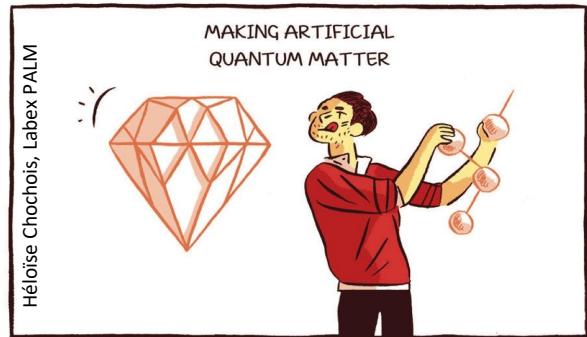


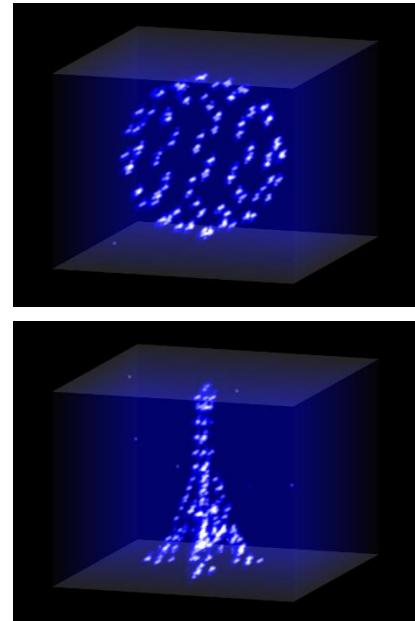
Etudier le problème à N -corps avec “quelques” atomes



Antoine Browaeys

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

SFP Orsay, 15 mai 2023



Le programme...

1. Physique à N -corps, simulation quantique et systèmes quantiques synthétiques
2. Construire un simulateur quantique à atomes de Rydberg
3. Exemples de simulation de magnétisme quantique

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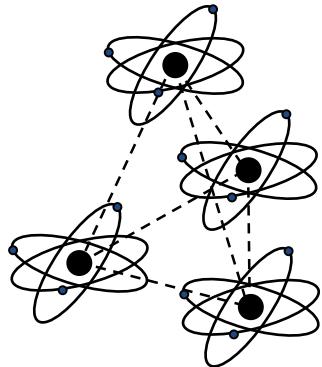
Le problème à N -corps en physique

But: comprendre ensembles de particules quantiques en interaction

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Microscopique



?



Macroscopique



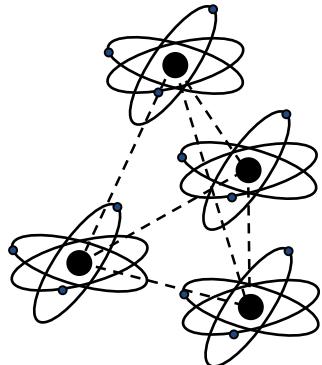
Lois quantiques



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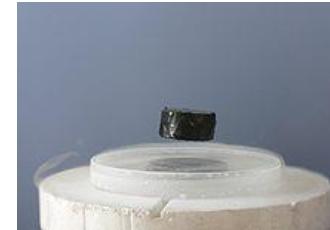
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Ce qu'il faut résoudre:

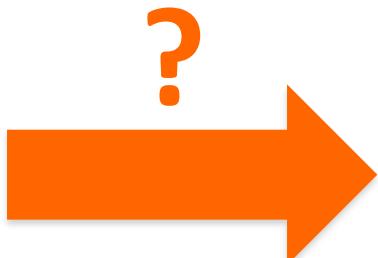
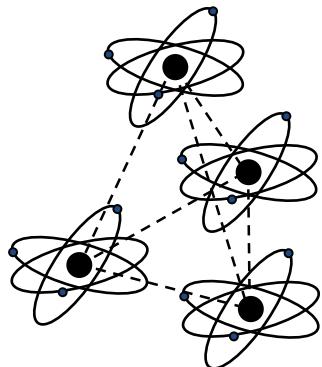
$$i\hbar \frac{\partial \Psi}{\partial t} = H_{\text{tot}} \Psi$$

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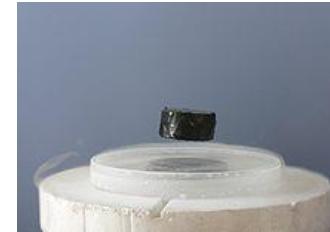
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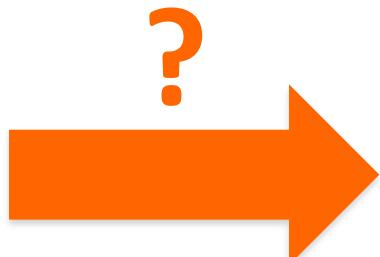
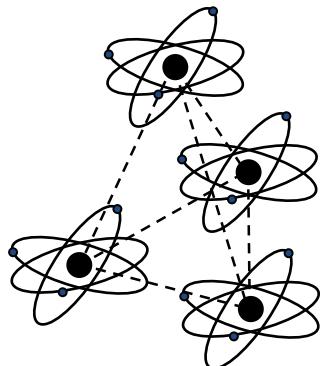
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Très, très, très...
bien connues !!

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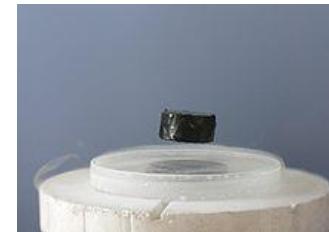
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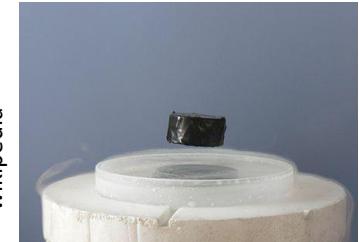
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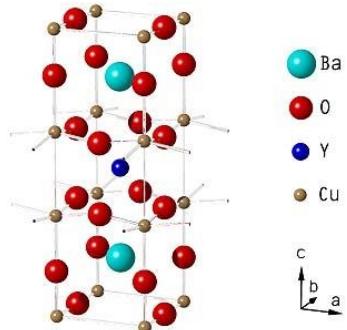
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$N \approx 10^{23}$!!!

Le problème à N -corps : de l'art de la modélisation...



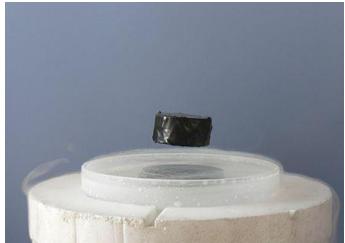
YBaCuO



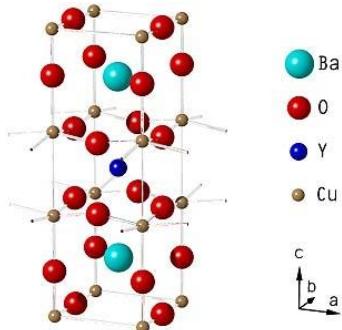
Observation phénomène compliqué
Ex: supraconductivité haute T_c

Le problème à N -corps : de l'art de la modélisation...

wikipedia



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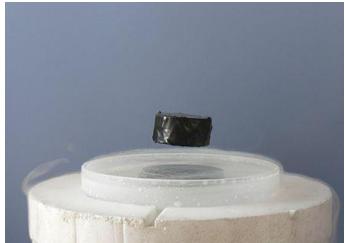
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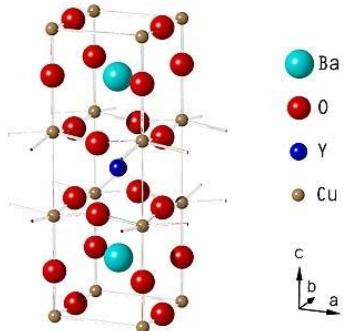
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simplification

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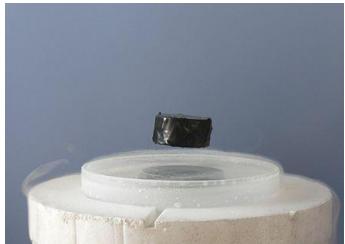
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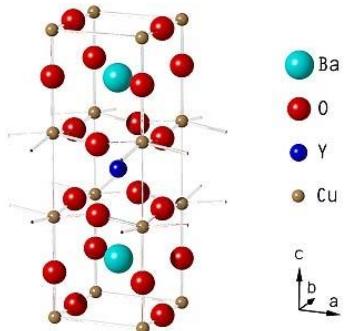
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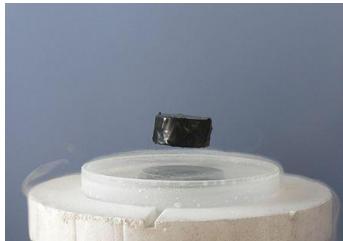
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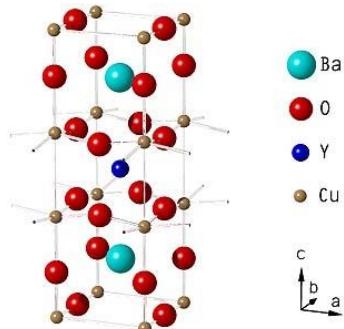
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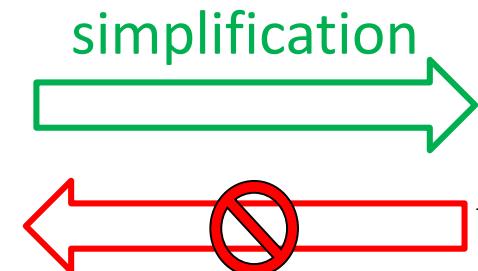
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Expérience sur
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Calculs trop durs...

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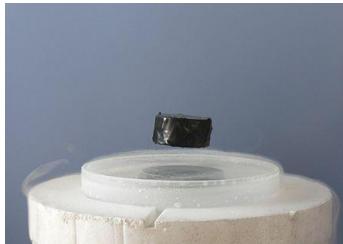
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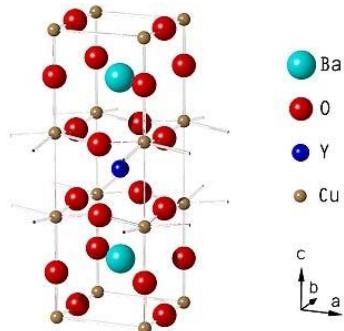
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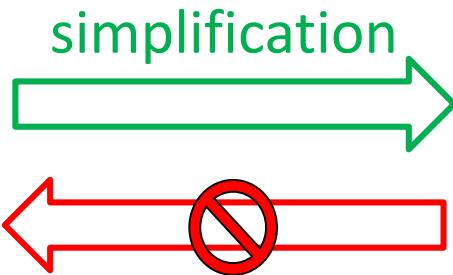


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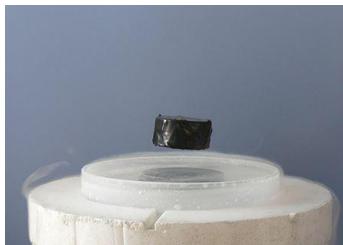
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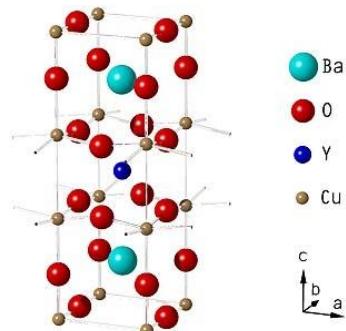
Problème: croissance exponentielle de $\dim \mathcal{H} \sim d^N$

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simplification



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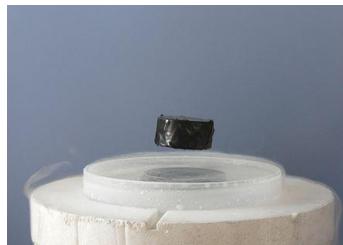
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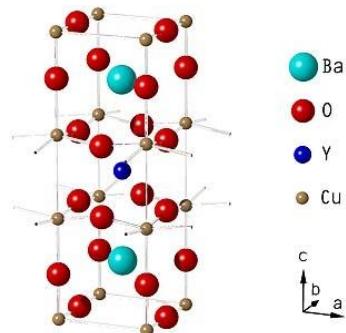
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wikipedia



YBaCuO

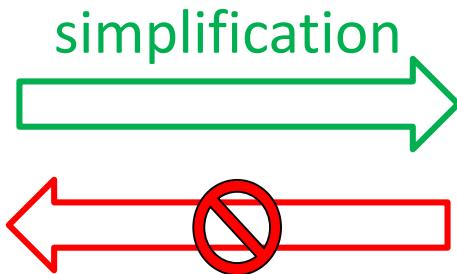


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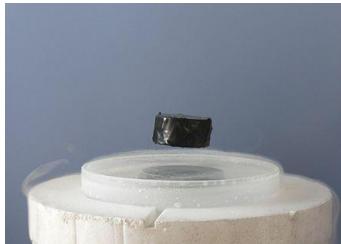
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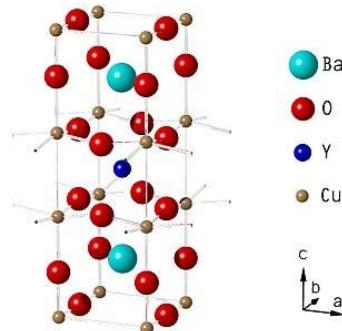
Record de calcul *ab-initio* (2023) $N \sim 50 \Rightarrow 2^{50} \sim 10^{15}$ (1000 To RAM)

Le problème à N -corps : de l'art de la modélisation...

wikipedia



YBaCuO



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Expérience sur
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simplification

Approximations possibles !!

MAIS mal contrôlées ou non valables
quand interactions dominent

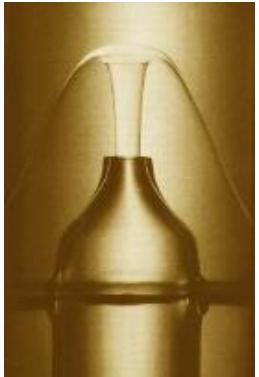
Problème:

= systèmes **fortement corrélés**

Ex:

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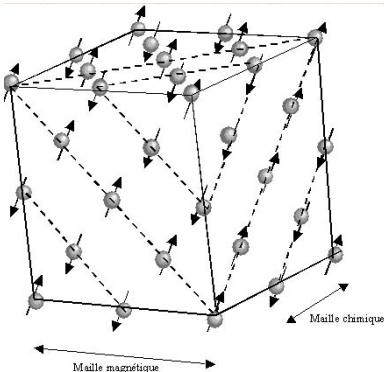
Systèmes fortement corrélés & applications



superfluidité



supraconductivité

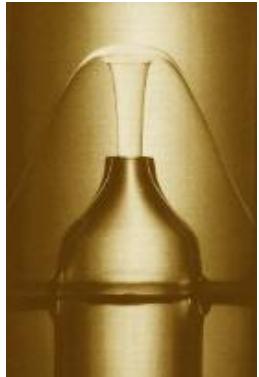


magnétisme



Étoile à neutrons

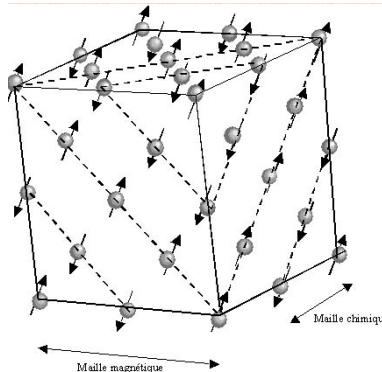
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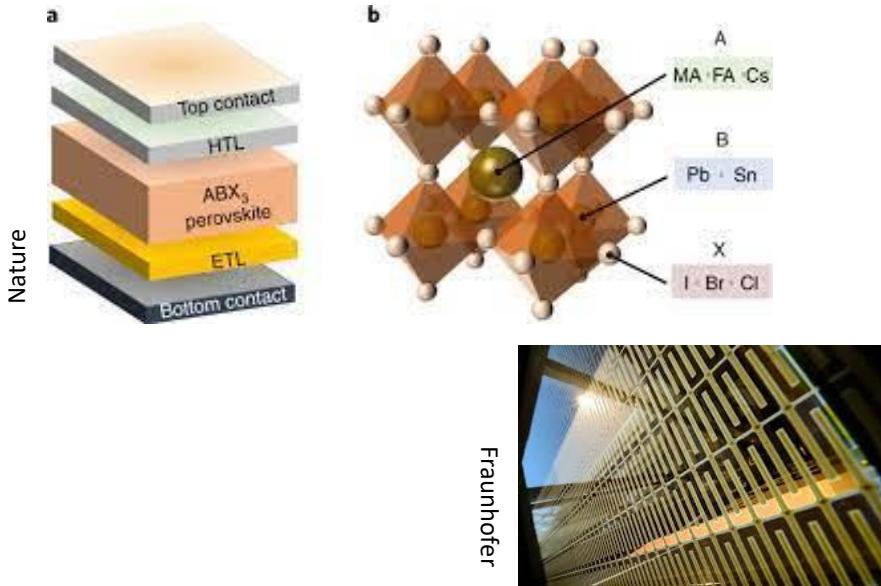


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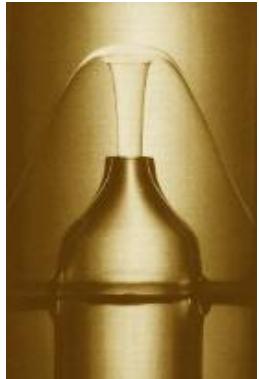


Étoile à neutrons

Perovskite: panneaux solaires



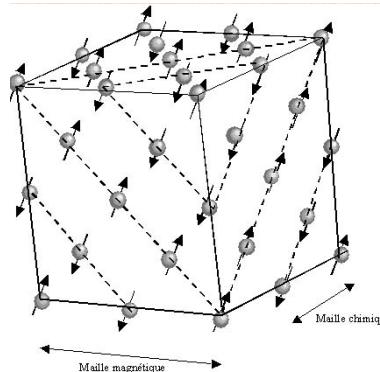
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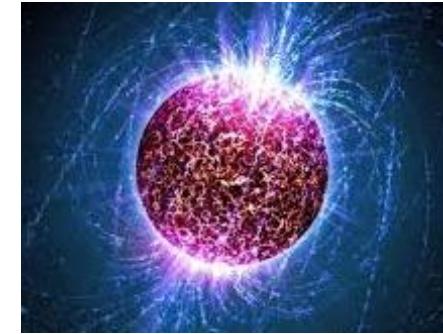
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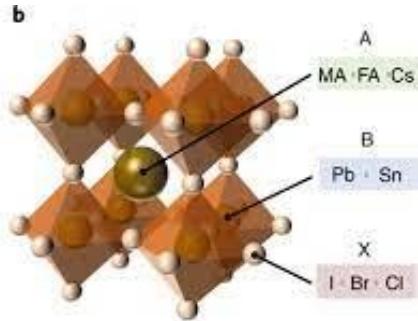
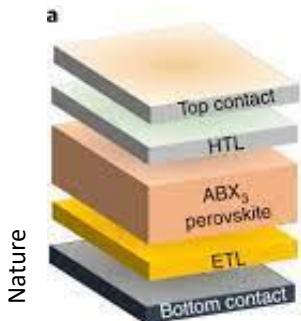


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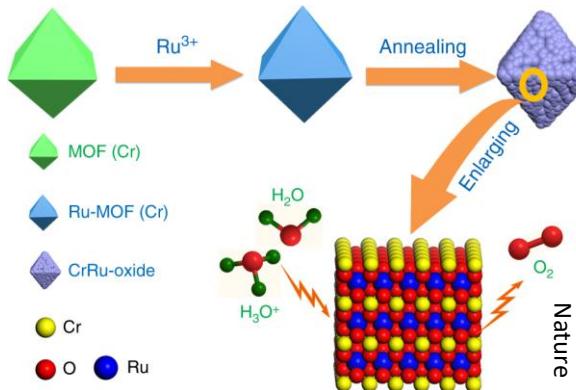


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Fraunhofer



Catalyse

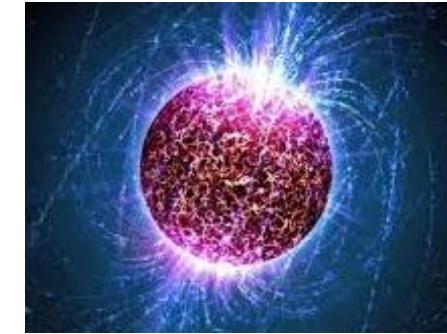
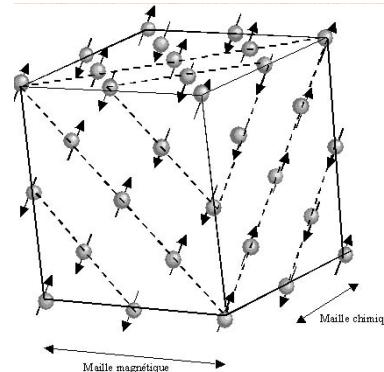
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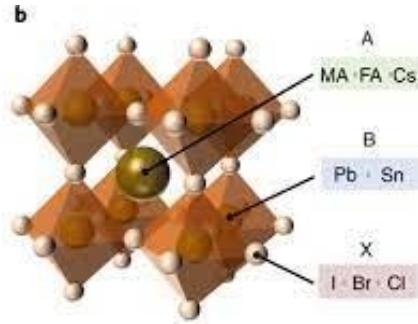
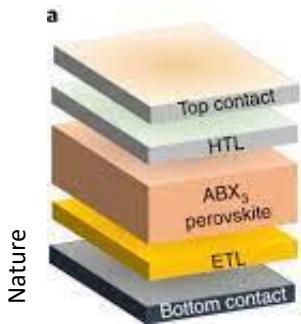
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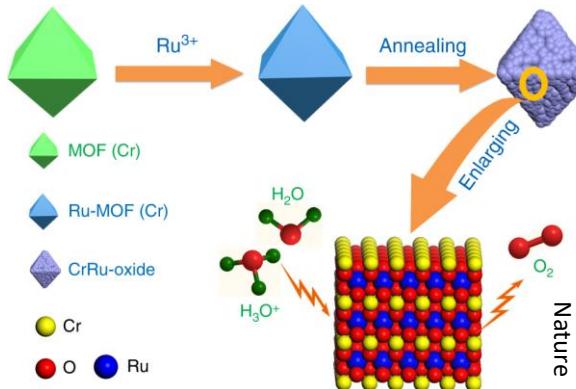
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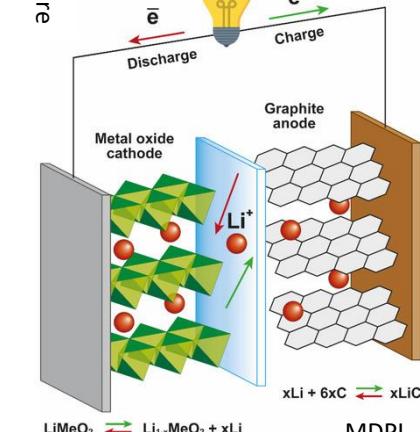


Fraunhofer



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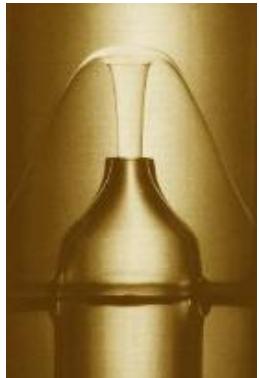
Batterie & cathode



LiMeO₂ \rightleftharpoons Li_{1-x}MeO₂ + xLi

MDPI

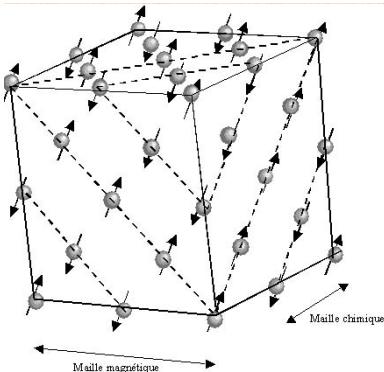
Le problème à N -corps par la simulation quantique



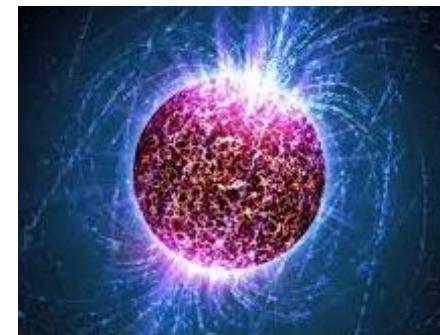
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Étoile à neutrons

Expérience sur
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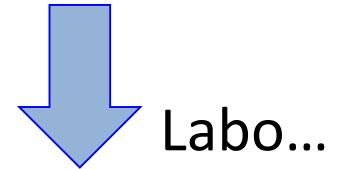
simplification



Calcul trop durs...

Hamiltonien modèle

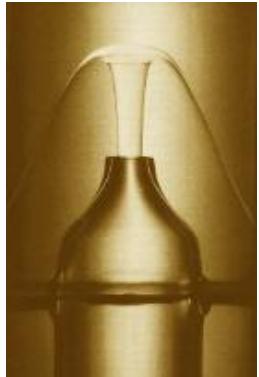
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Labo...

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

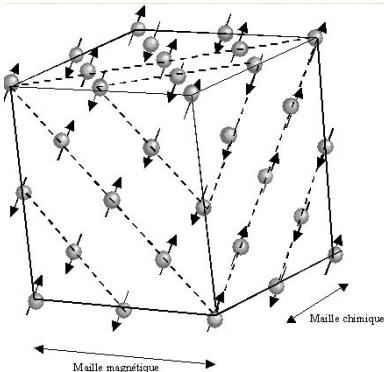
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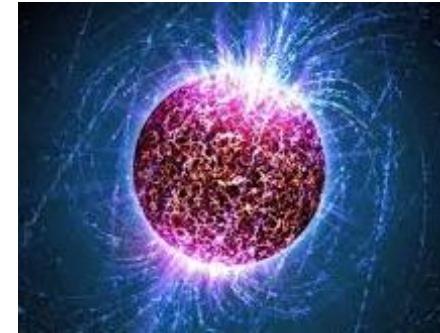
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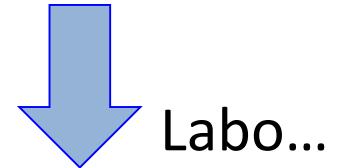
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Labo...

Mesure sur simulateur:
état fondamental =
supra?



Simulateur quantique =
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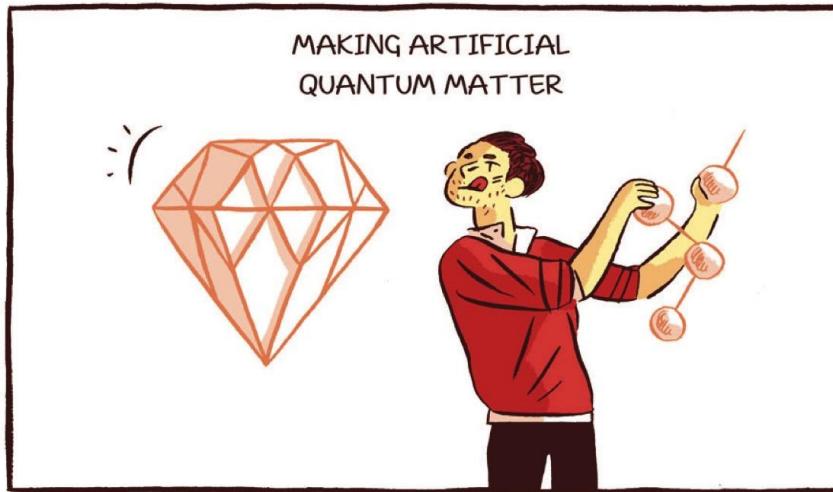
Problème à N -corps et systèmes quantiques synthétiques



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Héloise Chocois, Labex PALM



Systèmes quantiques **contrôlés** réalisant des
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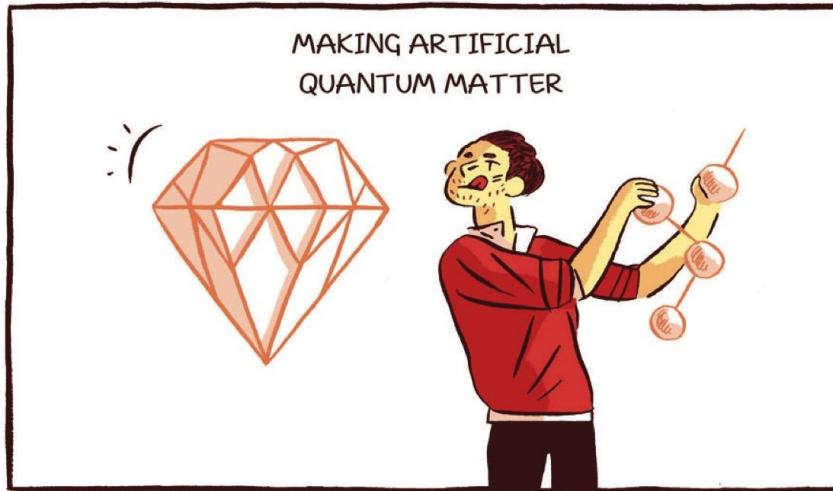
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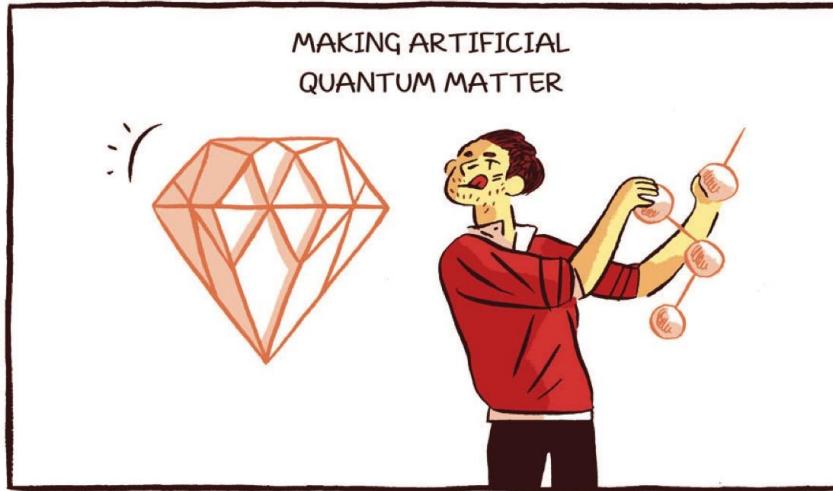
Problème à N -corps et systèmes quantiques synthétiques



R.P. Feynman

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

Héloise Chocois, Labex PALM



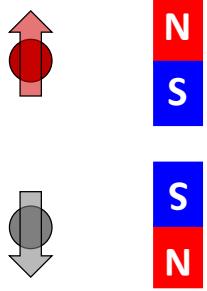
Systèmes quantiques **contrôlés** réalisant des
hamiltoniens à N -corps (y compris artificiels...)
= **simulateur quantique**

Plus grande **programmabilité** que systèmes réels
(géométrie, paramètres...)

Les “drosophiles” du physicien à N -corps



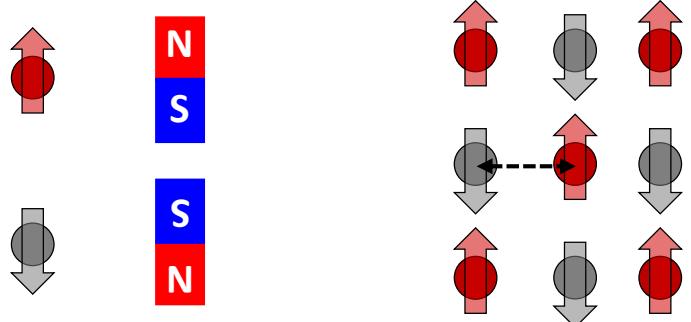
Modèles de spins en interaction



Les “drosophiles” du physicien à N -corps



Modèles de spins en interaction

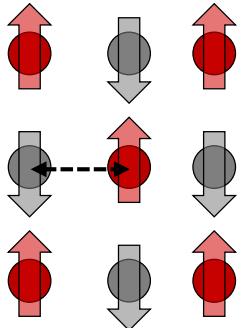
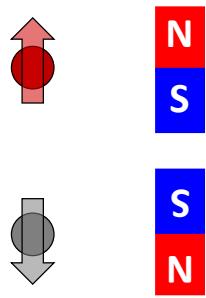


$$H_{ij} = J \mathbf{S}_i \cdot \mathbf{S}_j$$

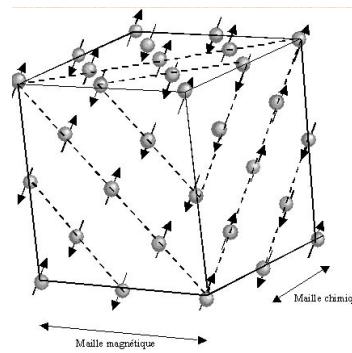
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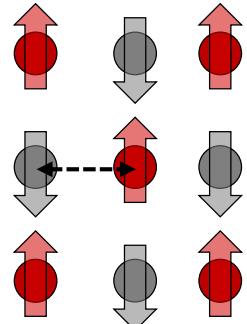
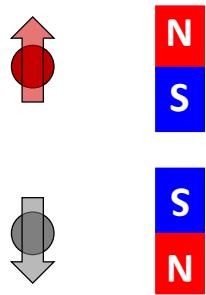


Magnétisme

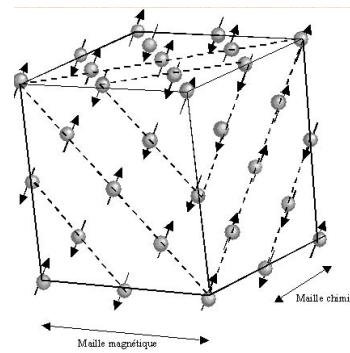
Les “drosophiles” du physicien à N -corps



Modèles de spins en interaction



$$H_{ij} = J \mathbf{S}_i \cdot \mathbf{S}_j$$



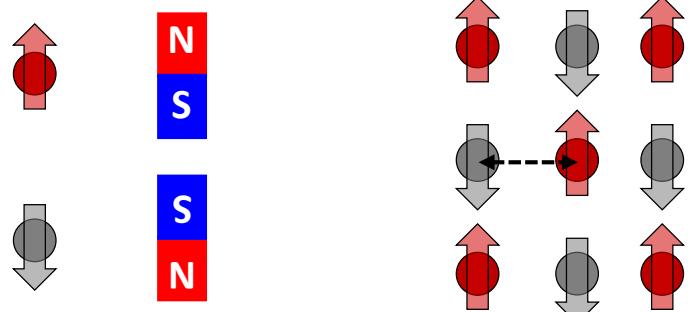
Magnétisme

nouveaux aimants pour moteurs
électriques, stockage information...?

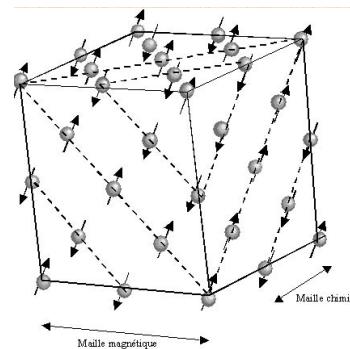
Les “drosophiles” du physicien à N -corps



Modèles de spins en interaction



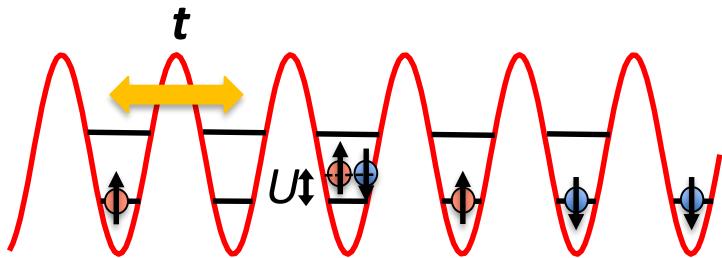
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Magnétisme

nouveaux aimants pour moteurs électriques, stockage information...?

Modèles transport / interactions

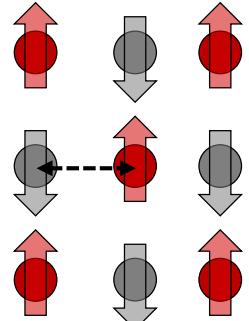
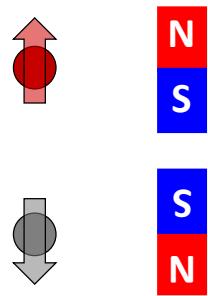


modèles de Hubbard

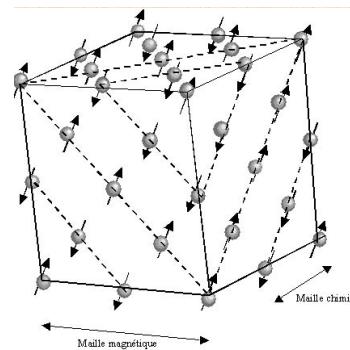
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Modèles de spins en interaction



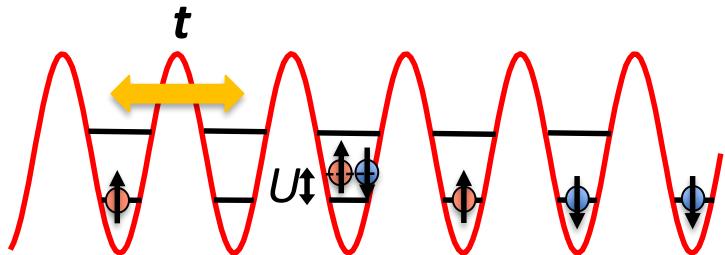
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Magnétisme

nouveaux aimants pour moteurs électriques, stockage information...?

Modèles transport / interactions



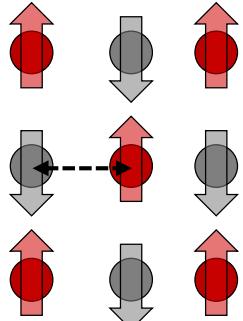
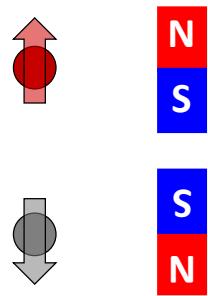
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Supra. haute T_c : stockage de l'électricité?

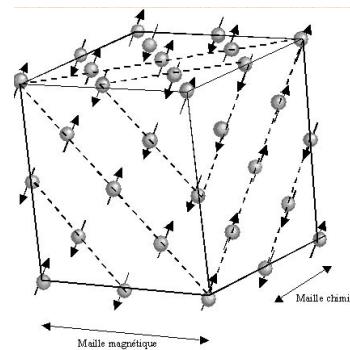
Les “drosophiles” du physicien à N -corps



Modèles de spins en interaction



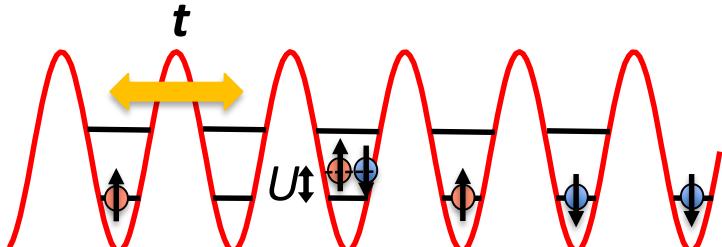
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Magnétisme

nouveaux aimants pour moteurs électriques, stockage information...?

Modèles transport / interactions



modèles de Hubbard

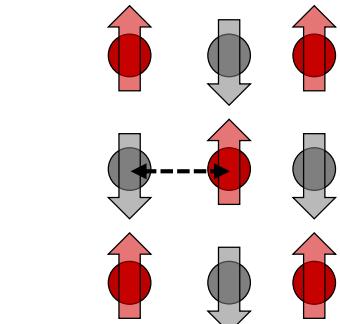
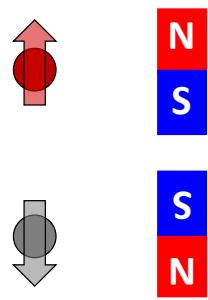
Supra. haute T_c : stockage de l'électricité?

Conduction : meilleurs matériaux conducteurs, batteries...?

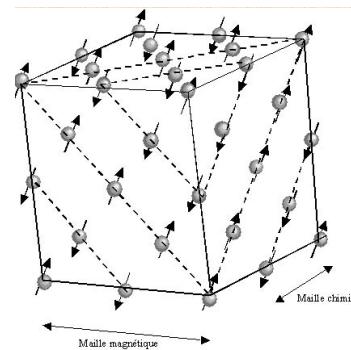
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Modèles de spins en interaction



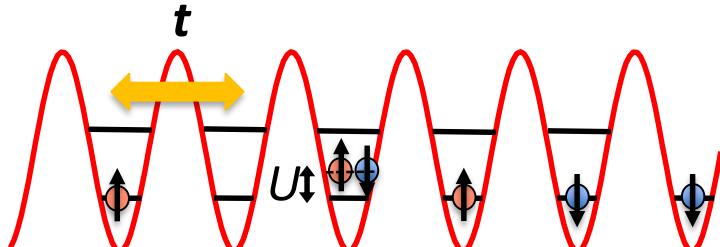
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Magnétisme

nouveaux aimants pour moteurs électriques, stockage information...?

Modèles transport / interactions



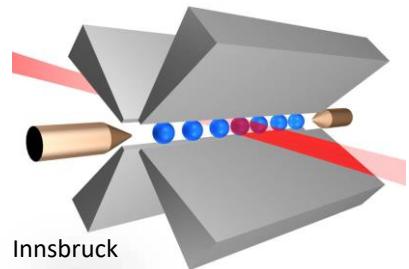
modèles de Hubbard

Supra. haute T_c : stockage de l'électricité?

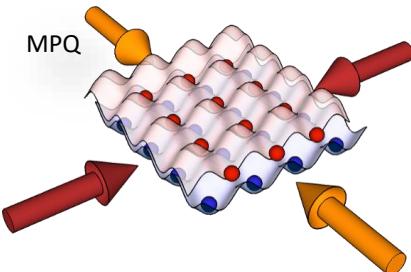
Conduction : meilleurs matériaux conducteurs, batteries...?

Modèles génériques pour étude problèmes à N -corps

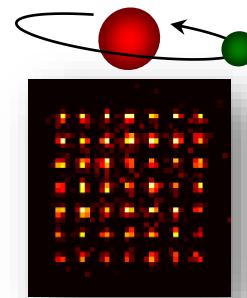
Ingénierie quantique avec des “atomes individuels”



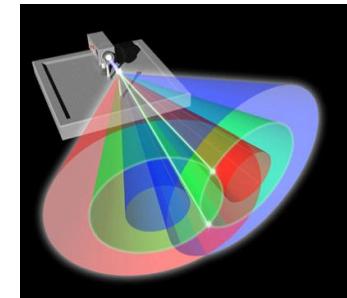
Ions piégés



Atomes et
molécules froides

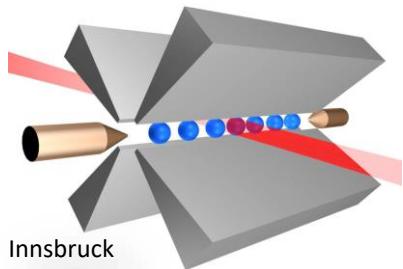


Atomes de Rydberg

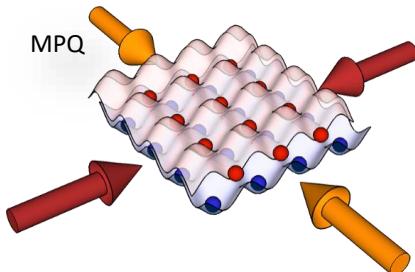


Photons

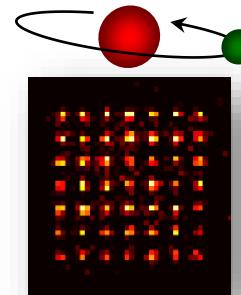
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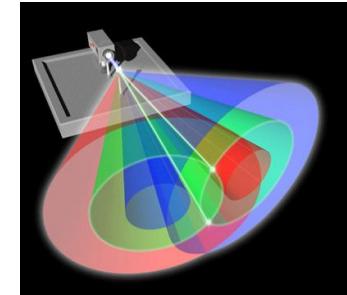
Ions piégés



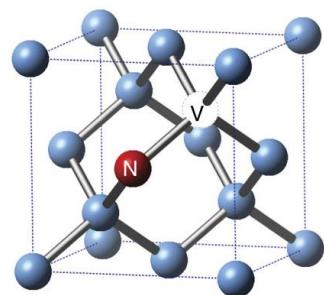
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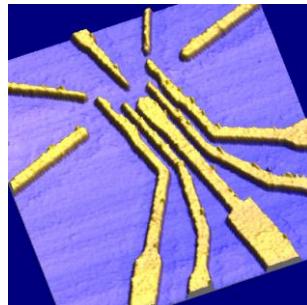
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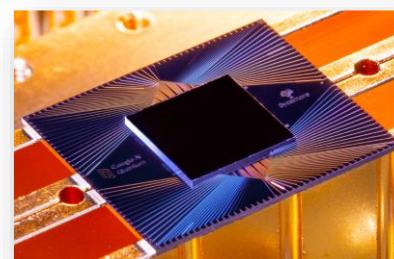
Photons



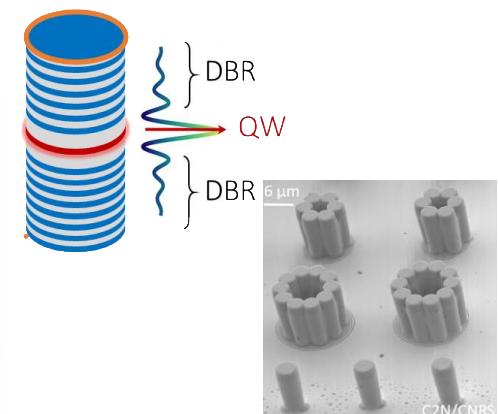
Centres NV, SiV



Boîtes quantiques

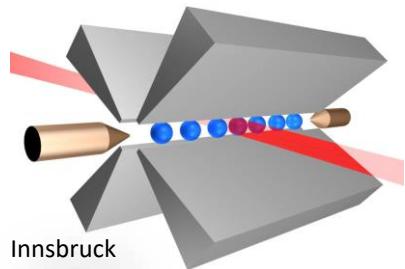


Circuit supraconducteurs

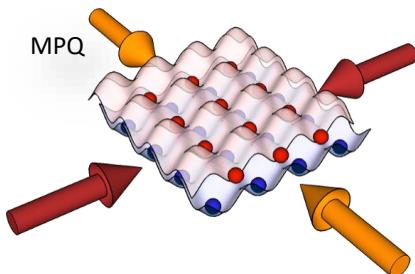


Polaritons dans $\frac{1}{2}$ conducteurs

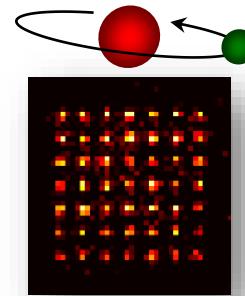
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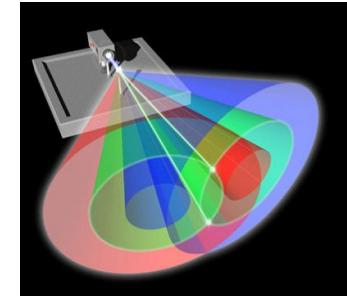
Ions piégés



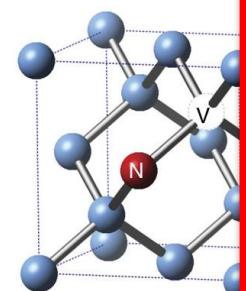
Atomes et molécules froides



Atomes de Rydberg

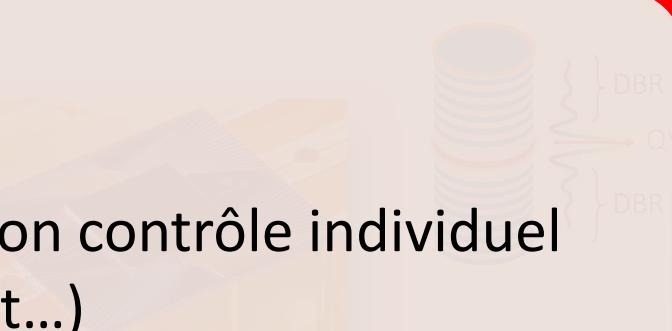


Photons



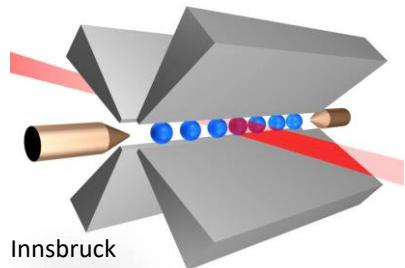
Centres NV

- “Scalable” : $N > 50$
- “Addressable” : très bon contrôle individuel (mais encore imparfait...)
- Programmable : géométrie, interactions...

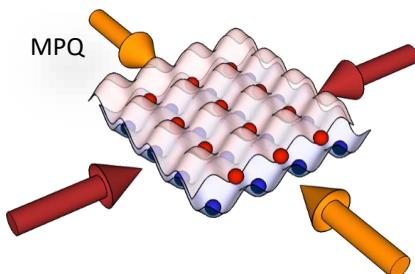


C2N/CNRS
dans ½ supraconducteurs

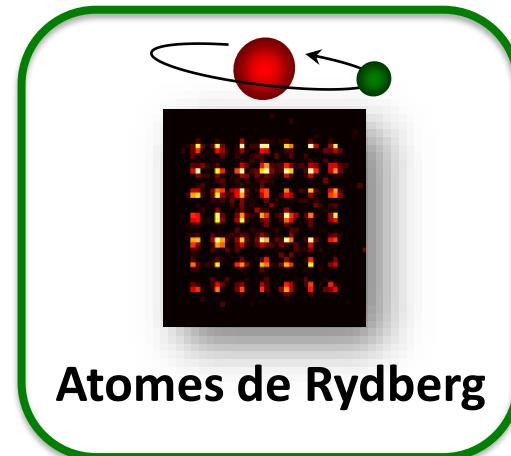
Ingénierie quantique avec des “atomes individuels”



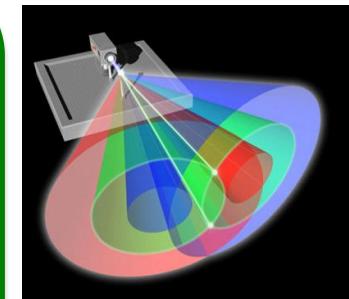
Ions piégés



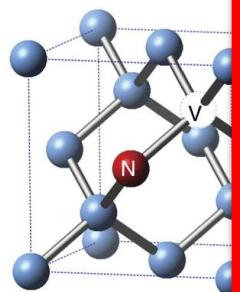
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Atomes de Rydberg

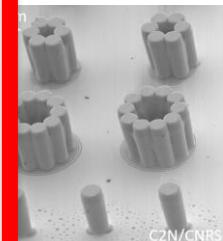


Photons



Centres NV

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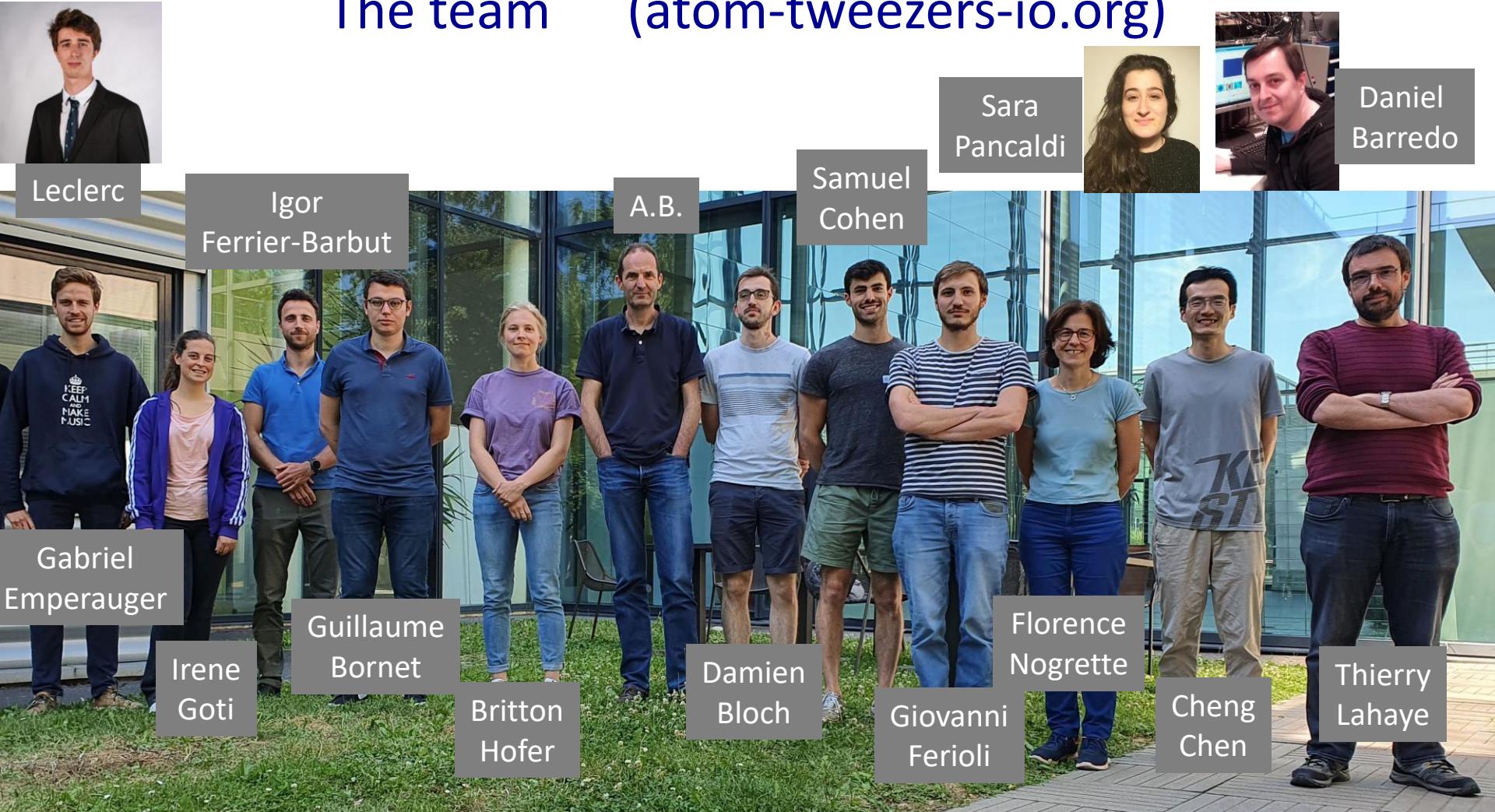


dans 1/2 supraconducteurs

Le programme...

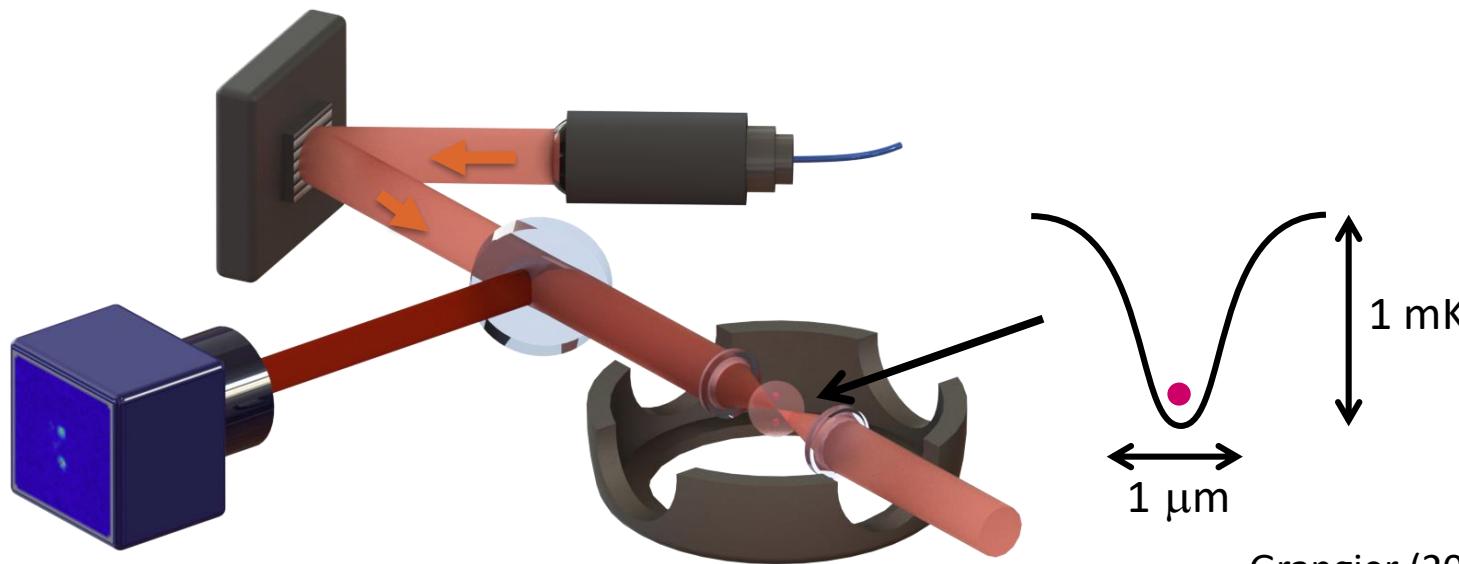
1. Physique à N -corps, simulation quantique et systèmes quantiques synthétiques
2. Construire un simulateur quantique à atomes de Rydberg
3. Exemples de simulation de magnétisme quantique

The team (atom-tweezers-io.org)



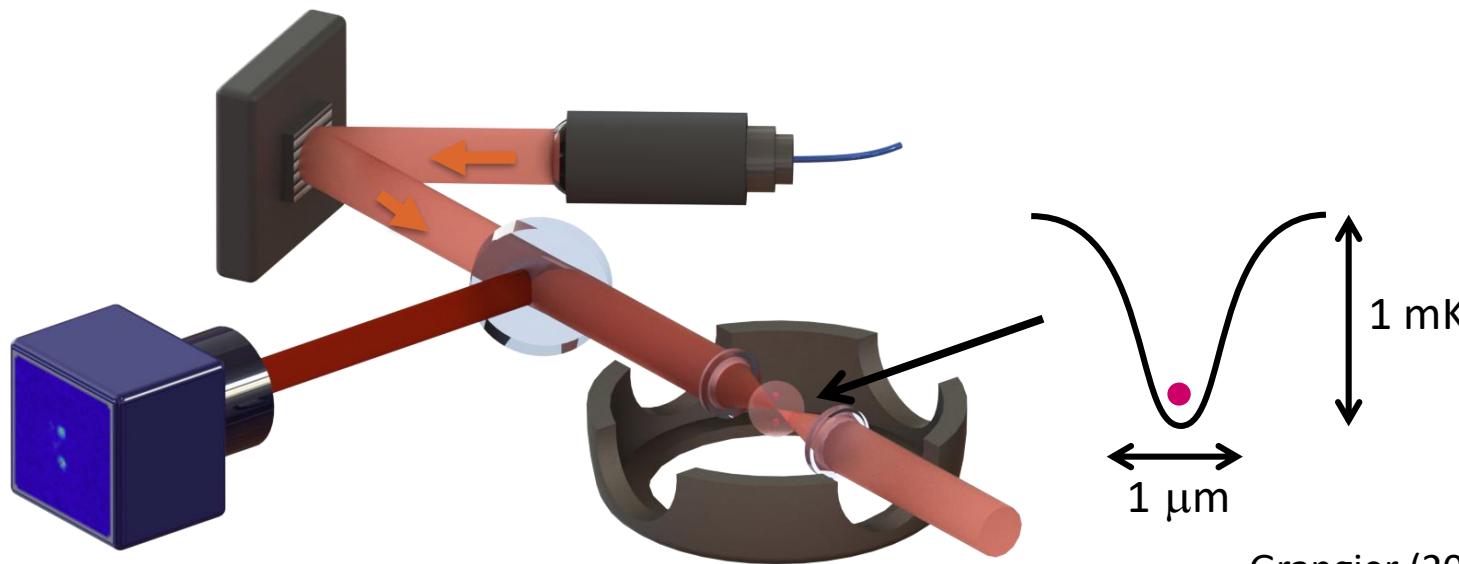
Theory: N. Yao (Harvard), A. Laüchli (Lausanne), T. Roscilde (Lyon)

Un atome dans une pince optique

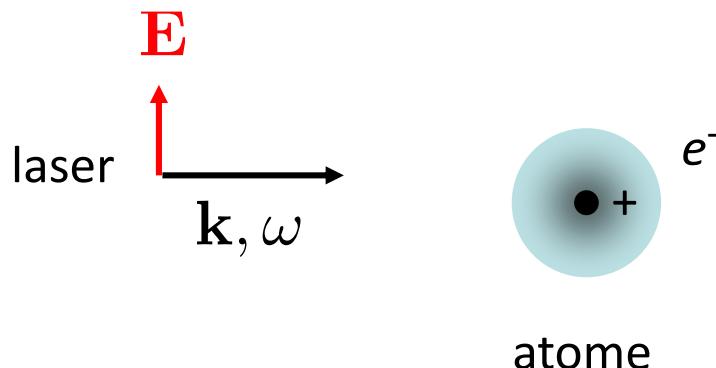


Grangier (2001)
Sortais (2007)

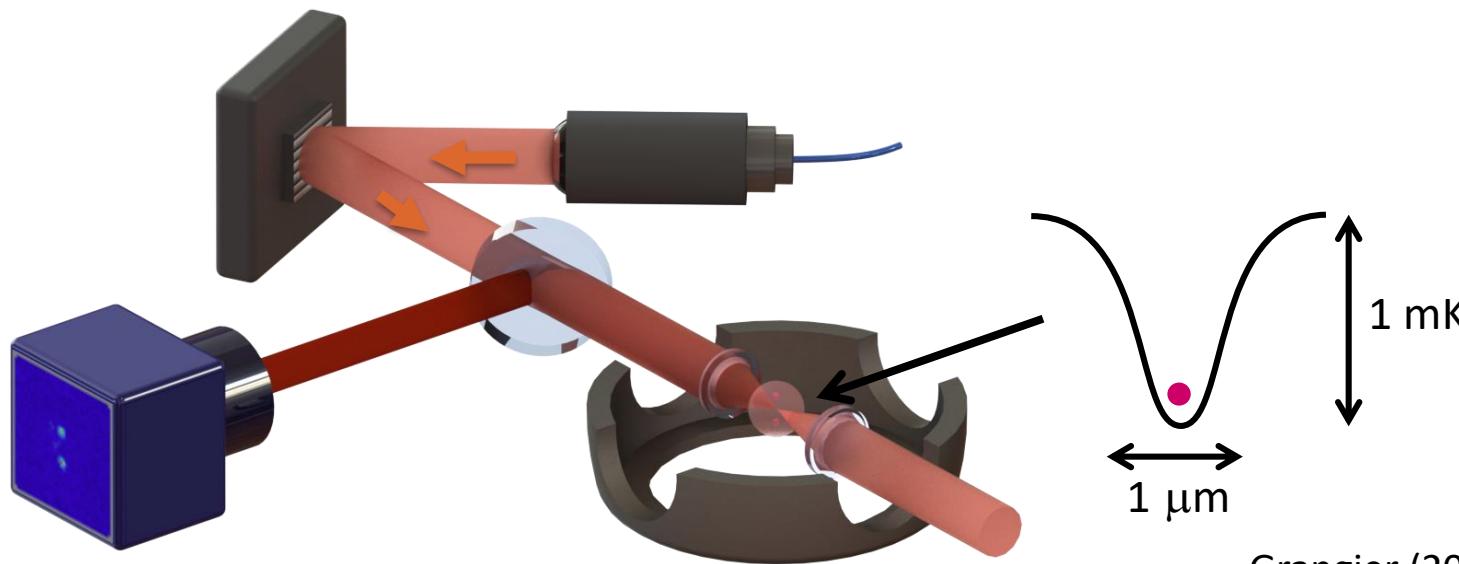
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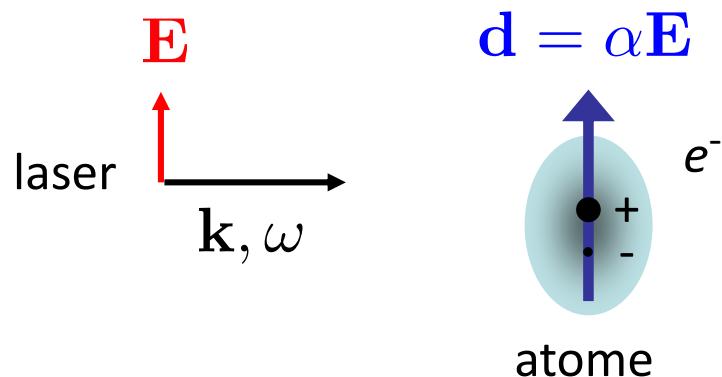
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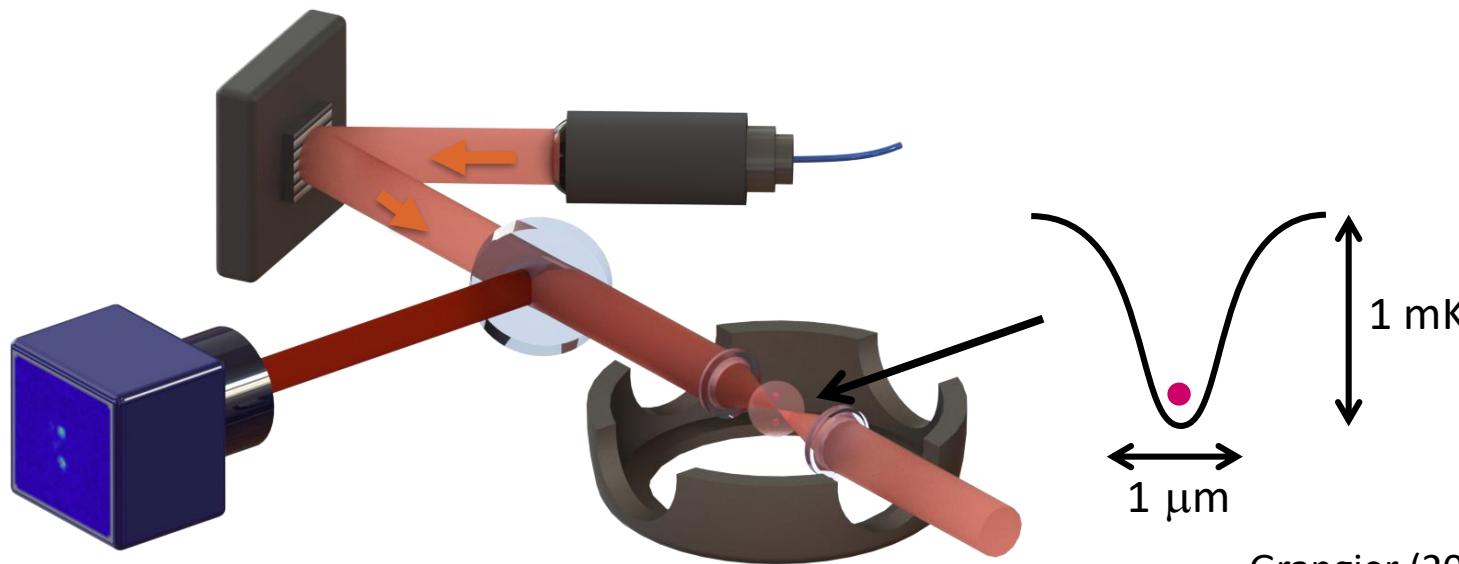
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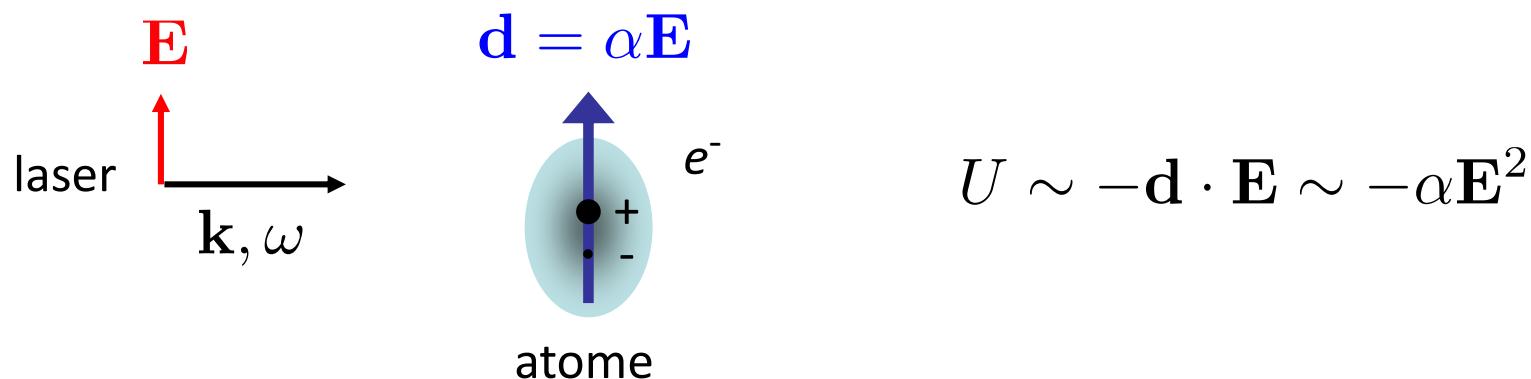
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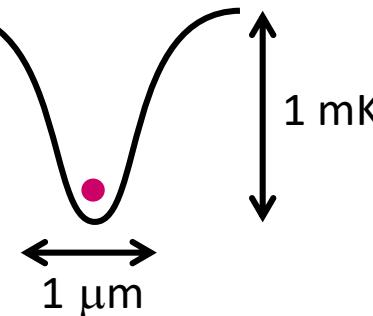
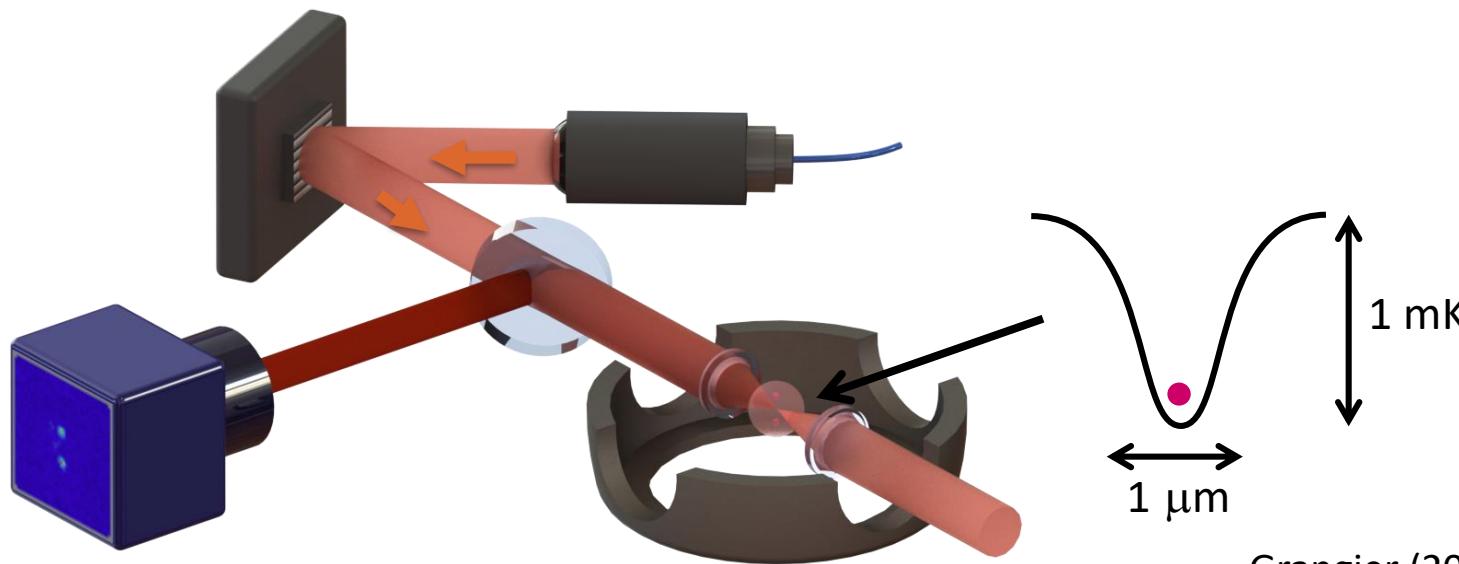
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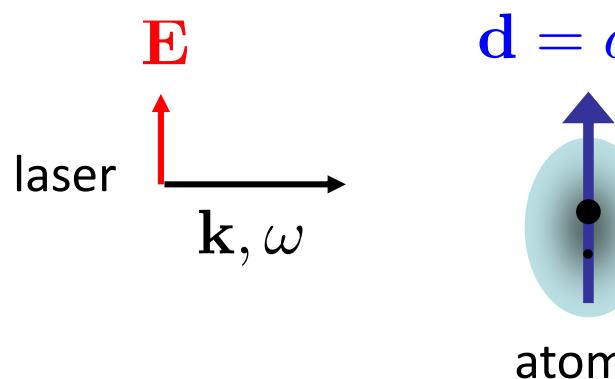
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Un atome dans une pince optique



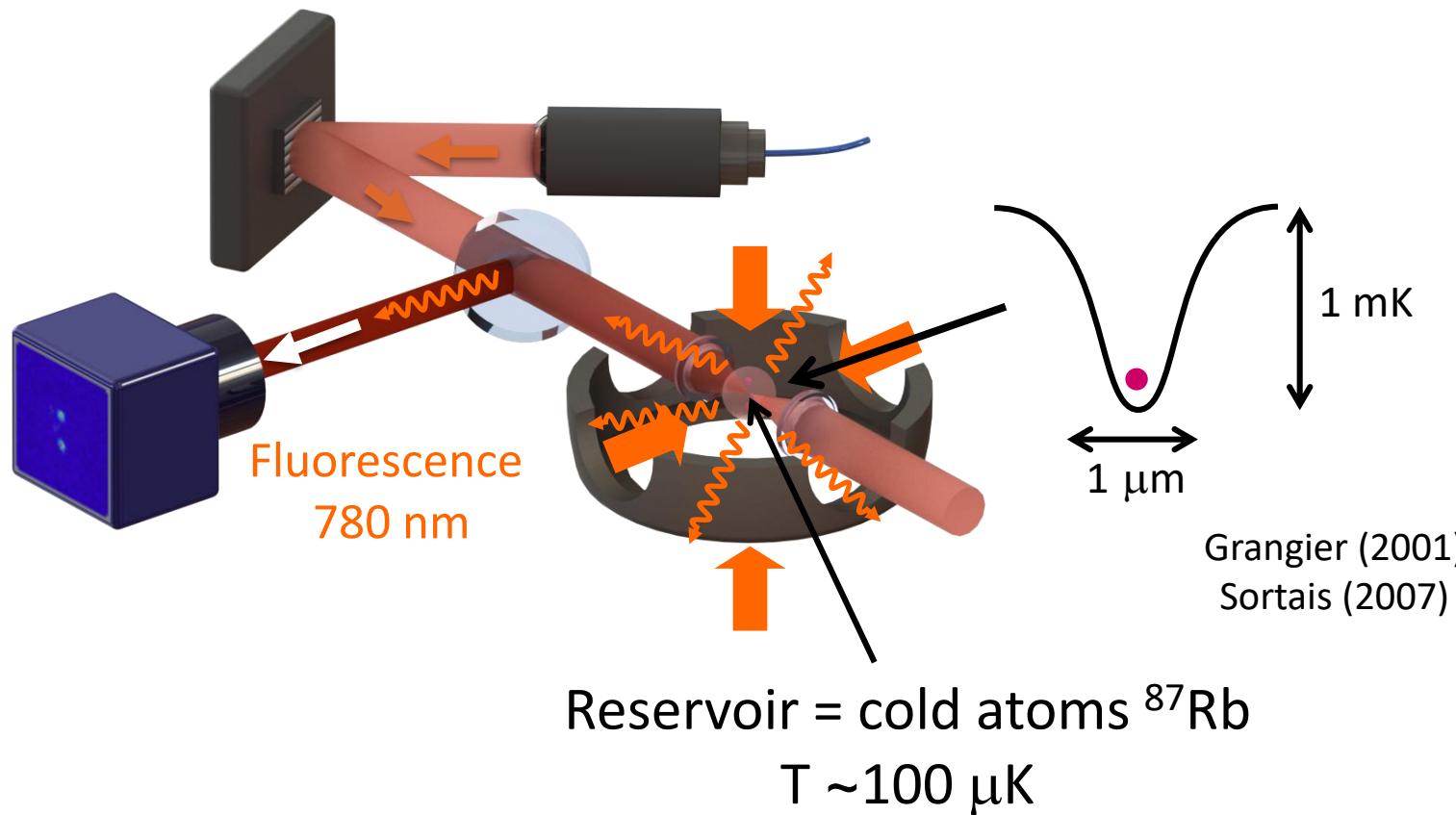
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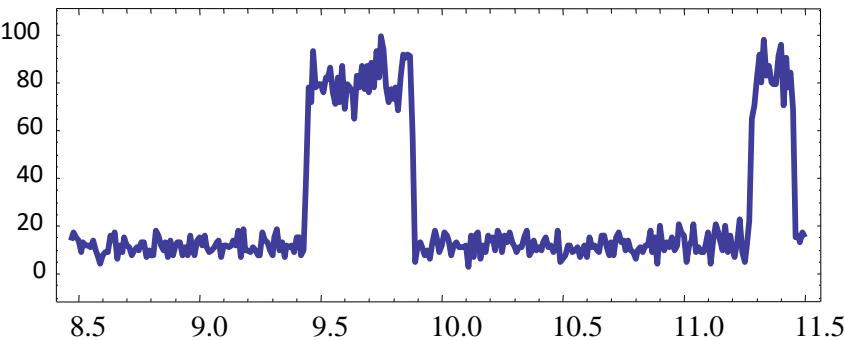
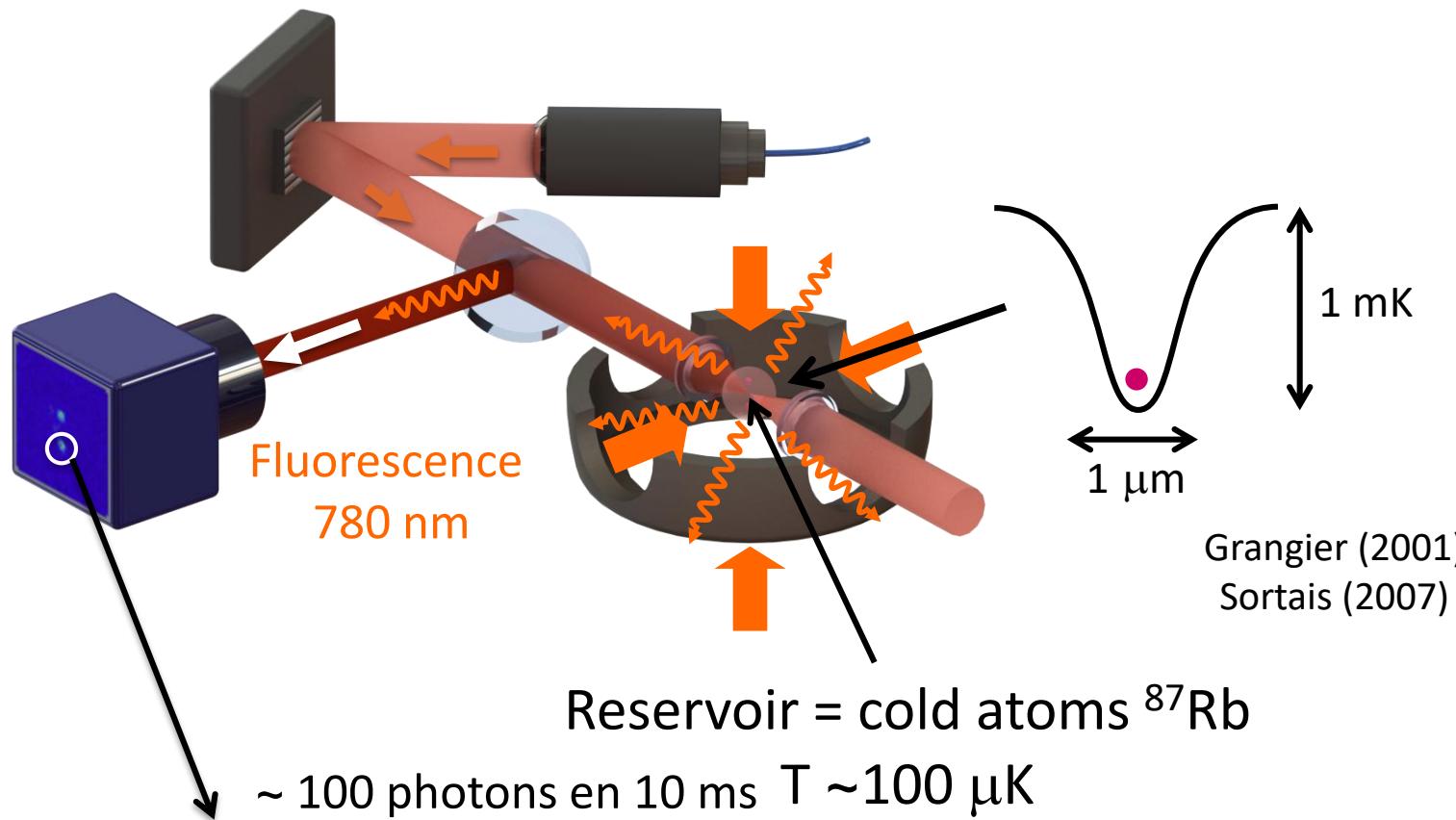
$$U \sim -\mathbf{d} \cdot \mathbf{E} \sim -\alpha \mathbf{E}^2$$

Force dipolaire

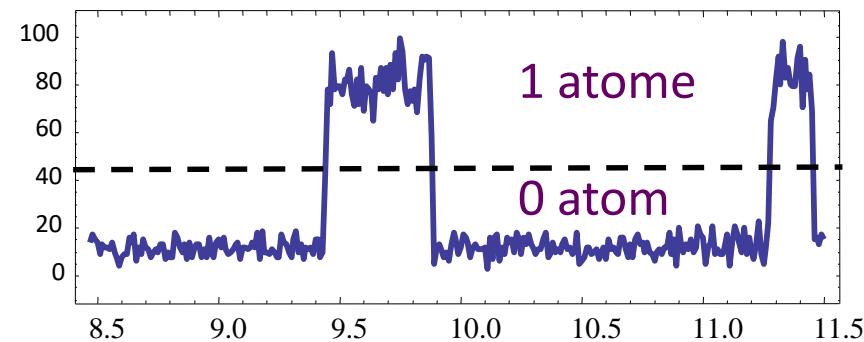
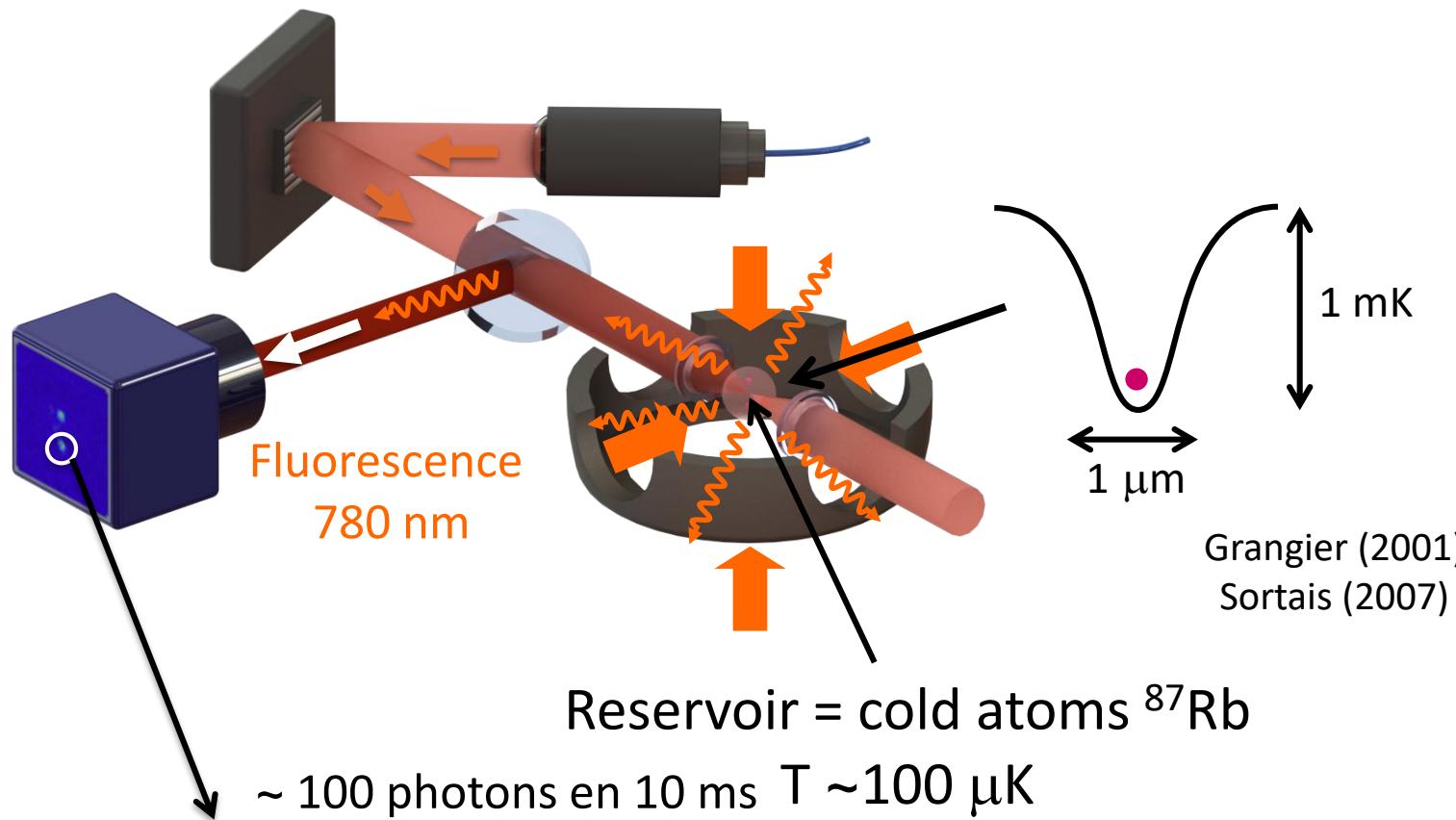
Un atome dans une pince optique



Un atome dans une pince optique



Un atome dans une pince optique



Single-atom trapping zoo (2023)

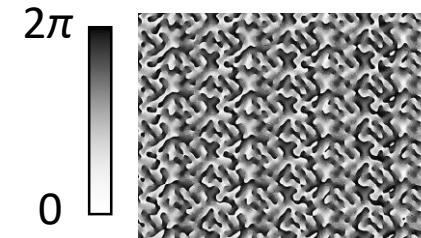
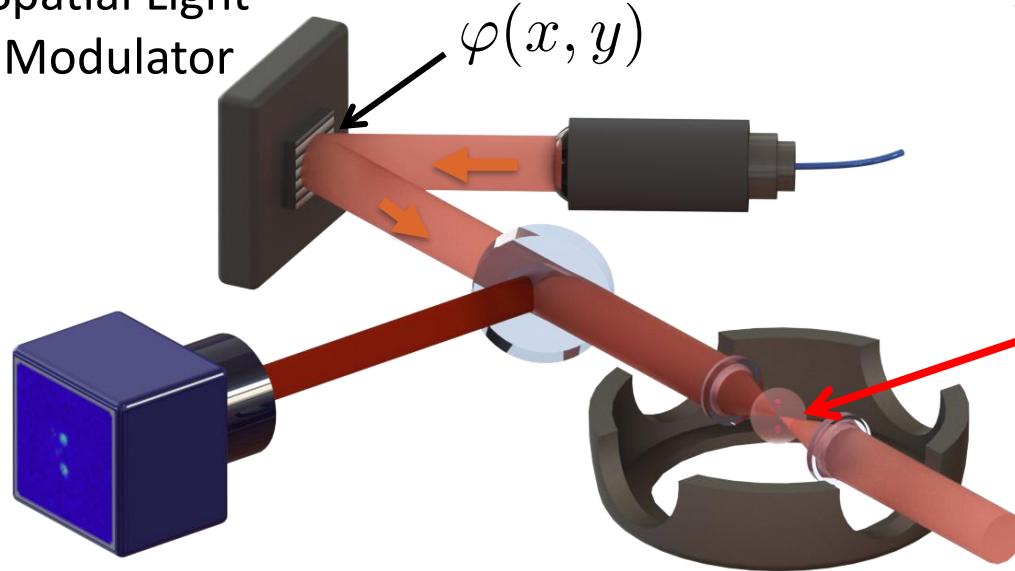
Laser cooled

Single atom

Lanthanides	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinides	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Atomes dans des matrices de pinces optiques

Spatial Light
Modulator



SLM pattern

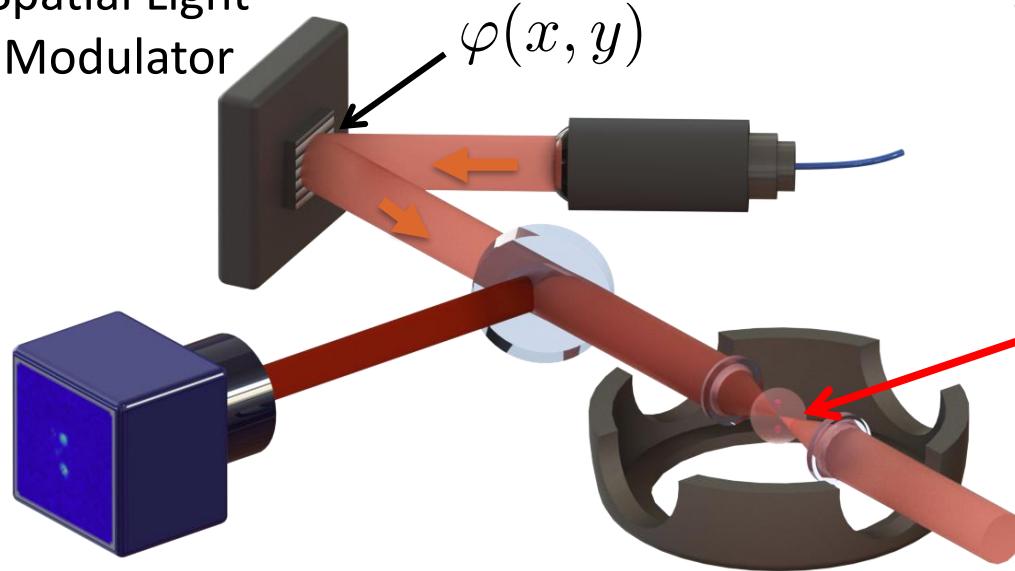
Nogrette, PRX (2014)

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

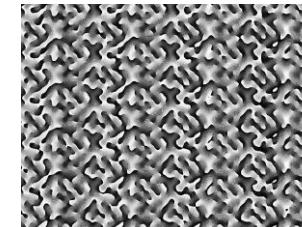


Atomes dans des matrices de pinces optiques

Spatial Light
Modulator



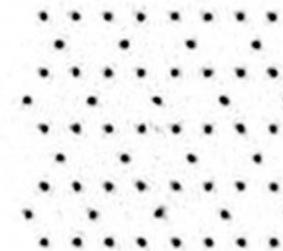
2π
0



SLM pattern

Nogrette, PRX (2014)

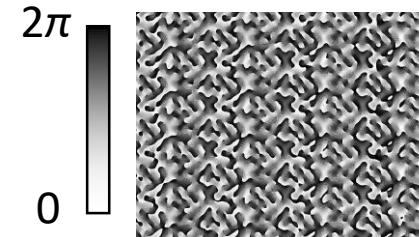
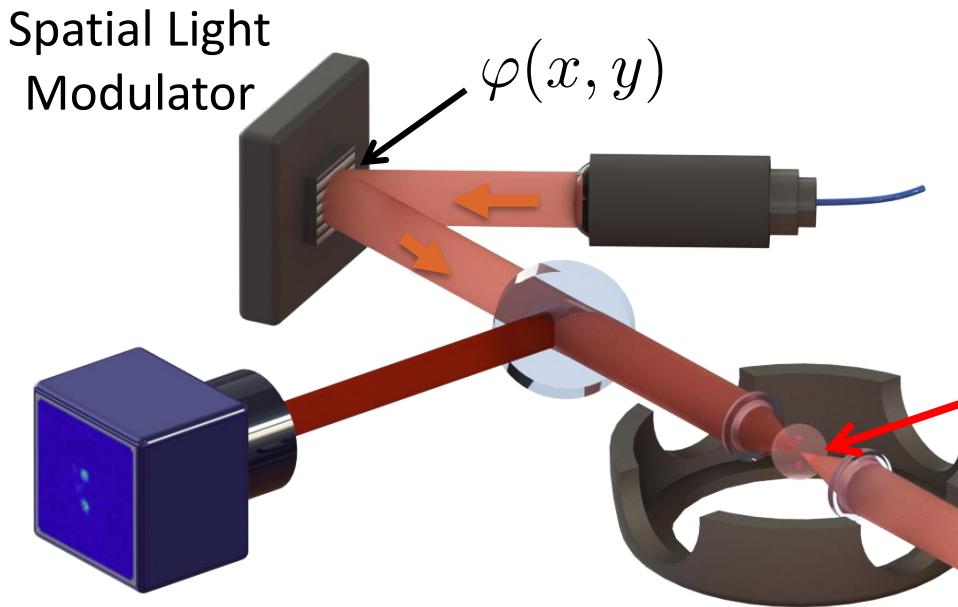
$$|\text{FT}[e^{i\varphi(x,y)}]|^2$$



$10 \mu\text{m}$



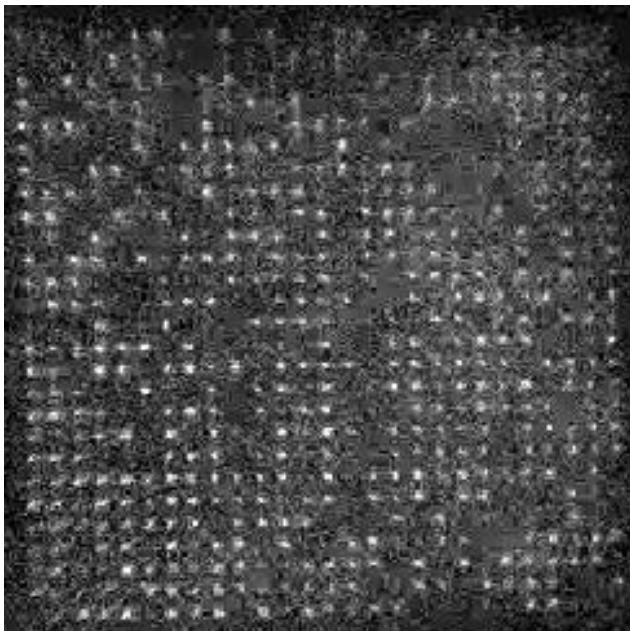
Atomes dans des matrices de pinces optiques



SLM pattern

Nogrette, PRX (2014)

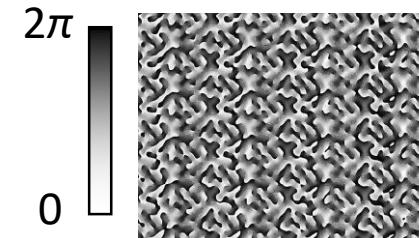
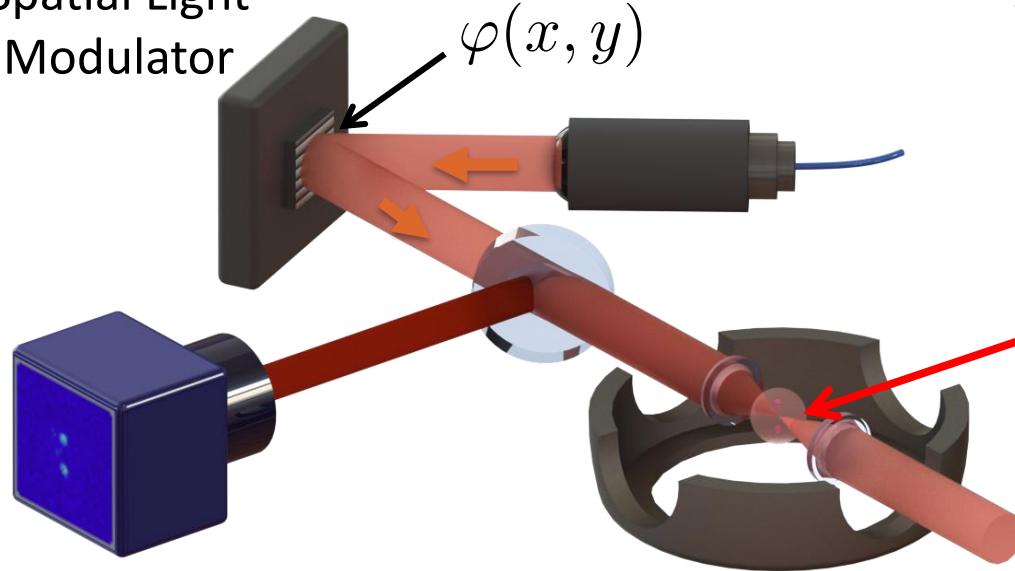
$$|\text{FT}[e^{i\varphi(x,y)}]|^2$$



Fluorescence (729 pièges)

Atomes dans des matrices de pinces optiques

Spatial Light
Modulator

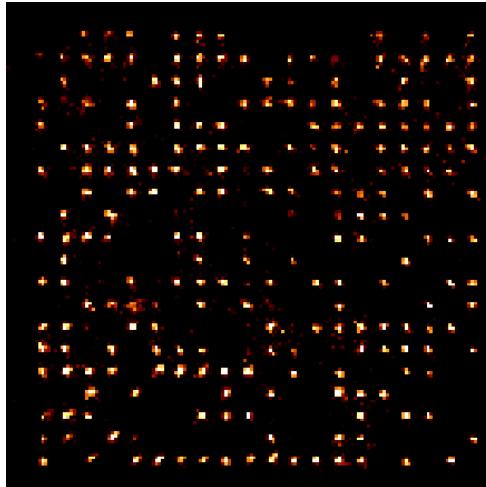


SLM pattern

Nogrette, PRX (2014)

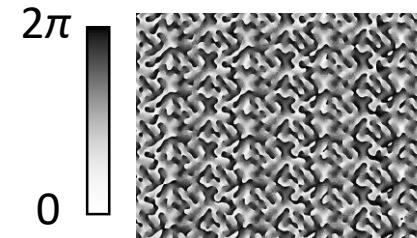
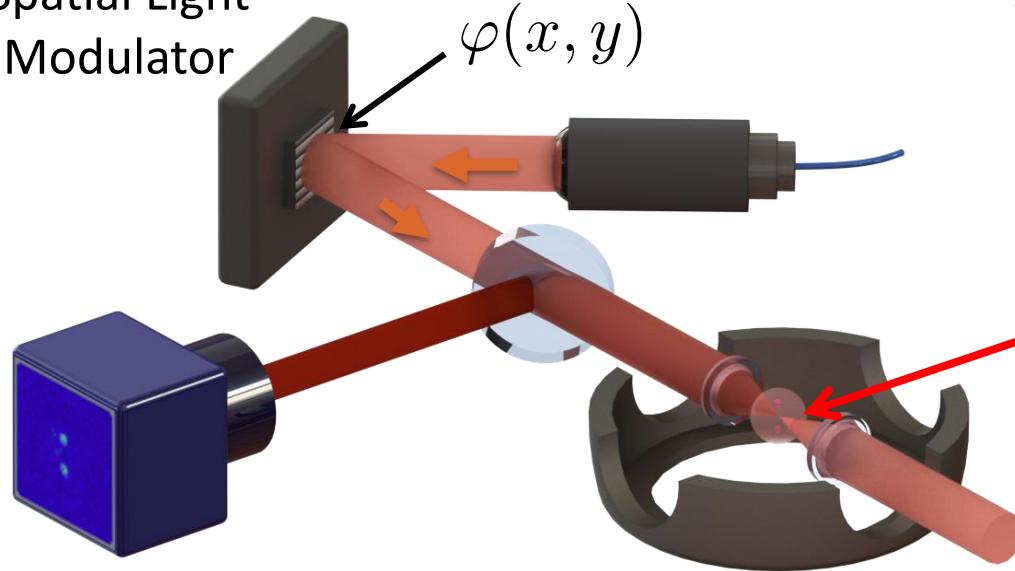
$$|\text{FT}[e^{i\varphi(x,y)}]|^2$$

Initial configuration



Atomes dans des matrices de pinces optiques

Spatial Light
Modulator

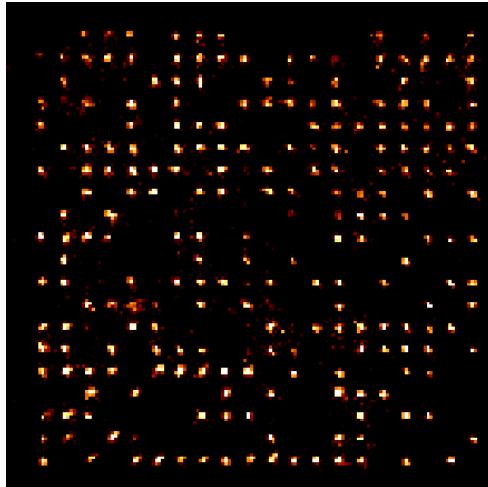


SLM pattern

Nogrette, PRX (2014)

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

Initial configuration

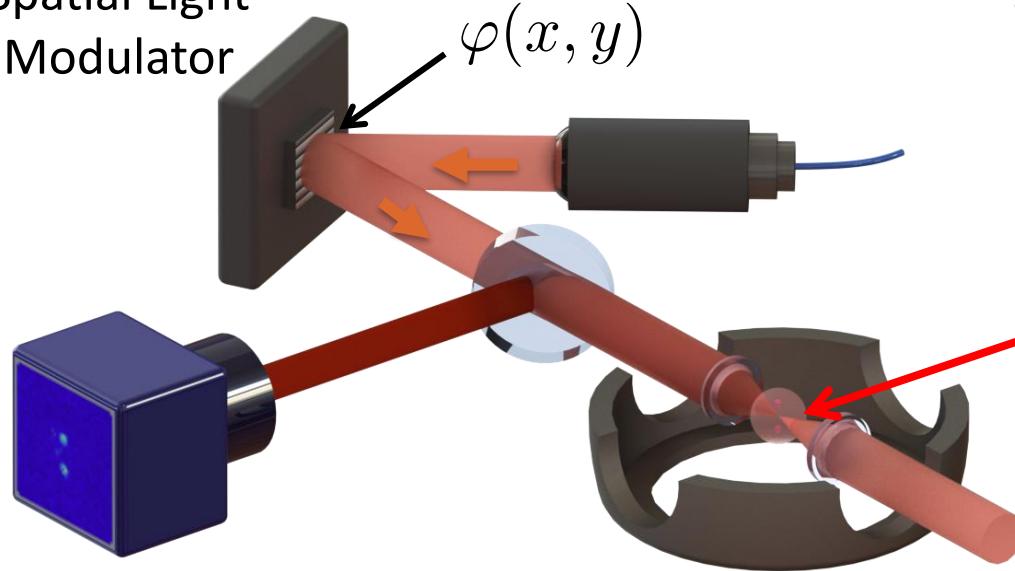


Assembling
process

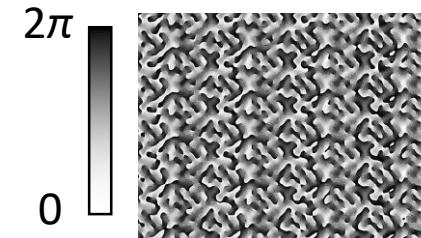
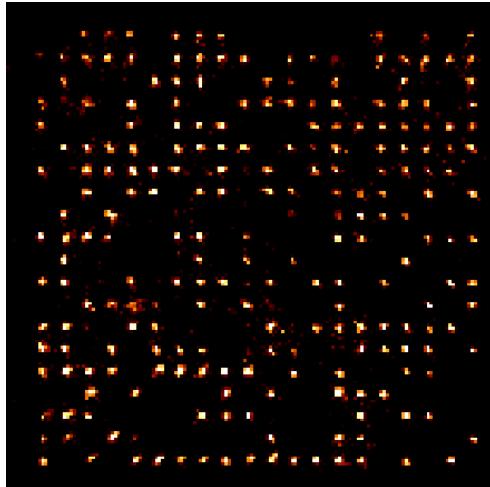


Atomes dans des matrices de pinces optiques

Spatial Light
Modulator



Initial configuration



SLM pattern

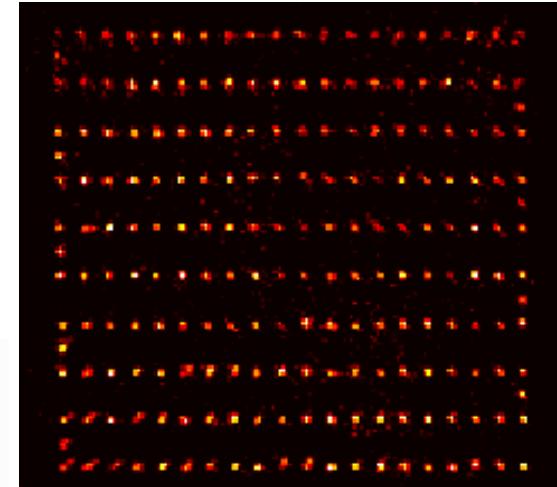
Nogrette, PRX (2014)

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

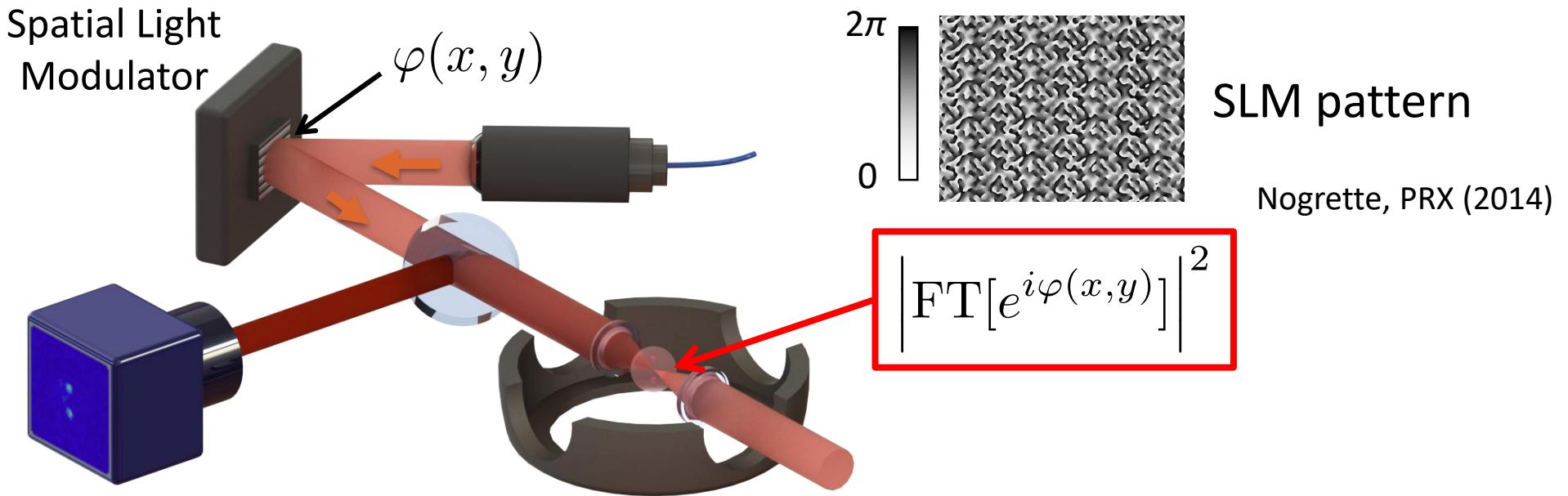
Assembling
process



Assembled configuration

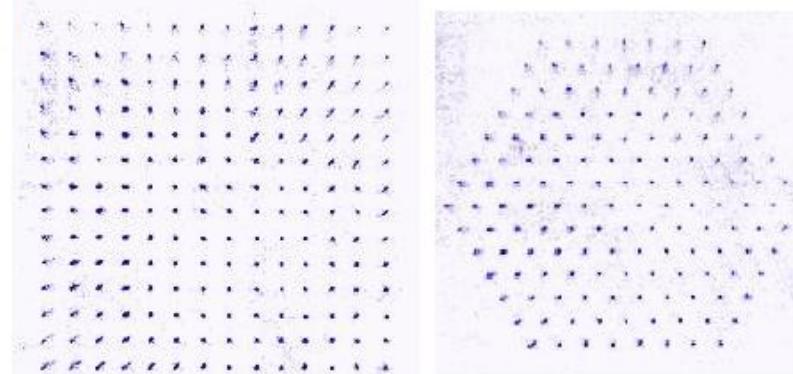
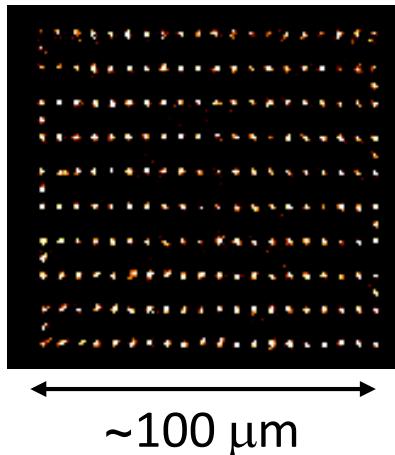


Atomes dans des matrices de pinces optiques



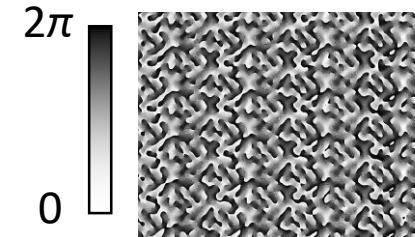
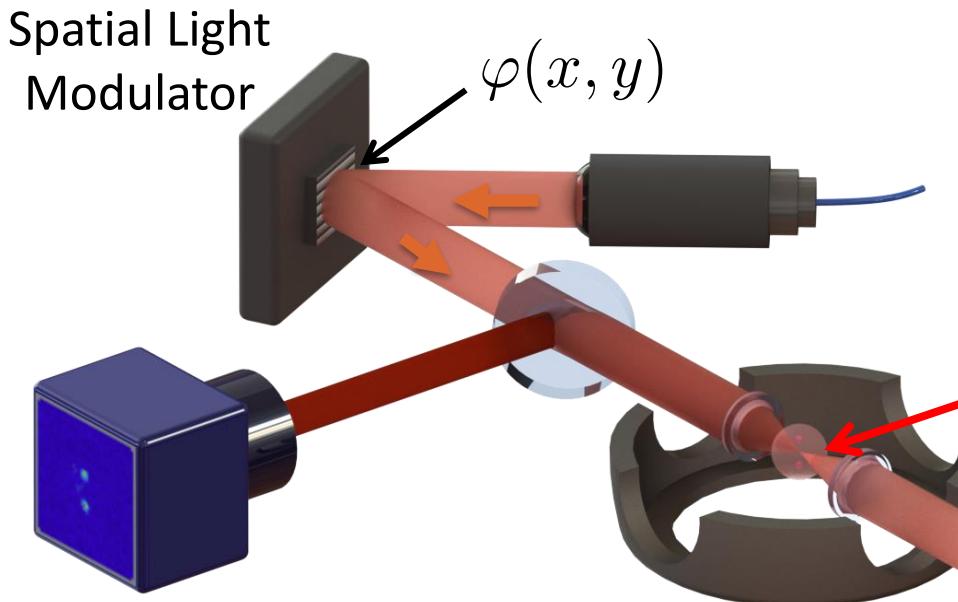
Assembled arrays of individual atoms ($N \sim 200$)

1D 2D Fluorescence: single shot!!



Barredo, Nature 2016 ; Schymik, PRA 2020

Atomes dans des matrices de pinces optiques



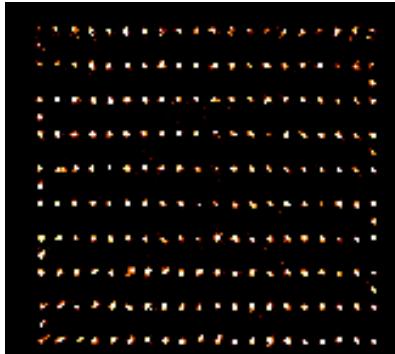
SLM pattern

Nogrette, PRX (2014)

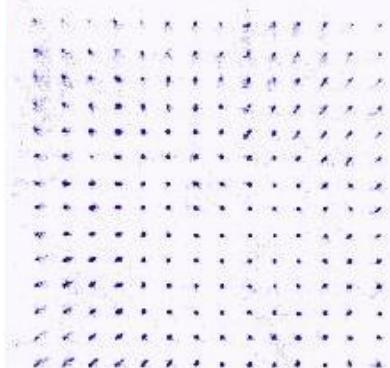
$$\left| \text{FT}[e^{i\varphi(x,y)}] \right|^2$$

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

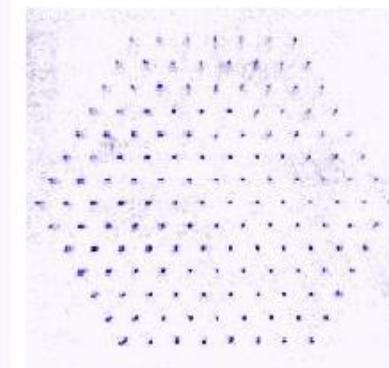
1D



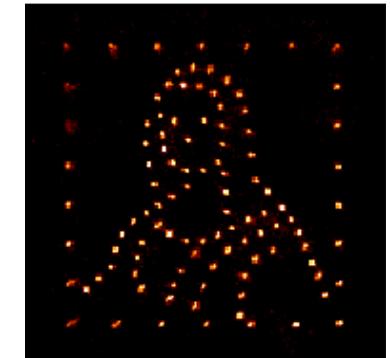
2D



Fluorescence: single shot!!



Random

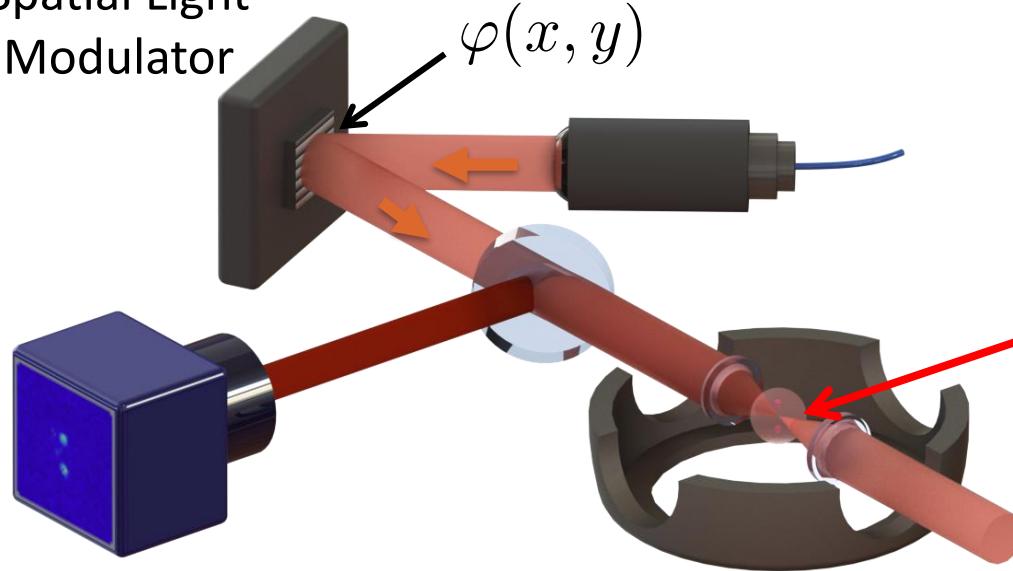


$\sim 100 \mu\text{m}$

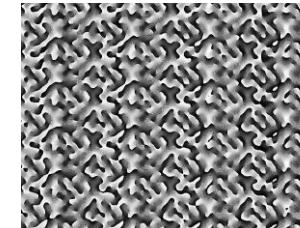
Barredo, Nature 2016 ; Schymik, PRA 2020

Atomes dans des matrices de pinces optiques

Spatial Light
Modulator



2π
0



SLM pattern

Nogrette, PRX (2014)

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

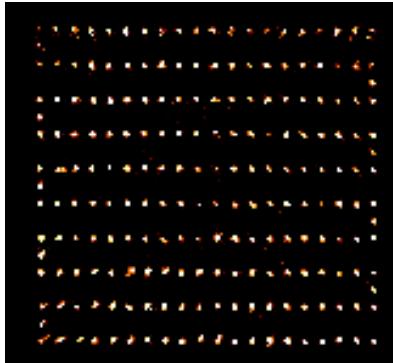
L. da Vinci



Random

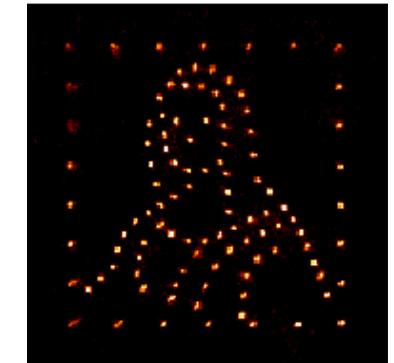
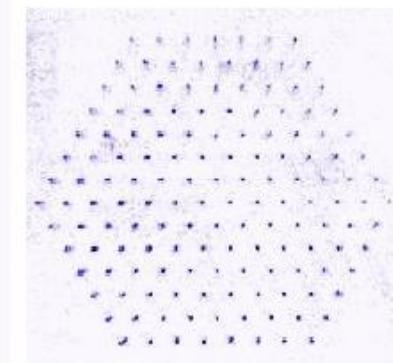
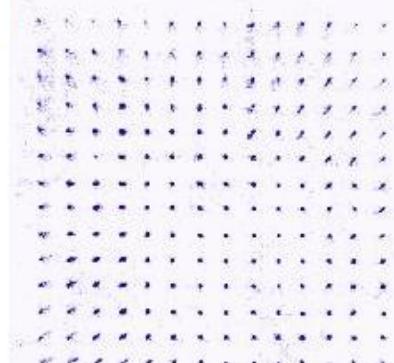
Assembled arrays of individual atoms ($N \sim 200$)

1D



2D

Fluorescence: single shot!!

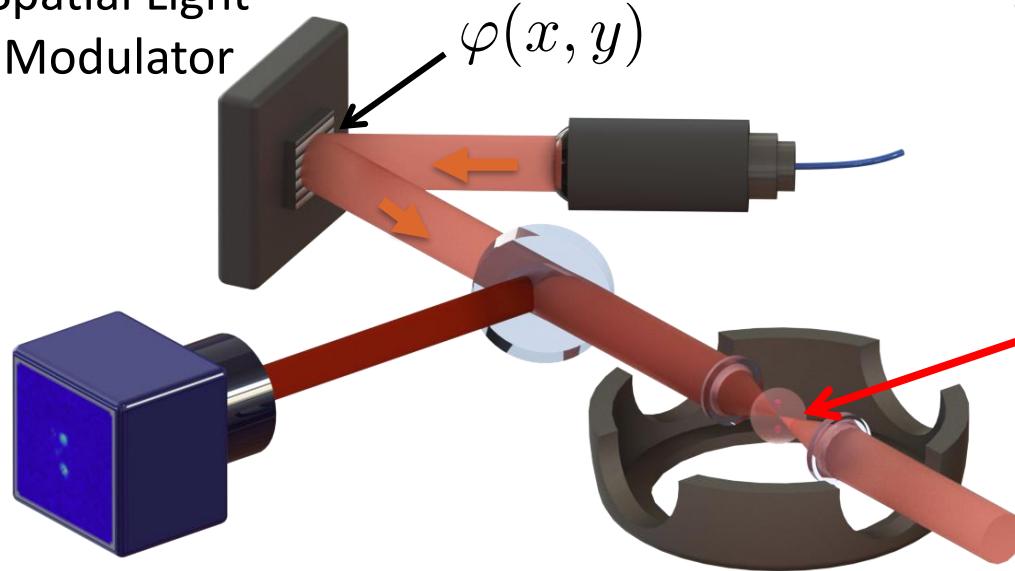


$\sim 100 \mu\text{m}$

Barredo, Nature 2016 ; Schymik, PRA 2020

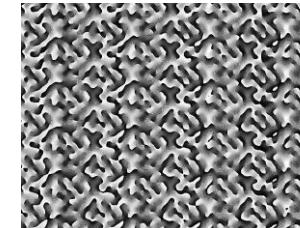
Atomes dans des matrices de pinces optiques

Spatial Light
Modulator



$$\varphi(x, y)$$

2π
0



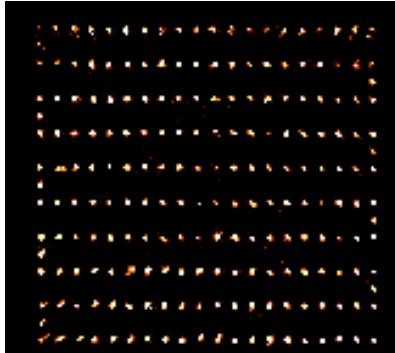
SLM pattern

Nogrette, PRX (2014)

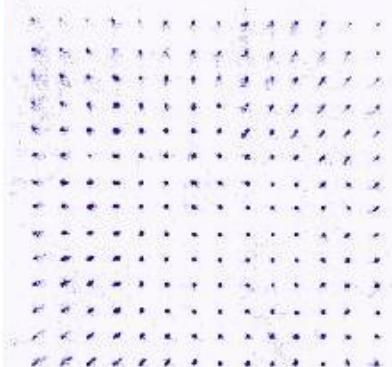
$$|\text{FT}[e^{i\varphi(x,y)}]|^2$$

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

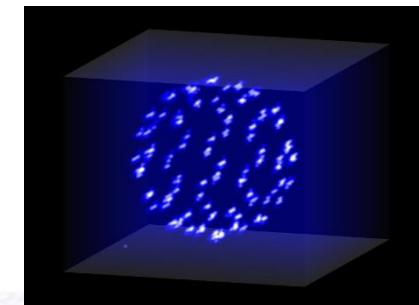
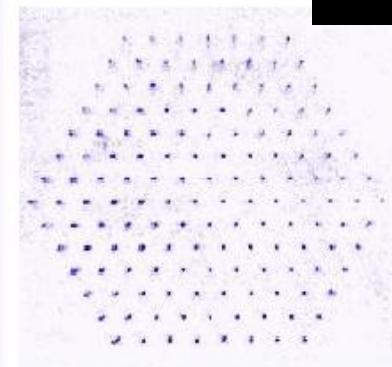
1D



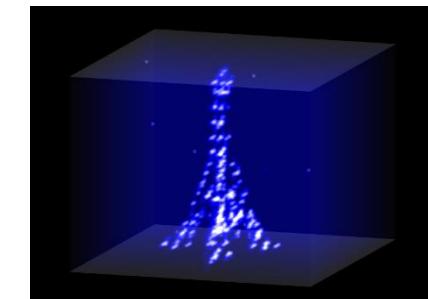
2D



Fluorescence: single shot!!



(averaged)



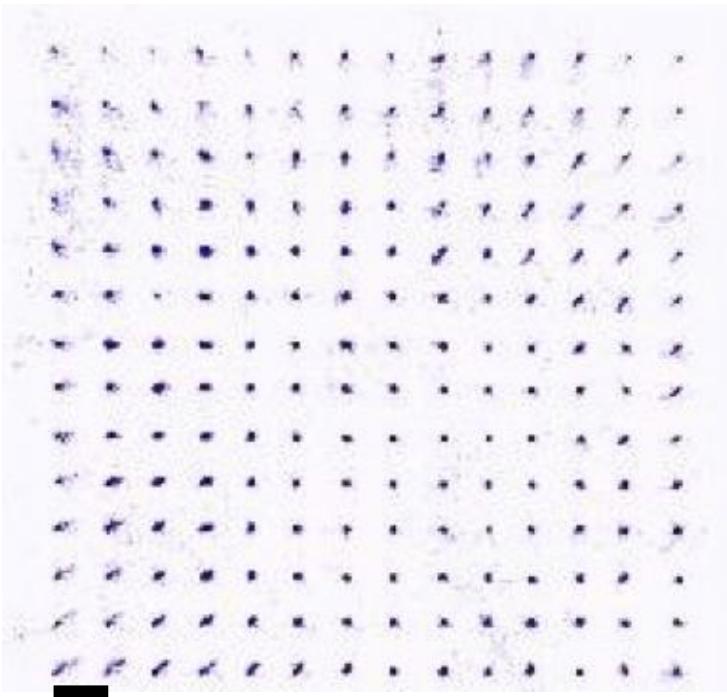
$\sim 100 \mu\text{m}$

Barredo, Nature 2016 ; Schymik, PRA 2020

Barredo, Nature (2018)

Et maintenant... les interactions

Matrice d'atomes

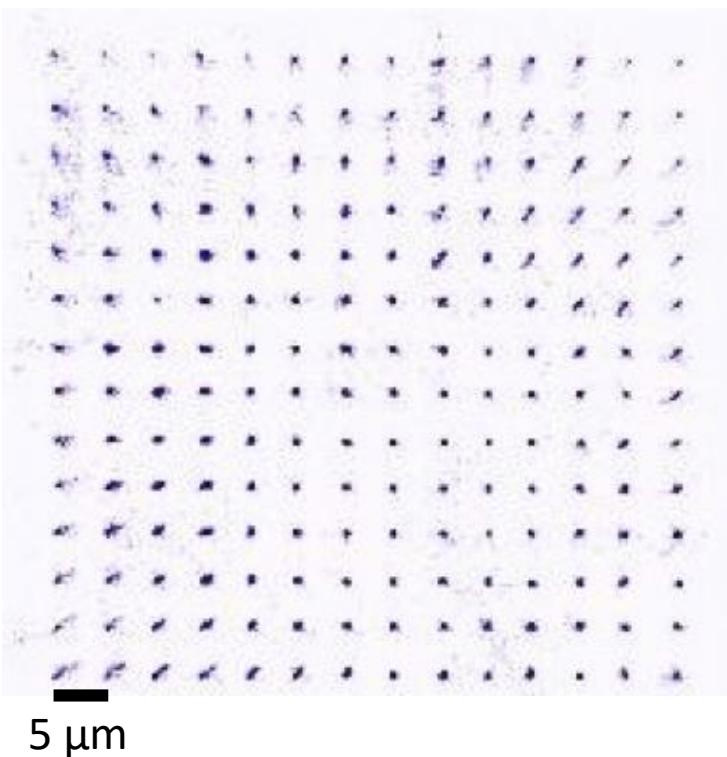


5 μm

Addressable!!

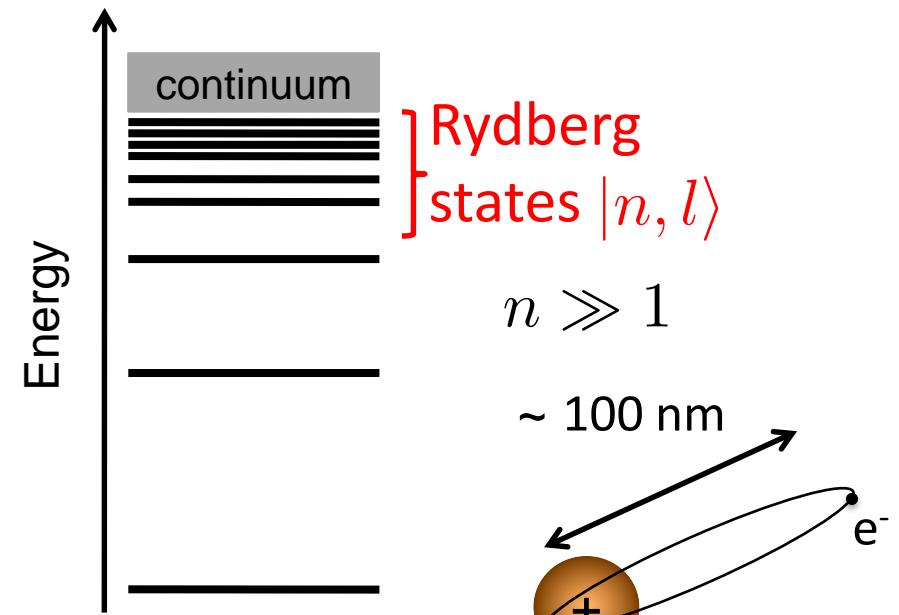
Et maintenant... les interactions

Matrice d'atomes



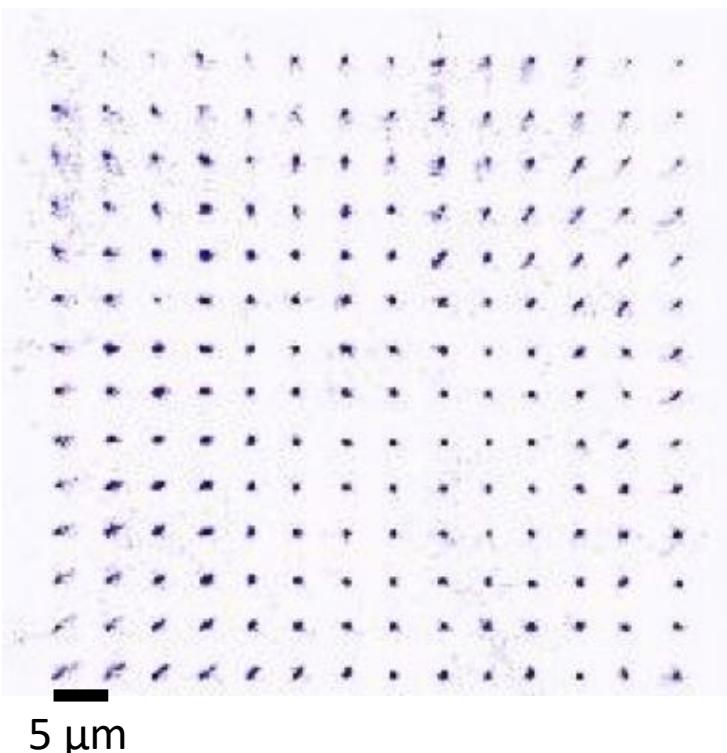
Addressable!!

Atomes de Rydberg



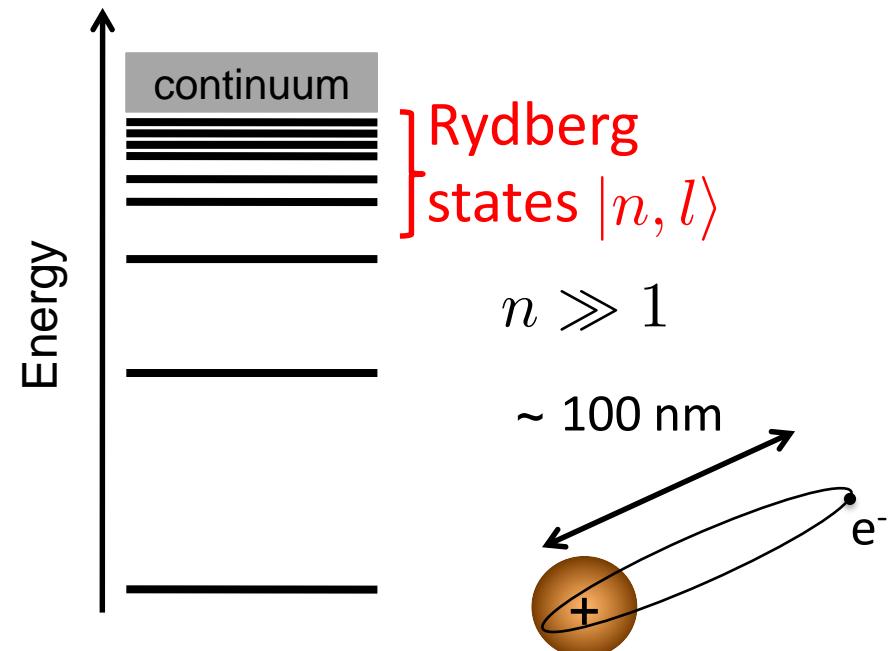
Et maintenant... les interactions

Matrice d'atomes



Addressable!!

Atomes de Rydberg



durée de vie $> 100 \mu\text{s}$

dipôle: $d_{n,n\pm 1} \sim n^2 e a_0$

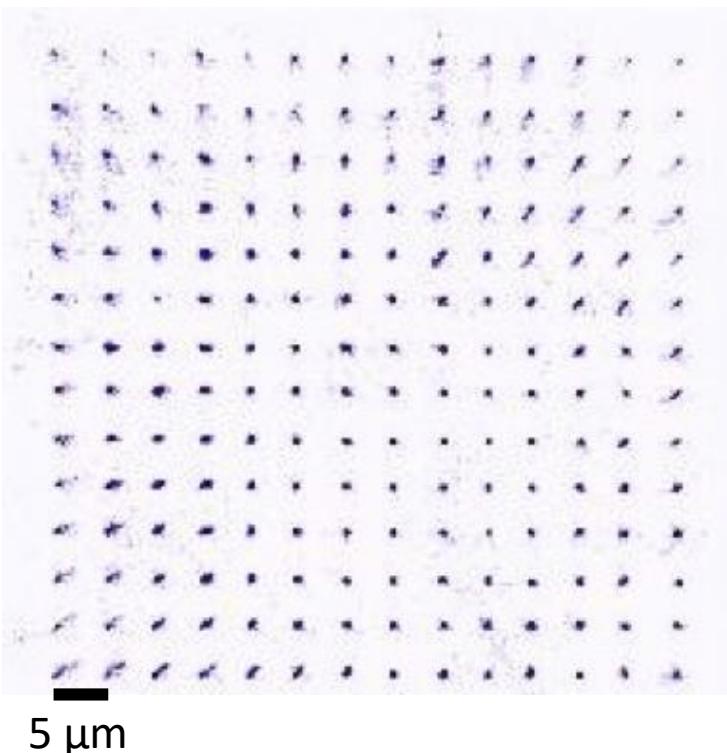
Lukin, Zoller 2000

Saffman, RMP 2010

Browaeys, Nat Phys 2020

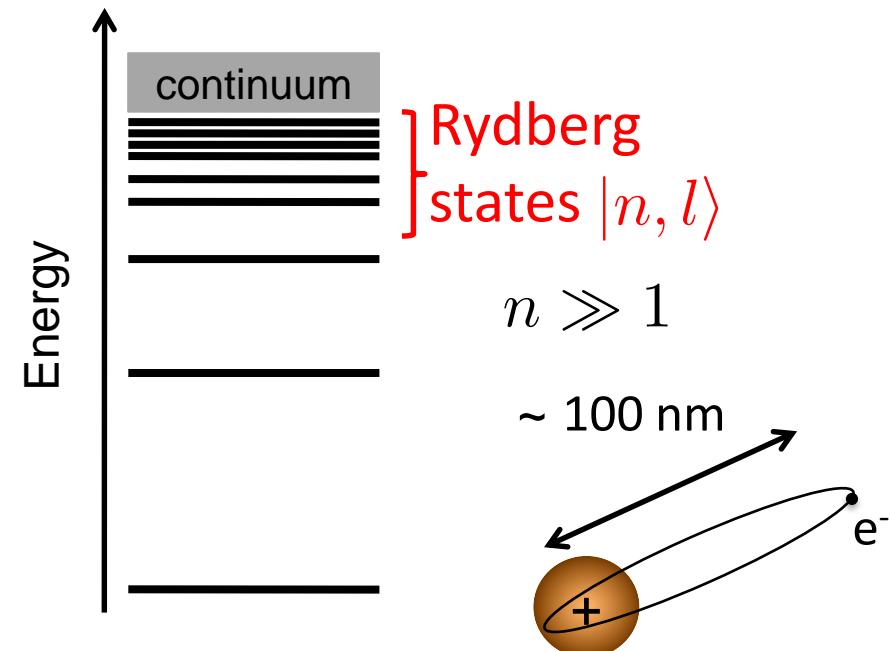
Et maintenant... les interactions

Matrice d'atomes



Addressable!!

Atomes de Rydberg



durée de vie > 100 μs

dipôle: $d_{n,n\pm 1} \sim n^2 e a_0$

⇒ Interactions dipôle-dipôle fortes

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

⇒ timescales < μsec

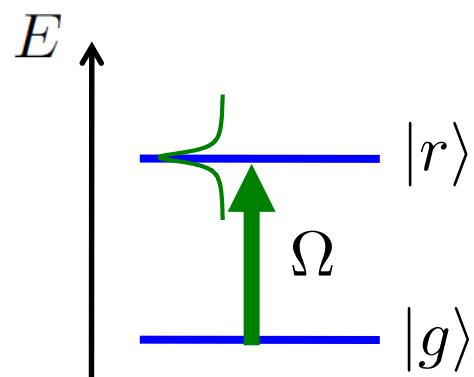
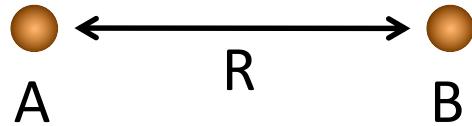
Lukin, Zoller 2000

Saffman, RMP 2010

Browaeys, Nat Phys 2020

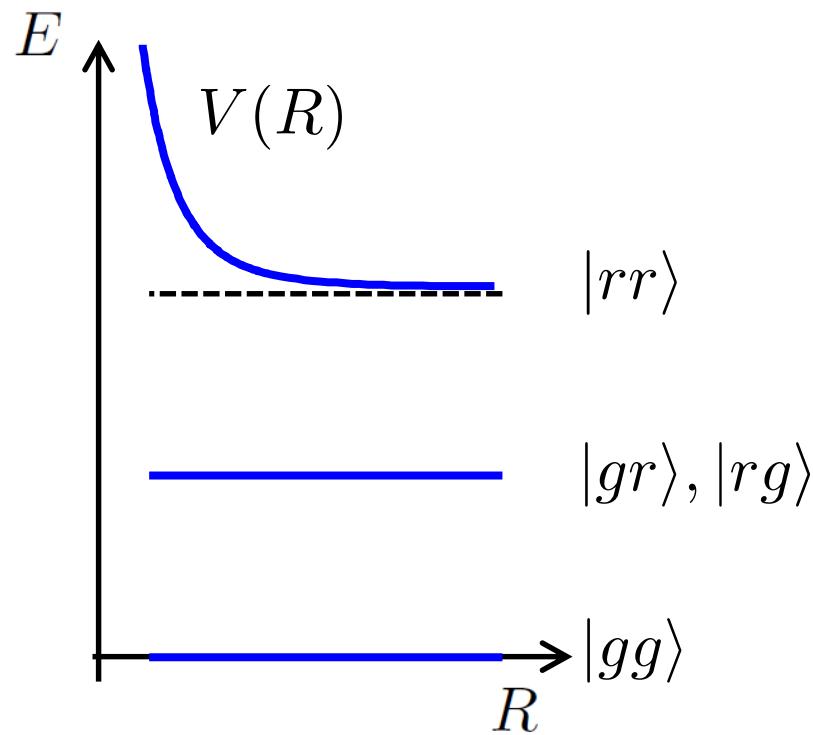
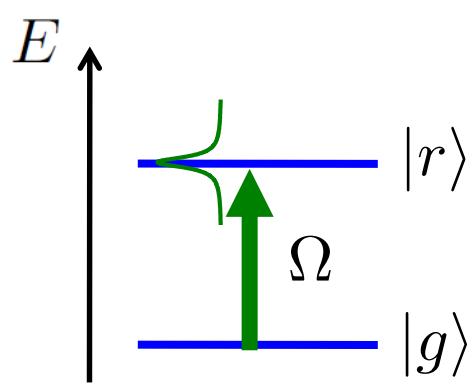
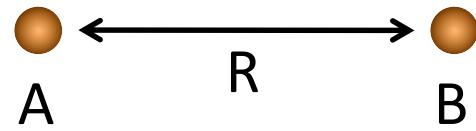
Rydberg Blockade & entanglement

D. Jaksch, PRL **85**, 2208 (2000)
M. D. Lukin, PRL **87**, 037901 (2001)



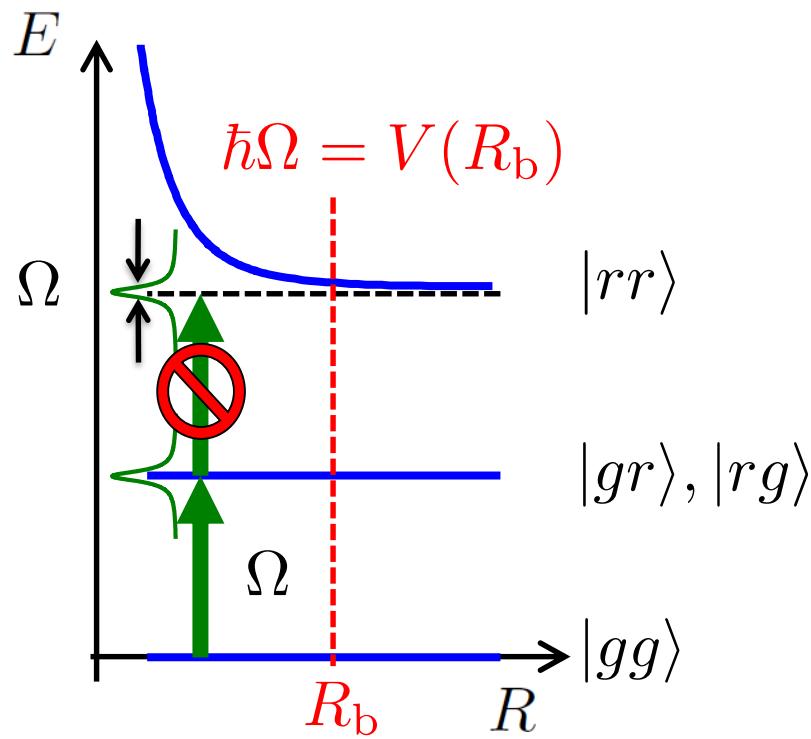
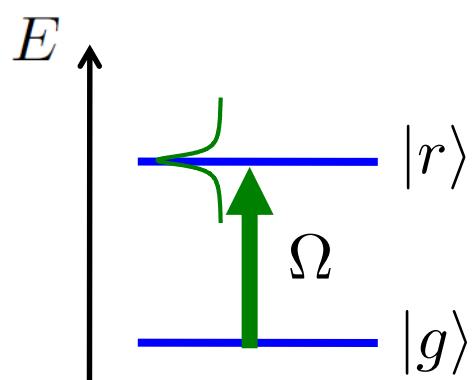
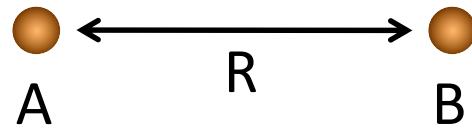
Rydberg Blockade & entanglement

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Rydberg Blockade & entanglement

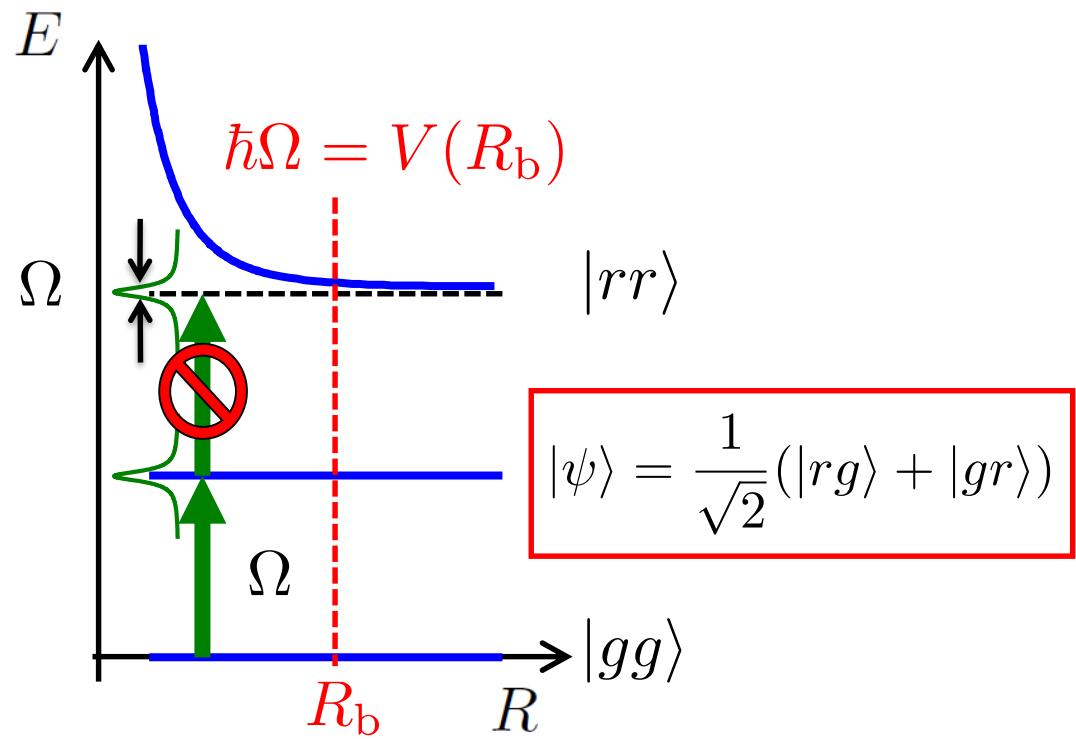
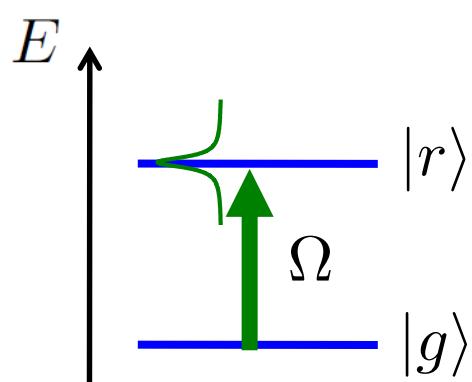
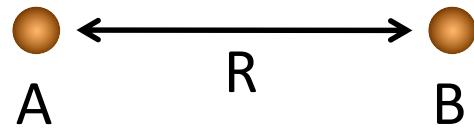
D. Jaksch, PRL **85**, 2208 (2000)
M. D. Lukin, PRL **87**, 037901 (2001)



If $\hbar\Omega \ll U_{\text{vdW}}$: no excitation of $|rr\rangle \Rightarrow \text{blockade}$

Rydberg Blockade & entanglement

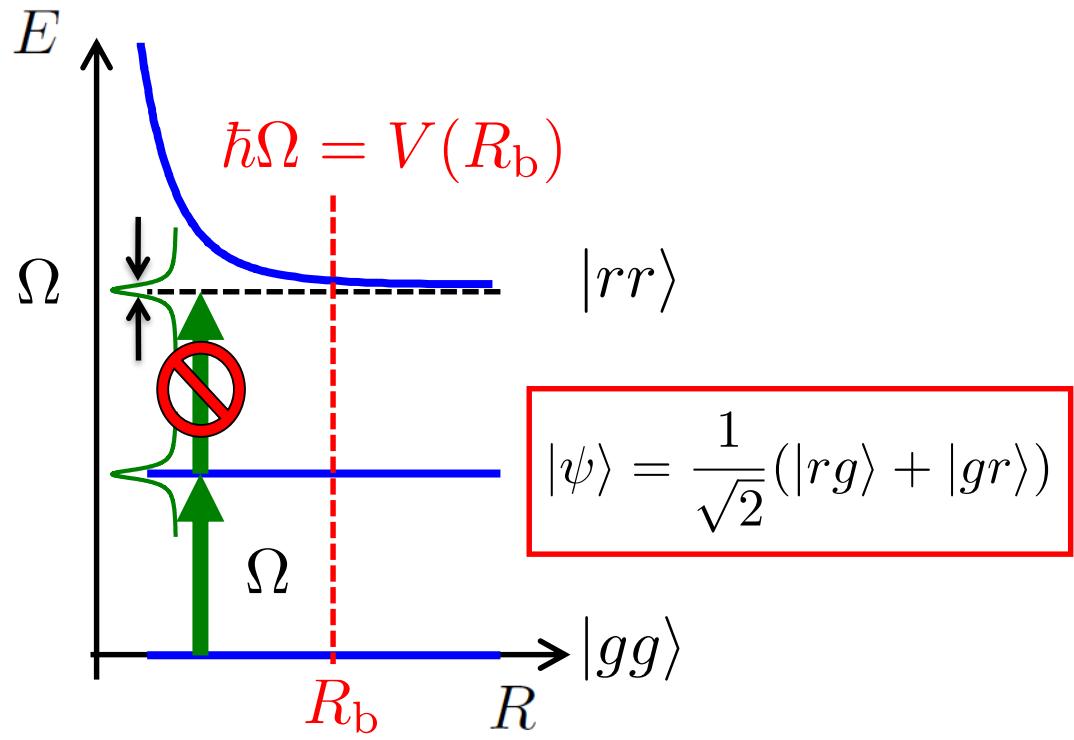
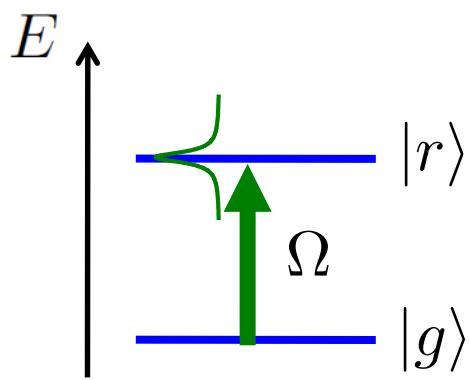
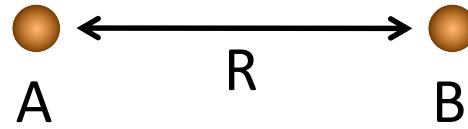
D. Jaksch, PRL **85**, 2208 (2000)
M. D. Lukin, PRL **87**, 037901 (2001)



Blockade \Rightarrow **entanglement and gates!!**

Rydberg Blockade & entanglement

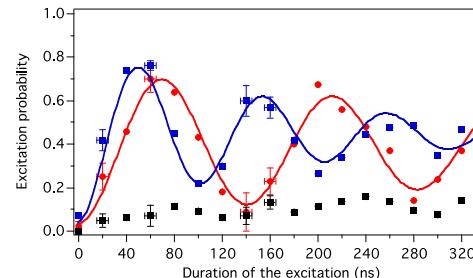
D. Jaksch, PRL **85**, 2208 (2000)
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Blockade \Rightarrow **entanglement and gates!!**

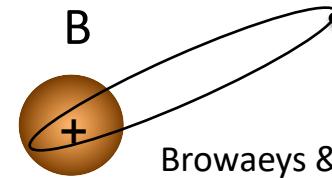
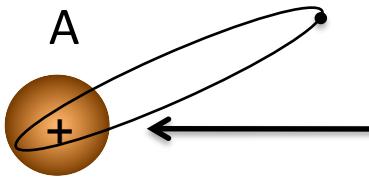
First demonstrations 2 atoms

IOGS
Nat. Phys. 2009



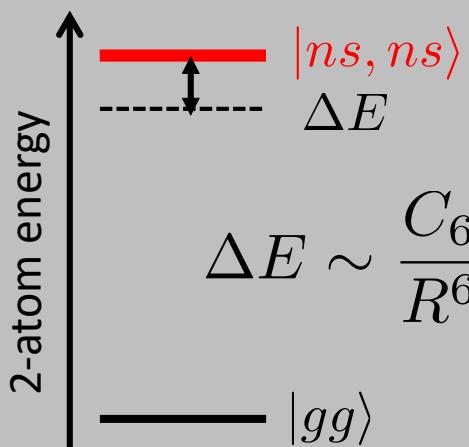
+ Univ. Madison
(USA)

Interactions entre atomes de Rydberg et modèles de spin

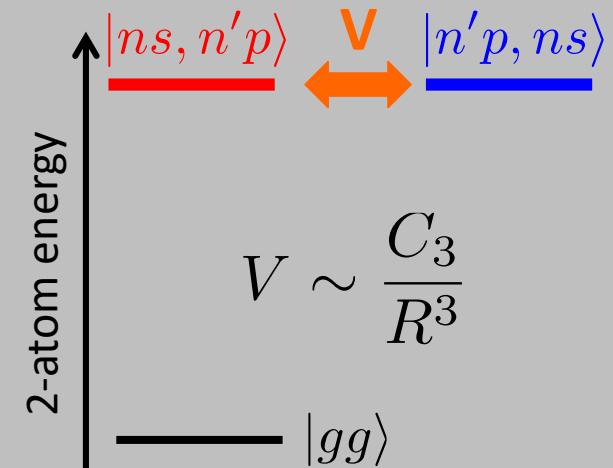


Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals

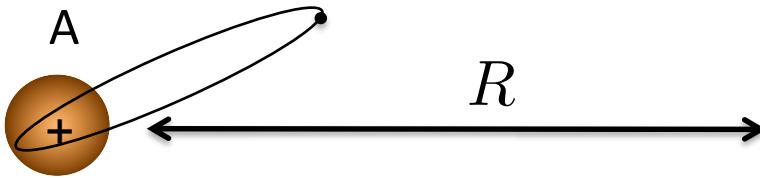


Resonant dipole



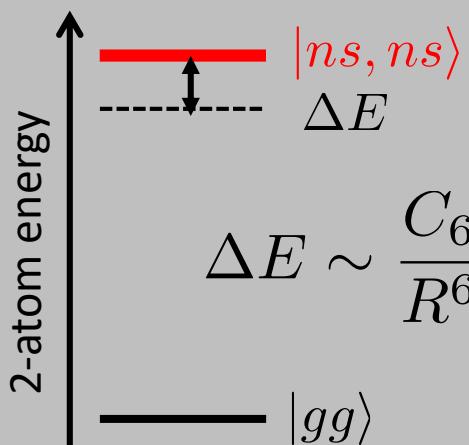
$$V \sim \frac{C_3}{R^3}$$

Interactions entre atomes de Rydberg et modèles de spin

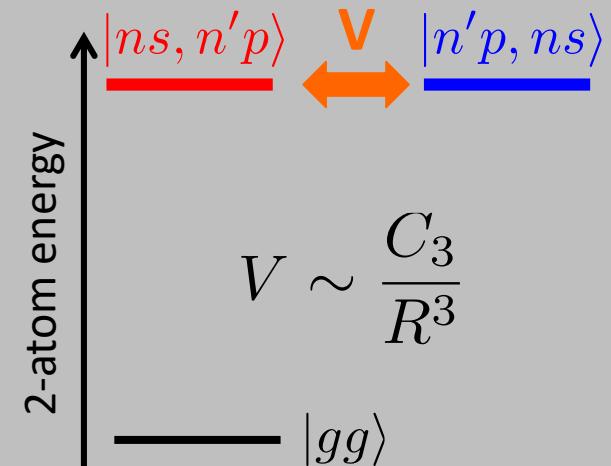


Browaeys & Lahaye, Nat.Phys. (2020)

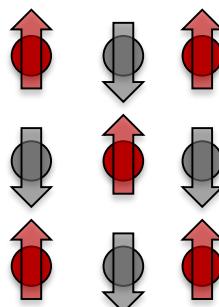
van der Waals



Resonant dipole



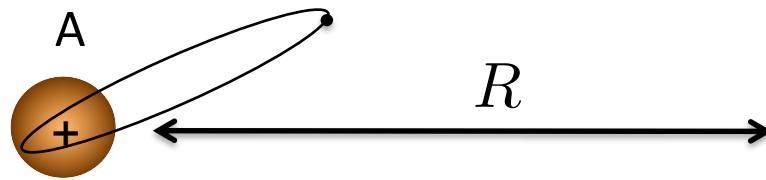
Spin 1/2



Modèle d'Ising (quantique)

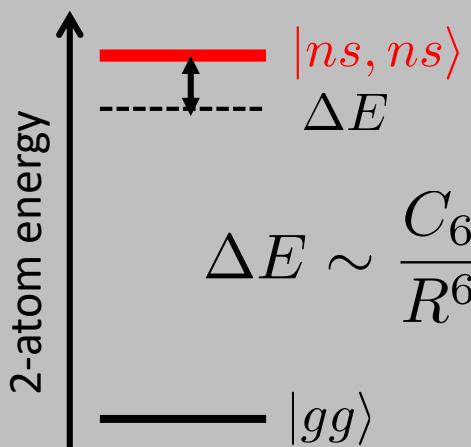
$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

Interactions entre atomes de Rydberg et modèles de spin

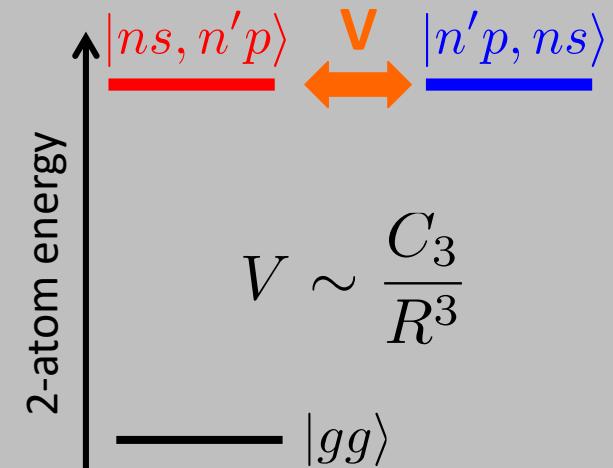


Browaeys & Lahaye, Nat.Phys. (2020)

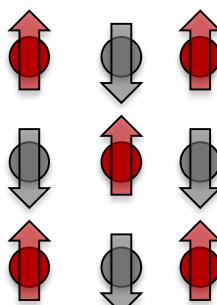
van der Waals



Resonant dipole

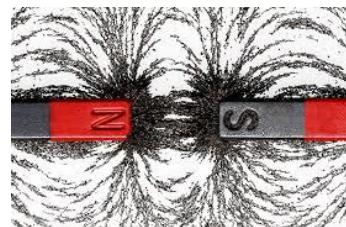
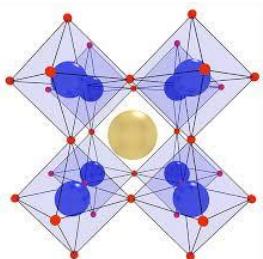


Spin 1/2

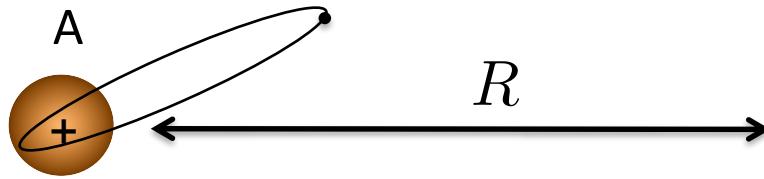


Modèle d'Ising (quantique)

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

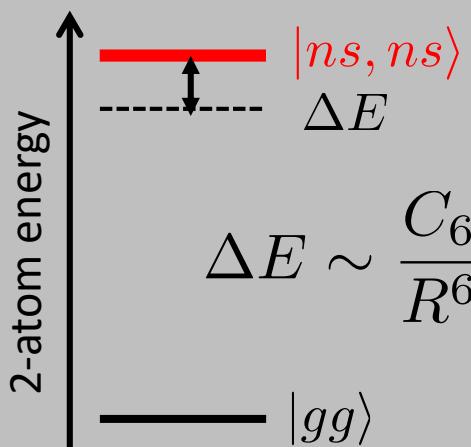


Interactions entre atomes de Rydberg et modèles de spin

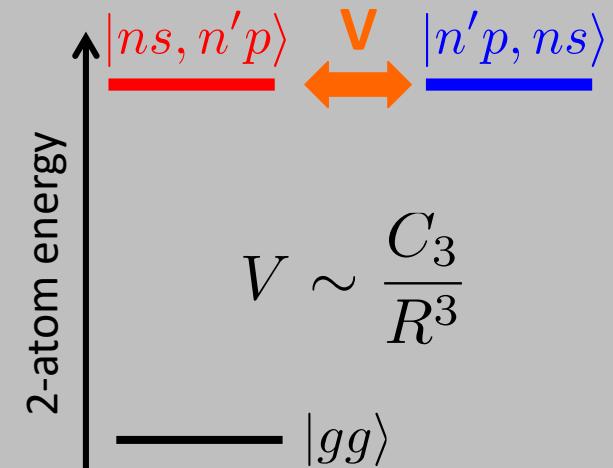


Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals

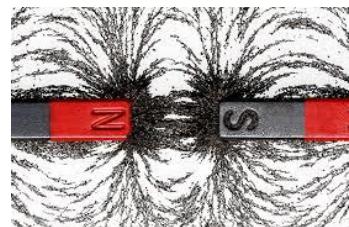
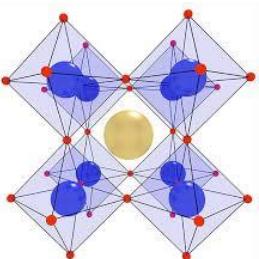


Resonant dipole

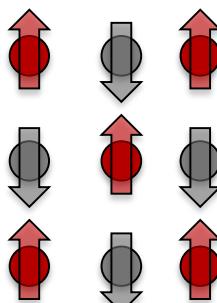


Modèle d'Ising (quantique)

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$



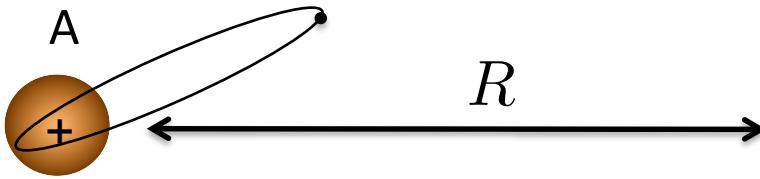
Spin 1/2



modèle XY

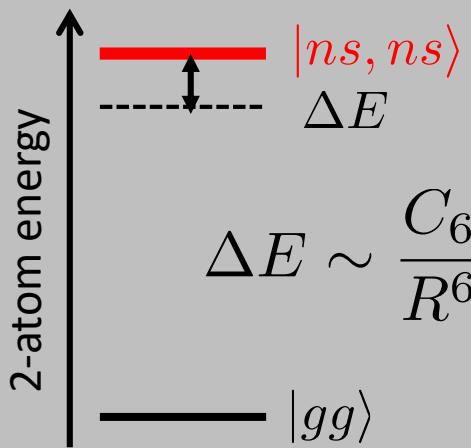
$$\hat{H} = \sum_{i \neq j} J_{ij} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

Interactions entre atomes de Rydberg et modèles de spin

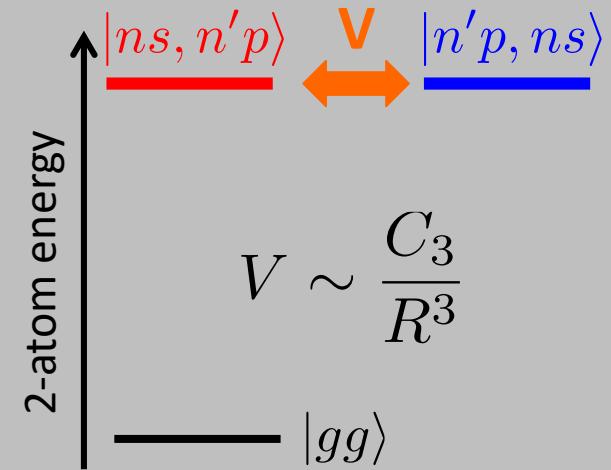


Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals

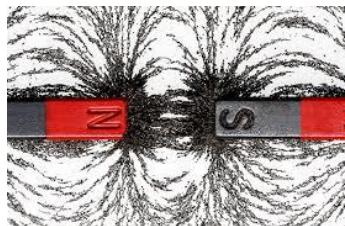
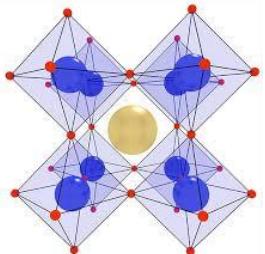


Resonant dipole

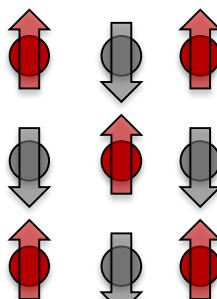


Modèle d'Ising (quantique)

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

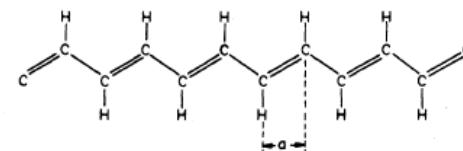


Spin 1/2



modèle XY

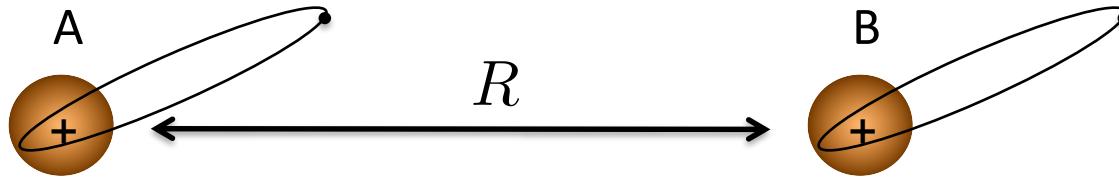
$$\hat{H} = \sum_{i \neq j} J_{ij} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$



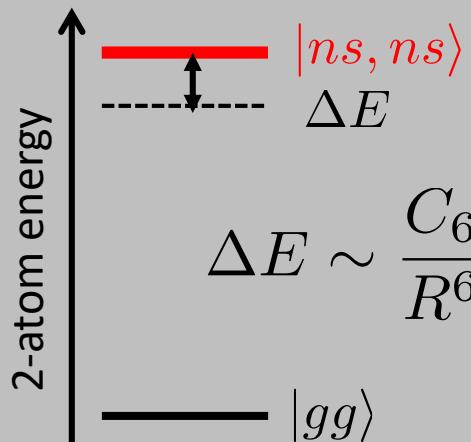
Le programme...

1. Physique à N -corps, simulation quantique et systèmes quantiques synthétiques
2. Construire un simulateur quantique à atomes de Rydberg
3. Exemples de simulation de magnétisme quantique

From van der Waals interactions to Ising model...

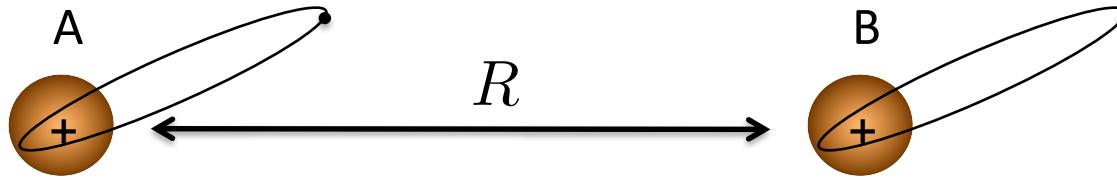


van der Waals

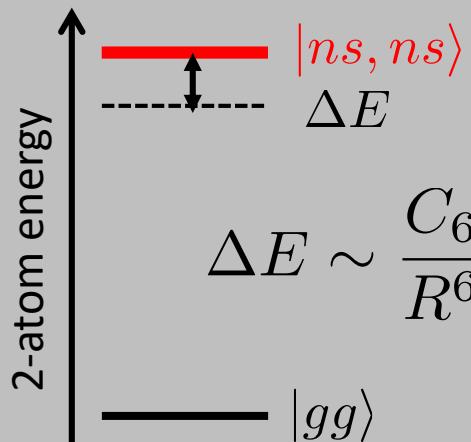


$C_6 \propto n^{11} \Rightarrow$ switchable interaction

From van der Waals interactions to Ising model...



van der Waals

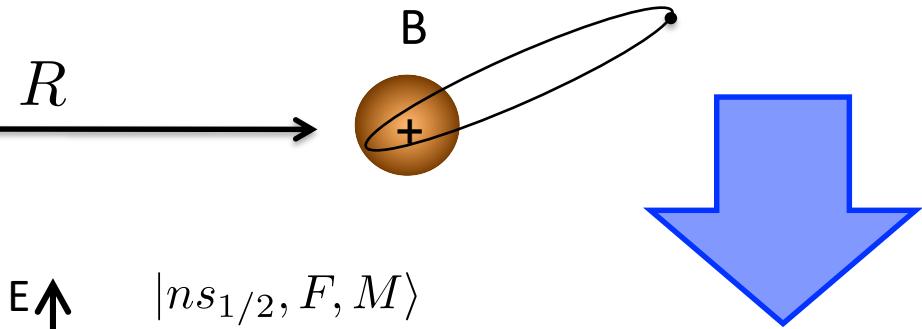
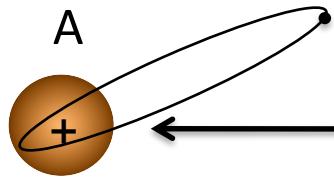


$C_6 \propto n^{11} \Rightarrow$ switchable interaction

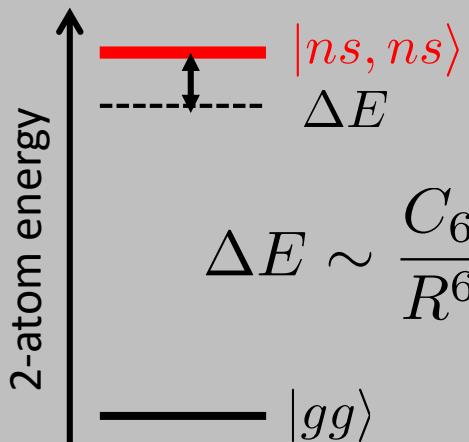
$$\hat{H}_{\text{int}} = \frac{C_6}{R^6} \hat{n}_1 \hat{n}_2 \sim J \hat{\sigma}_1^z \hat{\sigma}_2^z$$

Rydberg occupation number

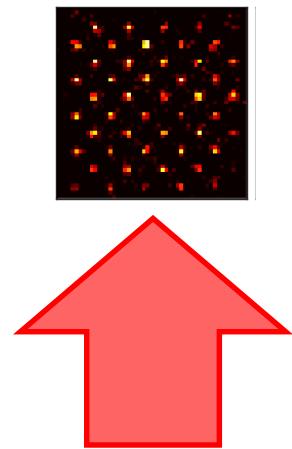
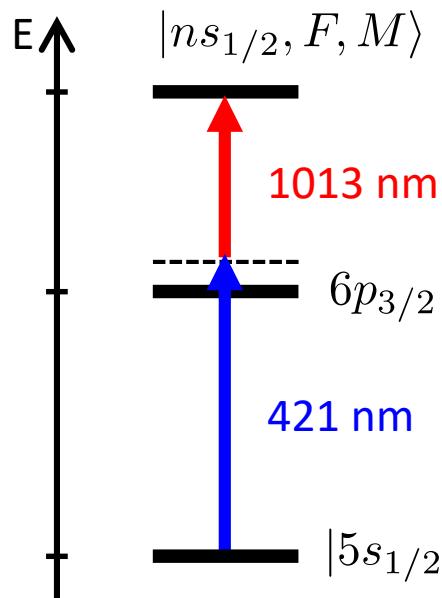
From van der Waals interactions to Ising model...



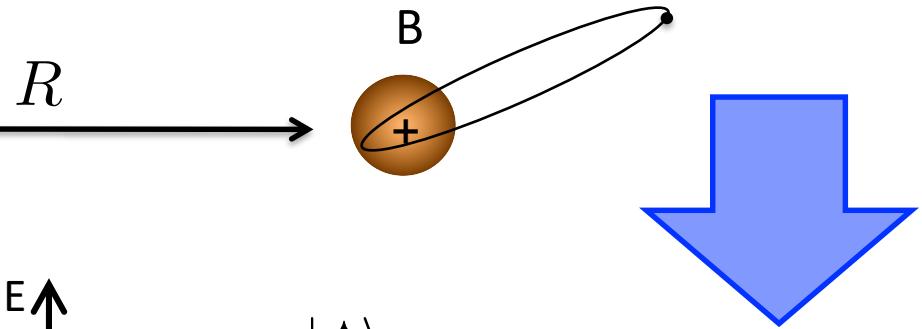
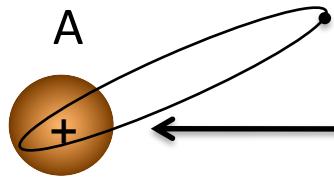
van der Waals



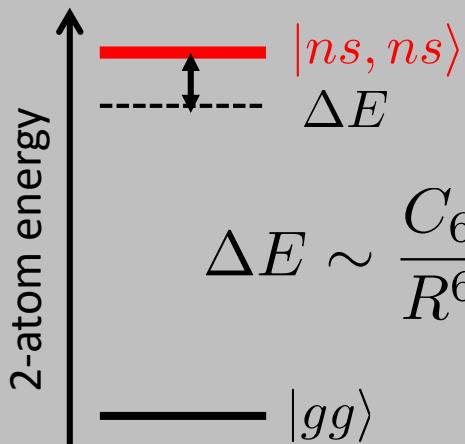
$$\Delta E \sim \frac{C_6}{R^6}$$



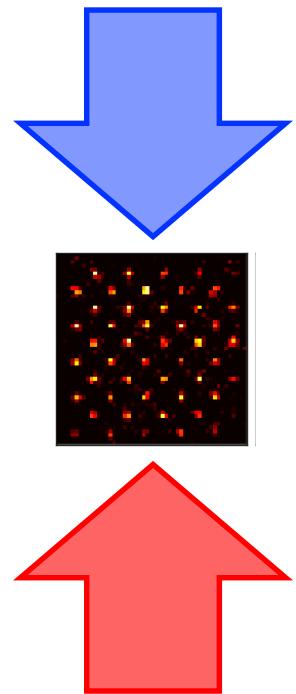
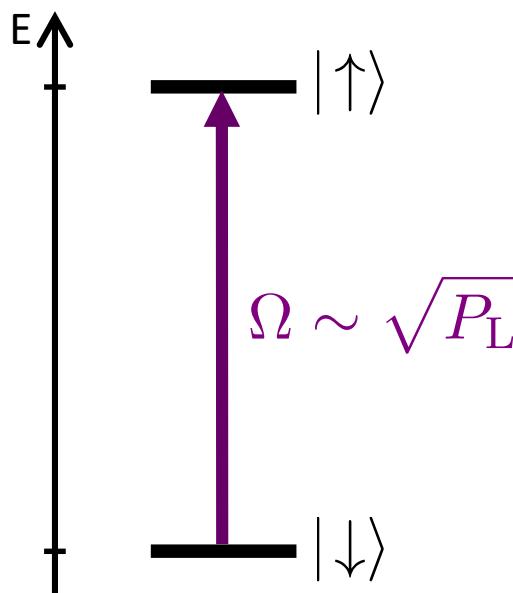
From van der Waals interactions to Ising model...



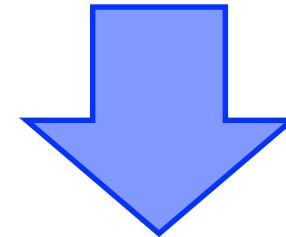
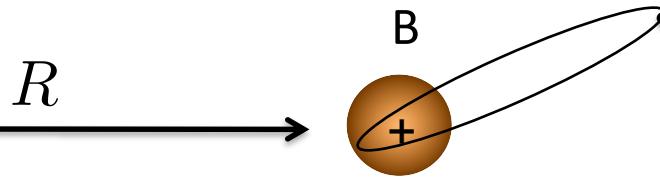
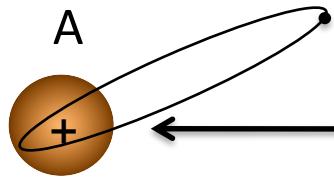
van der Waals



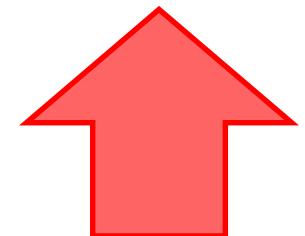
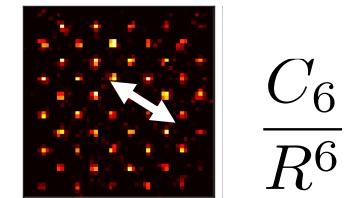
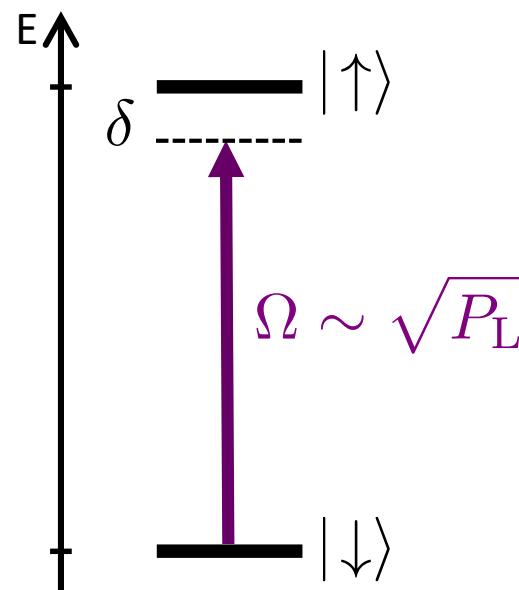
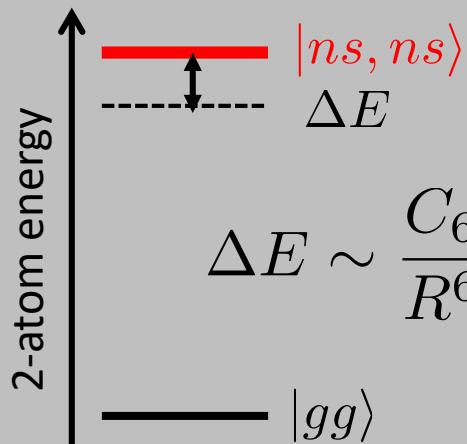
$$\Delta E \sim \frac{C_6}{R^6}$$



From van der Waals interactions to Ising model...



van der Waals



Quantum Ising-like model ($s=\frac{1}{2}$):

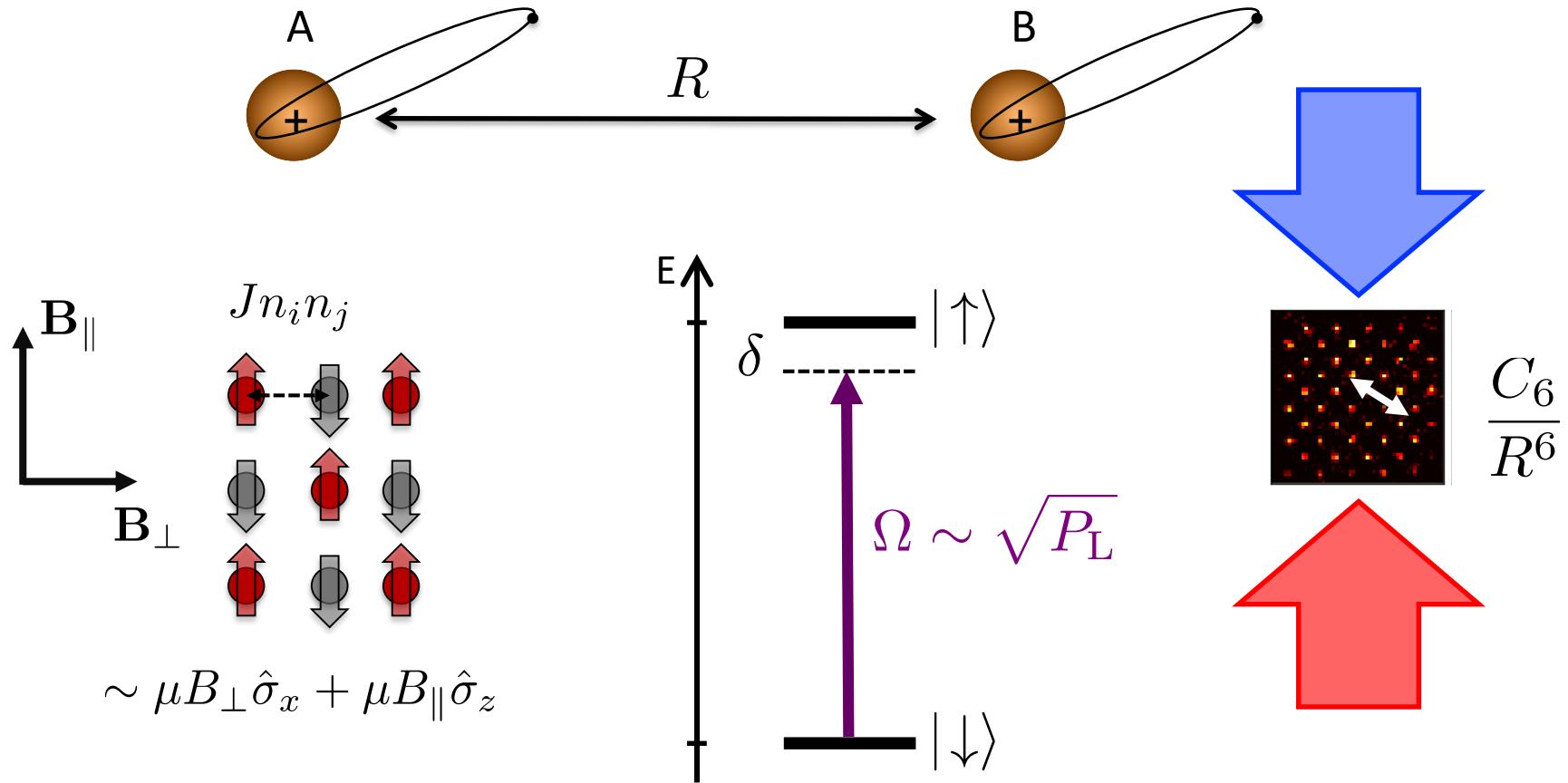
$$H = \frac{\hbar\Omega}{2} \sum_i \sigma_x^i + \hbar\delta \sum_i \hat{n}_i + \sum_{i < j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

Laser: B_\perp

B_\parallel

Spin-spin interaction

From van der Waals interactions to Ising model...

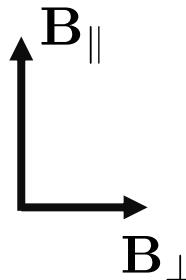
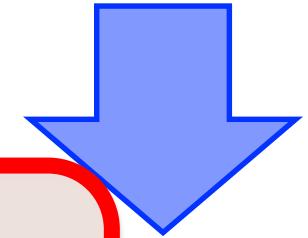
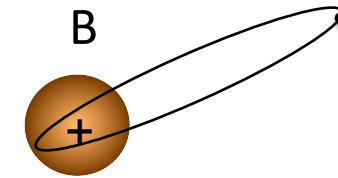
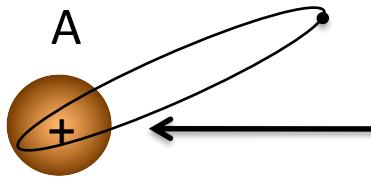


Quantum Ising-like model ($s=\frac{1}{2}$):

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

Laser: B_{\perp} B_{\parallel} Spin-spin interaction

From van der Waals interactions to Ising model...

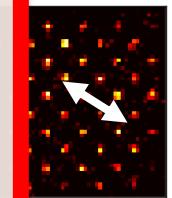


Simulation quantique analogique:

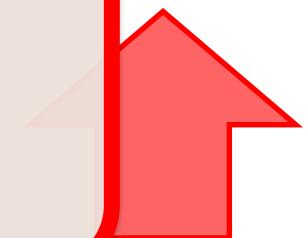
Emulation d'un système par un autre

Équations similaires conduisent aux
mêmes solutions

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



$$\frac{C_6}{R^6}$$



Quantum Ising-like model ($s=\frac{1}{2}$):

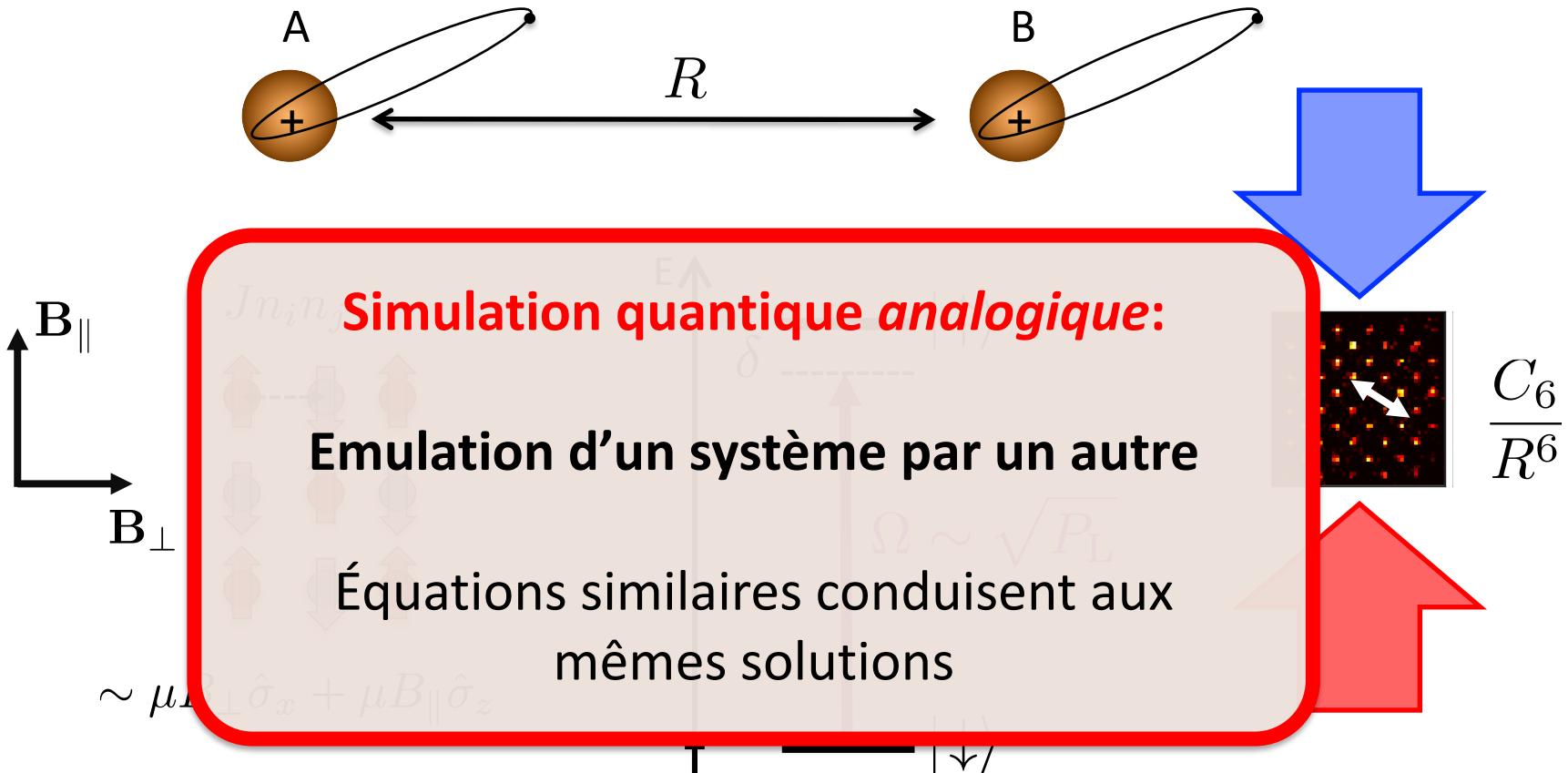
$$H = \frac{\hbar\Omega}{2} \sum_i \sigma_x^i + \hbar\delta \sum_i \hat{n}_i + \sum_{i < j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

Laser: B_{\perp}

B_{\parallel}

Spin-spin interaction

From van der Waals interactions to Ising model...



Quantum Ising-like model ($s=1/2$):

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

Laser: B_{\perp}

B_{\parallel}

Spin-spin interaction

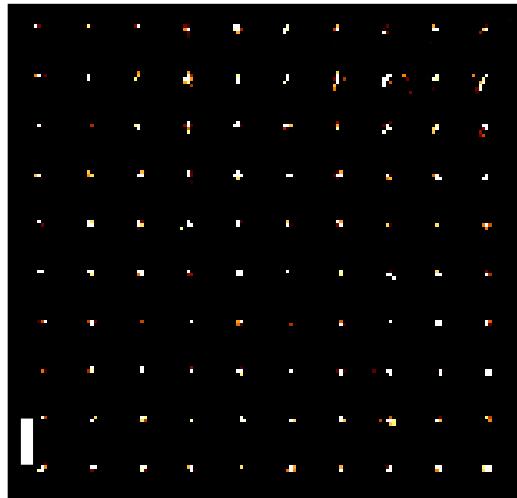
Experiment.

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

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

10 × 10 square array

Scholl et al. Nature (2021)

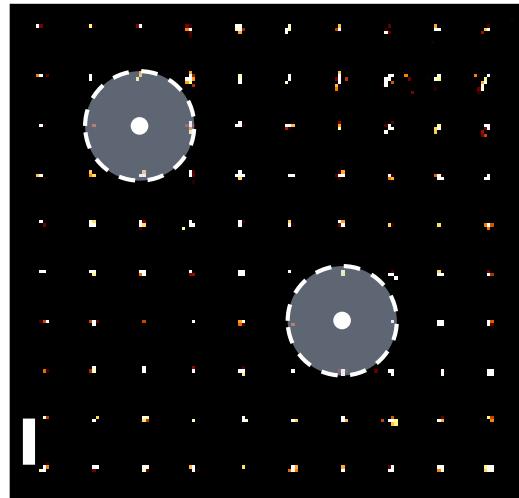


1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
2D: Lienhard PRX 2018, Bakr PRX 2018; Lukin Nature 2021

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

10 × 10 square array

Scholl et al. Nature (2021)



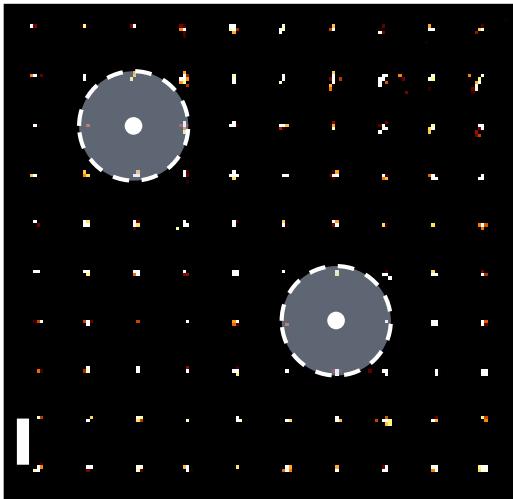
$$\frac{C_6}{a^6} \sim \Omega$$

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

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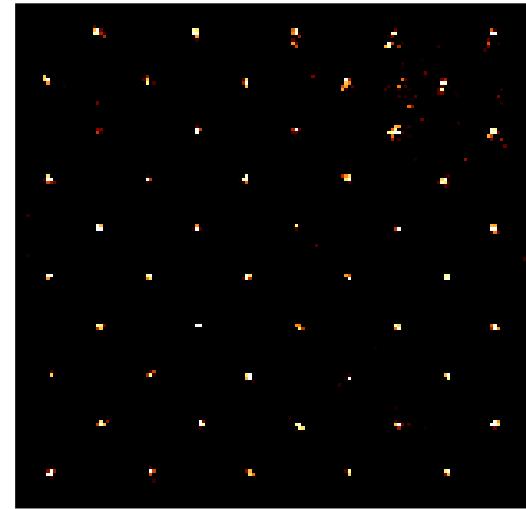
10 μm



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

sweep

Scholl et al. Nature (2021)



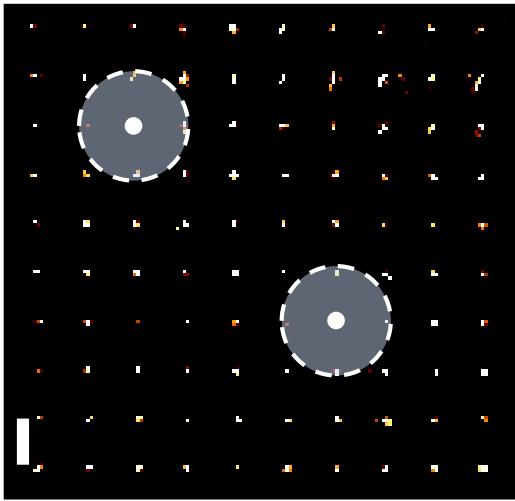
$n=75s$

1D: Pohl PRL 2010; Bloch Science 2015; Lukin Nature 2017, 2019;
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Preparation of a 2D Ising anti-ferromagnet on a square

10 × 10 square array

10 μm

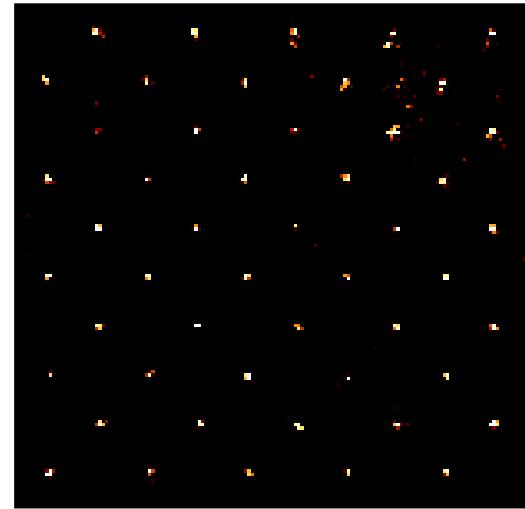


Scholl et al. Nature (2021)

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

sweep

= $|g\rangle$ bright
 = $|r\rangle$ dark



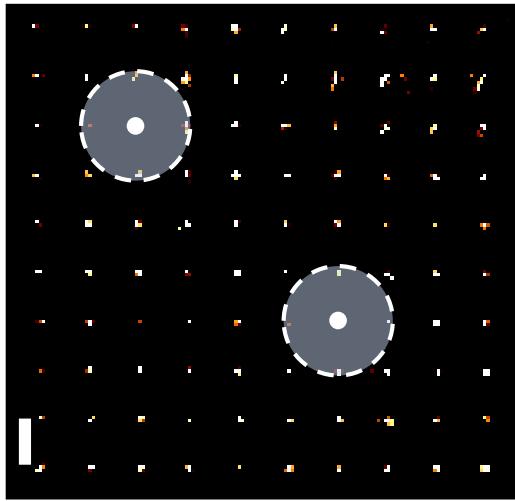
$n=75s$

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

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10 μm

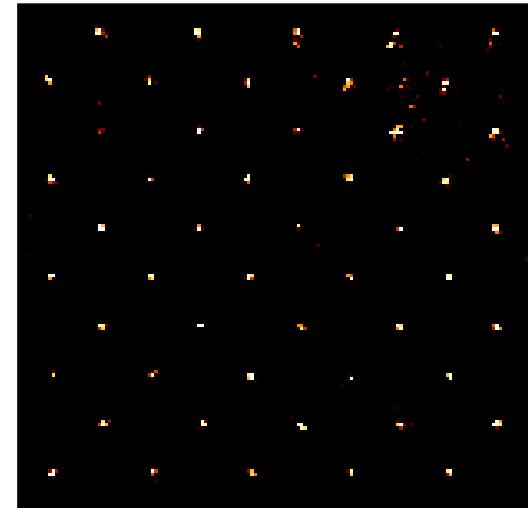


$\Omega(t), \delta(t)$

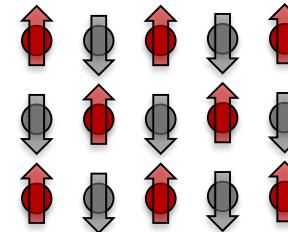
sweep

= $|g\rangle$ bright
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Scholl et al. Nature (2021)



AFM (Néel) ordering!

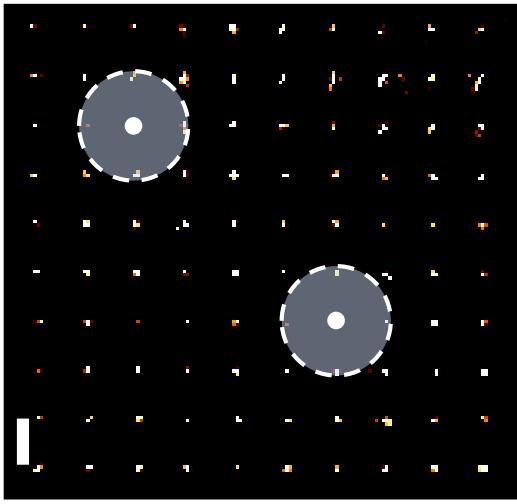


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Preparation of a 2D Ising anti-ferromagnet on a square

10 × 10 square array

10 μm

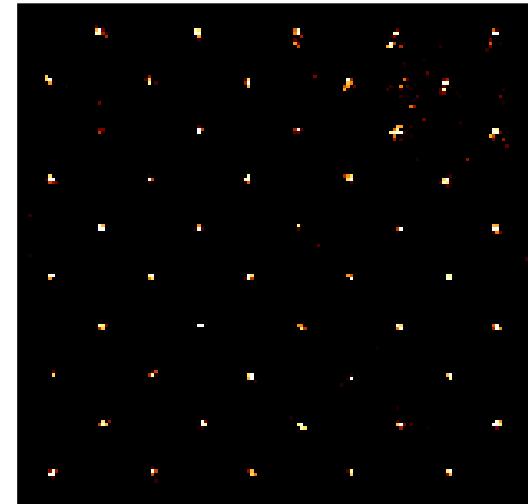


$\Omega(t), \delta(t)$

sweep

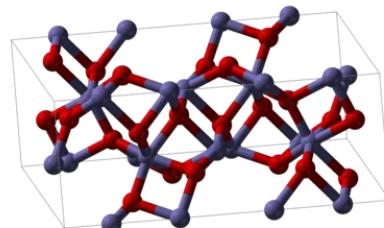
= $|g\rangle$ bright
 = $|r\rangle$ dark

Scholl et al. Nature (2021)

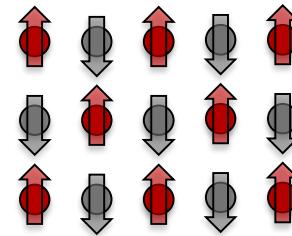


$n=75s$

Ex of antiferromagnets:
MnO, FeO, CoO, NiO, FeCl₂...



AFM (Néel) ordering!

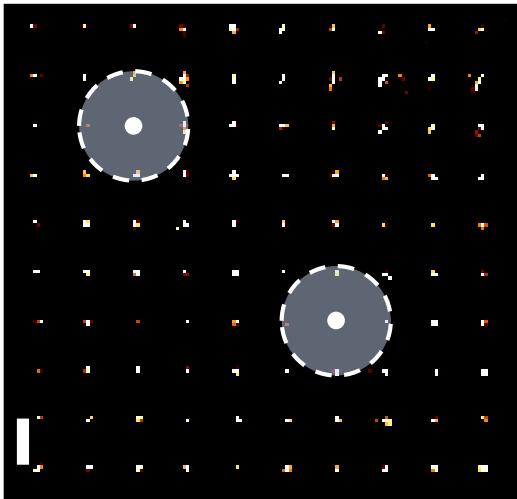


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Preparation of a 2D Ising anti-ferromagnet on a square

10 × 10 square array

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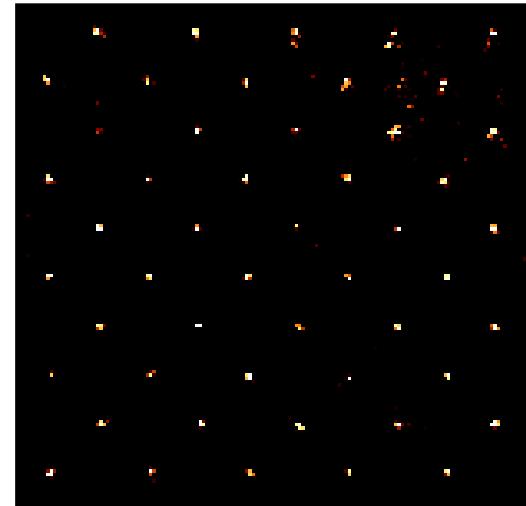


$\Omega(t), \delta(t)$

sweep

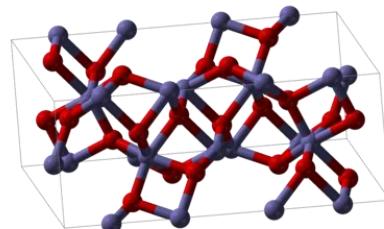
= $|g\rangle$ bright
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Scholl et al. Nature (2021)

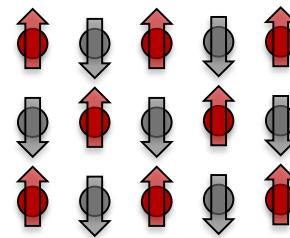


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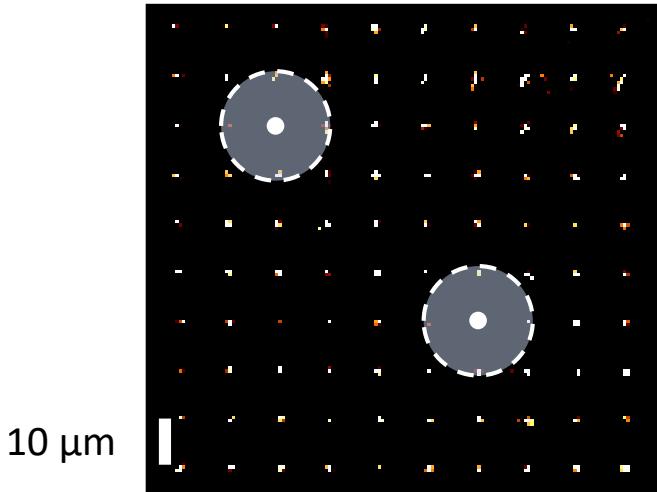
AFM (Néel) ordering!



First implementation of Quantum Ising Model in 2D!!!
(only approximate in real magnetic materials)

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

10 × 10 square array

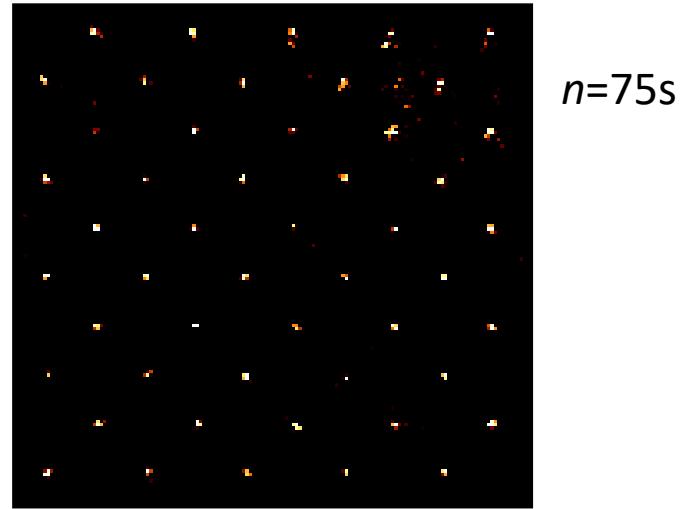


Scholl et al. Nature (2021)

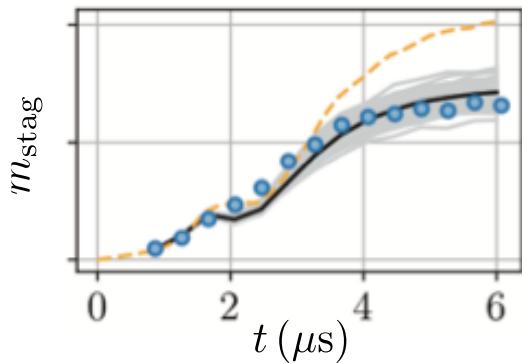
$\Omega(t), \delta(t)$

sweep

= $|g\rangle$ bright
 = $|r\rangle$ dark



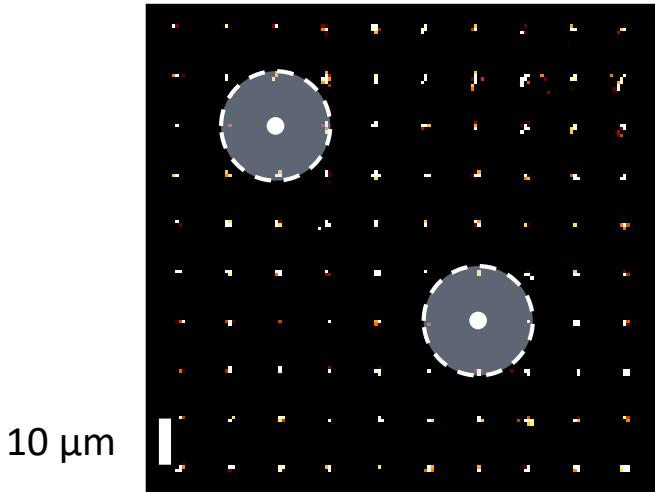
**Dynamics: push
numerical methods**



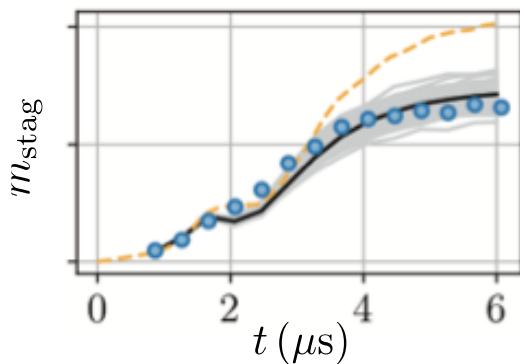
10x10 MPS: 14 days!!

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

10 × 10 square array



Dynamics: push
numerical methods



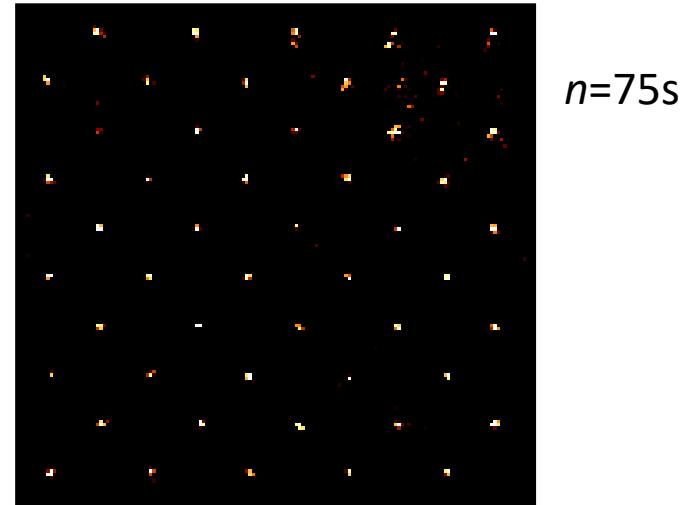
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Scholl et al. Nature (2021)

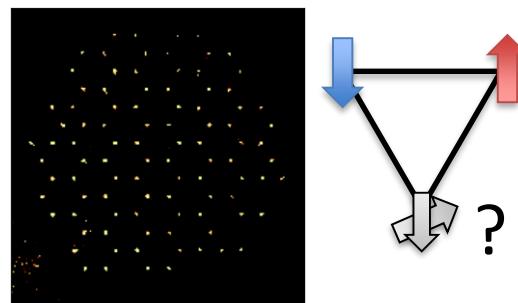
$\Omega(t), \delta(t)$

sweep

= $|g\rangle$ bright
 = $|r\rangle$ dark



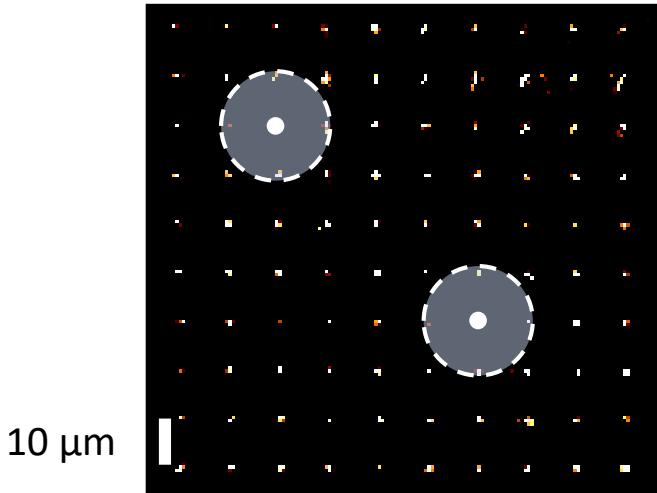
Explore new phases



Frustration

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

10 × 10 square array

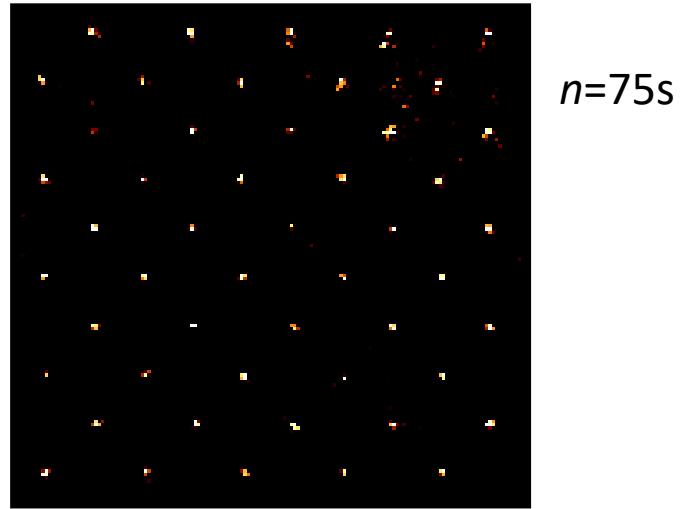


Scholl et al. Nature (2021)

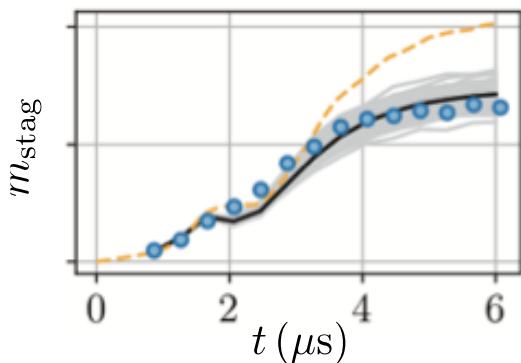
$$\Omega(t), \delta(t)$$

sweep

= $|g\rangle$ bright
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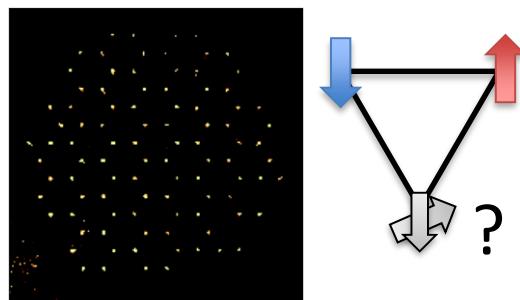


Dynamics: push numerical methods

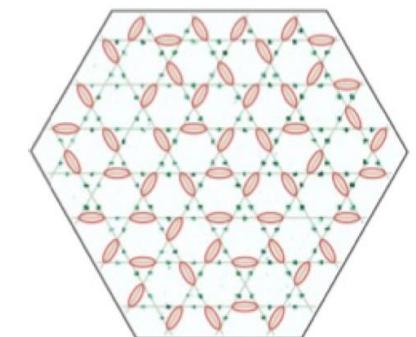


10x10 MPS: 14 days!!

Explore new phases

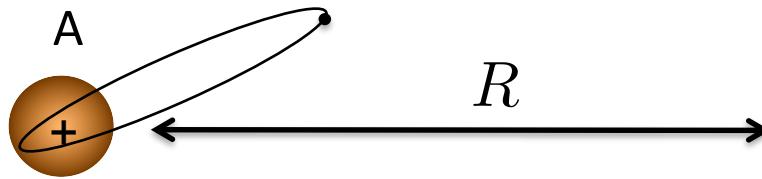


Frustration



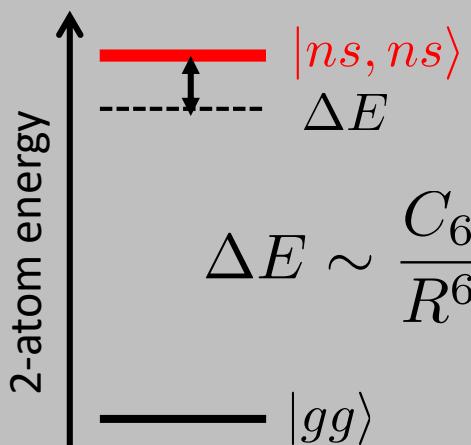
Spin liquid state
Lukin, Science 2021

Interactions between Rydberg atoms and spin models

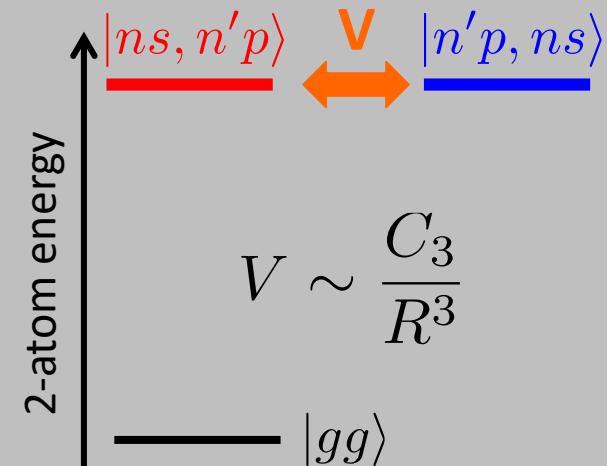


Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals



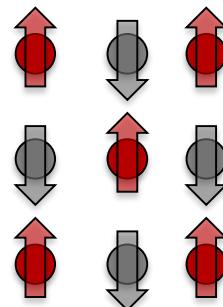
Resonant dipole



Quantum Ising

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

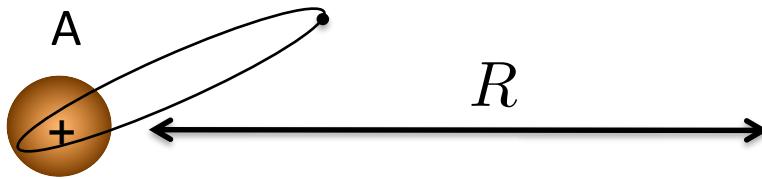
Spin 1/2



XY model

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

Interactions between Rydberg atoms and spin models



Browaeys & Lahaye, Nat.Phys. (2020)

Resonant dipole

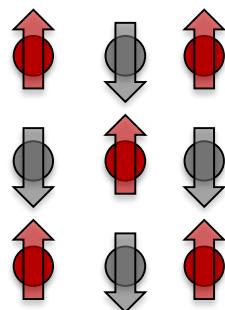
$$|ns, n'p\rangle \xrightleftharpoons[V]{} |n'p, ns\rangle$$

2-atom energy

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

$$|gg\rangle$$

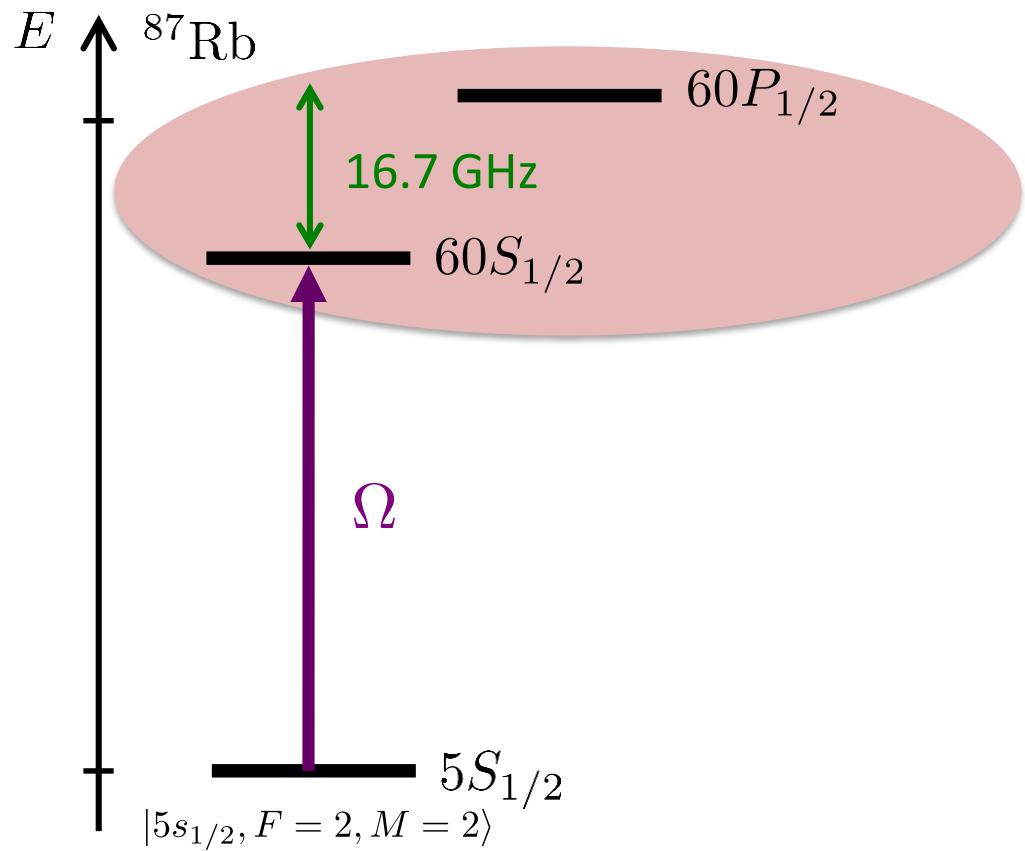
Spin 1/2



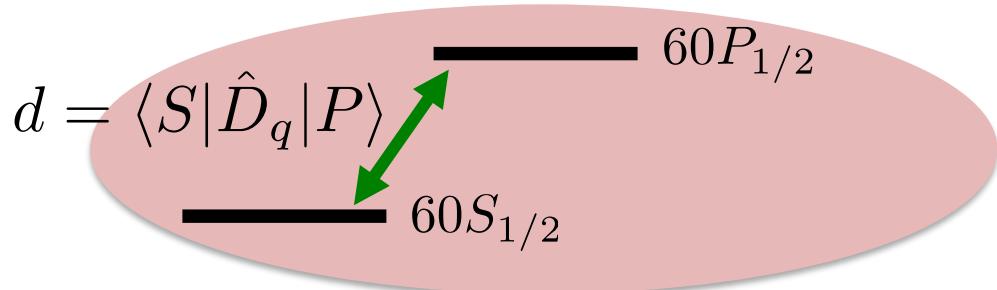
XY model

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

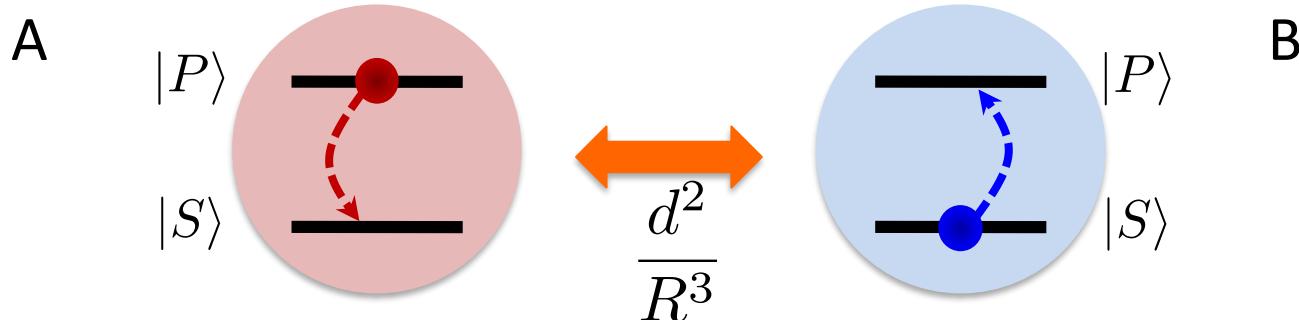
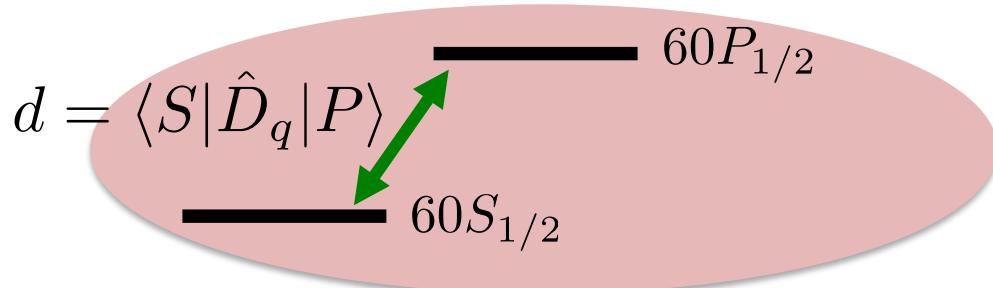
Resonant dipole-dipole interaction between Rydberg atoms



Resonant dipole-dipole interaction between Rydberg atoms



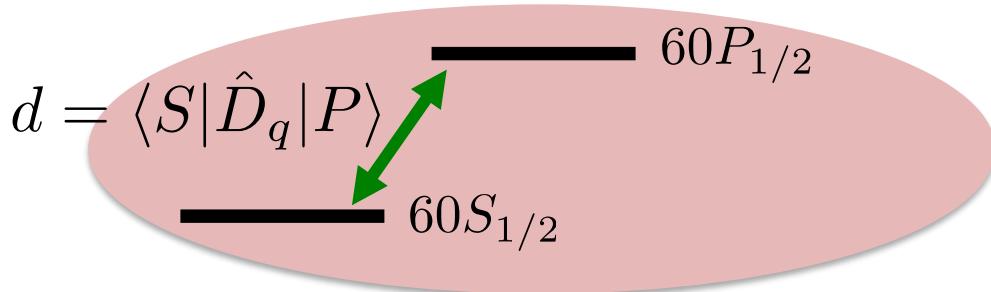
Resonant dipole-dipole interaction between Rydberg atoms



$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3} (\hat{\sigma}_A^+ \hat{\sigma}_B^- + \hat{\sigma}_A^- \hat{\sigma}_B^+)$$

“exchange” of P excitation (XY model)

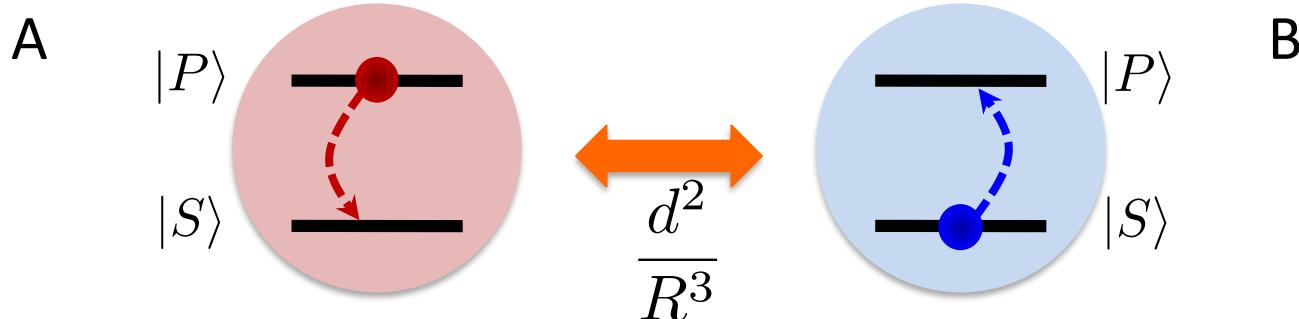
Resonant dipole-dipole interaction between Rydberg atoms



Mapping on spin $\frac{1}{2}$ system:

$$|S\rangle = |\downarrow\rangle$$

$$|P\rangle = |\uparrow\rangle$$



$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3} (\hat{\sigma}_A^+ \hat{\sigma}_B^- + \hat{\sigma}_A^- \hat{\sigma}_B^+)$$

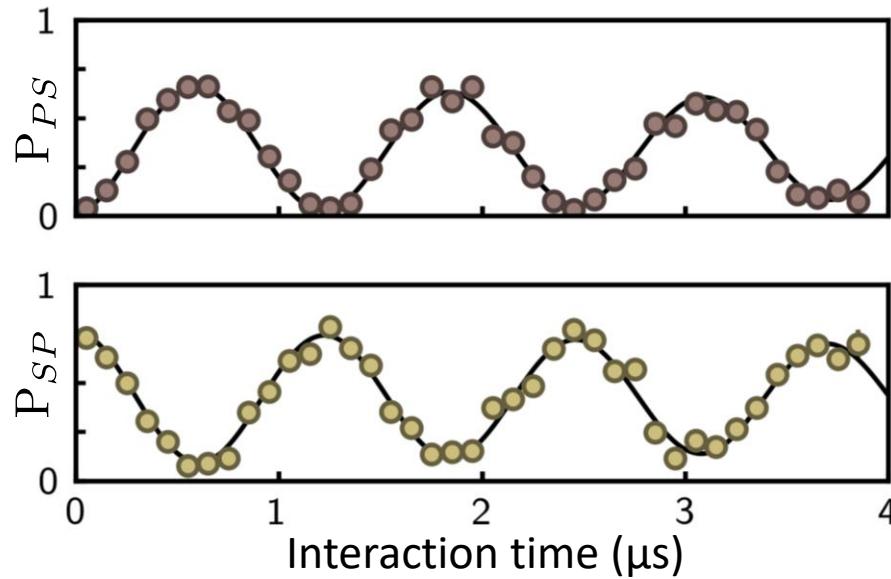
“exchange” of P excitation (XY model)

Resonant dipole-dipole interaction between Rydberg atoms

Prepare $|PS\rangle$ using microwaves + addressing beam

$$R = 30 \text{ } \mu\text{m}$$

$$\text{Frequency: } \frac{2C_3}{R^3}$$



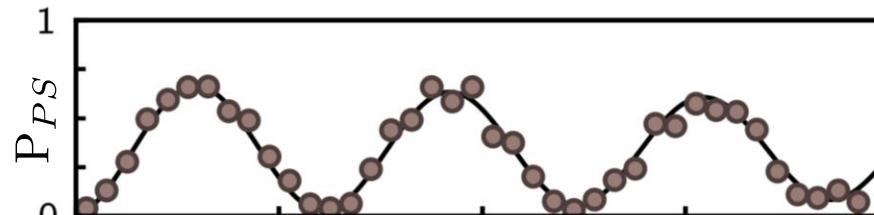
Barredo PRL (2015)
de Léséleuc, PRL (2017)

Resonant dipole-dipole interaction between Rydberg atoms

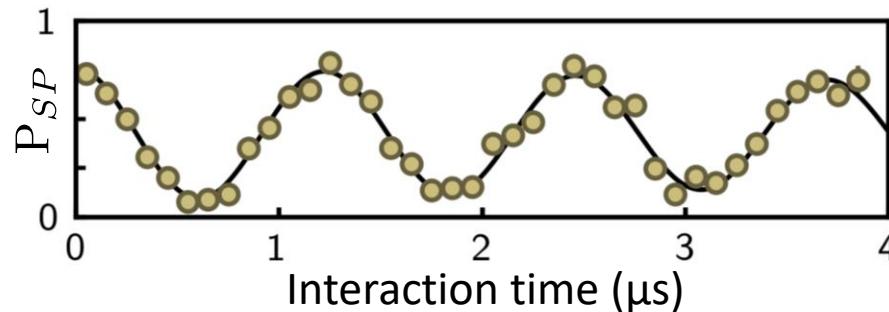
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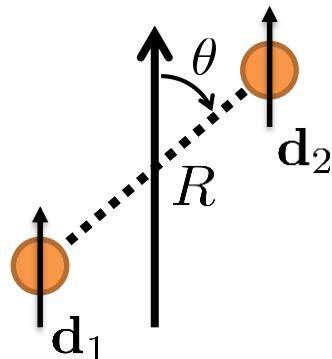


Barredo PRL (2015)
de Léséleuc, PRL (2017)

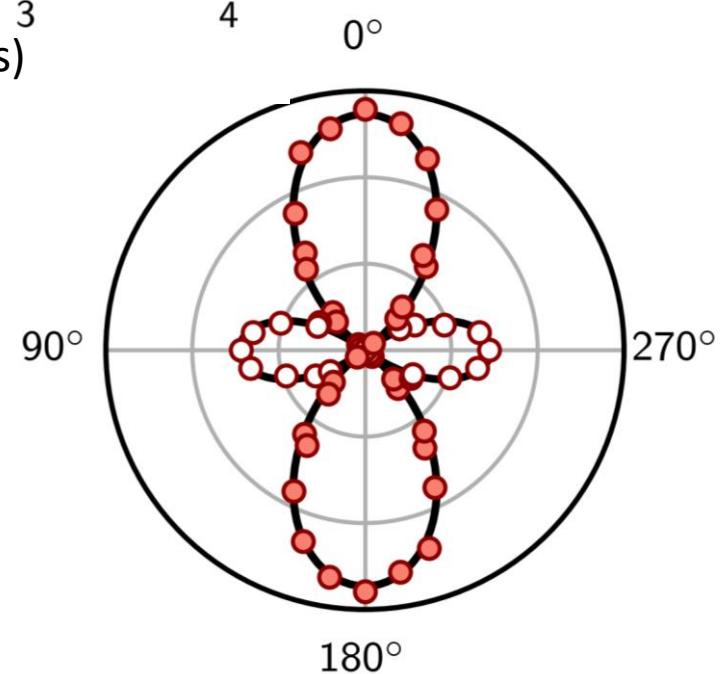


Interaction time (μs)

Quantization
axis (B)



$$C_3(\theta) \propto 1 - 3 \cos^2 \theta$$

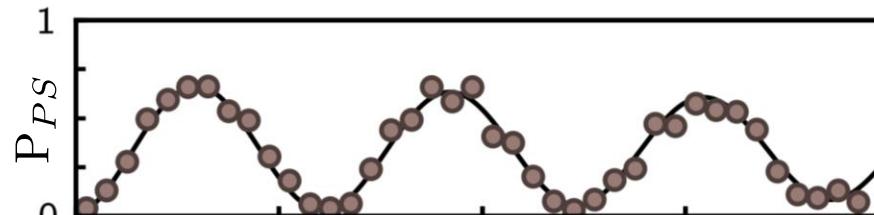


Resonant dipole-dipole interaction between Rydberg atoms

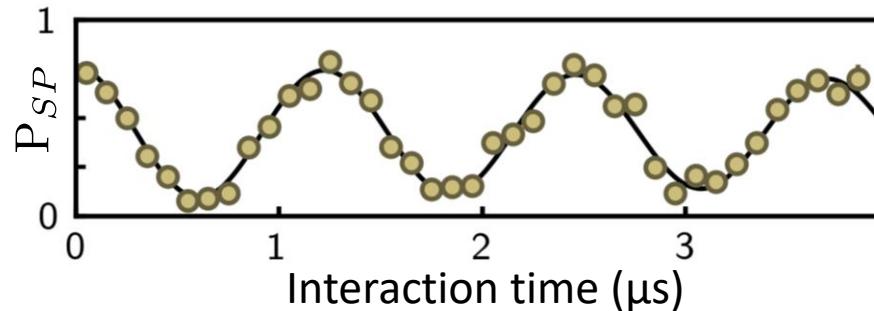
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$$R = 30 \text{ } \mu\text{m}$$

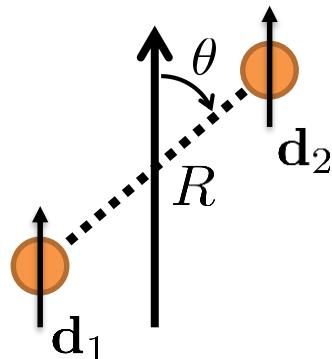
$$\text{Frequency: } \frac{2C_3}{R^3}$$



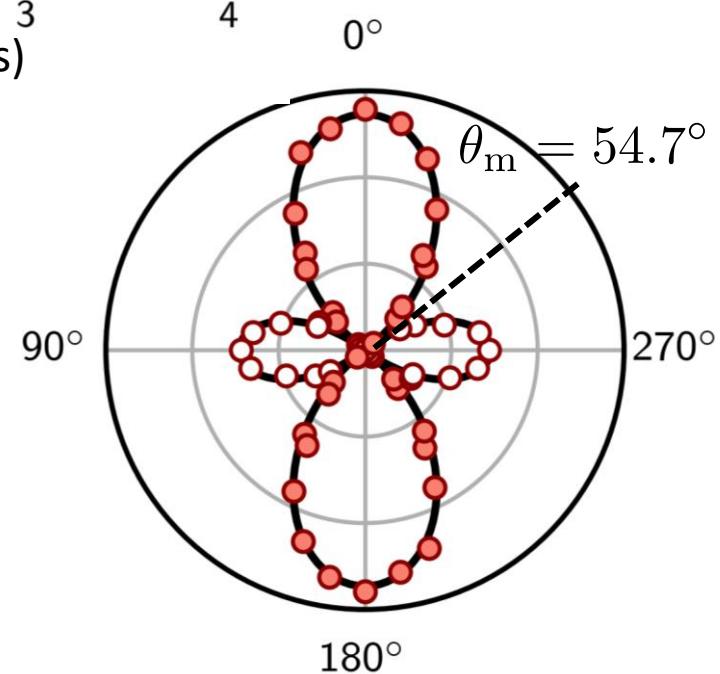
Barredo PRL (2015)
de Léséleuc, PRL (2017)



Quantization
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$$C_3(\theta) \propto 1 - 3 \cos^2 \theta$$

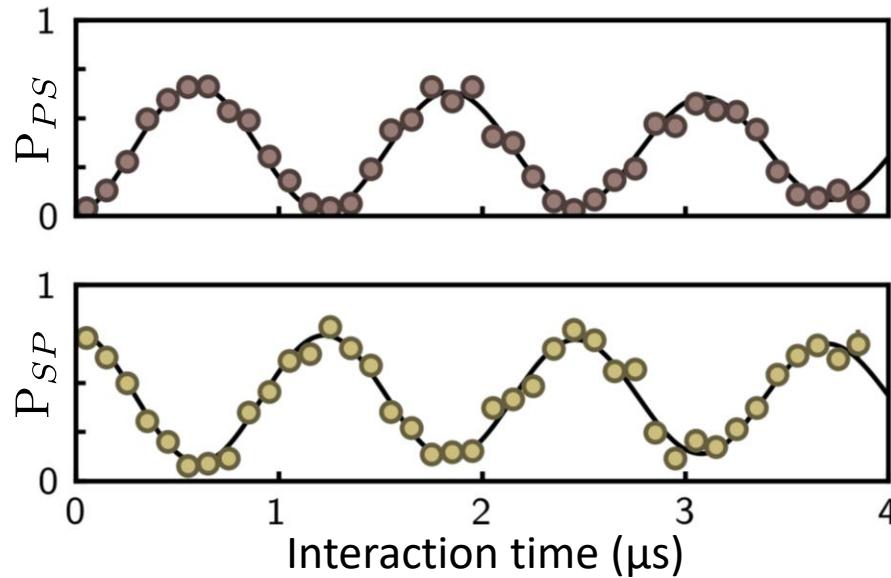


Resonant dipole-dipole interaction between Rydberg atoms

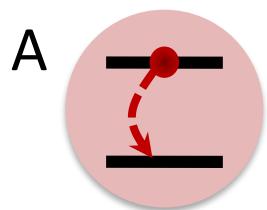
Prepare $|PS\rangle$ using microwaves + addressing beam

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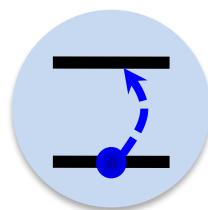
$$\text{Frequency: } \frac{2C_3}{R^3}$$



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



$$C_3/R^3$$



P excitation exchange

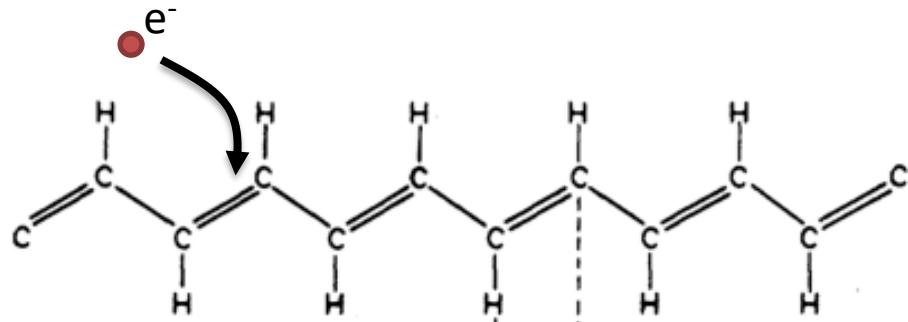


$$A \xrightarrow{J} B$$

Particle hopping

$$J|A\rangle\langle B|$$

The Su-Schrieffer-Heeger model



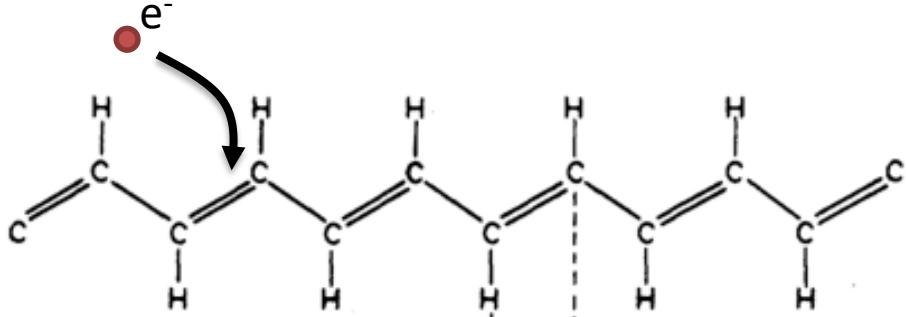
Electronic transport in
polyacetylene



Chemistry
2000

PRL 42, 1698 (1979)

The Su-Schrieffer-Heeger model



Electronic transport in
polyacetylene

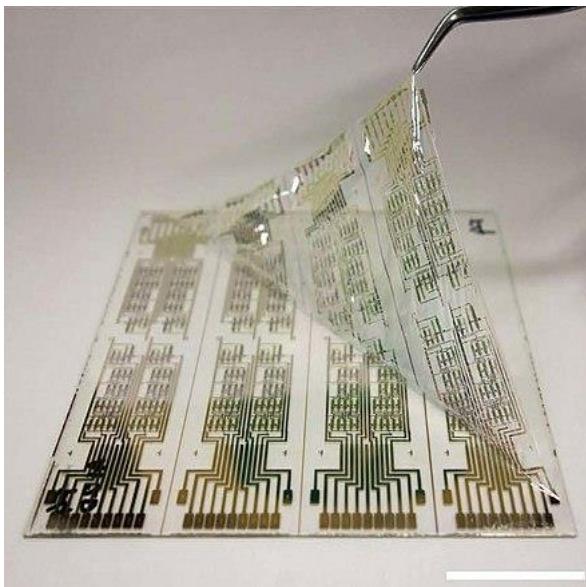
PRL 42, 1698 (1979)



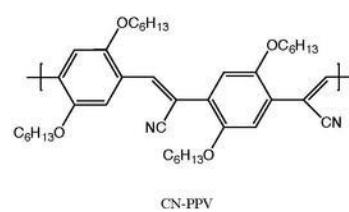
Chemistry

2000

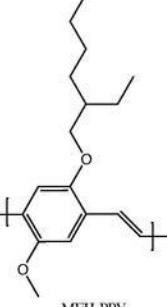
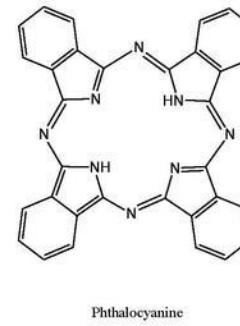
Wikipedia: Organic electronics



Organic CMOS circuit



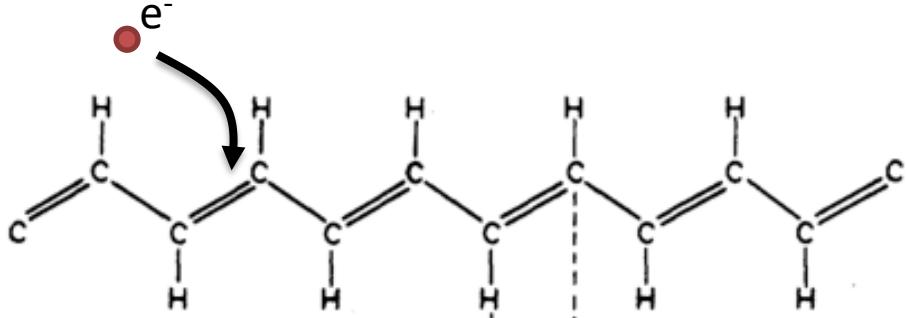
Polyacetylene



Poly(phenylene vinylene) PPV

MEH-PPV

The Su-Schrieffer-Heeger model



Electronic transport in
polyacetylene

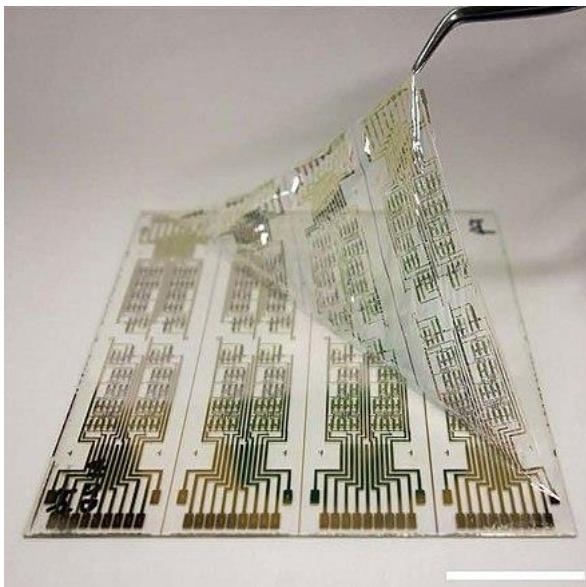


PRL 42, 1698 (1979)

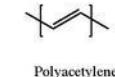
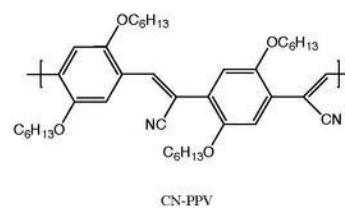
Chemistry

2000

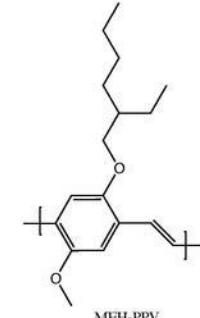
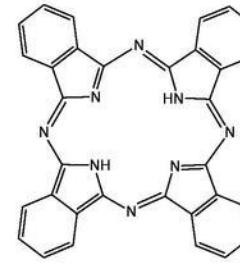
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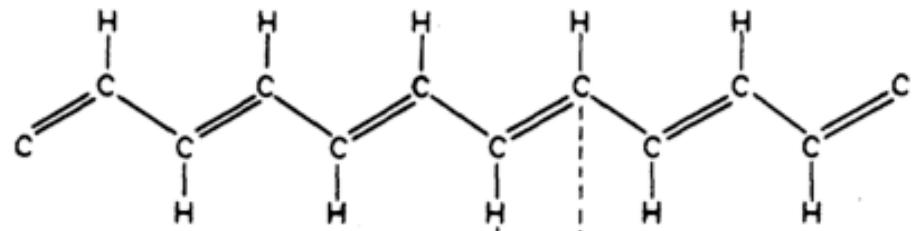


Poly(phenylene vinylene) PPV

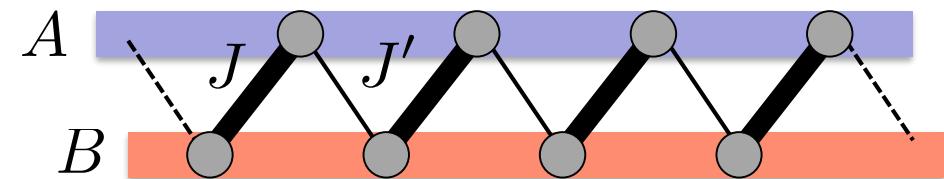


Now, considered as simplest example of **topological** model

The Su-Schrieffer-Heeger model

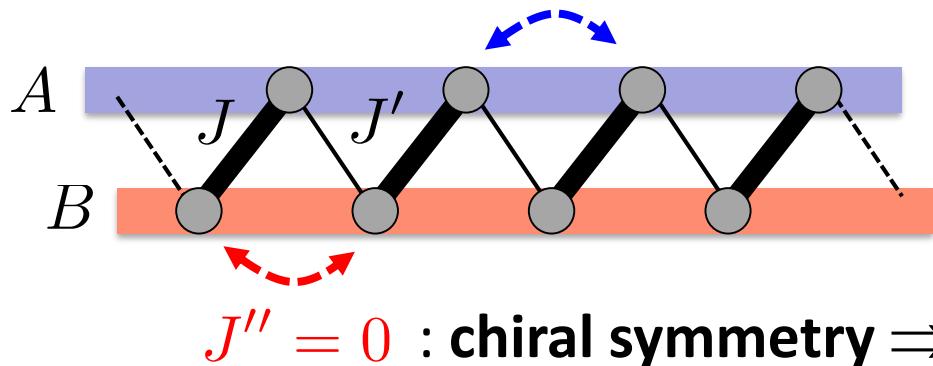


The Su-Schrieffer-Heeger model



Model: tight-binding
dimerization: $J > J'$

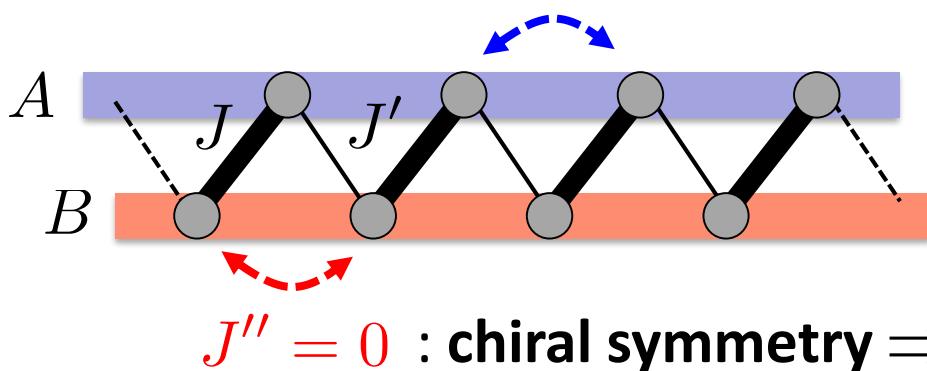
The Su-Schrieffer-Heeger model



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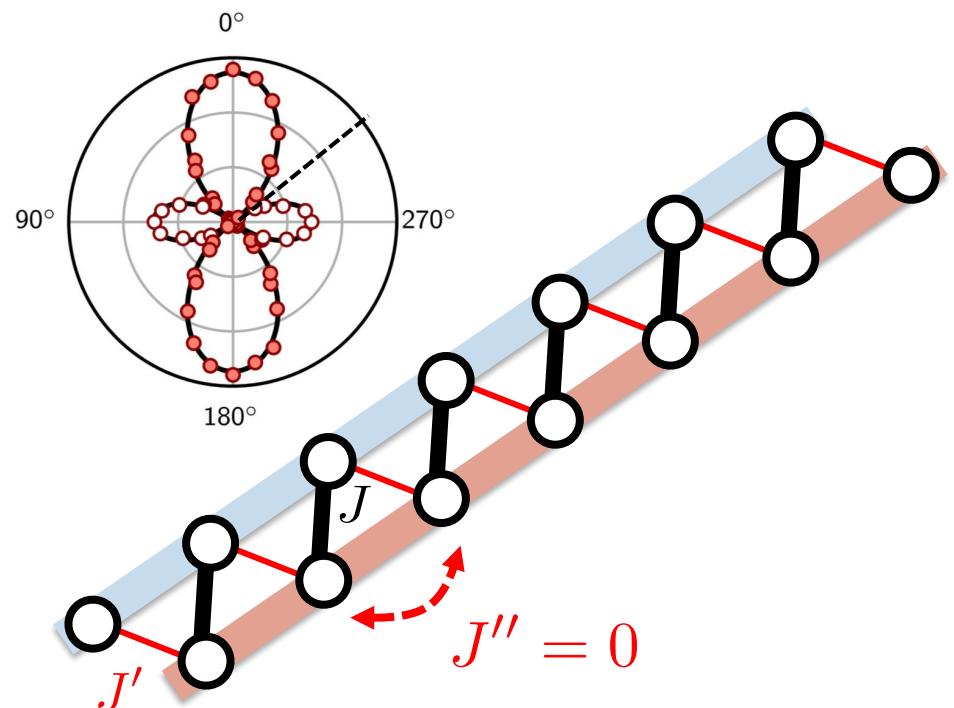
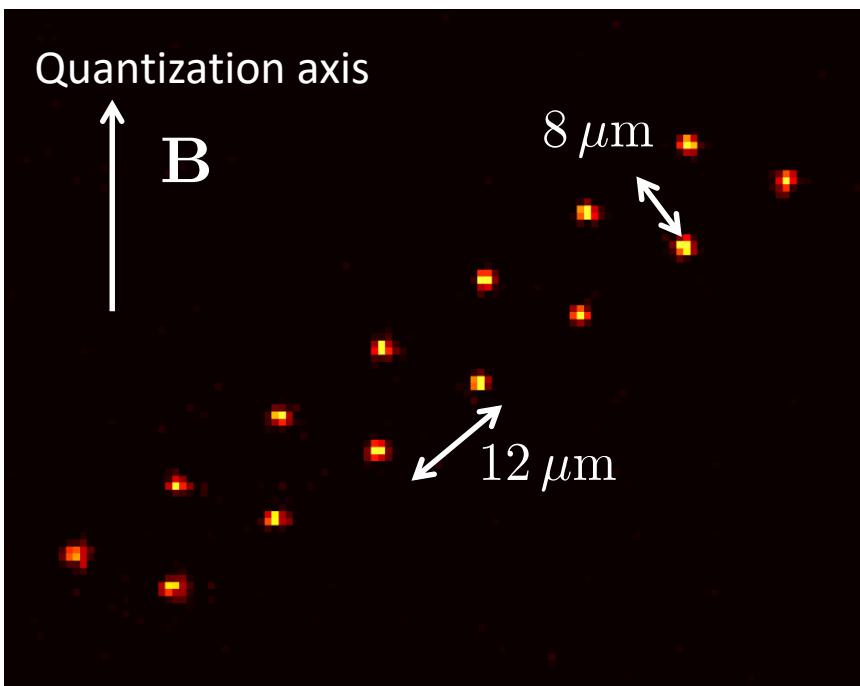
Implementation of SSH spin chain with Rydberg atoms

Science 365, 775 (2019)



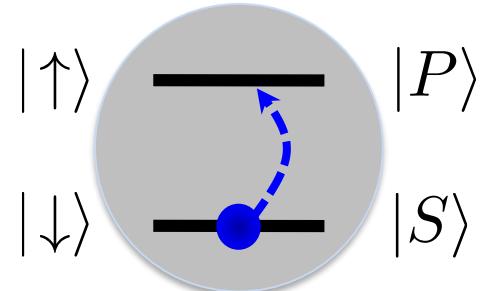
Model: tight-binding
dimerization: $J > J'$

$J'' = 0$: chiral symmetry \Rightarrow symmetric **single particle** spectrum



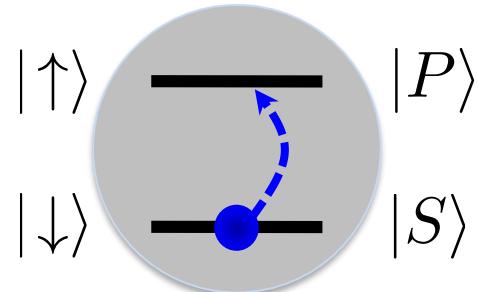
Spin excitations interact!!

Spin excitation = “particle”

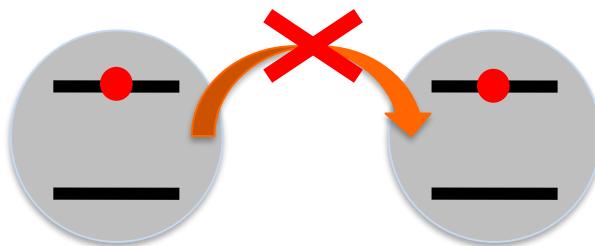


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Spin excitation = “particle”



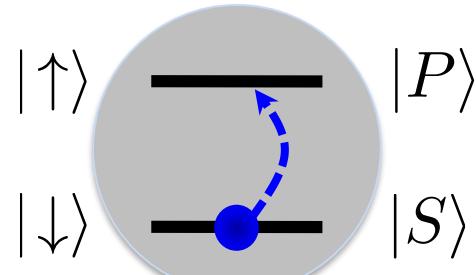
Atom cannot carry 2 excitations \Rightarrow excitations = **hard-core bosons**



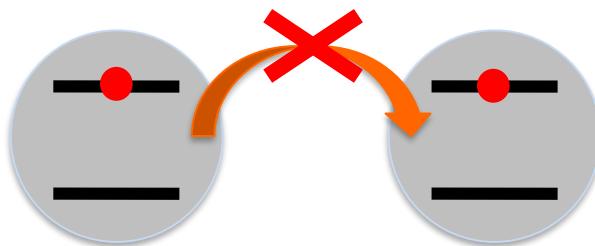
On-site interaction $U \rightarrow \infty$

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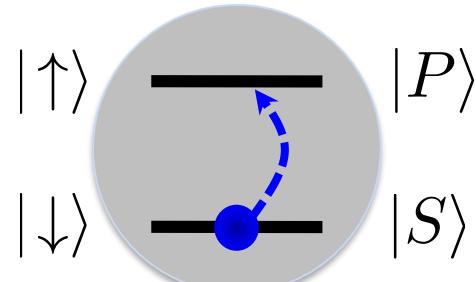


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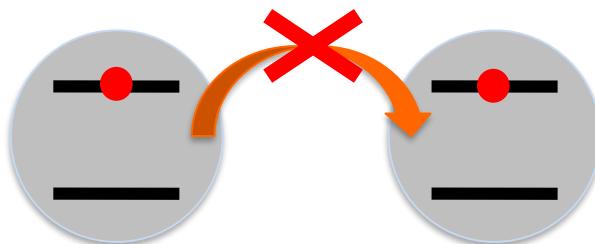


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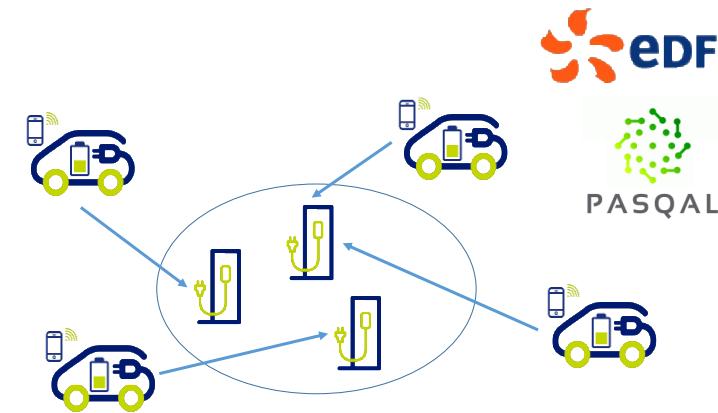


\Rightarrow The first **symmetry protected topological** phase...
Predicted in **2012**

Conclusion: Quantum Simulators can do more...!

Quant. sim. = machine to prepare quantum states

Optimization problems



Conclusion: Quantum Simulators can do more...!

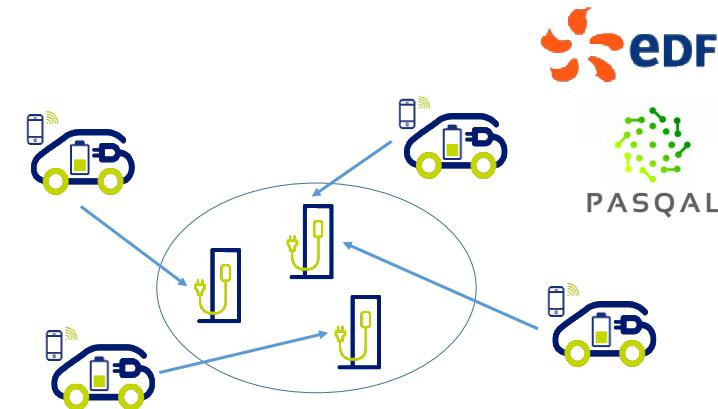
Quant. sim. = machine to prepare quantum states

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



Conclusion: Quantum Simulators can do more...!

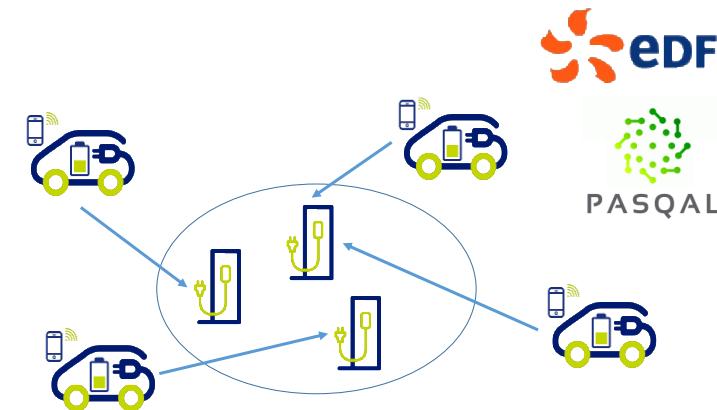
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$$H = \sum_i h_i n_i + \sum_{i < j} J_{ij} n_i n_j , \quad n_i = 0, 1$$

Solution = ground-state



Warning: competitive w.r. heuristic classical algo. $N > 2000-5000\ldots!$

Conclusion: Quantum Simulators can do more...!

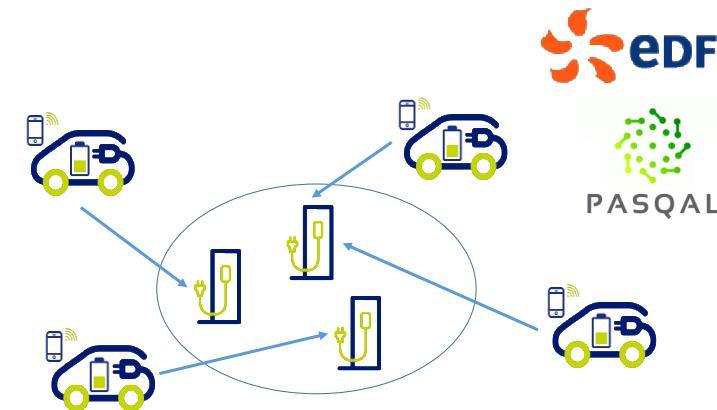
Quant. sim. = machine to prepare quantum states

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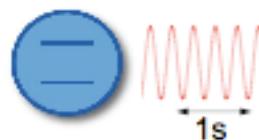
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Quantum metrology



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

Entangled
states →

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

Conclusion: Quantum Simulators can do more...!

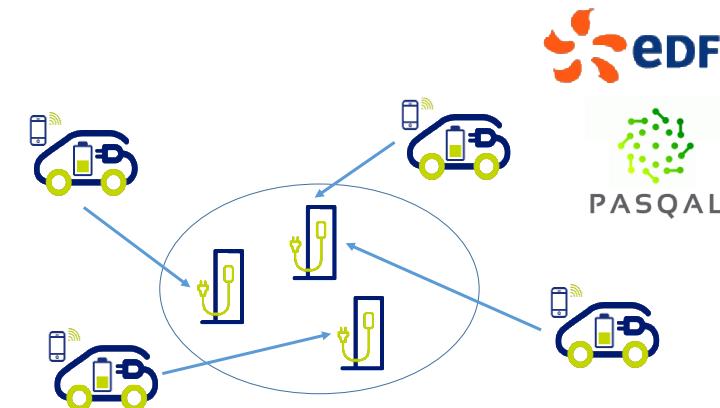
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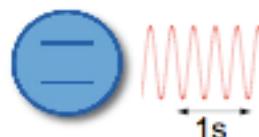
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Quantum metrology

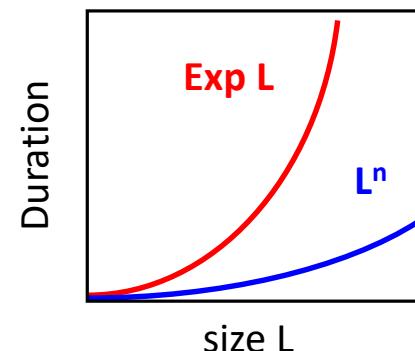


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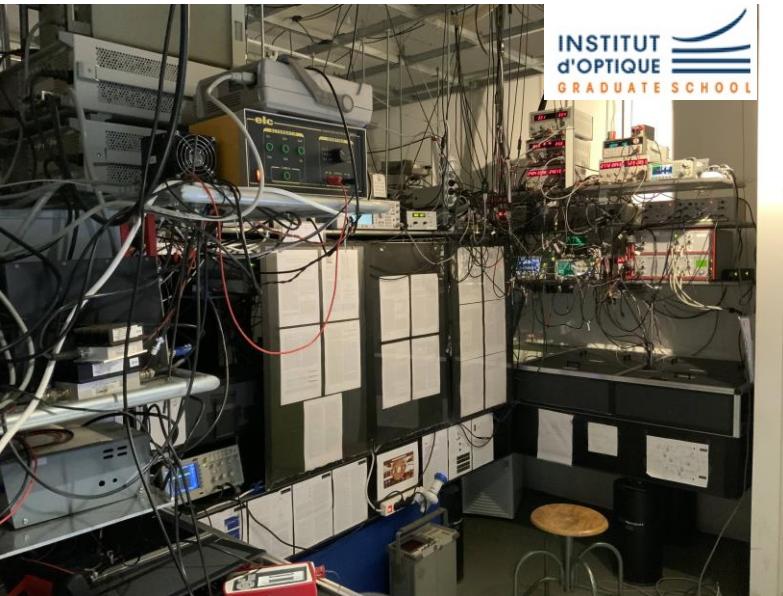
Quantum computer (very long-term...)



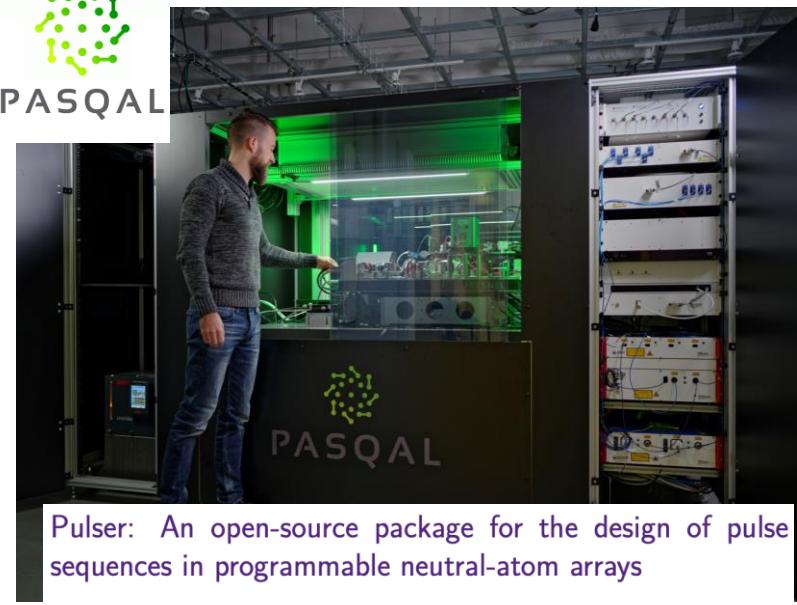
- Factoring
- List search
- ...

From a lab experiment to an industrial machine...

Engineering



Founded 2019



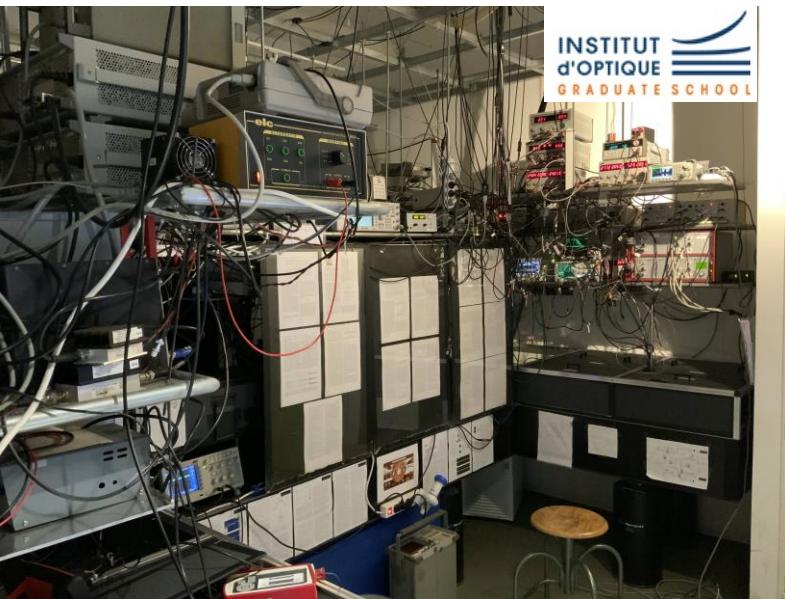
Pulser: An open-source package for the design of pulse sequences in programmable neutral-atom arrays

Henrique Silvério^{1,*}, Sebastián Grijalva^{1,*}, Constantin Dalyac¹, Lucas Leclerc¹, Peter J. Karalekas², Nathan Shammah², Mourad Beji¹, Louis-Paul Henry¹, and Loïc Henriet¹

Quantum (2022)

From a lab experiment to an industrial machine...

Engineering



Explore applications

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

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

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Quantum (2022)

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,†}

arXiv:2211.16337

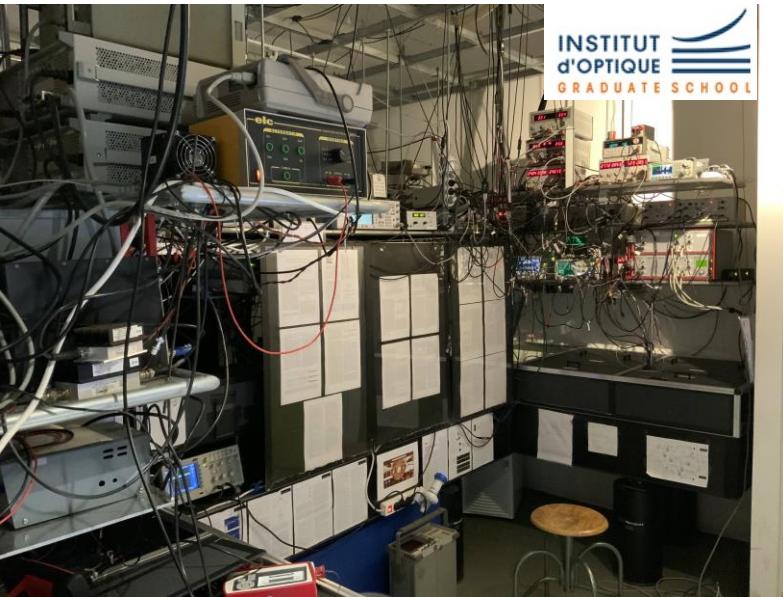
Financial Risk Management on a Neutral Atom Quantum Processor

Lucas Leclerc^{1,2,*}, Luis Ortiz-Gutiérrez¹, Sebastián Grijalva¹, Boris Albrecht¹, Julia R. K. Cline¹, Vincent E. Elfving¹, Adrien Signoles¹, and Loïc Henriet^{1,†}

arXiv:2212.03223

From a lab experiment to an industrial machine...

Engineering



Founded 2019



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Explore applica-



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

EPJ · ORG

RESEARCH

Qualifying quantum approaches for industrial optimization problems: a study in the field of smart-vehicle



Quantum (2022)

on a Neutral Atom

-Gutiérrez,^{1,*} Slimane
ablière,¹ Henrique
d Loïc Henriet¹,^t

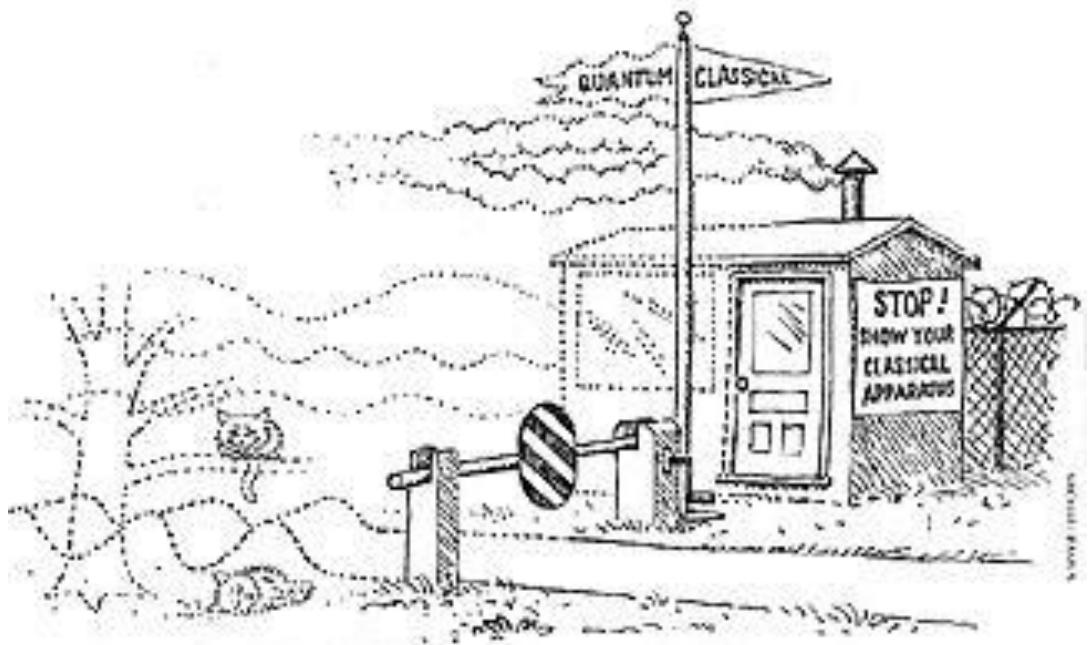
arXiv:2211.16337

Quantum Processor

¹, Boris Albrecht¹,
and Loïc Henriet¹^t

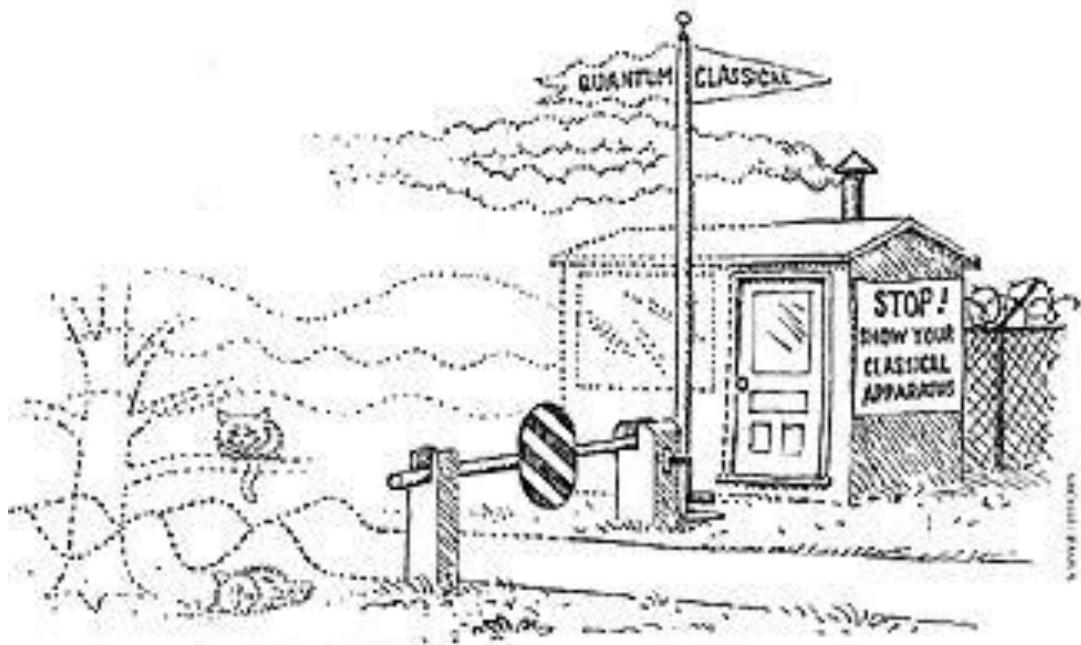
arXiv:2212.03223

How large can a *controlled* quantum system be?

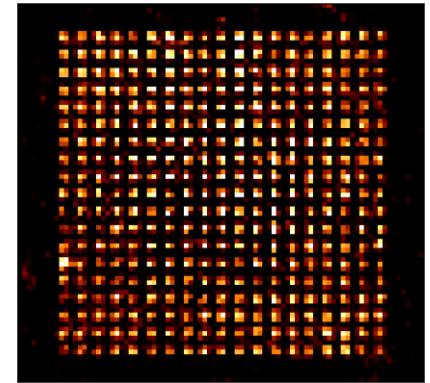


Physics Today
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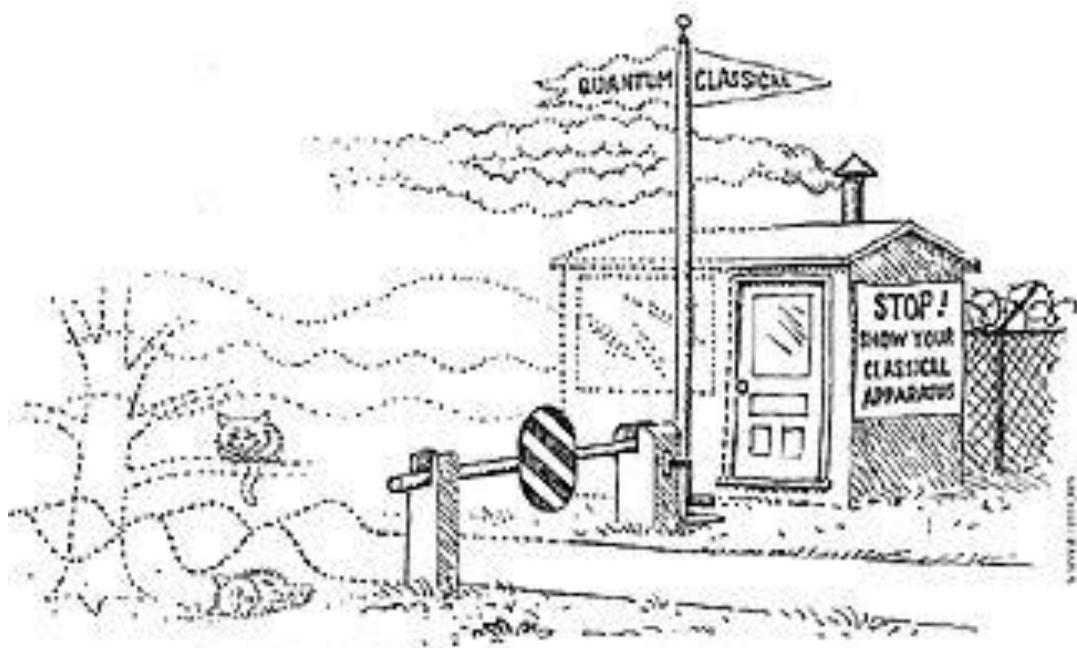
How large can a *controlled* quantum system be?



Physics Today



How large can a *controlled* quantum system be?



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