A Programmable Rydberg Quantum Simulator

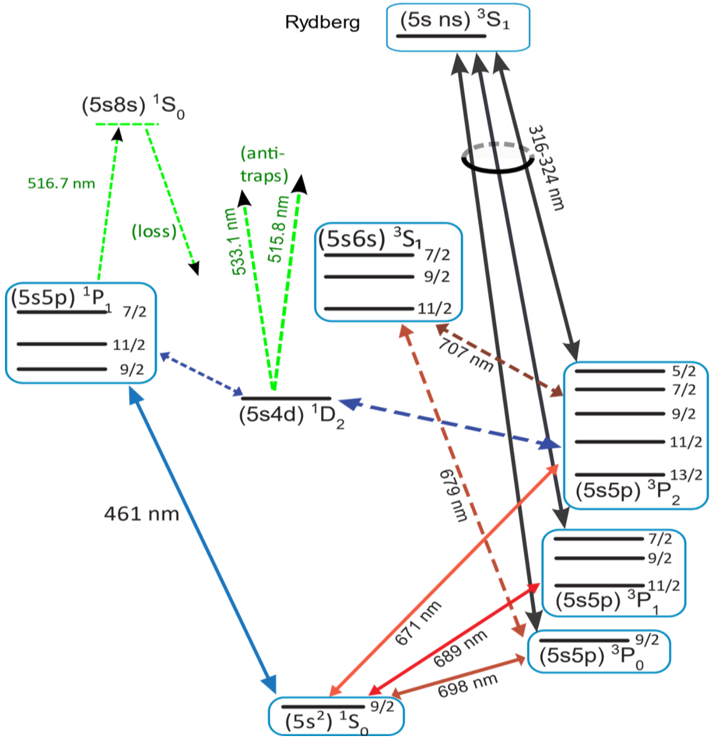
A. Urech[a] *, I. Knottnerus[a], T. Plassmann[a], R.J.C. Spreeuw[a], and F. Schreck[a]

[a] van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam,

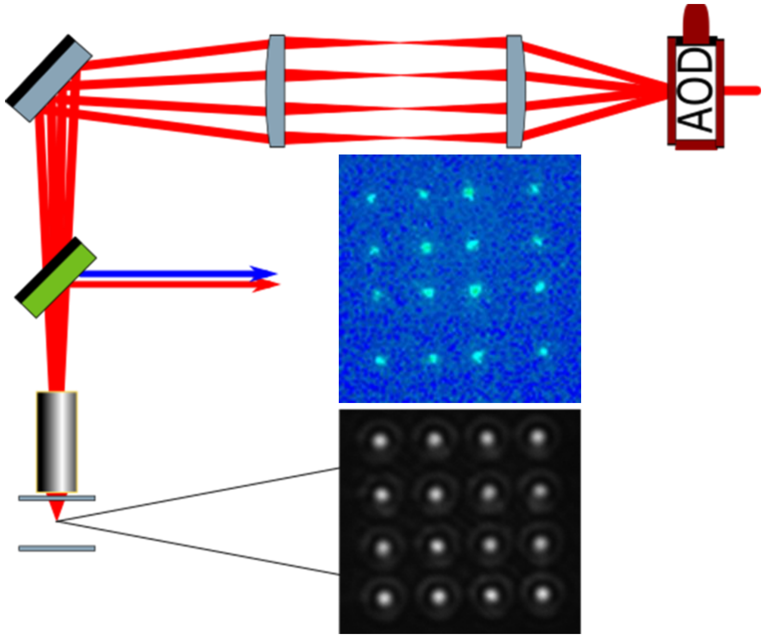
Science Park 904, 1098 XH Amsterdam, The Netherlands

* a.a.urech@uva.nl

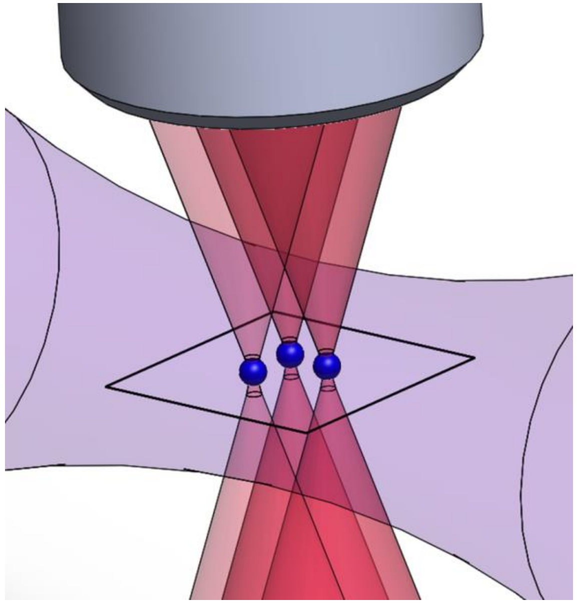
1. Optical tweezers with strontium



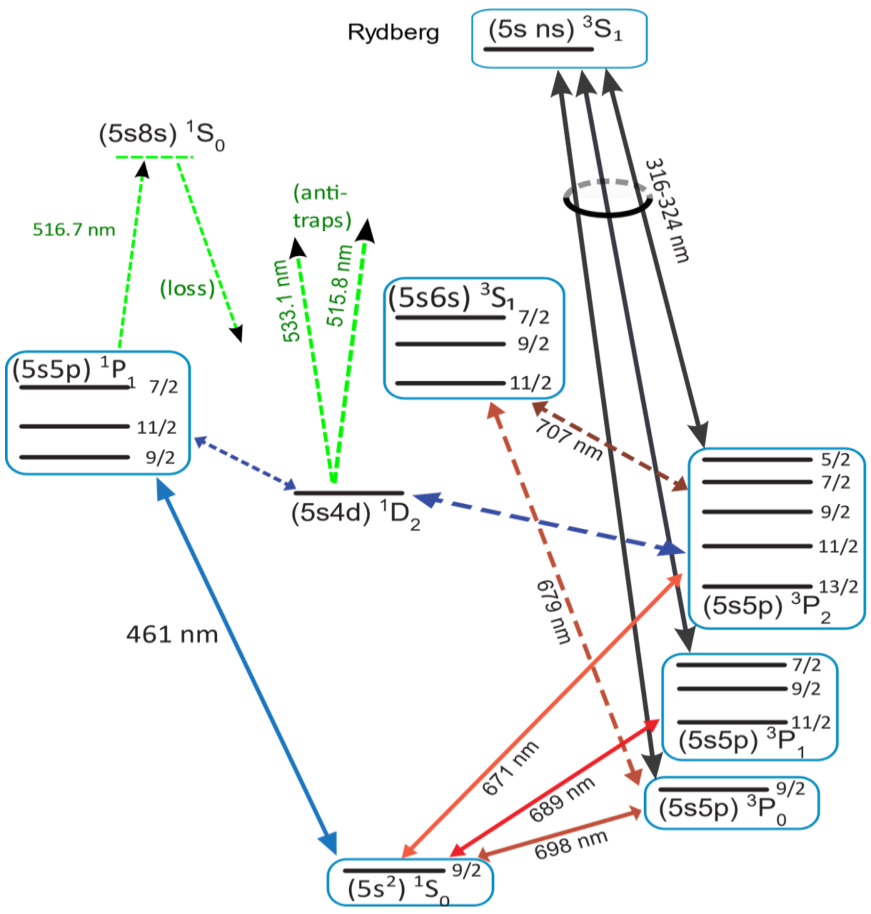
2. Upgrading tweezers



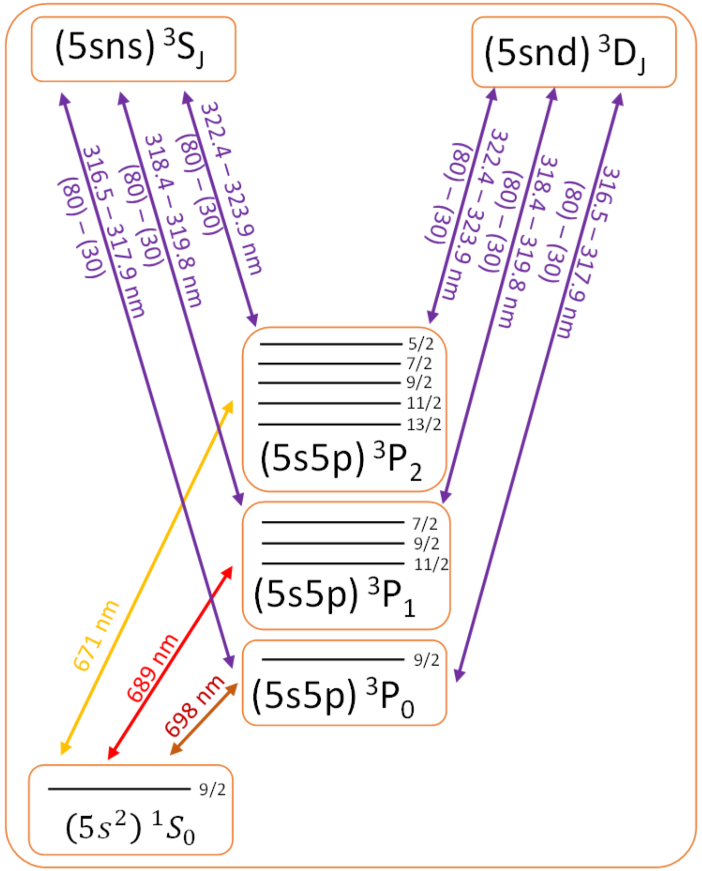
3. Rydberg laser construction



1. Level scheme of strontium

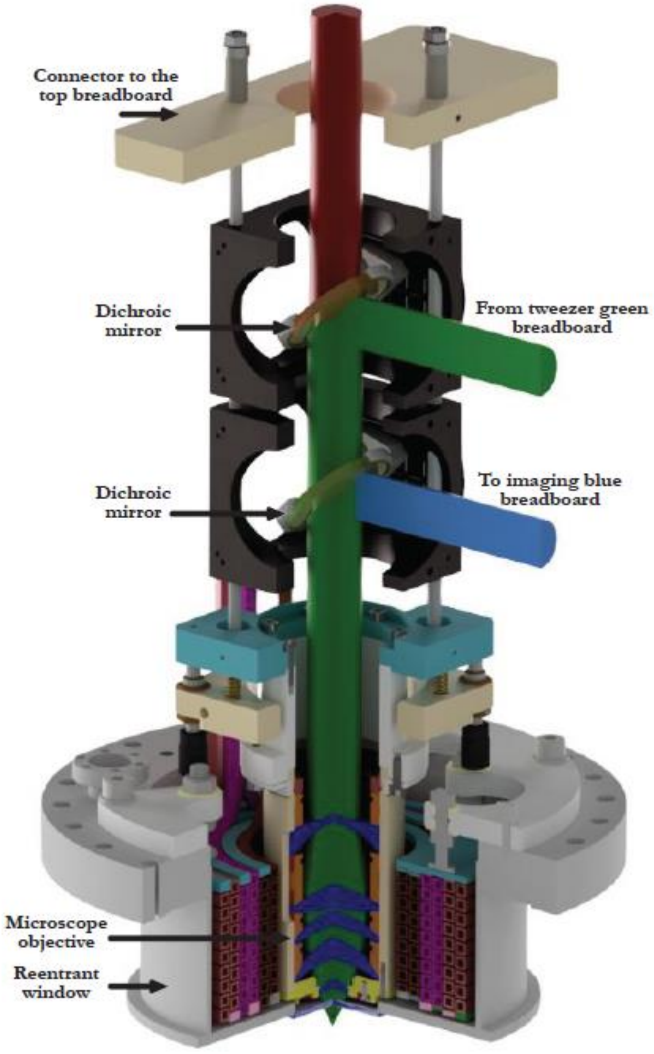


The relevant level scheme of strontium for imaging, cooling and manipulation of the internal state. The **hyperfine manifolds** of the fermionic isotope, ^{87}Sr, are included for these transitions along with the **Rydberg transitions** that we will use for engineering the interaction. The **leakage channel**, (5s4d) $^1D_2$, from the excited singlet $^1P_1$ state is also shown. The 10 nuclear spin states (I = 9/2) of ^{87}Sr together with the metastable ^3P_J states enable nearly lossless Raman transitions and protected qubit states



$^3P_0$	$^3P_1$	$^3P_2$
• Not magnetic	• 22 µs lifetime	• Magnetically tunable m_F-states
• Minutes lifetime		• Minutes lifetime

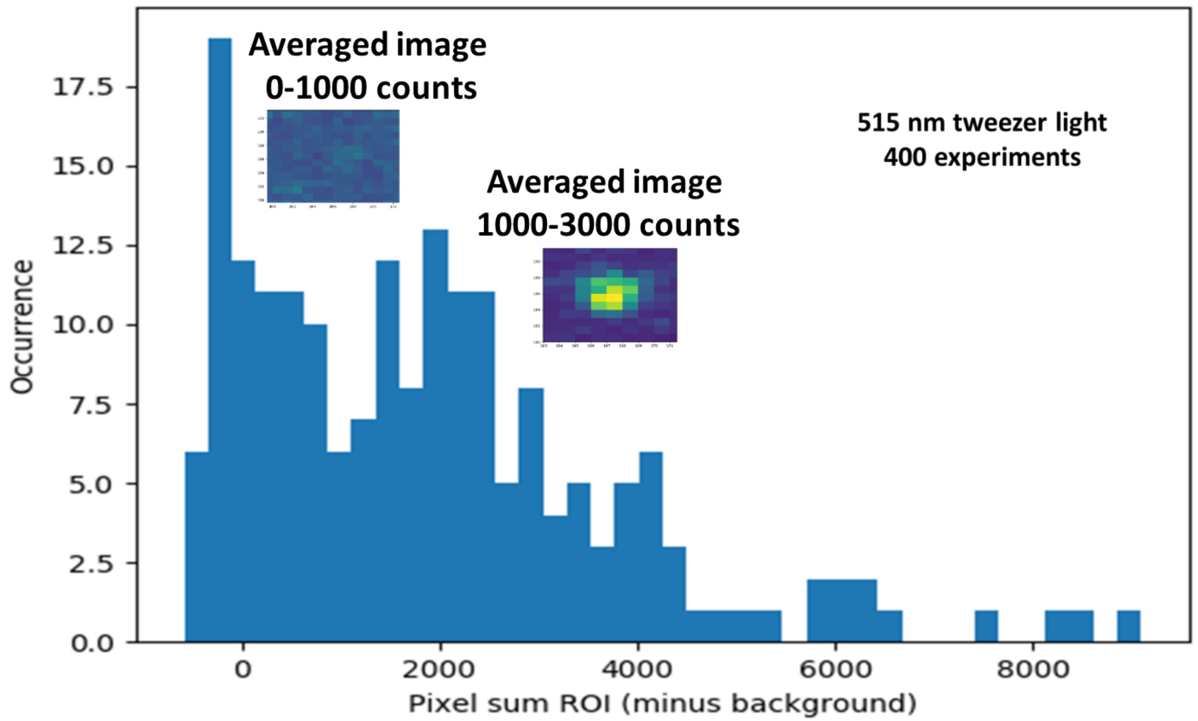
1. 515 nm Tweezers



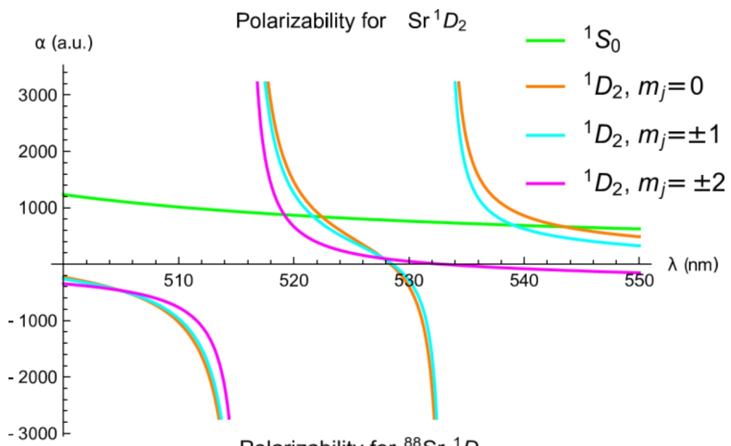
Original tweezer setup

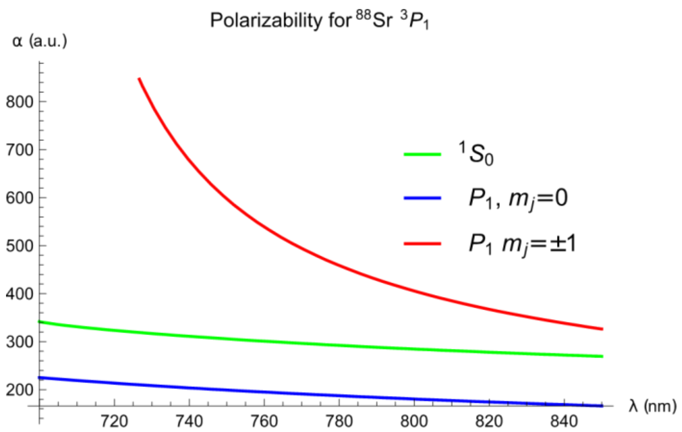
- 515 nm trap light
- Homebuilt objective using commercial lenses
- NA=0.44
- Trap depth of ~mK
- Limited choice of wavelength due to chromatic aberrations

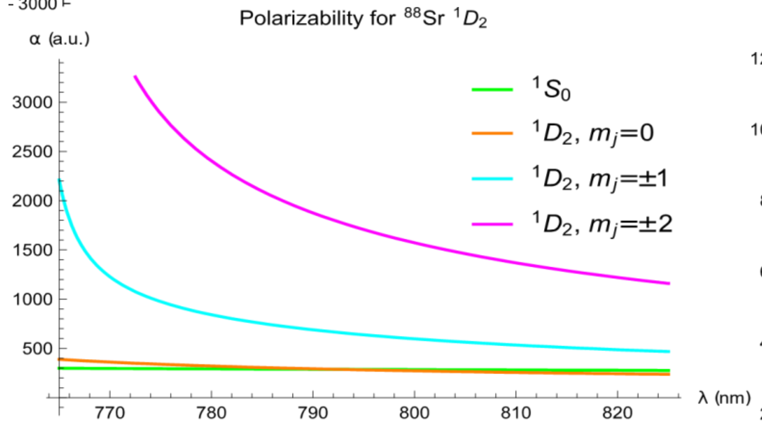
- Histogram of the number of counts collected from ^{88}Sr atoms during fluorescence imaging with a ~50% chance of a single atom remaining.
- Background emission of free running tweezer laser leads to amplified leakage to anti-trapped states resulting in an overlap in the 0 and 1 atom signals [1,2].

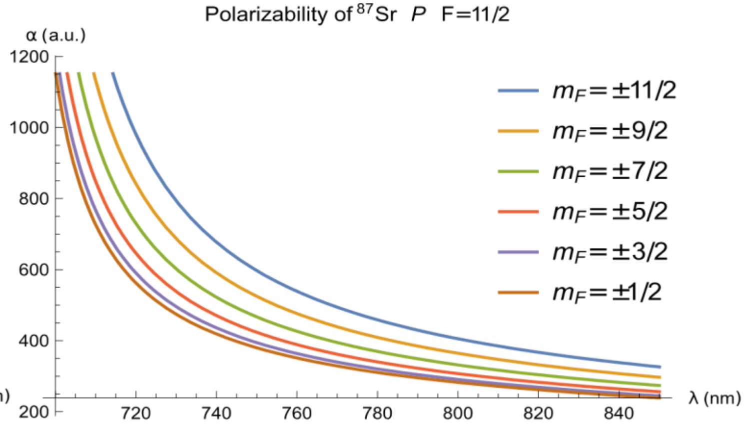


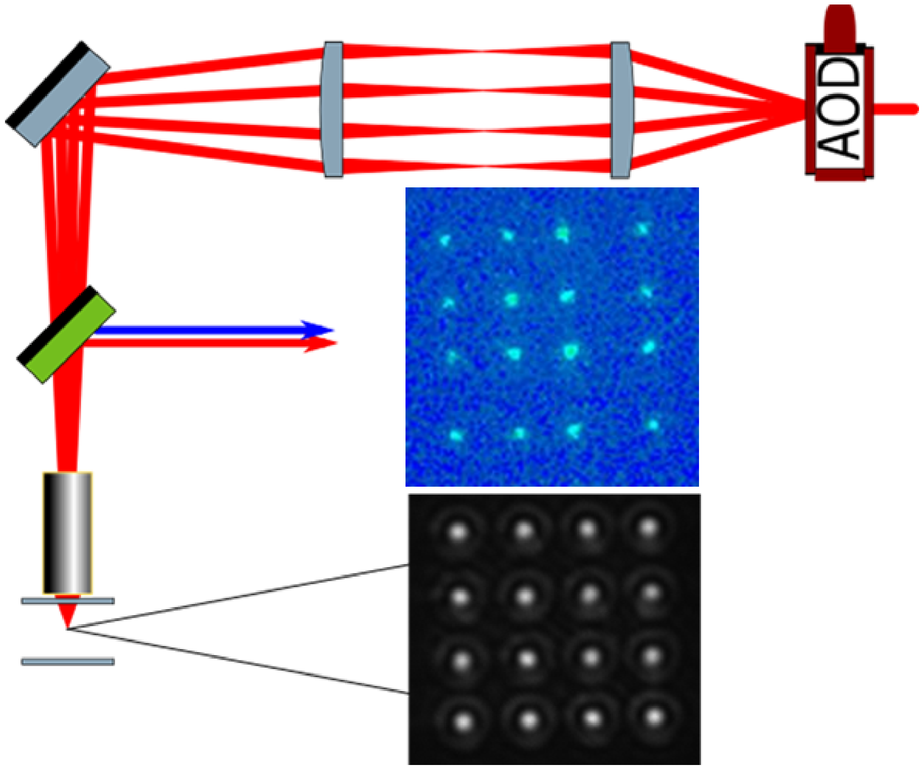
2. Upgrading tweezers











To mitigate any issues from off resonant scattering;

- Repumping (a crucial ingredient but still can lead to atom loss if atom is anti-trapped, λ = 448, 679, and 707 nm) [1- 4]
- Proper choice of tweezer wavelength (785-813 nm tweezers trap more excited states than 515 or 532 nm) [1- 4]
- Cooling and imaging on the same narrow line transition (reduces trap depth)

- Microscope, NA = 0.5
- Dichroic mirror for imaging with 461 or 689 nm light
- 2-D tweezer array
  - wavelength 785 nm
  - waists ~ 0.75 µm
  - Spacing between tweezers ~ 5 µm

3. Rydberg laser construction

Quantum Software Consortium

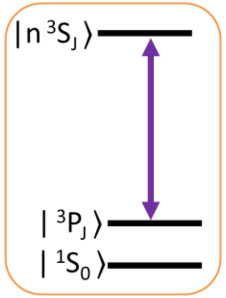
European Research Council
Established by the European Commission

NWO

QuSoft
Research Center for Quantum Software

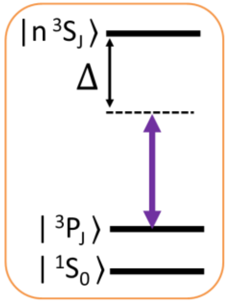
Rydberg states as a tool to tailor interactions

- Strong dipole-dipole interactions between Rydberg atoms
- Rydberg blockade for quantum information
- Off-resonant driving to dress with Rydberg state
- Attractive or repulsive anisotropic interactions selectable [5]



Rydberg excitation at 100 mW

Transition	Laser linewidth	Rabi-flops in 1/e coherence time
$^3P_1 \rightarrow 50\,^3S_J$	100 kHz	100
$^3P_1 \rightarrow 50\,^3S_J$	10 kHz	112
$^3P_1 \rightarrow 80\,^3S_J$	10 kHz	80
$^3P_2 \rightarrow 50\,^3S_J$	10 kHz	127



Rydberg dressing

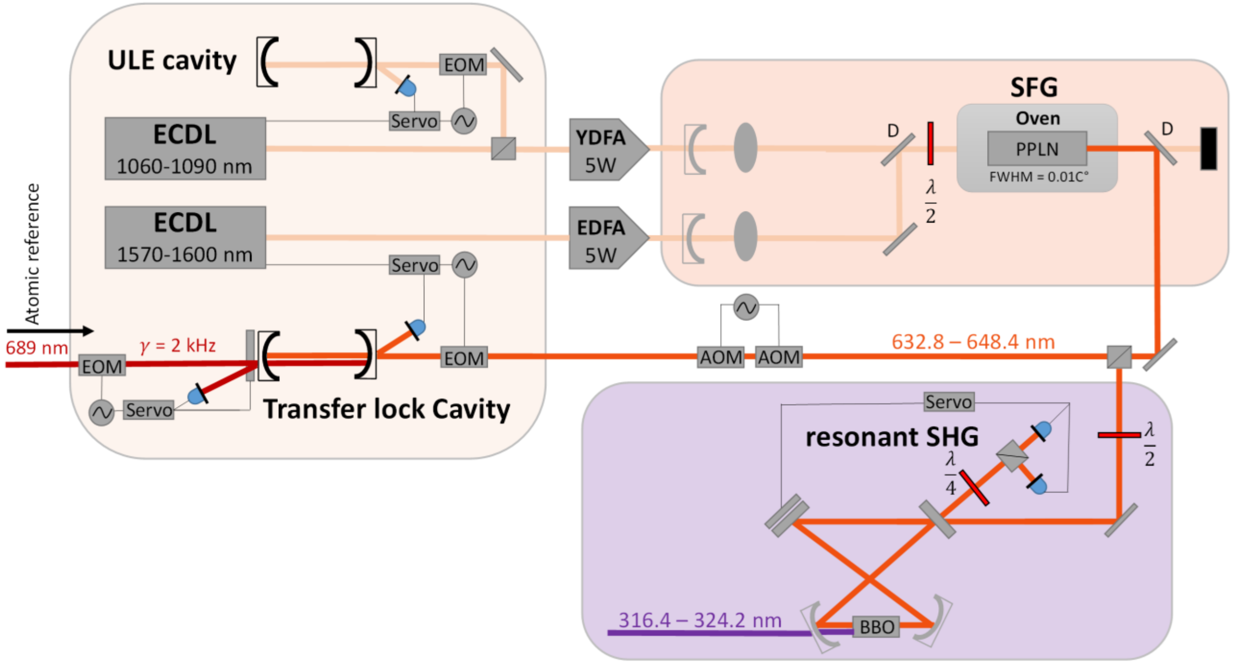
Transition	Lifetime $\tau' = \frac{\tau}{\epsilon^2}$	Interaction strength	Power ω_0 =100 μm	Δ
$^3P_1 \rightarrow 50\,^3S_J$	0.6 ms	100 kHz	0.06 W	0.5 GHz
$^3P_1 \rightarrow 50\,^3S_J$	0.6 ms	200 kHz	0.25 W	1.0 GHz
$^3P_1 \rightarrow 50\,^3S_J$	1.1 ms	200 kHz	2.0 W	4 GHz
$^3P_0 \rightarrow 50\,^3S_J$	1.1 ms	200 kHz	3.5 W	4 GHz

Extra possibilities using *divalent* strontium atoms

- Detection using the ion core [6]
- Trapping of Rydberg atoms using the ion core transitions [7]
- Fermionic and bosonic isotopes
- Interacting atomic lattice clocks [8]

Laser Requirements

- Tunable from 316.5 – 324.8 nm to exploit the features of all ^3P_J states
- kHz-linewidth for Rydberg state preparation with high fidelity
- Up to 1 W of output power for reaching sufficient interaction strength



Future plans and prospects

- Trap single ^{87}Sr atoms and perform state selective imaging
- Add SLM, enabling the production of arbitrary trap patterns and atom sorting [9]
- Perform quantum logic gates with qubits/qudits using nuclear spin states and coupling with the $^1S_0$-$^3P_{0,2}$ transition [10]
- Simulate artificial Gauge fields through Raman dressing of ultranarrow transitions
- Utilize nuclear spin states to study SU(N) physics

1. A. Cooper, J. P. Covey, I. S. Madjarov, S. G. Porsev, M. S. Safronova, and M. Endres, “Alkaline-Earth Atoms in Optical Tweezers”, Phys. Rev. X **8**, 041055 (2018).
2. M. A. Norcia, A.W. Young, and A. M. Kaufman, “Microscopic Control and Detection of Ultracold Strontium in Optical-Tweezer Arrays”, Phys Rev X 8, 041054 (2018).
3. M. A. Norcia, A. W. Young, W. J. Eckner, E. Oelker, J. Ye, and A. M. Kaufman, “Seconds-scale coherence in a tweezer-array optical clock”, arXiv:1904.10934v2 (2019).
4. I. S. Madjarov, A. Cooper, A. L. Shaw, J. P. Covey,1 V. Schkolnik, T. H. Yoon, J. R. Williams,2 and M. Endres, “An Atomic Array Optical Clock with Single-Atom Readout”, arXiv:1908.05619v2 (2019).
5. C. L. Vaillant *et al.*, “Long-range Rydberg–Rydberg interactions in calcium, strontium and ytterbium”, *J. Phys. B* **45**, 135004 (2012).
6. I. S. Madjarov, J. P. Covey, A. L. Shaw, J. Choi, A. Kale, A. Cooper, H. Pichler, V. Schkolnik, J. R. Williams, M. Endres, ”High-Fidelity Control, Detection, and Entanglement of Alkaline-Earth Rydberg Atoms” arXiv:2001.04455 (2020).
7. J. Wilson *et al*, “Trapped arrays of alkaline earth Rydberg atoms in optical tweezers”, arXiv:1912.08754 (2019).
8. L. I. R. Gil *et al.*, “Spin Squeezing in a Rydberg Lattice Clock” ,Phys. Rev. Lett. **112**, 103601 (2014).
9. D. Barredo, S. de Léséleuc, V. Lienhard, T. Lahaye, A. Browaeys, “An atom-by-atom assembler of defect-free arbitrary two-dimensional atomic arrays”, *Science 354*, 1021-1023 (2016).
10. A. Omran *et. al., “*Generation and manipulation of Schrödinger cat states in Rydberg atom arrays”, *Science* 365, 570–574 (2019).