Title: Coherent Light Shift of Alkaline-Earth Rydberg Atoms

Speakers: Patrick Cheinet

Collection: Cold Atom Molecule Interactions (CATMIN)

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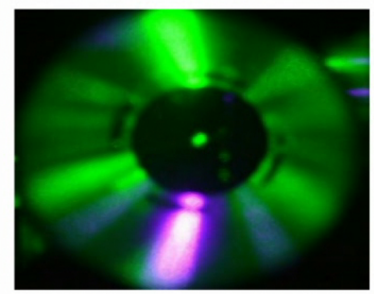
Coherent Light Shift on Alkaline-Earth Rydberg Atoms
Isolated Core Excitation without Auto-Ionization

K.-L. Pham, P. Pillet, T. F. Gallagher*, S. Lepoutre, P. Cheinet

Laboratoire Aime Cotton, CNRS, Universite Paris-Saclay, France
* Physics Department, University of Virginia, USA

K.-L. Pham et al., PRX Quantum **3**, 020327 (2022)



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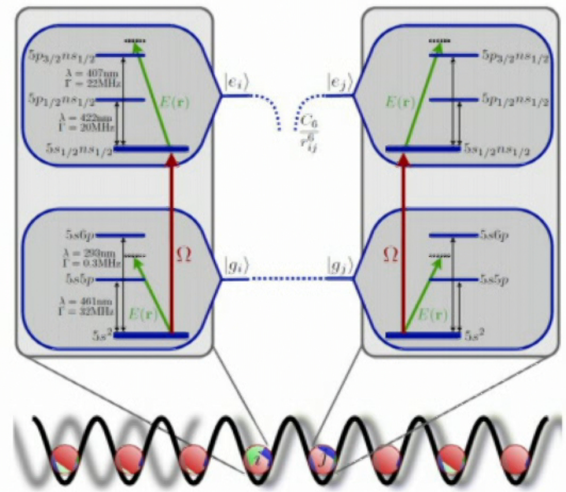
Motivations

- **Quantum simulation with cold alkali Rydberg atoms**
  Browaeys, Lukin, …

- **Towards divalent or multivalent atoms…**
  Sr : Kaufman (JILA) Jones, Adams (Durham)
  Endres (CalTech) Brune (LKB, Paris)
  Whitlock (Strasbourg) Weidemüller (Singapour)
  …
  Yb : Cheinet (LAC, Orsay) Thompson (Princeton)
  Er : Ferlaino (Innsbruck)
  …

- **But auto-ionization**
  H. Lehec et al., Phys. Rev. A **103**, 022806 (2021)



R. Mukherjee et al.
J. Phys B **44**, 184010 (2011)

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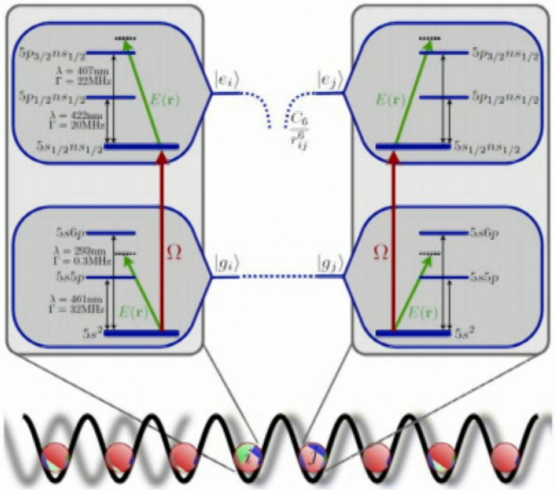

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New possibilities of divalent atoms ?

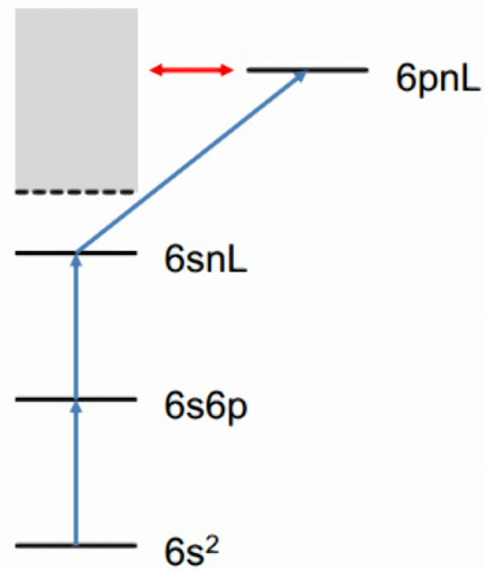
ICE : Isolated Core Excitation

- **Imaging or cooling with the core transition?**
  Close to resonance ➡ Auto-ionization!
  (doubly excited state lifetime = ps)

  McQuillen et al. PRA **87**, 013407 (2013)
  Lochead et al. PRA **87**, 053409 (2013)

  Possible solution : high enough orbital momentum L
  H. Lehec et al., Phys. Rev. A **103**, 022806 (2021)

  Circular states:
  R. C. Teixeira et al., PRL **125**, 263001 (2020)
  A. Muni et al., Nat. Phys. **18**, 502 (2022)



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New possibilities of divalent atoms ?

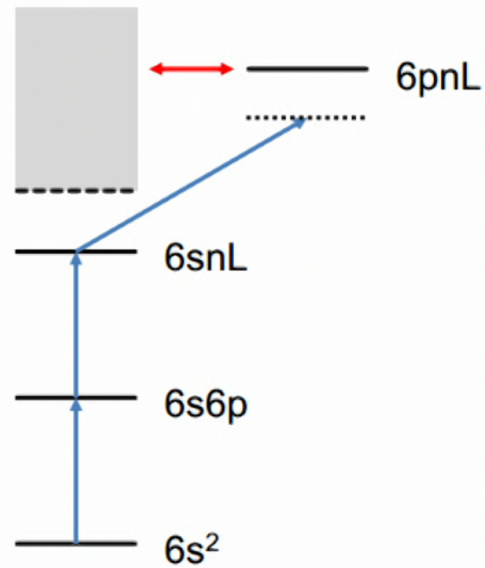
ICE : Isolated Core Excitation

- **Dipole traps / coherent shifts ?**

Far from resonance ➡ Any L possible?

R. Mukherjee et al. J. Phys B **44**, 184010 (2011)

Auto-ionization replaces spontaneous emission as leading decoherence process
Far off-resonance implies small auto-ionization…
but larger power implies possible photo-ionization



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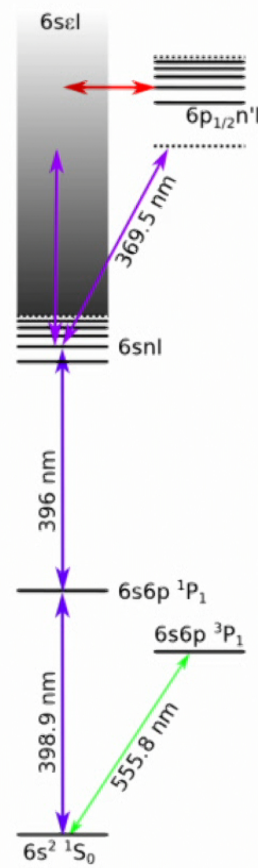
New possibilities of divalent atoms ?

ICE : Isolated Core Excitation

- **Dipole traps / coherent shifts ?**

Far from resonance ➡ Any L possible?
Structure with $6p_{1/2}n'l$ series?
To be studied…



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New possibilities of divalent atoms ?

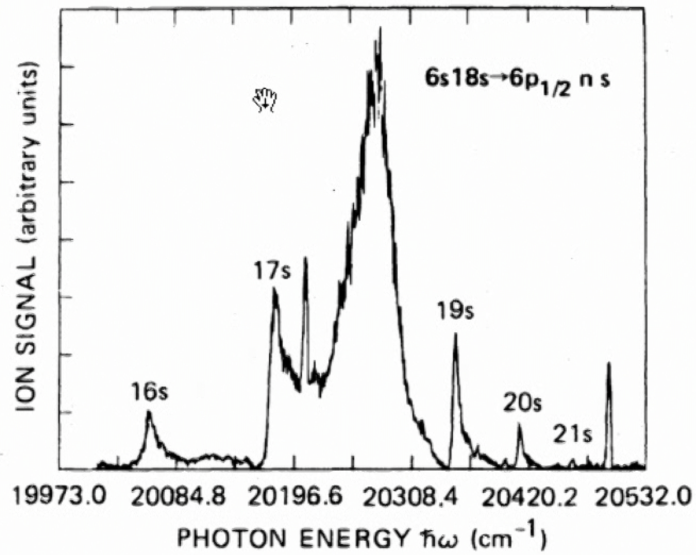
ICE : Isolated Core Excitation

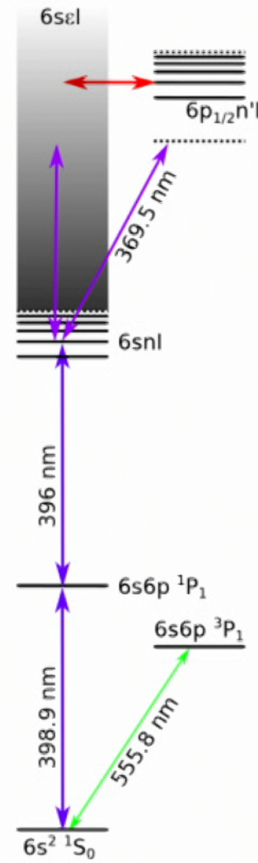
- **Dipole traps / coherent shifts ?**

Far from resonance ➡ Any L possible?
Structure with $6p_{1/2}n'l$ series?

YES !

in Ba : Tran et al.
PRA **26**, 3016 (1982)





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Low-L states, dipole trap?

- **Unforeseen risk**
  need to avoid auto-ionization resonances
  depend on chosen n and quantum defect δ_L

- **New idea**
  Use the interference related auto-ionization zeros

  closer to resonance ➡ less power needed
  less photo-ionization

  But is the auto-ionization reduced enough?
  Is the light shift sufficient?

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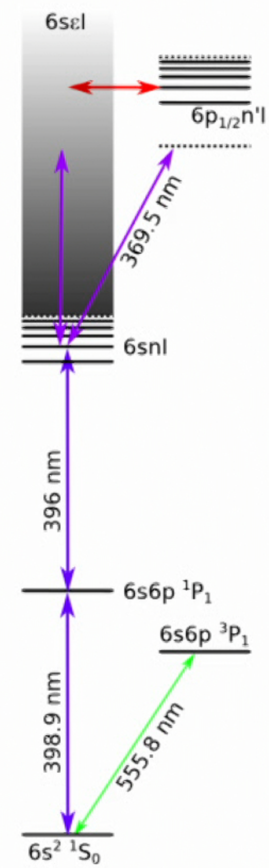
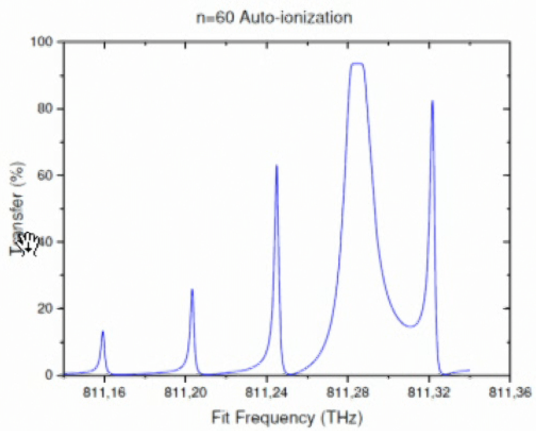


Auto-ionization spectrum

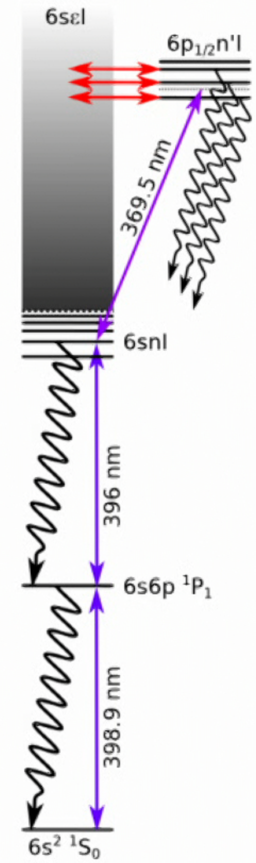
- **Theory**
  2-channel Multi-channel Quantum Defect Theory (MQDT)

$$\sigma \propto \nu'^3 \frac{R^2(1+\tan^2[\pi(\nu'+\delta')])}{R^4+\tan^2[\pi(\nu'+\delta')]} \left[\frac{\sin(\pi(\nu'-\nu))}{\pi(\nu'-\nu)}\right]^2$$



OBE also predict
Auto-ionization zeros…
And a sizable shift !

Optical Bloch Equations in Liouville formalism



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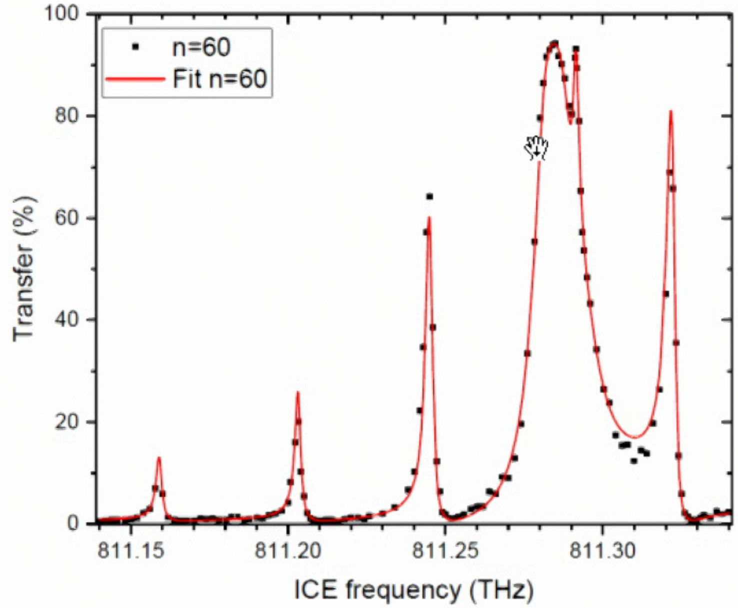
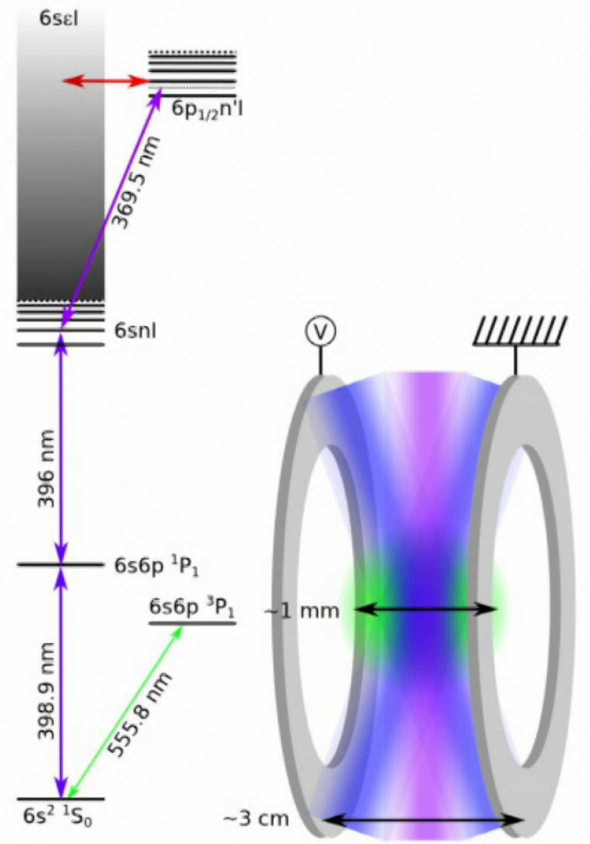
Auto-ionization spectrum

- **Results on ytterbium 6sns $^1S_0$**
  ~ 40 mW at 369.5 nm
  1 μs pulse, after Rydberg excitation
  scan 369.5 nm frequency





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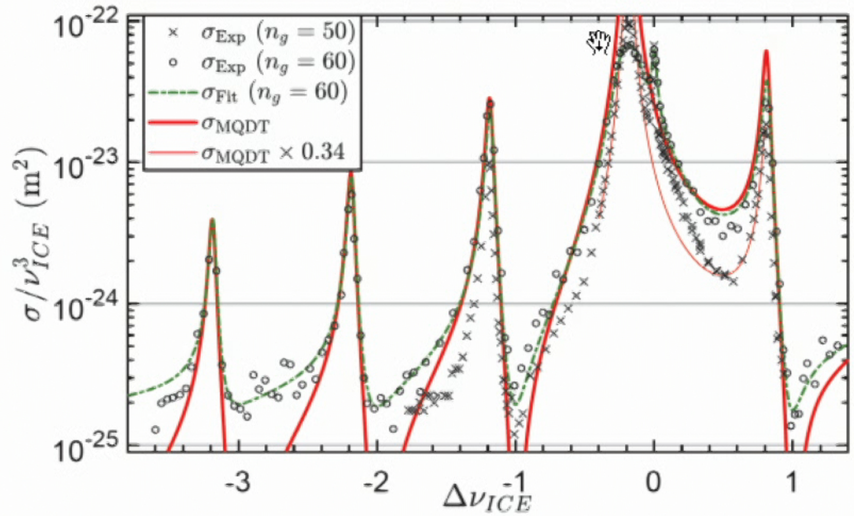
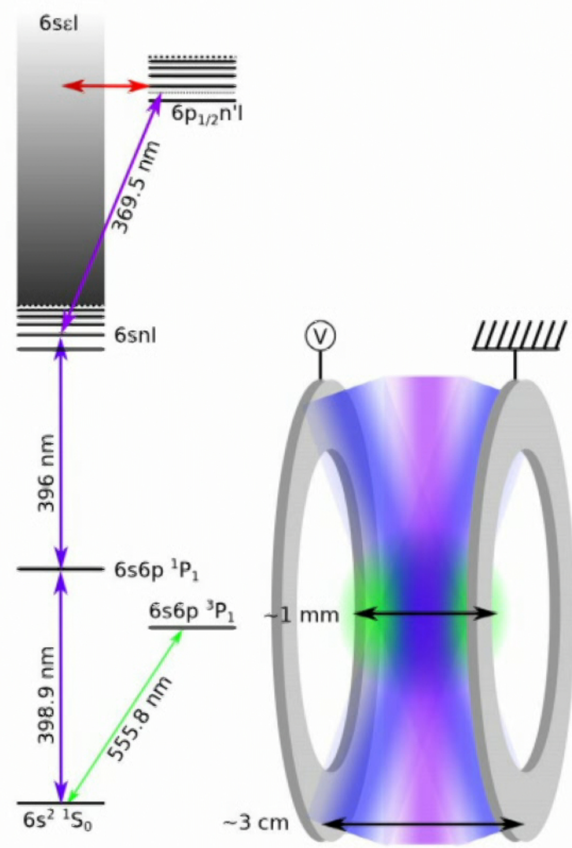
Auto-ionization cross-section

- **Extracting the auto-ionization cross-section**

$$\sigma \propto \nu'^3 \frac{R^2(1+\tan^2[\pi(\nu'+\delta')])}{R^4+\tan^2[\pi(\nu'+\delta')]}\left[\frac{\sin(\pi(\nu'-\nu))}{\pi(\nu'-\nu)}\right]^2$$

Universal law (independent of n) for : $\sigma/\nu'^3 = f(\nu'-\nu)$





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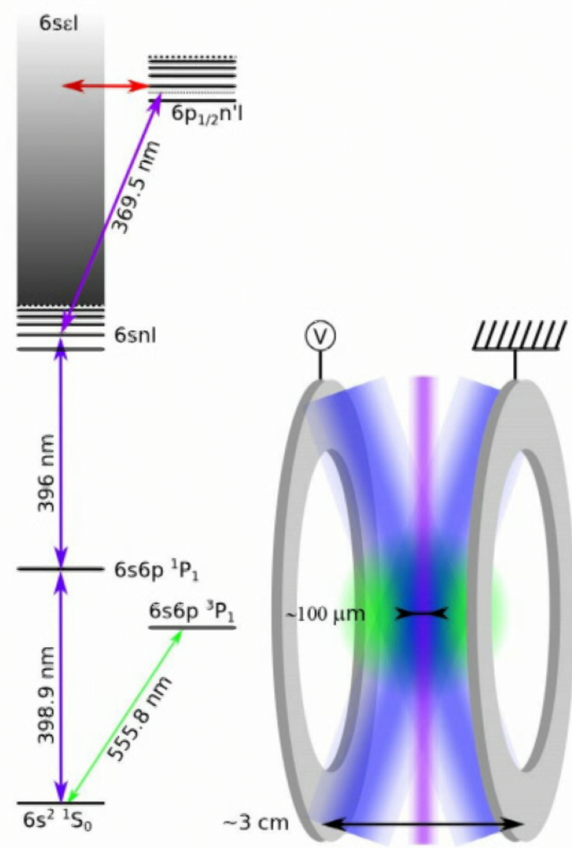
Induced shift

- **Expected light shift:**

$$\frac{\Delta E}{I} = P\int_0^{+\infty} \frac{\sigma\, dE'}{2\pi\, \omega_{ICE}\, (E_{ICE} - E')}$$

- **Observing the Light Shift**
  Observing the shift spectroscopically
  Focus ICE to 100 μm radius, simultaneous pulses

- **Different signals depending on auto-ionization**
  Strong AI: shifted atoms appear as ions
  Negligible AI: compare Rydberg signal with and without ICE light



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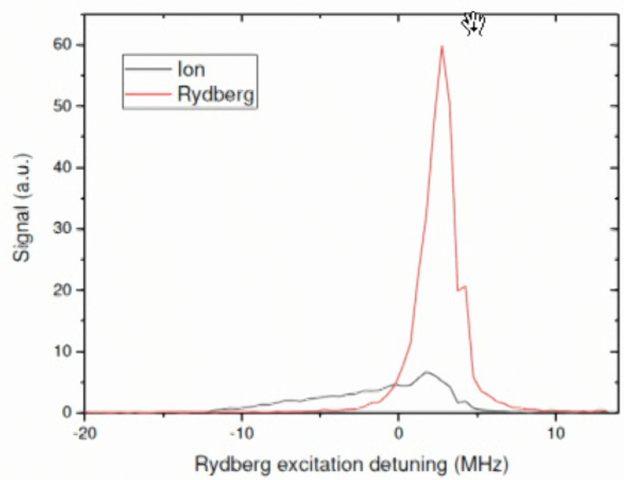
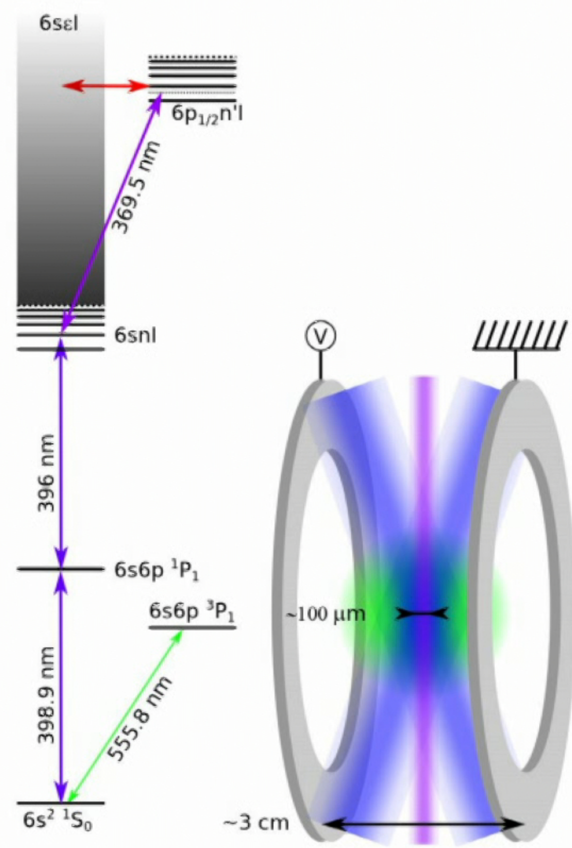
Induced shift

- **Strong autoionization**
- **Observing the Light Shift, red detuning**
  Observing the shift spectroscopically
  Focus ICE to 100 µm, simultaneous 4 µs pulses

n=50, ≈ -12 GHz ➡ Expected shift : ~10 MHz

$\Delta\nu_{ICE} \approx -0{,}35$





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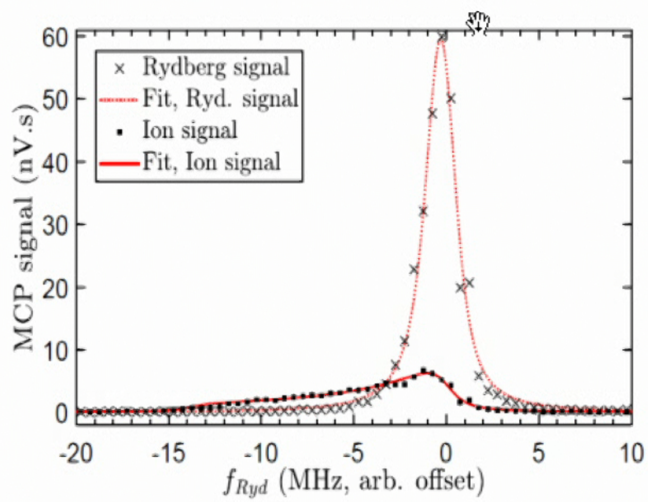
Induced shift

- **Strong autoionization**
- **Extracting the shift**

  Fitting with rate equation model…
  for Rydberg excitation and following ionization

  Expected shift : ~10 MHz
  Extracted shift : ~12 MHz



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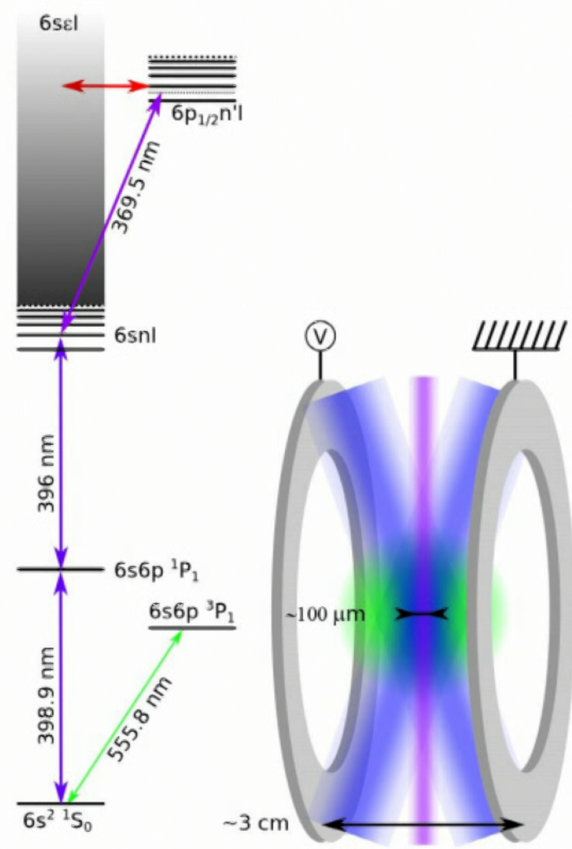
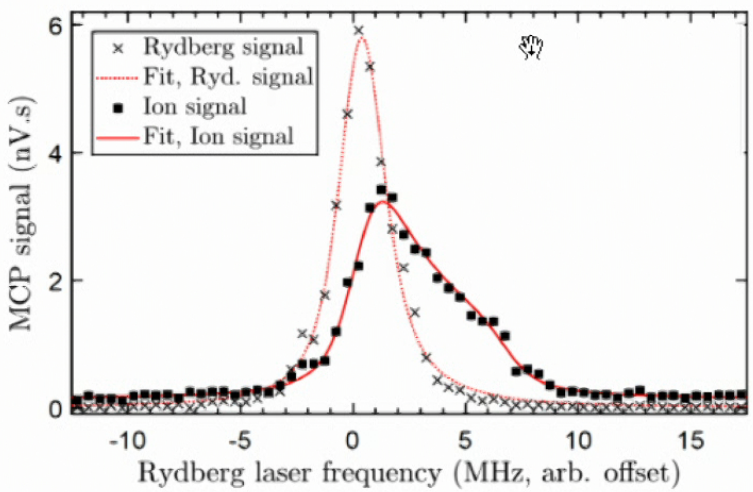


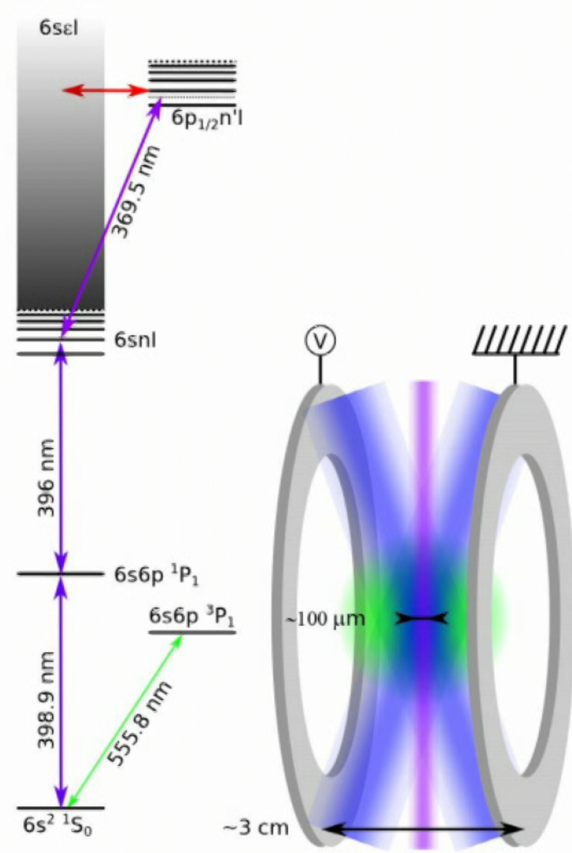
Induced shift

- **Strong autoionization**
- **Observing the Light Shift, blue detuning**
  Observing the shift spectroscopically

n=72, ≈ +7 GHz ➡ Expected shift : ~12 MHz

$\Delta\nu_{ICE} \approx 0{,}17$ Extracted shift : ~7 MHz





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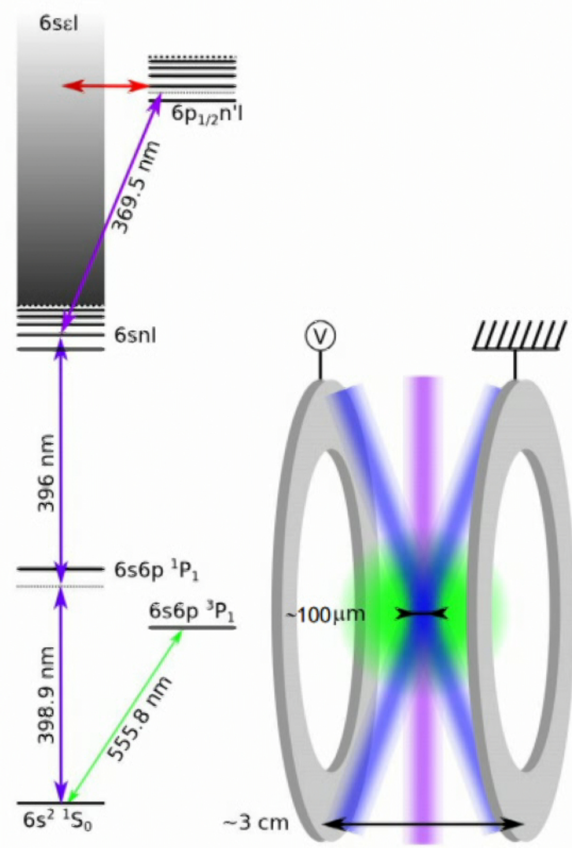
Induced shift

- **Negligible autoionization**
- **Observing the Light Shift, red detuning**
  Observing the shift spectroscopically
  Compare with and without ICE (6 µs)
  Check for residual ions



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Induced shift

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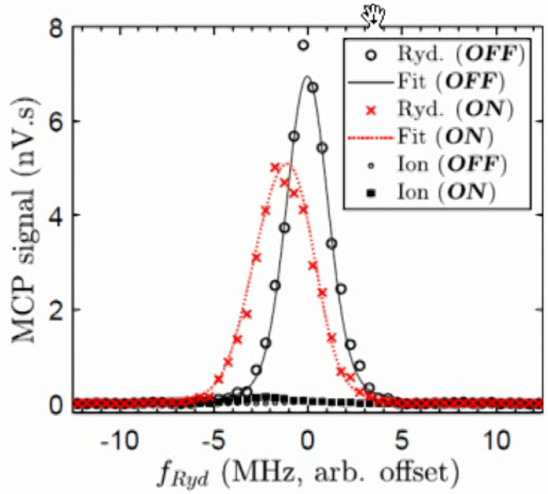
n=72, ~ -18 GHz ➡ Expected shift : ~3 MHz

First red zero

Residual ions: 2%



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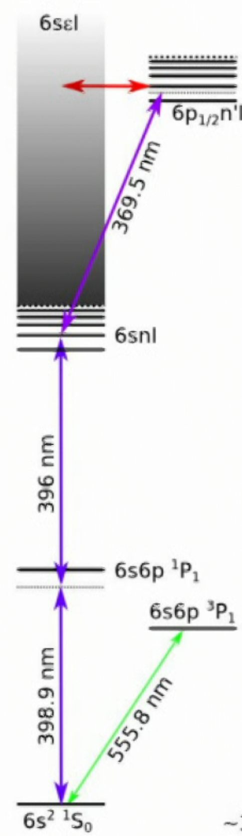
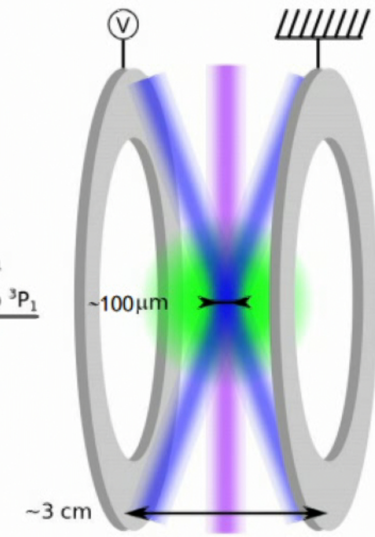




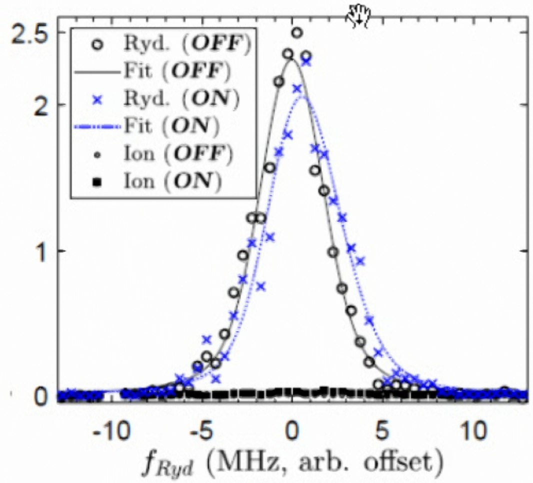
Induced shift

- **Negligible autoionization**
- **Observing the Light Shift, blue detuning**
  Observing the shift spectroscopically
  Compare with and without ICE (6 μs)
  Check for residual ions

n=72, ~ 24 GHz ➡ Expected shift : ~3 MHz

First blue zero

Residual ions: <0,5 %



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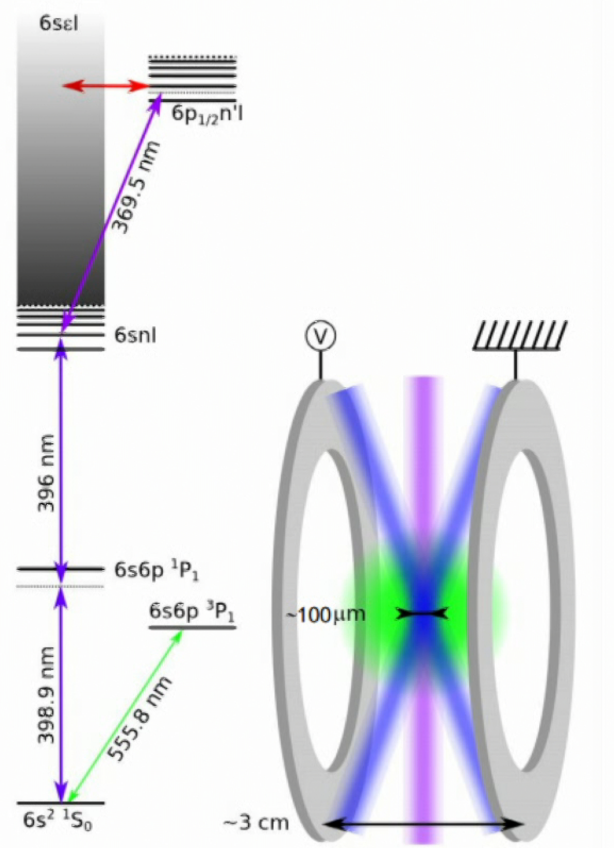


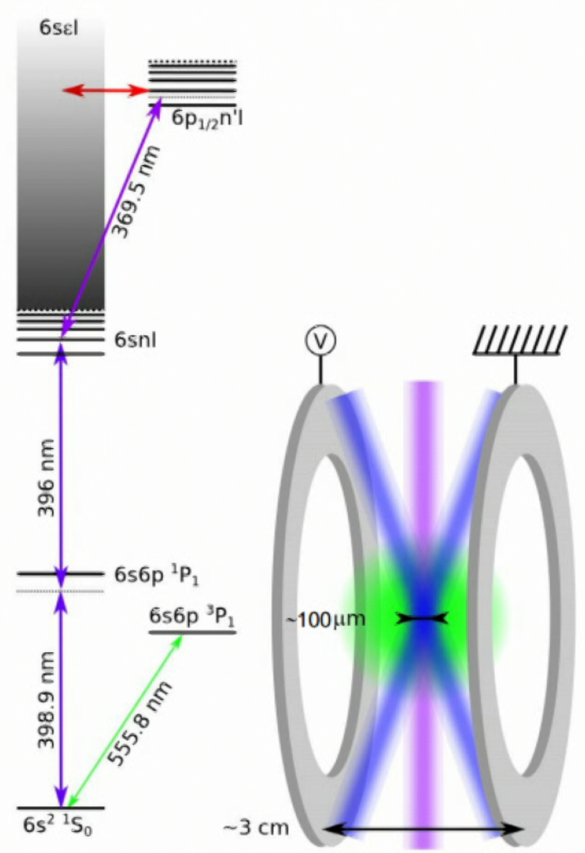
Induced shift

- **Negligible autoionization**
- **Observing the Light Shift, blue detuning**

  Observing the shift spectroscopically
  Compare with and without ICE (6 µs)
  Check for residual ions

  Trap depth of 3 MHz ≈ 300 µK
  Residual ions: <0,5%
  Lifetime > 1 ms > Rydberg lifetime
  Estimation limited by our experiment

  What is the real limit?
  Possibility to improve (if needed): next zeros?



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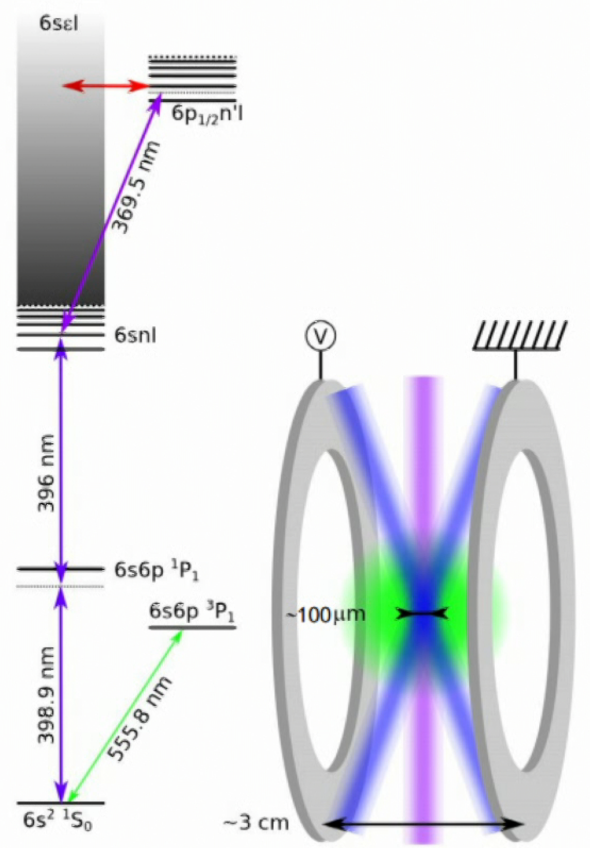

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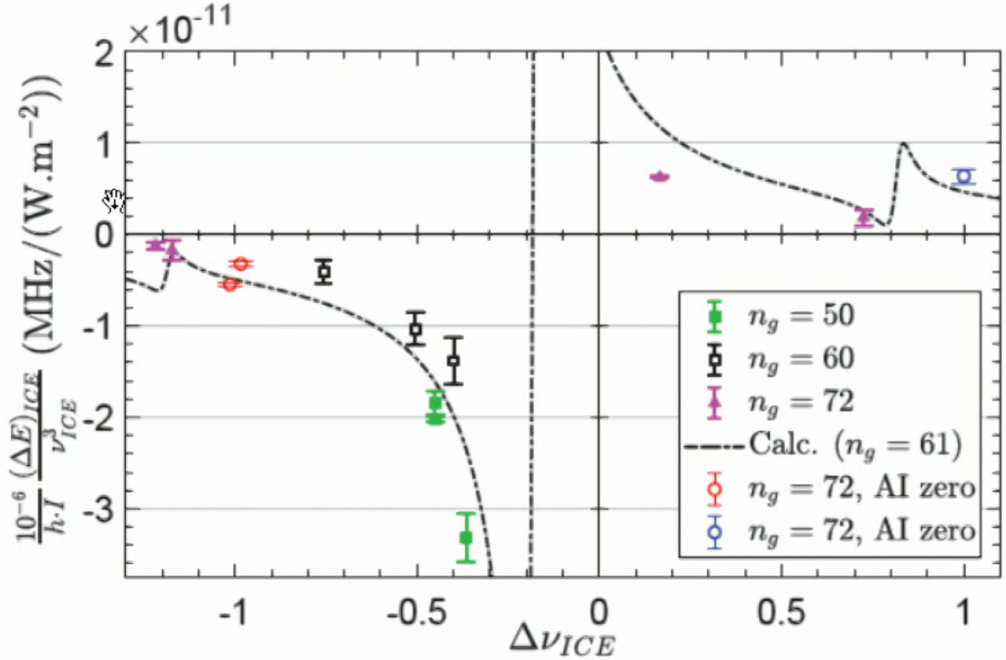
Induced shift

- **Light shift as a function of the detuning**

Universal law for $\frac{\Delta E}{I\,\nu'^3} = f(\nu' - \nu)$

Study for various n
and various detunings:

Very good agreement



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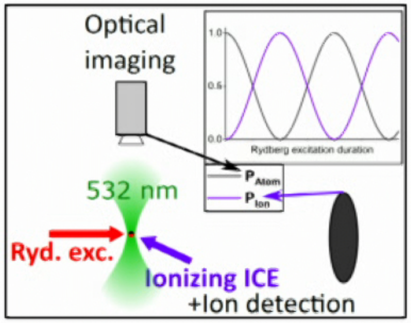
Perspectives

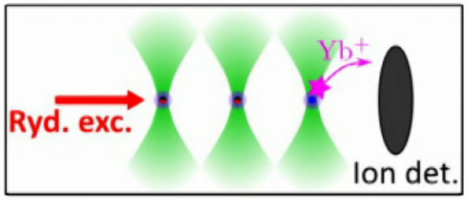
- **Joint detection**

  ➡ Improve detection fidelity



- **On purpose ionization**

  ➡ herald success or failure



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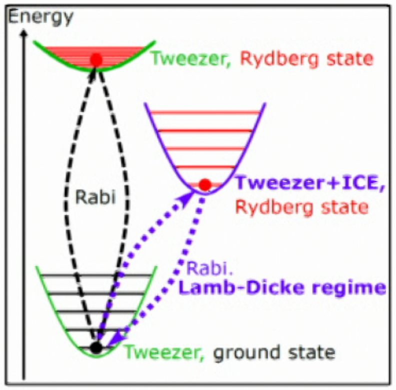
Perspectives

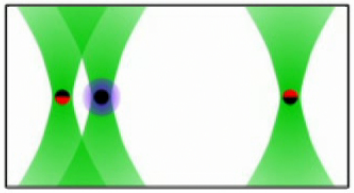
- **Trapping**

  ➡ Reach magic condition

- **Local addressing**

  ➡ Shifting of sites on- or off-resonance





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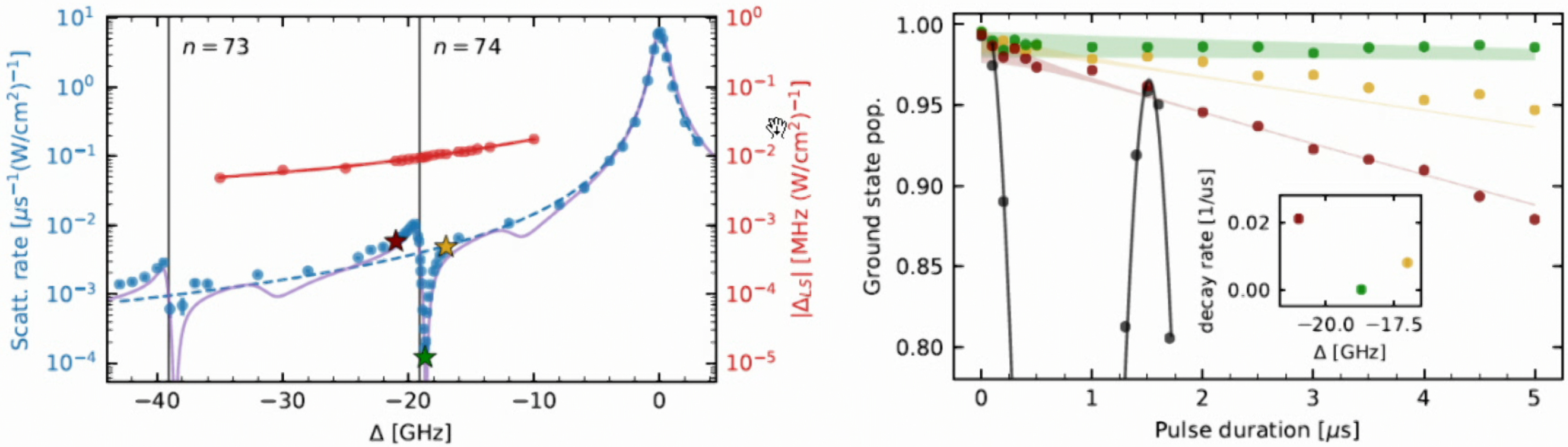
Perspectives

- **Recent use, from ytterbium $^3S_1$ states:**

  Burgers et al., PRX Quantum **3**, 020326 (2022)
  Shifting Rydberg excitation Rabi oscillation out of resonance:



(J. D. Thompson team, Princeton)

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