Erbium atoms in optical tweezers

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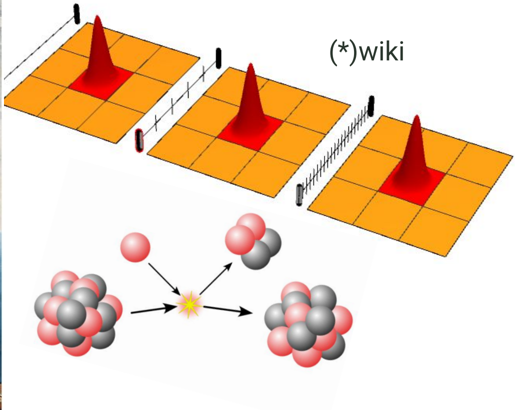
Trento, May 2025

Trento 2025

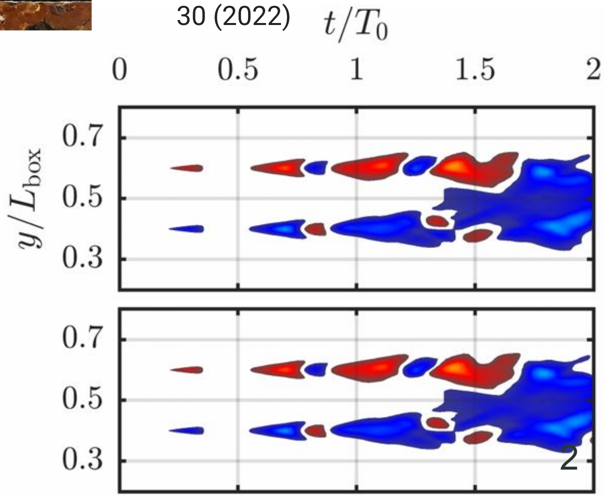
- quantum art, fluid dynamics, quantum chaos
- Ising models, Bose-Hubbard models, LGT
- Quantum Monte Carlo, tensor networks, dynamical mean-field theory, quantum cellular automata
- Zeno effect (*), ground state of nucleus, neutrino oscillations, and many more!!!

A. Crippa arXiv:2411.09549v3



(*)wiki

D. Jaksch,
Nature Computational Science 2, 30 (2022)



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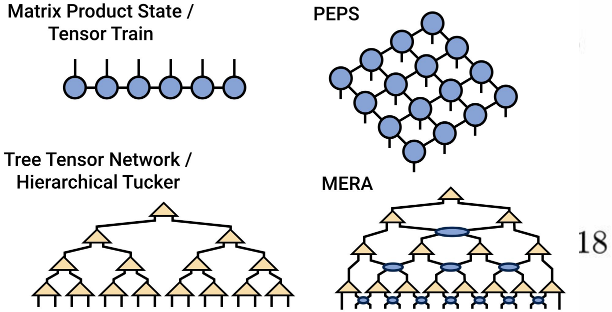

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Motivation

Quantum simulation

- Lattice gauge theories
- Artificial fields
- Dynamical fields

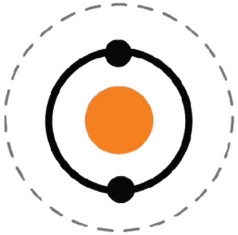
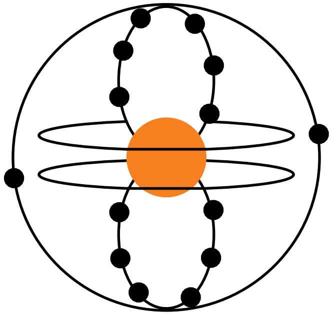
- Meth, Michael, et al. "Simulating 2D lattice gauge theories on a qudit quantum computer." *arXiv preprint arXiv:2310.12110* (2023).
- González-Cuadra, Daniel, et al. "Hardware efficient quantum simulation of non-abelian gauge theories with qudits on Rydberg platforms." *Physical Review Letters* 129.16 (2022): 160501.
- Ohler, Simon, et al. "Self-generated quantum gauge fields in arrays of Rydberg atoms." *New Journal of Physics* 24.2 (2022): 023017.

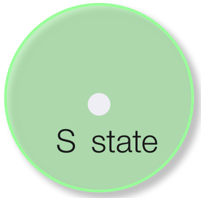
Illustration by Kharlamova

Agenda

1. Motivation
2. Why Erbium?
   - Complex structure, Multiple transitions
   - Rydberg states and advanced capabilities
3. LAC in lanthanides
   - Monte Carlo model
   - Which transition to use for LAC?
4. Rydberg states in lanthanides
   - First erbium Rydberg spectroscopy
   - Rydberg excitations in tweezers

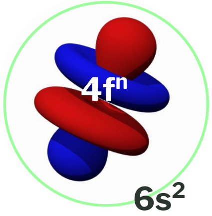
Choosing another atomic ‘flavour’

Alkali	Alkali-Earth	Lanthanides
		
$[\mathrm{Core}]\ ns^1$		$[\mathrm{Core}]\ 4f^n 6s^2$



Spherically symmetric

Anisotropic



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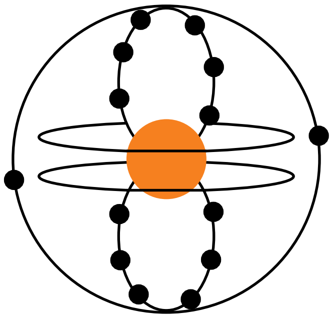
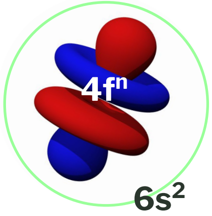
- Multivalent
- Highly-magnetic
- Tensorial polarizability
- Large angular momentum



$$[\mathrm{Core}]\ 4f^{12}6s^2$$

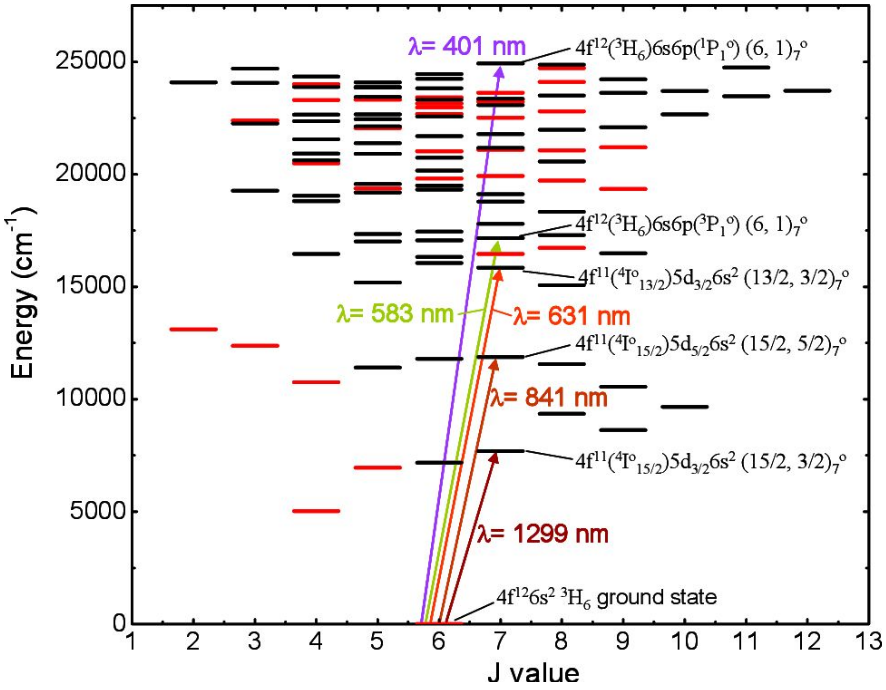
Anisotropic



Multiple transitions

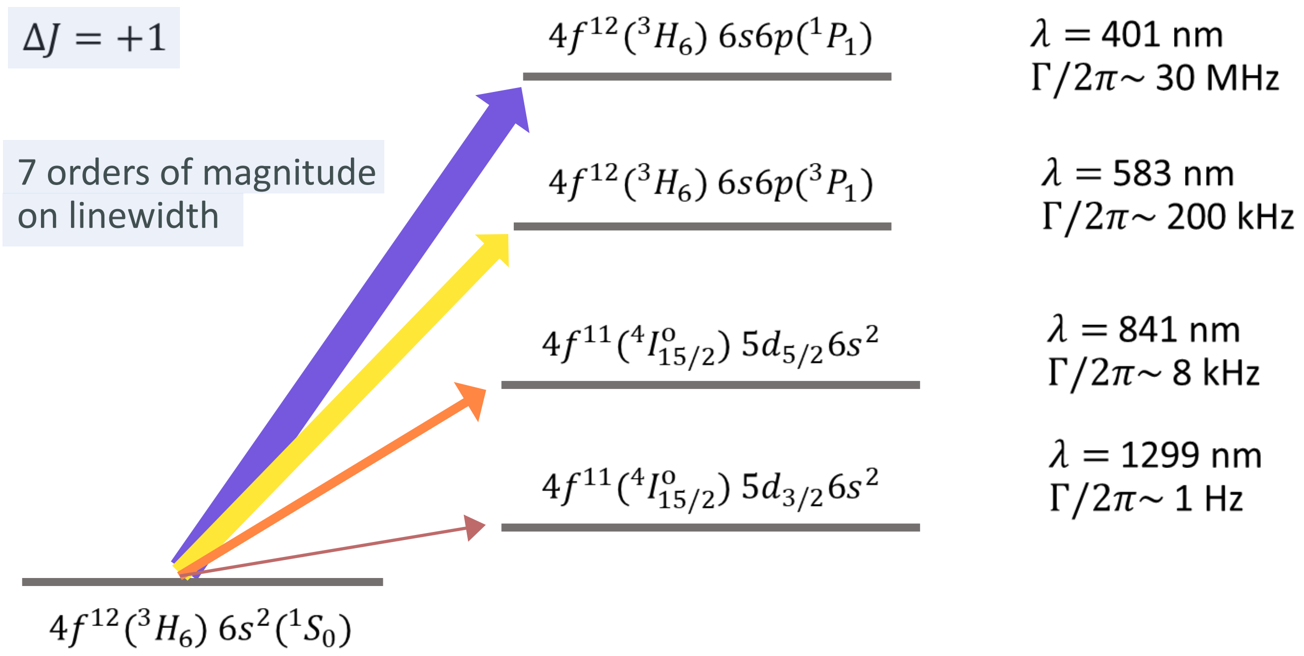
Multiple optical transitions

- Independent transition for different roles
- Rich level scheme with broad, narrow and ultra-narrow transitions



H. Y. Ban, et al. Opt. Express 13, 3185-3195 (2005)

Multiple optical transitions: ultra-narrow



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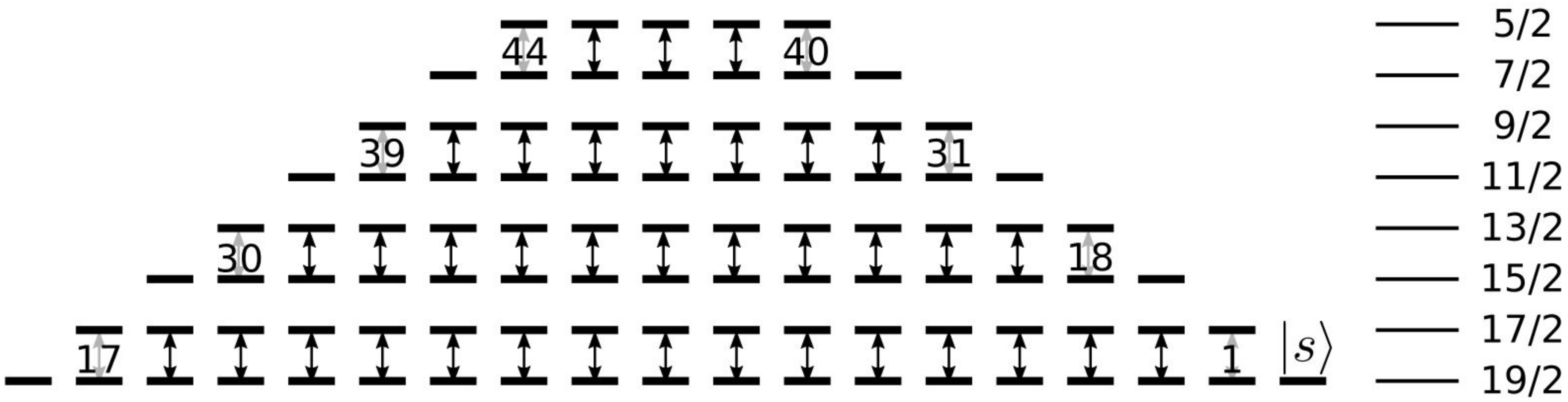
Huge manifolds ready to be ‘superposed’

- Fermionic Er: 96 levels!



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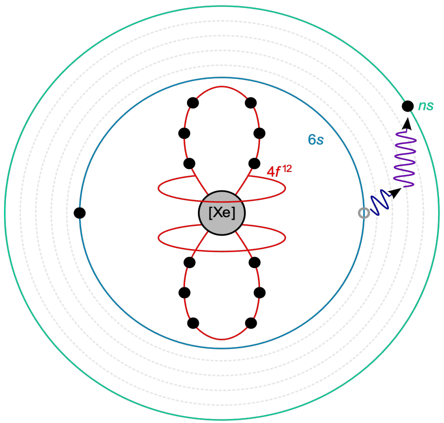
Rydberg states in lanthanides

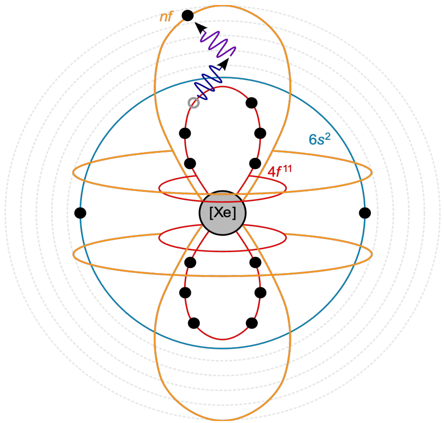
Another atomic species on tweezers… why?

Main motivation: move **Rydberg** physics towards an enhanced level of capabilities



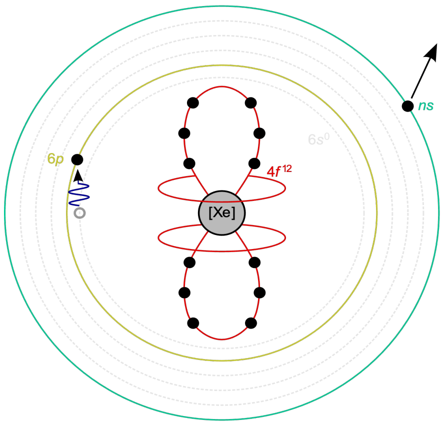
Excitation of one of the $6s^2\ e^-$

$[\mathrm{Xe}]\mathbf{4}\boldsymbol{f}^{\mathbf{12}}\mathbf{6s}\ \boldsymbol{nl}\ (l\ \text{even})$



Excitation of one of the $4f^{12}\ e^-$

$[\mathrm{Xe}]\mathbf{4}\boldsymbol{f}^{\mathbf{11}}\mathbf{6s}^{\mathbf{2}}\ \boldsymbol{nl}\ (l\ \text{odd})$



Isolated Core Excitation (ICE)

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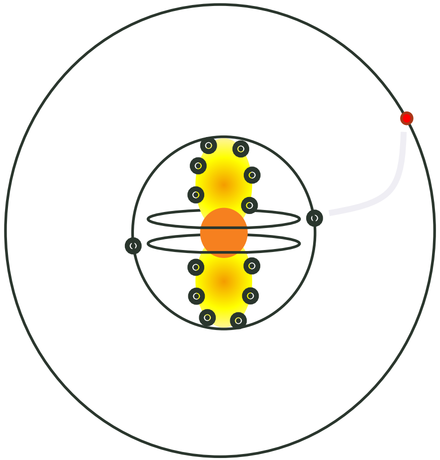
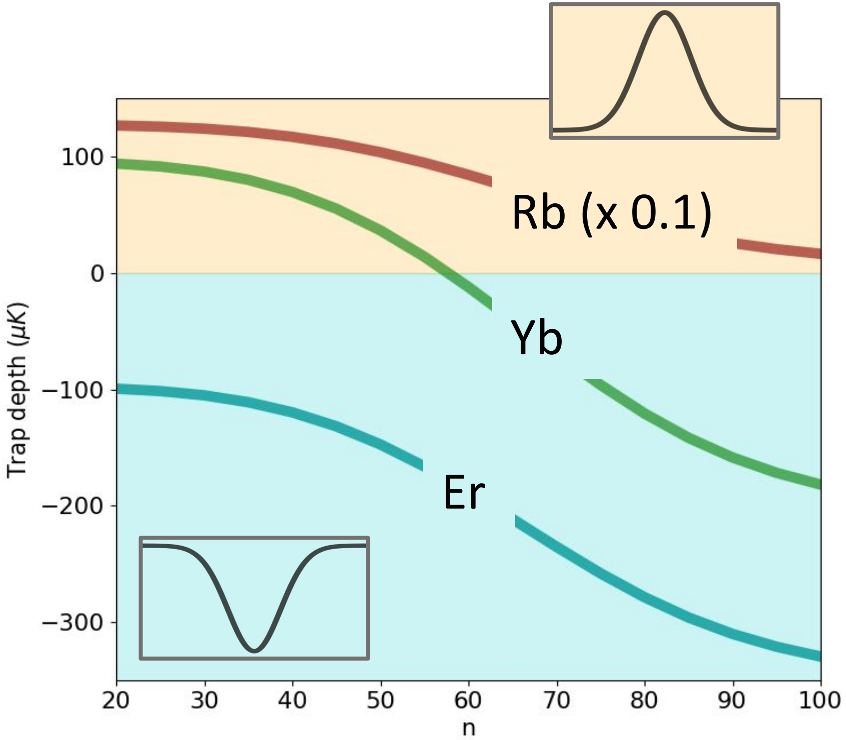
Are Rydberg atoms trappable?

- Erbium atoms has trappable core for all principal numbers





Wilson, et al., Phys. Rev. Lett. 128, 033201 (2022)

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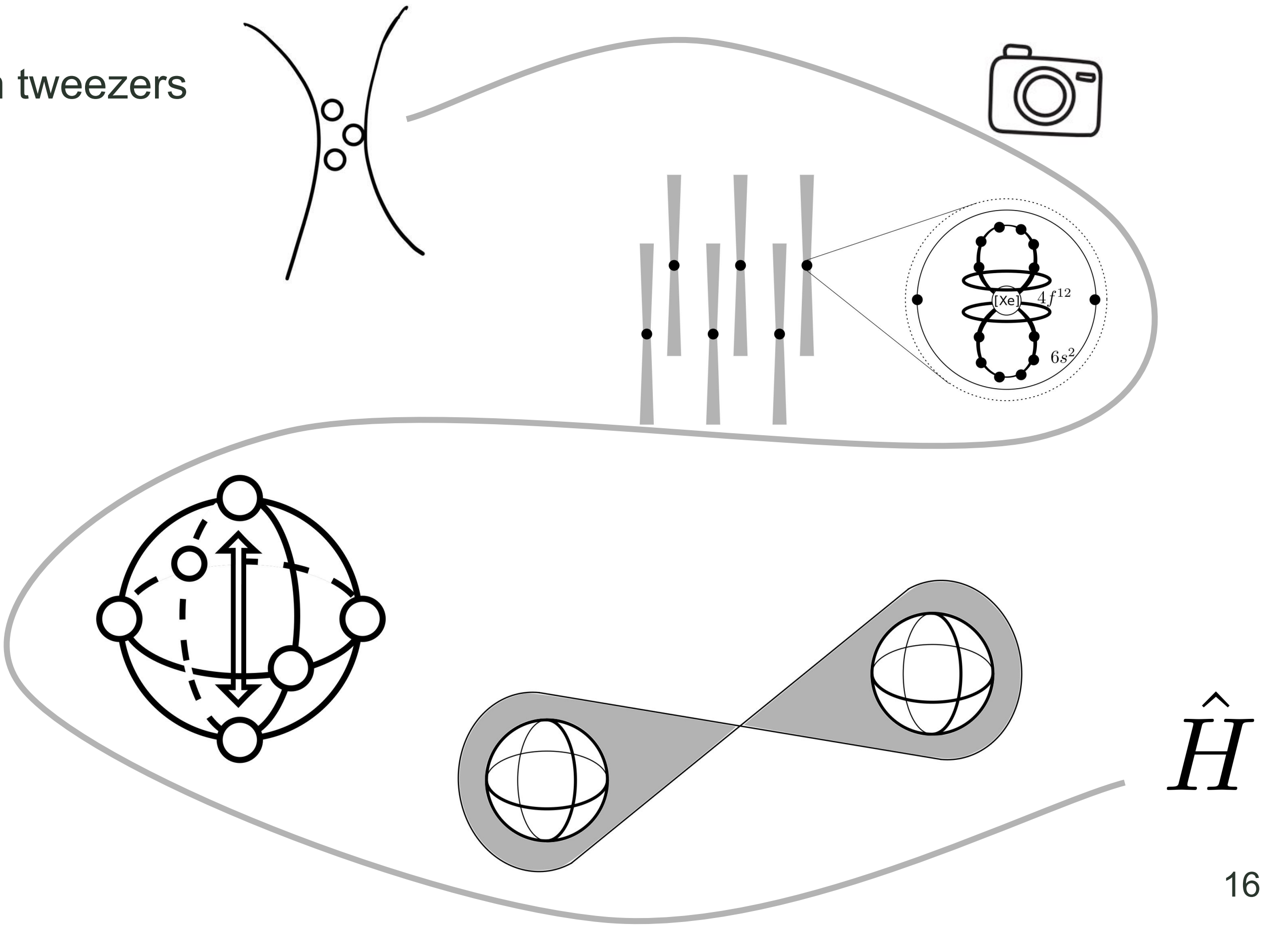
Roadmap to the goal!

Platform ingredients

- Single atoms trapped in tweezers
- Efficient imaging
  - Destructive
  - Non-destructive
- Coherent control
  - Single qubit gates
  - Two-qubit gates
- Apply all to your Hamiltonian



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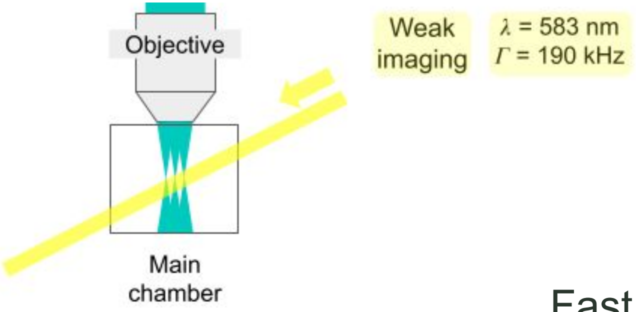
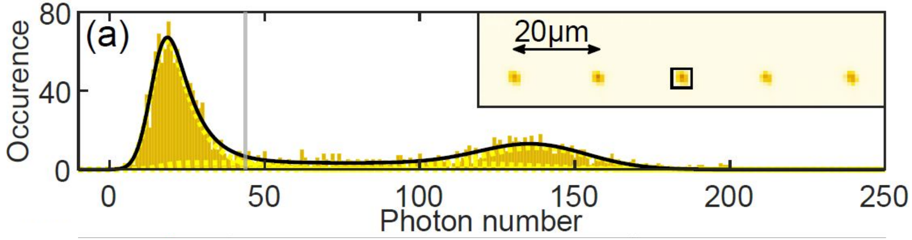
Imaging

Two types of imaging (yellow and blue)

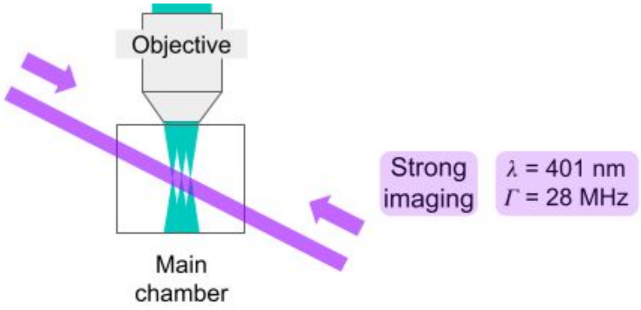
Slow imaging while trapped

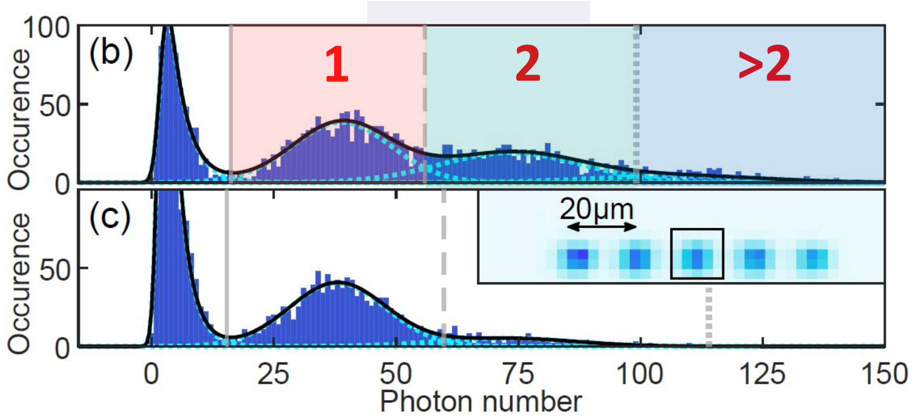




70 ms

Fast imaging in free space





30 µs

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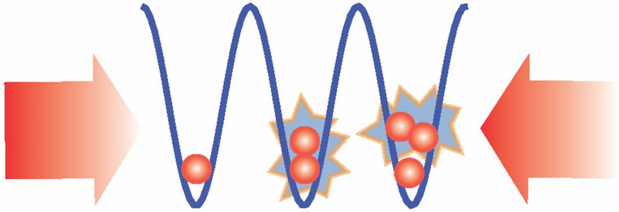
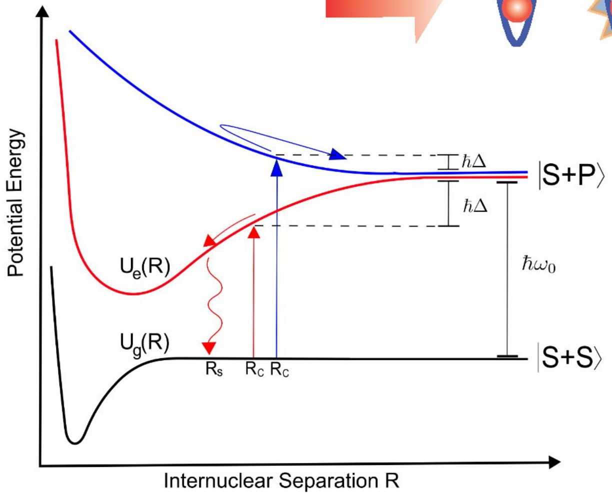
Grun, et al., PRL 133, 223402, (2024)

Light-assisted collisions in lanthanides

Can we use alkali as an example to follow?

- Loading into a tweezer is a stochastic process
- How loading happens in Alkali?
- What is a light-assisted collision?
- Which transition to use for this?





Fung et al., Technologies 4, 4 (2016)
Fuhrmanek et al. PRA 85, 062708 (2012)

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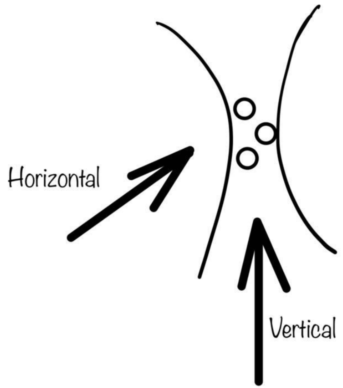
Monte Carlo model ingredients

- Study dynamics where atomic motion and internal-state changes happen on the same timescale
- What to include in the model?
  - tweezer potential
  - up to 3 atoms
  - up to 2 beams



In preparation

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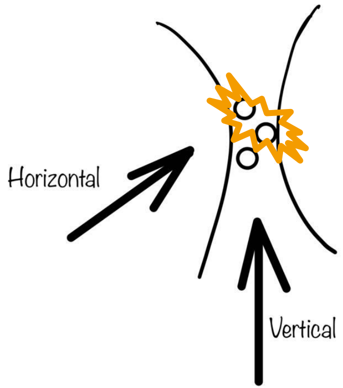
- Study dynamics where atomic motion and internal-state changes happen on the same timescale
- Which processes to include?
- Dipole-dipole interaction
    - Pair-ejection



$$V_{\text{int}}(r) = C_3/r^3$$
$$C_3 = \pm(3/4)\,\hbar\,\Gamma_{\text{L}}\ (\lambda_{\text{L}}/(2\pi))^3$$

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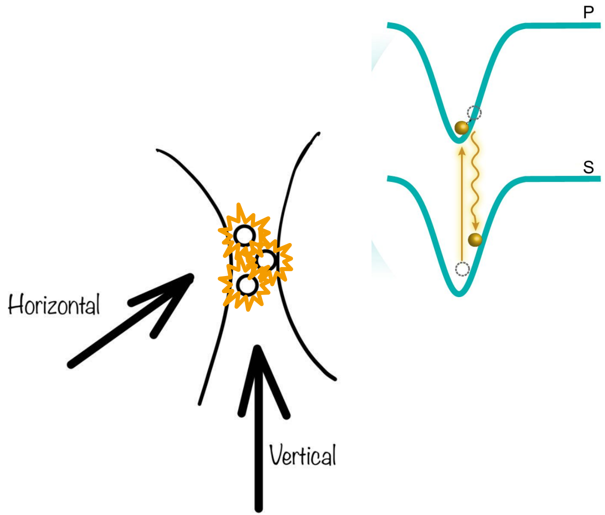
Monte Carlo model

- Study dynamics where atomic motion and internal-state changes happen on the same timescale
- Which processes to include?
- Dipole-dipole interaction
  - Pair-ejection
  - Absorption/Excitation probability
  - Recoil heating



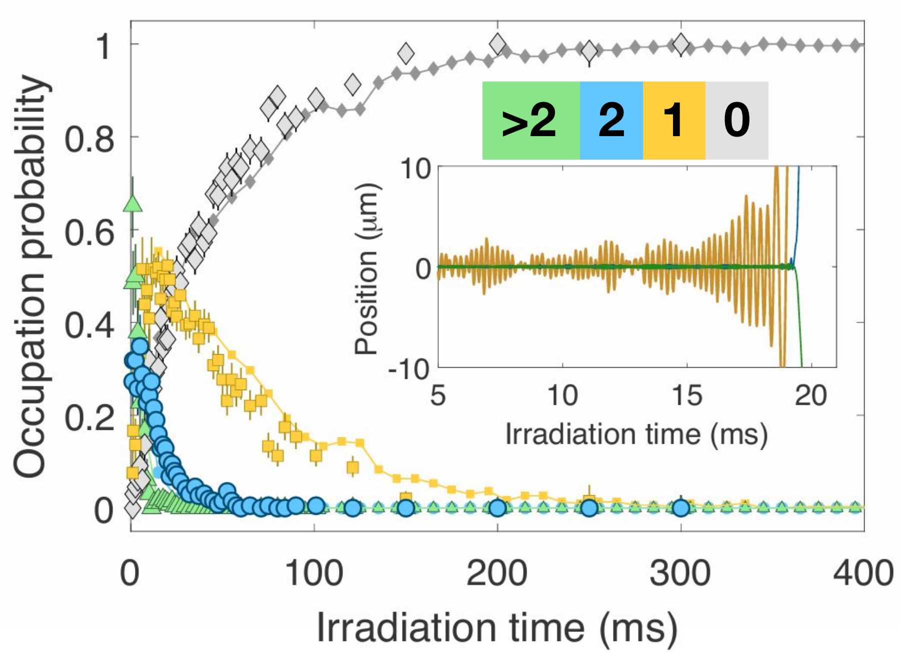
$$R_{\mathrm{scatt}}(s_{0,q},\Delta) = \frac{s_{0,q}\,\Gamma_{\mathrm{L}}/2}{1+s_{0,q}+(2\Delta_{i,q}/\Gamma_{\mathrm{L}})^2}$$

where the saturation parameter $s_{0,q} = I_q/I_{\mathrm{sat}}$

Comparison of model with experimental results

- Experimental sequence:
  - loading 3-4 atoms
  - Pulse of yellow light, variable duration
  - Ultrafast imaging
  - Analyze to find atom distribution for each experiment
- Great agreement for in-trap population
- But: after 20 ms single-atom population quickly declines

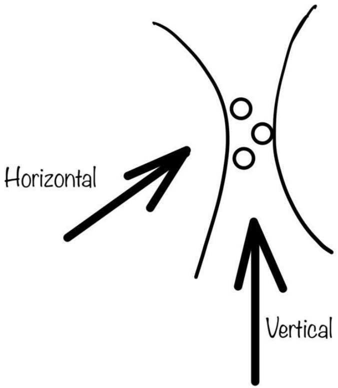
Recoil heating!!!

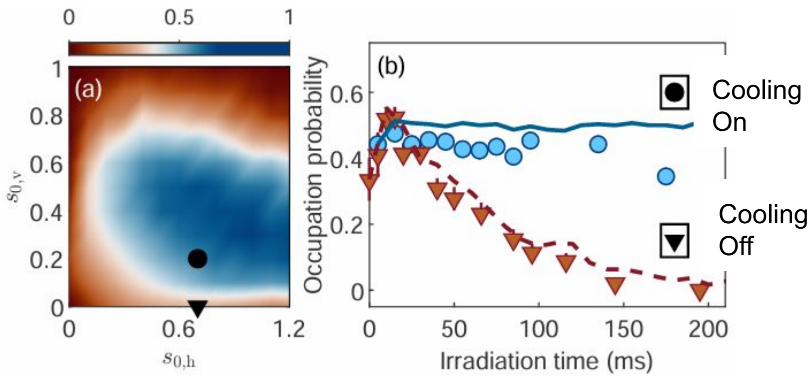


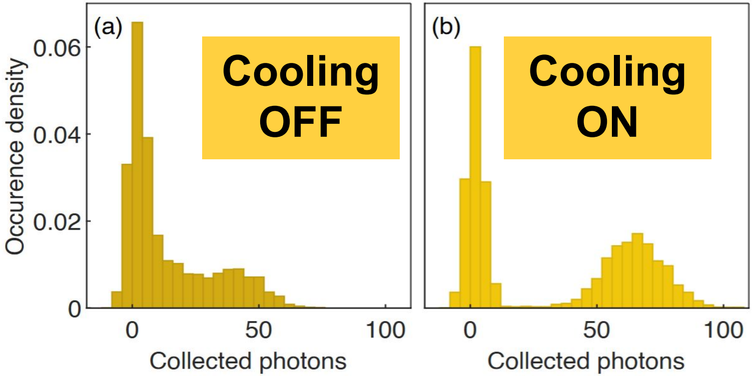
Solid Lines: parameter-free Monte Carlo simulations
Scatter: experimental points
Inset: the time-trajectory of the atom's position in the tweezer, which is spreading due to the recoil heating

Can we cool atoms down?

- Introducing the beam along vertical direction helps to improve survival probability!
- No more bridge
- Our fidelities improved
  94.1 % □ 99.96 %



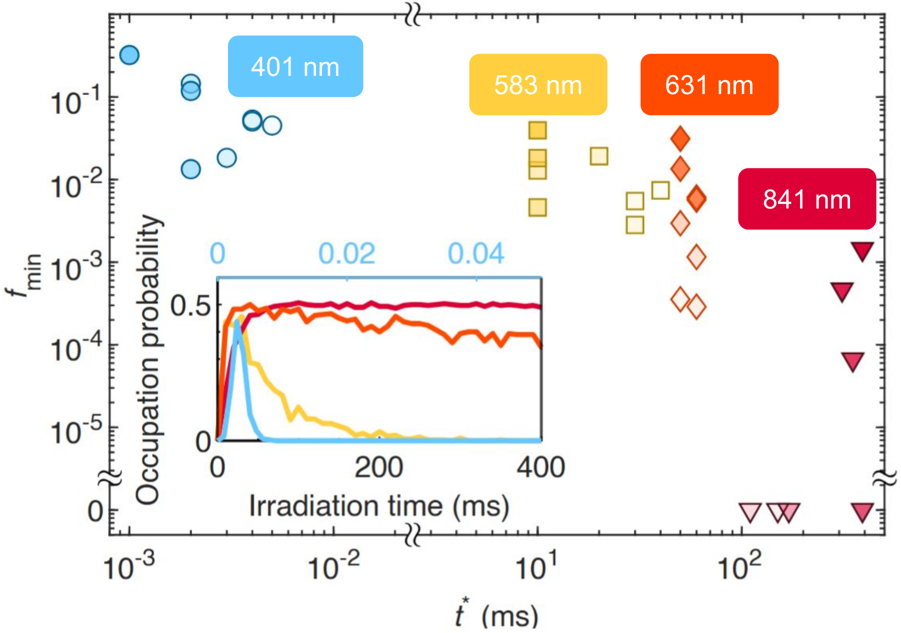




(a) Calculated two-dimensional intensity map of the product between single atom survival probability and normalized average photon scattering rate $(2/\Gamma_L)R_{scatt}$.
(b) Single-atom occupation probability vs. irradiation time.
(c)-(d) Imaging histograms

What if we use other transition?

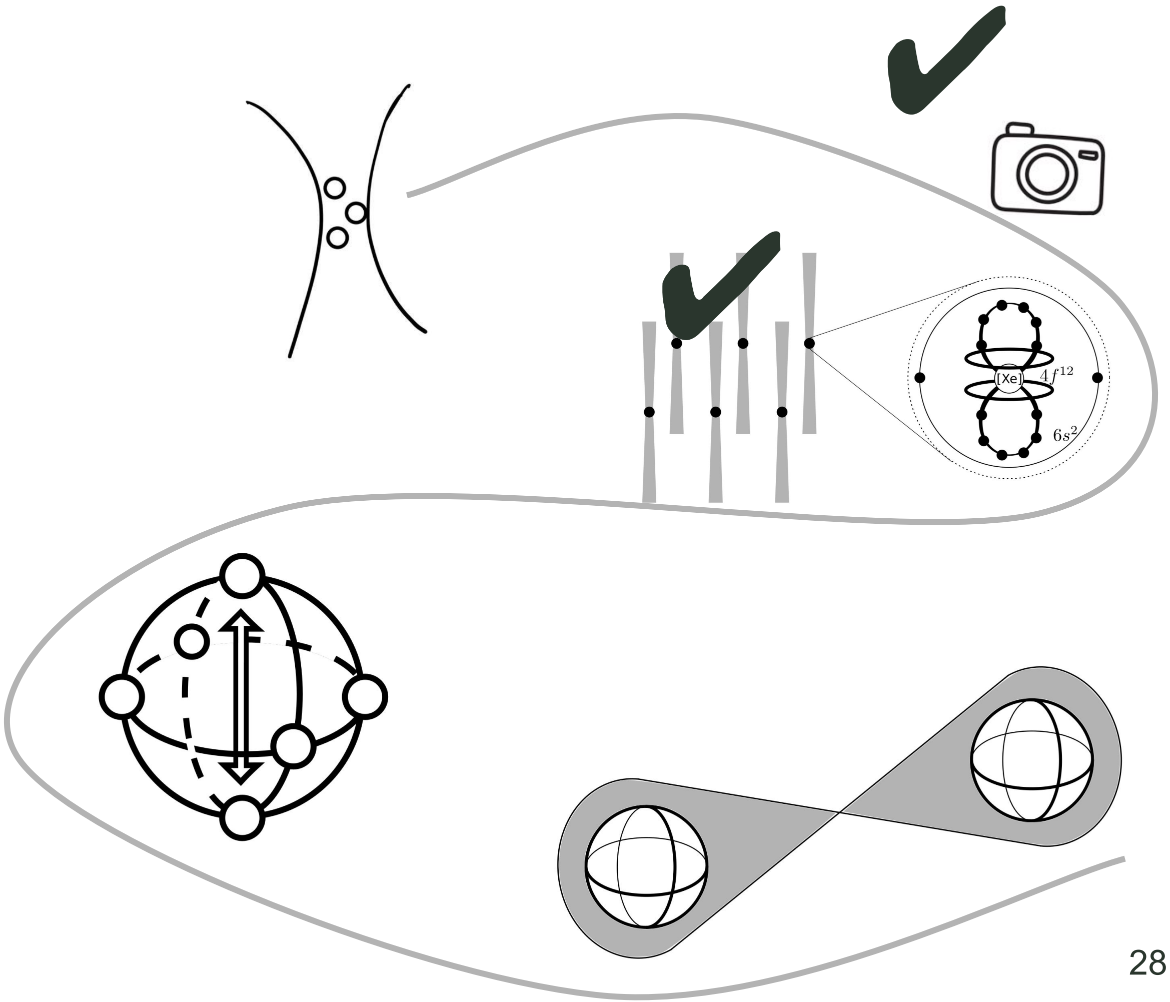
- $f(t)$ function is minimal for $P_0=P_1=0.5$ and $P_{2,3}=0$
- 401 nm transition can prepare single atoms in tweezers fast, but at the expense of lower fidelities
- 841 nm line demonstrates high fidelities at a cost of duration of LAC pulse



$$f(t) = [P_0(t) - 0.5]^2 + [P_1(t) - 0.5]^2 + P_2(t)^2 + P_3(t)^2$$

Some milestones are achieved

- Entanglement?



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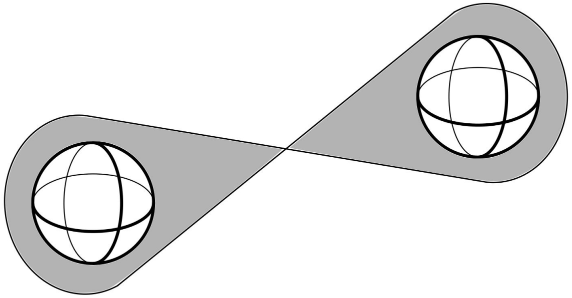
Can we just follow alkali as an example?

- Entanglement?
- Are there Ry states?
- Spectroscopy
- Is coherence preserved?
- Can we entangle two atoms?



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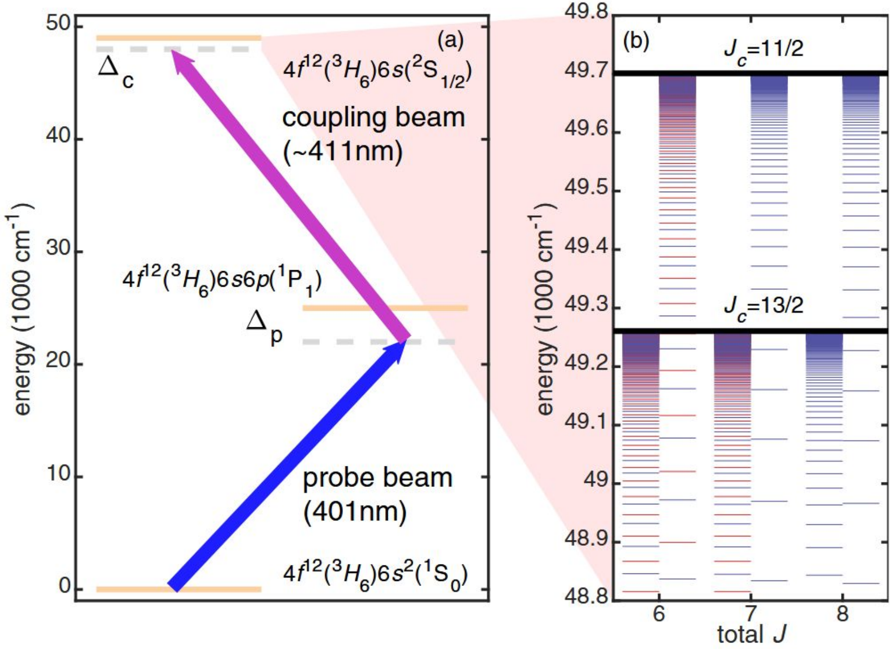
1. Motivation
2. Why Erbium?
   - Multiple transitions
   - Polarizability
3. LAC in lanthanides
   - Monte Carlo model
   - Which transition to use for LAC?
4. Rydberg states in lanthanides
   - First erbium Rydberg spectroscopy
   - Rydberg excitations in tweezers

- 500 states were assigned
  - ‘ns’ and ‘nd’ series were observed
  - principal numbers: 15 – 140
- Found coupling to ‘ng’ levels
- Zeeman spectroscopy at 10 G to assign J and g factor
- Two ionization thresholds



Trautmann, et al., PRR 3, 033165 (2021)

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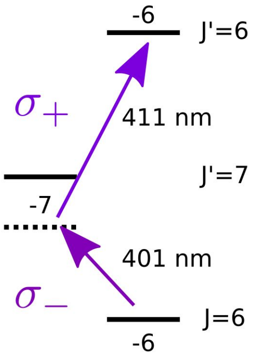
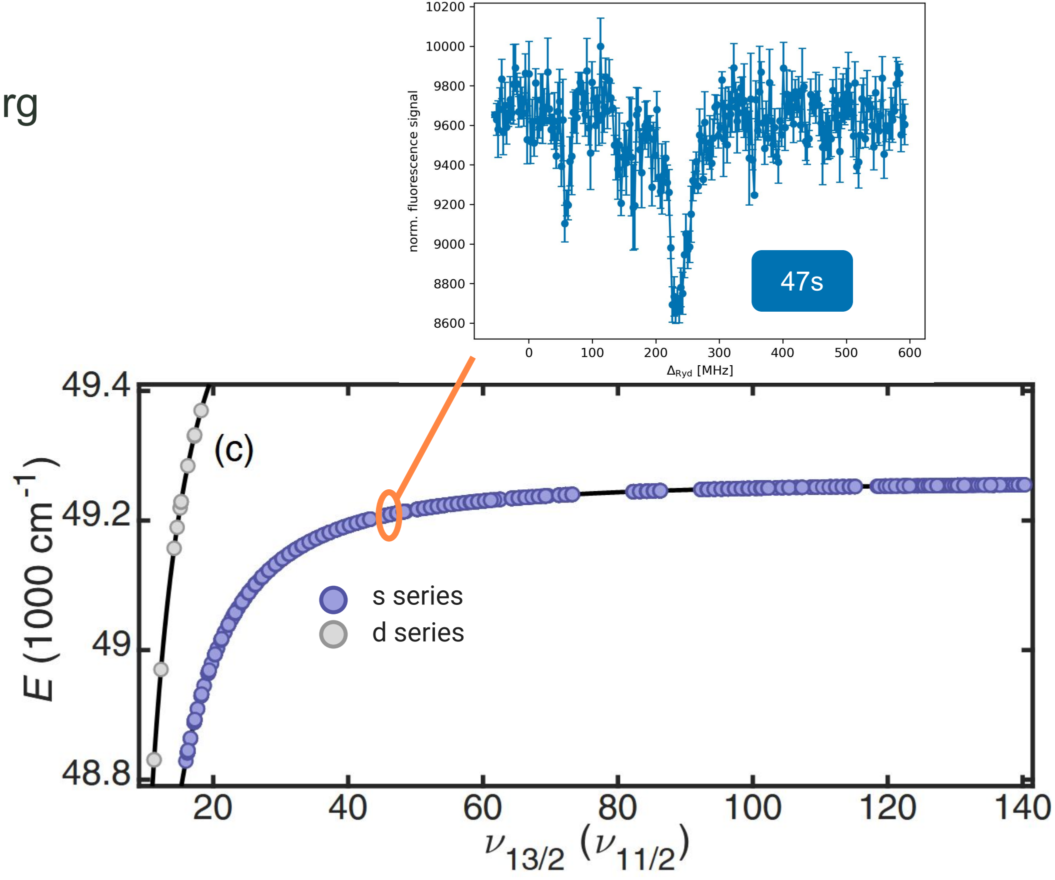
S and D series

- Well-behaved series follow Rydberg formula closely
- We re-confirm the earlier found resonances in tweezers

$$E_i = E_I - \frac{R_\mu}{(n-\mu_i)^2}$$





Trautmann, et al., PRR 3, 033165 (2021)

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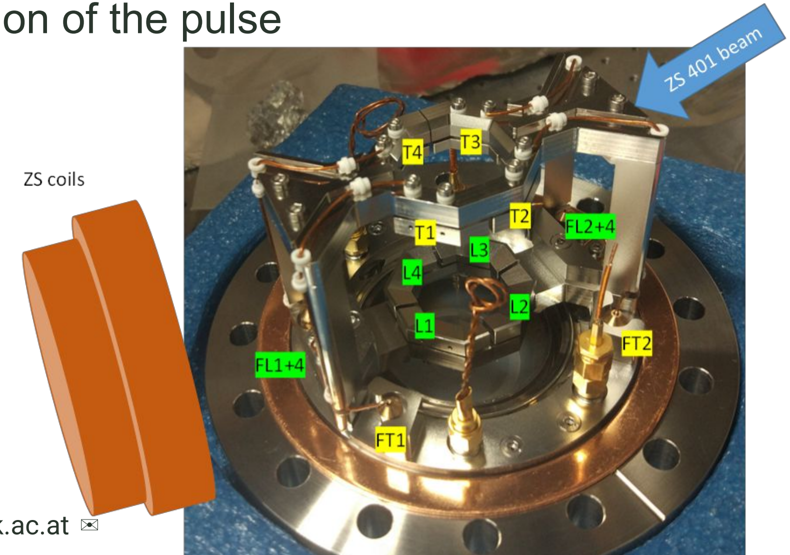
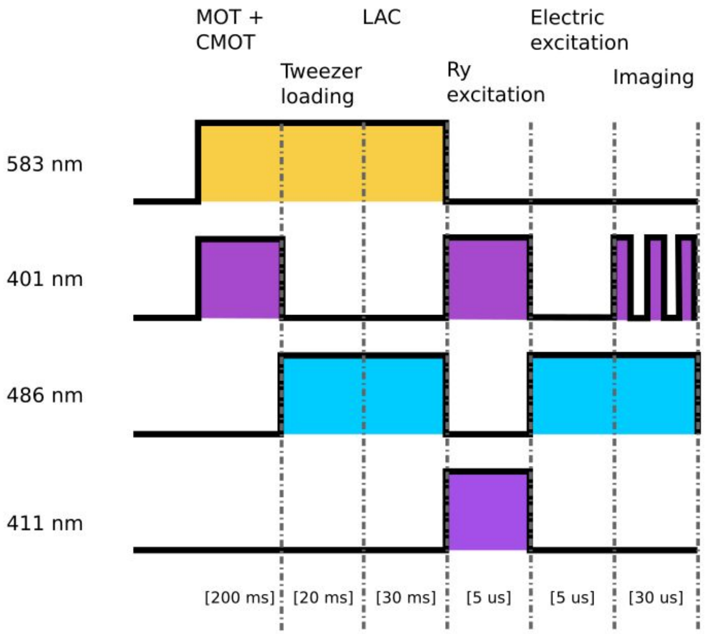
Pulse sequence

- We cool atoms with yellow light
- We switch high electric field applied to in-vacuum installed electrodes
- We switch tweezer light-off for the duration of the pulse





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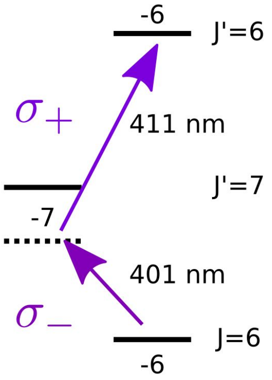
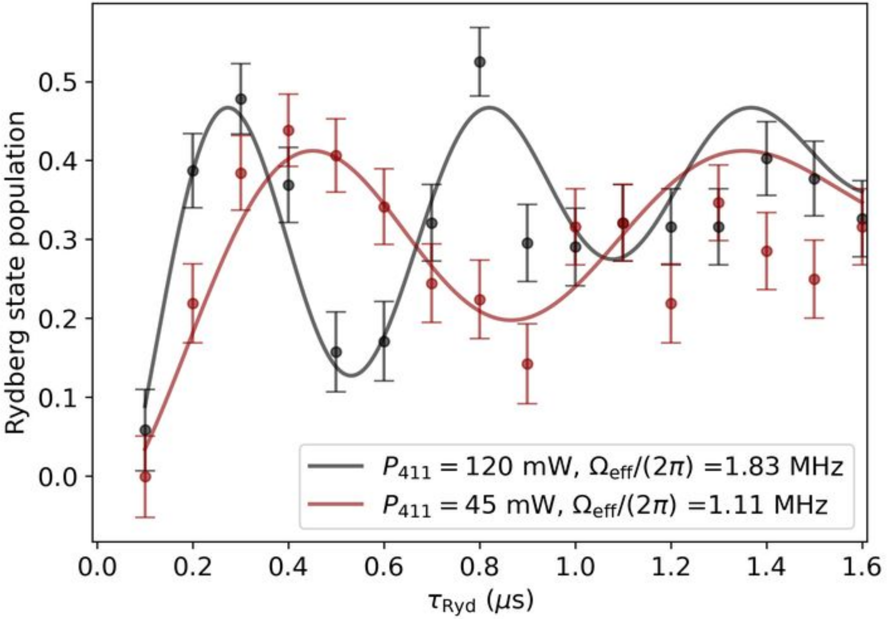
Rabi oscillations

- We see coherent oscillations between ground and excited states
- Estimated effective Rabi frequencies allow us to start probing the 'second' photon transition





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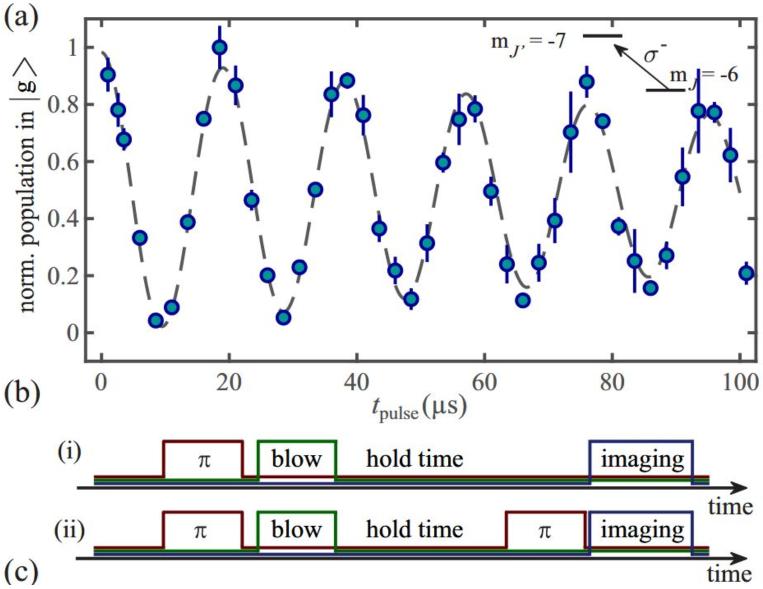
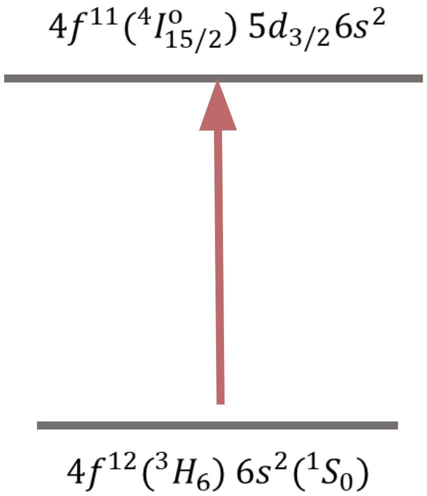
- Clock transition





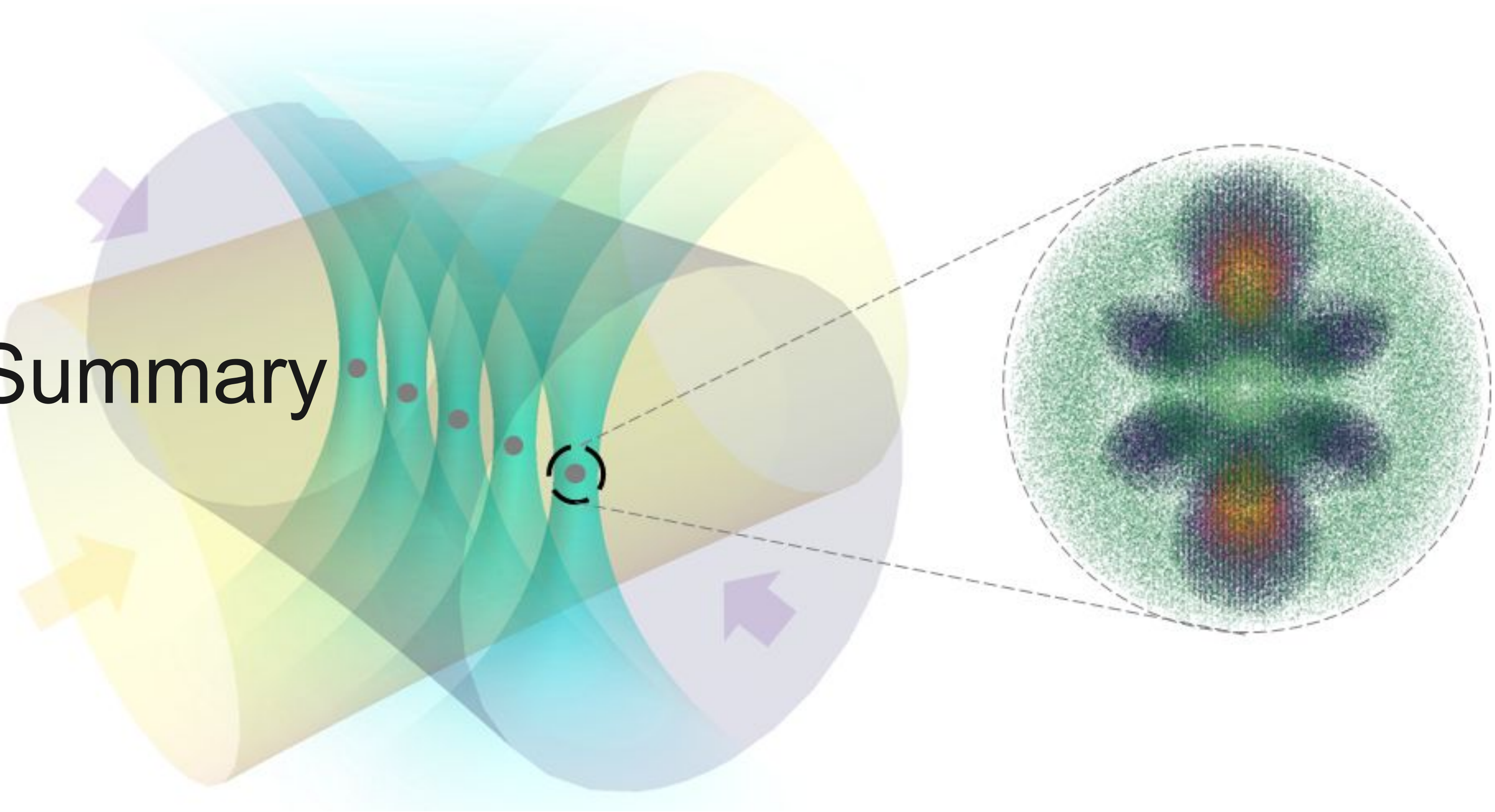
State shelving
Spin manipulation

$\lambda = 1299$ nm
$\Gamma/2\pi \sim 1$ Hz

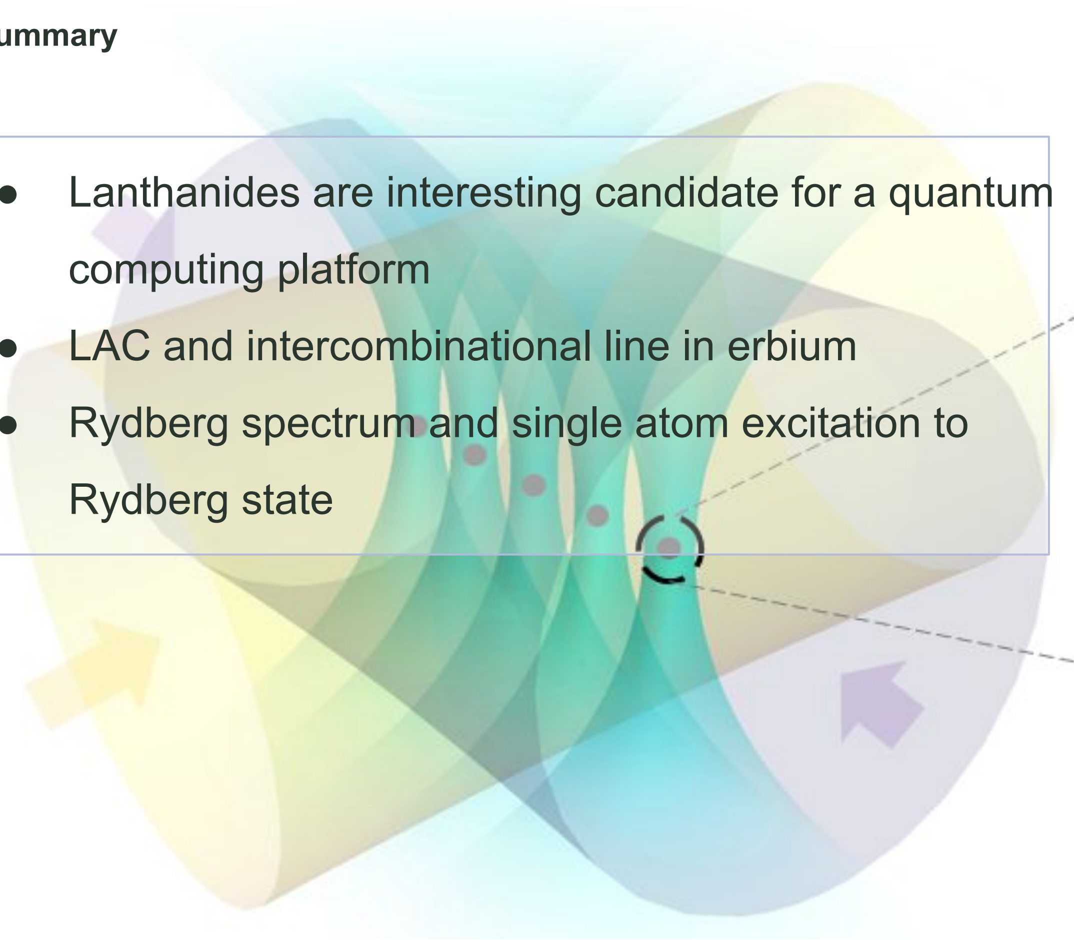
$\Delta J = +1$

Patscheider ..Ferlaino Phys. Rev. Res. 3, 033256 (2021)
Claude … Mark, Ferlaino, Phys. Rev. Res. 6, L042016 (2024)

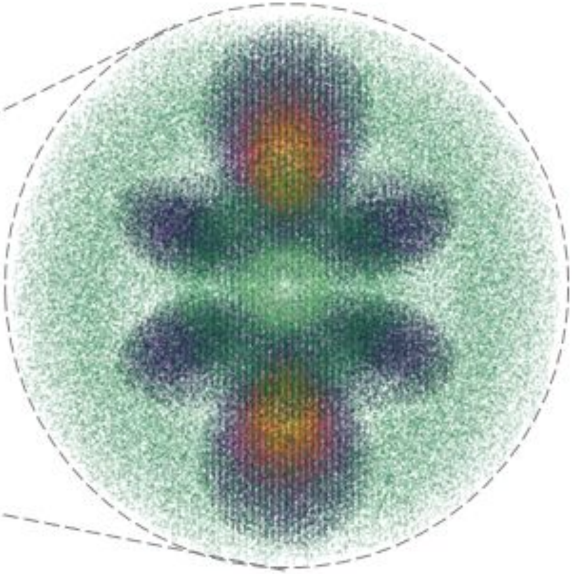
Summary



Summary



- Lanthanides are interesting candidate for a quantum computing platform
- LAC and intercombinational line in erbium
- Rydberg spectrum and single atom excitation to Rydberg state



Thank you

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L.B. Giacomelli

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