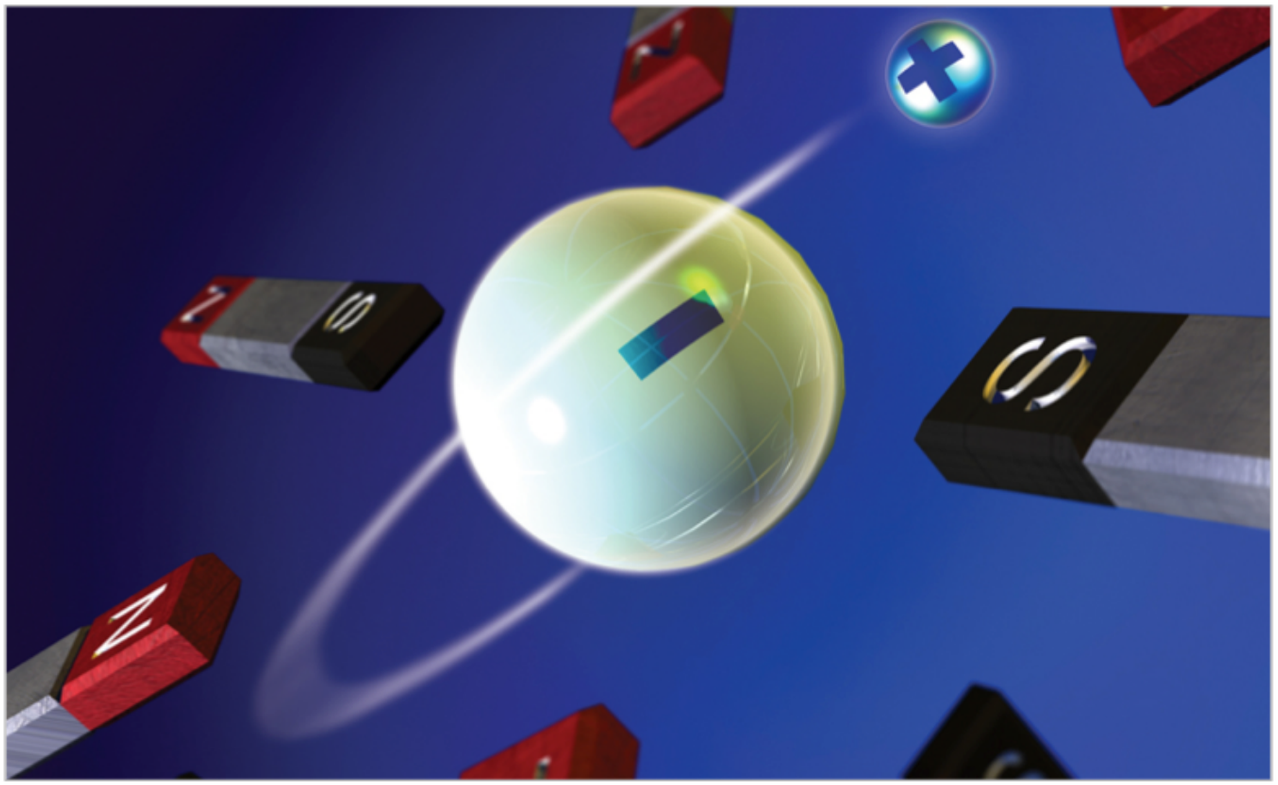
Precision Studies with Trapped Antihydrogen



Dr. Will Bertsche

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The Cockcroft Institute of Accelerator Science and Technology

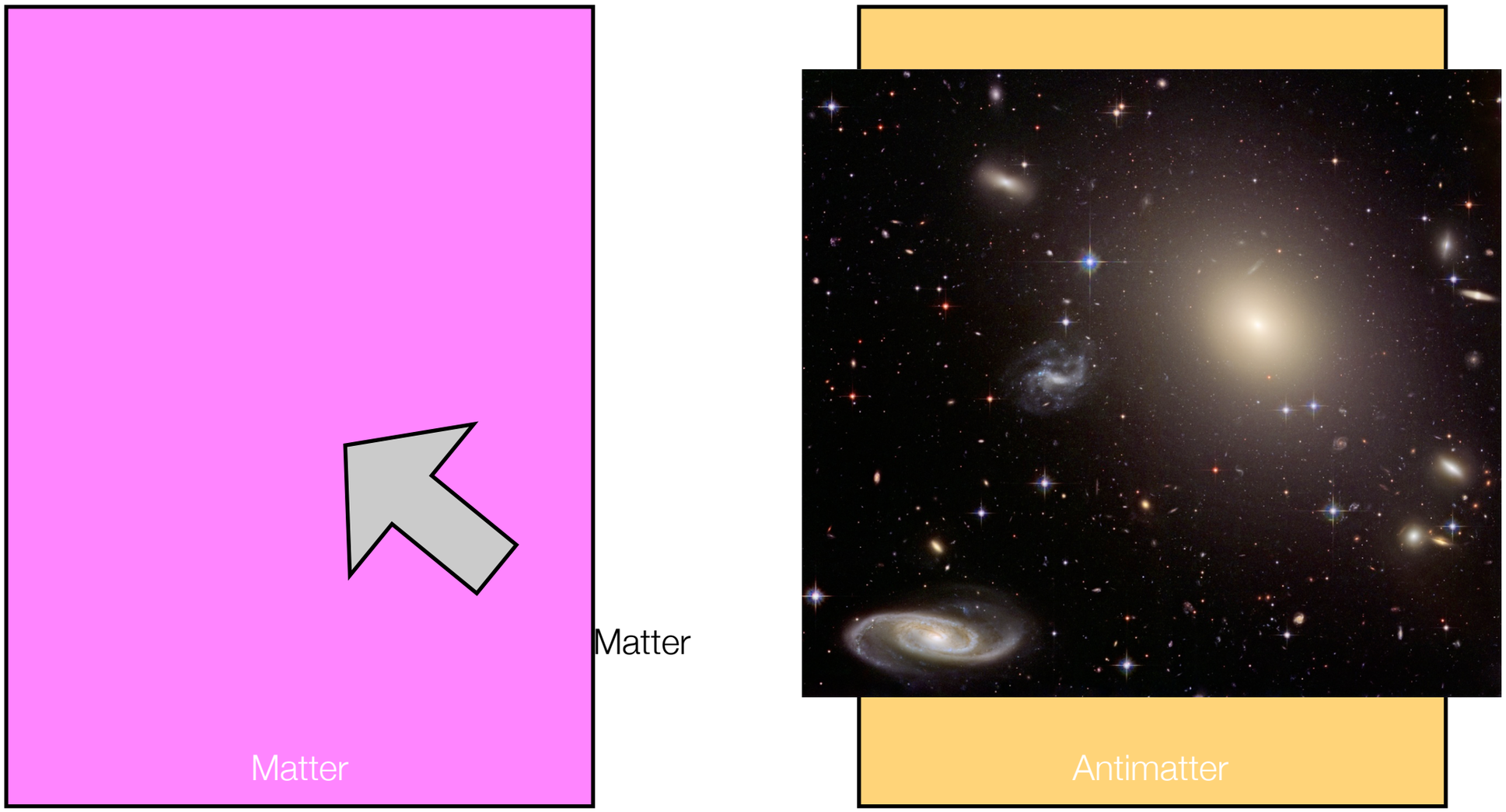
ALPHA

ALPHA Experiment @ CERN

- 17 institutions, ~60 members world-wide

What's the matter with Antimatter?

- Should be equal amounts produced at the beginning…

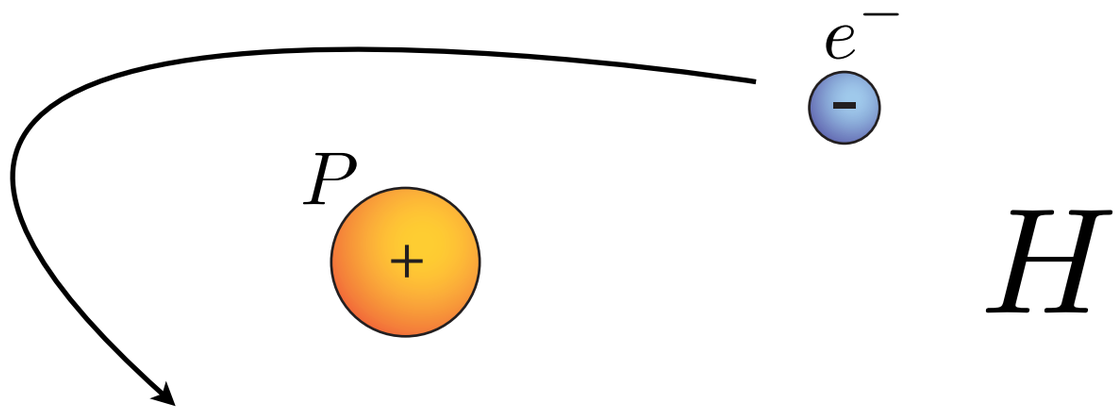


Possible Explanations: Fundamental Flaw?

- C. P. T. Symmetry?
- Weak Equivalence Principal?
- Lorentz Invariance?
- Swap Matter for Antimatter: ***uniquely sensitive***!

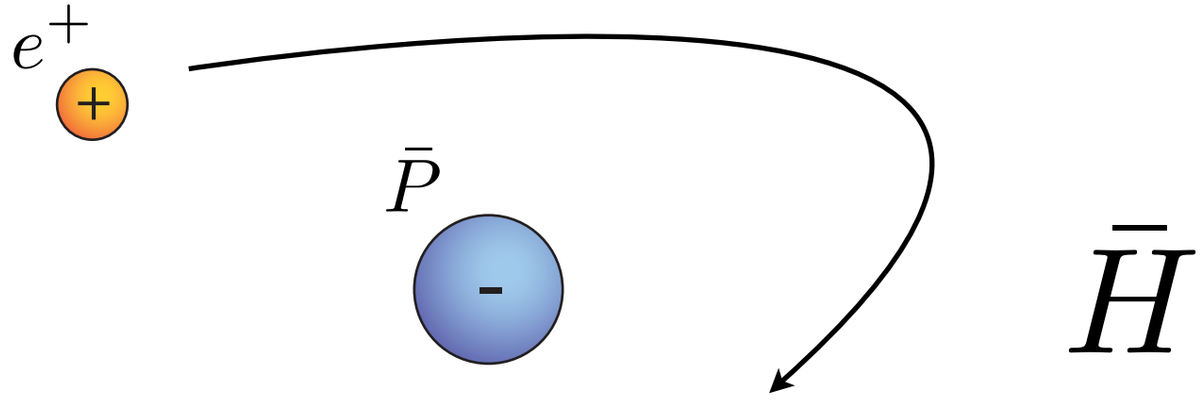
Atoms and antimatter: Hydrogen and Antihydrogen

Matter:



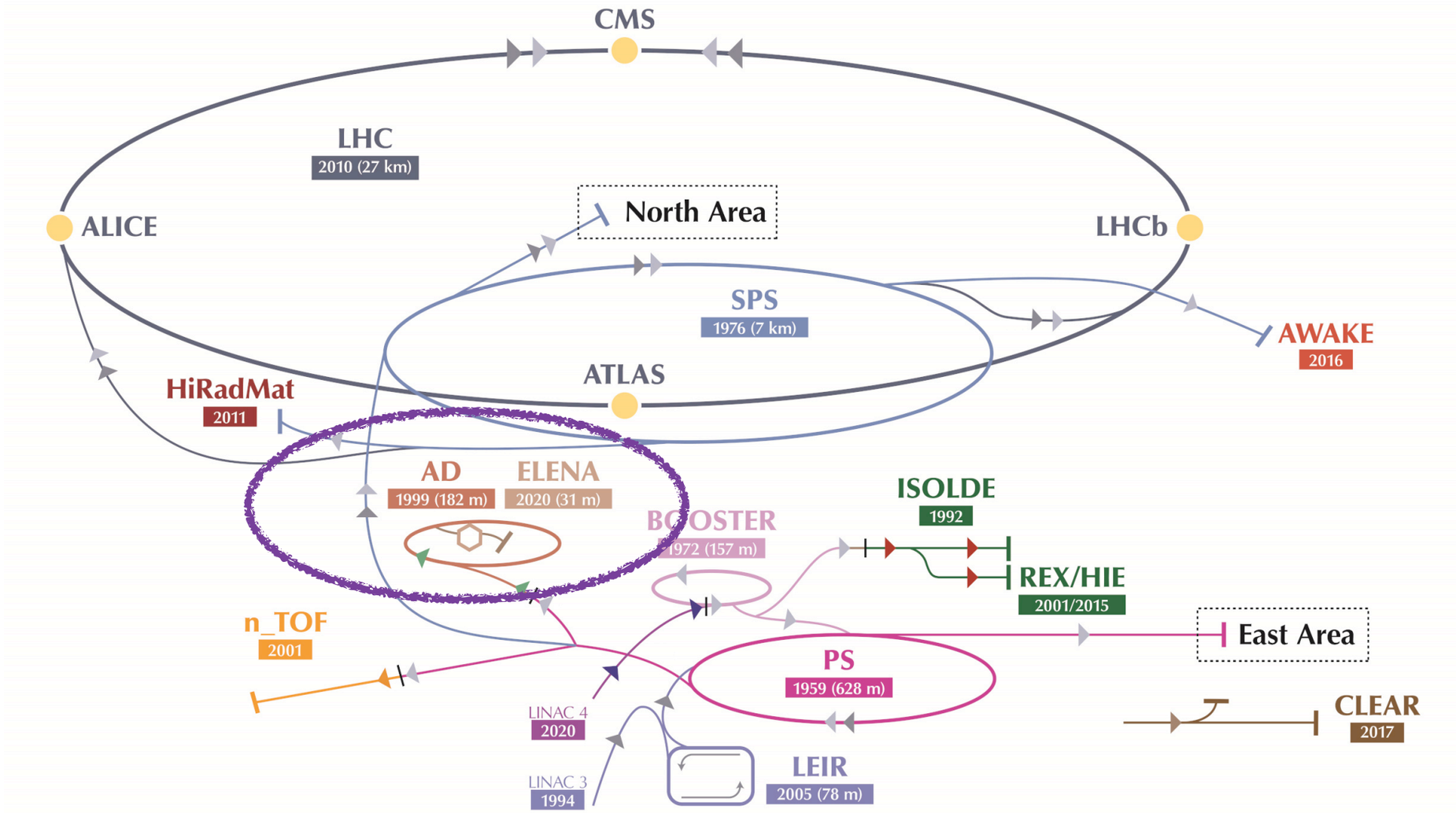
Hydrogen

Antimatter:



Antihydrogen

Antimatter sources:
Low energy antiprotons from CERN

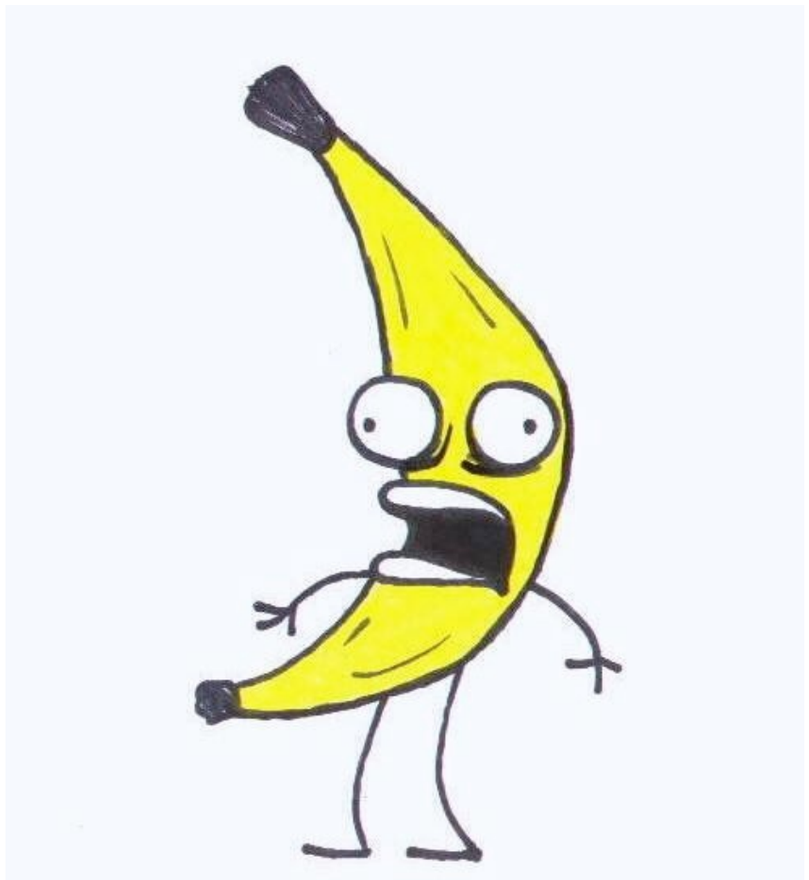


~ 5x10^6 antiprotons per minute, 1x10^5 per minute in experiment

Where do Positrons come from?

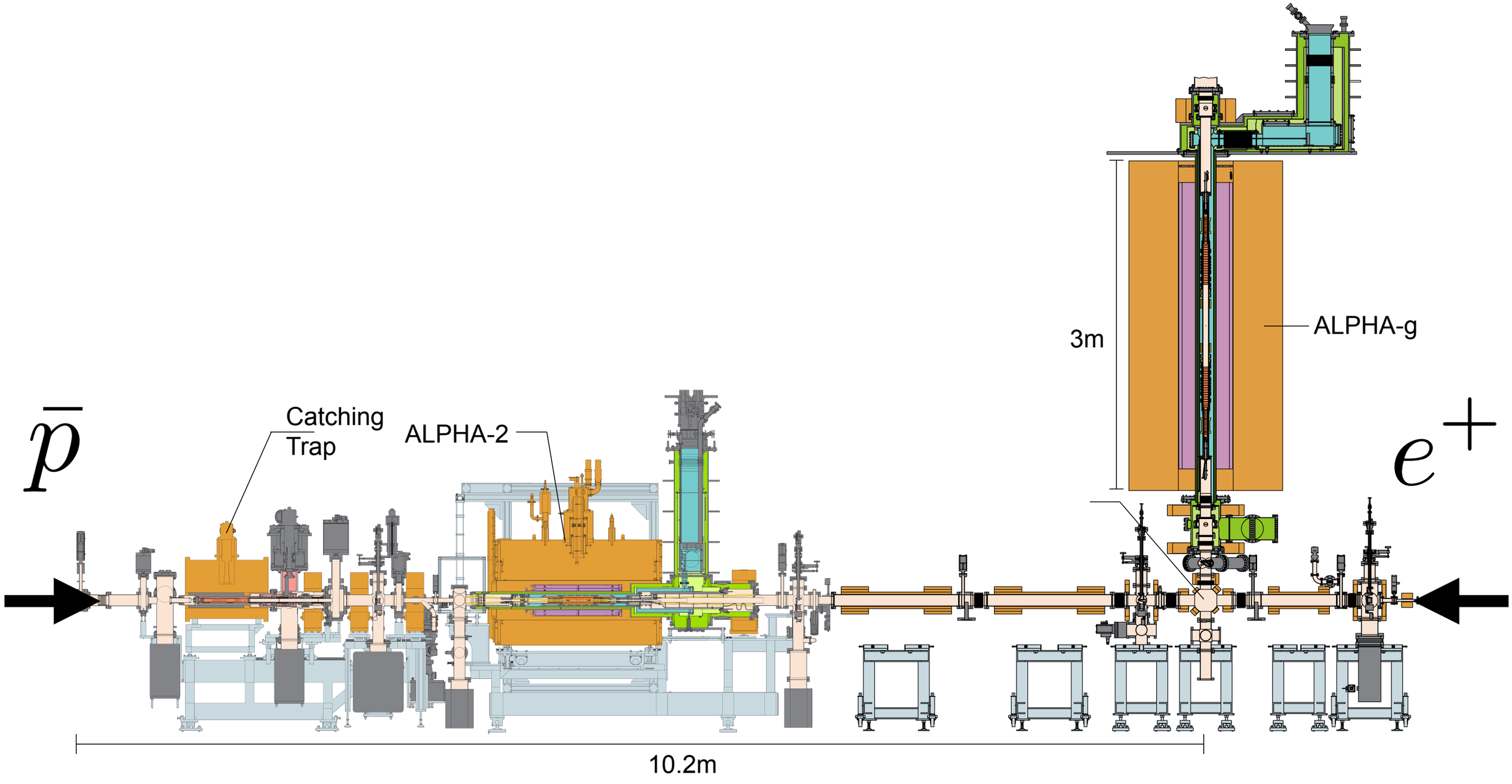
- Easy: Some radioactive isotopes

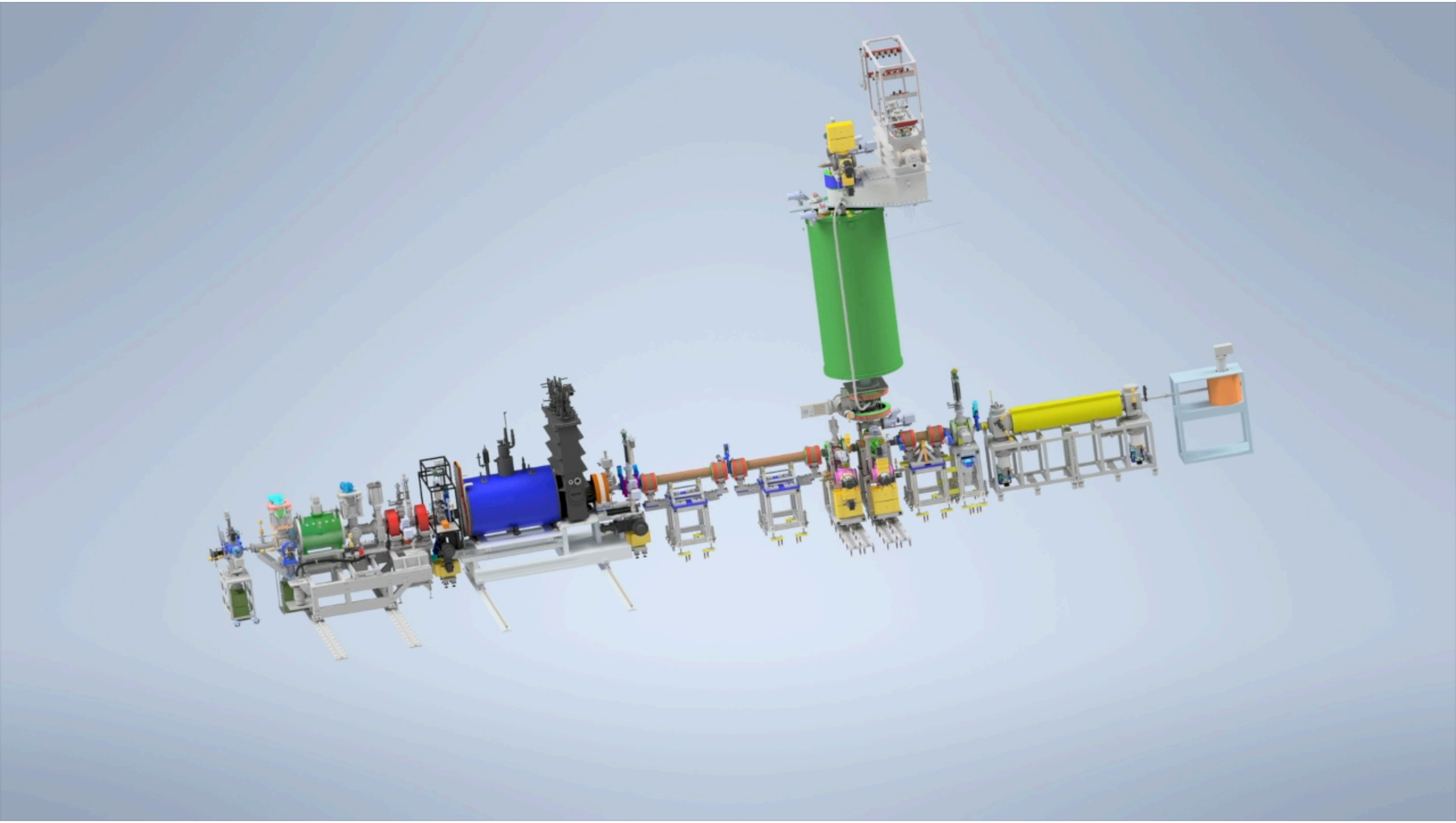
$$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^{+} + \nu_e + \gamma$$



"I am a banana!" Don Hertzfeld

ALPHA as installed, 2022





https://alpha.web.cern.ch/experimental-cycle

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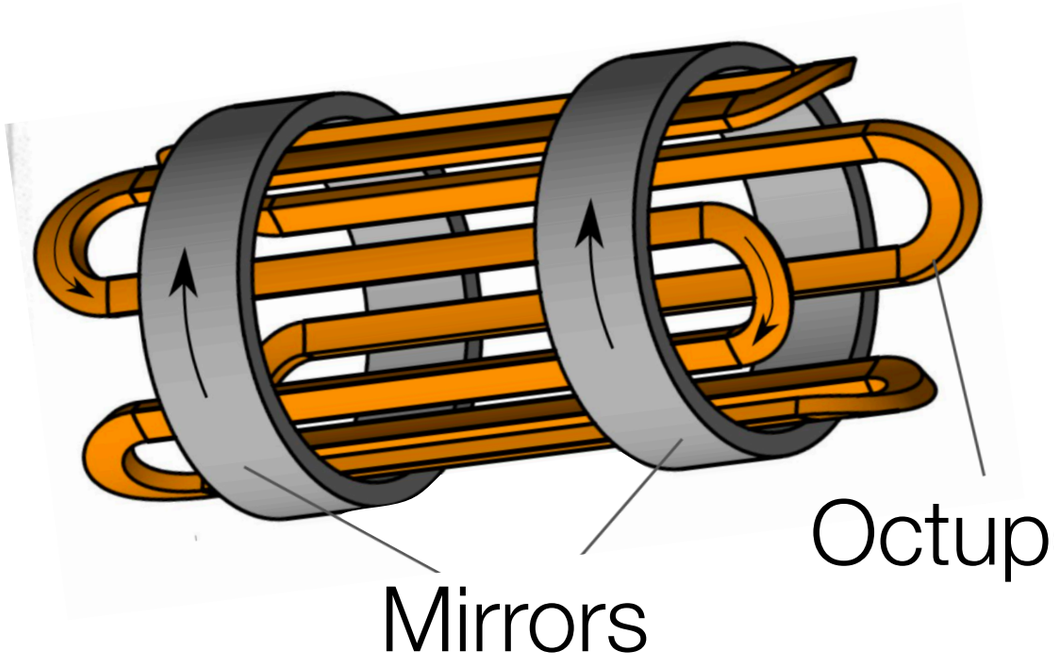
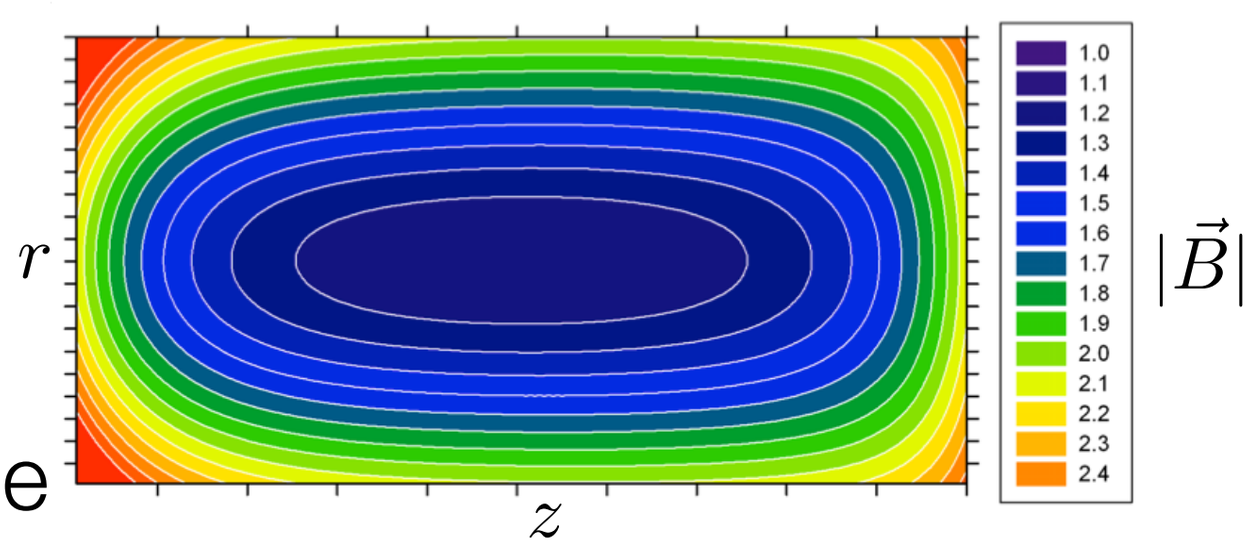
ALPHA

Trapping Antihydrogen

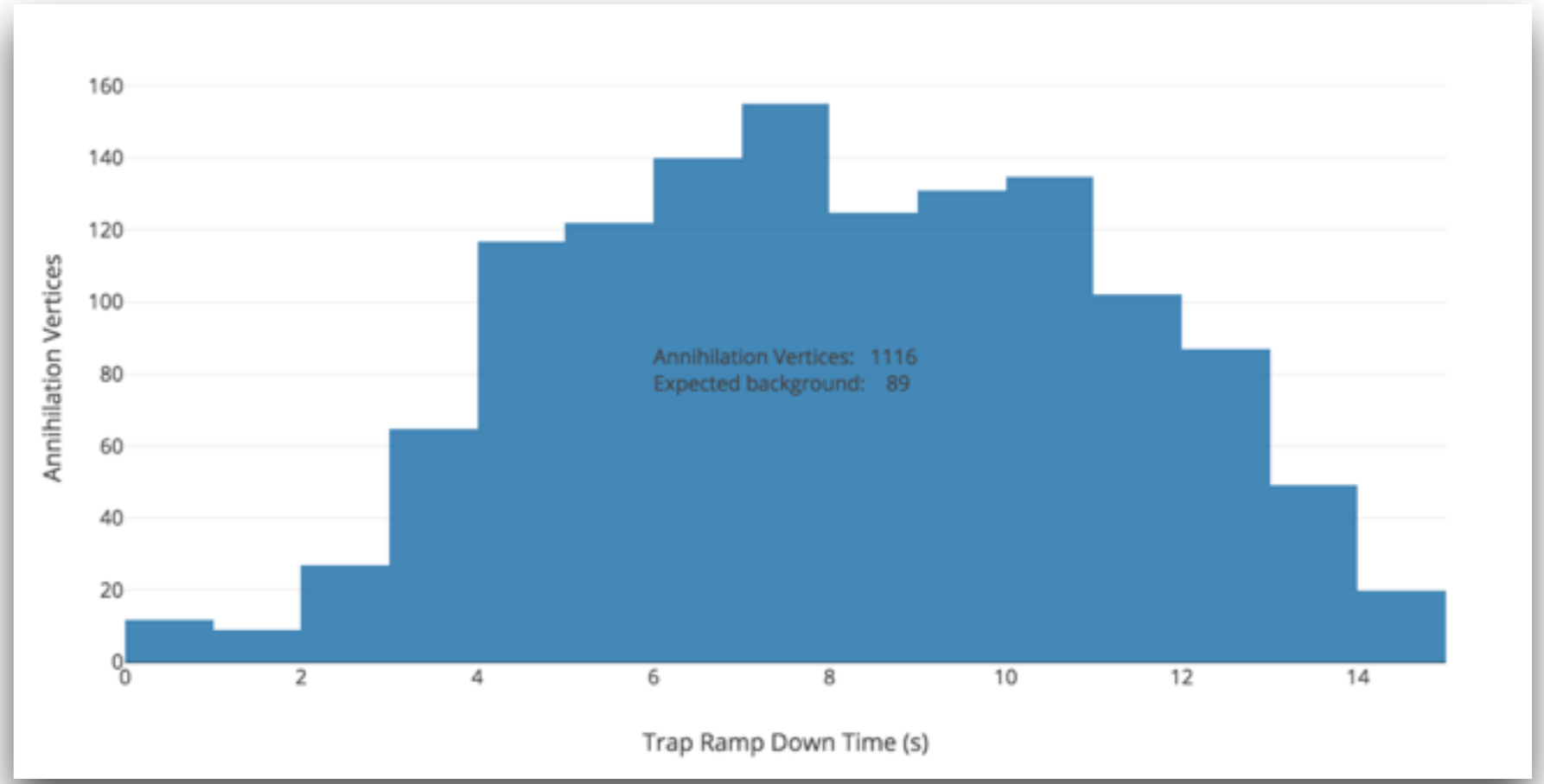
- Octupole-based ***magnetic minimum*** trap
- Low-field-seeking states are trapped
- Shallow potential well: **T < 0.5 K**





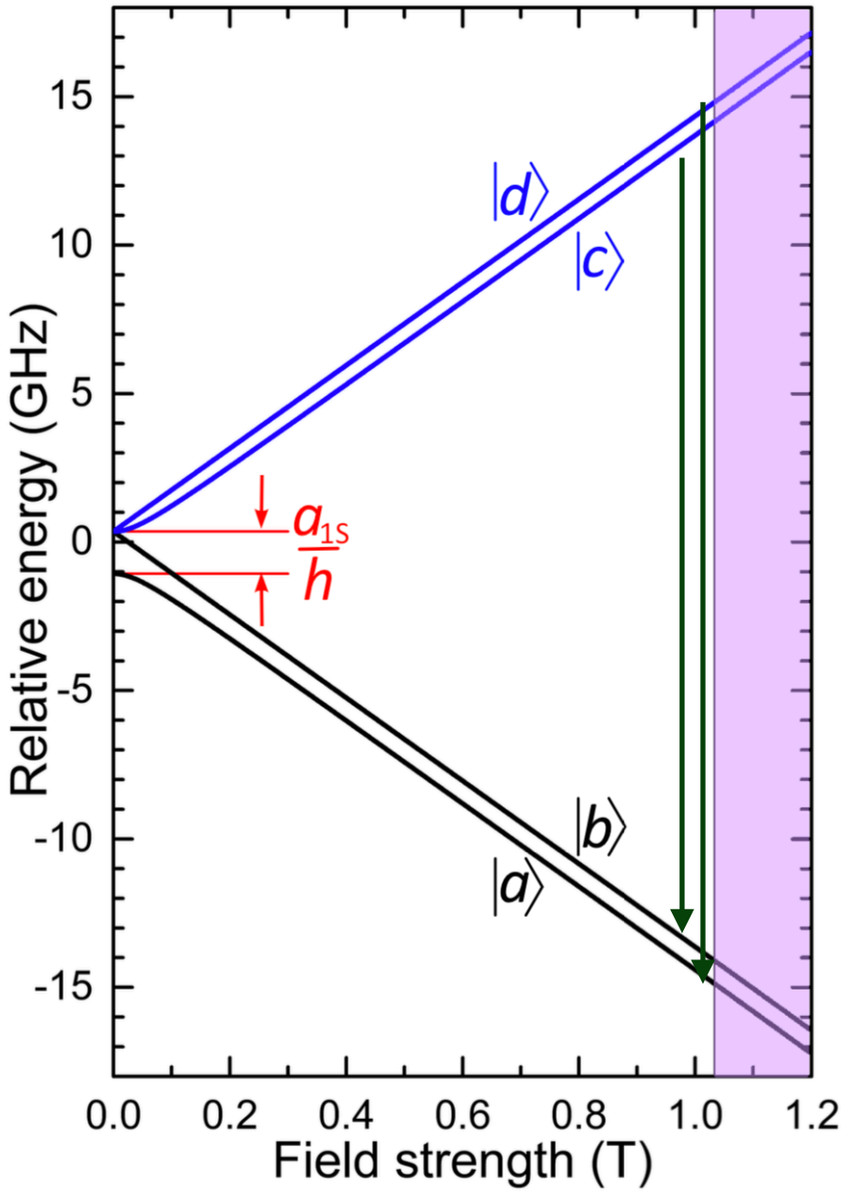
How much antihydrogen can we trap?

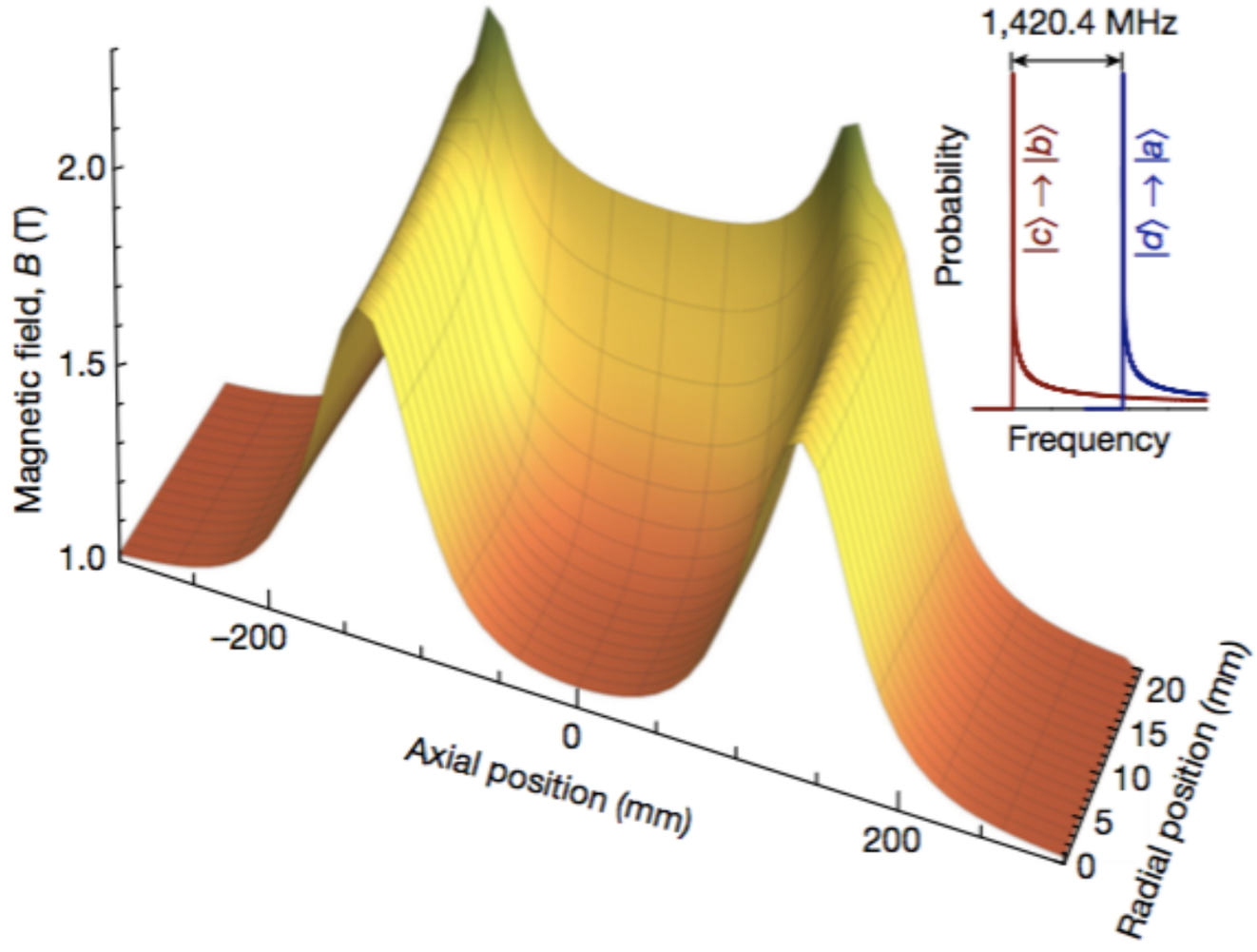
- ~1000 simultaneously trapped atoms (8 hours)



"Enhanced control and reproducibility of non-neutral plasmas." *Phys. Rev. Lett.* **120**, 025001 (2018).
"Antihydrogen accumulation for fundamental symmetry tests." *Nat. Commun.* **8**, 681 (2017).

Antihydrogen ground state hyperfine spectrum:

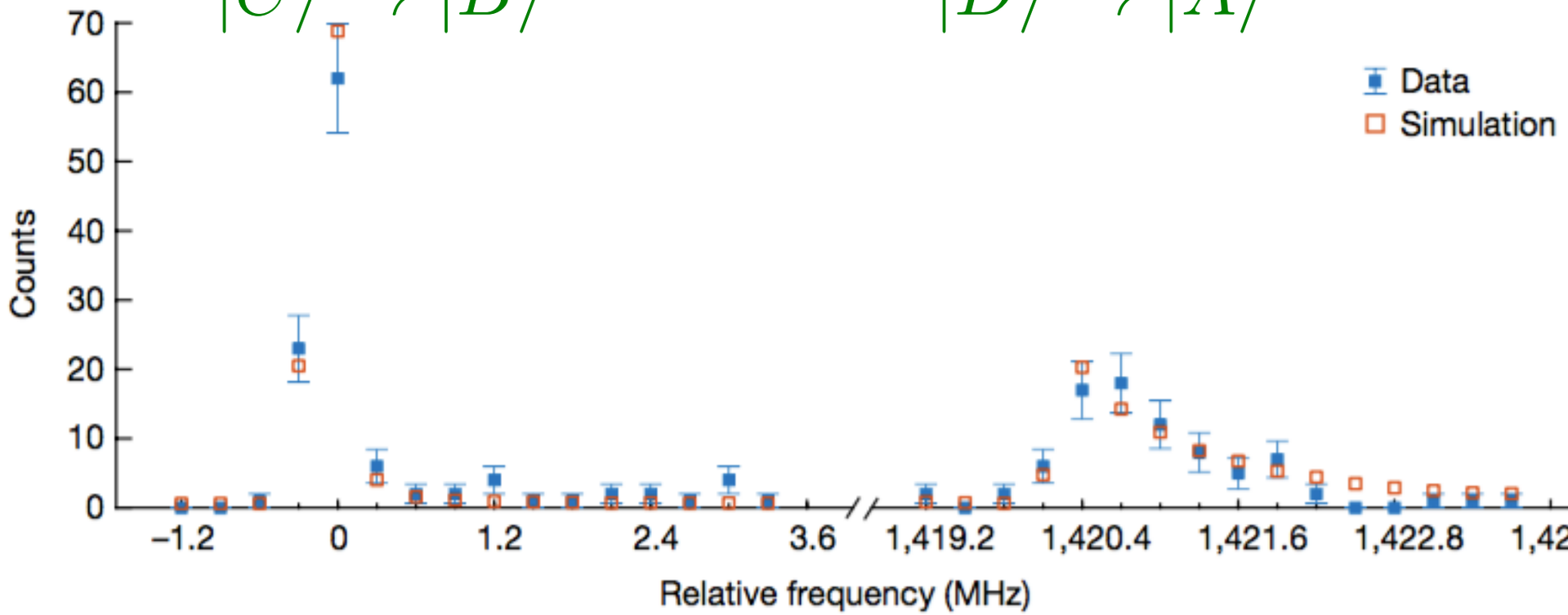




Antihydrogen hyperfine spectrum

Illuminate trap with successive microwave frequencies ~ 29 GHz
Count annihilations in each frequency bin

$|C\rangle \rightarrow |B\rangle$ $|D\rangle \rightarrow |A\rangle$

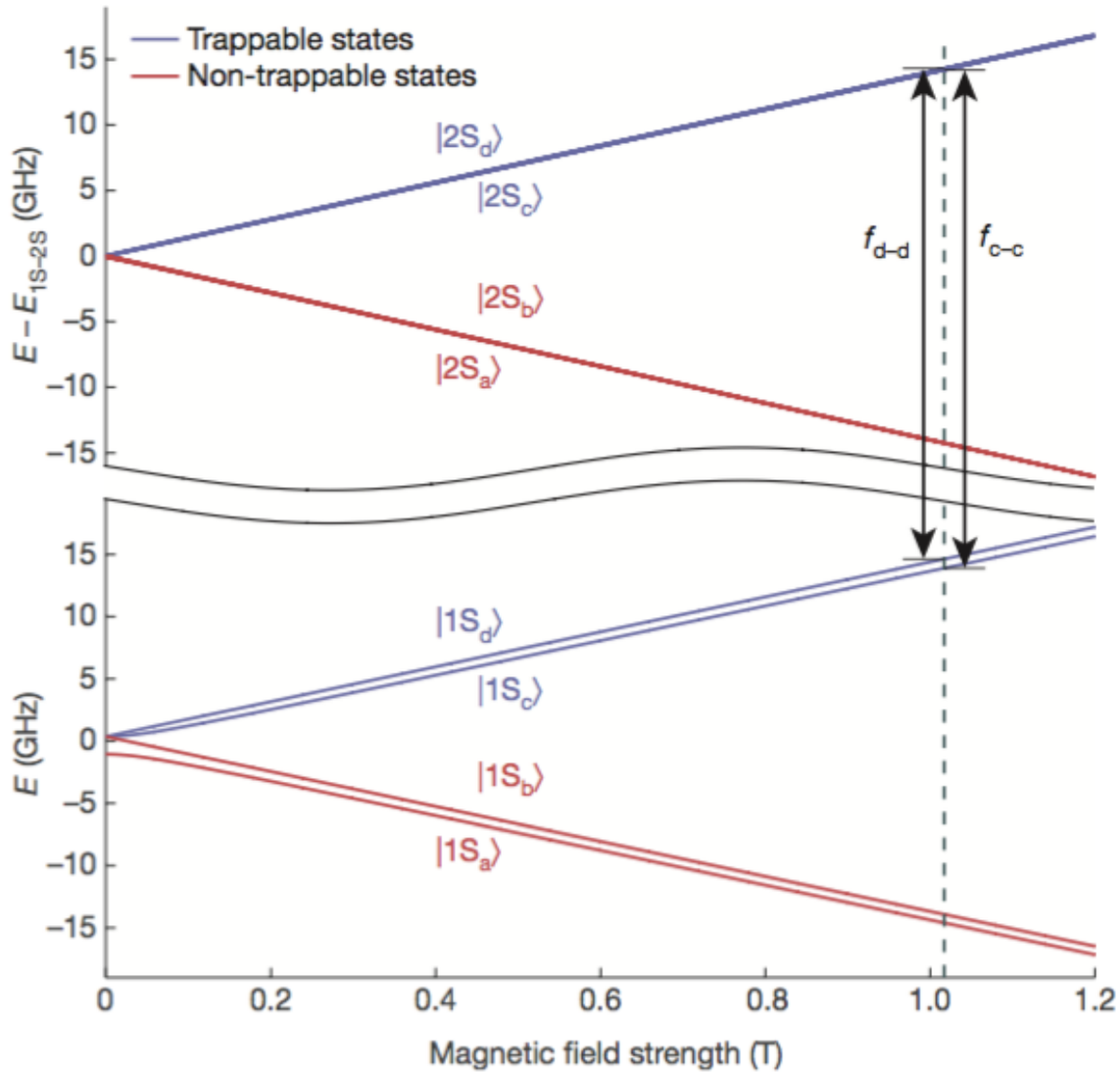


$$1,420.4 \pm 0.5\,\mathrm{MHz}$$

Ahmadi,M.*et al.* "Observation of the hyperfine spectrum of antihydrogen." *Nature* 548, 66–69 (2017).

1S - 2S Transition in (anti) hydrogen

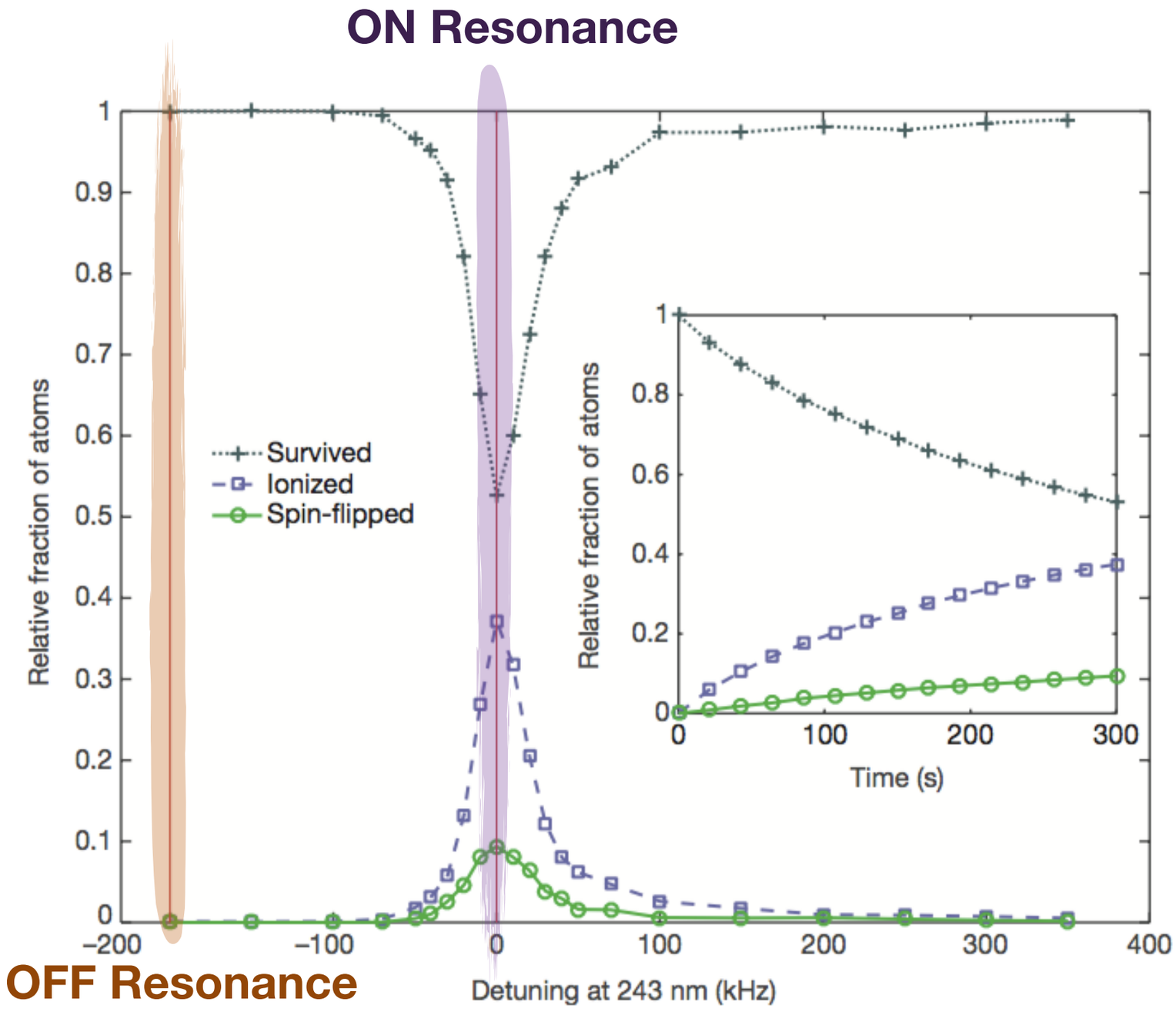
- 2 - photon Doppler-free spectroscopy (243 nm)
- Drive between trapped hyperfine states
- Compare against Hydrogen model in ALPHA trap



C. Parthey, et al. Phys. Rev. Lett. 107, 203001 (2011)

$$f_{d-d} = 2{,}466{,}061{,}103{,}064(2)\ \text{kHz}$$
$$f_{c-c} = 2{,}466{,}061{,}707{,}104(2)\ \text{kHz}$$

1S - 2S possible outcomes:
Simulations with hydrogen for **c** and **d** states

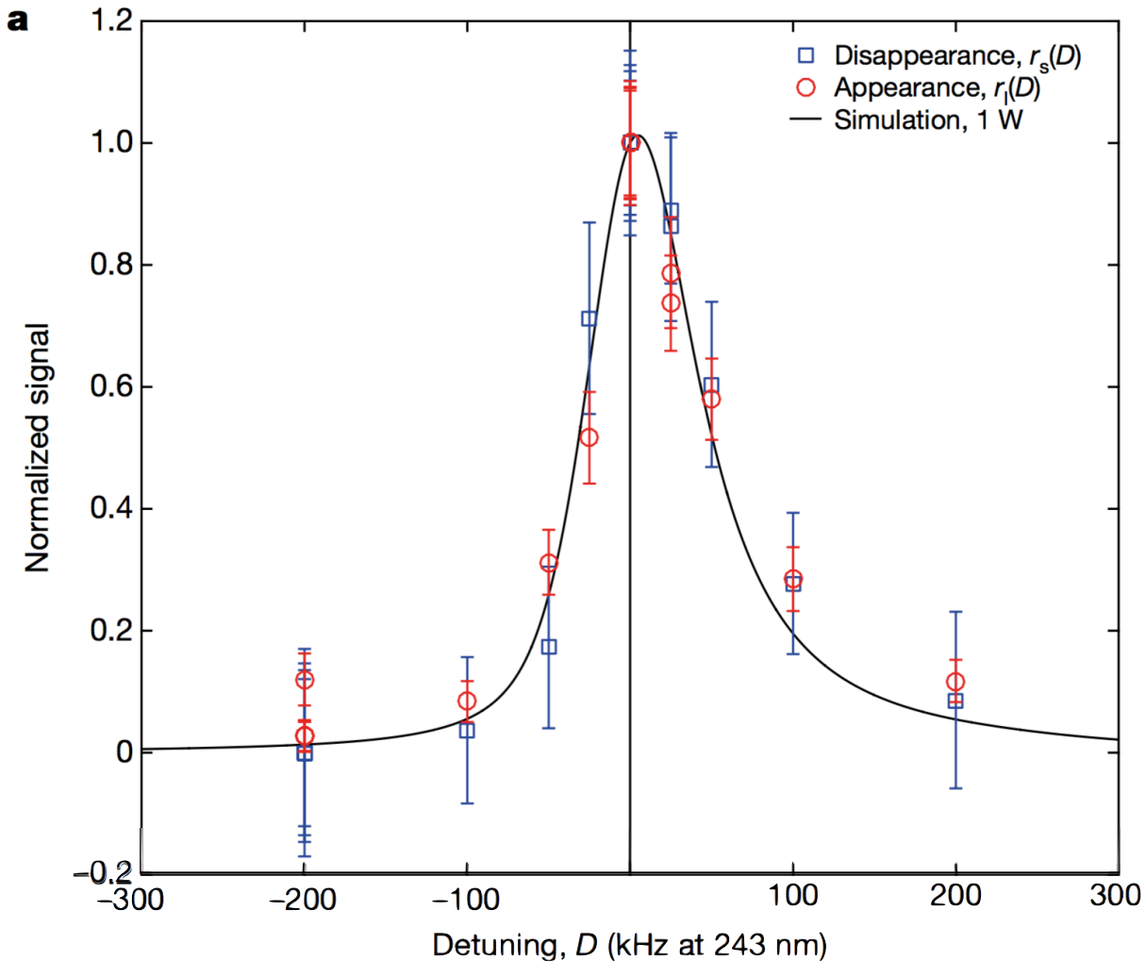


ON resonance:
47% Removal
(1 Watt circulating power)

OFF resonance:
200 kHz detuned

Precision measurements with Antihydrogen: 1S - 2S transition

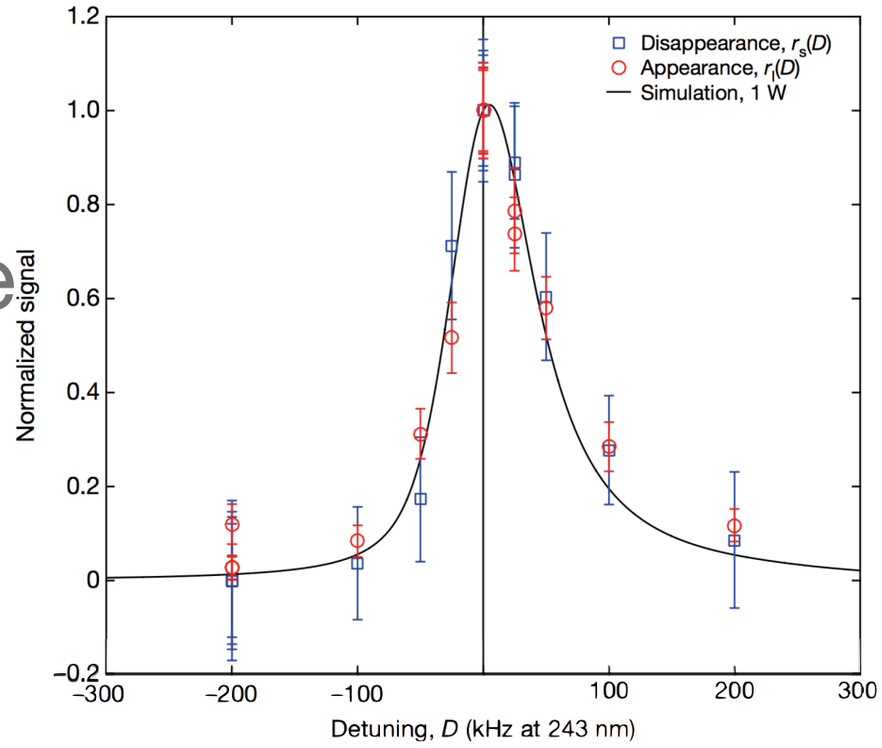
Best measurement to date (2018): CPT consistent at 2×10^{-12}



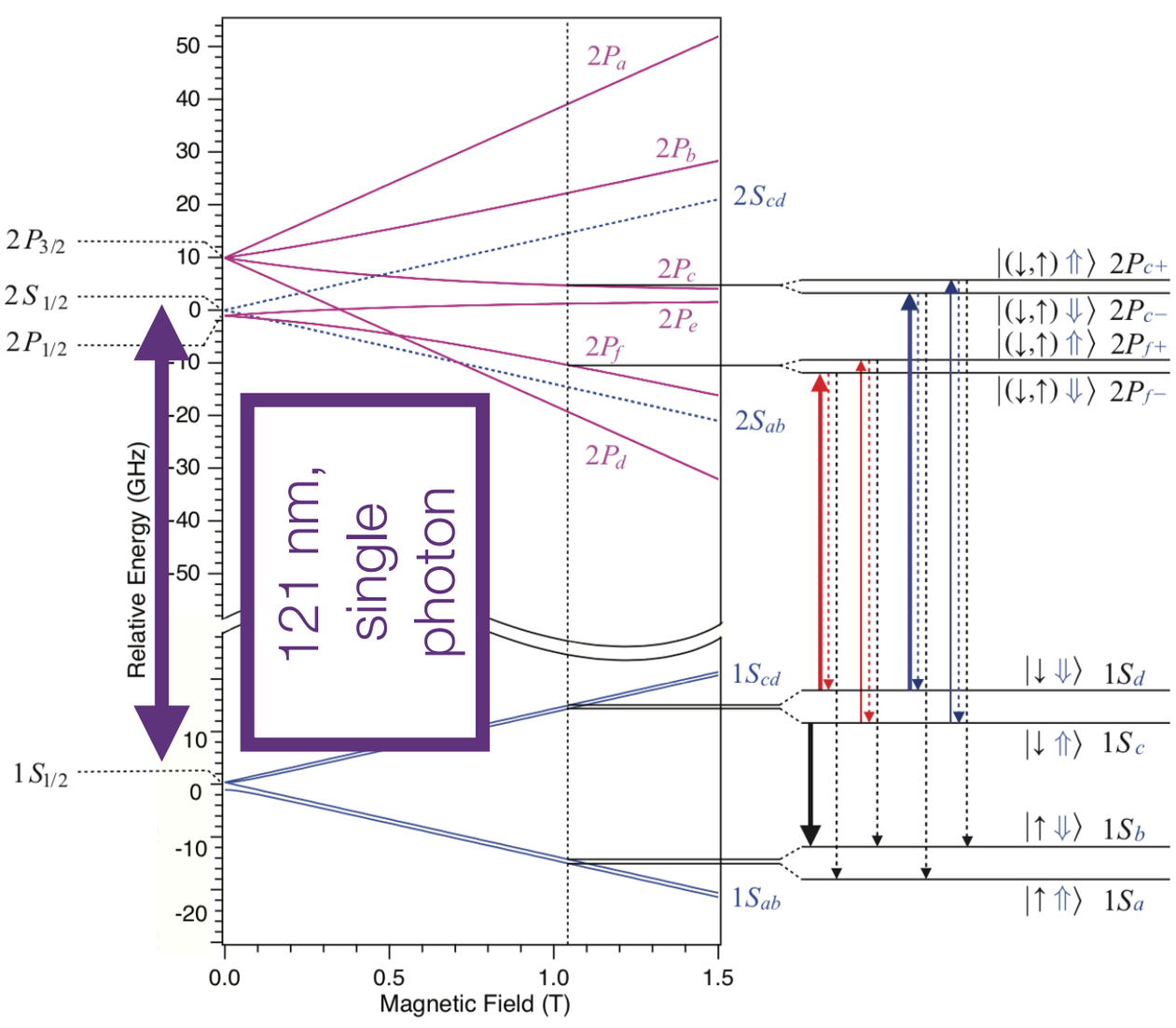
Ahmadi,M.*et al.* "Characterisation of the 1S-2S transition in antihydrogen." *Nature* 557, 71-75 (2018).

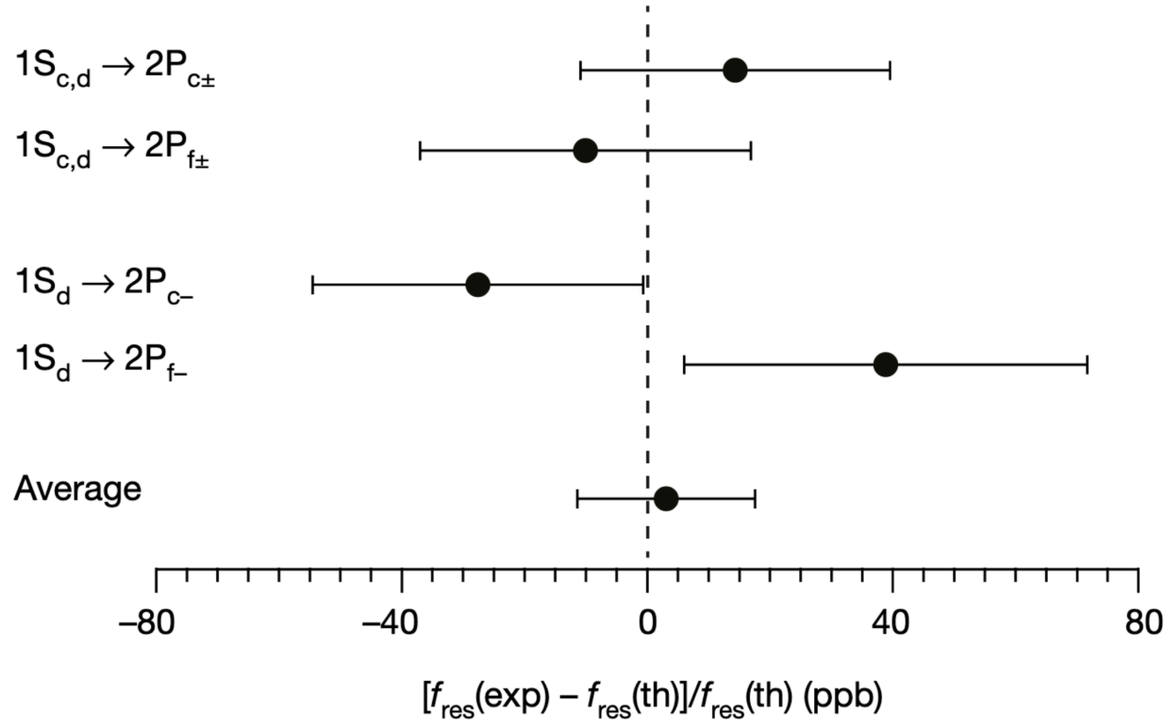
Precision measurements with Antihydrogen: 1S - 2S transition Limits

- Sample Statistics
- Temperature of antihydrogen sample
- Laser / trap volume
- Laser frequency stability
- Absolute precision of our clock (at ~ 8×10^{-13})



Antihydrogen 1S - 2P transitions: Fine structure

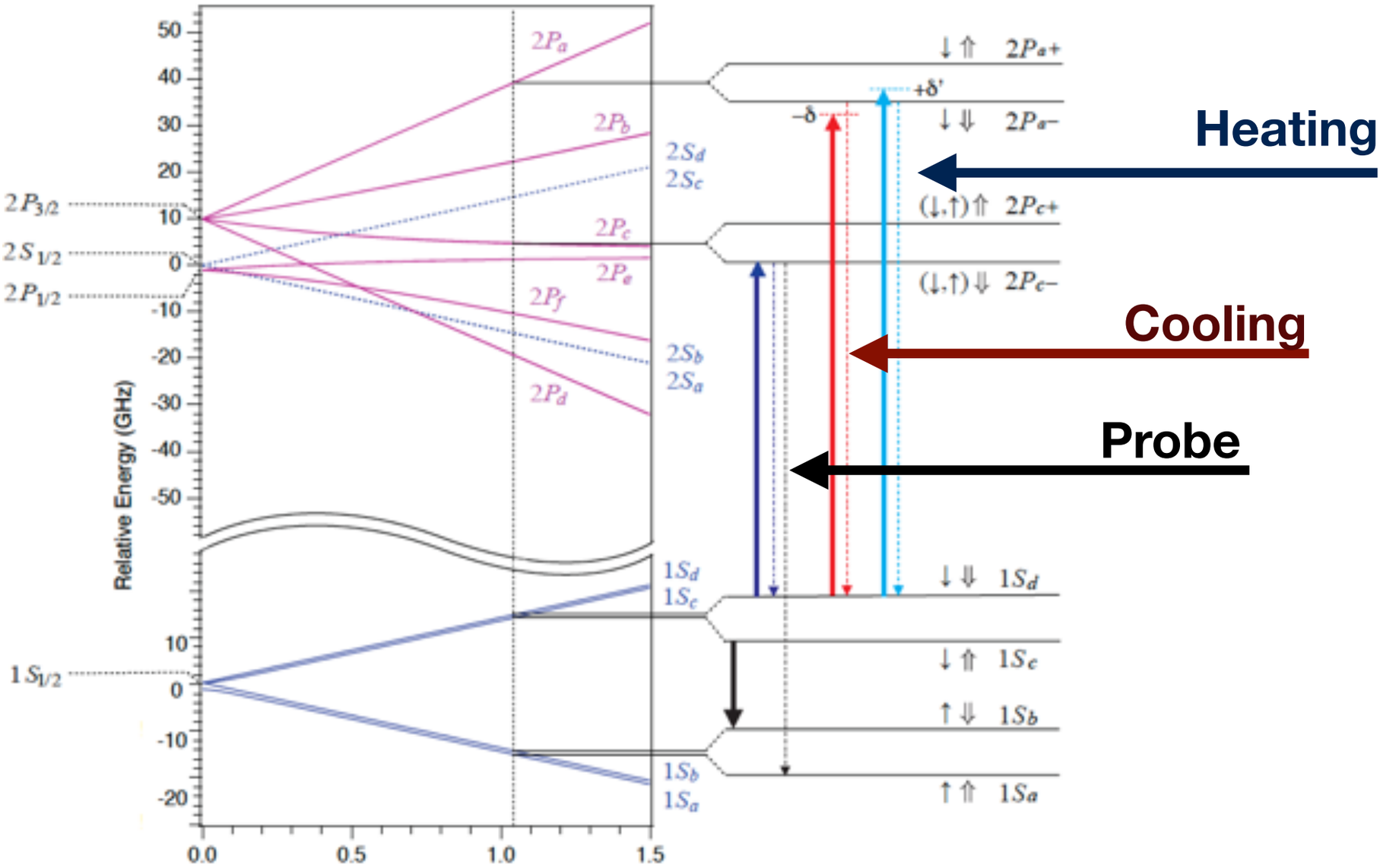




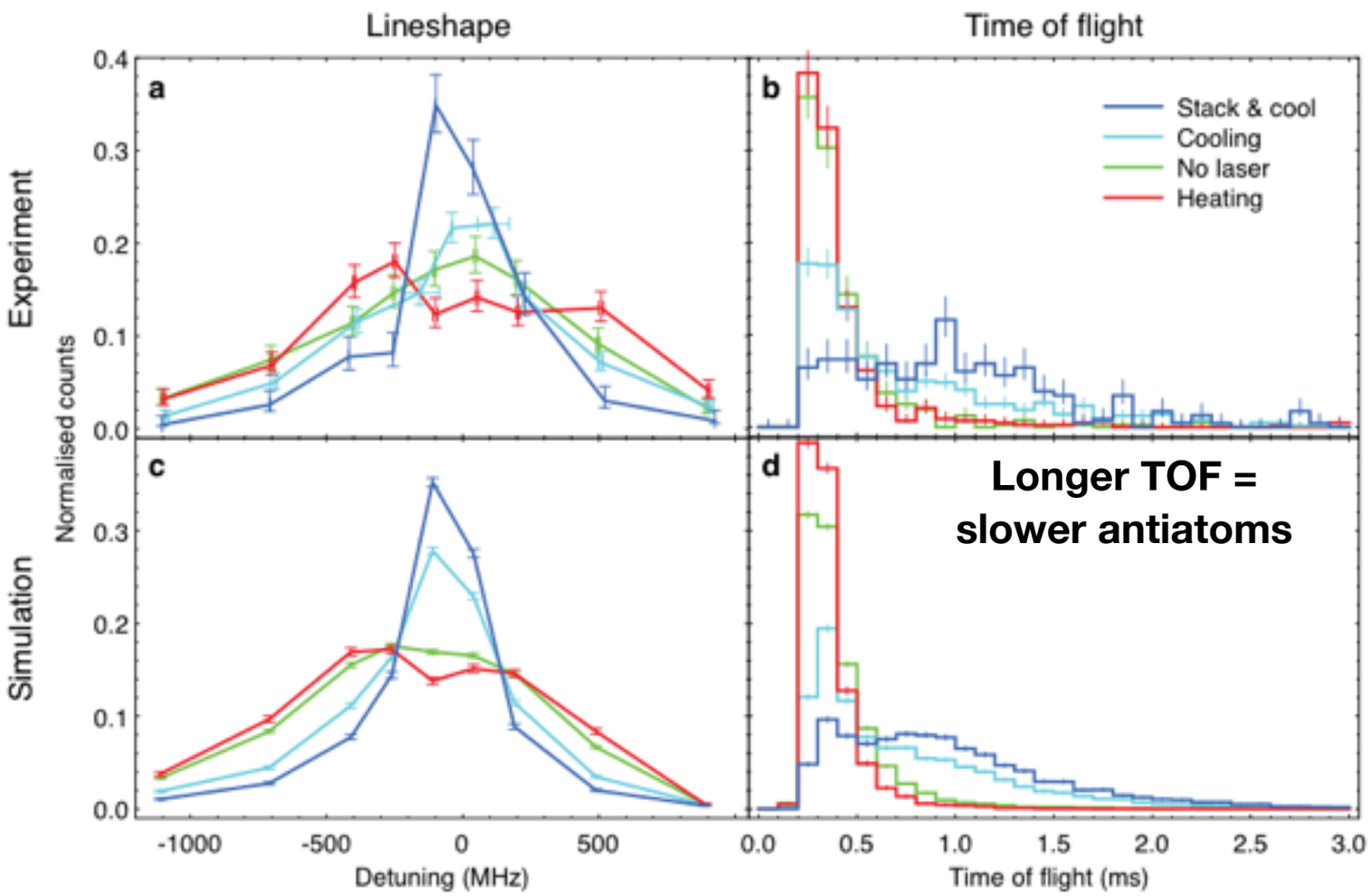
Lineshape: CPT at 20 ppb
Fine structure inferred at ~ 2%
Classic Lamb Shift inferred at ~ 11%

Ahmadi,M.*et al.* "Investigation of the fine structure of antihydrogen." *Nature* **578**, 375-380 (2020).

Antihydrogen Laser Cooling: Closed transitions



Antihydrogen Laser Cooling

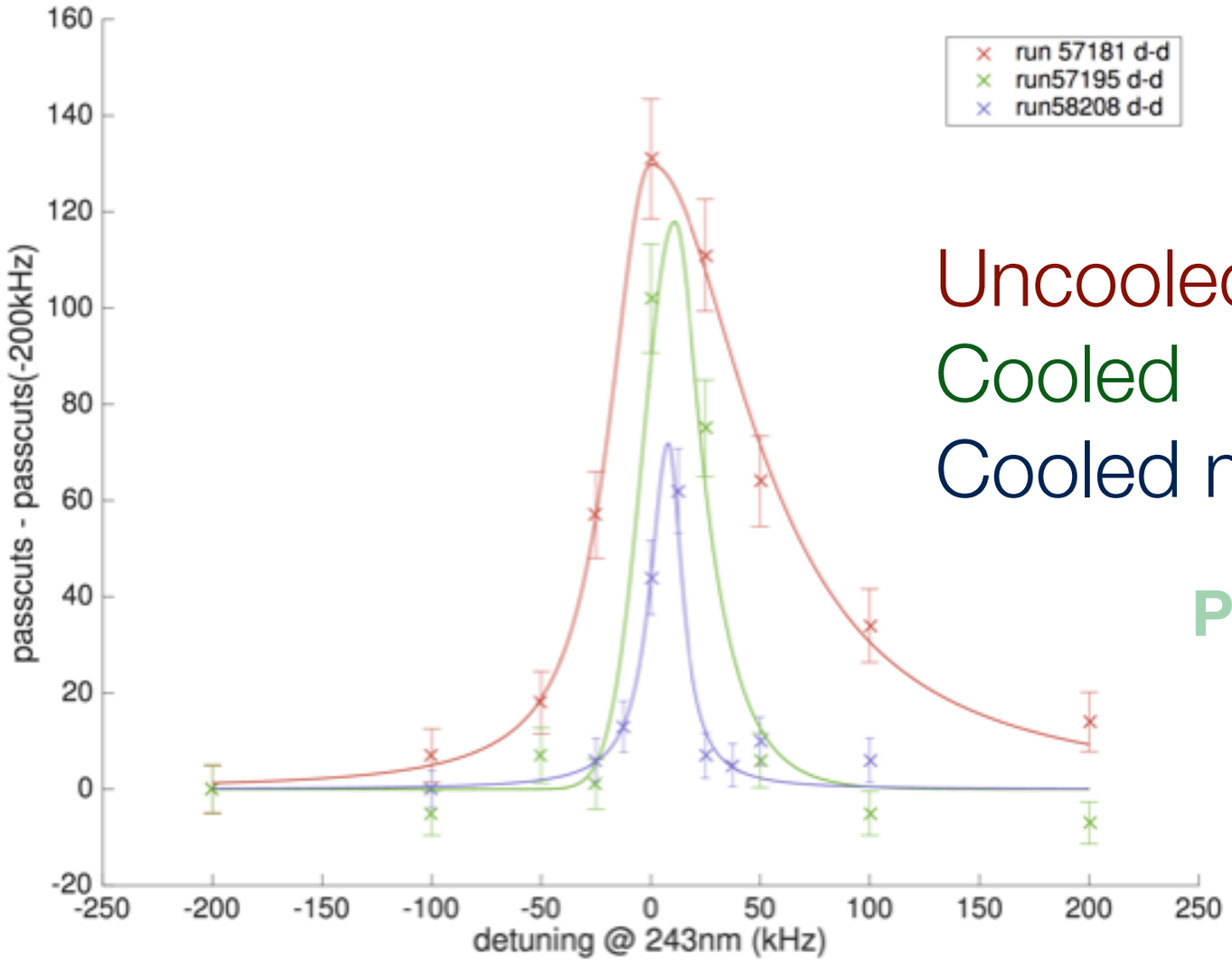


Non-thermal distribution:
Reduction of median energy by about an order of magnitude
~ 500 mK - 50 mK in about 3/4 of a day!

C. J. Baker, *et al.* "Laser cooling of antihydrogen atoms." *Nature* **592**, 35-42 (2021).

Revisit the 1S - 2S transition

- Measured lineshape is *narrower*



Uncooled (previously)

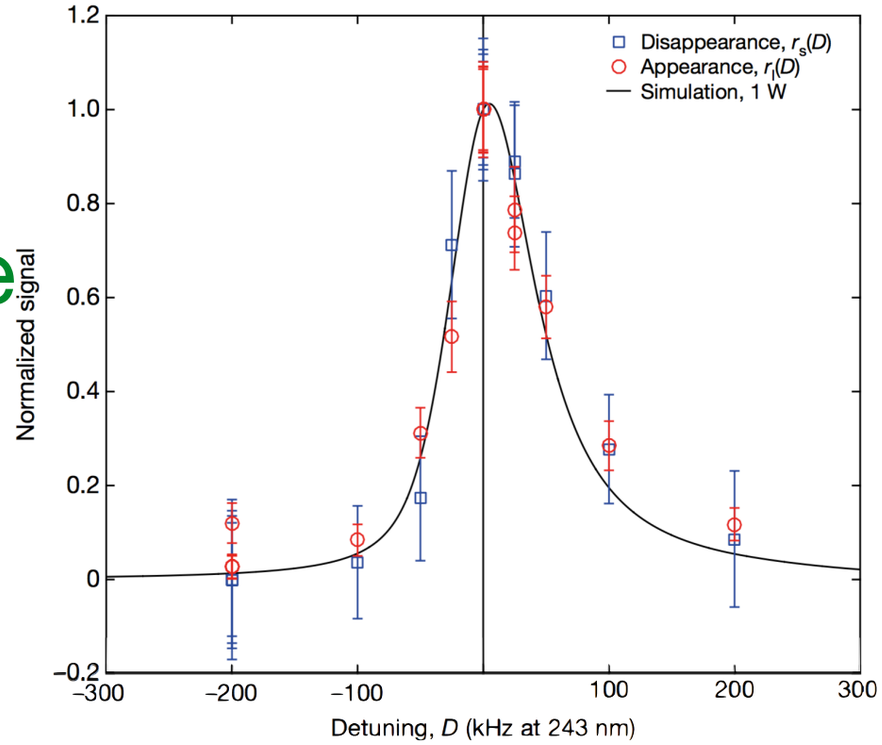
Cooled

Cooled more (small sample)

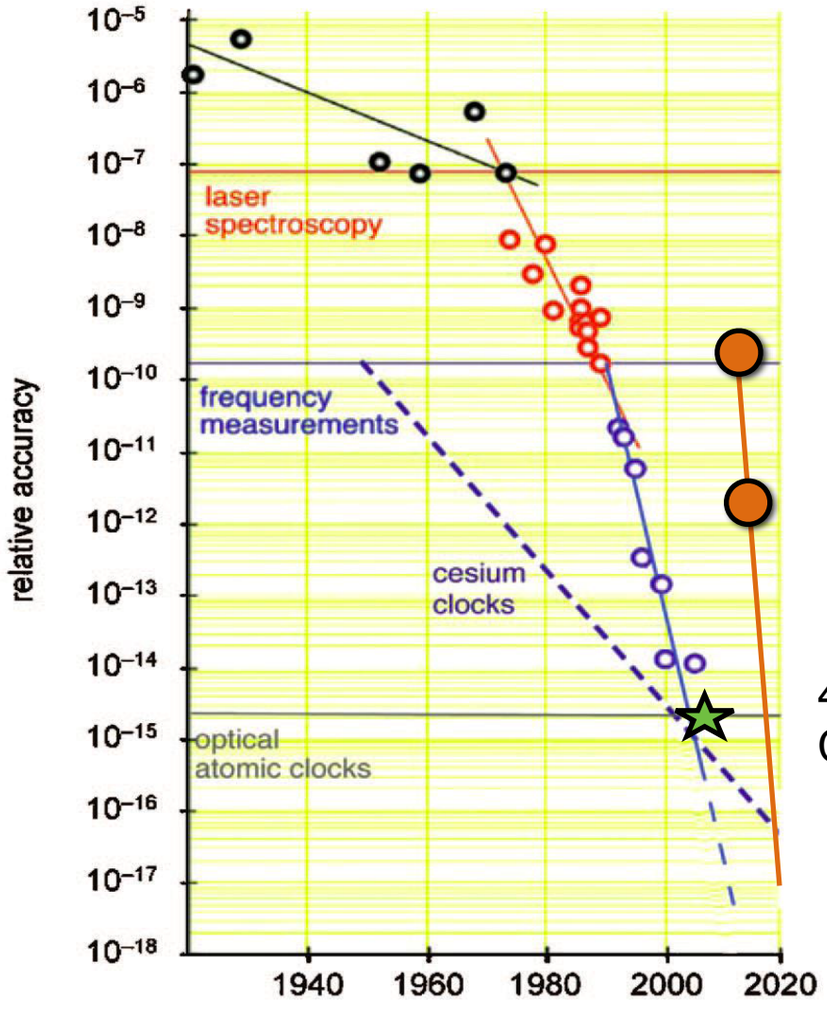
PRELIMINARY

Precision measurements with Antihydrogen: 1S - 2S transition Limits

- Sample Statistics
  - Improved trapping techniques
- Temperature of antihydrogen sample
  - Laser cooling
- Laser / trap volume
  - Improvements to laser cavity
- Laser frequency stability
  - Upgrade of clock reference (maser)
- Absolute precision of our clock (at ~ 8×10^{-13})
  - Local Cs fountain clock: a few 10^{-16}



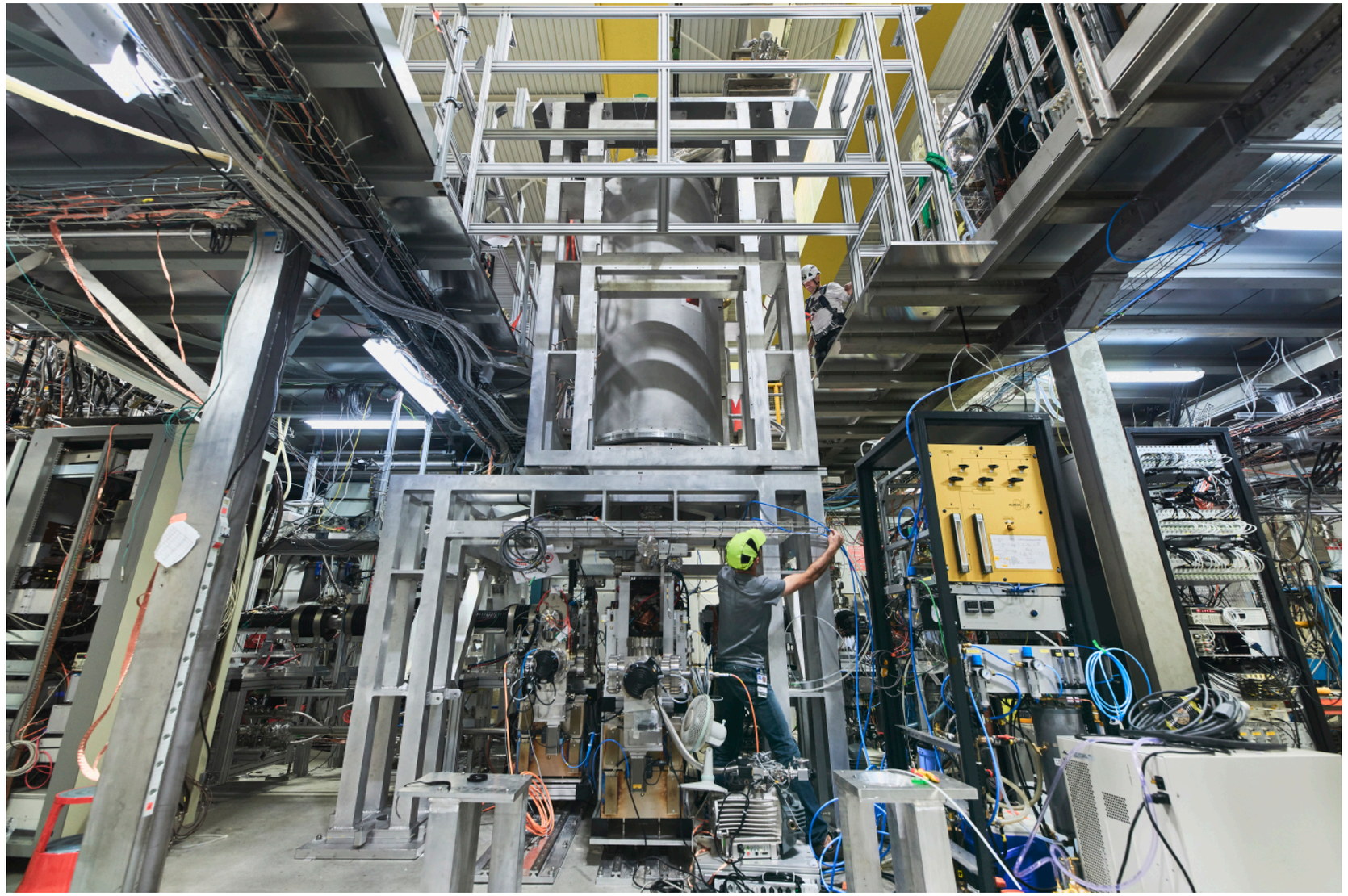
Hydrogen vs. Antihydrogen: 1S - 2S



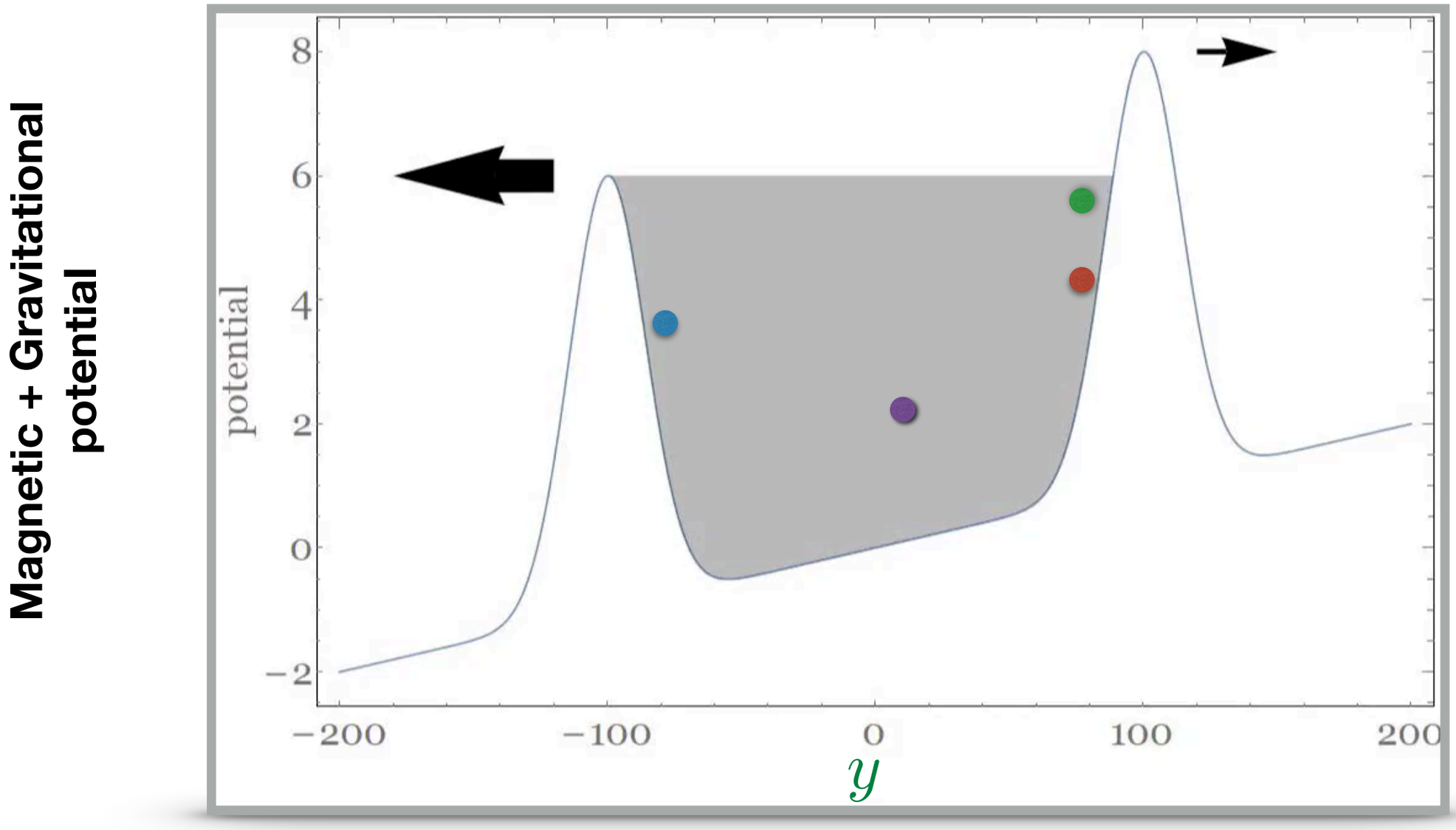
4.2×10^{-15}
C. G. Parthey et al., PRL **107**, 203001 (2011)

T. W. Hänsch, Rev. Mod. Phys. **78** 1297 (2005)
M. Ahmadi, et al. “Observation of the 1S-2S transition in trapped antihydrogen”. *Nature* **541**, 506 (2017)
M. Ahmadi, et al. “Characterization of the 1S-2S transition in antihydrogen”. *Nature* **557**, 71 (2018)

ALPHA-g: an antimatter gravity experiment

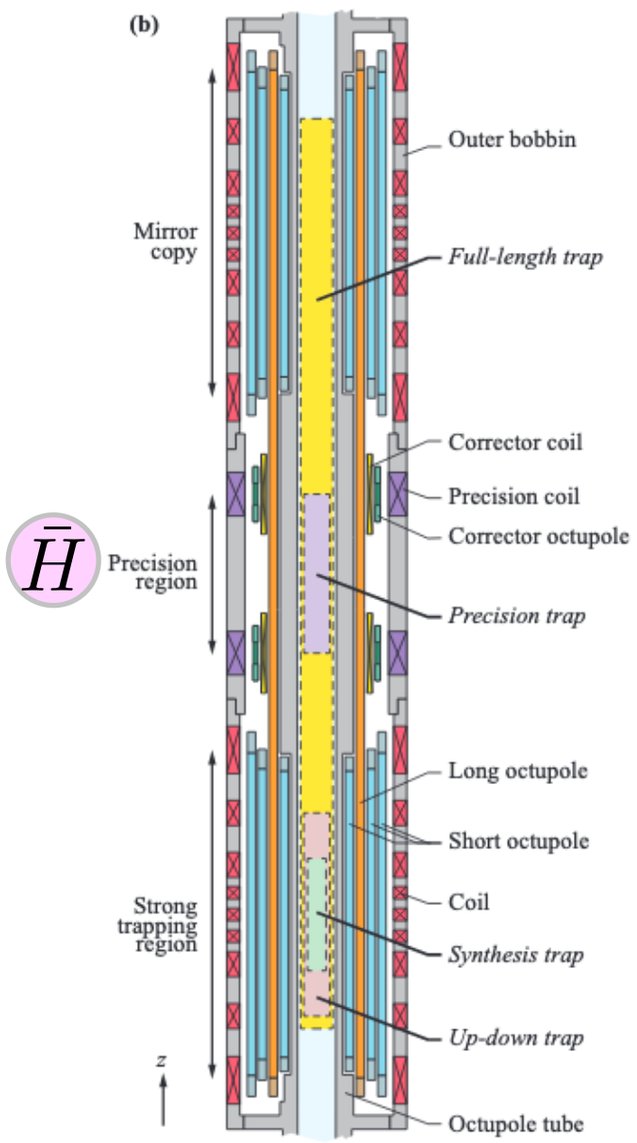


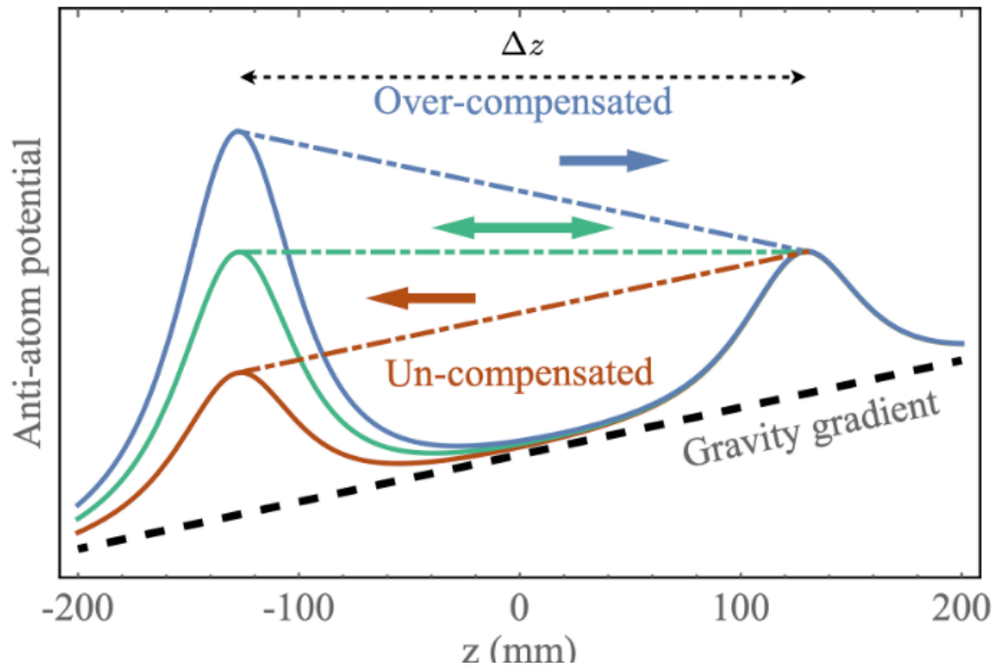
A simple Up / Down measurement

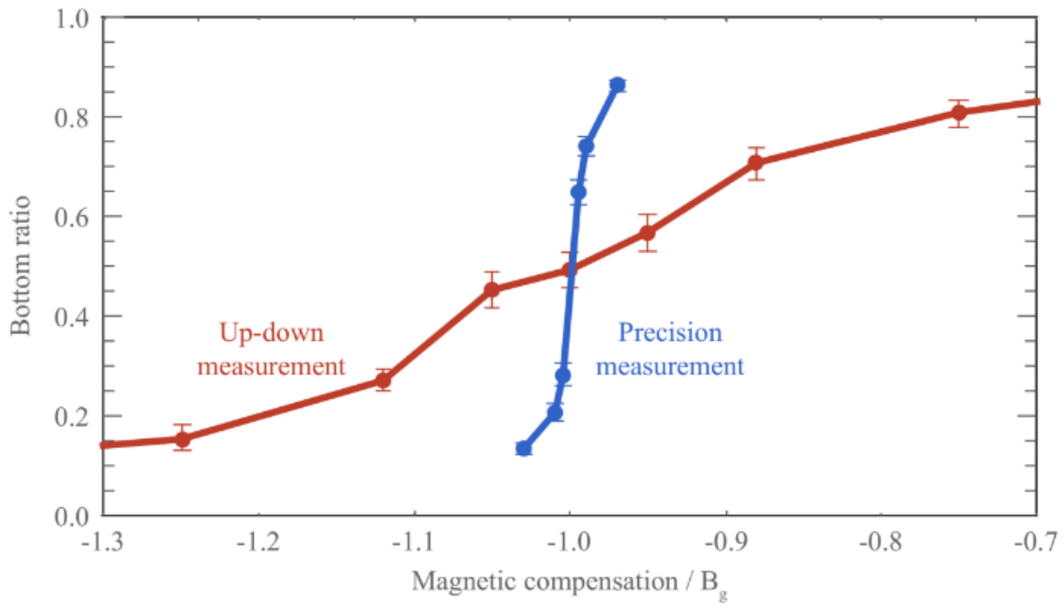


W. Bertsche, “Prospects for comparison of matter and antimatter gravitation with ALPHA-g”, RSTA, 376, 2116, 2018

ALPHA-g Measurement Scheme





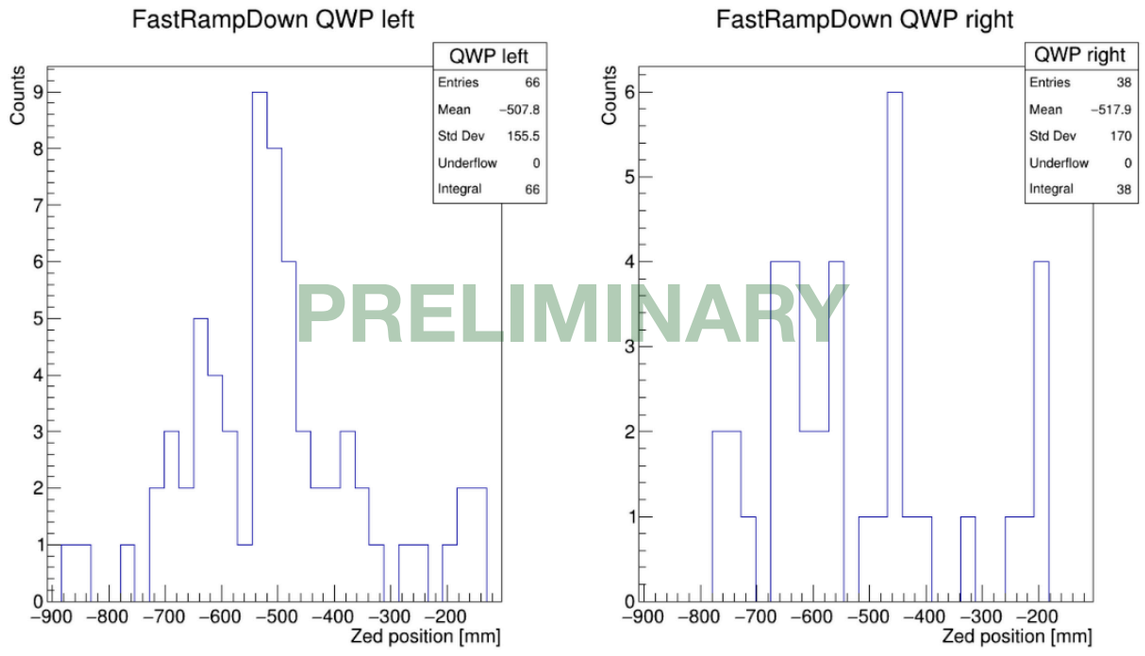


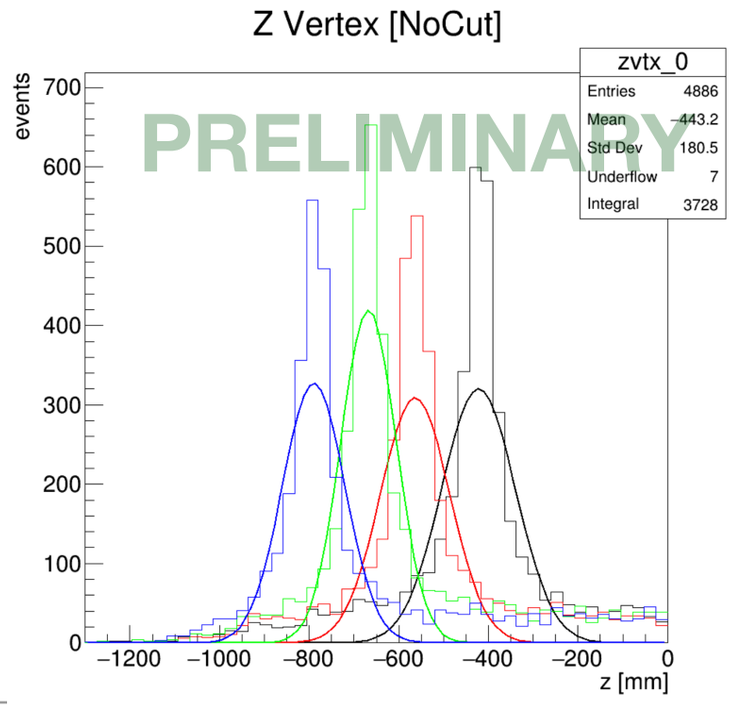
Up/Down Test:
"Antigravity"

Precision Test:
Measure *g*
To 1%

ALPHA-g commissioning

- Beamlines, traps, detectors commissioned in 2018
- Components repaired and upgraded (CERN LS-2)
- June 6, 2022: First antihydrogen production
- July 4, 2022: first trapping evidence
- To-date: systematic field and detector studies





Summary to date

Highest precision CPT measurements to date

- 1S - 2S to ~ 2 ppt
- 1S - 2P to ~ 20 ppb
- Hyperfine splitting ~400 ppm
- Fine structure constant (inferred) ~ 2%
- Lamb shift (inferred) ~ 11%
- Laser cooling of antihydrogen atoms
- Improved line shape of 1S-2S *(pub pending)*

Prospects: 2022-2025

- Hydrogen-level precision on 1S-2S
- Antimatter gravitation: ALPHA-g
  - Up / Down test
  - Precision measurement at 1%
- New spectroscopy efforts
  - Direct Lamb shift measurements,
  - Direct Ground State Hyperfine Splitting measurement
- Frame-dependent measurements
  - Complete measurements in fixed time-frames
  - (Earths position in solar system)