UNIVERSITÀ
DEGLI STUDI
FIRENZE

Andrea Fantini
PhD student

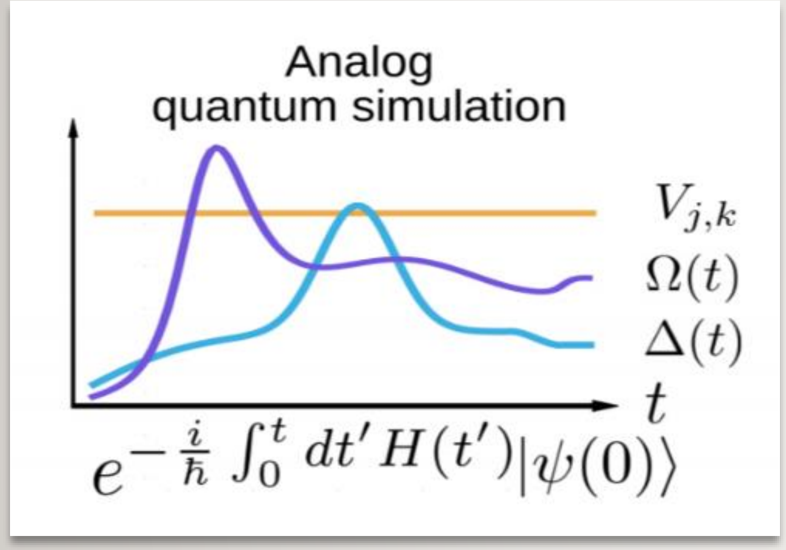
New Rydberg platforms for Quantum Simulation based on single neutral atoms trapped in Optical Tweezers

RICHARD FEYNMAN:

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Analog Quantum Simulator:
algorithm blocks are mapped on programmable spin models

Digital Q Simulator and Q Computer:
algorithm blocks are executed by quantum gates



OR

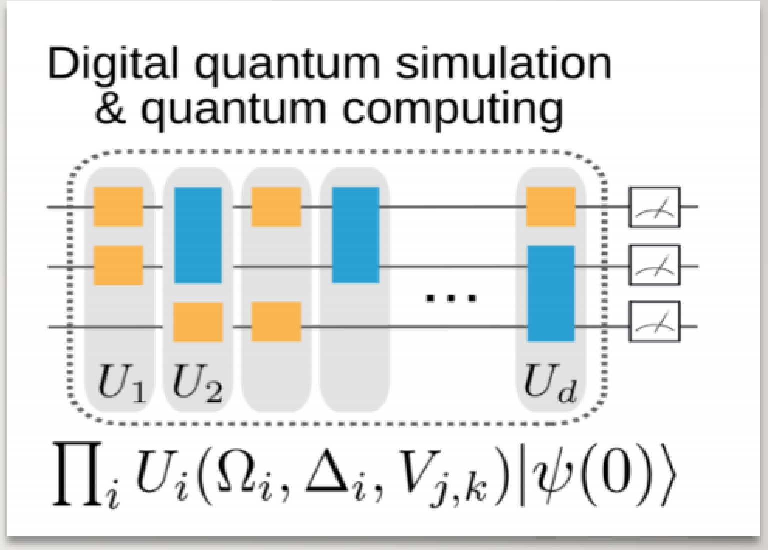
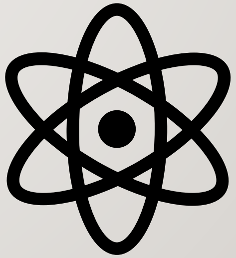


Image credits: M. Morgado and S. Whitlock, AVS Quantum Sci. 3, 023501 (2021)

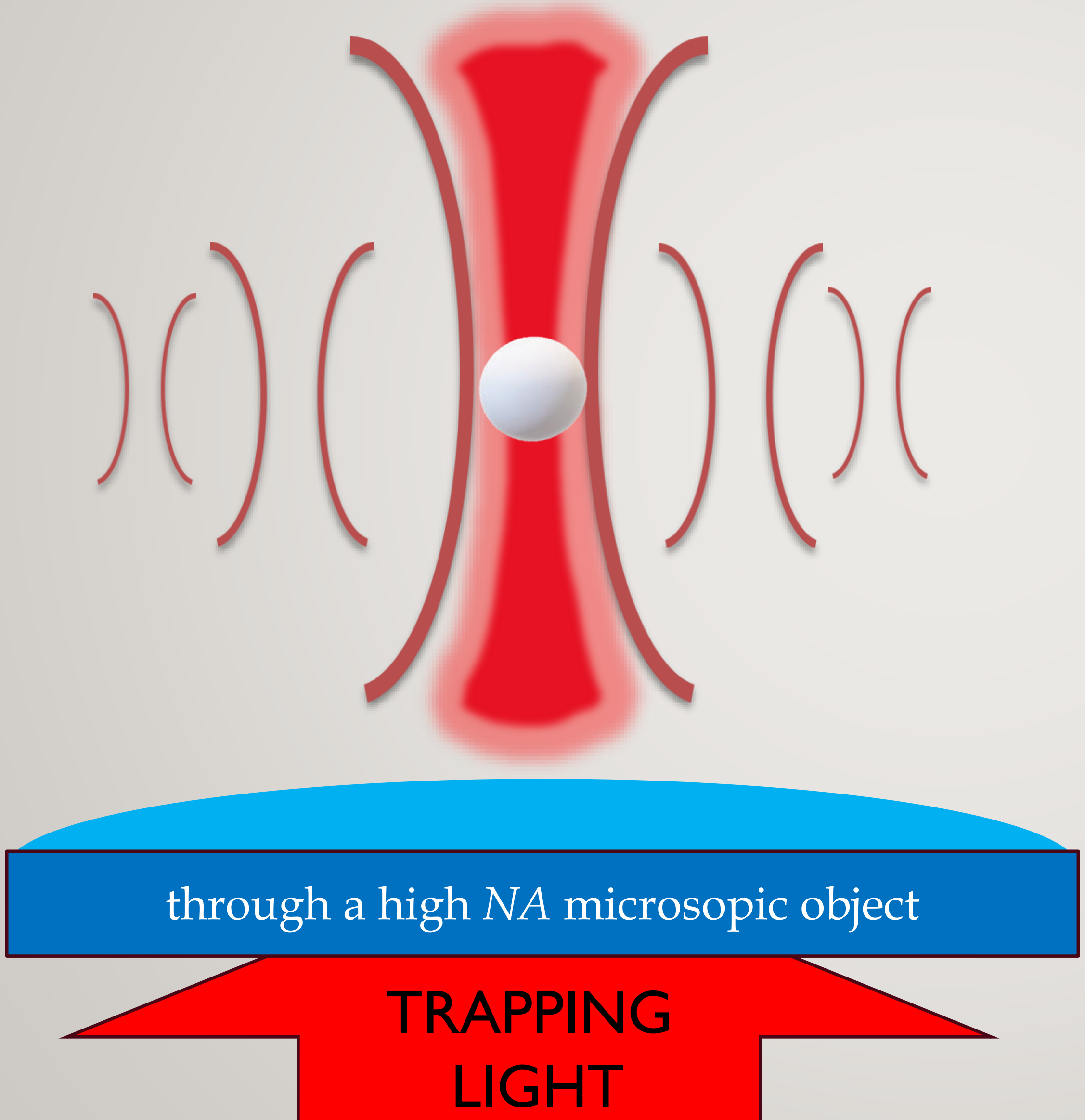
New classical-quantum hybrid machines:



Classical interface

Quantum Science cell

Individual atoms in Optical Tweezers



Tightly focused laser beams, deep trapping potential (~1 µm waist / ~1 mK depth)

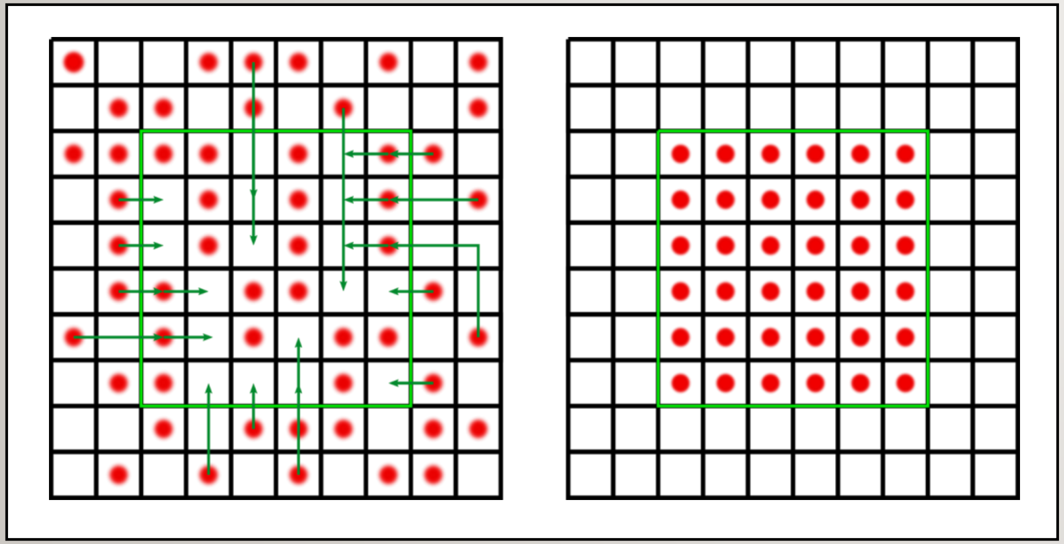
Atoms can be loaded directly from the Magneto Optical Trap, no evaporation required, fast exp. cycle (<1 s)

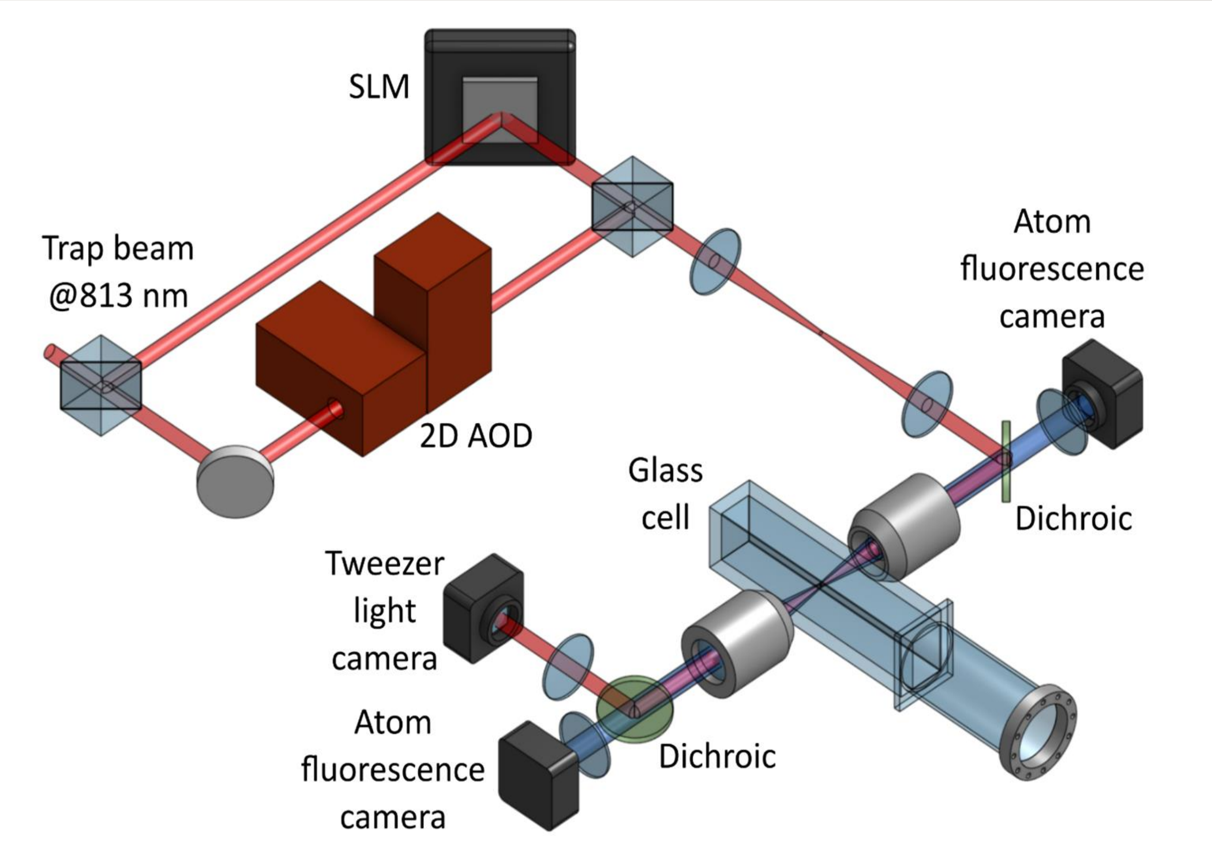
Easily scalable…

Scalability of the platform

Arrays of laser beams produced via Spatial Light Modulators (SLM) and/or Acousto-Optic Deflectors (AODs) focused through the microscope objective

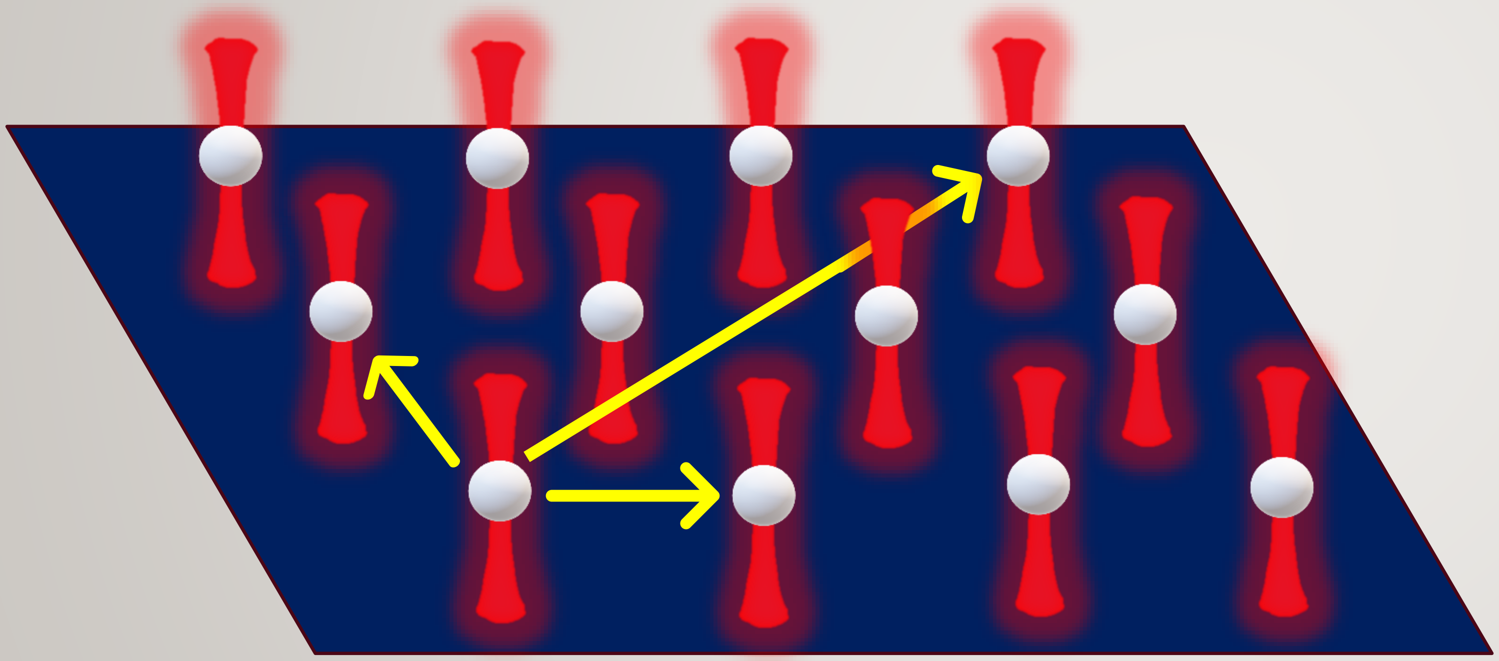
Loading from MOT → Induce pairwise losses → Image → Sort single atoms





Reconfigurable occupation for a defect-free array using AODs

Quantum Simulator: Individual atoms in Optical Tweezers



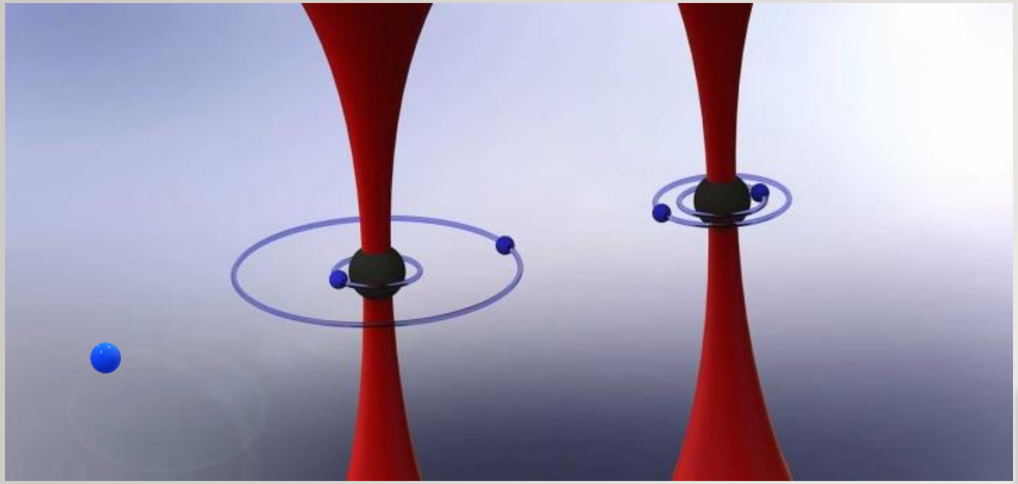
Rydberg interaction

A new platform combining very well known **optical techniques** for trapping and manipulating **neutral atoms** with addressability of **individual quantum objects**

Main differences with respect to traditional ultracold gases experiments:

- Mesoscopic systems (~100 atoms)
- Any topology available
- High repetition rates (> 1 Hz)

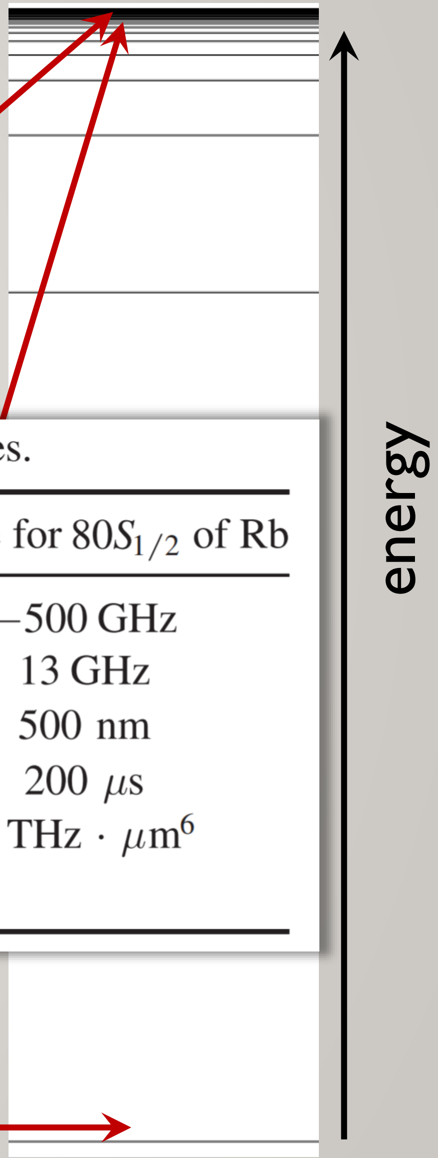
Rydberg Atom



$n=100$ $r \approx 1$ mm

Rydberg atoms have µm-range wavefunctions comparable with tweezer spacing

High-n atoms to induce interaction in the array



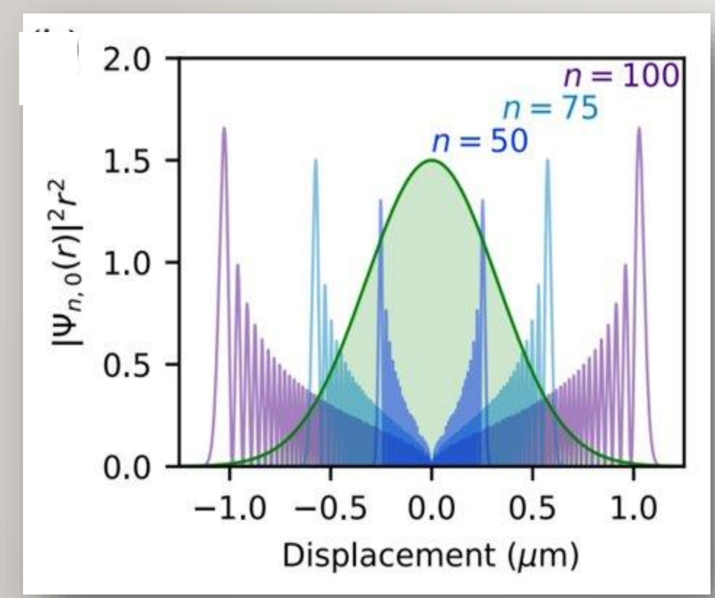


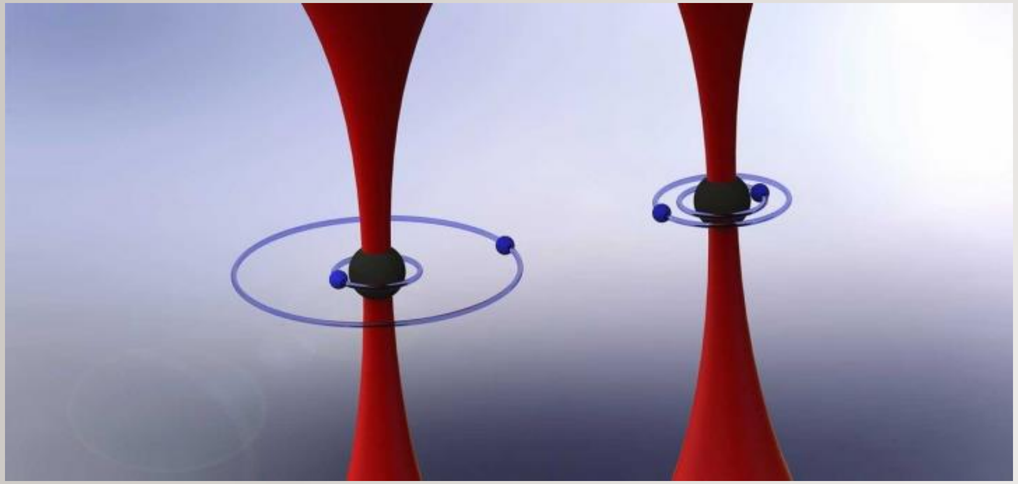
Table 1. Properties of Rydberg states.

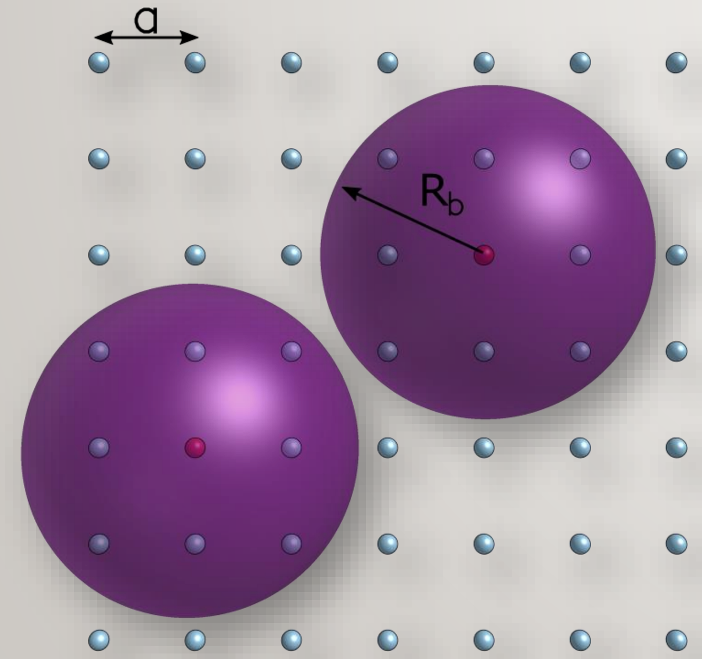
Property	n−scaling	Value for $80S_{1/2}$ of Rb
Binding energy E_n	n^{-2}	−500 GHz
Level spacing $E_{n+1} - E_n$	n^{-3}	13 GHz
Size of wavefunction $\langle r \rangle$	n^2	500 nm
Lifetime τ	n^3	200 μs
van der Waals coefficient C_6	n^{11}	4 THz · μm^6

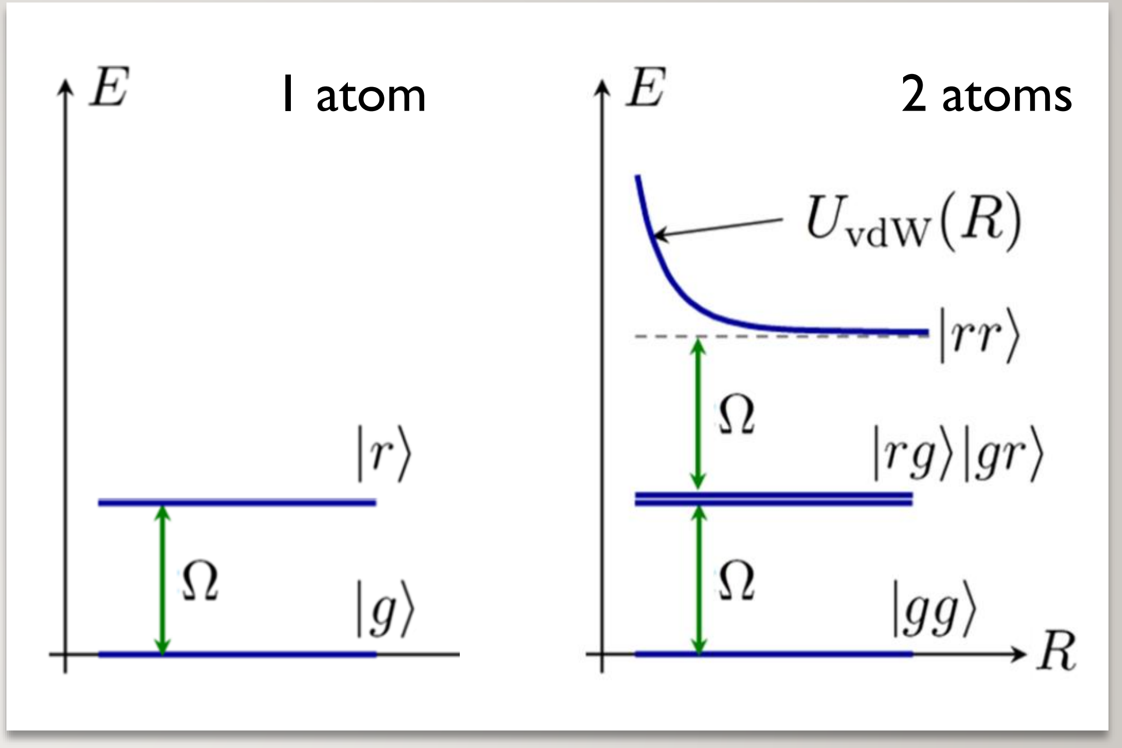
strongly influenced by *n*

$n=1$ $r \approx 10^{-4}$ mm

Rydberg Blockade







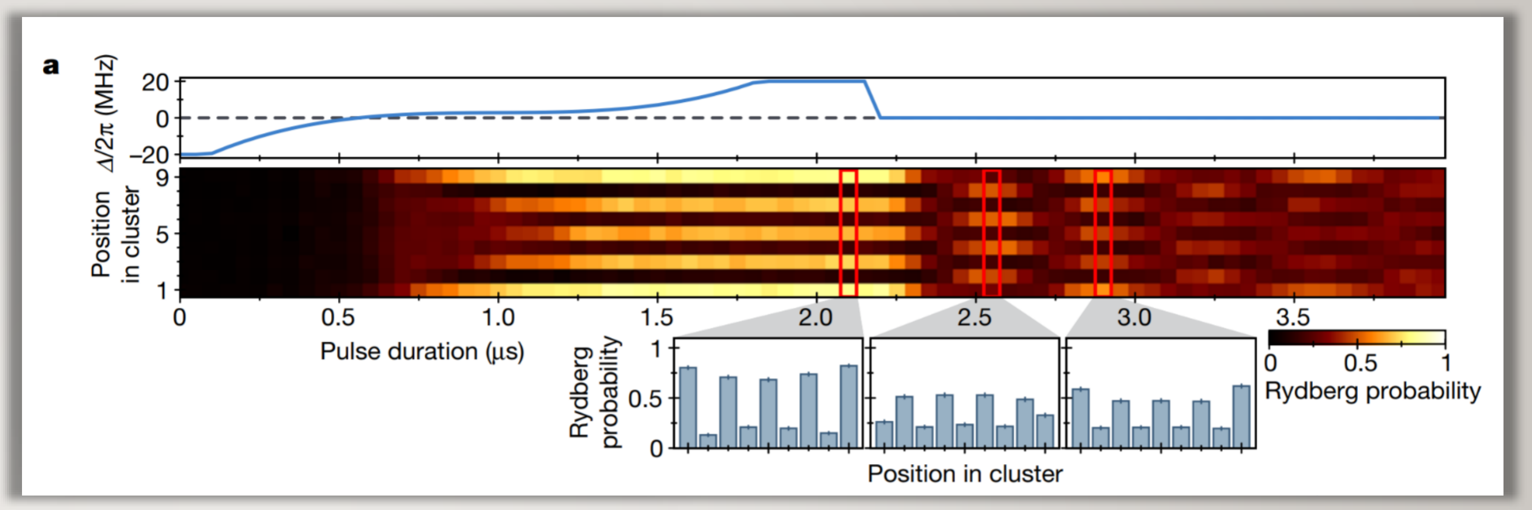
Strong VdW interaction blocks the simultaneous excitation of two nearby atoms to the Rydberg state

Generation of entangled state:

$$|\boldsymbol{\psi}\rangle = \frac{1}{\sqrt{2}}(|\boldsymbol{rg}\rangle + |\boldsymbol{gr}\rangle)$$

Rydberg Analog Simulator

Spin Models: $|\downarrow\rangle = |g\rangle$ $|\uparrow\rangle = |r\rangle$



Example: **Ising-like Hamiltonian**

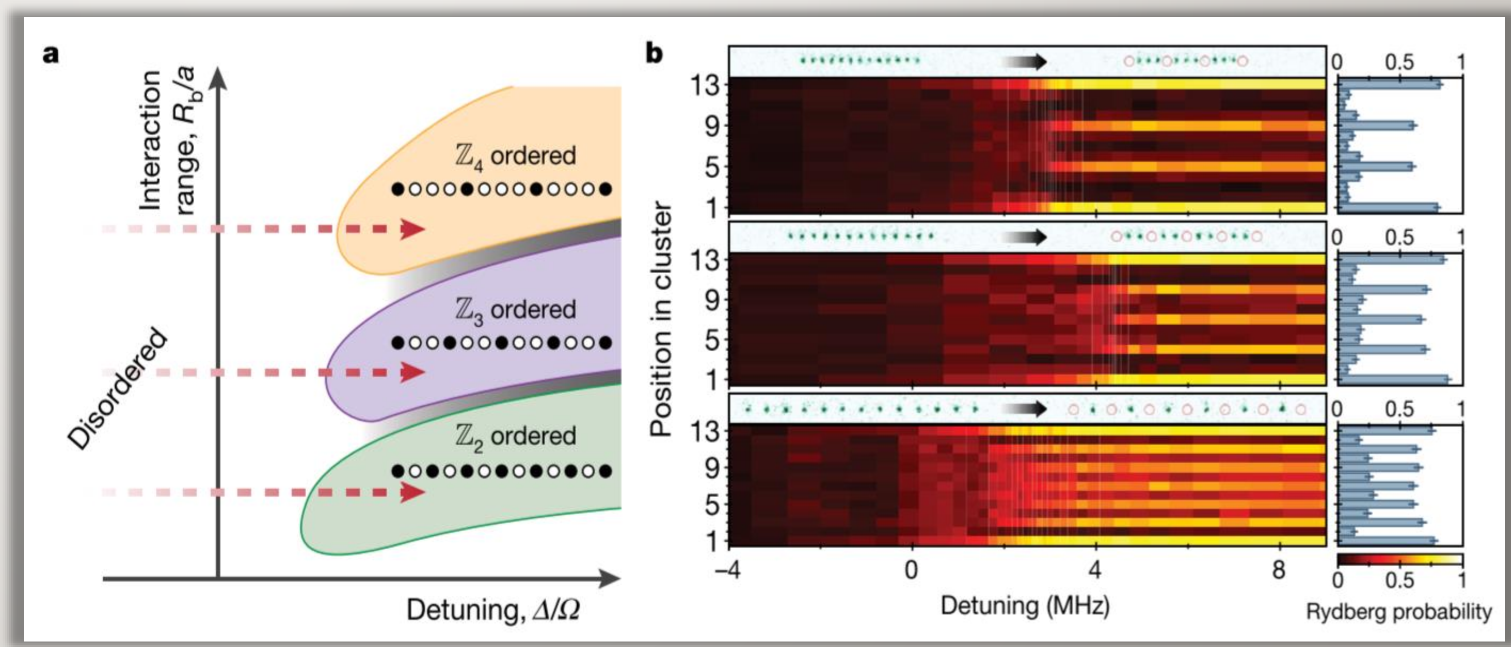
$$\frac{\mathcal{H}}{\hbar} = \frac{\Omega}{2}\sum_i \sigma_x^i - \Delta \sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

Transverse and longitudinal fields

Next-neighbour coupling

Onset of magnetic ordering

Direct access to correlation function with atomic resolution

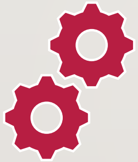


Bernien et al., Nature 551, 579 (2017)

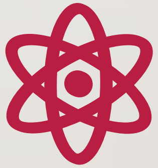
How we do it in Florence:

OUR WAY OUTLINE

Strontium Atom

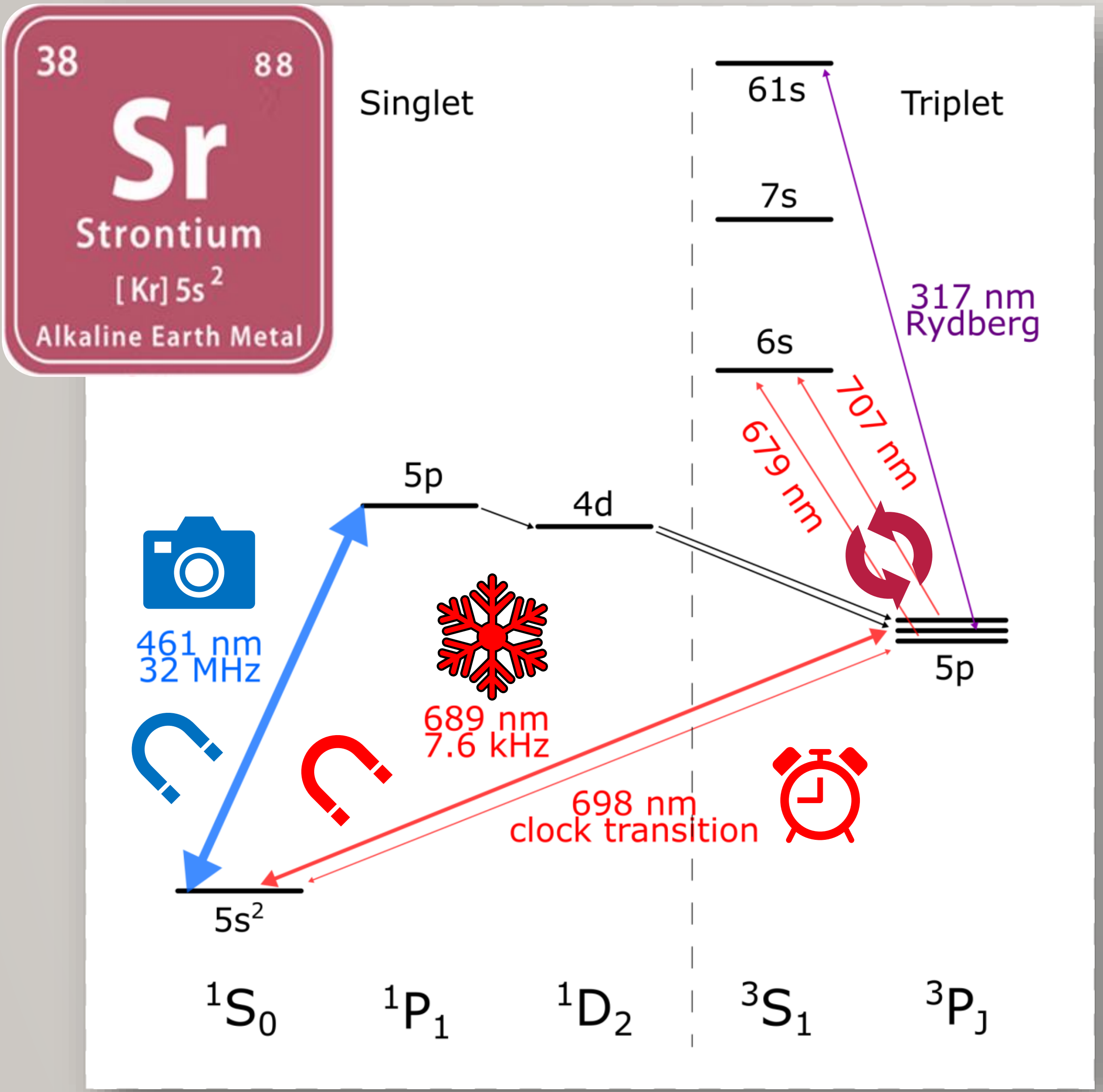


Experimental Setup



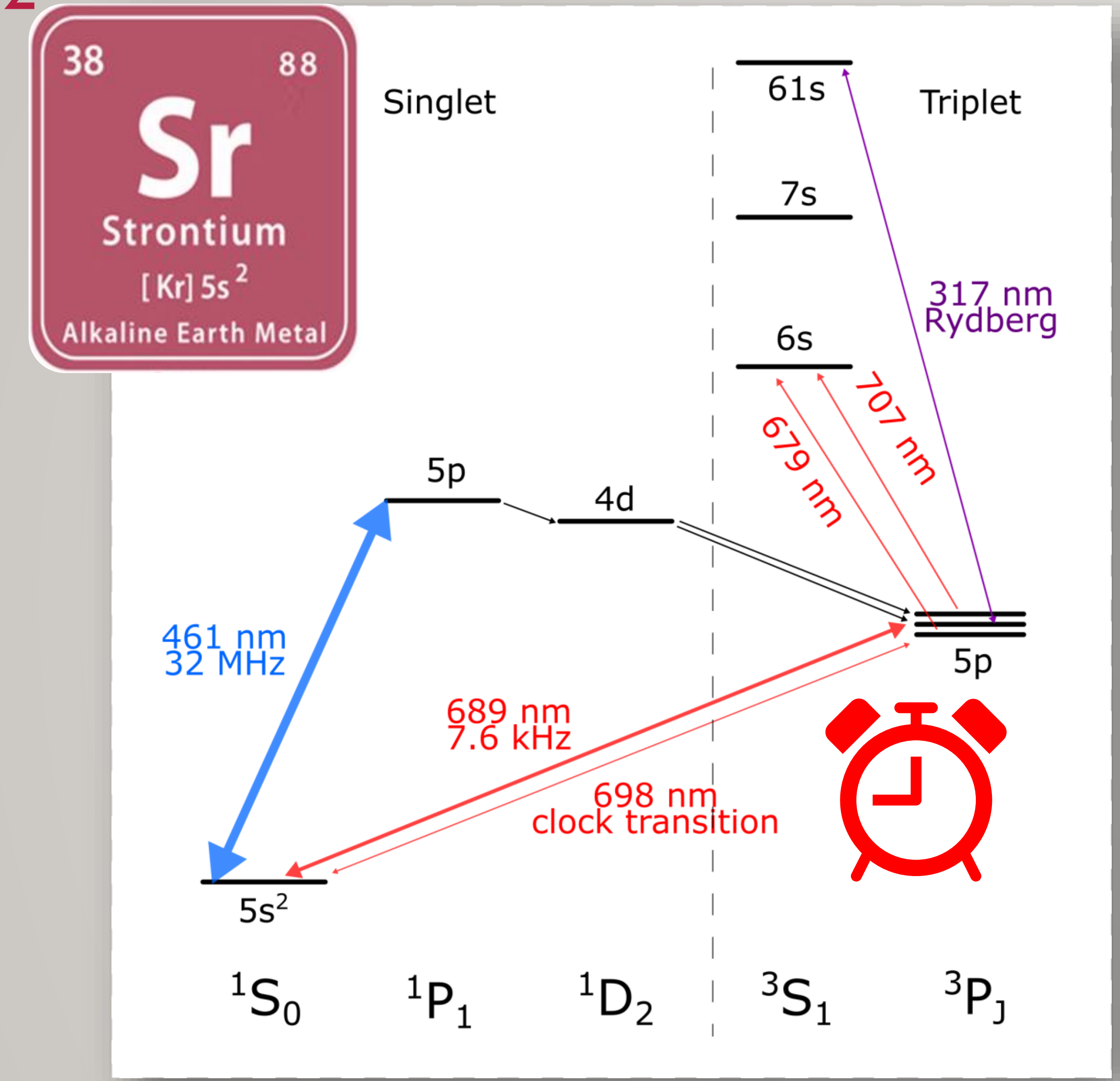
Single Atom Trapping and Detection

Control System



STRONTIUM ATOM

- Alkaline earth atom : 2 valence electrons
- 3 bosonic (^{84}Sr, ^{86}Sr, ^{88}Sr) and 1 fermionic (^{87}Sr) isotopes
- Two transitions useful for reaching µK via **M**agneto **O**ptical **T**rap (MOT)
- (Ultra) Narrow optical inter-combination transitions
- Long-lived metastable states, requiring narrow linewidth lasers



CLOCK TRANSITION

Magnetically accessible admixture of $^3P_0$ and m_j=0 of $^3P_1$ state

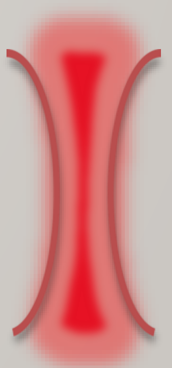
$$|\psi_{\text{clock}}(B)\rangle = |5s5p\ ^3P_0\rangle + \frac{\mu_C B}{\hbar\Delta_{01}}|5s5p\ ^3P_1\rangle$$

$$\mu_C \equiv \sqrt{\tfrac{2}{3}}(g_L - g_S)\mu_B$$

B field dependent linewidth <0.5 mHz even for1000 G field

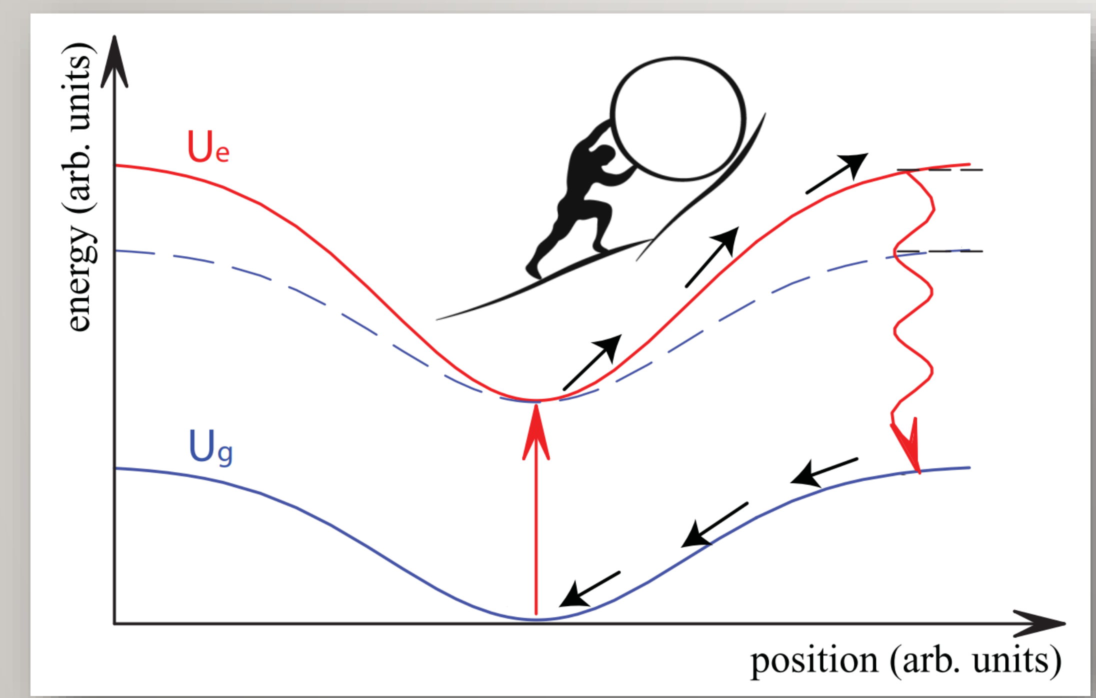
$$\Gamma_{\text{clock}}(B) = \Gamma_{^3P_1}\frac{\mu_C^2 B^2}{\hbar^2\Delta_{01}^2}$$

Tweezers @ magic wavelength 813nm



GROUND STATE COOLING

Sisyphus Cooling via single 689 beam



Adapted from V.V. Ivanon et al., PRA ***84****, 063417 (2011)*

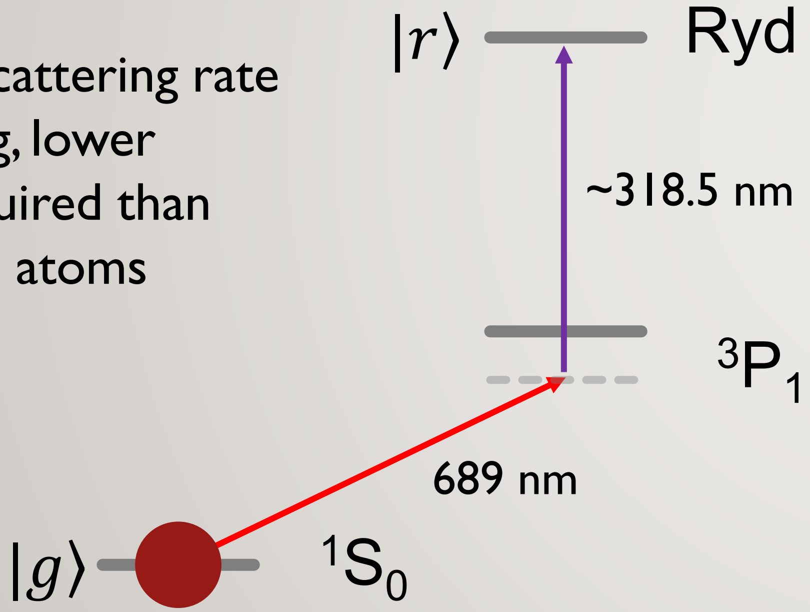
- $^3P_1$ potential different (deeper) than $^1S_0$
- $^1S_0 \rightarrow {}^3P_1$ transition linewidth smaller than trapping frequency
- Atoms excited to $^3P_1$ at the bottom of the trap
- More energy dissipated climbing the $^3P_1$ trapping potential than gained rolling down the $^1S_0$ potential

RYDBERG EXCITATION

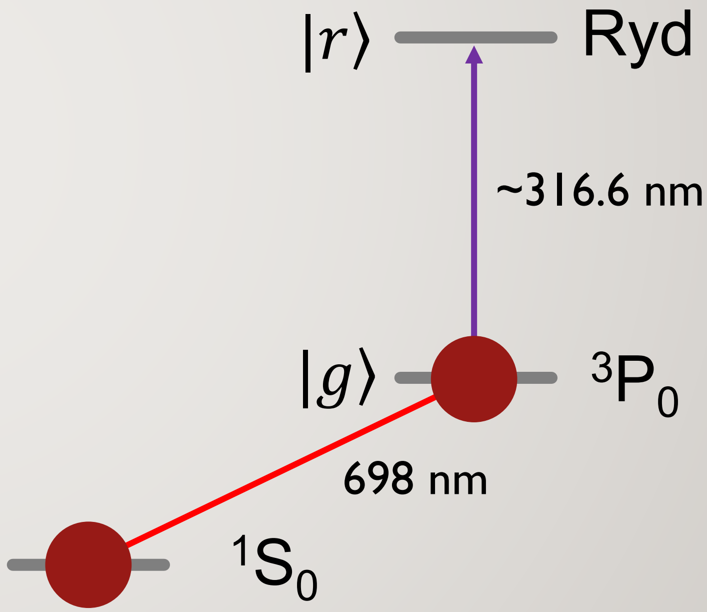
Rydberg excitation with 2E atoms: **2 schemes** with **MHz level coupling**

2-photon excitation
(through **off-resonant** $^3P_1$)

Reduced scattering rate and heating, lower power required than for alkaline atoms



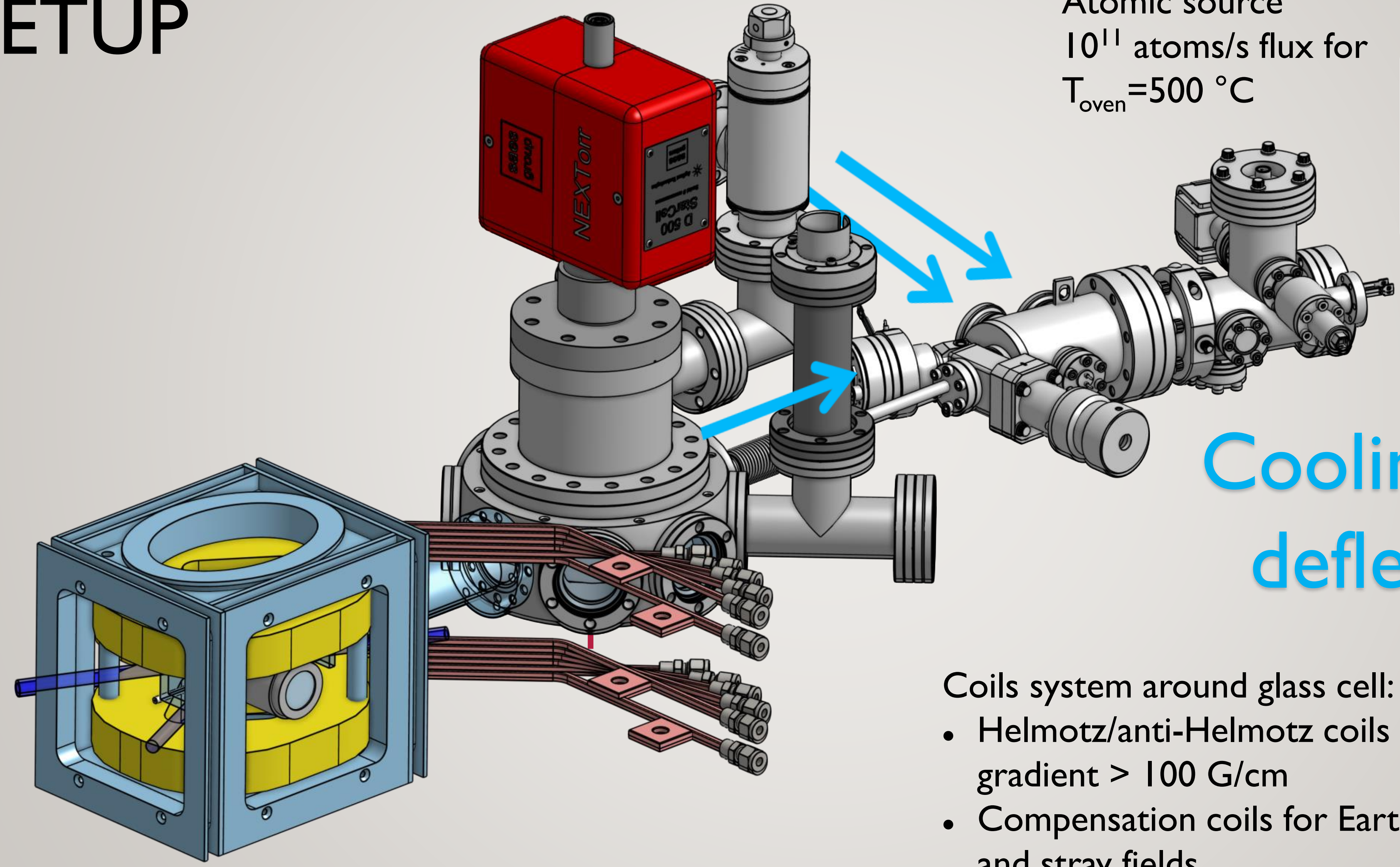
2-step excitation
(through **resonant** $^3P_0$)



Single-photon excitation from metastable state
Only available in 2E atoms

EXPERIMENTAL SETUP

Atomic source
10^{11} atoms/s flux for
T_{oven}=500 °C



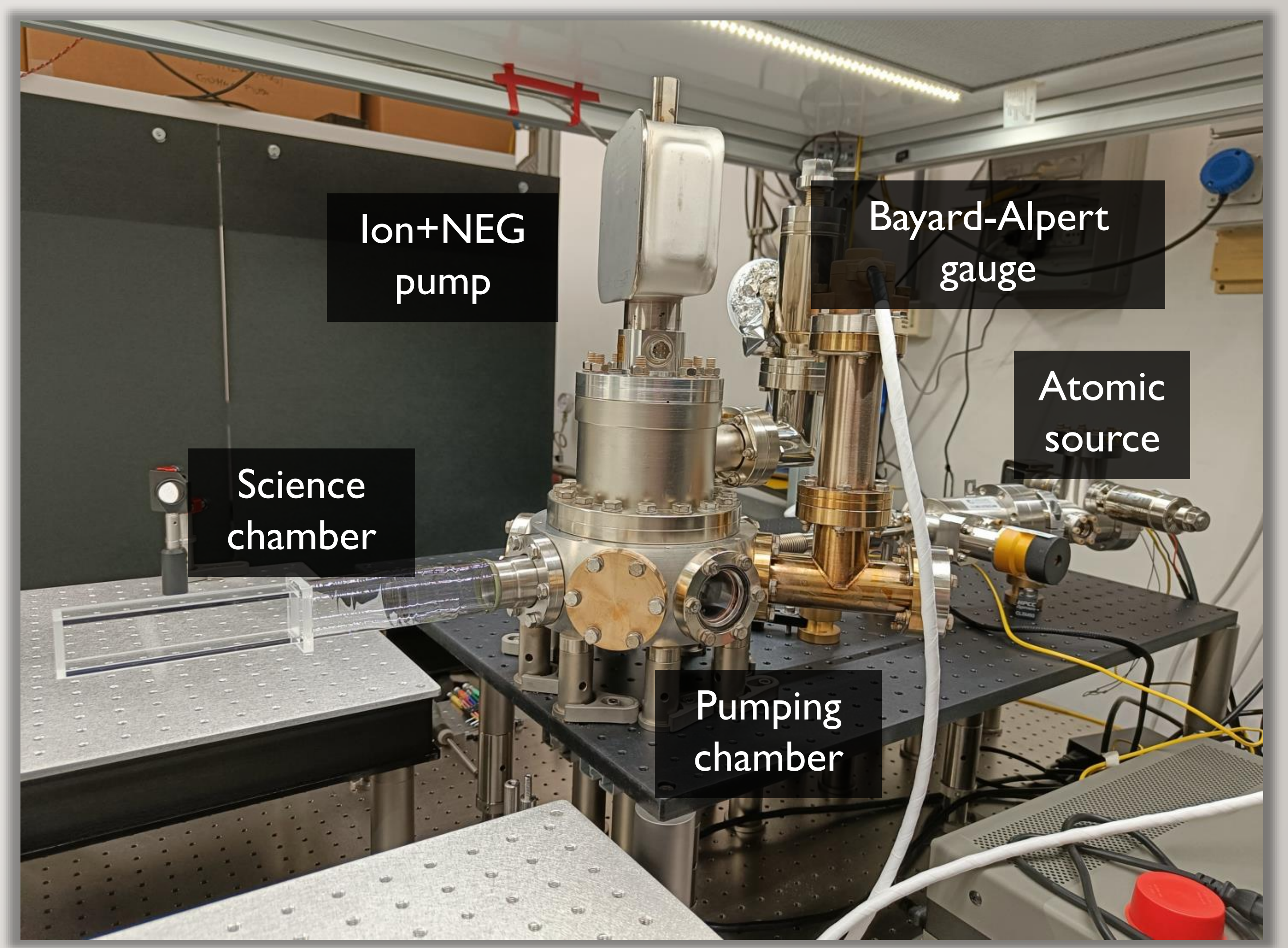
Cooling and deflection

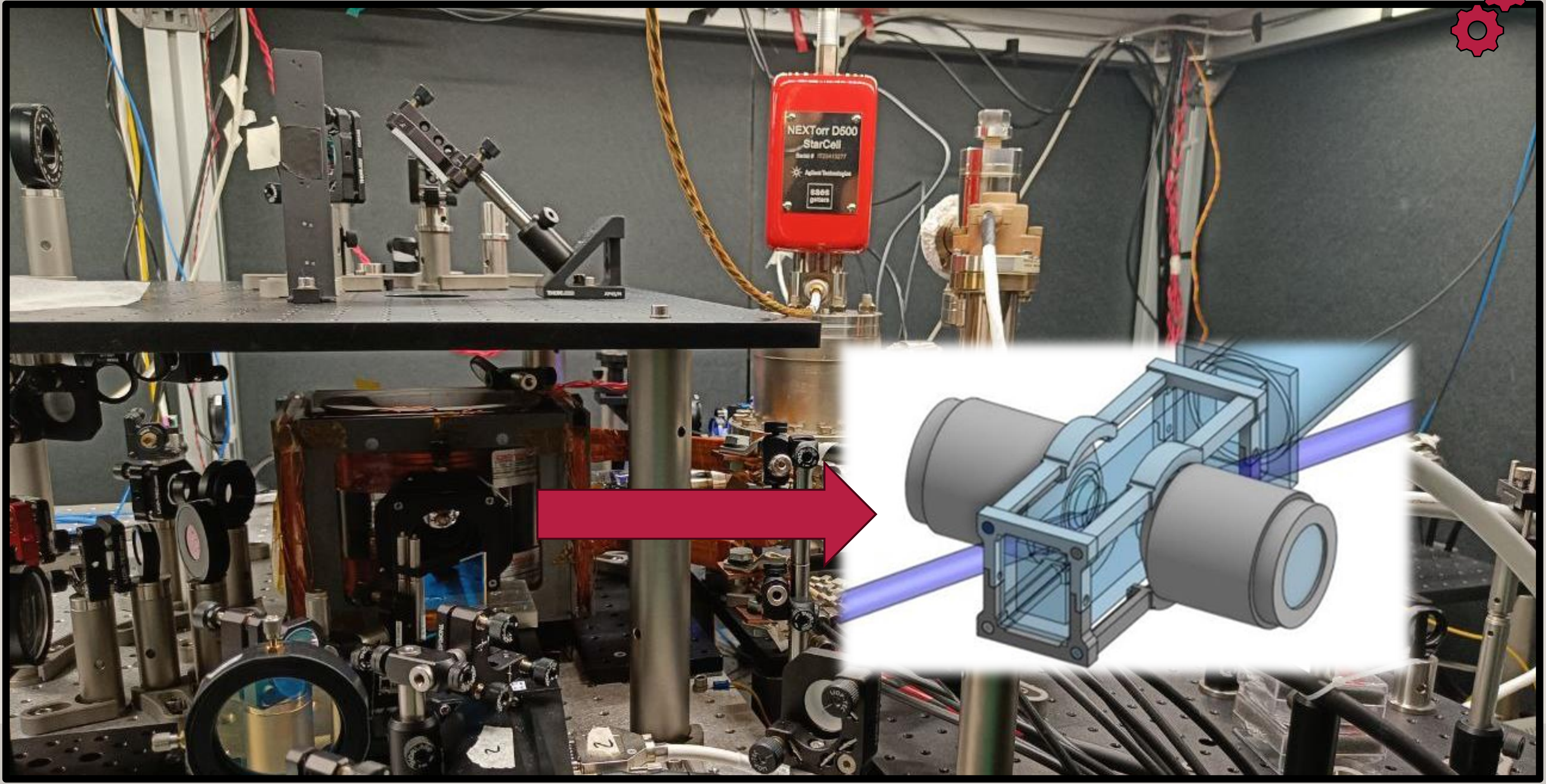
MOT beams

Coils system around glass cell:

- Helmotz/anti-Helmotz coils up to 950 G, gradient > 100 G/cm
- Compensation coils for Earth magnetic field and stray fields

ASSEMBLED VACUUM SYSTEM



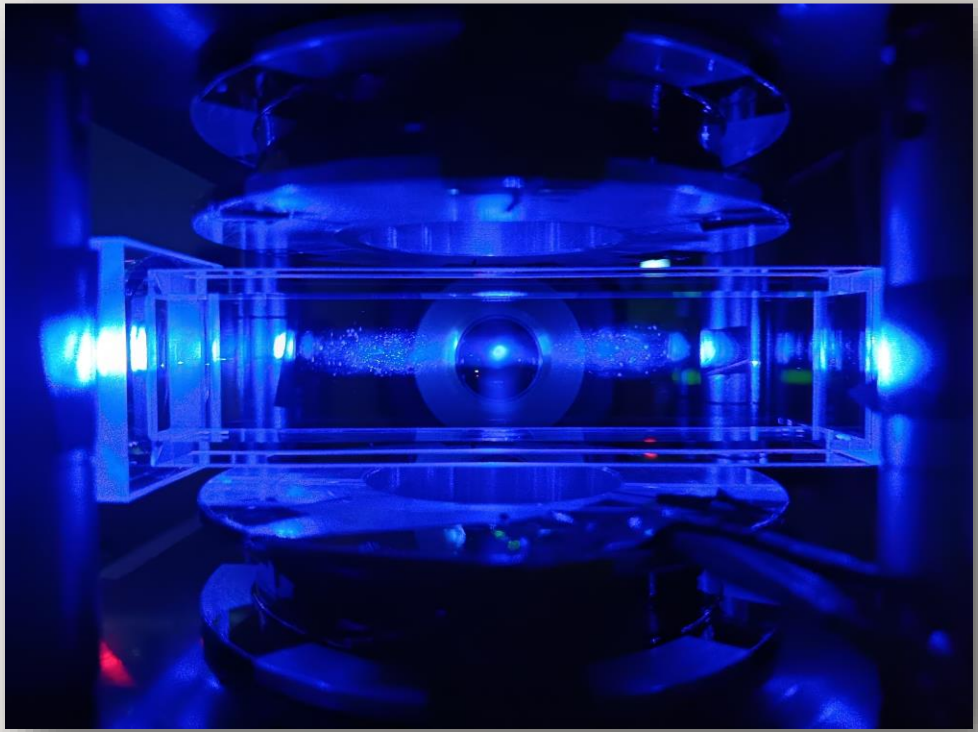

NEXTorr D500
StarCell

OBJECTIVE: for detection and manipulation of single atoms

Fluorescence detection and Tweezer focusing through Custom *Special Optics* objectives:

- NA = 0.55
- FOV 0.3x0.3 μm^2 at 461, 689 nm
- FOV 0.45x0.45 μm^2 at 813 nm
- Diffraction limited at 461 & 813 nm

SPECIAL OPTICS
A NAVITAR COMPANY



first Blue Mot with home-made coils (2023)

OUR WAY OUTLINE

Strontium Atom

Experimental Setup

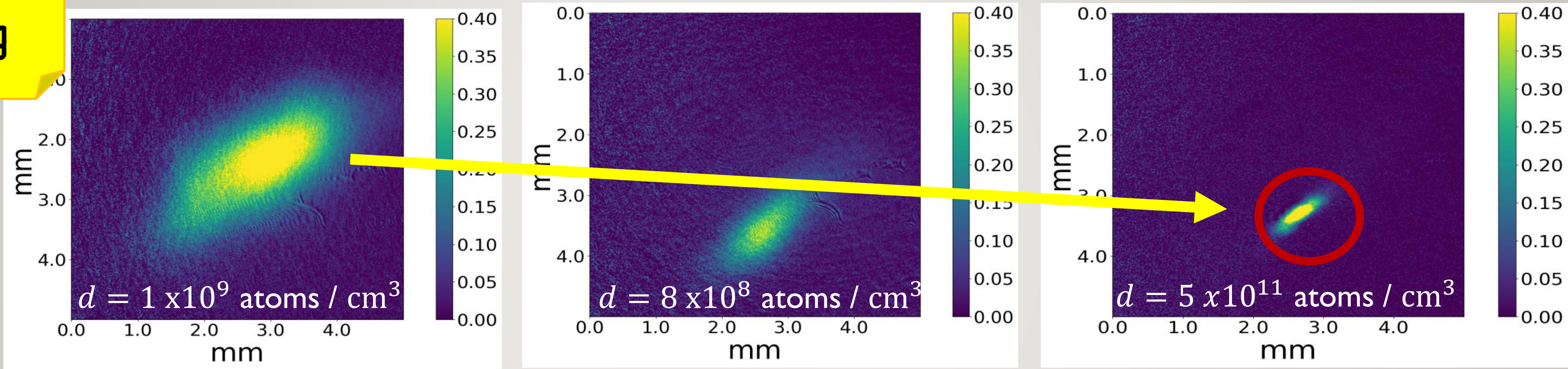
Single Atom Trapping and Detection

Control System

TRAPPING STEPS:

ABSORPTION imaging

Blue MOT | **Red multi frq MOT** | **Red single frq MOT**

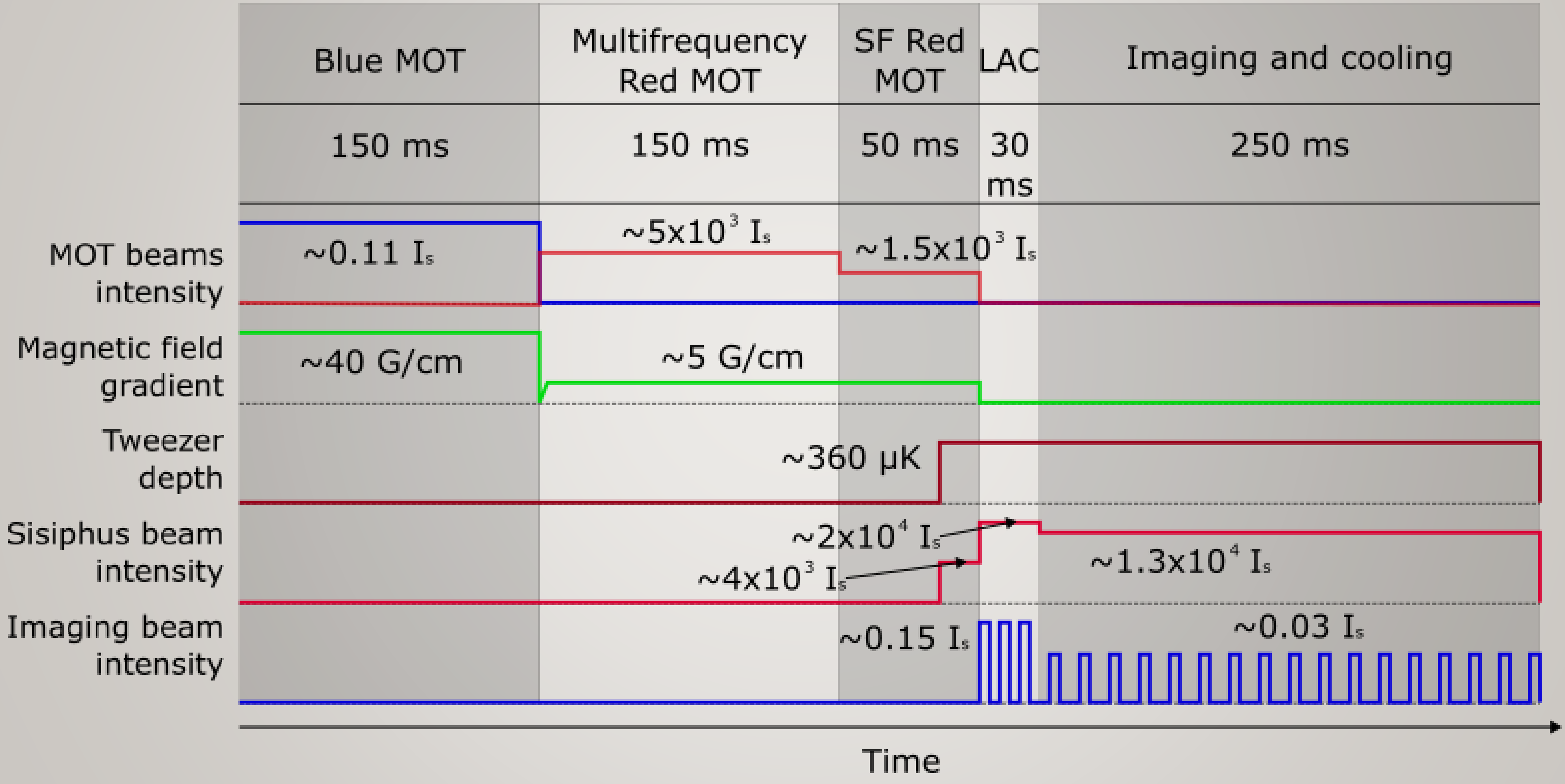


	Blue MOT	Red multi frq MOT	Red single frq MOT
Temperature	≈ 7 mK	≈ 14.5μK	≈ 5.6 μK
N. of atoms	≈ $3\text{x}10^6$	≈ $1.2\text{x}10^6$	≈ $1\text{x}10^6$

~ 1 atom / μm^3

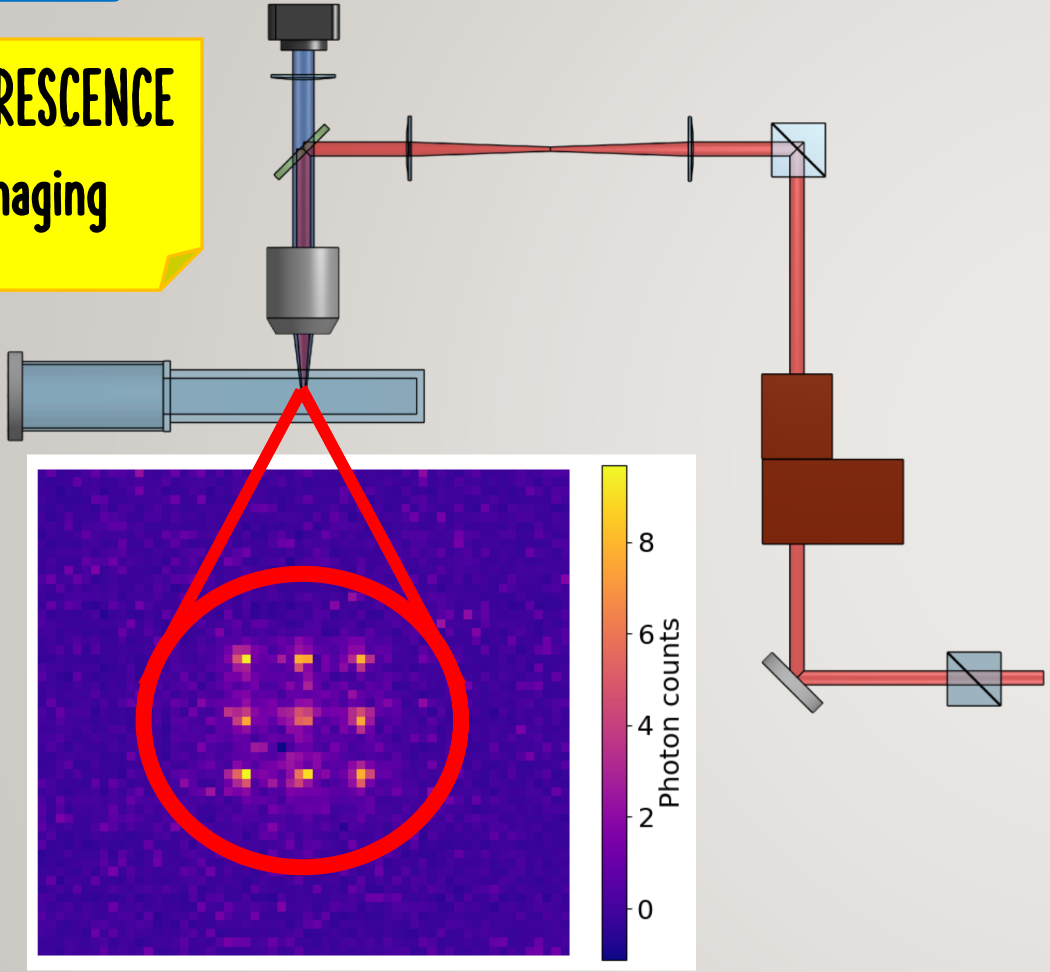
~ 1 atom / tweezer

EXPERIMENTAL SEQUENCE

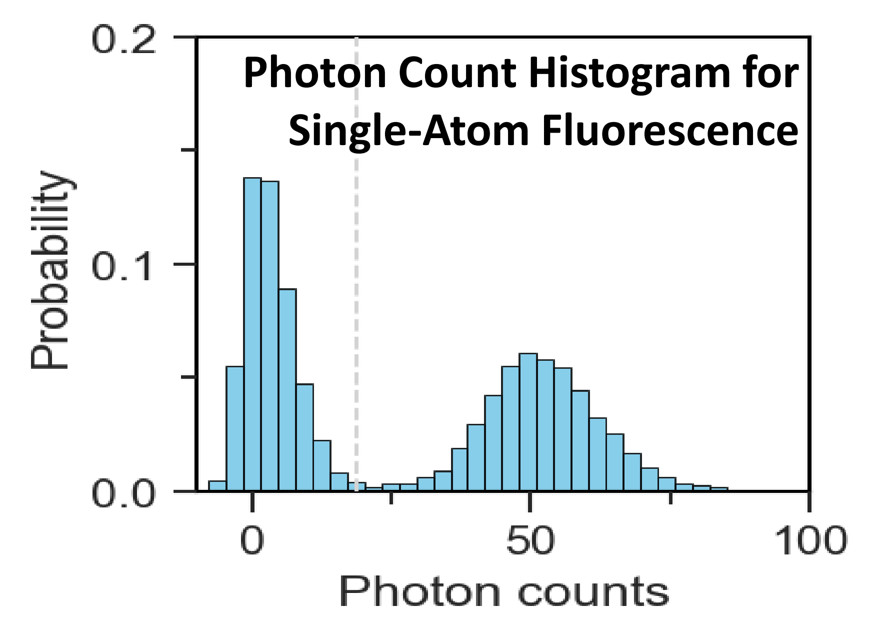


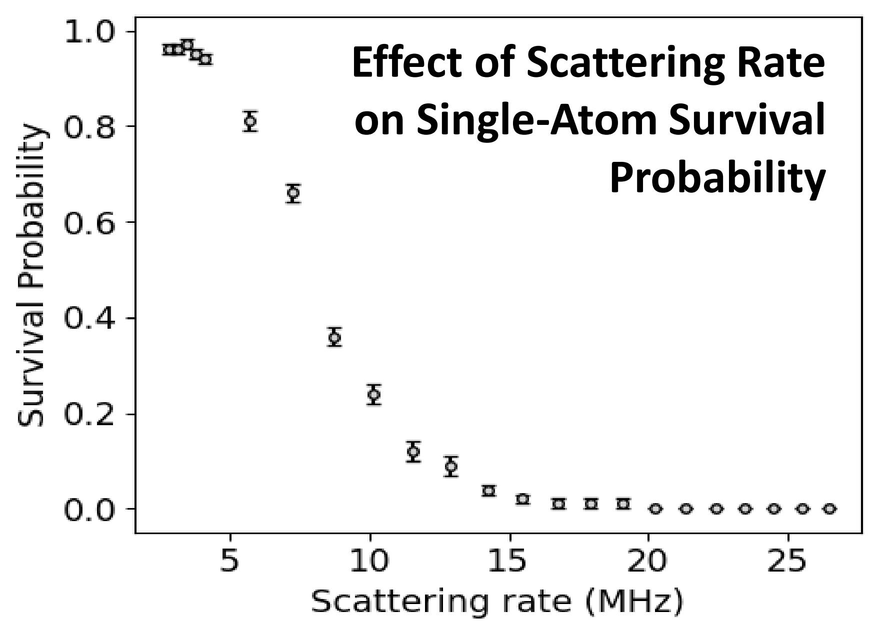
ACHIEVING SINGLE ATOMS

FLUORESCENCE imaging



Vacuum lifetime =378 ± 20 s
Survival Probability = 97 %





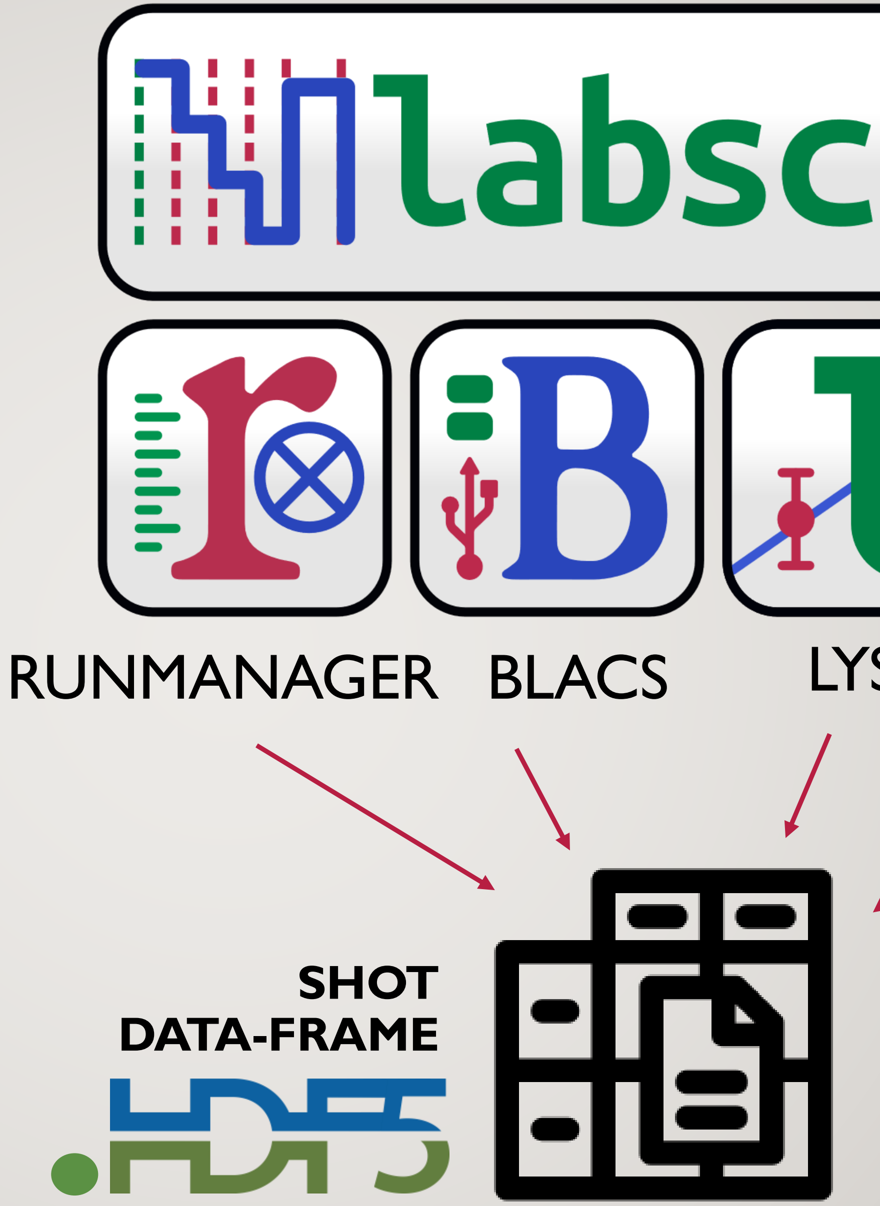
OUR WAY OUTLINE

- Strontium Atom
- Experimental Setup
- Single Atom Trapping and Detection
- Control System

LABSCRIPT-SUITE

- Open-source **Python**-based control system for heterogeneous hardware
- Multiple analysis-based **feedback** modes.
- **Extensible plugin** architecture (AI).
- Dynamic visualisation and analysis of output data.
- Remote operation & high-level scripting

python™



pandas

MONASH University

https://labscriptsuite.org/

PROGRESS STATUS

Exp. setup	Magneto-optical trap (MOT) at 461 nm	Magneto-optical trap (MOT) at 689 nm	Loading an array of optical tweezers	Detection of single atoms	Sorting	Rydberg excitation, experi-ments
✓	✓	✓	✓	✓	🕒	🕒

CONCLUSIONS AND OUTLOOK

Wide statistics
with high
repetition rate
and handy e- structure

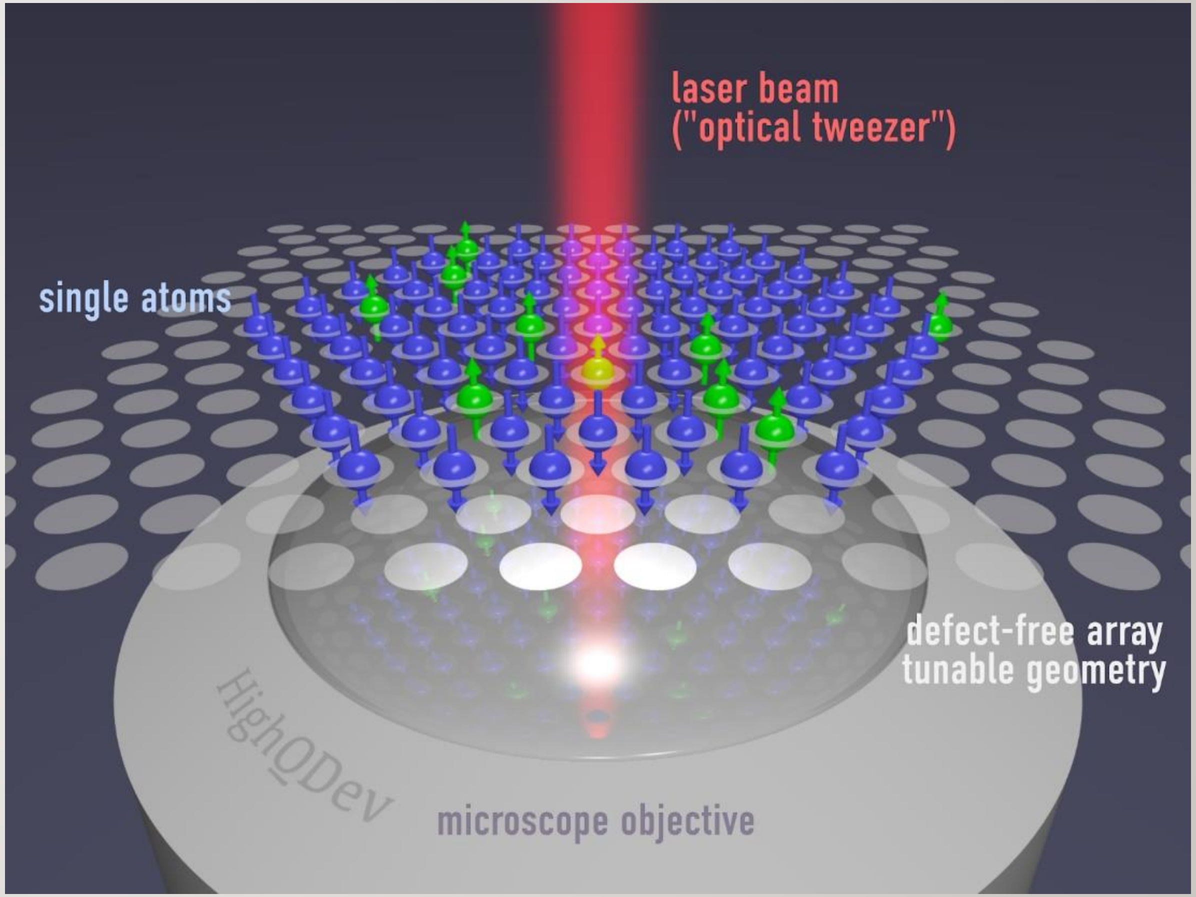
New platform for a large variety of topics in quantum physics:

Quantum simulation / many-body physics

- Quantum magnetism
- Out-of-equilibrium dynamics
- Direct measurement of entanglement
- Energy transport across topology & disorder

Quantum-technology-oriented applications

- Quantum computing
- Programmable quantum devices
- Optimization and annealing
- Applications to quantum/sensing metrology



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SR LAB

MUR | QUANTERA

Funding:

- CNR PASQUA Infrastructure
- QuantERA ERA-NET Cofund in Quantum Technologies project MENTA
- MUR PRIN 2022SJCKAH "HIGHEST"
- MUR PNRR M4C2 investment 1.2 project MicroSpinEnergy

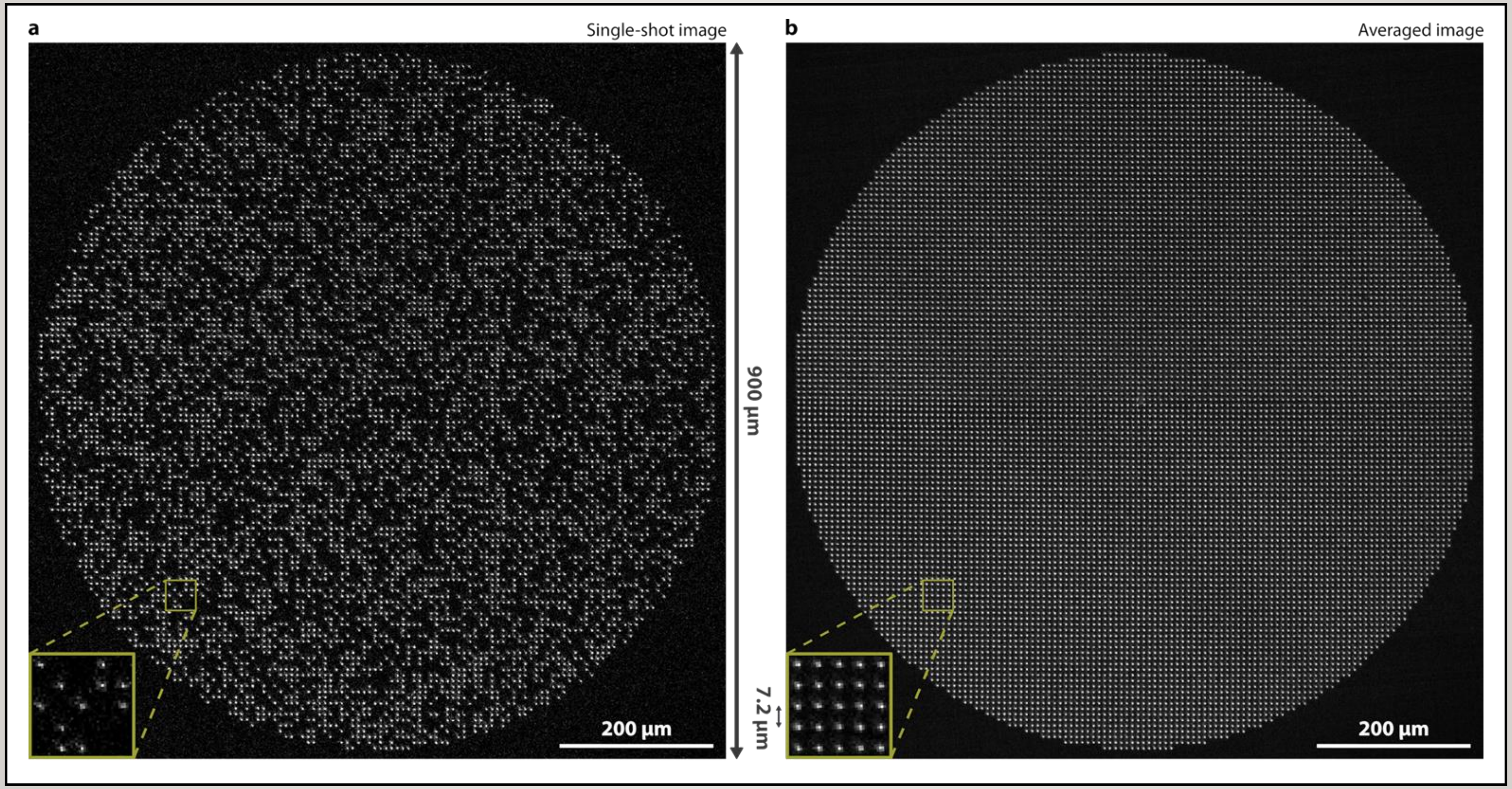
Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

EXTRA SLIDES

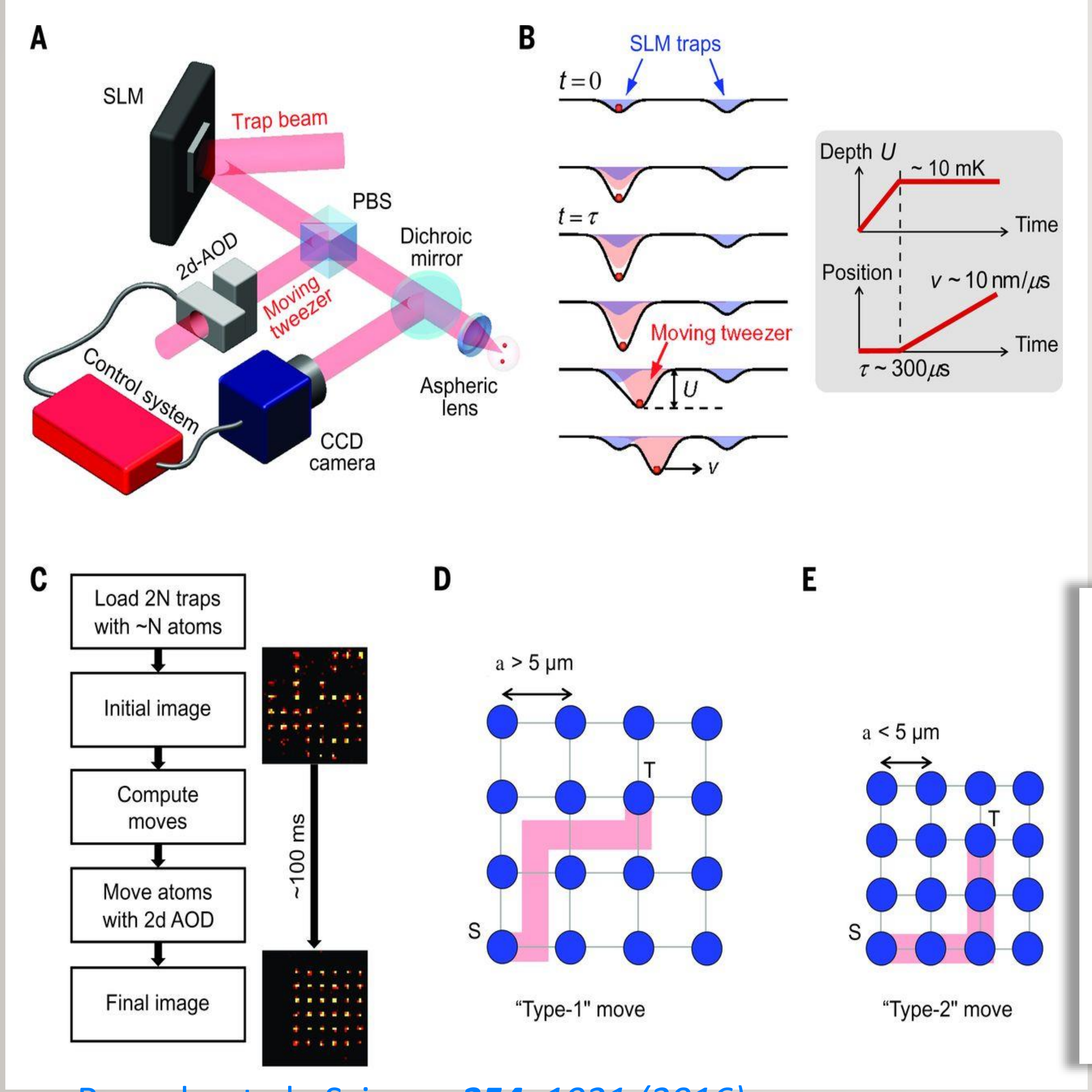
SCALABILITY OF THE PLATFORM

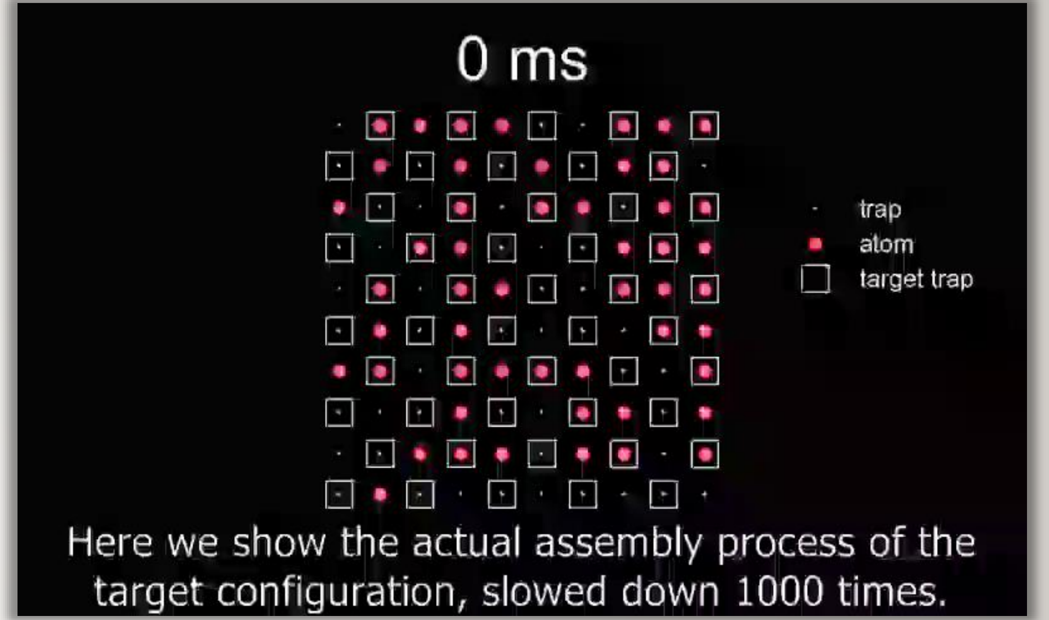


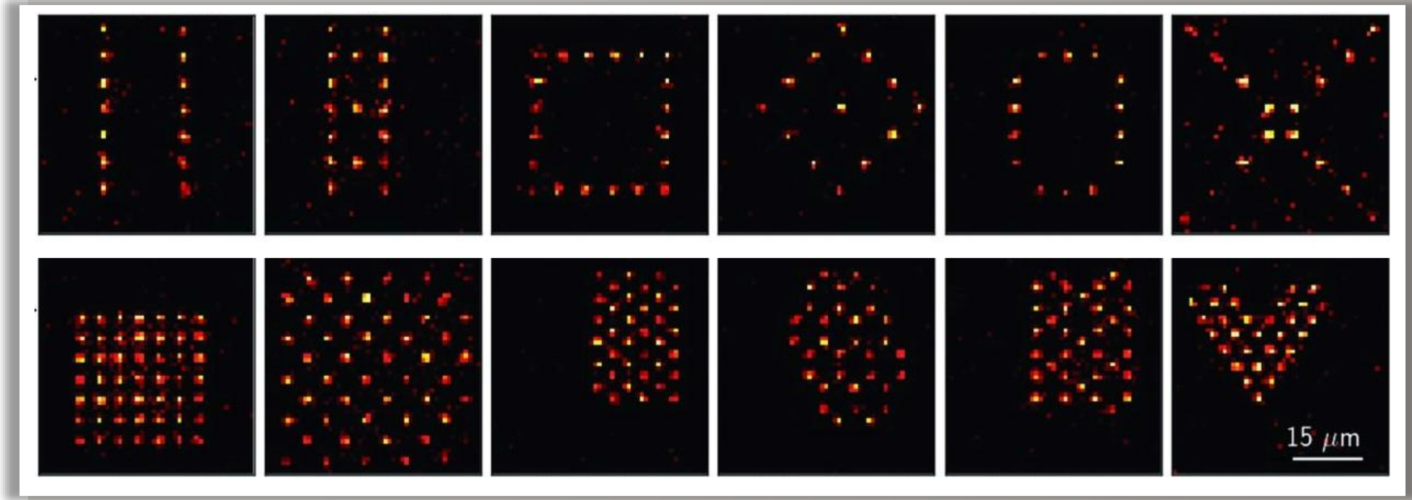
Scalable system with more than 1000 atoms

H. J. Manetsch et al. *A tweezer array with 6100 highly coherent atomic qubits* (2024)

RECONFIGURABLE ARRAYS OF OPTICAL TWEEZERS







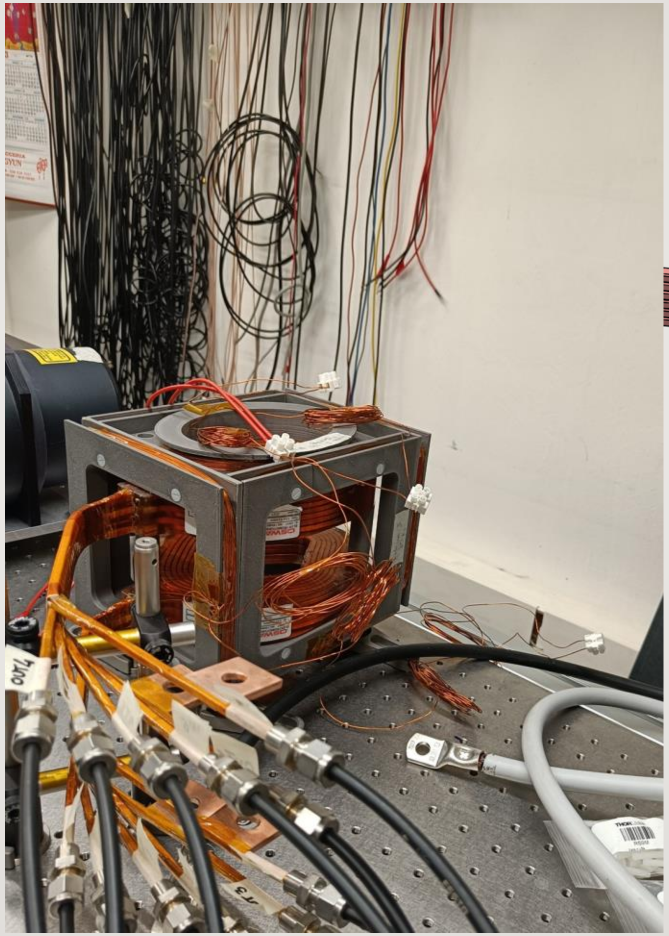
Barredo et al., Science ***354**, 1021 (2016)*

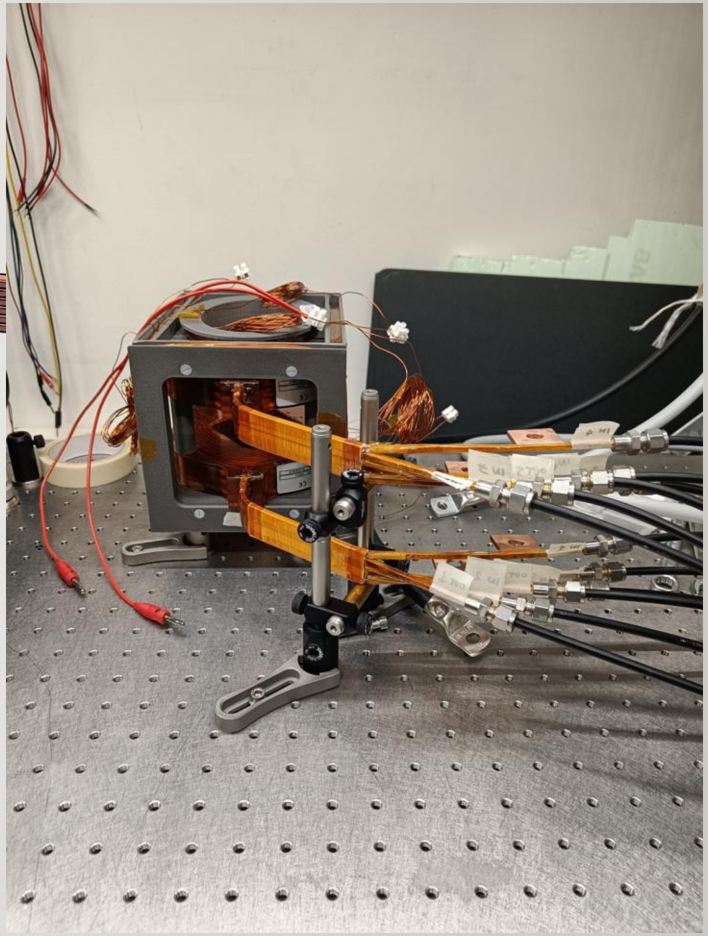
KEY ELEMENTS OF THE MACHINE

Cooling and trapping			Tweezer preparation			Q. Simulation experiments	
Exp. setup	Magneto-optical trap (MOT) at 461 nm	Magneto-optical trap (MOT) at 689 nm	Loading an array of optical tweezers	Detection of single atoms	Sorting	Rydberg excitation	Array state detection
Vacuum system, lasers, coils	$N>10^6$ atoms	$\rho>3\mathrm{x}10^{10}$ atoms/cm^3 $T \sim 5\ \mu K$		$F>99.9\%$ $S>99.9\%$		$\Omega/2\pi >$ 1 MHz	

COILS ASSEMBLY

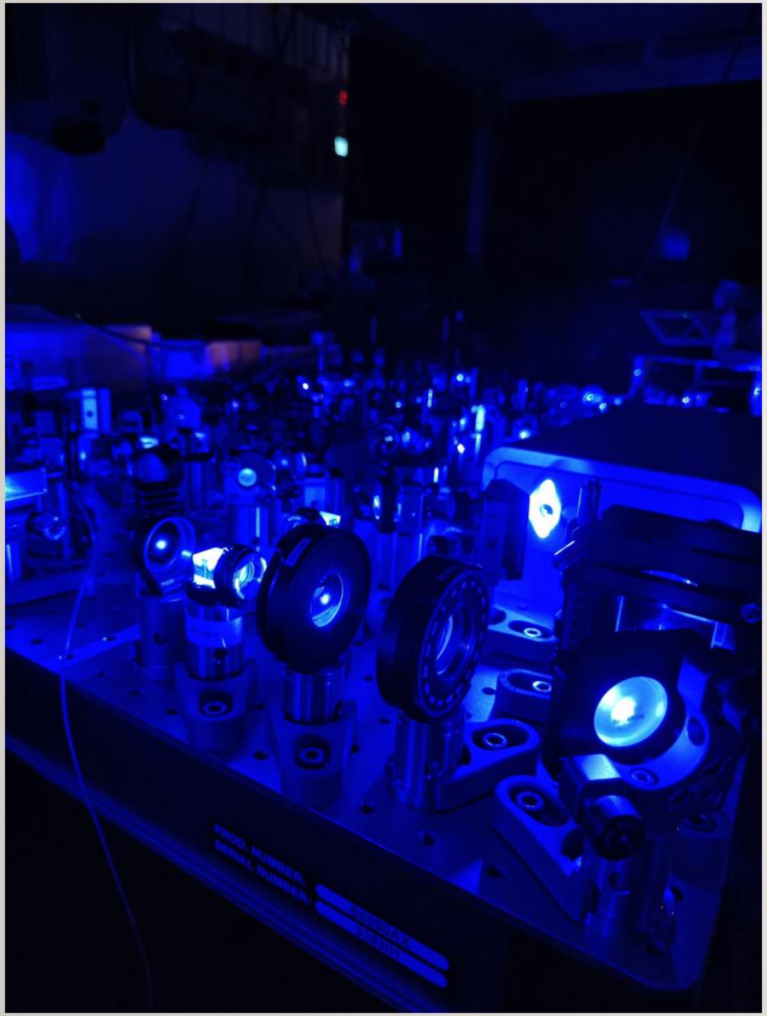
- Gradient > 50 G/cm in all the directions in anti-Helmholtz configuration to generate the MOTs
- Magnetic field > 900 G in one direction to excite the bosonic isotopes on the doubly forbidden clock transition
- Power dissipation up to 2.5 kW, use of hollow-core conductor for water cooling
- Form factor maximizing the optical access to the glass cell
- Independent set of compensation coils, to compensate for stray external fields and tune the position of the red MOT

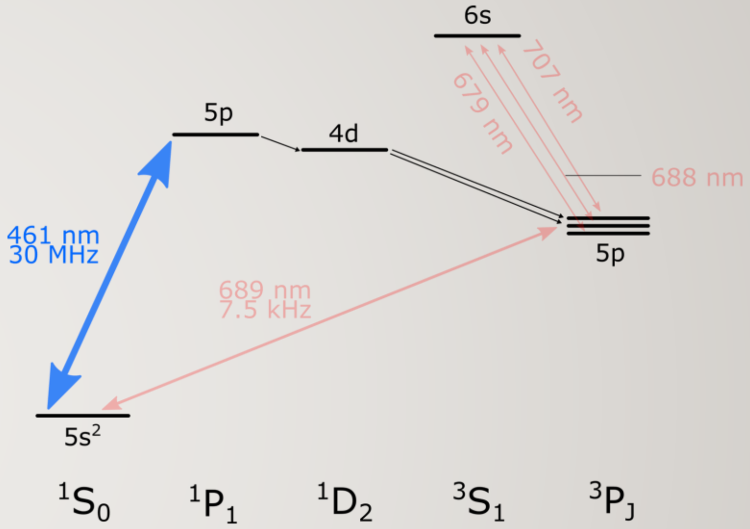




December 2023

BLUE LASER 461 NM



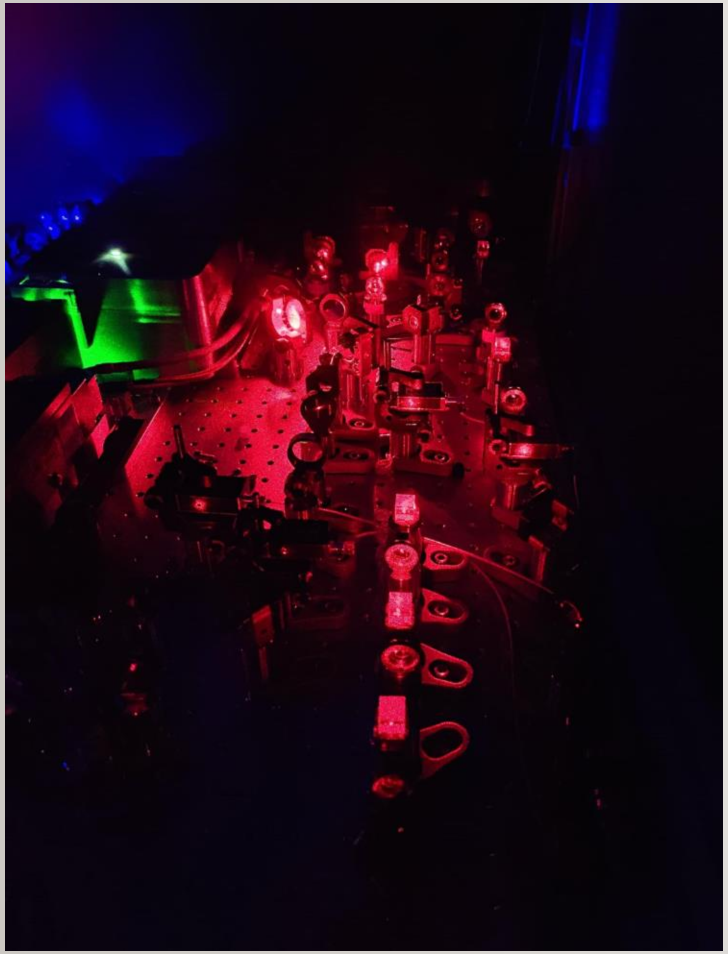


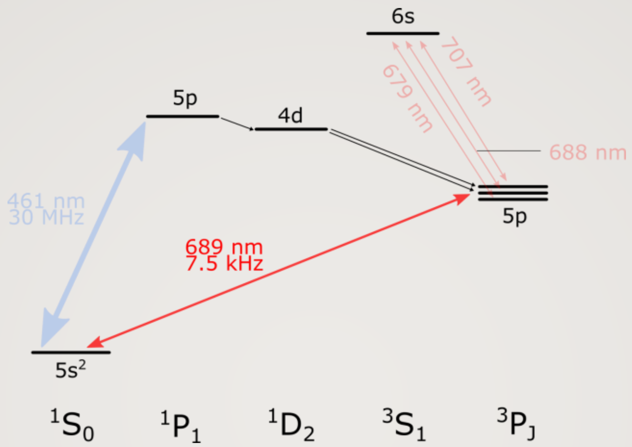
Injection-locked amplifier (ILA), P > 700 mW.
1° MOT stage, Zeeman Slower and 2D MOT beams, absorption and fluorescence imaging.

Locked on a spectroscopic signal (saturation spectroscopy).

May 2023

RED LASER 689 NM

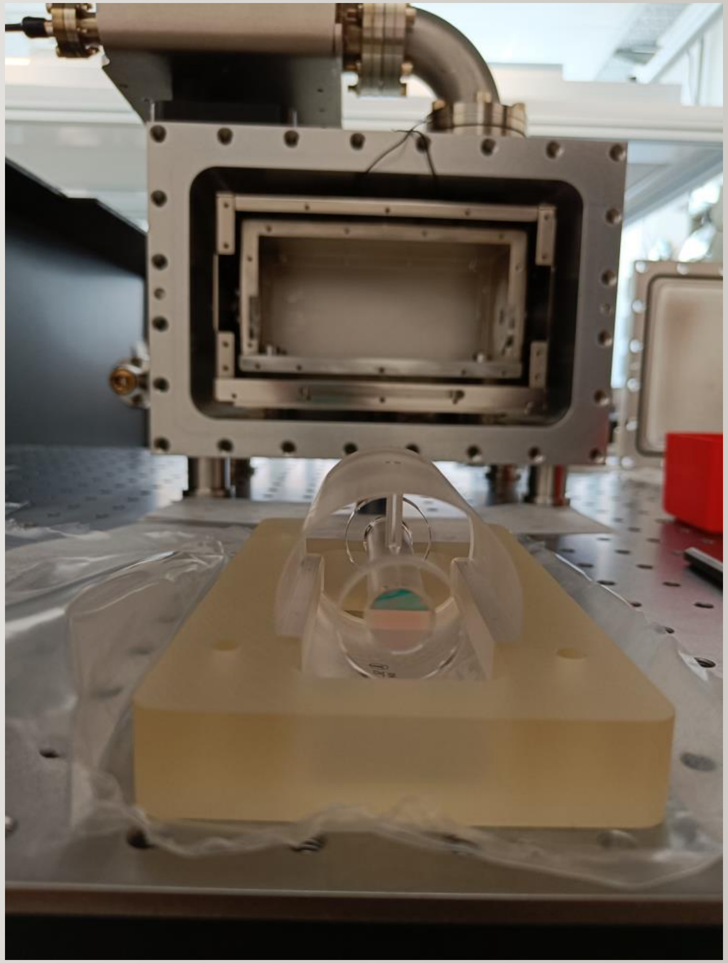




TiSa MSquared laser, P > 1.5 W, low high-frequency noise.

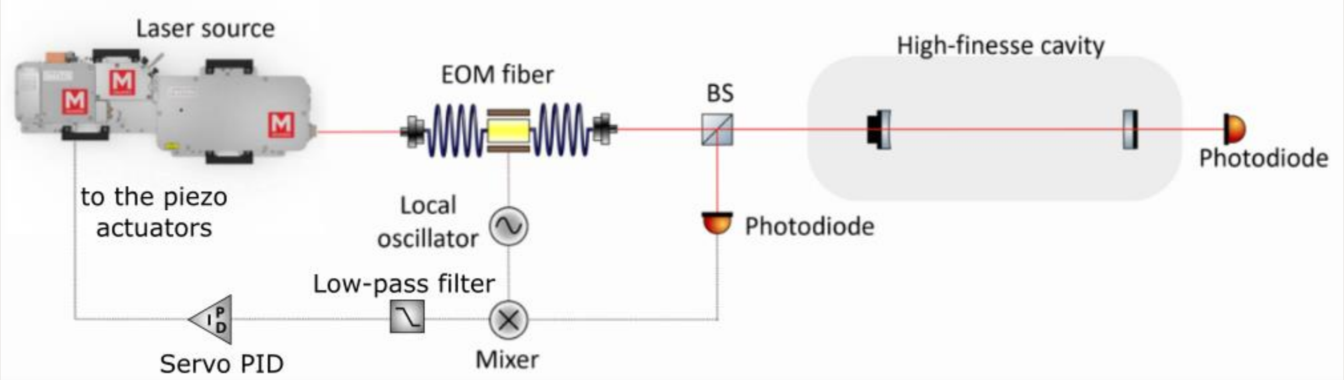
2° MOT stage, in-tweezer cooling, Rydberg excitation

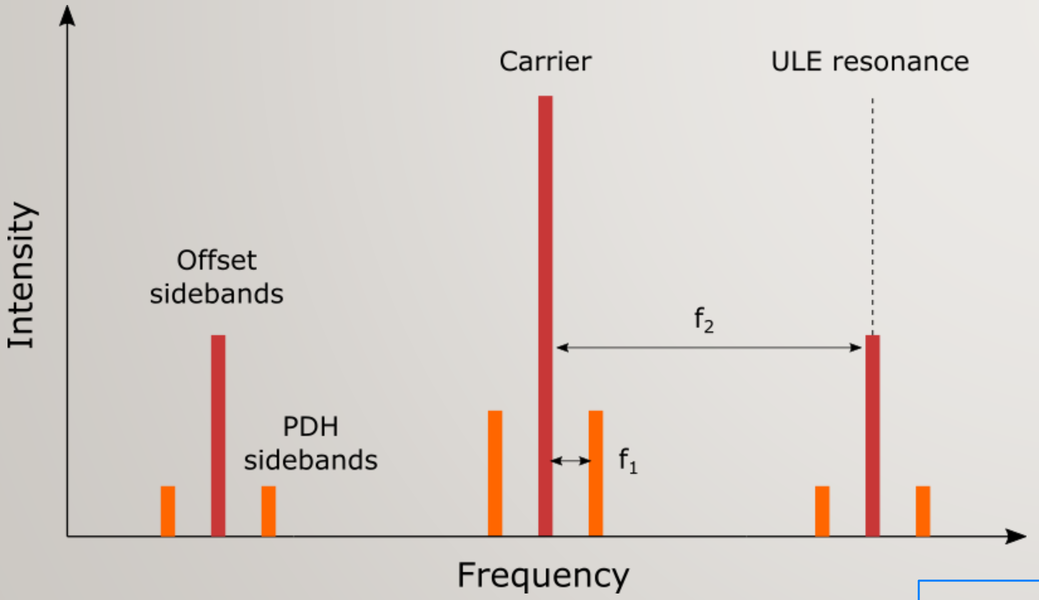
Ultra-low expansion (ULE) cavity from Stable Laser System (Finesse ~ 265k)

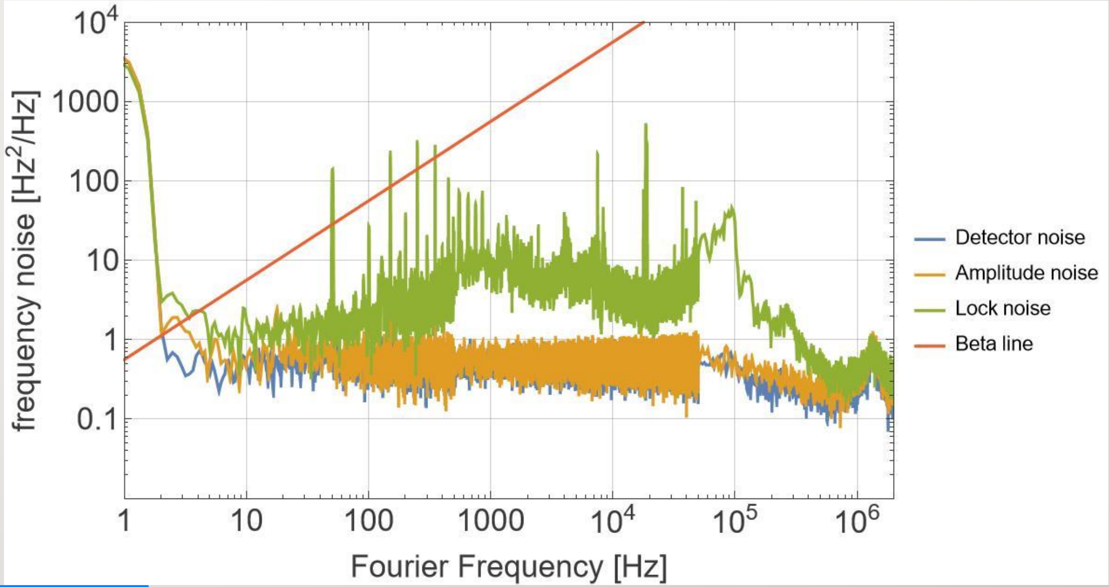


September 2023

POUND-DREVER-HALL OFFSET LOCKING

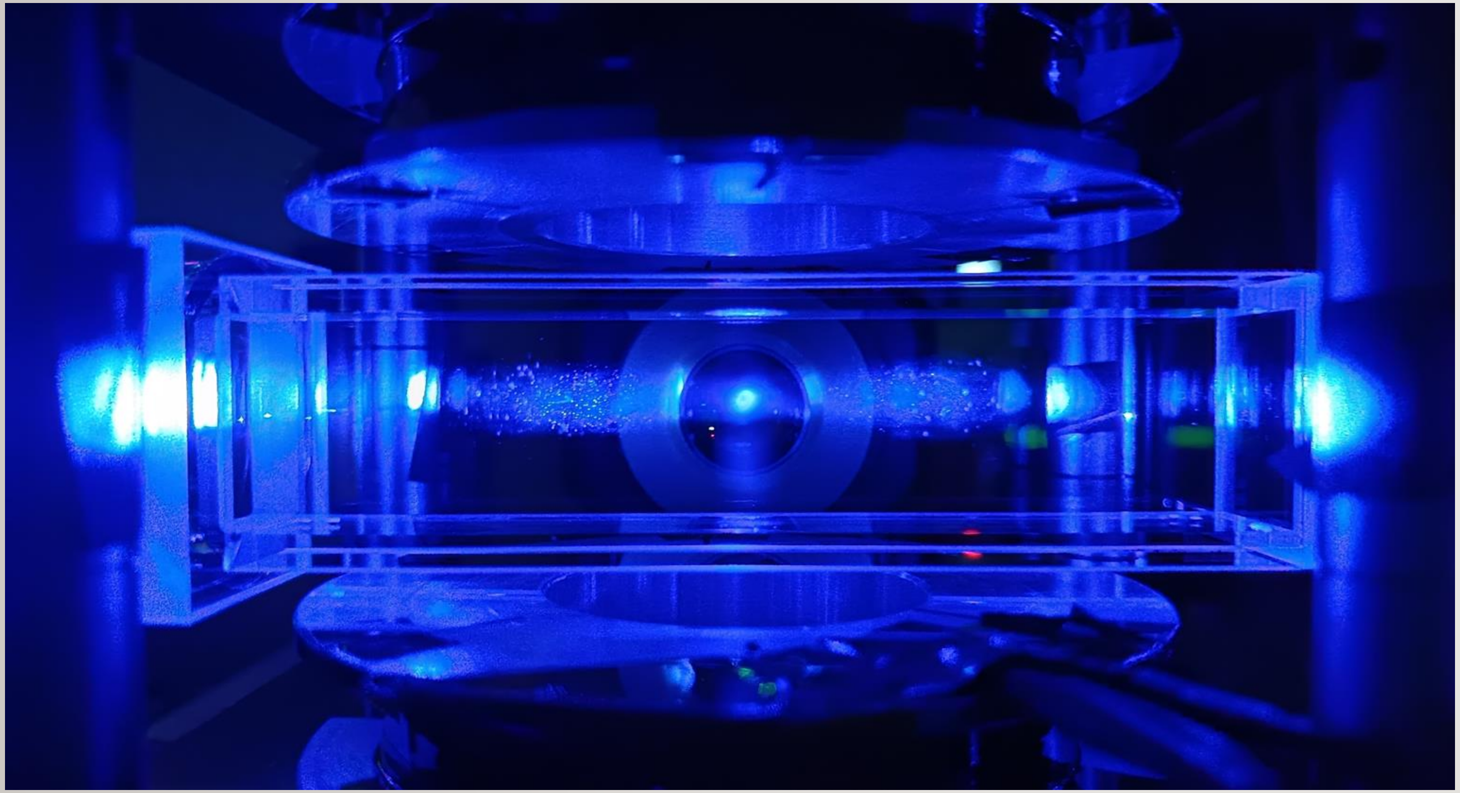






December 2023

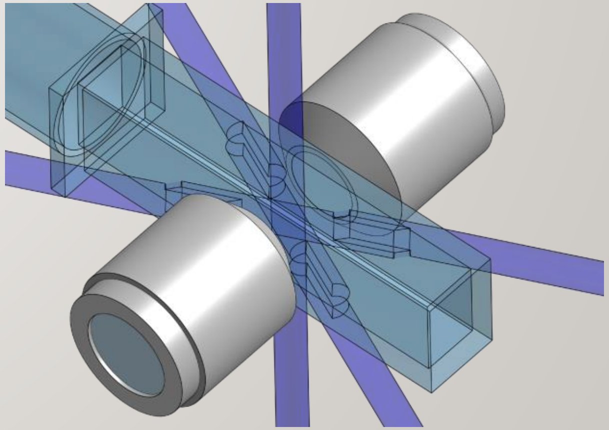
BLUE MOT (461 NM)



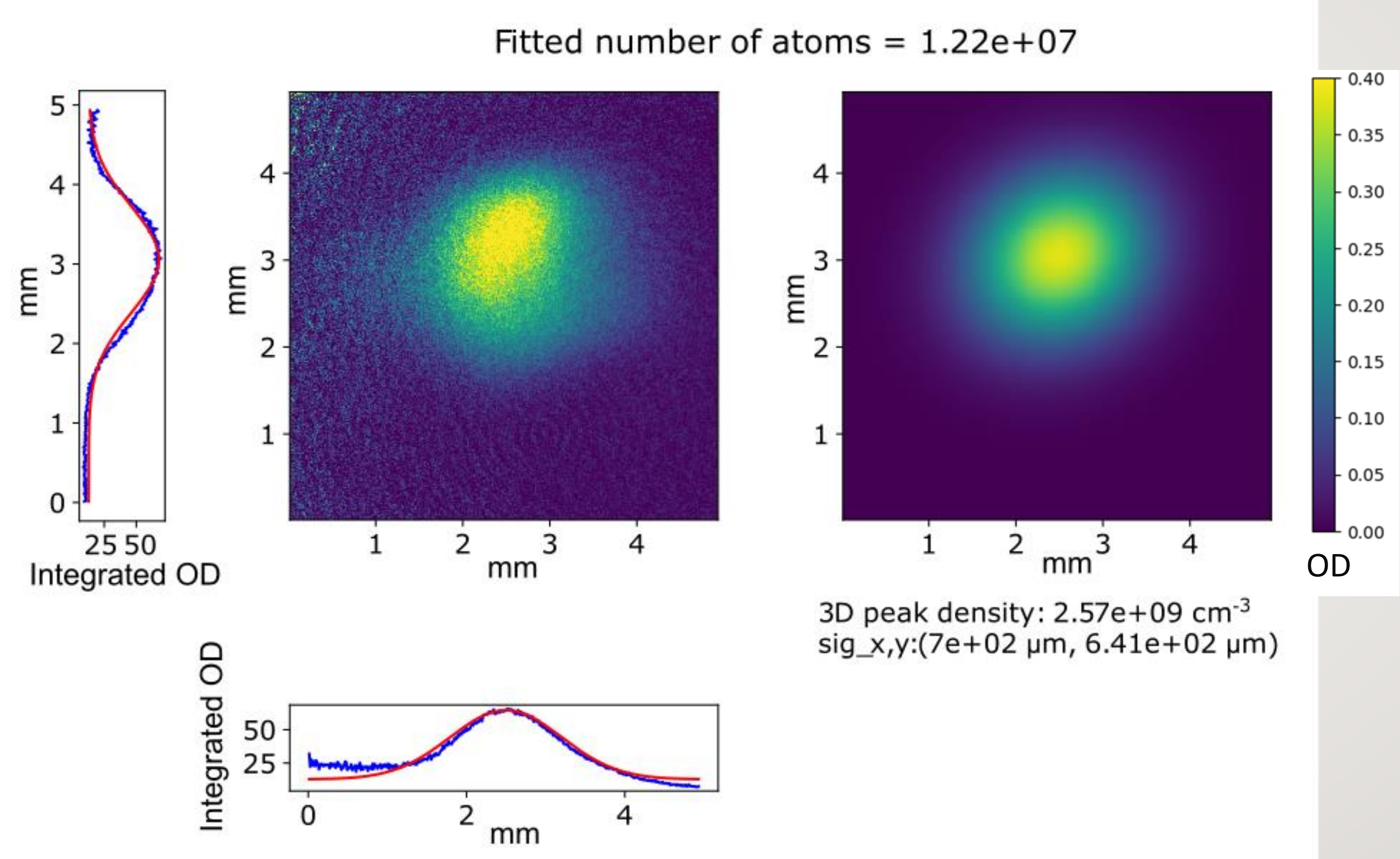
September 2023

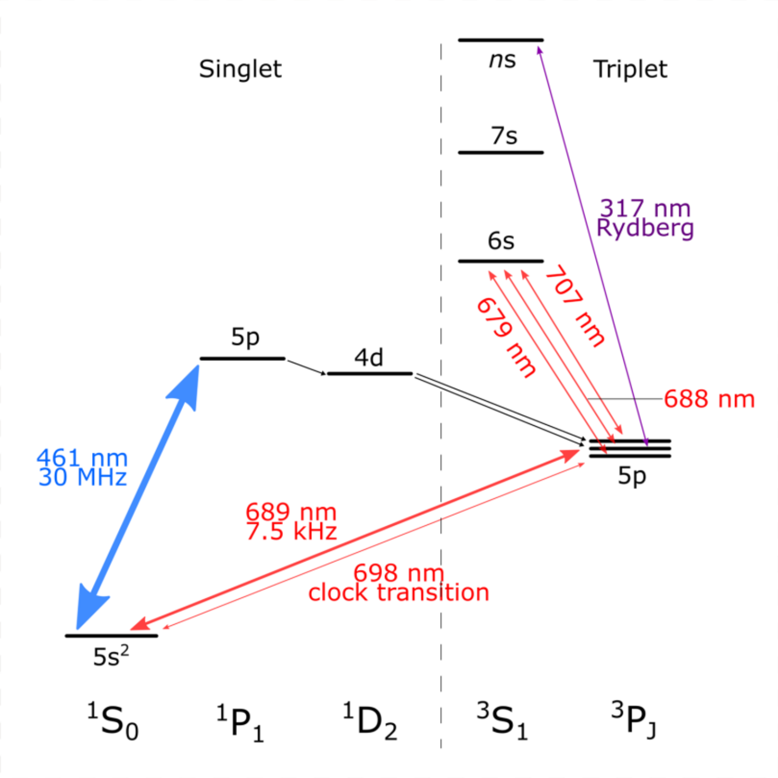
3D blue MOT @461 nm captured in a quartz glass cell

- Non-orthogonal planar beams to fit the microscope objectives size
- Three retro reflected beams, each of them with 4 mW power
- Magnetic field gradient of 50 G/cm
- T=6.8 mK
- Density $n=2*10^9$ cm^{-3}



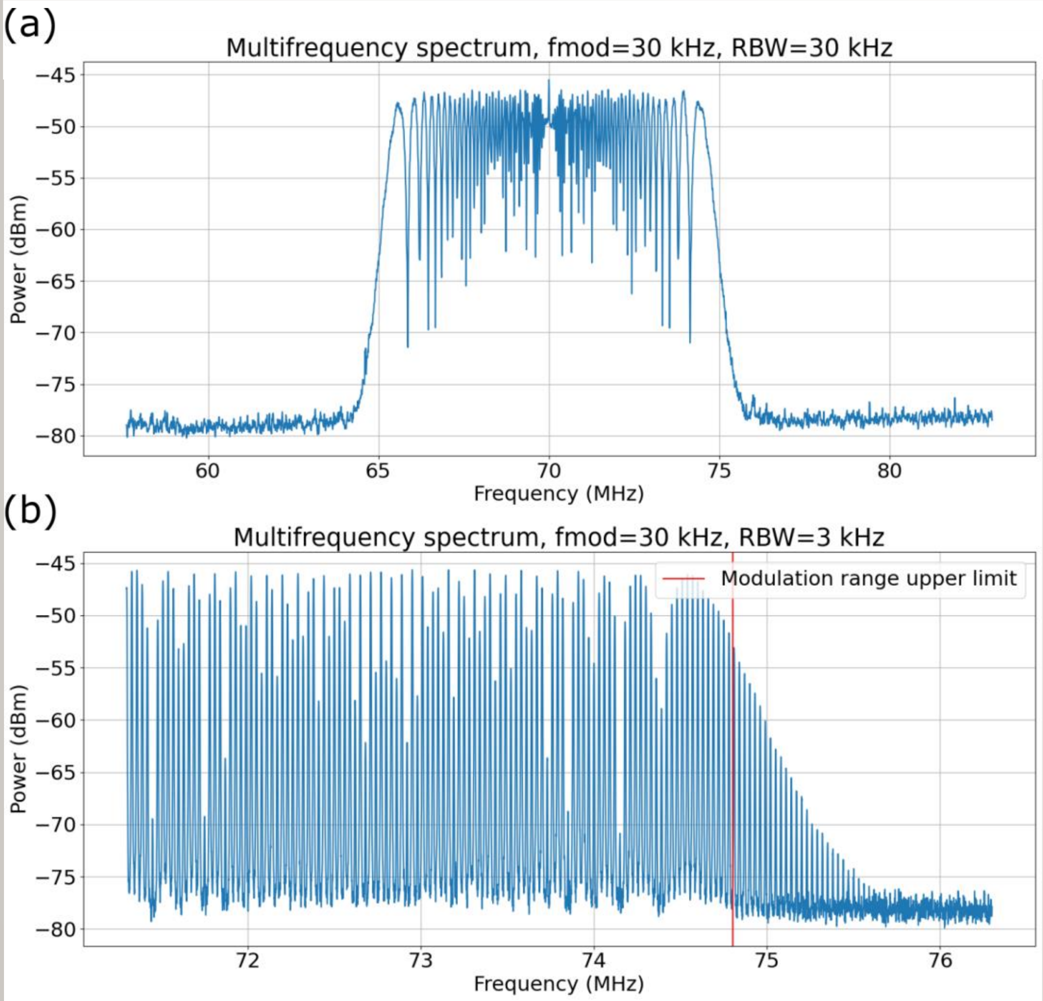
BLUE MOT (461 NM)





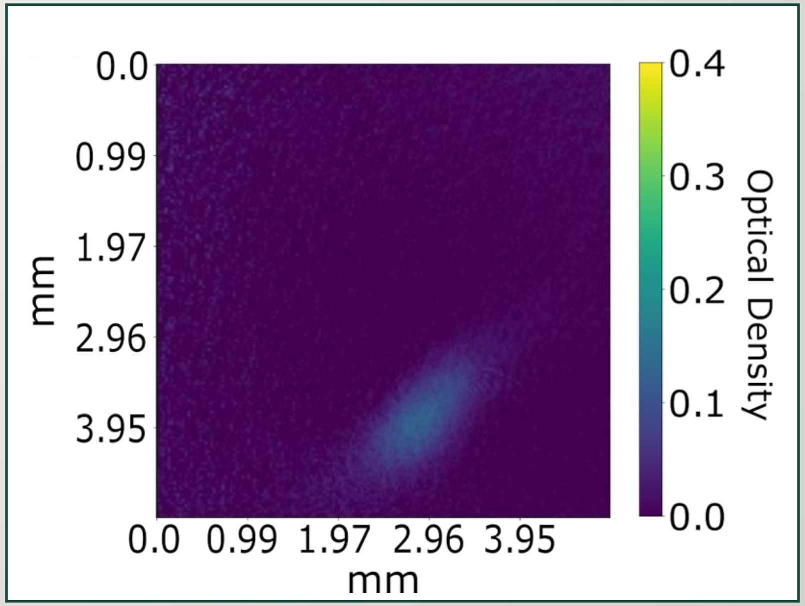
September 2023

RED MOT MULTIFREQUENCY (689 NM)



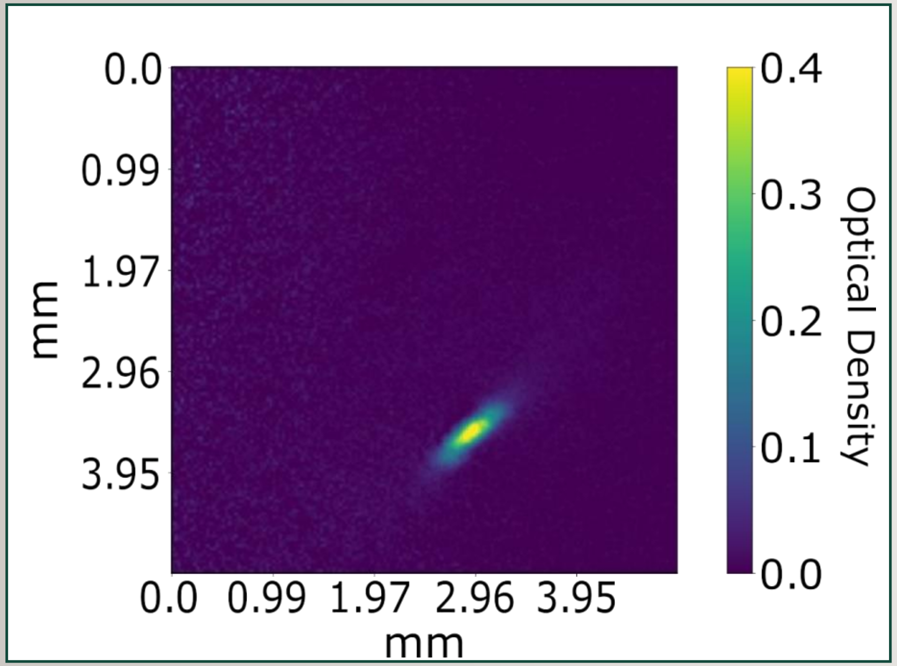
Multifrequency red MOT @689 nm. Artificially broadened linewidth with a comb of frequencies

- Three retro-reflected beams, each of them with 2 mW power
- Magnetic field gradient of 2 G/cm
- Temperature T=21 μK
- Density $n=5*10^9$ cm^{-3}



June 2024

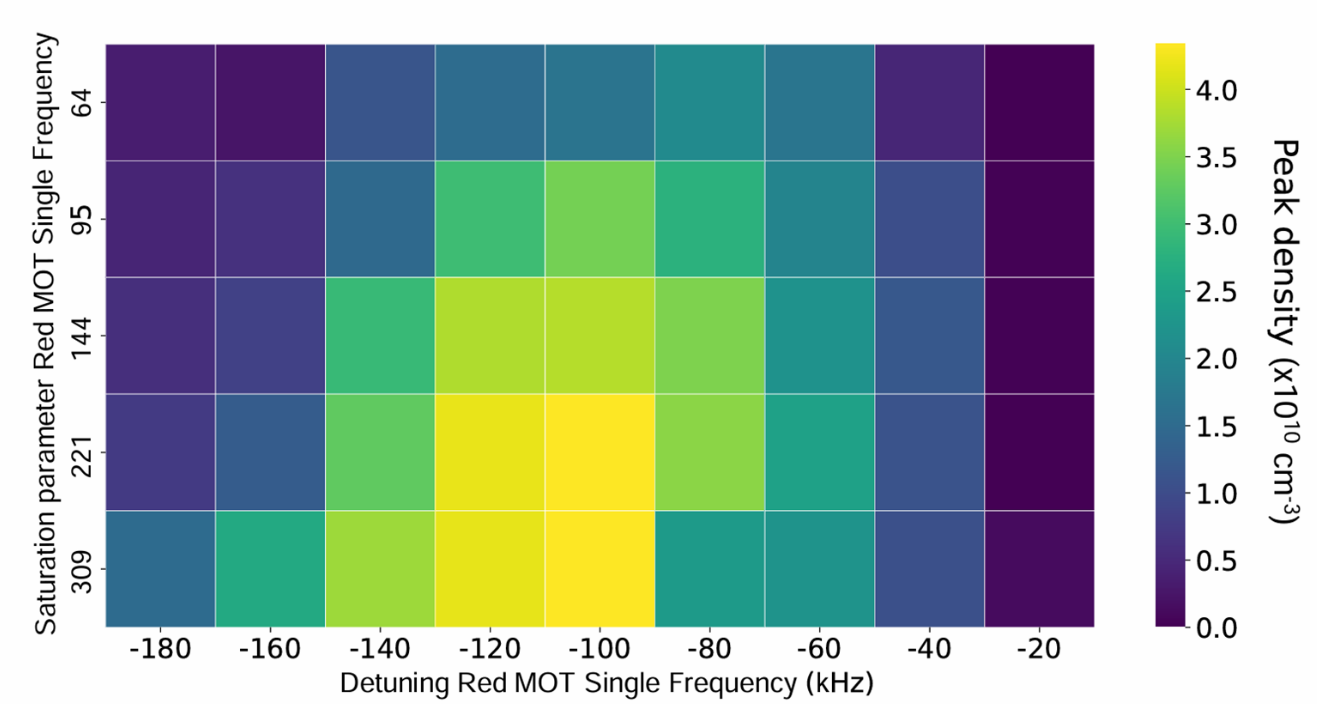
RED MOT SINGLE FREQUENCY (689 NM)



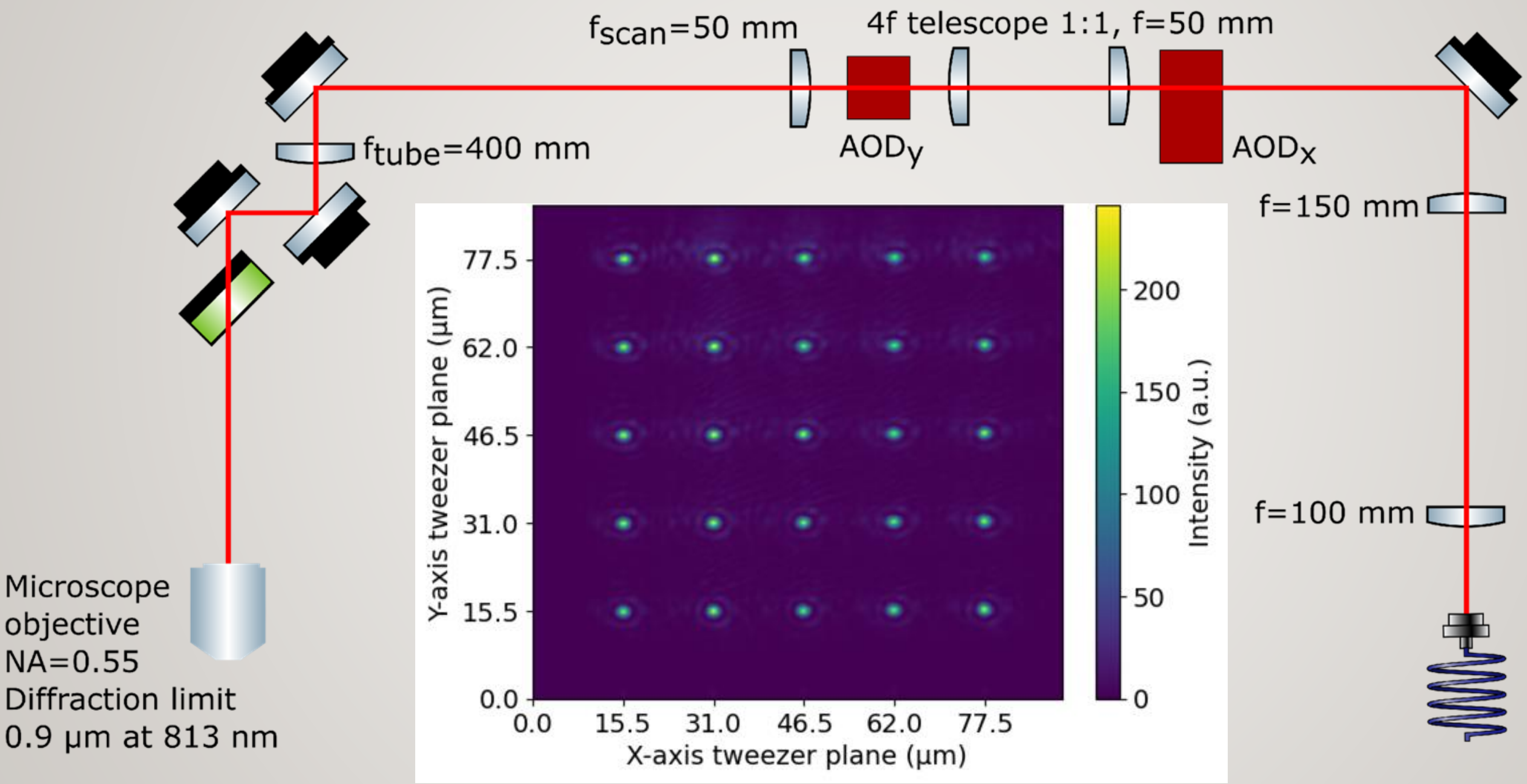
July 2024

Single frequency red MOT @689 nm.

- Three retro-reflected beams, each of them with 0.6 mW power
- Magnetic field gradient of 2 G/cm
- Temperature T=5.4 μK
- Density $n=4*10^{10}$ cm^{-3}

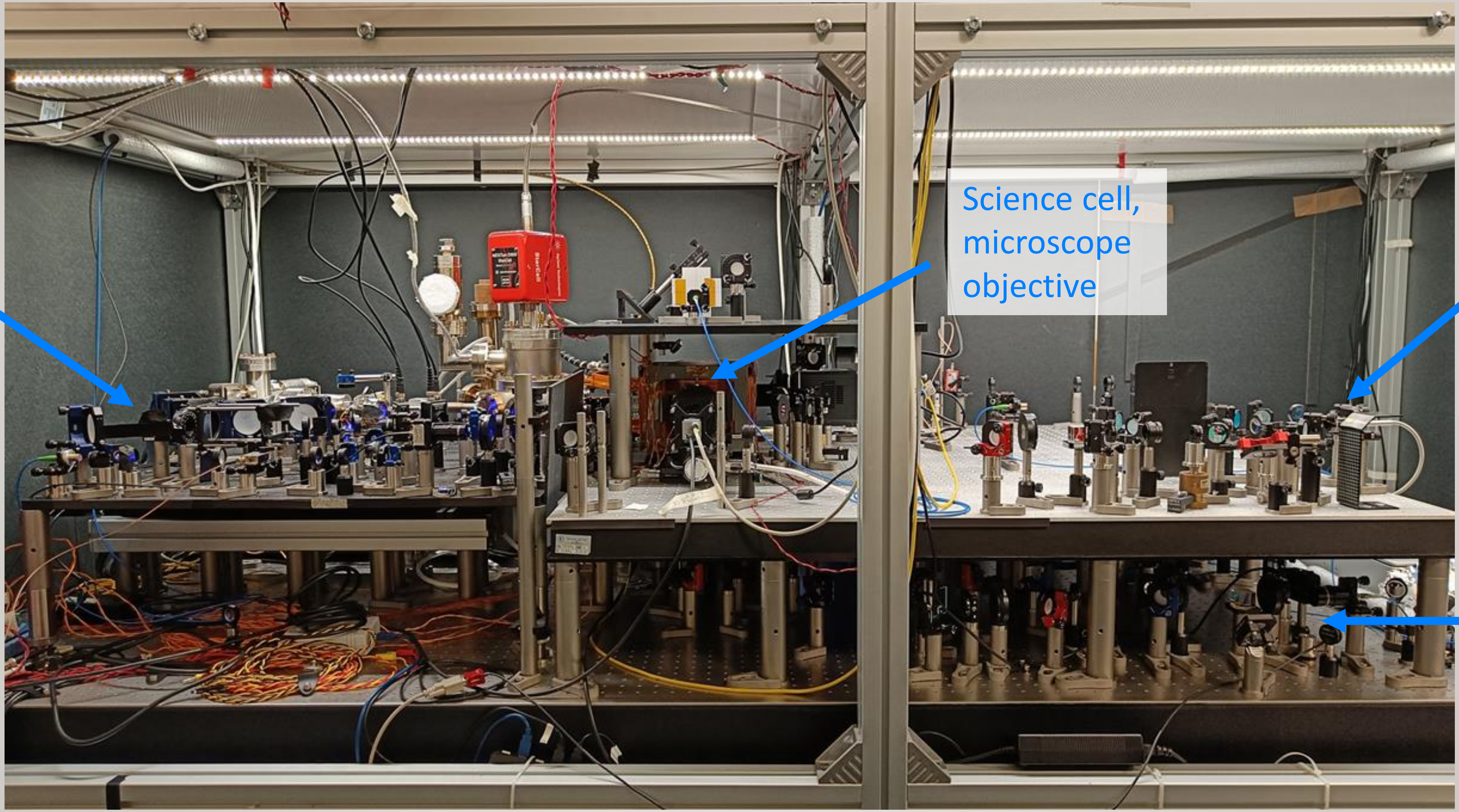


GENERATION OF A 2D ARRAY OF OPTICAL TWEEZERS

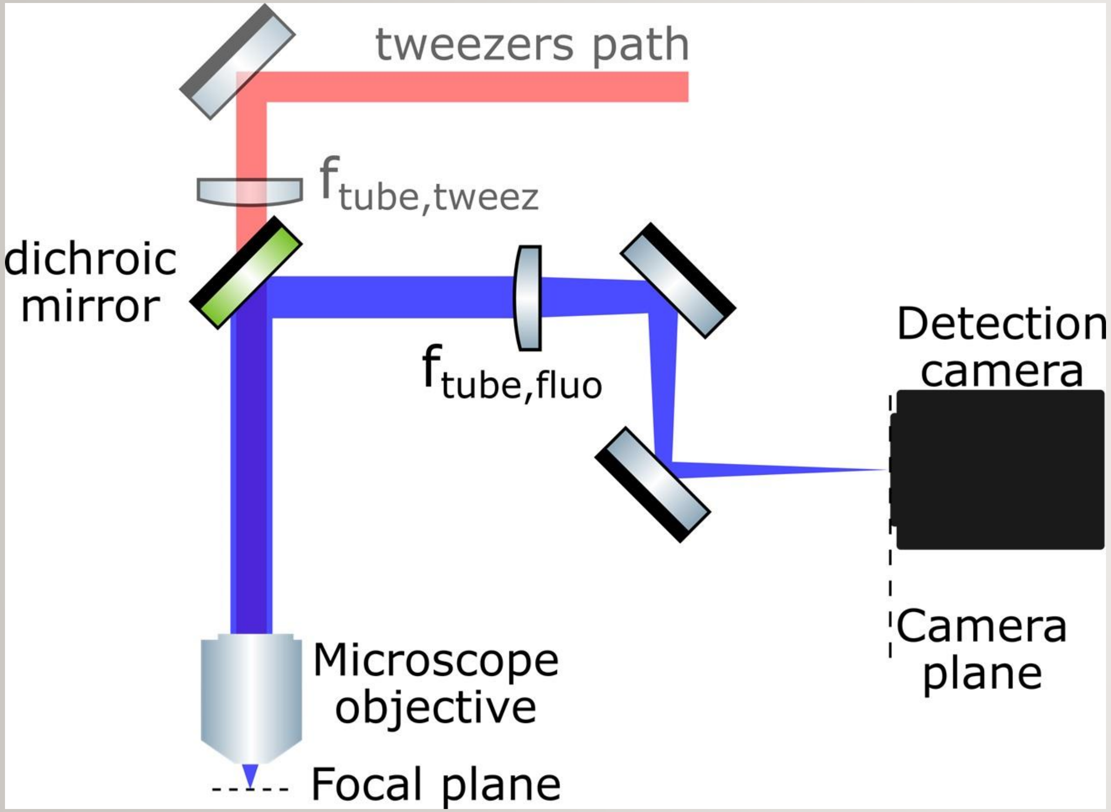


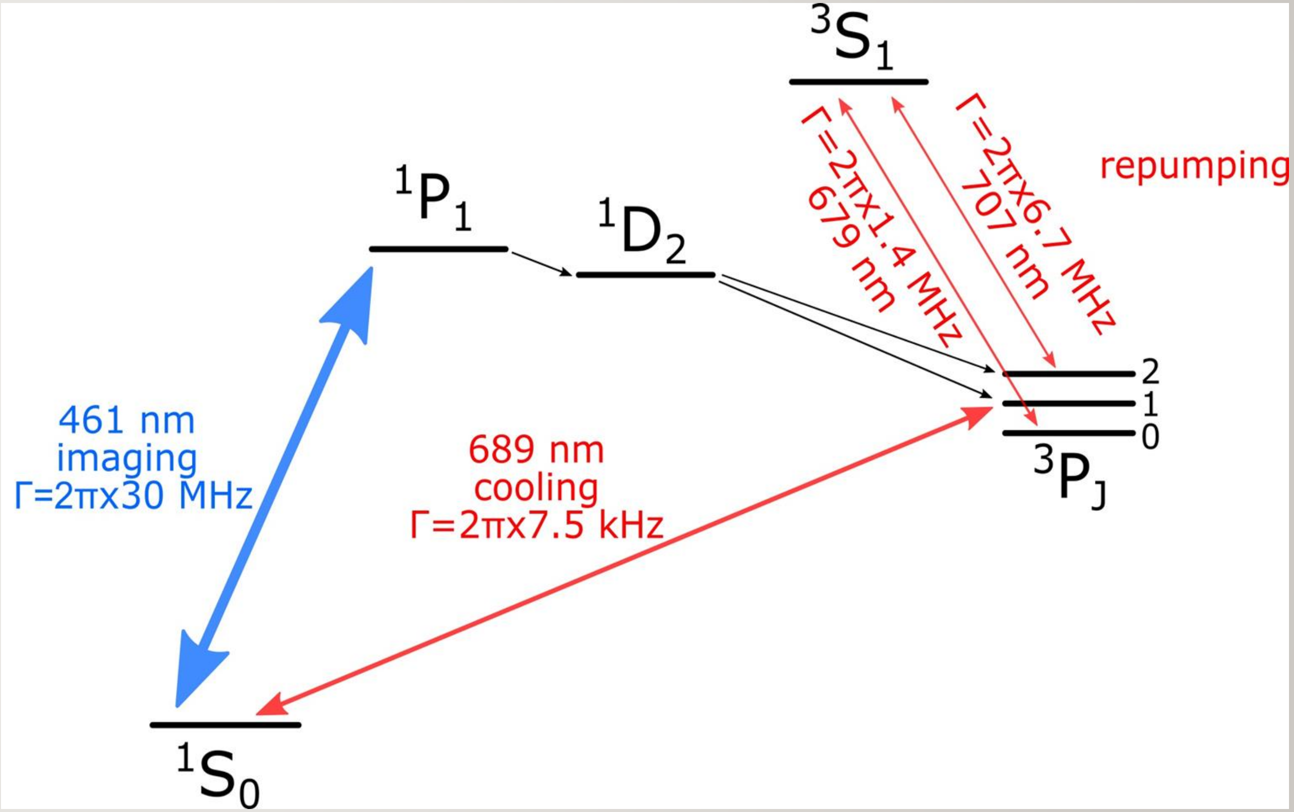
August 2024

OVERVIEW OF THE APPARATUS

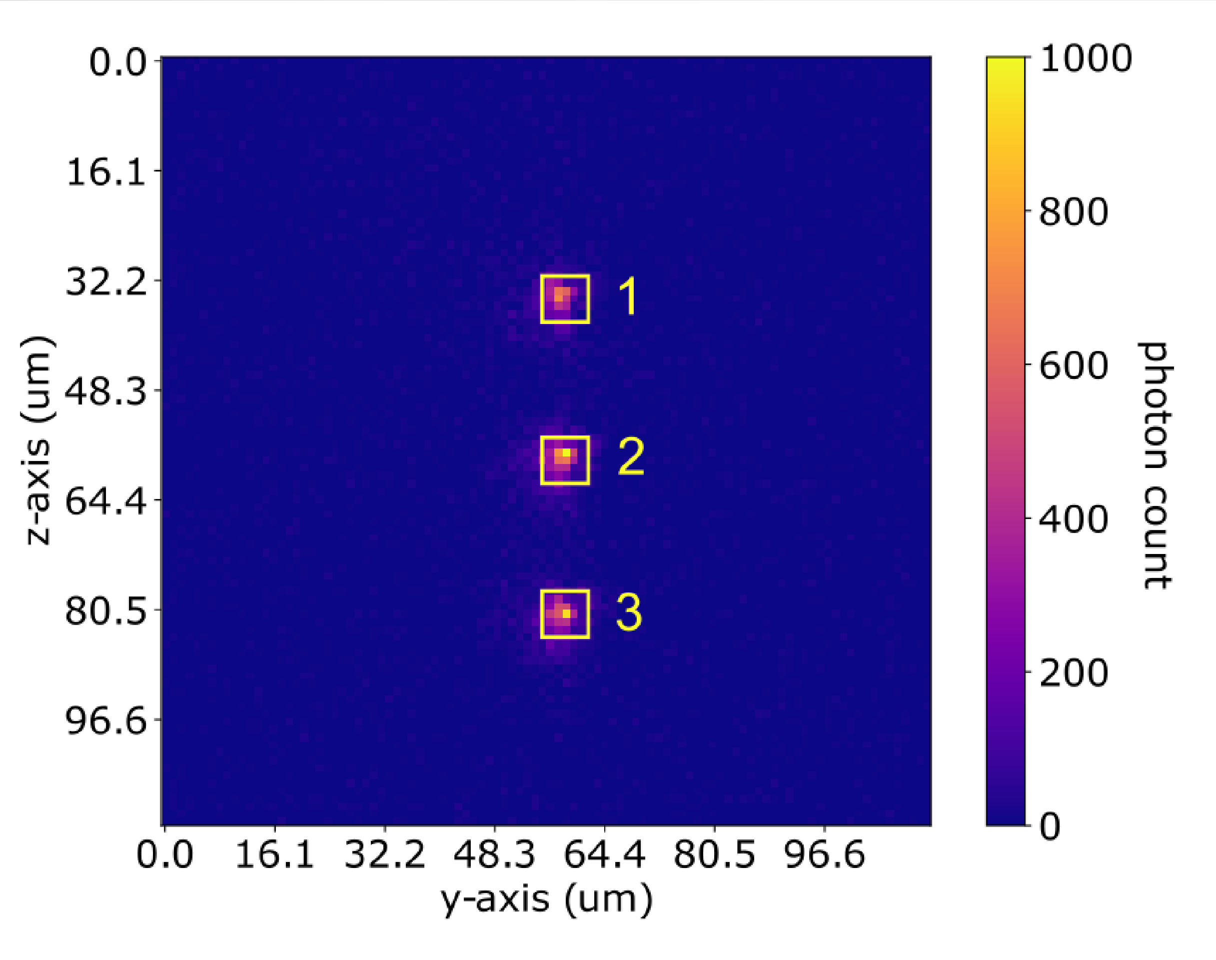


FLUORESCENCE IMAGING





FLUORESCENCE IMAGING



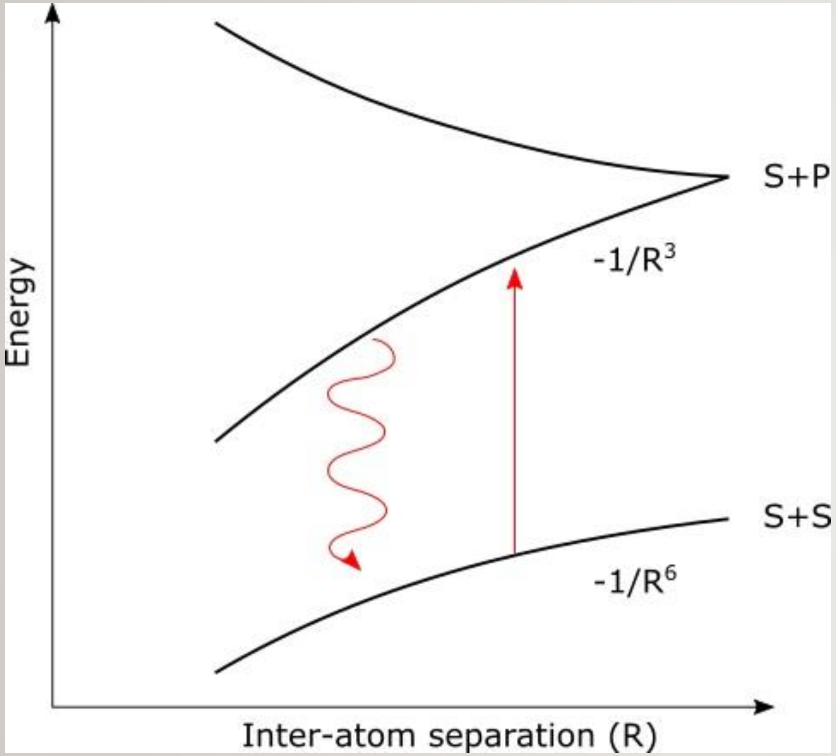
1D array with 3 tweezers

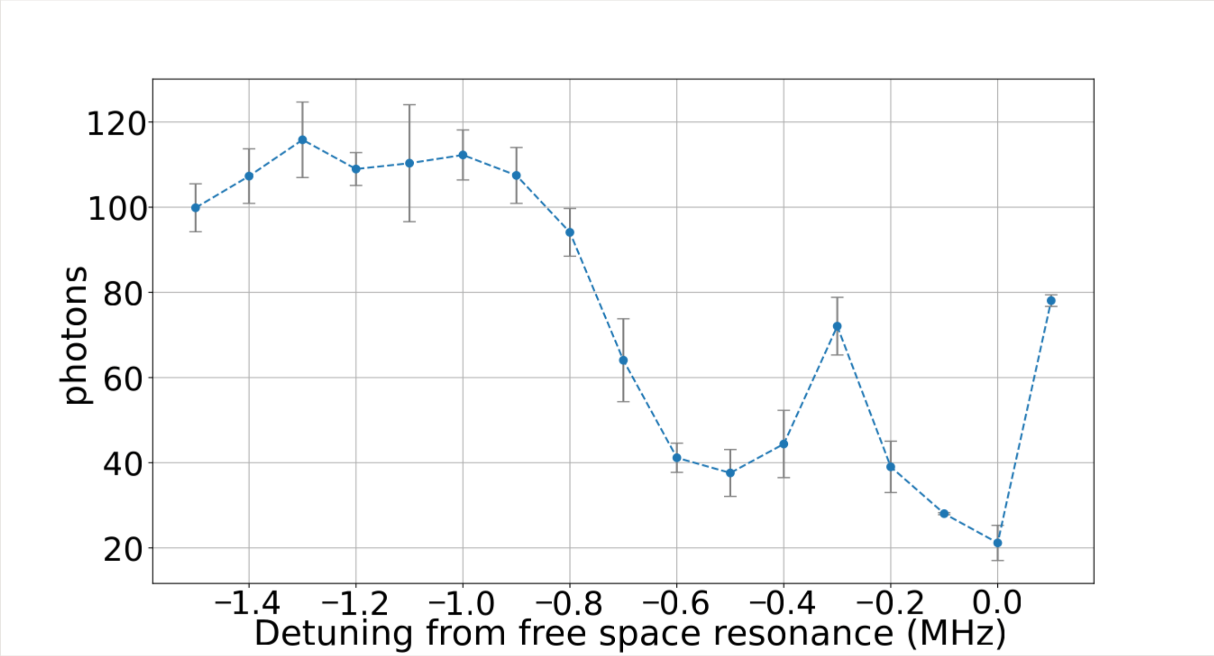
7x7 pixels Region Of Interest (ROI) around each tweezer to collect the fluorescence signal

Multiple atom occupation after the tweezer loading from the red MOT

October 2024

PAIRWISE LIGHT-ASSISTED COLLISIONS (LAC)

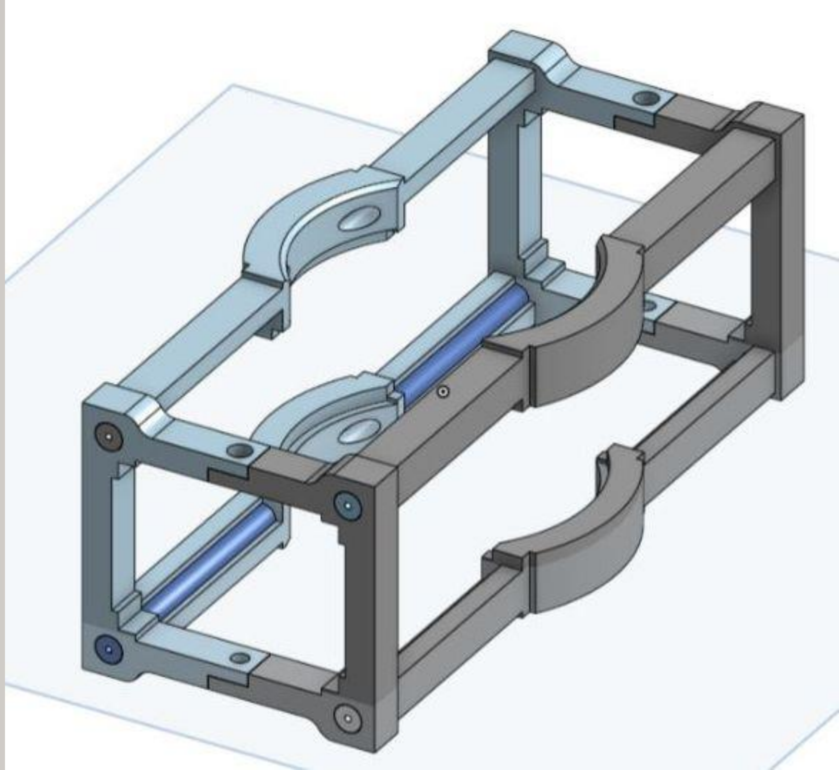




Pairwise losses induced by exciting two atoms to a molecular excited state. The energy gained by the pair in the relative frame is enough to lose both the atoms

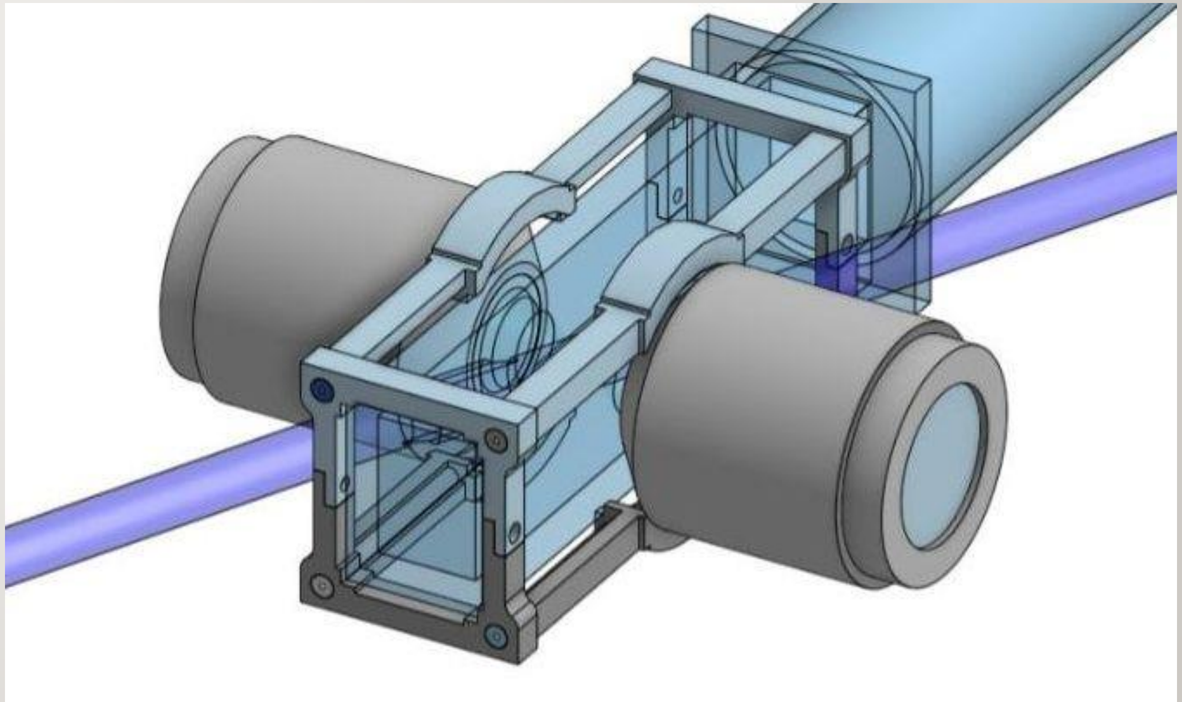
PLANNED DEVELOPMENTS

ELECTRIC FIELD CONTROL



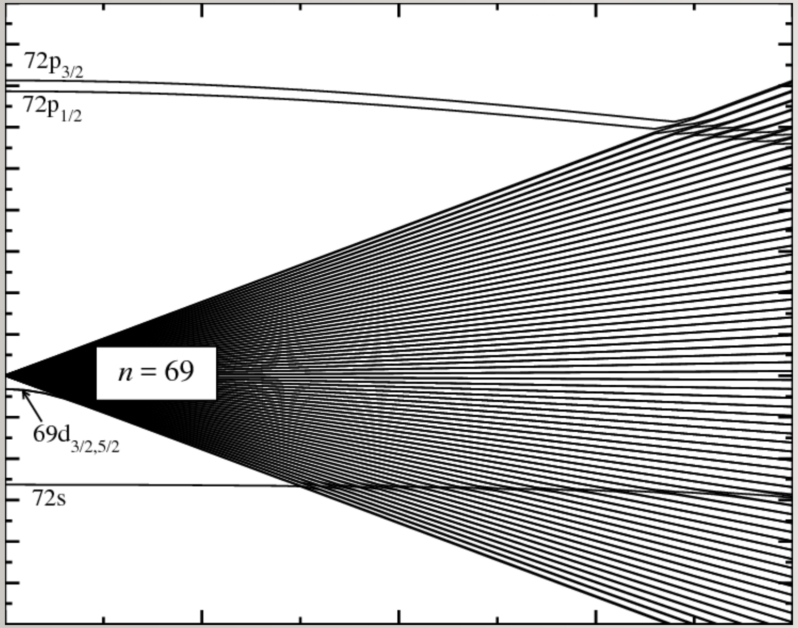
We have designed an 8 rod-shaped electrode system to:

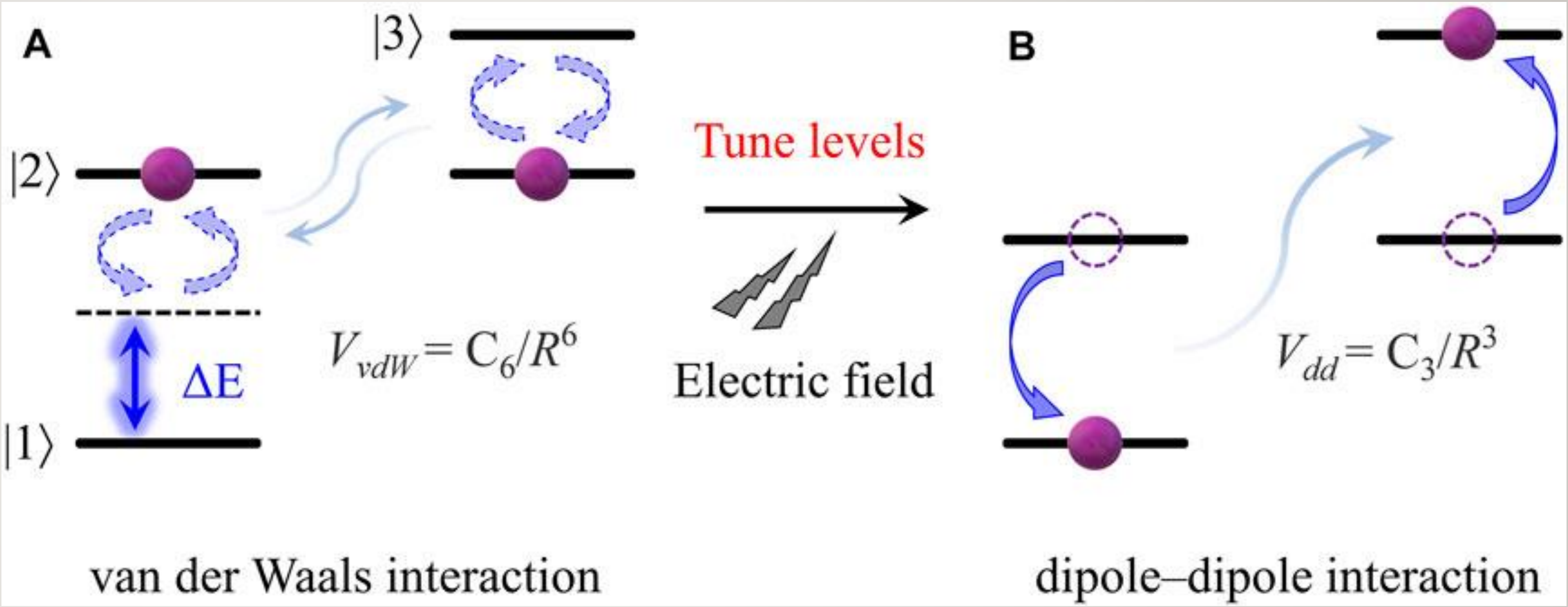
- Compensate stray electric fields in 3D
- Apply an electric field up to 100 V/m



- 8 rod electrodes
- 3D printed plastic holder for custom precise shape (to be finalized)
- 2 parts for optimum assembly and stability
- Voltages applied by 16 or 20 bit DACs.

ELECTRIC FIELD CONTROL FOR INTERACTION TUNING

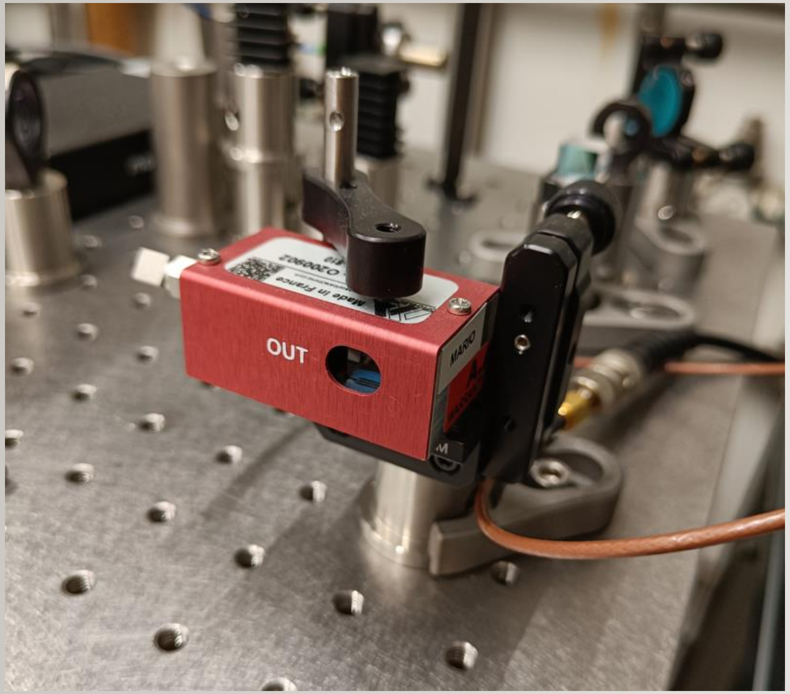




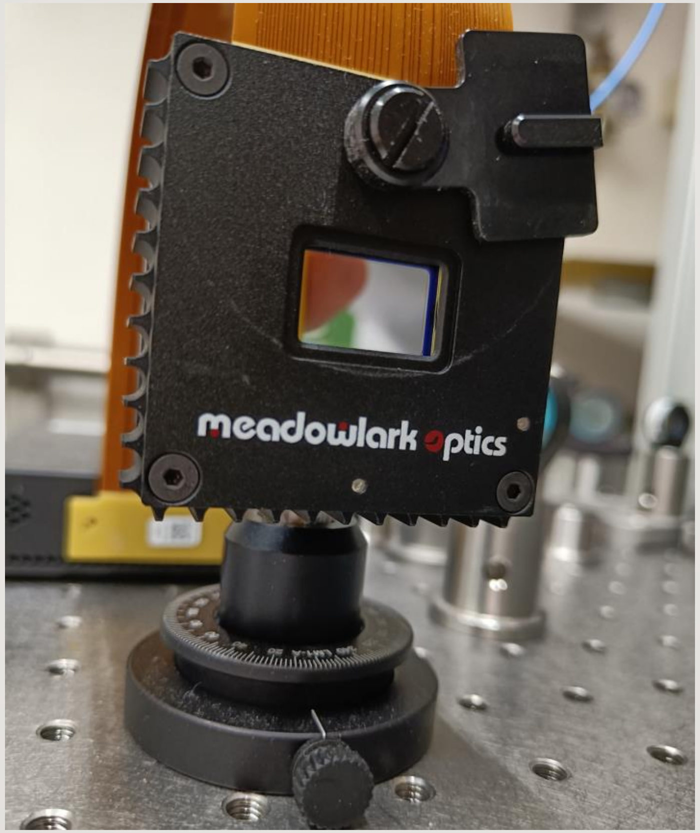
Nolan Samboy and Robin Côté
J. Phys. B: At. Mol. Opt. Phys. 44 184006 (2011)

Jiao Y et al. Front. Phys. 10:892542 (2022)

REORDERING WITH AODS AND SLM



AA Opto Electronic DTSX-400-810 AOD
- 7.5 mm active aperture
- Diffraction efficiency > 70%
- Up to 400 dots
- Two devices in crossed configuration to obtain a 2D deflection

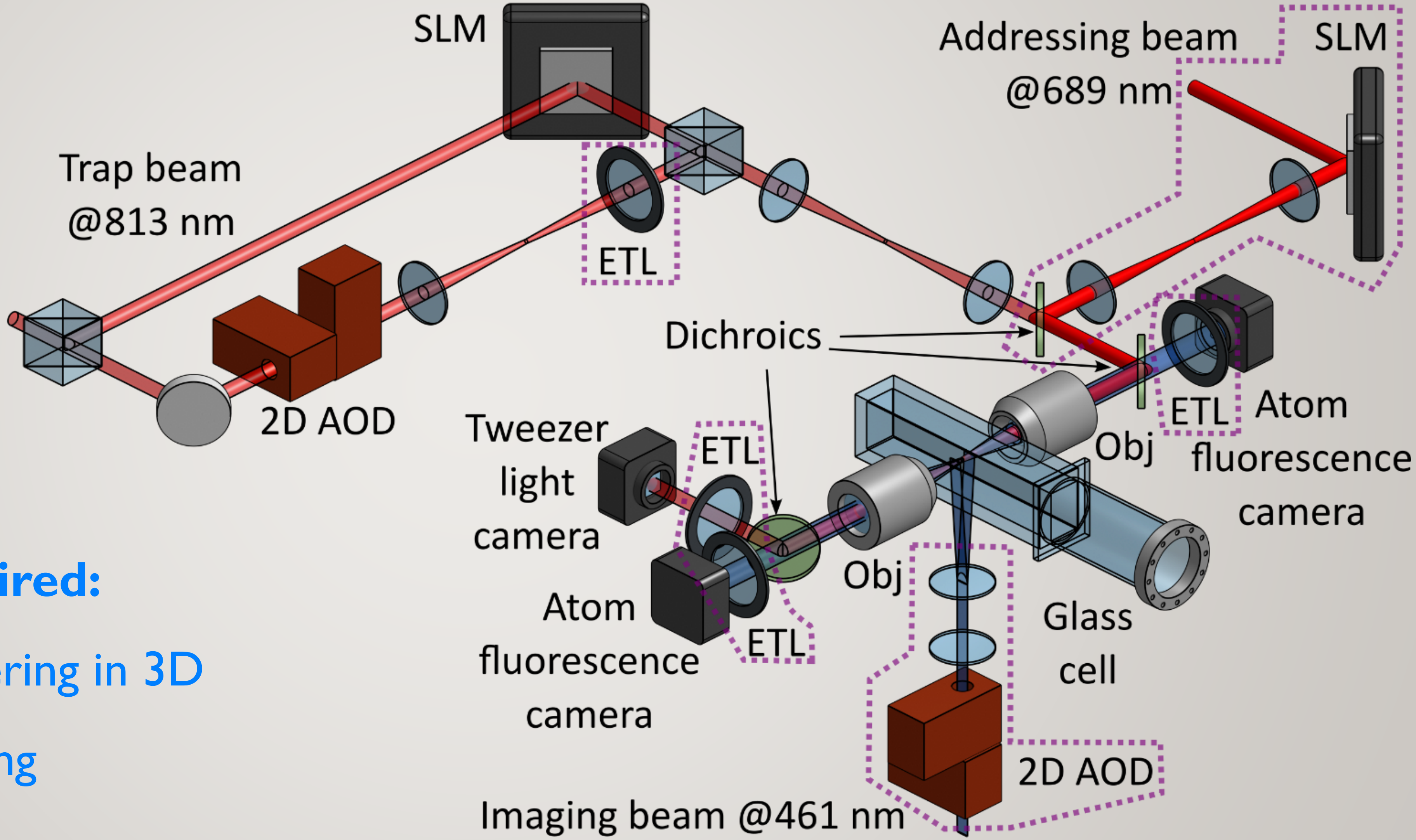


Meadowlark 1920x1200 E-Series SLM
- 1920x1200 resolution
- Analog phase control (LCOS)
- Refresh rate up to 60 Hz

Meadowlark 1024x1024 Series SLM
- 1024x12024 resolution
- Analog phase control (LCOS)
- Refresh rate up to 1400 Hz
- Enables reordering via SLM
- makes 3D configurations easy

TOWARDS ATOMS IN 3D OPTICAL TWEEZER ARRAYS

Towards 3D arbitrary structures of optical tweezers with single site addressability and manipulation

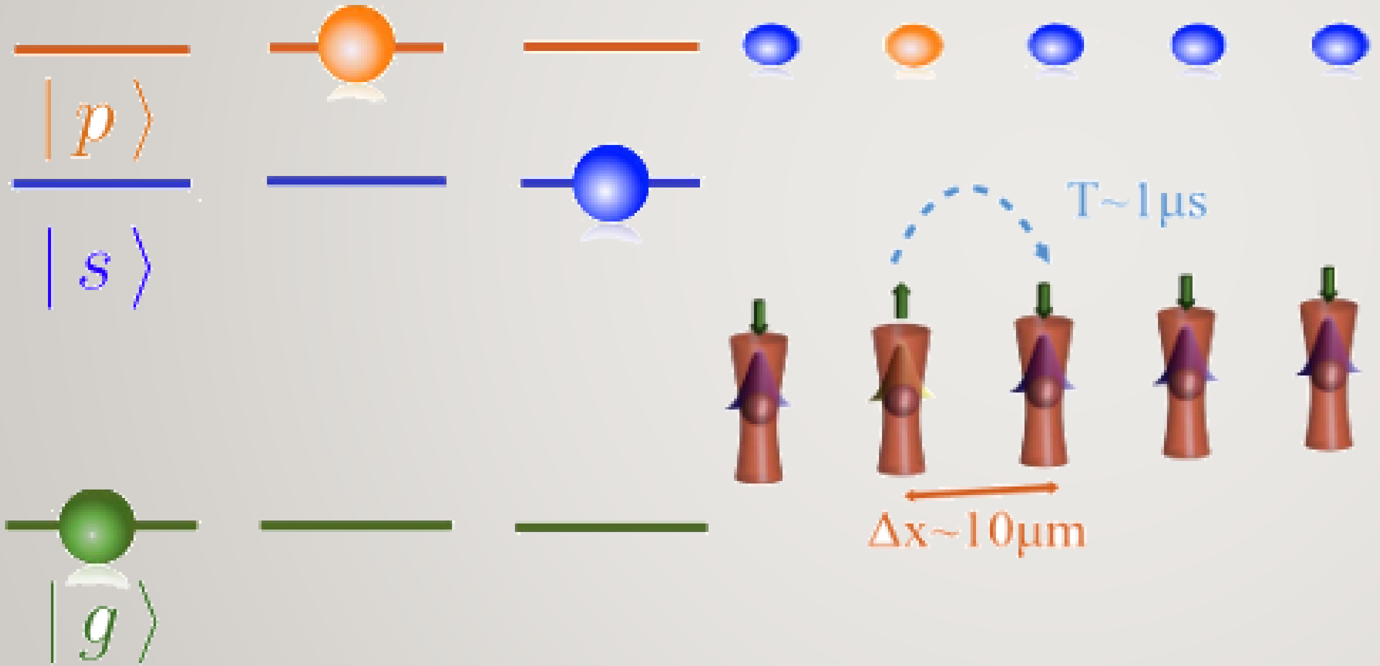


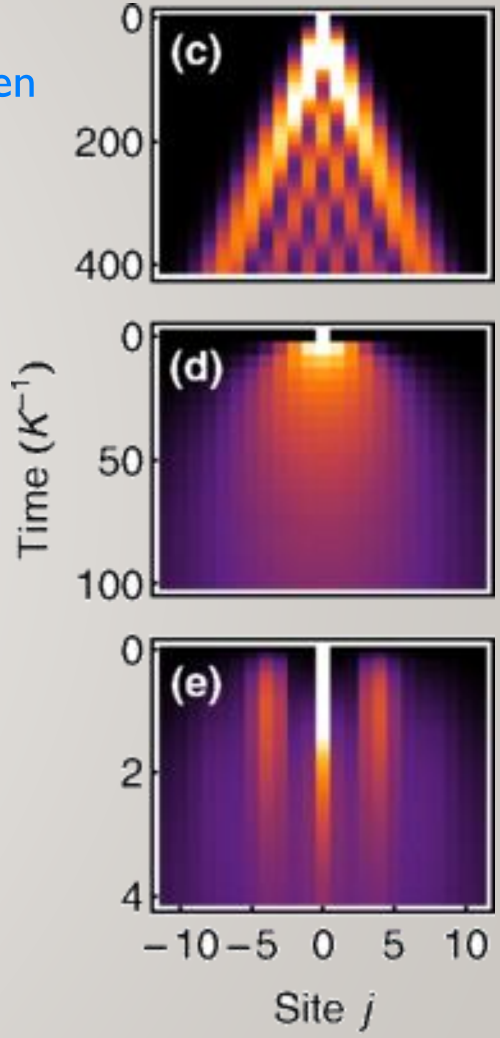
3 components required:

- Trapping and reordering in 3D
- Volumetric addressing
- Volumetric detection

OUTLOOK: ENERGY TRANSPORT ACROSS TOPOLOGY & DISORDER

Introducing a second Rydberg state as an impurity allows to explore many interaction-driven particle-transport models, mimicking energy transport processes in biological systems such as photosynthesis.





Schempp et al, Phys. Rev. Lett. 2015, Vol. 115

The impact of engineered disorder and dissipation sources will be explored (e.g. combining Rydberg excitation with local detuning beams, continued vs pulsed imaging).

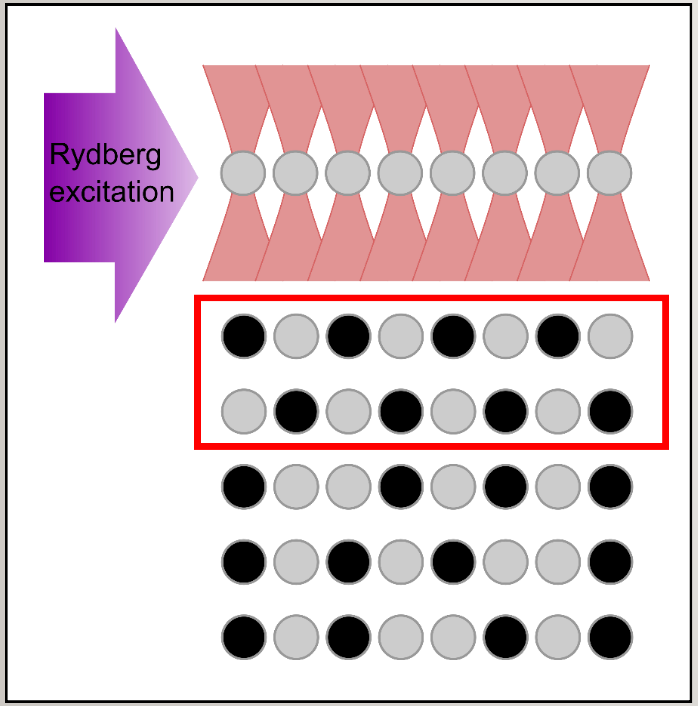
Dimensionality and topology, created exploiting the programmable nature of the tweezer array, will play a mayor role.

OUTLOOK: MULTIPARTICLE ENTANGLEMENT

$$\frac{\mathcal{H}}{\hbar} = \sum_i \frac{\Omega_i}{2}\sigma_x^i - \sum_i \Delta_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

Rydberg Hamiltonian on an array with even number of sites, with magnetic ordering.

Omran et al., Science **365**, 570 (2019)



Greenberger-Horne-Zeilinger entangled state

$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|1010\ldots10\rangle + |0101\ldots01\rangle)$$