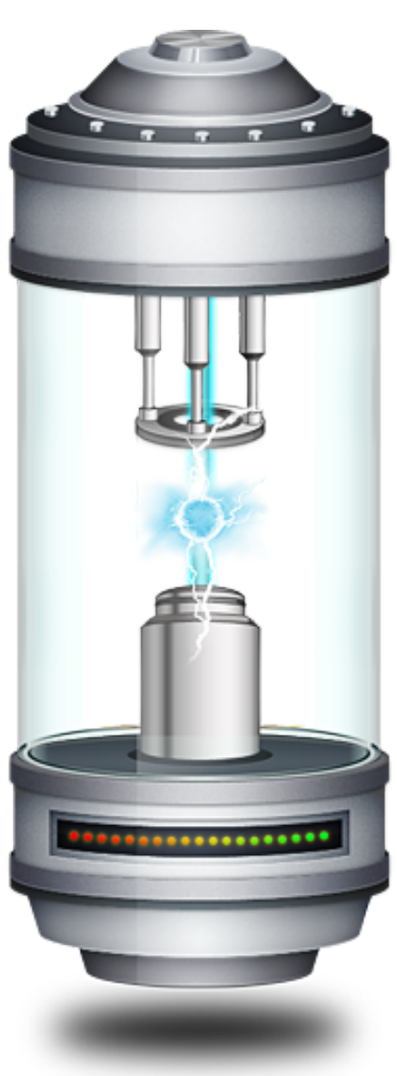
⚠ CAUTION

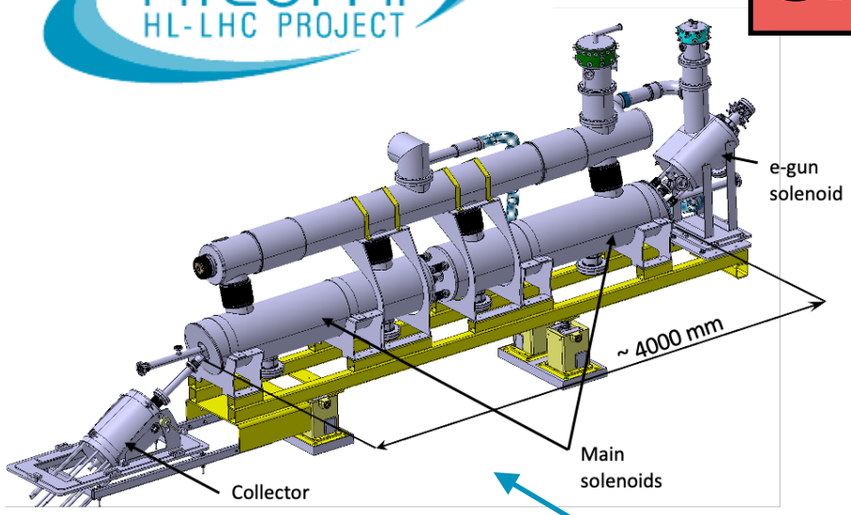
ANTIMATTER IS SENSITIVE TO LIGHT AND VIBRATIONS

PLEASE SILENCE YOUR PHONES AND AVOID FLASH PHOTOGRAPHY IF POSSIBLE



SAMEED MUHAMMED

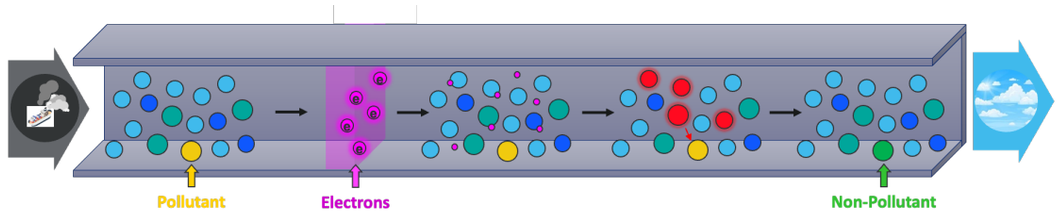
HiLumi HL-LHC PROJECT

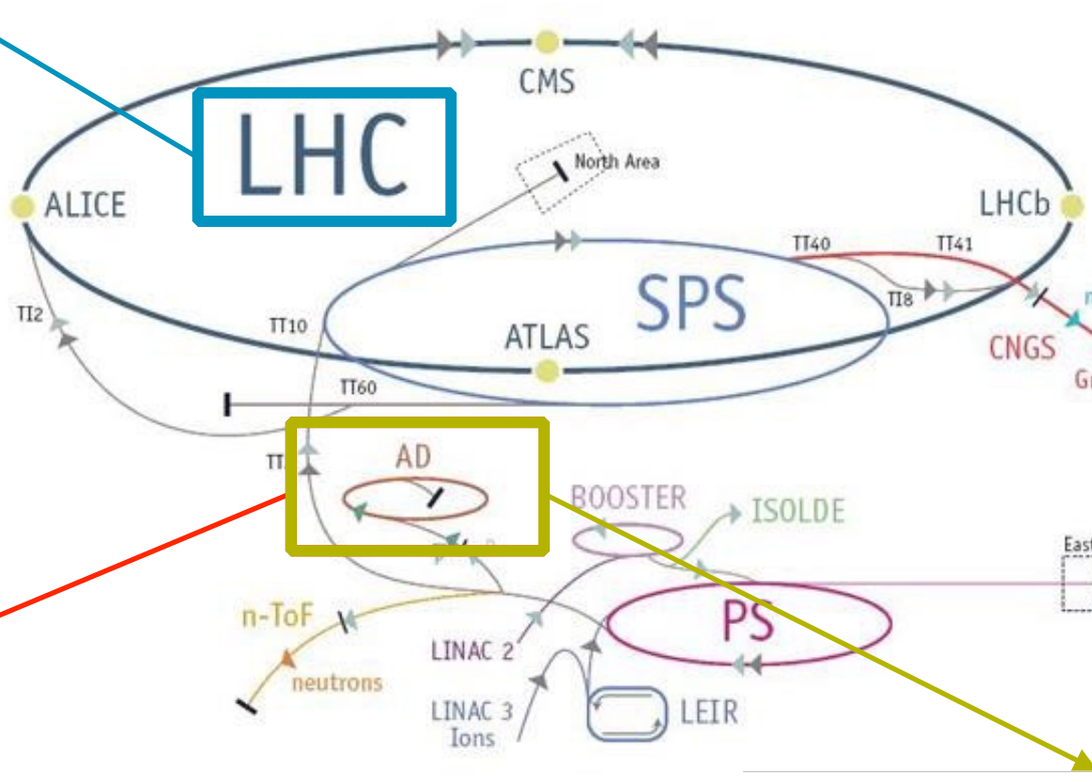


CERN

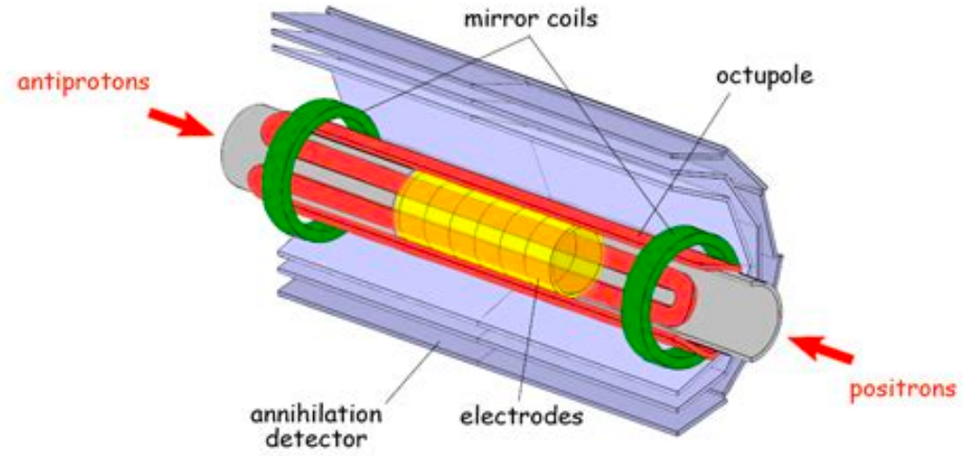
UTMOST CLEEN

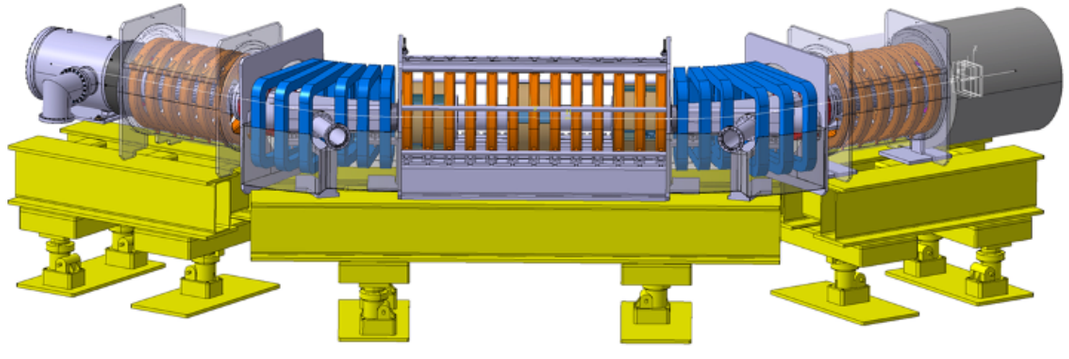
CERN technology





ALPHA





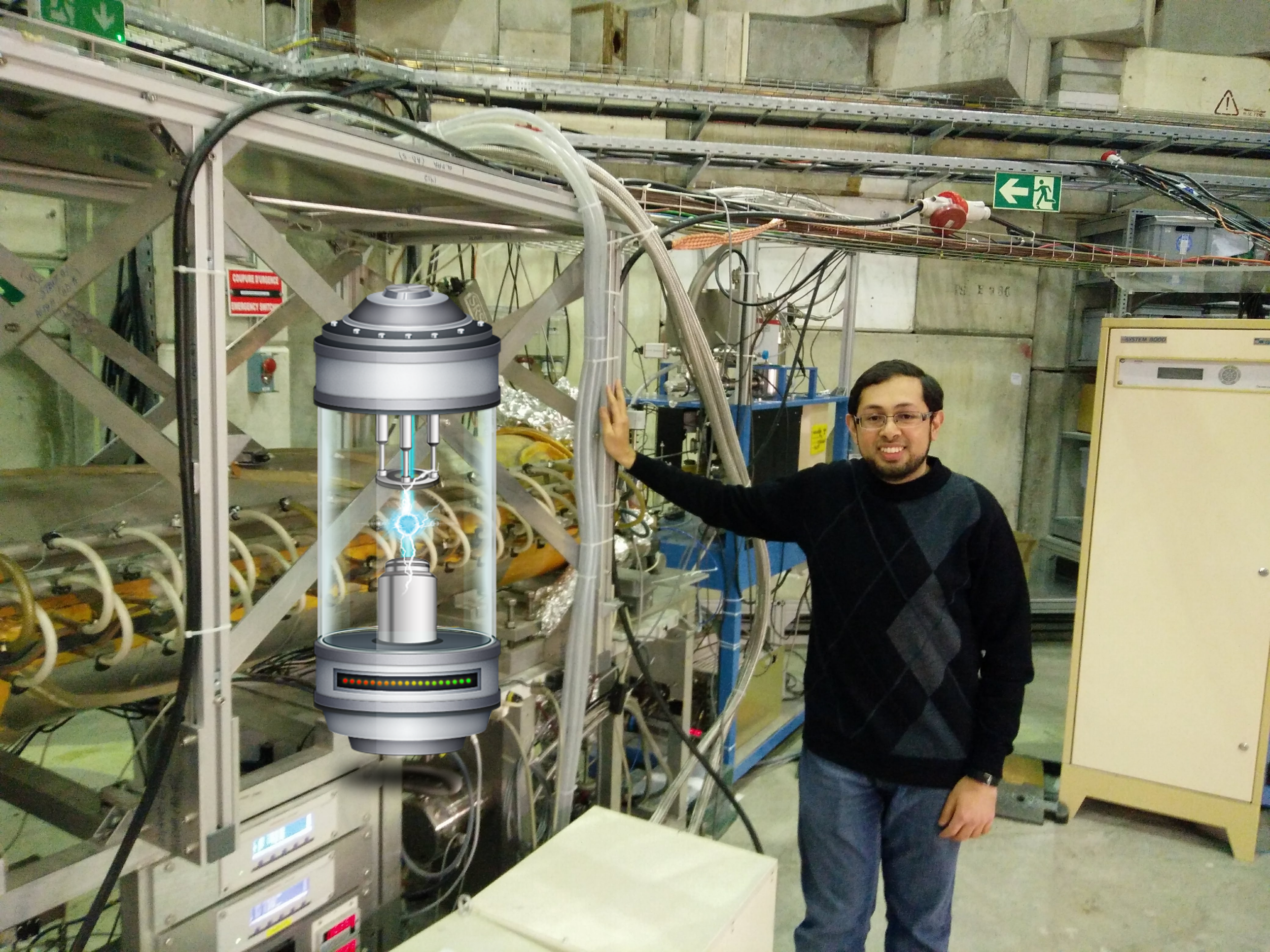
Islamabad

2007 - 2011
Cornell University (USA)

2011 - 2012
KAUST (Saudi Arabia)

2013 - Present
CERN (Switzerland)

ANTIMATTER FACTORY



WHAT'S THE MATTER WITH ANTIMATTER?

VIDEO OF THE

FIRST DISCOVERY

OF

ANTIMATTER

Highlights

- Antimatter is real
- We can create and trap antimatter
- We can see and study antimatter (with our detectors)
- We can use antimatter (for example in medical imaging)
- Antimatter physics is really cool and really fun!

WHAT IS MATTER?

WHAT IS MATTER?

Quarks

Up

Charm

Top

Down

Strange

Bottom

Leptons

Electron

Muon

Tau

Electron Neutrino

Muon Neutrino

Tau Neutrino

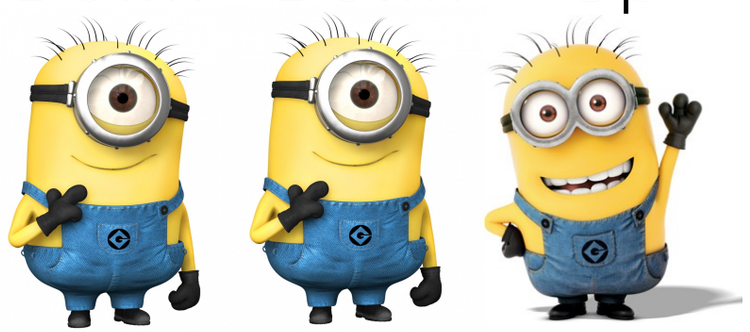
WHAT IS MATTER?

Quarks

Up Up Down

= p

Down Down Up

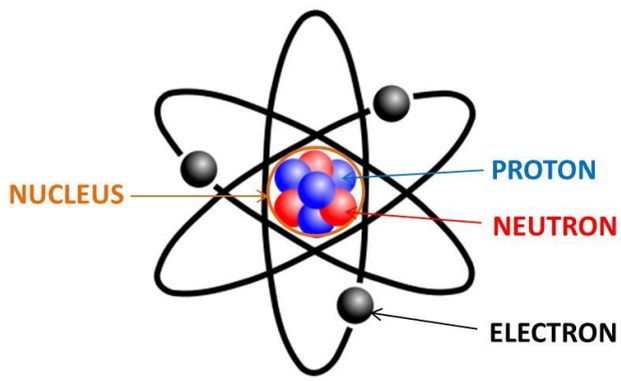


= n

Leptons

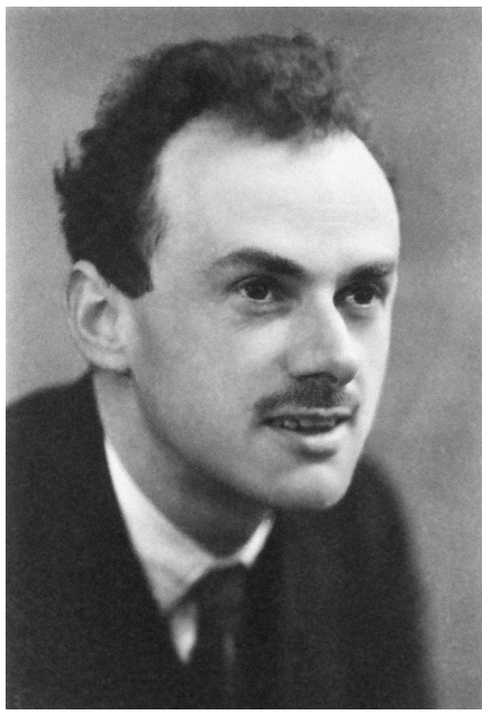
Electron

-



SO, WHAT IS ANTIMATTER?

Paul Dirac (1928)



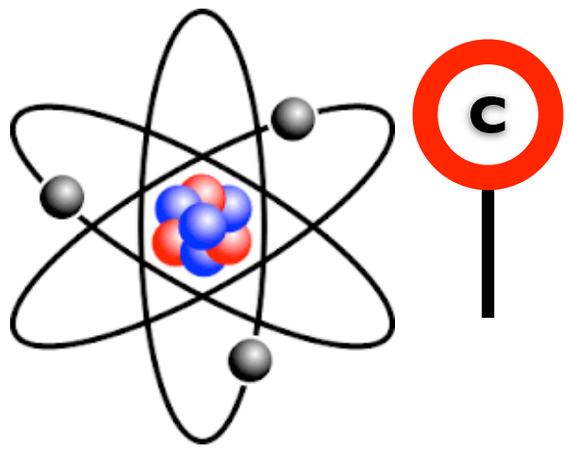
Quantum Theory

+

Special Relativity

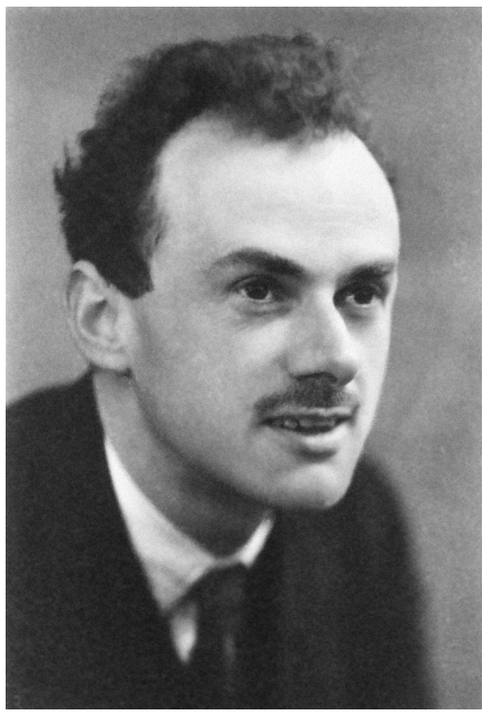
↓

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$



SO, WHAT IS ANTIMATTER?

Paul Dirac (1928) **Carl Anderson (1932)**



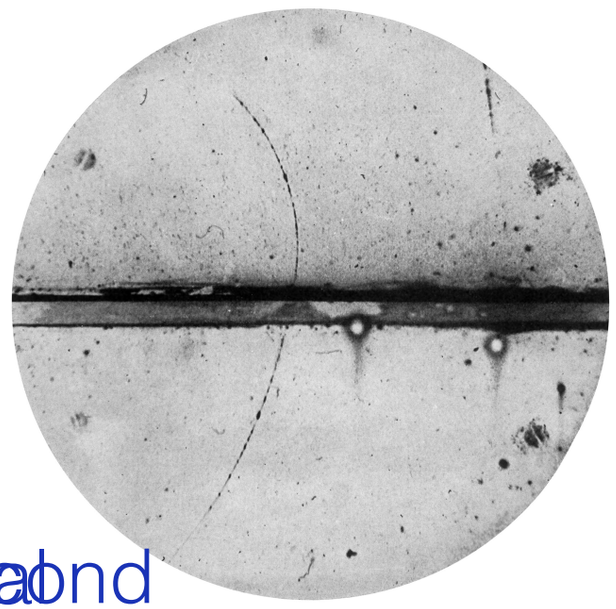
2 solutions!

+ solution -> electron

- solution -> unphysical

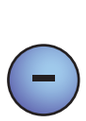
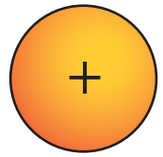
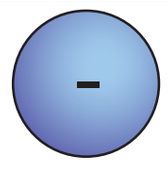
$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

…this means **anti-electron**!

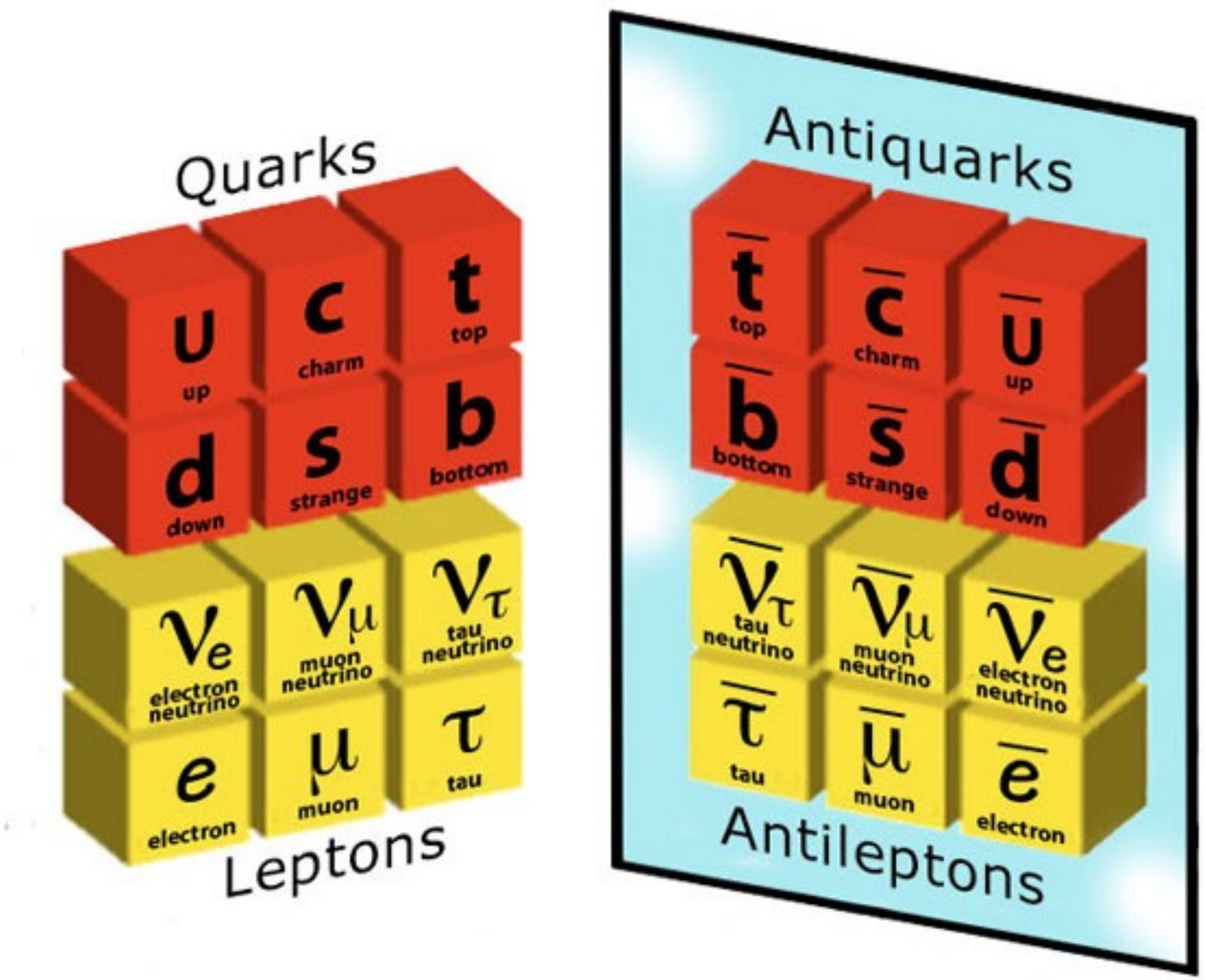


SO, WHAT IS ANTIMATTER?

- Matter particles have "twins" with same mass, but opposite charge

	Electron	Proton
Matter:		
	e^-	P
Antimatter:	Positron 	Antiproton 
	e^+ (1932)	$\bar{P}$ (1955)

SO, WHAT IS ANTIMATTER?



same mass

same spin

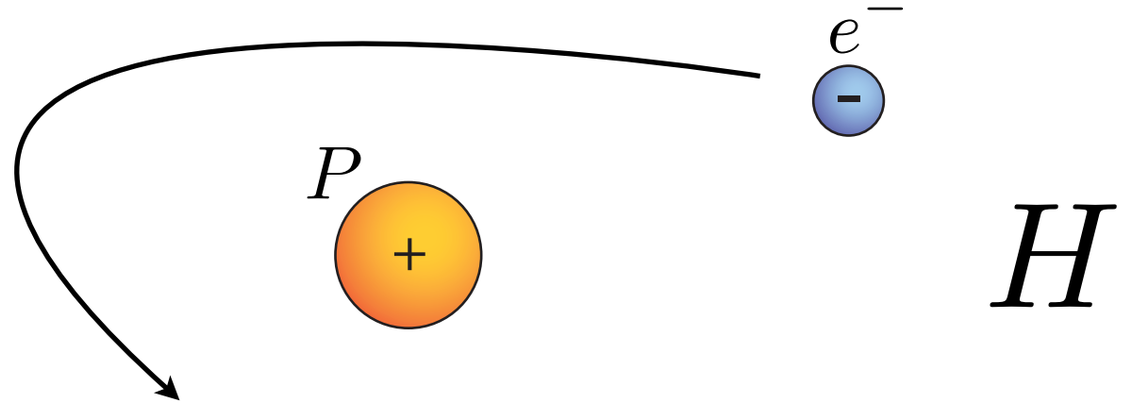
opposite charge

SO, WHAT IS ANTIMATTER?

- Neutral (anti)atoms

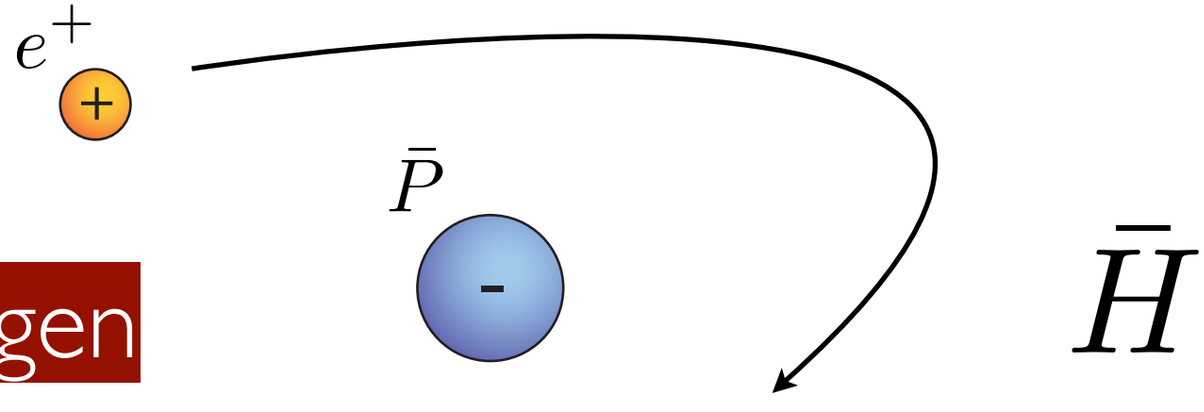
Matter:

Hydrogen



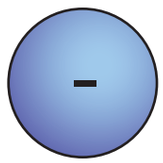
Antimatter:

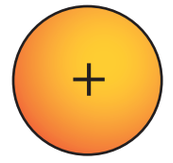
Antihydrogen



WHEN MATTER MEETS ANTIMATTER…

Watch Out!

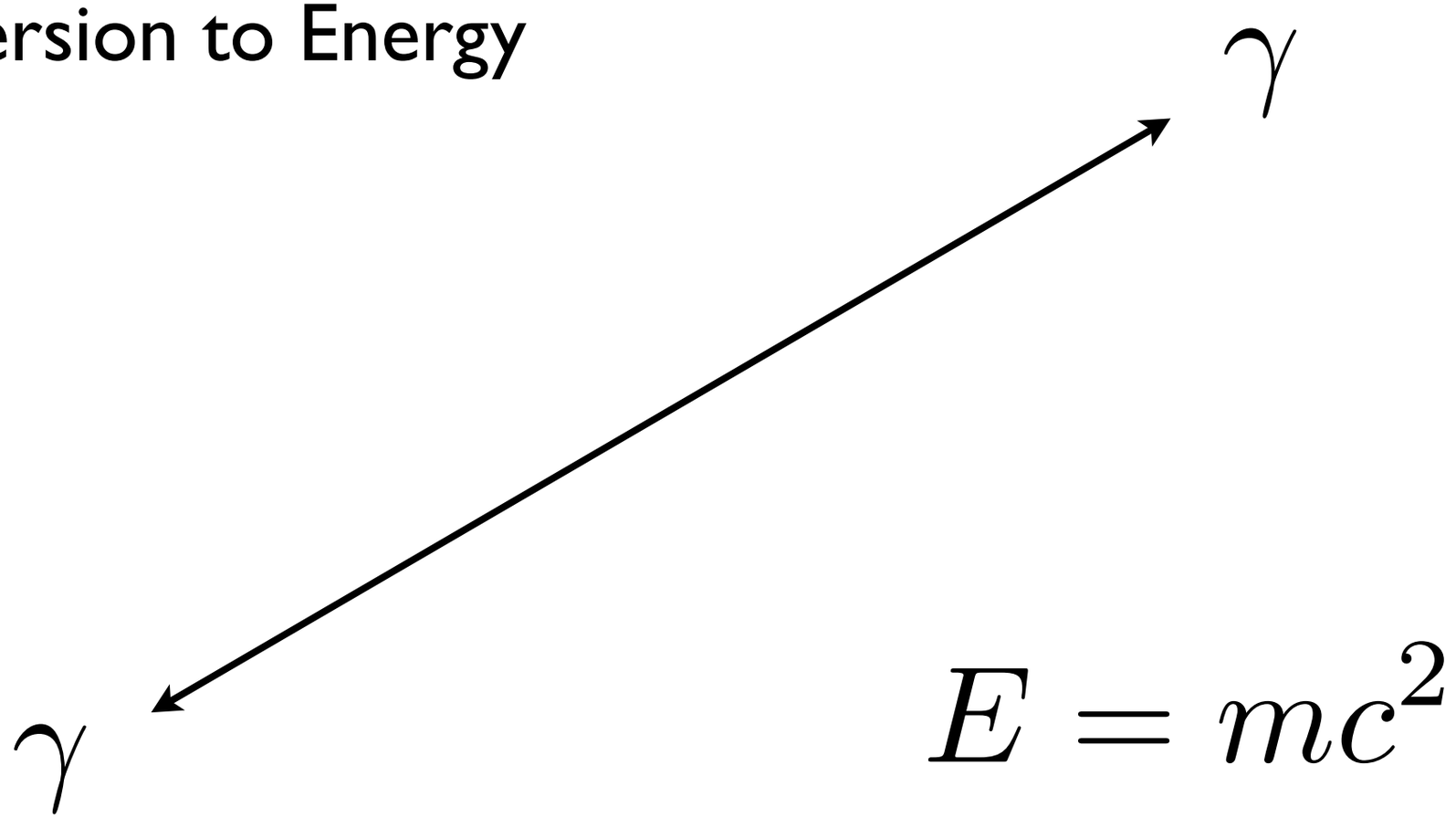




WHEN MATTER MEETS ANTIMATTER…

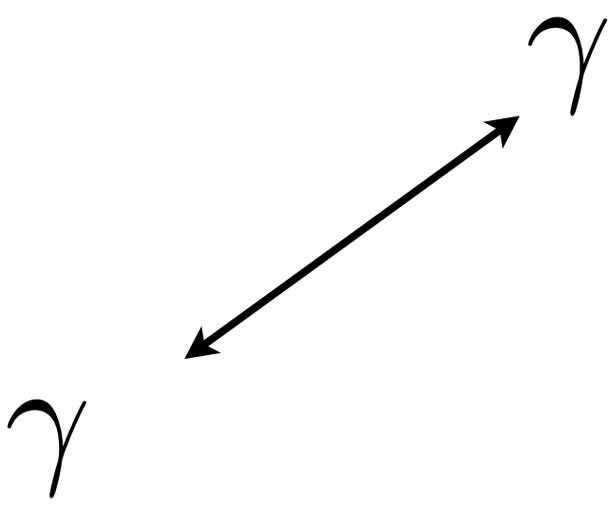
Watch Out!

- Annihilation!
- Conversion to Energy

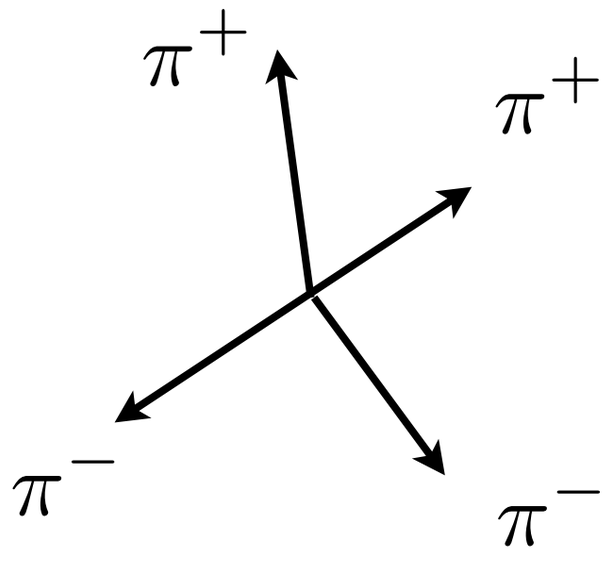


WHEN MATTER MEETS ANTIMATTER…

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

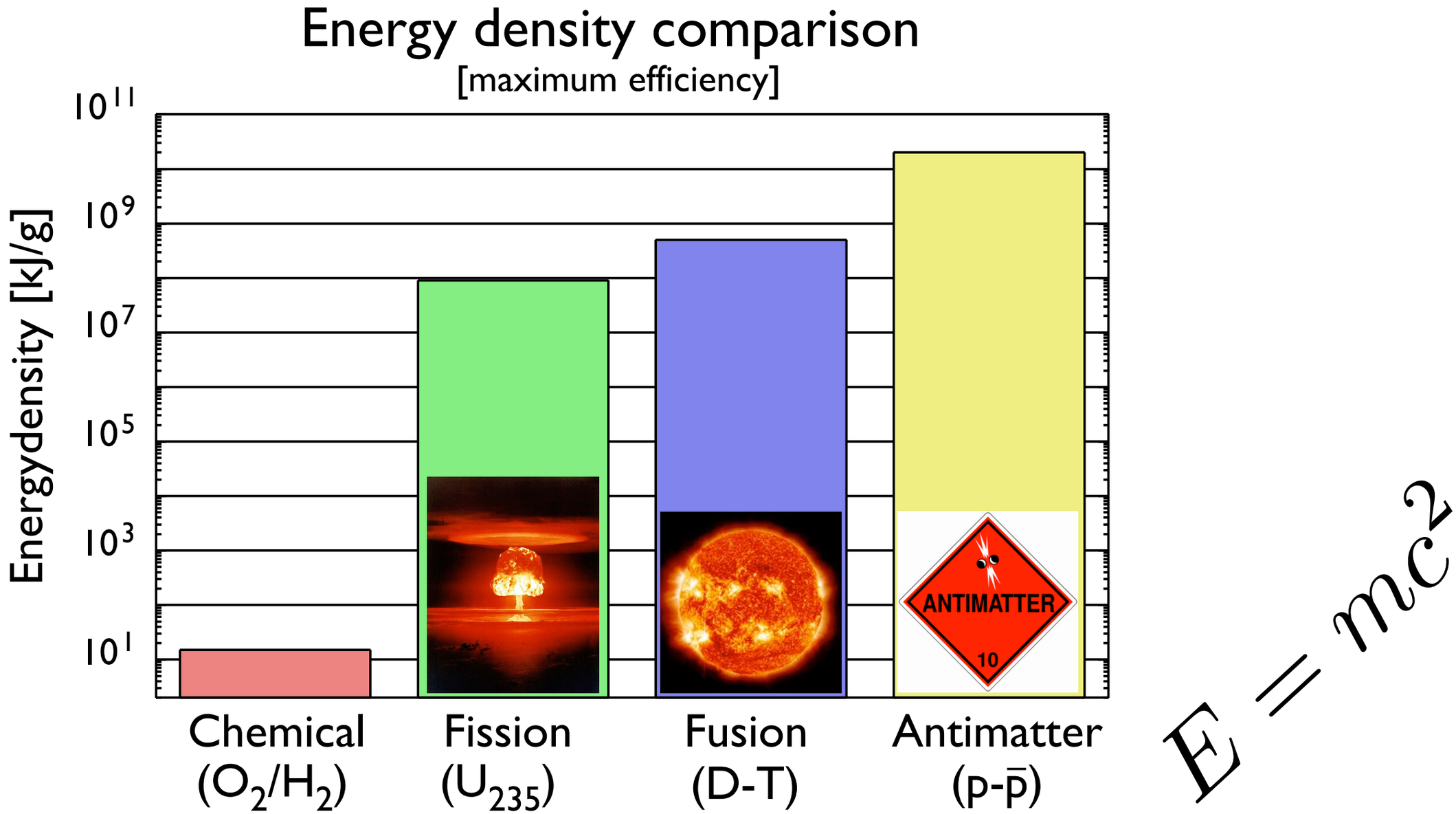


positron / electron
Annihilation



proton / antiproton
Annihilation

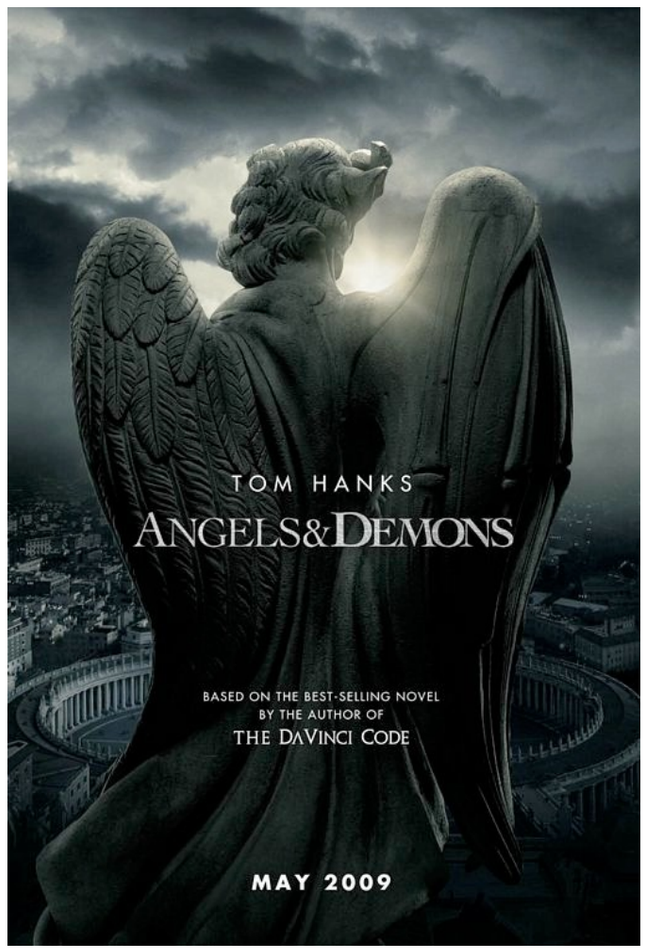
HOW MUCH ENERGY IS THERE IN ANTIMATTER?



$$E = mc^2$$

HOW TO USE ENERGY FROM ANTIMATTER?

- Starships? - need “only” 1 ton to go to alpha centauri!
- Bombs? - need “only” 1/4 g to blow up the Vatican!



HOW MUCH ENERGY IS THERE IN ANTIMATTER?

10 grains of (anti)rice = 0.25 grams

$E = 2\ mc^2 = 2\ (0.25 \times 10^{-3})(3 \times 10^8)^2$ = 45 Trillion Joules

1 kiloton of TNT = 4.2 Trillion Joules

10 grains of rice + 10 grains of anti-rice = 10 kiloton of TNT

atomic bomb dropped on Hiroshima = 14 kiloton of TNT

and contained 64kg of enriched uranium!

More than enough to destroy the Vatican City!

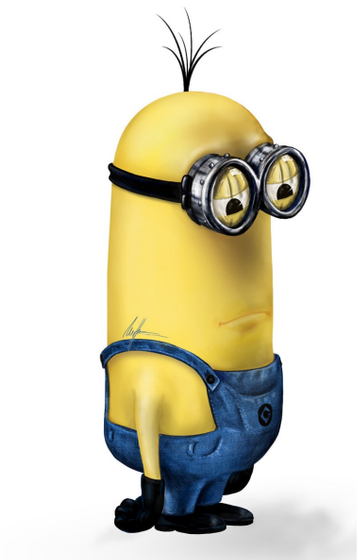
How long before we have an Antimatter Bomb?

TIME AND COST OF PRODUCING ANTIMATTER

~30 Million antiprotons every 2 minutes

In order to create 0.25 grams, we just need to wait…

20 Trillion Years!!!!!!!!!

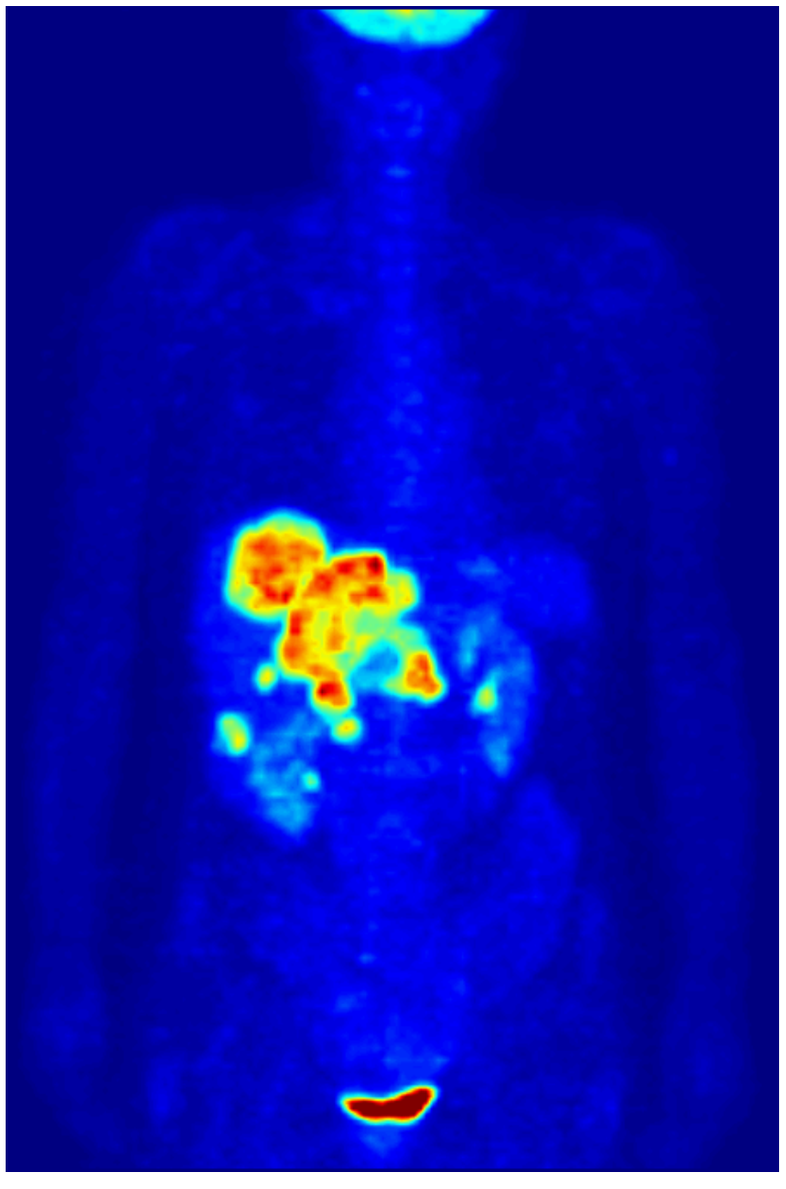


Antimatter NOT a viable weapon! :)

Antimatter NOT a future energy source!

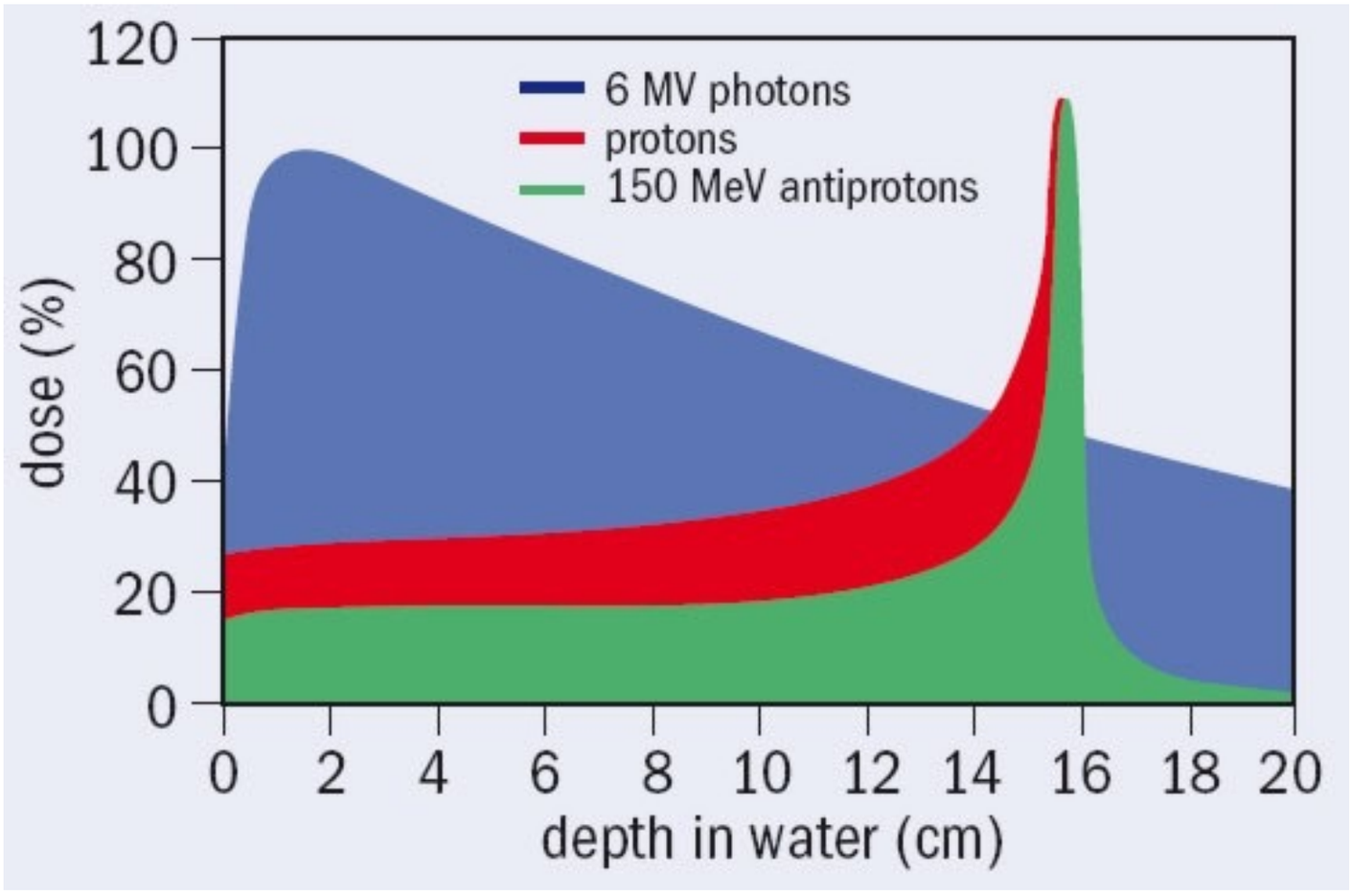
WHAT IS ANTIMATTER USED FOR?

POSITRON EMISSION TOMOGRAPHY (PET) SCAN



ANTIPROTON RADIATION THERAPY

Antiproton Cell Experiment (ACE) at CERN



Plot of energy deposited by different forms of radiation

- antiprotons four times as potent as protons
- clinical applications still many years away

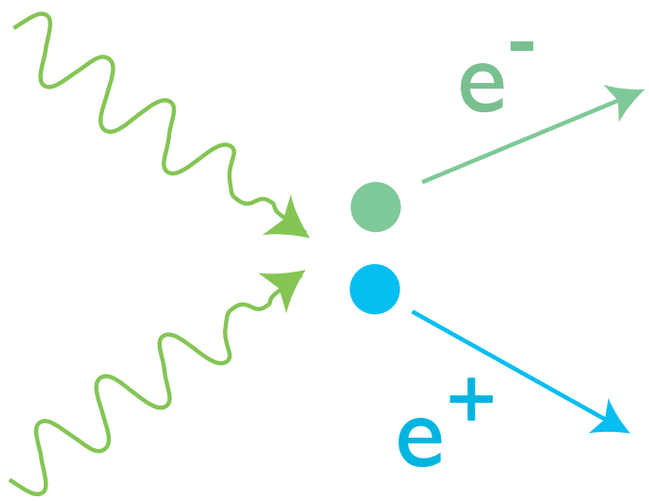
CAN WE ALSO USE ANTIMATTER TO SOLVE SOME OF THE PUZZLES OF THE UNIVERSE?

THE PUZZLE

- Annihilation is symmetric - like a mirror image.

- So is pair-production (the opposite process).

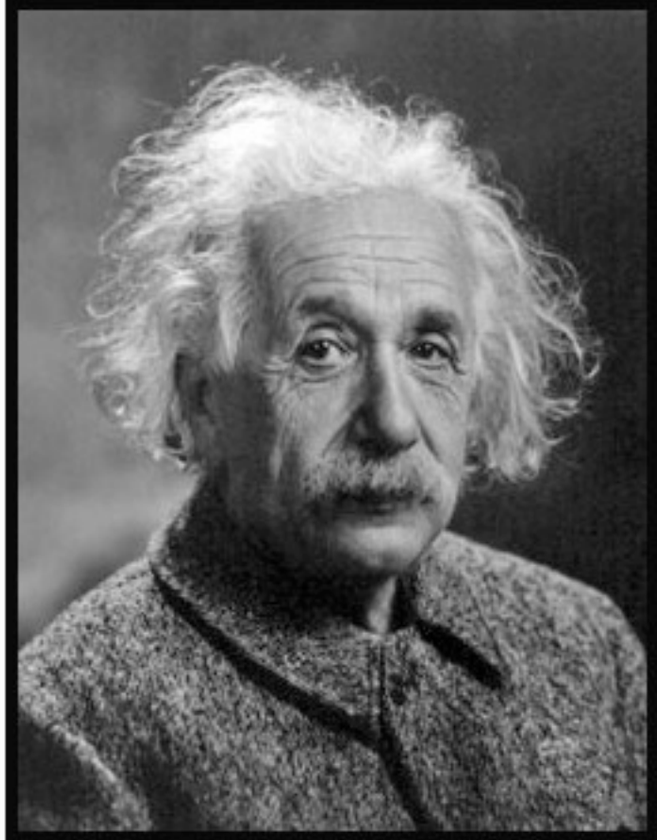
E = 2x511 keV



E = 2x511 keV

- The Universe started from energy, the big bang… so there should be equal amounts matter & antimatter… but there isn't… and it's worse...

Fraction of Antimatter in the Visible Universe?



On the big Bang theory: For every one billion particles of antimatter there were one billion and one particles of matter. And when the mutual annihilation was complete, one billionth remained - and that's our present universe.

(Albert Einstein)

Going through the looking glass…

We need to determine what, if anything is different about antimatter…

INVESTIGATING THE ANTIMATTER WORLD

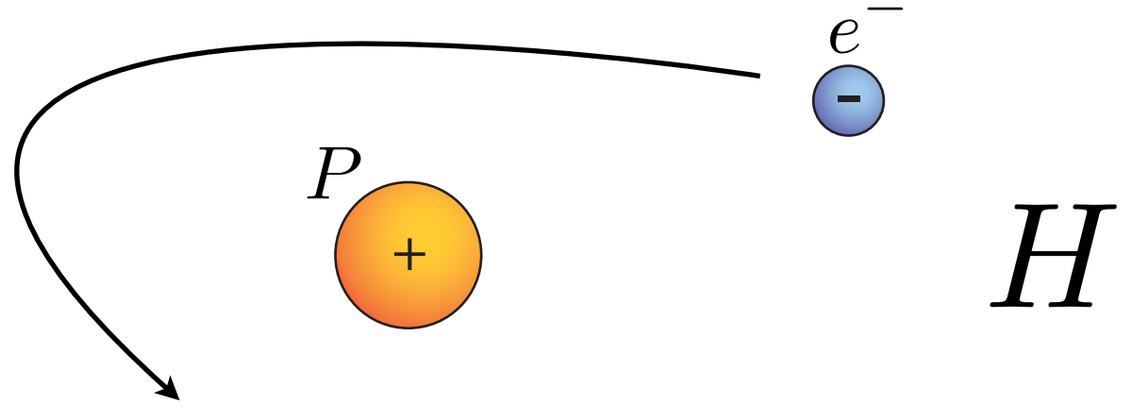
- Scientists are looking at antiparticles individually, like positrons, antiprotons, etc.

- But we are also looking at more complex antimatter systems, like **anti-atoms…**

THE SIMPLEST (ANTI)ATOM

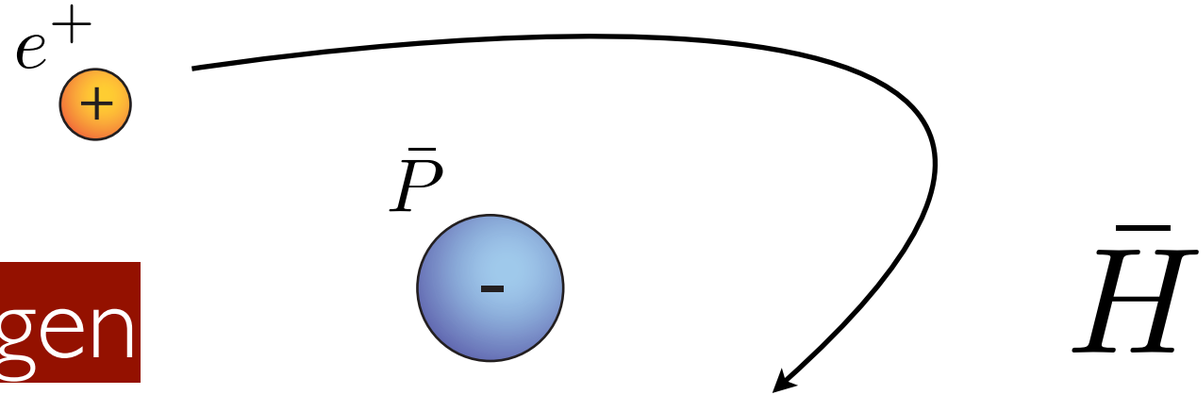
Matter:

Hydrogen



Antimatter:

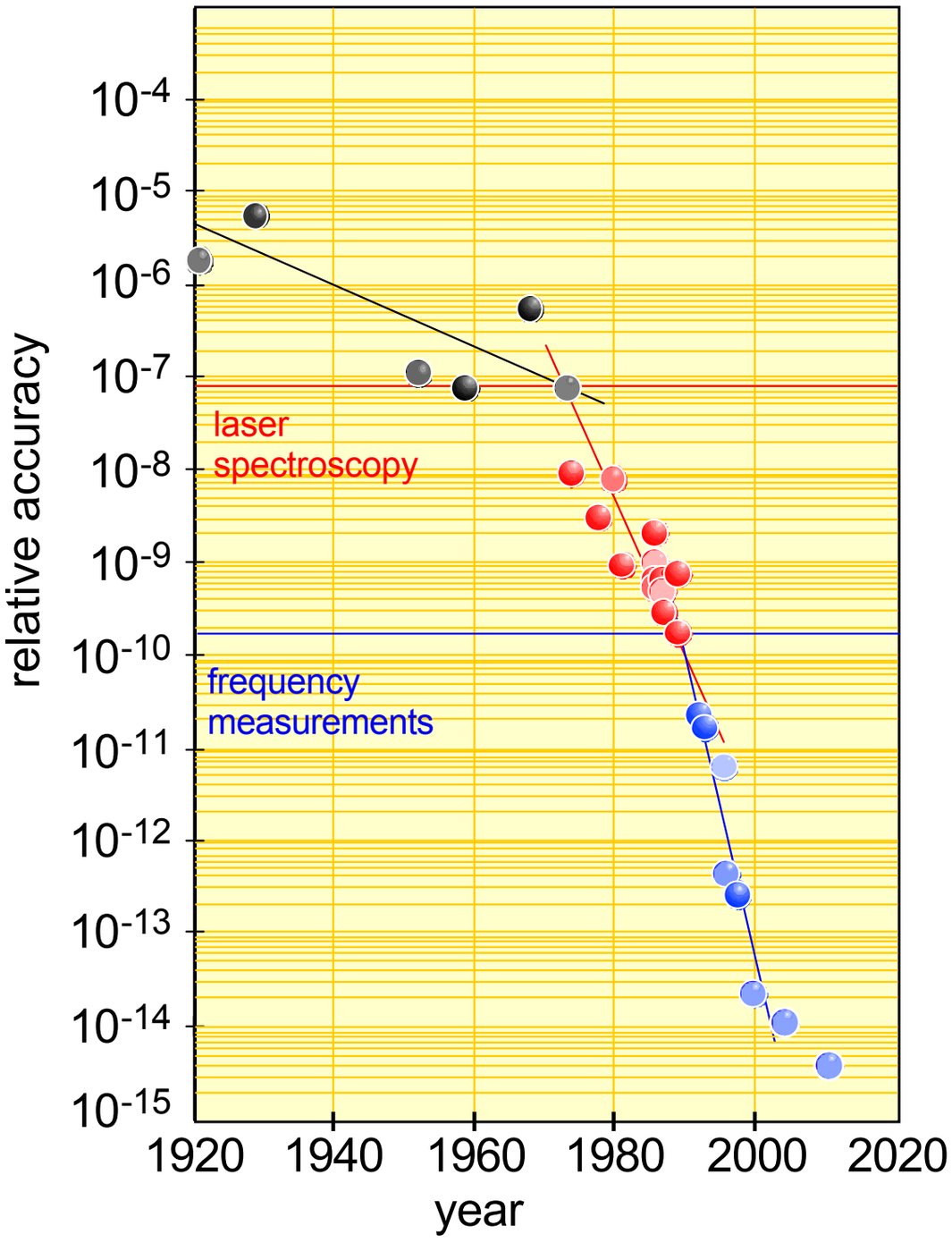
Antihydrogen



WHY IS ANTIHYDROGEN IMPORTANT?

- Only pure antimatter system so far
- Antihydrogen is neutral
- High-precision comparisons with hydrogen

ANTIHYDROGEN SPECTROSCOPY



- H-$\bar{\text{H}}$ comparison by 1s-2s two photon spectroscopy.

Motivation for 1S-2S Spectroscopy

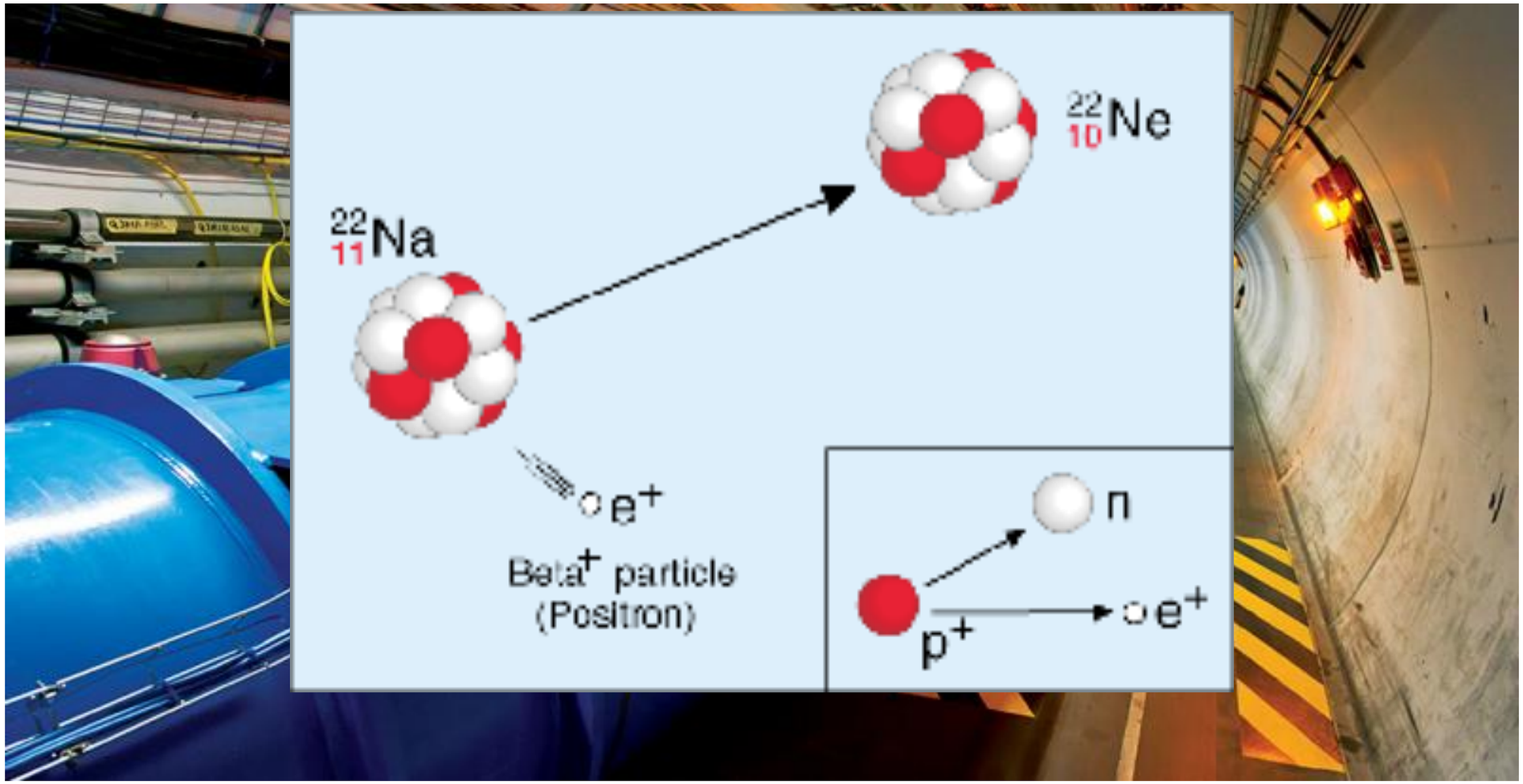
- The 1S-2S transition frequency in hydrogen is one of the most precisely measured numbers in physics:

$$f_{1S-2S} = 2466061413187035(10)\ \text{Hz}$$

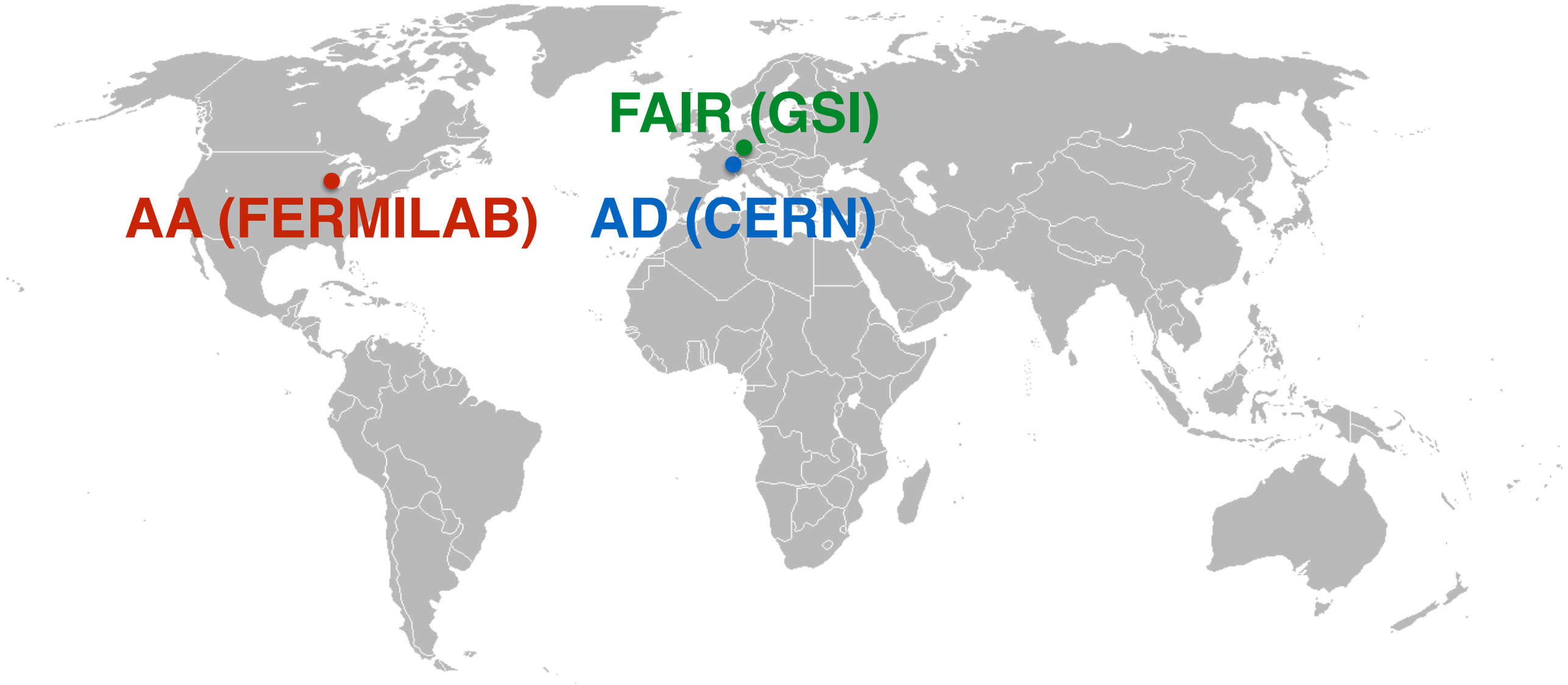
LET'S MAKE SOME ANTIHYDROGEN!

- Positrons: β^+ decay from a radioactive source

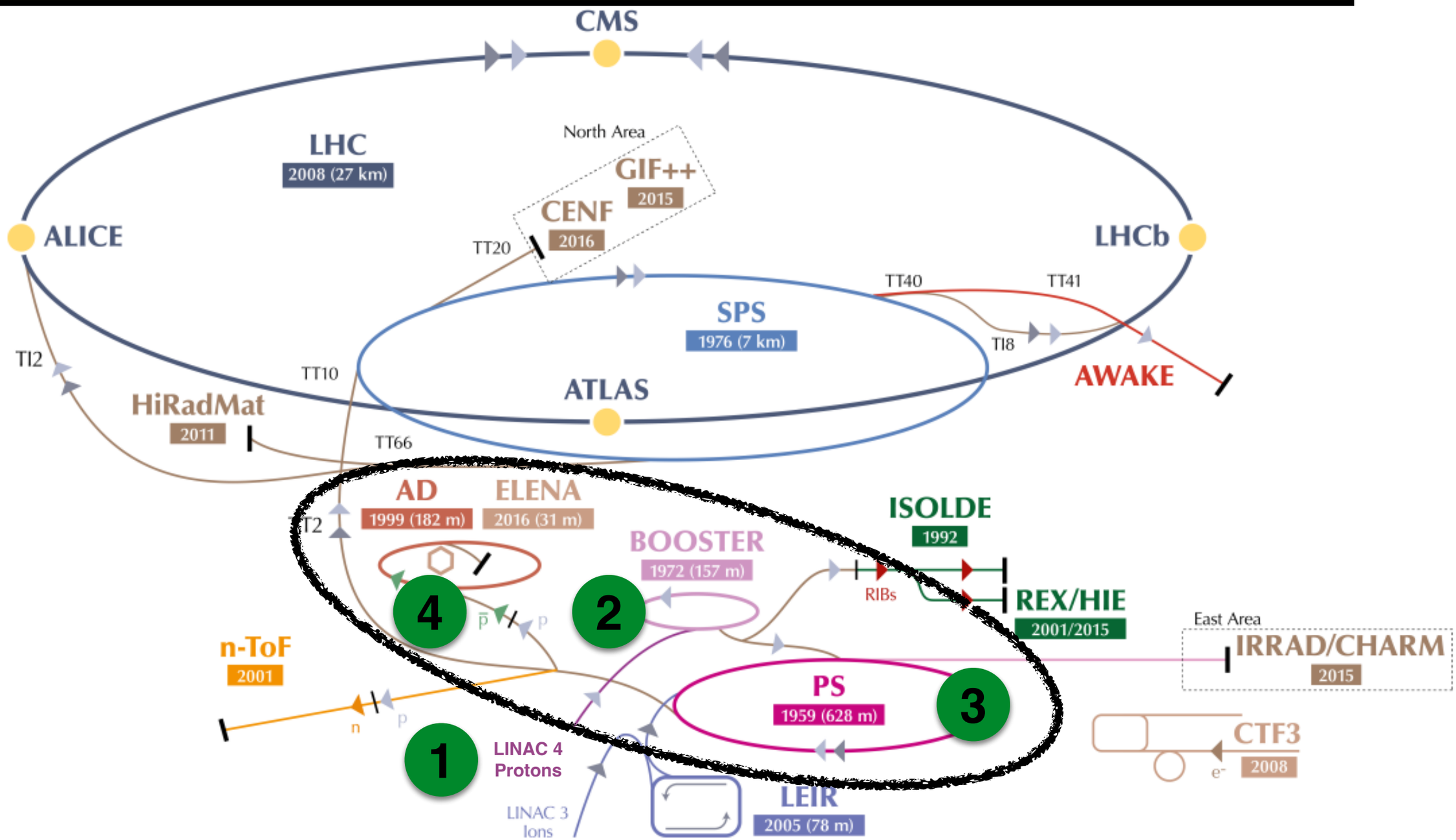
- Antiprotons: high-energy collisions in a particle accelerator



WHERE TO MAKE ANTIPROTONS?



Antiproton Decelerator (AD) at CERN



p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) $\bar{p}$ (antiprotons) e⁻ (electrons)

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron AD Antiproton Decelerator CTF3 Clic Test Facility

AWAKE Advanced WAKefield Experiment ISOLDE Isotope Separator OnLine REX/HIE Radioactive EXperiment/High Intensity and Energy ISOLDE

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

CHARM Cern High energy AcceleRator Mixed field facility IRRAD proton IRRADiation facility GIF++ Gamma Irradiation Facility

CENF CErn Neutrino platForm

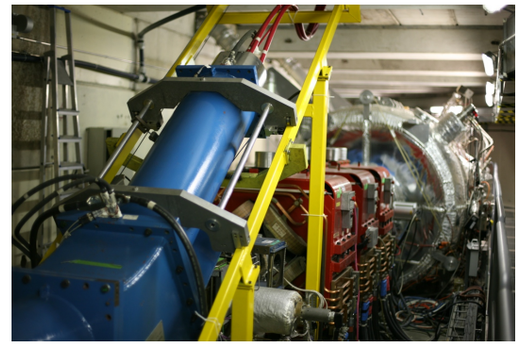
THE ANTIPROTON DECELERATOR

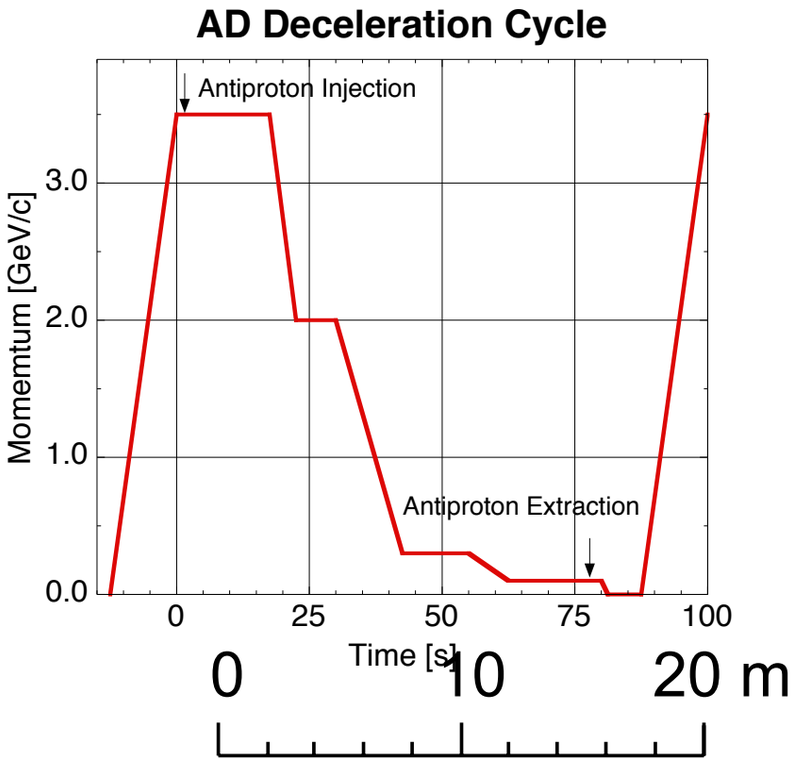
1 Antiproton Production

2 Injection at 3.5 GeV/c

3 Deceleration and Cooling (3.5 - 0.1 GeV/c)

4 Extraction (2×10^7 in 200 ns)





ACE

AEGIS

BASE

ATRAP

ASACUSA

ALPHA

(ATHENA)

GBAR (projected)

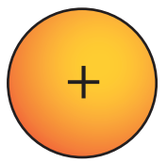
Stochastic Cooling

Electron Cooling

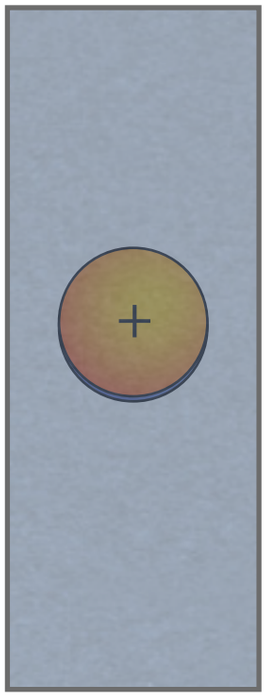
ANTIPROTON PRODUCTION

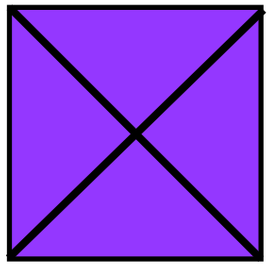
- Energetic proton creates Proton/Antiproton pair
- Charge/Mass selected

Cern Proton Synchrotron



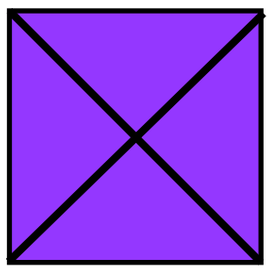
26 GeV/c





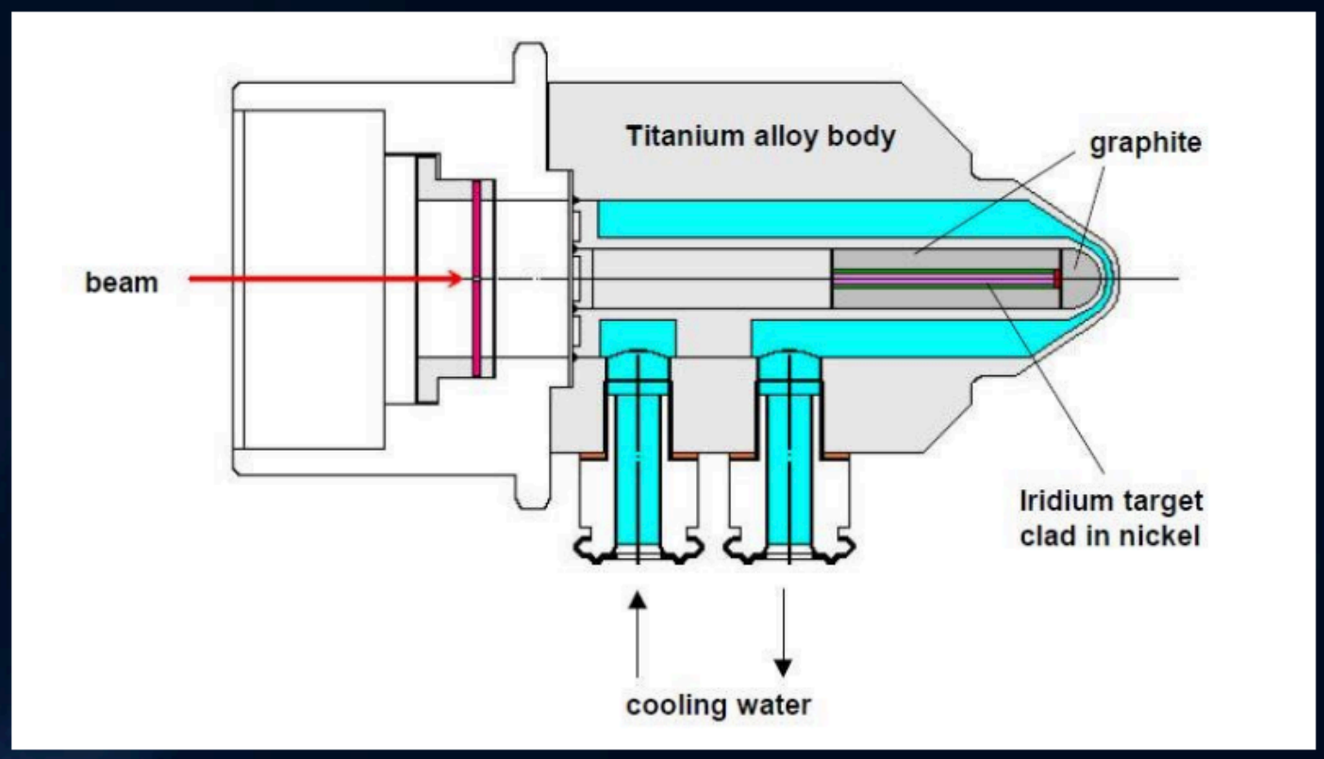
3.7 GeV/c

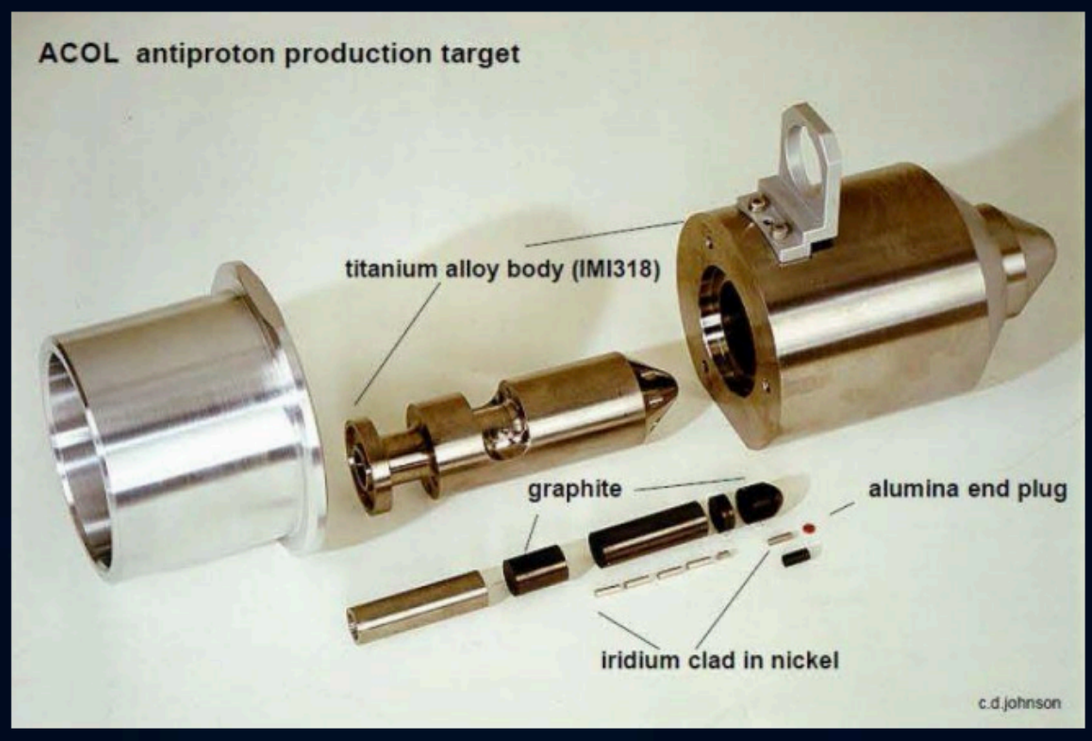
(and other stuff)



Making antiprotons at the AD

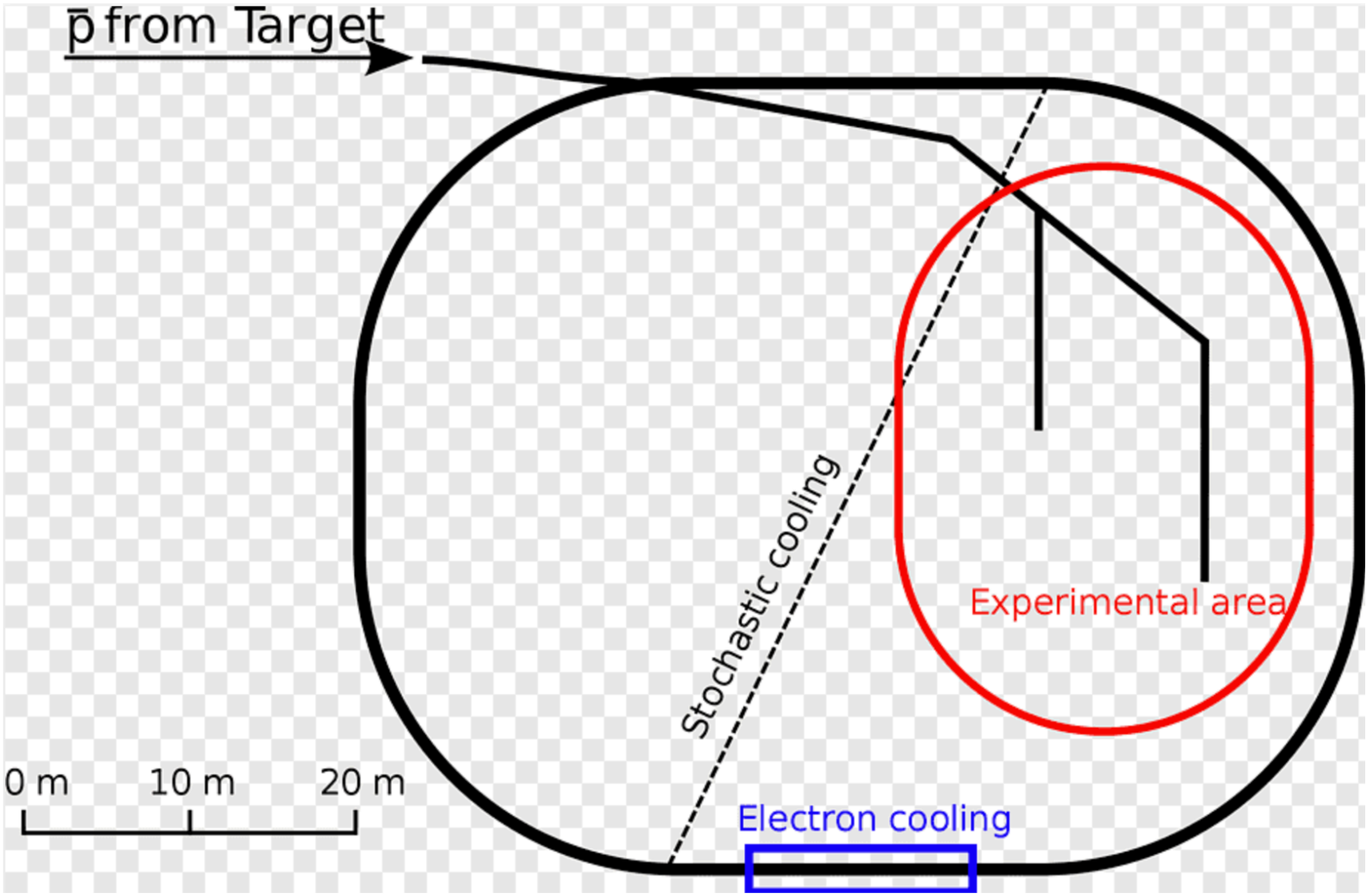
$$p + N \rightarrow N^* + \bar{p} + p + X$$





Ref. :C. Torregrosa, A. Perillo-Marcone, M. Calviani, CERN-ACCC-NOTE-2015-0004

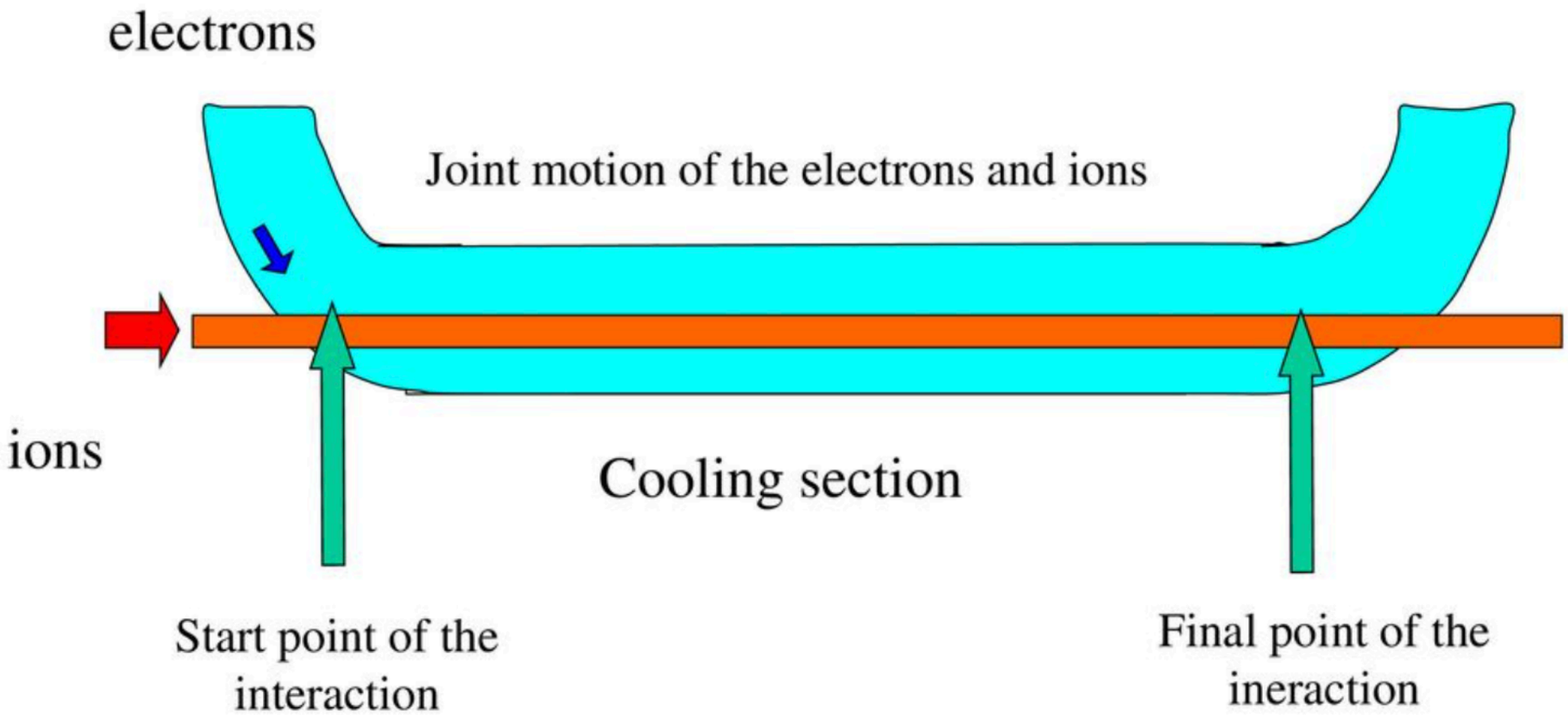
ANTIPROTON COOLING



ELECTRON COOLING

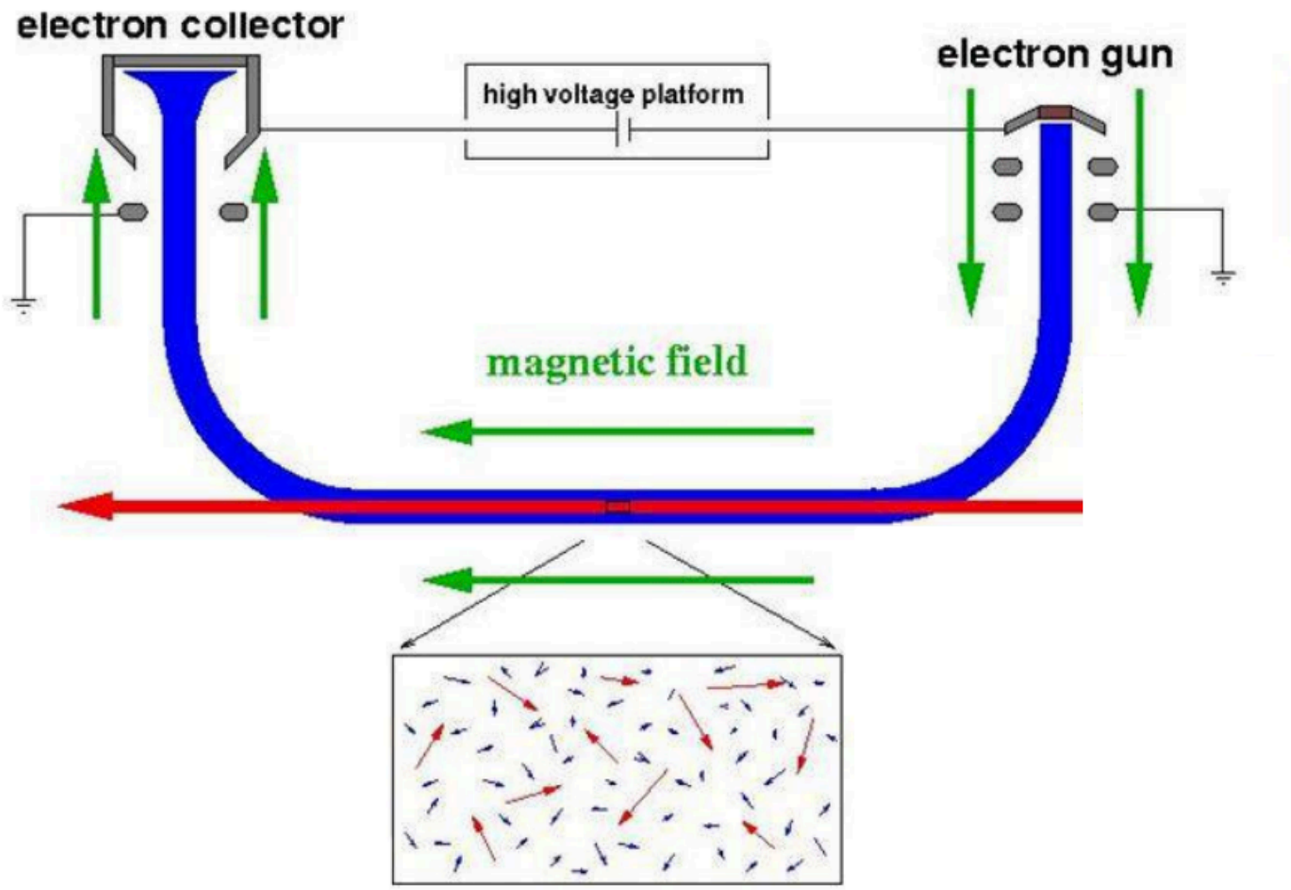
Scheme of the electron cooling

The energy transfer from the hot ions to the cold electrons



ELECTRON COOLING

- **Superposition** of cold intense e^- beam with pbarsat **same velocity**
- Momentum transfer by Coulomb collisions
- Cooling results from energy loss in co-moving gas of free electrons



In the beam frame:
Cold electrons interact with
Hot pbars

$$v_e = \beta_e c = \beta_p c = v_p$$

$$E_e = \frac{m_e E_p}{m_p}$$

m_e...electron mass

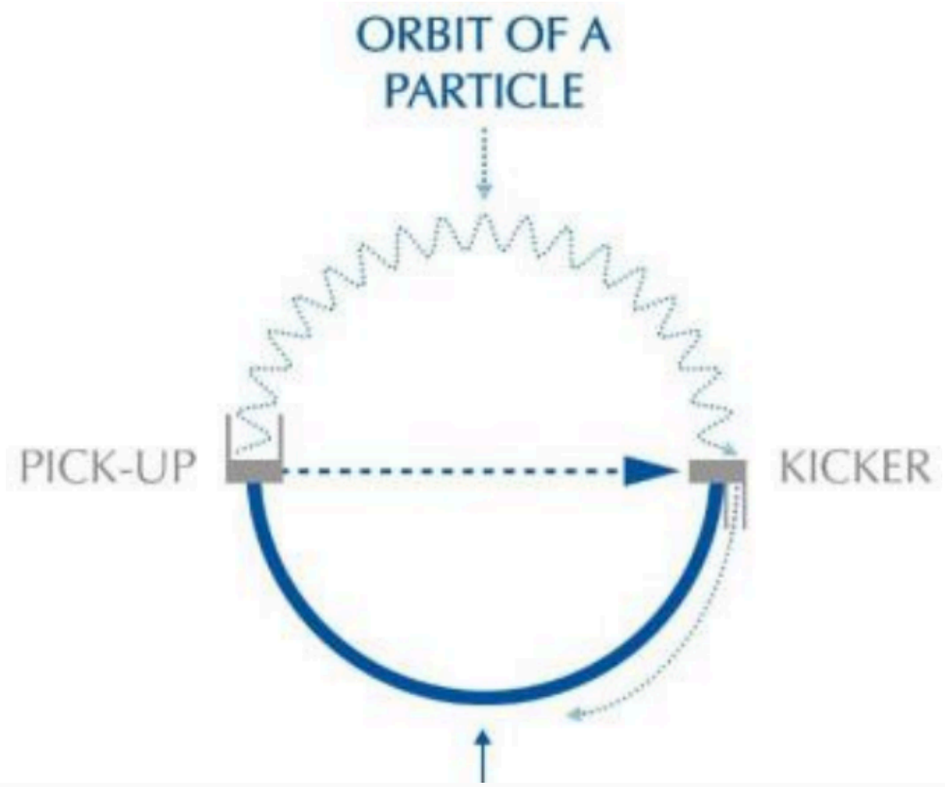
m_p... $p$mass

E_e...electron kinetic energy

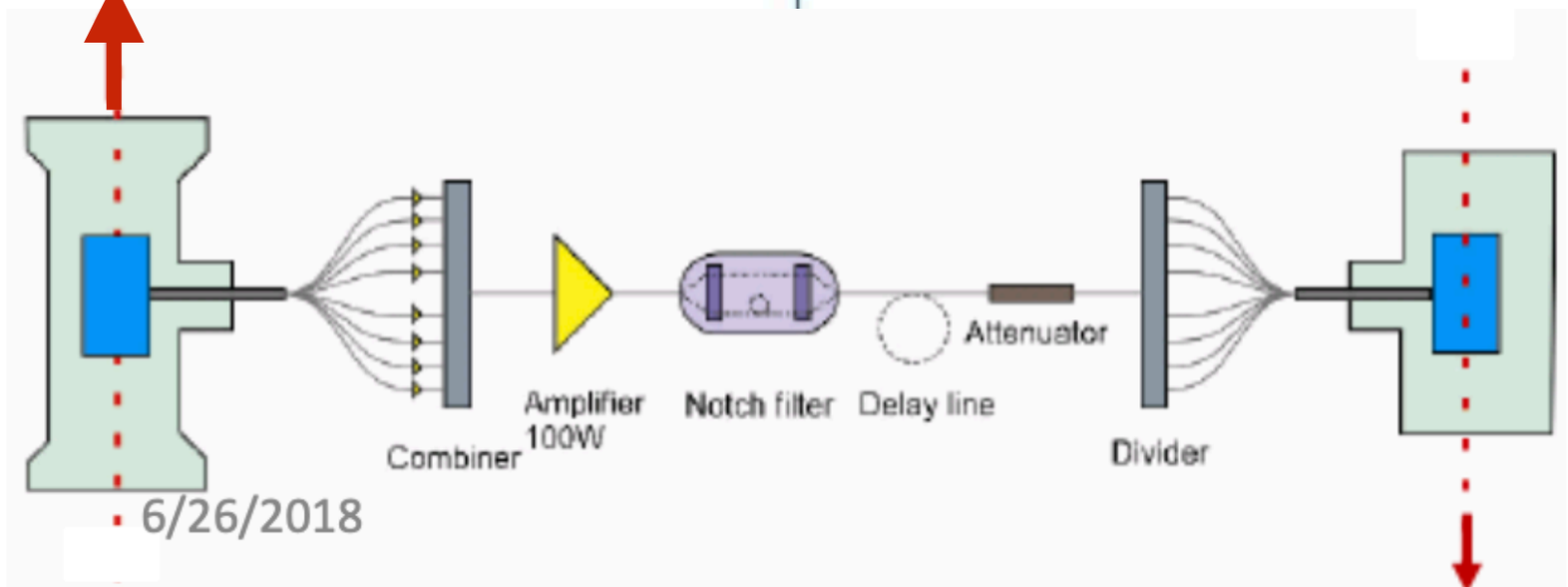
E_p... Pbar kinetic energy

e.g. 220 keV electrons cool 400 MeV pbars

STOCHASTIC COOLING

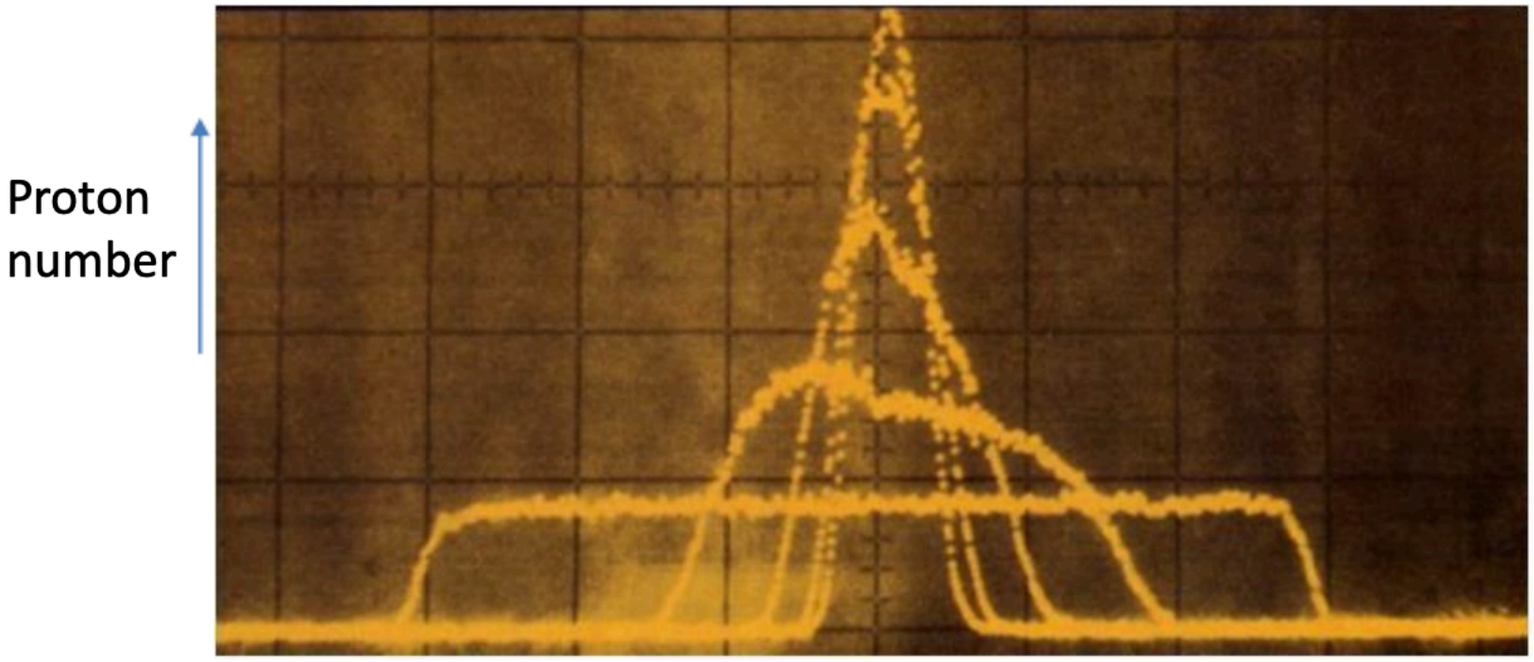


Beam



STOCHASTIC COOLING

Tested first time 1977 together with electron cooling at CERN in the ICE (initial cooling experiment)

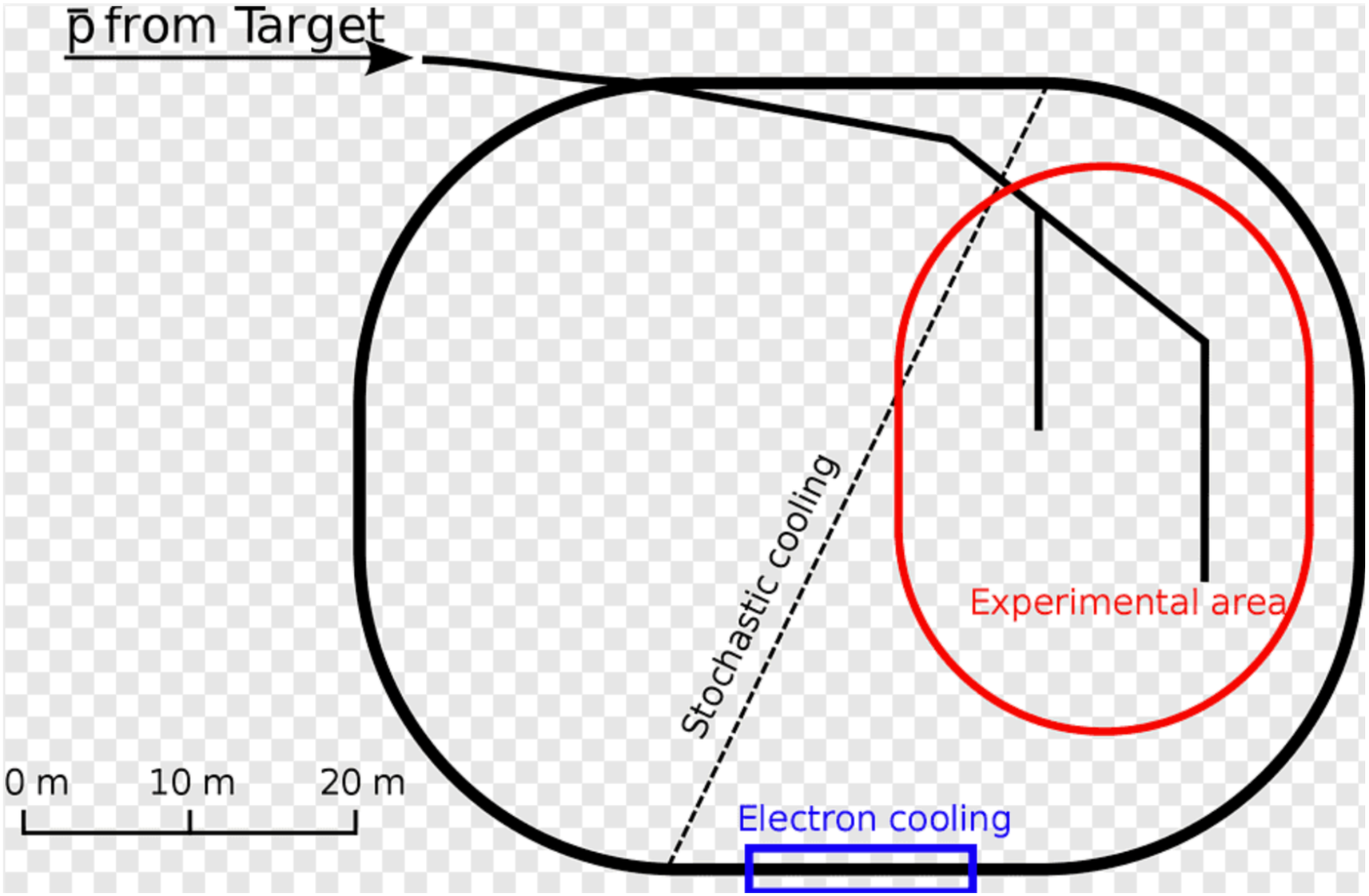


Stochastic cooling
invented at CERN by
Simon van der Meer

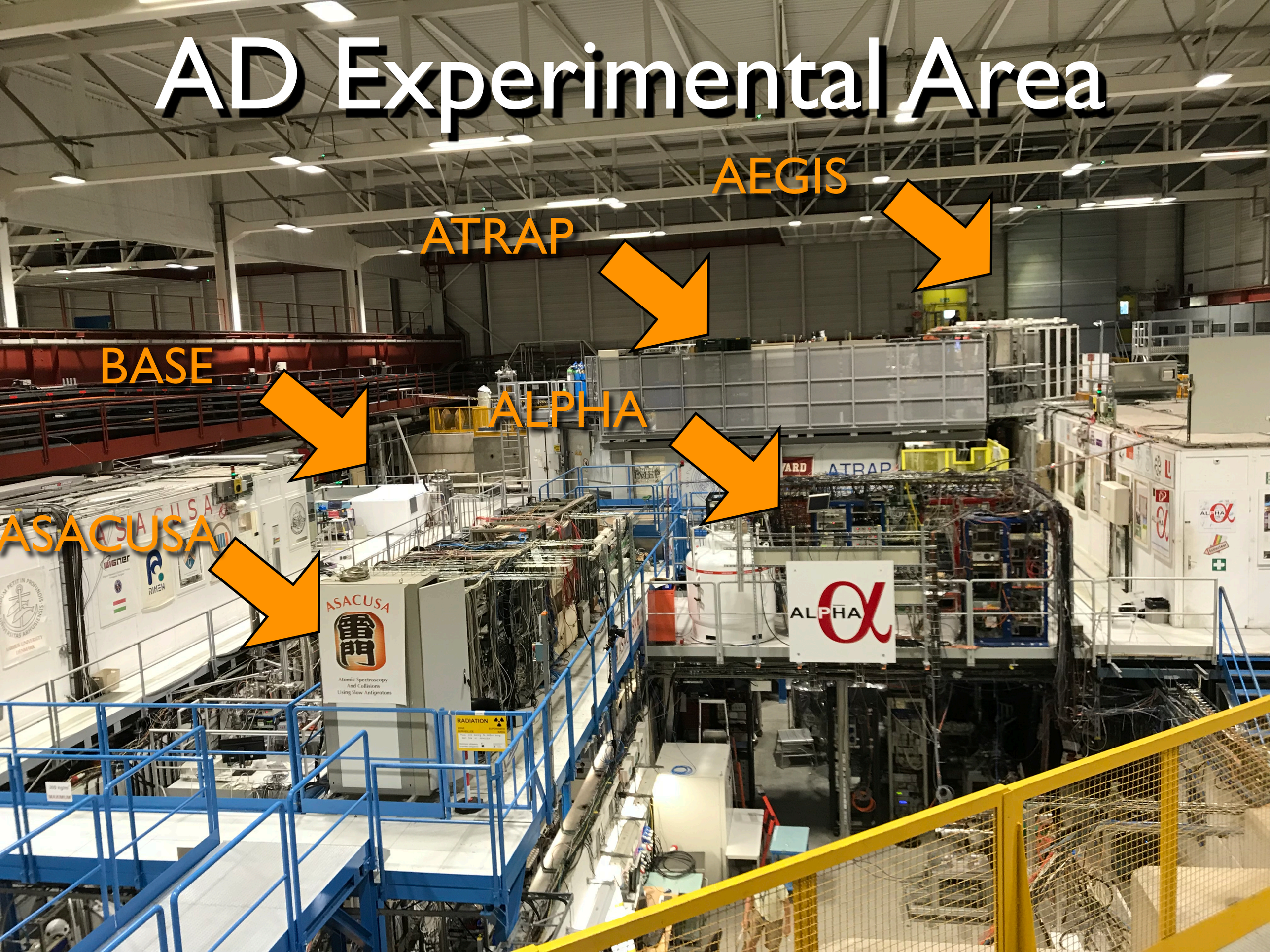
Nobel Prize 1984

Btw. Stochastic cooling system at AD completely renovated during LS2

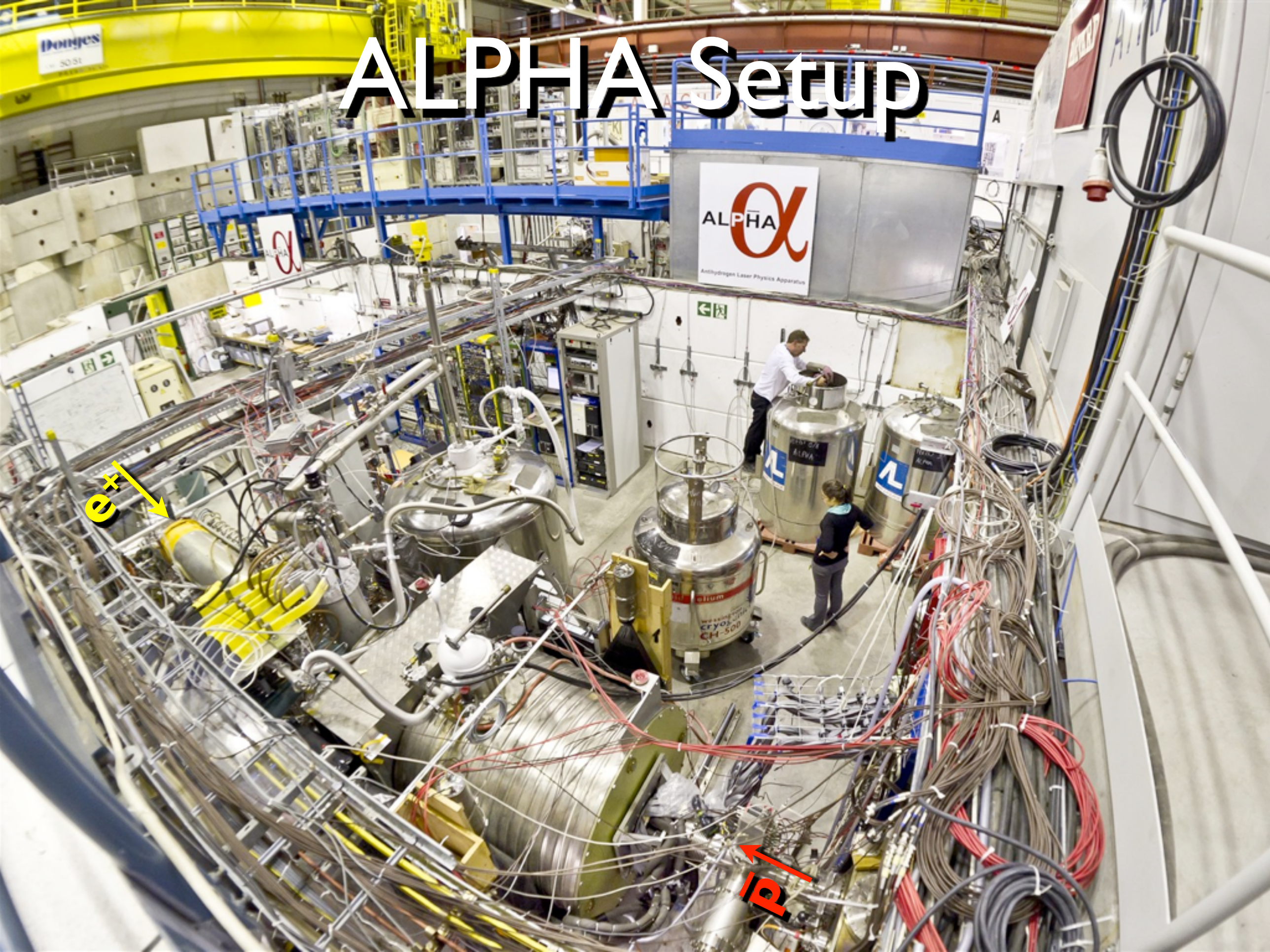
AD EXPERIMENTAL AREA



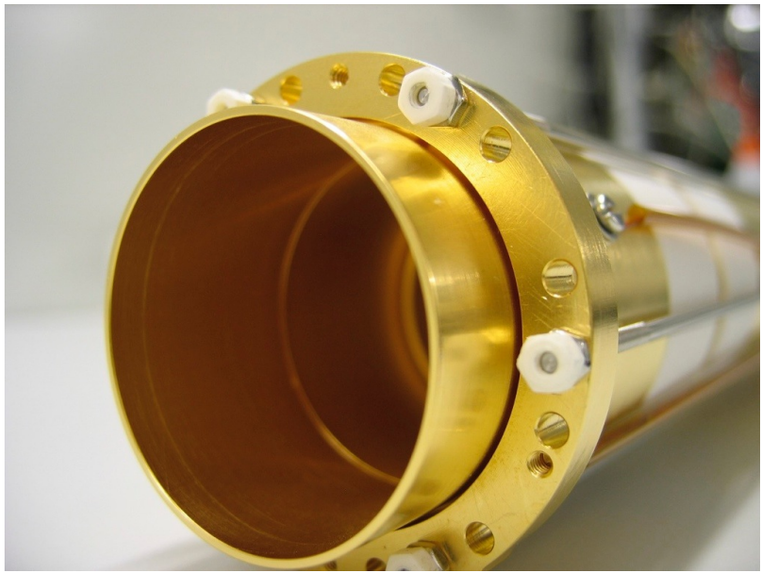
AD Experimental Area

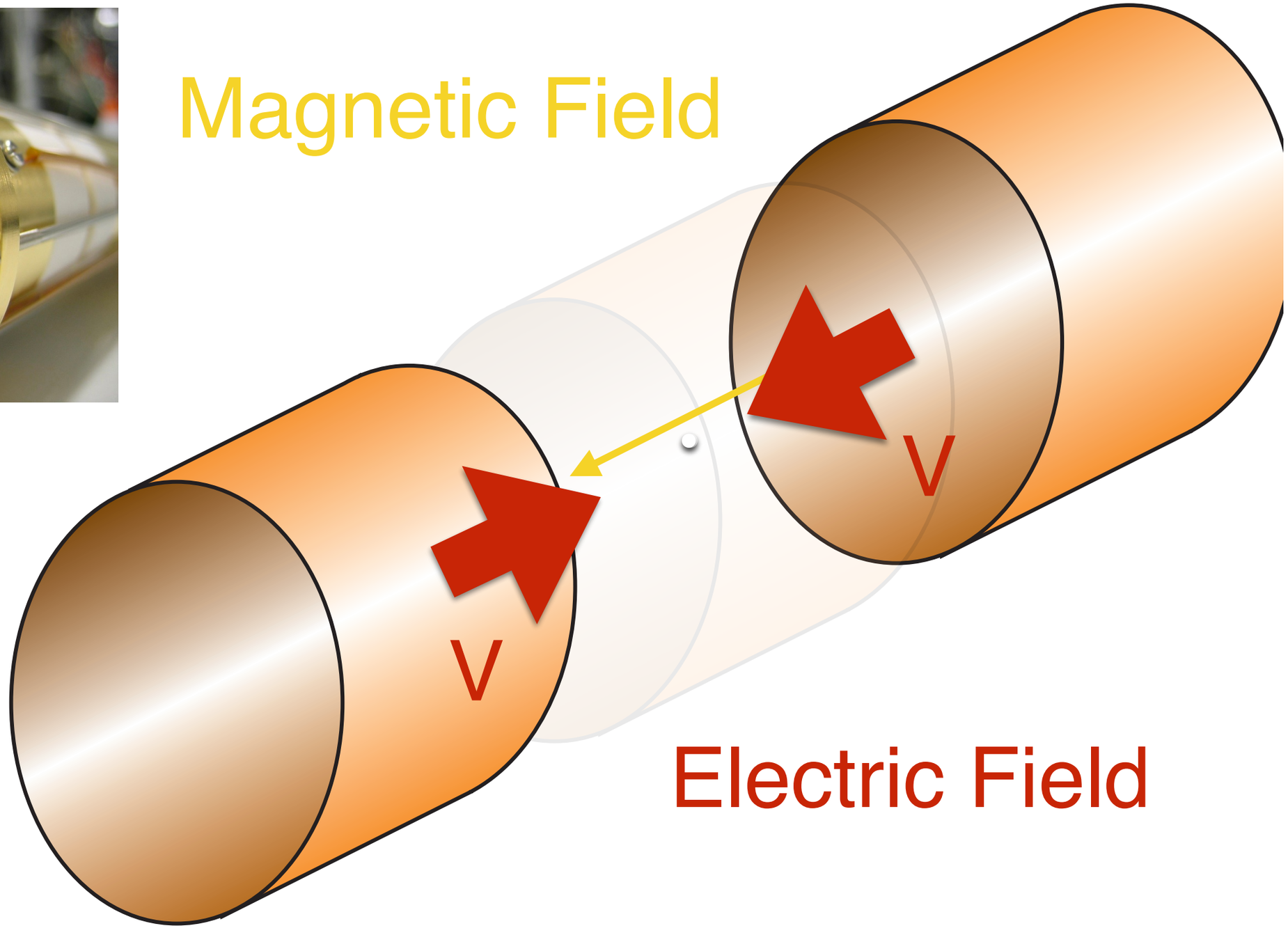


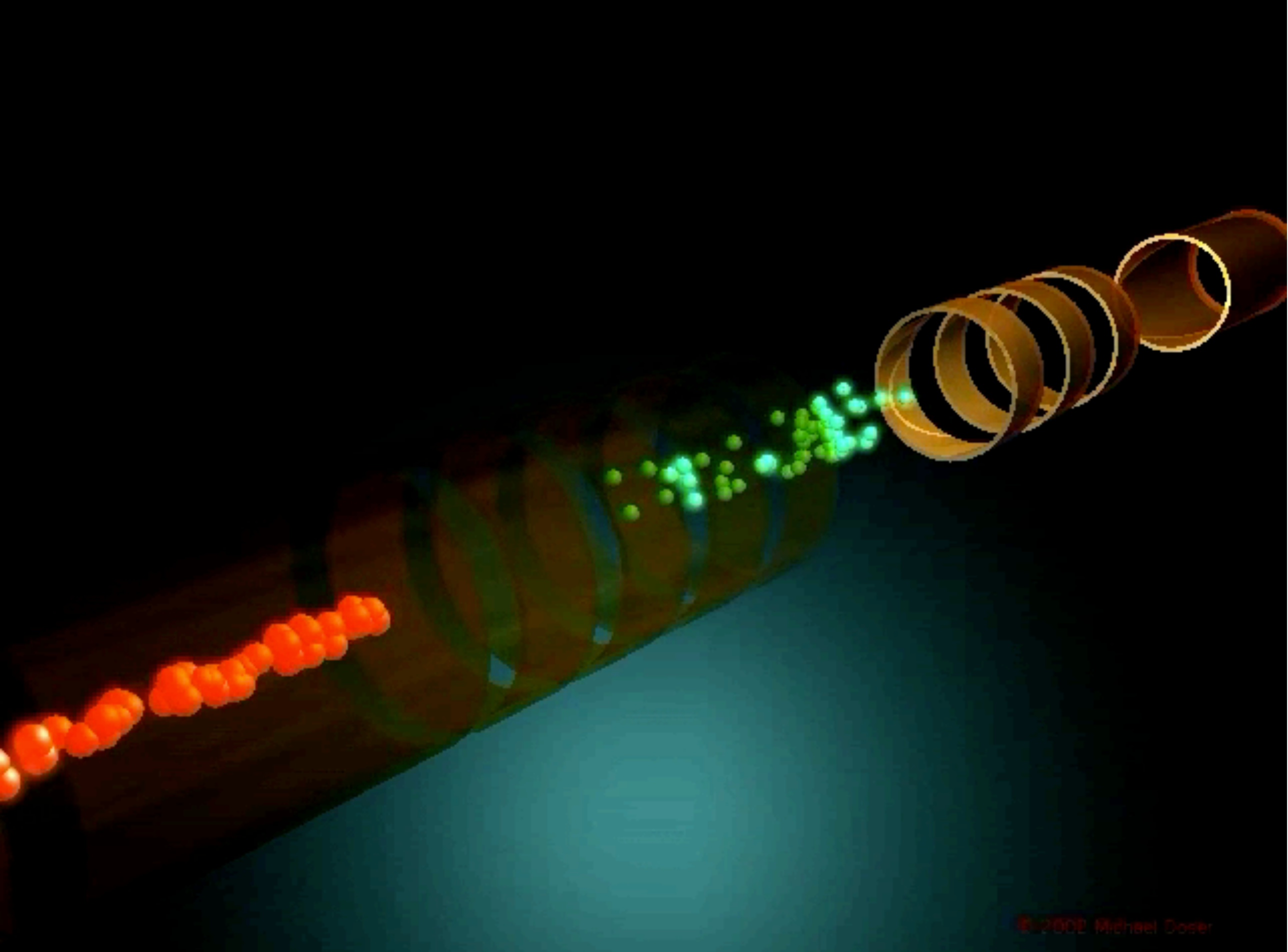
ALPHA Setup



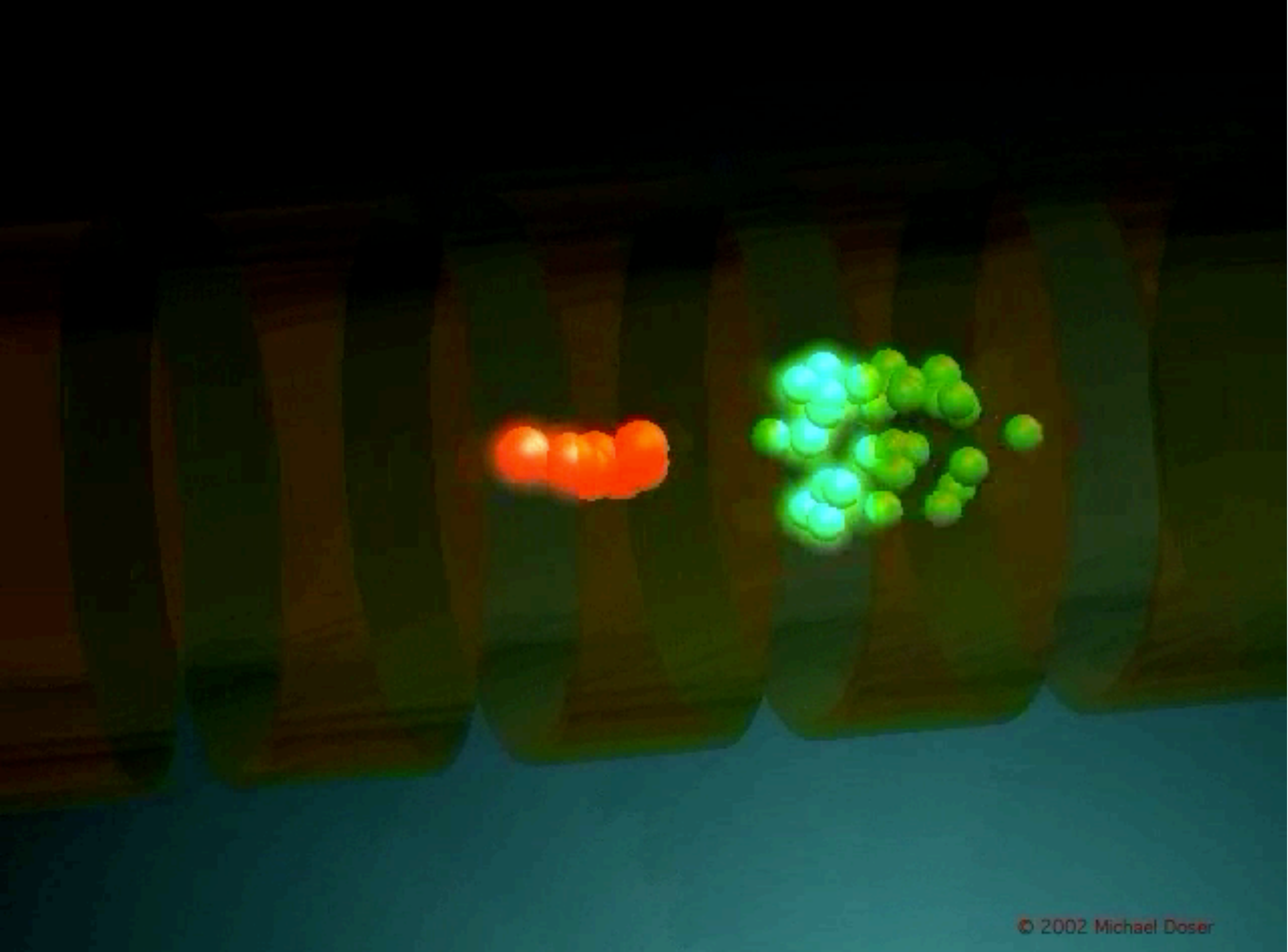
How are we holding on to this “stuff” !?



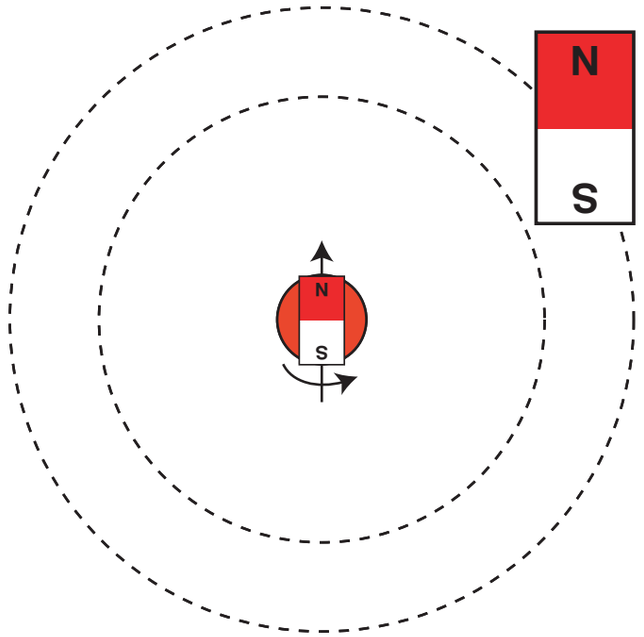



©2002 Michael Dose

Atoms are Neutral

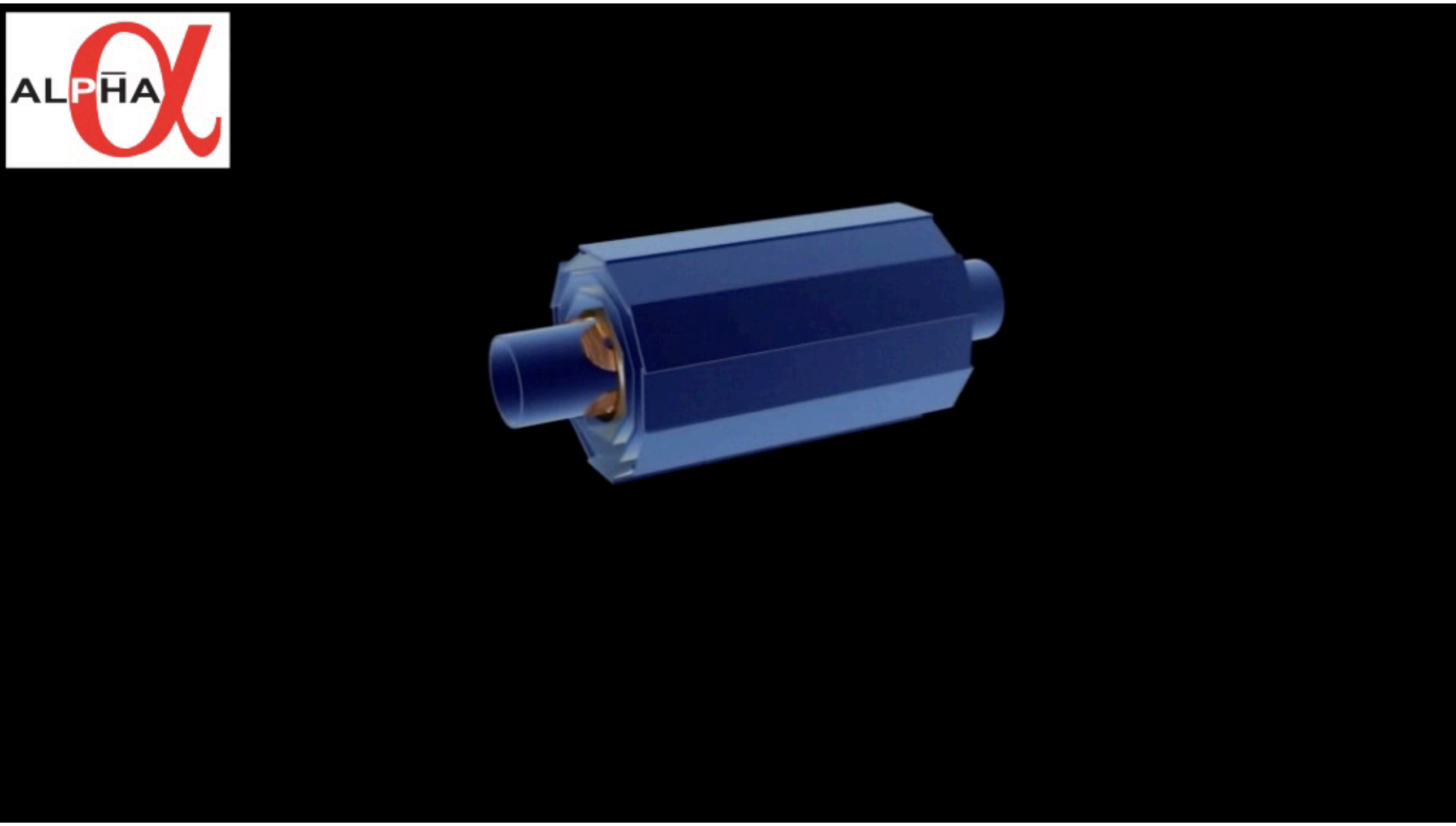


Atoms are tiny magnets…

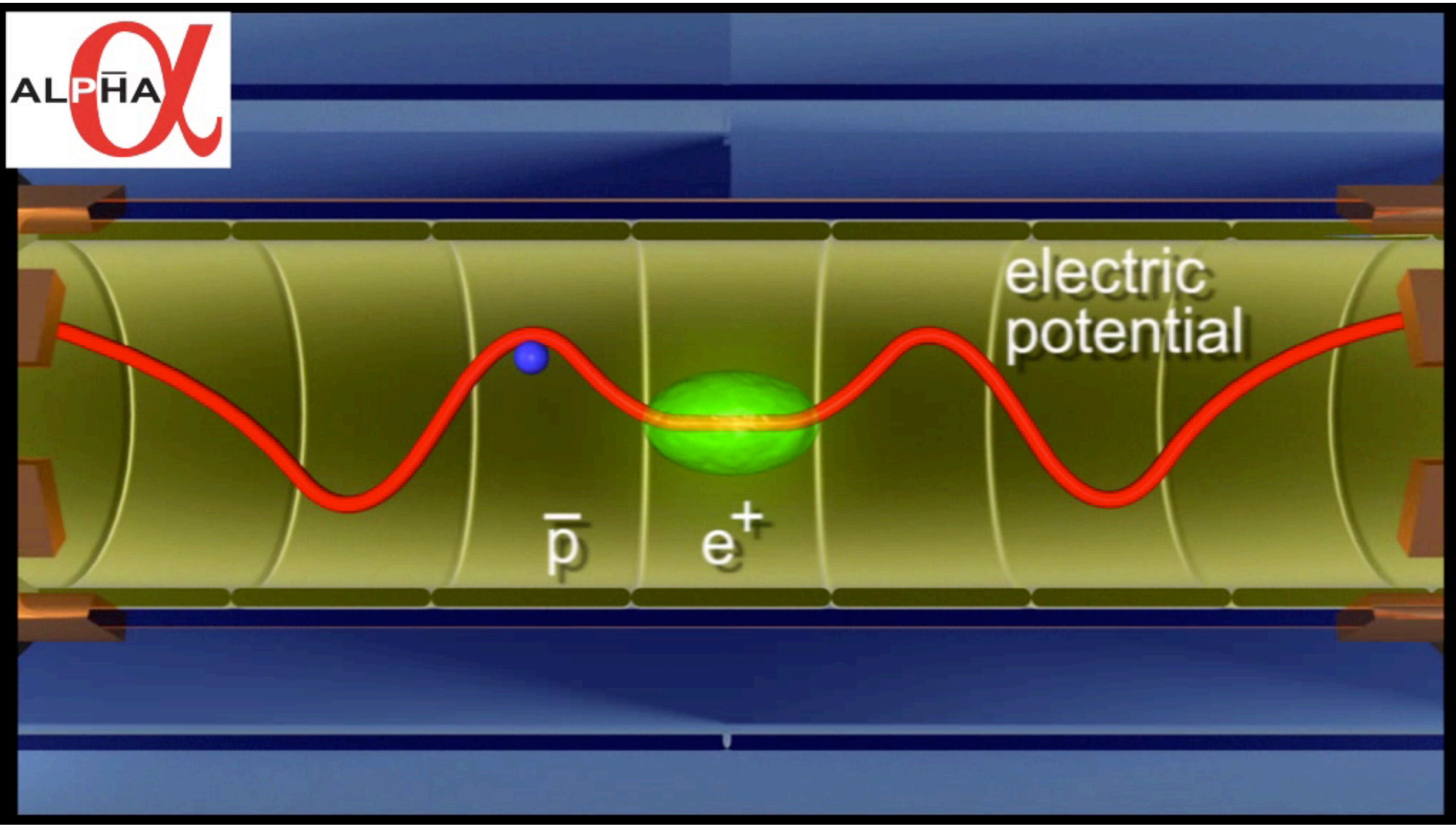


Suspending magnets by magnets…

Antihydrogen trapping



Antihydrogen trapping



EVOLUTION OF ANTIHYDROGEN PRODUCTION

Quick History Lesson

1995
first antihydrogen atoms created at LEAR facility at CERN

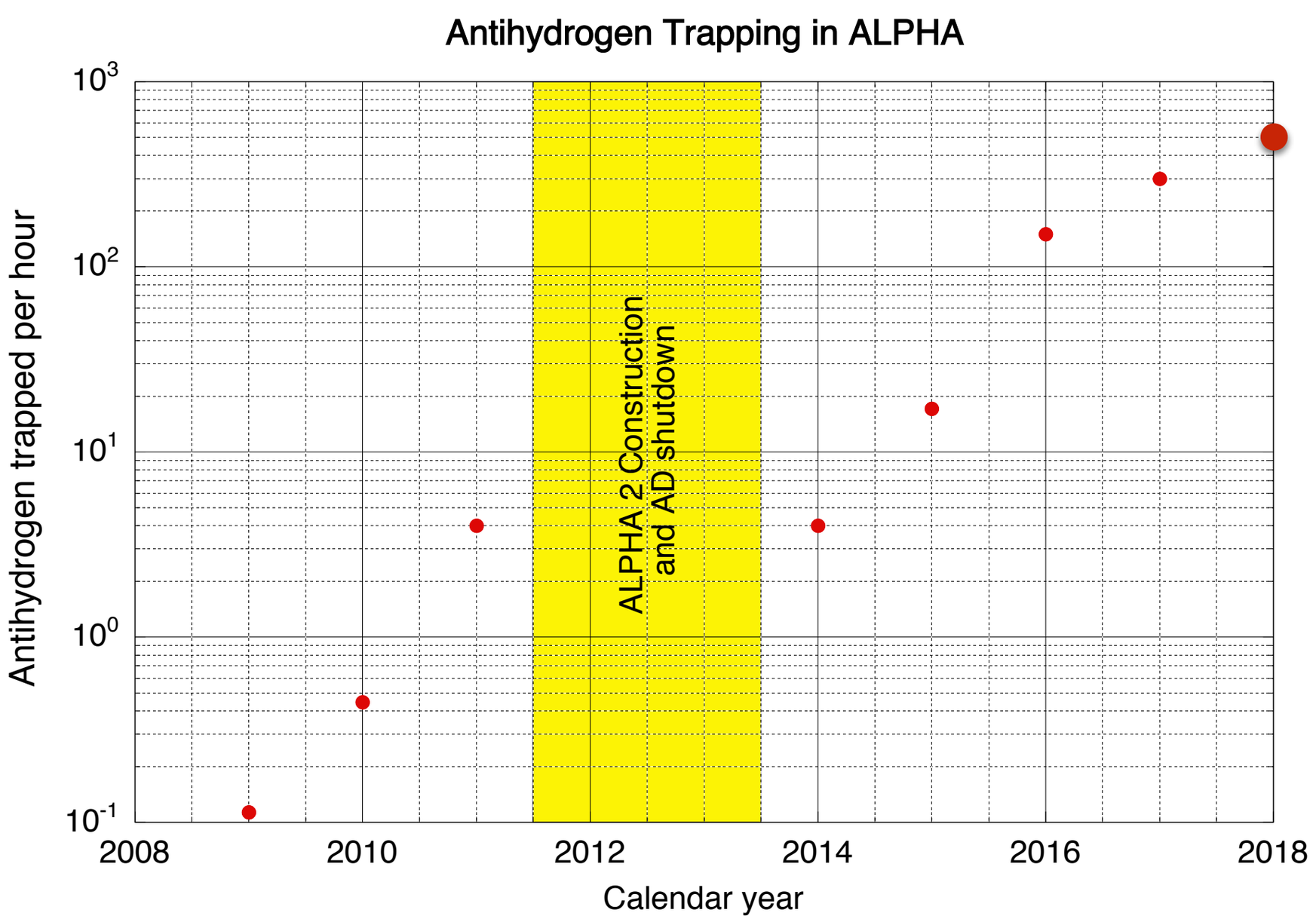
2002
ATHENA and ATRAP created thousands of “cold” antihydrogen atoms

2010
first “trapped” antihydrogen made at ALPHA

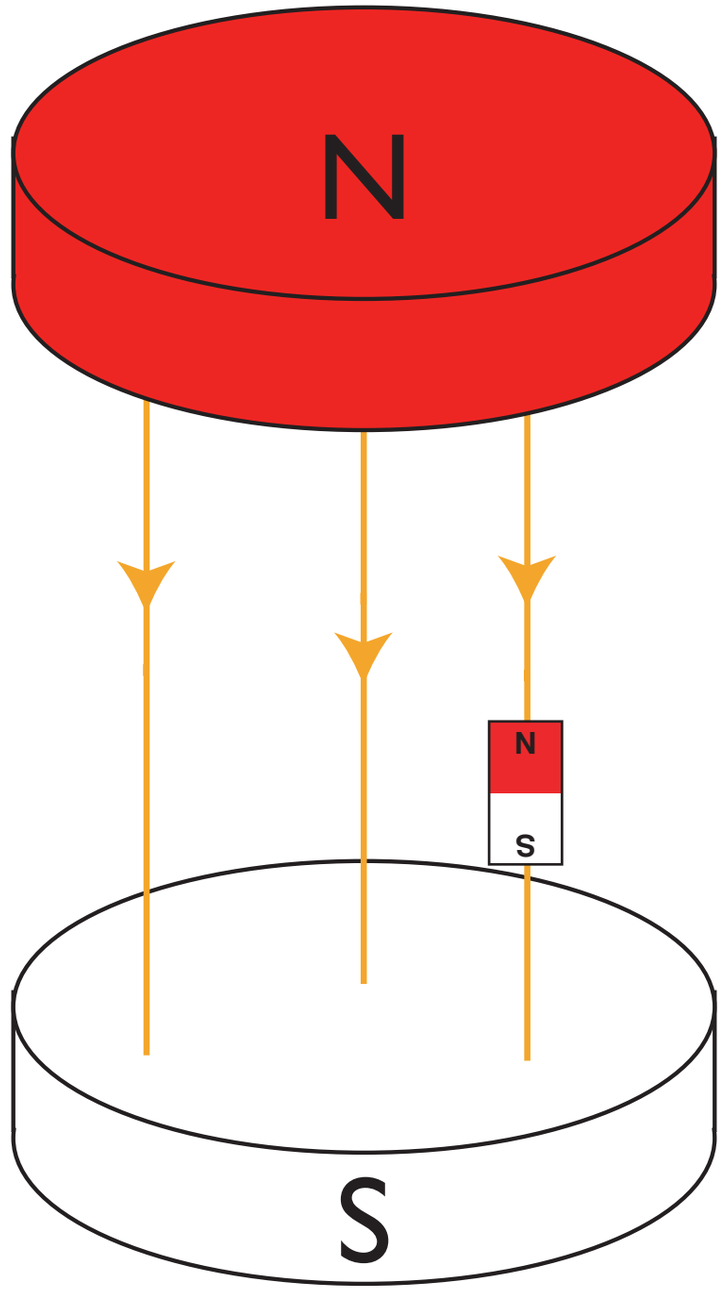
2011
ALPHA traps antihydrogen for 1,000 seconds

2014
ALPHA-2 goes online!

EVOLUTION OF ANTIHYDROGEN TRAPPING

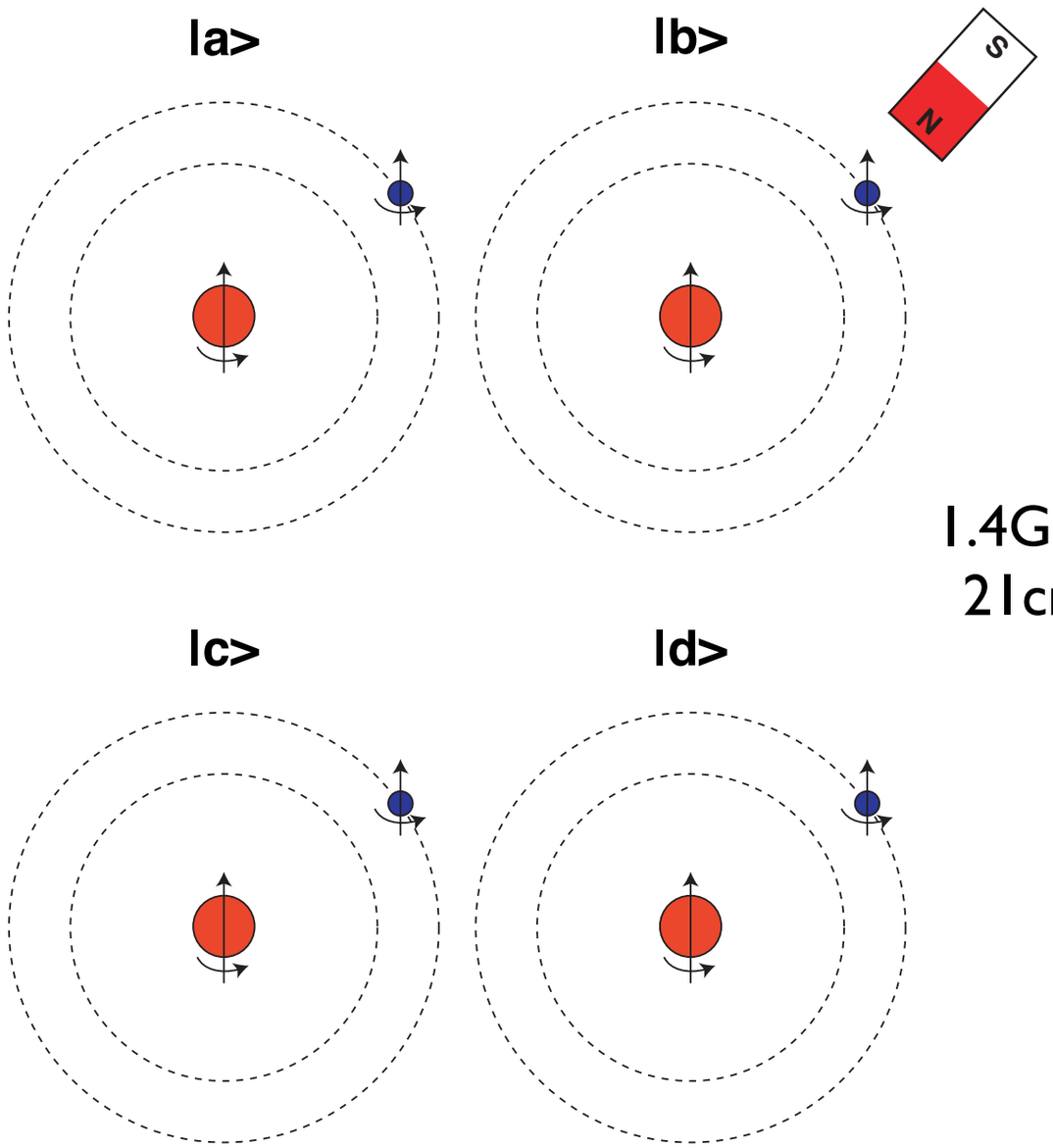


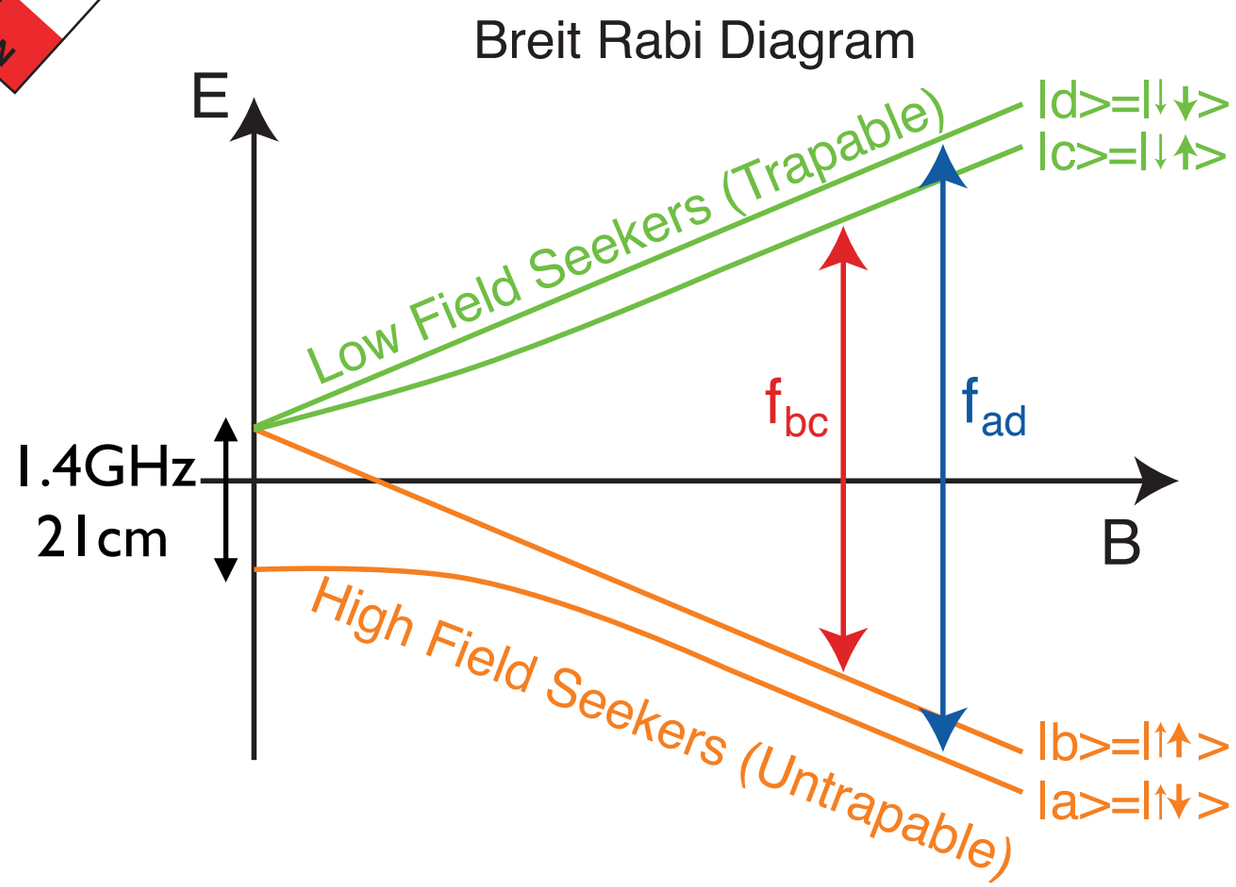
Magnetic Traps



anti-parallel field -> trapped

Magnetically Trapped Atoms



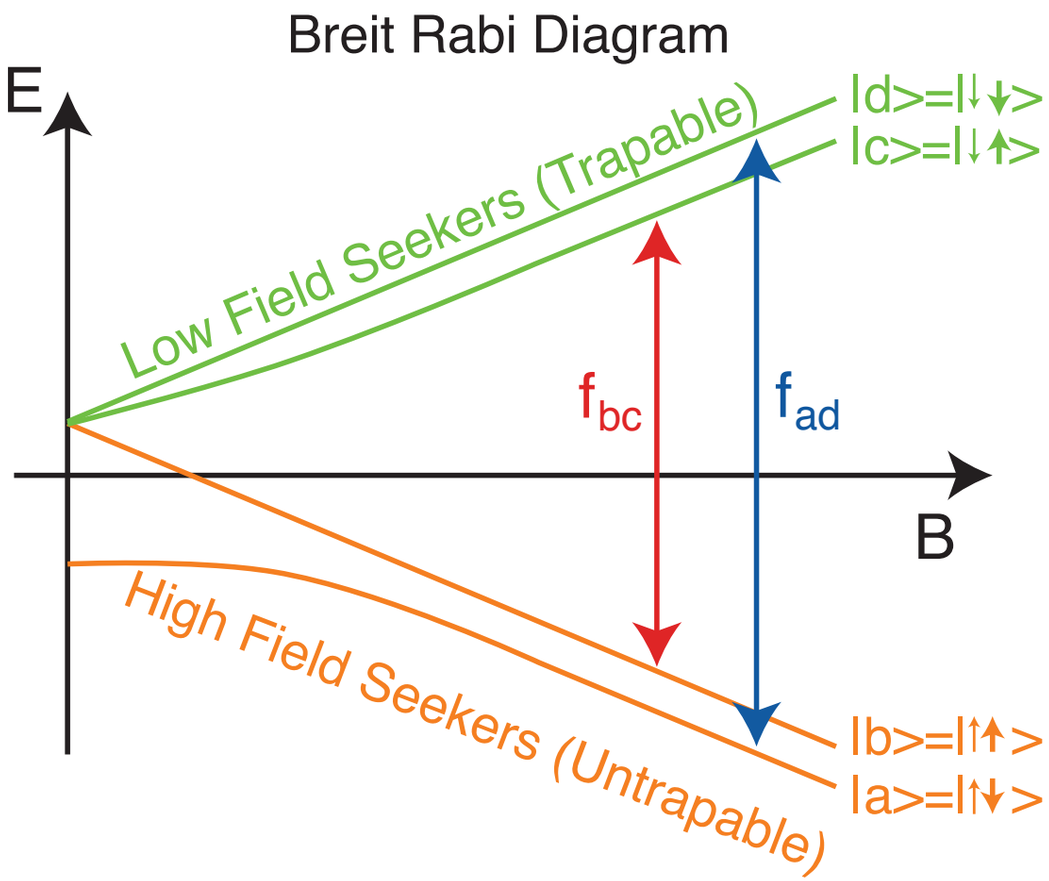


FIRST QUANTUM TRANSITIONS

- A trapped atom in the ground state, even if there is only one, is a platform for starting to compare antihydrogen and hydrogen.

- Diagnostic of one $\bar{H}$: Annihilation detection

- Method : Lose $\bar{H}$ resonantly from the trap by inducing a spin flip



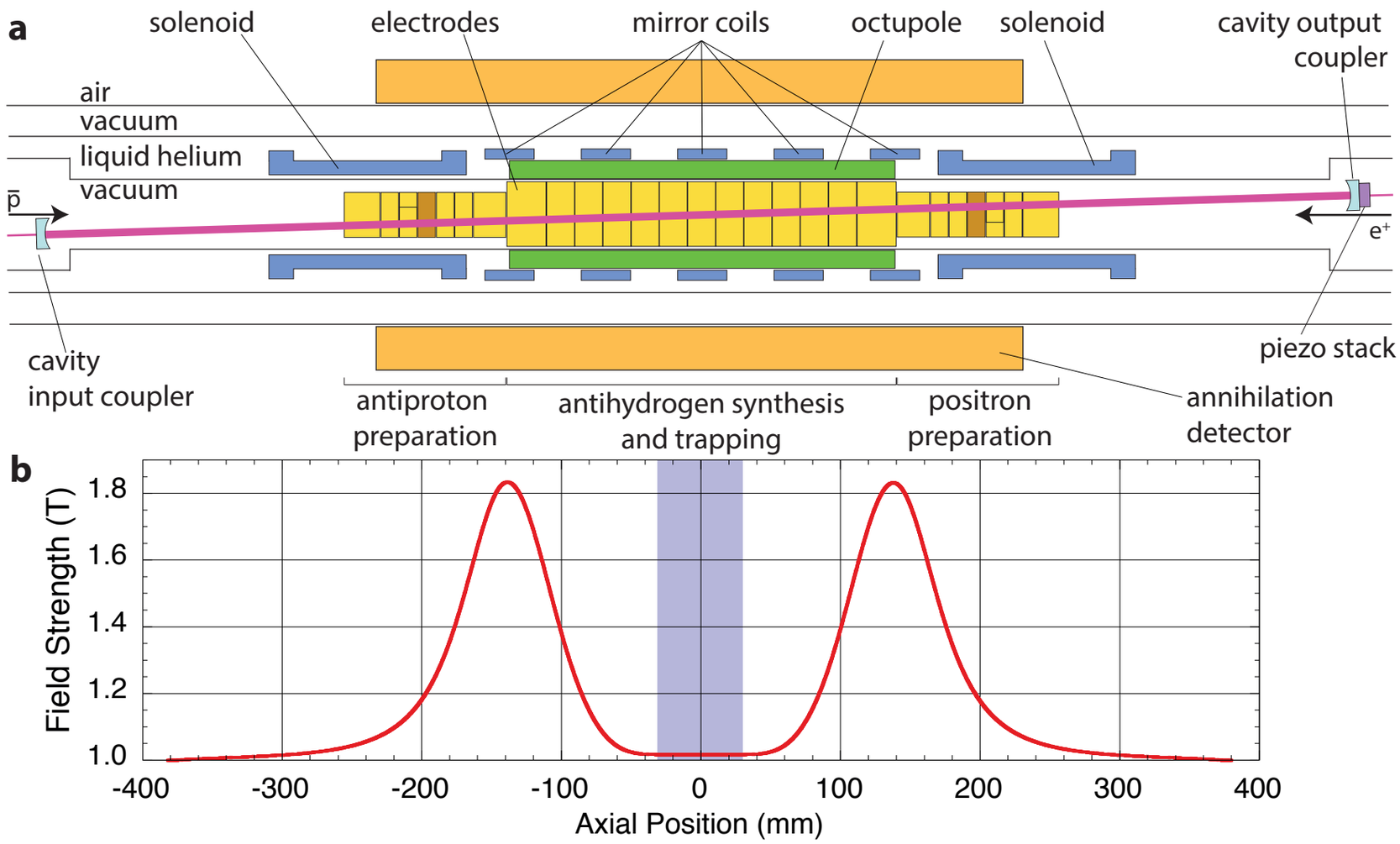
GRALLATOR

microwave

spectroscopy

1S - 2S Excitation

1s-2s Setup


a
solenoid
electrodes
mirror coils
octupole
solenoid
cavity output coupler
air
vacuum
liquid helium
vacuum
p̄
e+
cavity input coupler
piezo stack
antiproton preparation
antihydrogen synthesis and trapping
positron preparation
annihilation detector
b
Field Strength (T)
1.8
1.6
1.4
1.2
1.0
-400
-300
-200
-100
0
100
200
300
400
Axial Position (mm)

Experimental Procedure 2016

- Create trapped antihydrogen atoms by mixing antiproton and positron plasmas (about 20 atoms)
- Clear out any remaining charged particles
- 300s laser exposure
- Ramp down magnets to detect remaining atoms

- 3 types of trials:
  - On Resonance
  - Off Resonance
  - No Laser
- 11 repetitions of each trial were conducted

Results: Disappearance Mode

- Count the atoms left in the trap after laser exposure

Type	Detected Event	Background	Uncertainty
On Resonance	67	0.7	8.2
Off Resonance	159	0.7	13
No Laser	142	0.7	12

(detector efficiency: 0.688)

On and Off Resonance differ by 92 ± 15 counts

Results: Appearance Mode

- Look for annihilations during the 300s laser exposure times

Type	Detected Event	Background	Uncertainty
On Resonance	79	28.4	8.9
Off Resonance	27	28.4	5.2
No Laser	30	28.4	5.5

(detector efficiency: 0.376)

Milestone achieved after 30 years of hard work!

LETTER

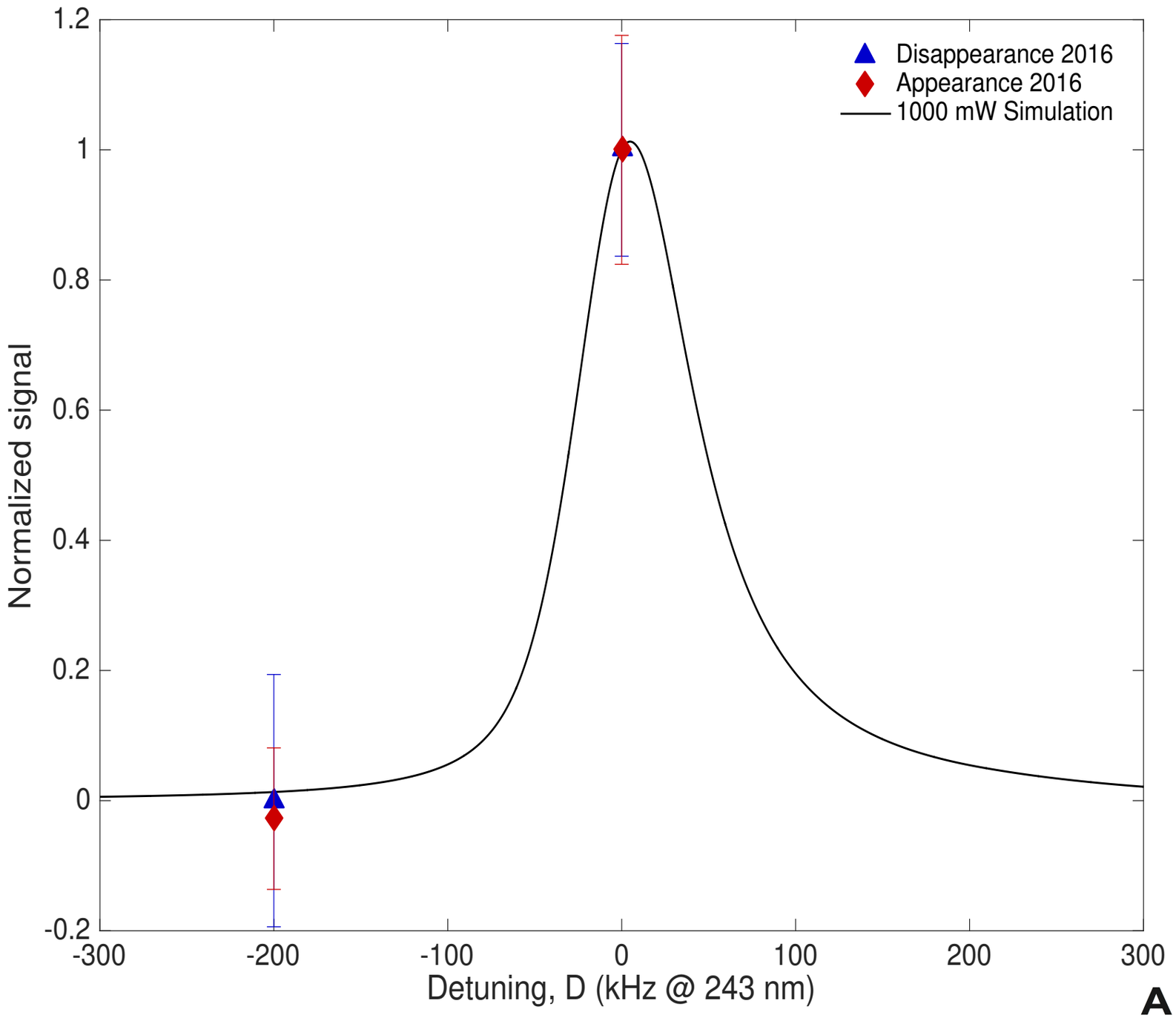
OPEN

doi:10.1038/nature21040

Observation of the 1S–2S transition in trapped antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], E. Butler[6], A. Capra[7], C. Carruth[8], C. L. Cesar[9], M. Charlton[3], S. Cohen[10], R. Collister[7], S. Eriksson[3], A. Evans[11], N. Evetts[12], J. Fajans[8], T. Friesen[2], M. C. Fujiwara[7], D. R. Gill[7], A. Gutierrez[13], J. S. Hangst[2], W. N. Hardy[12], M. E. Hayden[14], C. A. Isaac[3], A. Ishida[15], M. A. Johnson[4,5], S. A. Jones[3], S. Jonsell[16], L. Kurchaninov[7], N. Madsen[3], M. Mathers[17], D. Maxwell[3], J. T. K. McKenna[7], S. Menary[17], J. M. Michan[7,18], T. Momose[12], J. J. Munich[14], P. Nolan[1], K. Olchanski[7], A. Olin[7,19], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[20], R. L. Sacramento[9], M. Sameed[3], E. Sarid[21], D. M. Silveira[9], S. Stracka[22], G. Stutter[2], C. So[11], T. D. Tharp[23], J. E. Thompson[17], R. I. Thompson[11], D. P. van der Werf[3,24] & J. S. Wurtele[8]

2016 Result



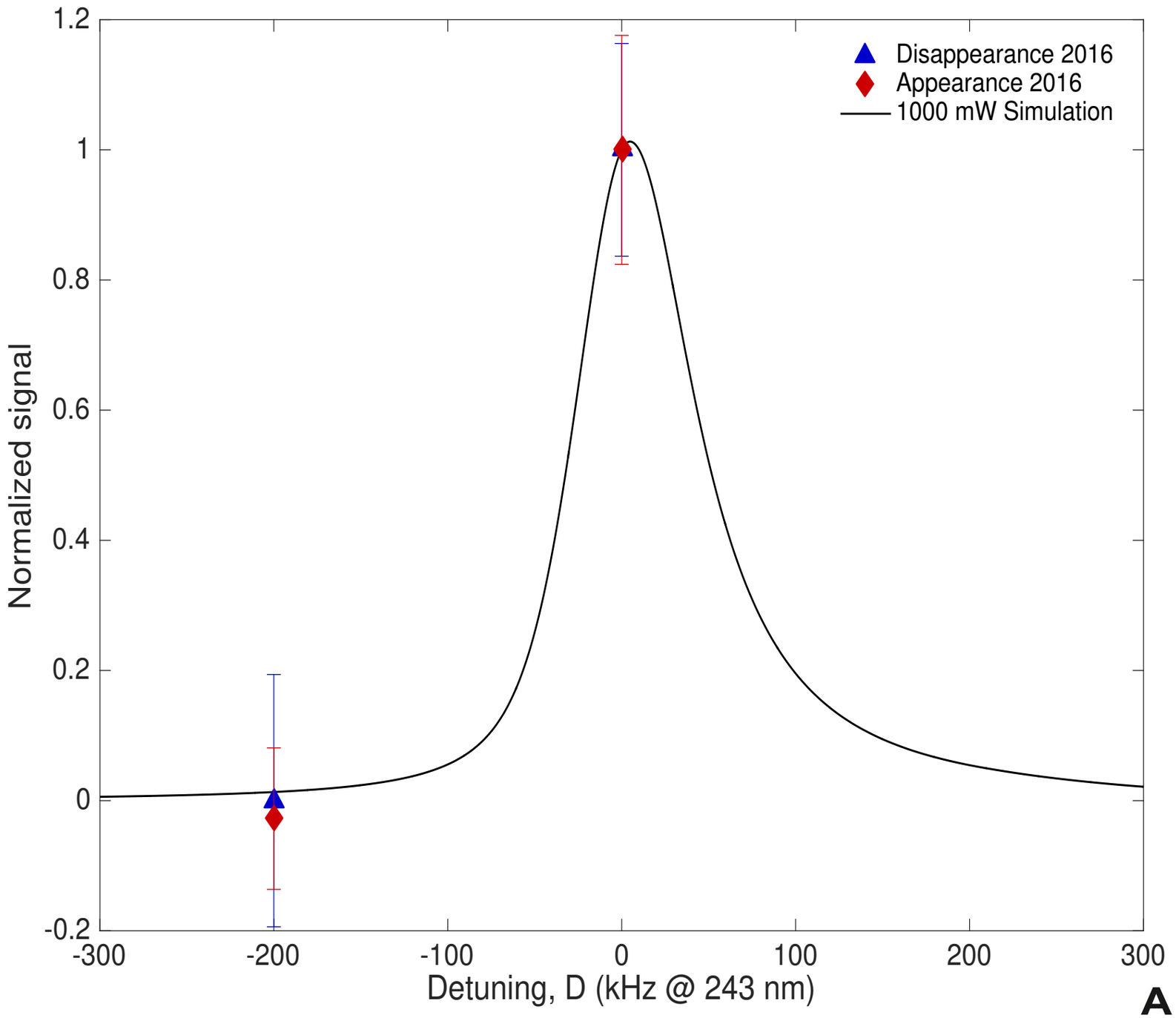
A

Experimental Procedure 2017

- Trap antihydrogen (about 40 atoms)
- Clear out any remaining charged particles
- 300s laser exposure at fixed frequency near transition
- Ramp down magnets to detect remaining atoms

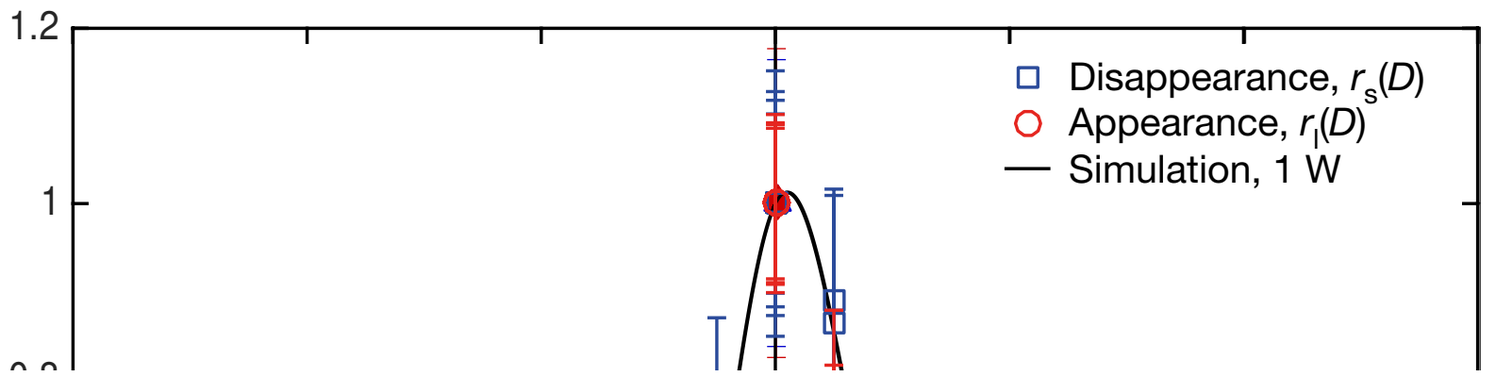
- Interspersed trials of 4 different laser frequencies in a frequency “set”
- 4 sets of 4 frequencies completed over 10 weeks
- 9 unique laser frequencies used on ~15,000 atoms

2016 Result



A

2017 Result



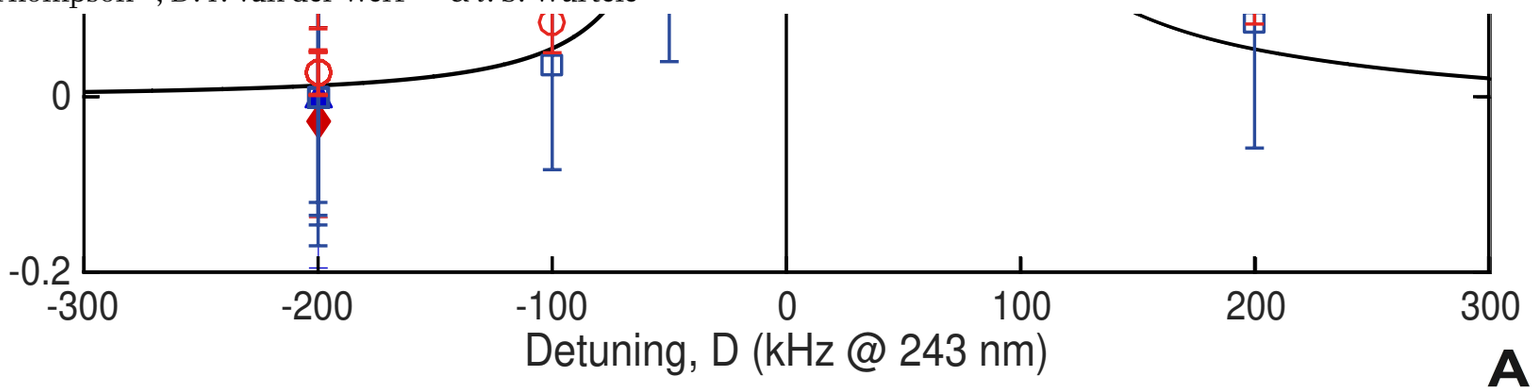
LETTER

OPEN

https://doi.org/10.1038/s41586-018-0017-2

Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], A. Capra[6], C. Carruth[7], C. L. Cesar[8], M. Charlton[3], S. Cohen[9], R. Collister[6], S. Eriksson[3], A. Evans[10], N. Evetts[11], J. Fajans[7], T. Friesen[2], M. C. Fujiwara[6], D. R. Gill[6], J. S. Hangst[2]*, W. N. Hardy[11], M. E. Hayden[12], C. A. Isaac[3], M. A. Johnson[4,5], J. M. Jones[3], S. A. Jones[2,3], S. Jonsell[13], A. Khramov[6], P. Knapp[3], L. Kurchaninov[6], N. Madsen[3], D. Maxwell[3], J. T. K. McKenna[6], S. Menary[14], T. Momose[11], J. J. Munich[12], K. Olchanski[6], A. Olin[6,15], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[16], R. L. Sacramento[8], M. Sameed[3,4], E. Sarid[17], D. M. Silveira[8], G. Stutter[2], C. So[10], T. D. Tharp[18], R. I. Thompson[10], D. P. van der Werf[3,19] & J. S. Wurtele[7]



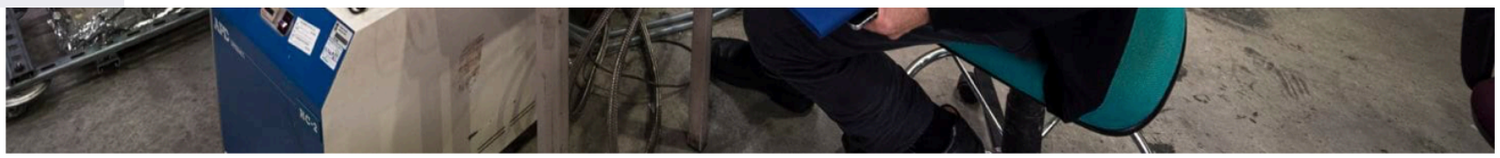
“Media” Coverage

Science

In breakthrough experiment, scientists shine a light on antimatter

Sameed Muhammed, a Pakistani physicist, is part of the CERN team that made a breakthrough discovery on antimatter

By Muneeb Ahmad on August 11, 2017 - Like us now! Like

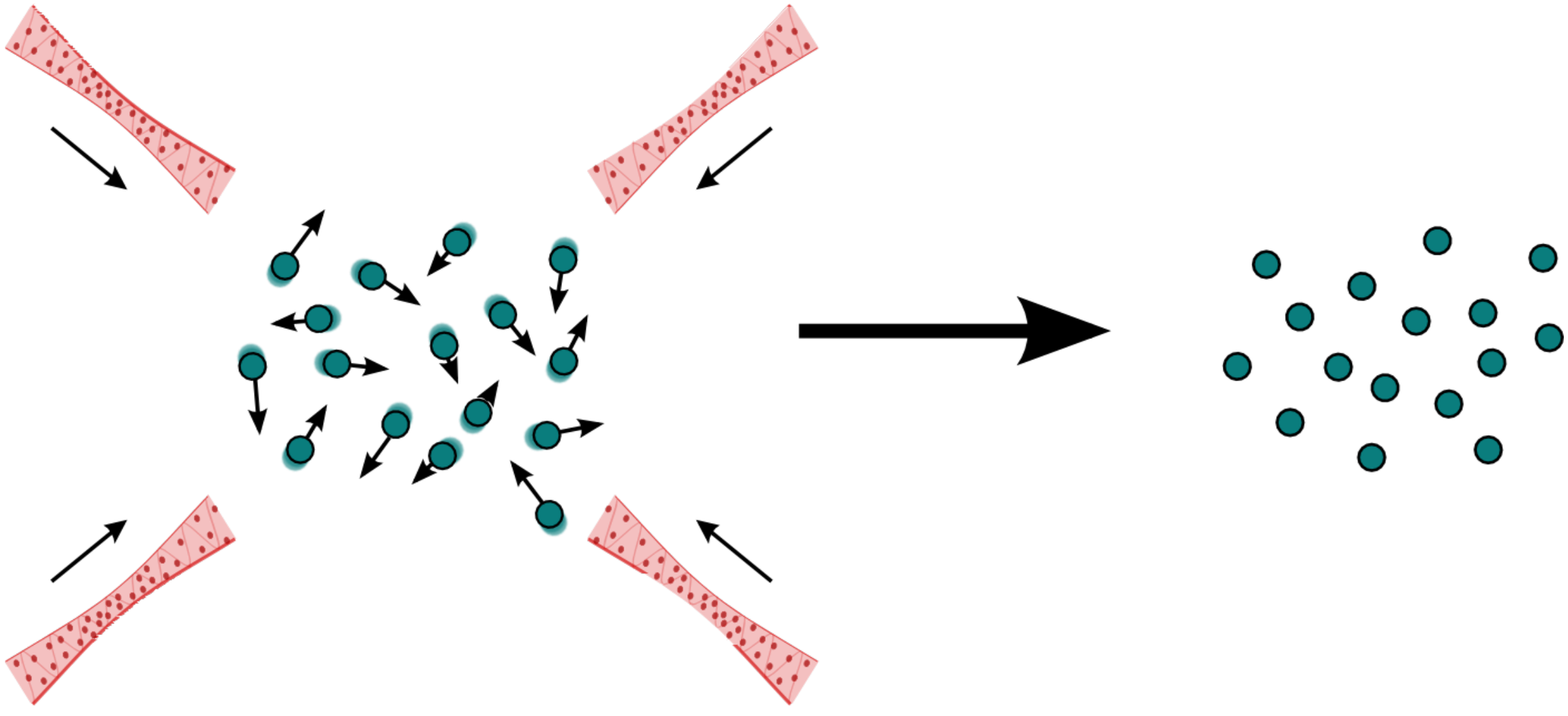


Physicist Jeffrey Hangst in the ALPHA-2 lab at CERN, where researchers are probing antimatter with laser beams to illuminate its secrets. (CERN)

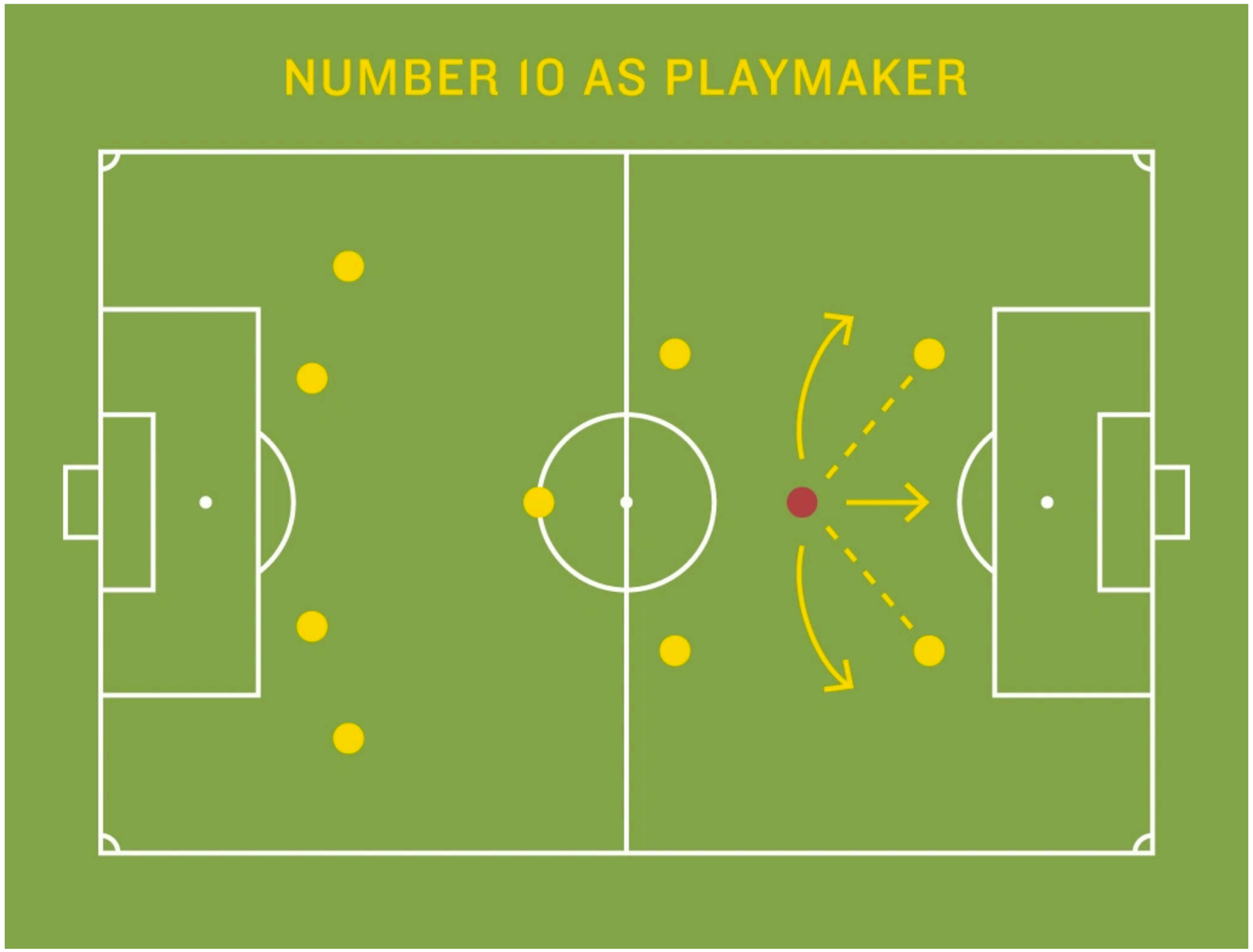
Trending Posts

- How to check or pay your traffic E-Challan online
- How Salaried Employees can file Income Tax in Pakistan
- How to open an account in Bank AL-Habib
- A burglar in Karachi made Rs. 4.5 million in 35 hours by stealing over 100 high-end phones

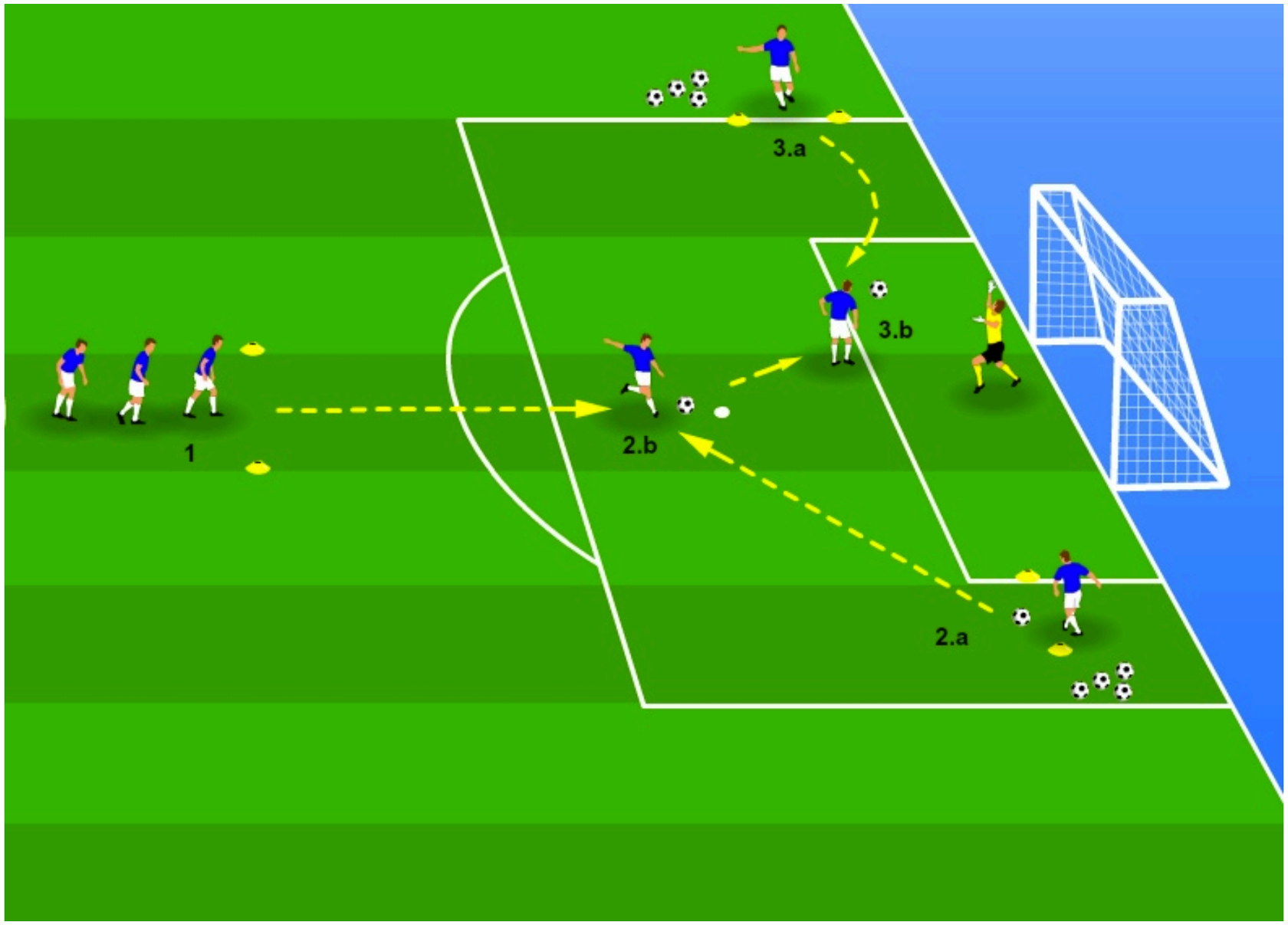
Laser Cooling Antimatter



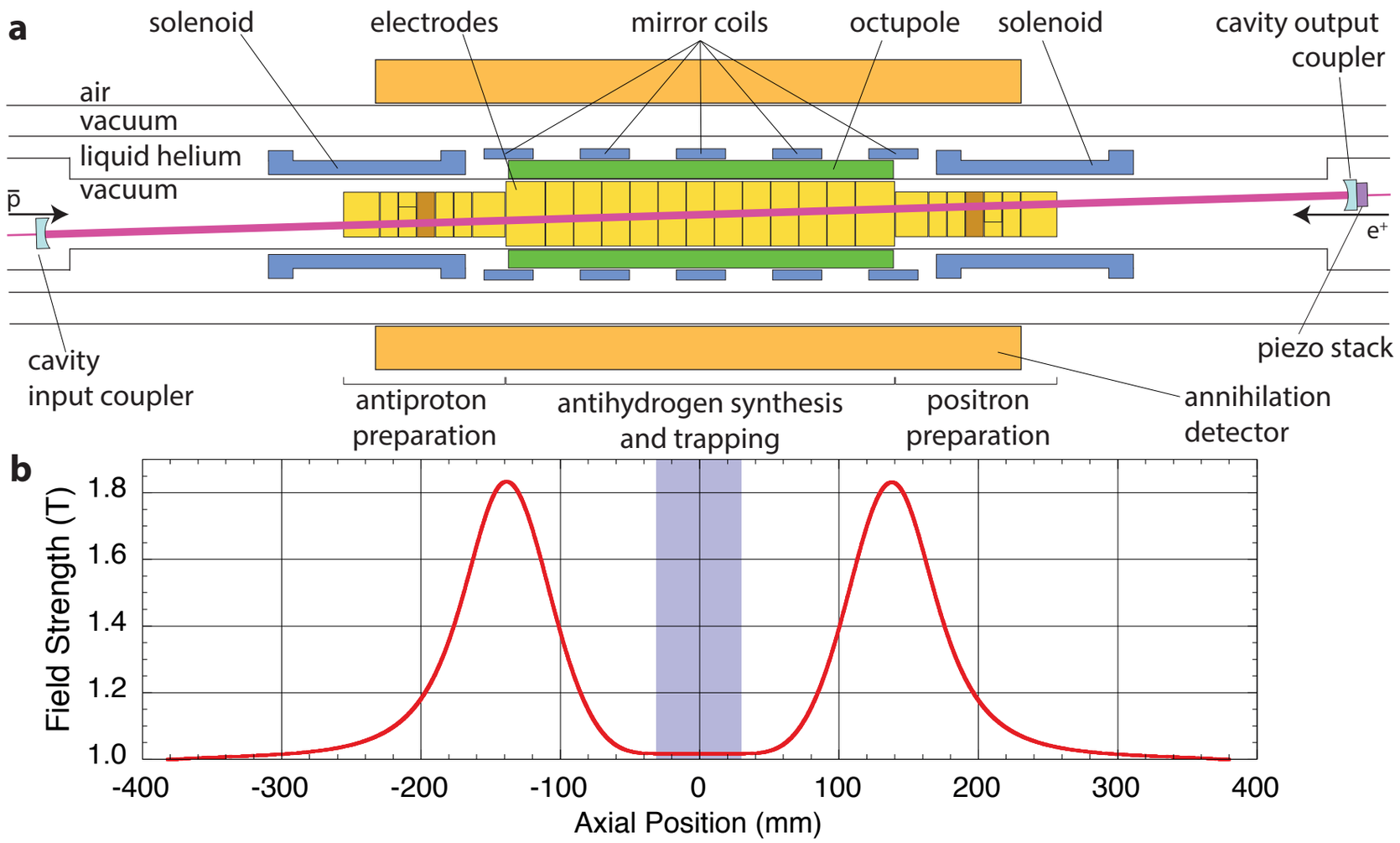
Laser Cooling Antimatter



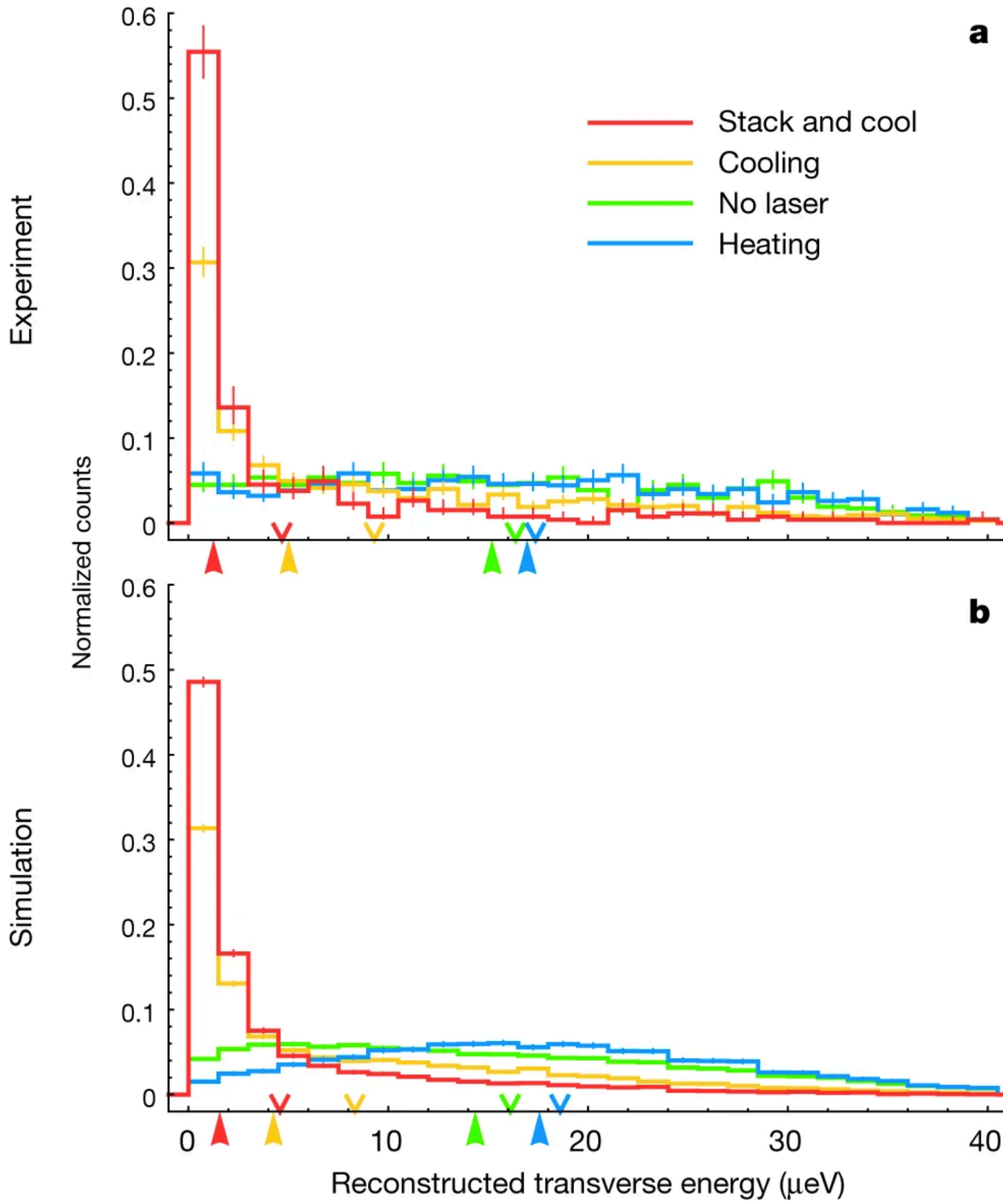
Laser Cooling Antimatter



Laser Cooling Setup



2021 Result


a
b
Stack and cool
Cooling
No laser
Heating
Experiment
Simulation
Normalized counts
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
Reconstructed transverse energy (μeV)

2021 Result

The Cornell Daily Sun

COVID-19 Briefing | News | Opinion | Sports | Arts & Culture | Science | Dining | Multimedia | Specials

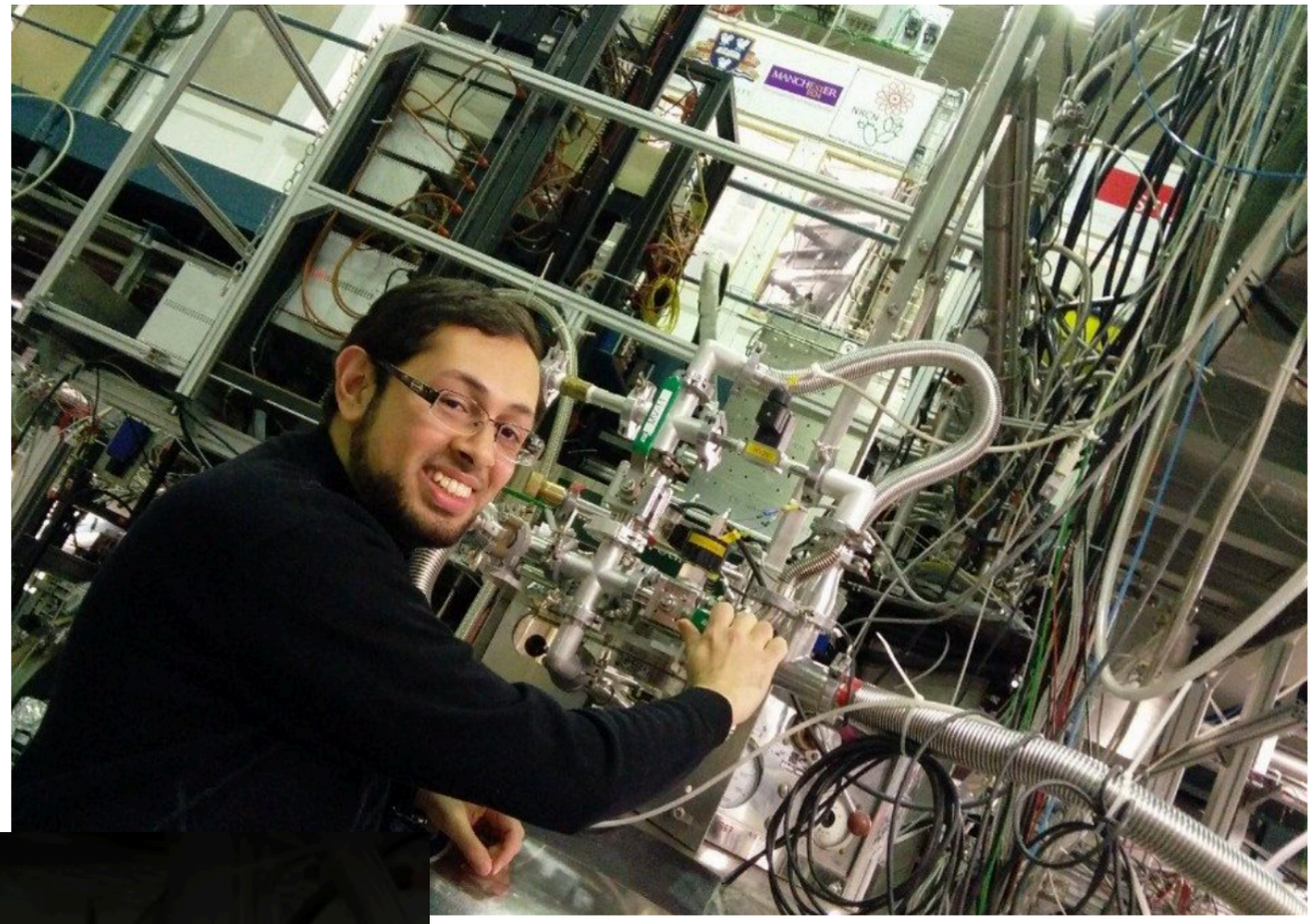
Courtesy of Sameed

T-MAGAZINE | NEXT STORY

WHERE DID THE ANTIMATTER GO?

A young Pakistani scientist at CERN explores the fundamental questions about the mysterious elusive material

Dr Muhammed Sameed, Life Member of KSS: An Integral Part of the Recent Groundbreaking Experiment on Antimatter at CERN



er of KSS: An Integral Part of the Recent Groundbreaking Experiment on

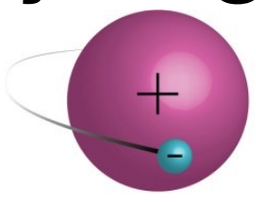
eed, Life Member of Khwarizmi Science Society and a Pakistani physicist working
xperiment team members for achieving the groundbreaking laser cooling of anti-
on the cover of Nature magazine, issue April 2021! This is the first time in history
novement in atoms with the use of photons, has been successfully applied to
unterpart to matter.

ALPHA-g

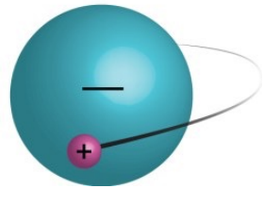
(2018)

Motivation for Antimatter Gravity

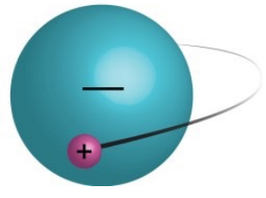
Hydrogen

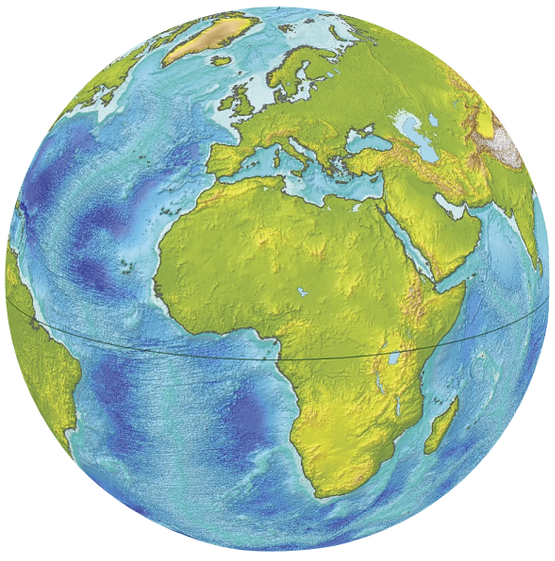


Antihydrogen

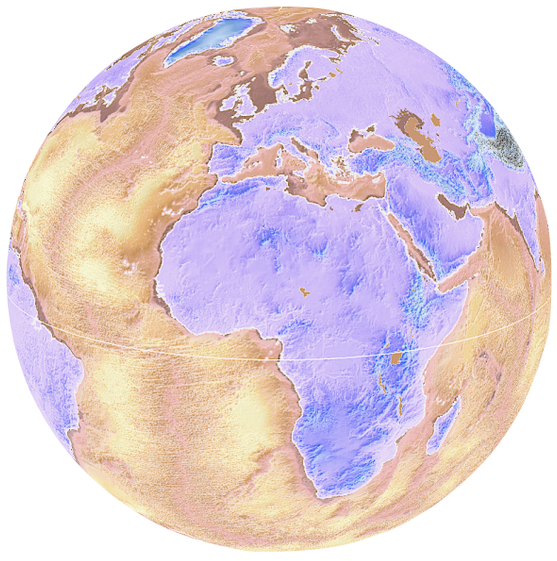


Antihydrogen

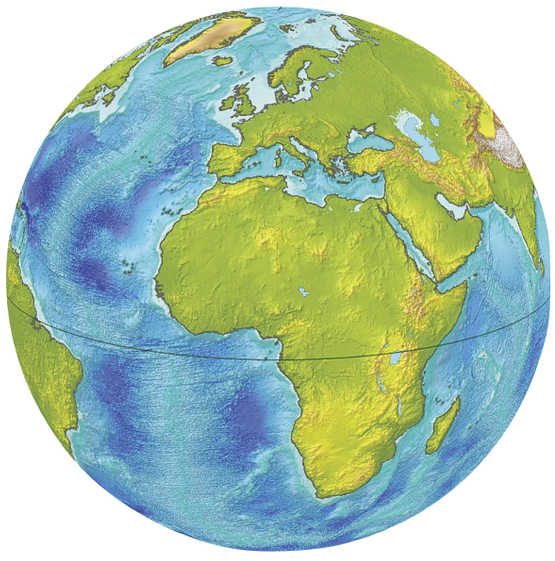




Earth



Anti-Earth

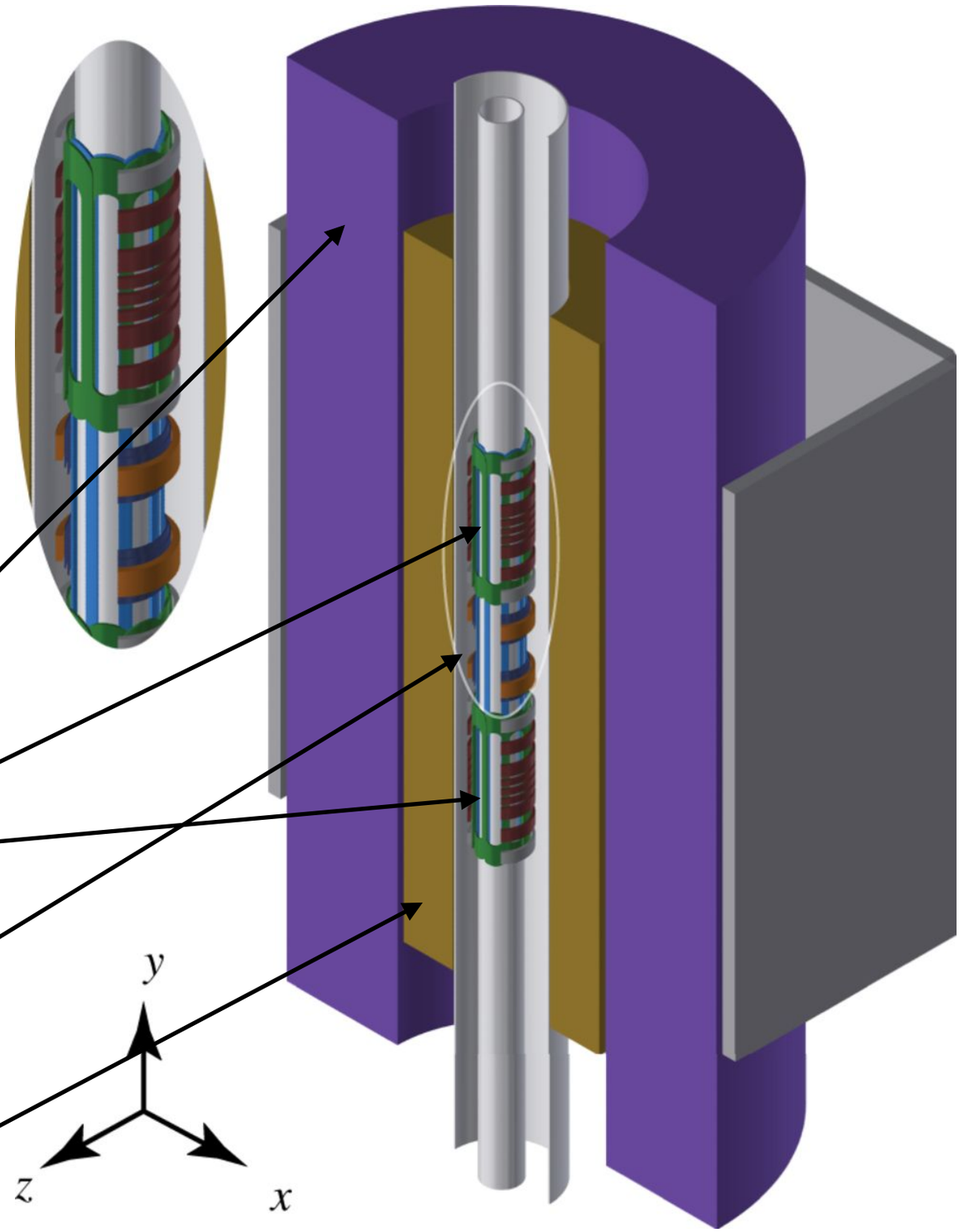


Earth

ALPHA-g

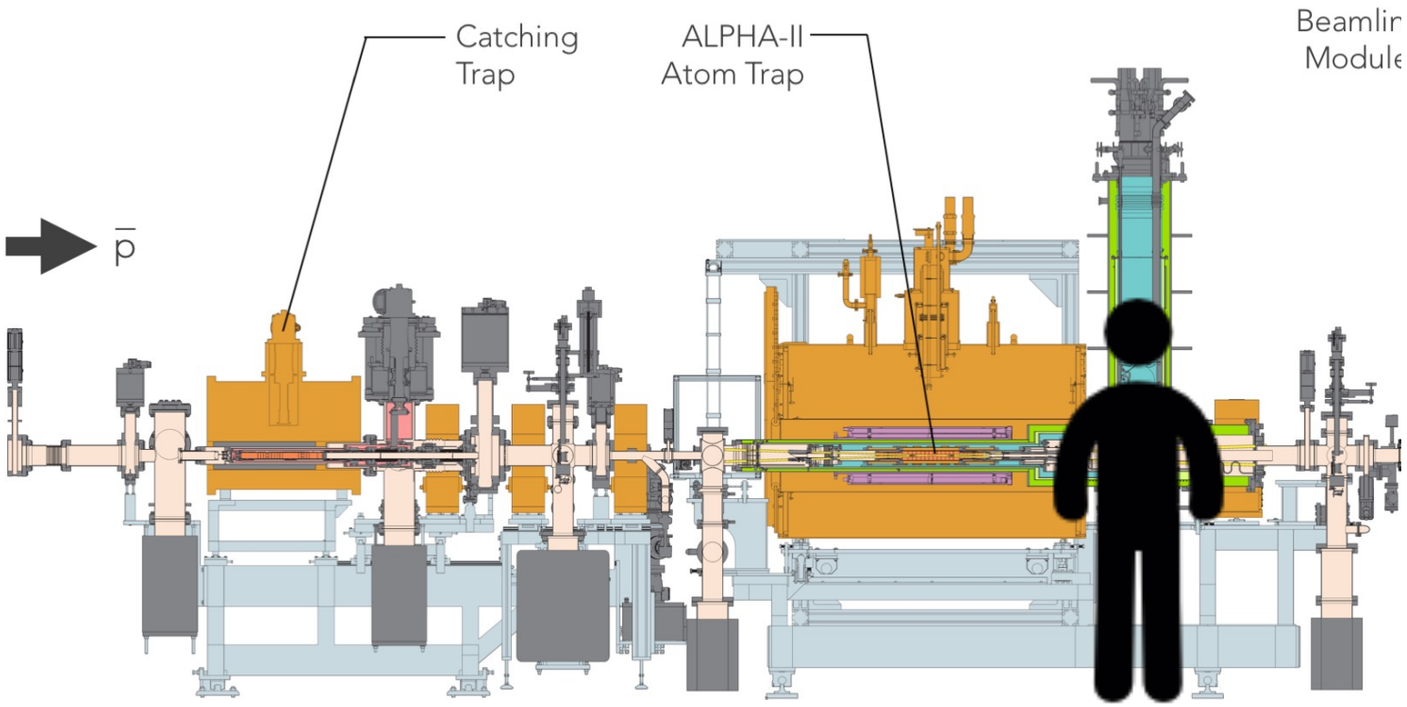
- Conceptually simple experiment:
  1. Create and trap antihydrogen atoms in a vertical trap
  2. Release the atoms
  3. Observe the annihilation distribution of the released atoms

- ALPHA-g features
  - 3m long, 50cm bore superconducting solenoid to provide background magnetic field
  - Two independent and identical antihydrogen traps to cancel systematics
  - One analysis trap in the center for precision measurements
  - A radial time-projection chamber (rTPC) annihilation detector



ALPHA-g Status (Jan 2018)

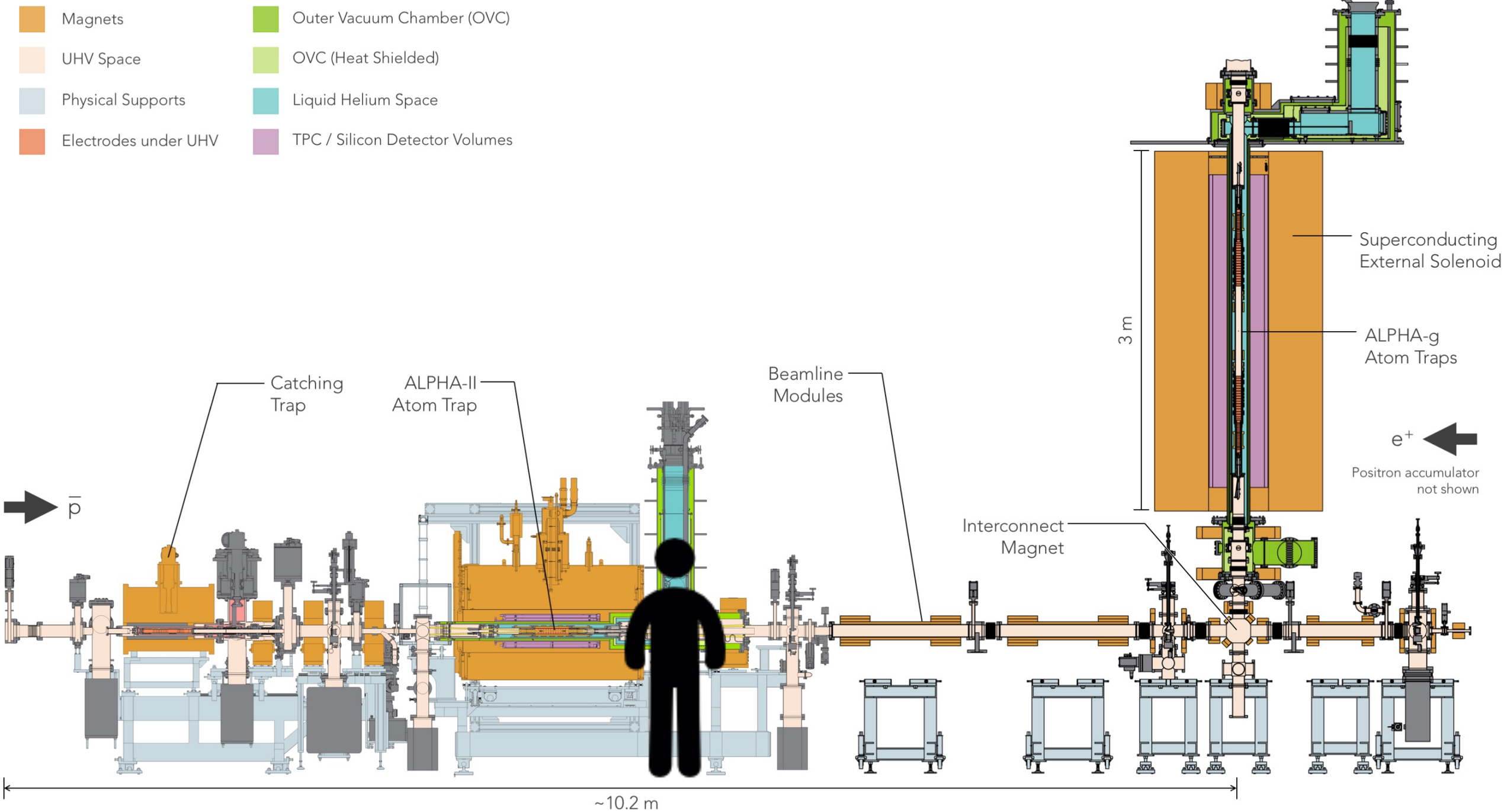
Magnets
UHV Space
Physical Supports
Electrodes under UHV
Outer Vacuum Chamber (OVC)
OVC (Heat Shielded)
Liquid Helium Space
TPC / Silicon Detector Volumes



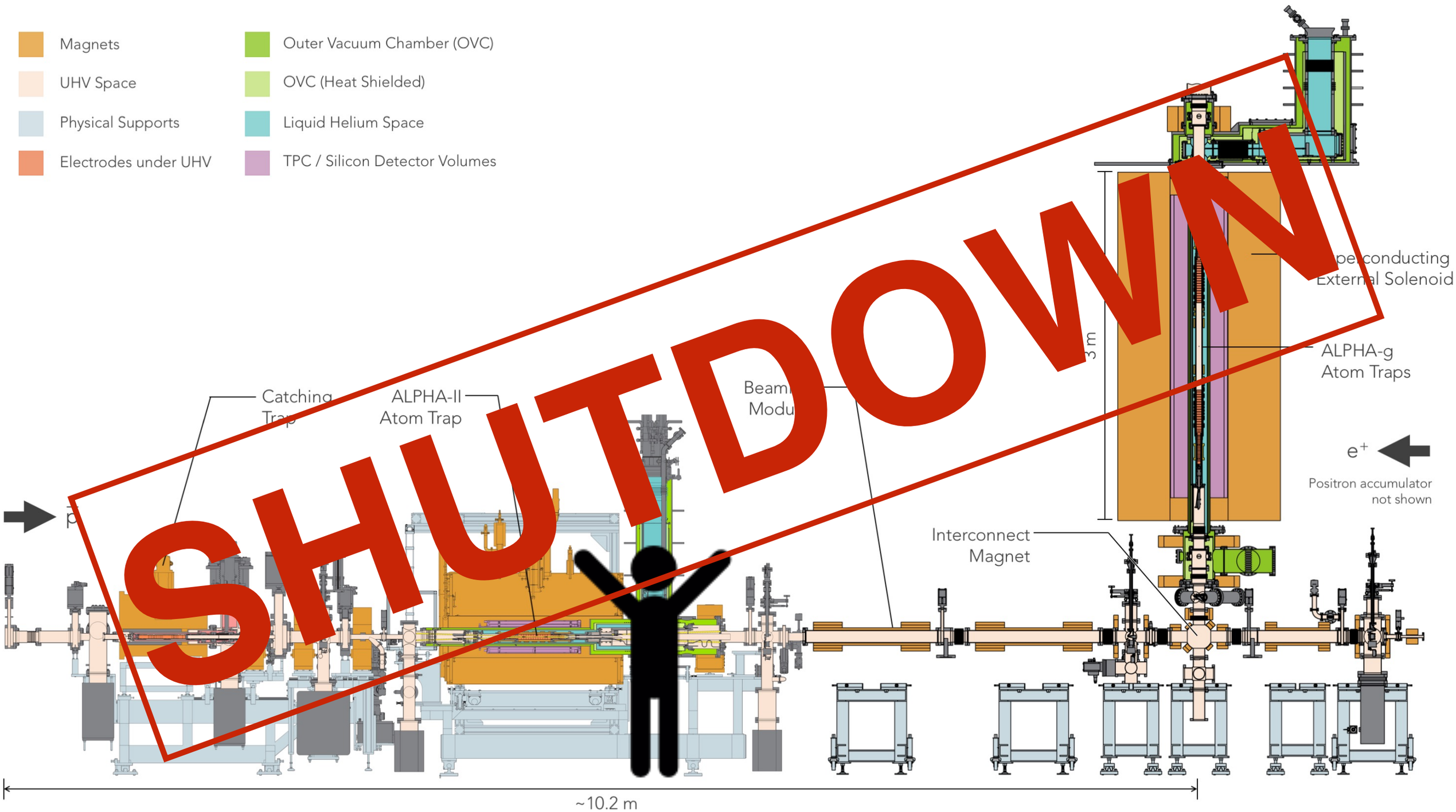
e^+

Positron accumulator not shown

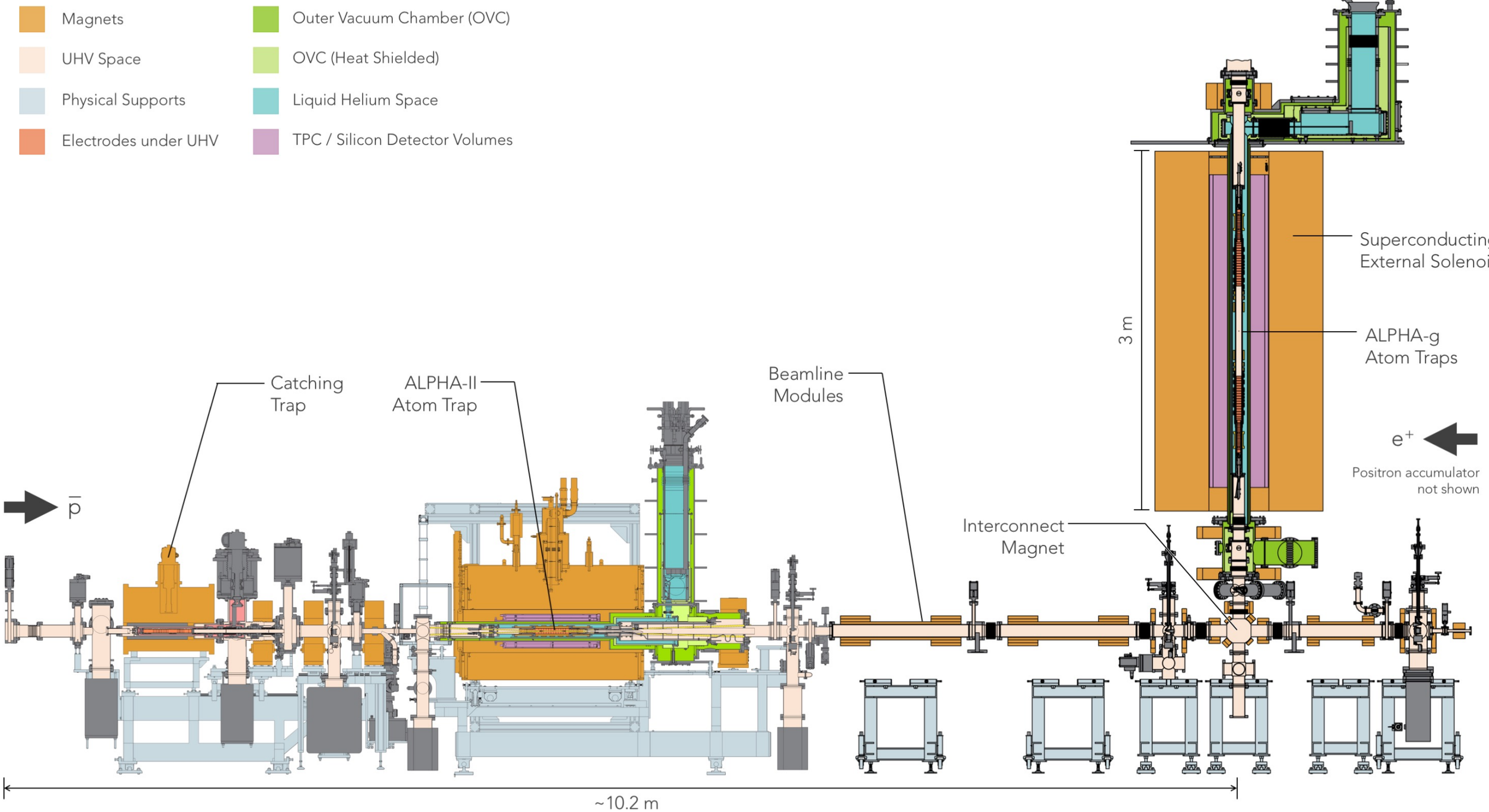
ALPHA-g Target (Sep 2018)



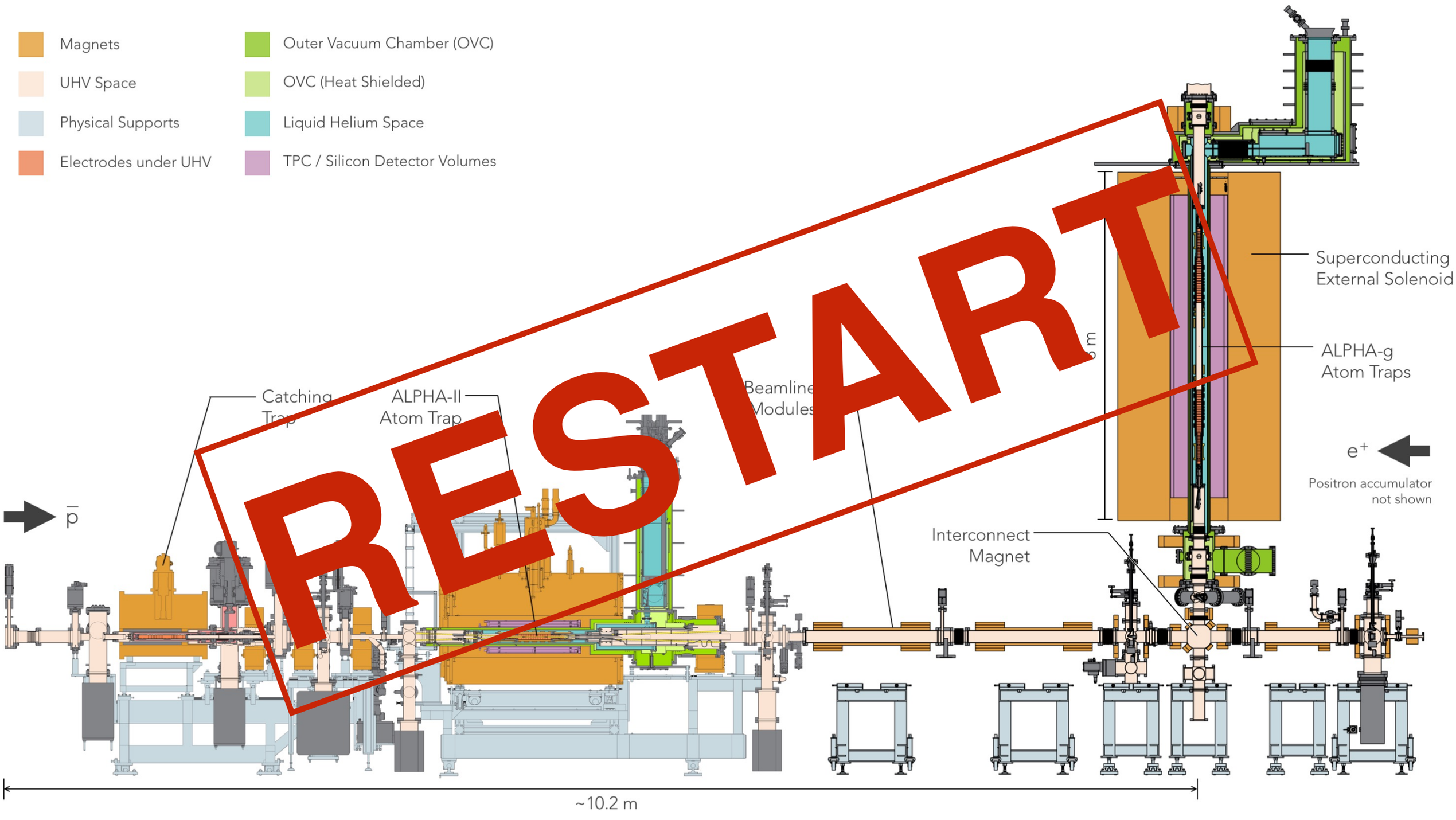
ALPHA-g Completed (Nov 2018)



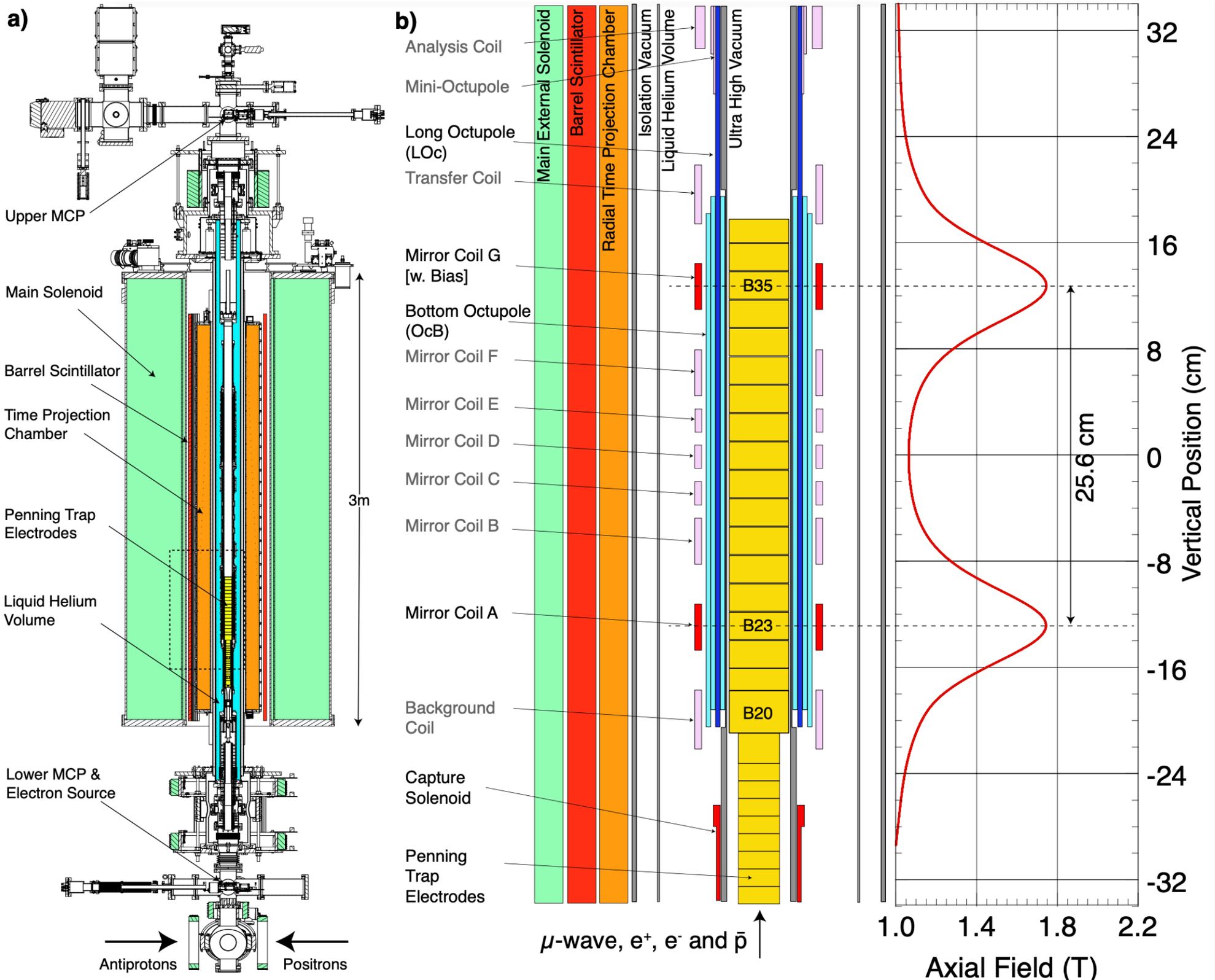
ALPHA-g Upgrades (2019 - 2021)



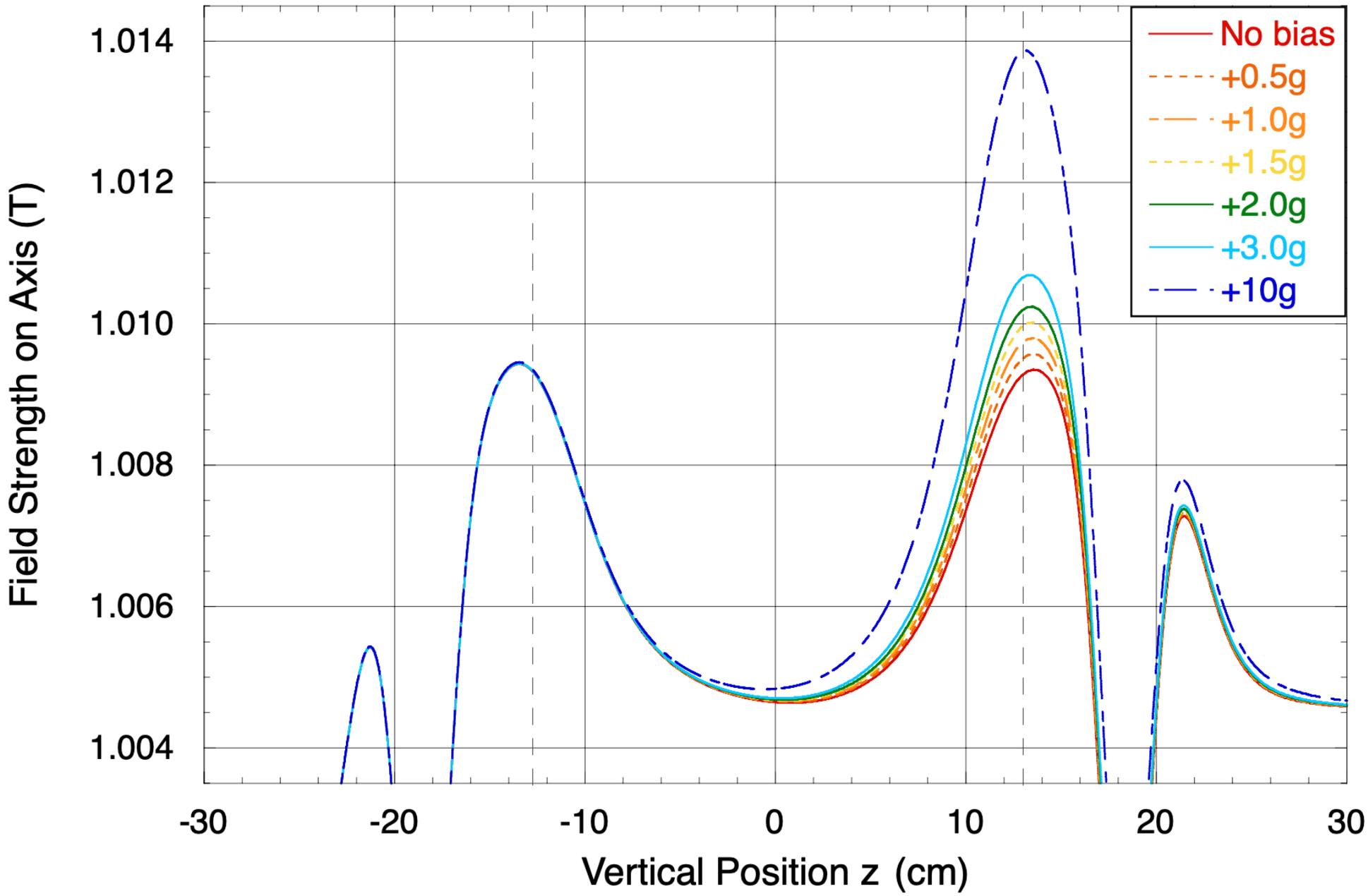
ALPHA-g Restart (April 2022)



ALPHA-g Restart (April 2022 - Now)



ALPHA-g Restart (April 2022 - Now)



ALPHA-g Restart (April 2022 - Now)

Results Coming Soon!

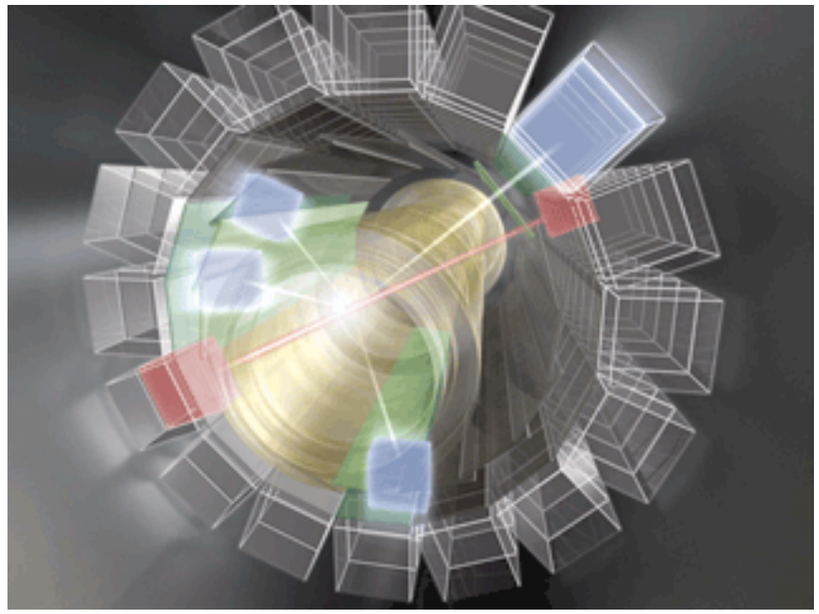
Where does this leave us ?

- We have created and trapped antihydrogen - an atom Nature has never made.

- We have had the first quantum jumps and now additionally a glimpse ($\sim 10^{-12}$) inside…

- We have chilled antihydrogen atoms to less than 1 mK above absolute zero!!!

- We are now ready to make measurements on antimatter gravity… finally! :)



And the missing antimatter ?

- It's still gone.
- We have seen no difference between the anti-world and the normal world so far
- But we are getting very very close to finding out where it is hiding! :)

WHAT'S IN A BANANA?

Potassium

An average b | of potassium

3 naturally occurrin n: K^{39}, K^{40}, and K^{41}

For naturally c 17 ppm is K^{40}

K^{40} is unstable ar of 3.938×10^{16} s

1 out of every 100 oduces a positron

Bananas => Potassium => Antimatter!!!

WHAT'S IN A BANANA?

Bananas => Potassium => Antimatter!!!

1 banana = 450mg of potassium

= 6.93 x 10^{21} atoms of potassium

= 8.11 x 10^{17} atoms of K^{40}

= 21 decays of K^{40} per second

= 1 positron produced every 81 minutes

DURING A 1-HOUR LECTURE
~1 POSITRONS EMITTED BY A BANANA

WHAT'S THE ANTIMATTER WITH YOU?

I'M GOING BANANAS!

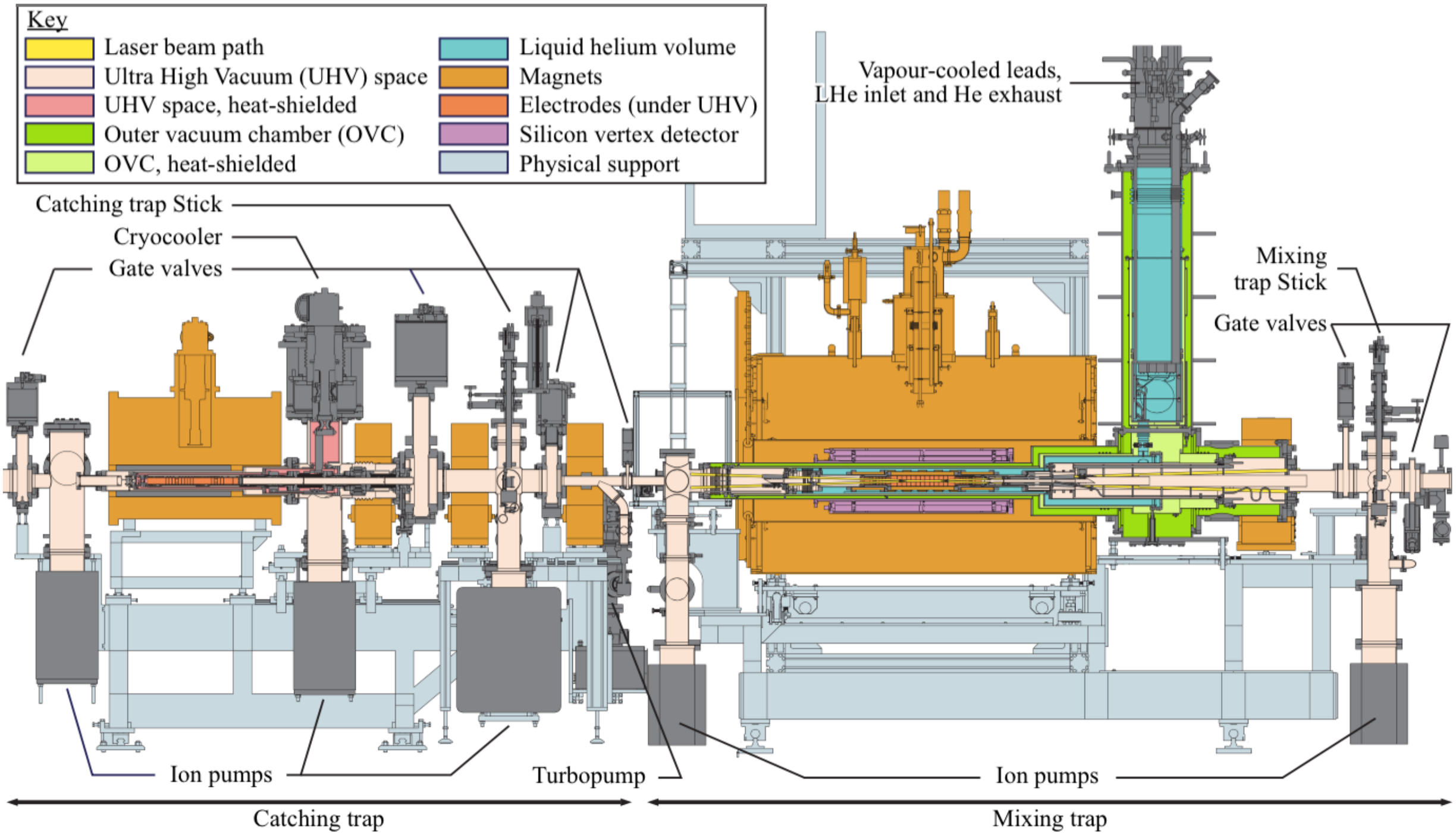
Summary

- Antimatter is real
- We can create and trap antimatter
- We can see and study antimatter (with our detectors)
- We can use antimatter (for example in medical imaging)
- Antimatter physics is really cool and really fun!

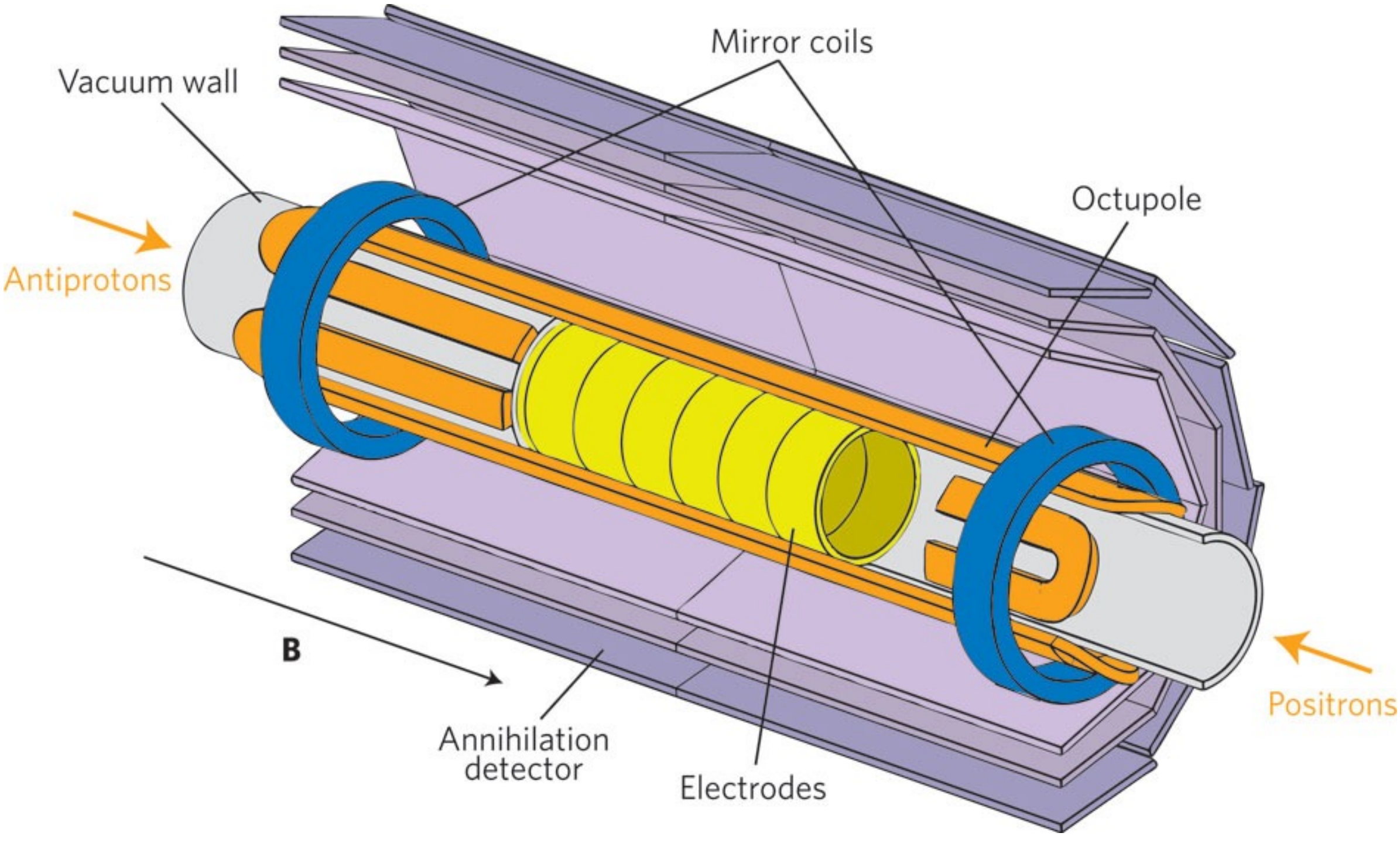
Thank You!

Questions?

ALPHA-2 EXPERIMENT



ALPHA-2 EXPERIMENT



ANTIMATTER VS DARK MATTER

Quarks

Up

Charm

Top

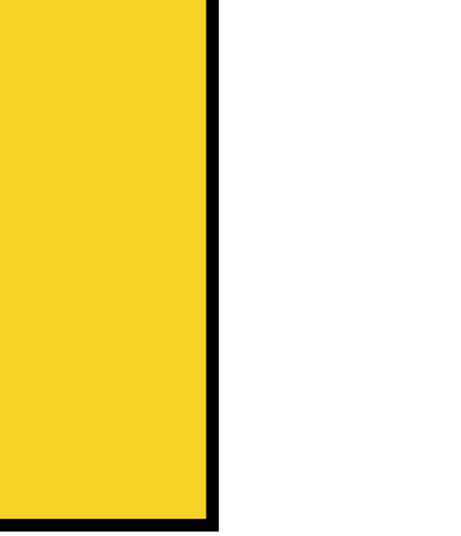
Leptons

Electron

Muon

Tau

DARK MATTER



Down

Strange

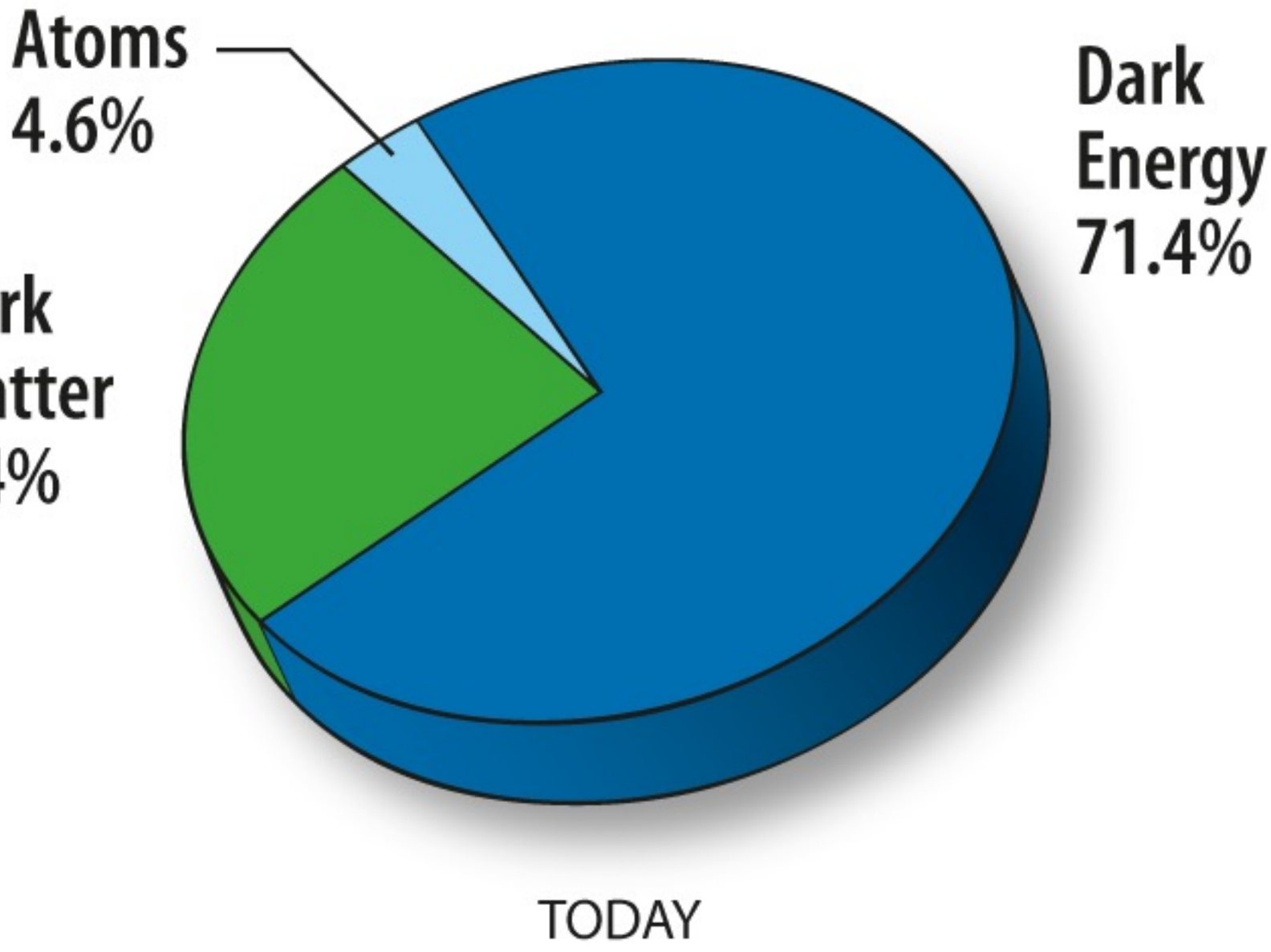
Bottom

Electron Neutrino

Muon Neutrino

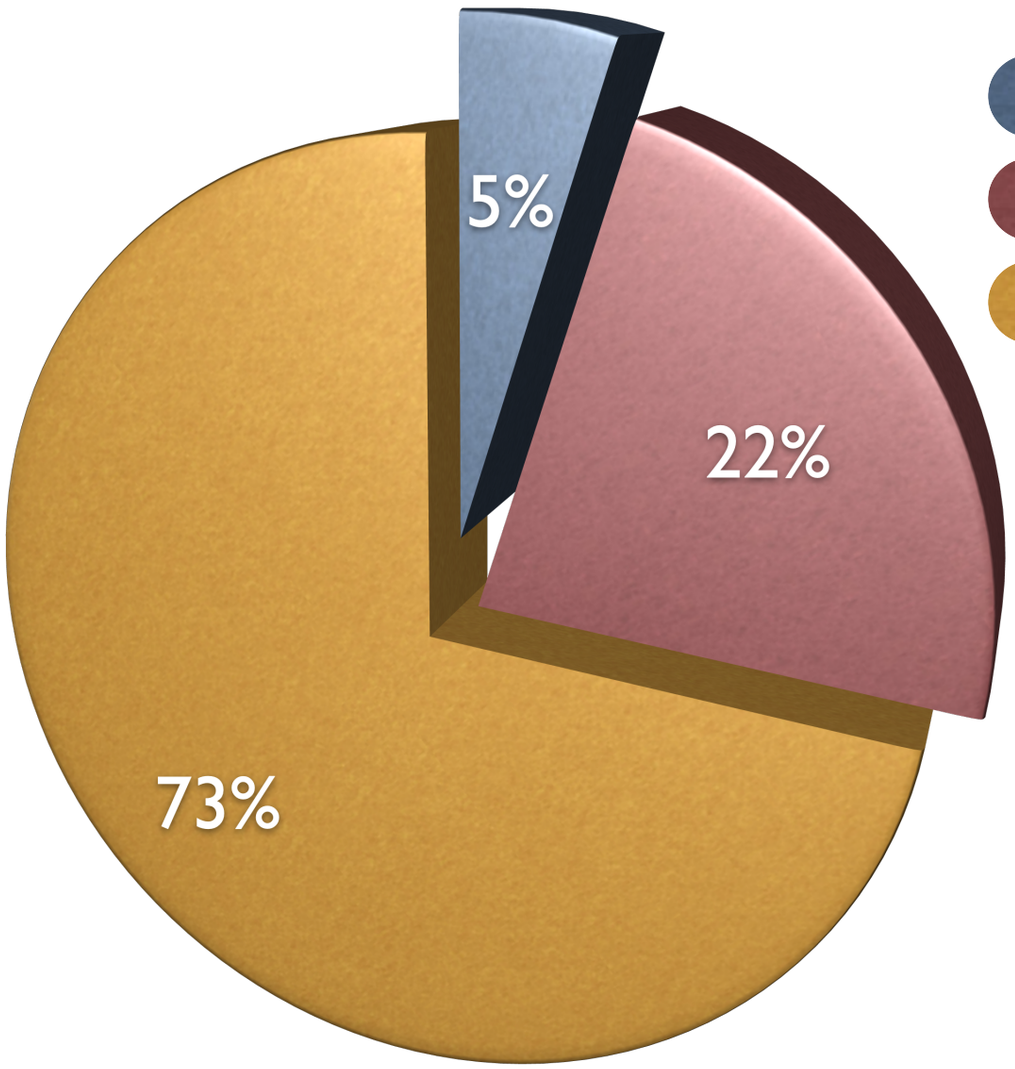
Tau Neutrino

ANTIMATTER
VS
DARK MATTER



DARK MATTER

Energy Budget of The Universe

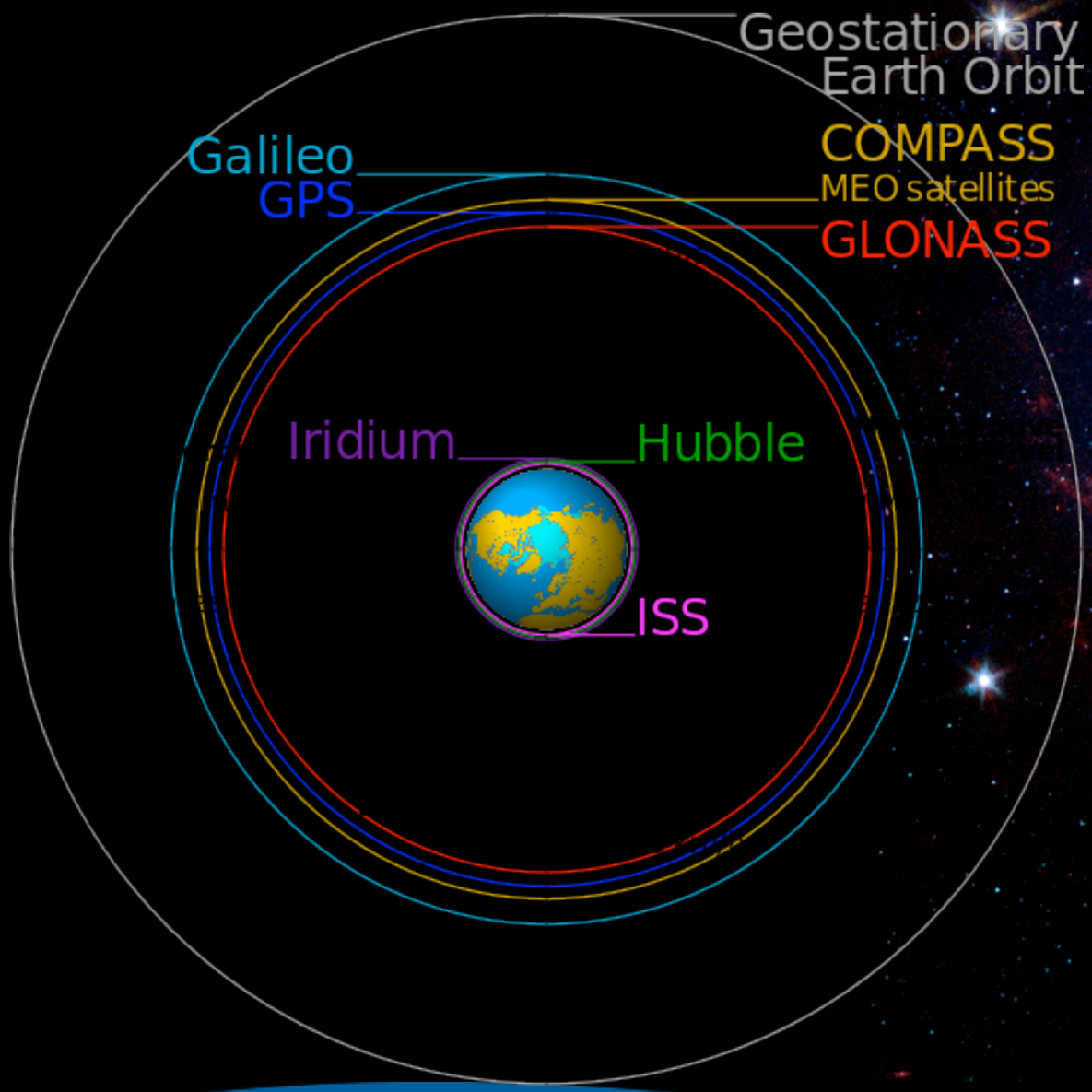


- Known [normal matter]
- Known unknowns [dark matter]
- Unknown unknowns [dark energy]

Antimatter ? : 0%

Swansea University
Prifysgol Abertawe

Dark Matter !?



Swansea University
Prifysgol Abertawe


Thank you
for listening!