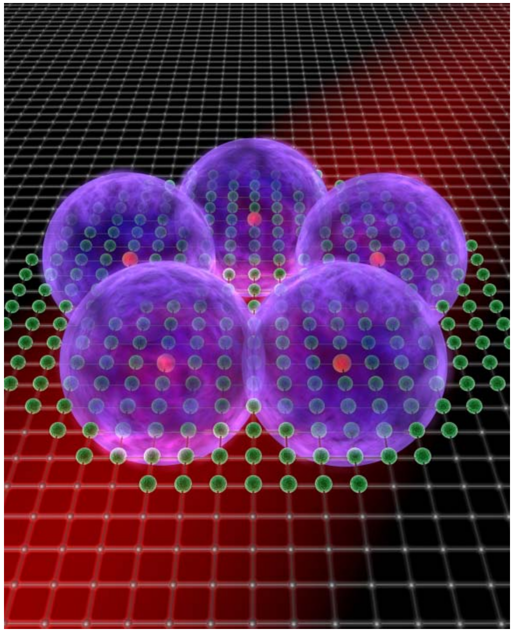
Simulatori quantistici con atomi di Rydberg

Oliver Morsch

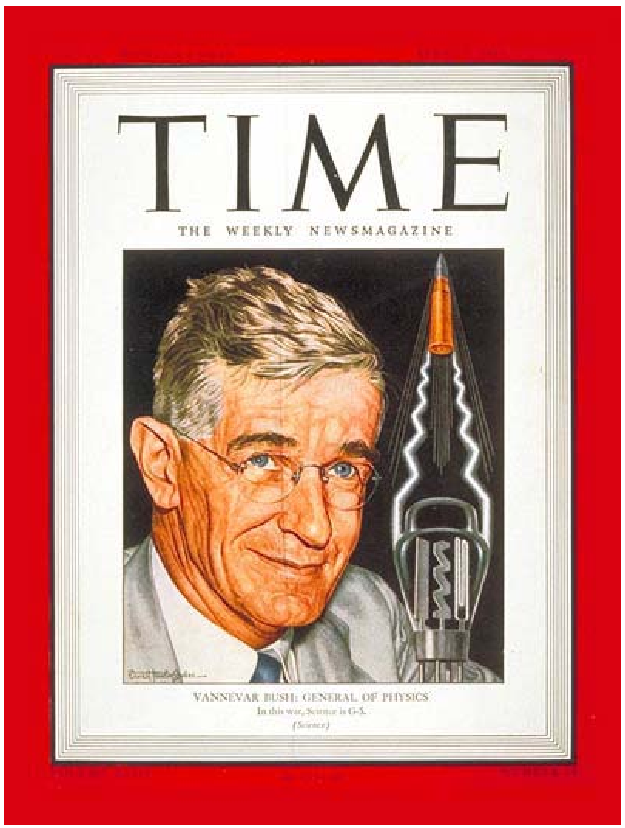
INO-CNR and Dipartimento di Fisica, Pisa, Italy



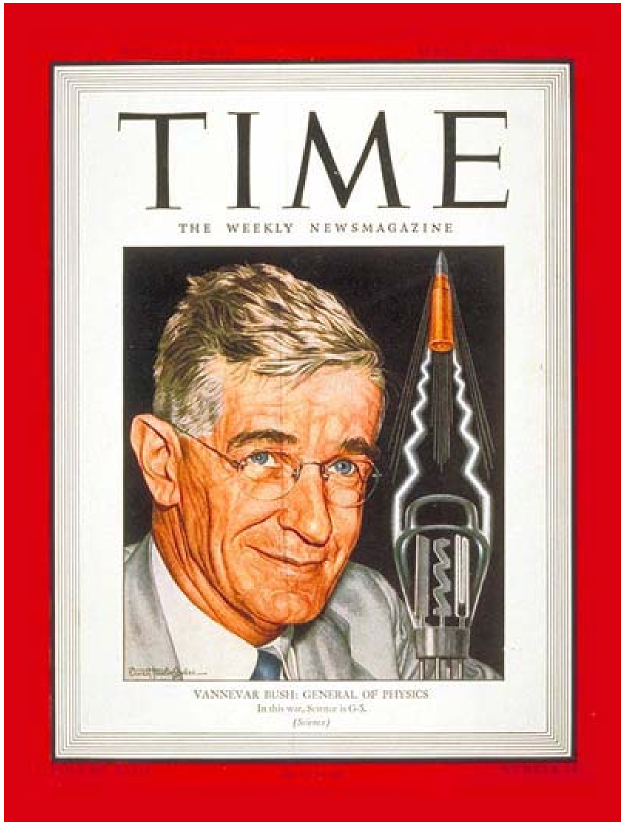
- M. Martinez-Valado,C. Simonelli, M. Archimi, R. Faoro, E. Arimondo, D. Ciampini
- P. Huillery, P. Pillet (Paris); I. Lesanovsky (Nottingham)

INO

Istituto Nazionale di Ottica

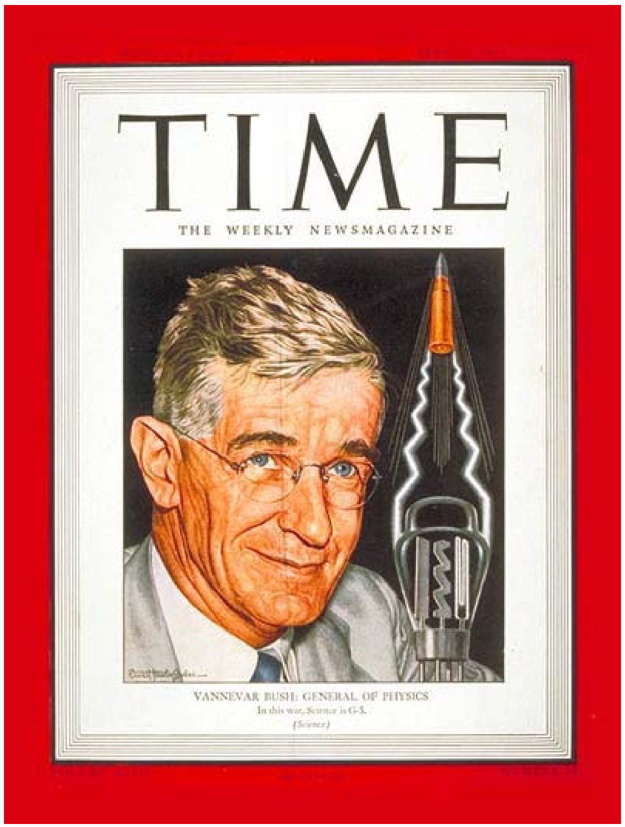

TIME
THE WEEKLY NEWSMAGAZINE
VANNEVAR BUSH: GENERAL OF PHYSICS
In this war, Science is G-5.
(Science)

← ? →



← ? →

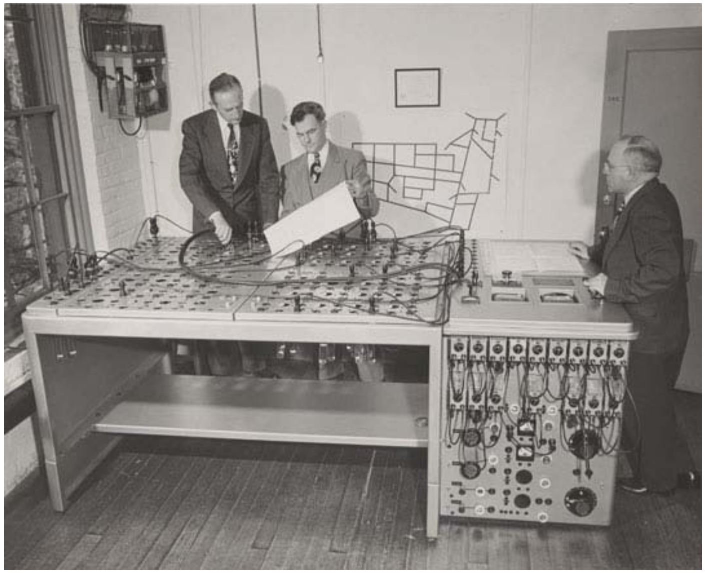
Richard Feynman



Vannevar Bush

← ? →

Richard Feynman



ac network analyzers, ca. 1925-1960

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

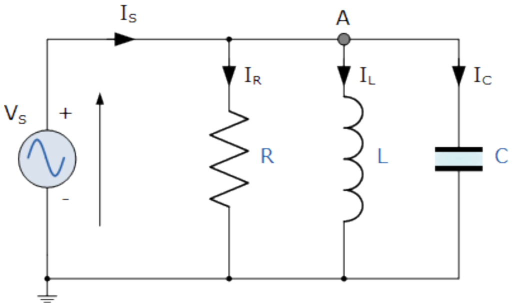
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

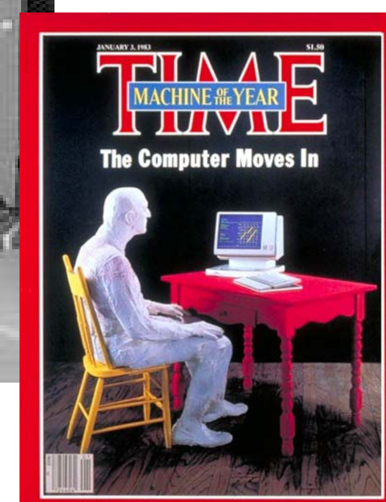
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

network analyzer finds solutions through measurements on a scale model; effectively performs an **analogue computation** (later used for other calculations, e.g. elasticity, Schrodinger's equation…)

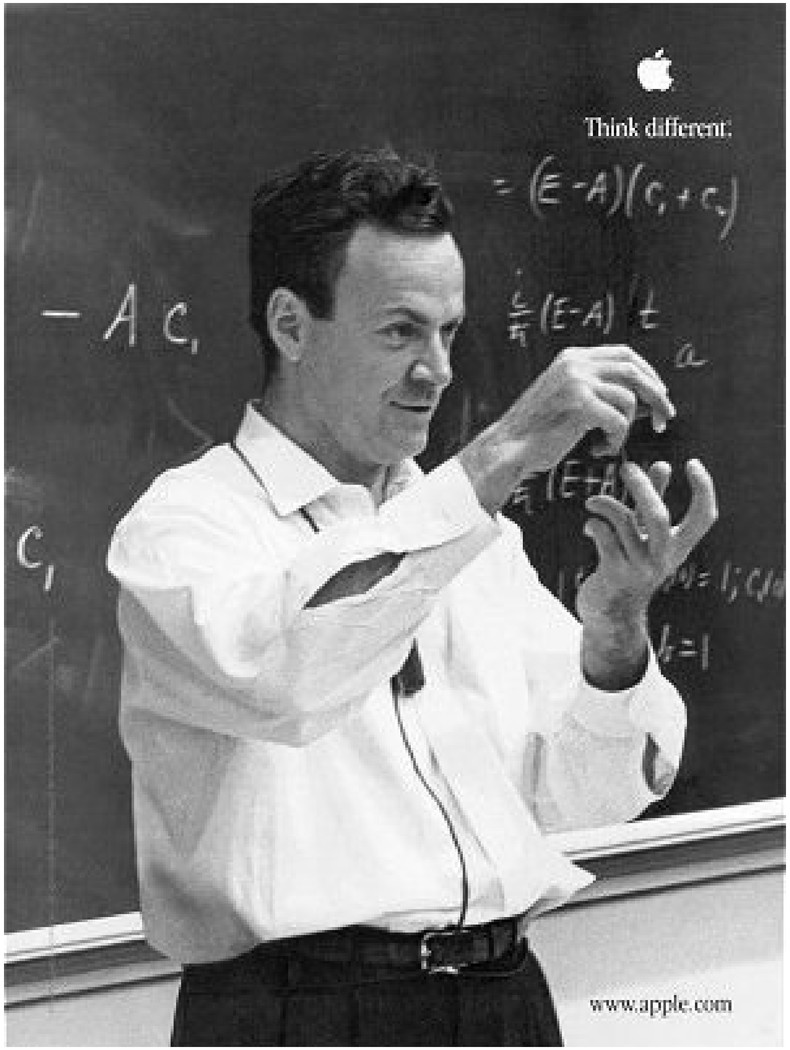




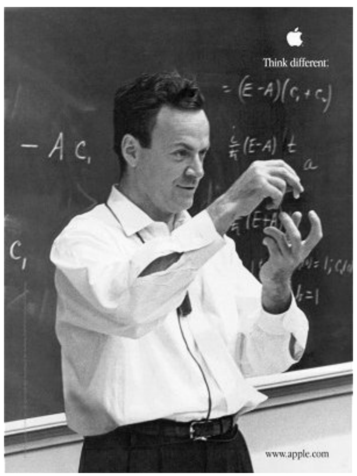
analogue computer →

digital computer

Feynman’s problem



Feynman’s problem



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don’t know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there’s no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don’t have to pay any attention to computers. It’s interesting anyway to entertain oneself with the idea that we’ve got something to learn about physical laws; and if I take a relaxed view here (after all I’m here and not at home) I’ll admit that we don’t understand everything.

The first question is, What kind of computer are we going to use to simulate physics? Computer theory has been developed to a point where it realizes that it doesn’t make any difference; when you get to a *universal computer*, it doesn’t matter how it’s manufactured, how it’s actually made. Therefore my question is, Can physics be simulated by a universal computer? I would like to have the elements of this computer *locally intercon-*

Feynman’s problem

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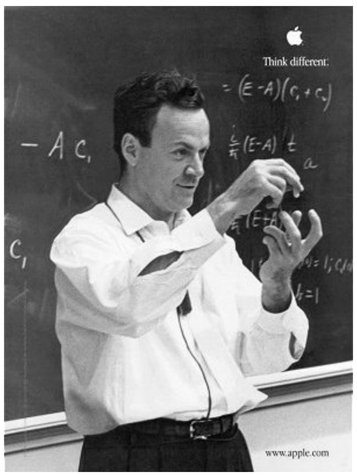

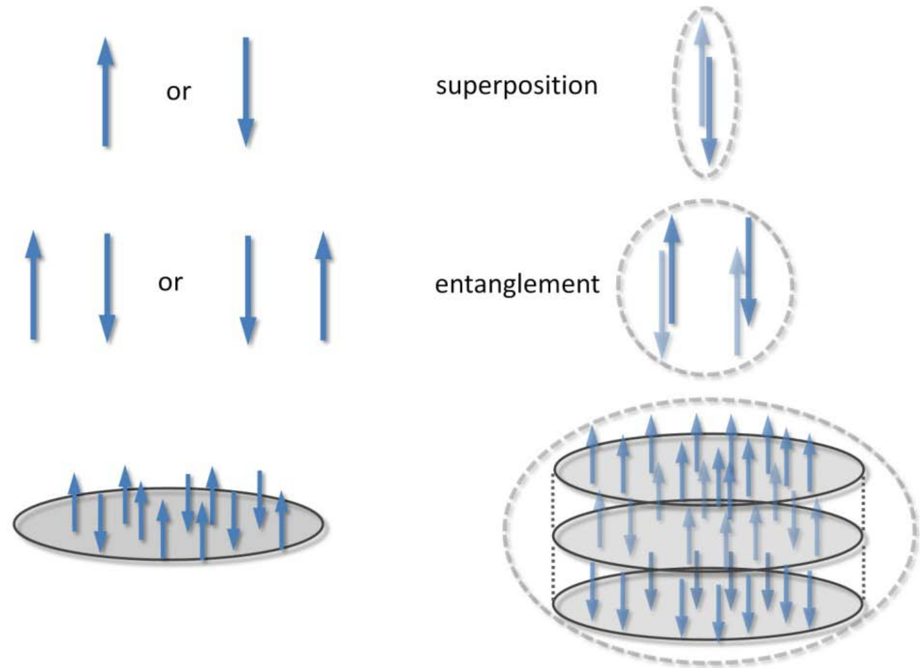

classical world *quantum world*

Feynman’s problem

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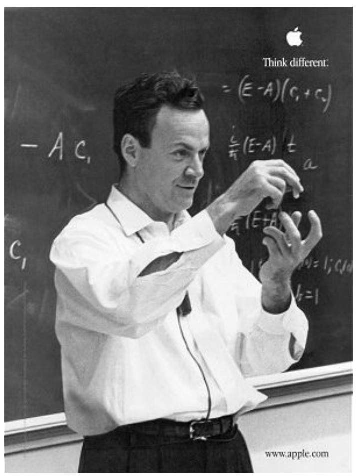
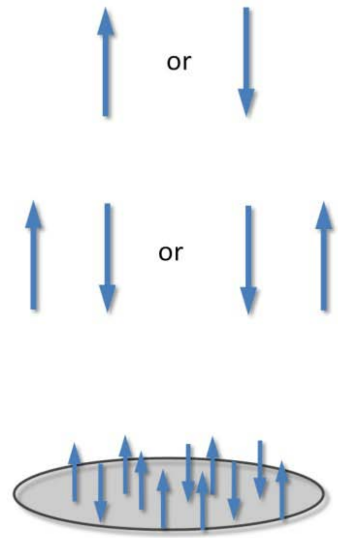
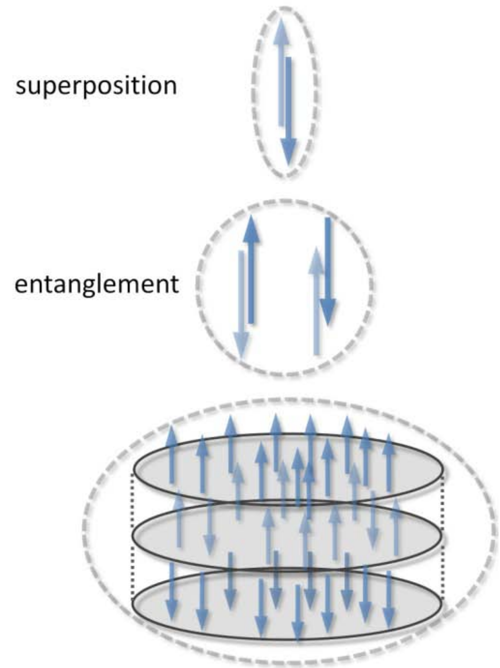




classical world

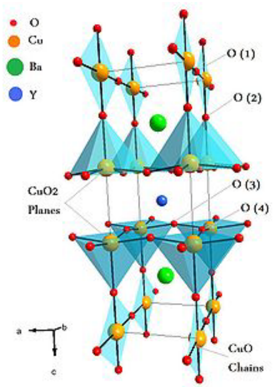


quantum world

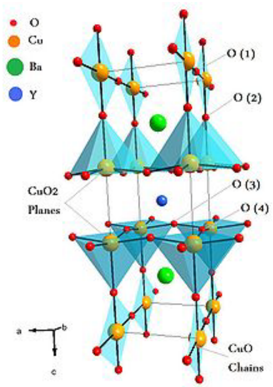
A fully quantum calculation for 40 particles requires 1 TB of memory; the memory requirements for 80 particles exceed the amount of information stored in the history of mankind. **Consequence:** we need

- quantum computer or
- **quantum simulator** (= analogue quantum computer)

Quantum simulators

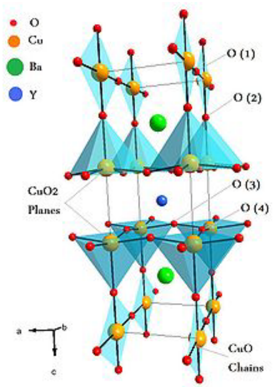


Quantum simulators



$$\hat{H} = \sum_i \hat{H}_i + \sum_{j,k} \hat{U}_{jk} + \sum_l \hat{V}_l + \ldots$$

Quantum simulators



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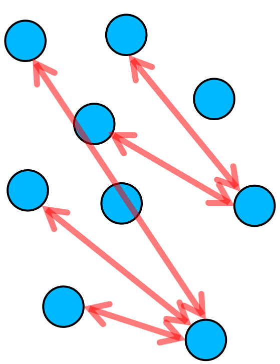
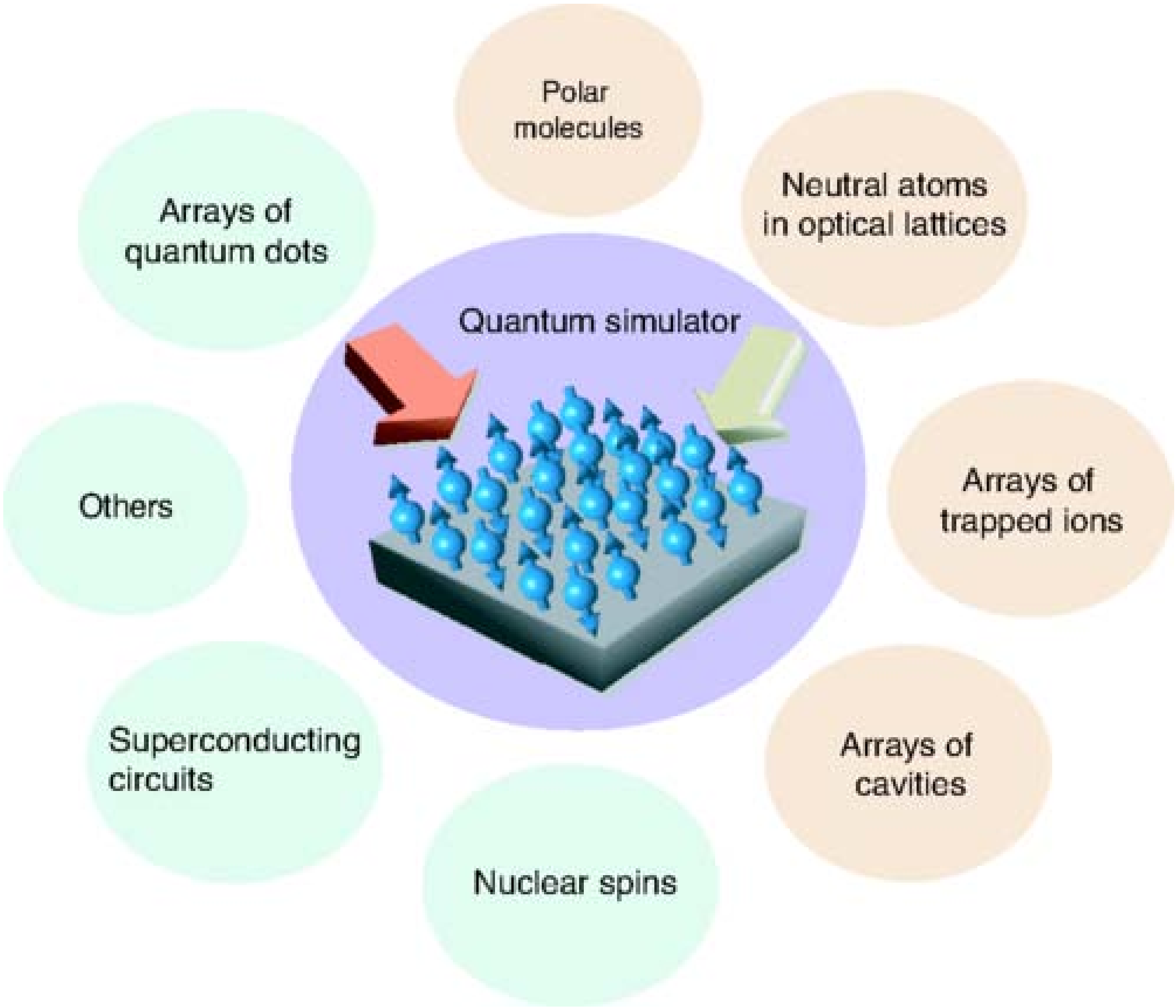
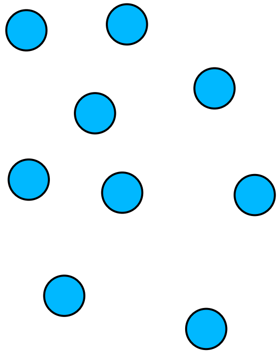


Quantum simulators

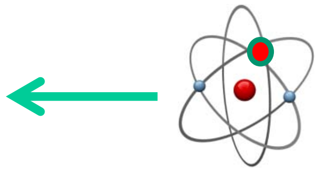


An ideal quantum simulator

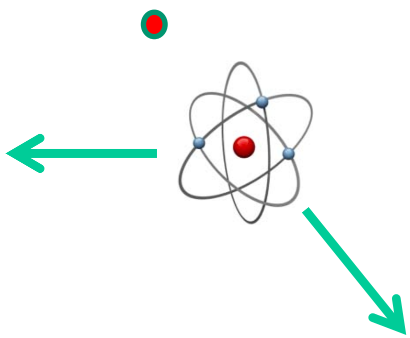


a collection of controllable
quantum systems:
ultra-cold atoms (MOT, BEC,..)

Ultracold atoms



assorbimento di un fotone -> atomo prende l'impulso

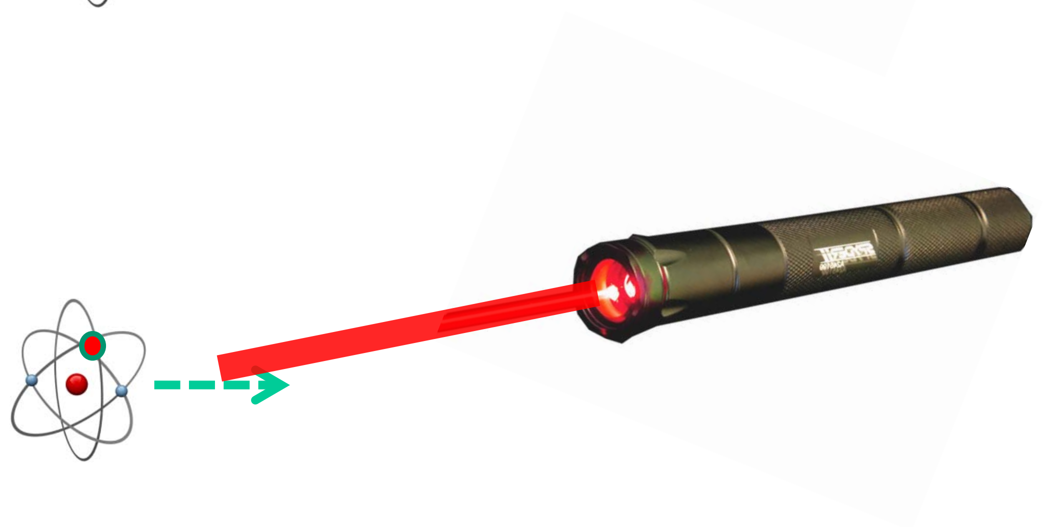


Emissione del fotone -> atomo prende un altro impulso (in una direzione a caso)

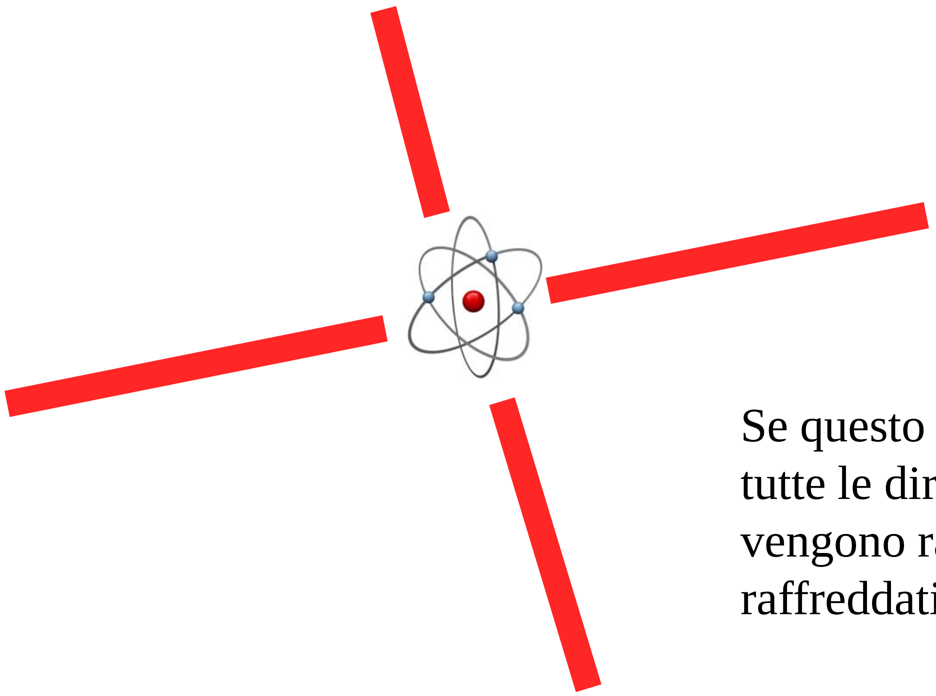
Effetto complessivo: l'atomo aquisisce energia

Ultracold atoms

Se la probabilità di assorbire un fotone dipende dalla direzione di moto dell’atomo, l’impulso che prende l’atomo è nella direzione opposta al moto -> effetto “freno”

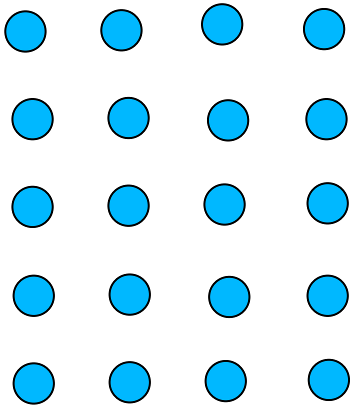


Ultracold atoms



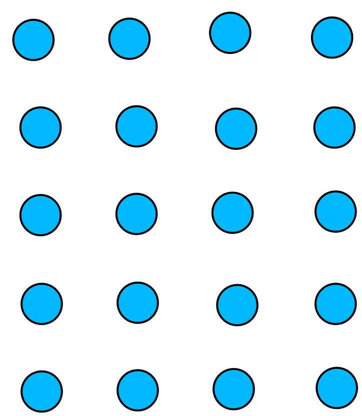
Se questo effetto “freno” agisce in tutte le direzioni spaziali, gli atomi vengono rallentati e quindi raffreddati!

An ideal quantum simulator



to simulate an ordered system (crystal,…):
cold atoms in optical lattices

An ideal quantum simulator

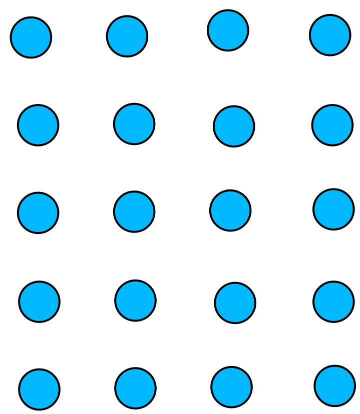


to simulate an ordered system (crystal,…):
cold atoms in optical lattices.

Interactions can come from on-site repulsion, Hamiltonian is then

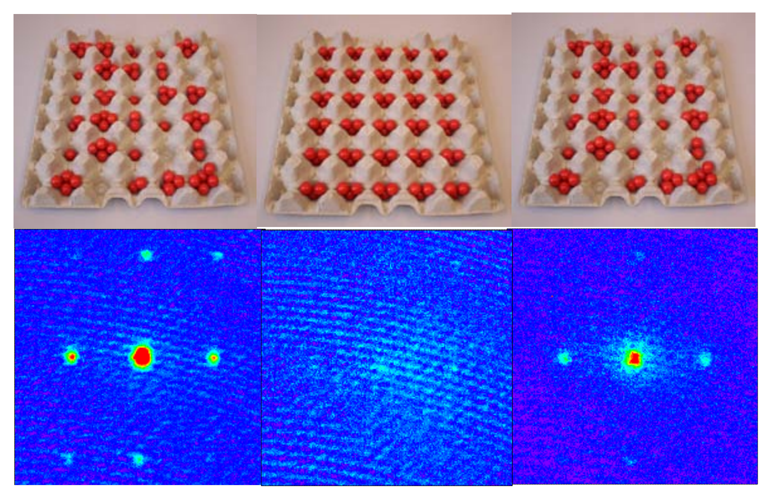
$$\mathcal{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \, \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i \left(\hat{n}_i - 1 \right).$$

An ideal quantum simulator

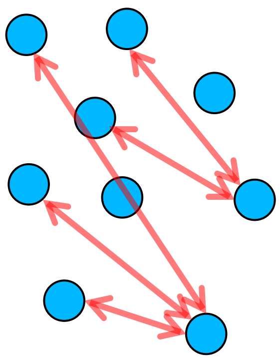


$$\mathcal{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1).$$

Bose-Hubbard model: superfluid to Mott insulator transition (Greiner *et al.,* Nature **415**, 39-44 (2002); Zenesini *et al.*, PRL**102**, 100403 (2009))

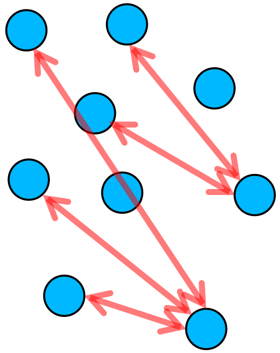


An ideal quantum simulator

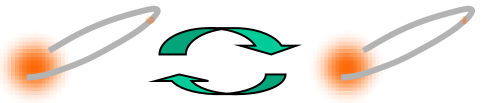


In order to study **strongly correlated many-body systems**, need strong interactions between nearest neighbours, next nearest neighbours…
Ideally, these should be controllable to implement a range of Hamiltonians

An ideal quantum simulator



Possible solution:
Excite atoms to
Rydberg states



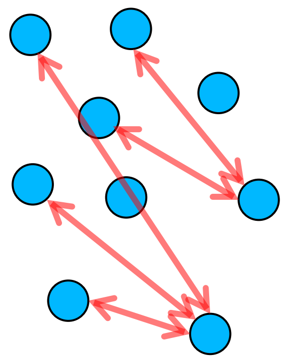
Rydberg atom

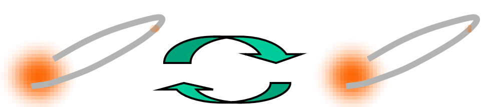
An ideal quantum simulator

Lifetime: ~ n^3
n=100 1 ms

Polarizability ~ n^7
Dipole moment : ~ n^2 ea_0
n=100 10,000 D (H_2O ~2 D)

→ strong van-der-Waals or dipole-dipole interaction; **orders of magnitude larger than contact interaction in ultra-cold gases (up to GHz at micrometer distances)!**

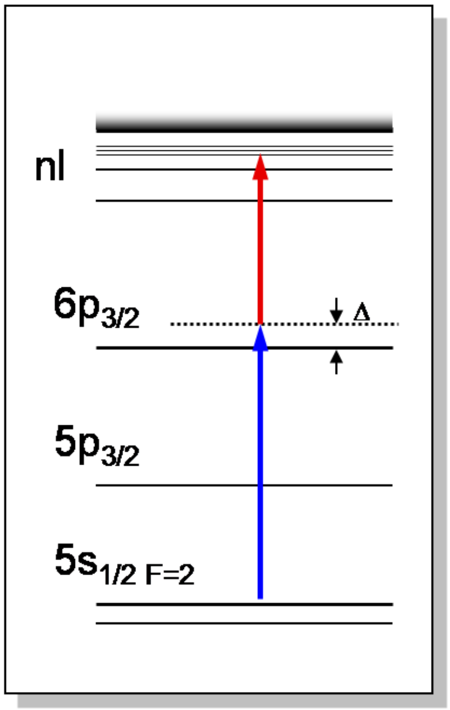


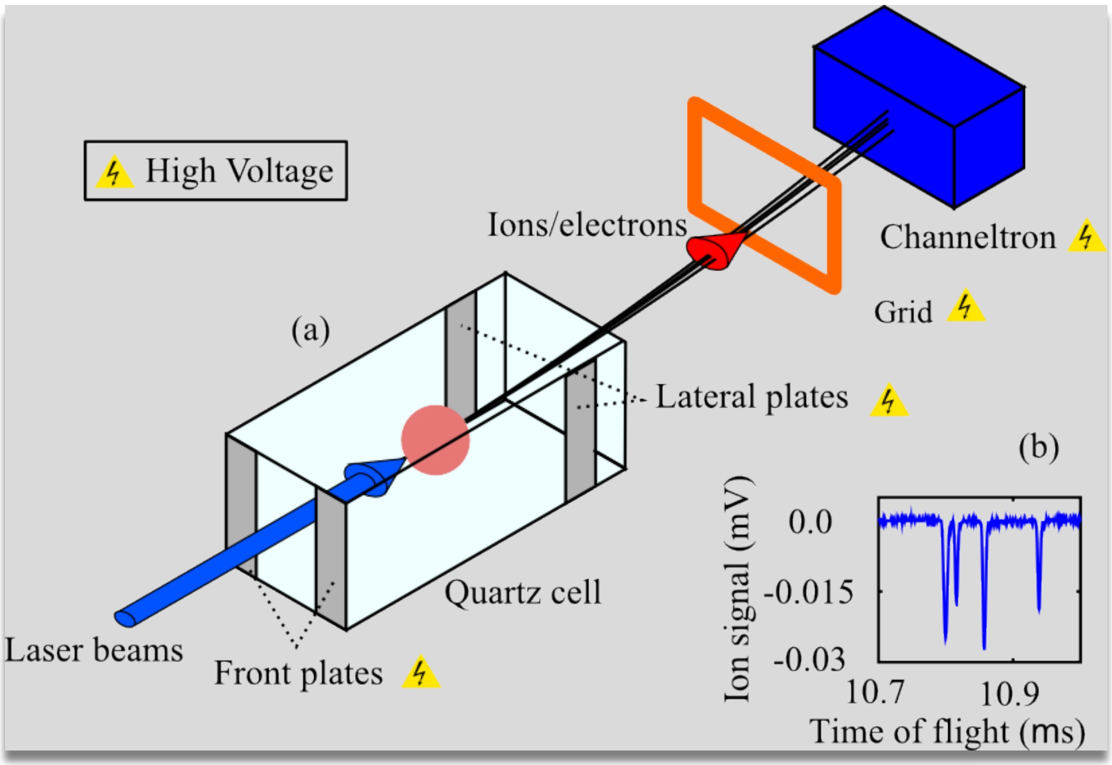


Possible solution:
Excite atoms to **Rydberg states**

Rydberg atom

Towards a quantum simulator with cold Rydberg atoms

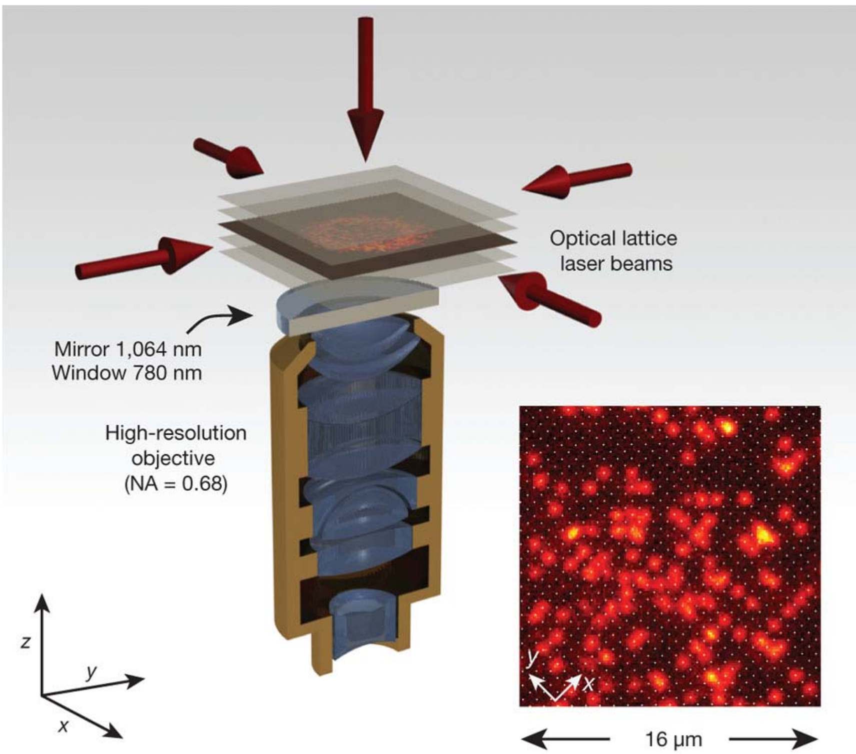


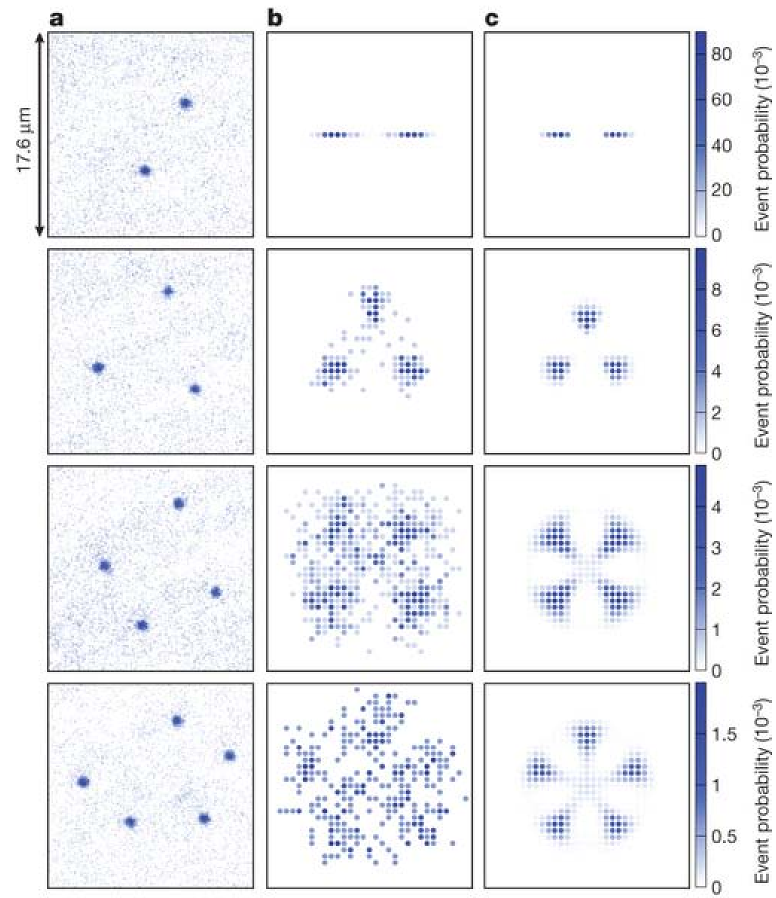


Caveat:

Even then, Feynman acknowledged that desperation for research funding was driving a tendency by scientists to hype the applications of their work. Otherwise, a friend told him, "we won't get support for more research of this kind." Feynman's reaction was characteristically blunt. "I think that's kind of dishonest," he said.

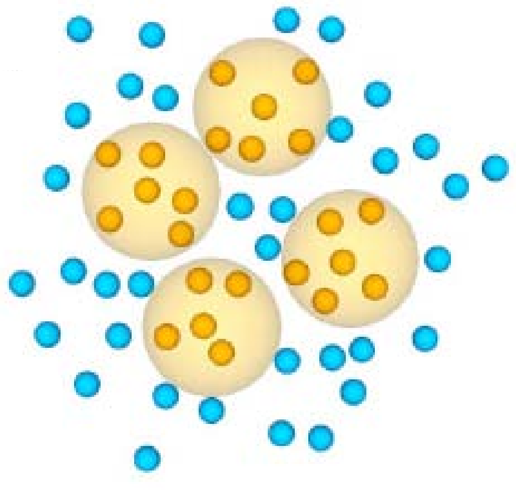
"Looking into the system": spatial resolution

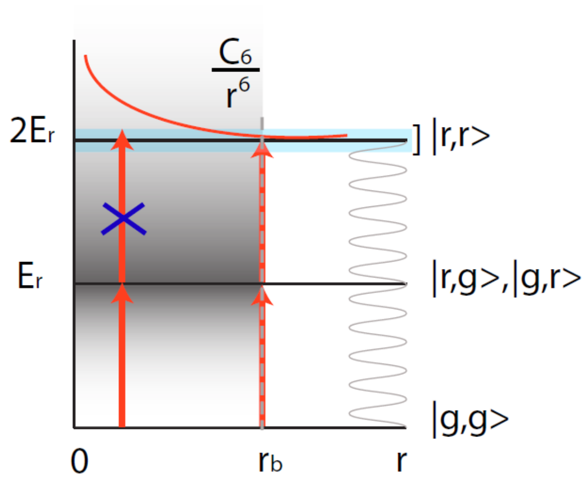




Immanuel Bloch, MPQ Munich

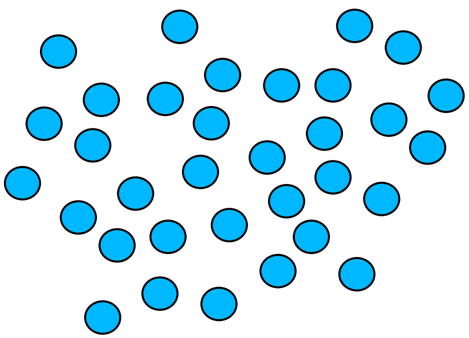
“Looking into the system”: counting statistics

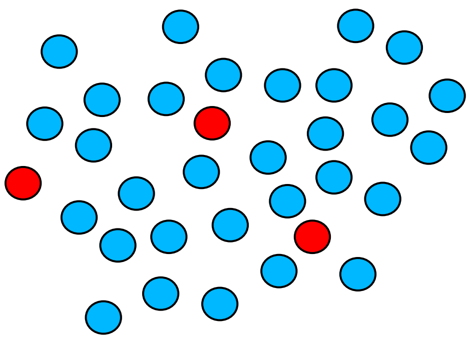


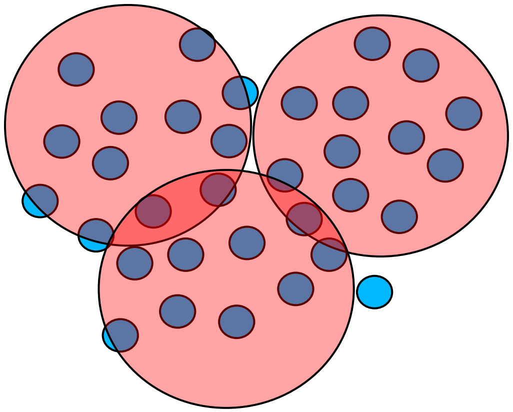


Van-der-Waals interaction shifts additional excitations within the blockade volume out of resonance
-> **dipole blockade**

"Looking into the system": counting statistics







$$Q = \frac{\left\langle N_e^2 \right\rangle - \left\langle N_e \right\rangle^2}{\left\langle N_e \right\rangle} - 1$$

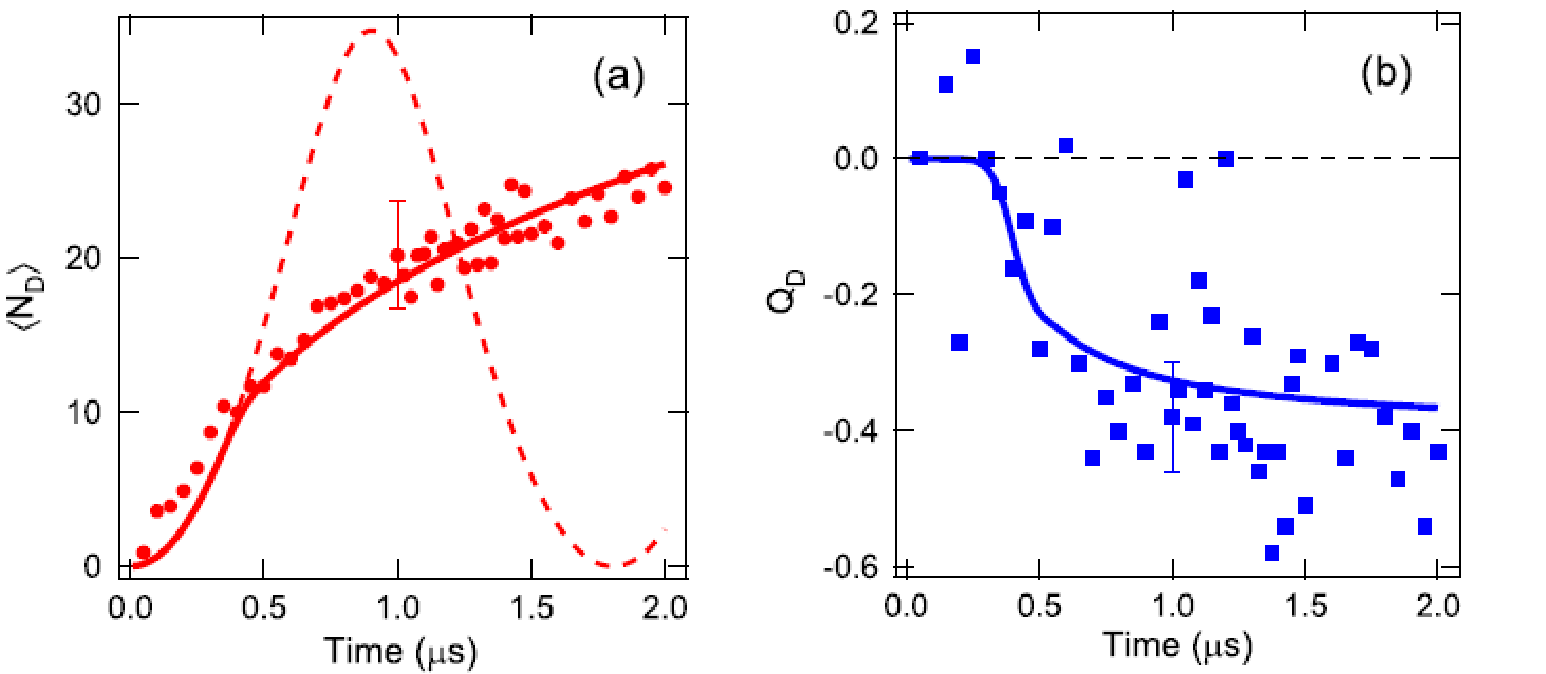
$$Q = -P_e \approx -0.1$$

$$Q = -P_e^{coll} \approx -1$$

$Q = 0$: Poissonian counting statistics

$Q \approx -1$: strongly sub-Poissonian counting statistics indicating anti-correlation of excitations

“Looking into the system”: counting statistics

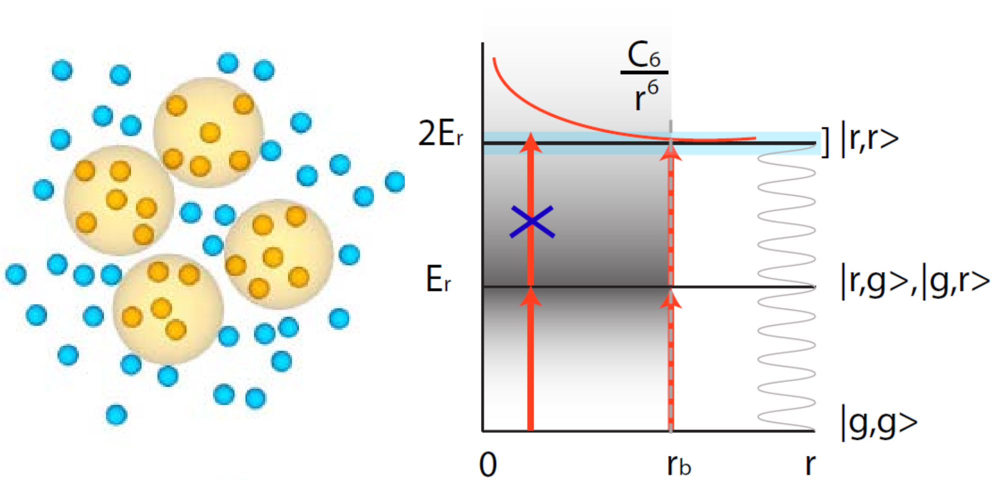


PRL 109, 053002 (2012) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 2012

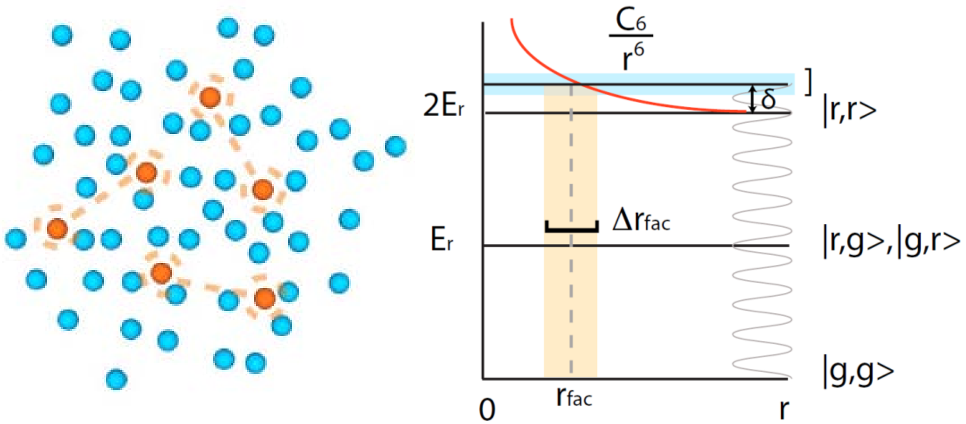
Cooperative Excitation and Many-Body Interactions in a Cold Rydberg Gas

Matthieu Viteau,[1] Paul Huillery,[1,2,3] Mark G. Bason,[1] Nicola Malossi,[1,4] Donatella Ciampini,[1,3,4] Oliver Morsch,[1] Ennio Arimondo,[1,3,4] Daniel Comparat,[2] and Pierre Pillet[2]

“Looking into the system”: ***full*** counting statistics

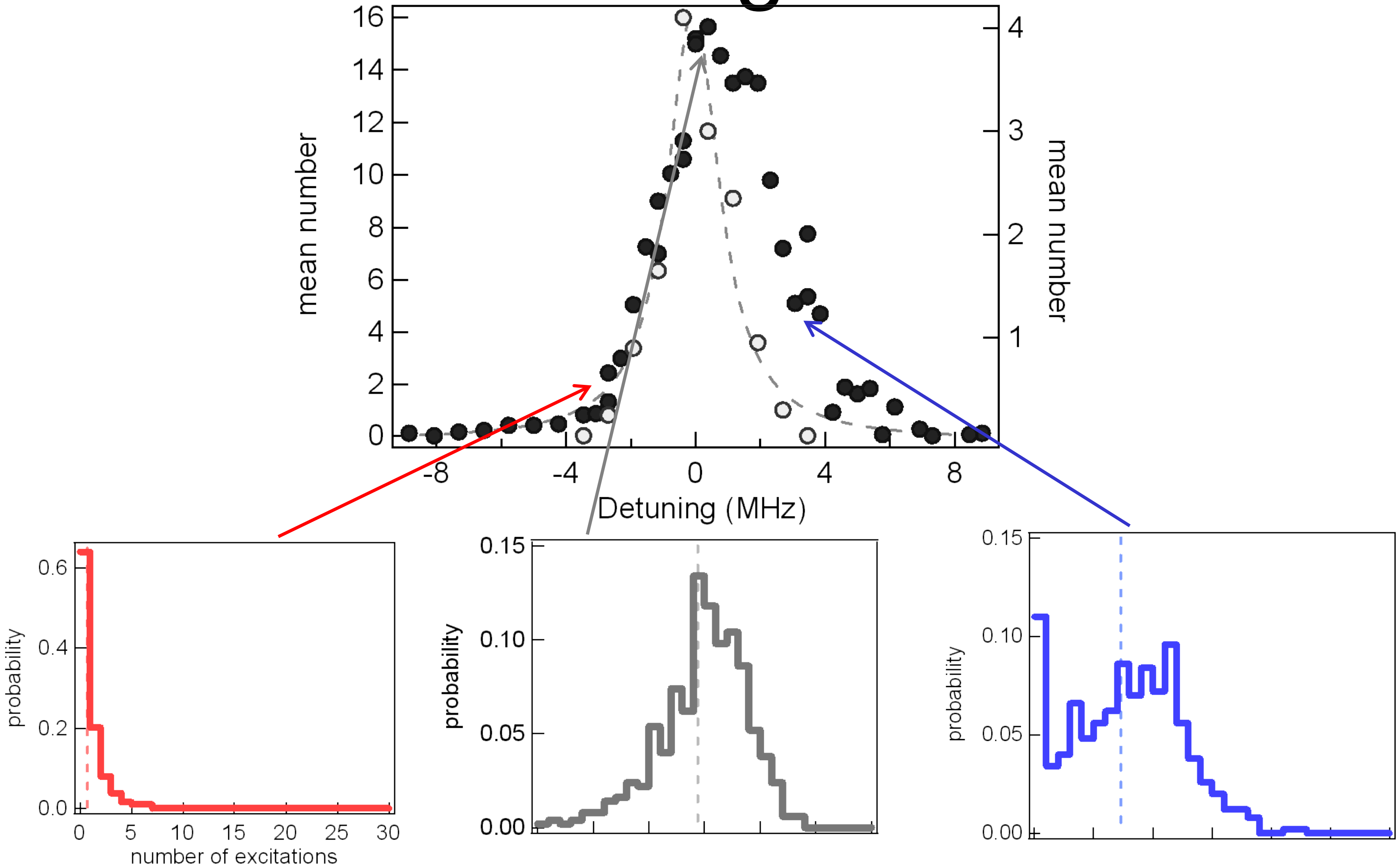


Resonant excitation:
exclusion due to dipole blockade

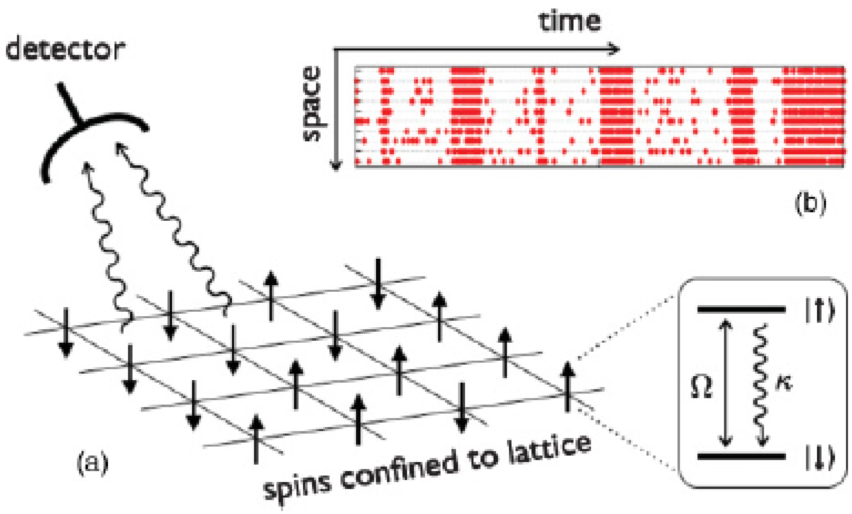


Off-resonant excitation:
inclusion due to two-photon resonant pair excitation or single-photon excitation of a single atom at resonant distance from an already excited one (“facilitation”)

"Looking into the system": ***full*** counting statistics



Simulating a dissipative Ising system



$$H = \sum_j \left[-\Delta |e\rangle\langle e|_j + \frac{\Omega}{2}(|e\rangle\langle g|_j + |g\rangle\langle e|_j) \right] + \frac{V}{N-1} \sum_{j<k} |e\rangle\langle e|_j \otimes |e\rangle\langle e|_k,$$

PHYSICAL REVIEW A **85**, 043620 (2012)

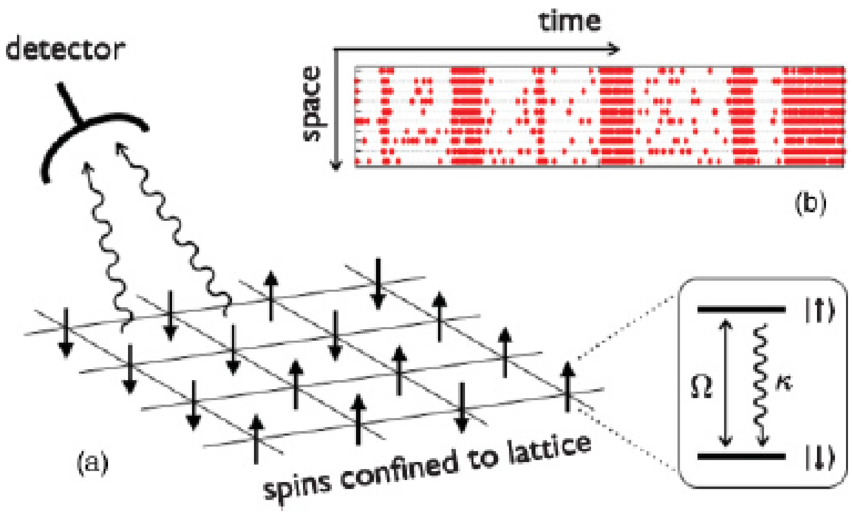
Dynamical phases and intermittency of the dissipative quantum Ising model

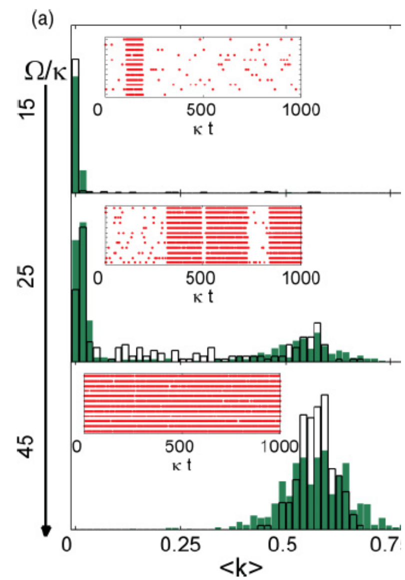
Cenap Ates,[1,2] Beatriz Olmos,[1,2] Juan P. Garrahan,[1] and Igor Lesanovsky[1,2]

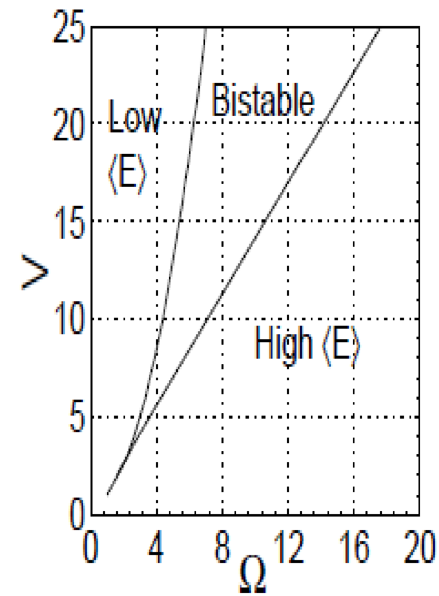
Spatial correlations of one dimensional driven-dissipative systems of Rydberg atoms

Anzi Hu,[1] Tony E. Lee,[2] and Charles W. Clark[1]

Simulating a dissipative Ising system







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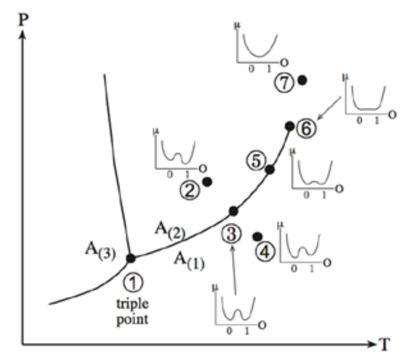

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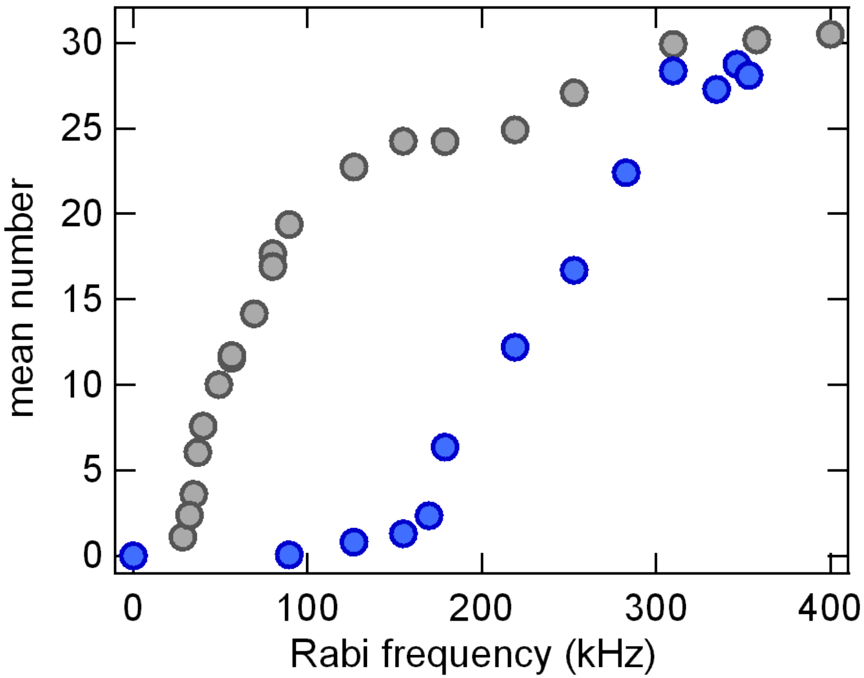
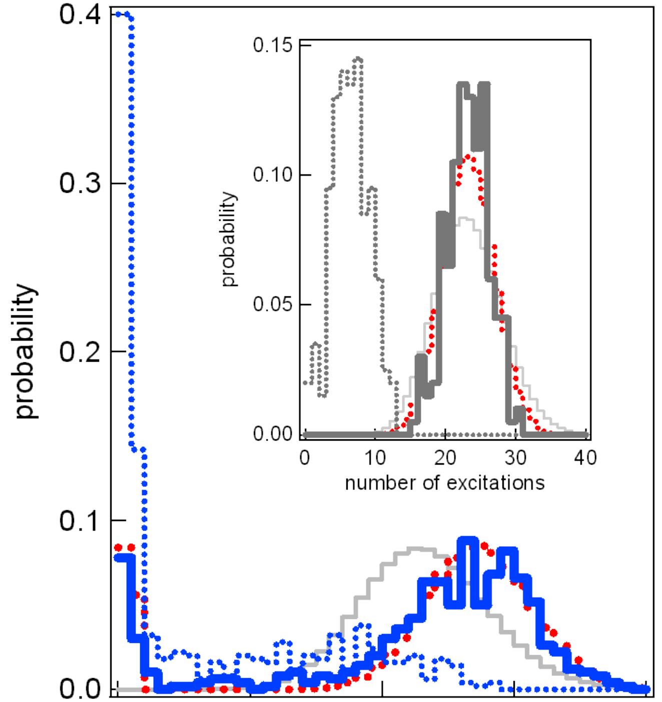
Anzi Hu,[1] Tony E. Lee,[2] and Charles W. Clark[1]

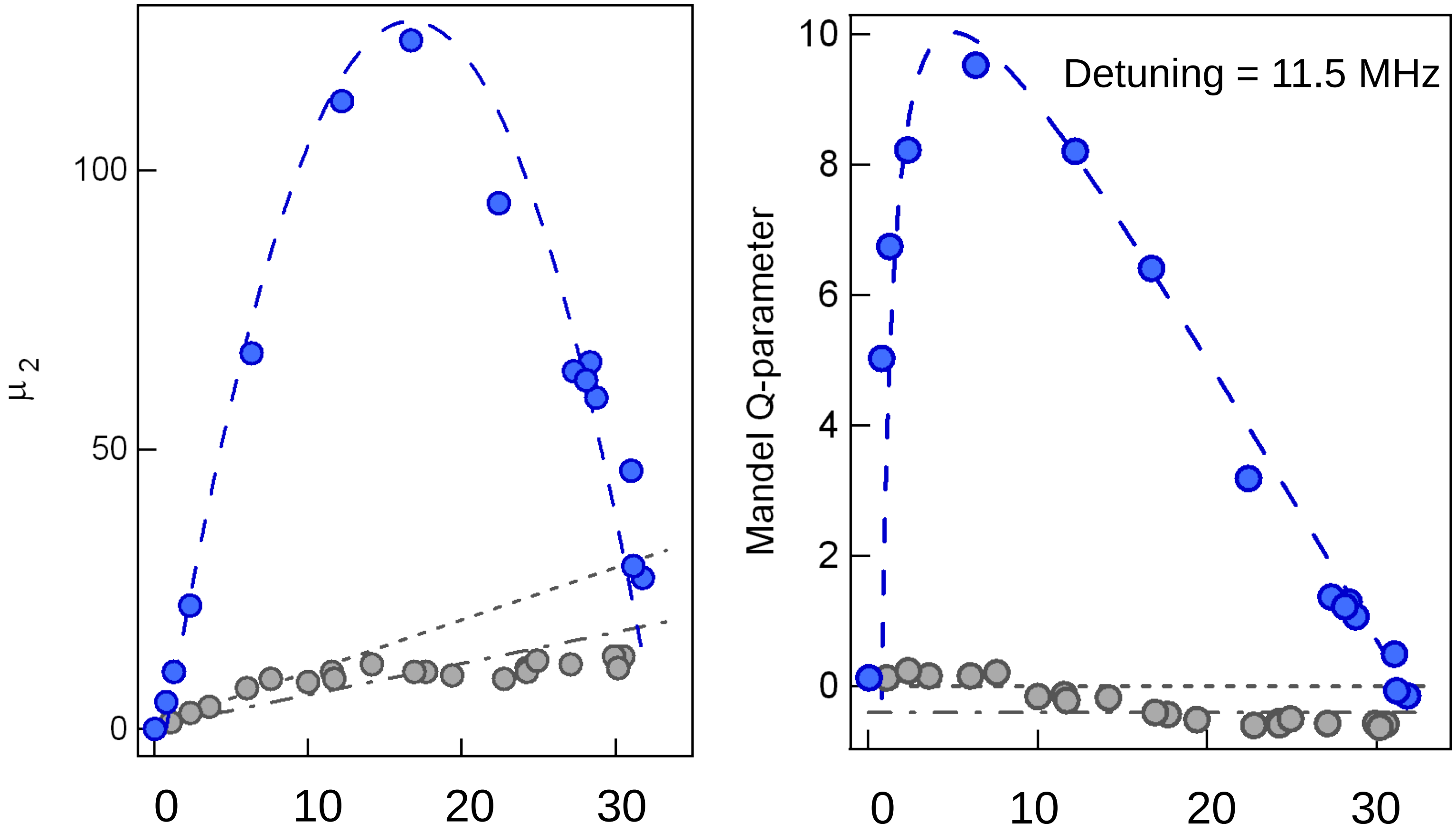
Simulating a dissipative Ising system





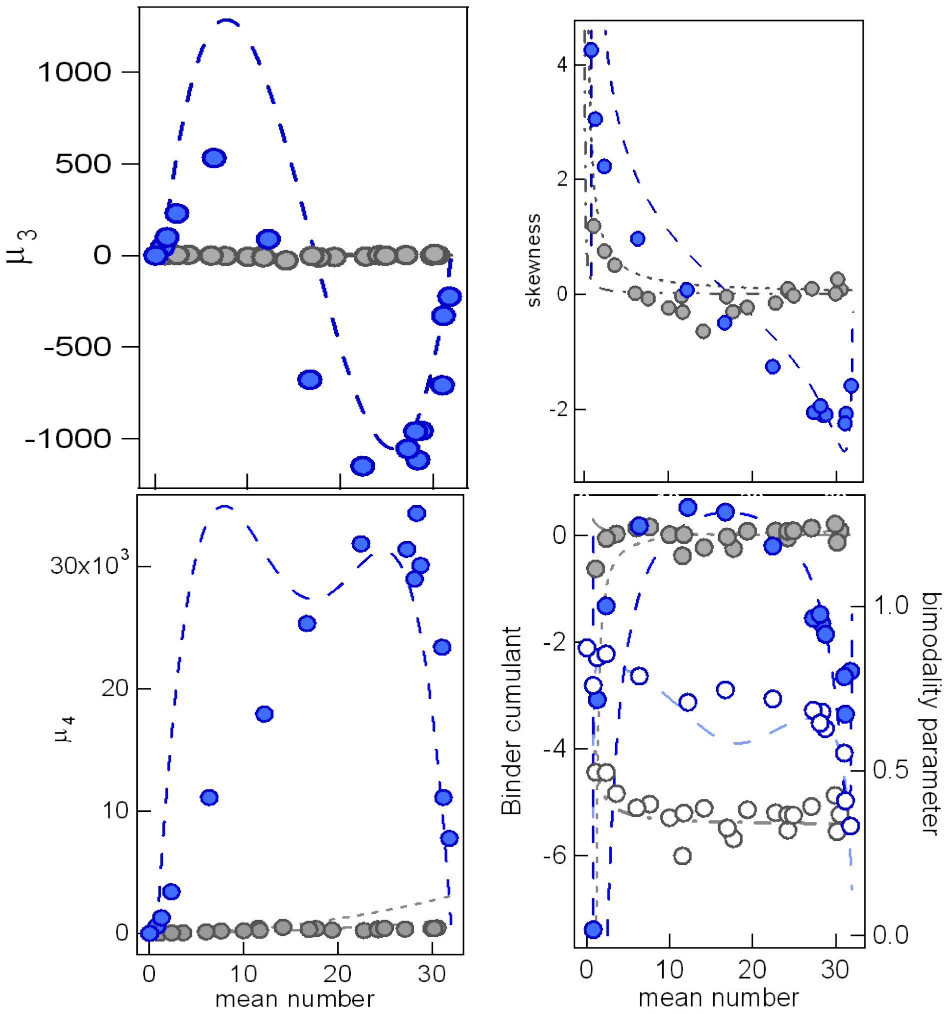
- **on resonance**, the distribution becomes highly sub-Poissonian for large mean numbers
- **off resonance**, the distribution is bimodal with varying weights of the two modes

Simulating a dissipative Ising system



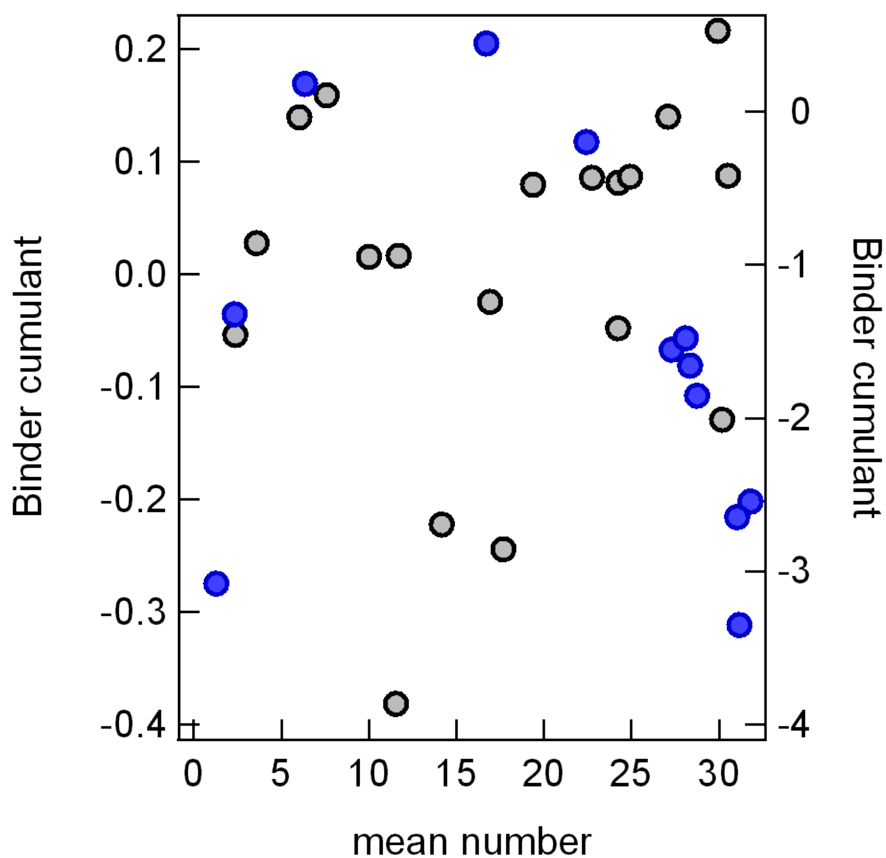
- **on resonance** (grey) the counting statistics goes from Poissonian to highly sub-Poissonian (negative Q-factor)
- **off resonance** (blue) the variance is positive and peaks at half the maximum number

Simulating a dissipative Ising system



- the higher central moments reveal subtle details of the counting distribution, so they can be used to test model predictions with high accuracy

Simulating a dissipative Ising system

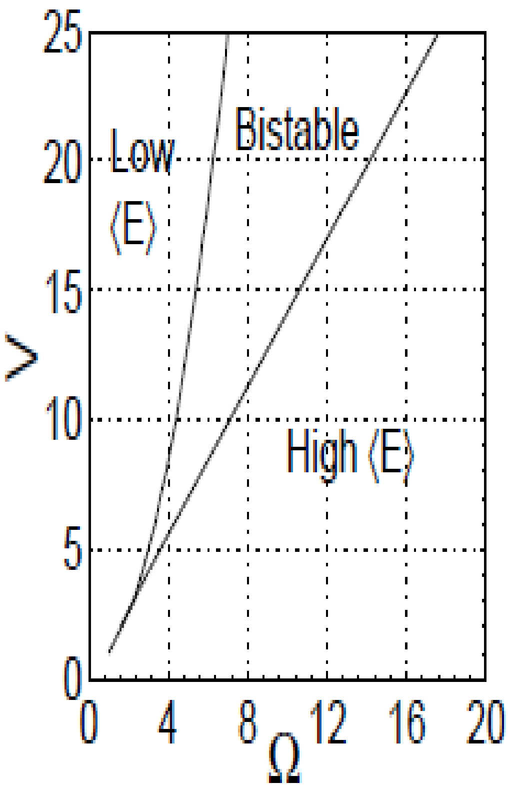


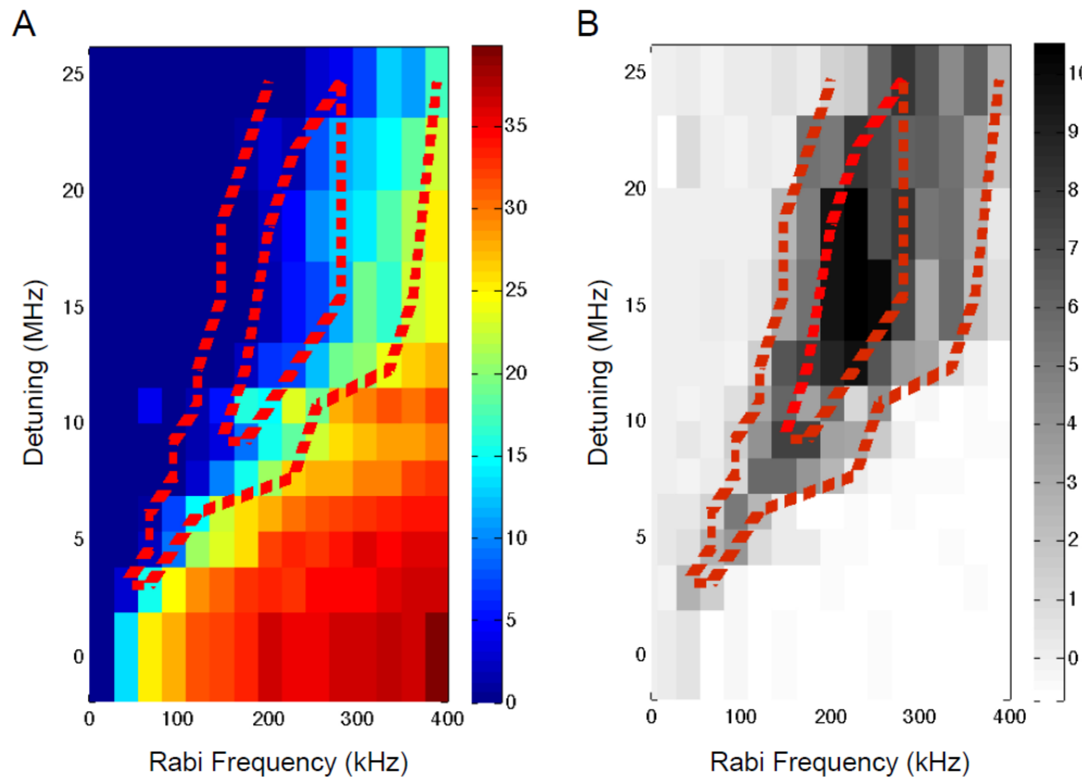
- the **Binder cumulant** shows a characteristic dependence on the mean number both on resonance and off resonance

- possibly useful for identifying phase transitions (finite size scaling)?

$$U_4 = 1 - \langle m_4 \rangle / 3 \langle m_2 \rangle^2$$

Simulating a dissipative Ising system





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Full Counting Statistics and Phase Diagram of a Dissipative Rydberg Gas

N. Malossi,[1,2] M. M. Valado,[1,2] S. Scotto,[2] P. Huillery,[3] P. Pillet,[3] D. Ciampini,[1,2,4] E. Arimondo,[1,2,4] and O. Morsch[1,2]

Towards a quantum simulator with cold Rydberg atoms

✓ **creation and detection** of Rydberg excitations in a cold cloud

✓ **revealing strong Rydberg-Rydberg interactions** through counting statistics

✓ using **full counting statistics** as a tool for gaining insight into the system

✓ using cold Rydberg atoms to **simulate a dissipative Ising system**

➢ study **dynamics**

➢ **finite size scaling**

➢ move towards **coherent regime**

➢ **ordered structures** (optical lattice) to implement Ising Hamiltonians

➢ …. the sky's the limit!