Manipulation, measurement and control of simple quantum systems

COLLÈGE DE FRANCE 1530

Serge Haroche,
Quantum Science workshop
City U
Hong Kong, November 8th 2017

ECOLE NORMALE SUPERIEURE

Manipulation of simple quantum systems to test quantum principles and demonstrate quantum information procedures

Cold Ions and neutral atoms
Rydberg atoms
Photons in cavities or in fibres
Josephson qubits
Quantum dots….

Review methods to:

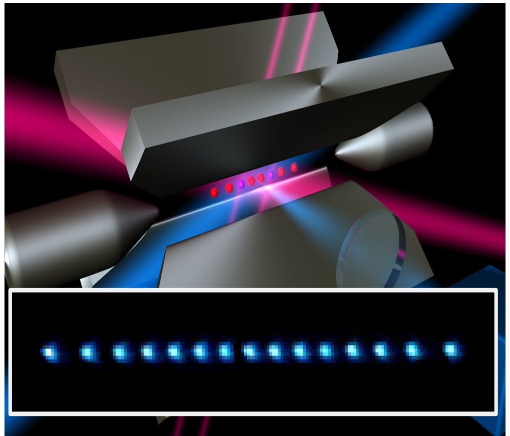
- Prepare quantum states
- Measure and reconstruct them (quantum non demolition procedures)
- Control their evolution (Hamiltonian engineering)

Optical methods for real atoms, inspired from optics for artificial ones

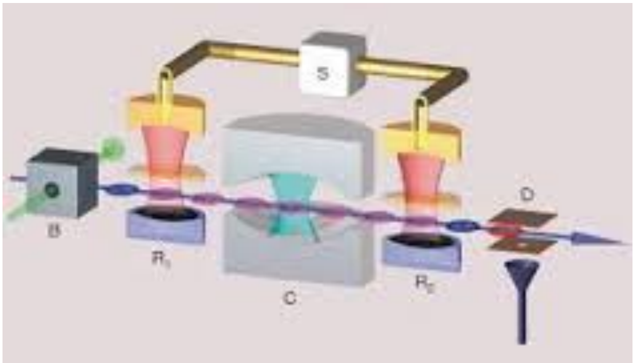
Outline

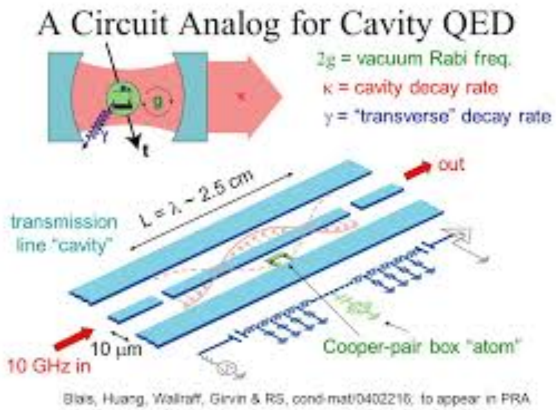
1. Description of simple quantum systems and tools to manipulate them
2. A simple model: spin coupled to a harmonic oscillator
3. Non-destructive measurements and quantum jumps
4. Mesoscopic state superpositions: Schrödinger cats
5. Example of Hamiltonian engineering: Quantum Zeno Dynamics of a Rydberg atom
6. Conclusion: related talks in this workshop: Quantum computing, simulation & metrology

1.
Simple quantum systems and tools to manipulate them

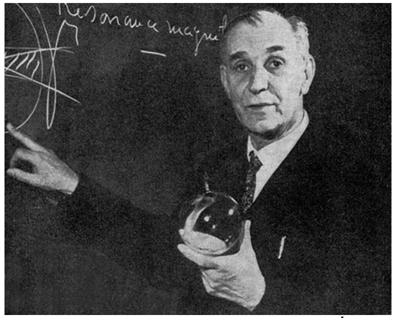


P. Schindler et al., New. J. Phys. 15, 123012 (2013)

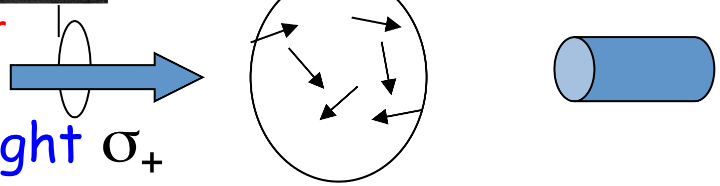


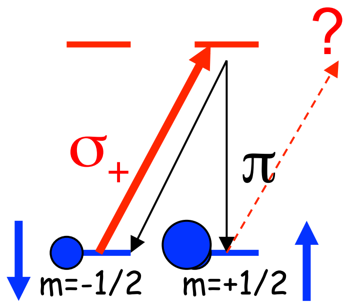


Optical Pumping (OP): the « mother » of quantum state manipulation methods



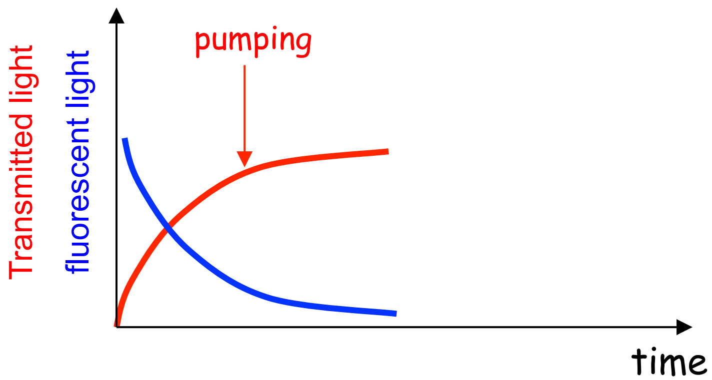
A.Kastler





After a few cycles of absorption-fluorescence, atoms are pumped in state m=+1/2: oriented magnetic moments

During pumping, the number of atoms absorbing light decreases and transmitted light increases

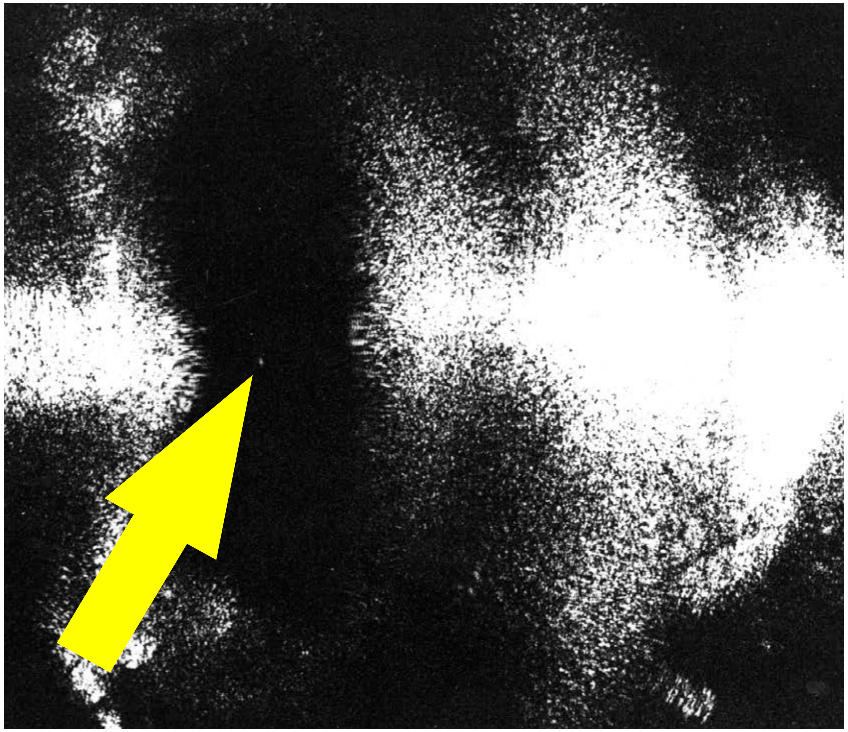


Transmitted (or fluorescent) light measures degree of atomic polarization

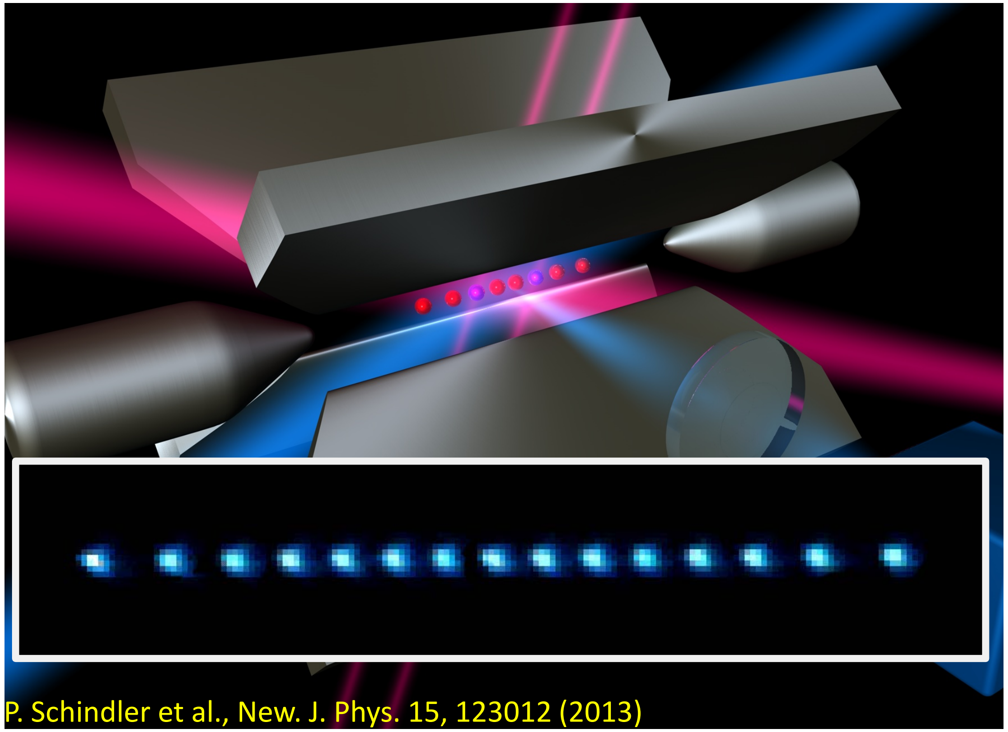
OP has introduced the basic ingredients of quantum state manipulation: exchange of photons between matter and radiation to prepare and detect quantum states

Lasers have tremendously increased precision and sensitivity to the point where single particles can be detected and controlled

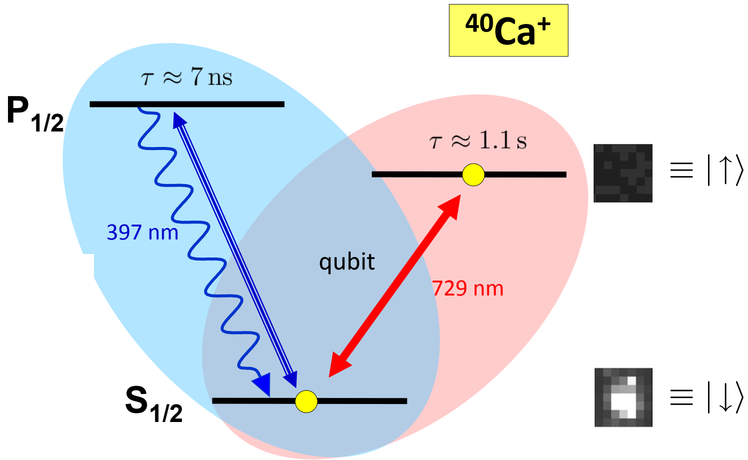
Trapped ions



First Single Ion detection:
P.Toschek et al, 1978



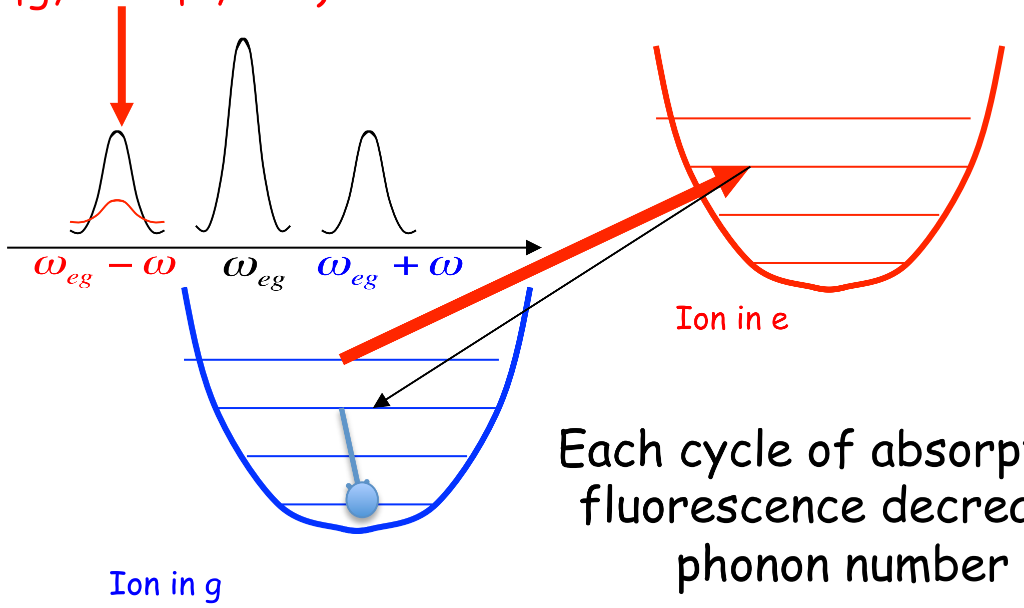
An ion chain in Innsbruck lab (R.Blatt)



Single-ion selective state detection:
blue fluorescence observed if ion in ↓, disappears if ion is shelved in ↑

Cooling a trapped ion to the ground state of motion by optical pumping (red-sideband cooling)

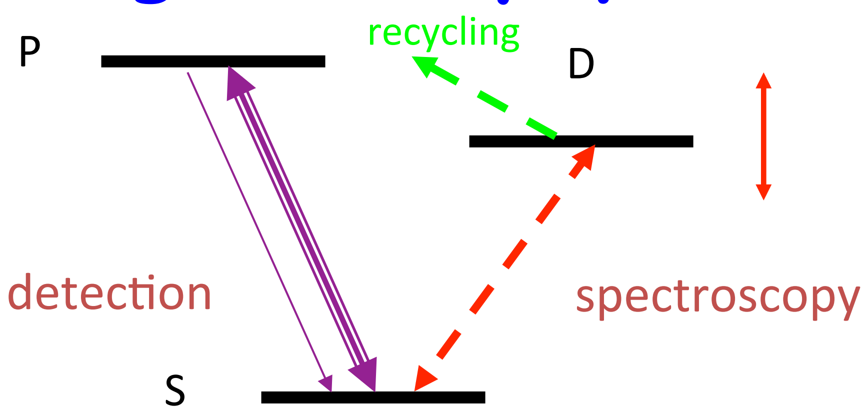
Pumping on « red side-band » transition |g,n> ➔ |e, n-1>)



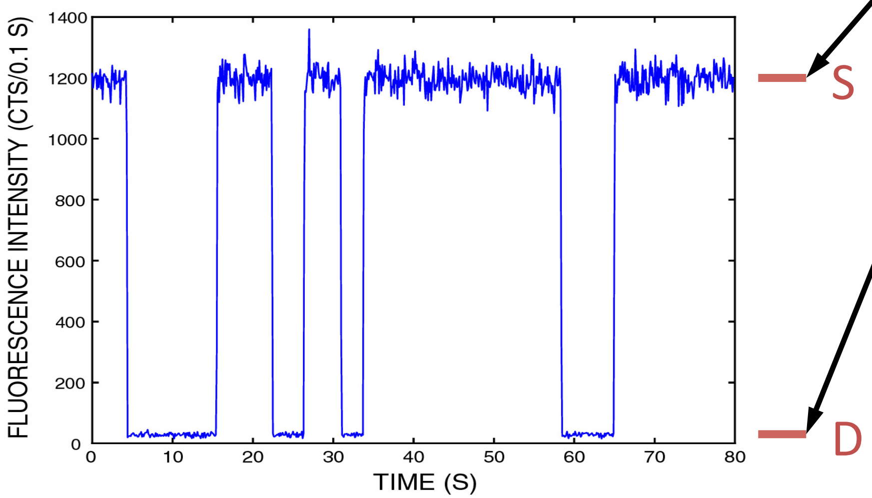
Each cycle of absorption-fluorescence decreases phonon number

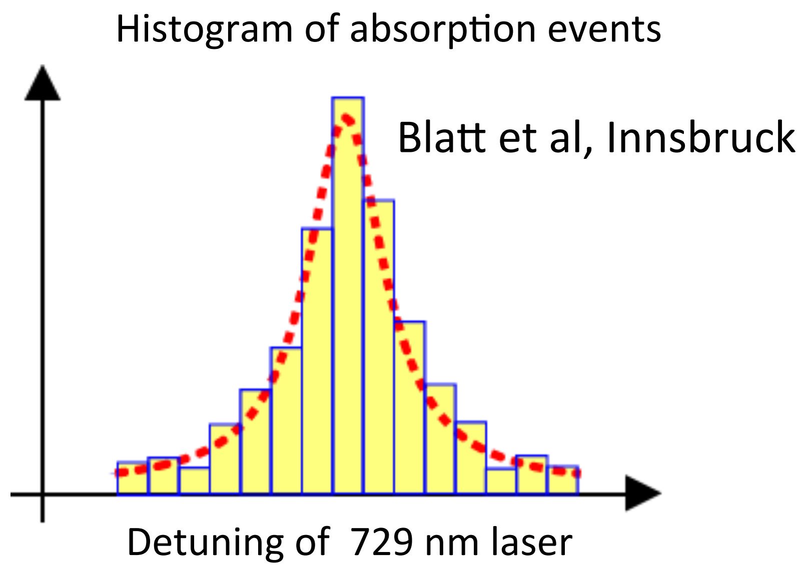
Progress of cooling is monitored by decrease of red side band fluorescence

Non-destructive continuous detection of single ion by quantum jump spectroscopy



Absorption and recycling produce fluorescence jumps (digital signal)

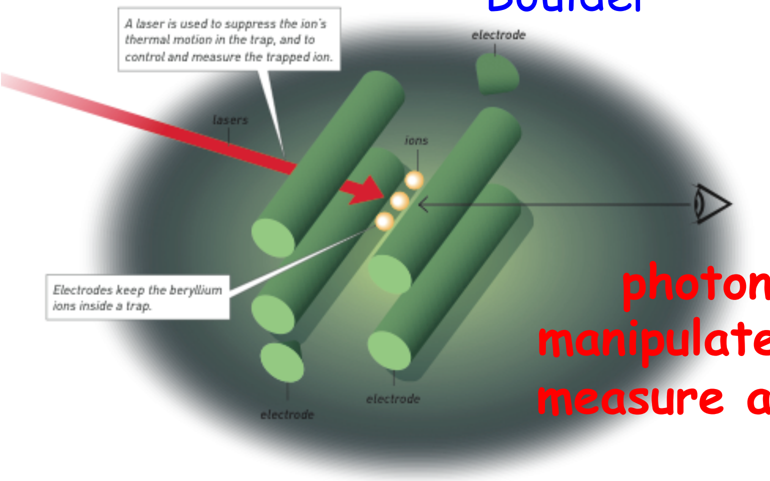




Here, disposable photons are used for QND measurement of atom ***(quantum information, atomic clocks…)***. Symmetrical process uses disposable atoms to count photons in a cavity non-destructively.

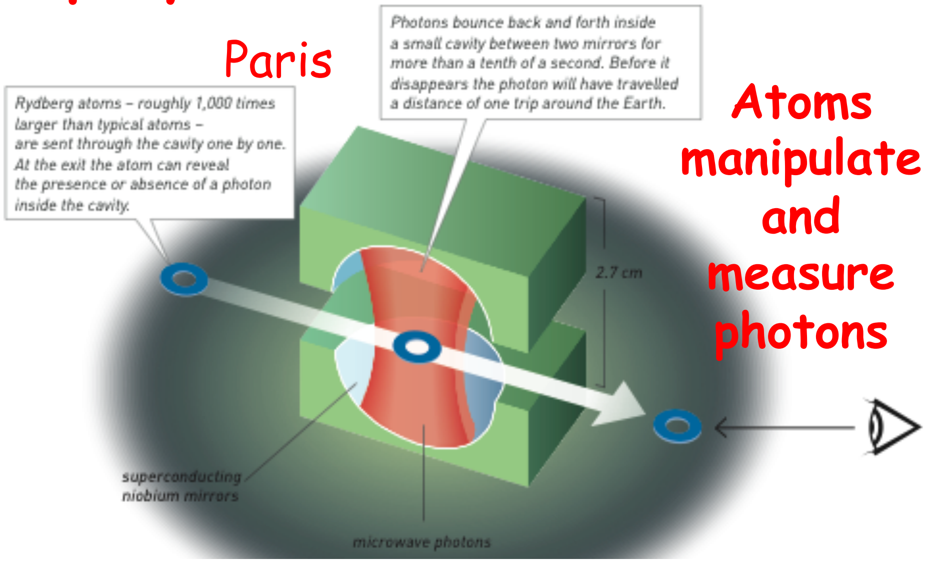
Comparing Ion Trap and cavity QED (« in vivo » physics)

Boulder



photons manipulate and measure atoms

Paris



Atoms manipulate and measure photons

Exchanging the roles of matter and radiation

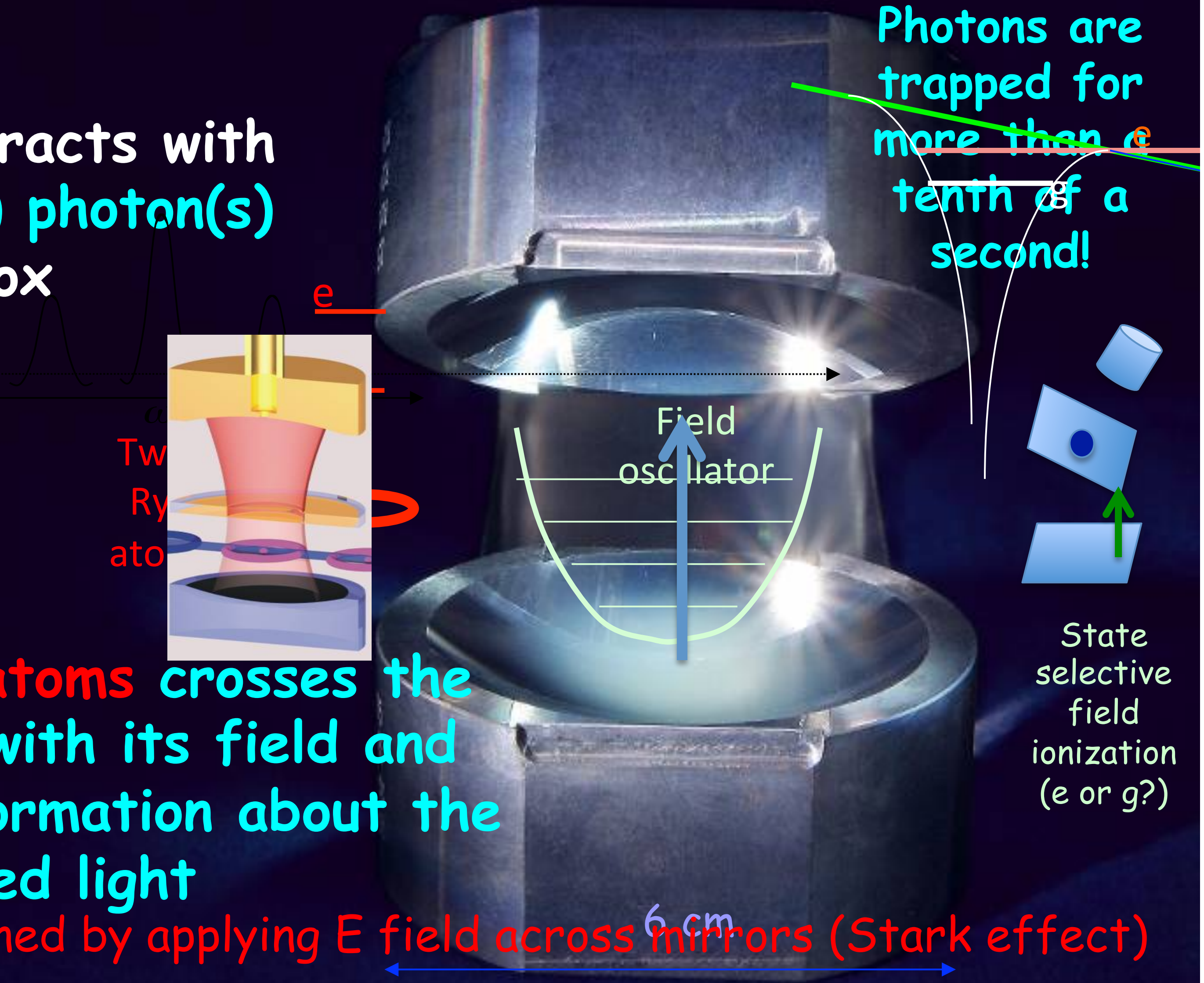
Two sides of the same coin: manipulating non destructively atoms with photons or photons with atoms

Cavity QED with special Rydberg atoms

Principle of Cavity QED experiment: an atom coupled to a field oscillator

One atom interacts with one (or a few) photon(s) in a box

Photons are trapped for more than a tenth of a second!

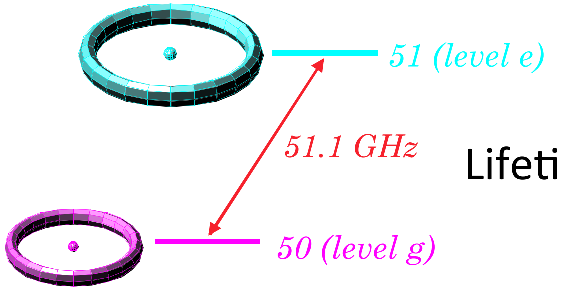


A sequence of atoms crosses the cavity, couples with its field and carries away information about the trapped light

Atomic frequency tuned by applying E field across mirrors (Stark effect)

Qubit state controled by classical microwave applied before C in auxiliary cavity

CQED withs real or artificial atoms: atomic vs superconducting qubit

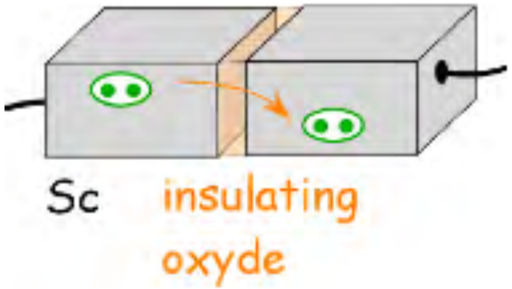


Lifetime: 30ms

Atomic CQED: Rydberg atom with very large electric dipole (~1000 debye)

Circuit QED: a mesoscopic dipole: 10^4 to 10^6 debye!

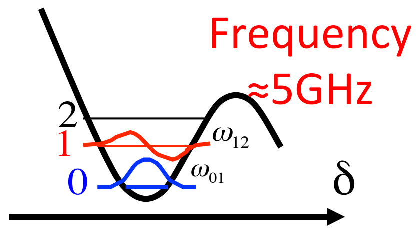
R.Schoelkopf and S.Girvin, Nature, 451, 664 (2008)



N, δ

Josephson sc junctions inserted in various circuits (phase, charge or flux qubits of various kinds)

A quantum system with charge (N) and phase (δ) as conjugate variables. δ plays role of position and N the role of momentum in phase qubit



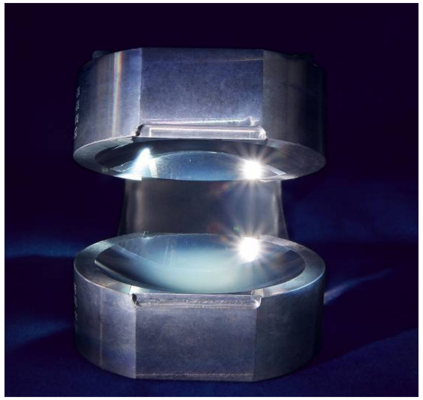
Like a quantum particle in anharmonic potential

Qubit tuned and detected by varying magnetic flux

Photon traps in CQED and Circuit QED

Atomic CQED: superconducting (Nb) Fabry-Perot

Photon lifetime: T_c= 0.1 s (Q=4.10^{10})

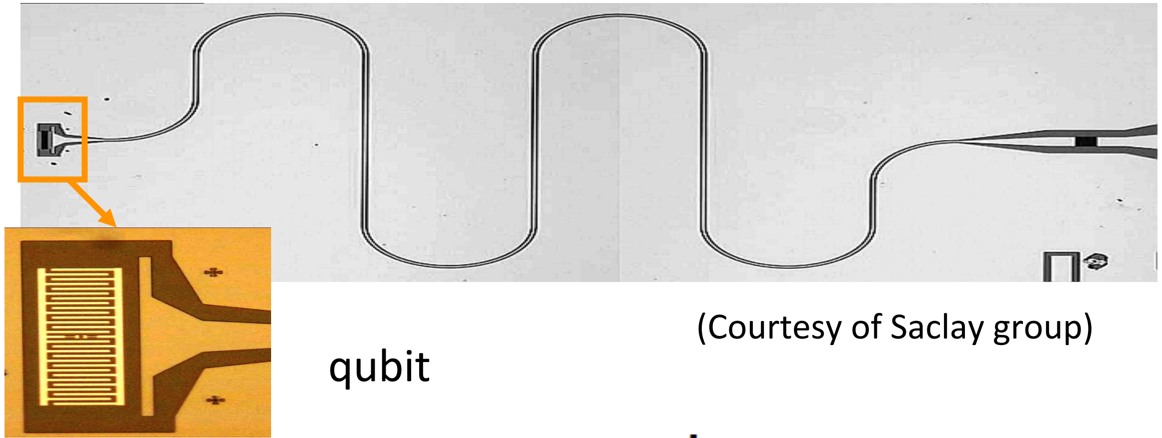


T=800mK

S.Kuhr et al, Appl.Phys.Lett. 90, 164101 (2007)

Circuit QED:

Coplanar Nb line with qubit inserted



T=20mK

qubit

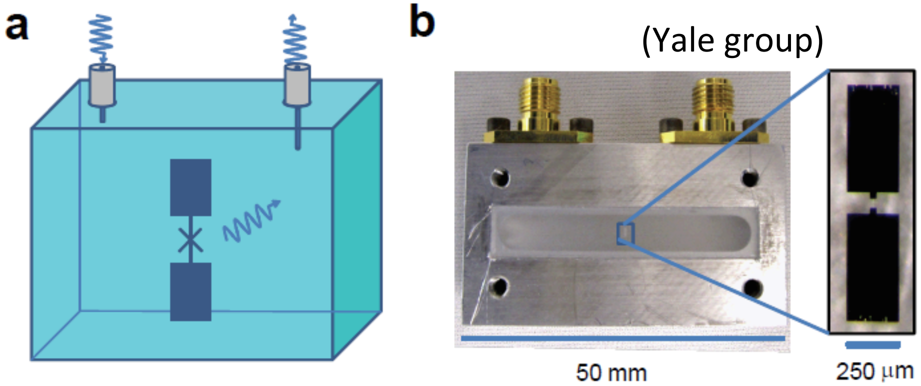
(Courtesy of Saclay group)

T_c ~100 ns to 1μs

or..

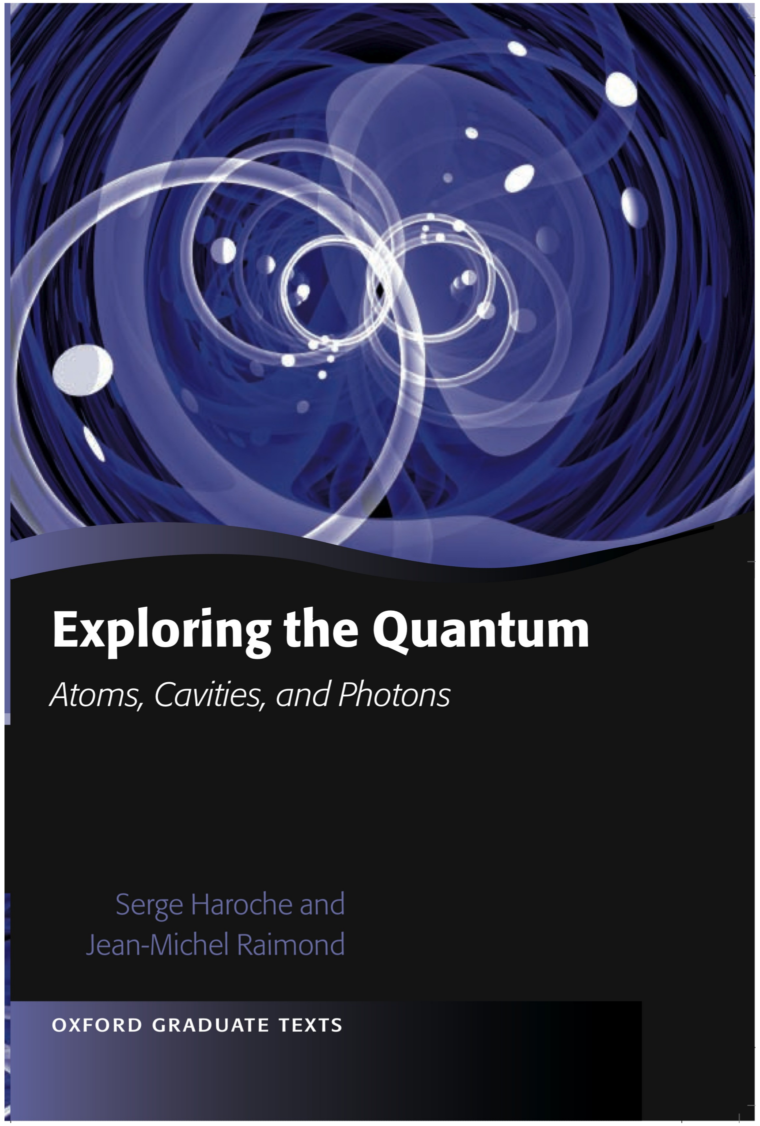
3D superconducting box with qubit suspended inside with a large antenna (huge dipole)

T_c ~ 1 ms (Q ~10^9)



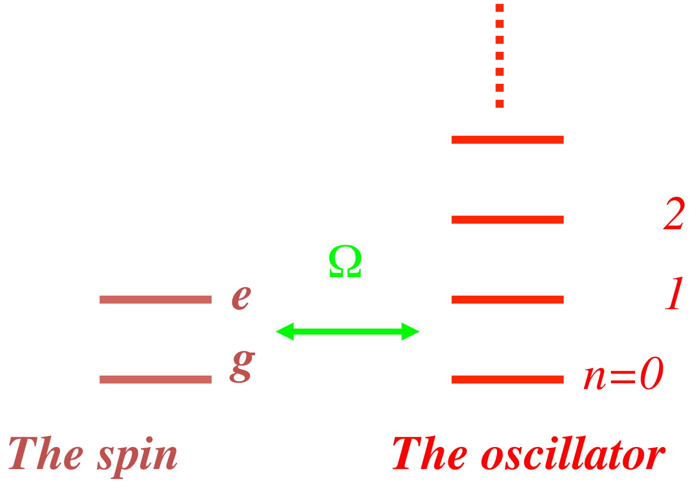
(Yale group)

Paik et al, PRL, 107, 240501 (2011)



2.
A simple model:
a spin (qubit) coupled to a harmonic oscillator

An ubiquitous model describing analytically the coupling of a quantum oscillator to a two-level system (spin or qubit)

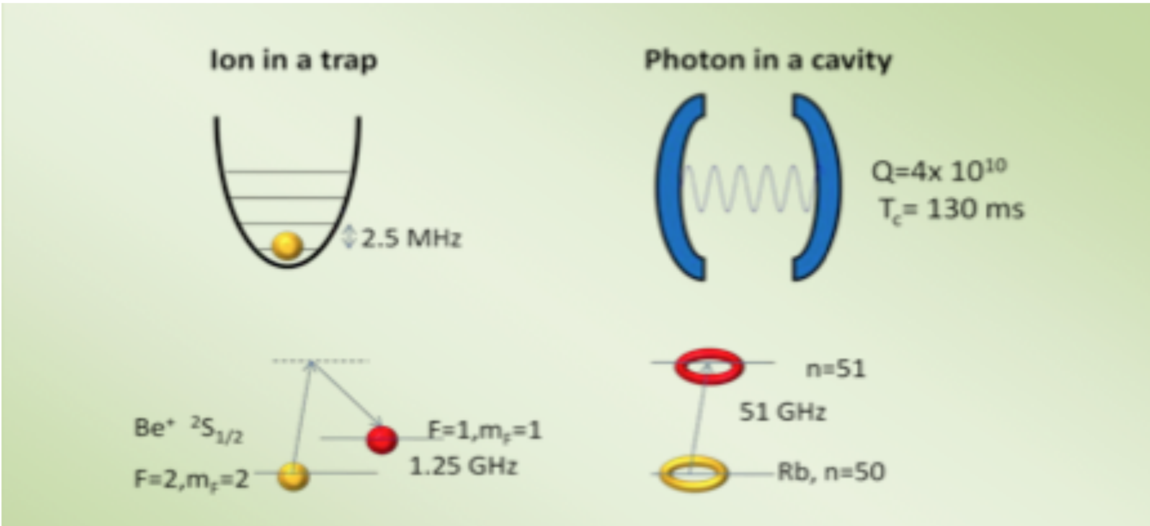


Trapped ion:

« spin »: 2 internal states of ion

Oscillator: quantized ion motion in trap

Coupling: lasers inducing transitions changing the internal state of ion and its exernal state of motion



Trapped Photon

« spin »: 2 states of a Rydberg atom

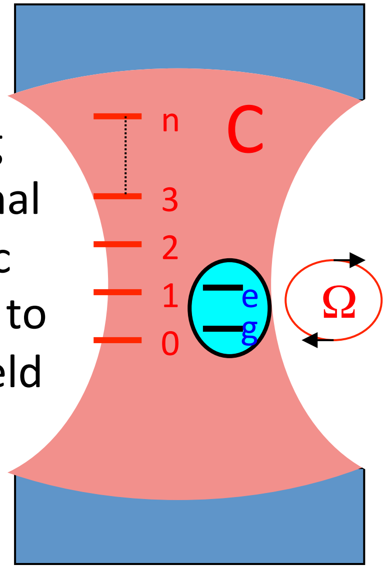
Oscillator: field mode in cavity

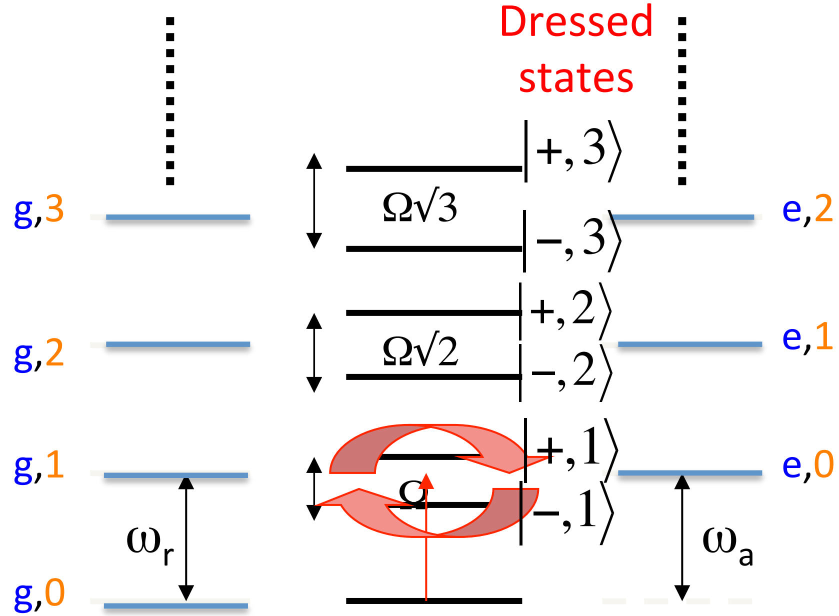
Coupling: photon absorption and emission of atoms in cavity.

CQED or Circuit QED

Strong atom-cavity coupling

Coupling proportional to atomic dipole and to vacuum field in C





ENS CQED

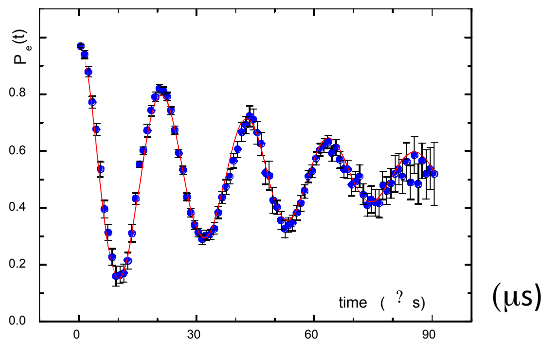
J.Martinis Group

At resonance:

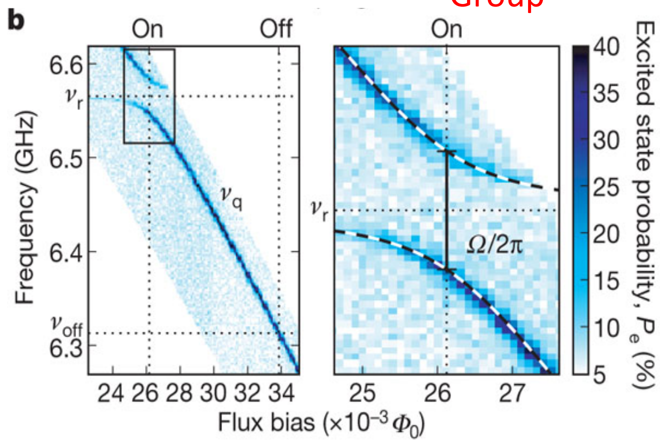
Vacuum Rabi oscillation

&

Vacuum Rabi splitting



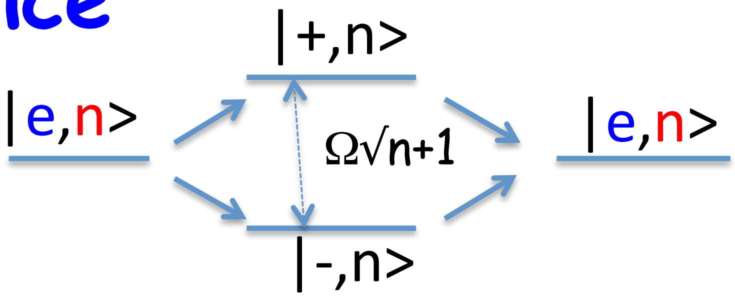
Vacuum Rabi oscillation between |e0> and |g,1> in Atomic CQED: $\Omega/2\pi = 50$kHz



Spectroscopy of coupled qubit-resonator in Circuit QED (Vacuum Rabi splitting): $\Omega/2\pi$=36MHz

Rabi oscillation in Fock state: a quantum interference

$$\left|\Psi(0)\right\rangle = \left|e\right\rangle \otimes \left|n\right\rangle = \frac{1}{\sqrt{2}}\left[\left|+n\right\rangle + \left|-n\right\rangle\right]$$

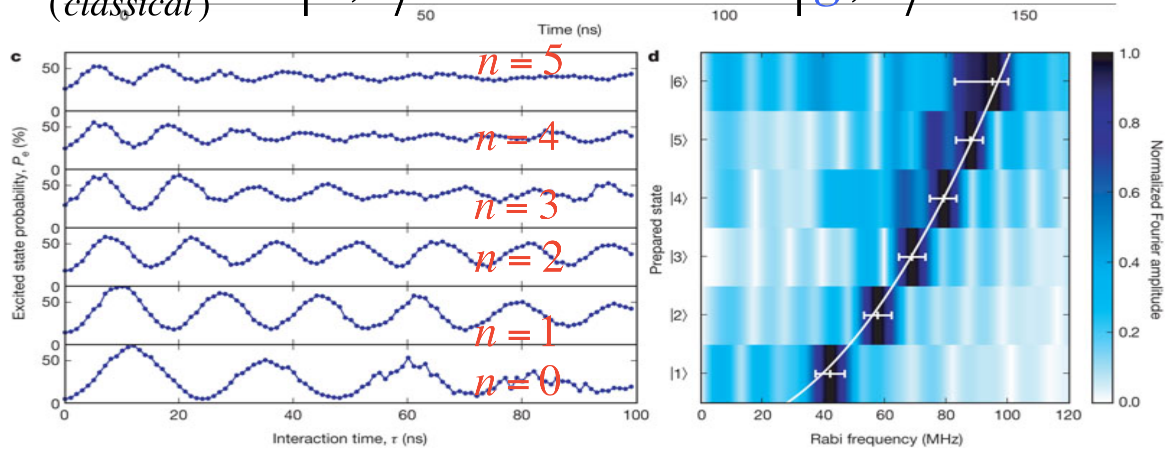


$$\left|\Psi(t)\right\rangle = \frac{1}{\sqrt{2}}\left[e^{-i\Omega\sqrt{n+1}\,t/2}\left|+n\right\rangle + e^{i\Omega\sqrt{n+1}\,t/2}\left|-n\right\rangle\right] = \cos\frac{\Omega\sqrt{n+1}t}{2}\left|e,n\right\rangle + \sin\frac{\Omega\sqrt{n+1}t}{2}\left|g,n+1\right\rangle$$

Atom-field entanglement

Circuit QED experiment: Fock states prepared by sequence of Rabi flops

$$\left|e,0\right\rangle \xrightarrow{Rabi(\Omega t=\pi)} \left|g,1\right\rangle \xrightarrow[(classical)]{qubit\ rotation} \left|e,1\right\rangle \xrightarrow{Rabi(\Omega\sqrt{2}t=\pi)} \left|g,2\right\rangle \rightarrow \quad etc\ldots$$



After |n> state preparation, Rabi oscillation $P_g(t)$ recorded by scanning time t and averaging over large number of realizations (from n=0 to 5)

M.Hofheinz et al, Nature, 454, 310 (2008)

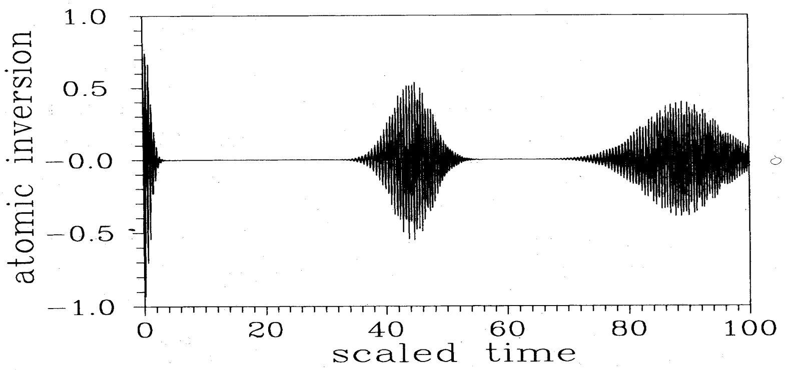
Rabi oscillation in a coherent field

$$|\alpha\rangle = \sum_n C_n |n\rangle \quad ; \quad C_n = e^{-|\alpha|^2/2}\frac{\alpha^n}{\sqrt{n!}} \quad (\bar{n} = |\alpha|^2 \,;\, \Delta n = \sqrt{\bar{n}} = |\alpha|)$$

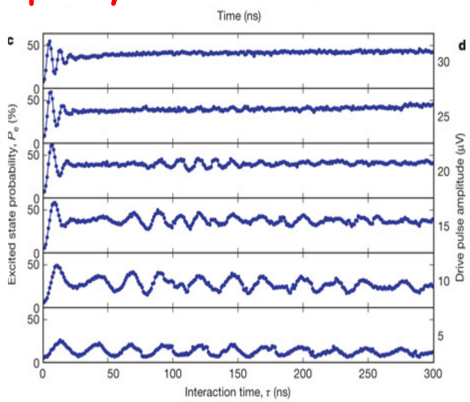
Exact evolution: $$|e\rangle \otimes |\alpha\rangle \rightarrow \sum_n C_n \left[\cos\frac{\Omega\sqrt{n+1}t}{2}|e,n\rangle + \sin\frac{\Omega\sqrt{n+1}t}{2}|g,n+1\rangle \right]$$

Large field $\left(\bar{n} \gg 1 ; \frac{\Delta n}{\bar{n}} = \frac{1}{\sqrt{\bar{n}}} \ll 1\right)$ $\quad P_e(t) \approx \cos^2\frac{\Omega\sqrt{\bar{n}}t}{2}$ $\quad$ Classical Rabi oscillation

Small fields: Rabi oscillations are rapidly washed out….then revive:

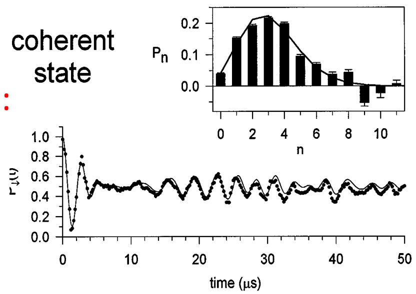


$\bar{n} = 25$

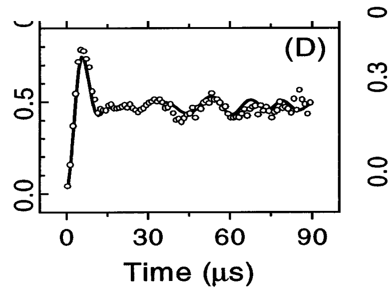


Circuit QED (Hofheintz et al, Nature, 454, 310, 2008)

Trapped ions: Meekhof et al, PRL, 76, 1796 (1996).

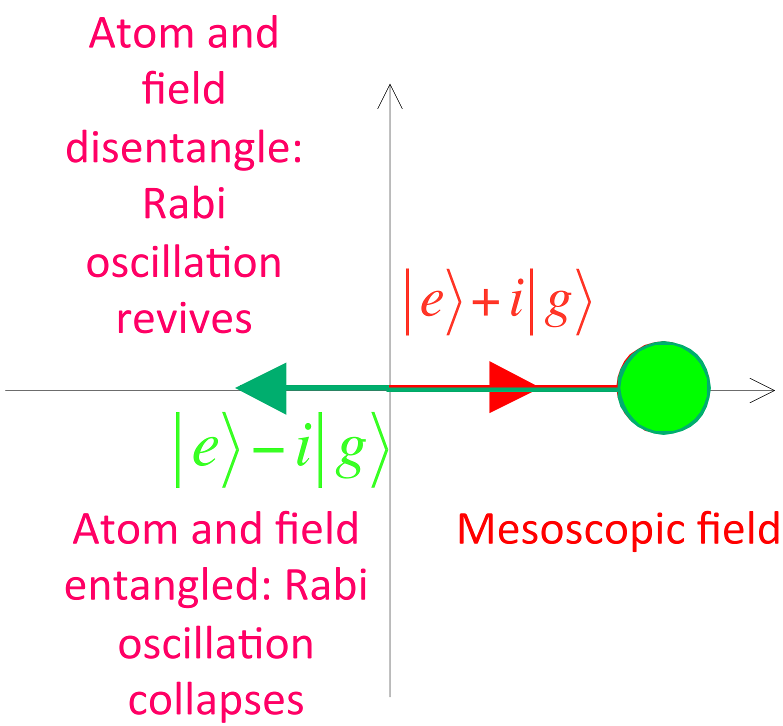


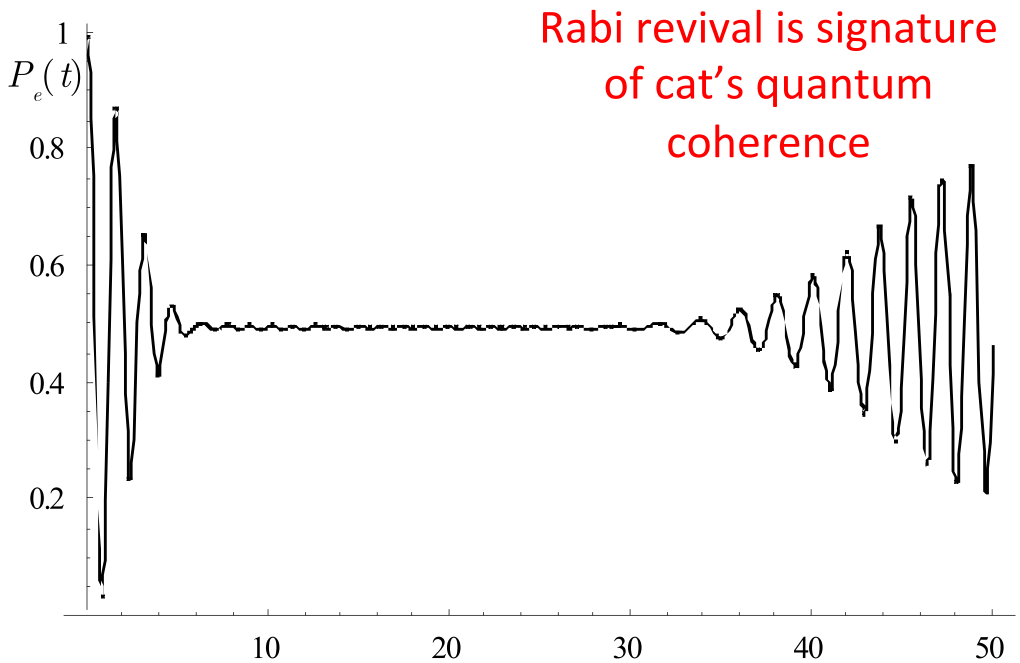
CQED: Brune et al, PRL, 76, 1800 (1996)



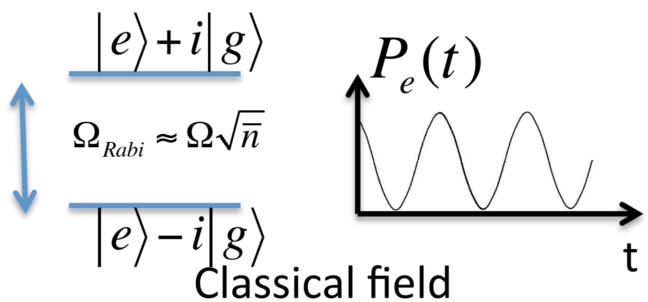
Oscillation Collapse due to dispersion of Rabi frequencies, revivals related to periodic disentenglement between atom and field

Schrödinger cats prepared by resonant atom initially in upper state e: Rabi oscillation collapses and revives as field components separate and recombine (Bohr's complementarity)





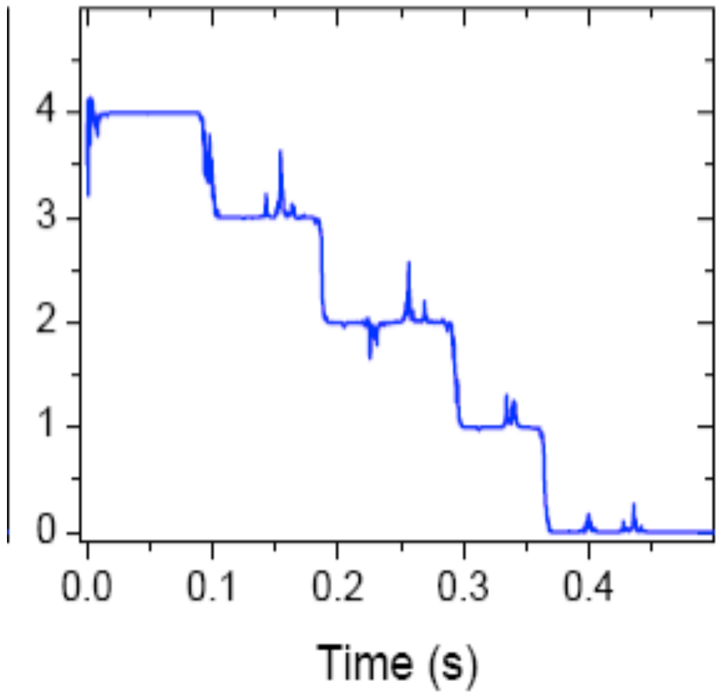
Atom-field entanglement oscillations



At classical limit, collapse and revival times rejected to t = ∞

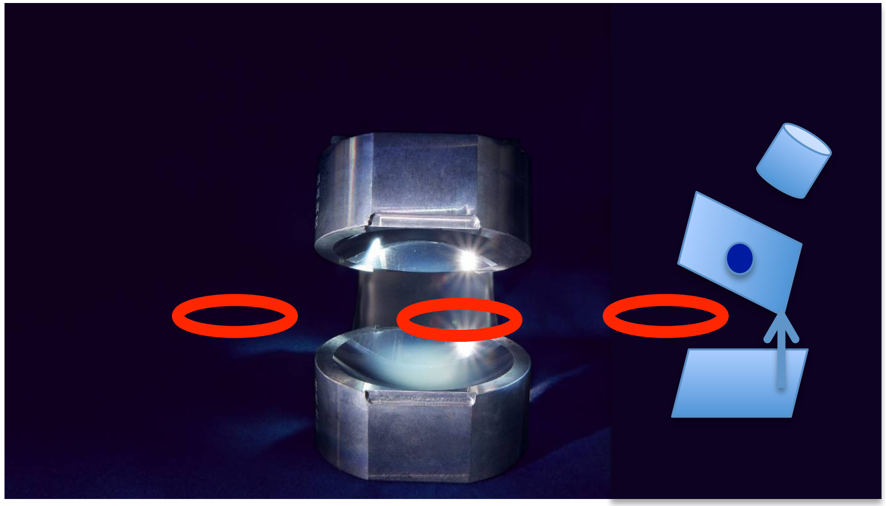
A.Auffeves et al, Phys.Rev.Lett. 91, 230405 (2003)

3.
Non destructive measurements and quantum jumps of fields



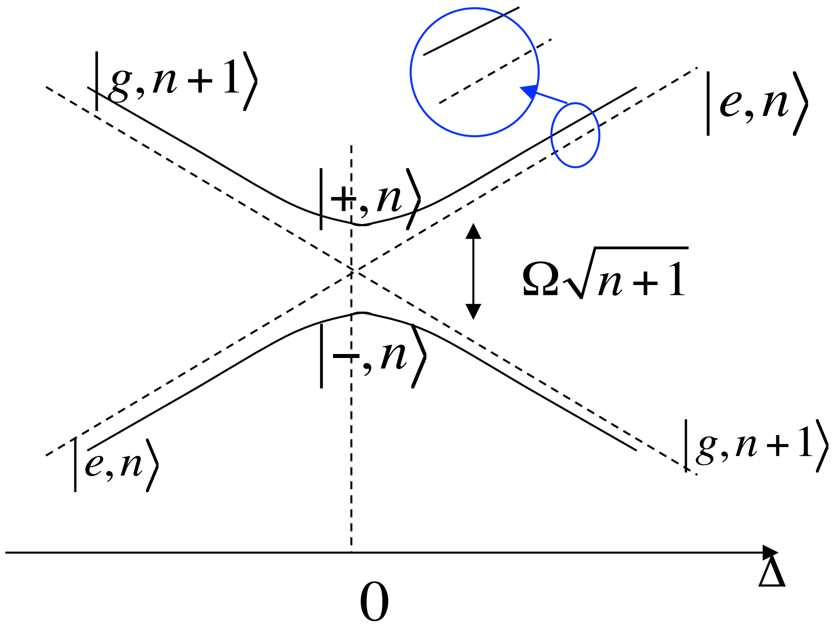
S.Gleyzes et al, Nature, 446, 297, 2007

How to realize non-destructive photon counts in cavity QED?



Use information carried by slighly off-resonant Rydberg atoms to measure the light-shifts induced by photons. The atoms are destroyed when detected, but the photons are not (non-resonant interaction). The process is the counter part of the non-destructive detection of atoms by photon counting in ion trap or cold atom physics. Quantum jumps of photons, analogous to those of ions or atoms, are observed in the sequence of atomic events when field suddenly changes due to external processes.

Non-Resonant coupling: light shifts in CQED



$$E_{\pm,n} = (n+1/2)\hbar\omega_{oh} \pm \frac{\hbar}{2}\sqrt{\Delta^2 + \Omega^2(n+1)}$$

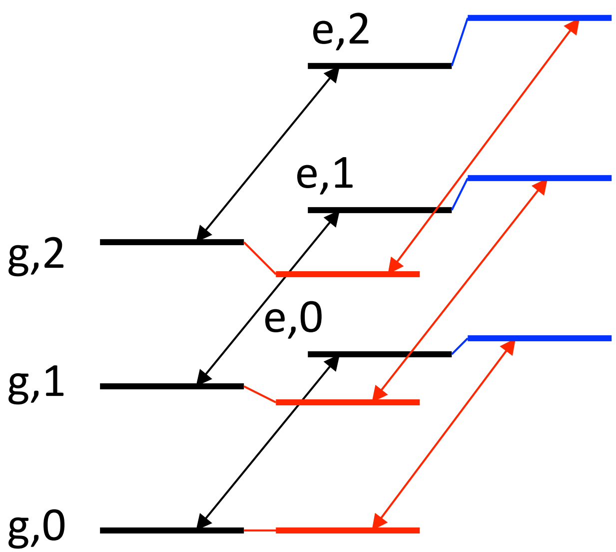
Anticrossing of dressed qubit

Second order perturbation theory
(shift proportional to n):

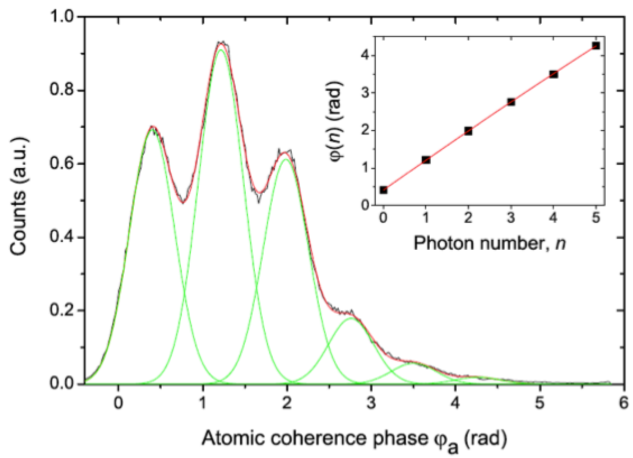
$$E_{\pm,n} \approx (n+1/2)\hbar\omega_C \pm \hbar\left(\frac{\Delta}{2} + \frac{\Omega^2(n+1)}{4\Delta}\right)$$

Phase shift per photon: $\varphi_0 = \dfrac{\Omega^2 t}{2\Delta}$

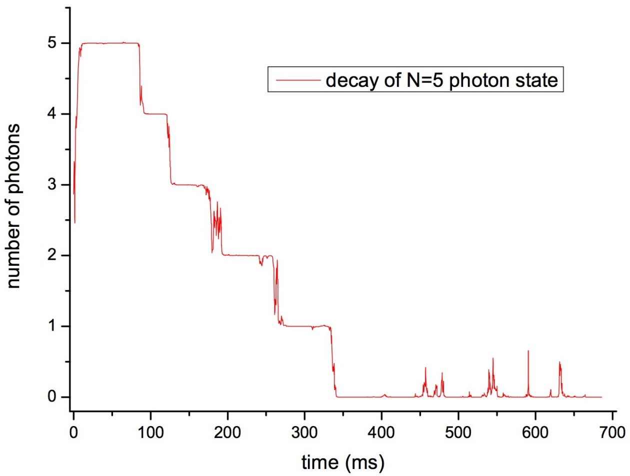
Quantized light shifts and QND photon counting



The light shift proportional to n is measured by Ramsey spectroscopy:

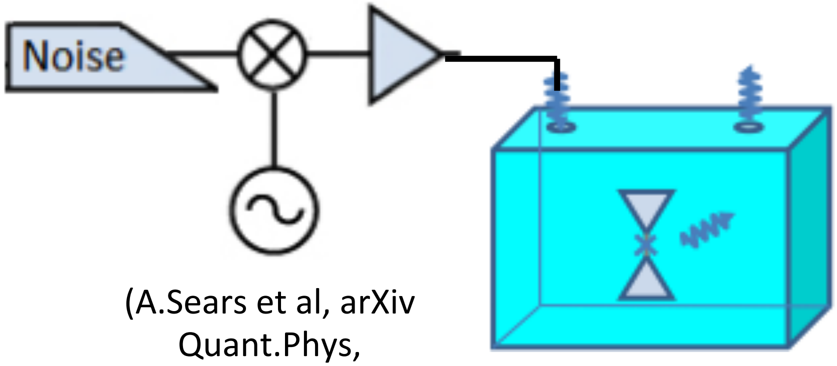


Single photon shifts Rydberg atom resonance by 3 kHz



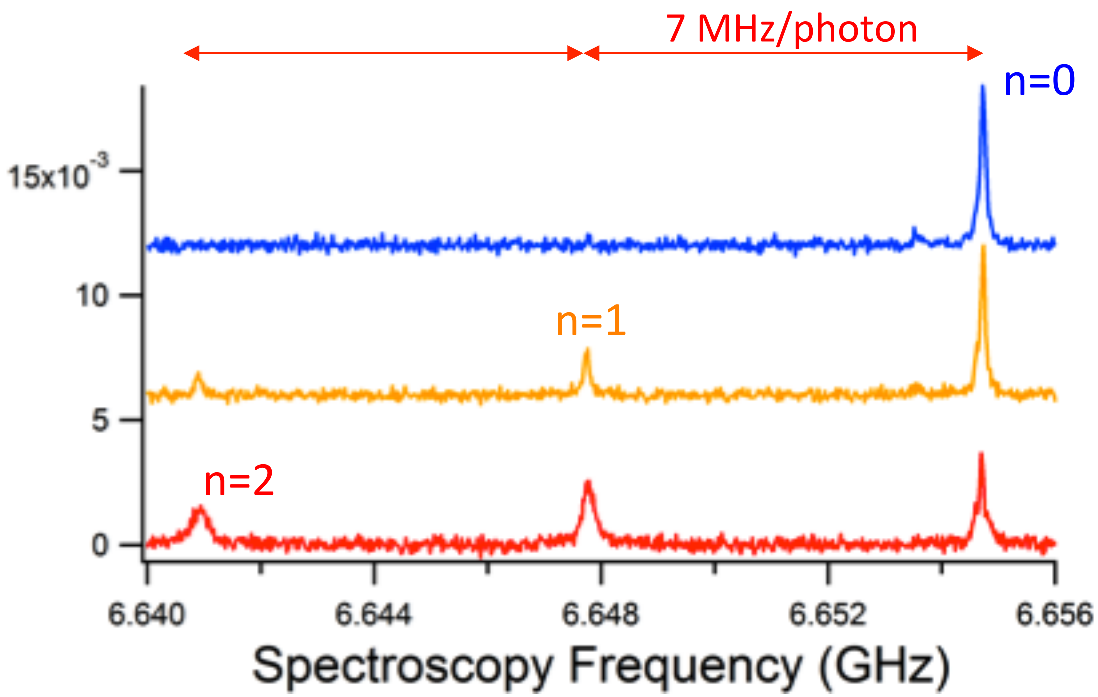
QND photon counting and observation of field quantum jumps

Light shifts of Josephson qubits (Yale)



(A.Sears et al, arXiv Quant.Phys, 1206-1265 (2012)

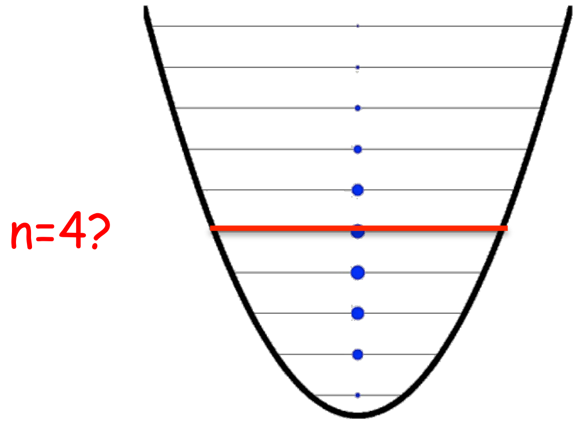
A single rf photon shifts qubit resonance by 7MHz!



Applications to quantum information (conditional gates)

Schuster et al, Nature, 445, 515 (2006); Johnson et al, Nature Physics, 6, 663 (2010)

Use light shifts to project photon number in cavity



Does cavity contain n_0 photons or not?

Amounts to measuring the projector on $|n_0>$

Observable with eigenvalue 1 if n_0 photons, 0 otherwise

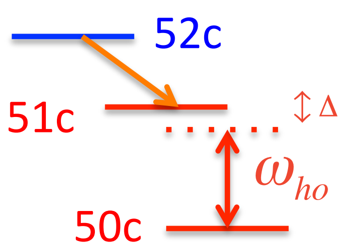
How to do it with a single atom?

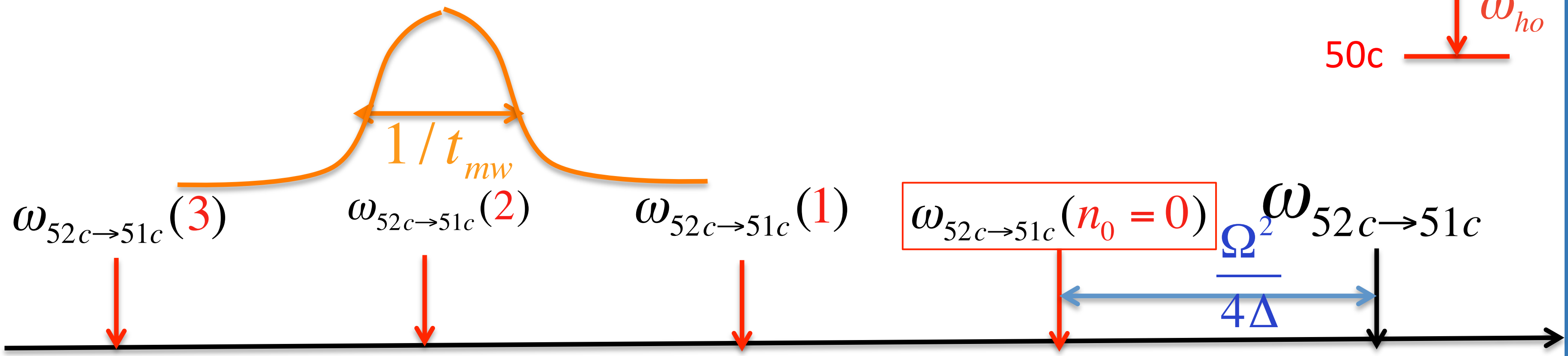
Perform high resolution spectroscopy of atom-cavity system resolving in one shot single photon light shifts

Atom-cavity spectrum on the 51c -52c transition (Cavity detuned by Δ from 51c-50c transition)

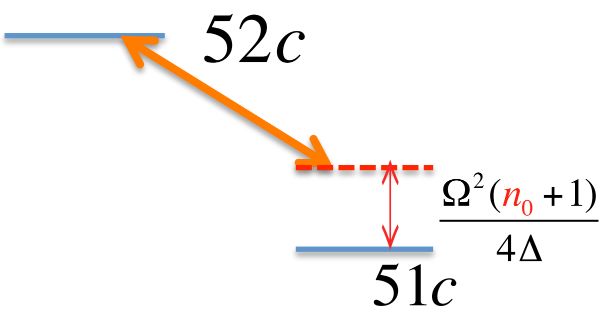
Cavity photons shift level 51c but not 52c

$$\omega_{52c\to 51c}(n_0) = \omega_{52c\to 51c} - \frac{\Omega^2(n_0+1)}{4\Delta}$$





If microwave is properly tuned, atom prepared in 52c is transferred by microwave to 51c only if n_0 photon in cavity.



Requires high resolution, hence long interrogation time t_{mw} (cold atoms)

$$\frac{\Omega^2 t_{mw}}{4\Delta} > 1$$

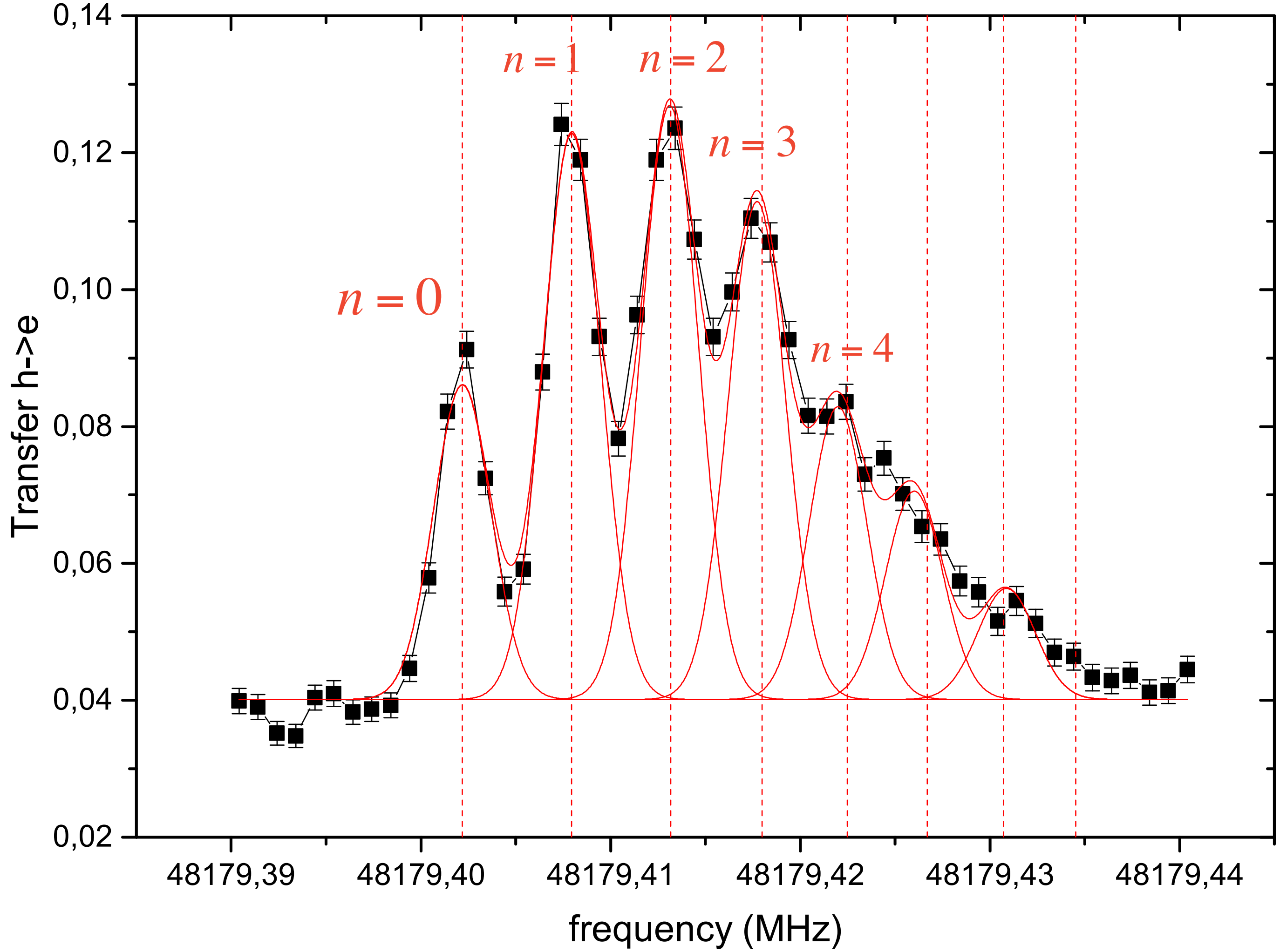
Probing system with this precision requires long time and slow atoms….

A modified version of the Cavity QED set-up with a vertical atomic beam

An atomic fountain fed by atoms cooled in a MOT. Atoms spend several milliseconds in cavity at top of parabolic trajectory

Circular Rydberg states are prepared in cavity by circularly polarized radiofrequency photons (see below)

Transfer 52c to 51c versus microwave frequency exhibits resolved photon numbers from 0 to 6 (coherent field in cavity)

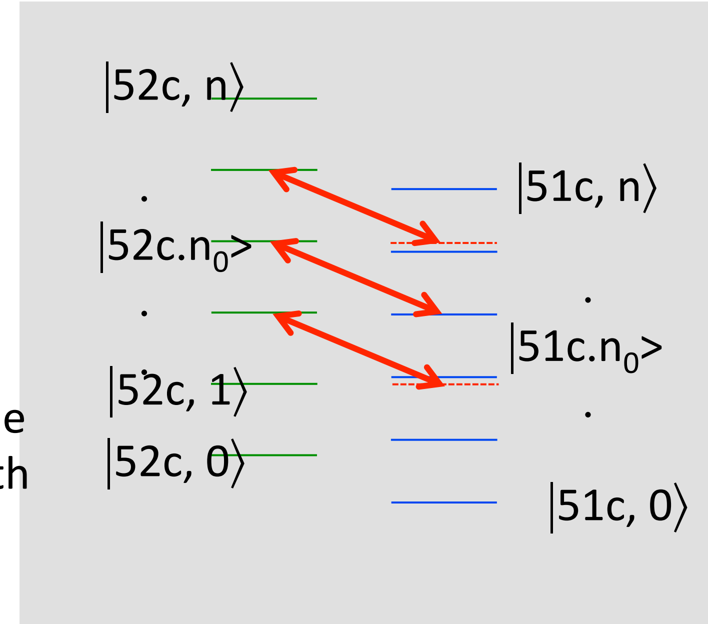


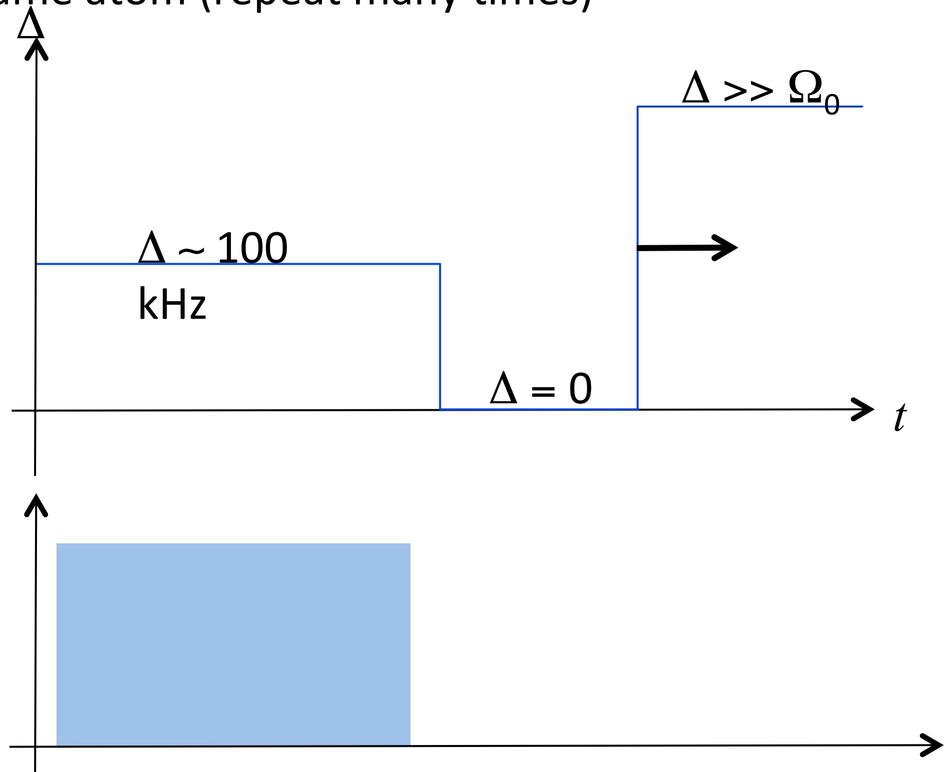
Photon number filter

Atom, initially in 52c with cavity containing coherent field and detuned by Δ from 51c-50c frequency is irradiated during 0.3 ms by mw at $\omega_{52c\text{-}51c}$ (n_0) frequency.

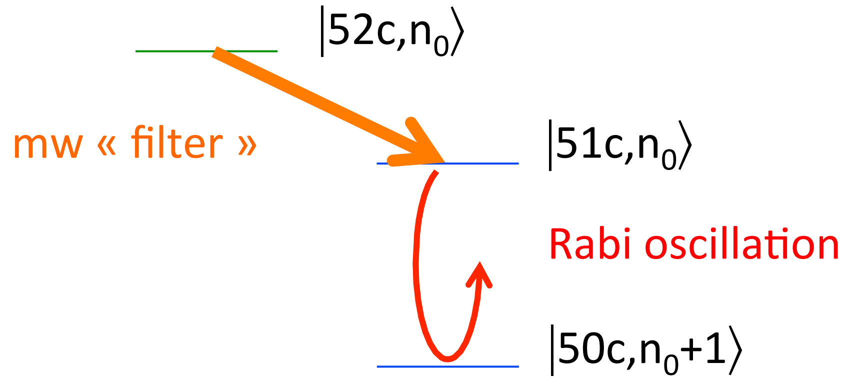
If atom detected in 51c, n_0 photon are selected in cavity

To prove it, set cavity to resonance (Δ=0) during variable time t before detecting atom in 51c and record Rabi oscillation with same atom (repeat many times)



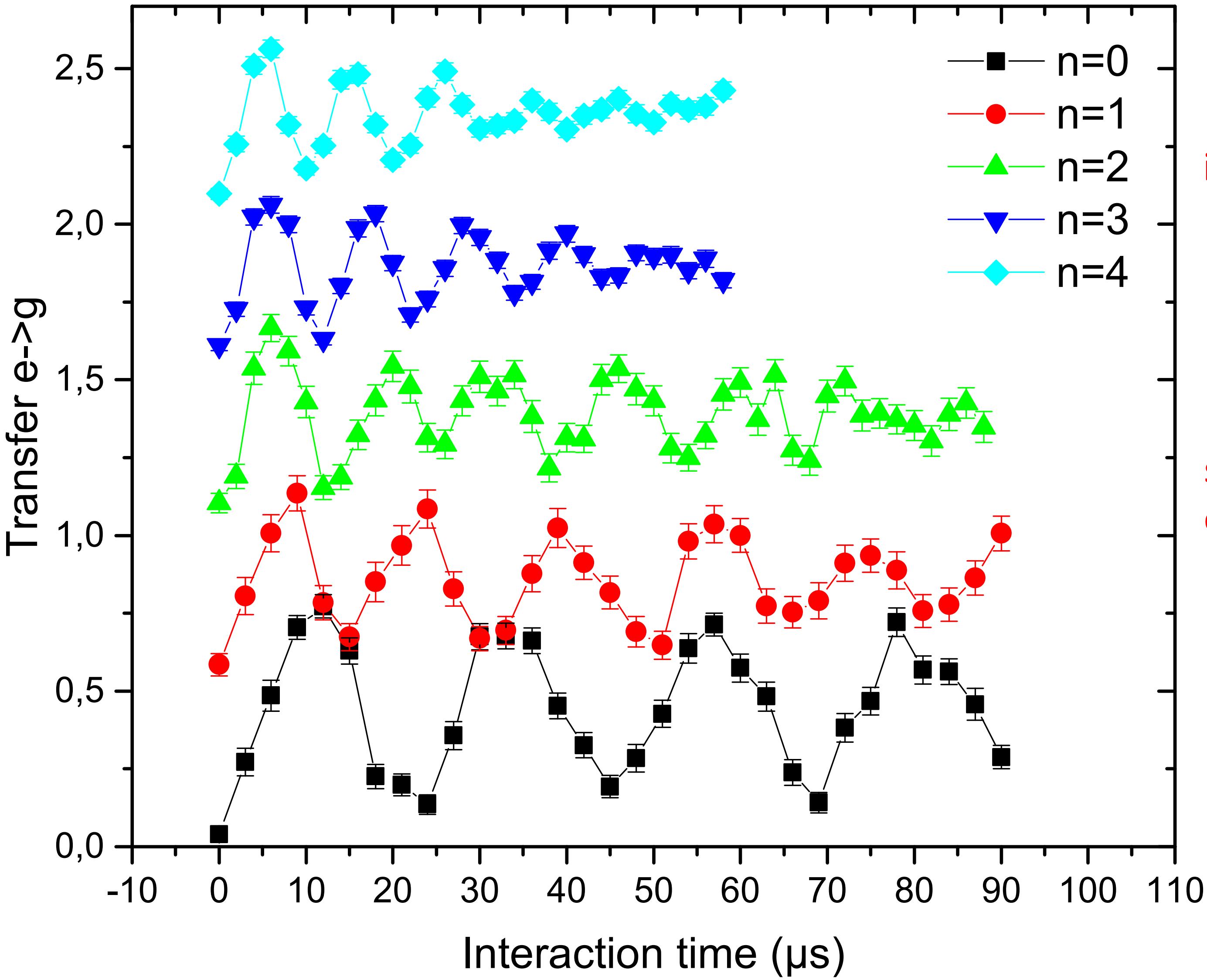


MW spectroscopy pulse (duration 320 μs)



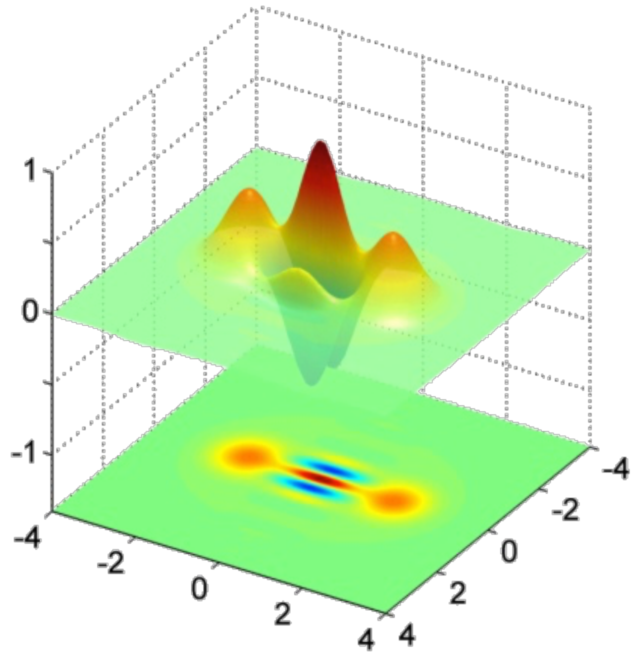
Rabi oscillations after selection of n_0 photons by same atom (n_0=1 to 4)

Preliminary results (PhD of Frederic Assemat)



Generalizing this idea, a recent experiment in Circuit QED using a multi-frequency microwave generates arbitrary superposition of Fock states (W.Wang et al, Phys.Rev.Lett 223604 (2017))

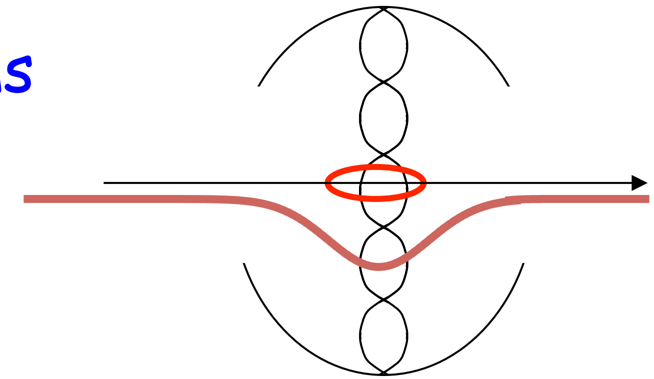
4.
Photonic Schrödinger cats in Cavity QED and Circuit QED



Single atom index effect: relation with light shifts and optical dipole force

Atom in N-photon light-potential gains kinetic energy

$$\Delta E_N = N \Delta E_1$$



Energy is borrowed from field whose frequency becomes ω−δ, N photons losing energy

$$N\hbar\delta$$

Energy conservation: $\delta = \frac{\Delta E_1}{\hbar}$

During atom-cavity crossing time, field undergoes phase shift:

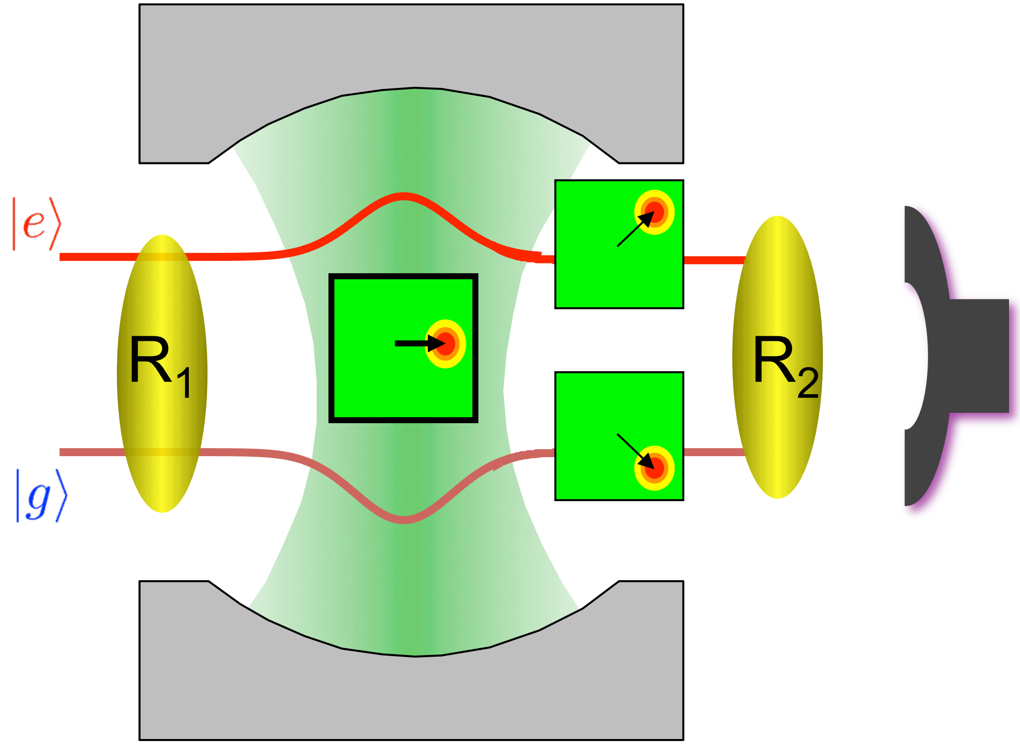
$$\Delta\phi \sim \pm \pi/2$$

$$\Delta\phi = \pm\int \frac{\Delta E_1(z)}{\hbar}\frac{dz}{v} = \pm\frac{\varphi_0}{2}$$

Sign depends on atom's state (upper or lower state of transition)

A single atom shifts field frequency by same amount that a single photon shifts atomic transition frequency

How single atom prepares Schrödinger cat state of light: single atom index effect

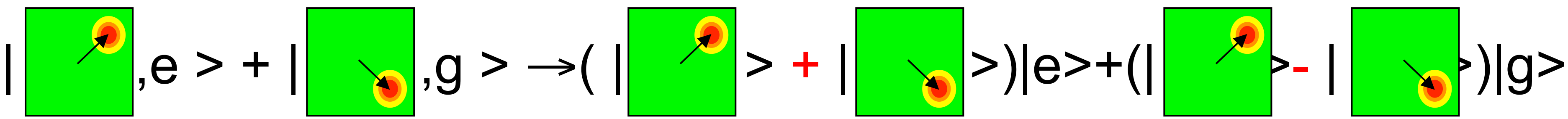


1.Coherent field is prepared in C

2. Single atom is prepared in R_1 in a superposition of e and g

3. Atom shifts the field phase in two opposite directions as it crosses C: superposition leads to entanglement in typical Schrödinger cat situation

4. Atomic states mixed again in R_2 maintains cat's ambiguity:



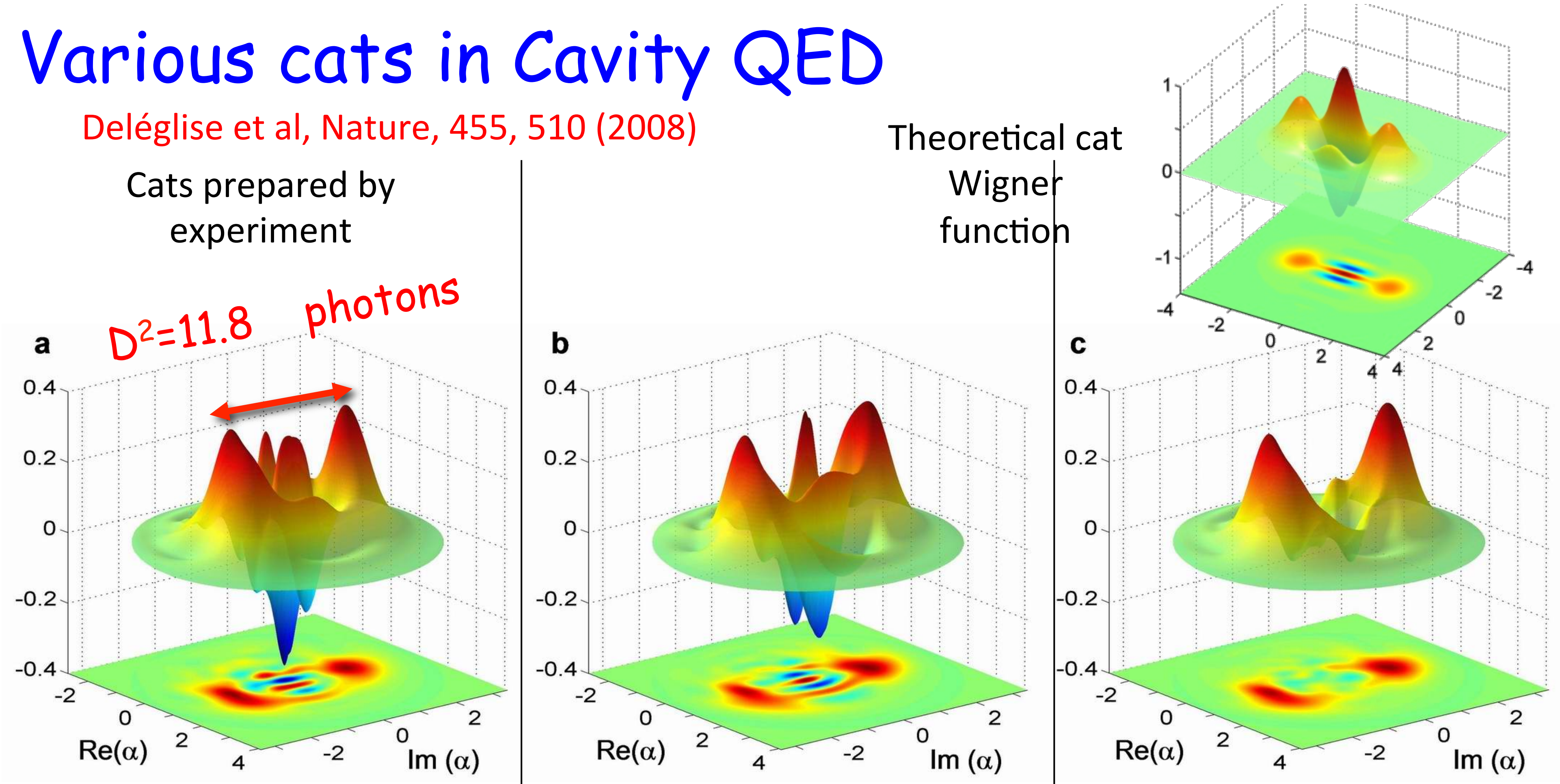
Detecting atom in e or g projects field into + or - cat state superposition!

Various cats in Cavity QED

Deléglise et al, Nature, 455, 510 (2008)

Cats prepared by experiment

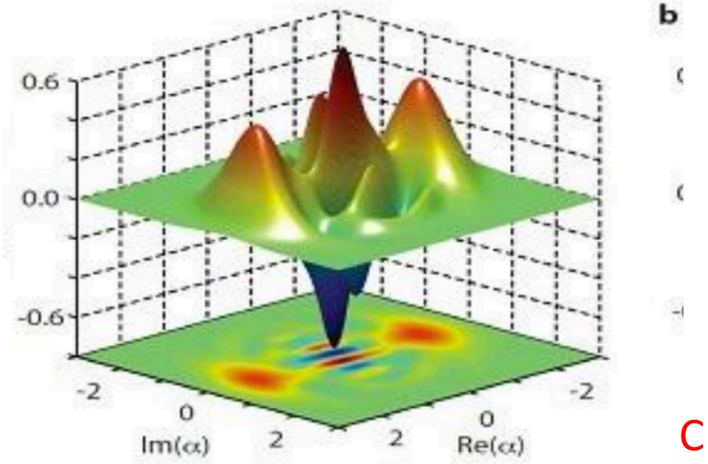
Theoretical cat Wigner function



Even cat	Odd cat	Statistical Mixture
$\vert\beta e^{i\chi}\rangle + \vert\beta e^{-i\chi}\rangle$	$\vert\beta e^{i\chi}\rangle - \vert\beta e^{-i\chi}\rangle$	$\vert\beta e^{i\chi}\rangle\langle\beta e^{i\chi}\vert + \vert\beta e^{-i\chi}\rangle\langle\beta e^{-i\chi}\vert$
(preparation atom detected in e)	(preparation atom detected in g)	(preparation atom detected without discriminating e and g)

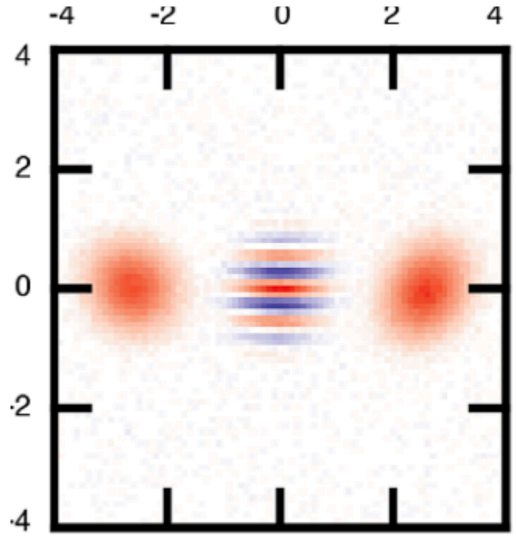
State reconstruction by performing QND measurements on many copies of state translated in phase plane

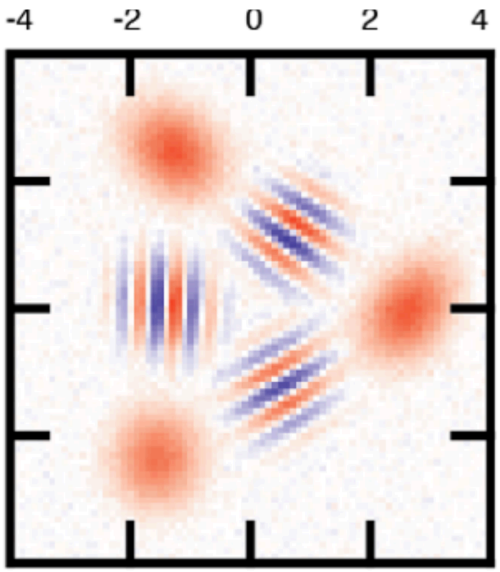
Schrödinger cats in Circuit QED (Schoelkopf lab in Yale)



Superposition of two coherent states of opposite phase…

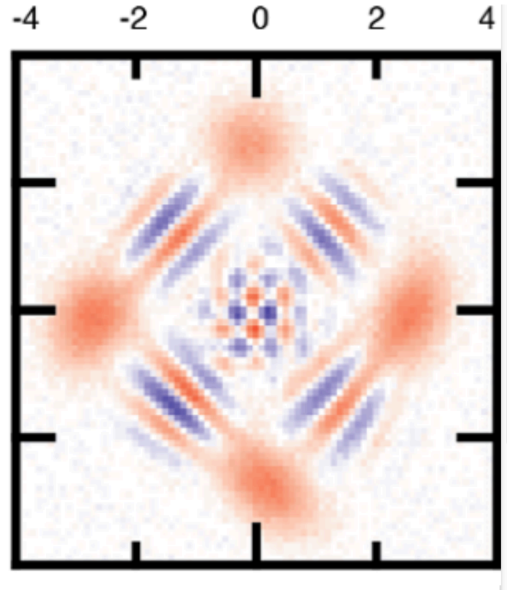
B.Vlastakis et al, Science, 342, 607 (2013)
C.Wang et al, Science, 352, 6289 (2016)





…and superpositions of three and four coherent states

Similar cats in J.Martinis Group (UCSB)



5.
An example of hamiltonian engineering: quantum Zeno dynamics of a Rydberg atom

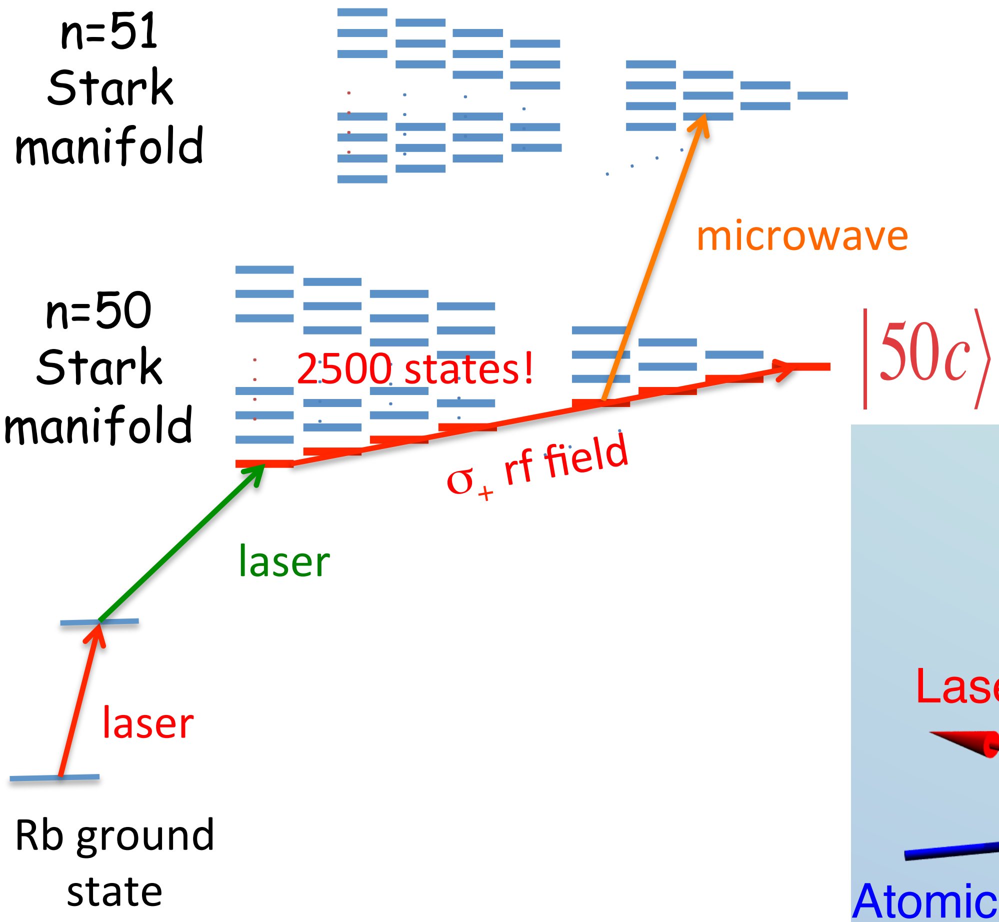
Freeze coherent evolution starting from non-degenerate state of measured observable..

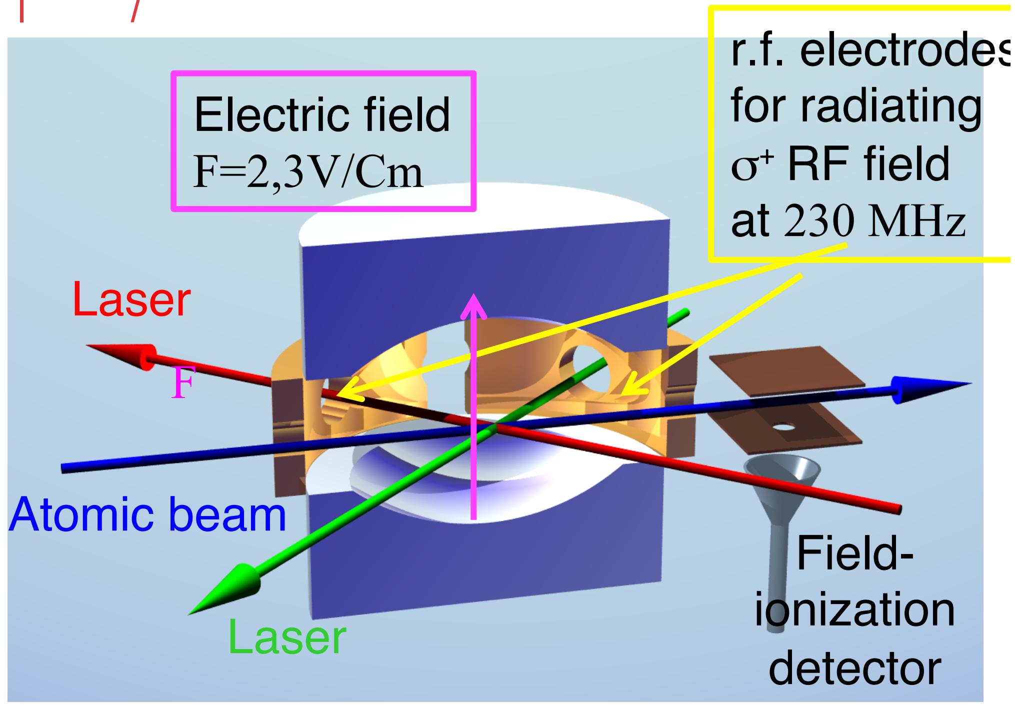
..or restrict evolution in subspace of degerenate eigenstates of a system

J-M. Raimond et al, PRA 86, 032120 (2012)

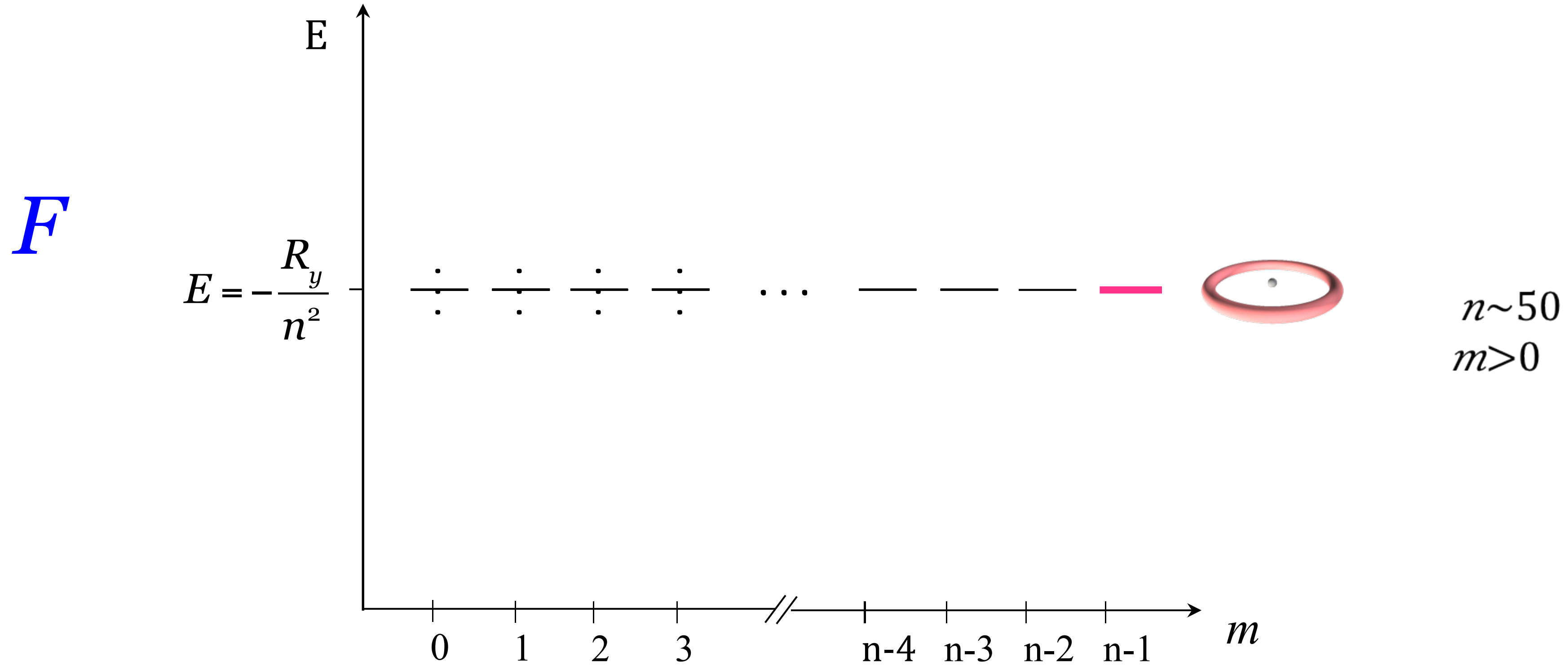
The Rydberg atom experimental set-up (how to prepare a circular state and study its evolution from there)

Each ladder state individually addressed by state selective microwave transition towards upper manifold, followed by field ionization: the probability to be in each state can be followed as a function of time for dynamical studies

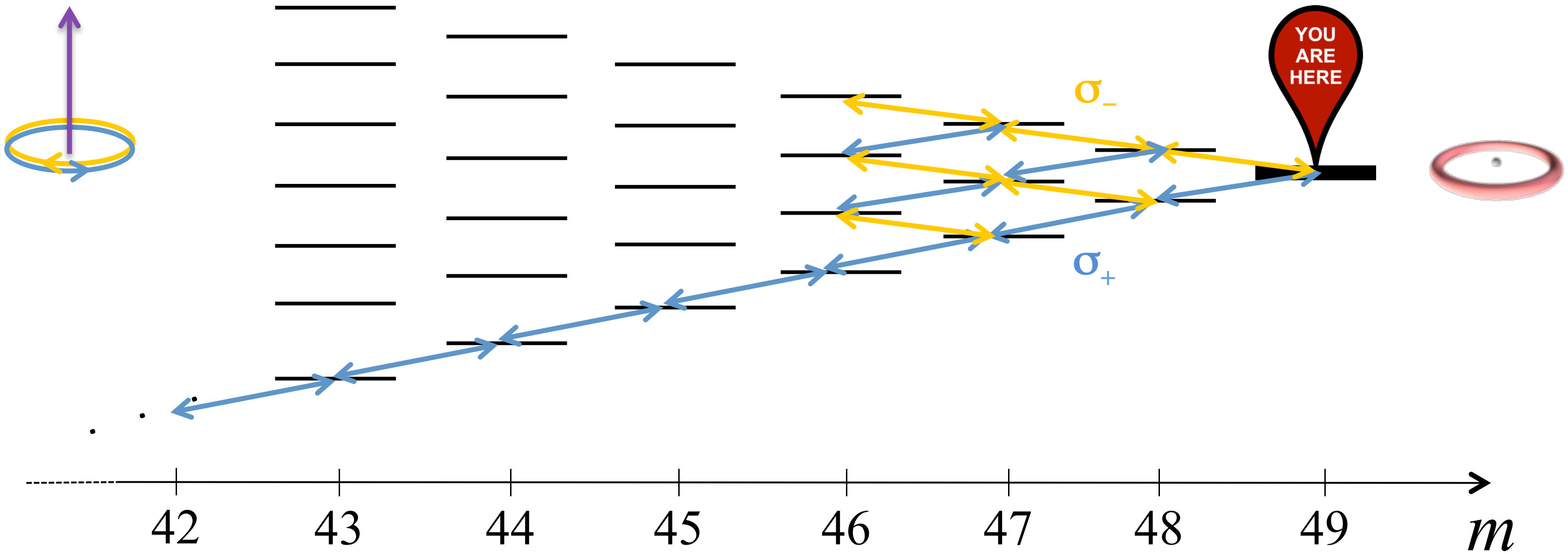




Rydberg manifold in an electric field F

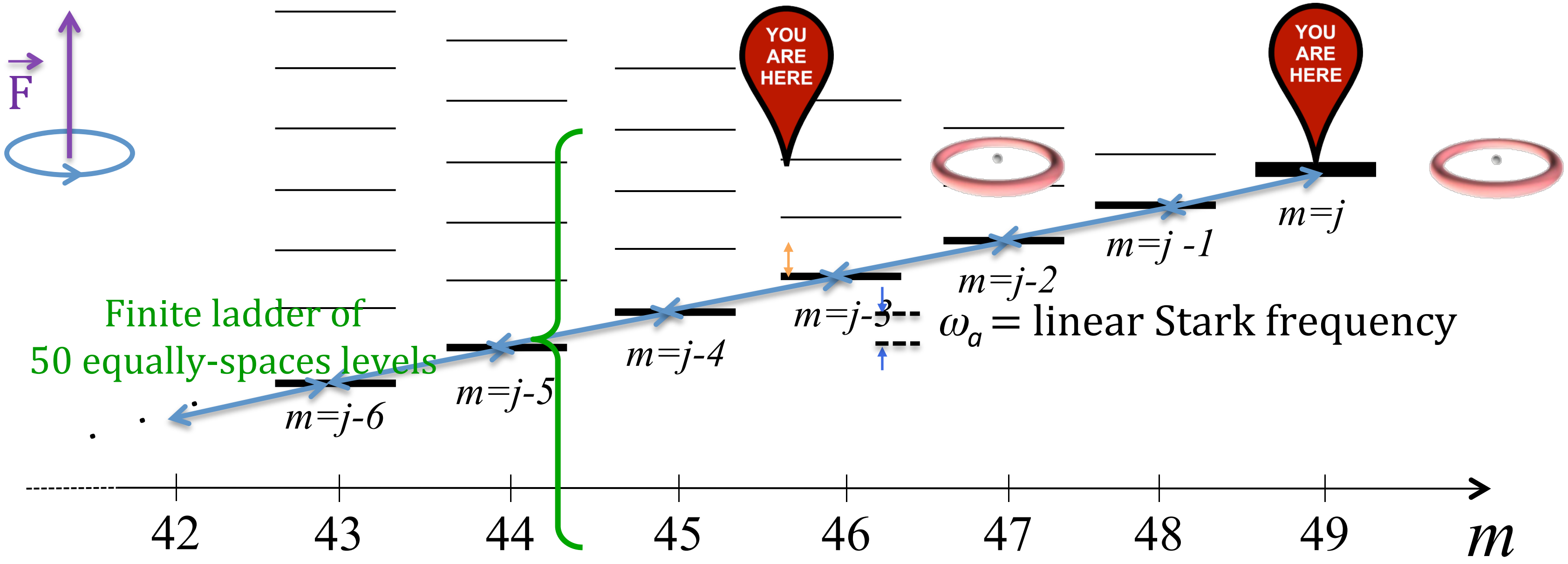


The n = 50 Rydberg manifold in an electric field (Stark levels):

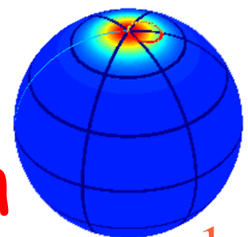


σ_+ radiofrequency transitions

A circular Rydberg atom interacting with a σ_+ resonant rf evolves along a ladder of states, like a large angular momentum

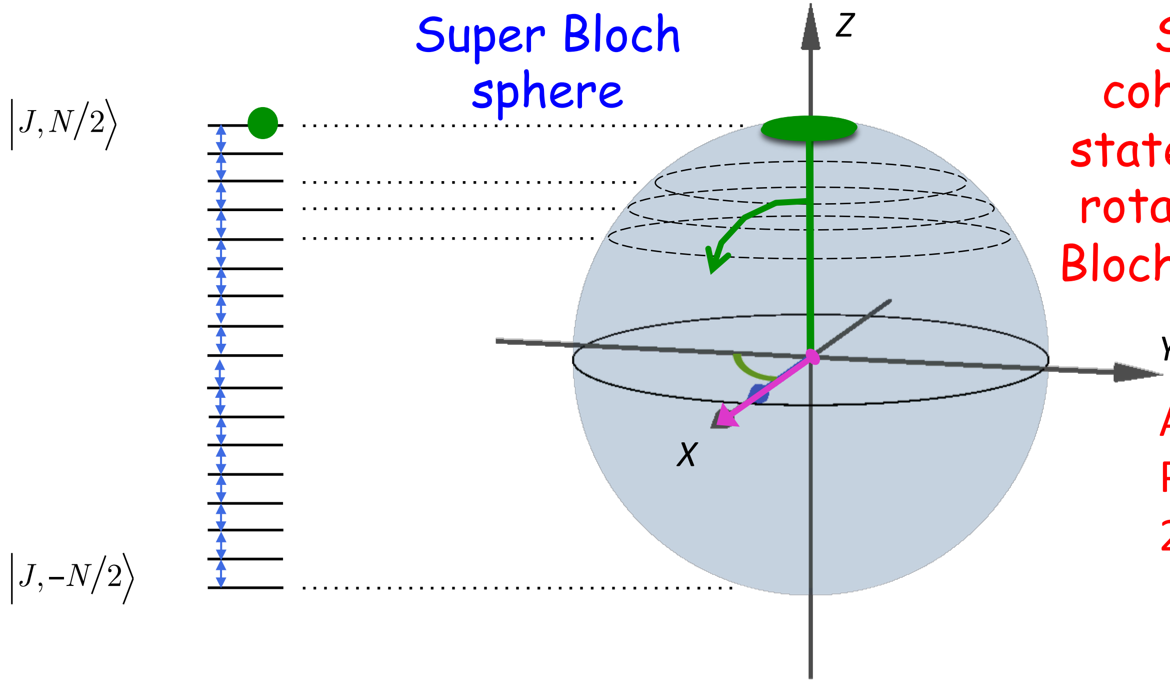


The evolution can be pictured on a generalized Bloch sphere, as for an ensemble of N spins 1/2



$$J = \frac{n-1}{2}$$

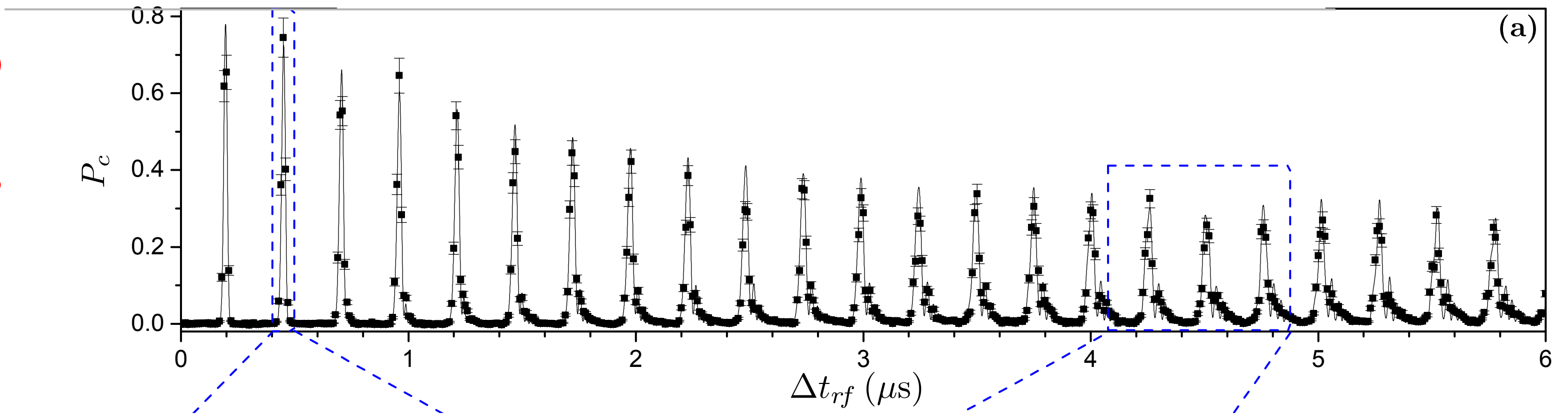
Coherent rotation of a large spin coupled to a resonant σ_+ rf field



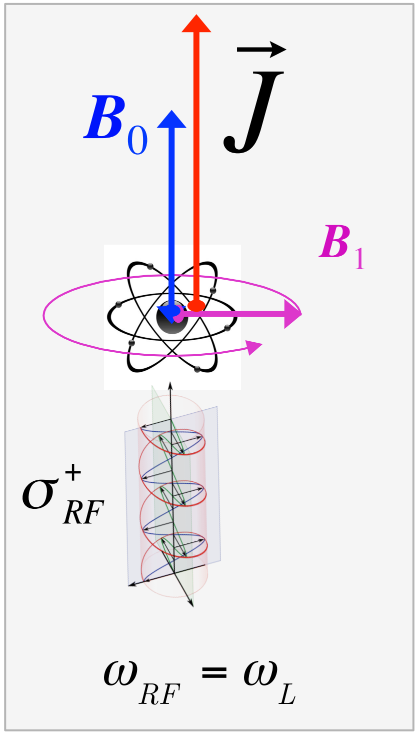
Spin coherent state (SCS) rotating on Bloch sphere

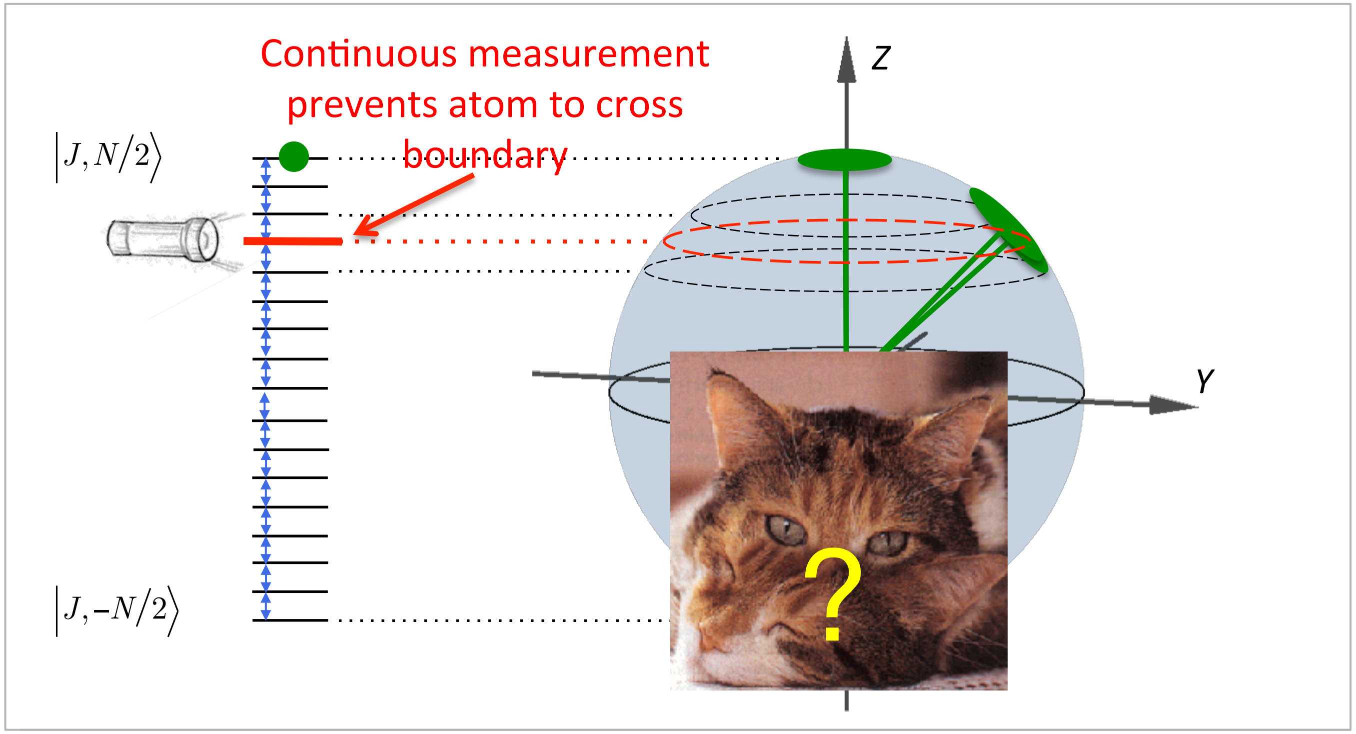
A.Signoles et al, Phys.Rev.Lett., 118, 253603 (2017)

Probability to find spin at North Pole as a function of time



Quantum Zeno Dynamics of a SCS





+ repeated measurement asking question:
is system in |J,m>?:
Observable is projector on this state, admitting all the other states as eigenvectors with degenerate eigenvalue 0.

$$\hat{H} = \hat{H}_0 + \hat{V}_{RF}$$

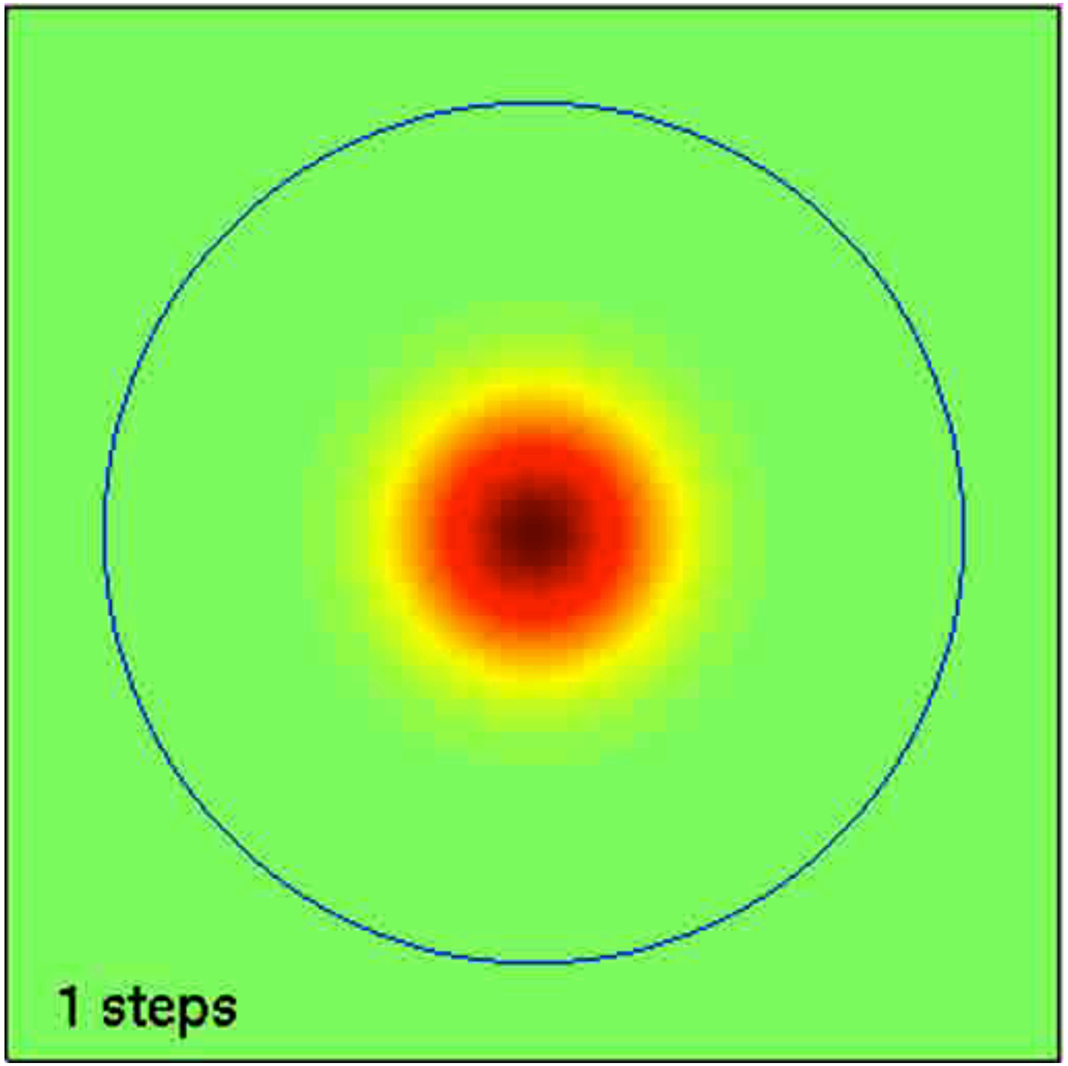
- Zeeman hamiltonian in $\boldsymbol{B}_0$ $E(m_j) = \hbar\omega_L . m_j$

- Coupling with a resonant rotating field $\boldsymbol{B}_1$ $\omega_{RF} = \omega_L$

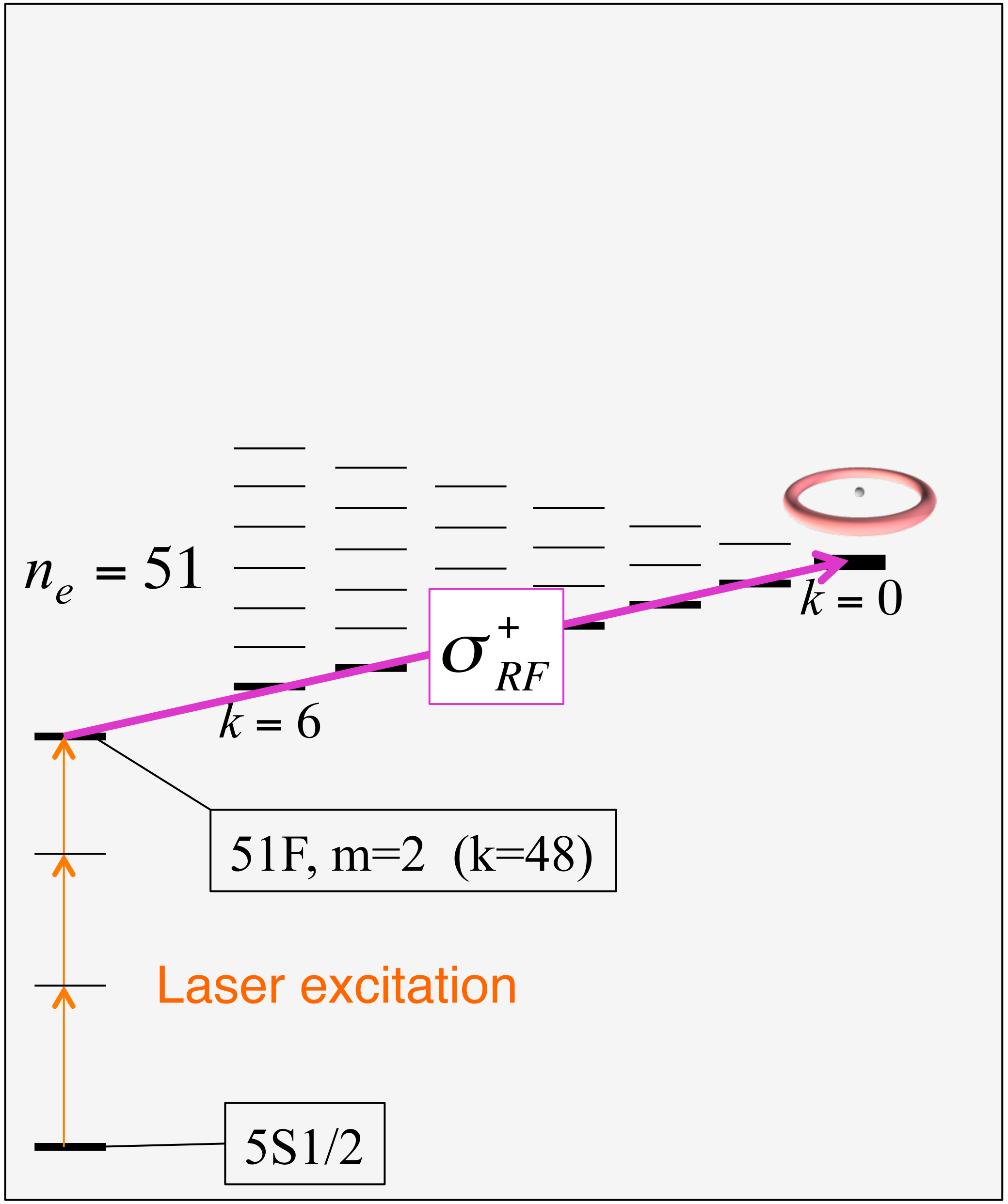
➙ ***J*** bounces on a border set by the measurement

Simulation of the QZD corresponding to a spin initially at the north pole and submitted to the resonant rf field while the level |J,m=J-5> is continuously watched (A view from the North Pole of the Bloch Sphere)

Periodic motion with transient generation of Schrödinger cat like states!

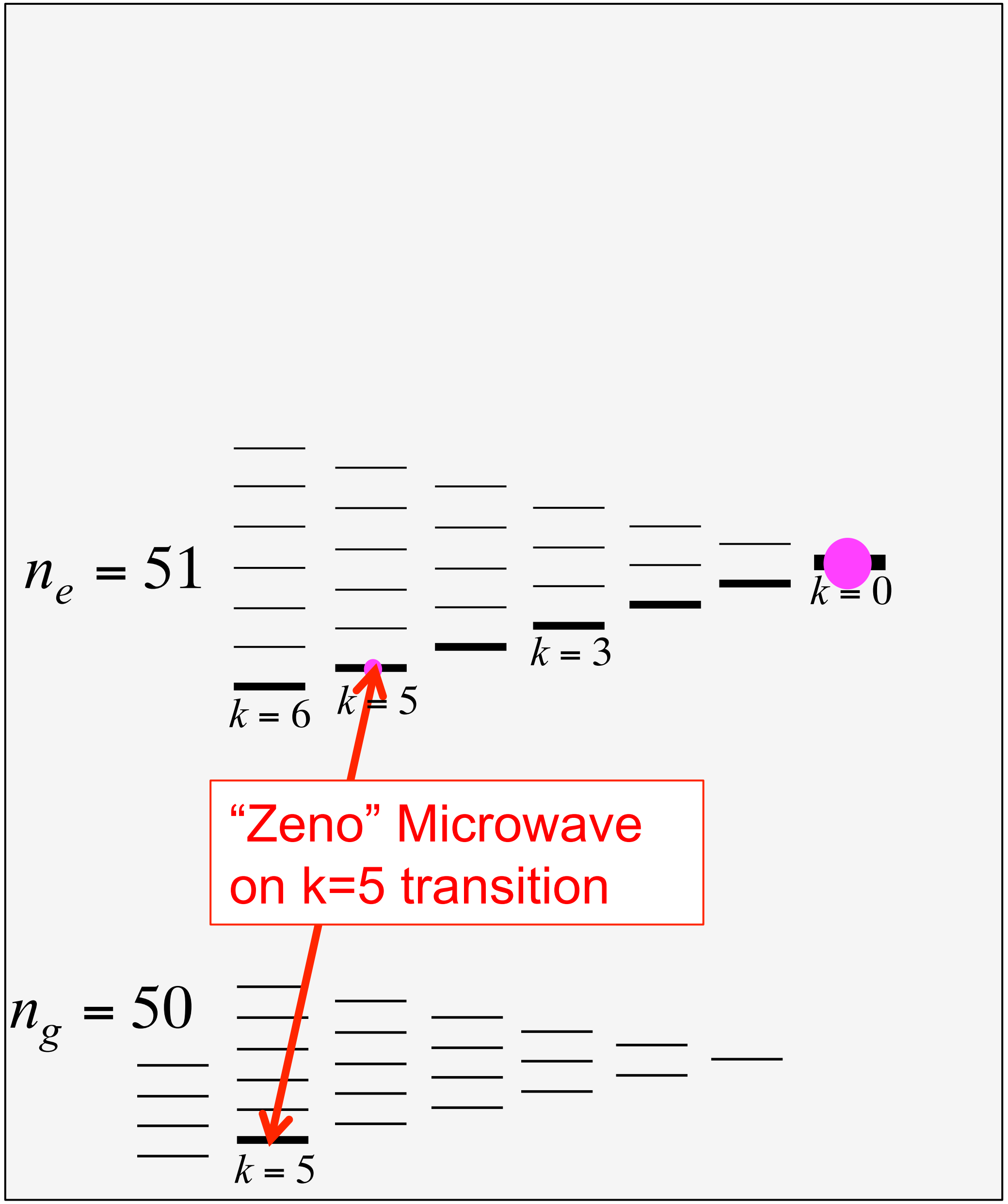


Characterization of QZD: state preparation

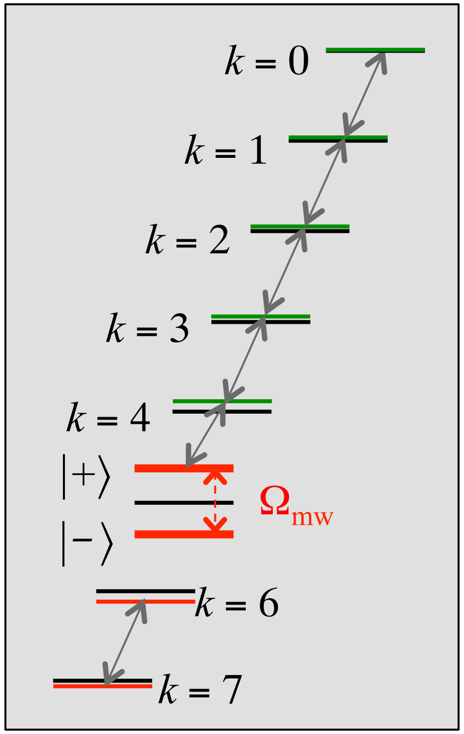


1. Preparation of |n=51,k=0〉 (circular state)

Measuring population $P(k, t)$

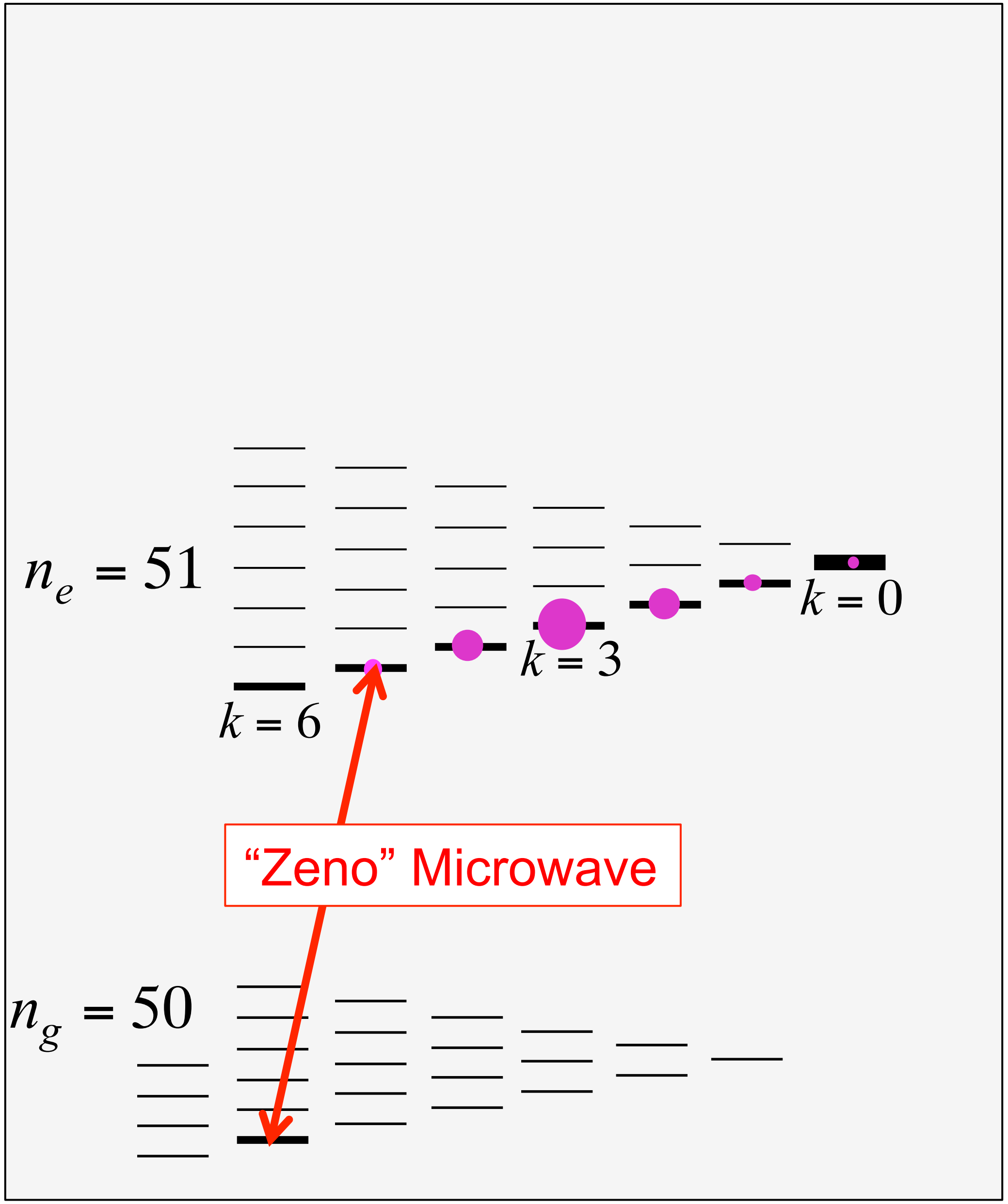


1. Preparation of |51,k=0⟩ (circular state)
2. Evolution for duration t.



The Zeno microwave opens a gap creating a border in the Hilbert space

Measuring population $P(k, t)$



1. Preparation of |51,k=0⟩ (circular state)
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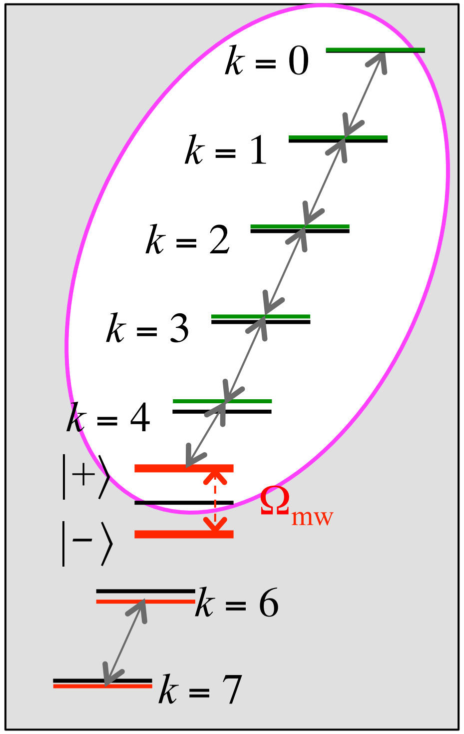
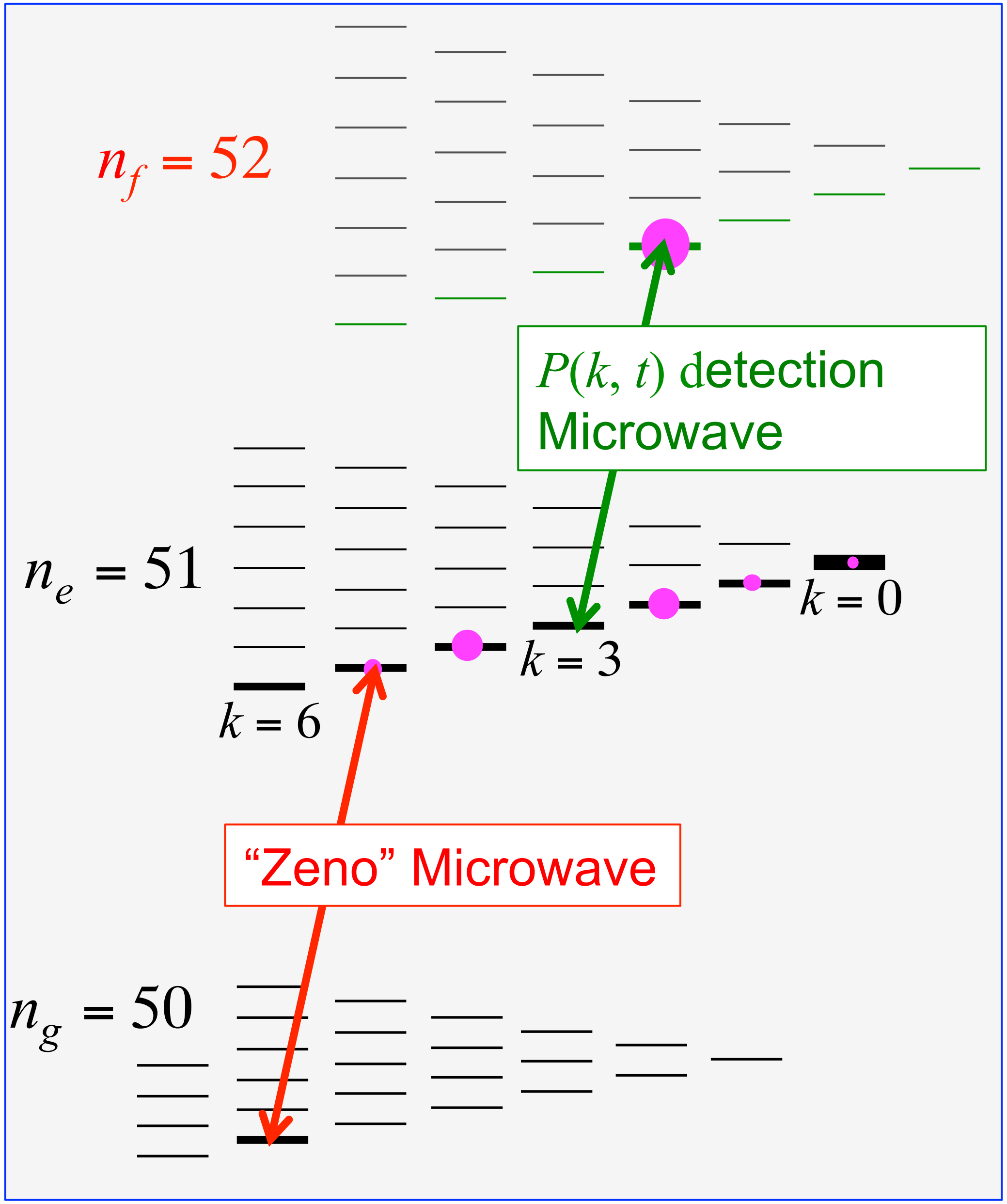


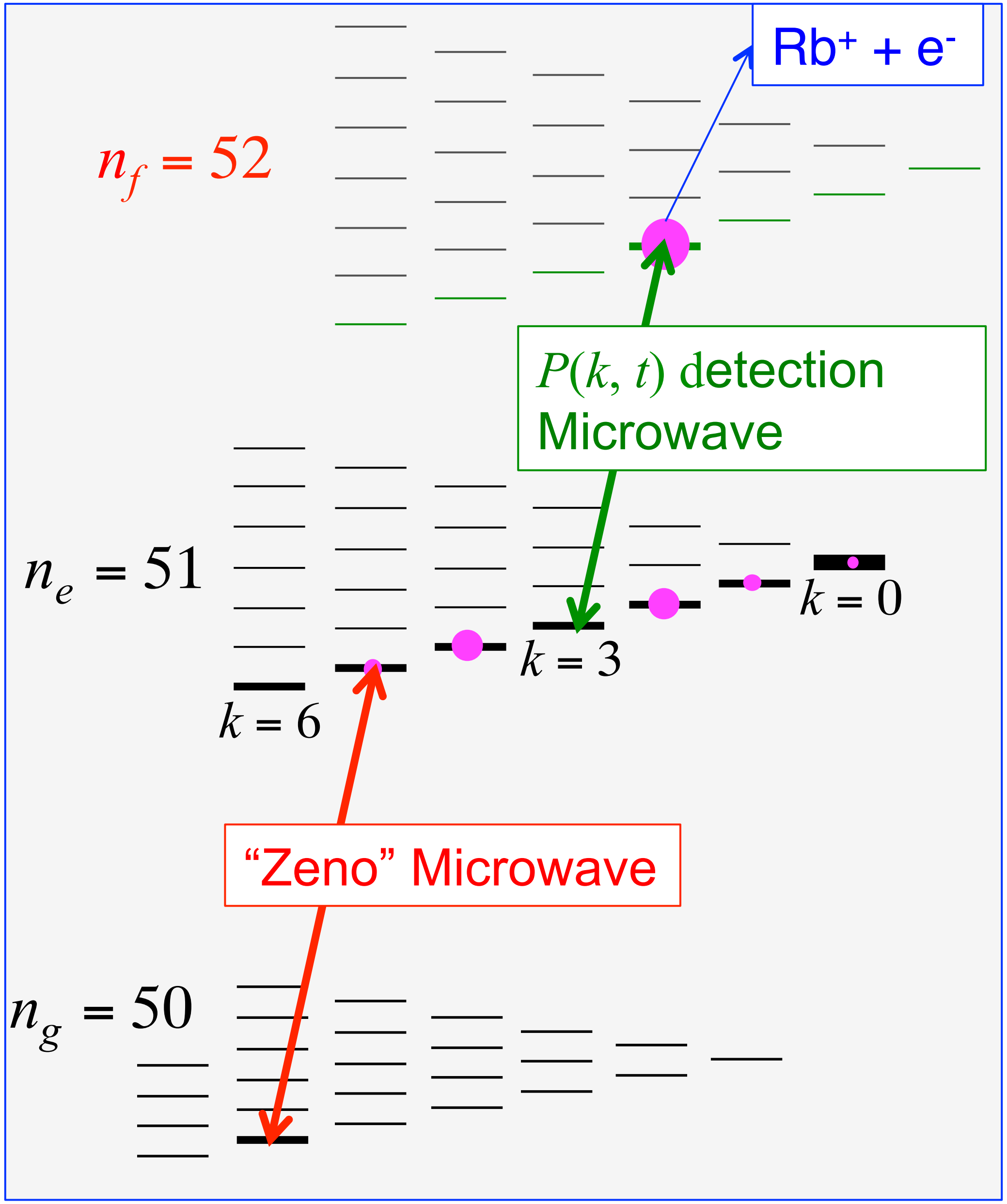
The Zeno microwave opens a gap creating a border in the hilbert space

Measuring population $P(k, t)$



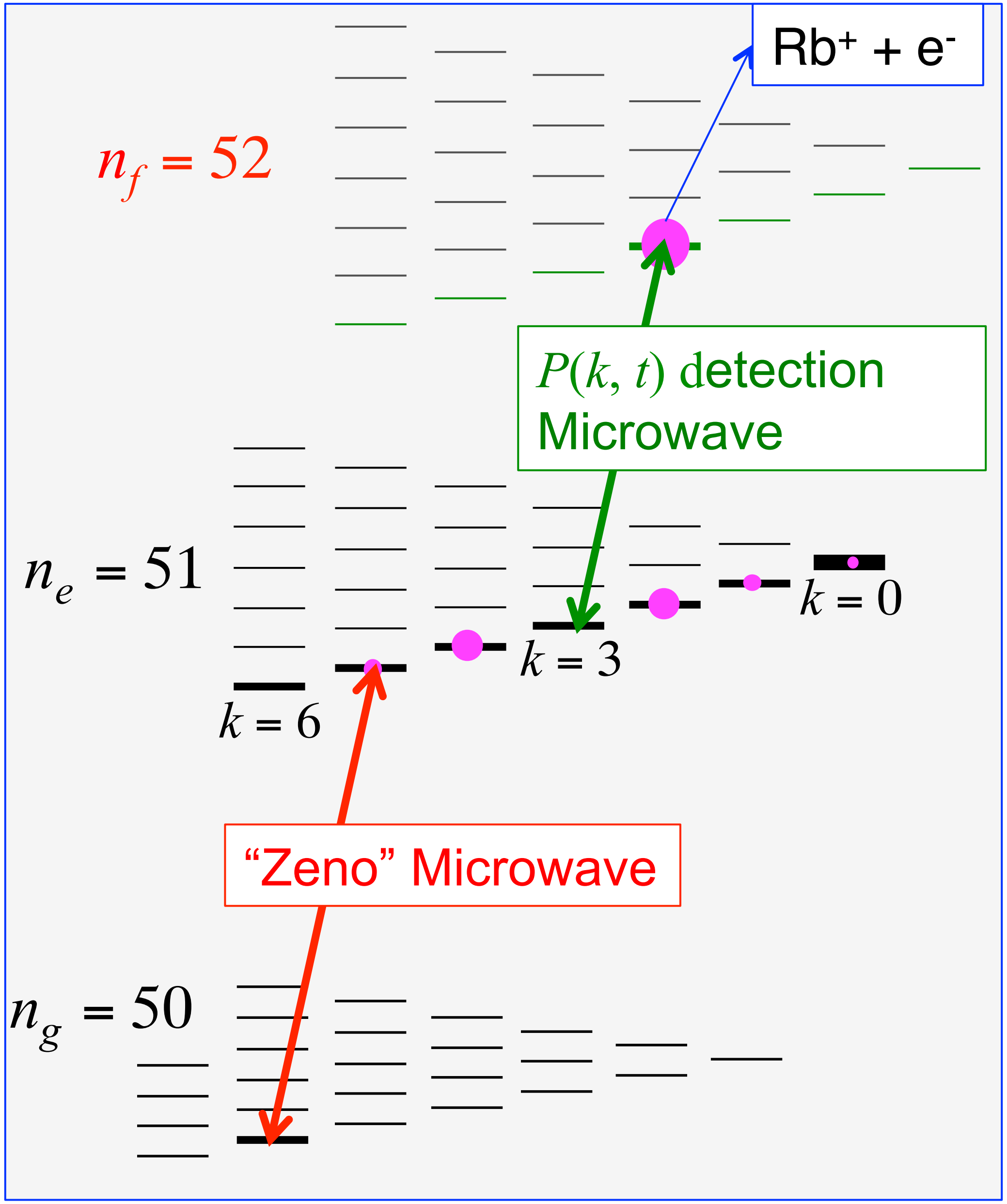
1. Preparation of |51,k=0〉 (circular state)
2. Evolution for duration t.
3. Selective detection of population in state |51,k〉 by microwave transfer to |52,k〉.

Measuring population $P(k, t)$



1. Preparation of |51,k=0⟩ (circular state)
2. Evolution for duration t.
3. Selective detection of population in state |51,k⟩ by microwave transfer to |52,k⟩.
4. ionization of n=52.

Measuring population *P*(*k*, *t*)



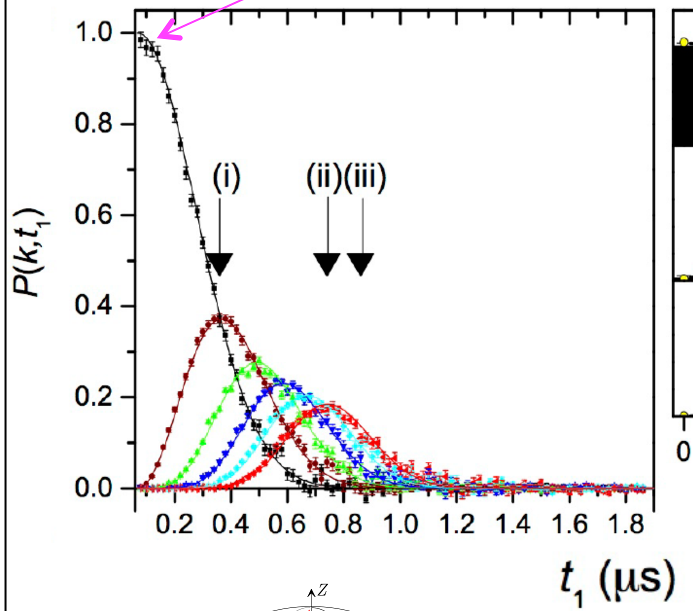
1. Preparation of |51,k=0〉 (circular state)
2. Evolution for duration t.
3. Selective detection of population in state |51,k〉 by microwave transfer to |52,k〉
4. ionization of n=52.

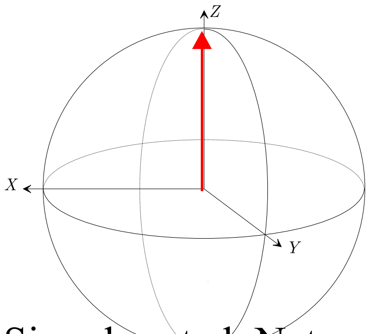
5. Resume for different k.

Probing the free "spin" rotation

- Evolution of $P(k, t)$:

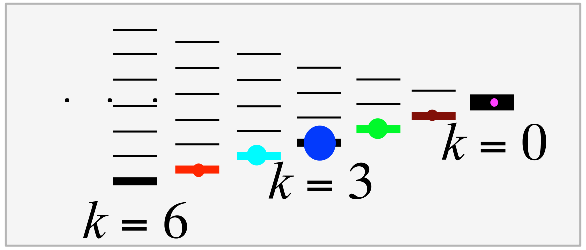
Initial state: k=0; m_J=+J





Free rotation

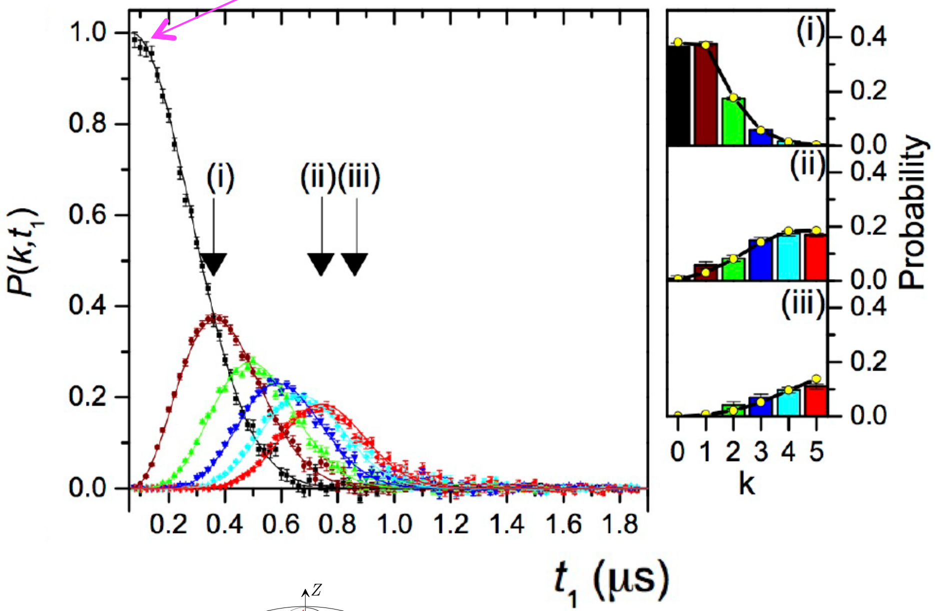
Signoles et al. Nature Physics 10 , 715 (2014)

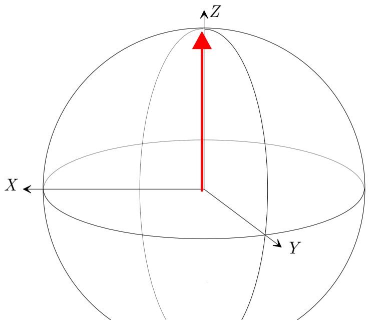


…and the QZD dynamics

- Evolution of $P(k, t)$:

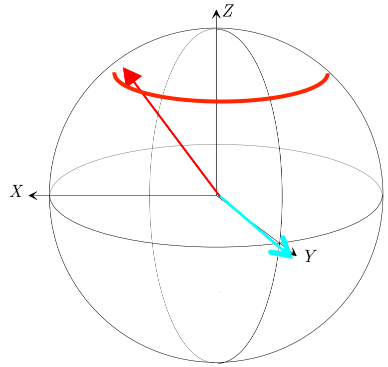
Initial state: k=0; $m_J=+J$



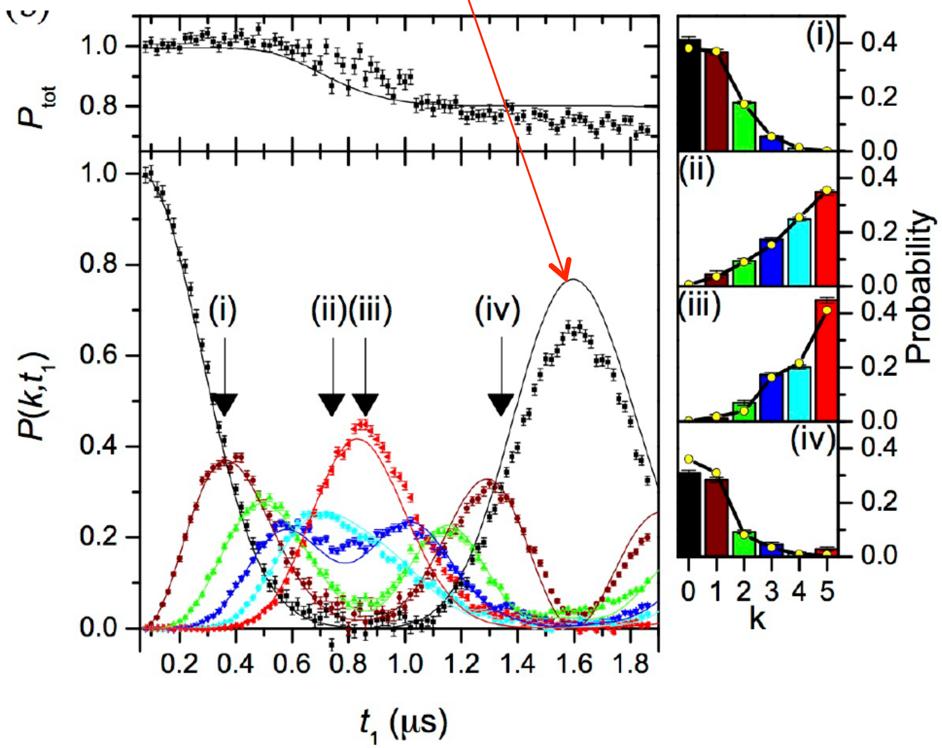


Free rotation

Confined QZD in H_{North}



Back to the initial state



Signoles et al. Nature Physics 10 , 715 (2014)

Full reconstruction of spin state at inversion time

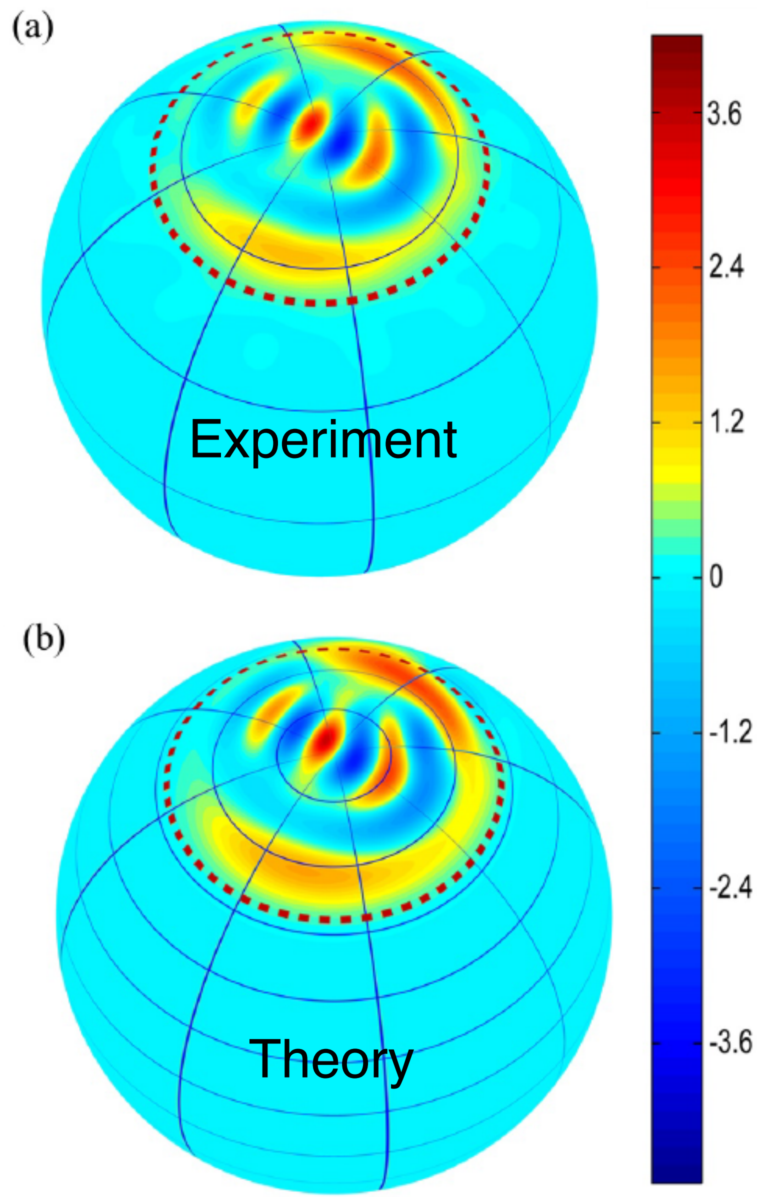
Measuring P(k,t) after many rotations of the state ➝reconstruction of the full spin density operator

- State reconstructed by Maxlike method based on P(k, t) measurement after many different spin rotations

- Measured state very similar to numerical simulation

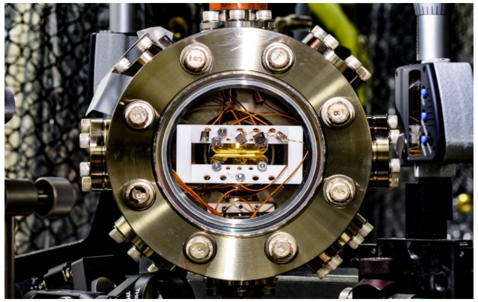
- A genuine quantum superposition of two spin coherent states with opposite azimuthal phases

An example of
« Hamiltonian engineering »



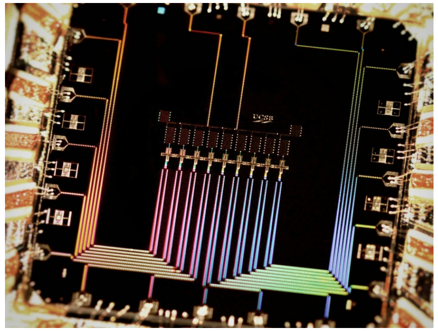
A.Signoles et al, Nature Physics, 10, 715 (2014)

Conclusion: Related talks in this workshop



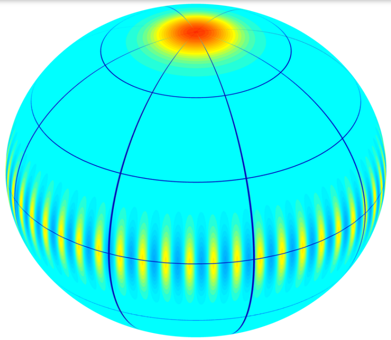
Ion trap (University of Maryland picture)

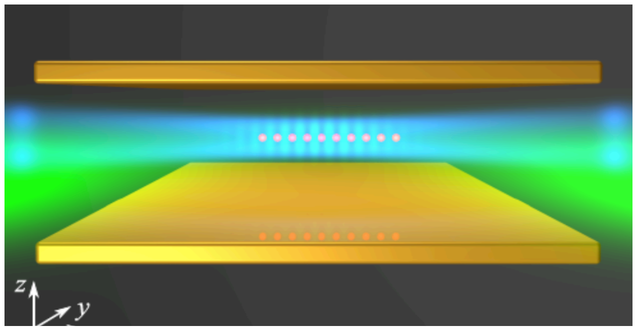
Manipulating real or artificial atoms for quantum computer research (talks by R. Blatt and D. Wineland on trapped ions)



Superconducting qubits (UCSB picture)

Non Classical states and Quantum Metrology (L.Davidovich and J-M.Raimond)





Quantum simulation with circular Rydberg atoms (J-M.Raimond)

Permanent team: S. H, Jean-Michel Raimond, Michel Brune, Sébastien Gleyzes, Igor Dotsenko, Clément Sayrin