The mystery of antimatter

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CERN guide

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Many thanks to Tommy Eriksson, AF expert, for a lot of the slides

Source of antimatter

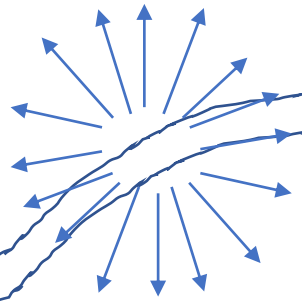
Releases a positron every 75 minutes on average

$$^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{18}\mathrm{Ar} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$$

0.001 % of decays

Talk overview

big bang



Paul Dirac

theory ?

1

2

3

4

experiments

Andrei Sakharov

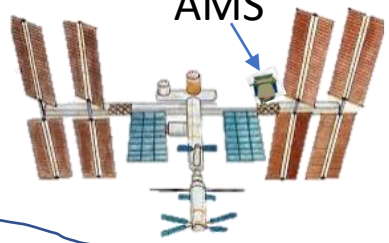
antimatter decelerator

extra low energy antimatter

ALPHA

ASACUSA

AMS



Gbar

antimatter

?

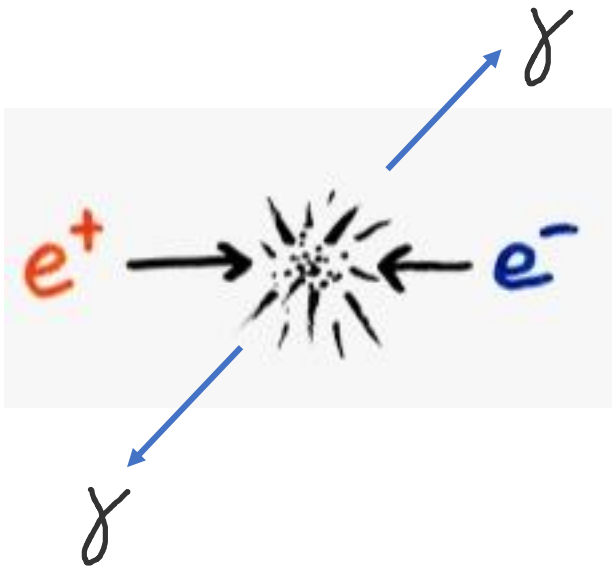
arrival

What is antimatter?

Antimatter is a material composed of antiparticles. These have the same mass as particles of ordinary matter, but have opposite charge and properties, such as lepton and baryon number.

Encounters between a particle and an antiparticle lead to both of them being destroyed (transformed into energetic photons).

positron



electron

Paul Dirac: key discovery

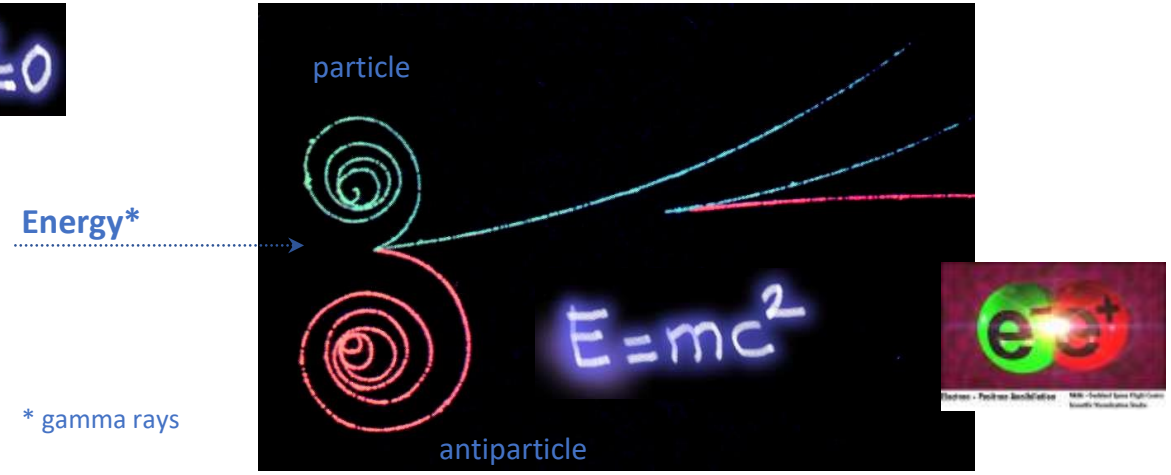
Paul A. M. Dirac

Nobel prize 1933

Relativity + Quantum Theory

⇒ 'Antiparticles'

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



* gamma rays

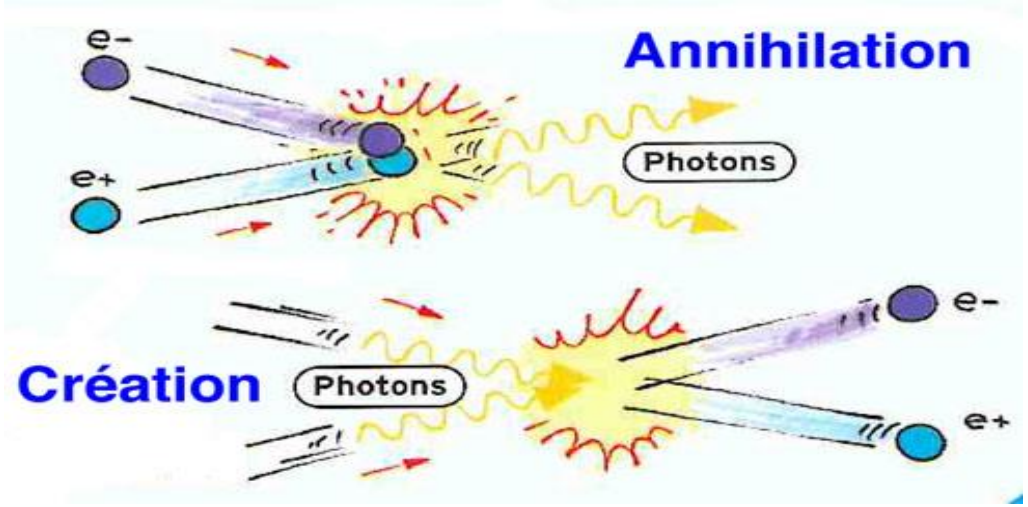
Properties of antimatter

Every particle has an antiparticle

Example:

Electron: **Mass = 0.511 (MeV)** **Charge = -1**

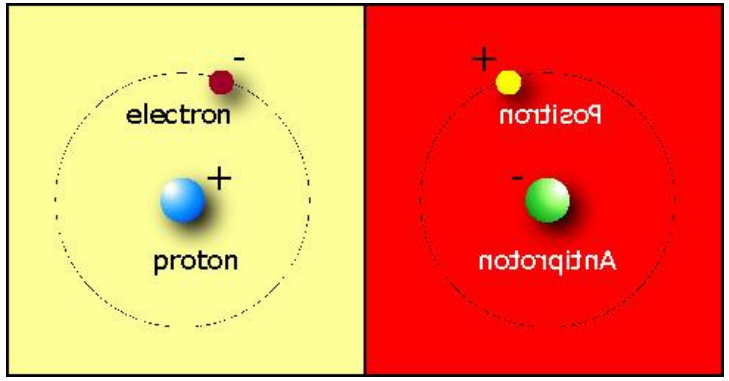
Positron: **Mass = 0.511 (MeV)** **Charge = +1**



Is the universe symmetric?

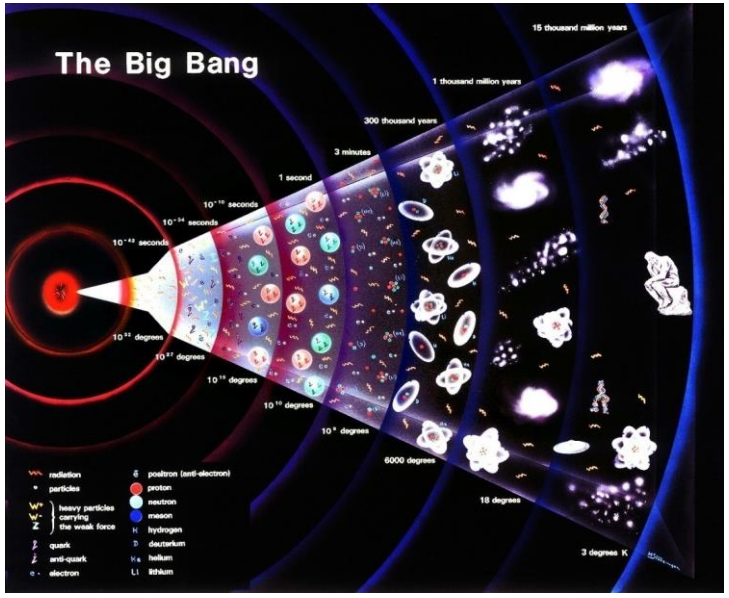
1933 Dirac (from his Nobel lecture)

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons.



It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind.

Let’s go to the origin



Big Bang

13.7 billion years ago

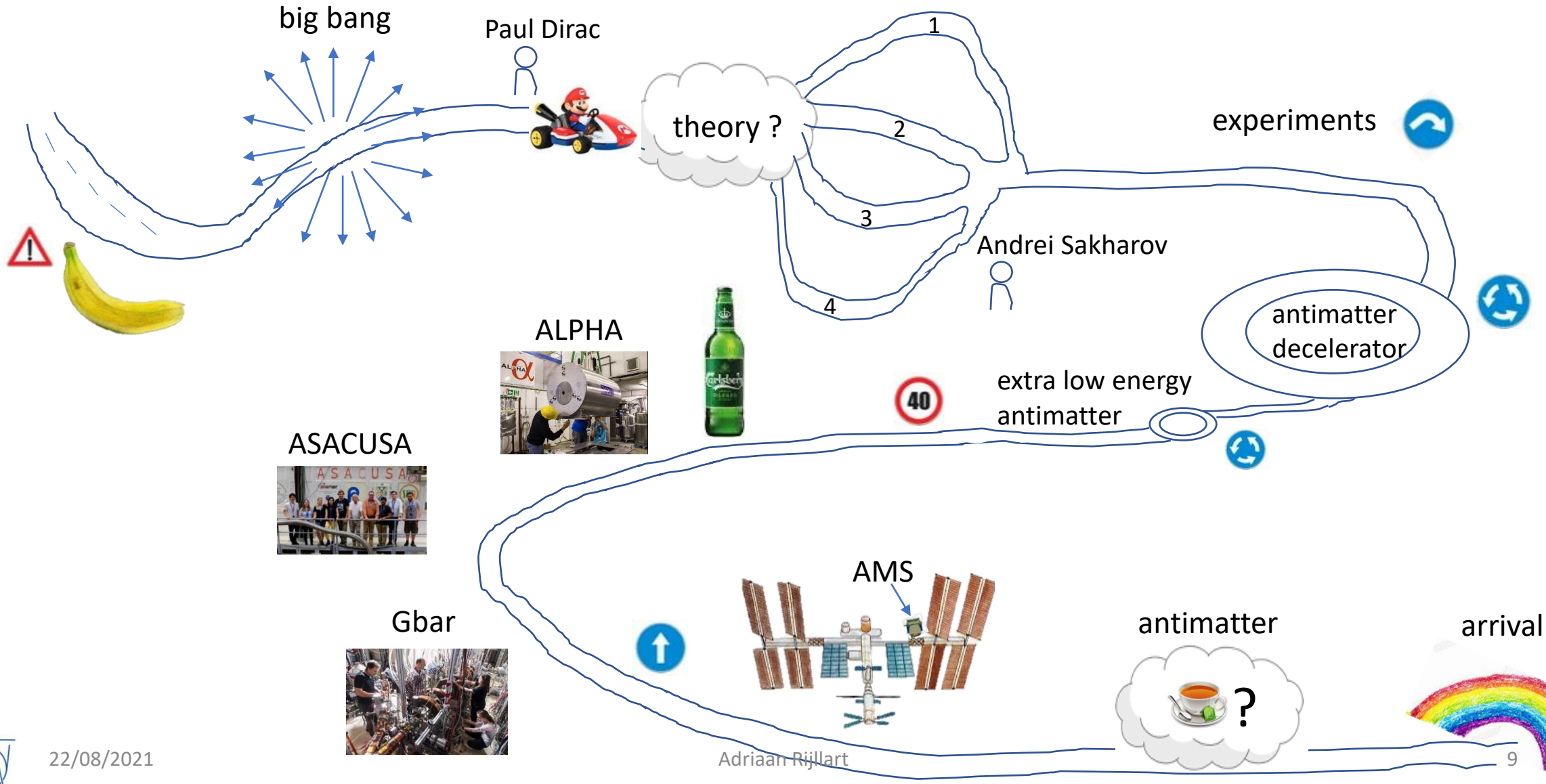
How did the energy transform into mass ?

(…and atoms, stars, planets)

Big Bang: 50 % matter - 50 % antimatter

Now: 100 % matter - 0 % antimatter

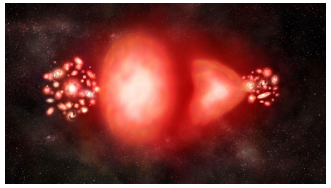
Talk overview



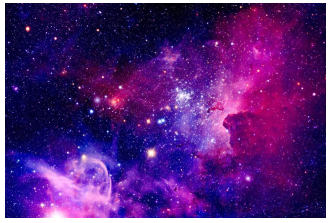
How to explain?

Four theories:

1. Antigravity

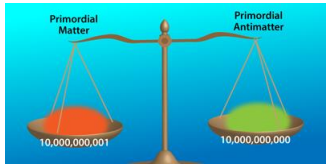


2. Antimatter galaxies

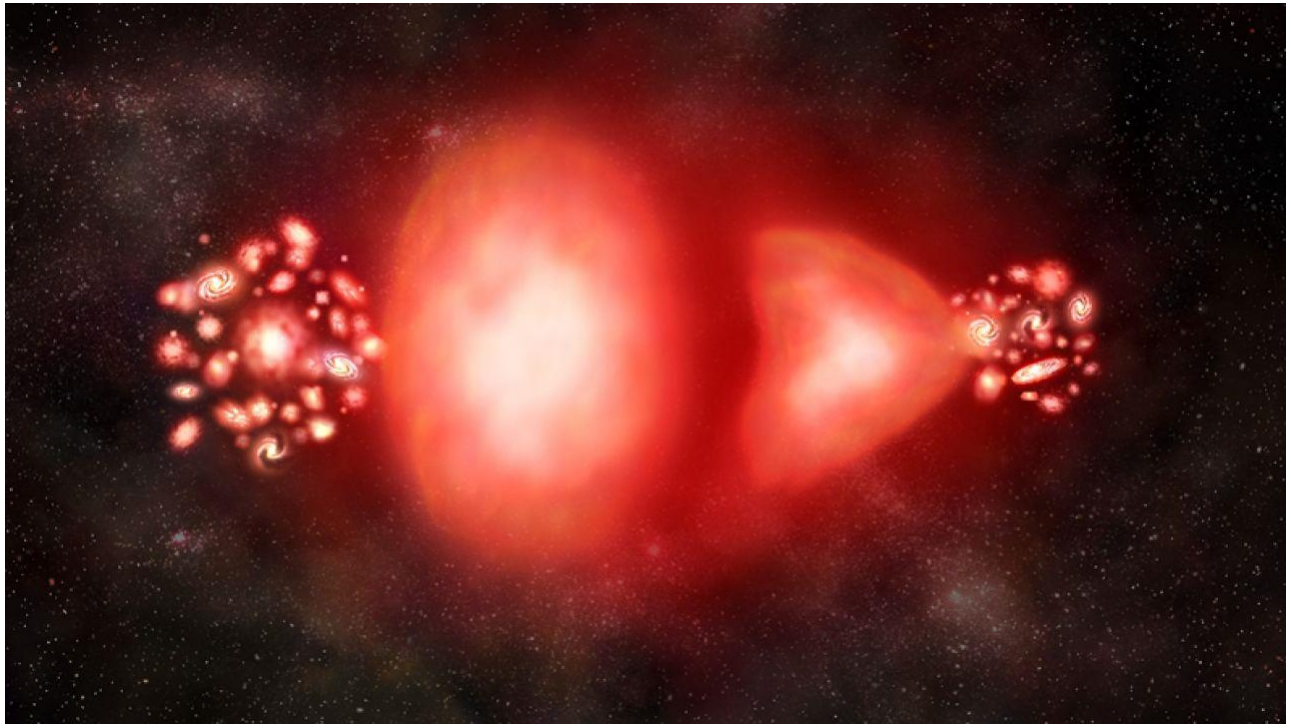


3. Heavy neutrinos

4. Particle asymmetry



1. Antigravity



After the big bang there was equal quantity of matter and antimatter

If matter and antimatter repel each other (antigravity) then they separated and occupy different parts of the universe

How to detect?

2. Antimatter galaxies

After the big bang there was equal quantity of matter and antimatter

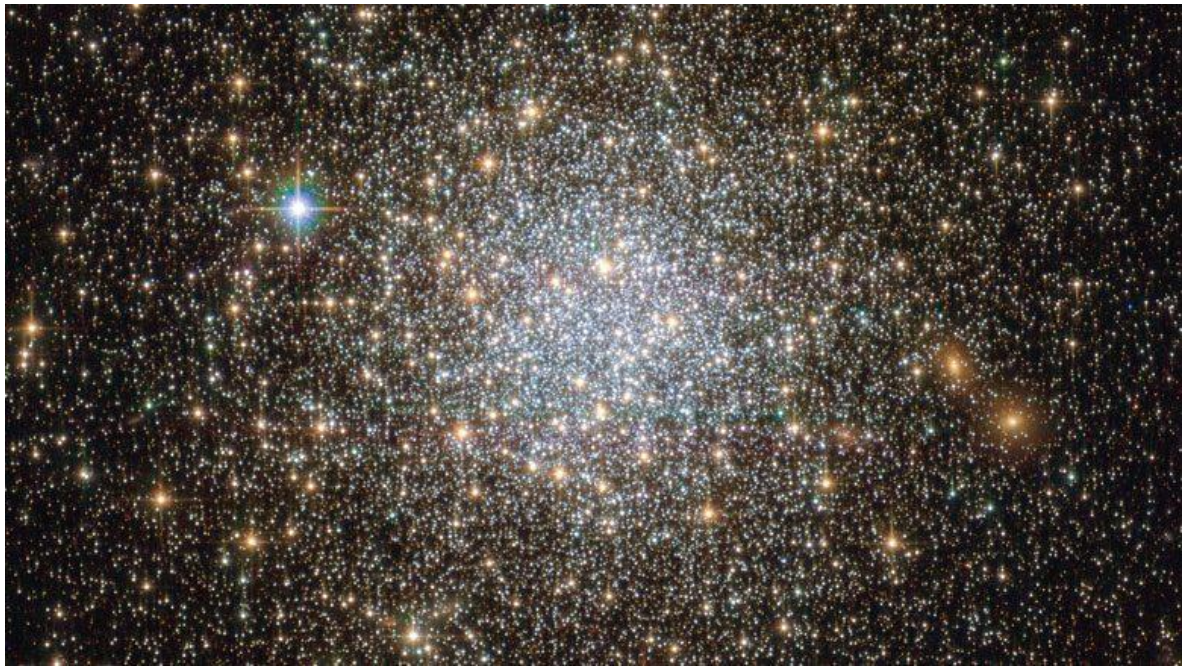
Half of the galaxies are matter, the other half antimatter

This would make intergalactic gamma rays emerging from collisions between matter and antimatter (which we don't see)

Perhaps the Leidenfrost effect at the boundaries, where matter and antimatter collide, could reduce the gamma rays (so we don't see them)

Detect weak gamma rays in between galaxies!

3. Heavy neutrinos



Heavy neutrinos and antineutrinos may have existed in the early universe

CP symmetry breaking, which could happen in light neutrinos (and therefore in heavy neutrinos) could have tipped the balance in favour of matter by asymmetric decay

How to determine this?

Measure CP symmetry breaking in neutrinos!

4. Particle asymmetry

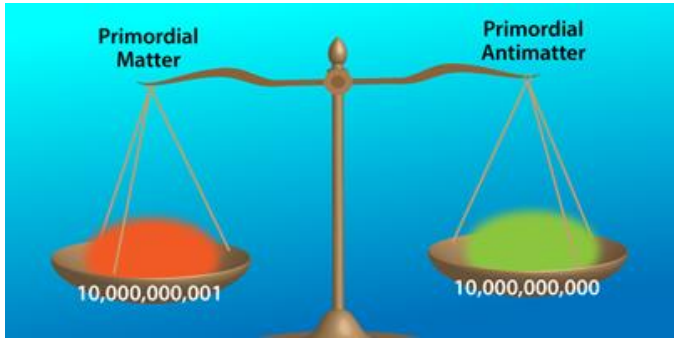
Andrei D. Sakharov
Nobel peace prize 1975

Particles and antiparticles have (slightly) different decay rates*
(*this would break the CPT theorem)

Small imbalance (1,000,000,001 : 1,000,000,000)
Occurs during cool-down of Universe

Most particle-antiparticle pairs annihilate to radiation

Galaxies, stars, planets, us = 'left-over'



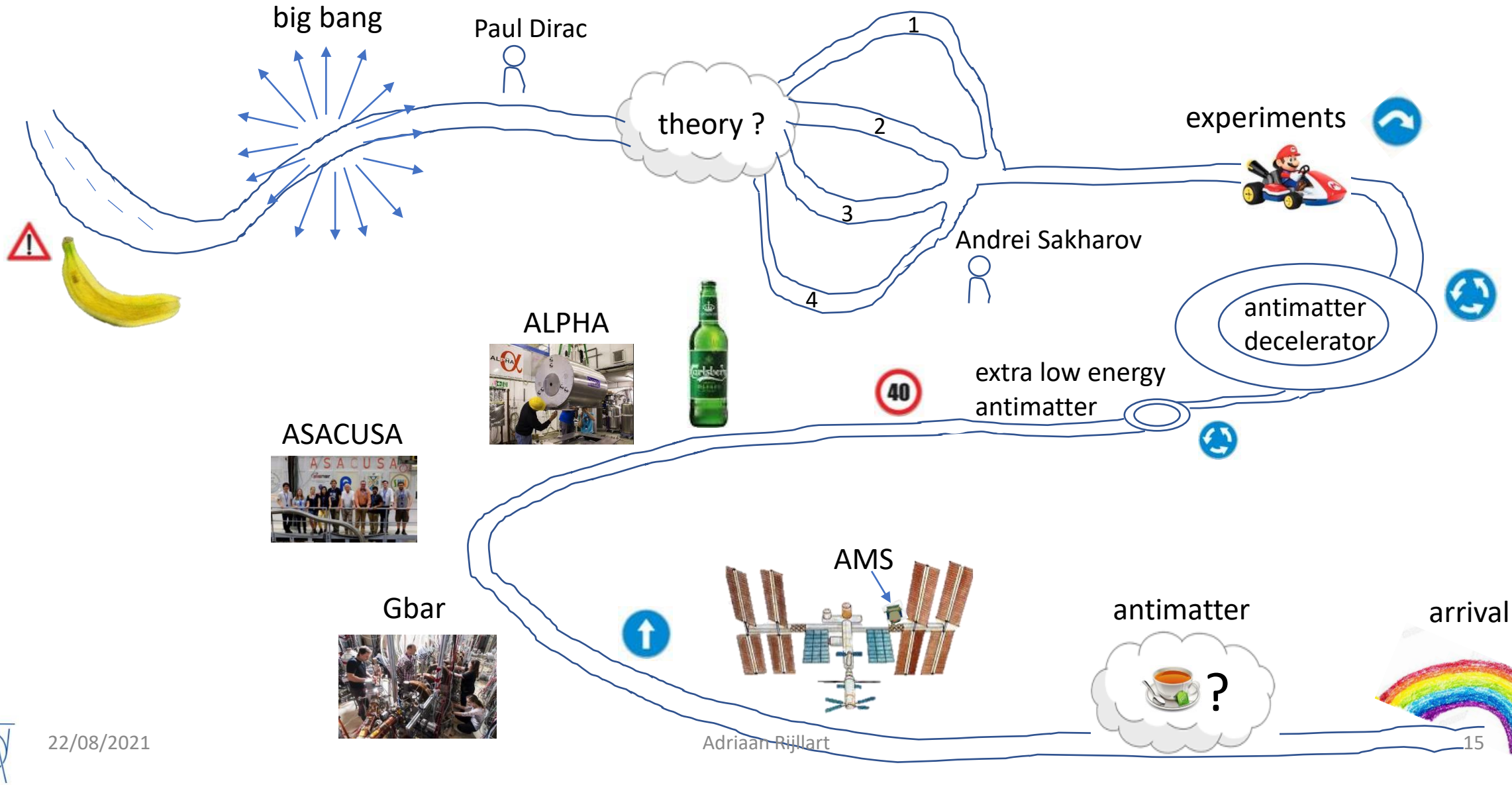
⇒ Could matter and antimatter be different?
⇒ What kind of asymmetry ?

CPT theorem of physics wrong? : "NO" !!

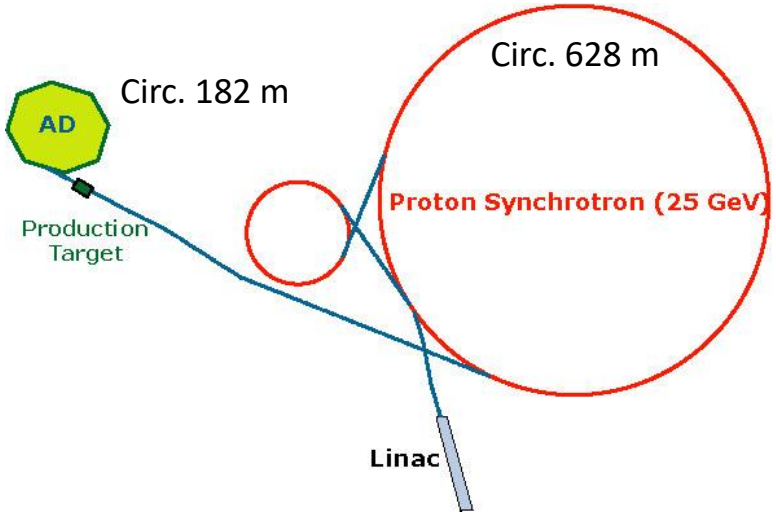
Experimental physicists : "Let's see … "

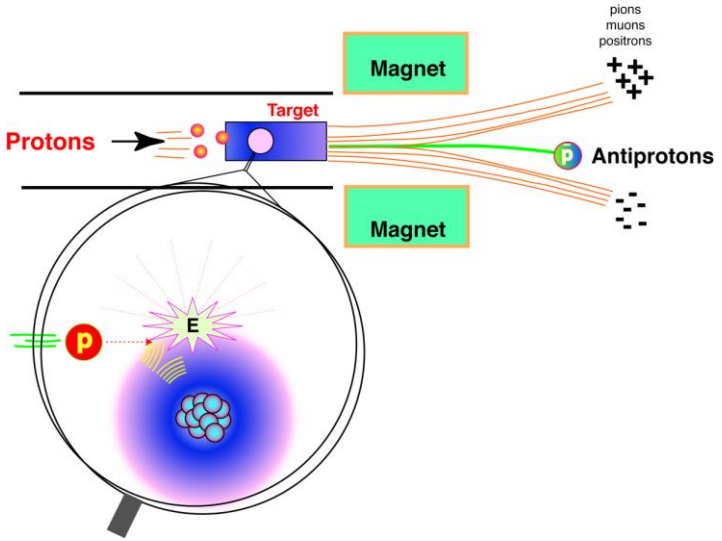
Compare: Mass - charge - magnetic moment - lifetime - gravitation …..

Talk overview



Experimentalists: Let's make antimatter





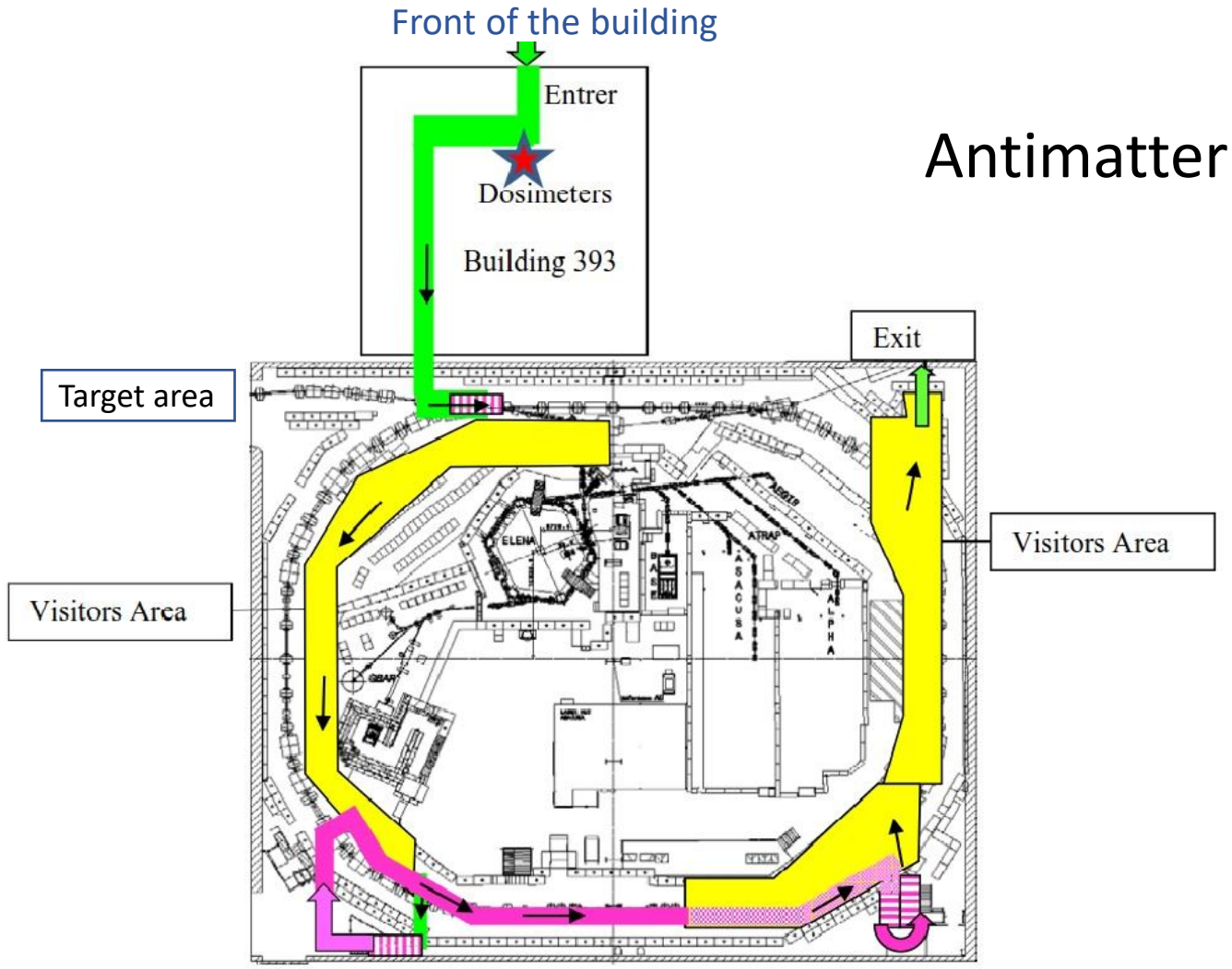
Needs (at least) 6.2 GeV of (proton) energy to produce antiprotons

Use the kinetic energy of 25 GeV protons readily available at the PS

Magnetic fields used to filter particles with correct polarity/energy

50,000,000 antiprotons (per 100 s) available at 5.3 MeV for the AD experiments

Places you will see



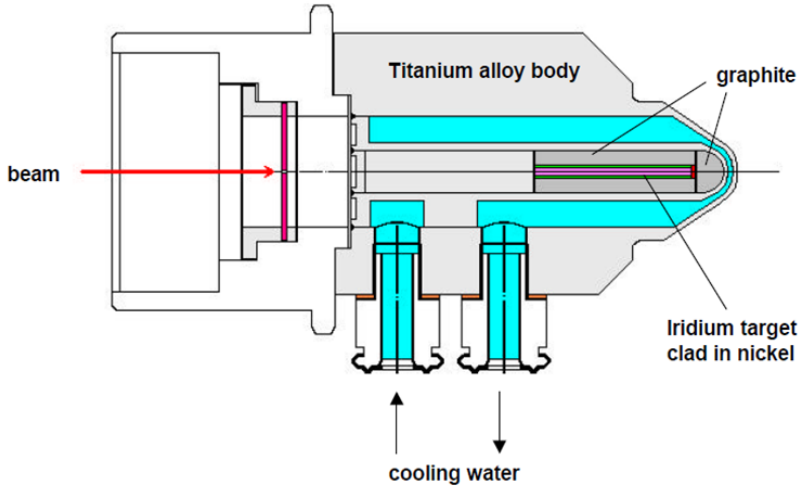
Antimatter factory

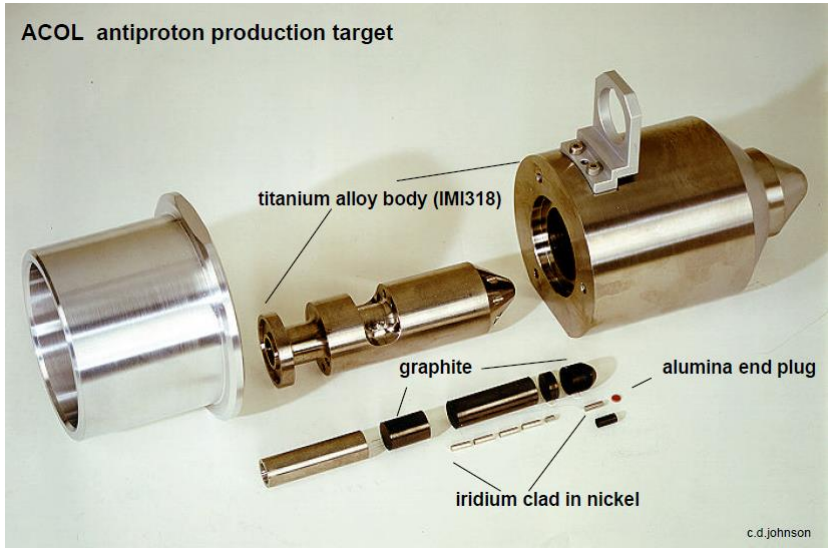
Experimentalists: Let's make antimatter

Shoot protons on a metal: 1.5 x 10^{13} protons yields 5 x 10^{7} antiprotons in the AD

Production target:

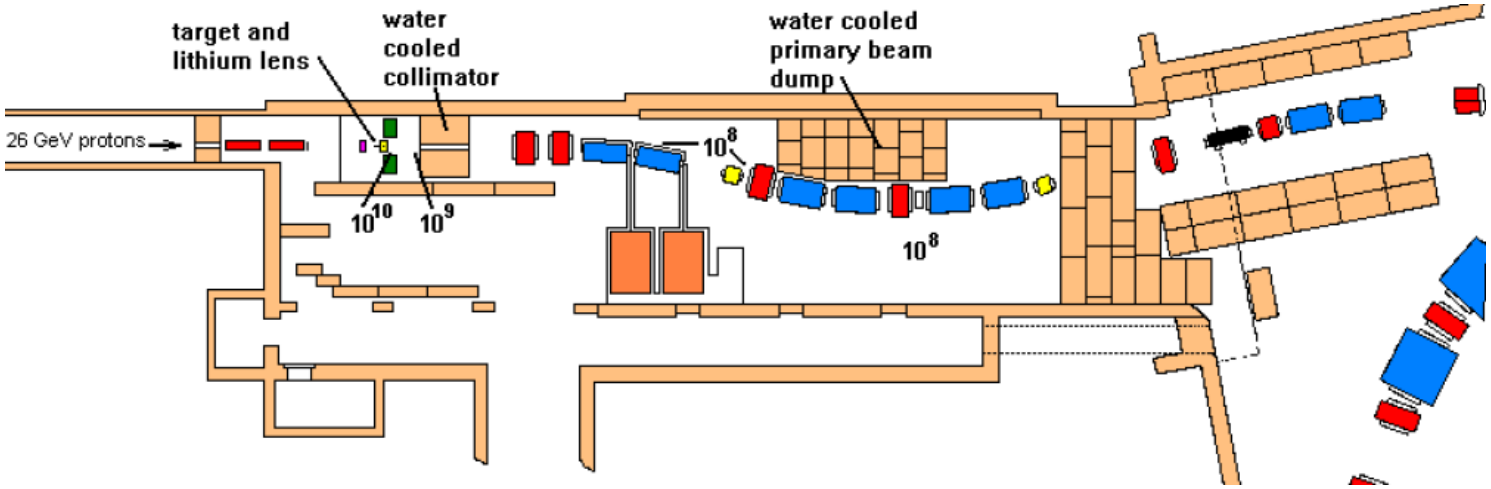
- Iridium production material
- 3*55mm rod
- Graphite cladding
- Water-cooled Ti alloy body





Antiproton production target area

PS



AD

Double spectrometers (reduce the momentum spread of antiprotons and associated particles)

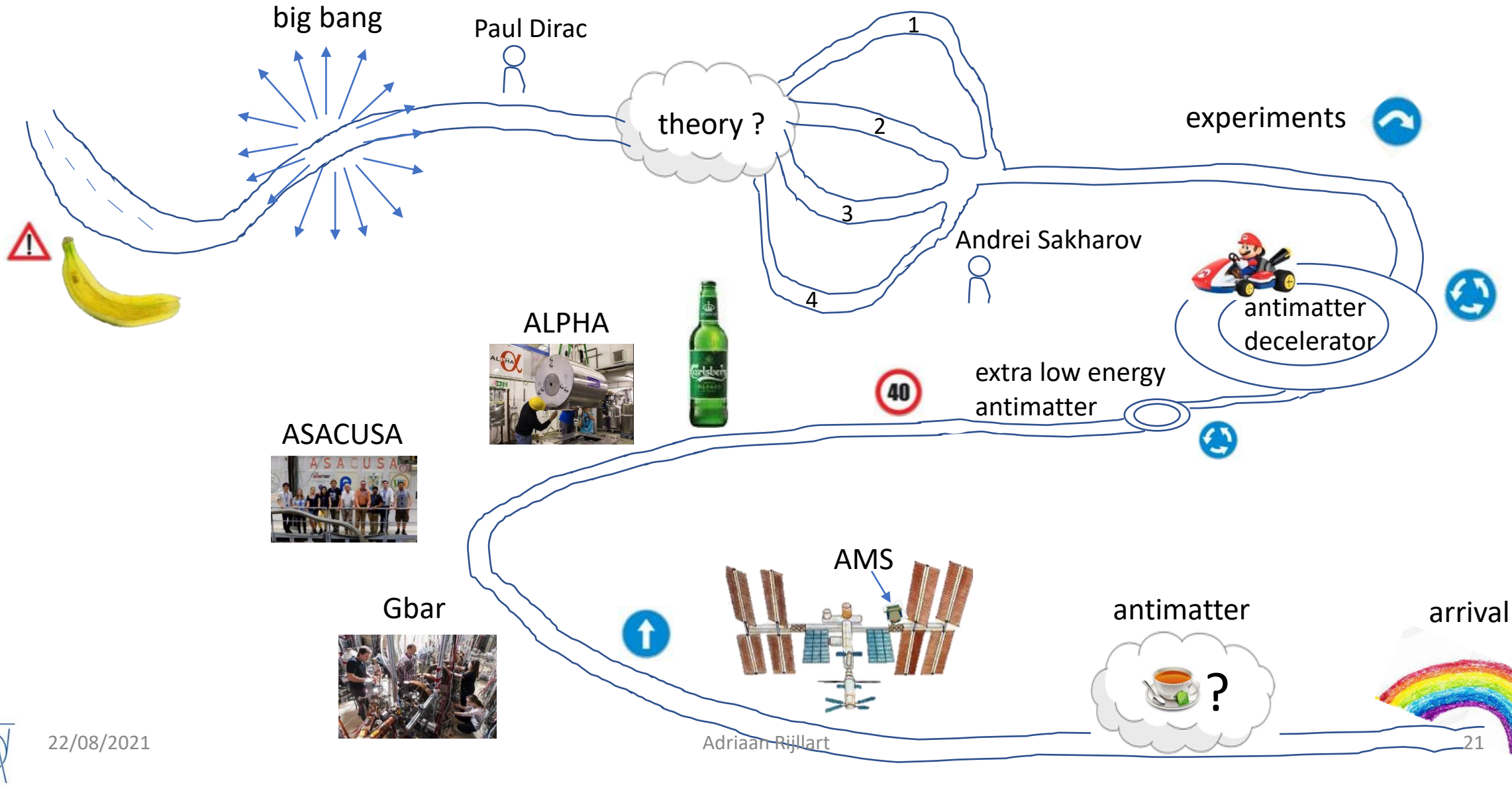
Antiproton Decelerator

Picture of the Antiproton Accumulator (AA) and Antiproton Collector (AC) rings (roof removed)

The outer ring (AC) was retained and converted into AD in 1998

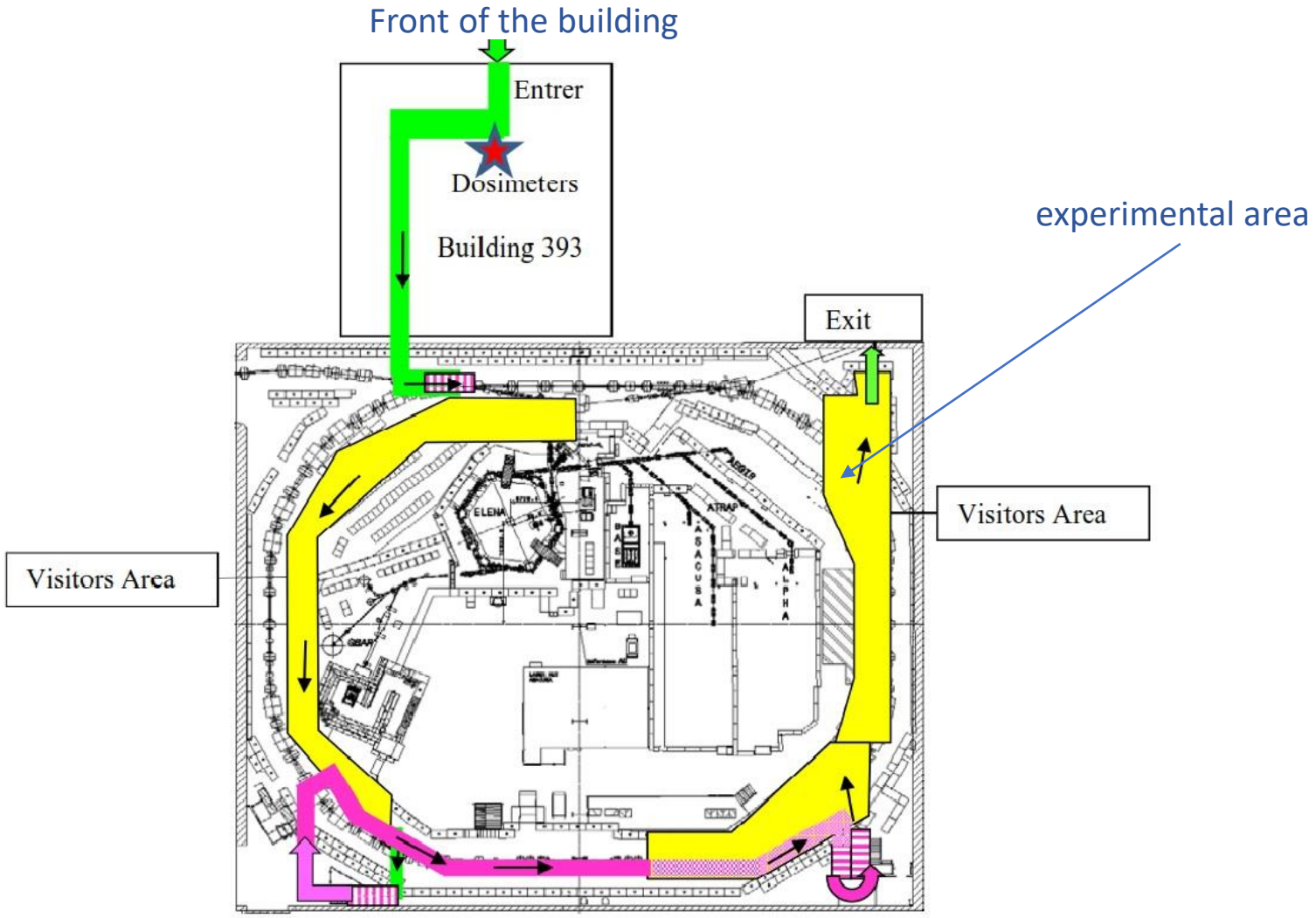
The AA was removed

Talk overview



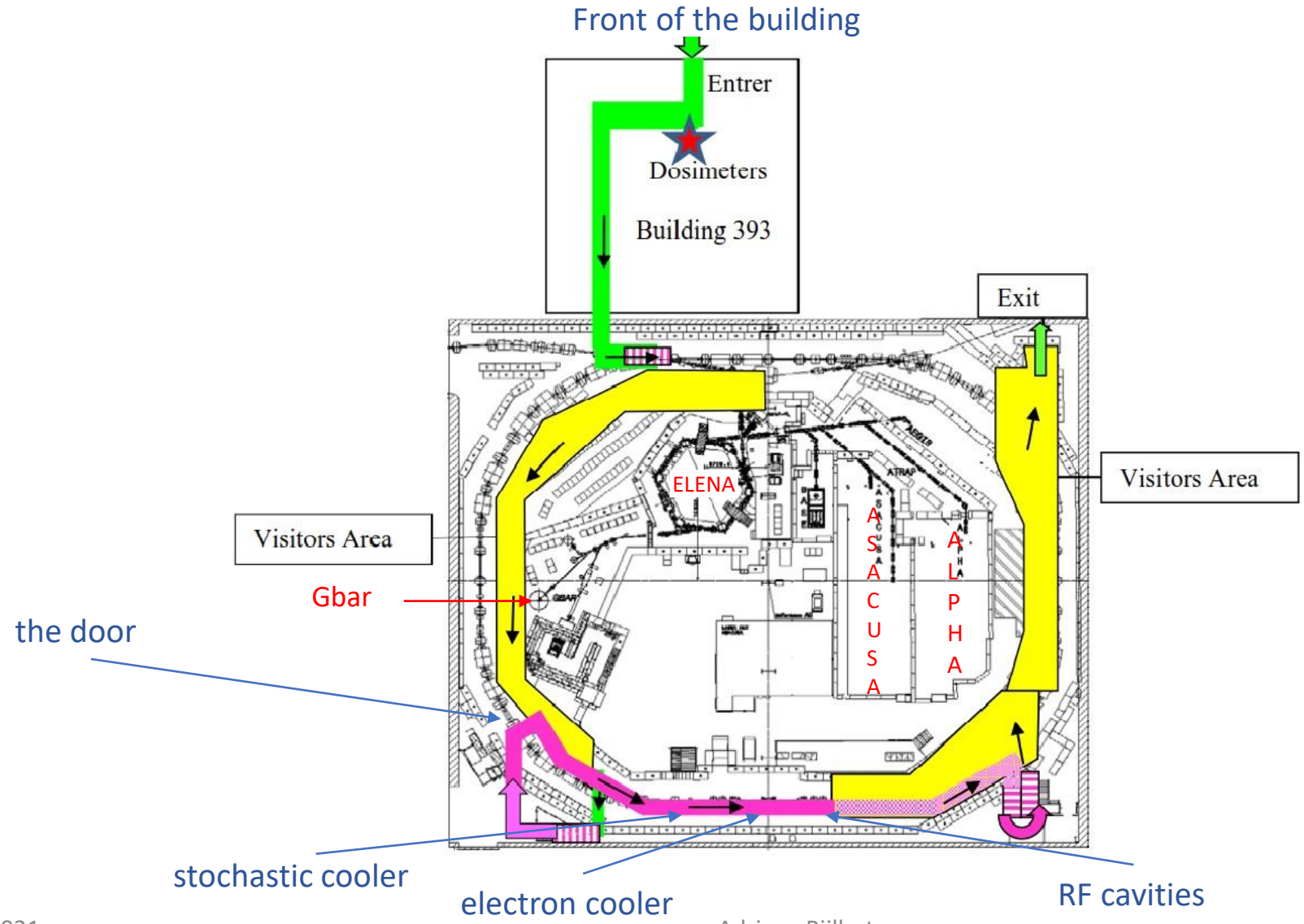
Antimatter factory

Places you will see



Antiproton experiments walkthrough

Places you will see



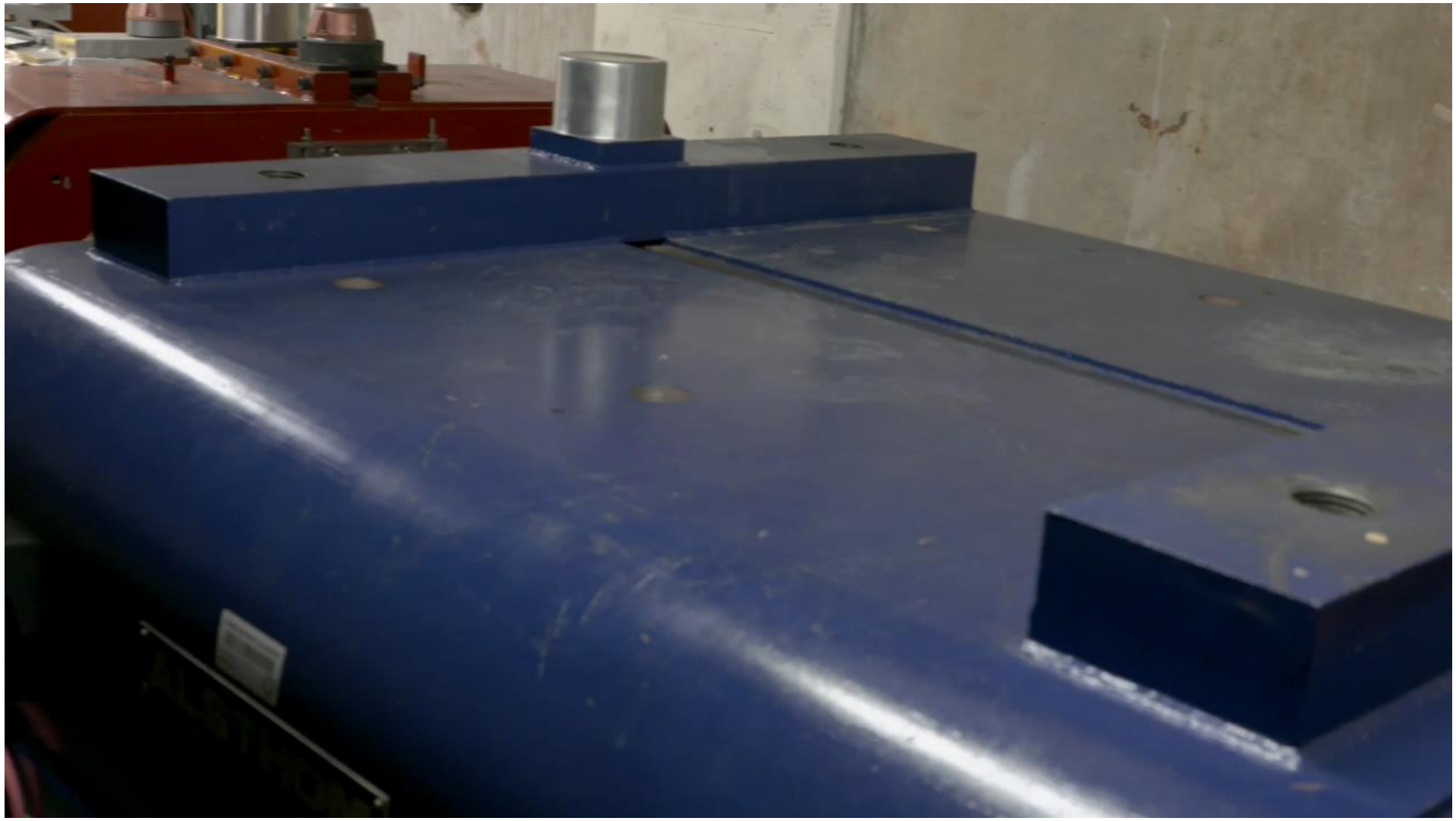
The door

AD ring access point with:

- badge reader
- Database check
- retina scanner
- interlock key
- 1 person at the time check

Similar to the door used in Angels & Demons movie !

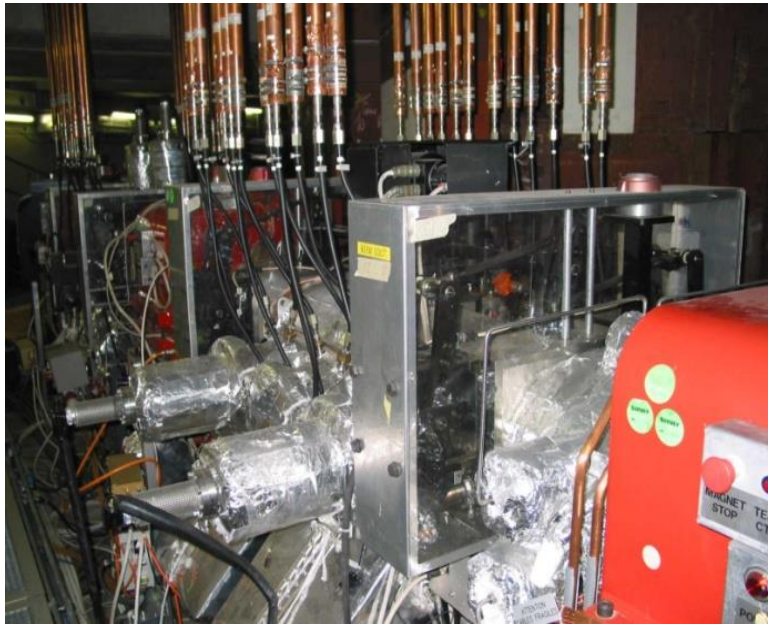
Inside the decelerator



Stochastic cooling of antiprotons

- Invented by Simon Van der Meer (Nobel Prize -84)
- Aim of cooling:
  - reduction of transverse and longitudinal emittances
  - Increase of phase space density
- Pickup and kicker must be correctly placed
- Moving p/u and kicker follow beam size for optimum gain and signal to noise
- Large system bandwidth: 1–1.6 GHz
- Cryogenic cooling of certain components to reduce thermal noise

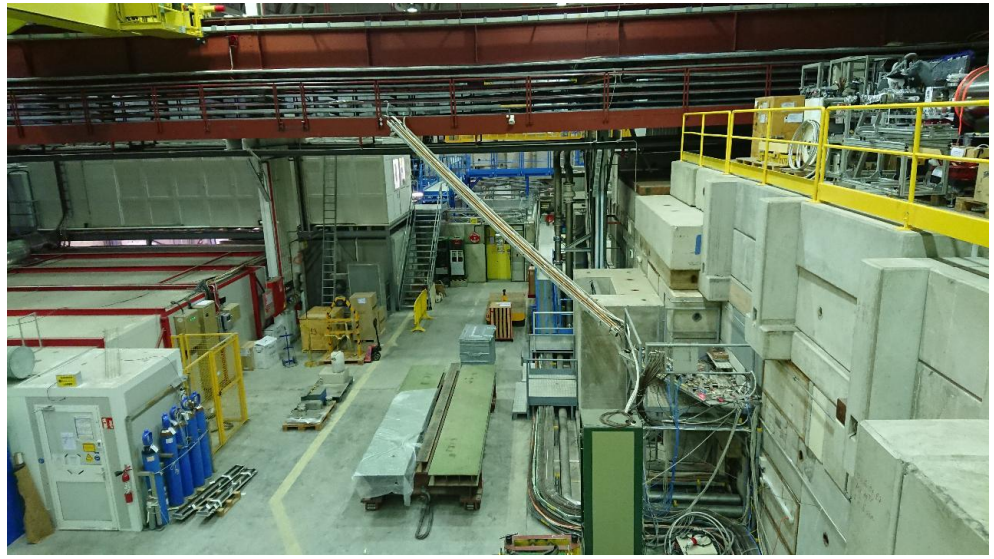
pick up

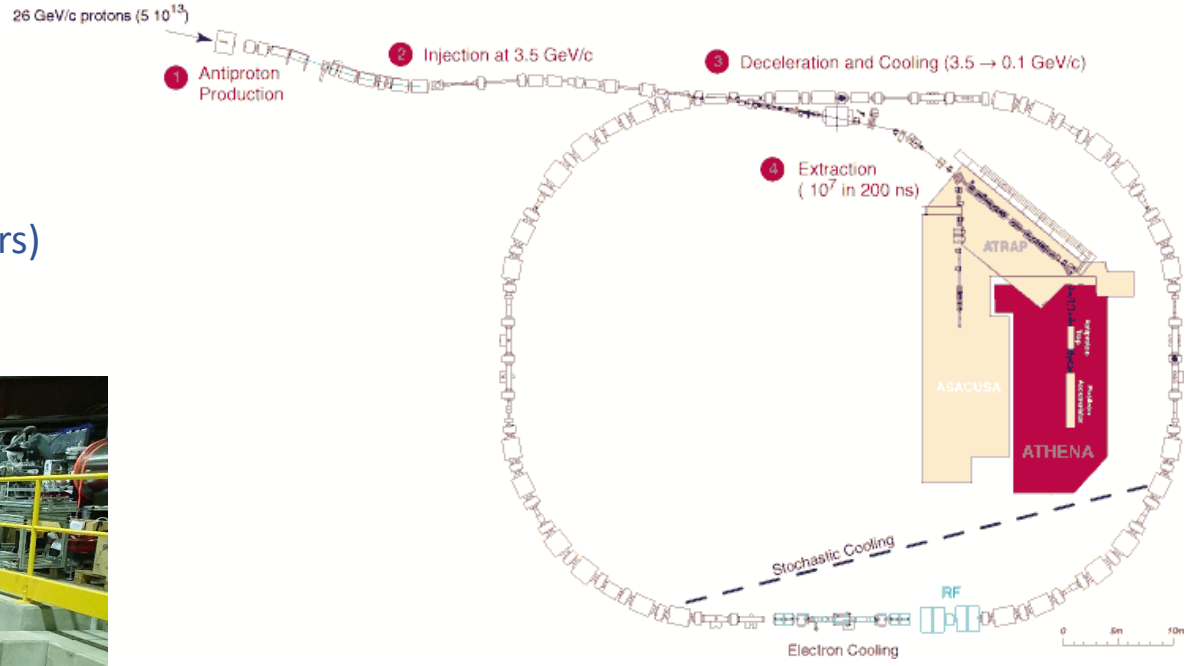


kicker

Stochastic cooling of antiprotons

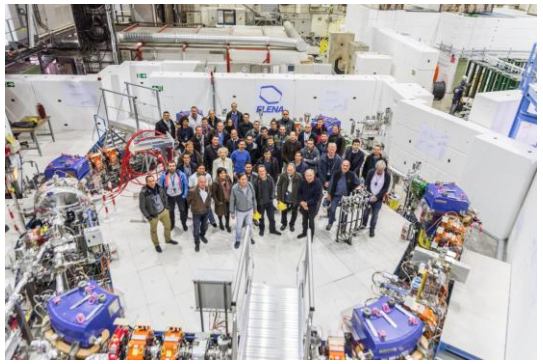
Stochastic cooling transfer line (pick-ups to kickers) routed shortest possible way





Stochastic cooling of antiprotons

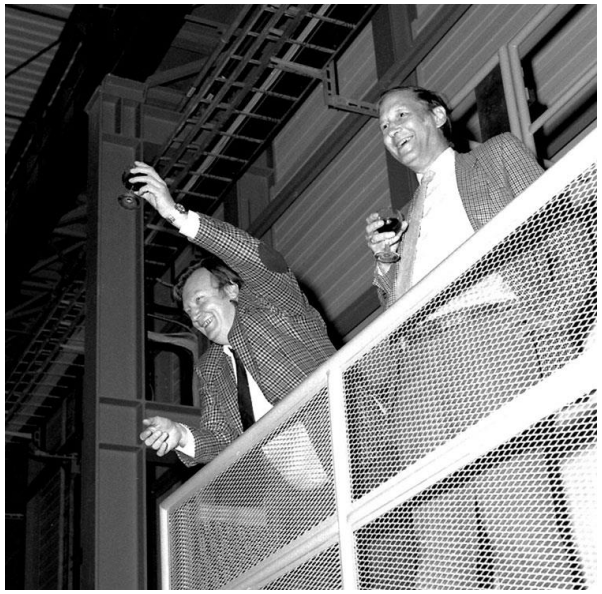
How did the antiproton facility evolve?



- **Antiprotons have been used since ~1980, in the beginning mainly for high energy proton-antiproton experiments in the SPS**
- **1980-1986** **AA** (Antiproton Accumulator)
  - 3.57 GeV/c Antiproton Accumulator ring
  - p/pbar collisions in SPS and in 1983 the discovery of the W and Z bosons !!!
  - 1984 Nobel prize for Carlo Rubbia and Simon van der Meer !!!
- **1986-1996** **AAC (AA+AC)** (AC: Antiproton Collector)
  - Large acceptance Antiproton Collector ring added to increase capture
  - Production rate increased 10-fold to $6*10^{10}$ pbars/h
  - 10^{12} pbars stored (peak). p/pbar collisions in SPS
  - + low energy experiments in LEAR
- **1998 - 2017** **AD** (Antiproton Decelerator)
- **2018-** **AD + ELENA** (Extra Low ENergy Antiproton ring)
  - AC converted from fixed energy storage ring to Decelerator.
  - Addition of a smaller ring for further deceleration with beam cooling. Many more antiprotons can be captured with cool 100 keV pbars.
  - $5*10^{7}$ pbars slowed down to 100 MeV/c (5.3MeV kinetic). Local experimental area.

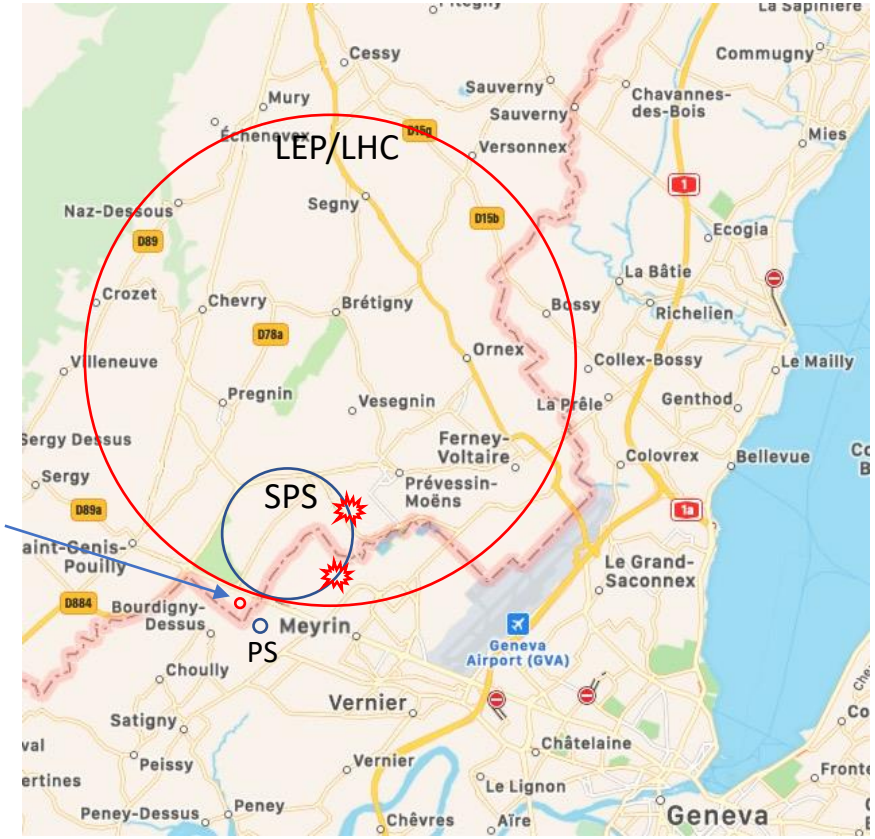
A break-through moment

Simon and Carlo



1983 Discovery of the W and Z bosons
1984 Nobel prize for Carlo Rubbia and Simon van der Meer

Accelerating science



To go quickly to higher energy collisions to do a discovery (and beat the competition!):

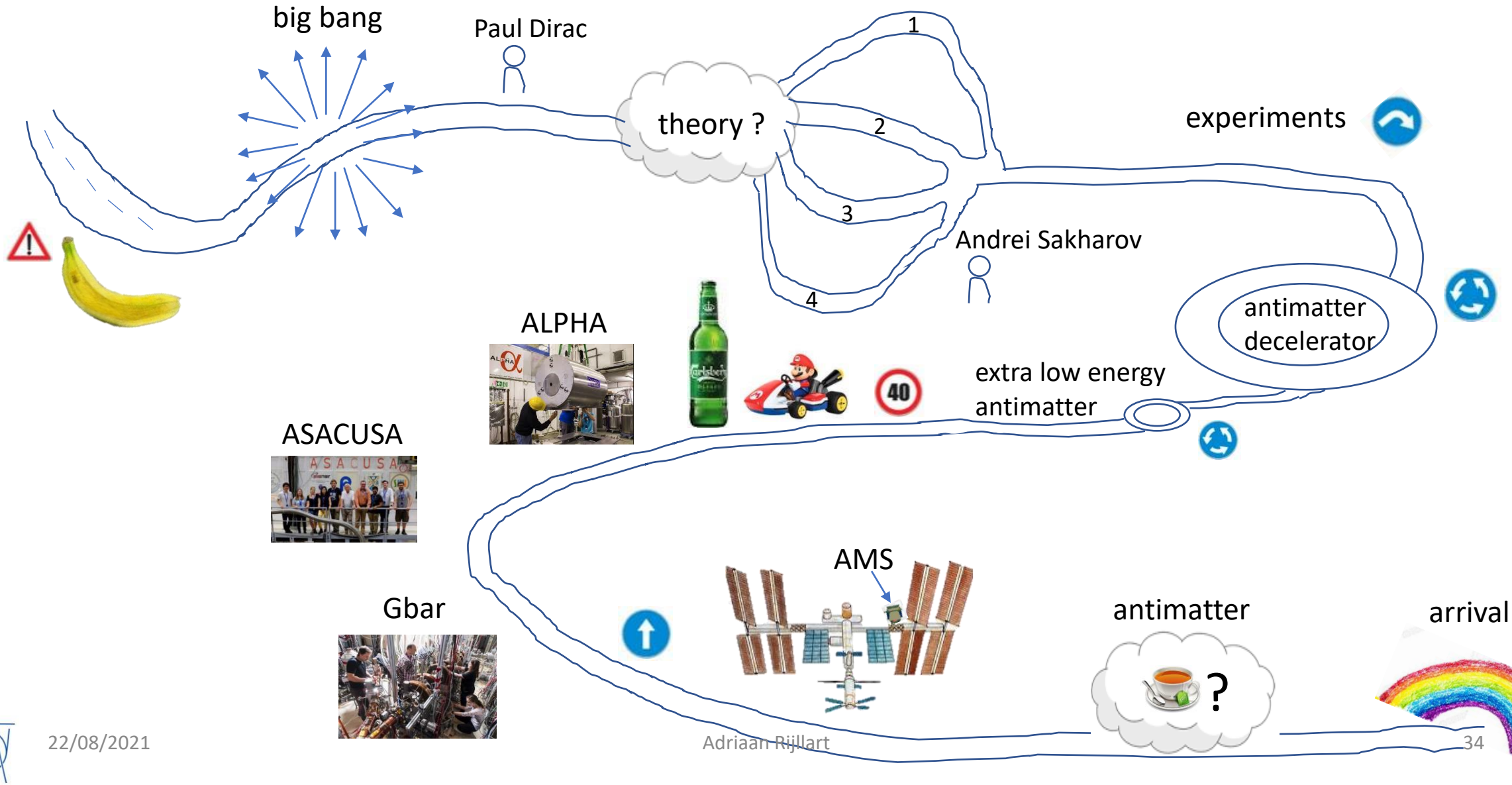
- Construct a big ring (takes time)
  - Takes time to decide

- Turn the existing SPS into a collider (double the energy!)
  - Using antiprotons (they can circulate in opposite direction in the same magnetic field!)
  - But antiprotons are hard to get by and you need many to have good statistics

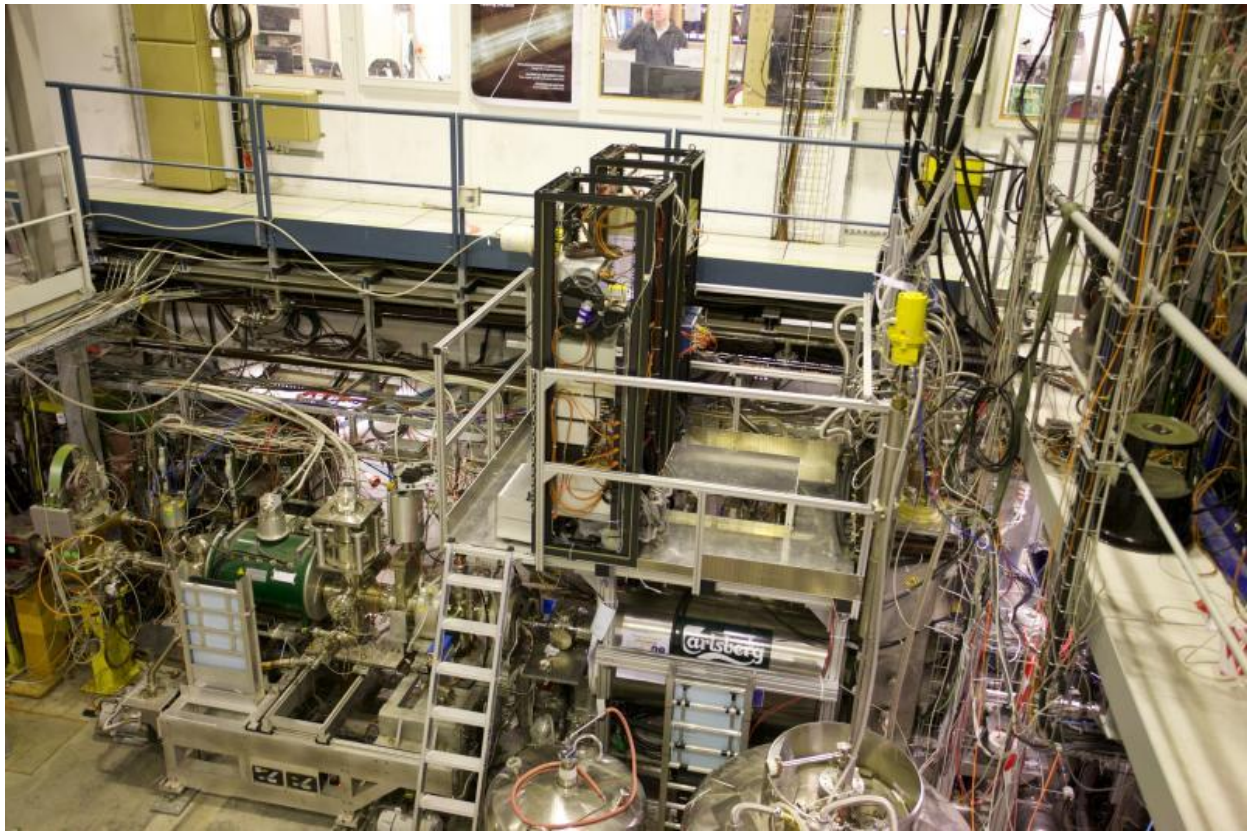
- There is a way: construct a small Antiproton Accumulator
- Critical problem: how to cool the very large momentum spread so they can be accumulated

- The solution: stochastic cooling! (new invention)

Talk overview



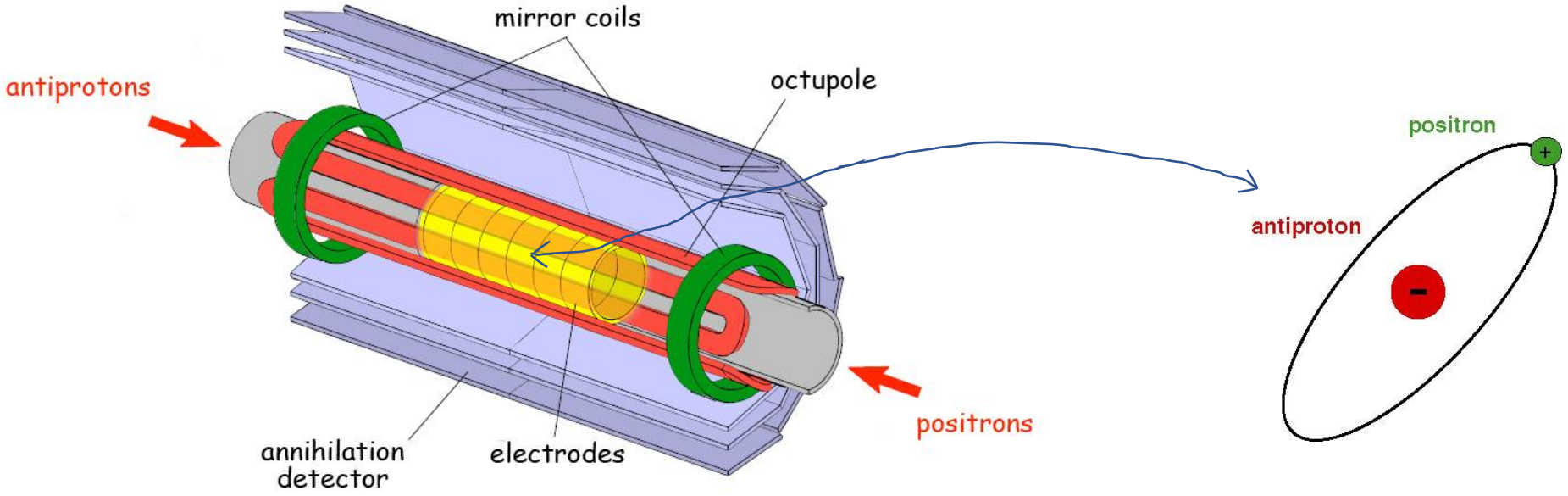
Beer



Sponsor of the ALPHA experiment

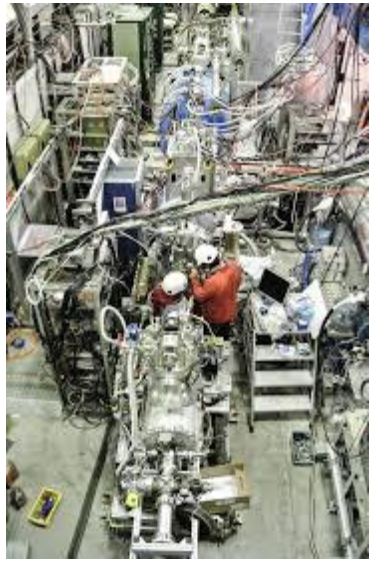
Antihydrogen

Penning trap

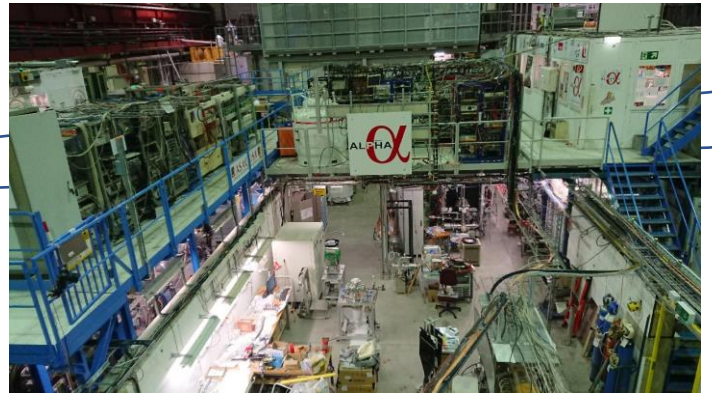


Passing by 3 experiments

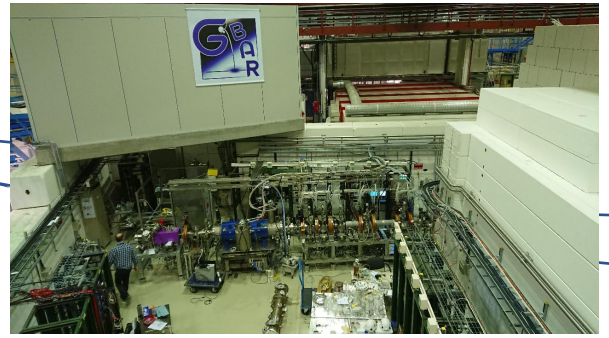
ASACUSA



ALPHA



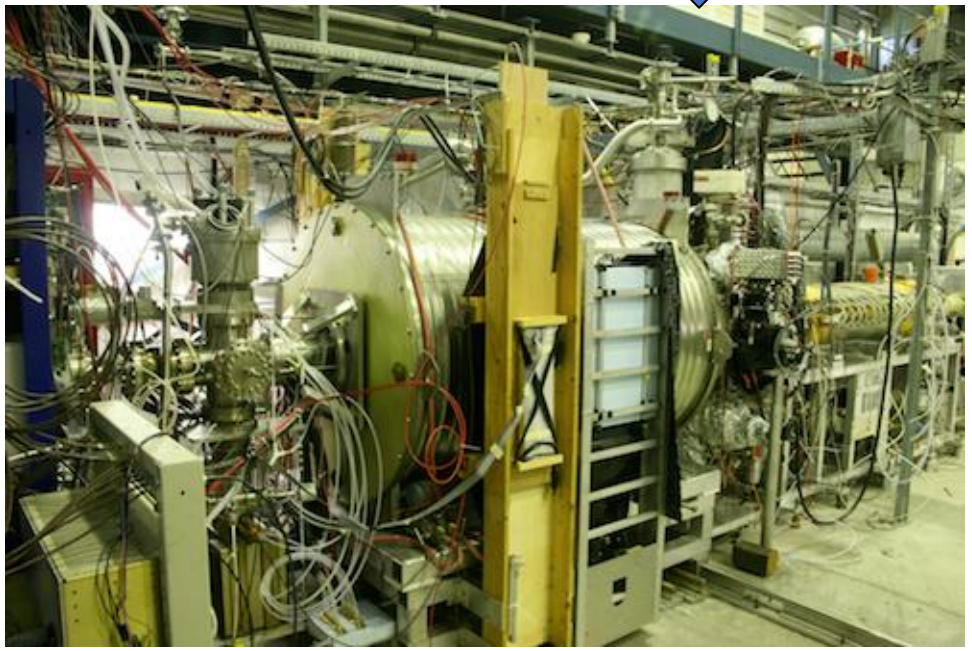
Gbar



ALPHA experiment

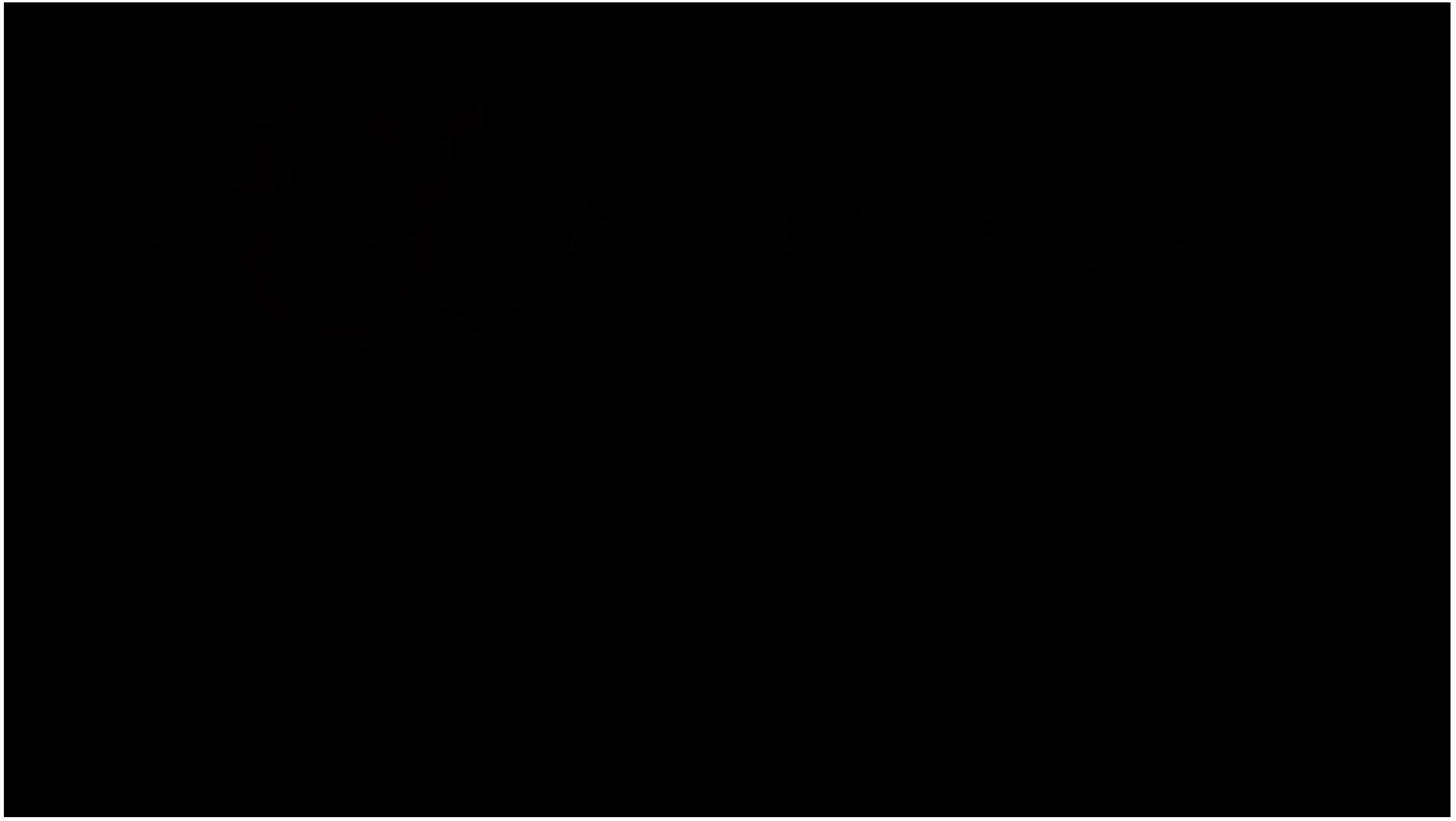
Penning trap inside….

….fully assembled ALPHA experiment



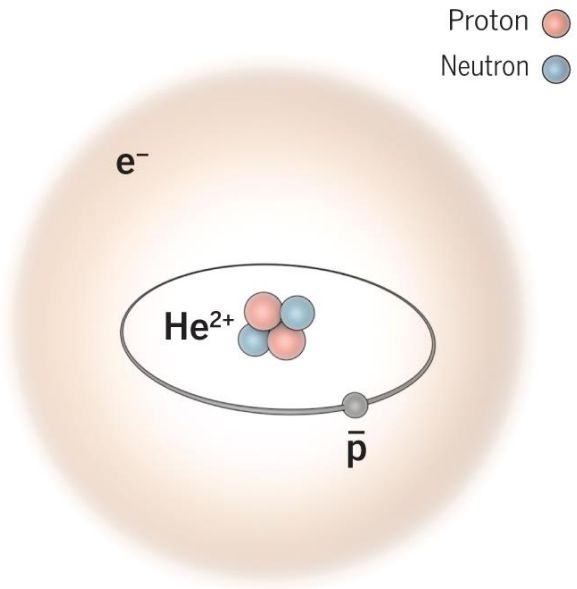
ALPHA experiment

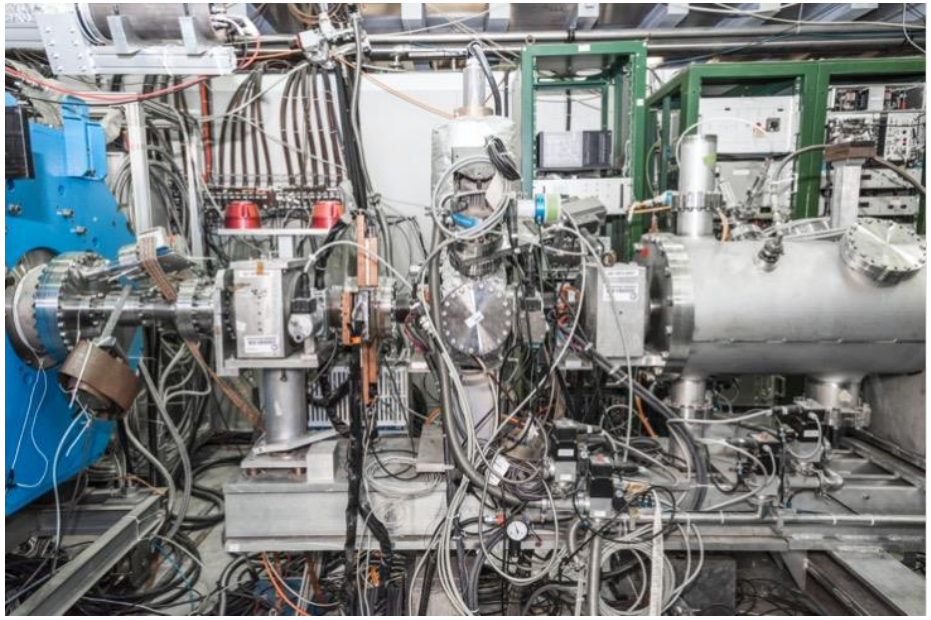
ALPHA experiment



ASACUSA: compare mass proton-antiproton

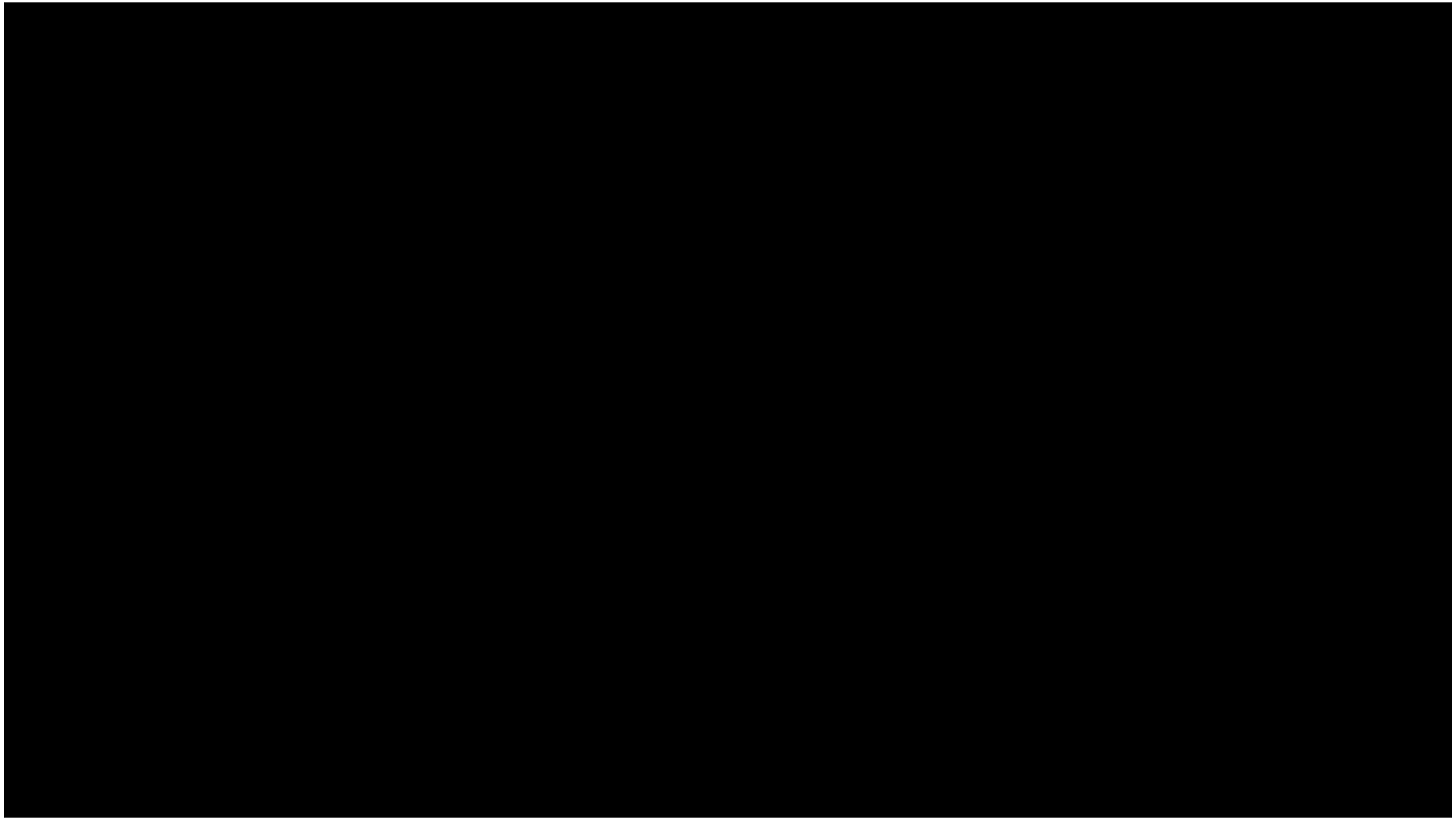
Atomic Spectroscopy And Collisions Using Slow Antiprotons





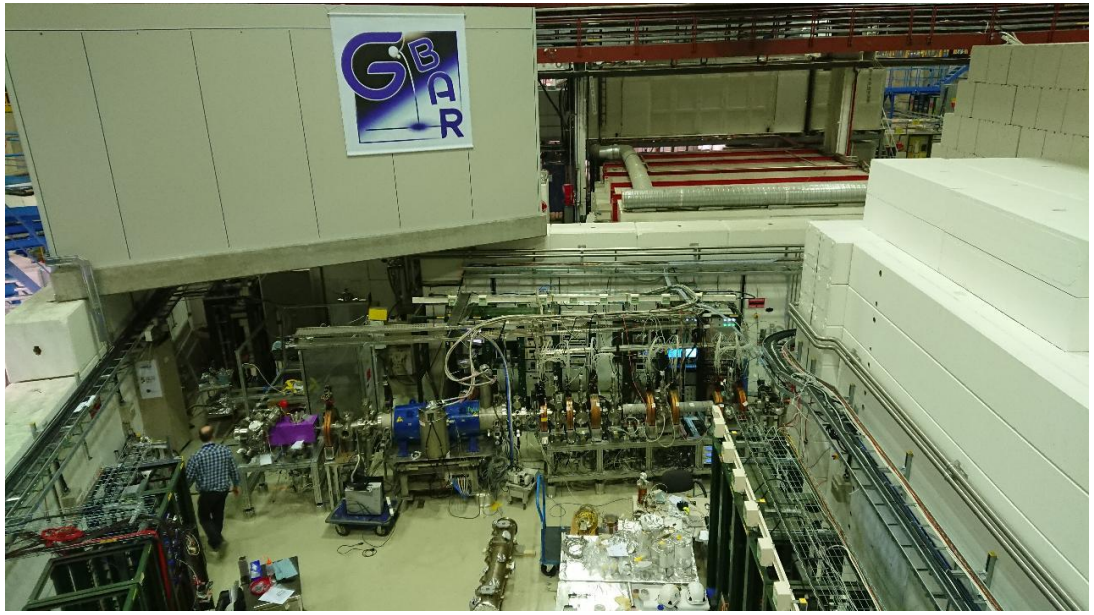
antiprotonic helium

ASACUSA: Antiprotonic helium



Gbar: antigravity

Drop antihydrogen in the gravitational field of the earth

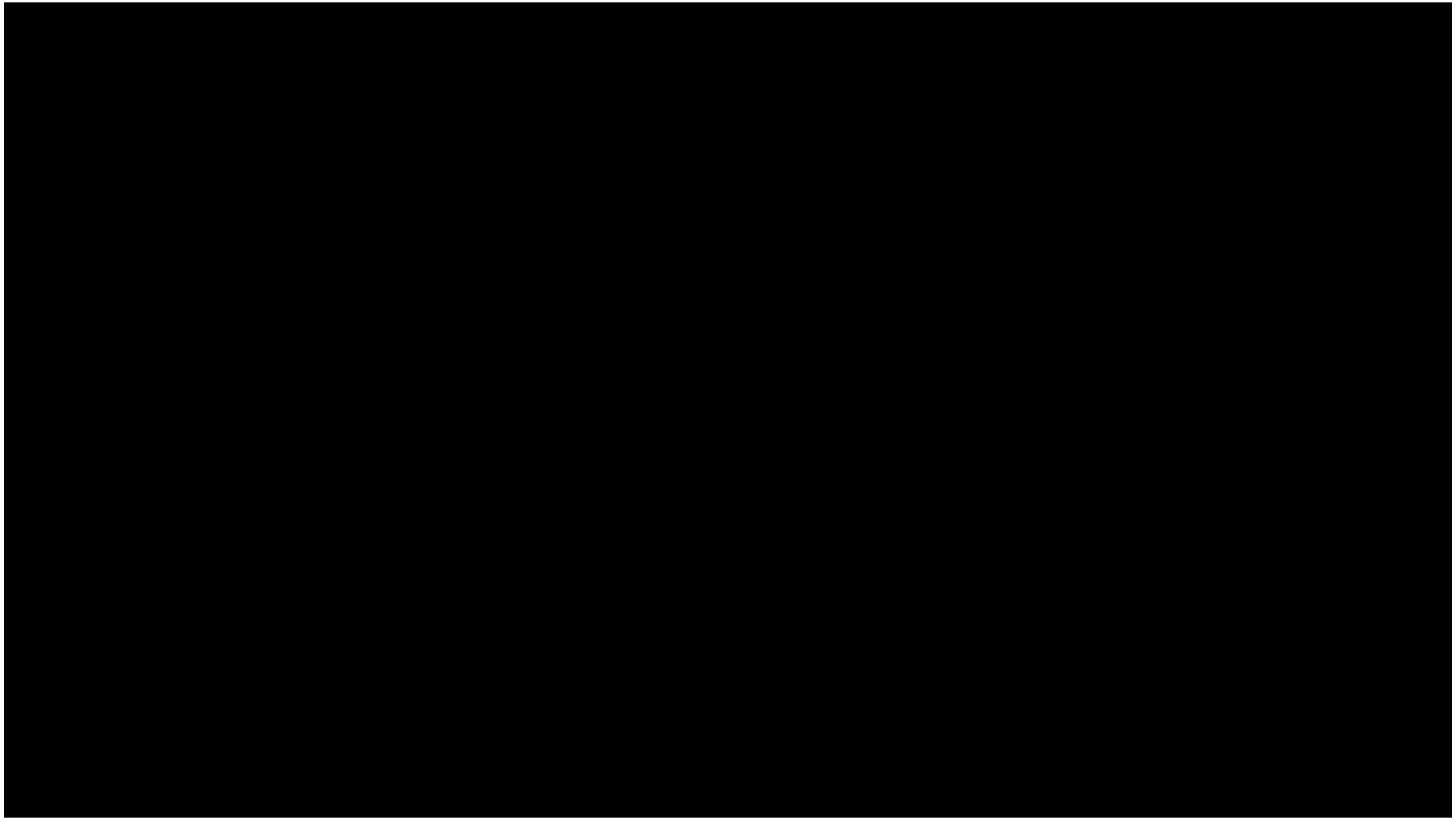


The experiment:

- Positron beam line and trapping equipment
- Pbar line from ELENA under hut
- Free fall vessel to be installed

ALPHA-g

Drop antihydrogen in the gravitational field of the earth



From antiprotons to antihydrogen

Cool Antiprotons …

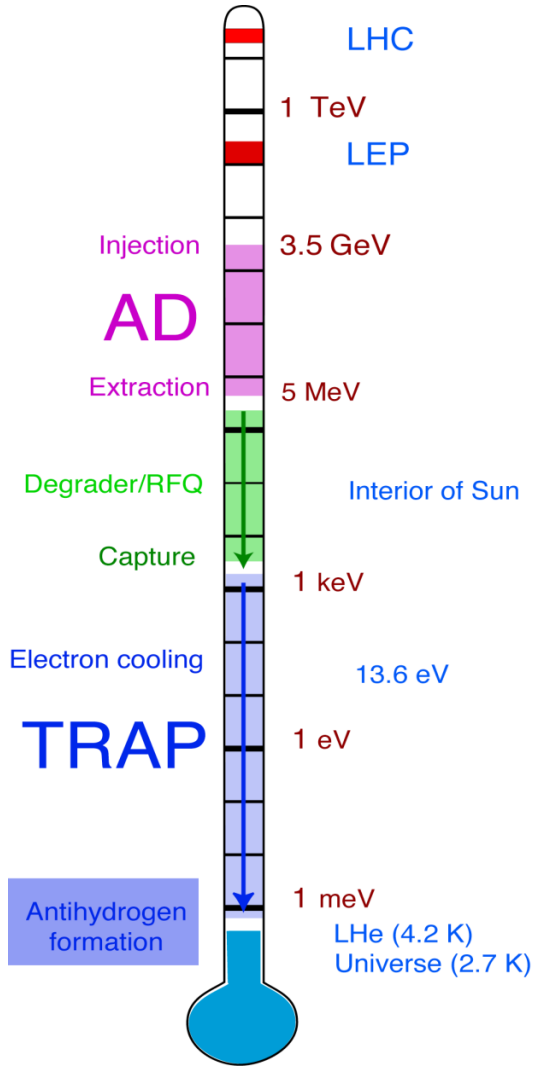
Antiprotons produced at almost the speed of light

Slow antiprotons down to (almost) rest

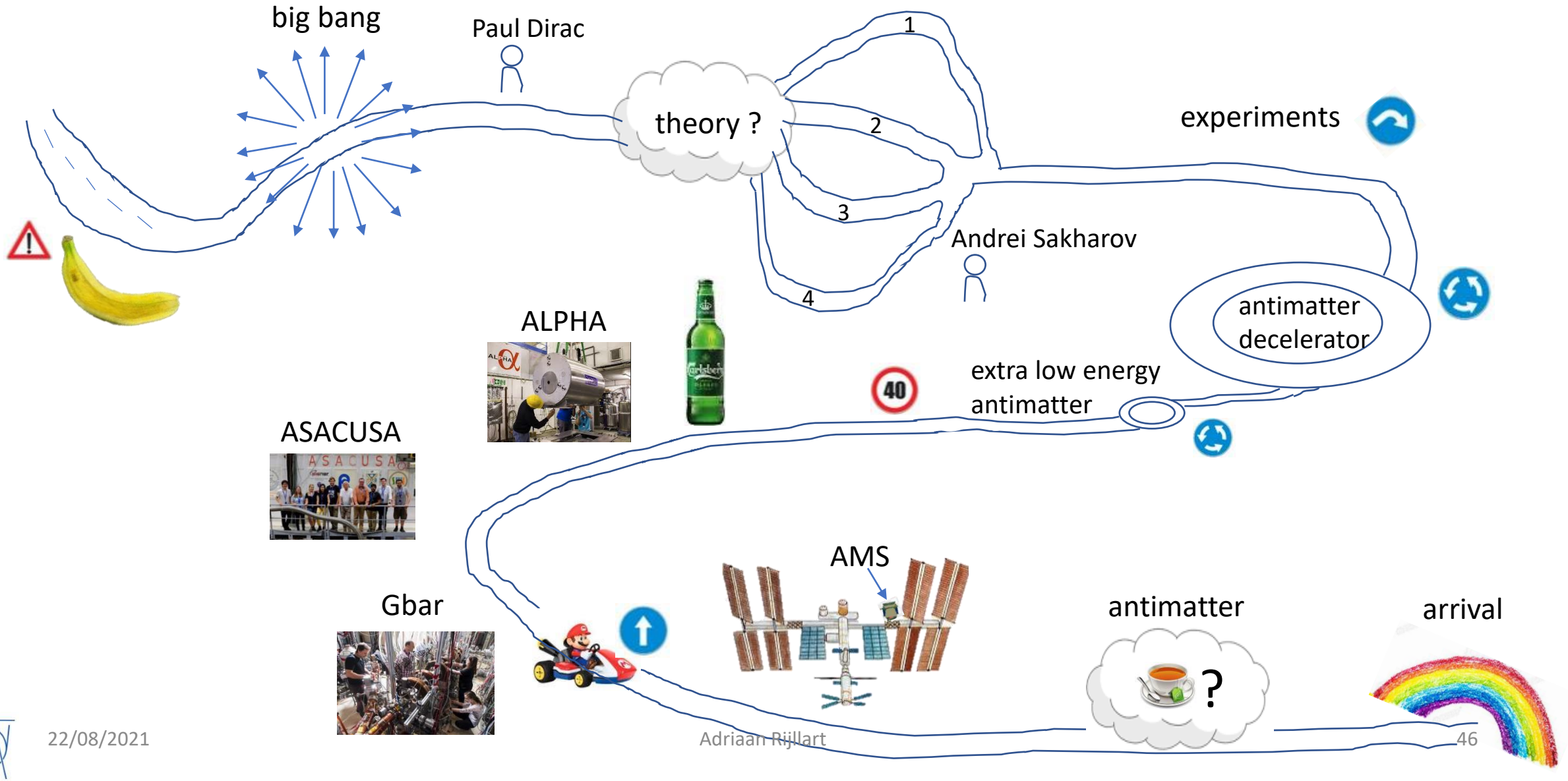
Accumulate positrons

Mixing for antihydrogen formation

… Cold Antihydrogen

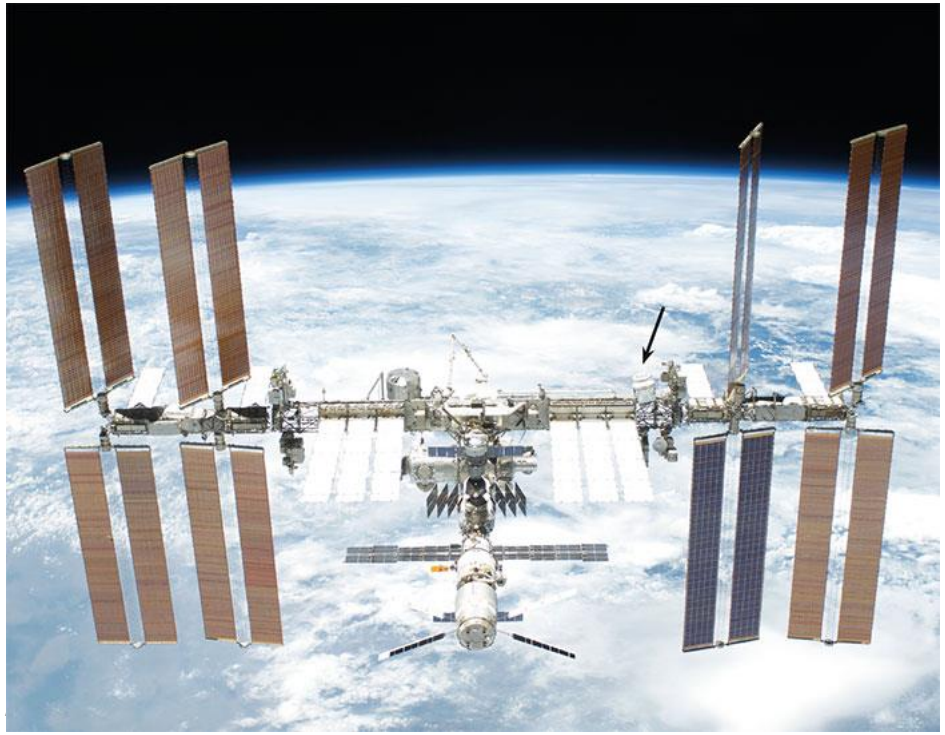


Talk overview

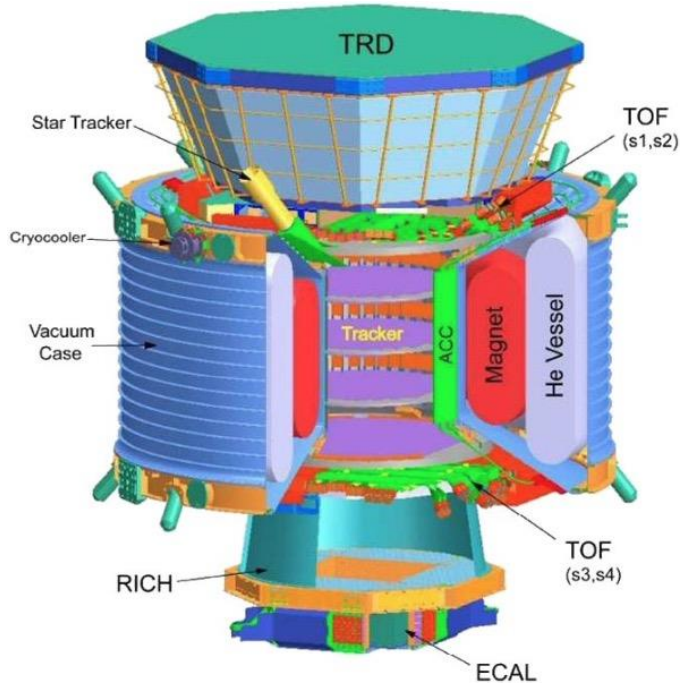


Antimatter in space

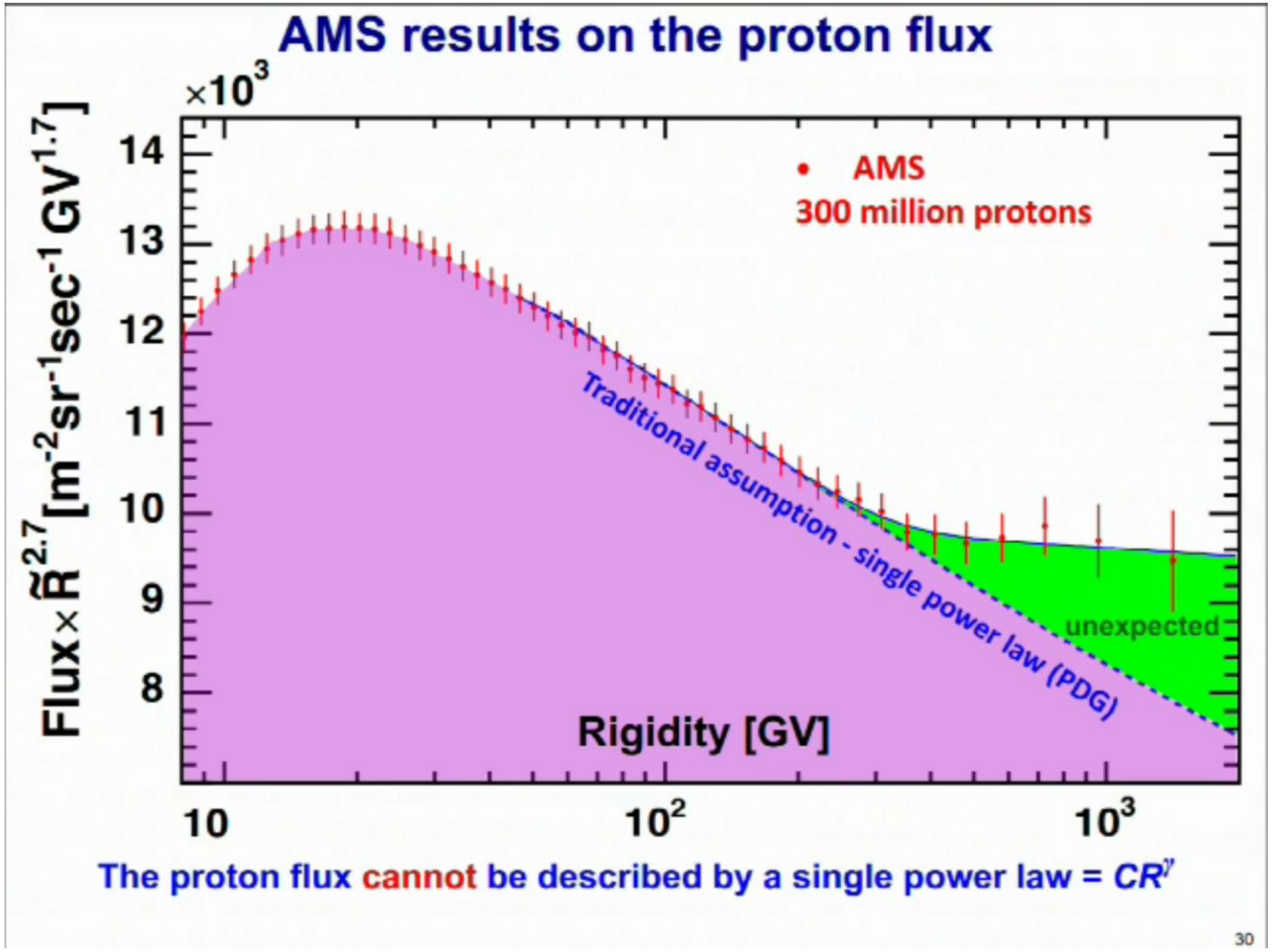
- Charged particles from space collide with the atmosphere and are lost
- To study them, you need to be in space
- The Alpha Magnetic Spectrometer (AMS-02) was mounted on the International Space Station (ISS) in 2011



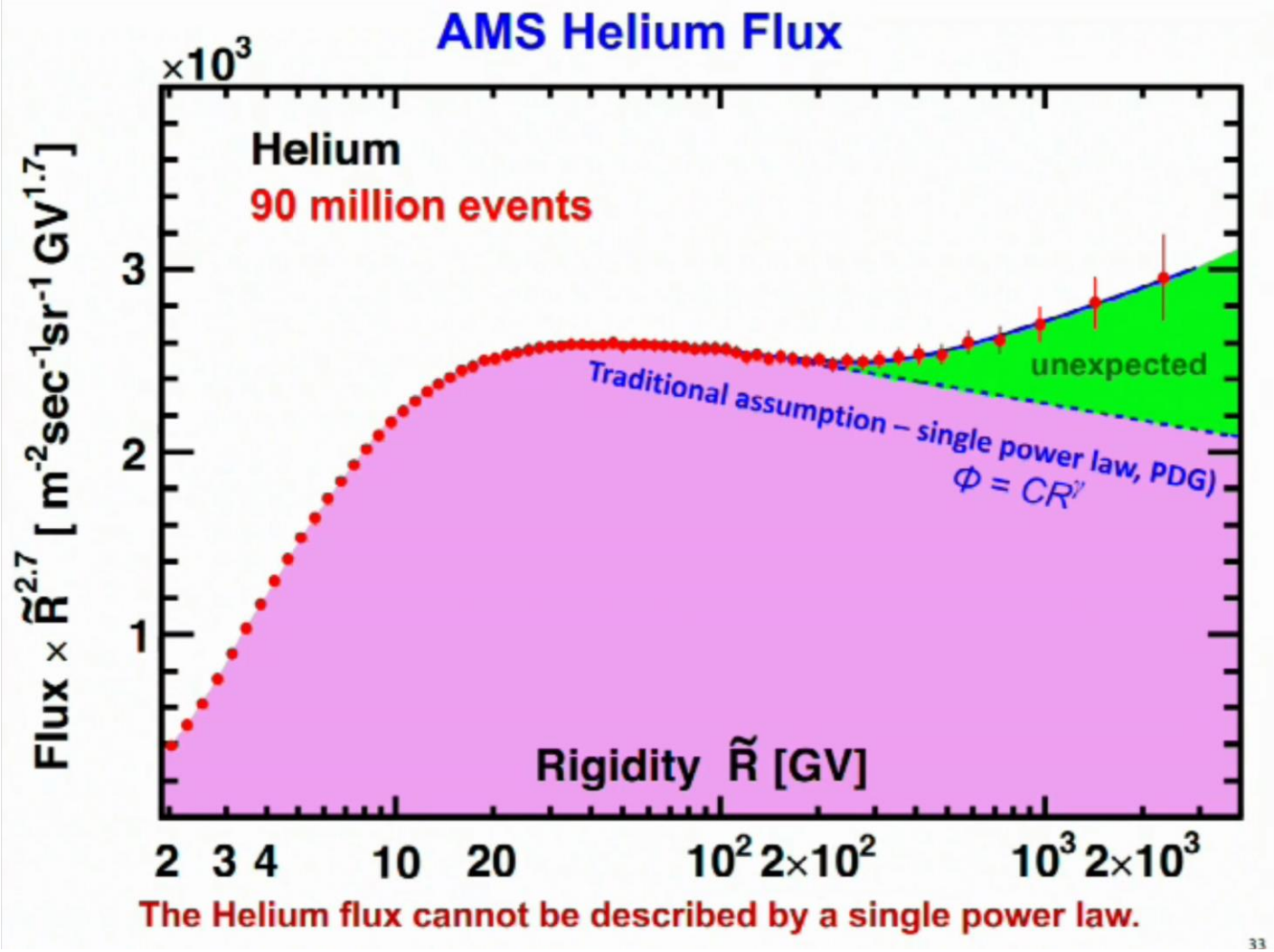
AMS-02


TRD
Star Tracker
TOF
(s1,s2)
Cryocooler
Vacuum
Case
Tracker
ACC
Magnet
He Vessel
TOF
(s3,s4)
RICH
ECAL

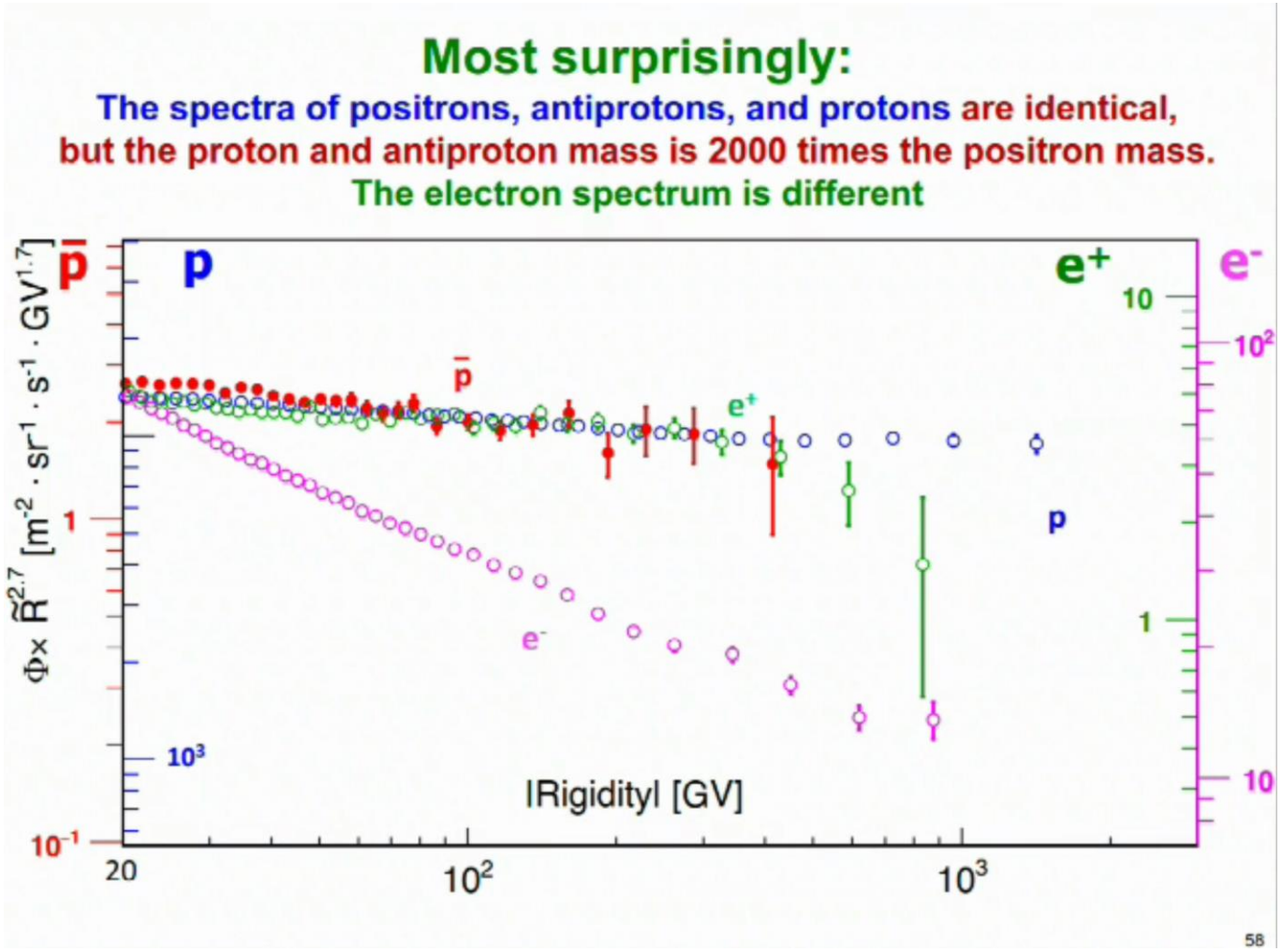
Proton flux


AMS results on the proton flux
$\times 10^3$
14
13
12
11
10
9
8
Flux $\times \tilde{R}^{2.7}$ [$m^{-2}sr^{-1}sec^{-1}GV^{1.7}$]
AMS
300 million protons
Traditional assumption - single power law (PDG)
unexpected
Rigidity [GV]
10
10^2
10^3
The proton flux cannot be described by a single power law = CR^{γ}
30

Helium flux

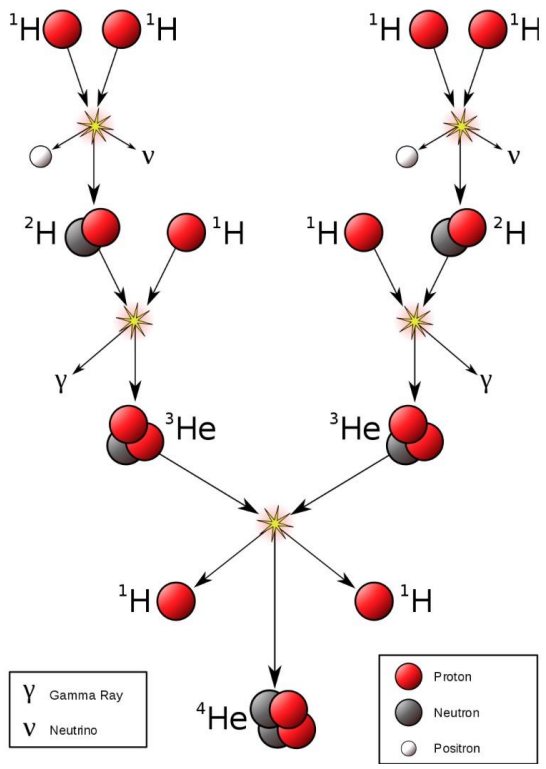

AMS Helium Flux
Helium
90 million events
unexpected
Traditional assumption – single power law, PDG)
$\Phi = CR^{\gamma}$
Flux × $\tilde{R}^{2.7}$ [$m^{-2}sec^{-1}sr^{-1}GV^{1.7}$]
×10³
3
2
1
Rigidity $\tilde{R}$ [GV]
2 3 4 10 20 10² 2×10² 10³ 2×10³
The Helium flux cannot be described by a single power law.
33

AMS-02

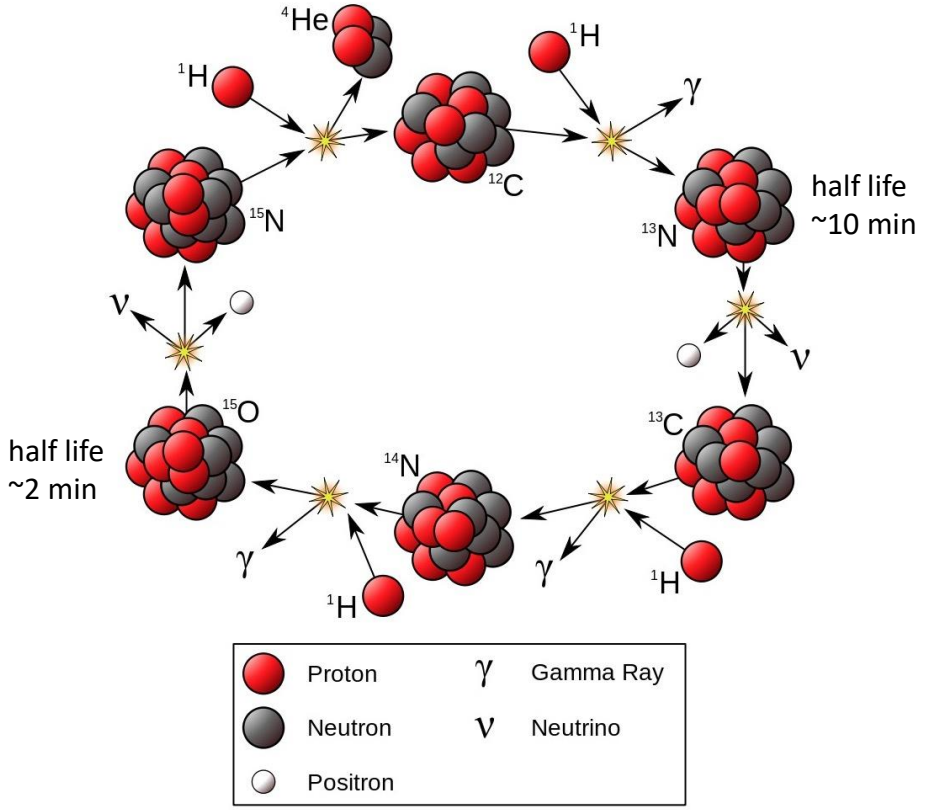

Most surprisingly:
The spectra of positrons, antiprotons, and protons are identical,
but the proton and antiproton mass is 2000 times the positron mass.
The electron spectrum is different
p̄
p
e+
e-
Φ× R̃^2.7 [m^-2 · sr^-1 · s^-1 · GV^1.7]
IRigidityI [GV]
58

Ratio of C/O and N/O

Light stars: hydrogen fusion



Massive stars: CNO cycle catalysed fusion

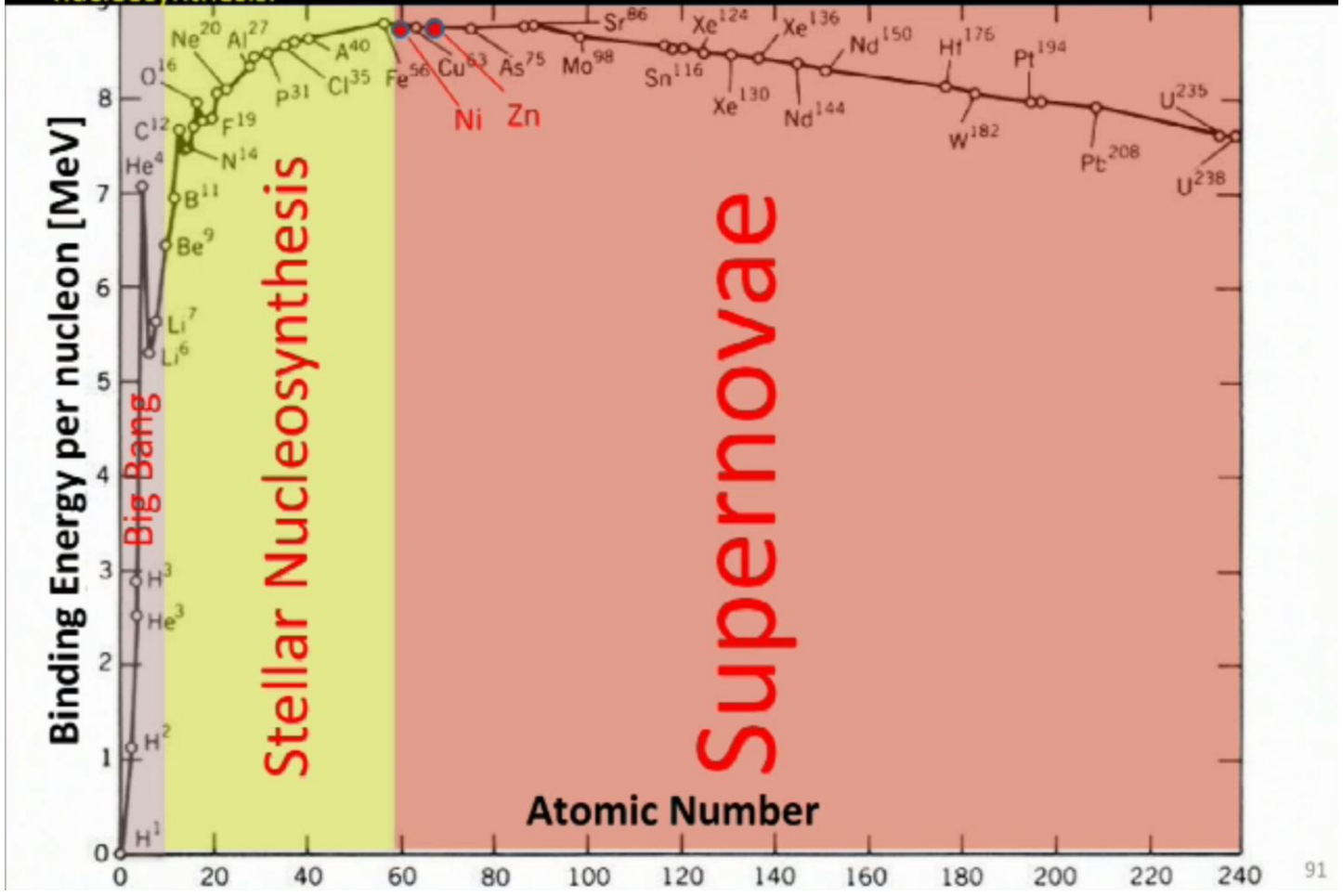


In the Solar System: C/O = 0.54 N/O = 0.17

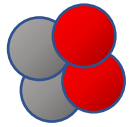
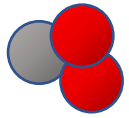
In Galactic Cosmic Rays: C/O = 0.90 N/O = 0.09

Heavier nuclei

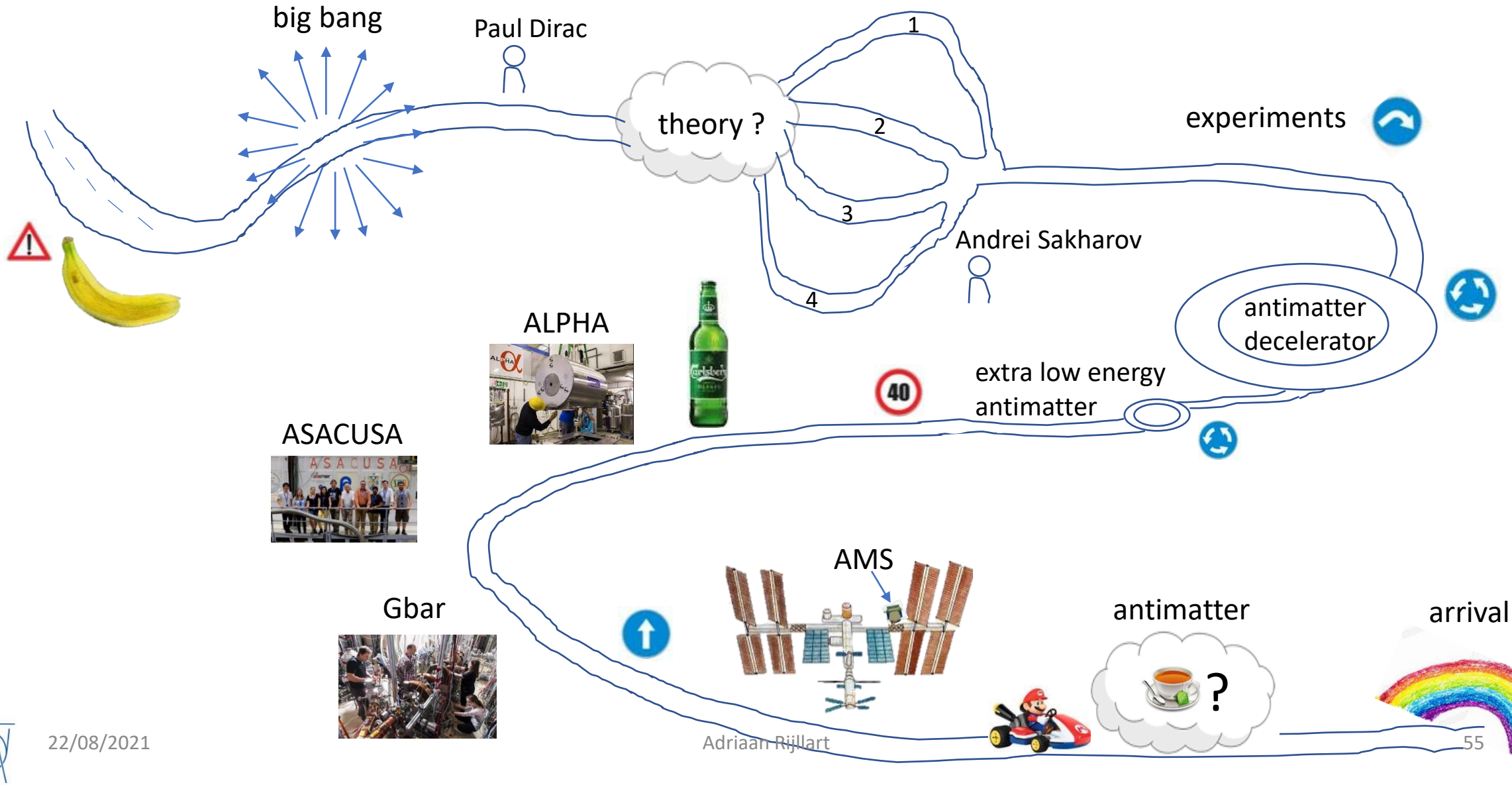
D. The lightest elements created by supernova are Nickel and Zinc. AMS will be able to study their properties for the first time and compare them with elements produced by stellar nucleosynthesis.



Anti-alpha

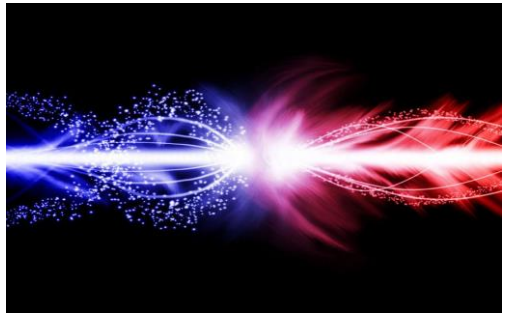
matter particles	antimatter particles
helium-4 	antihelium-4
helium-3  1.38 ppm	antihelium-3

Talk overview



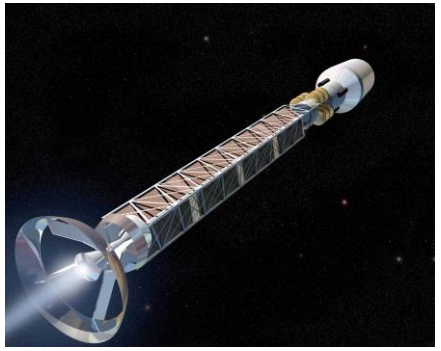
Energy release

1 g antimatter + 1 g matter = 43 kilotons TNT explosion (10^{14} J)



1000 times more than nuclear fission per gram
100 times more than nuclear fusion per gram

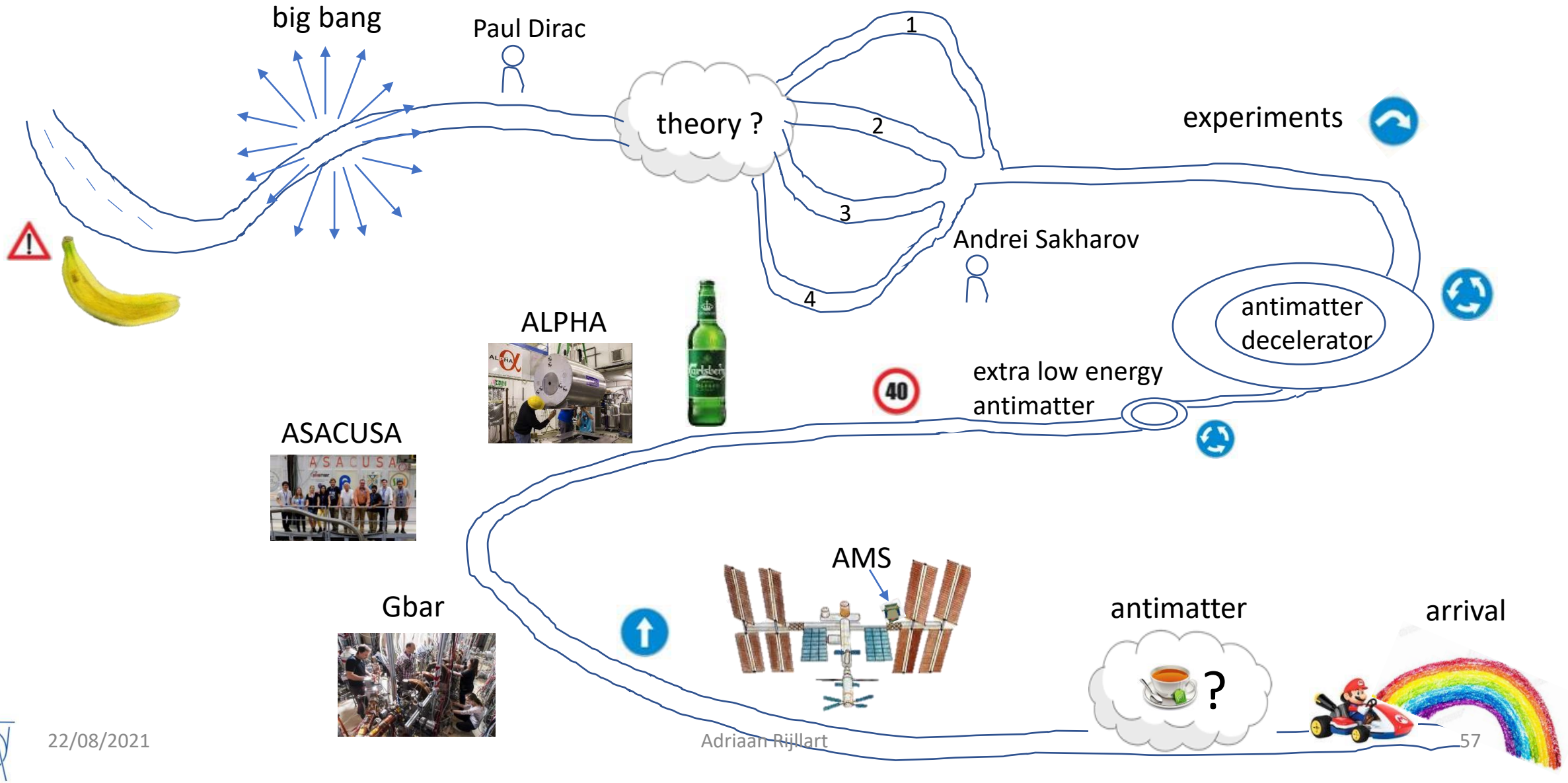
US project in 2004: to investigate the use of positrons as rocket fuel or explosive



For CERN antimatter factory to accumulate 1 g of antiprotons will take at 30 million years (taking 100% efficiency)

In 20 years the amount of energy produced in the form of antimatter at CERN would barely heat a cup of tea

Talk overview



Maybe one day …

from Star Trek

Thank you for your participation !!