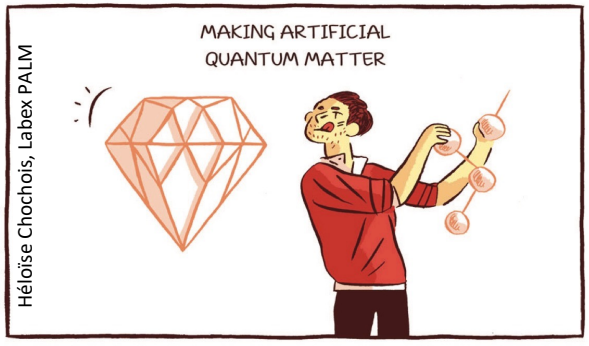
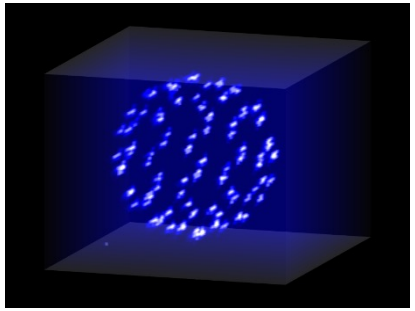
Introduction à la simulation quantique

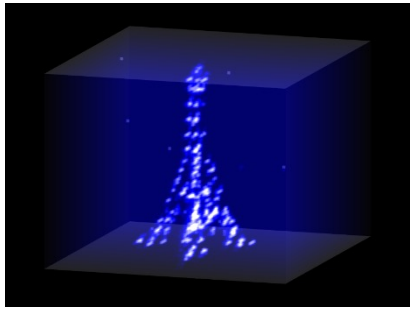


Antoine Browaeys

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

IMT Nantes, 10 novembre 2022





Le programme…

1. Physique à N-corps, simulation quantique et systèmes quantiques synthétiques

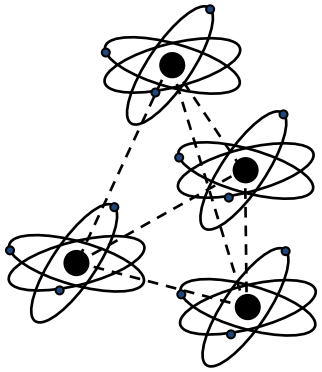
2. Exemples de simulateurs quantiques: ions et atomes

3. Exemples de simulation quantique
   - A. Exploration du diagramme des phases
   - B. Dynamique hors-équilibre

Le problème à N-corps en physique

But: comprendre ensembles de particules quantiques en interaction

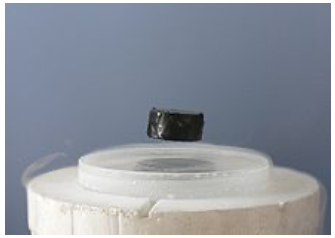
Microscopique



Lois quantiques

?

Macroscopique



Ce qu'il faut résoudre: $$i\hbar\frac{\partial\Psi}{\partial t} = H_{\text{tot}}\Psi$$

$$H_{\text{tot}} = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\nabla_i^2 + \sum_{i=1}^{N}\sum_{j\neq i}\frac{q_i q_j}{r_{ij}} + \frac{\mu_{\text{B}}^2}{r_{ij}^3}\mathbf{s}_i\cdot\mathbf{s}_j$$

$N \approx 10^{23}$!!!

Complexité quantique: difficulté exponentielle

Fonction d'ondes à *N*-corps: $\Psi = \Psi(1, 2, ..., N)$

« Taille » de la fonction d'onde ??

Exemple: particules à 2 d. de liberté (spin…) $\psi_i = \begin{pmatrix} a \\ b \end{pmatrix}$

$\Rightarrow$ Ψ nécessite 2^N composantes

Coder sur ordi. Ψ pour $N = 40 \Rightarrow 2^{50} \sim 10^{15}$ = 1000 To RAM !!

Record de calcul *ab-initio* (2022) $N \sim 50$

Des méthodes d'approximation…

$$H_{\text{tot}} = \sum_{i=1}^{N} \frac{p_i^2}{2m_i} - \frac{e^2}{r_i} + \sum_{i=1}^{N} \sum_{j \neq i} \frac{e^2}{r_{ij}}$$

Approx 1 : négliger interactions (mauvaise…)

$$H_{\text{tot}} = \sum_{i=1}^{N} H_i \Rightarrow \Psi(1, 2, ...N) = \psi_1 \psi_2 ... \psi_N, \quad H_i \psi_i = E_i \psi_i$$

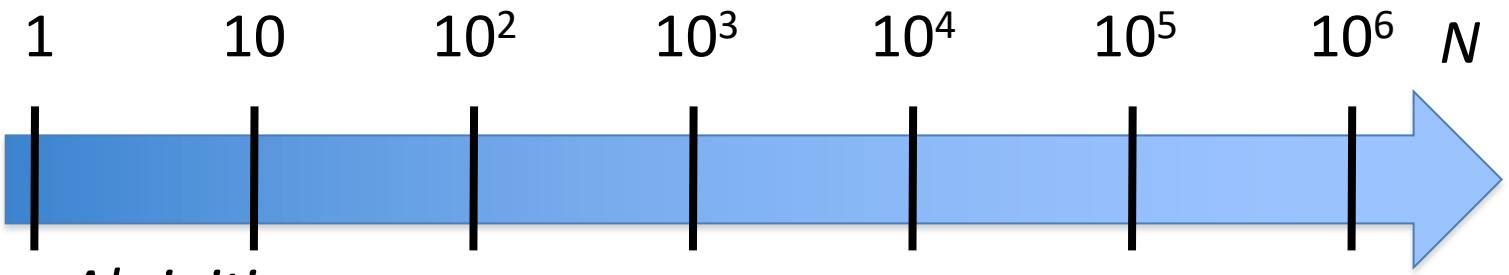
Approx 2 : champ moyen + perturbation (phys. atom, nucléaire, moléculaire, théorie des bandes phys. solide…)

$$H_{\text{tot}} = \sum_{i=1}^{N} \frac{p_i^2}{2m_i} + V(r_i) + \left[\sum_{i=1}^{N} \sum_{j \neq i} \frac{e^2}{r_{ij}} - \frac{e^2}{r_i} - V(r_i) \right]$$

Méthode + raffinée : Monte Carlo Quantique, fonctionnel densité, DMRG, t-DMRG, Tensor Networks, Matrix Product states…

… qui ne marchent pas toujours !

Quand **interactions dominent** (systèmes **fortement corrélés**)



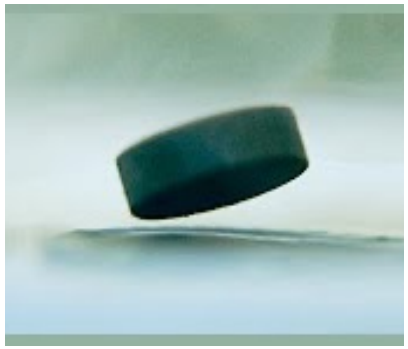
Ab-initio
(état station., dynamique)

Monte Carlo, DMRG…)

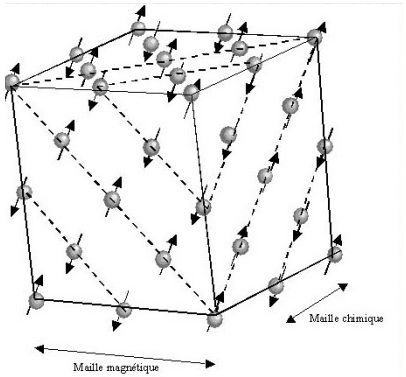
RIEN…
(sauf part. indép.)

Exemples

superfluidité



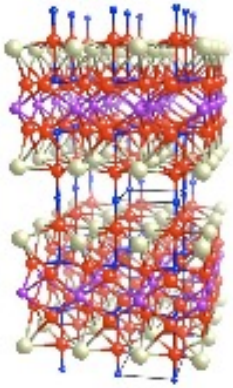
supraconductivité



magnétisme

neutron star

Simulation quantique: exemple de démarche



Observation phénomène compliqué

Ex: supraconductivité haute T_c

Expérience sur vrai système

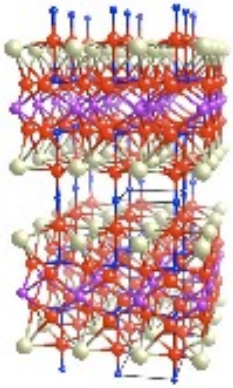
simplification

Hamiltonien modèle

$$H_{\text{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g (a_i^\dagger)^2 (a_i)^2$$

Calculs trop durs…

Simulation quantique: exemple de démarche



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$$H_{\text{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g (a_i^\dagger)^2 (a_i)^2$$

"Préparable"

$$|\psi(t)\rangle = e^{-\frac{i}{\hbar} H_{\text{model}} t} |\psi(0)\rangle$$

Lab…

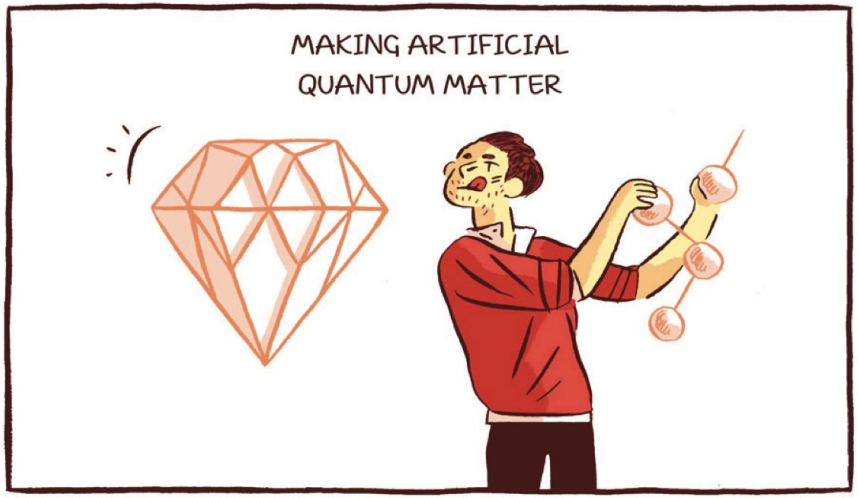
Simulateur quantique = Ingénierie d'atomes gouvernés par H_{model}

Résultat mesure sur simulateur: **état fondamental = supra?**

Problème à N-corps et systèmes quantiques synthétiques

R.P. Feynman

Simulating Physics with Computers, Int. J. Theo. Phys. **21** (1982)



i.e. systèmes quantiques **contrôlés** réalisant des **hamiltoniens à *N*-corps** (y compris artificiels…)

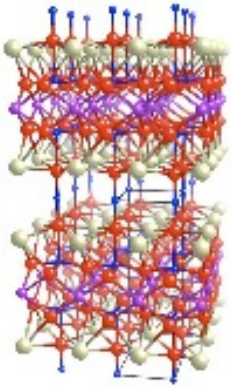
Plus grande programmabilité que systèmes réels
(geométrie, paramètres…)

+

Nouvelles sondes, méthodes d'étude (ex.: dynamique…)

Qu'est ce que l'on peut simuler et à quoi ça peut servir…?

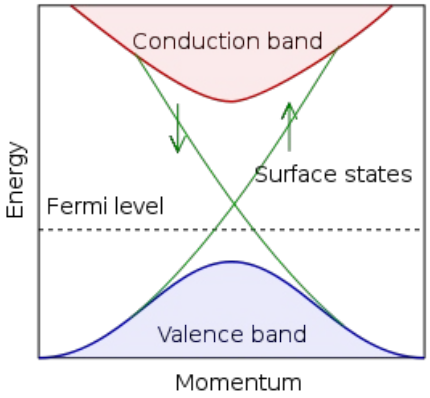
Supra-conductivité haute Tc



Vers le stockage de l'électricité?

Propriétés de conduction des métaux

influence du désordre et des interactions



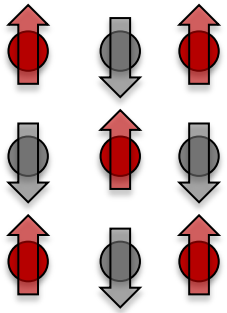
Vers des métaux meilleurs conducteurs électriques?

Magnétisme quantique

vers de nouveaux aimants pour moteurs électriques, stockage information…?

Les systèmes à N-corps les plus simples: spins en interaction

Particules de spin 1/2 sur un réseau:

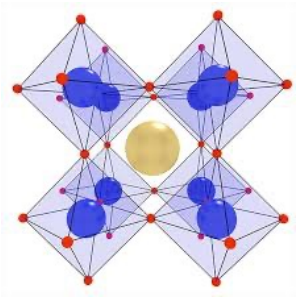


$$H \sim J\,\mathbf{S}_i \cdot \mathbf{S}_j$$

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

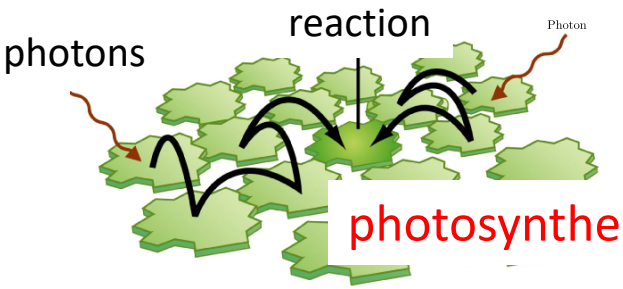
XY model $$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^{+} \hat{\sigma}_j^{-} + \hat{\sigma}_i^{-} \hat{\sigma}_j^{+} \right)$$

Magnétisme

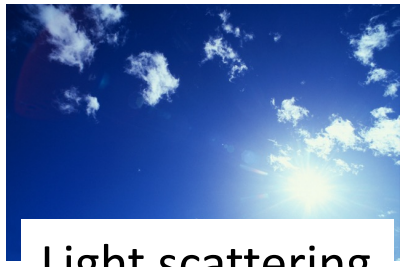


Perovskite
$Y_2Ti_2O_7$

Propriétés de transport

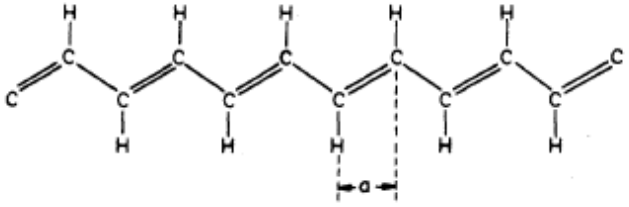


photosynthesis



Light scattering

excitons



Modèles génériques pour étude de transition de phase, dynamique…

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   - A. Ions piégés
   - B. Atomes ultra-froids dans des réseaux optiques
   - C. Atomes froids dans des pinces optiques

3. Exemples de simulation quantique

Manipulation de particules individuelles: Le point de vue d'un père fondateur…

..., nous ne faisons **jamais** d'expériences avec **juste un** électron, un atome ou une (petite) molécule. Dans des expériences de pensée, nous supposons parfois que nous le faisons ; cela conduit invariablement à des conséquences **ridicules**.

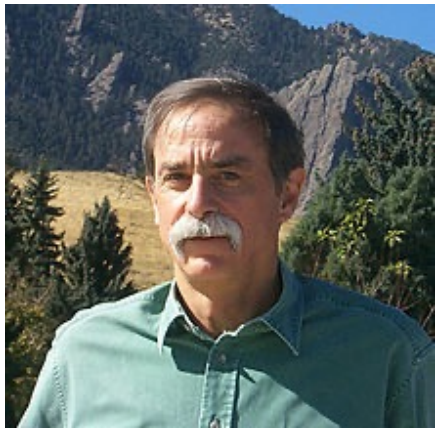
E. Schrödinger

British Journal of the Philosophy of Science III (10), (1952)

60 ans plus tard…

2012

S. Haroche (France)

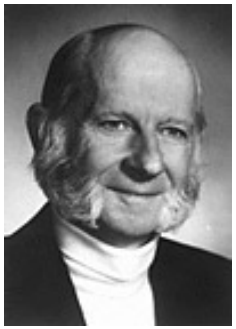


D. Wineland (USA)

« pour le développements de méthodes expérimentales permettant de mesurer et de manipuler des systèmes quantiques individuels »

Piégeage de particules uniques: les débuts…

H. Dehmelt



1989

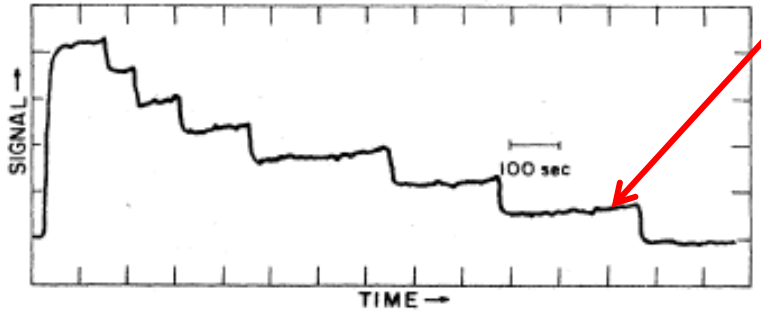
W. Paul: techniques de piégeage d'ions

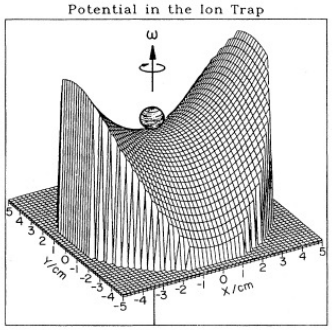
VOLUME 31 19 NOVEMBER 1973 NUMBER 21

Monoelectron Oscillator

D. Wineland, P. Ekstrom, and H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 13 August 1973)

Electron unique





1er ion unique:

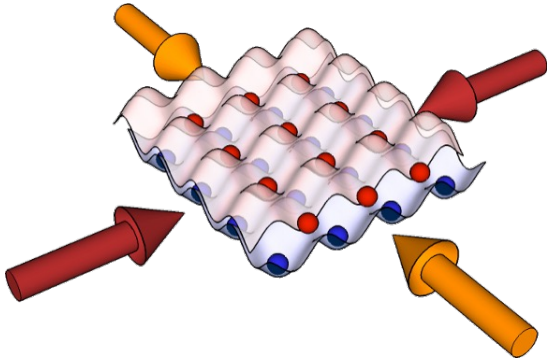
PHYSICAL REVIEW A VOLUME 22, NUMBER 3 SEPTEMBER 1980

Localized visible Ba^+ mono-ion oscillator

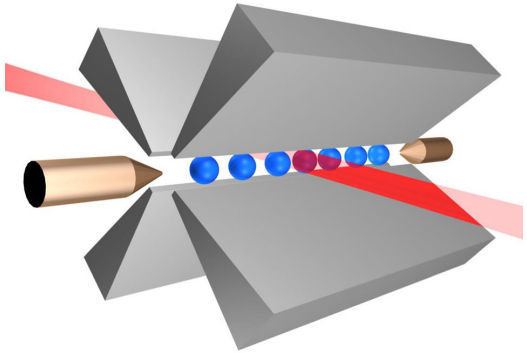
W. Neuhauser, M. Hohenstatt, and P. E. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, Federal Republic of Germany

H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 11 September 1979)

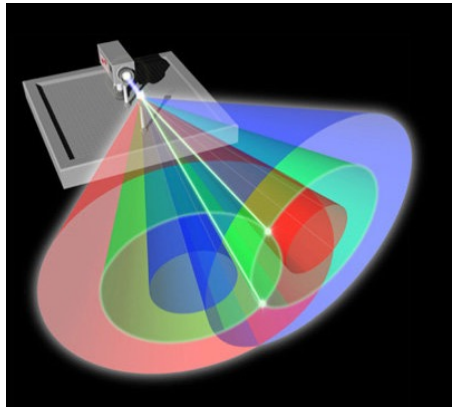
Ingénierie Quantique avec des systèmes *individuels*



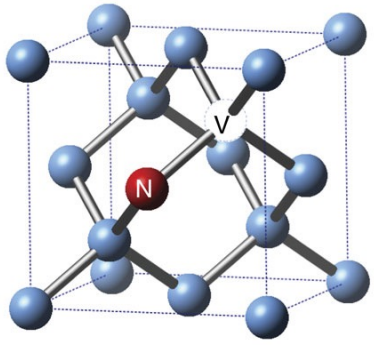
Atomes et molécules froides



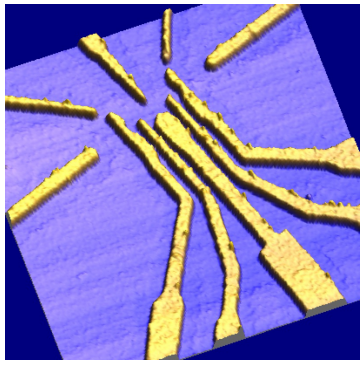
Ions piégés



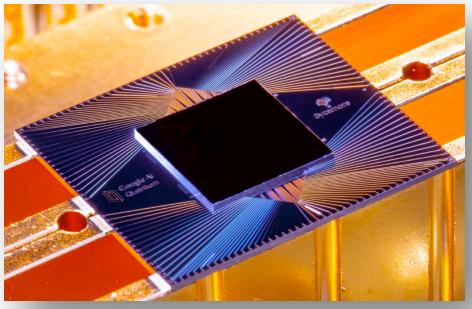
Photons



Centres NV

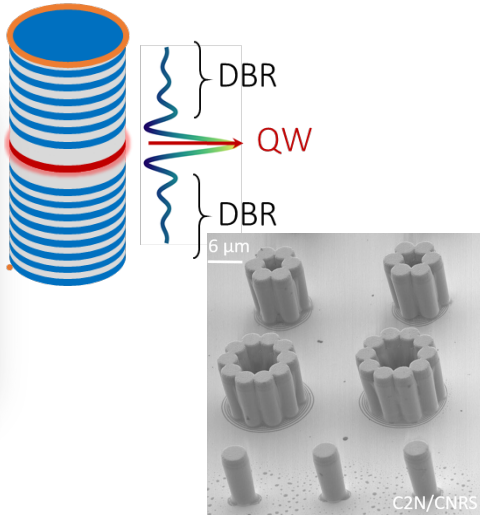


Spin électronique



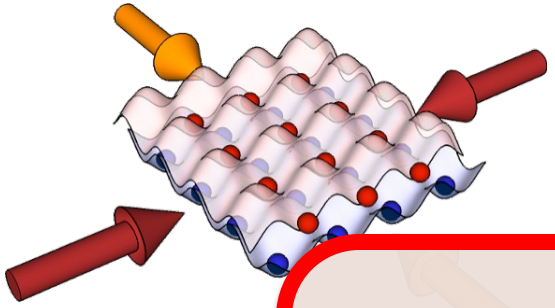
Sycamore processor, Google Inc.

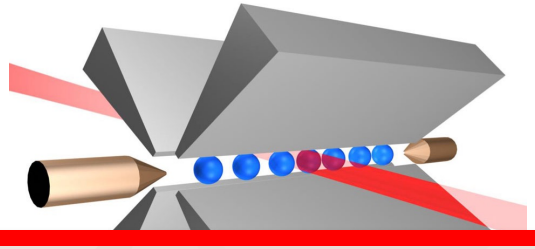
Circuits supracond.

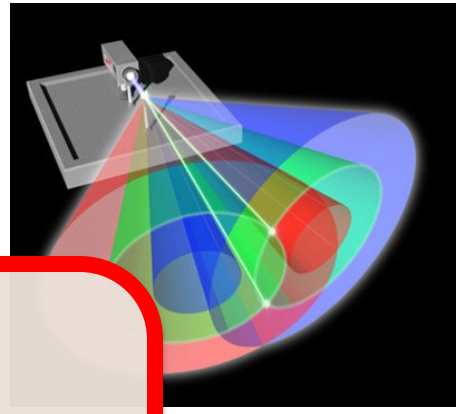


Polaritons (½ cond.)

Ingénierie Quantique avec des systèmes *individuels*







Atomes et molécules froides

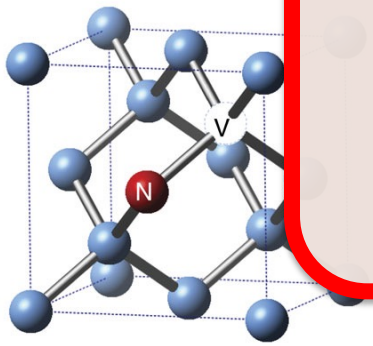
Photons

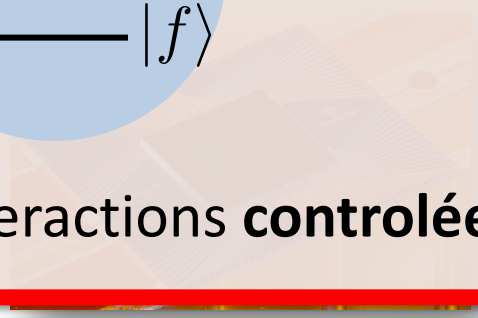
Système à 2 niveaux :

$|e\rangle$

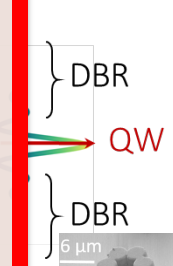
$|f\rangle$

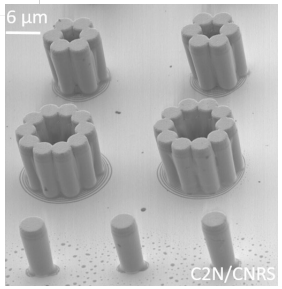
Adressable + interactions **controlées**





Sycamore processor, Google Inc.

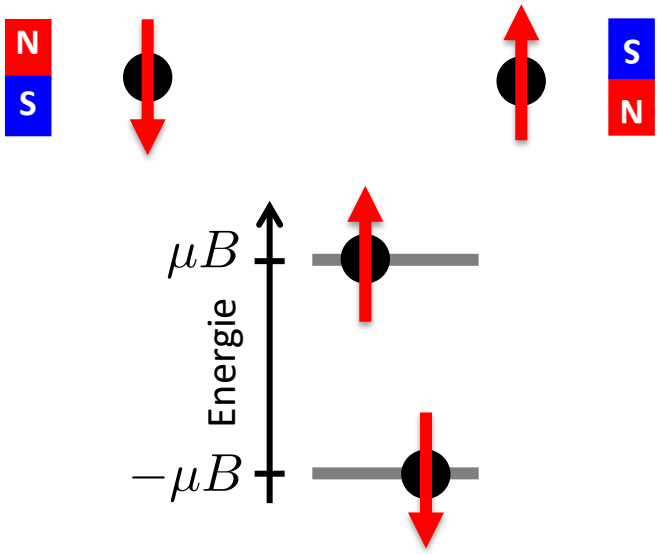




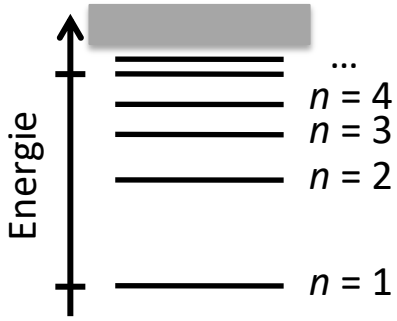
Centres NV **Spin électronique** **Circuits supracond.** **Polaritons (½ cond.)**

Correspondance entre système à 2 niveaux et spin 1/2

Spin ½ dans un champ B

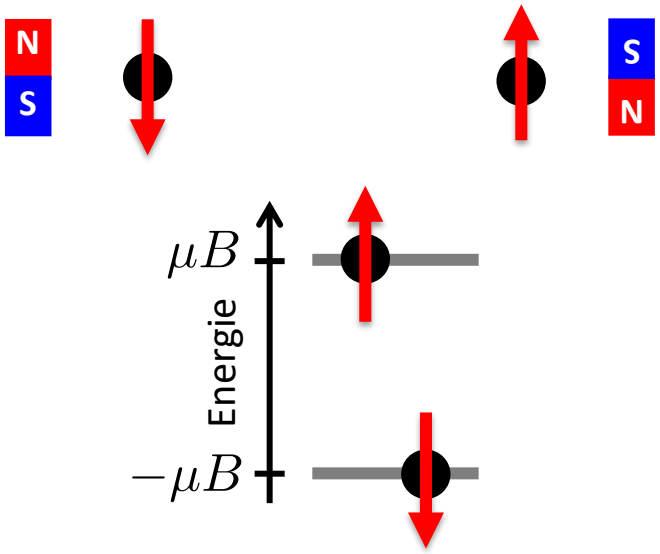


Atomes

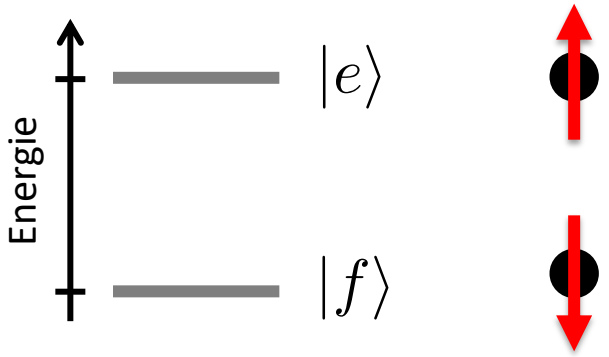


Correspondance entre système à 2 niveaux et spin 1/2

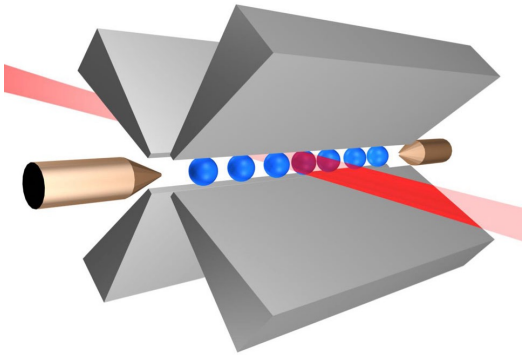
Spin ½ dans un champ B



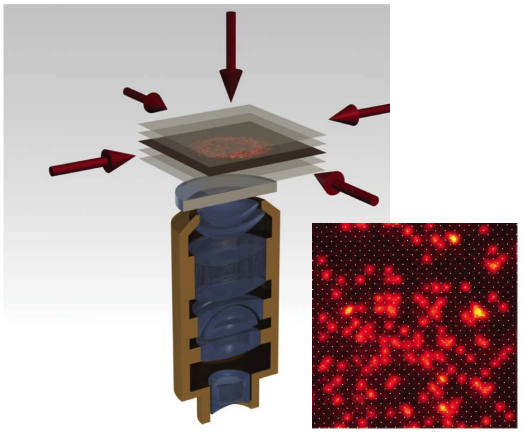
Atomes « à 2 niveaux »



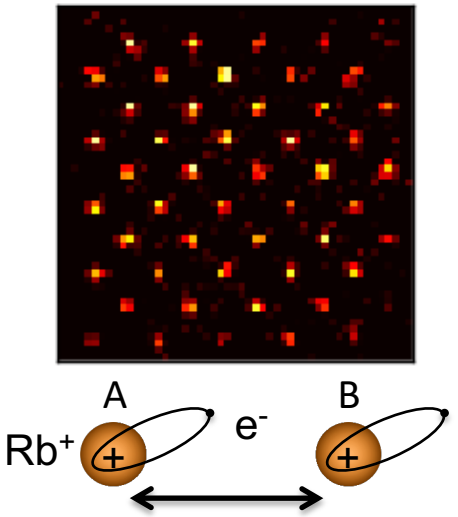
Exemples de réseaux d'atomes individuels



Ions piégés



Atomes dans
réseaux optiques



Atomes dans
pinces optiques

Scalable: plus de 100 atomes

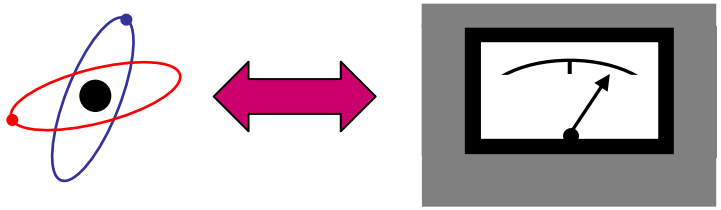
Adressable: manipulations et mesures locales

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

Programmable: contrôle géométrie, interactions…

Pourquoi ingénierie quantique est-elle si difficile ?

Superposition quantique = **très fragile**!! **Décoherence**

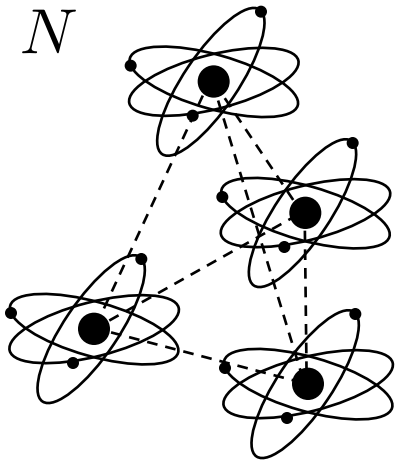


$\alpha|g\rangle + \beta|e\rangle$ Environnement “mesure”

Mélange statistique (classique)

$|g\rangle, |\alpha|^2$ or $|e\rangle, |\beta|^2$

Plus c’est gros, plus ça « décohère »…



$N\,\Gamma$

Environnement

Le programme…

1. Physique à N-corps, simulation quantique et systèmes quantique synthétiques

2. Exemples de simulateurs quantiques
   - A. Ions piégés
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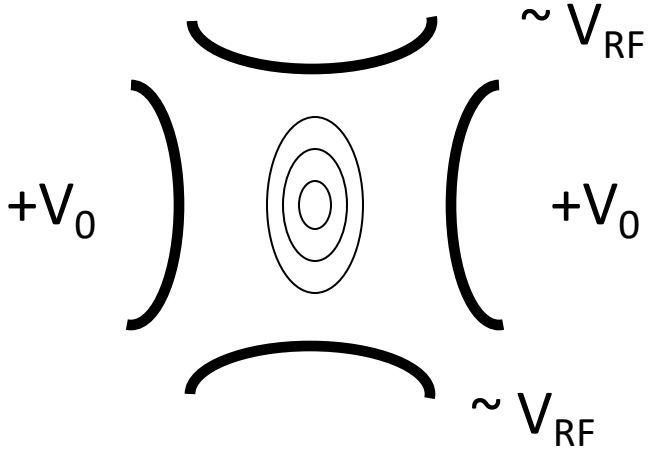
   - C. Atomes froids dans des pinces optiques

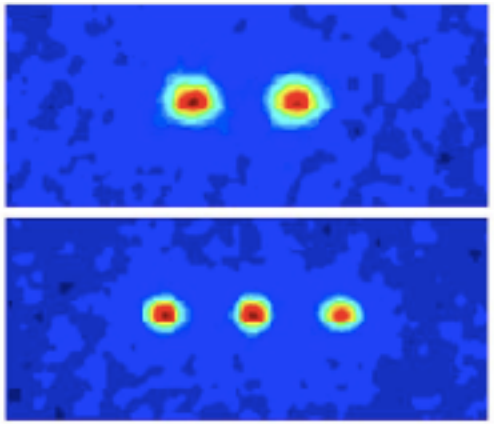
3. Exemples de simulation quantique

Piégeage d'ions refroidis par laser

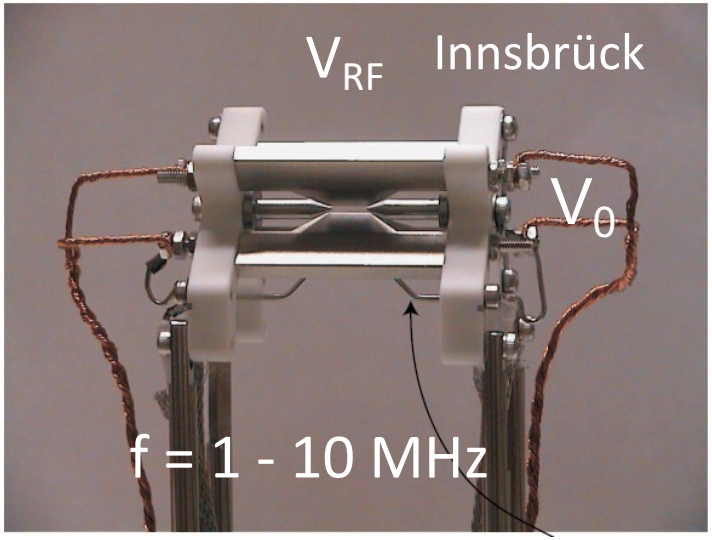
Piège de Paul (RF + statique)

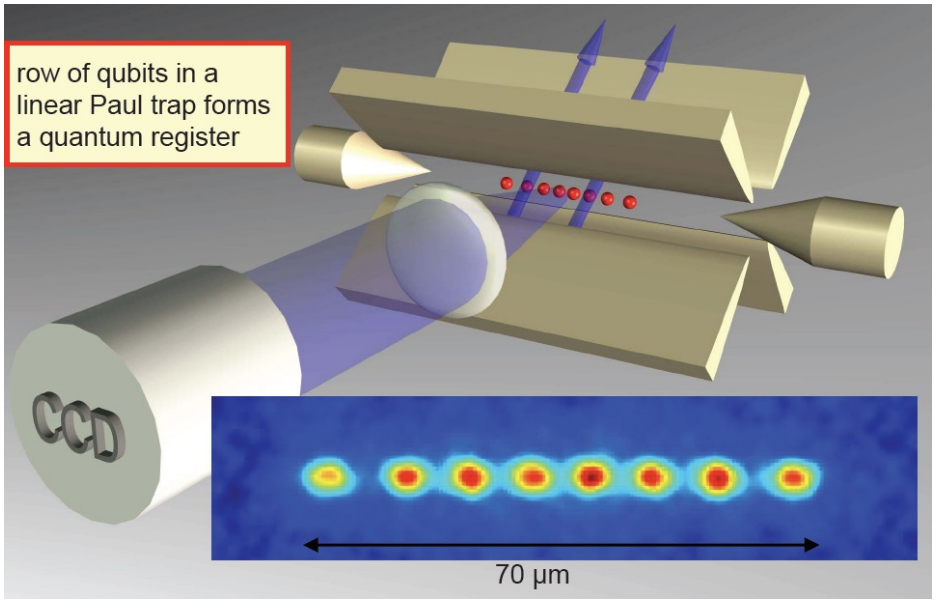


Répulsion de Coulomb
$\Rightarrow$ Cristal ionique



Piège de Paul linéaire

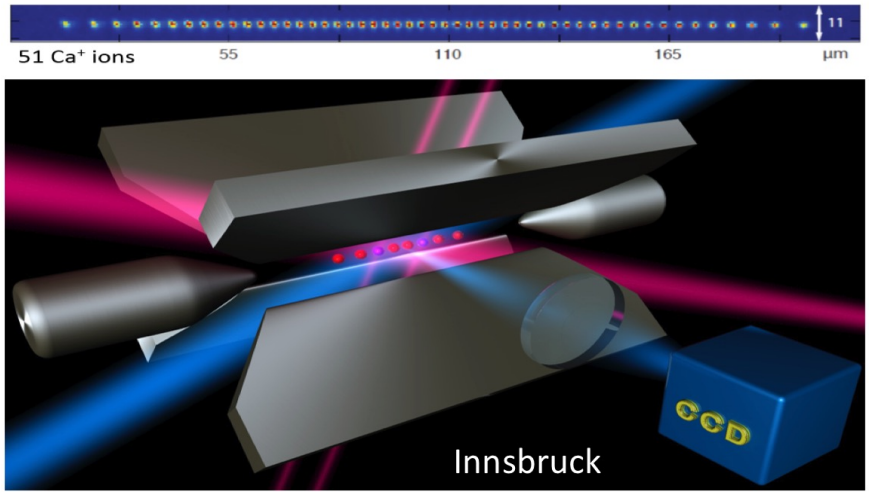




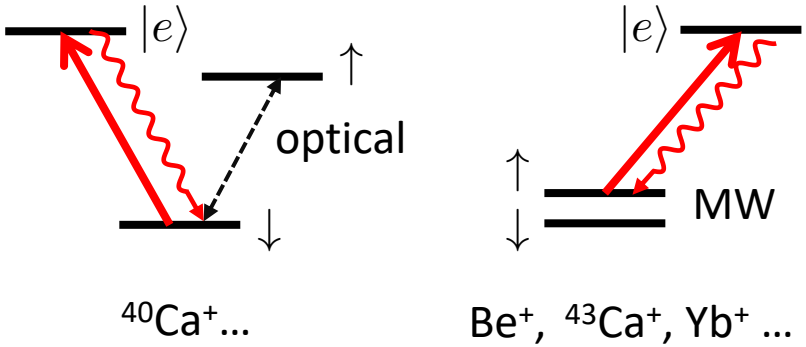
Innsbrück

Simulateur à ions piégés: modèles de spin

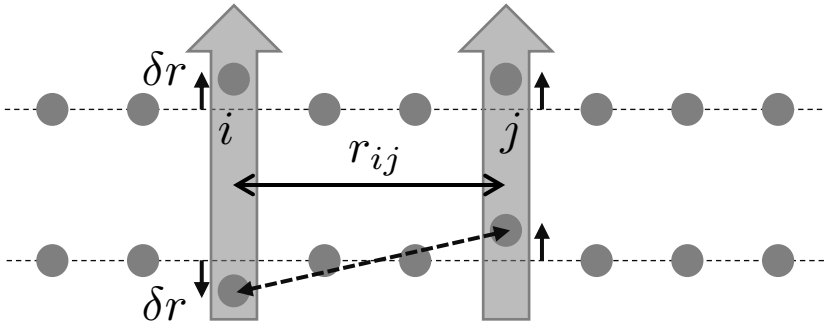
Cristal de Coulomb



« Coder » le spin 1/2



Force lumineuse dépendant de l'état



Les Hamiltoniens

$$H_{\mathrm{XY}} = \sum_{i,j} J_{ij}(\hat{\sigma}_i^{+}\hat{\sigma}_j^{-} + \hat{\sigma}_i^{-}\hat{\sigma}_j^{+})$$

$$H_{\mathrm{Ising}} = \sum_{i,j} J_{ij}\hat{\sigma}_i^{x}\hat{\sigma}_j^{x} + \frac{\delta}{2}\sum_{i}\hat{\sigma}_i^{z}$$

$$J_{ij} \approx \frac{J_0}{|i-j|^{\alpha}} \ , \ \alpha = 0.5 - 2.5$$

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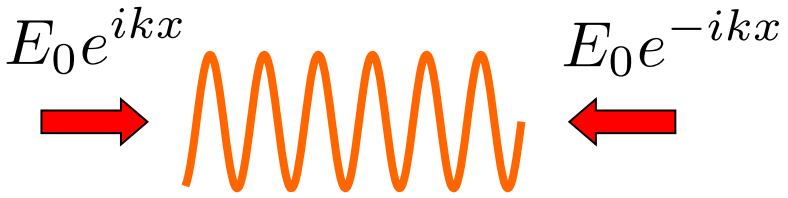
3. Exemples de simulation quantique

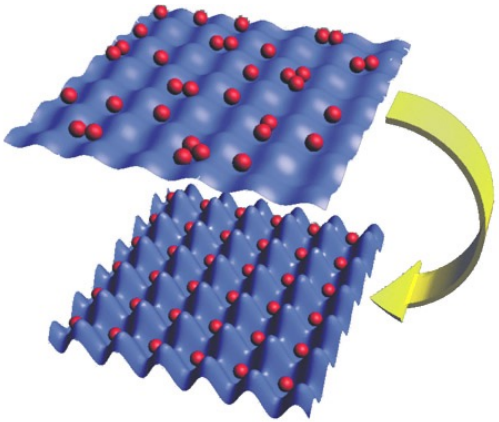
Atomes ultra-froids dans les réseaux optiques

Force dipolaire: $\mathbf{F} \propto -\nabla I(\mathbf{r})$



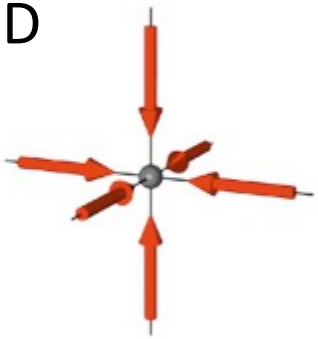
$$I(x) = 2E_0^2(1 + \cos 2kx)$$

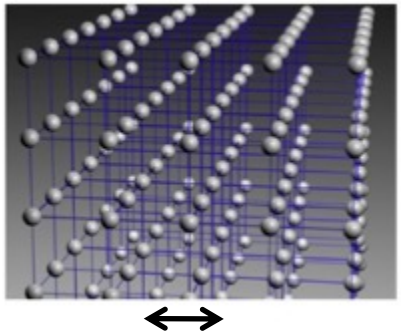
Chaque site contient 1 atome !



Boson (Rb, Na, ^{7}Li, ^{39}K, ^{4}He*),
Fermion (^{6}Li, ^{40}K),
Magnetic atoms (Cr, Dy…)

3D

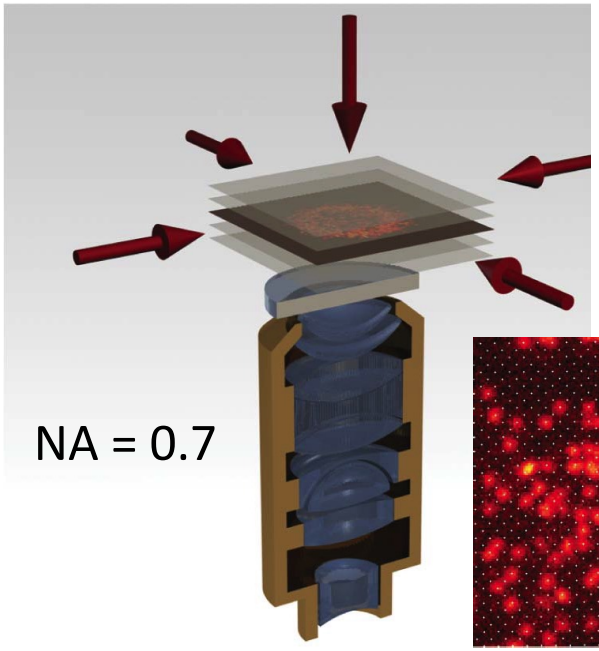




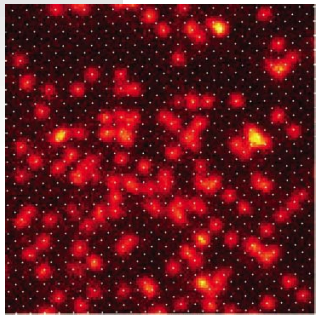
(M. Greiner thesis)

λ/2 = 0.5 μm

Quantum gas microscope



Single-site resolution (< 1 μm)

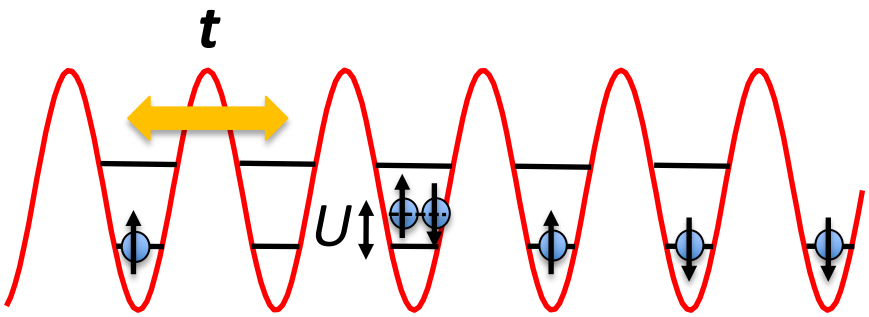


Harvard, MPQ

16 μm

Réseaux optiques: modèles de Hubbard et de spin

Compétition effet tunnel / interaction



U contrôlable par B!!

Modèles d'Hubbard

$$H = -t \sum_{\langle i,j \rangle} (a_i^\dagger a_j + \text{h.c.}) + \frac{U}{2} \sum_i n_i (n_i - 1)$$

Modèle le plus simple:
conductivité / interaction

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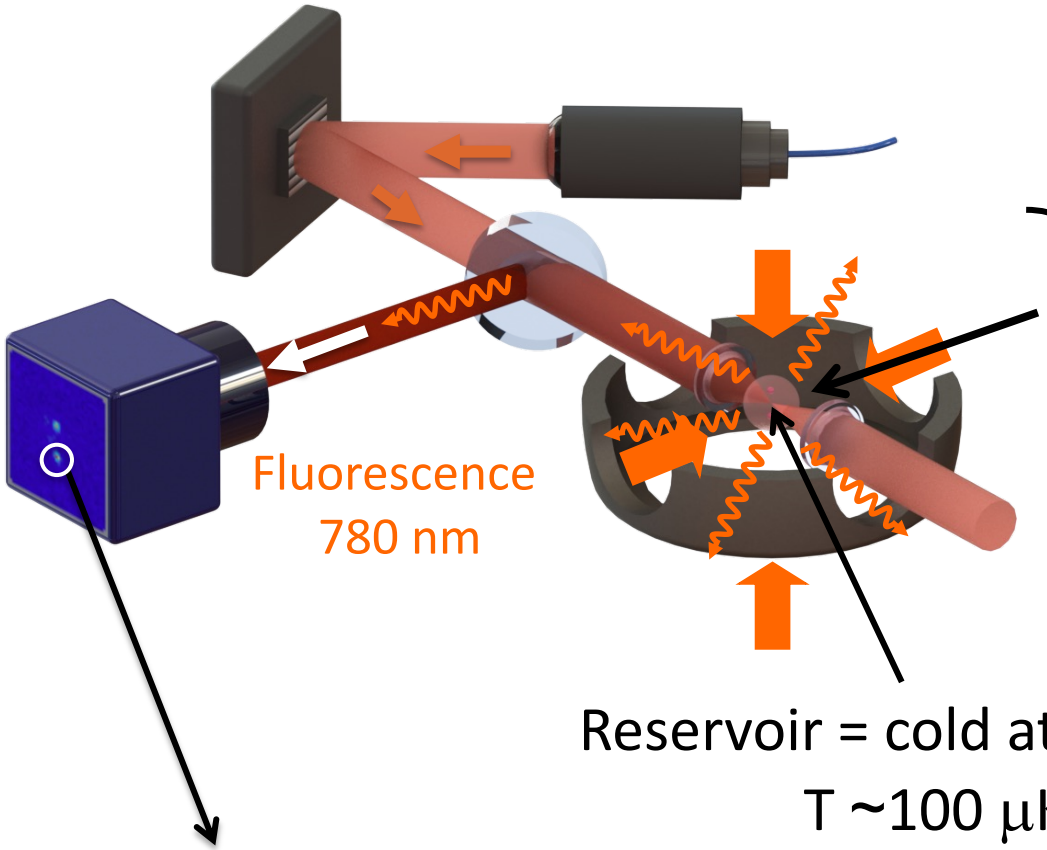
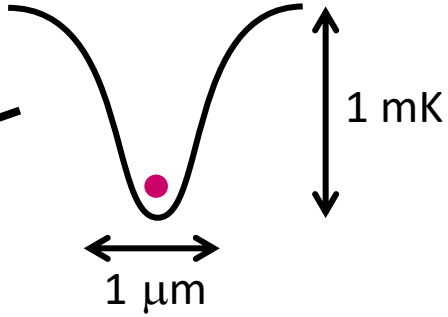
   - C. Atomes froids dans des pinces optiques

3. Exemples de simulation quantique

Atomes dans des matrices de pinces optiques

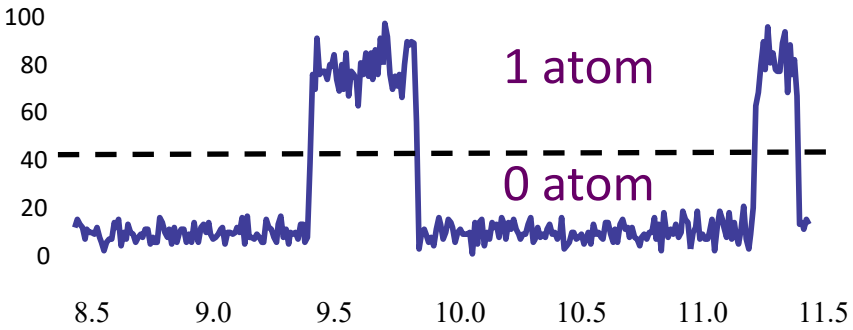


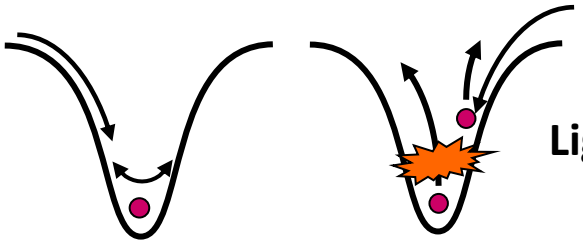


Grangier (2001)
Sortais (2007)

Reservoir = cold atoms ^{87}Rb

T ~100 μK



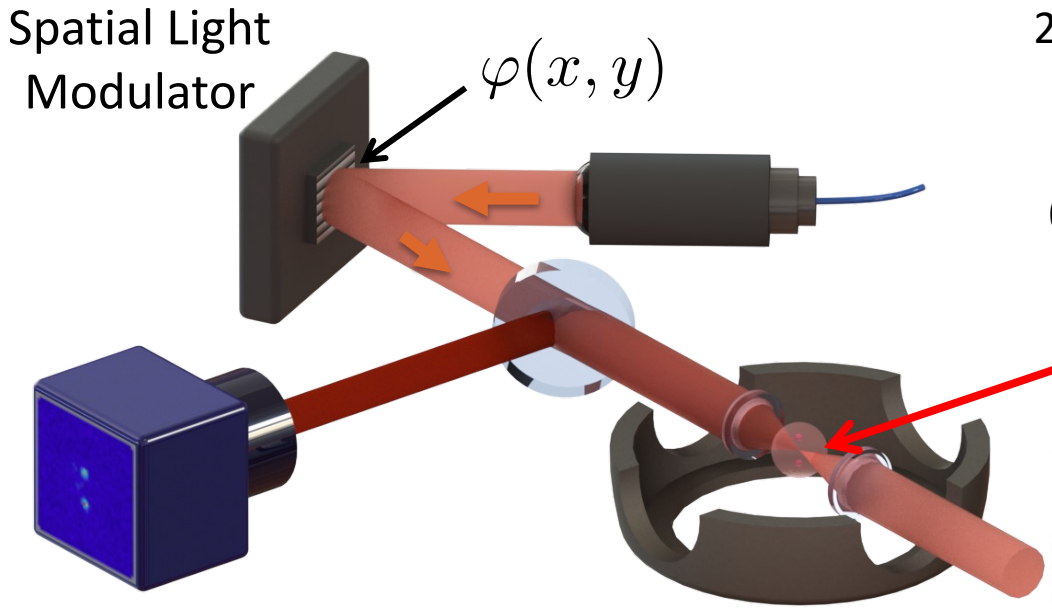


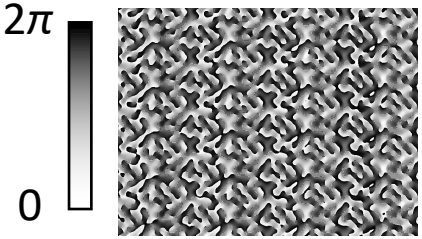
Light-assisted collisions

Non-deterministic

single-atom source

Atomes dans des matrices de pinces optiques

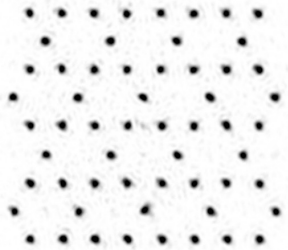




SLM pattern

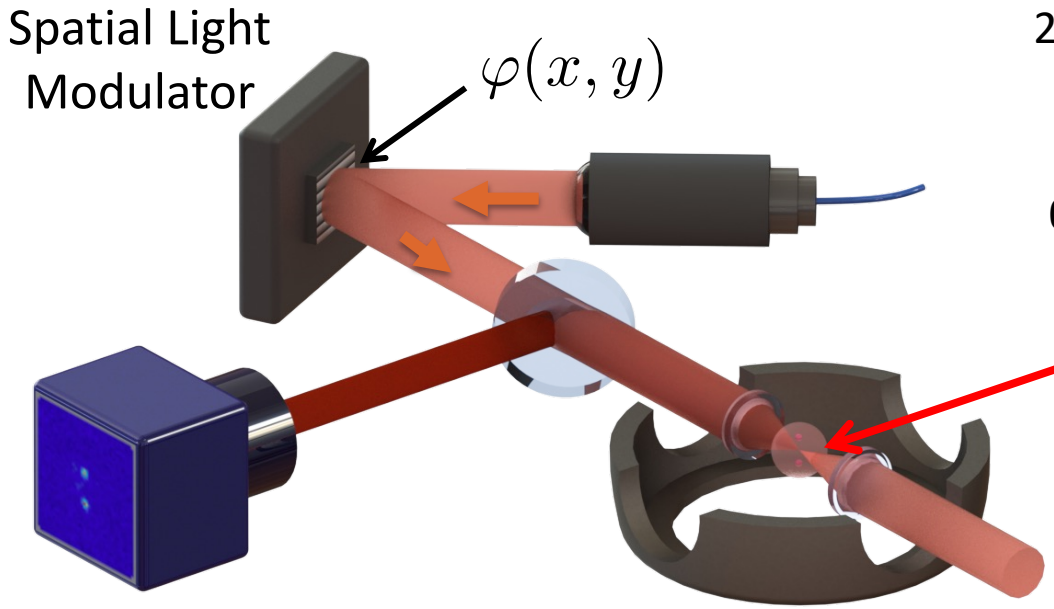
Nogrette, PRX (2014)

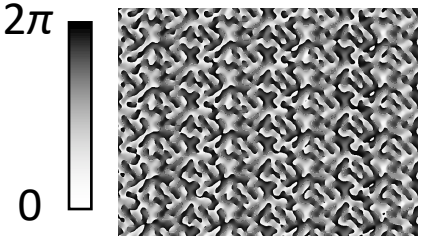
$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$



10 µm

Atomes dans des matrices de pinces optiques



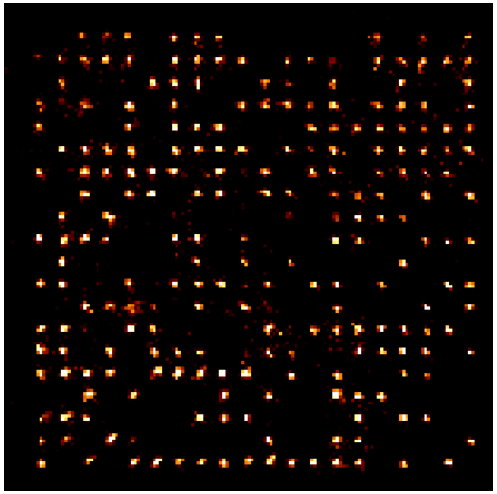


SLM pattern

Nogrette, PRX (2014)

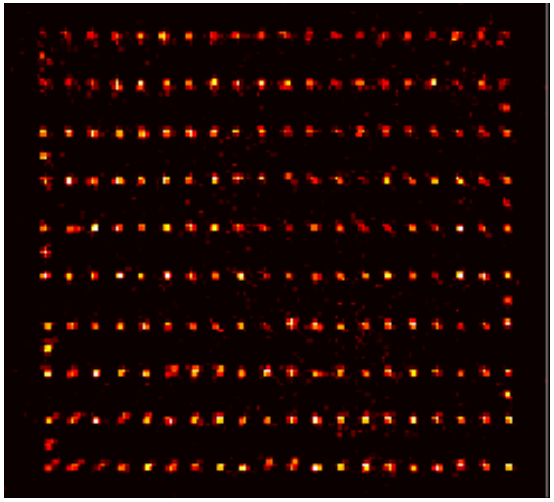
$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

Initial configuration

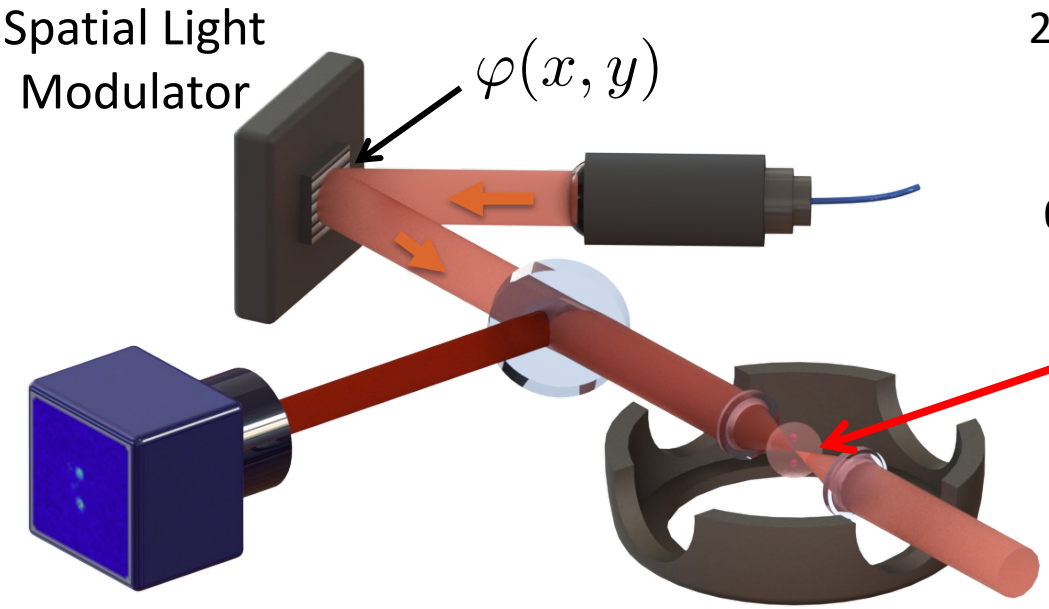


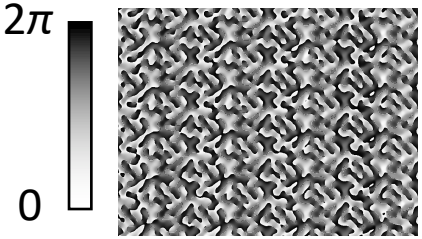
Assembling process

Assembled configuration



Atomes dans des matrices de pinces optiques





SLM pattern

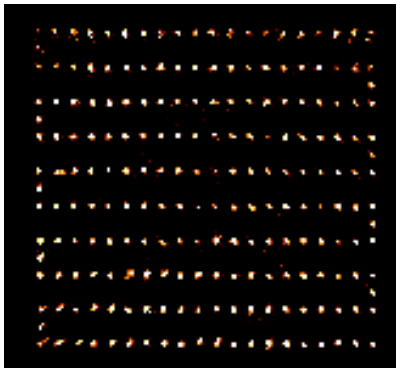
Nogrette, PRX (2014)

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

L. da Vinci

Assembled arrays of individual atoms ($N \sim 200$)

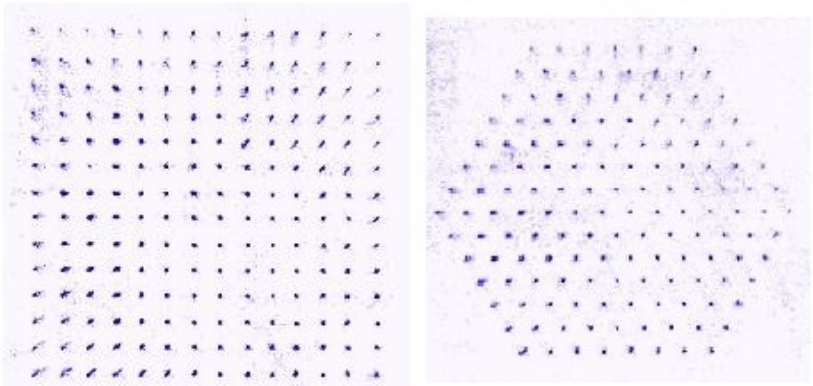
1D



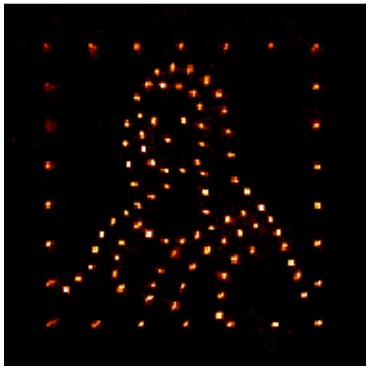
~100 µm

2D

Fluorescence: single shot!!



Random

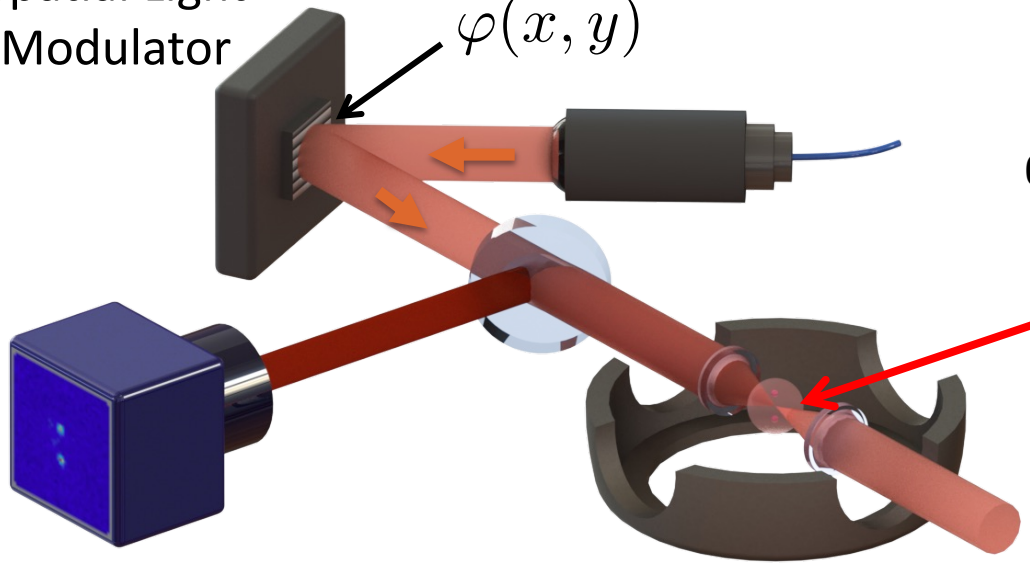


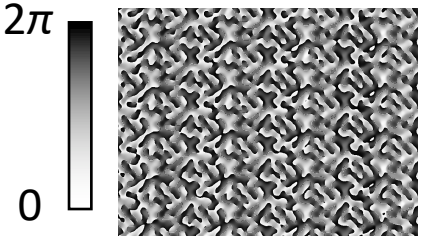
Barredo, Nature 2016 ; Schymik, PRA 2020

Atomes dans des matrices de pinces optiques

Spatial Light Modulator

$\varphi(x, y)$



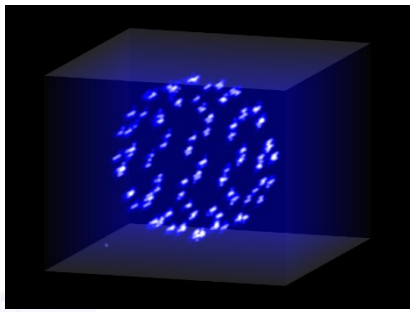


SLM pattern

Nogrette, PRX (2014)

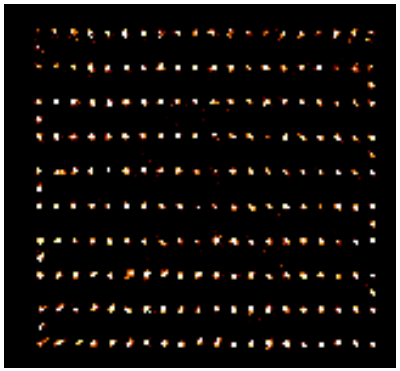
$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

Assembled arrays of individual atoms ($N \sim 200$)



(averaged)

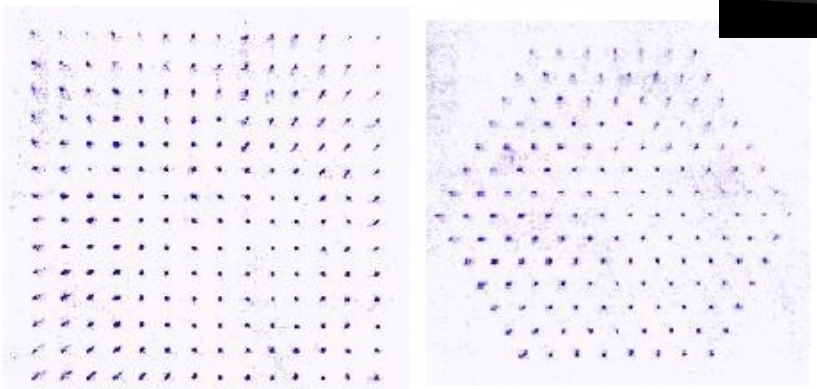
1D



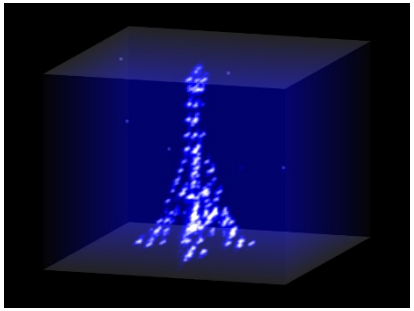
~100 µm

2D

Fluorescence: single shot!!



Barredo, Nature 2016 ; Schymik, PRA 2020

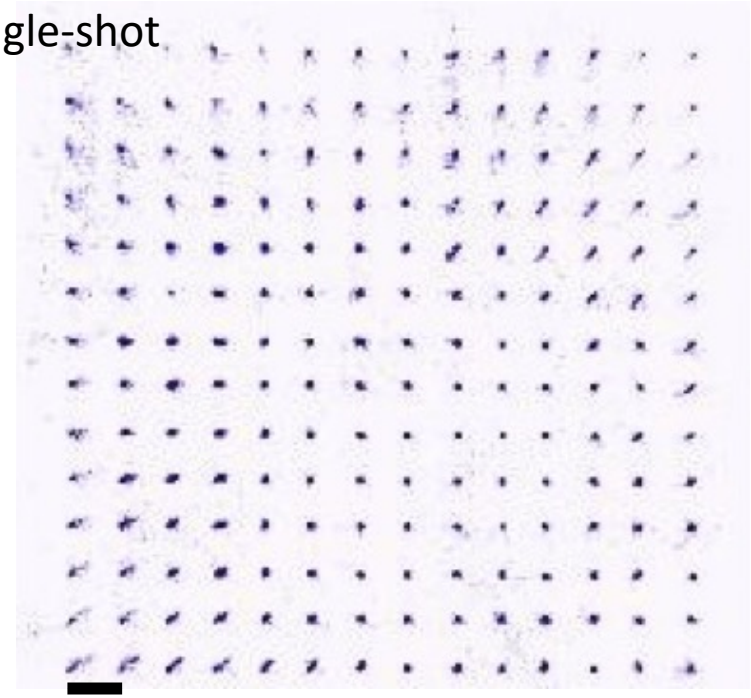


Barredo, Nature (2018)

Arrays of interacting Rydberg atoms

Arrays of atoms

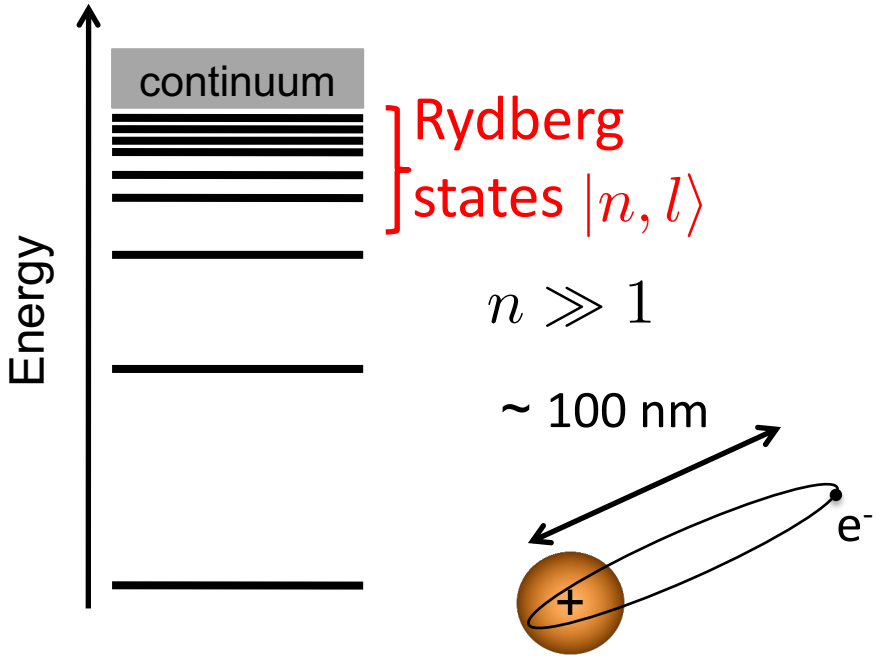
Single-shot



5 µm

Addressable!!

Rydberg atoms



Lifetime > 100 µs

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

⇒ Large dipole-dipole interactions

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

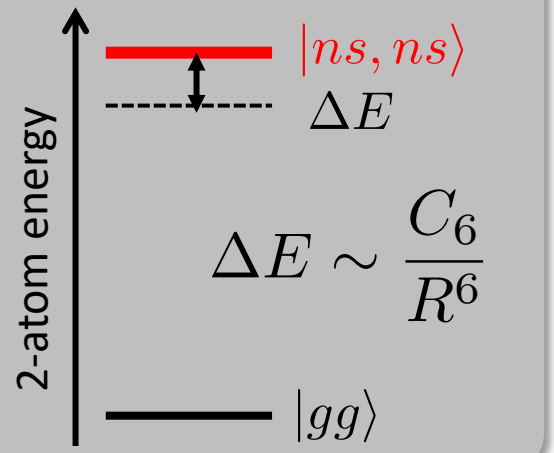
⇒ timescales < µsec

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

Interactions between Rydberg atoms and spin models

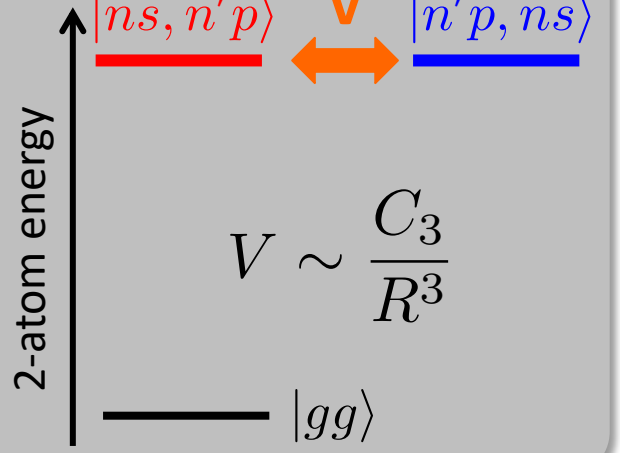
Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals



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

Resonant dipole



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

Quantum Ising

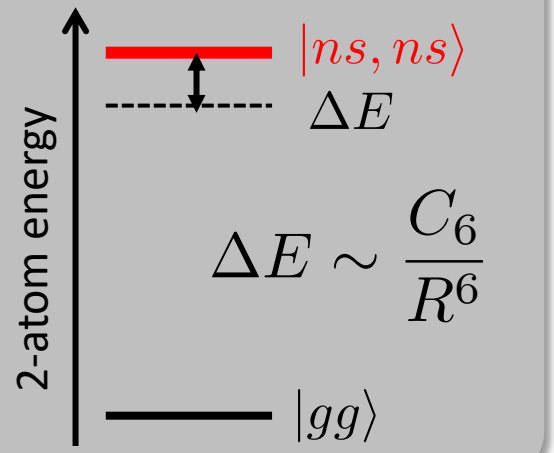
$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

XY model

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

From van der Waals interactions to Ising model…

van der Waals



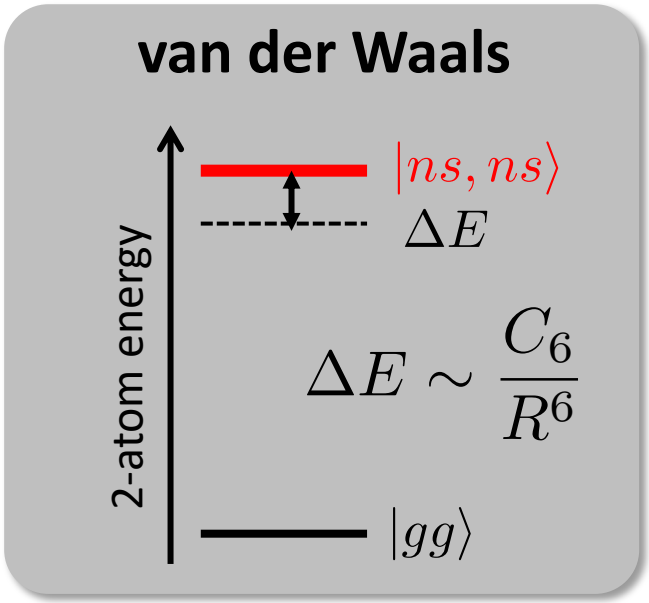
$$\Delta E \sim \frac{C_6}{R^6}$$

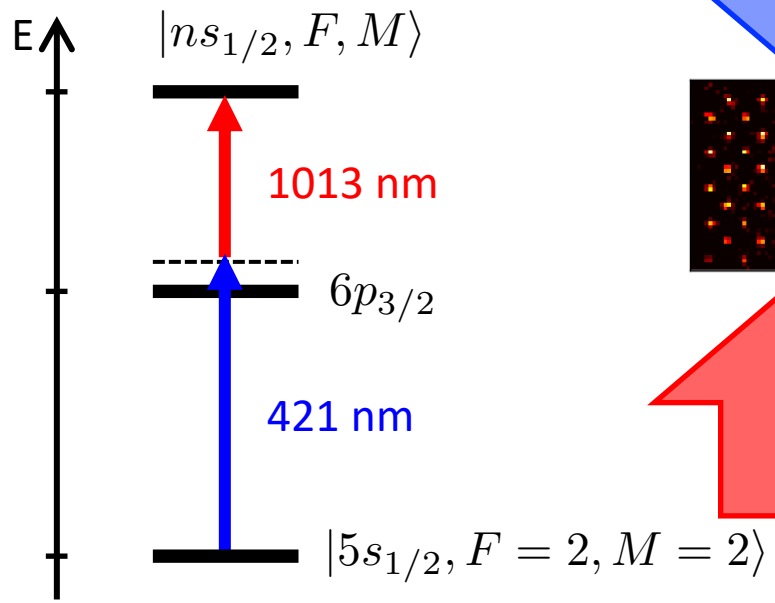
$C_6 \propto n^{11} \Rightarrow$ switchable interaction

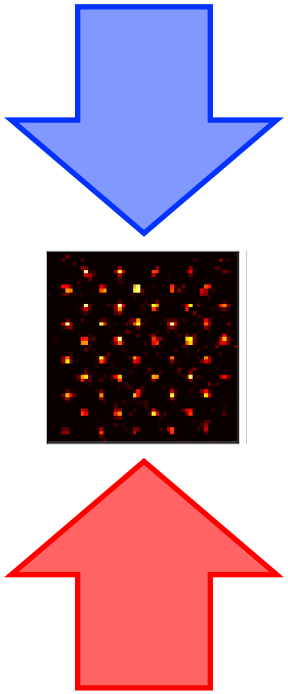
$$\hat{H}_{\text{int}} = \frac{C_6}{R^6}\hat{n}_1\hat{n}_2 \sim J\,\hat{\sigma}_1^z\hat{\sigma}_2^z$$

Rydberg occupation number

From van der Waals interactions to Ising model…

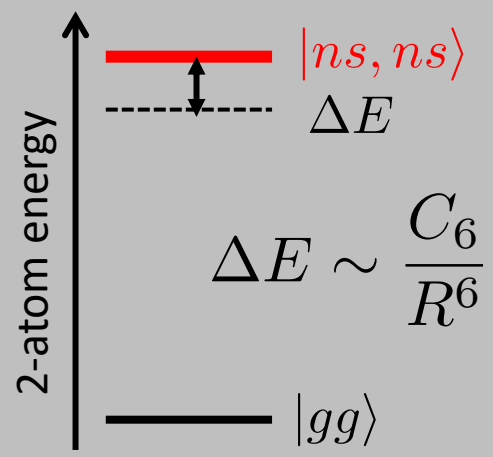


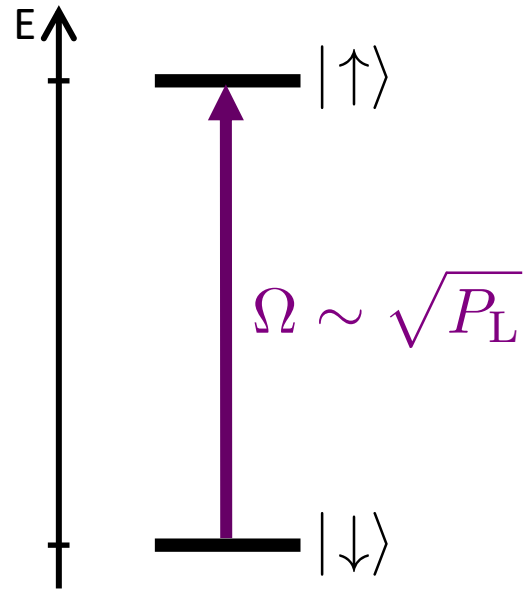


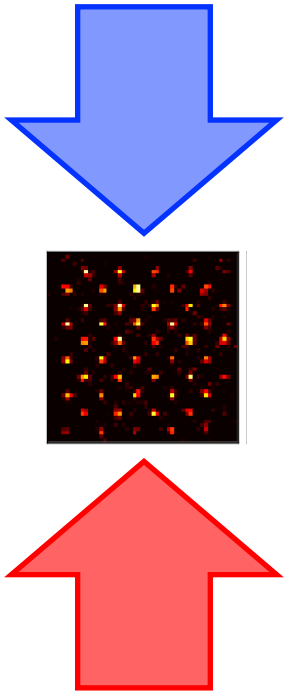


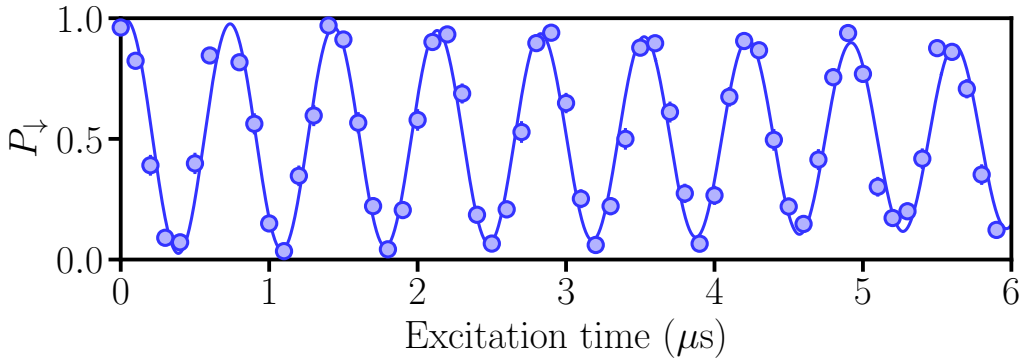
From van der Waals interactions to Ising model…

van der Waals



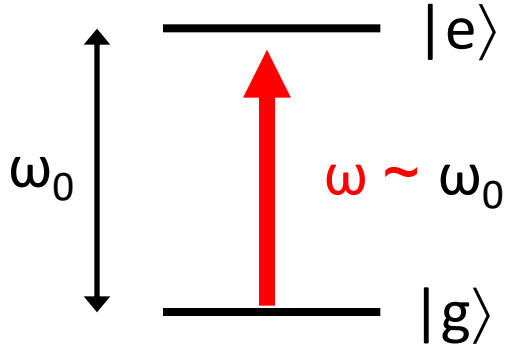






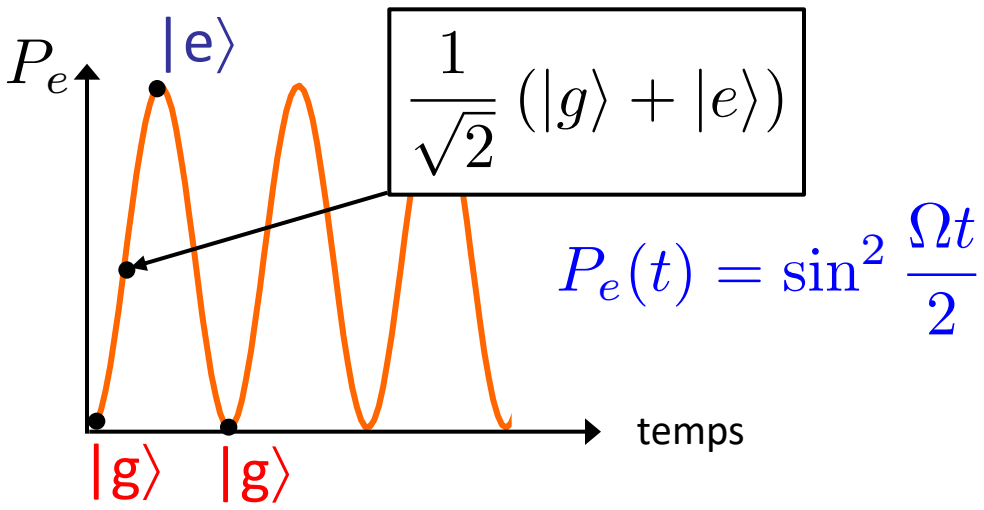
Les oscillations de Rabi à un atome

Oscillations de Rabi (1930s!): émission stimulée

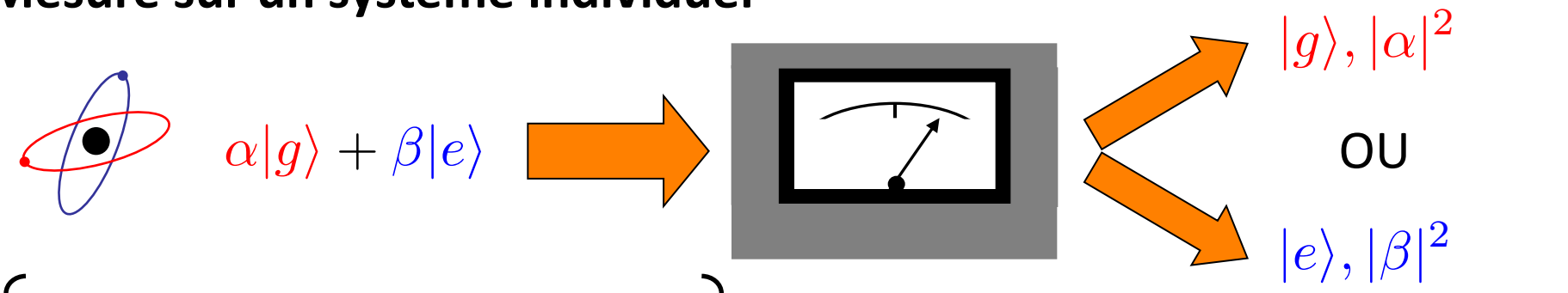


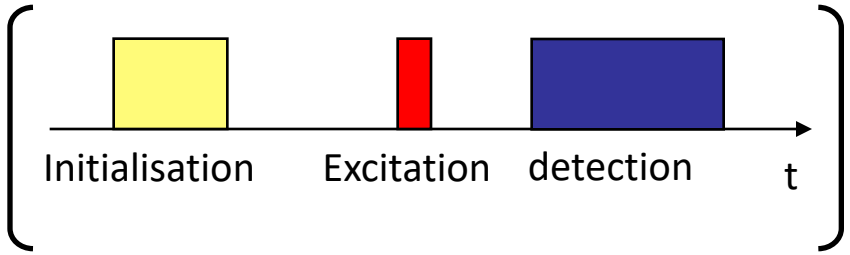
Ω = fréquence de Rabi

$$\propto \sqrt{\text{Intensity}}$$



Mesure sur un système individuel





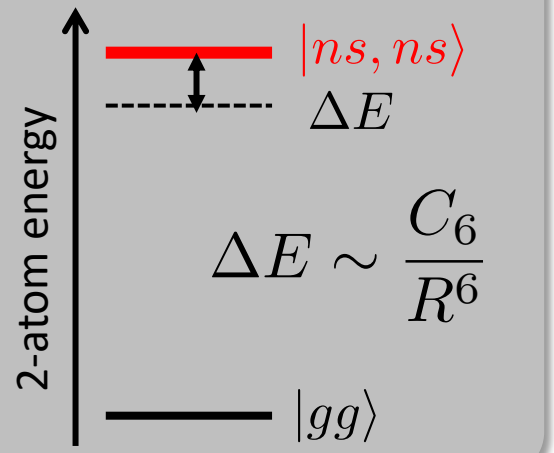
× **100**

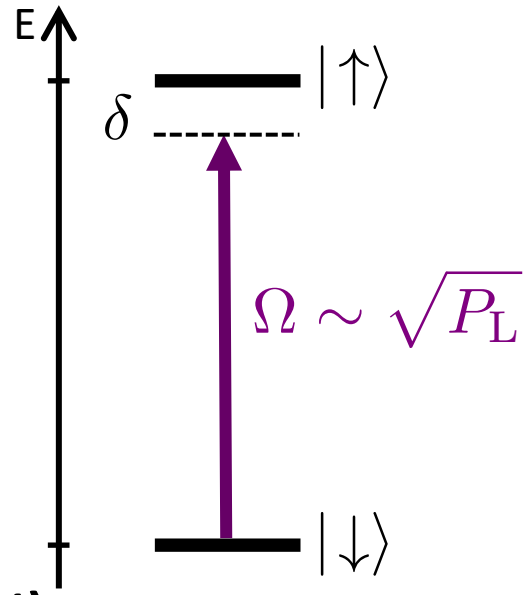
|g⟩, |e⟩, |e⟩, |g⟩, …, |e⟩, |g⟩

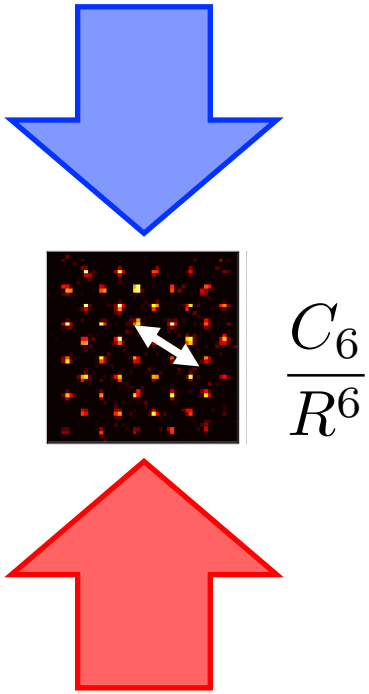
⇒ Probabilité P(g)

From van der Waals interactions to Ising model…

van der Waals



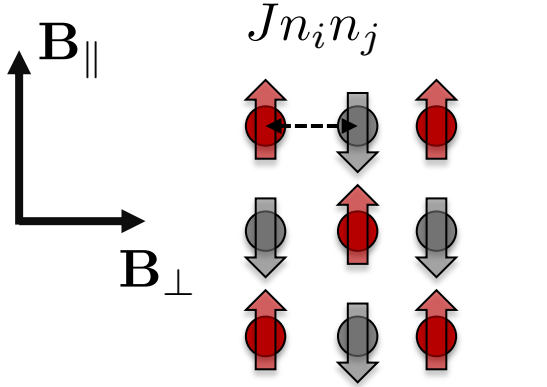




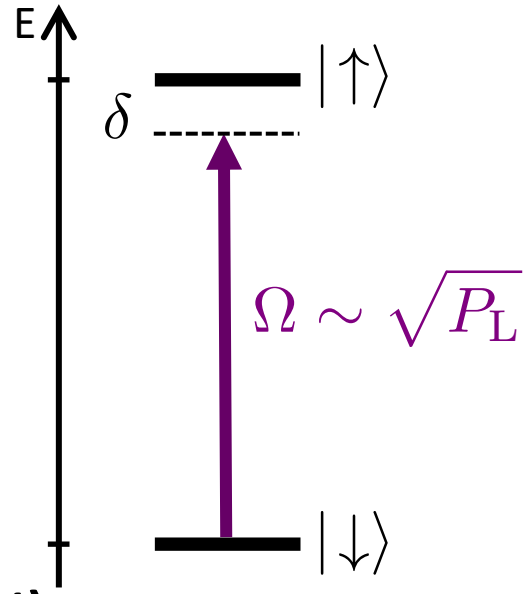
Quantum Ising-like model (s=½):

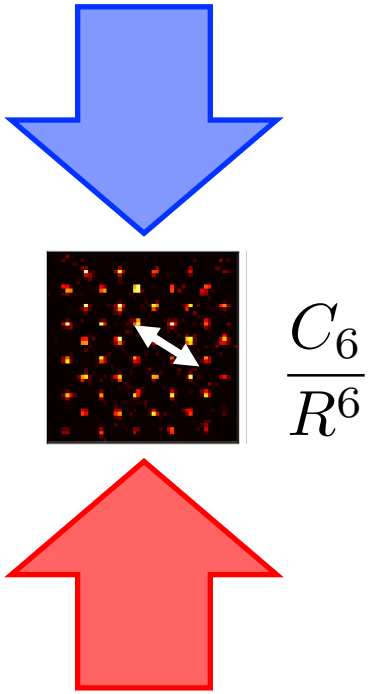
$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i + \hbar\delta\sum_i \hat{n}_i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

From van der Waals interactions to Ising model…



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





Quantum Ising-like model (s=½):

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

Experimt[t].

$$\frac{C_6/a^6}{\Omega} = [0-20]$$

Laser: $B_\perp$ $B_\parallel$ Spin-spin interaction

Le programme…

1. Physique à N-corps, simulation quantique et systèmes quantique synthétiques

2. Exemples de simulateurs quantiques: ions et atomes

3. Exemples de simulation quantique

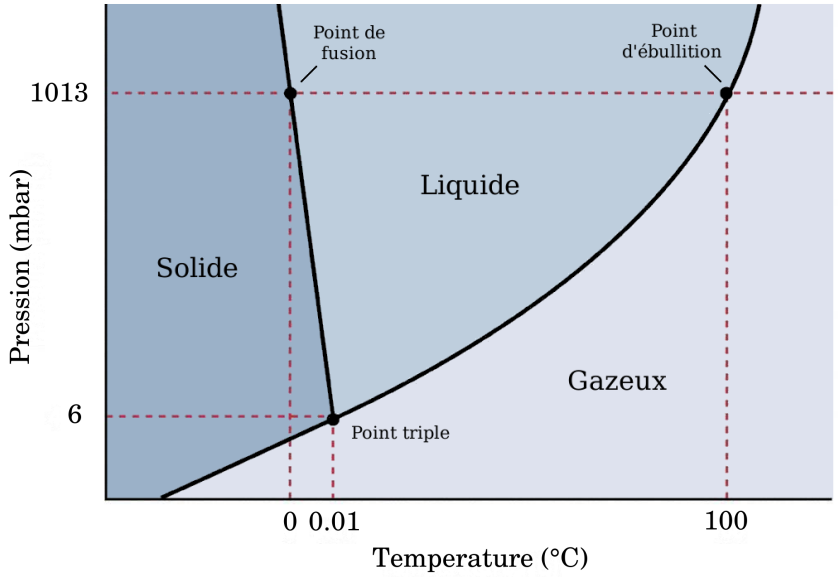
    A. Exploration du diagramme des phases

    B. Dynamique hors-équilibre

Diagramme des phases

Etat fondamental d'un système en fonction de paramètres de contrôle

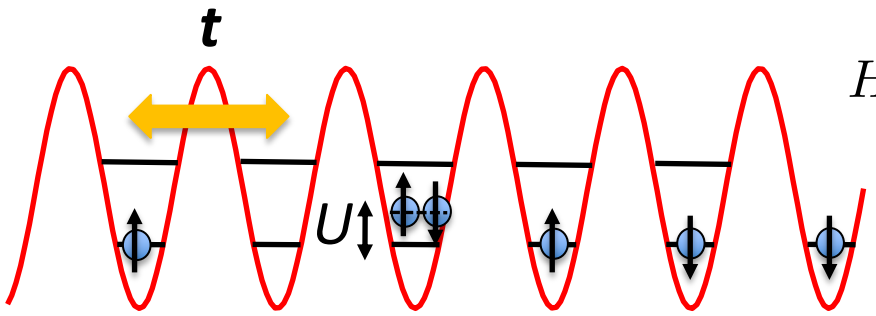
Diagramme des phases de l'eau (*P*,*T*)



Système quantique: $\langle \Psi_f | O | \Psi_f \rangle (T, B, M...)$

Atoms in optical lattices implements Hubbard models

Competition tunneling / interaction

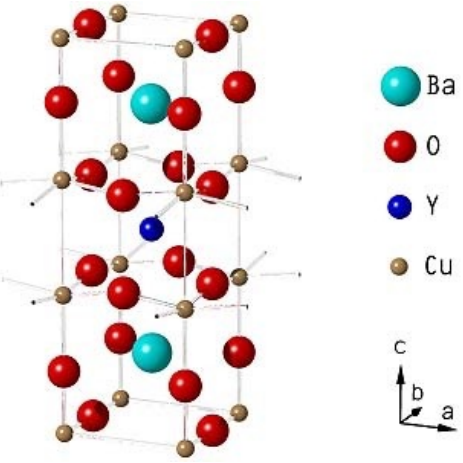


$$H = -t \sum_{\langle i,j \rangle,\sigma} (c^{\dagger}_{i\sigma} c_{j\sigma} + \text{h.c.}) + U \sum_{i} n_{i\downarrow} n_{i\uparrow}$$

Fermi-Hubbard models

U tunable by B-field!!

The simplest model to describe interplay conductivity / interactions

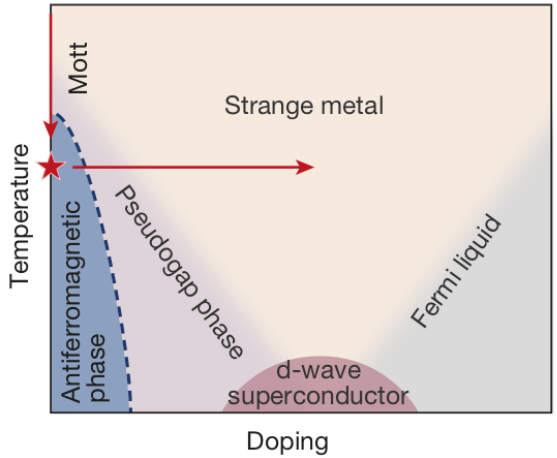


YBa_2Cu_3O7

$d \sim 0.4$ nm

$T_c = 92$ K

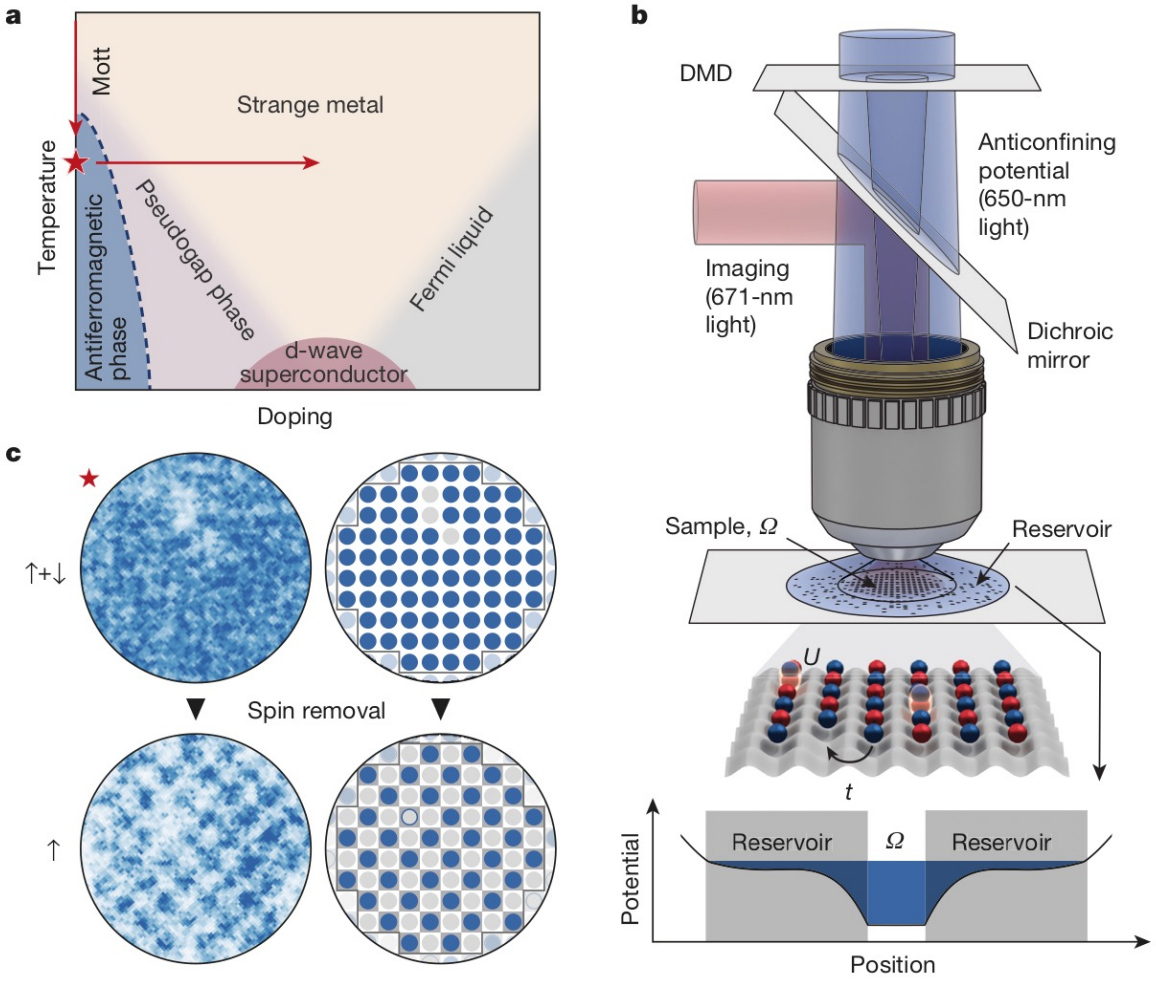
YET: not solved!



Believed to explain high-Tc superconductivity

Accessing the AF phase using a quantum simulator

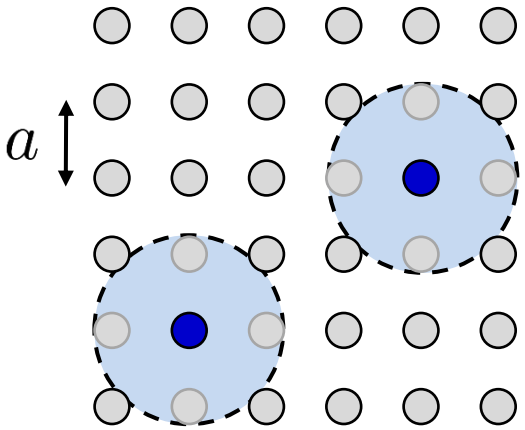
Greiner, Nature 2017



Also: Bloch (MPQ), M. Koehl (Bonn), Kuhr (Glasgow), Zwierlein (MIT), Thywissen (Toronto)…

2D Ising anti-ferromagnet on a square

Nearest neighb. interaction

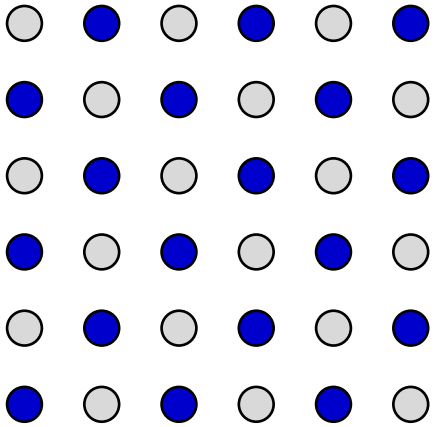


$$\frac{C_6}{a^6} \sim \Omega$$

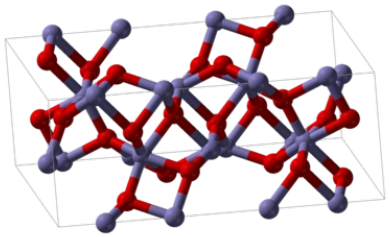
$$\circ = |g\rangle$$

$$\bullet = |r\rangle$$

Anti-ferromagnetic ground state

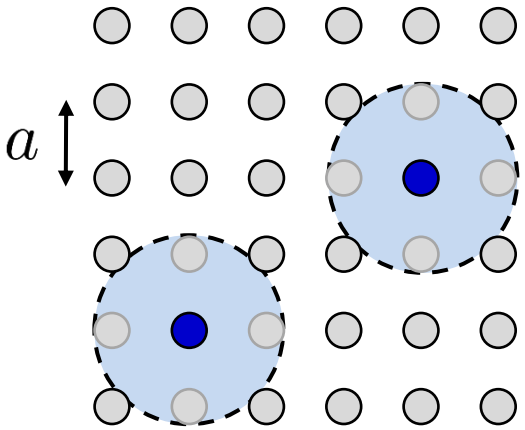


Ex of antiferromagnets: MnO, FeO, CoO, NiO, $FeCl_2$…



2D Ising anti-ferromagnet on a square

Nearest neighb. interaction



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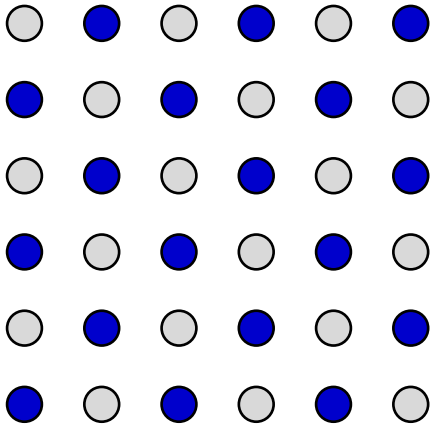
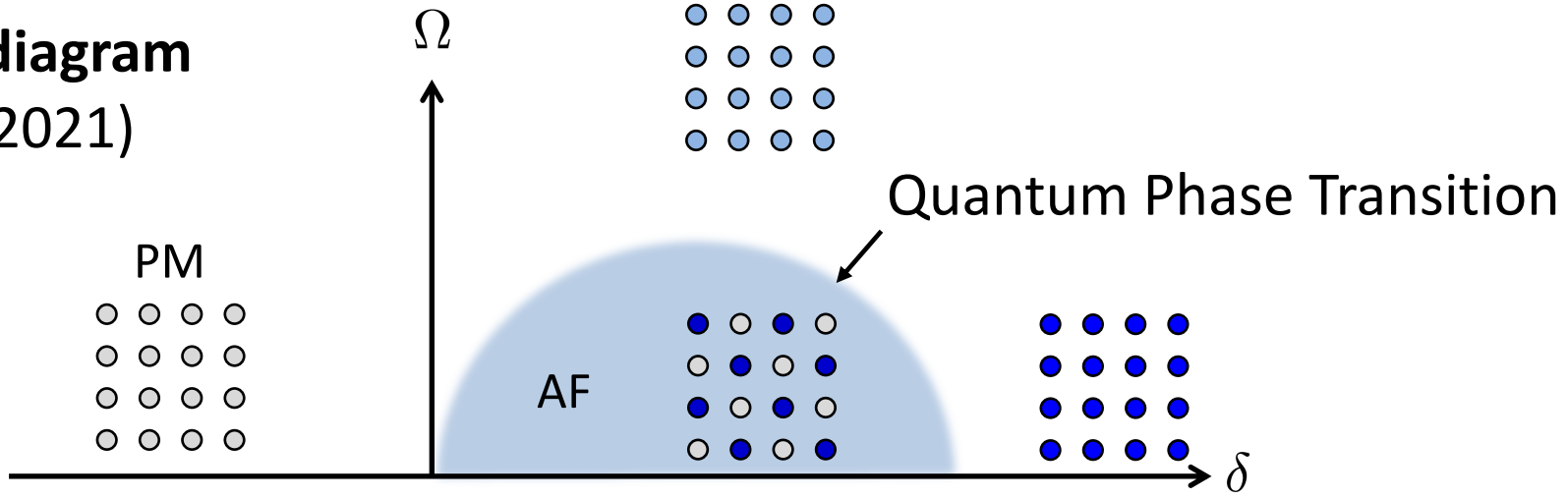
Anti-ferromagnetic ground state



2D phase diagram

(1970 - 2021)



Known by Quantum Monte-Carlo

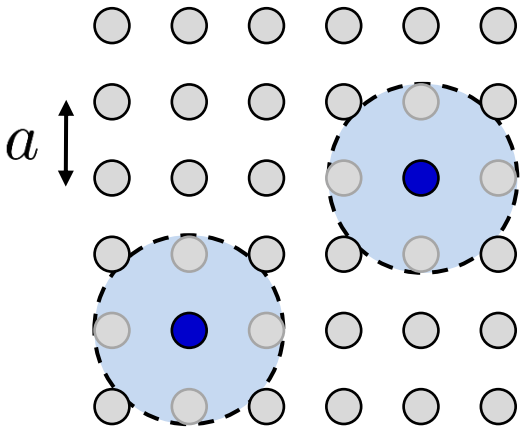
Never measured in 2D…!!!

Fey, Schmidt PRL 2019

Sachdev & Lukin PRL 2020

2D Ising anti-ferromagnet on a square

Nearest neighb. interaction



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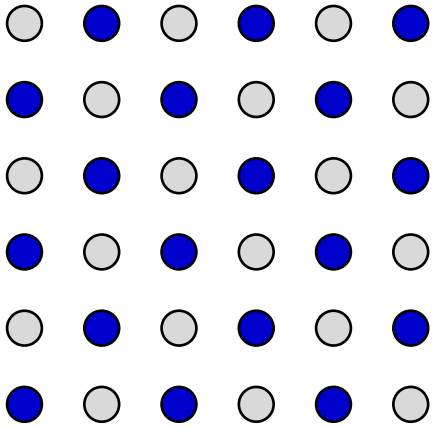
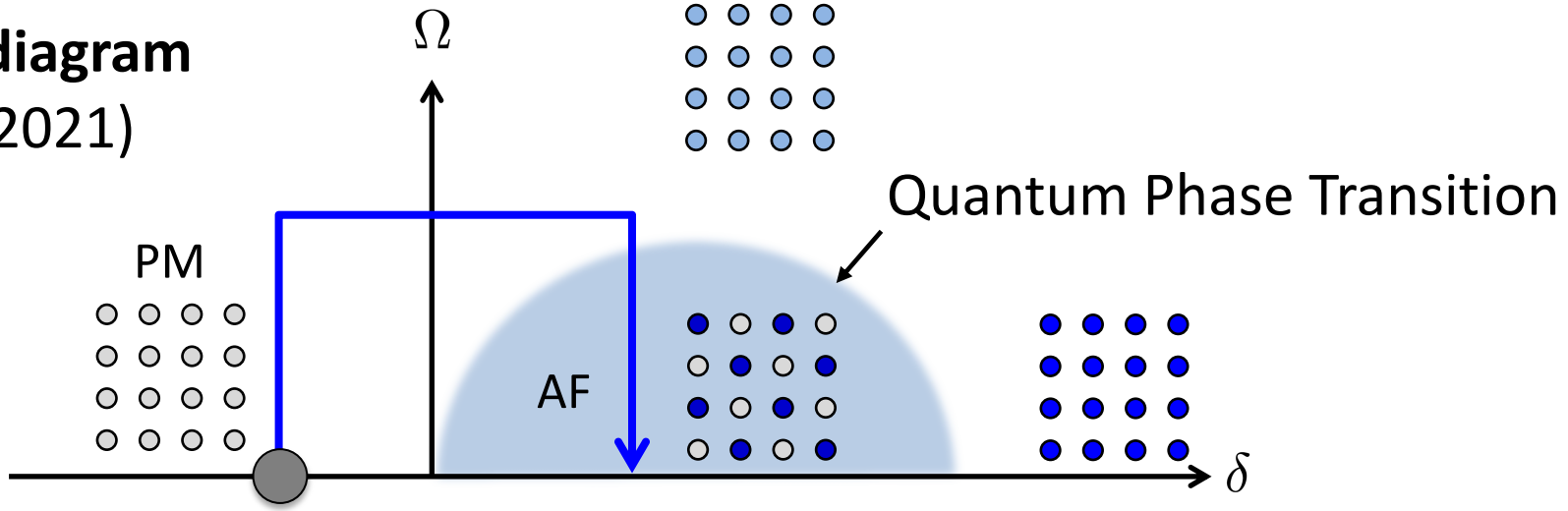
Anti-ferromagnetic ground state



2D phase diagram

(1970 - 2021)

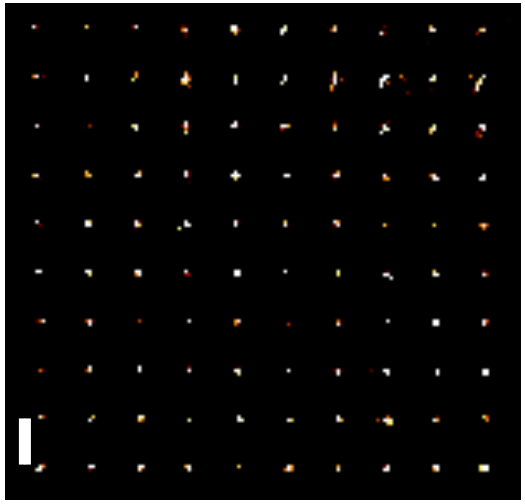


$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2} \sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

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

Scholl et *al.* Nature (2021)

10 × 10 square array



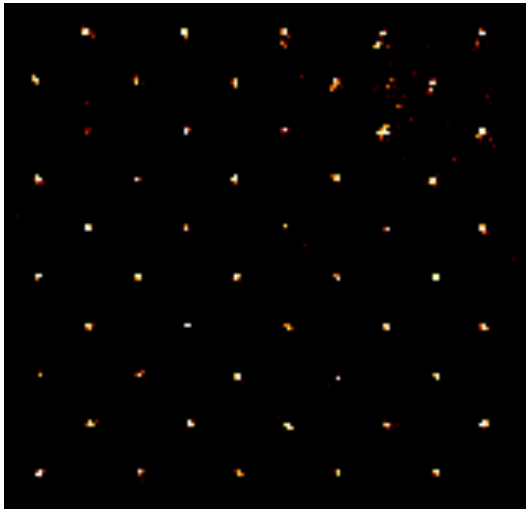
10 μm

$\Omega(t), \delta(t)$

sweep

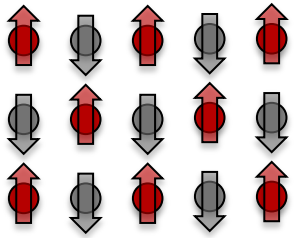
$= |g\rangle$ bright

$= |r\rangle$ dark



n=75s

Perfect AF (Néel) ordering!

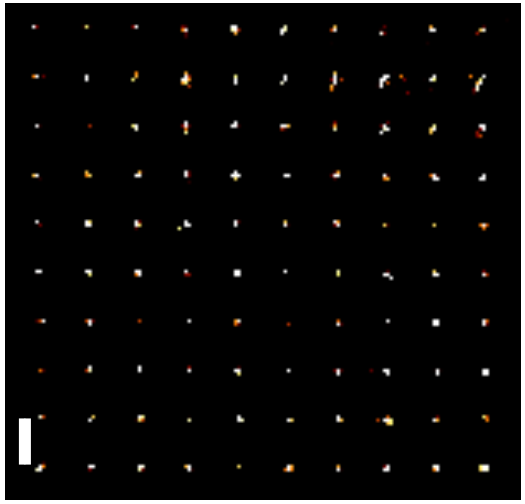


1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin Nature 2021

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

Scholl et *al.* Nature (2021)

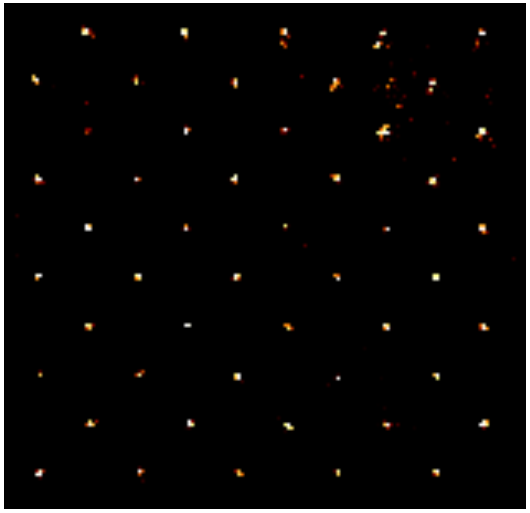
10 × 10 square array



10 µm

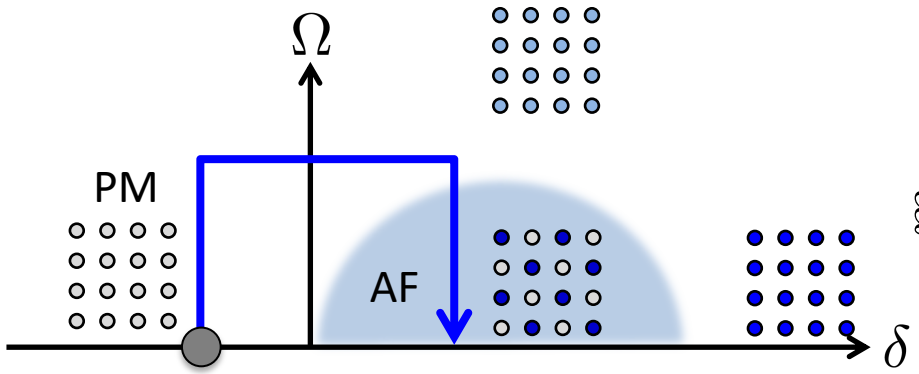
$\Omega(t), \delta(t)$

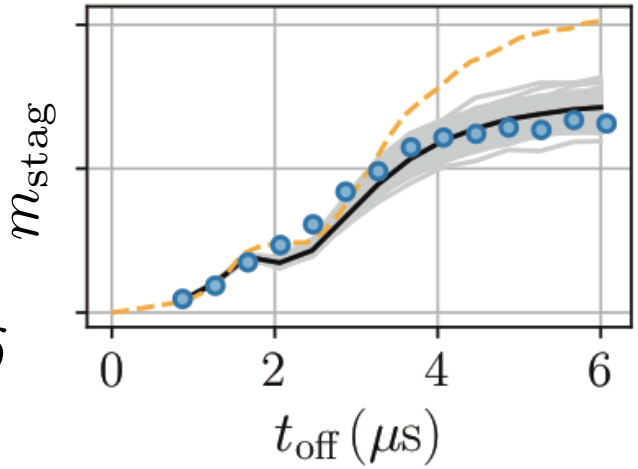
sweep



n=75s

Staggered magnetization: $m_{\text{stag}} = \langle |n_A - n_B| \rangle$





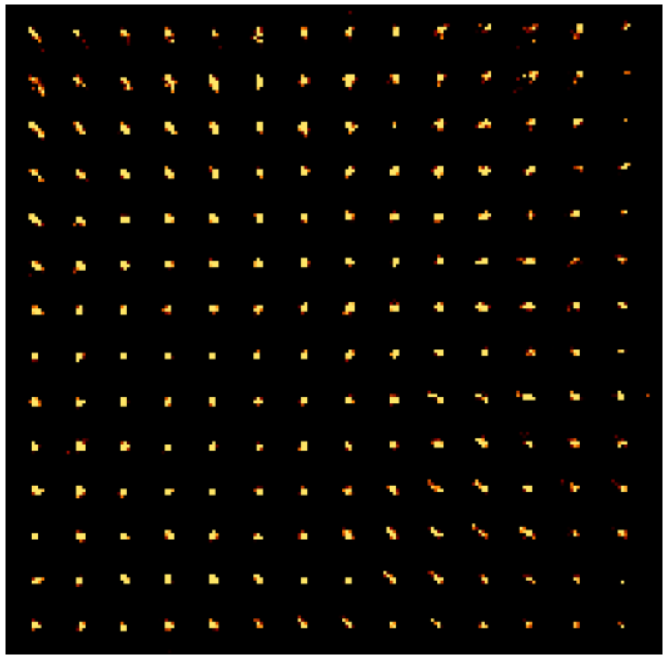
Accurate MPS limited to 10 x 10 (14 days!!)

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

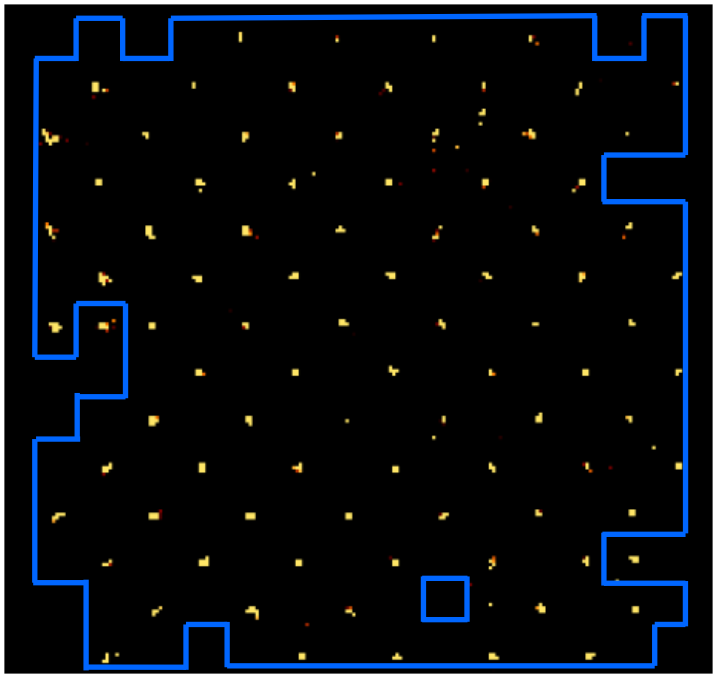
Preparation of a 2D Ising anti-ferromagnet on a square

Scholl et *al.* Nature (2021)

14x14 square array



sweep



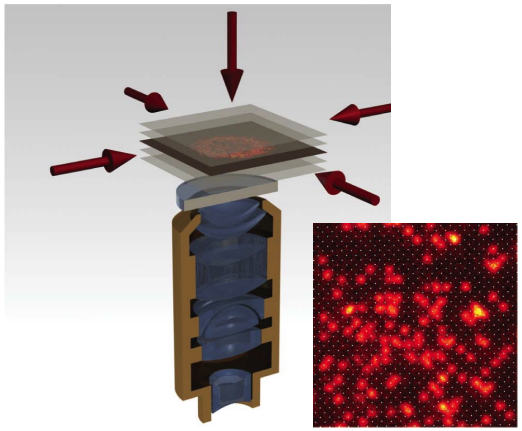
182-atom antiferromagnetic cluster!

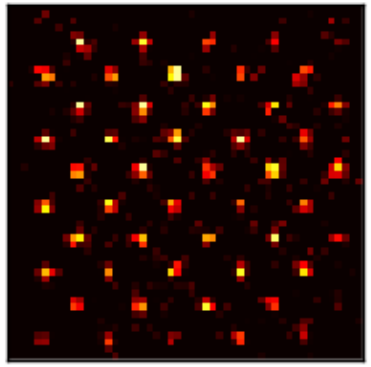
2022: Data beyond $N > 100$ to test of new tensor network methods…!!

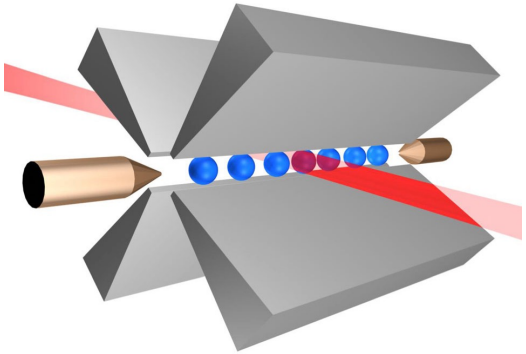
M. Heyl, M. Dalmonte, S. Montangero

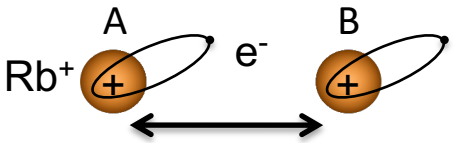
Conclusion

Useful quantum simulators already exist, and challenge theory!!









A very active field internationally

PASQuanS

Programmable Atomic Large-Scale Quantum Simulation
(10 groups + 5 industries, coord.: A. Browaeys & I. Bloch)

Startups recently created to develop industry graded simulators

INSTITUT d'OPTIQUE GRADUATE SCHOOL

PASQAL

ColdQuanta

atom computing

Applications: scientific computing, optimization in finance and industry…

Conclusion: Quantum Simulators can do more…!

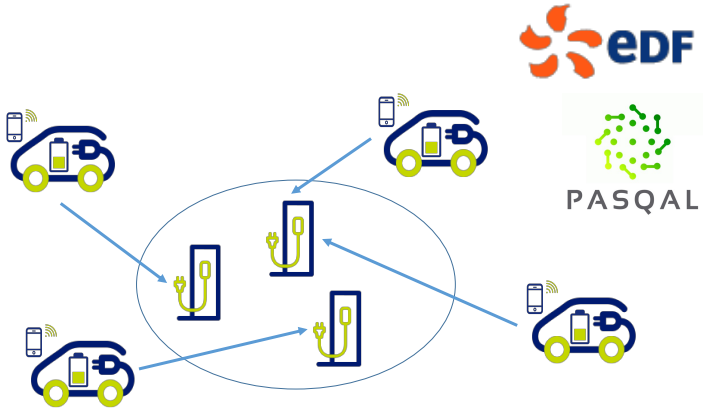
Quant. sim. = machine to prepare quantum states

Optimization problems

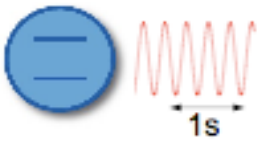
Mapped onto Ising model

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

Solution = ground-state

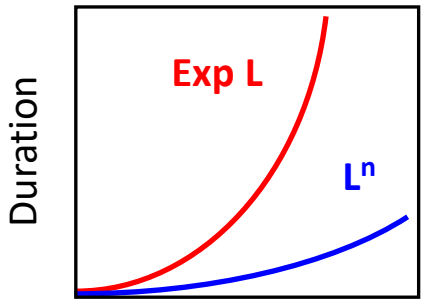


Quantum metrology



$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \quad \xrightarrow{\text{Entangled states}} \quad \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

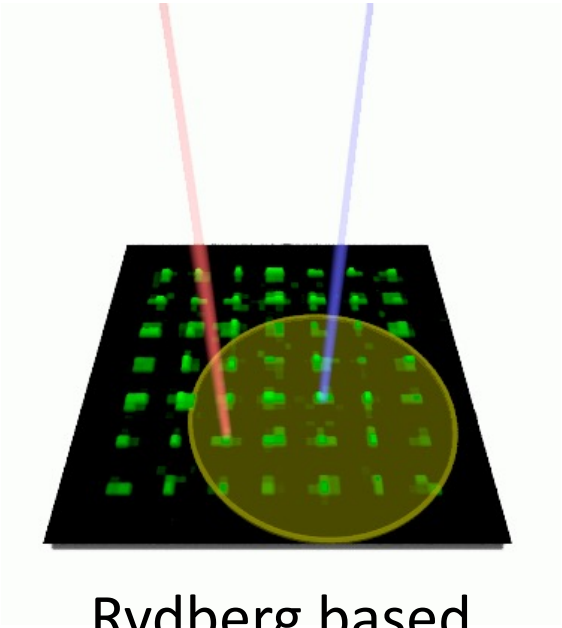
Quantum computer (long-term…)



Outlook: towards Industrial Simulators

PASQAL

www.pasqal.io



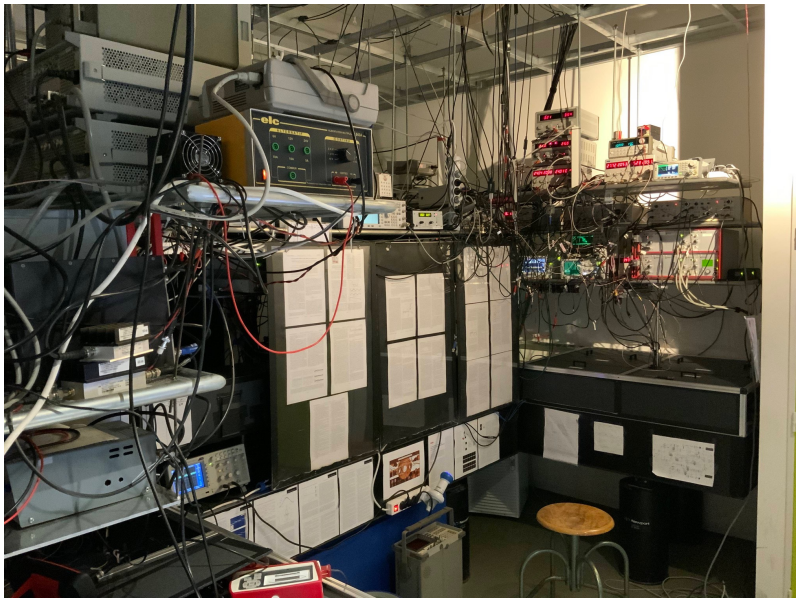
Rydberg based technology

- Founded april 2019 (90 staff sept. 2022)
- **Applications**: scientific computing, optimisation in finance, industries…
- Software et hardware

USA

Henriet, Quantum 2020

From a lab experiment to an industrial machine…



Jobs opportunities !!

References:

"Quantum Simulation", I.M. Georgescu *et al.*, Rev. Mod. Phys. **49**, 153 (2014)

"Quantum Simulation with ultra-cold atoms in optical lattices", C. Gross and I. Bloch., Science 3**57**, 995 (2017)

"Many-Body Physics with individually controlled Rydberg Atoms", A. Browaeys and T. Lahaye, Nat. Phys. **16**, 132 (2020)

"Programmable quantum simulation of spin systems with trapped ions", C. Monroe *et al.*, arXiv:1912.07845