



Swansea University
Prifysgol Abertawe



Antihydrogen Physics -with some ML assistance

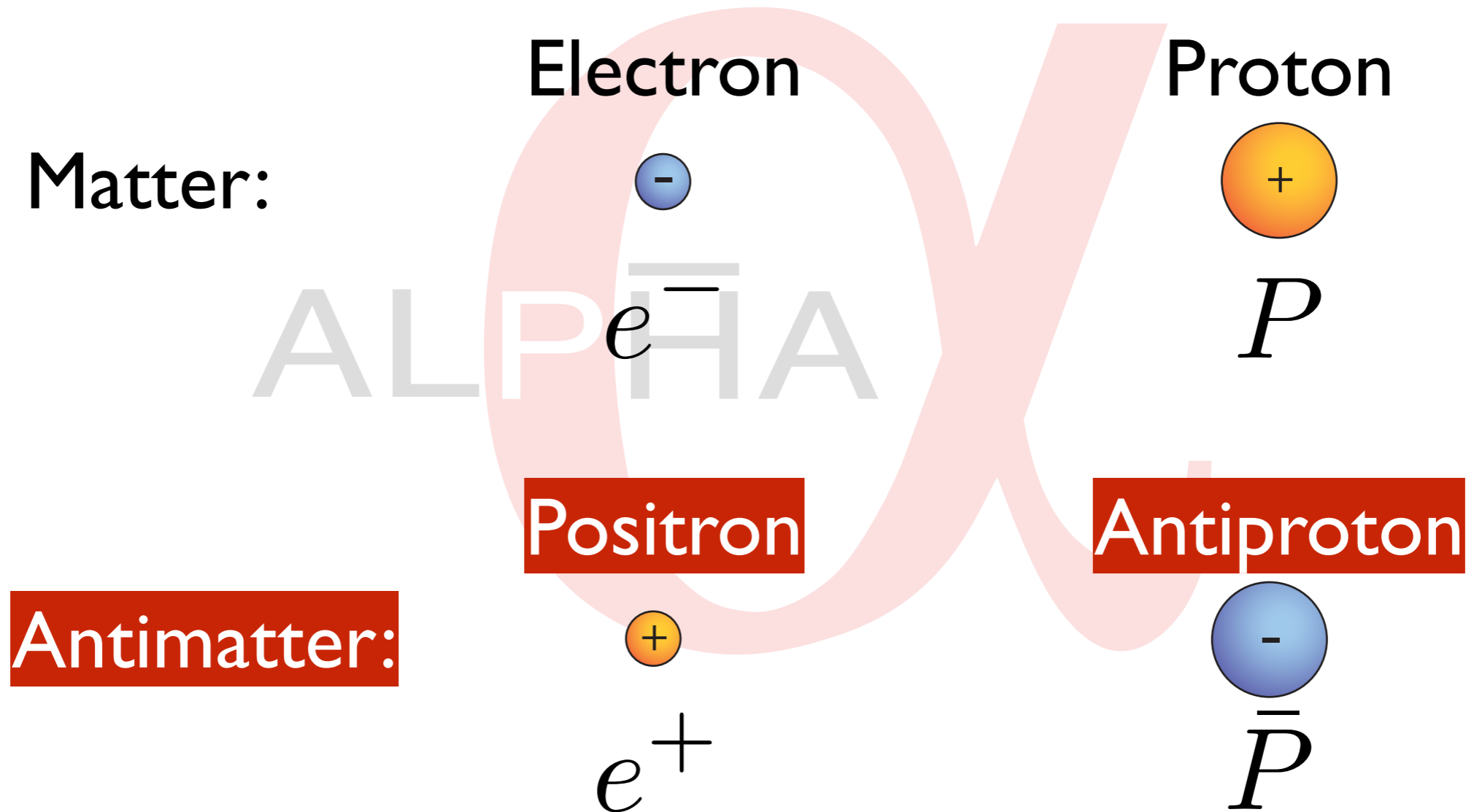
Prof. Niels Madsen
Swansea University



Workshop for Korea-UK AI/ML Research in Fundamental Sciences
Sejong University, Seoul, South Korea, November 3, 2022

What is antimatter?

- Particles have “twins” same mass, opposite charge

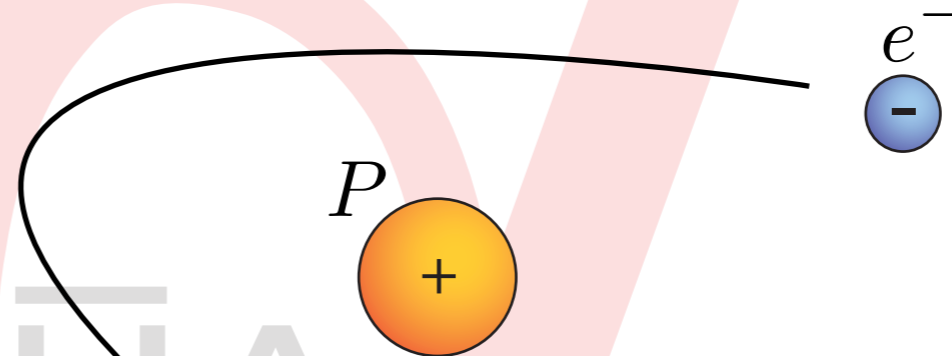


What is antimatter?

- Neutral antimatter atoms

Matter:

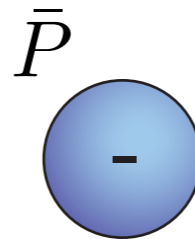
Hydrogen



H

Antimatter:

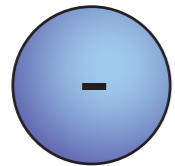
Antihydrogen



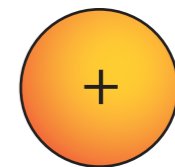
\bar{H}

What is Antimatter?

- What happens when they meet their twin?

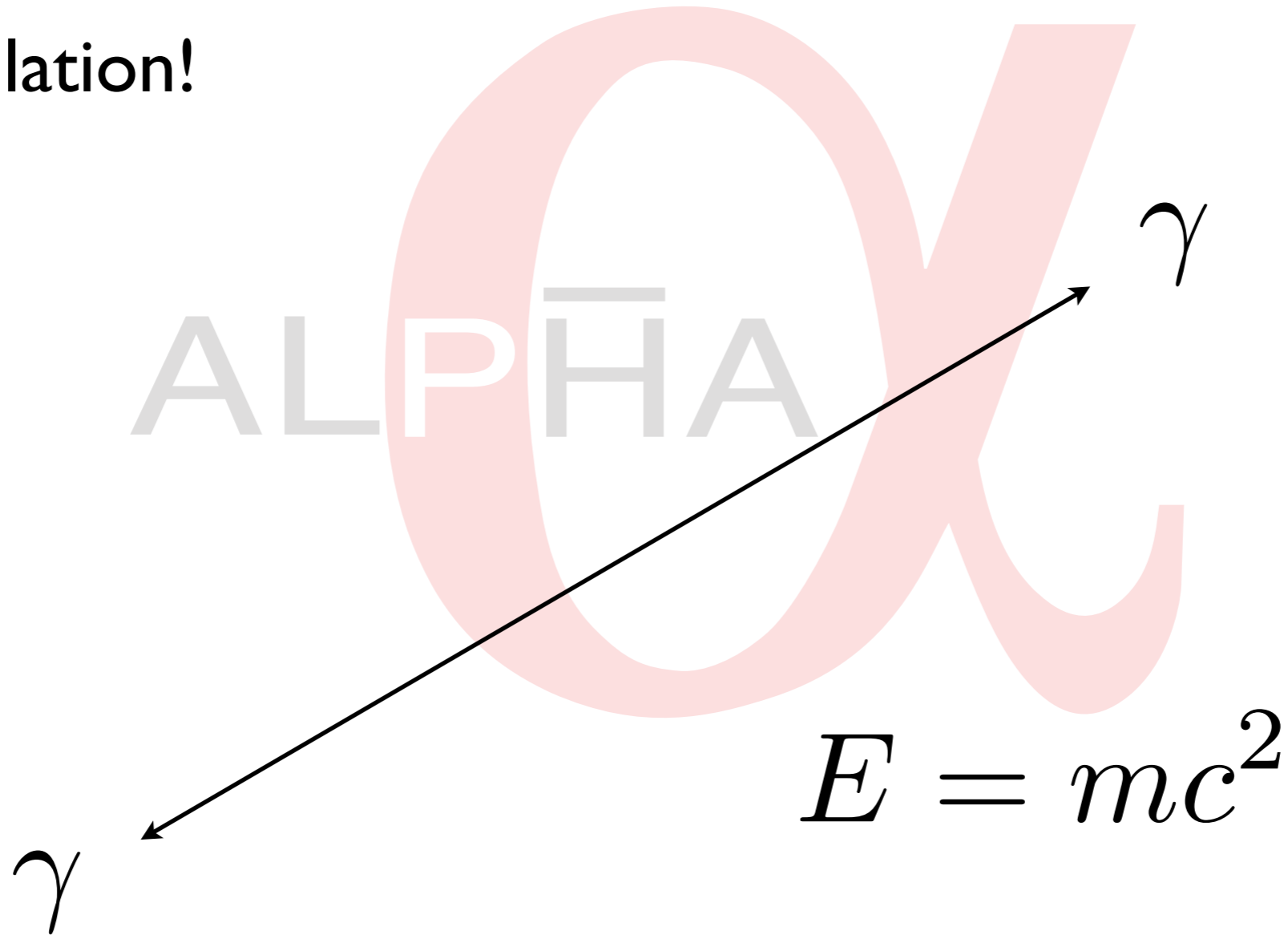


ALPHA



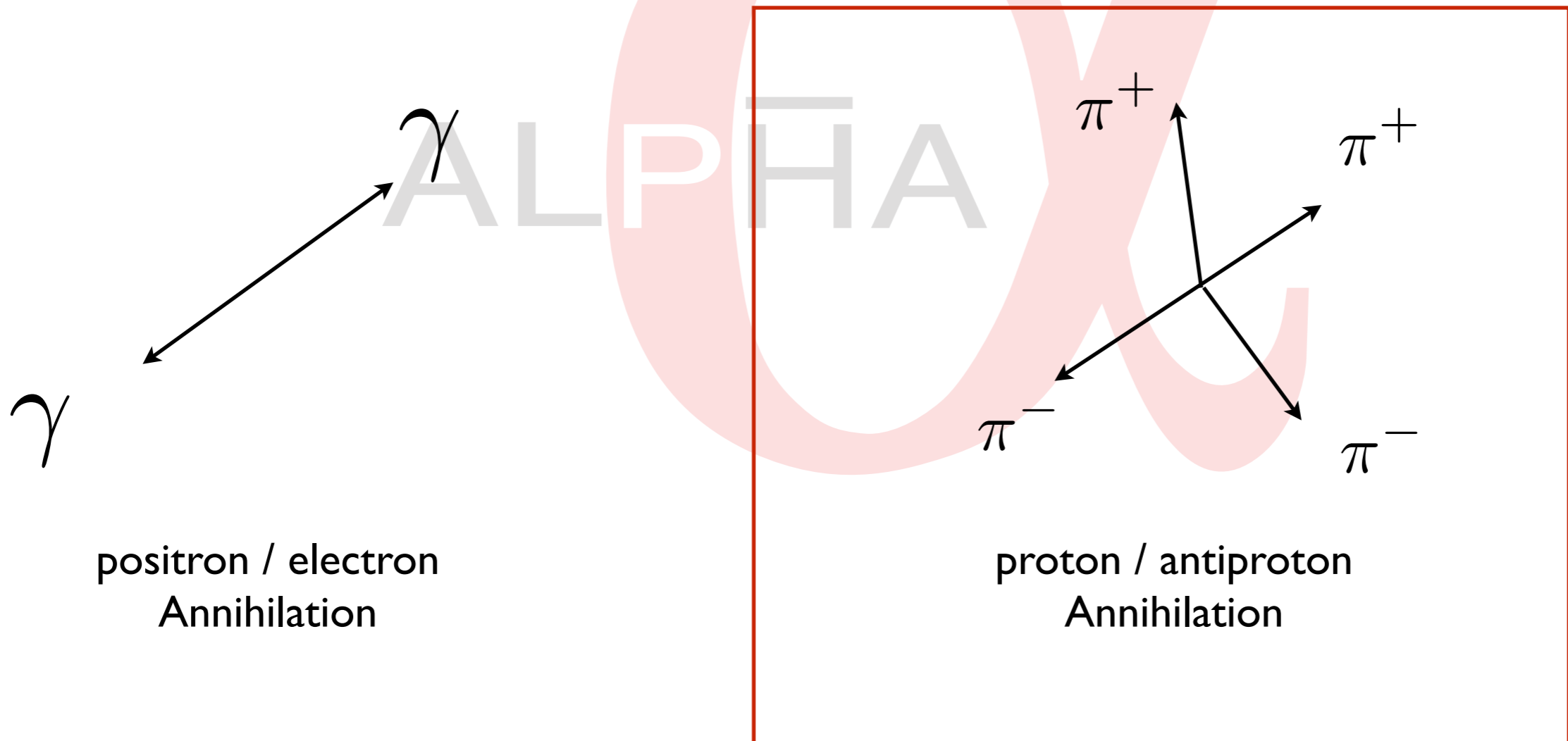
What is Antimatter?

- Annihilation!



Annihilations

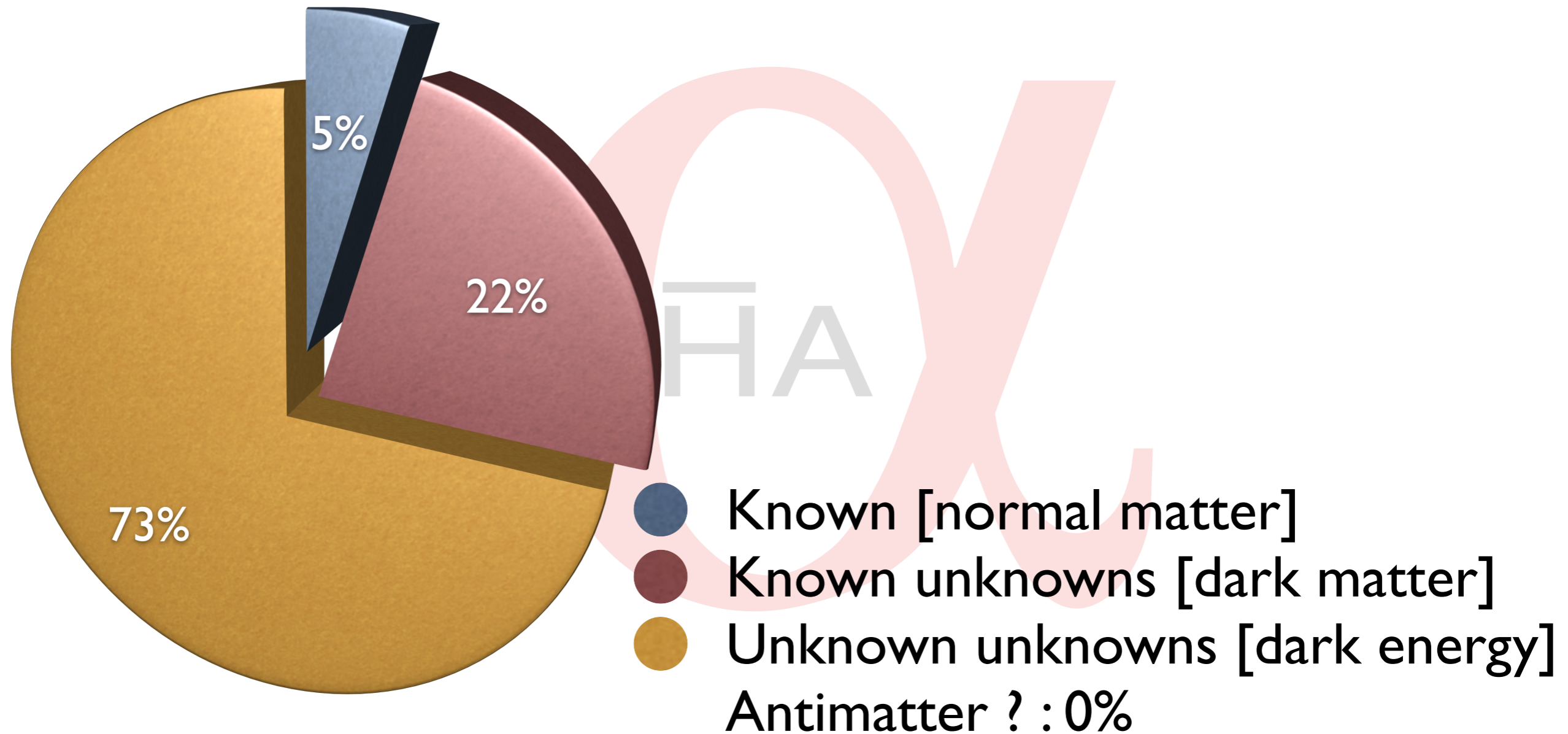
- Positron / Electron: photons (511 keV)
- Antiproton / Proton: Many possibilities - Pions, etc.



Why make Antihydrogen

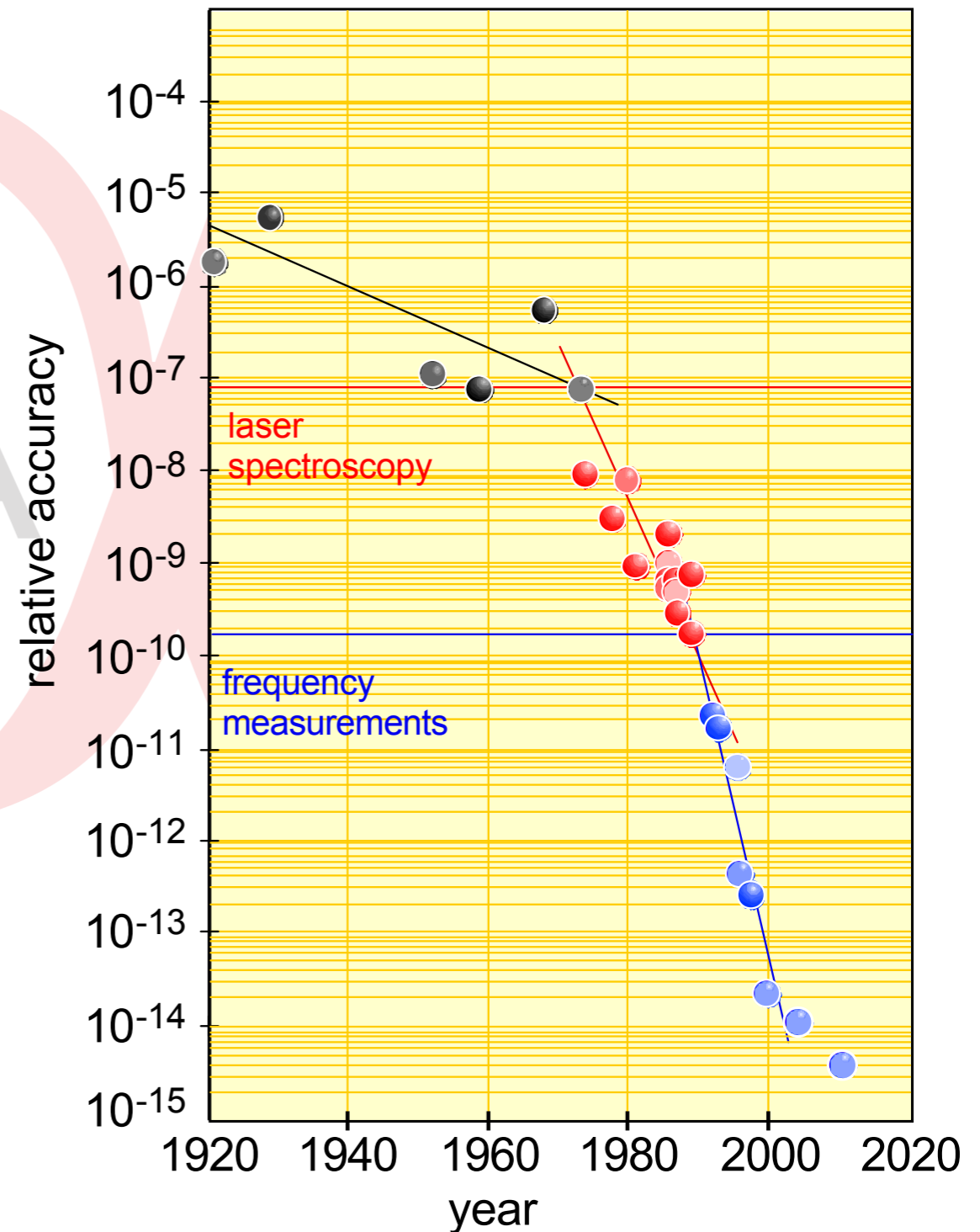
- Physical laws identical under CPT transformation: Antihydrogen must be identical to Hydrogen!
- Baryon Asymmetry: The universe seems made almost entirely of matter! Really? Why?
- Gravity: How does antimatter respond to gravity? Weak equivalence principle! Insights for quantum gravity? Dark Energy ?
- Note: **ANY** difference between \bar{H} and H will imply new physics!

Energi Budget of the Universe



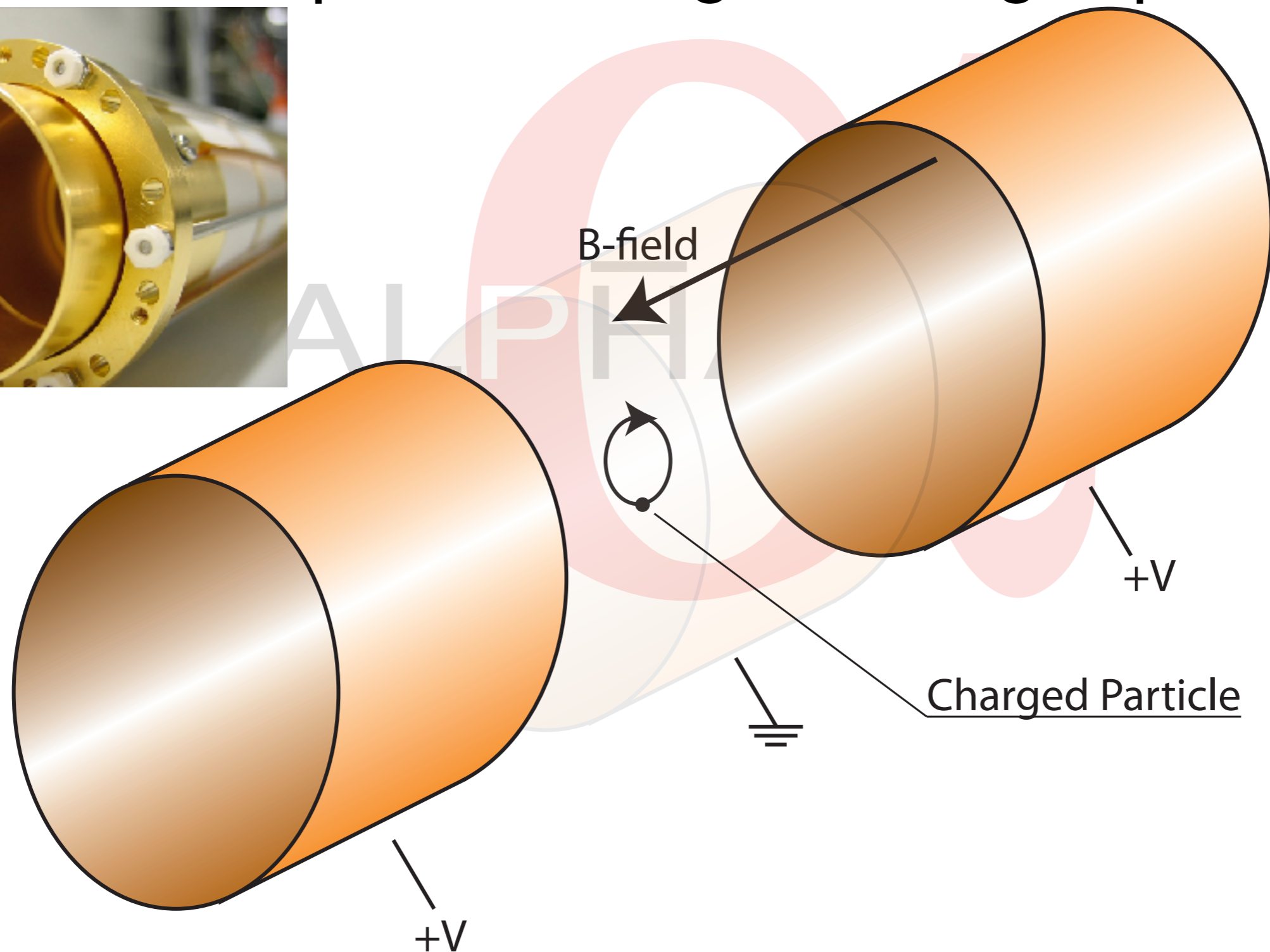
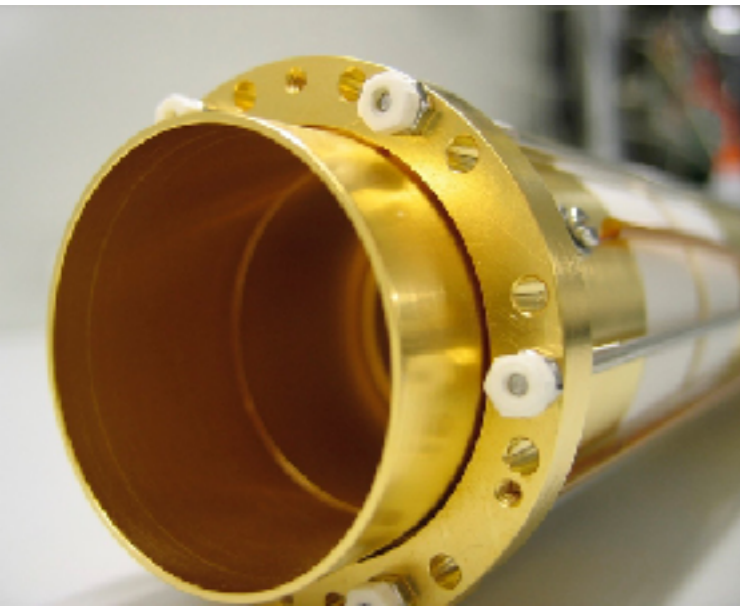
Why/how does \bar{H} help?

- Only pure antimatter system so far!
- Antihydrogen is neutral!
- Spectroscopic techniques can be brought to bear.
- Ex: H - \bar{H} comparison by $1s$ - $2s$ two photon spectroscopy.



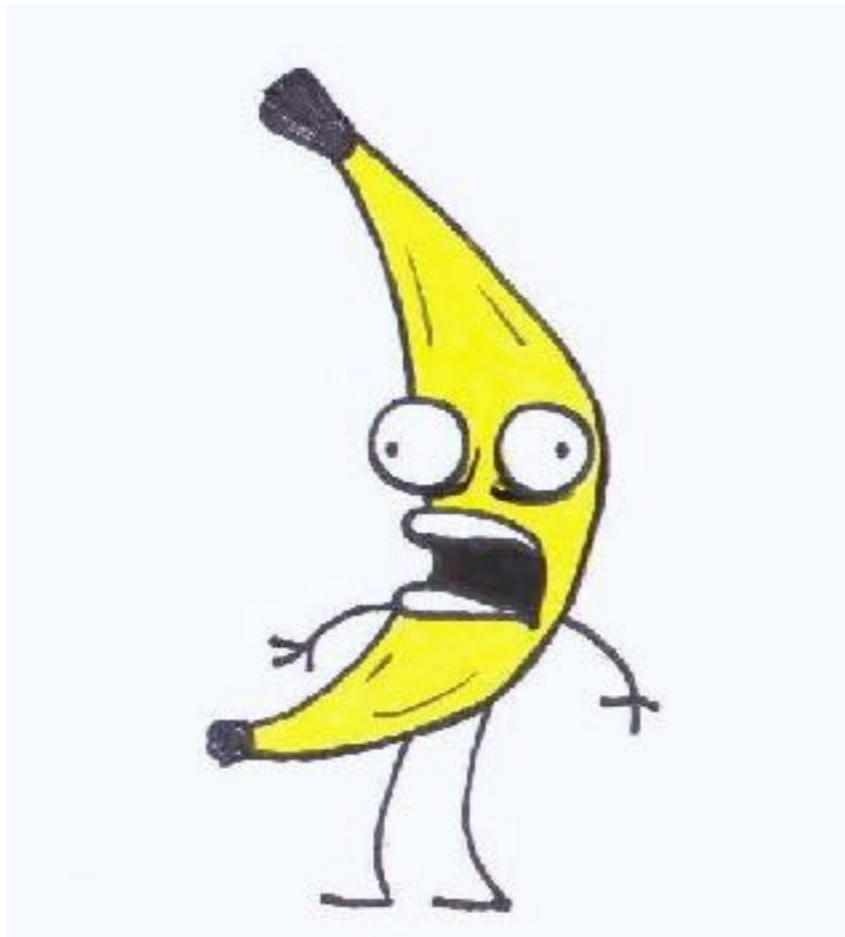
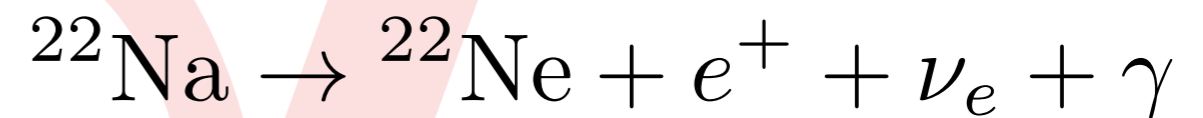
Charged Particle Traps

- All our traps are Penning-Malmberg traps



Where do Positrons come from?

- Fairly Easy: Positive β^+ decay in radioactive isotopes
 - Potassium-40 in Bananas: ~ 1 positron / hour
 - We use Sodium-22 source: $\sim 10^6$ / sec



"I am a banana!" Don Hertzfeld



Lake Geneva

Airport

Meyrin Site

LHC

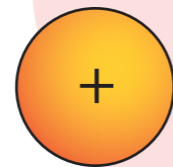


Where do Antiprotons come from?

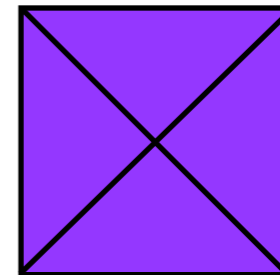
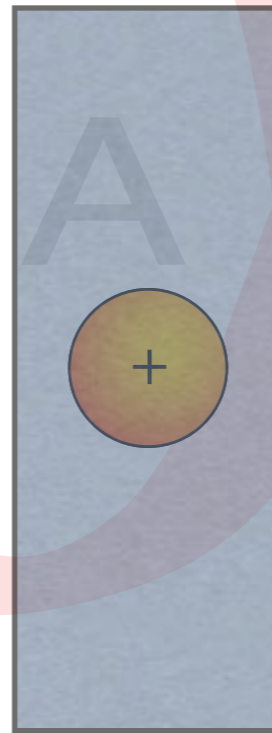
- Energetic proton creates Proton/Antiproton pair
- Charge/Mass selected



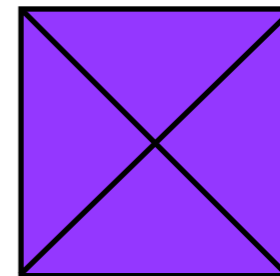
Cern Proton Synchrotron



26 GeV/c

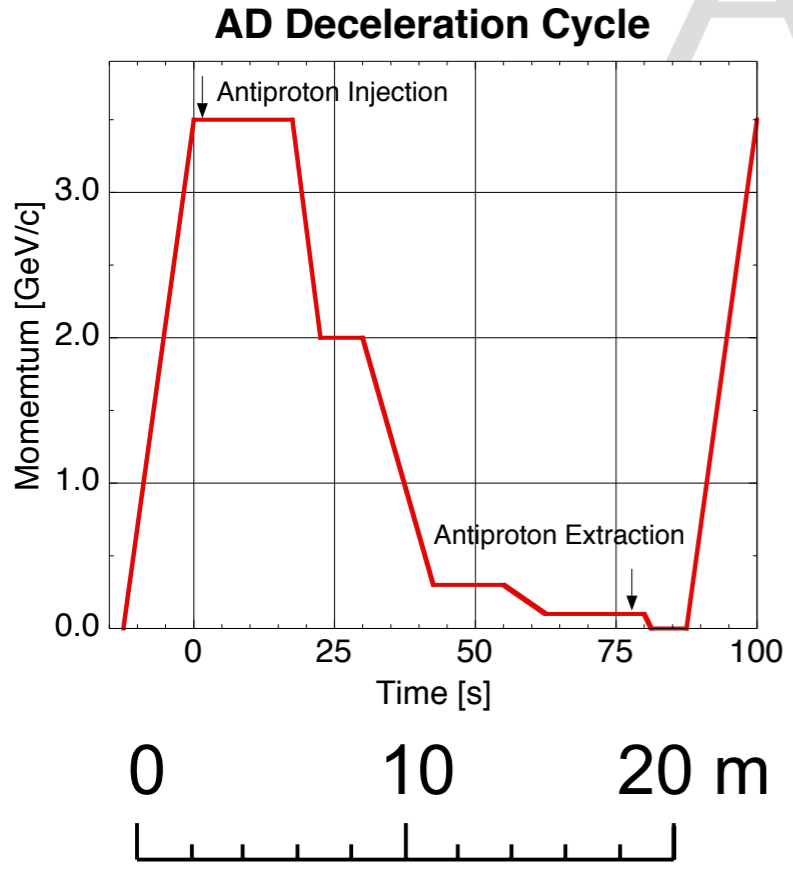
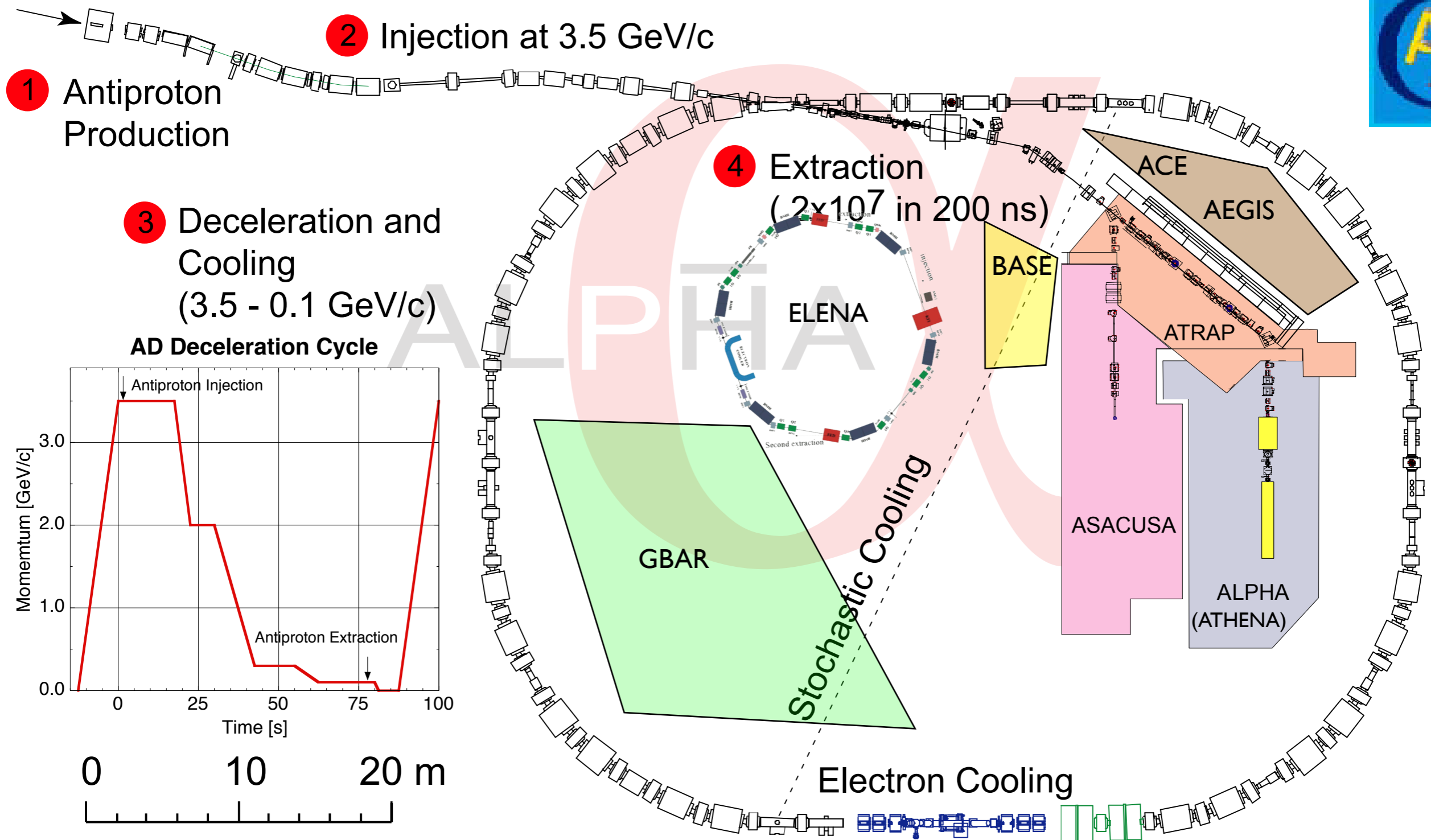


3.7 GeV/c



(and other stuff)

Antiproton Decelerator



(Old) ALPHA Setup

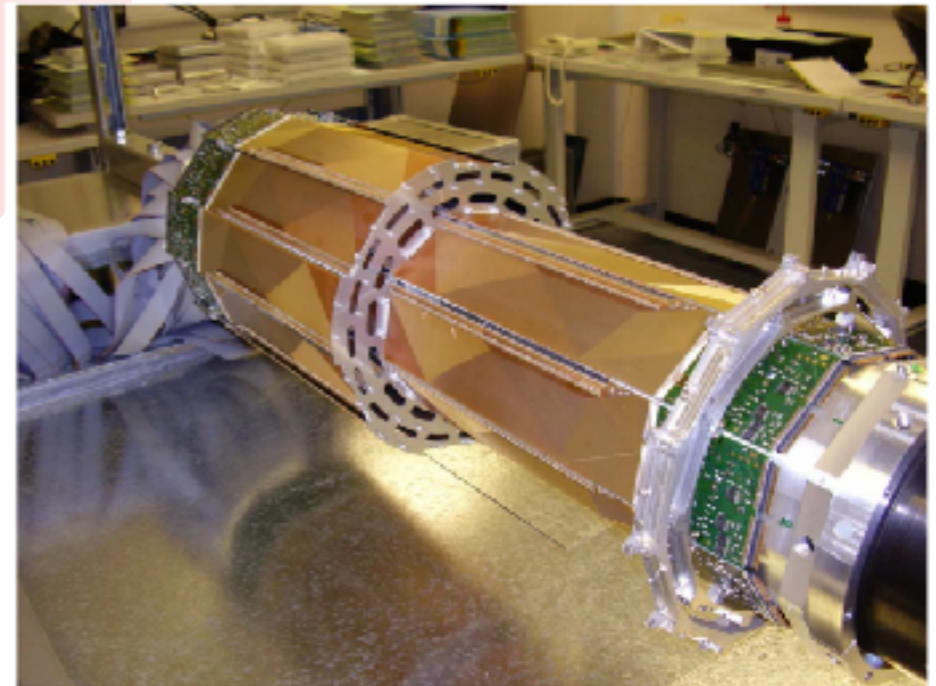
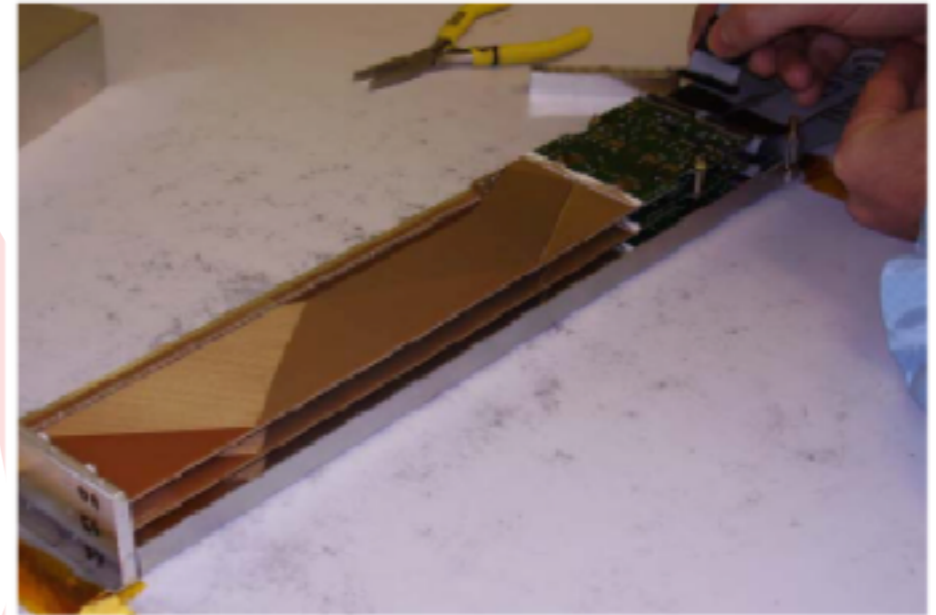
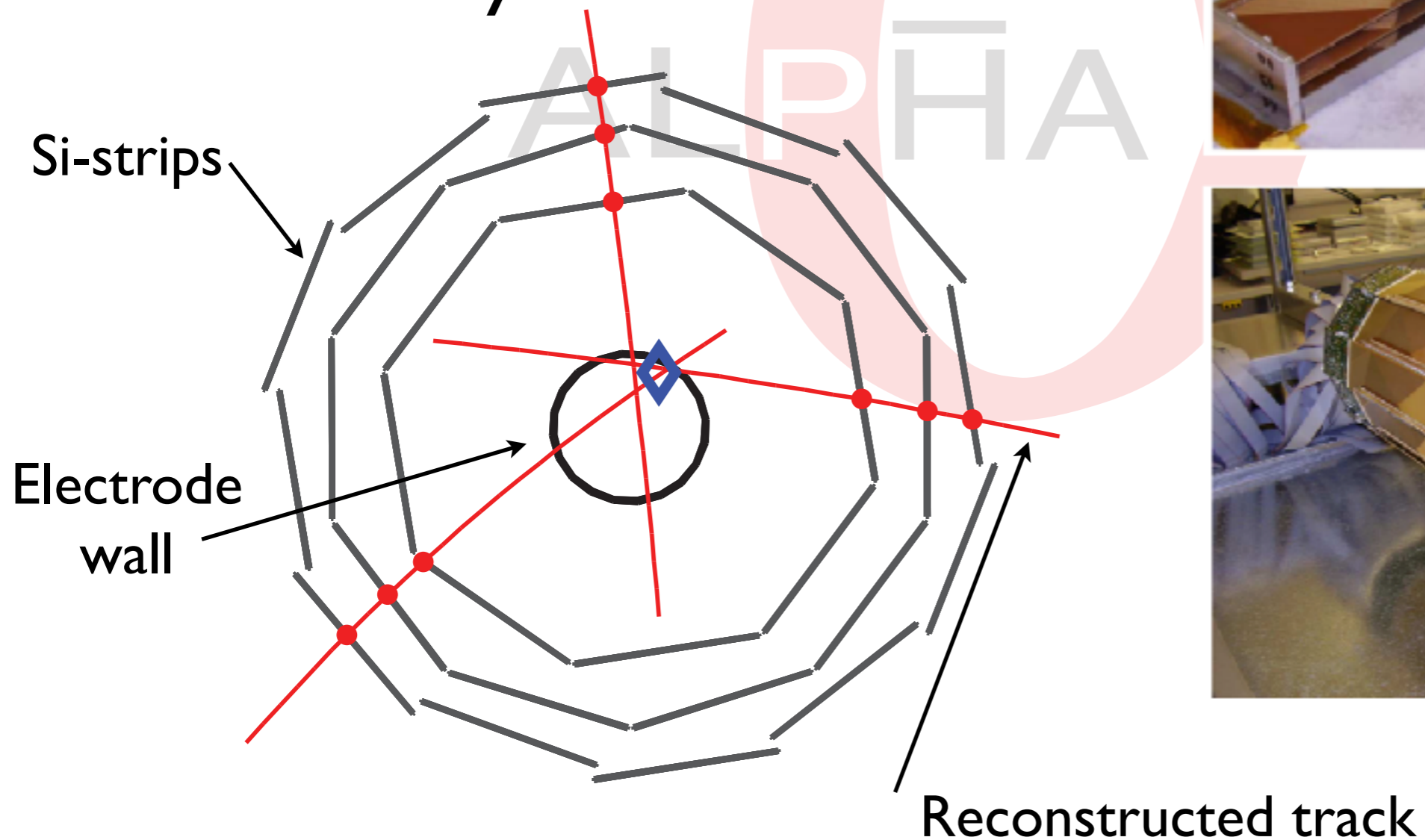


e^+

p^+

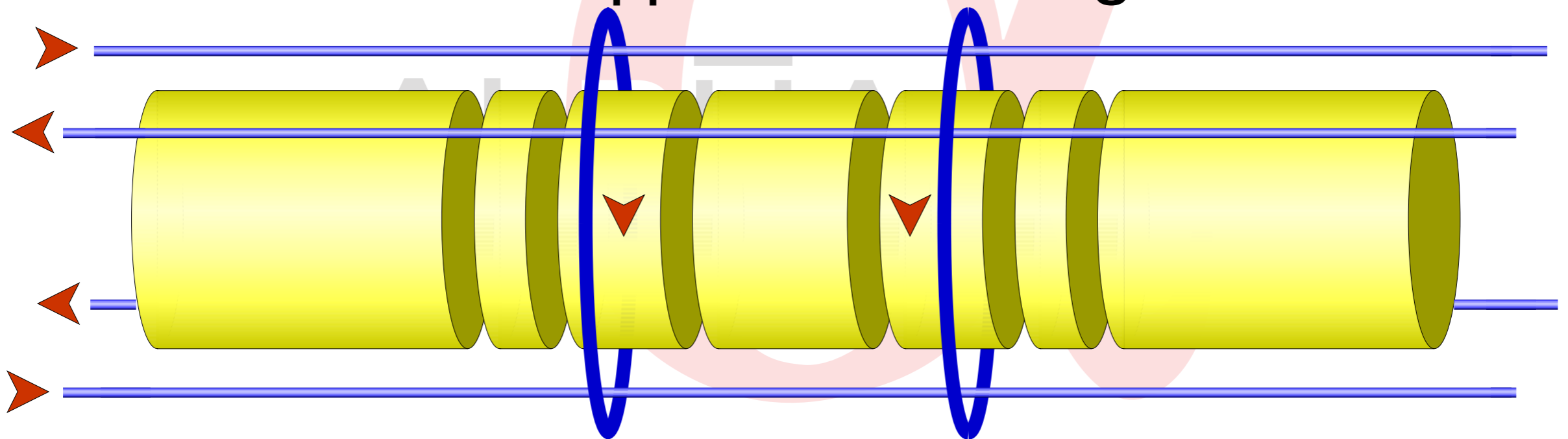
Annihilation Detection

- Si-strip detection
- Vertex resolution $\sim 1\text{mm}$
- Efficiency $\sim 50\%$



(Anti)Atom Trap

- Atoms can be trapped on their magnetic dipole-moment. $U = -\bar{\mu} \cdot \bar{B}$
- Atoms can be trapped in a 3D magnetic minimum.



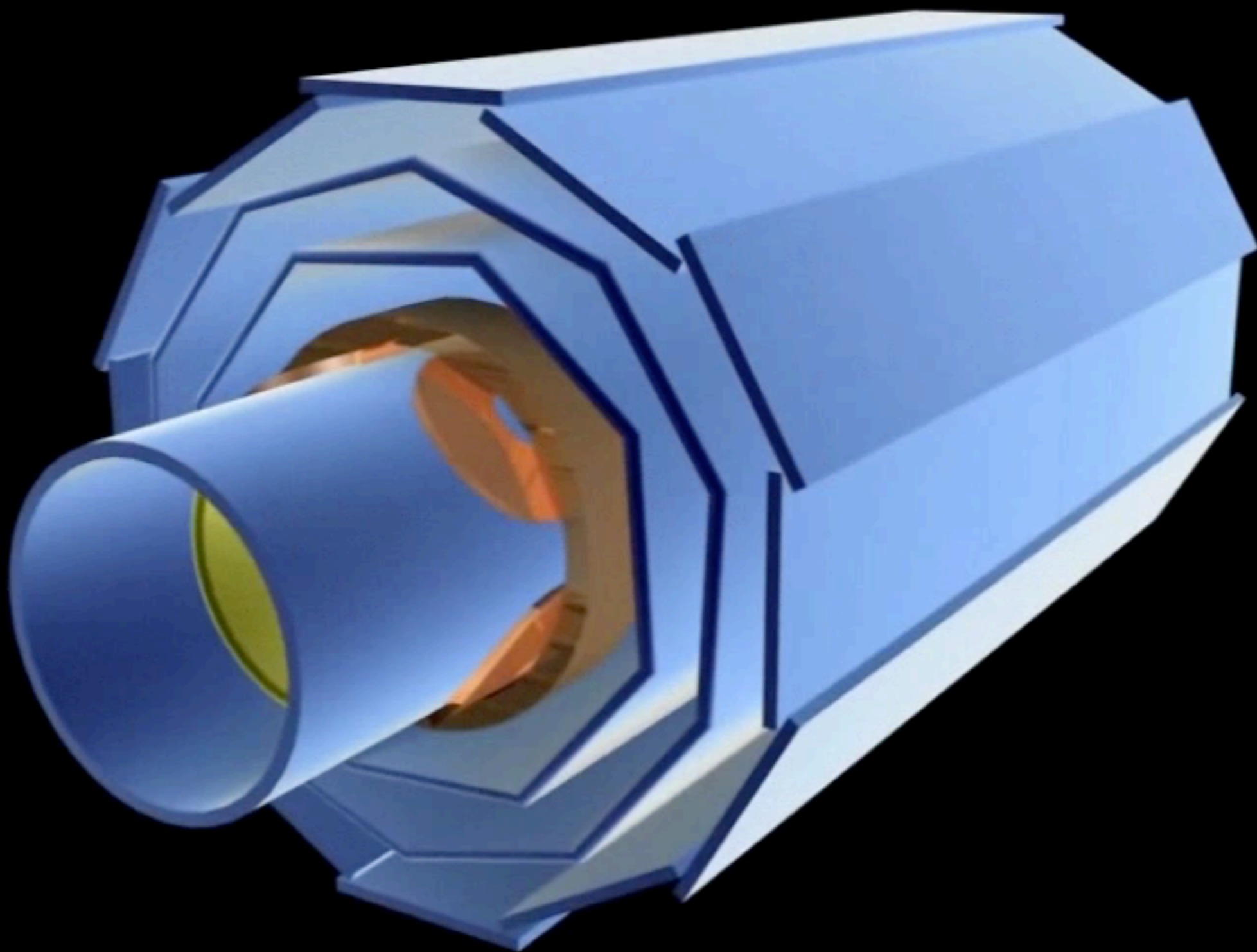
Ioffe-Pritchard Geometry

$$\Delta B = \sqrt{B_{sol}^2 + B_{wall}^2} - B_{sol}$$

Shallow : ~ 0.7 K/T for H ground state

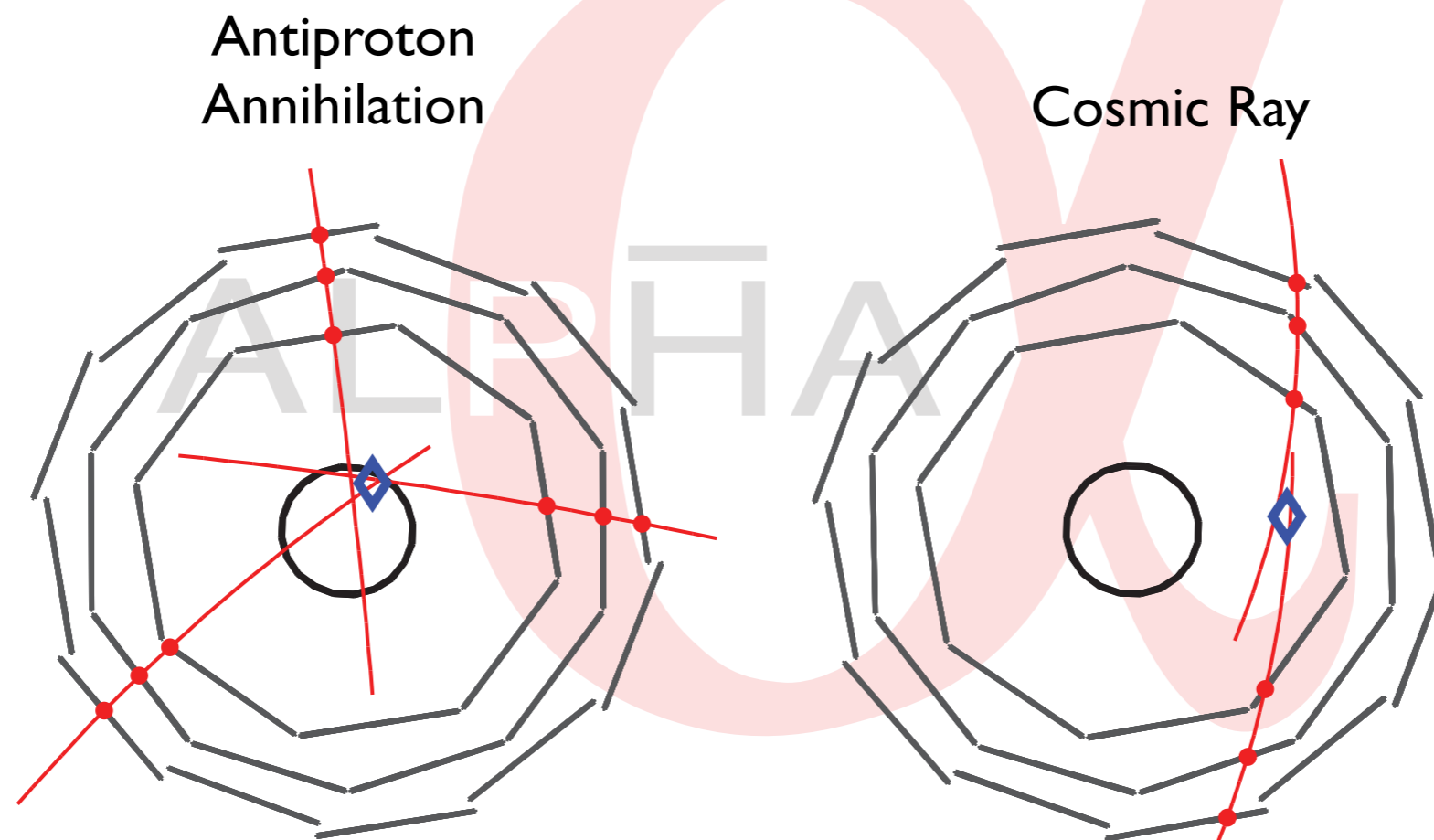


Geim : Ig Noble Price (2000)
[unrelated: Noble price in 2010]



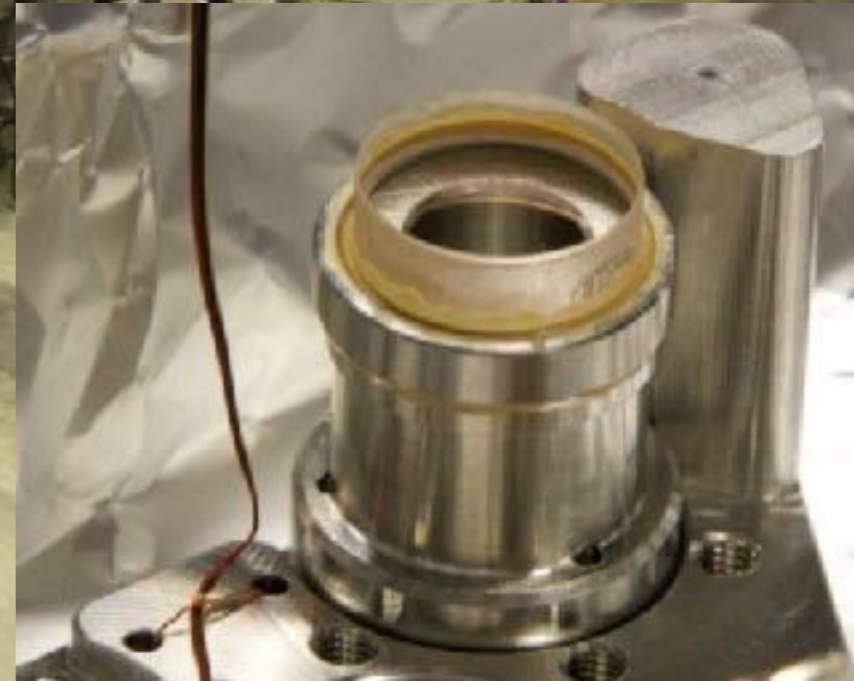
Cosmic Background

- One fake signal to worry about : cosmic rays!



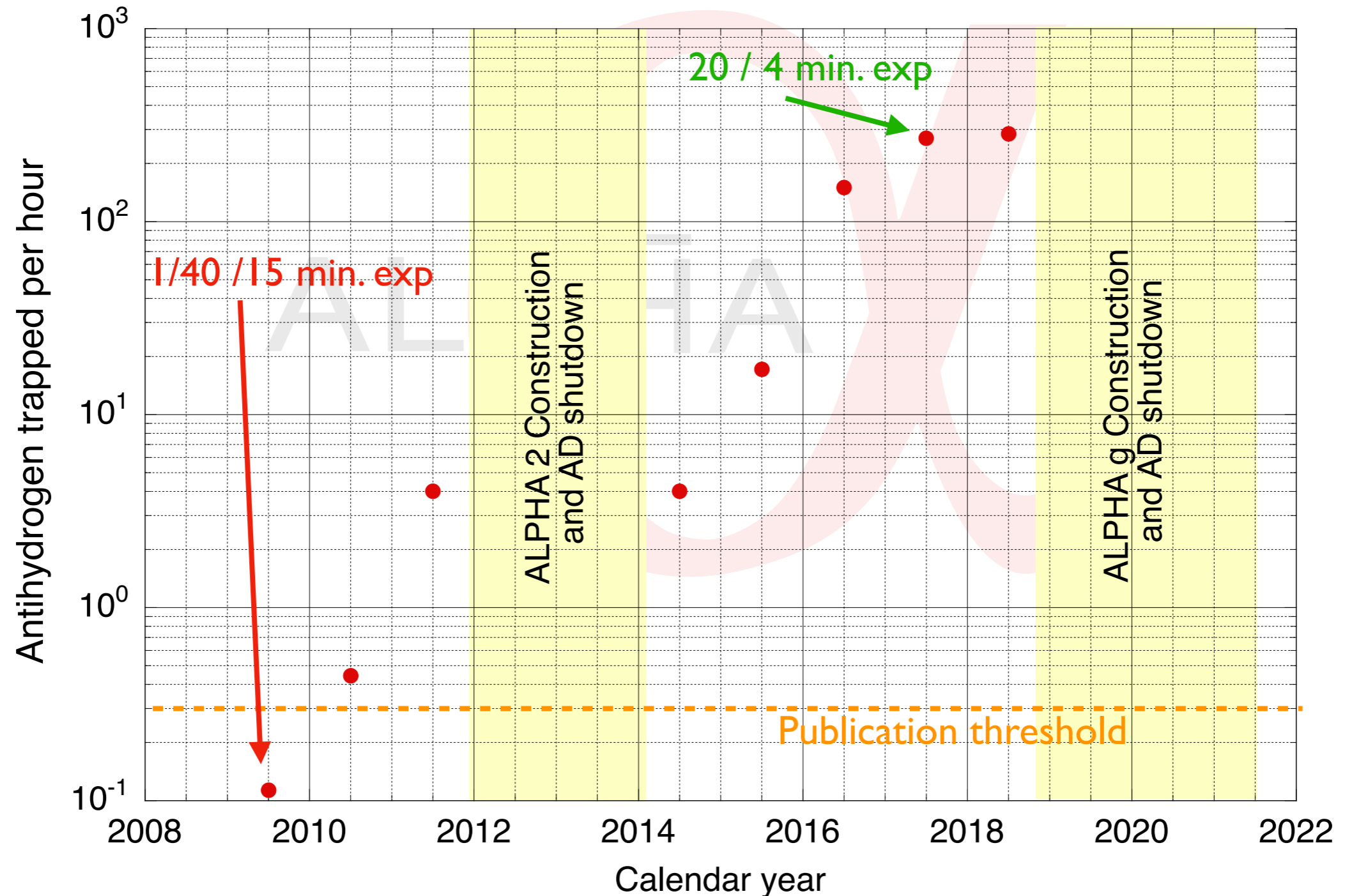
- Example (2010/11) : 1.4/1000 cosmic “fakes” / experiment

ALPHA upgraded 2013



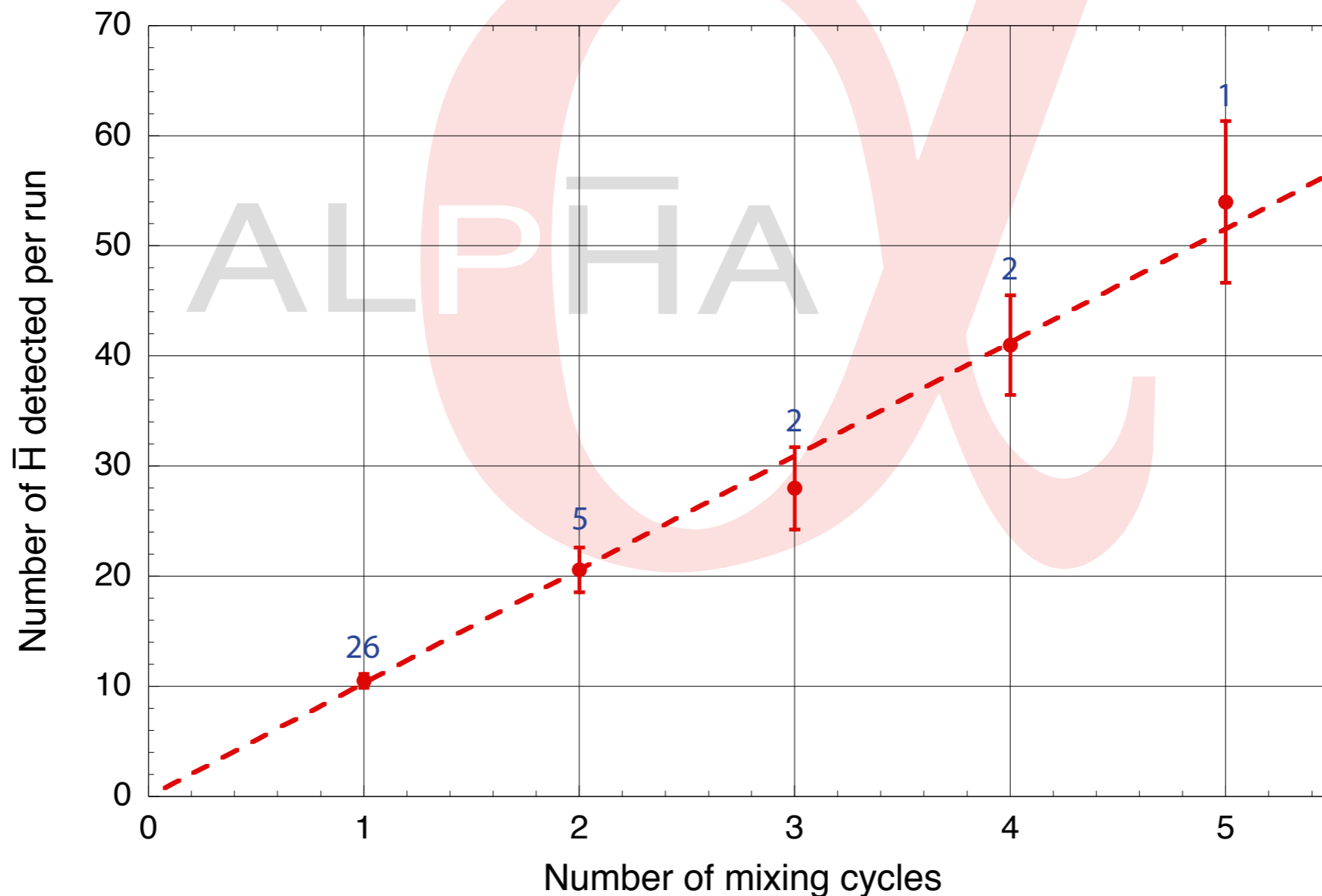
Trapping evolution

Trapping history in ALPHA since first trapping in 2010



Antihydrogen stacking

- Charged particles become “annoying” plasmas - neutral don't talk much : Stacking.





1S - 2S Excitation

Experimental sequence

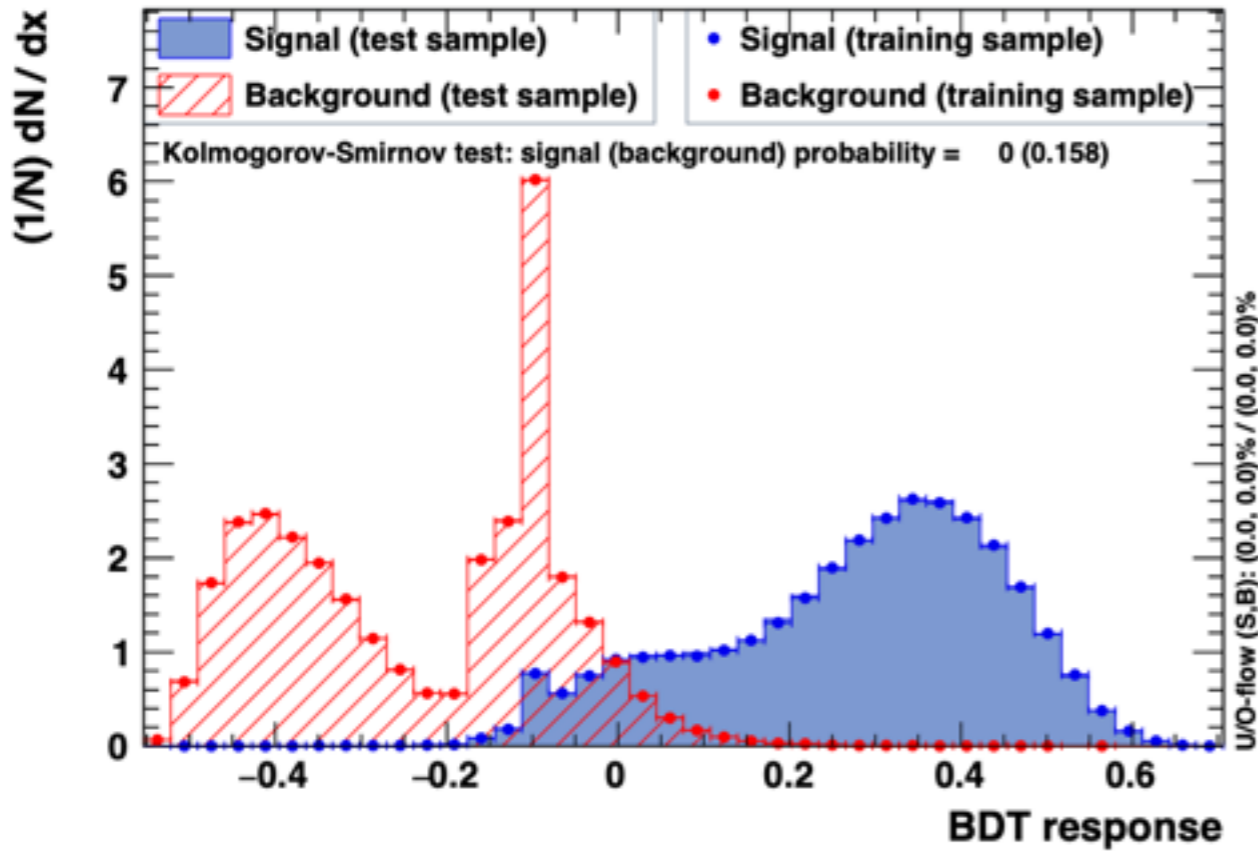
- Mix 90,000 antiprotons and 1.6 million positrons in the hbar trap
- Eject remaining charged particles
- Allow trapped antihydrogen to decay to ground state, then three options :
 1. Inject laser ON resonance; **300 s** c-c then **300 s** d-d
 2. Inject laser OFF resonance; **300 s** c-c then **300 s** d-d
 3. No laser; **600 s** total
- Ramp down trap magnets (in **1.5s**), detect any antihydrogen that escapes.

Multi-variate analysis

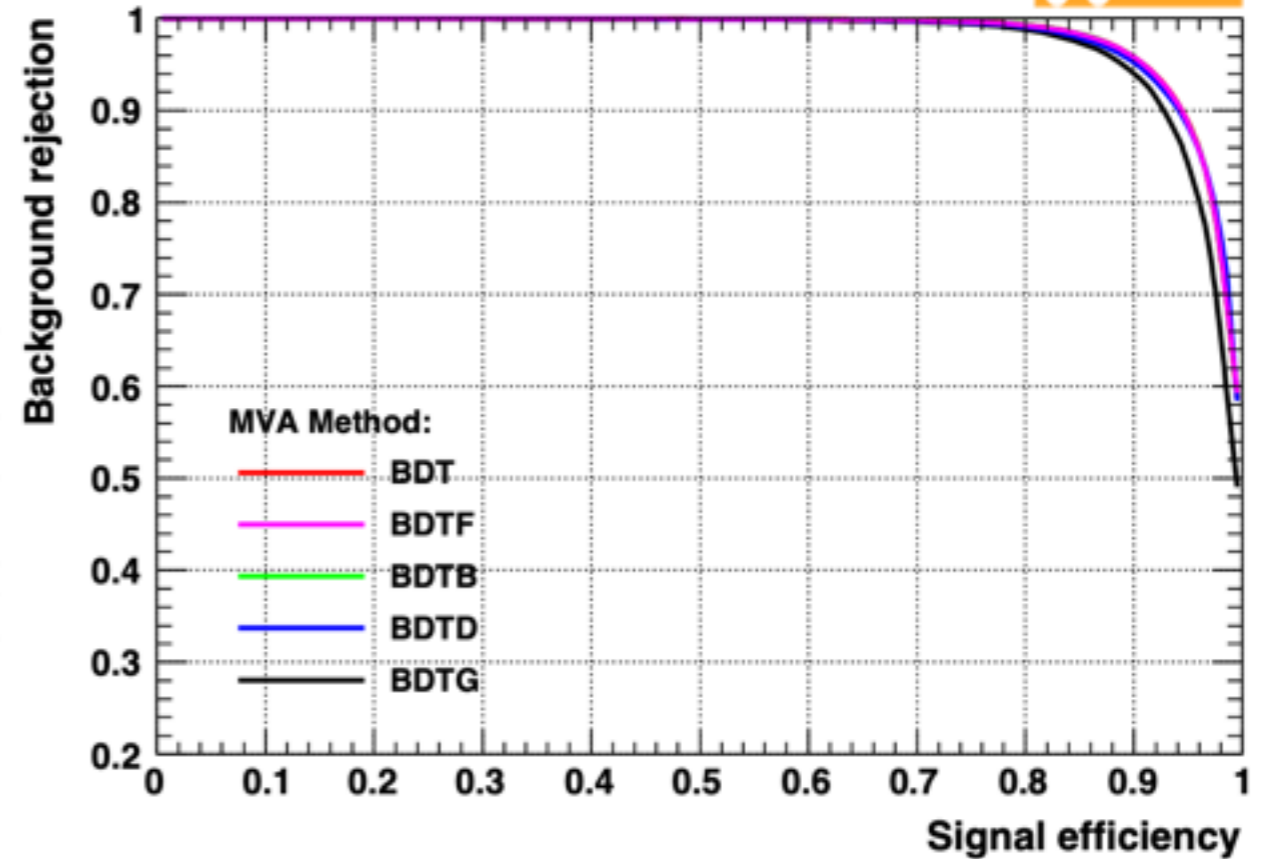
- “Simple” data :
 - (a) Hits on silicon detector units.
 - (b) Reconstruct tracks
 - (c) Reconstruct annihilation points.
- Old fashioned :
 - e.g. require >2 tracks for a “real” event vs. a cosmic ray event.
- MVA :
 - Lots of variables (e.g. curvatures, #tracks, overlaps, ...) -
 - use “pure” samples of annihilations (mixing) and background to train decision “tree” / “forest”.

Boosted Decision Trees

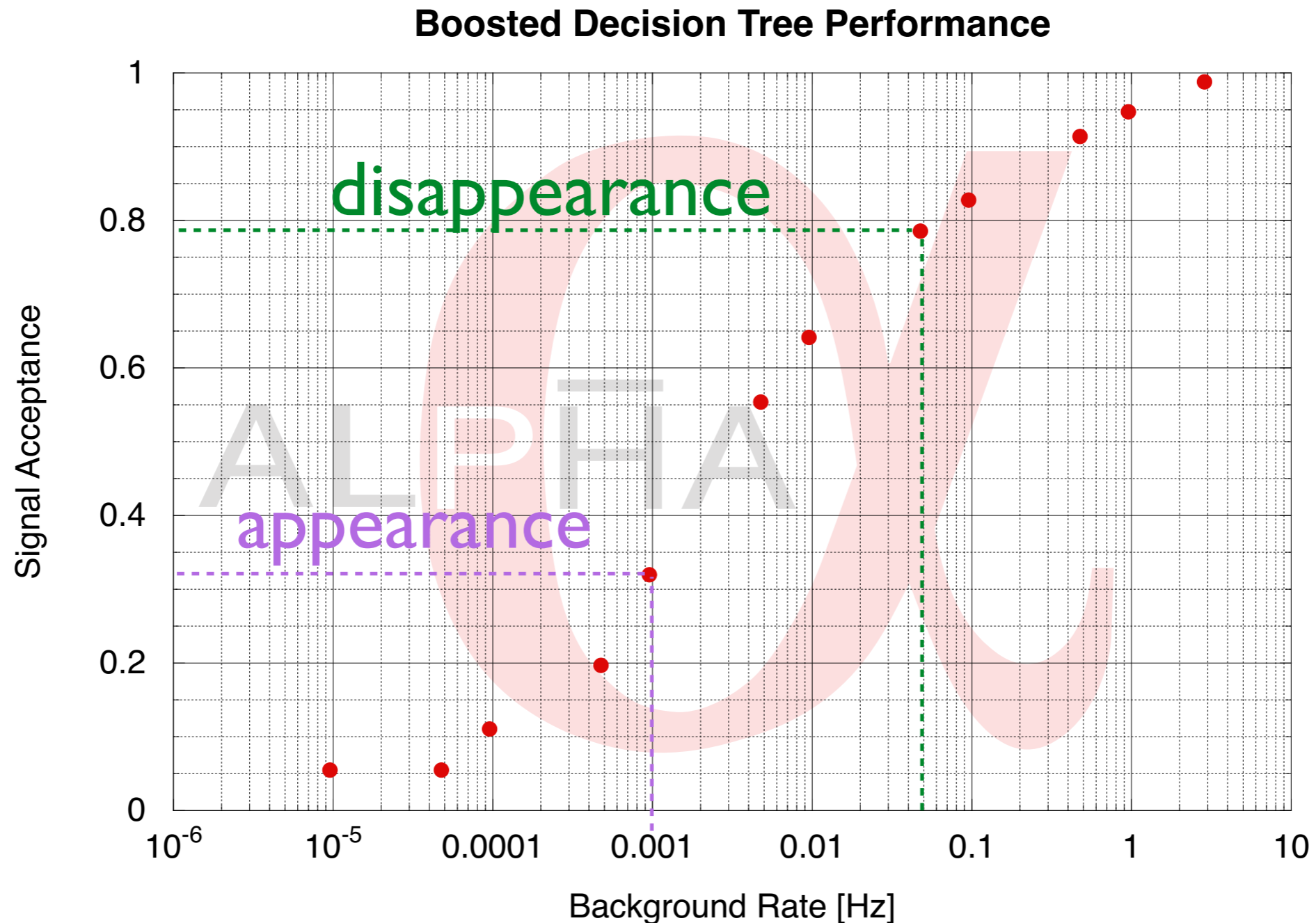
TMVA overtraining check for classifier: BDT



Background rejection versus Signal efficiency



Performance (on samples)



- Depending on experiment, we (first) choose the MVA that best matches circumstances

Disappearance

- Results from 11 trials (1.5s windows!)

Type	Detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No Laser	142	0.7	12

- On-Off differ by 92 ± 15 detected (58 ± 6)% removed. 47% predicted by simulation. (detector efficiency here is 0.688)

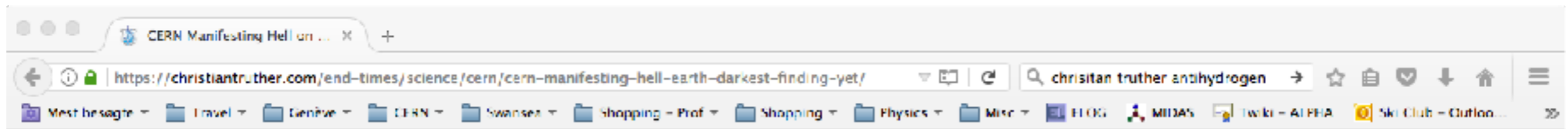
Appearance

- Window : **600s** laser exposure. (same trials)

Type	Detected events	Background	Uncertainty
Off resonance	27	28.4	5.2
On resonance	79	28.4	8.9
No Laser	30	28.4	5.5

- Difference on/off : 52 ± 10 .
(Detector efficiency here is 0.376)
- Budget: **antiatoms missing = $92/0.688 \cong 134$**
annihilations = $52/0.376 \cong 138$

No comment...



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End Times Science From Hell The CERN Files

CERN Manifesting Hell on Earth with Their Darkest Finding Yet

By Emily - 12/21/2016

14



Up until recently, scientists were in the dark regarding the composition of antimatter, but now researchers at CERN have shined a light on it.



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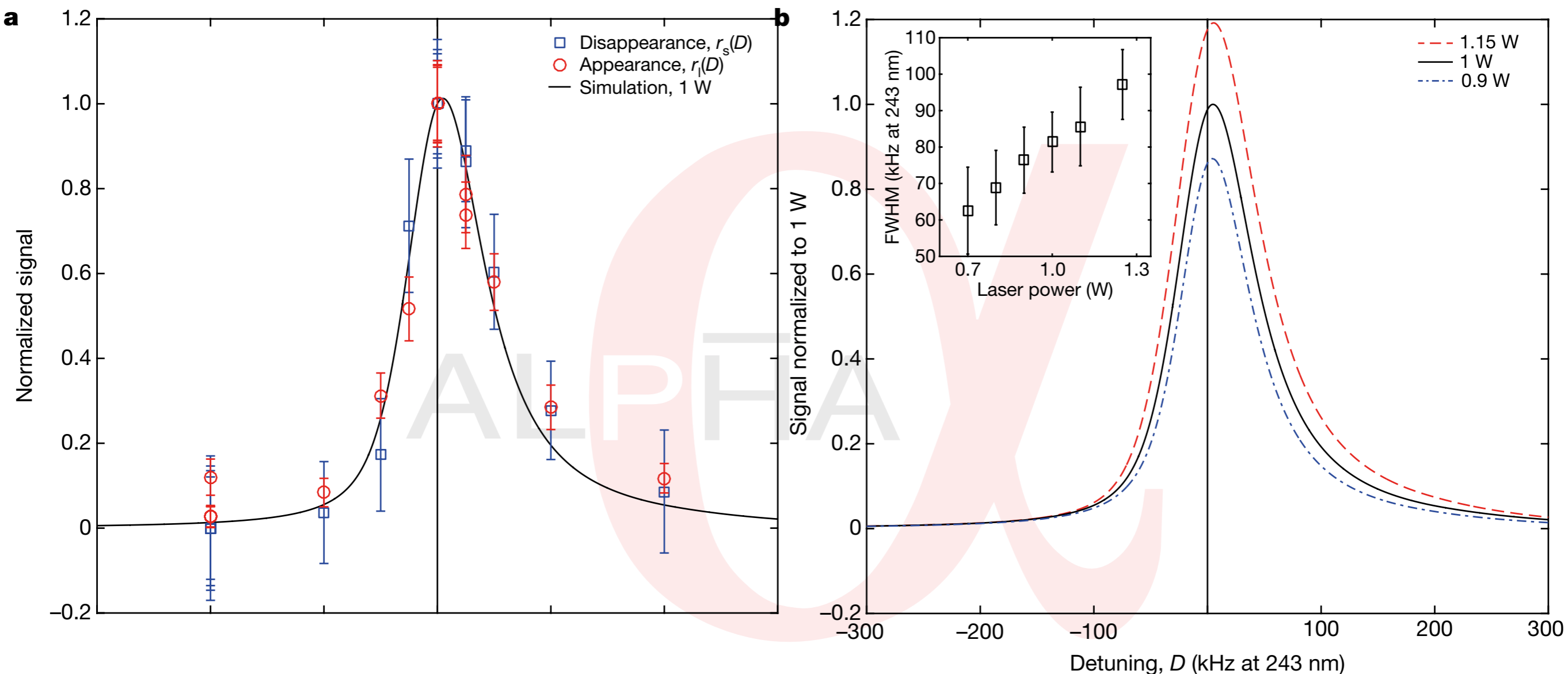
CERN's Frankenstein Science is Magnetically Conjuring Demons from the

1S-2S Lineshape

ALPHA



Spectral Lines of \bar{H}



- Appearance scaled response detuning D : $L(D)/L(0)$ ($L = \text{lost } \bar{H}$)
 Disappear.: $[S(-200\text{kHz}) - S(d)] / [S(-200\text{kHz}) - S(0)]$ ($S = \text{survived}$)
- Fit result: $P1 = 1135(50\text{mW})$, $P2 = 904(30)\text{mW}$, $P3 = 1123(43)\text{mW}$,
 $P4 = 957(31)\text{mW}$ and $df = -0.44 \pm 1.9\text{kHz}$ (@ 243nm)

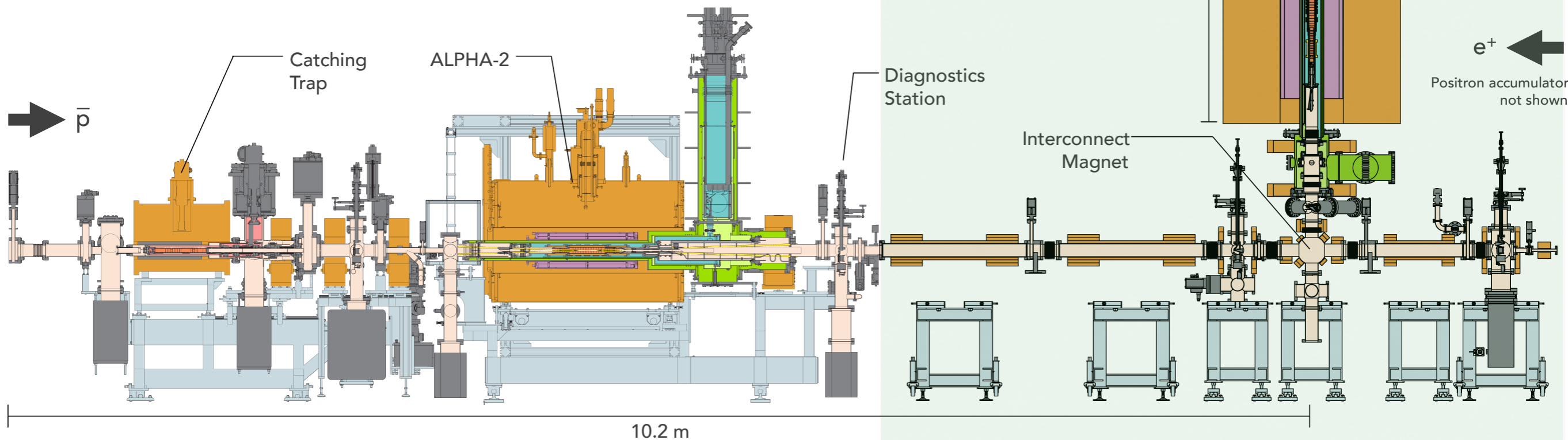
Result

- At a magnetic field of 1.03285(63) T :
- $f_{d-d}^{\text{exp}} = 2,466,061,103,079.4(5.4)$ kHz
- $f_{d-d}^{\text{calc}} = 2,466,061,103,080.3(0.6)$ kHz
- Consistency to 2×10^{-12}
- Hydrogen precision state of the art : 4.2×10^{-15}
- Used ~ 15000 antihydrogen atoms.
- The most precise and accurate measurement on antimatter to date.

ALPHA-g addition

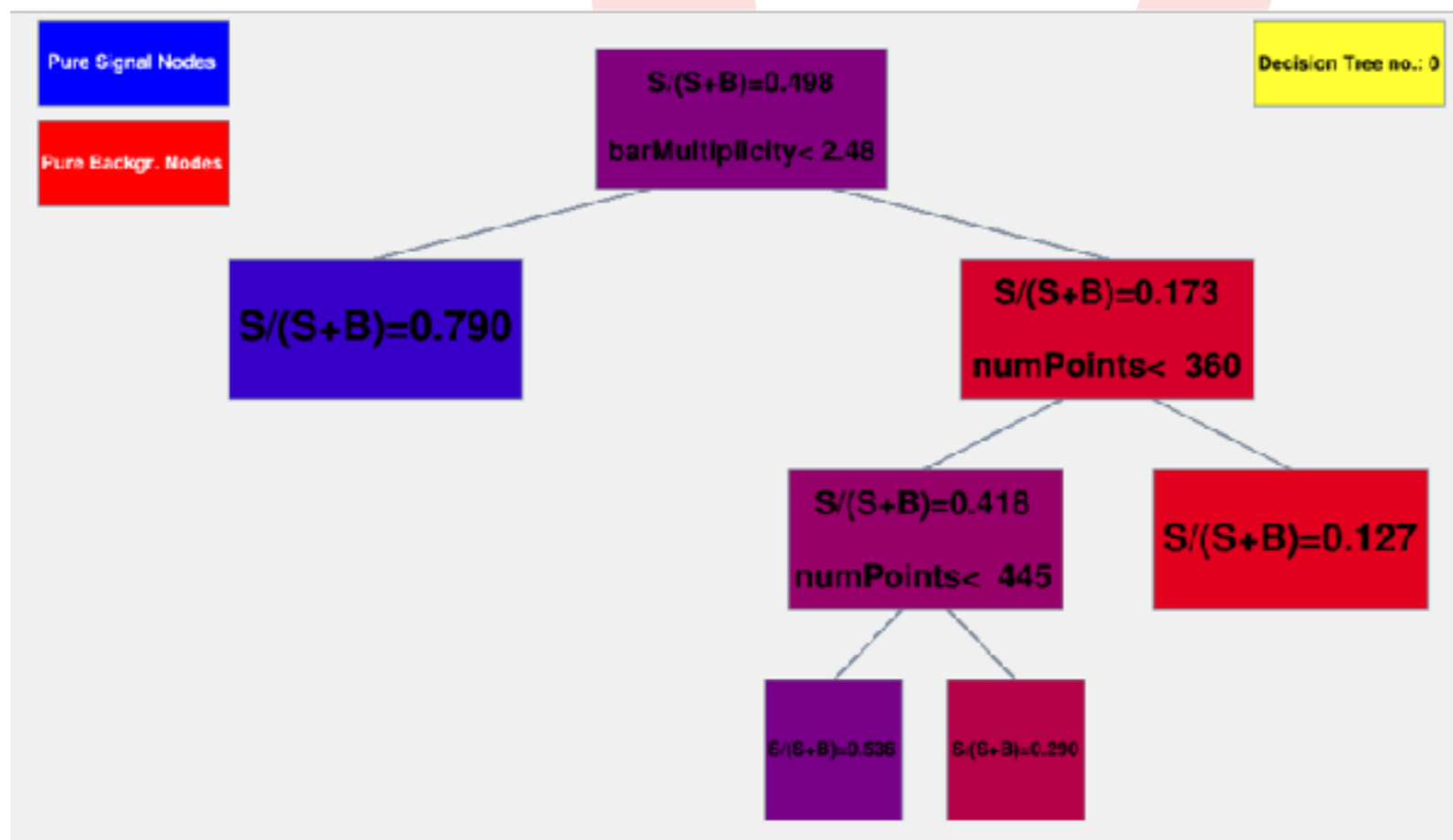
Addition of gravity experiment (vertical trap)
 e^+/\bar{p} beamline needs

- Magnets
- UHV Space
- Physical Supports
- Electrodes under UHV
- Outer Vacuum Chamber (OVC)
- OVC (Heat Shielded)
- Liquid Helium Space
- TPC / Silicon Detector Volumes

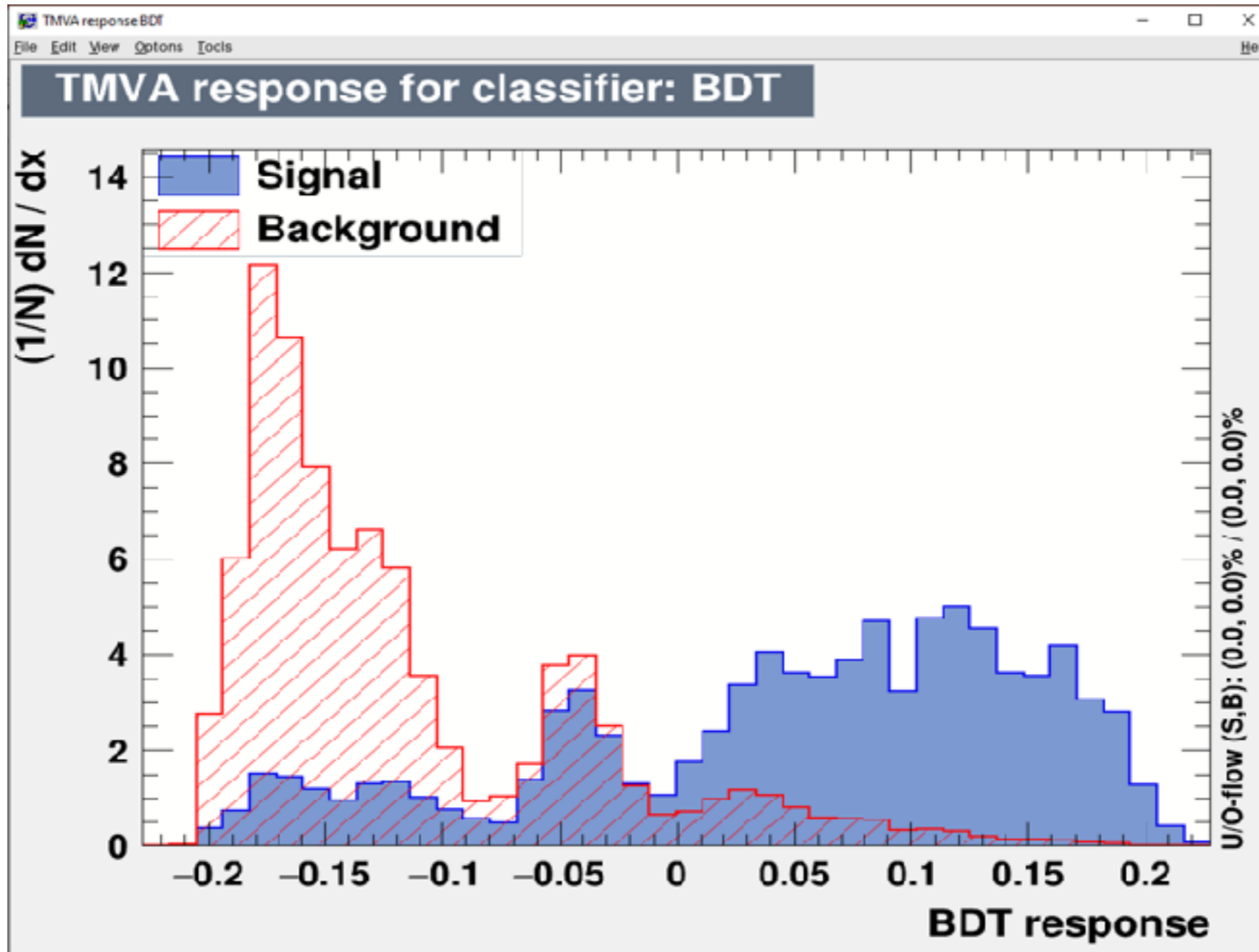


A-g new detectors

- Two detectors :
 - Radial Time Projection Chamber (wire chamber)
 - Barrel Scintillator detector
 - Large solid angle for cosmic rays...
- BDT example



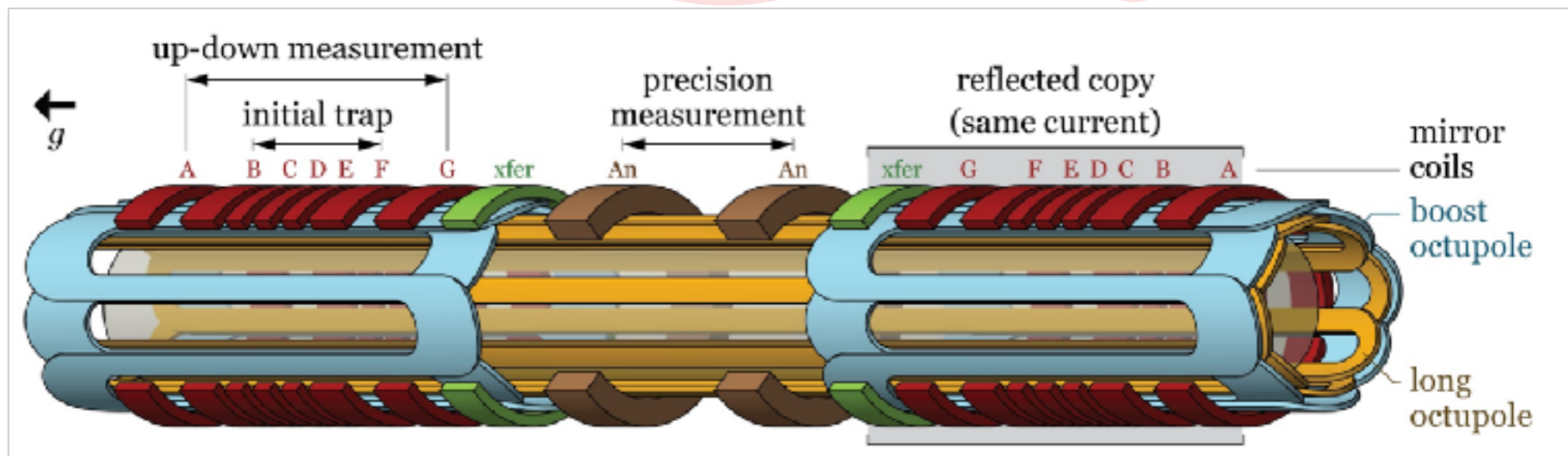
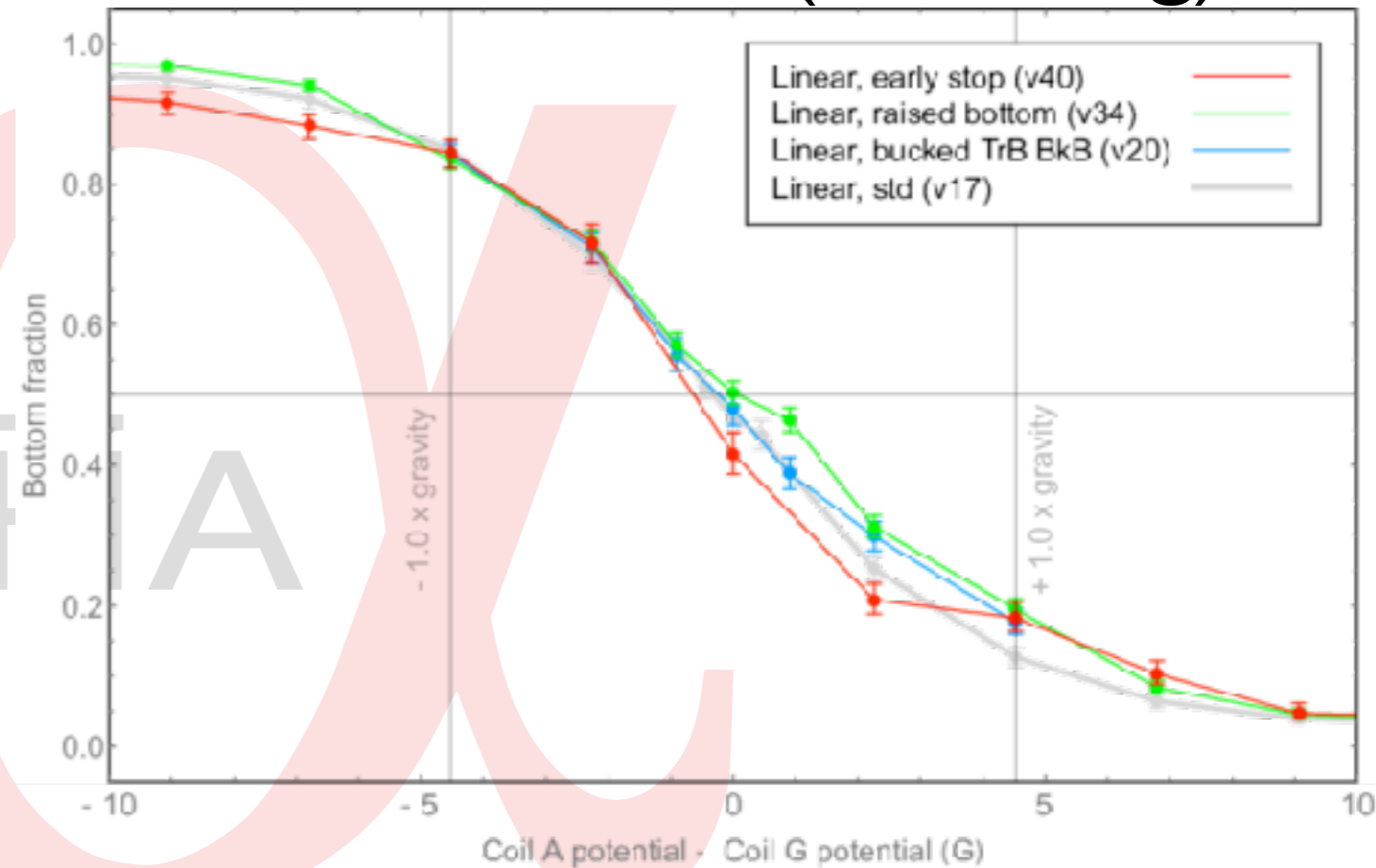
BDT Response (ex.)



Gravity Experiment (live!)

Simulations (normal g)

- Trap Antihydrogen in vertical trap
- Slowly (20s) lower the vertical walls of the trap to let them escape.



More is done/coming...

- GS Hyperfine splitting (Nature **548**, 66 (2017))
- 1S-2P transitions (Nature **561**, 211 (2018); Nature **578**, 375 (2020))
- Laser-cooling of Antihydrogen 1S-2P (Nature **592**, 35 (2021))
- Sympathetically cooled positrons (Nat. Com. 12, 6139 (2021))
- Higher precision measurements (improved metrology and statistics) - and more states (to extract fundamental consts.)
- Gravity measurements ongoing - hoping for some results in the last few weeks of beamtime

Thank you
for listening!



wessington
CRYO
CH-1000

ALPHA

