Confined quantum Zeno dynamics of a watched atomic arrow

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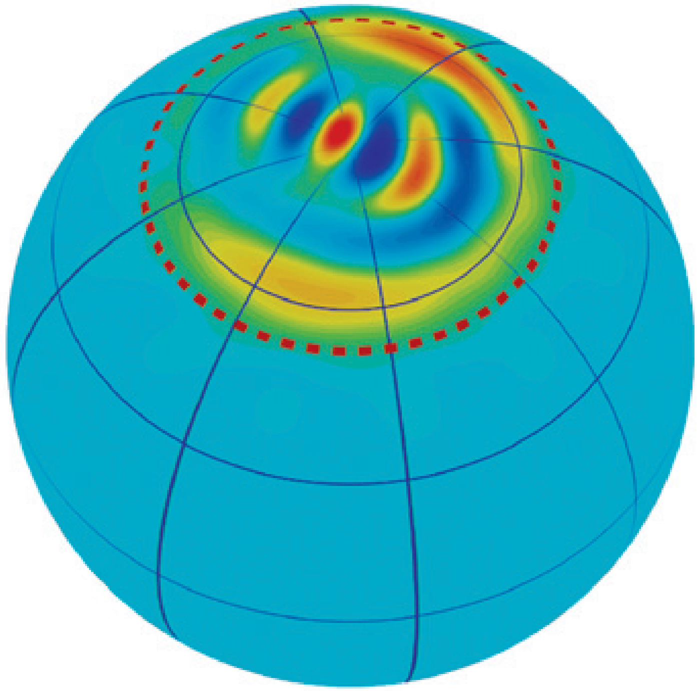
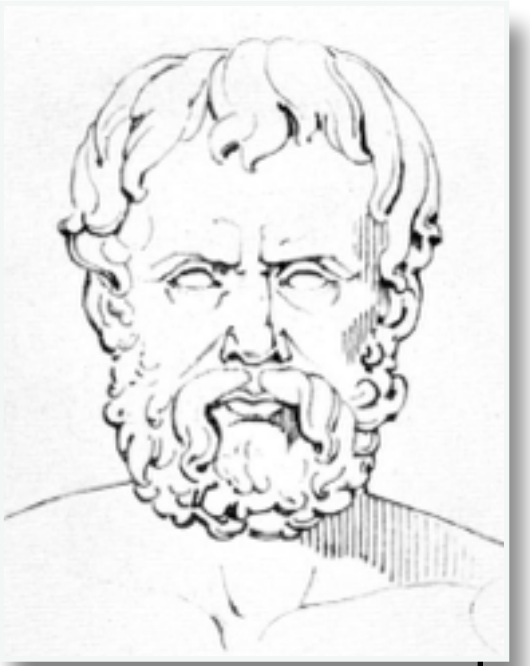
Nature Physics **10**, 715 (2014)



Stefan Walter
Condensed Matter Journal Club
07.10.2014

Zeno of Elea (c. 490 – c. 430 BC)



Zeno's paradoxes:

- Achilles and the tortoise
- Arrow paradox
  "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."
- and others

Quantum Zeno (1977)

<u>Quantum Zeno effect:</u>

[B. Misra and E. C. G. Sudarshan, J. Math. Phys. 18, 756 (1977)]
[Turing 1954]
[Degasperis, Fonda, Ghirardi 1974]

In a quantum world, a watched arrow never moves.
Repeatedly asking:
"Are you still in your initial state?" blocks its coherent evolution (measurement back-action)

$$P_s(t) = \left|\langle\Psi_0|e^{-iHt}|\Psi_0\rangle\right|^2$$
$$= 1 - \frac{t^2}{t_Z^2} + \dots$$

$$t_Z = \left[\langle\Psi|H^2|\Psi\rangle - \langle\Psi|H|\Psi\rangle^2\right]^{-\frac{1}{2}}$$

$$P_s^N(T) \approx (1 - \frac{T^2}{N^2 t_Z^2})^N$$

<u>Experiments:</u>

Wayne M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland,
Phys. Rev. A 41, 2295

M. C. Fischer, B. Gutiérrez-Medina, and M. G. Raizen,
Phys. Rev. Lett. 87, 040402

Quantum Zeno dynamics (2002)

Quantum Zeno dynamics:

[P. Facchi and S. Pascazio, Phys. Rev. Lett. 89, 080401 (2002).]
[P. Facchi and S. Pascazio, J. Phys. A 41, 493001 (2008).]

More freedom to the system.
Instead of pinning it to a single state, it sets a border in its evolution.

Repeatedly asking:
“Are you beyond the border?” makes this limit impenetrable.

→ Designing border (by choosing the measured observable) allows to dynamically tailor the system’s Hilbert space.

Idea of the experiment

- Large (J=25) atomic angular momentum (arrow on Bloch sphere)
- angular momentum projection on polar axis quantized

  $J - k \, , k = 0 \ldots 2J$

  $|J, J-k\rangle$

- Initially in $|J, J\rangle$, dynamics induced by resonantly driving transitions between eigenstates
- At each stage of the rotation, system is in a spin coherent state (average value of $J-k$: projection of arrow on the polar axis)
- Repeatedly measuring the value of the projection

  ➡ Freezing the rotation

  ➡ Realizing the quantum Zeno effect

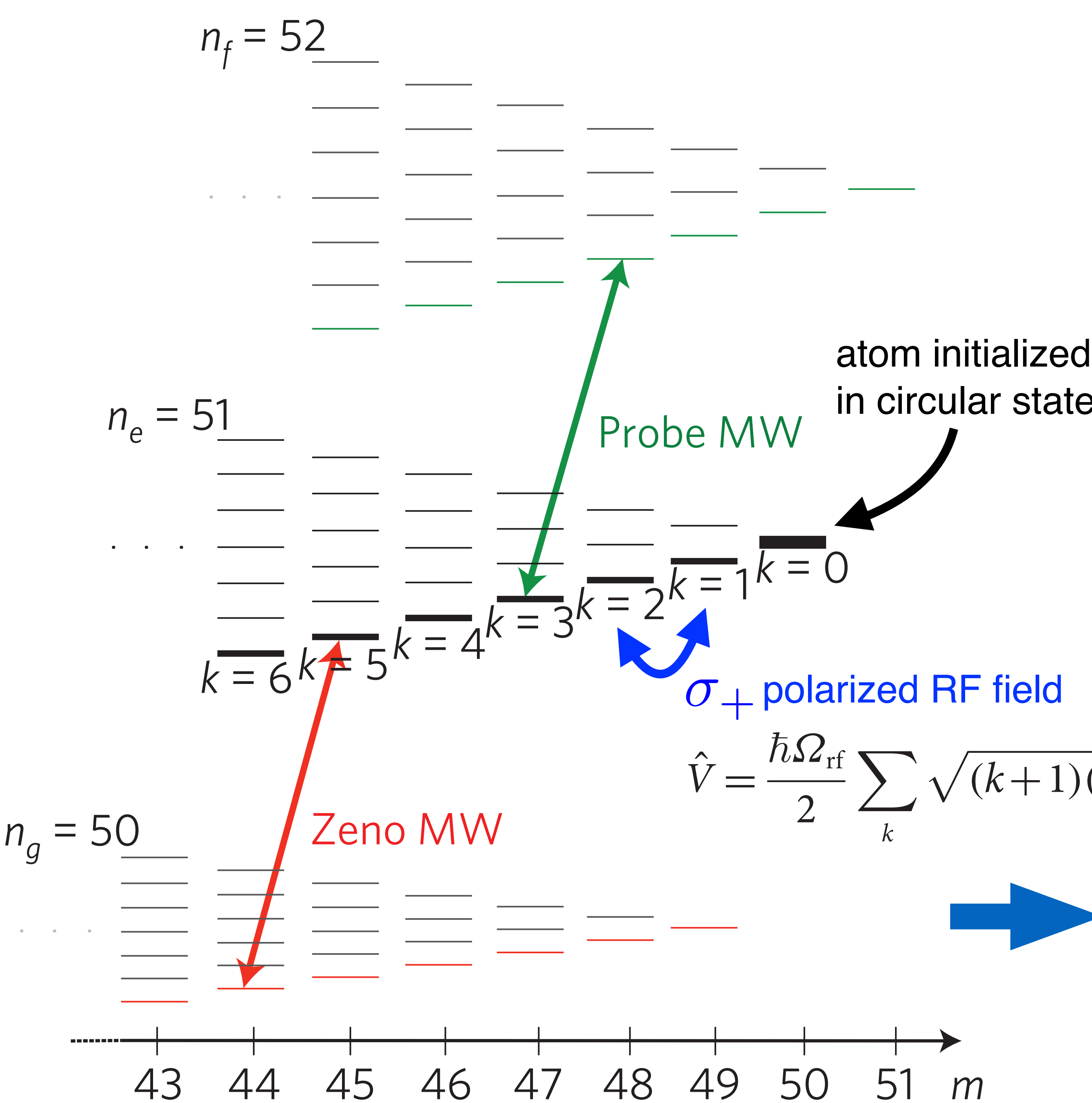
Idea of the experiment

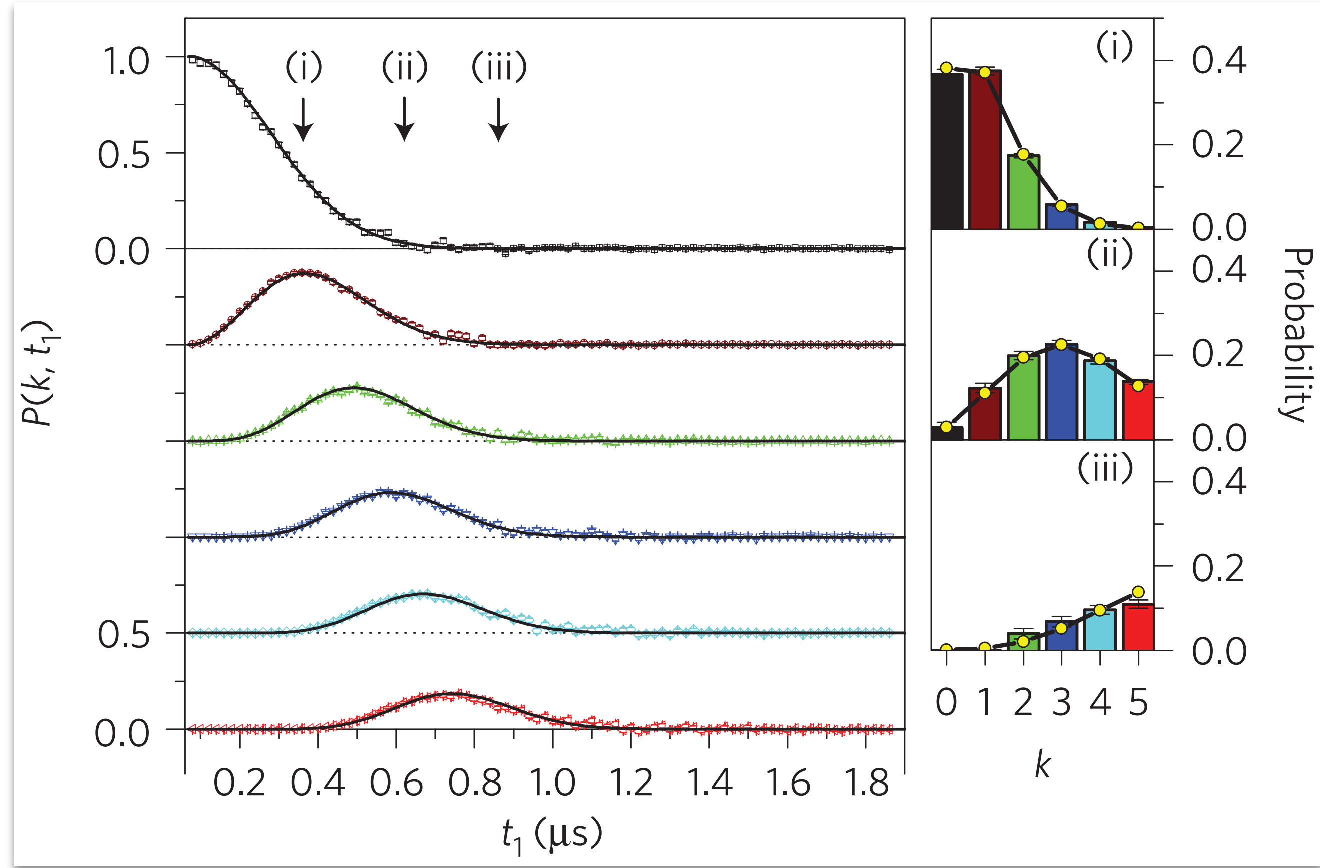
Realizing quantum Zeno dynamics:

- Applying continuously a selective unitary evolution addressing only one of the $|J, J-k\rangle$ states
  → Creating a well-defined "limiting latitude"
- The spin is forbidden to cross the limiting latitude
- J=25 spin realized in subspace of Stark manifold of a Rydberg atom

Realization of the experiment

Zeno dynamics OFF:



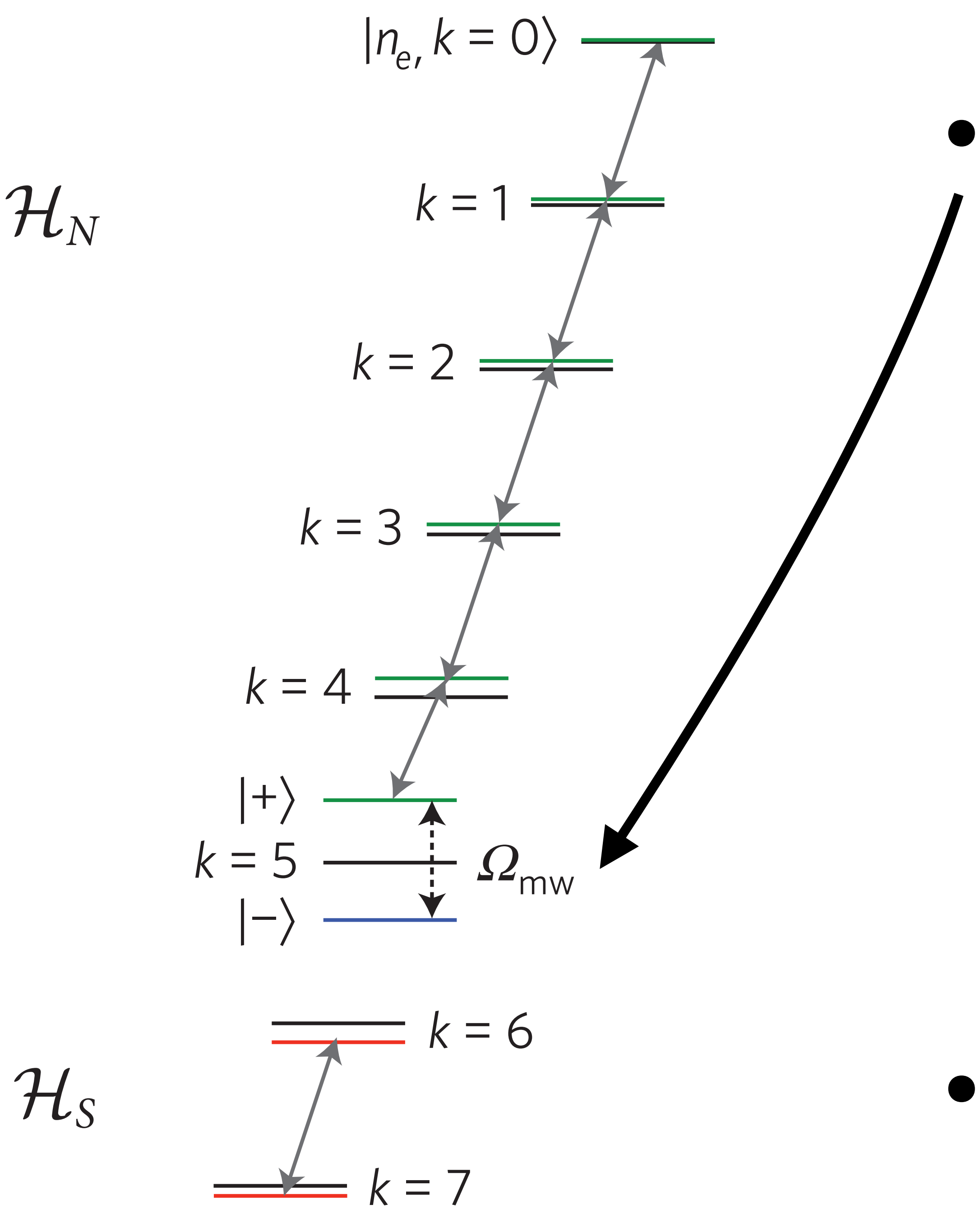


$$\hat{V} = \frac{\hbar\Omega_{\rm rf}}{2} \sum_k \sqrt{(k+1)(n_e - k - 1)} |n_e, k+1\rangle\langle n_e, k| + \text{h.c.}$$

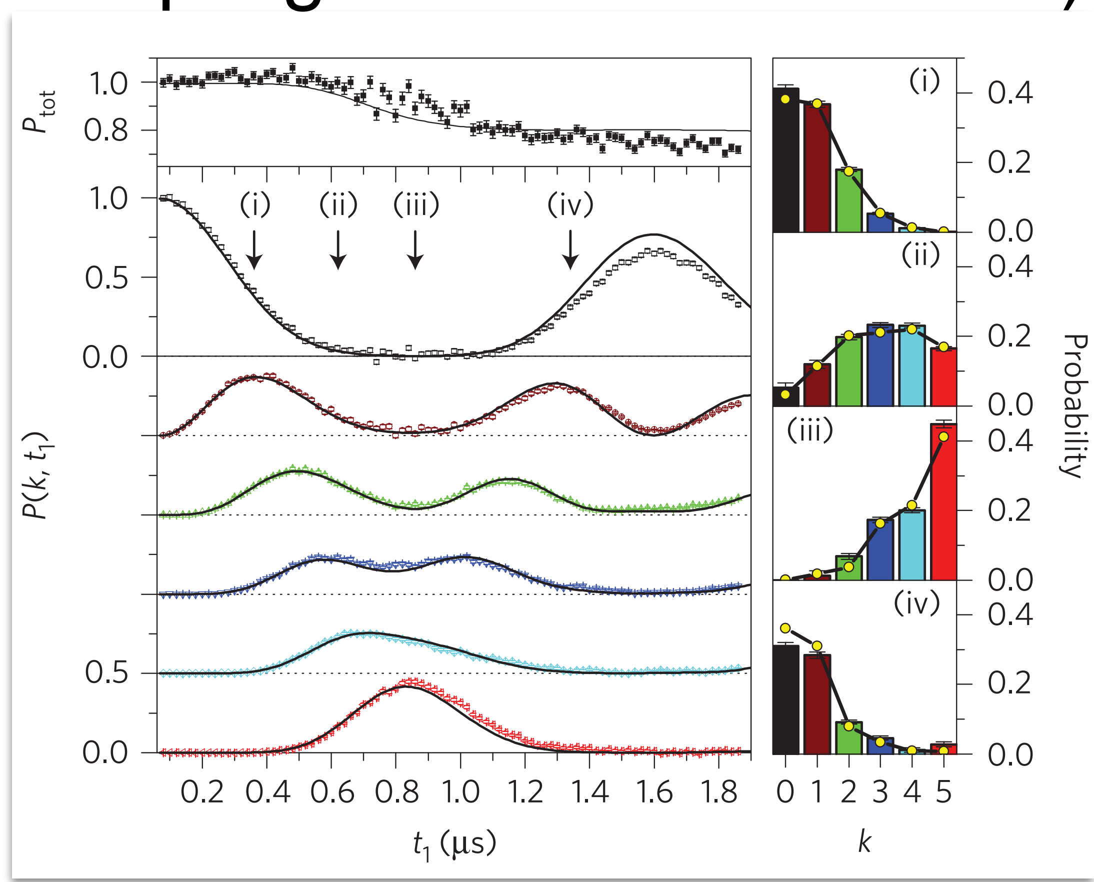
atomic states moves up and down the ladder

Realization of the experiment

Zeno dynamics ON:



- Selectively addressing one of the spin states with ‘Zeno’ continuous MW resonant on the transition $|n_e, k_z\rangle \rightarrow |n_g, k_z\rangle$
- Zeno MW opens a gap (> coupling matrix element of V)

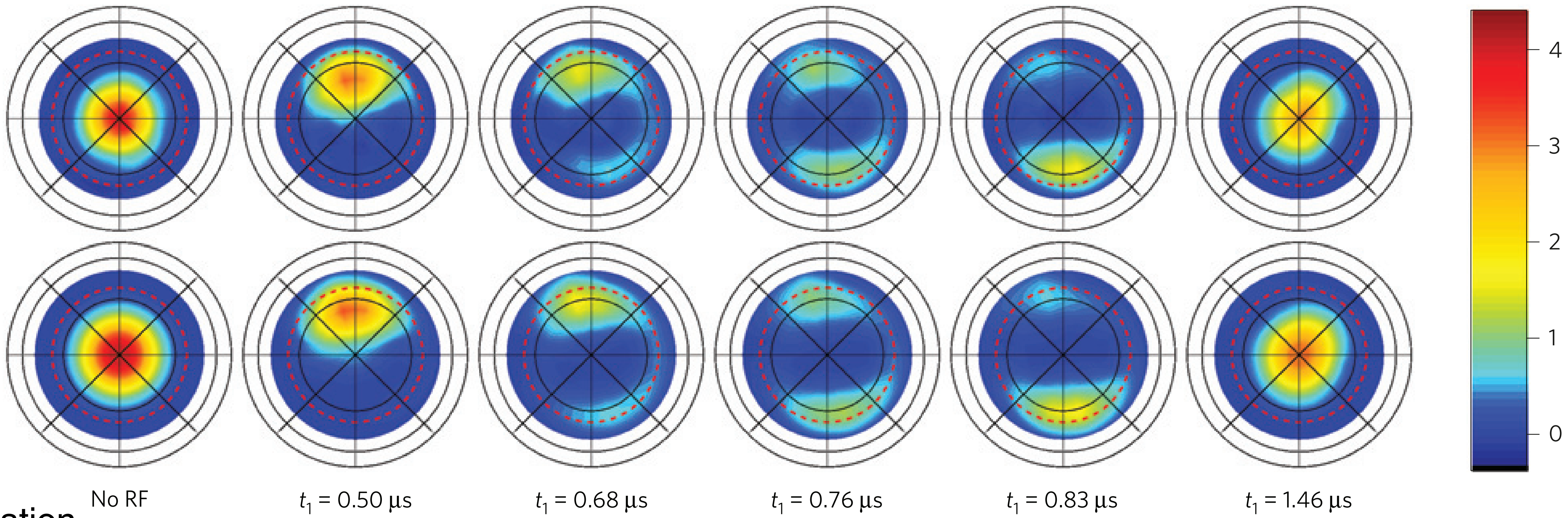


- Impossible for RF drive to induce transitions towards states below $|+\rangle$

Q-function

Zeno dynamics ON:

experiment

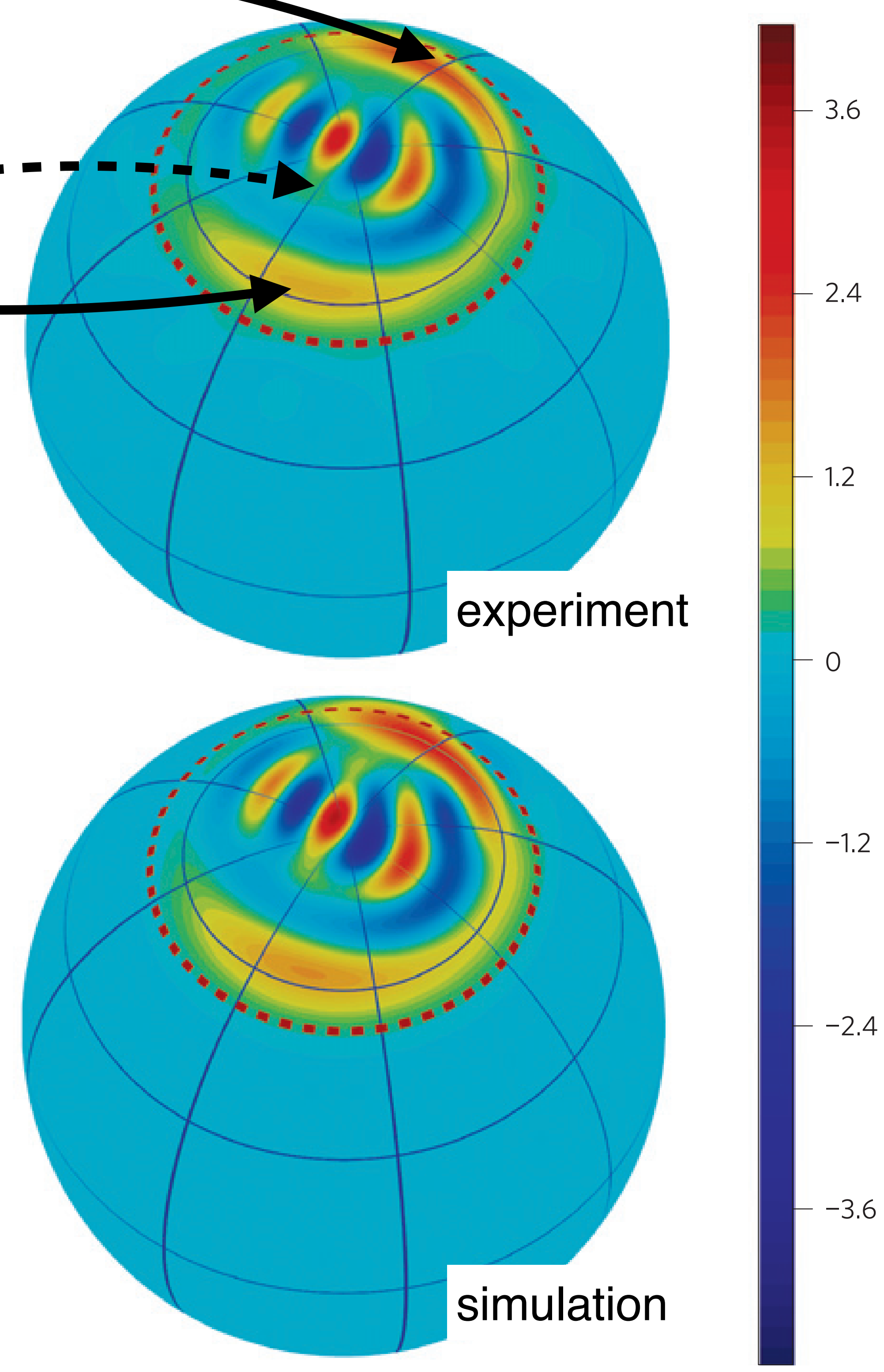


simulation

Wigner function

spin coherent state components

interference fringes



genuin quantum superposition of two distinct mesoscopic states

Conclusion

- Methods can be applied to SC qubits and circuit QED
- Reduce leakage through Zeno barrier
  to generate even larger cat states
- QZD induces very non-classical dynamics
  inside Zeno subspace
- Generation of Schrödinger cat spin states
  useful for quantum metrology [cf. (spin) squeezed states]