Erbium in optical tweezers

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Overview

- Motivation
- Introduction
  - Erbium.
  - Our experiment – a lab tour.
- Physics
  - Polarisability.
  - Single atoms & pairwise losses.
  - Additional losses.
- Outlook

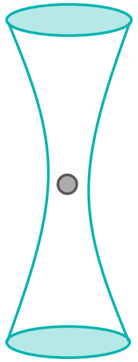
Optical tweezer experiments

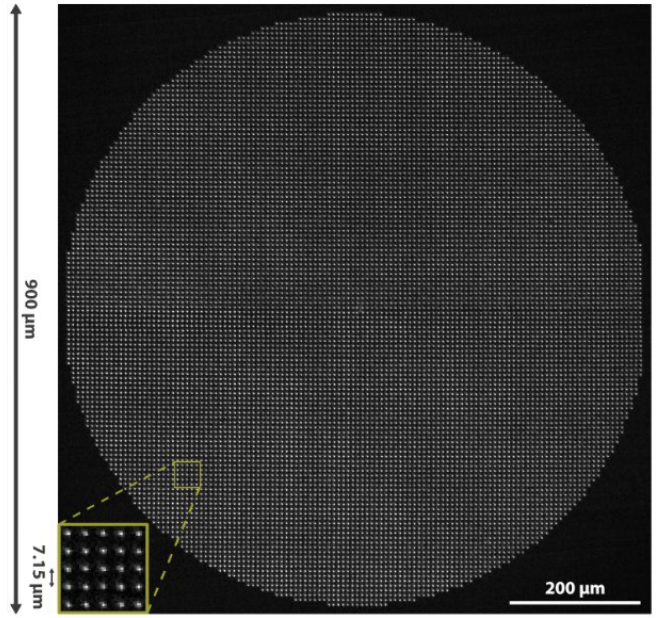
- Highly focussed optical dipole trap (waist ~1 µm)
- Large scale, reconfigurable arrays of trapped single atoms.
- Long-range interactions through Rydberg states.
- Quantum computing:
  - Implement universal (quantum) gate set.
  - Solve generic problems.

(Henriet et al., Quantum 2020)

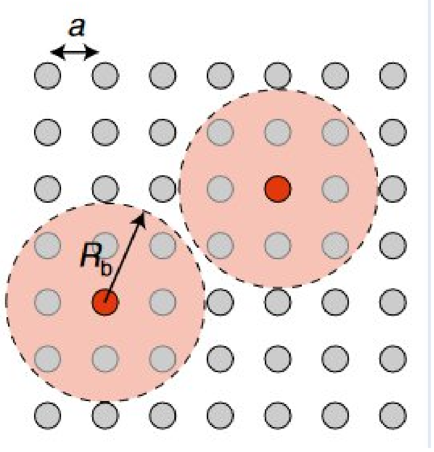
- Quantum simulation
  - Map hard problem into implementable Hamiltonian.

(Ebadi, …, Lukin, Nature, 2021)





6100 trapped Cs atoms
Manetsch, …, Endres, arXiv 2403.12021v2, 2024



Long-range Rydberg interactions
Browaeys & Lahaye, Nature Physics, 2020

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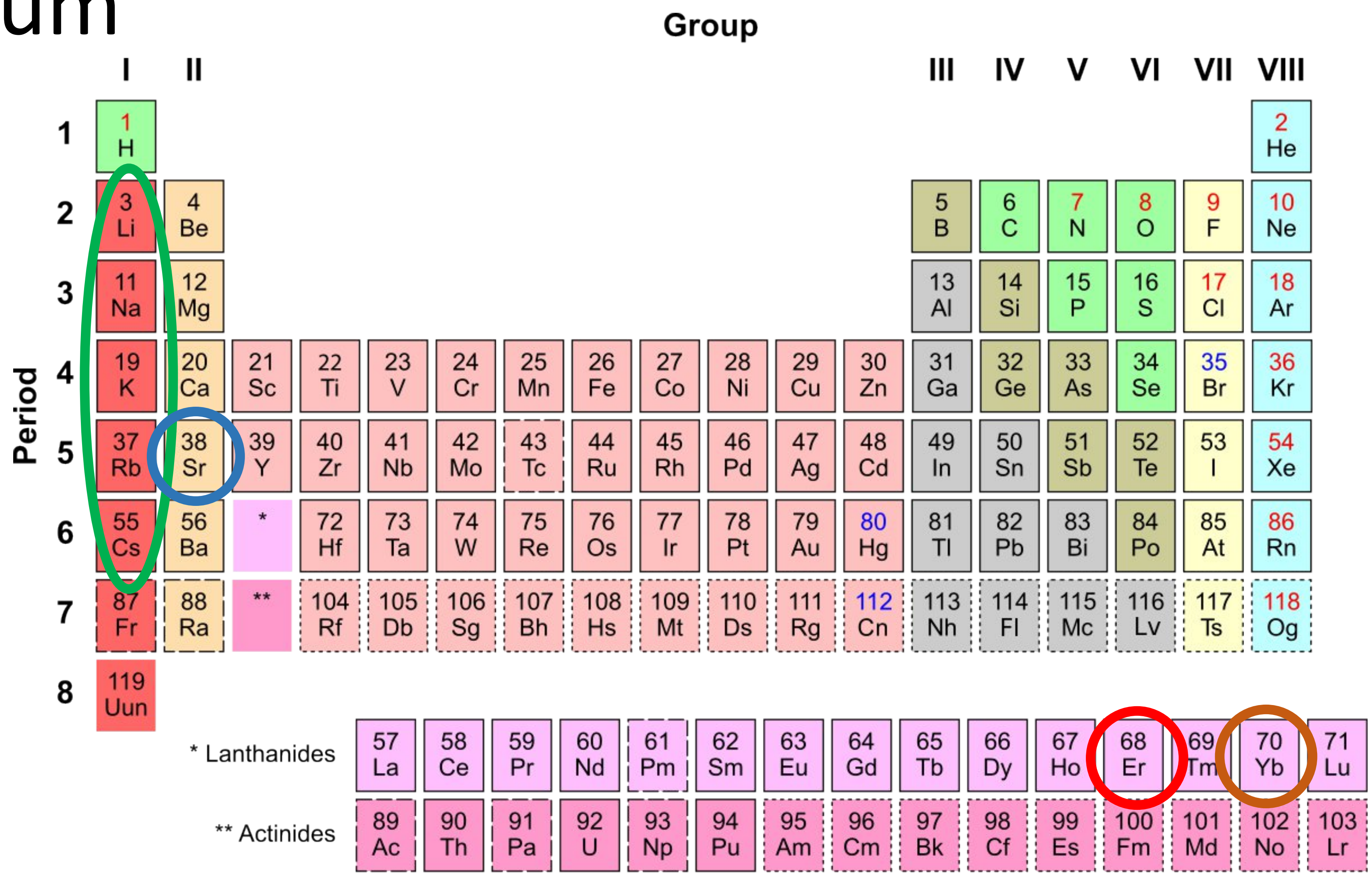
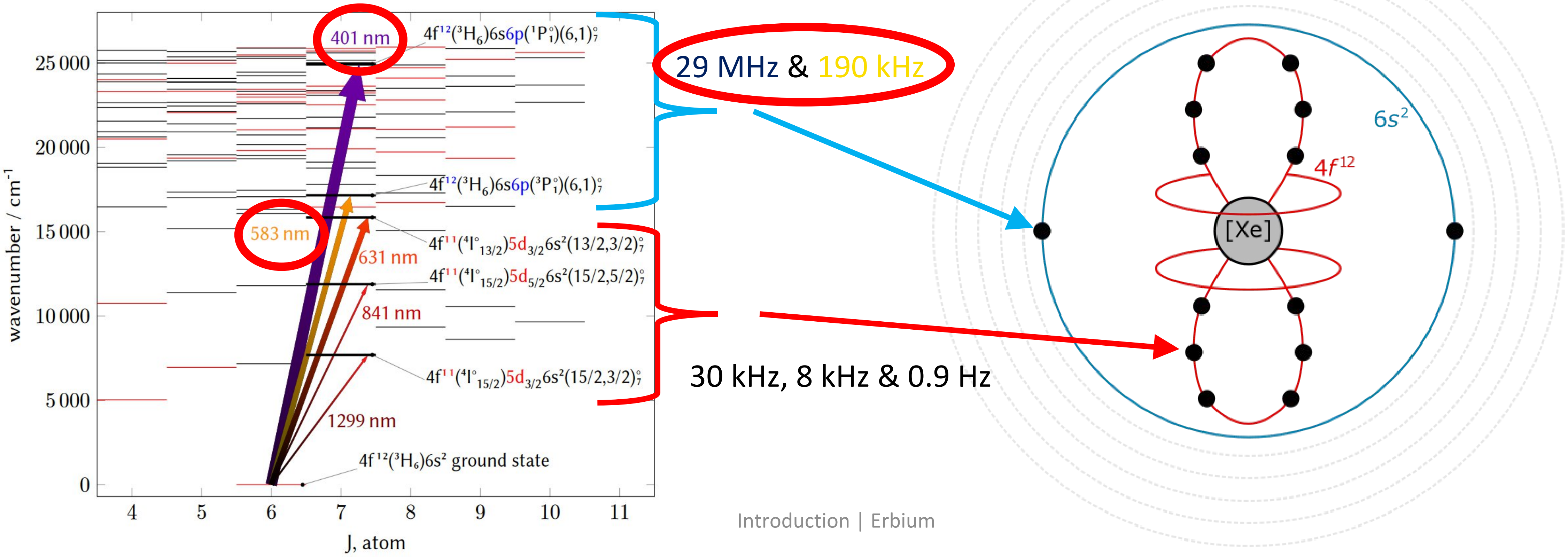
Erbium



Adapted from image in the Wikimedia commons by Armtuk (CC BY-SA 3.0 DEED)

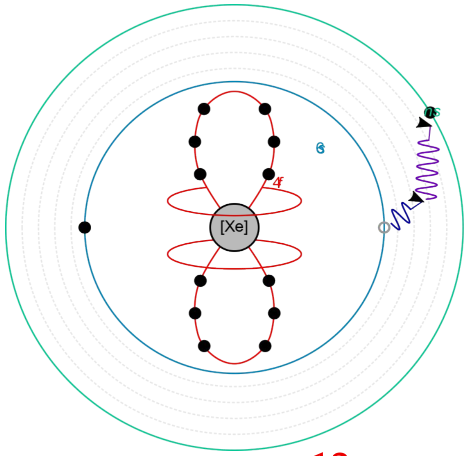
Erbium

- ^{167}Er: $I = 7/2$ – 8 state hyperfine manifold.
- Five cycling transitions ($J = 6 \rightarrow 7$) from stretched states ($m_J = \pm 6$).
- Linewidths from $\Gamma/2\pi = 29$ MHz to 0.9 Hz.

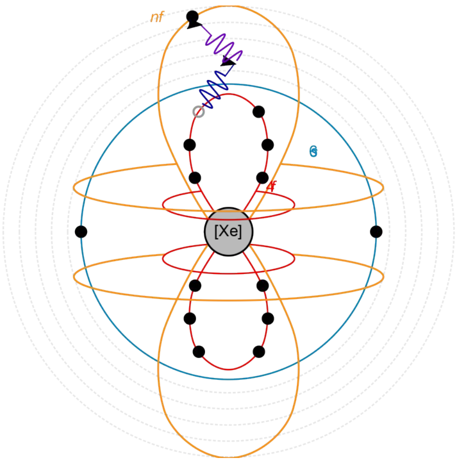


Erbium Rydberg States

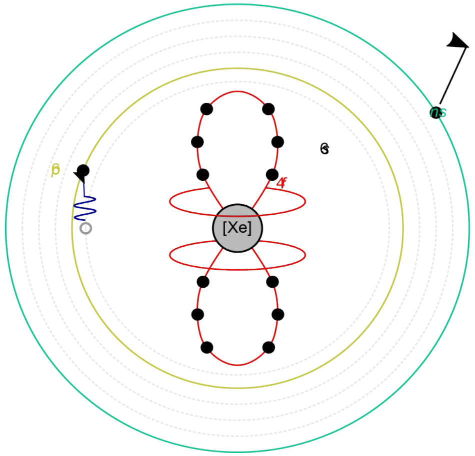
- Many excitation possibilities from many electrons:
  - Doppler free.
  - Low spontaneous emission rate.
  - Large effective Rabi frequency.
- Isolated core excitations.
  (Pham, …, Cheinet, PRX Quantum, 2022)
- s to g two photon transition.
  (Trautmann, …, Ferlaino, Phys. Rev. Research, 2021)
- Direct Rydberg state trapping.



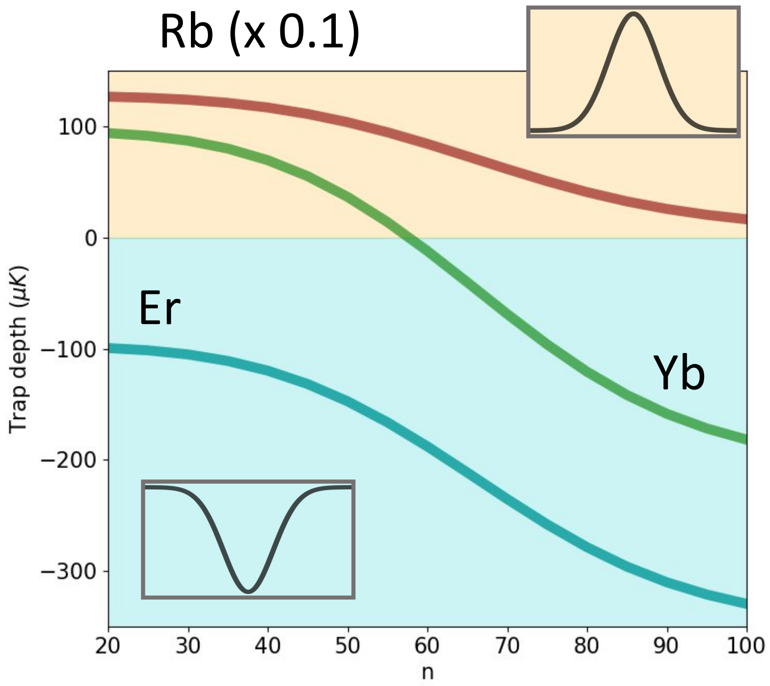
$$|\mathrm{Ryd}_s\rangle = [\mathrm{Xe}]\,4f^{12}6s\; ns/nd$$



$$|\mathrm{Ryd}_f\rangle = [\mathrm{Xe}]\,4f^{11}6s^2 np/nf/nh$$

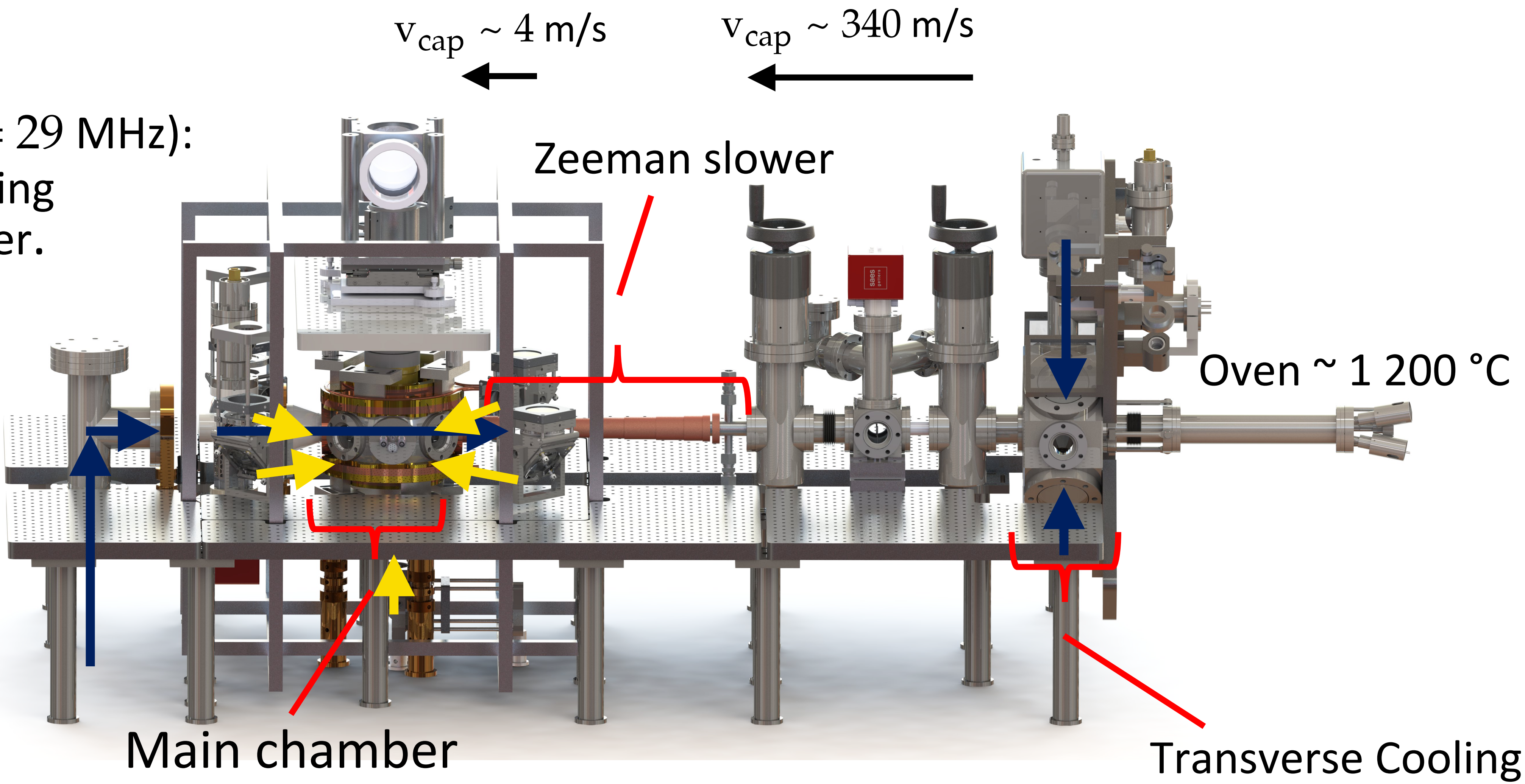


$$|\mathrm{Er}^+\rangle = [\mathrm{Xe}]\,4f^{12}6p$$



The experiment: vacuum system

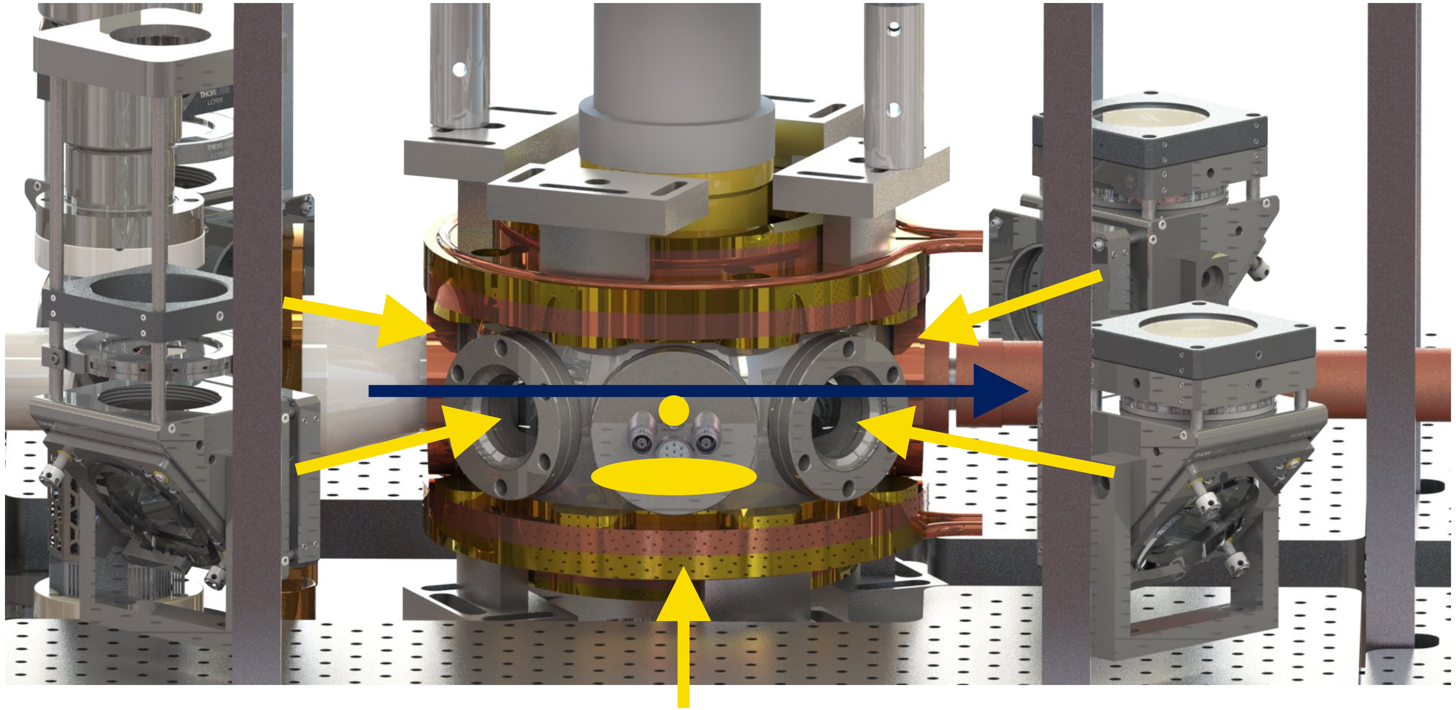
- 401 nm ($\Gamma/2\pi = 29$ MHz): Transverse cooling & Zeeman slower.

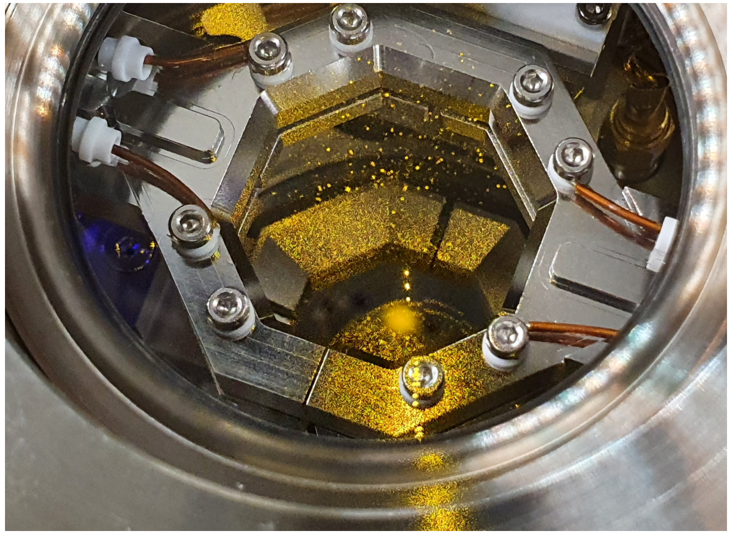


- 583 nm ($\Gamma/2\pi = 190$ kHz): Magneto-optical trap (MOT).

MOT (583 nm, $\Gamma/2\pi = 190$ kHz)

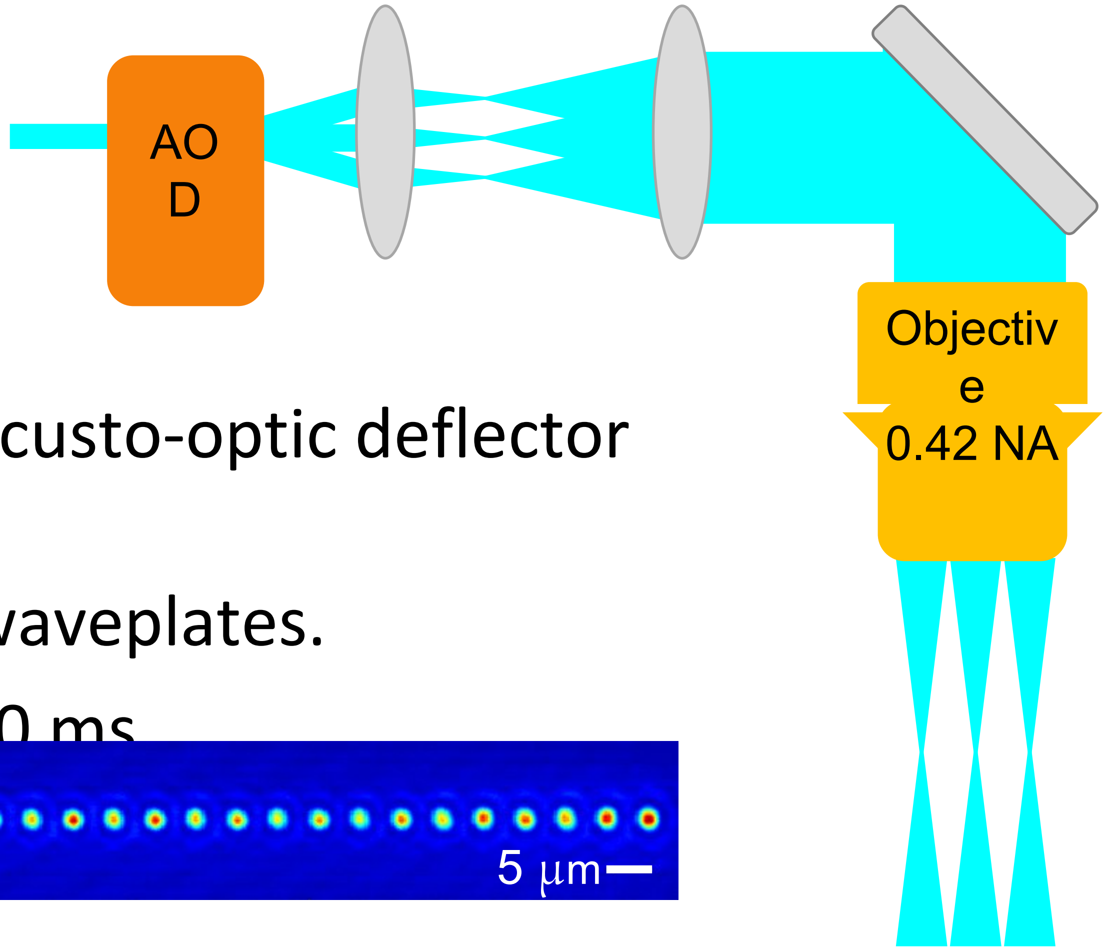
- 2 counter-propagating horizontal beams & 1 vertical beam in quadrupolar B-field.
- Free optical access from top.
- ~35 ms loading time.
- 230 ms compression.
- Final temperature ~7 μK with ~100 000 atoms



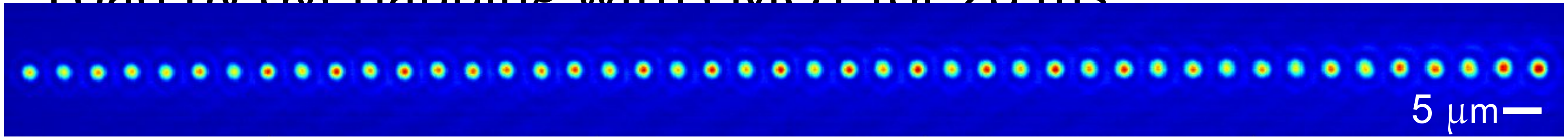


Optical tweezers

- Tightly focussed (waist 1.05(4) µm) dipole traps using 488 nm light.

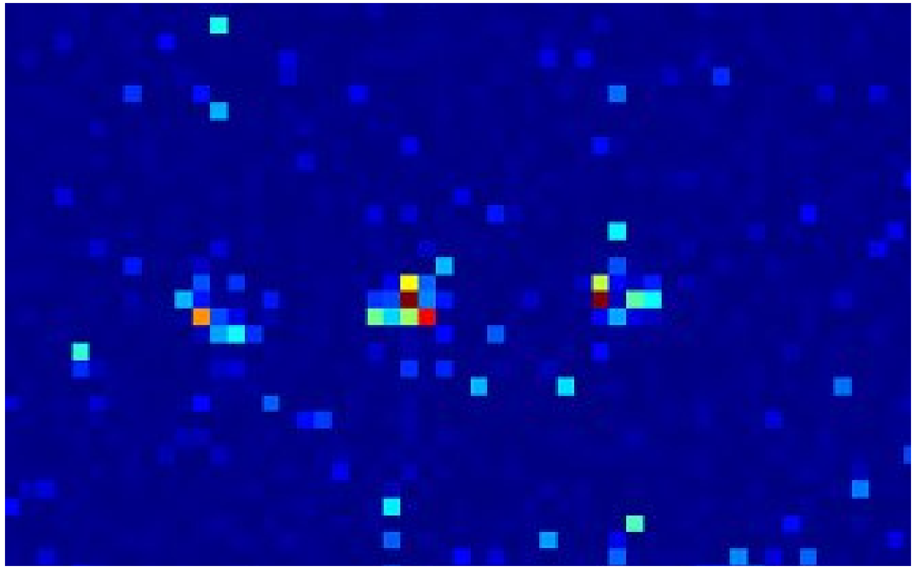


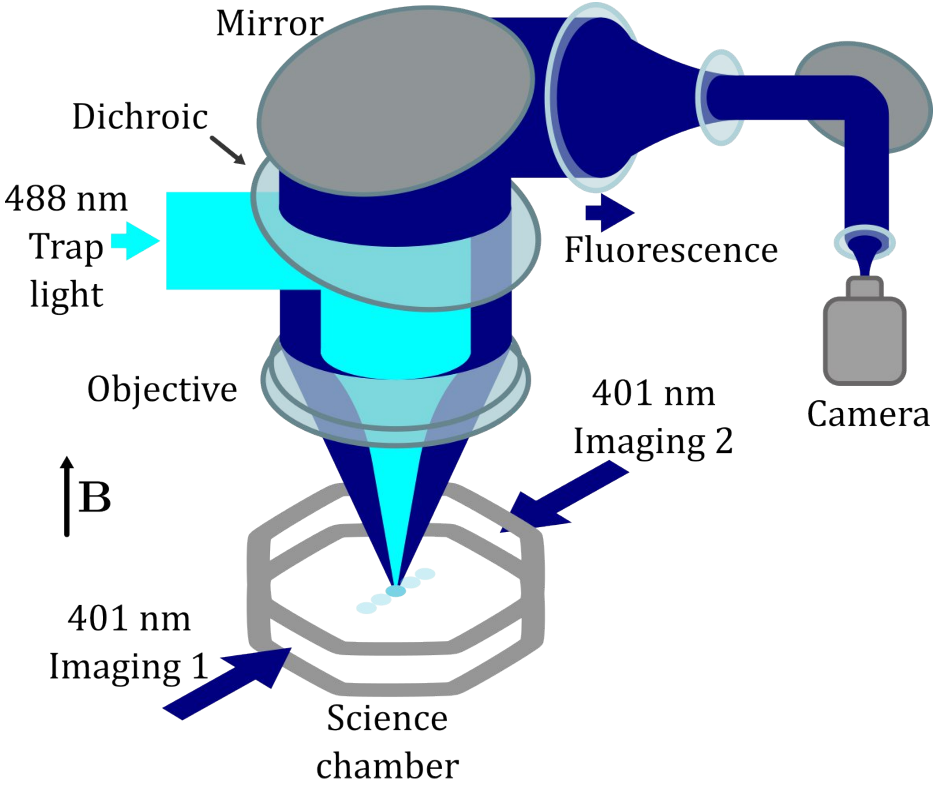
- Re-configurable array generated by acusto-optic deflector (AOD).
- Polarisation control with motorised waveplates.
- Load by overlapping with cMOT for 20 ms



Fast Imaging (401 nm, $\Gamma/2\pi = 29$ MHz)

- Fast fluorescence imaging (~30 µs) on broad 401 nm transition.
- “Free” of atomic dynamics.
- Destructive.
- Useful diagnostic tool or final readout.

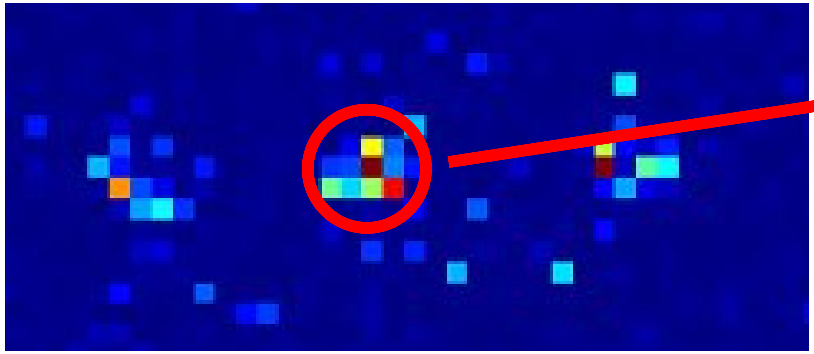




Bergschneider, …, Jochim, Phys. Rev. A, 2018
Su, …, Greiner, arXiv 2404.09978v1, 2024

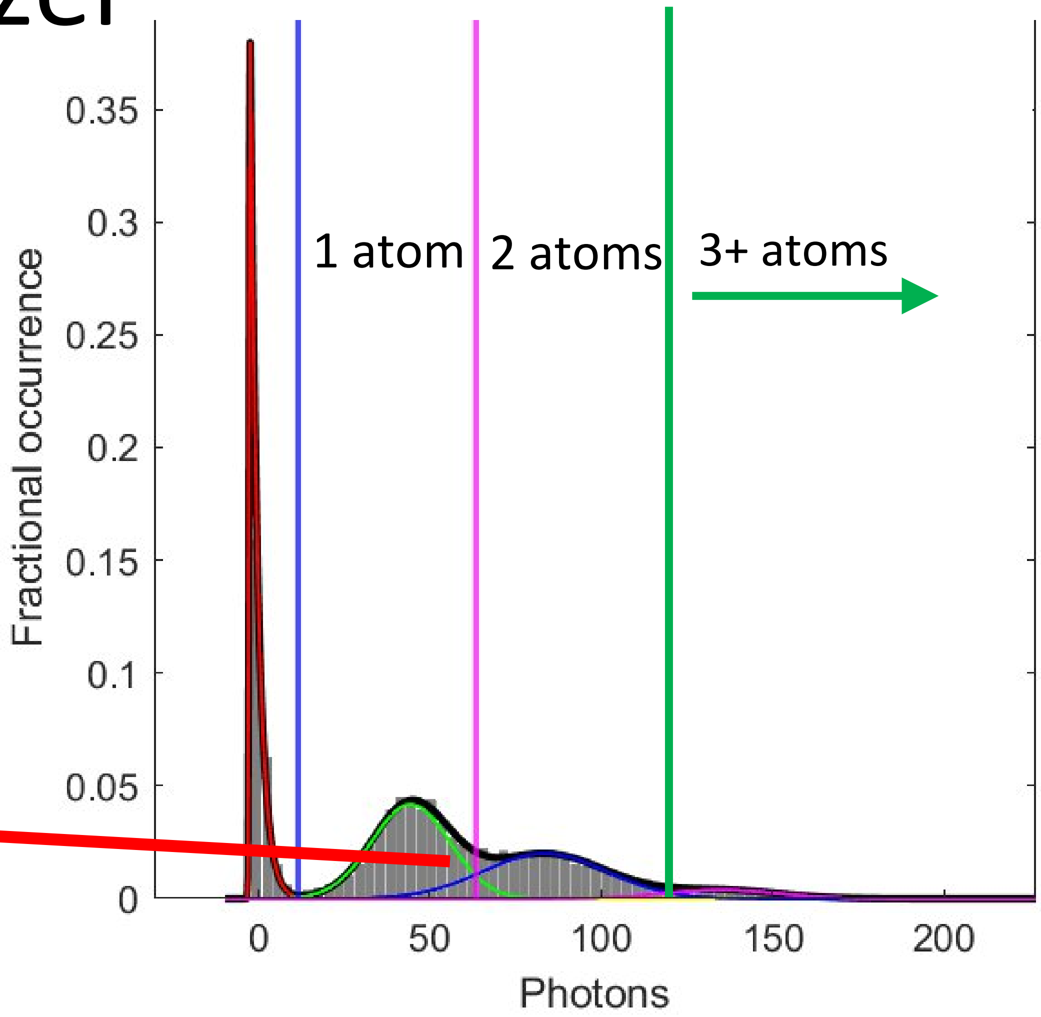
Counting atoms per tweezer

- Take many images to get statistics on fluorescence signal distribution.
- Fit distribution peaks.
- Define thresholds and calculate fidelities.
- Categorise subsequent signals based on defined thresholds.



52 photons

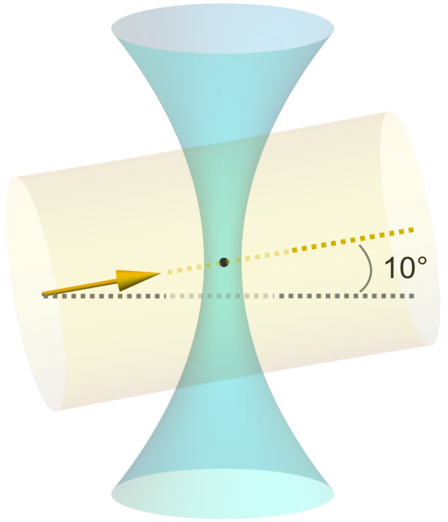
= 1 atom

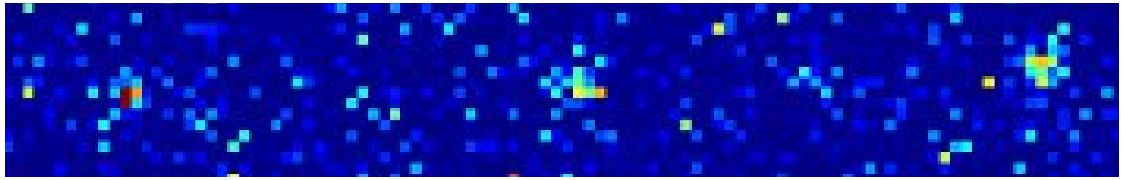


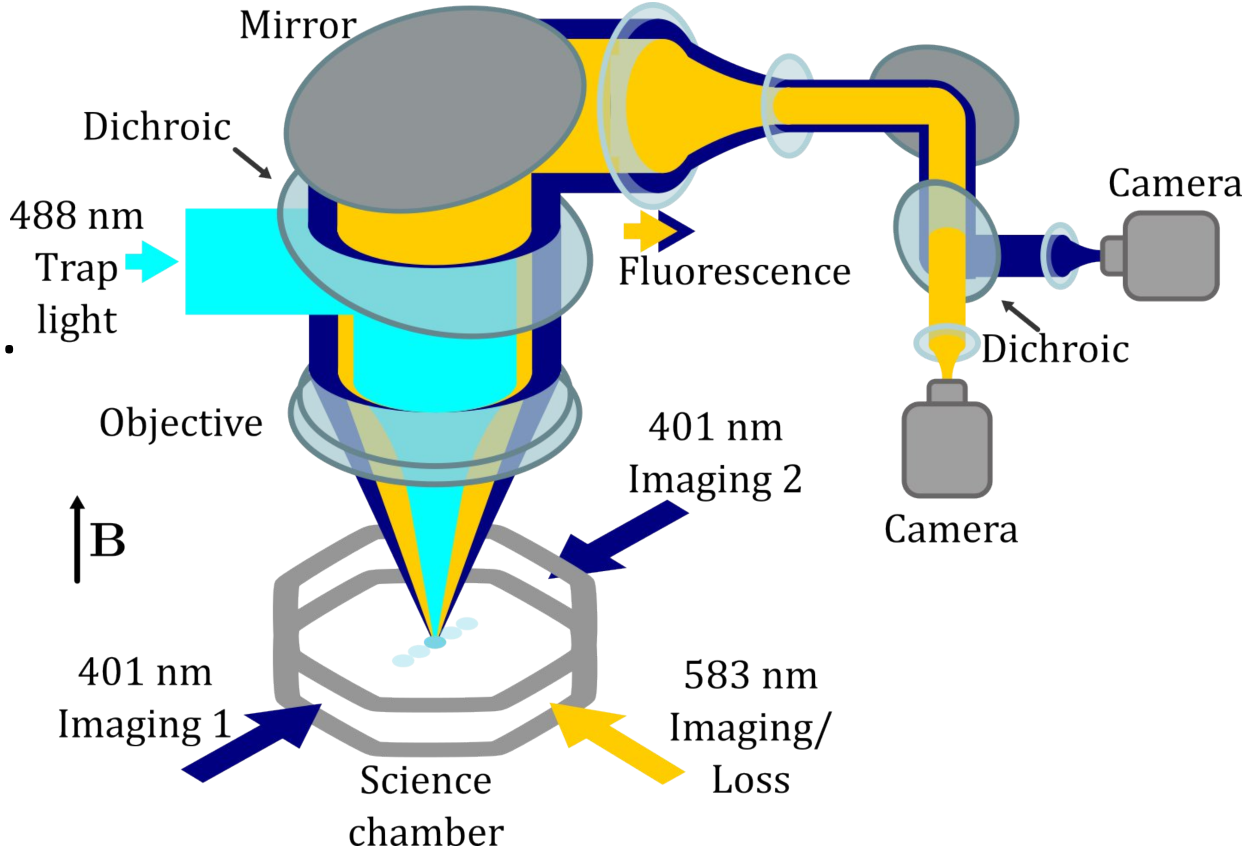
- Typical fidelities:
  - 0:1 – 99.5 %; 1:2 – 92 %;

Slow imaging (583 nm, $\Gamma/2\pi = 190$ kHz)

- Slow (80 ms) fluorescence imaging on narrower 583 nm transition of single atoms.
- **Non-destructive** – simultaneous cooling.
- 10° beam tilt – axial overlap.







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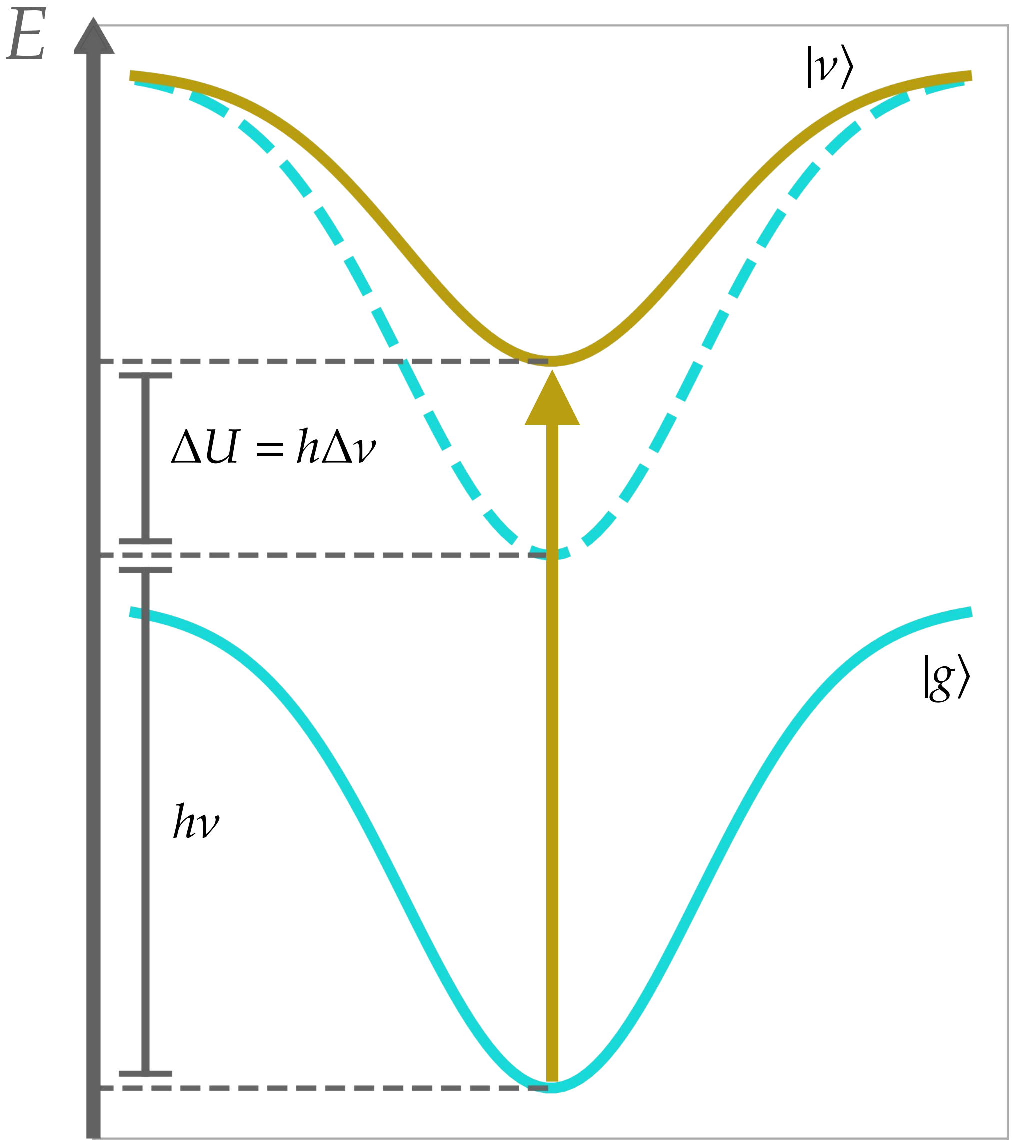
Atomic polarisability

- Trapping potential depth depends on atomic polarisability, α.
- A priori, different in ground and excited states.
- Difference in trap depth between ground and excited states
  $\Delta U(\mathbf{r}) = U_{|\nu\rangle} - U_{|g\rangle} = -\frac{\Delta\alpha(\nu,\chi)}{2\epsilon_0 c} I(\mathbf{r})$.
- AC Stark shift ("light shift"), $\Delta\nu$.
- Heating.



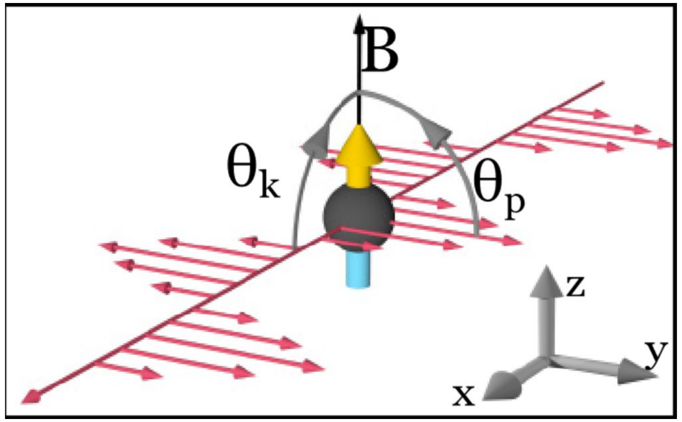
Erbium polarisability

Typically very small for alkalis

$$\alpha_{\text{total}} = \alpha_s(\omega) + \cos(\theta_k)\ \sin(2\chi)\ \alpha_v(\omega) + \alpha_t(\omega, \cos^2(\theta_p))$$

Where:

- χ, ellipticity of trapping light.
- θ_k, angle between trapping light & quantisation axis.
- θ_p, angle between polarisation & quantisation axis.



Becher, …, Ferlaino, Phys. Rev. A, 2018

- We fix, $\theta_p = \pi/2$ & $\theta_k = \pi$.

$$\Rightarrow \alpha_{\text{total}} = \alpha_s(\omega) - \sin(2\chi)\ \alpha_v(\omega) + \alpha_t(\omega, 0)$$

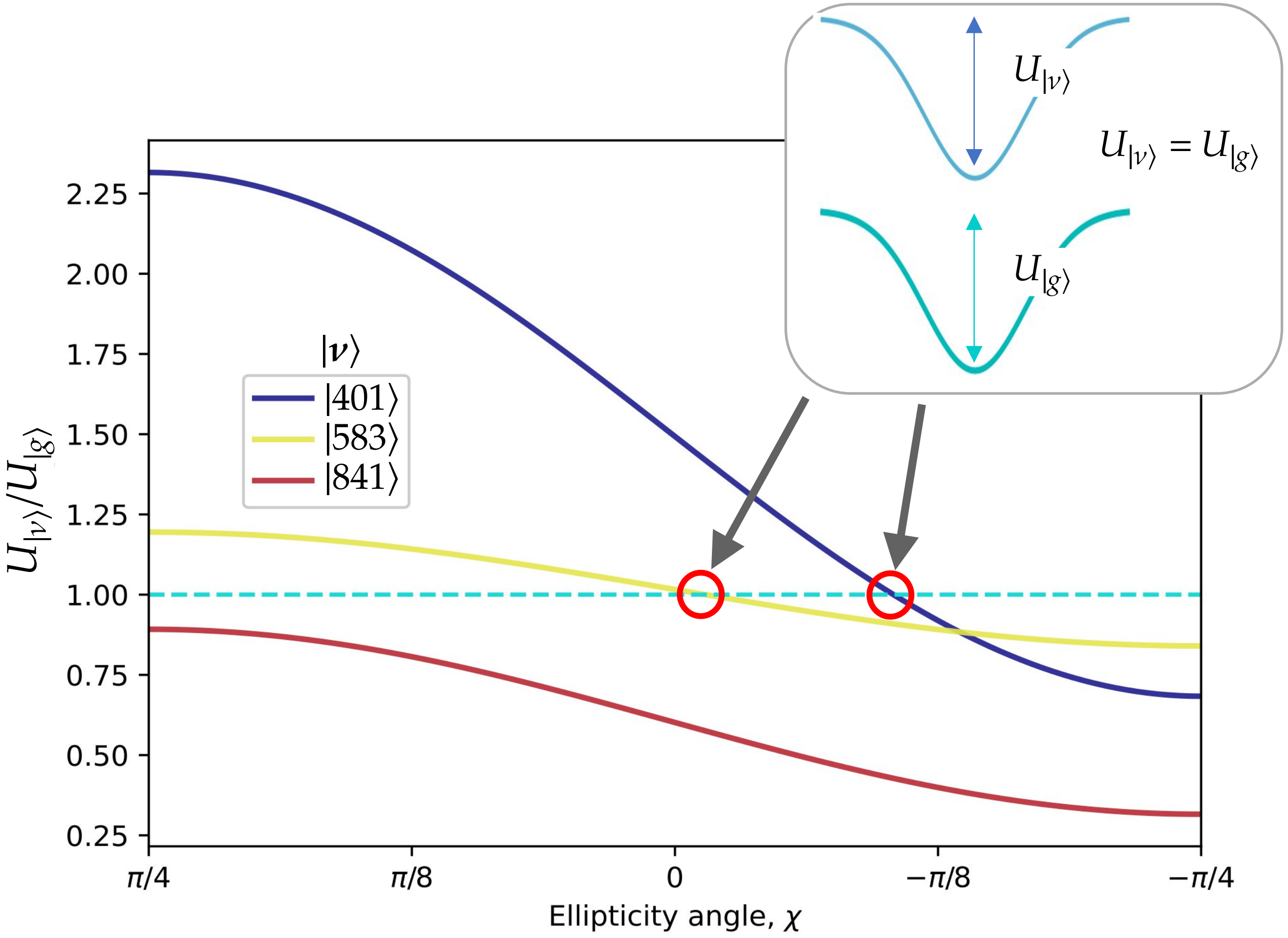
- Tune polarisability using trap light ellipticity, χ.

Magic conditions

$$\Delta U(\mathbf{r}) = U_{|\nu\rangle} - U_{|g\rangle} = -\frac{\Delta\alpha(\nu,\chi)}{2\epsilon_0 c} I(\mathbf{r}).$$

- Tune polarisability using ellipticity of trapping light χ.
- "Magic condition" for $U_{|\nu\rangle}/U_{|g\rangle} = 1$.
- Motorised waveplates to control trap light polarisation.
- Need to be relatively magic to efficiently load tweezers.

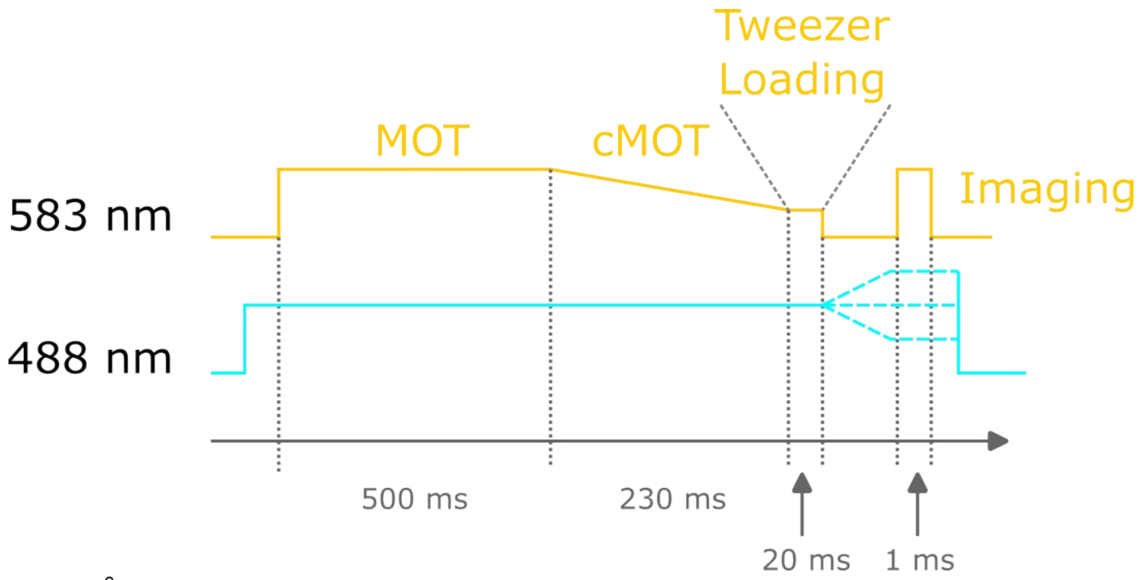
Maxence Lepers ICB

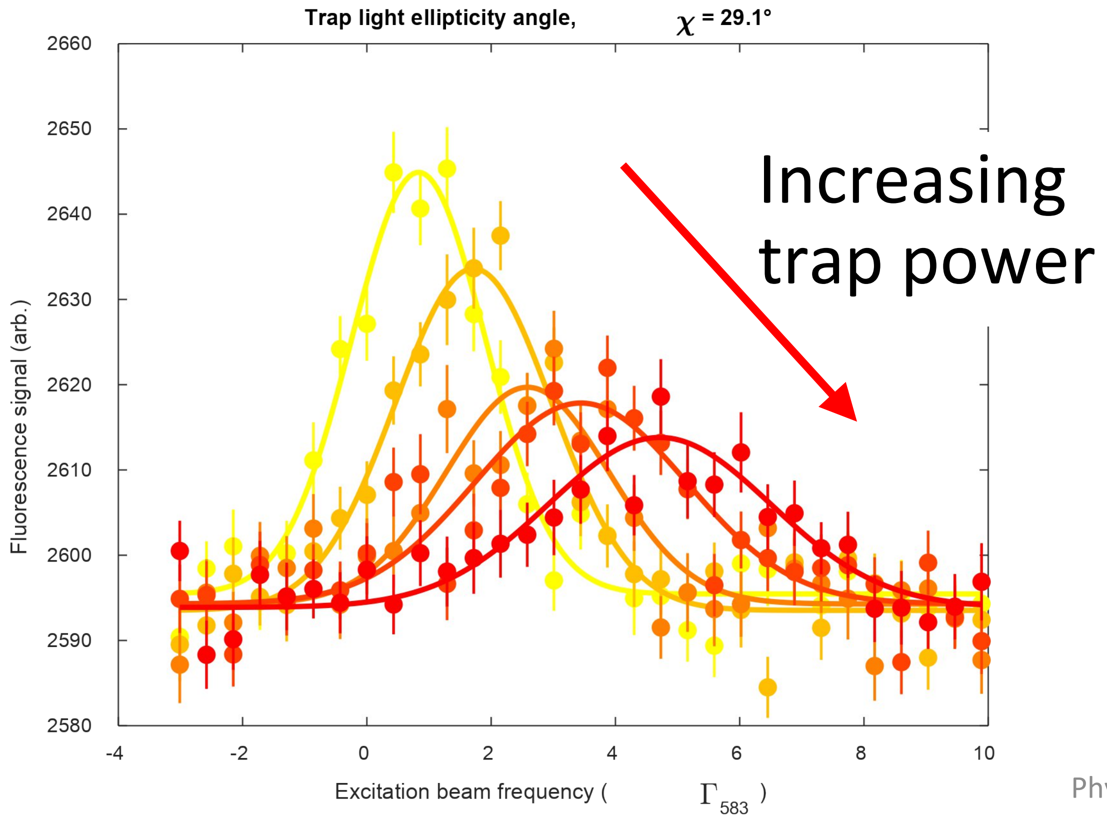


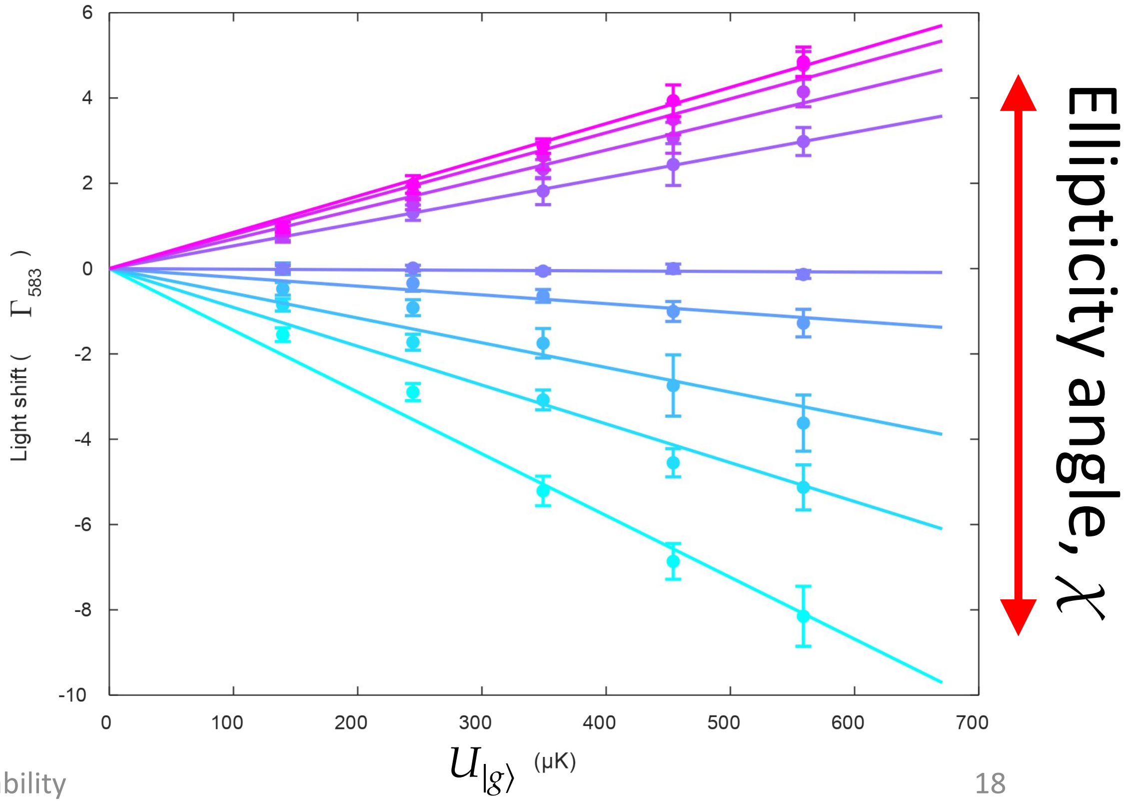
(583 nm, $\Gamma/2\pi = 190$ kHz)

Light shift measurement

- 583 nm fluorescence spectroscopy (destructive, 1 ms).
- Scan trap power & ellipticity.



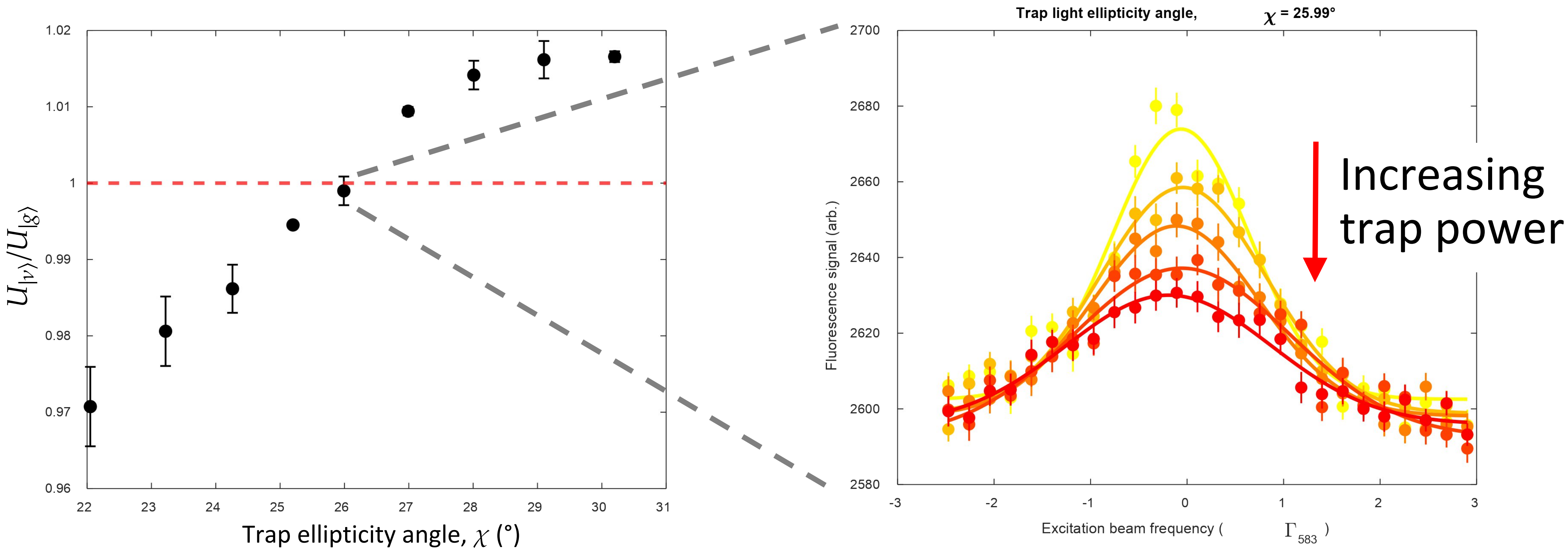




(583 nm, $\Gamma/2\pi = 190$ kHz)

Finding the magic

- Magic condition found at $\chi \approx 26°$

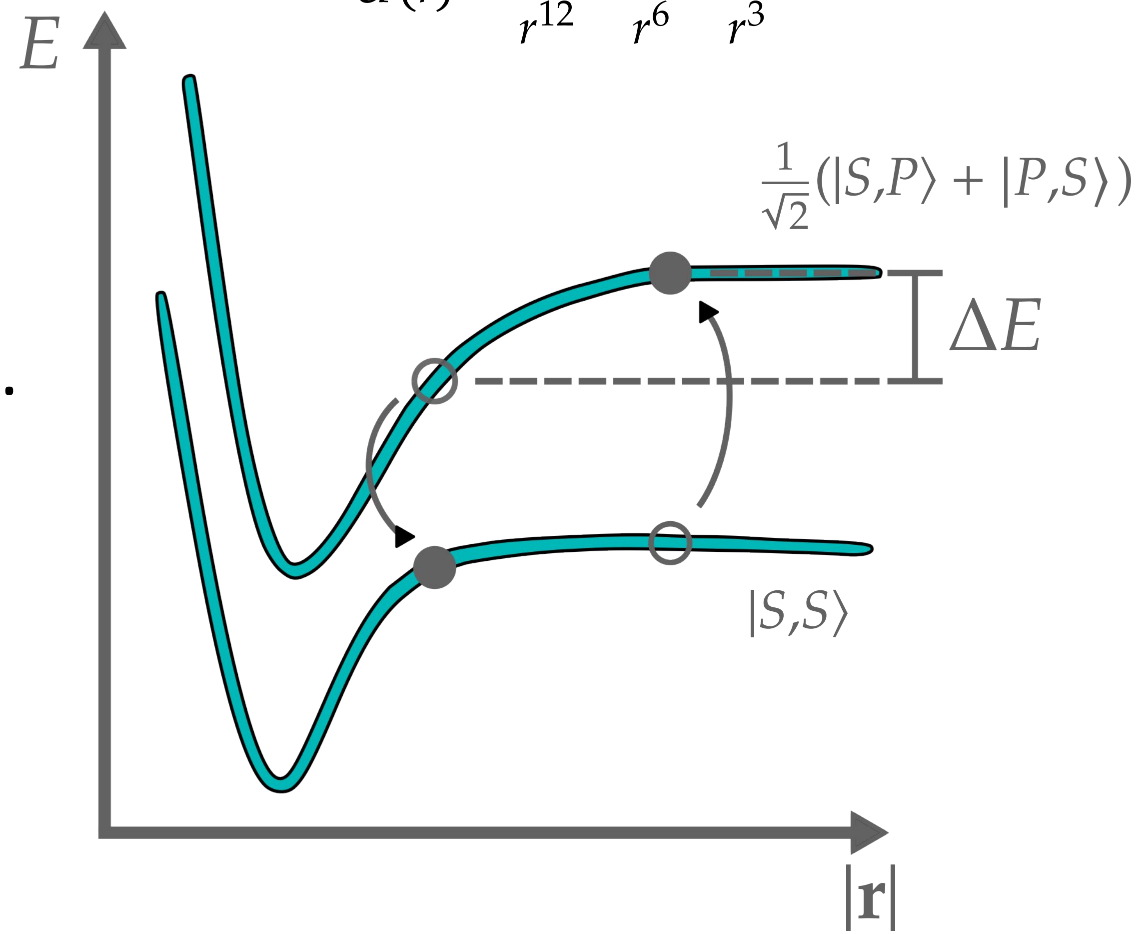


White et al., in preparation

Single atoms

- ~5 atoms in each trap after loading.
- Induce losses to get single atoms.
- Light-assisted collisions: pairwise losses.
- ~ 50 % single atom probability.

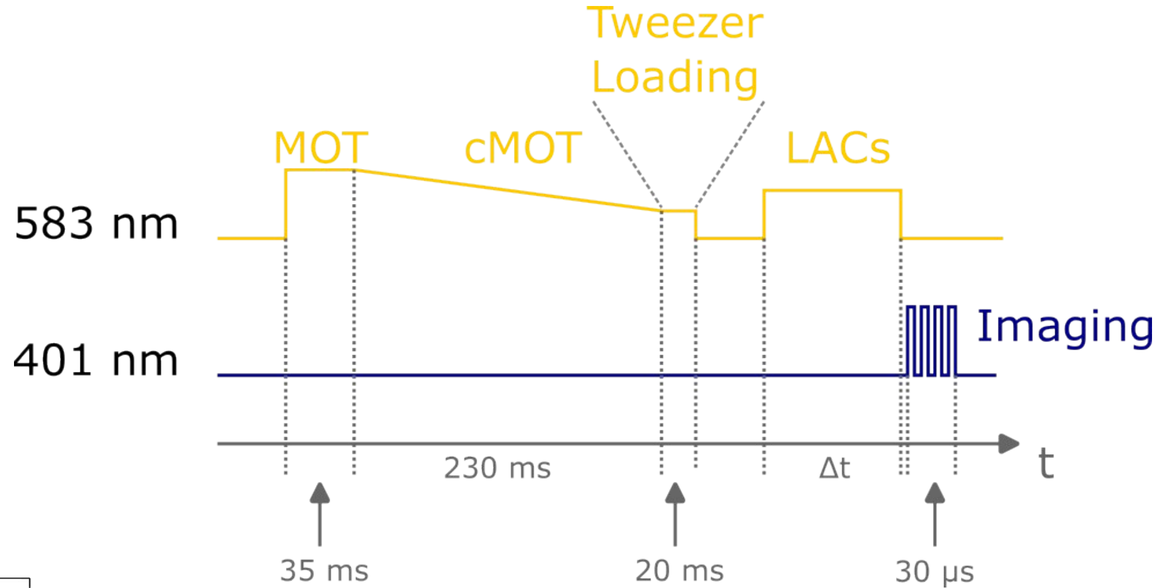
$$U(r) = \frac{C_{12}}{r^{12}} - \frac{C_6}{r^6} - \frac{C_3}{r^3}$$

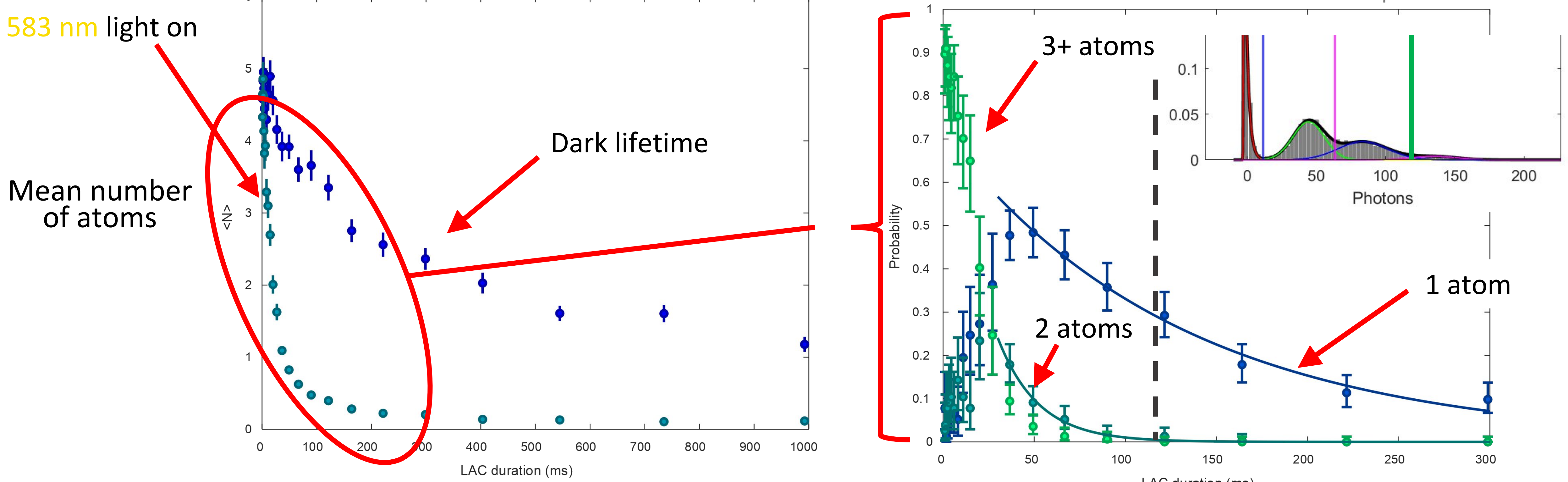


($583\ \text{nm}$, $\Gamma/2\pi = 190\ \text{kHz}$)

Light-assisted collisions

- Probe atom number in single tweezer at different Δt.



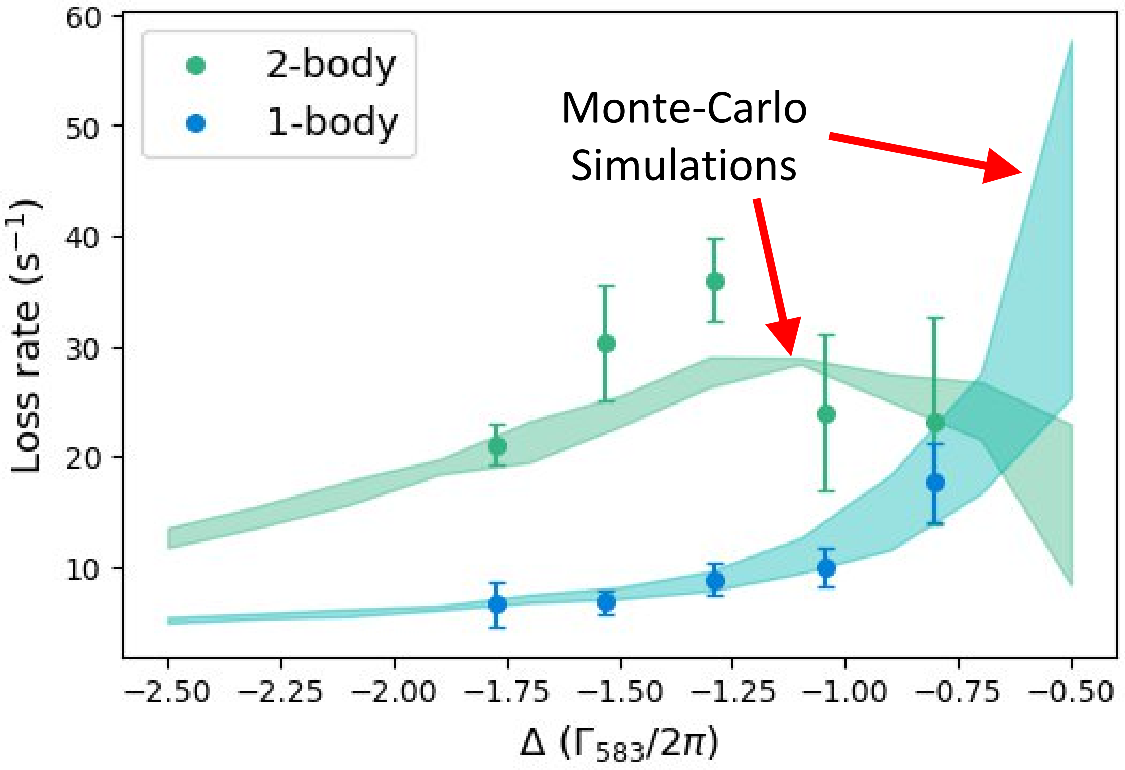


White et al., in preparation

($583\ nm$, $\Gamma/2\pi = 190$ kHz)

Relative loss rates

- Repeat for different 583 nm detunings.
- Good agreement with Monte-Carlo simulations.
    - 1-body: single body heating.
- "Optimum" detuning.
    - Maximum 2-body loss relative to 1-body.



Svetlana Kotochigova Temple University

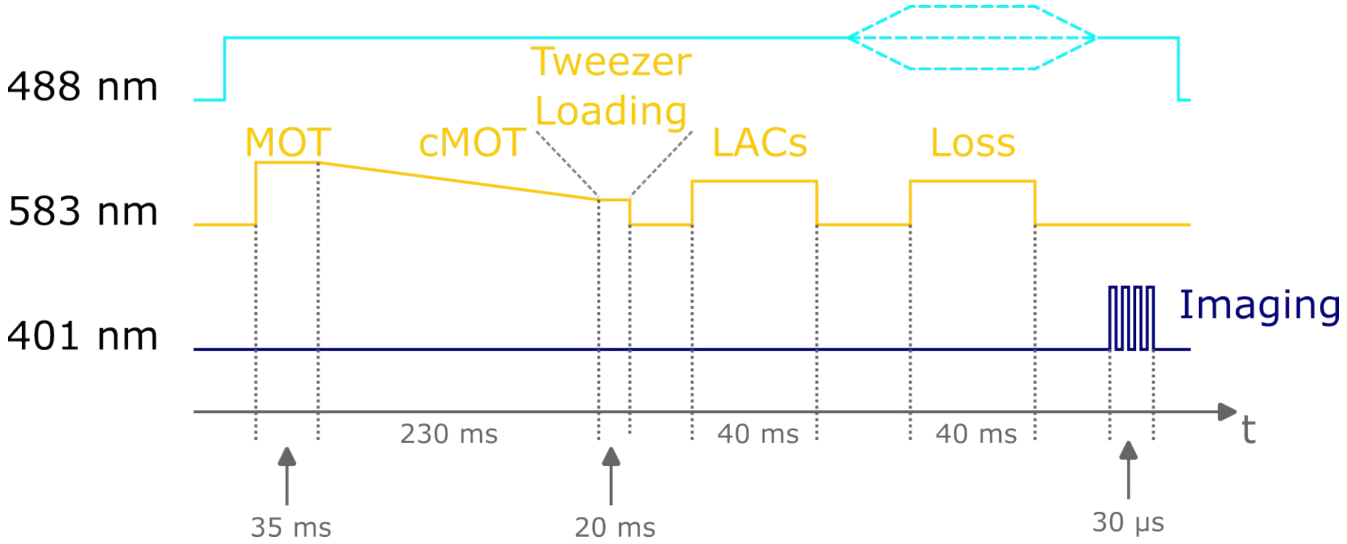
$$U(r) = -\frac{C_3}{r^3}$$

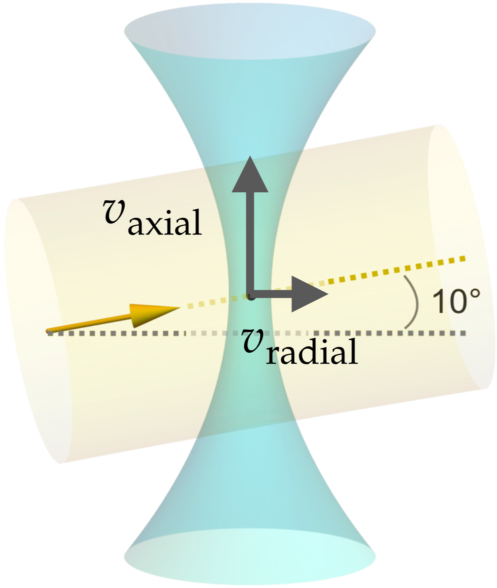
White et al., in preparation

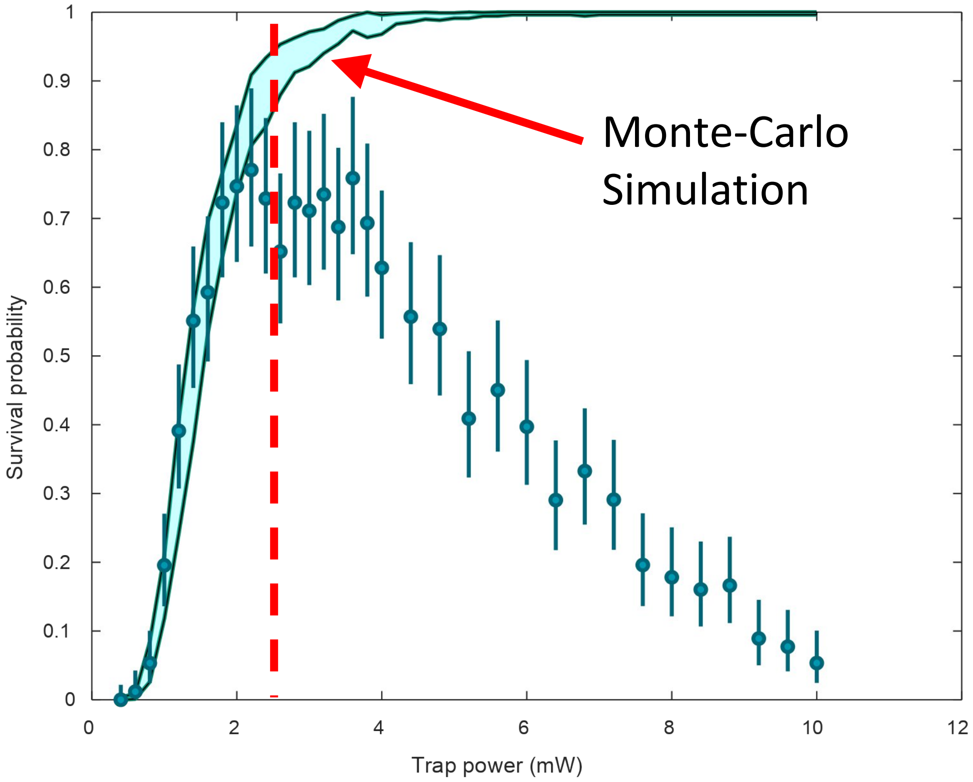
(583 nm, $\Gamma/2\pi = 190$ kHz + 488 nm)

Single-body losses

- Start from single atoms.
- Scan 488 nm trap power.
- Turn on 583 nm LAC-condition light.
- Measure survival.
- Losses at high trap powers.
- Primary loss mechanism we have is single-body heating.





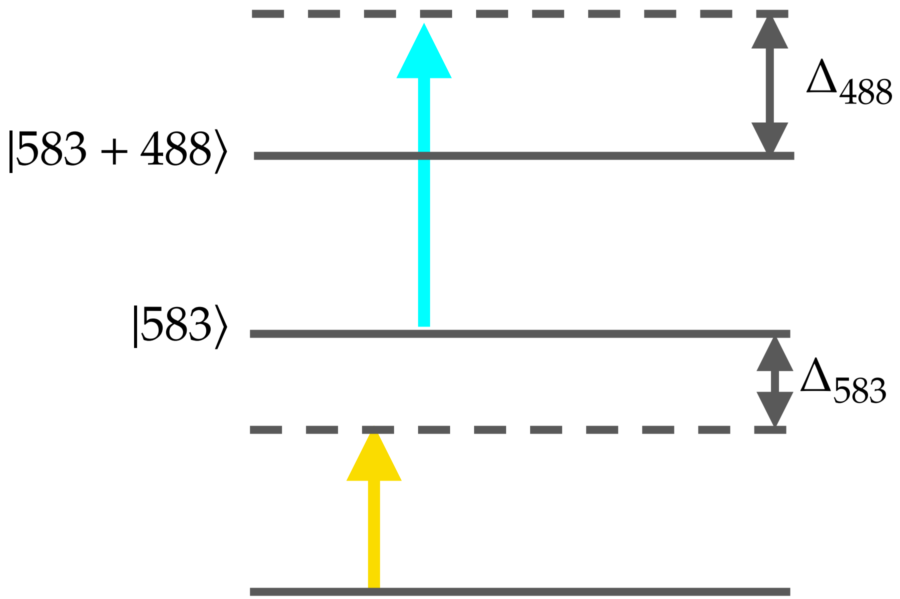


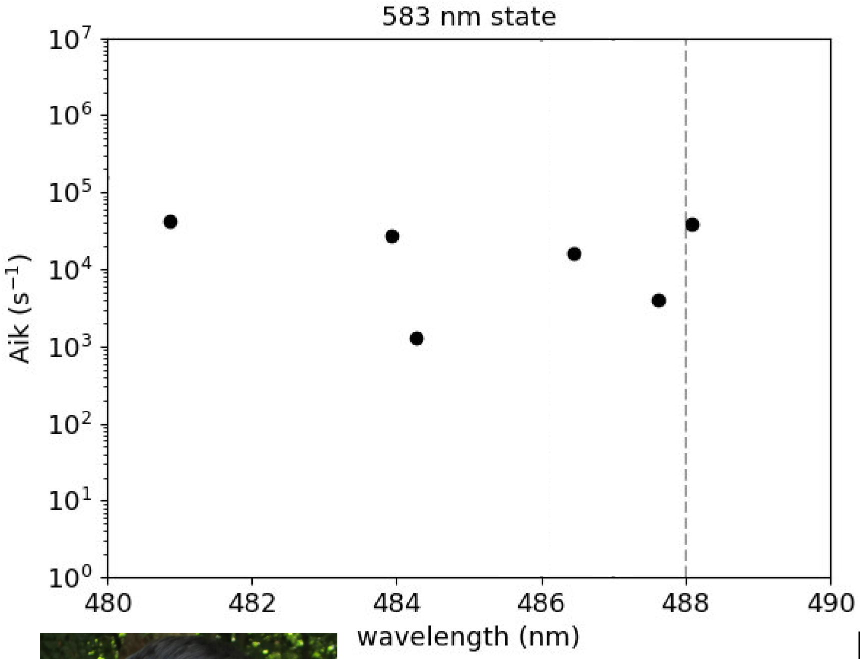
White et al., in preparation

$(583\ \text{nm}, \Gamma/2\pi = 190\ \text{kHz} + 488\ \text{nm})$

Trap-related loss mechanisms

- Coupling to excited state.

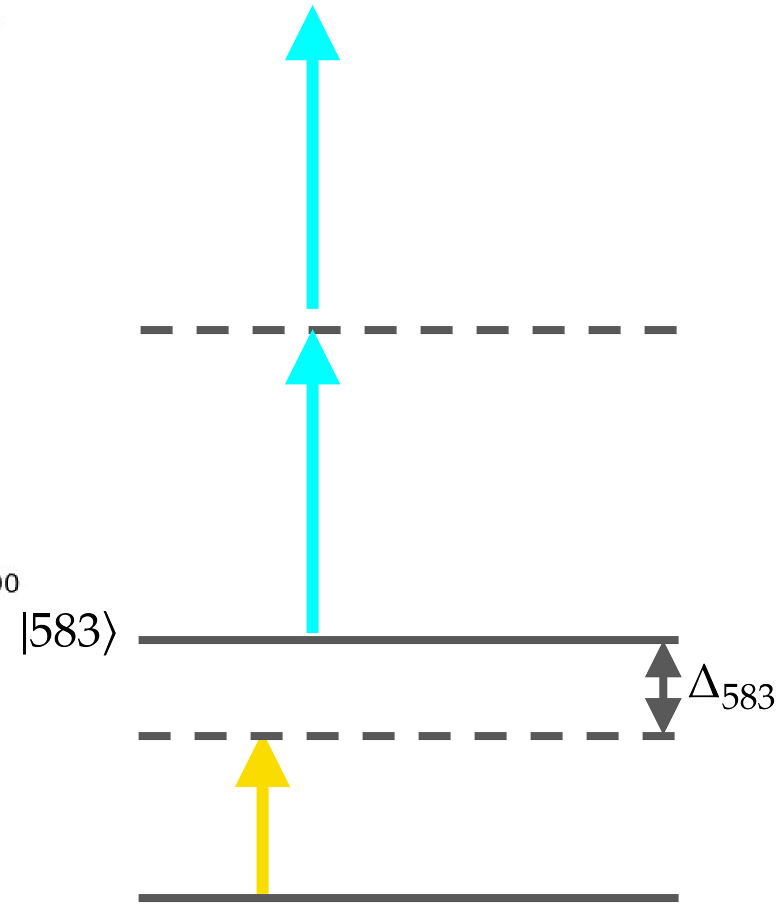




Maxence
Lepers
ICB

- State predicted with
  - $\Delta_{488} \approx 100$ GHz.
  - $\Gamma/2\pi \approx 10$ kHz
- Free running trap laser.

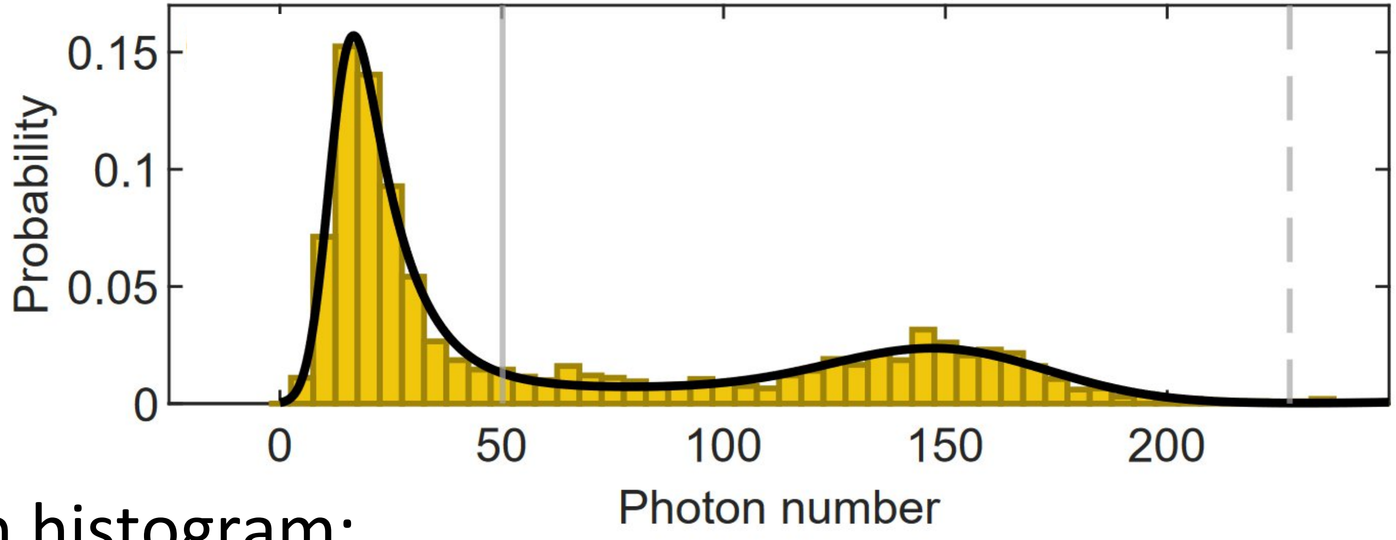
- Photoionisation.



(583 nm, $\Gamma/2\pi = 190$ kHz)

Non-destructive imaging

- Single-body losses give ~70 % survival for 583 nm imaging.
  - Not good enough for desired experiments: many imaging steps e.g. for re-arrangement.



- “Bridge” in histogram:
  - 0:1 atom fidelity of ~93 %.
  - (99.5 % for 401 nm imaging).

Outlook

- Axial direction cooling
  - Vertical 583 nm beam through objective.
  - Additional 841 nm ($\Gamma/2\pi = 8$ kHz) beam.
- Two photon effects: 486 nm laser.
  - Lockable & tuneable (~1 nm).
  - Larger detuning from predicted 583 nm + 488 nm state.
  - Additional predicted magic condition for 841 nm.
- Trap and imaging system aberrations: new objective with 1” input.
  - No more 3” & 4” optics or compensation glass.
  - Reduce trap waist (measure 1.05 µm, theoretical is ~0.6 µm).
  - Less imaging system aberrations – shorter imaging times.
- Implement spatial light modulator (SLM) – 2D tweezer arrays.
- Resolved sideband cooling with 841 nm to motional ground state.
- Further explore Rydberg state excitations.
- Electrodes and MCPs

The Team

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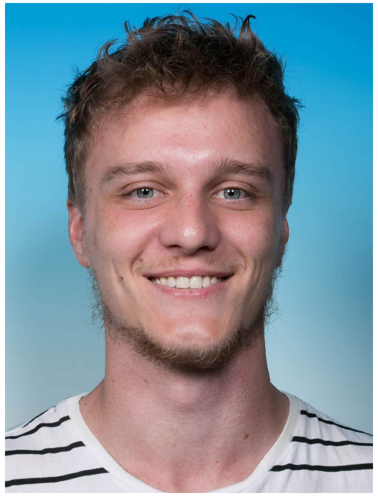


Daniel
Schneider Grün

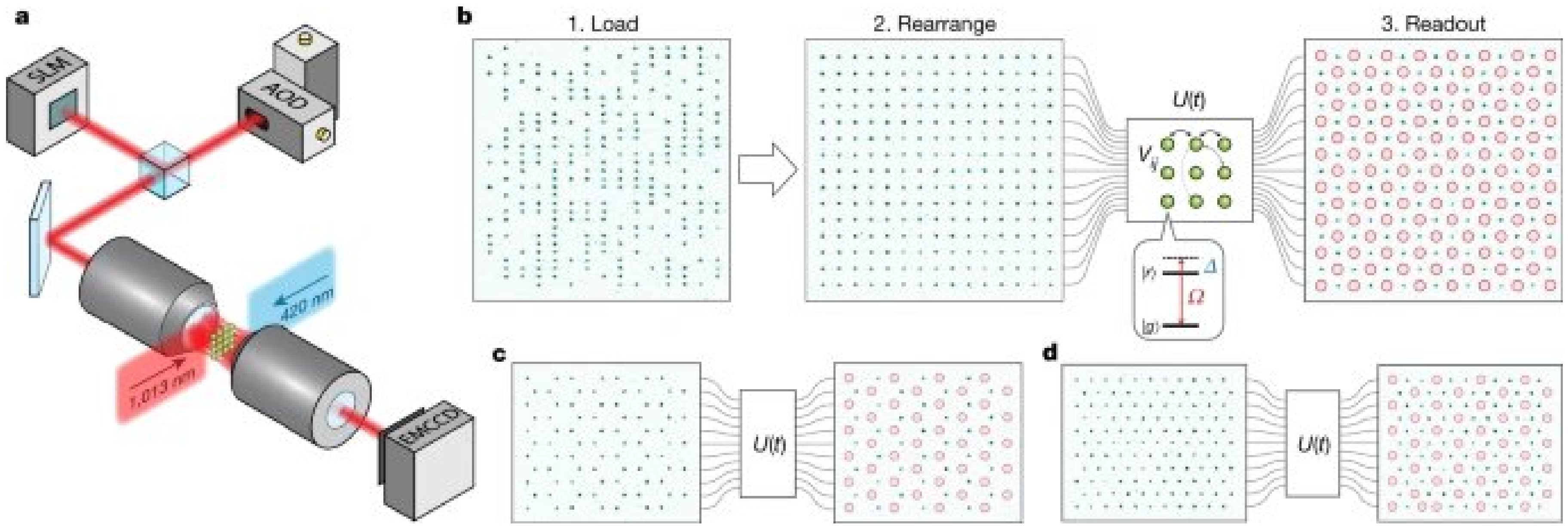
Riccardo
Donofrio

Julián
Maloberti

Backup slides

- ‘ere be dragons.

Lukin – Quantum simulation

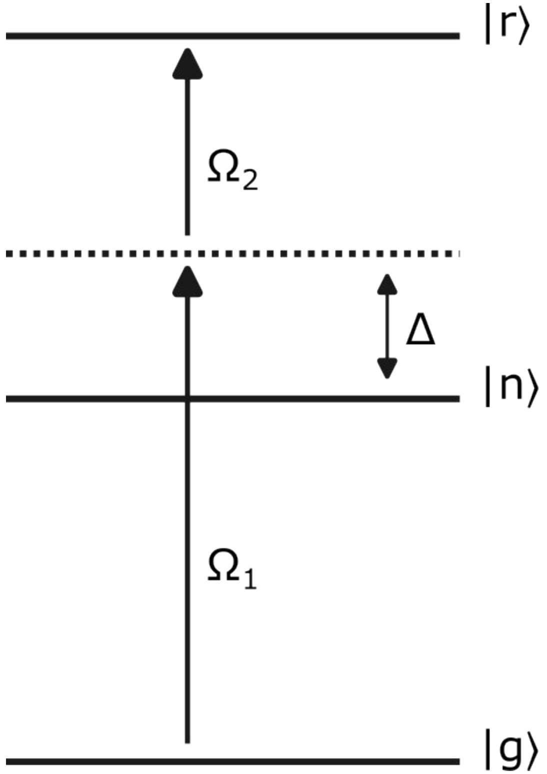


- Quantum phases of matter on a 256-atom programmable quantum simulator
- Re-arrangement: 50–100 ms for arrays of up to a few hundred atoms
- Filling fractions exceeding 99%
- *Nature* **volume 595**, pages 227–232 (2021)

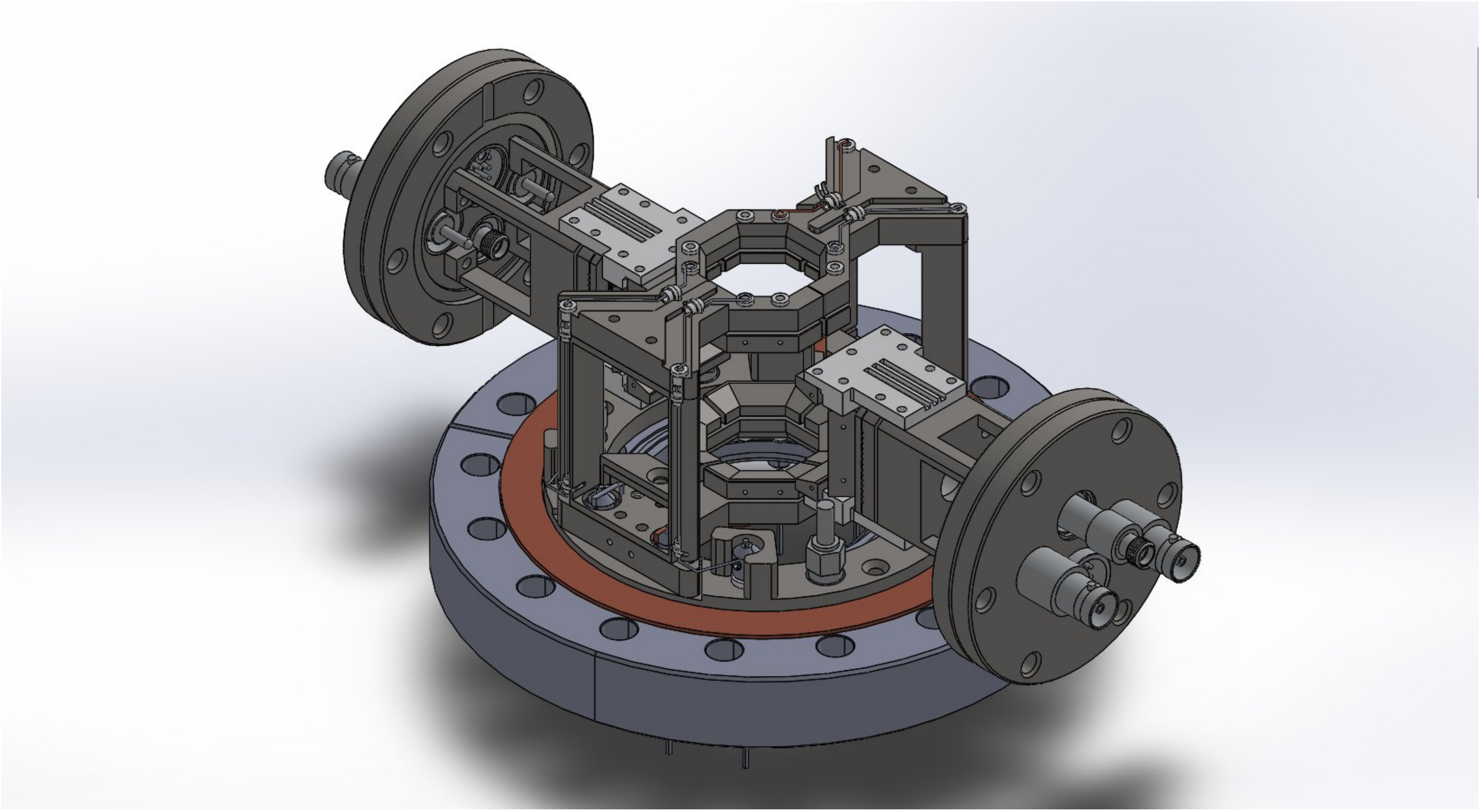
Rydberg dephasing

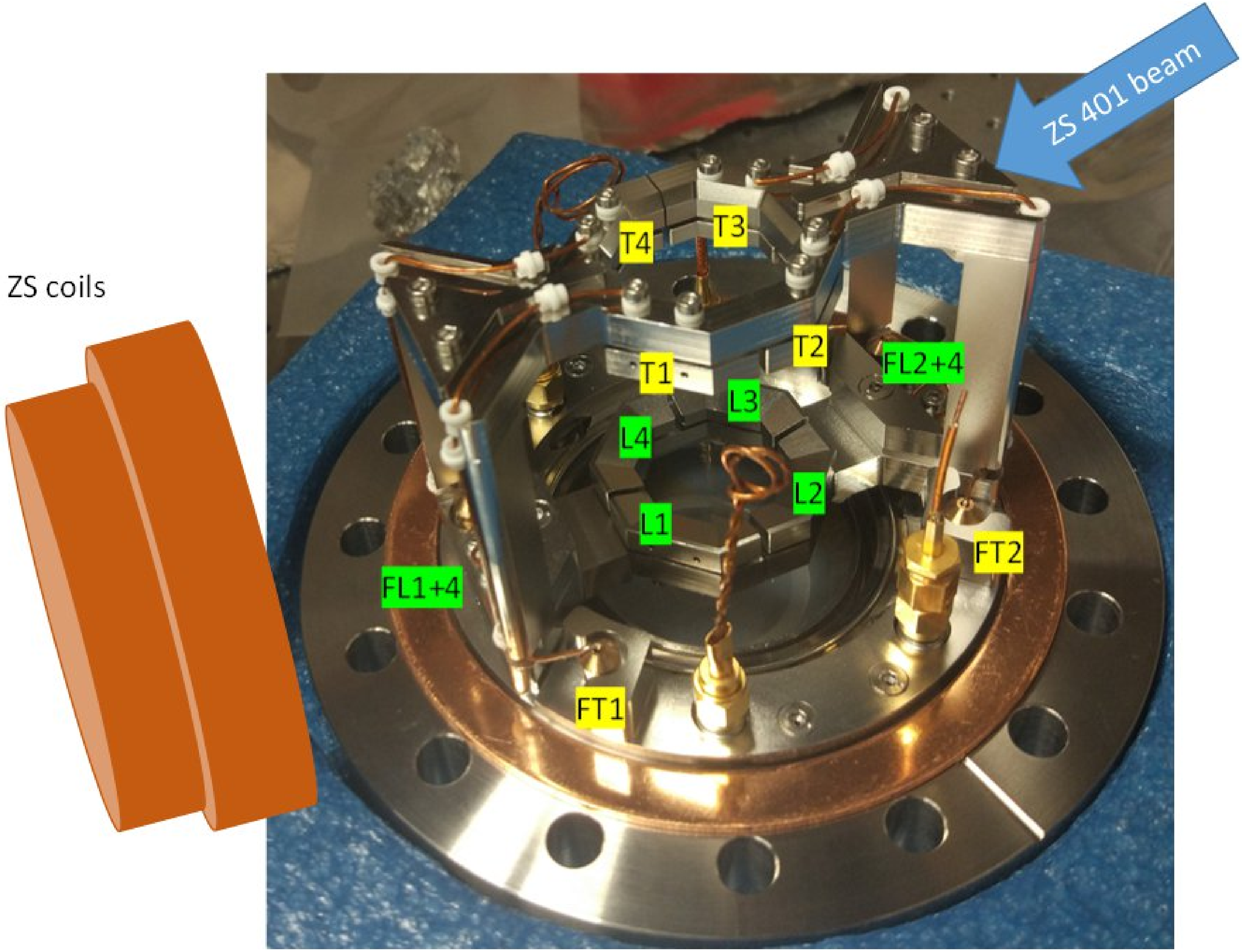
Let $s_{|\mathrm{i}\rangle} = I/I_{\mathrm{sat}}$, then:

- Effective Rabi, $\Omega_{\mathrm{eff}} = \frac{\Omega_1 \Omega_2}{2\Delta} = \frac{\Gamma_{|n\rangle}\Gamma_{|r\rangle}}{4\Delta}\left(s_{|n\rangle} s_{|r\rangle}\right)^{1/2}$.
- Off-resonant scattering rate, $\mathrm{R_i} \approx \frac{\Gamma_{|\mathrm{i}\rangle}}{4}\frac{\Omega_{\mathrm{i}}^2}{\Delta^2} = \frac{\Gamma_{|\mathrm{i}\rangle}^3}{8\Delta^2}\ s_{|\mathrm{i}\rangle}$.



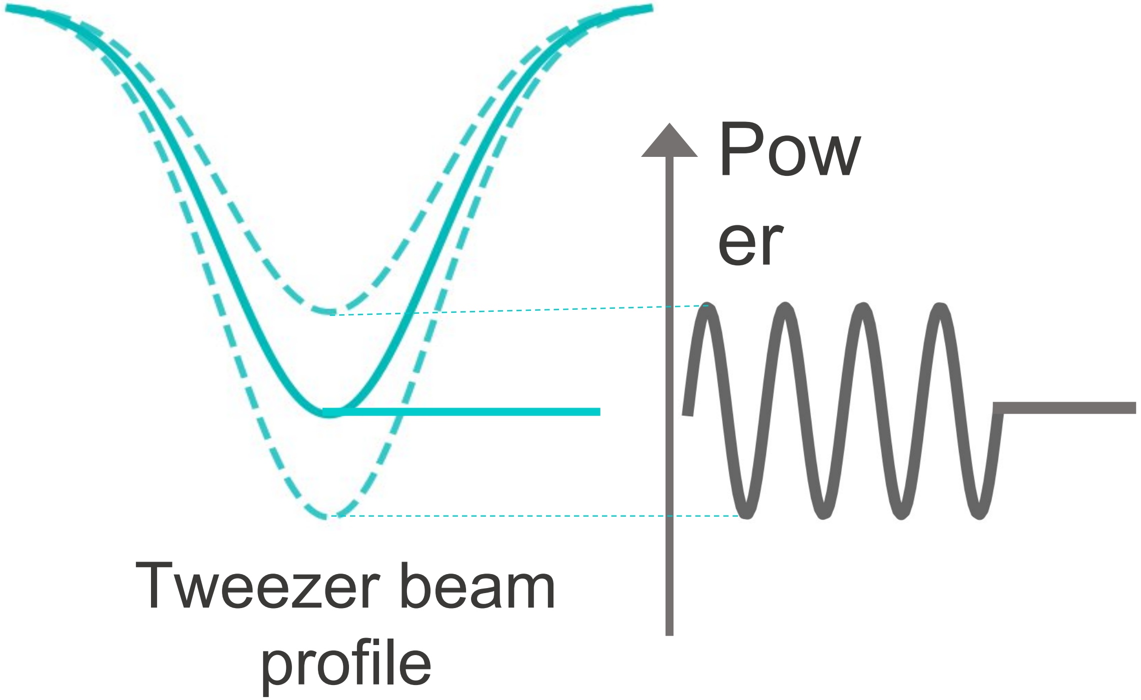
Electrodes and MCPs

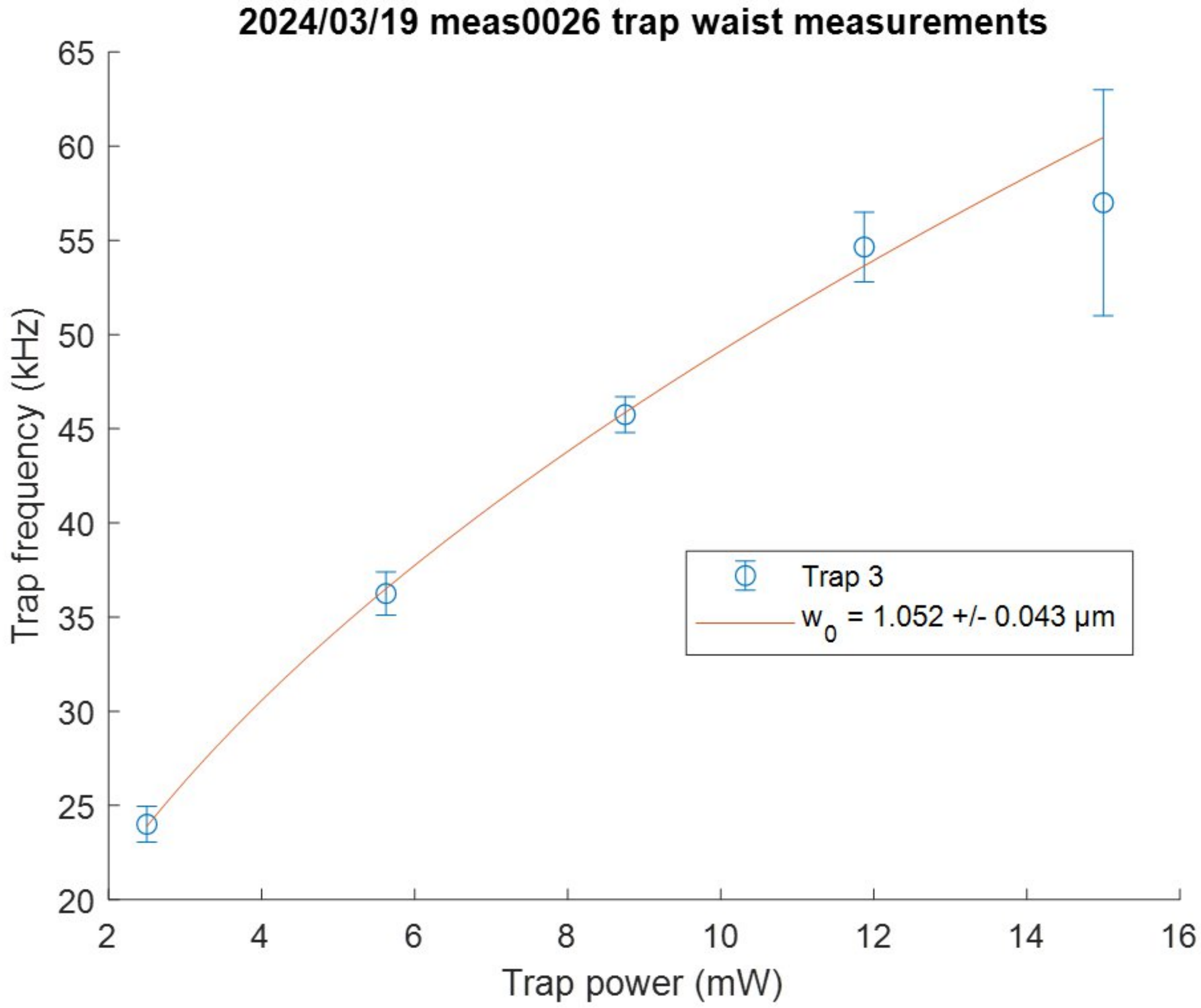



ZS coils
ZS 401 beam
T4
T3
T2
T1
FL2+4
L3
L4
L2
L1
FT2
FL1+4
FT1

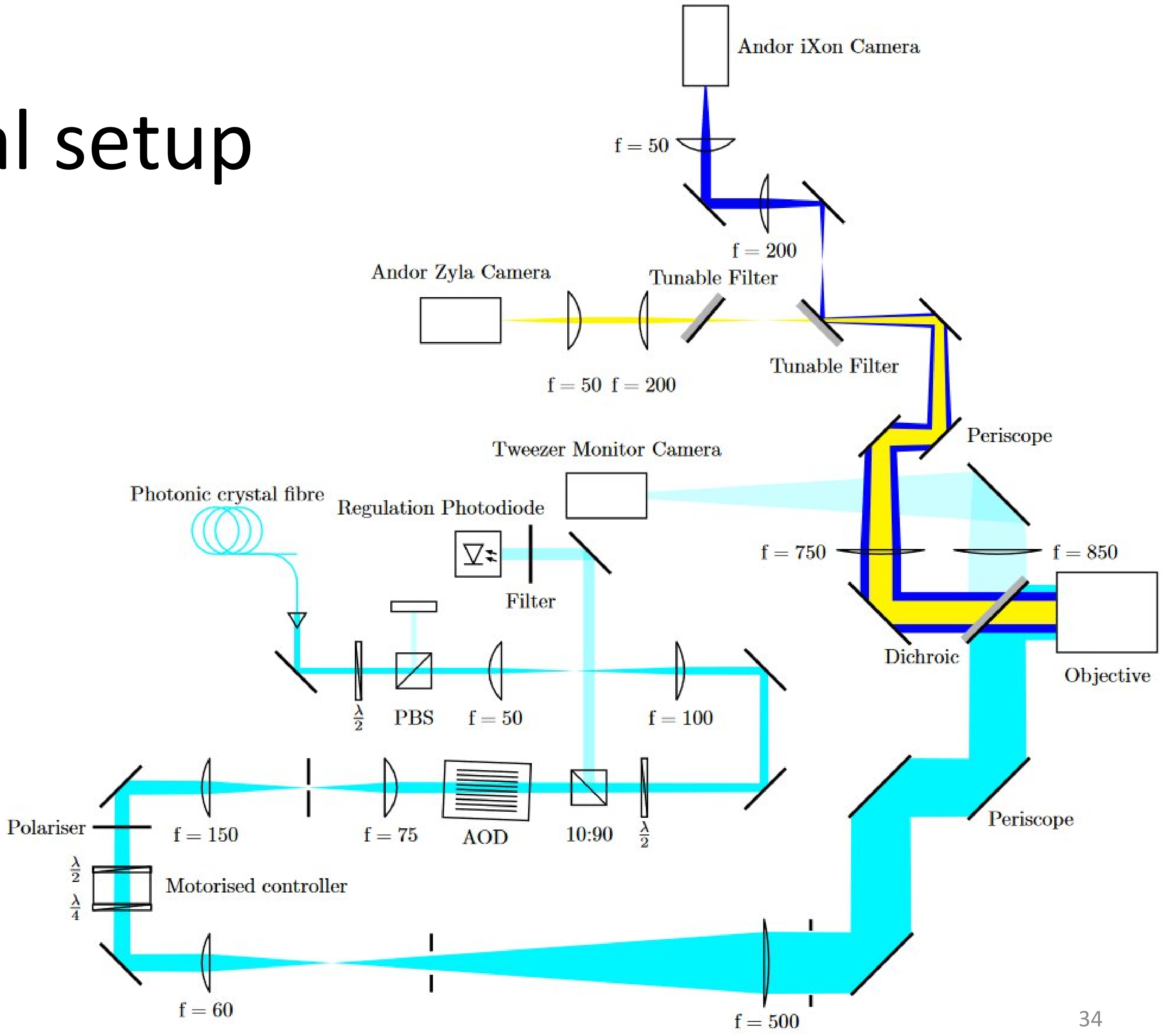
Trap waist

- Measure radial trap frequency using parametric heating.





Tweezer optical setup



Atomic polarisability

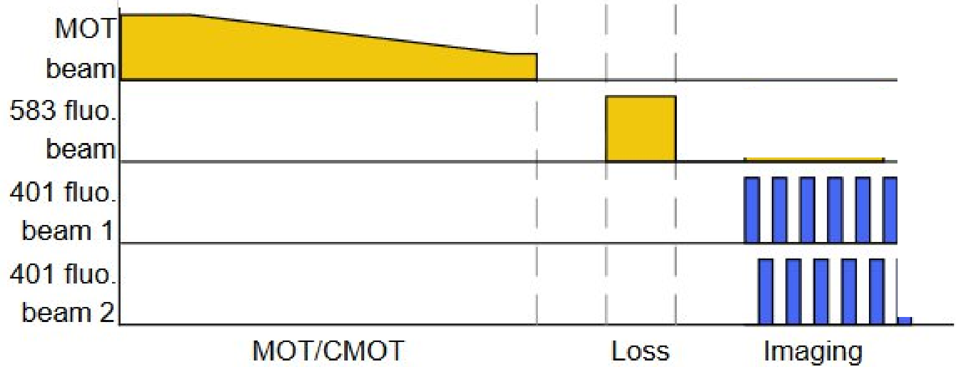
$$\alpha(\alpha_t) = \alpha_s(\lambda_t) + |\mathbf{u}^* \times \mathbf{u}| \cos\theta_k \frac{m_J}{2J}\alpha_v(\lambda_t) + \frac{3m_J^2 - J(J+1)}{J(2J-1)} \frac{3\cos^2\theta_p - 1}{2}\alpha_t(\lambda_t).$$

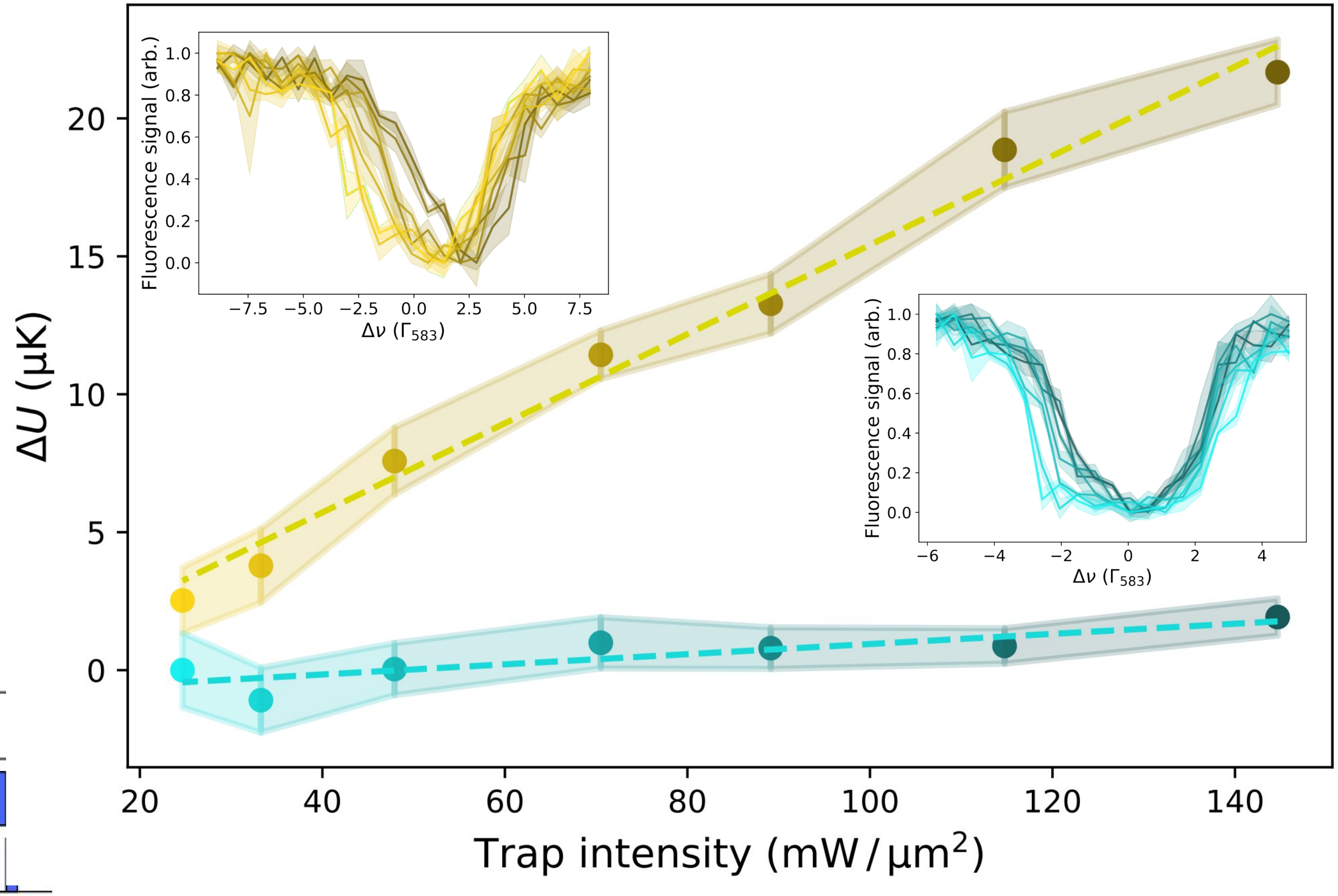
$\mathbf{u}^* \times \mathbf{u} = \sin(2\chi)$

polarization vector $\mathbf{u}$

fix $\theta_p = \pi/2$ and $\theta_k = \pi$

583 Loss Spec (401 Img)



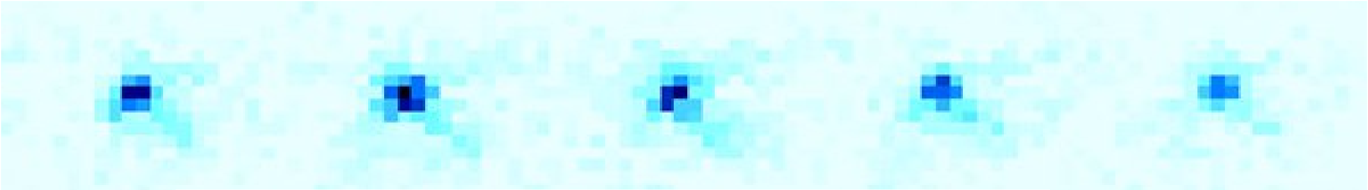


401 imaging

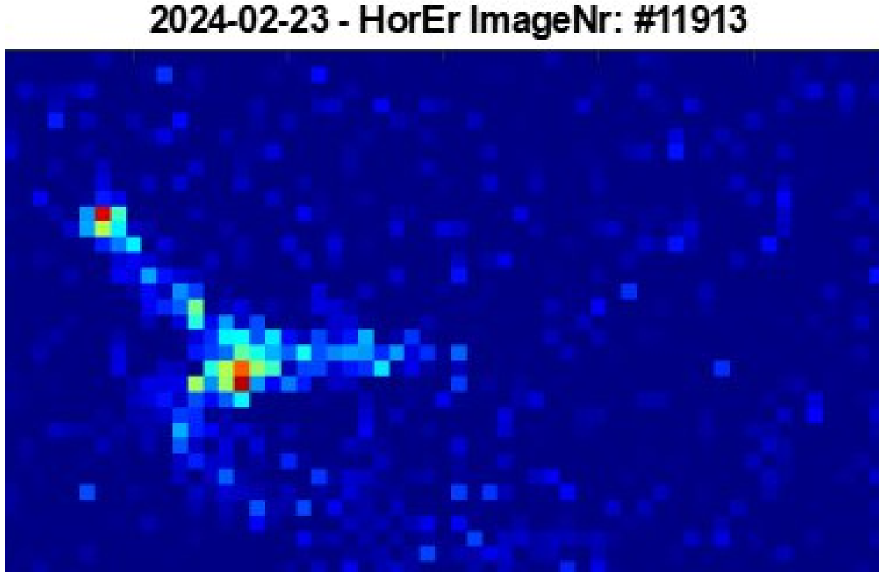
- Alternating pulsed beams – ~1.5 us pulse length.

Well explored in Su, …, Greiner, arXiv 2404.09978v1, 2024

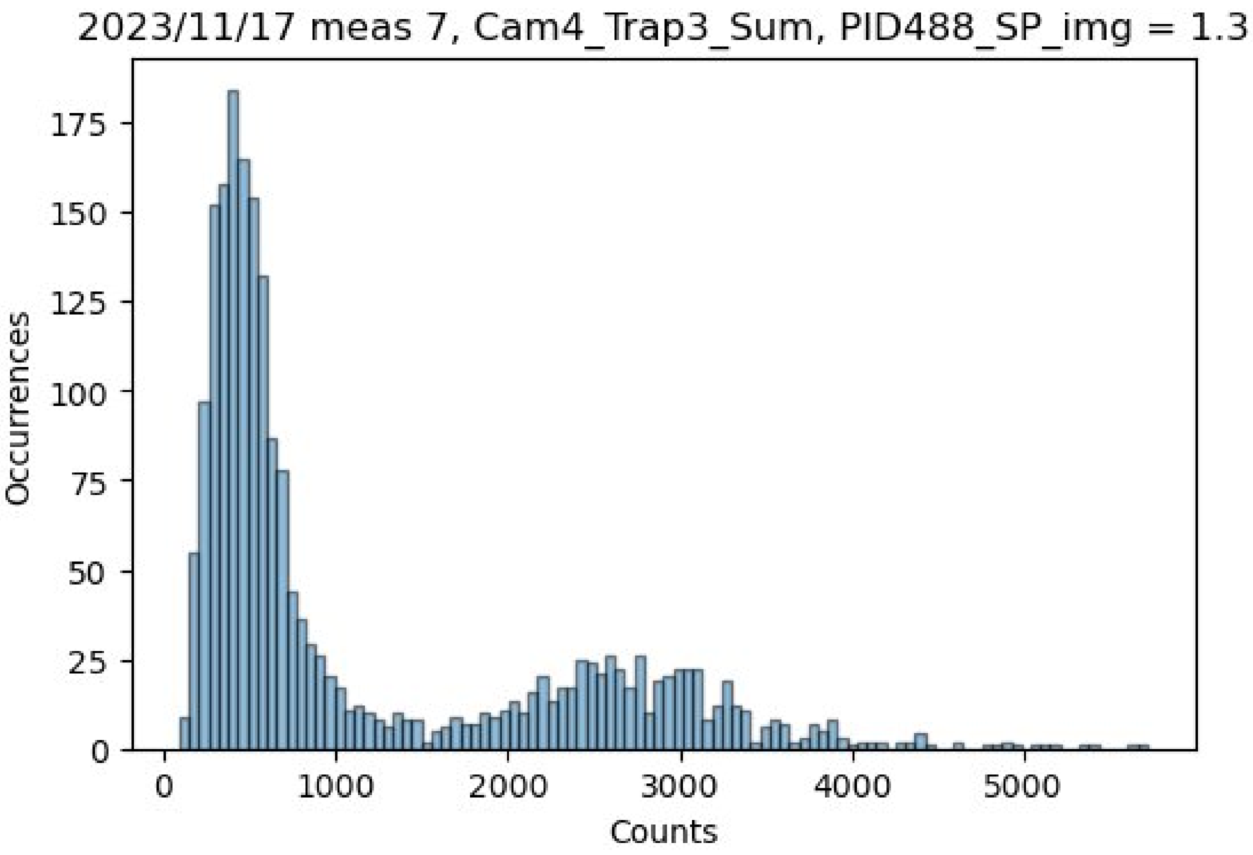
- Averaged image:

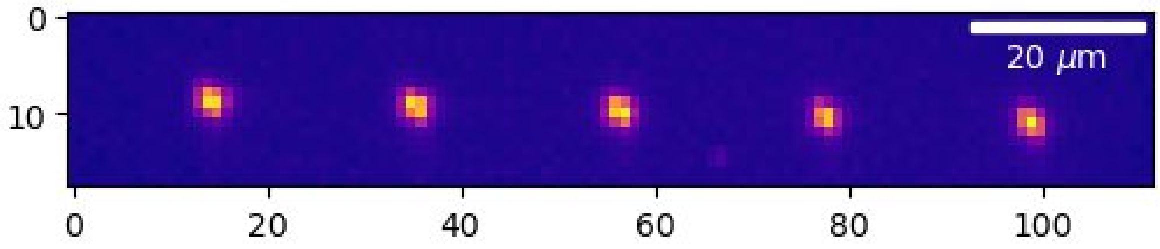


- Longer time image:

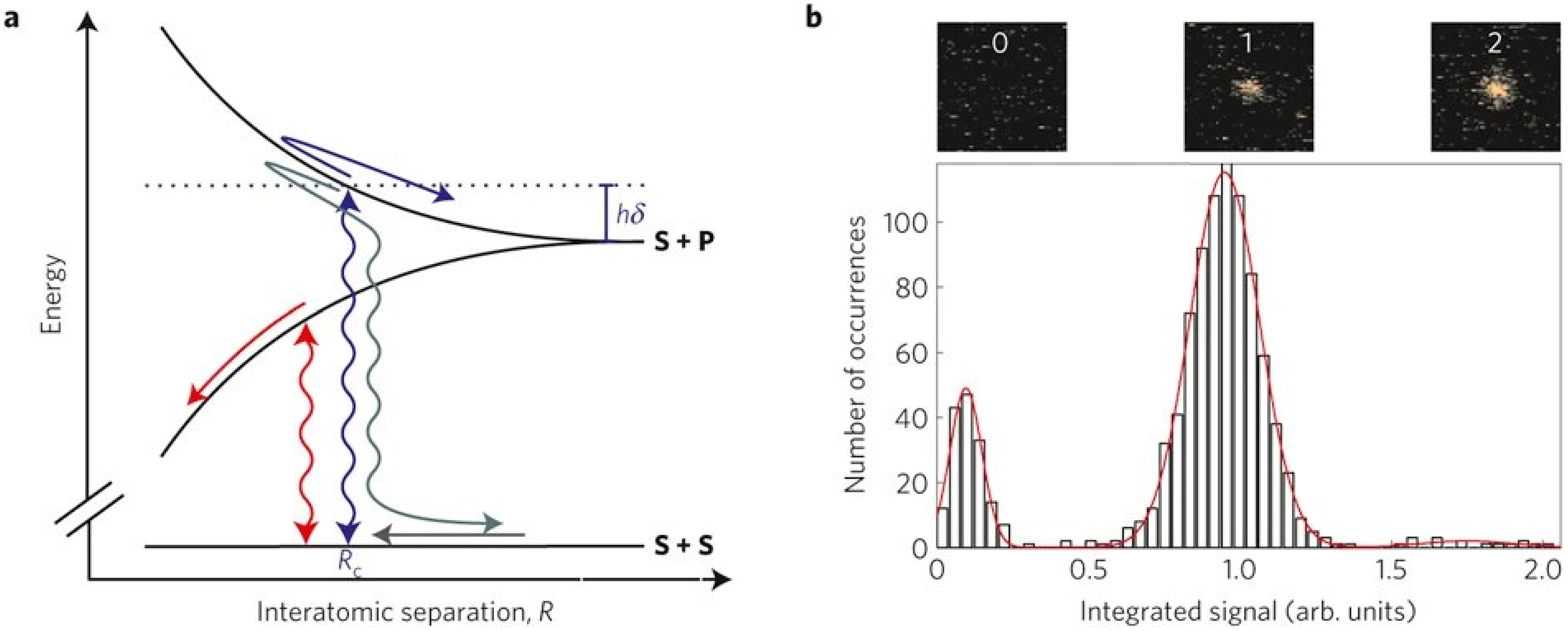


583 nm imaging



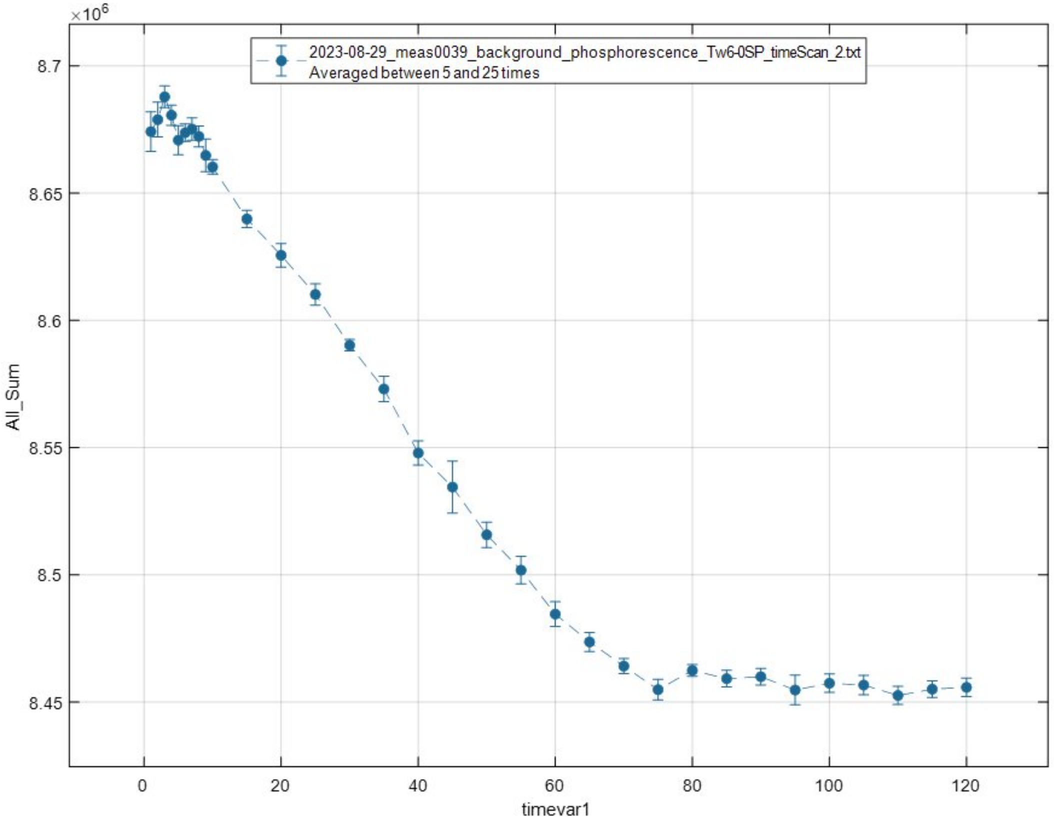


Blue-enhanced loading

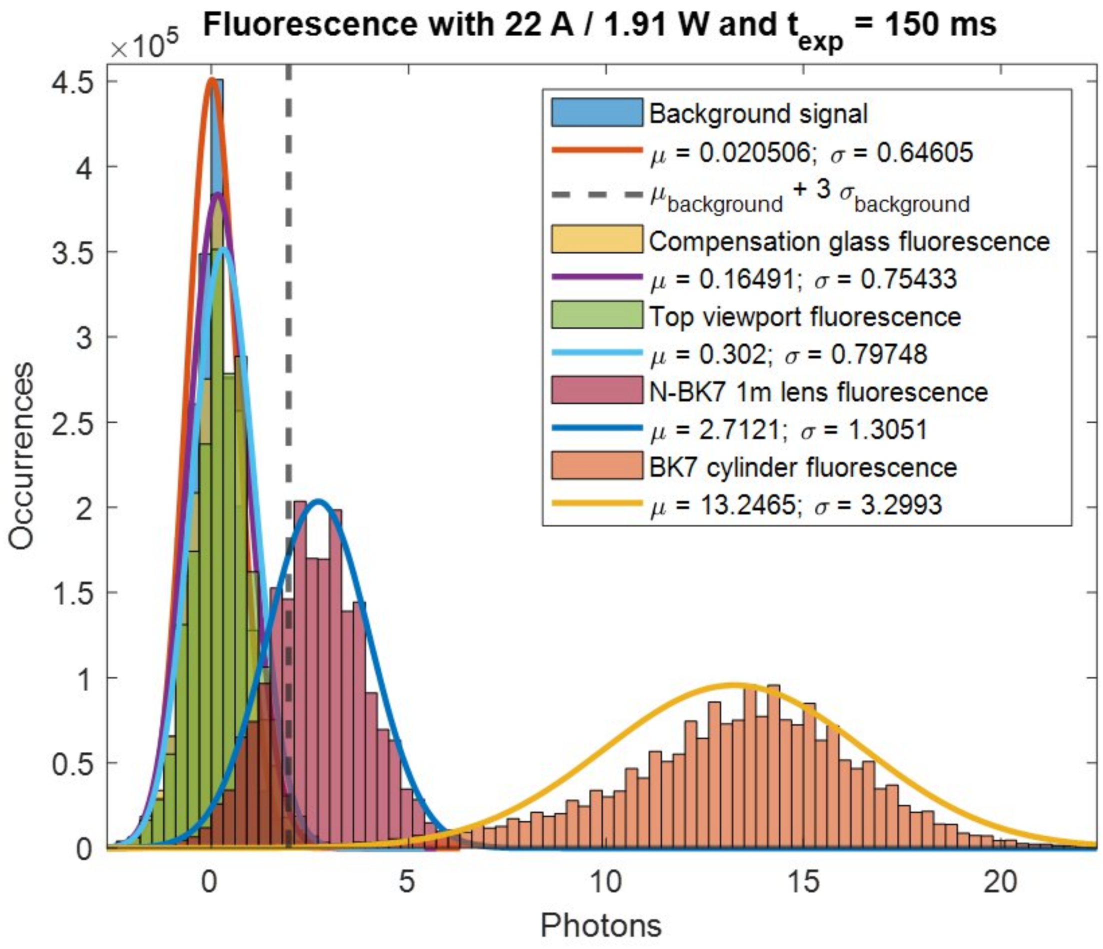


Grünzweig, …, Anderson
Nature Physics 6, 951–954 (2010)

Auto-fluorescence/phosphorescence



2023-08-29_meas0039_background_phosphorescence_Tw6-0SP_timeScan_2.txt
Tweezer light on (atten. = 0 dB, SP = 6, centre freq. = 92.5 MHz, spacing = 0 MHz, num. = 1) -> MOT (t = 35 ms) -> Compress MOT (t = 230 ms) -> Ramp to tweezer hold bias (x = -0.2 A, y = -0.1 A, z = 2 A) -> Tweezer hold (t = 50 ms) -> Ramp to tweezer imaging bias (x = -0.2 A, y = -0.1 A, z = 2 A) -> Imaging (t_exp = 150 ms, 583 img1. freq. = 0 MHz, 583 img1. atten. = 31 dB, 583 img2. freq. = 115.65 MHz, 583 img2. atten. = 4 dB) -> End



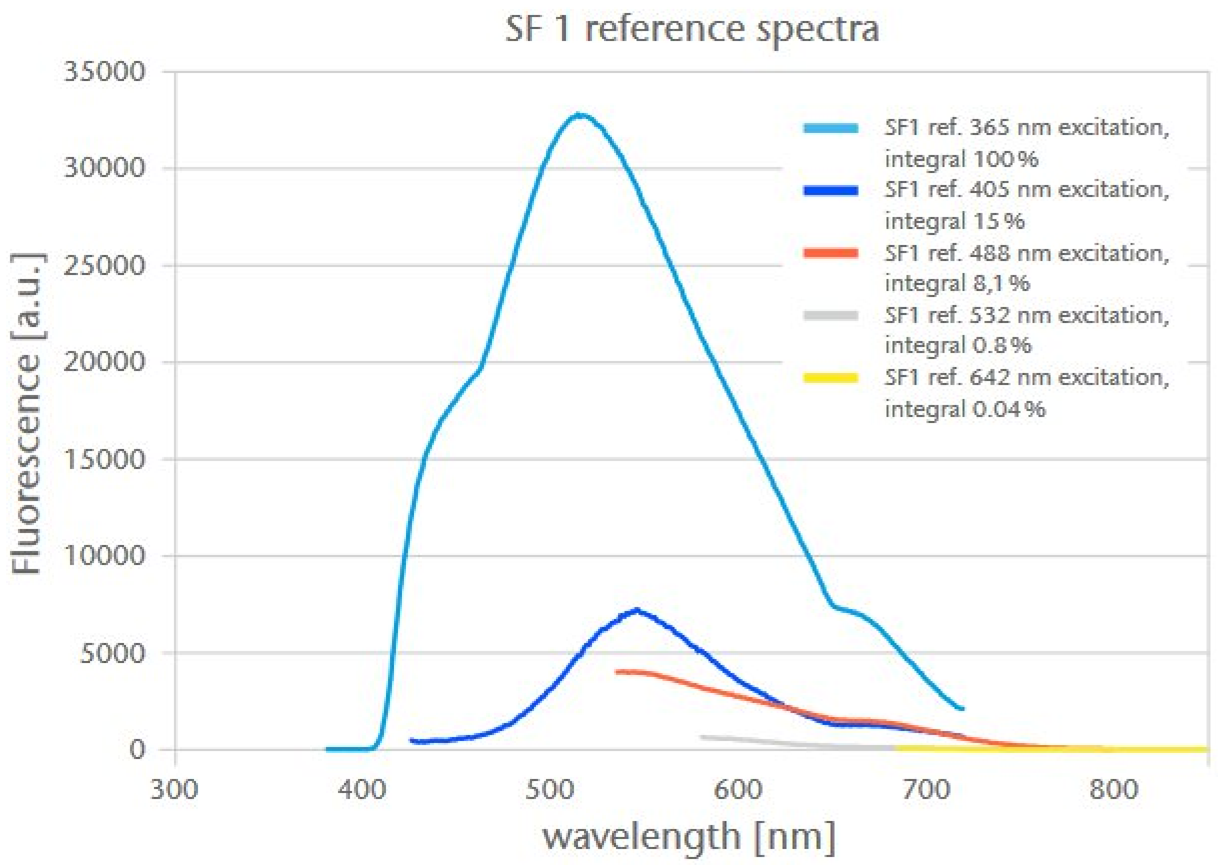
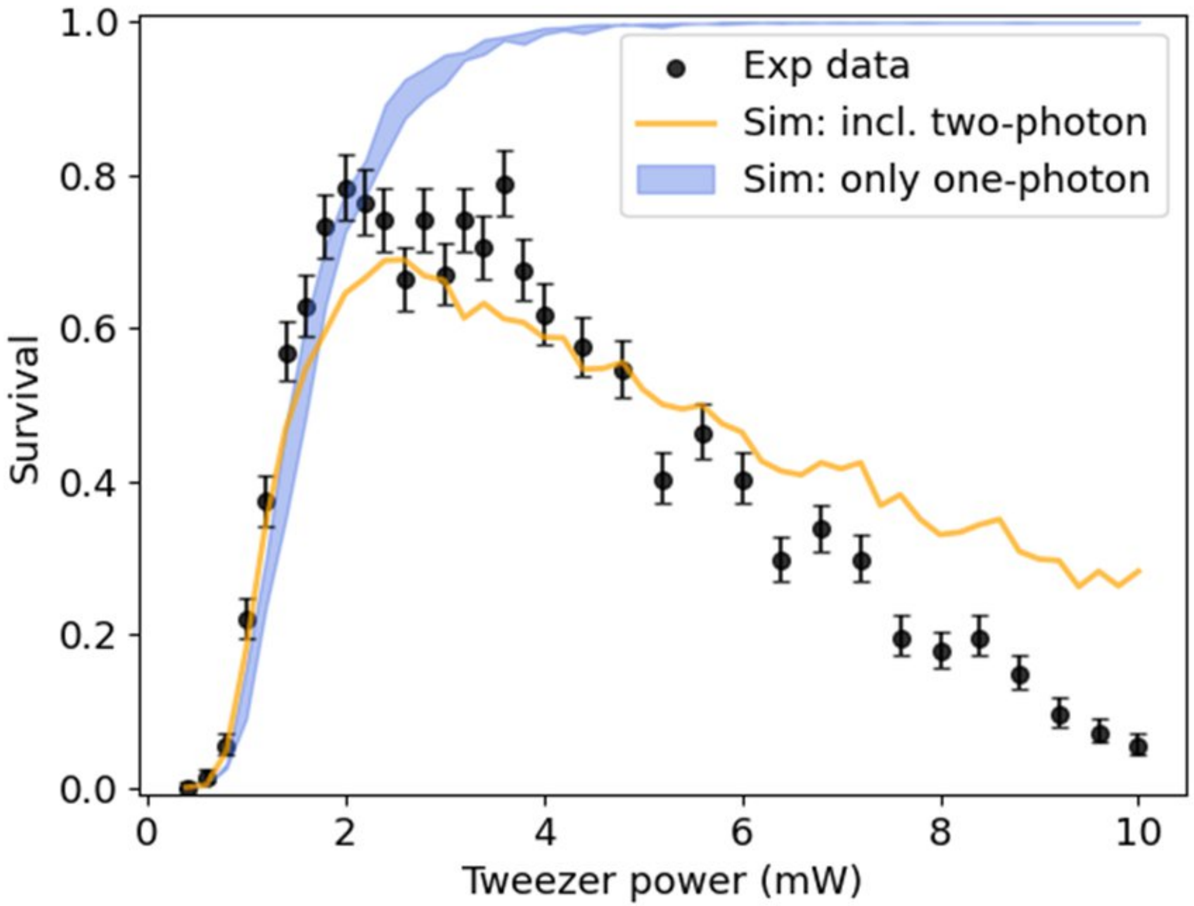


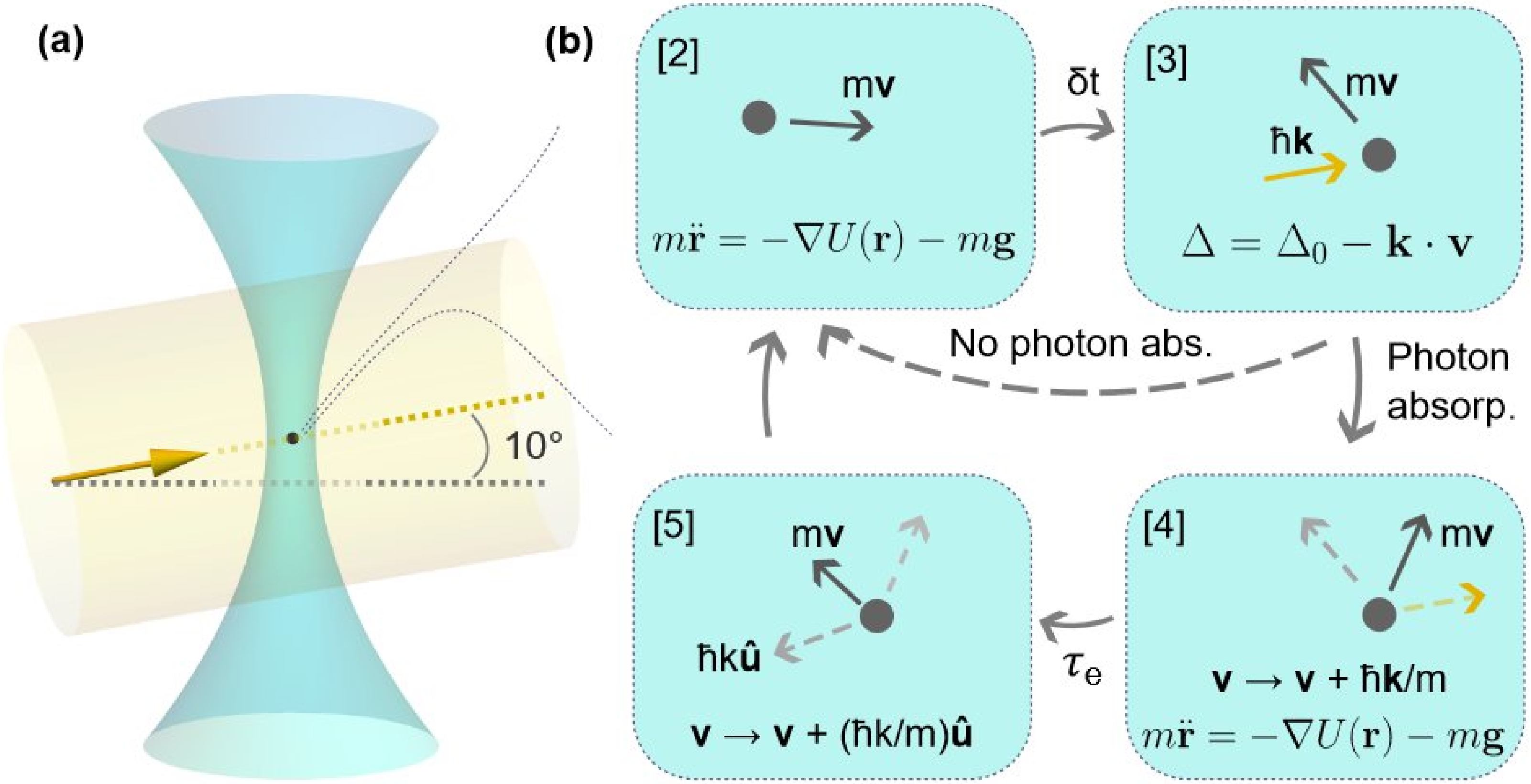
Fig. 13: SF1 reference sample spectrum for 365 nm, 405 nm, 488 nm, 532 nm and 642 nm excitation.

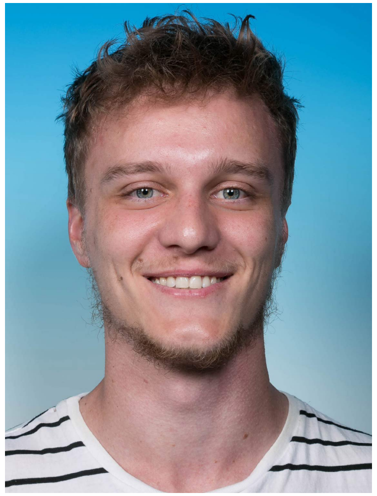
Two photon loss simulation

- $\Gamma_2/(2\pi)$ ~ 61 kHz
- Δ_2 ~ 1 cm^(-1) ~ 2π×30 GHz



Monte Carlo





Daniel
Schneider Grün

Svetlana
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Temple University

6s electron excitations

1^{st} photon	2^{nd} photon	$\Delta\lambda$ / nm	$\Gamma_{\|n\rangle}$ / kHz	$J_{\|n\rangle}$	Excited state
401	411	10	30 000	7	$4f^{12}(^3H)6s6p$
583	312	271	180	7	$4f^{12}(^3H_6)6s6p(^3P°_1)$
426	388	38	300	5	$4f^{12}(^3H)6s6p$
420	393	27	30	6	$4f^{12}(^3F)6s6p(^3P°)$
419	394	25	300	5	$4f^{12}(^3F)6s6p(^3P°)$
418	394	24	600	5	$4f^{12}(^3H)6s6p$
391	422	31	900	7	$4f^{12}(^3H)6s6p(^3P°)$

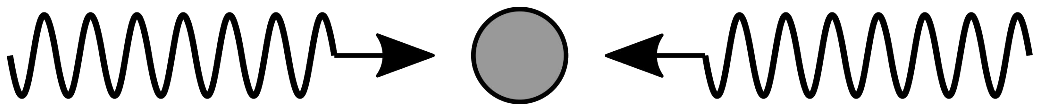
$4f$ electron excitations

1^{st} photon	2^{nd} photon	$\Delta\lambda$ / nm	$\Gamma_{\|n\rangle}$ / kHz	$J_{\|n\rangle}$	Excited state	Remarks
389	329	60	7000	5	$4f^{11}(^4F°)5d6s^2$	
1299	207	1092	1e-3	7	$4f^{11}(^4I°_{15/2})5d_{3/2}6s^2$	x2 1 Photon
365	349	16	0.3	7	$4f^{11}(^4I°)5d^2(^3P)\ 6s$	
357	357	0	1	7	$4f^{11}5d6s^2$	
353	360	6	50	7	$4f^{11}(^4I°)5d6s6p$	
342	372	30	3	5	$4f^{11}(^4F°)5d6s^2$	
338	377	39	0.2	6	$4f^{11}(^4I°)5d^2(^1D)\ (^4G°)6s$	

- Doubled Ti:Sapph range is ~335-525 nm (M-Squared website).
- Many unassigned levels in NIST < 400 nm.
- Only a few states have rate information.

Dephasing: photon recoil

- Doppler shift from photon recoil [1]



Solutions:

- Counter-propagating beams at similar wavelengths.
- 3-photon excitations
- Excitation from motional ground state.
- Gets less important at larger Rabi frequencies (> 1 MHz) [2].

[1] Doppler- and recoil-free laser excitation of Rydberg states via three-photon transitions https://doi.org/10.1103/PhysRevA.84.053409
[2] Analysis of imperfections in the coherent optical excitation of single atoms to Rydberg states https://doi.org/10.1103/PhysRevA.97.053803