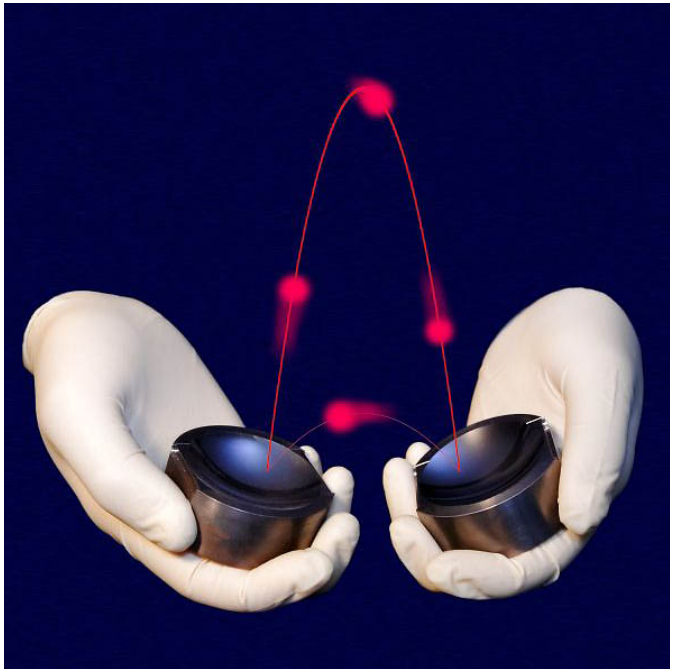
Confined quantum Zeno dynamics of a watched angular momentum

J.M. Raimond

Université Pierre et Marie Curie

Laboratoire Kastler Brossel
Physique quantique et applications



Zeno's arrow paradox (450 bc)

- *If everything when it occupies an equal space is at rest, and if that which is in locomotion is always occupying such a space at any moment, the flying arrow is therefore motionless. —Aristotle, Physics VI:9, 239b30*

- A flying arrow cannot move!
  - An interesting paradoxical view on a common situation depicting the difficulty to figure out infinitesimal quantities
  - Of course, the arrow moves (and is famous for moving fast towards Achille's foot)
    - No paradox at all for our modern understanding of space, time and differential calculus

Quantum Zeno effect

- A watched quantum arrow never moves
  - coherent evolution of a system and frequently repeated quantum measurements
    - a quantum jump evolution between eigenstates of the measured quantity
    - Each new measurement has a large probability to project the system back onto its initial state
      - an evolution much slower than without measurements
      - No evolution at all in the limit of zero delay between measurements

- Observed on a variety of matter/field quantum systems
  - Inhibition of the growth of a coherent field by frequent QND photon number measurement

J. Bernu et al, PRL **101** 180402

Quantum Zeno dynamics

- More freedom for a watched quantum system
  - Sets a boundary in the Hilbert space
    - Asking frequently « have you crossed the boundary » makes it impenetrable
  - Coherent evolution with Hamiltonian H
  - Repeated measurement of an observable with a degenerate eigenvalue μ (eigenspace E_μ, projector P_μ)
    - State initially in E_μ remains in E_μ and evolves under the effective hamiltonian $H_\mu=P_\mu H P_\mu$

- Confined dynamics can be utterly counterintuitive and lead to interesting states
  - State preparation through Hilbert space tailoring
  - Many possibilites for quantum manipulations/quantum information

P. Facchi and S. Pascazio, PRL, **89** 080401

Equivalent approaches

- Repeated quantum measurement with degenerate eigenspaces E_μ
- Repeated unitary kicks U_k with degenerate eigenspaces E_μ
  - Closely related to 'Bang Bang' control techniques
- Continuous application of a state-selective perturbation H with degenerate eigenspaces E_μ

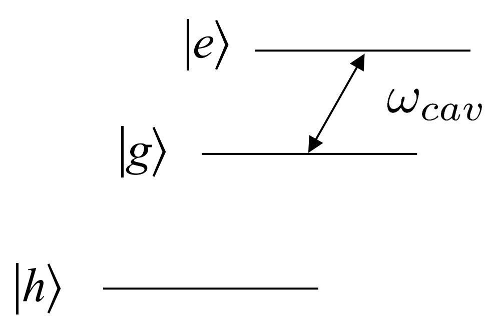
  - All lead to a confined dynamics in one of the eigenspaces E_μ
    - A 'watched' quantum arrow does move, but in a limited domain

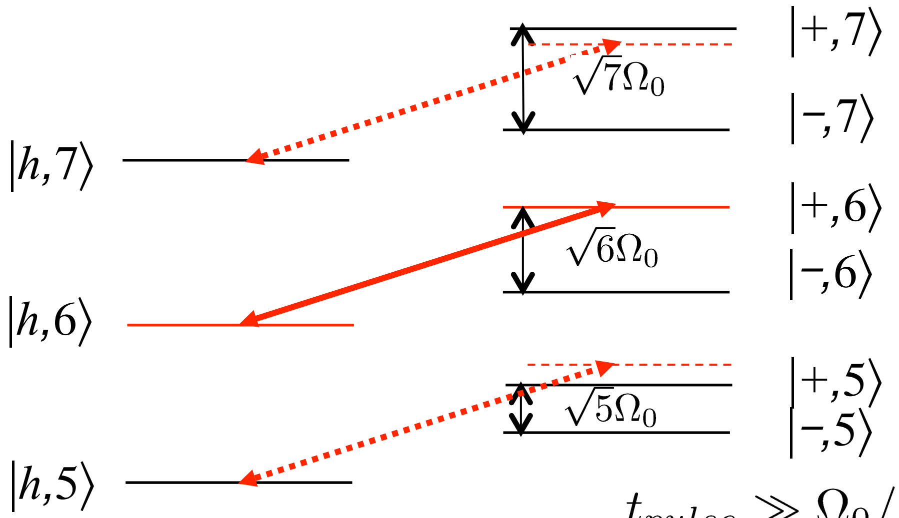
P. Facchi et al J. Phys. A **41** 493001
F. Schäfer et al, Nature Comm, **5** 3194

Towards a cavity QED implementation

Raimond et al, PRL 105, 213601

- Measurement: a yes/no question
  - Are there exactly *s* photons in the cavity or not ?
- If frequently repeated
  - Confinement of the dynamics in the subspaces with less or more than *s* photons: a circular wall with radius $\sqrt{s}$ in phase plane
  - Quantum Zeno dynamics in two disjoint subspaces
- Use the dressed states to implement photon-number selectivity
  - And the long interaction times to probe the dressed states with high resolution pulse

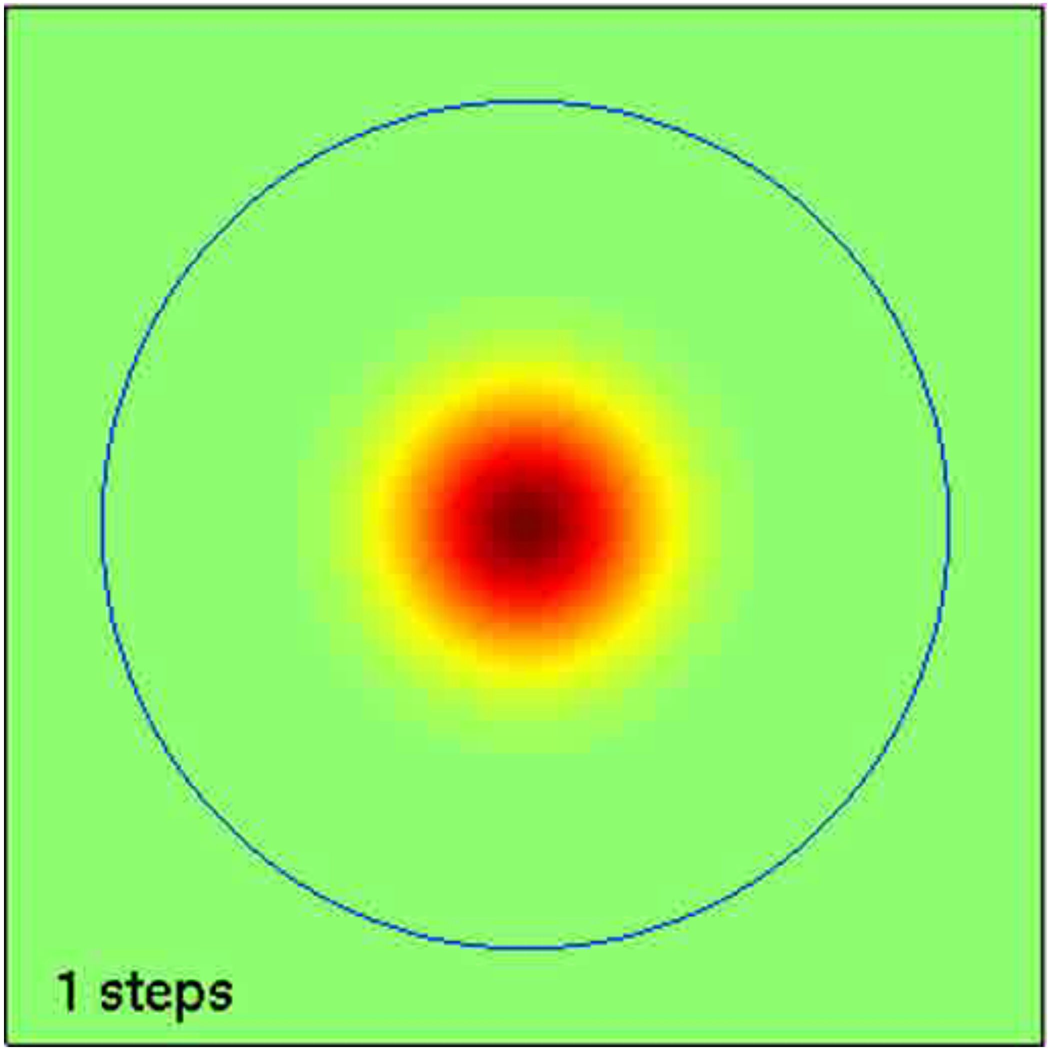




$t_{pulse} \gg \Omega_0/\sqrt{n}$

Dynamics inside the exclusion circle

- 150 steps, *s*=6



For circuit QED, see Bretheau et al, Science 348, 776

Phase space tweezers

- A radius 1 EC (s=1)
  - Blocks a coherent component
    - No evolution at all: recover standard zeno effect

- Phase space tweezer
  - An EC with *s*=1 and a slowly varying center (controlled displacements before and after interrogation). No free dynamics
    - The 'blocked' coherent component adiabatically follows the slow motion of the EC even in the absence of other source of evolution
      - A means to pick at will a coherent component and to displace it arbitrarily without affecting others
      - A synthesis of nearly arbitrarily complex cat states

Raimond et al, PRA 86 022120

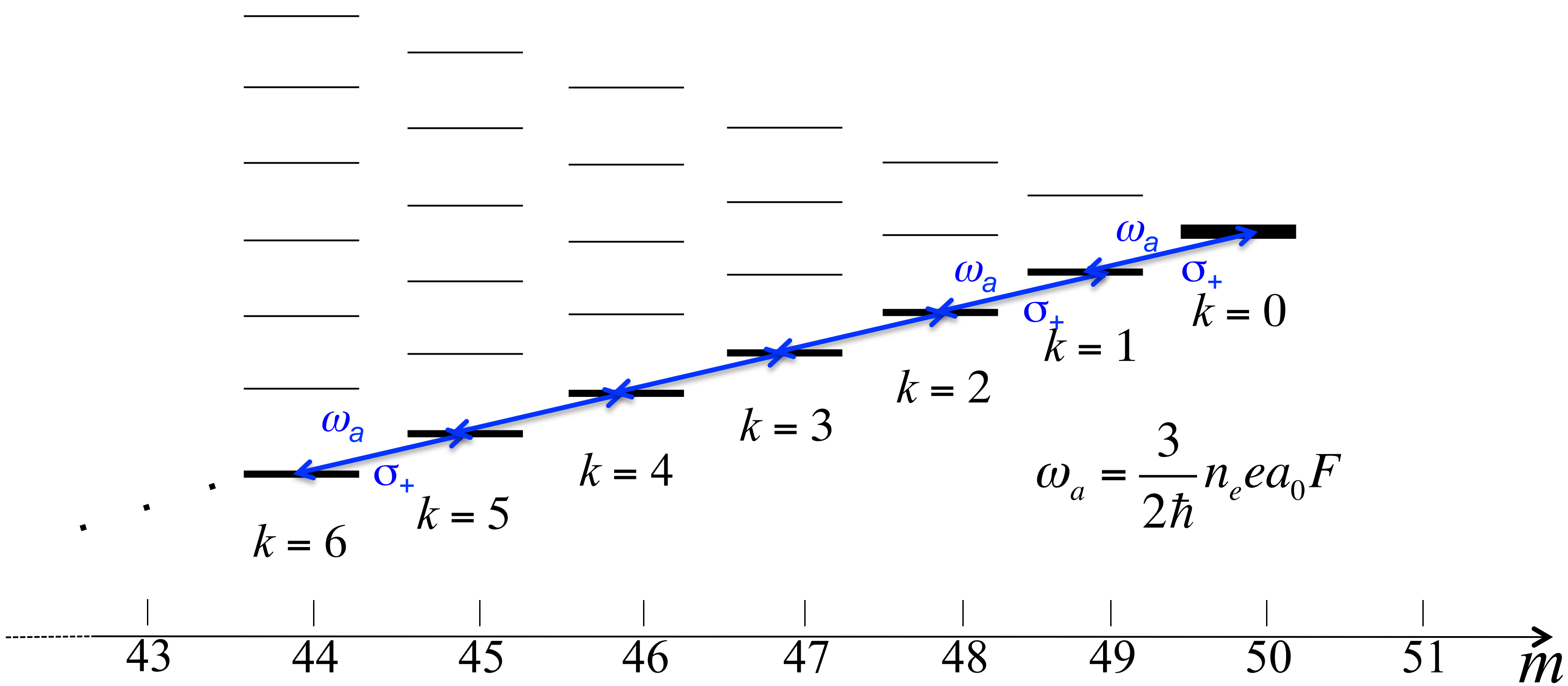
First QZD inplementation in the Stark manifold of a Rydberg atom

- Same basic principle as in cavity QED
  - A simple and rich system
    - A single Rydberg atom in a static electric field
      - A large Hilbert space (2500 levels !)
  - Clear demonstration of the main QZD features
    - Generation of mesoscopic quantum state superpositions
  - Promising perspectives for quantum-enabled metrology

See also Schäfer et al, Nature Comm 5, 3194

An arrow (angular momentum) in a Rydberg manifold

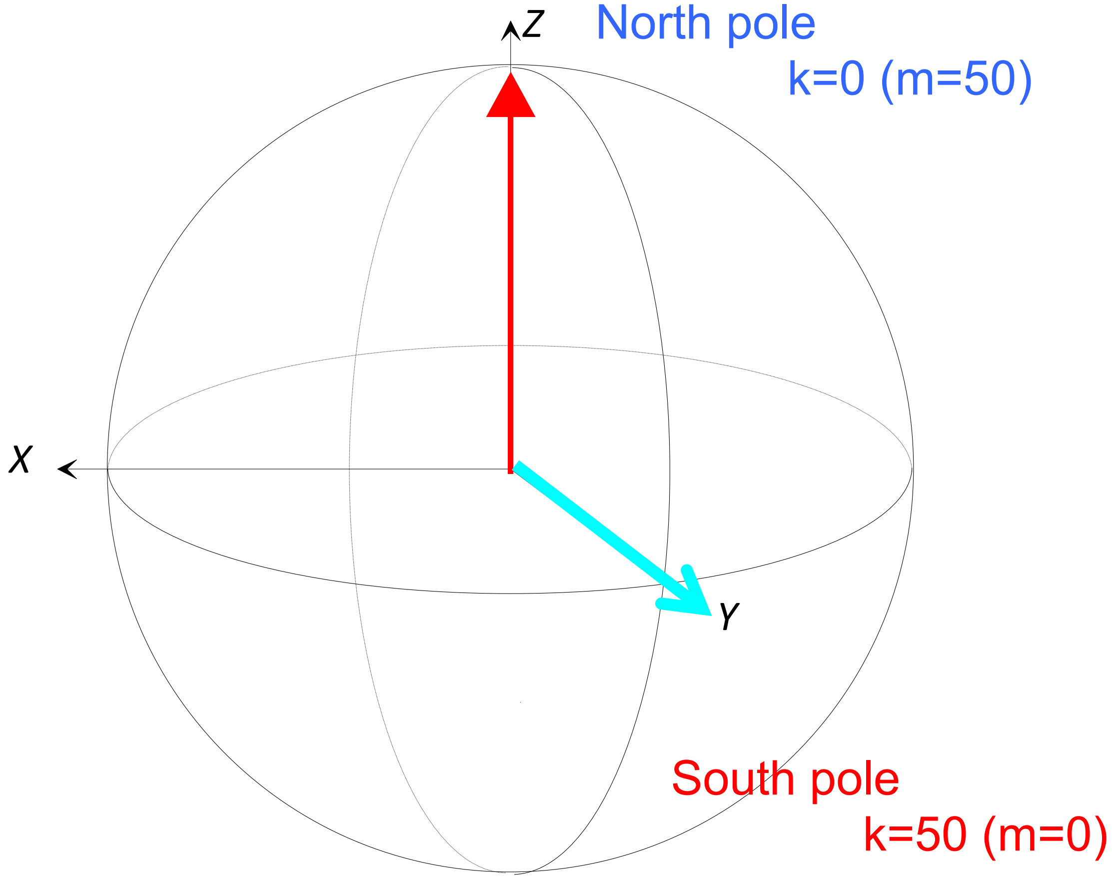
- Rydberg manifold n_e=51 in an electric field: Stark levels



- From the circular state, a ladder of 51 equidistant levels |k> separated by the linear Stark frequency.
- Driven simultaneously by a resonant σ_+ r.f.; equivalent to a spin J=25.

Unrestricted motion on a generalized Bloch sphere

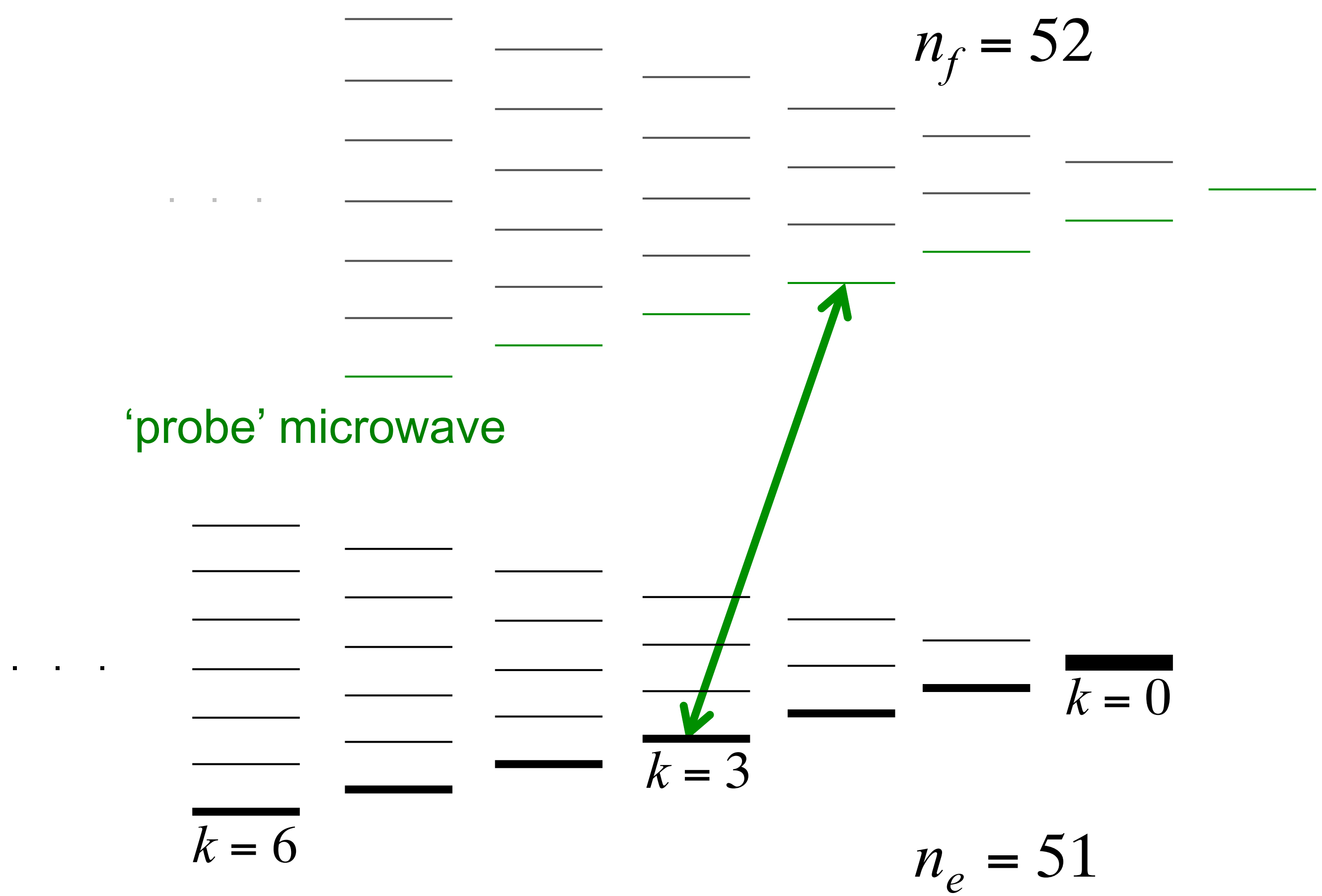
- Rotation of the angular momentum under resonant r.f. excitation



  - At any time in a spin coherent state (SCS): a rotating arrow
  - Near the poles: an harmonic oscillator

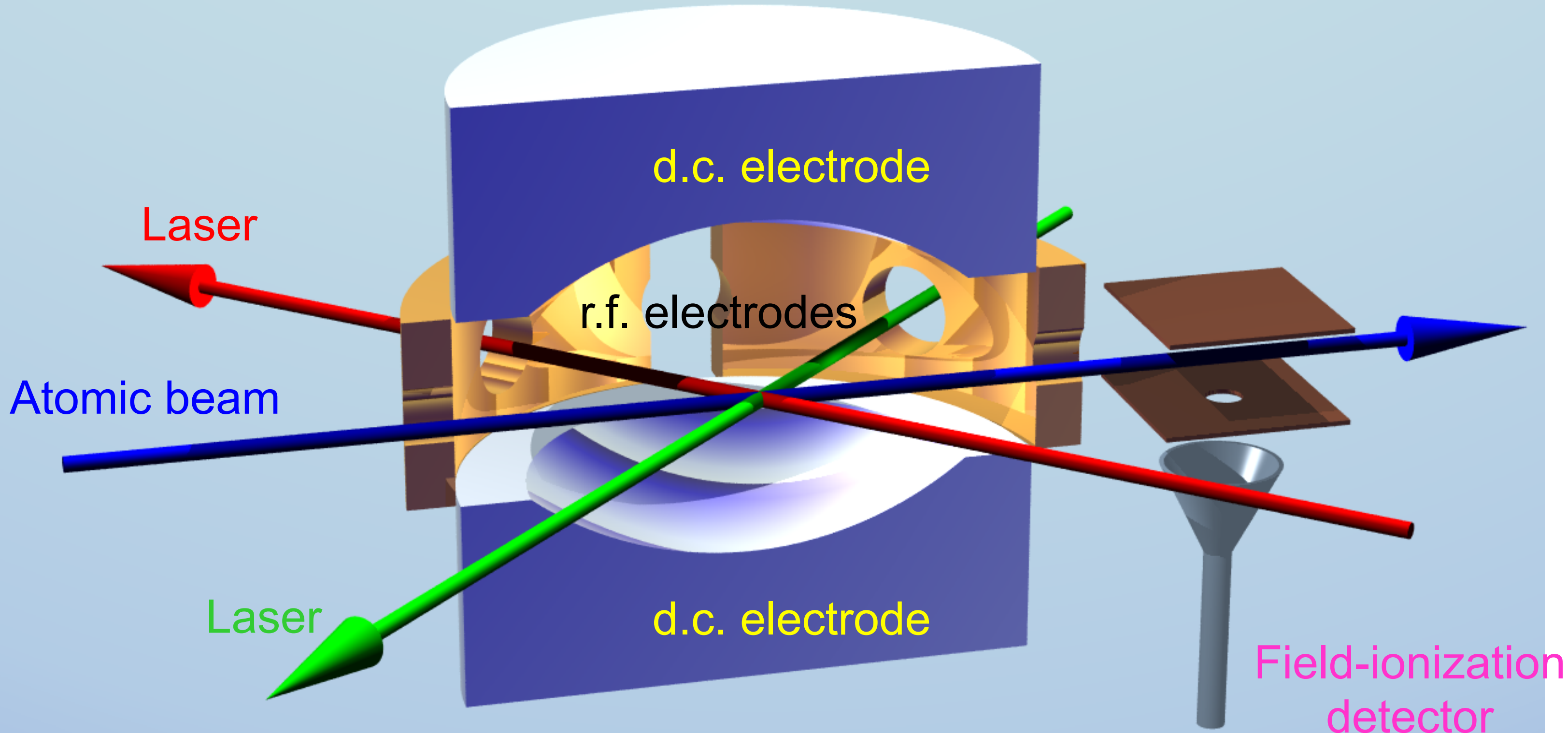
Probing the unrestricted spin rotation

- Selective measurement of the |*k*> levels population *P*(*k*, *t*)



  – Field ionization resolves manifolds 52 and 51

A simple experimental set-up

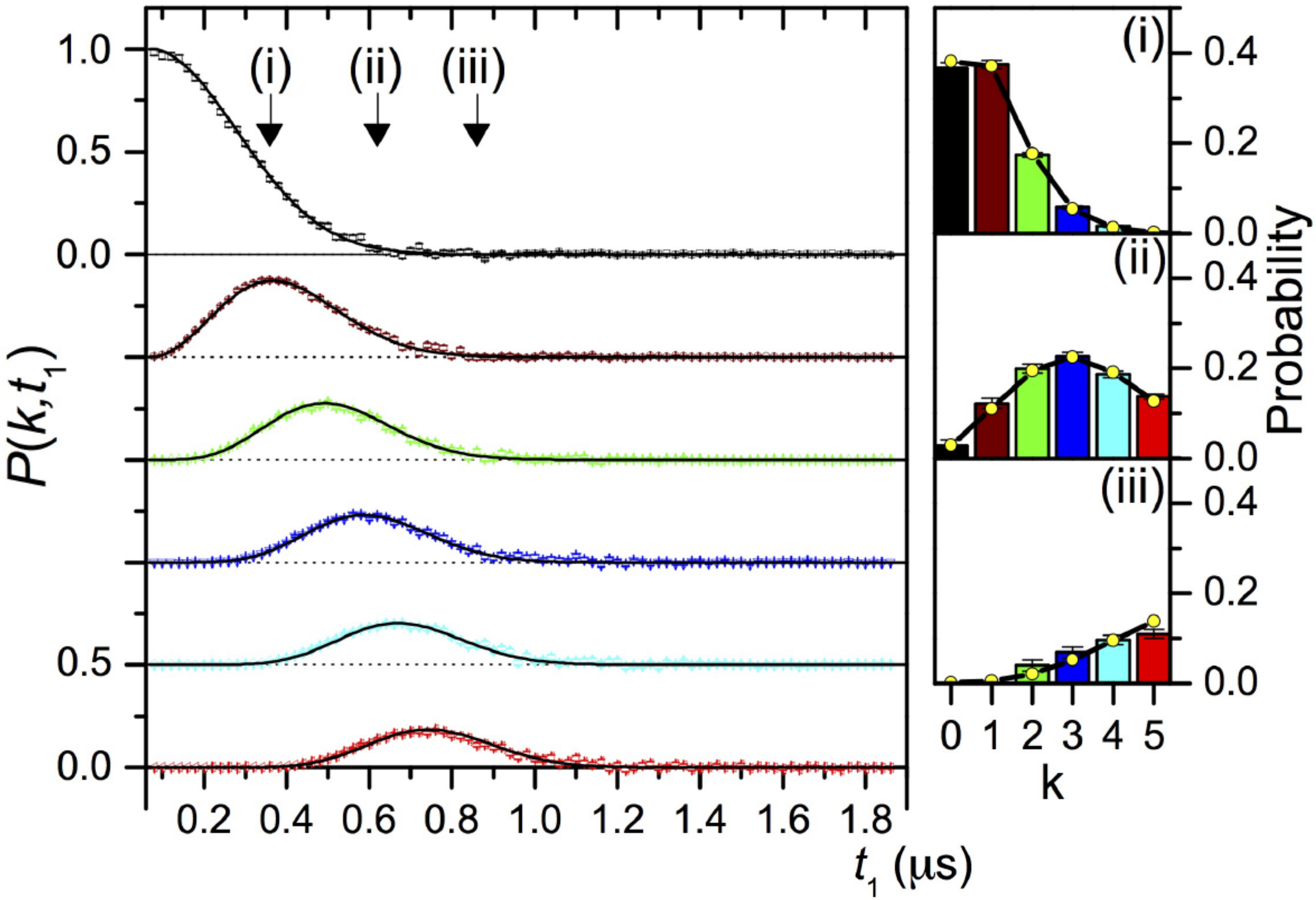


- Laser preparation of a high *k* (low *m*) state
- Initialization in the circular state (r.f.-induced adiabatic rapid passage in the spin state ladder)
- σ_+ r.f. polarization with a fine tuning of the potentials on the r.f. electrodes

Probing the unrestricted spin rotation

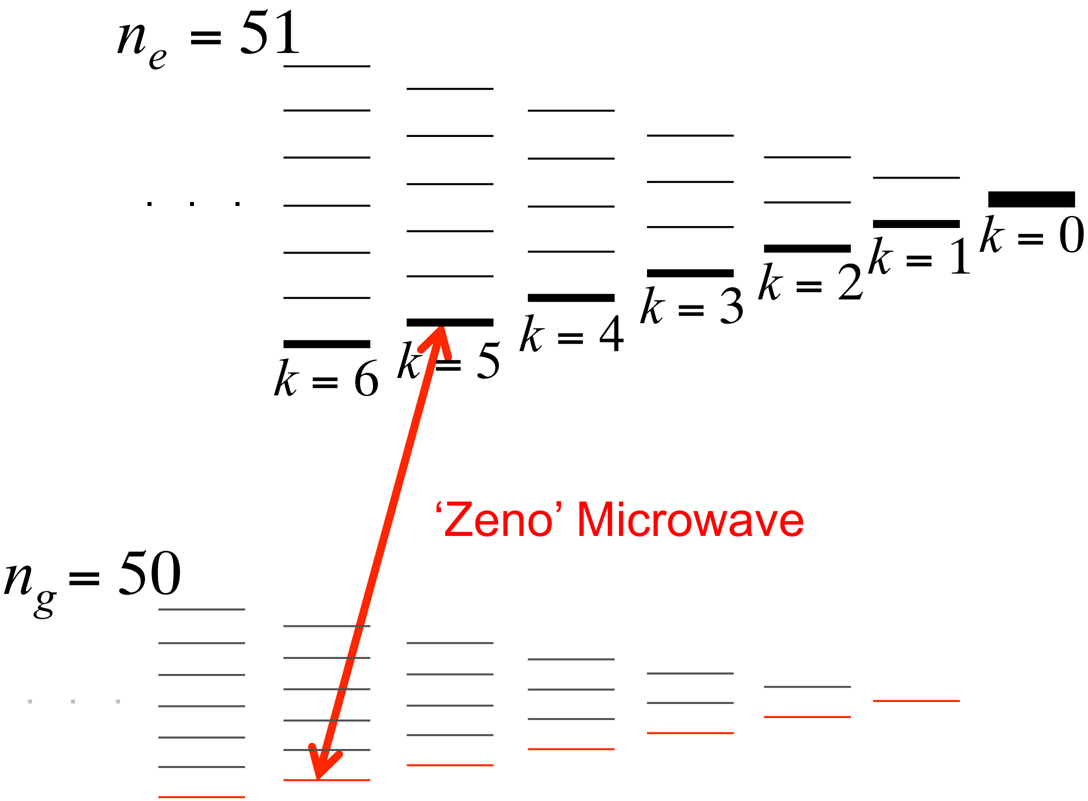
A. Signoles et al. ArXiv 1402.0111 and Nature Physics, 10, 715

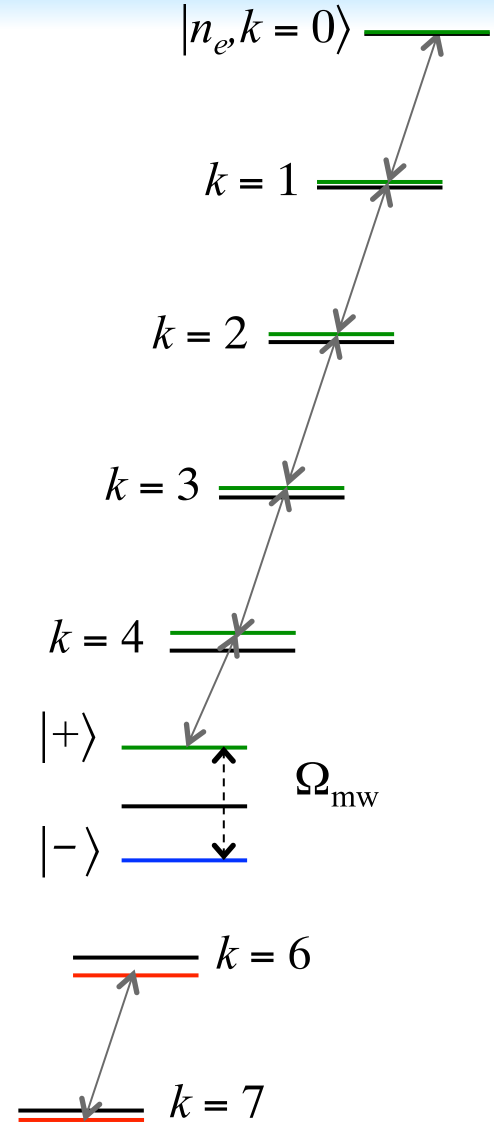
- Evolution of *P*(*k*, *t*)



Enforcing Zeno interrogation

- State-selective addressing of the spin states ladder





  - A 'gapped' spin ladder
    - First six levels (including +) isolated from the others
  - Confined dynamics in the vicinity of the North pole

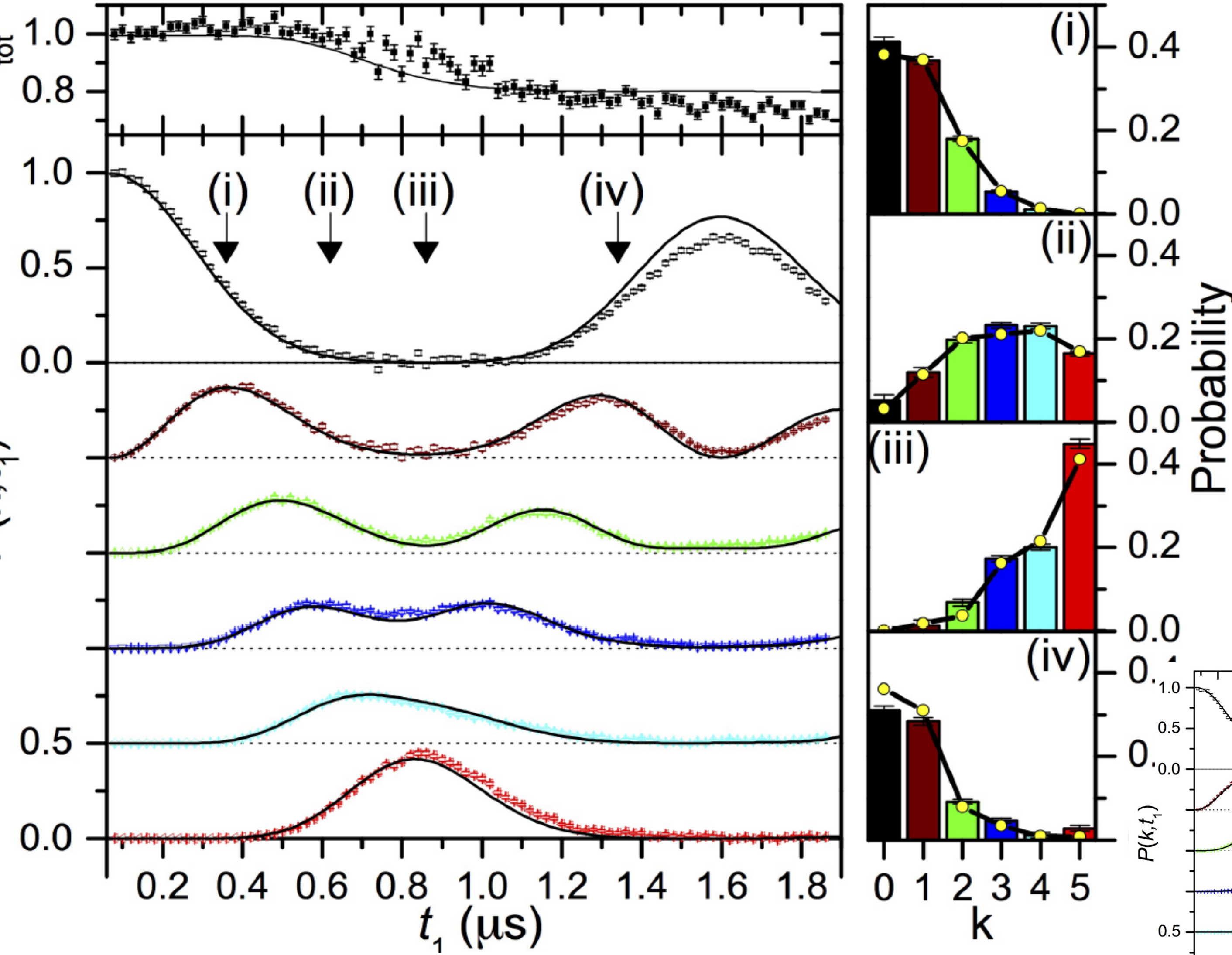
Timing

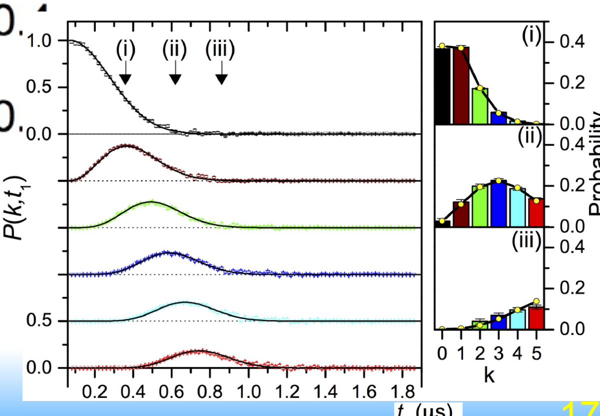
- A simple sequence
  - Preparation of the initial circular state
  - Switching on of the Zeno state-selective microwave
  - Application of the rf inducing spin rotation for a time t
  - Slow (adiabatic) switching off of the Zeno microwave
    - Maps the populated dressed state |+> onto |k=5>
  - Probe final spin states populations

Evidence of the confined dynamics

A. Signoles et al. ArXiv 1402.0111 and Nature Physics, 10, 715

- $P(k, t)$ in Zeno dynamics

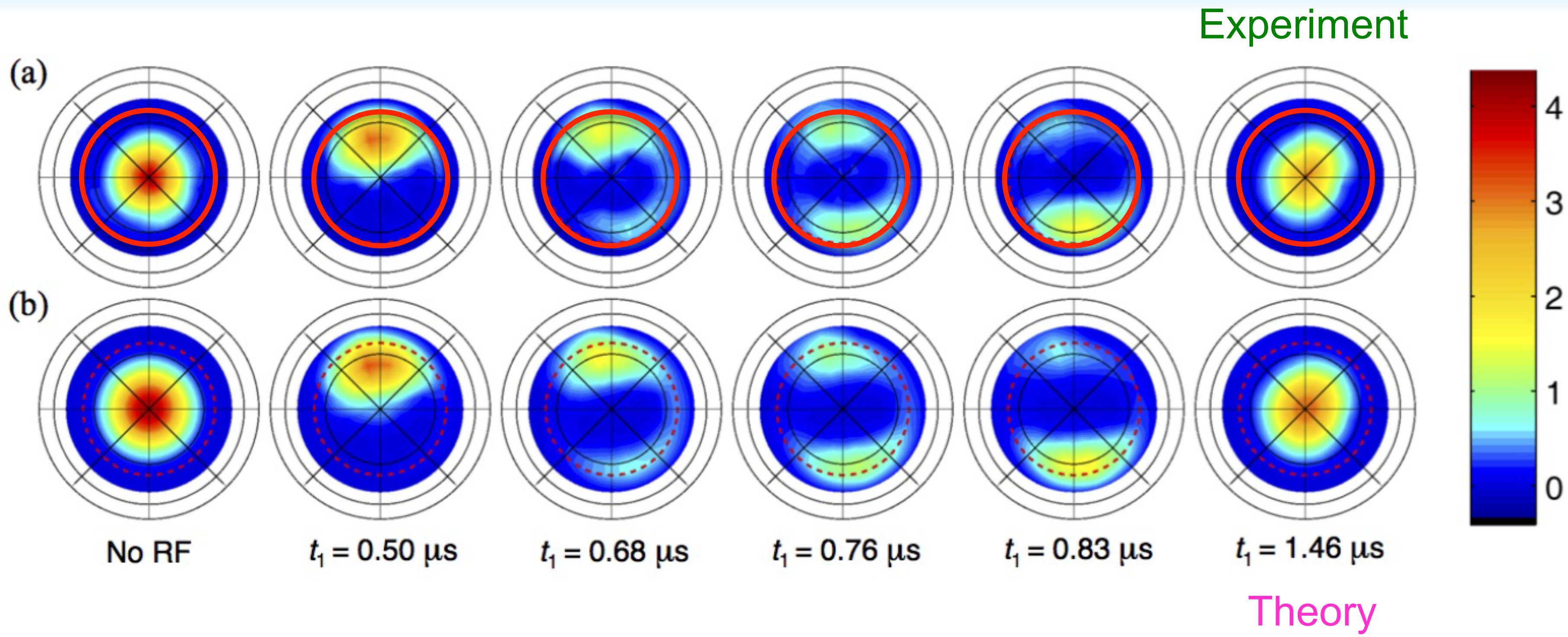




Evidence of the confined dynamics

- Time-resolved measurement of the spin's Q function
  - Analogous to the Husimi Q function for a field
  - A positive quasi-probability distribution on the Bloch sphere
  - Proportional to the probability for finding the spin in $k=0$ after a rotation $R(\Theta,\phi)$
  - Measurement procedure
    - Apply an intense r.f. with adjustable phase and amplitude:
      - Controlled rotation of the spin's state
    - Apply probe microwave to measure $P(0)$
    - Interpolate measurements on the polar cap of the Bloch sphere

Q function snapshots

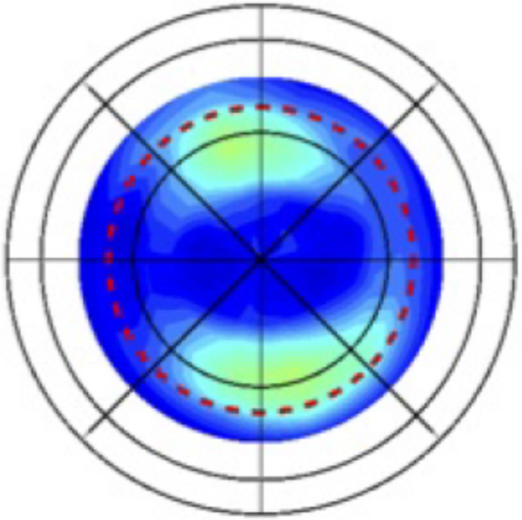


- Clear evidence of the confinement in the polar cap
  - Zeno interrogation: a Limit Latitude (LL) that the spin cannot cross
- Rapid azimuthal phase inversion when the spin reaches the LL
  - C.f. confined dynamics of a field
- Excellent agreement with a complete numerical simulation
  - Good understanding of the dynamics and measurement process

A. Signoles et al. ArXiv 1402.0111 and Nature Physics, 10, 715

Coherence at inversion time ?

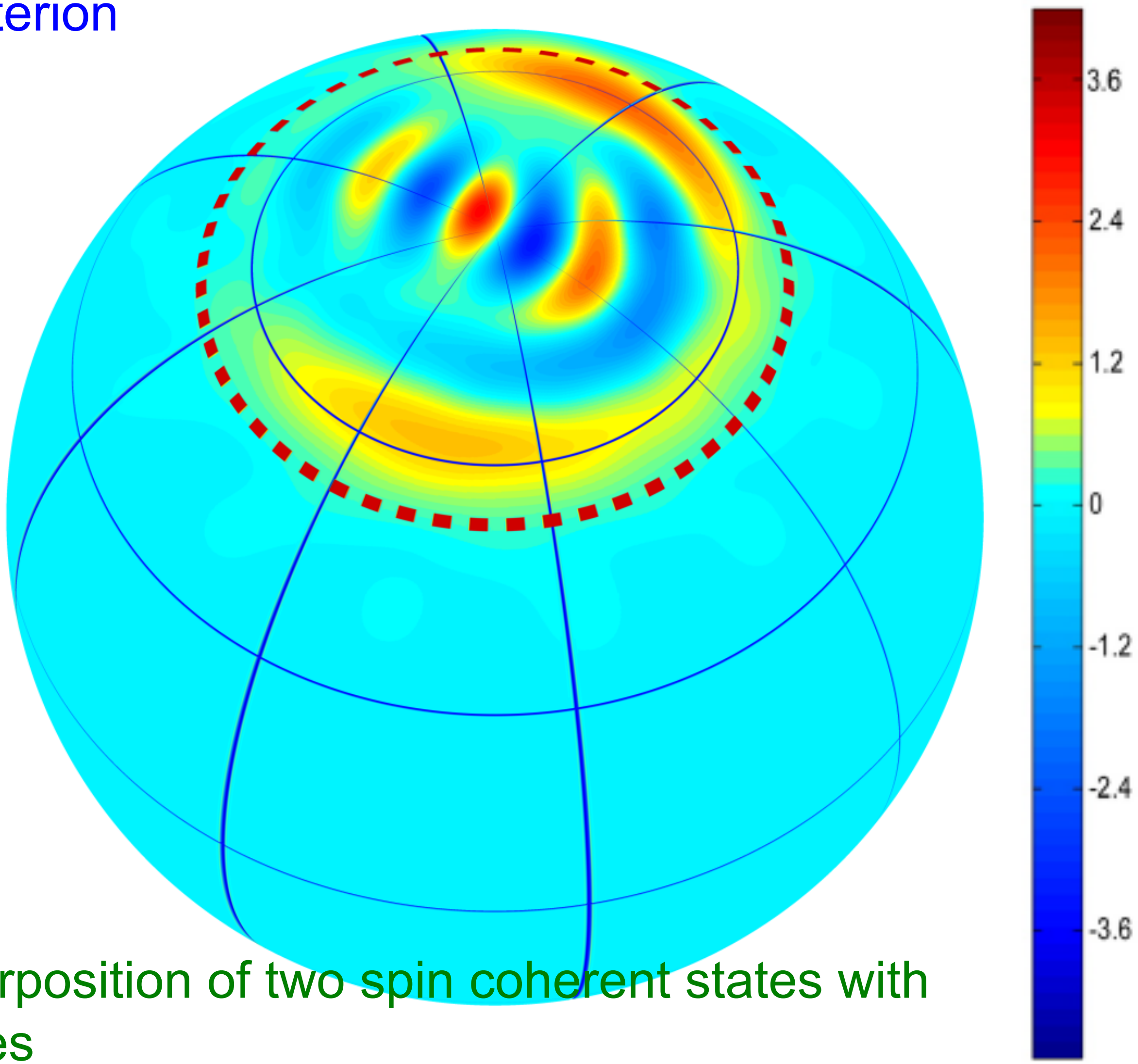
- Expect a quantum superposition of two Spin Coherent States with opposite azimuthal phases
  - Reminiscent of the Schrödinger cat metaphor
  - An interesting quantum resource for
    - Decoherence studies
    - Electric and magnetic field quantum-enabled metrology
  - Q function does not measure the coherence



- A direct measurement of the spin's Wigner function
  - Adjustable rotation, measurement of the P(*k*)s for a few *k* values and many rotation parameters
  - MaxLik reconstruction of the complete atomic density matrix
  - Projection on the spin states
    - 10% population leaks out of the spin ladder due to experimental imperfections
  - Plot the field's Wigner function on the Bloch sphere

Spin's Wigner function at phase inversion time

- A clear nonclassicality criterion
  - Negative W values



- A genuine quantum superposition of two spin coherent states with opposite azimuthal phases
  - Another type of Schrödinger kitten

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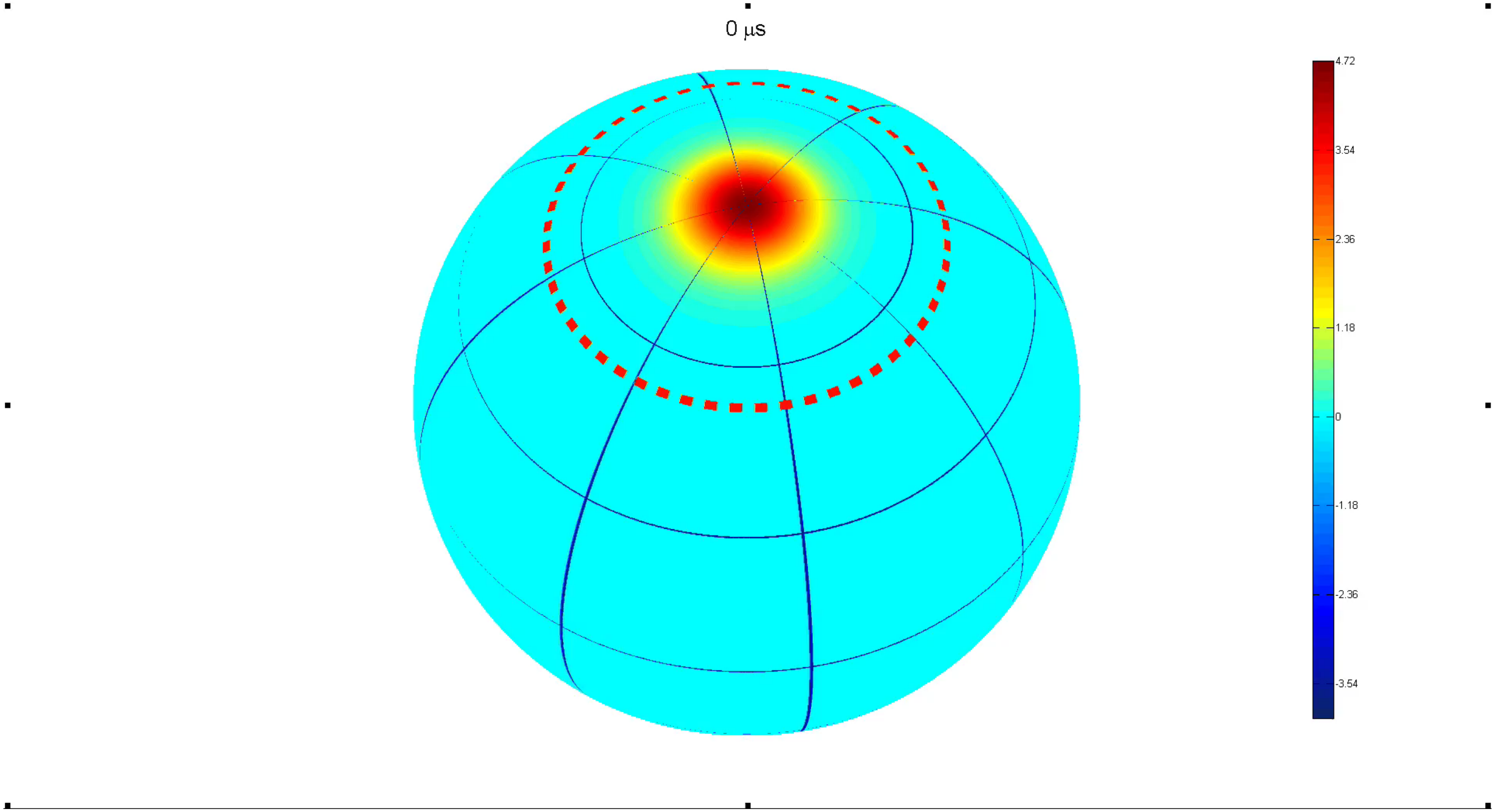
A movie of the Wigner function

- A theoretical computation of W



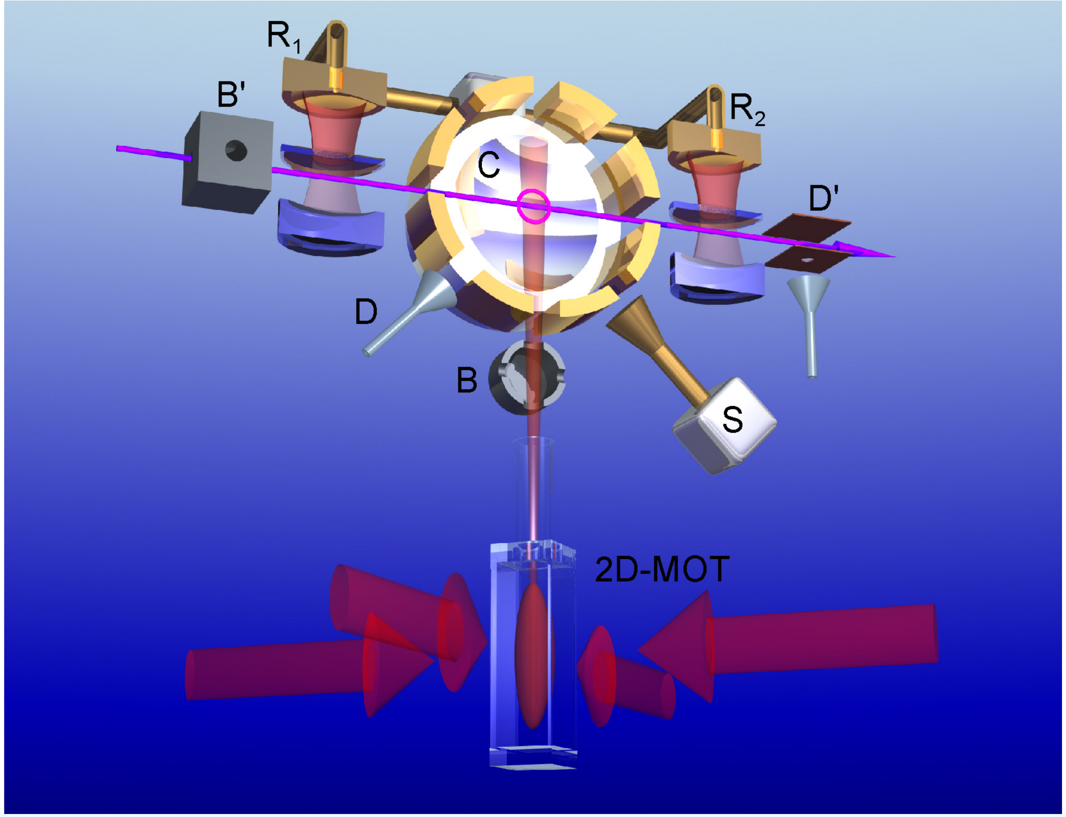
  – Excellent agreement with measurements at phase inversion time
    - Mutual fidelity 0.93

Perspectives

- Main limitations of the present set-up
  - Static field inhomogeneity limits coherence time to a few μs
  - Limited resolution of the electronic sequencer
- With an improved set-up
  - Larger spaces
    - Quantum-enabled measurements of electric and magnetic fields
  - Alternate interrogation/rotation
    - Transposition of the ‘phase space tweezers’ proposed in CQED
    - Synthesis of nontrivial complex spin states
  - Quantum control
    - Optimal control techniques for state synthesis
- Applications to quantum enabled metrology
  - Engineer field sensitive state superpositions
    - Time and space-resolved measurements of weak electric and magnetic field

A new dedicated cavity QED set-up

- Achieving long interaction times
  - A set-up with a stationary Rydberg atom in a cavity
  - Circular state preparation and detection in the cavity
  - Interaction time ms range
  - For QZD and more



A team work

- S. Haroche, M. Brune,
  J.M. Raimond, S. Gleyzes, I. Dotsenko,
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  - S. Gerlich
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  - QZD: P. Facchi, S. Pascazio
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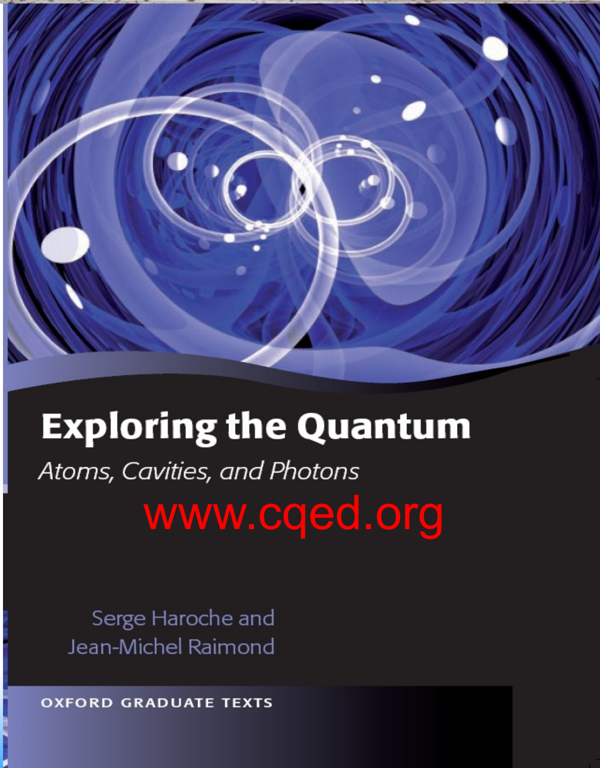

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