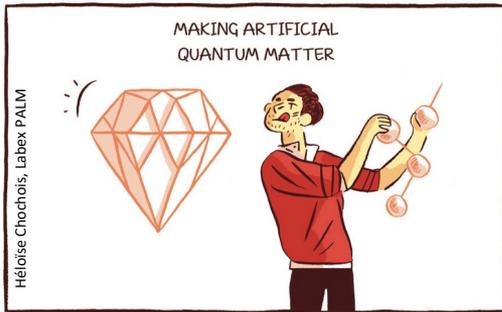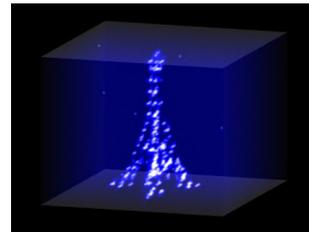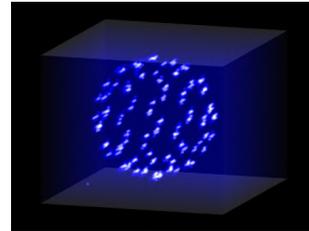# Assembler la matière quantique atome par atome

Antoine Browaeys

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

Collège de France, February 10th, 2026

The program

1. **Many-body problem and quantum simulation**

2. Example of synthetic quantum system: arrays of individual atoms with Rydberg interactions

3. Examples of simulations: spin models and magnetism
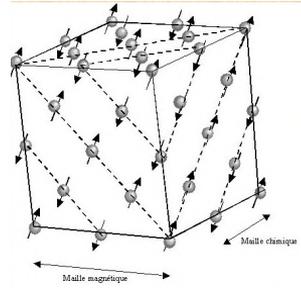
The context: "many-body problem"

Goal: Understand ensembles of ***strongly*** interacting quantum particles
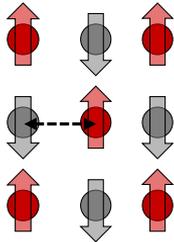
superfluidity superconductivity magnetism neutron star

Questions: phase diagram, excitation, thermalization, dynamics, …

Microscopic description = models

$\hat{H}_{\text{Heis.}} = J \, \vec{S}_i \cdot \vec{S}_j$

$\hat{H}_{\text{Ising}} = J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$

$H_{\text{FH}} = -t \sum_{\langle i,j \rangle, \sigma} c_{i\sigma}^\dagger c_{j\sigma} + U \sum_i n_{i\downarrow} n_{i\uparrow}$

U

Difficulty: exponential scaling of $\dim H \sim d^N$ Record *ab-initio* for s = ½ : $N \lesssim 50$
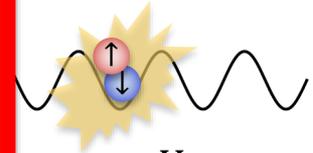
Approximations possible !!

But… poorly controlled or not valid when interactions dominate

= **Strongly correlated** systems
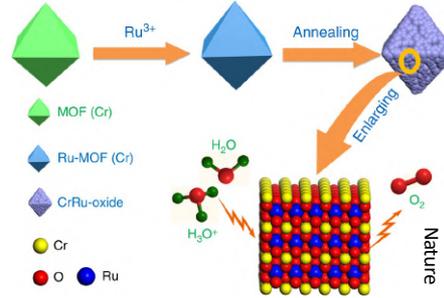
The context: "many-body problem"

Perovskite:
solar panels
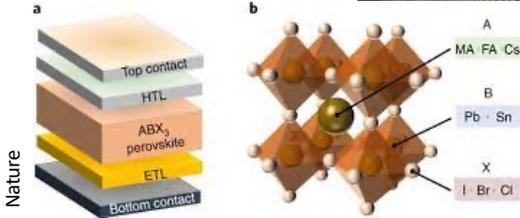
Catalysis

Batteries &
cathode
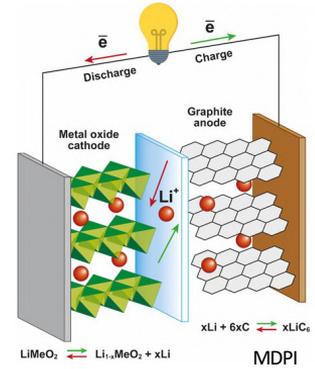
Microscopic description = models
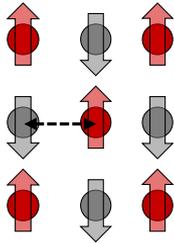
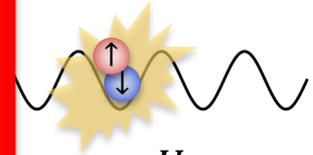$\hat{H}_{\text{Heis.}} = J_{ij} \vec{S}_i \cdot \vec{S}_j$

$\hat{H}_{\text{Ising}} = J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$

$H_{\text{FH}} = -t \sum_{\langle i,j \rangle, \sigma} c_{i\sigma}^{\dagger} c_{j\sigma} + U \sum_i n_{i\downarrow} n_{i\uparrow}$

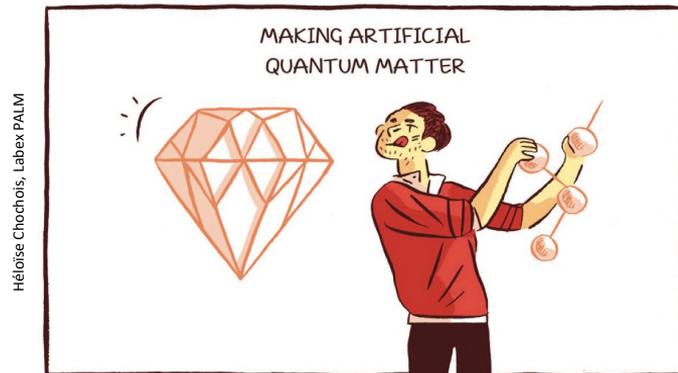**Difficulty**: exponential scaling of $\dim H \sim d$ ... Record *ab-initio* for s = ½ : $N \lesssim 50$

Approximations possible !!

But... poorly controlled or not valid when interactions dominate

= **Strongly correlated** systems

One approach: many-body physics with synthetic quantum systems

R.P. Feynman

Int. J. Theo. Phys. **21** (1982)

Héloïse Chochois, Labex PALM

MAKING ARTIFICIAL QUANTUM MATTER

Quantum simulation

Georgescu, Rev. Mod. Phys. (2014)

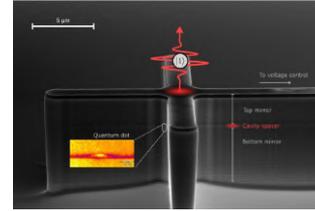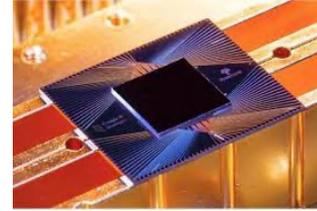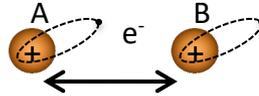**Well-controlled** quantum systems implementing many-body Hamiltonians
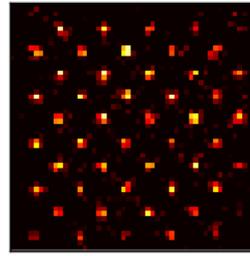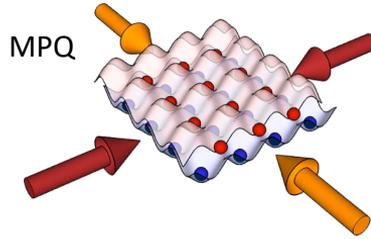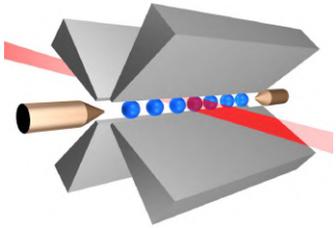= quantum simulator

Larger tunability than "real" systems (geometry, interactions...)

+

New types of probe & methods (e.g. out-of-equilibrium)

A new way to look at many-body using quantum information concepts
(entanglement...)

Engineering with individual quantum systems (examples)

Trapped ions

Atoms in optical lattices

Atoms in tweezer arrays

Supercond. Circuits

Photons

Engineering with individual quantum systems (examples)

Trapped ions **Atoms in optical lattices** **Atoms in tweezer arrays** **Supercond. Circuits** **Photons**
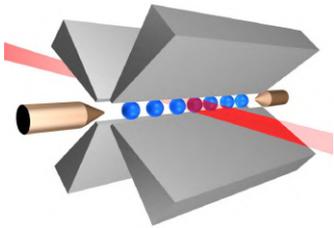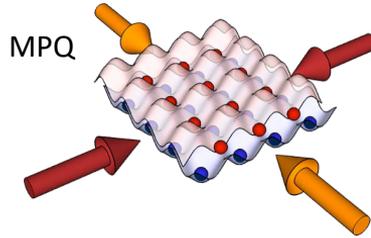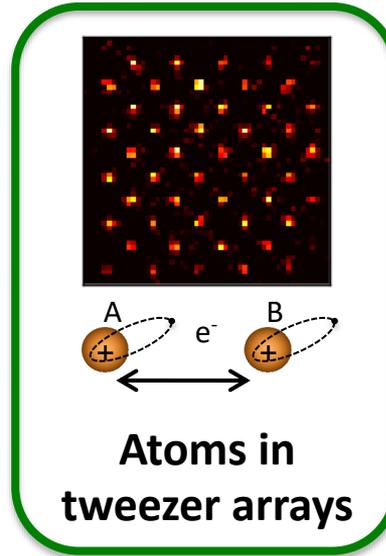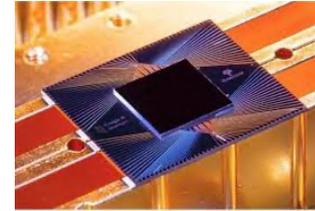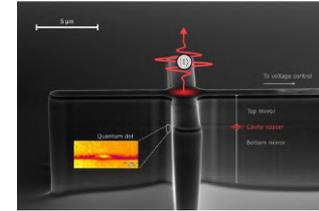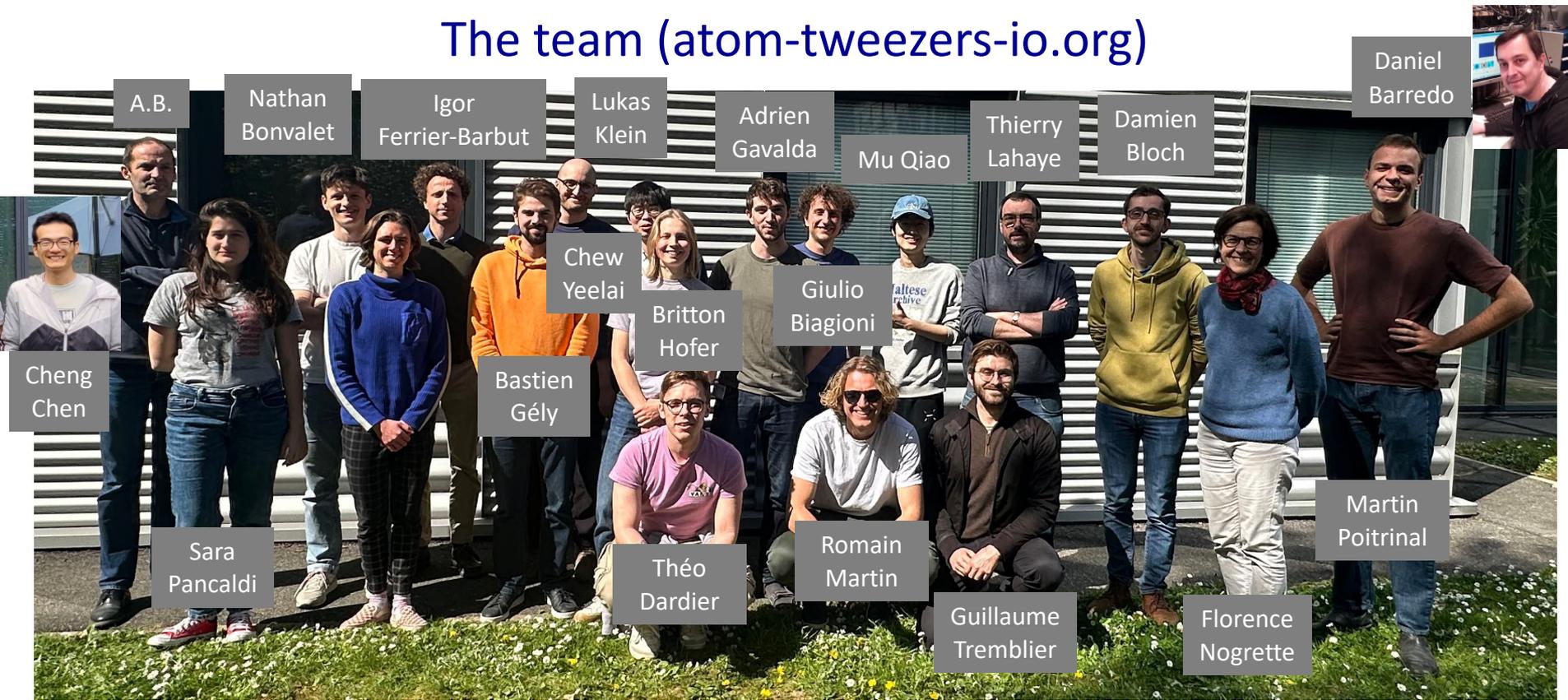
Scalable: beyond 1000 particles

Addressability: local manipulations and measurement

$$\langle \sigma_i^\alpha \rangle, \langle \sigma_i^\alpha \sigma_j^\beta \rangle, \dots$$

Programmable: controlled geometry, interactions...

# The team (atom-tweezers-io.org)

Theory: E. Demler (ETHZ), A. Bohrdt, F. Grusdt, N. Yao (Harvard), A. Laüchli (Lausanne), T. Roscilde (Lyon), H-P Büchler (Stuttgart), A. Asenjo-Garcia (NY), D. Chang (ICFO), A.-M. Rey (JILA), F. Robicheaux (Perdew)

Our experiments: many-body physics with synthetic quantum systems

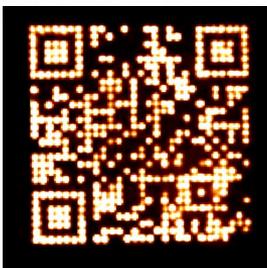## Tunable arrays of individual Rydberg atoms

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

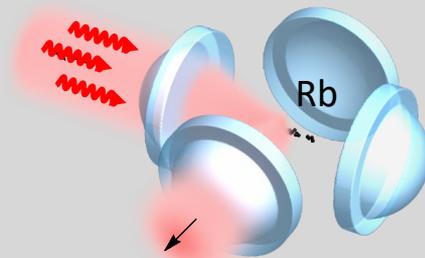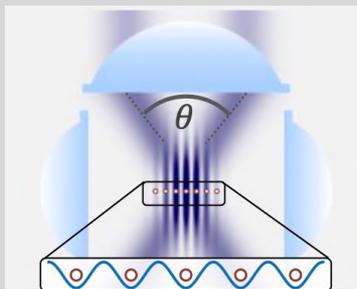## Light-induced interactions in atomic ensembles

Rb
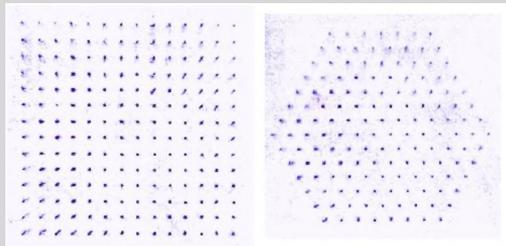
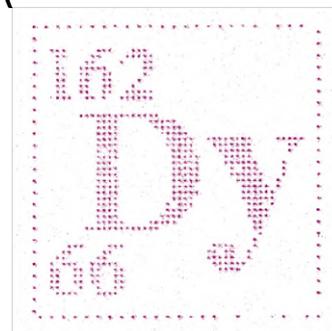$r \sim \lambda$

Light-induced interactions in arrays of Dy atoms

θ

$r \sim \lambda$

I. Ferrier-Barbut

PRL 2023, PRA 2024, 2025
PRXQ 2025

INSTITUT d'OPTIQUE GRADUATE SCHOOL
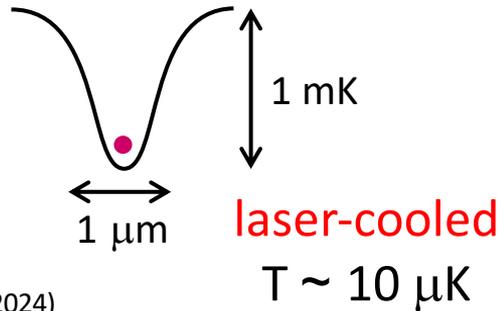
The program

1. Many-body problem and quantum simulation

2. Example of synthetic quantum system: arrays of individual atoms with Rydberg interactions

3. Examples of simulations: spin models and magnetism

Assembled arrays of *individual* ^{87}Rb atoms in optical tweezers

Diffraction (spatial light modulator)

Laser

Camera

1 mK

1 μm

laser-cooled

T ~ 10 μK
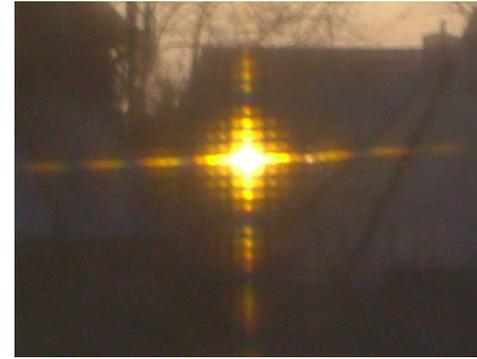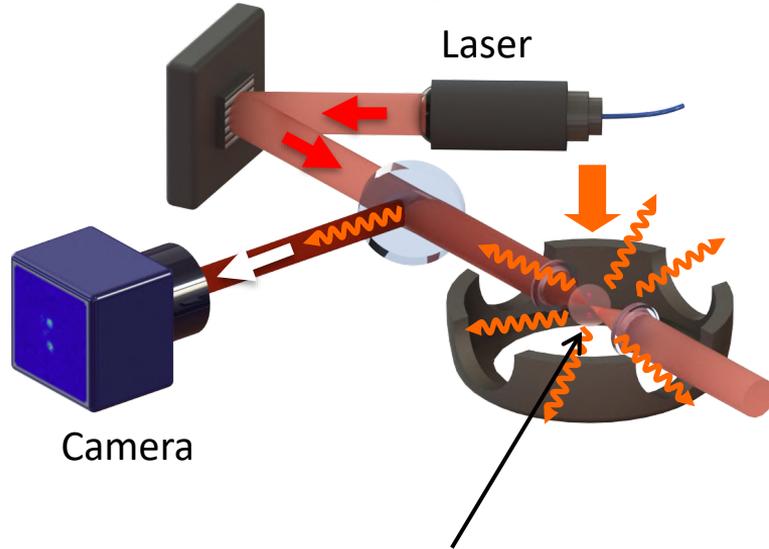
Grangier (2001)
Sortais (2007)
Bergamini (2004)
Nogrette (2014)
Barredo (2016-18)
Schymik (2021-22)
Pichard, PR Applied (2024)

Assembled arrays of *individual* ^{87}Rb atoms in optical tweezers

Diffraction (spatial light modulator)
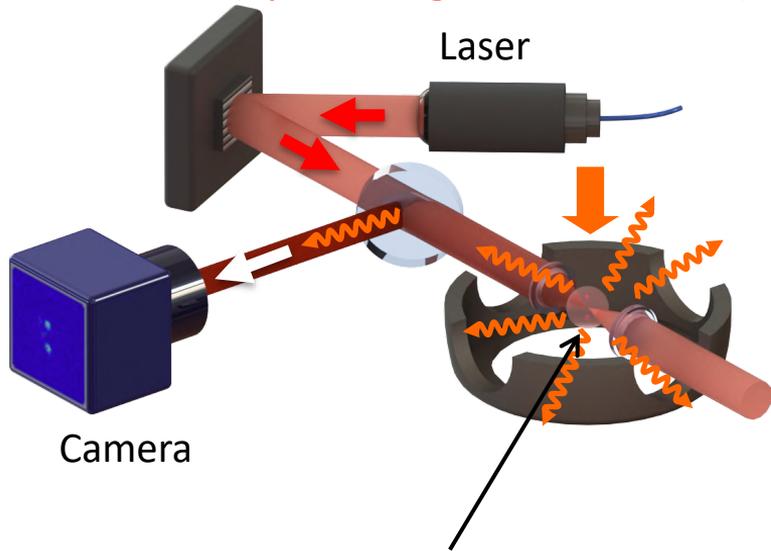
Laser

Camera

Fluorescence:
single shot!!

1 mK

1 μm

Grangier (2001)
Sortais (2007)
Bergamini (2004)
Nogrette (2014)
Barredo (2016-18)
Schymik (2021-22)
Pichard, PR Applied (2024)

1d

100 μm

2d

3d   (averaged)

90 μm

110 μm   120 μm

Assembled arrays of *individual* ^{87}Rb atoms in optical tweezers

Diffraction (spatial light modulator)
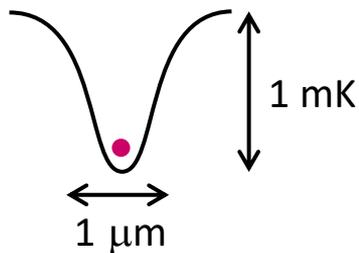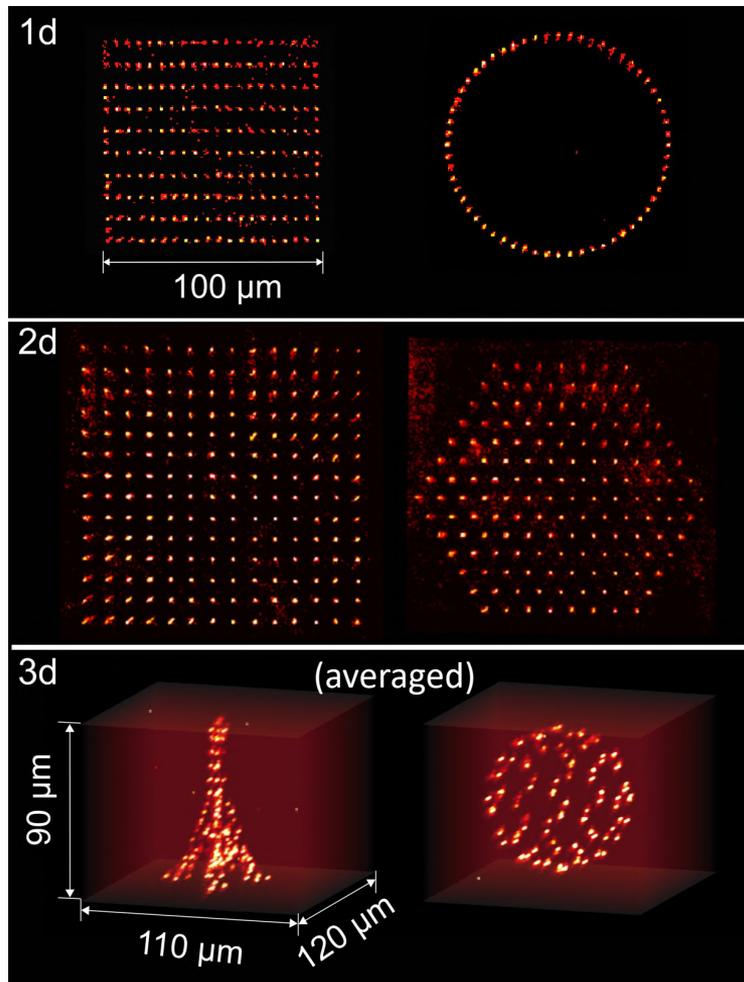
Laser

Camera

Pasqal

~ 1024 atoms
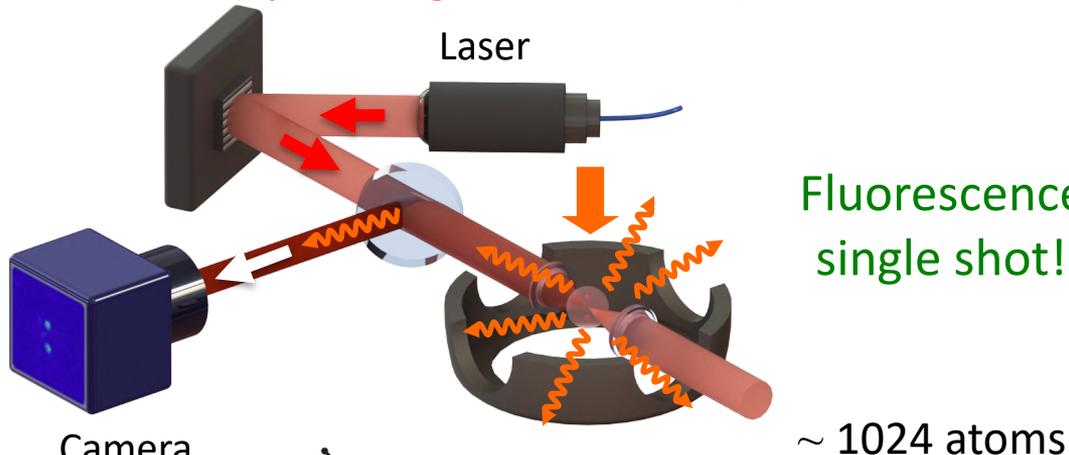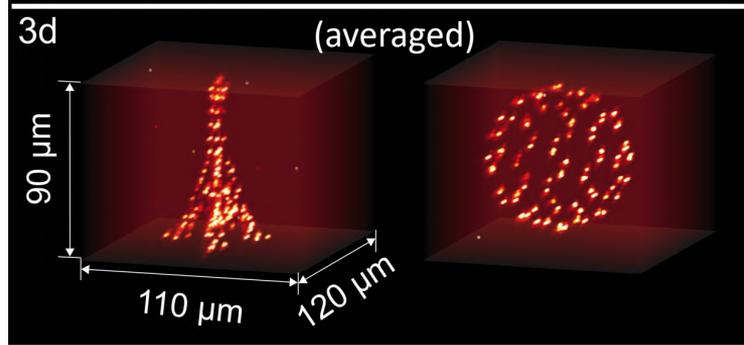
Fluorescence: single shot!!

Grangier (2001)
Sortais (2007)
Bergamini (2004)
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Barredo (2016-18)
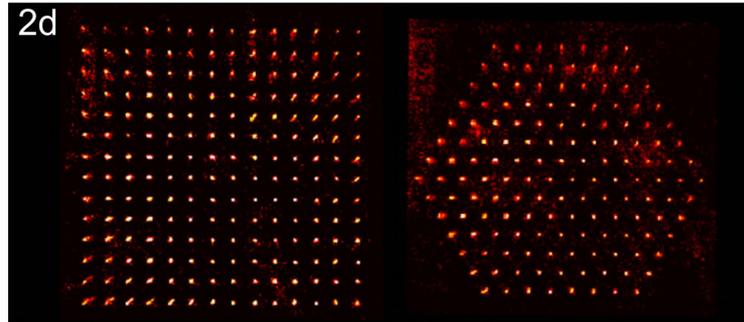Schymik (2021-22)
Pichard, PR Applied (2024)

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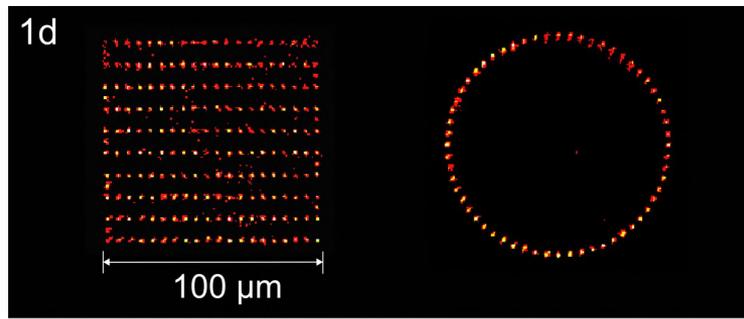
Single-atom trapping zoo (2026)
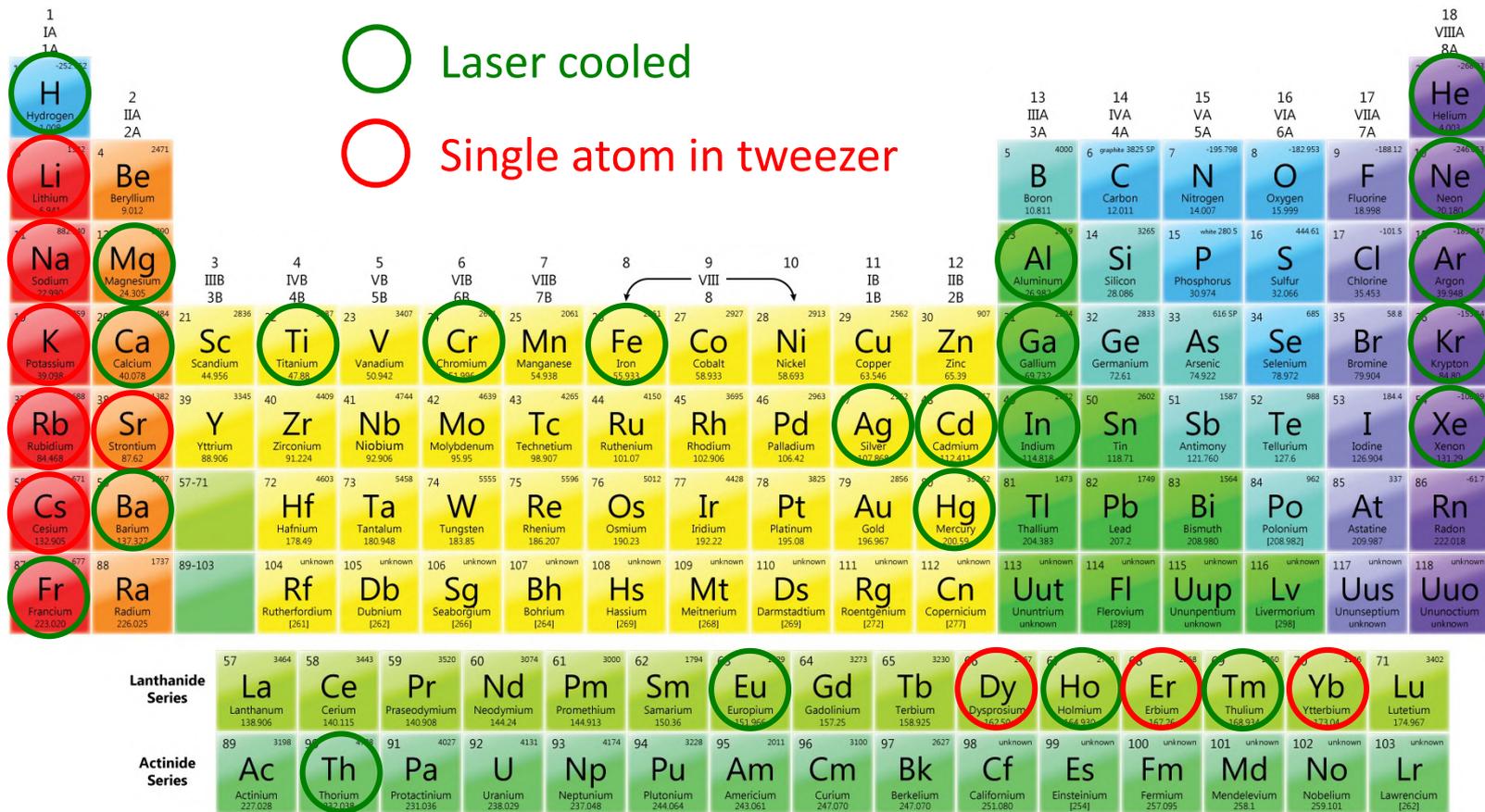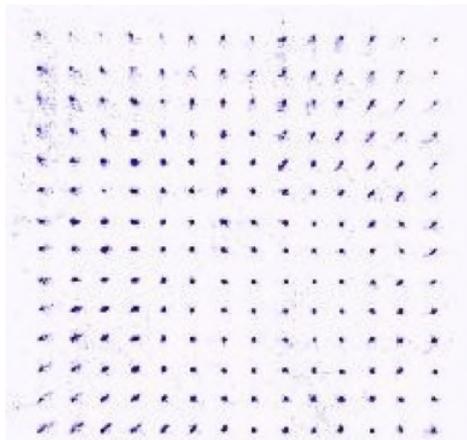
And now... the interactions

Arrays of ^{87}Rb atoms

5 µm

Rydberg atoms

J. Rydberg
1854-1919

continuum

Rydberg states $|n, l\rangle$

$n \gg 1$

~ 100 nm

e⁻

+

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

And now... the interactions

Rydberg atoms

J. Rydberg
1854-1919
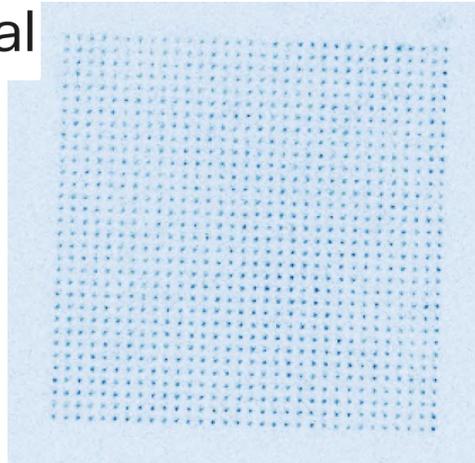
continuum

Rydberg
states $|n, l\rangle$

$n \gg 1$

~ 100 nm

e⁻

+

Energy

classical diameter $4a_0(n\text{-}\ddot{a}_0)^2$ [ì m]

leukocyte

throm-
bocyte

red blood
cells

typical
bacteria

bacteriophage

helicobacter
pylori

bluetongue virus

viruses

principal quantum number n

J. Balewski, PhD thesis

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

And now… the interactions

Arrays of ^{87}Rb atoms

5 μm

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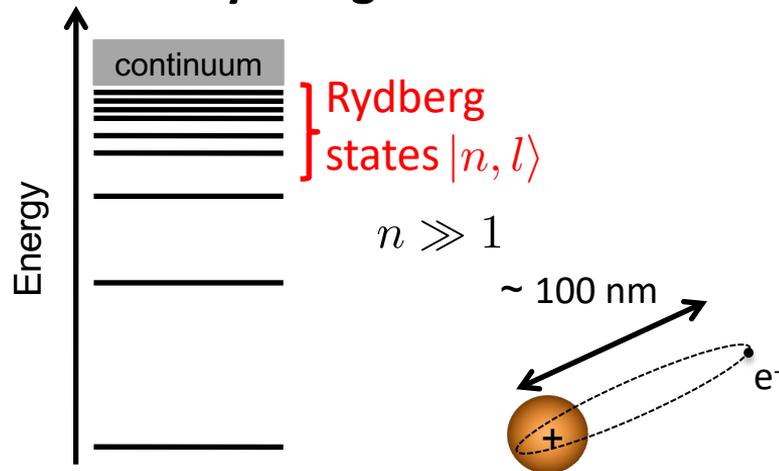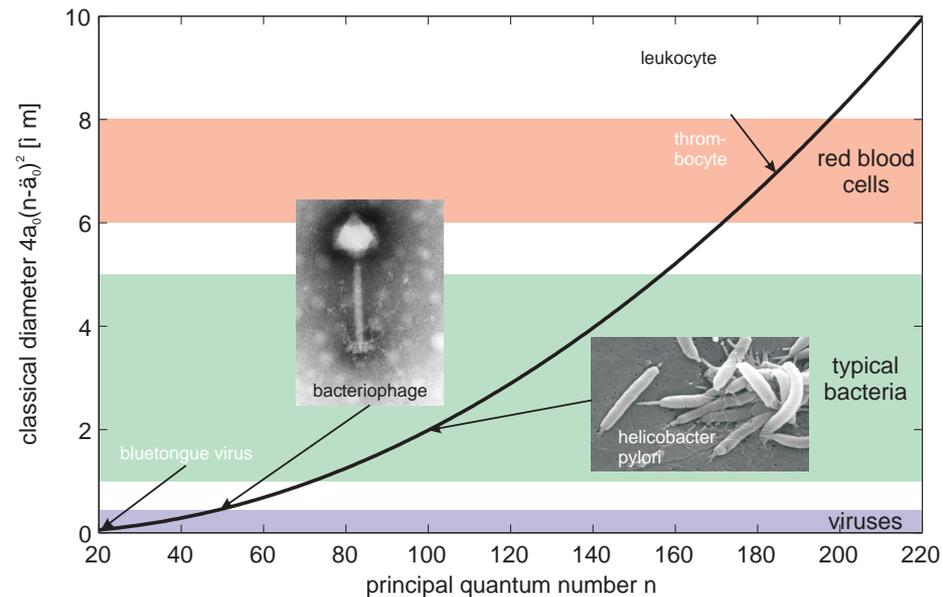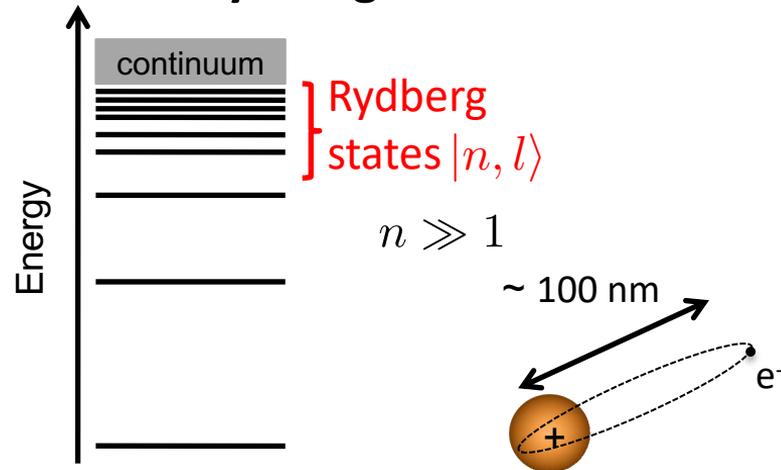
Lifetime $\propto n^3$ > 100 μs

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

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

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

$\Rightarrow$ **timescales < μsec**
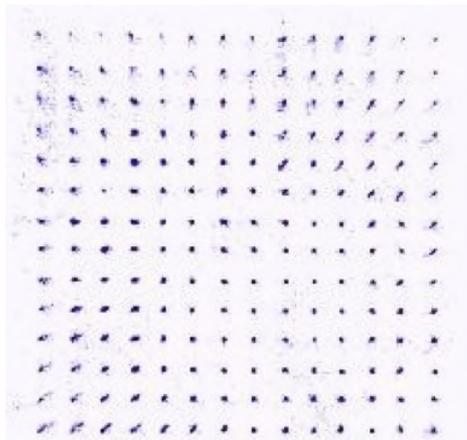
Lukin, Zoller… 2000
Saffman, RMP 2010
Browaeys, Nat Phys 2020

And now... the interactions

Arrays of ^{87}Rb atoms

5 μm

Rydberg atoms
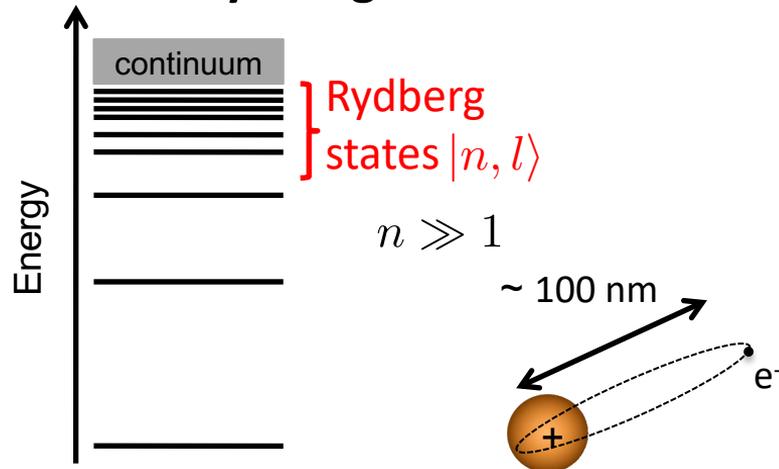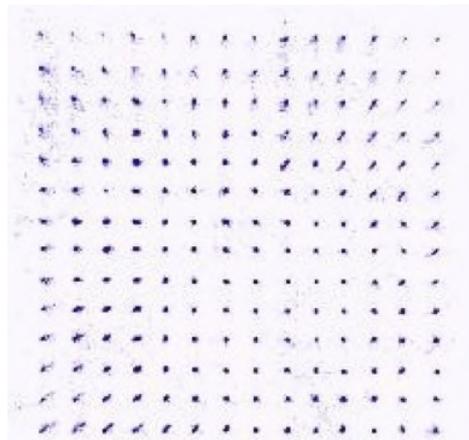
J. Rydberg
1854-1919

continuum

$\left.\begin{array}{l}\end{array}\right\}$ Rydberg states $|n, l\rangle$

$n \gg 1$

~ 100 nm

e⁻

Energy
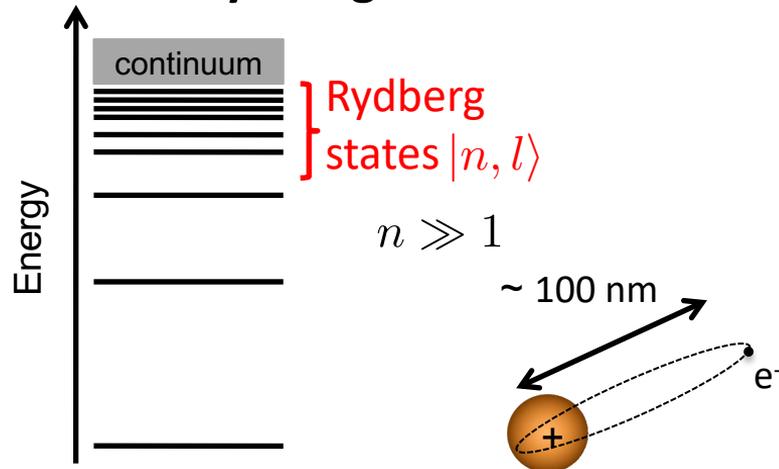
1st demonstrations of controlled Rydberg interactions between two atoms
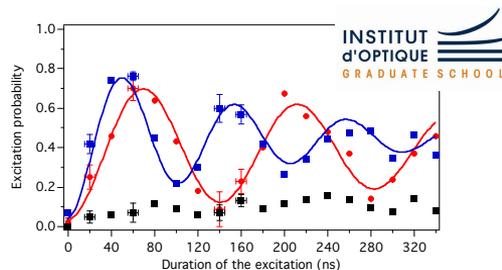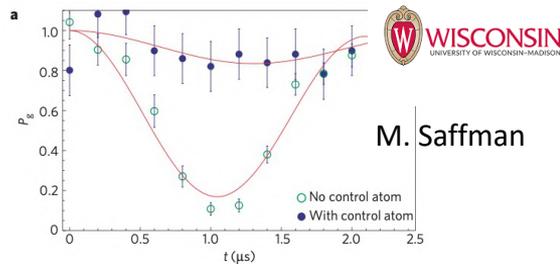
INSTITUT
d'OPTIQUE
GRADUATE SCHOOL

Nat. Phys. 2009

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

M. Saffman

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

18

And now… the interactions

Arrays of ^{87}Rb atoms

Rydberg atoms

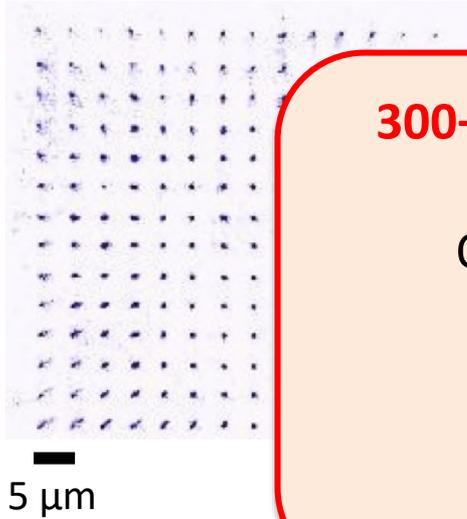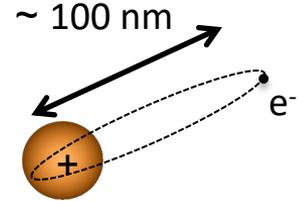continuum

Rydberg states $|n, l\rangle$

$n \gg 1$

~ 100 nm

e⁻

+

5 μm

300+ in construction worldwide…

Optical clocks & metrology
Quantum simulation
Quantum computing
Light-matter interface

…

1ˢᵗ demonstrations of ~~entanglement~~ **two atoms**
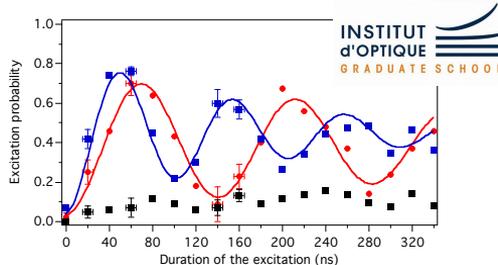
Excitation probability

Duration of the excitation (ns)

INSTITUT d'OPTIQUE
GRADUATE SCHOOL

Nat. Phys. 2009

P_{gg}

t (μs)

No control atom
With control atom

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

M. Saffman

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

19
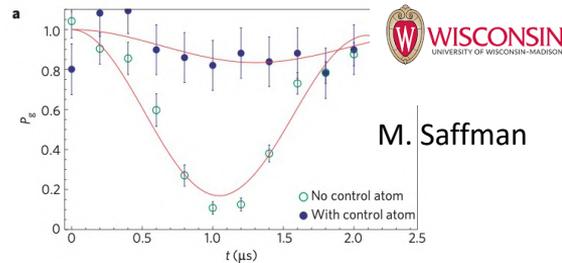
The Pasqal adventure: towards industry grade simulators (2019)
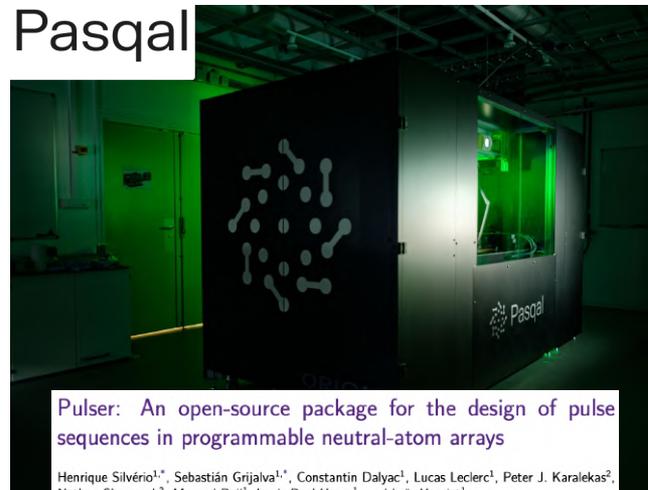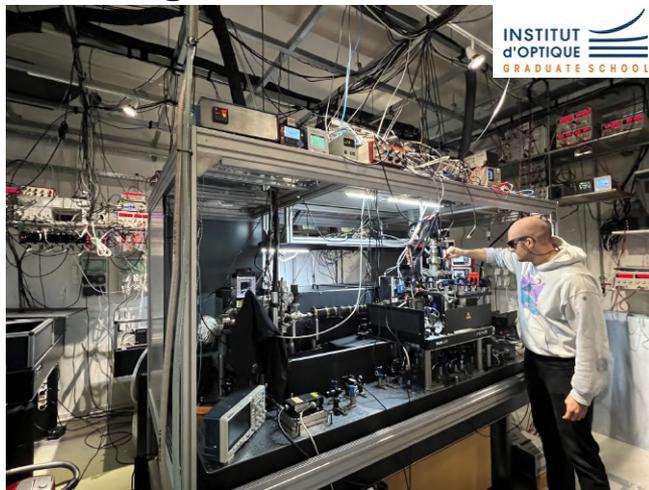
Engineering

Quantum 2022

Explore applications

Quantum Feature Maps for Graph Machine Learning on a Neutral Atom Quantum Processor

Boris Albrecht,[1,*] Constantin Dalyac,[1,2,*] Lucas Leclerc,[1,3,*] Luis Ortiz-Gutiérrez,[1,*] Slimane Thabet,[1,2,*] Mauro D'Arcangelo,[1] Vincent E. Elfving,[1] Lucas Lassablière,[1] Henrique Silvério,[1] Bruno Ximenez,[1] Louis-Paul Henry,[1] Adrien Signoles,[1] and Loïc Henriet[1,†]

Phys. Rev. A 2023

Financial Risk Management on a Neutral Atom Quantum Processor

Lucas Leclerc,[1,2,*] Luis Ortiz-Gutiérrez,[1] Sebastián Grijalva,[1] Boris Albrecht,[1] Julia R. K. Cline,[1] Vincent E. Elfving,[1] Adrien Signoles,[1] and Loïc Henriet[1†]

Phys. Rev. Research 2023

Leveraging Analog Quantum Computing with Neutral Atoms for Solvent Configuration Prediction in Drug Discovery

Mauro D'Arcangelo[1,+], Daniele Loco[2,+], Fresnel team[1], Nicolaï Gouraud[2,3,4], Stanislas Angebault[2], Jules Sueiro[2], Pierre Monmarché[3], Jérôme Forêt[2], Louis-Paul Henry[1], Loïc Henriet[1,*], and Jean-Philip Piquemal[2,4,*]

Phys. Rev. Research 2024

Dalyac et al. *EPJ Quantum Technology* (2021) 8:12
https://doi.org/10.1140/epjqt/s40507-021-00100-3

EPJ Quantum Technology
a SpringerOpen Journal

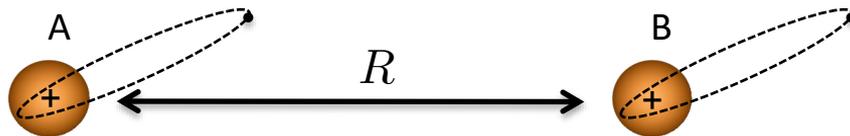**RESEARCH**   **Open Access**

Qualifying quantum approaches for hard industrial optimization problems. A case study in the field of smart-charging of electric vehicles
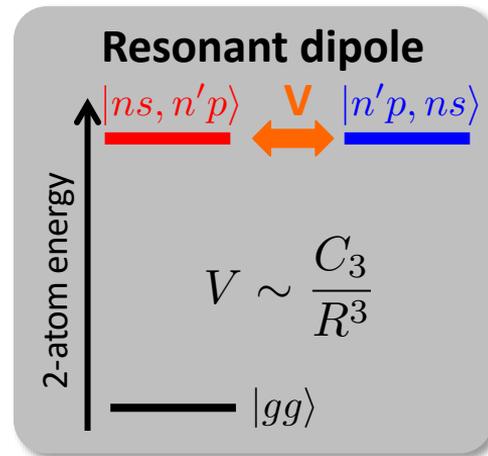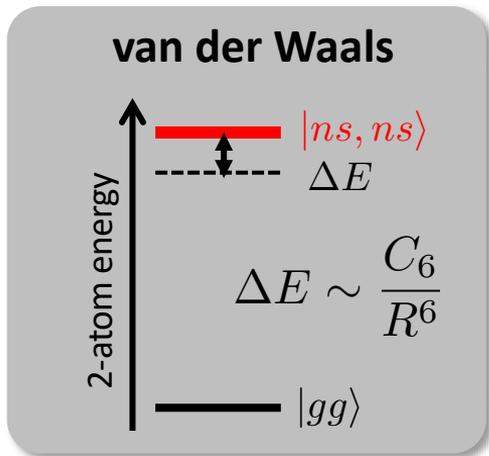
The program

1. Many-body problem and quantum simulation

2. Example of synthetic quantum system: arrays of individual atoms with Rydberg interactions

3. Examples of simulations: spin models and magnetism

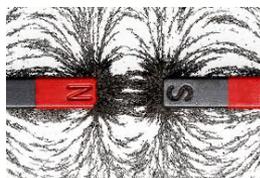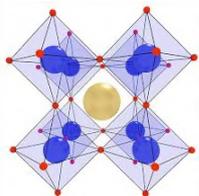# Interactions between Rydberg atoms and spin models
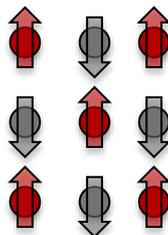

Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals

2-atom energy

$|ns, ns\rangle$

ΔE

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

$|gg\rangle$

Resonant dipole

2-atom energy

$|ns, n'p\rangle$ **V** $|n'p, ns\rangle$

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

$|gg\rangle$

Spin 1/2

Ising model

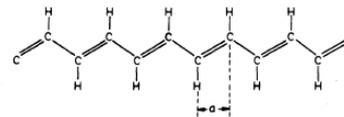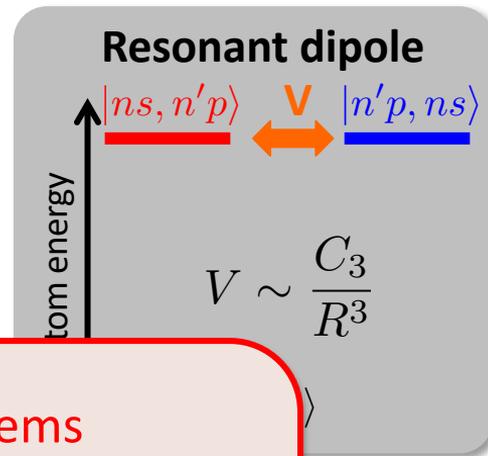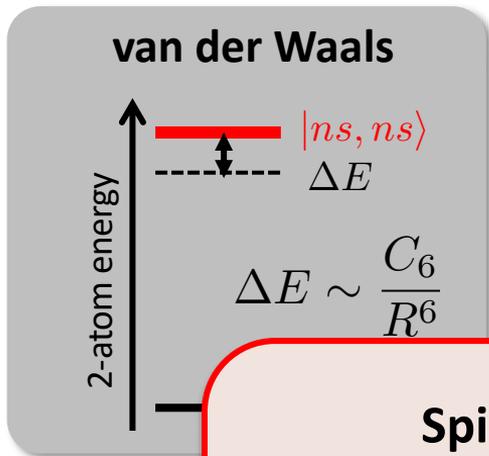$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{n}_i \hat{n}_j$$

XY model

$$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$
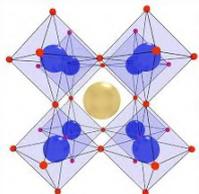
Interactions between Rydberg atoms and spin models

A

B

R

Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals

$|ns, ns\rangle$

ΔE

2-atom energy

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

Resonant dipole

$|ns, n'p\rangle$ **V** $|n'p, ns\rangle$

tom energy

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

Isin ...

$\hat{H} = $ ...

... $\hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$

Spin models = generic systems
to study many-body questions:

Quantum phase transition, out-of equilibrium,
thermalization, topology, entanglement...

From van der Waals interaction to the Ising spin model

van der Waals: $\Delta E \sim \dfrac{C_6}{R^6}$

$|r\rangle$ $|f\rangle$

$|r\rangle$ $|f\rangle$

Ex: N_2, H_2, O_2

Interaction energy
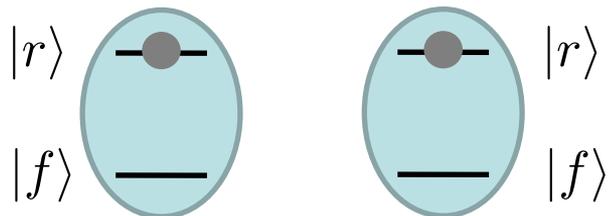
$N - N$

R

$\propto \dfrac{1}{R^6}$
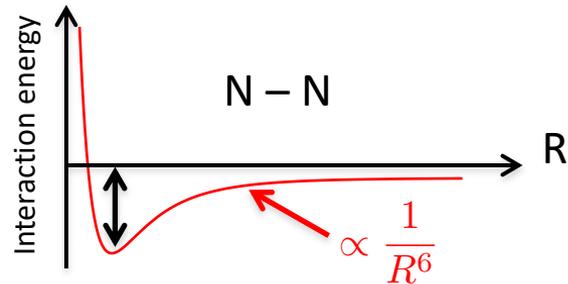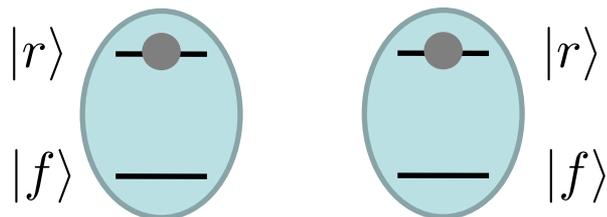
From van der Waals interaction to the Ising spin model

van der Waals: $\Delta E \sim \dfrac{C_6}{R^6}$

$C_6 \propto n^{11} \Rightarrow$ switchable interaction

Ground state: $n = 5$
Rydberg: $n = 50$ $\times 10^{11}$
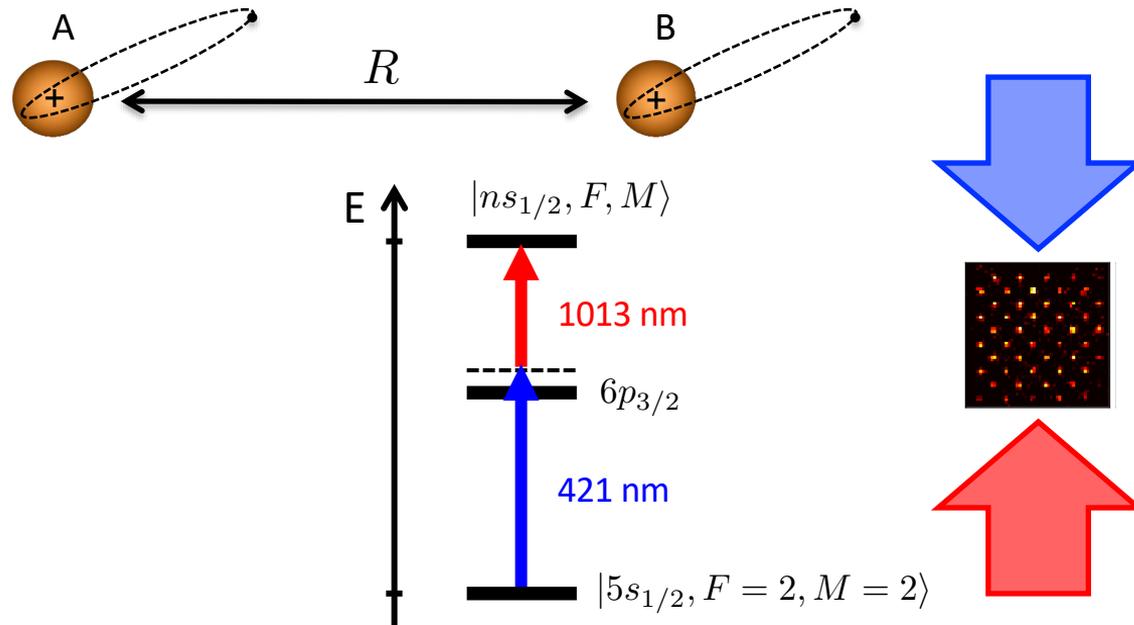
Ising - like!!

$$\hat{H}_{\text{int}} = \frac{C_6}{R^6}\hat{n}_1\hat{n}_2 \sim J\,\hat{\sigma}_1^z\hat{\sigma}_2^z$$

"Equivalent" to interaction between spins

$U_{\text{int}} = J$ $U_{\text{int}} = -J$

Rydberg $n_{1,2} = 1$
Ground state $n_{1,2} = 0$

From van der Waals interaction to the Ising spin model

A

B

R

E

$|ns_{1/2}, F, M\rangle$

1013 nm

$6p_{3/2}$

421 nm

$|5s_{1/2}, F = 2, M = 2\rangle$

From van der Waals interaction to the Ising spin model

$$\Omega \sim \sqrt{P_{\mathrm{L}}}$$

From van der Waals interaction to the Ising spin model

$$\sim \mu B_\perp \hat{\sigma}_x + \mu B_\parallel \hat{\sigma}_z$$

$$\Omega \sim \sqrt{P_\mathrm{L}}$$

$$\frac{C_6}{R^6}$$
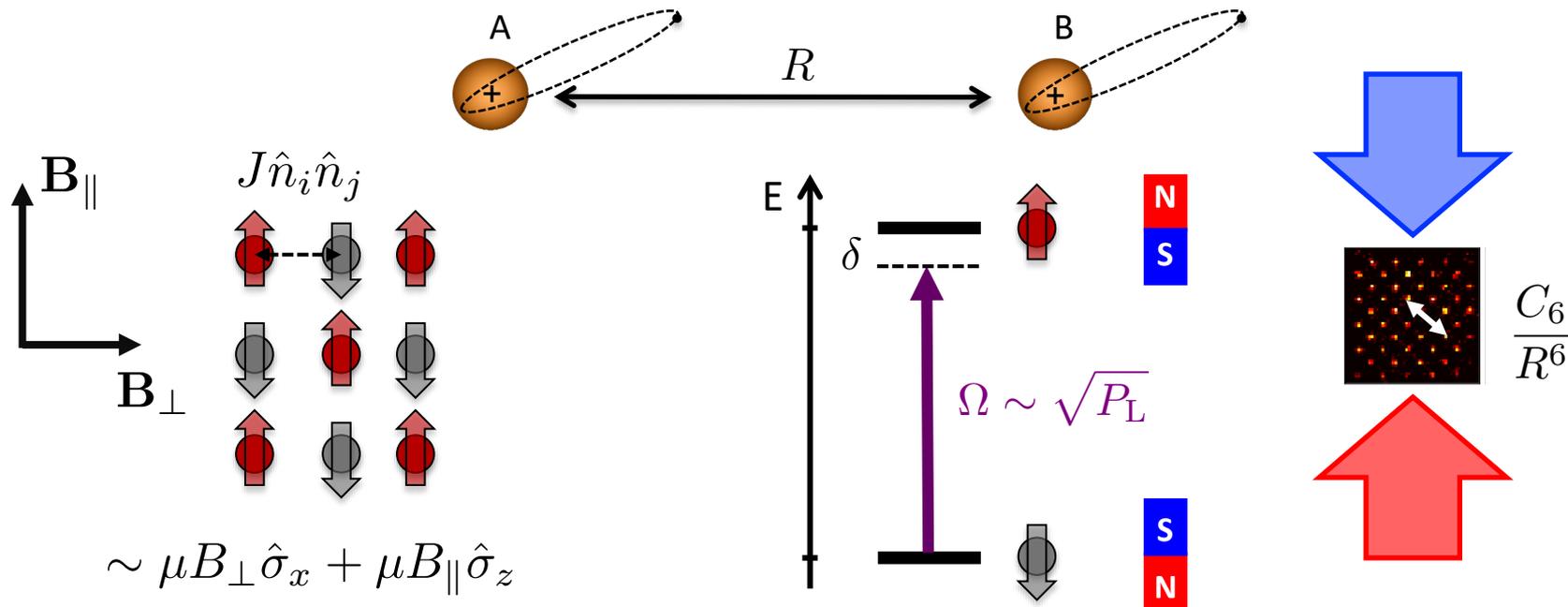
Quantum Ising model:

$$H = \frac{\hbar\Omega}{2}\sum_i \hat{\sigma}_x^i + \hbar\delta\sum_i \hat{\sigma}_z^i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$
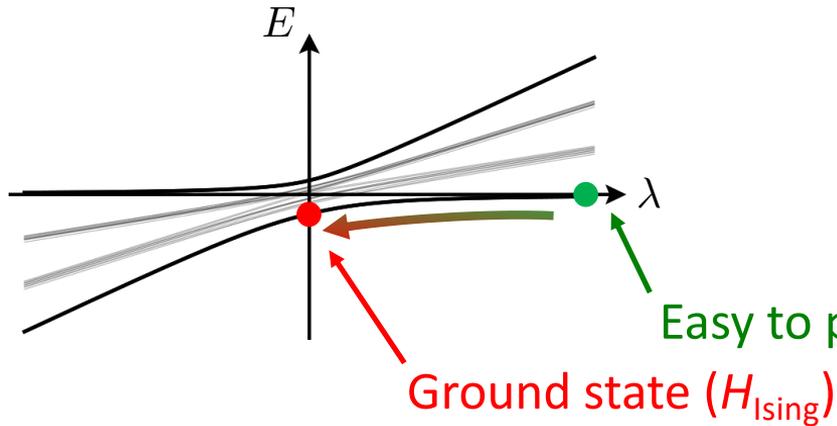
Laser: $B_\perp$ $B_\parallel$ spin-spin interactions

From van der Waals interaction to the Ising spin model

Quantum simulation:

Emulate a system by another one

Similar equations lead to same solutions!!

$\mathbf{B}_\parallel$

$J\hat{n}_i\hat{n}_j$

$\mathbf{B}_\perp$

$\sim \mu B_\perp \hat{\sigma}_x +$

$\dfrac{C_6}{R^6}$
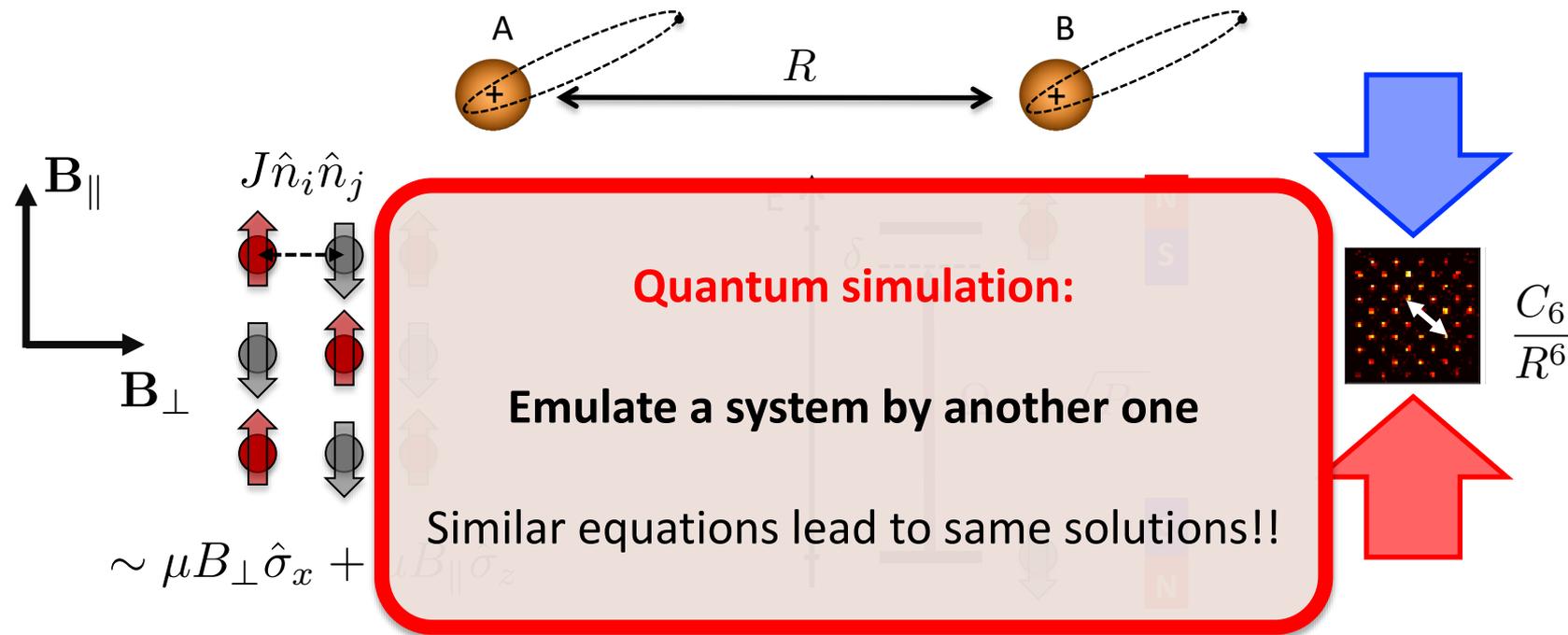
Quantum Ising model:

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

Laser: $\quad B_\perp \qquad\qquad B_\parallel \qquad$ spin-spin interactions

Controlled parameters:
From negligible to dominant interactions

29

An antiferromagnet on a square array

Adiabatic state preparation:

$$H = \lambda H_{\mathrm{z}} + H_{\mathrm{Ising}} \quad \text{Vary} \quad \lambda \gg 1 \rightarrow 0$$

Easy to prepare (H_z)
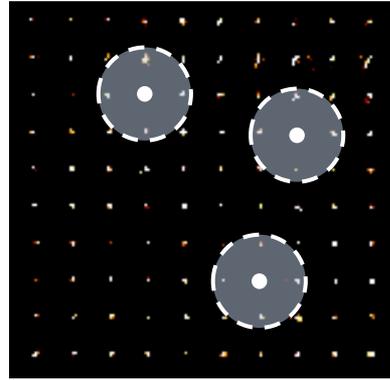
Ground state (H_{Ising})

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

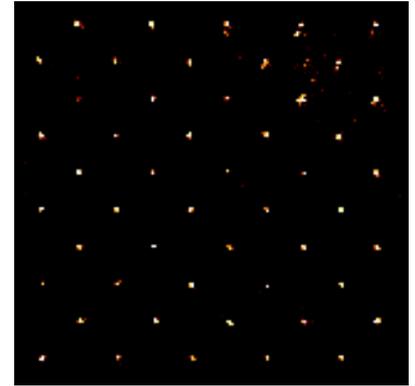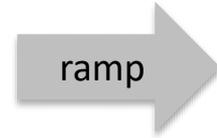# An antiferromagnet on a square array

Adiabatic state preparation:

$$H = \lambda H_{\mathrm{z}} + H_{\mathrm{Ising}} \quad \text{Vary} \quad \lambda \gg 1 \to 0$$

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

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

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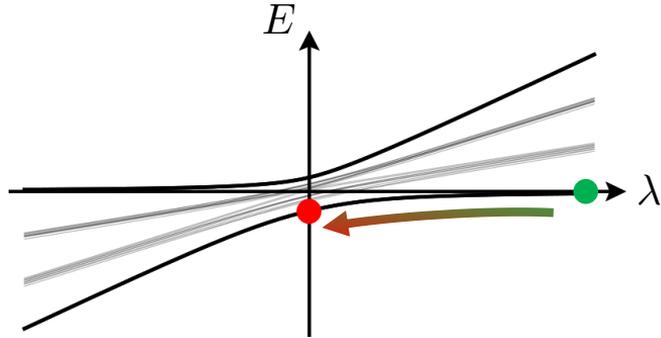
$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

$$\frac{C_6}{a^6} \sim \Omega$$

$\downarrow = |f\rangle$ "bright"

$\uparrow = |r\rangle$ "dark"

Anti-ferromagnetic ordering!
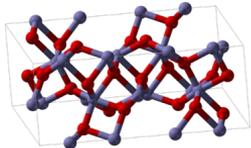
Ex: MnO, FeO, CoO, NiO, FeCl$_2$...

Scholl et *al.* Nature (2021)
Also: Lukin Nature 2021

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

32

An antiferromagnet on a square array

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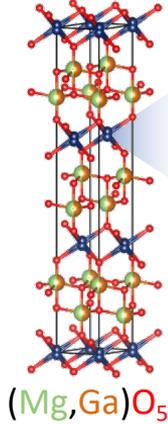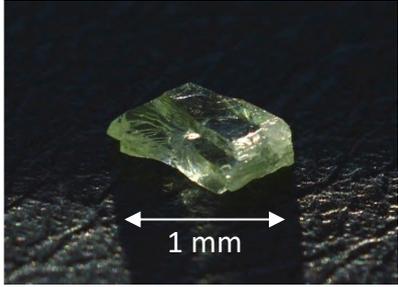
$\Omega(t), \delta(t)$

ramp
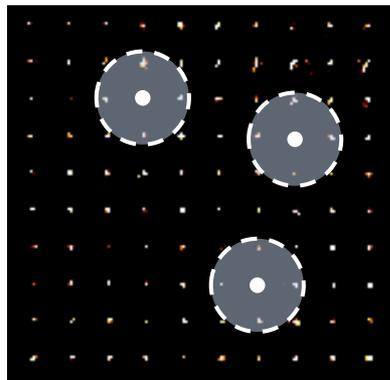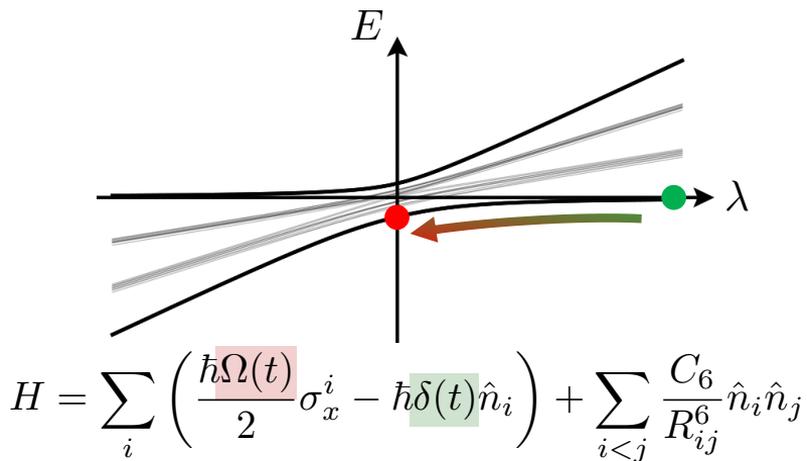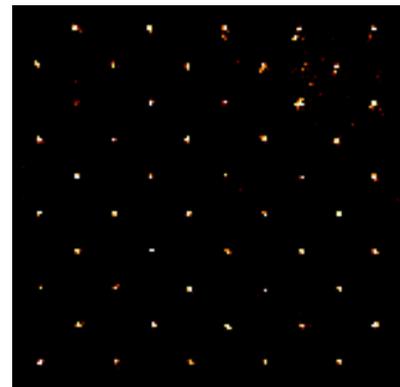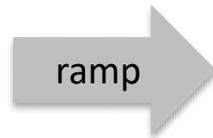
Dynamics: push numerical methods
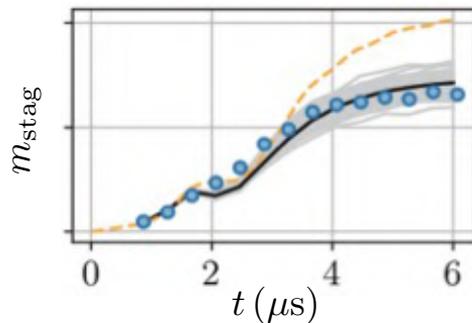
State of-the-art simulation (2021):
MPS limited to 10 x 10
(14 days on super supercomputer!!)

Quantum simulation of a real frustrated material: TmMgGaO$_4$

1 mm

(Mg,Ga)O$_5$

Tm^{3+}

O

Theoretical modeling

$$H_{\mathrm{TMGO}} = J_1 \sum_{\langle i,j \rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z + J_2 \sum_{\langle\langle i,j \rangle\rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

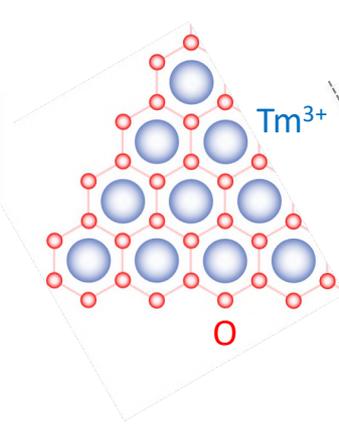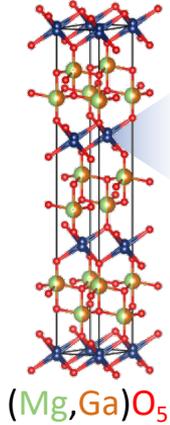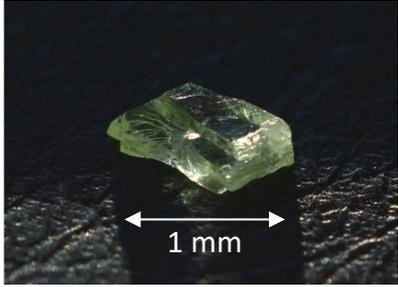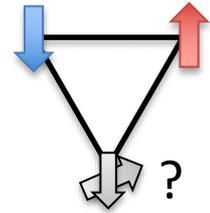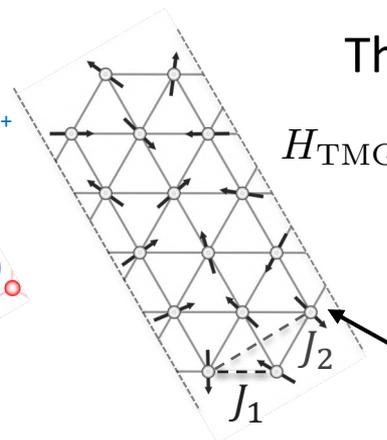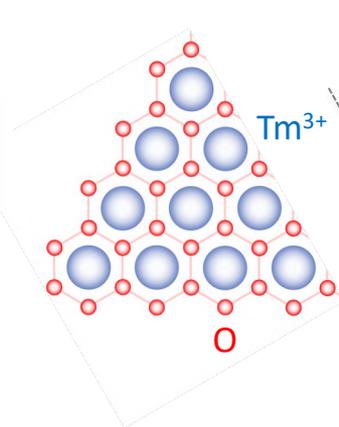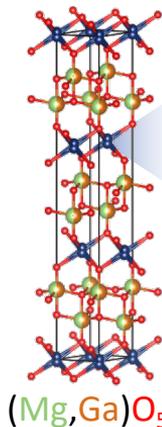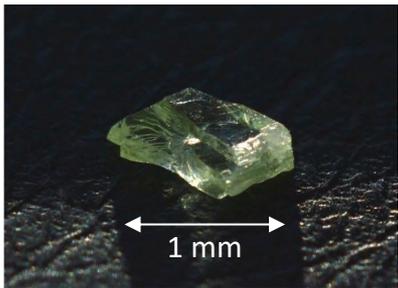$$+ \sum_i \Delta_x \hat{\sigma}_i^x + \Delta_z \hat{\sigma}_i^z,$$

Δ_x, Δ_z

J_2

J_1
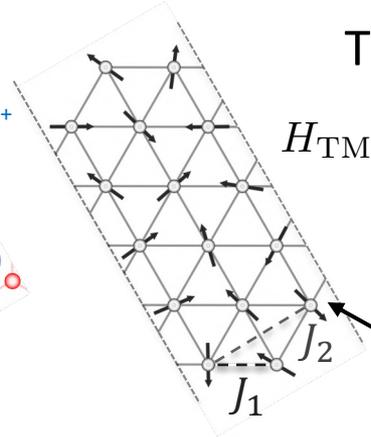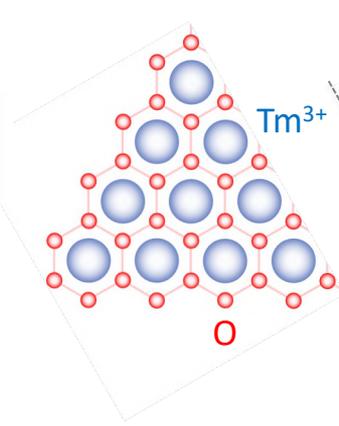
Liu, PRR **2**,043013 (2021)

Simplication

Understand material

Quantum simulation of a real frustrated material: TmMgGaO$_4$

1 mm

(Mg,Ga)O$_5$
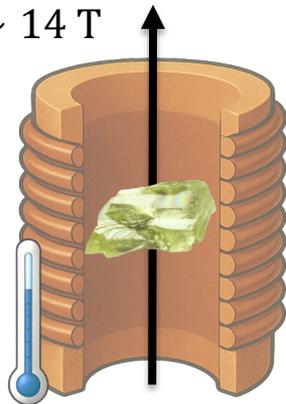
Tm^{3+}

O

J_2

J_1

Δ_x, Δ_z
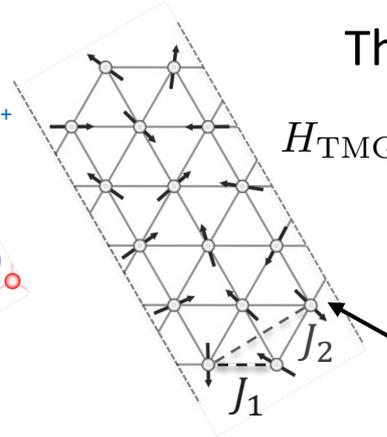
Theoretical modeling

$$H_{\text{TMGO}} = J_1 \sum_{\langle i,j \rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z + J_2 \sum_{\langle\langle i,j \rangle\rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

$$+ \sum_i \Delta_x \hat{\sigma}_i^x + \Delta_z \hat{\sigma}_i^z,$$

Liu, PRR **2**,043013 (2021)

?

Frustration

Quantum simulation of a real frustrated material: TmMgGaO$_4$

(Mg,Ga)O$_5$

Tm^{3+}

O

Theoretical modeling

$$H_{\text{TMGO}} = J_1 \sum_{\langle i,j \rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z + J_2 \sum_{\langle\langle i,j \rangle\rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z$$
$$+ \sum_i \Delta_x \hat{\sigma}_i^x + \Delta_z \hat{\sigma}_i^z,$$

Δ_x, Δ_z J_2 J_1

Liu, PRR **2**,043013 (2021)

Macroscopic measurement

$\mu_0 H \sim 14$ T

$M(T,H)$

$$\chi(T,H) = \left(\frac{\partial M}{\partial H} \right)_T$$

$\Delta_z = \mu_0 H$

$T \sim 20$ mK

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Los Alamos NATIONAL LABORATORY

Simulation on Quantum Processor
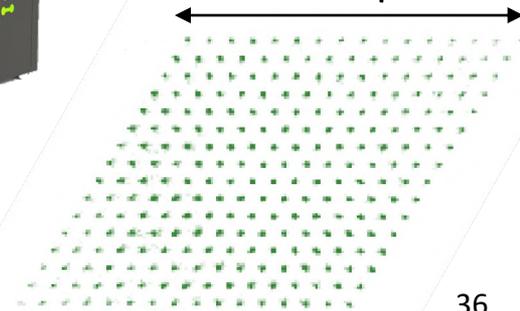

$N = 256$

$\sim 120 \ \mu m$

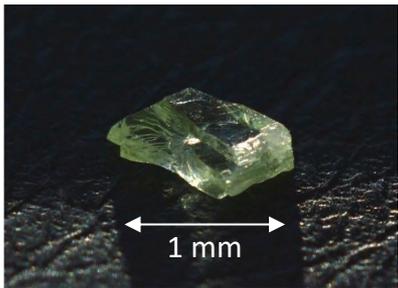$$M = \frac{1}{N} \sum_i \langle \hat{\sigma}_i^z \rangle$$

$\Delta_x = \Omega$

$\Delta_z = \delta$

36

Quantum simulation of a real frustrated material: TmMgGaO₄
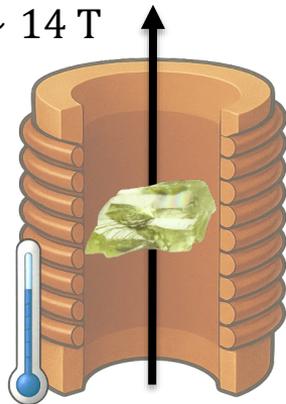

$1\ mm$

$(Mg,Ga)O_5$

Tm³⁺

O

Theoretical modeling

$$H_{\mathrm{TMGO}} = J_1 \sum_{\langle i,j \rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z + J_2 \sum_{\langle\langle i,j \rangle\rangle} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

$$+ \sum_i \Delta_x \hat{\sigma}_i^x + \Delta_z \hat{\sigma}_i^z,$$

Δ_x, Δ_z J_2 J_1

Liu, PRR **2**,043013 (2021)

Macroscopic measurement

$\mu_0 H \sim 14\ T$

$M(T,H)$

$\chi(T,H) = \left(\dfrac{\partial M}{\partial H} \right)_T$

$T \sim 20\ mK$

Simulation on Quantum Processor

PASQAL

$N = 256$

$\sim 120\ \mu m$

$M = \dfrac{1}{N} \sum \langle \sigma_i^z \rangle$

$\Delta_x = \Omega$

$\Delta_z = \delta$

$$H_{\mathrm{TMGO}} \approx 10^{-5} \times H_{\mathrm{QPU}}$$

MAGNETIC FIELD LABORATORY

Los Alamos NATIONAL LABORATORY

Quantum simulation of a real frustrated material: TmMgGaO$_4$

T = 0K

Δ_z/J_1

Transition scan

$S(\mathbf{q}_{1/3})$

Δ_x/J_1

1/3

PM

Preliminary

$\int \chi_{AC} dH$ (a.u.)

$T/J_1 = 7 \times 10^{-3}$
(TMGO)

$\Delta_z = \mu_0 H$ (T)

Quantum simulation of a real frustrated material: TmMgGaO$_4$

NATIONAL HIGH **MAGNETIC** FIELD LABORATORY   **Los Alamos** NATIONAL LABORATORY   Pasqal

T = 0K

Δ_z/J_1

2   4   6   8   10

- - - Transition scan

0   $S(\mathbf{q}_{1/3})$ 1

Δ_x/J_1

1.5

1.0

0.5

1/3   PM

Preliminary

Adiabatic state preparation on QPU
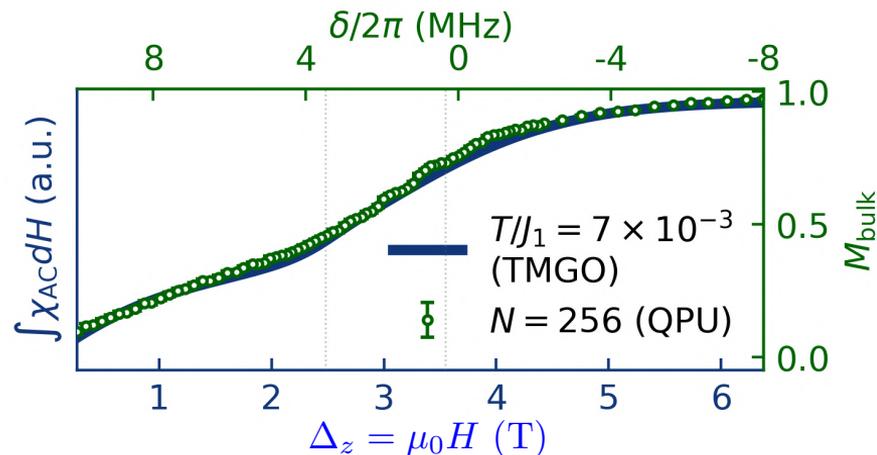
$\delta/2\pi$ (MHz)

8   4   0   -4   -8

$\int \chi_{AC} dH$ (a.u.)

1.0

$T/J_1 = 7 \times 10^{-3}$ (TMGO)

$N = 256$ (QPU)

0.5

M_{bulk}

0.0

1   2   3   4   5   6

$\Delta_z = \mu_0 H$ (T)

Quantum simulation of a real frustrated material: $TmMgGaO_4$

T = 0K
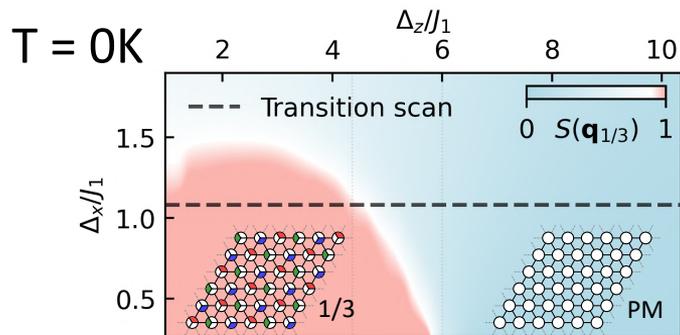
Adiabatic state preparation on QPU
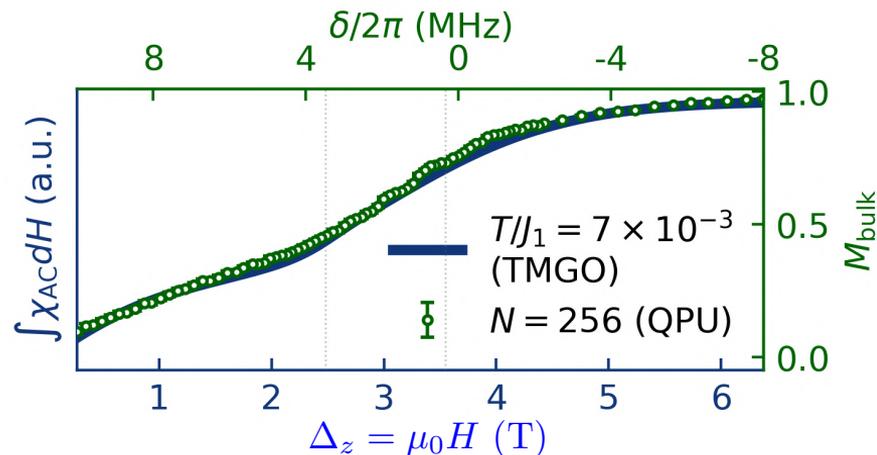
Comparison between 3 QPU's & theory

Preliminary
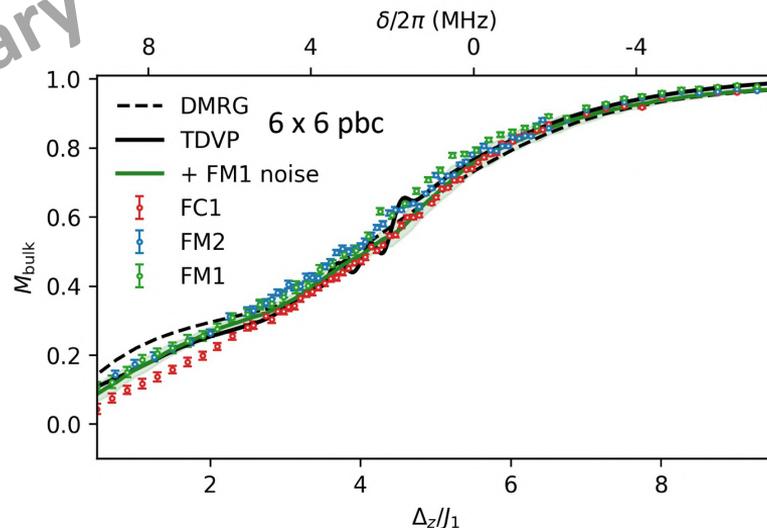
$TmMgGaO_4$: $1/J_1 \sim$ ps

QPU: $1/J_1 \sim$ μs $\Rightarrow$ slow dynamics
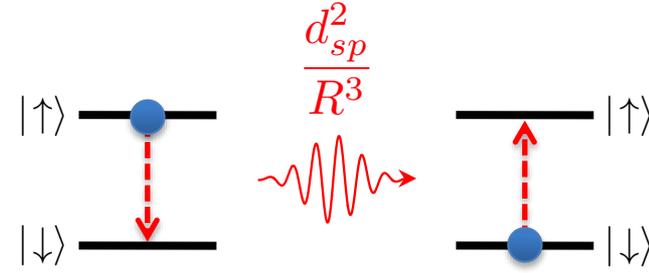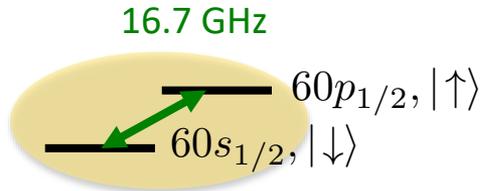
Single-site resolution: magnetic domain

Resonant interaction between Rydbergs and XY spin model

Browaeys & Lahaye, Nat.Phys. (2020)
Barredo PRL (2015), de Léséleuc PRL (2017)
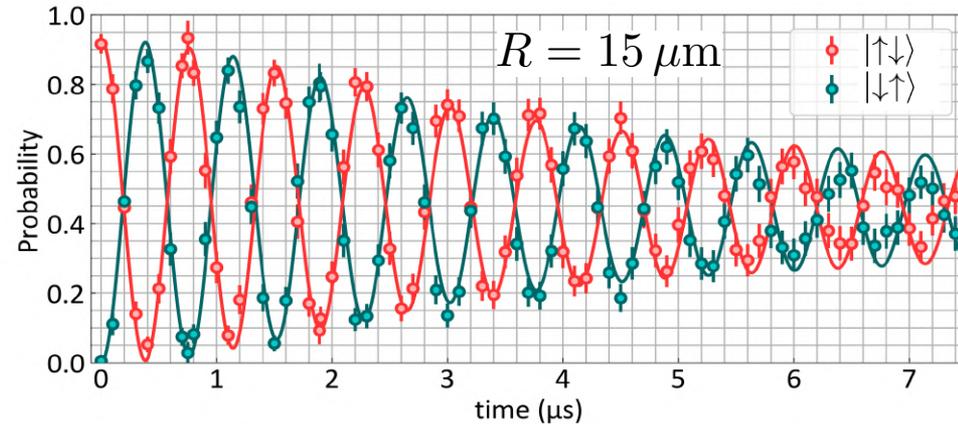Emperauger PRA (2025)

Resonant interaction between Rydbergs and XY spin model

Browaeys & Lahaye, Nat.Phys. (2020)
Barredo PRL (2015), de Léséleuc PRL (2017)
Emperauger PRA (2025)

$$\frac{d_{sp}^2}{R^3}$$

16.7 GHz

$60p_{1/2}, |\uparrow\rangle$

$60s_{1/2}, |\downarrow\rangle$
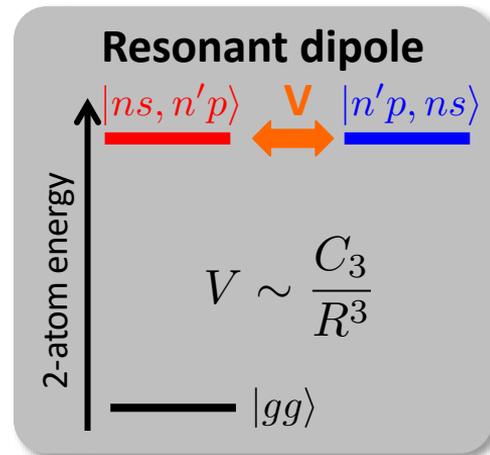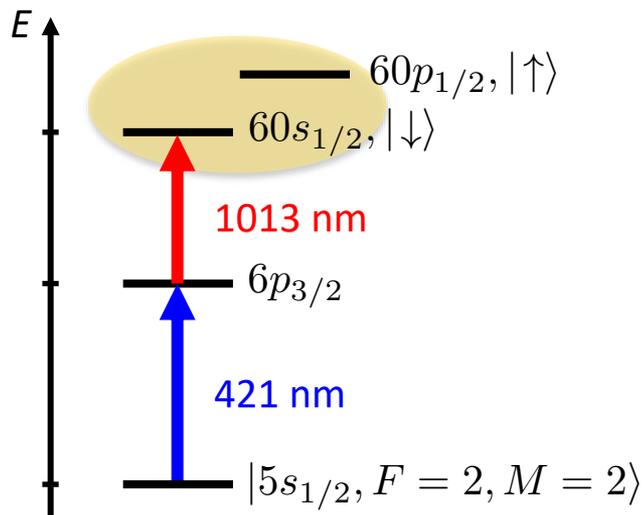
Non radiative "exchange" of excitation

$$\hat{H}_{\mathrm{XY}} = \frac{C_3}{R_{ij}^3}(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

$$= \frac{C_3}{2R_{ij}^3}(\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

$R = 15\,\mu\mathrm{m}$

$|\uparrow\downarrow\rangle$
$|\downarrow\uparrow\rangle$

Probability

time (µs)

Dipolar interactions leads to frustration…

$1/R^3 \Rightarrow$ frustration!!

AFM: $J < 0$

vs.
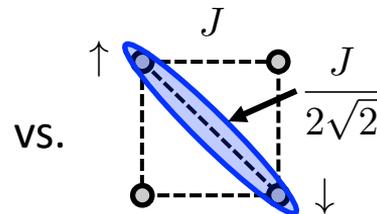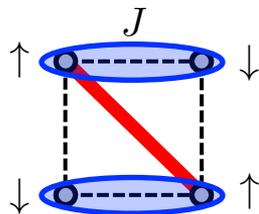
Hard to calculate
$N > 100$!!

Preparation of long-range order FM phase (10 x 10)

$$C^x(\mathbf{d}) \sim \langle \sigma_{\mathbf{r}}^x \sigma_{\mathbf{r+d}}^x \rangle$$

FM

AFM

Frustration!

$|C^x(d)|$

d (sites)
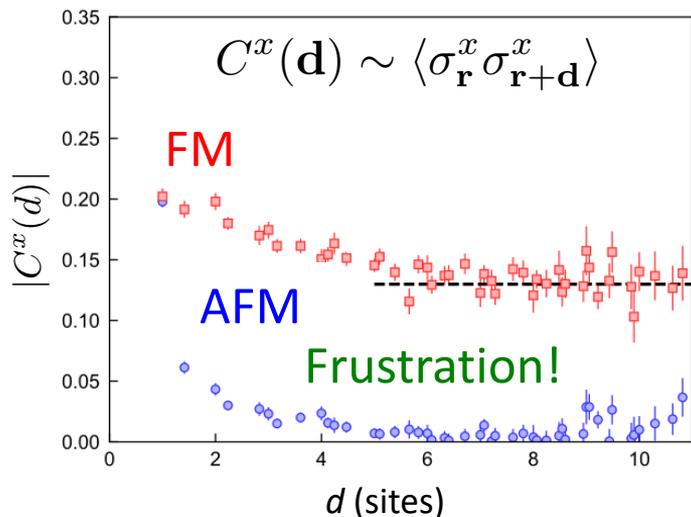
Dynamics following quench: spin waves

Wikipedia

$$S_y(x,t) \sim e^{i[qx - \omega(q)t]}$$

AFM

$\omega(q)/J$

$|\mathbf{q}|$

FM

$\omega(q)/J$

$|\mathbf{q}|$
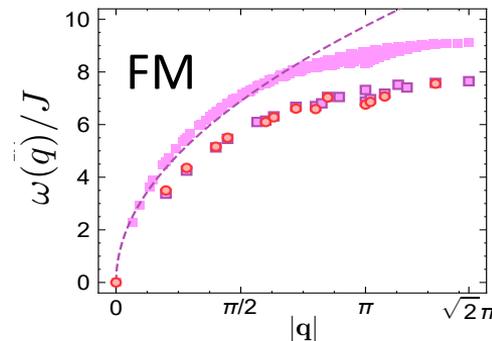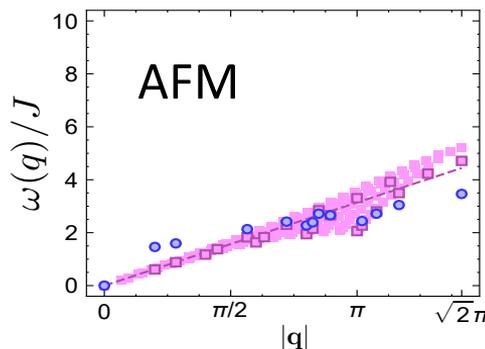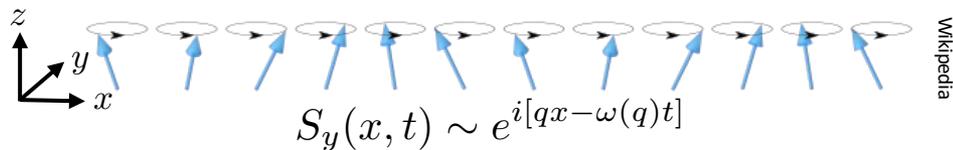
$1/r^3$ Interaction modifies spin wave dispersion

Chen *et al.*, Nature 2023

C. Cheng *et al.*, Science 2025 ; Büchler PRL 2012

43

Quantum simulators implementing *spin models* can do more...

Optimization problems

Cost function = Ising Hamiltonien

$$H = \sum_i h_i n_i + \sum_{i<j} J_{ij} n_i n_j \ , \quad n_i = 0, 1$$

Solution optimization = ground state

Warning: competitive w.r. heuristic
classical algorithms
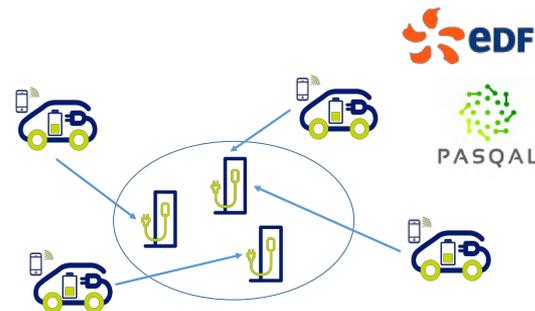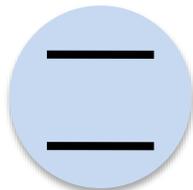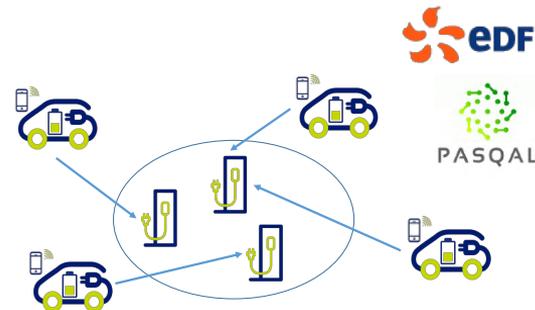$N > 2000 - 5000$ & clock rate $\sim$ kHz...

arXiv:2502.04291

Quantum simulators implementing *spin models* can do more…

Optimization problems

Cost function = Ising Hamiltonien

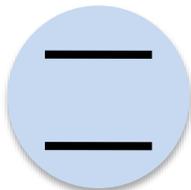$$H = \sum_i h_i n_i + \sum_{i<j} J_{ij} n_i n_j \ , \quad n_i = 0, 1$$

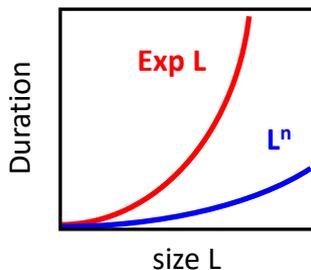Solution optimization = ground state

Quantum metrology

^{133}Cs

F=4

F=3

1 sec = 9 192 631 770 cycles

States with quantum correlations

$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}}$$

$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

Gain x 10 - 100

45
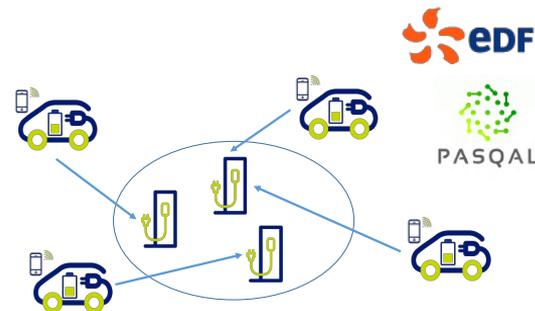
Quantum simulators implementing *spin models* can do more…

Optimization problems

Cost function = Ising Hamiltonien

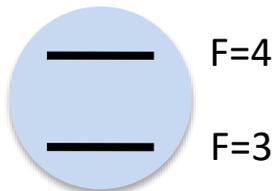$$H = \sum_i h_i n_i + \sum_{i<j} J_{ij} n_i n_j \ , \quad n_i = 0, 1$$

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Gain x 10 - 100

Universal quantum computer
(likely long-term…)

Exp L

L^n

Duration

size L

- Factoring
- Search algorithm
- …

Quantum simulators implementing *spin models* can do more...

Optimization problems

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Gain x 10 - 100

Universal quantum computer
(likely long-term...)

Rydberg based quantum computers today

Zoning architecture

Harvard, 2023
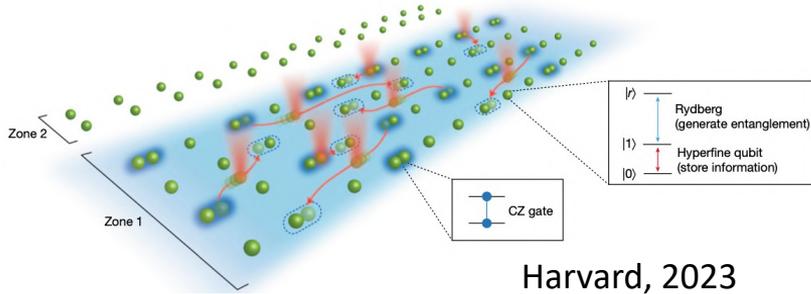
Single qubit gates $F > 99.97\%$
Two-qubit gates $F > 99.2\%$
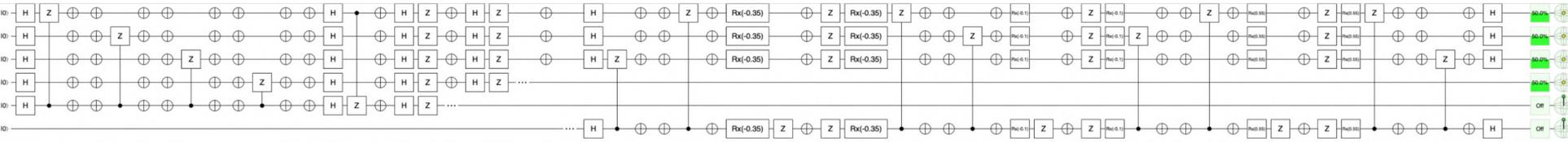
Proof of principle logical encoding and quantum error detection/correction (2025)

Harvard, Quera, Atom Computing, Infleqtion, Pasqal…
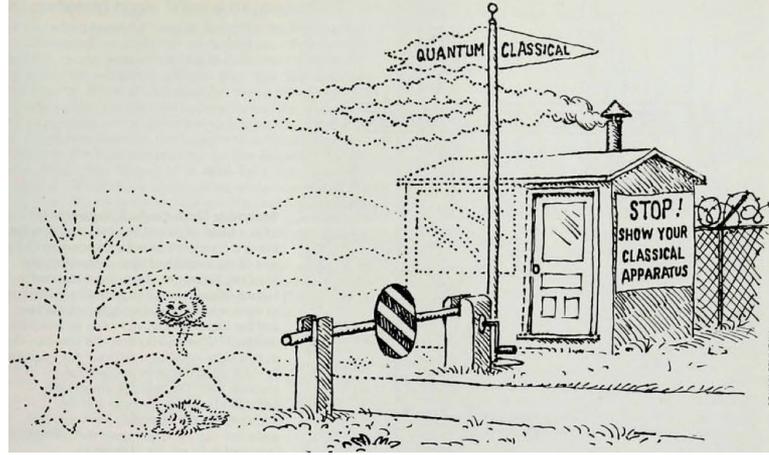
Today: circuits with ~ 100 gates

Pasqal

Factorization RSA-2048 (Shor): ~ 10^{12} gates on ~ 10 million qbits …

Quantum chemistry (Fe_7MoS_9Co): 100-1000 logical qubits ~ 10^{14} gates
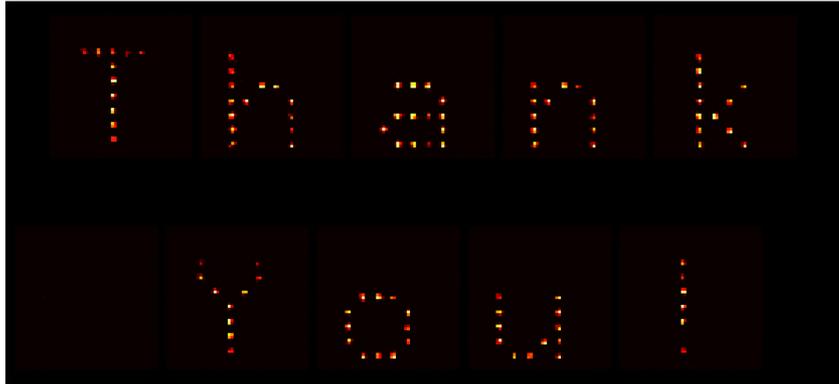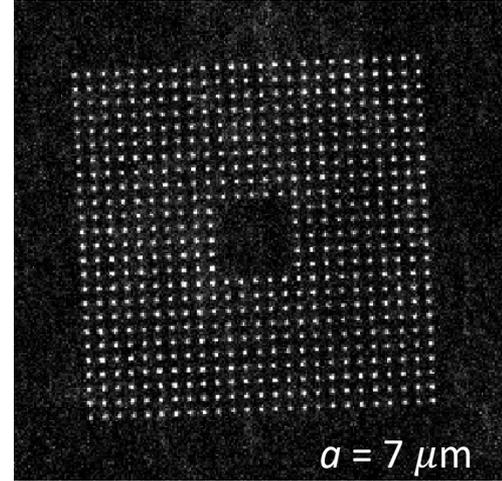
How large can a *controlled* quantum system be?

Zurek, Physics Today 1991

$a = 7 \mu m$

atom-tweezers-io.org