ALPHA and the 1S-2S transition in antihydrogen

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Reasons for Studying Antimatter

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?

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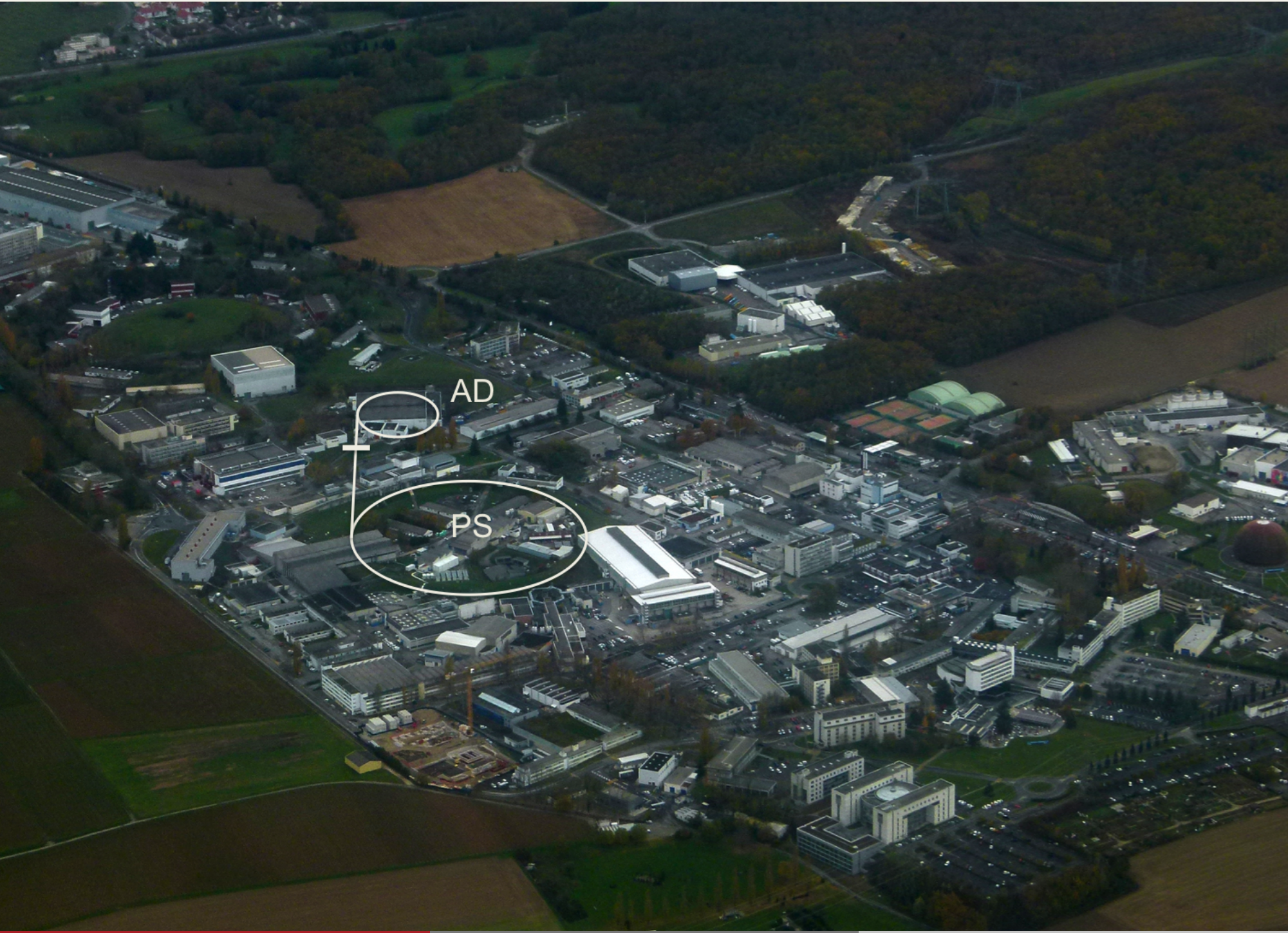
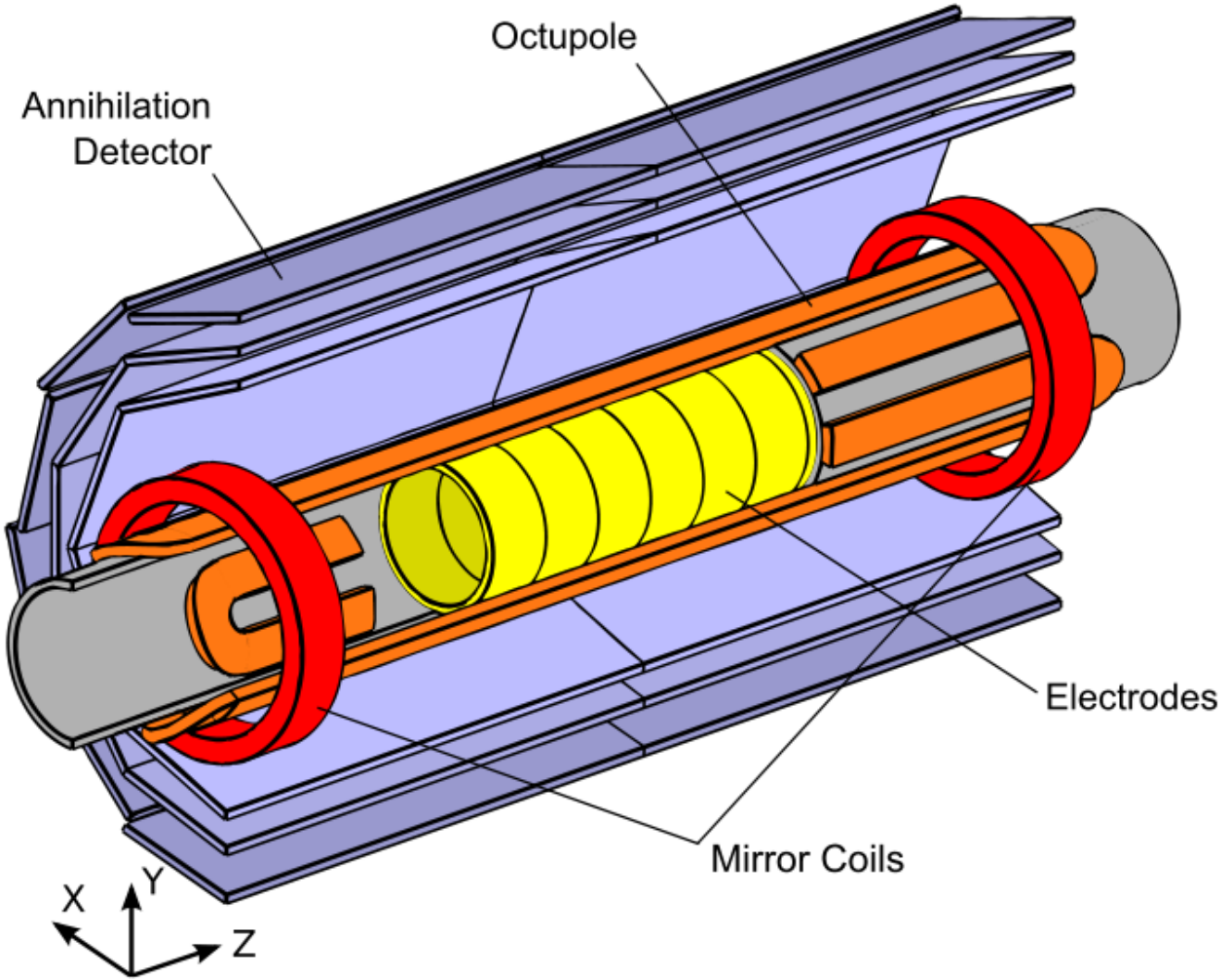
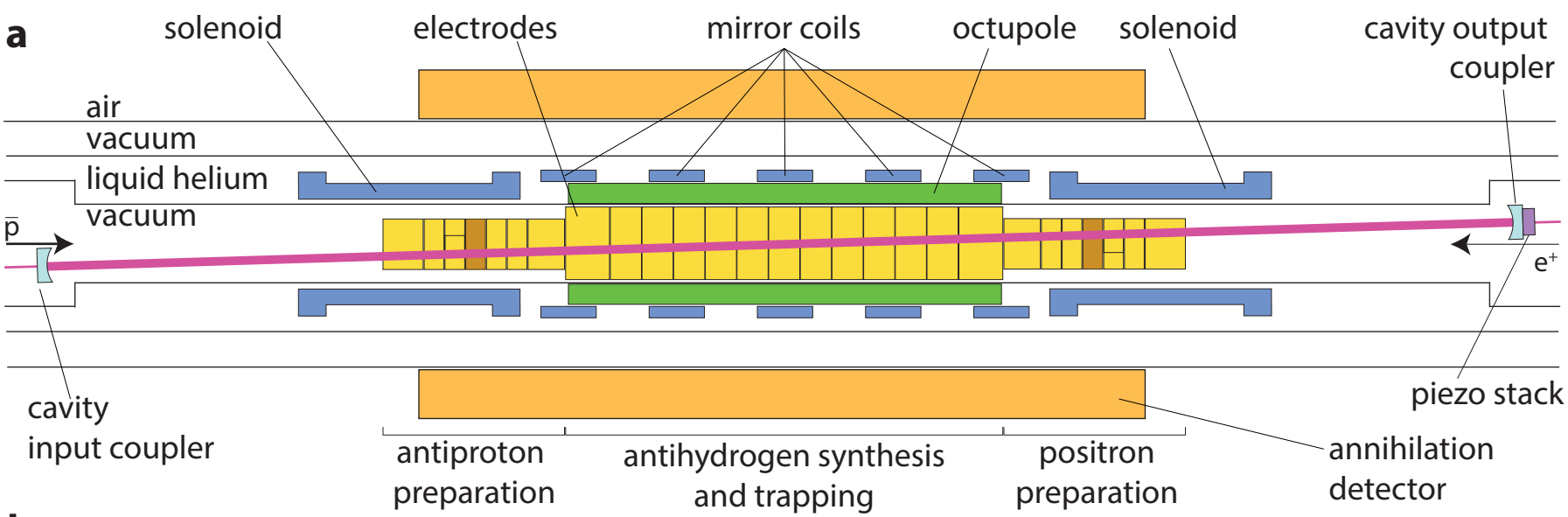

AD
PS

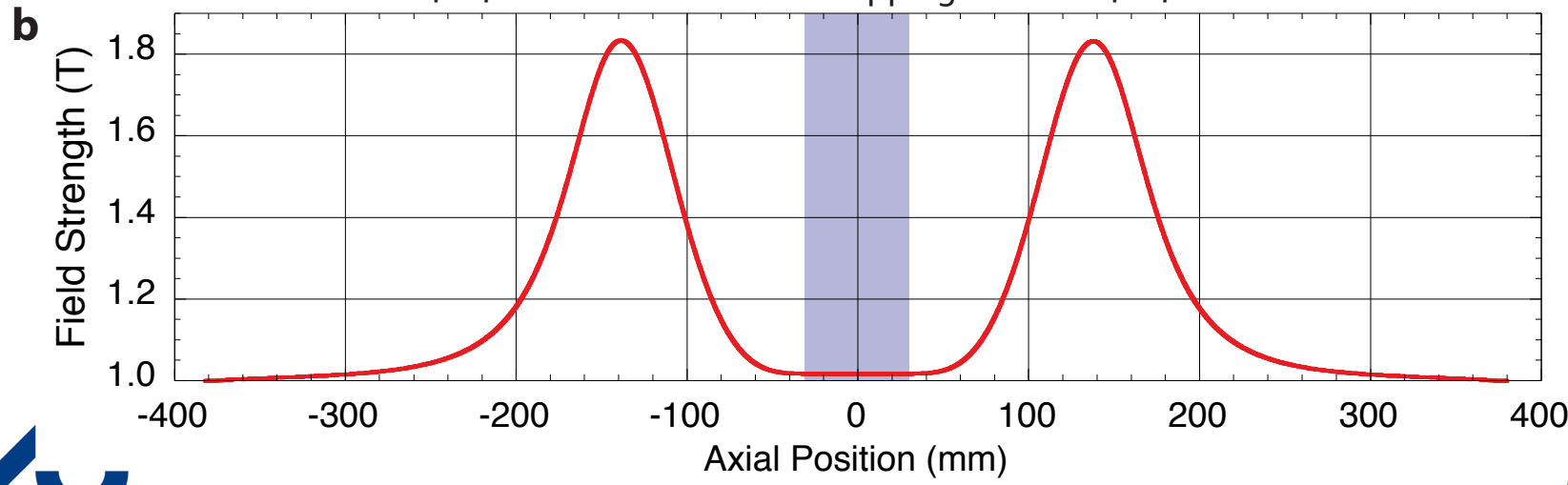
The ALPHA Experiment

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



The ALPHA Experiment





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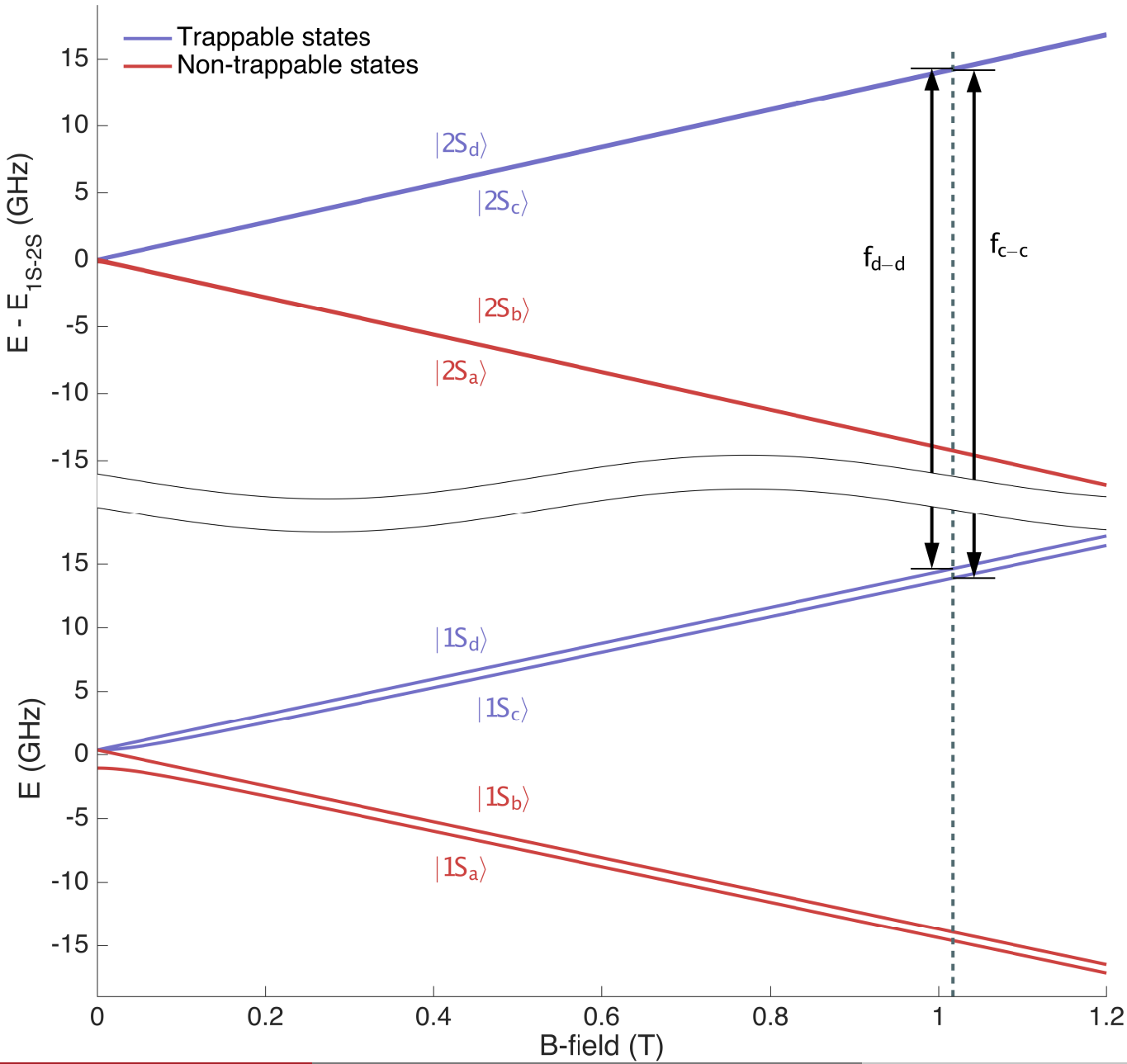
Hydrogen 1S and 2S Hyperfine Structure



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Experimental Procedure

- Mix 90,000 $\bar{p}$ with 1.6 million e^+ in the magnetic trap
- Clear out any remaining charged particles
- 300s hold time at d-d frequency
- 300s hold time at c-c frequency
- Ramp down magnets to detect remaining atoms

3 types of trials:

- On resonance
- Off resonance
- No laser

11 repetitions of each type were conducted

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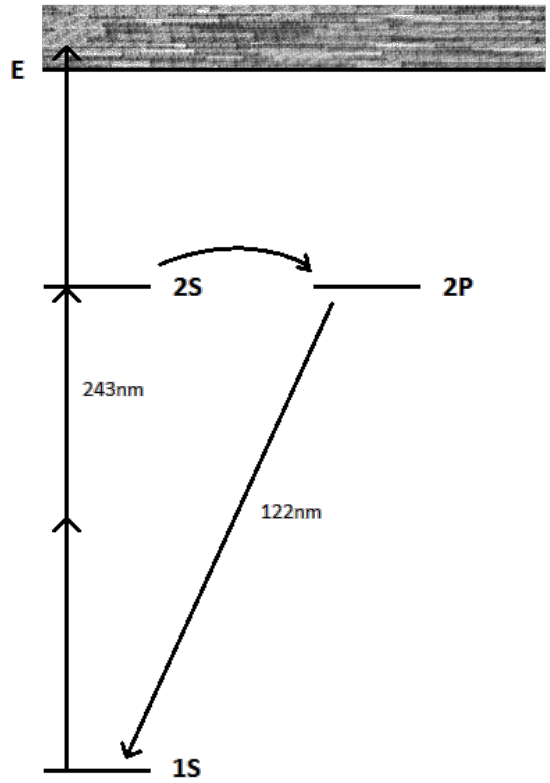
Simulation

Simulate the atoms in the the magnetic fields, including:

- Magnetic and (motional) electric fields
- Mixing between 2S and 2P states
- Photo-ionisation of the 2S state
- 2S and 2P decay rates and spin-flips
- Transition time broadening
- AC Stark shift



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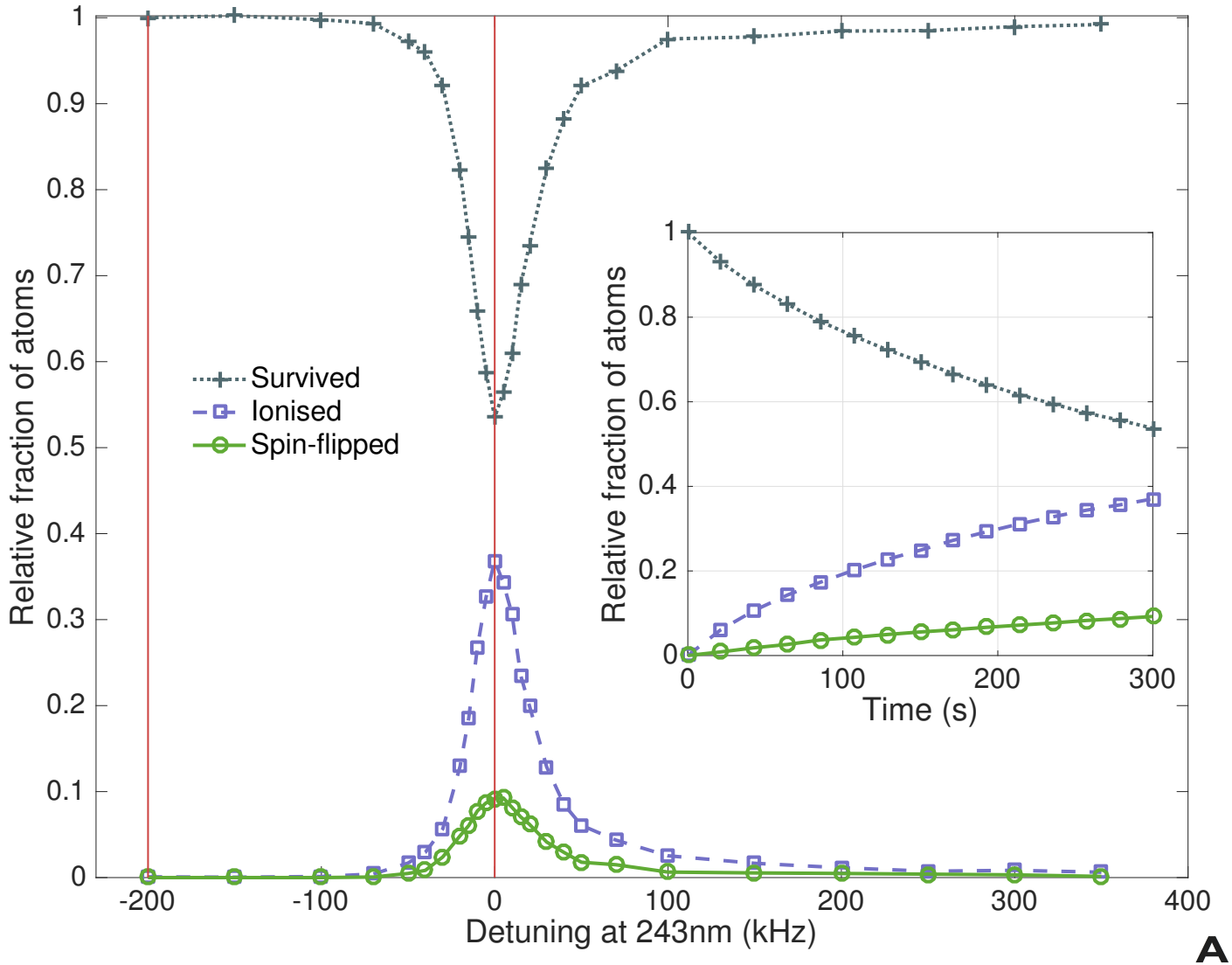
Simulation



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Data: Disappearance mode

Count the atoms left in the trap after the laser exposure.
On- and off- resonance differ by 92 ± 15 counts

Type	Detected events	Background	Uncertainty
Off-resonance	159	0.7	13
On-resonance	67	0.7	8.2
No laser	142	0.7	12

Detector efficiency here is 0.688

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Data: Appearance mode

Look for annihilations during the 300s hold times

Type	Detected events	Background	Uncertainty
d-d off resonance	15	14.2	3.9
d-d on resonance	39	14.2	6.2
No laser	22	14.2	4.7
c-c off resonance	12	14.2	3.5
c-c on resonance	40	14.2	6.3
No laser	8	14.2	2.8
total off resonance	27	28.4	5.2
total on resonance	79	28.4	8.9
total No laser	30	28.4	5.5

Detector efficiency here is 0.376

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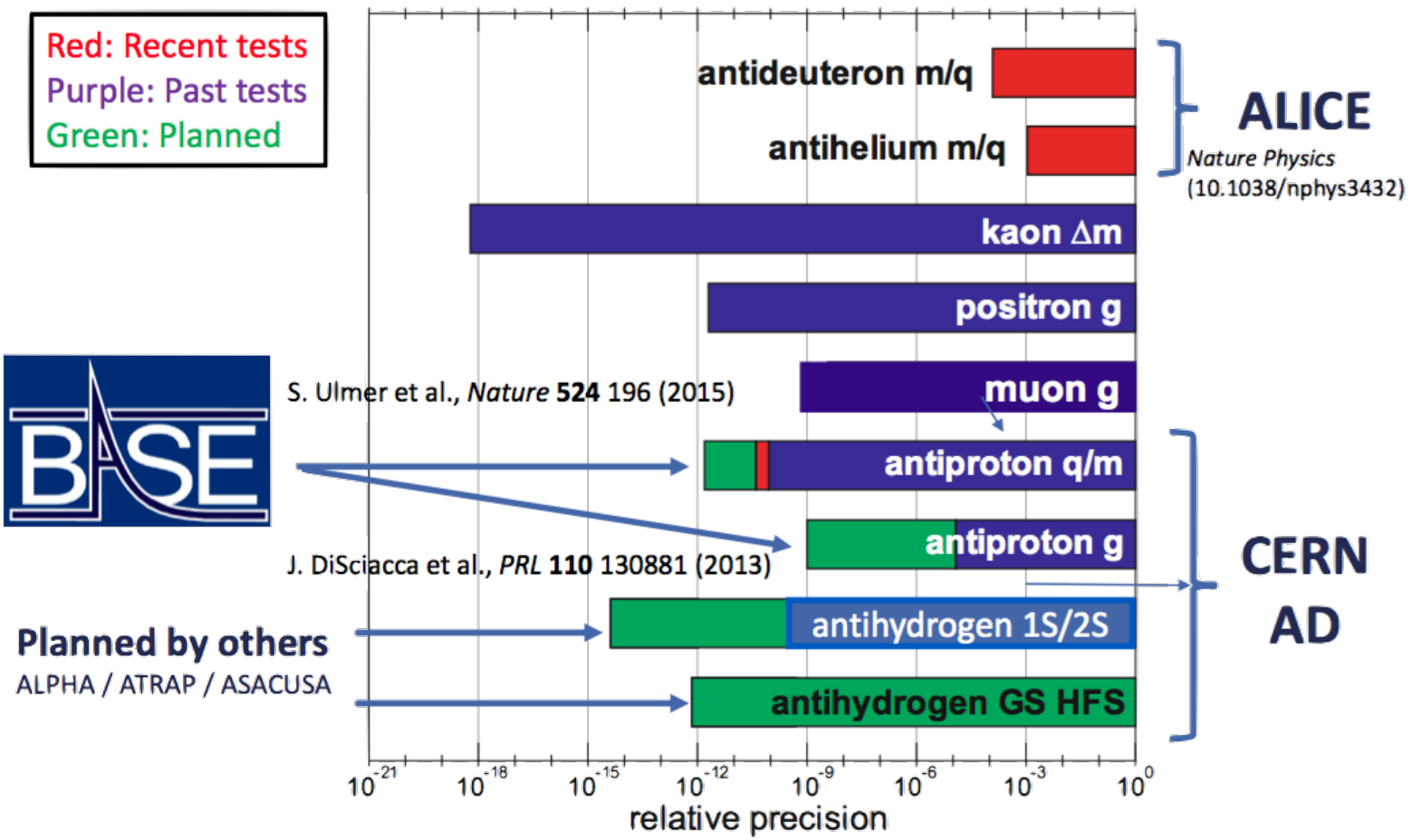
CPT Tests and Relative Precision



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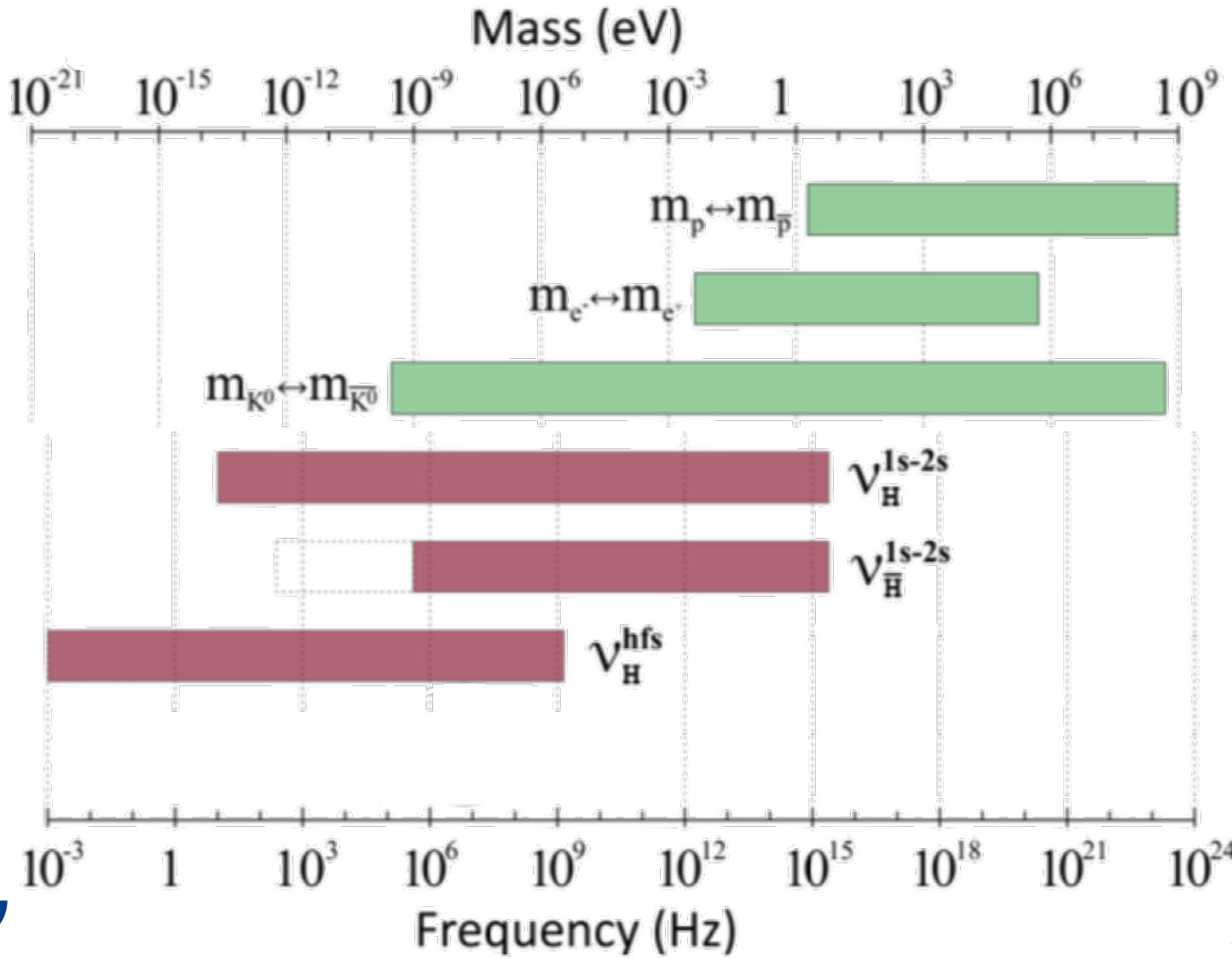
CPT Tests and Energy Scales



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Extra Slides

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Sakharov Conditions

For the Universe to start out with $B = 0$ and end up with $B > 0$, the following conditions must be met:

1. At least one process exists which does not conserve B
2. C- and CP- violation
3. Interactions out of thermal equilibrium

The Standard Model has processes like the sphaleron, which fulfill 1 , but these have not been observed.
The electroweak force does fulfill 2 , but the strong force does not.

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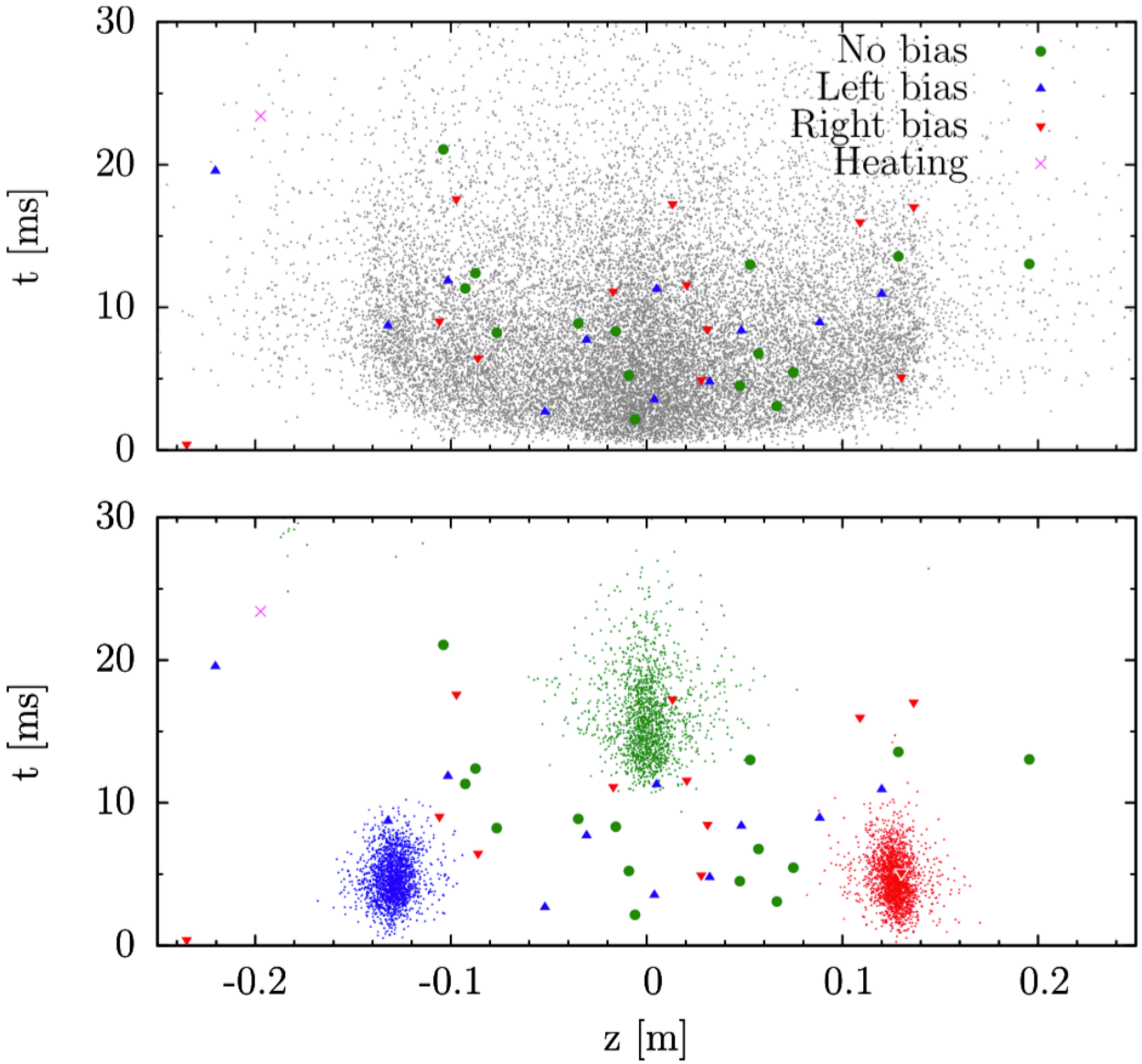
Antiproton Discrimination



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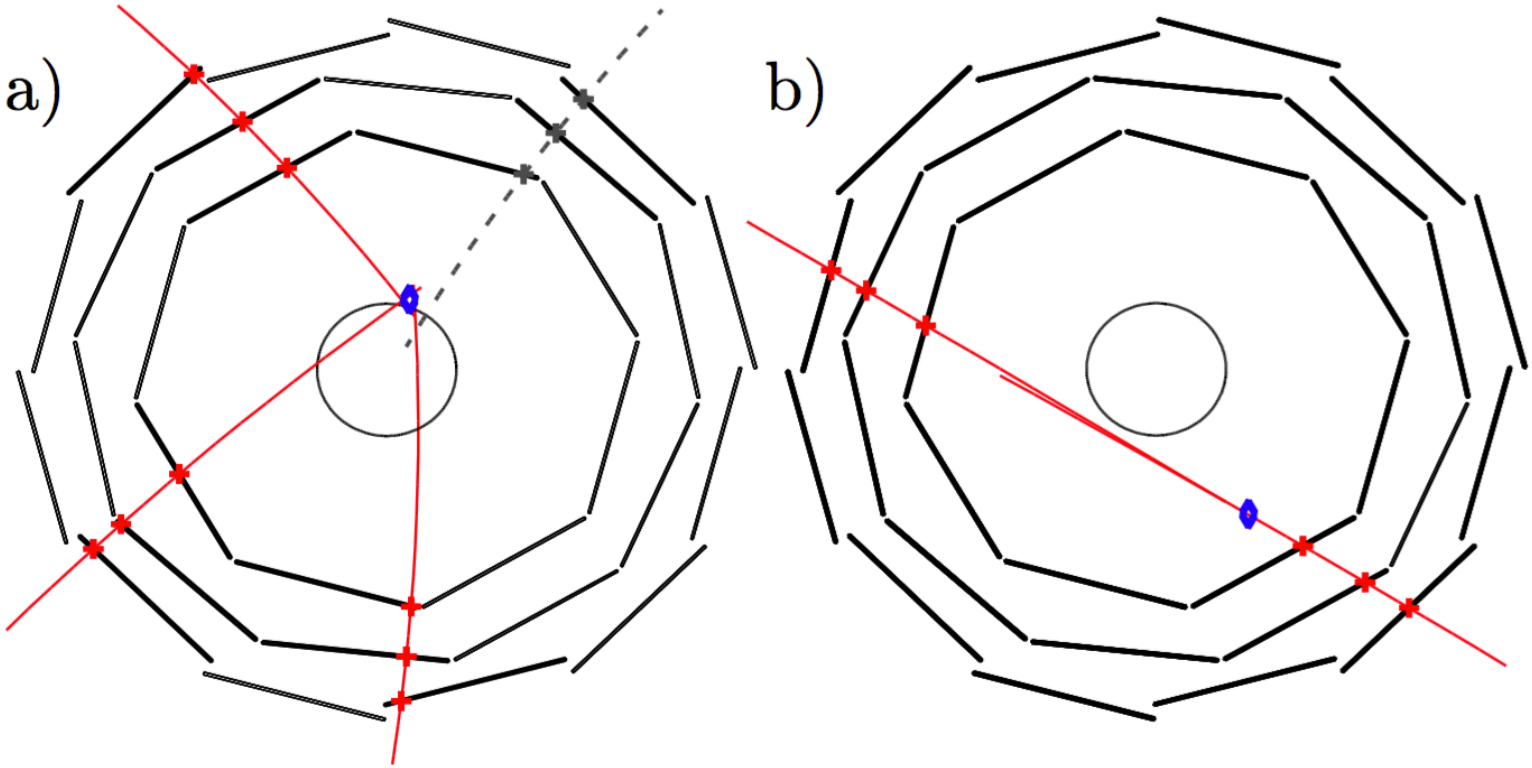
Cosmic Event Rejection



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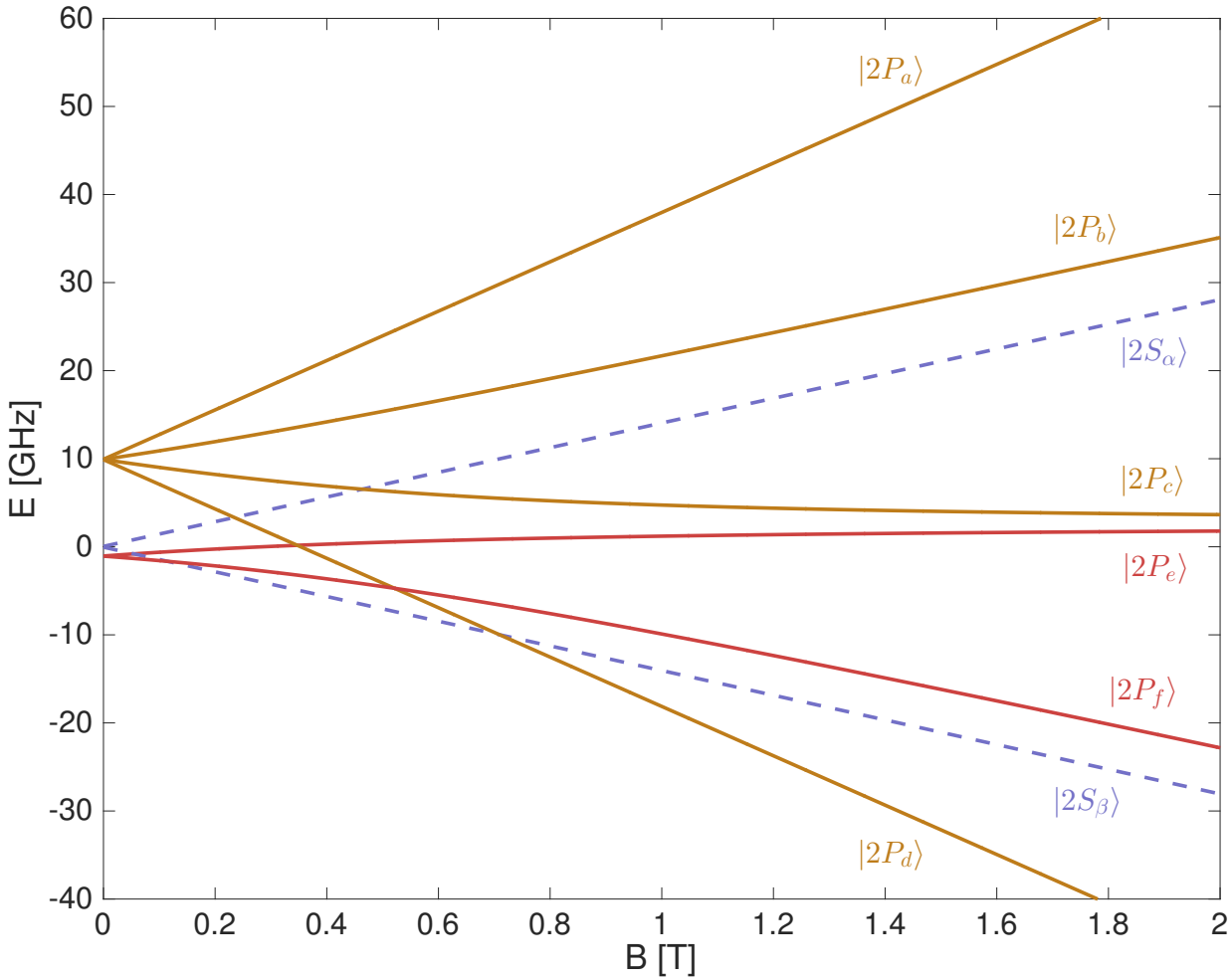
N=2 Energies



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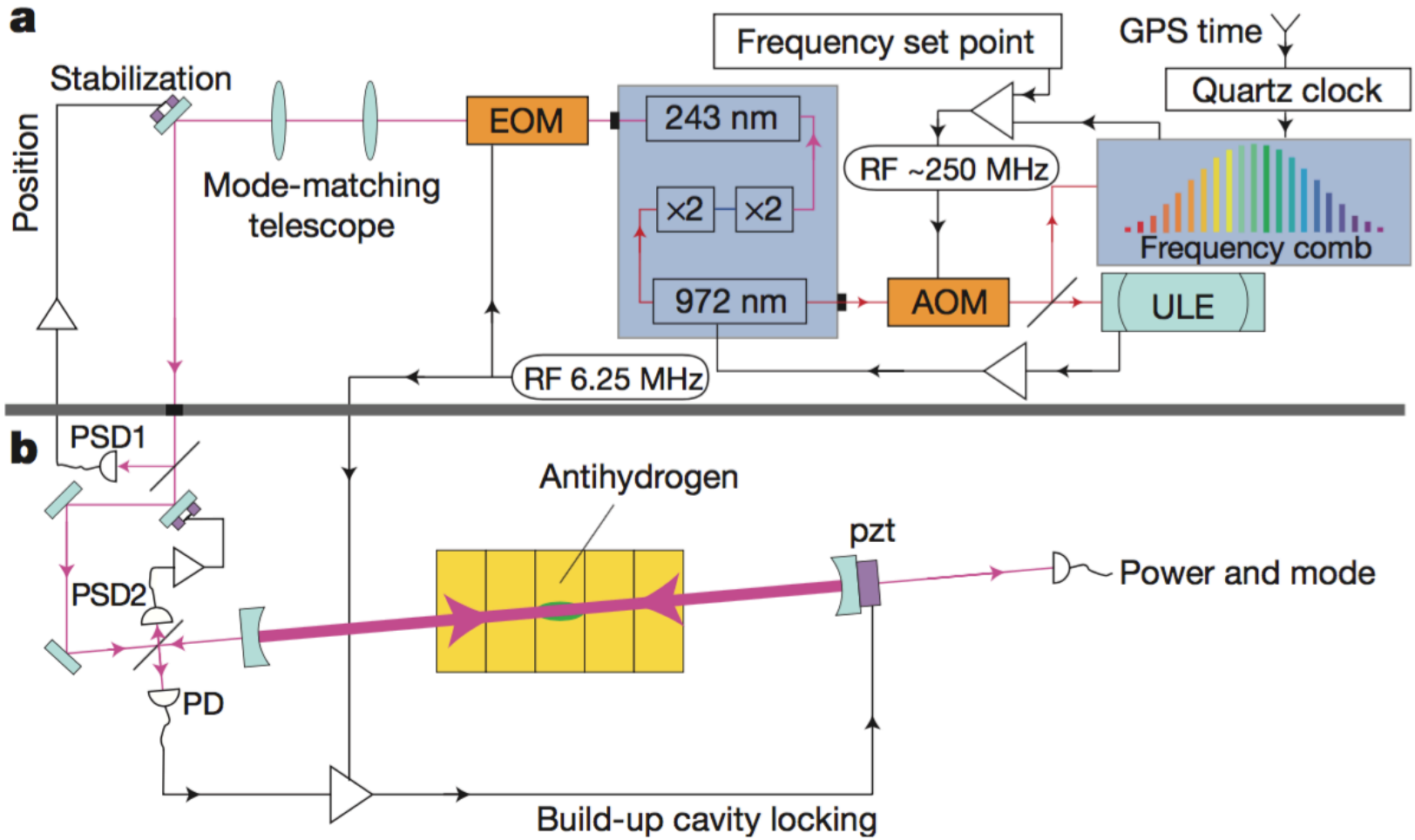
Frequency Control System



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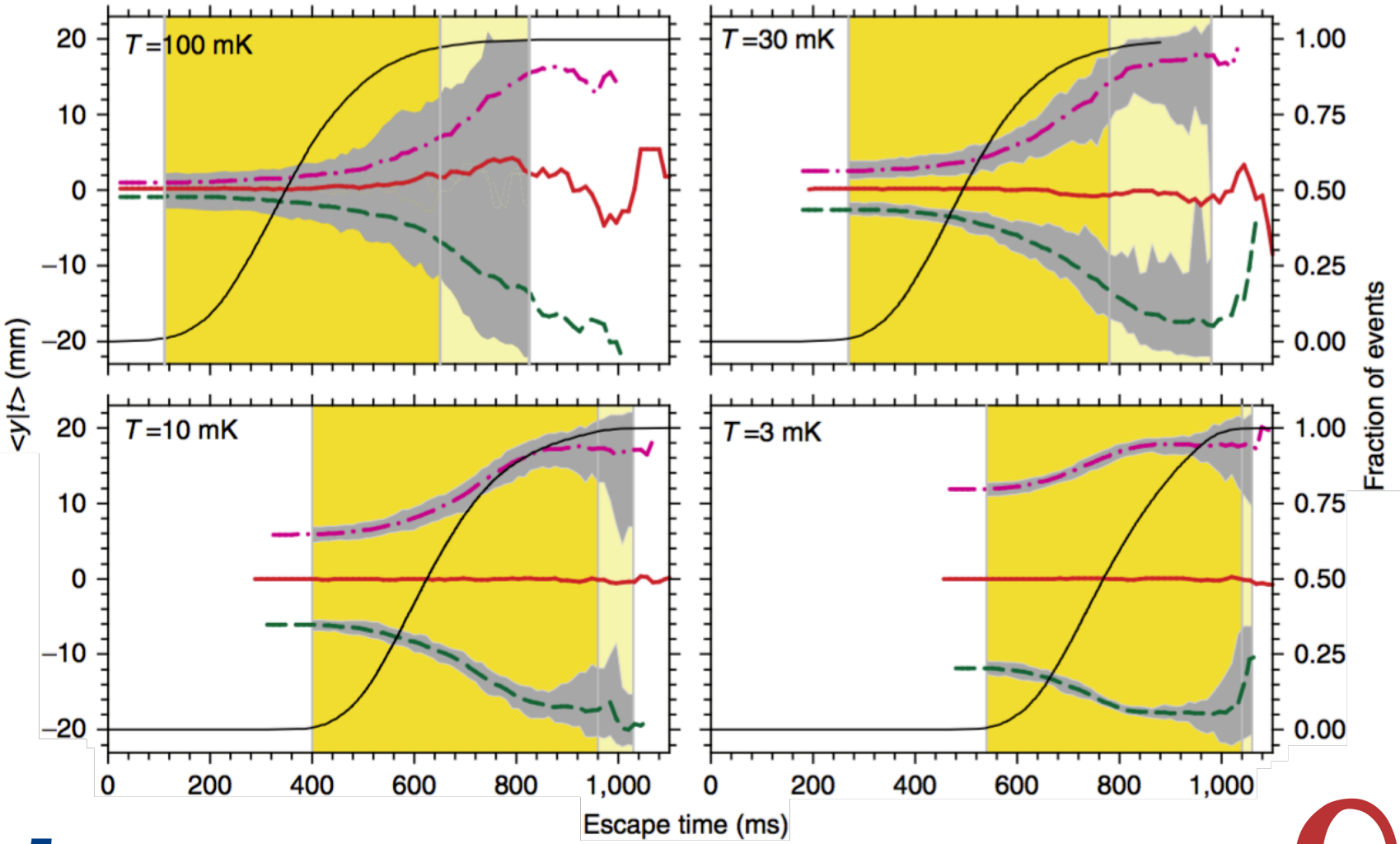
Antimatter Gravity

Sensitivity is greatly increased with a colder sample of antihydrogen



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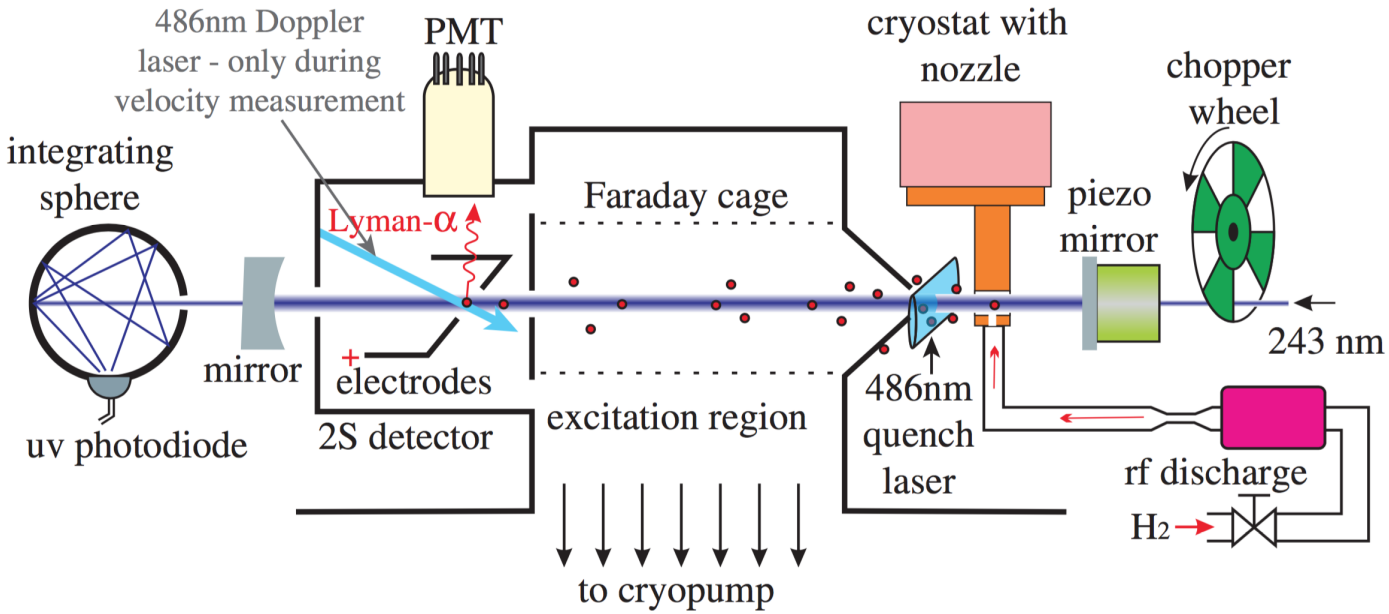
1S-2S Transition in Hydrogen

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



Hänsch et al. 2011

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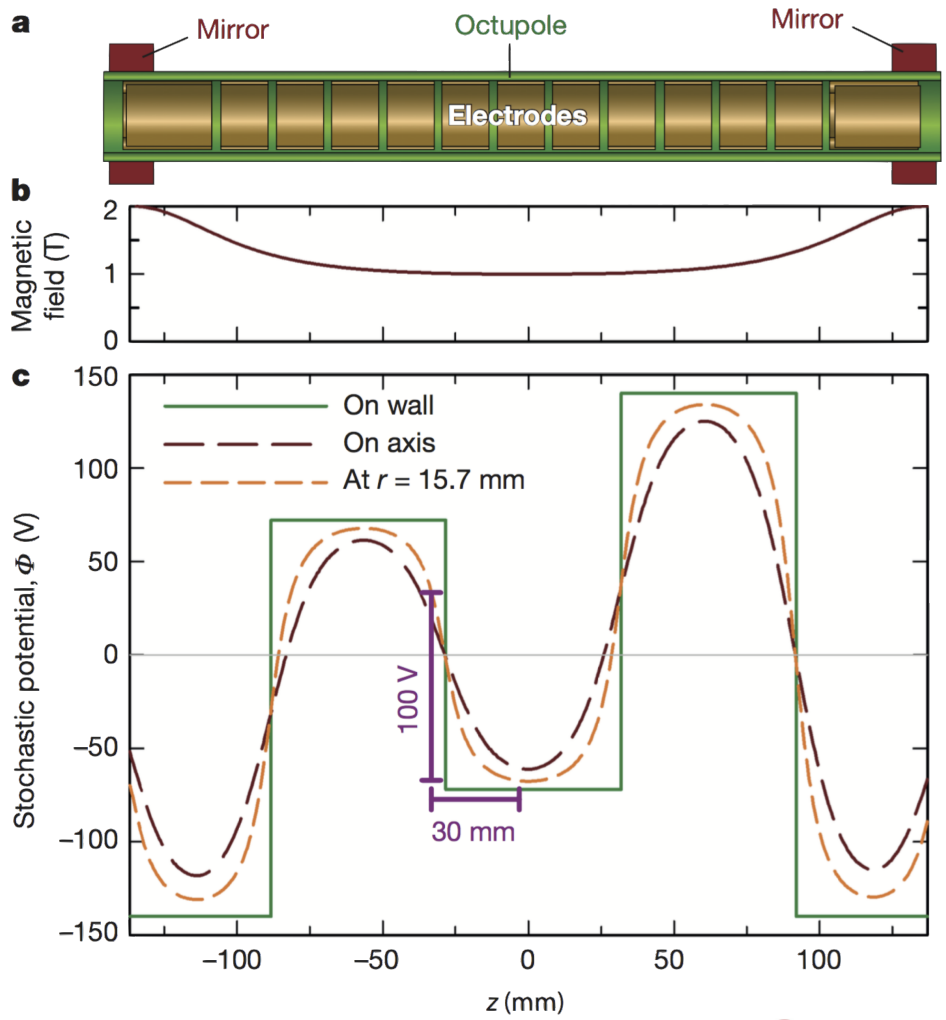
Charge Neutrality of Antihydrogen

1. Apply stochastically varying electric fields to the trapped antihydrogen
2. If antihydrogen is charged, it can be accelerated out of the magnetic trap by the stochastic fields
3. From the surviving atoms, deduce a limit on the charge of the antihydrogen atom



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Baryon Asymmetry

- Observations show no evidence for large scale antimatter in the Universe
- No satisfactory explanation, consistent with experiment, has been given
- This is one of the main arguments for the incompleteness of the Standard Model in its current form

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CPT Symmetry

- Combination of the Charge conjugation, Parity inversion, and Time reversal symmetries
- C, P, and CP are each broken in the standard model
- No process has been observed to break CPT symmetry
- CPT symmetry is proven to hold in any quantum field theory which:
  - Is Lorentz invariant
  - Is local
  - Has a Hermitian Hamiltonian
  - Is flat

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Weak Equivalence Principle

In Einstein's general relativity, *any body must experience the same acceleration in the gravitational field, regardless of its composition*

This is expected to hold true for antimatter, but a direct, model-independent test has not been made

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