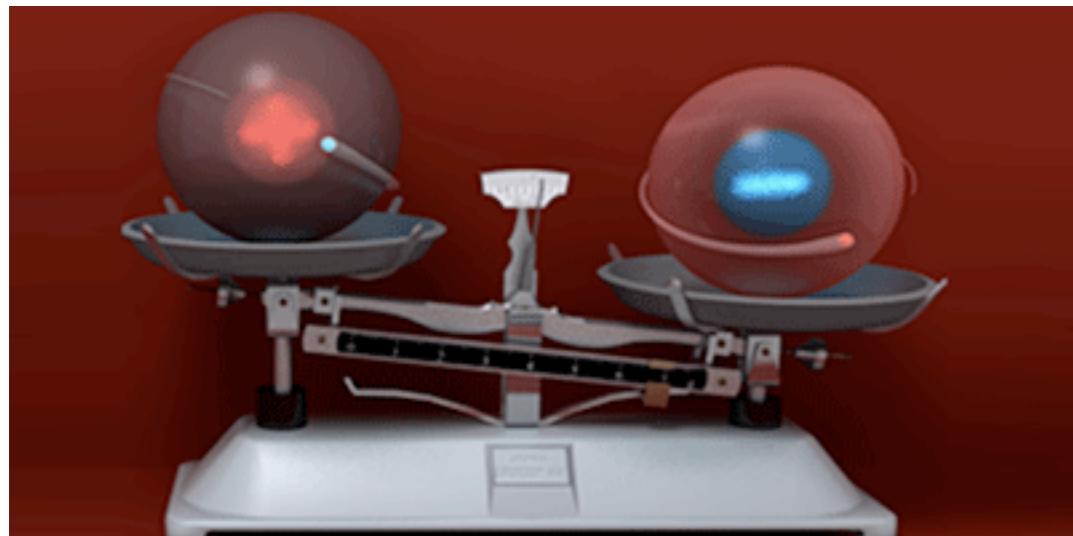


Gravitational studies with Antihydrogen



Dr. Will Bertsche

The University of Manchester
The Cockcroft Institute



The University of Manchester



1

ALPHA Experiment @ CERN



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



THE
UNIVERSITY
OF
BRITISH
COLUMBIA

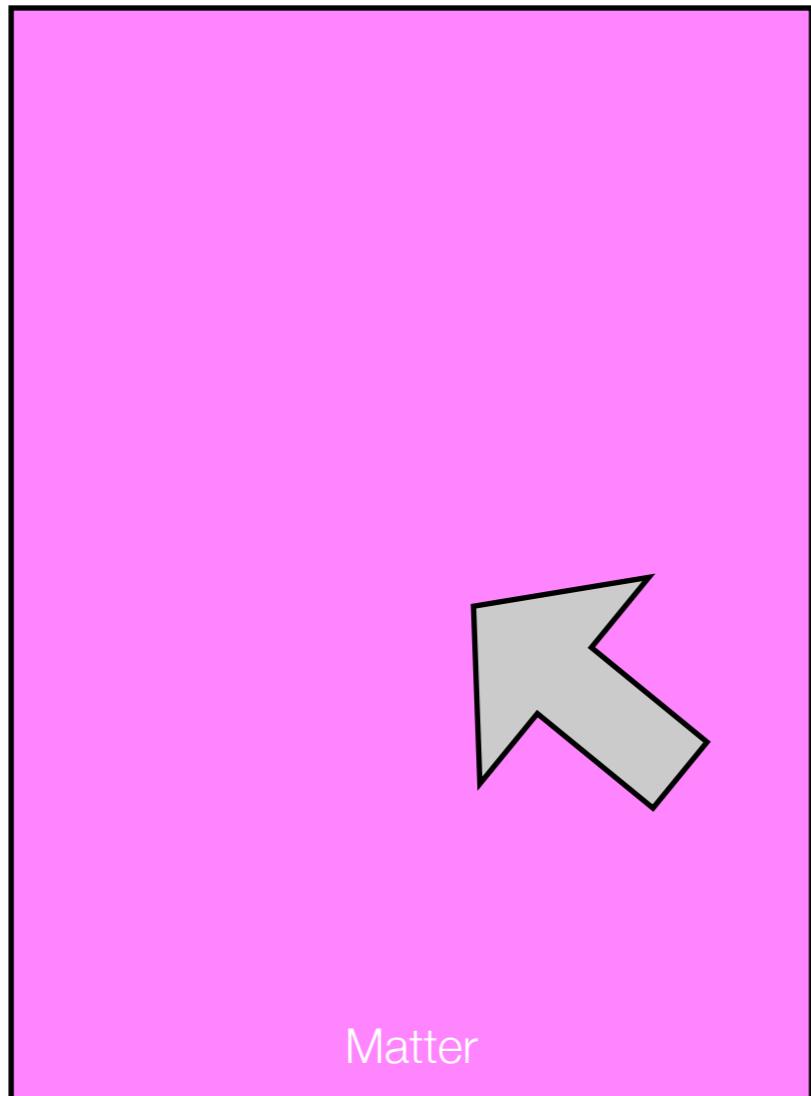


MANCHESTER
1824



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



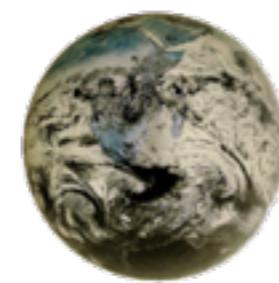
Anti-Apple



Anti-Apple



Earth

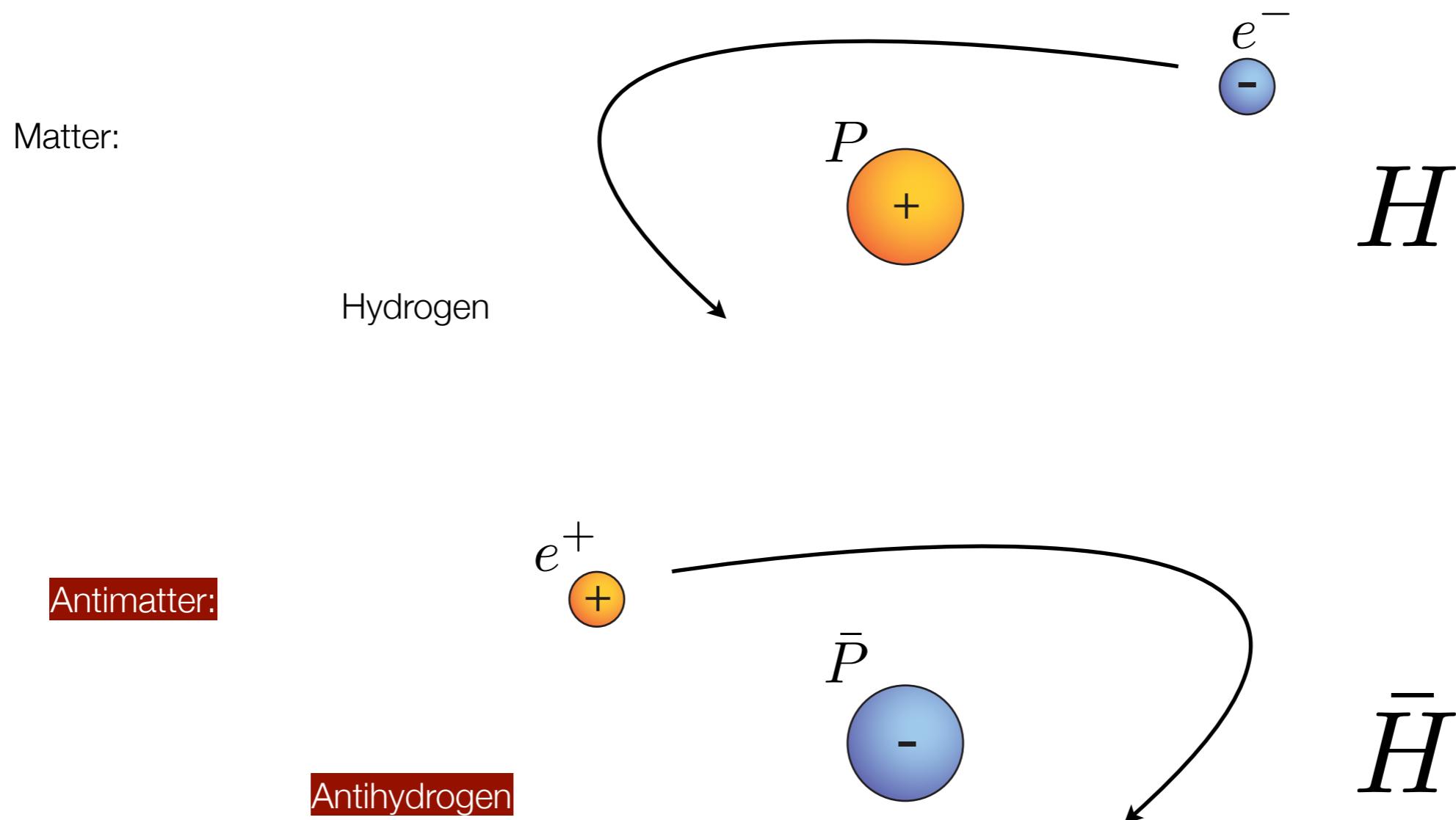


Anti-Earth



Earth

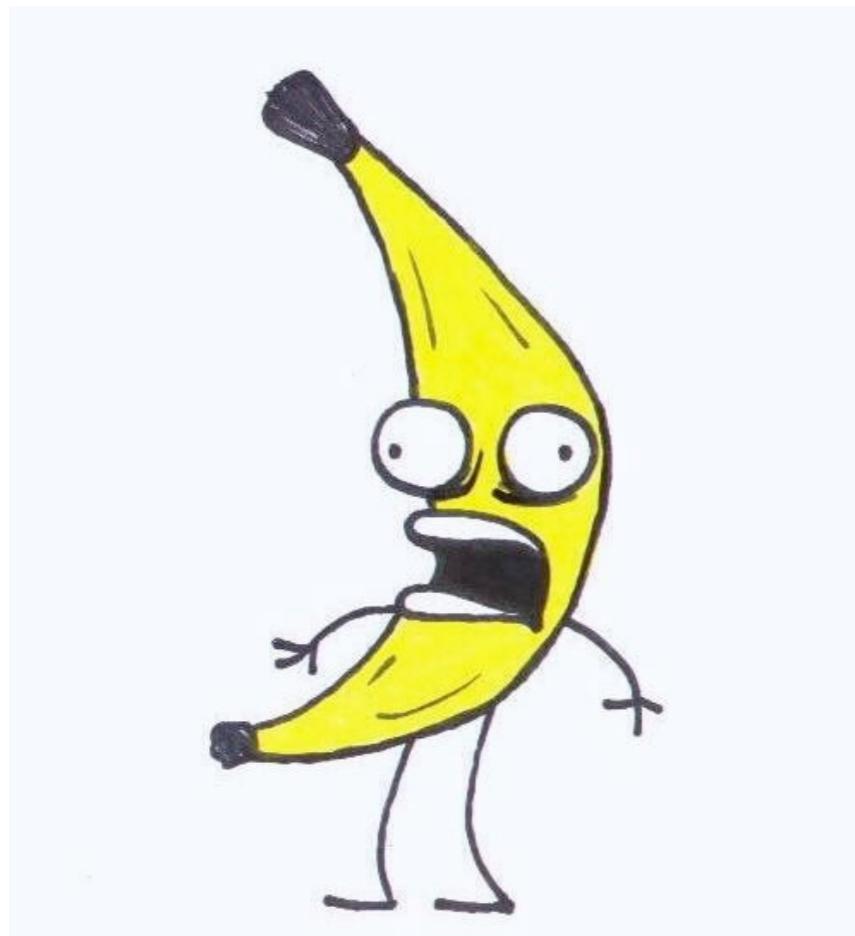
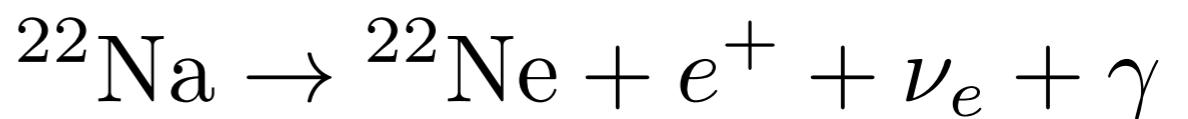
Atoms and antimatter: Hydrogen and Antihydrogen



Where do Positrons come from?

- Easy: Some radioactive isotopes

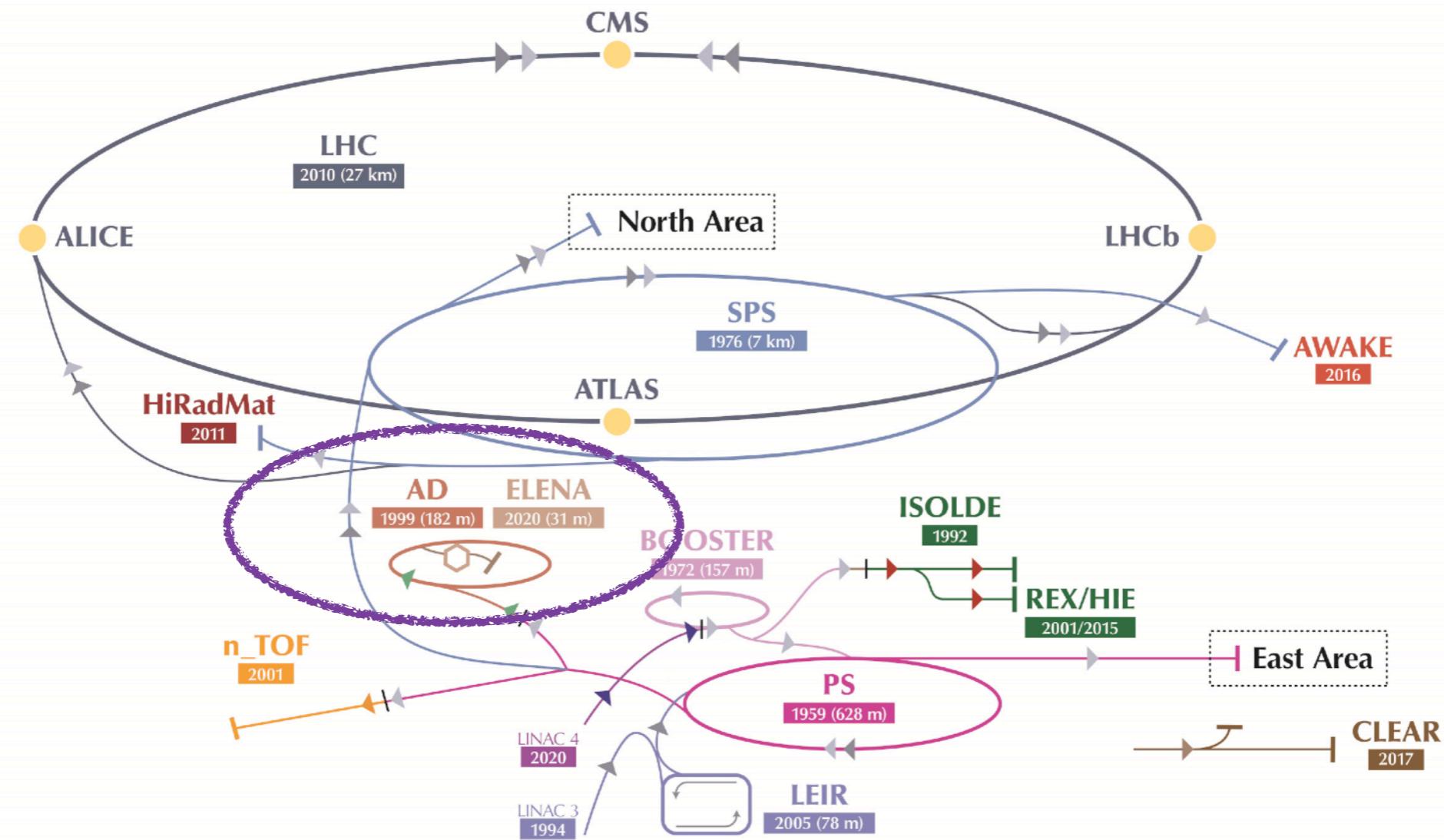
Banana Equivalent Dose (potassium):
~ 15 positrons / second



"I am a banana!" Don Hertzfeld

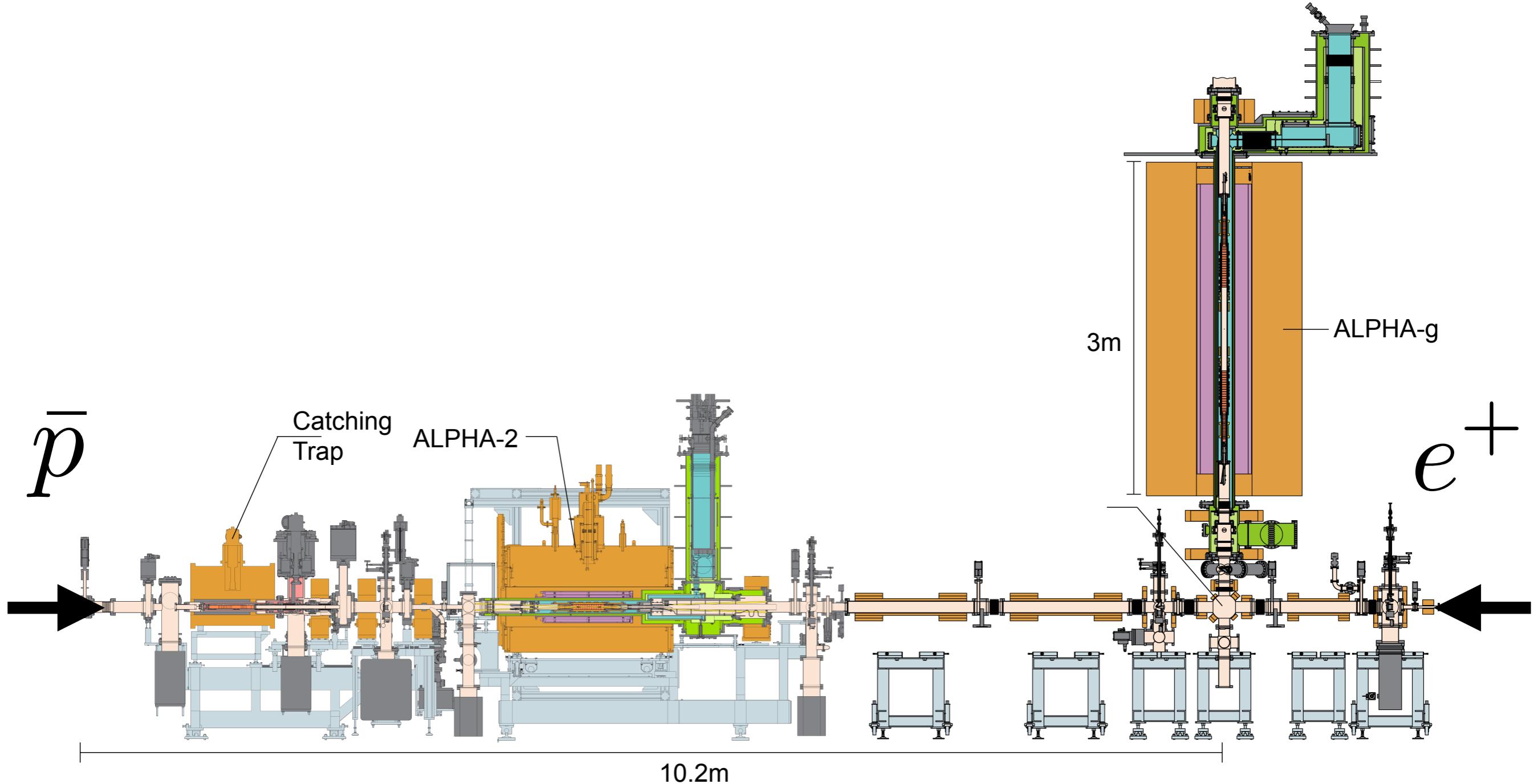


Low energy antiprotons from CERN



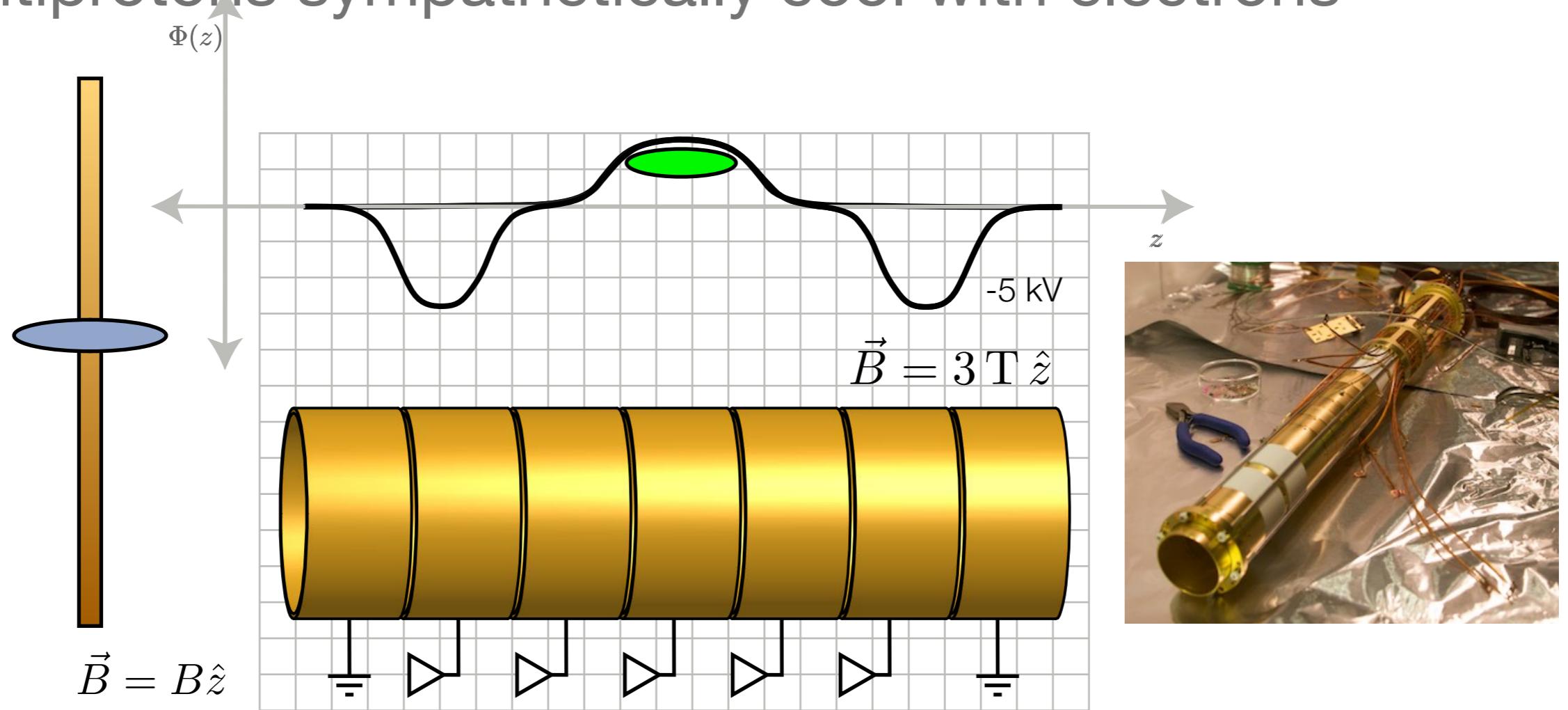
~ 5×10^6 antiprotons per minute from ELENA, ~ 2×10^5 per minute in ALPHA

ALPHA as installed, 2022



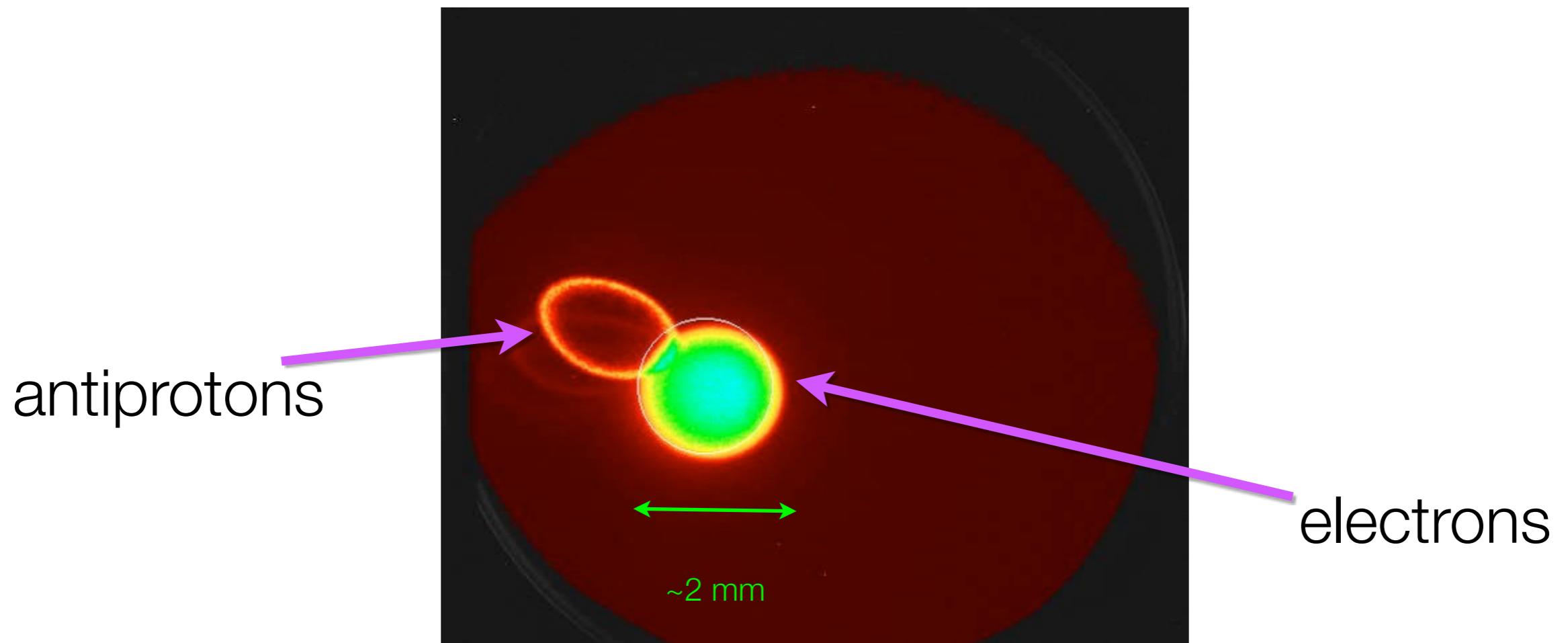
Capturing Antiprotons in a Penning-Malmberg Trap

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



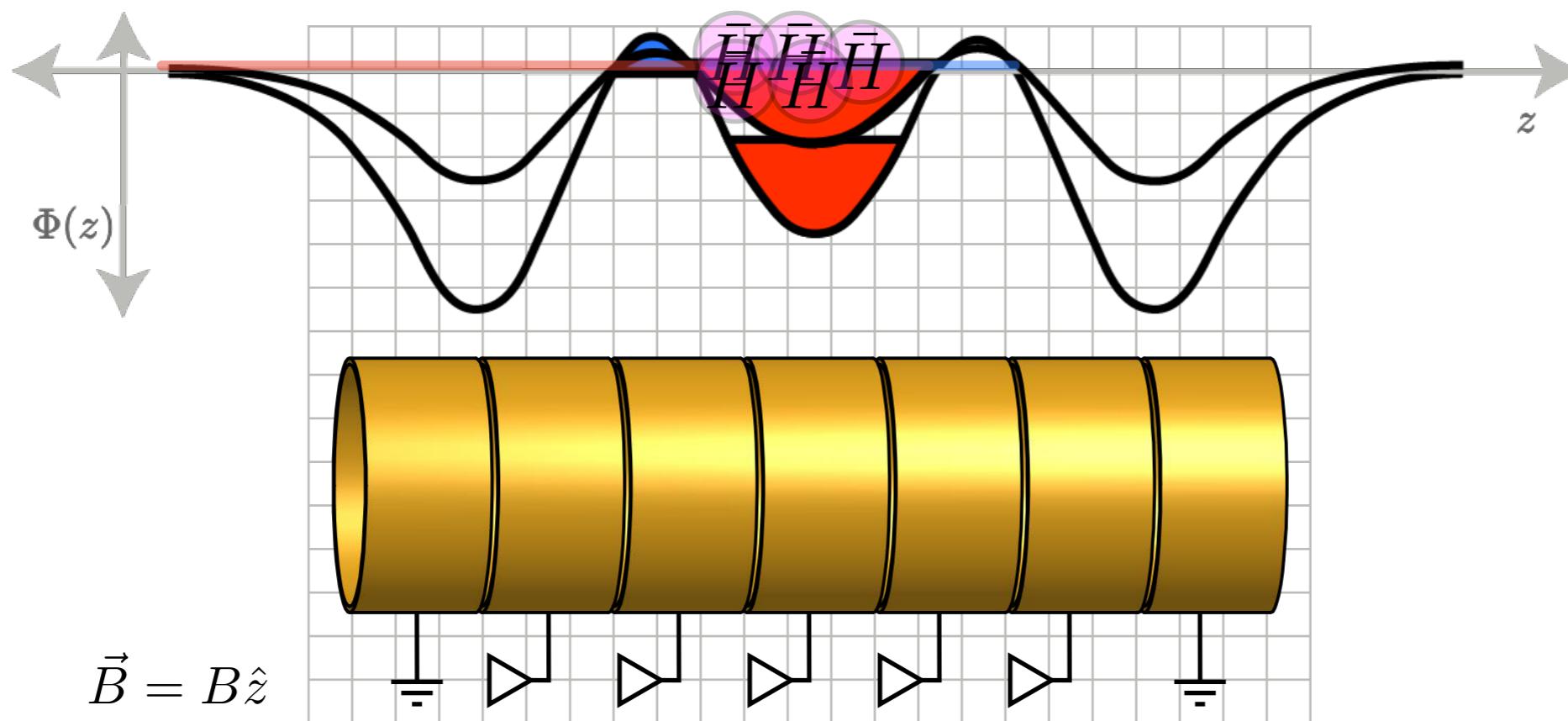
Antiproton / Electron Plasma

- Image the equilibrium Antiproton / Electron plasma



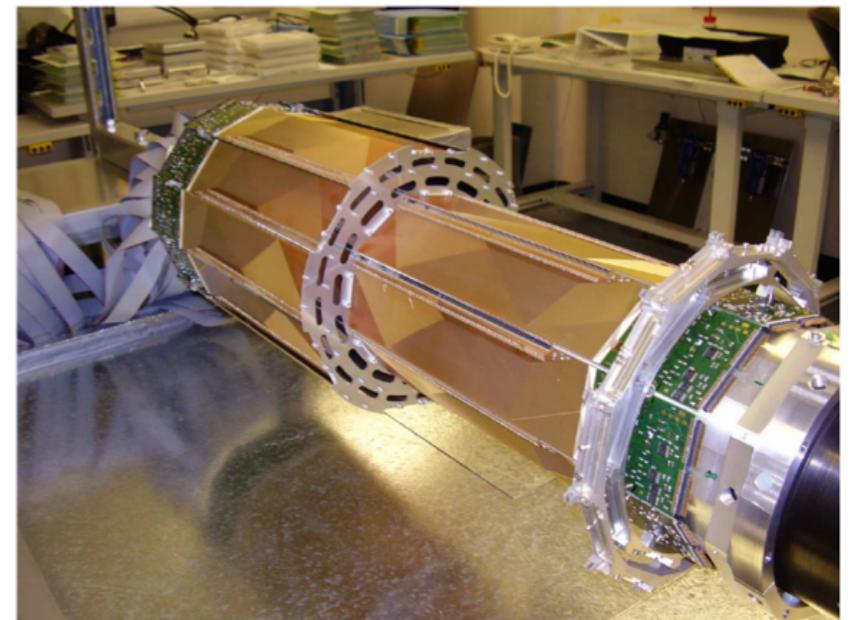
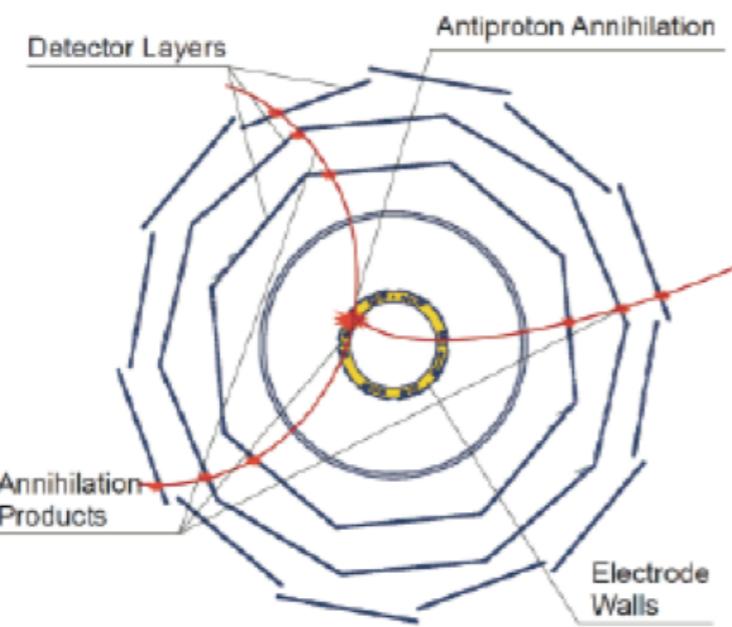
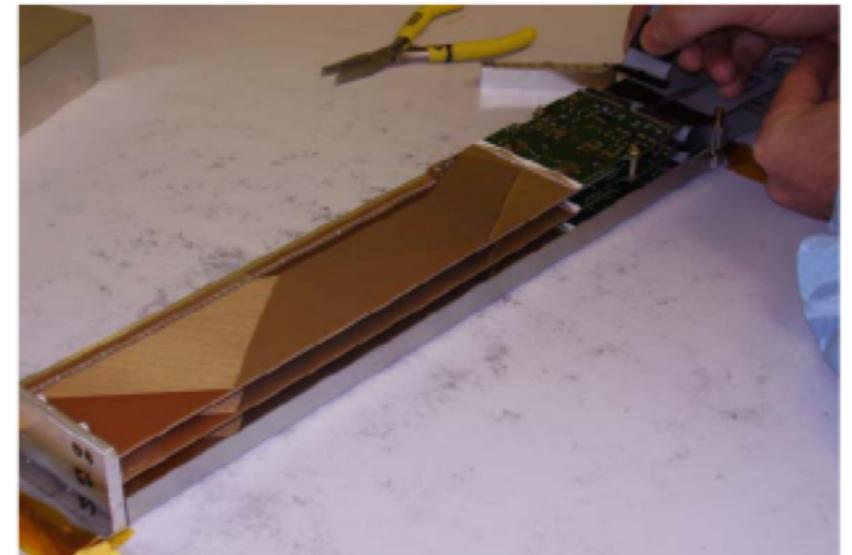
Antihydrogen Formation: Mixing Antiprotons and Positrons

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

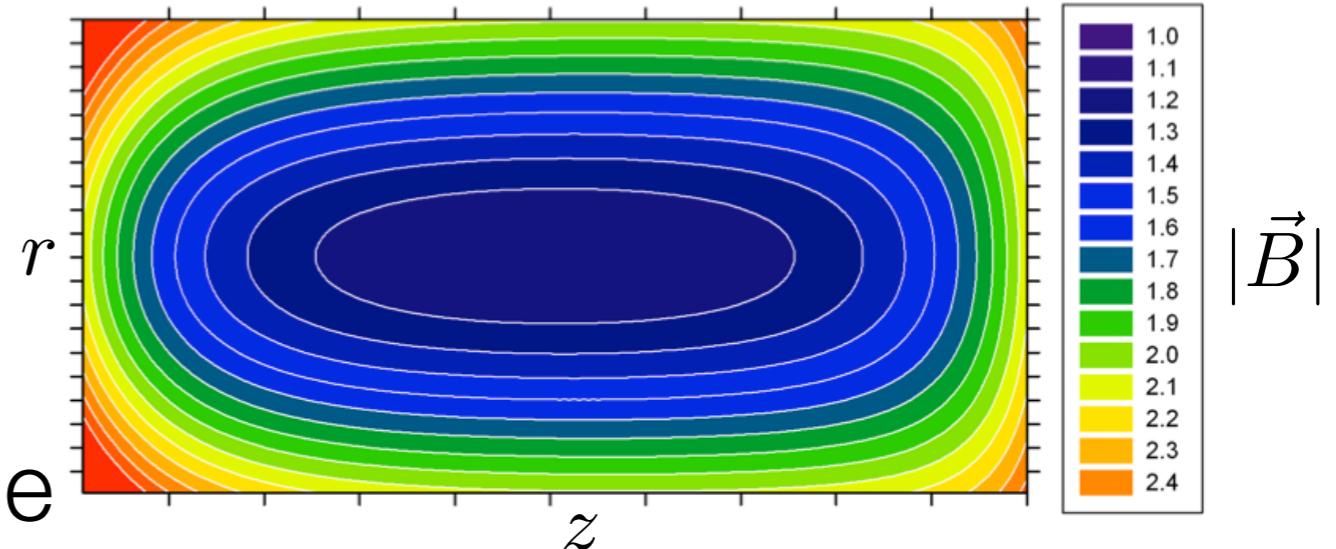
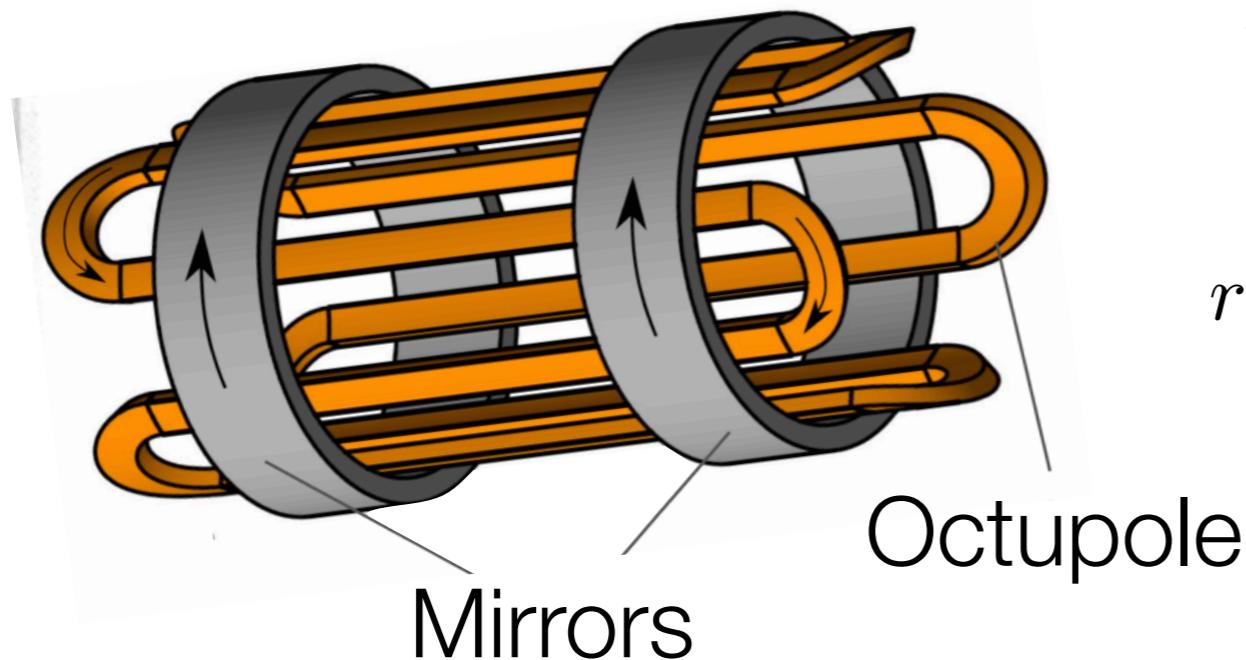
- Silicon-strip detector
- 3D ‘Digital Camera’
- Vertex resolution ~ 6 mm
- $> 70\%$ efficiency for annihilations



Trapping Antihydrogen

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

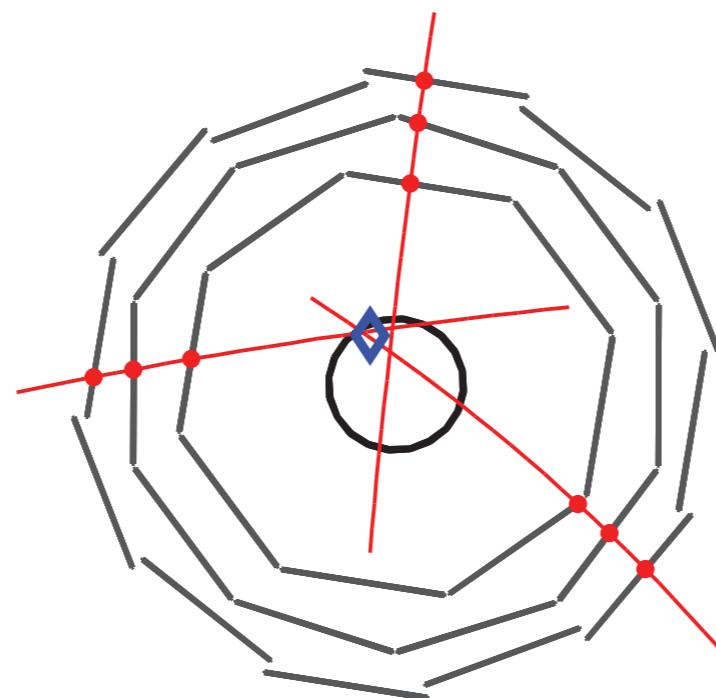
$$\vec{F} = \mu_H \vec{\nabla} |\vec{B}|, \quad U = \vec{\mu}_H \cdot \vec{B}$$



A little ALPHA history

Trapping Antihydrogen: Search

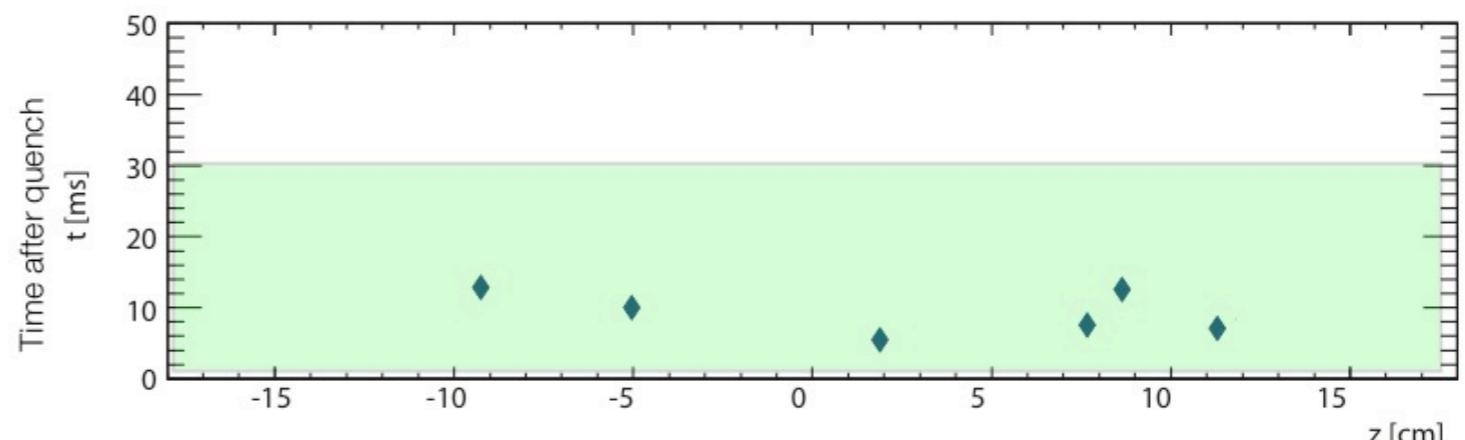
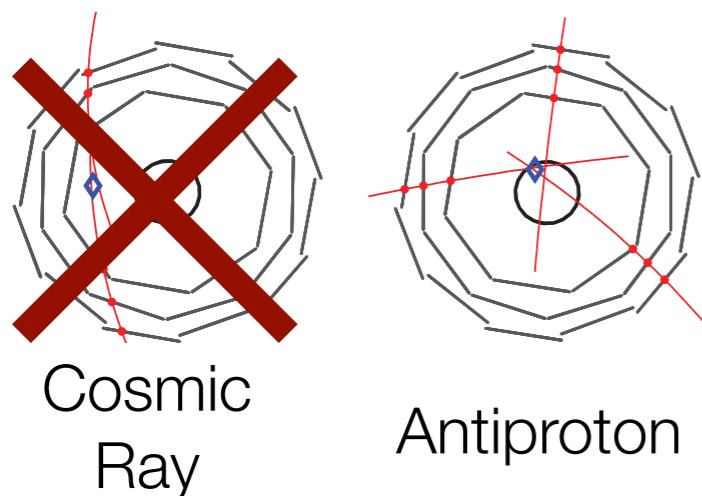
1. Turn on magnetic trap
2. Mix and Form Antihydrogen
3. Eject remaining charged particles
4. Rapidly shut off trap (< 30 ms quench in ALPHA-1)
5. Detect annihilations



A little ALPHA history

Trapped Antihydrogen Detection

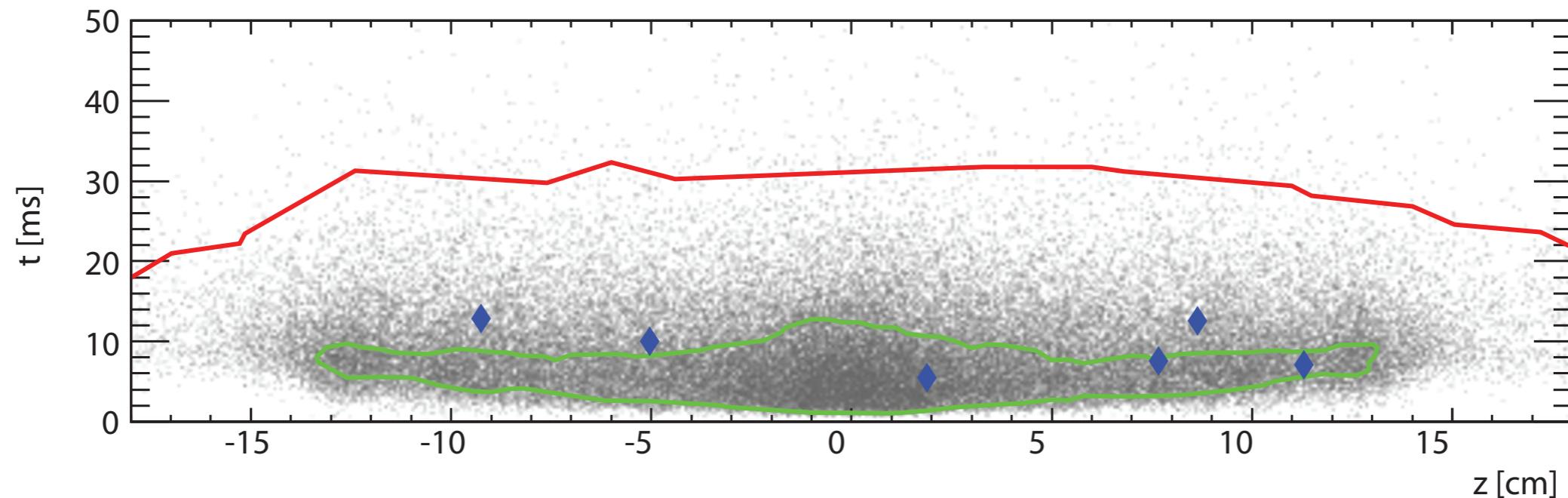
- Pattern / Time / Spatial Information from Detector
- Reject cosmic rays
- Accept antiproton annihilations
- Only look at events during the quench (time)



A little ALPHA history

Antihydrogen Expectation?

- Simulate Antihydrogen atoms in trap through quench



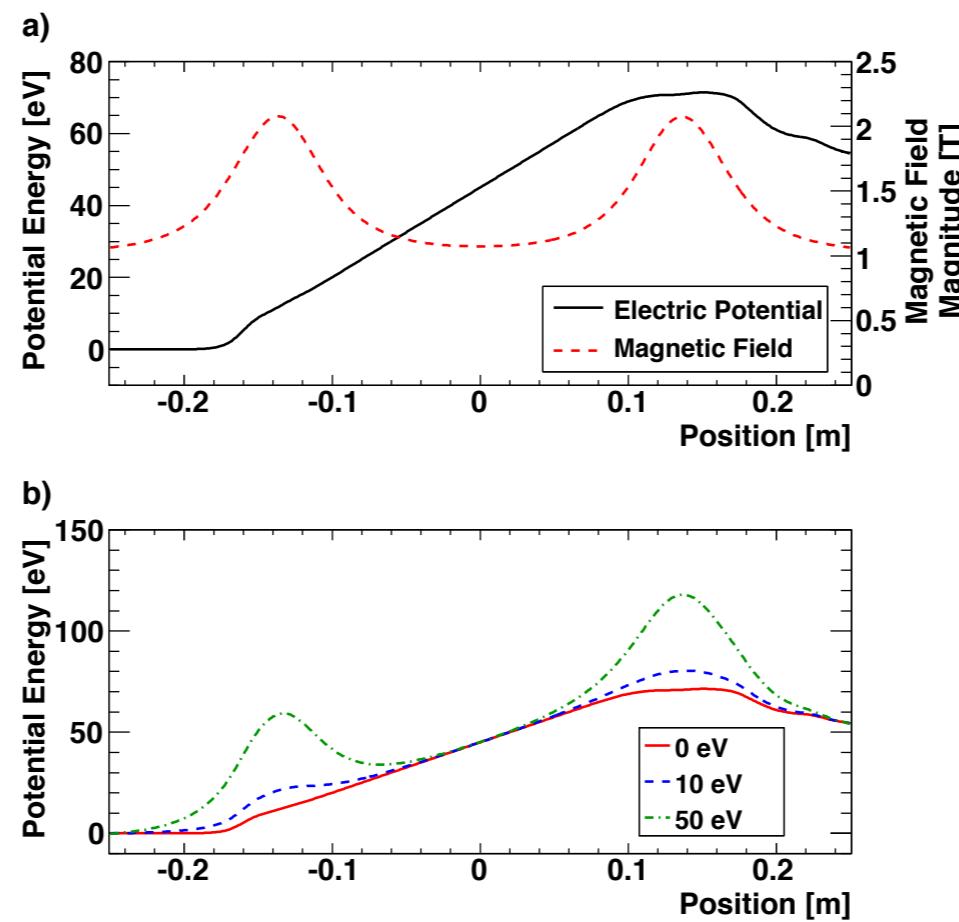
- Mirror-trapped antiprotons might remain...

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

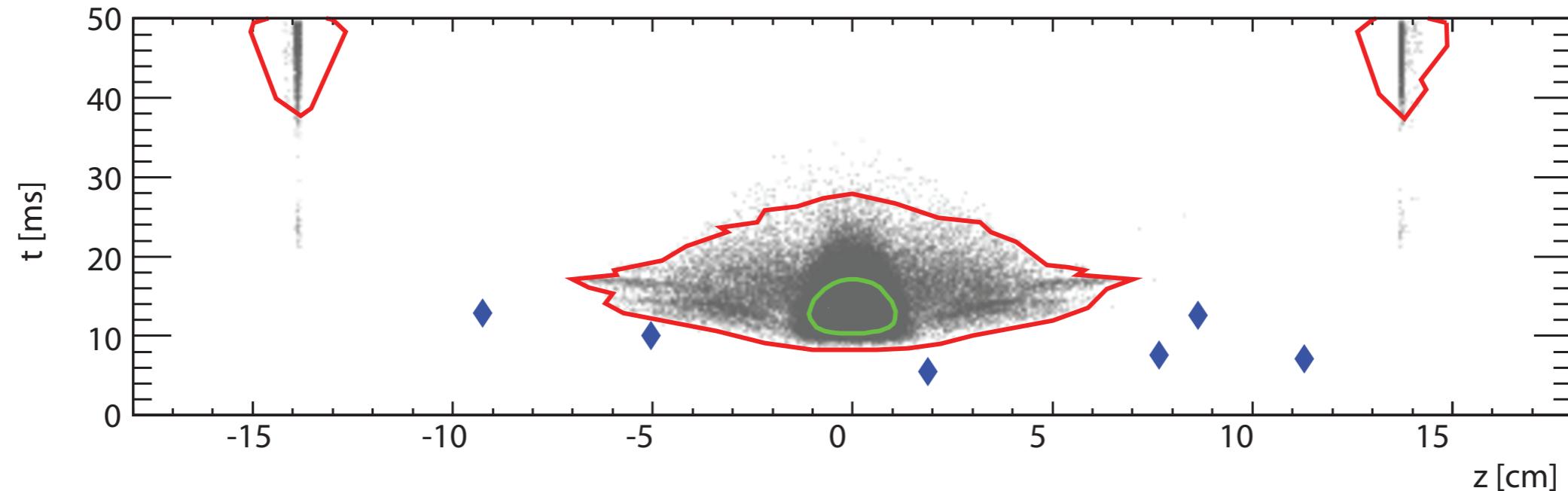
$$U_{\bar{p}}(z, r = 0) = q(\phi - \phi_0) + E_{\perp} \frac{B_{\parallel} - B_0}{B_0}$$



A little ALPHA history

Are events Mirror-Trapped Antiprotons?

- Simulate mirror-trapped antiprotons in quench

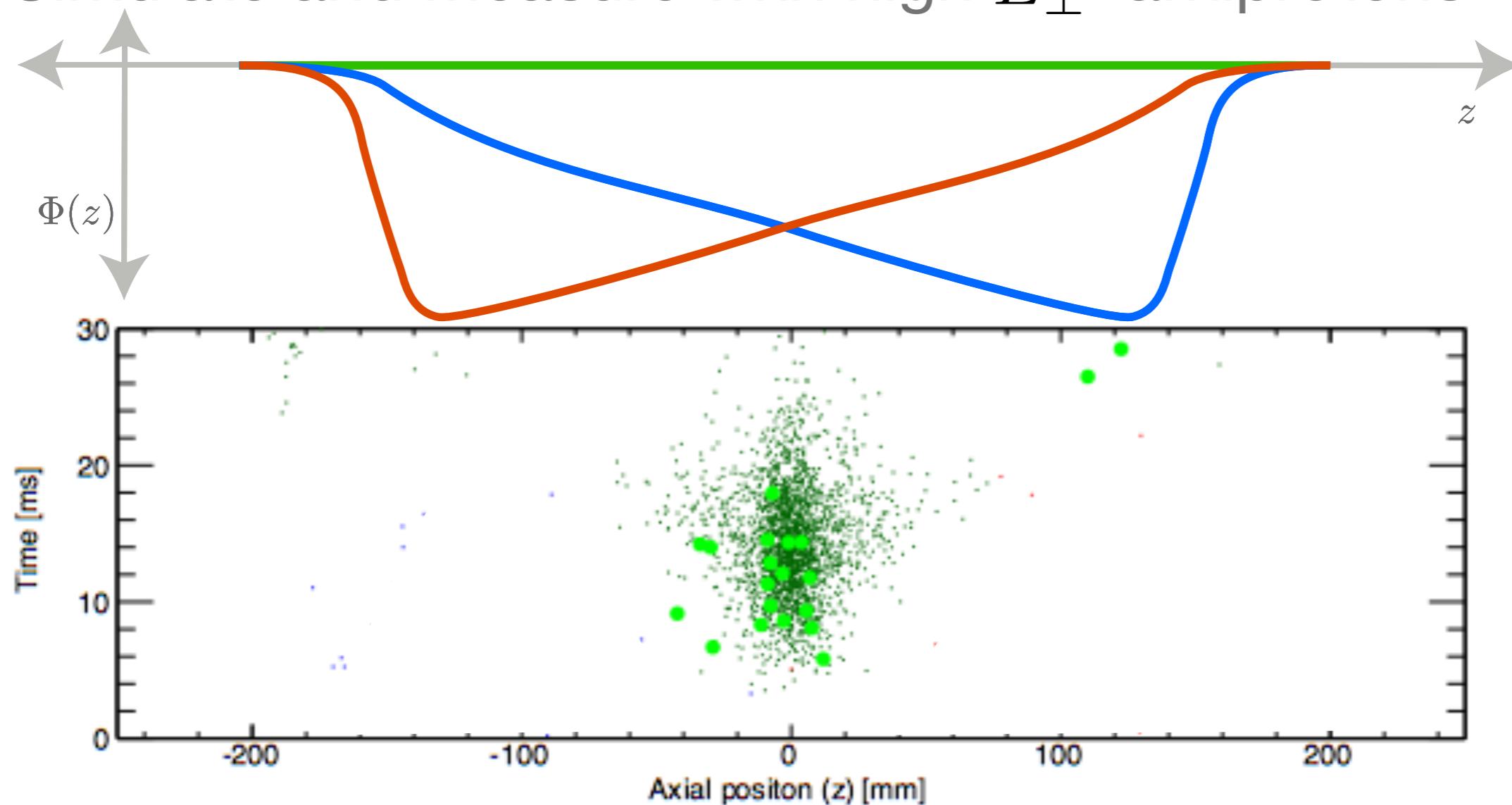


- Different from antihydrogen events, surely...

A little ALPHA history

Quench With Bias Electric Field

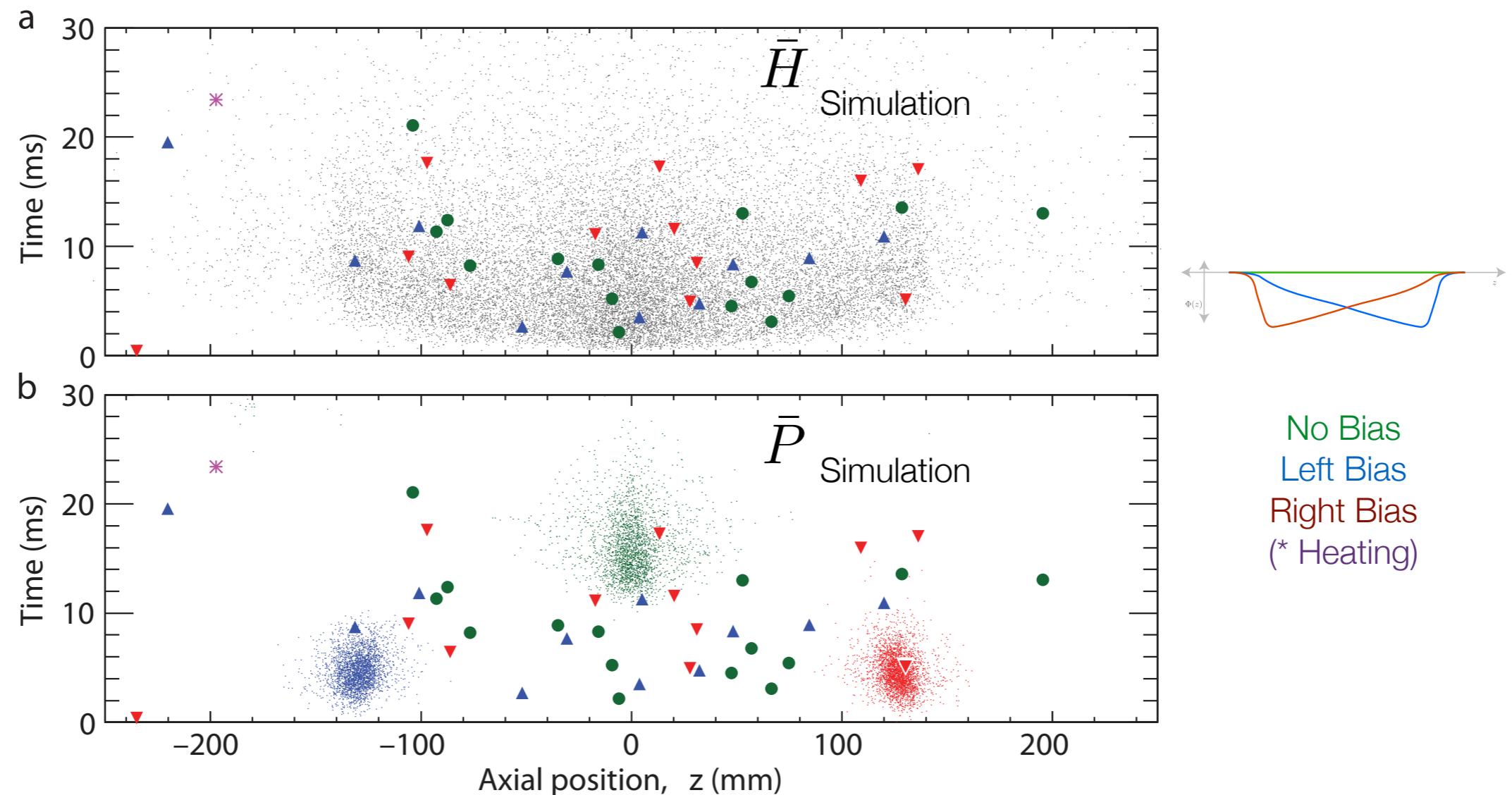
- Electric Fields deflect charged particles, not atoms
- Simulate and measure with high E_{\perp} antiprotons



A little ALPHA history

Antihydrogen Search with Bias Fields

- No spatial bias in signal: Trapped Antihydrogen



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”

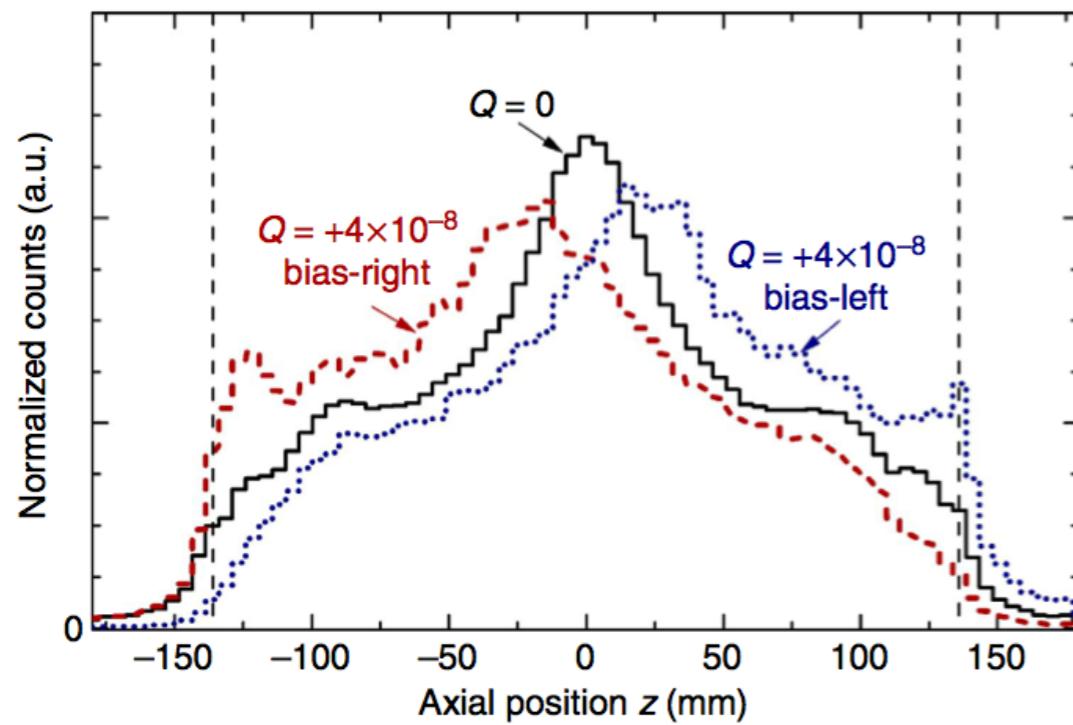
$$\bar{H} \text{ charge} = Qe$$

- Magnetic atom trap + bias field potential:

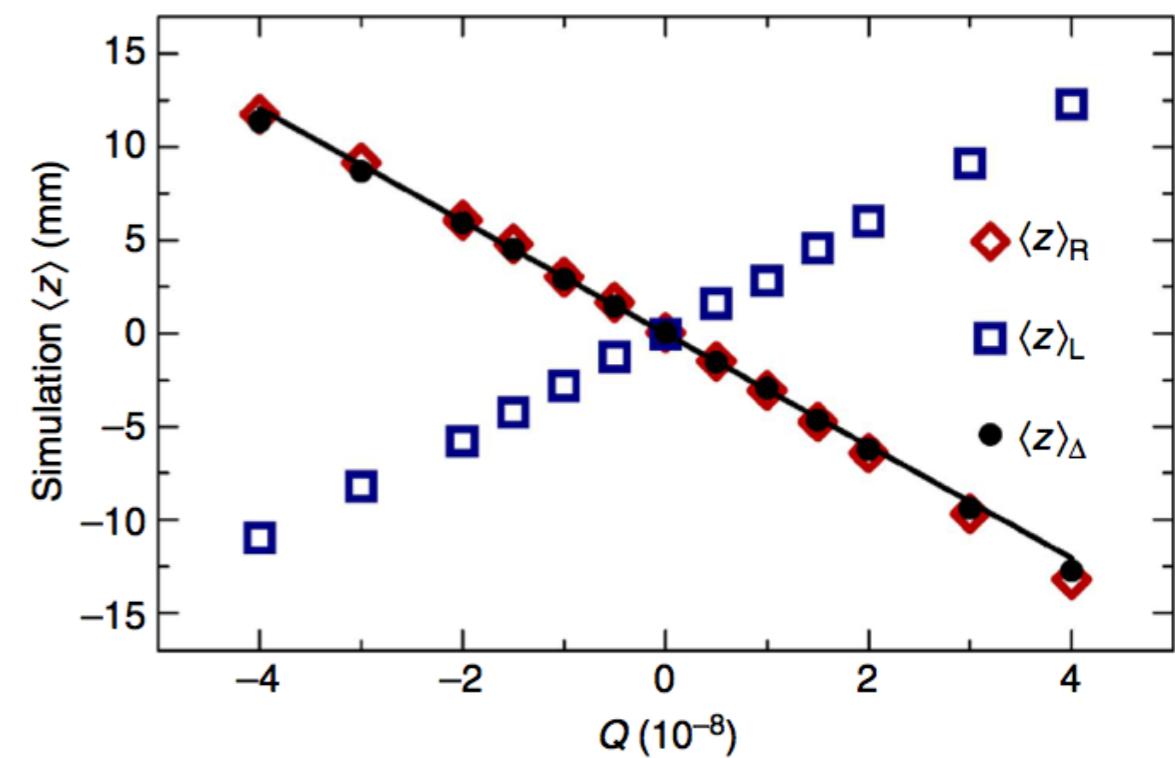
$$U(z) = \mu_{\bar{H}} B(z) - \frac{QeE}{k_B} z$$

Measurements with Potentials: Charge neutrality

Simulate Hbar Annihilations

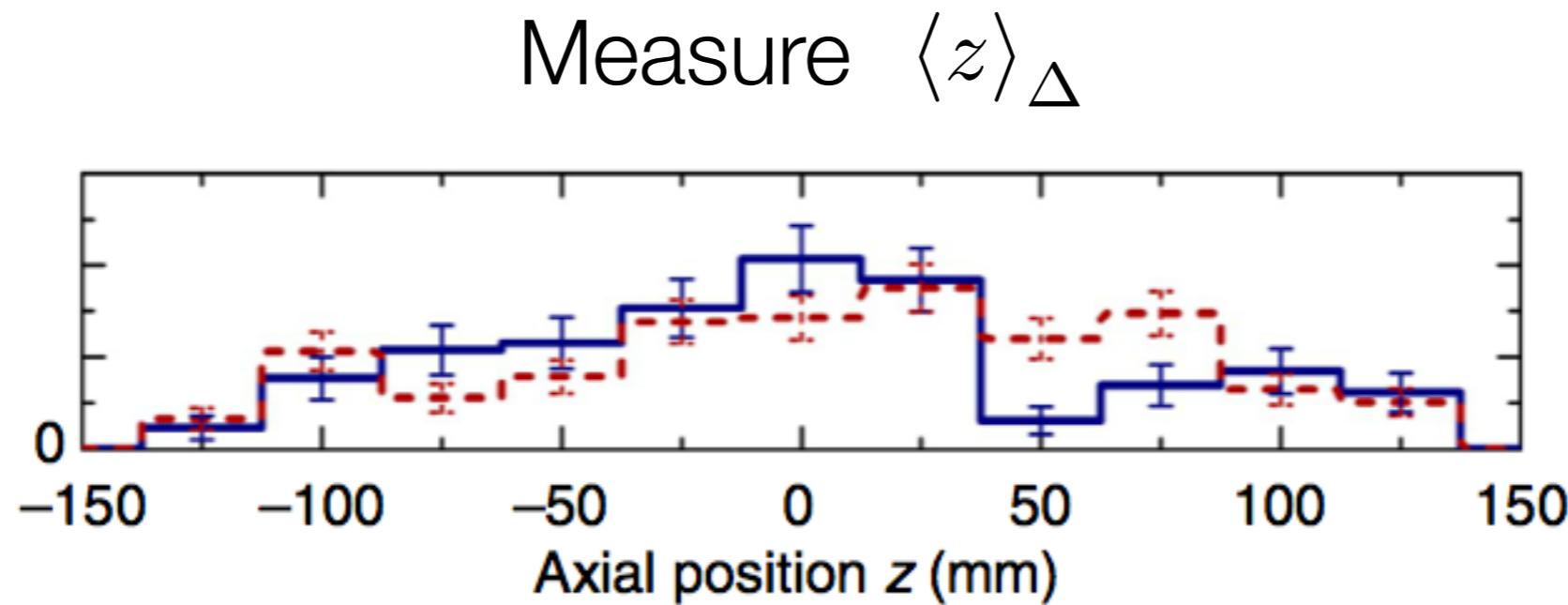


Relate $\langle z \rangle_{\Delta} \longleftrightarrow Q$



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

Measurements with Potentials: Charge neutrality



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

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

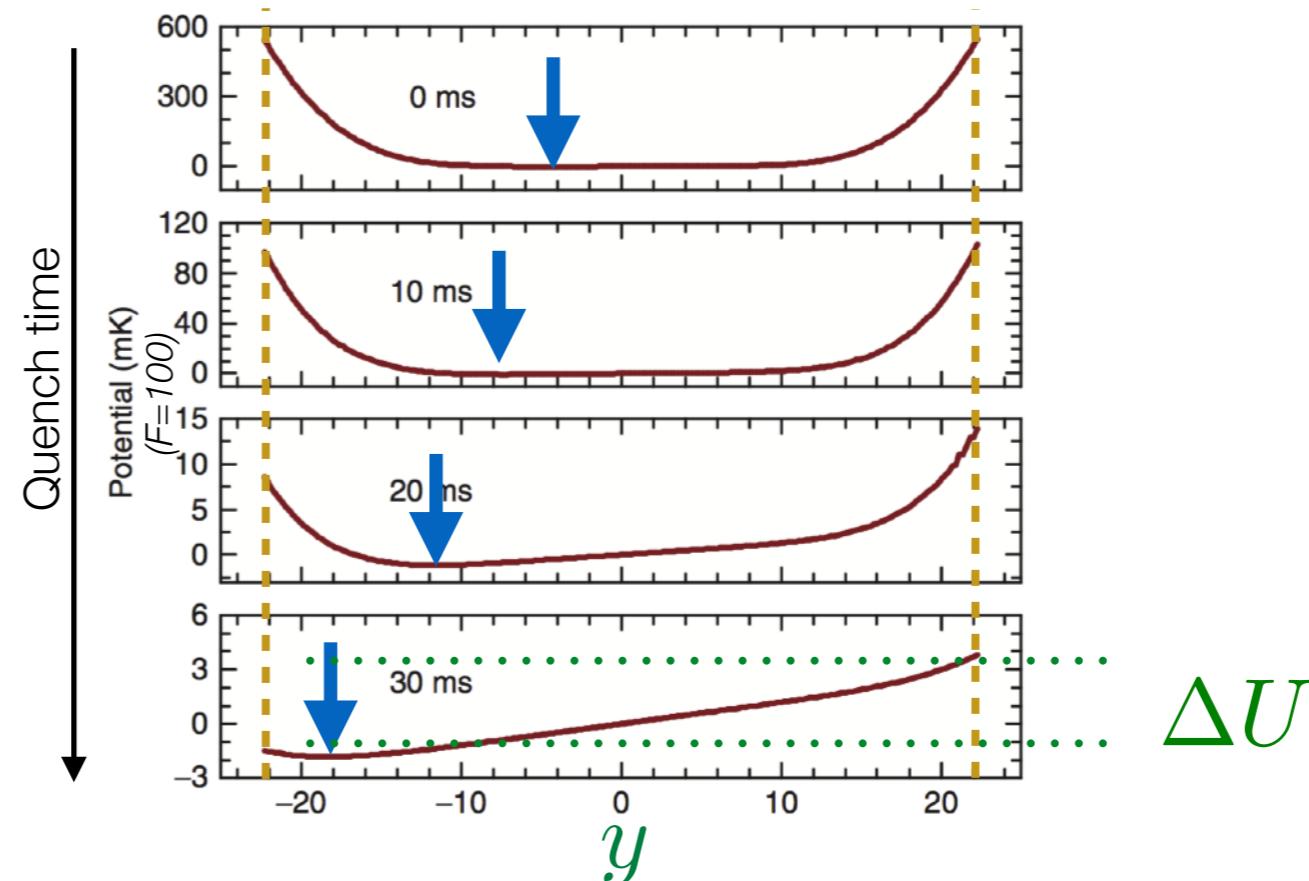
C. Amole *et al.* “An experimental limit on the charge of antihydrogen”, Nat. Comm. 5, 3955 (2014)

Measurements with Potentials: Gravitation?

- Do atoms and anti-atoms gravitate differently?

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

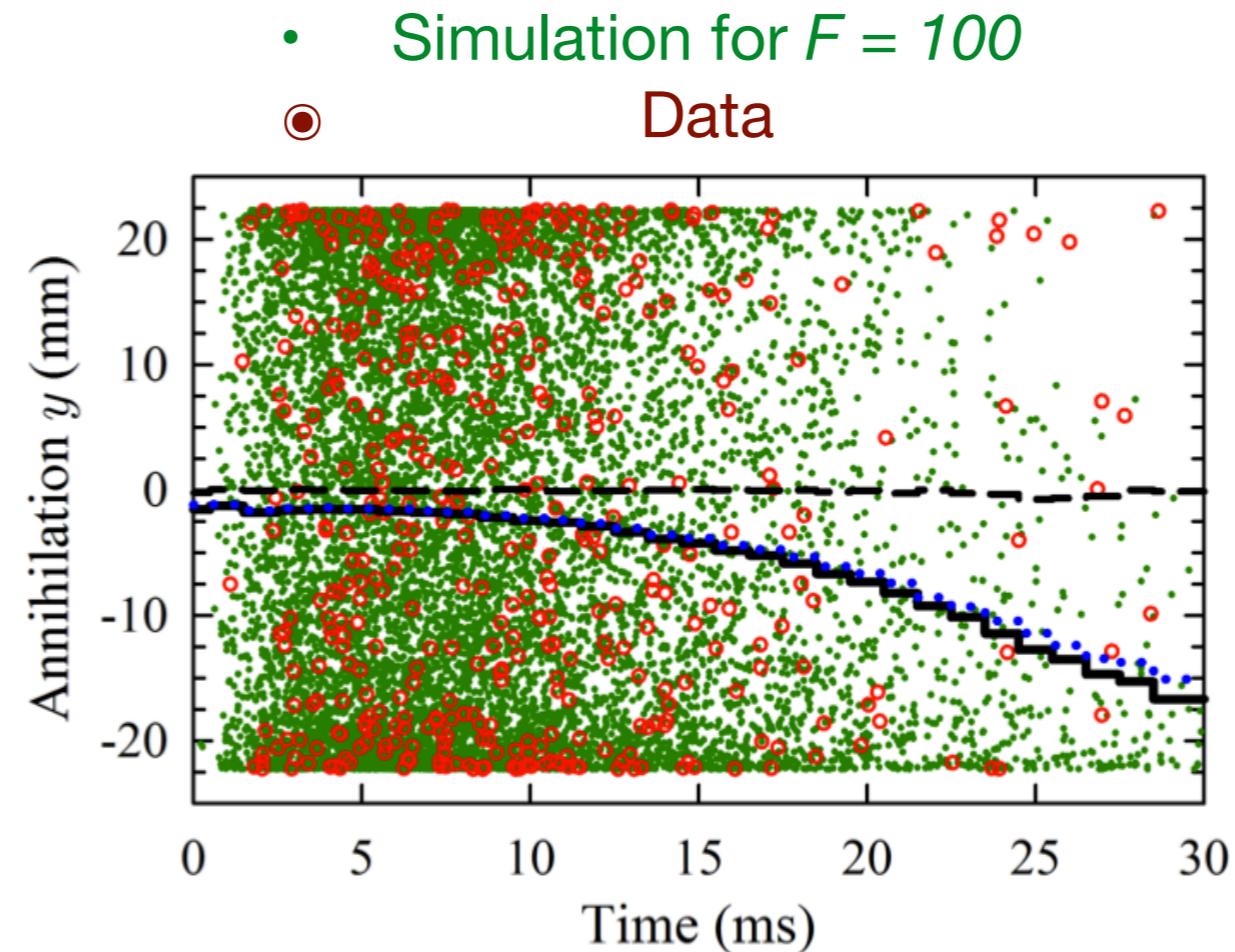
$$U(y) = \mu_{\bar{H}} B(y) + F \cdot mgy$$



Measurements with Potentials: Gravitation? (ALPHA-1)

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

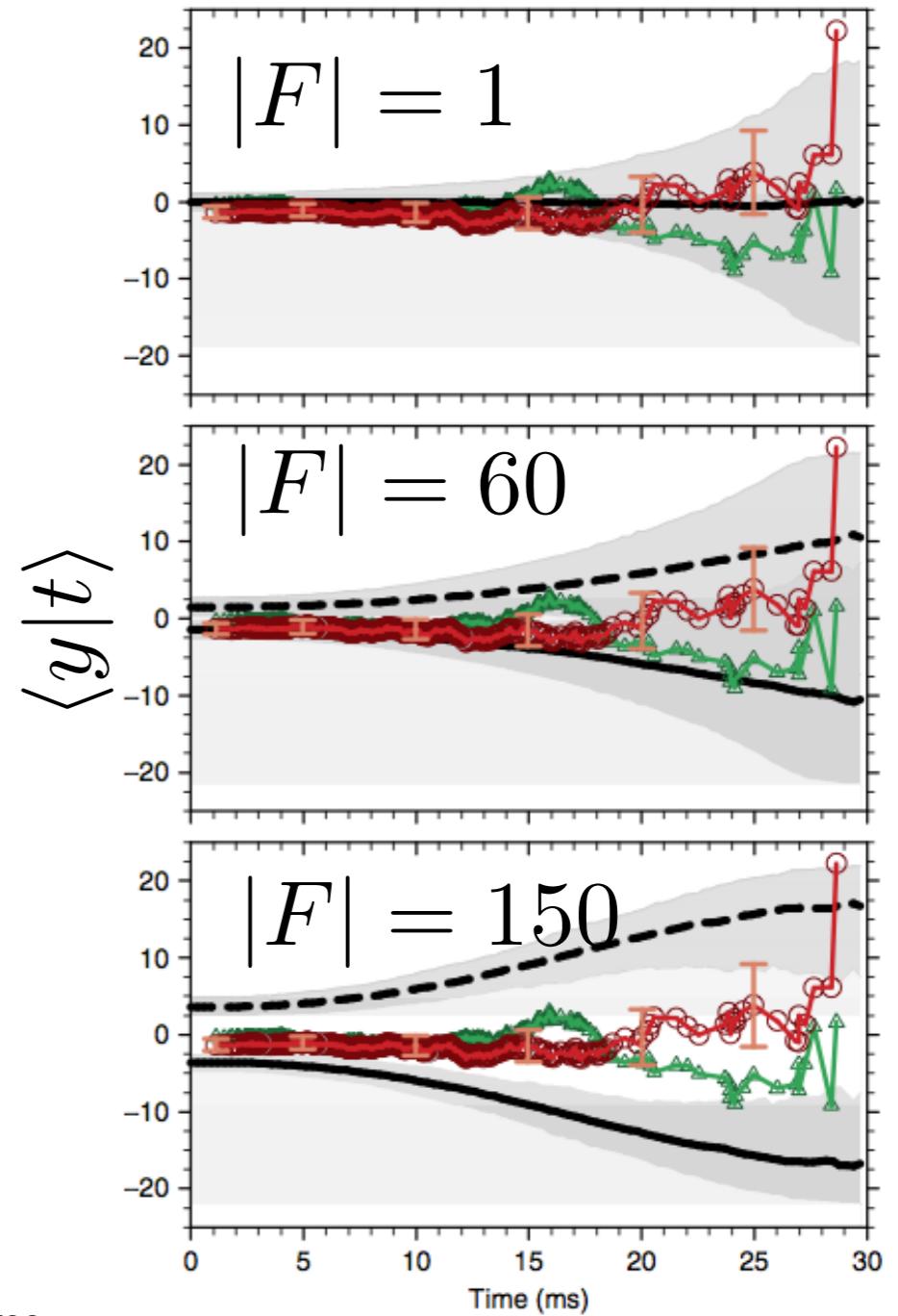
$$F_{\text{antimatter}} = F \cdot mg$$



Measurements with Potentials: Gravitational Deflection: Precision?

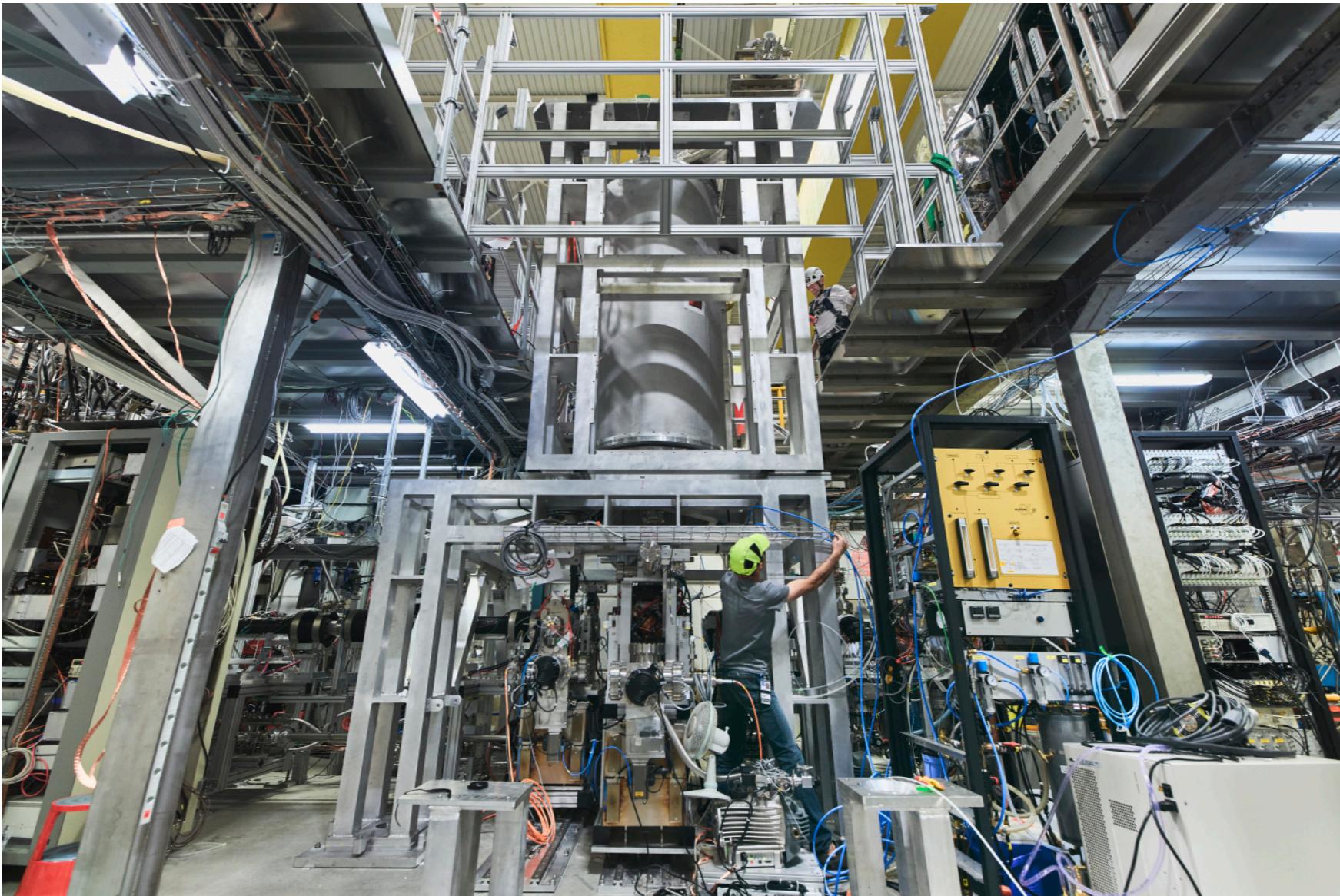
- Simulate various F , exclude
 $-65 < F < 110$
- Not very precise!
 - short distance, hot population!
- **Need over 200 meters for deflecting hydrogen!**

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



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

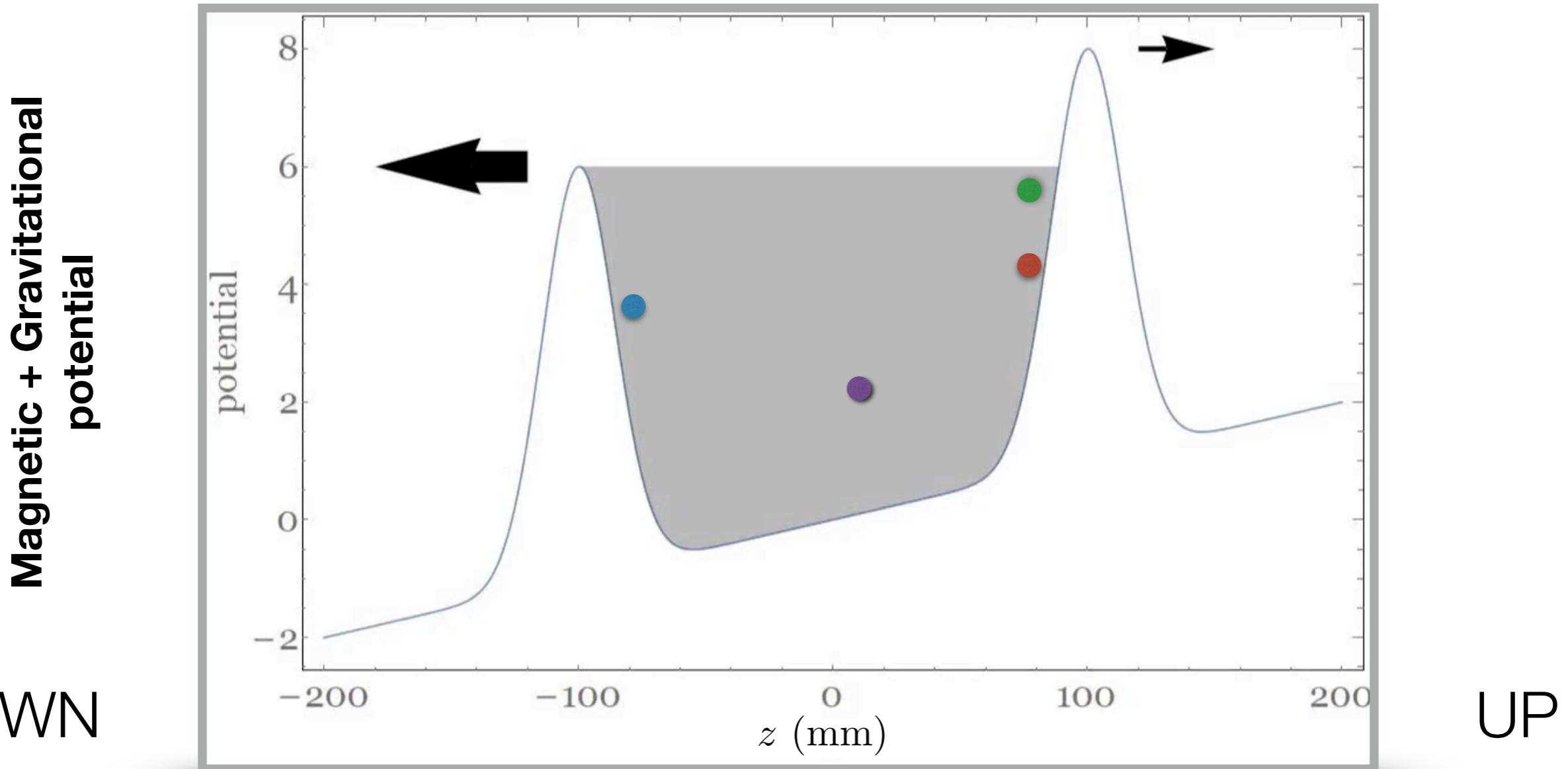
ALPHA-g: an antimatter gravity experiment





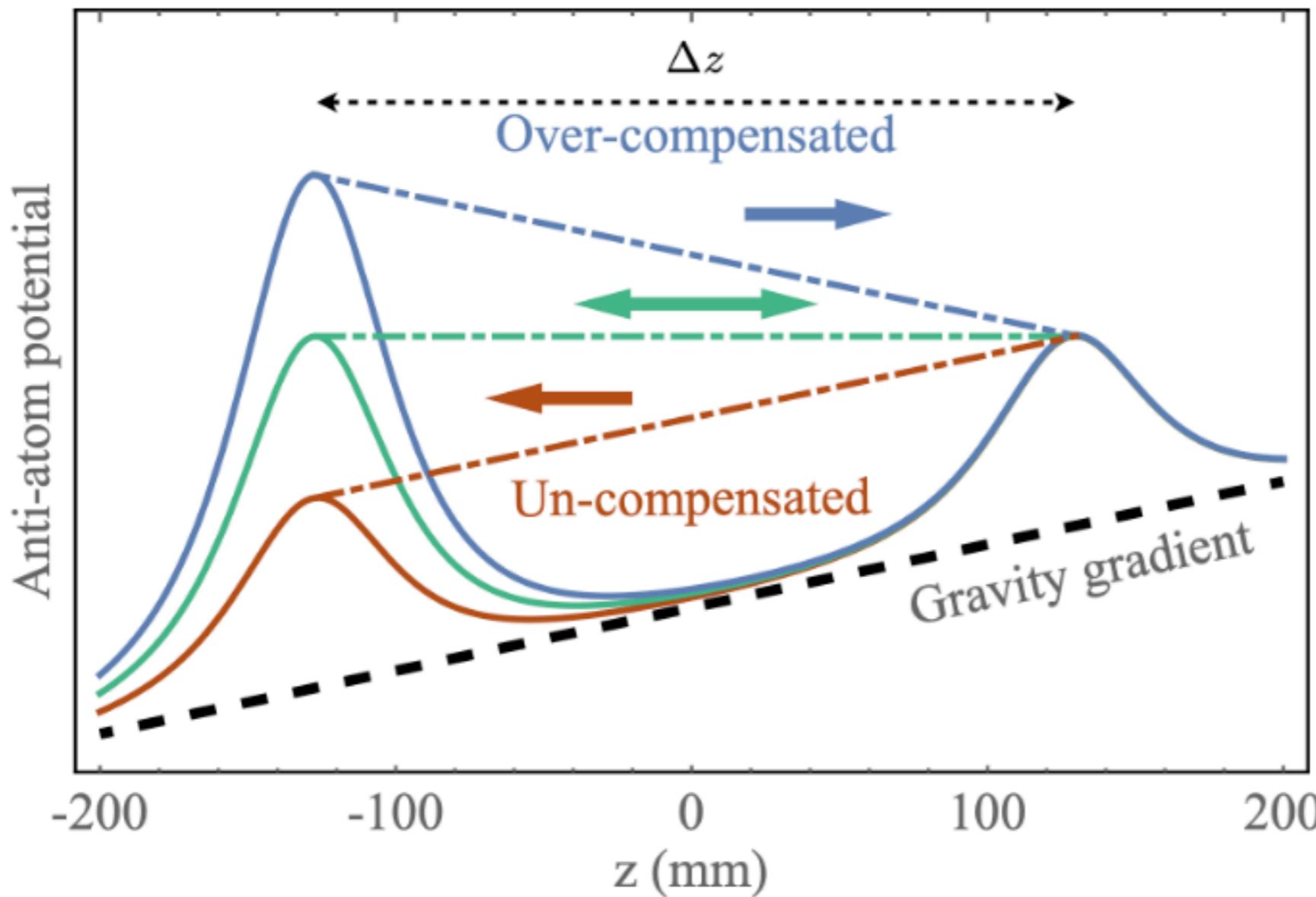
P. Traczyk and M. Brice, CERN <https://cernbox.cern.ch/s/3OAsgoCXxXMPTas>

A simple Up / Down measurement: Matched fields



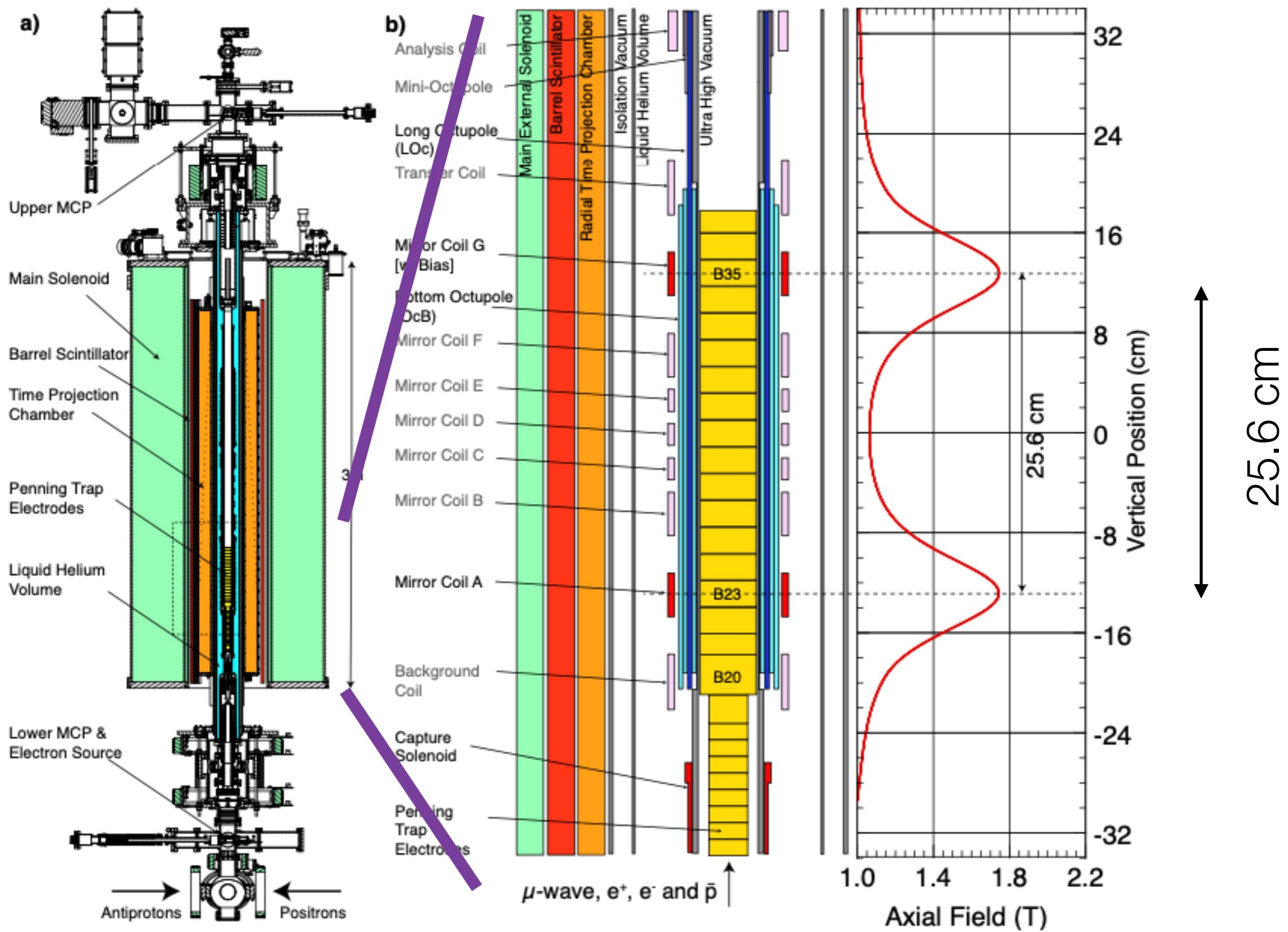
W. Bertsche, "Prospects for comparison of matter and antimatter gravitation with ALPHA-g", RSTA, 376, 2116, 2018

A simple Up / Down measurement: Matched fields



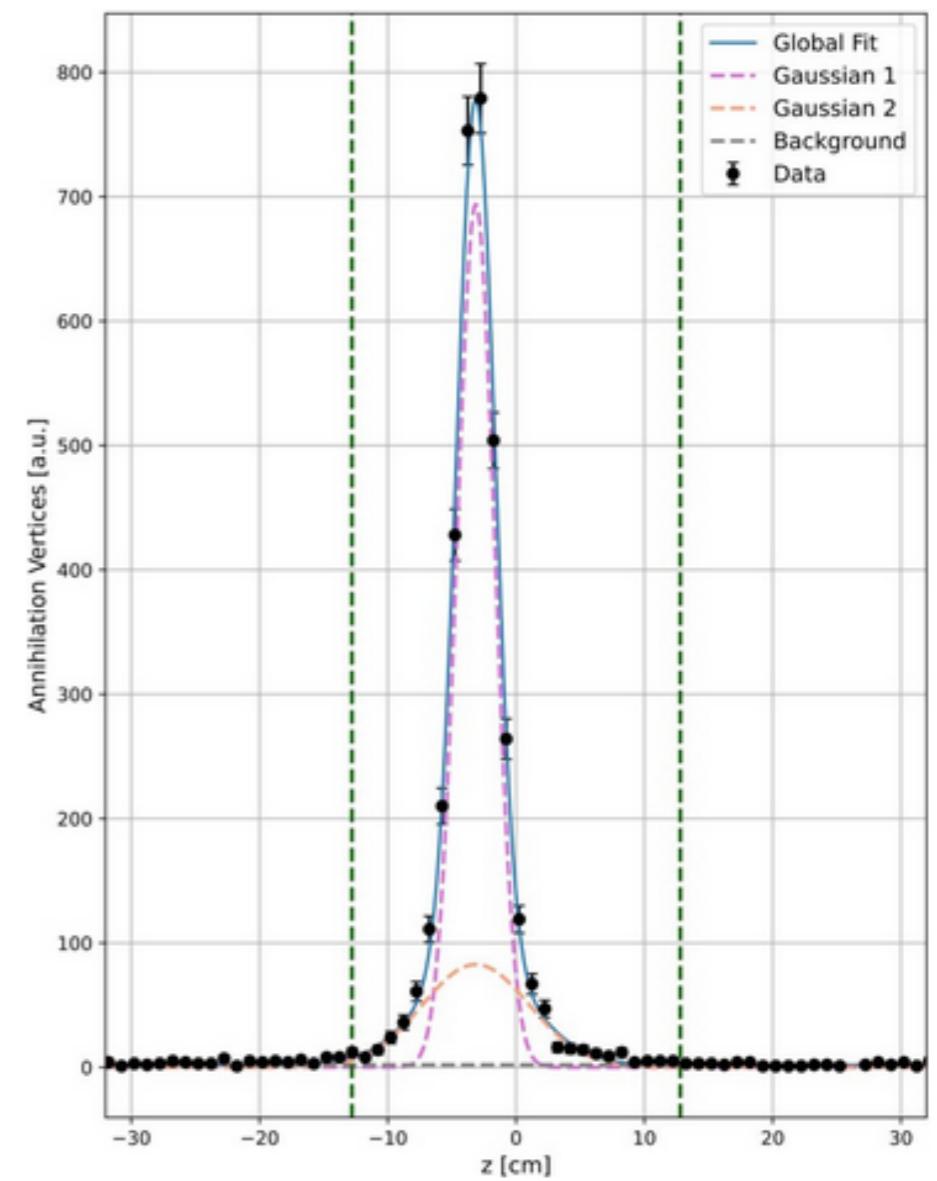
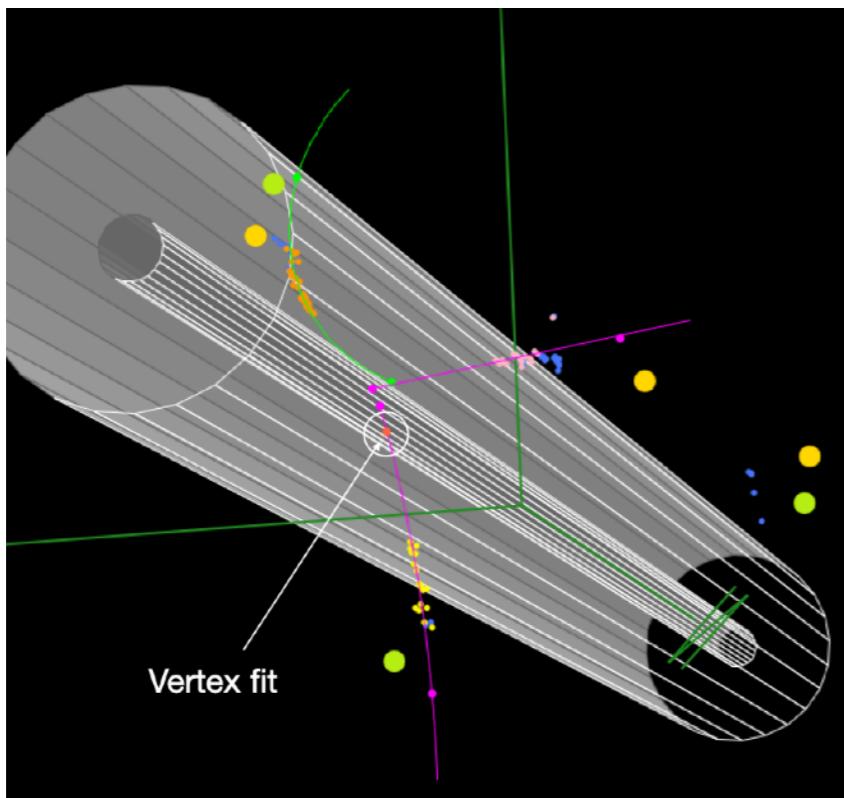
Matched,
Uncompensated
B-Field

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



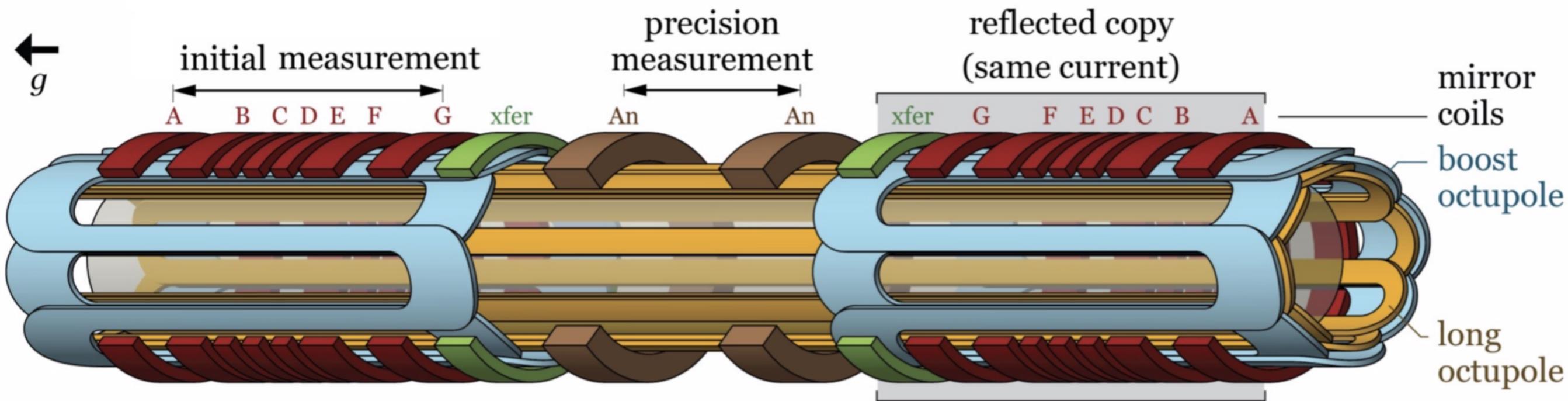
ALPHA-g Antihydrogen Detection

- 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



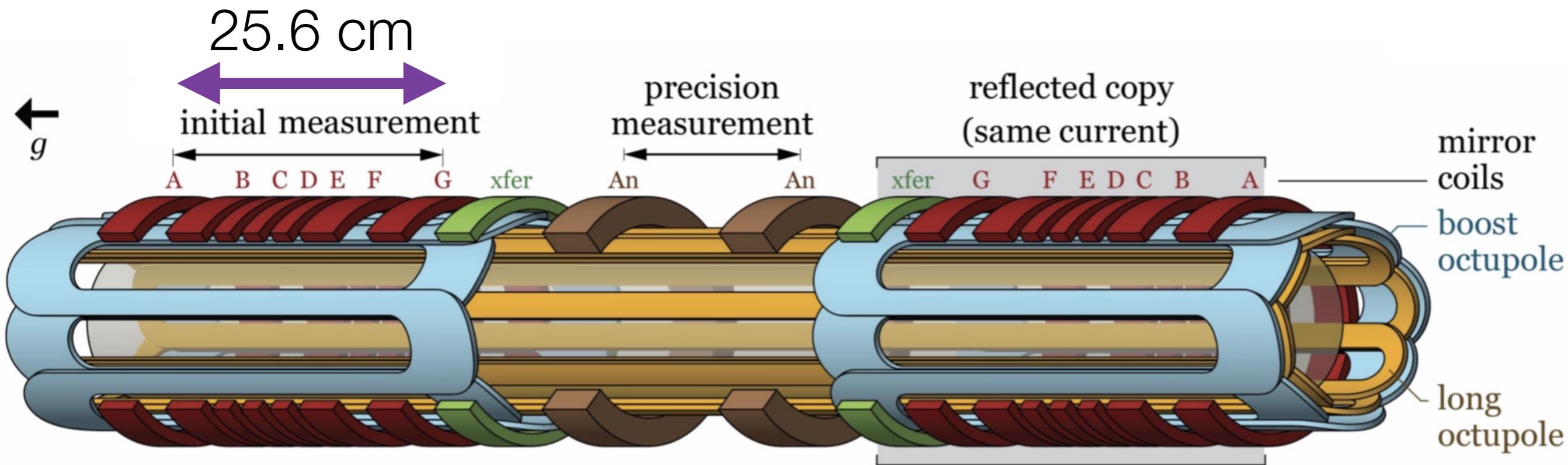
Magnetic Balance

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

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

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

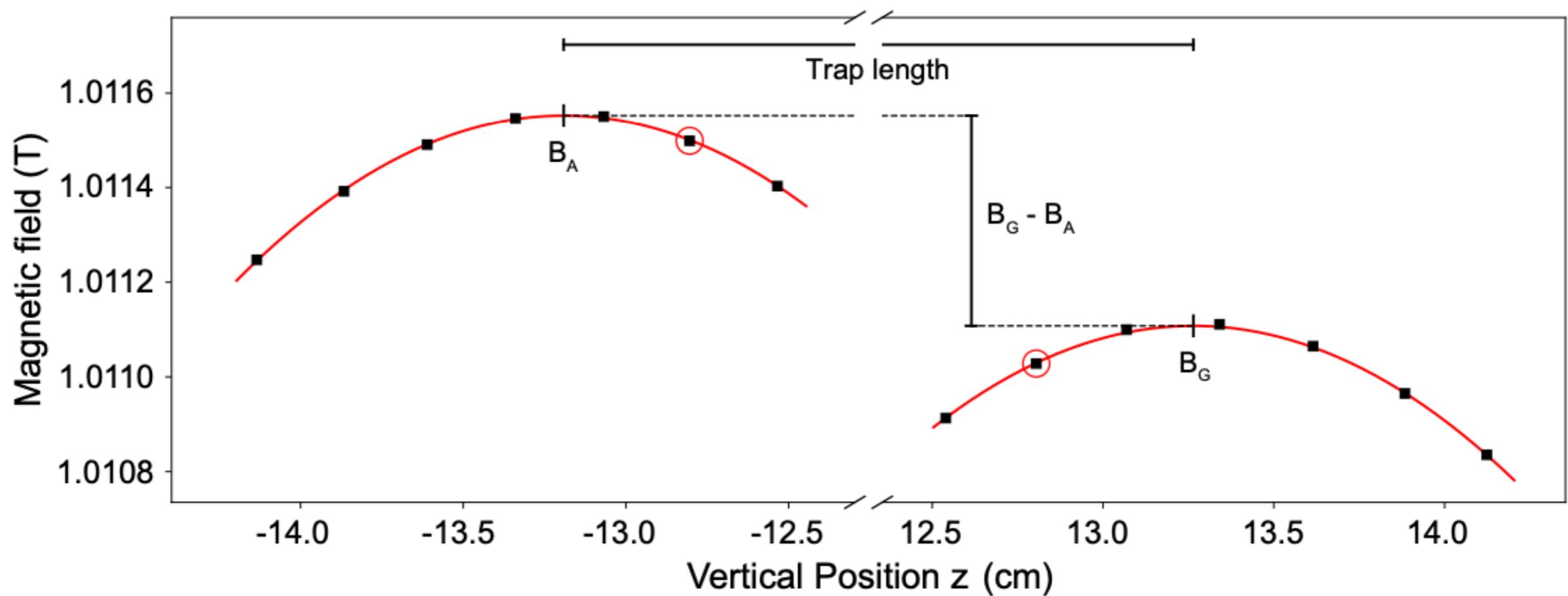
$$\Delta U_g \sim 300 \mu\text{K}$$



Magnetic Balance

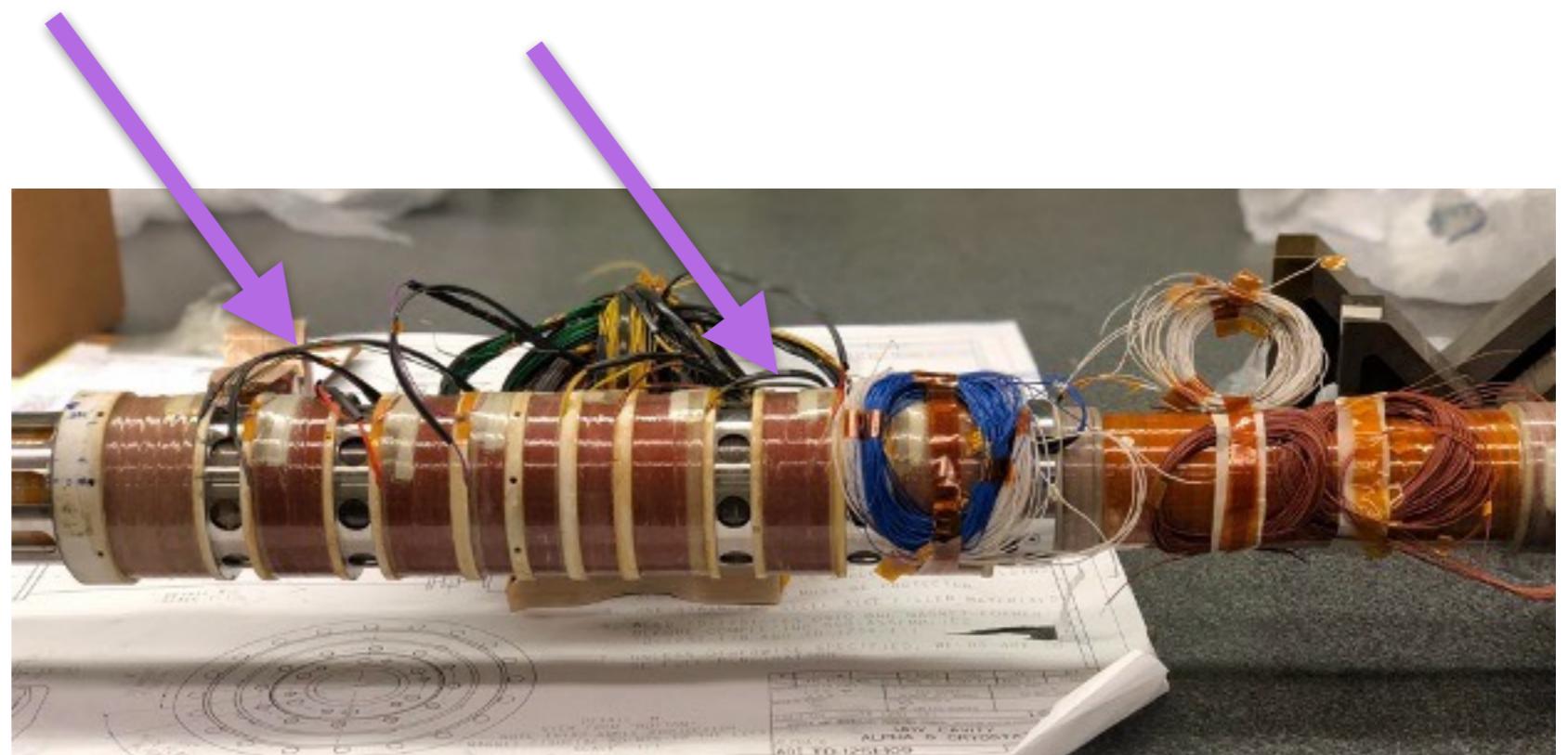
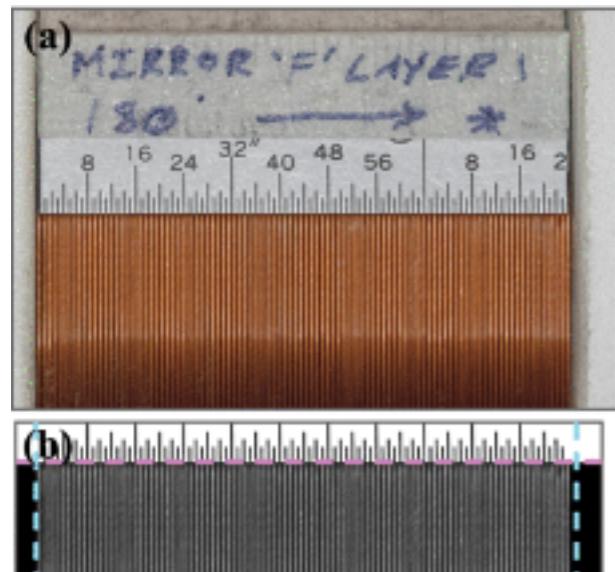
- 1 g balance bias ~ -4.5 Gauss
- Nominal bias from field map

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



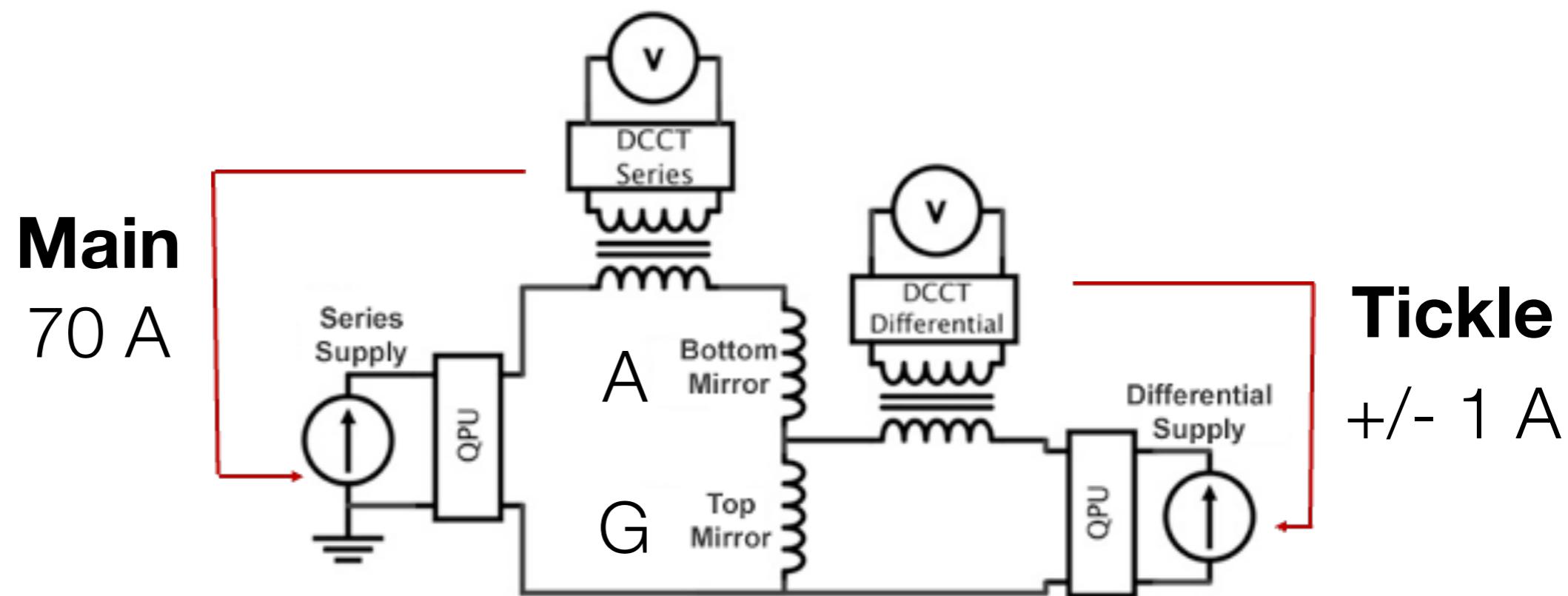
Magnet Construction

- 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

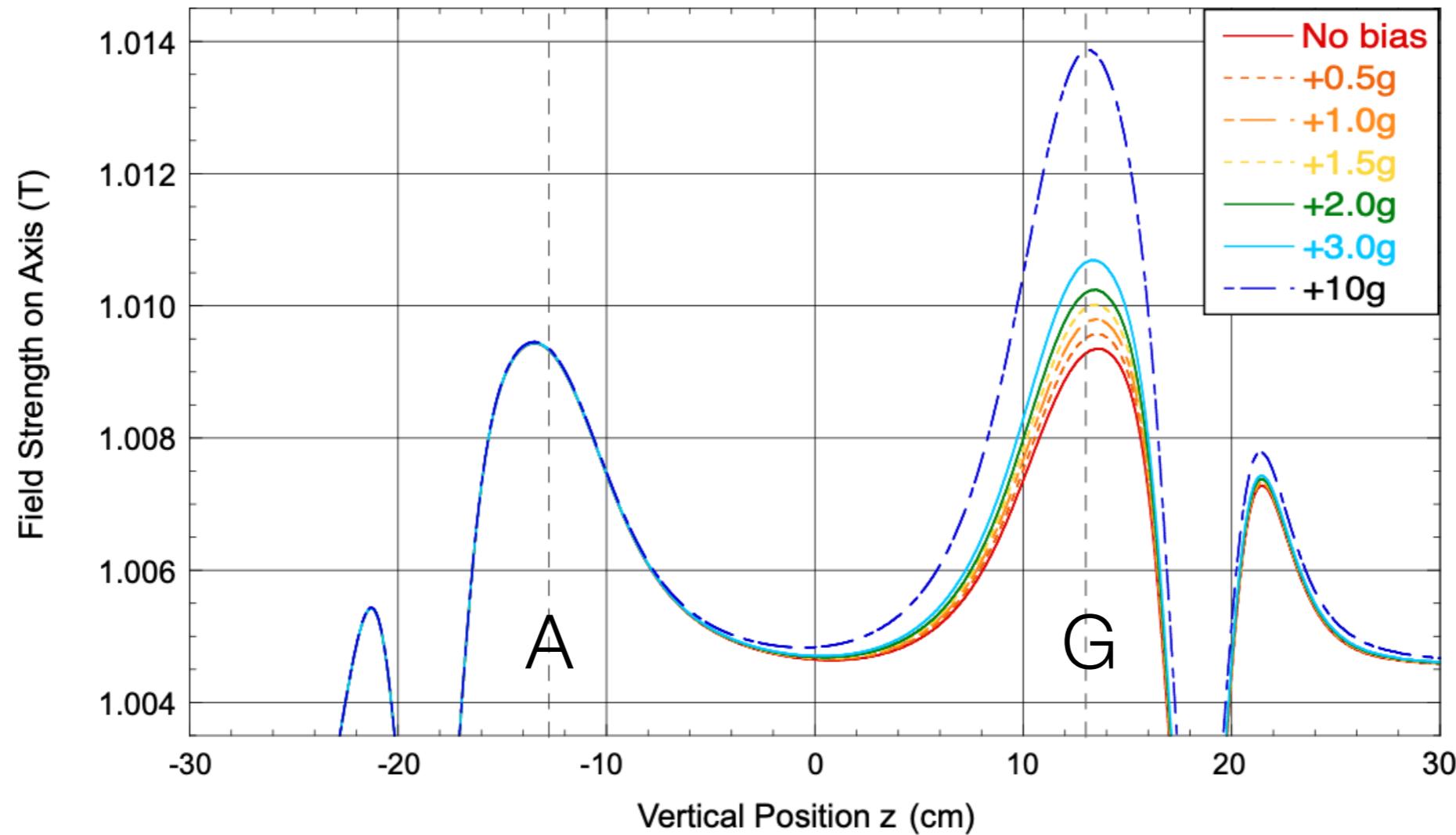
- Need continuous sub-mA control of currents
- Full mirror fields ~ 70 A in series
- **Importance is difference current**
- Bias + correction maintained by parallel “Tickle” supply



Magnetic Balance

- 1 g balance bias ~ -4.5 gauss

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



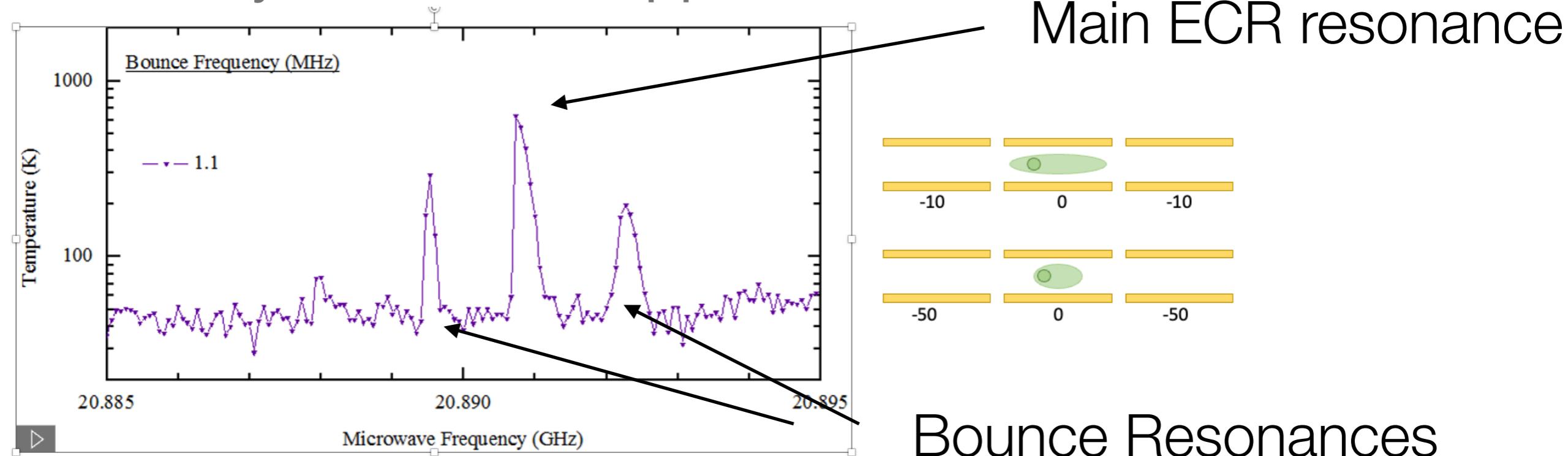
Magnetic Field Measurements: Probes

- 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

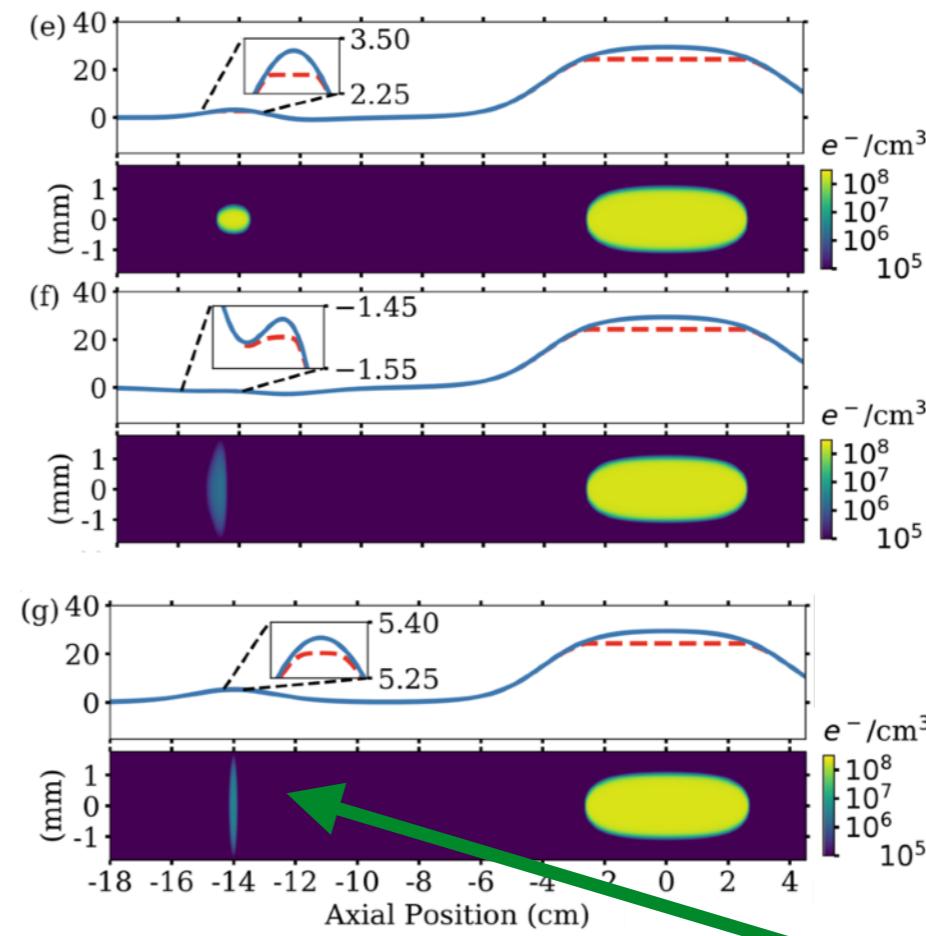
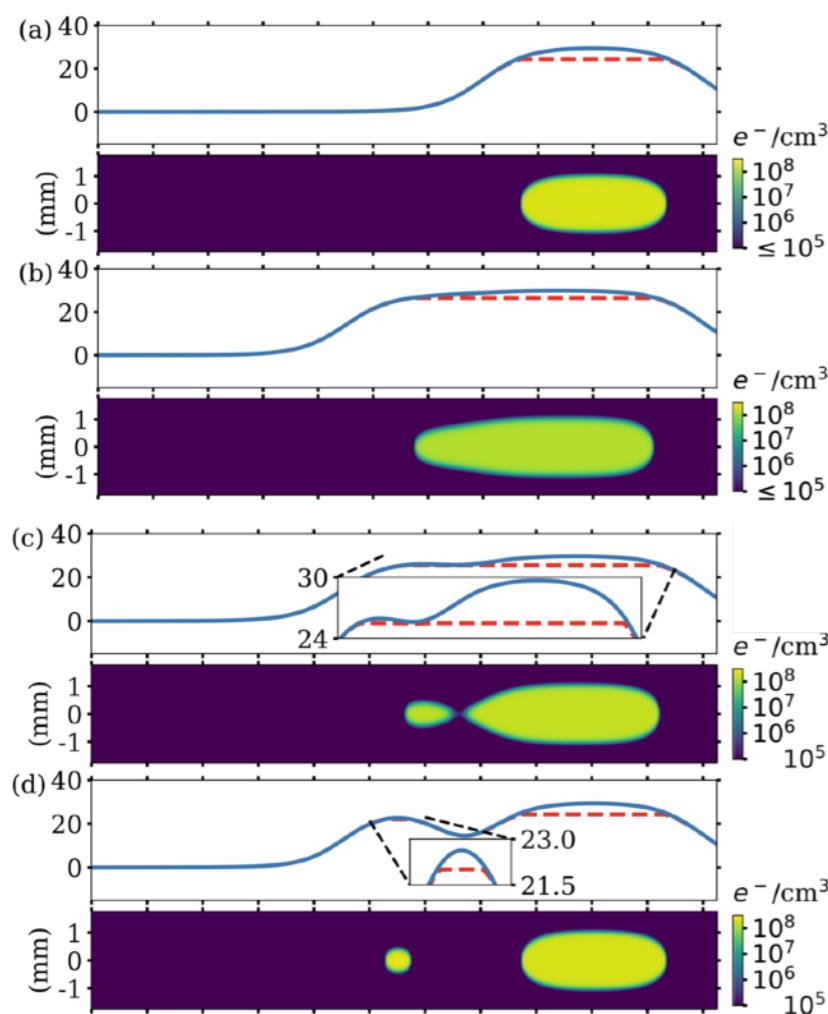


ALPHA, [In situ electromagnetic field diagnostics with an electron plasma in a Penning–Malmberg trap](#), New J. of Physics, 16, (2014).

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)



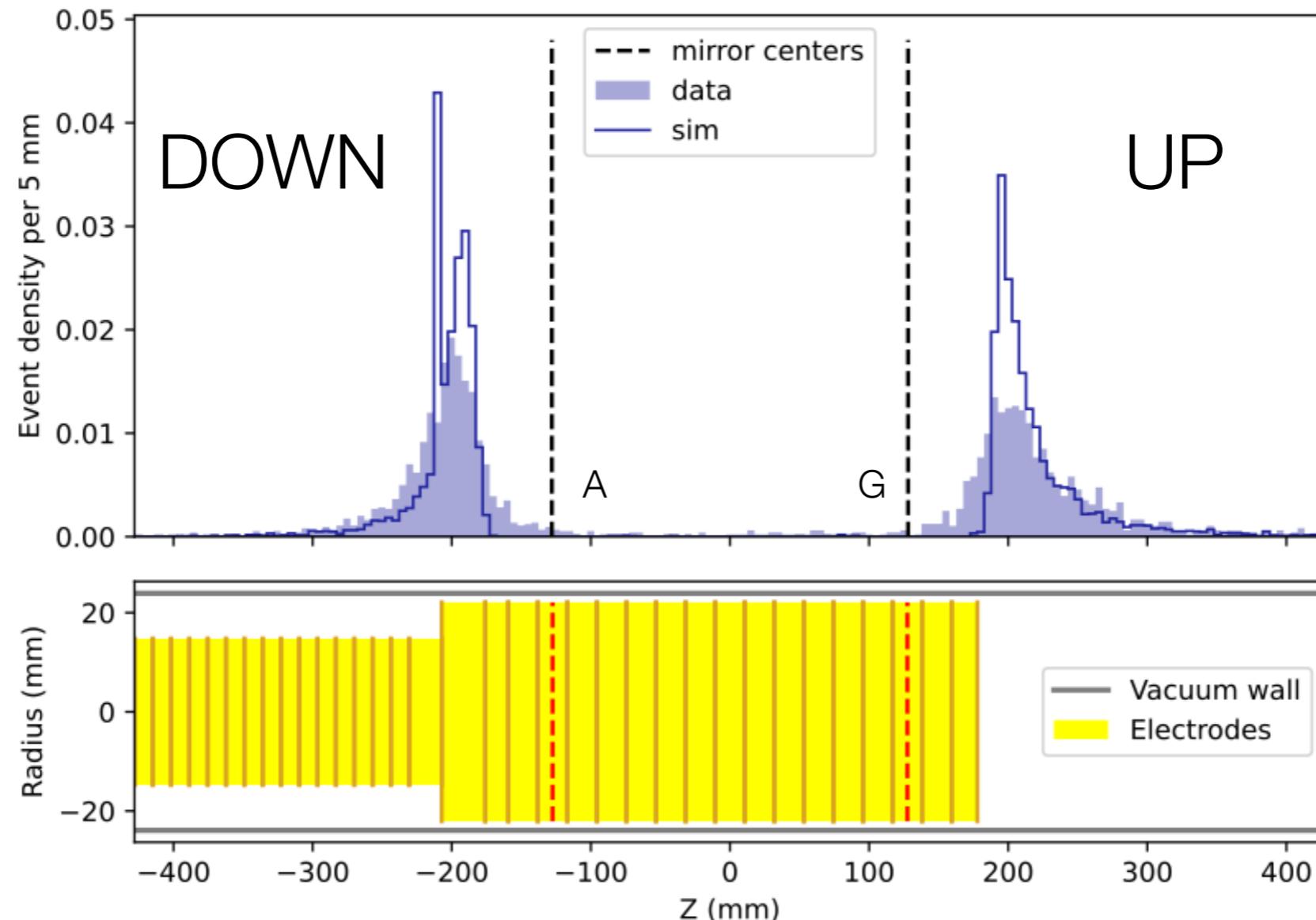
Microwave
Illumination
Here

Gravity Experiment

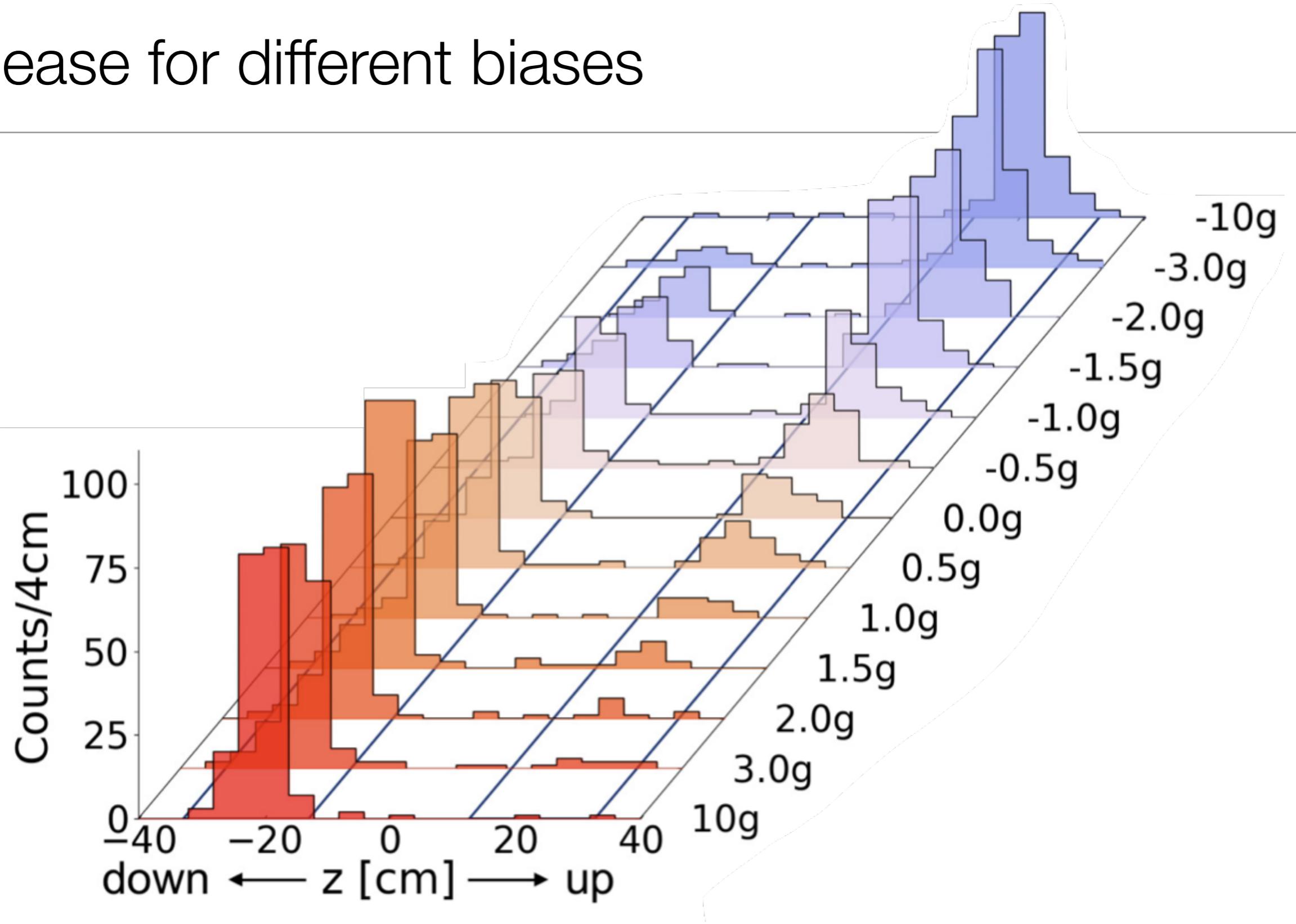
- Make, trap and stack antihydrogen (~ 50 stacks)
- Ramp down long octupole
- Measure magnetic field at full trapping current + bias
 - Under Mirrors A and G
- Ramp down to ~ 10 's Gauss residual trap (~ 18 s)
 - Maintain constant magnetic bias (current control)
- Identify up/down annihilation events 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

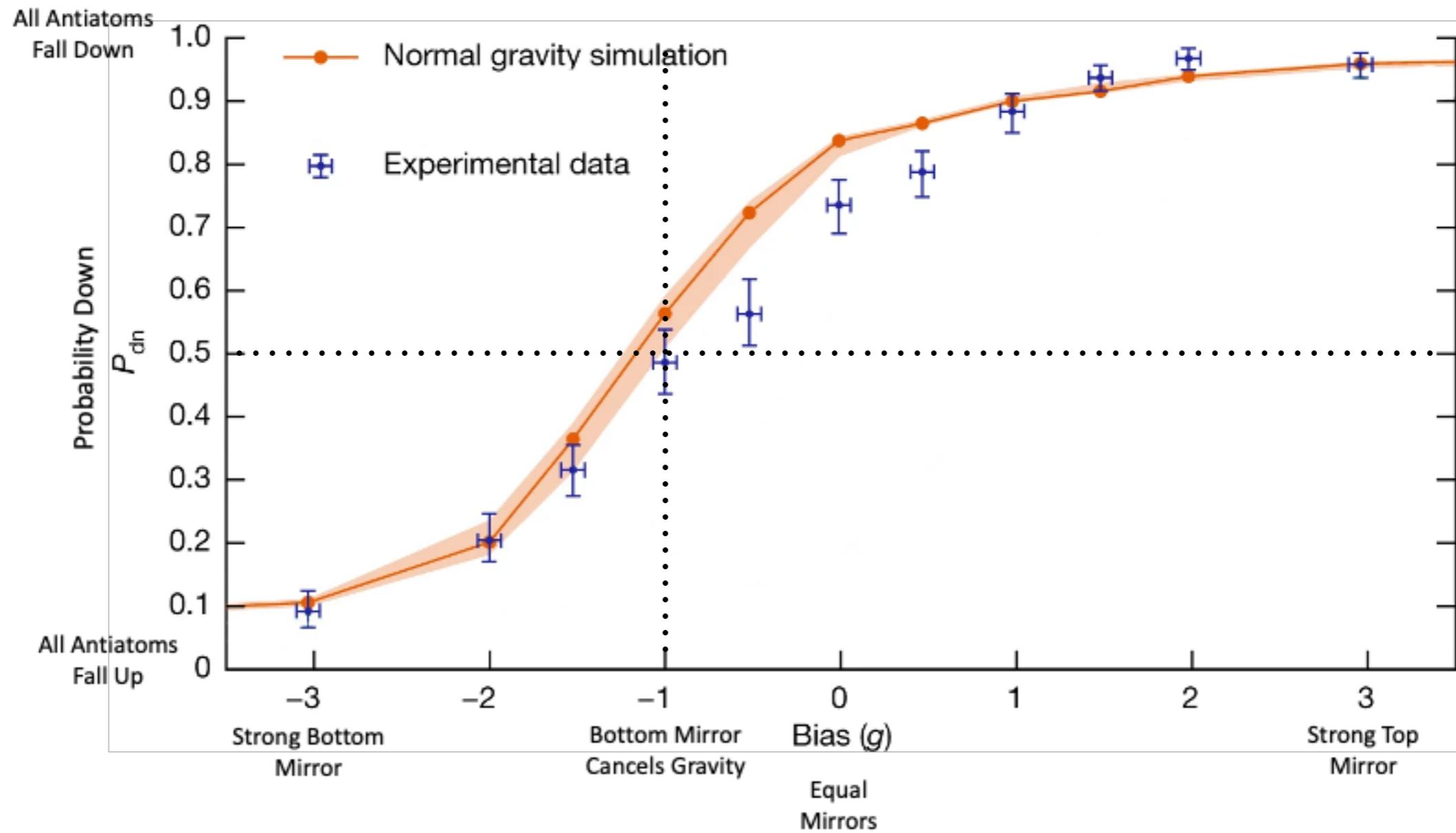
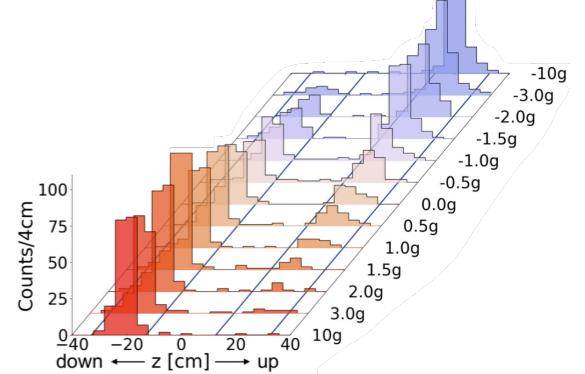
- Escaping antihydrogen leave going Up or Down



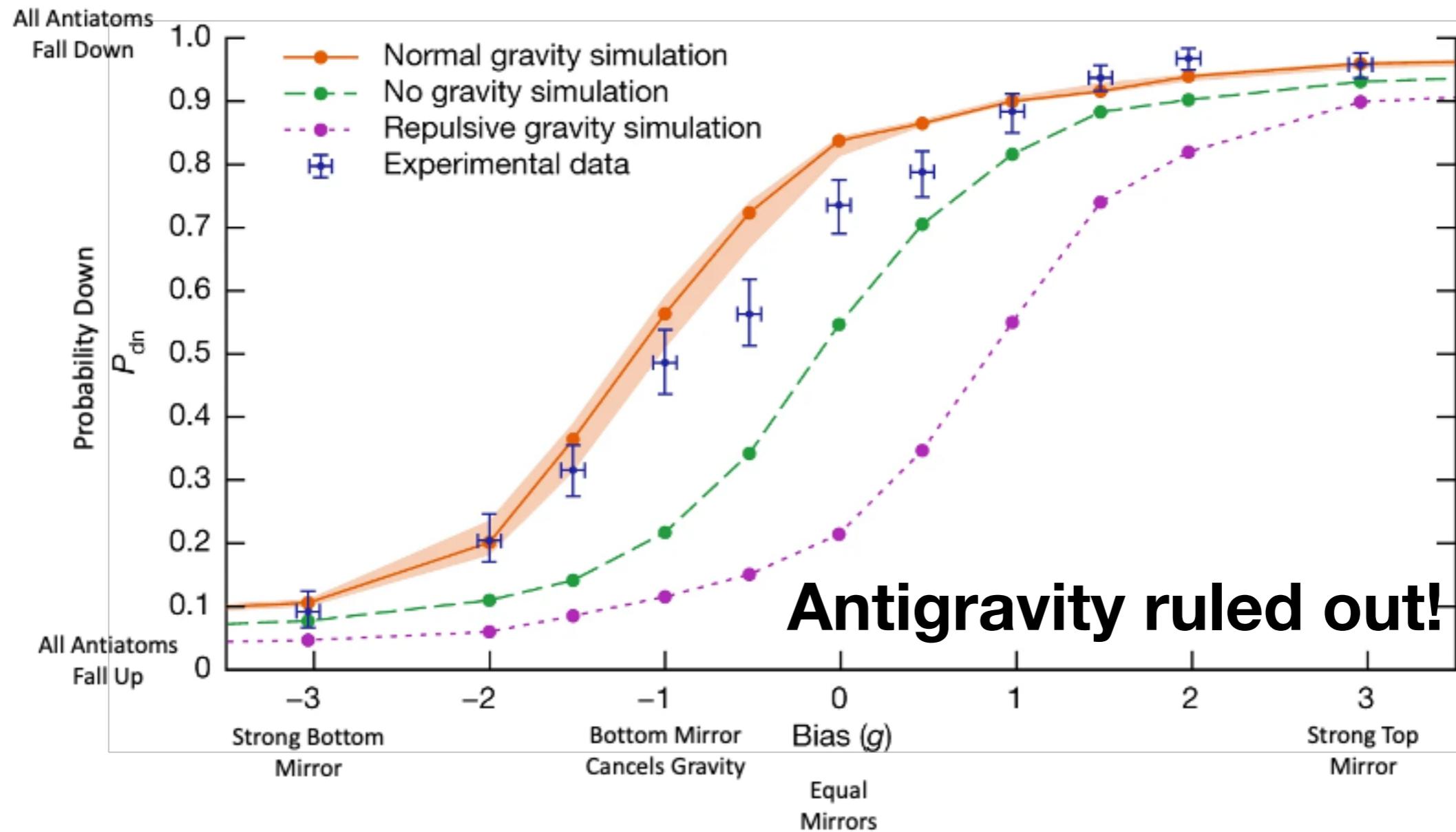
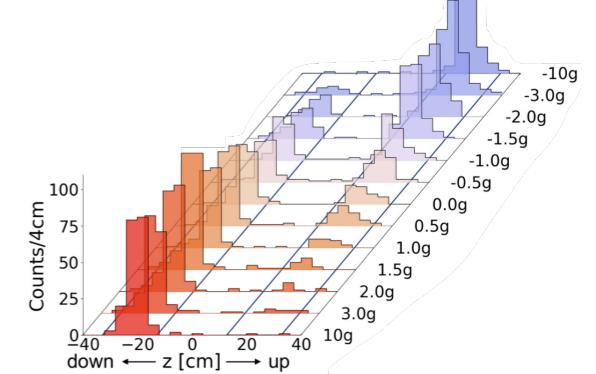
Release for different biases



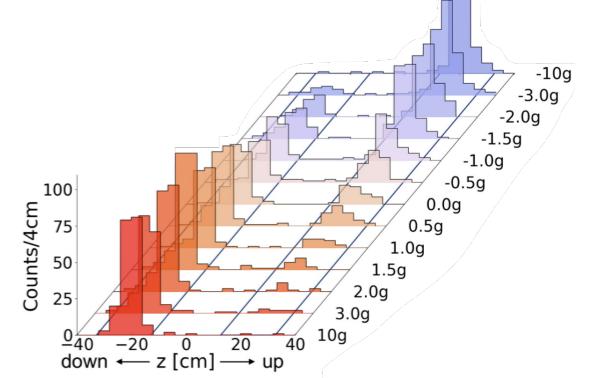
Release for different Biases



Release for different Biases

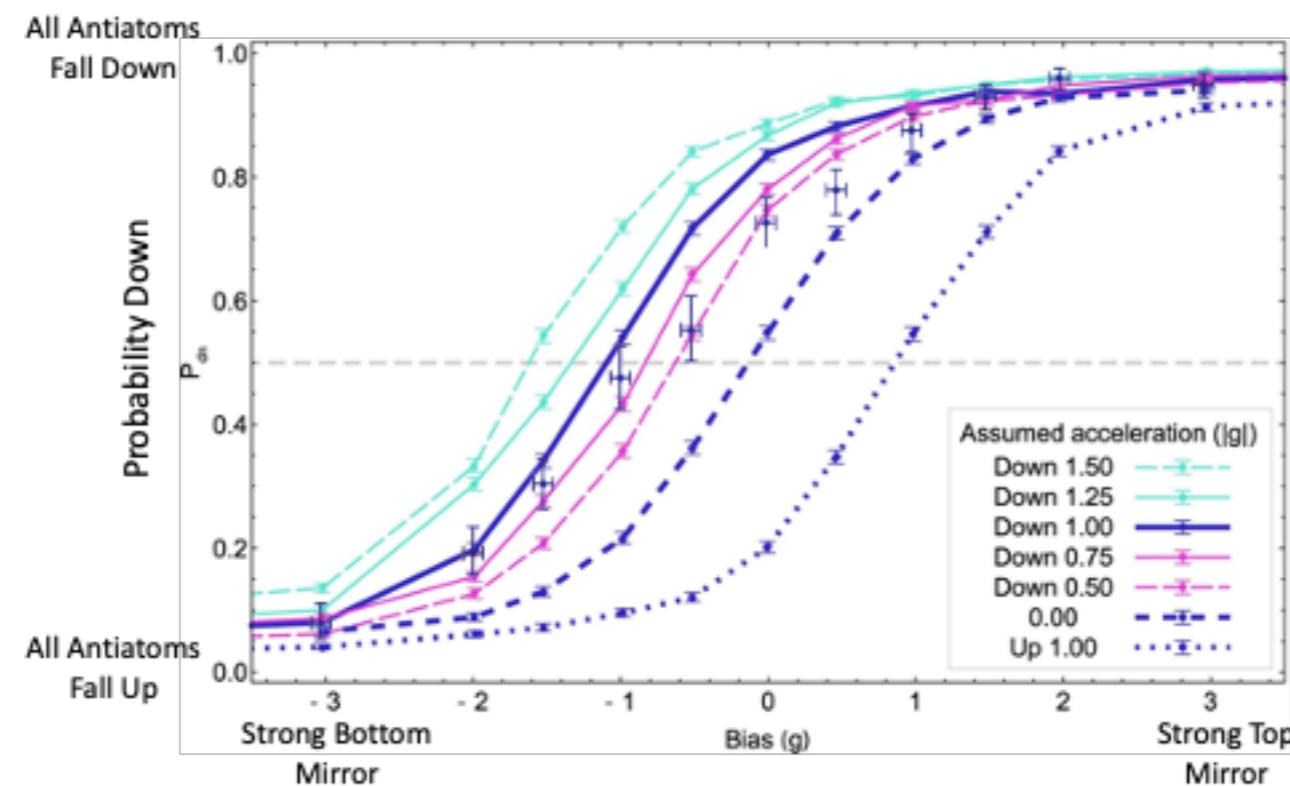


Calculating Antimatter g



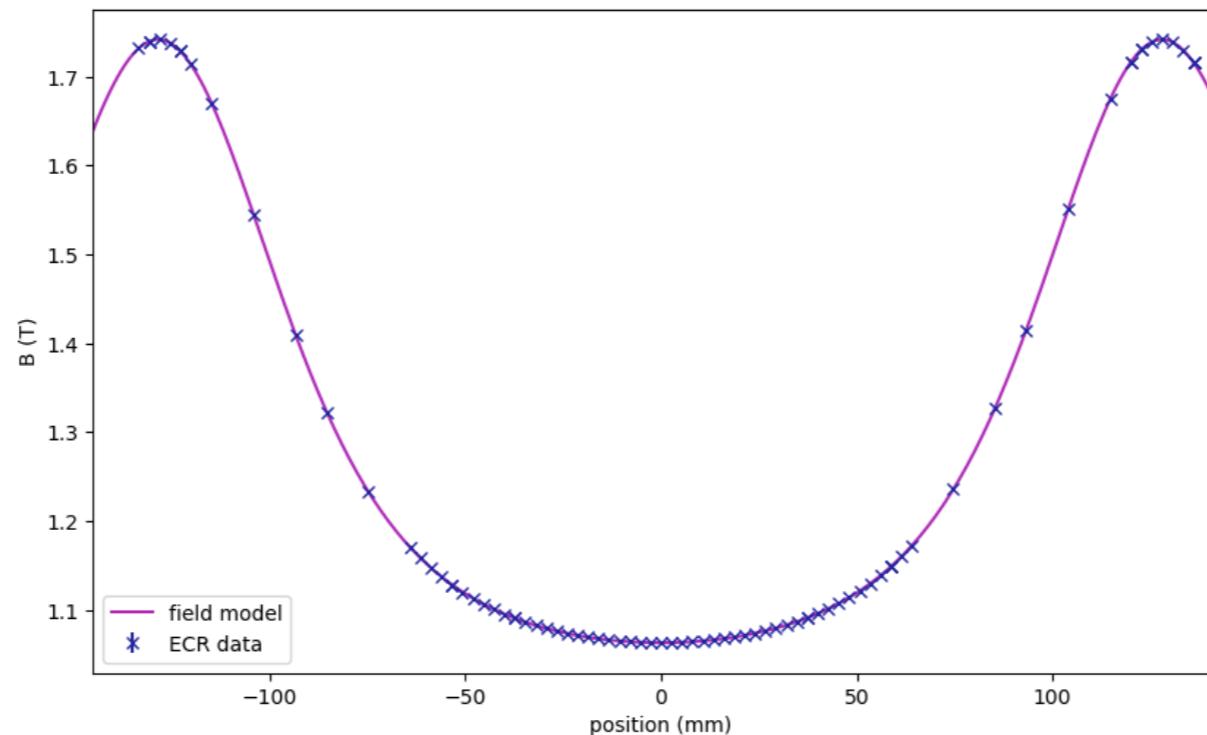
- Perform numerous simulated accelerations
- Find best fit to data

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



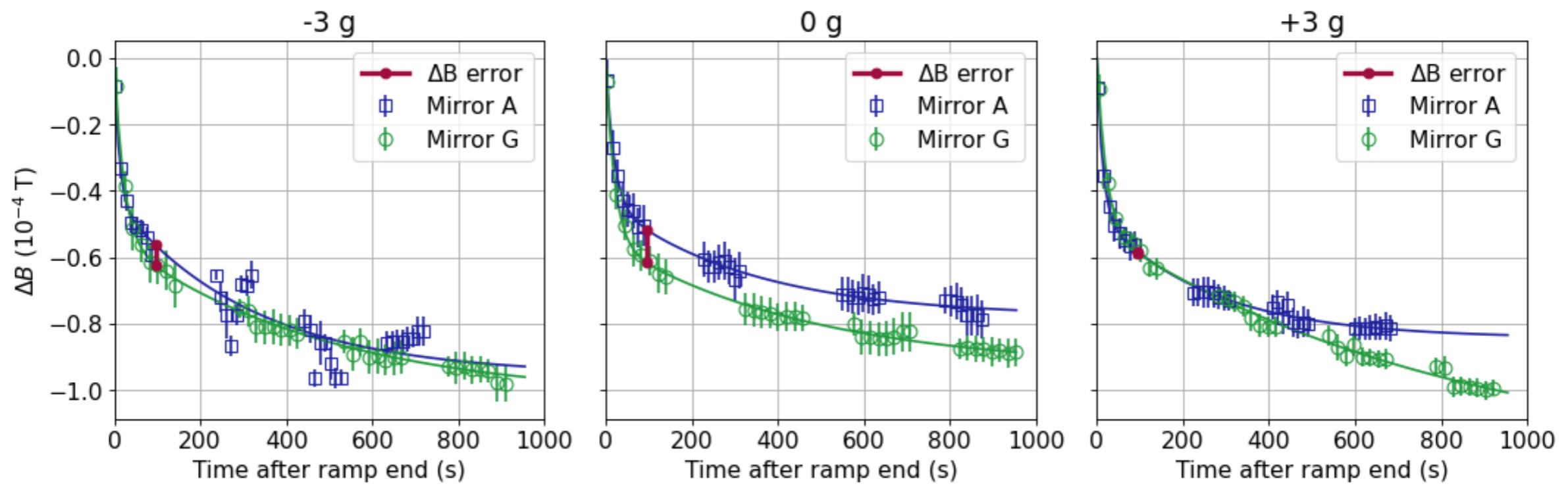
Limits to the measurement: field measurements

- 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!*)



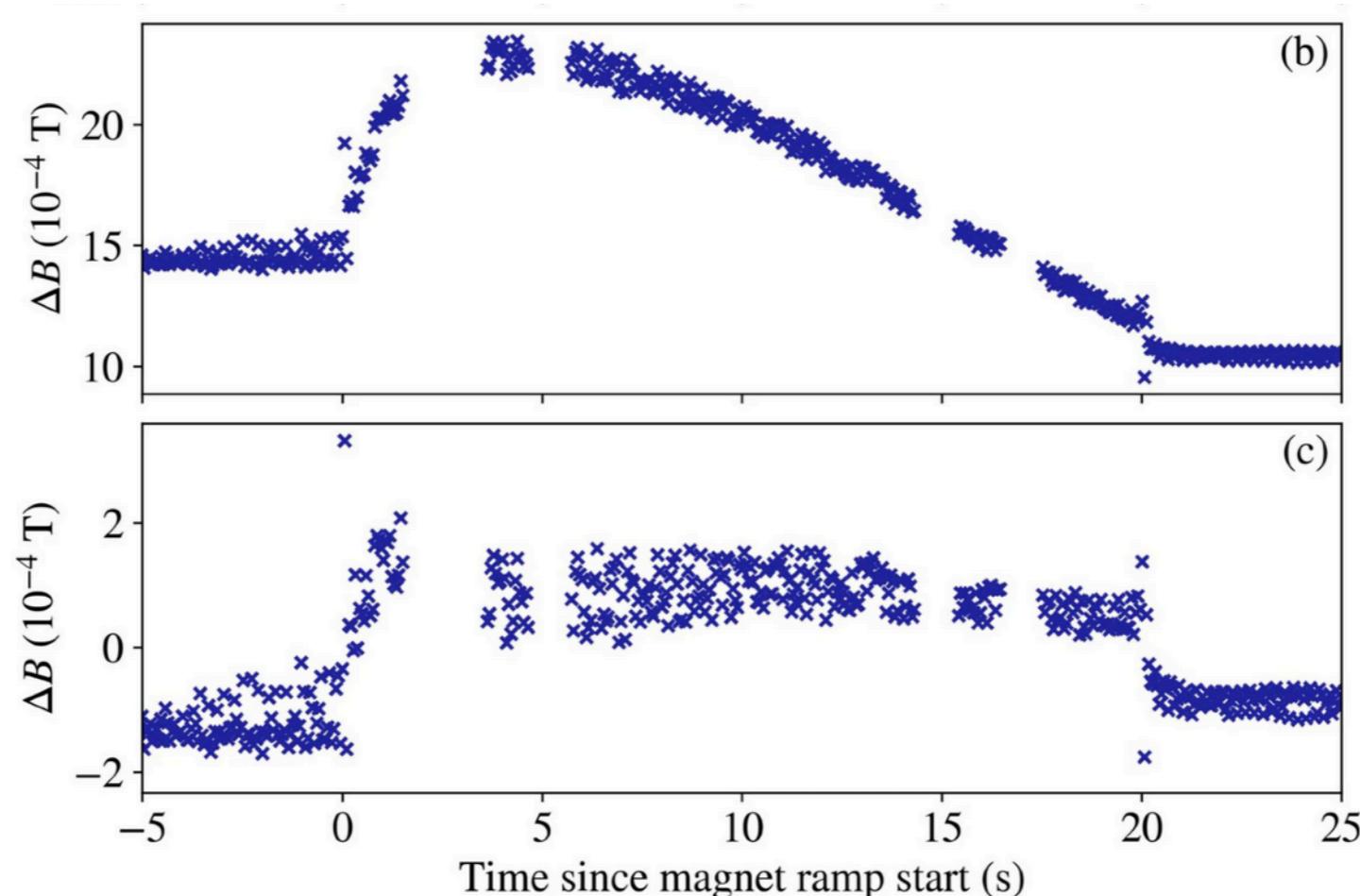
Limits to the measurement: field measurements

- 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



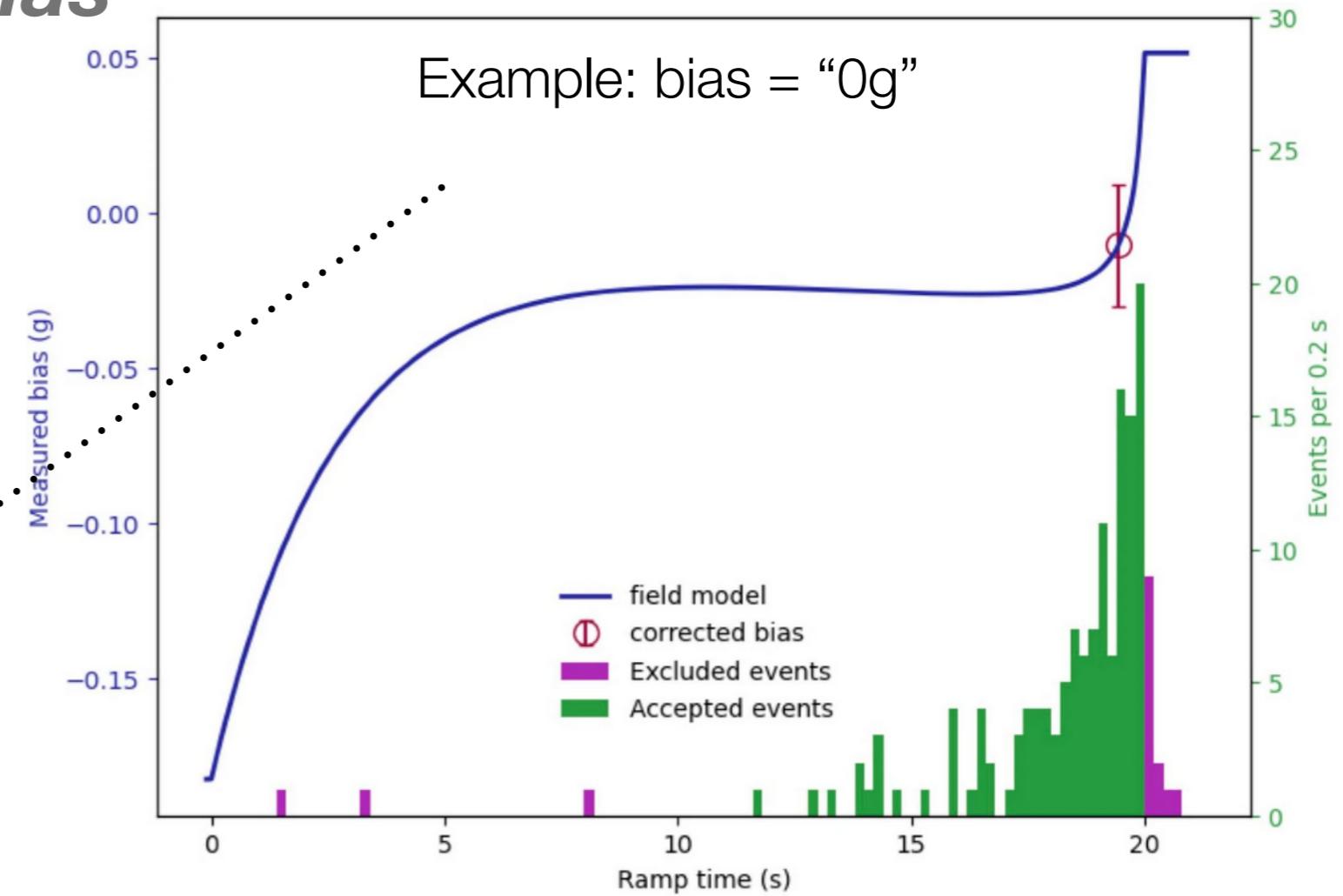
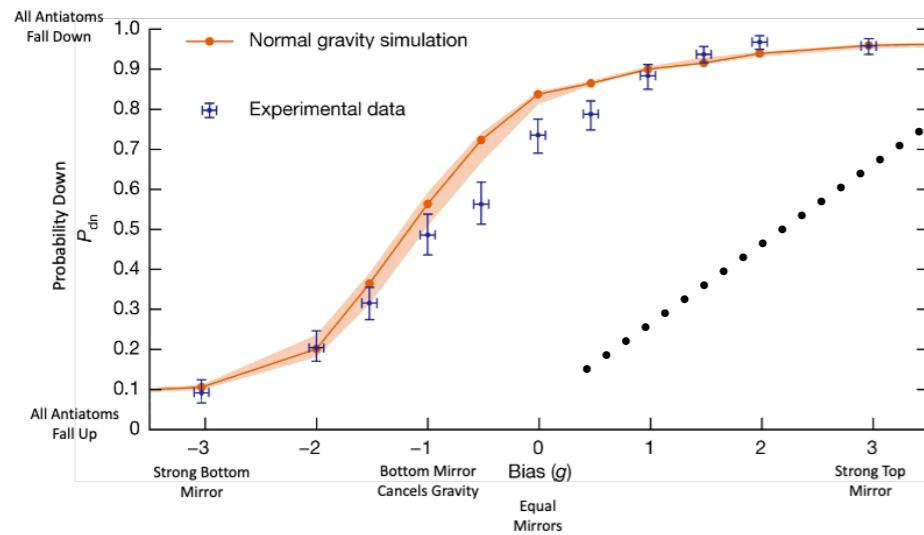
Limits to the measurement: field measurements

- 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

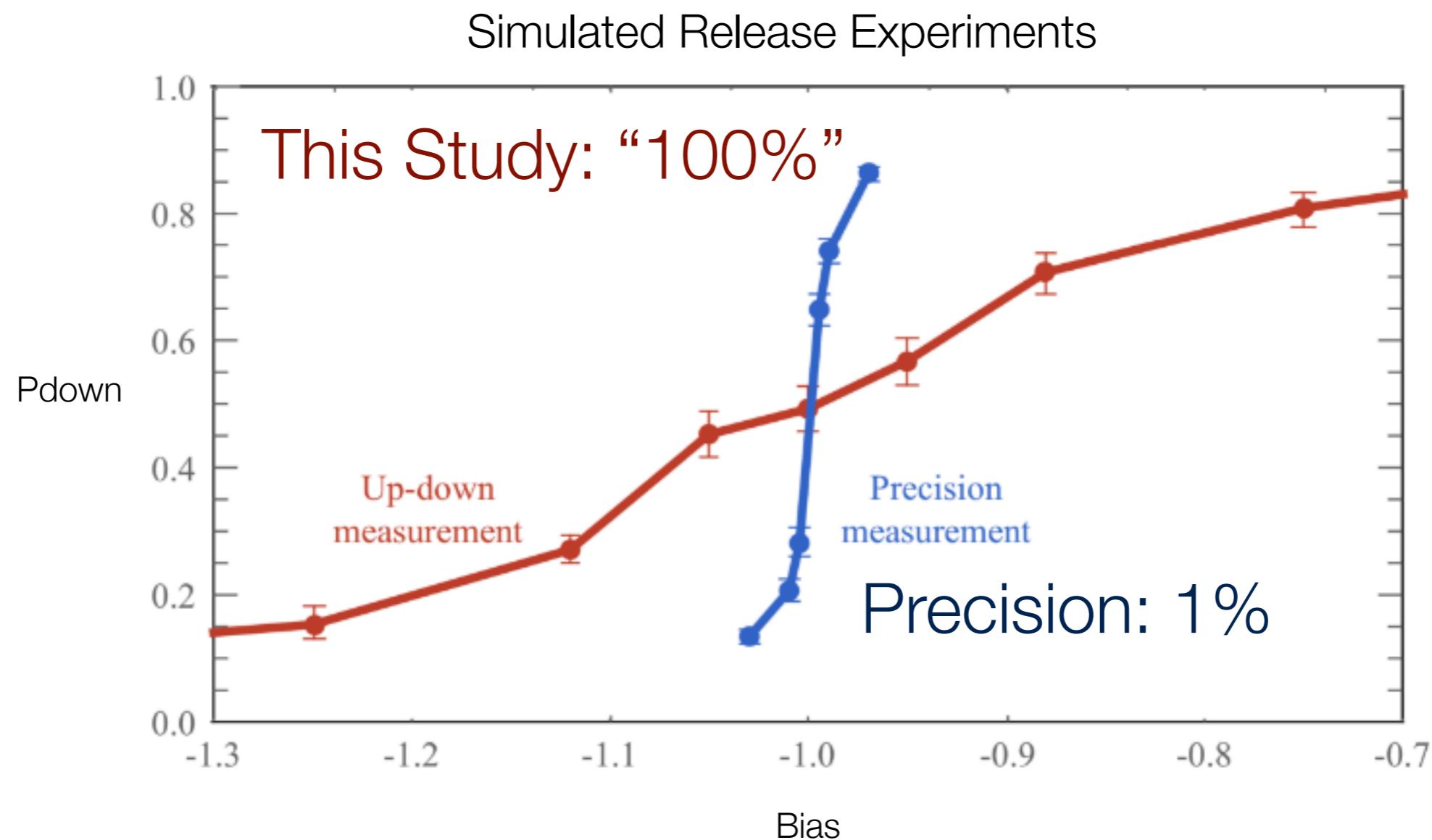
- Many aspects contribute to error.
- Largest (0.16 g) is uncertainty from estimated off-axis asymmetry in the octupole field (unmeasured)

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

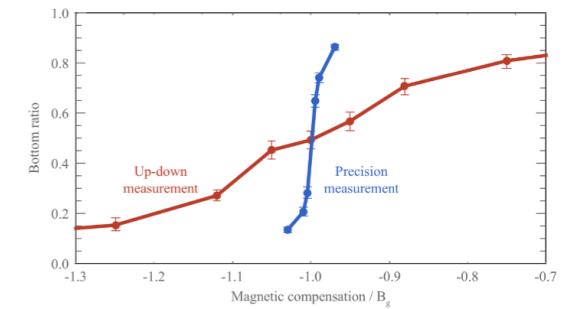
	Uncertainty	Magnitude (g)
Statistical and Systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03

Future prospects with ALPHA-g: 1% Measurements

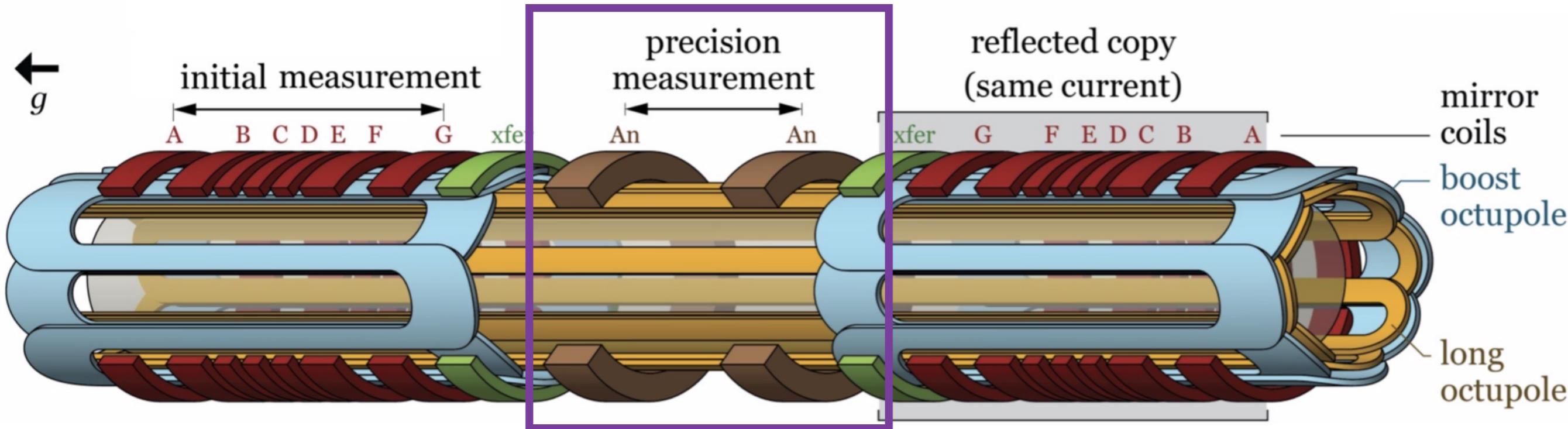
- Make the release curve steeper



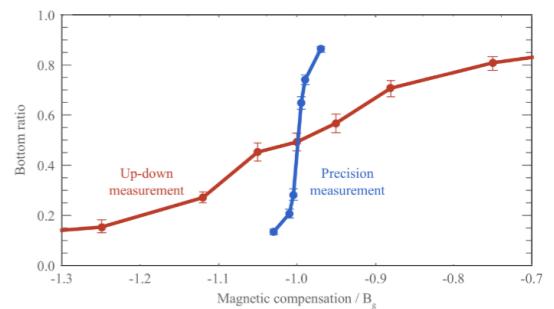
Future prospects with ALPHA-g: 1% Measurements



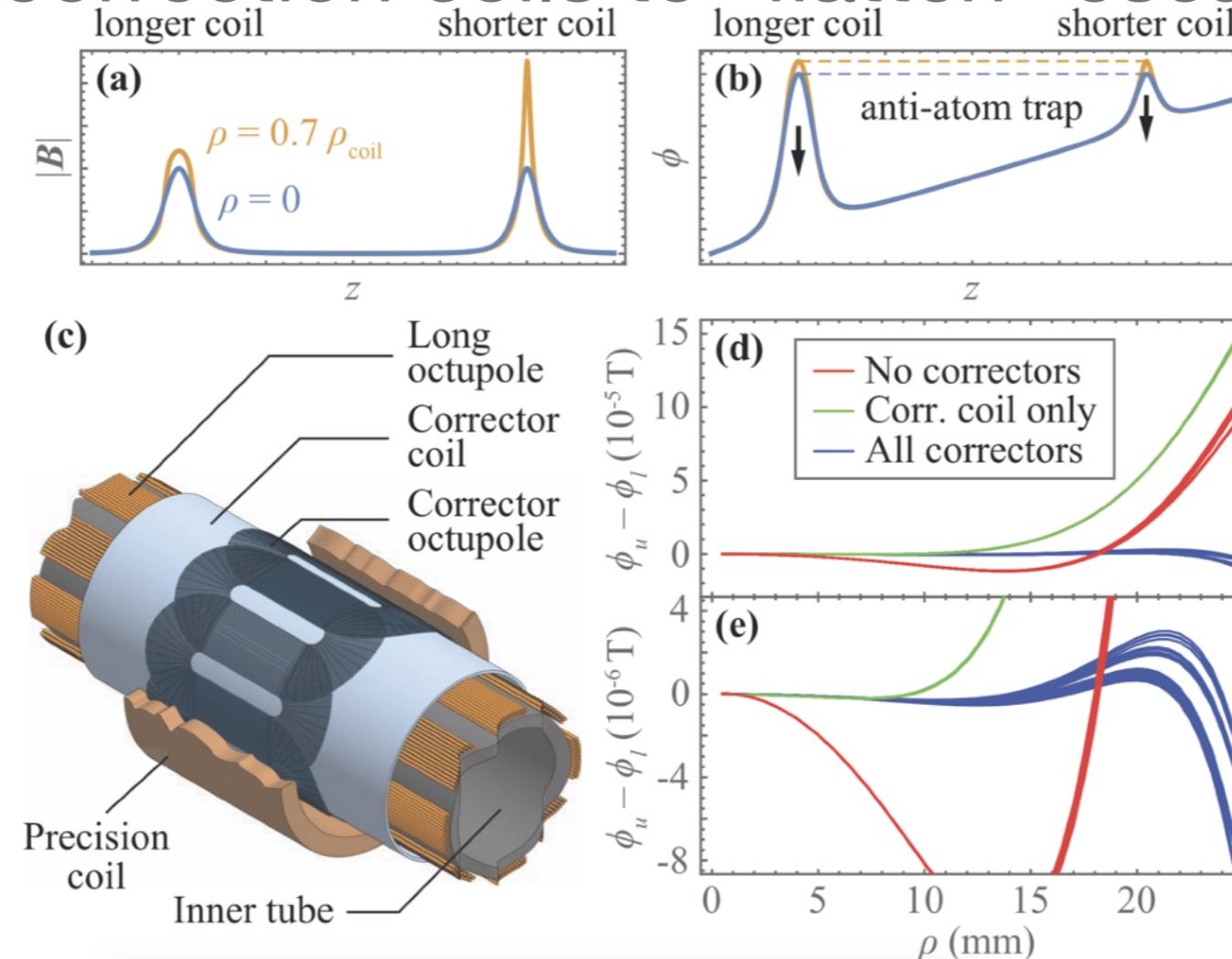
- Precision region
 - symmetrizes superconducting material
 - + detection geometry
 - Improves shape of applied bias potential



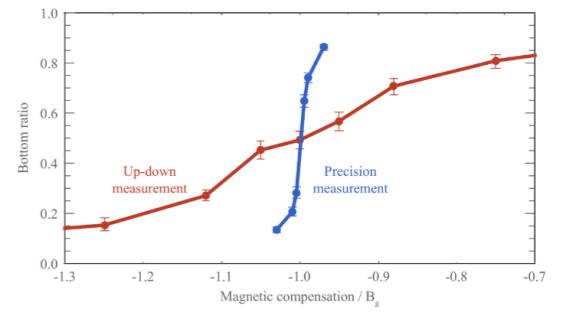
Future prospects with ALPHA-g: 1% Measurements



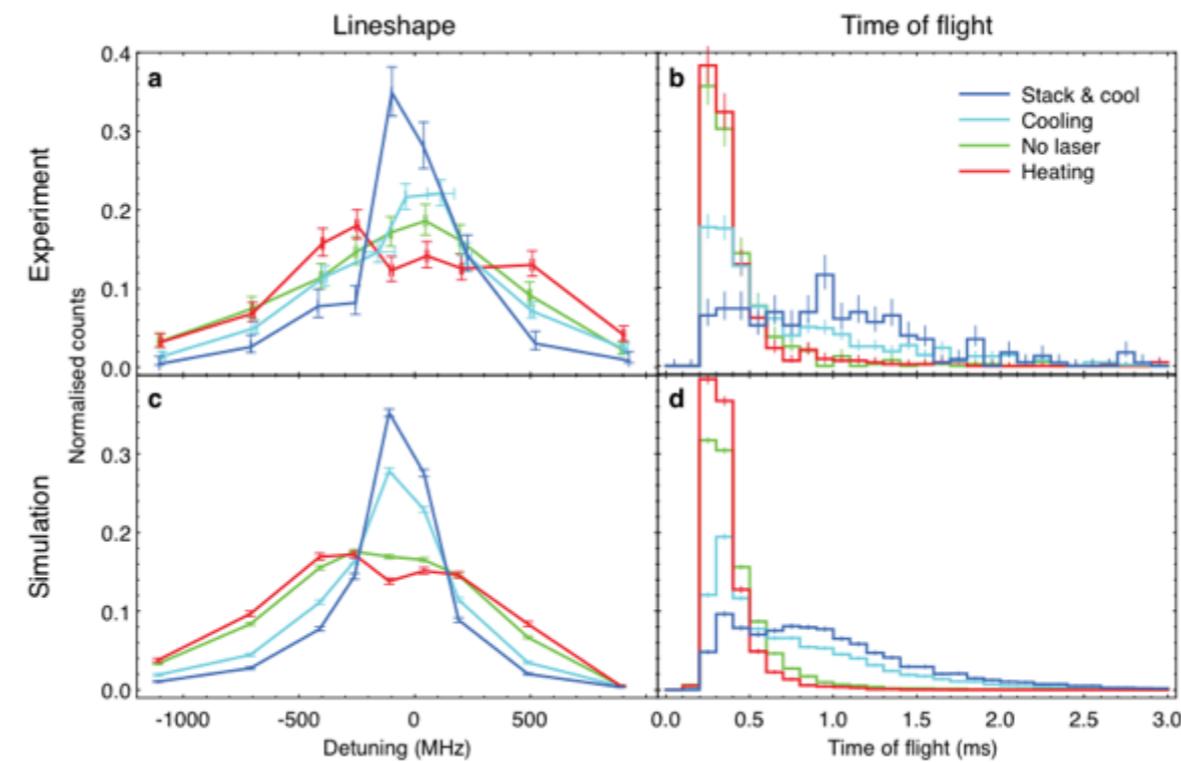
- Generally, escape bias is a function of radius
 - *Broadens and shifts release curve*
- Additional correction coils to “flatten” escape bias



Future prospects with ALPHA-g: 1% Measurements



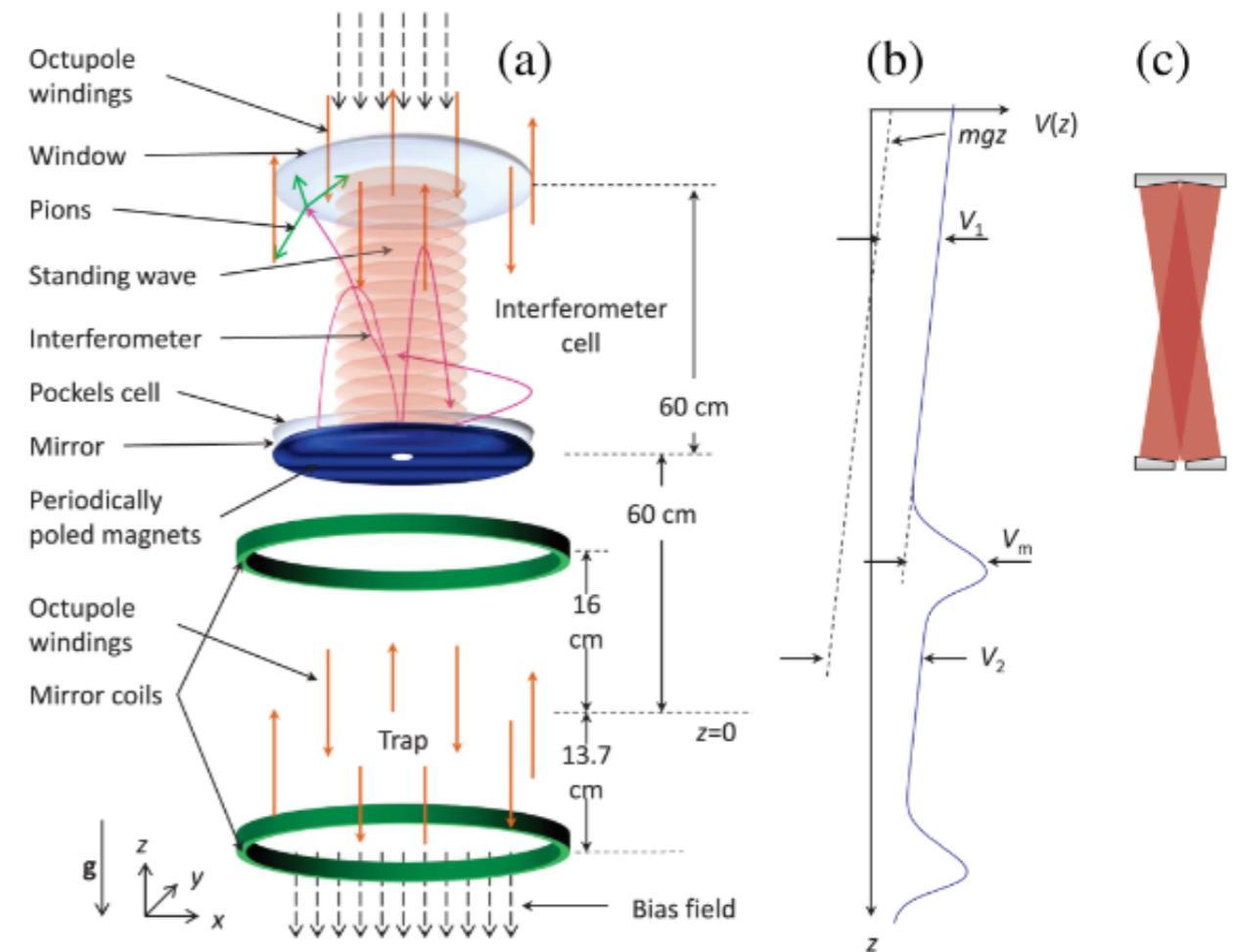
- Improve distribution: Doppler Laser Cooling
- Slower atoms more sensitive to potential
- avoid off-axis fields
- $500 \text{ mK} > 20 \text{ mK} > 300 \text{ uK}$



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*



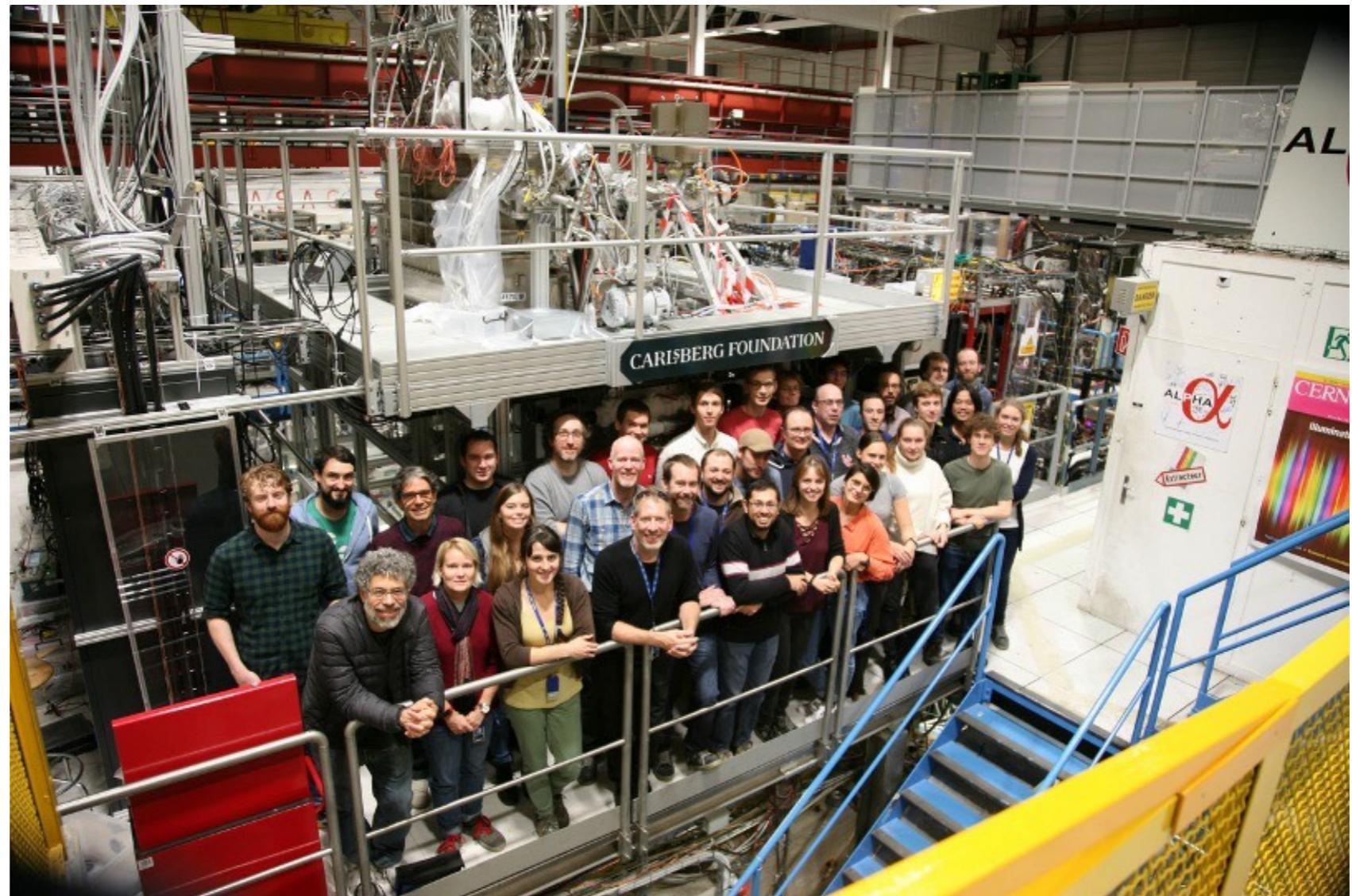
P. Hamilton, A. Zhmoginov, F. Robicheaux, J. Fajans, J. S. Wurtele, and H. Müller
Phys. Rev. Lett. 112, 121102

Thanks for your attention!

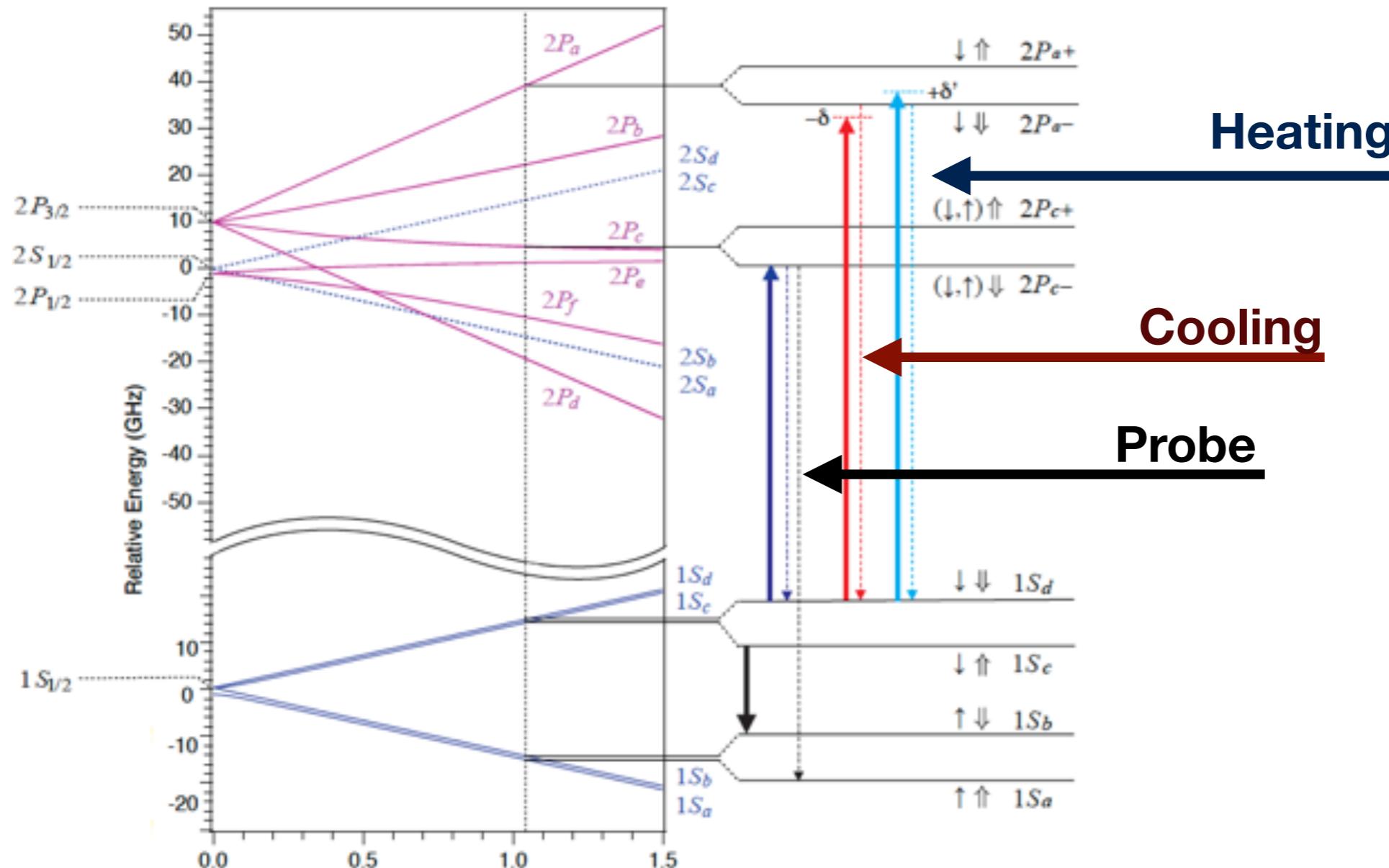
Anti-Apple



Earth

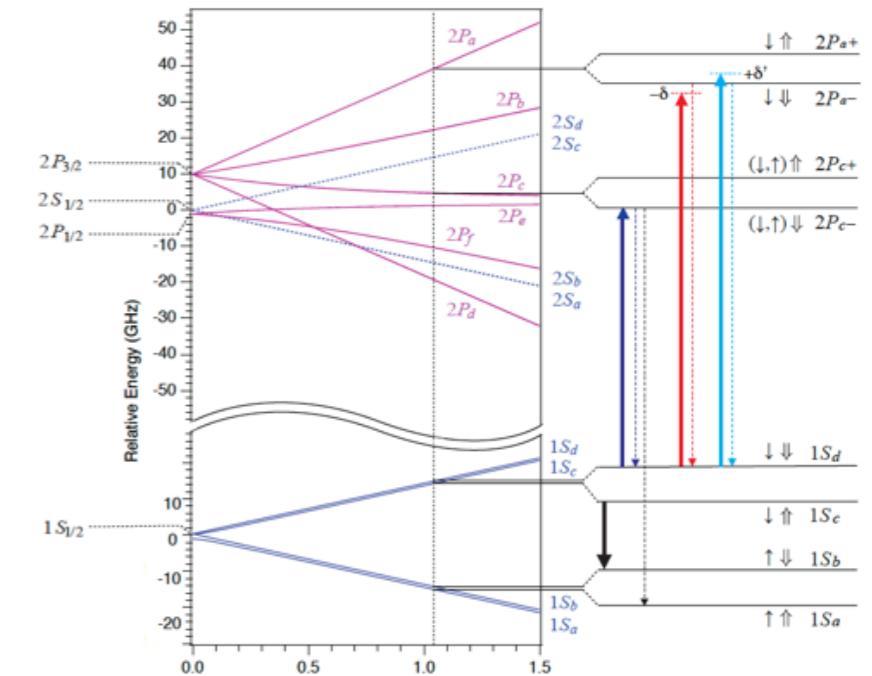


Antihydrogen Laser Cooling: Closed transitions

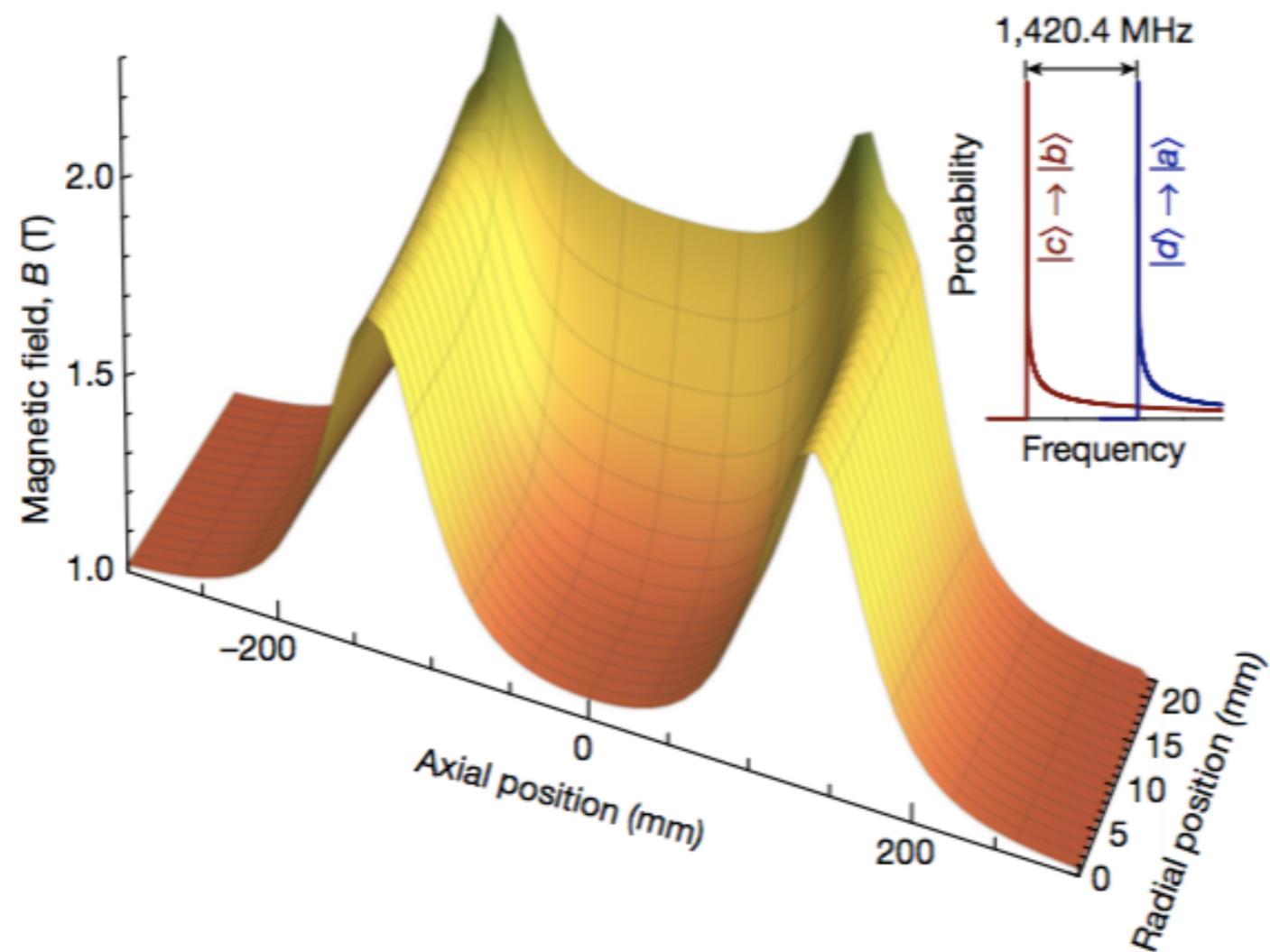
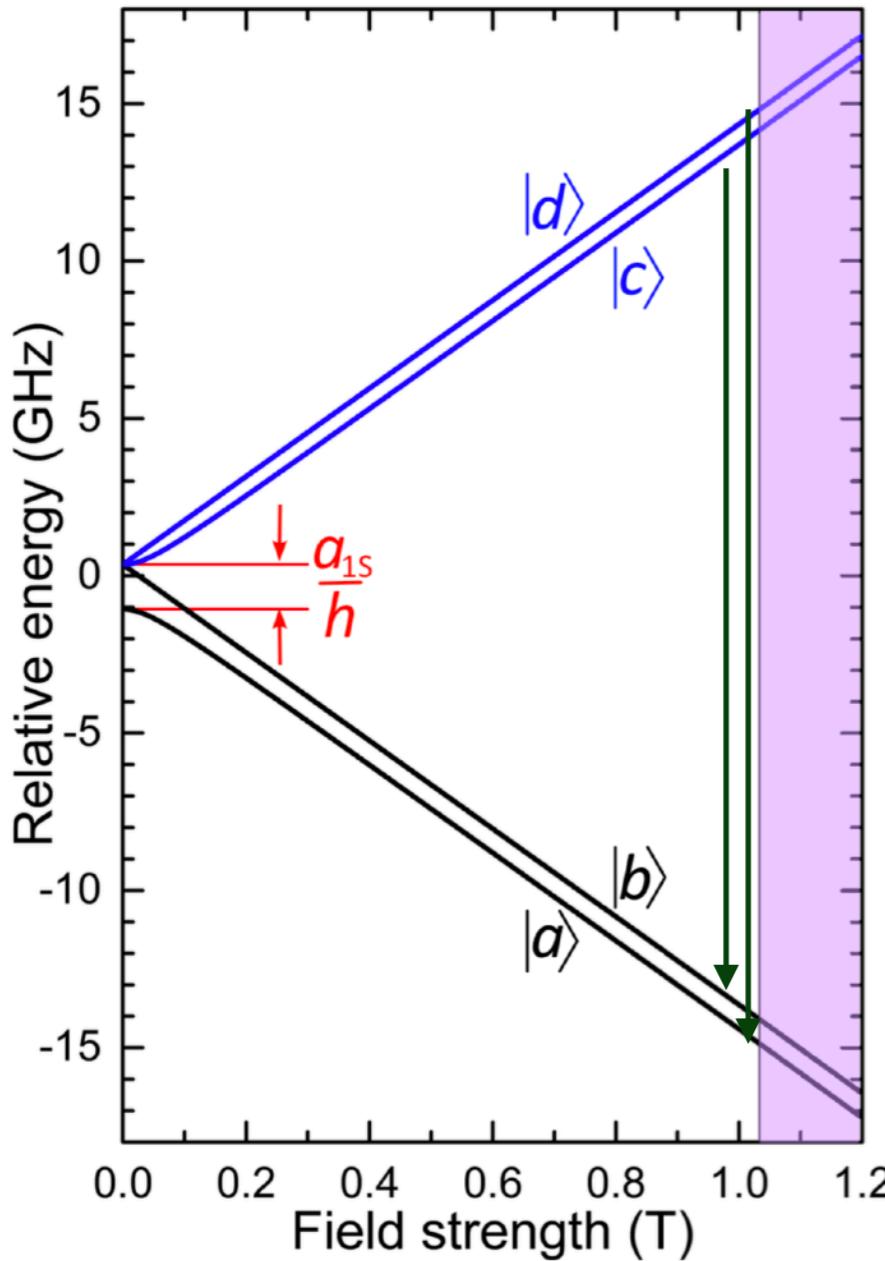


Antihydrogen Laser Cooling

- 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:

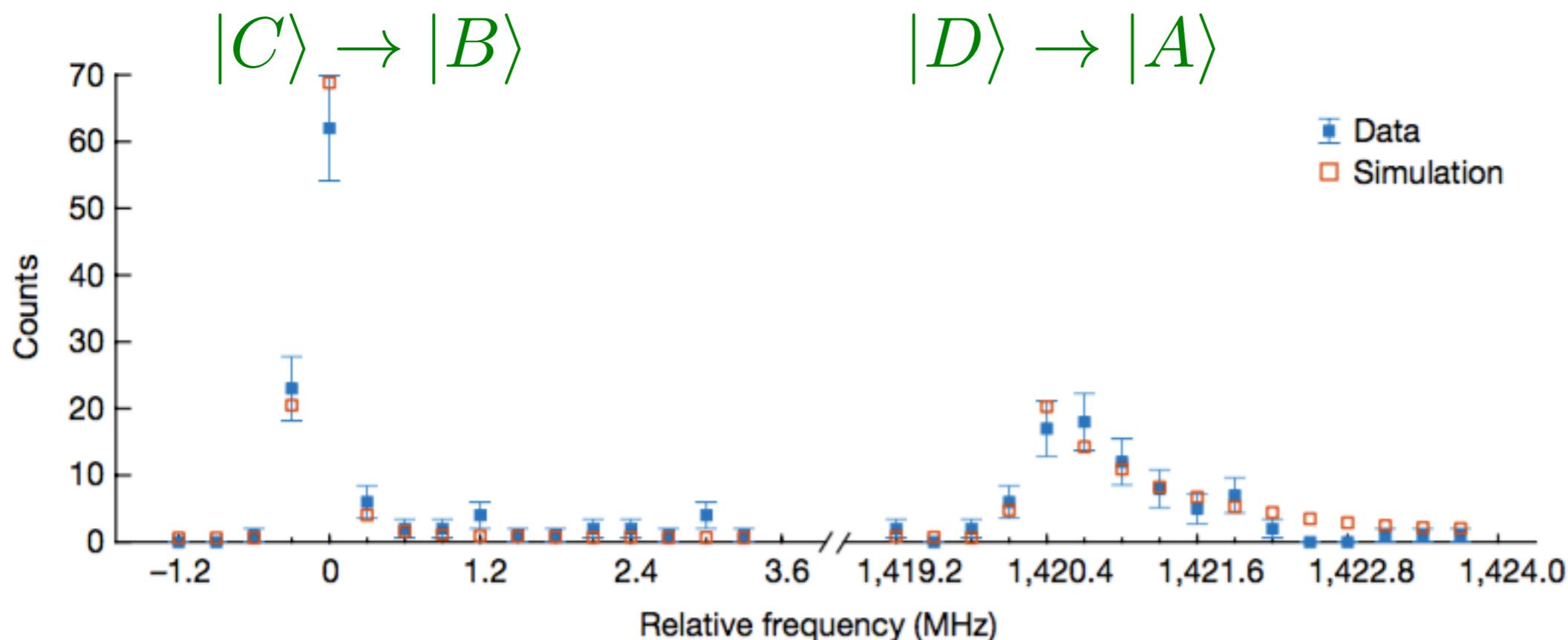


Antihydrogen hyperfine spectrum

Illuminate trap with successive microwave frequencies ~ 29 GHz

Count annihilations in each frequency bin

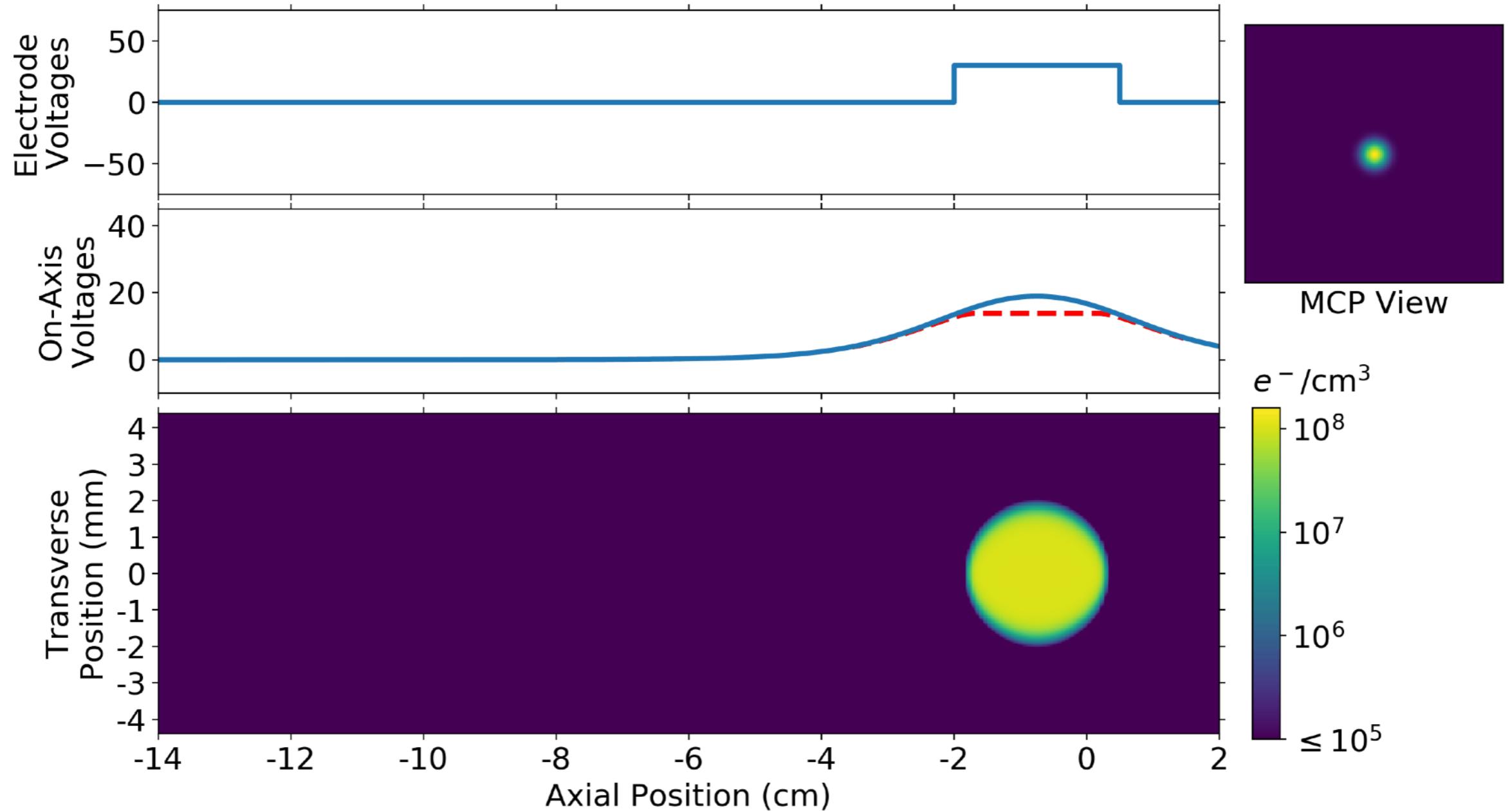
Compare with atomic Montecarlo simulation



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

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