Updates from the ALPHA-g experiment

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60th Rencontres de Moriond,
Electroweak Interactions & Unified Theories

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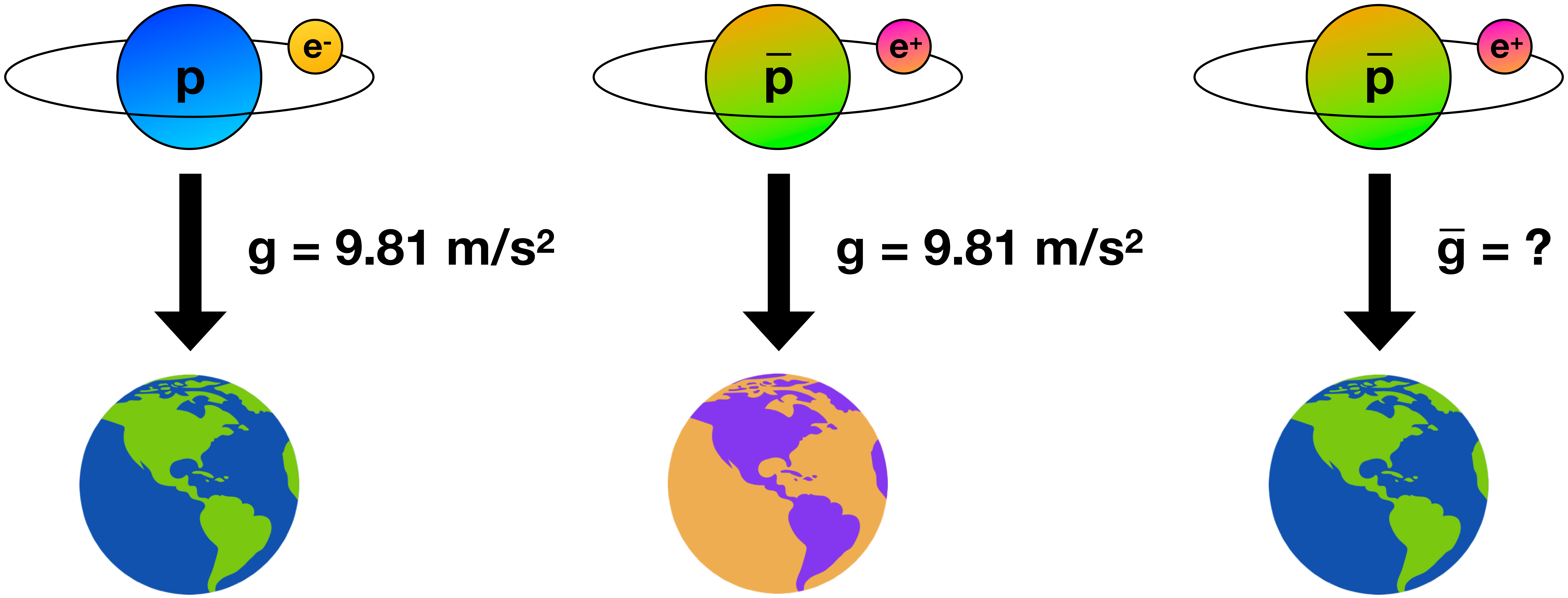
Discovery, accelerated



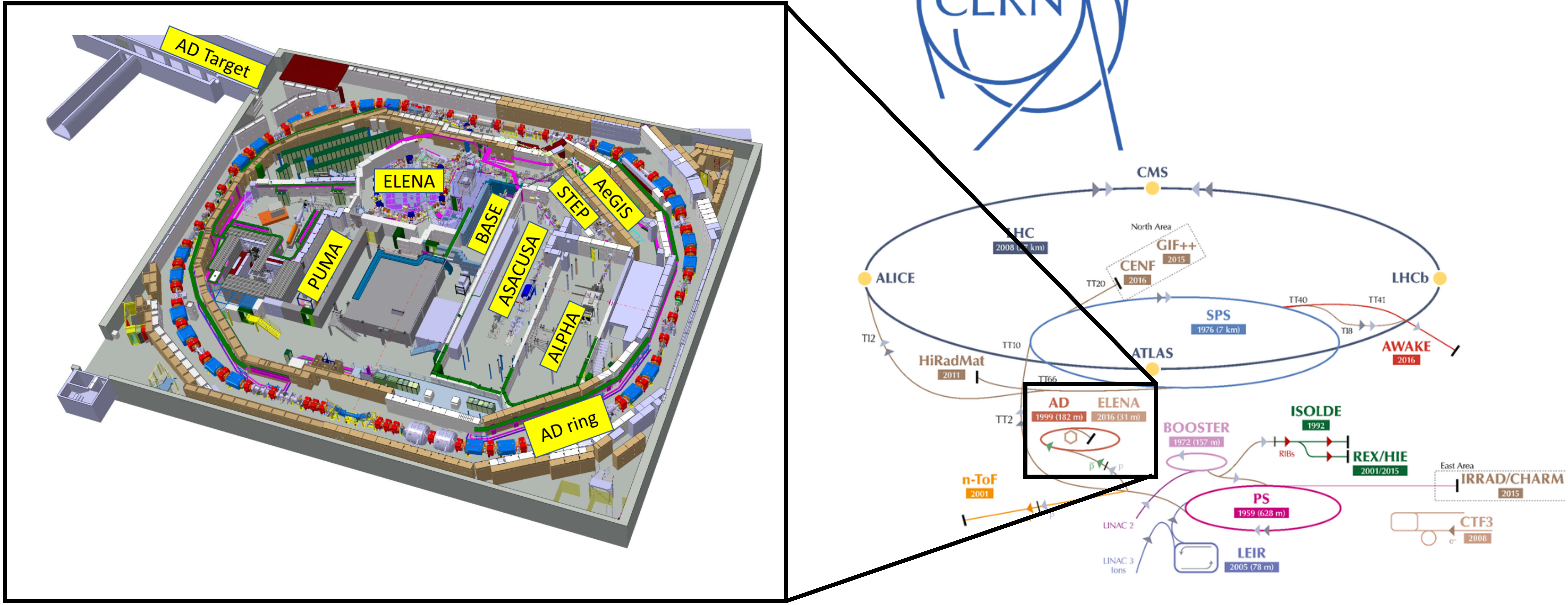
Hydrogen on Earth
(known)

Anti-hydrogen on anti-Earth
(CPT conjugate)

Anti-hydrogen on Earth
(ALPHA-g experiment)

Weak equivalence principle (WEP): $\bar{g} = g$

The Antiproton Decelerator



The ALPHA collaboration

Antihydrogen **L**aser **PH**ysics **A**pparatus

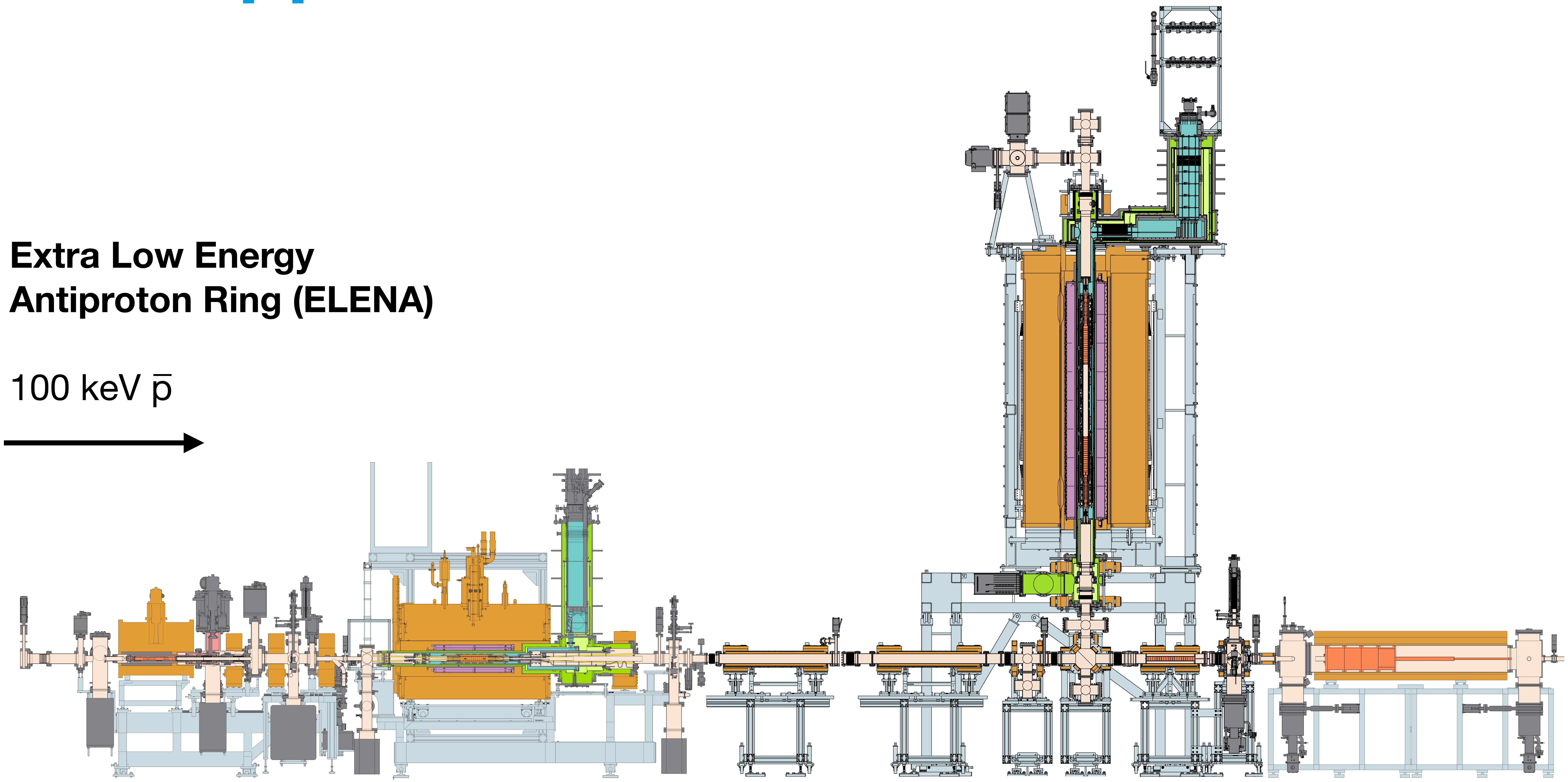
~ 50 people from ~20 institutions from ~10 countries

ALPHA apparatus

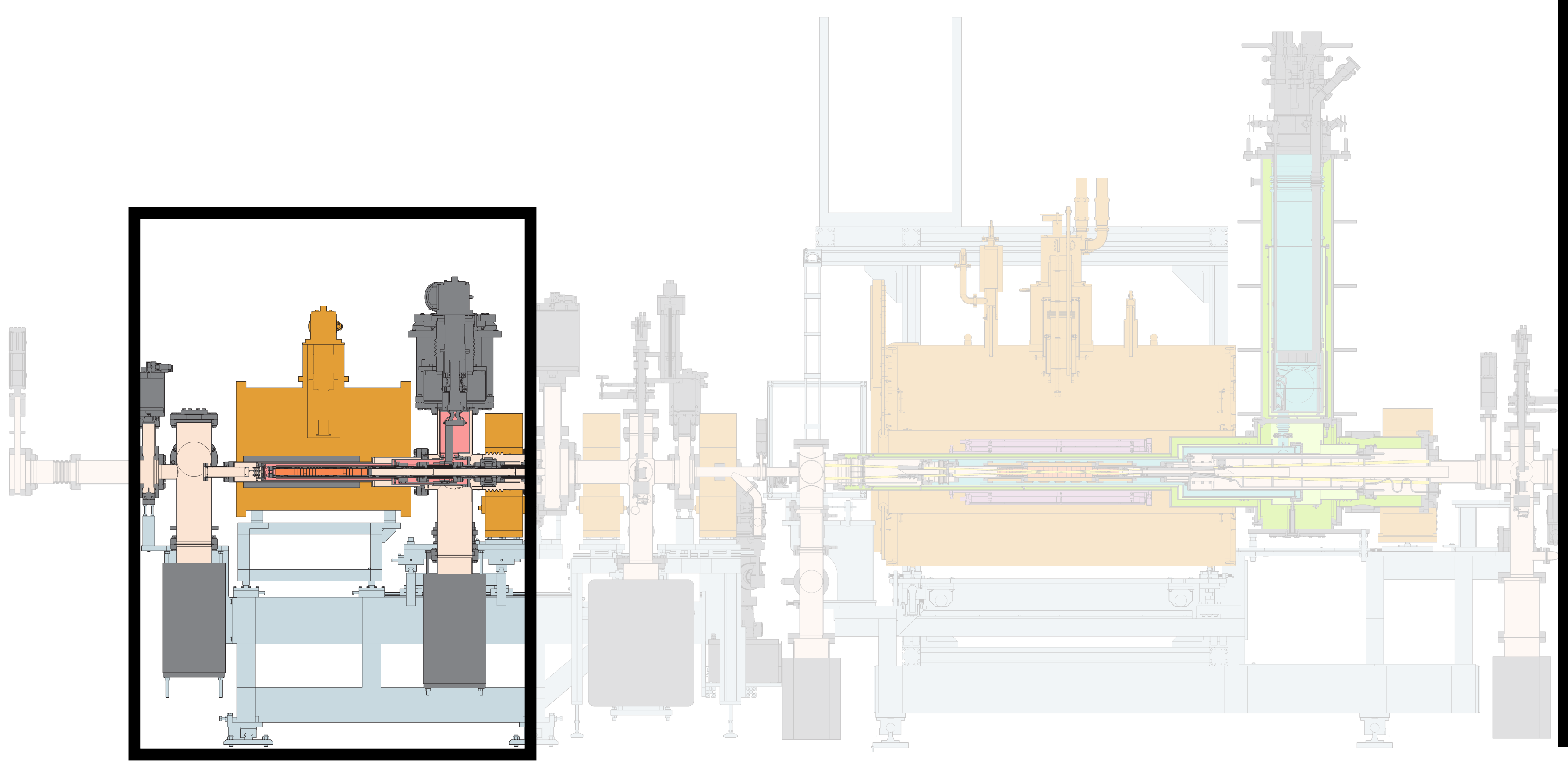
Extra Low Energy
Antiproton Ring (ELENA)

100 keV $\bar{p}$

→

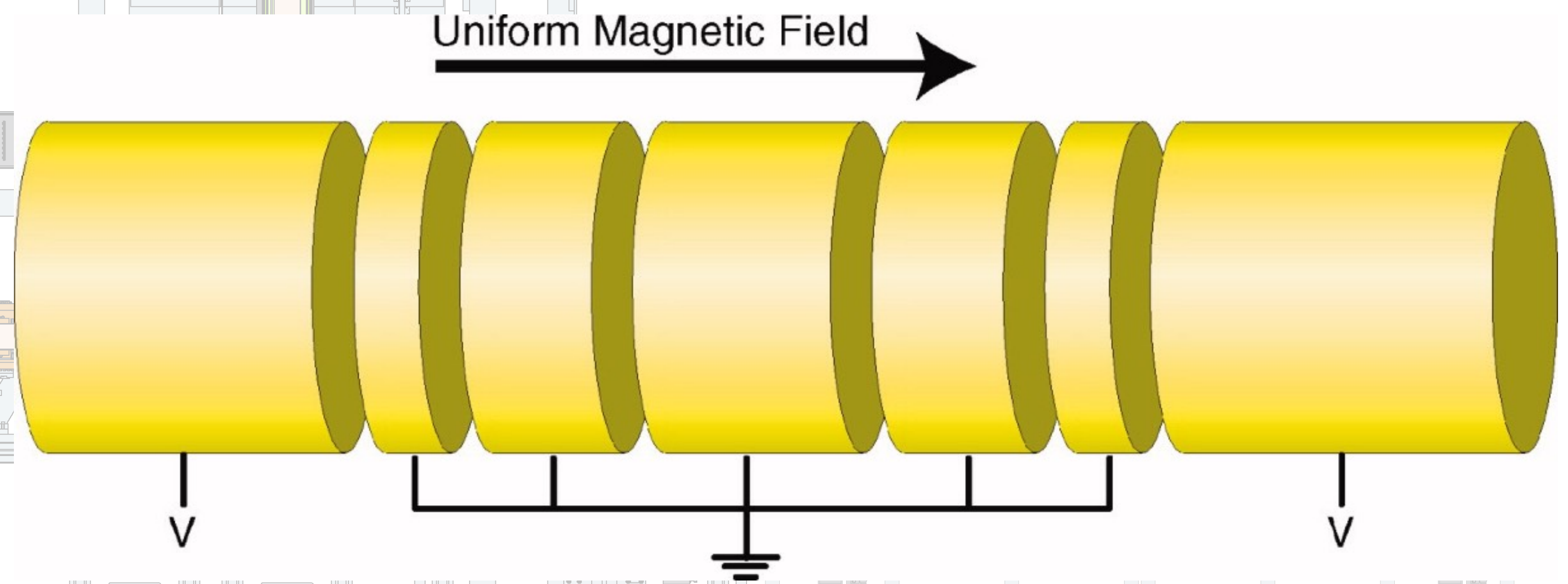


ALPHA apparatus

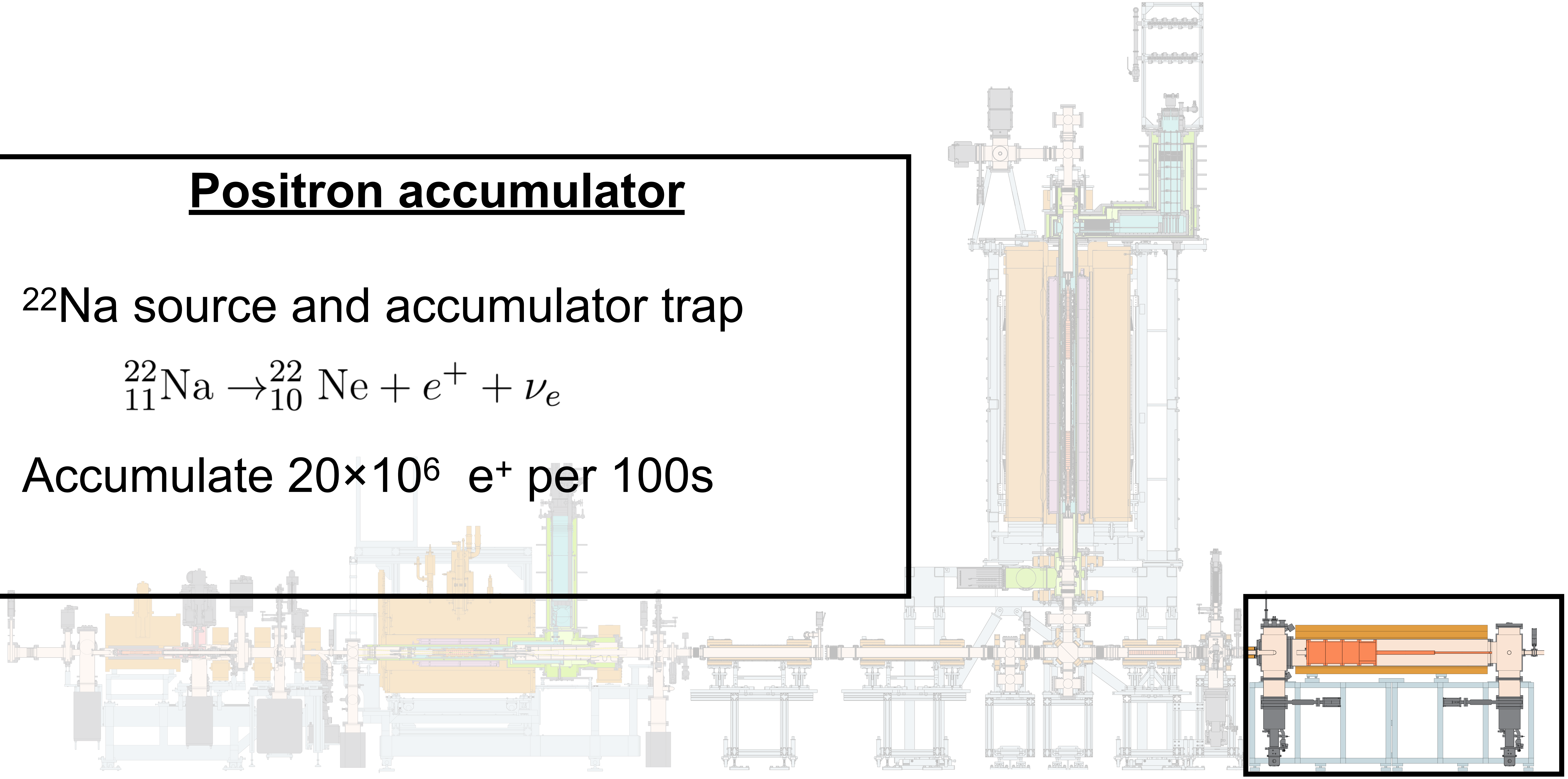


Catching trap

- Penning-Malmberg charged particle trap
- Receives 7.5×10^{6} $\bar{p}$ from ELENA
- Catches and cools 5×10^{5} $\bar{p}$



ALPHA apparatus



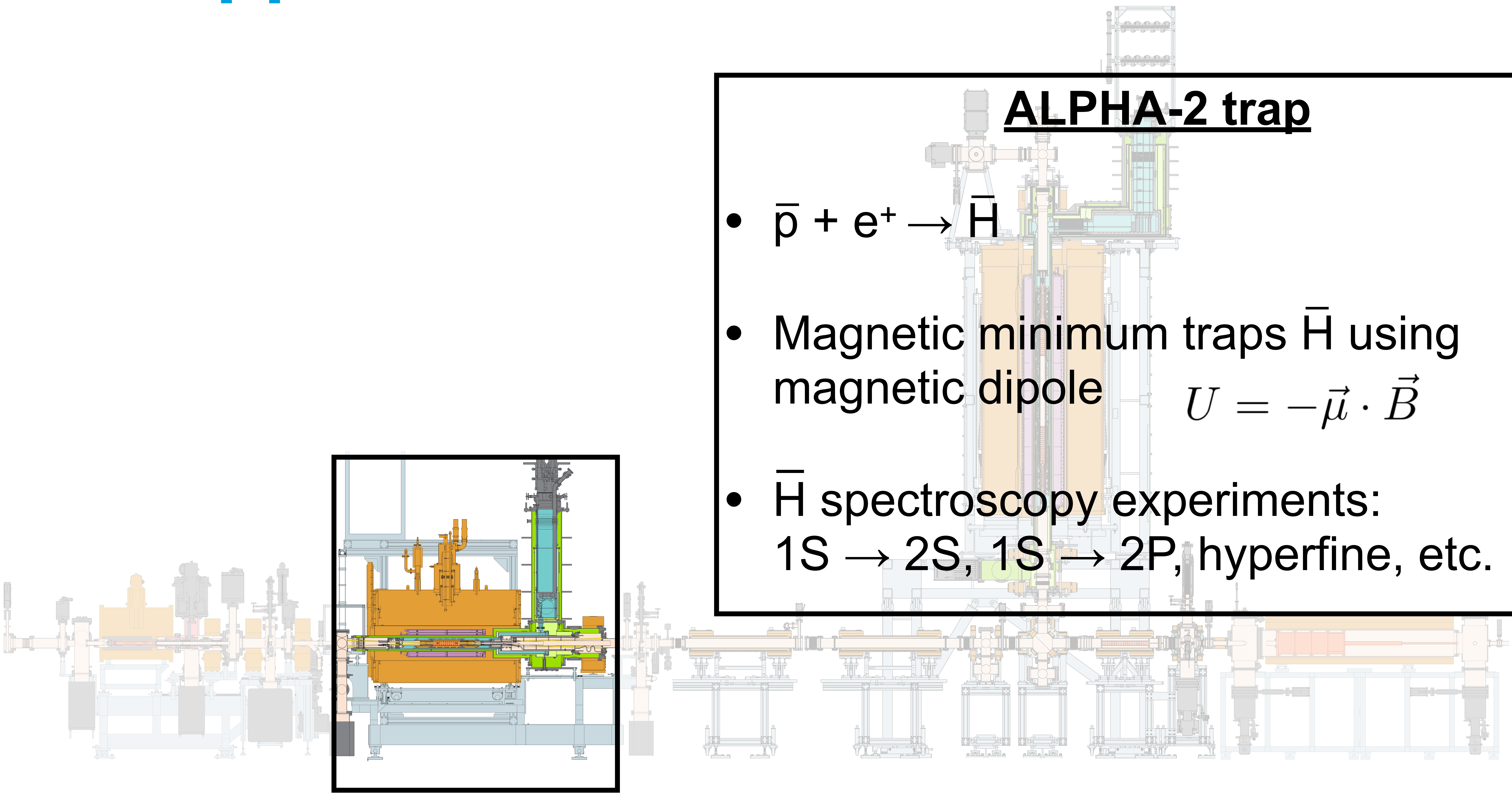
Positron accumulator

- ^{22}Na source and accumulator trap

$$^{22}_{11}\mathrm{Na} \rightarrow ^{22}_{10}\mathrm{Ne} + e^{+} + \nu_{e}$$

- Accumulate 20×10^{6} e^{+} per 100s

ALPHA apparatus



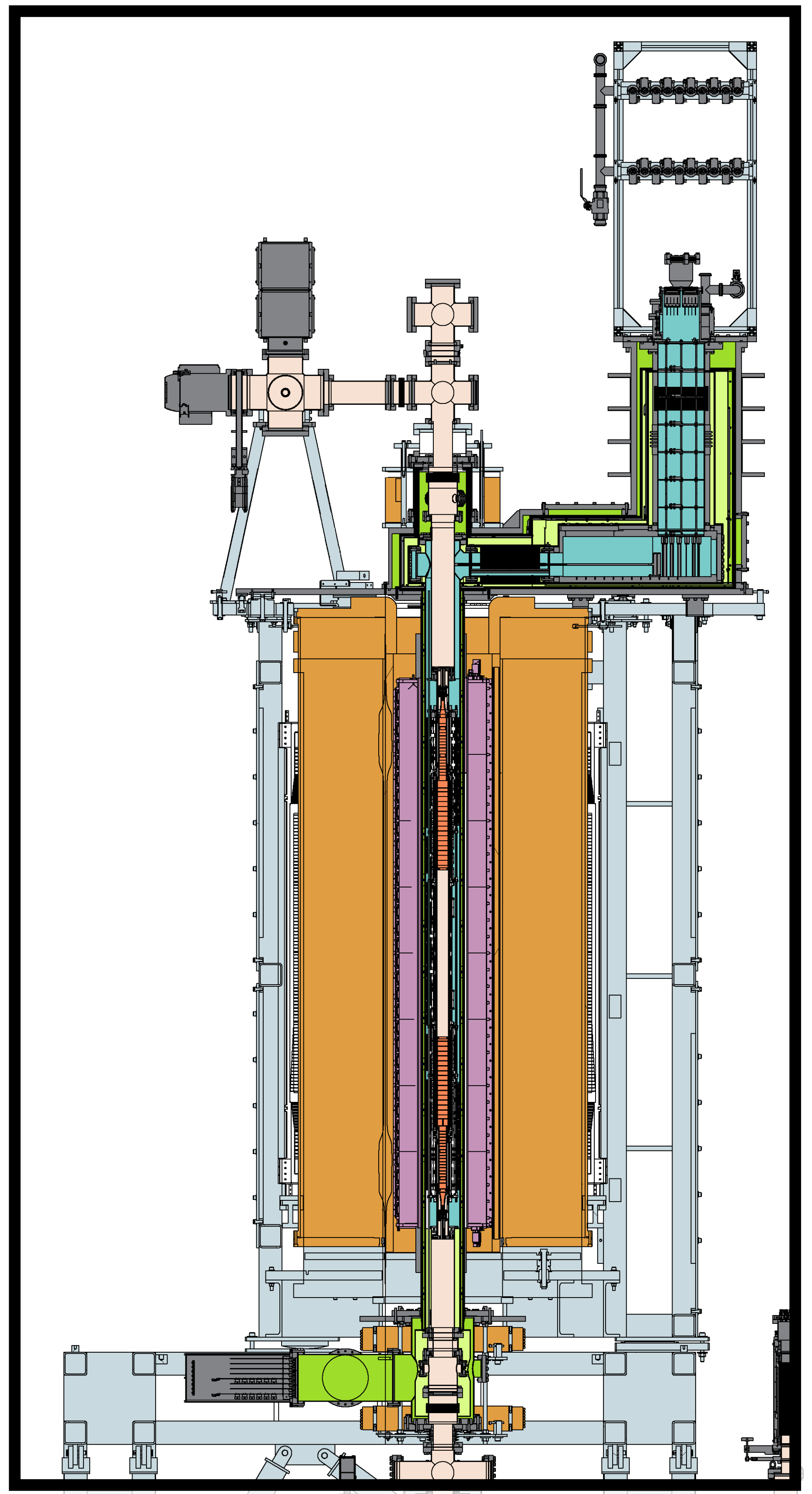
ALPHA-2 trap

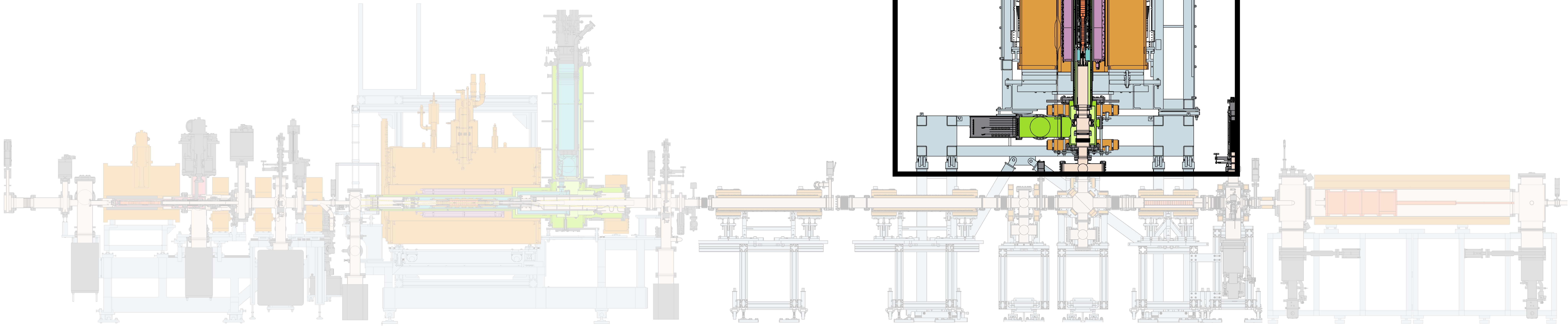
- $\bar{p} + e^+ \rightarrow \bar{H}$
- Magnetic minimum traps $\bar{H}$ using magnetic dipole $U = -\vec{\mu} \cdot \vec{B}$
- $\bar{H}$ spectroscopy experiments: 1S → 2S, 1S → 2P, hyperfine, etc.

ALPHA apparatus

ALPHA-g trap

- Similar trap, implemented vertically.
- Used to measure $\bar{H}$ gravity.

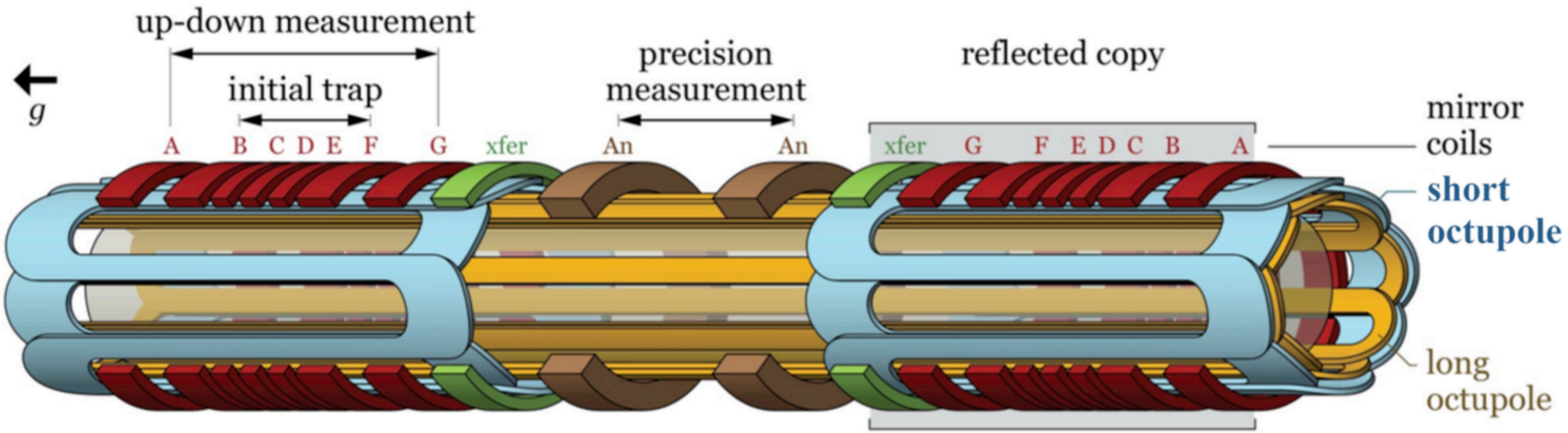




ALPHA-g neutral trap

- Superconducting octupole magnets + mirror coils
- Trap $\bar{\mathrm{H}}$ with $E_k < 500\ \mathrm{mK} = 43\ \mu\mathrm{eV}$

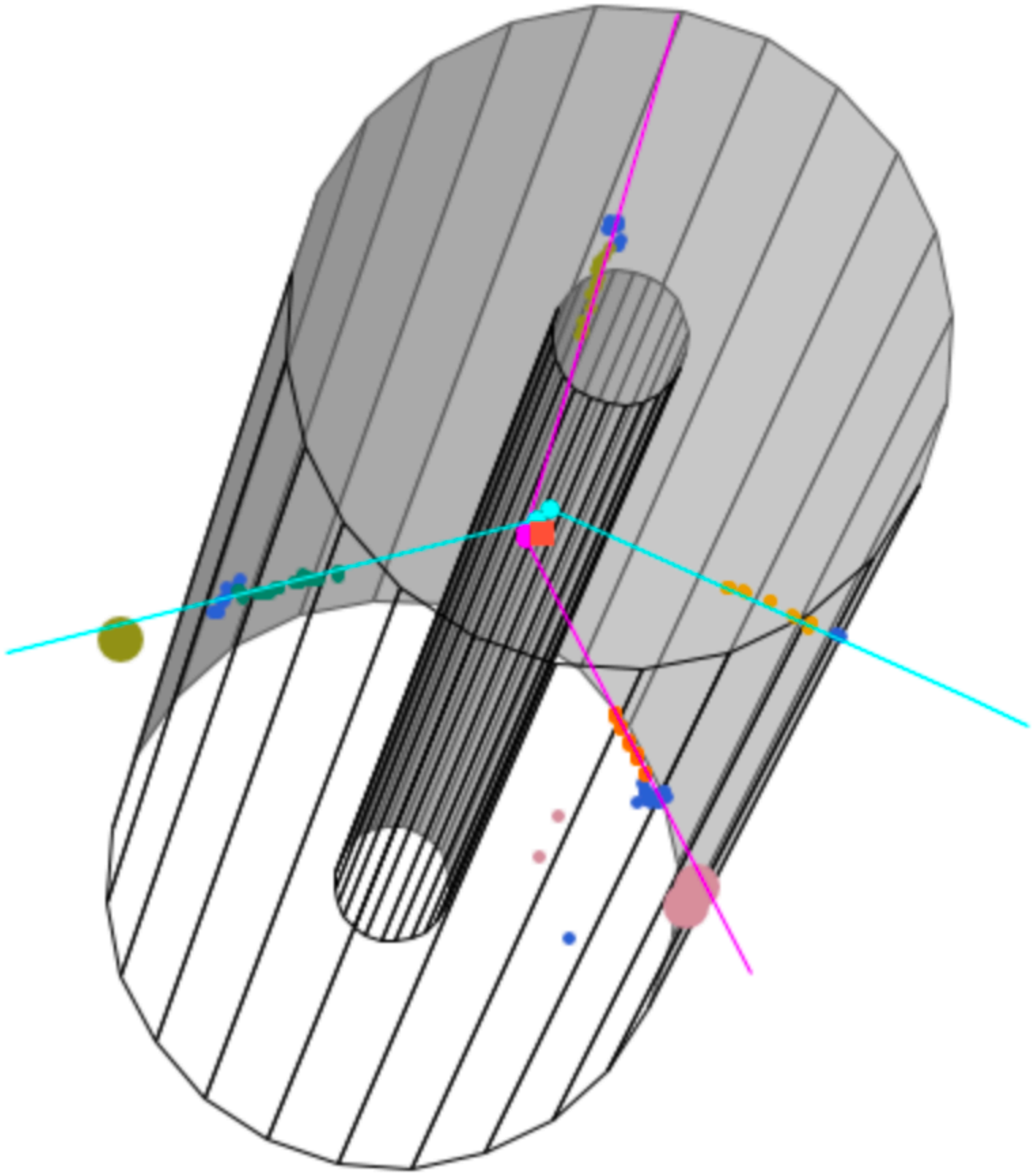
$$U = -\vec{\mu} \cdot \vec{B}$$



ALPHA-g radial TPC

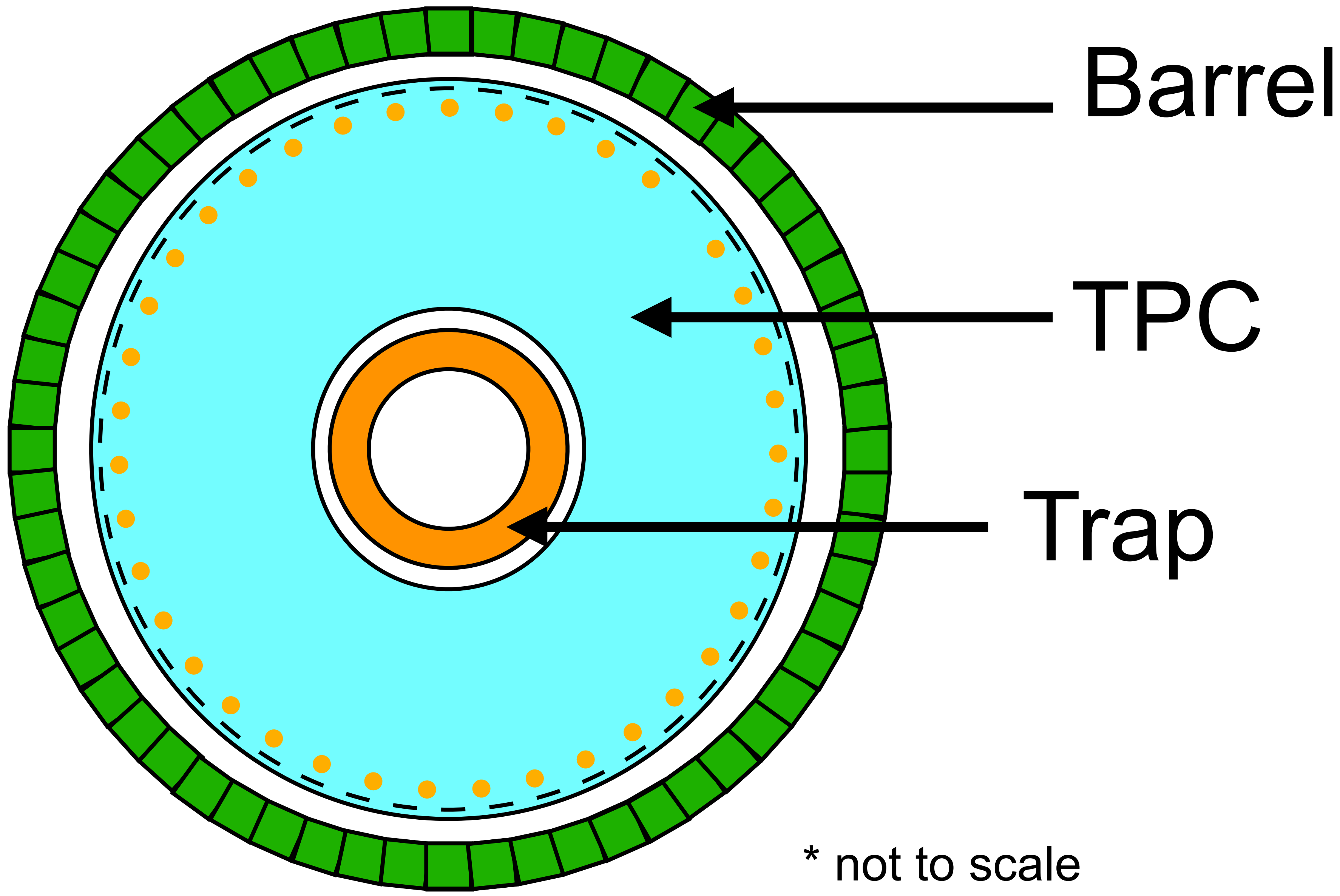
- 70% Ar, 30% CO_2 gas, 256 anode wires (2.3m long), 18432 readout pads
- Detects $\bar{\mathrm{H}}$ annihilating on trap walls $\bar{p}p \longrightarrow N\pi$
- Track pions → find annihilation vertex within 2 cm
- Designed and built at TRIUMF

2.3 meters



ALPHA-g barrel scintillator

- 64 plastic scintillator (EJ-200) bars, 2.6m long, with SiPM + TDC readout
- Reduces cosmic ray muon background using time of flight
- Designed and built at TRIUMF

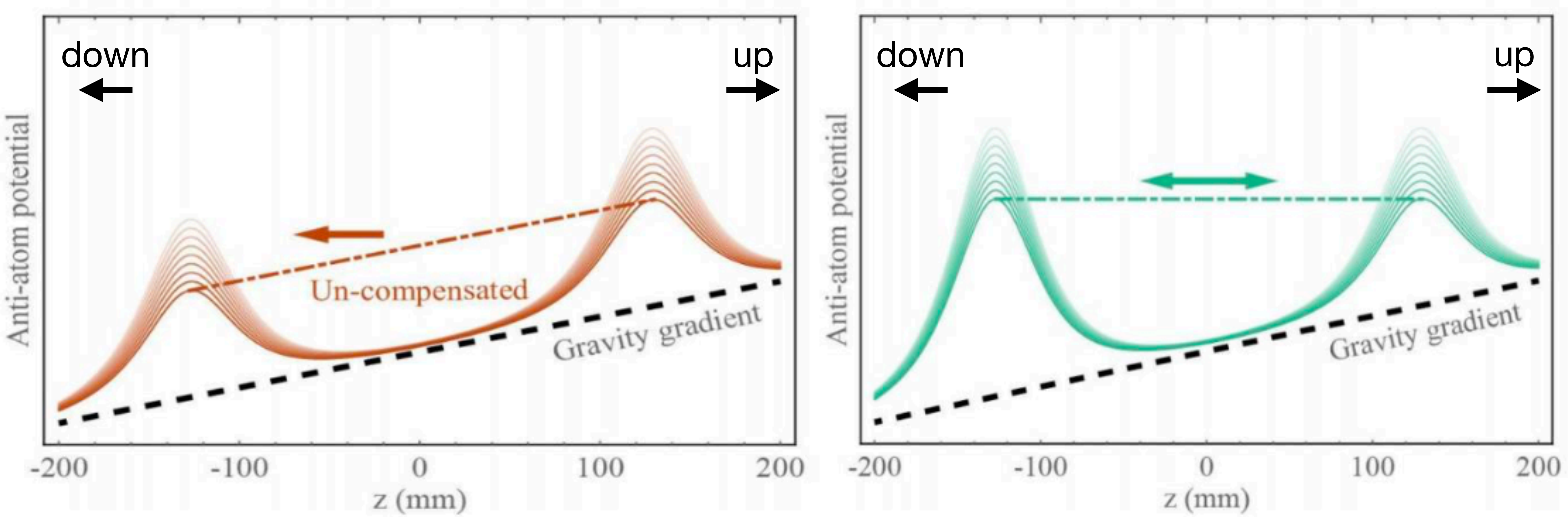


ALPHA-g measurement principle

- Slowly ramp down mirror coils so $\bar{\mathrm{H}}$ escapes vertically.
- Detect annihilations in "up" and "down" regions.
- Use different magnetic biases (gravity compensation).

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

(units of g)



ALPHA-g 2022 Results

TRIUMF ALPHA

Article

Observation of the effect of gravity on the motion of antimatter

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Check for updates

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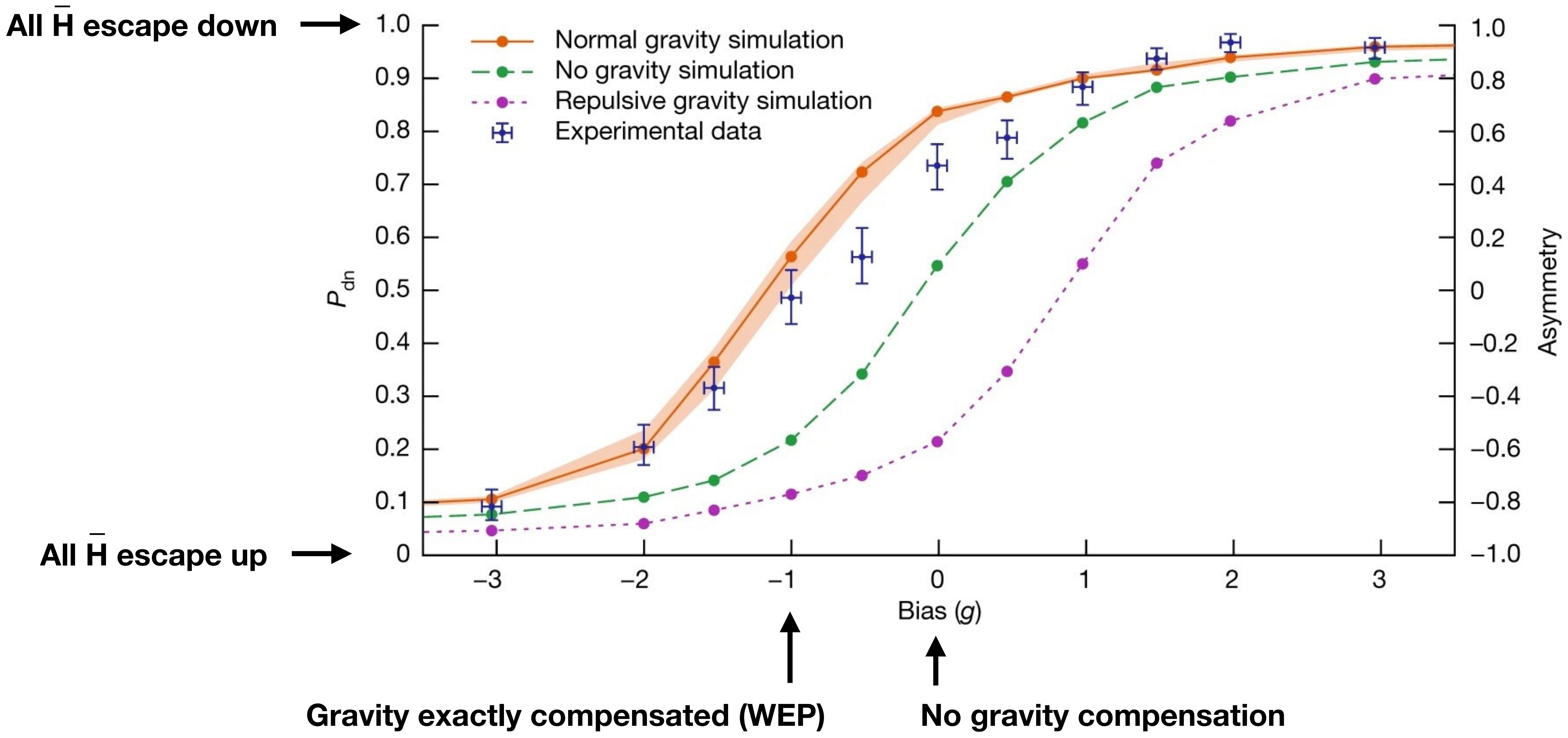
Einstein's general theory of relativity from 1915[1] remains the most successful description of gravitation. From the 1919 solar eclipse[2] to the observation of gravitational waves[3], the theory has passed many crucial experimental tests. However, the evolving concepts of dark matter and dark energy illustrate that there is much to be learned about the gravitating content of the universe. Singularities in the general theory of relativity and the lack of a quantum theory of gravity suggest that our picture is incomplete. It is thus prudent to explore gravity in exotic physical systems. Antimatter was unknown to Einstein in 1915. Dirac's theory[4] appeared in 1928; the positron was observed[5] in 1932. There has since been much speculation about gravity and antimatter. The theoretical consensus is that any laboratory mass must be attracted[6] by the Earth, although some authors have considered the cosmological consequences if antimatter should be repelled by matter[7–10]. In the general theory of relativity, the weak equivalence principle (WEP) requires that all masses react identically to gravity, independent of their internal structure. Here we show that antihydrogen atoms, released from magnetic confinement in the ALPHA-g apparatus,

ALPHA-g 2022 Results

Nature **621,** 716–722 (2023)

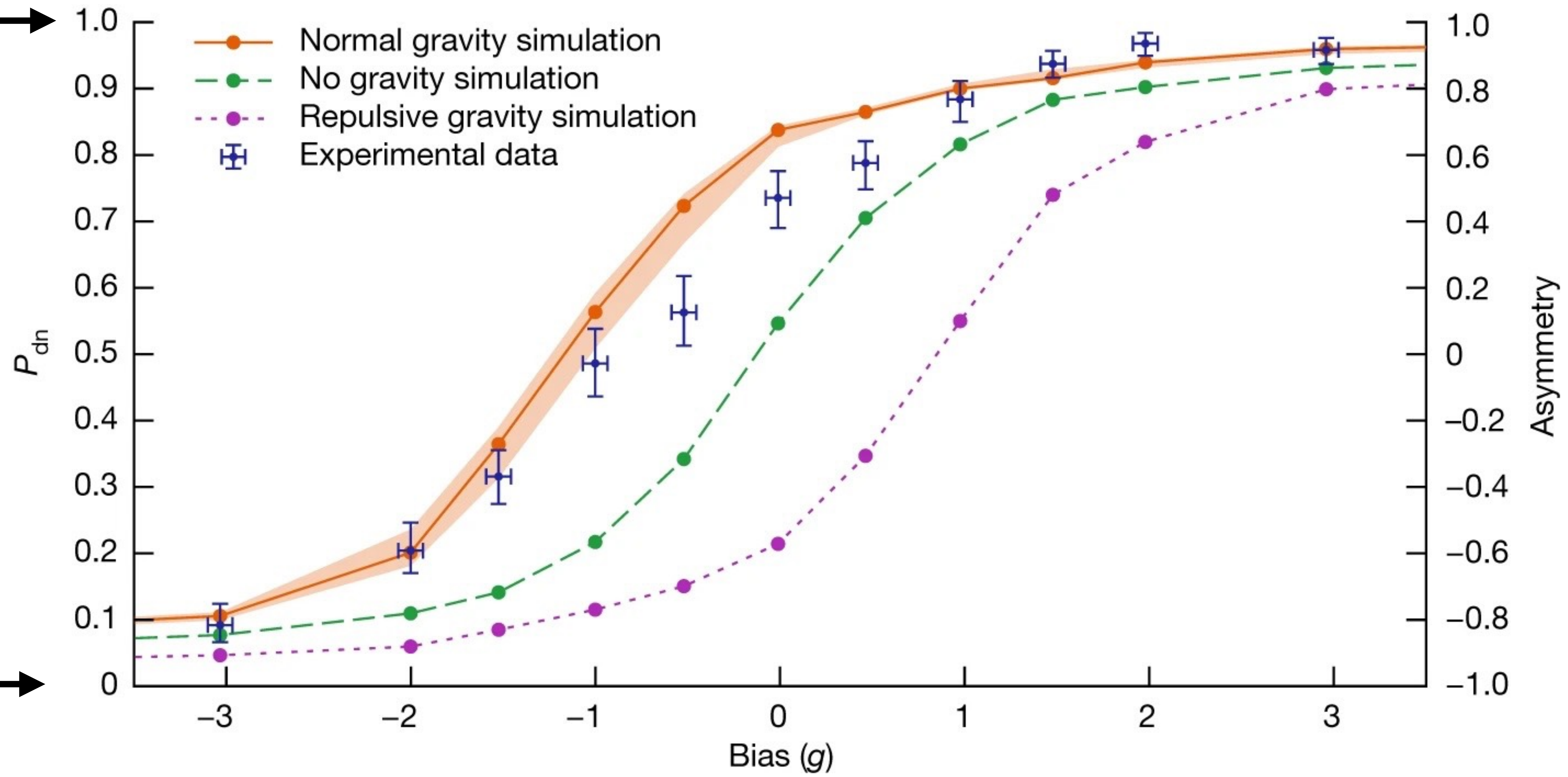


ALPHA-g 2022 Results

Nature **621,** 716–722 (2023)

All $\bar{H}$ escape down →

All $\bar{H}$ escape up →

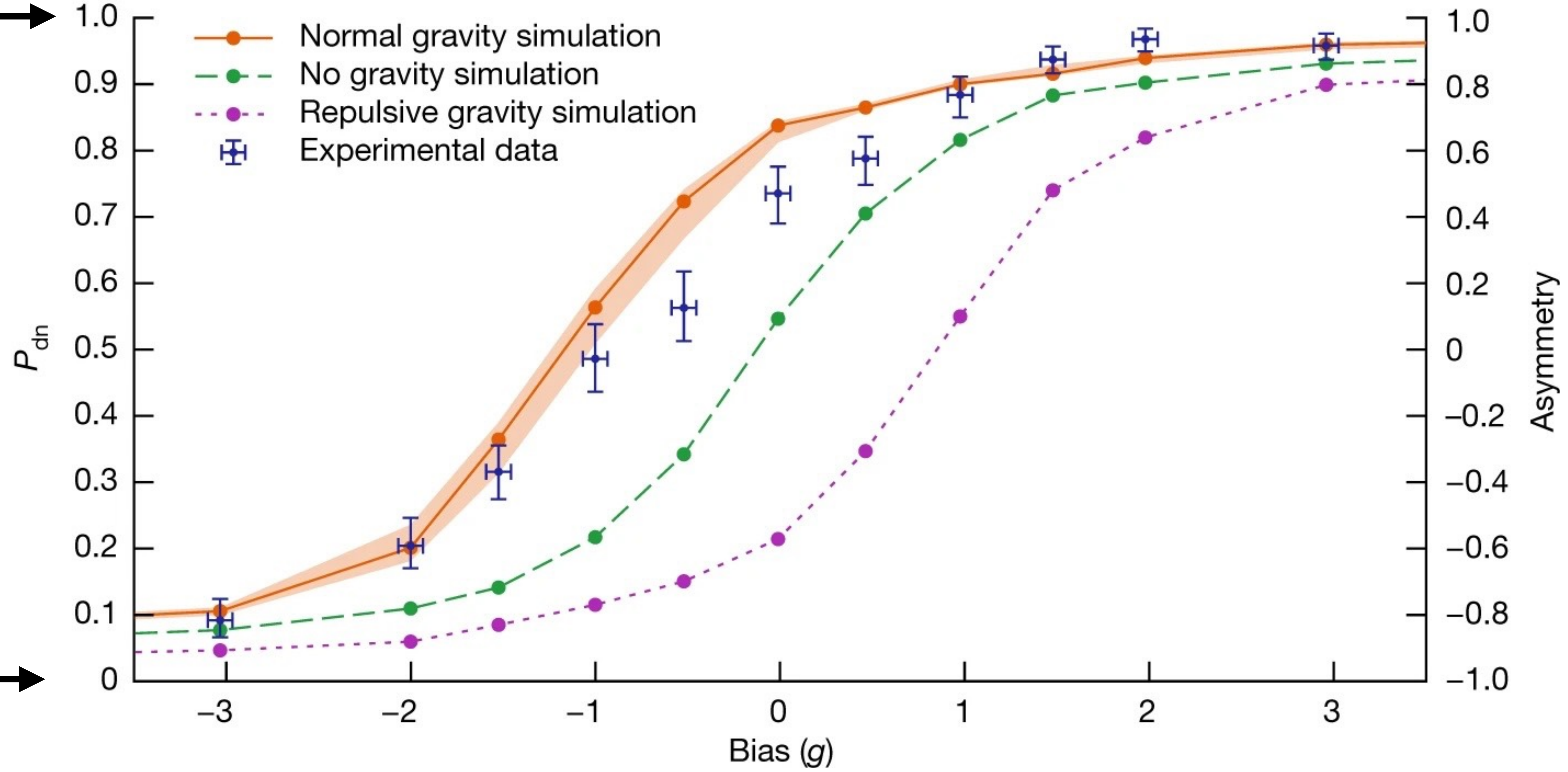


$$\bar{g}/g = (0.75 \pm 0.13\ (\text{statistical+systematic})\ \pm 0.16\ (\text{simulation}))$$

ALPHA-g 2022 Results

Nature **621,** 716–722 (2023)

All $\bar{H}$ escape down →



All $\bar{H}$ escape up →

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

Consistent with WEP at ~1σ level

2022 Uncertainties

Bias determination (x-axis)

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

Determination of $a_{\bar{g}}$ (y-axis)

Uncertainty	Magnitude (g)
Finite data size	0.06
Detector efficiency calibration	0.12
Other sources	0.01

Simulation model

Uncertainty	Magnitude (g)
Modelling of magnetic fields	0.16
$\bar{H}$ initial energy distribution	0.03

2022 Uncertainties

Bias determination (x-axis)

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Low statistics for data and calibration (around ~2000 $\bar{H}$ in dataset)

→ Want more $\bar{H}$ production

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Peak field size and z-location fit	[illegible]
Field decay asymmetry (A to G) after ramp	[illegible]
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	Magnitude (g)
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$\bar{H}$ kinetic energy uncertainty

→ Want colder $\bar{H}$

2022 Uncertainties

Bias determination (x-axis)

Uncertainty	Magnitude (g)
ECR sp...	
Repeatab...	
Peak fie... loc...	
Field dec... (A to G) after ramp	
Bias variation in time	0.02
Field modelling	0.05

Determination of $a_{\bar{g}}$ (y-axis)

Uncertainty	Magnitude (g)
Finite data size	0.06
...y	0.12
	0.01

...n model

Uncertainty	Magnitude (g)
Modelling of magnetic fields	0.16
$\bar{H}$ initial energy distribution	0.03

Limited B field knowledge (especially off-axis)

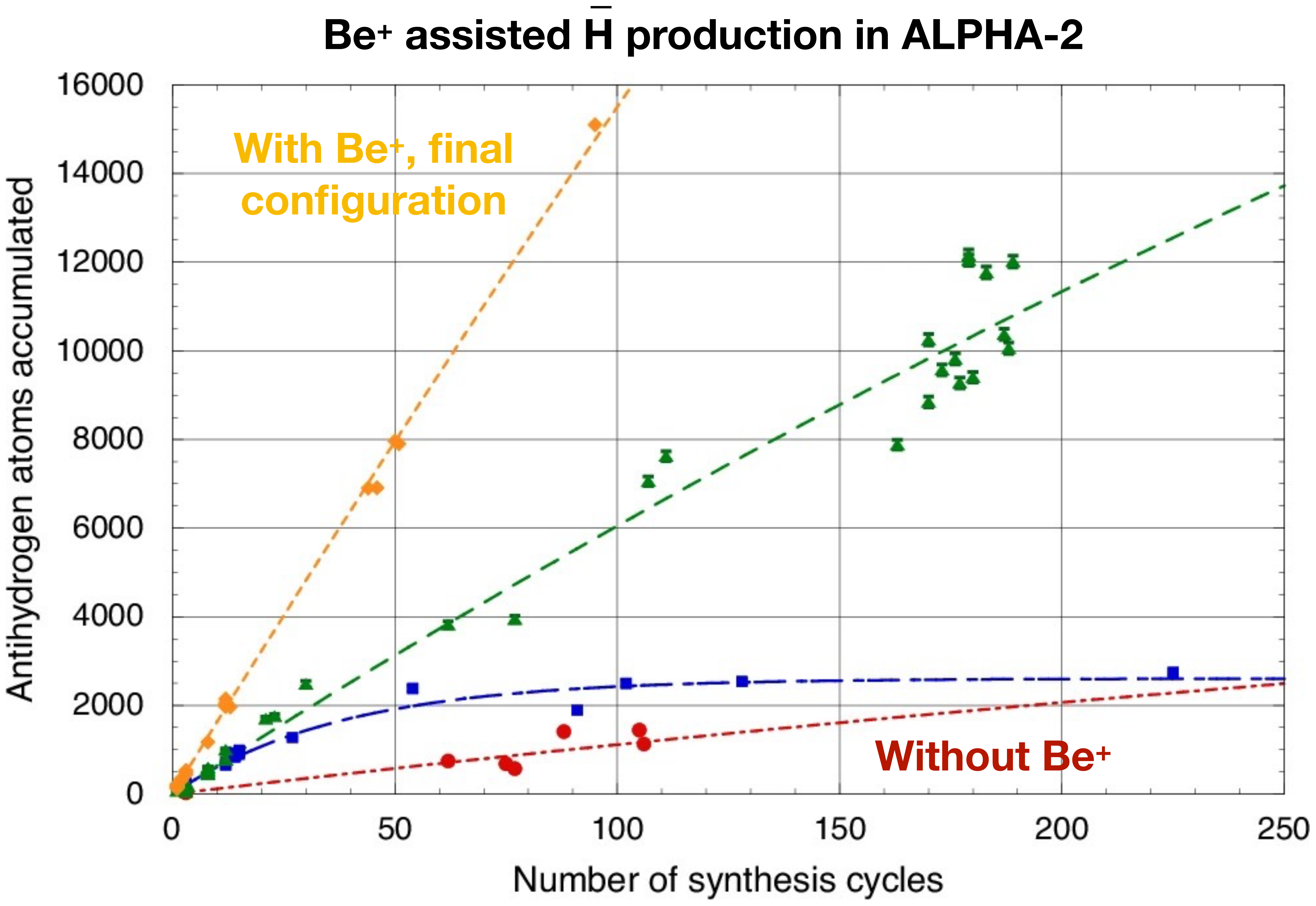
→ Better B field characterization

→ Colder $\bar{H}$ (stays closer to axis)

Be$^+$ assisted $\bar{H}$ production

- Be$^+$ plasma is ablated into ALPHA-g
- Be$^+$ laser cooled by 313 nm laser
- e^+ cooled via Coulomb interactions
- More $\bar{H}$ created cold enough to be trapped.
- ALPHA-g: ~250 $\bar{H}$ per 120 second cycle

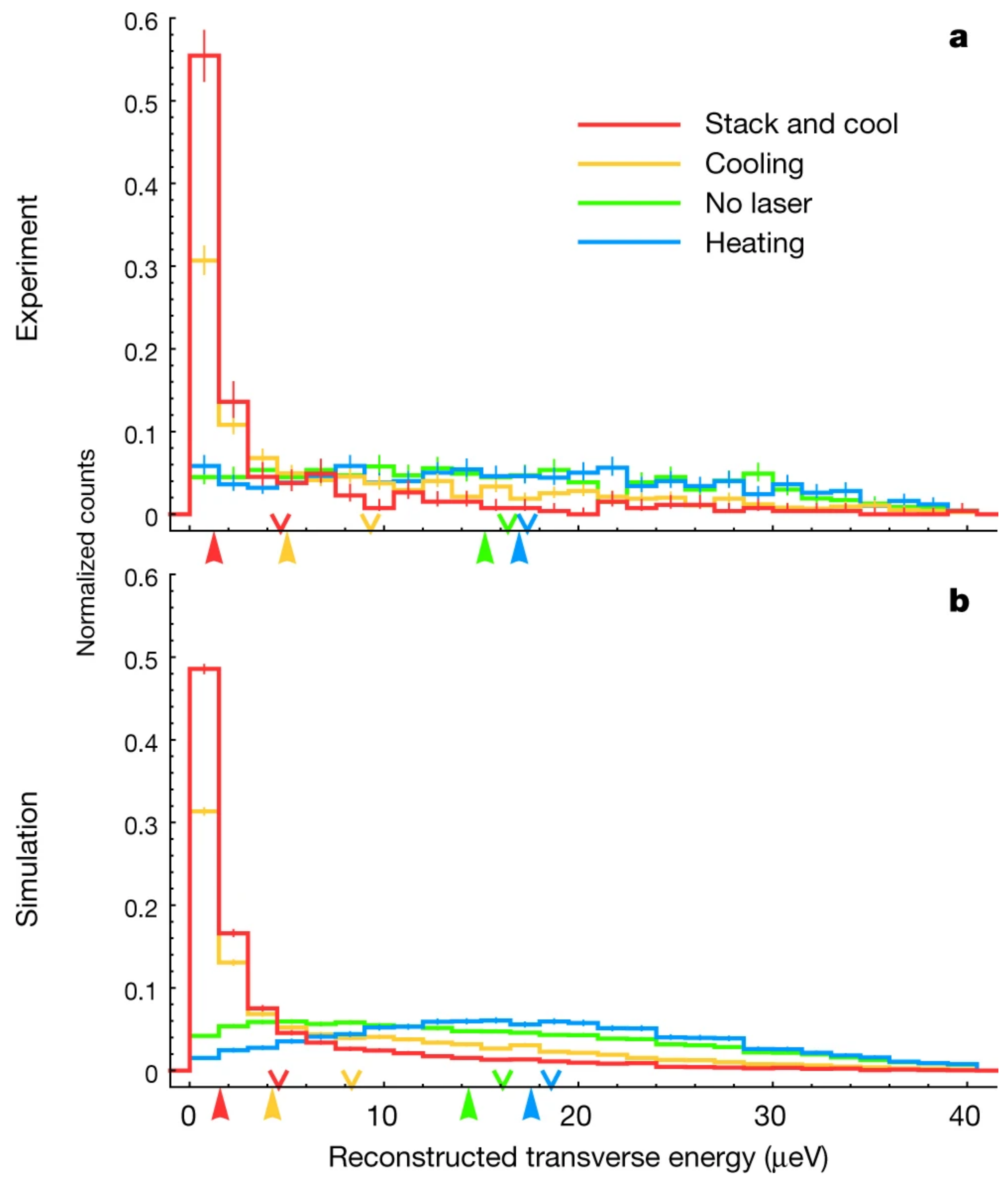
  (improved from ~2 $\bar{H}$ in 2022)



Nature Communications **16**, 10106 (2025)

Laser cooling of $\bar{H}$

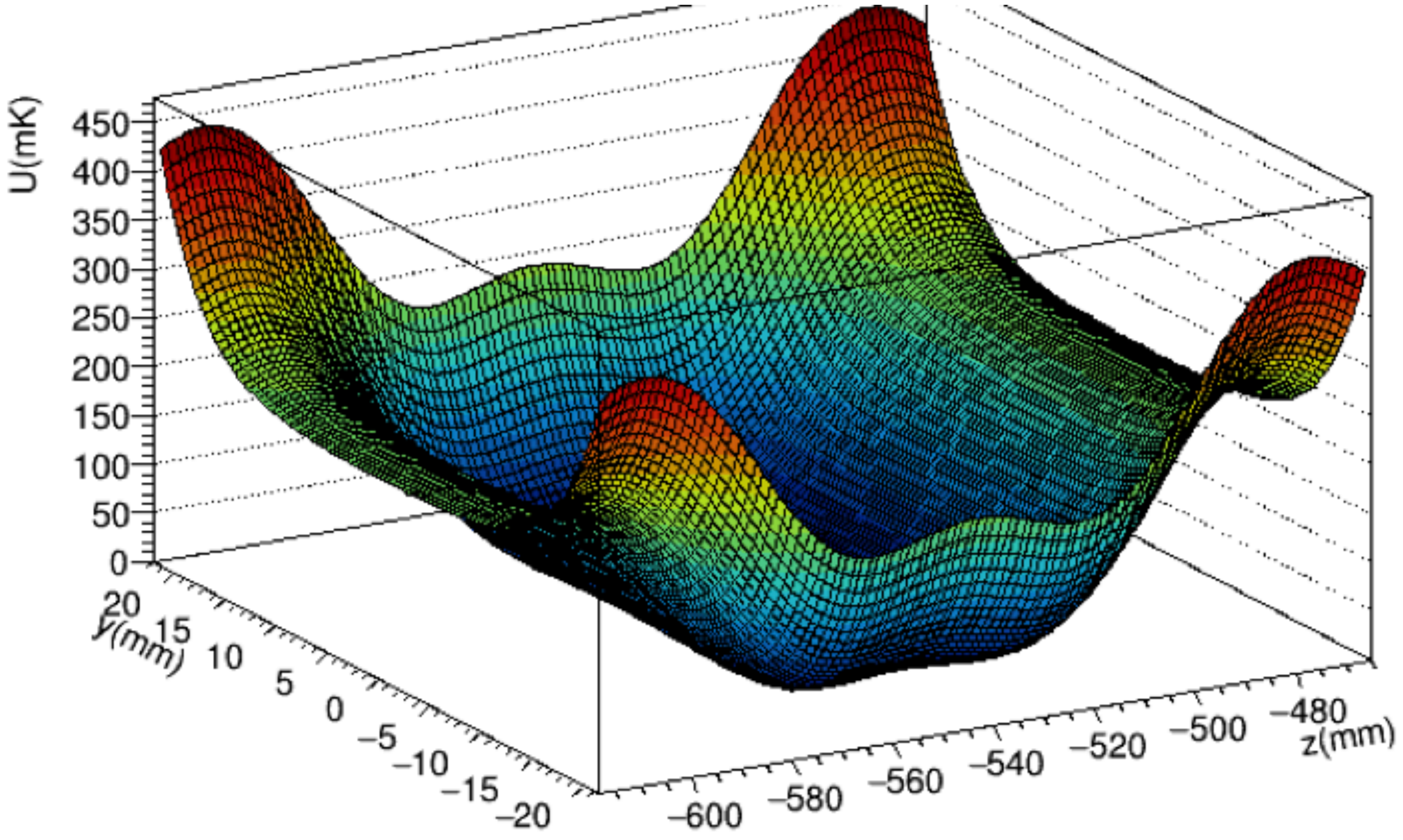
- Anti-hydrogen laser cooled using 121.6 nm Lyman-α laser (-240 MHz detuning)
- $\bar{H}$ cooled from 500 mK (trap depth) to ~10 mK (E_k ~ 1 μeV)
- Demonstrated in ALPHA-2 in 2021.
- Achieved in ALPHA-g in 2025.



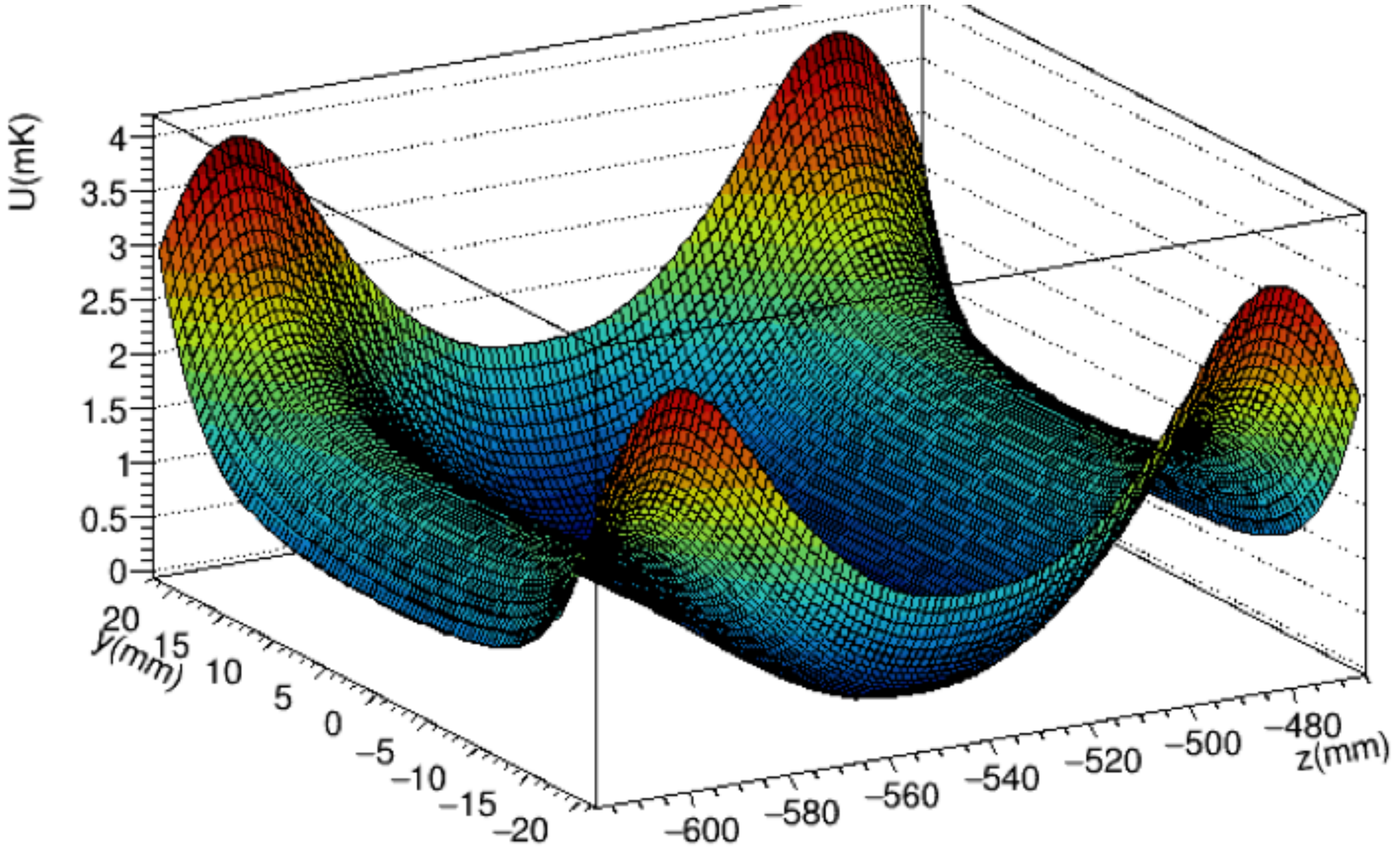
Nature **592**, 35–42 (2021)

$\bar{H}$ adiabatic cooling

- Adiabatically expand the trap potential, cooling $\bar{H}$ further to ~1 mK (E_k = 0.1 μeV)
- Successfully combined with laser cooling in ALPHA-g.



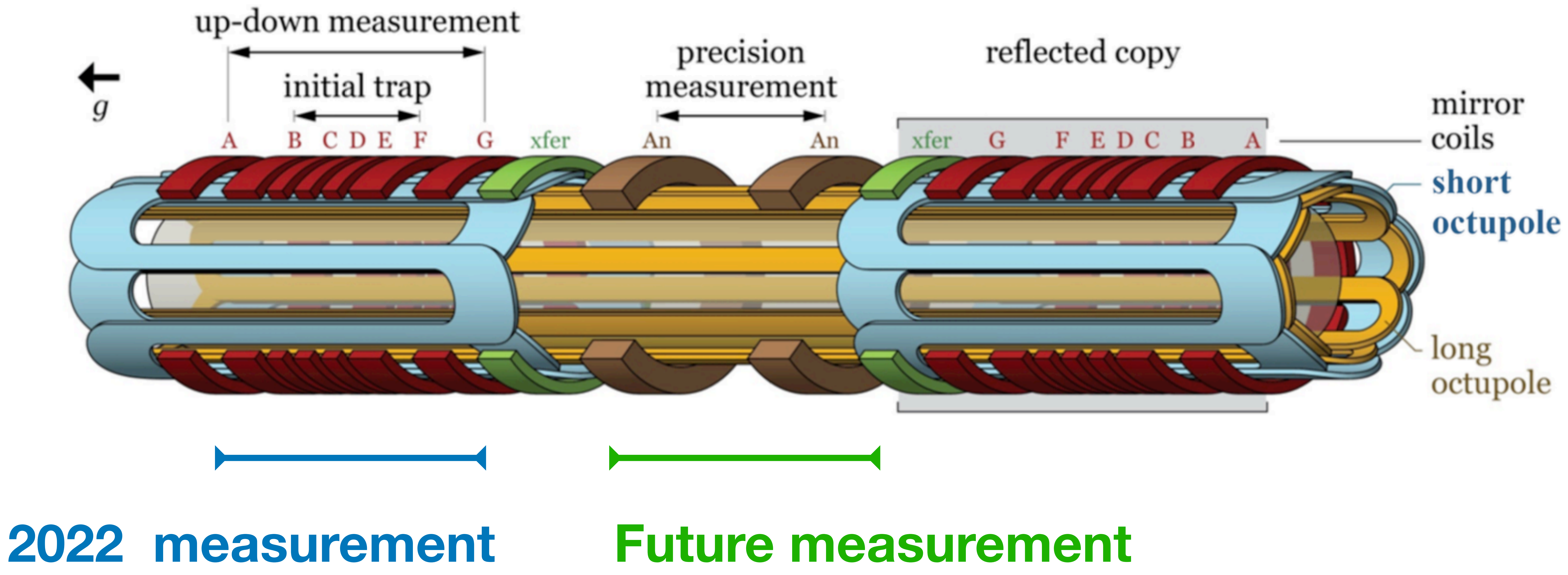
Before adiabatic cooling



After adiabatic cooling

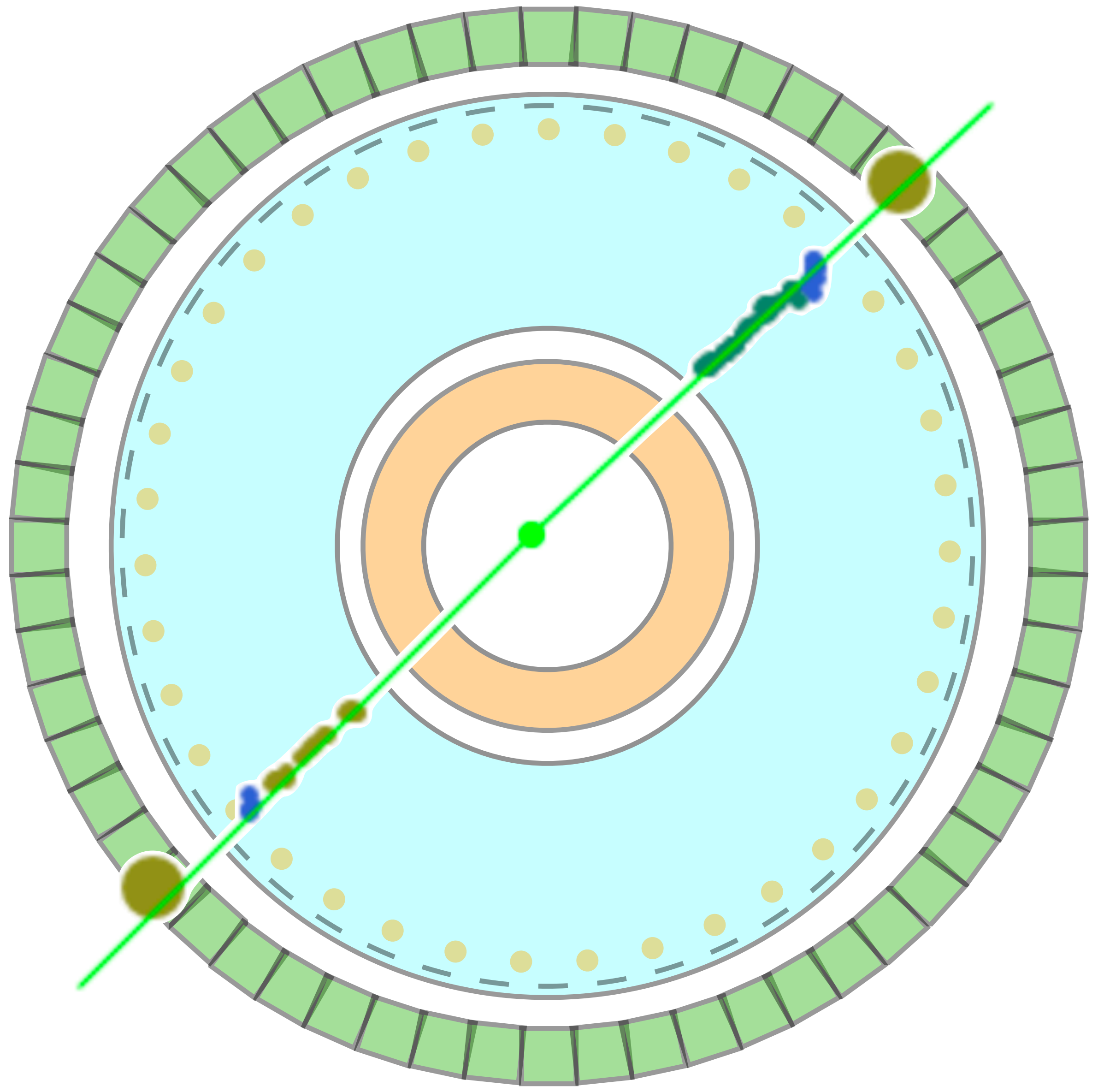
Commissioning precision region

- Precision trap: B fields are more easily controlled and understood
- Magnet commissioning ongoing

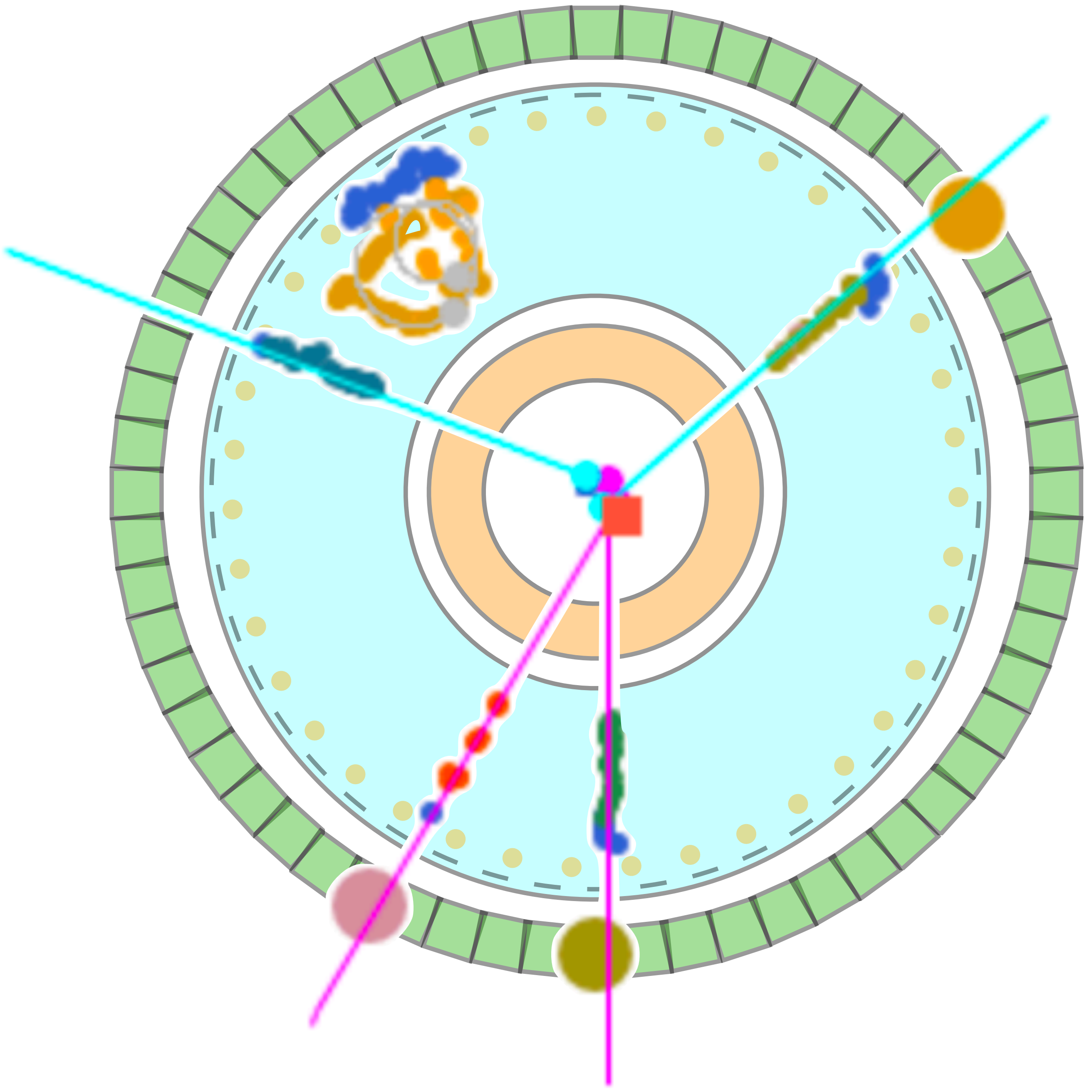


Cosmic ray background

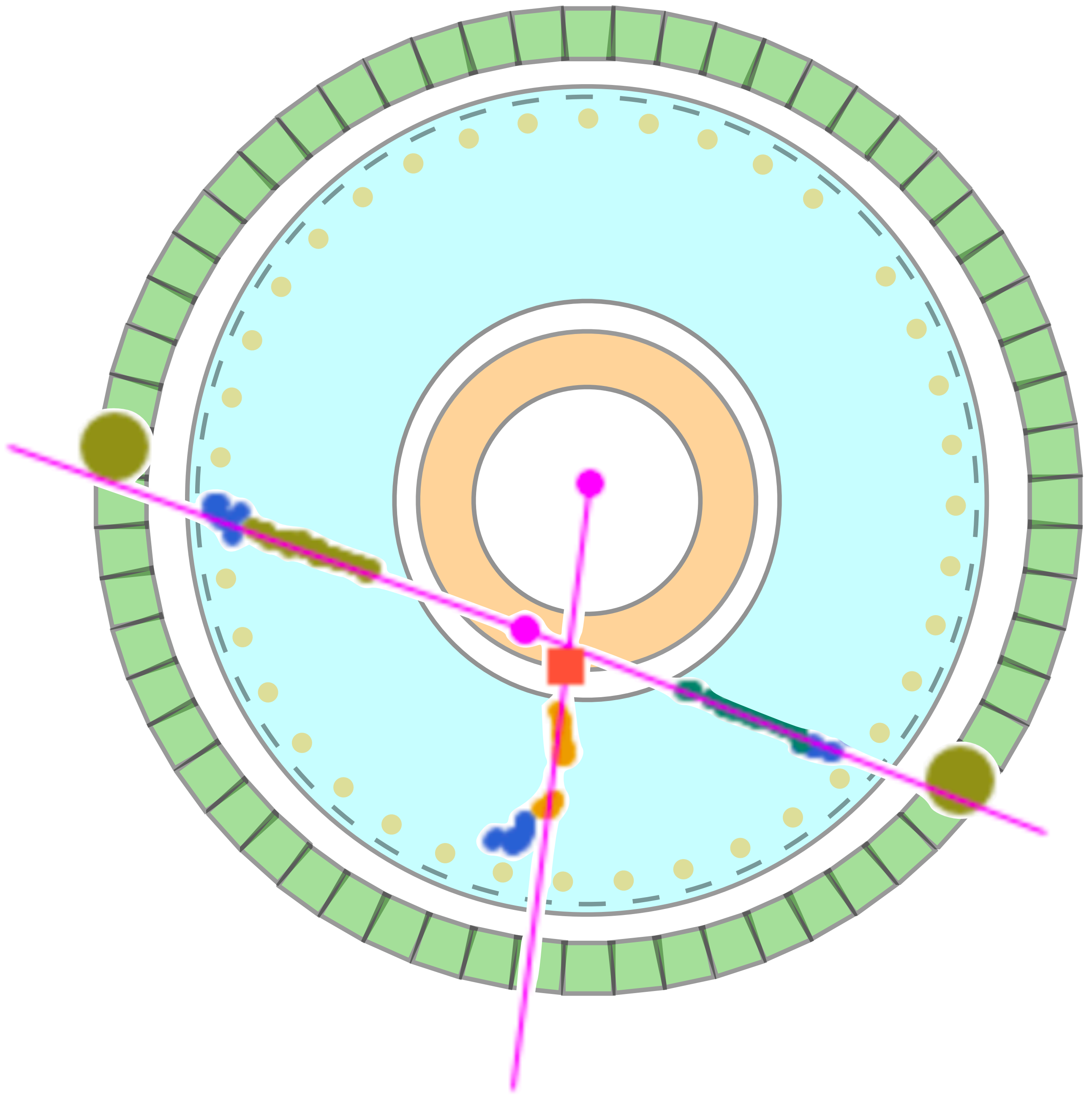
- Main background → cosmic ray muons



Clear cosmic ray muon



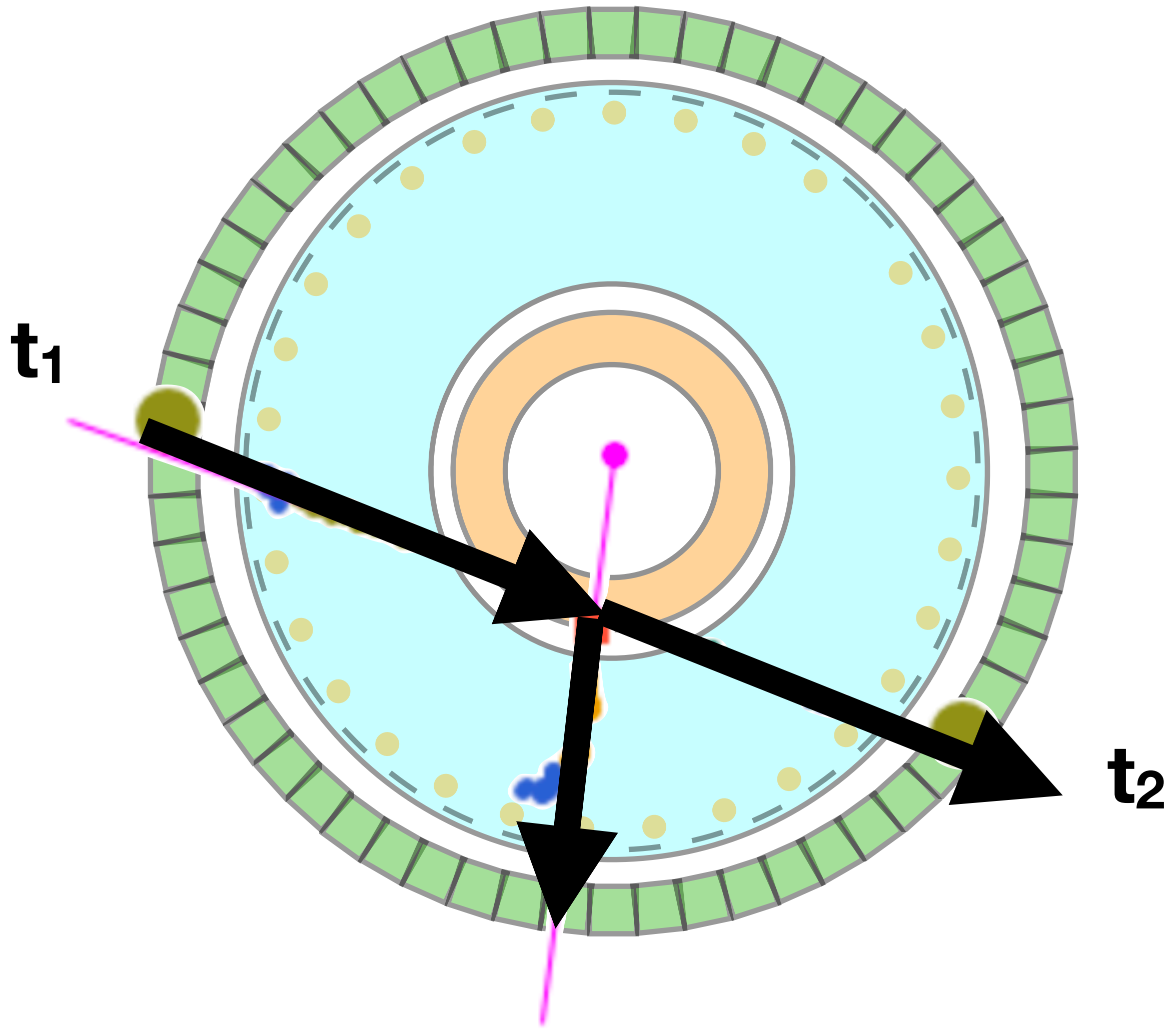
Clear $\bar{H}$ annihilation



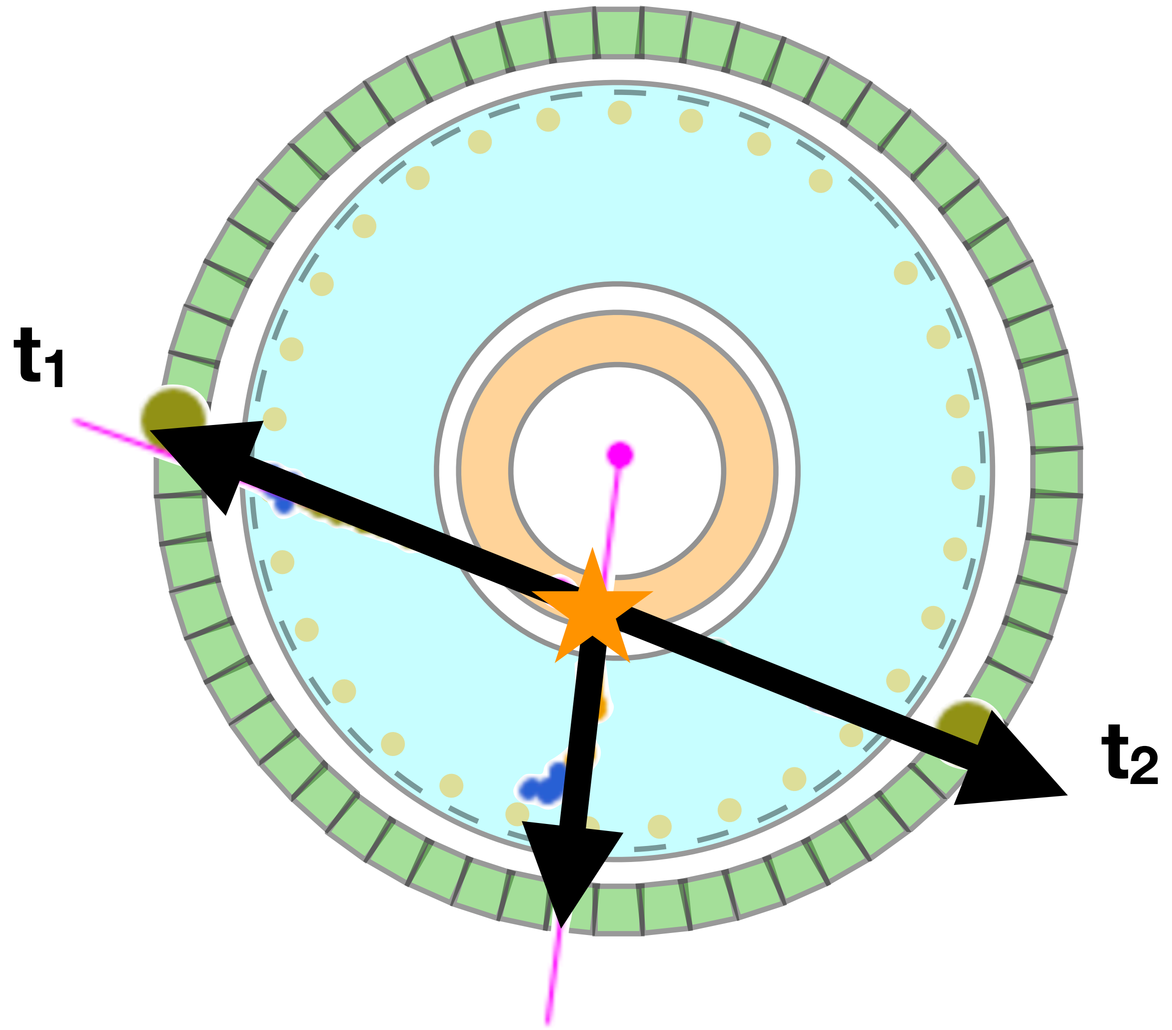
Low multiplicity $\bar{H}$ annihilation?
Muon interaction?

Time of flight measurement

Cosmic ray case:
TOF = $t_2 - t_1$ = ~1.5 ns

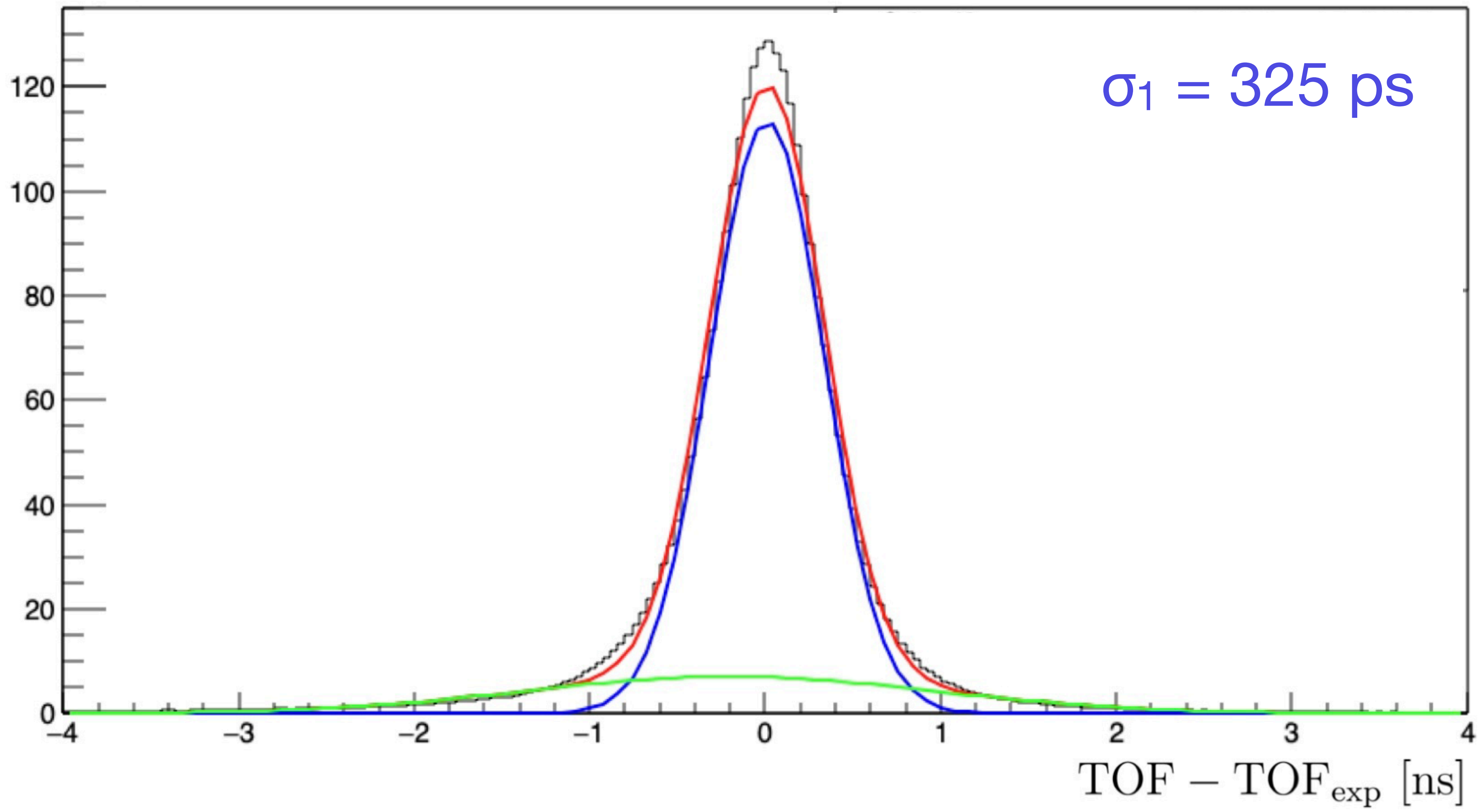


$\bar{H}$ annihilation case:
TOF = $t_2 - t_1$ = ~ 0.5 ns



- 325 ps TOF resolution (after calibration campaign)

Cosmic ray TOF resolution (double Gaussian fit)



BDT-based background rejection

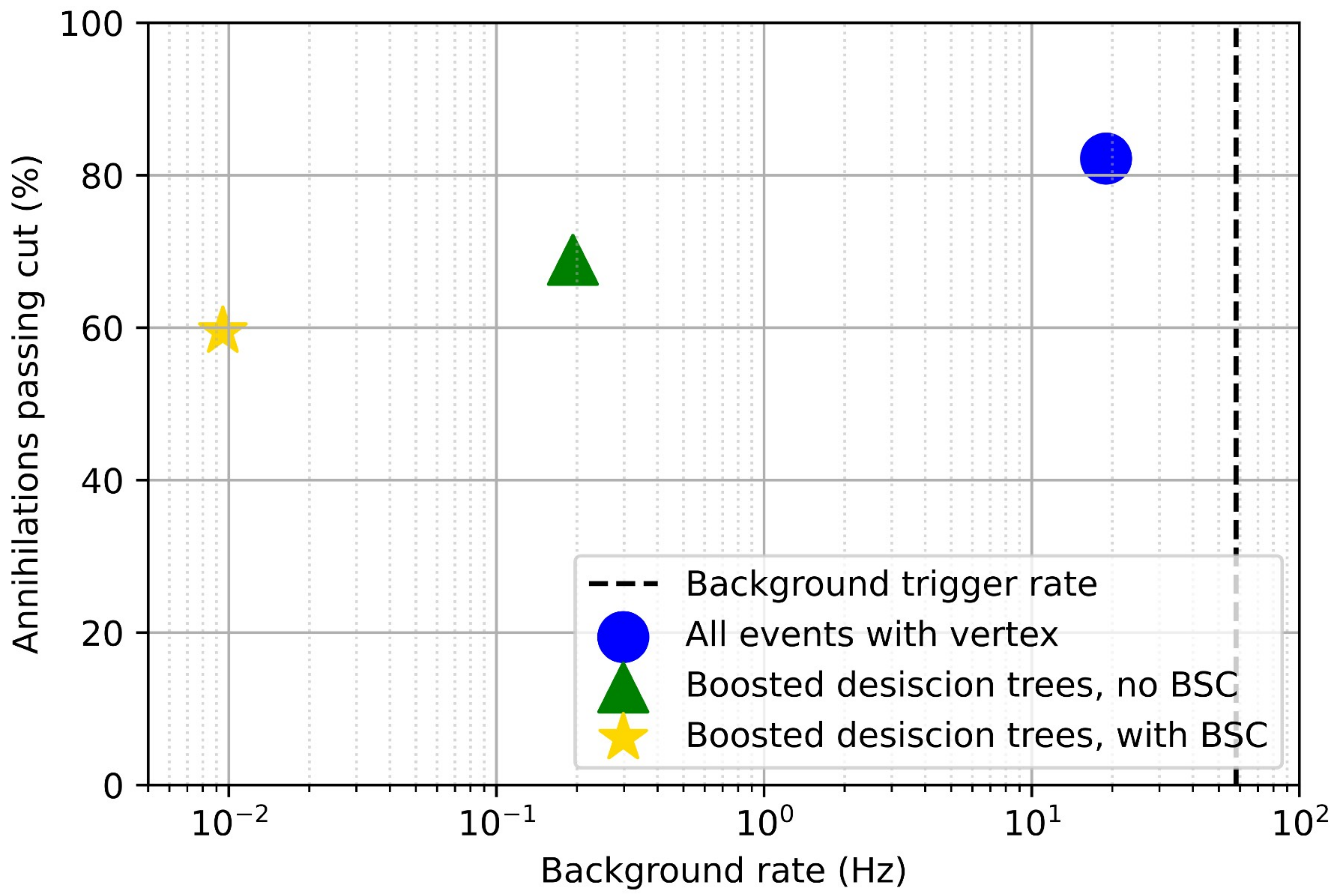
- BDT trained to reject cosmic rays (2022)
  58 Hz background trigger rate → 0.2 Hz

- Particle time of flight using barrel scintillator now available

    - BDT retrained including TOF
      58 Hz → 10 mHz

- Allows for slower $\bar{H}$ release

    - Steeper escape curve

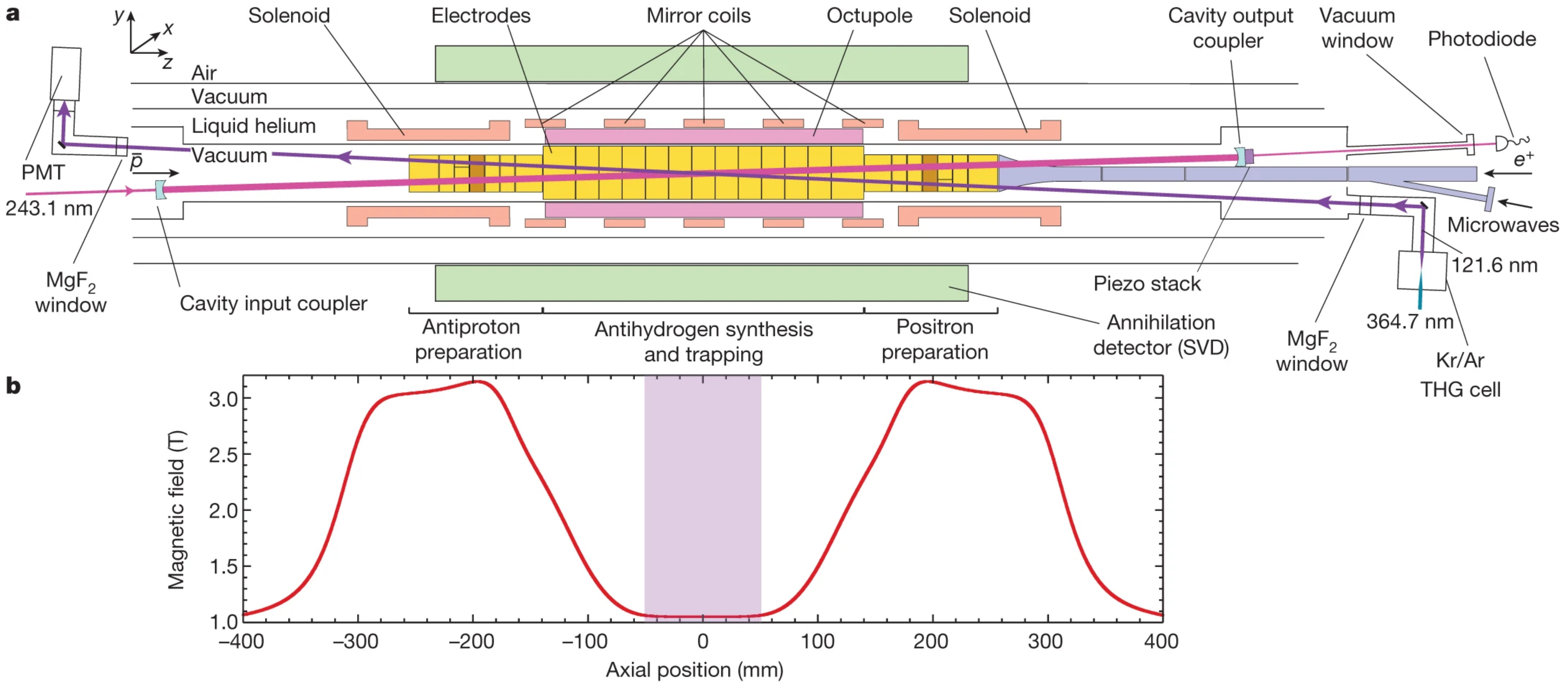


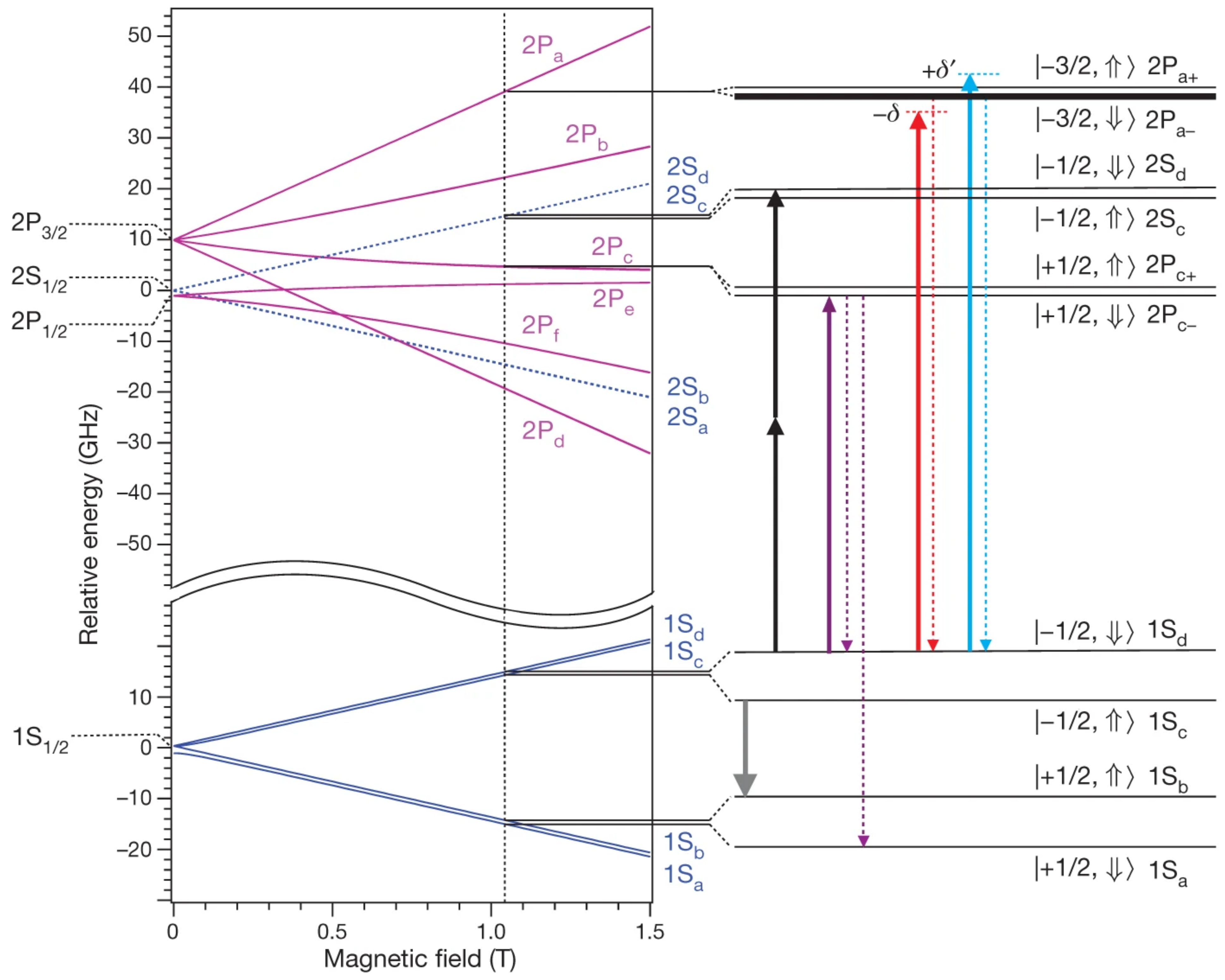
Summary

- ALPHA-g measured gravity acting on anti-hydrogen in 2022.
    - Consistent with weak equivalence principle.
- Looking towards a more precise measurement of $\bar{g}$.
    - Laser cooling + adiabatic cooling demonstrated in ALPHA-g → ~1 mK $\bar{H}$.
    - Be^+ cooling of e^+ greatly improved $\bar{H}$ production rate.
    - Cosmic ray background further suppressed using particle time of flight.

Backup

Laser cooling





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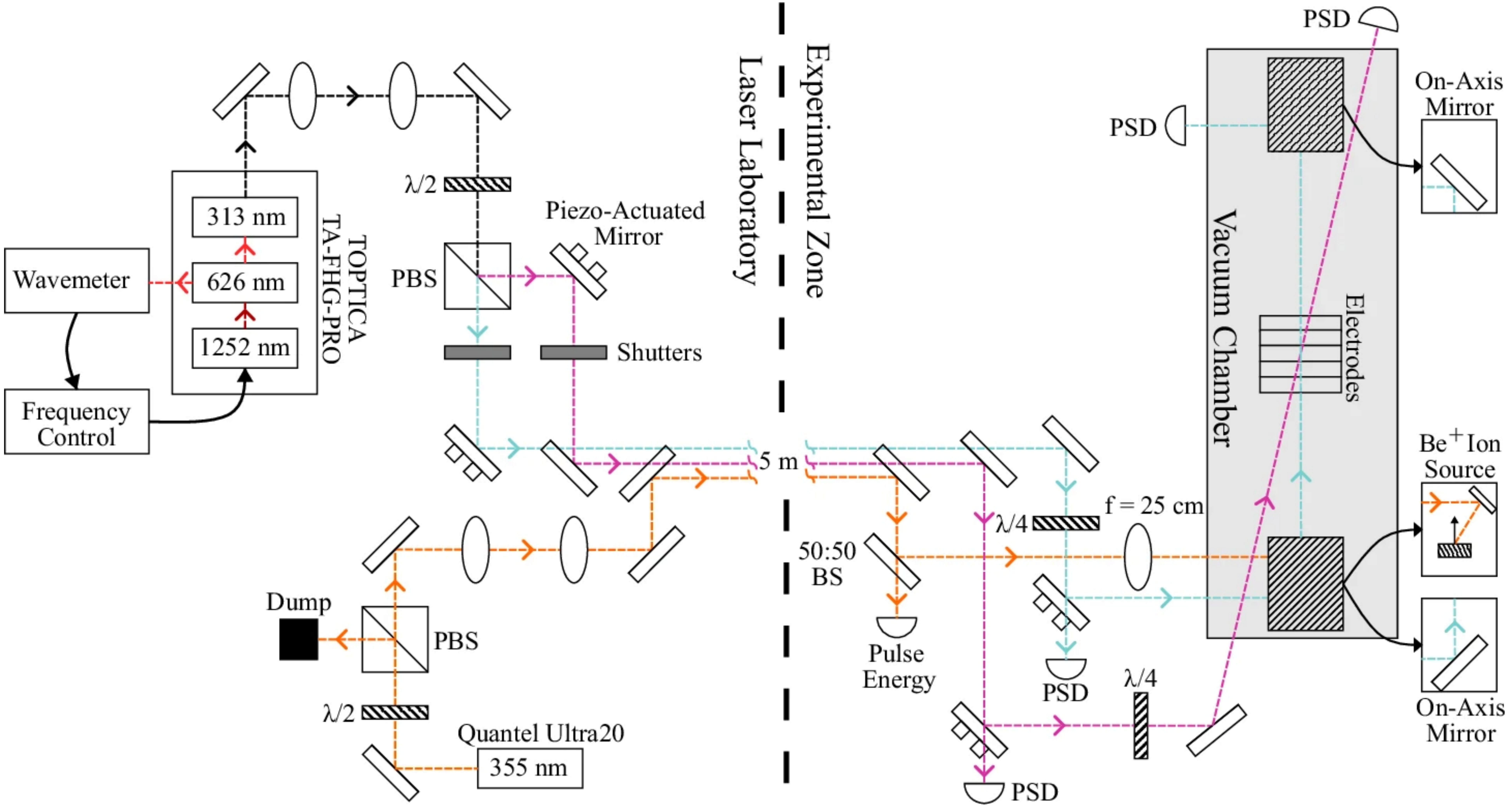
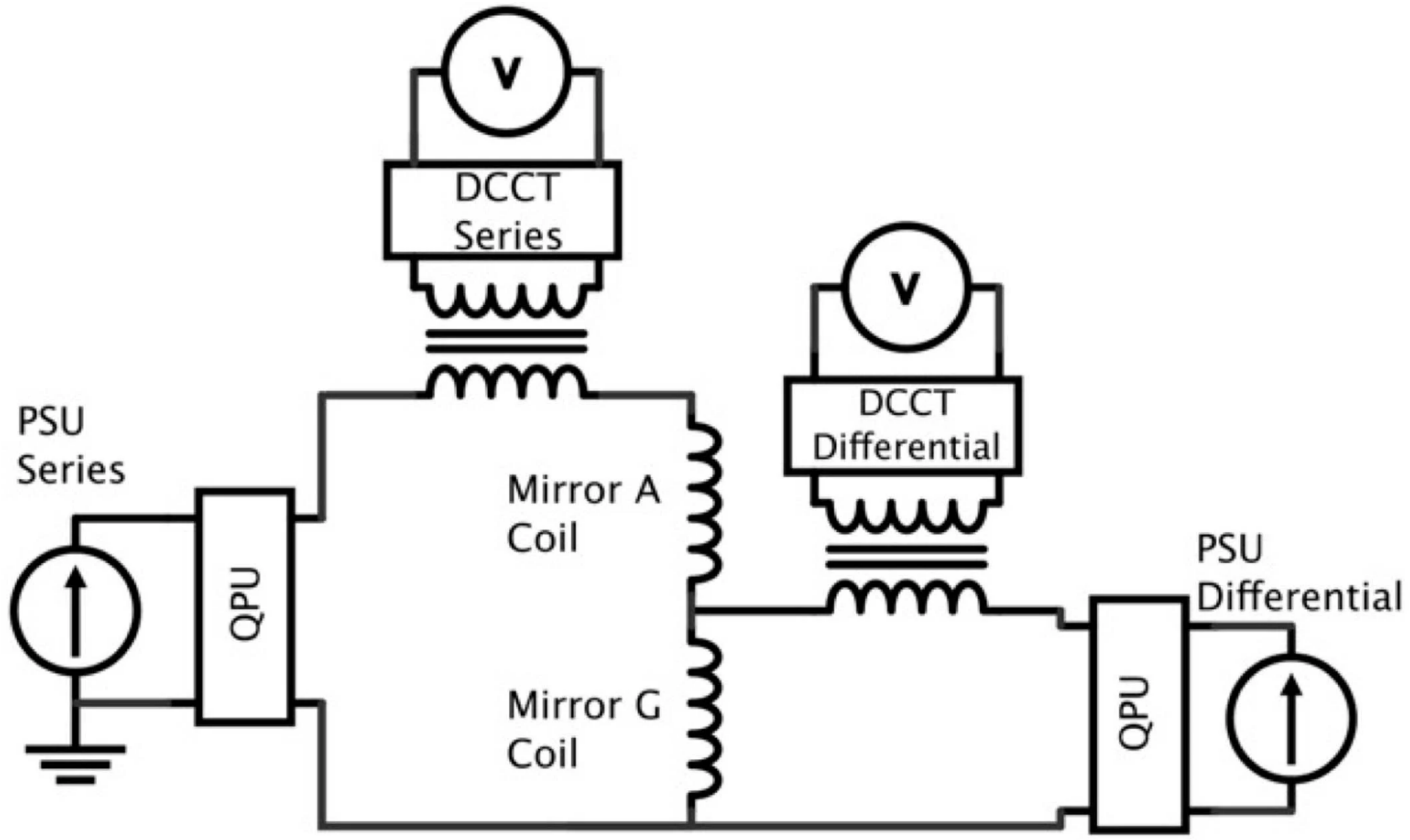
Be+ Laser cooling



Nature Communications **16**, 10106 (2025)

Magnet 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



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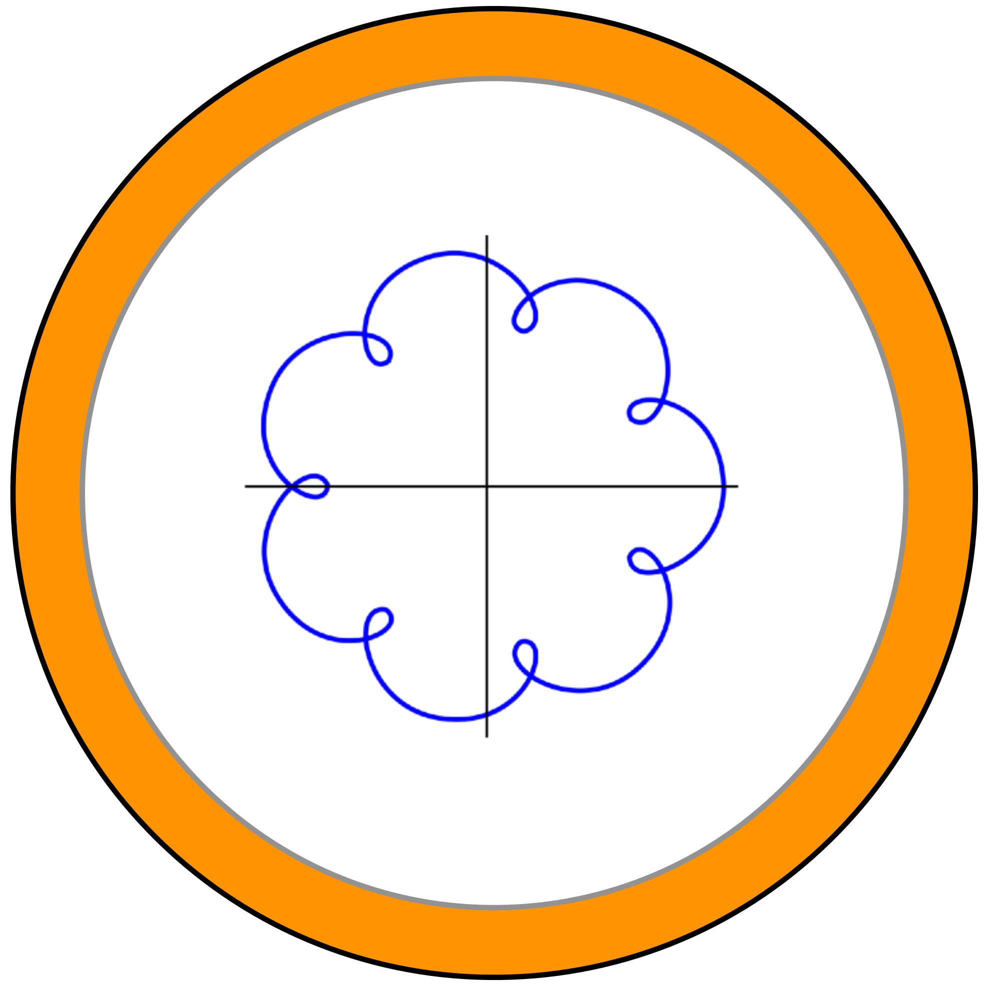
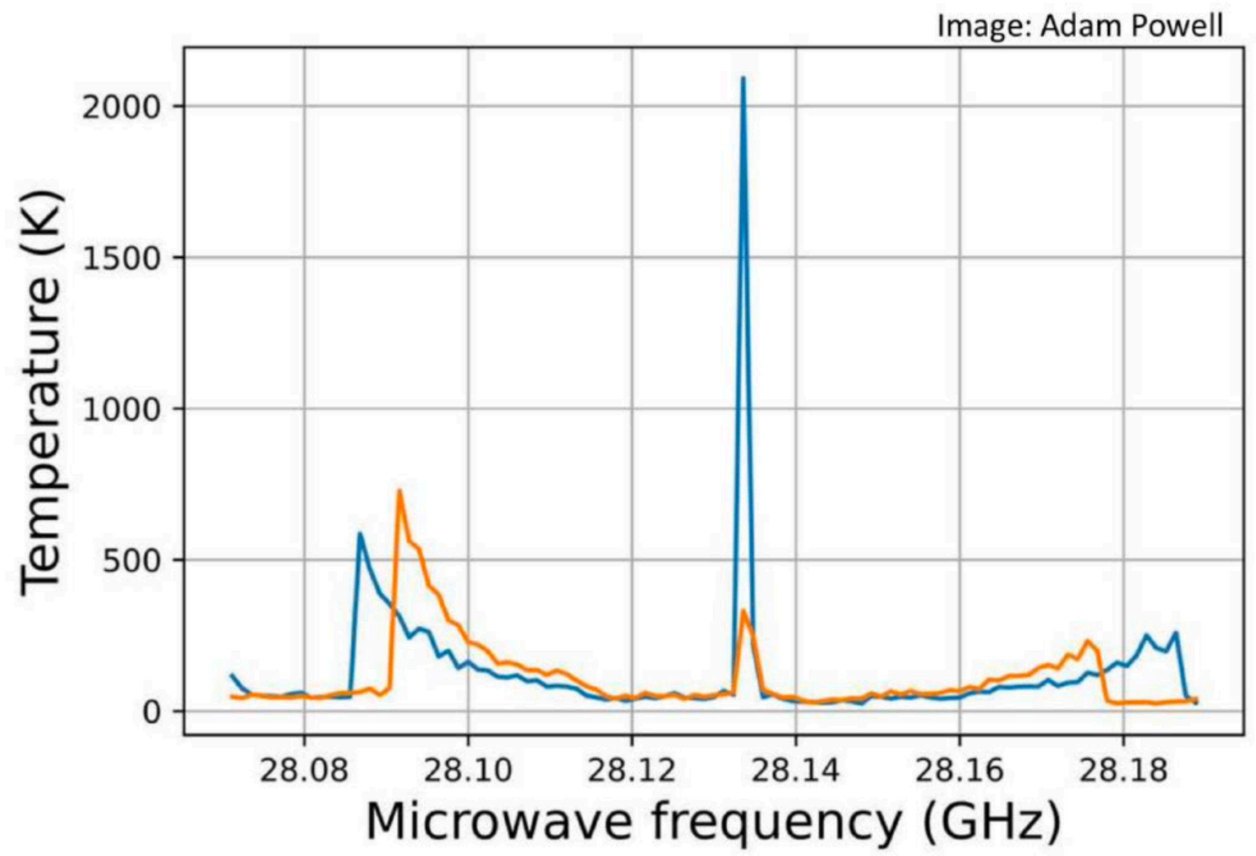
Electron Cyclotron Resonance





- Charged particle motion in Penning trap:

  Magnetron drift + cyclotron motion (+ axial bounce)

- Cyclotron motion frequency: $\omega_c = qB/m$

- Exploit this to measure B:

  1. Create electron plasma
  2. Inject microwaves near frequency ω_c
  3. Observe resonant heating