Testing atomic QED theory with metastable helium Bose-Einstein condensates

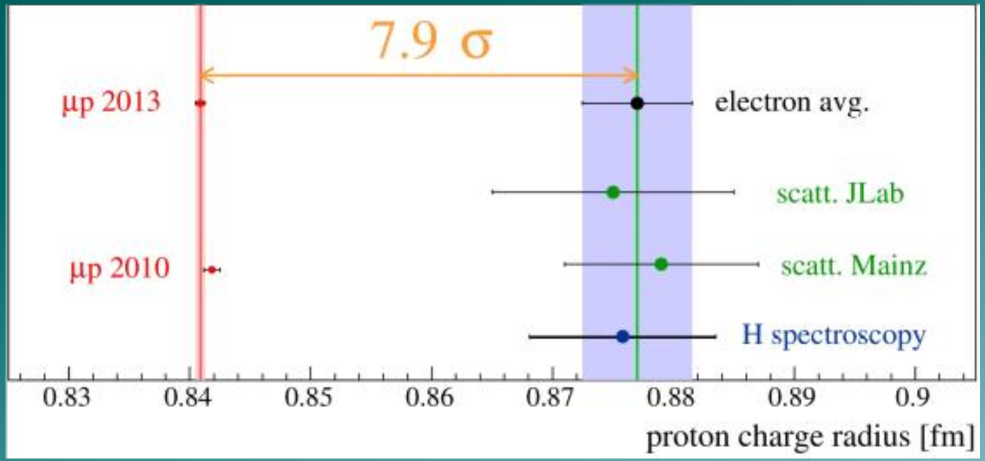
Sean Hodgman

Australian National University

He BEC group, DQST, RSPhys, ANU*

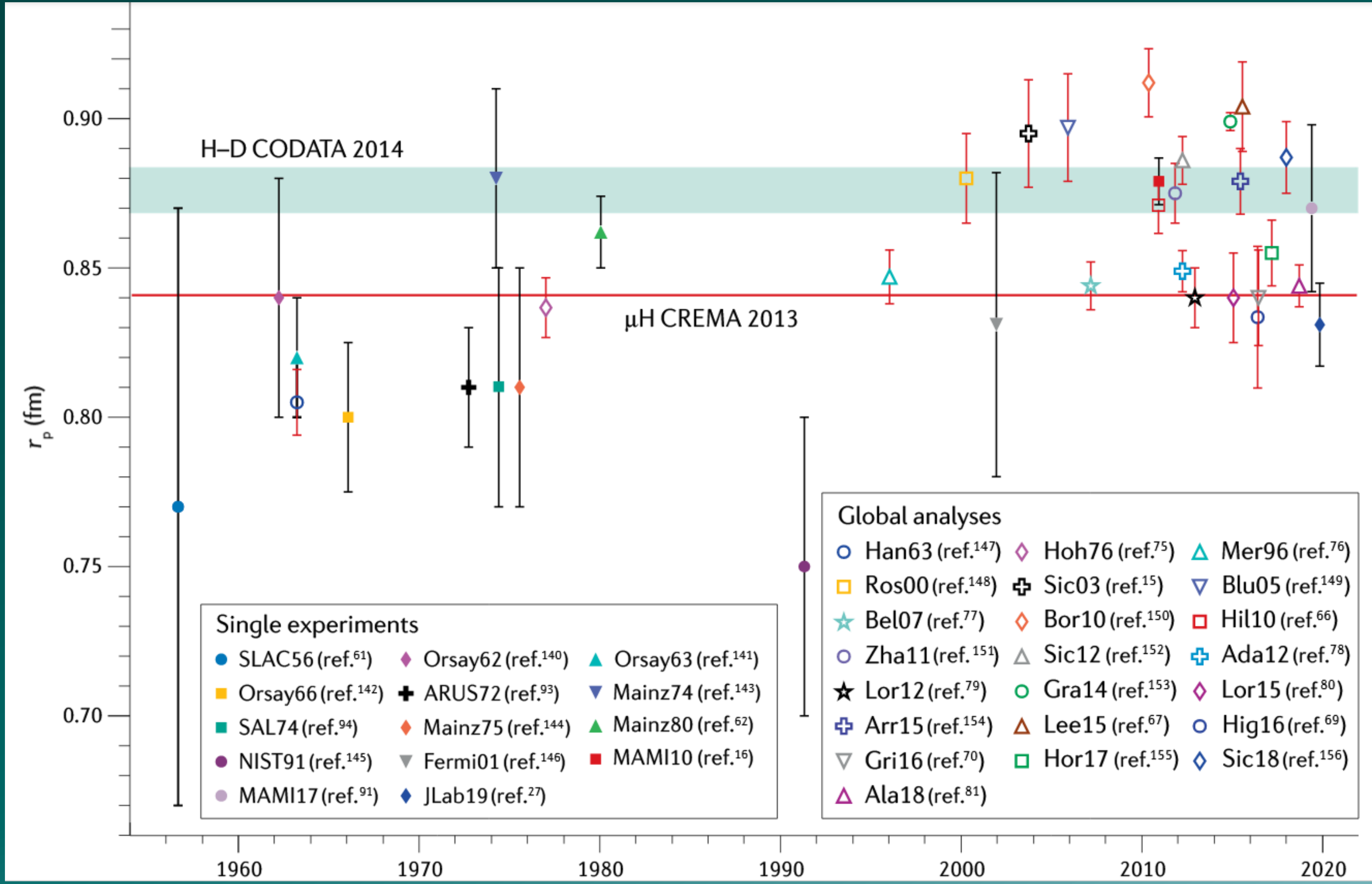
Atomic QED Theory

- Describes light-atom interaction
- One of the most accurate theories
- Experimental predictions extensively tested (often to ~10^{-8} level)
  - Lamb shift of energy levels, anomalous magnetic moment etc
- Interesting discrepancies still being discovered



Proton Radius Puzzle

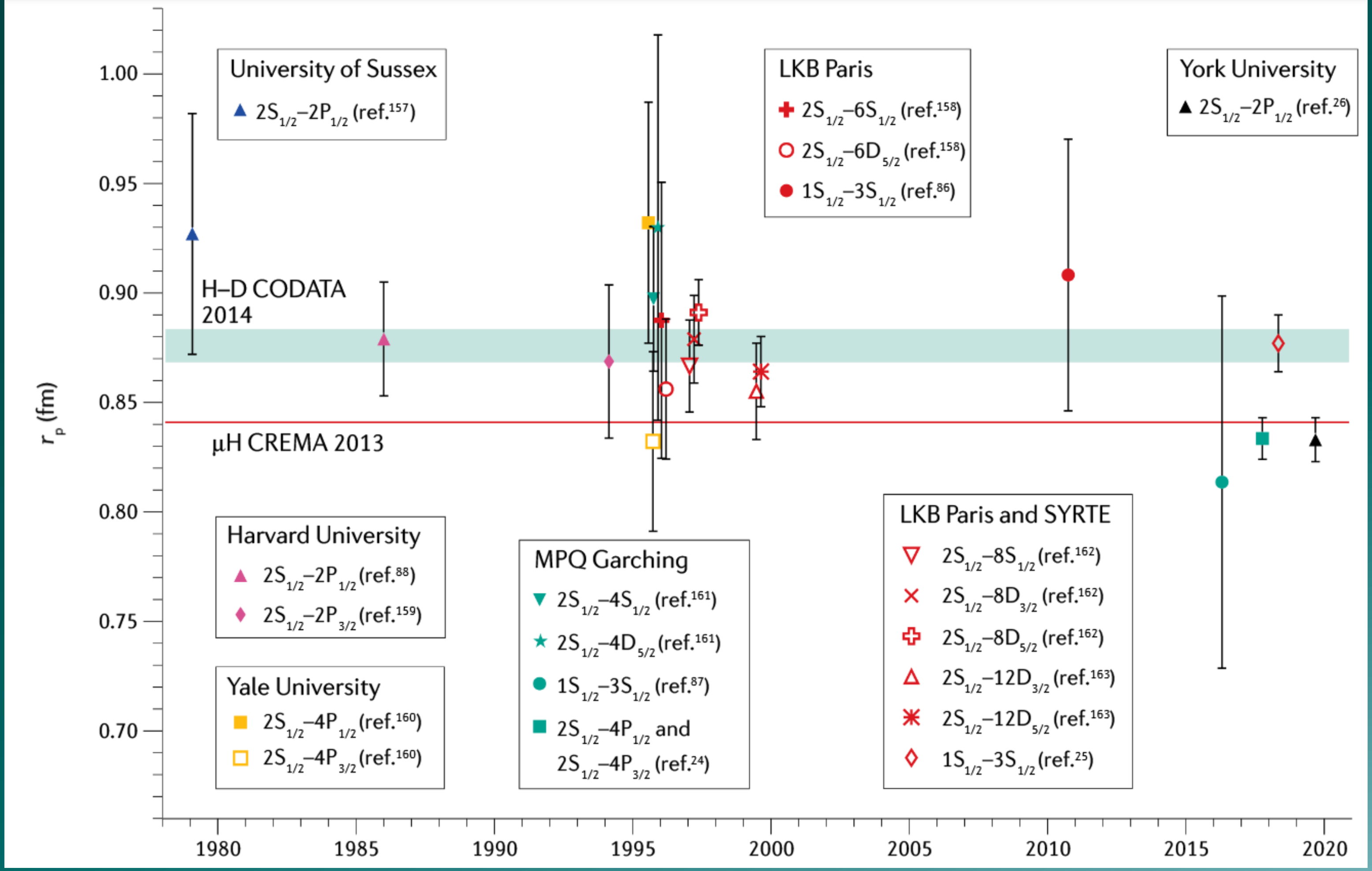
- Pre 2010 - 2 types of measurement:
  - Electron scattering



Karr, JP., Marchand, D. & Voutier, E. The proton size. *Nat Rev Phys* **2,** 601–614 (2020)

Proton Radius Puzzle

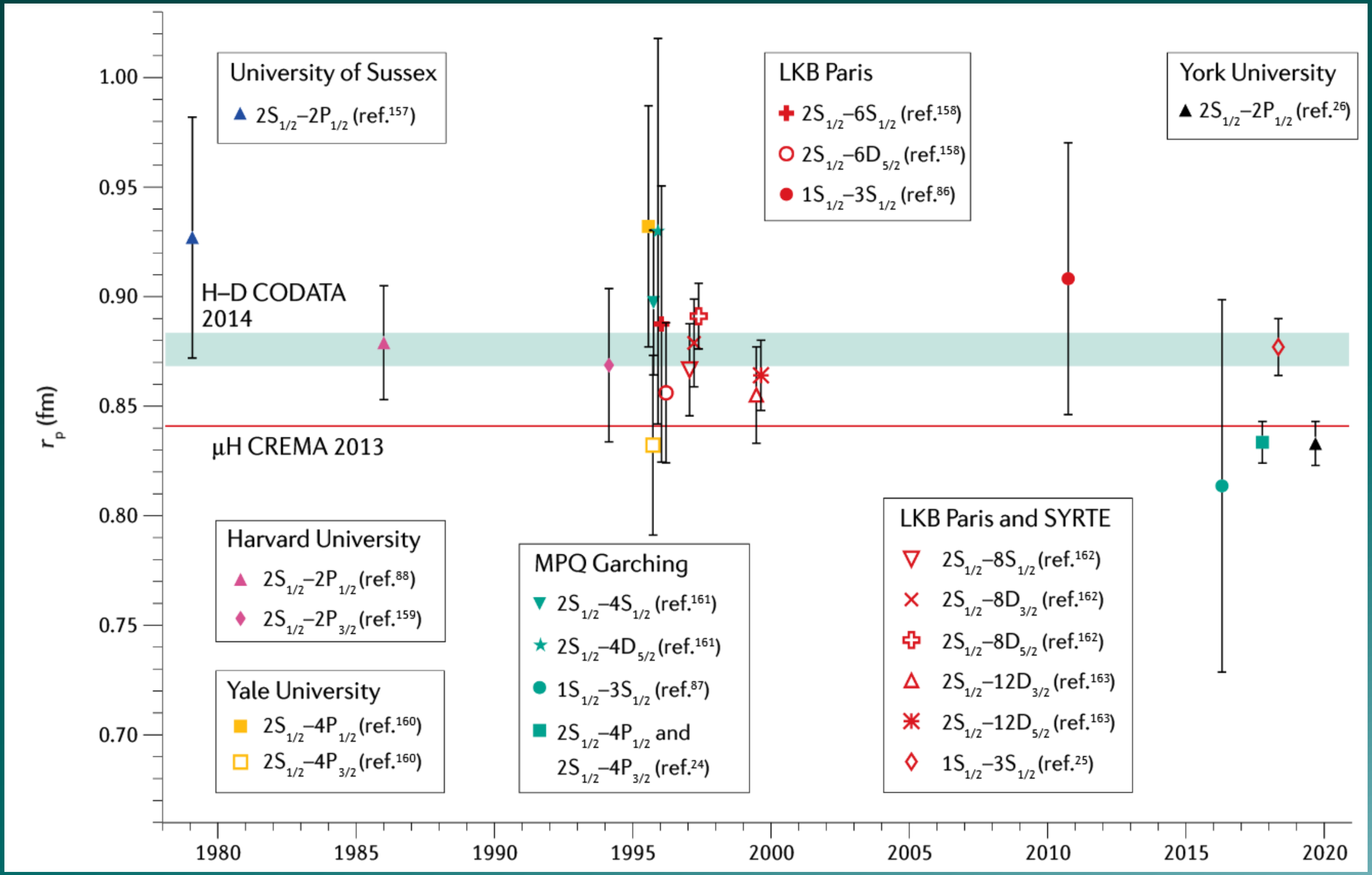
- Pre 2010 - 2 types of measurement:
  - Electron scattering
  - H spectroscopy



Karr, JP., Marchand, D. & Voutier, E. The proton size. *Nat Rev Phys* **2,** 601–614 (2020)

Proton Radius Puzzle

- Pre 2010 - 2 types of measurement:
  - Electron scattering
  - H spectroscopy
- In 2010 (refined 2013), spectroscopy with muonic Hydrogen measured a radius 4% smaller than CoDATA value!

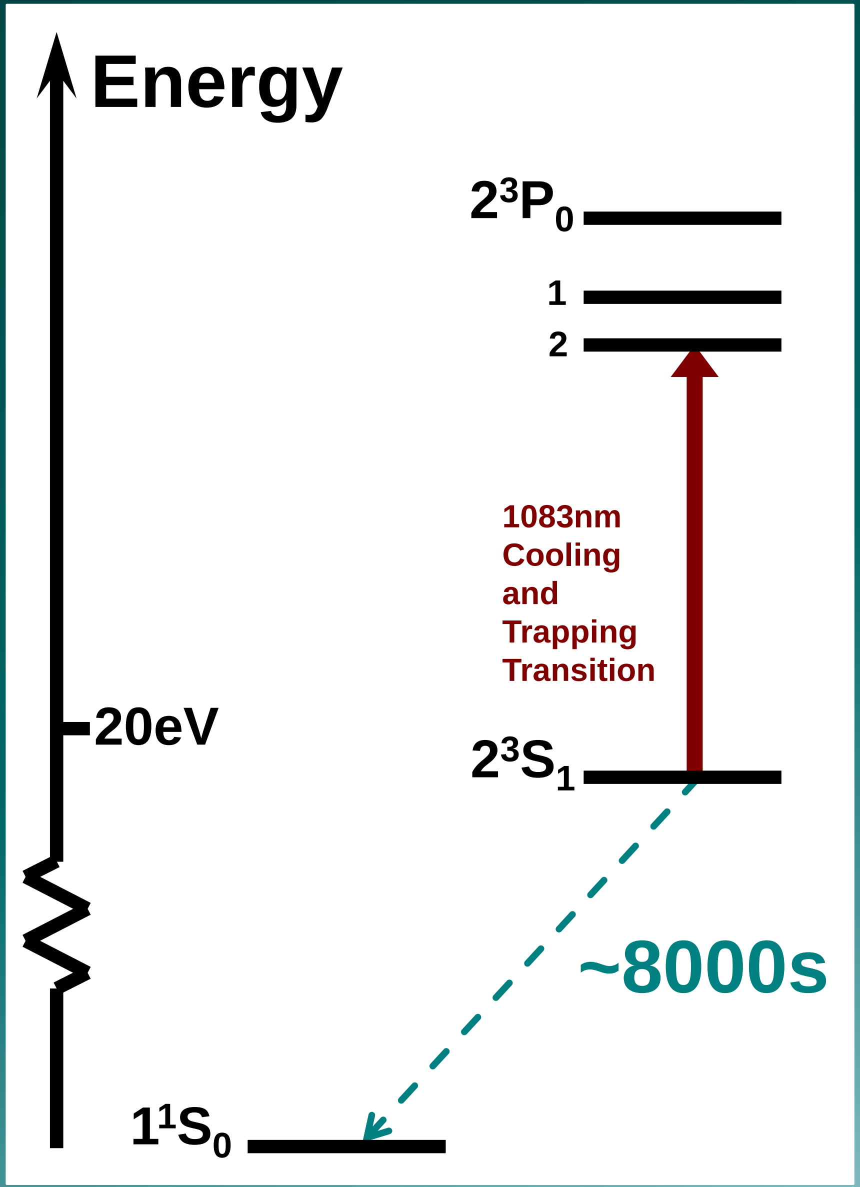


Antognini, A. et al. *Science* **339**, 417–420 (2013)

Karr, JP., Marchand, D. & Voutier, E. The proton size. *Nat Rev Phys* **2**, 601–614 (2020)

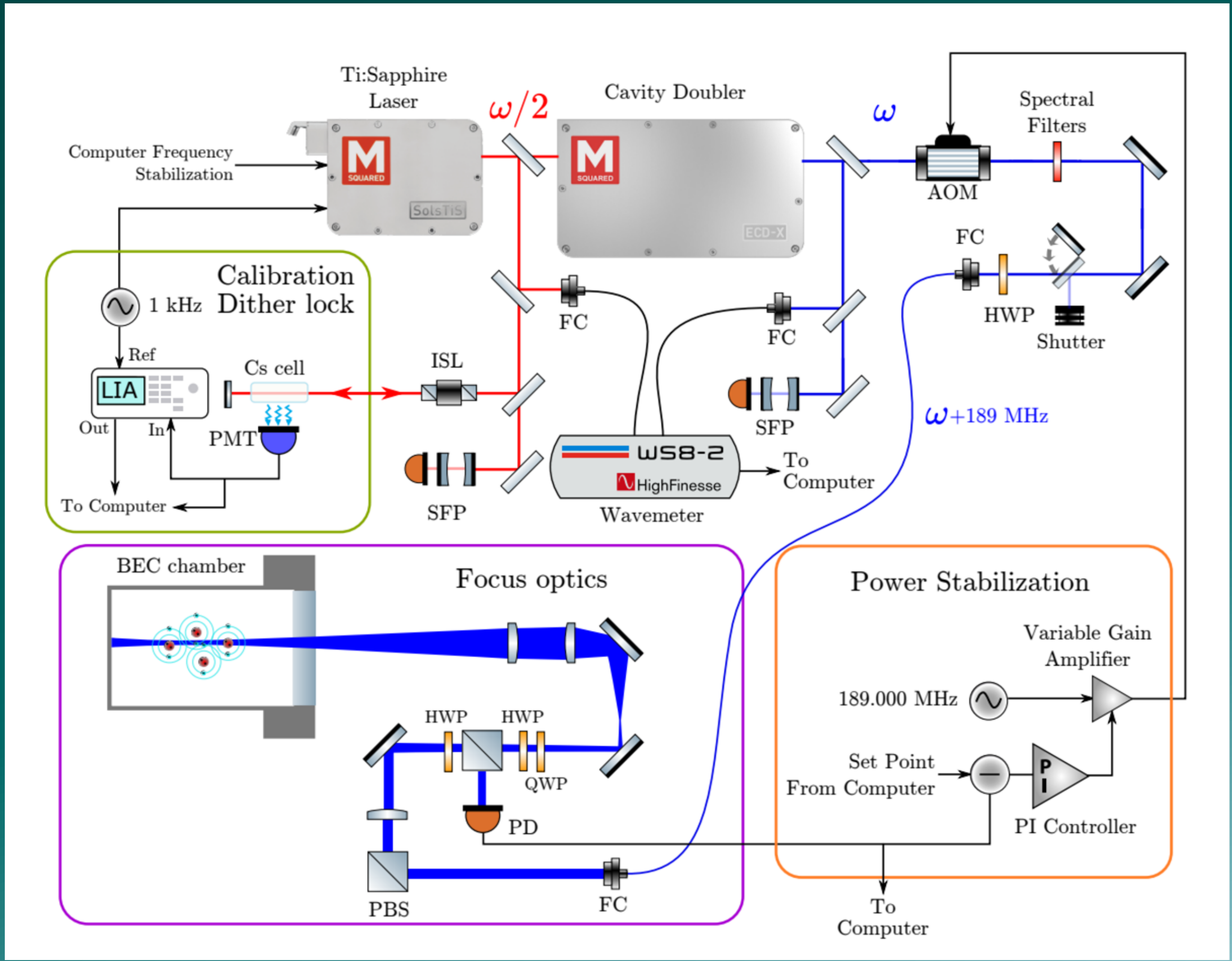
Helium Atomic Structure

- Simplest multi-electron atom
- Ideal testbed for atomic QED theory
- Can test predictions such as:
  - Energy levels
  - Transition rates
- We trap ultracold He*
  - BEC at ~1uK



Tuneable Laser

- Frequency doubled M-squared Ti:Sapphire laser
  - Single frequency
  - Linewidth <MHz
  - Tuneable ~402-428nm
- (borrowed from SUT)

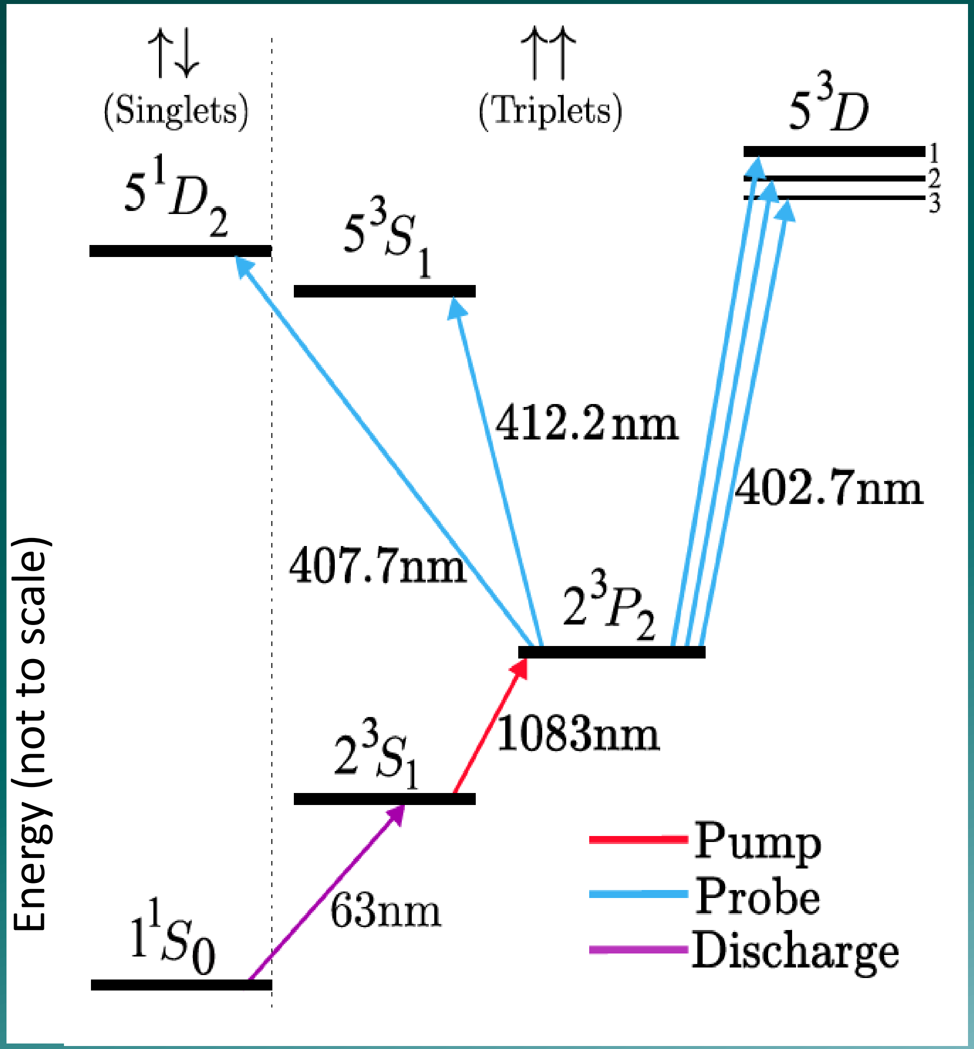


Chris Vale

Sacha Hoinka

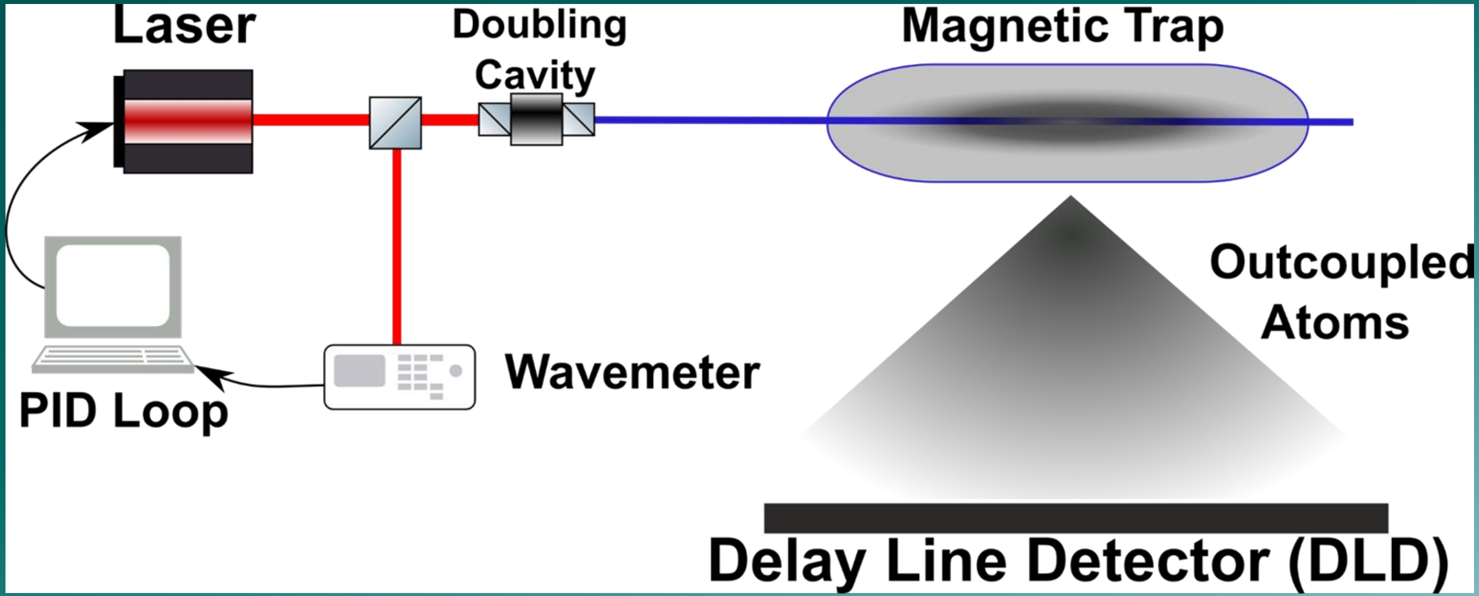
$2^3P \rightarrow n=5$ Transitions

- Several transitions from 2^3P level close to 400nm
- None measured accurately (last measurement in 1960)
  - 93σ discrepancy with modern theory!
- Spin forbidden $2^3P \rightarrow 5^1D_2$ transition never observed



Experimental Technique

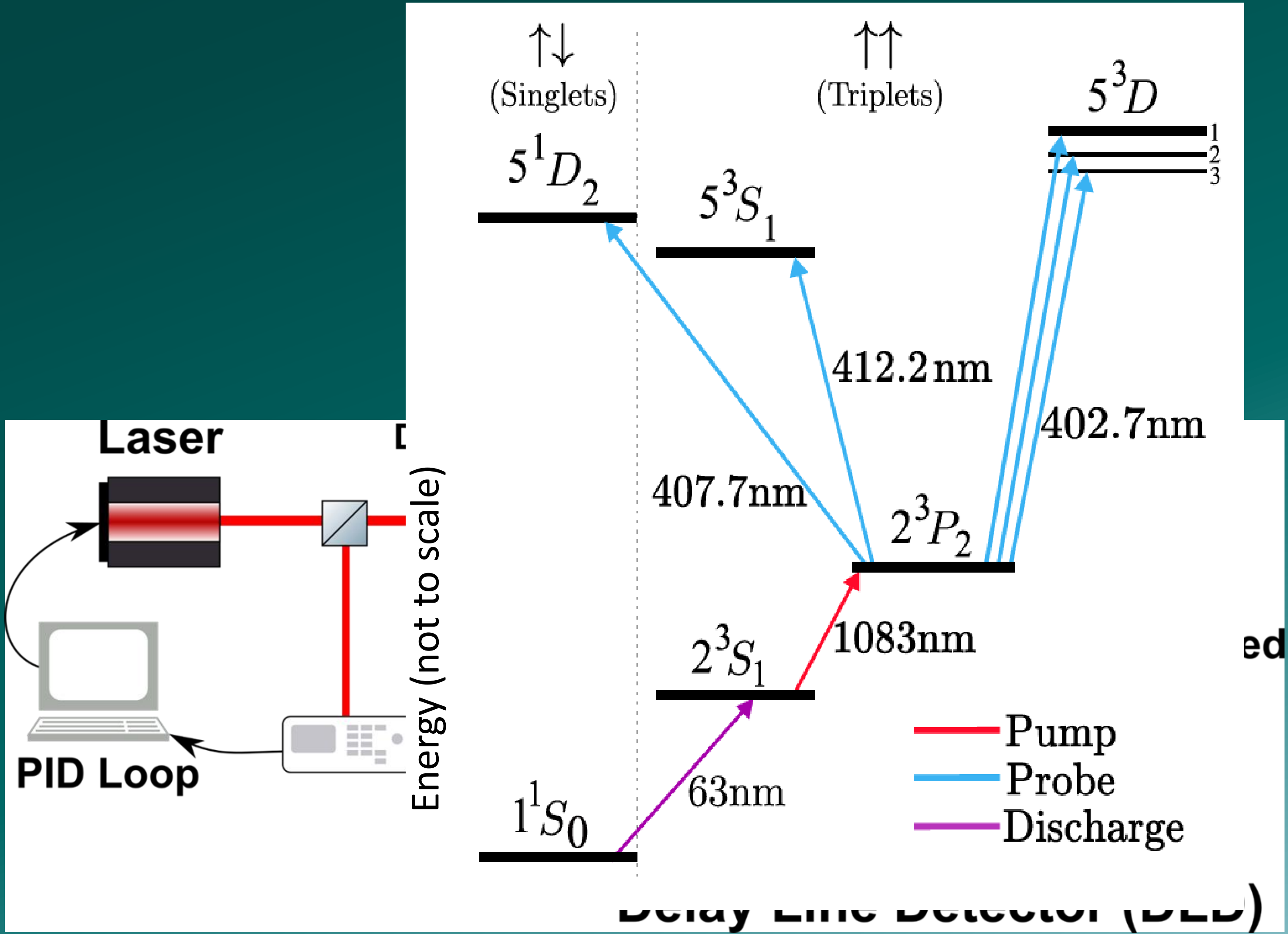
- Shine laser onto cold atoms
- Measure disturbance



Experimental Technique

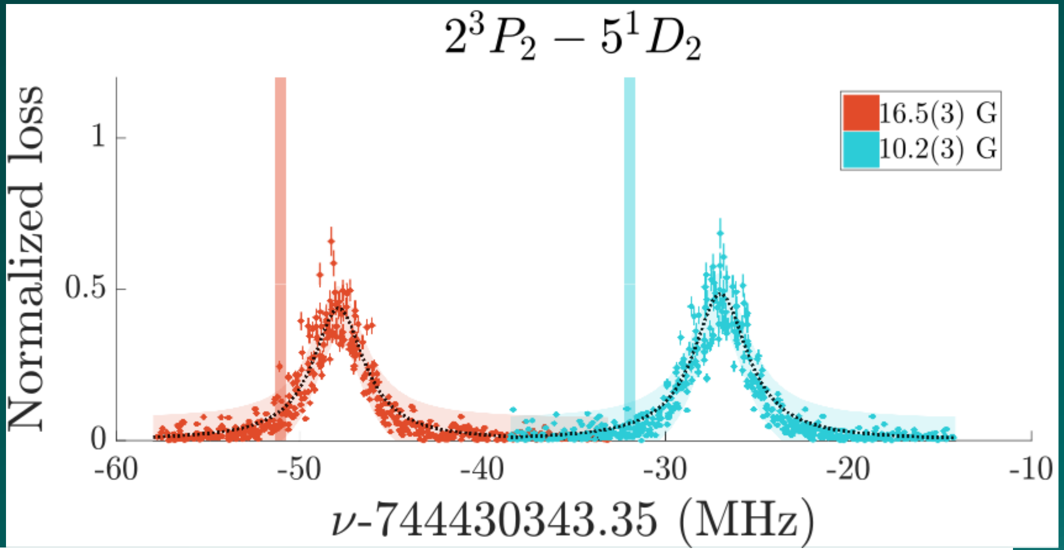
- Shine laser onto cold atoms
- Measure disturbance

- During laser cooling stage (excited state transition)



Experimental Results

- 1 Transition first measurement
- 4 measurements vastly improved
- All agree with theory



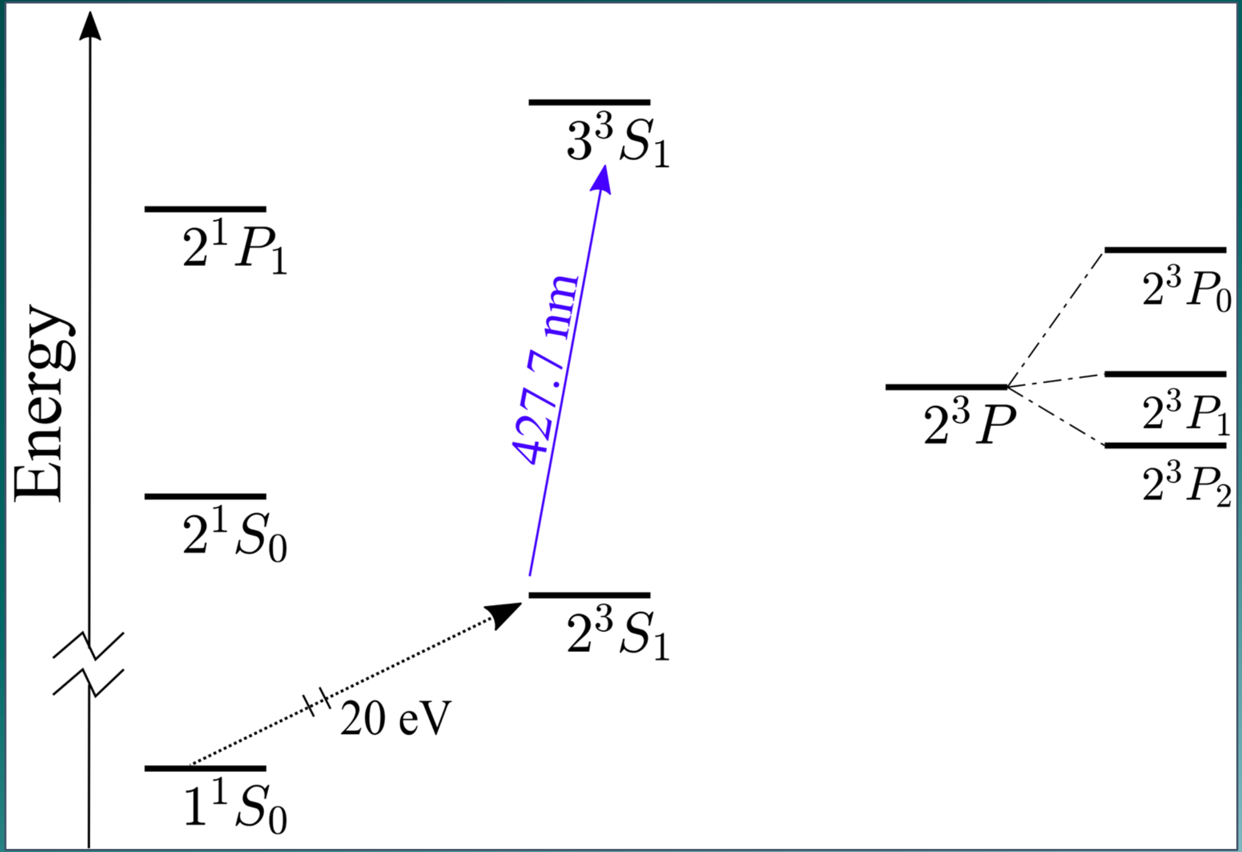
Transition	f_{exp}	f_{theory}	Diff.	FWHM_{exp}	FWHM_{pred}
$2^3P_2 - 5^3\mathrm{S}_1$	727,303,248(3)	727,303,244.6(4)	3(3)	3.4(5)	1.5
$2^3P_2 - 5^3\mathrm{D}_1$	744,396,496(7)	744,396,511.1(7)	-16(7)	5.8(6)	2.6
$2^3P_2 - 5^3\mathrm{D}_2$	744,396,220(7)	744,396,227.6(7)	-8(7)	4.2(5)	2.6
$2^3P_2 - 5^3\mathrm{D}_3$	744,396,194(7)	744,396,208.3(7)	-14(7)	4.0(1)	2.6
$2^3P_2 - 5^1\mathrm{D}_2$	744,430,343(7)	744,430,343.1(7)	0(7)	3.2(1)	2.2

J. A. Ross *et. al.* Phys. Rev. A **102**, 042804 (2020)

Forbidden Transition

- Highly forbidden $2^3S_1 \rightarrow 3^3S_1$
- Extremely weak
- Differing Einstein A predicted:
  - $A=6.5\times10^{-9}$ s^{-1} (1/A=4.89 yrs) [1]
  - $A=12\times10^{-9}$ s^{-1} (1/A=2.71 yrs) [2]

"This discrepancy does not have experimental impact since this rate is too small...to be measured" [1]



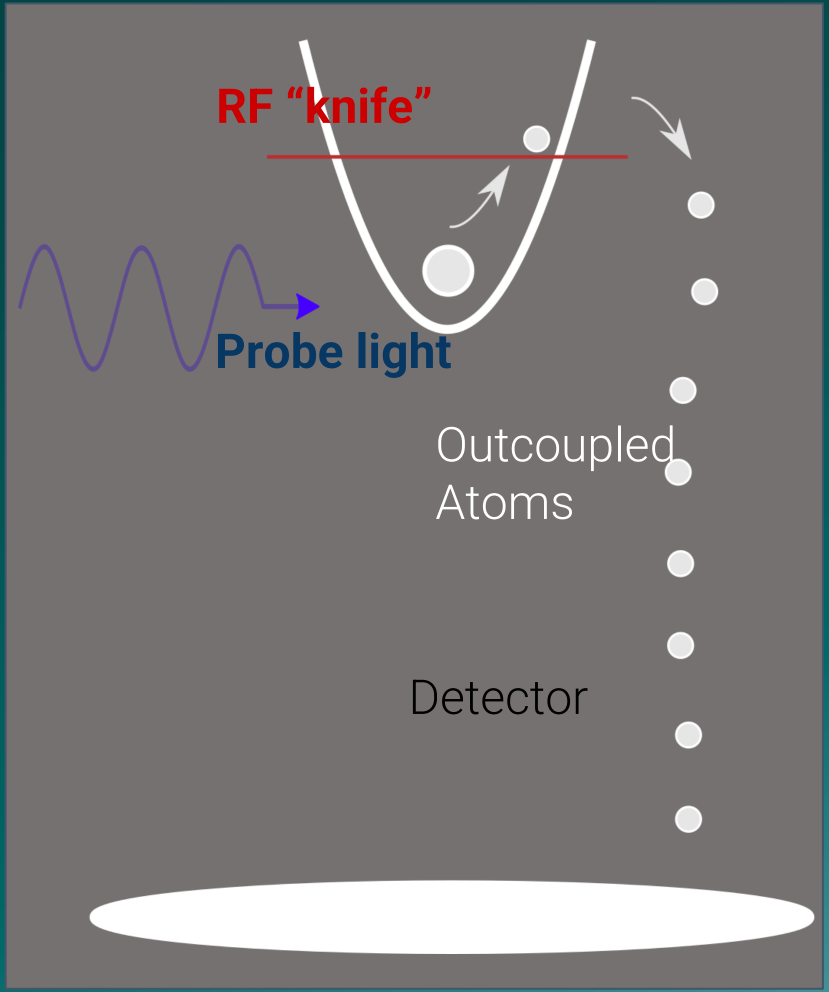
[1]G. Łach *et al.*, Phys. Rev. A **64**, 042510 (2001)
[2]A. Derevianko *et al.*, Phys. Rev. A **58**, 4453 (1998)

Forbidden Transition Measurement

- Cold atoms extremely sensitive
- Directly excite BEC atoms with probe beam
- Detect resulting:

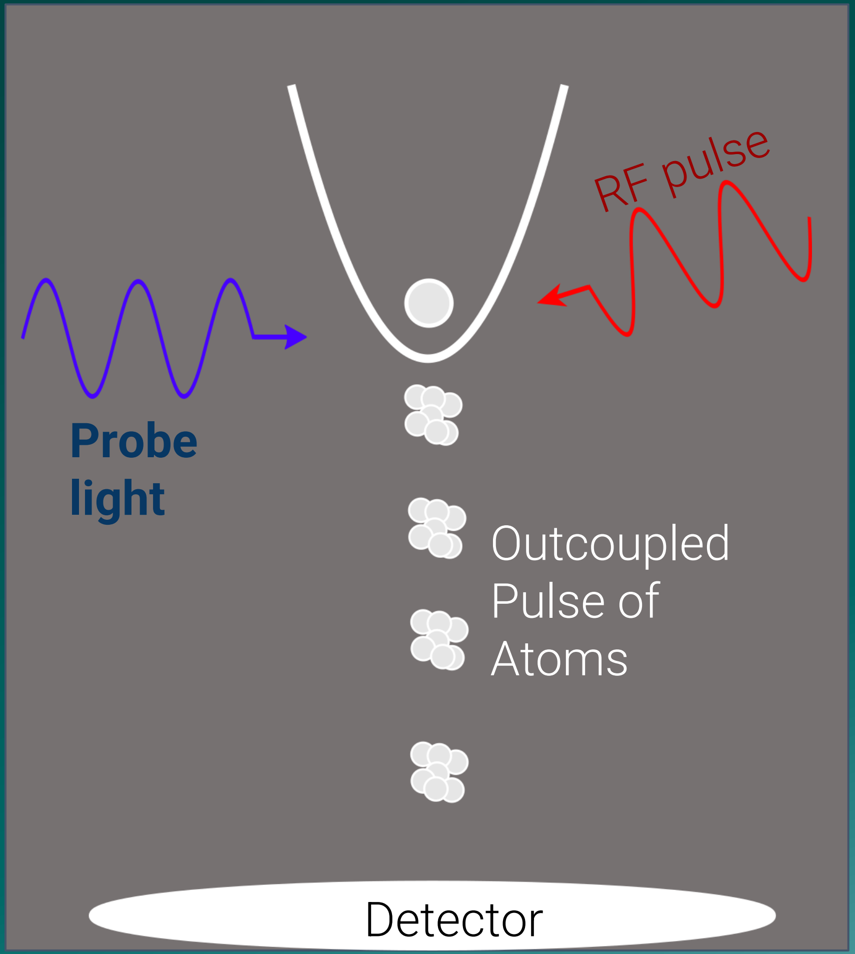
Forbidden Transition Measurement

- Cold atoms extremely sensitive
- Directly excite BEC atoms with probe beam
- Detect resulting:
  - Atom loss



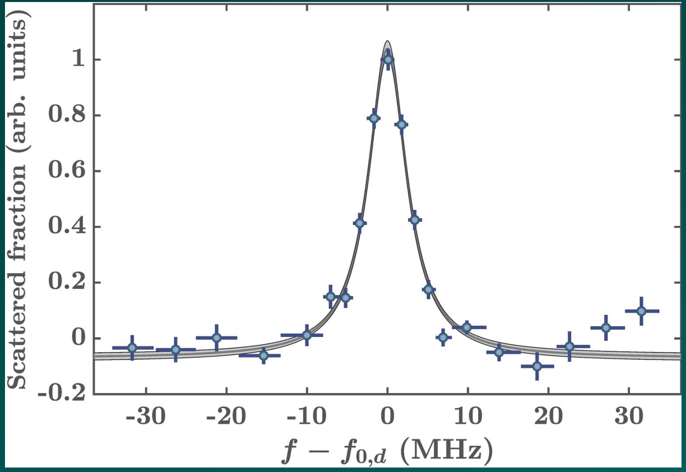
Forbidden Transition Measurement

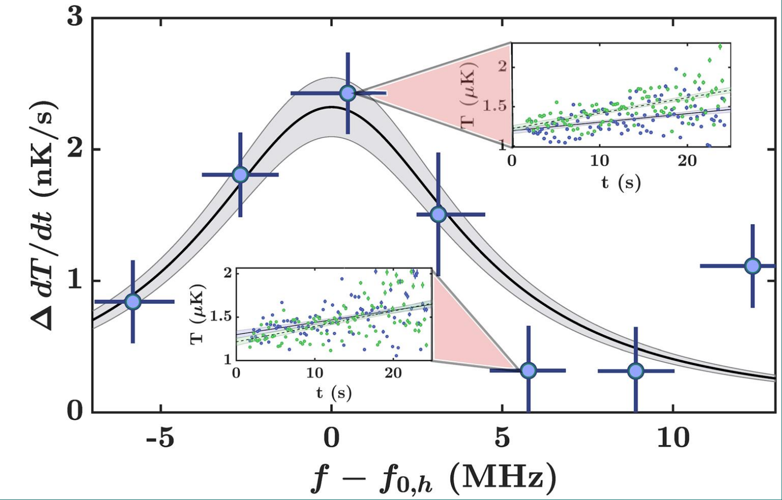
- Cold atoms extremely sensitive
- Directly excite BEC atoms with probe beam
- Detect resulting:
  - Atom loss
  - Temperature increase



Forbidden Transition Summary

- First observation of this transition
- Agrees with theory
- Unable to distinguish Einstein A coefficient theory discrepancy



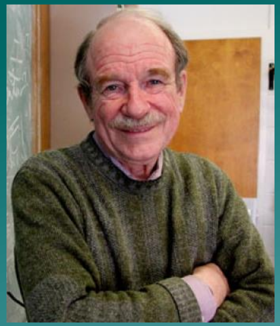


Method	Center Freq (MHz)	3^3S_1 State Lifetime (ns)	Einstein A Coeff ($10^{-9}s^{-1}$)
Direct	700, 939, 271(5)	50(20)	-
Heating	700, 939, 271(5)	40(30)	7(4)
Theory	700, 939, 269(8)	35.9(2)	6.48, 11.7

K. F. Thomas *et. al.* Phys. Rev. Lett. **125**, 013002 (2020)

Helium Tuneout Frequency Measurement

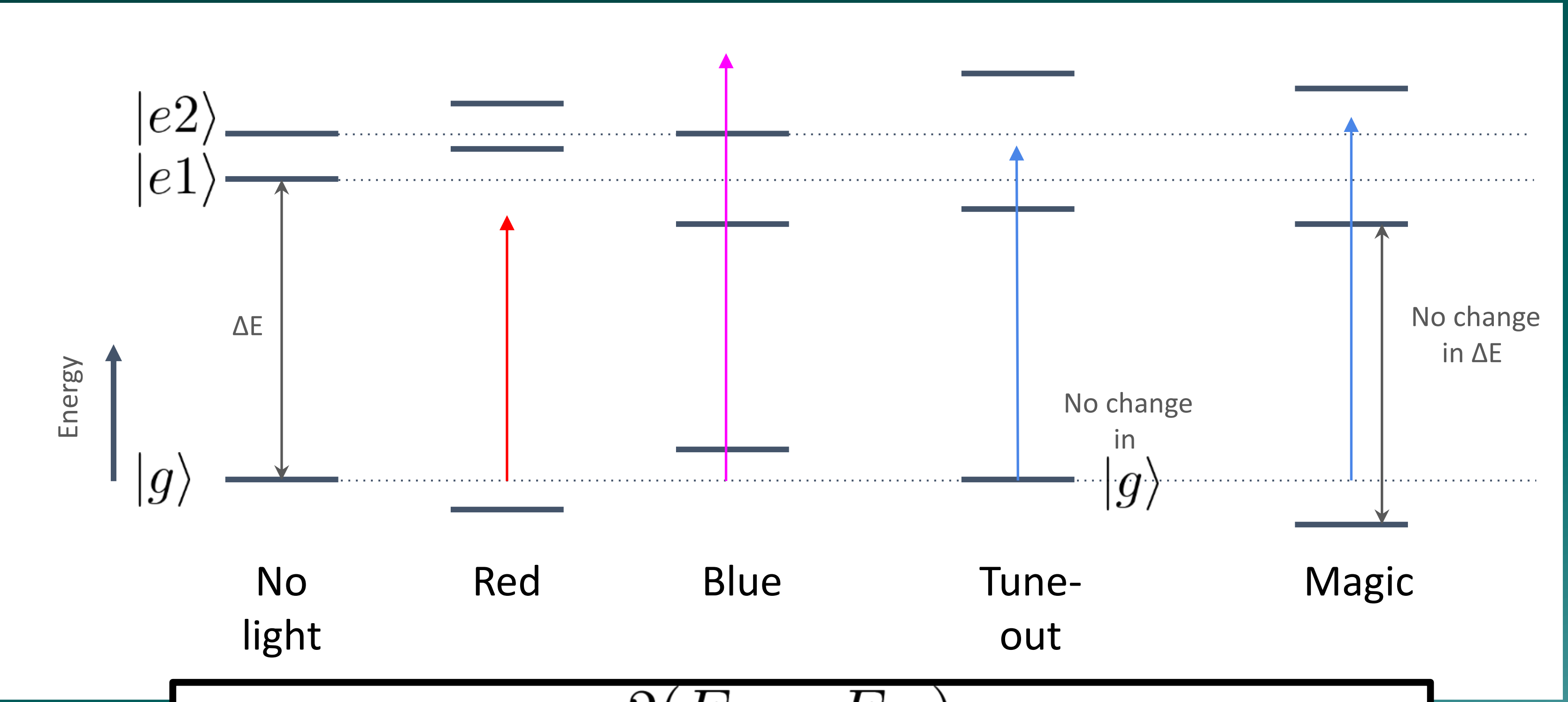
Li-Yan Tang



Gordon Drake

What is a Tuneout Frequency?

- Where all contributions to atomic polarisability cancel

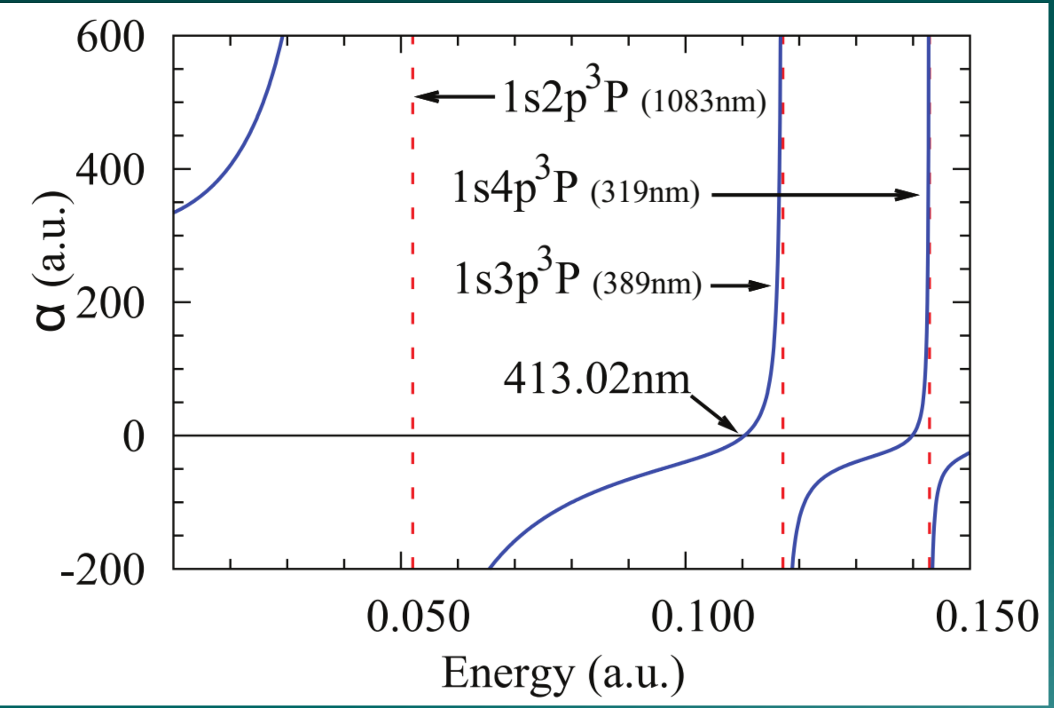


$$\alpha(\omega) = \sum_{n \neq m} \frac{2(E_n - E_m)}{(E_n - E_m)^2 - (\hbar\omega)^2} |\langle n|\mathbf{d} \cdot \mathbf{v}|m\rangle|^2$$

Why a Tuneout Frequency

- Alternative to measuring energy level spacing
  - Depends on all levels
- Null measurement
- Measuring Helium tune out at 413nm to 175MHz (100fm) accuracy:

"… would constitute the most precise measurement of transition rate information ever made for helium." –Jim Mitroy



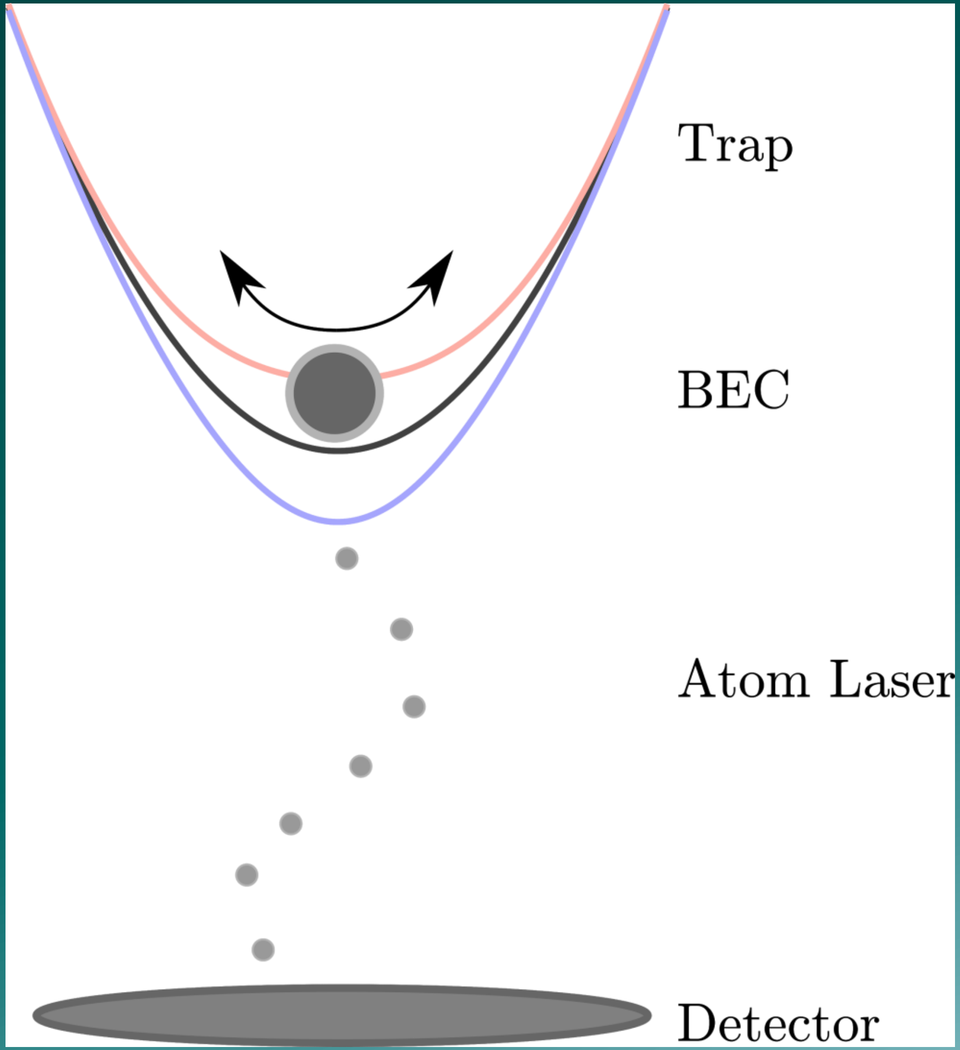
PHYSICAL REVIEW A **88**, 052515 (2013)

Tune-out wavelengths for metastable helium

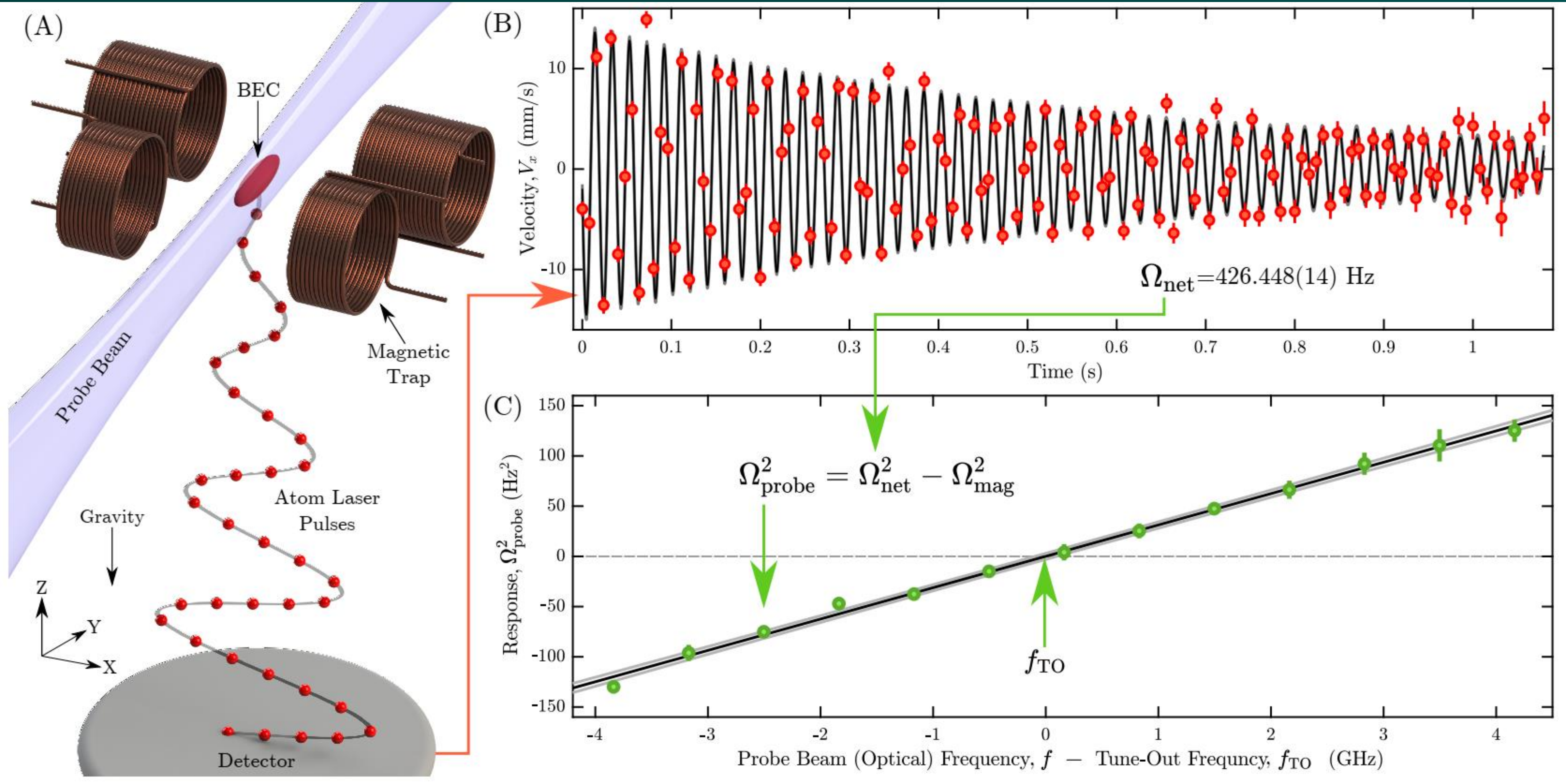
J. Mitroy[1] and Li-Yan Tang[1,2]

Tuneout Measurement

- Use probe laser to perturb magnetic trap
- Measure trap frequency via BEC oscillation and outcoupling trains of small pulses
- Scan laser frequency until no change in trap frequency



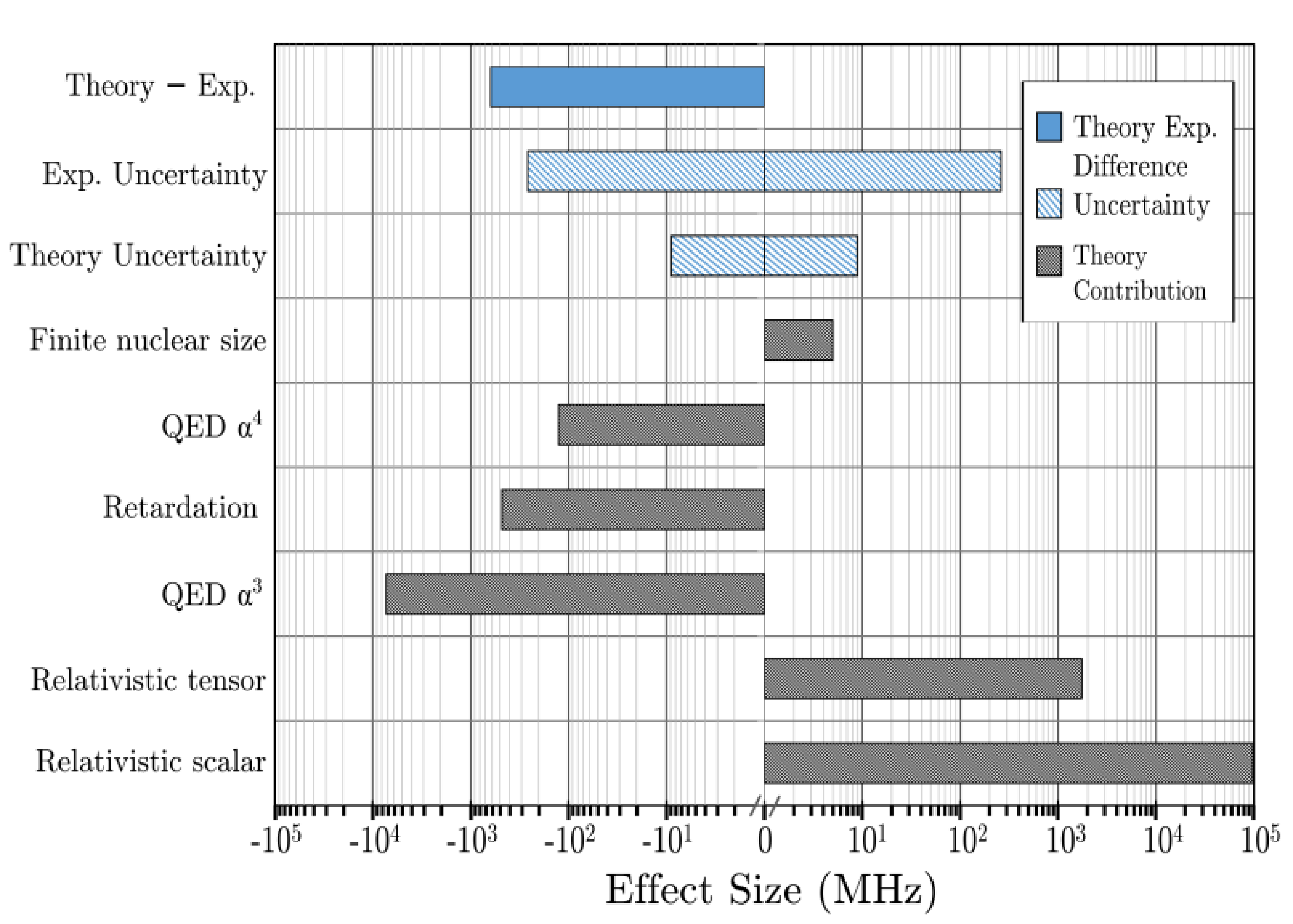
Trap Frequency Measurement



Tuneout Frequency Result

- Final value:
  f_{TO} = 725,736,700 $(40_{stat}, 260_{sys})$ MHz
- Agrees with theory value 725,736,252 (9)MHz
- 20-fold improvement on previous best measurement
- Resolves QED terms

B. M. Hensen *et. al.* Science **376**, 199 (2022)



Further Information

- Transitions:

  J. A. Ross *et. al.* Phys. Rev. A **102**, 042804 (2020)

  K. F. Thomas *et. al.* Phys. Rev. Lett. **125**, 013002 (2020)

- Tuneout:

  B. M. Hensen *et. al.* Science **376**, 199 (2022)

Group Members


Kieran Thomas


David Shin


Bryce Henson


Jacob Ross


Andrew Truscott

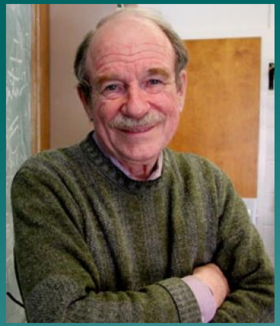

Ken Baldwin


Carlos Kuhn

Theory Collaborators:

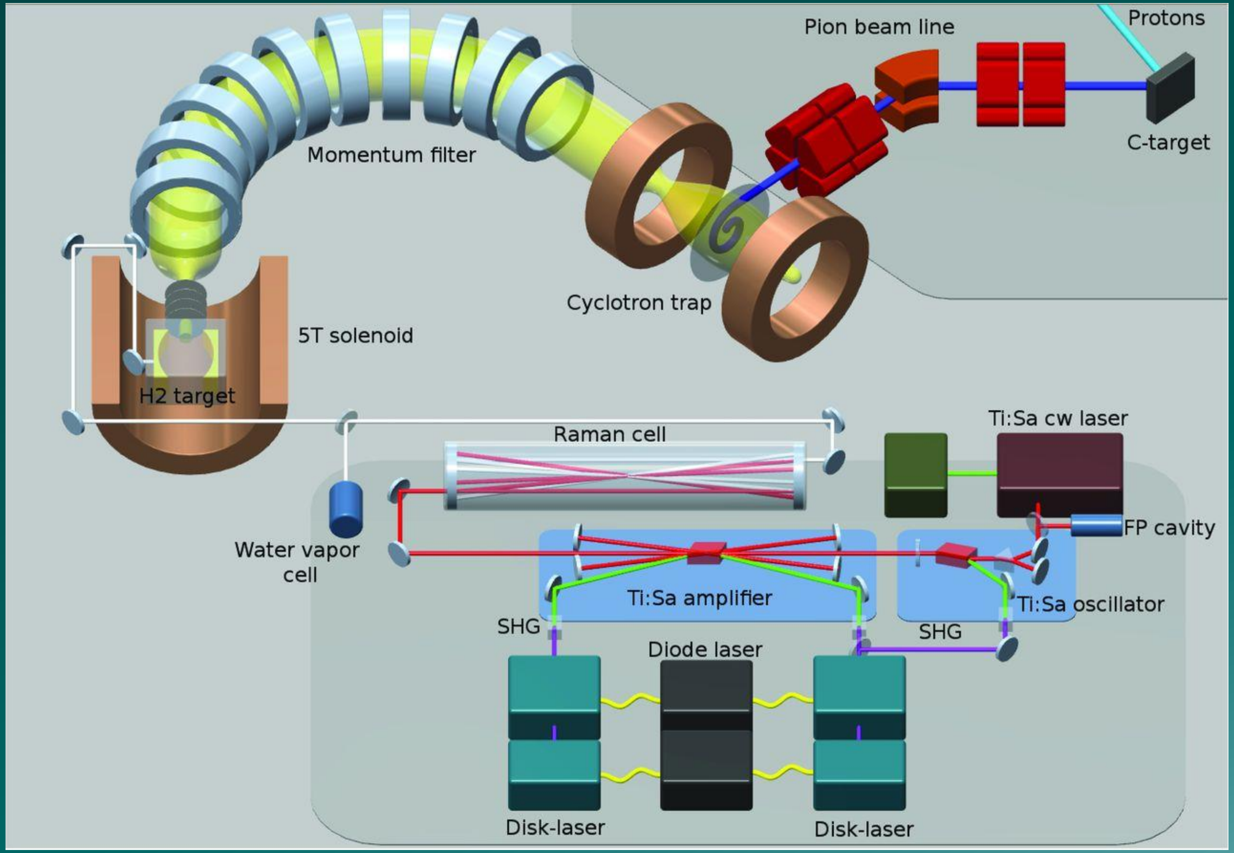

Danny Cocks


Li-Yan Tang


Gordon Drake

Proton Radius Puzzle

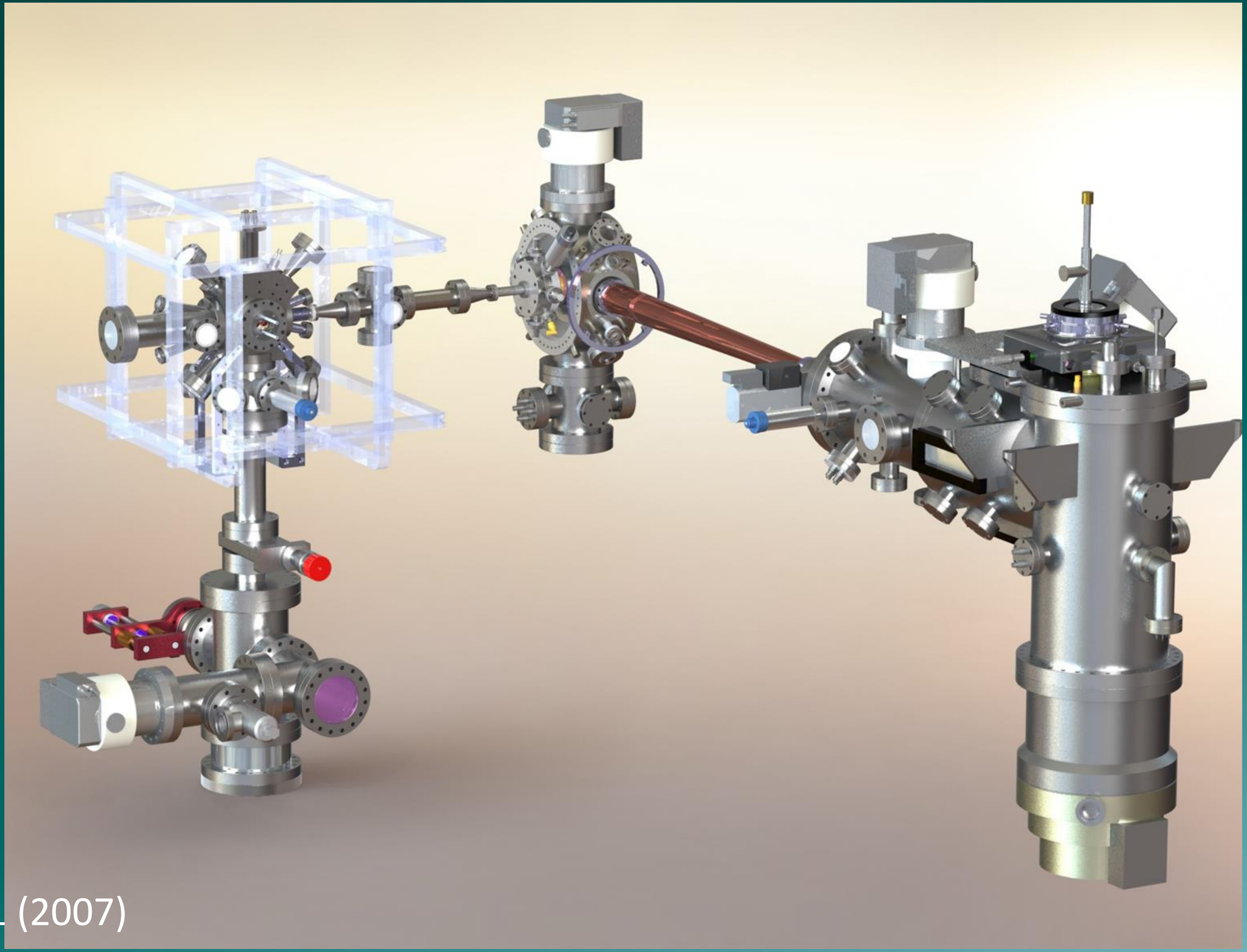
- In 2010 (refined 2013), new spectroscopy with muonic Hydrogen measured a radius 4% smaller than CoDATA value!



Antognini, A. et al. *Science* **339**, 417–420 (2013)

Experimental System

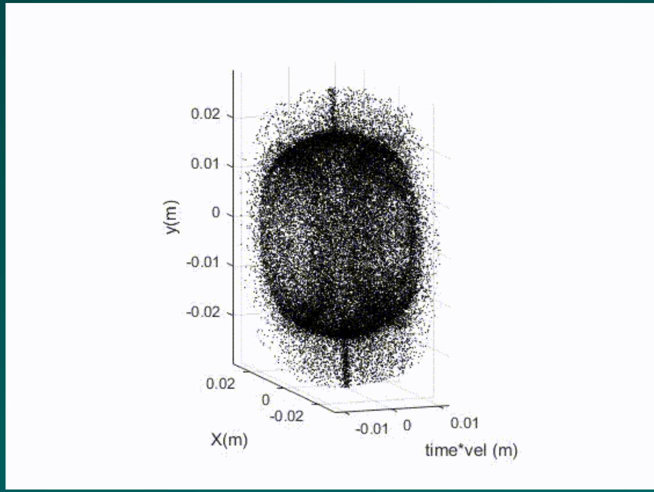
- Ultracold temperature achieved via:
  - Cryogenic cooled source
  - Laser cooling stages
  - Magnetic trapping and evaporation
  - Ultrahigh vacuum system

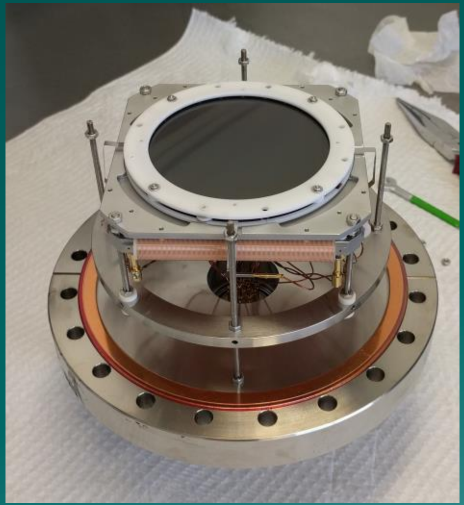


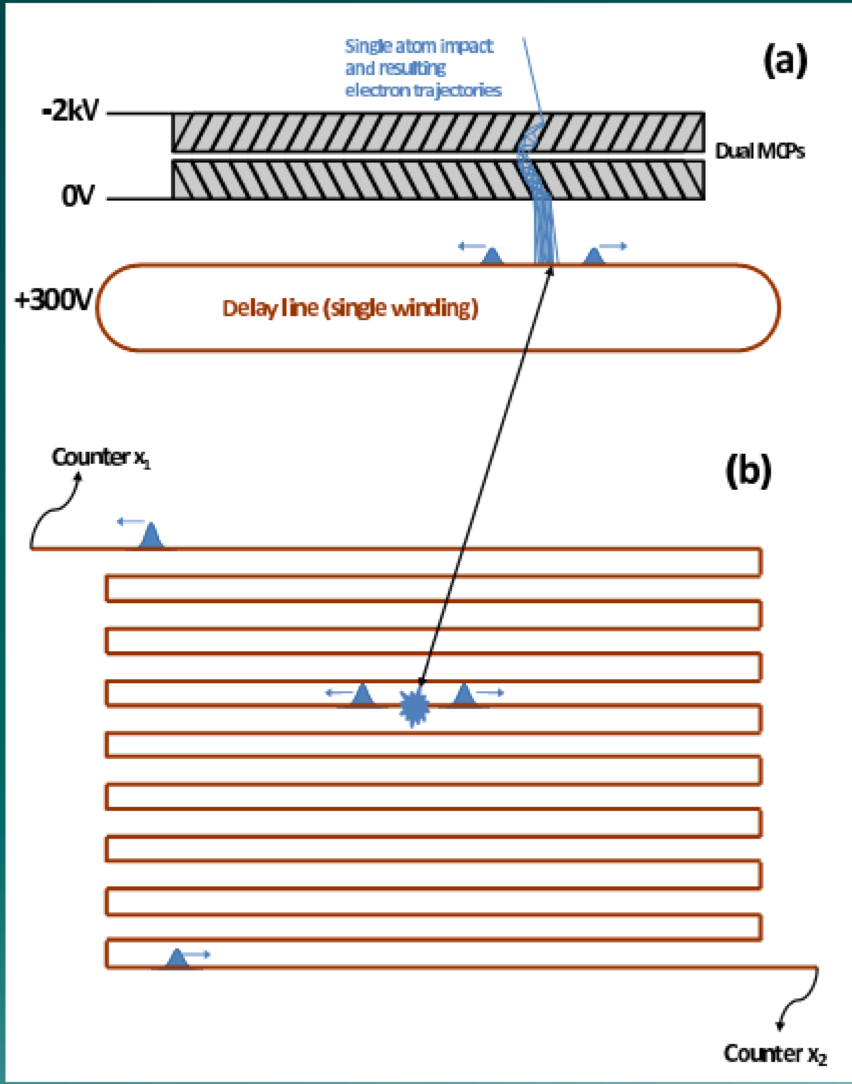
R.G. Dall & A.G. Truscott *Opt. Commun.* **270**, 255-261 (2007)
A.H. Abbas *et. al.* Phys. Rev. A **103**, 053317 (2021)

Single Atom Momentum Detection

- 3D resolved single atom detection via MCP-DLD detector
- Atoms measured after trap release and time-of-flight (TOF)
- Plots 3D momentum distribution

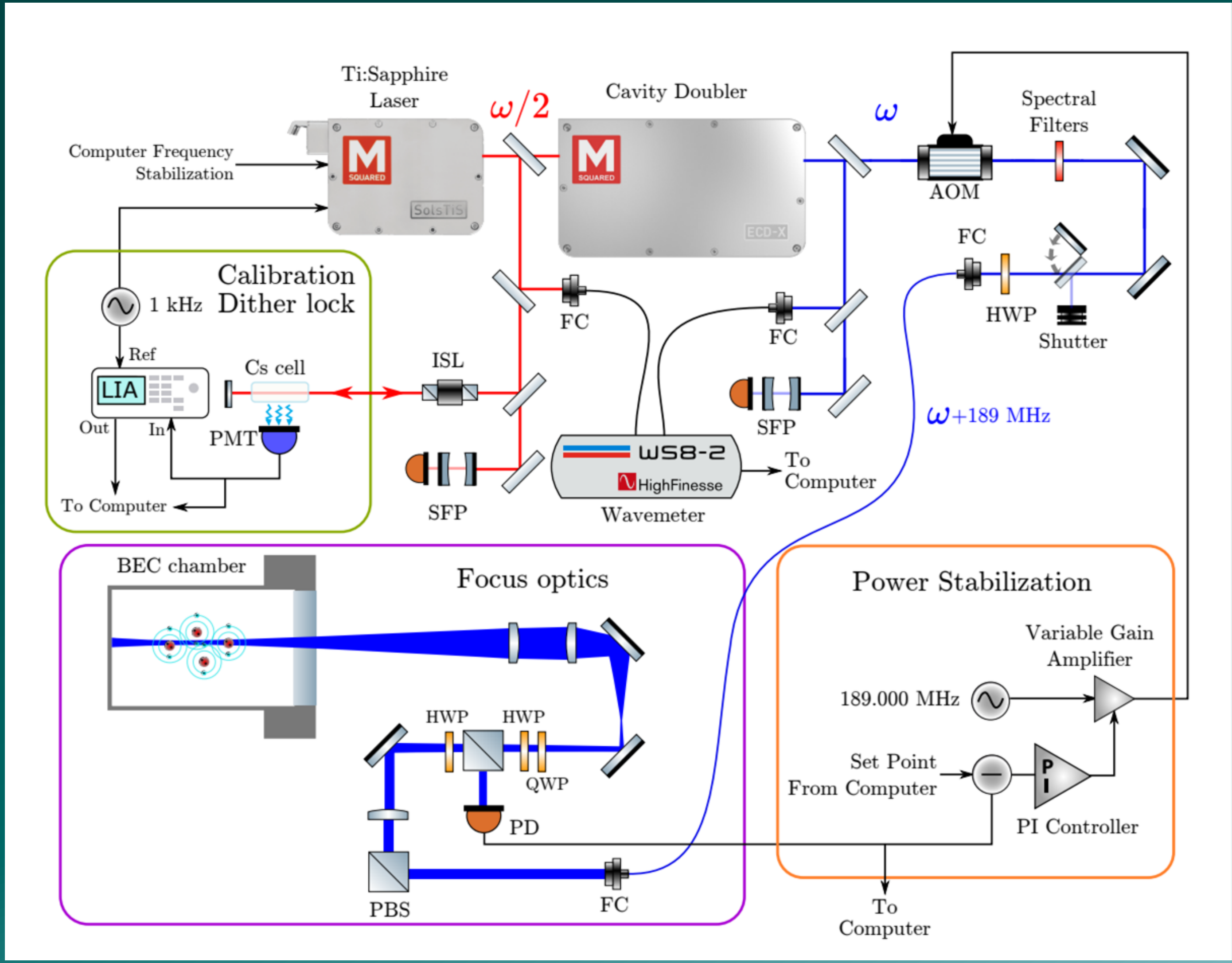






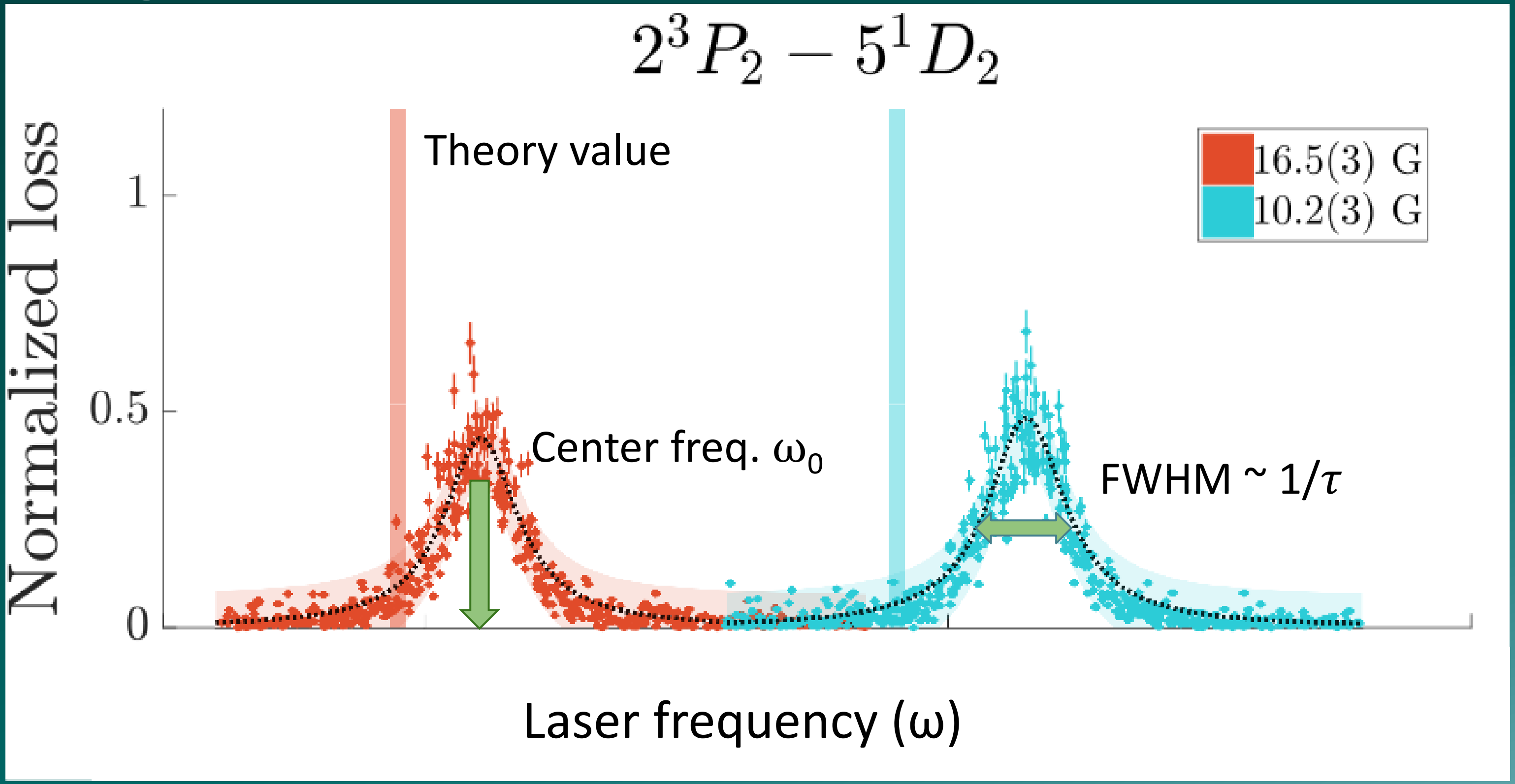
Laser System

- Frequency stabilised by locking to Cs reference
- Monitored via HighFinesse wavemeter
  - ~4MHz accuracy for our transitions
- Power stabilisation
- Fibre coupled to atoms

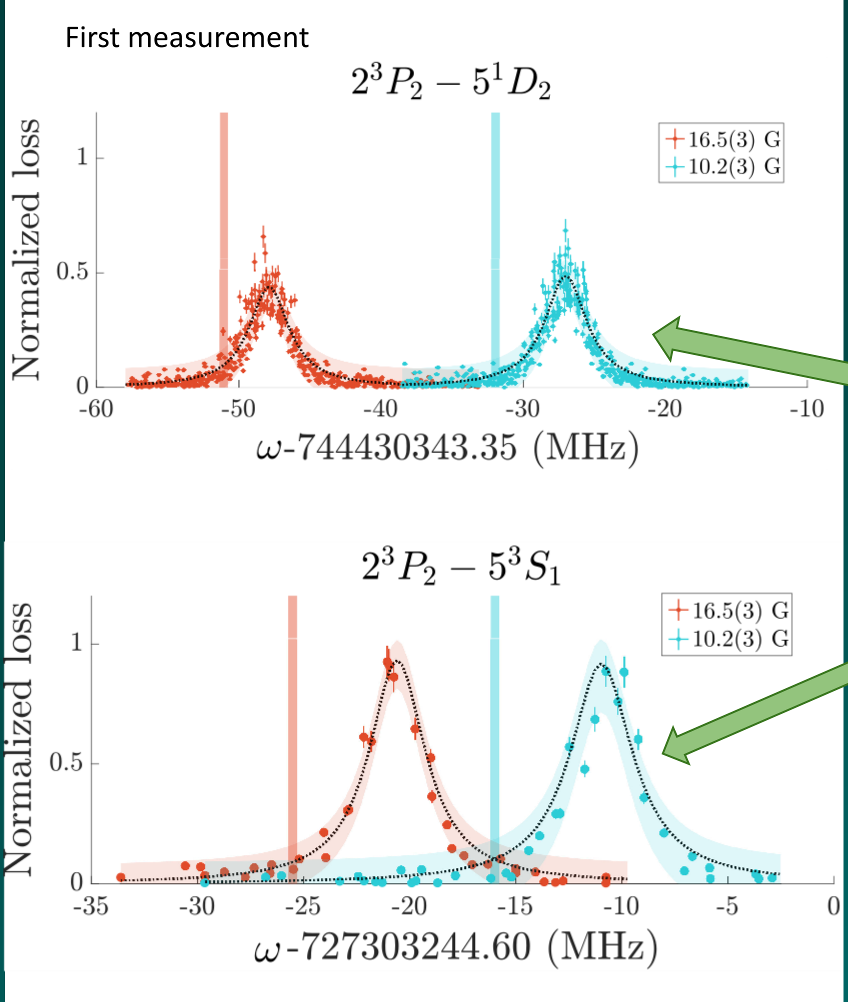


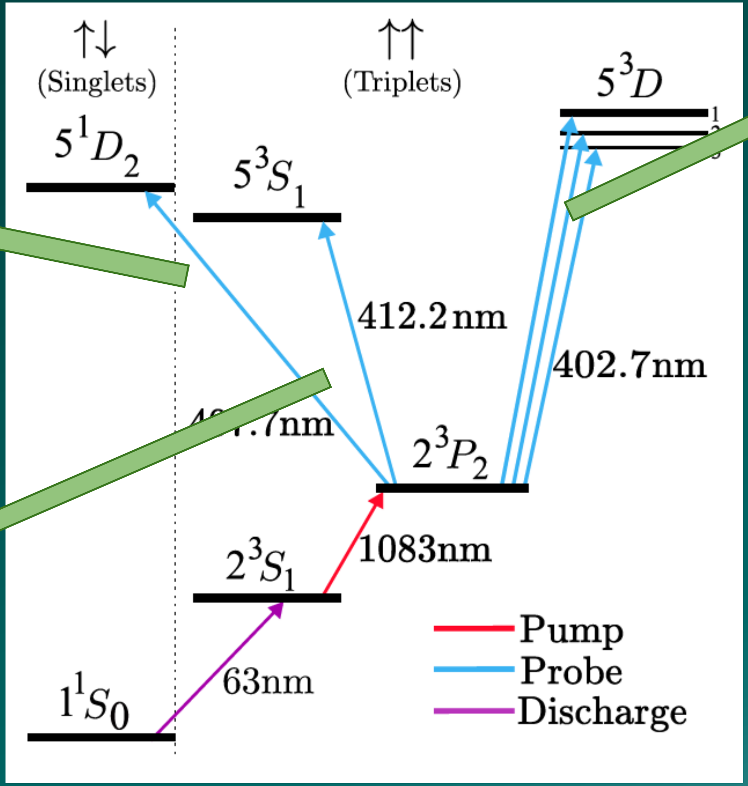
Experimental Results

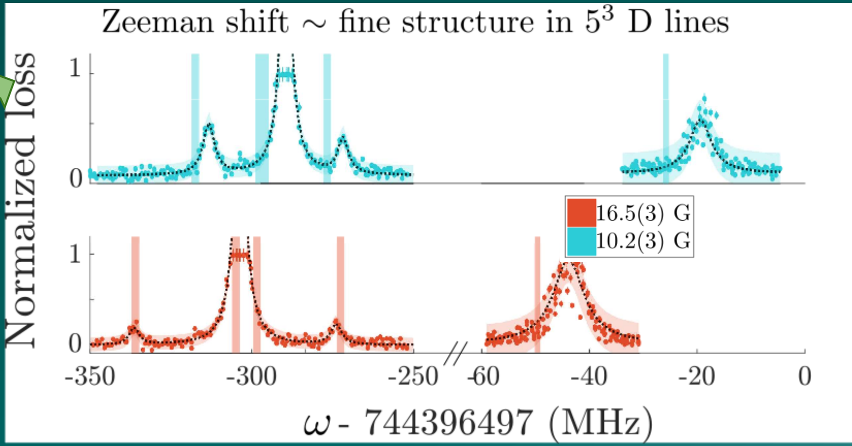
- Measured transitions at different magnetic fields



Experimental Results

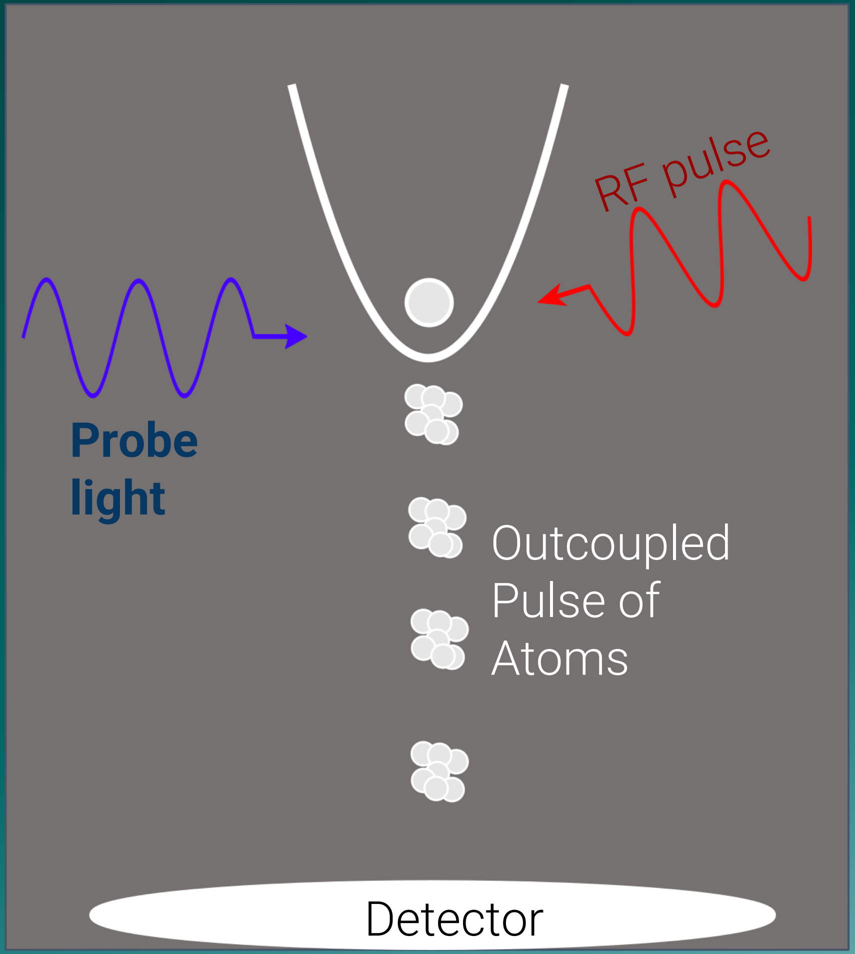






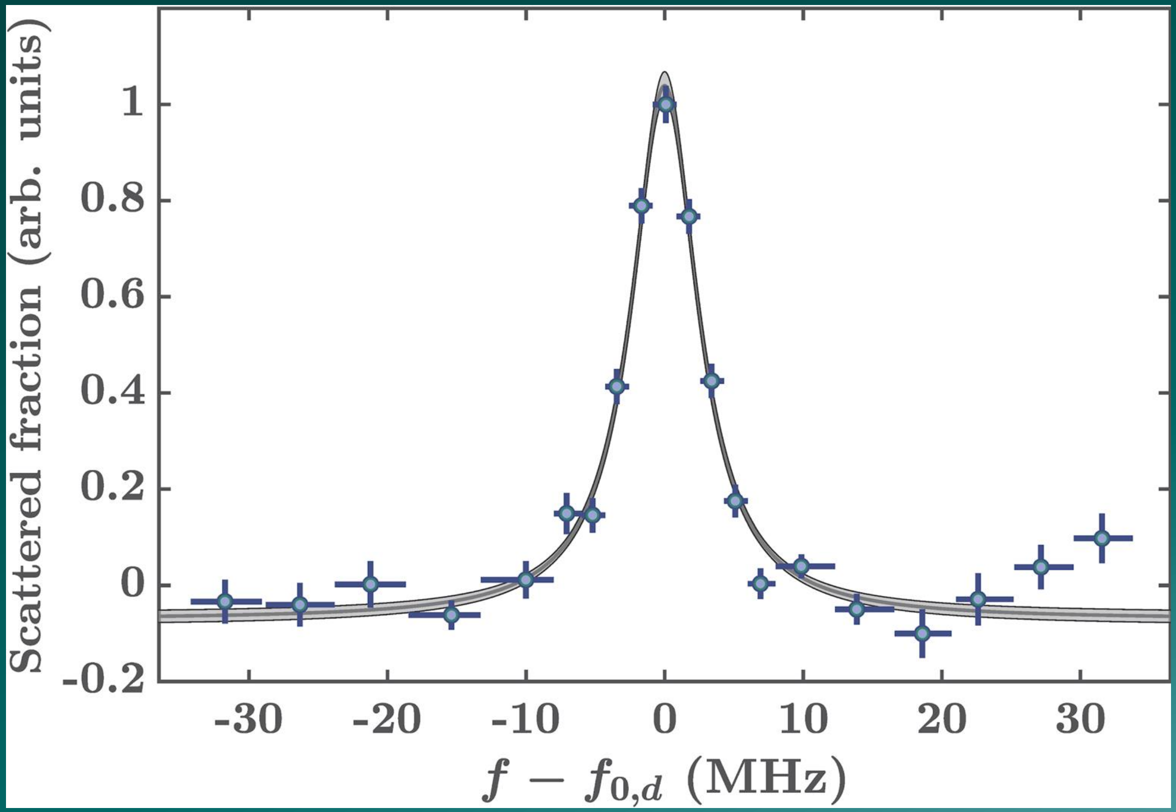
Forbidden Transition Heating Method

- Photon scattering from probe beam causes heating
- Outcouple multiple small pulses of atoms over time
- Temperature fit to each pulse gives heating rate



Forbidden Transition Direct Measurement

- Atom loss peak gives transition frequency:
  700,939,270(5) MHz
  (427.701045(3)nm)
- FWHM gives lifetime:
  - 50(20)ns
- Unable to measure Einstein A coefficient with this method without QE



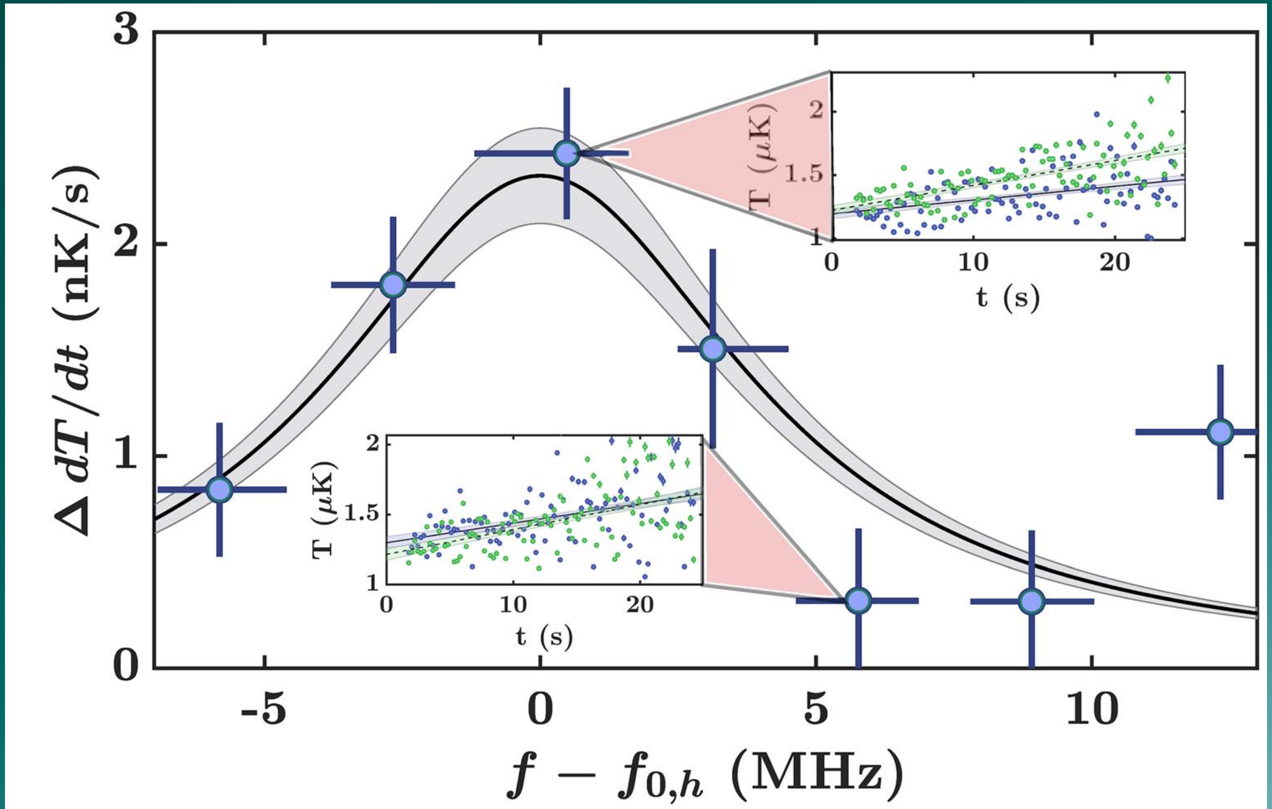
Forbidden Transition Heating Results

- Temperature fit to outcoupled pulses gives heating rate due to probe beam
- Heating rate gives transition rate of:

  $A=(7\pm4)\times10^{-9}\ s^{-1}$

  $1/A = (5\pm2)$ years

- Theory = 4.98 or 2.71 years



A Few Detai

- The tuneout we measure depends on beam polarisation via Stokes parameters:

$$f_{\mathrm{TO}}(\mathcal{Q}_{\mathcal{A}},\mathcal{V}) = f^{S}_{\mathrm{TO}} + \frac{1}{2}\beta^{V}\cos(\theta_k)\,\mathcal{V} - \frac{1}{2}\beta^{T}\Big[3\,\mathrm{si}$$

- Scan beam Stokes parameters to account for this