Antihydrogen Spectroscopy and Antimatter Gravity in ALPHA

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Motivations

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Spaceships!

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(Sadly, not practical)

Motivations

Antimatter allows for direct tests of fundamental symmetries and may hold clues to some of the biggest unanswered questions in physics:

- Why is there no antimatter in the Universe (Baryon asymmetry)
- Is CPT symmetry conserved?
- Does the weak equivalence principle hold for antimatter?

1S-2S Spectroscopy

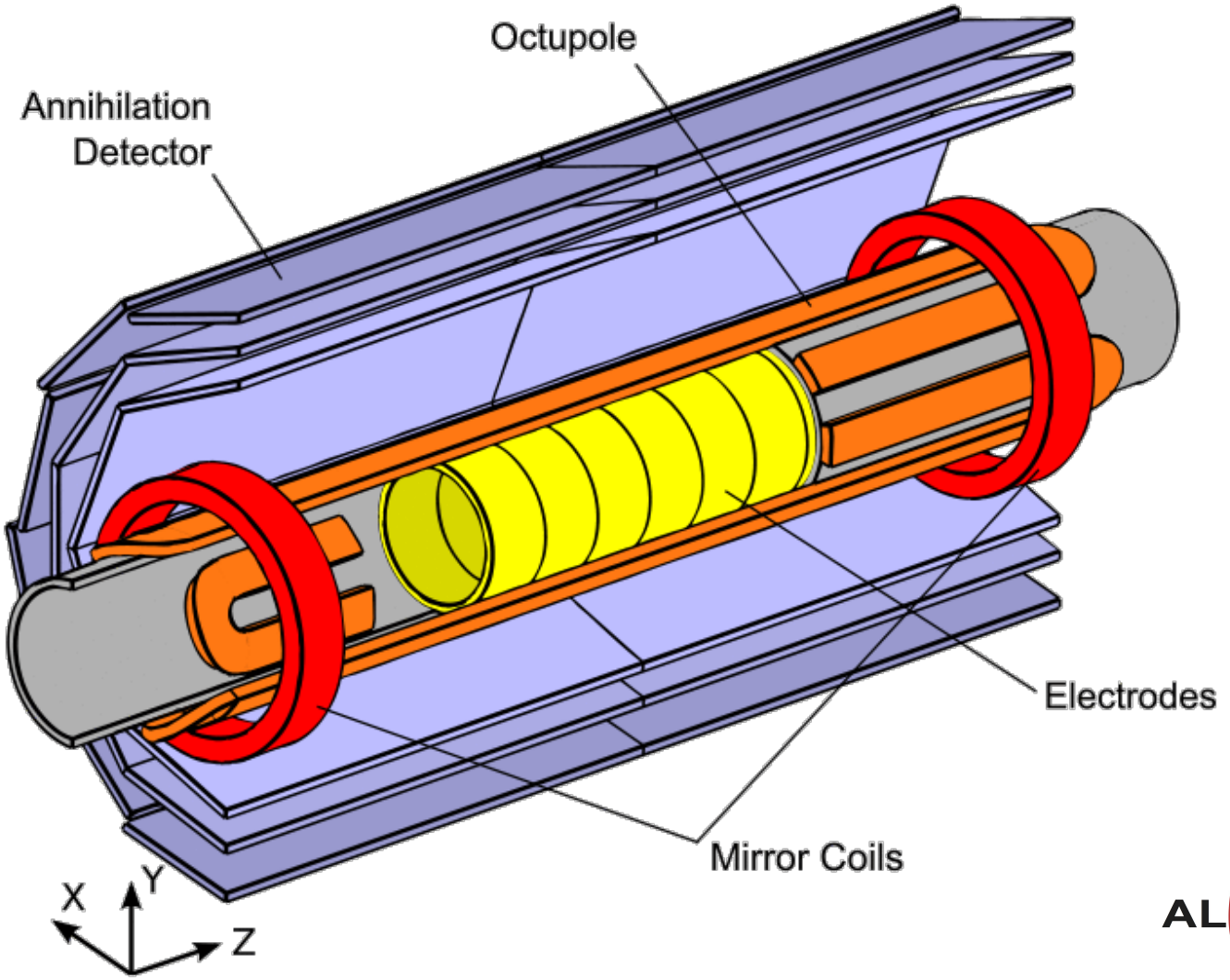
The 1S-2S transition frequency in hydrogen is one of the most precisely measured numbers in physics:

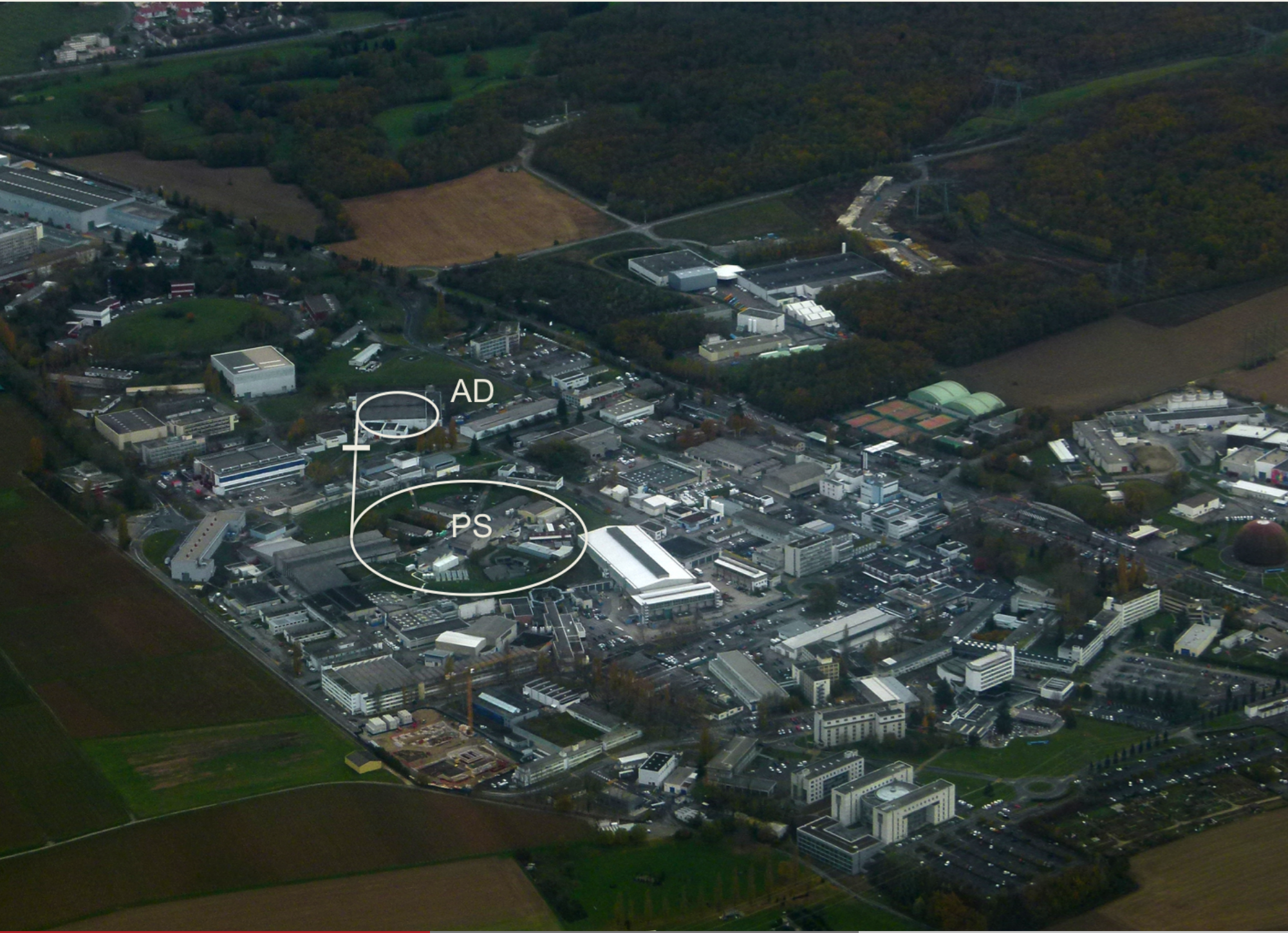
$f_{1S-2S} = 2\ 466\ 061\ 413\ 187\ 035\ (10)$ Hz

Comparing this value with its equivalent in antihydrogen is one of the most appealing and conceptually simple matter / antimatter comparisons, and one of the main motivations for for building an antiproton decelerator.

The ALPHA Experiment

Antihydrogen **L**aser **PH**ysics **A**pparatus



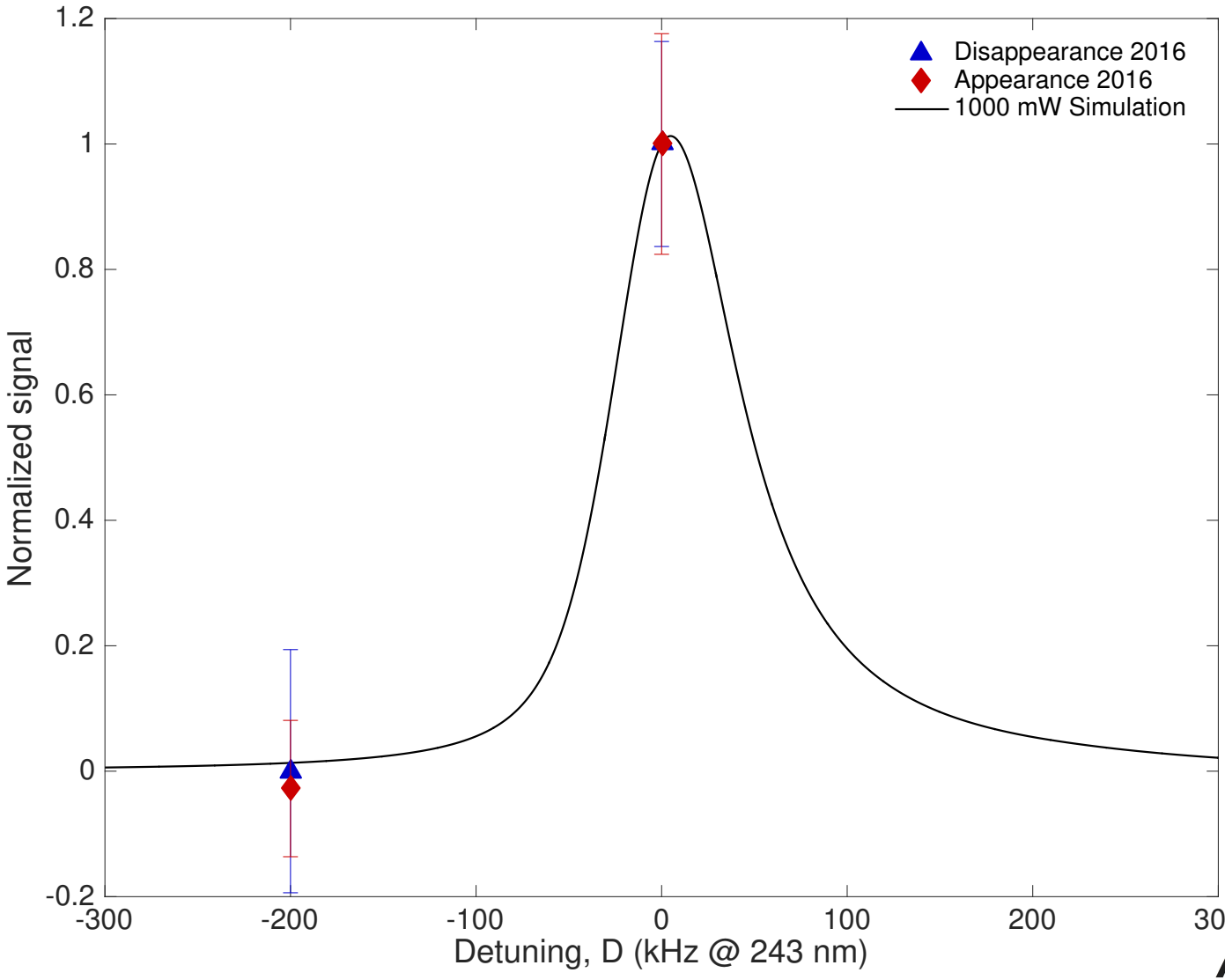

AD
PS

Typical Numbers

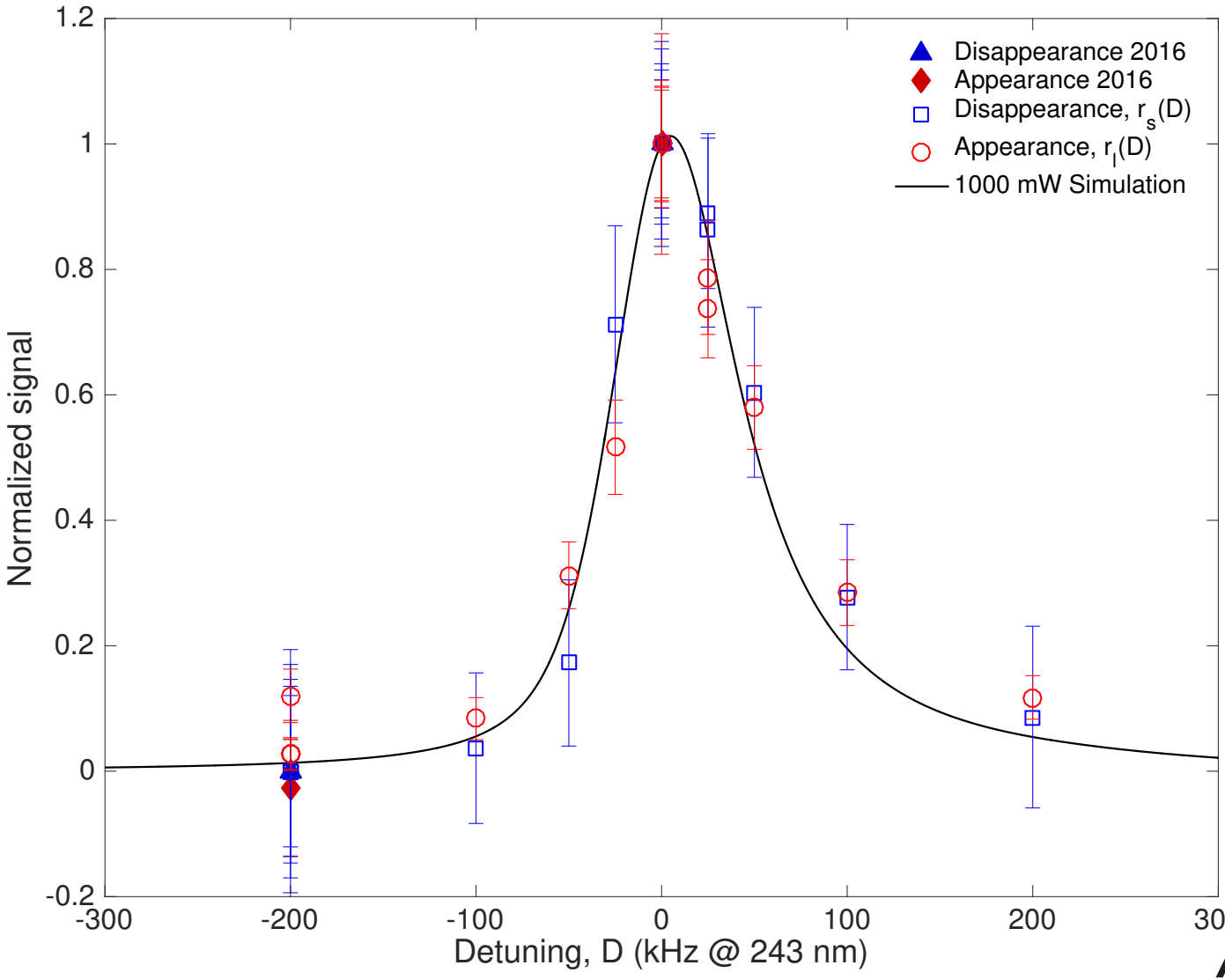
- 3×10^7 $\bar{p}$ delivered by the AD every $\sim$100s at 5.3 MeV
- 100,000 $\bar{p}$ captured and cooled after degrading foil
- About 50,000 $\overline{\mathrm{H}}$ produced by mixing with $\sim 3 \times 10^6$ e^+
- 30 atoms remain trapped in 0.5 K deep magnetic well
- Best spectroscopic measurement to date involved 15,000 trapped ground state atoms and a measurement campaign of 10 weeks

Antihydrogen Trapping in ALPHA

2016 Result


Disappearance 2016
Appearance 2016
1000 mW Simulation
Normalized signal
Detuning, D (kHz @ 243 nm)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-300
-200
-100
0
100
200
300

2017 Result


Disappearance 2016
Appearance 2016
Disappearance, r_s(D)
Appearance, r_l(D)
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0.4
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-200
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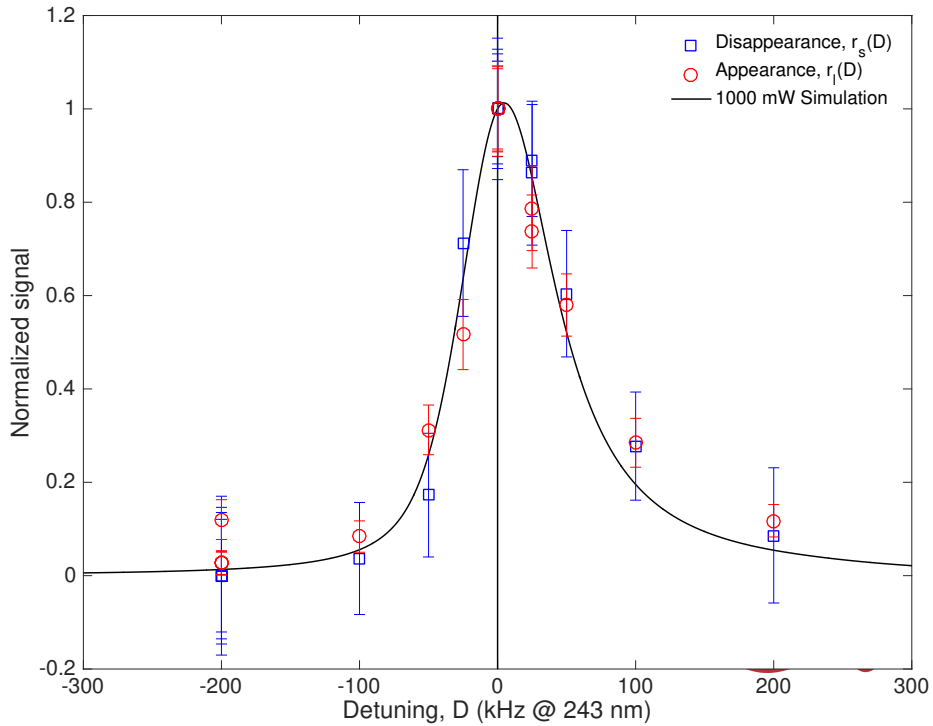
0
100
200
300

1S-2S Spectroscopy: Best Result

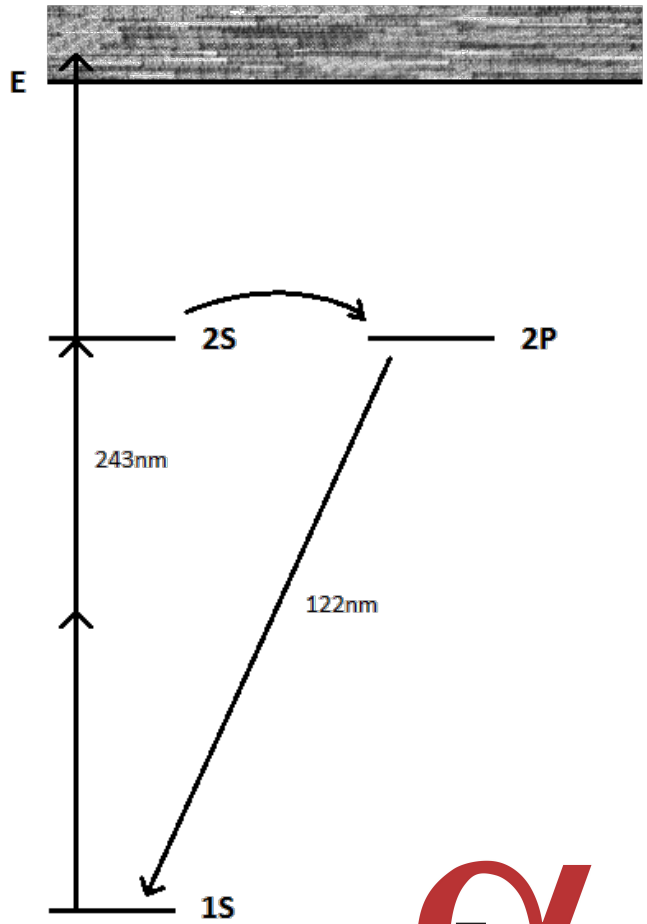
- Transition frequency determined with uncertainty of 2×10^{-12}
- This is the most precise direct measurement on any antimatter system to date.
- Excellent agreement with ordinary hydrogen
- Width is dominated by transit time



Challenges of Antihydrogen Spectroscopy

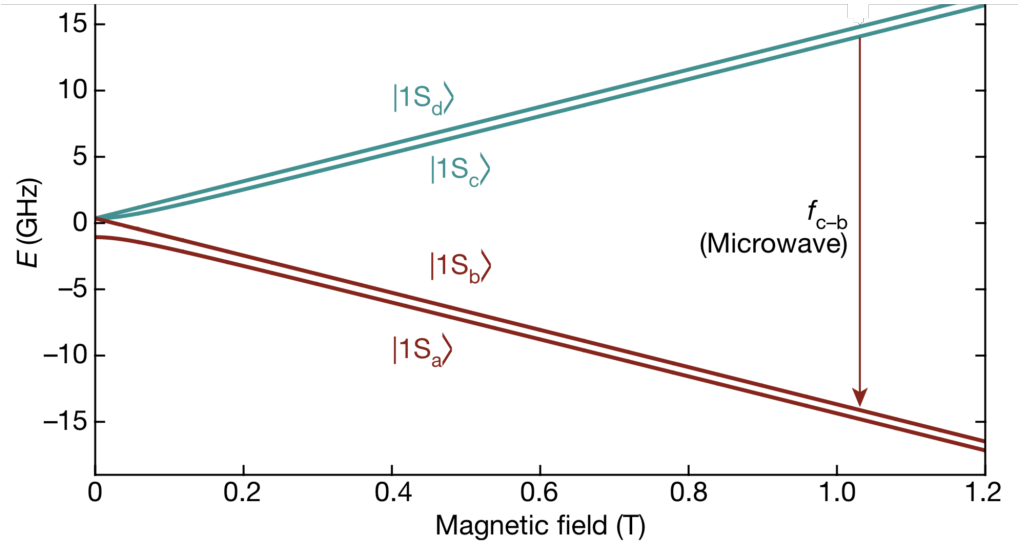
- Few atoms available
- Detection is difficult
- Complex apparatus since traps for neutral atoms and constituent charged particles must be superimposed

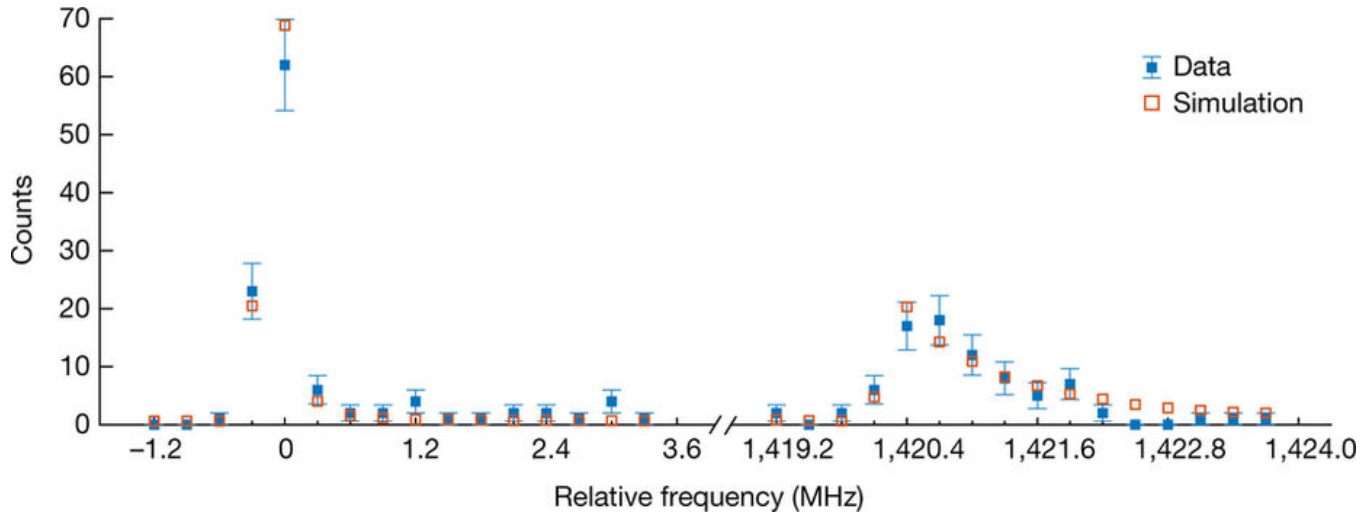
Design experiments such that resonance leads to annihilation



Ground State Hyperfine Spectroscopy

Transition converts atom from trapped to un-trappable





$$\Delta\nu = 1420.4 \pm 0.5\,\text{MHz}$$

ALPHA-g

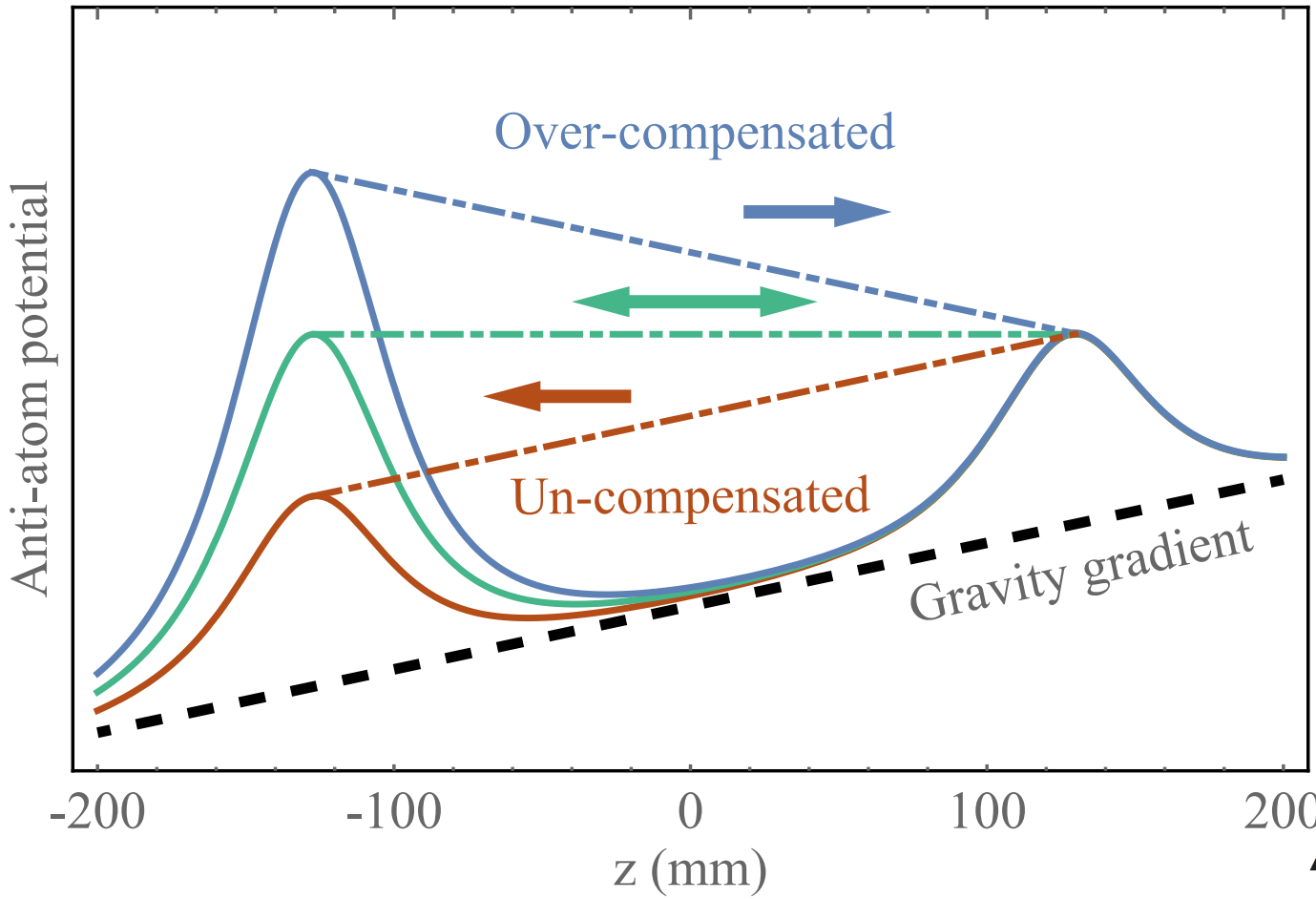
Carefully release magnetically trapped antihydrogen atoms to record their gravitational acceleration

The challenge: We trap atoms with $E_K < 0.5$ K ≈ 50 μeV

Gravitational potential is about 1.2 mK per meter

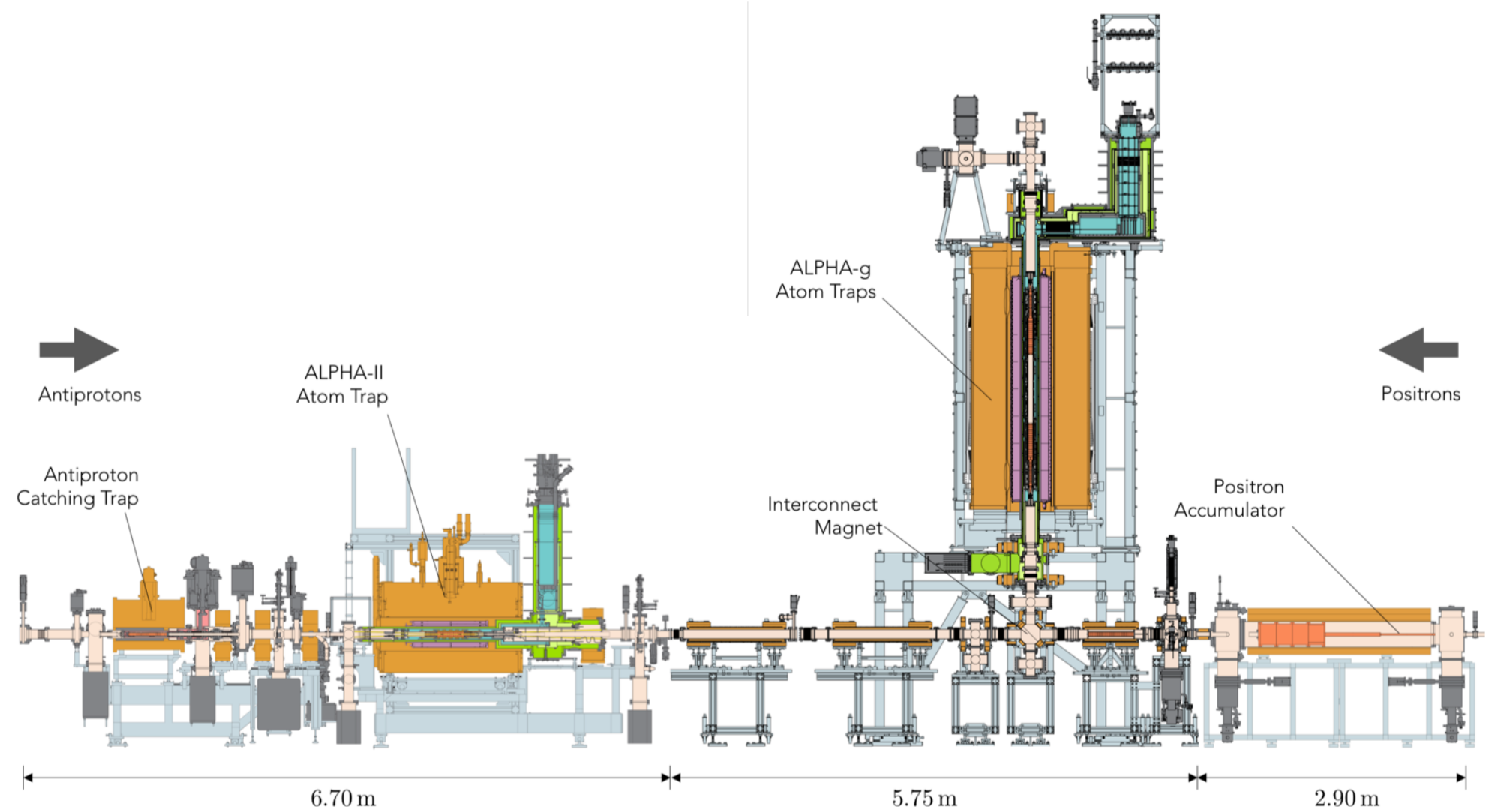
Gravity Measurement

Balance the escape by compensating the gravitational potential with magnetic potential



ALPHA-g

New experiment to directly measure the gravitational acceleration of antimatter.

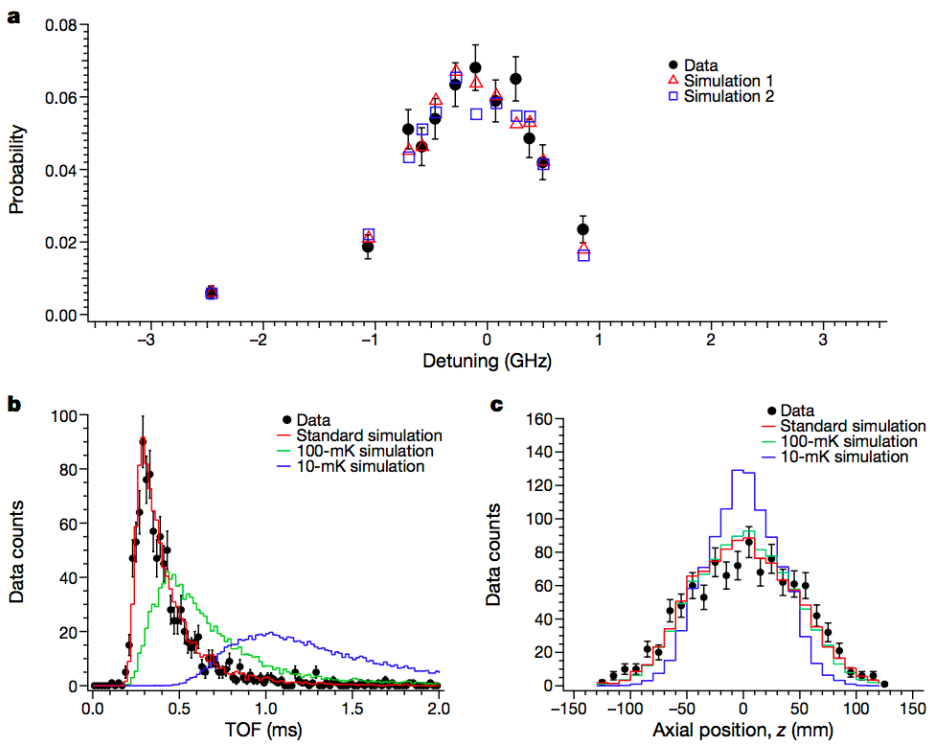


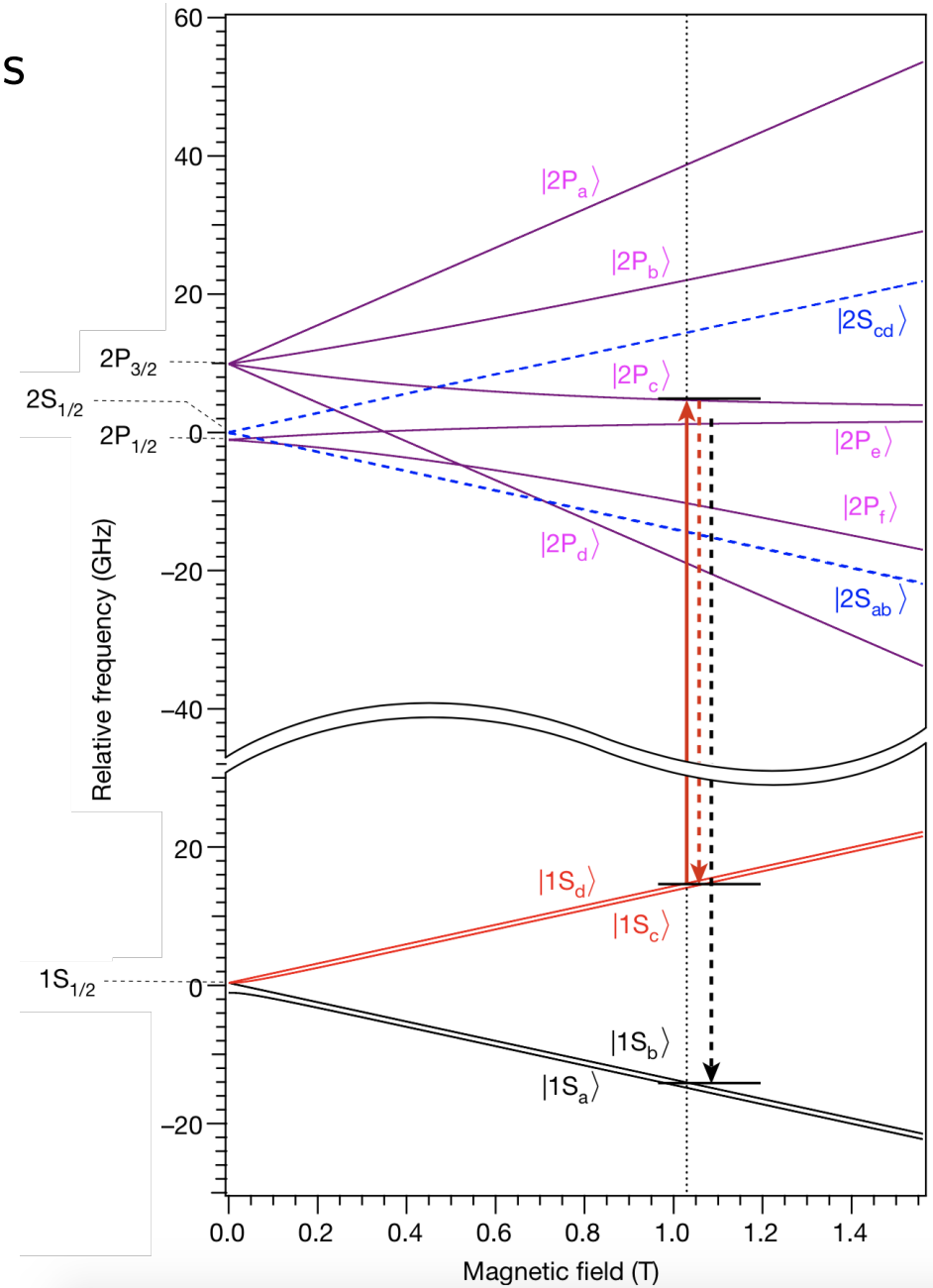
1S-2P: Laser Cooling!

Momentum from absorbed photons slows down atoms

Need closed transition (1S-2P$_a$)

This makes everything better!

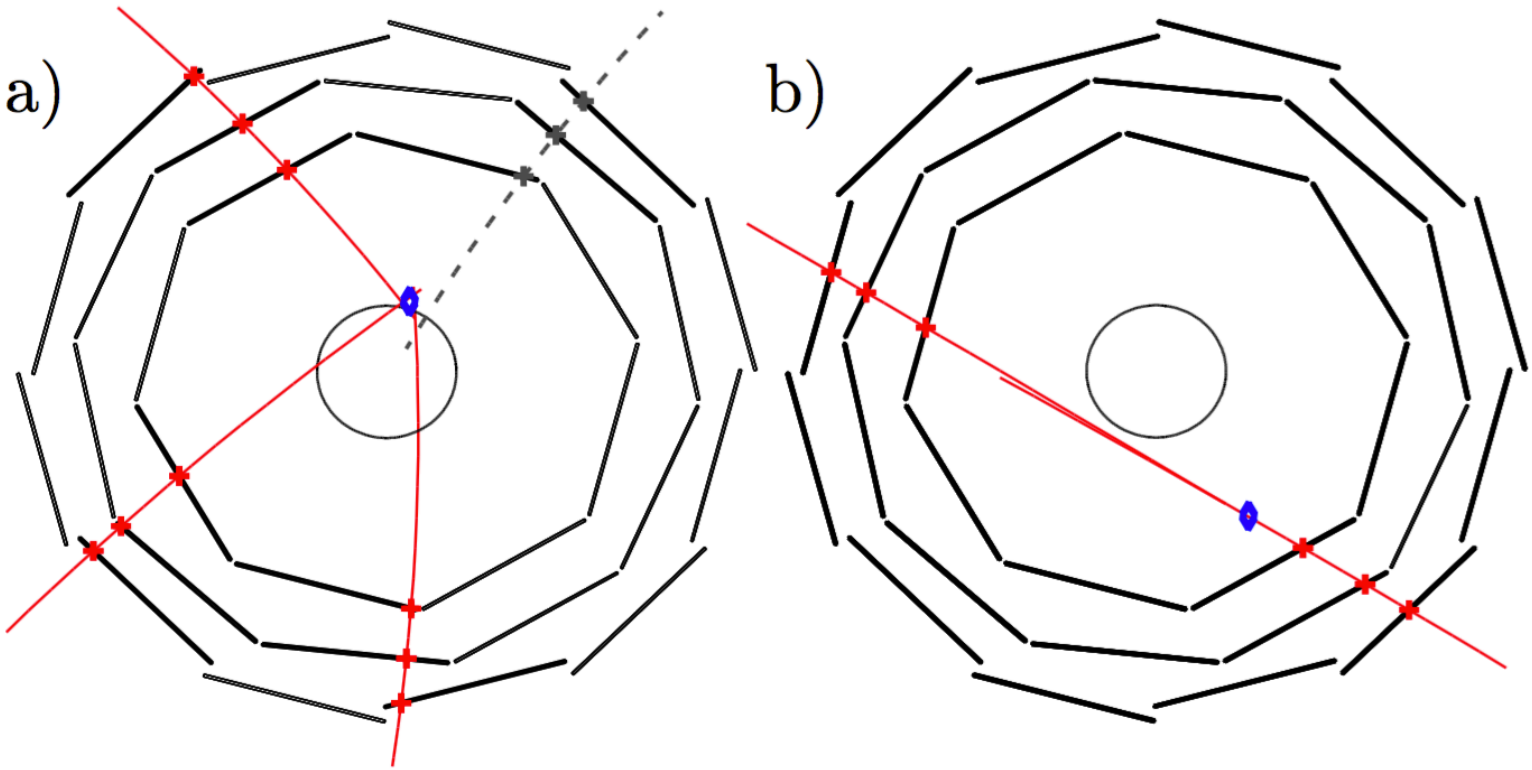




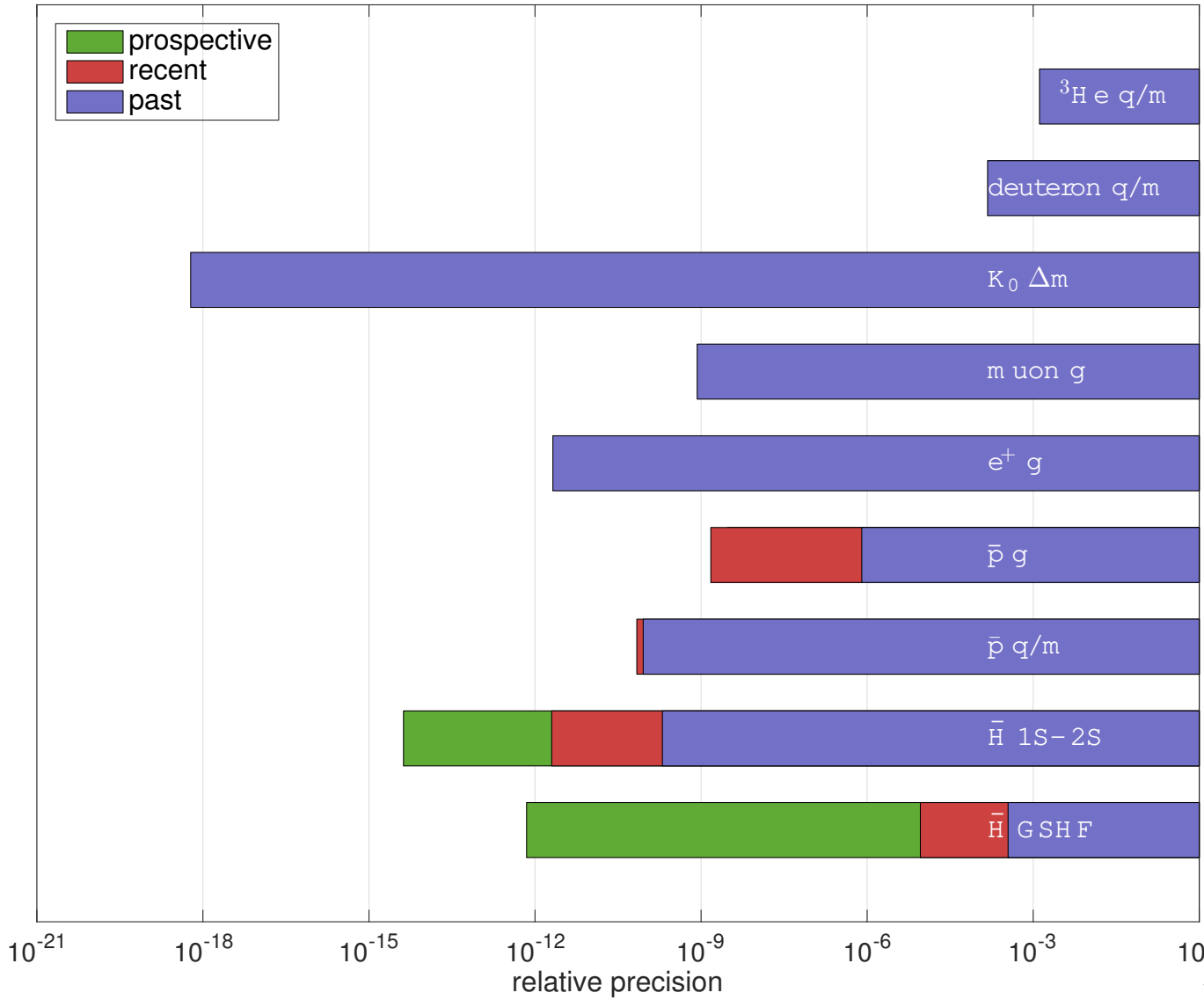
Thank you for your Attention

backup slides

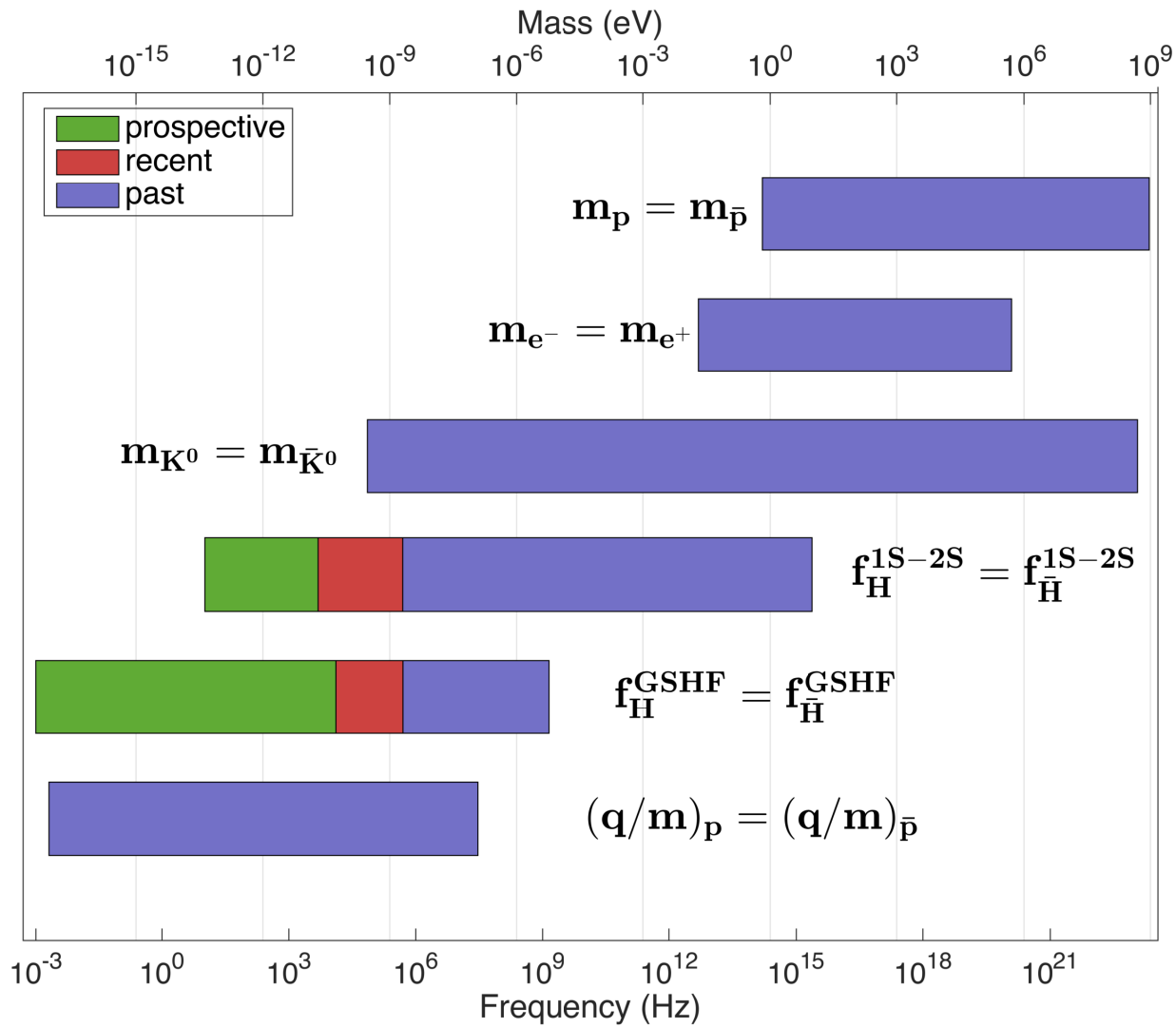
Cosmic Event Rejection



CPT Tests and Relative Precision

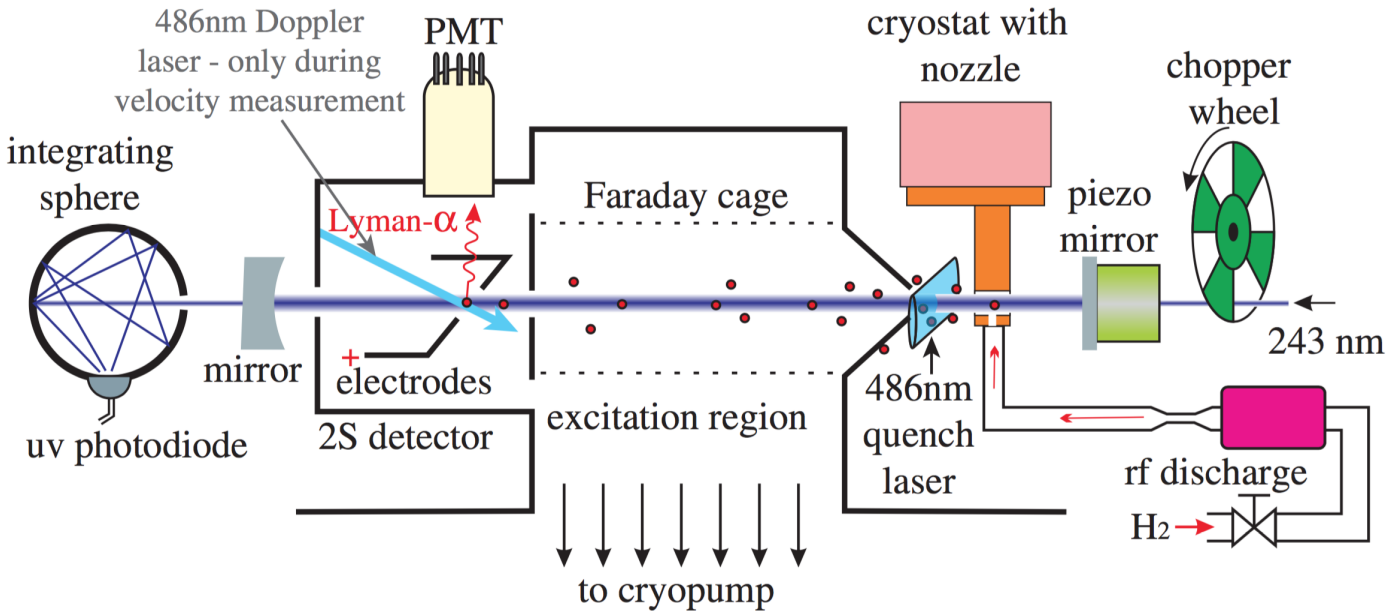


CPT Tests and Absolute Energy Difference



1S-2S Transition in Hydrogen

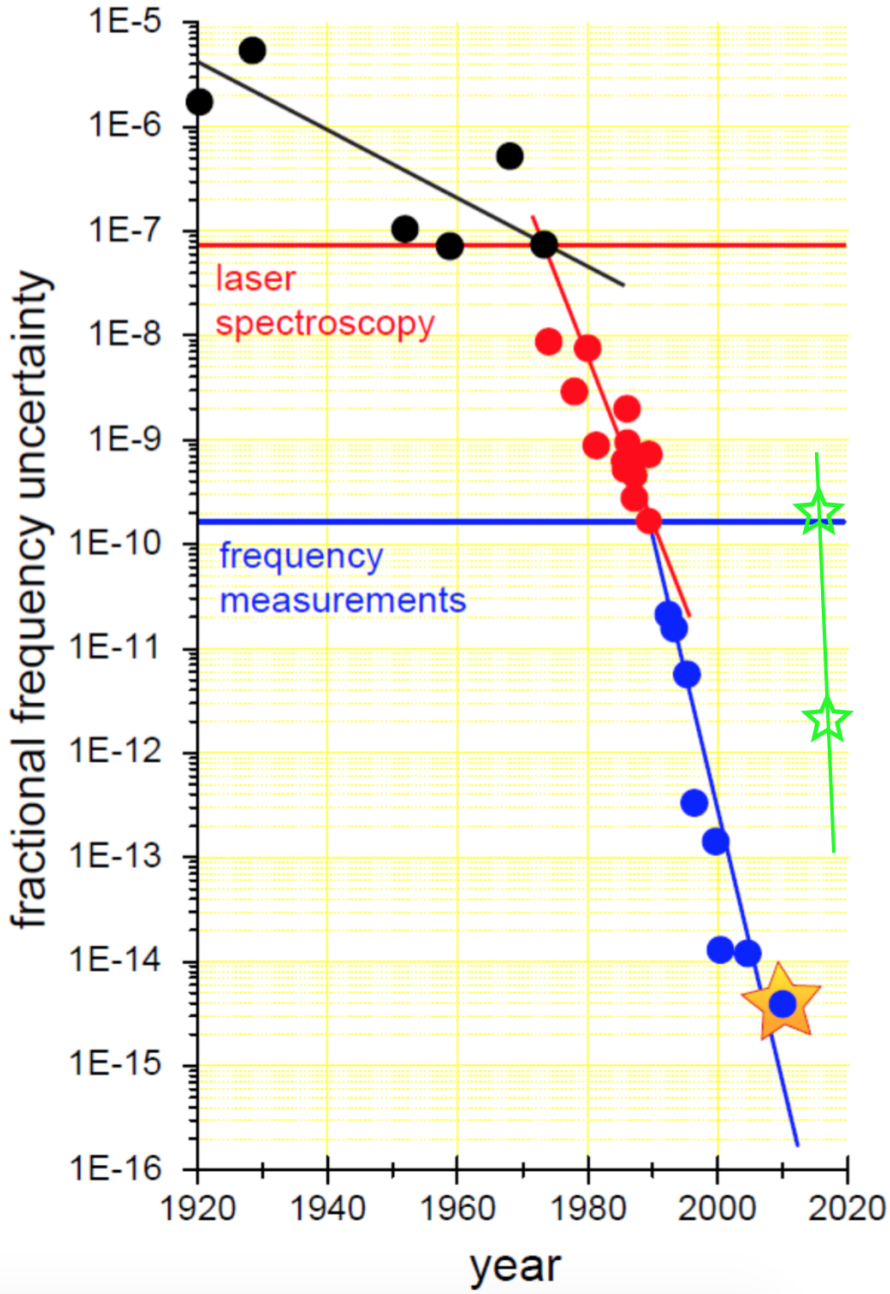
- $f_{1S-2S} = 2\,466\,061\,413\,187\,035\,(10)$ Hz
- Measured with a cold hydrogen beam



Hänsch et al. 2011

An Unrealistic Projection

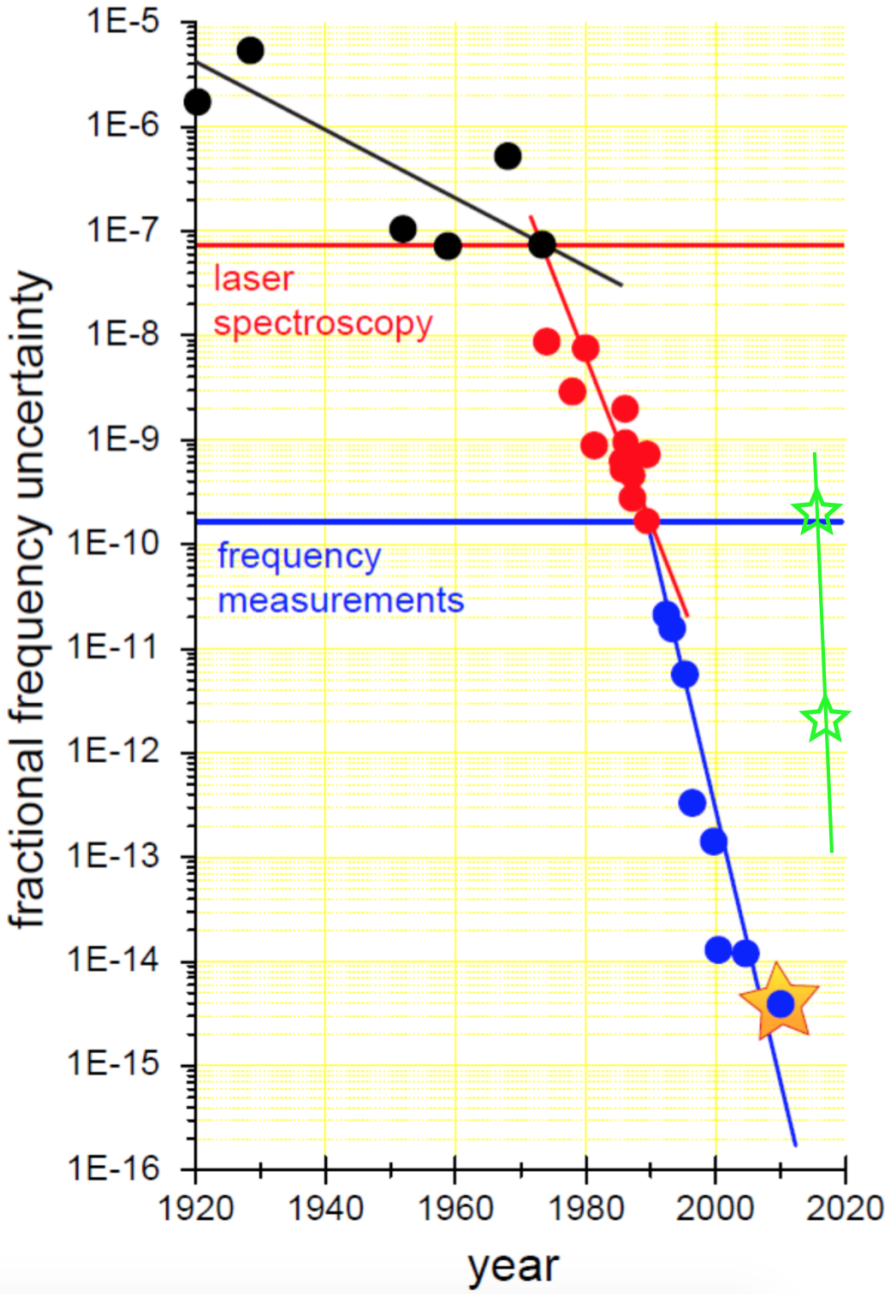
Antihydrogen measurements (green are improving in precision faster than measurements in ordinary matter.



An Unrealistic Projection

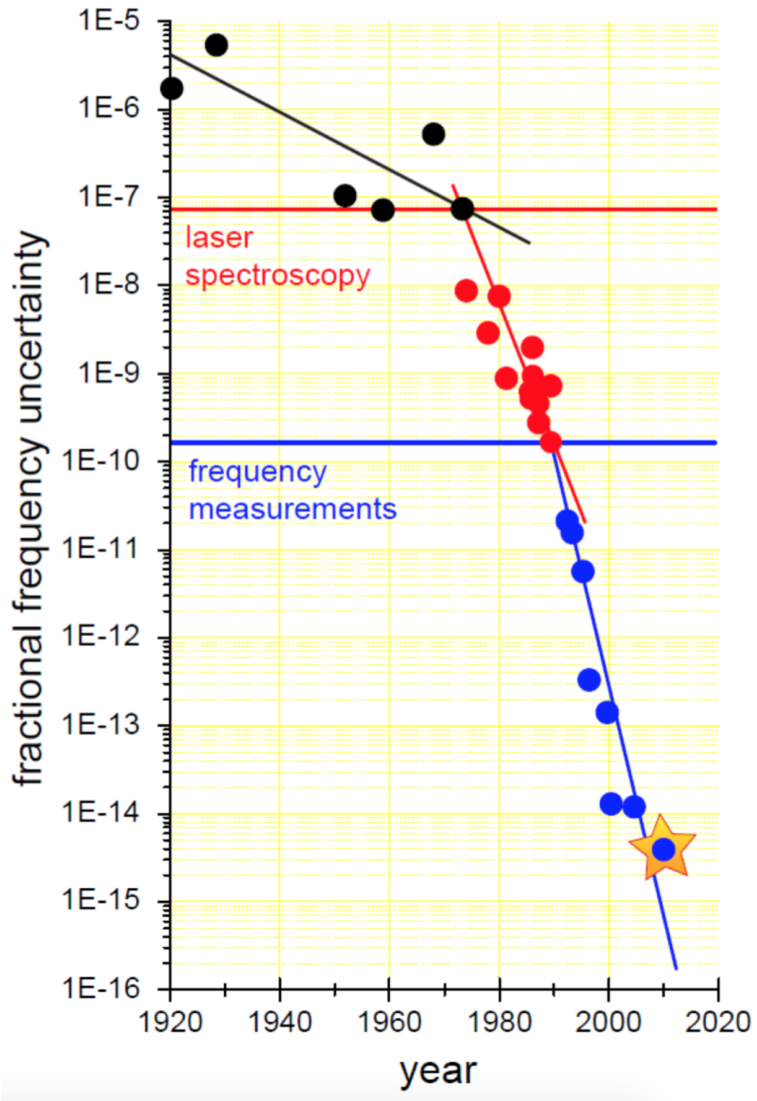
Antihydrogen measurements (green are improving in precision faster than measurements in ordinary matter.

However, no antiprotons available until 2021

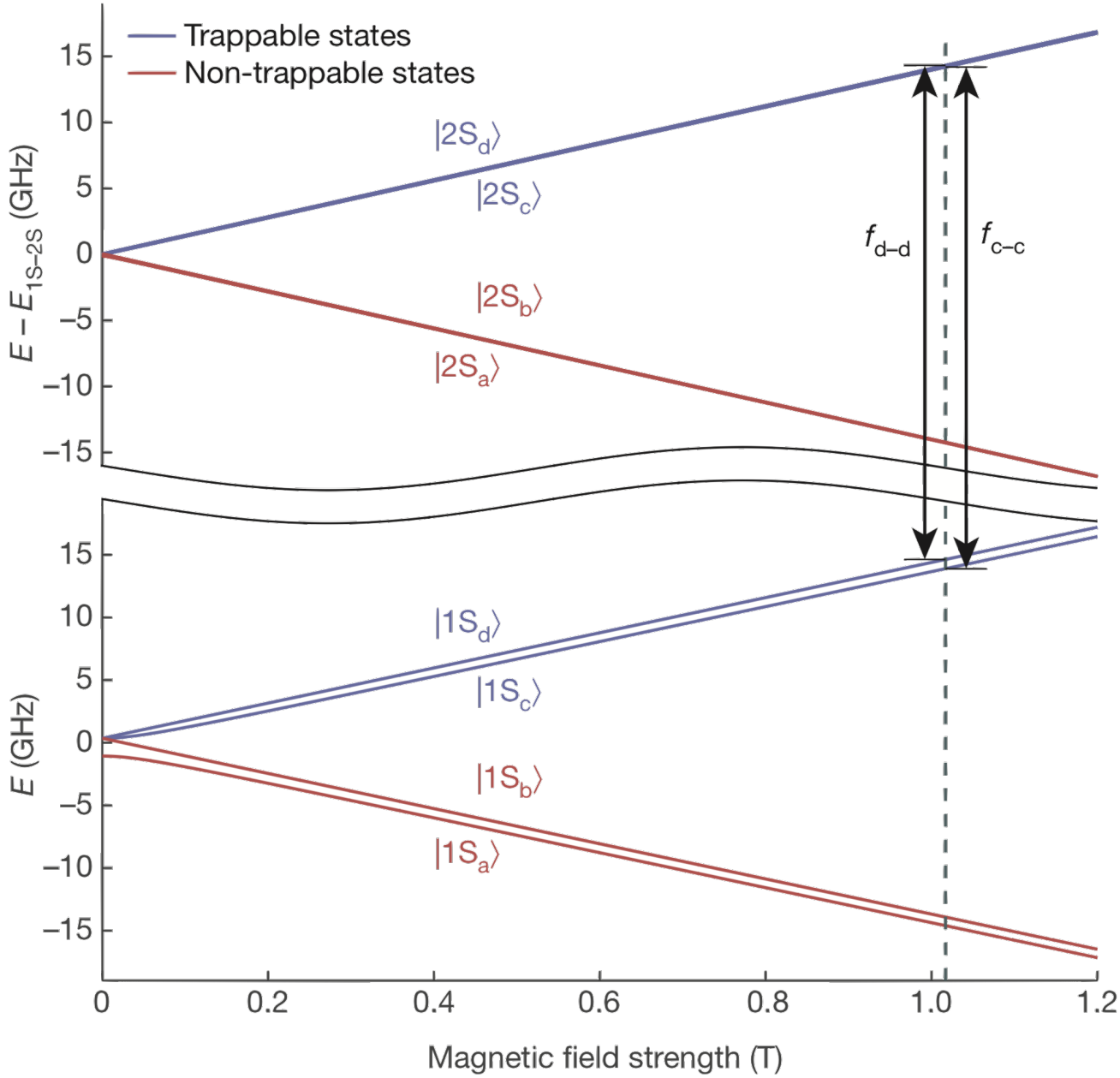


Why Antihydrogen?

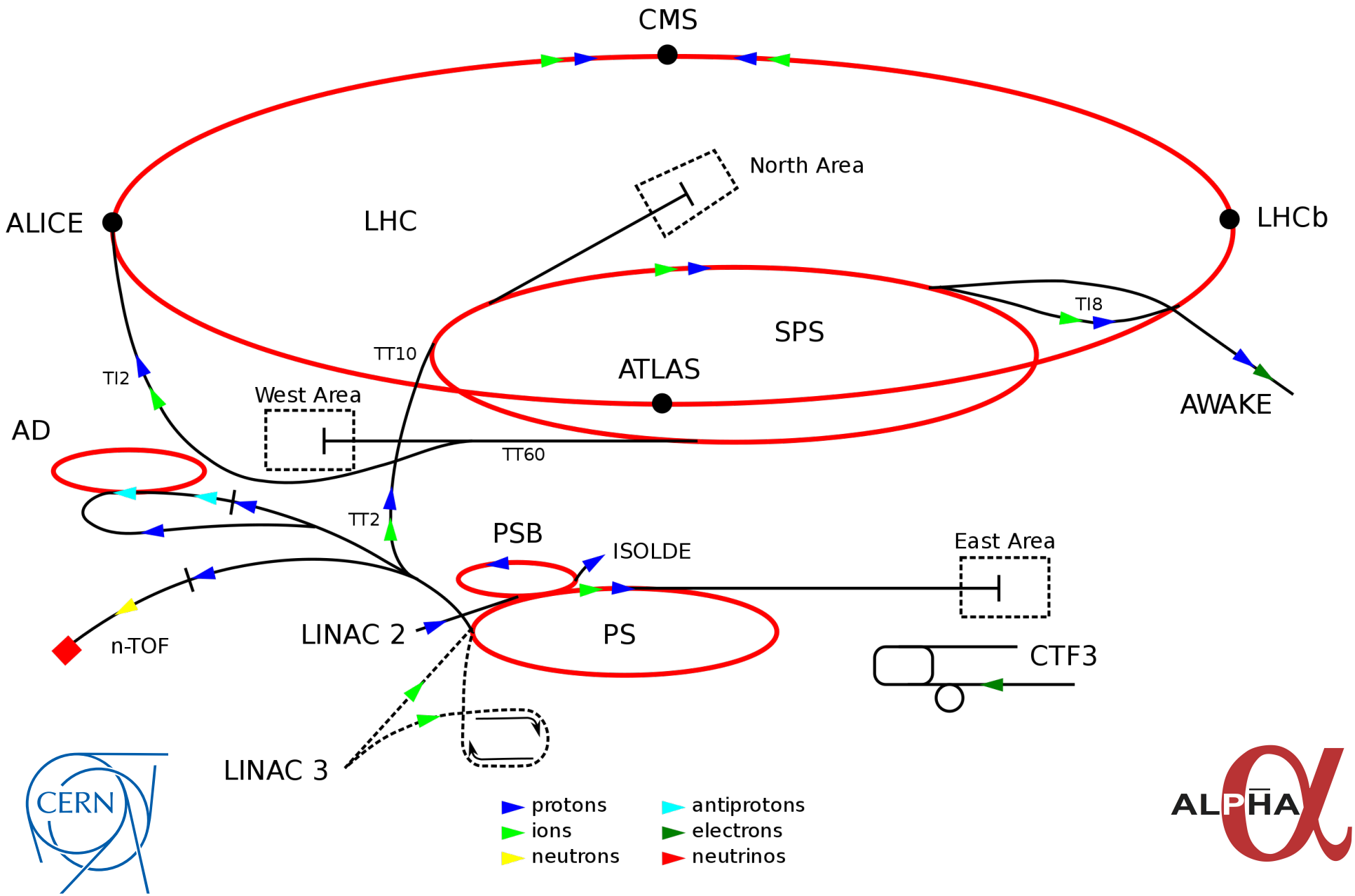
- Use the toolbox of atomic physics for high precision measurements
- Antimatter counterpart to the best understood atomic system
- Electrically neutral for gravity measurements



Hyperfine States in (Anti-)Hydrogen



CERN Accelerator Complex



Spectroscopy Apparatus

Cavity mirrors are in UHV and at cryogenic temperatures.