Collaborations and fundings

# Towards quantum Zeno dynamics with Rydberg atoms in a cavity

*Cavity Quantum Electrodynamics group*
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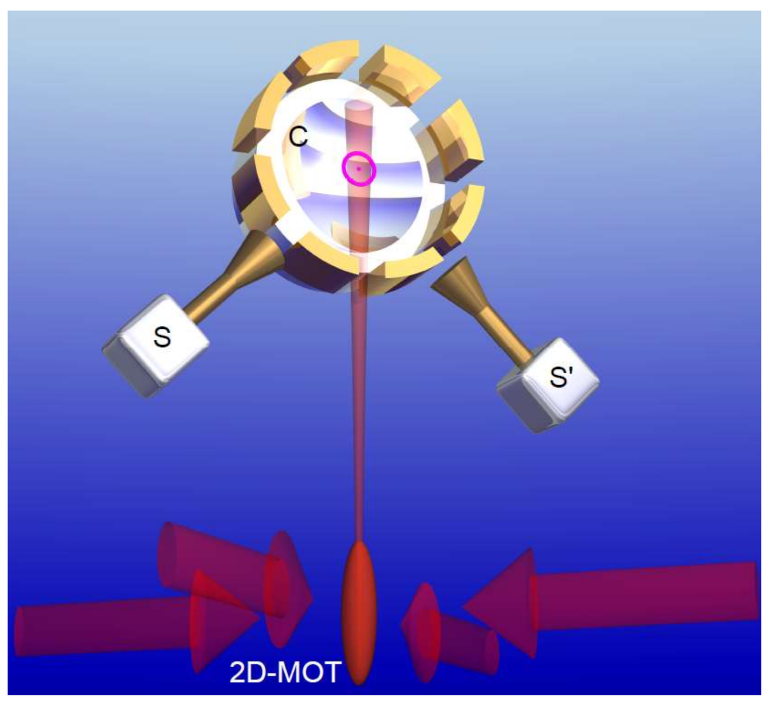
## Main Ideas

- A series of frequent measurement can block the evolution of a quantum system : the so-called quantum Zeno effect (QZE)
- When the measurement has degenerate eigenvalues, the evolution of the system is restricted to a subspace of its Hilbert space, giving rise to Quantum Zeno Dynamics (QZD)
- An implementation of QZD is possible in a state-of-the-art Cavity Quantum Electrodynamics (CQED) experiment, in construction at ENS.

## References

J.-M. Raimond *et al.* Phys. Rev. Lett. **105**, 213601
J.-M. Raimond *et al.* (to be published)

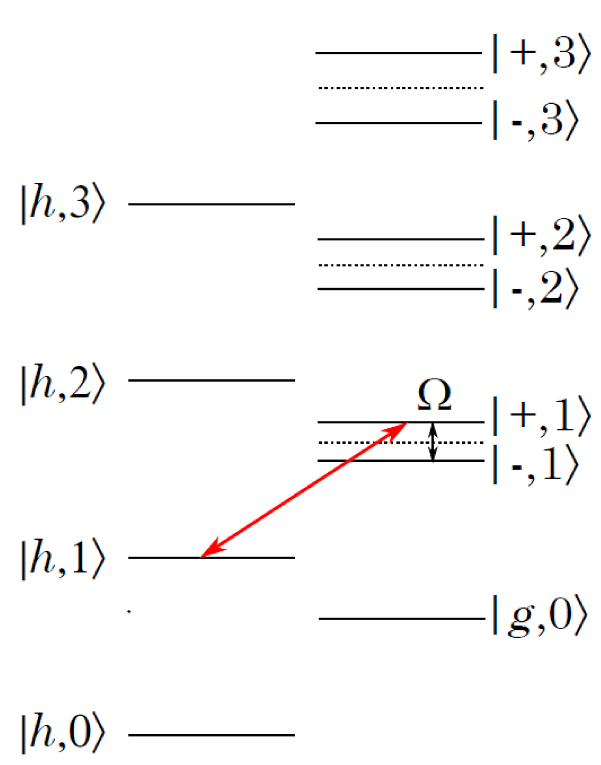
## A Cavity QED setup




- Superconducting Fabry-Perot cavity
- Mode at 51,1GHz with **lifetime up to 130 ms**
- Atoms out of a 2D-MOT are cooled and slowed via 3D moving molasses : **long residence in the mode waist (~10ms)**
- Preparation inside the cavity into circular Rydberg states $|g\rangle$ and $|e\rangle$ with **lifetimes of ~30ms**
- Atom and cavity are **strongly coupled**

Possible to achieve multiple manipulations on an atom in interaction with the field

## Quantum Zeno dynamics in CQED




### System

- A circular Rydberg atom (levels $|h\rangle$,$|g\rangle$,$|e\rangle$) coupled to a high-*Q* microwave cavity
- Levels $|g\rangle$ and $|e\rangle$ are strongly coupled to the cavity resulting in dressed states :

$$|g,0\rangle, \quad |\pm,n\rangle = \frac{1}{\sqrt{2}}(|e,n-1\rangle \pm |g,n\rangle), \quad n \geq 1,$$

where *n* is the number of photons in the cavity.

- A microwave source *S'* probes transitions between the levels $|h,n\rangle$ and the dressed states

### Evolution

- A source *S* injects photons in the cavity mode :

$$H = \alpha a^\dagger + \alpha^* a$$

### Quantum Zeno Dynamics

- Initial state $|h,0\rangle$,
- Coherent evolution over a time $\tau$ injects a small coherent field $|\beta = -i\alpha\tau/\hbar\rangle$ in the cavity,
- The source *S'* is tuned to perform a $\phi$=**2**$\pi$ Rabi pulse on the $|h,s\rangle \to |+,s\rangle$ transition ($s \geq 1$),
- The atom ends up in $|h\rangle$ , the field experiences the kick :

$$U_s = \mathbb{1} - 2|s\rangle\langle s|$$

- Coherent evolution and kick are repeated.

Total evolution : $U_K^{(N)}(t) = (U_s \exp -iHt/\hbar)^N , \quad t = \tau/N$ converges in the limit $N \to \infty$ to :

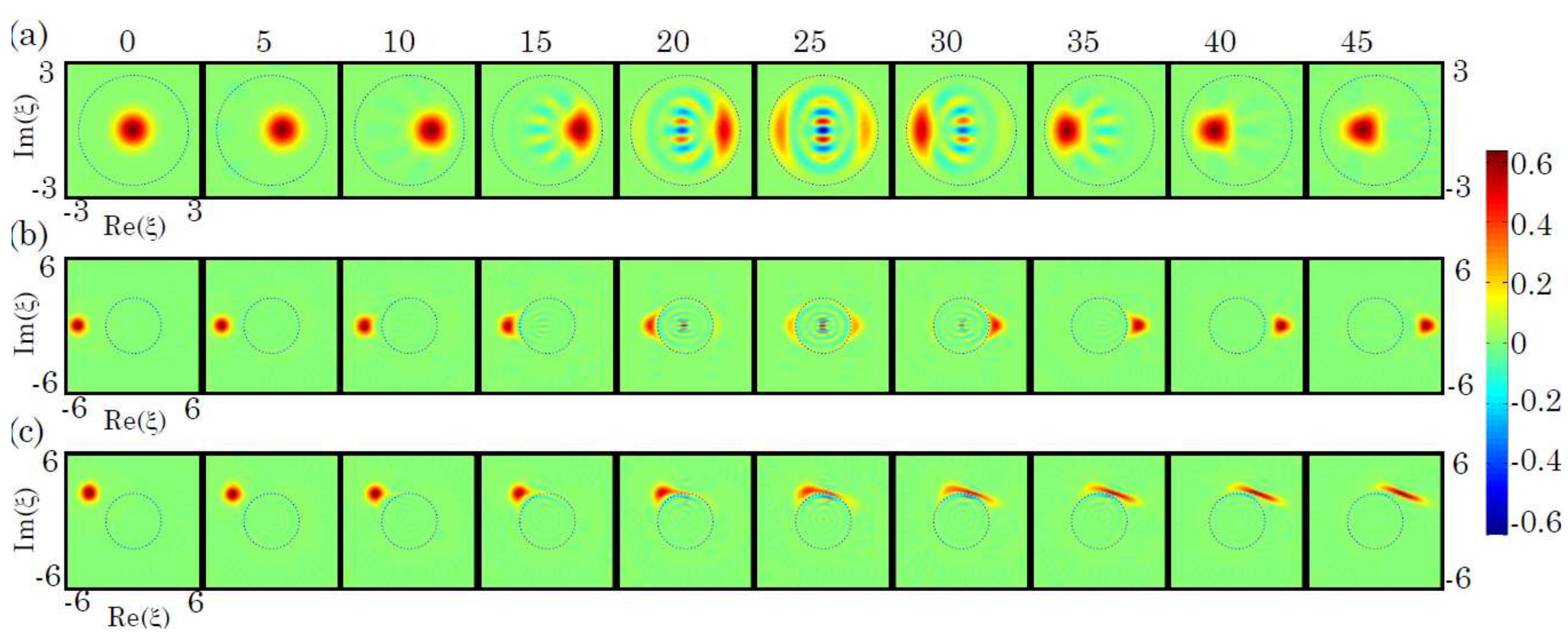
$$\boxed{H_Z = H_{<s} + H_{>s}}$$

Restriction of *H* to the subspace containing less than *s* photons

Restriction of *H* to the subspace containing more than *s* photons

## Confined dynamics in QZD

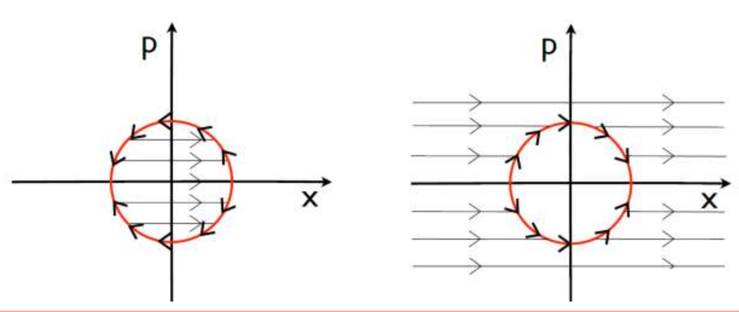
For *s=6* the coherent growth is confined inside or outside an **exclusion circle** (EC)




*Snapshots of the field Wigner function W(ξ) as a function of the number of steps N under QZD, for different initial field states.*

**Generation of Mesoscopic Field State Superpositions (MFSS) and squeezing**

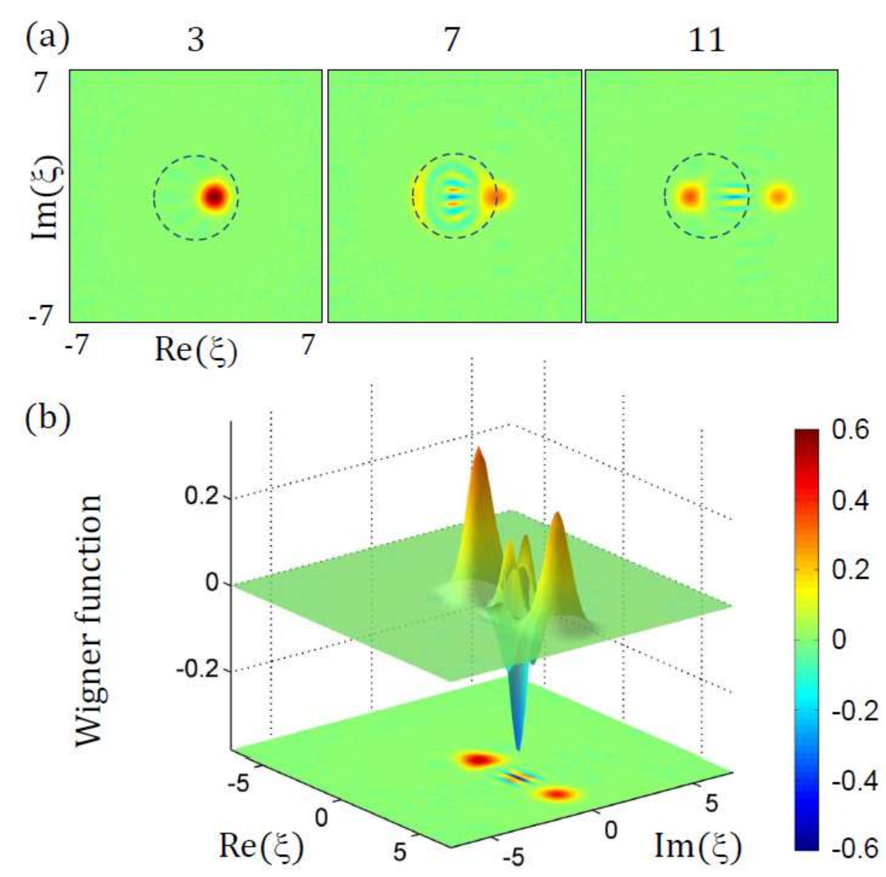
can be explained by the semi-classical vector field :




## Imperfect confinement and MFSS generation

- The $\phi = 2\pi$ Rabi pulse can be replaced by an **arbitrary** $\boldsymbol{\phi \neq 0}$**.** The field is still kicked and never contains *s* photons : no atom-field entanglement and perfect QZD for $N \to \infty$ .
- For finite $N$, different values of $\phi$ and $\beta$ (displacement per step) make the EC **semi-transparent.**

*For $\beta = 0.345$, and $\phi = 3.03$ rad, a MFSS containing 24 photons is generated in a few steps.*
*(a) Snapshots of W(ξ) for different number of steps*
*(b) Final Wigner function (N=14). Fidelity is 75% w.r.t. an ideal MFSS*



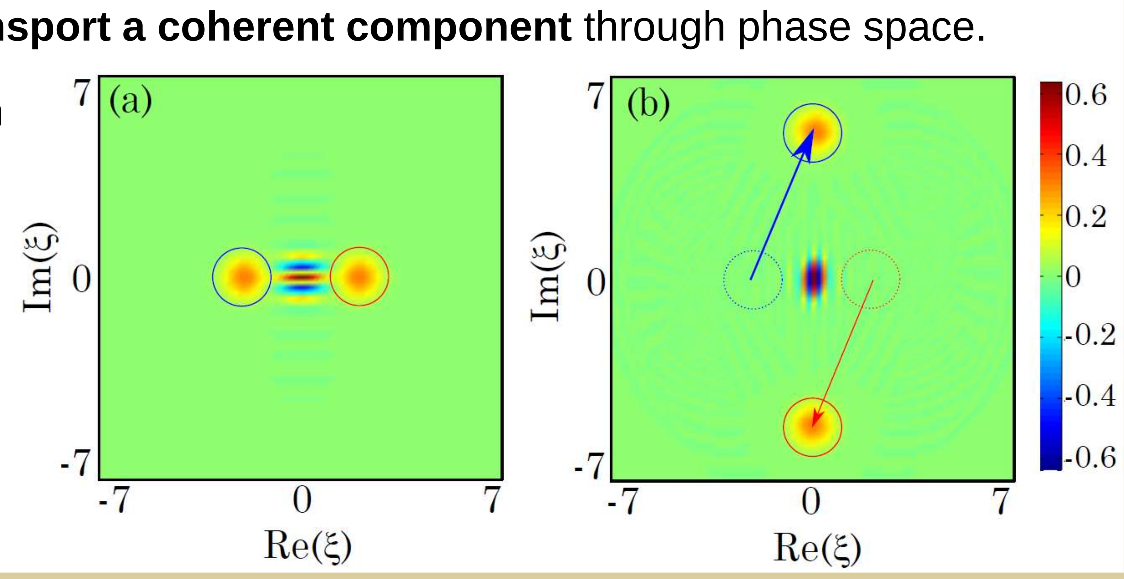

## Phase space tweezers

- The exclusion circle can be translated : apply the kick operation on a translated state

$$U_s \to D(\gamma) U_s D(-\gamma), \qquad D(\gamma) = \exp(\gamma a^\dagger - \gamma^* a)$$

- Without coherent injection, an EC with *s=1* translated to successive amplitudes $\gamma_i, \ |\gamma_i - \gamma_{i+1}| \ll 1$ will **trap and transport a coherent component** through phase space.
- Such **phase space tweezers** can be used to amplify a MFSS :

*The state* $|2\rangle + |-2\rangle$ (a) *is turned in 100 steps (50 for each component) into the state* $|5i\rangle + |-5i\rangle$ (b)




## Arbitrary state synthesis

**Principle :** "pull" with tweezers any superposition of coherent components from the vacuum

- **Step 1 :** split the amplitude of the vacuum between two atomic states :

$$|g,0\rangle \to a_1|g,0\rangle + b_1|h,0\rangle$$

(Use a narrowband source $S_2$ to address specifically this transition)

- **Step 2 :** protect the $|g,0\rangle$ component : "shelving" to a level $|i\rangle$

$$a_1|i,0\rangle + b_1|h,0\rangle$$

(Hard $\pi$ pulse with a source $S_3$)

- **Step 3 :** tweezing from 0 to $\gamma_1$ acts only on the $|h,0\rangle$ component

$$a_1|i,0\rangle + b_1|h,\gamma_1\rangle$$

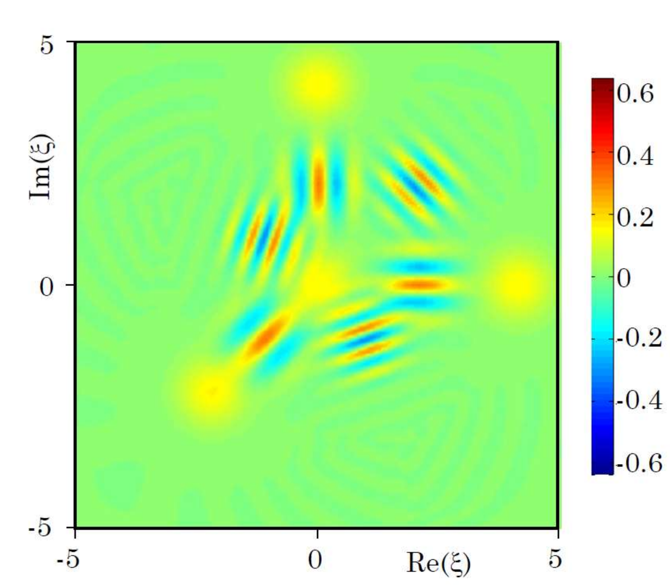
- **Step 4 :** restore the $|g,0\rangle$ component with $S_3$

$$a_1|g,0\rangle + b_1|h,\gamma_1\rangle$$

- **Iterate from step 1 :**

Coefficients $a_i$ and $b_i$ can be tuned to produce an arbitrary state $|\psi_t\rangle = \sum_{j=1}^{m} c_j|\gamma_j\rangle$

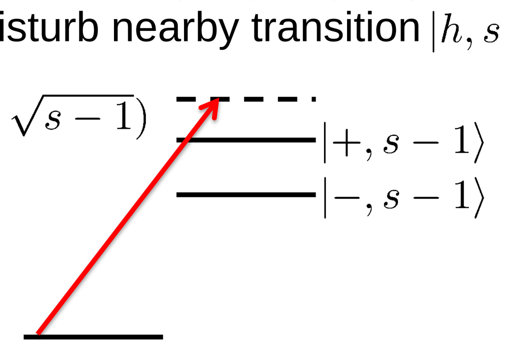
*(right) Wigner function W(ξ) of the state*
$$|4\rangle + |4i\rangle + |3e^{i5\pi/4}\rangle + |0\rangle$$
*obtained with 99% fidelity*




## Realistic experiment

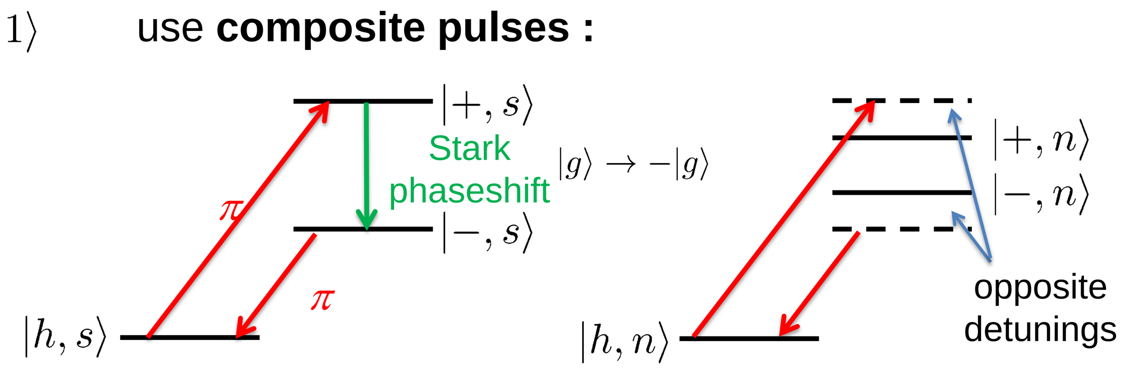
- Source *S'* addressing $|h,s\rangle \to |+,s\rangle$ should not disturb nearby transition $|h,s-1\rangle \to |+,s-1\rangle$

$\delta = \frac{\Omega}{2}(\sqrt{s} - \sqrt{s-1})$




- Pulse duration chosen for a $\boldsymbol{p_p\pi}$ **pulse** ($p_p$ even) on $|h,s-1\rangle \to |+,s-1\rangle$

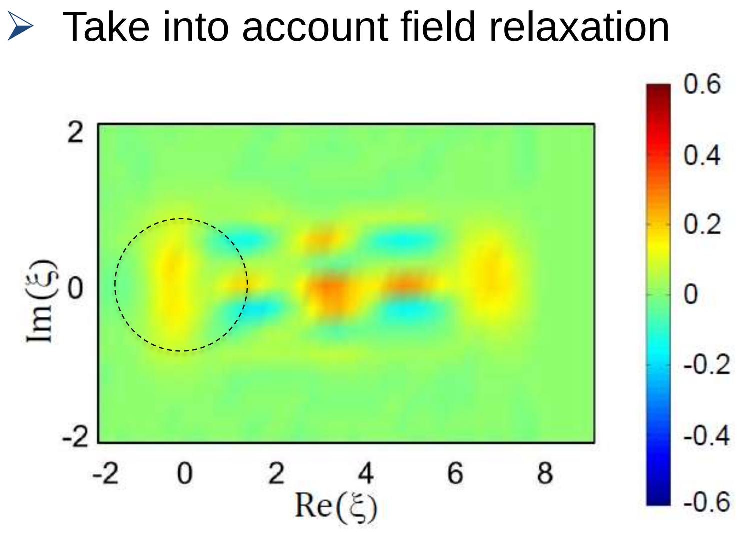
- Phase shifts on $|h,n\rangle$ levels (light shift effect) : use **composite pulses :**




- **Low spurious transfers and phase shifts**

### Promising simulations

- Take into account field relaxation




*Two collisions with an s=3 EC produce a three-component MFSS in 4.4ms*
*Fidelity w.r.t. an ideal MFSS is 69%*