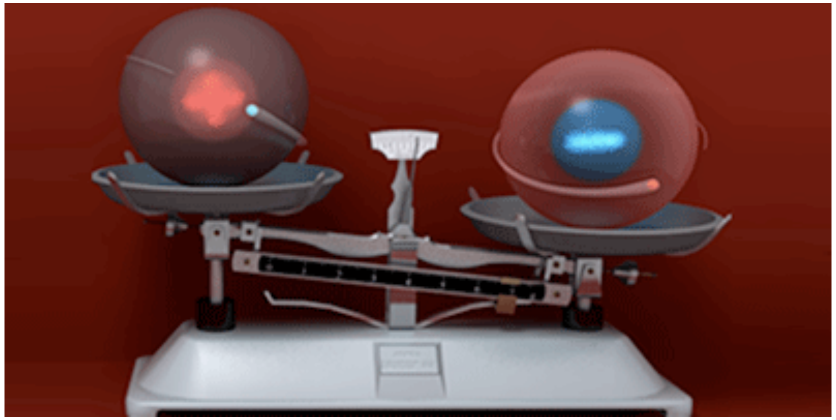
Gravitational studies with Antihydrogen



Dr. Will Bertsche
The University of Manchester
The Cockcroft Institute

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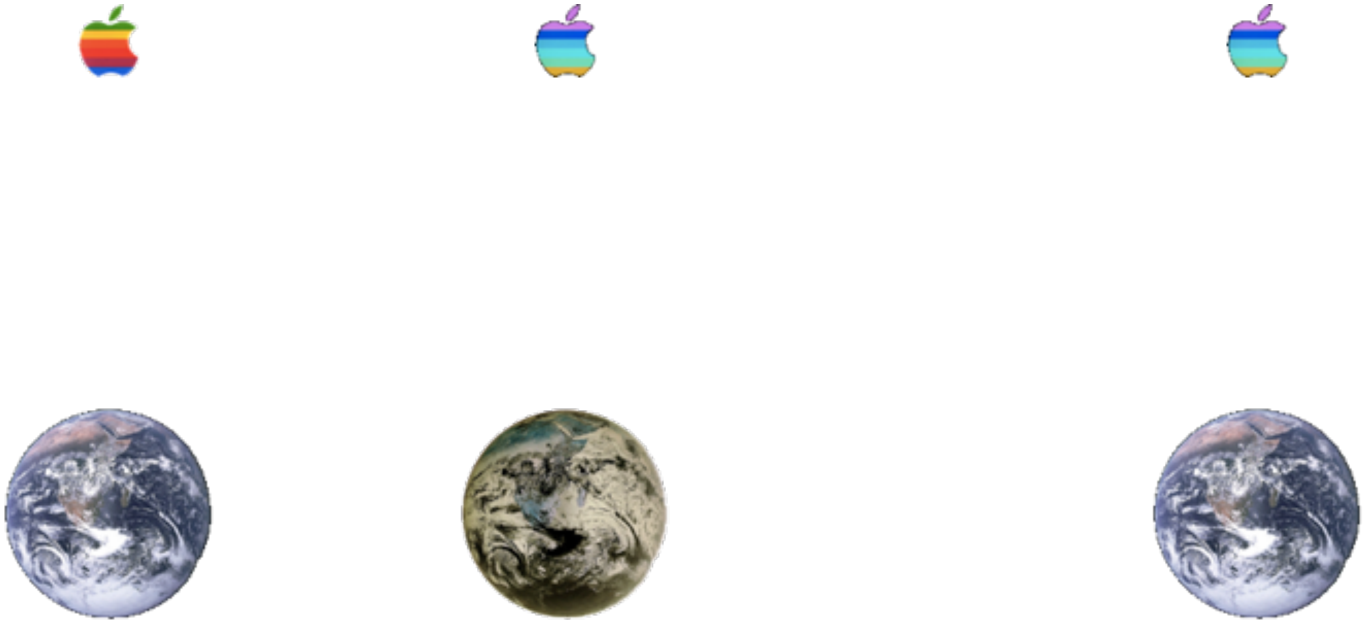
ALPHA

Possible Explanations: Fundamental Flaw?

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

This talk:
Free-Fall Weak Equivalence Principle

- Galilean Gravity?



Apple Anti-Apple Anti-Apple

Earth Anti-Earth Earth

Gravity and antimatter

- **Numerous theoretical arguments against unexpected Antimatter gravitation**
  - Photon behaviour,
  - CPT theorem,
  - Morrison’s argument,
  - Schiff’s argument,
  - Good’s argument,
  - Gerar ‘ Hooft’s argument, etc.
- Most of these arguments have been challenged
  - See review: Nieto, M. M. & Goldman, Physics Reports (1991): doi.org/10.1016/0370-1573(91)90138-C

Gravity and antimatter

- **Some theoretical arguments for different Antimatter gravitation**
  - Kowitt's theory, Santilli and Villata's theory, Cabbolet's theory, etc.
- Predictions remain untested to varying degrees…
  - See review: Nieto, M. M. & Goldman, Physics Reports (1991): doi.org/10.1016/0370-1573(91)90138-C
  - https://en.wikipedia.org/wiki/Gravitational_interaction_of_antimatter

Gravity and antimatter

- **Experimental evidence against unexpected antimatter gravitation**
  - **Eötvös Style Experiments** (https://arxiv.org/abs/0712.0607), **Supernova 1987a** (https://journals.aps.org/prd/abstract/10.1103/PhysRevD.39.1761), **Cyclotron Frequency Shifts** (https://www.nature.com/articles/s41586-021-04203-w), **Neutral Kaon Oscillations** (https://arxiv.org/abs/hep-ex/9903005), **Synchrotron losses** (doi/10.1016/0370-1573(91)90138-C), etc.
- Again, most of these experimental arguments have been challenged
  - See review: Nieto, M. M. & Goldman, Physics Reports (1991): doi.org/10.1016/0370-1573(91)90138-C
  - “However, for the antimatter, all of them exploit some additional assumptions, such as gravitational properties of virtual particles, physical significance of the absolute values of the gravitational potentials, CPT-invariance, etc” T. Kalaydzhyan, Scientific Reports (2016), 10.1016/0370-1573(91)90138-C

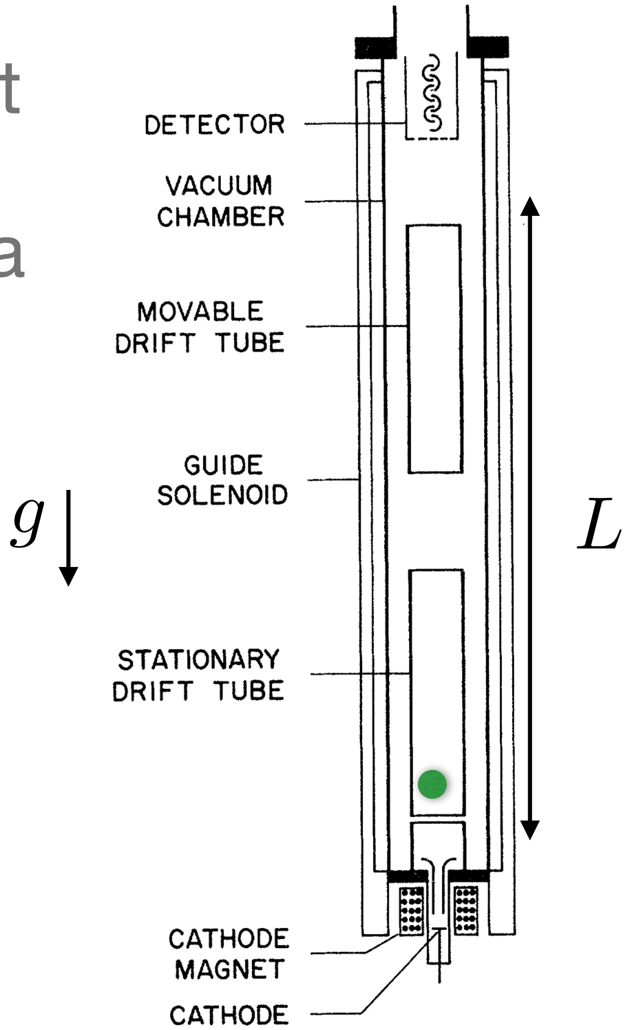
Gravity and antimatter “free-fall” experiments

- Prior experiments that proposed to test antimatter investigated *charged* antimatter did not succeed
- Positrons and Antiprotons.
- Challenging because gravitation force so weak compared to forces from stray electric fields

$$\frac{m_e g}{e} \sim 10^{-11}\,\mathrm{V/m}$$

Gravity and antimatter: Fairbanks Experiment

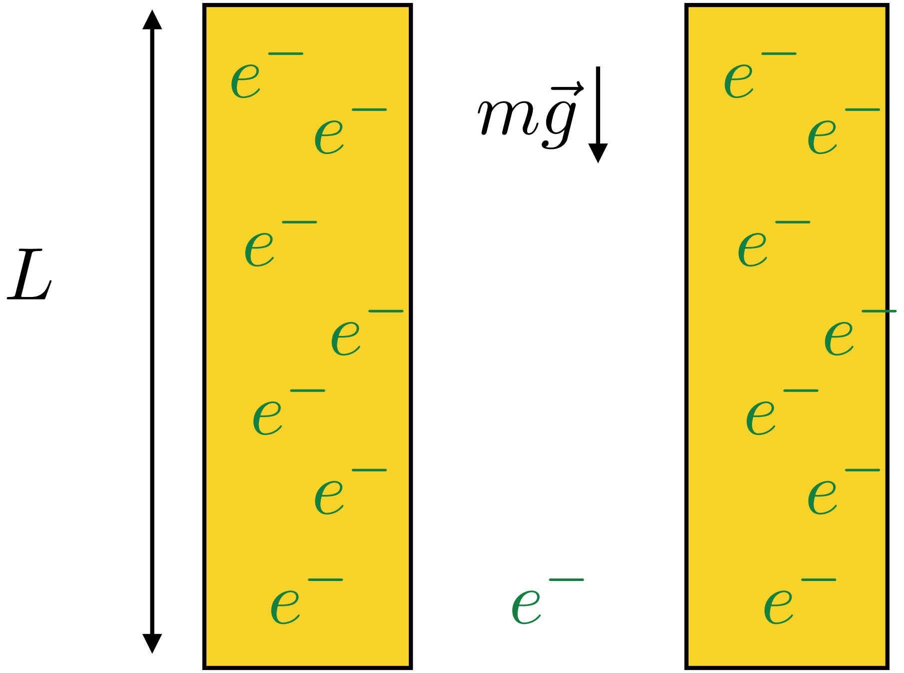
- Electron demo for a positron experiment
- Pulse electrons with a low velocity into a shielded drift tube
- Measure drift time *t* over length *L*
- *Infer gravitational acceleration g*



F. C. Witteborn and W. M. Fairbank, Experimental Comparison of the Gravitational Force on Freely Falling Electrons and Metallic Electrons, Phys. Rev. Lett. 19, 1049 (1967).

Gravity and antimatter: Fairbanks Experiment

- Problem: Electrons sag in drift tube walls due to gravity



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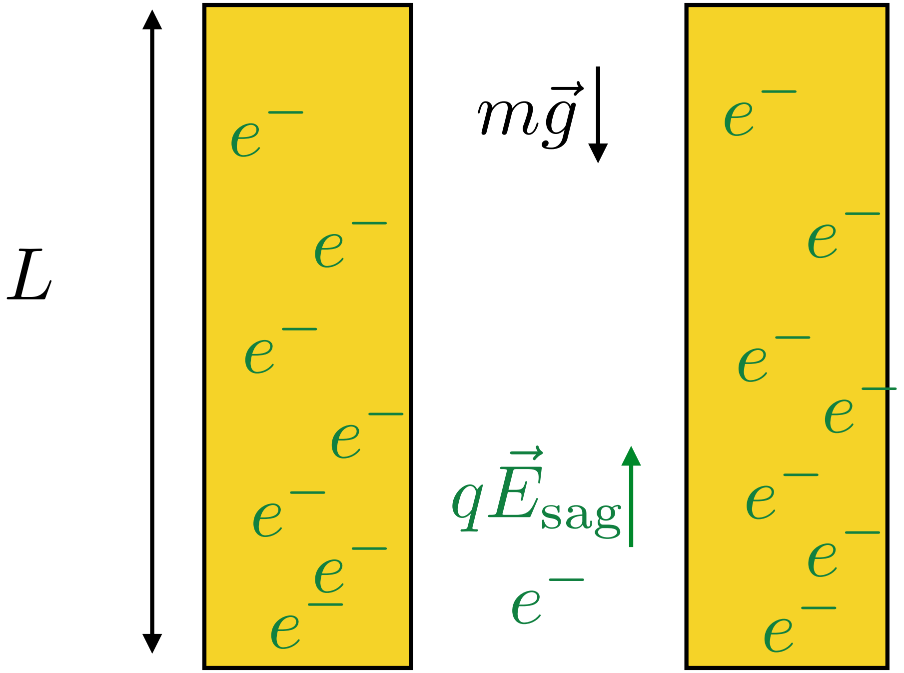
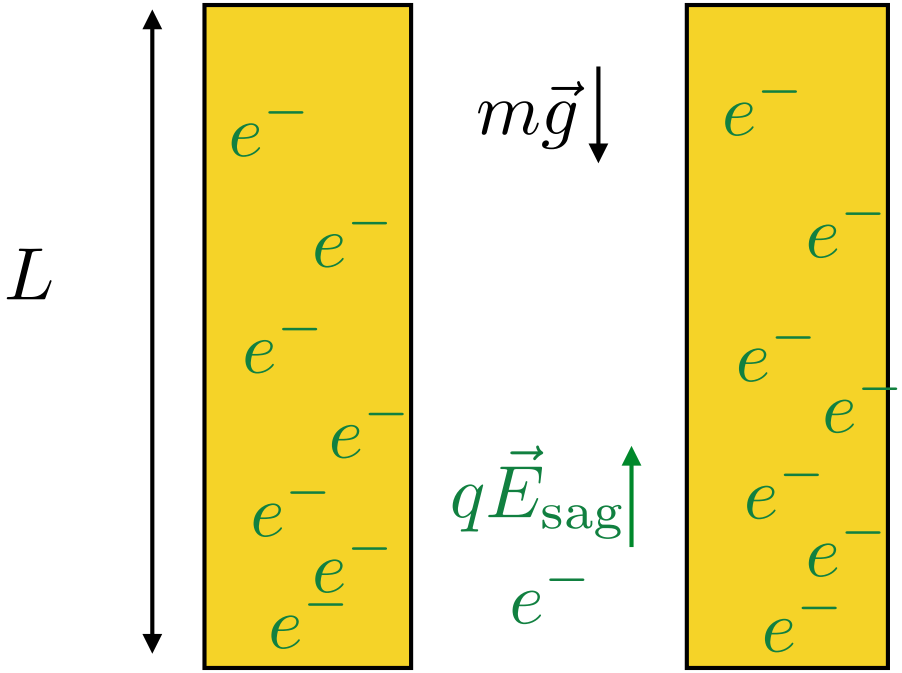


F. C. Witteborn and W. M. Fairbank, Experimental Comparison of the Gravitational Force on Freely Falling Electrons and Metallic Electrons, Phys. Rev. Lett. 19, 1049 (1967).

Gravity and antimatter: Fairbanks Experiment

- Problem: Electrons sag in drift tube walls due to gravity
- Electrons nearly did not accelerate ($a < 0.09$ ms^{-2})!



Schiff and MV. Barnhill, Gravitation-induced electric field near a metal, Phys. Rev. 151 (1966).

Gravity and antimatter

- Numerous systematics with drift tube: ion sag, patch potentials, etc…
- Fairbanks Experiment not repeated with positrons: Poor sources at the time
- PS-200 - Antiproton experiment at CERN: *Incomplete* (LEAR shutdownm ~ 1996)
- ***TO DATE: No gravity measurements on any charged particle***

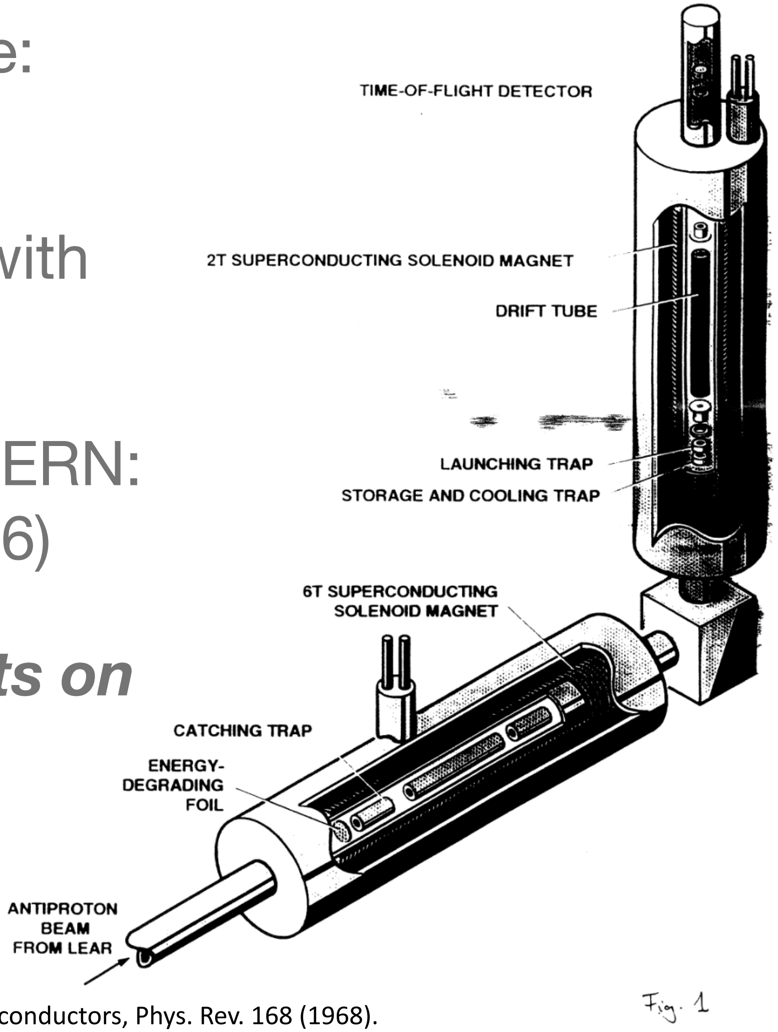


Fig. 1

A.J. Desser, F.C. Michel, H.E. Rorschach, G.T. Trammell, Gravitationally induced electric fields in conductors, Phys. Rev. 168 (1968).
PS 200 Collaboration Report: http://cds.cern.ch/record/310553/files/cm-p00047643.pdf

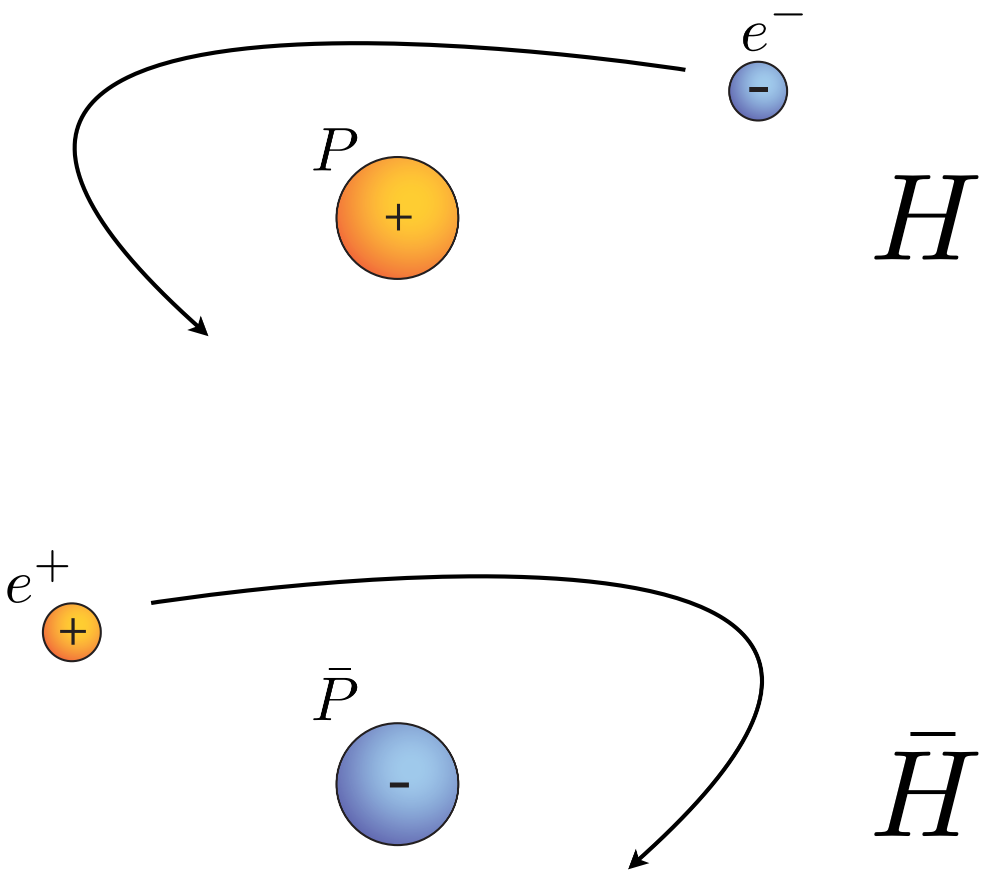
Gravity and antimatter: Neutral efforts

- ALPHA (CERN): (trapped Hbar)
- Gbar (CERN): (Hbar fountain)
- AEgIS (CERN): (Hbar beam)
- LEMMINg (PSI): Muonium
- Efforts with Positronium…

Atoms and antimatter: Hydrogen and Antihydrogen

Matter:

Hydrogen



Antimatter:

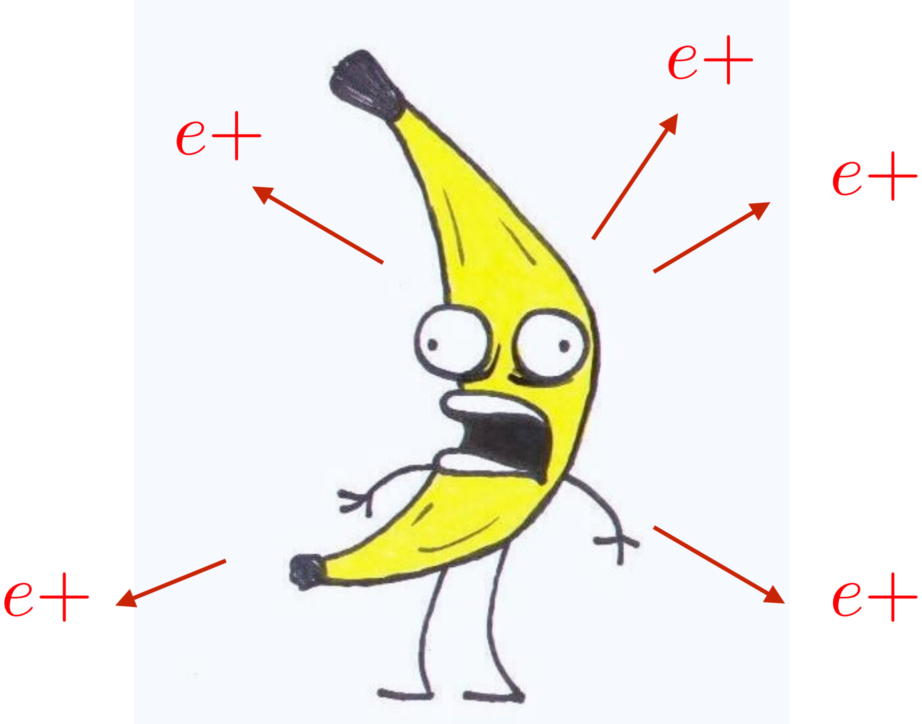
Antihydrogen

Where do Positrons come from?

- "Easy" … some radioactive isotopes

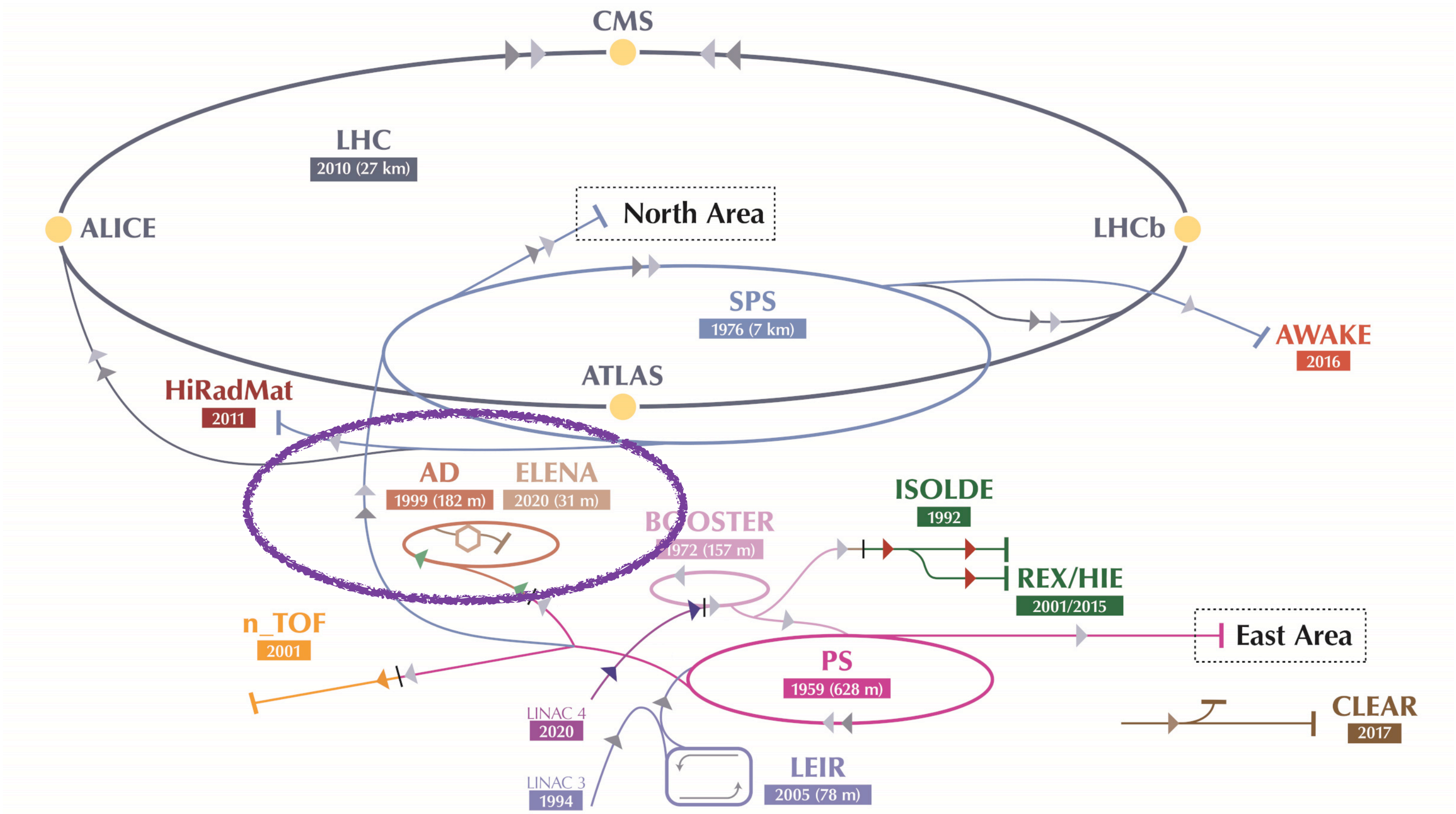
Banana Equivalent Dose (potassium):
~ 15 positrons / second

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



"I am a banana!" Don Hertzfeld

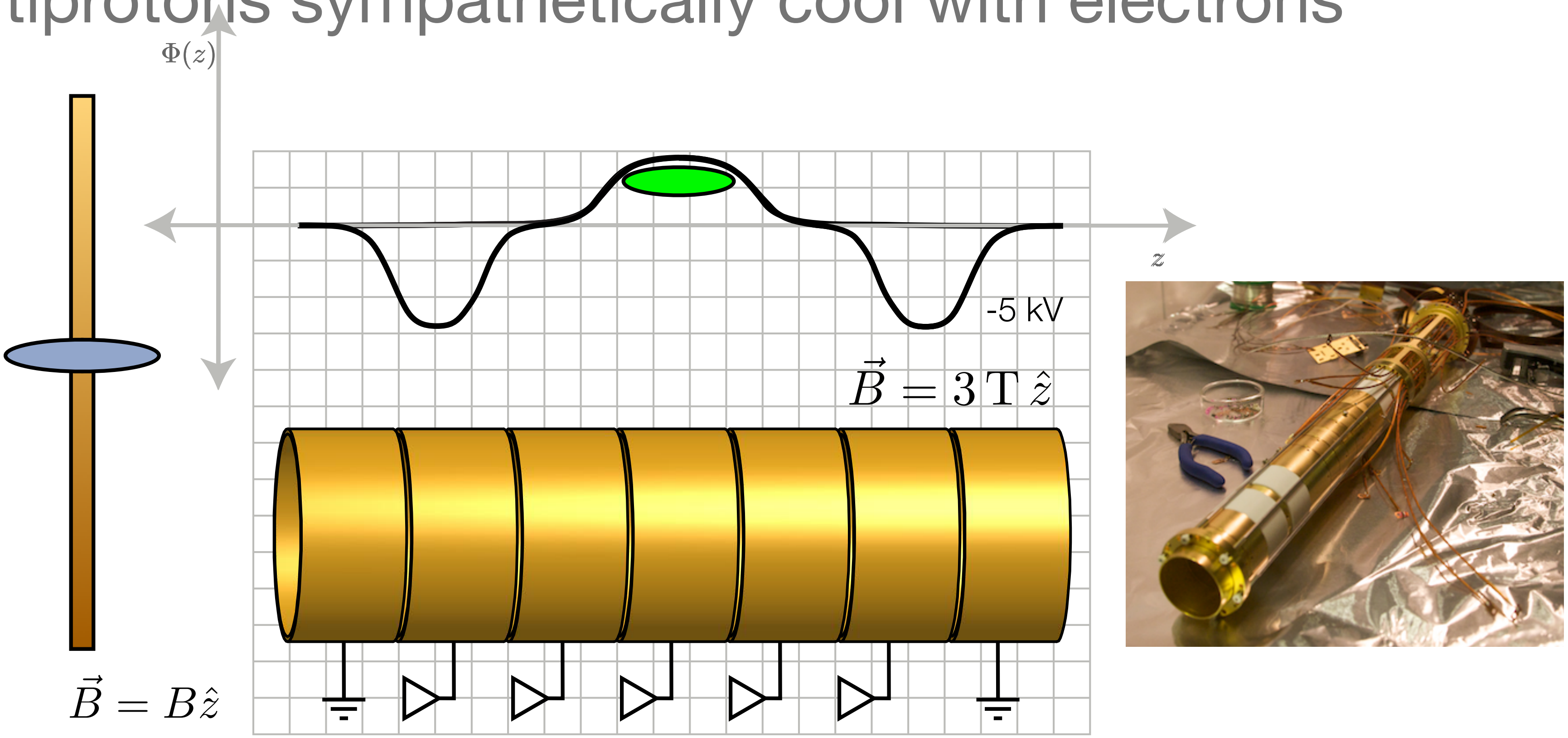
Low energy antiprotons from CERN



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

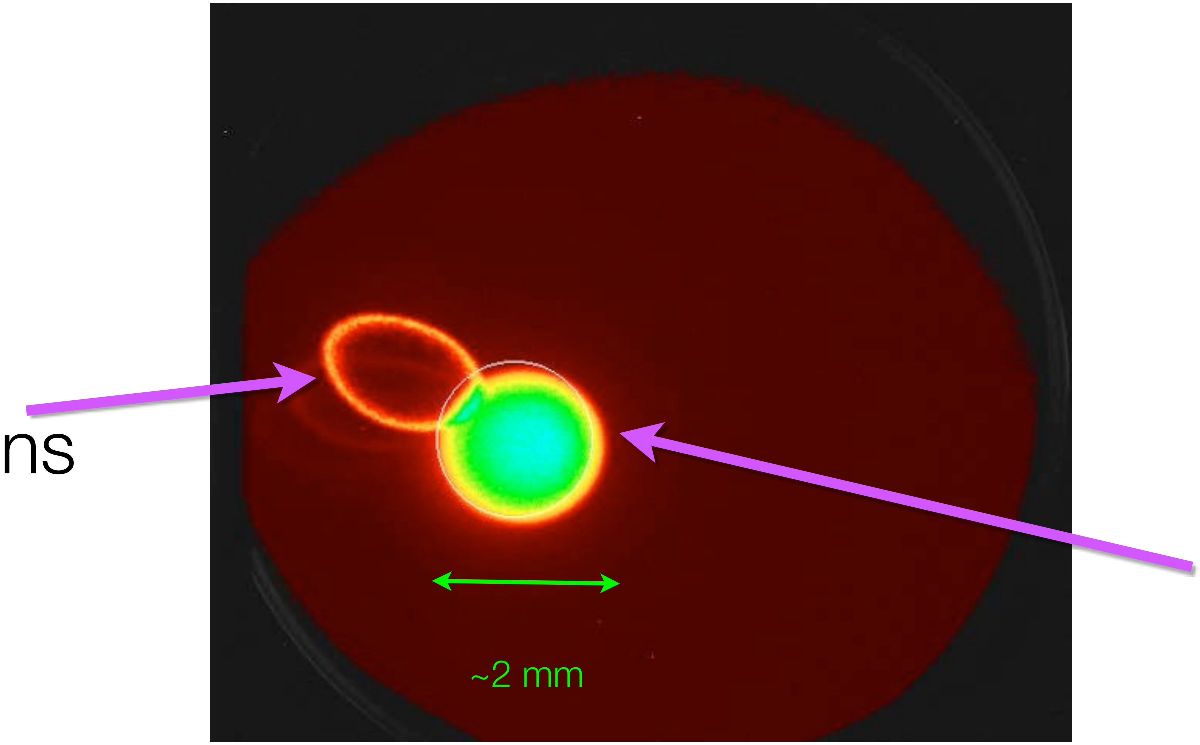
Capturing Antiprotons in a Penning-Malmberg Trap

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



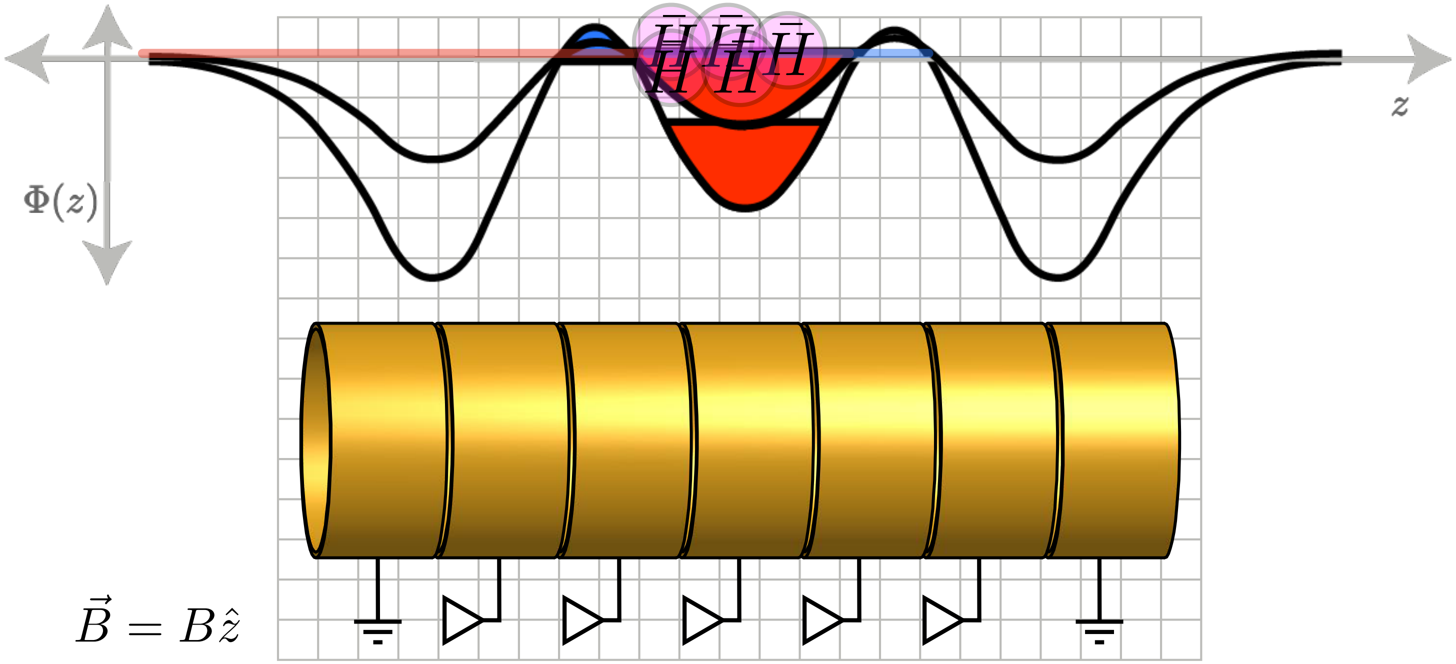
Antiproton / Electron Plasma

- Image the equilibrium Antiproton / Electron plasma



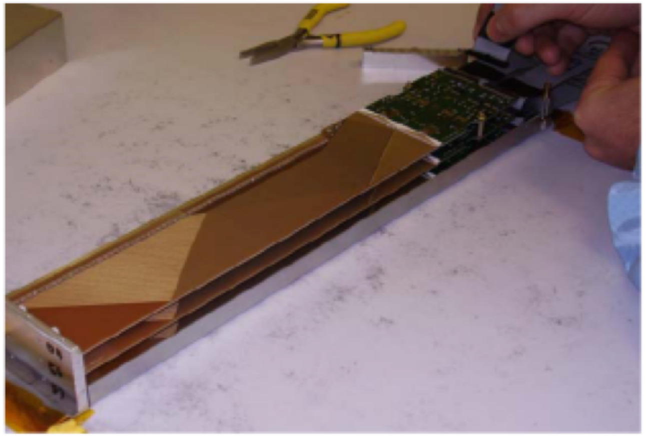
Antihydrogen Formation:
Mixing Antiprotons and Positrons

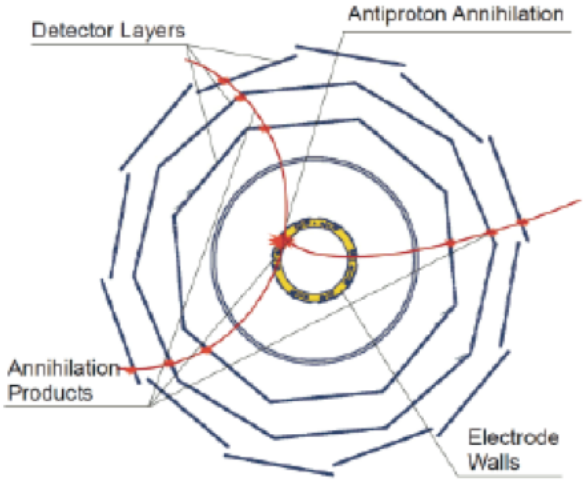
1. Merge Antiproton and Positron plasmas
2. Antiprotons and Positrons equilibrate and cool
3. Form Antihydrogen: atoms exit electrostatic trap

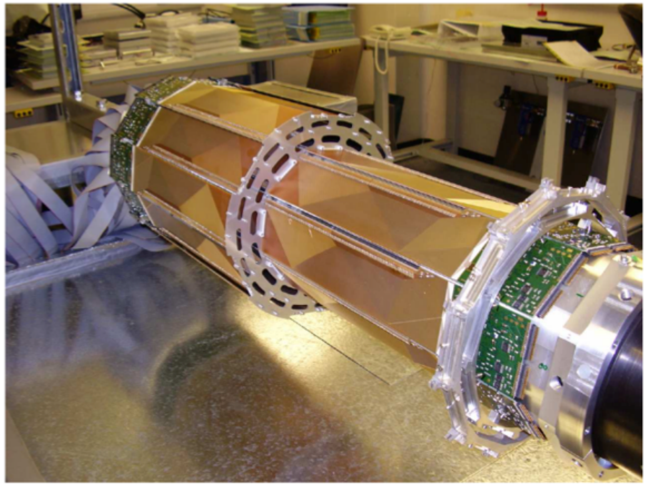


Annihilation Detection: ALPHA-1, ALPHA-2

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



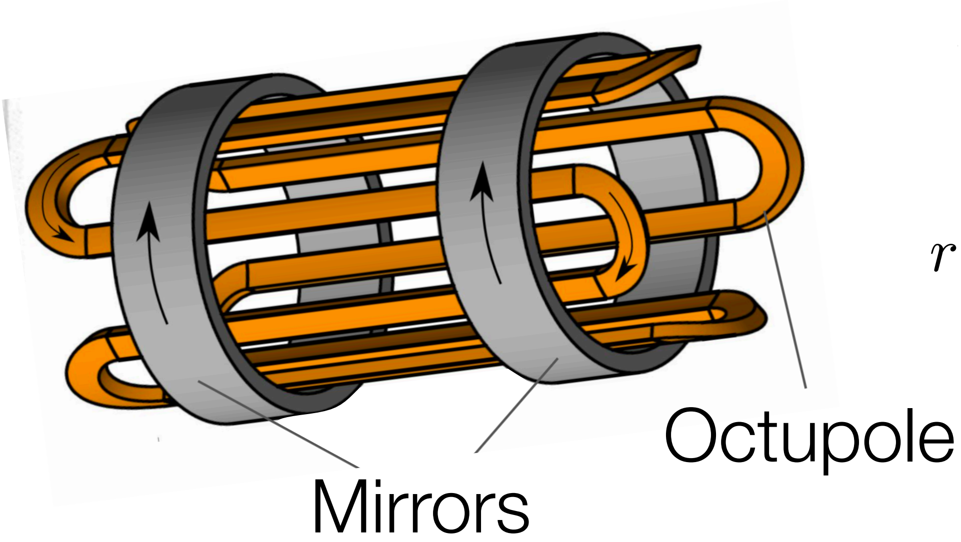


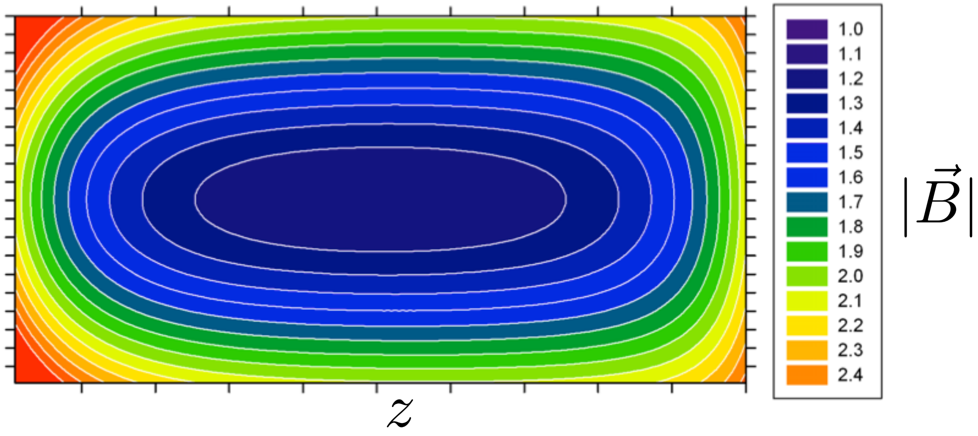


Trapping Antihydrogen

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

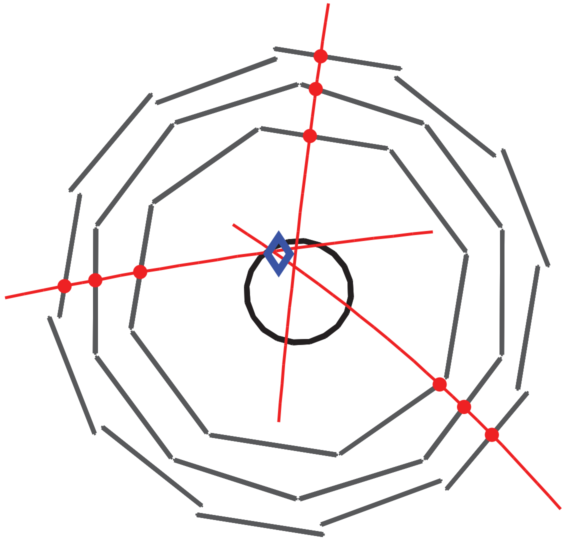
$$\vec{F} = \mu_H \vec{\nabla}|\vec{B}|, \; U = \vec{\mu}_H \cdot \vec{B}$$





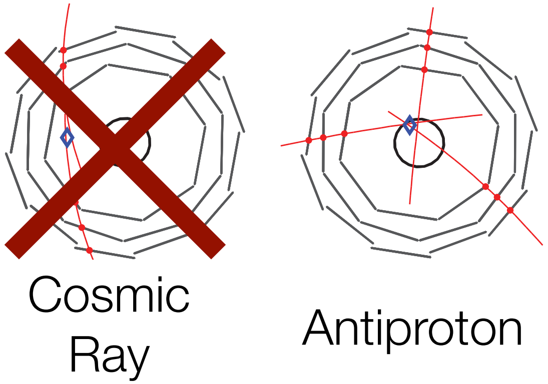
A little ALPHA history
Trapping Antihydrogen: Search

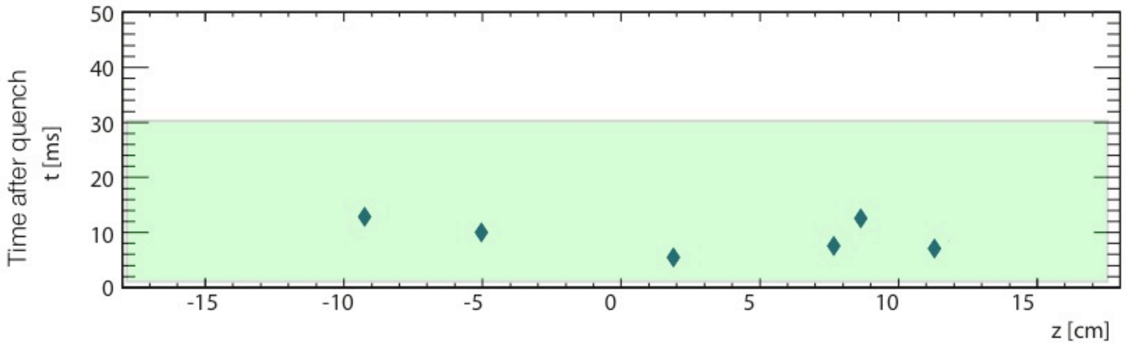
1. Turn on magnetic trap
2. Mix and Form Antihydrogen
3. Eject remaining charged particles
4. Rapidly shut off trap (< 30 ms quench in ALPHA-1)
5. Detect annihilations



A little ALPHA history
Trapped Antihydrogen Detection

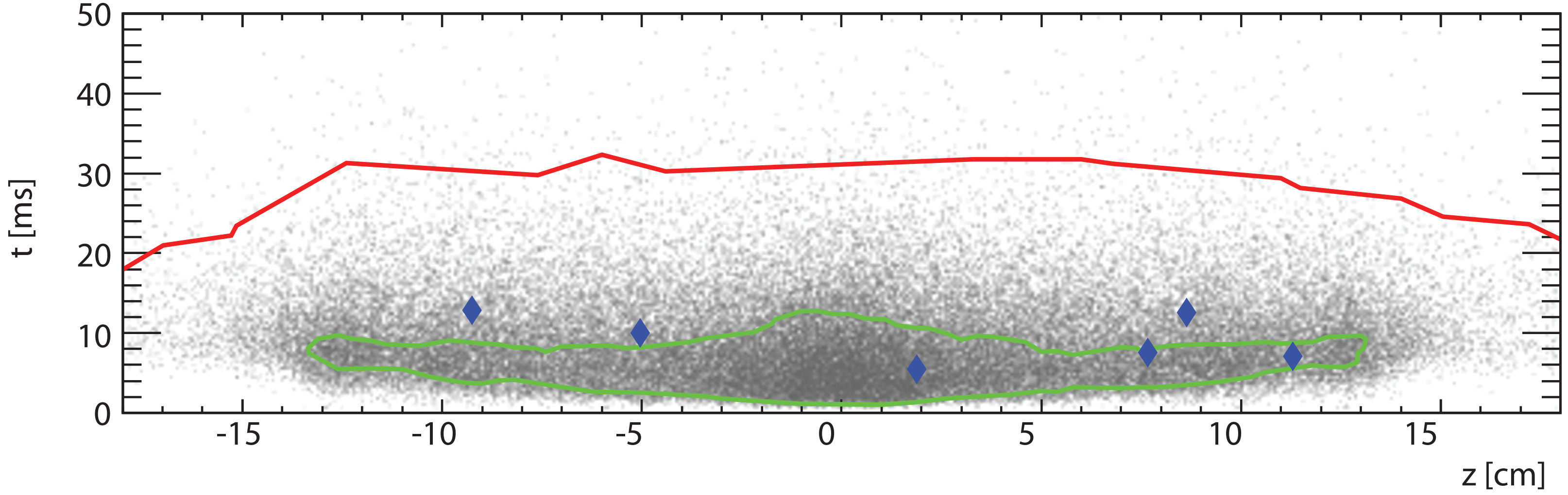
- Pattern / Time / Spatial Information from Detector
- Reject cosmic rays
- Accept antiproton annihilations
- Only look at events during the quench (time)





A little ALPHA history
Antihydrogen Expectation?

- Simulate Antihydrogen atoms in trap through quench

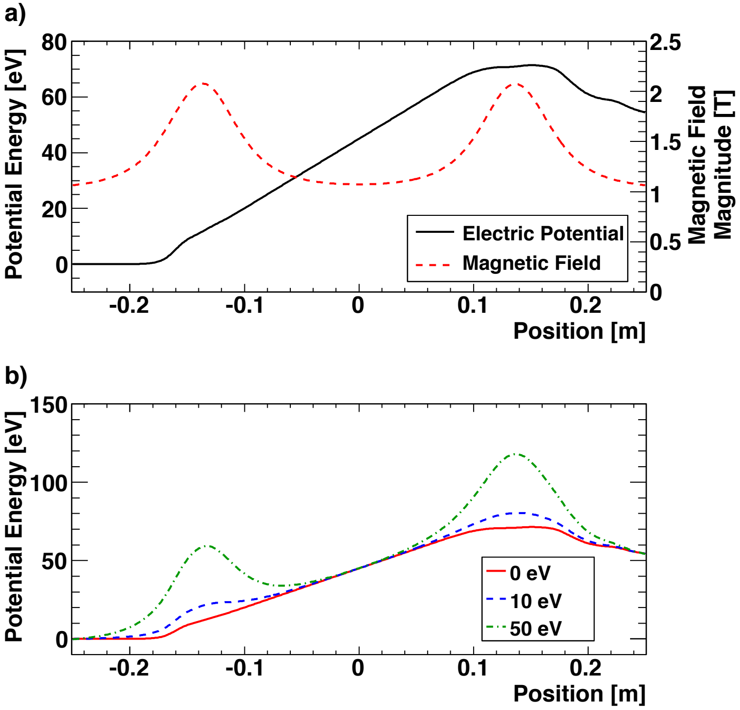


- Mirror-trapped antiprotons might remain…

A little ALPHA history
High $E_\perp$, Mirror-Trapped Antiprotons Background?

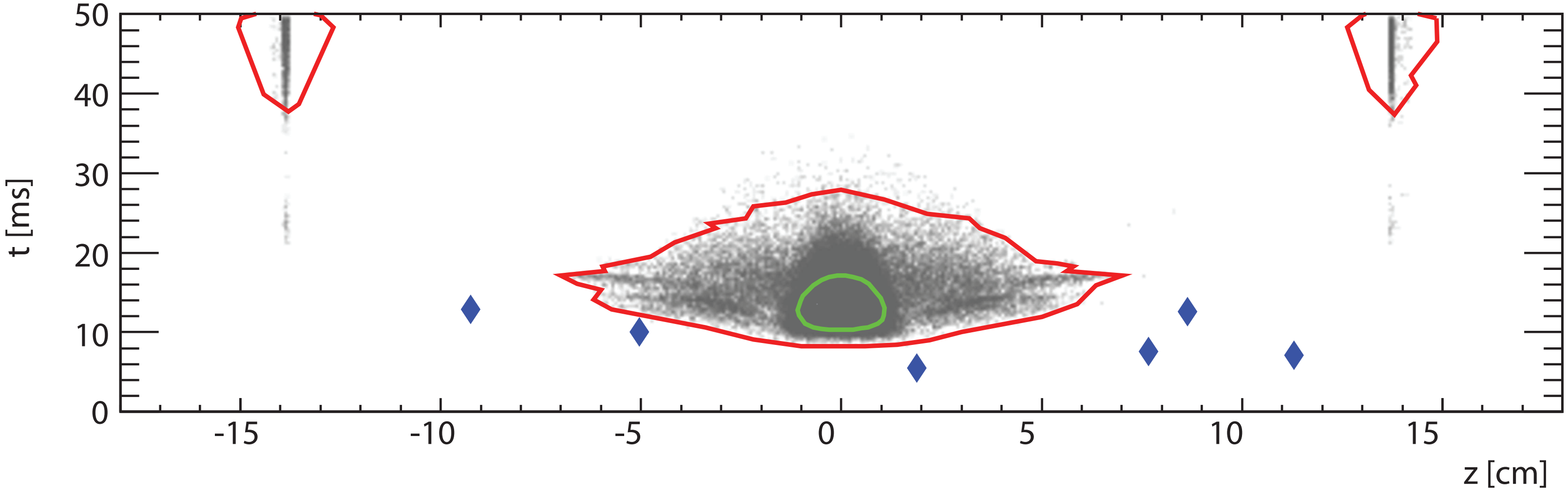
- *Simulate behavior of atoms and antiprotons in potential*
  - *Antiprotons with high perpendicular energy can be mirror-trapped by B fields*

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



A little ALPHA history
Are events Mirror-Trapped Antiprotons?

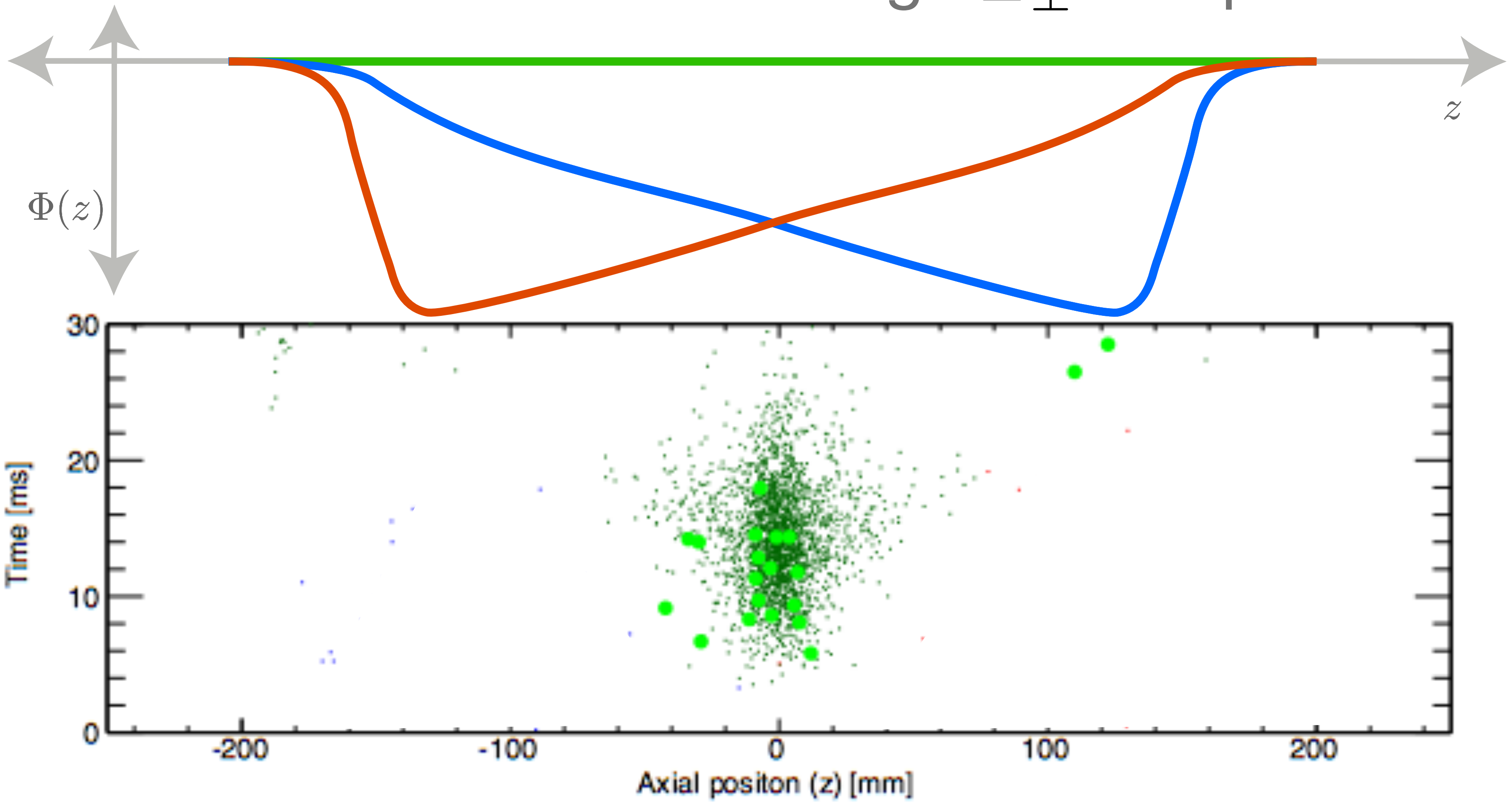
- Simulate mirror-trapped antiprotons in quench



- Different from antihydrogen events, surely…

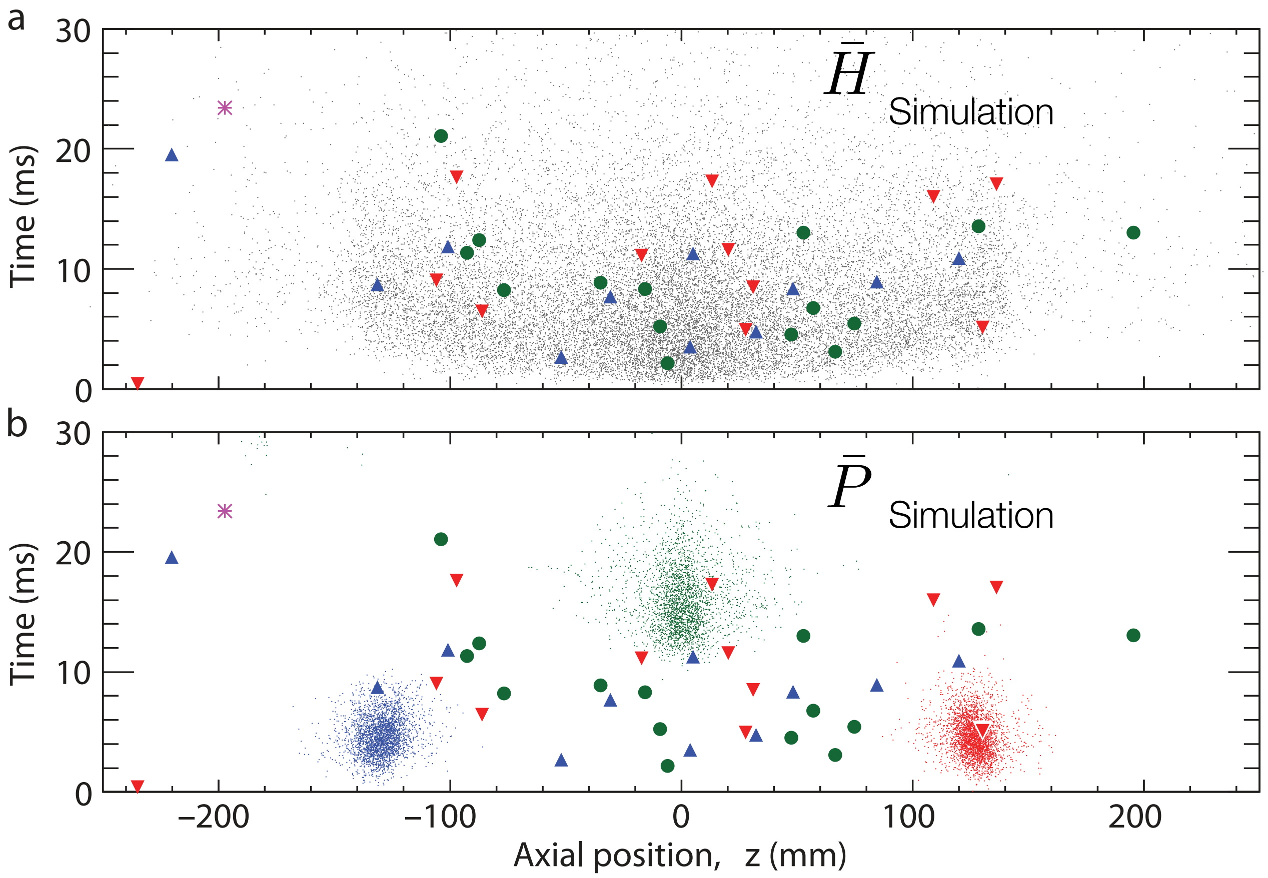
A little ALPHA history
Quench With Bias Electric Field

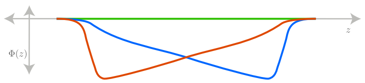
- Electric *Fields deflect charged particles, not atoms*
- Simulate and measure with high $E_\perp$ antiprotons



A little ALPHA history
Antihydrogen Search with Bias Fields

- No spatial bias in signal: Trapped Antihydrogen





No Bias
Left Bias
Right Bias
(* Heating)

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”

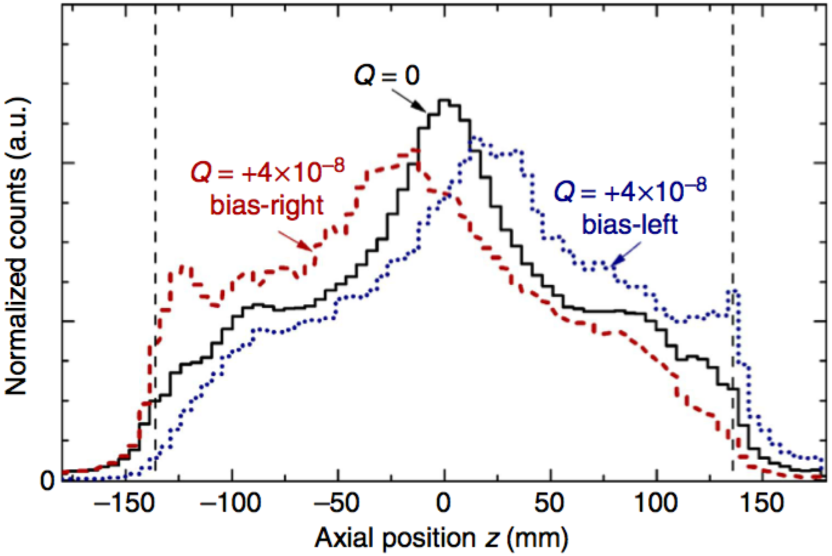
$$\bar{H}\ \text{charge} = Qe$$

- Magnetic atom trap + bias field potential:

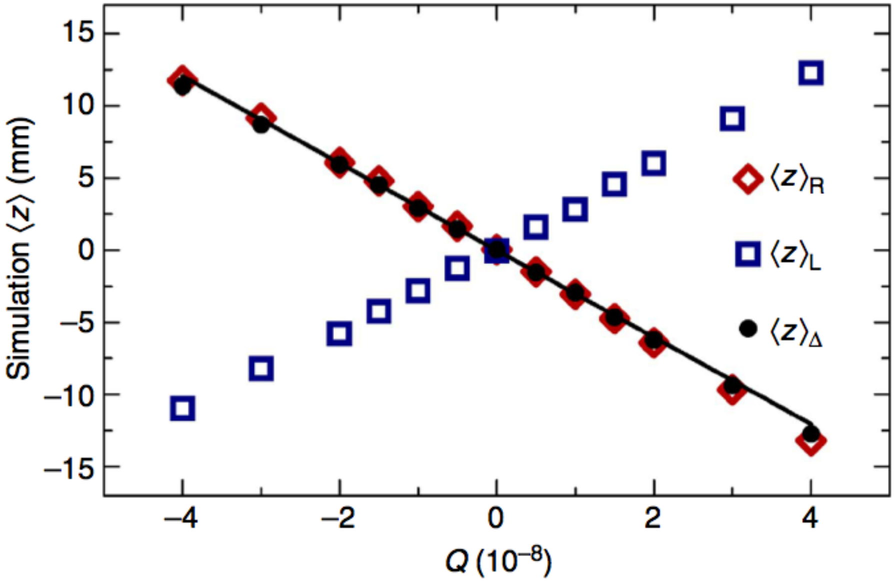
$$U(z) = \mu_{\bar{H}} B(z) - \frac{QeE}{k_B} z$$

Measurements with Potentials: Charge neutrality

Simulate Hbar Annihilations



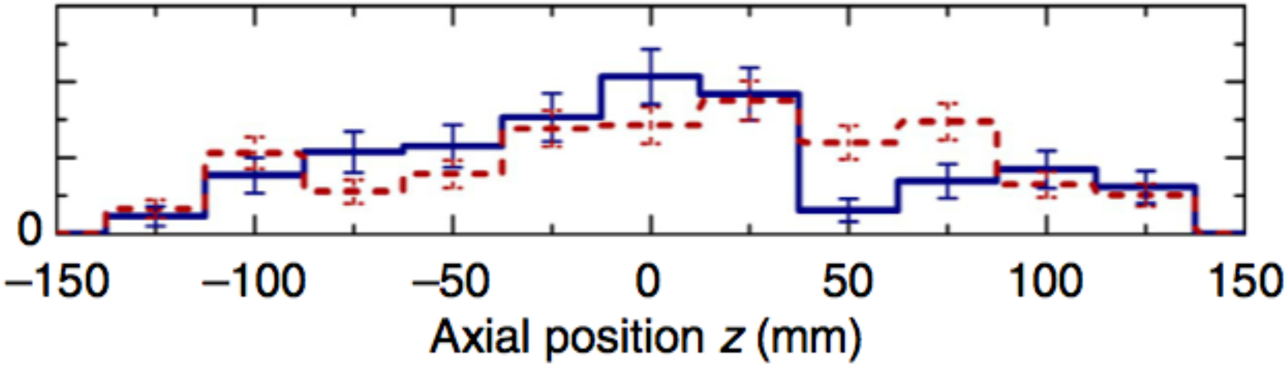
Relate $\langle z \rangle_\Delta \longleftrightarrow Q$



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

Measurements with Potentials:
Charge neutrality

Measure $\langle z \rangle_\Delta$



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

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

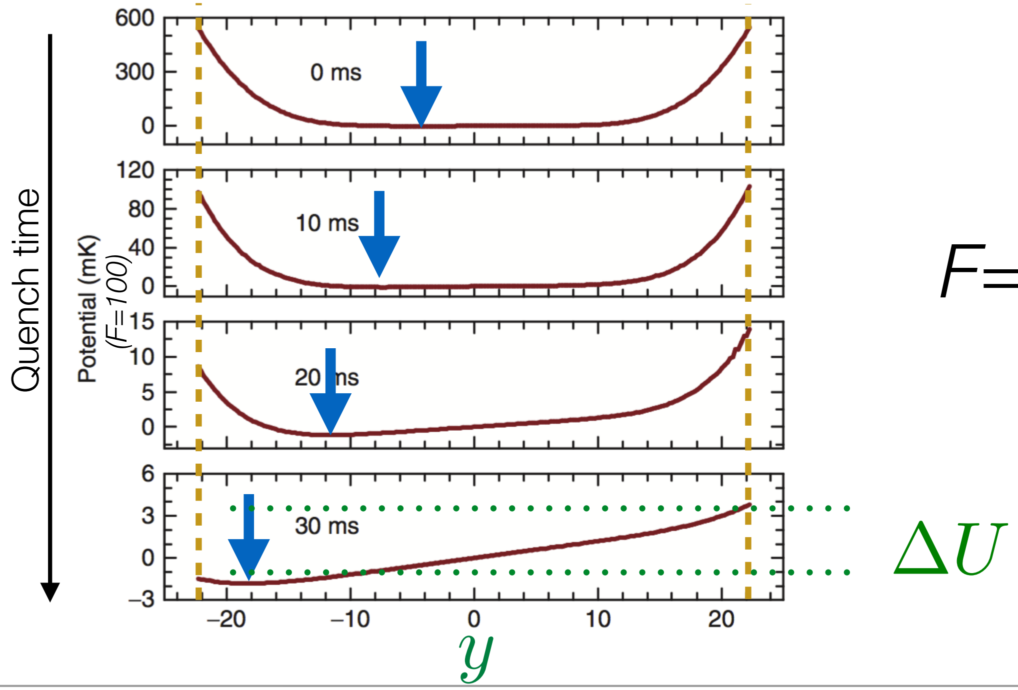
C. Amole *et al.* “An experimental limit on the charge of antihydrogen”, Nat. Comm. 5, 3955 (2014)

Measurements with Potentials: Gravitation?

- Do atoms and anti-atoms gravitate differently?

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

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

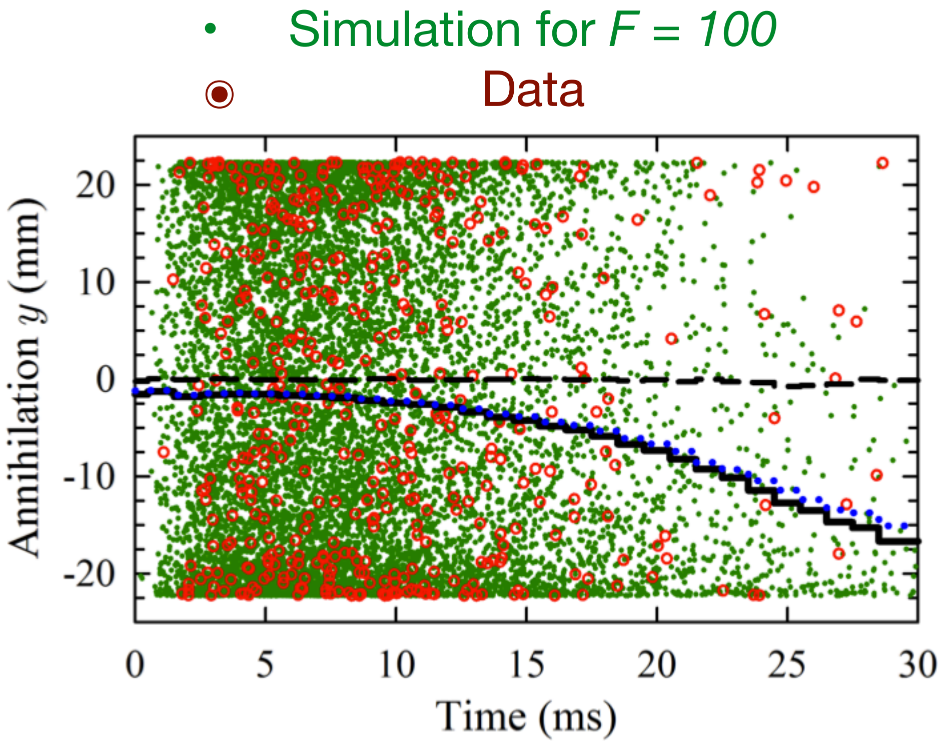


F=100

Measurements with Potentials: Gravitation? (ALPHA-1)

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

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



Measurements with Potentials: Gravitational Deflection: Precision?

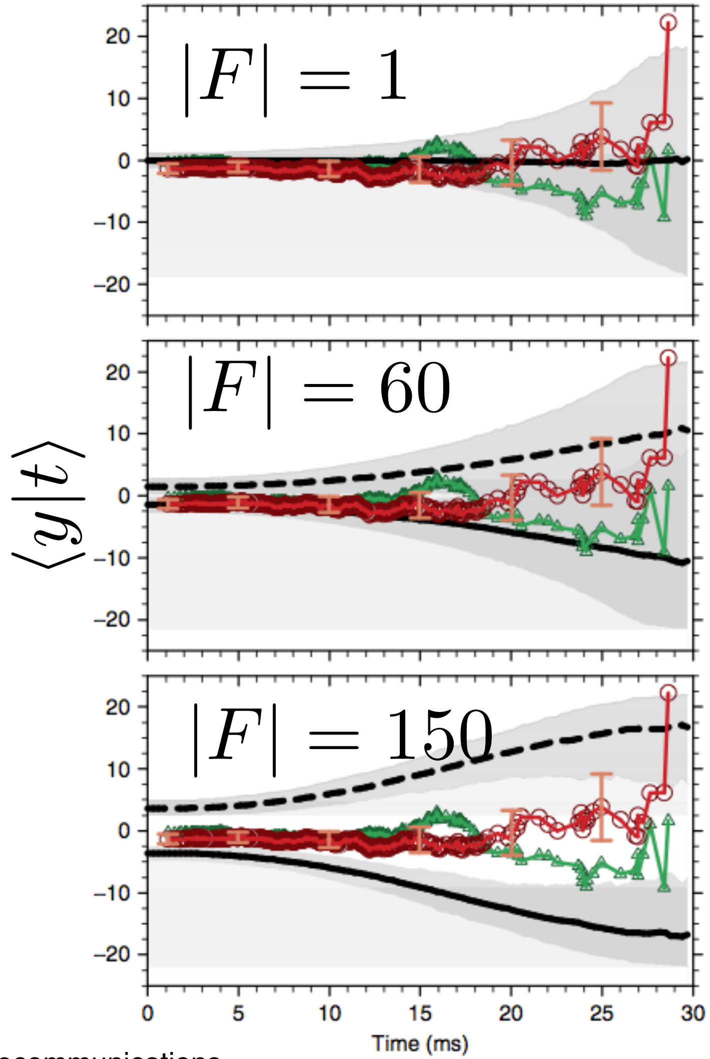
- Simulate various ***F**, exclude*

$$-65 < F < 110$$

- Not very precise!
  - short distance, hot population!

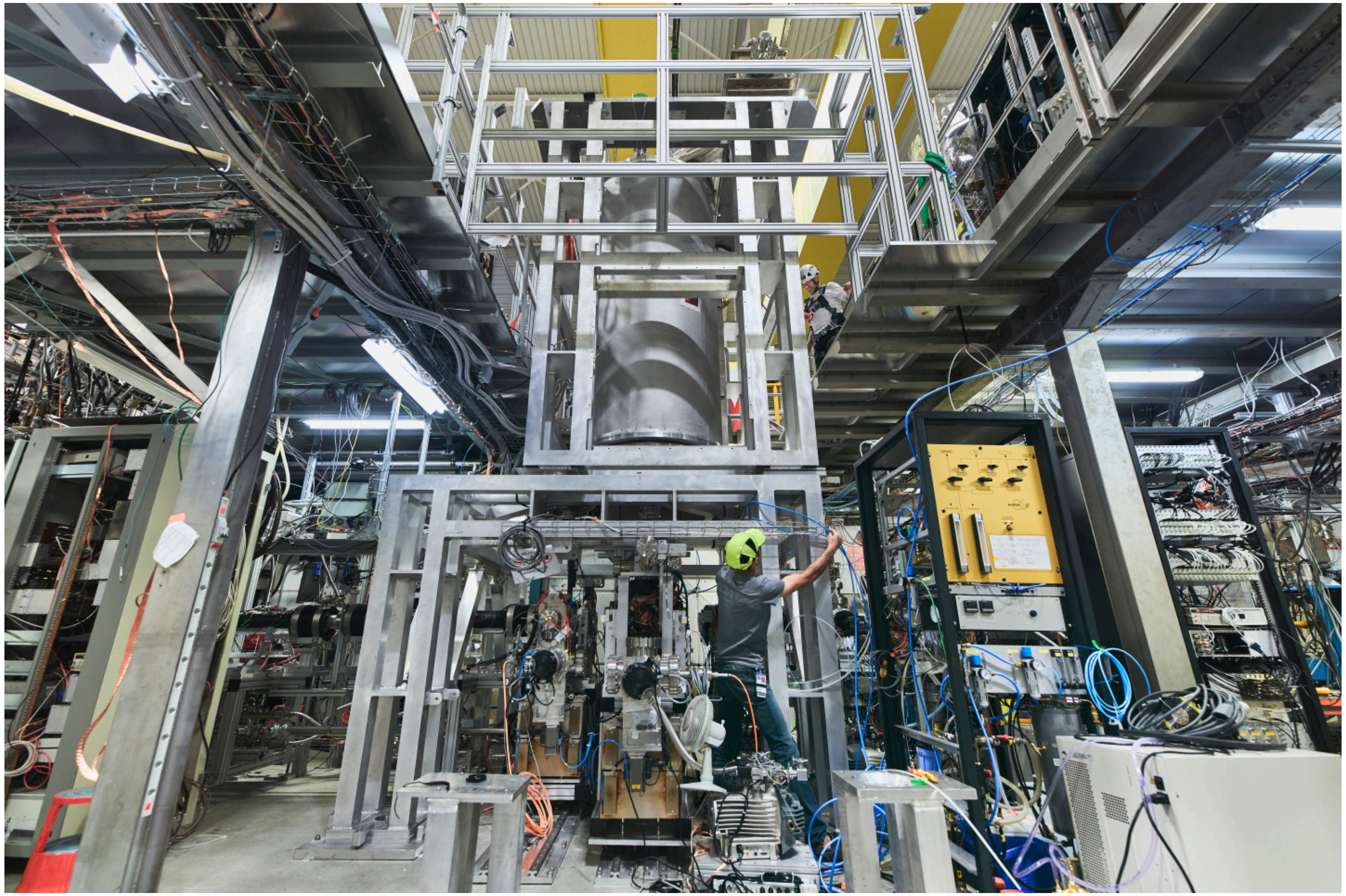
- ***Need over 200 meters for deflecting hydrogen!***

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



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

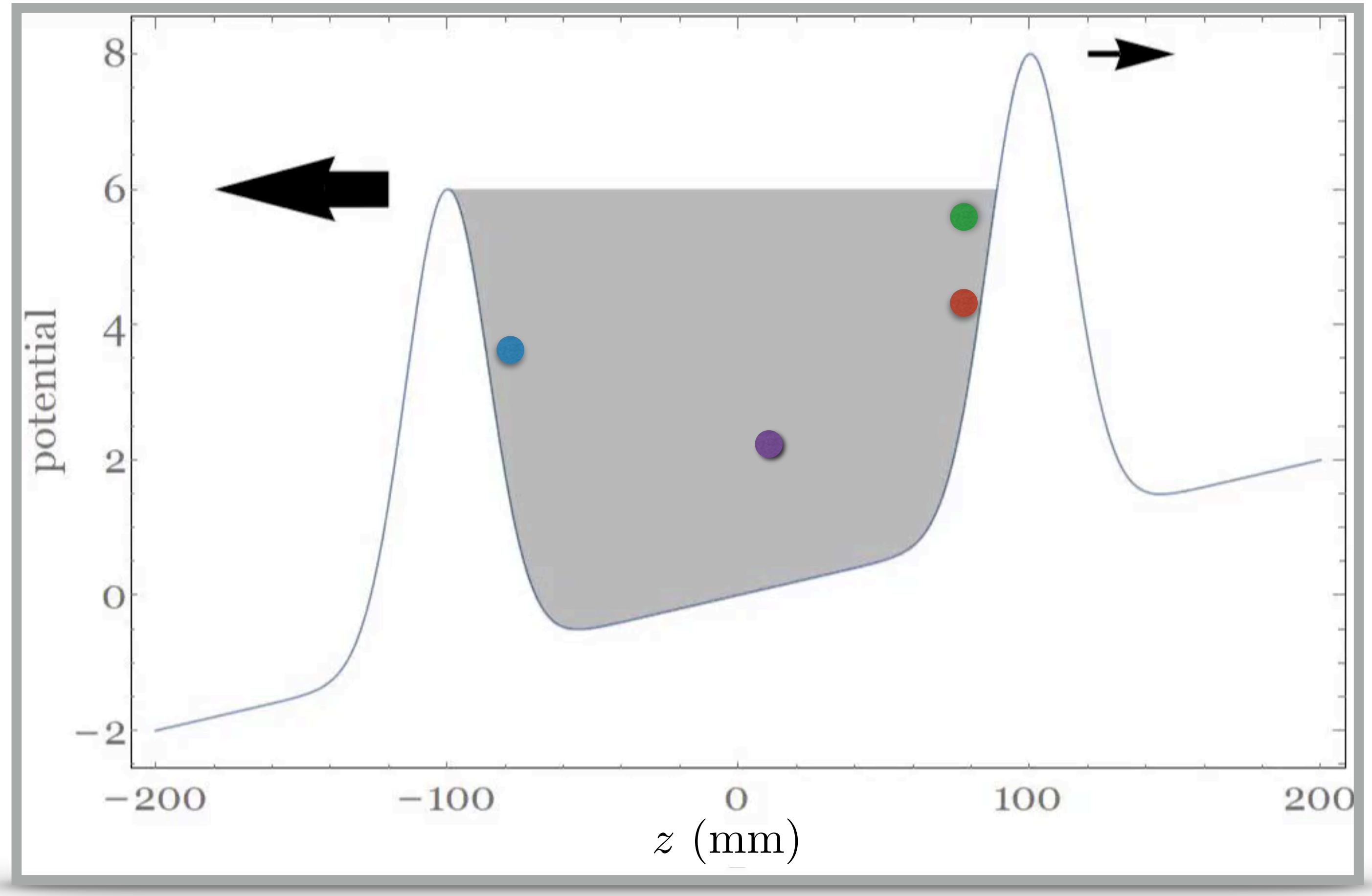
ALPHA-g: an antimatter gravity experiment



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

A simple Up / Down measurement: Matched fields

Magnetic + Gravitational potential



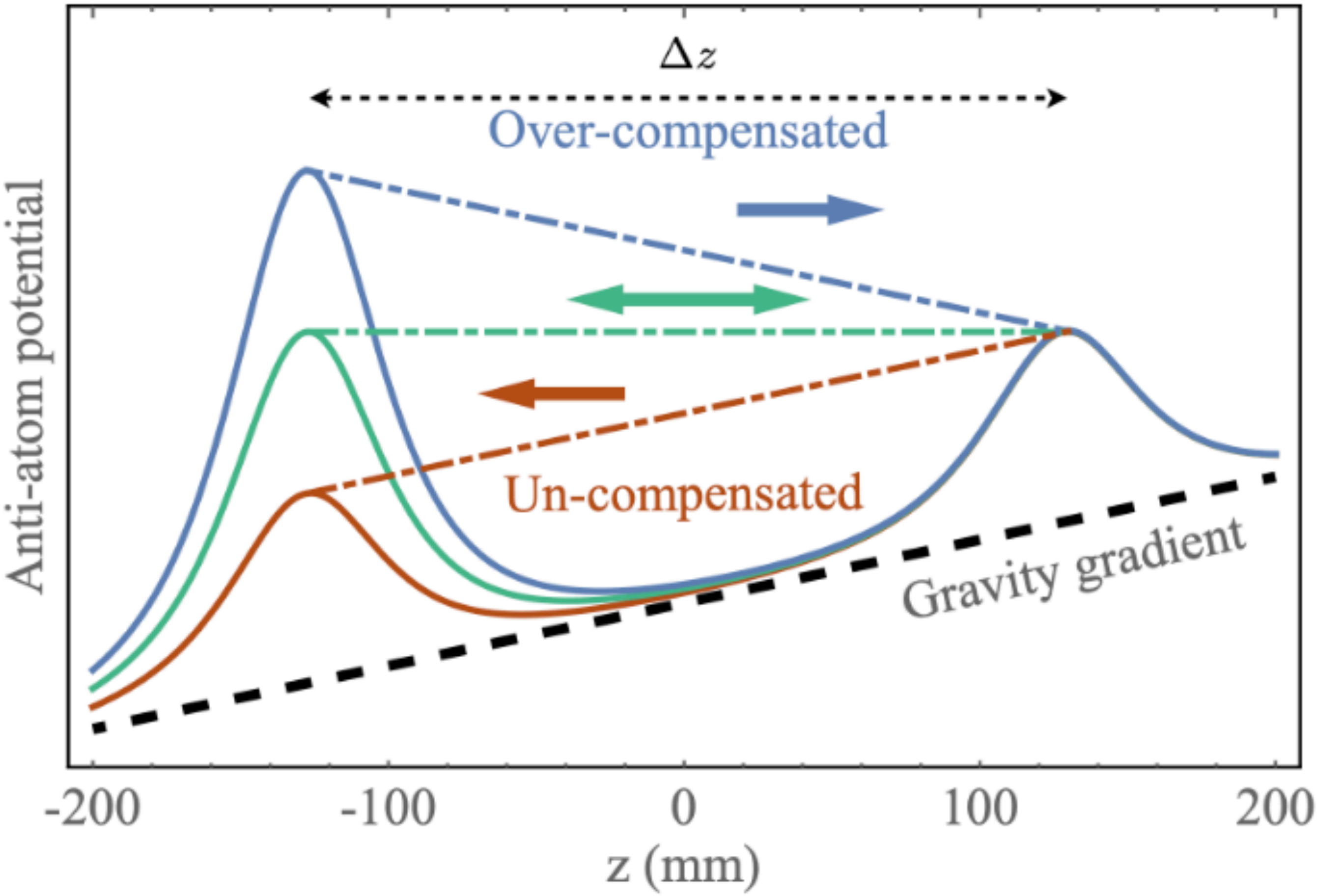
DOWN

UP

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

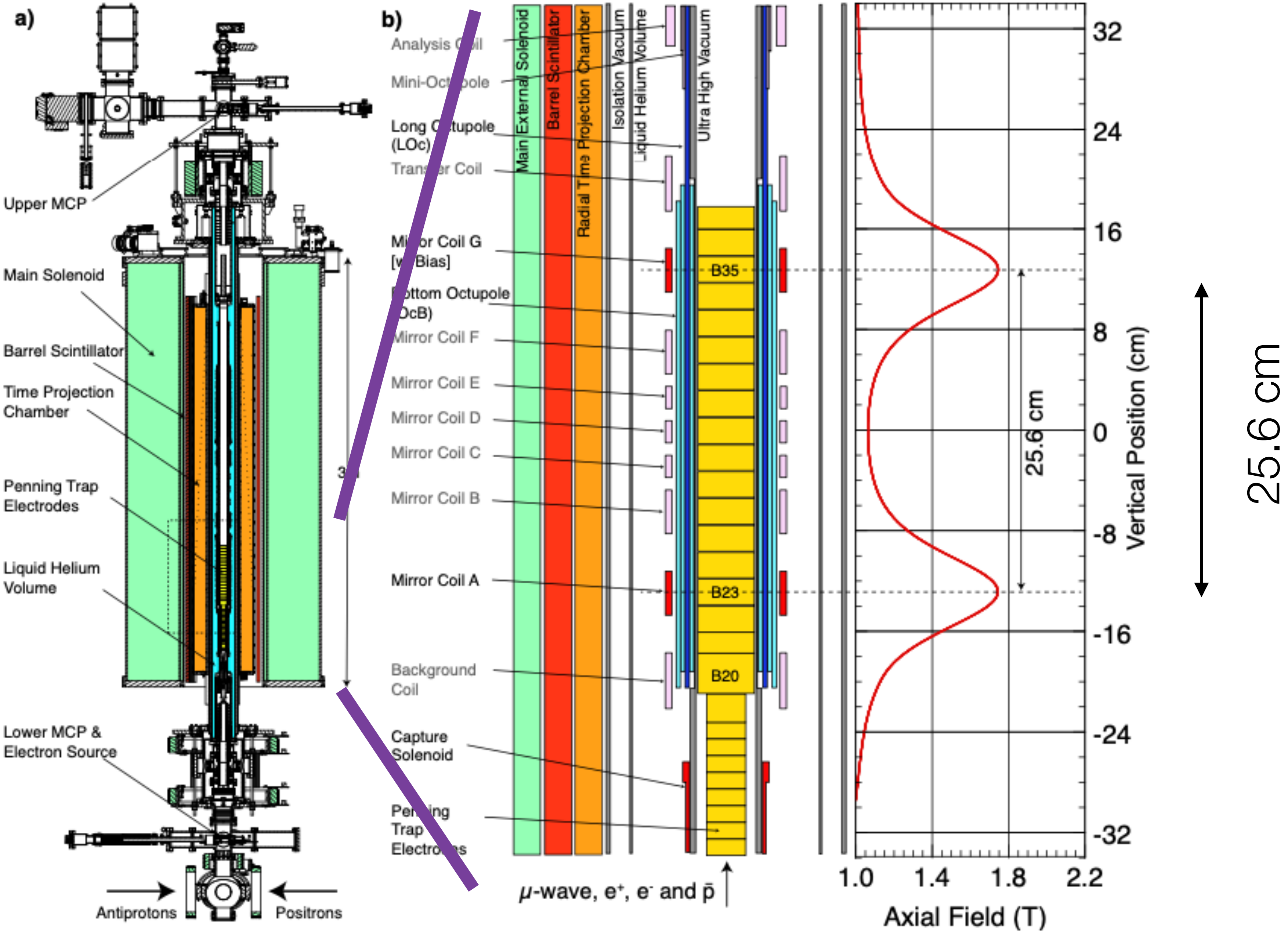
W. Bertsche, “Prospects for comparison of matter and antimatter gravitation with ALPHA-g”, RSTA, 376, 2116, 2018

A simple Up / Down measurement: Compensating "bias" fields



Matched,
Uncompensated
B-Field

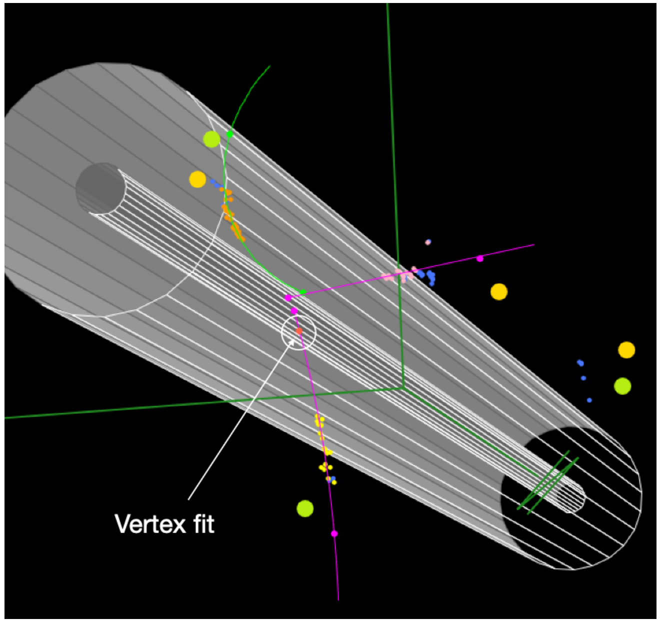
500 mK atoms:
~80% down,
~20% up

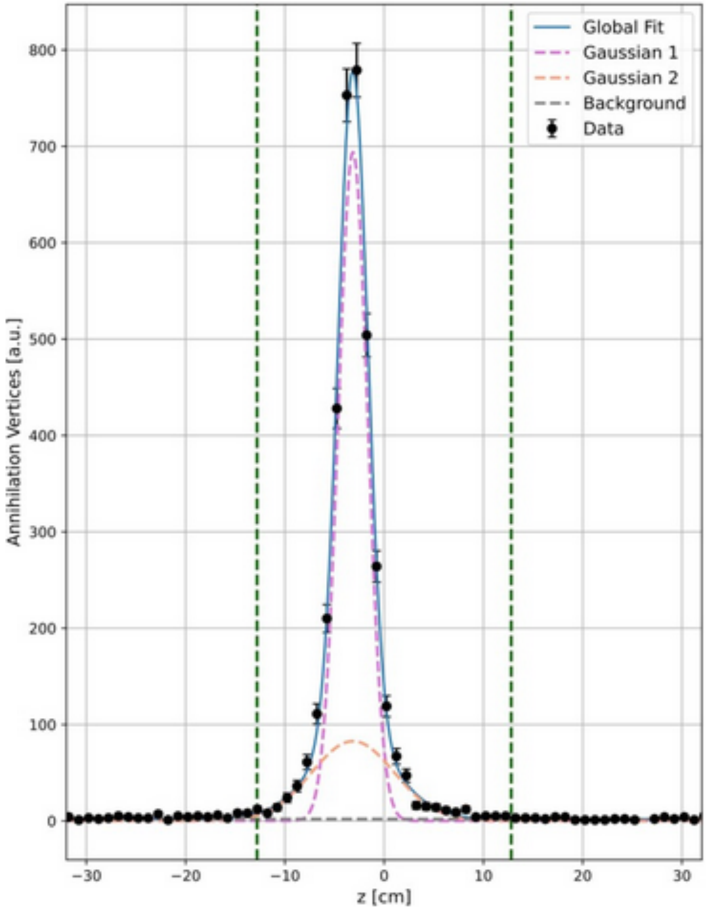


Birmingham HEP Seminar, May 2024

ALPHA-g Antihydrogen Detection

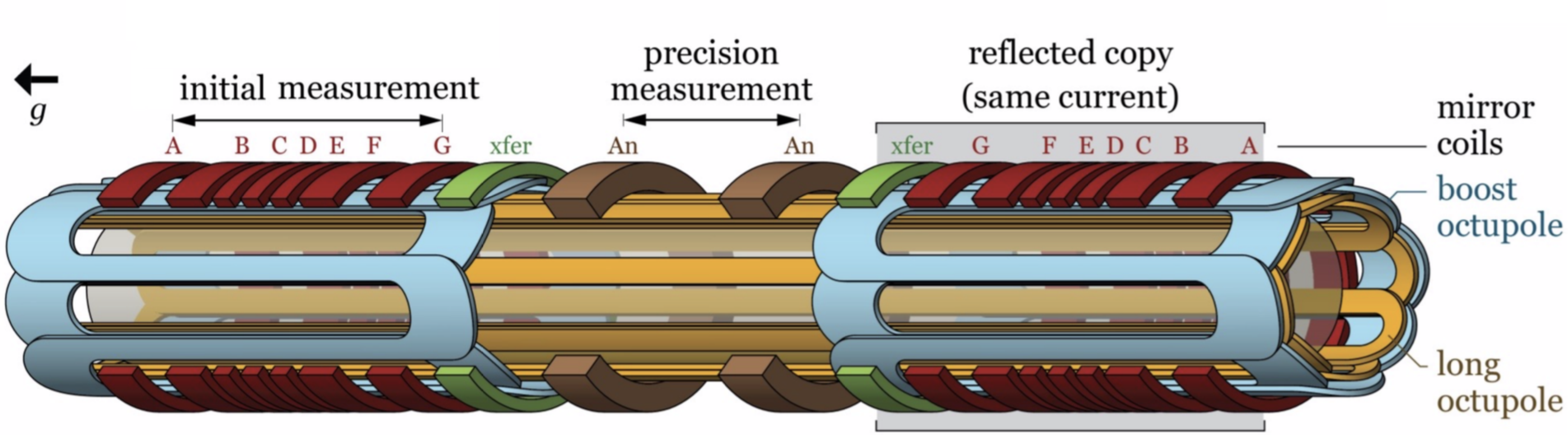
- Radial Time Projection Chamber (rTPC)
- Barrel Scintillator Veto (cosmics)
- *z*-resolution ~ **2 cm (<< 25.6 cm)**





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



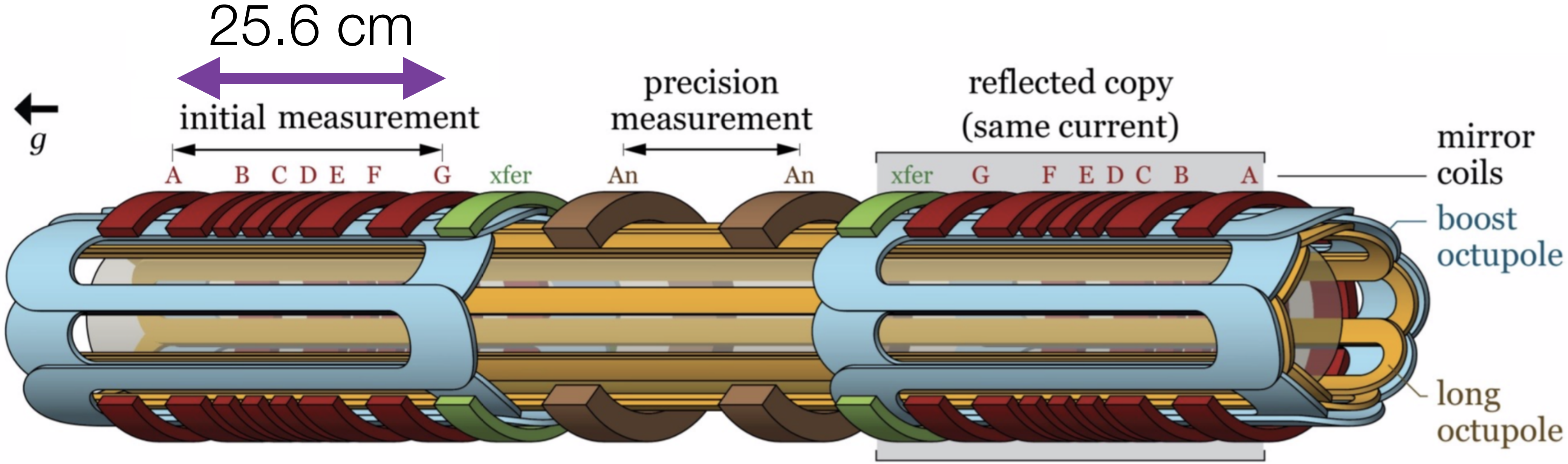
Magnetic Balance

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

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

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

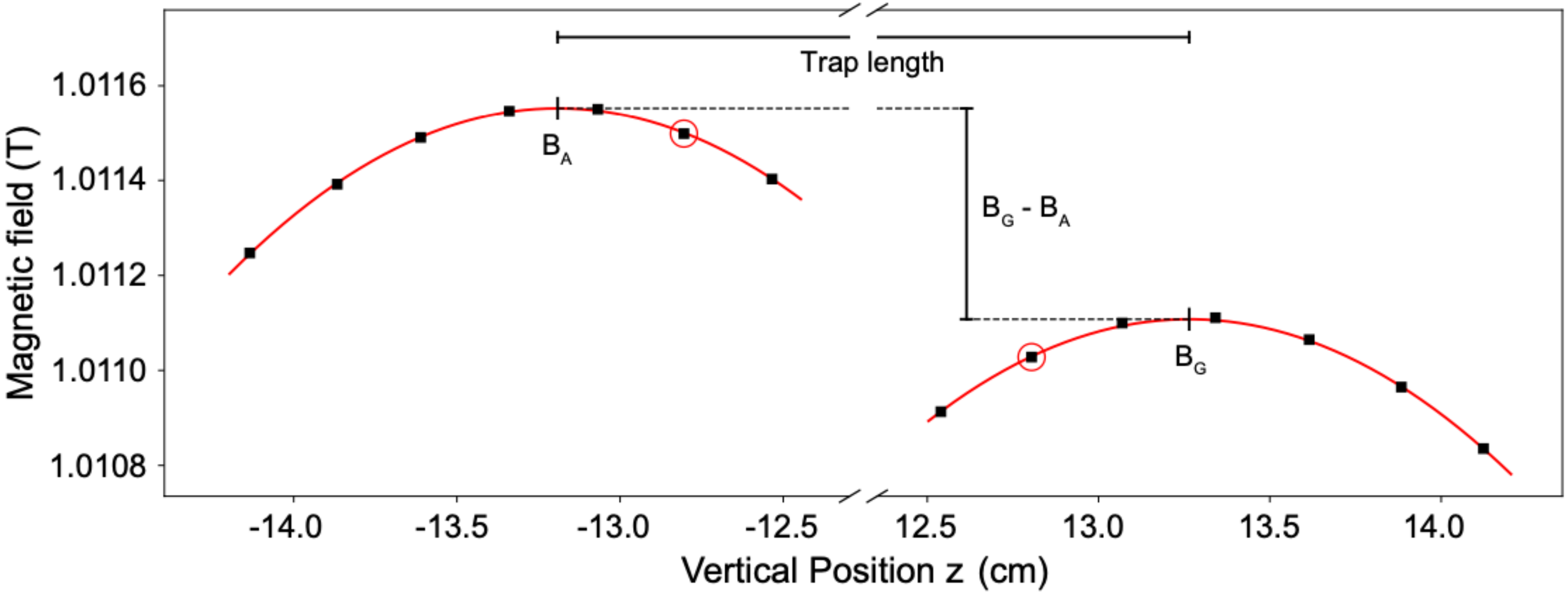
$$\Delta U_g \sim 300\,\mu\text{K}$$



Magnetic Balance

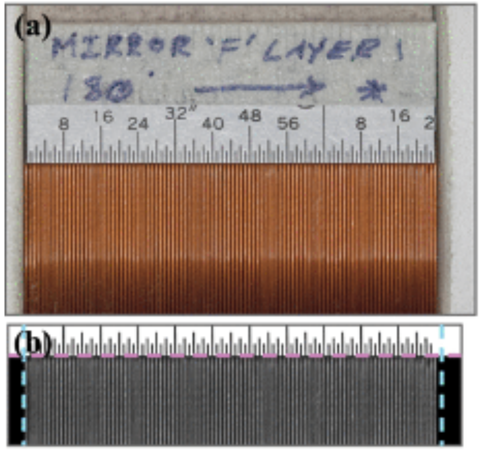
- 1 g balance bias ~ -4.5 Gauss
- Nominal bias from field map

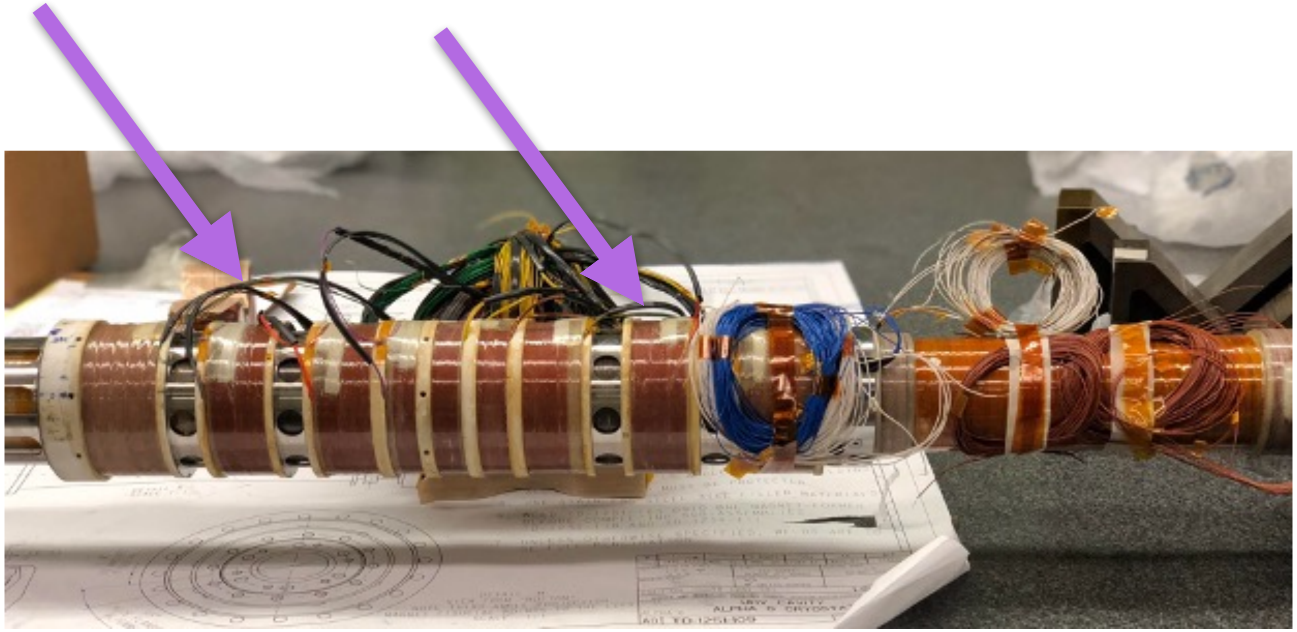
$$\text{bias} = \frac{\mu_B \left(B_G - B_A\right)}{m_H \left(z_G - z_A\right)}$$



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



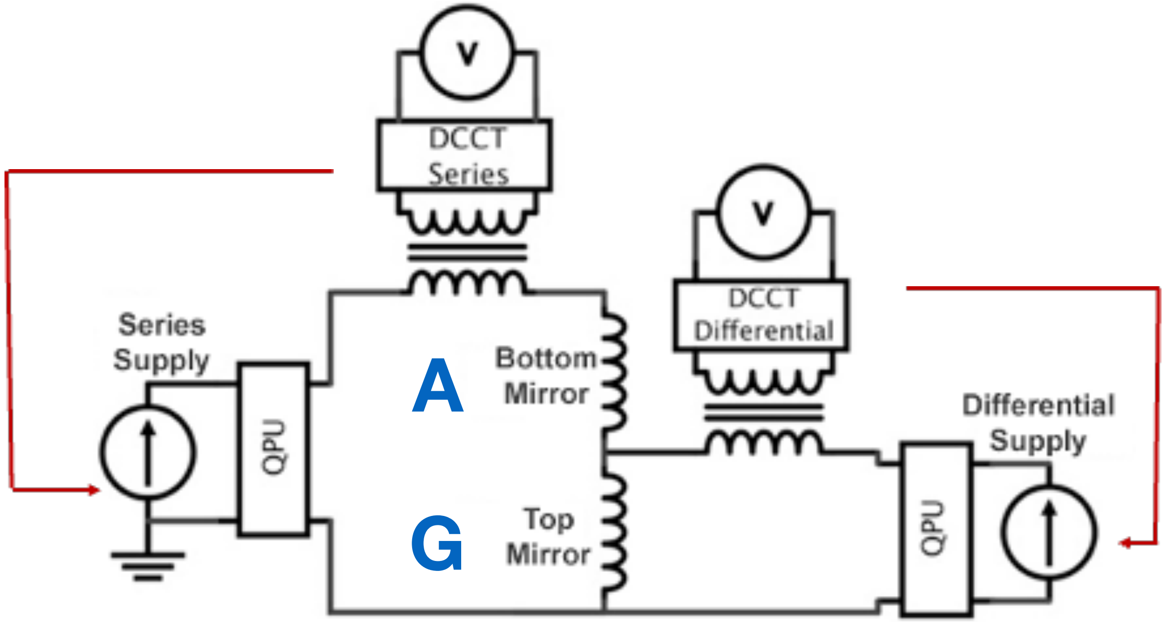


Magnet Current Control: Controlling a Bias

- **Importance is *difference* current**
- Main mirror **A+G** currents ~ 70 A in series
- Bias + correction on **G** by parallel “Tickle” supply
- Sub-mA continuous control is required

Main

70 A



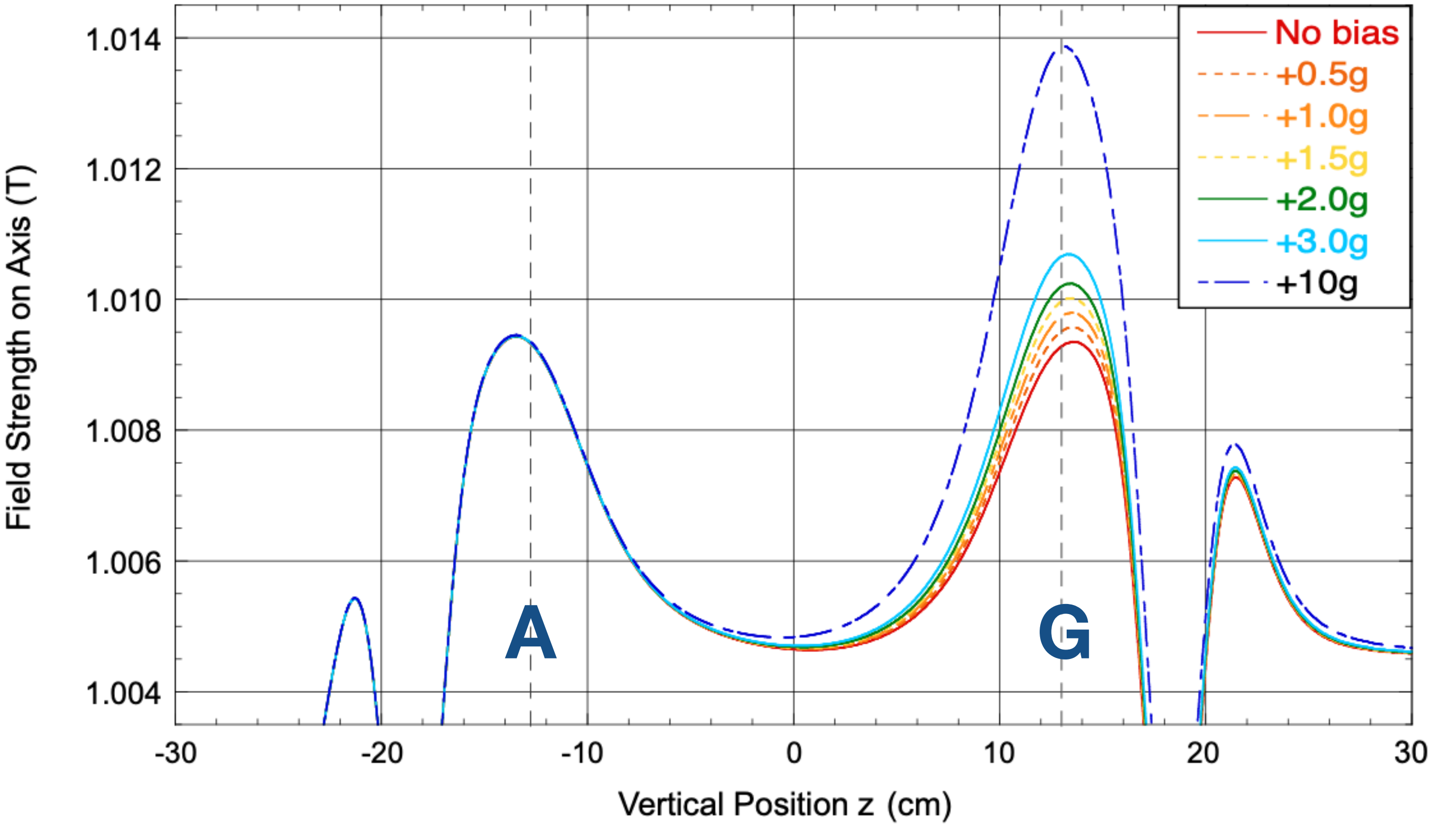
Tickle

+/- 1 A

Magnetic Balance

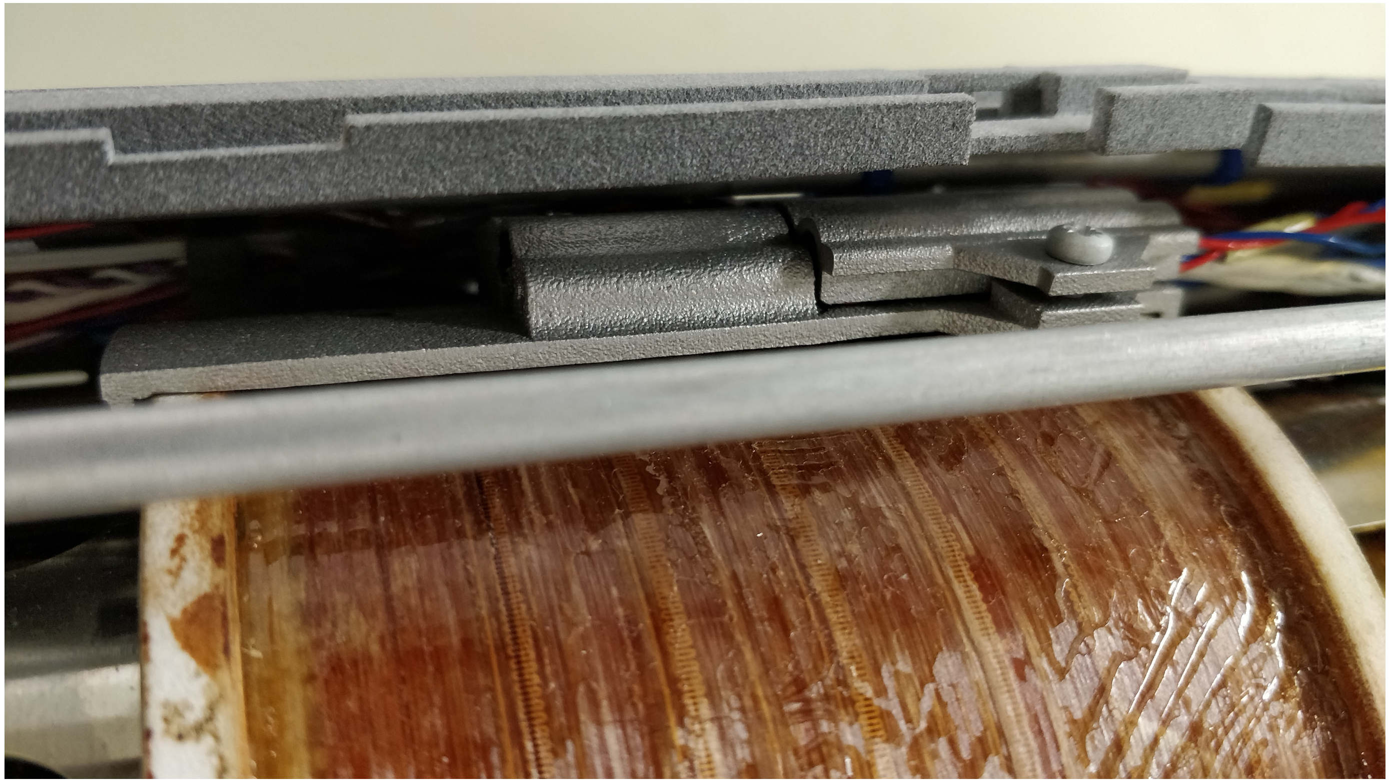
- 1 g balance bias ~ -4.5 gauss

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



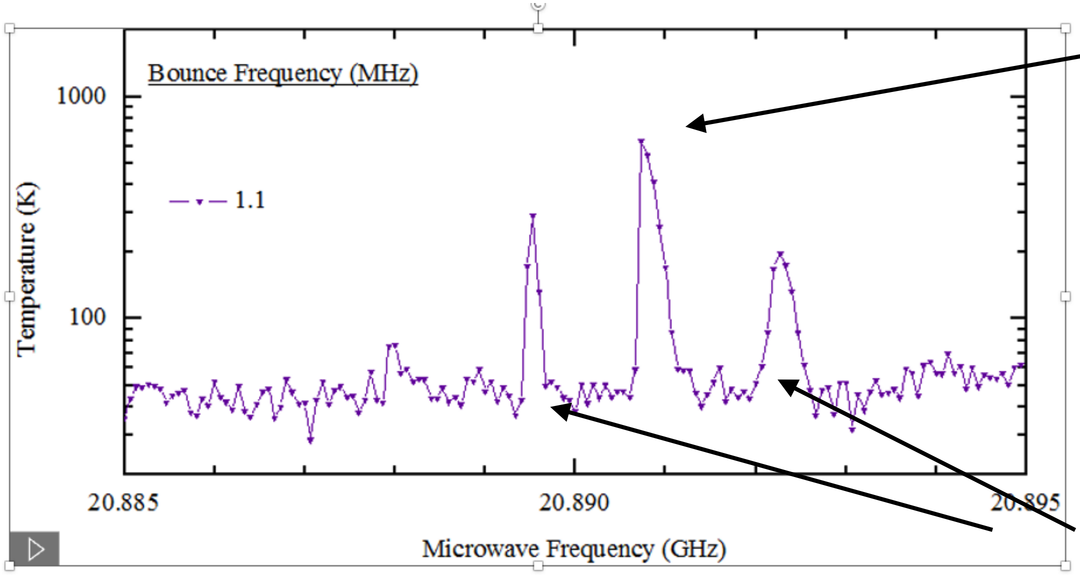
Magnetic Field Measurements: Probes

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

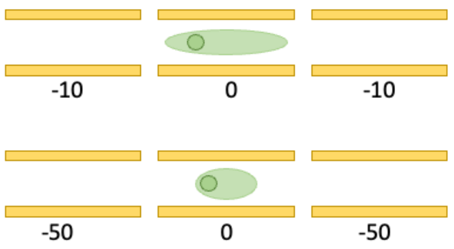


Magnetic Field Measurements: ECR

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



Main ECR resonance

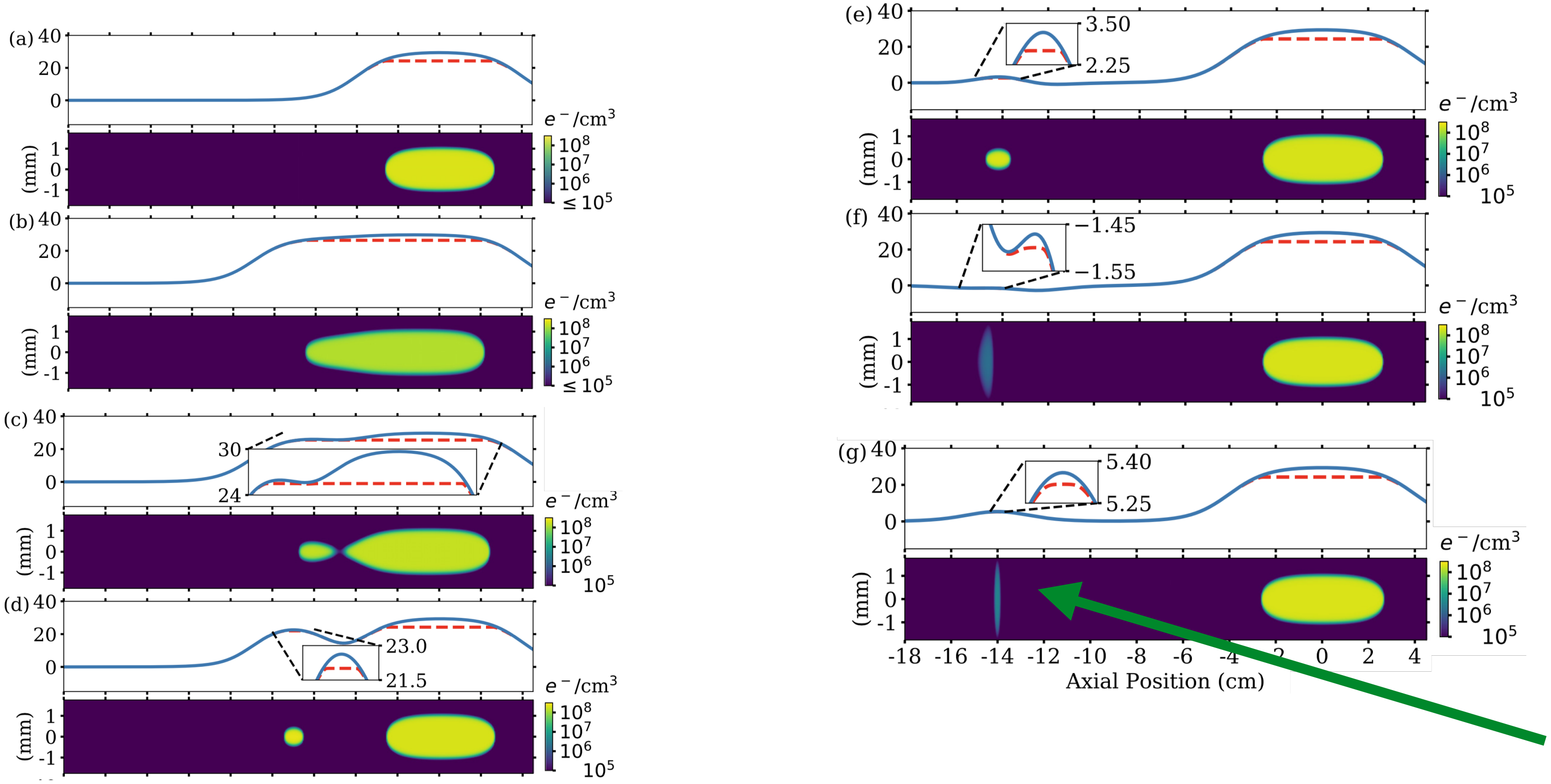


Bounce Resonances

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)



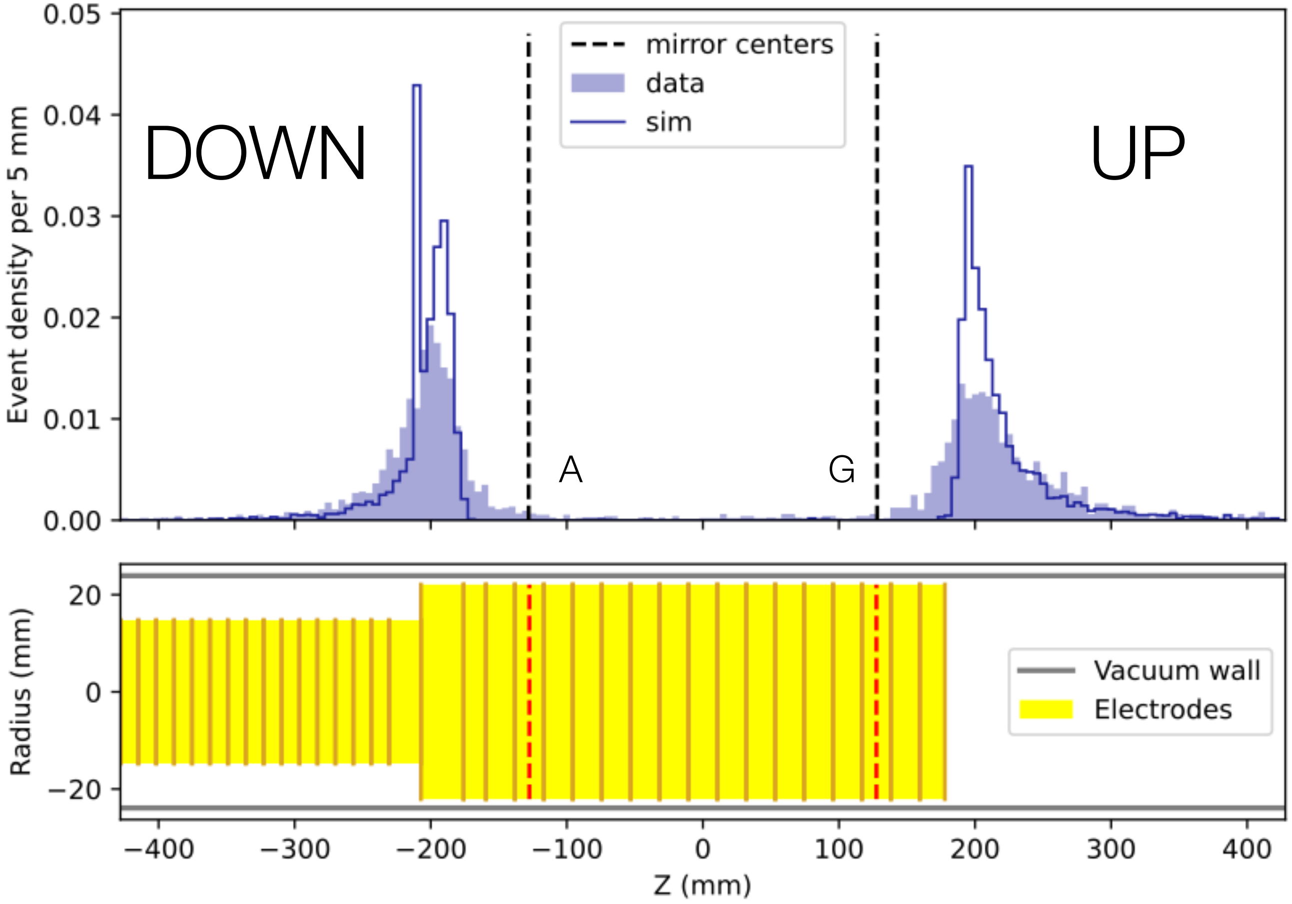
Microwave
Illumination
Here

Gravity Experiment

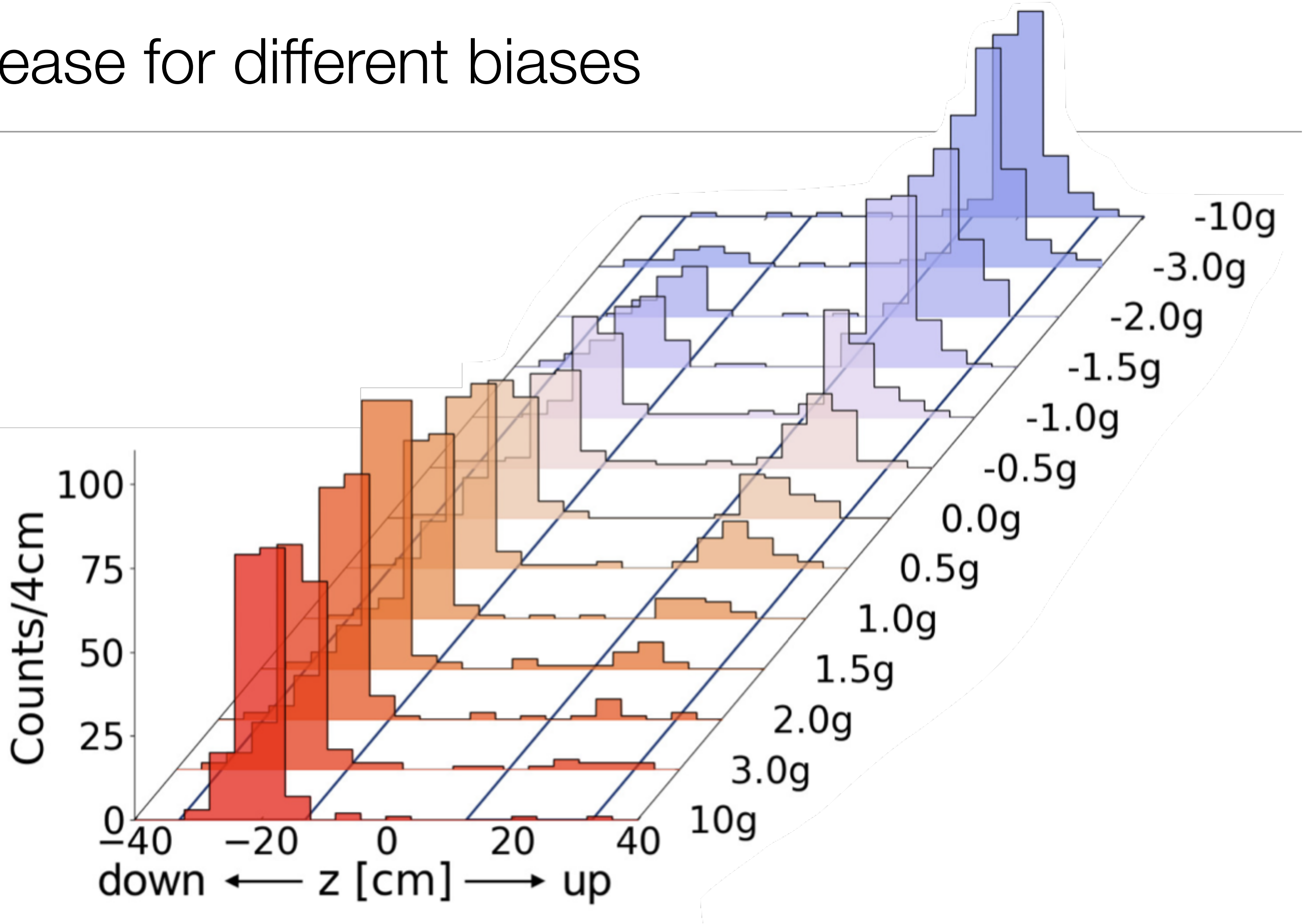
- Make, trap and stack antihydrogen (~ 50 stacks)
- Ramp down long octupole
- Measure magnetic field at full trapping current + bias
  - Under Mirrors A and G
- Ramp down to ~ 10’s Gauss residual trap (~ 18 s)
  - Maintain constant magnetic bias (current control)
- Identify up/down annihilation events along the way.
- Measure magnetic field again (check bias)
- Repeat for many magnetic biases
  - Statistics collected for ~ 300 Hbar per bias (~ 7 trials each bias)

Annihilation events

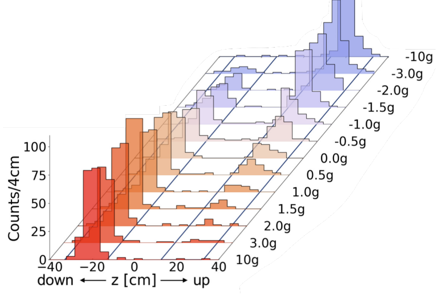
- Escaping antihydrogen leave going Up or Down
  -

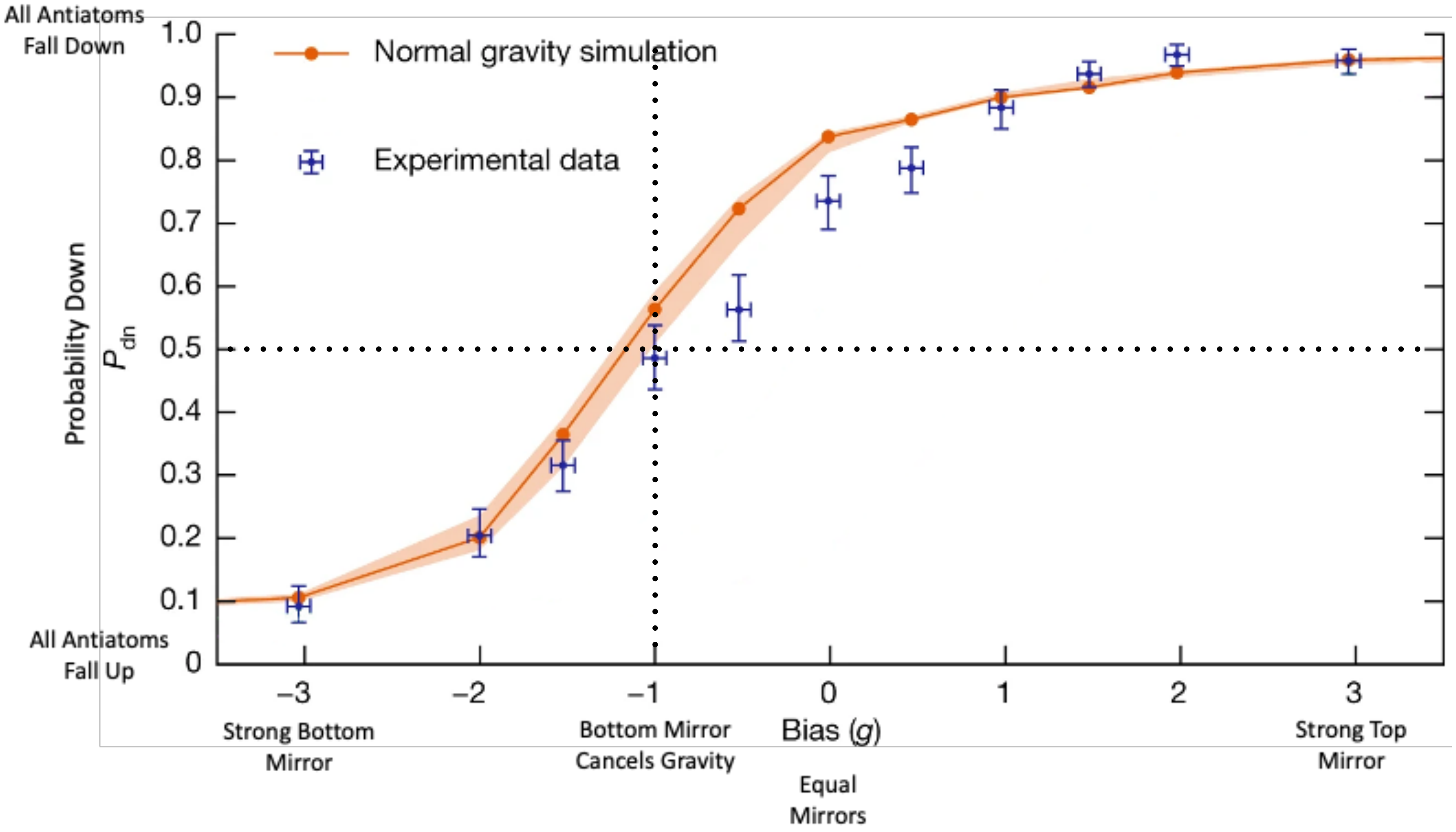


Release for different biases

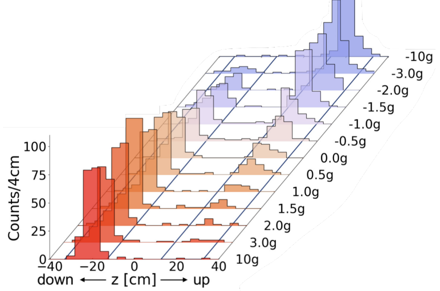


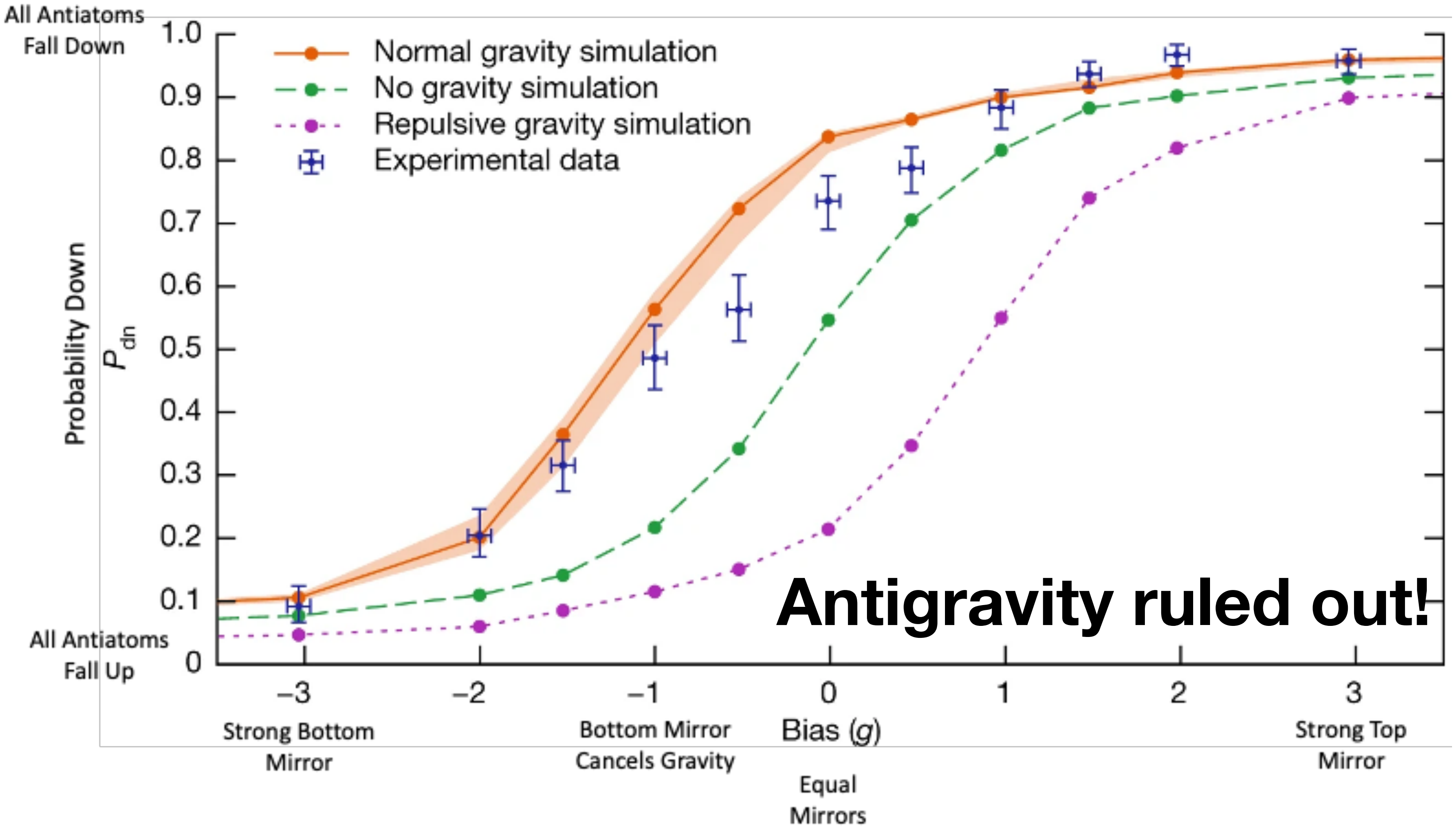
Release for different Biases



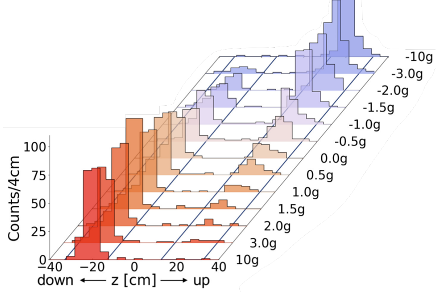


Release for different Biases





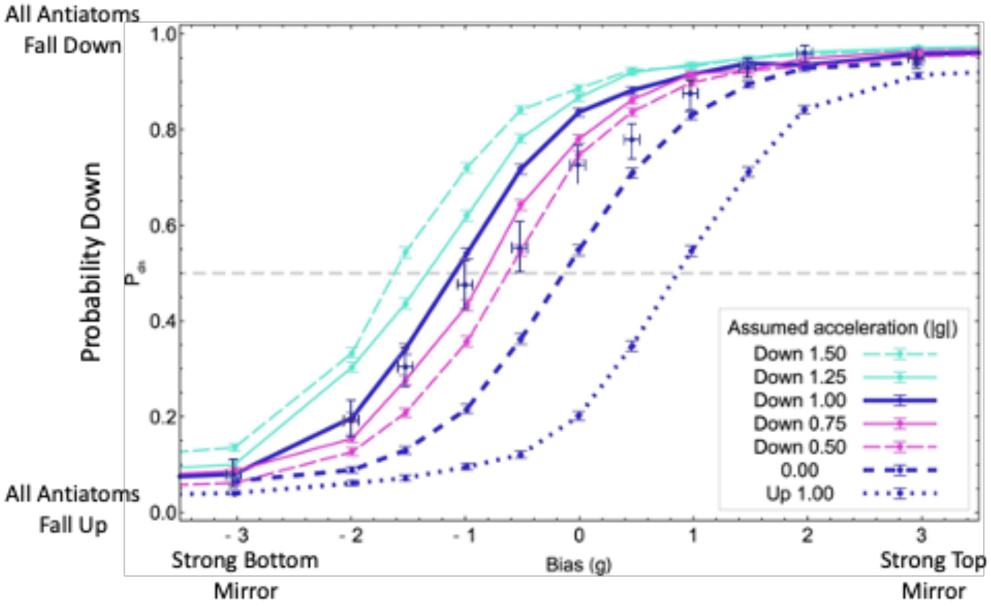
Antigravity ruled out!



Calculating Antimatter g

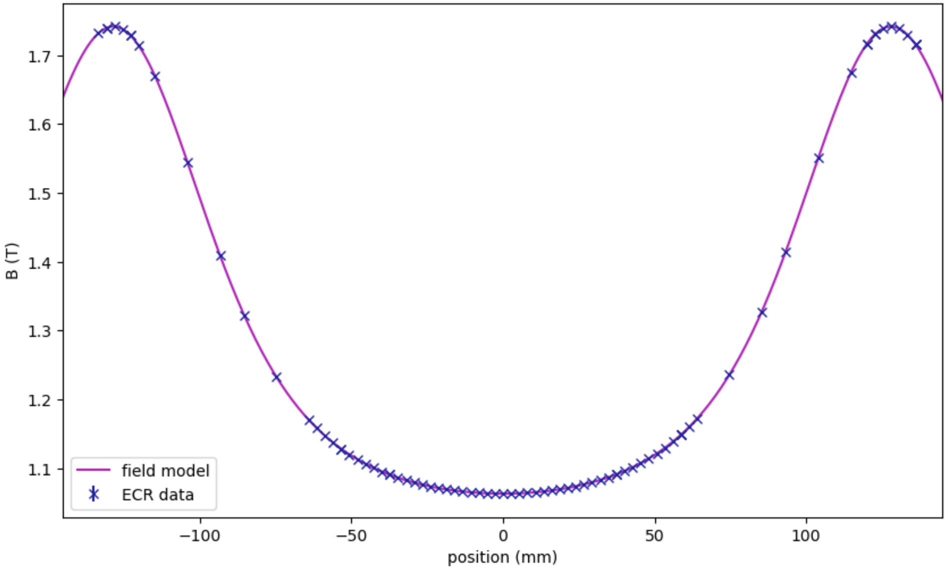
- Perform numerous simulated accelerations
- Find best fit to data

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



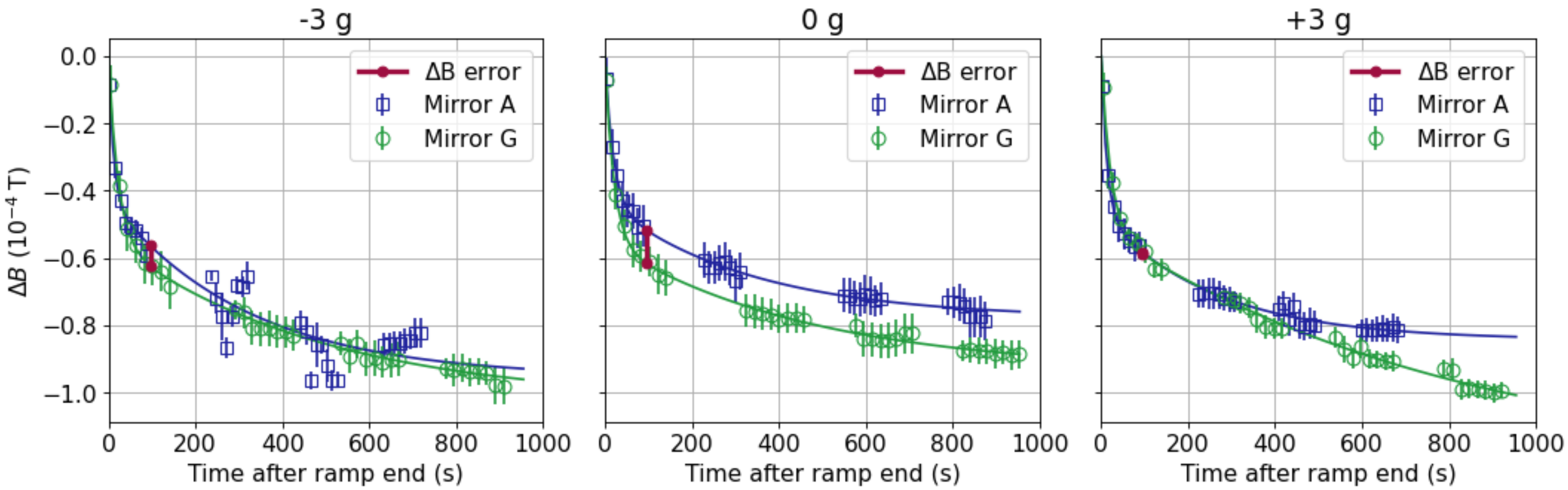
Limits to the measurement: field measurements

- Need to model both controlled currents, and uncontrolled **persistent currents**.
- Induced **persistent currents**: ~ 10 Gauss on axis *(recall, 1 g bias is ~4.5 G!)*



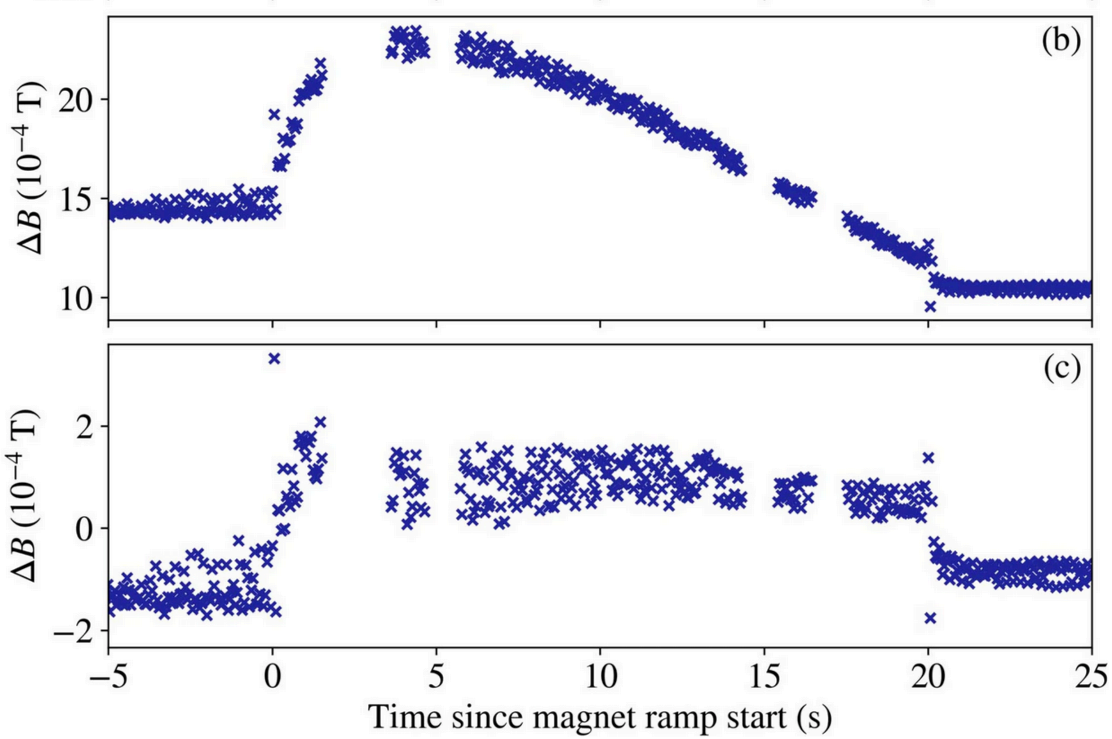
Limits to the measurement: field measurements

- 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 for error



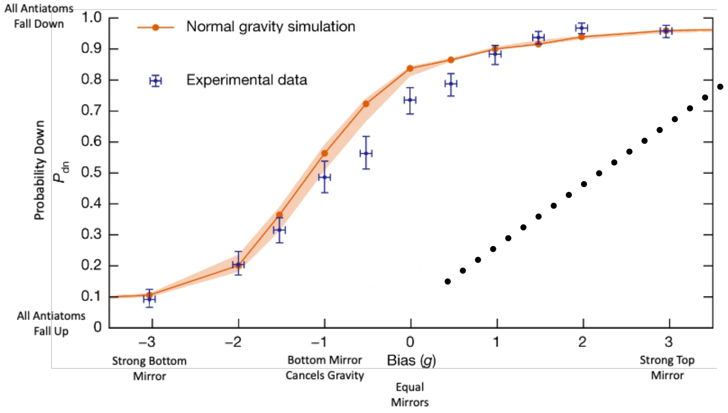
Limits to the measurement: field measurements

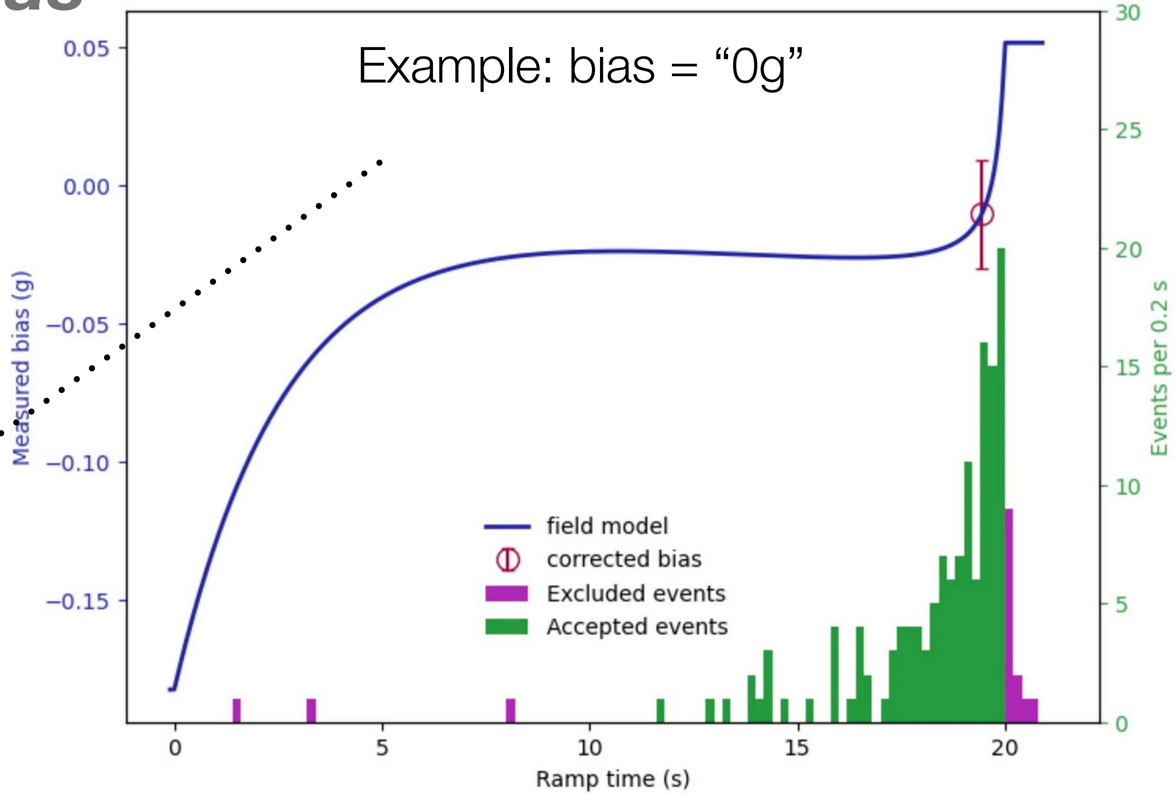
- Persistence currents during ramp
- Imaged Electron Magnetron Frequency: time-resolved B-field during a given release



Limits to the measurement: Bias time dependence

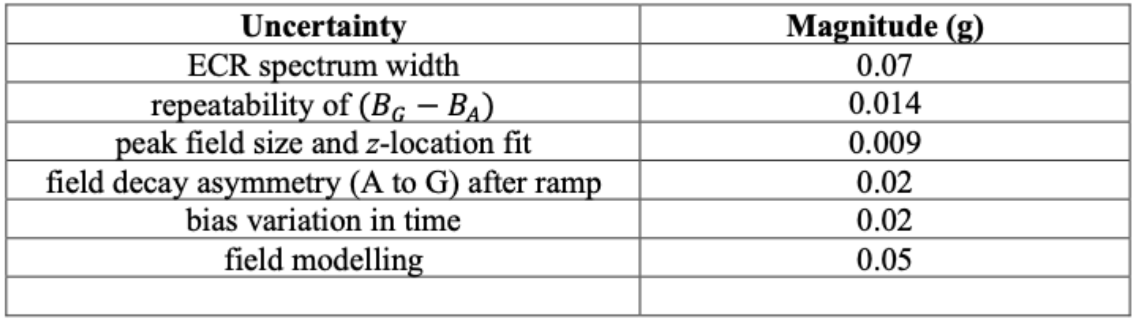
- Experiment bias: linear *current difference*
- Geometry of magnets + persistence currents results in a ***time-dependent bias***
- Field for simulation
- Weighted mean: “***bias label***”



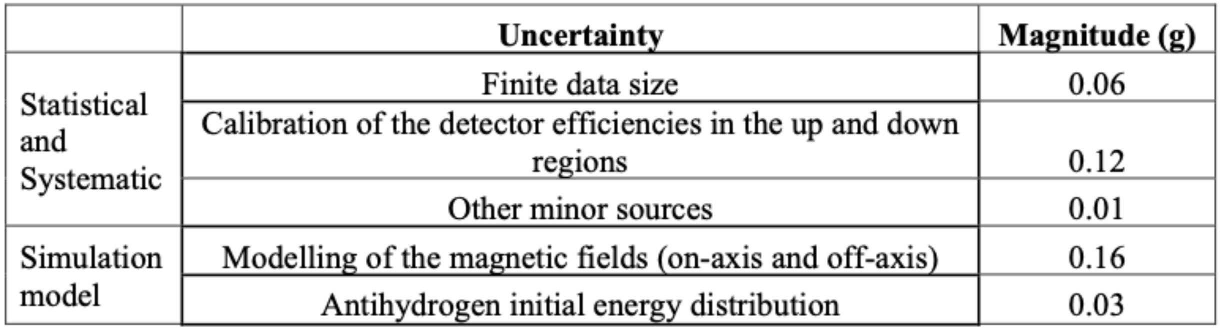


Uncertainty tables

- 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

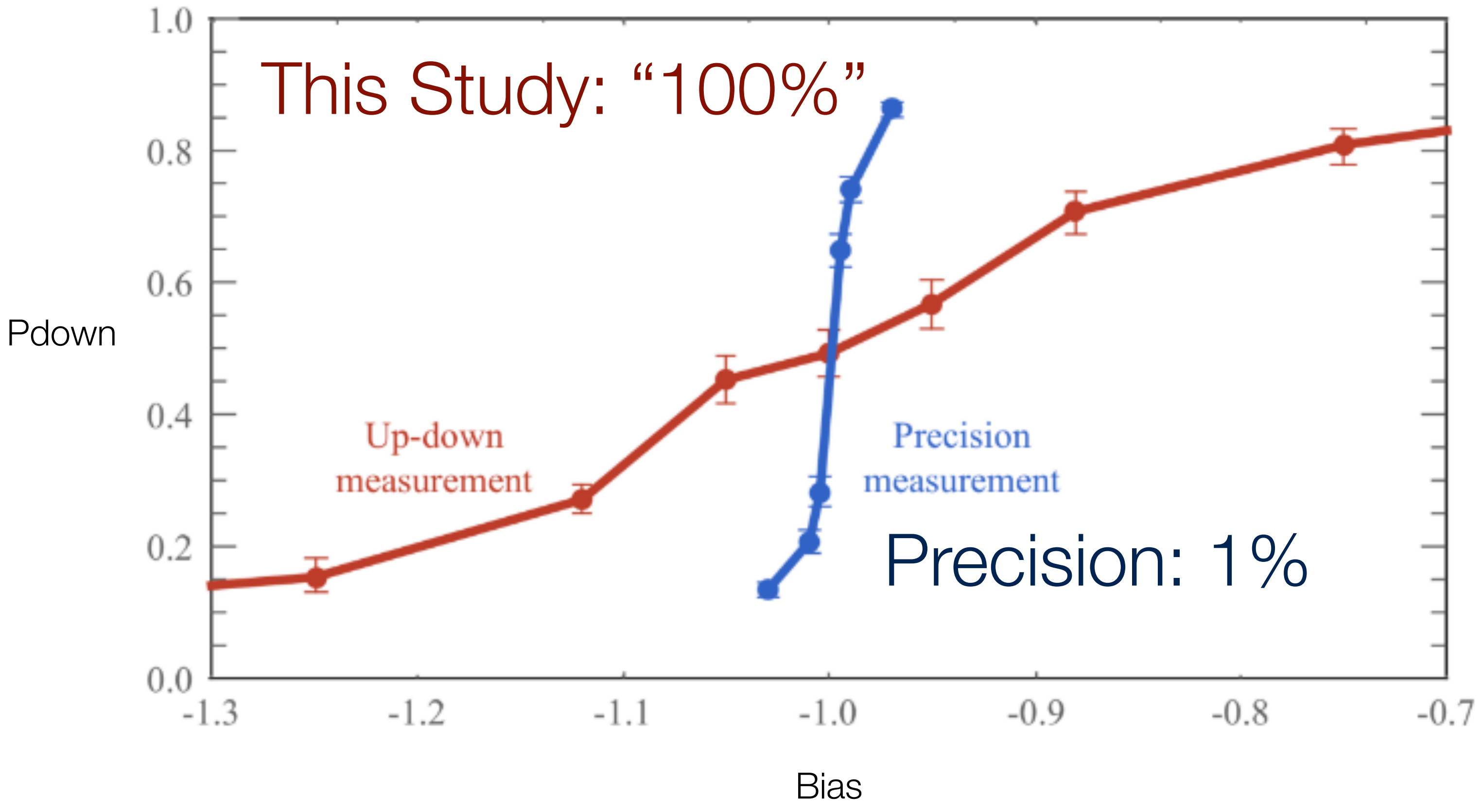


	Uncertainty	**Magnitude (g)**
Statistical and Systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03

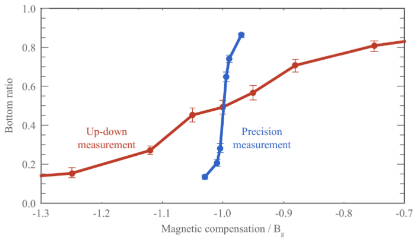
Future prospects with ALPHA-g:
1% Measurements

- Make the release curve steeper

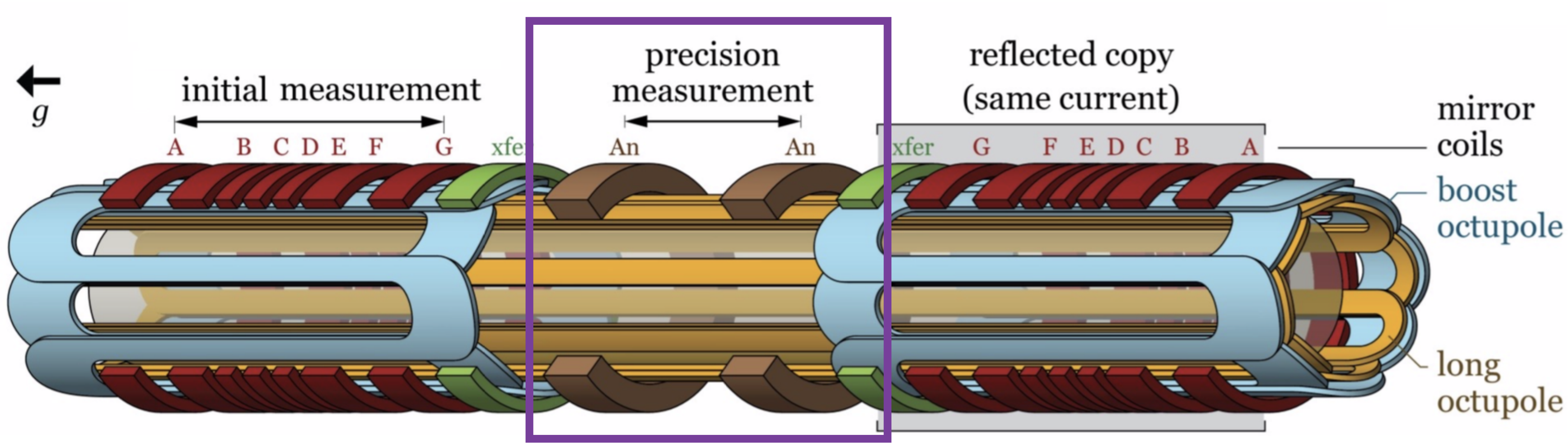
Simulated Release Experiments



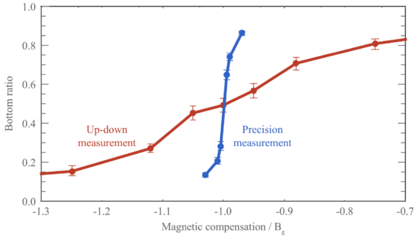
Future prospects with ALPHA-g: 1% Measurements



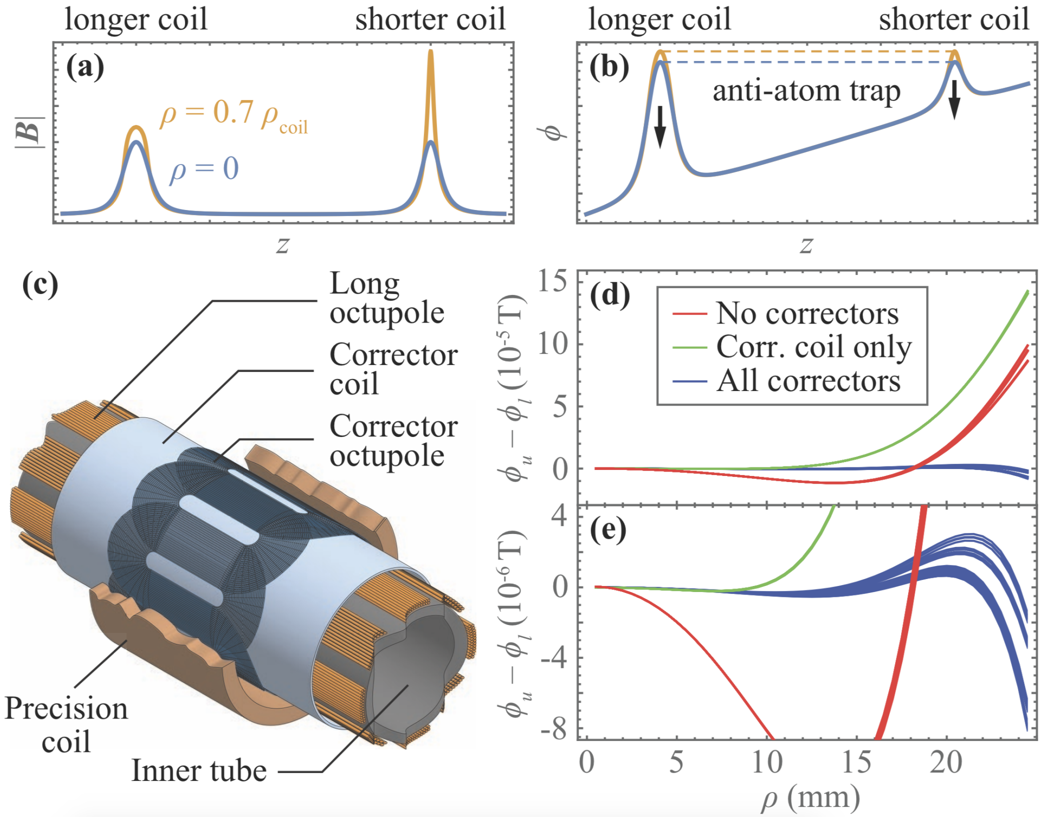
- Precision region
  - symmeterizes superconducting material
  - + detection geometry
  - Improves shape of applied bias potential



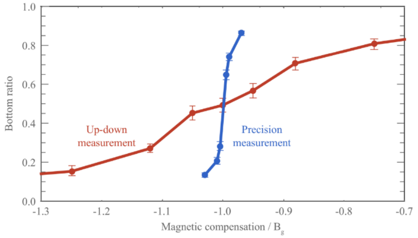
Future prospects with ALPHA-g:
1% Measurements



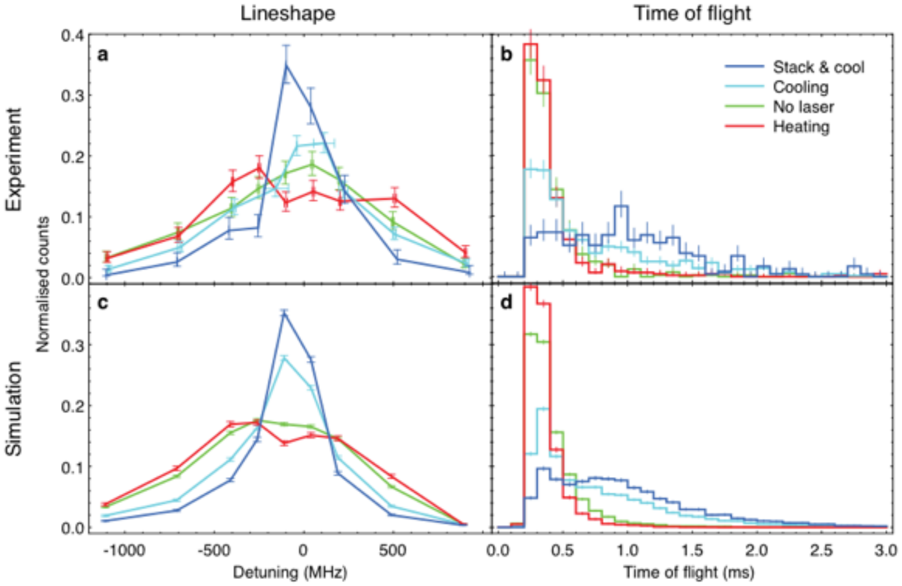
- Generally, escape bias is a function of escape radius
- Additional correction coils to “flatten” escape bias



Future prospects with ALPHA-g: 1% Measurements



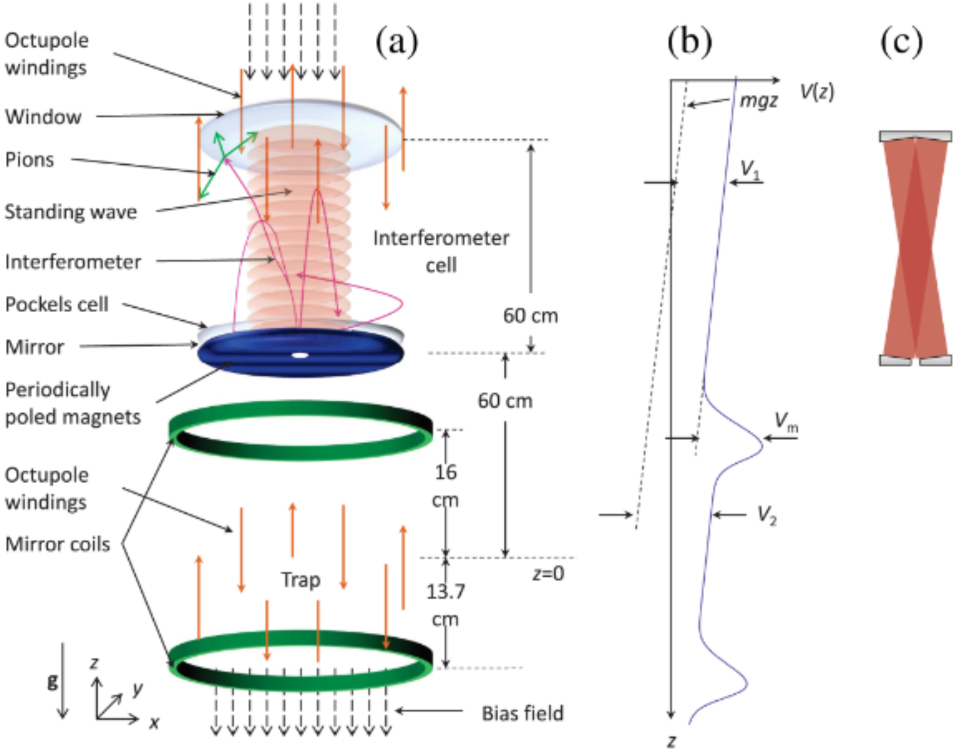
- Improve distribution: Doppler Laser Cooling
- Slower atoms more sensitive to potential
- avoid off-axis fields
- 500 mK > 20 mK > 300 uK (gravitational PE)



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*



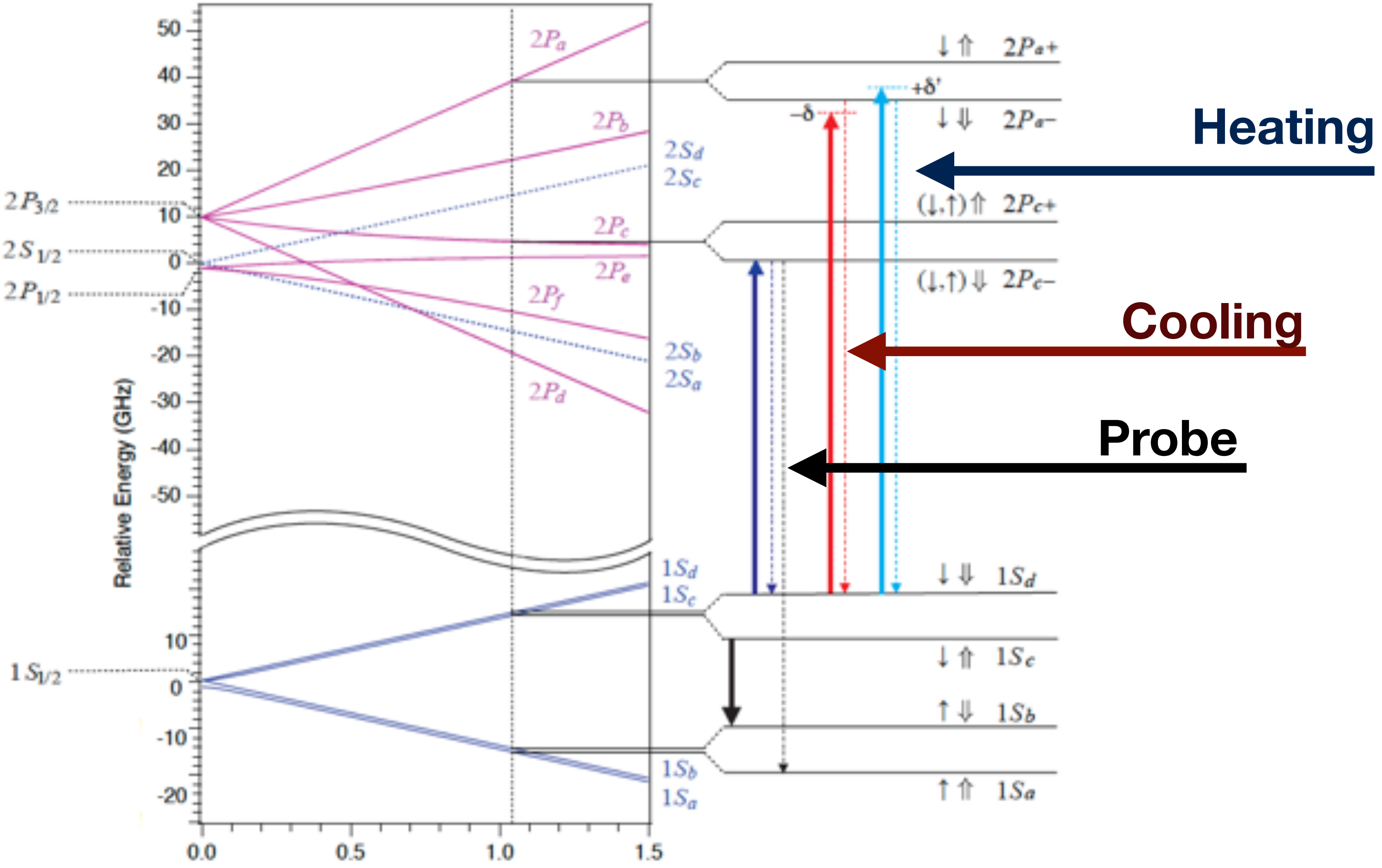
P. Hamilton, A. Zhmoginov, F. Robicheaux, J. Fajans, J. S. Wurtele, and H. Müller
Phys. Rev. Lett. 112, 121102

Thanks for your attention!

Anti-Apple

Earth

Antihydrogen Laser Cooling: Closed transitions

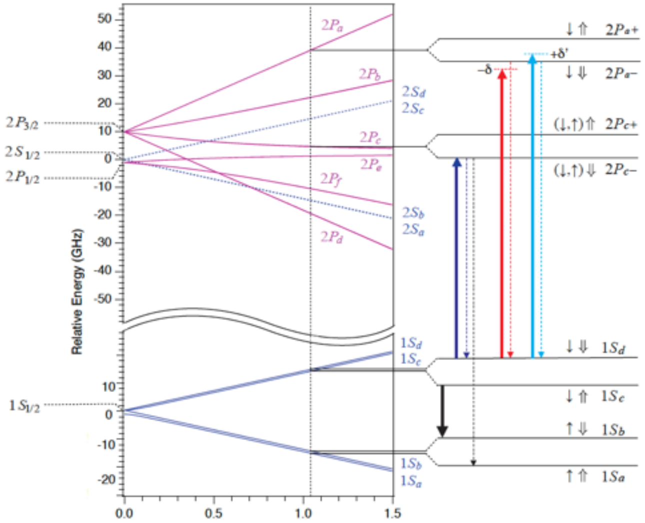


Heating

Cooling

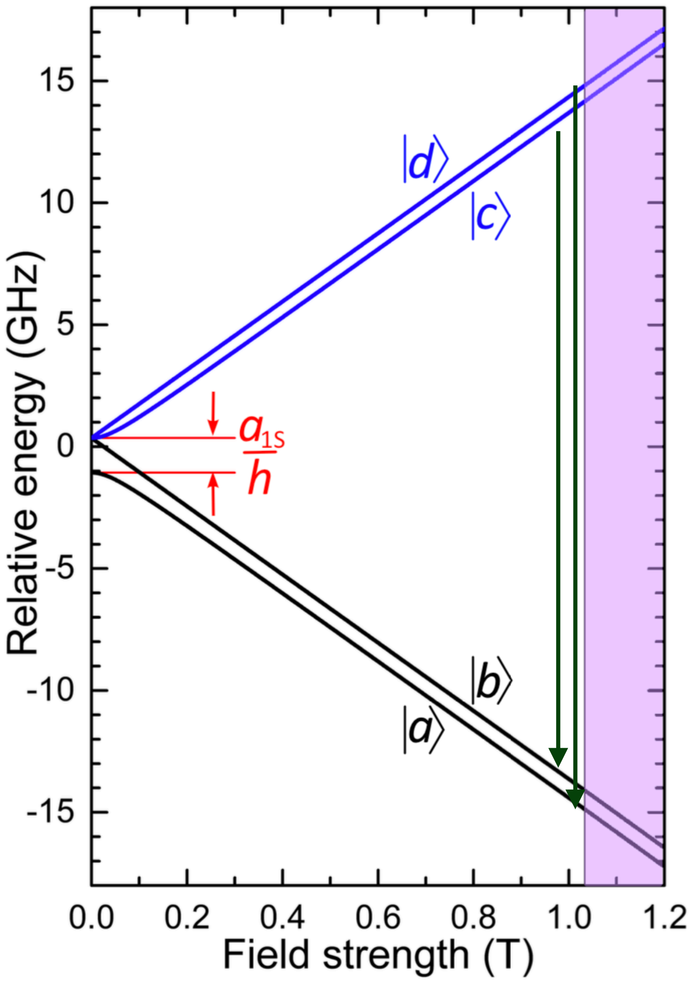
Probe

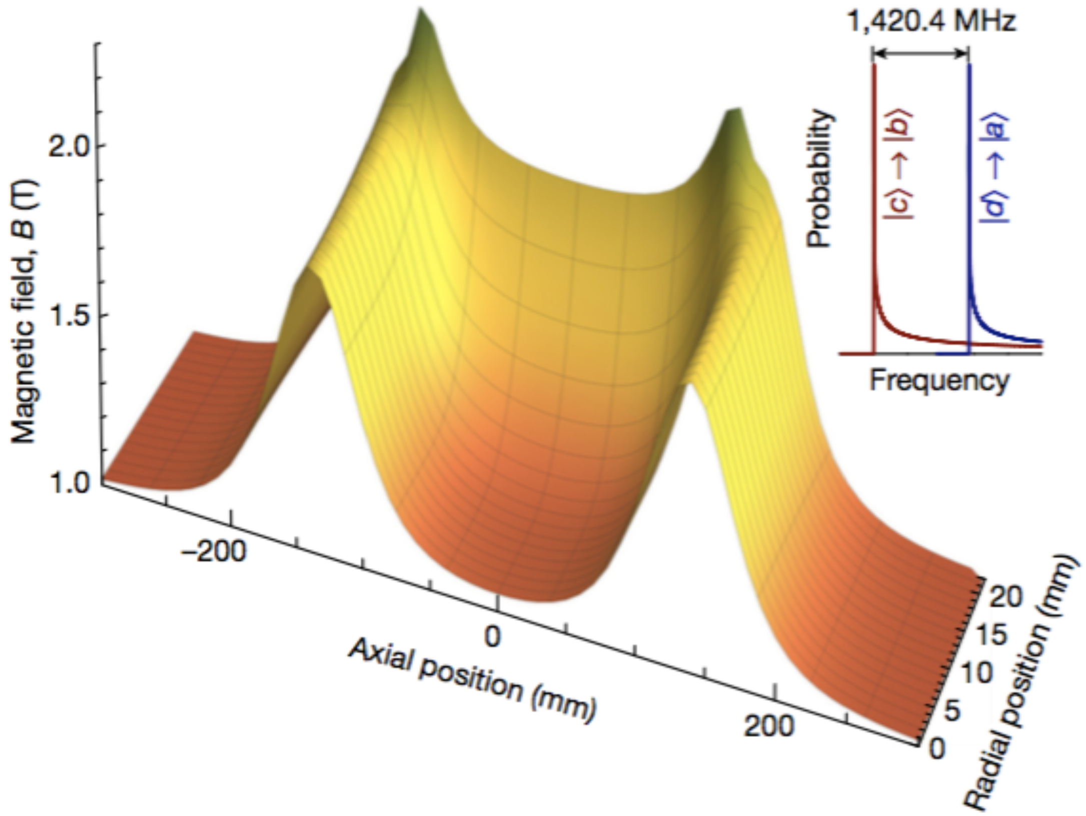
Antihydrogen Laser Cooling



- 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:

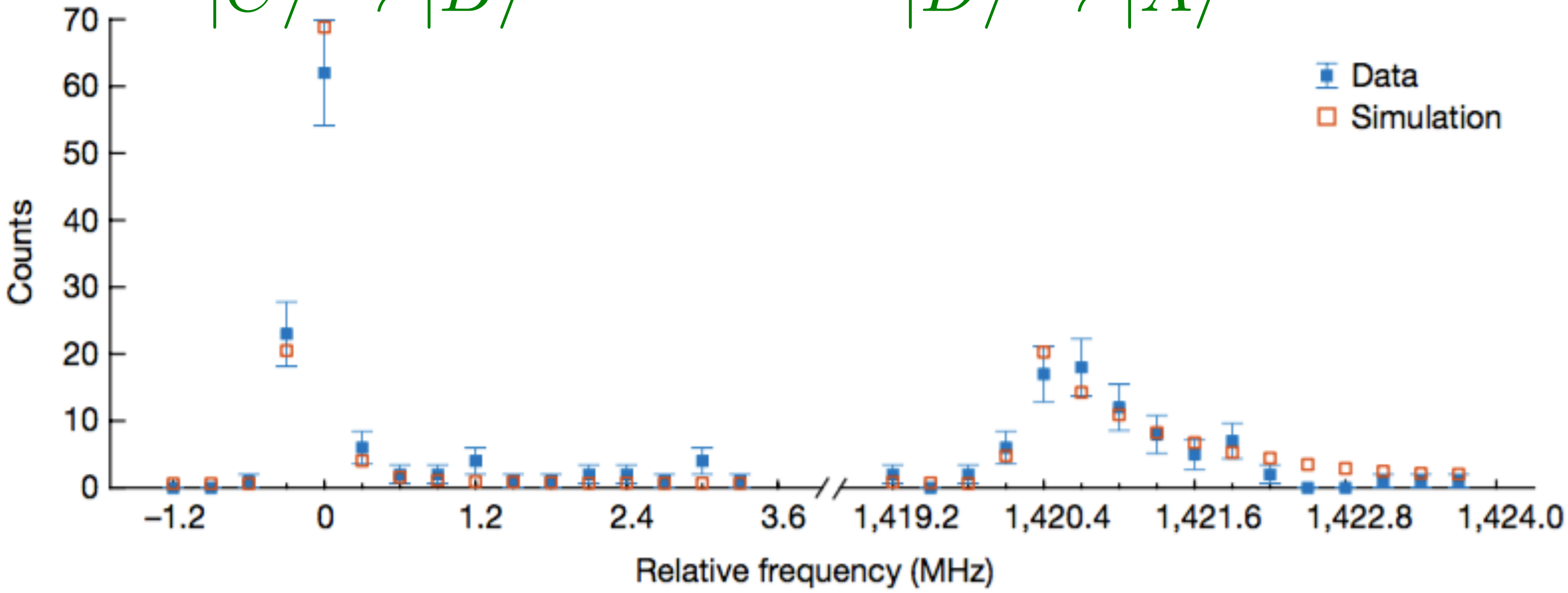




Antihydrogen hyperfine spectrum

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

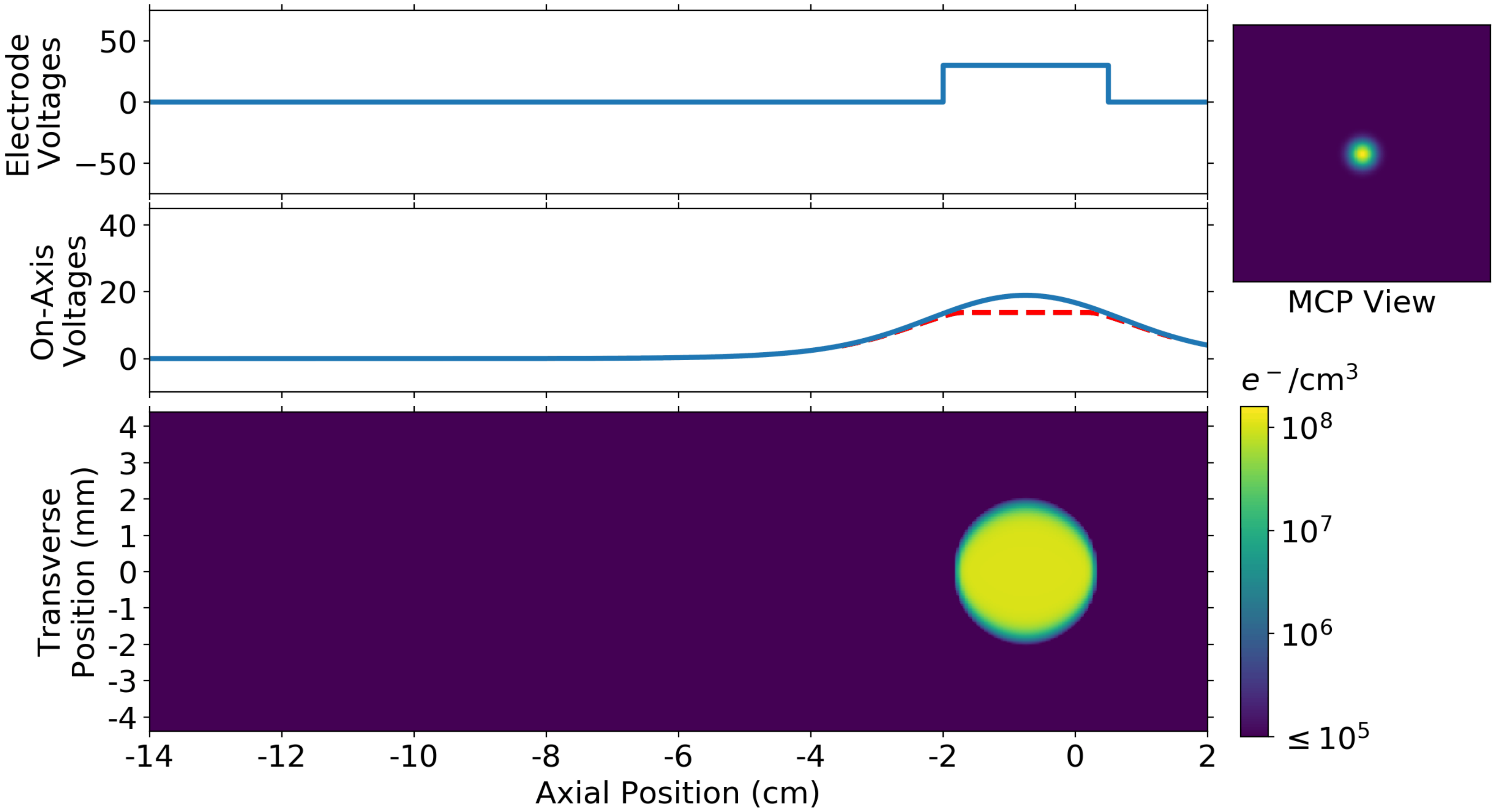
$|C\rangle \rightarrow |B\rangle$ $|D\rangle \rightarrow |A\rangle$



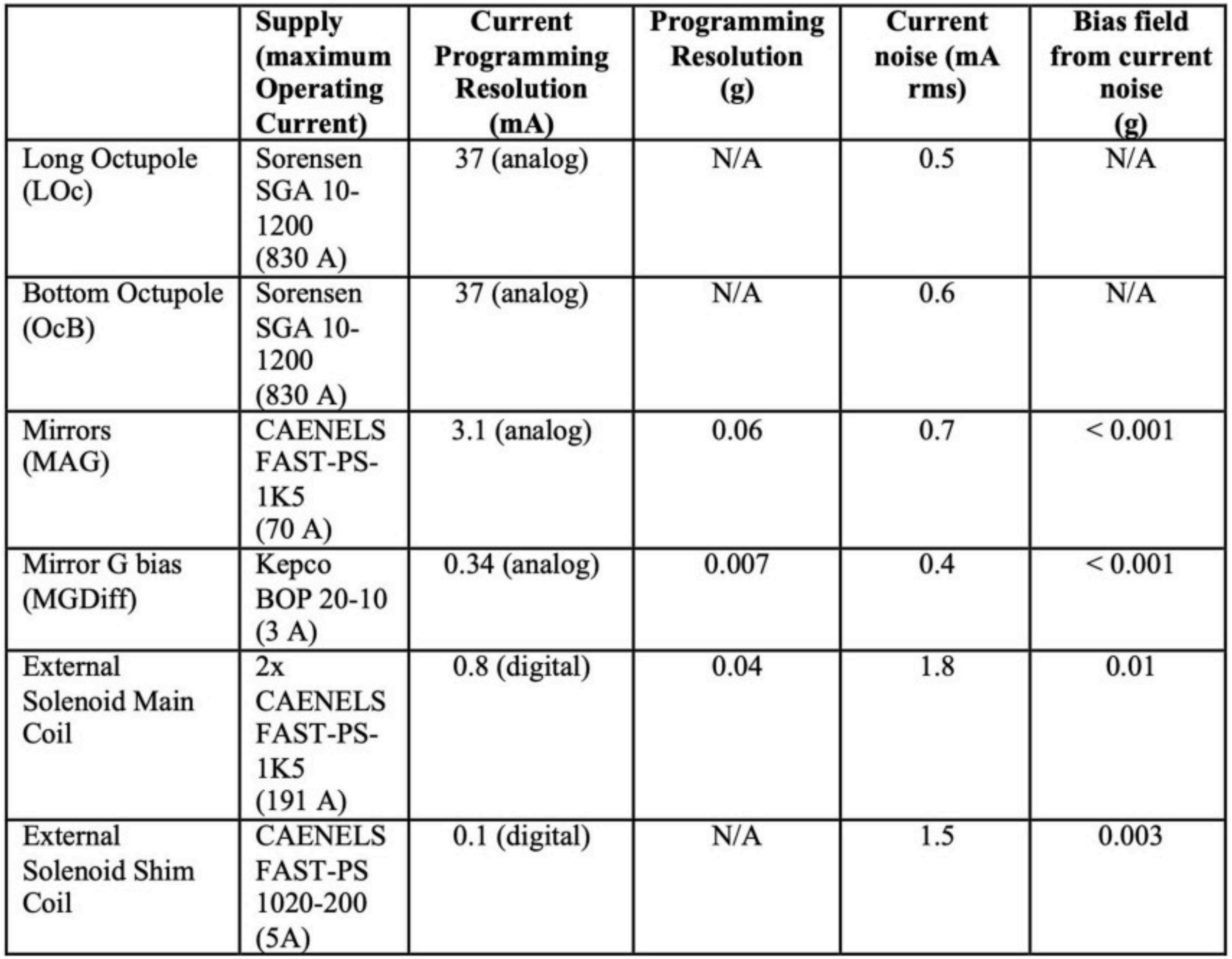
$$1,420.4 \pm 0.5\,\mathrm{MHz}$$

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