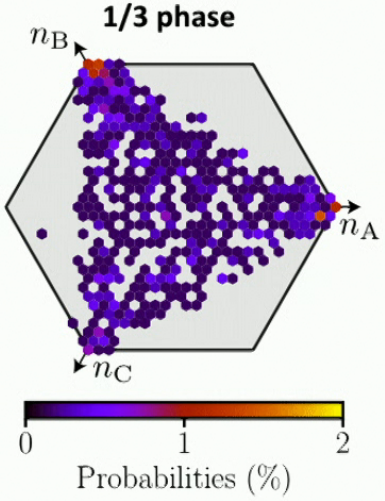
Staggered magnetisation: $m_{\text{stag}} = n_A + n_B\, e^{i\frac{2\pi}{3}} + n_C\, e^{i\frac{4\pi}{3}}$

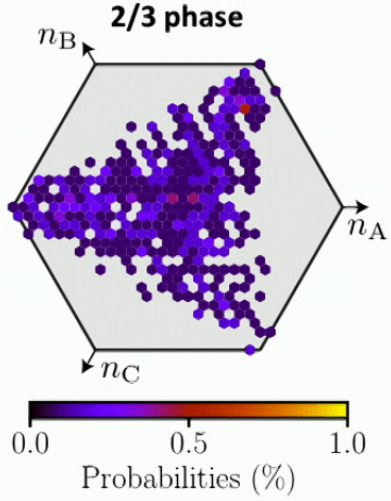
2D Ising anti-ferromagnet on a triangle



108-atom array

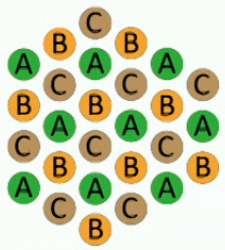




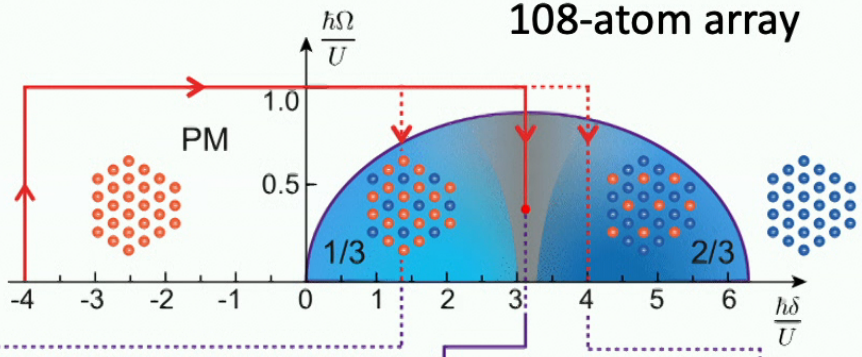


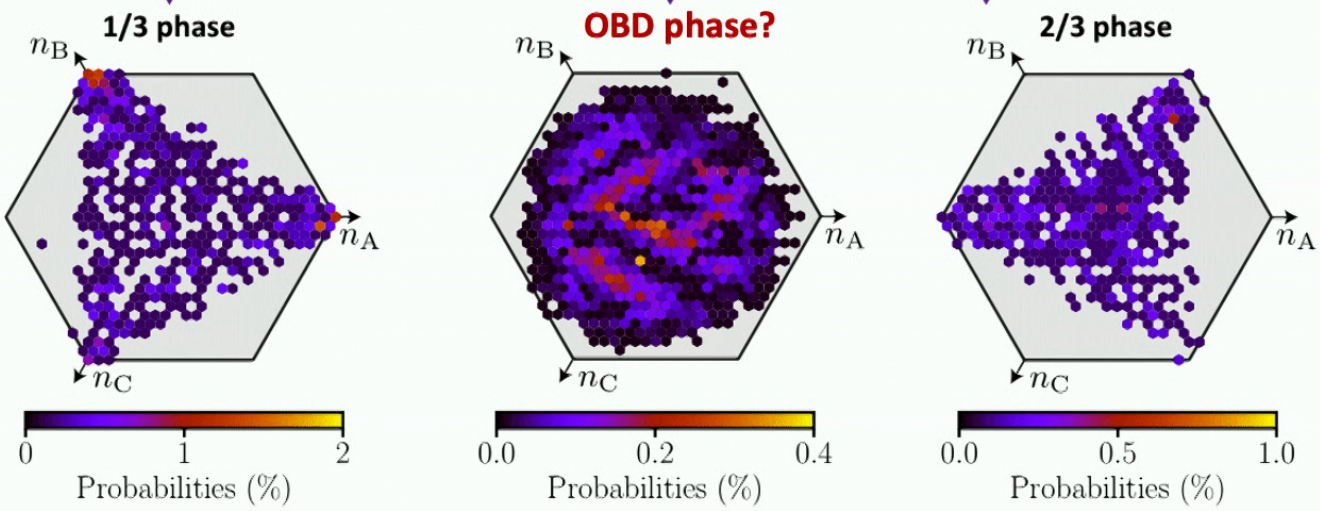
Staggered magnetisation: $m_{\text{stag}} = n_A + n_B\, e^{i\frac{2\pi}{3}} + n_C\, e^{i\frac{4\pi}{3}}$

2D Ising anti-ferromagnet on a triangle



108-atom array

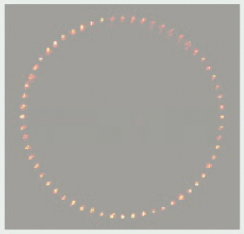




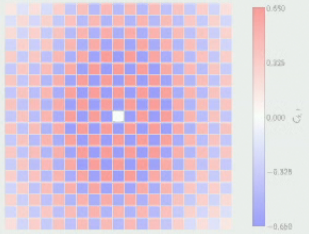
Staggered magnetisation: $m_{\text{stag}} = n_A + n_B\, e^{i\frac{2\pi}{3}} + n_C\, e^{i\frac{4\pi}{3}}$

Outline

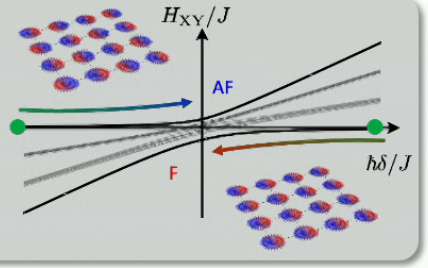
1. Assembled arrays of Rydberg atoms



2. Ising model on square and triangular lattices

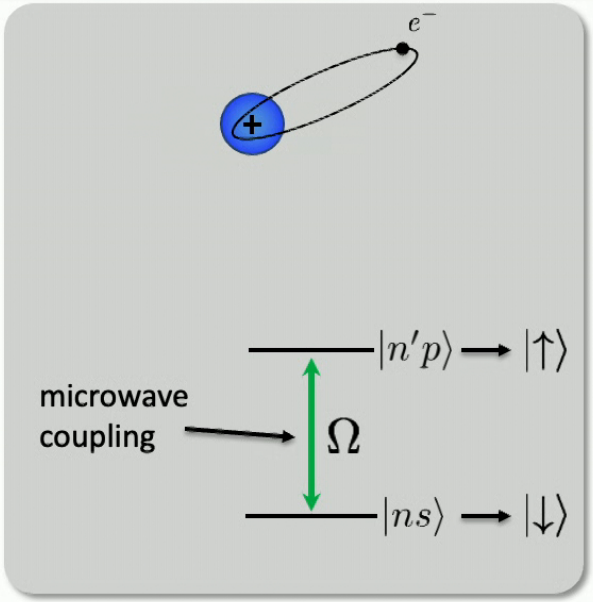


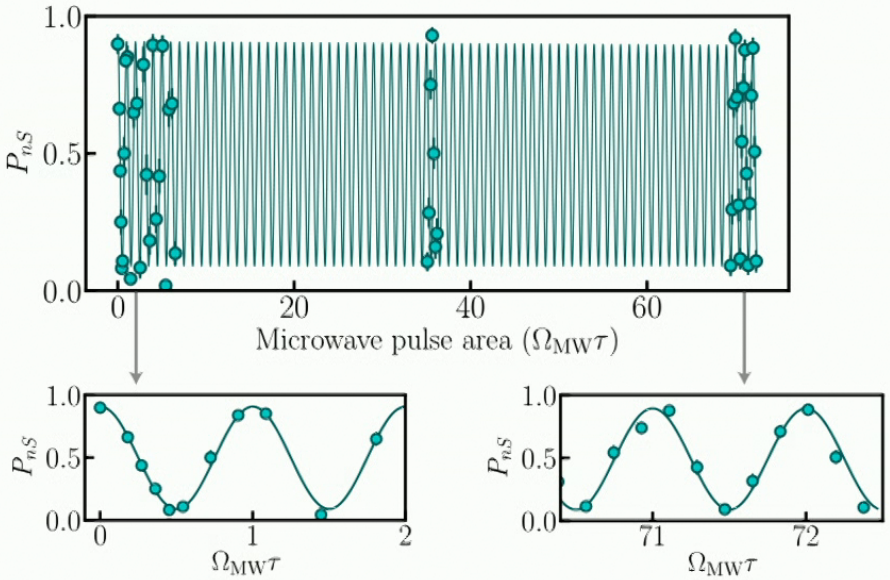
3. XY ferro- & anti-ferromagnets



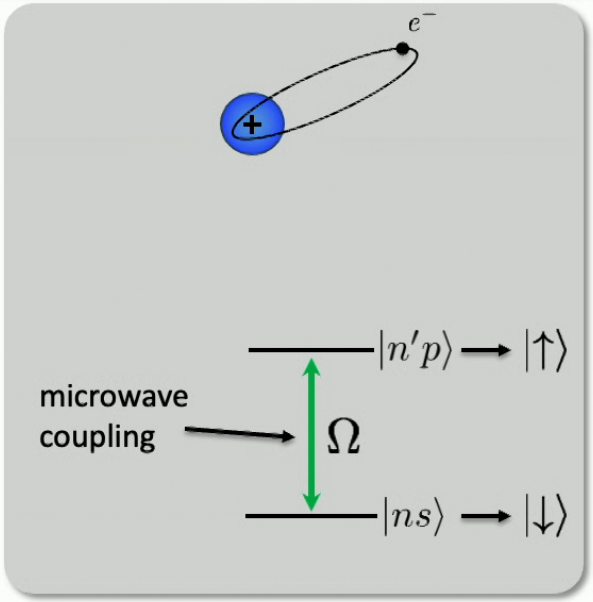
Norman Yao

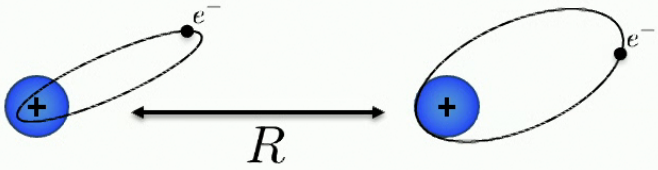
Coherent excitation between two Rydberg states



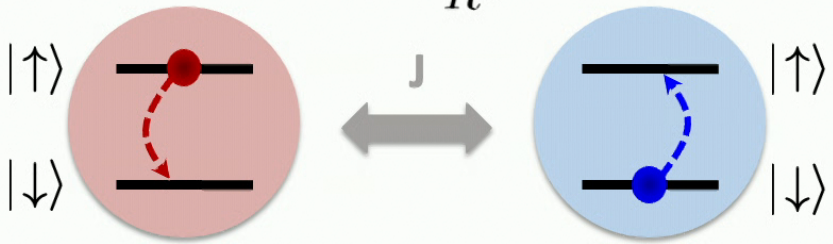


Resonant dipole-dipole interaction





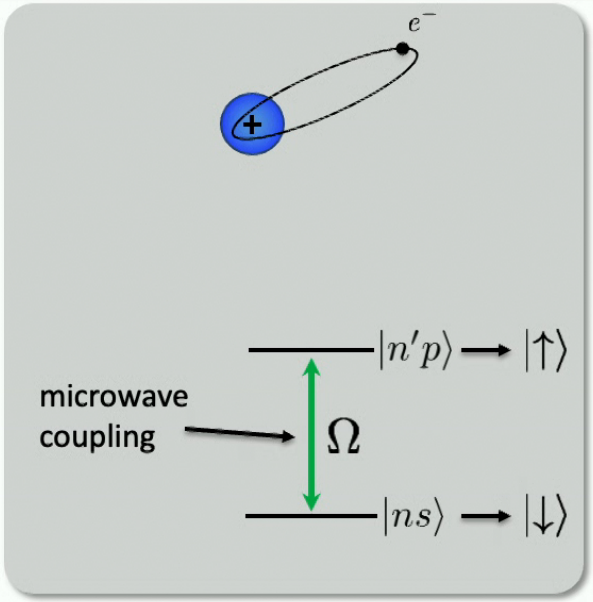
$$J \sim \frac{C_3}{R^3}$$

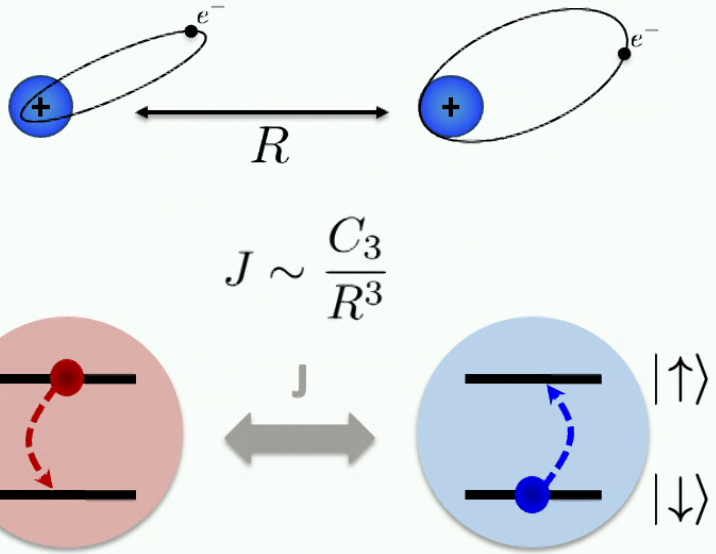


XY model:

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

Resonant dipole-dipole interaction





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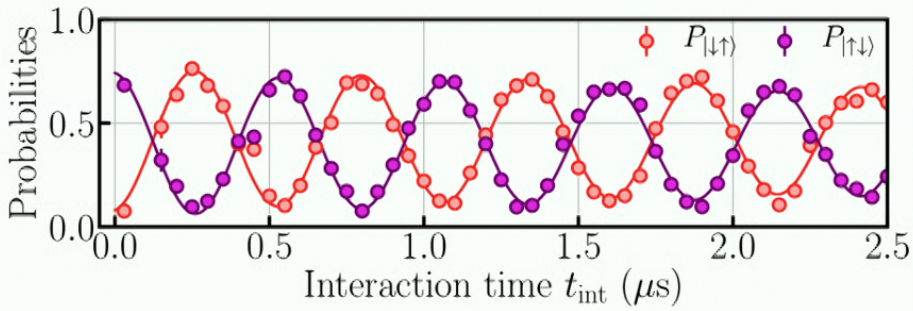
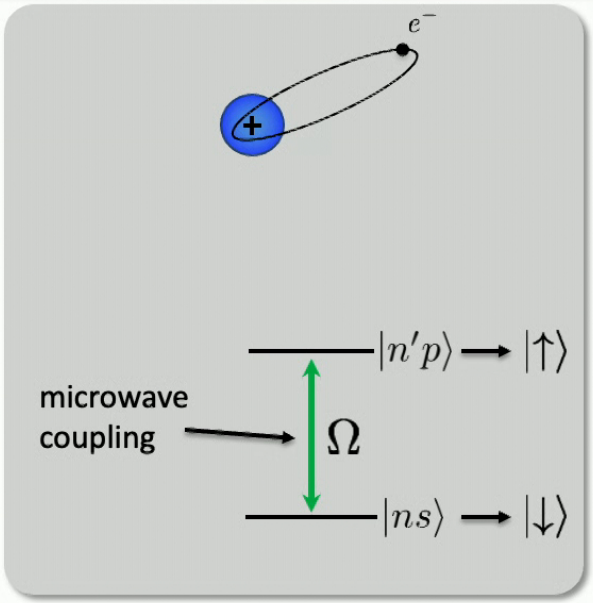
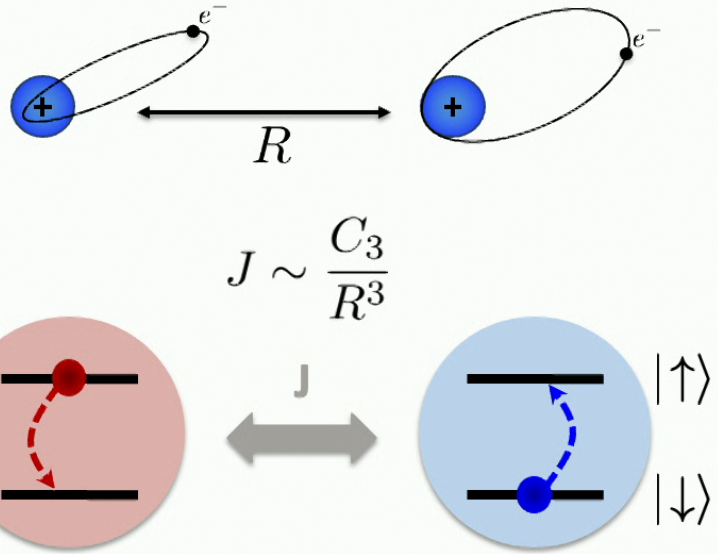


Barredo *et al.*, PRL, **124**, 023201 (2020)

Resonant dipole-dipole interaction





Studies conducted using the resonant dipole-dipole interaction:

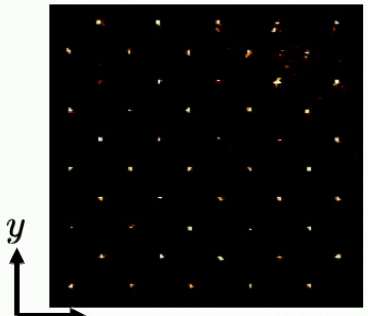
- Preparation of a many-body topological phase — Léséleuc *et al.*, Science, **365**, 775 (2019)
- Implementation of a density-dependent Peierls phase — Lienhard *et al.*, PRX, **10**, 021031 (2020)
- Floquet engineering of XXZ Hamiltonians — Scholl *et al.*, PRX Quantum, **3**, 02303 (2022)

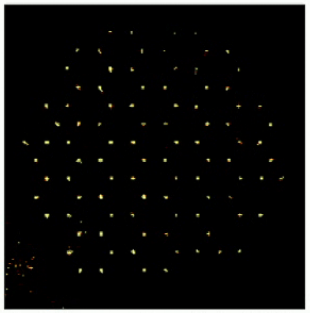
Ising vs XY model

Ising model

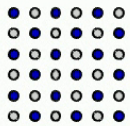
$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

Antiferro $J_{ij} < 0$





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



$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$

$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

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

Ising vs XY model

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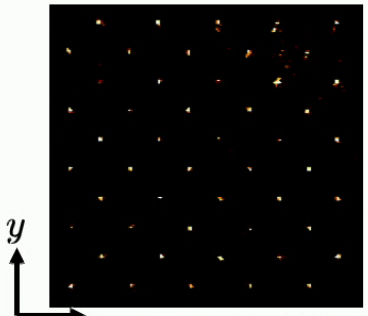
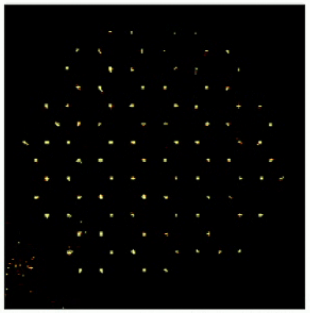
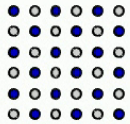




y x Square (1/2) Triangle (1/3)



$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

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XY model

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

Competing order along *x* / along *y*

Ising vs XY model

Ising model

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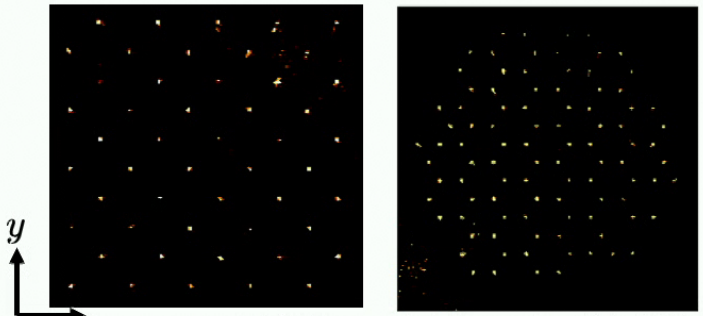
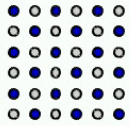
Antiferro $J_{ij} < 0$



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



$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$

$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$

Ground state (1/2, 1/3…) =
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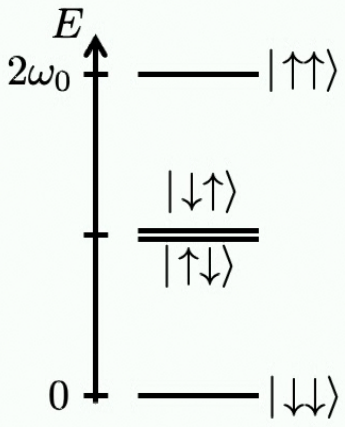
XY model

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

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



Ising vs XY model

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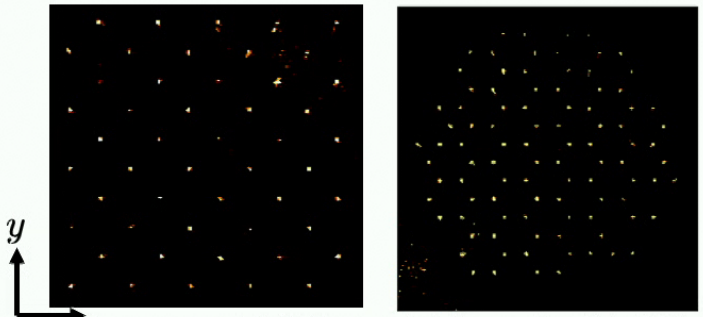
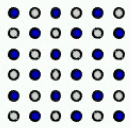


Square (1/2) Triangle (1/3)



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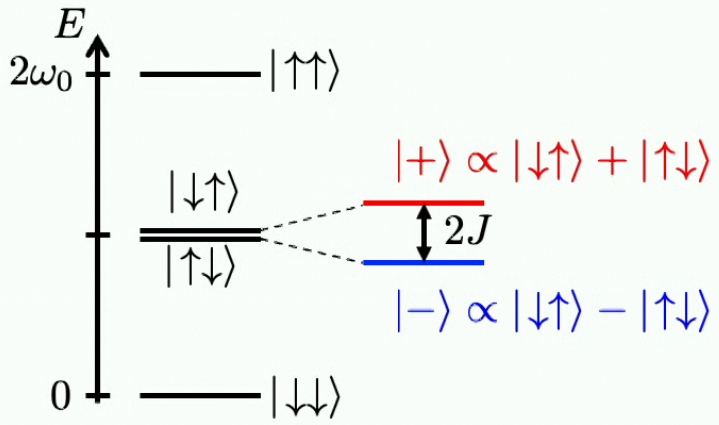
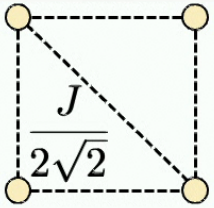
$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

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



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

XY model on a square lattice (1/2 filling)

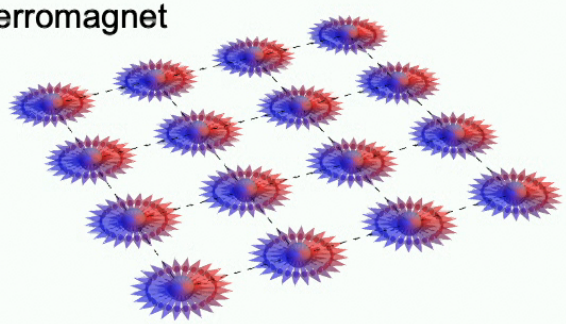


Ansätze wavefunctions

continuous $U(1)$ symmetry

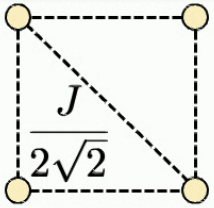
$M^z = \sum_i \sigma_i^z$ conserved

XY ferromagnet



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

XY model on a square lattice (1/2 filling)



Ansätze wavefunctions

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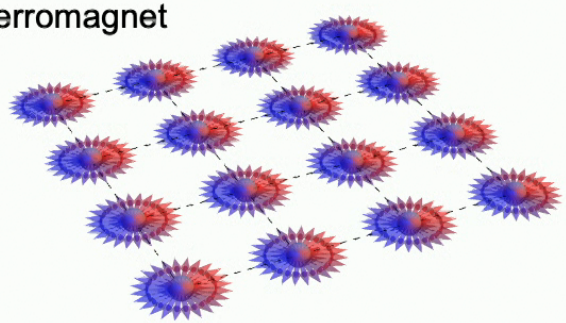
XY ferromagnet



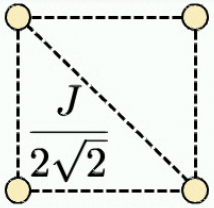
$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi} \mathrm{e}^{-\mathrm{i}\phi \mathrm{S}_z} |\mathrm{FM}\rangle_{\mathrm{X}}$$

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

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

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

XY model on a square lattice (1/2 filling)

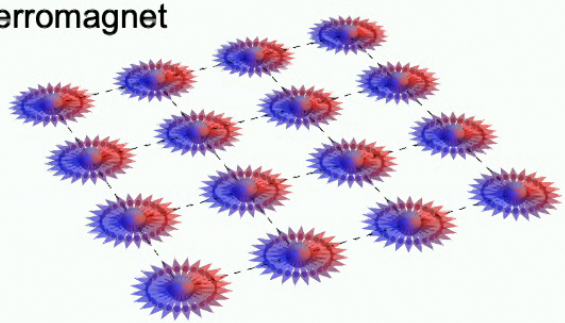


Ansätze wavefunctions

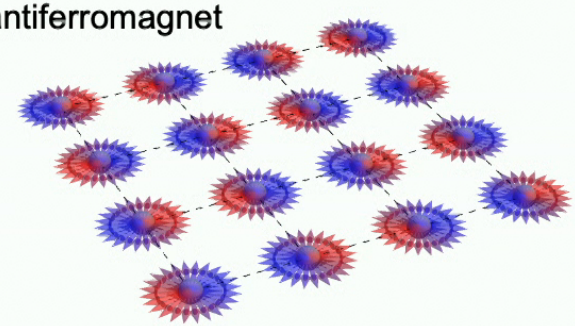
continuous $U(1)$ symmetry

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

XY ferromagnet



XY antiferromagnet



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

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

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

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

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

Experimental preparation of XY ferro- & anti-ferromagnets

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

staggered

Experimental preparation of XY ferro- & anti-ferromagnets

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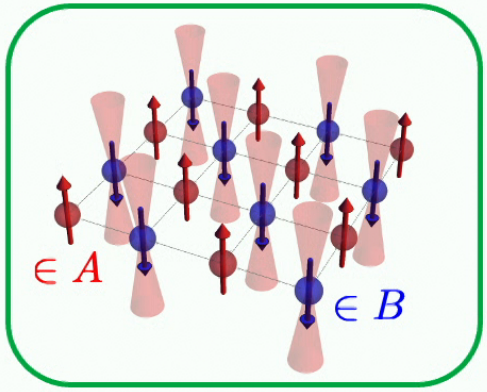
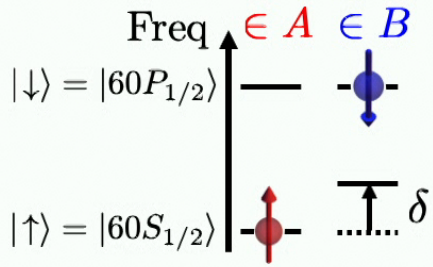
1. Prepare a classical Néel state along *z*: checkerboard pattern



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



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

Experimental preparation of XY ferro- & anti-ferromagnets

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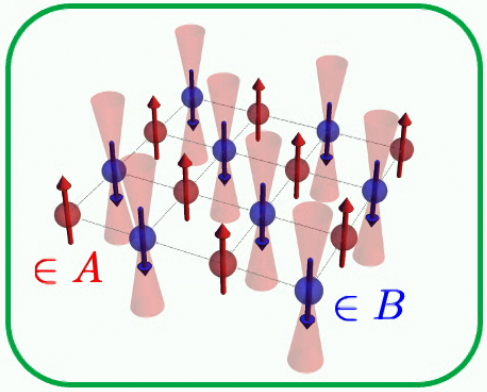
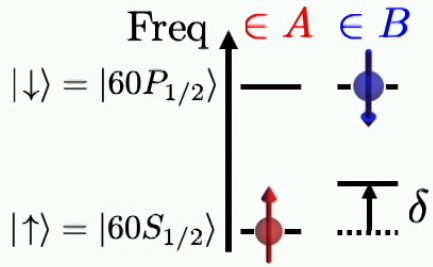
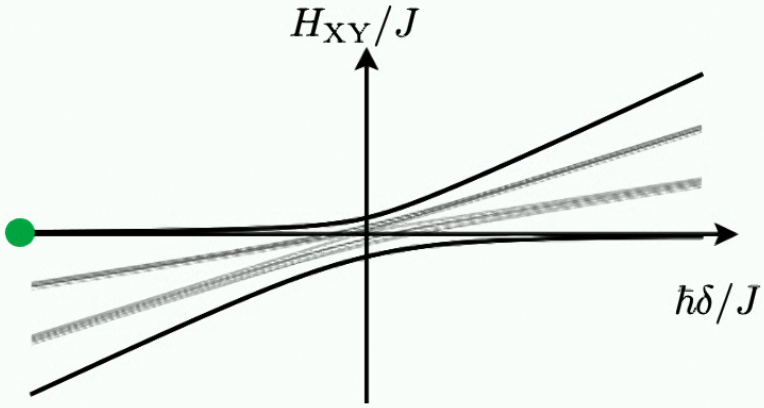
2. Adiabatically decrease δ to "melt" into XY AF





Q. Phase transition



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

Experimental preparation of XY ferro- & anti-ferromagnets

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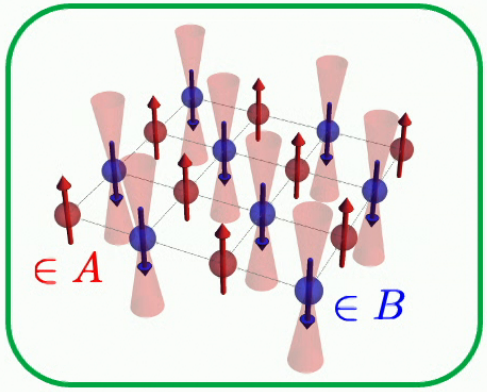
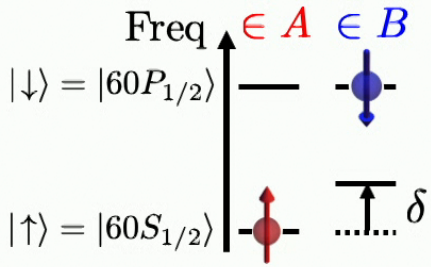
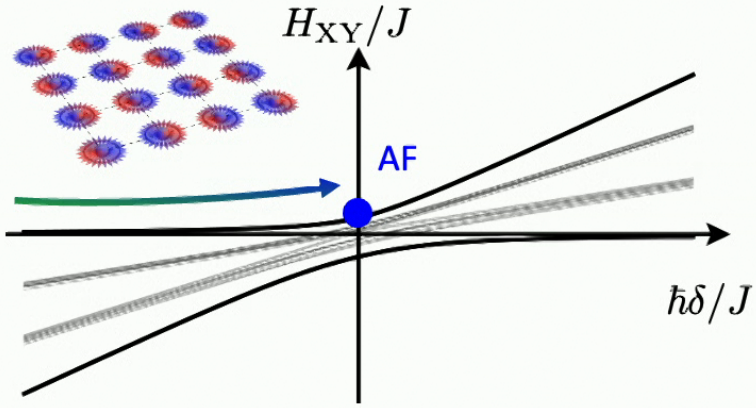




Q. Phase transition



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

Experimental preparation of XY ferro- & anti-ferromagnets

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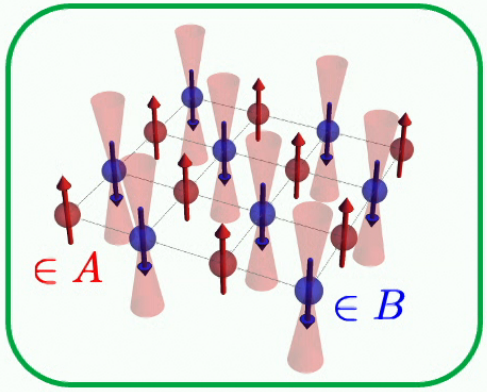
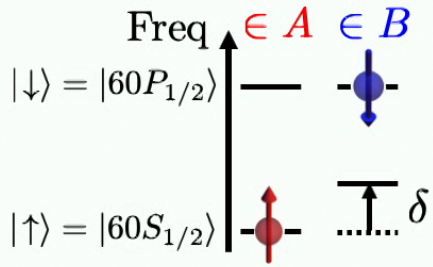
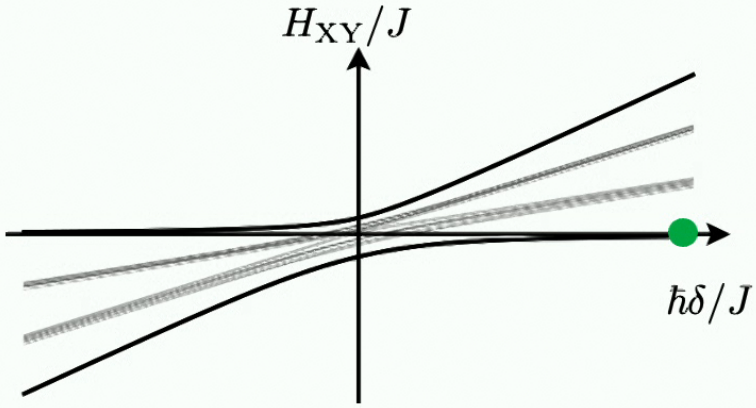
2. Adiabatically decrease δ to "melt" into XY F





Q. Phase transition



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

Experimental preparation of XY ferro- & anti-ferromagnets

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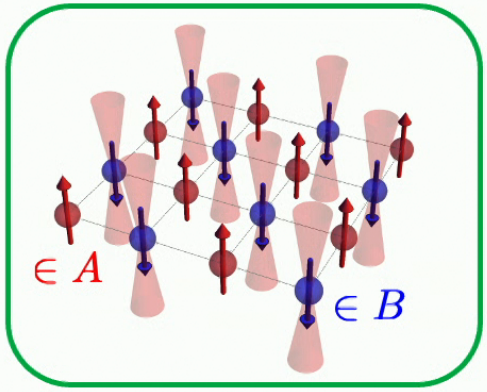
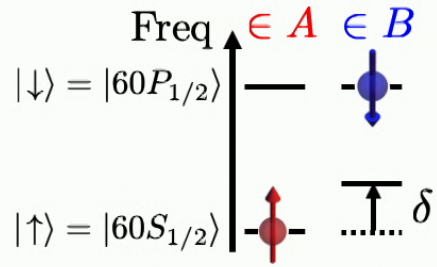
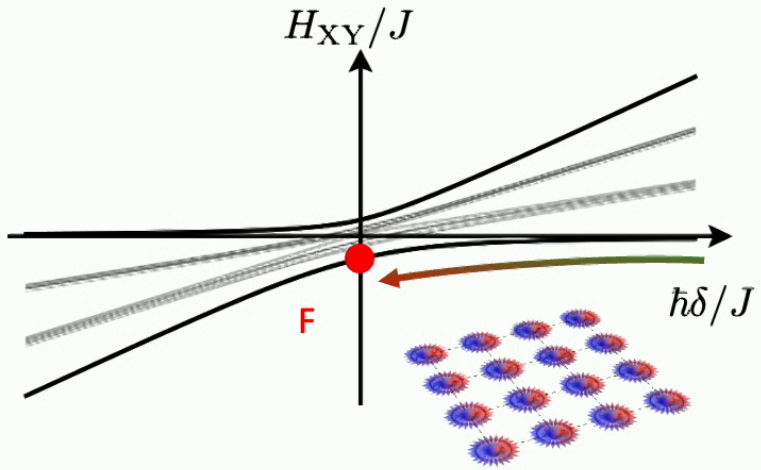




Q. Phase transition



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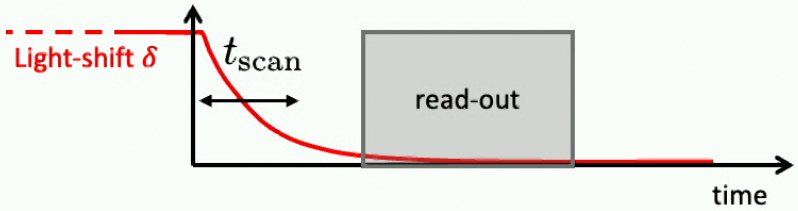
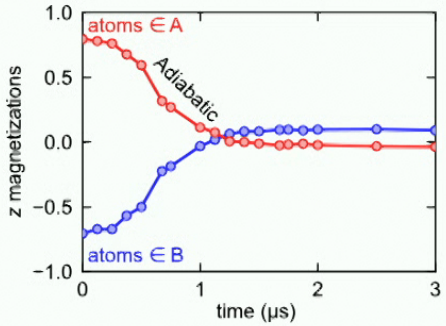
Experimental preparation of XY ferro- & anti-ferromagnets

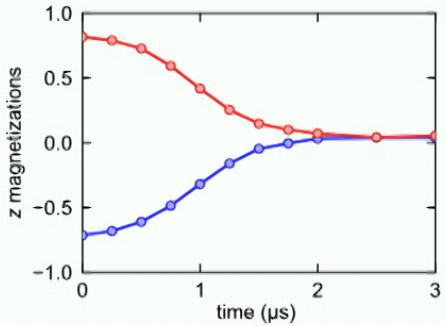


42 atoms

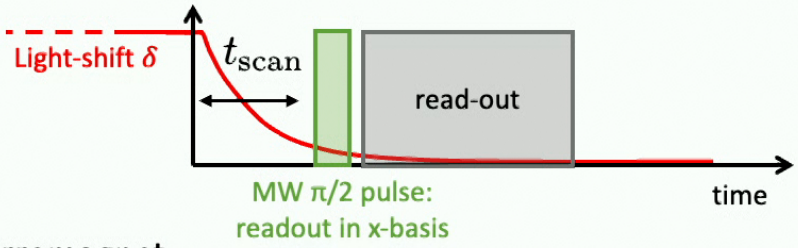
Ferromagnet



Antiferromagnet

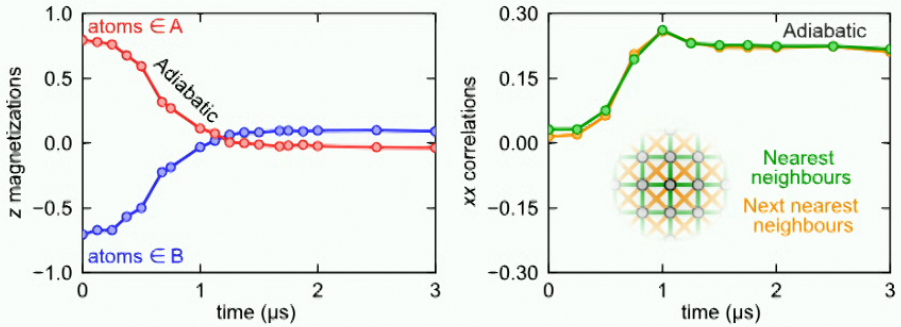


Experimental preparation of XY ferro- & anti-ferromagnets

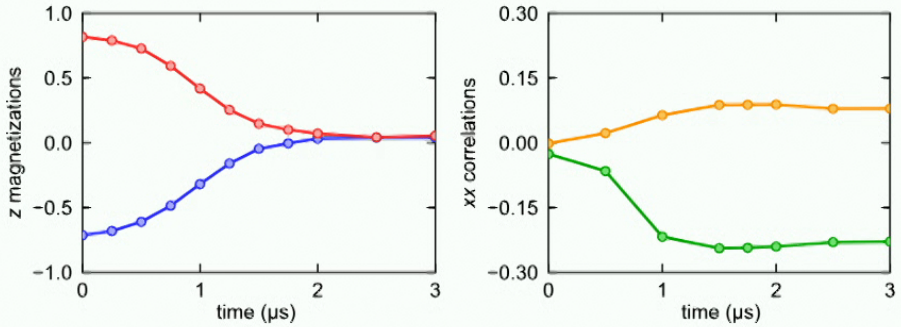


42 atoms

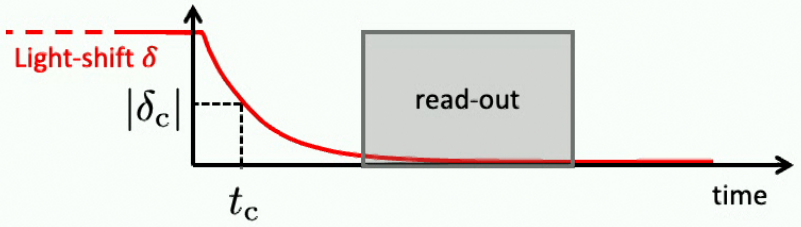
Ferromagnet



Antiferromagnet

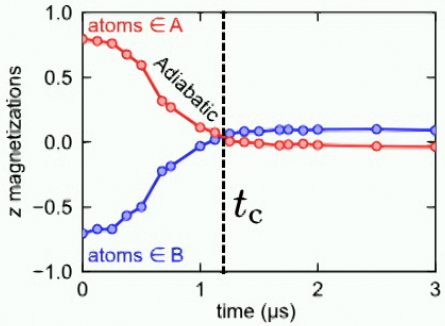


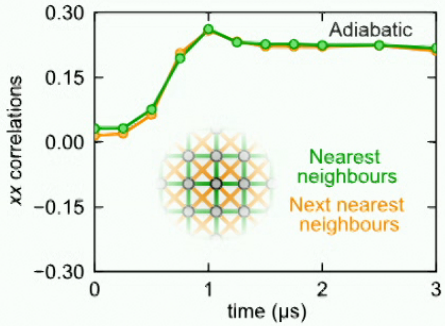
Experimental preparation of XY ferro- & anti-ferromagnets



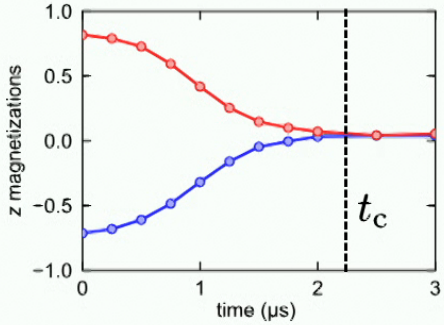
42 atoms

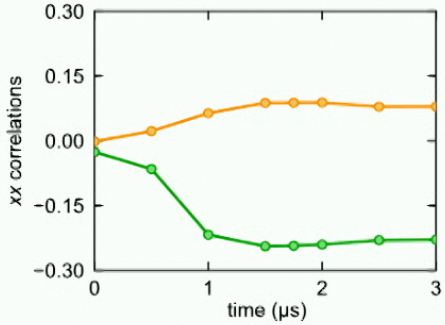
Ferromagnet





Antiferromagnet

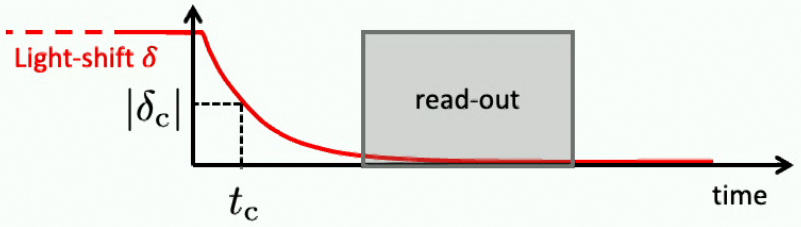




If only NN interactions:

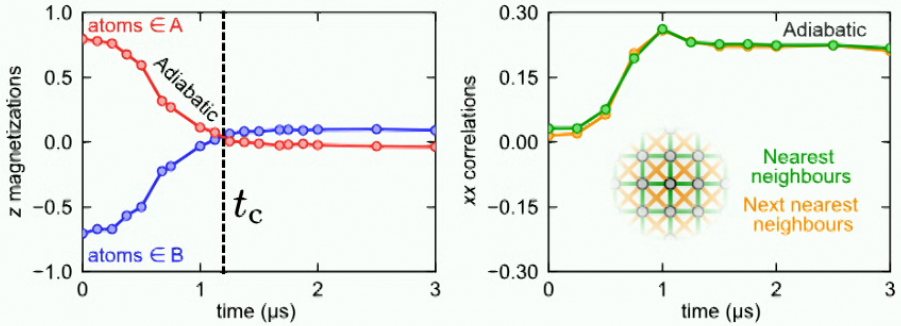
$$|\delta_c^{\mathrm{AFM}}| = |\delta_c^{\mathrm{FM}}|$$

Experimental preparation of XY ferro- & anti-ferromagnets

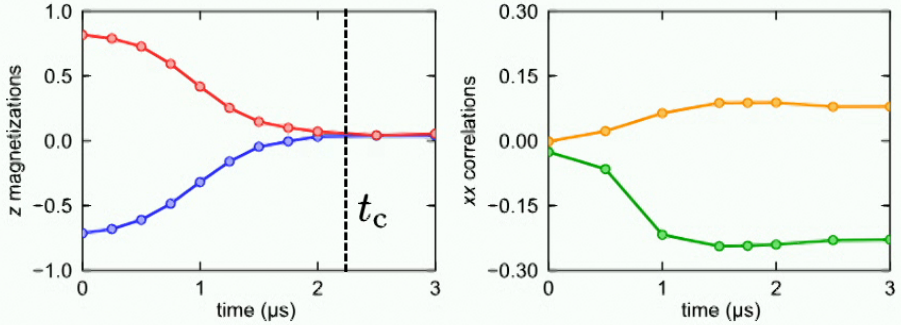


42 atoms

Ferromagnet



Antiferromagnet



If only NN interactions:

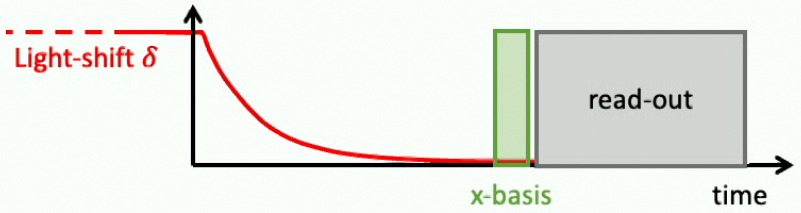
$$|\delta_c^{\mathrm{AFM}}| = |\delta_c^{\mathrm{FM}}|$$

Long-range dipolar interactions:

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

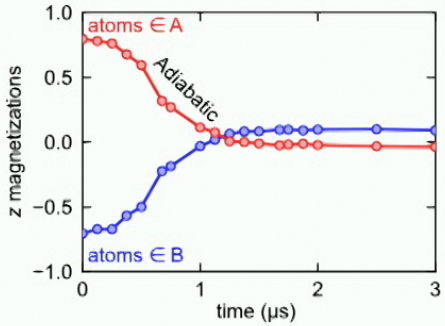
AFM weakly frustrated interactions

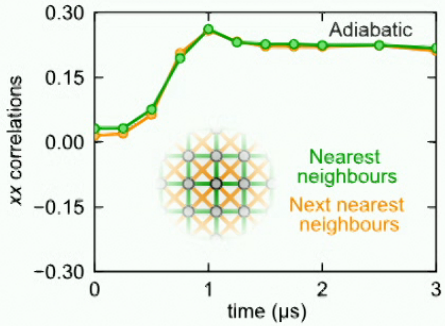
Experimental preparation of XY ferro- & anti-ferromagnets

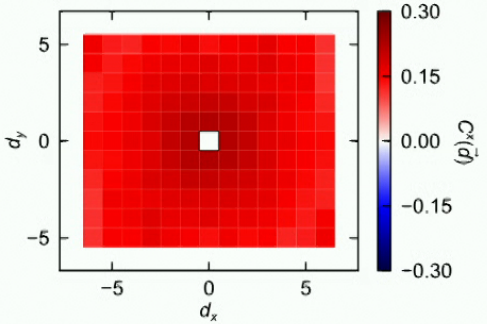


42 atoms

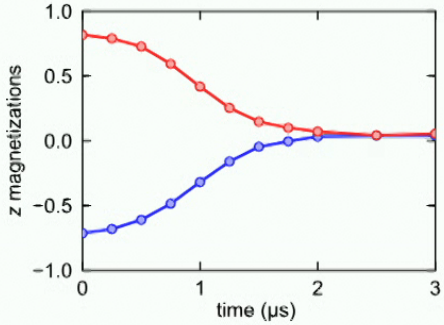
Ferromagnet

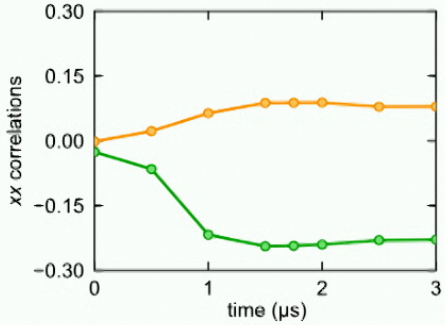


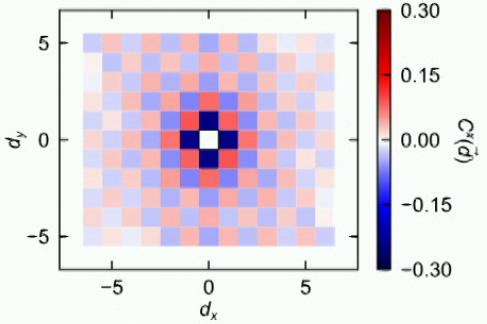




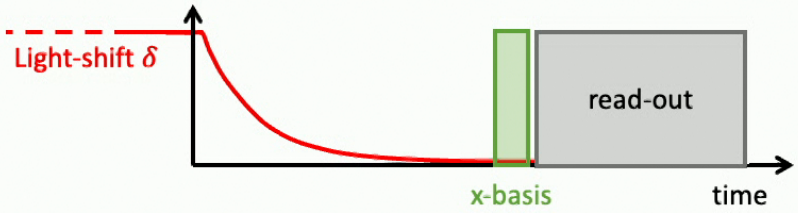
Antiferromagnet







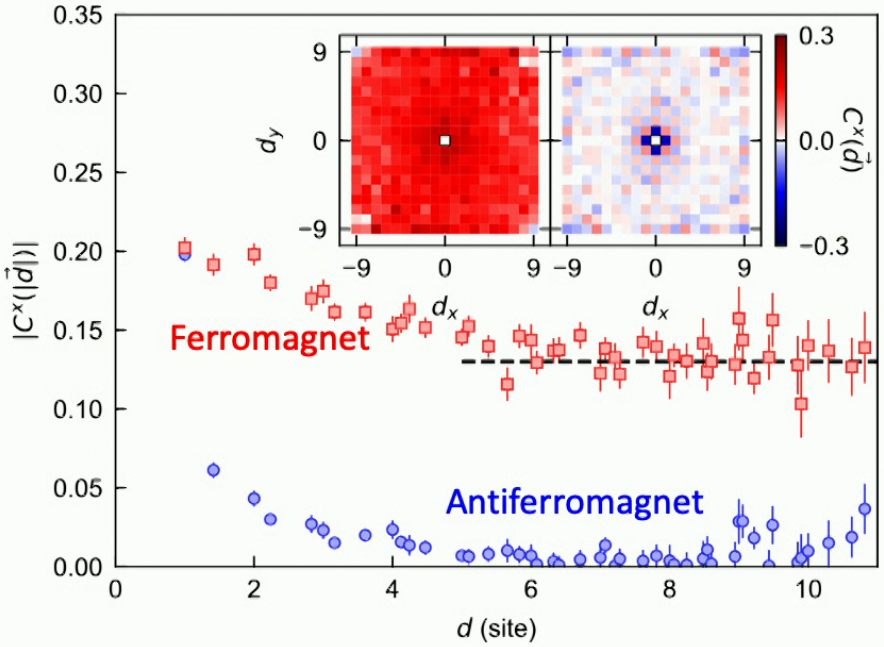
Characterization of XY ferro- & anti-ferromagnets



100 atoms

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

WORK IN PROGRESS



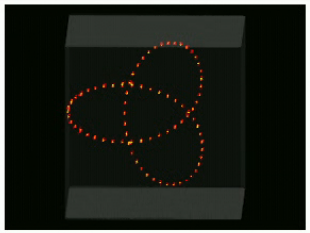
Ferromagnet:
Long-range order

Antiferromagnet:
Correlations decay to 0

Important role of $1/r^3$ interactions

Summary and outlook

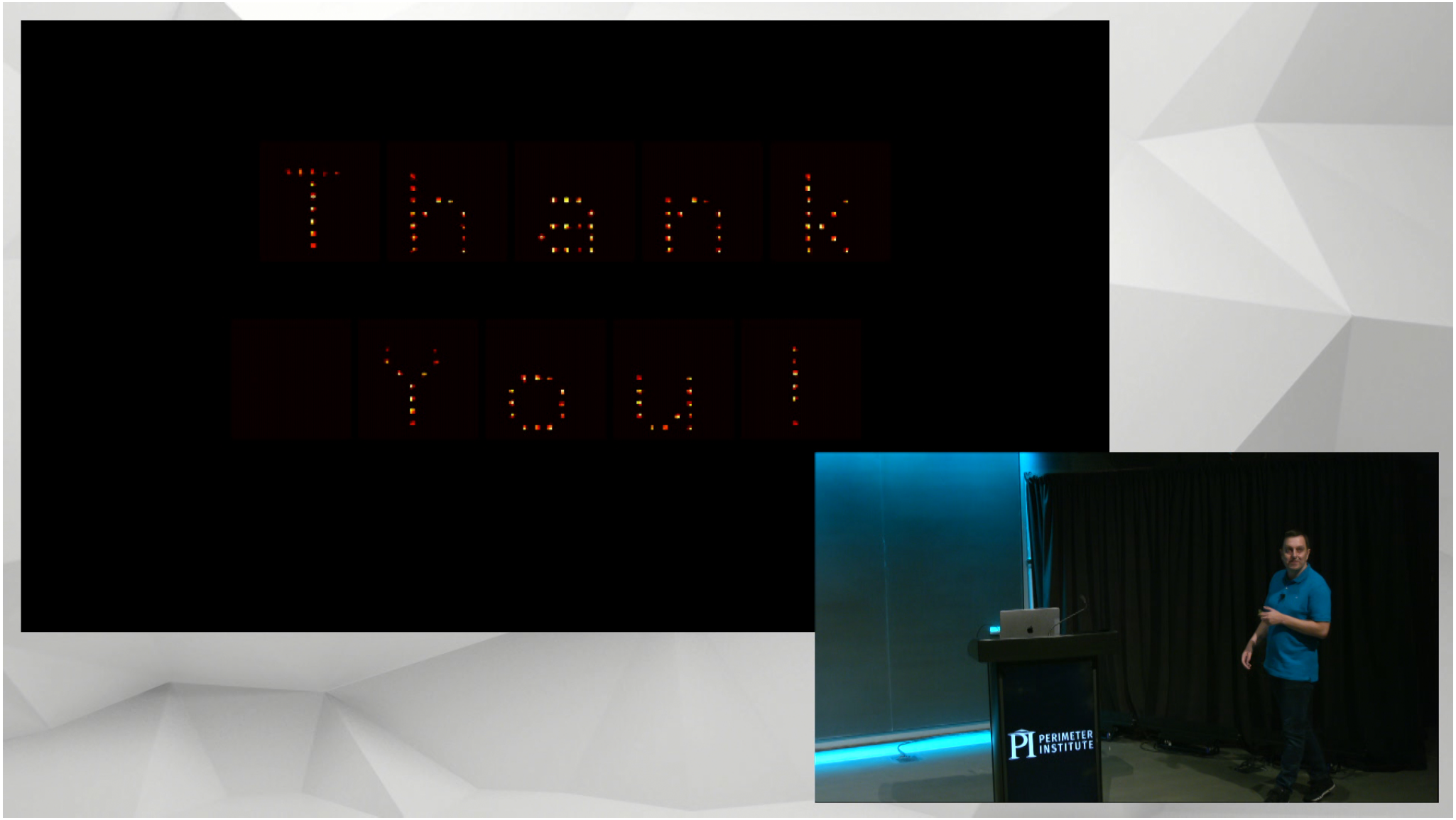
A platform to build synthetic matter



- Single-particle resolution & addressing
- More than **200 atoms**, arbitrary geometries in 1D, 2D and 3D
- Tunable interactions ⇒ implementation of **many-body *H***

Future directions:

- Topological matter in 2D
- Observation of frustrated phases (order by disorder)
- Scalability to 1000 spins realistic in near term (cryogenic setup)


thank
you!
PERIMETER
INSTITUTE