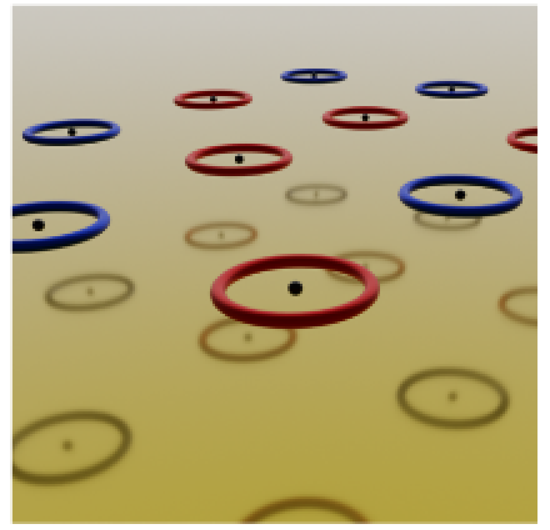

# Toward Quantum Simulation with Circular Rydberg Atoms

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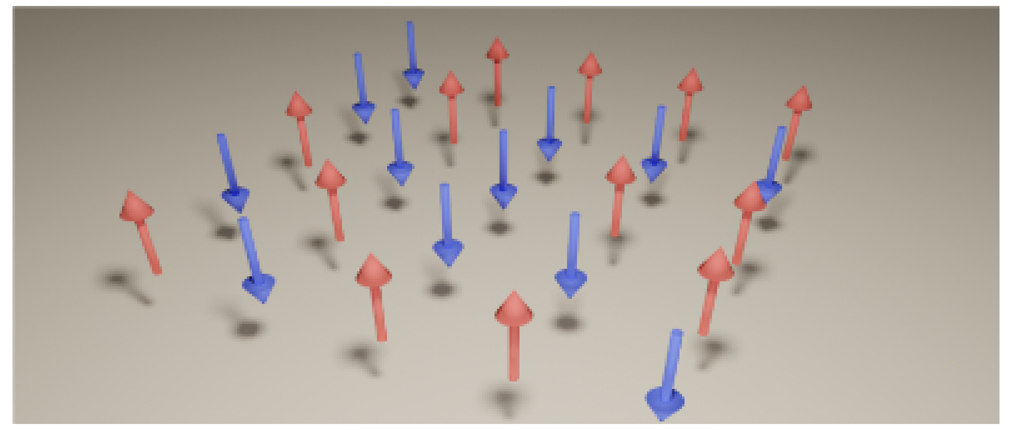
## Quantum simulation of a spin array using circular Rydberg atoms

### Classical simulation of N-spin arrays:

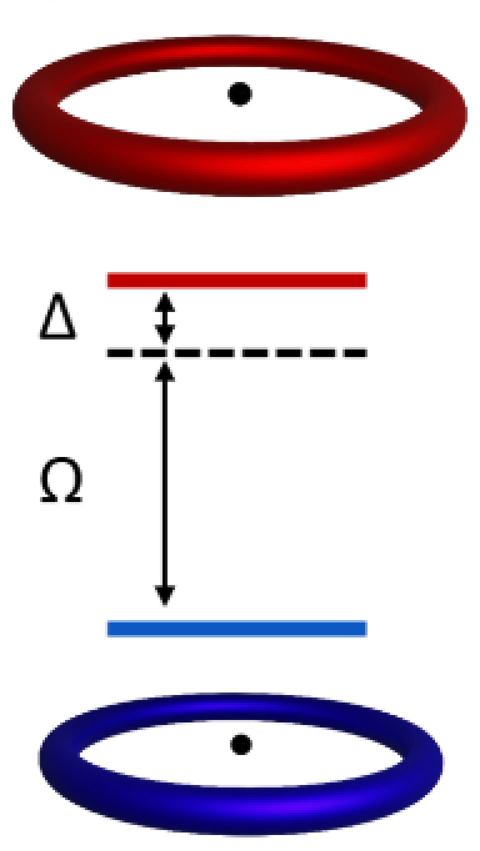
- Exact diagonalisation only for $N \approx 50$
- Dynamics hard to simulate

→ Quantum simulation !



### Requirements:

- Spins ½ in a defect free array with arbitrary geometry
- Long lifetimes and strong interactions
- Fully tunable Hamiltonian




### Spin ½: circular Rydberg states

- Circular levels: $n \gg 1, l = m_l = n-1$, orbit $\approx n^2 a_0$
- **Long-lived** states: ≈ 30ms at 0K, up to 50s in a spontaneous emission inhibition structure
- **Huge dipole-dipole interaction** at few microns, tunable by static electric and magnetic fields
- Spin ½ = Two circular states
- Effective longitudinal and transverse magnetic field = MW dressing

→ XXZ Hamiltonian with **dynamically tunable parameters**:

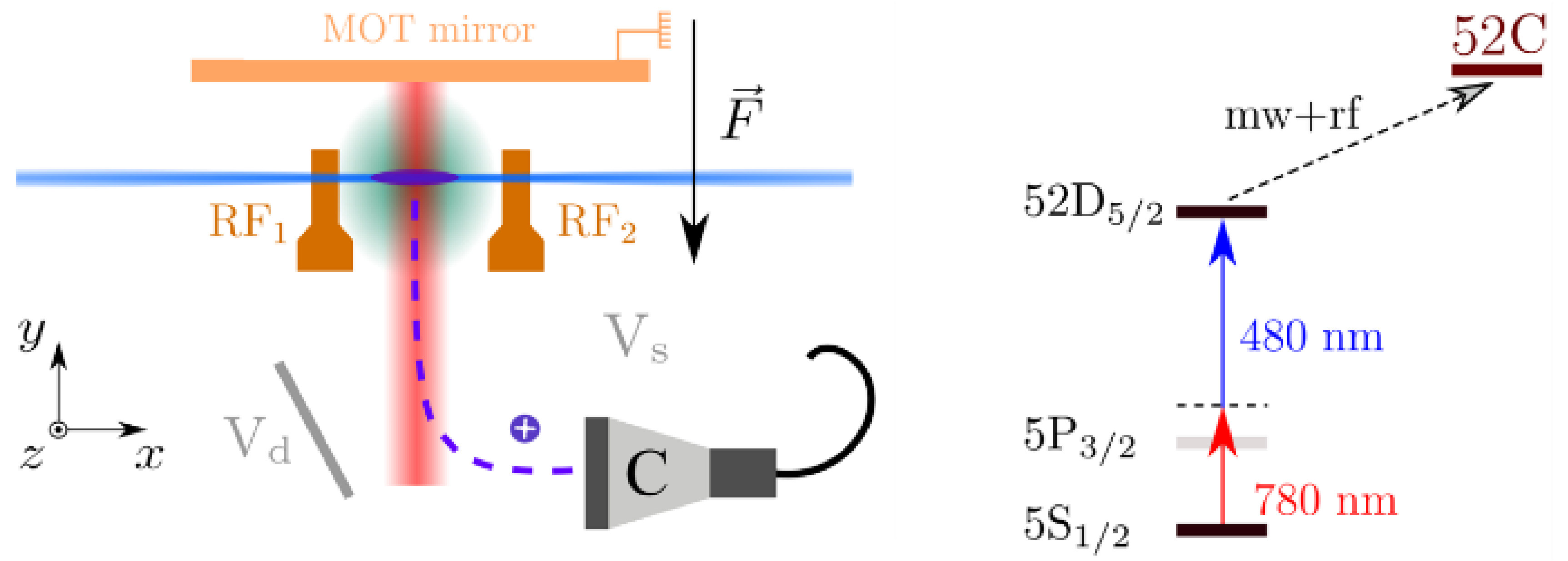
$$H/\hbar = \frac{\Delta}{2}\sum_j \sigma_j^z + \frac{\Omega}{2}\sum_j \sigma_j^x + J_z \sum_{\langle j,j'\rangle} \sigma_j^z \sigma_{j'}^z + J \sum_{\langle j,j'\rangle} \left(\sigma_j^x \sigma_{j'}^x + \sigma_j^y \sigma_{j'}^y\right)$$

T.L. Nguyen et al., PRX **8**, 011032 (2018)

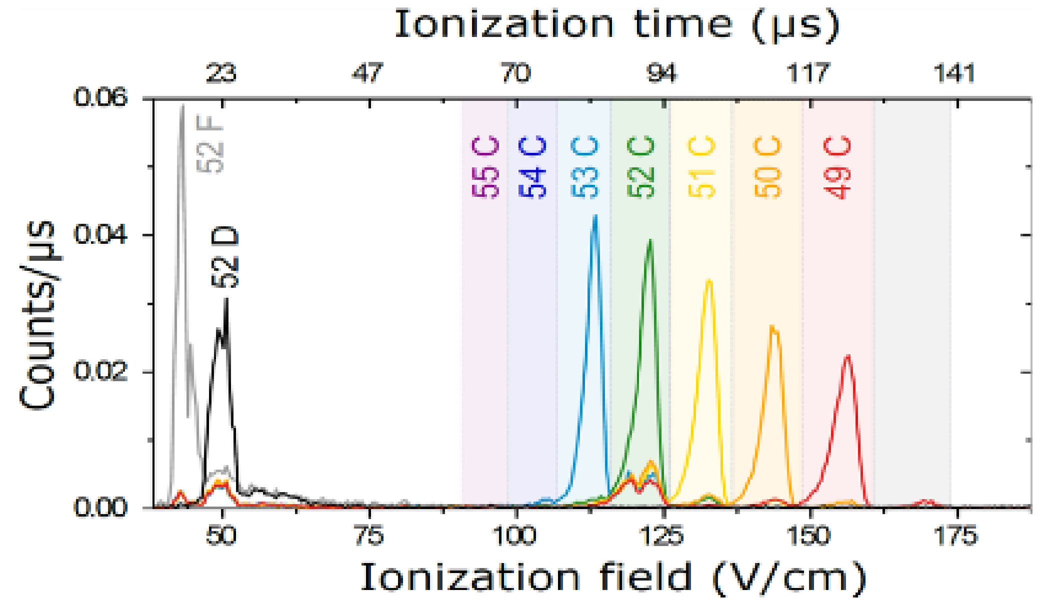
# 2D trapping of cold circular Rydberg atoms in a cryostat

## Preparation and detection:

- Cryogenic environment at 4K
- Atomic cloud of $^{87}$Rb, molasses-cooled to 10µK
- Two-photon optical excitation, then MW transfert and RF adiabatic passage for circularization

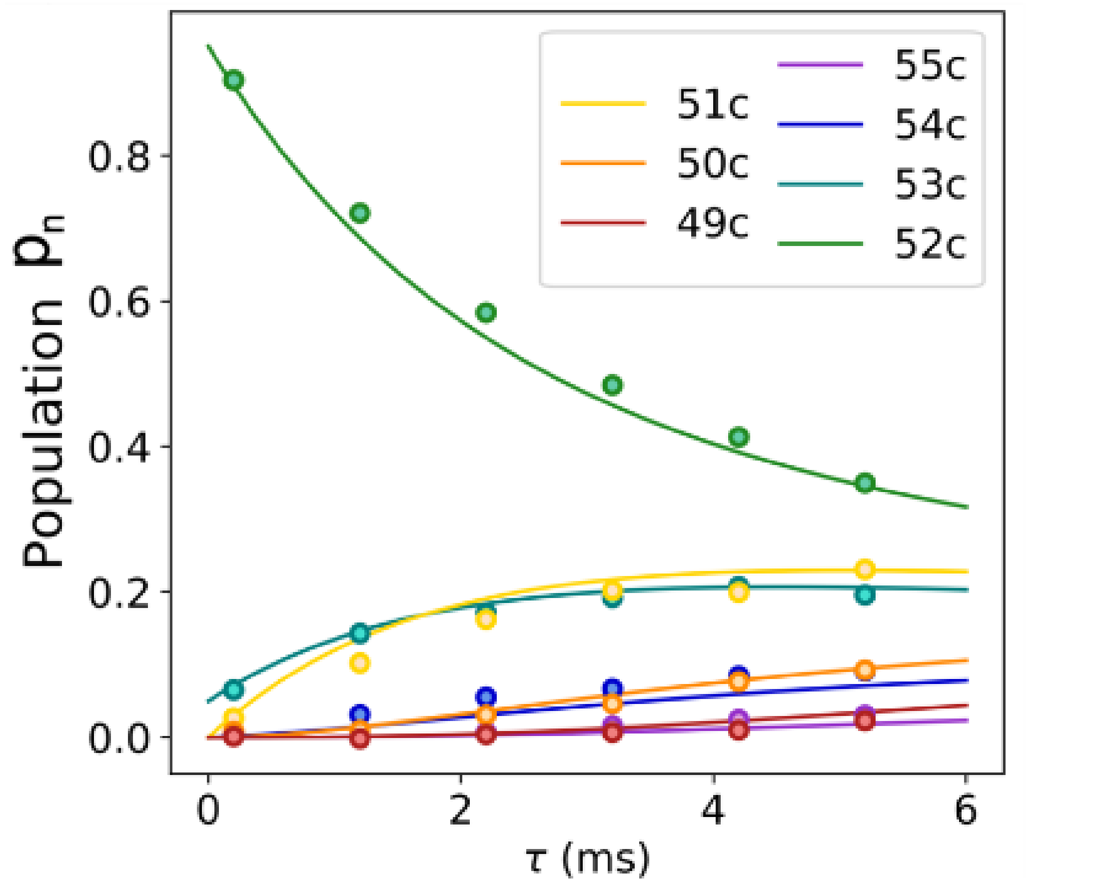



- Detection: state-selective field ionization




## Lifetime of circular states:

- Circular state populations $p_n$




- Fit to rate equation model

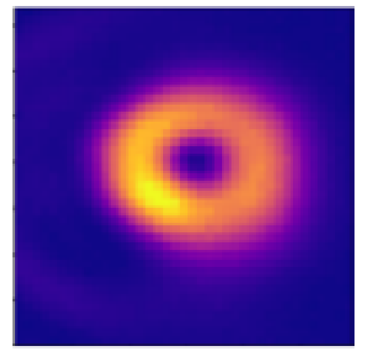
→ Lifetime: $T_1$ ≈ 4ms for 52C

→ Blackbody radiation: temperature 11K

→ Good control of the MW blackbody radiation with radar absorbing material

T. Cantat-Moltrecht et al., PRR **2**, 022032 (2020)

## Trapping detection:

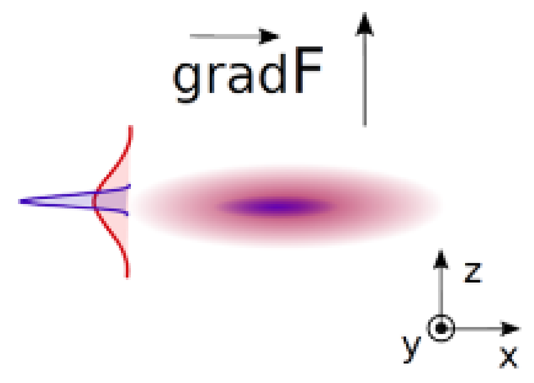


w = 37µm, P = 4,3W, λ = 1064nm

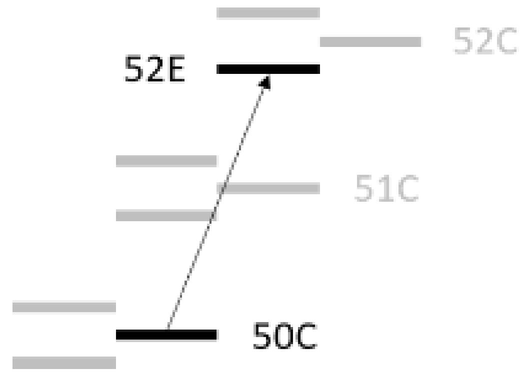
- Ponderomotive trapping : Rydberg atoms = **low field seeker**
- Hollow beam ($LG_{0,1}$) produced by a SLM

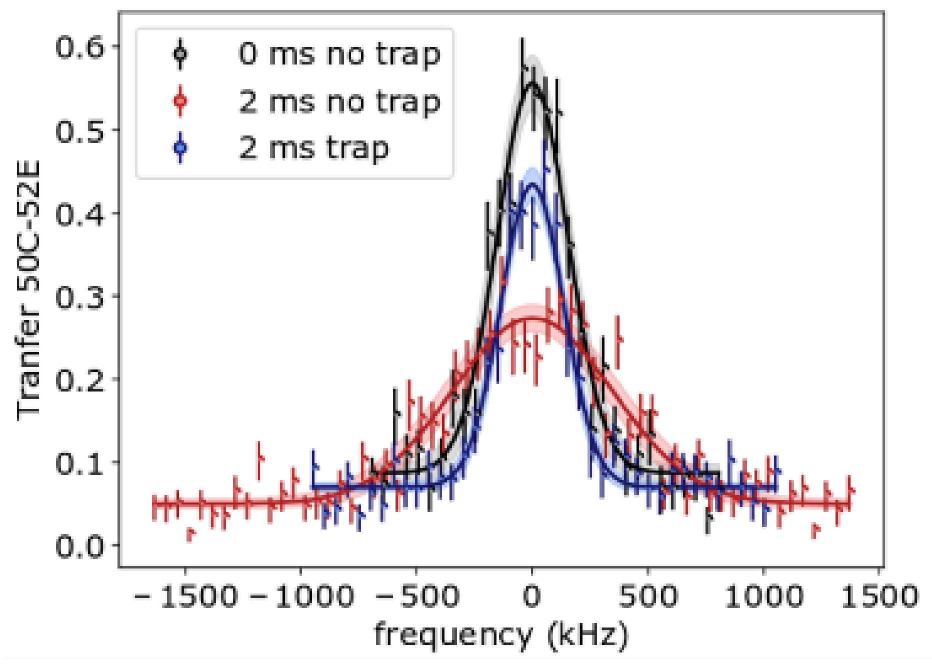
→ Trap depth ≈ 80µK

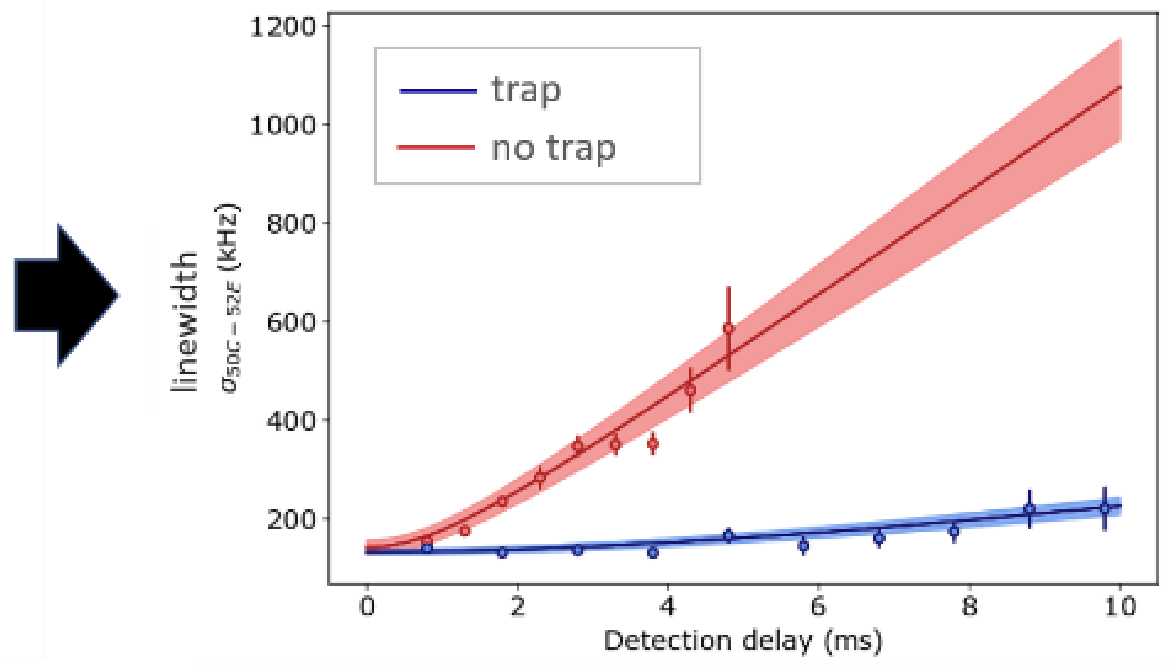
- Thermal **broadening of the cloud** in an electrical field gradient encoded in the broadening of the line
- Spectroscopy of an **electrical-field-sensitive** MW transition between Rydberg states




→ Trapping over 10ms without atom loss, first laser trapping of circular Rydberg states



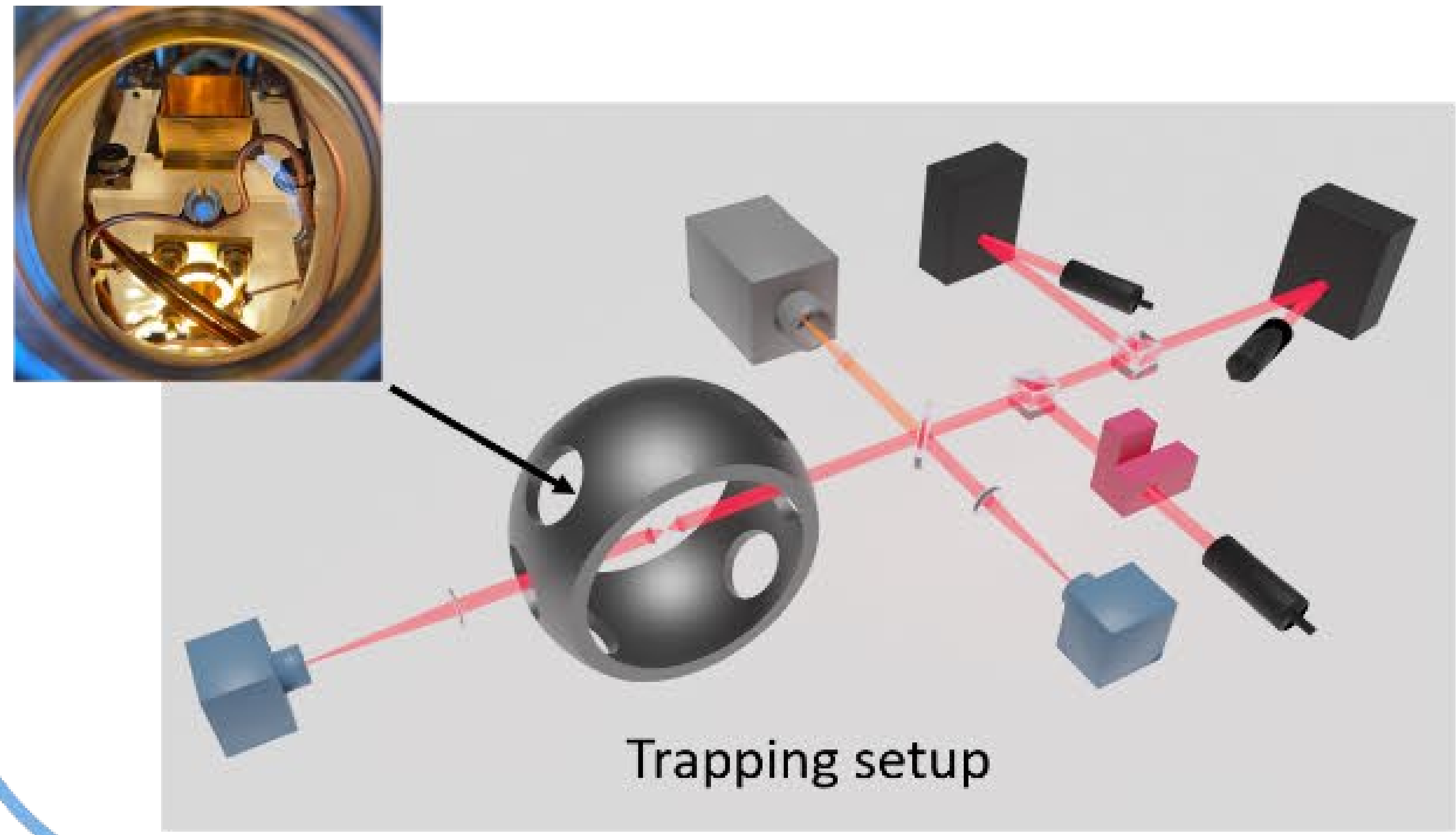




R.G. Cortiñas et al., PRL **124**, 123201 (2020)

# New setup for single-atom trapping

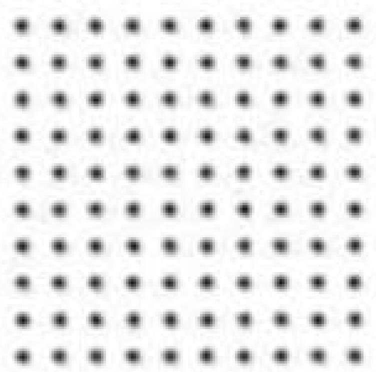
## New setup:

- All former capabilities (MOT, Rydberg excitation, circularization) + **optical trap**
- **Single atom displacement**
- Atom detection by **fluorescence**
- New Rydberg excitation scheme
- Preliminary UHV chamber at 300K

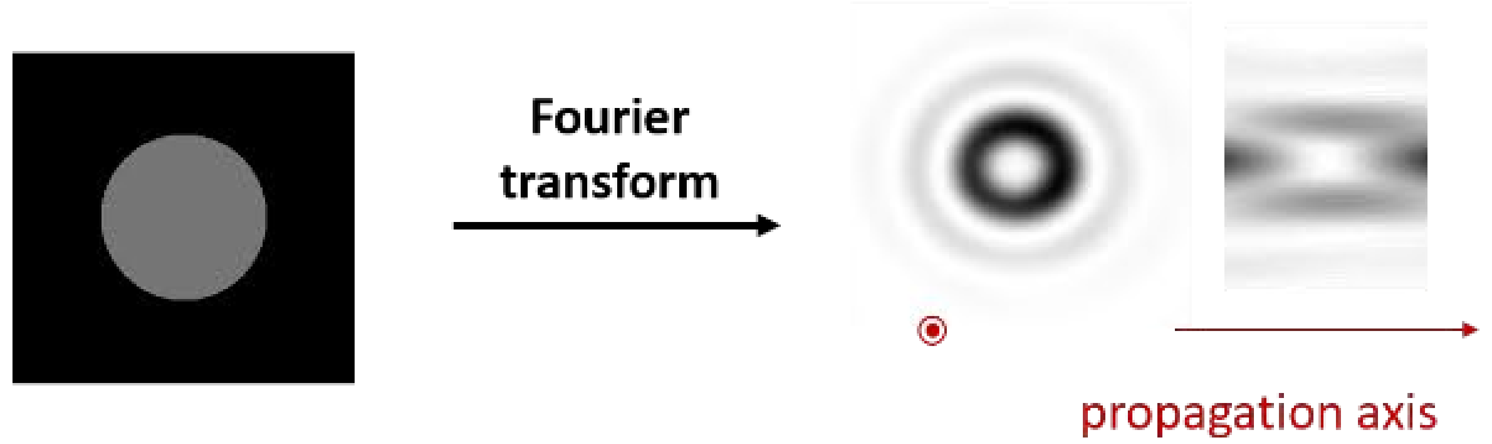


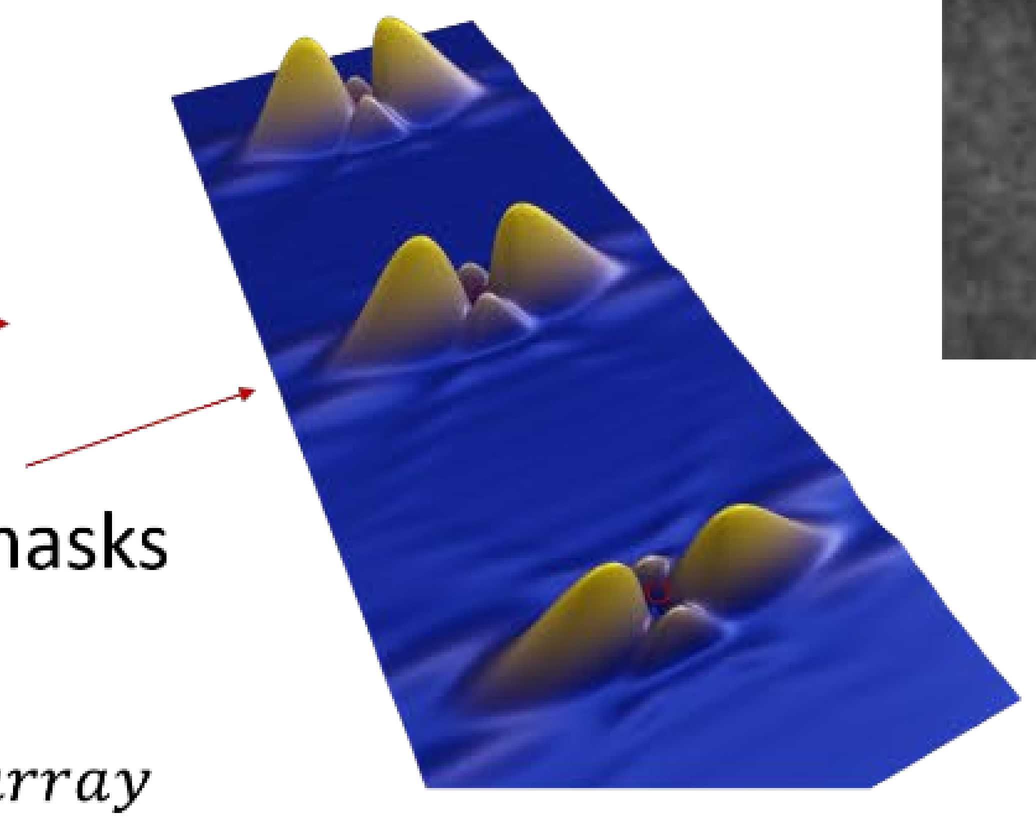

## Trap array generation:

- **Phase modulation** of a laser beam with a spatial light modulator (SLM)
- **Optical Fourier transform** with short focal aspheric lens hold in a sapphire cube



- Gerchberg-Saxton phase-retrieval algorithm → phase mask to produce an **array**
- Phase mask to produce a **bottle beam** (BoB) for 3D trapping



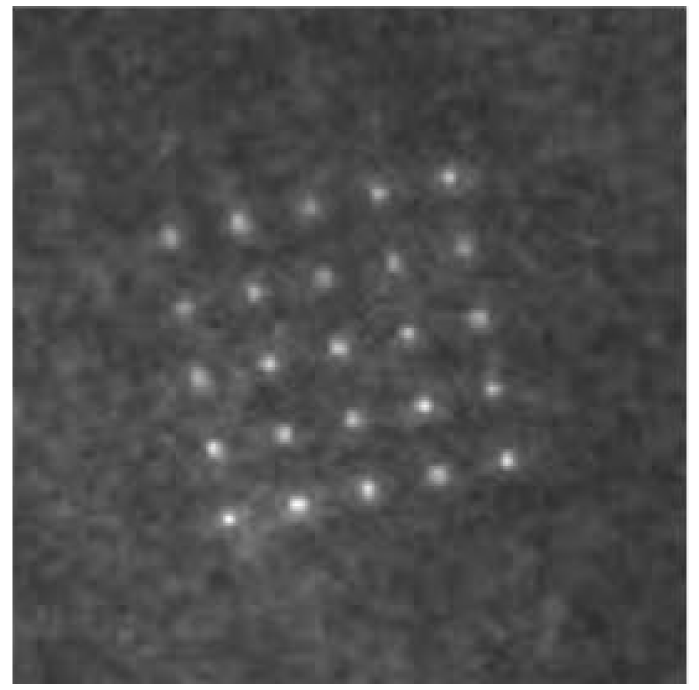



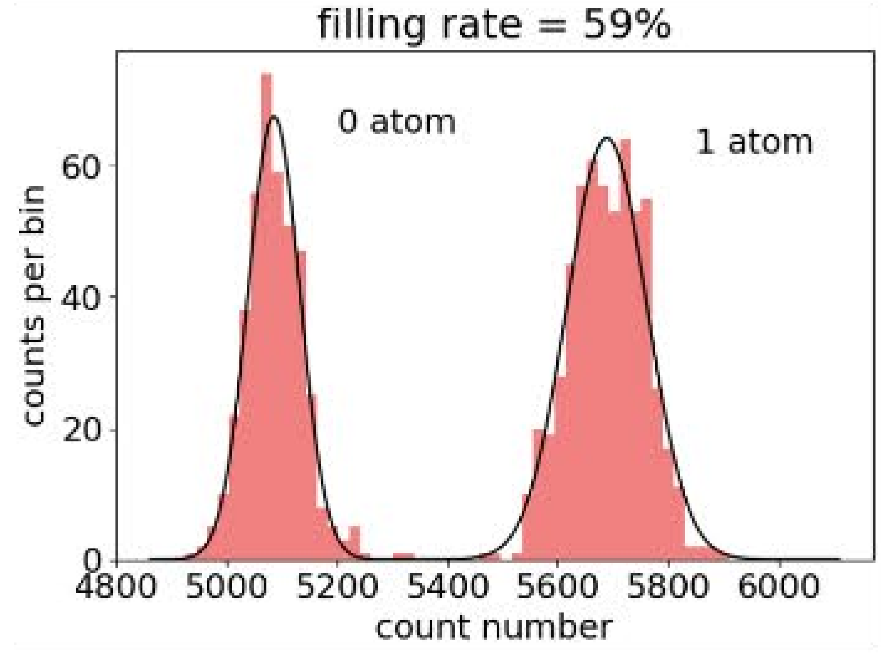
- Simple addition of BoB and array phase masks for BoBs array:

$$F_{atoms} = \mathrm{TF}\left[e^{i\varphi_{BoB}+i\varphi_{array}}\right] = F_{BoB} * F_{array}$$

## Single fundamental atom trapping:

- Laser cooling of Rb atoms and dipole trapping in **optical tweezer**, 2.5mW per trap, w = 1.1µm
- **Fluorescence** imaging





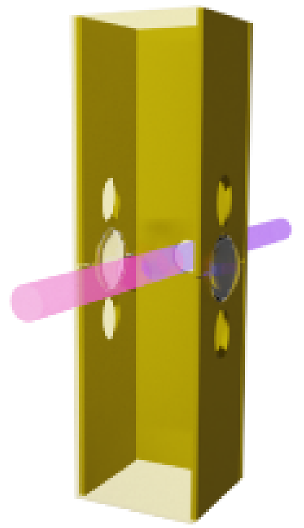

- Histogram: sub-Poissonian distribution of atoms

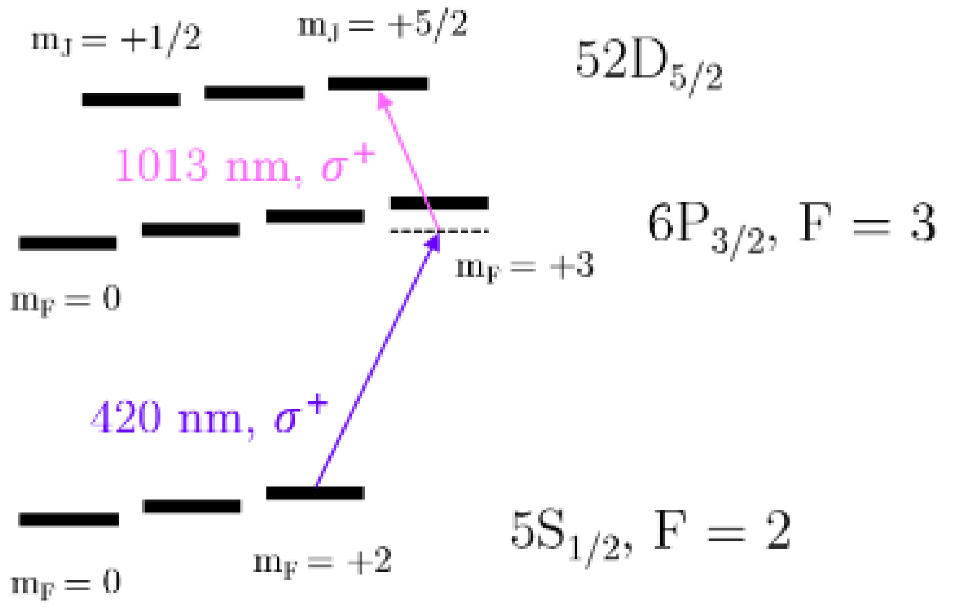
  → Separated histogram: efficient atom detection

## Rydberg excitation of single atoms

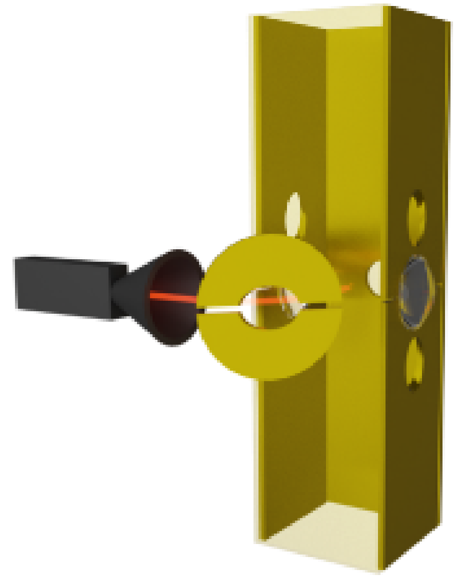
### Laser excitation to Rydberg states:

- **Electric field** offset and gradients precise control with goldened electrodes
- Optical pumping to $5S_{1/2}, F = 2, \boldsymbol{m_F = +2}$
  → **state purification**
- Two-photon laser $\pi$-pulse to $\boldsymbol{52D_{5/2}, m_J = +5/2}$

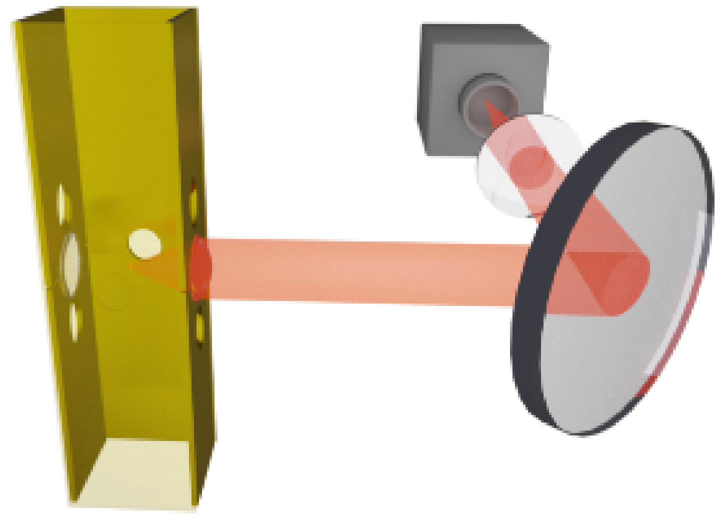


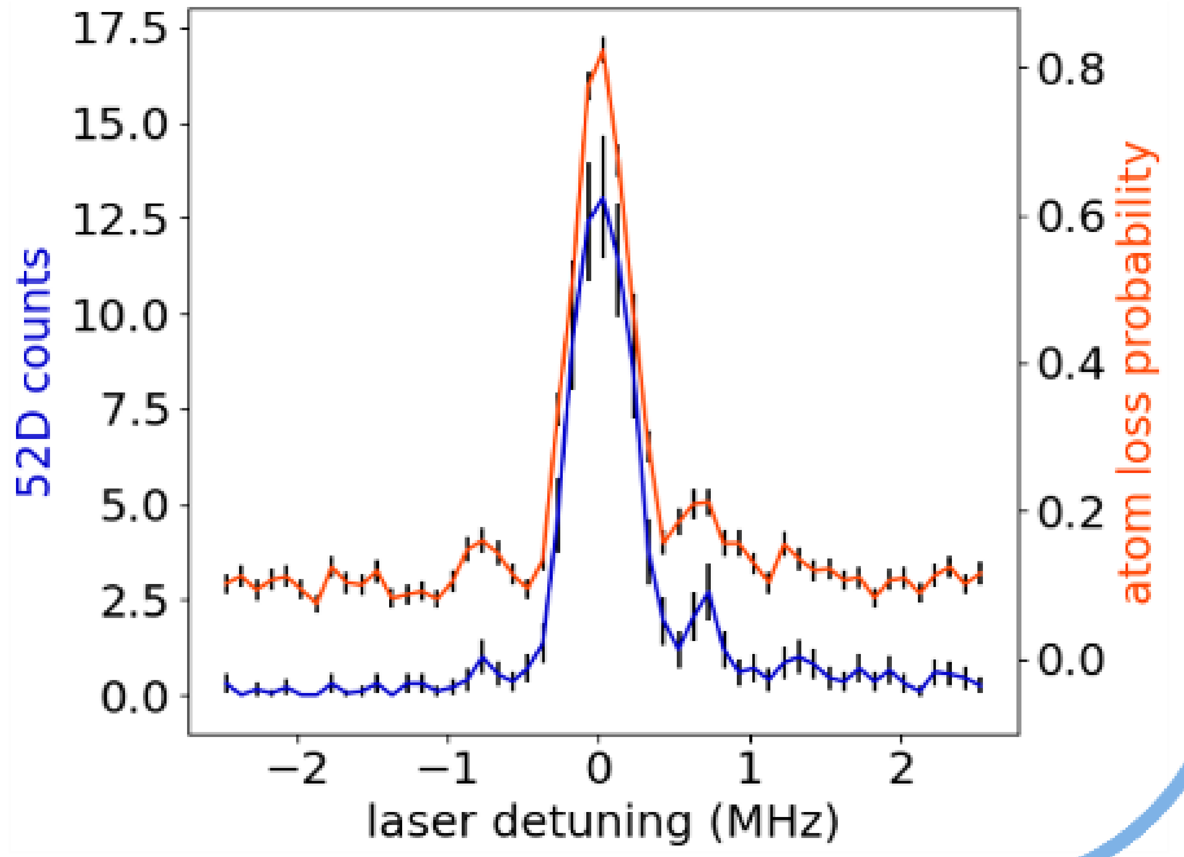



### Rydberg preparation, two modes of detection:



- **Ionisation** in a electric field and ions detection with a channeltron
- **Fluorescence:** excitation to untrapped Rydberg atoms → **no fluorescence**






## Next steps

### Room temperature setup:

- Single circular-atom **trapping**
- Two-atom **interaction** measurement

### Cryostat:

- UHV chamber - cryostat swapping
  → circular atom **lifetime x 100**
- **New quantum simulation**