

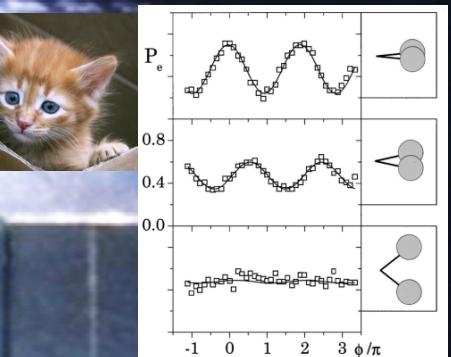
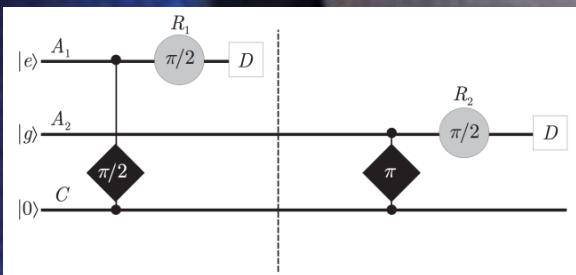
$$\hat{H} = \hbar\omega_c(\hat{a}^\dagger\hat{a}) + \hbar\omega_a(\hat{\sigma}_+\hat{\sigma}_-) + \hbar g(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+)$$

Fundamental Quantum Physics

Cavity QED

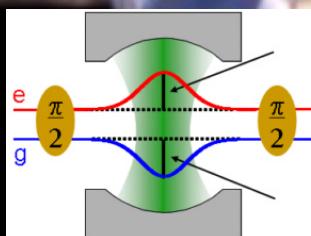
Experiment at LKB
S.Haroche, J.M. Raimond

Quantum Information

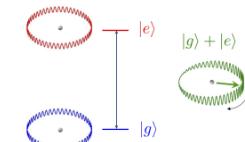


Complementarity

QND measurements



Des horloges atomiques ultra-précises
Horloge mécanique Horloge atomique



Outline

Aim and orders of magnitude

Apparatus

Rabi Oscillations

Ramsey Interferometry

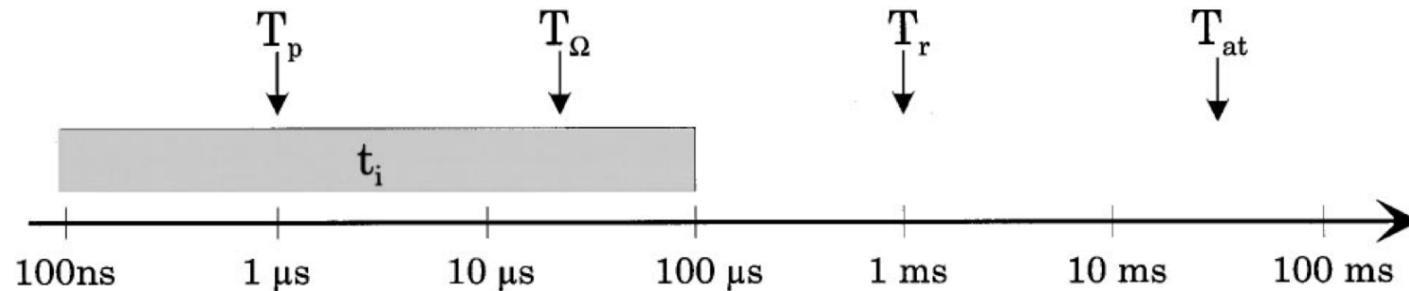
Conclusion

Interaction: light field \leftrightarrow atom

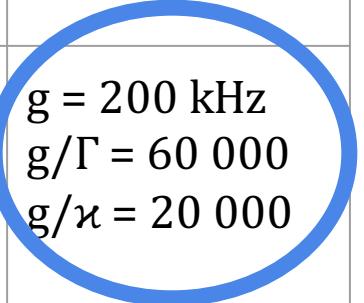
Jaynes Cummings model

$$\hat{H} = \hbar\omega_c(\hat{a}^\dagger\hat{a}) + \hbar\omega_a(\hat{\sigma}_+\hat{\sigma}_-) + \hbar g(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+)$$

Strong coupling regime: $\kappa, \Gamma \ll g \ll \omega_a, \omega_c$



How to access the strong coupling regime

	Groundstate $\tau = 100 \text{ ns}$ $\Gamma \sim 10 \text{ MHz}$	Rydberg state $\tau = 30 \text{ ms}$ $\Gamma \sim 30 \text{ Hz}$
Optical 300 THz 0.1 - 1 μm $\kappa \sim \text{MHz}$	$g = 3 \text{ GHz}$ $g/\Gamma = 300$ $g/\kappa = 300$	$g = 400 \text{ MHz}$ 
Microwaves 51 GHz 6 cm $\kappa \sim 10 \text{ Hz}$	$g = 3 \text{ kHz}$ 	 $g = 200 \text{ kHz}$ $g/\Gamma = 60 \, 000$ $g/\kappa = 20 \, 000$

$$g = \sqrt{\frac{w_c|d|^2}{2\epsilon_0\hbar V}}$$

Property	n dependence
Binding energy	n^{-2}
Energy between adjacent n states	n^{-3}
Orbital radius	n^2
Geometric cross section	n^4
Dipole moment $\langle nd er nf\rangle$	n^2
Polarizability	n^7
Radiative lifetime	n^3
Fine-structure interval	n^{-3}

How to access the strong coupling regime

Rydberg
Atoms

$g = 400 \text{ MHz}$



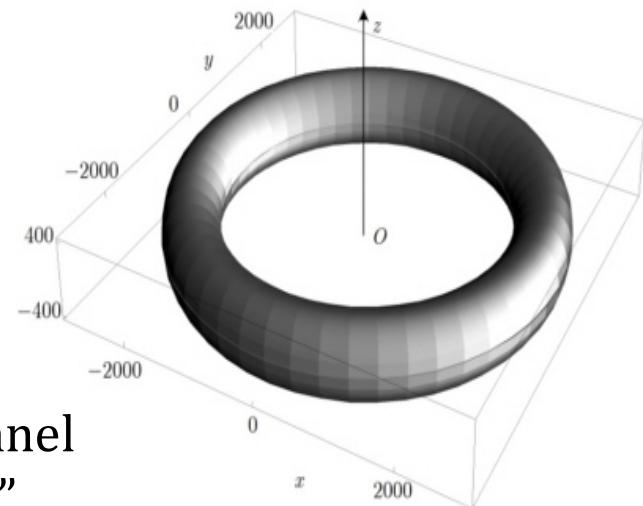
$g = 200 \text{ kHz}$

$g/\Gamma = 60\,000$

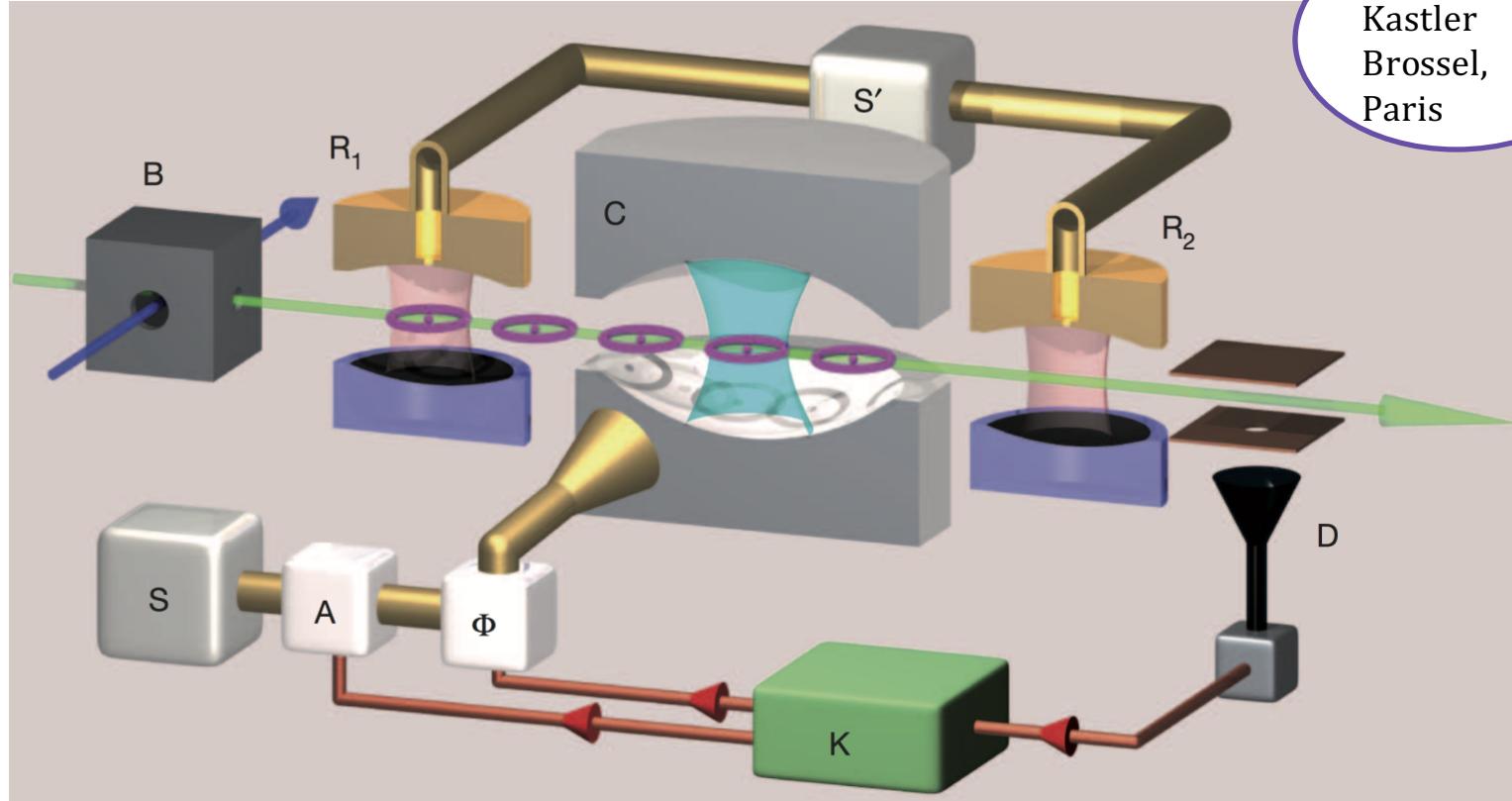
$g/\kappa = 20\,000$

Circular state:

- maximum l, m
- most “classical” state
- long lifetime $\tau \propto n^3$
- very good 2-level-system (in directing el.field)
 $\Delta l = \pm 1 \rightarrow$ unique decay channel
- “sensitive and selective detection”

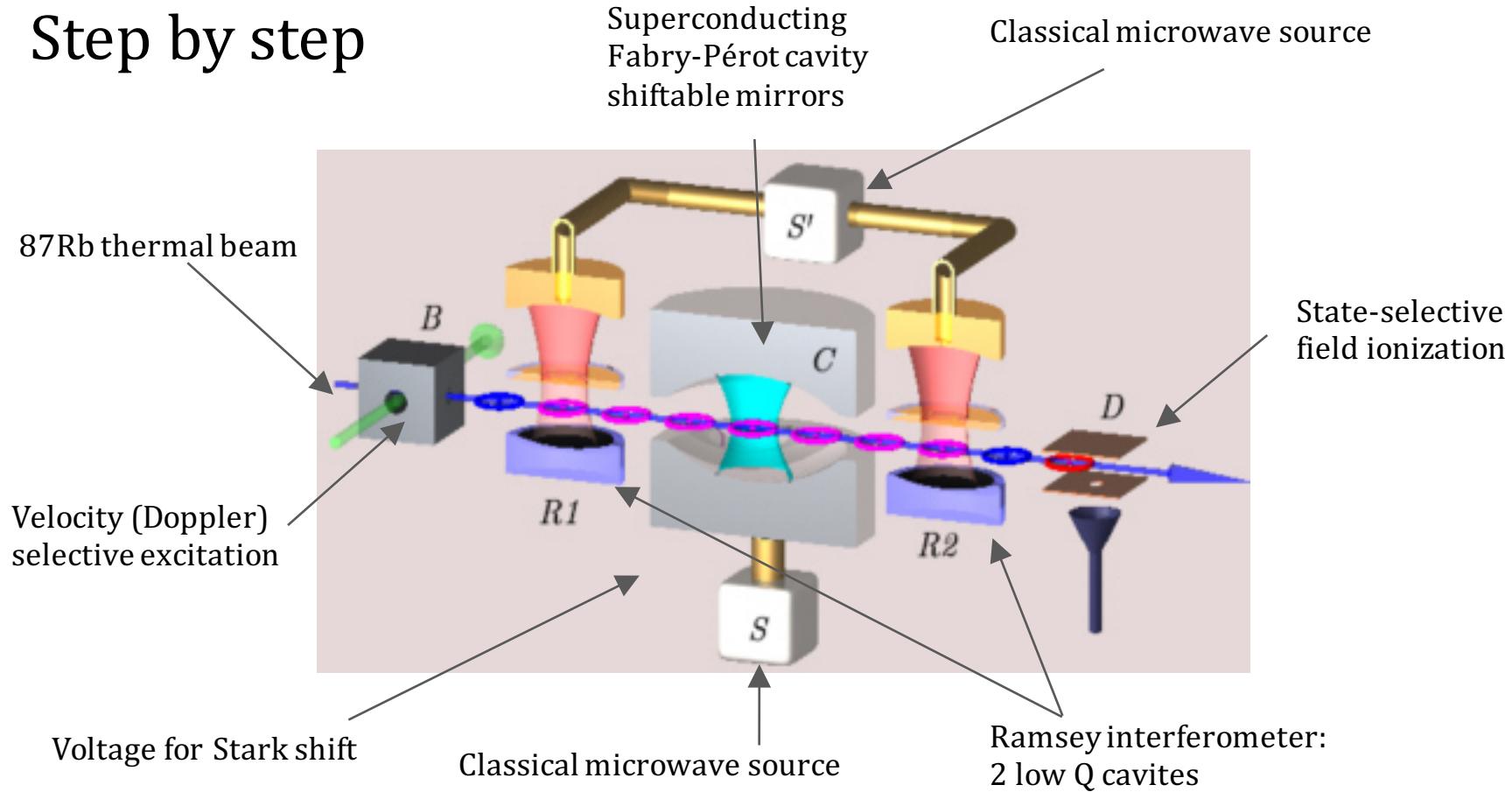


Overview of the setup



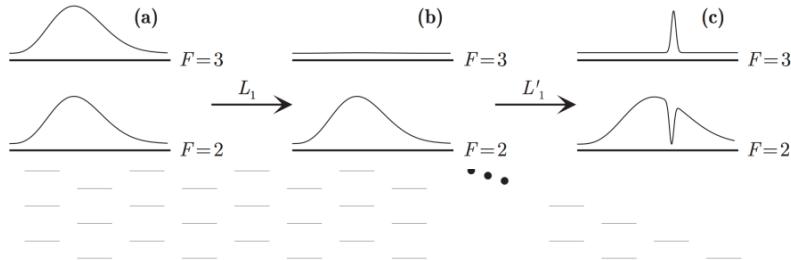
Laboratoire
Kastler
Brossel,
Paris

Step by step



Circular State Preparation

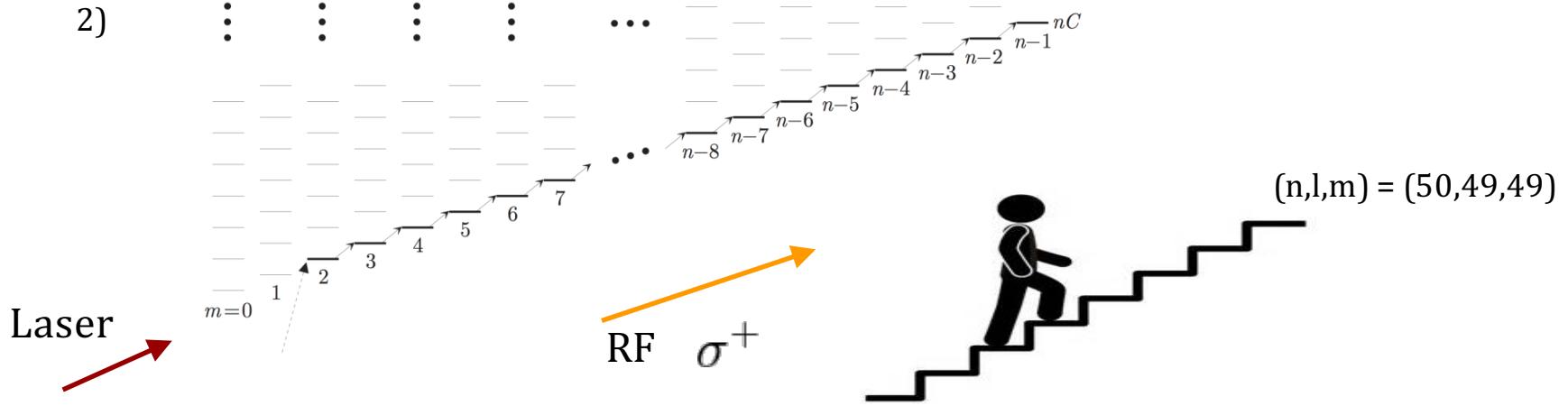
1)



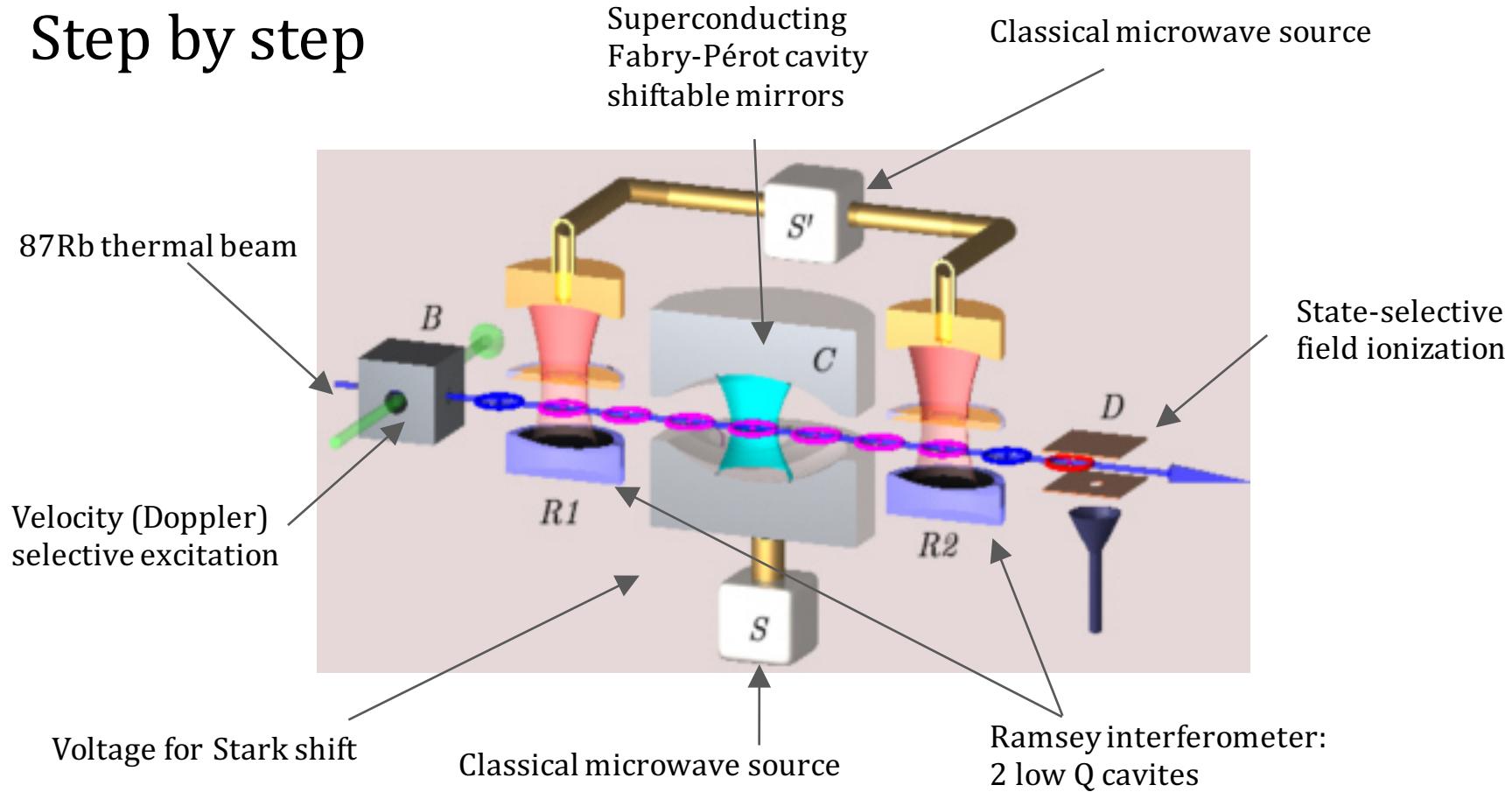
$$v = 503 \pm 2 \text{ ms}^{-1}$$

$$\Delta x = \pm 1 \text{ mm}$$

2)



Step by step



$$Q = 3 \cdot 10^8$$

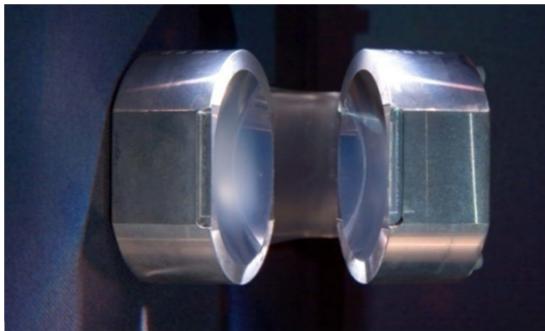
$$T_r = 1 \text{ ms}$$

(today: 0.13 s)

Superconducting Fabry-Pérot Cavity

Superconducting
Highly polished
Niobium mirrors

- Diameter 50 mm
- Curvature 40 mm
- Length 27 mm
- 9 antinodes



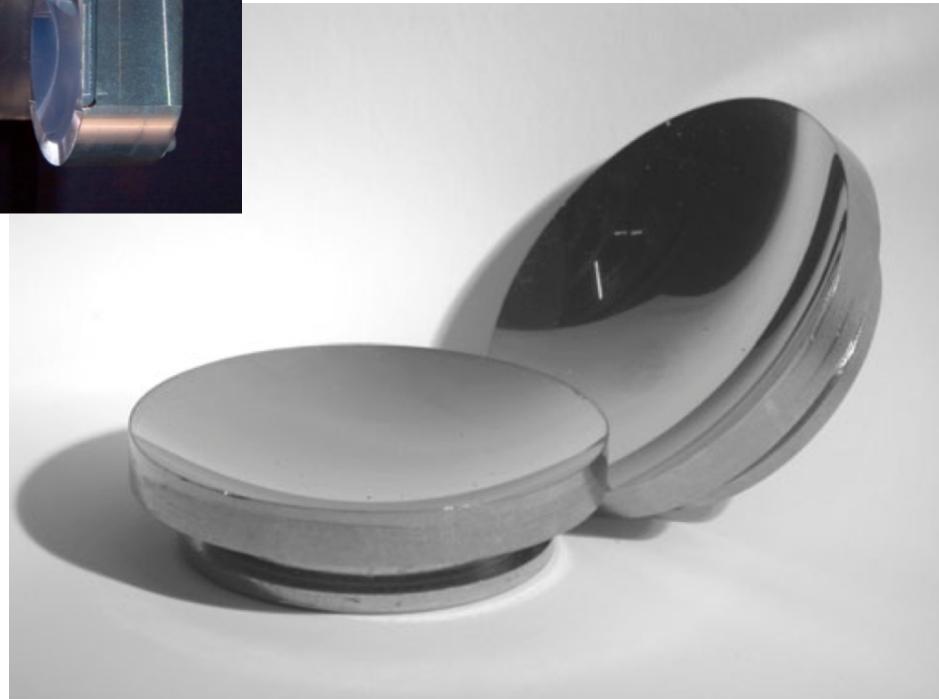
Cryostat → 0.8 K

Liquid Nitrogen

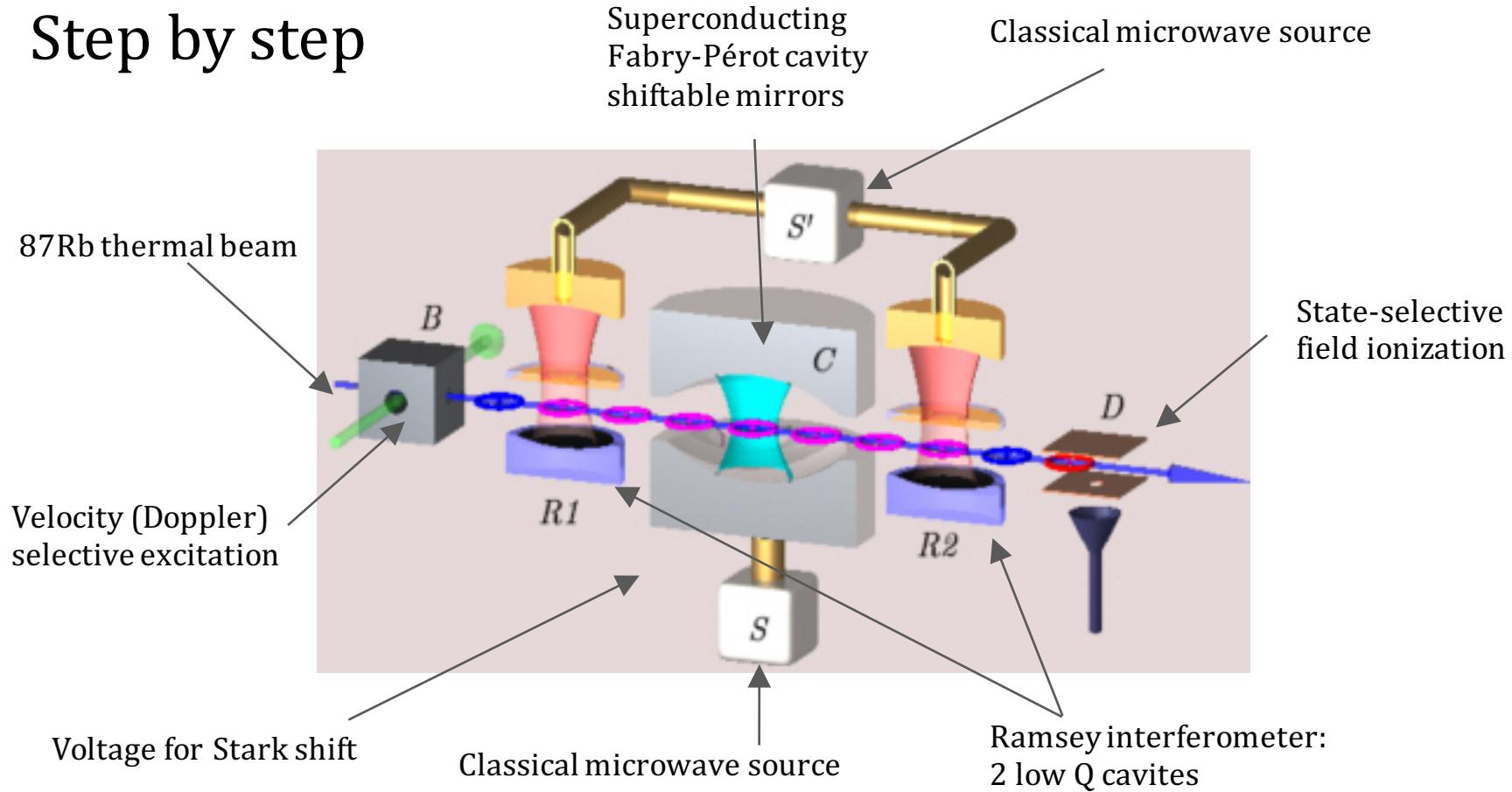
Liquid Helium-4

Liquid

Helium-3

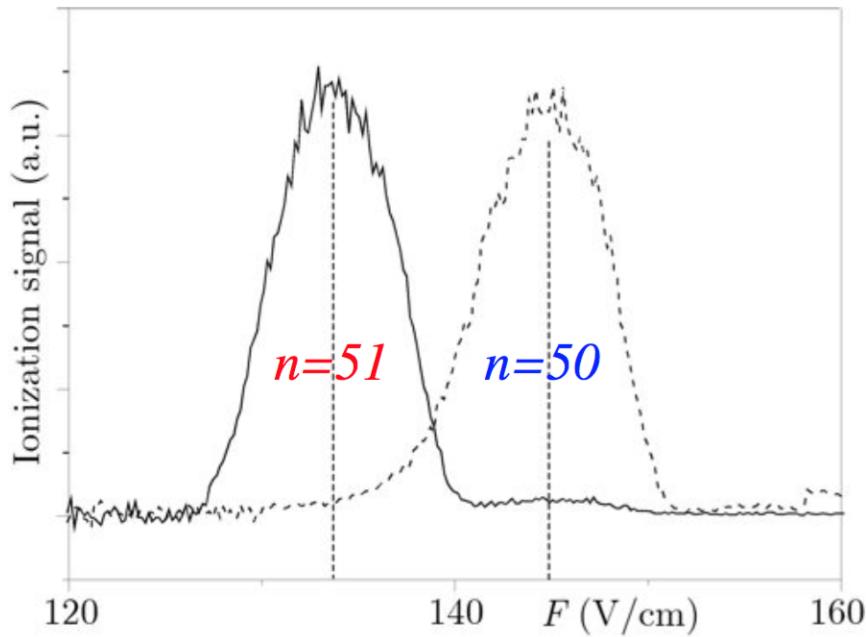


Step by step

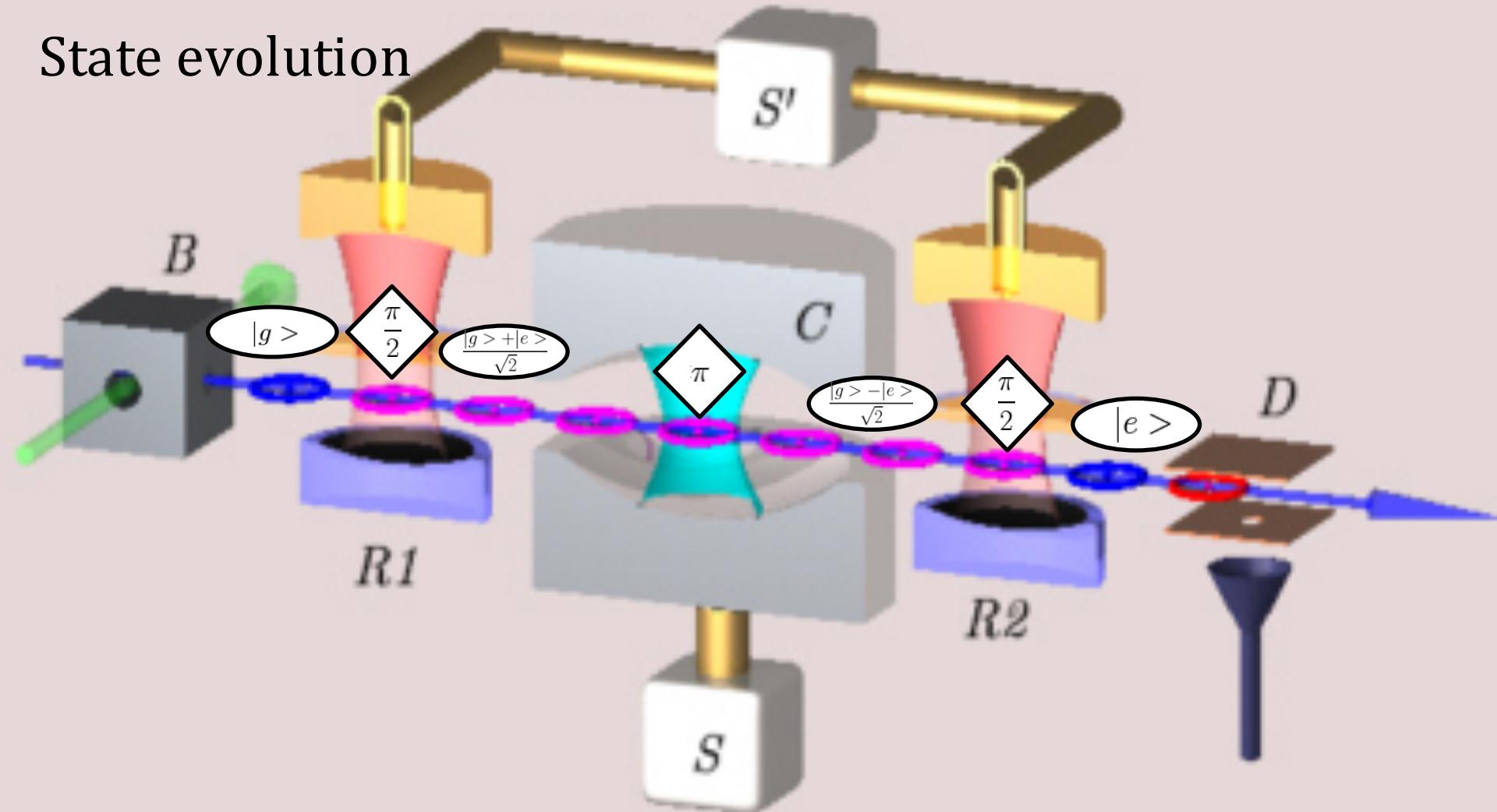


Detection

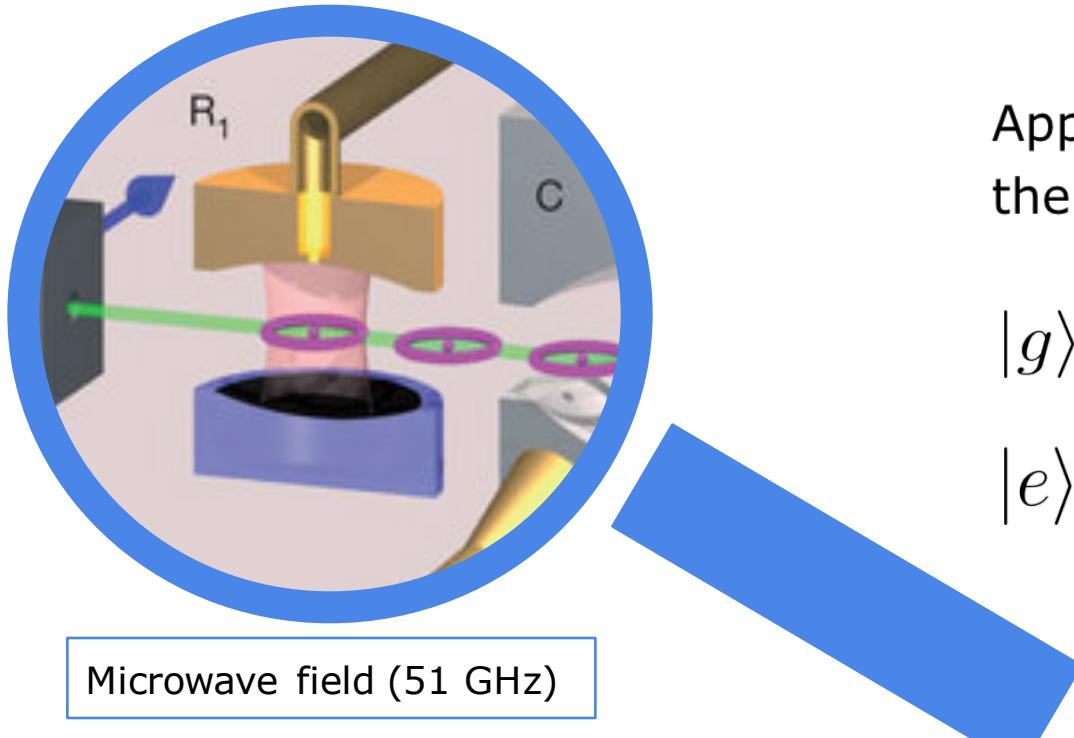
- Electric field ionizes atoms depending on their main quantum number n
- adjustable
- circular state purity 98 %
- Up to 80% detection efficiency
90% fidelity after selection



State evolution



Ramsey Interferometry



Applying a $\frac{\pi}{2}$ - pulse to the Rydberg atoms:

$$|g\rangle \rightarrow (|g\rangle - |e\rangle)/\sqrt{2}$$

$$|e\rangle \rightarrow (|e\rangle + |g\rangle)/\sqrt{2}$$

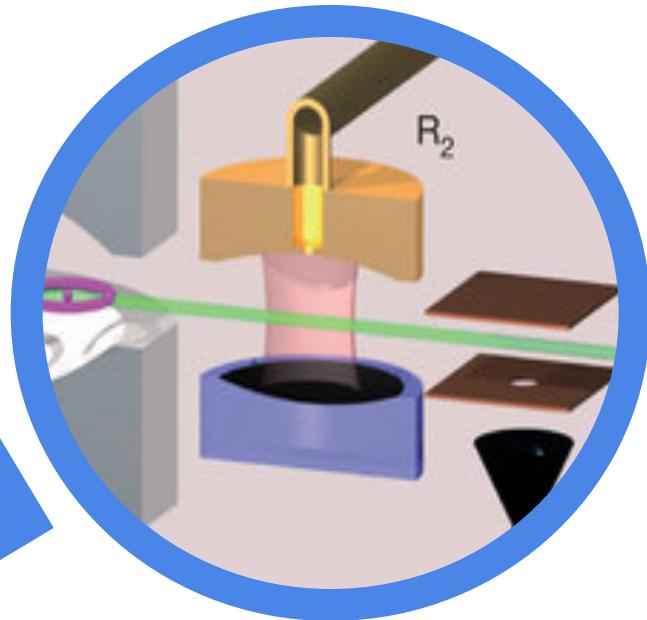
Microwave field (51 GHz)

Ramsey Interferometry

Applying another $\frac{\pi}{2}$ - pulse
after time T .

$$|e\rangle \rightarrow (|e\rangle + \exp(i\phi) |g\rangle)/\sqrt{2}$$

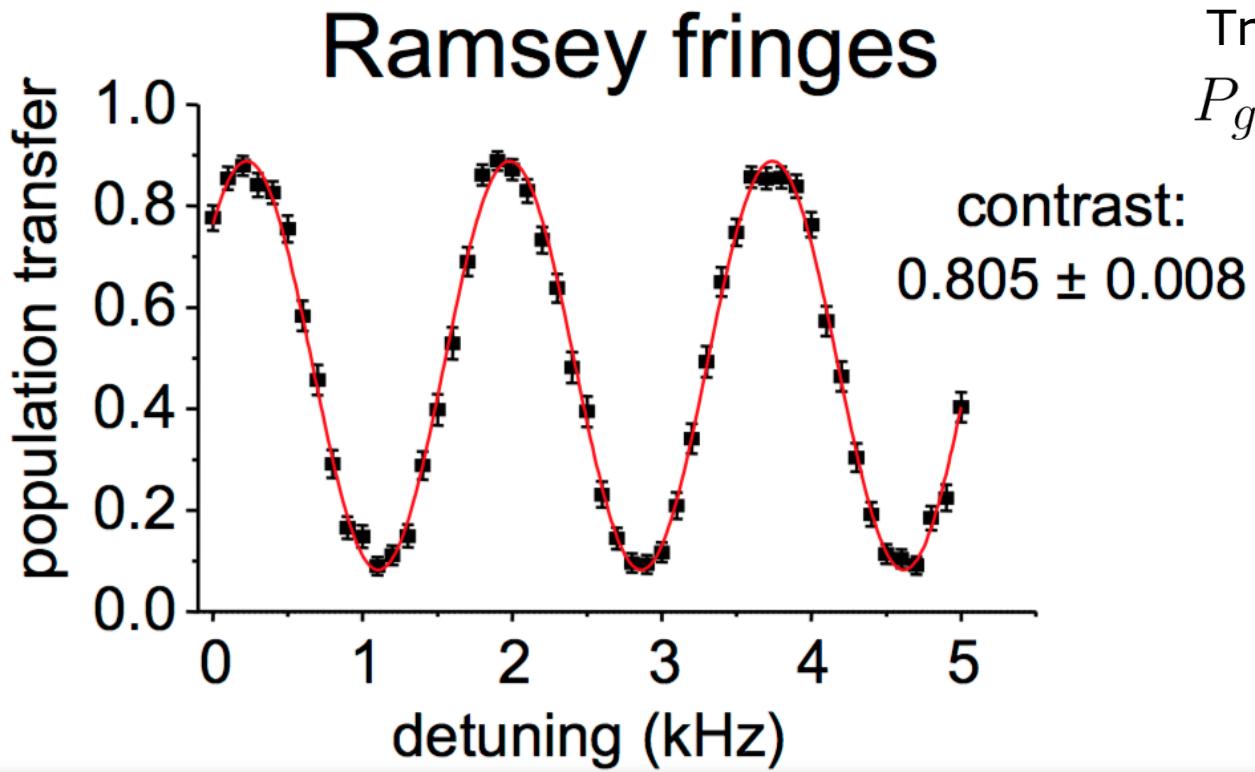
$$|g\rangle \rightarrow (|g\rangle - \exp(-i\phi) |e\rangle)/\sqrt{2}$$



Microwave field (51 GHz)

Ramsey Interferometry

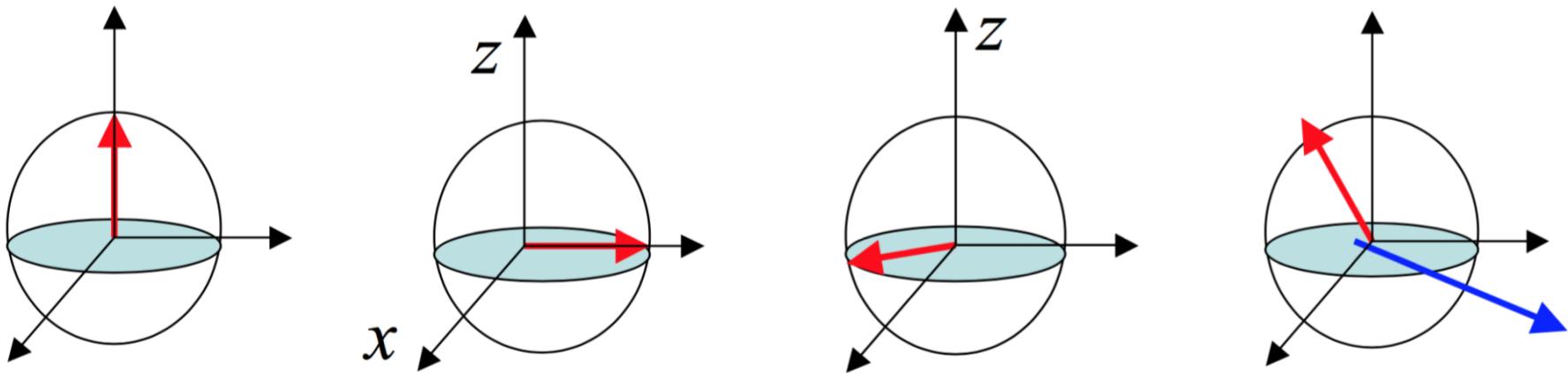
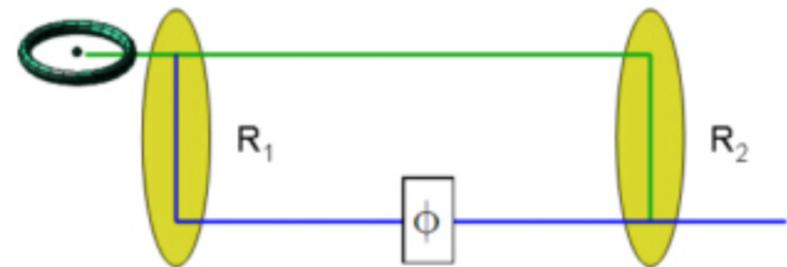
Acquired phase shift
 $\phi = (\omega_r - \omega_{eg})T$



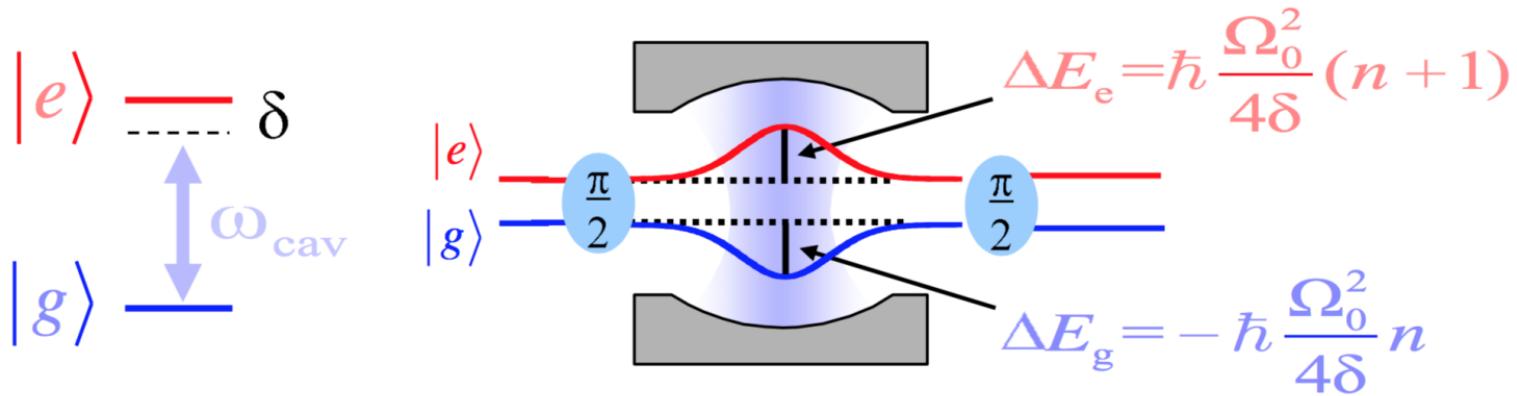
Transition probability

$$P_g = 1 - P_i = (1 - \cos\phi)/2$$

Ramsey Interferometry



Quantum Non-Demolition measurement of light

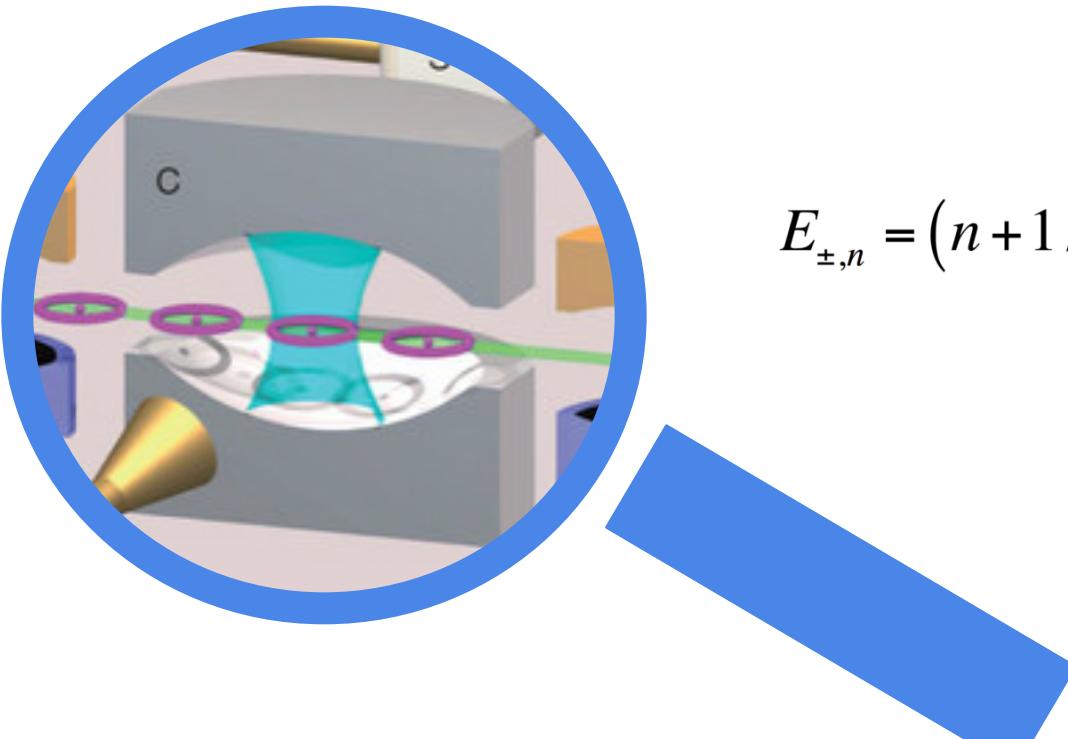


- count photons without destruction
- 1. Ramsey zone: $\pi/2$ pulse \rightarrow superposition
- Cavity: phase shift
- 2. Ramsey zone: $\pi/2$ pulse \rightarrow photon number

$$\Delta\varphi = \Phi(n+1/2)$$

Rabi Oscillations

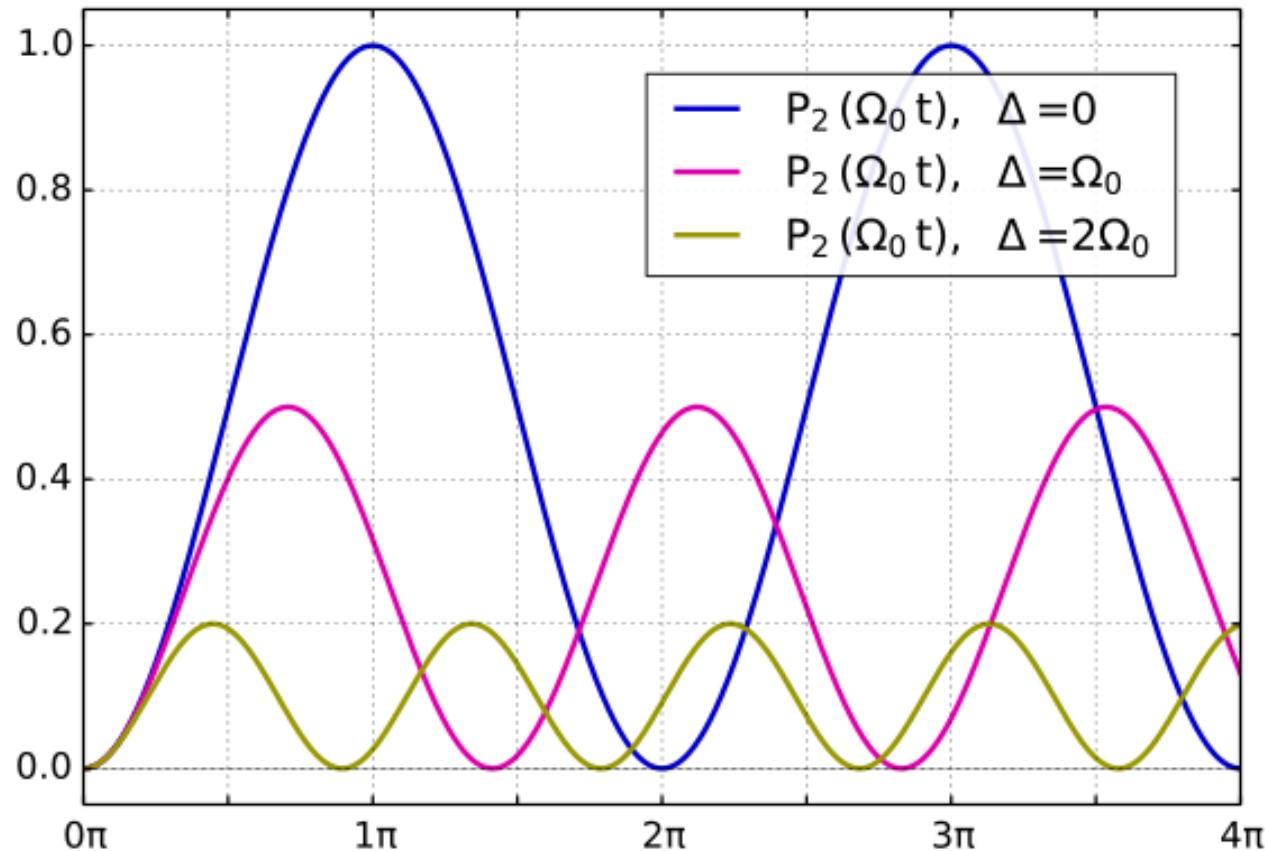
$$H = \hbar\omega_{eg}\sigma_z + \hbar\omega(a^\dagger a + 1/2) - i\frac{\hbar\Omega}{2}f(x)(\sigma_+a - \sigma_-a^\dagger)$$



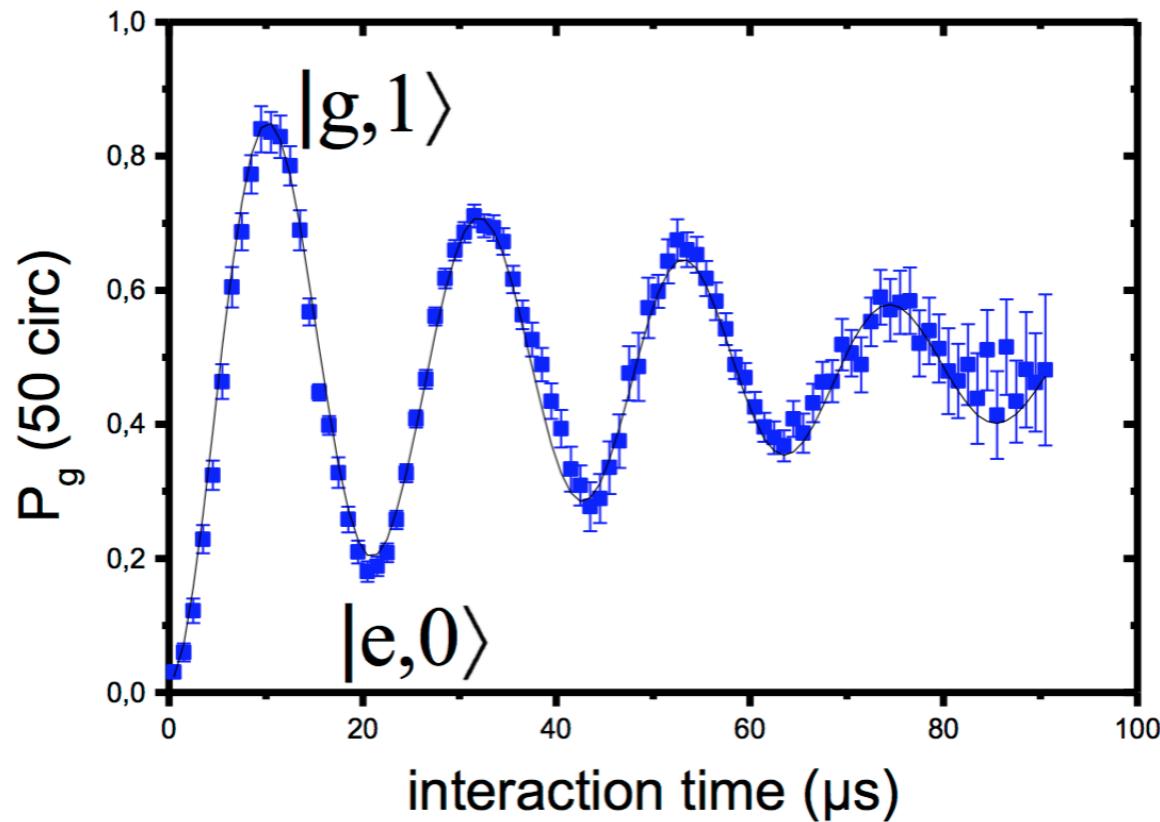
$$E_{\pm,n} = (n + 1/2)\hbar\omega_{oh} \pm \frac{\hbar}{2}\sqrt{\Delta^2 + \Omega^2(n + 1)}$$

Rabi Oscillations

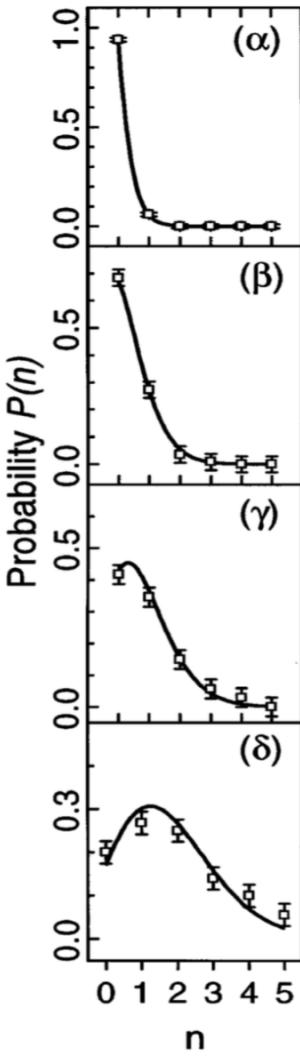
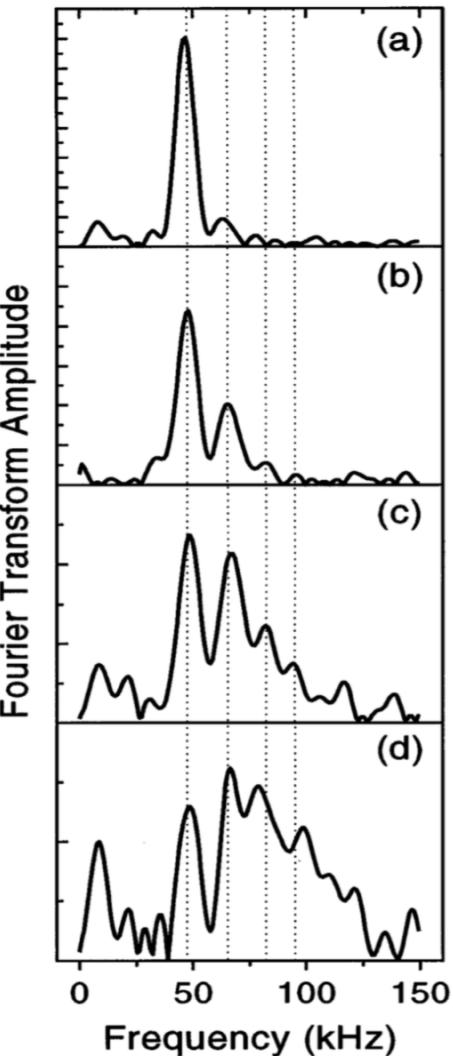
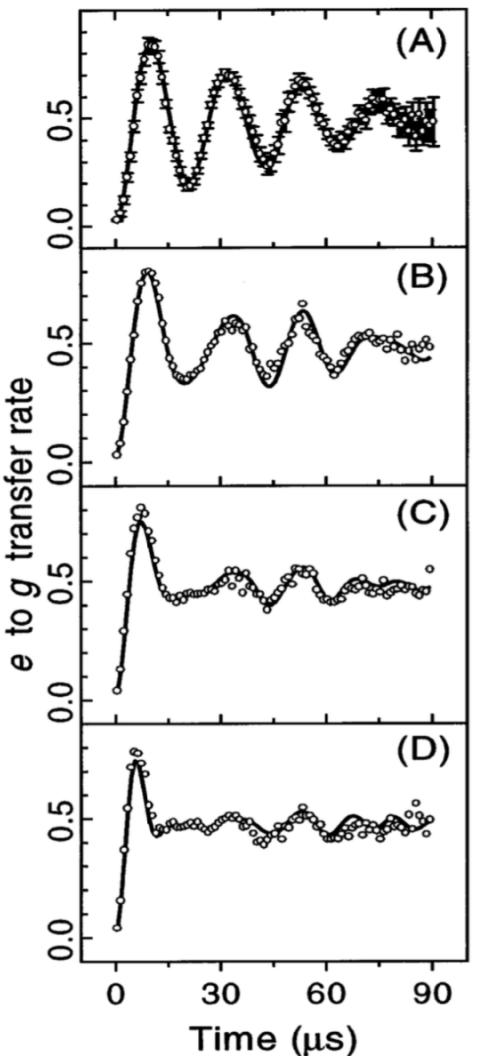
$$P_e = \frac{1 + \cos \Omega t_i}{2}$$



Rabi Oscillations



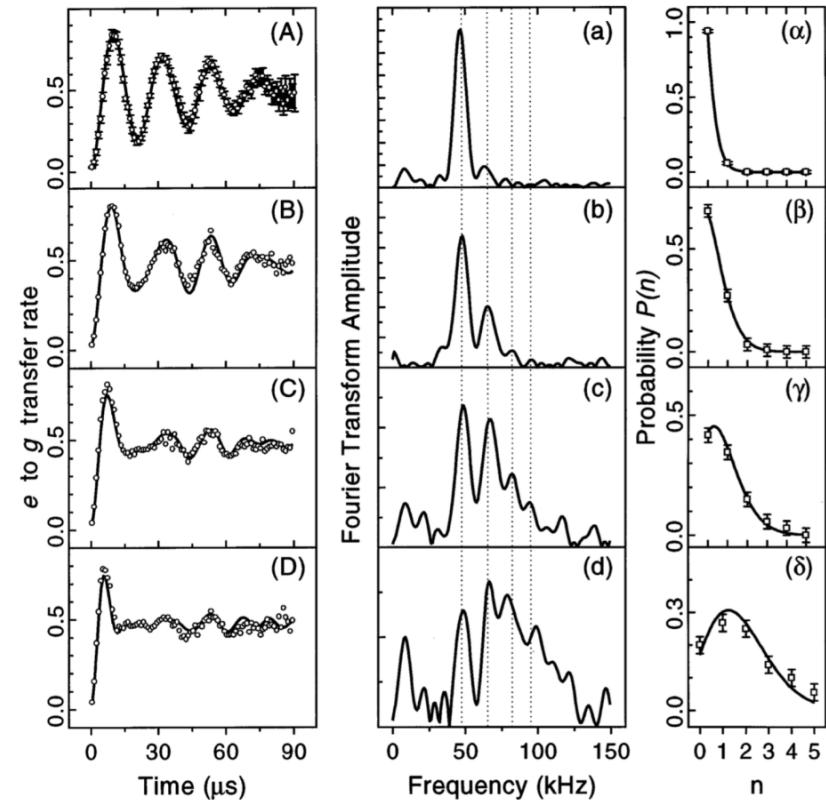
Coherent field



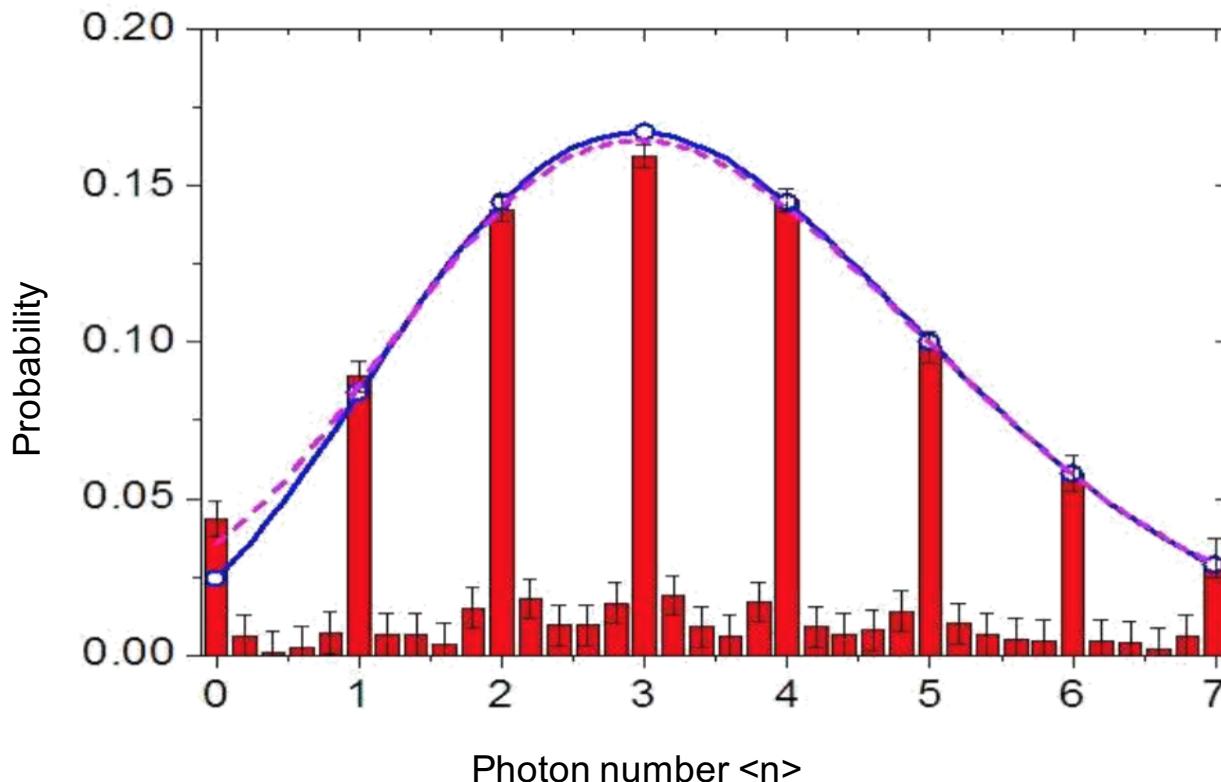
Large number of photons: Collapse and Revival

$$\text{Coherent state: } |\alpha\rangle = \sum_{n=0} \alpha^n \frac{e^{\frac{-|\alpha|^2}{2}}}{\sqrt{n!}} |n\rangle$$

$$P_{eg}(t) = \sum_n P(n) \sin^2 \Omega \sqrt{n+1} t$$



Coherent state



So what?

Where are the difficulties?

Problems to solve

- **Quality/finesse of cavity**
- **Decoherence time**
- Control Rydberg states
- Strong Coupling
- Screen room-temperature blackbody field
- Selection mechanism for velocity

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