
# The effect of gravity on antimatter

## The ALPHA experiment

UNIVERSITÀ DEGLI STUDI DI BRESCIA

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INFN

# Antimatter and gravity

Over the last century, the general theory of relativity has passed a number of stringent experimental tests [1]. Among its core tenets, still experimentally unchallenged, is the Einstein equivalence principle (EEP). The EEP, in its modern form [2], consists of three parts: the universality of free fall, also known as the weak equivalence principle (WEP), local Lorentz invariance (LLI) and local position invariance (LPI). The WEP implies that **all objects fall at the same rate**, regardless of their internal composition or structure

[1] Will, C.M. The confrontation between general relativity and experiment. Living Rev. Relativ. 2014, 17, 1–117.

[2] Dicke, R.H. Experimental relativity. Relativ. Groups Topol. Relativ. Topol. 1964, 165–313

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Antimatter was discovered ~15 years after General Relativity

Does the WEP hold for antimatter too?

# Antimatter and gravity

"A person in a closed windowless chamber who feels his feet pressed to the floor will not be able to tell whether it's because the chamber is in outer space being accelerated upward or because it is at rest in a gravitational field. If he pulls a cent coin from his pocket and lets it go, it will fall to the floor at an accelerating speed in either case. Likewise, a person who feels she is floating in the closed chamber will not know whether it's because the chamber is in free fall or hovering in a gravity-free region of outer space"

*Excerpt From "Einstein" by Walter Isaacson*

# Antimatter and gravity

Even if WEP is widely expected to hold for antimatter, a violation *is not a-priori excluded* and more importantly … no direct measurement is (*was*) available …

- Attempts for a quantum theory of gravity typically result into new interactions which may violate the WEP (e.g. **Kaluza-Klein theory**)

  **Int. J. Mod. Phys. D18**, 251–273 (2009)

- A subset of the gravitationally coupled minimal SME (Standard Model Extension) envisages mechanisms to break CPT and Lorentz invariance with consequences also on the gravitational behaviour of antimatter

  V. Alan Kostelecký and Arnaldo J. Vargas **PHYSICAL REVIEW D 92,** 056002 (2015)

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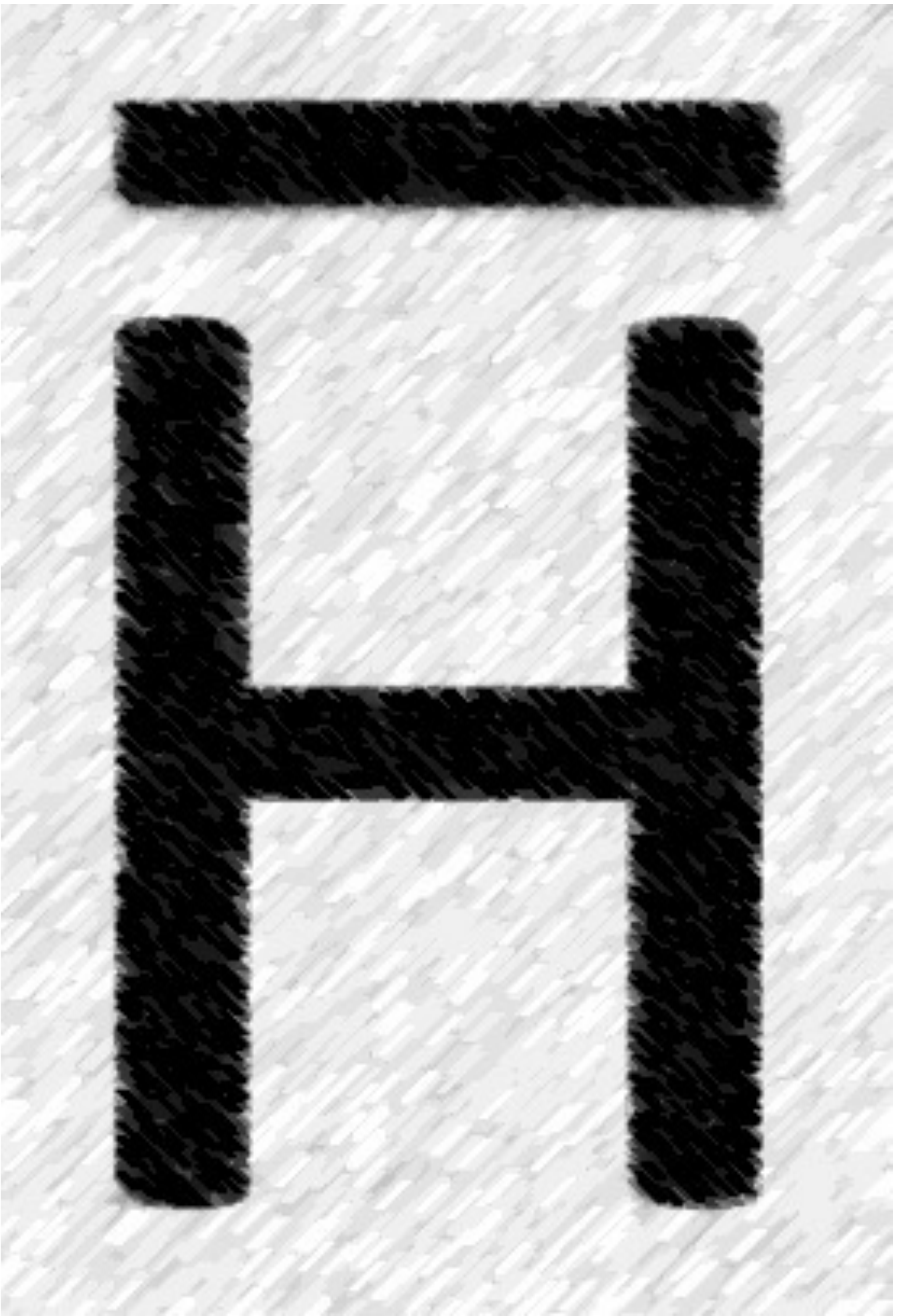
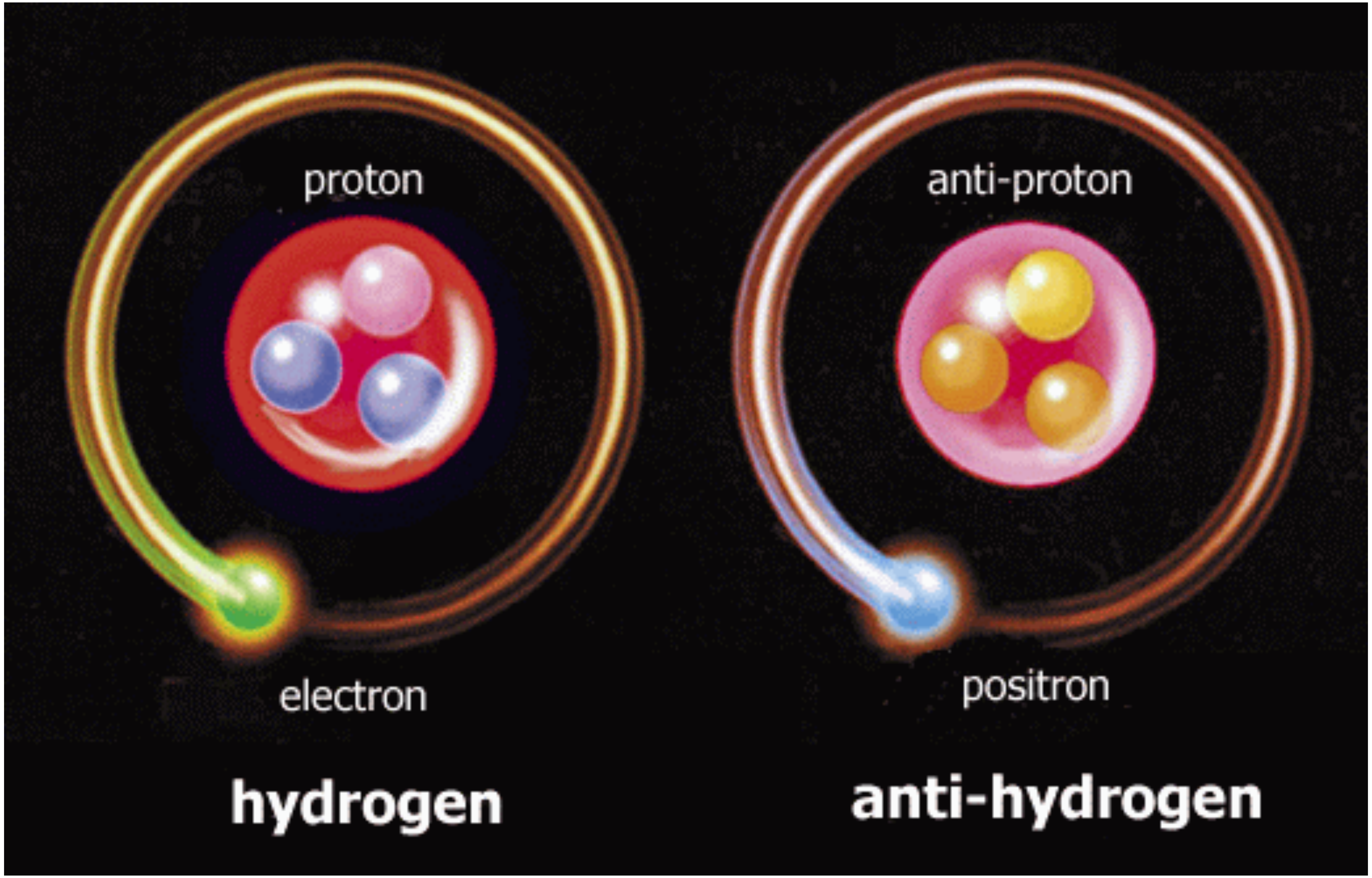
V. Alan Kostelecký and Arnaldo J. Vargas **PHYSICAL REVIEW D 92,** 056002 (2015)

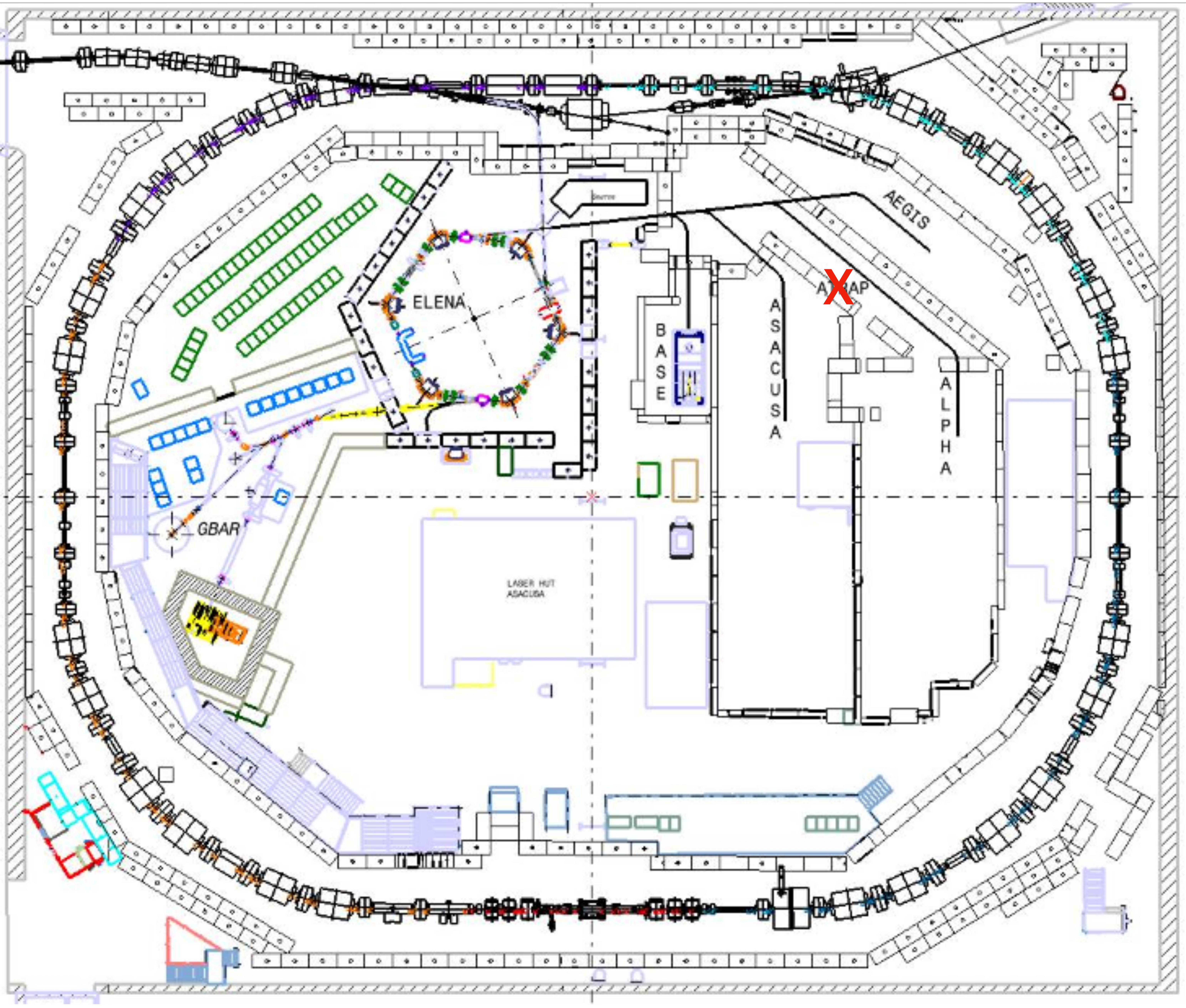
- **Previous attempts:**
  - **1967**: **Fairbank** and **Witteborn** tried to use positrons — **Phys. Rev. Lett. 19**, 1049 (1967)
  - **1989**: PS-200 experiment at CERN tried to use (4 K) antiprotons — **Nucl. Instr. and Meth. B**, 485 (1989)
  - Both **unsuccessful** because of stray E and B fields

# Antihydrogen





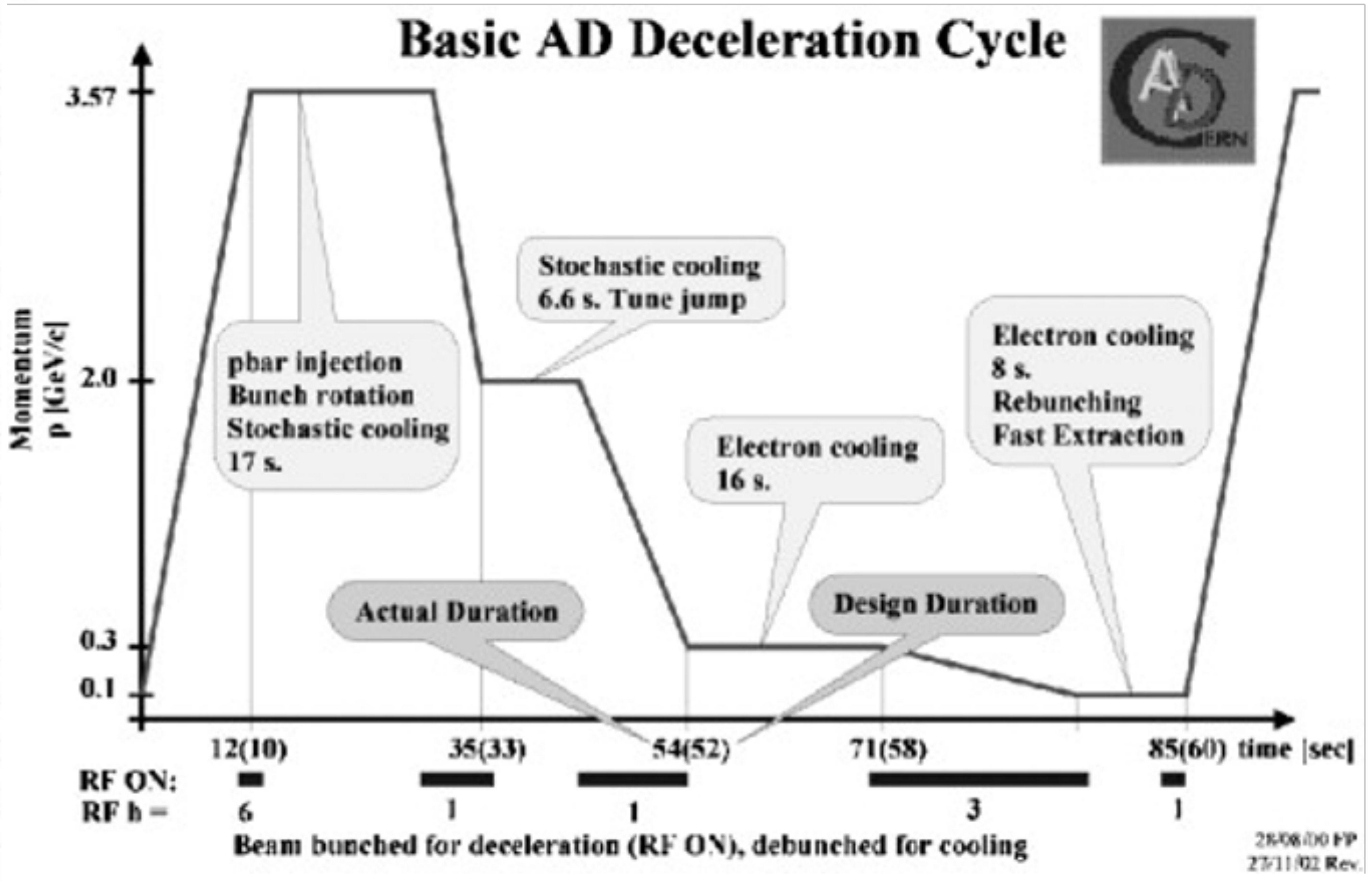
Antimatter factory experiments on the floor: BASE, AEgIS, ALPHA, ASACUSA, GBAR




# Antihydrogen

## The "Antimatter Factory": two accelerators in tandem

- AD (Antiproton Decelerator) since 2000
  - Decelerate to 5 MeV kinetic energy
- ELENA (Extra Low ENergy Antiproton) since 2018
  - $10^7$ antiprotons at 100 keV per bunch (~100 s)



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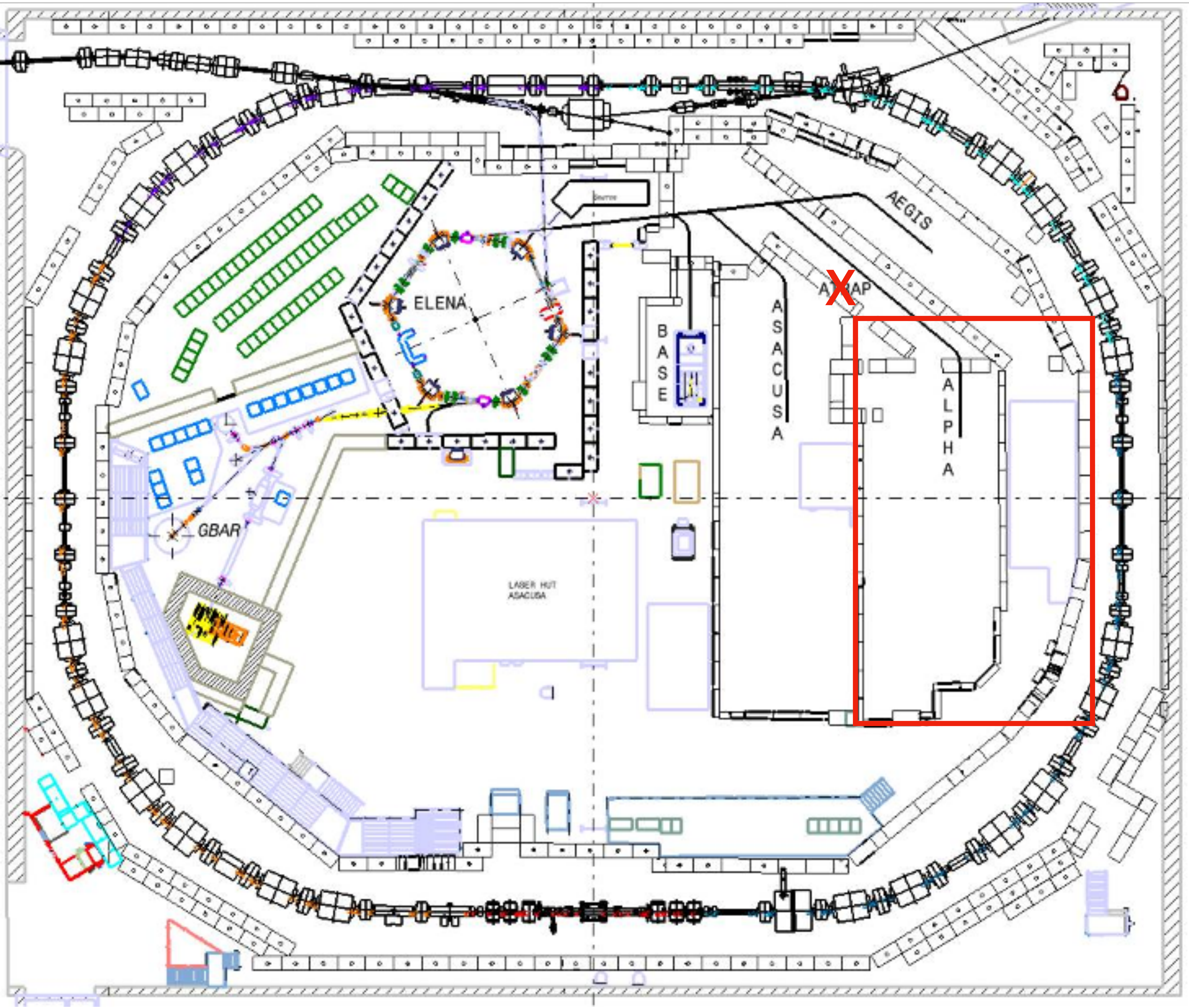


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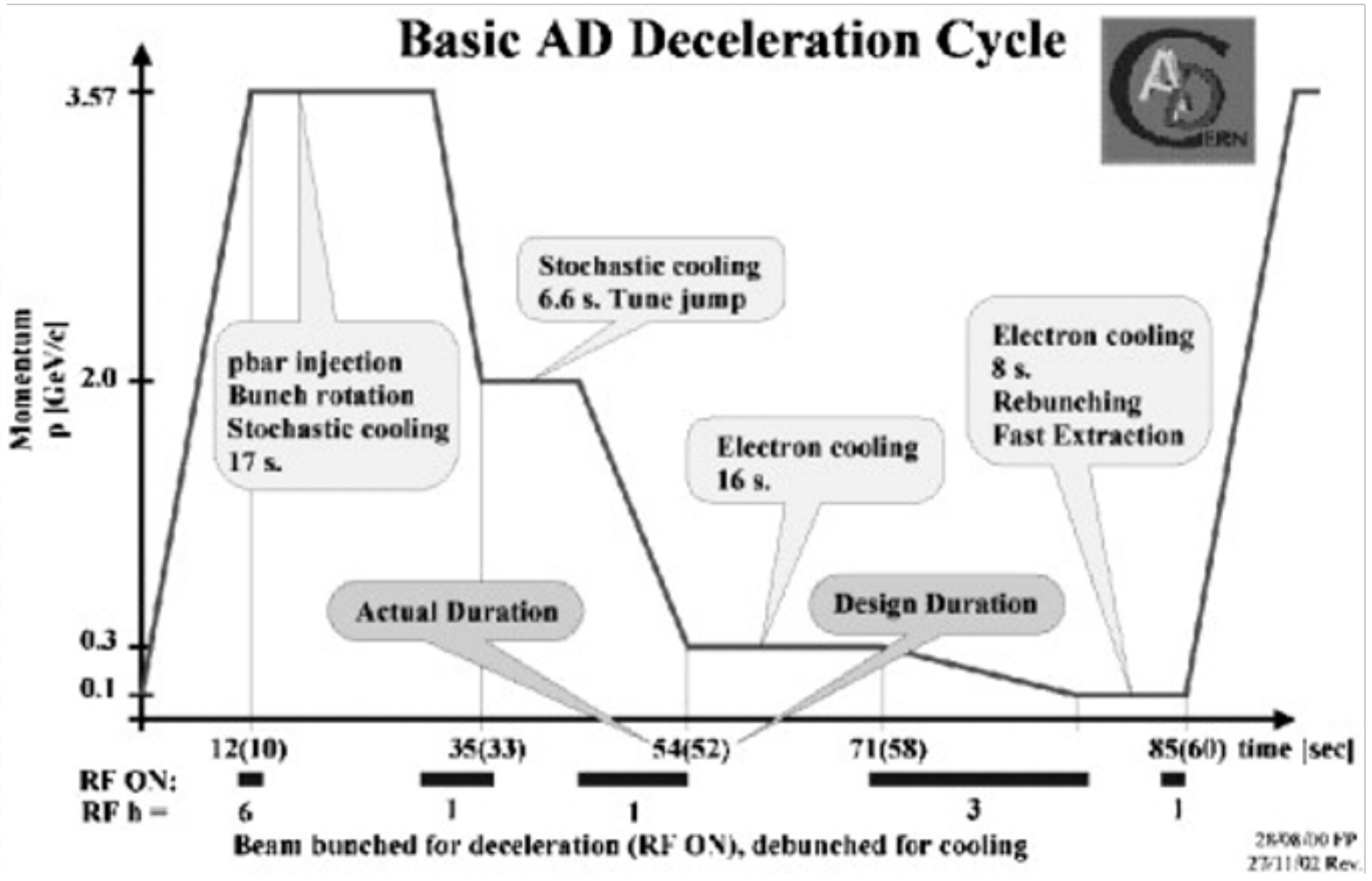
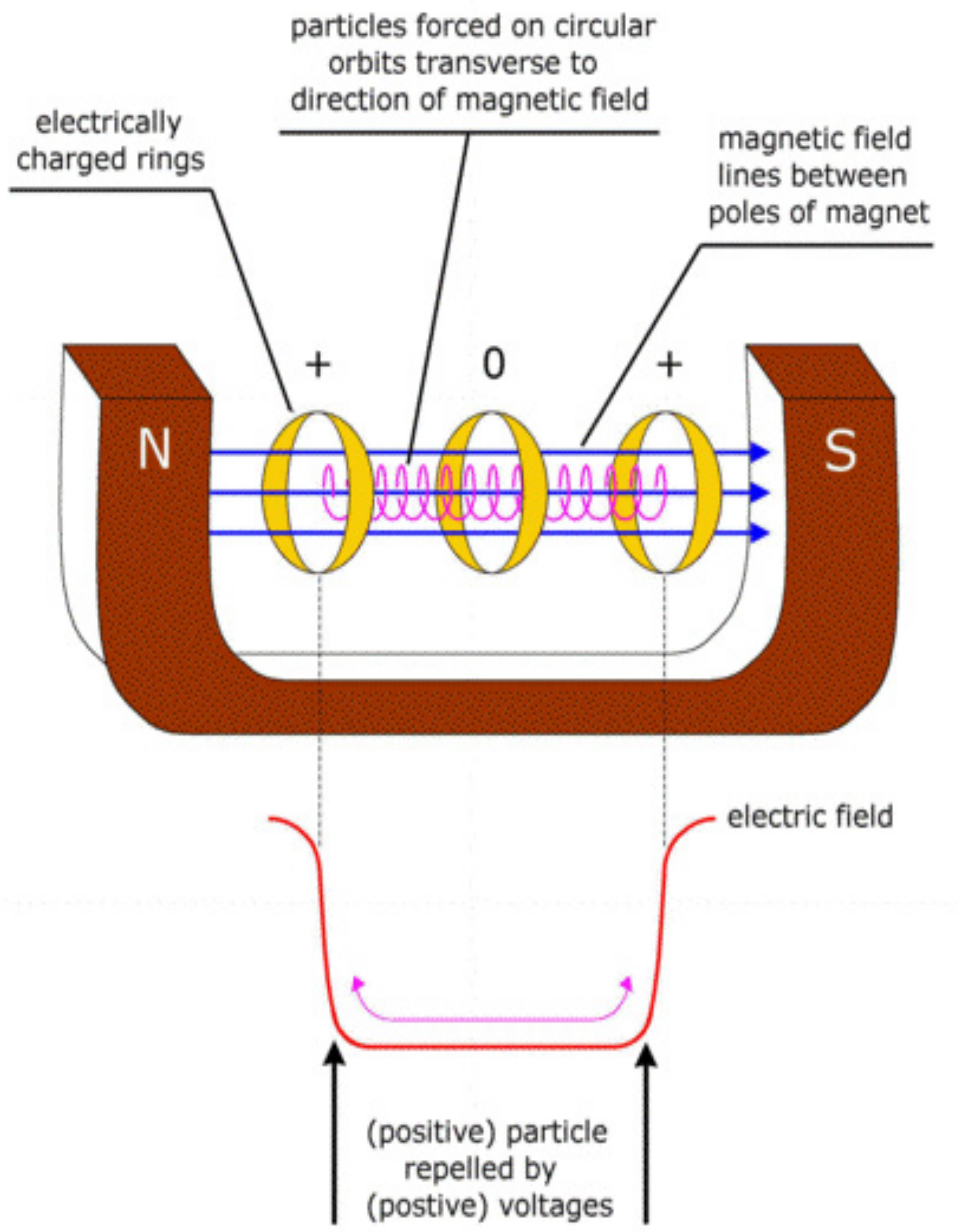


# Antihydrogen

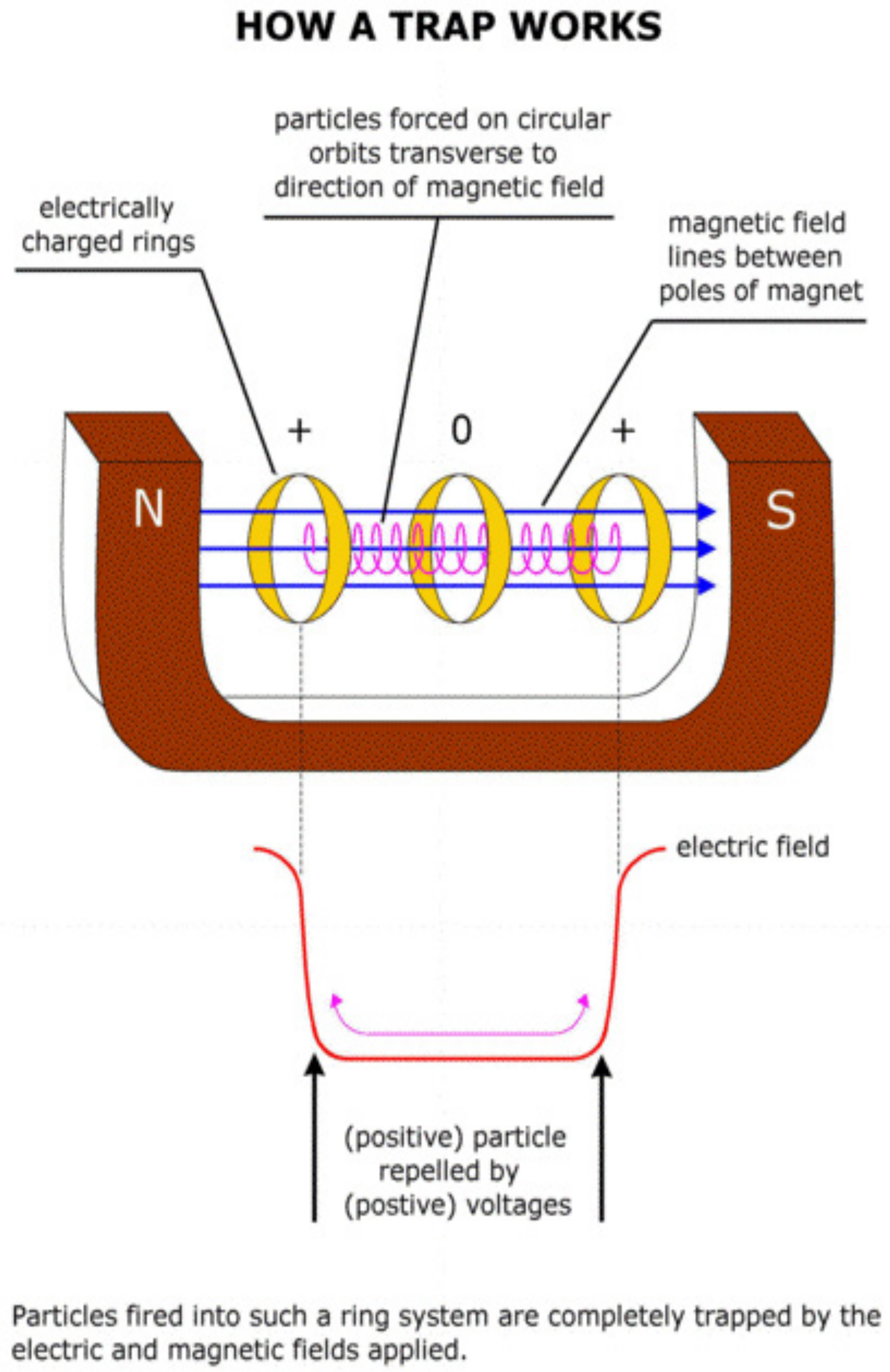

# Antihydrogen

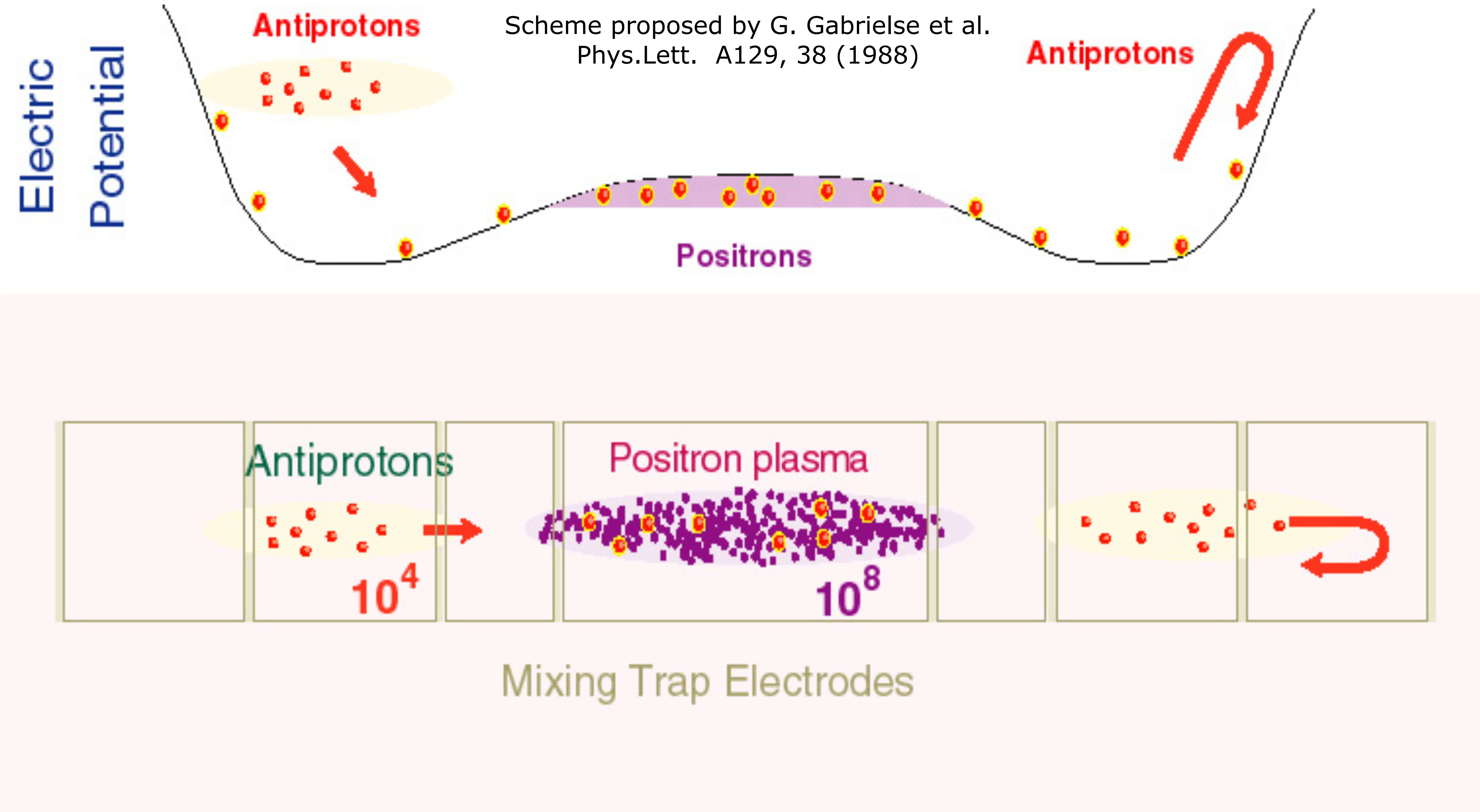
## HOW A TRAP WORKS




Particles fired into such a ring system are completely trapped by the electric and magnetic fields applied.

# Antihydrogen



# How to trap antihydrogen?

Antihydrogen has a dipole magnetic moment => gradients of the magnetic field are used

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Antihydrogen has a dipole magnetic moment => gradients of the magnetic field are used

# How to detect antihydrogen?

Making it annihilate and detecting annihilation byproducts with particle detectors

# The ALPHA experiment

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

INFN (Pavia, Pisa) Italy

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

# The ALPHA experiment

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## ALPHA-g

Antihydrogen gravity

## ALPHA-2

Antihydrogen spectroscopy

o) "*Trapped antihydrogen*" - Nature 468.7324 (2010)

o) "*Confinement of antihydrogen for 1,000 seconds*" - Nature Physics 7.7 (2011)

o) "*Resonant quantum transitions in trapped antihydrogen atoms*" - Nature 483.7390 (2012)

o) "*Observation of the hyperfine spectrum of antihydrogen*" - Nature 548.7665 (2017)

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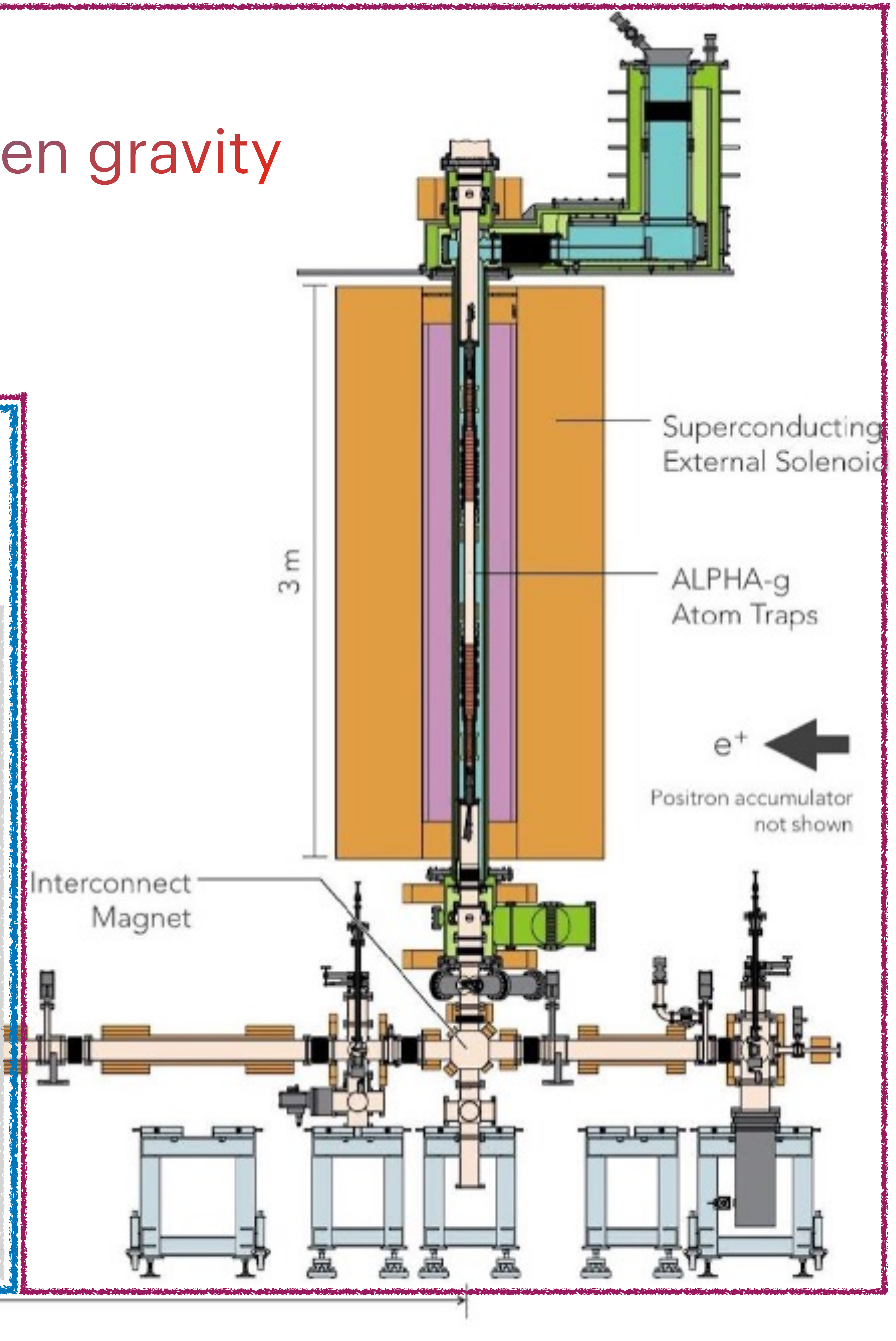

# The ALPHA experiment

## ALPHA-g

### Antihydrogen gravity

Measurement campaign 2022
Results published on Nature
on 28 September 2023

## ALPHA-2

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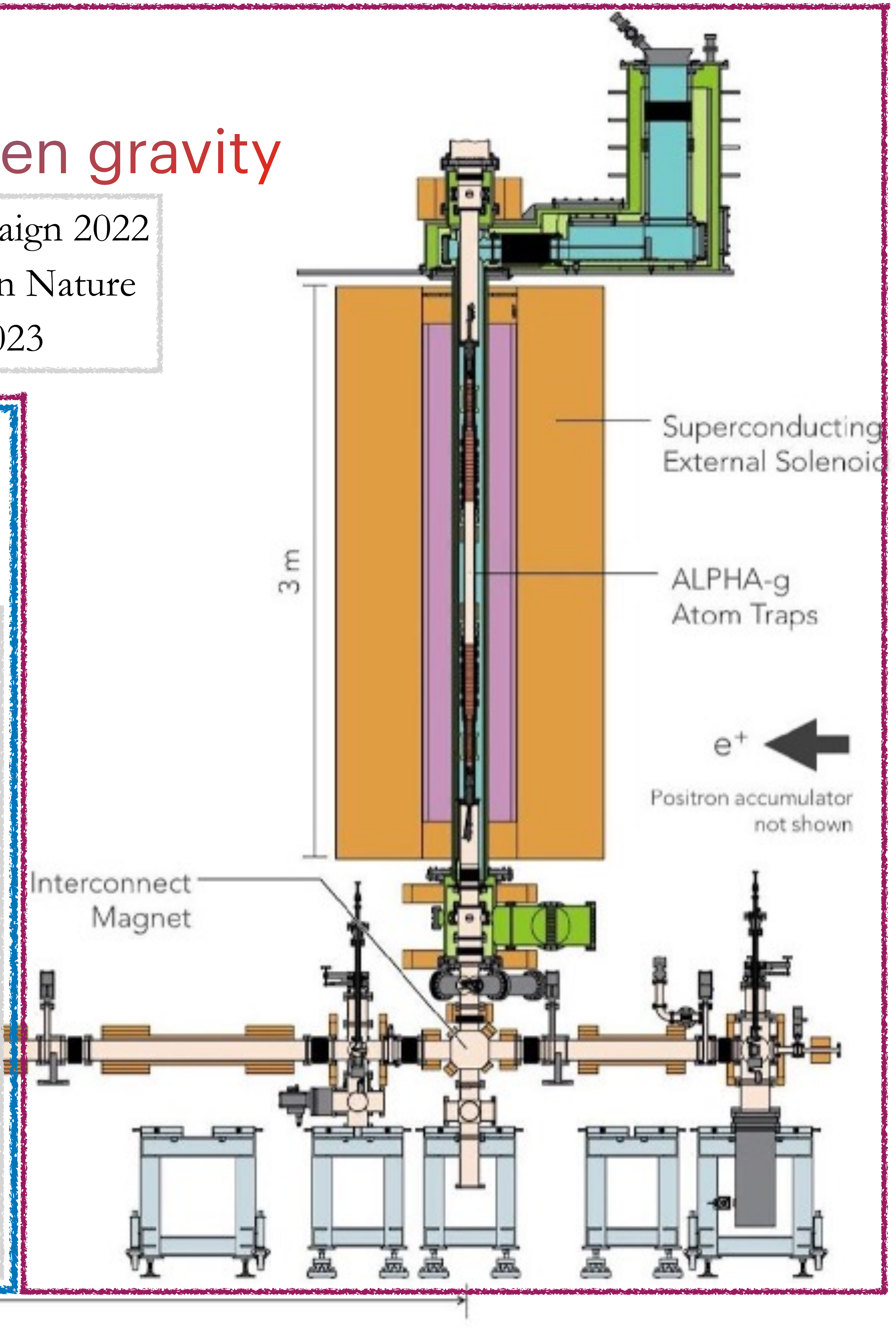
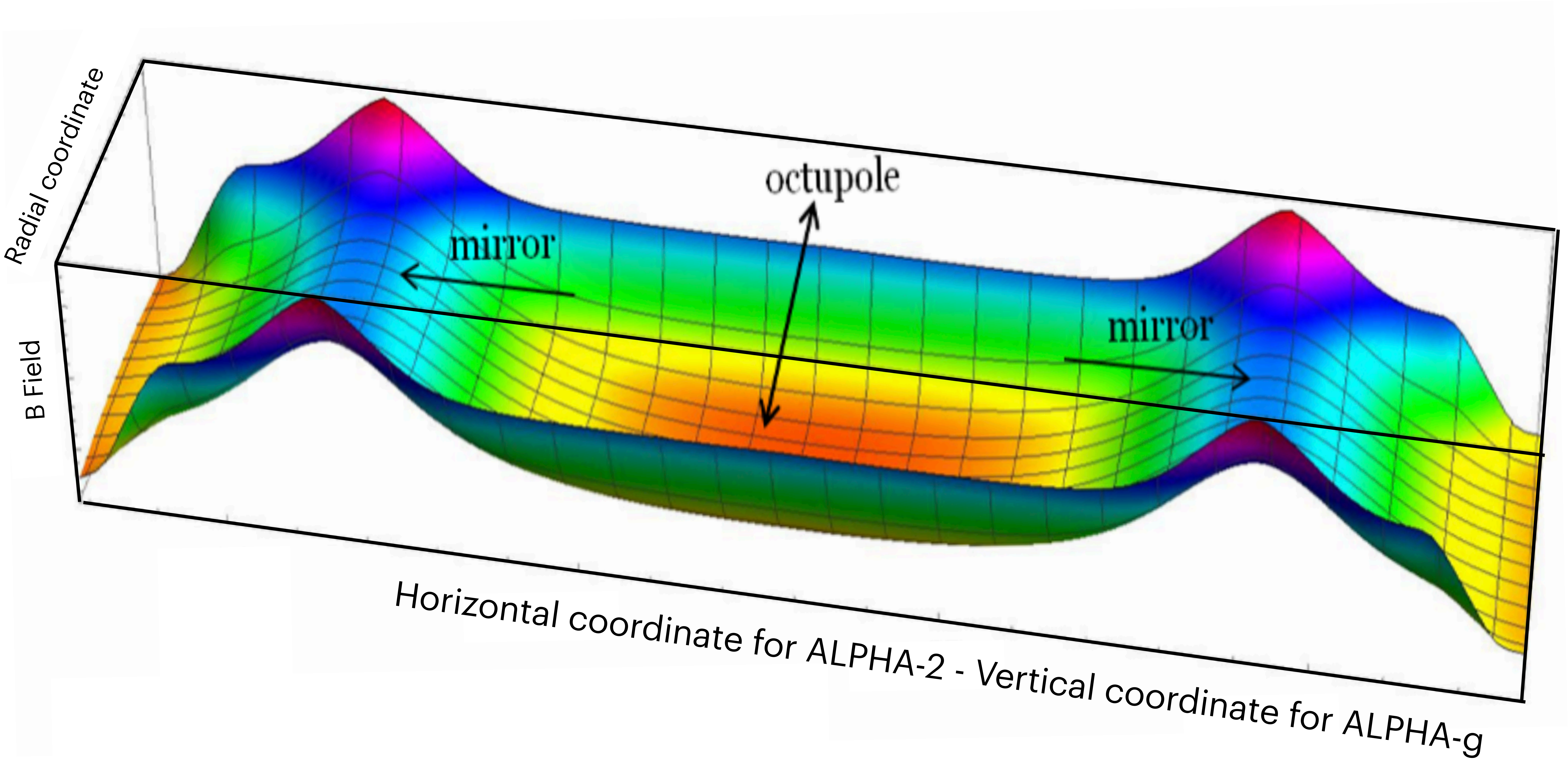


# How ALPHA experiment drops antihydrogen

https://www.youtube.com/watch?v=prhmw9CavR0

# Magnetic fields for anti-hydrogen trapping



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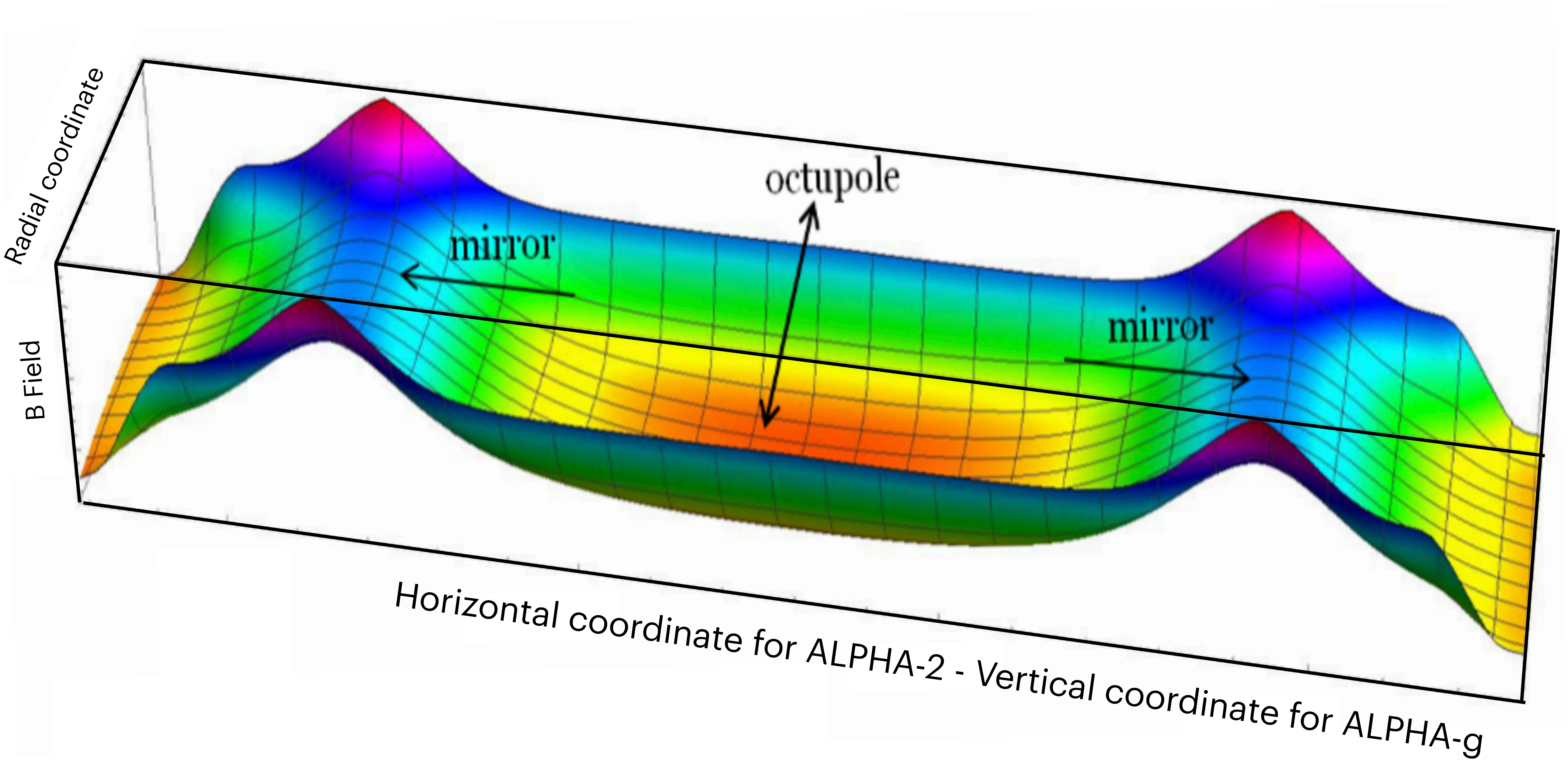
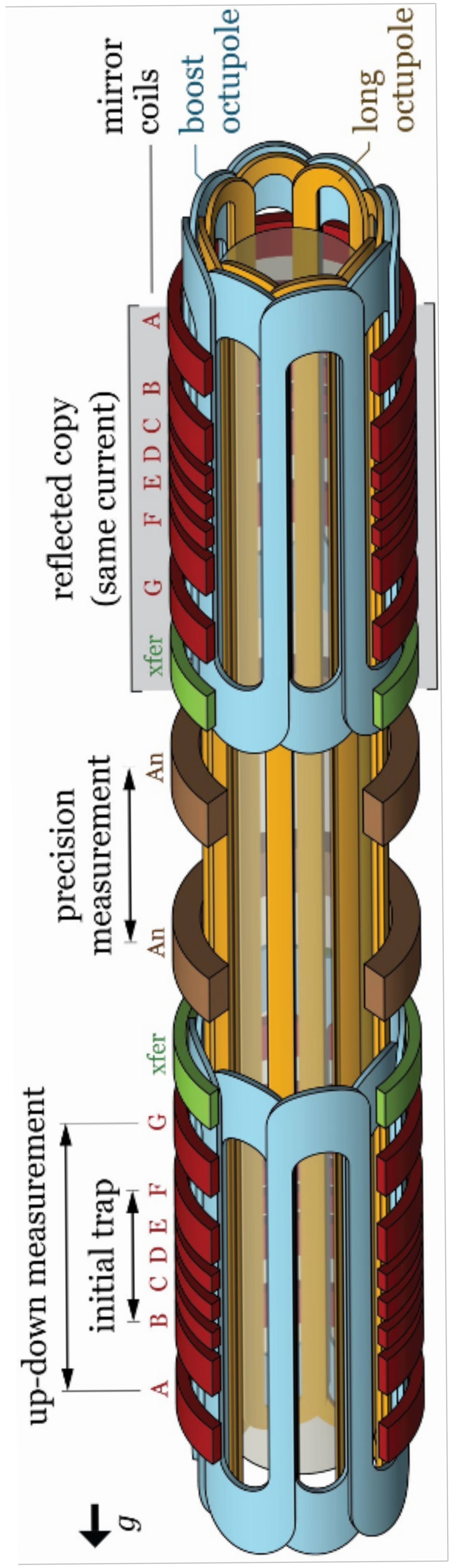
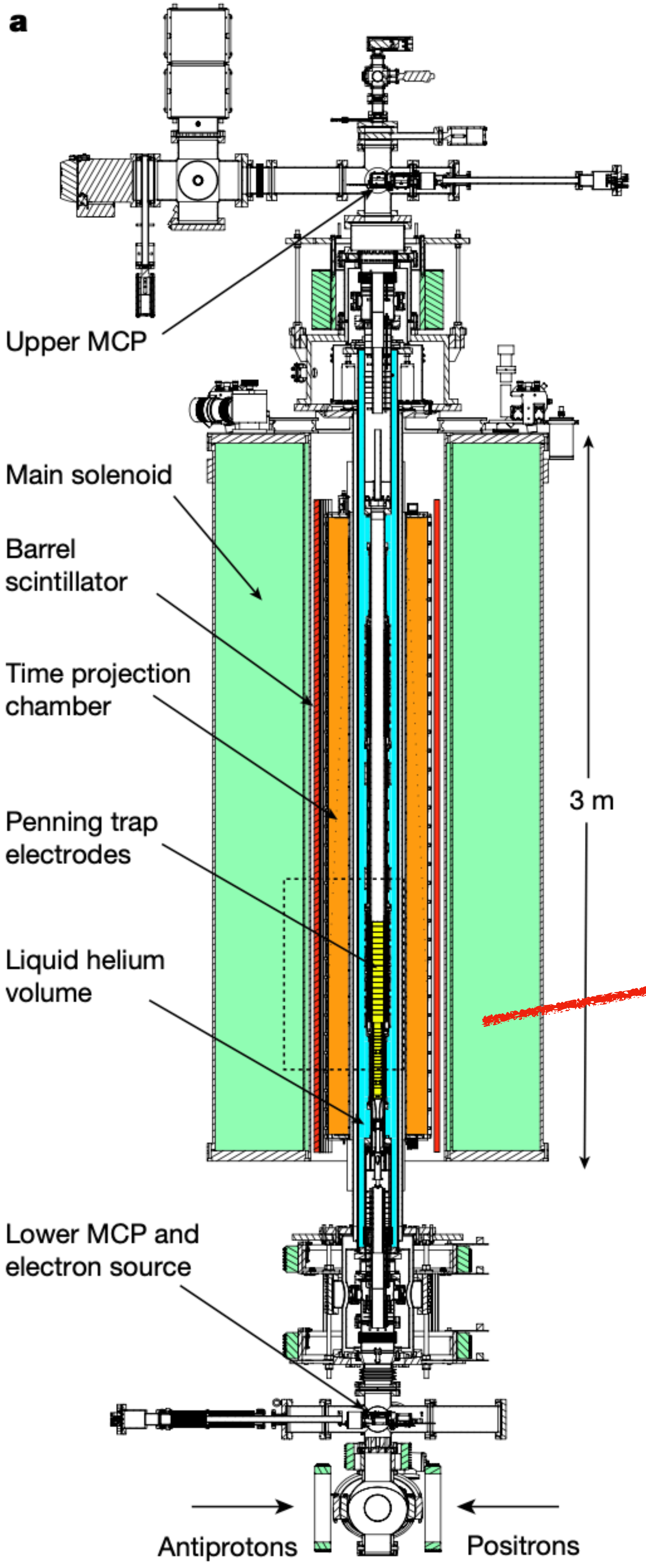
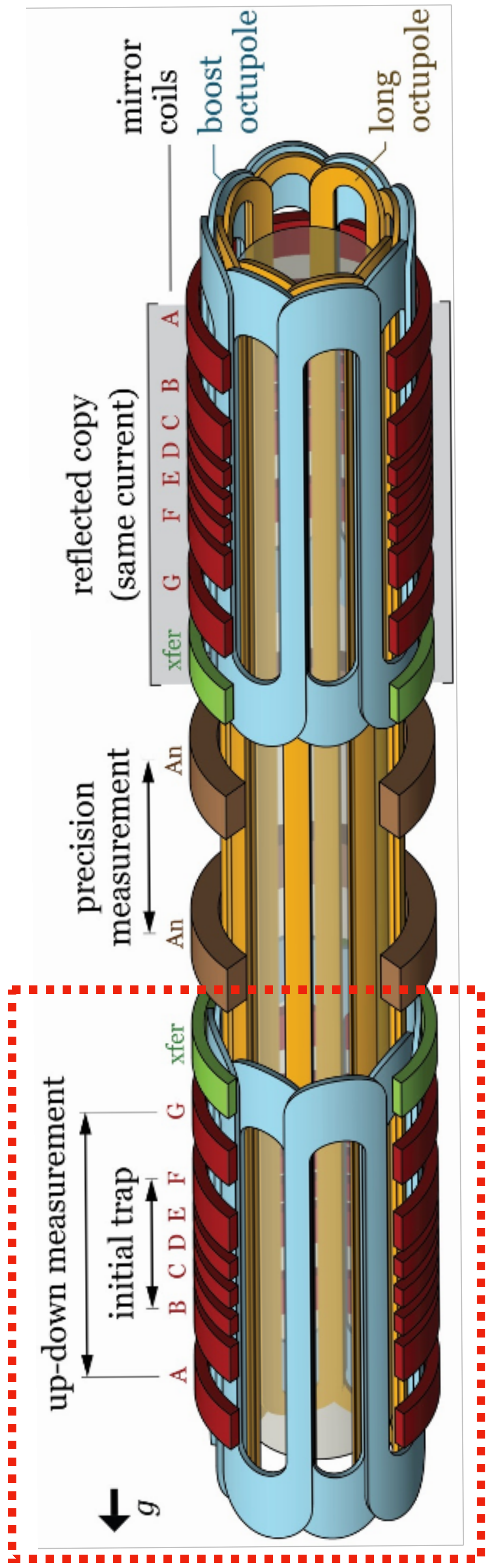



## The ALPHA-g magnets system



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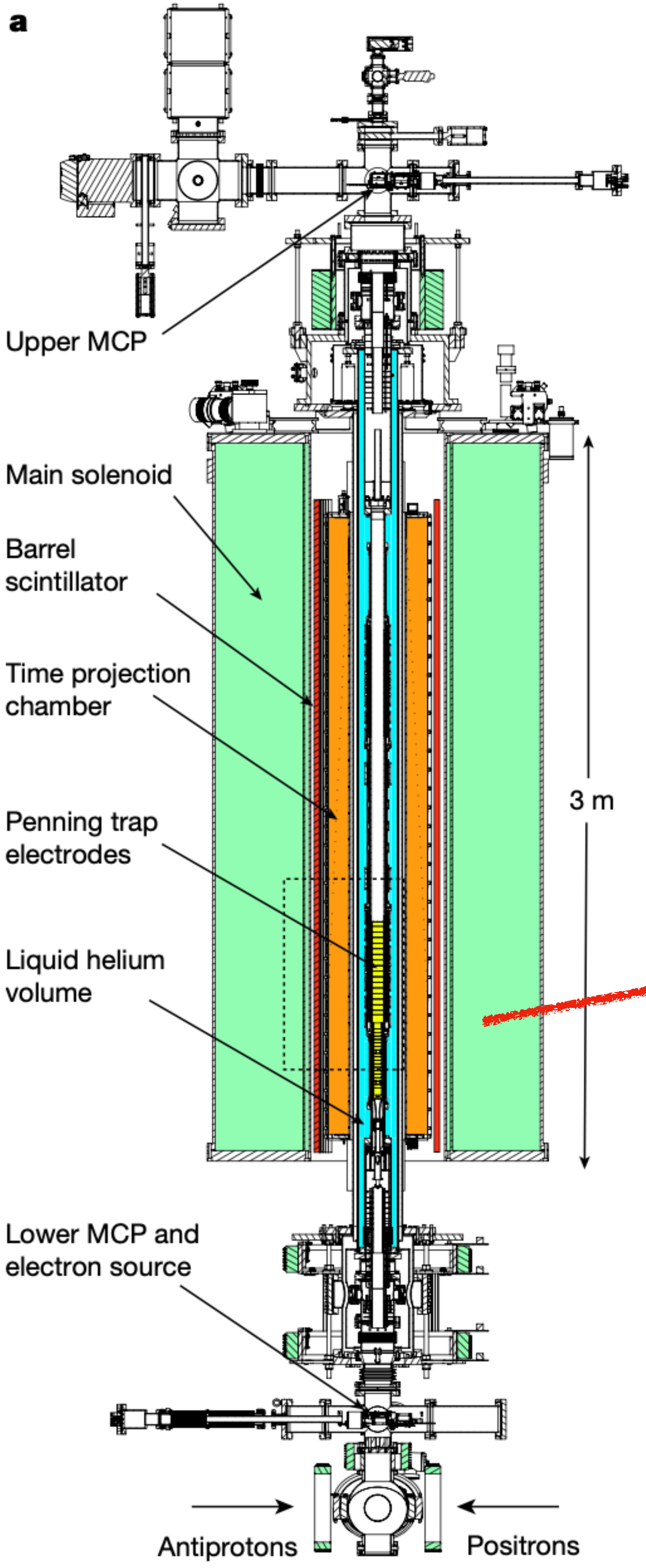
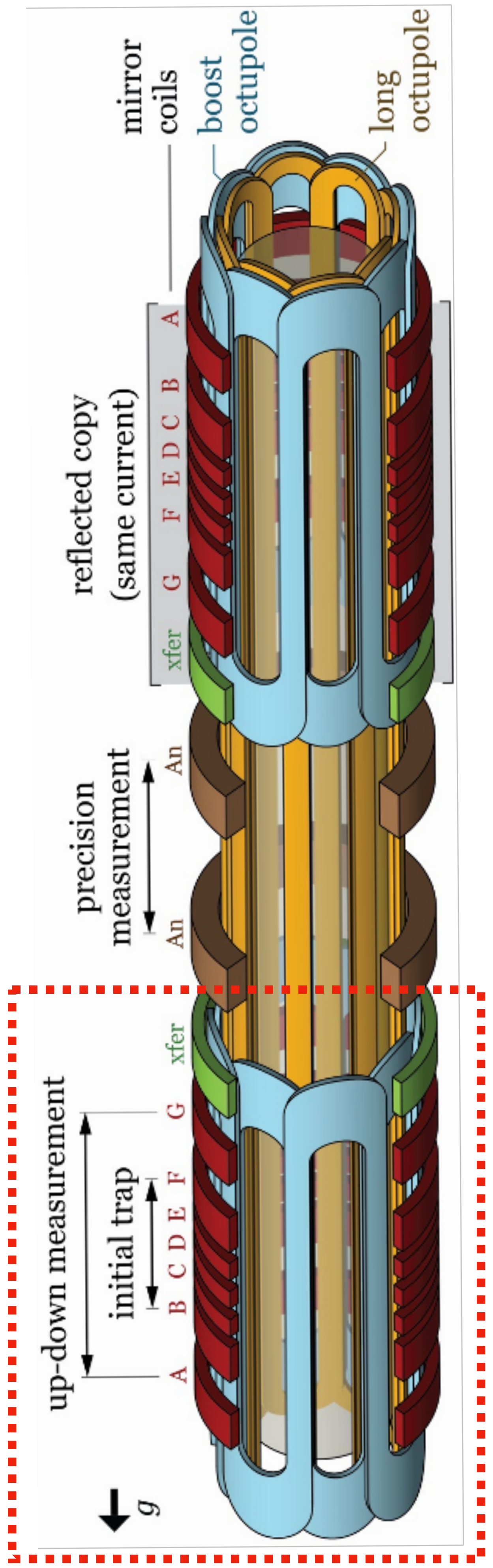
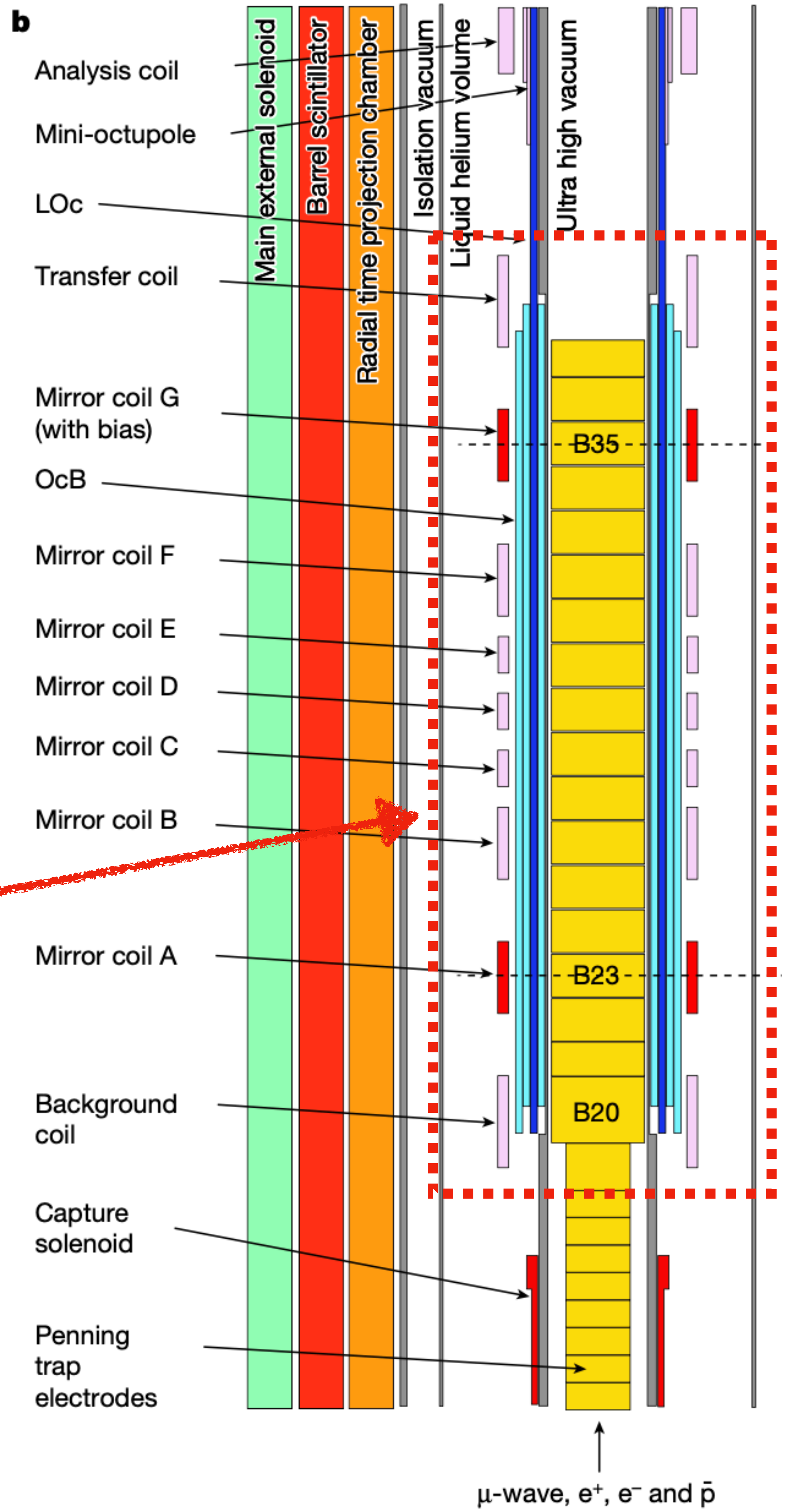
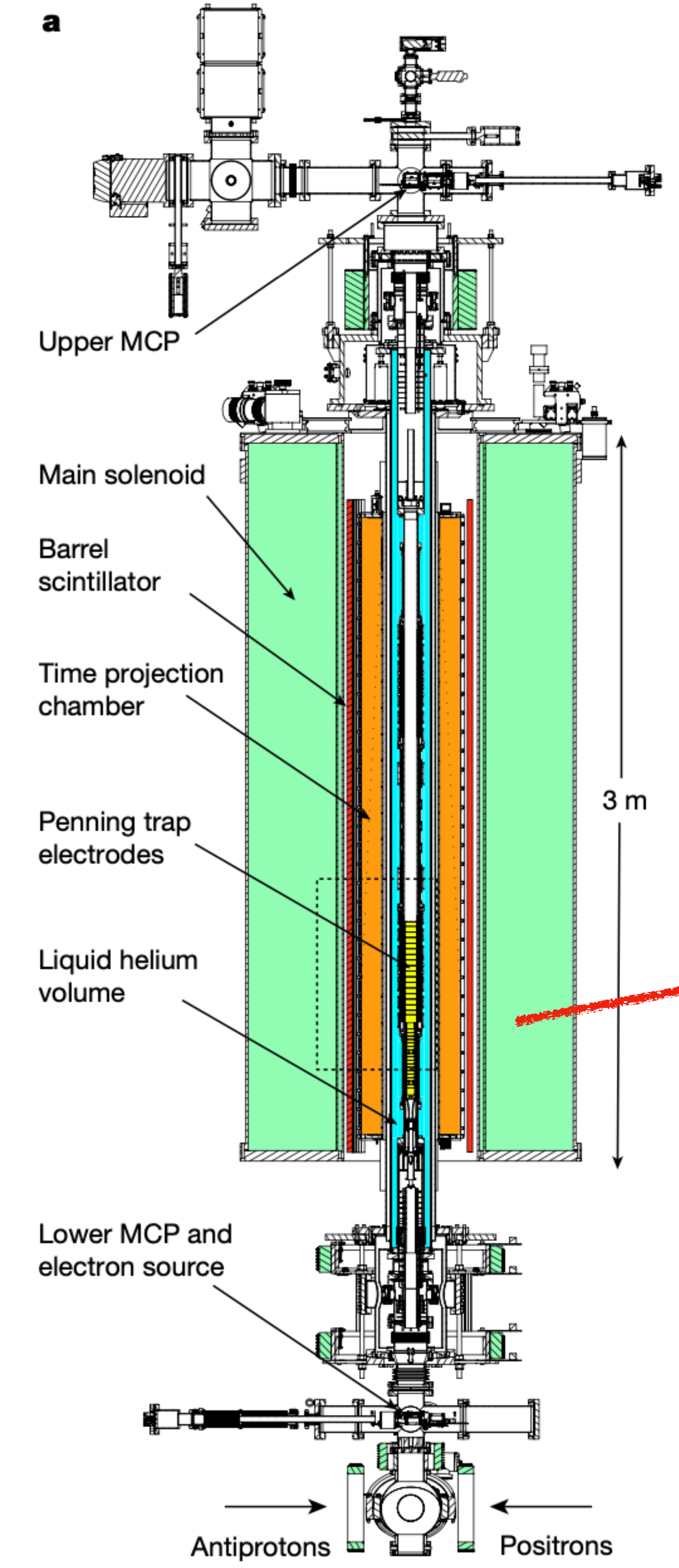
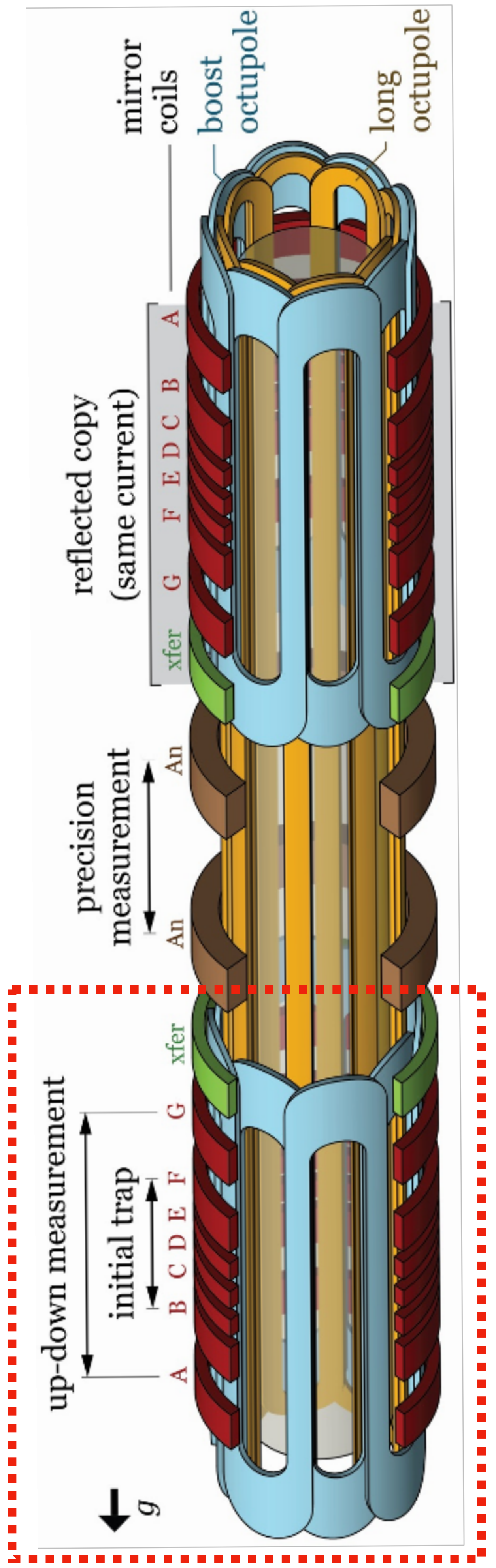
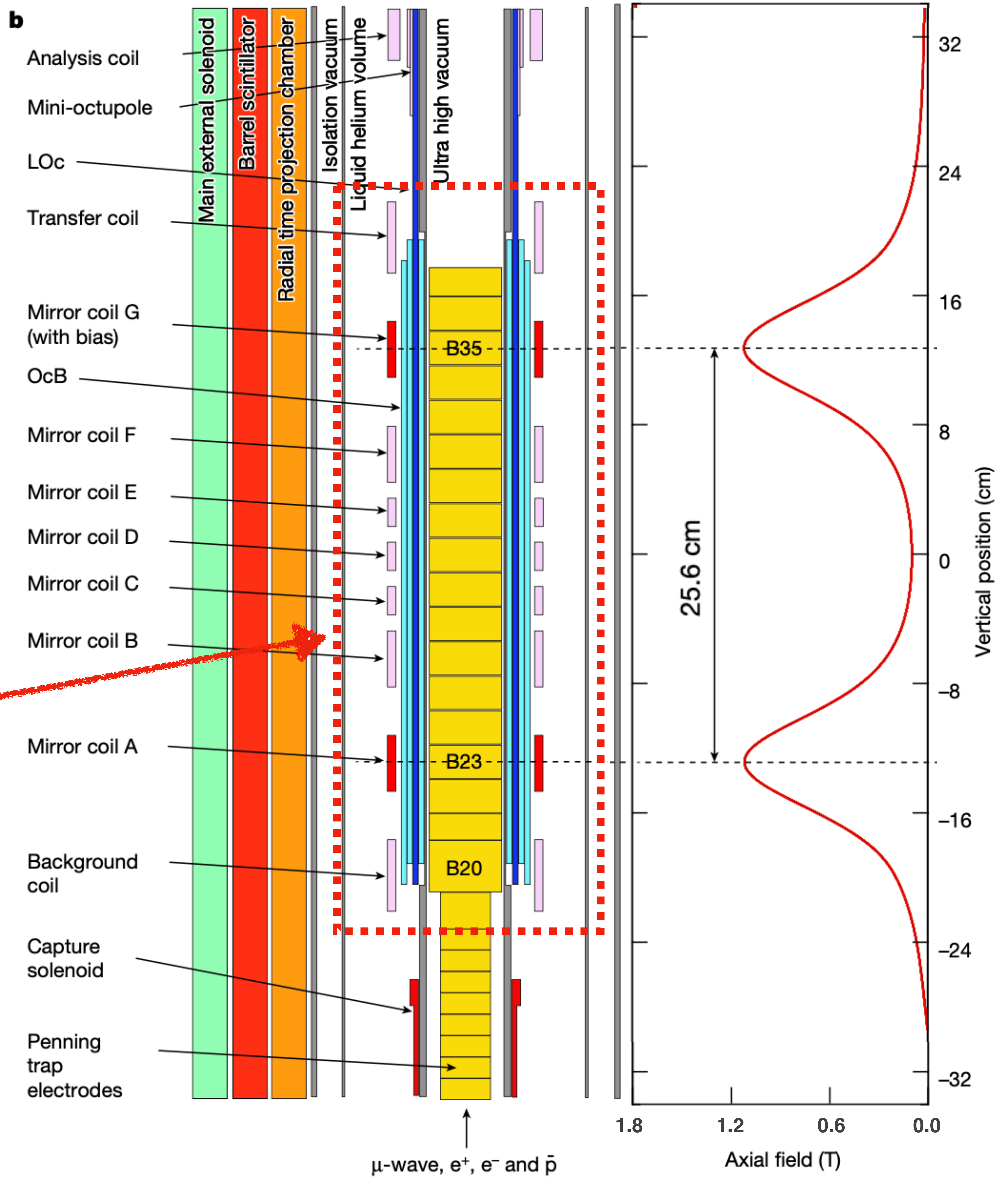




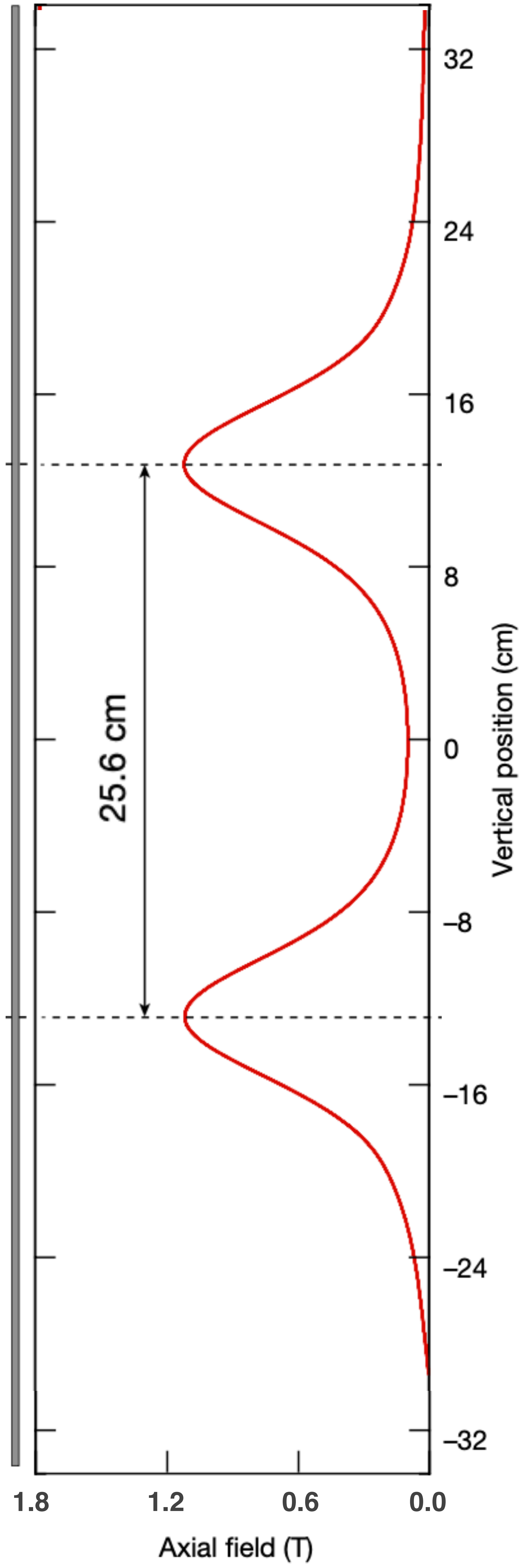




# The ALPHA-g experiment

# The gravity measurement

- Motion of antihydrogen is due to a combination of magnetic-trap field and gravitational field

- The magnetic field difference between top and bottom mirrors is used to compensate gravity



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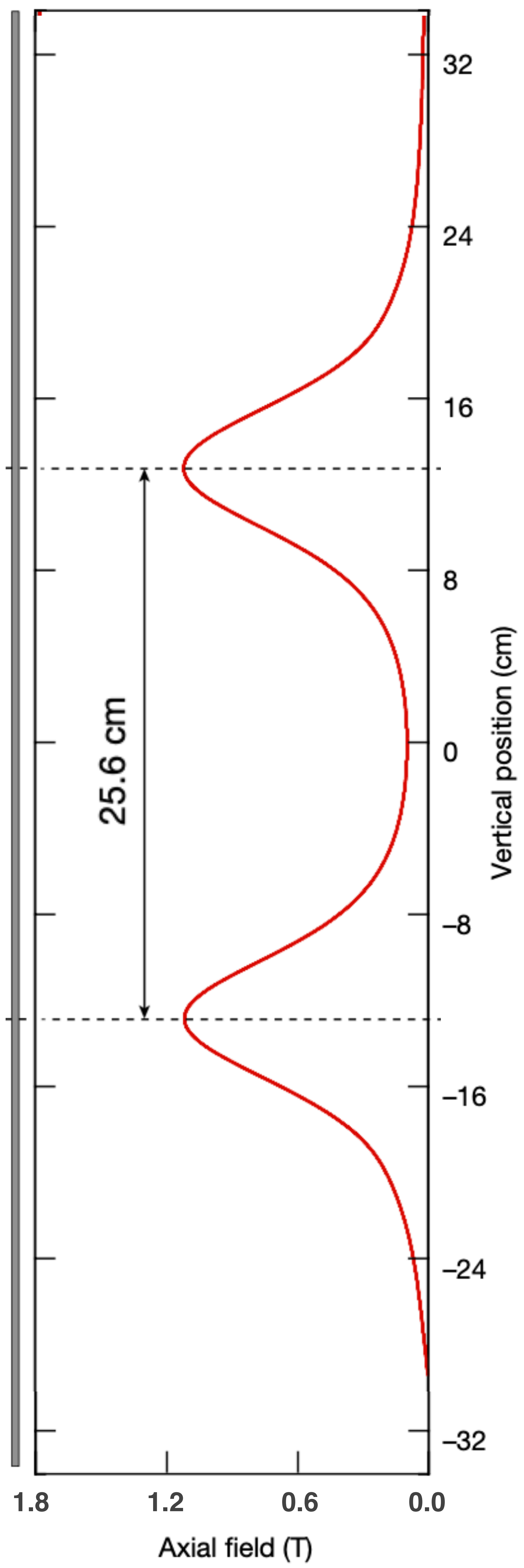
**For hydrogen/(antihydrogen?):**

gravitational potential energy (difference) $= m_H\, g\, \Delta z$

maximum magnetic potential energy $= \mu_B\, B$

To equilibrate the gravitational force, a $B_{top} - B_{bot} = m_H\, g\, \Delta z / \mu_B$ is needed

**=> 4.53 Gauss (for hydrogen) corresponds to "1 g"**



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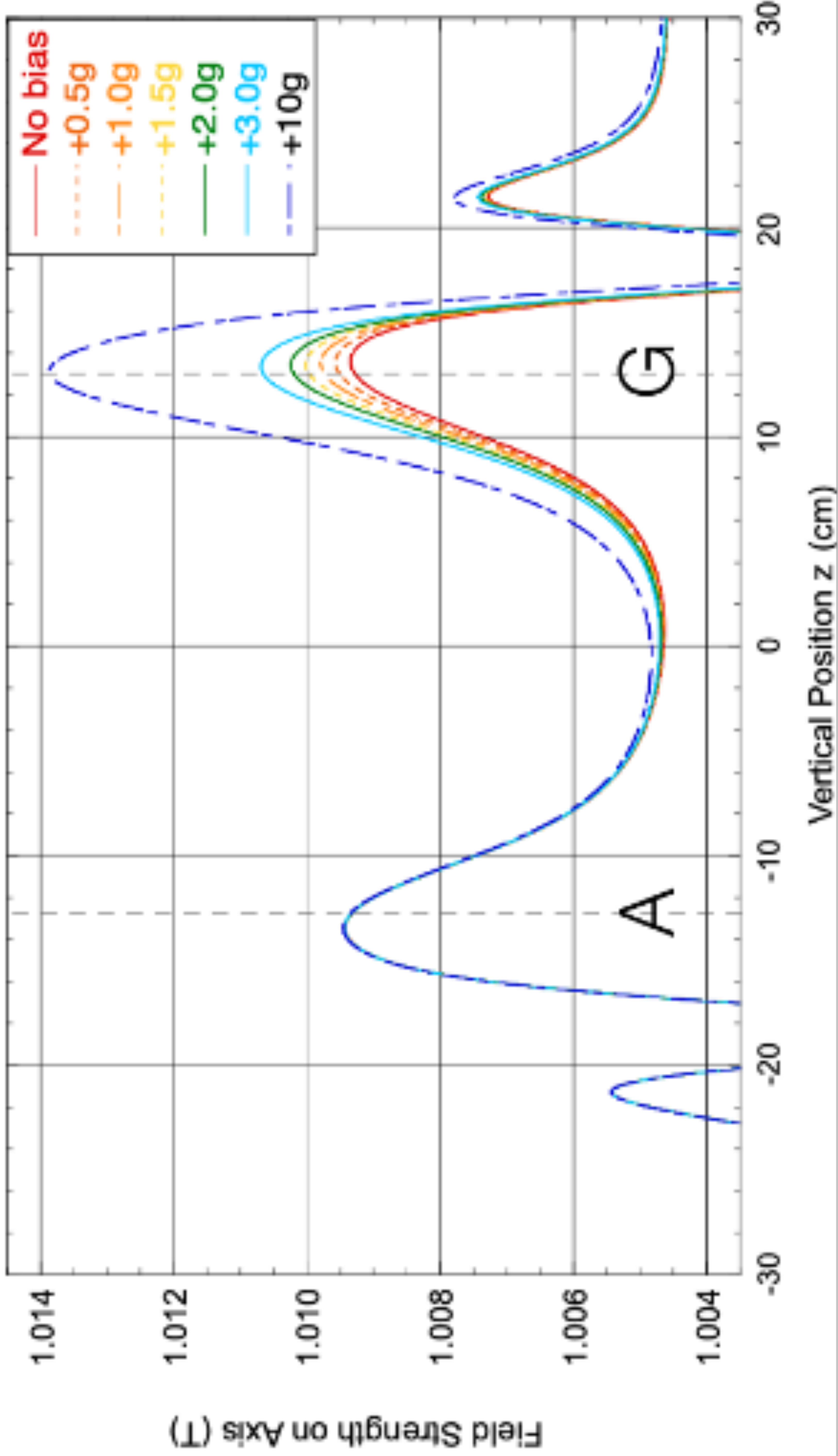

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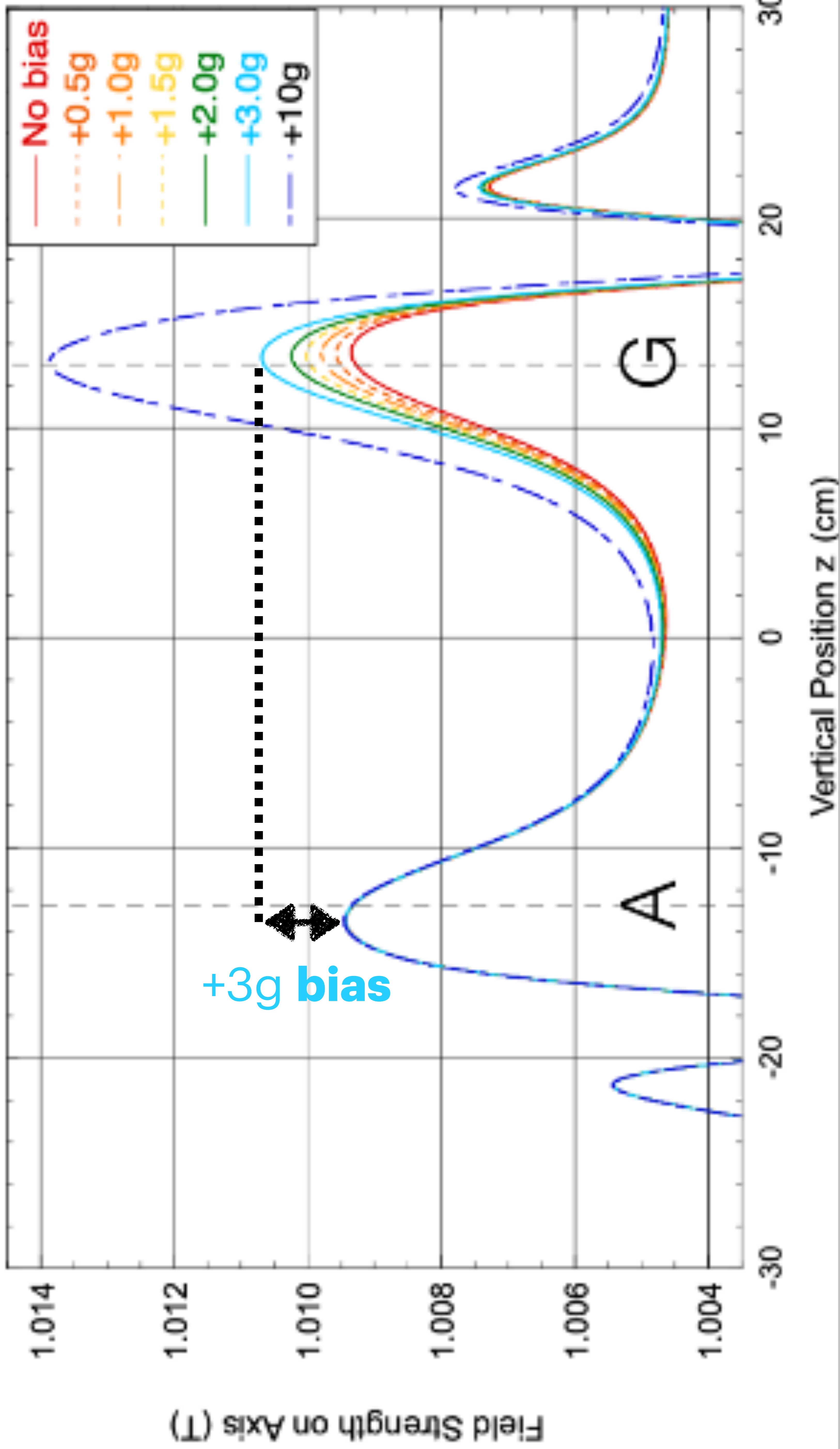
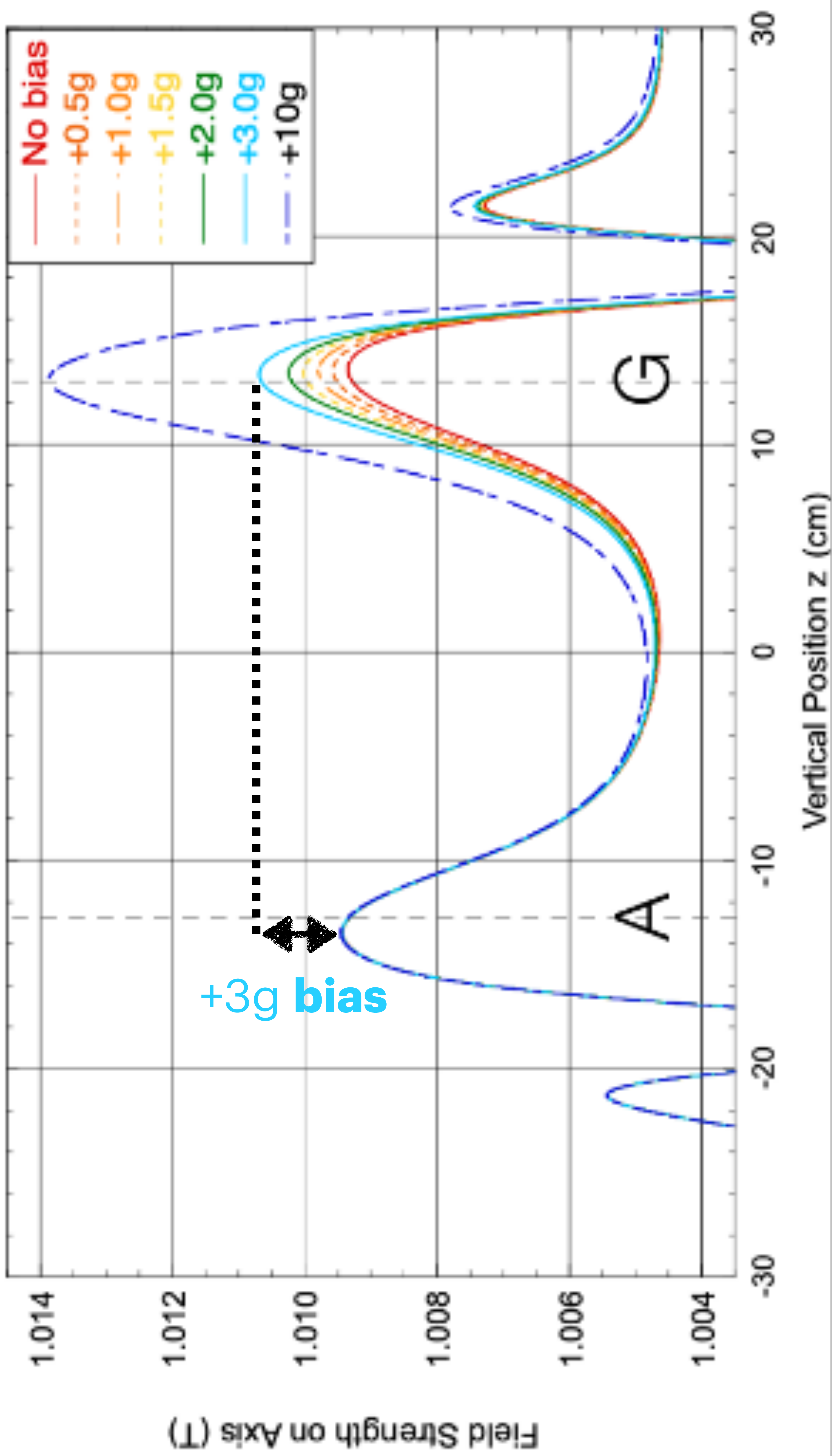


# The gravity measurement

**Measurement strategy**

1) Lower the mirror’s B walls keeping a constant [$B_{top}$ - $B_{bot}$] “**bias**”

2) Monitor the antihydrogens while escaping the trap (up or down?)



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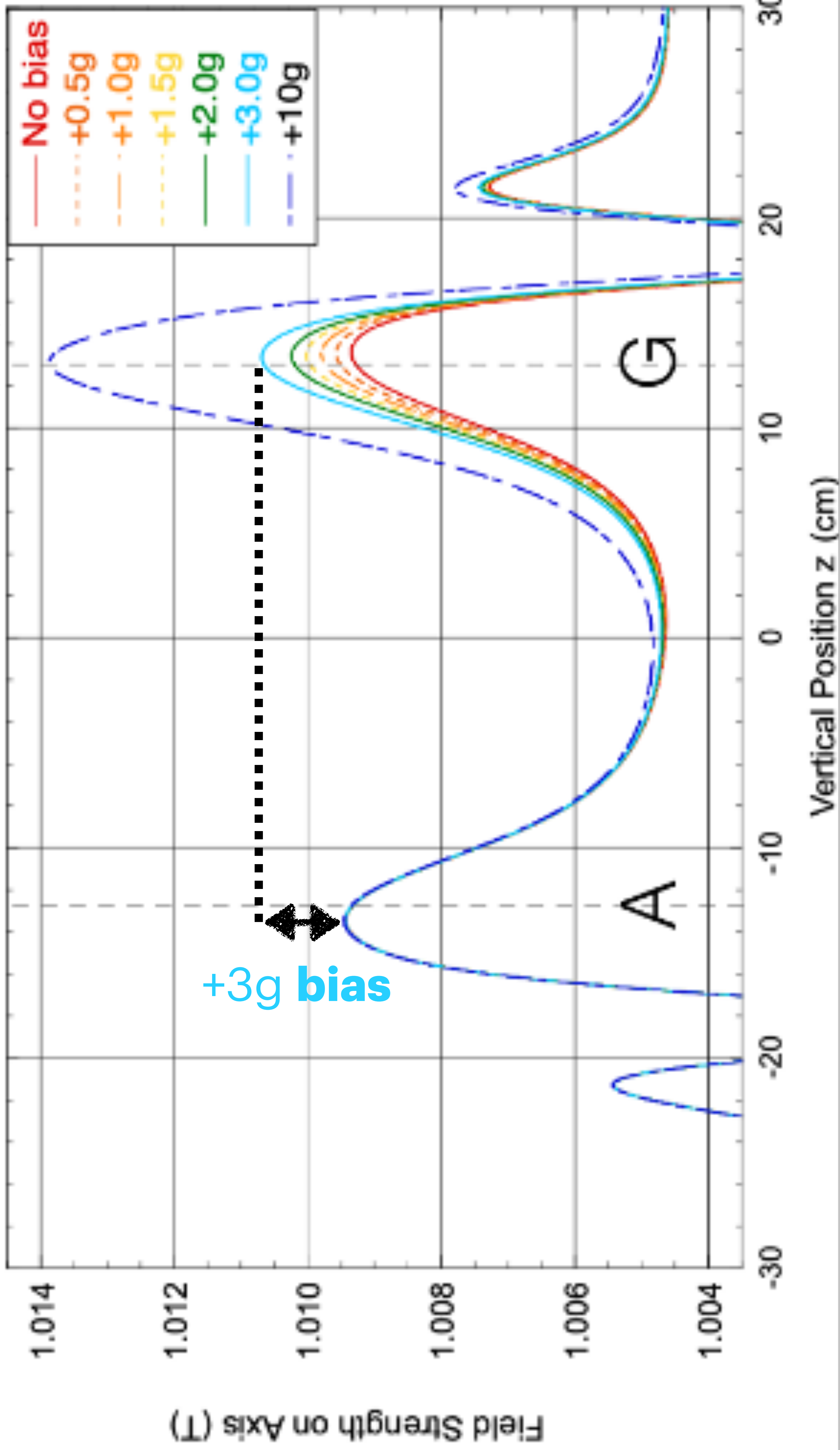
**Some parameters:**

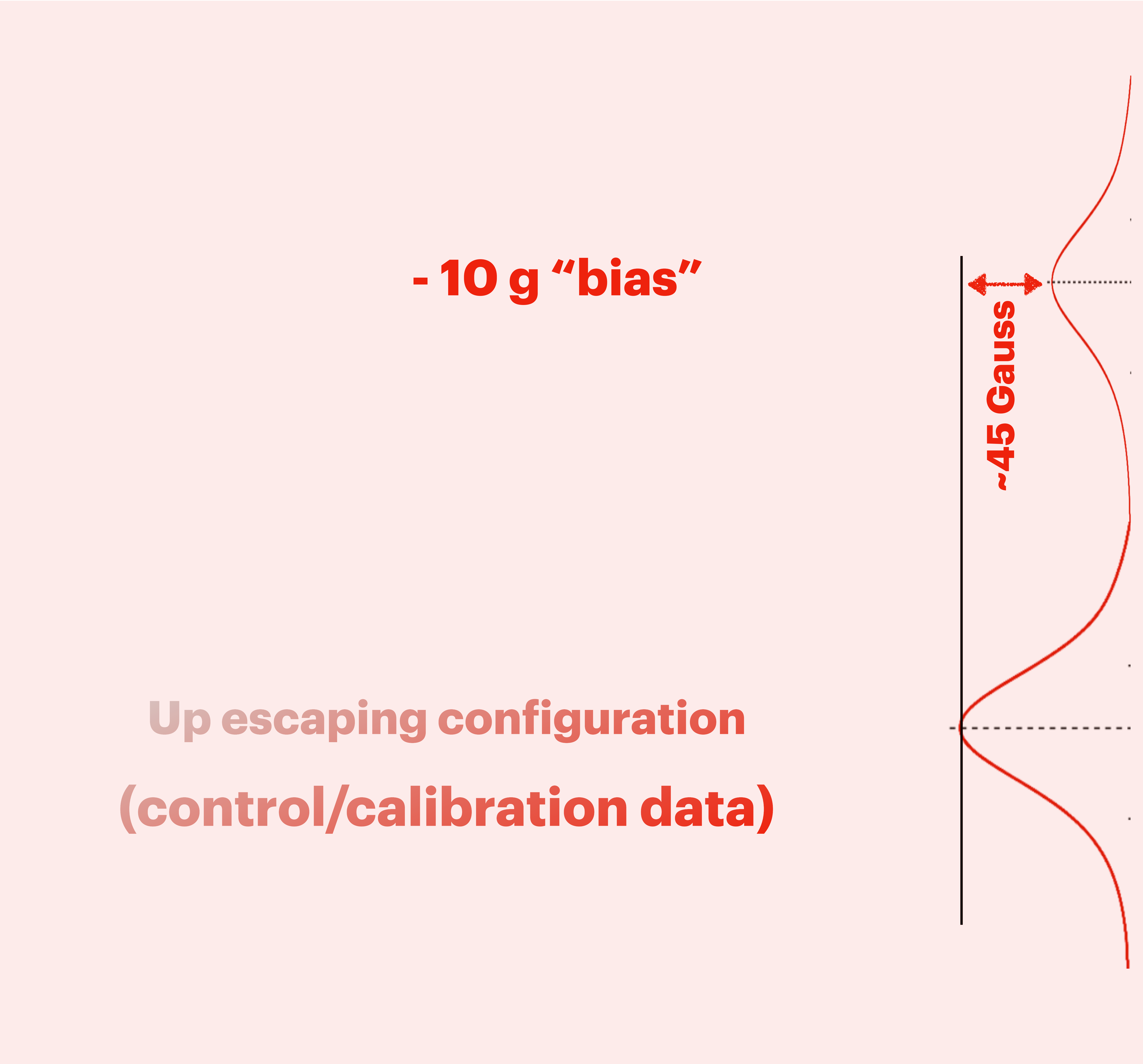
-ramp time of 20 s from B ~ 1 T to ~ 0 (also 130 s were tested)

-antihydrogen temperature of less than 0.55 K, corresponding to velocities <= 65 m/s (real temperature/energy distribution is unknown)



# The gravity measurement

**Distributions of the vertical coordinate reconstructed annihilation vertices**



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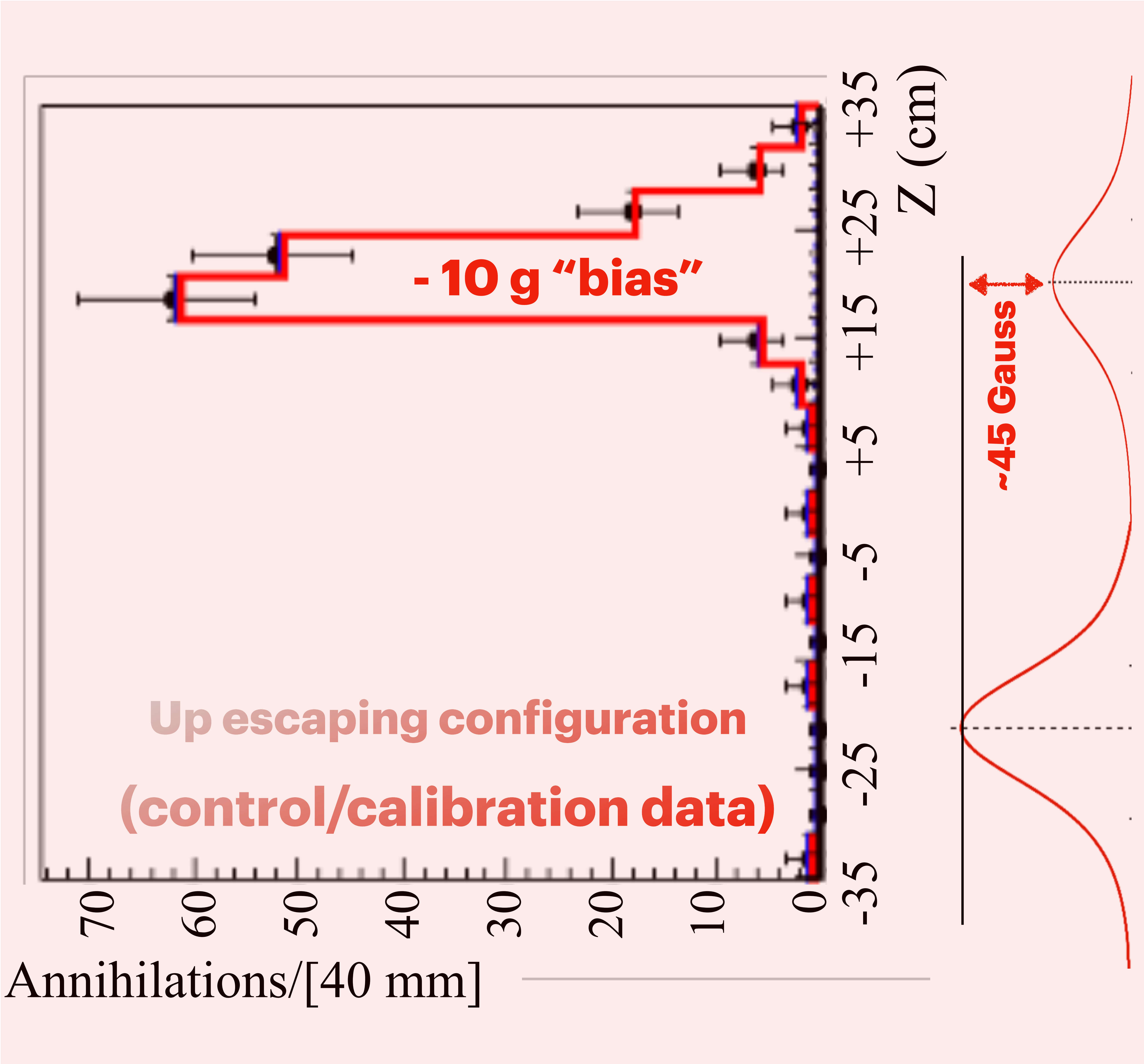


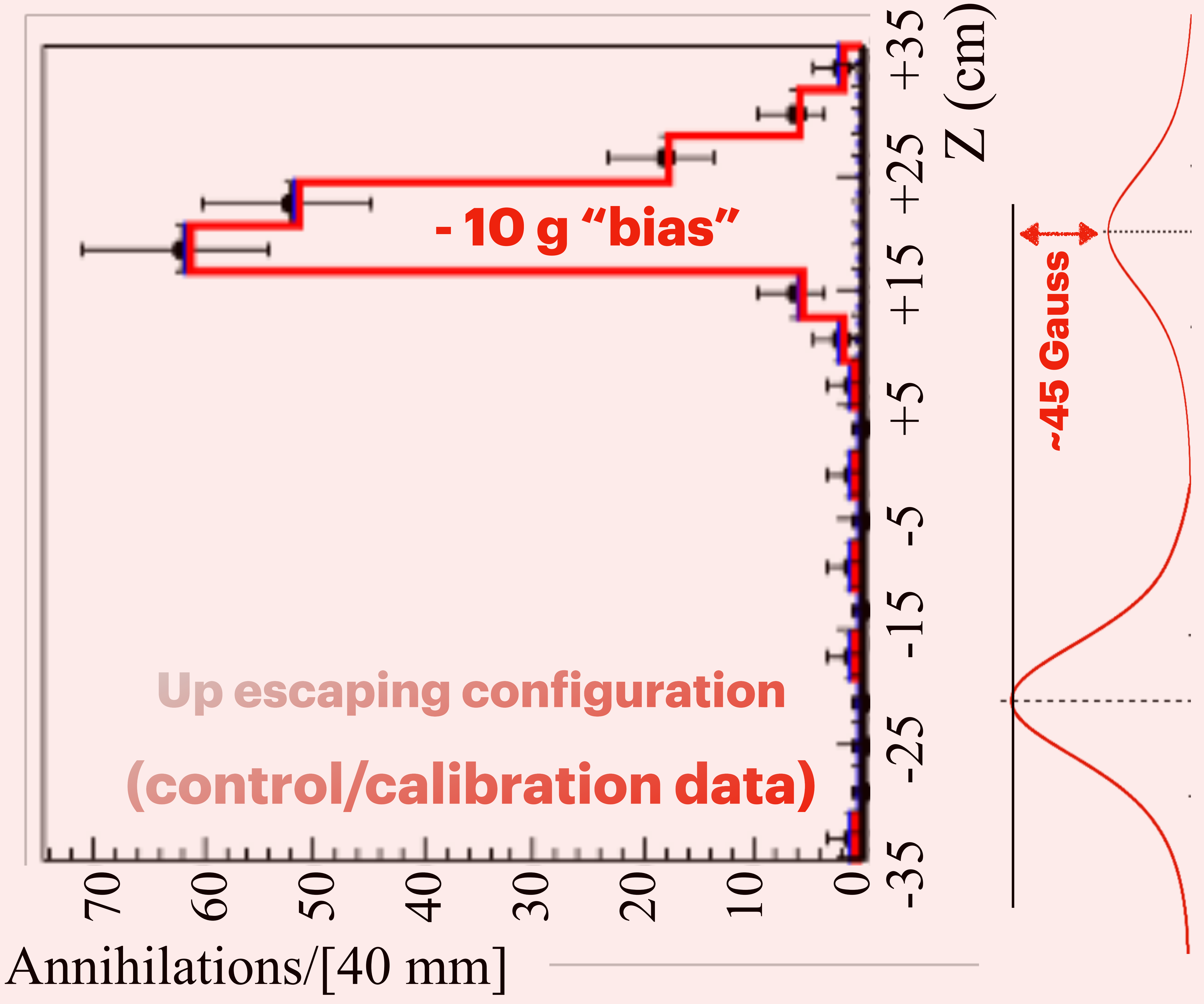
# The gravity measurement

**Distributions of the vertical coordinate reconstructed annihilation vertices**

(control/calibration data)

**Down escaping configuration**

**+ 10 g “bias”**

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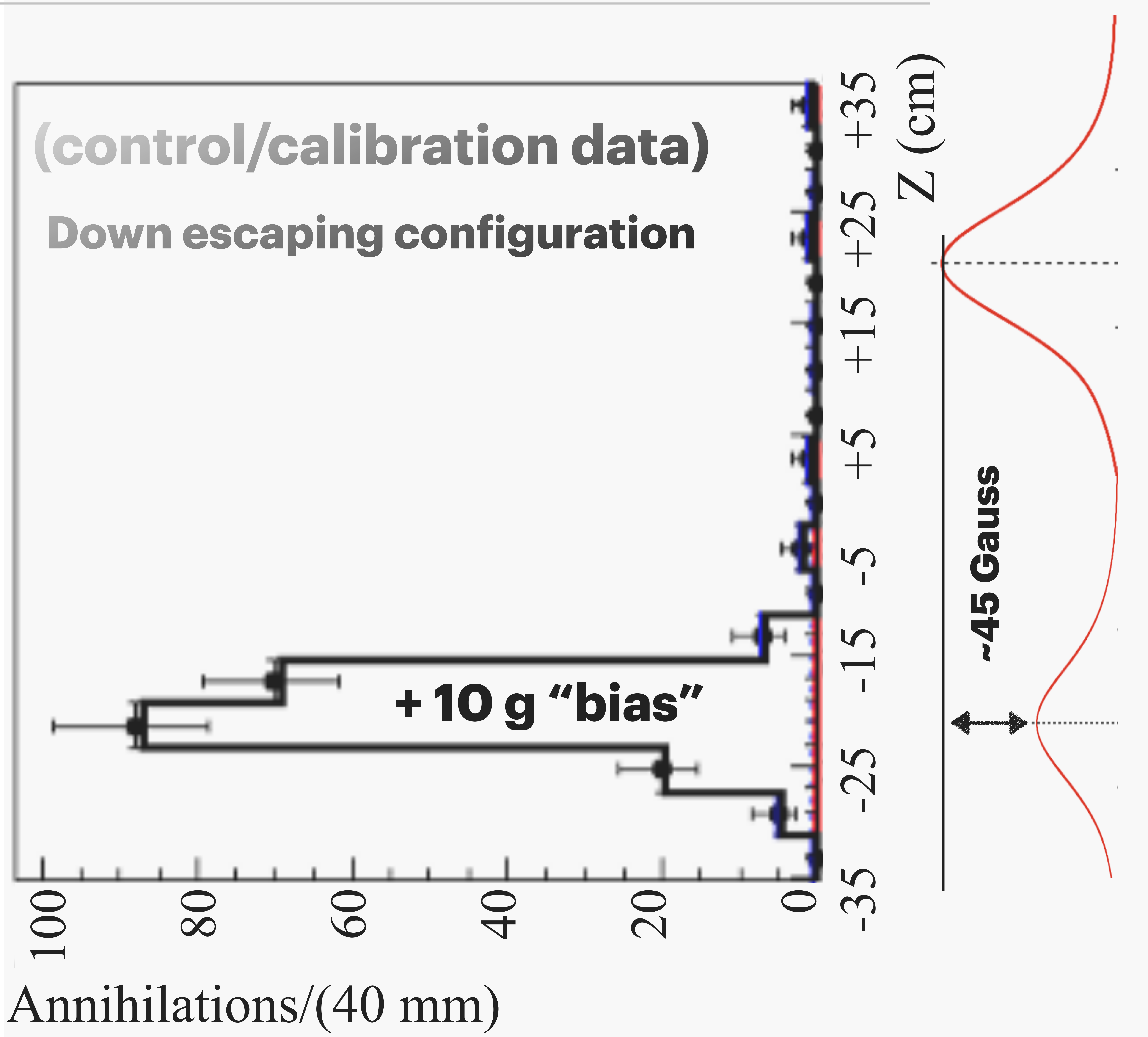
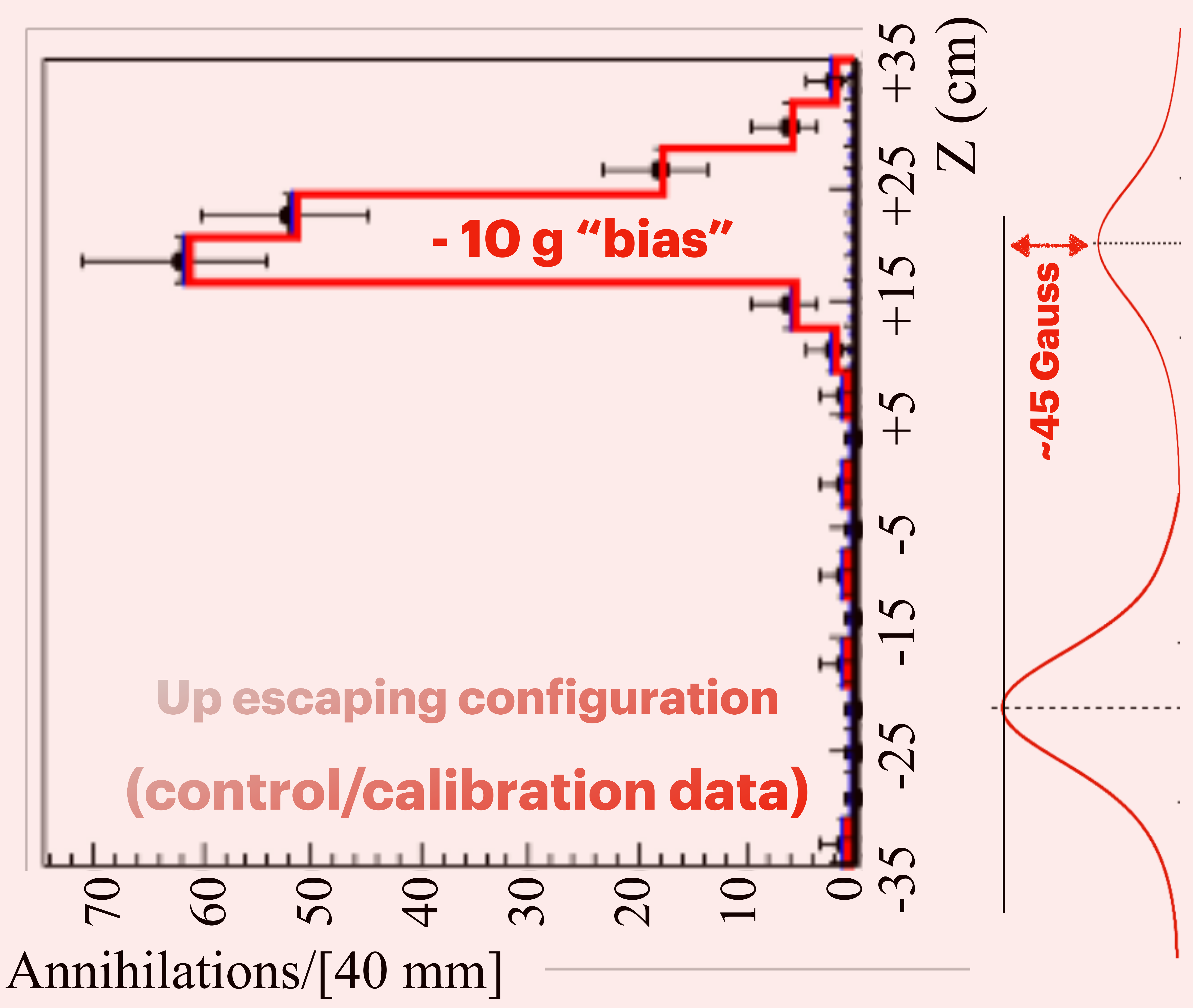
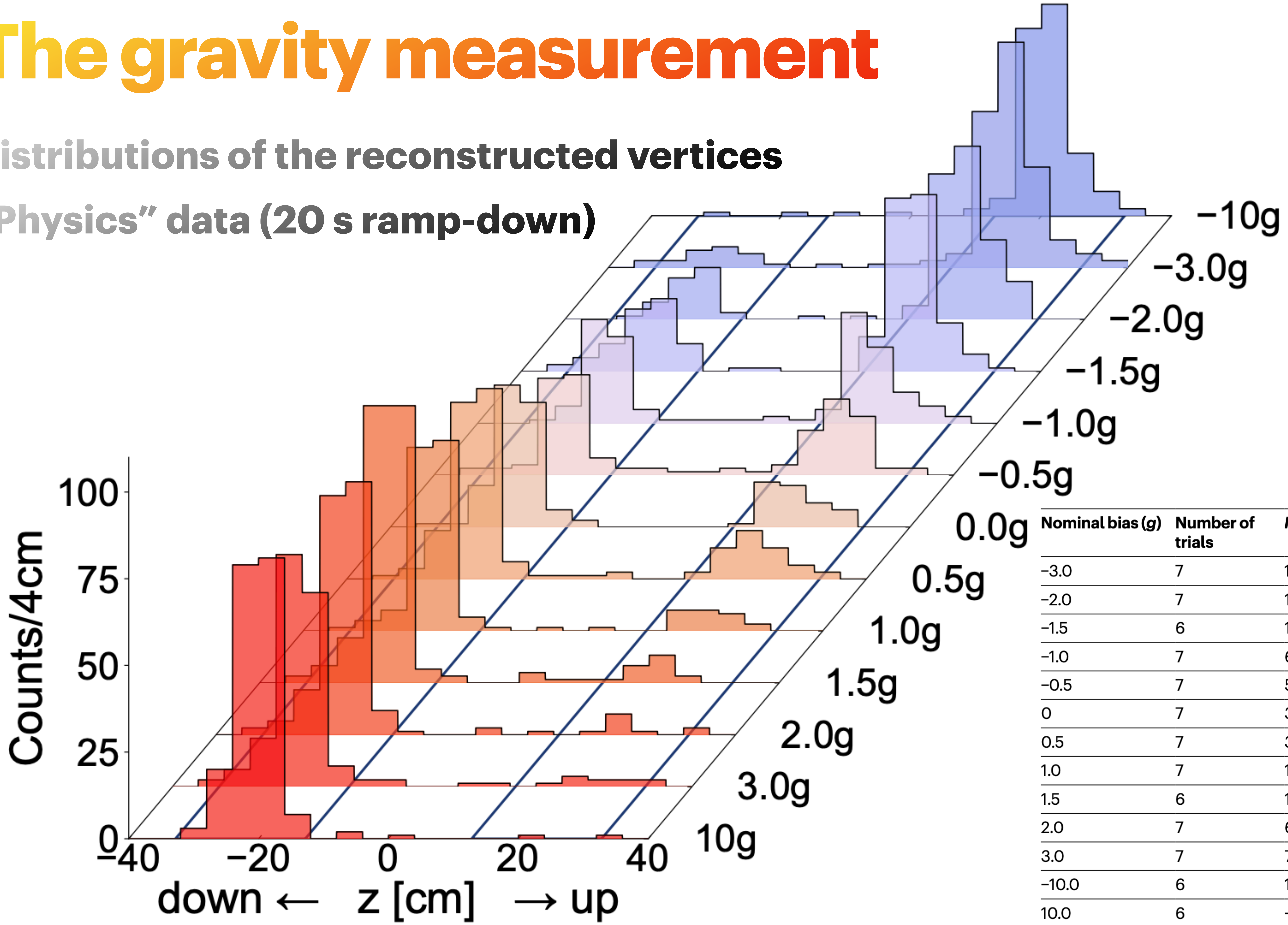


# The gravity measurement

## Distributions of the reconstructed vertices

## "Physics" data (20 s ramp-down)

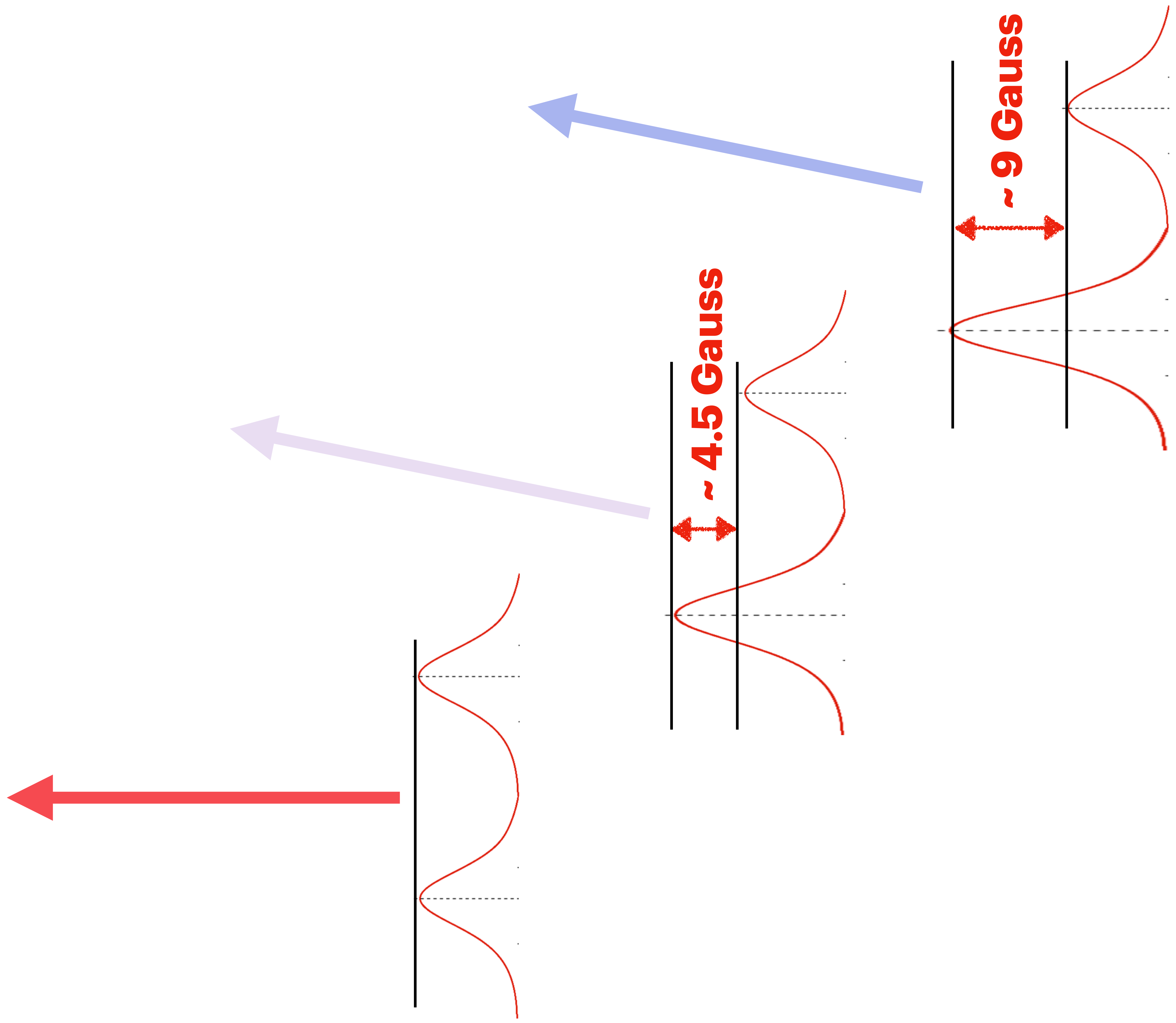



| Nominal bias (*g*) | Number of trials | $N_{up}$ (events) | $N_{dn}$ (events) | Events during LOc ramp-down |
|---|---|---|---|---|
| −3.0 | 7 | 151.7 | 16.5 | 199.2 |
| −2.0 | 7 | 128.7 | 33.5 | 168.2 |
| −1.5 | 6 | 128.9 | 57.7 | 192.0 |
| −1.0 | 7 | 69.7 | 62.5 | 183.2 |
| −0.5 | 7 | 55.7 | 67.5 | 201.2 |
| 0 | 7 | 36.7 | 94.5 | 144.2 |
| 0.5 | 7 | 36.7 | 124.5 | 177.2 |
| 1.0 | 7 | 17.7 | 119.5 | 185.2 |
| 1.5 | 6 | 13.9 | 180.7 | 234.0 |
| 2.0 | 7 | 6.7 | 163.5 | 228.2 |
| 3.0 | 7 | 7.7 | 147.5 | 199.2 |
| −10.0 | 6 | 142.9 | 0.7 | 169.0 |
| 10.0 | 6 | −0.1 | 185.7 | 213.0 |

# The gravity measurement

Distributions of the reconstructed vertices

"Physics" data (130 s ramp-down)



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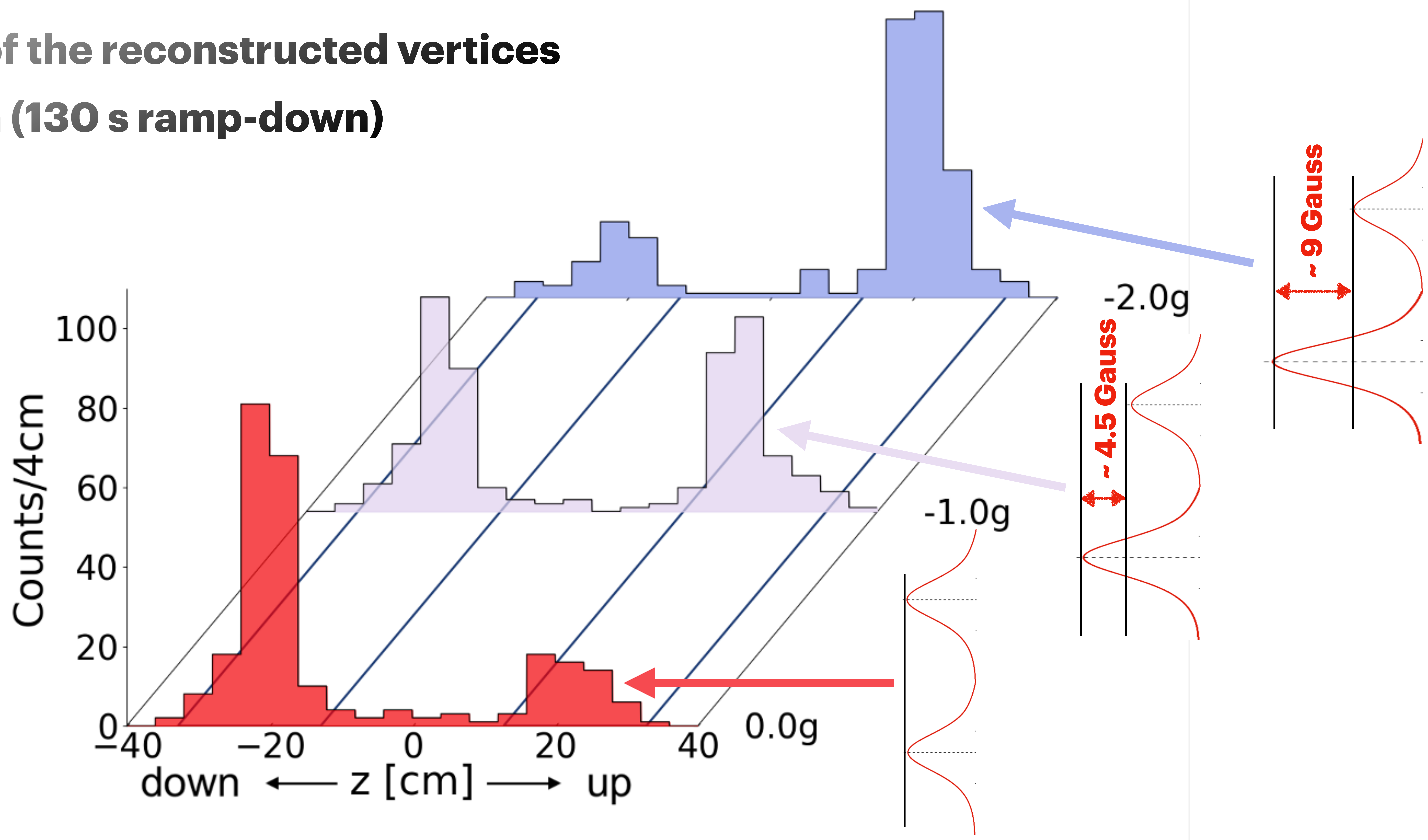

# The gravity measurement

## Antihydrogen dynamics in the traps

The B field is not perfectly uniform in the trap, since it changes when moving, both axially and radially, from the trap center

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**When travelling inside the trap well, antihydrogen atoms experience different B field (different magnetic force), while experiencing the same gravitational force**

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**When travelling inside the trap well, antihydrogen atoms experience different B field (different magnetic force), while experiencing the same gravitational force**

To extract the value of the gravitational acceleration, a detailed and complex simulation of the ALPHA magnetic trap and of the antihydrogen dynamics is needed

Asymmetry = $(N_{dn}-N_{up})/(N_{dn}+N_{up})$

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$$a_g = [0.75 \pm 0.13 \text{ (statistical + systematic)} \pm 0.16 \text{ (simulation)}]\ g$$

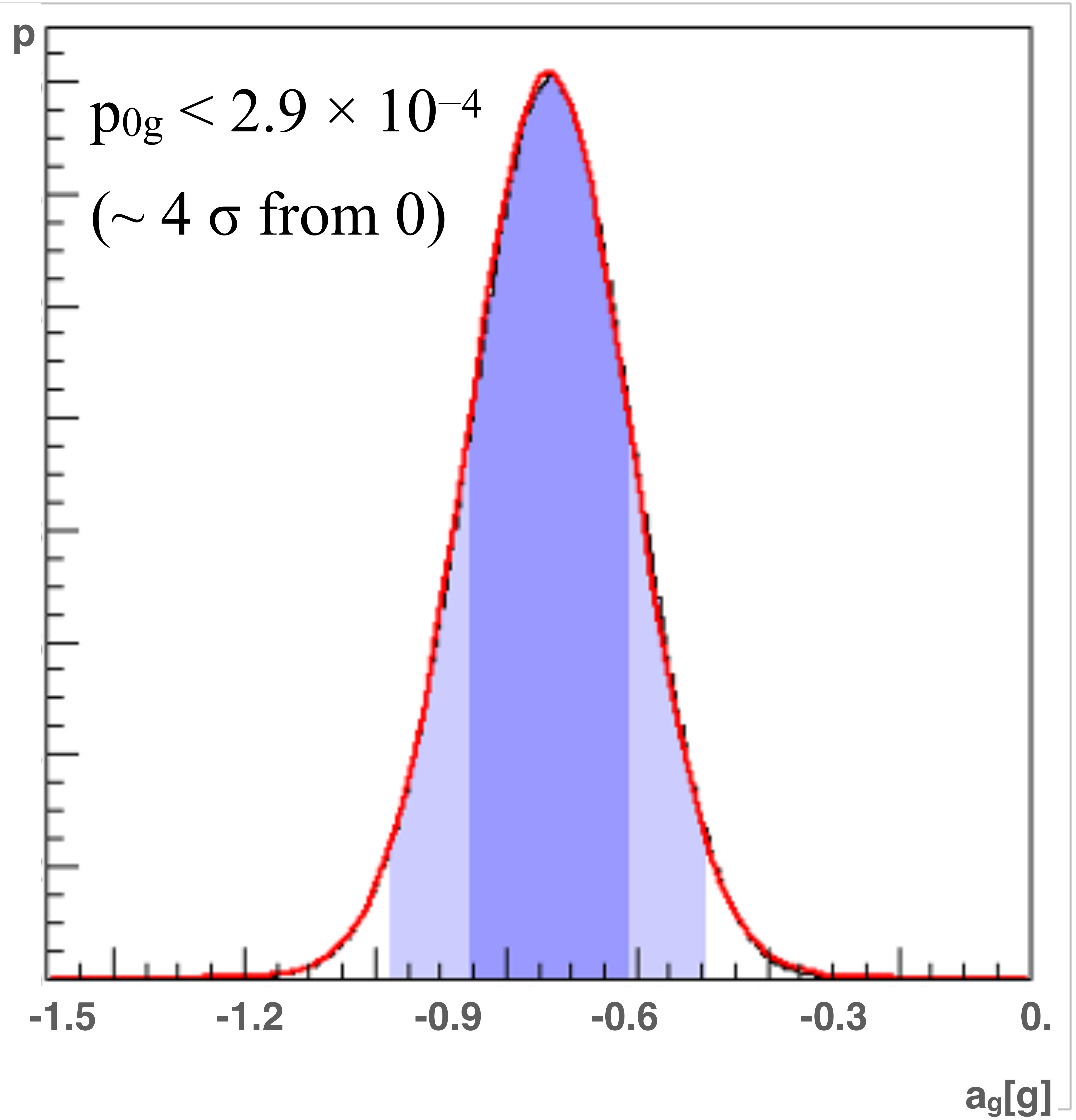


**Table 2 | Uncertainties in the bias determination**

| 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 | correlated |
| Bias variation in time | 0.02 | |
| Field modelling | 0.05 | correlated |

Summary of the uncertainties in the derived bias values, expressed in units of the local acceleration of gravity for matter (9.81 m s$^{-2}$). See Methods for definitions and details.

**Table 3 | Uncertainties in the determination of $a_{\bar{g}}$**

| | 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 |

Summary of the uncertainties involved in the determination of the gravitational acceleration $a_{\bar{g}}$. The uncertainties are one standard deviation and are expressed in units of the local acceleration of gravity for matter (9.81 m s$^{-2}$). See Methods for the details.

# What's next

**Extrapolating the gravity behaviour from antihydrogen to antimatter is not straightforward**

- There are various contributions to the (anti)proton mass (e.g. nuclear binding energy may account ~ 70%) => sensitivity to antimatter gravitational effects is reduced: require better precision

**Phys. Rev. Lett. 121, 212001 (2018)**

- Proposals to study lepton systems exist (e.g., muonium, positronium)

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**Future steps for a better understanding**

- few % precision is a reasonable target for next measurements (colder antihydrogen, better B field control, slower ramps, etc.) **[ALPHA-g is expected to take data in the coming weeks]**
- To reach event better precisions (potentially to ~ $10^{-6}$ range) upgrades are needed:
  - fountain spectroscopy and atom interferometry
  - clock-tests with spectroscopy (e.g., annual variations)

# CONCLUSIONS

anti-apples fall on Earth