Unravelling the gravity of antimatter

First results from the ALPHA-g experiment

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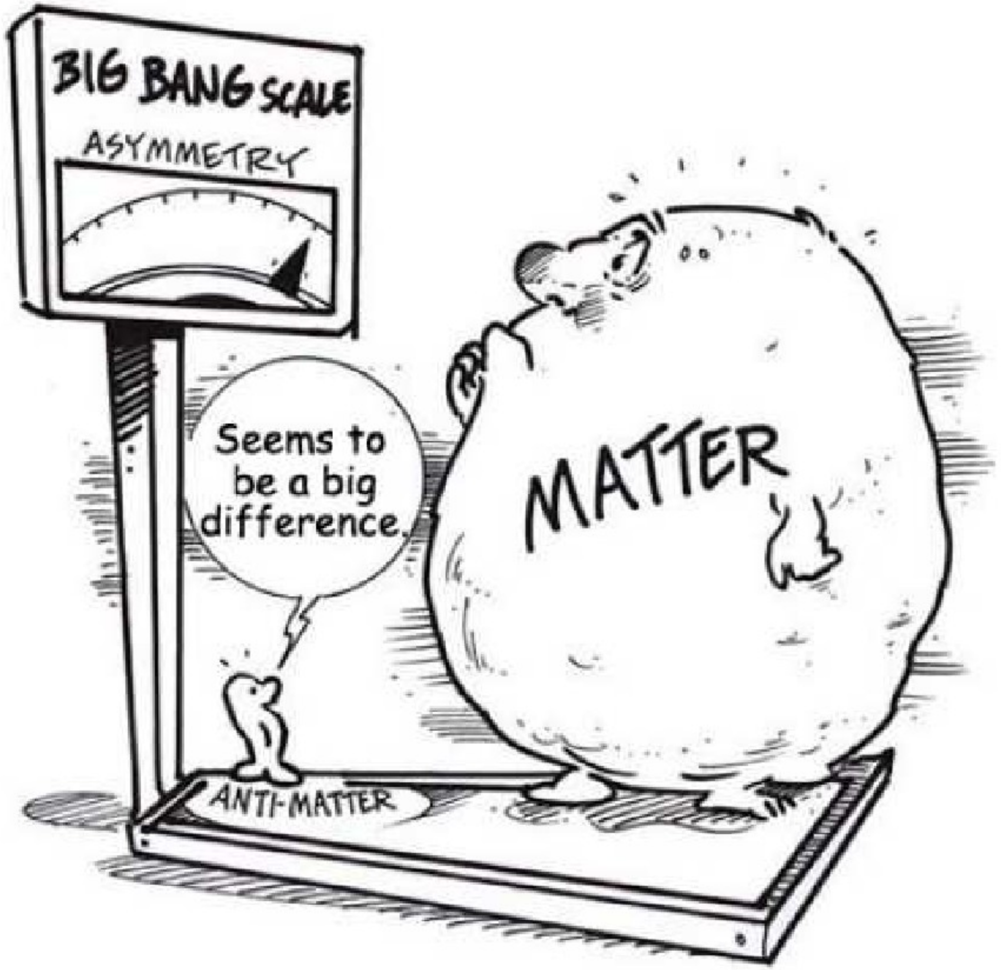
Missing Antimatter



- SM – does not account for matter-antimatter asymmetry
- CPT theorem - H and have the same energy levels
- Comparison = direct test of fundamental symmetry

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CPT symmetry and antimatter gravity in general relativity

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PACS 04.90.+e – Other topics in general relativity and gravitation
PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries
PACS 98.80.-k – Cosmology

Abstract – The gravitational behavior of antimatter is still unknown. While we may be confident that antimatter is self-attractive, the interaction between matter and antimatter might be either attractive or repulsive. We investigate this issue on theoretical grounds. Starting from the CPT invariance of physical laws, we transform matter into antimatter in the equations of both electrodynamics and gravitation. In the former case, the result is the well-known change of sign of the electric charge. In the latter, we find that the gravitational interaction between matter and antimatter is a mutual repulsion, *i.e.* antigravity appears as a prediction of general relativity when CPT is applied. This result supports cosmological models attempting to explain the Universe accelerated expansion in terms of a matter-antimatter repulsive interaction.

Weak Equivalence Principle

Equivalence of inertial and gravitational mass

$$F = m_i a$$

$$F = m_g G \frac{M}{r^2}$$

$$m_i = m_g$$

$$a = G \frac{M}{r_2}$$

Weak Equivalence Principle

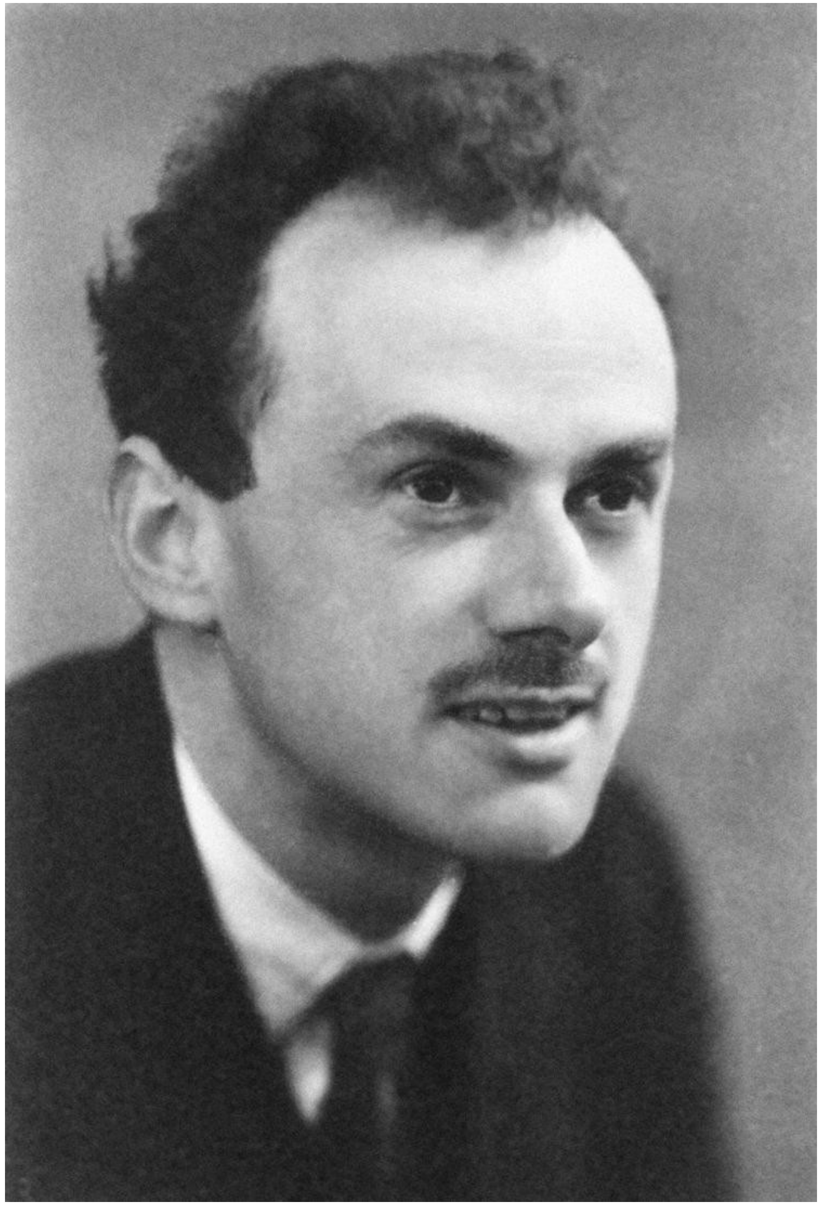
All masses behave the same in response to gravity, regardless of their internal structure

Antihydrogen is a neutral particle

This is the first direct ballistic test of antimatter in a gravitational field

Hydrogen vs Antihydrogen

Dirac Equation



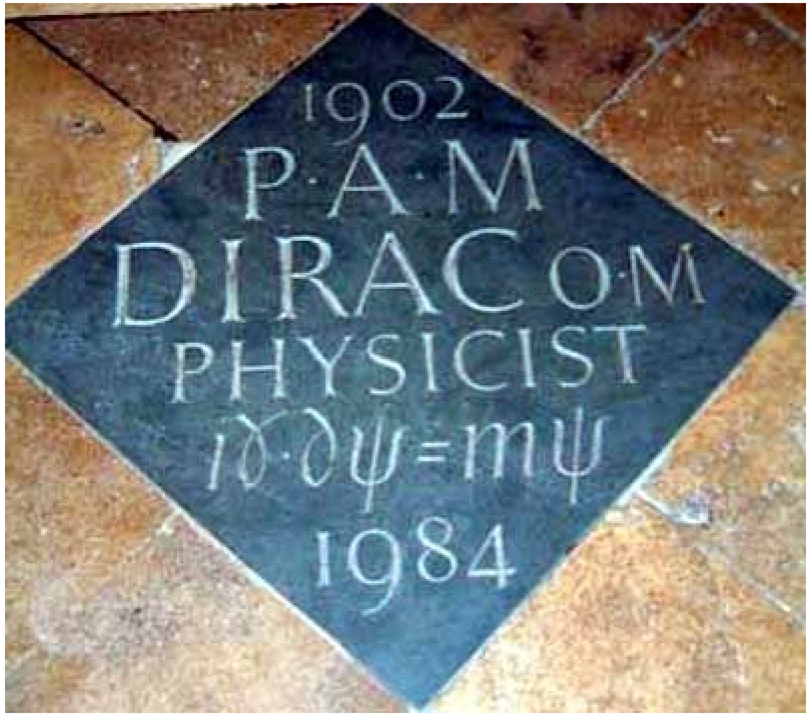
Nobel Prize in 1933

Linked quantum mechanics and special relativity to describe an electron moving at relativistic speeds

Two Solutions:

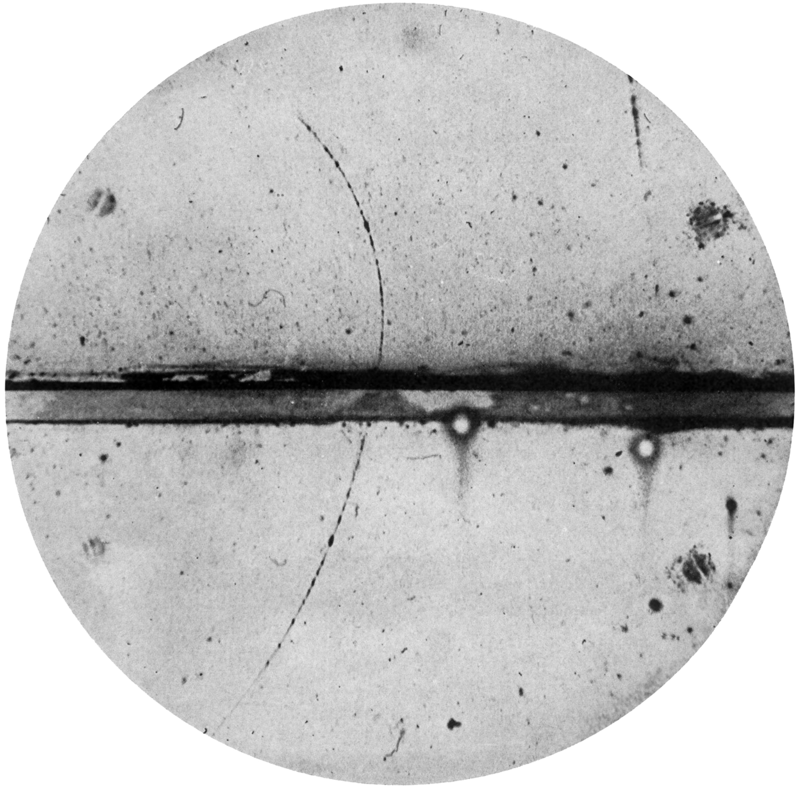
e^- ⟶ +ve E

e^+ ⟶ +ve E

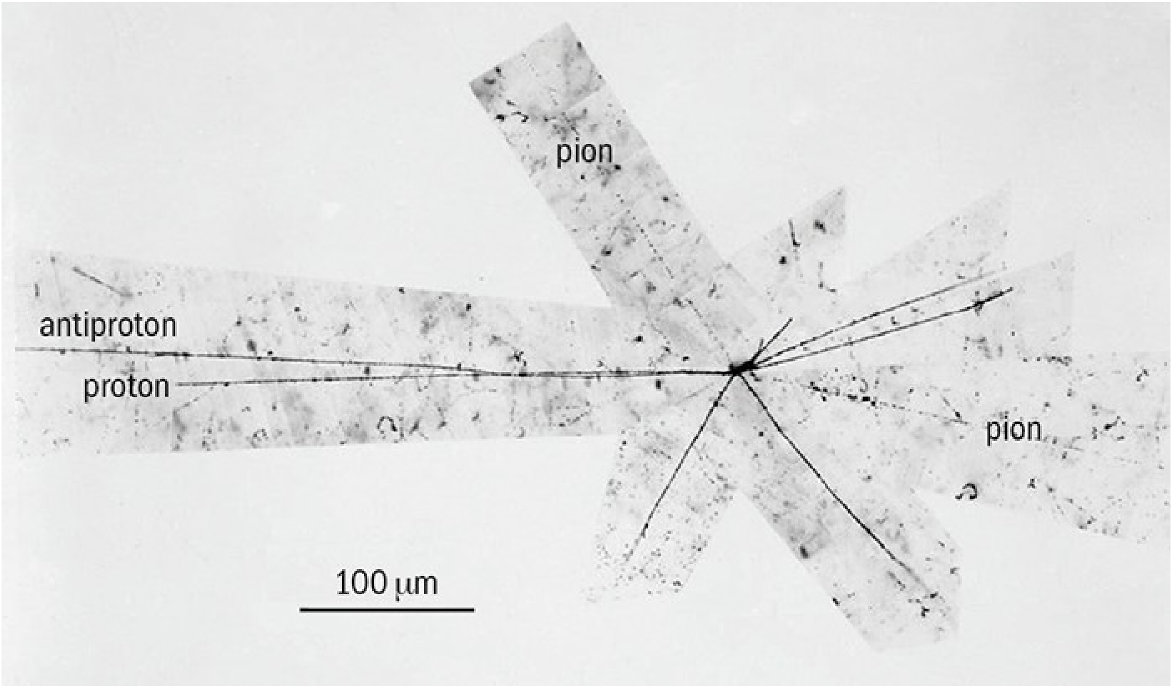


Westminster Abbey

Positrons and antiprotons



Positron discovery 1932
1936 Nobel prize – Carl Anderson



Antiproton discovery 1955
1959 Nobel prize
Emilio Segre and Owen Chamberlain

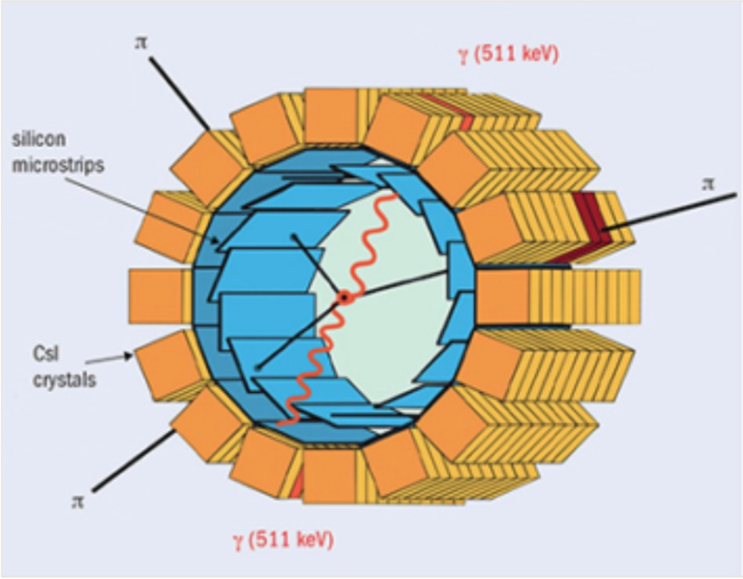
st Antihydrogen Atoms

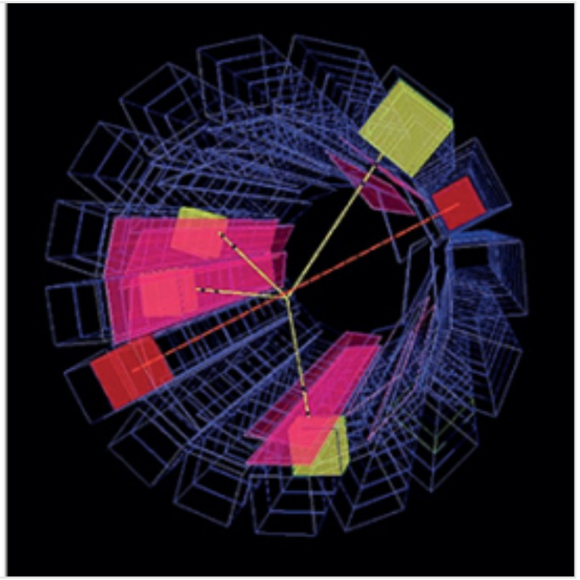
ATHENA
2002

Low Energy Antiproton Ring (LEAR)
1995

Nine atoms were produced in collisions between antiprotons and xenon gas. Each one remained in existence for about forty billionths of a second before annihilating.

Creation of thousands of antihydrogen atoms





LETTER

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Trapped antihydrogen

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38 annihilation events in 335 trials

172 ms between formation and release from the trap

ARTICLES
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nature physics

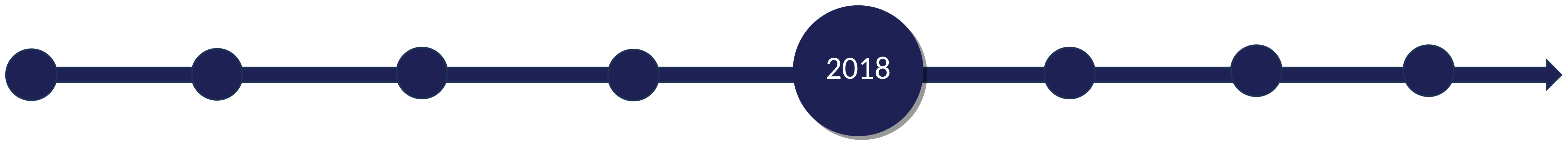
Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

2011

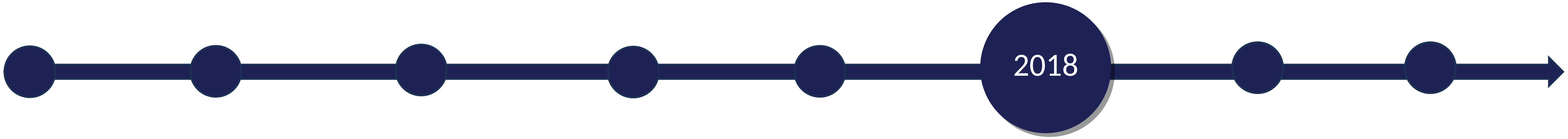

2013

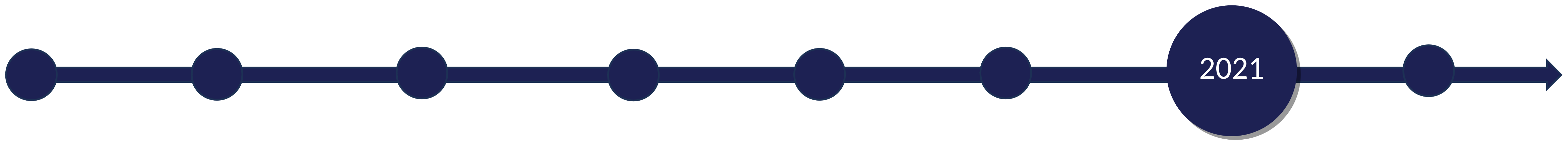

2016

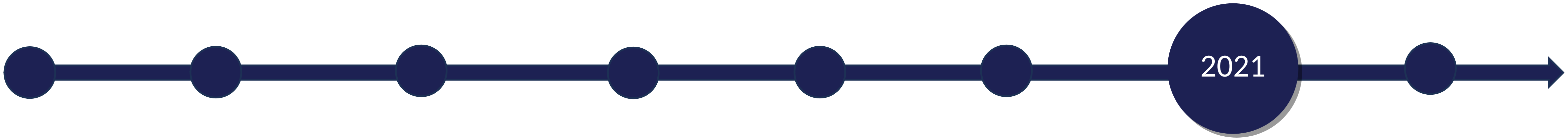

2018

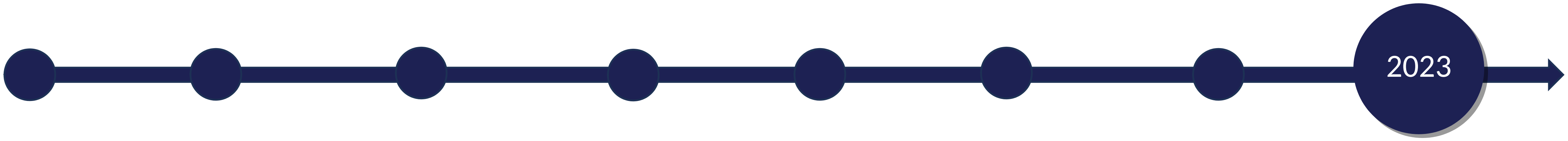
CPT invariant to a relative precision of

15,000 antihydrogen atoms over 10 weeks



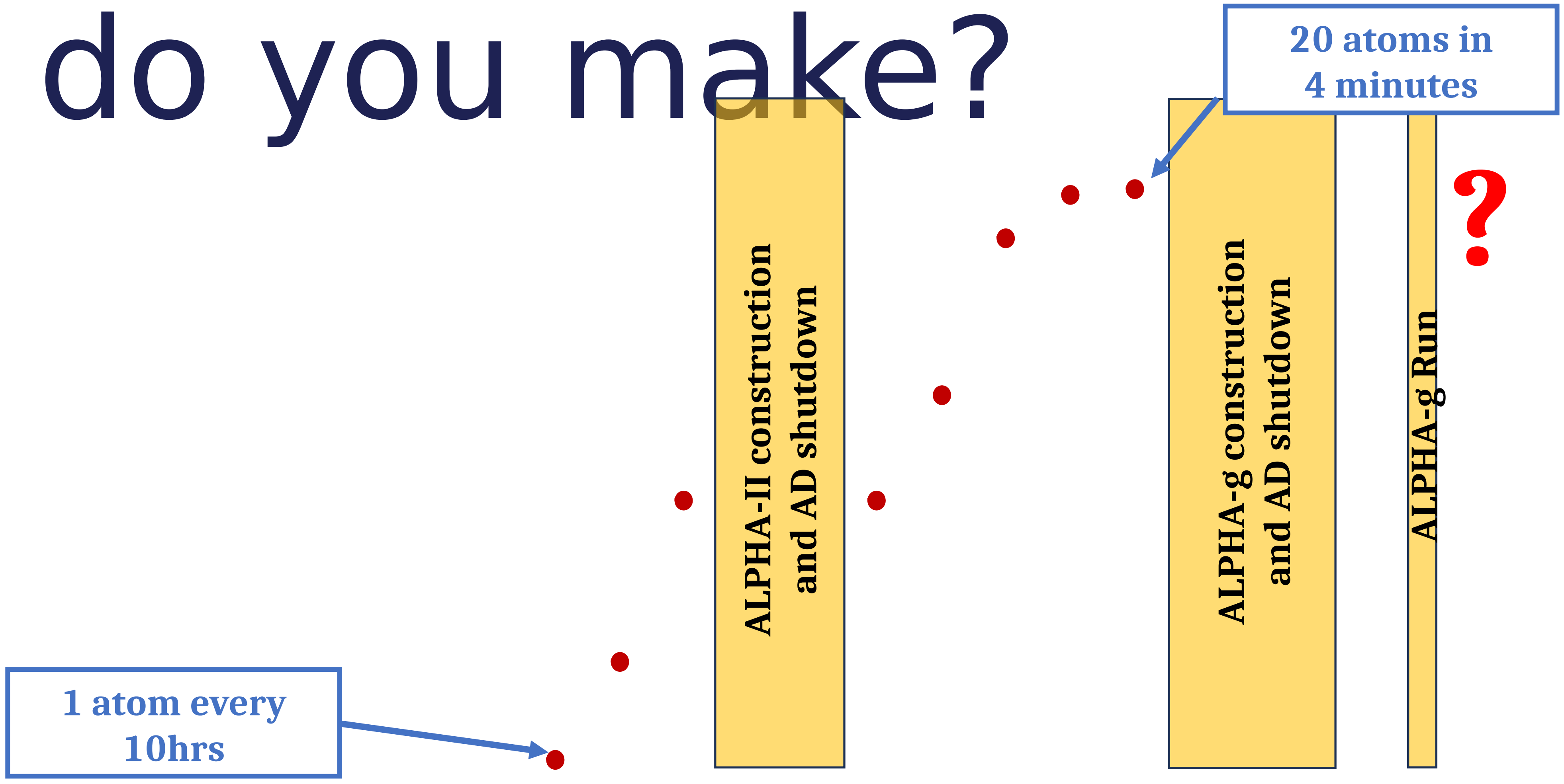

2021


2021


2023

Making Antiprotons

How much antihydrogen do you make?



Detectors

radial Time Projection Chamber (rTPC)

- Active gas region contains 70% Ar and 30% CO_2
- 18,432 readout channels = 576-fold segmentation in z and 32-fold in
- Used for reconstructing the vertices of Hbar annihilations

- The high voltage across the gas causes, any electrons that have been ionised by the passing pion, to accelerate and create a cascade of electrons as they drift to the outside wall giving a pulse of charge which we can record.

- The delayed arrival of the longer orange traces allows us to reconstruct the entire track.

- Since the pions interact with the entire gas volume, many points can be reconstructed, giving us a great accuracy in determining the track.

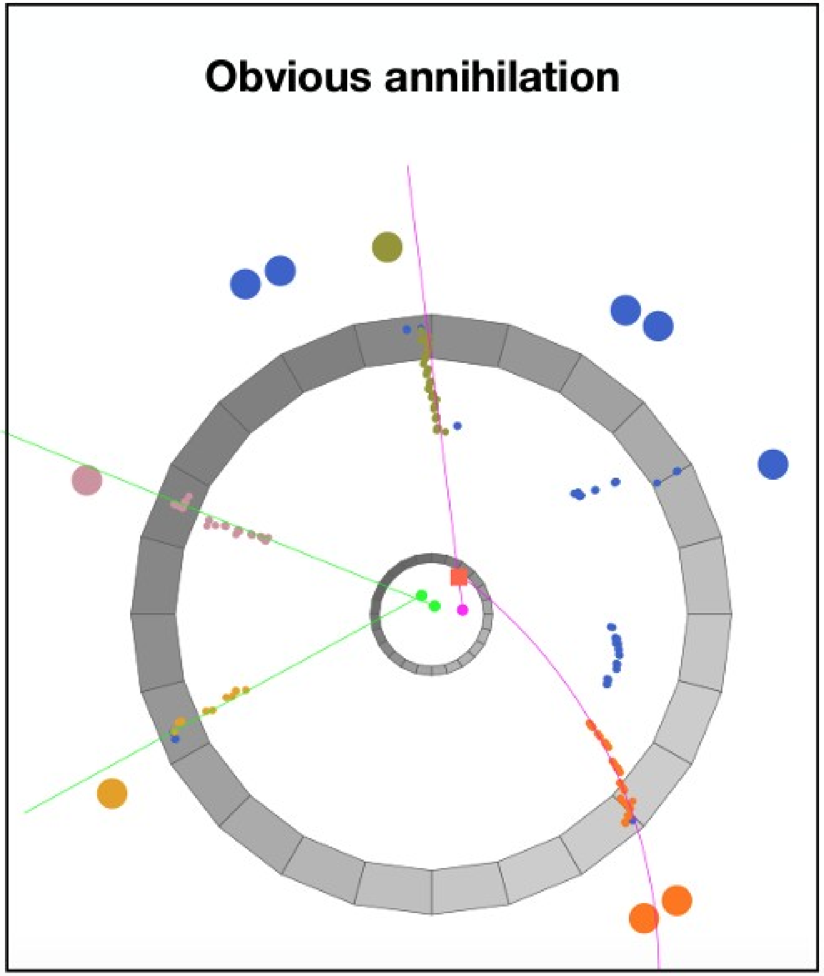
Barrel Scintillator

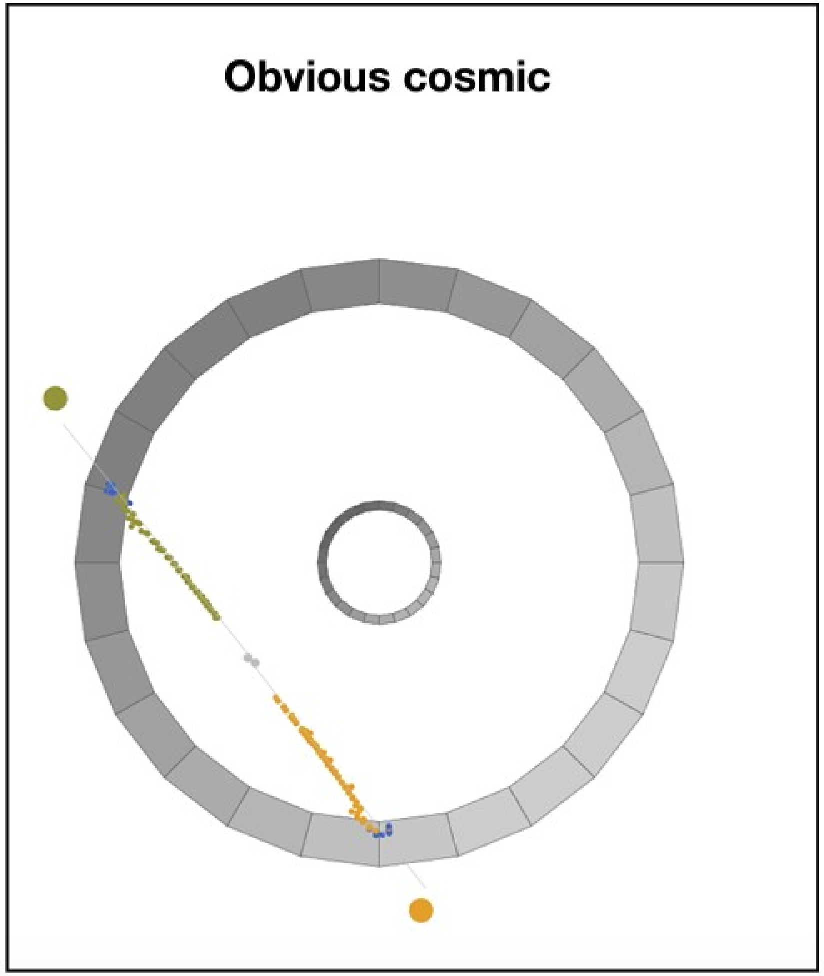
64 trapezoidal scintillating bars in a barrel shape.

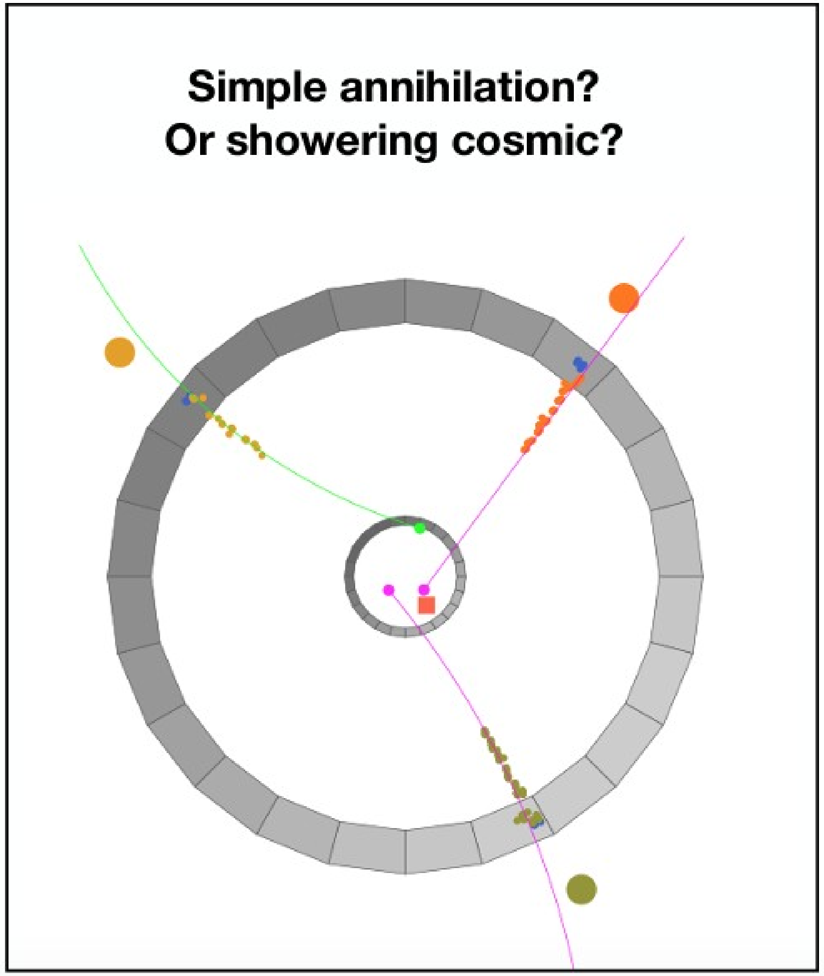
Each bar is readout at both ends with SiPM sensors for a total of 128 channels.

Used for suppression of cosmic background

Background Suppression



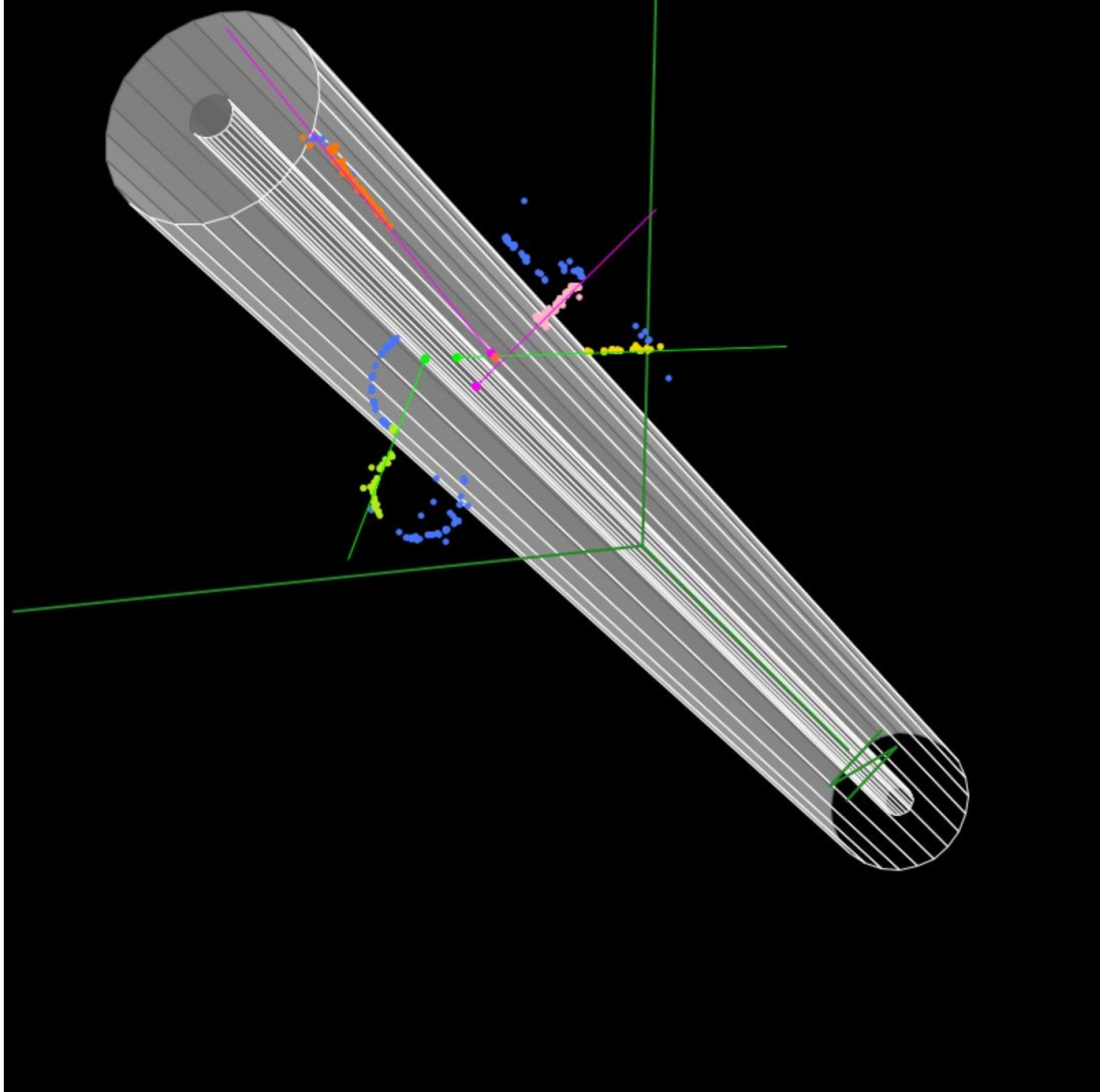




Reconstruction

1. Charged pion makes three ionization clusters per mm in the drift region of the rTPC.
2. Fit a helix to the locations of the clusters.
3. Vertex is found where two helices pass closest together.

Z vertex resolution of 2cm



Magnetic Field Bias

escapes when its kinetic energy exceeds the gravitational potential and the magnetic potential at one of the mirror coils.

$B_A = B_G$

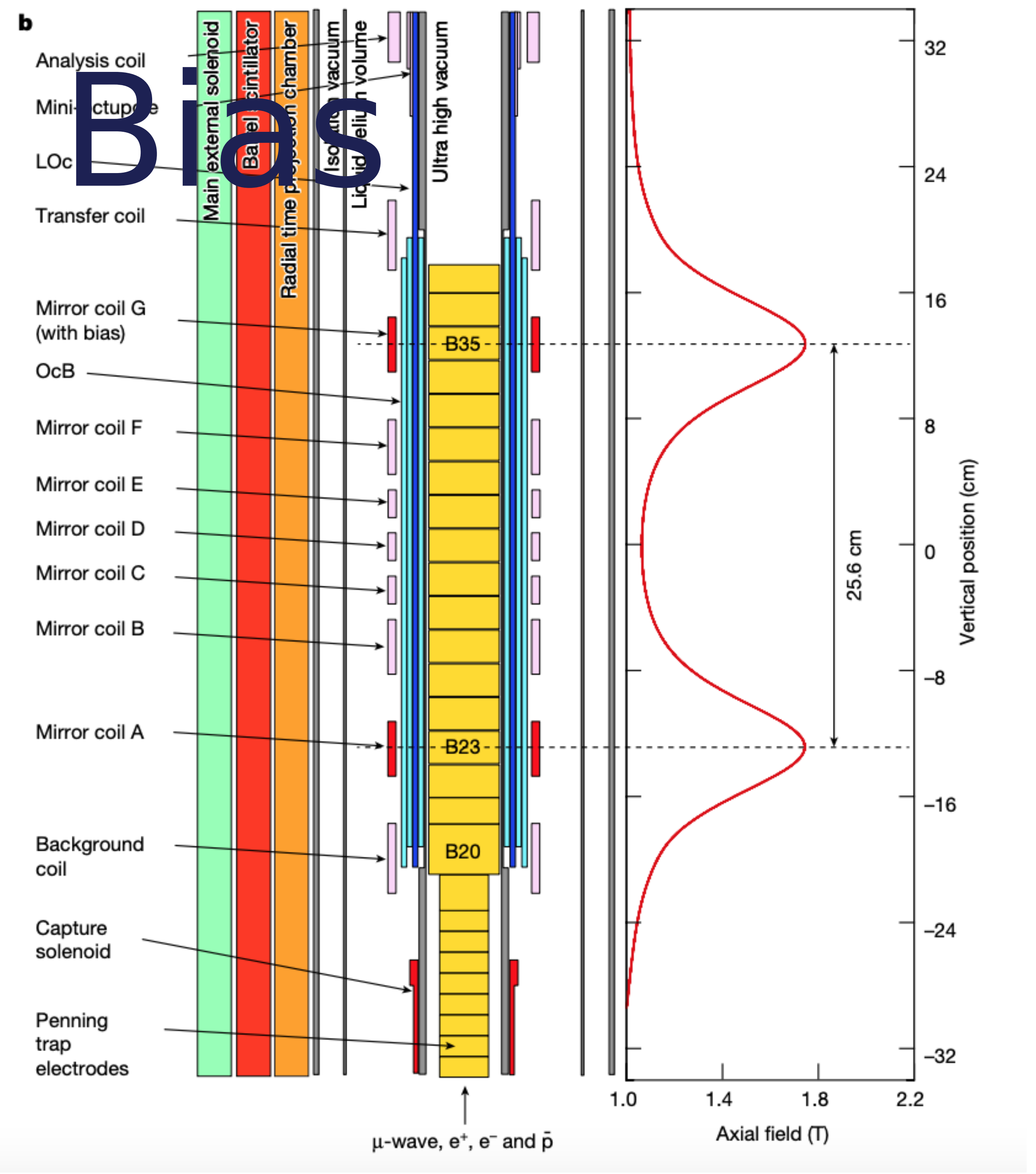
80% of Hydrogen atoms would escape out the bottom

We can counteract or supplement gravity by adding a differential current to one of the mirror coils.

g → vertical gradient 1.77×10^{-3} T m^{-1}
→ between mirror coils 4.53×10^{-4} T.

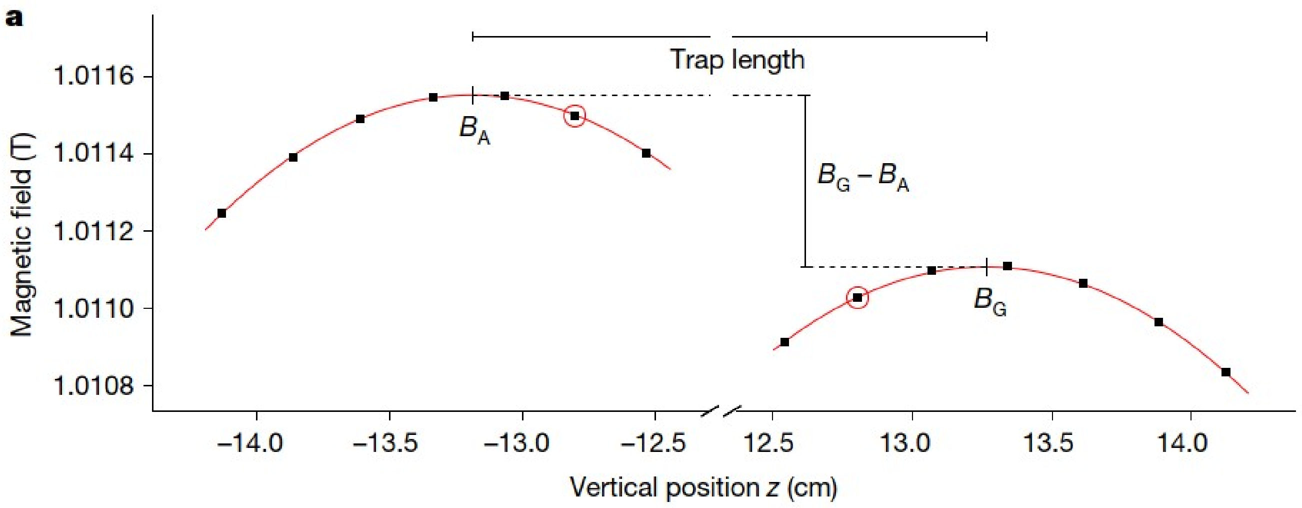
$B_G - B_A = -4.53 \times 10^{-4}$ T

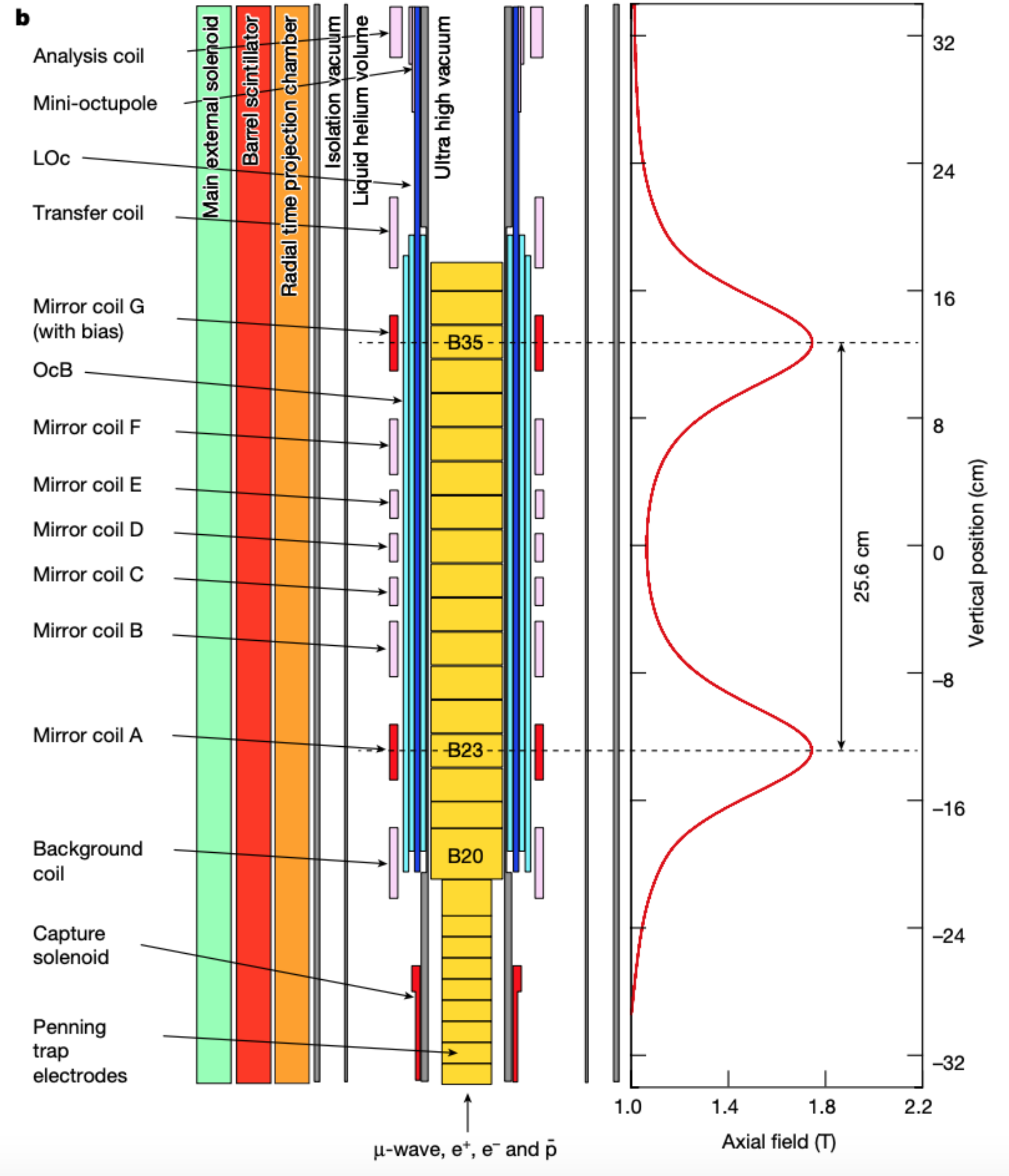
Gravity is balanced by the magnetic field and 50% of the should go up and 50% should go down.



Magnetic Field

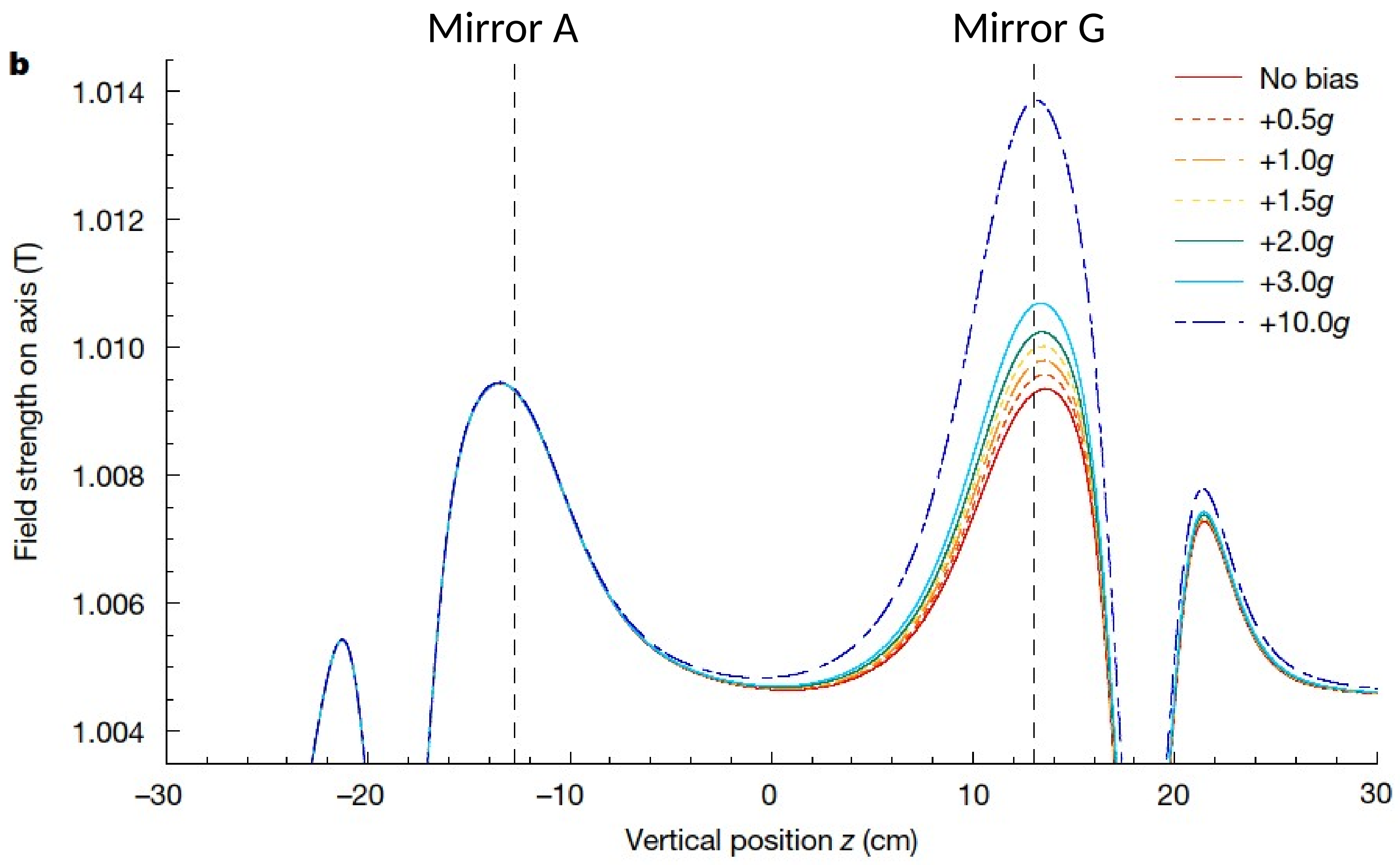
$$\frac{\mu_B(B_G - B_A)}{m_H(z_G - z_A)}$$





-1g balances the downward force of gravity for Hydrogen

Final on-axis well shapes



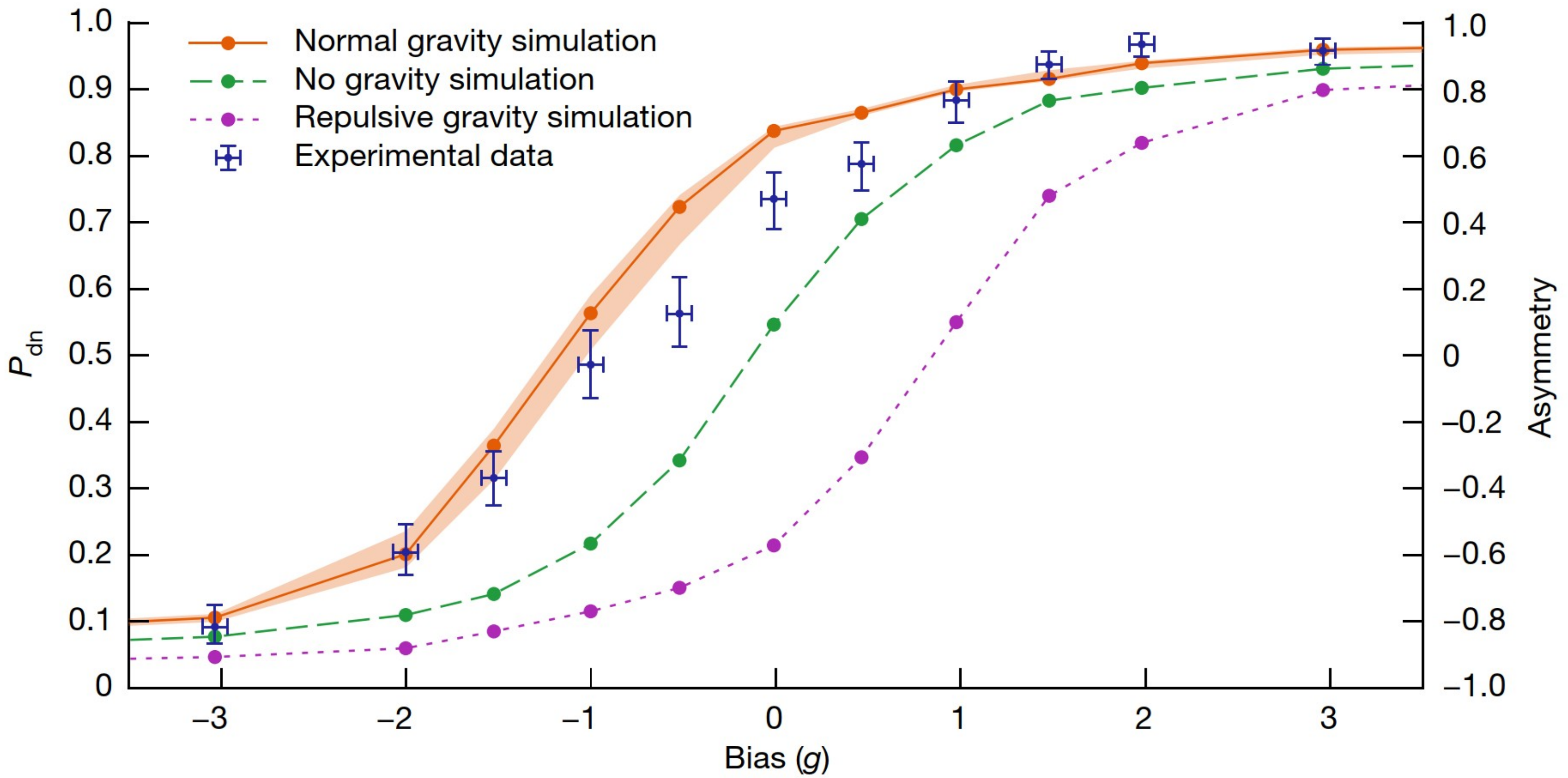
Method

- Stack antihydrogen – 4hrs, 100 atoms per trial
- Ramp down the long octupole to eliminate transverse confinement above mirror G – releases transversely energetic Hbar – about 50%, so used to indicate total no. of Hbar.
- ECR measurement under both mirror coils
- Release with a chosen bias over 20s (ramp down mirror coils)
- Repeat ECR to characterize the final axial well
- Interleave different bias measurements over 30 days (repeat 6/7 times each)

Raw data

Uncorrected for background or detector efficiency

Results: Probability to escape downwards



$$A = 2P_{dn} - 1$$

Results: gravitational acceleration of antihydrogen

$$a_{\overline{g}} = \left(0.75 \pm 0.13 \pm 0.16\right) g$$

$g = 9.81\, m\, s^{-2}$

simulation

Statistical + systematic

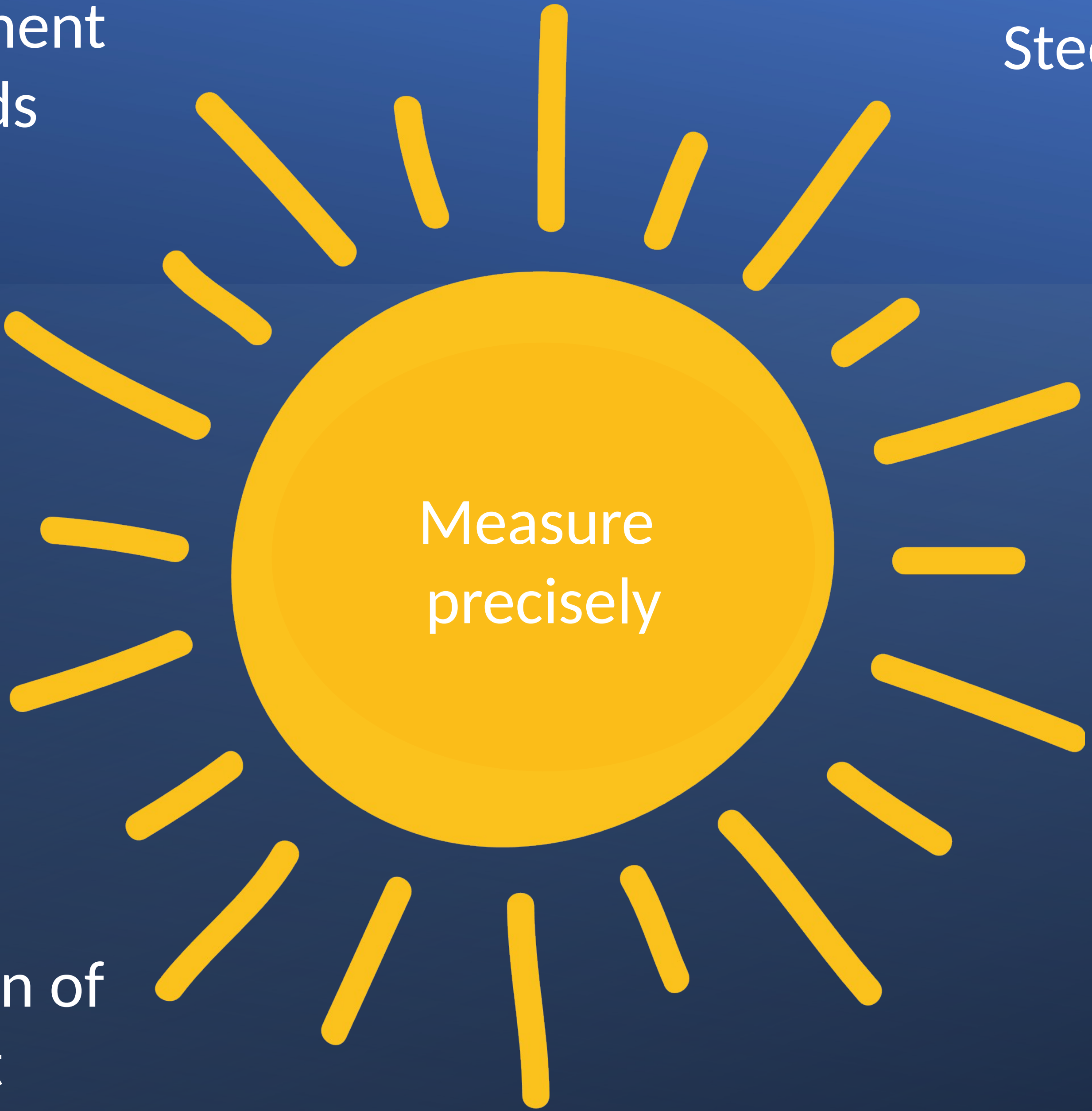
Consistent with downward gravitational acceleration of 1g for antihydrogen

Improve measurement of magnetic fields

ECR (on and off axis)

Beryllium ion magnetometry

Use precision region of the experiment



Benchmark and refine simulations

Steeper escape curve

Colder antihydrogen atoms

Laser cooling

Adiabatic expansion cooling

CERN

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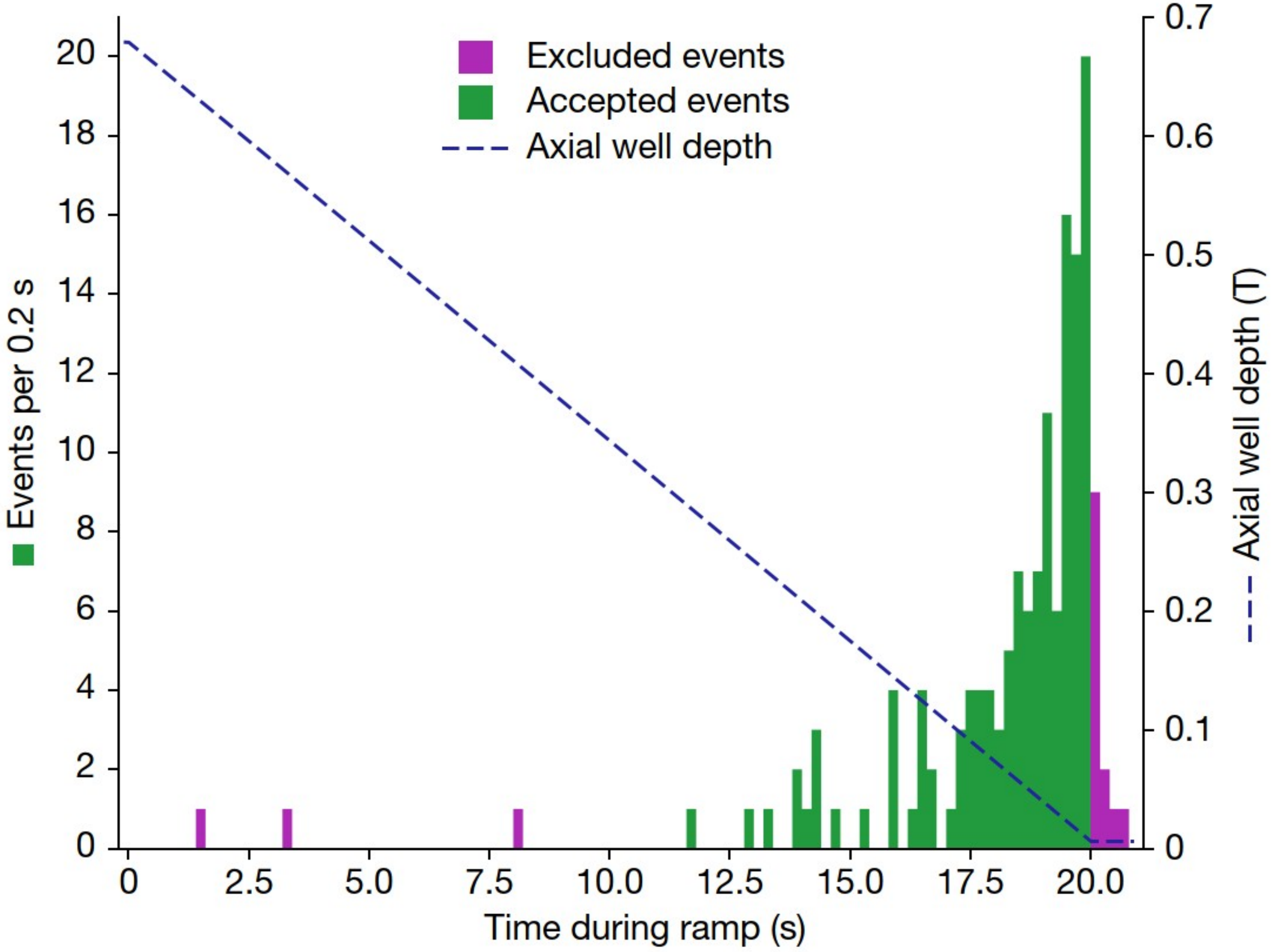
Time and z-cut

- ± 10g calibration runs – force the atoms out of bottom or the top of the trap
- **Z-cut**: exclude events between the physical mirror centres or more than 0.2m outside the mirror centres
- **Detector efficiency** for the up and down detector regions, using annihilations in the LoC rampdown for normalization
- **Time-cut**: number of atoms before 10s is negligible, 20s is when the axial well reaches its minimum



Uncertainties

Bias Determination

Uncertainty	Magnitude (g)
ECR spectrum width	0.07
Repeatability of ($B_G - B_A$)	0.014
Peak field size and z-location fit	0.009
Field decay asymmetry (A to G) after ramp	0.02
Bias variation in time	0.02
Field modelling	0.05

Determination

	Uncertainty	Magnitude (g)
Statistical and systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03