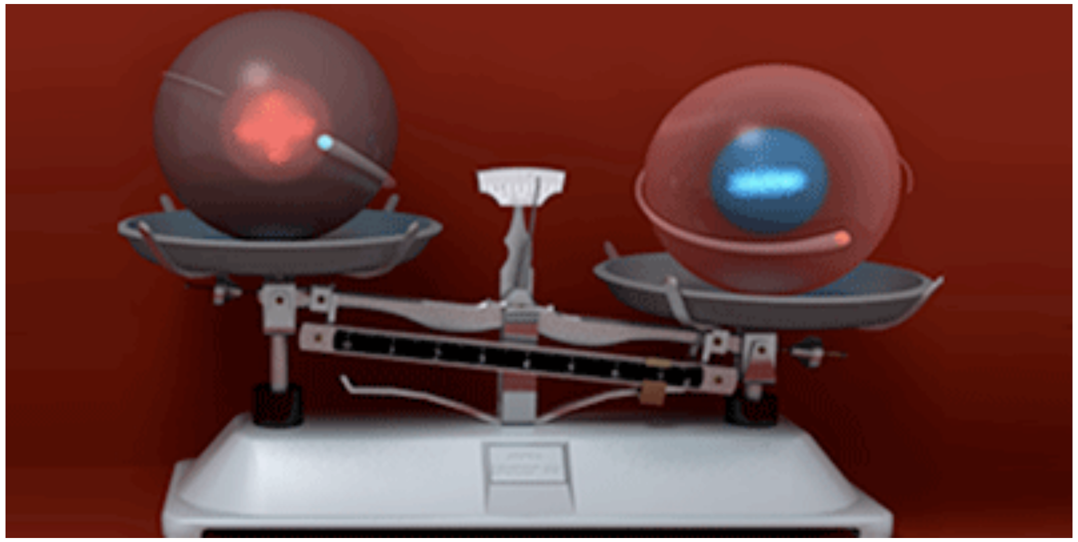
Gravitational studies with Antihydrogen



Dr. Will Bertsche

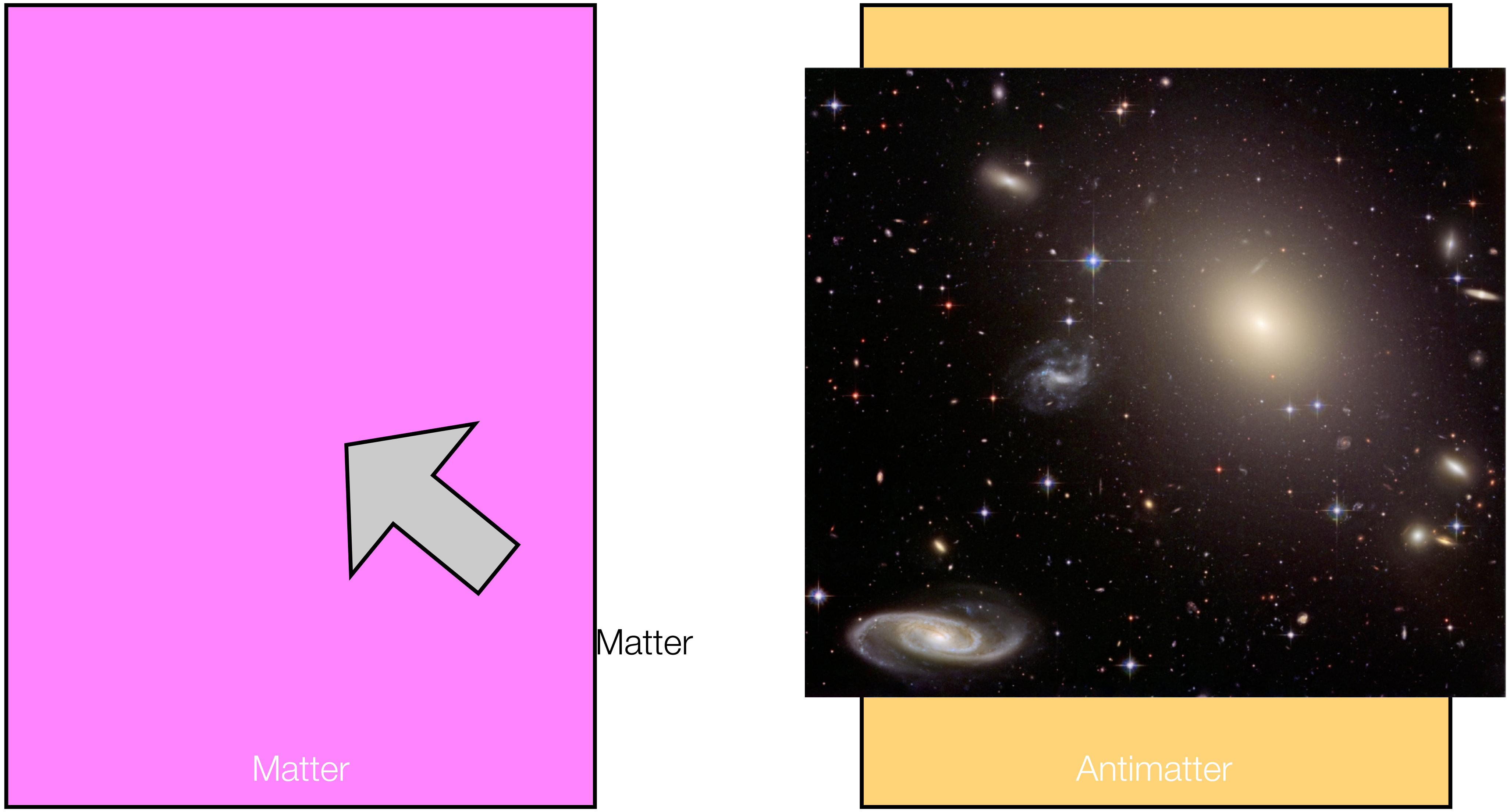
The University of Manchester
The Cockcroft Institute

ALPHA Experiment @ CERN

- 18 institutions, ~60 members performing precision studies with trapped antihydrogen atoms at CERN

What’s the matter with Antimatter?

- Should be equal amounts produced at the beginning…

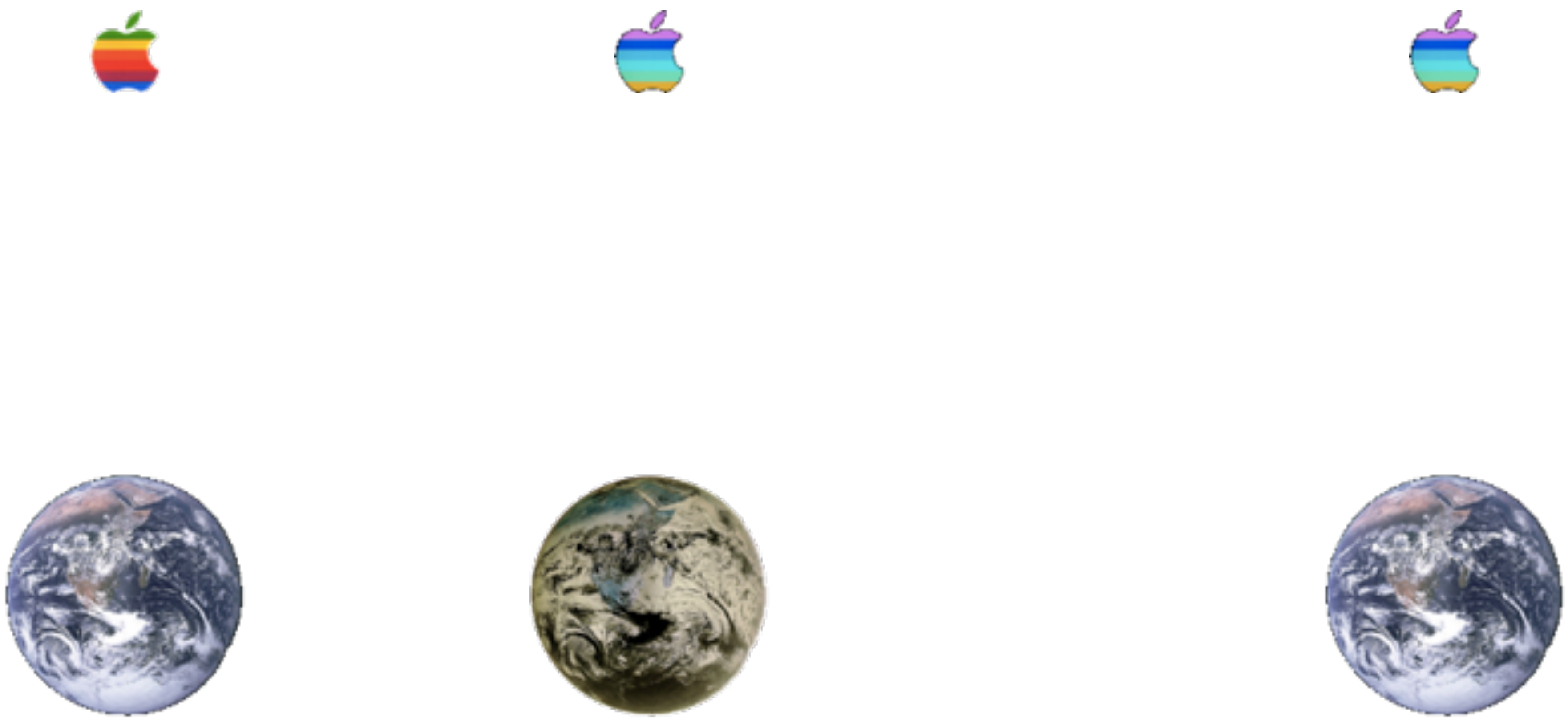


Possible Explanations: Fundamental Flaw?

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

This talk:
Free-Fall Weak Equivalence Principle

- Gravity?



Apple

Anti-Apple

Anti-Apple

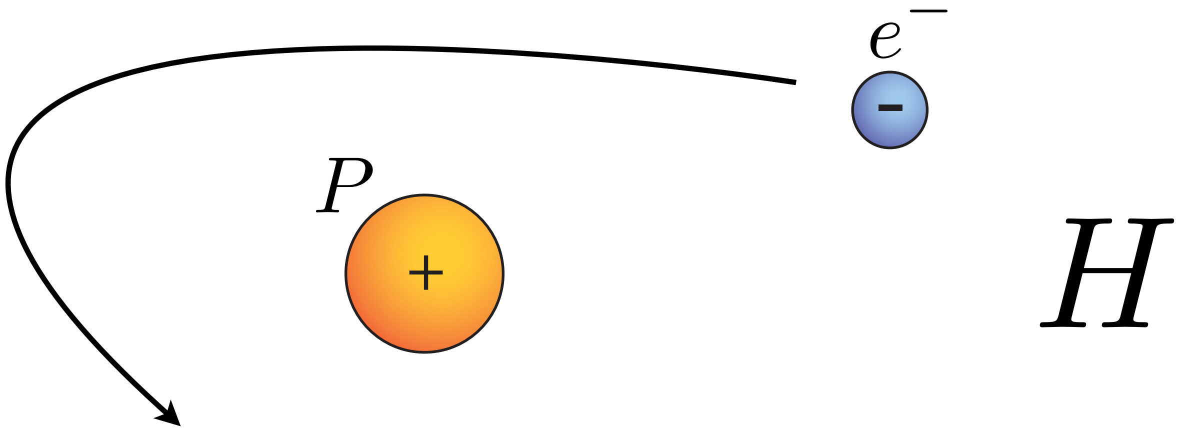
Earth

Anti-Earth

Earth

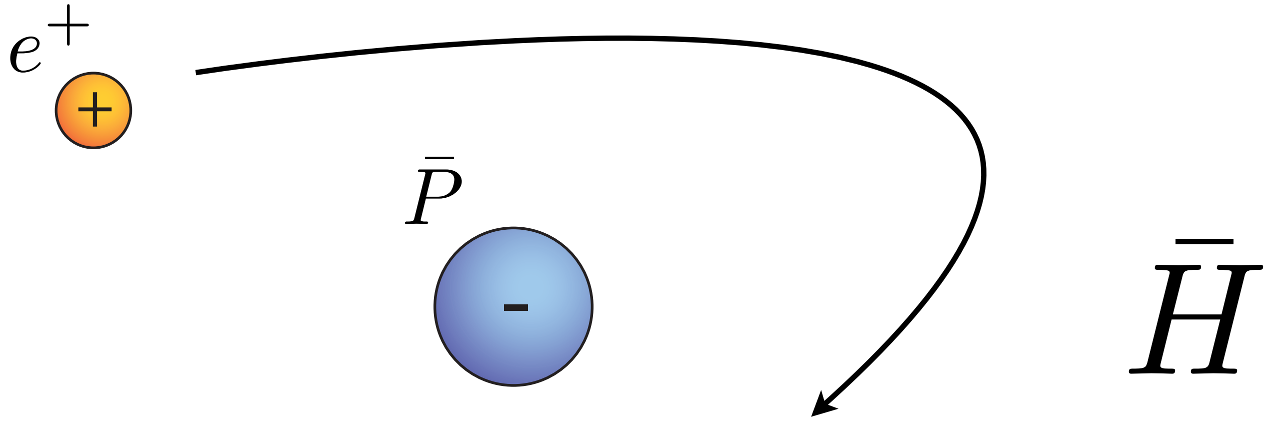
Atoms and antimatter: Hydrogen and Antihydrogen

Matter:



Hydrogen

Antimatter:



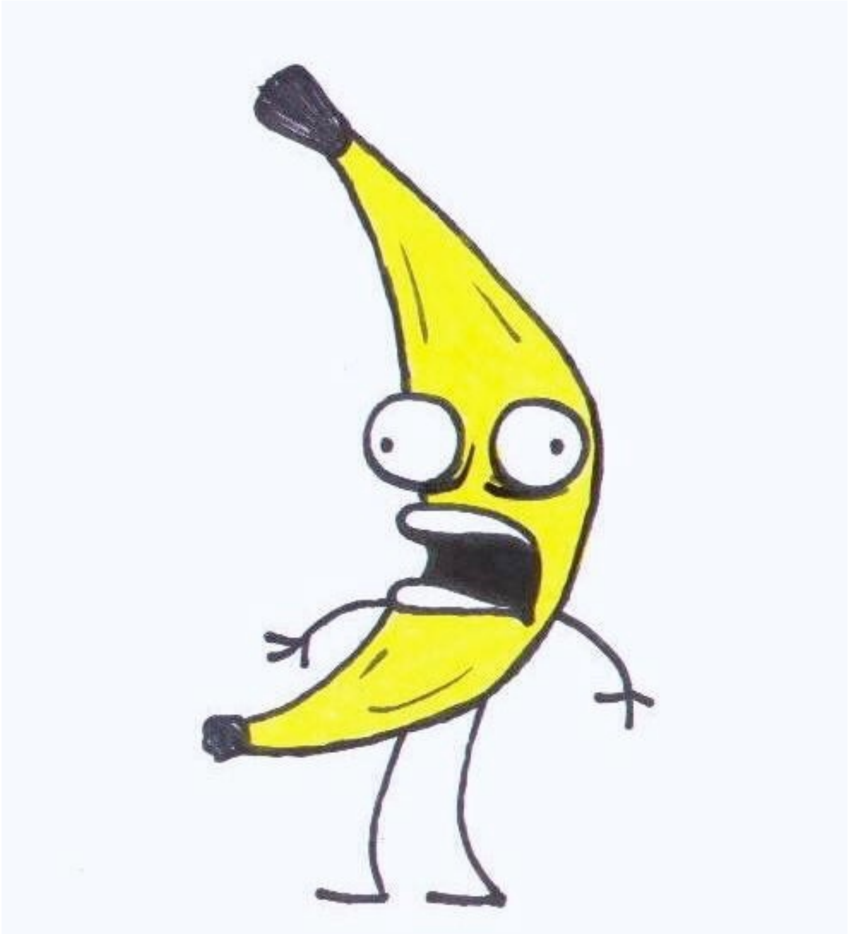
Antihydrogen

Where do Positrons come from?

- Easy: Some radioactive isotopes

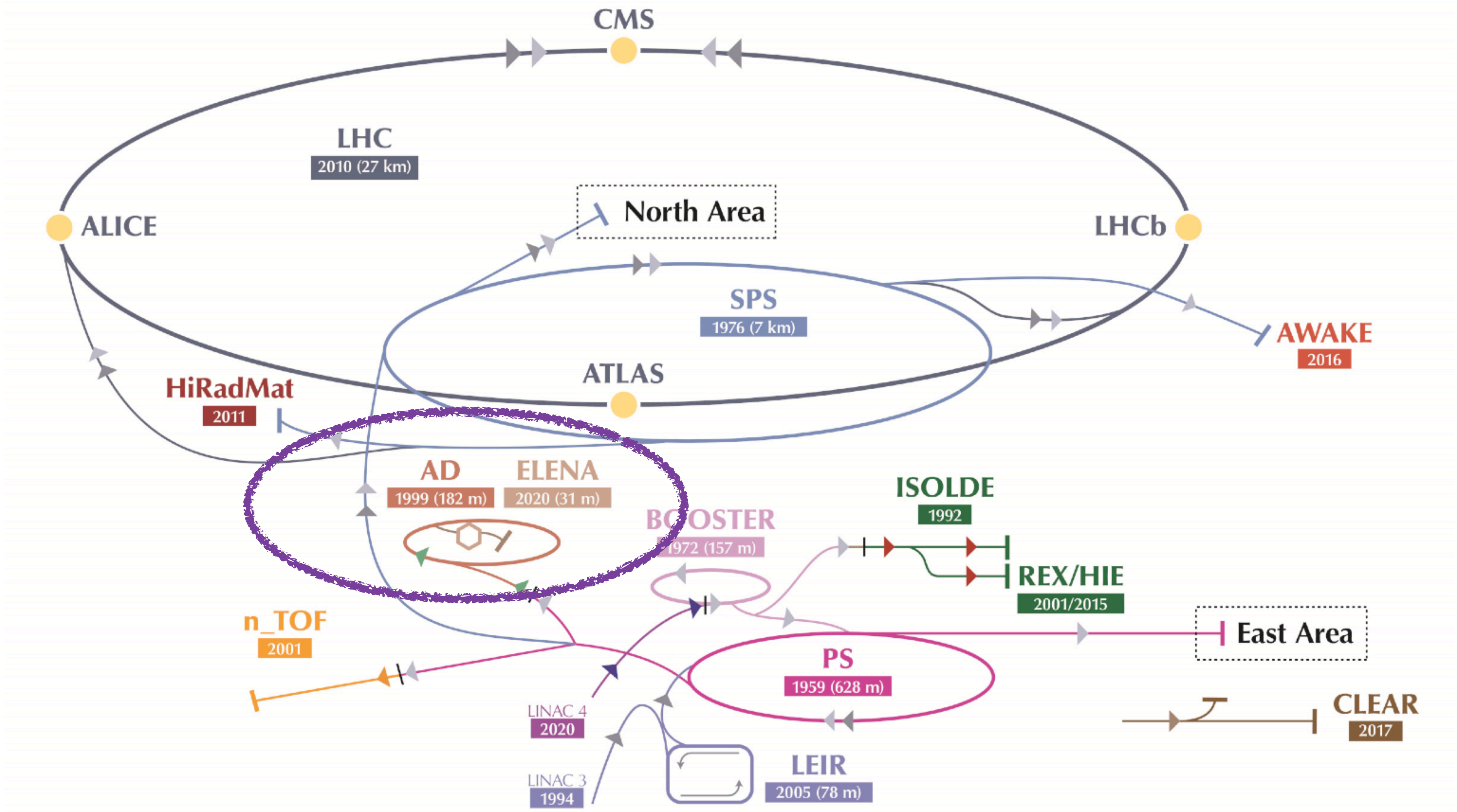
Banana Equivalent Dose (potassium):
~ 15 positrons / second

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



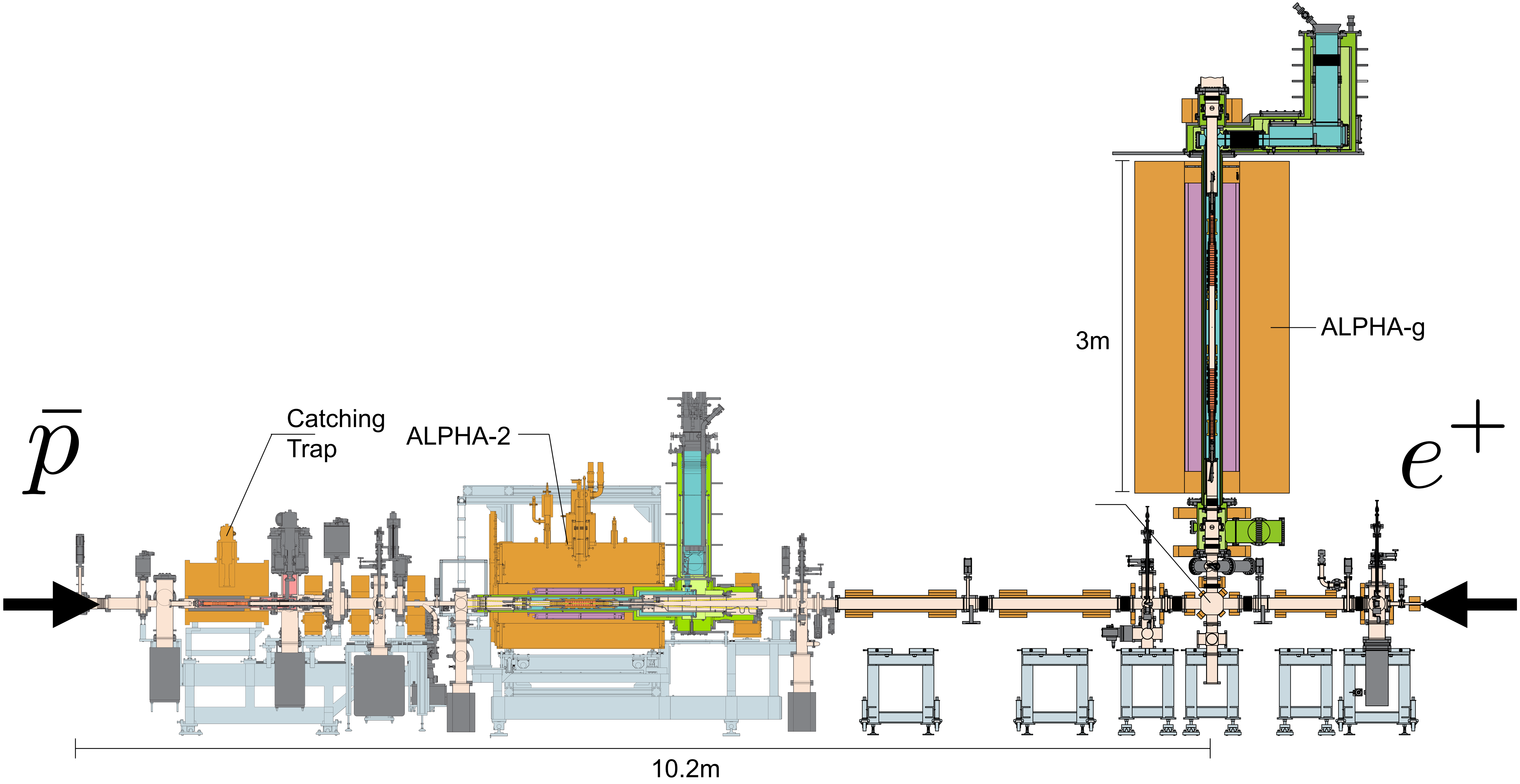
“I am a banana!” Don Hertzfeld

Low energy antiprotons from CERN



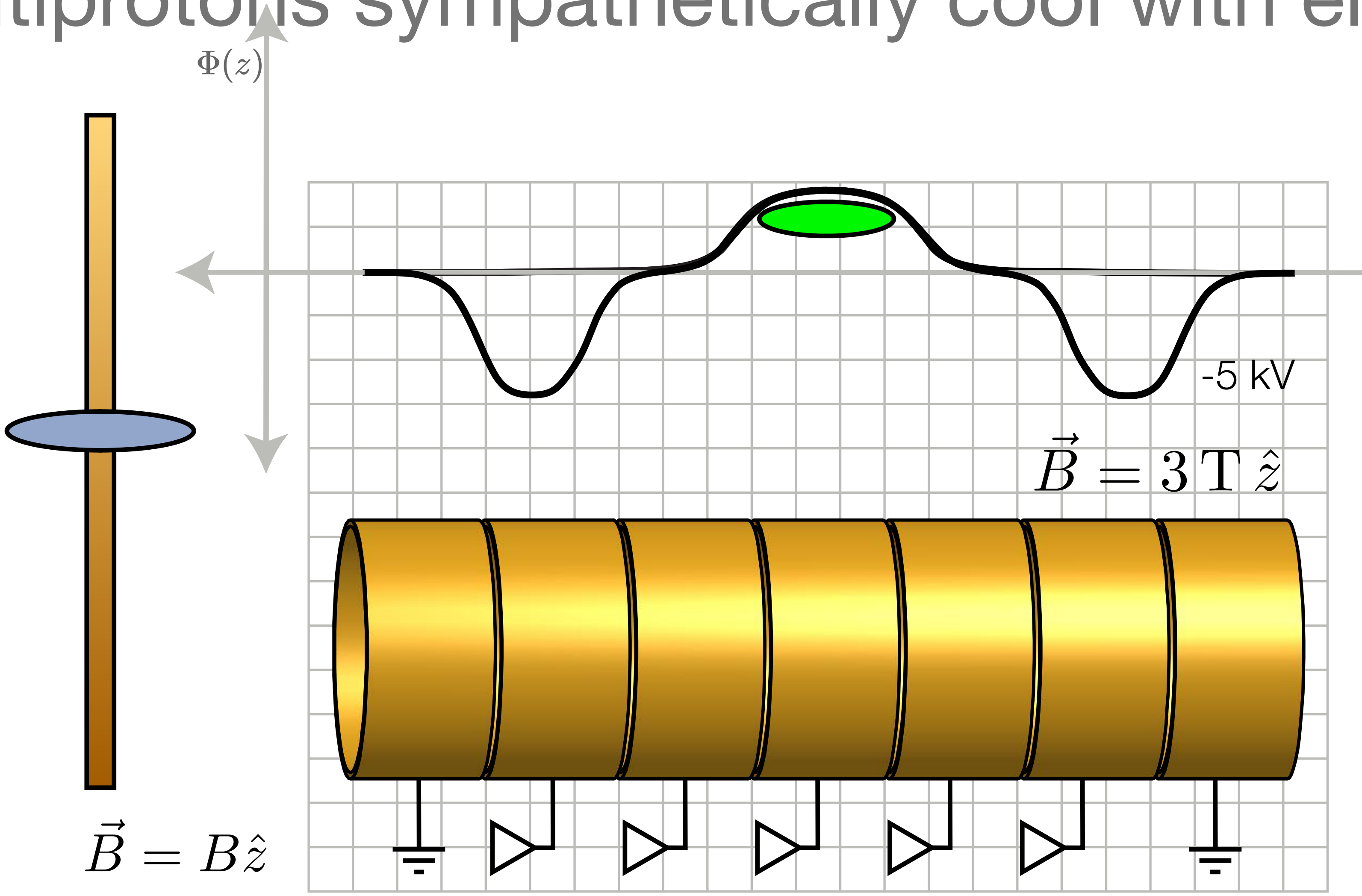
~ 5x10^6 antiprotons per minute from ELENA, ~2x10^5 per minute in ALPHA

ALPHA as installed, 2022



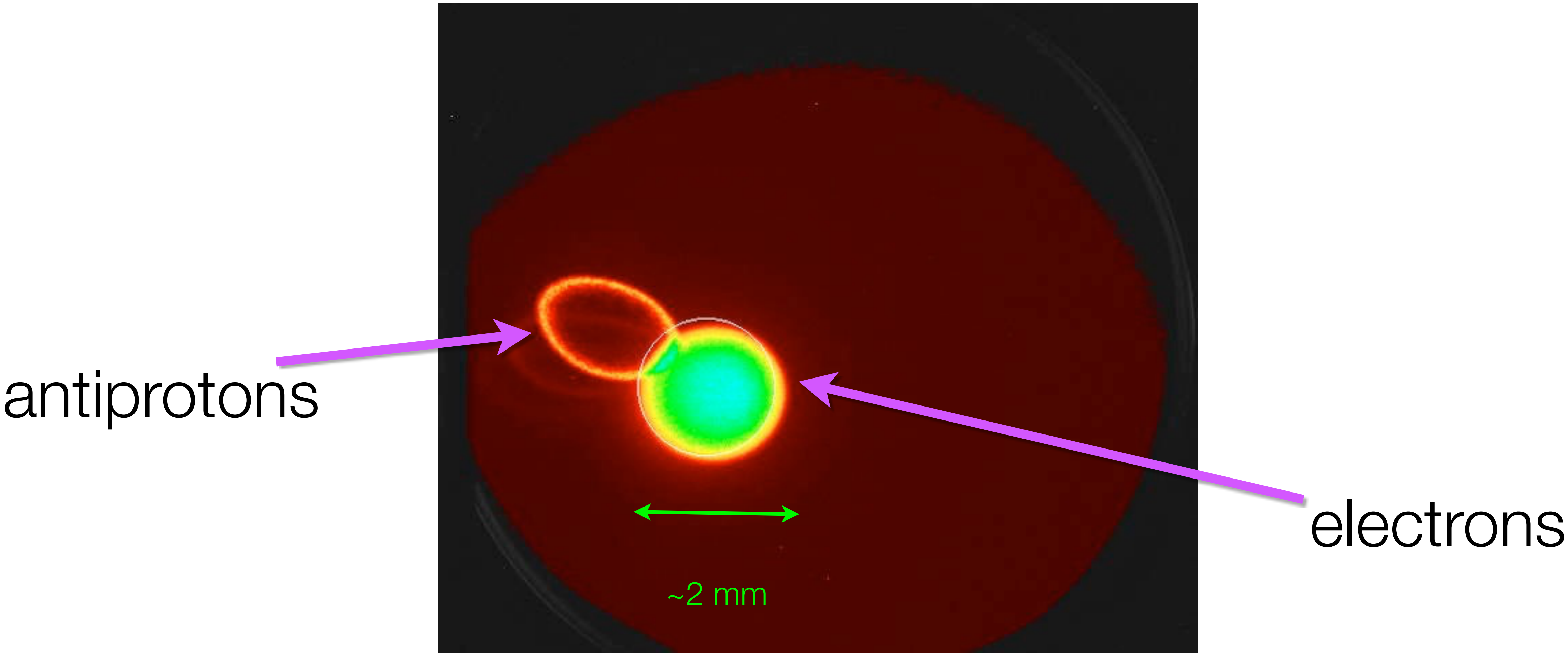
Capturing Antiprotons in a Penning-Malmberg Trap

- Degrade antiprotons in Al Foil - 100 keV is still a lot…
- Trap ~ 200,000 per bunch (< 5 keV)
- Antiprotons sympathetically cool with electrons



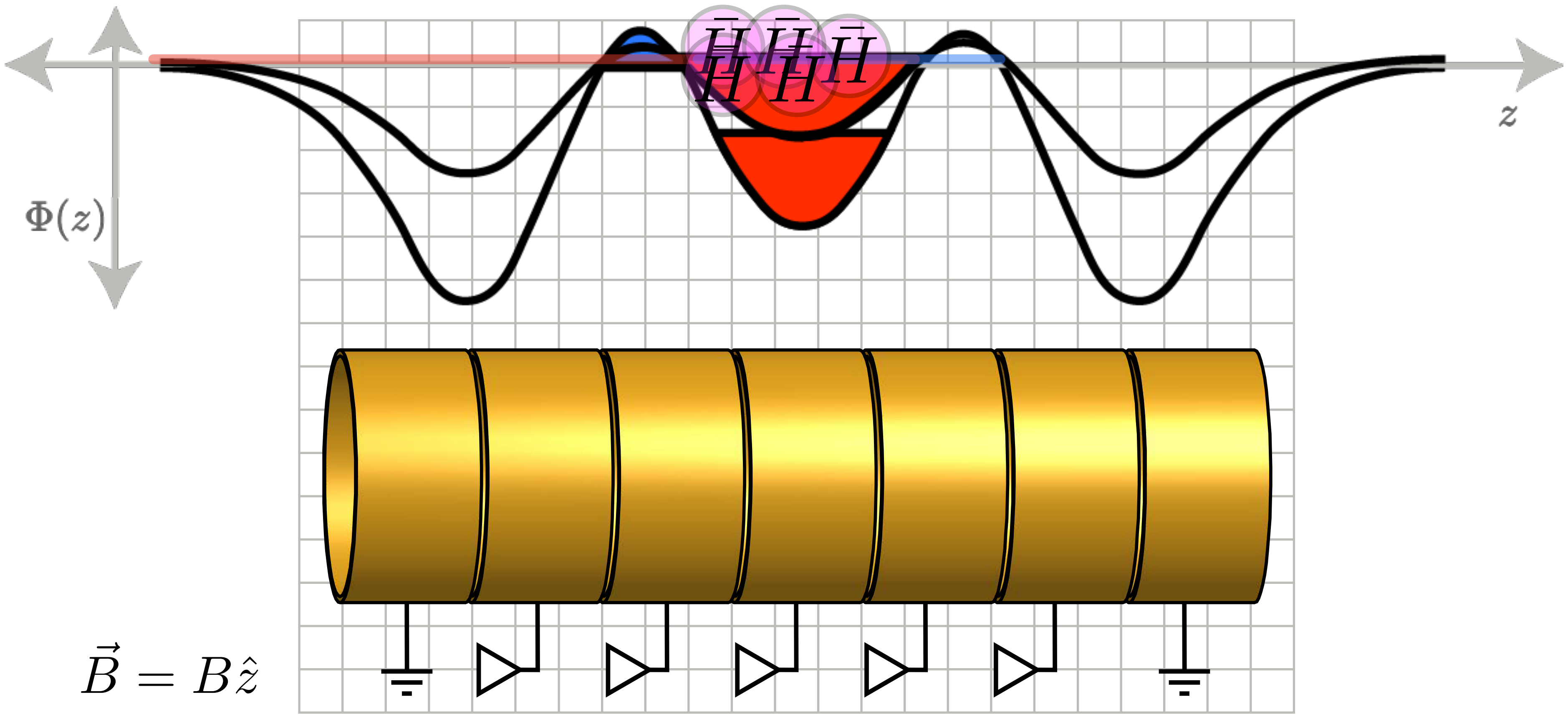
Antiproton / Electron Plasma

- Image the equilibrium Antiproton / Electron plasma



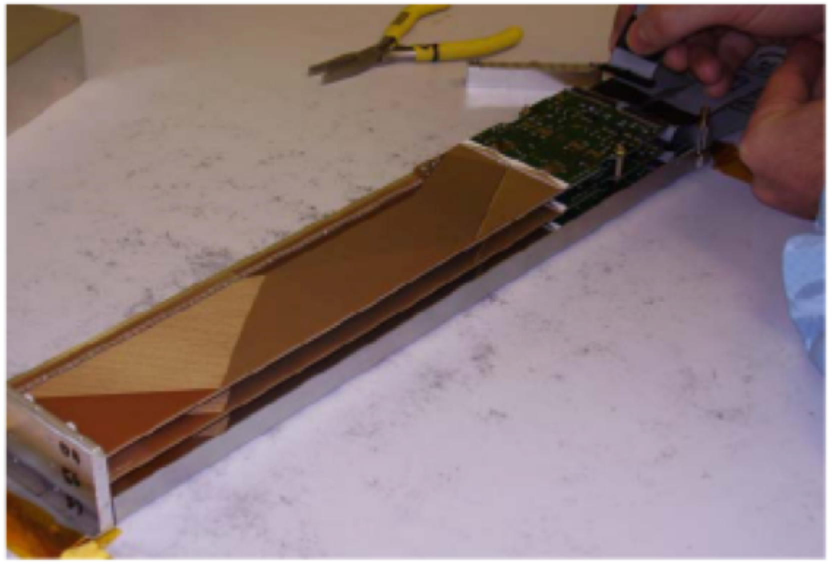
Antihydrogen Formation:
Mixing Antiprotons and Positrons

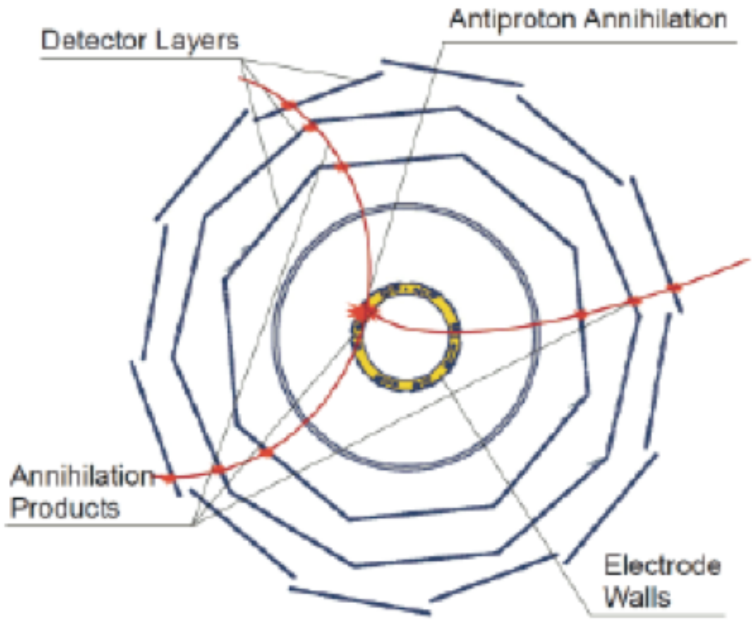
1. Merge Antiproton and Positron plasmas
2. Antiprotons and Positrons equilibrate and cool
3. Form Antihydrogen: atoms exit electrostatic trap

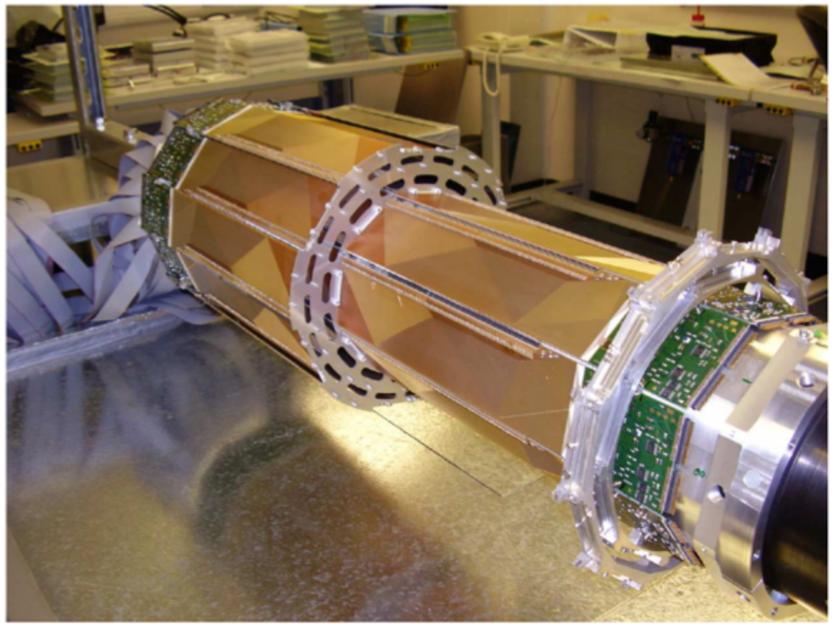


Annihilation Detection: ALPHA-1, ALPHA-2

- Silicon-strip detector
- 3D ‘Digital Camera’
- Vertex resolution ~ 6 mm
- > 70 % efficiency for annihilations



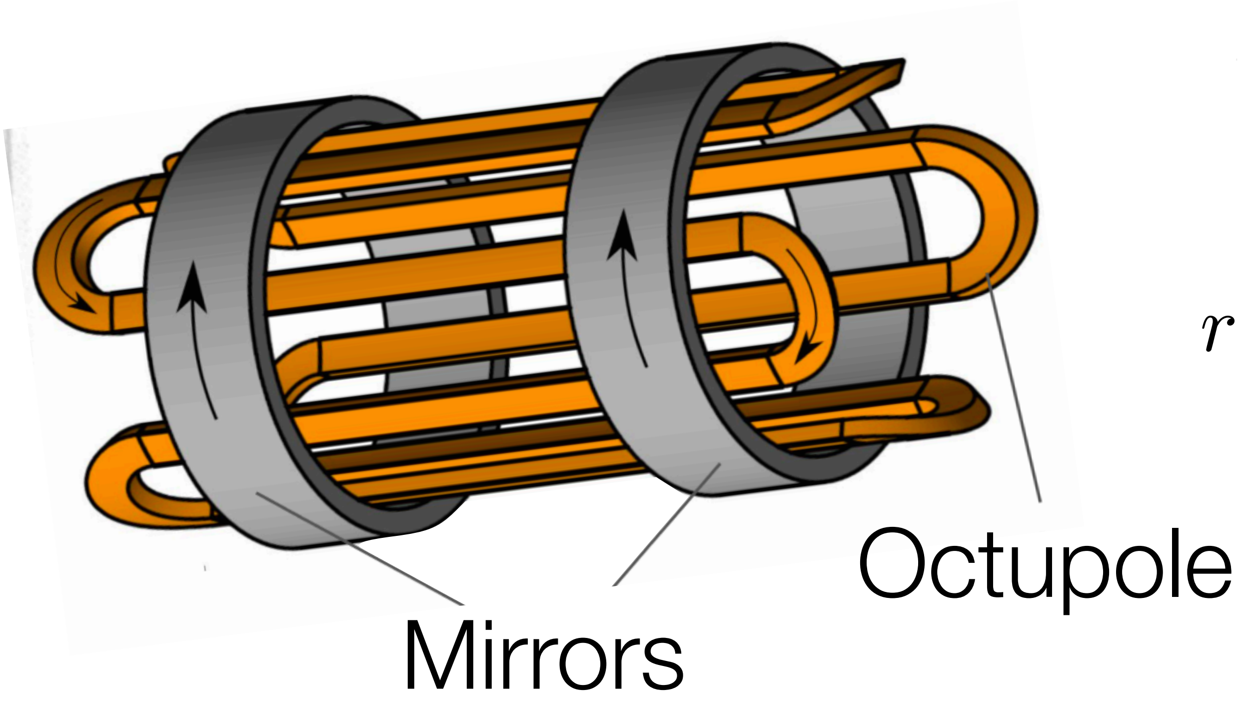


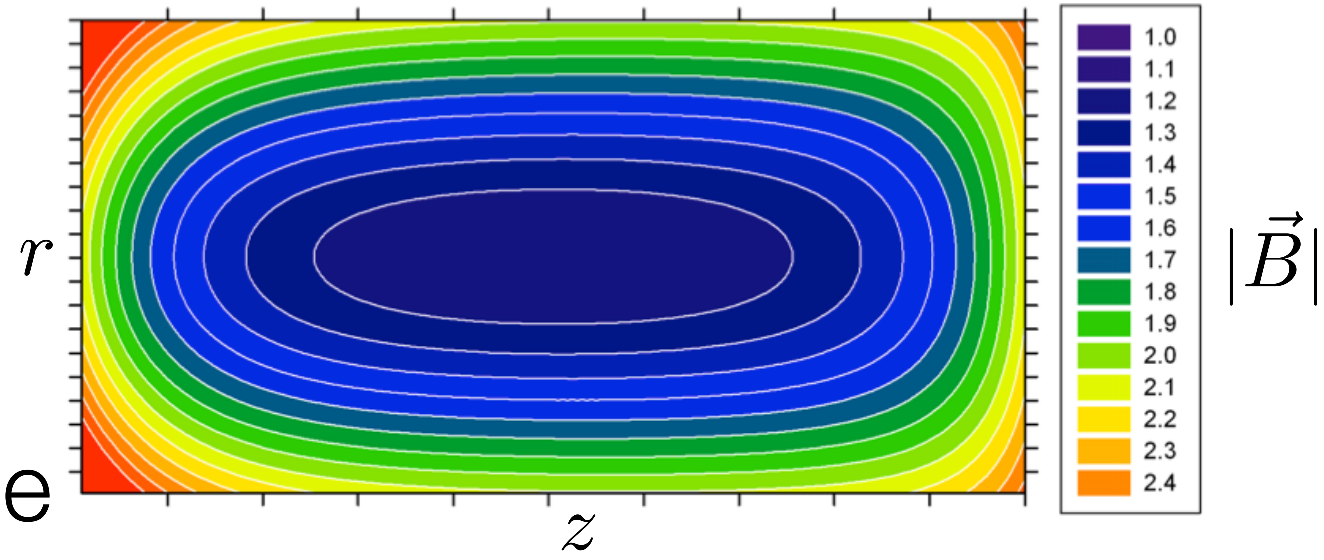


Trapping Antihydrogen

- Octupole-based ***magnetic minimum*** trap
  - Octupole + 2 mirrors
- Low-field-seeking magnetic states are trapped
- Shallow potential well: **T < 0.5 K**

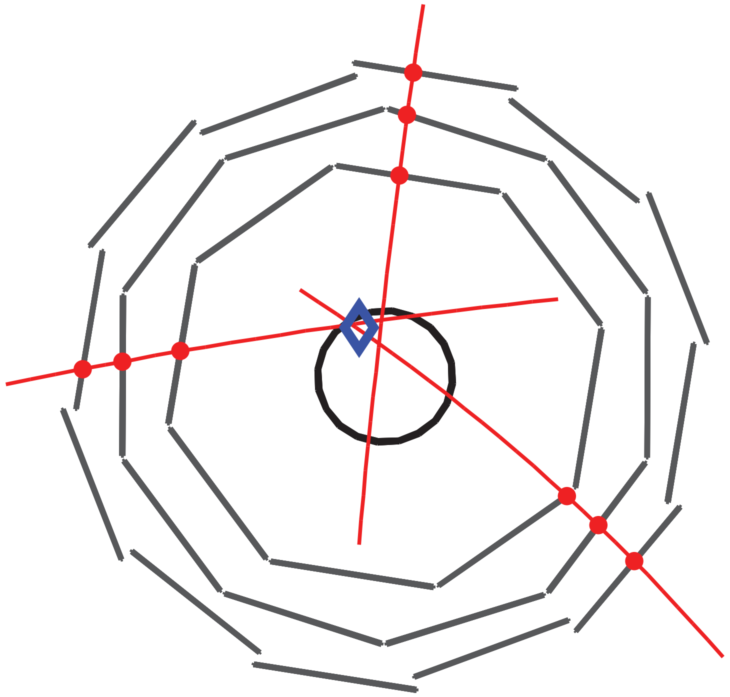
$$\vec{F} = \mu_H \vec{\nabla}|\vec{B}|, \; U = \vec{\mu}_H \cdot \vec{B}$$





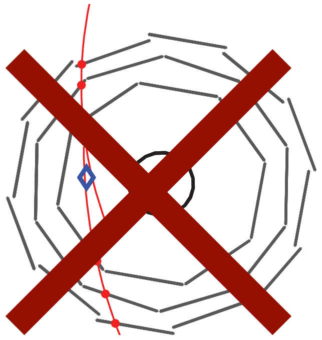
A little ALPHA history
Trapping Antihydrogen: Search

1. Turn on magnetic trap
2. Mix and Form Antihydrogen
3. Eject remaining charged particles
4. Rapidly shut off trap (< 30 ms quench in ALPHA-1)
5. Detect annihilations

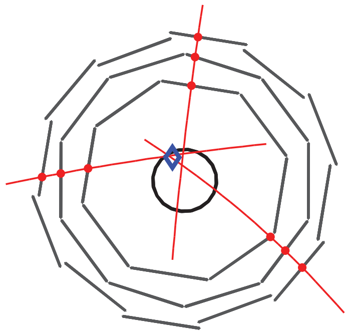


A little ALPHA history
Trapped Antihydrogen Detection

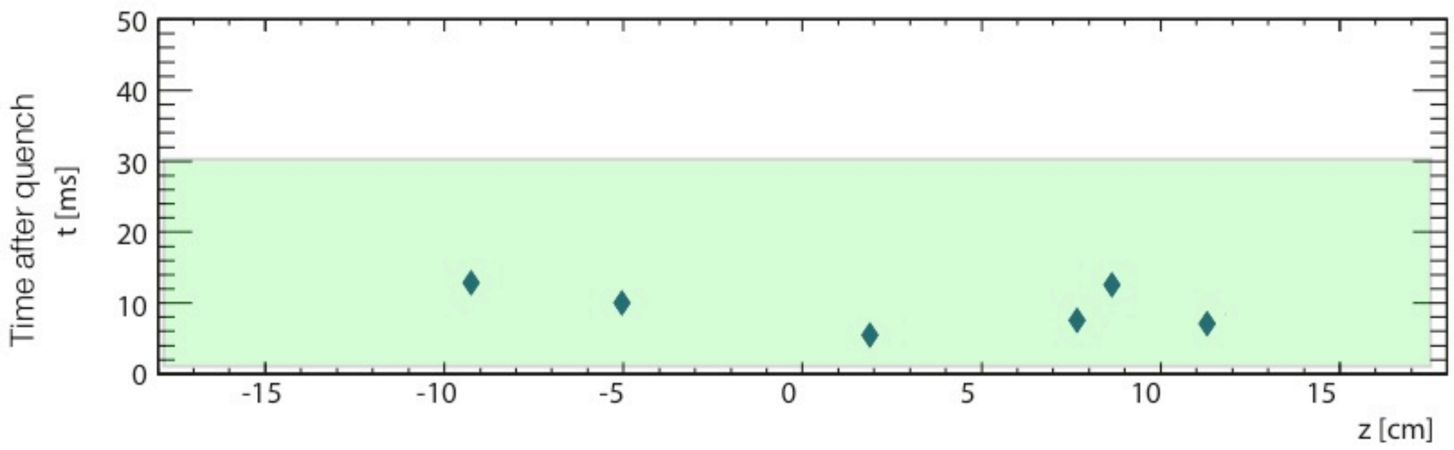
- Pattern / Time / Spatial Information from Detector
- Reject cosmic rays
- Accept antiproton annihilations
- Only look at events during the quench (time)



Cosmic Ray

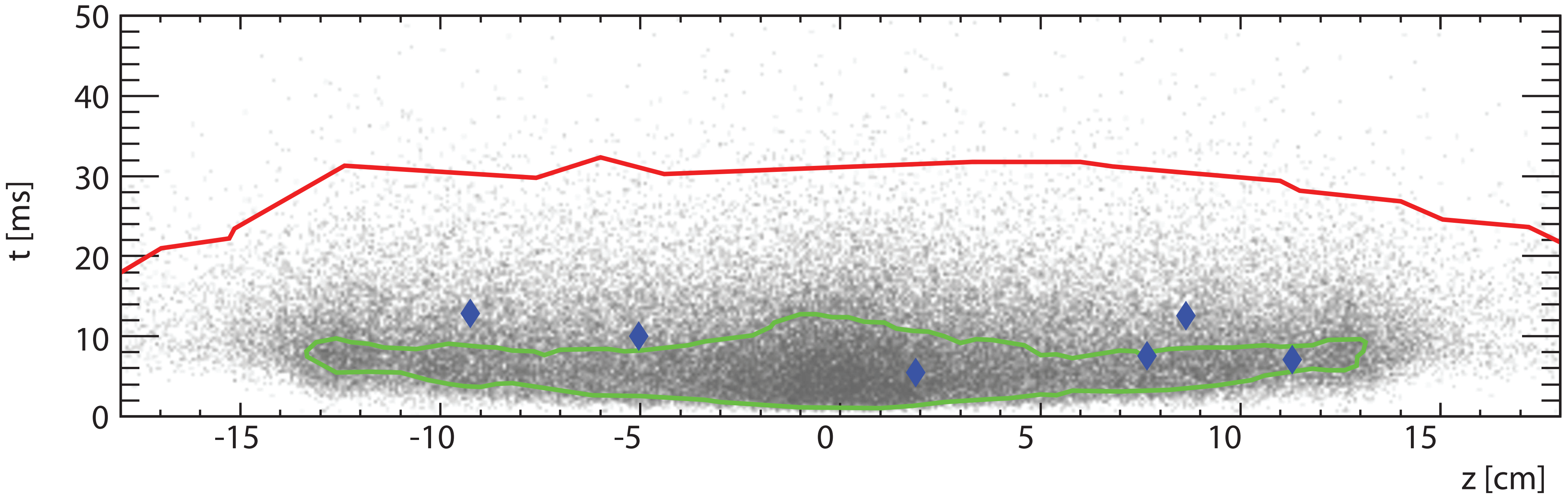


Antiproton



A little ALPHA history
Antihydrogen Expectation?

- Simulate Antihydrogen atoms in trap through quench



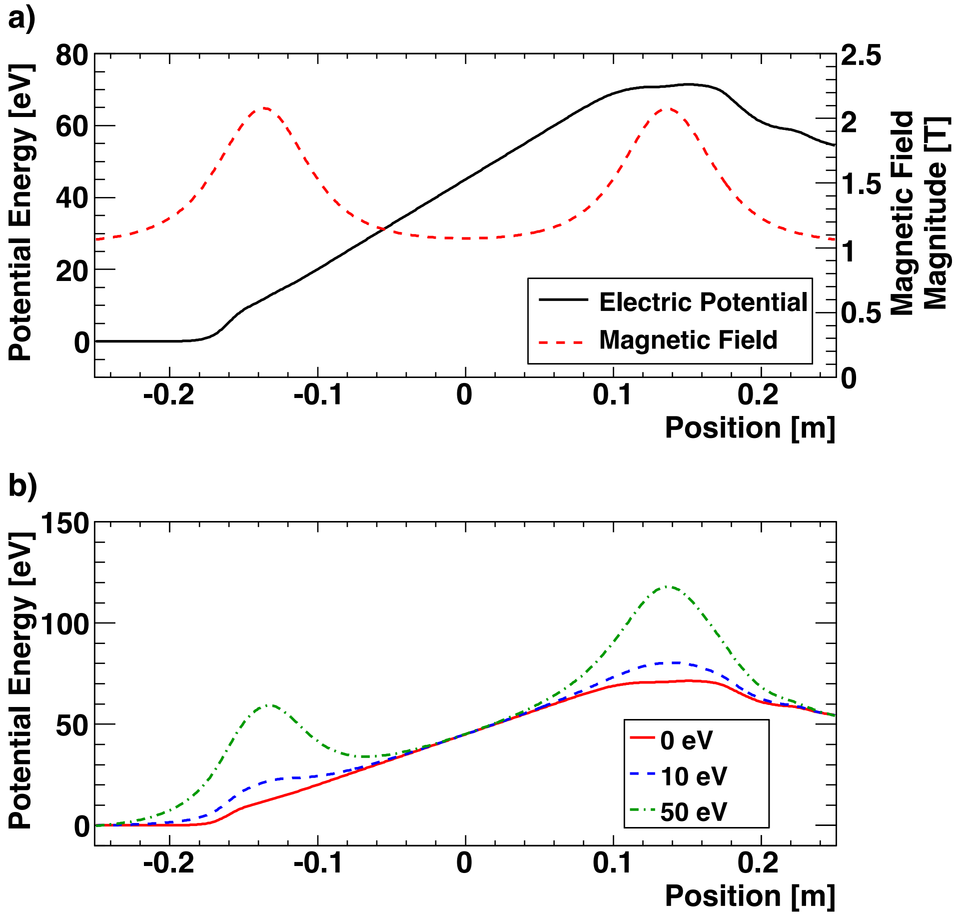
- Mirror-trapped antiprotons might remain…

A little ALPHA history

High $E_\perp$, Mirror-Trapped Antiprotons Background?

- *Simulate behavior of atoms and antiprotons in potential*
  - *Antiprotons with high perpendicular energy can be mirror-trapped by B fields*

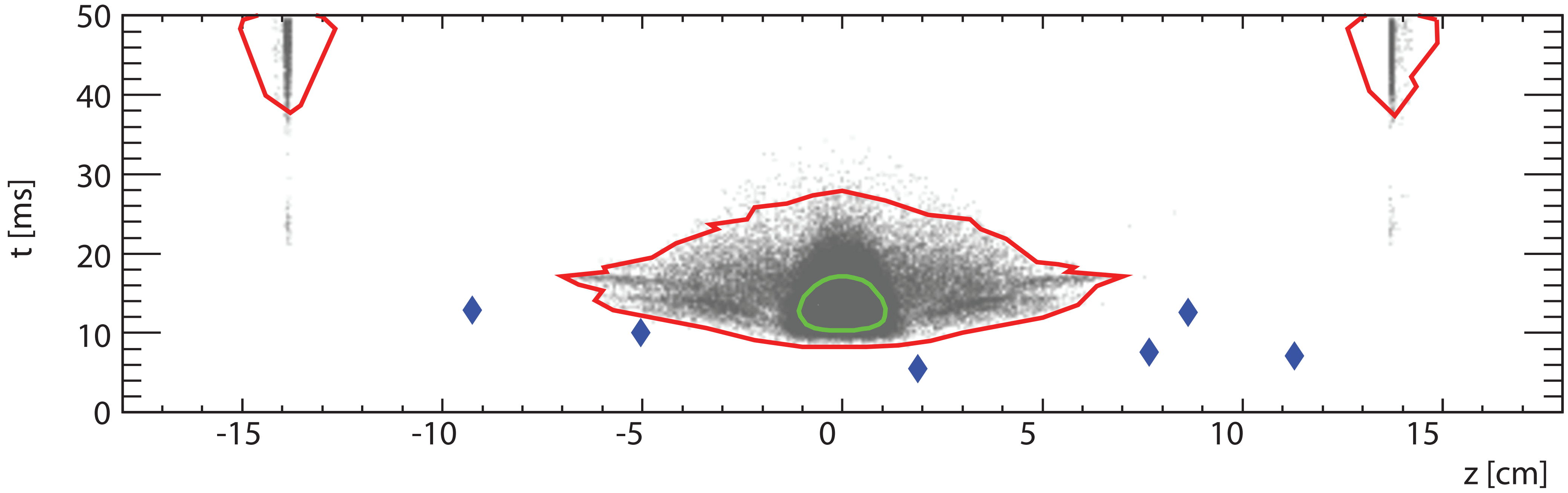
$$U_{\bar{p}}(z, r = 0) = q(\phi - \phi_0) + E_\perp \frac{B_\parallel - B_0}{B_0}$$



A little ALPHA history

Are events Mirror-Trapped Antiprotons?

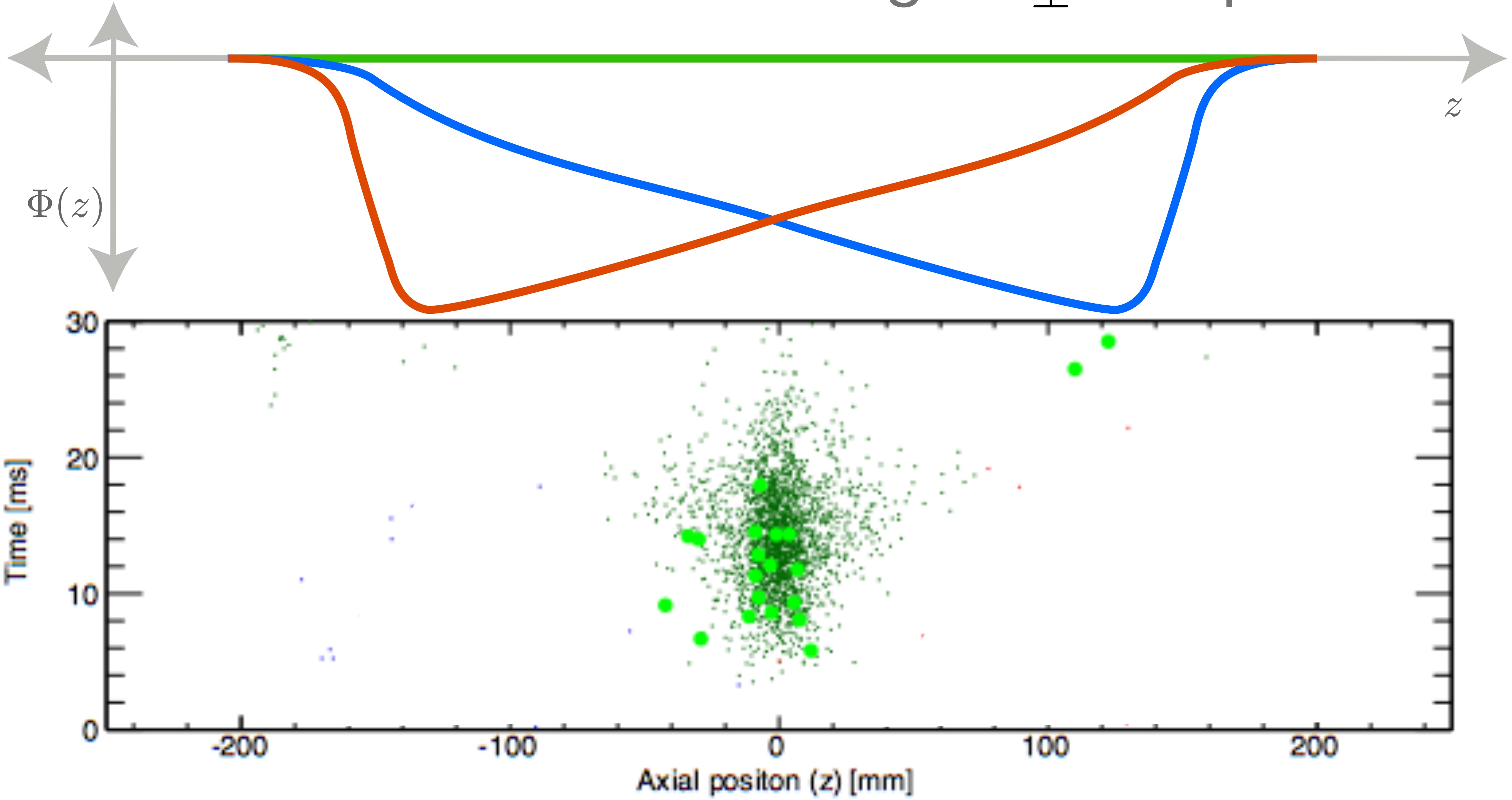
- Simulate mirror-trapped antiprotons in quench



- Different from antihydrogen events, surely…

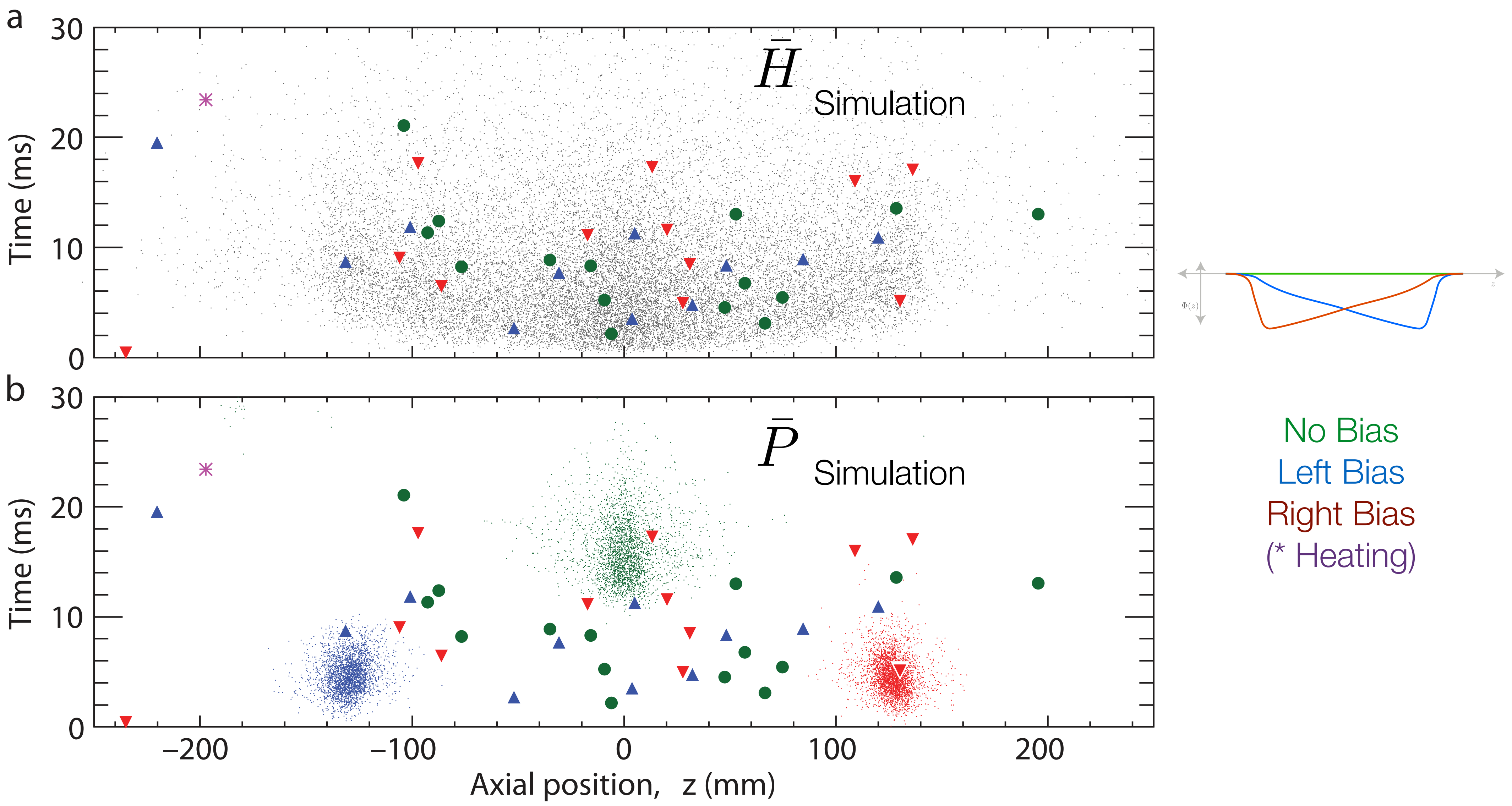
A little ALPHA history
Quench With Bias Electric Field

- Electric *Fields deflect charged particles, not atoms*
- Simulate and measure with high $E_\perp$ antiprotons



A little ALPHA history
Antihydrogen Search with Bias Fields

- No spatial bias in signal: Trapped Antihydrogen



E. B. Andresen *et al.* “Trapped Antihydrogen”, *Nature* 468, 673–676

Measurements with Potentials: Charge neutrality

- What if the **E**-fields did deflect the atoms?

- Antihydrogen “charge anomaly”

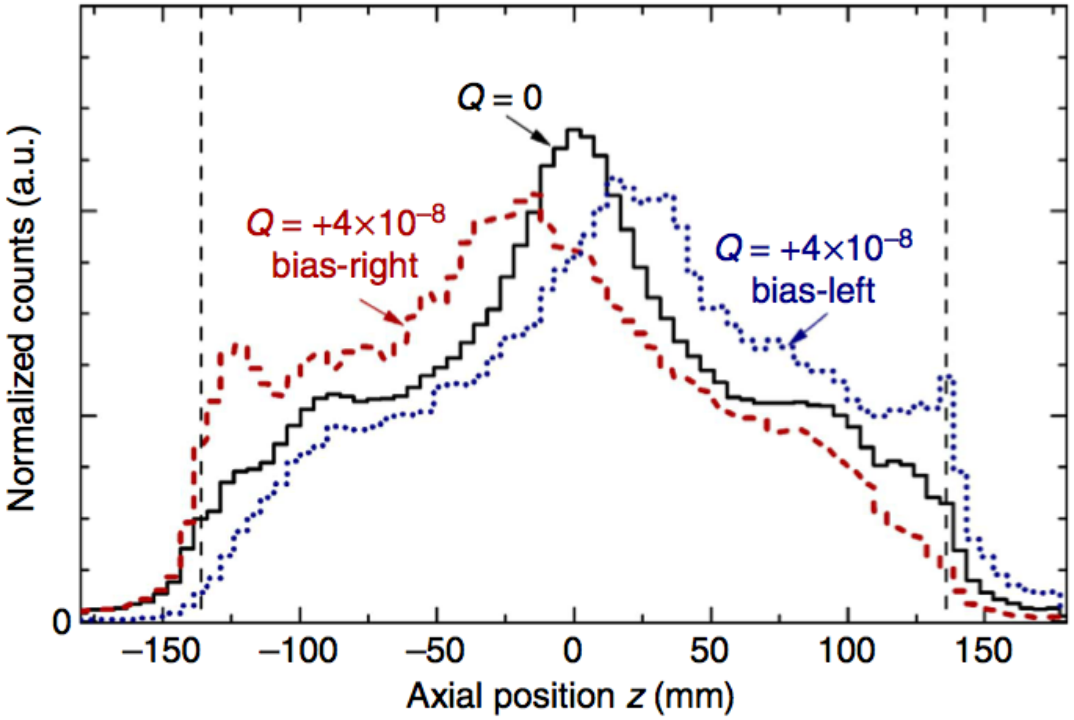
$$\bar{H} \text{ charge} = Qe$$

- Magnetic atom trap + bias field potential:

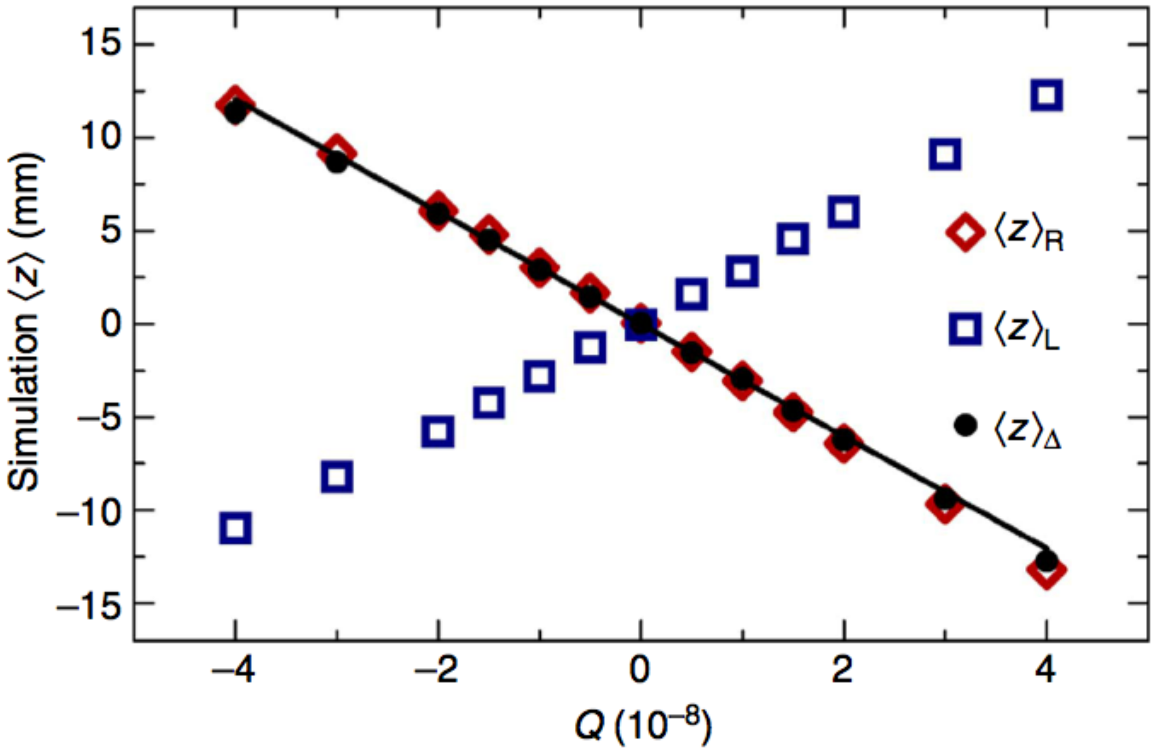
$$U(z) = \mu_{\bar{H}} B(z) - \frac{QeE}{k_B} z$$

Measurements with Potentials: Charge neutrality

Simulate Hbar Annihilations



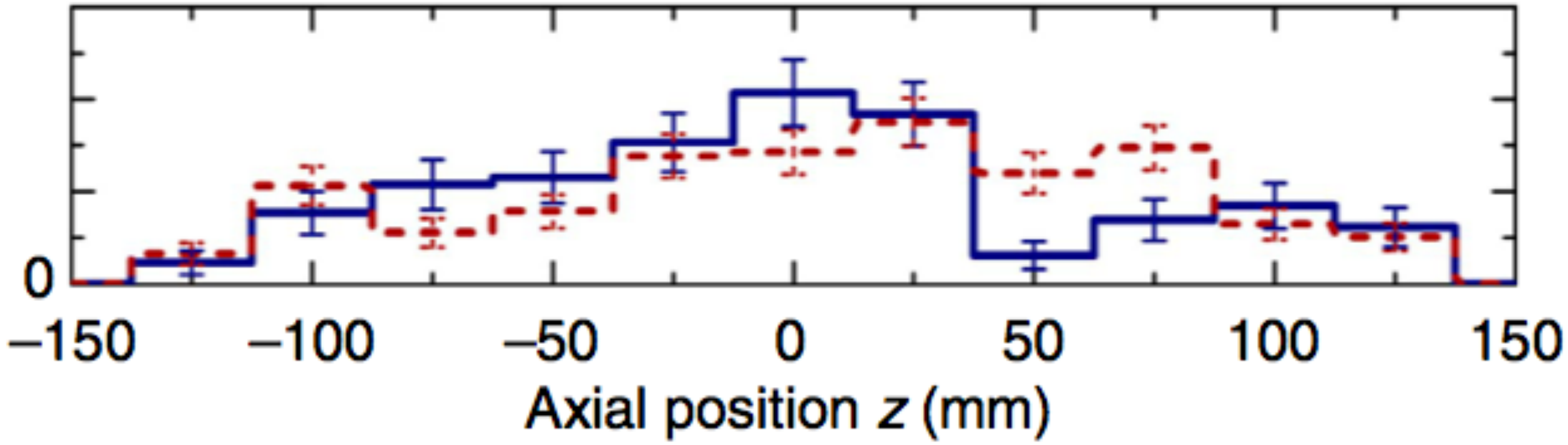
Relate $\langle z \rangle_\Delta \longleftrightarrow Q$



$$Q = \frac{4\mu_{\bar{H}}\beta k_B}{e\,(E_R - E_L)}\langle z \rangle_\Delta$$

Measurements with Potentials:
Charge neutrality

Measure $\langle z \rangle_\Delta$



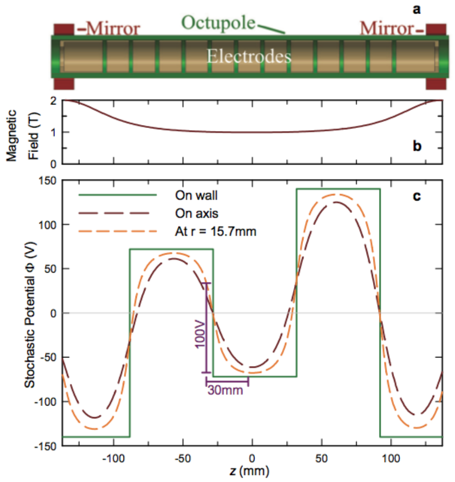
$$\langle z \rangle_\Delta = 4.1 \pm 3.4\,\mathrm{mm}$$

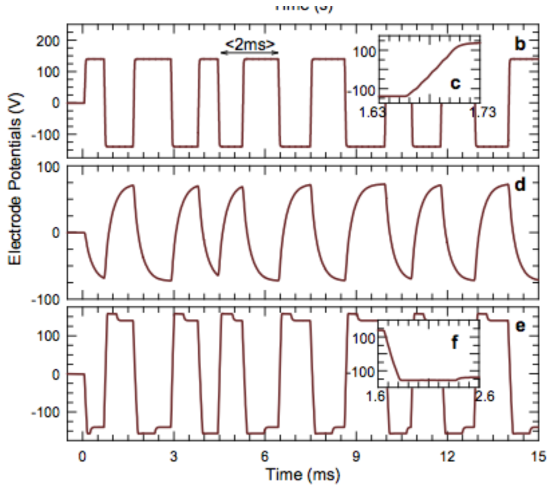
$$Q = (-1.3 \pm 1.1 \pm 0.4) \times 10^{-8}$$

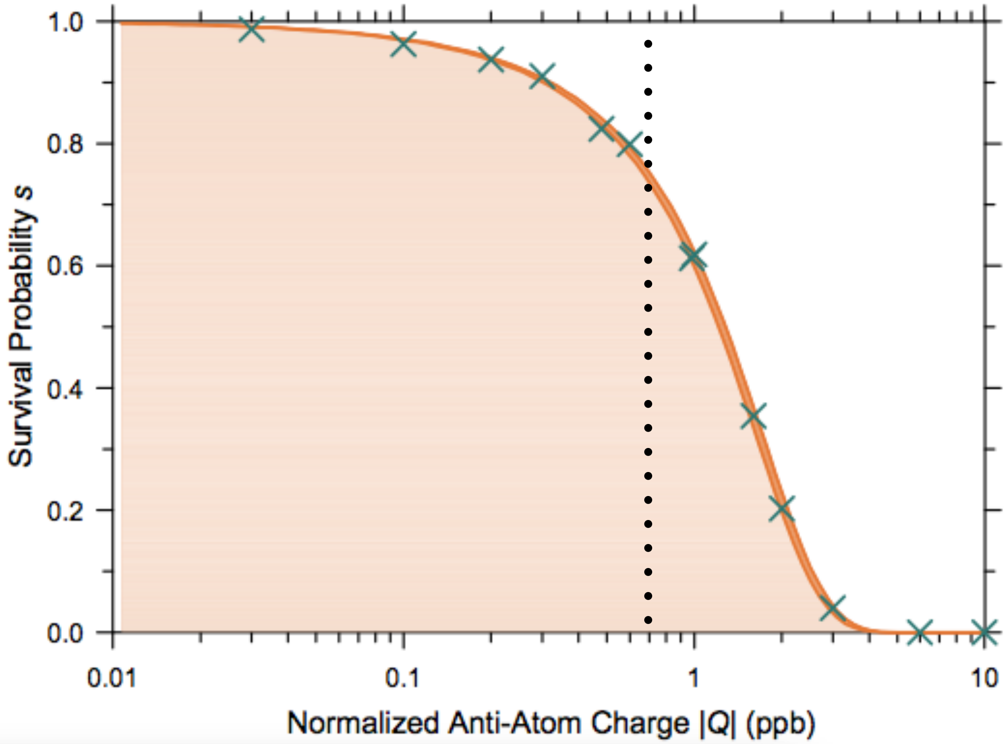
C. Amole *et al.* “An experimental limit on the charge of antihydrogen”, Nat. Comm. 5, 3955 (2014)

Measurements with Potentials:
Charge neutrality

- Can improve precision through electrostatic drive: Stochastic Heating







$$|Q| < 0.71 \cdot 10^{-9}$$

LETTER

OPEN

doi:10.1038/nature16491

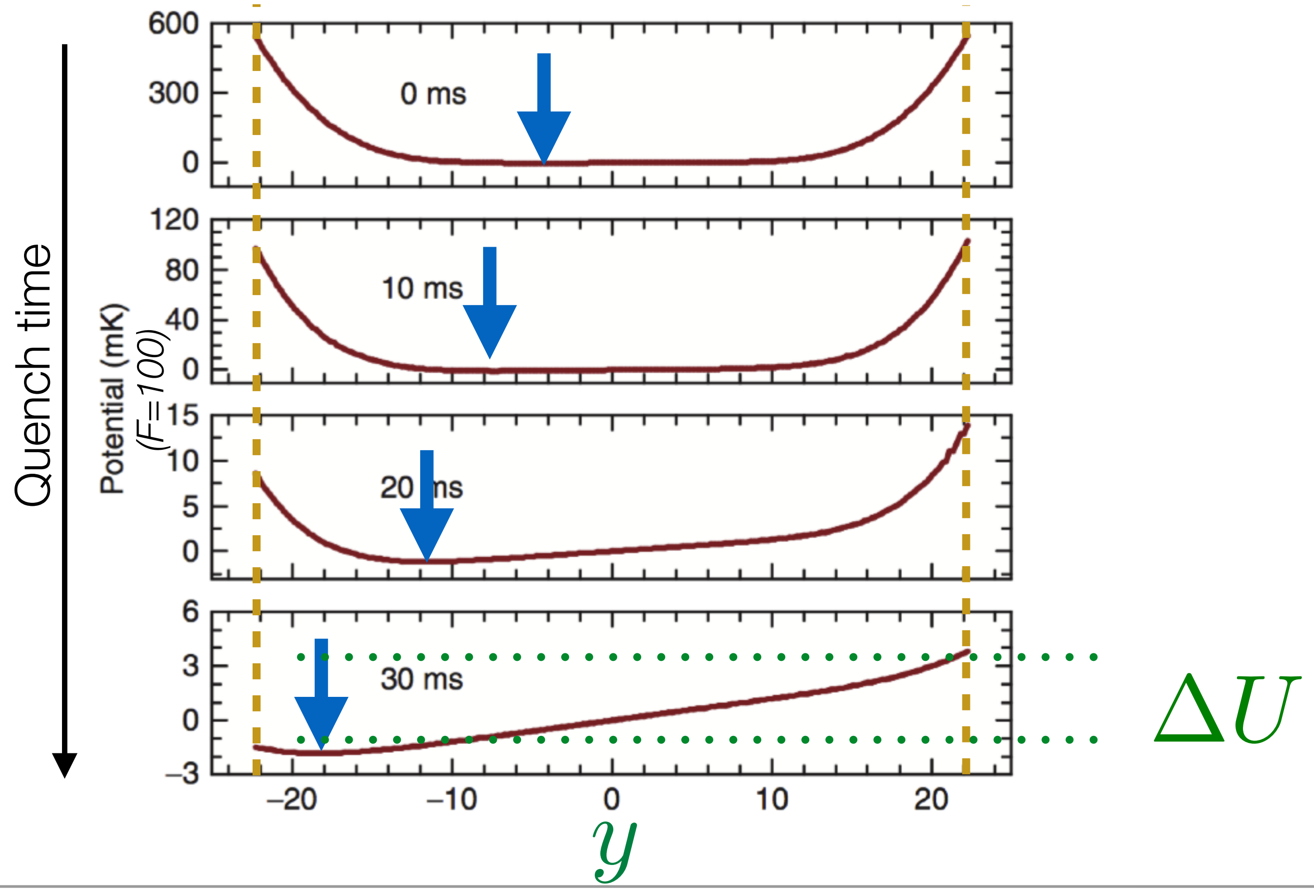
An improved limit on the charge of antihydrogen from stochastic acceleration

Measurements with Potentials: Gravitation?

- Do atoms and anti-atoms gravitate differently?

$$F_{\text{antimatter}} = F \cdot mg$$

$$U(y) = \mu_{\bar{H}} B(y) + F \cdot mgy$$



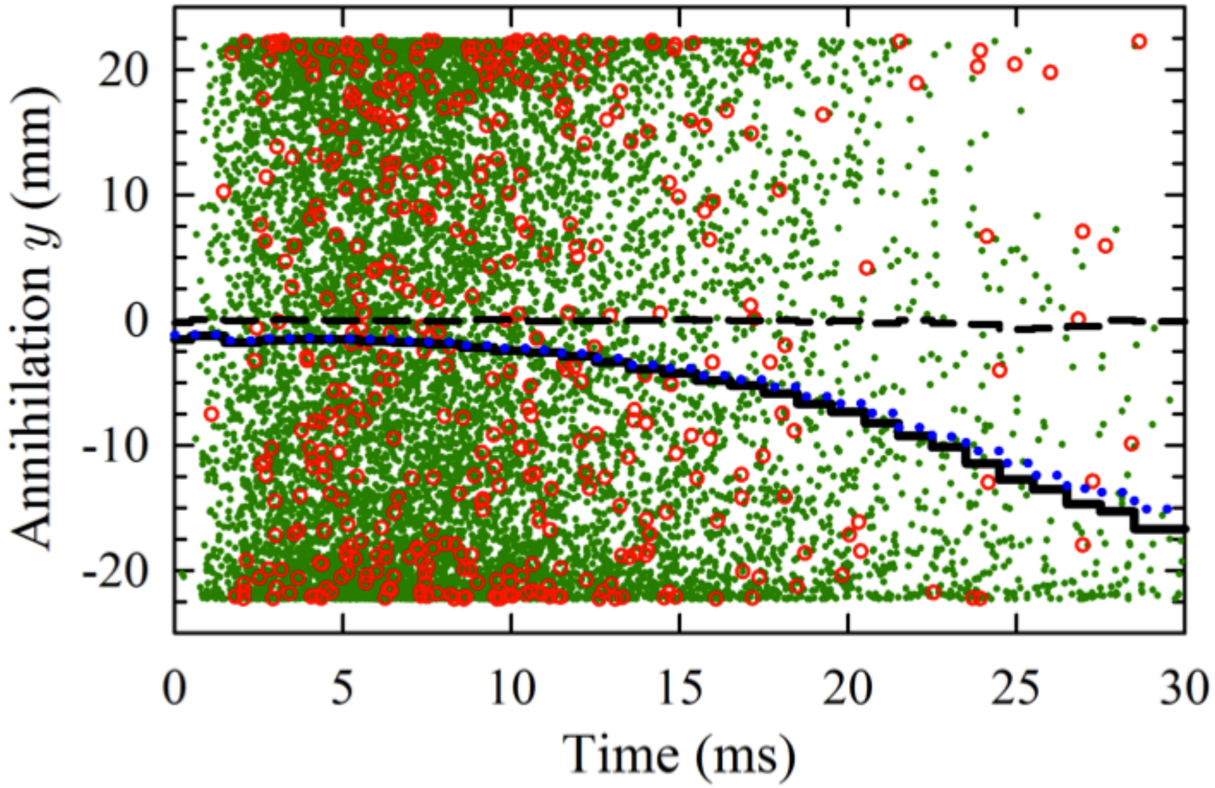
Measurements with Potentials: Gravitation? (ALPHA-1)

- Antihydrogen will fall out the bottom (or top) of the trap

$$F_{\mathrm{antimatter}} = F \cdot mg$$

• Simulation for $F = 100$

◉ Data



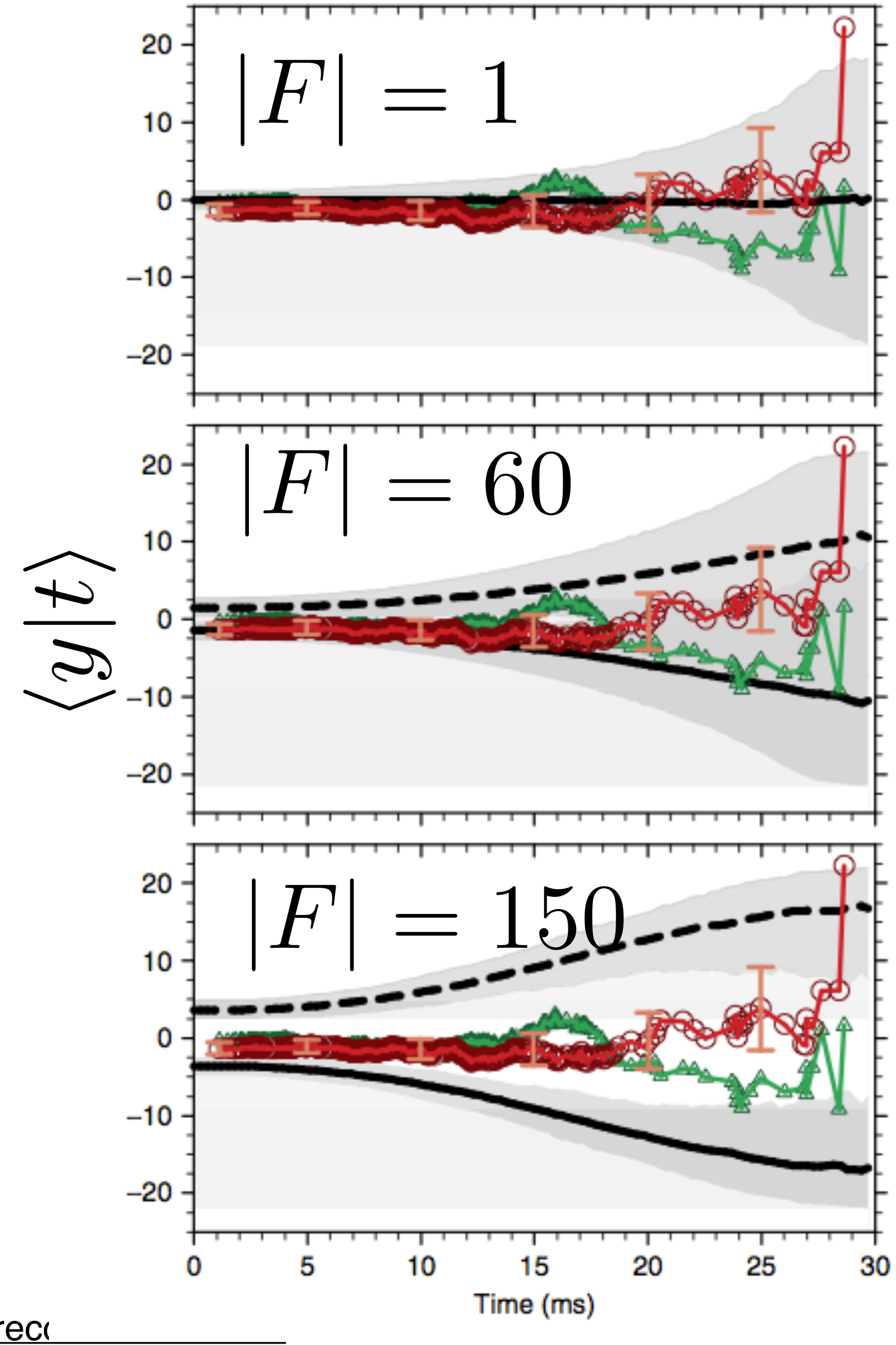
Measurements with Potentials: Gravitational Deflection: Precision?

- Simulate various ***F***: RCA during quench

$$-65 < F < 110$$

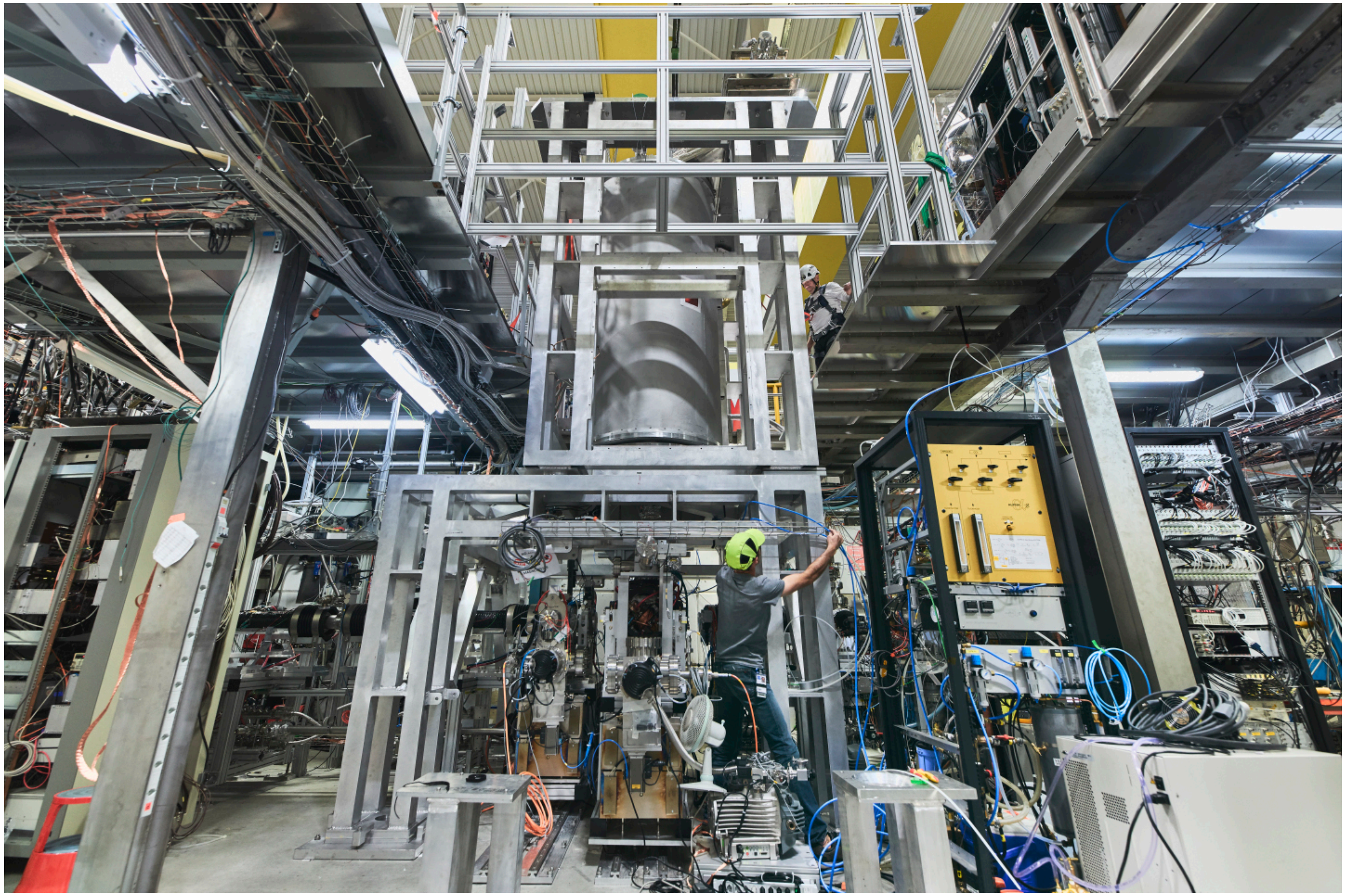
- Not very precise:
  - Poor statistics
  - hot population
  - short distance, no systematic control

$$\Delta U_{F=1} \approx 10^{-3}\,\mathrm{mK\,mm}^{-1}$$



NATURE COMMUNICATIONS | 4:1785 | DOI: 10.1038/ncomms2787 | www.nature.com/naturec

ALPHA-g: an antimatter gravity experiment

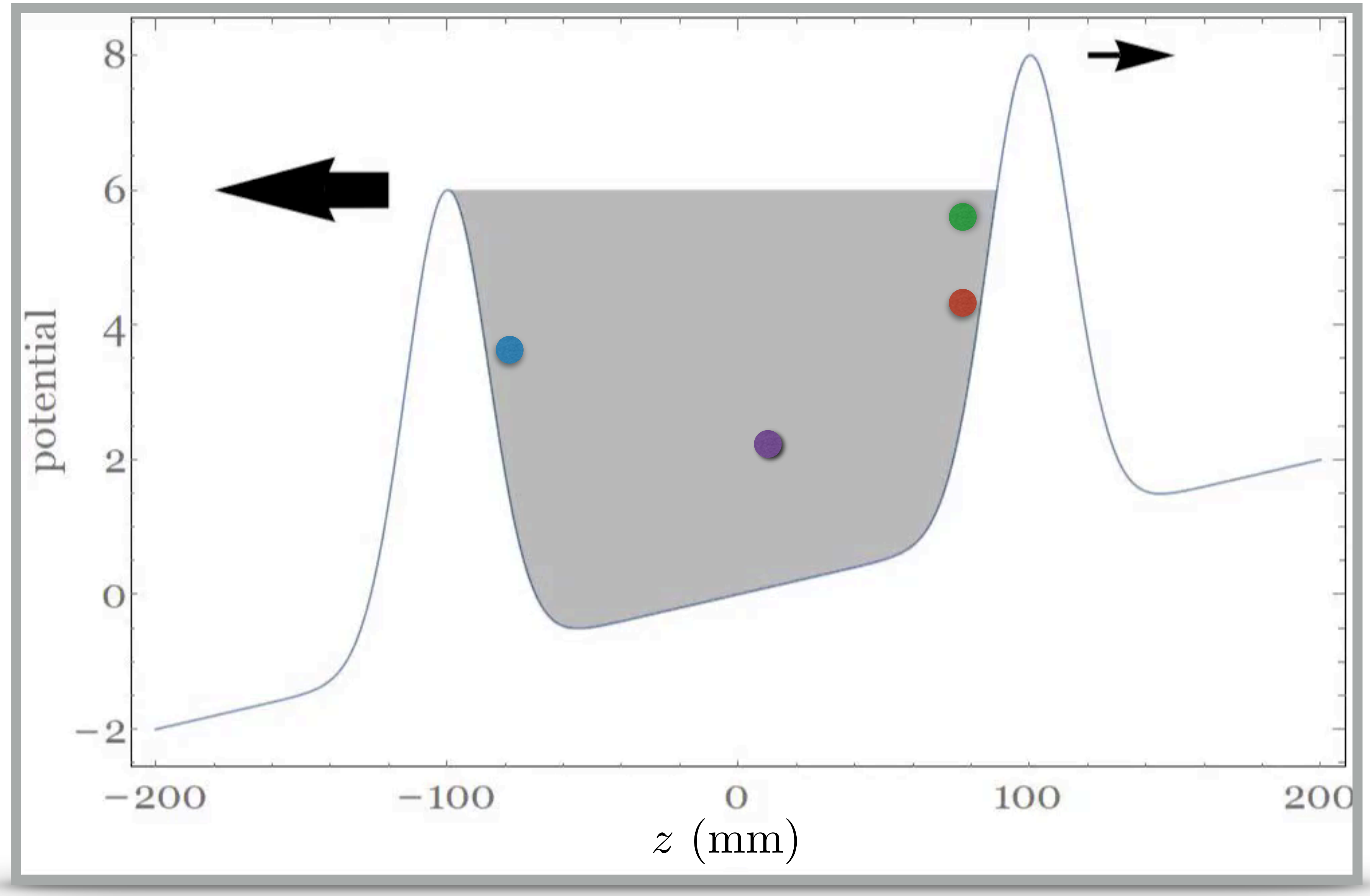


P. Traczyk and M. Brice, CERN https://cernbox.cern.ch/s/3OAsgoCXxXMPTas

A simple Up / Down measurement: Matched fields

Magnetic + Gravitational potential

DOWN

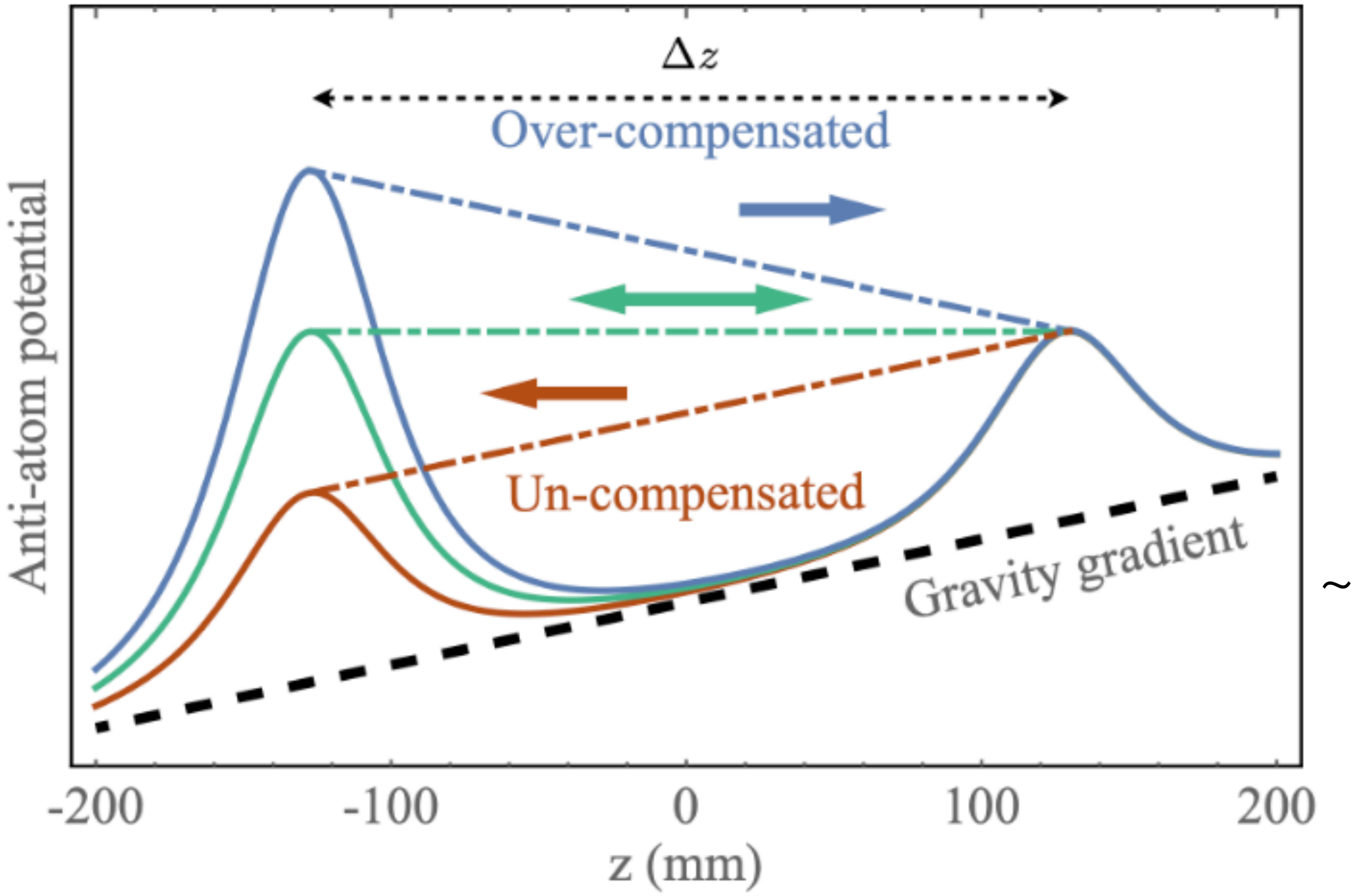


UP

$$U(z) = \mu_H B(z) - mgz$$

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

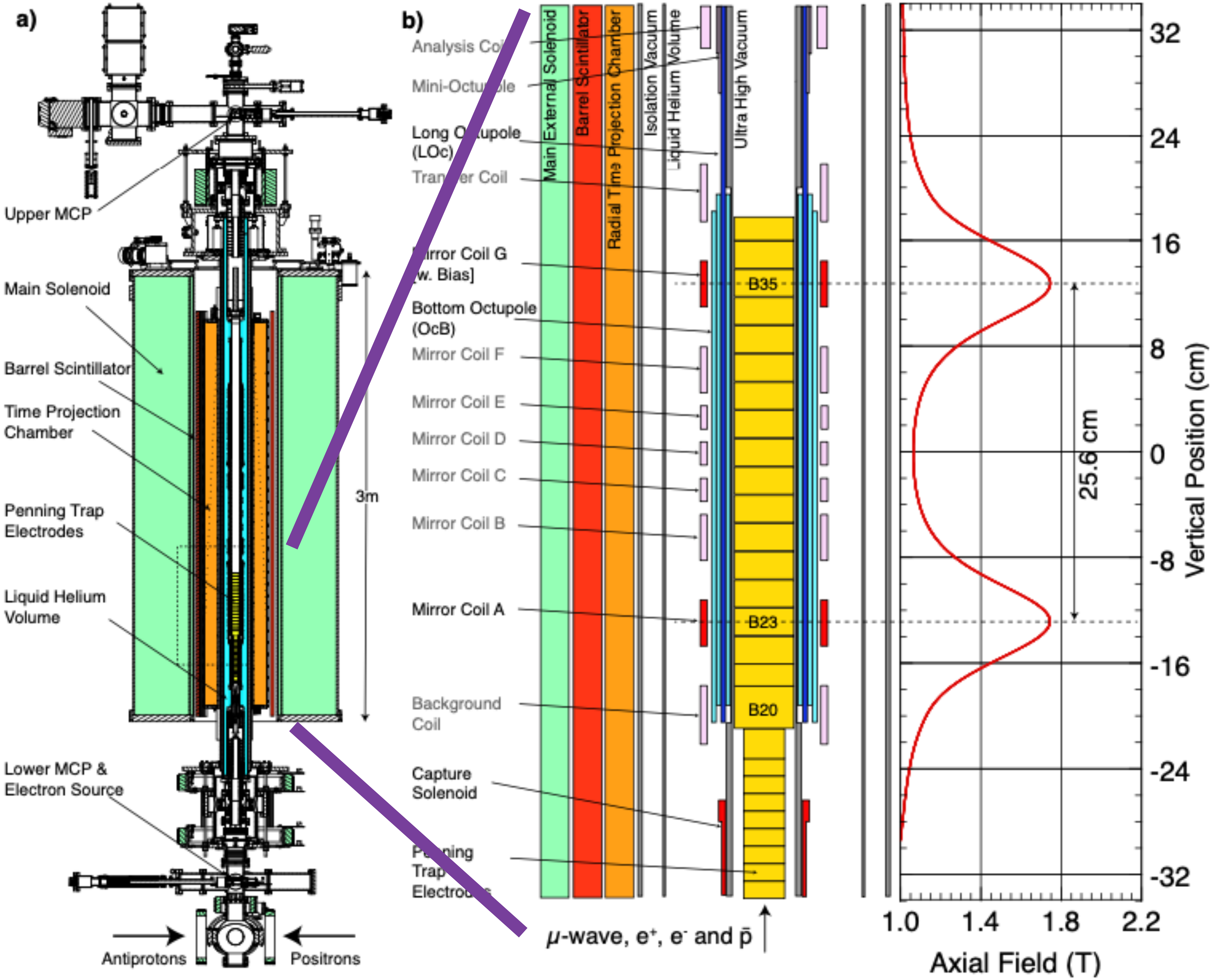
ALPHA-g Measurement Scheme



Up/Down Test:

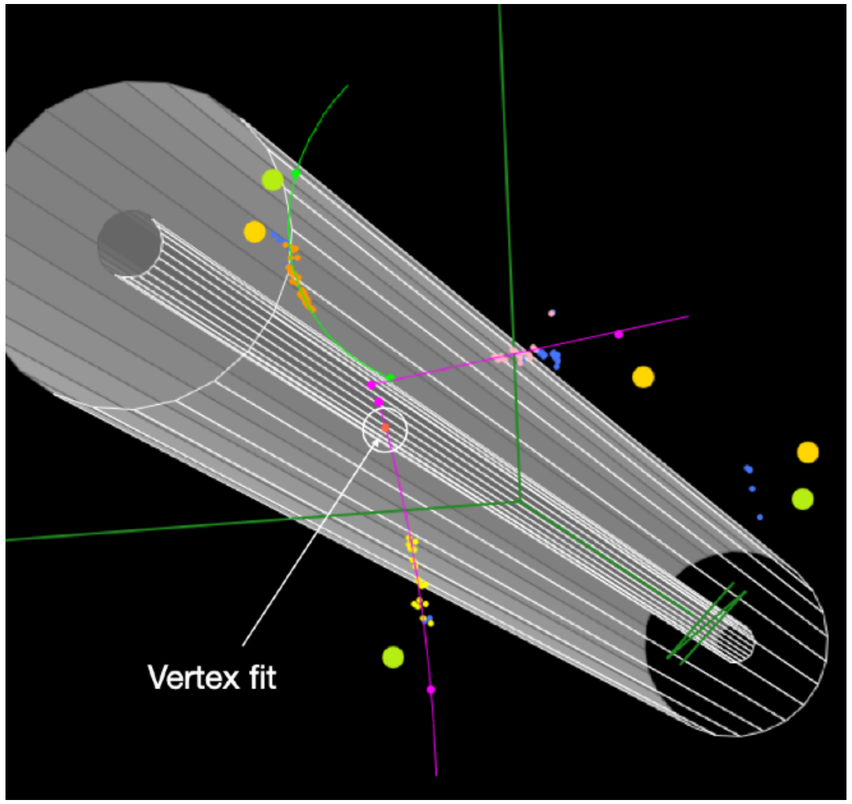
When balanced:

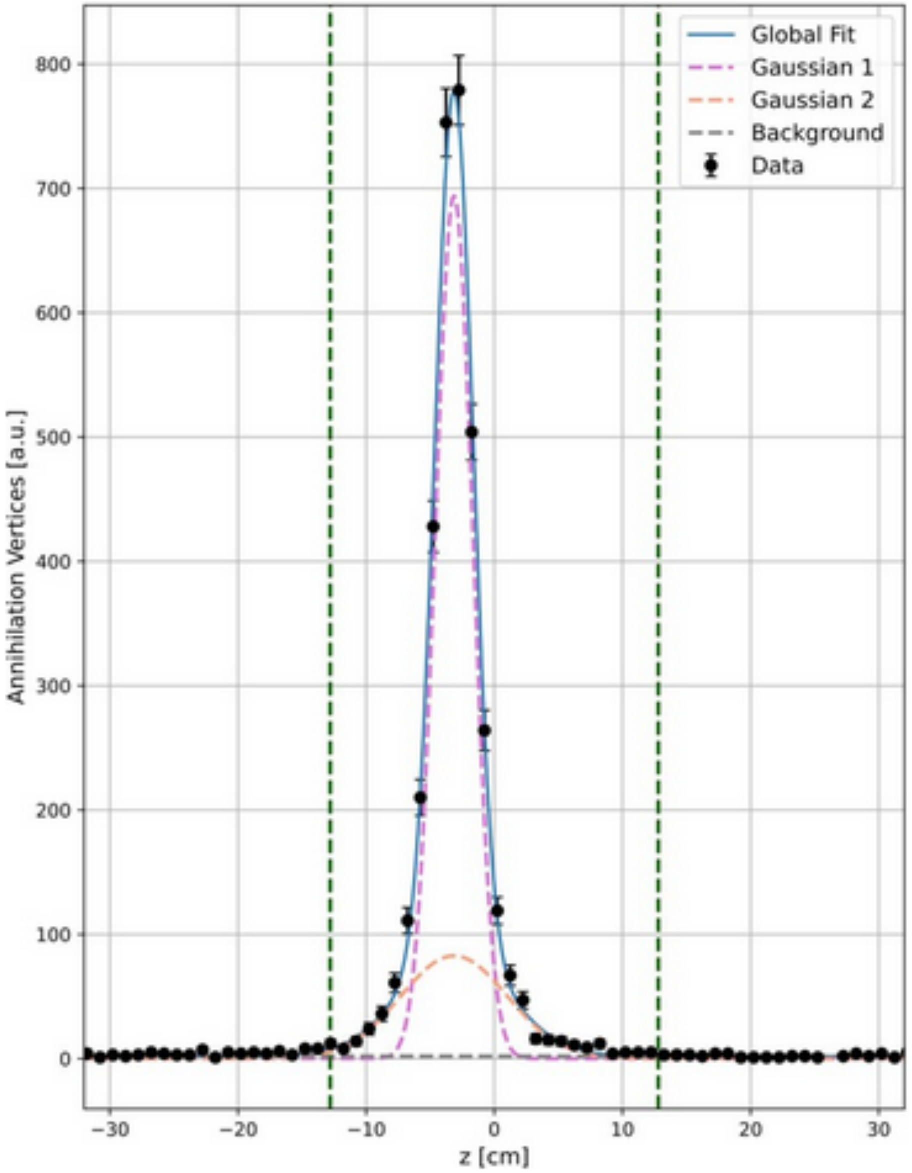
500 mK Hbar,
~20% up, ~80% down

a)
Upper MCP
Main Solenoid
Barrel Scintillator
Time Projection Chamber
Penning Trap Electrodes
Liquid Helium Volume
Lower MCP & Electron Source
3m
Antiprotons
Positrons
b)
Analysis Coil
Mini-Octupole
Long Octupole (LOc)
Transfer Coil
Mirror Coil G [w. Bias]
Bottom Octupole (OcB)
Mirror Coil F
Mirror Coil E
Mirror Coil D
Mirror Coil C
Mirror Coil B
Mirror Coil A
Background Coil
Capture Solenoid
Penning Trap Electrodes
Main External Solenoid
Barrel Scintillator
Radial Time Projection Chamber
Isolation Vacuum
Liquid Helium Volume
Ultra High Vacuum
B35
B23
B20
μ-wave, e^+, e^- and $\bar{p}$
25.6 cm
32
24
16
8
0
-8
-16
-24
-32
Vertical Position (cm)
1.0
1.4
1.8
2.2
Axial Field (T)

Detecting Antihydrogen: ALPHA-g

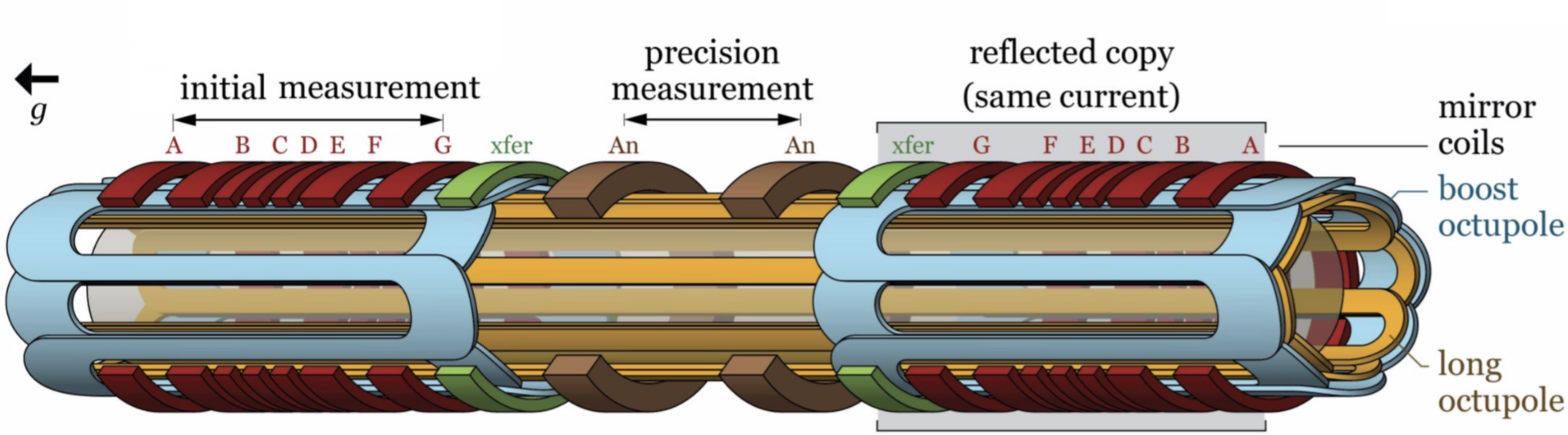
- Radial Time Projection Chamber (rTPC)
- Barrel Scintillator Veto detector
- z-resolution ~ 2 cm (<< 25.6 cm)





ALPHA-g magnets

- Duplicated Bottom and Top traps
  - Strong octupoles for initial trapping
- Precision Analysis Region
- Long octupole running the full length of machine
  - Transfer Hbar between regions



Magnetic Balance

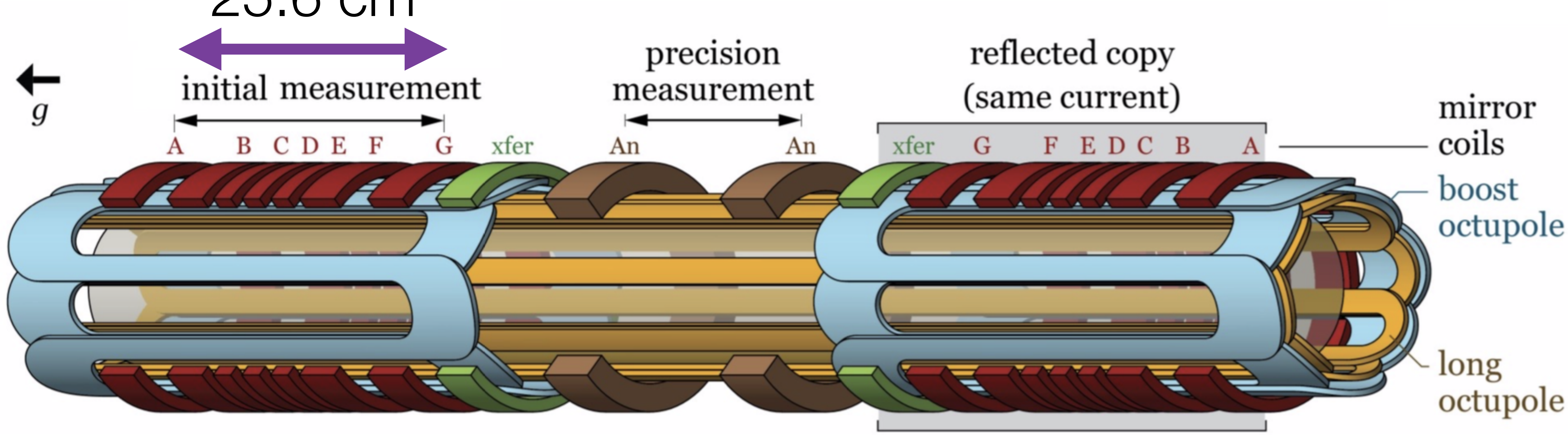
- 1 g balance ‘bias’ ~ **-4.5 Gauss**, Mirrors A-G
- Magnetic bias in units of 9.81 m/s^2

$$\text{bias} = \frac{\mu_B \left(B_G - B_A\right)}{m_H \left(z_G - z_A\right)}$$

$$\Delta B_{1g} \sim 4.5\,\text{Gauss}$$

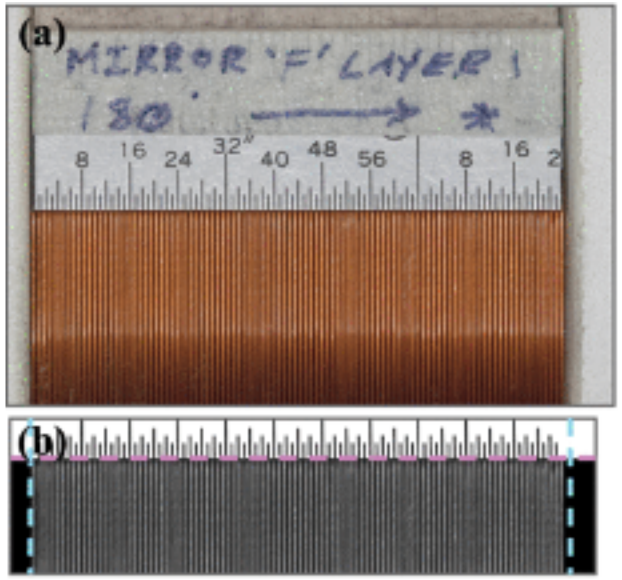
$$\Delta U_g \sim 300\,\mu\text{K}$$

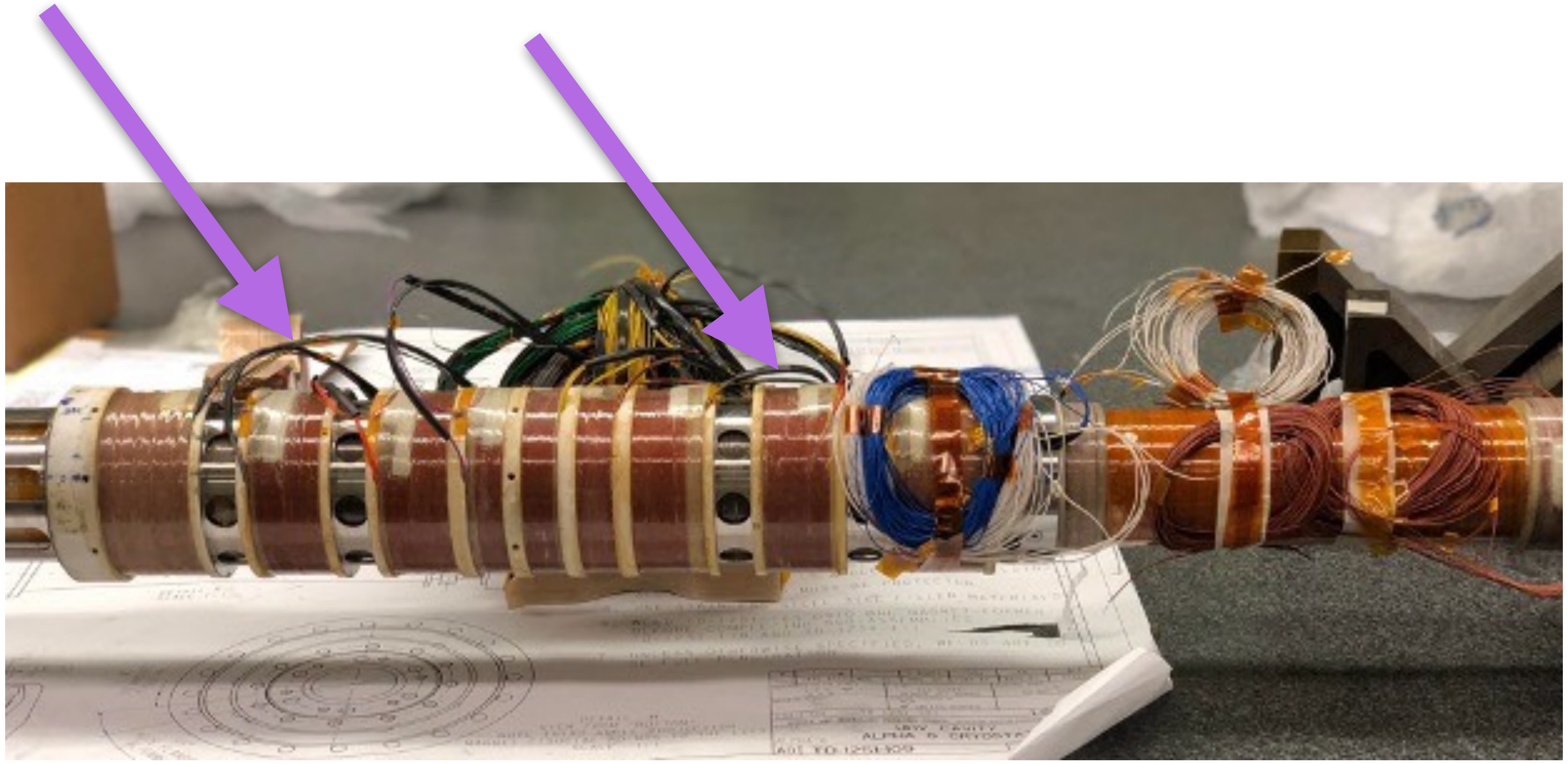
25.6 cm



Magnet Construction

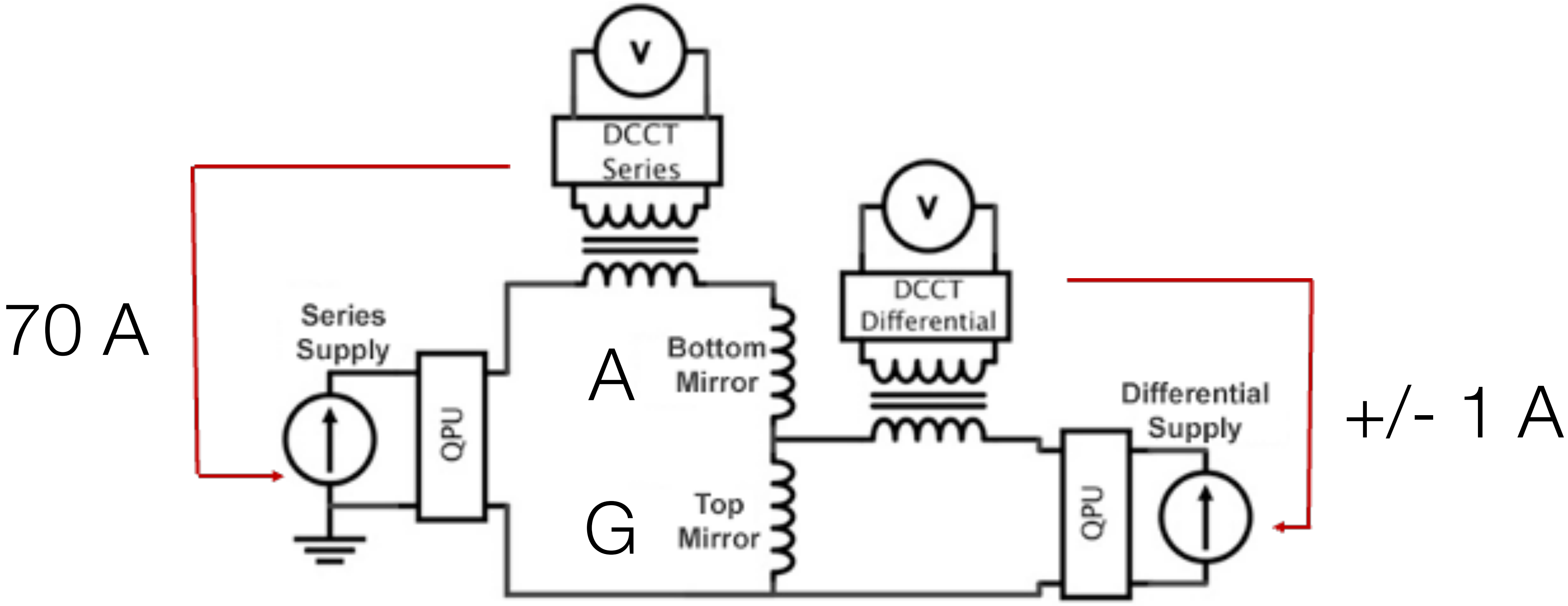
- Goal is to make Bottom and Top identical at 0.01%
- Monitor construction on each layer - feedback to next
- Measure field differences, correct with current





Magnetic Field Control

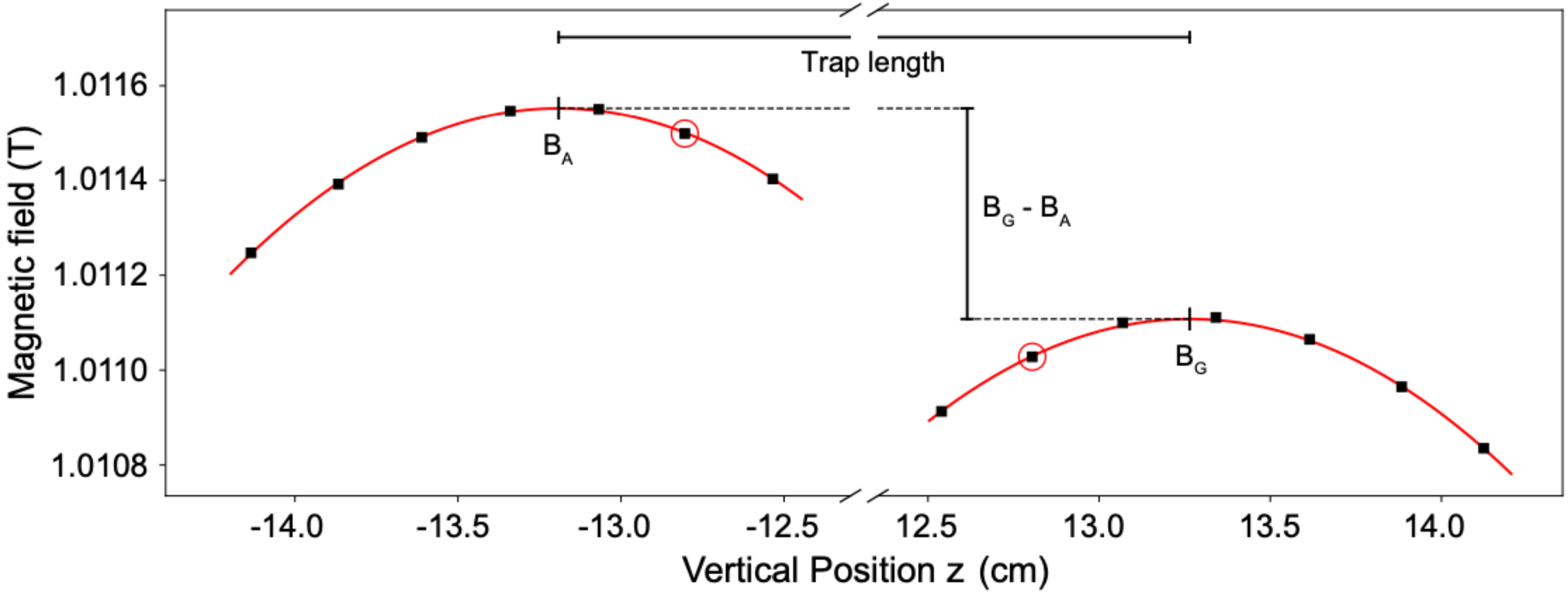
- Need continuous sub-mA control of currents
- Full mirror fields ~ 70 A in series
- Importance is *difference* current
- Bias + correction maintained by parallel “Tickle” supply



Magnetic Balance

- 1 g balance bias ~ -4.5 Gauss
- Nominal bias from field map

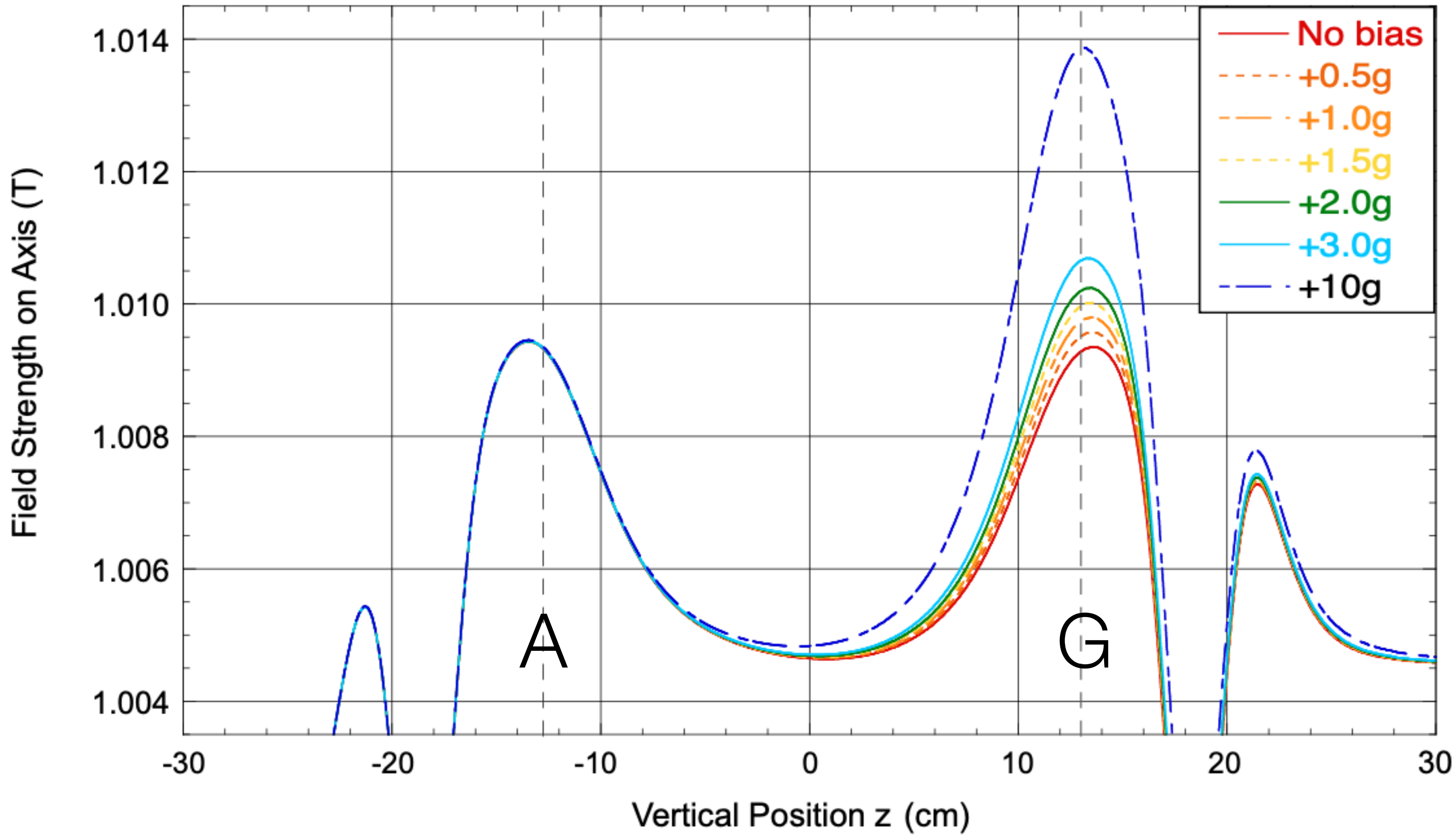
$$\text{bias} = \frac{\mu_B \left(B_G - B_A\right)}{m_H \left(z_G - z_A\right)}$$



Magnetic Balance

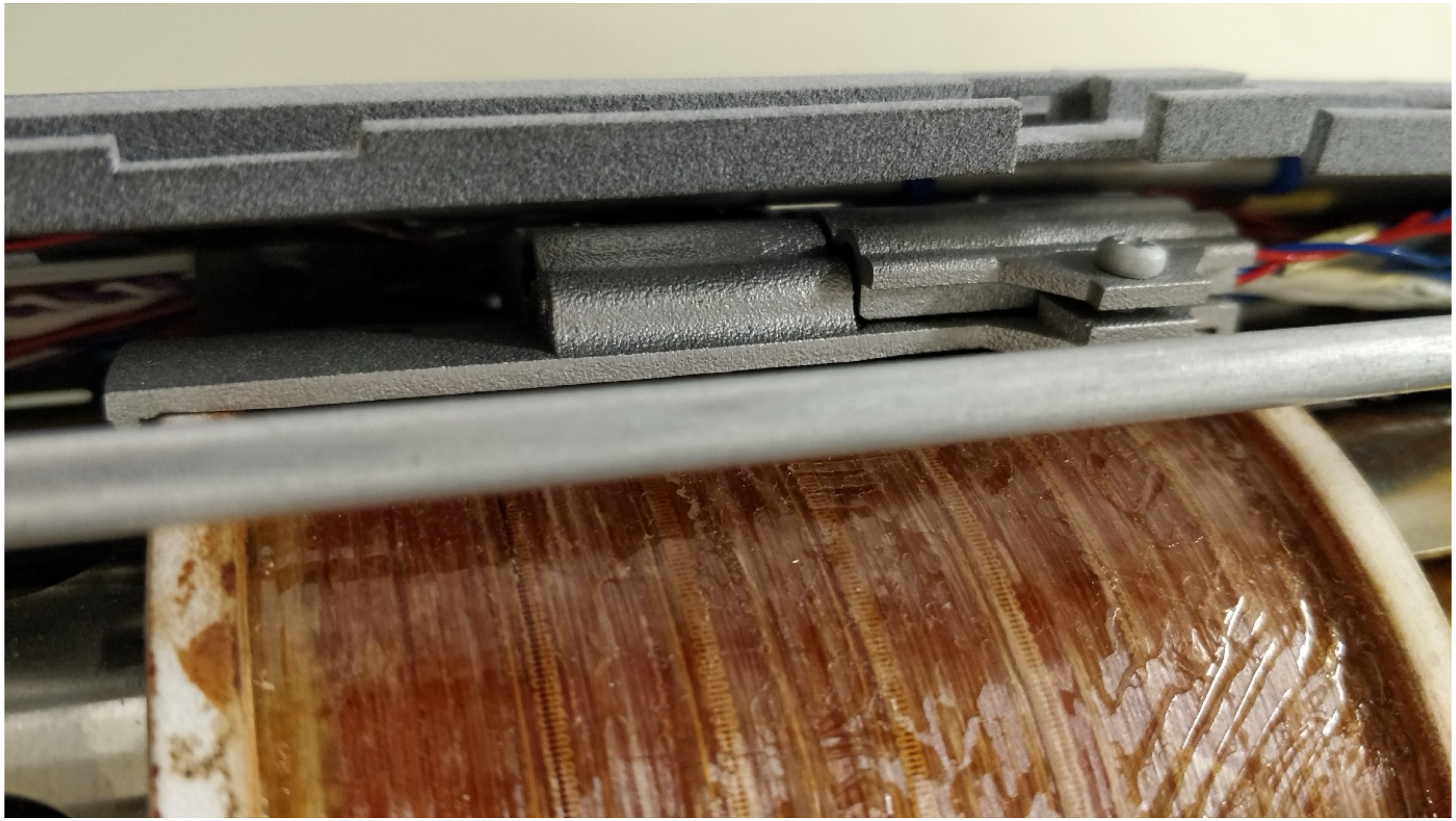
- 1 g balance bias ~ -4.5 gauss

$$\text{bias} = \frac{\mu_B \left(B_G - B_A\right)}{m_H \left(z_G - z_A\right)}$$



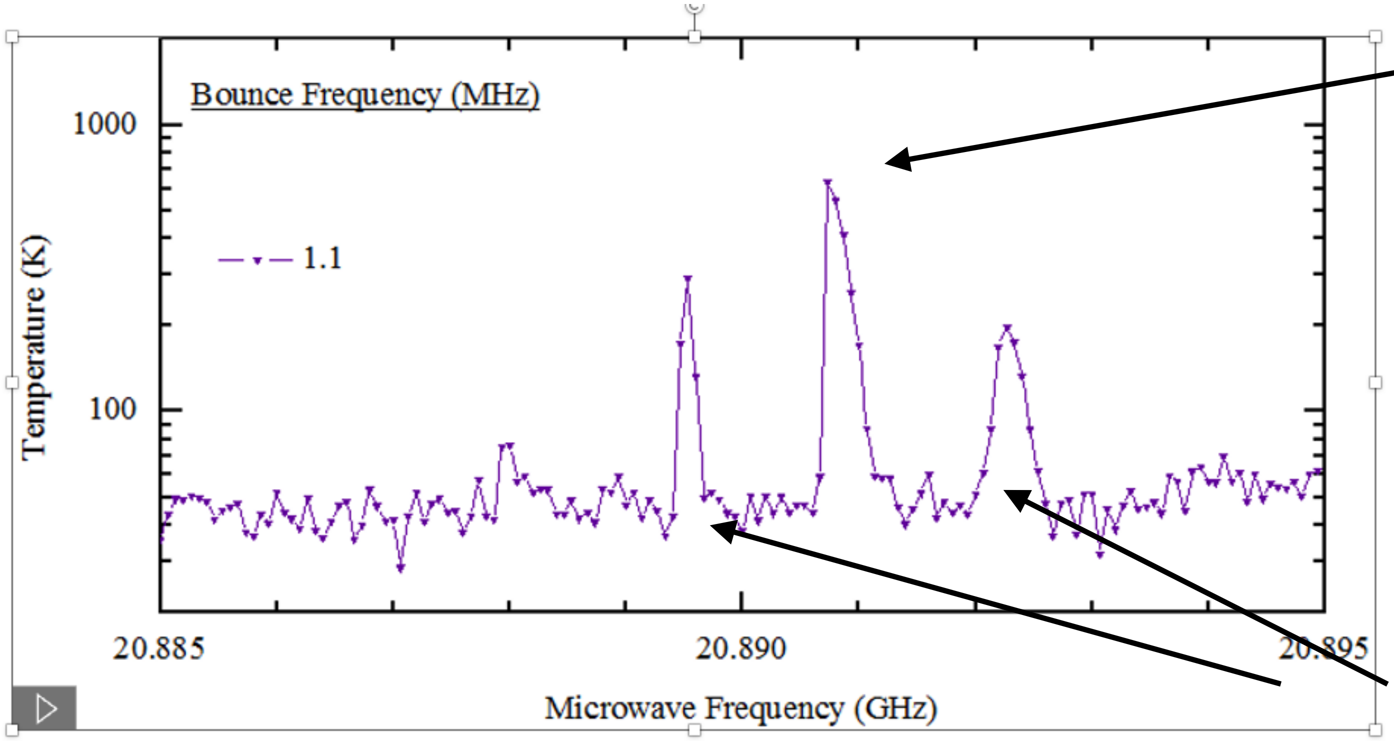
Magnetic Field Measurements: Probes

- Aluminum NMR probe + Hall Probe + temperature
- Insufficient to infer *in situ* fields around the atoms

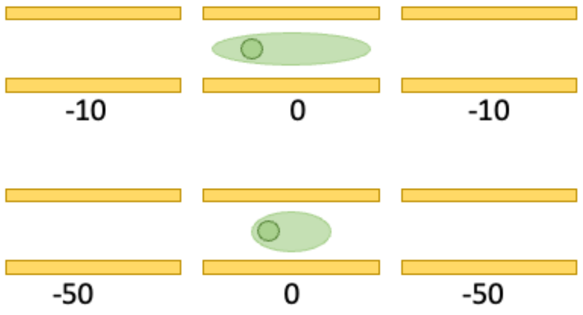


Magnetic Field Measurements: ECR

- Localize a plasma in the penning trap
- Illuminate with microwaves:
- Electron Cyclotron Resonance: Heats plasma: Spectra
- Accuracy: down to ~ 1 ppm



Main ECR resonance

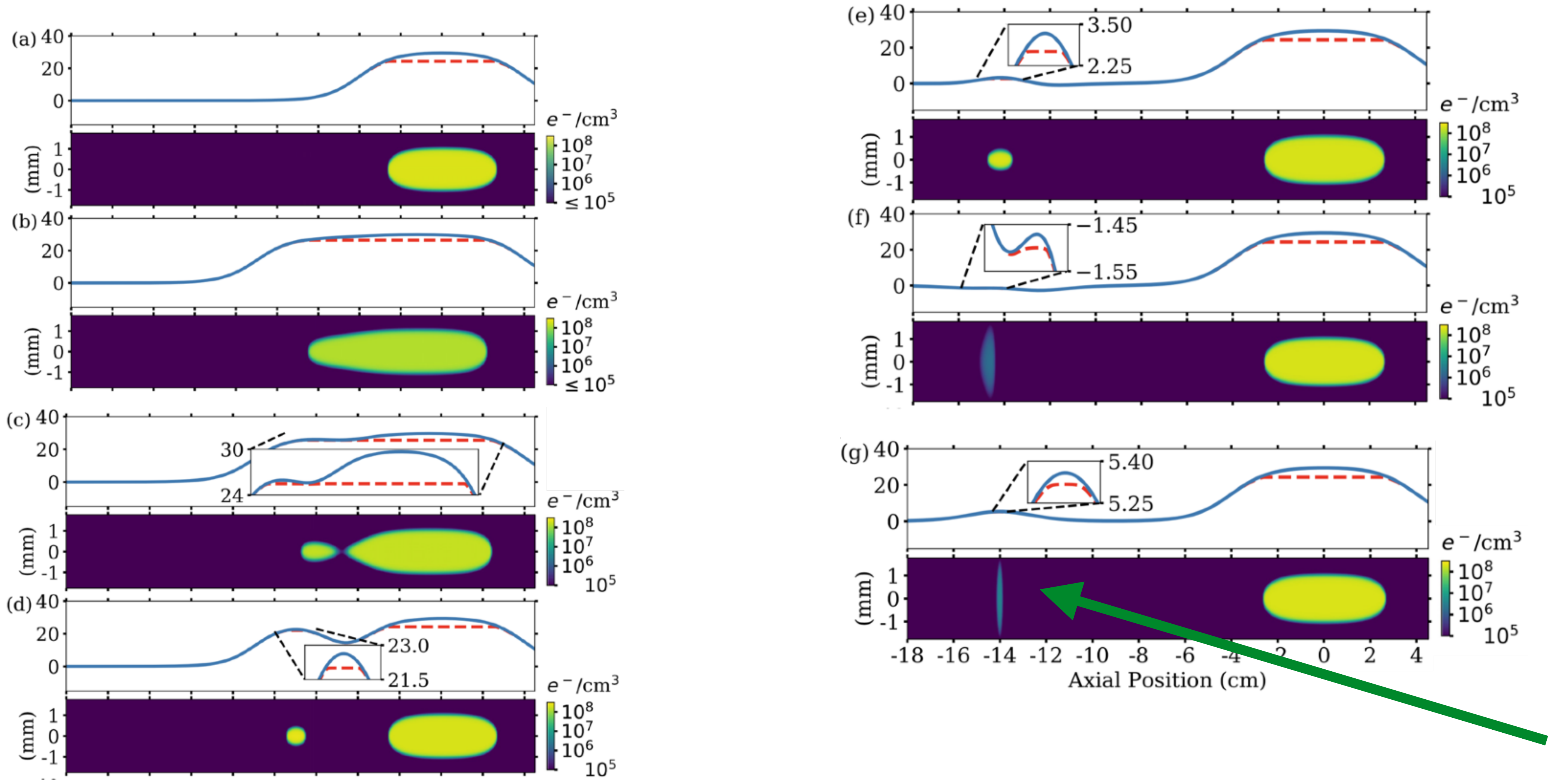


Bounce Resonances

ALPHA, In situ electromagnetic field diagnostics with an electron plasma in a Penning–Malmberg trap, New J. of Physics, 16, (2014).
E.D. Hunter, A. Christensen, J. Fajans, T. Friesen, E. Kur, and J.S. Wurtele, Electron cyclotron resonance (ECR) magnetometry with a plasma reservoir, Phys. Plasmas 27, 032106 (2020).

Magnetic Field Measurements: ECR

- Localize plasma ‘scoops’ for ECR: ~ 1 mm resolution
- Map field in time / location
  - Relatively slow (many scoops)



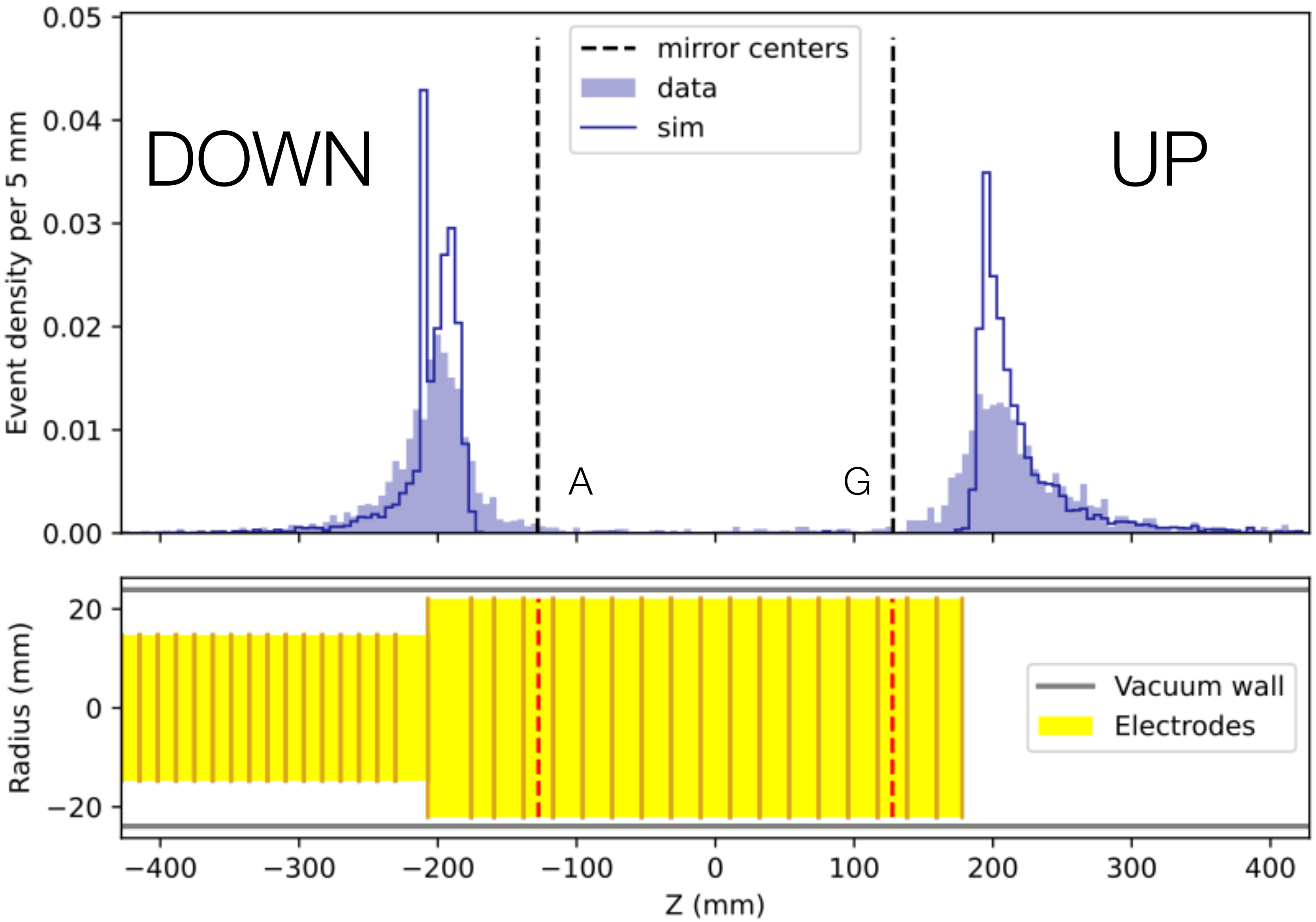
Microwave
Illumination
Here

Gravity Experiment

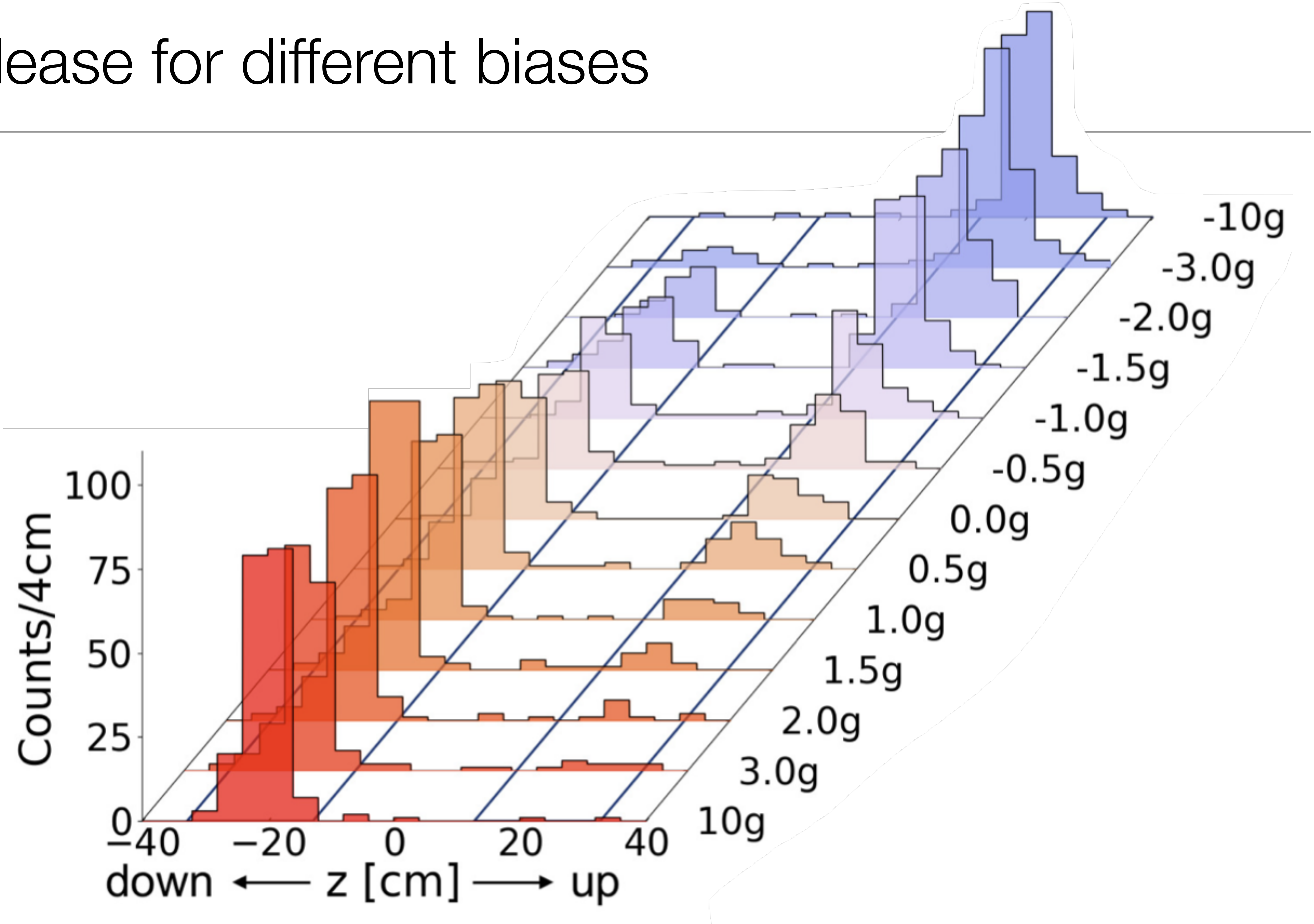
- Make, trap and stack antihydrogen (~ 50 stacks)
  … while recording annihilation events along the way …
- Ramp down long octupole
- Measure magnetic field at full trapping current + bias
  - Under Mirrors A and G
- Ramp down to ~ 10’s Gauss residual trap
  - Maintain constant magnetic bias (current control)
- Measure magnetic field again
- Repeat for many magnetic biases
  - Statistics collected for ~ 300 Hbar per bias

Annihilation events

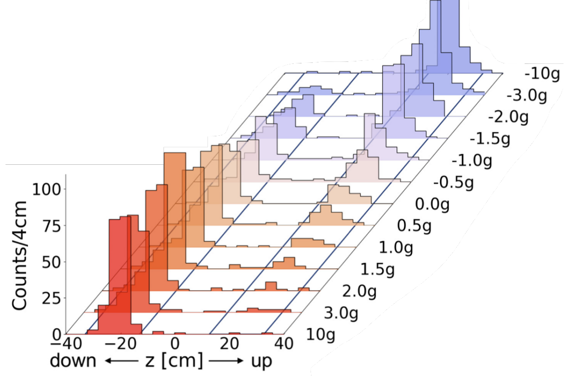
- Escaping antihydrogen leave going Up or Down
  - relative efficiencies from penning trap, detector details

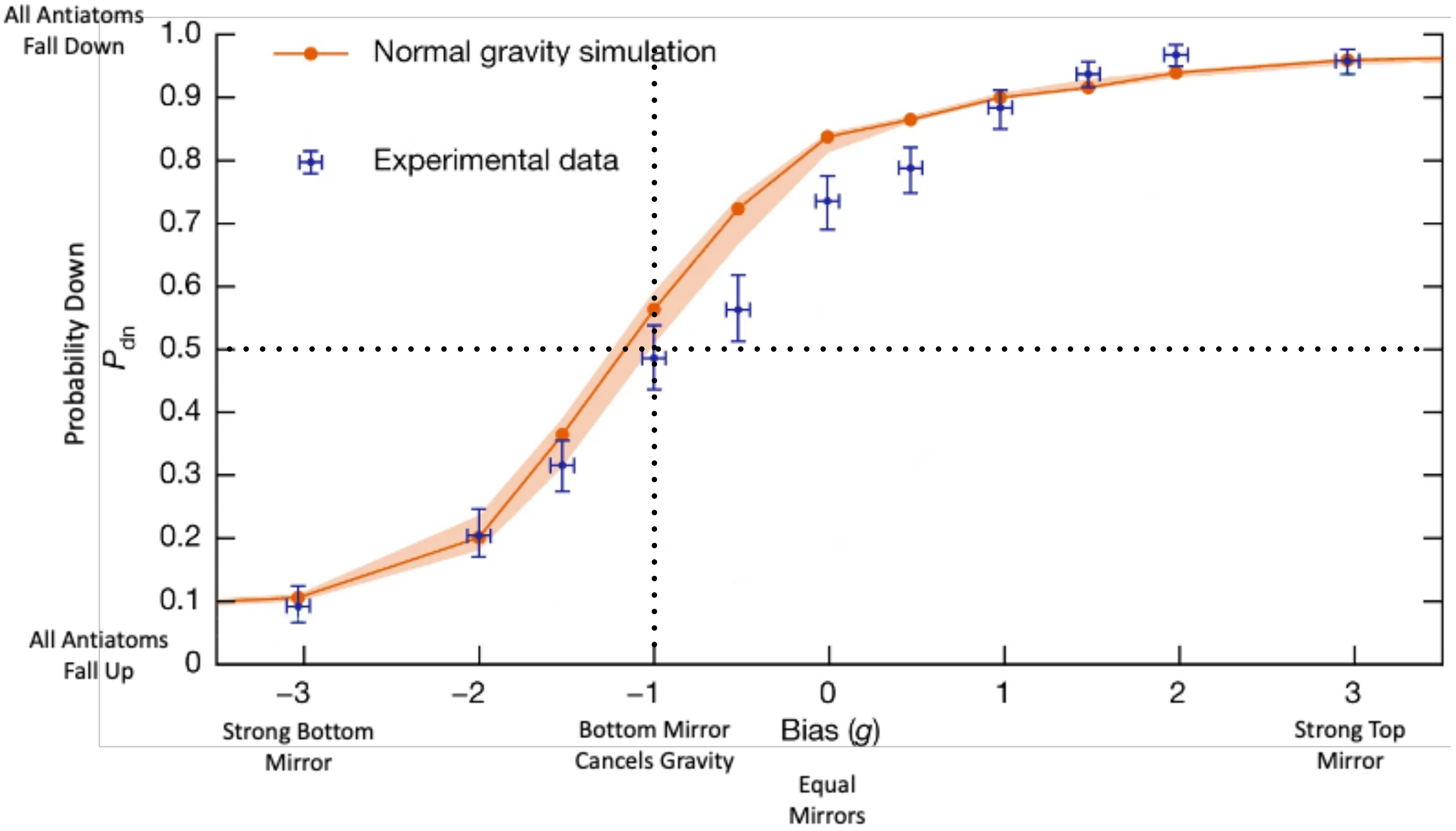


Release for different biases

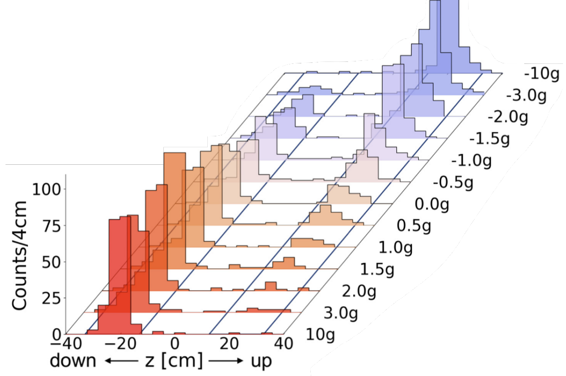


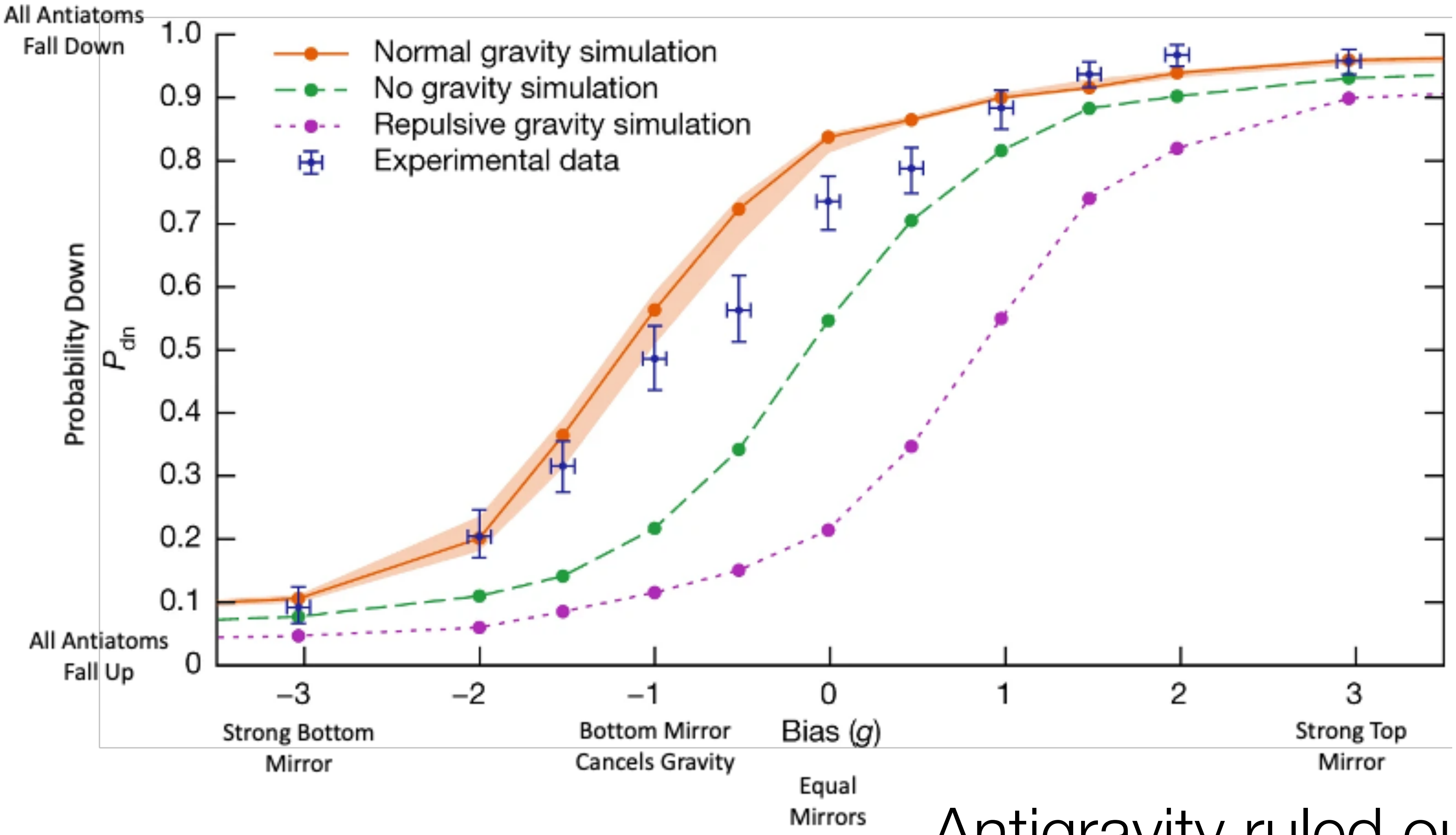
Release for different Biases



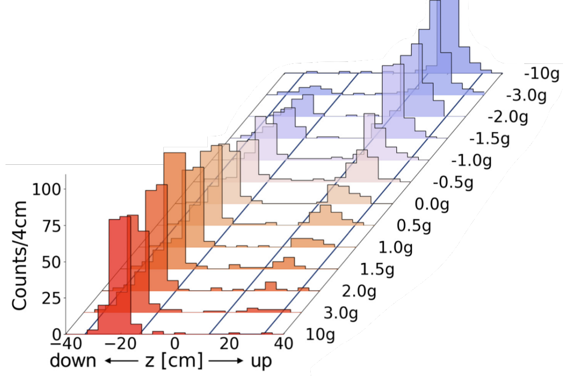


Release for different Biases





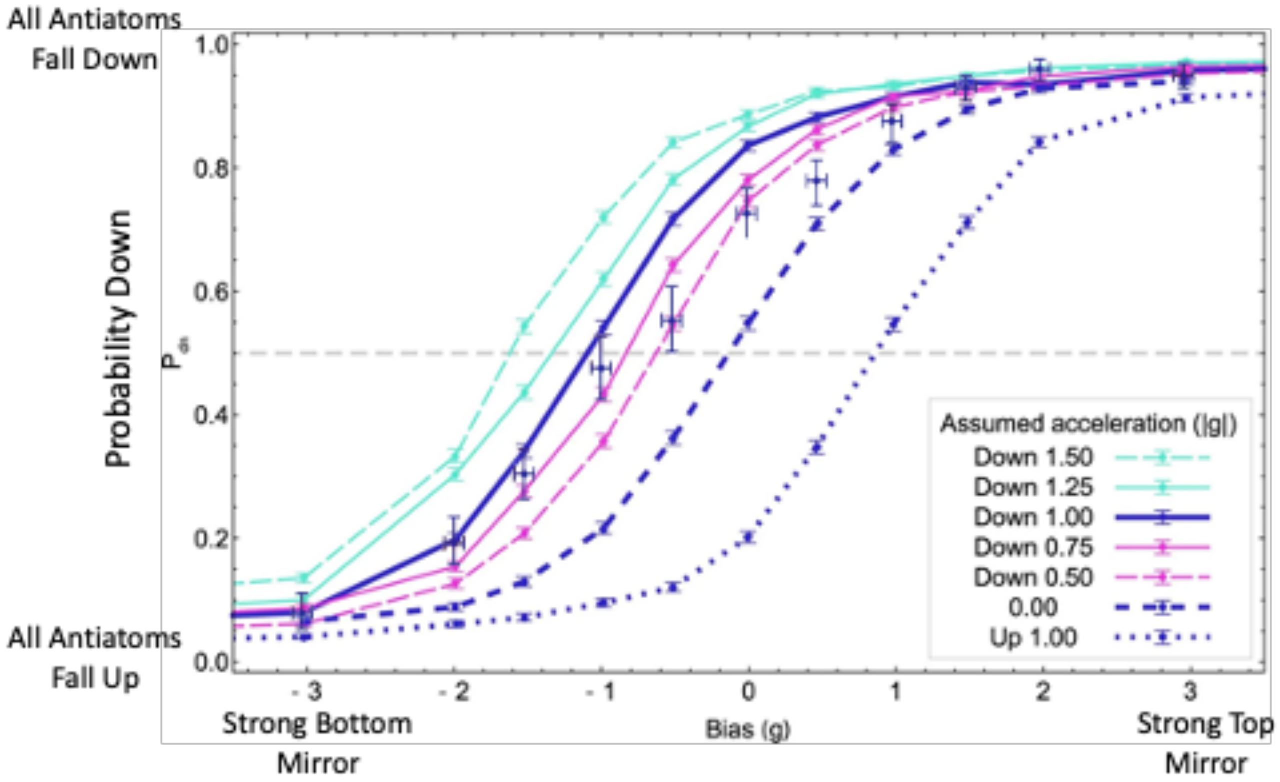
Antigravity ruled out!



Calculating Antimatter g

- Execute numerous simulated accelerations
- Find best fit to data

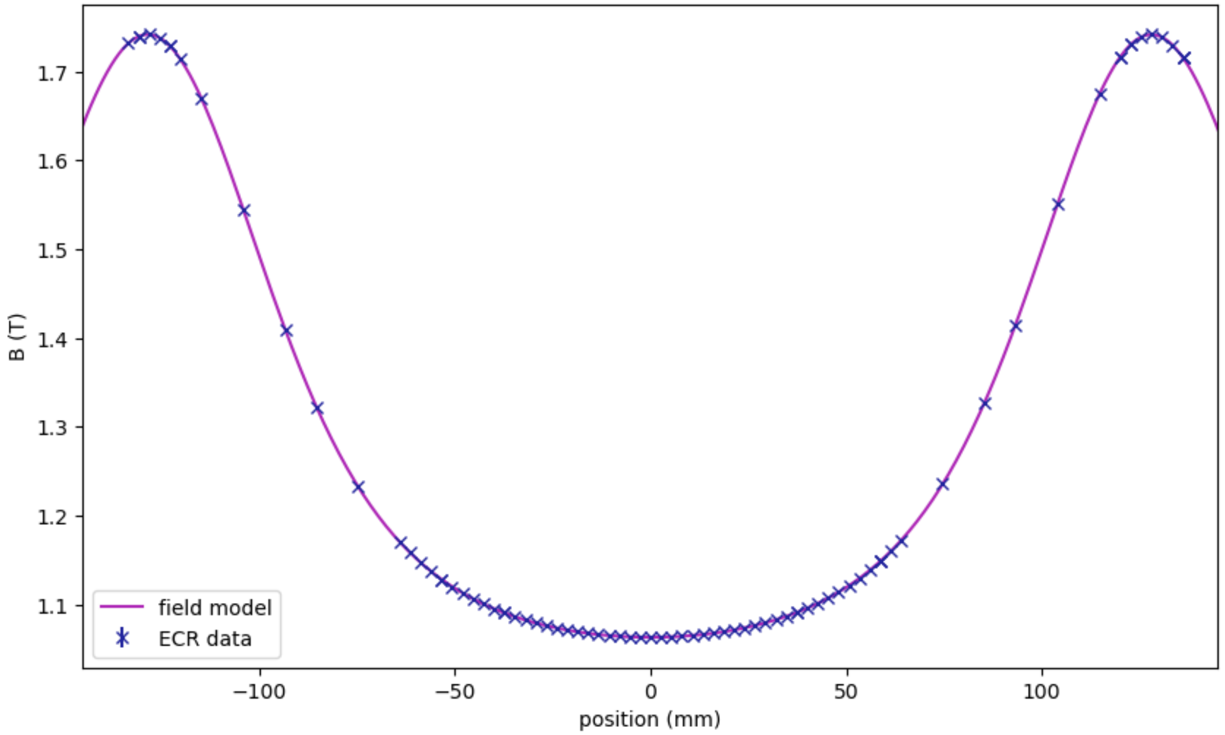
$$\bar{g} = [0.75 \pm 0.13\ (\text{statistical} + \text{systematic})\ \pm 0.16\ (\text{simulation})]\, g$$



Limits to the measurement: field measurements

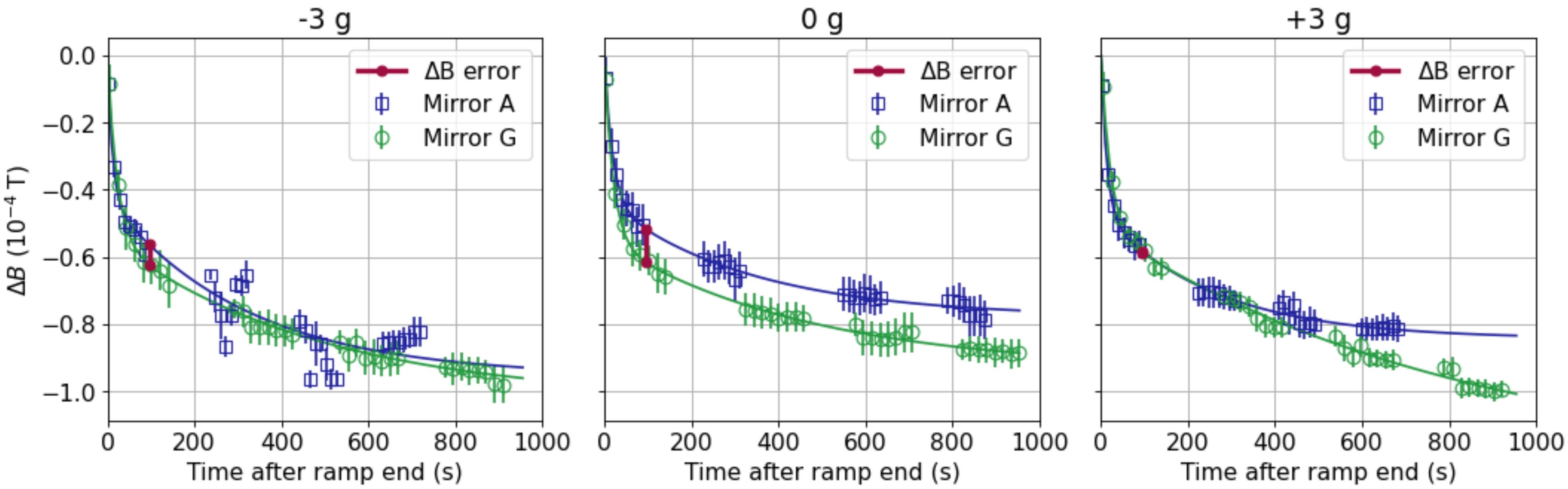
- Need to model both controlled currents, and uncontrolled persistent currents.

- Induced persistent currents responsible for a field of ~ 10 Gauss on axis



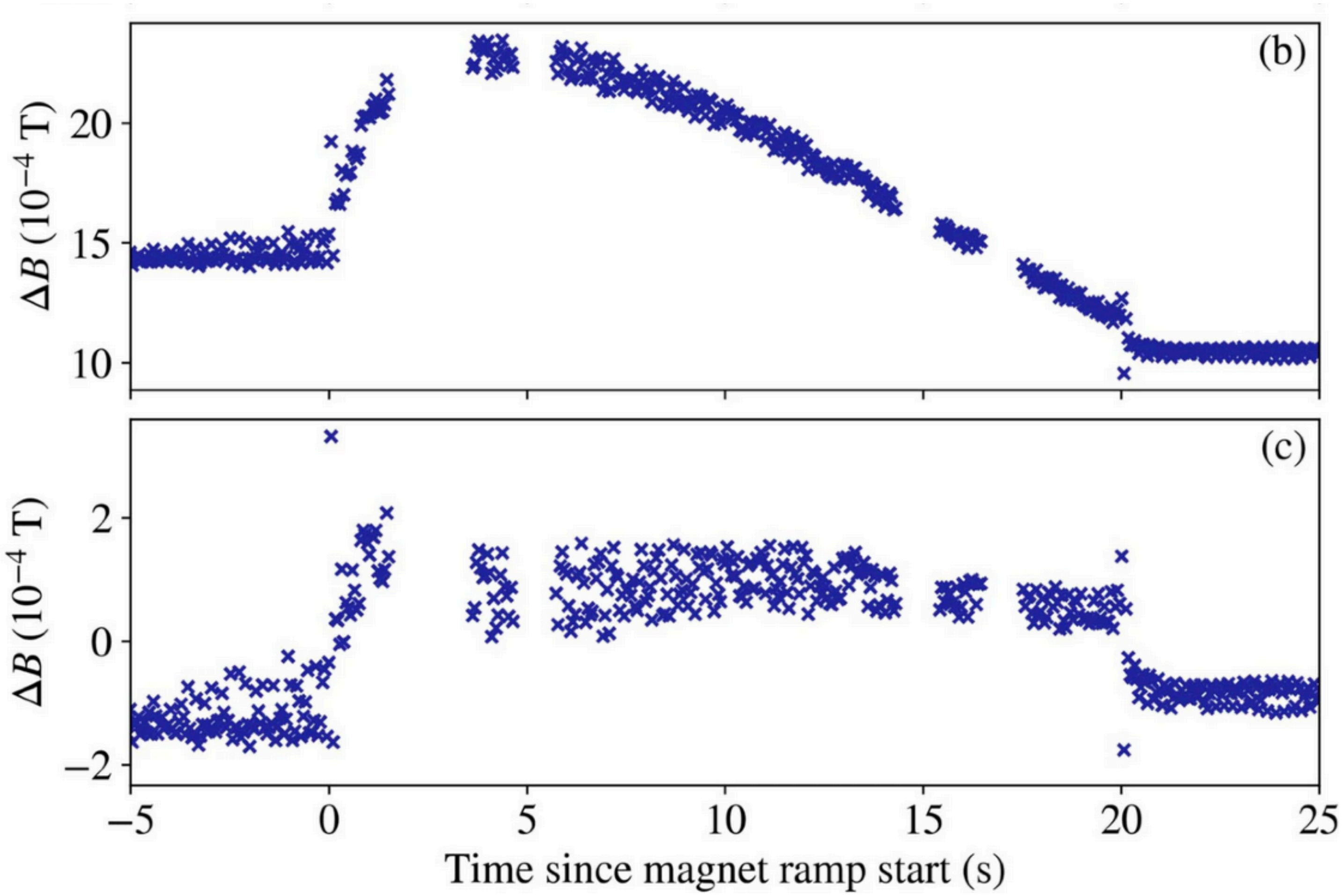
Limits to the measurement: field measurements

- Persistent currents contribute significantly to the field
- These currents decay in time (ECR)
- No significant difference in the decay of Mirrors A, G
  - Largest observed difference used to be conservative



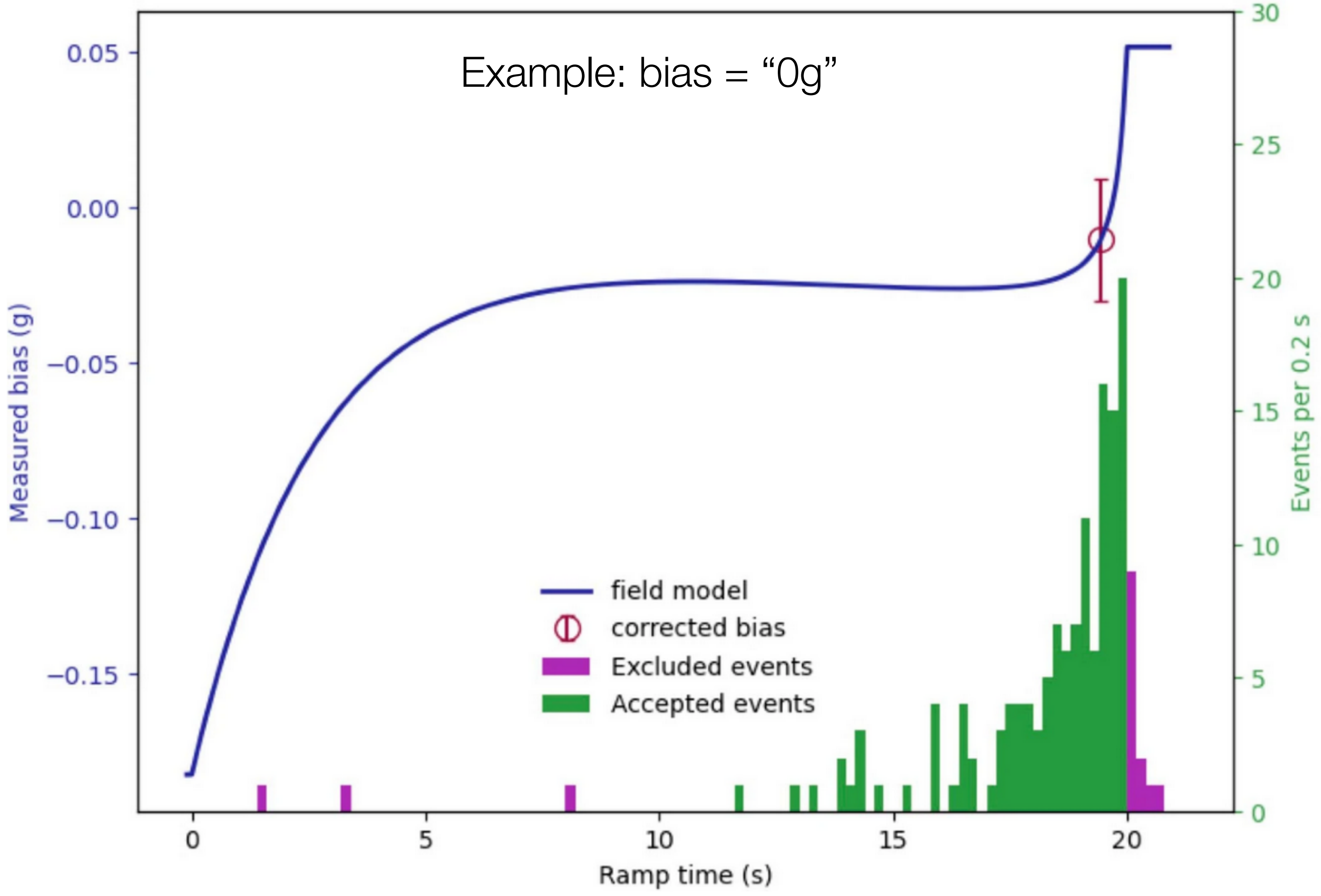
Limits to the measurement: field measurements

- Persistence currents are time-dependent during ramp
- Imaged Electron Magnetron Frequency: time-resolved B-field during a given release



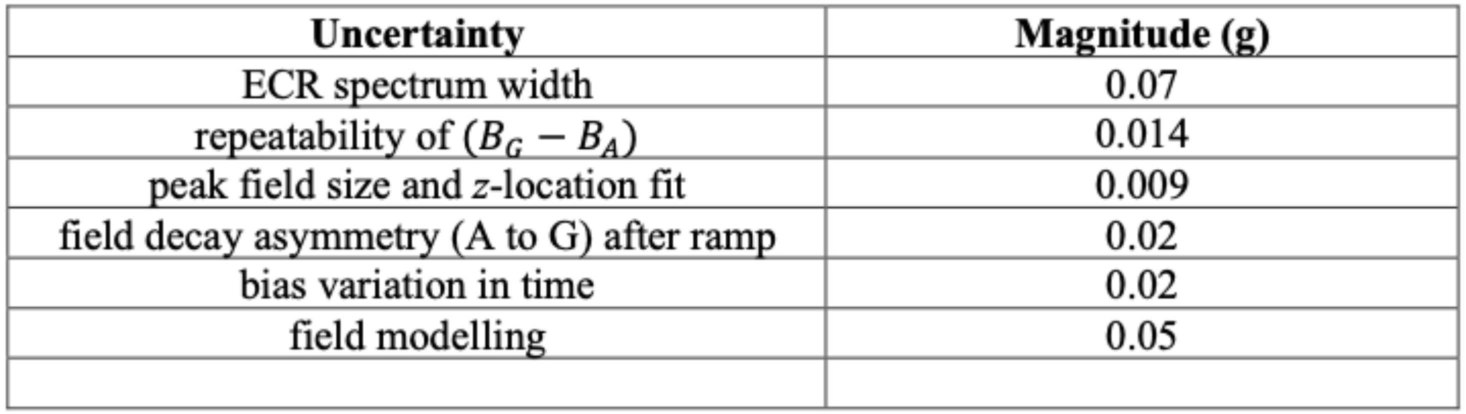
Limits to the measurement: Bias time dependence

- Experiment bias: linear *current difference*
- Geometry of magnets + persistence effects results in a time-dependent bias
- Field for simulation
- Weighted mean: *bias label*

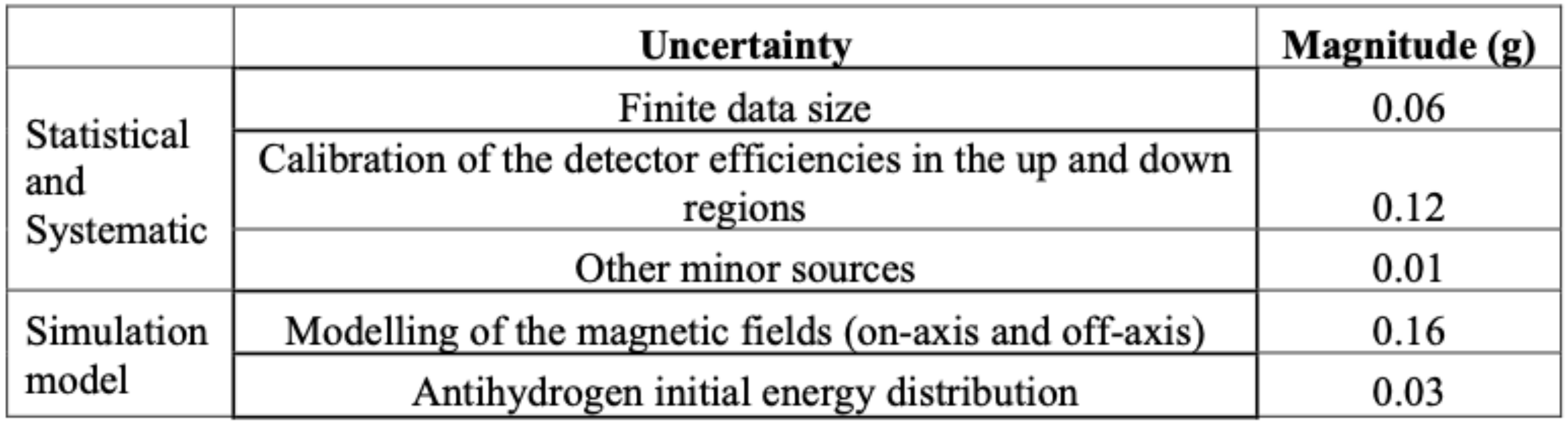


Uncertainty tables

- Many aspects contribute to error.
- Largest (0.16 g) is uncertainty from estimated off-axis asymmetry in the octupole field (unmeasured)



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

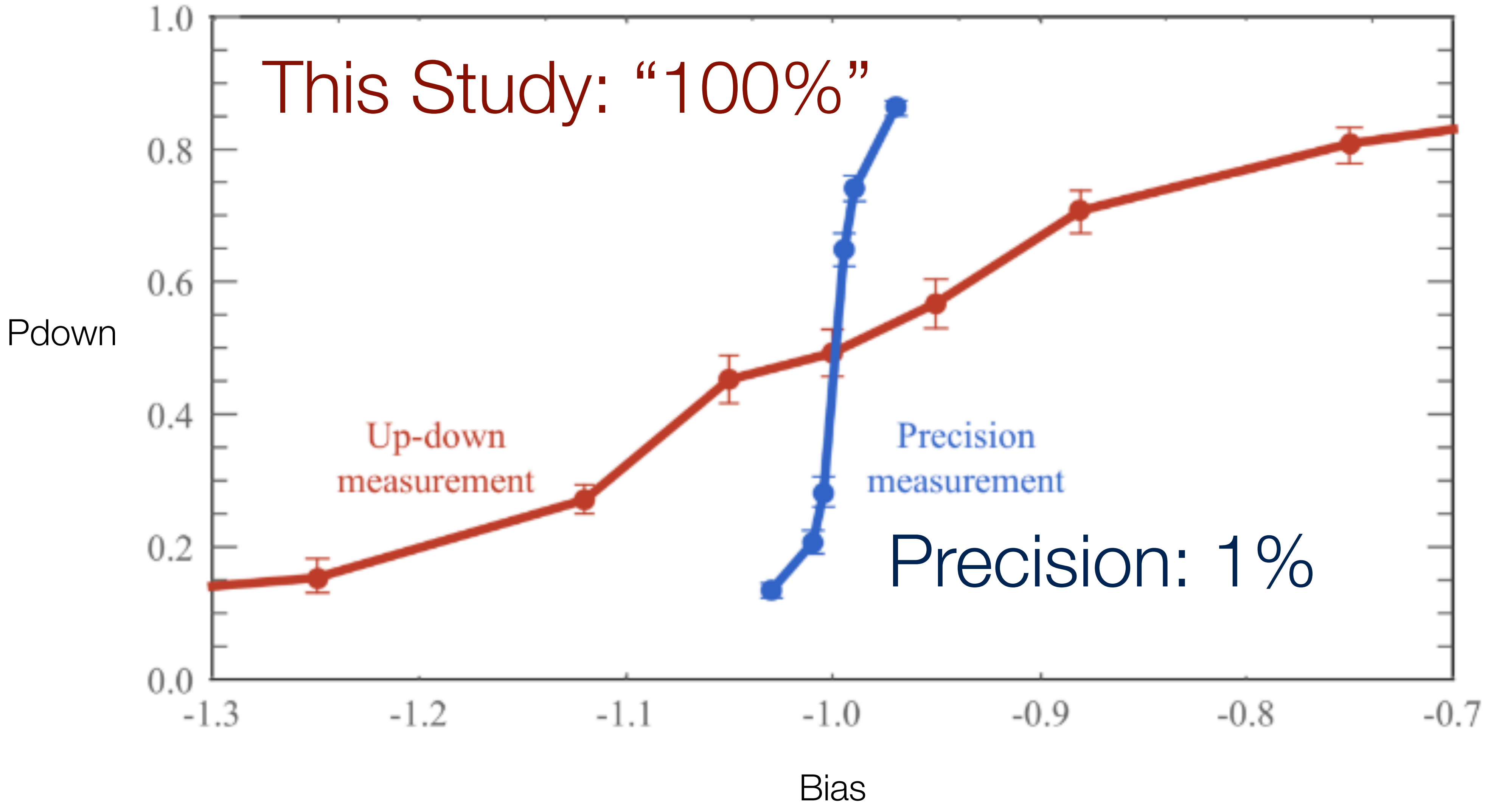


	Uncertainty	**Magnitude (g)**
Statistical and Systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03

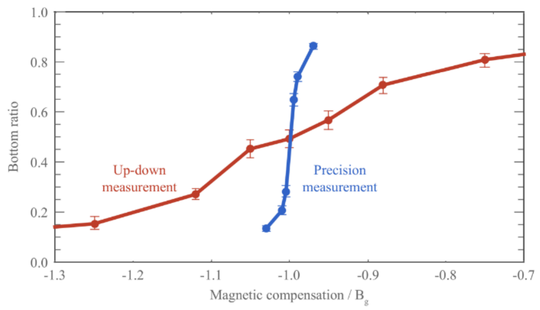
Future prospects with ALPHA-g:
1% Measurements

- Make the release curve steeper

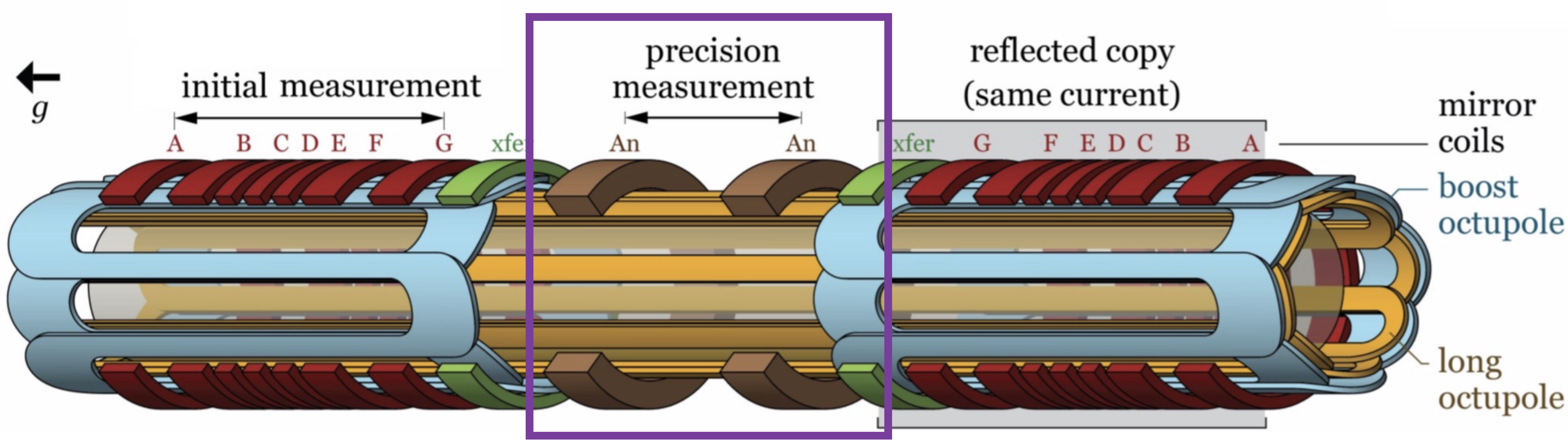
Simulated Release Experiments



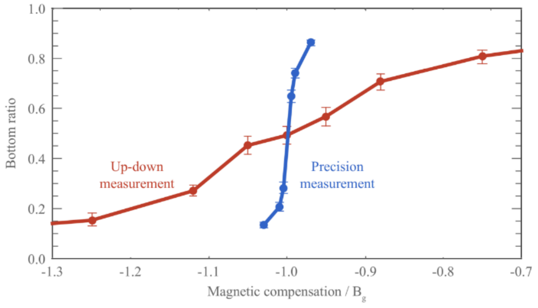
Future prospects with ALPHA-g: 1% Measurements



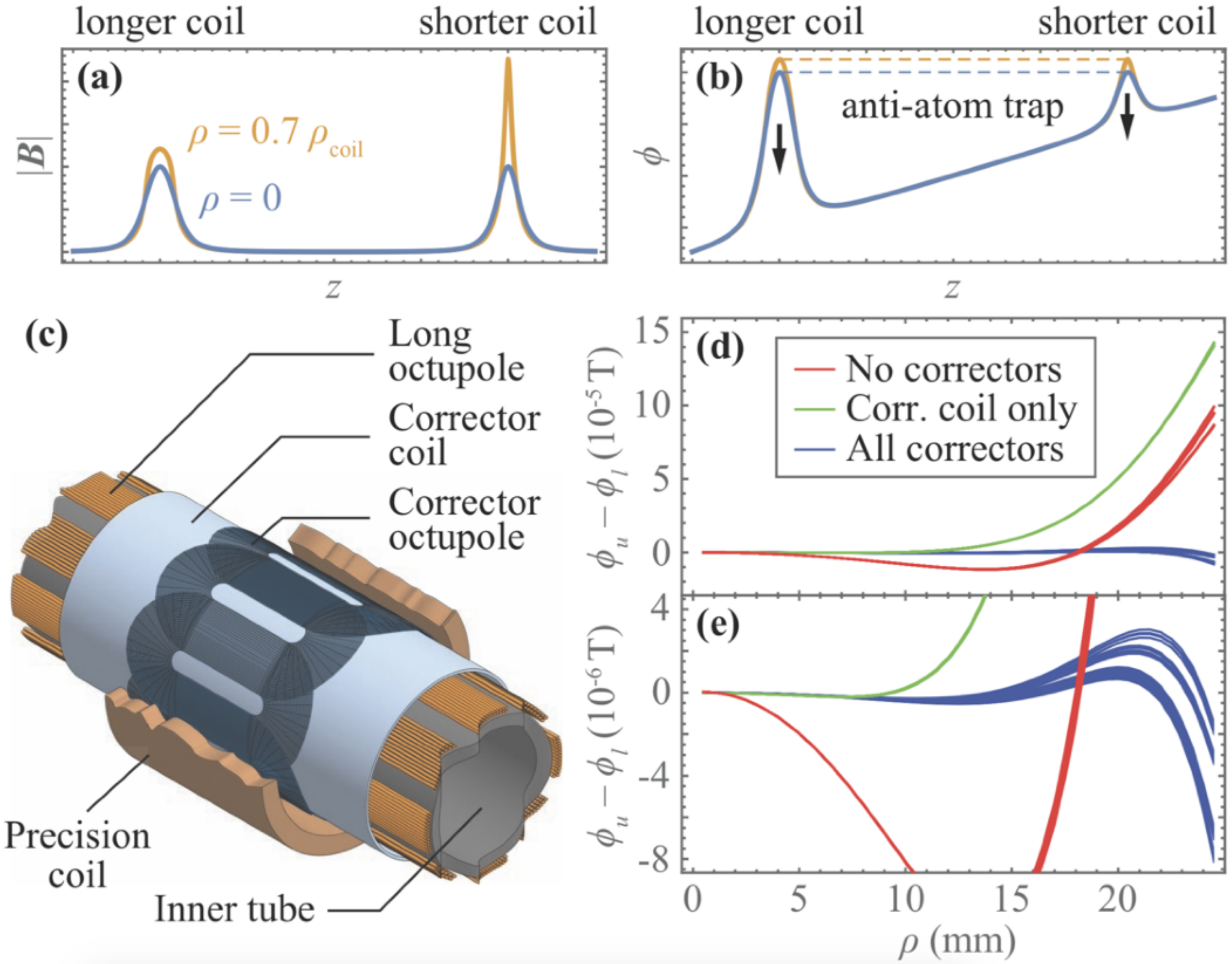
- Precision region
  - symmeterizes superconducting material
  - + detection geometry
  - Improves shape of applied bias potential



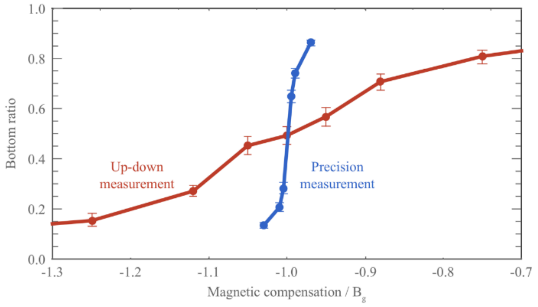
Future prospects with ALPHA-g: 1% Measurements



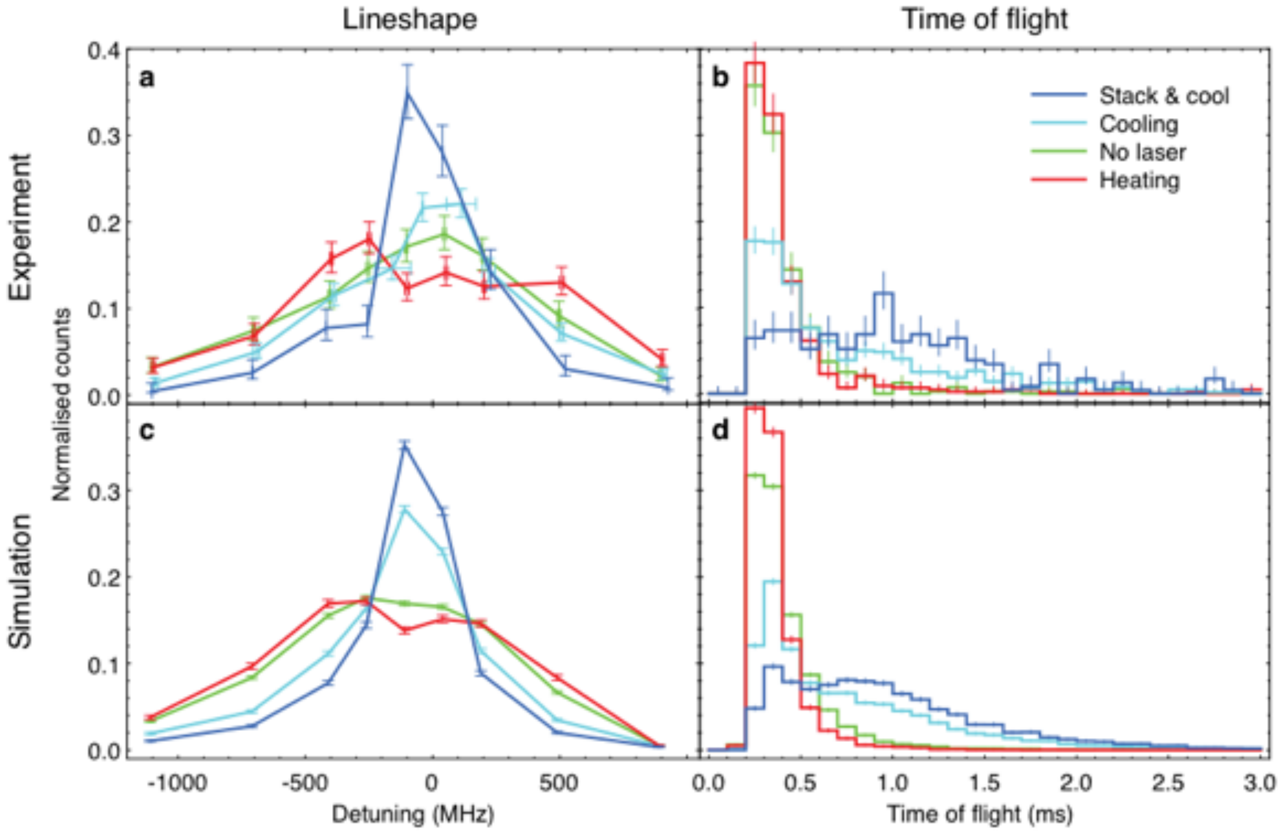
- Generally, escape bias is a function of radius
  - Broadens and shifts release curve
- Additional correction coils to "flatten" escape bias



Future prospects with ALPHA-g: 1% Measurements



- Improve distribution: Doppler Laser Cooling
- Slower atoms more sensitive to potential
- 500 mK > 50 mK > 300 uK



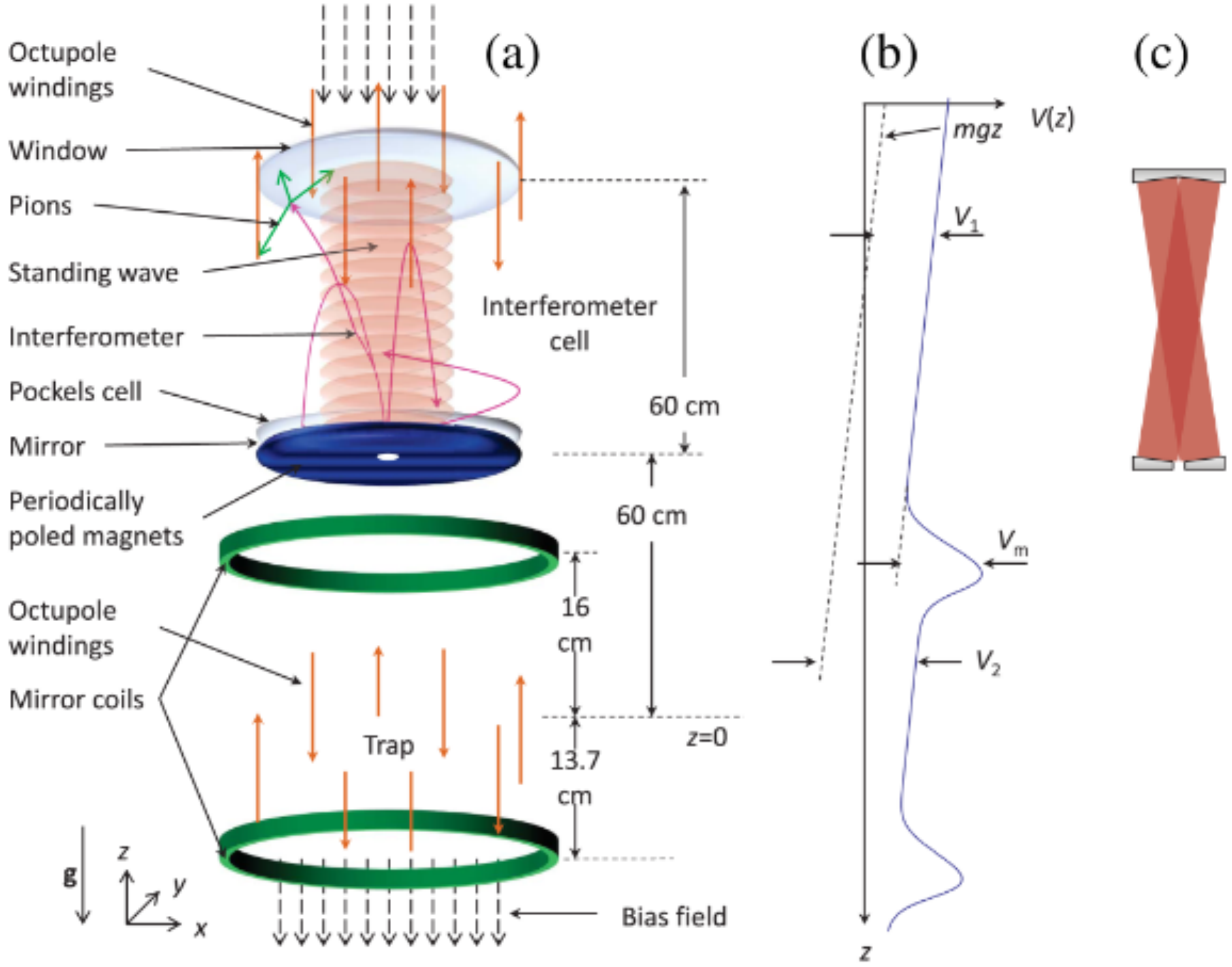
Reduction of median energy by about an order of magnitude

Presently:
~ 500 mK to 50 mK in about half a day

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

Beyond 1% with trapped antihydrogen atoms

- Antimatter interferometry for gravity measurements
- Colder atoms
- Different geometry
- Challenging Lasers
- *… towards ppm precision with trapped atoms*



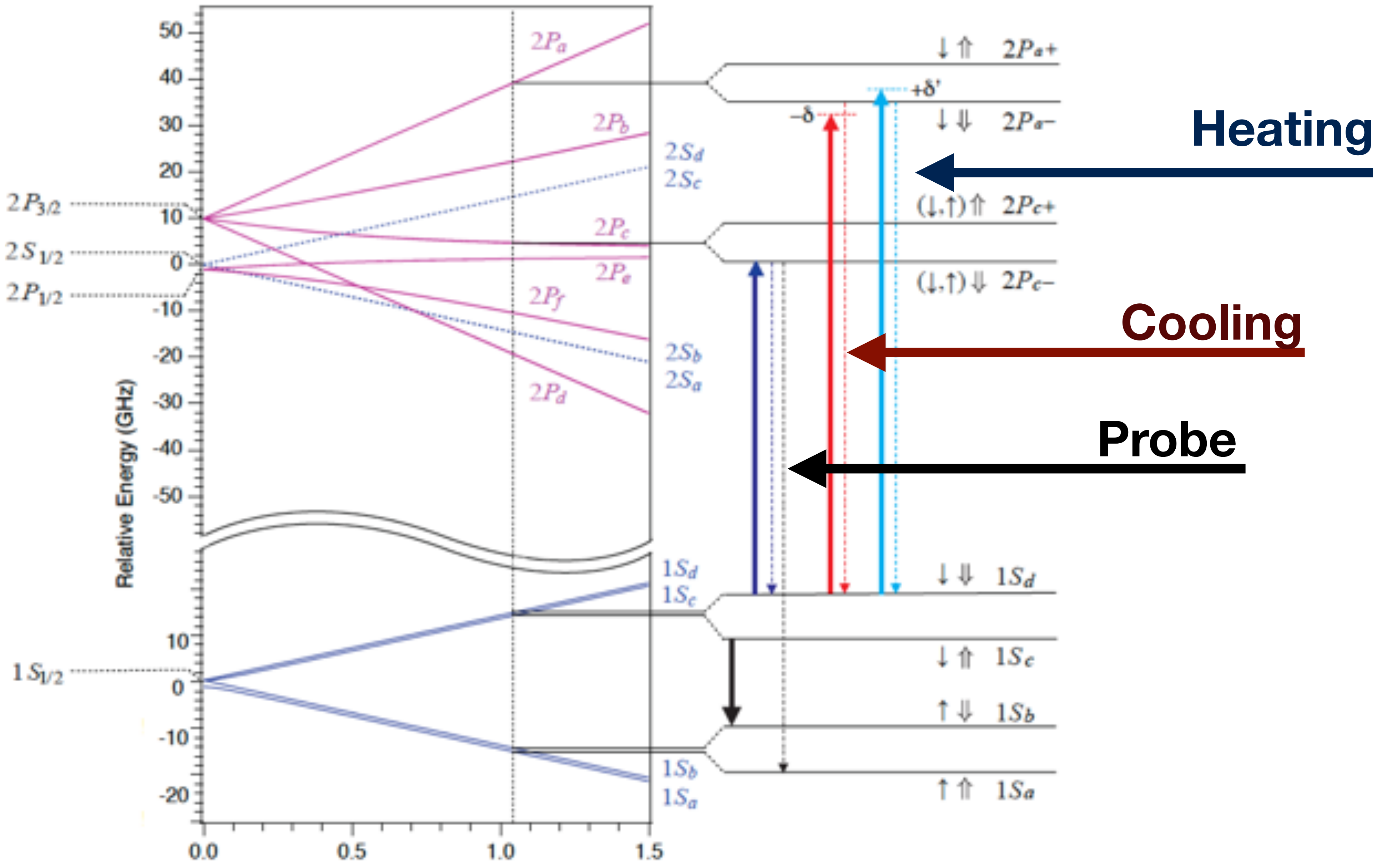
P. Hamilton, A. Zhmoginov, F. Robicheaux, J. Fajans, J. S. Wurtele, and H. Müller
Phys. Rev. Lett. 112, 121102

Thanks for your attention!

Anti-Apple

Earth

Antihydrogen Laser Cooling: Closed transitions



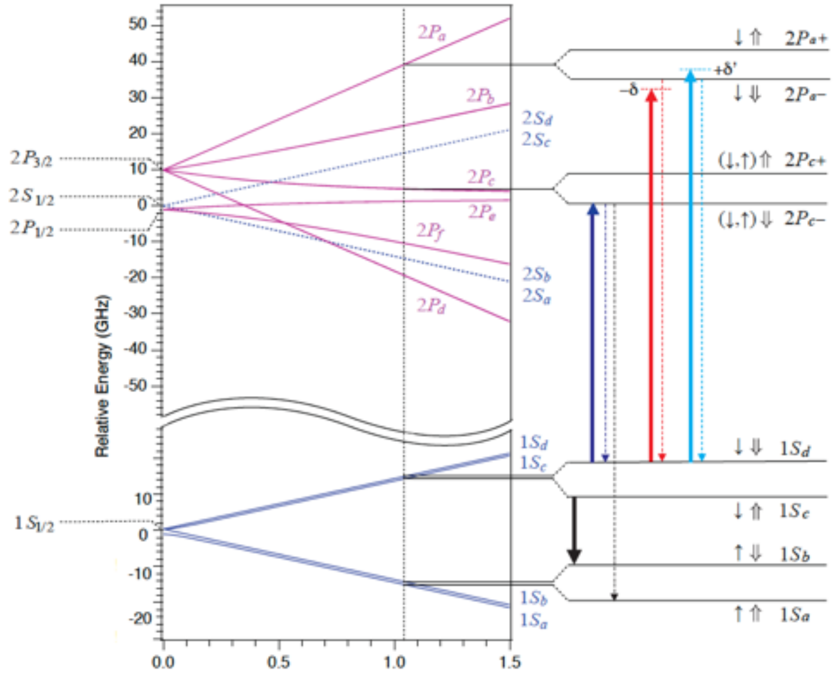
Heating

Cooling

Probe

Antihydrogen Laser Cooling

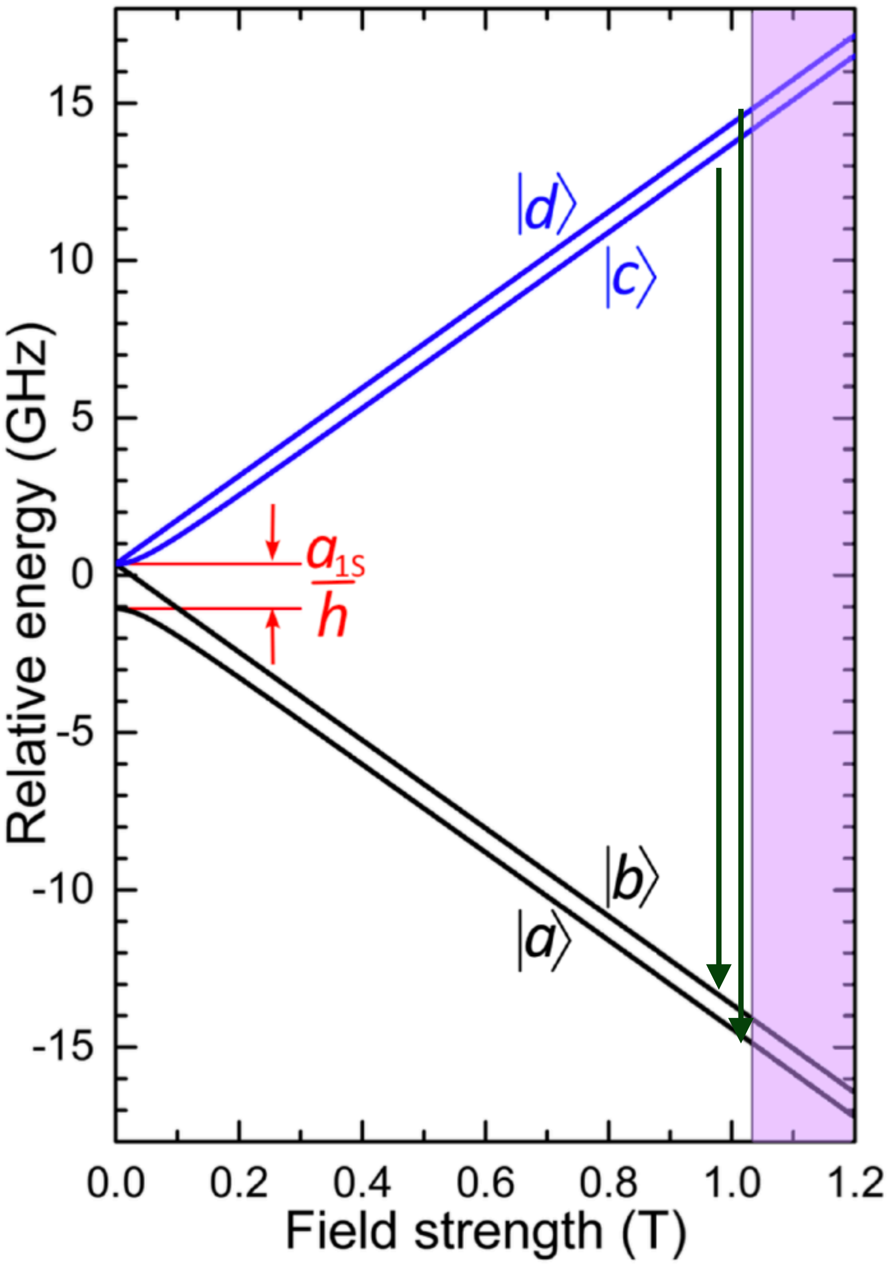
- Stack antihydrogen for ***hours***
- Clean ***c***-state atoms (microwaves)
- Illuminate $1S_d \leftrightarrow 1P_a$ for ***hours***

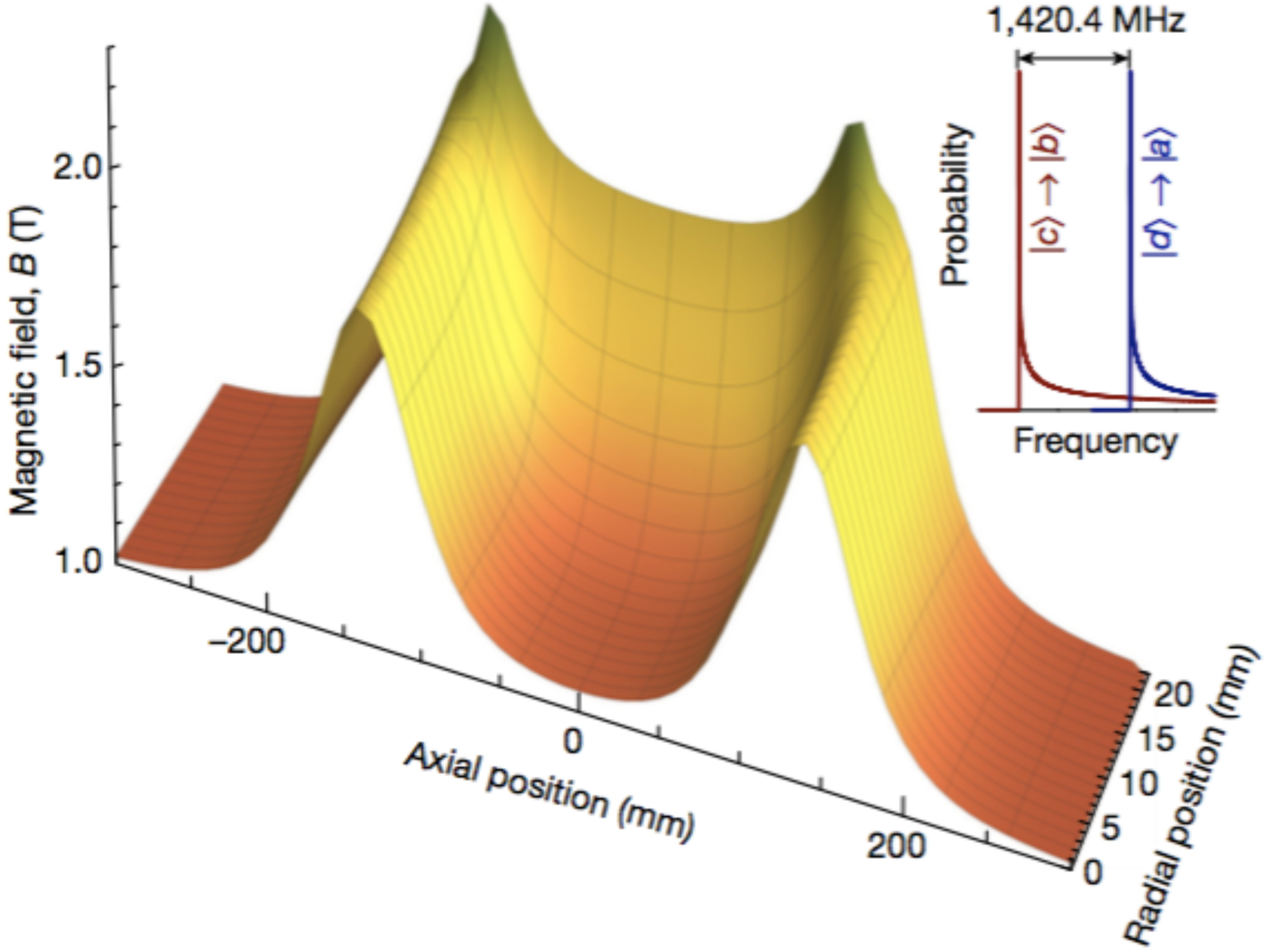


- Probe using $1S_d \leftrightarrow 2P_c$ transition: measure line shape for ***hours***
- Measure time of flight for atoms hitting the wall

- ***Conditions:***
  - red detuning, blue detuning, no laser, cooling during stacking

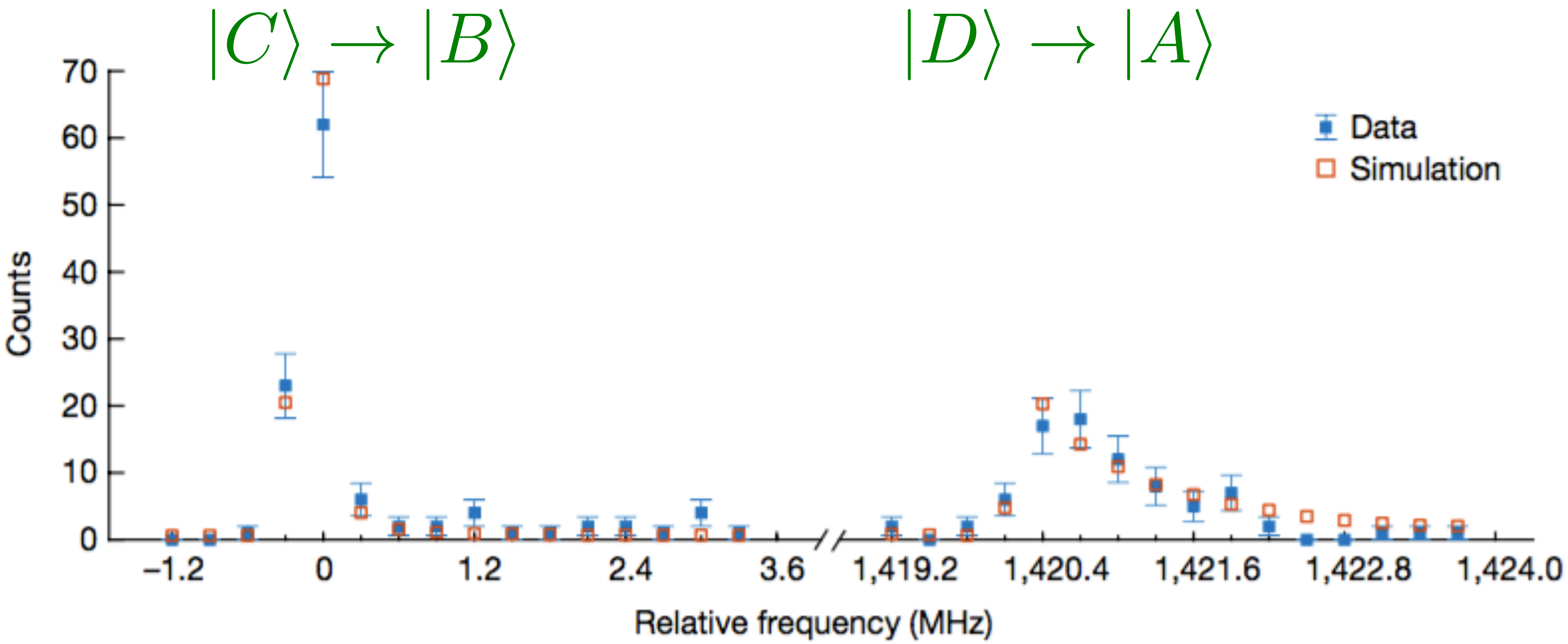
Antihydrogen ground state hyperfine spectrum:





Antihydrogen hyperfine spectrum

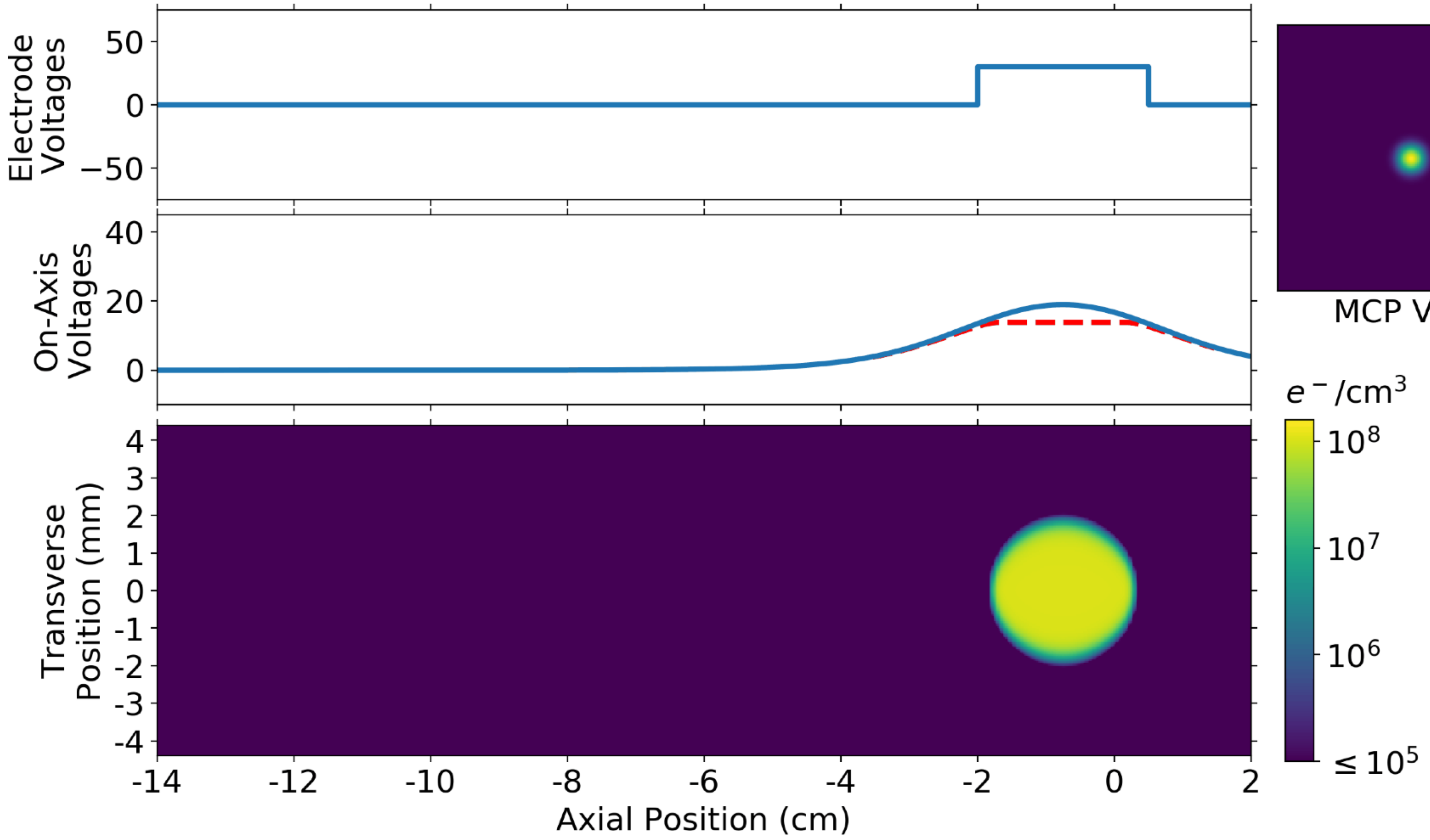
Illuminate trap with successive microwave frequencies ~ 29 GHz
Count annihilations in each frequency bin
Compare with atomic Montecarlo simulation



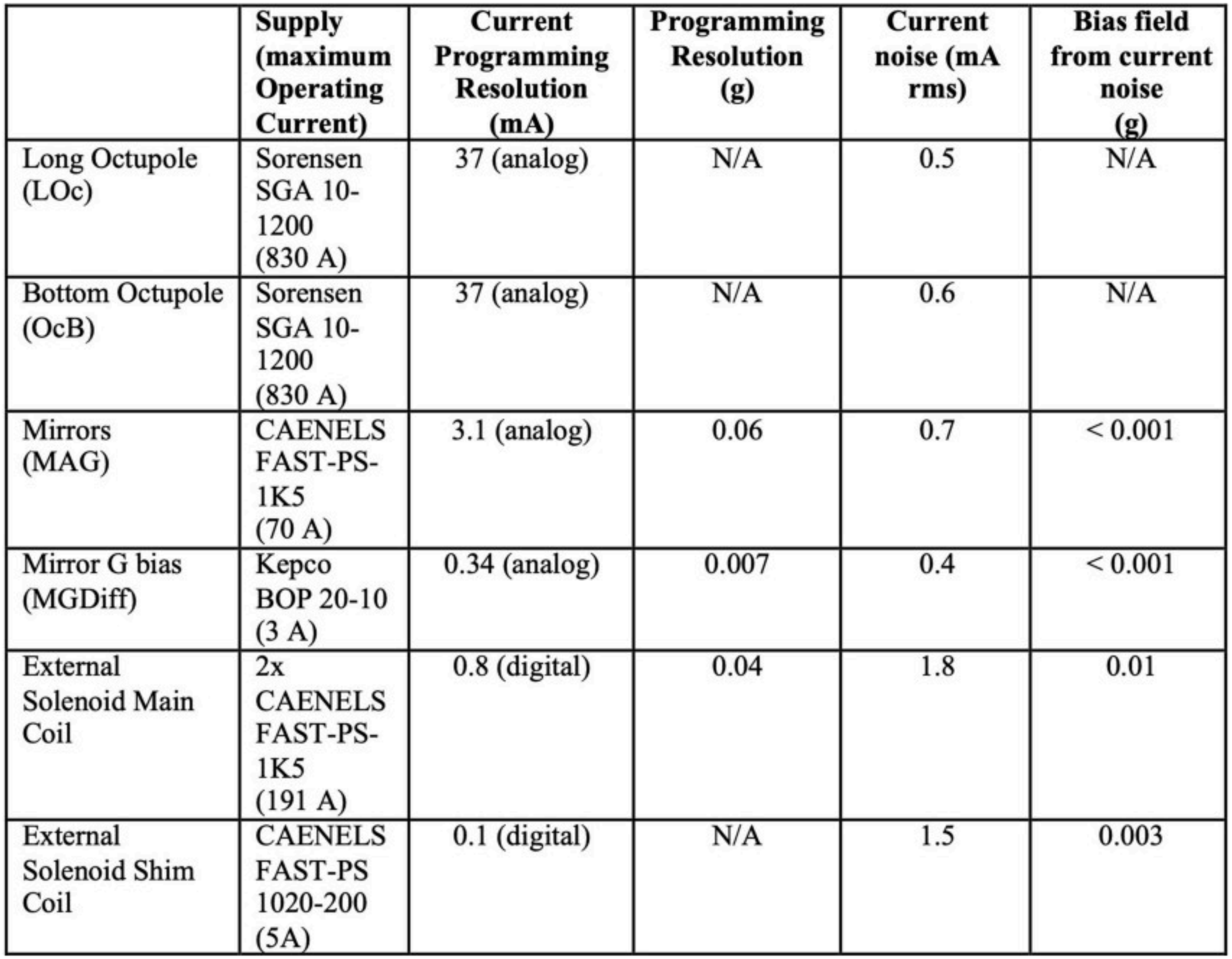
$$1,420.4 \pm 0.5\,\mathrm{MHz}$$

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

Limits to the measurement: Patch “Magnetronmetry”



Current control



	Supply (maximum Operating Current)	Current Programming Resolution (mA)	Programming Resolution (g)	Current noise (mA rms)	Bias field from current noise (g)
Long Octupole (LOc)	Sorensen SGA 10-1200 (830 A)	37 (analog)	N/A	0.5	N/A
Bottom Octupole (OcB)	Sorensen SGA 10-1200 (830 A)	37 (analog)	N/A	0.6	N/A
Mirrors (MAG)	CAENELS FAST-PS-1K5 (70 A)	3.1 (analog)	0.06	0.7	< 0.001
Mirror G bias (MGDiff)	Kepco BOP 20-10 (3 A)	0.34 (analog)	0.007	0.4	< 0.001
External Solenoid Main Coil	2x CAENELS FAST-PS-1K5 (191 A)	0.8 (digital)	0.04	1.8	0.01
External Solenoid Shim Coil	CAENELS FAST-PS 1020-200 (5A)	0.1 (digital)	N/A	1.5	0.003