Antimatter - lost in the universe created and applied on earth

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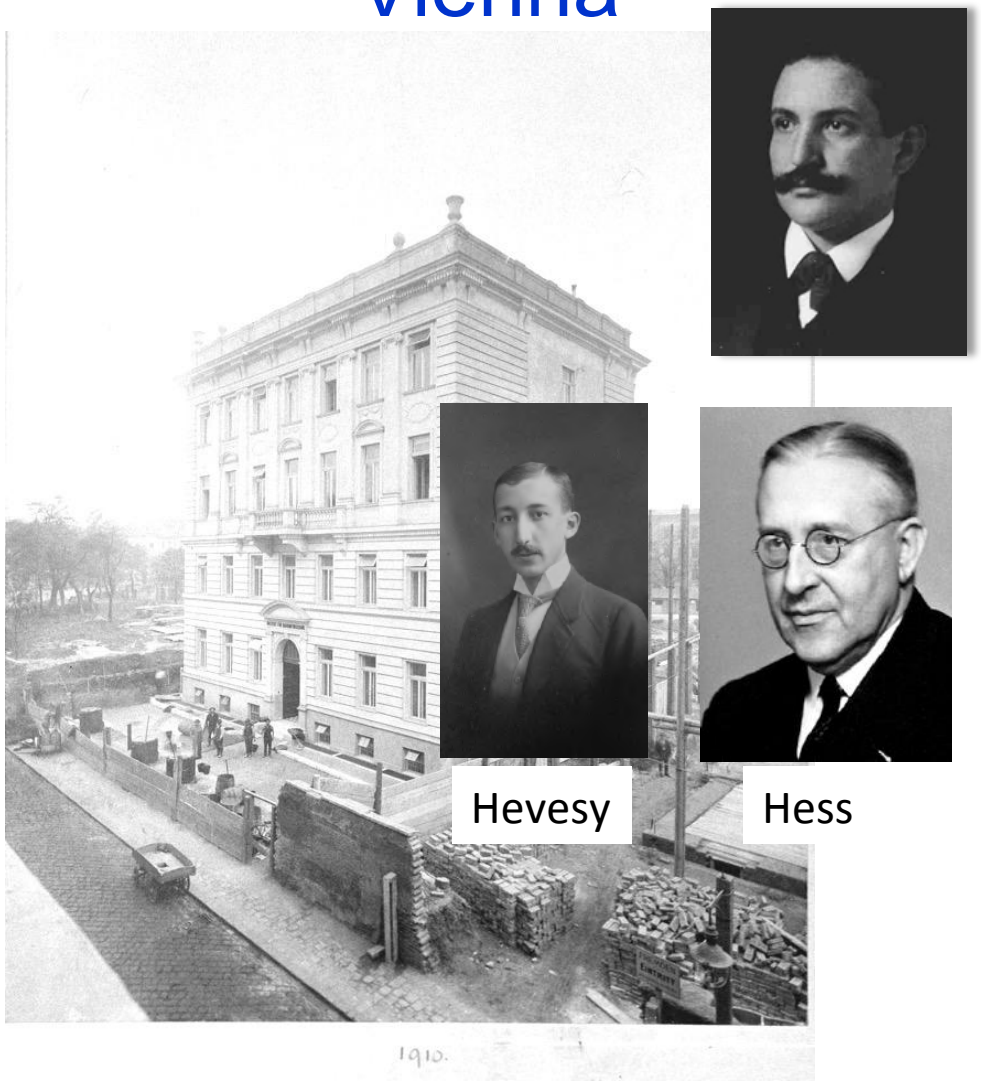


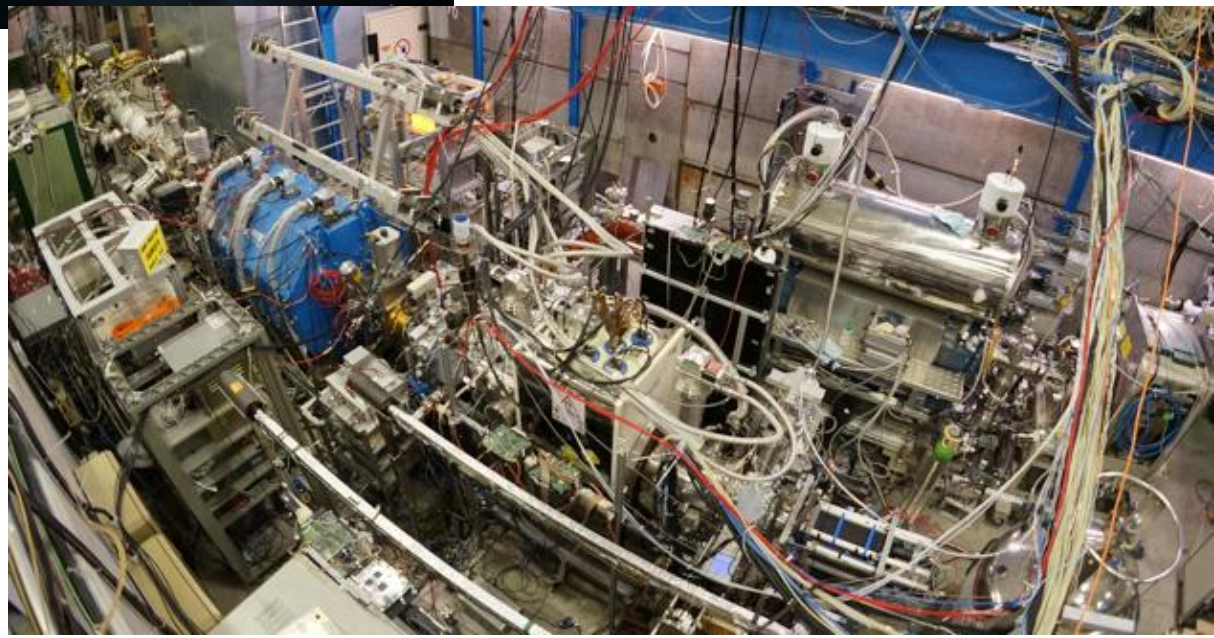
Radiuminstitut founded 191
First Director: Stefan Meyer

- 1st institute of Austrian Academy
- St. Meyer - Pioneer in radioactivity research
- 2 nobel laureates (V. Hess, G. Hevesy)

- Research in Subatomic Physics:
  Strong interaction-Hadronic Physics and Precision Experiments like Antihydrogen Research

SCIENCE FICTION

REALITY AT EARTH



Content

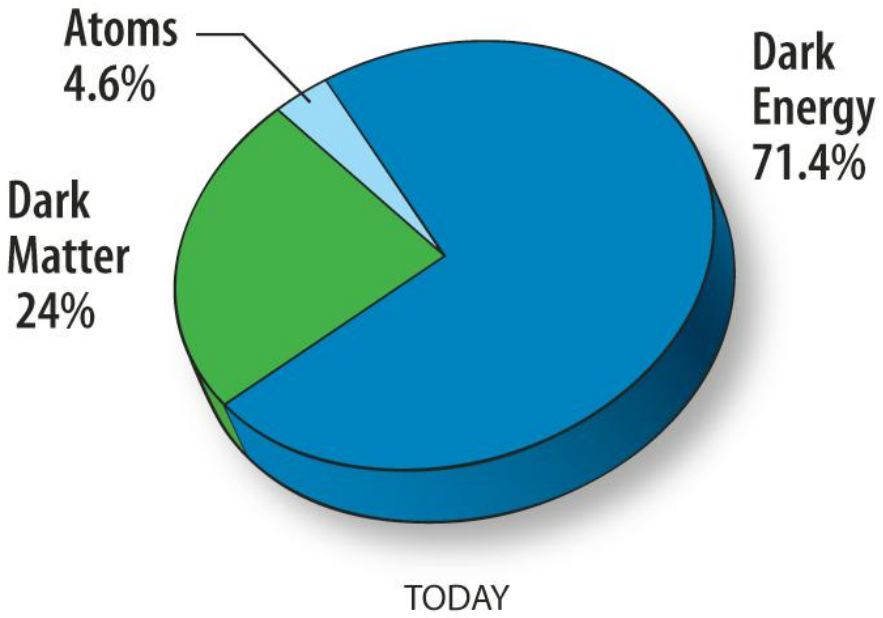
- No (primordial) antimatter in the universe?
- Production of antimatter in the lab
- Experiments with antimatter
- Application of antimatter

Antimatter absence in universe

No antimatter in the universe?

According to present findings universe consists of

- Matter (Atoms)
- Dark matter
- Dark energy



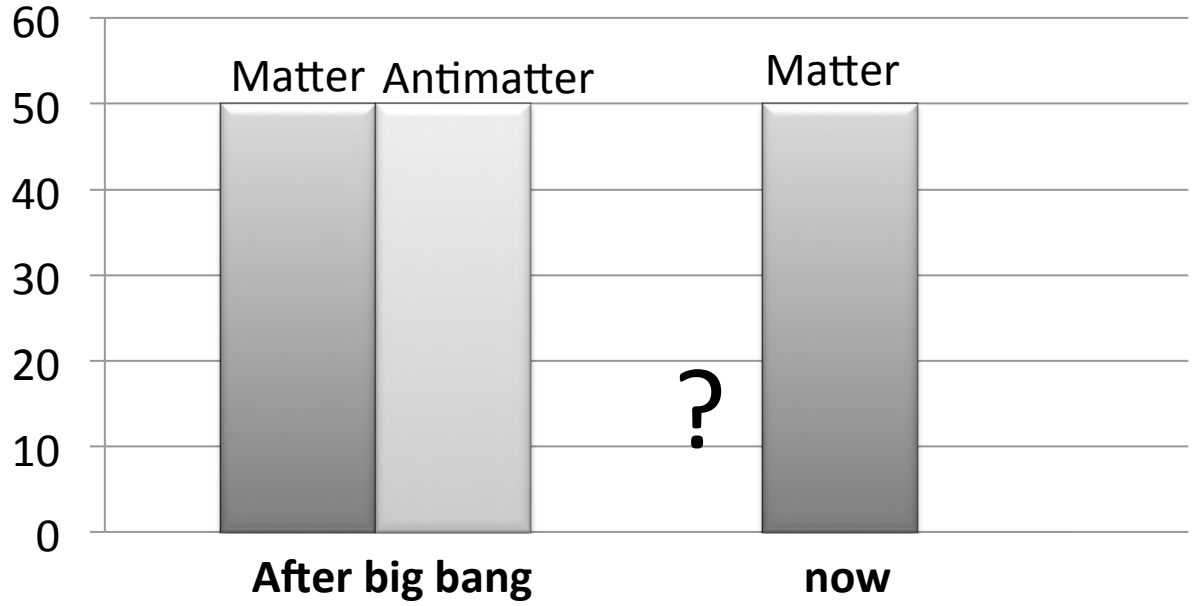
And

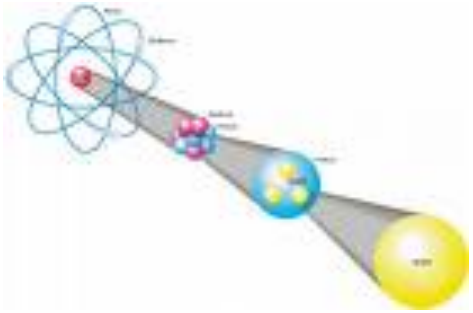
Only approx. 0% (?)

Antimatter

Victory of matter ?

- Matter and Antimatter were produced after the Big Bang in the same ratio
- Antimatter seems to be not present in the universe today
- The dominance of matter in the visible universe is impressive – why the ratio changed dramatically?

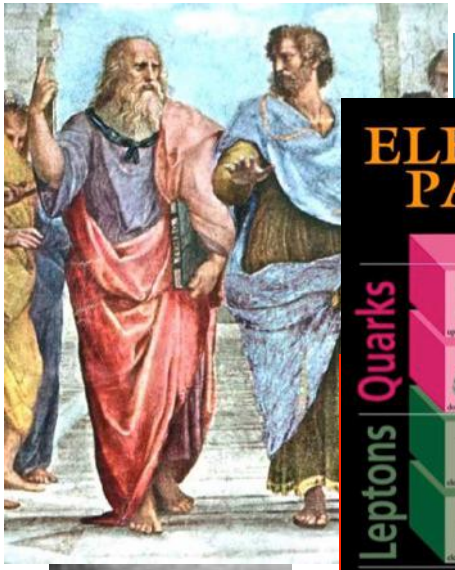


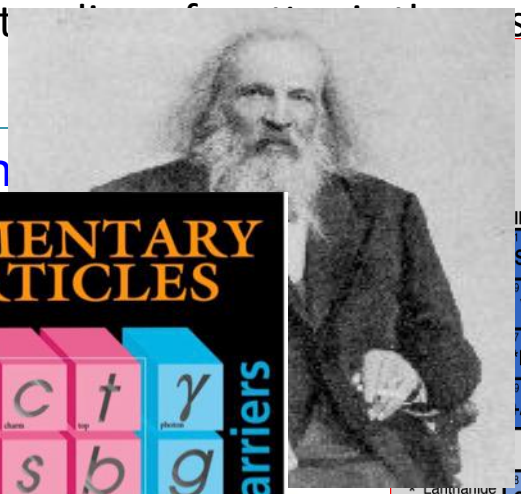


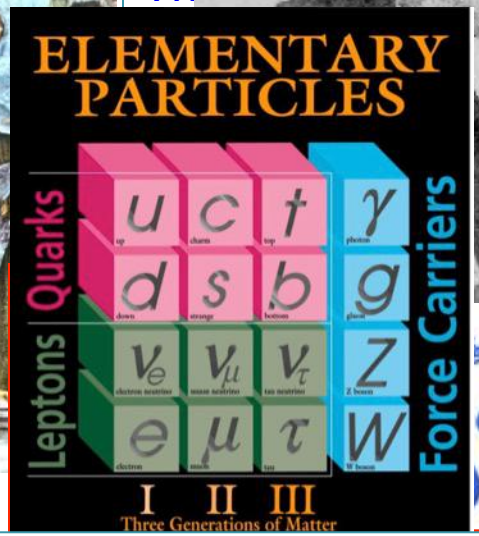
Matter

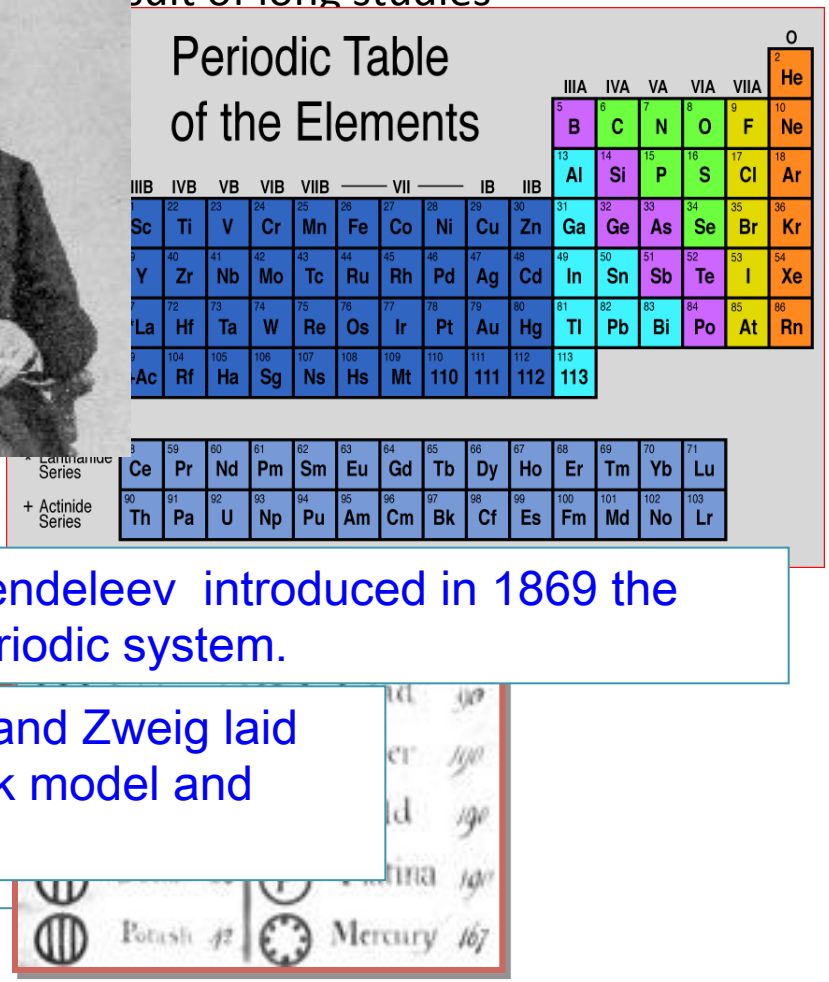
What is matter?

The present understa sult of long studies





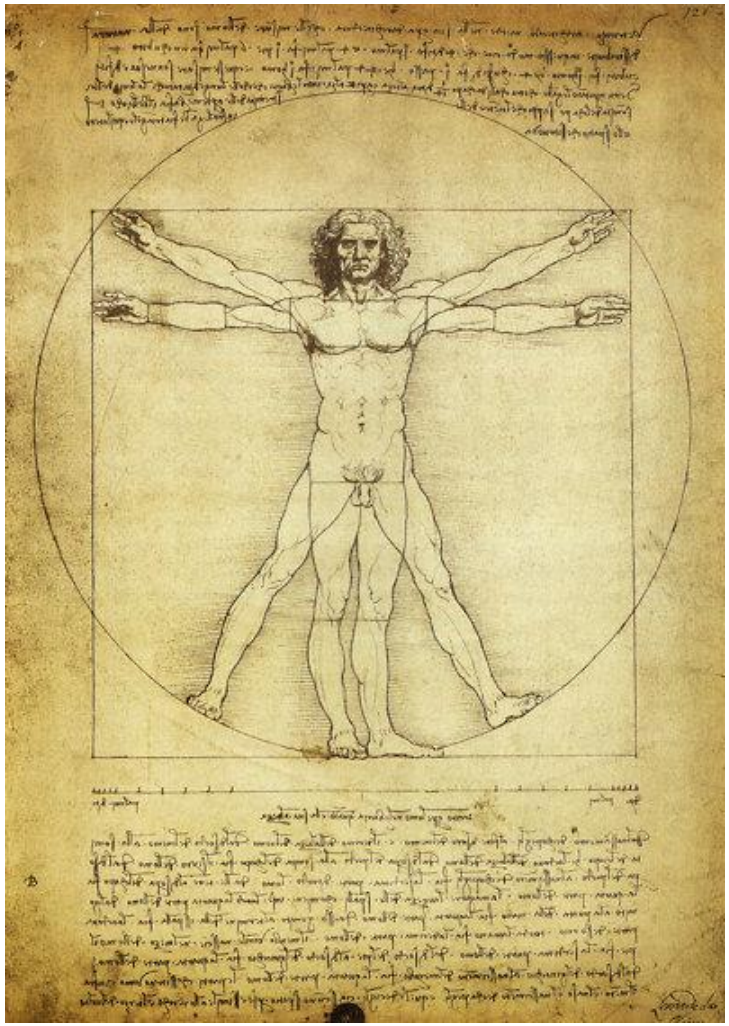




Mendeleev introduced in 1869 the periodic system.

1963 Murray, Gell-Mann, and Zweig laid the foundation of the quark model and QCD

Atoms



Nature, human made out of „Stardust“

Binding in atom due to electromagnetic interaction

Human with 70 kg consists of about 70% water, i.e. about 50 kg

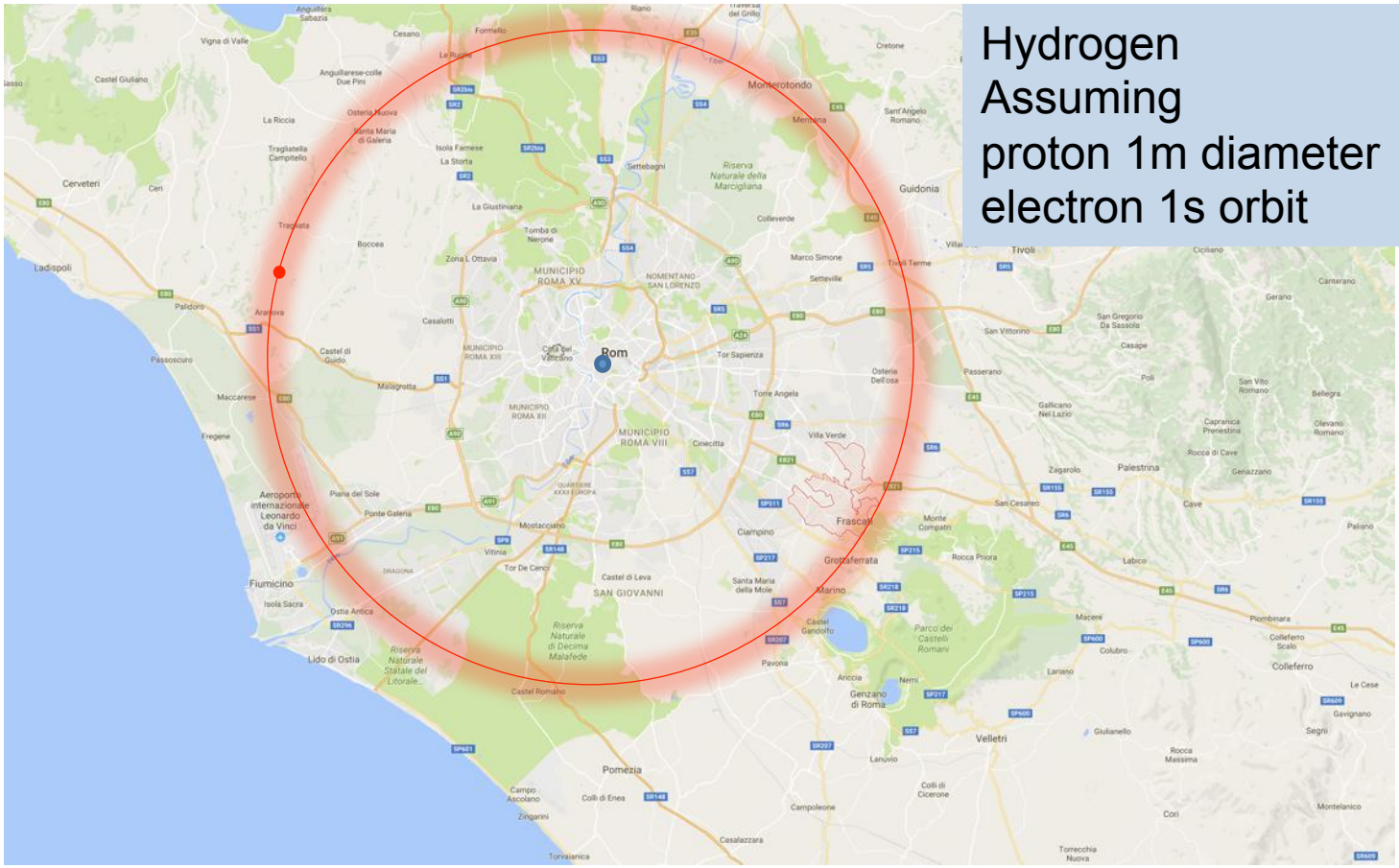
1mol 18 g contains
600000…0000000 (6×10^{23}) molecules H_2O

50 kg H_2O are about 3000 mol

→2×10^{27} molecules → 6×10^{27} atoms

→Mass of the atoms is approx. given by the mass of the protons and neutrons:
→ m(elektron) ~ 0.0002m (proton)

Size relation in an atom



Hydrogen
Assuming
proton 1m diameter
electron 1s orbit

Milestones

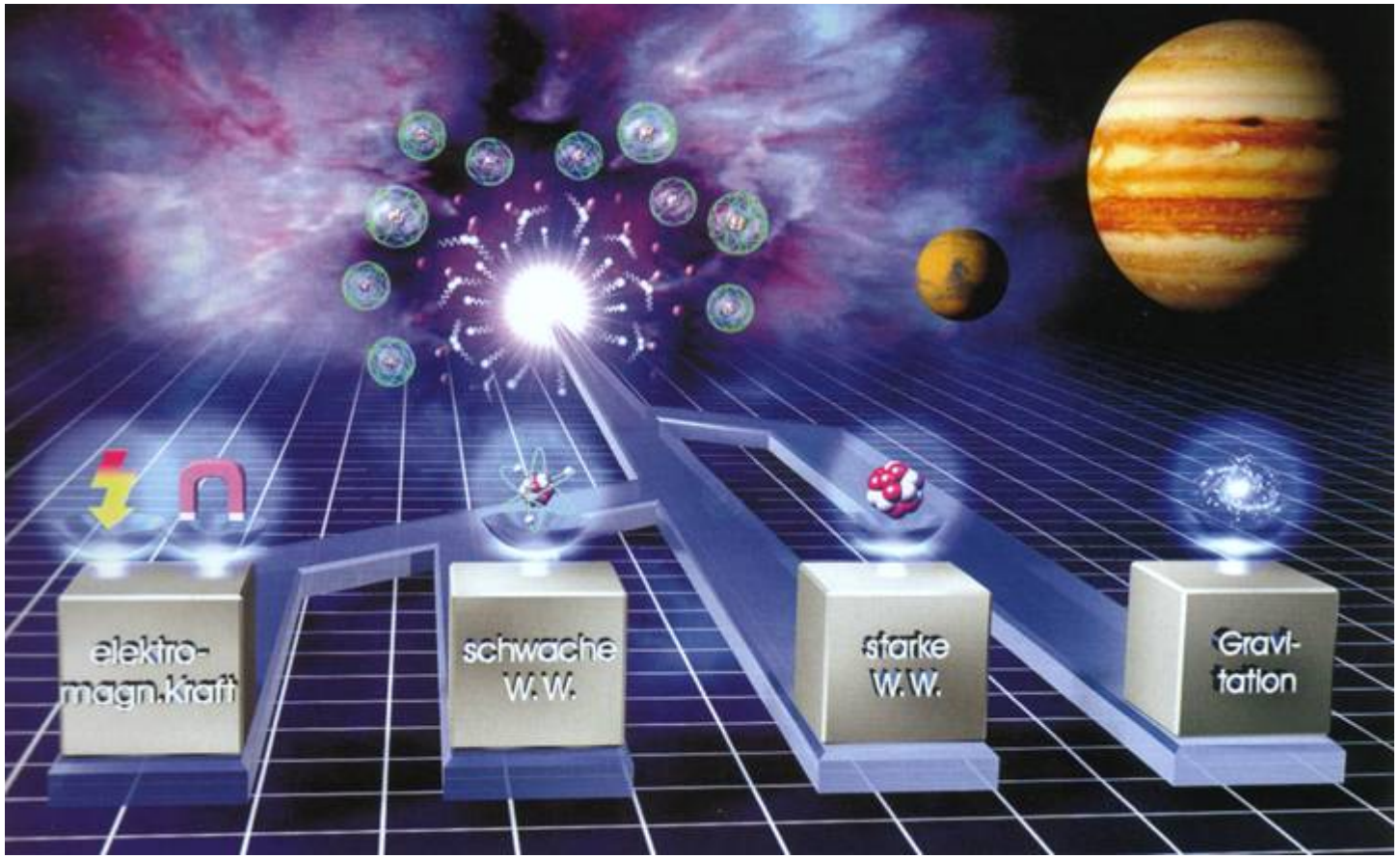
1896	Radioactivity discovered
1897	Electron discovered by J.J. Thomson
1898	Discovery of the elements Polonium and Radium by Maria Sklodowska Curie and Pierre Curie
1900	Discovery of the gamma radiation by P.U. Villard
1902	Identification of beta-rays by H. Becquerel
1909	Identification of alpha-rays als helium nuclei by E. Rutherford
1911	Rutherford experiment: Discovery of the atomic nucleus
1919	Identification of the proton
1932	Discovery of the neutron by J. Chadwick

Electron

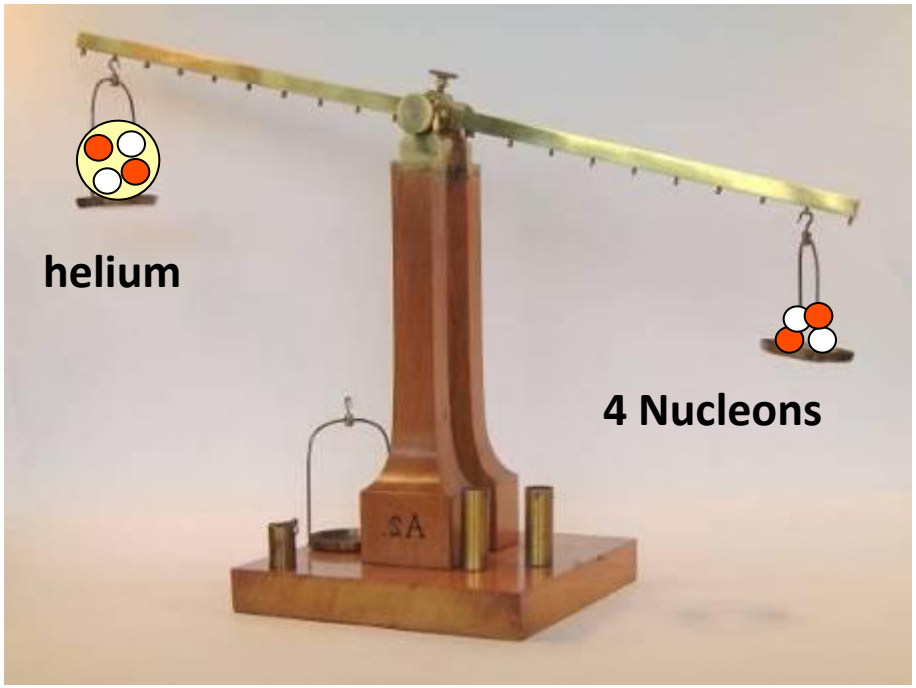
Proton

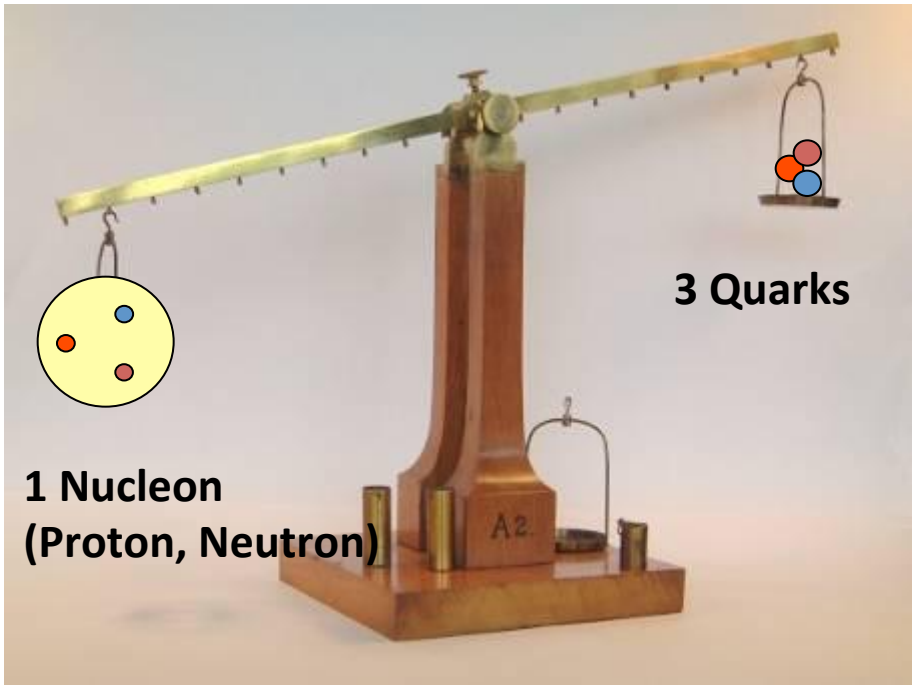
Neutron

4 Fundamental interactions



Problem of the hadron masses



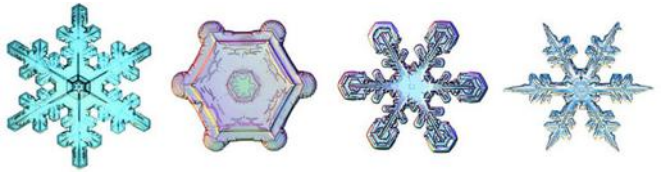


$3 \times m_{quark} \sim 3 \times 10 = 30\ MeV/c^2$

about 30-times smaller than

$m_{Nukleon} \sim 1000\ MeV/c^2$!

Symmetry breaking- hadron mass

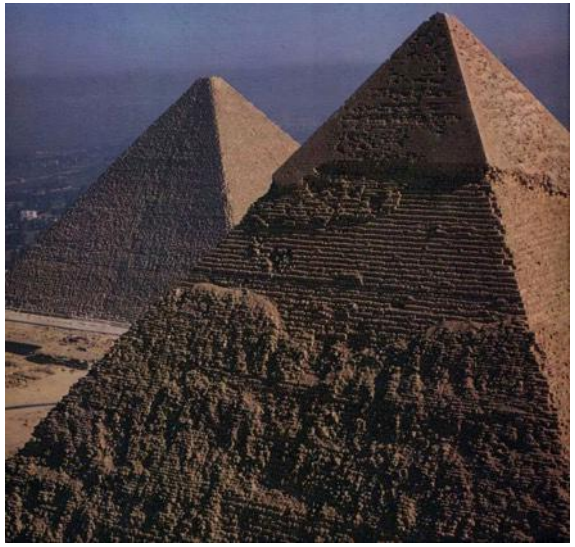


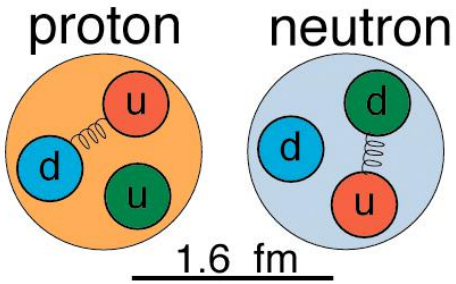
- Chiral Symmetry (CS) broken
- CS explicit broken: $m_u \neq m_d \neq 0$
- CS spontaneous broken → QCD binding energy
- Hadrons get Mass

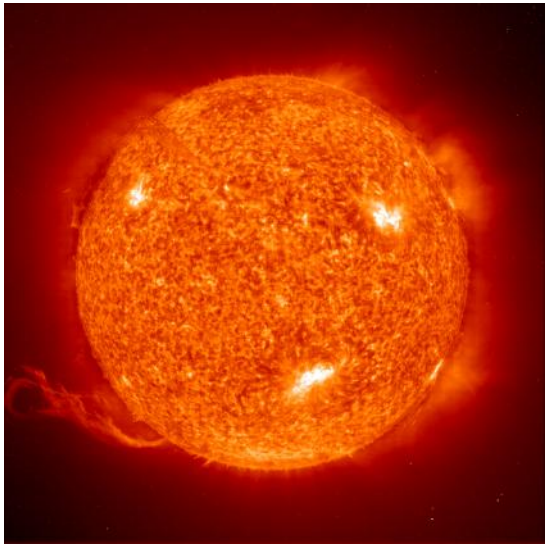
Yoichiro Nambu 2008 Nobel Prize

Buridians Esel – verhungert er?

The mass of the matter all around us mainly consists of protons and neutrons







Matter content

- **Baryon density**
  (protons, neutrons, ...)

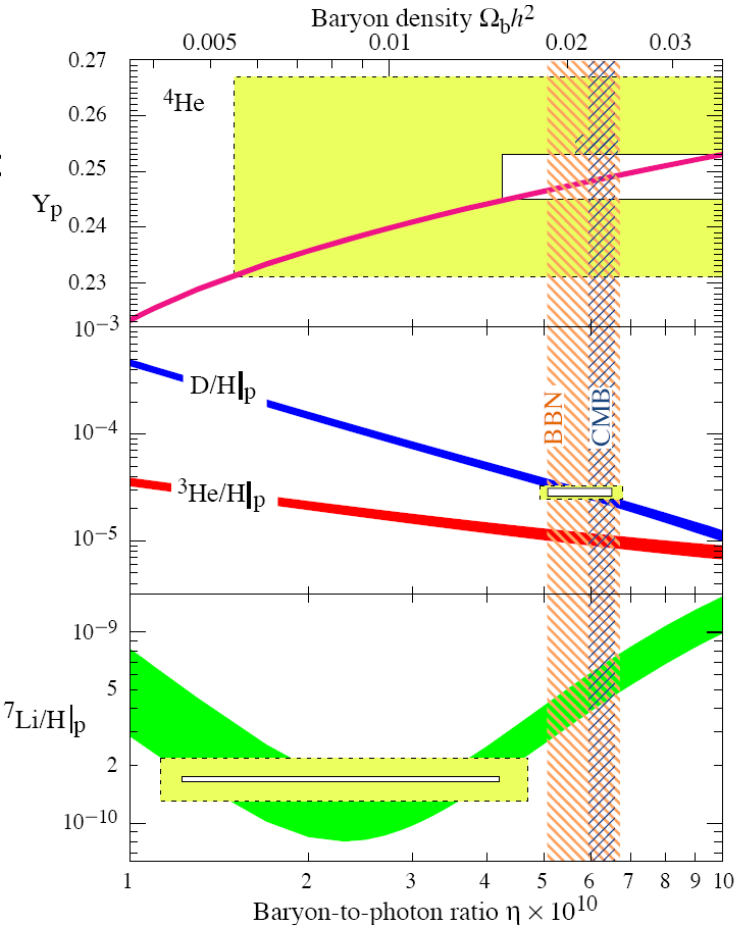
- **Normalization** on the photon density in cosmic 3K background radiation (MWB)

- $$\eta \equiv \frac{n_b}{n_\gamma} \approx (2.6 \ldots 6.2) \times 10^{-10}$$
  1 baryon in about 5 m^3
  or: 10^{78} baryons in visible universe

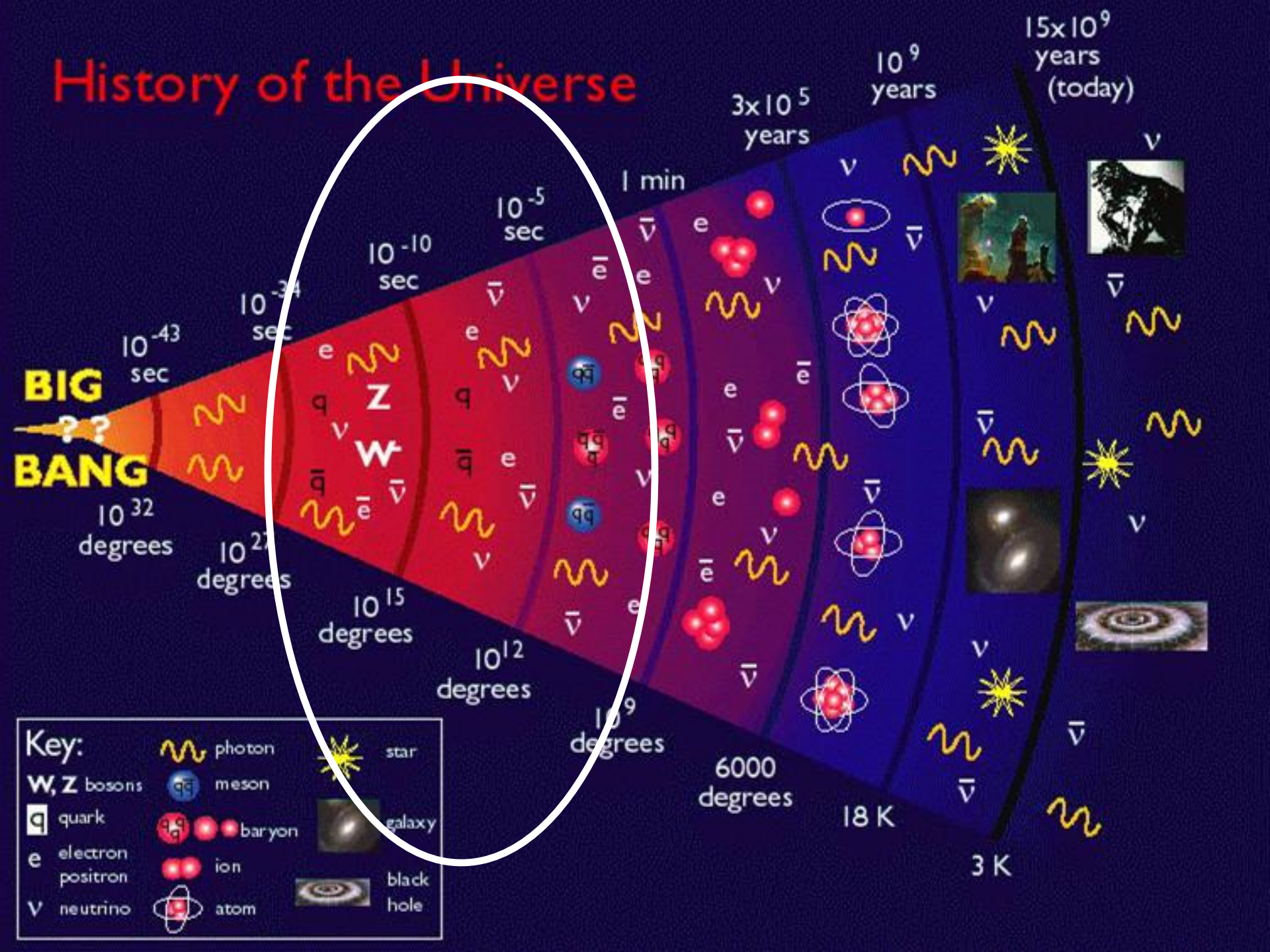
$$n_\gamma \approx 420\ \mathrm{cm}^{-3}$$

- From the MWB anisotropy:

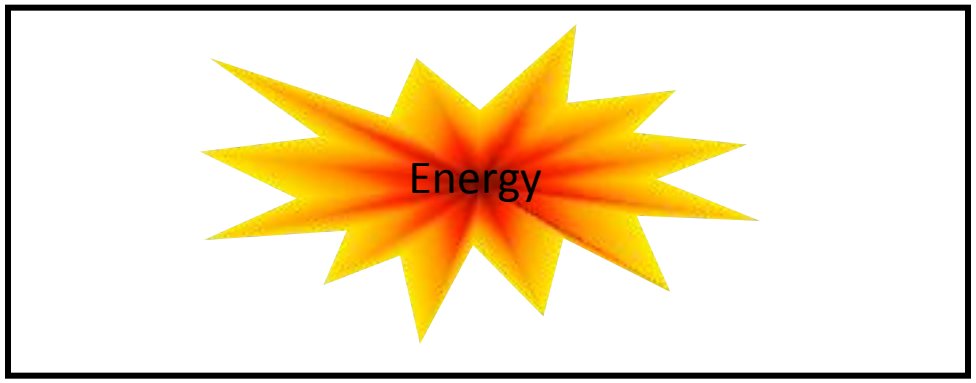
$$\rho_B = (1.8 \ldots 4.3) \times 10^{-31}\ \mathrm{g\ cm}^{-3}$$



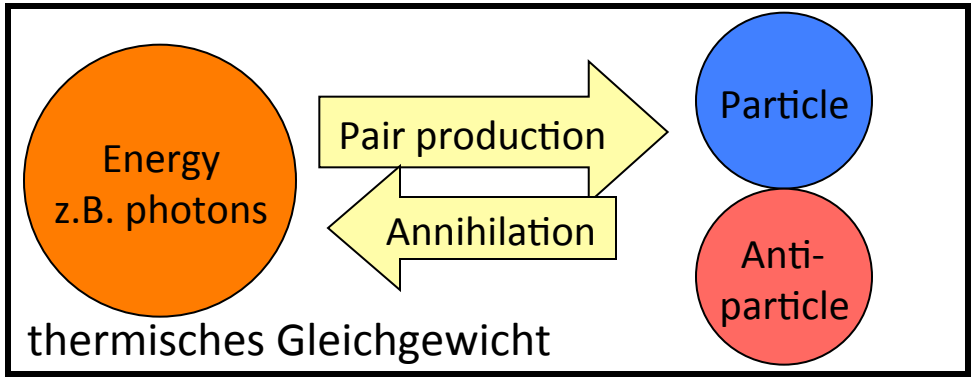
$$\eta = (6.0^{+0.8}_{-1.1}) \times 10^{-10}$$


History of the Universe
BIG
BANG
10 -43 sec
10 -34 sec
10 -10 sec
10 -5 sec
1 min
3x10 5 years
10 9 years
15x10 9 years (today)
10 32 degrees
10 27 degrees
10 15 degrees
10 12 degrees
10 9 degrees
6000 degrees
18 K
3 K
Key:
W, Z bosons
quark
e electron positron
ν neutrino
photon
meson
baryon
ion
atom
star
galaxy
black hole

Matter creation in simple model

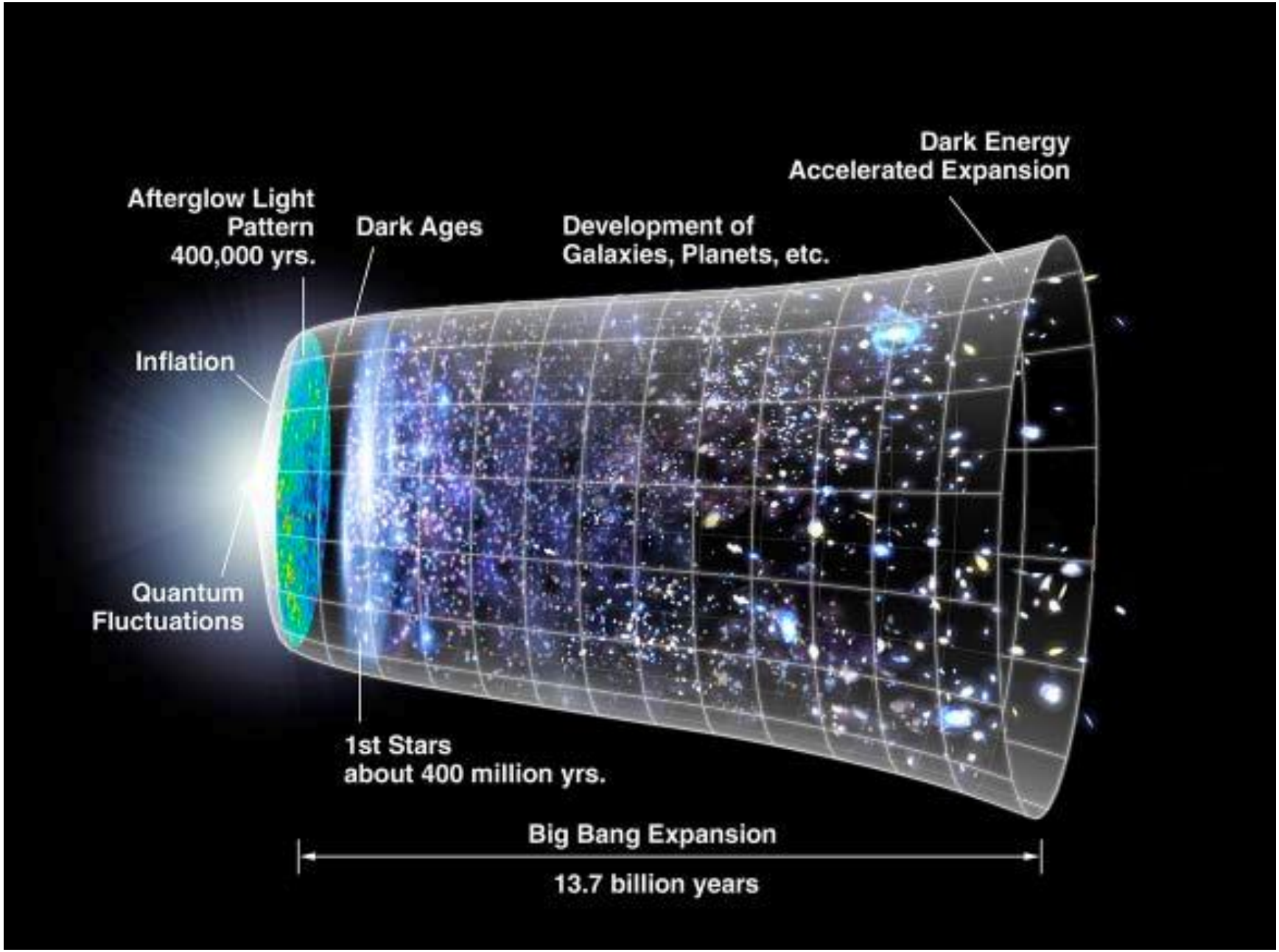


The universe is given by the expansion from a very dense and hot initial state.

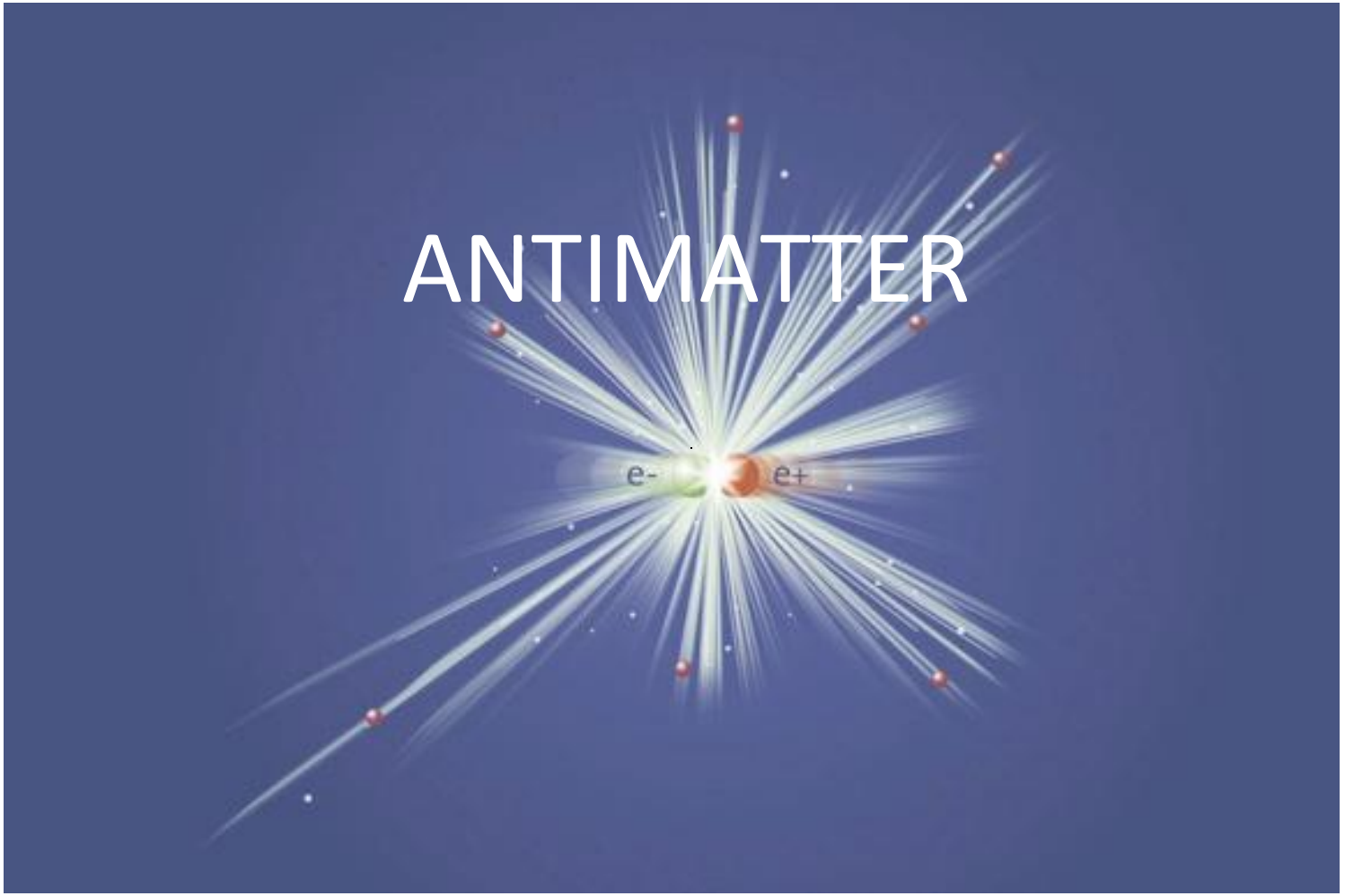


- Particles and antiparticles are formed at the same time
- In thermal equilibrium

- With the expansion of the universe the annihilation stops


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

ANTIMATTER



Historical notes

- **Antimatter** was coined by the English scientist Sir Arthur Schuster (Schuster, Nature, 58, 367 (1898)), who speculated with anti-worlds – 1 year after the discovery of the electron by J.J. Thomson (Thomson 1897) and 30 year before P.M. Dirac formulated his theory of antimatter. The possibility of energy production from annihilations was already considered by A. Schuster.

Theory and Prediction

1928 Paul Dirac,
Nobel prize 1933

Prediction

Dirac-equation for free electron

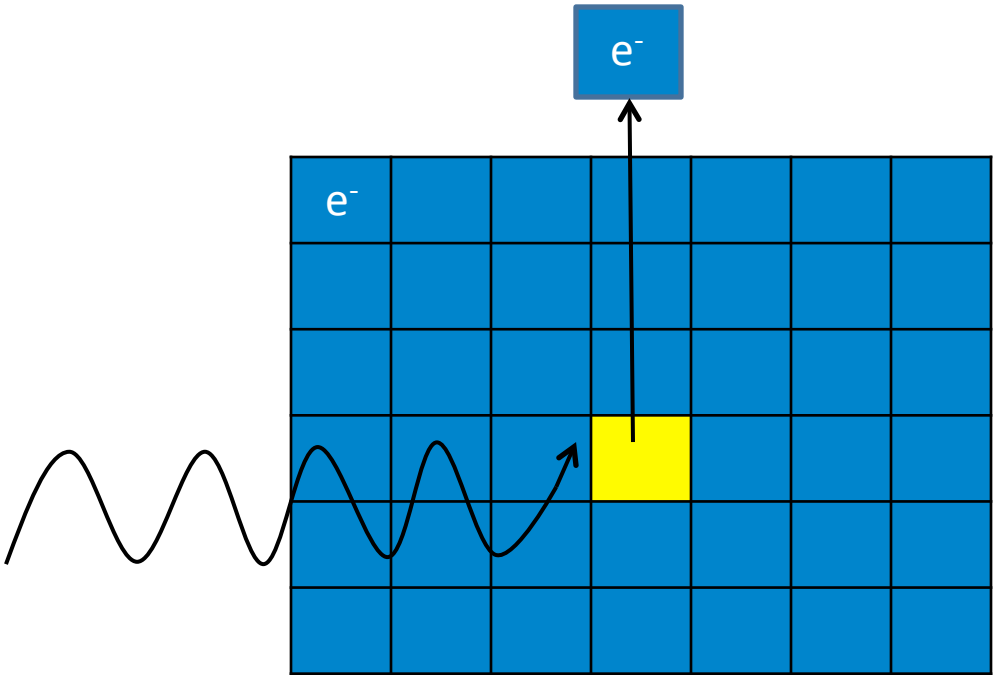
$$\left(i\hbar \frac{\partial}{\partial t} + i\hbar c\, \vec{\hat{\alpha}} \cdot \vec{\nabla} - \hat{\beta} m_e c^2 \right) \vec{\Psi}(\vec{r}, t) = \vec{0}$$

Solution has 2 Eigenwerte
What means solutions with negative energy?

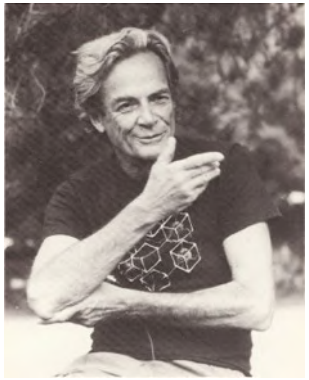
$$E_{\pm} = \pm \sqrt{c^2 \left| \vec{p} \right|^2 + m_e^2 c^4}$$

Interpretation

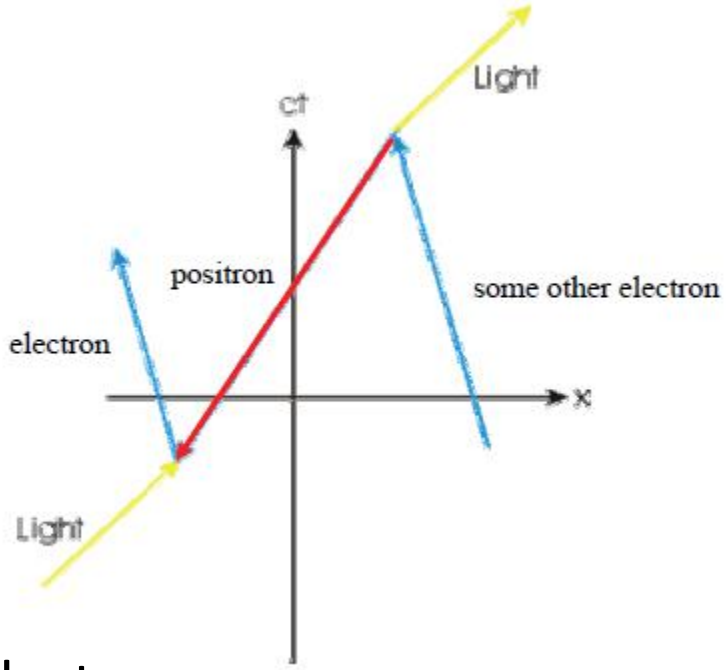
Dirac: All states with negative energy are occupied – if an electron via energy gets positive value – a hole in Dirac-sea results
→ Antiparticle (Positron e^+)



Alternative Interpretation



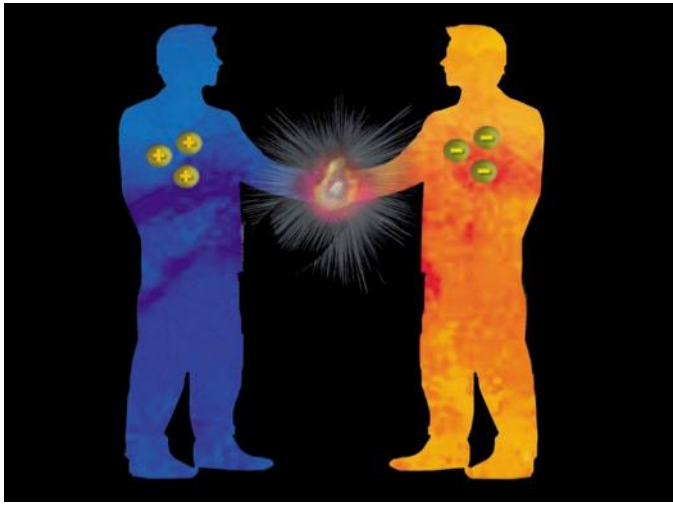
Feynman-Stückelberg 1949



- Positron is a particle
- Positron is ein positively charged electron, which is running back in time

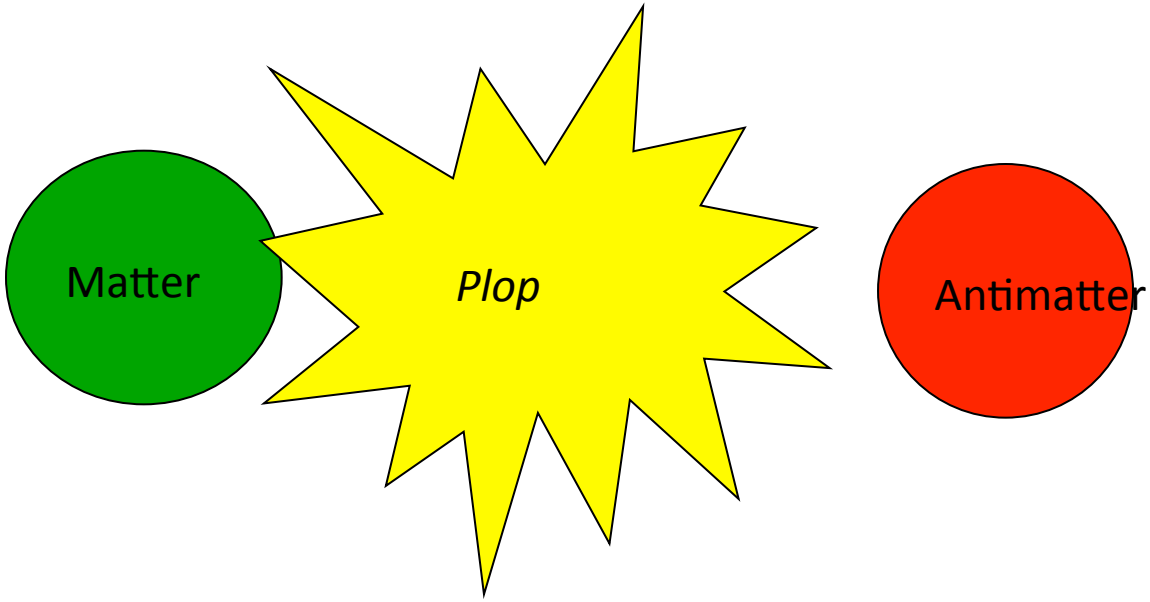
Properties of Antimatter

Charged matter particles: antimatter particle has opposite charge.
If matter meets antimatter annihilation takes place.



All other properties (e.g. mass) of matter and antimatter are the same (CPT theorem), deviation(s) indicate symmetry breaking

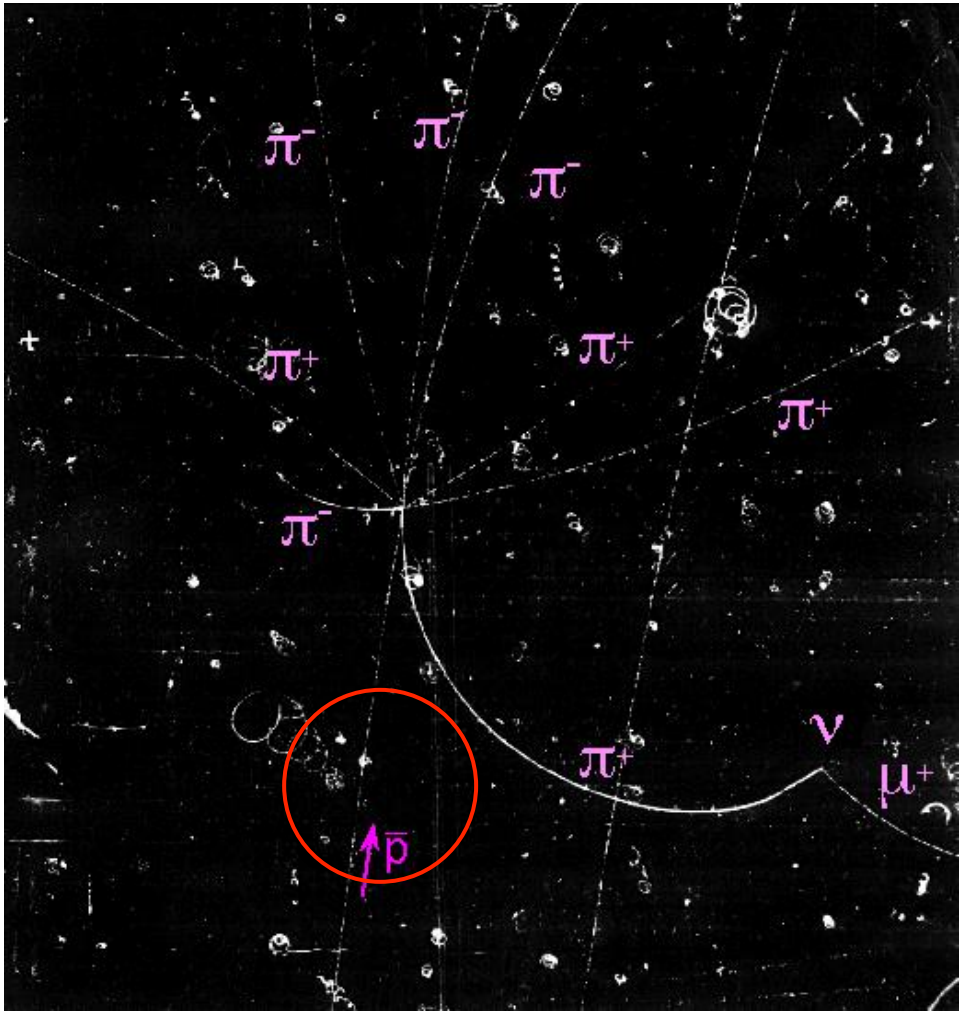
Annihilation of Antimatter



Good for us for us, there is no antimatter near to us.

The absence of antimatter der points to the difference between matter and antimatter. A proven difference is the violation of CP symmetry (only seen K and B systems so far).

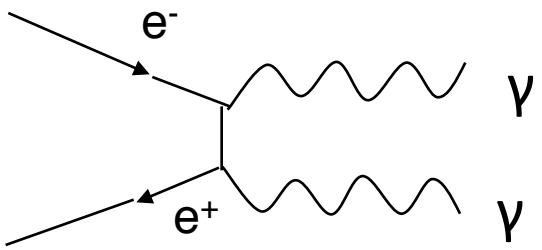
Antiproton-proton Annihilation

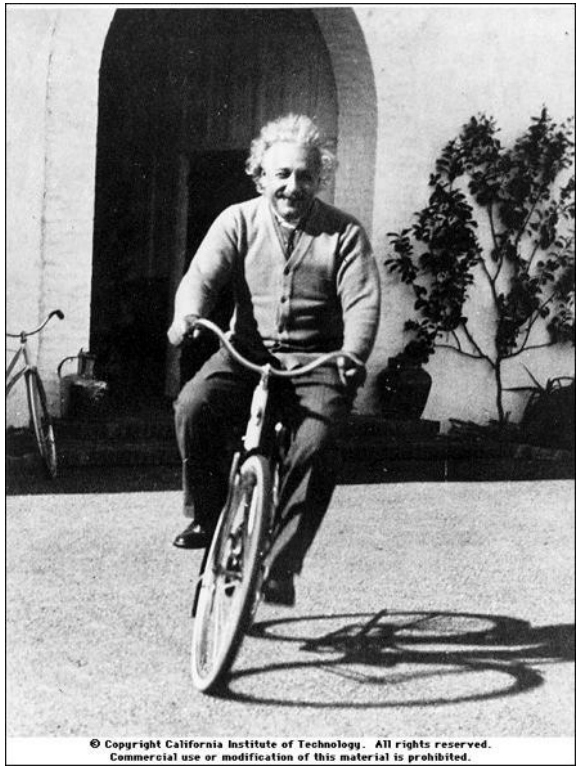


Antiproton annihilates with proton at rest (bubble chamber picture)

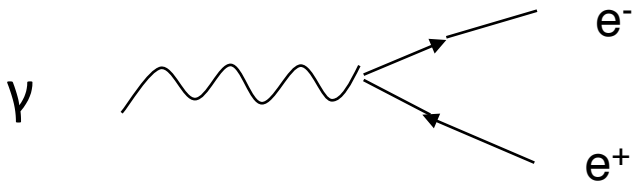
Matter ←→ Energy

- Einstein formulated the equivalence of matter and energy
- Annihilation if matter and antimatter meet



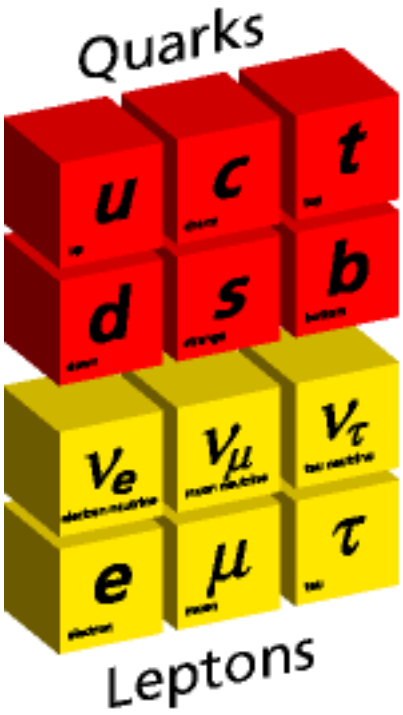


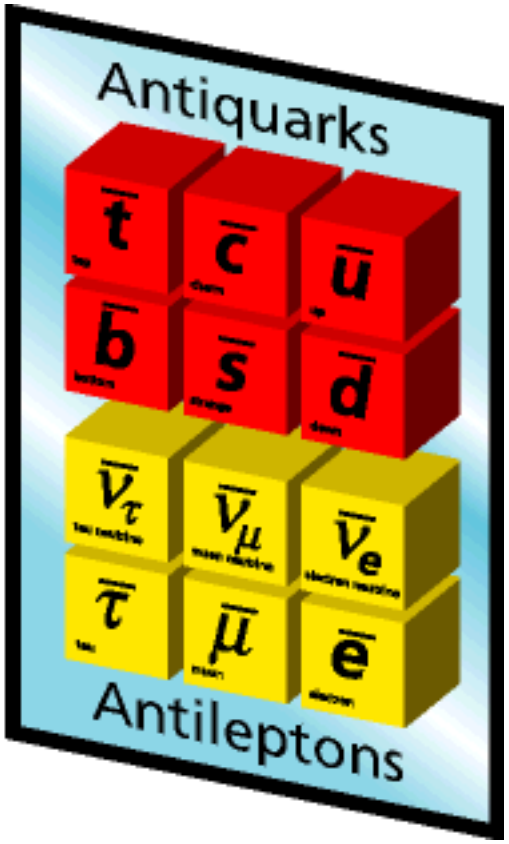
- Energy can create pairs of matter and antimatter



More about Antimatter

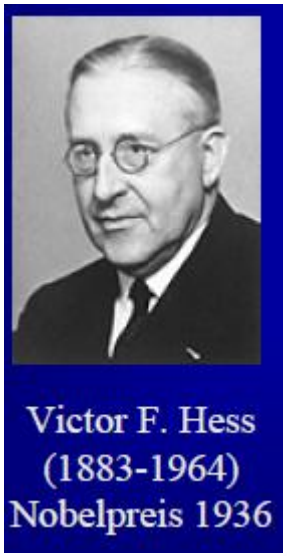
- All charged leptons and quarks have antimatter partners
- Photon is its own antiparticle
- Neutrino own antiparticles?

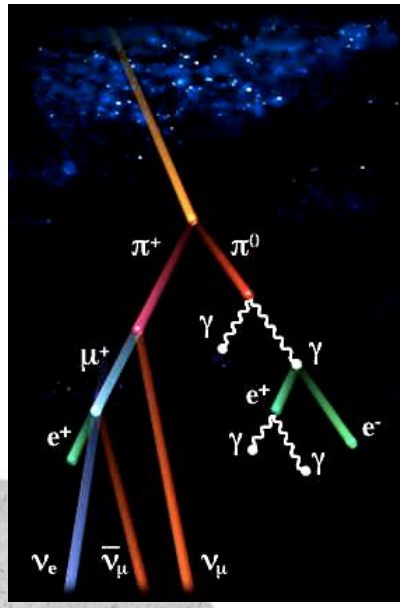




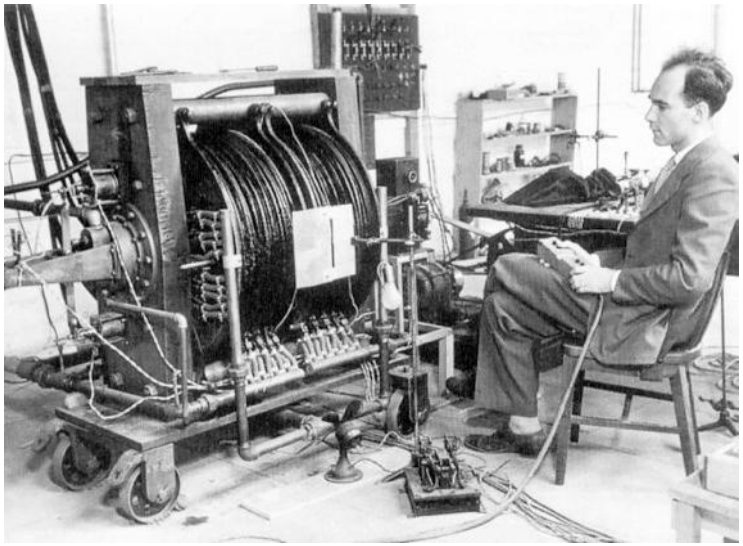
Discoveries

Discovery of Antimatter





C.D. Anderson 1932 (Nobel-Preis 1936)



Lead plate

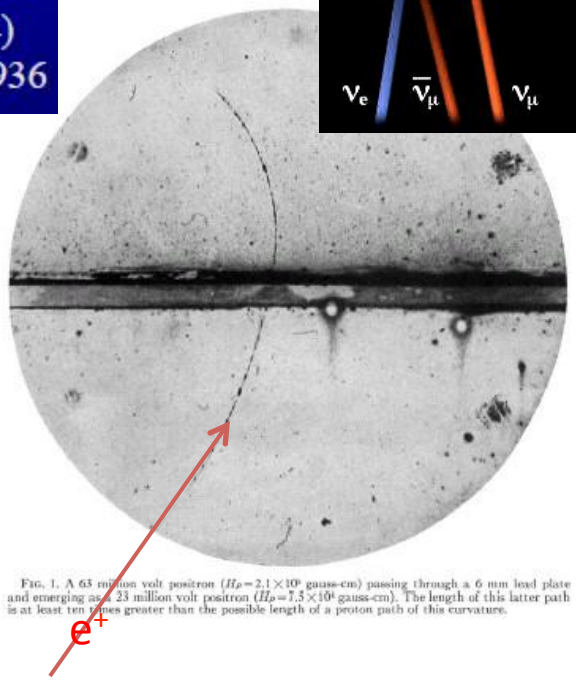


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Discovery of the positrons
In cosmic radiation
Using a cloud chamber
with magnetic field

Detection of pair production= Creation of Antimatter (Positron)

Carl D. Anderson

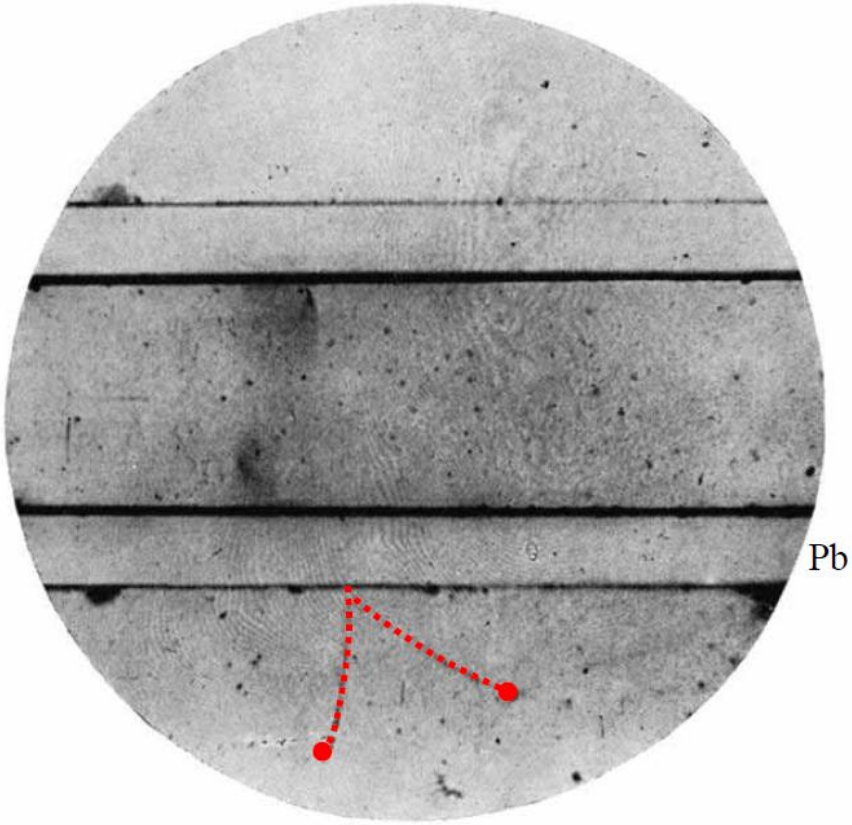


FIG. 2. A positron of 20 million volts energy ($H\rho = 7.1 \times 10^4$ gauss-cm) and a negatron of 30 million volts energy ($H\rho = 10.2 \times 10^4$ gauss-cm) projected from a plate of lead. The range of the positive particle precludes the possibility of ascribing it to a proton of the observed curvature.

Discovery of heavy Anti-particles

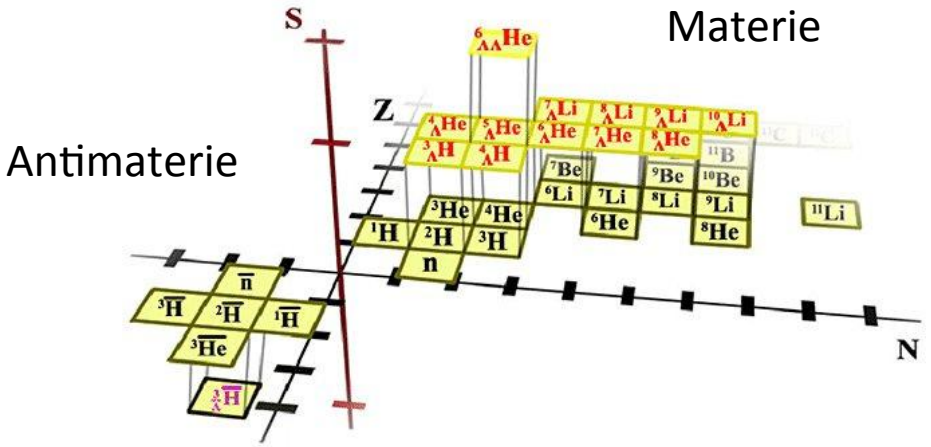
1955 Antiproton - Chamberlain, Segre, Wiegand and Yppsilantis

1956 Antineutron: Piccioni et al.

1964 Antideuteron: Zichichi et al.

2003 Antihelium

2010 Strange Antimatter (Antihypertriton) at RHIC (März 2010, STAR Collaboration)



Antiproton observation

Nobel prize in physics 1959

Chamberlain, Segre, Wiegand and Ypsilantis
Physical Review 100 (1955) 947

Observation of Antiprotons*

OWEN CHAMBERLAIN, EMILIO SEGRÈ, CLYDE WIEGAND, AND THOMAS YPSILANTIS

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received October 24, 1955)

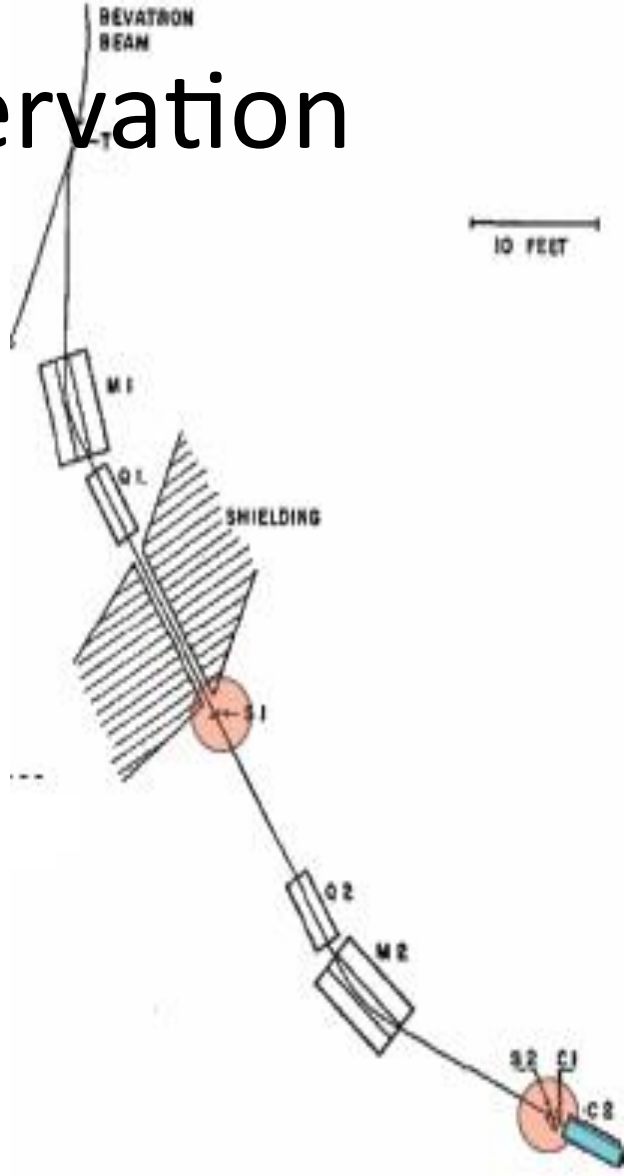
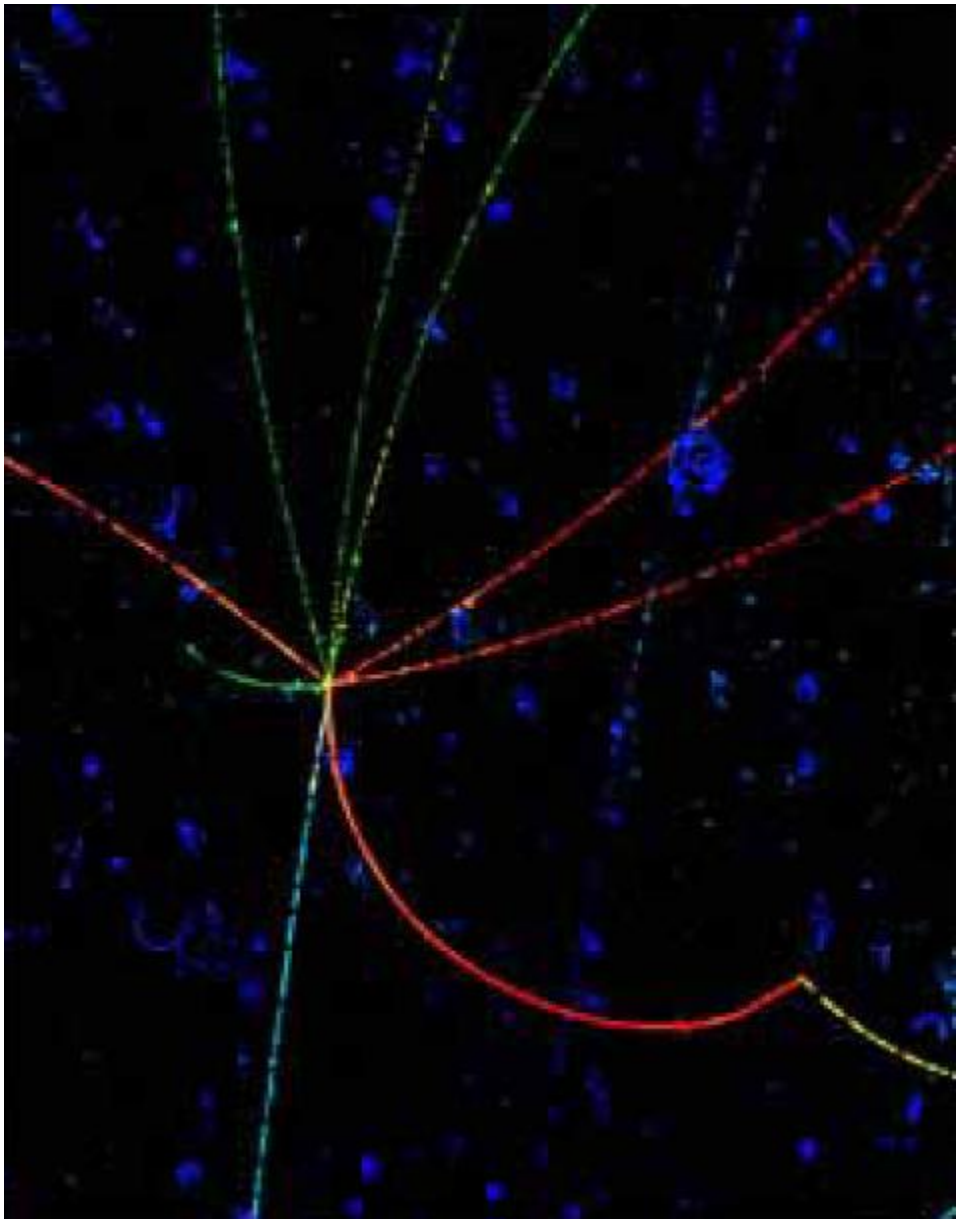


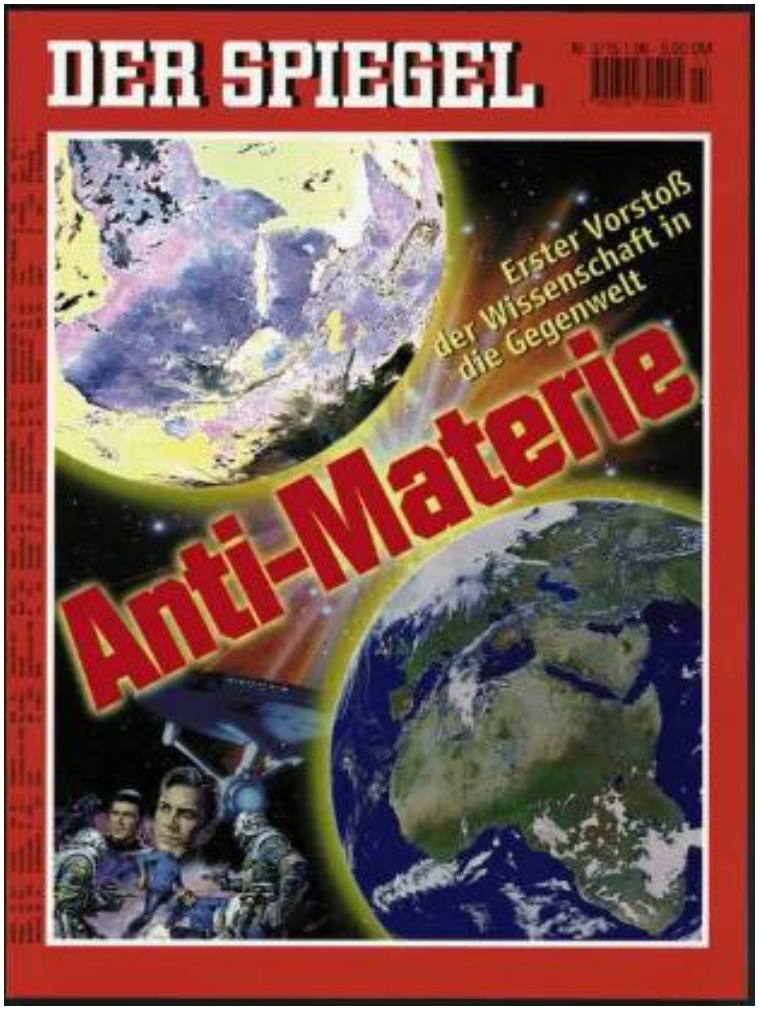
FIG. 1. Diagram of experimental arrangement. For details see Table I.



Nachweis von Antiprotonen

$\bar{p}p \longrightarrow \pi^+\pi^-\,\pi^+\pi^-\,\pi^+\pi^-\,\pi^+\pi^-$

Anti-hydrogen



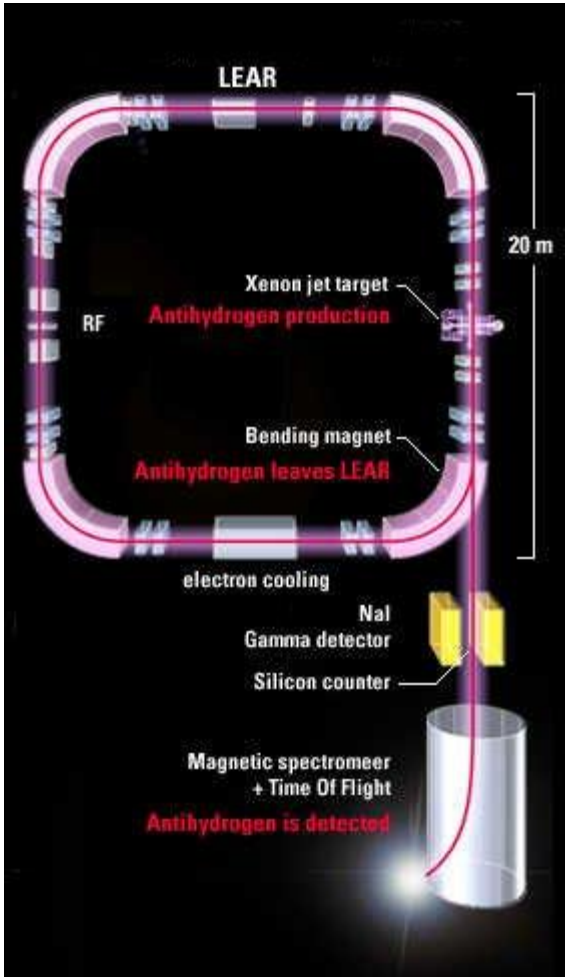
First Antimatter-atom synthesized in Laboratory out of anti-particles (antiproton+positron)

LEAR (Low Energy Antiproton Ring)

Installed at CERN:

Very successful in hadron spectroscopy (extracted antiprotons) and first detection of

Neutral antimatter (antihydrogen)



ELSEVIER

1 February 1996

PHYSICS LETTERS B

Physics Letters B 368 (1996) 251–258

Production of antihydrogen

G. Baur [a], G. Boero [b], S. Brauksiepe [a], A. Buzzo [b], W. Eyrich [c], R. Geyer [a], D. Grzonka [a], J. Hauffe [c], K. Kilian [a], M. LoVetere [b], M. Macri [b], M. Moosburger [c], R. Nellen [a], W. Oelert [a], S. Passaggio [b], A. Pozzo [b], K. Röhrich [a], K. Sachs [a], G. Schepers [e], T. Sefzick [a], R.S. Simon [d], R. Stratmann [d], F. Stinzing [c], M. Wolke [a]

[a] *IKP, Forschungszentrum Jülich GmbH, Germany*
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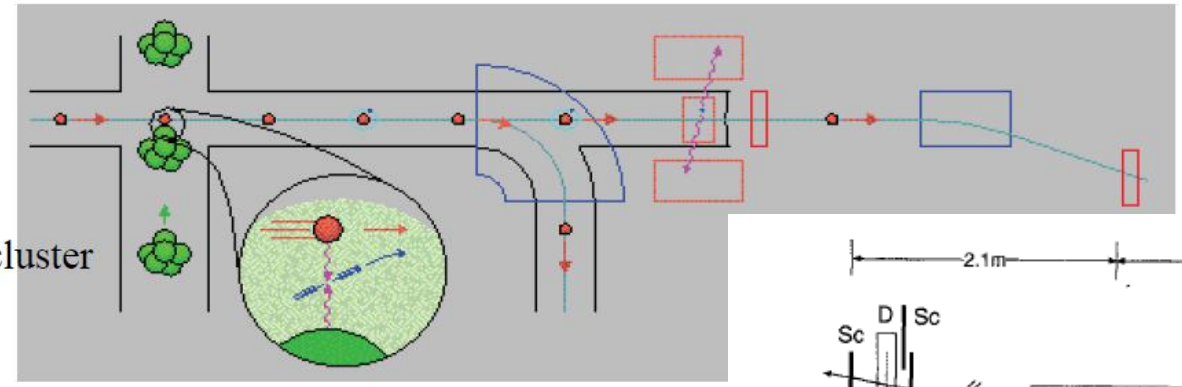
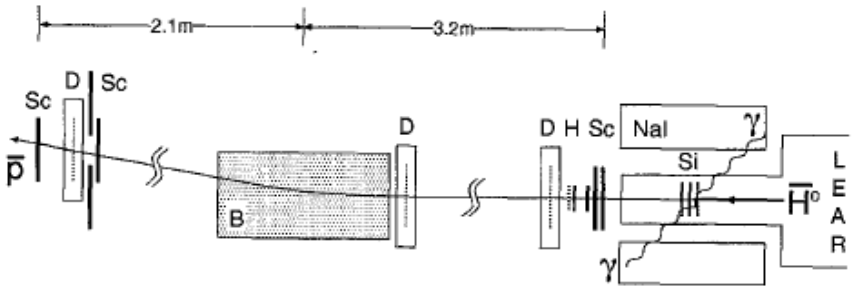
Editor: L. Montanet

11 antihydrogen atoms produced

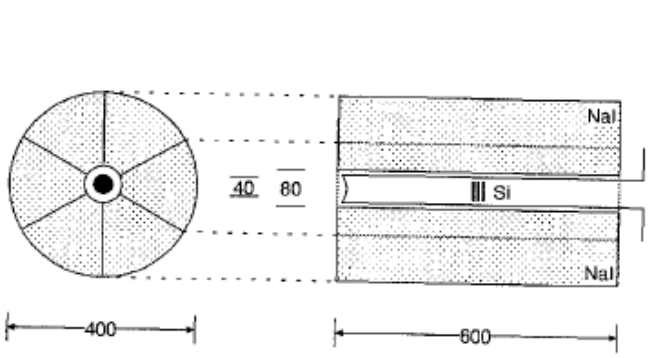
Thus, it can be concluded that *11* $\overline{H}^0$ *atoms have been observed.* The $\overline{H}^0$ production rate is in good agreement with the expected value following the theoretical $\gamma\gamma$-production mechanism [6,8]. No production of $\overline{H}^0$ has ever been reported or observed before.

1995 Experiment 210 at LEAR

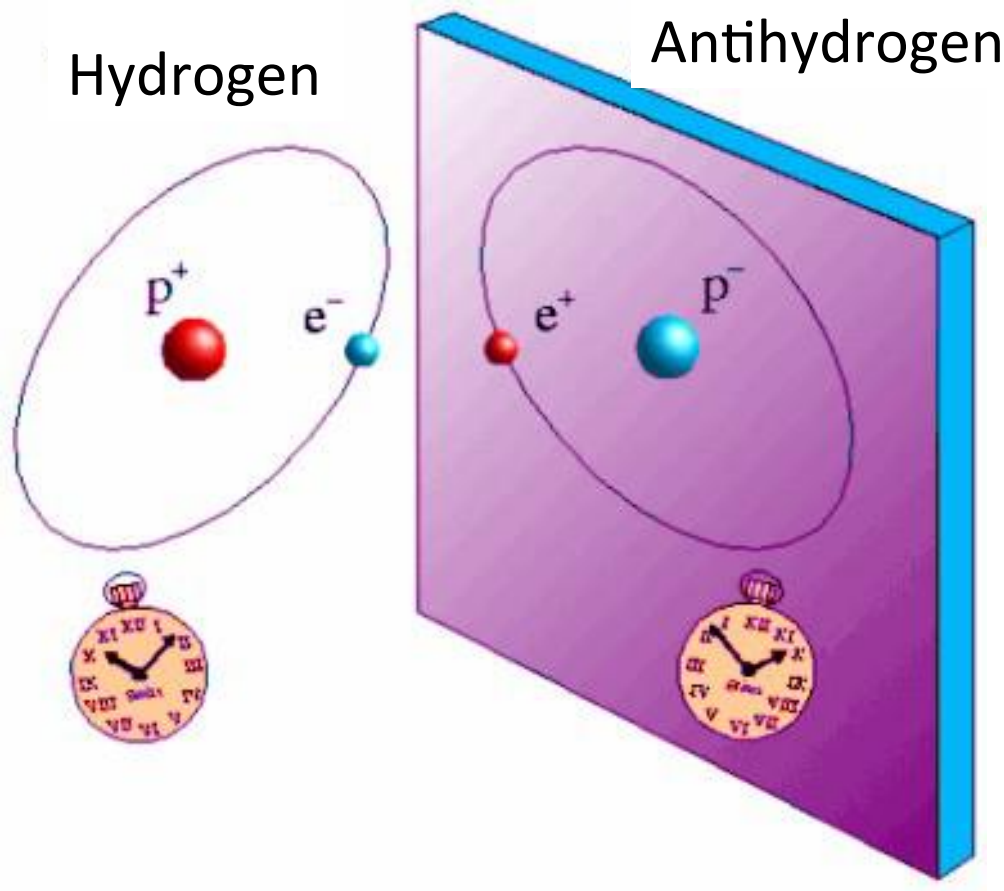




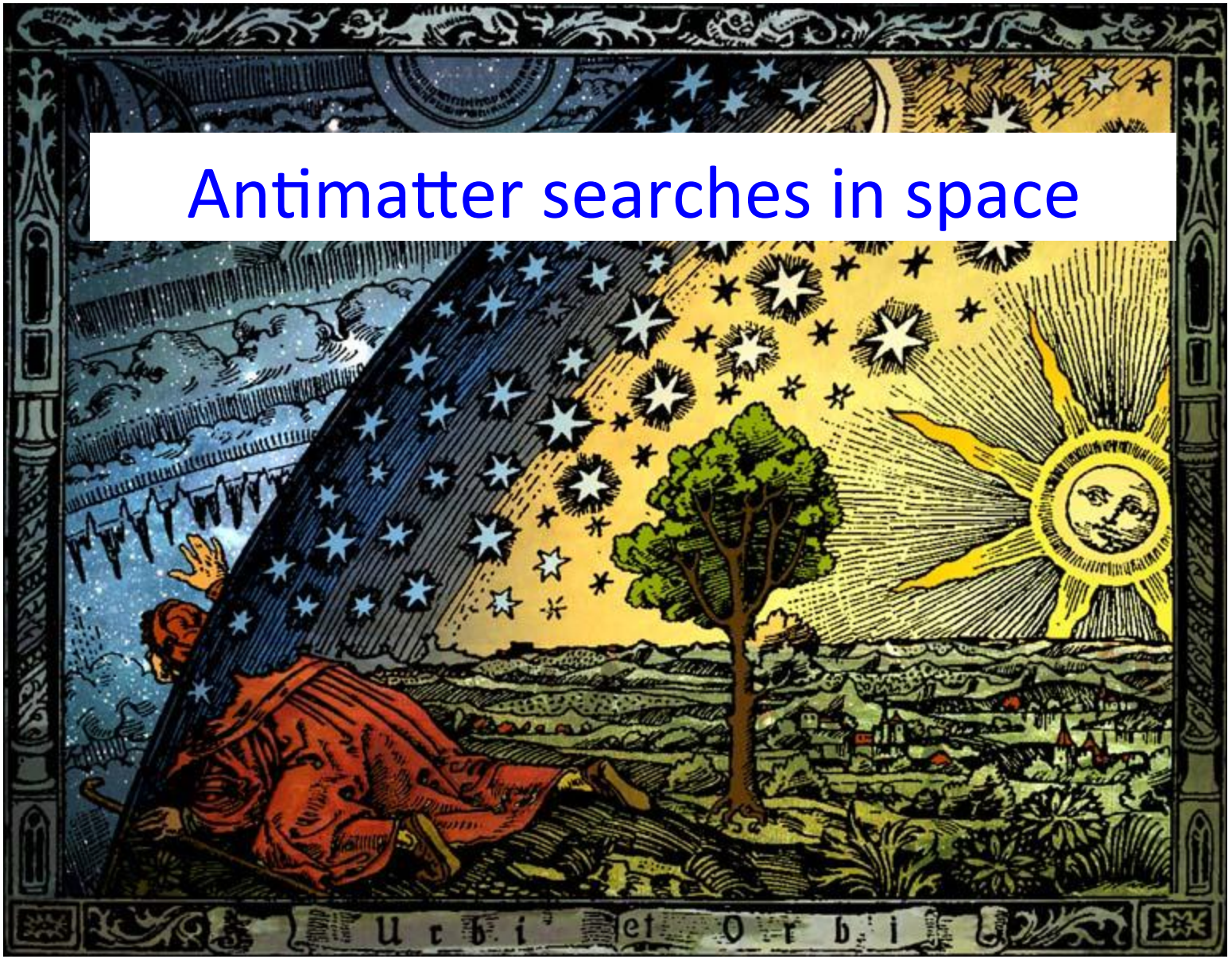
Probability=
0.000 000.000.000.000.01
11 Antihydrogen-atoms (pbar-e^+) identified



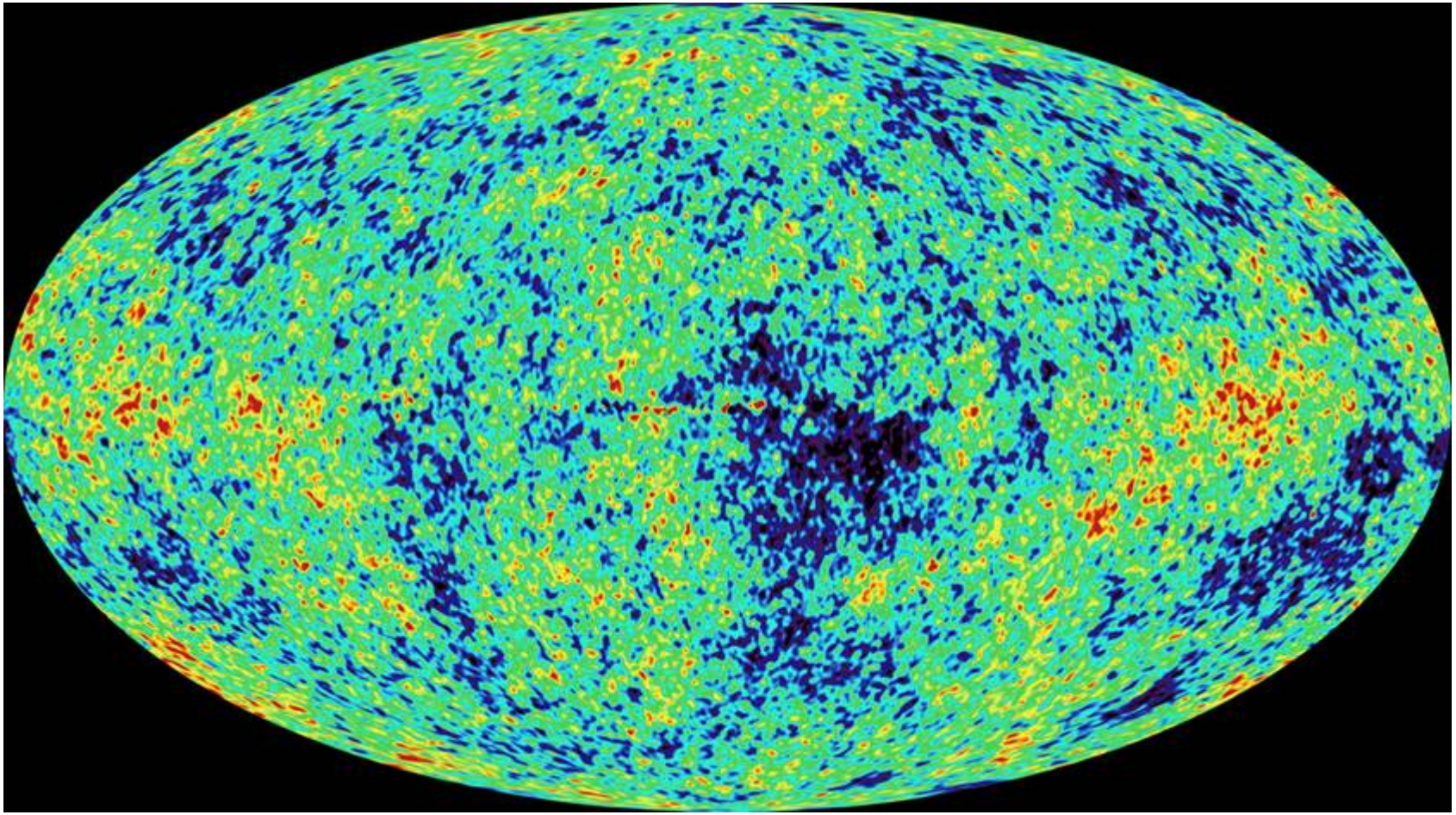
Antimatter = Mirror of Matter?



Antimatter searches in space

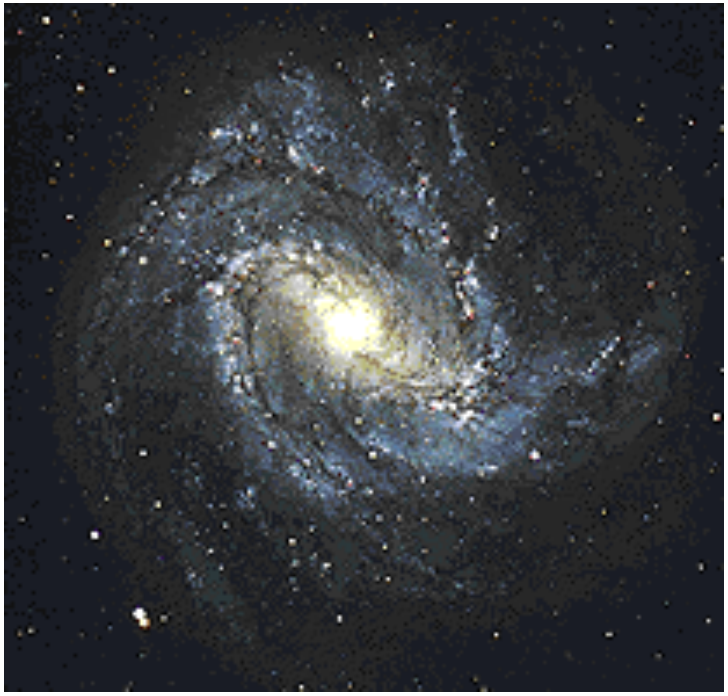


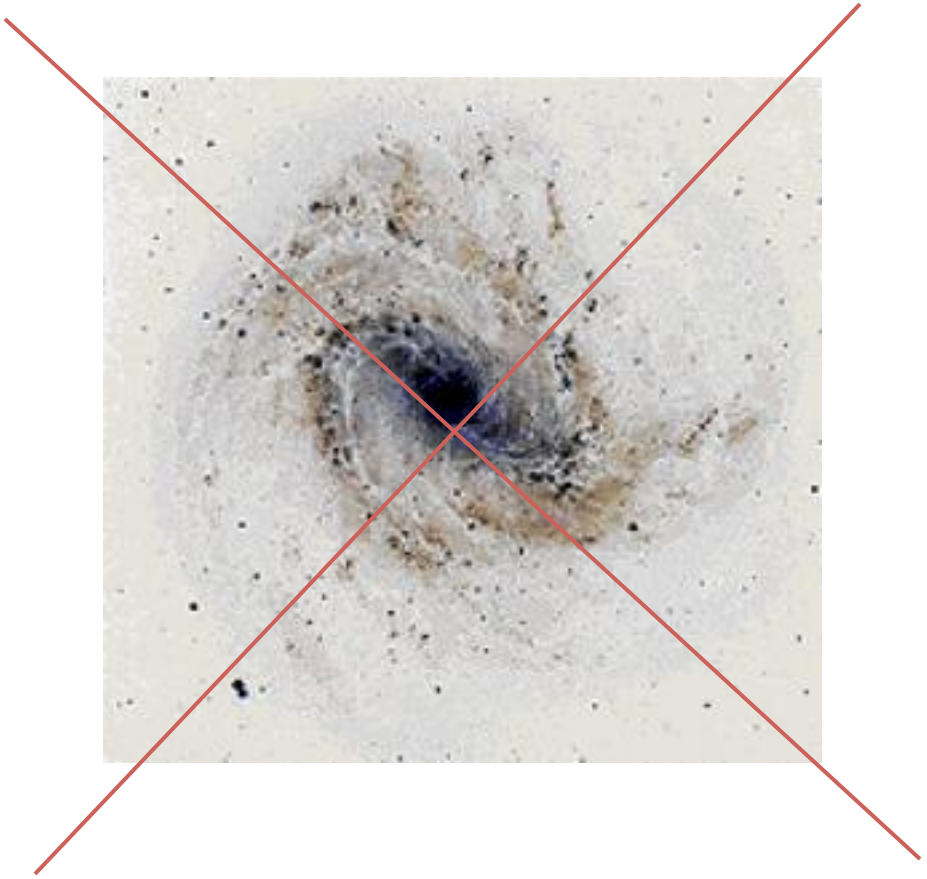
MWB (Microwave Background):
Picture of the big bang



Cosmic background radiation at 2.7 K

No Antimatter in the Universe?





Creation of Matter

- Planck-era 10^{-43} s after Big Bang
- 10^{-34} s very hot plasma (10^{30} K) with quarks, leptons and other particles
- 10^{-34} – 10^{-32} s symmetry breaking, only quarks and leptons
- 10^{-10} s Symmetry breaking, separation of strong and electromagnetic interaction
- 10^{-6}s Quarks in hadrons (proton, neutron …)

Possible scenario for Matter dominated world

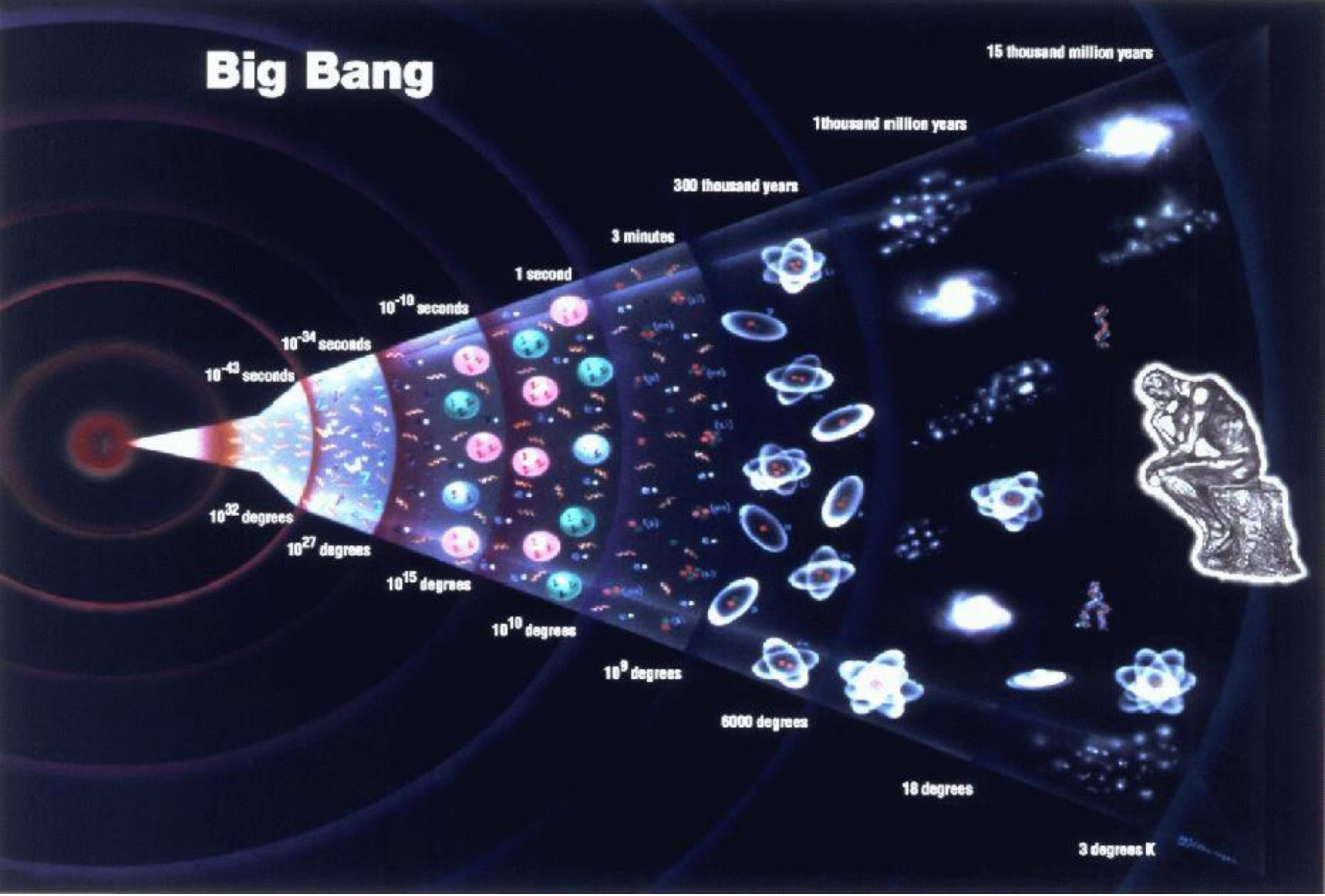
- Antimatter-Matter Asymmetry in hadronization
- In the cooling phase protons cannot be created
- Pair-destruction

1 000 000 001 protons annihilate with
1000 000 000 antiprotons

1 protons left over

- After 1 s the same happens with electron-positron pairs

- Out of these tiny left overs our material world developed.
- Afterwards expansion

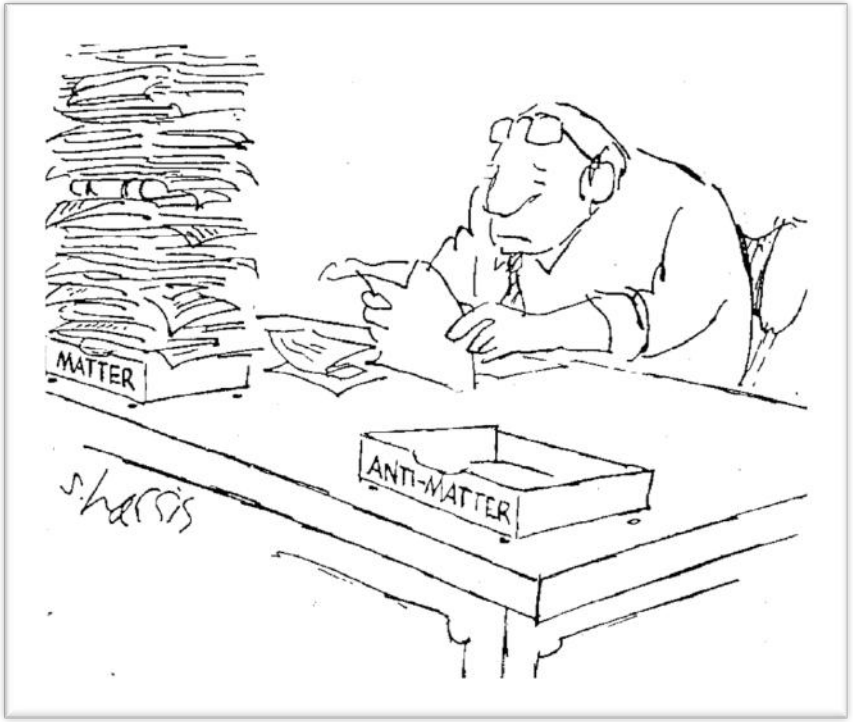

Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K

Our (visible) world around of matter only

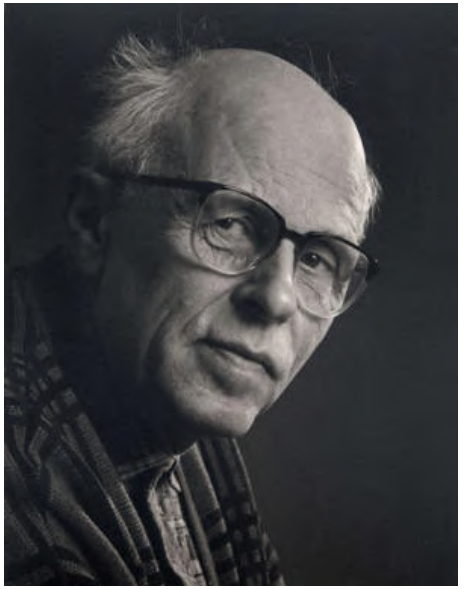
... No antimatter

Antimatter observed:

- Produced by particle accelerators
- Produced by cosmic rays
- Decay of radioactive isotopes (e.g. positron emitters)



Criteria for Matter-Antimatter-Asymmetry



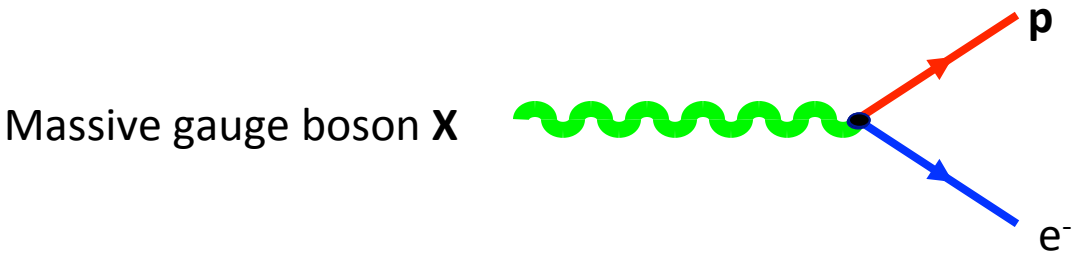
A. Sakharov

Sakharov Criteria:

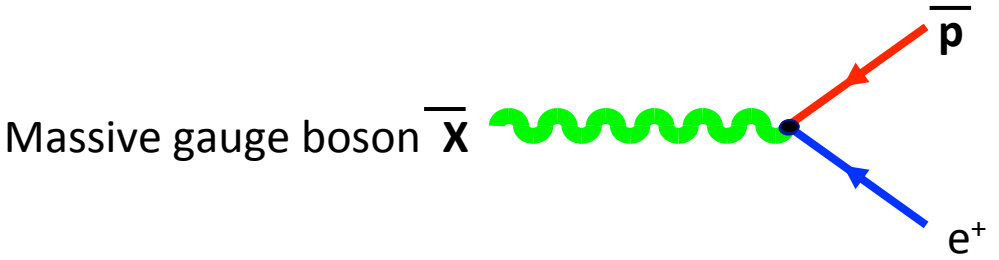
- Baryon-Number Violation
- Deviation from thermal Equilibrium
  - Expansion of the Universe
  - Phase transitions
- Symmetry violation (T...CP)
  - CP-violation too small to explain the observed asymmetry in the framework of the standard model ?
  - → New Physics?

Baryon number violation

- A possibility is the a asymmetry of the decay
  – massive gauge bosons



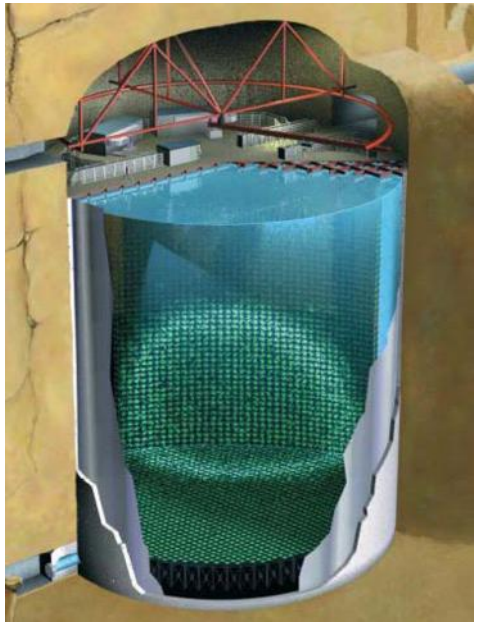
- CP conjugated reaction



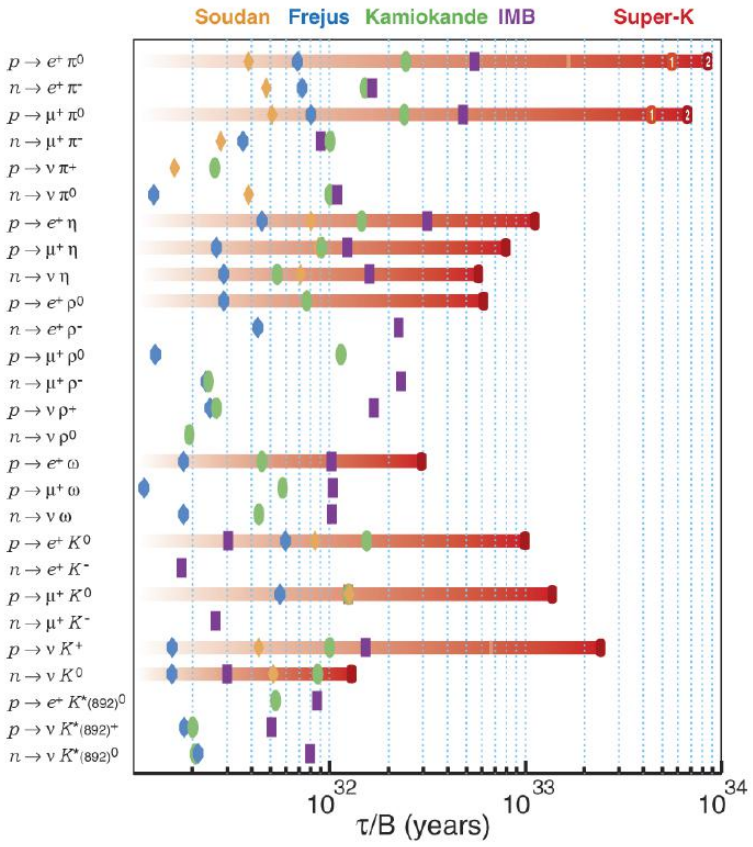
If both processes occur with the same probability then the baryon net bilance (protons) is zero − in spite of the baryon number violation.

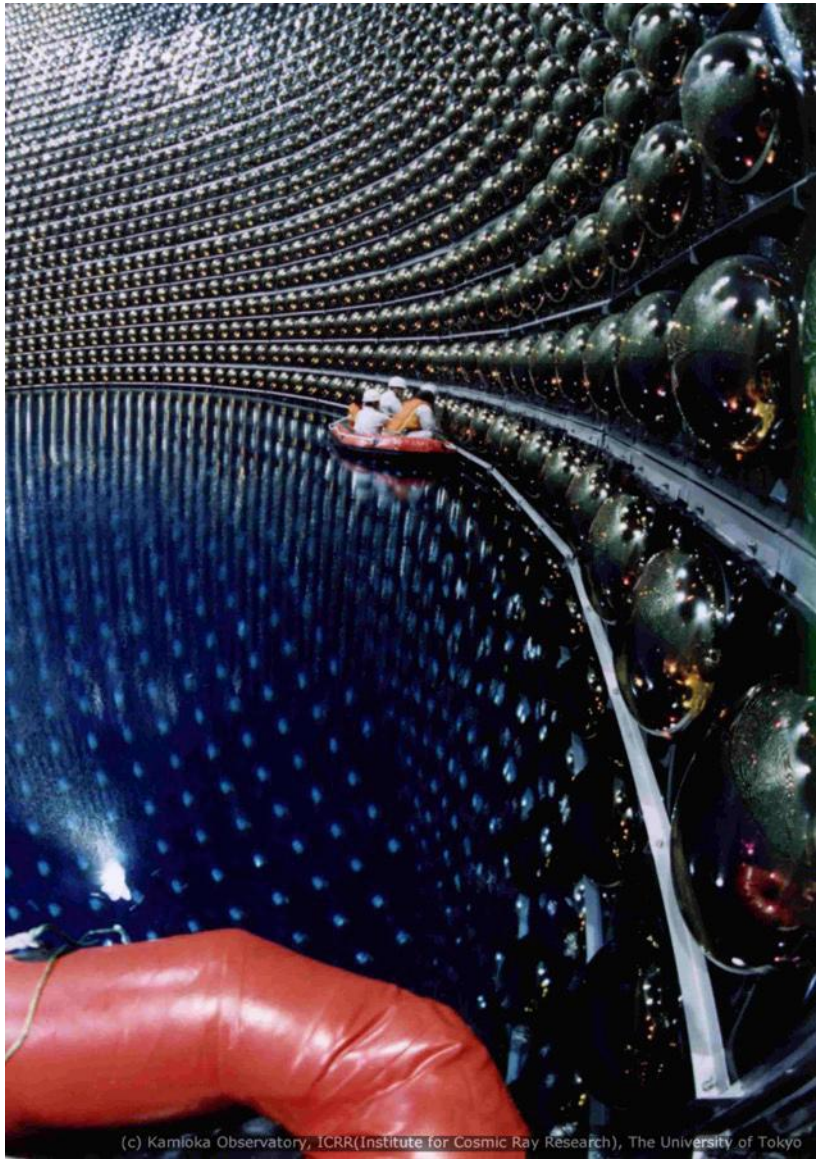
Baryon number-Violation

- Up-to-now no indication
- Proton very stable
- T> 10^{31} – 10^{33} years

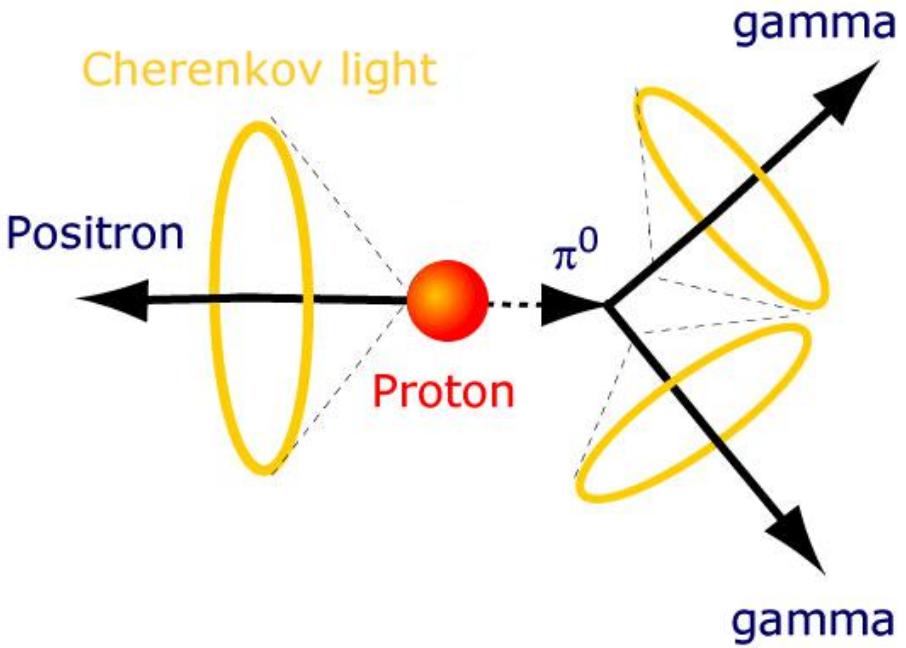


Super-Kamiokande (50 kt water)





Reaction investigated (Cherenkov light) for proton decay



$P \rightarrow p^+ + \gamma\gamma$

Deviation from thermal equilibrium

- In equilibrium the Baryon-producing reaction and the reverse reaction (baryon decay) have equal probability
- No enhancement of baryons
- In a phase of thermal non-equilibrium baryon-production prevails.

Studies on Antimatter

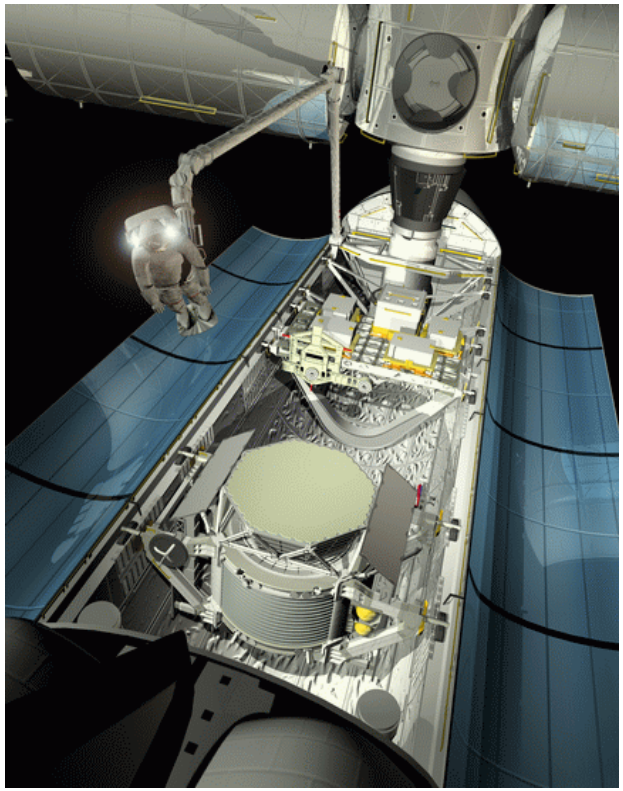
- Direct Search with detectors in space

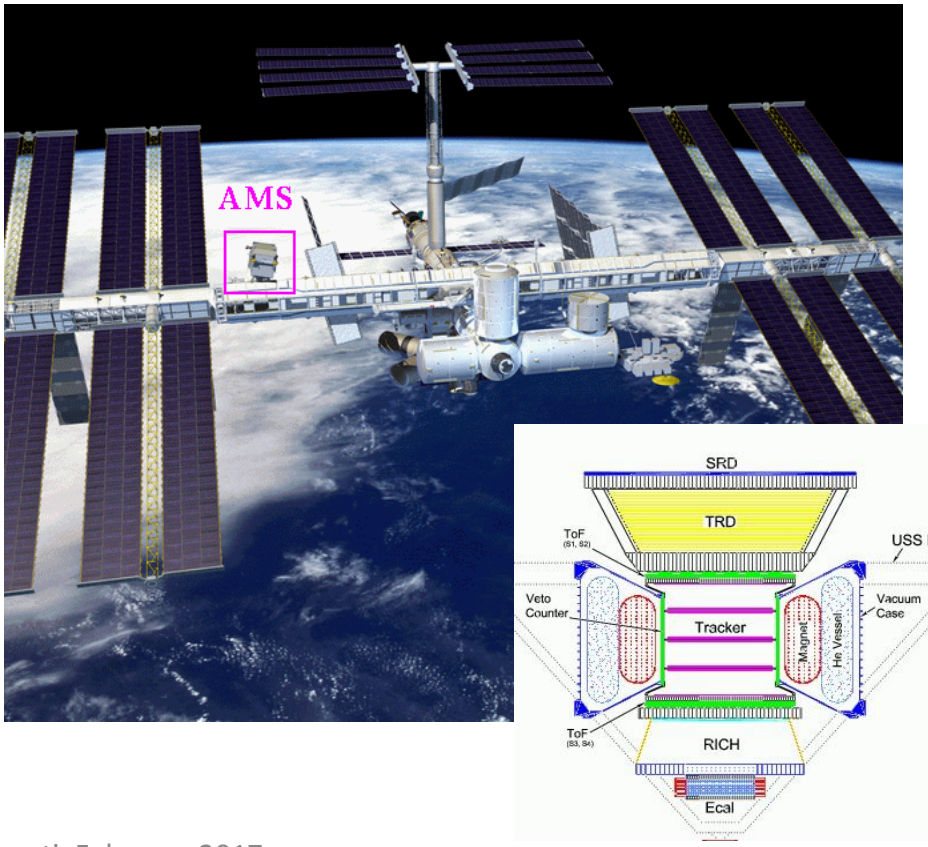
  (Signatures of annihilation processes, direct evidence of antimatter)

- Studies with artificially produced antimatter in the laboratory: Precision measurements of the properties and search for indications for violation of fundamental symmetries (e.g. CPT Symmetry)

Alpha Magnetic Spectrometer (AMS) Experiment

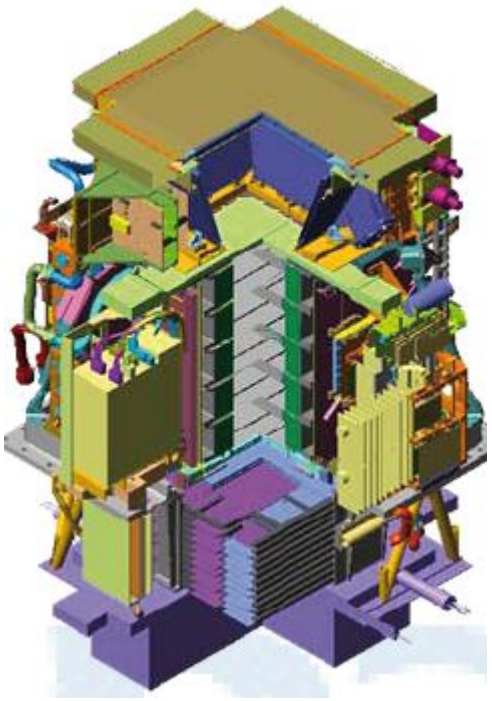
AMS is a spectrometer system, which is installed on the ISS for direct searches of cosmic antimatter



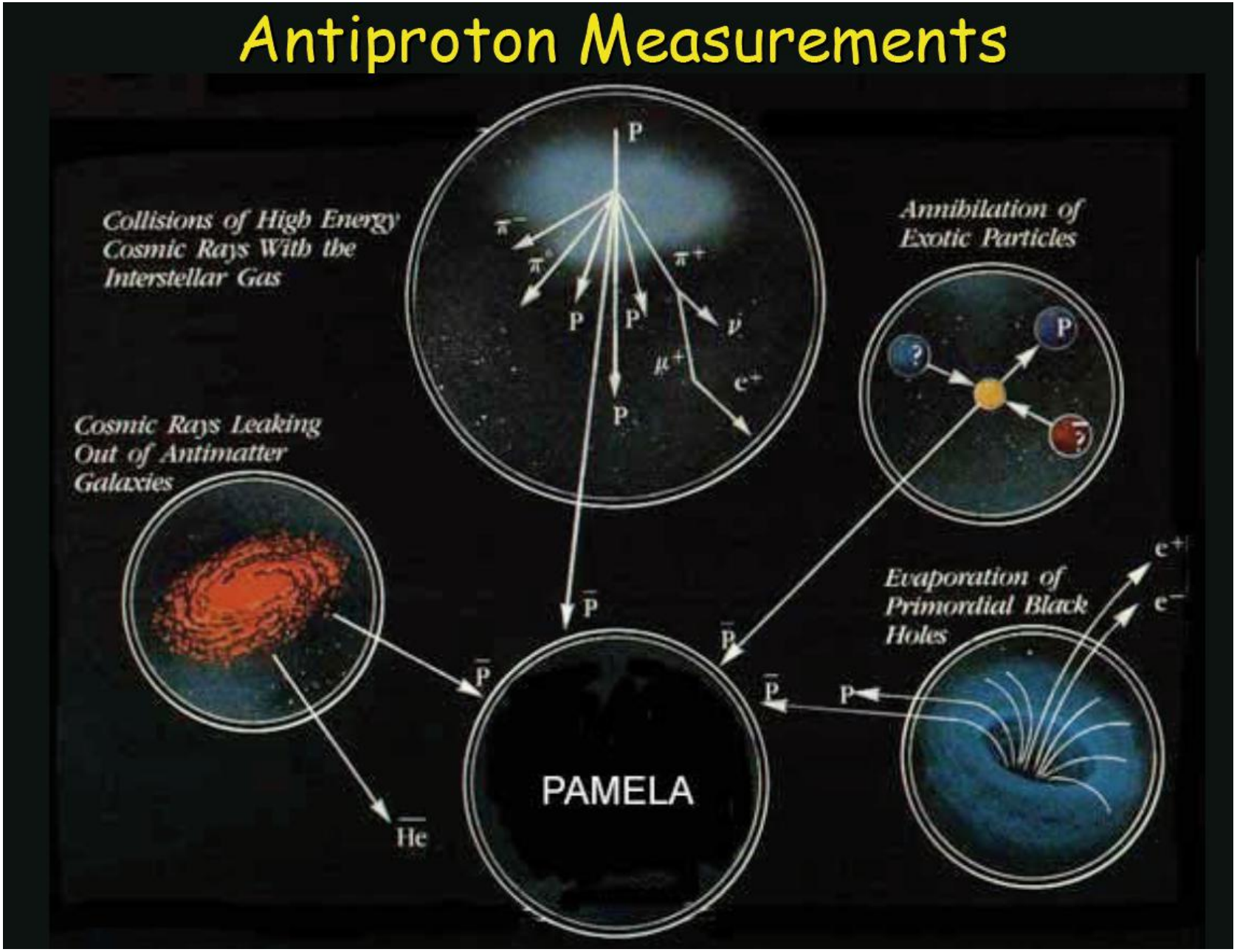


Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

In orbit Juni 15, 2006, on board of satelite DK1 started with Soyuz rocket from Bajkonour.

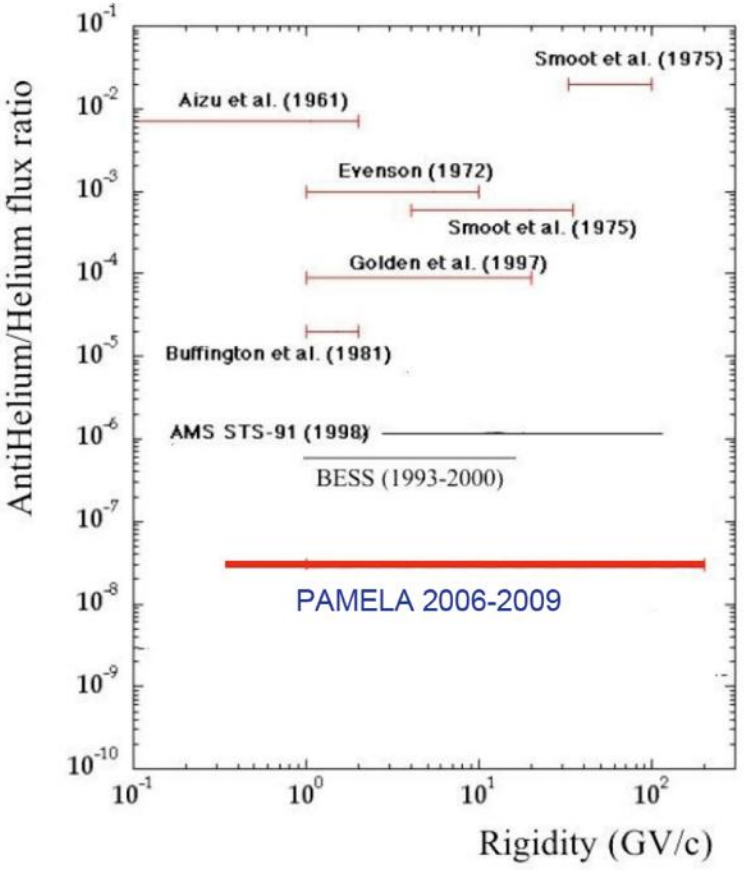


Antiproton Measurements



Findings

- AMS at the ISS detected 3.000 000 He-Atome and no anti-helium atom (He-atoms are produced only very rarely in secondary processes).
- Gamma radiation measurements give a limit for antimatter in 50 – 100 Mpc (150 – 300 10^{16}m, 150 – 300 lightyears) distance



Searches with antimatter in the laboratory

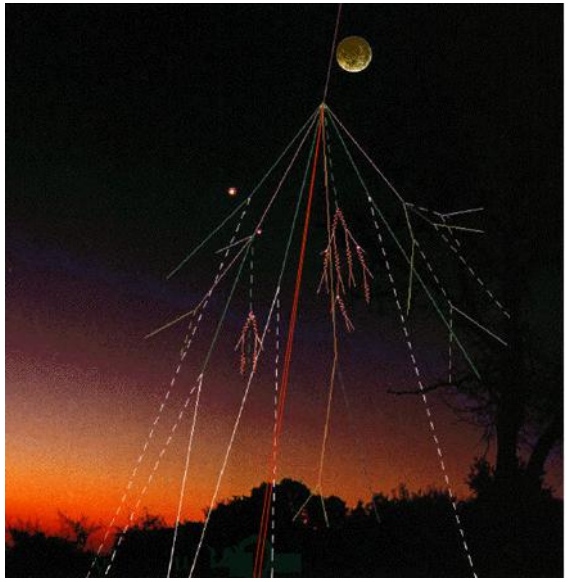
Antimatter: Radioactive decay, cosmics

β^+ - decay

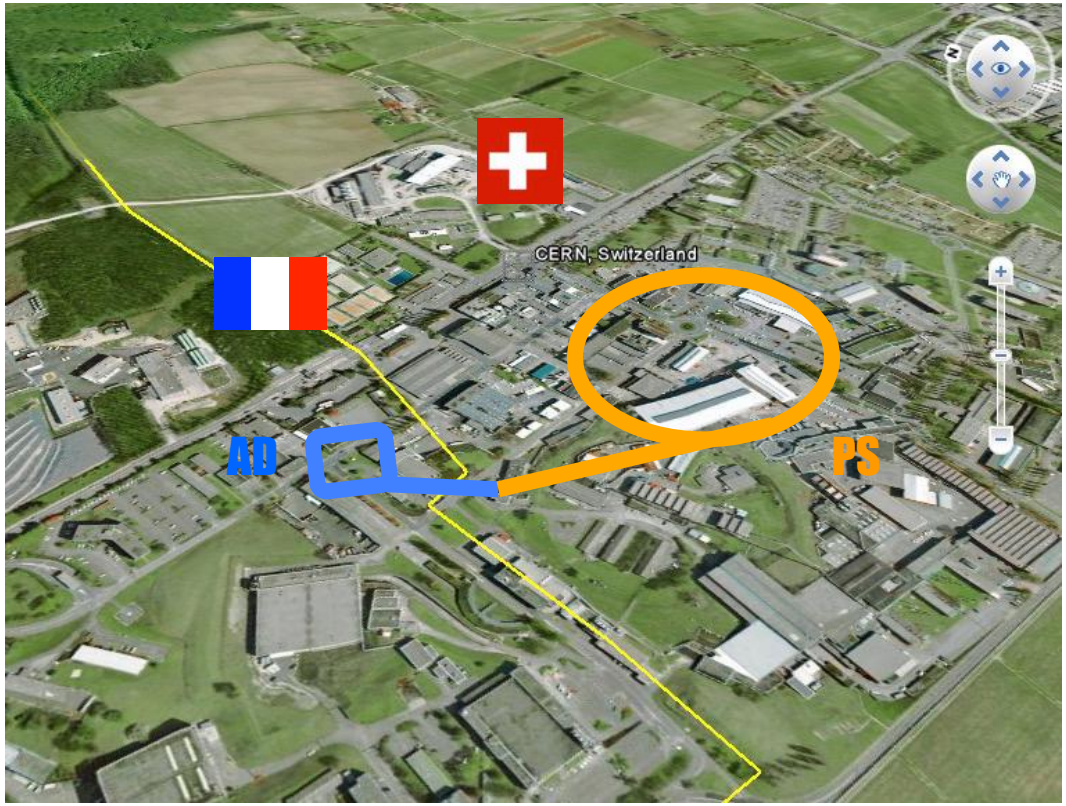
$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + e^+ + \nu_e$$

Cosmic rays

e^+, μ^+, π



Production with particle accelerators



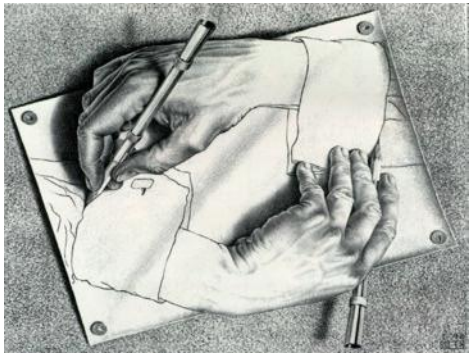
Antiproton Decelerator (AD) of CERN

Symmetries

C: Charge conjugation : particle→antiparticle

P: Parity (space mirror): $x \rightarrow -x$

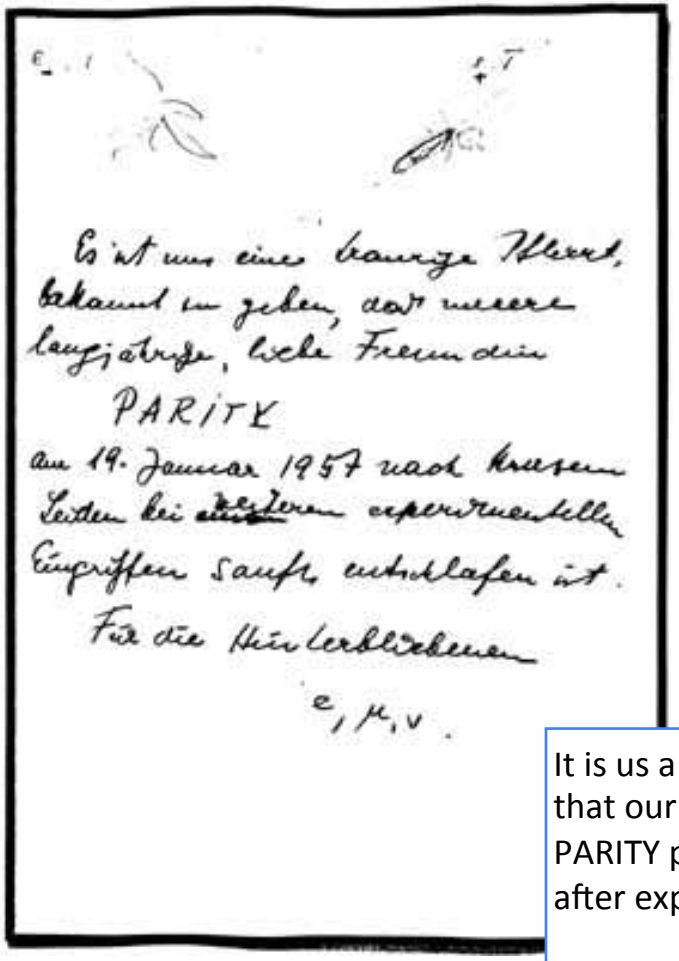
T : Time reversal: $t \rightarrow -t$.

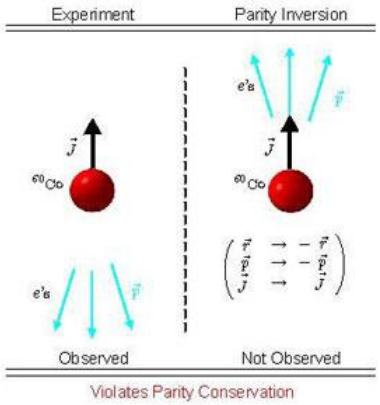


Broken symmetries

- Parity P → in weak interaction
- Combined CP → in kaon/B-meson sector
- CPT unbroken?

First symmetry violation (P)


Es ist uns eine bauige Pflicht,
bekannt zu geben, daß unsere
langjährige, liebe Freundin
PARITY
am 19. Januar 1957 nach kurzem
Leiden bei ihrer experimentellen
Einprüfung sanft entschlafen ist.
Für die Hinterbliebenen
e, μ, ν.

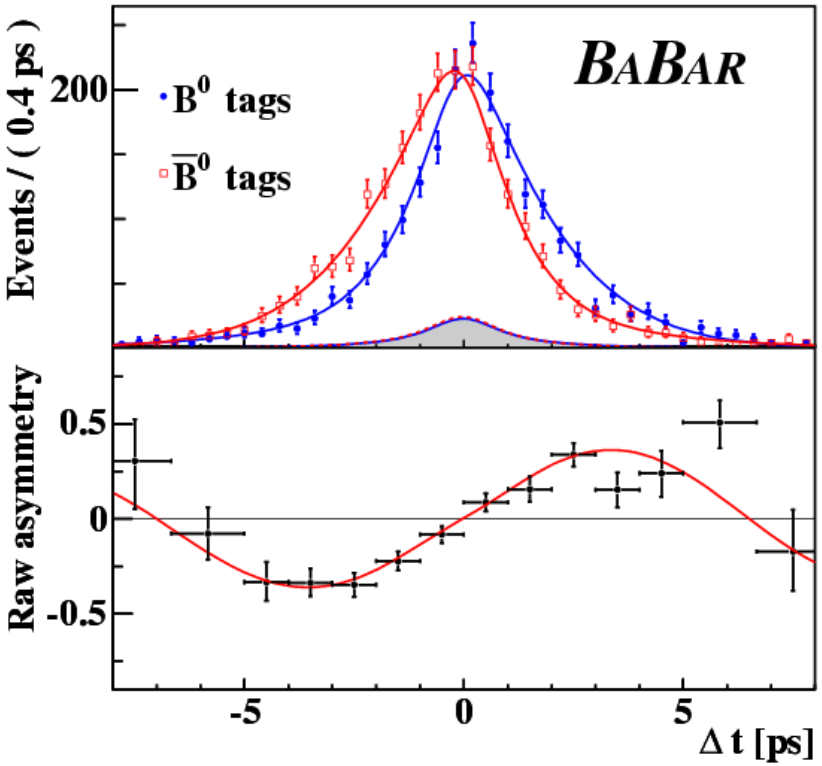


It is us a sad duty to communicate
that our long-term dear friend
PARITY passed away on January 19, 1957
after experimental treatment

For the surviving dependent
e, μ, ν

W. Pauli 1955: Work on CPT symmetry as a pillar of quantum field theory. Pauli was shocked when in beta-decay experiments a Violation of the P symmetry was found

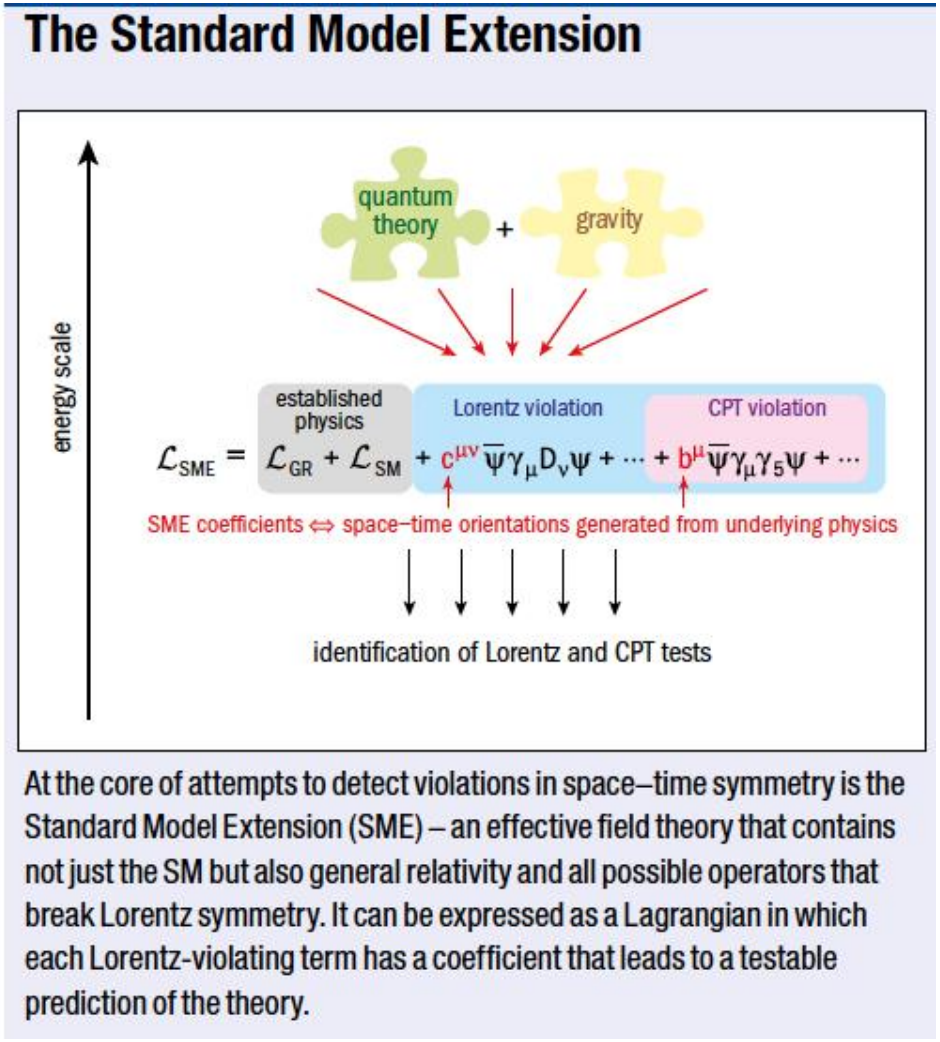
CP Violation in K- und B-meson system (Belle, Babar)



Differrence between matter and antimaterie was found, but the effect seems to be too small for an explanation of the matter-antimatter asymmetry.

CPT/Lorentz violation

recent theoretical work: Standard Model Extension (SME)



CPT and Lorentz symmetry

→ Corner stones of the underlying structure of space-time

→ SME (Alan Kostelecky, Indiana University)

CPT Violation Searches in Neutral Systems

Neutral meson systems provide unique opportunities to test the Equality of masses of particle and antiparticle, c.f. neutral kaons

	neutral K system	$\left\|m_{K^0} - m_{\overline{k}^0}\right\| / m_K < 10^{-18}$	CPLEAR
New! →	neutral B system	$\left\|m_{B^0} - m_{\overline{B}^0}\right\| / m_B < 10^{-14}$	J.B., F.B., M.N. from BABAR data
New! →	proton- anti-proton	$\left\|m_p - m_{\overline{p}}\right\| / m_p < 8 . 10^{-10}$	ASACUSA Antiprotonic Helium

Experiments with low-energy antiprotons

Search for (small) differences between matter and antimatter

CPT Tests

Comparison of 2s-1s transition in hydrogen and anti-hydrogen via 2-photon-spectroscopy (ALPHA, ATRAP am AD)

Comparison of the hyperfine structure ASACUSA am AD

Gravitation

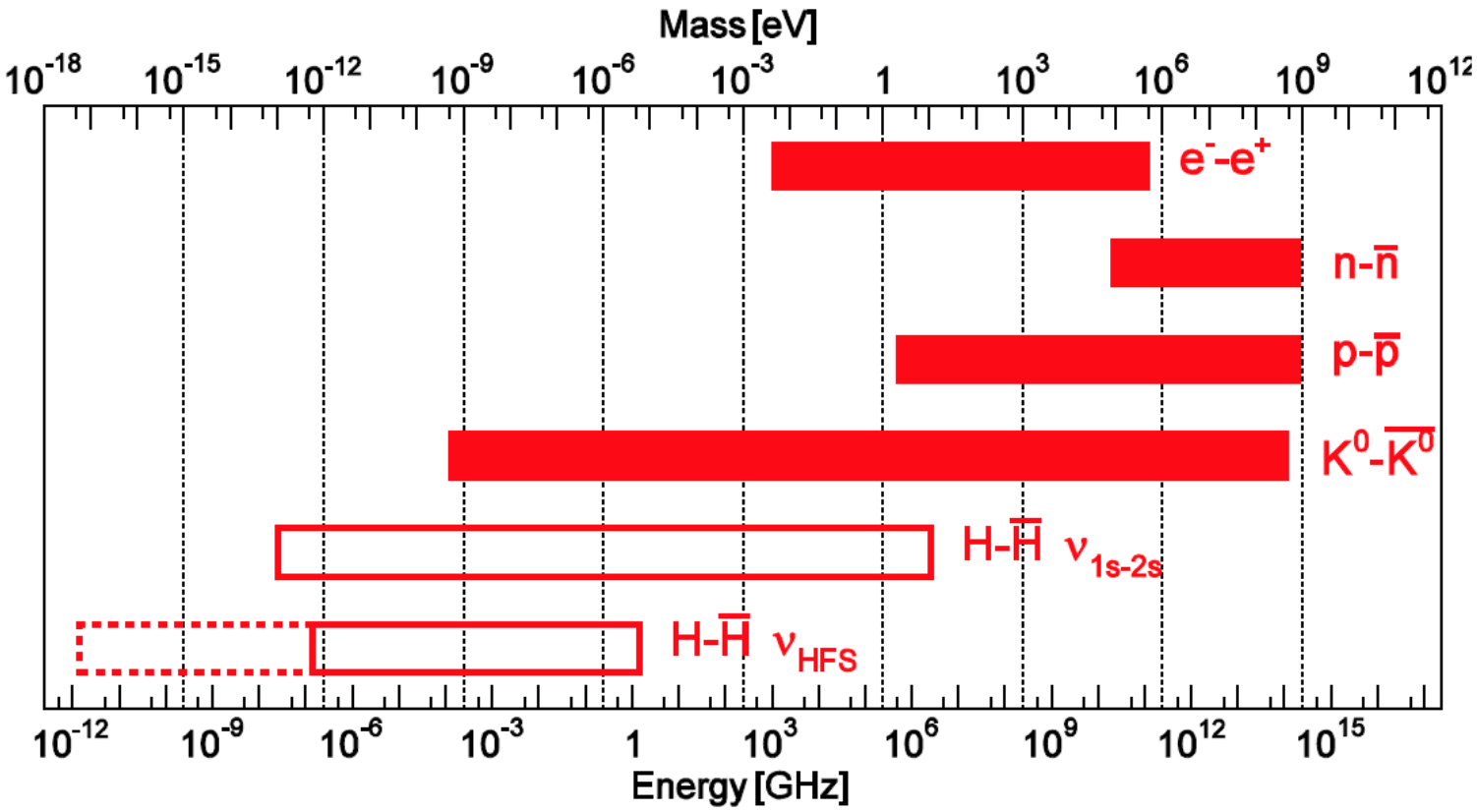
Comparison of the gravitational force on anti-hydrogen (neutral anti-matter).In charged anti-matter the effects due to the electromagnetic force overrule AeGIS am AD

CPT Symmetry

C, P, (T?) are broken – why not CPT?

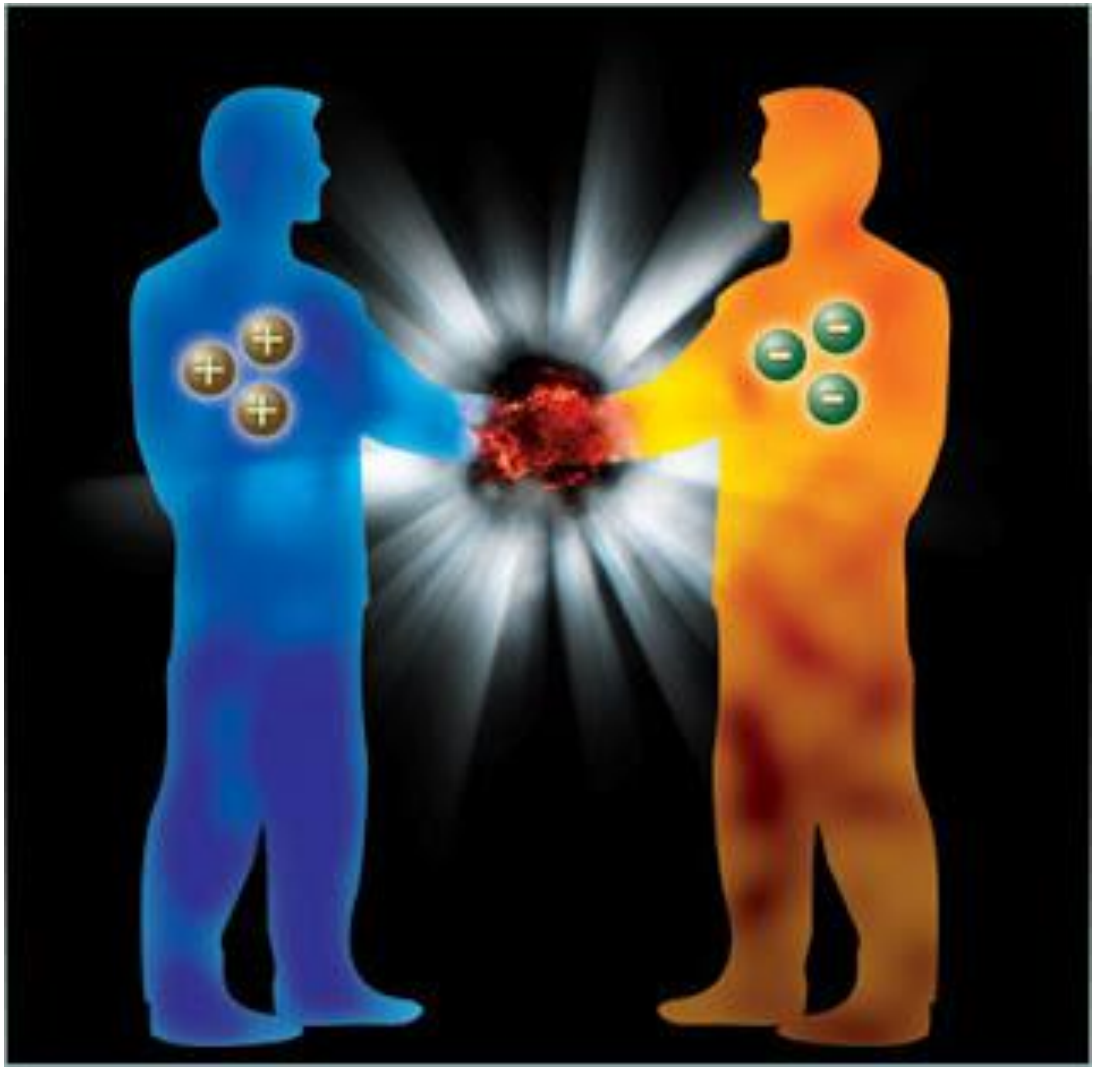
Lev Okun

CPT Test: Materie - Antimaterie

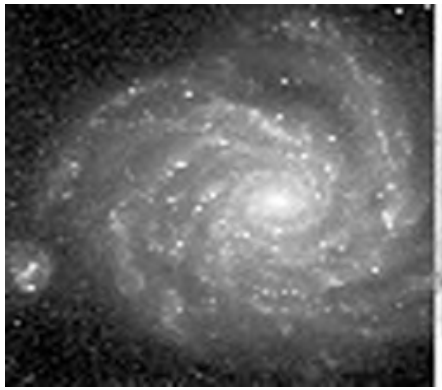


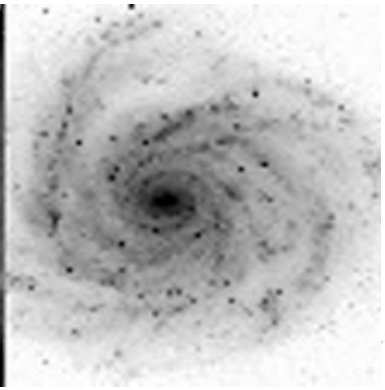
Anti-hydrogen

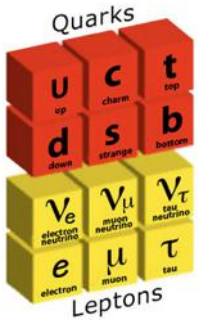
CPT tests with antiprotons

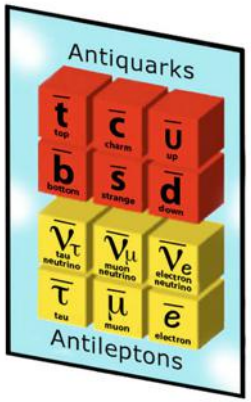


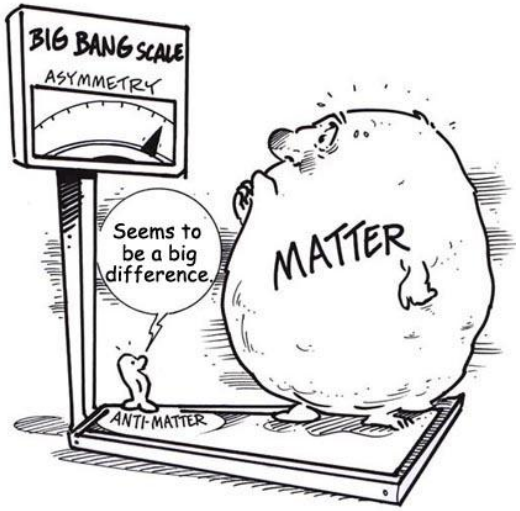
Matter-antimatter asymmetry

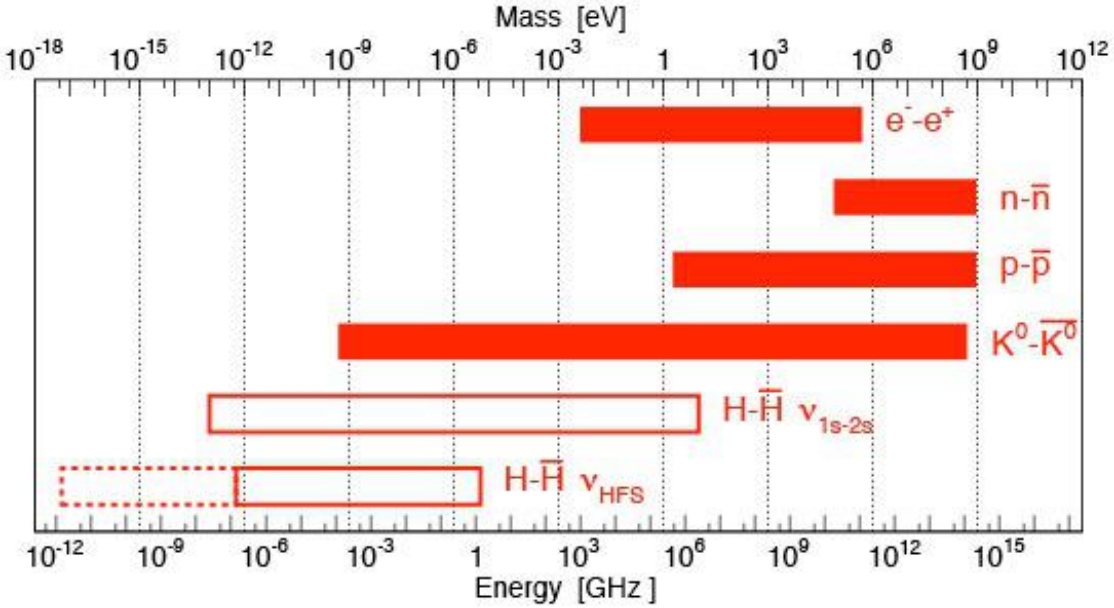


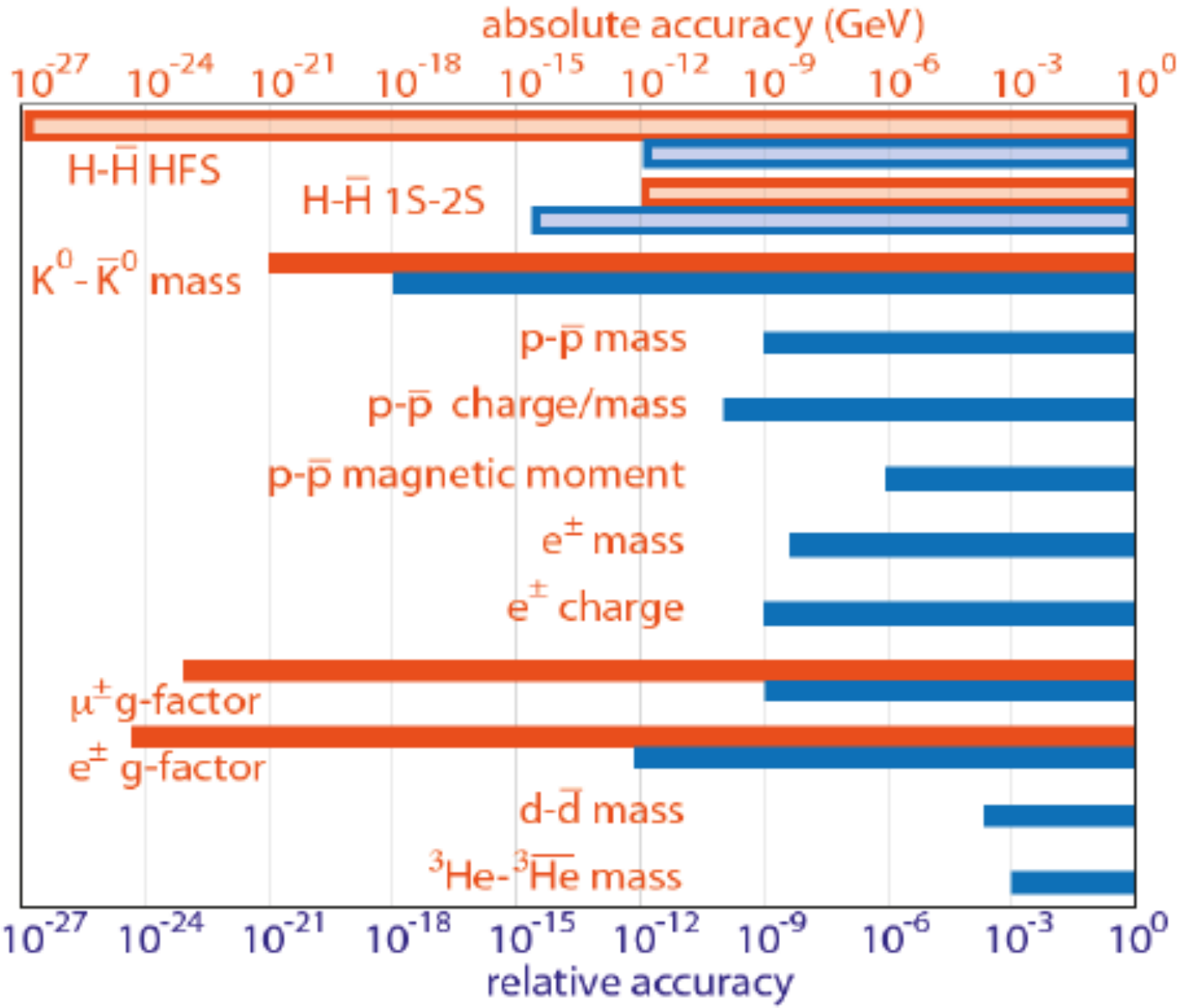












From NUPECC LRP Draft Dec2016

CPT Symmetry and matter-antimatter asymmetry?

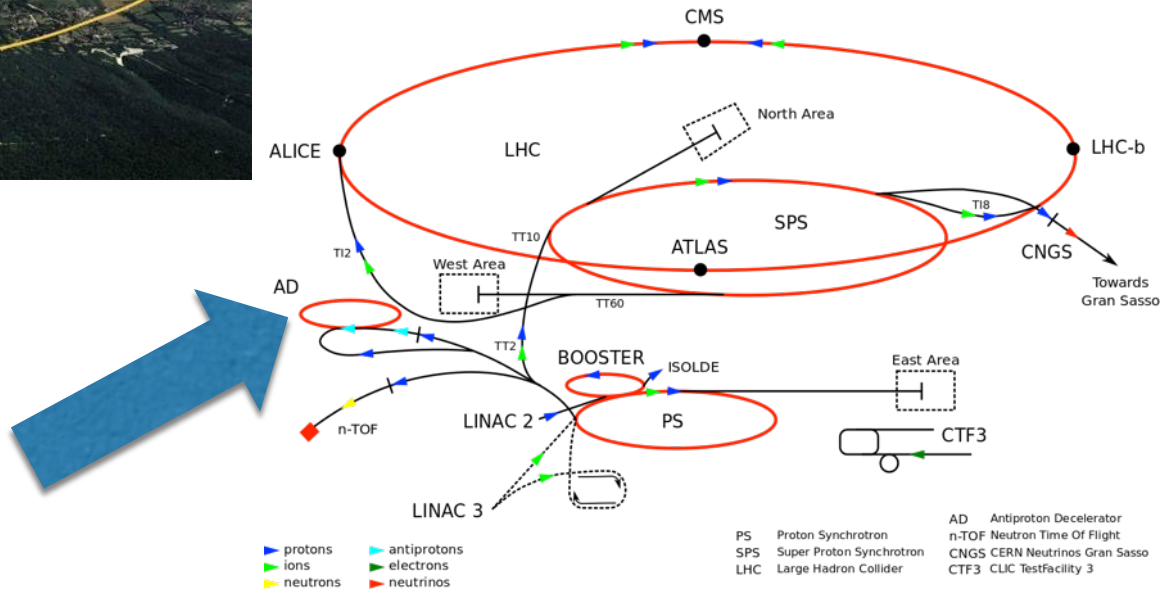
- CPT mathematical theorem, not valid e.g. in string theory, quantum gravity
- possible hint: antimatter absence in the universe
  - Big Bang -> if CPT holds: equal amounts matter/antimatter
  - Standard scenario for Baryogenesis (Sakharov 1967)
    - Baryon-number non-conservation
    - C and CP violation
    - Deviation from thermal equilibrium
- Currently known CPV not large enough
    - Other source of baryon asymmetry?
    - CPT non-conservation?

Antiproton Production

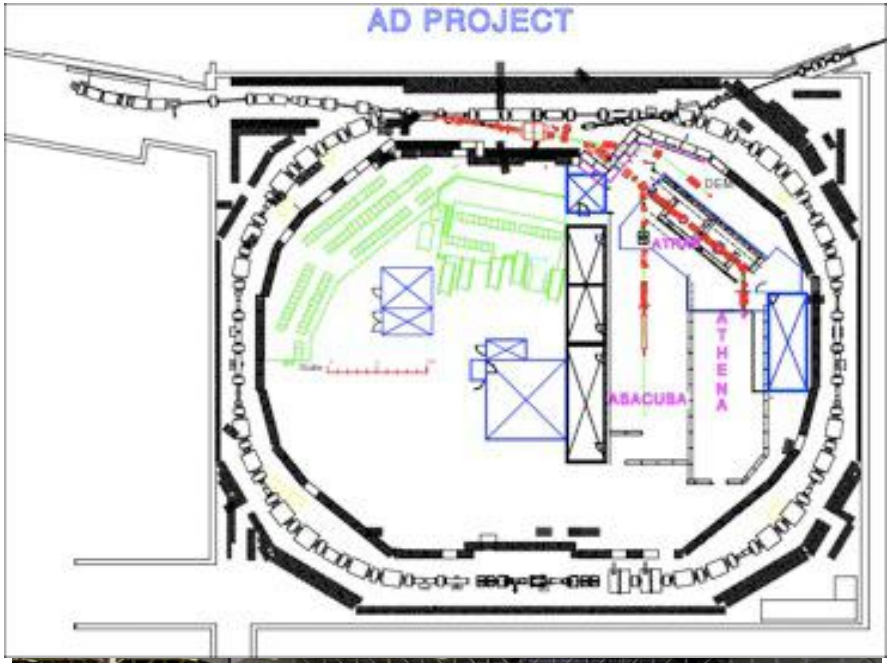
- Threshold 6 m_p (5.6 GeV)
- PS: 26 GeV
- Antiprotons of 3.7 GeV/c
- Low-energy beam
  - Accumulation
  - Deceleration
  - Cooling (stochastic, electron)
- Since 2000
  - All-in-one machine: AD

CERN Accelerators

AD Facility



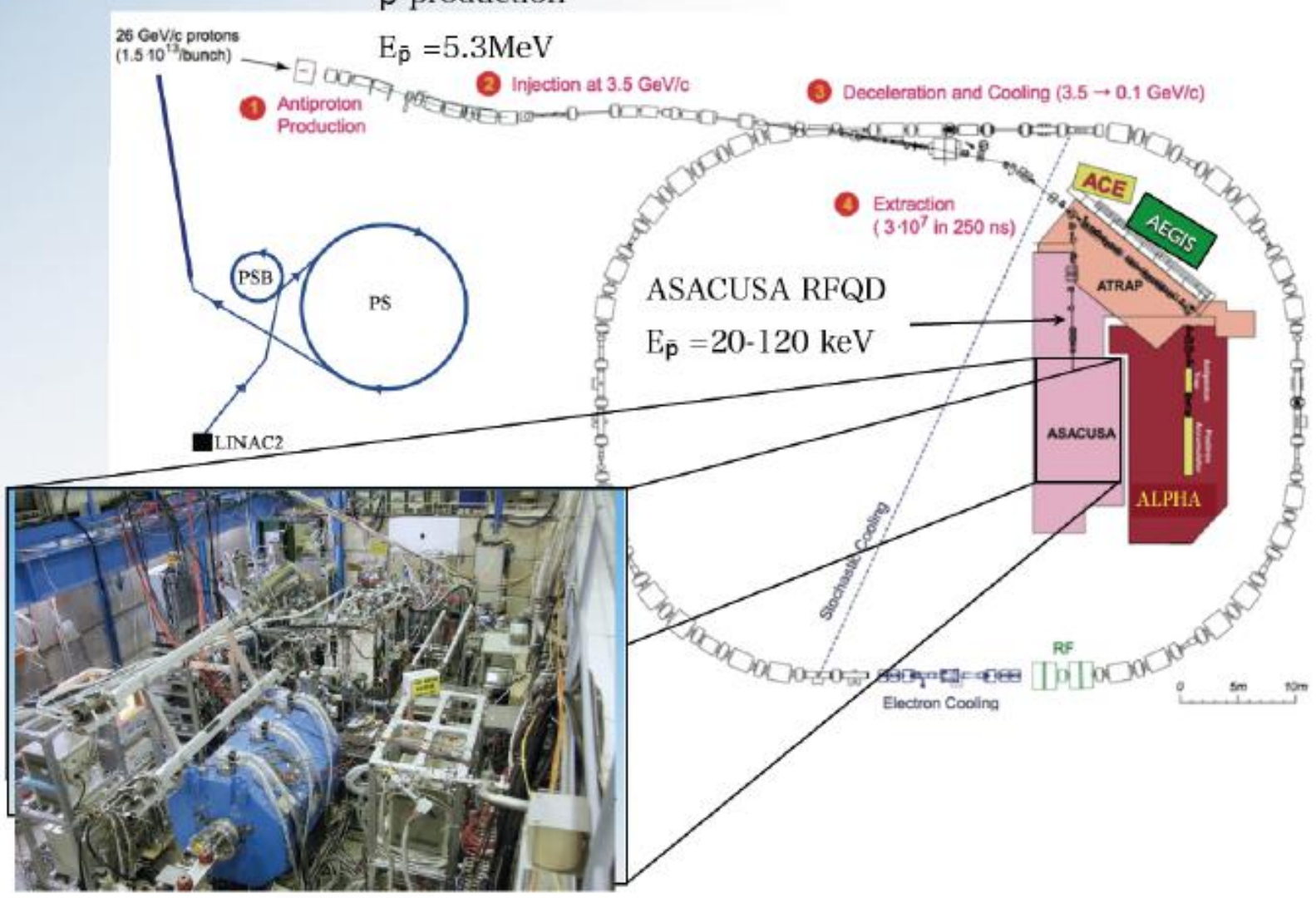
AD @ CERN



- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85−120 seconds

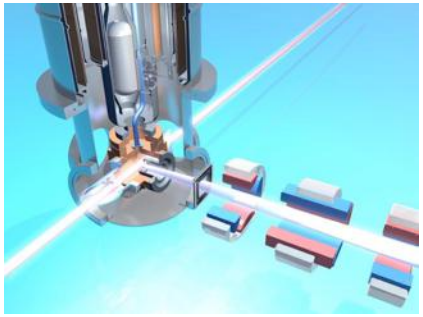
INGREDIENTS FOR $\bar{H}$

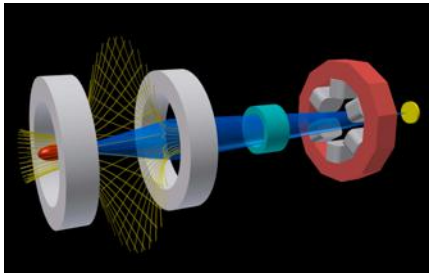
The antiproton source

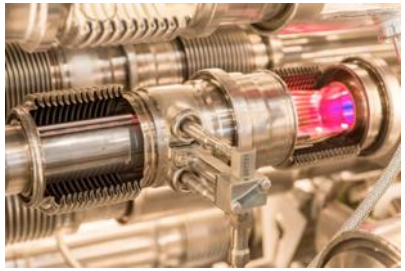


Antimatter Experiments at CERN-AD

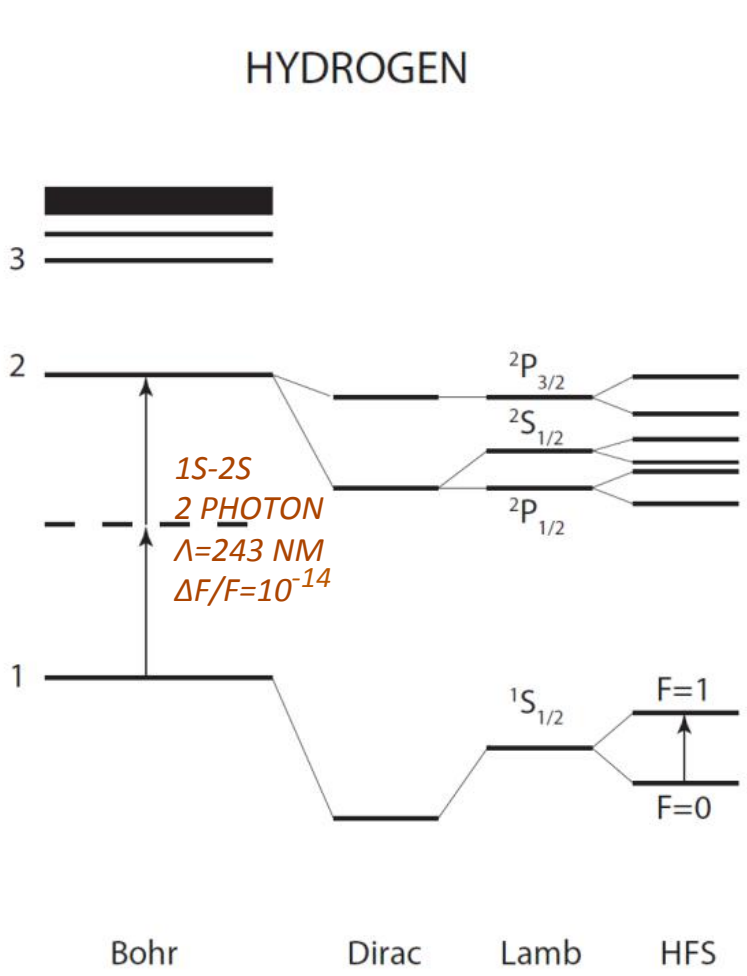
- ATRAP - G. Gabrielse, Harvard
- ALPHA - J. S. Hangst, Aarhus
  - Antihydrogen trapping and 1S-2S spectroscopy
- ASACUSA* - R.S. Hayano, Tokyo
  - Antiprotonic atoms, collisions, antihydrogen hyperfine structure
- AEgIS* - M. Doser, CERN
  - Antimatter gravity
- GBAR - P. Perez, Saclay
  - Antimatter gravity
- BASE - S. Ulmer, RIKEN
  - $\bar{p}$ magnetic moment
- ACE - M. Holzscheiter, Heidelberg
  - biological effects of $\bar{p}$ annihilations

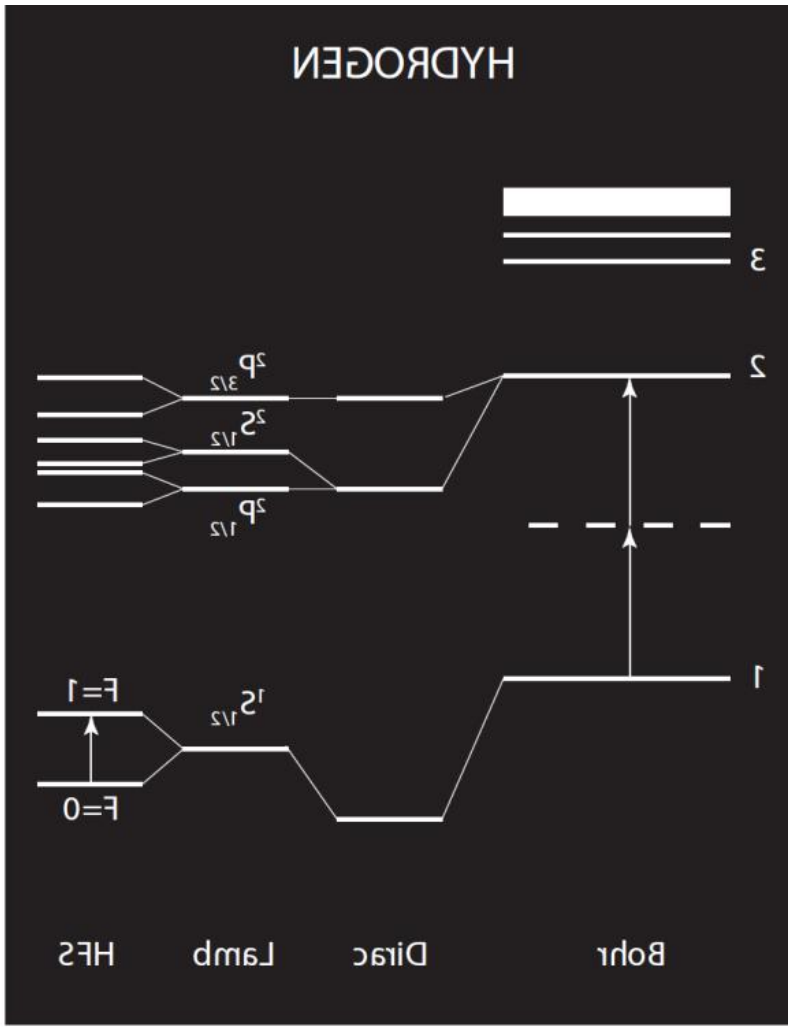






Antihydrogen Spectroscopy





Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

Breaking news

ALPHA

ALPHAExperiment

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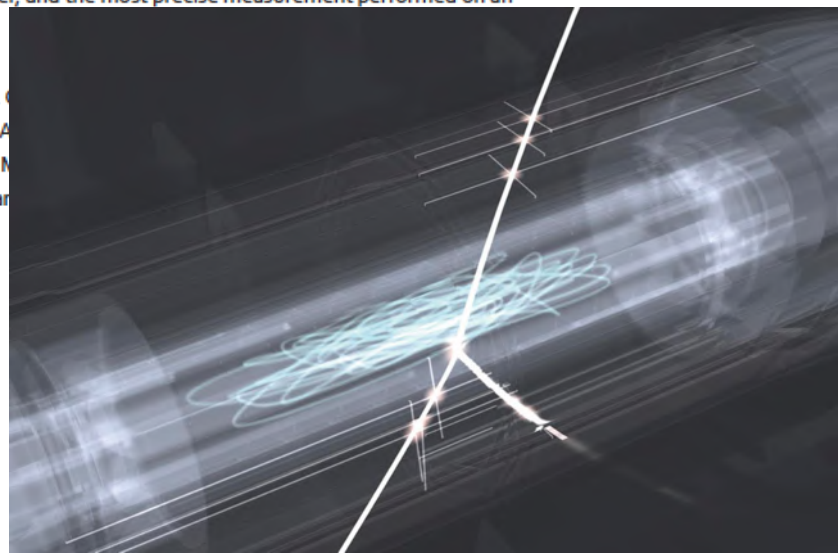
Observation of the 1S-2S transition in trapped antihydrogen

We report the observation of the 1S-2S transition in magnetically trapped atoms of antihydrogen in the ALPHA-2 apparatus at CERN. We determine that the frequency of the transition, driven by two photons from a frequency stabilised laser at 243 nm, is consistent with that expected for hydrogen in the same environment. This represents the first laser excitation of an internal quantum state of an atom of antimatter, and the most precise measurement performed on an anti-atom. Our result is consistent with CPT invariance at a relative precision of ~ 2×10^{-10}.

M. Ahmadi, B.X.R. Alves, C.J. Baker, W. Bertsche, E. Butler, A. Capra, C. Carruth, C.L. Cesar, M. Charlton, S. (
Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, A. Gutierrez, J.S. Hangst, W.N. Hardy, M.E. Hayden, C.A. Isaac, A
Kurchaninov, N. Madsen, M. Mathers, D. Maxwell, J.T.K. McKenna, S.Menary, J.M. Michan, T. Momose J.J. M
Rasmussen, F. Robicheaux, R.L. Sacramento, M. Sameed, E. Sarid, D.M. Silveira, G. Stutter, C. So, T.D. Thar
J.S. Wurtele, published online in Nature, December 2016.

December 2016 (Nature)

Rel. precision 2×10^{-10}



ASACUSA @ CERN

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Searches for CPTV with antimatter

Spectroscopy of antiprotonic helium

Microwave spectroscopy of Rydberg state transitions

Laser spectroscopy of Rydberg state transitions

With theory – $m_{antiproton}/m_{electron}$

Comparison with $m_{proton}/m_{electron}$ – CPT test

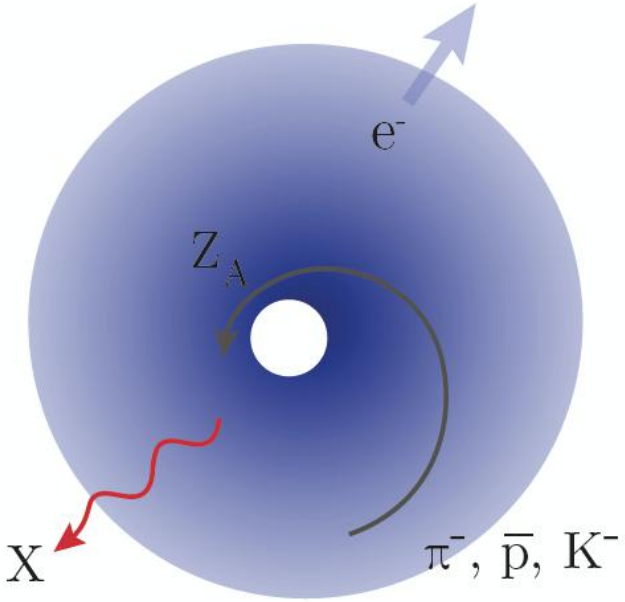
Production of antihydrogen beam

Rabi-type spectroscopy of antihydrogen beam

Comparison with spectroscopy of hydrogen beam

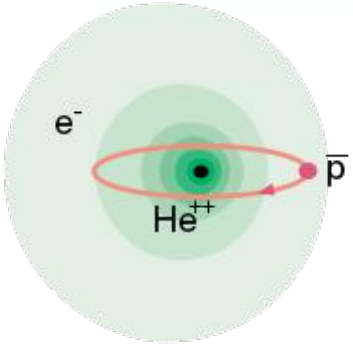
Comparison of the H-H_{bar} hyperfine structure – CPT test

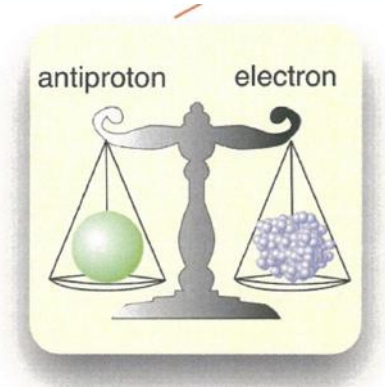
Antiprotonic helium – an exotic "atomcule"



Transitions in low-lying n states:
Nuclear scattering length,
c.f. kaonic hydrogen 2p-1s
(SIDDHARTA-LNF)

Transitions in higher n states:
Particle masses (neg. charged),
c.f. masses of π^-, K^-, Σ^-, p_{bar}



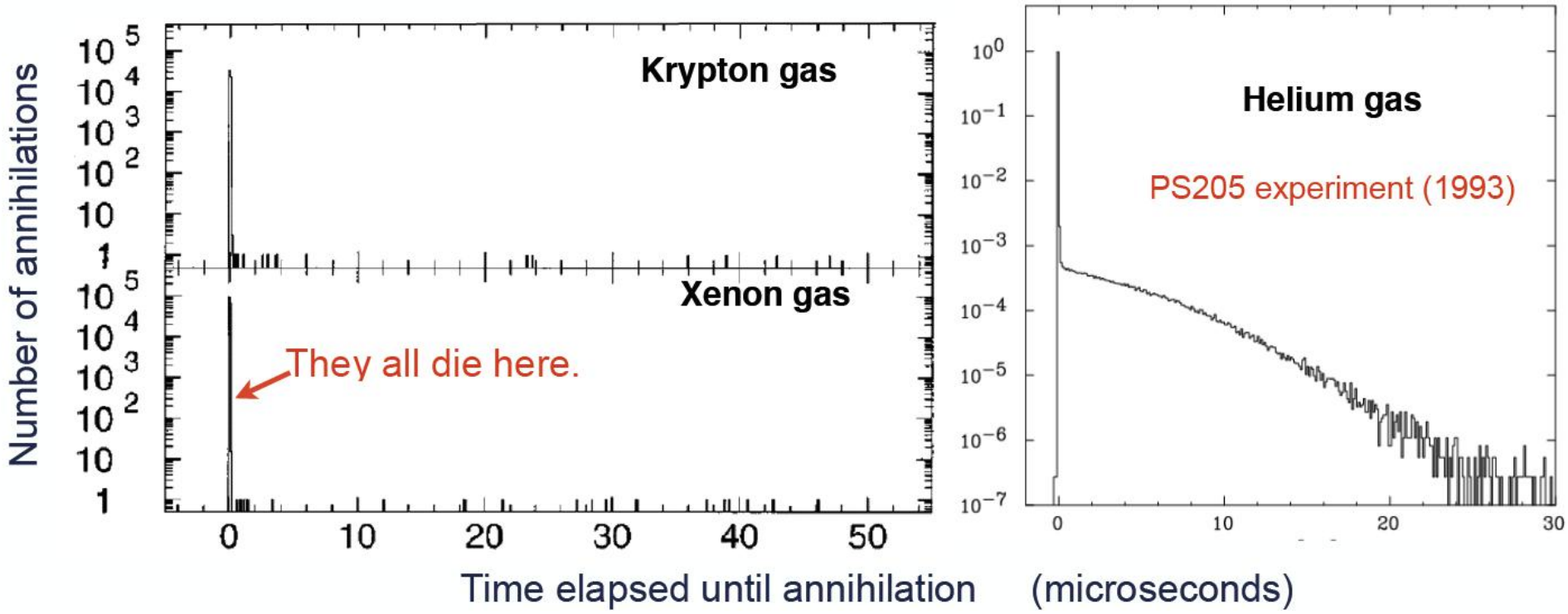


$$\nu(n,n') = Rc\frac{M_{\bar{p}}}{m_e}Z_{\mathrm{eff}}^2\left(\frac{1}{n^2}-\frac{1}{n'^2}\right)$$

R_c known to high precision (6×10^{-12})

Antiprotonic helium: metastable states

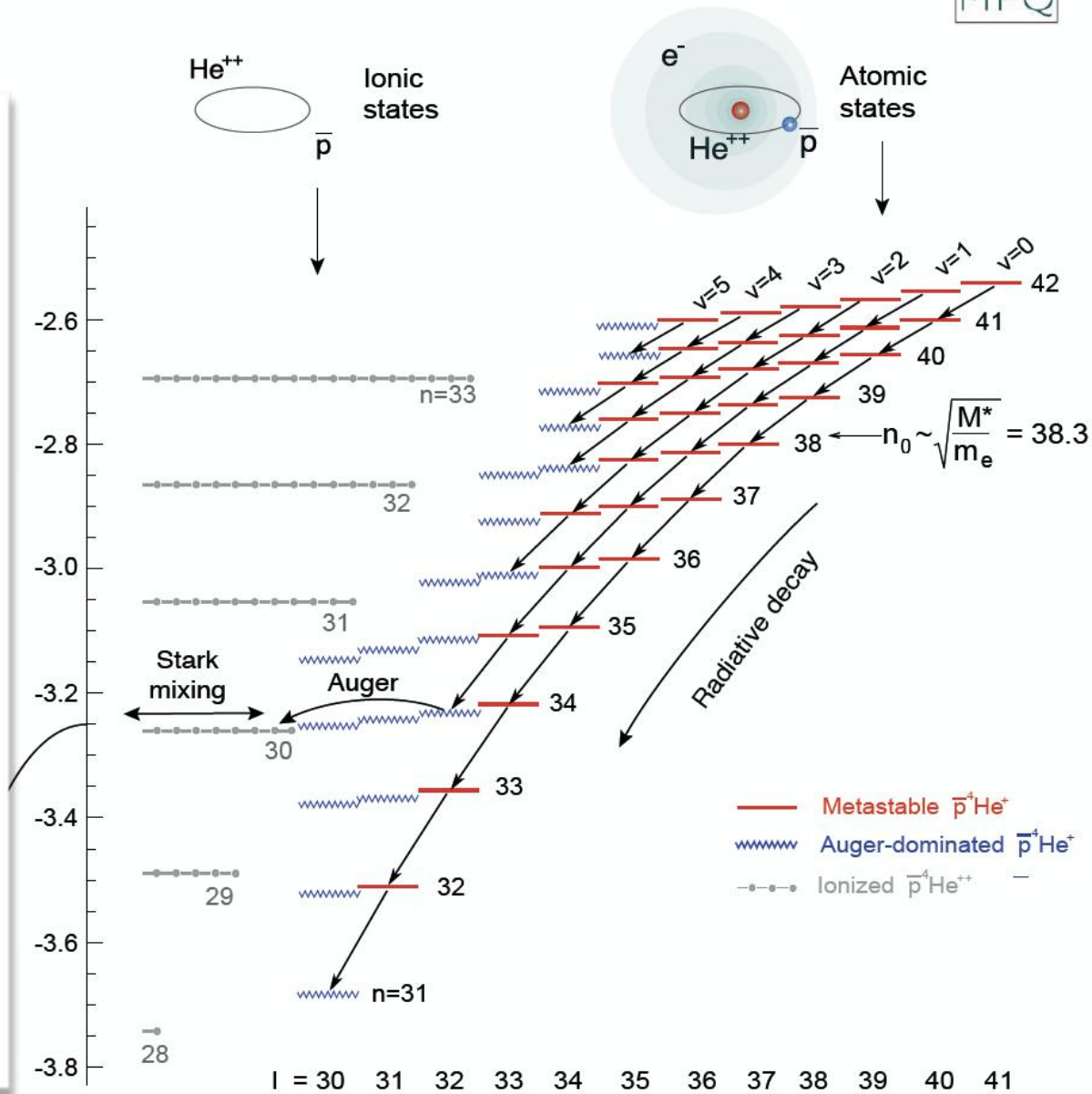
In helium approx.
3% p_{bar} survive in μs range



Energy levels of $\bar{p}He^+$

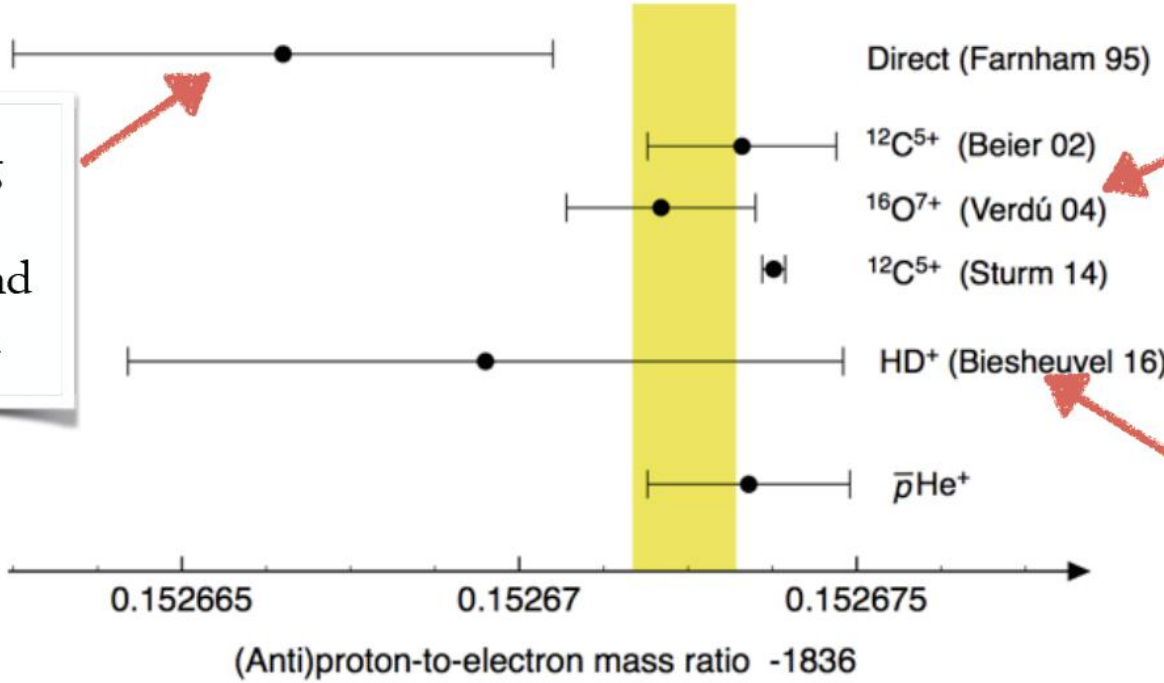
- Metastability: Auger ionization is suppressed for certain high-lying (Rydberg) states (degeneracy in ℓ lifted, weak Stark mixing)
- Both helium isotopes can sustain antiprotons in near-circular ($\ell \sim$ n-1) metastable states for μs-scaled lifetimes
- At lower ℓ, probability of Auger ionization increases rapidly: Auger-dominated 3-body states with ns-scaled lifetimes

Transitions: optical photons!



(Anti)proton-to-electron mass ratio 2016

Penning trap, proton and electron

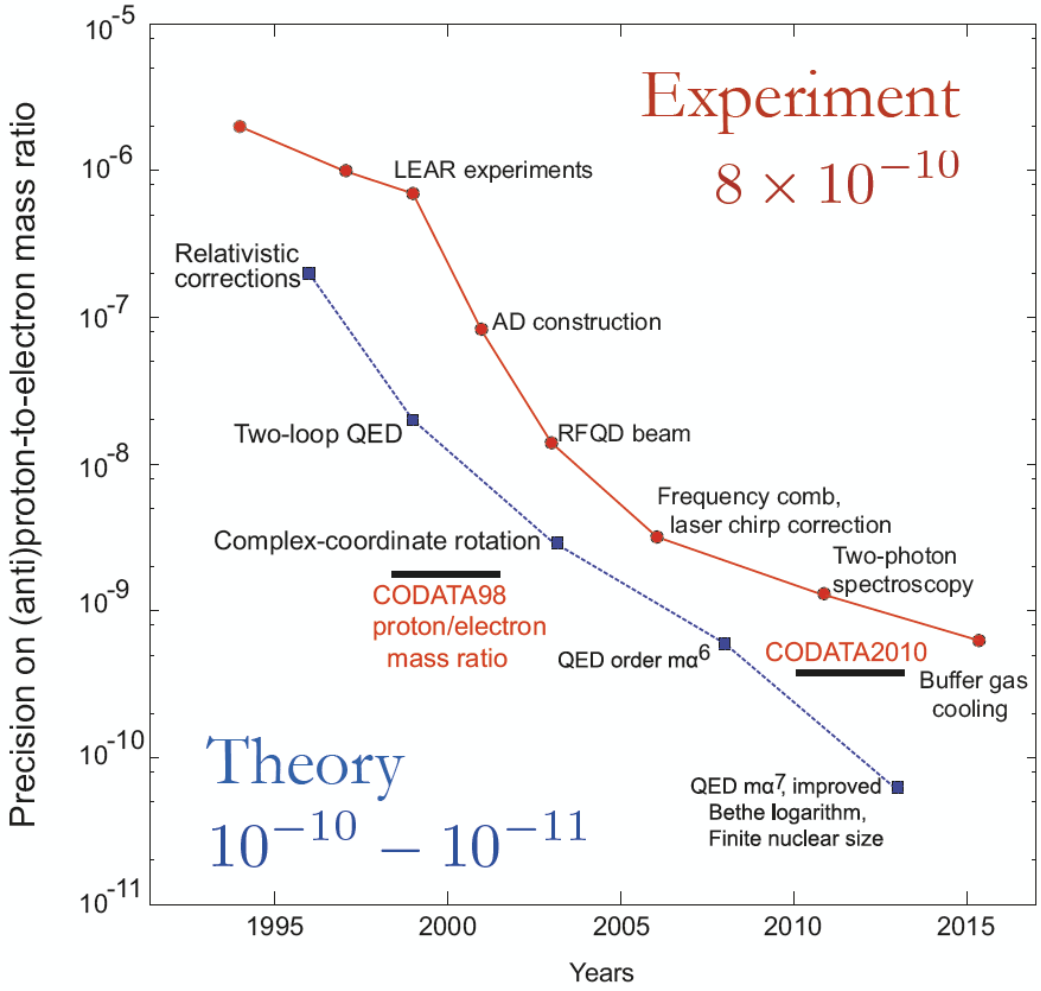


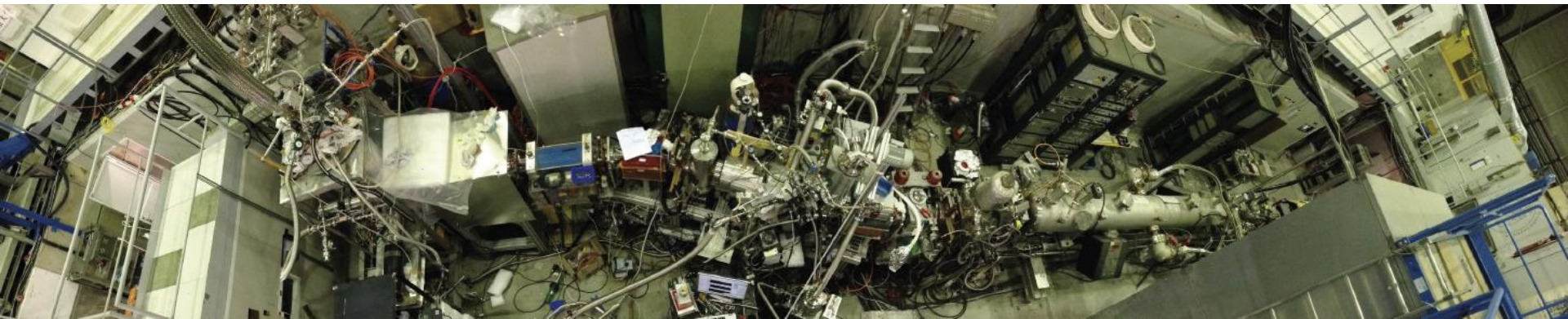
Hydrogenic ions + theoretical g-factor (bound)

Laser spectroscopy HD+ in ion trap

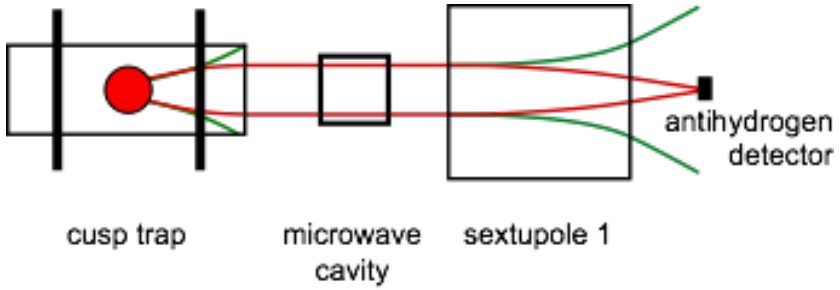
This measurement:

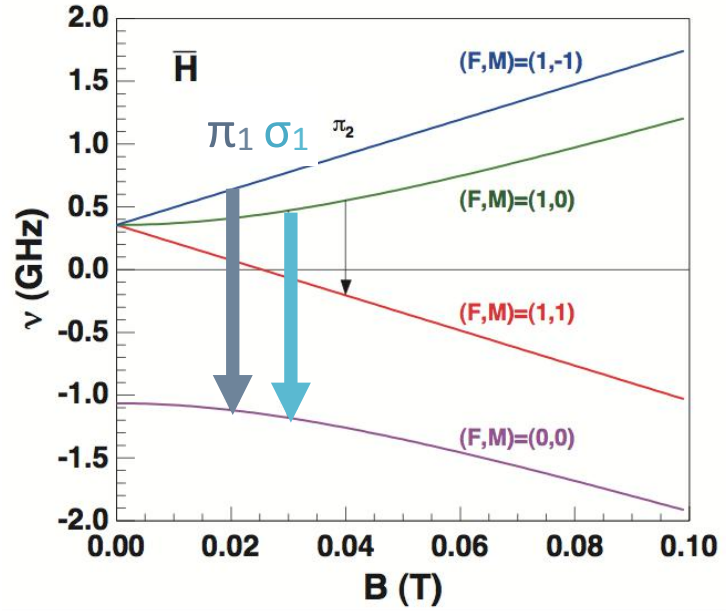
$m_{\bar{p}}/m_e = 1836.1526734\ (15)$


Experiment
8×10^{-10}
LEAR experiments
Relativistic corrections
AD construction
Two-loop QED
RFQD beam
Frequency comb, laser chirp correction
Complex-coordinate rotation
Two-photon spectroscopy
CODATA98 proton/electron mass ratio
QED order mα^6
CODATA2010
Buffer gas cooling
Theory
$10^{-10} - 10^{-11}$
QED mα^7, improved Bethe logarithm, Finite nuclear size
Precision on (anti)proton-to-electron mass ratio
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1995
2000
2005
2010
2015
Years



HFS measurement in an atomic beam





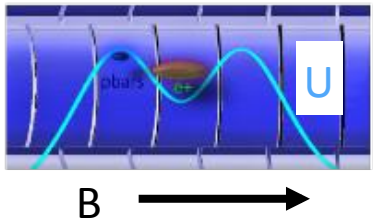
- atoms evaporate - no trapping needed
- cusp trap provides polarized beam
- spin-flip by microwave
- spin analysis by sextupole magnet
- low-background high-efficiency detection of antihydrogen

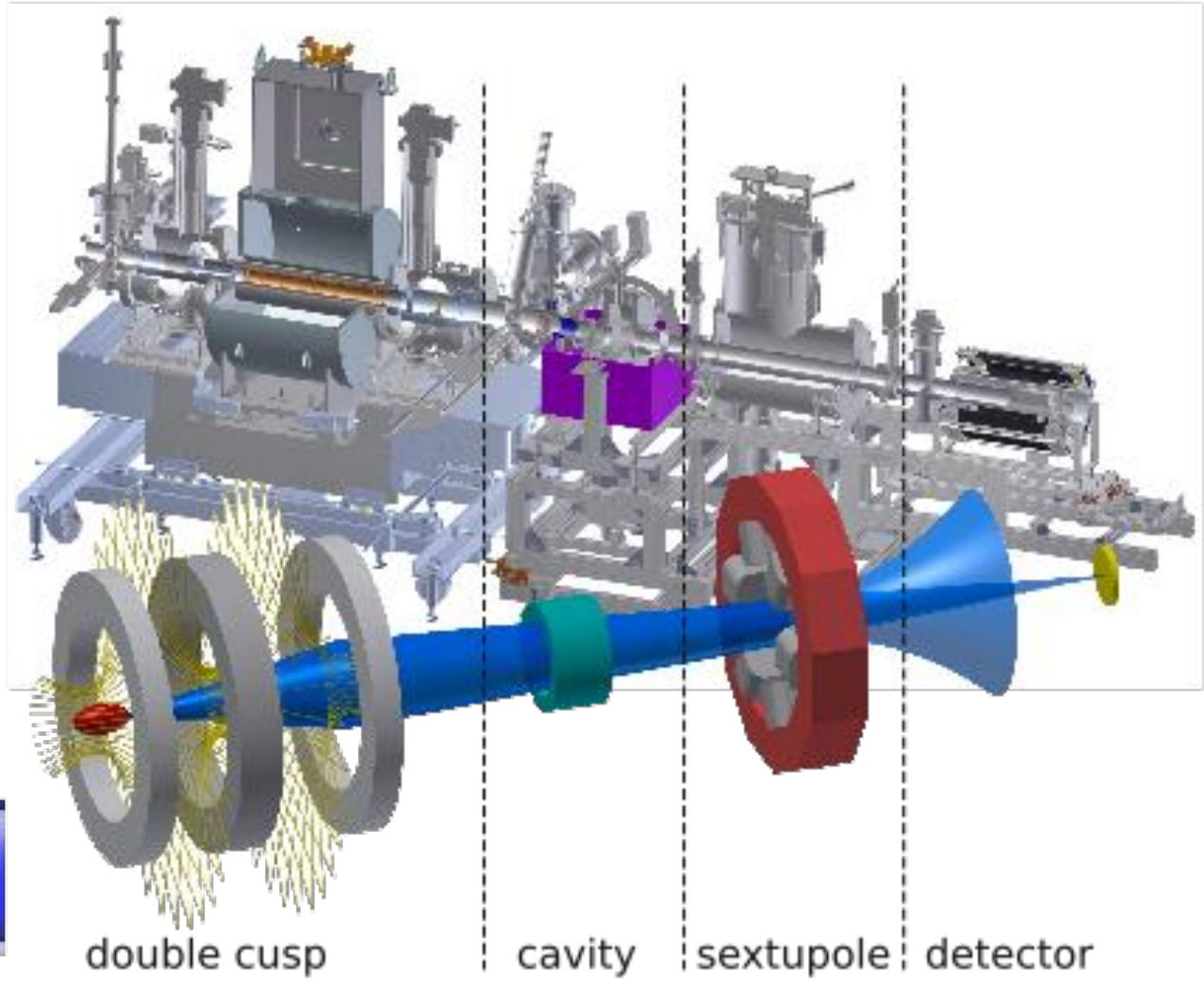
achievable resolutionbetter 10^{-6} for $T \leq 100$ K

E.W. et al. ASACUSA proposal addendum
CERN-SPSC 2005-002

Experimental setup HFS line

$\bar{H}$ production
1st time achieved
in 2010 in
nested Penning trap





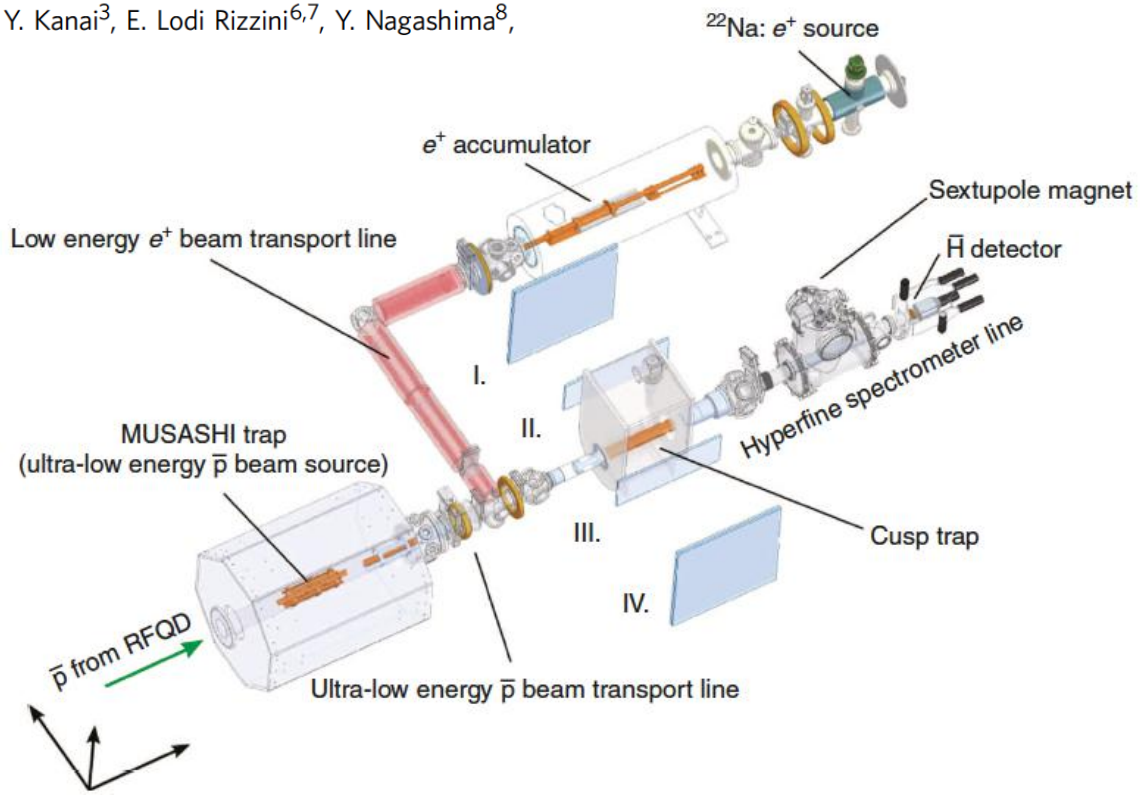
ARTICLE

Received 25 Jun 2013 | Accepted 11 Dec 2013 | Published 21 Jan 2014

DOI: 10.1038/ncomms4089 OPEN

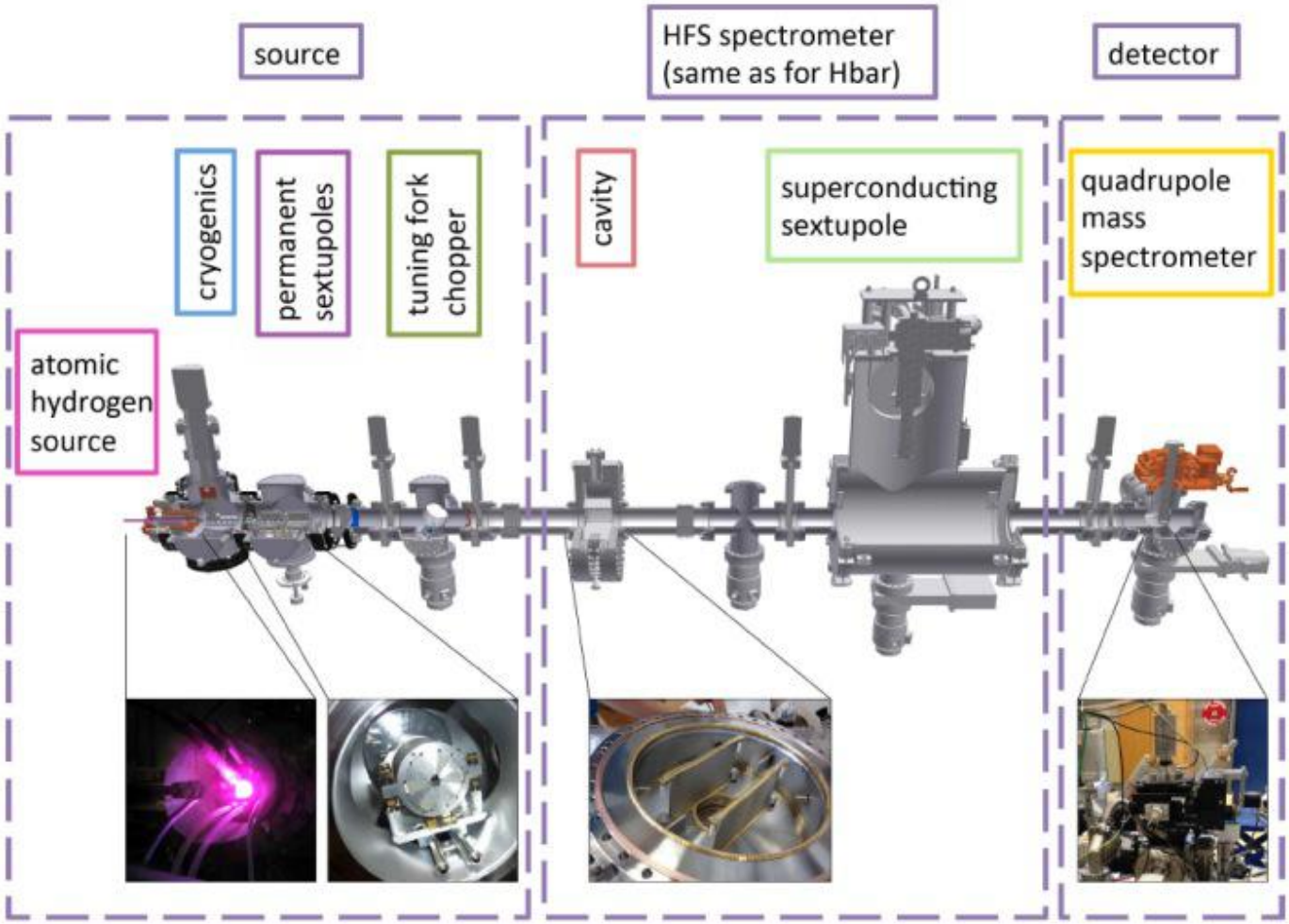
A source of antihydrogen for in-flight hyperfine spectroscopy

N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[5], M. Leali[6,7], C. Malbrunot[4,†], V. Mascagna[6,7], O. Massiczek[4], K. Michishio[8], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[9], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[1], H.A. Torii[1], L. Venturelli[6,7], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[9], Y. Kanai[3], E. Lodi Rizzini[6,7], Y. Nagashima[8], Y. Matsuda[1], E. Widmann[4] & Y. Yamazaki[1,3]

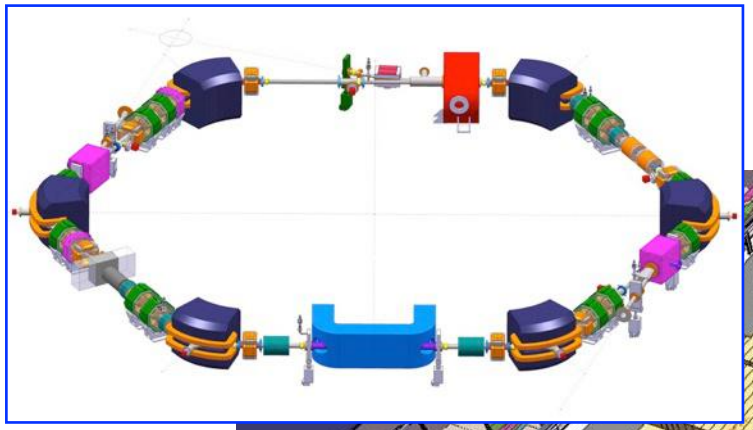


in-flight spectroscopy. A total of 80 antihydrogen atoms are unambiguously detected 2.7 m downstream of the production region, where perturbing residual magnetic fields are small.

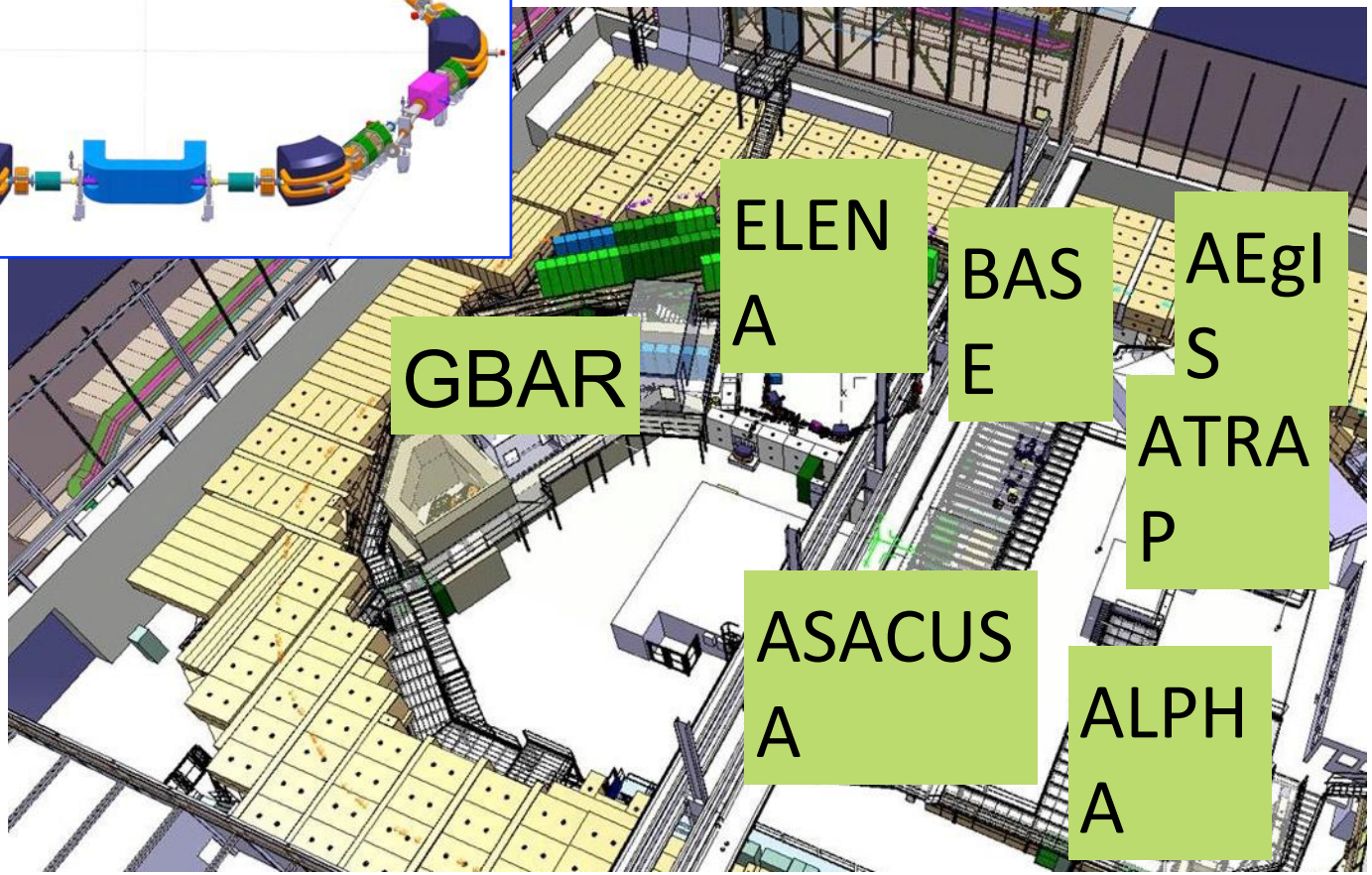
H beam setup


source
HFS spectrometer
(same as for Hbar)
detector
cryogenics
permanent
sextupoles
tuning fork
chopper
cavity
superconducting
sextupole
quadrupole
mass
spectrometer
atomic
hydrogen
source

In construction: AD & ELENA



New decelerator: 5 MeV → 100 keV



ELENA operation after 2017

Physics Case: Simple and Clear

- Comparisons of simplest atom (H) and anti-atom (Hbar) with highest possible precision

Given that:

- Hydrogen: one of best studied system in all physics (c.f. Nobel Prize 2005)
- Cold Antihydrogen: produced in large quantities

→ H-Hbar comparison: Obvious thing to do!

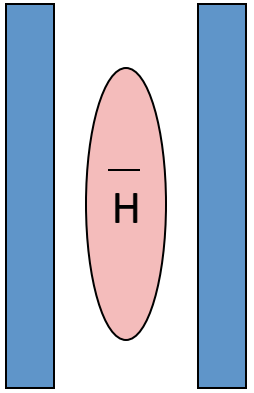
- Some of best CPT tests, 1st Antimatter Gravity
- CERN Review: "no guarantee, but imperative duty"

Technically very challenging. Similarities with ion traps, UCN, but antiparticles difficult

Examples: with1000 trapped Hbars

- 10^{-12} precision ($\Delta f \sim 1$ kHz) in 1s-2s laser transition (Hänsch 1993)
  - e+ mass, charge improved by 4 orders of magnitude
  - X 10 more stringent CPT test than K^0 in absolute energy scale (within effective field theory)

- With laser cooling
  - Direct test on gravity on antimatter



Vertical Hbar trap

$$\frac{1}{2}kT = mgh$$

Vertical height ~1 m for Hbar at 2 mK

- Precision and feasibility fundamentally limited by number of Hbars

AD + ELENA

- AD: 3.5 GeV/c → 100 MeV/c (5 MeV)

  a unique deceleration & cooling ring
- Degrader: 5 MeV → 5 keV

  ~10^{-4} trapping efficiency: >99.9% pbars lost!

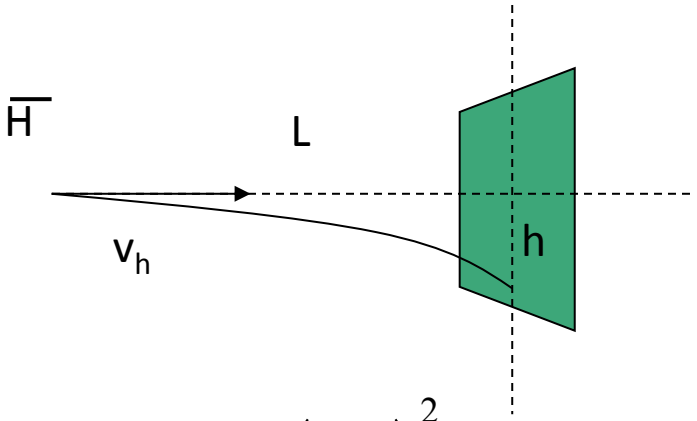
- ELENA: 5 MeV → 100 keV

  Deceleration and electron cooling

  Up to 4 orders of magnitude increase in Hbar production efficiency!

Gravitationswirkung auf Antwasserstoff

- Prinzip



$$h = \frac{g}{2}\left(\frac{L}{v_h}\right)^2$$

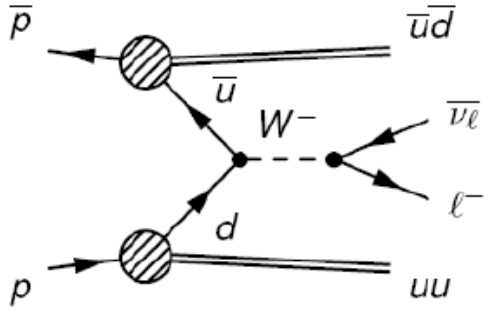
- Horizontal anti-hydrogen beam, velocity ≈100 m/s
- Horizontal flight path about 1 m
- Vertical gravitation-effect: 0.000 002 m bei 500m/s

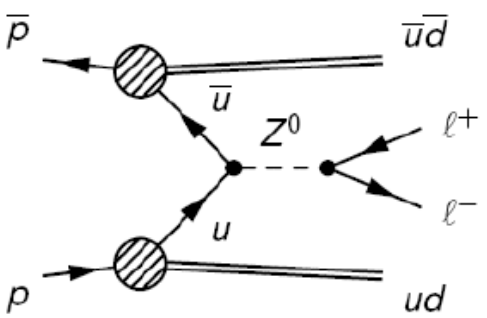
AeGIS Experiment am AD/CERN

Antiprotons at higher energies

Antiproton-proton collisions at high opened the way to major findings in physics

- W, Z boson in the UA1 experiment at CERN (1984 Nobel prize C. Rubbia and S. Van-de-Meer)





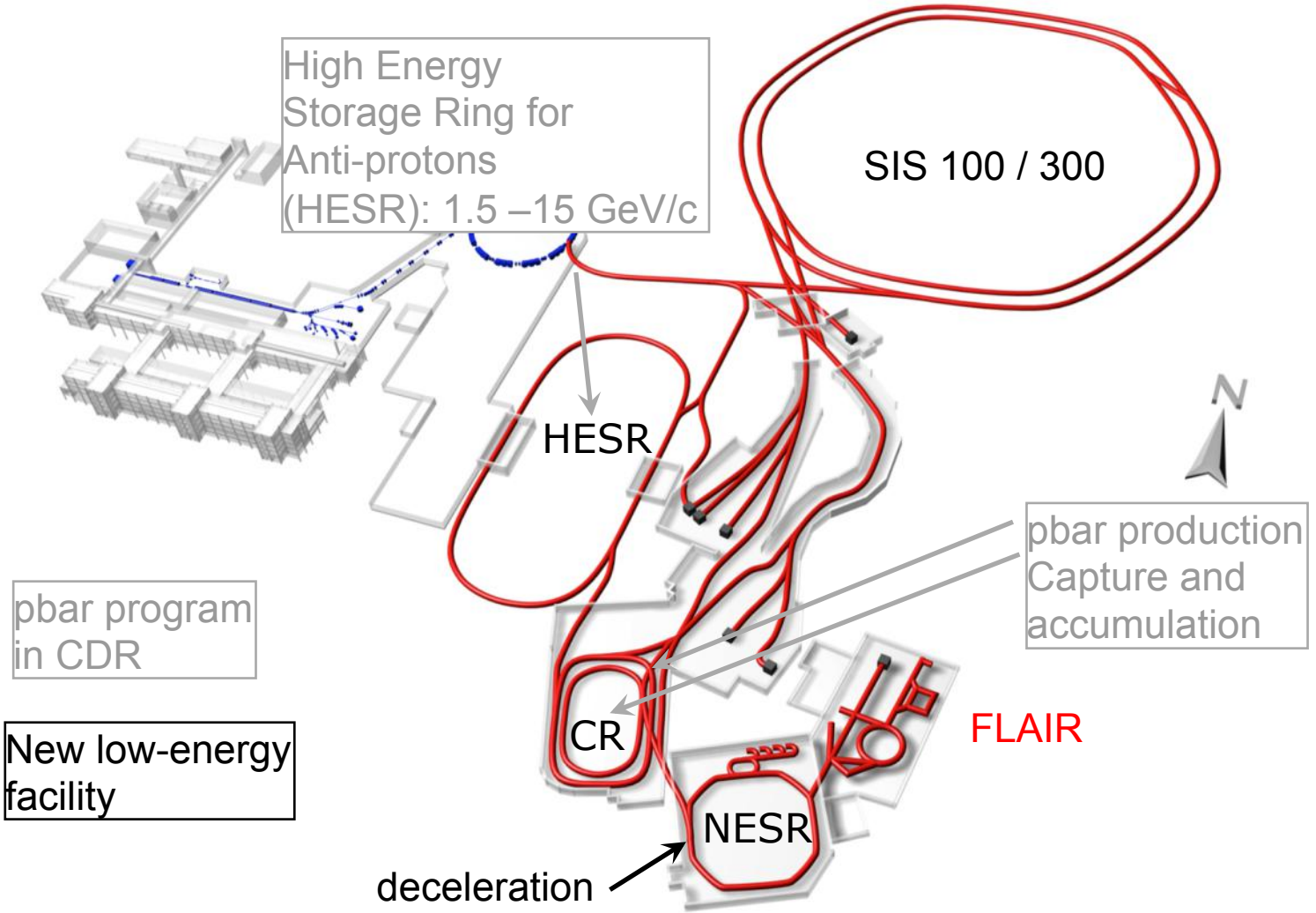
- Experiments at Fermilab/USA Tevatron (Discovery Top quark)

Experiments with antiprotons at higher energies

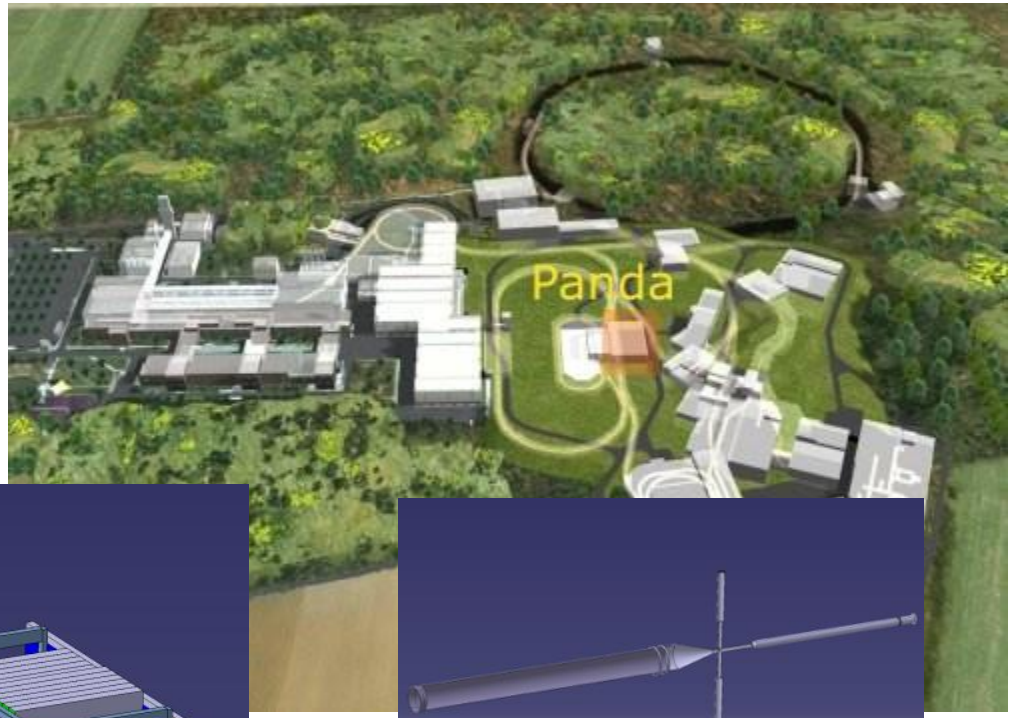
Precision studies of the strong force
Search for exotic bound states „glueballs“
Spektroscopy of hypernuclei
Formfactors

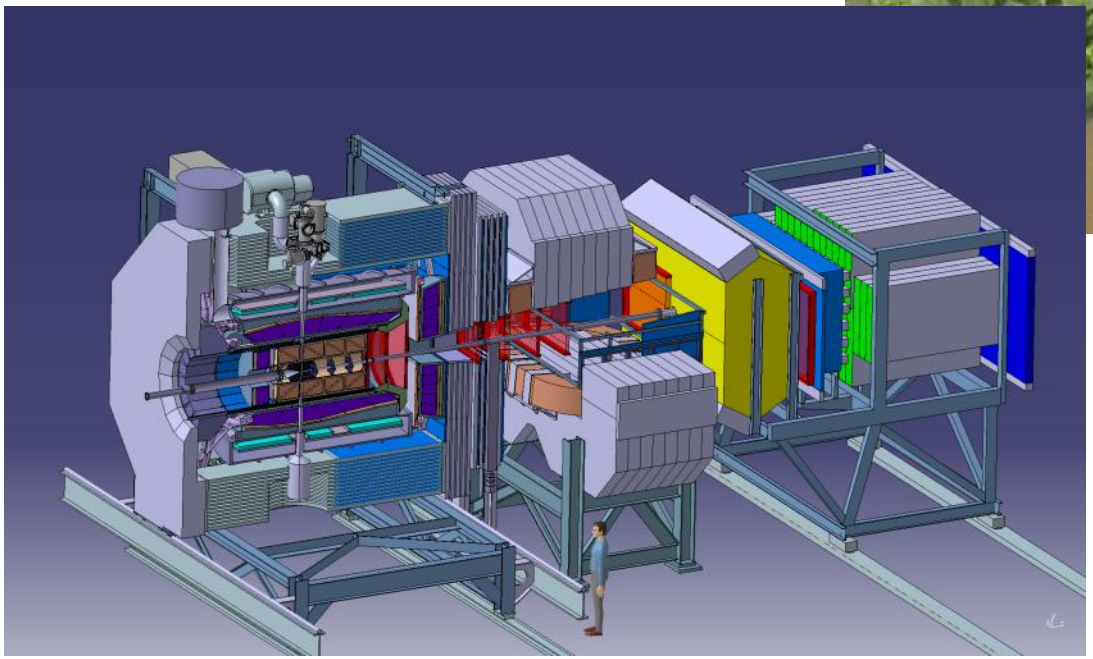
Test of the theory of strong interaction (QCD) in the intermediate range Low-energy High-energy

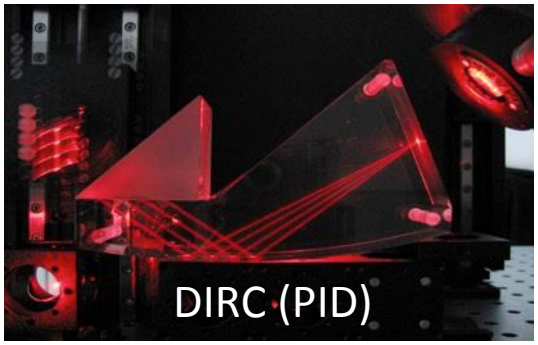
Antiprotons at FAIR



HESR and PANDA





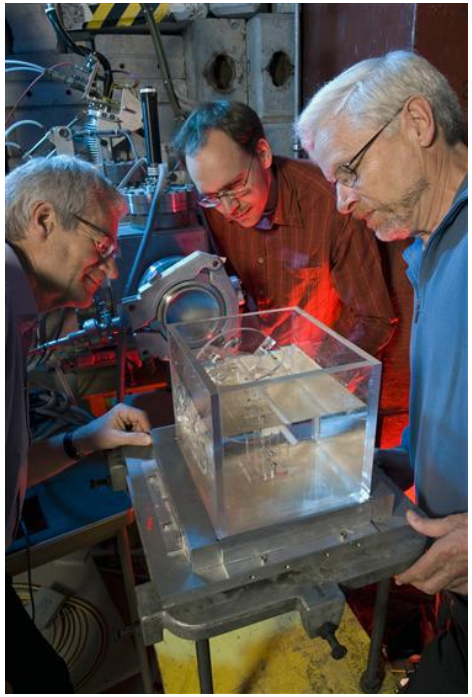


Application of antimatter

Applications of Antimatter

Several important applications in medicine are based on the annihilation of antimatter with matter:

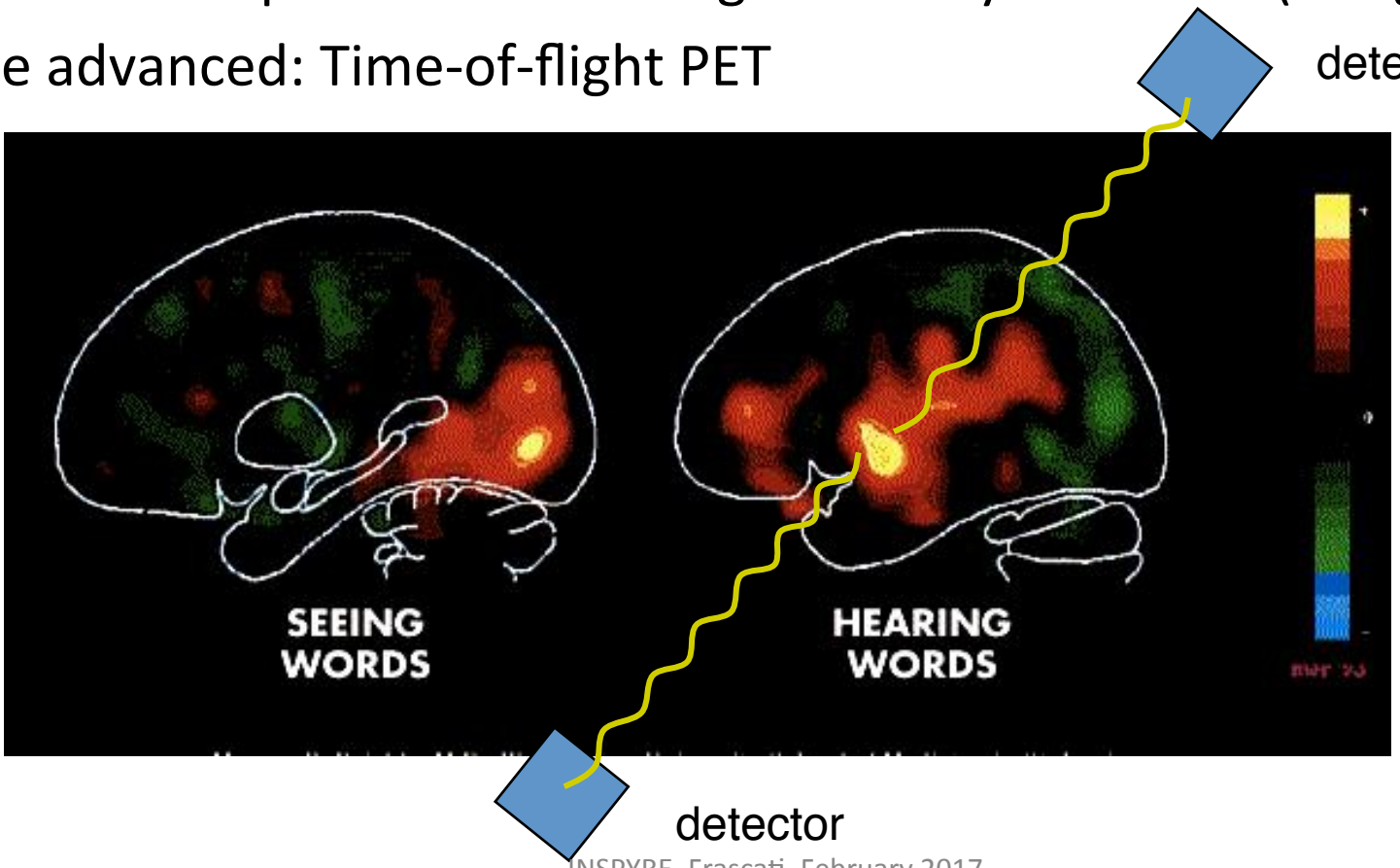
Diagnostics (PET): Standard in tumor diagnostics



R&D in tumor treatment?
(ACE am AD)

Positron Emission Tomography (PET)

- PET use positrons from the beta+ decay of radioactive isotopes (e.g. ^{18}F, FDG, Fluordesoxyglucose, sugar with tracer). The annihilation produce 2 photons emitted back-to-back which can be detected with position-sensitive gamma-ray detectors (inorg. scint.).
- More advanced: Time-of-flight PET

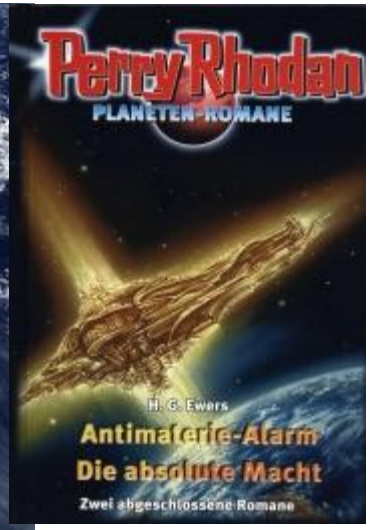


Attraction of antimatter

Since the discovery of antimatter possible applications were studied and discussed – also in science fiction literature.

Proven applications in medicine (PET)

Dreams and Science Fiction:
Propulsion of spaceships
Anti-Universes
Weapons .....



Antimatter in Science Fiction

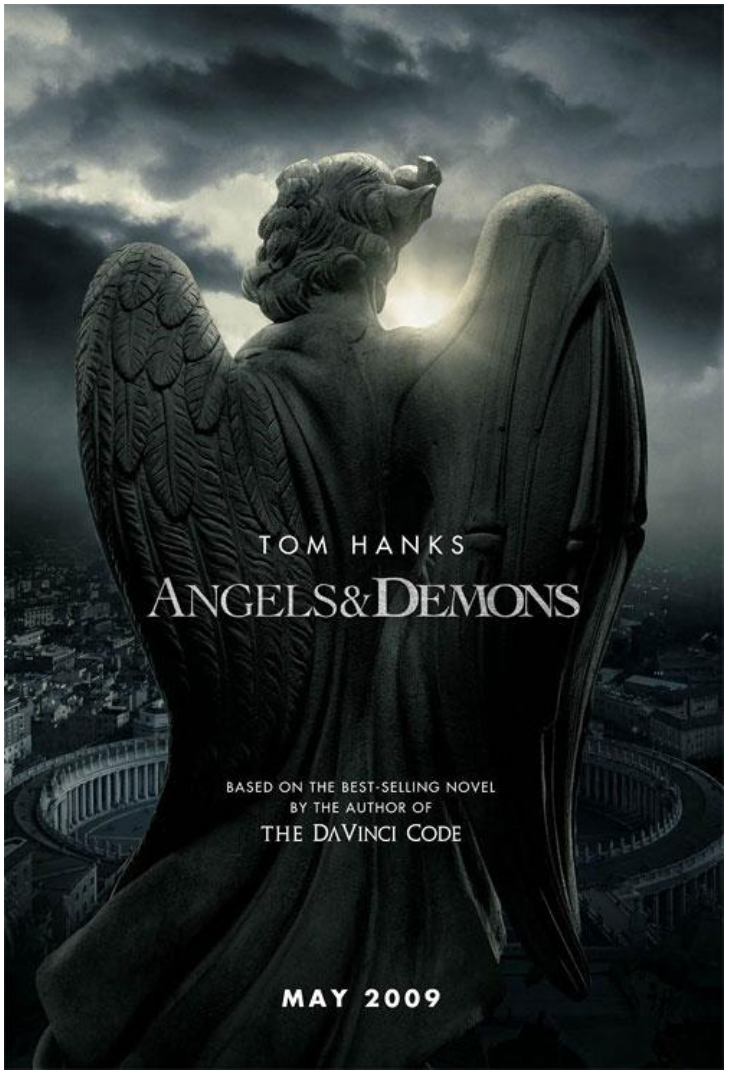
The annihilation of antimatter leads to therelease of a huge amount of energy – about 106 times the energy of nuclear reactions:

As an example: Annhilation of 1 kg antimatter with 1 kg matter:

$2\ 10^{17}$ J is equal to 43 000 000 ($4.3\ 10^{7}$) tons of the explosive TNT (c.f. Hiroshima atomic bomb 13 000 t)

But: CERN can produce per year 0.000 000 001 g (1 ng) antiprotons.

Science fiction



Summary

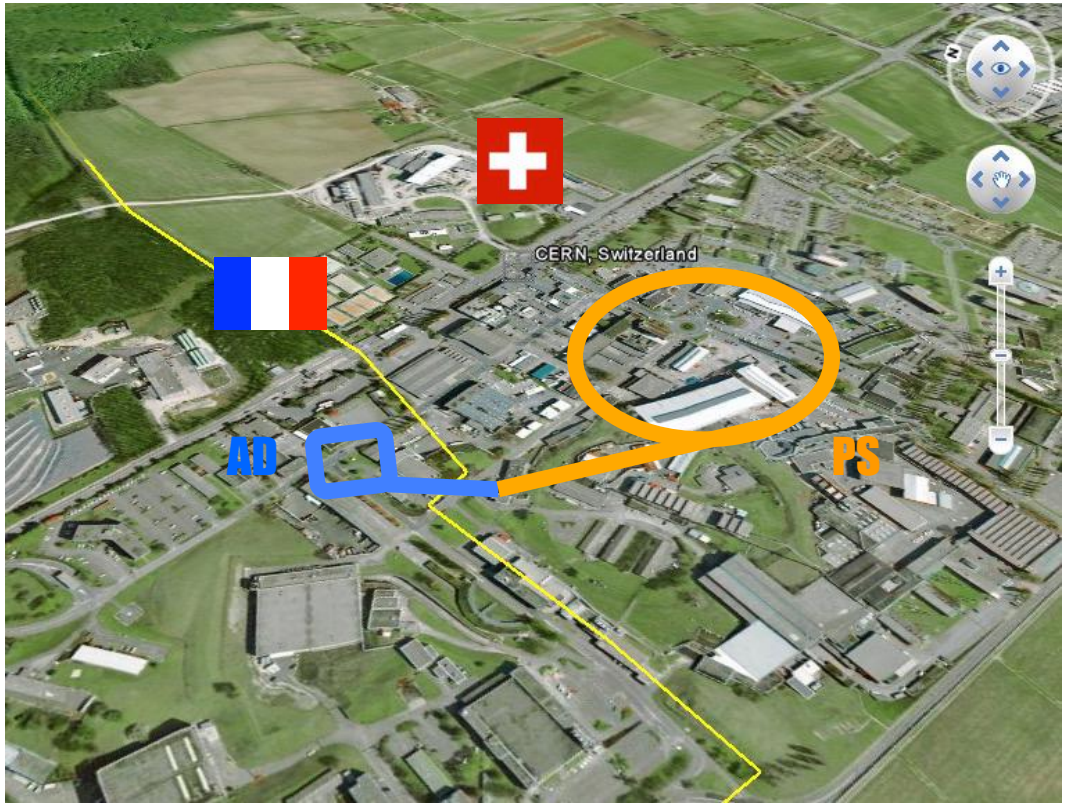
- In the big bang theory a baryon asymmetry is required to explain the dominance of matter.
- The CP violation is seen in the meson sector (K, B) but so far not in the baryon sector. Furthermore the CP violation is (too) small.
- According to the Standard Model of particle physics we should not exist, i.e. the Standard Model seems to be incomplete ...
- Research with exterrestic probes and precision experimentds in the laboratory are under way and can help to shed light on this problem.
- An explanation is not existing but this research is a fascinating research field covering experimental and theoretical particle physics as well as cosmology.

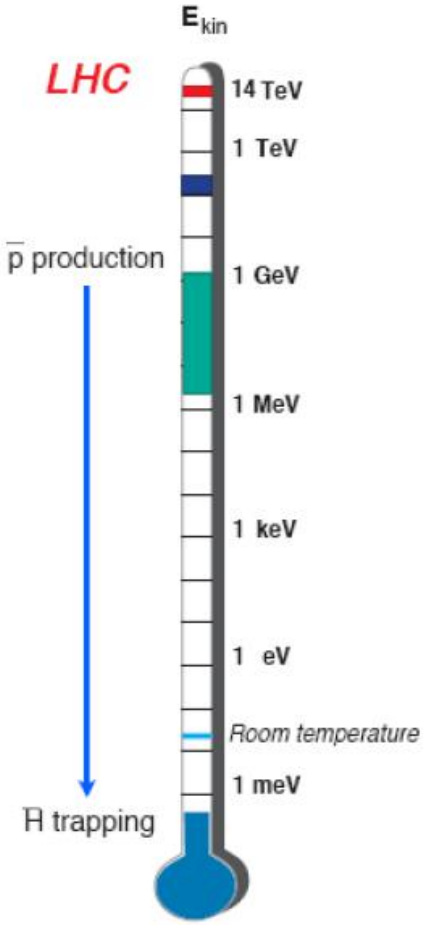

Thank you for your attention

SPARE

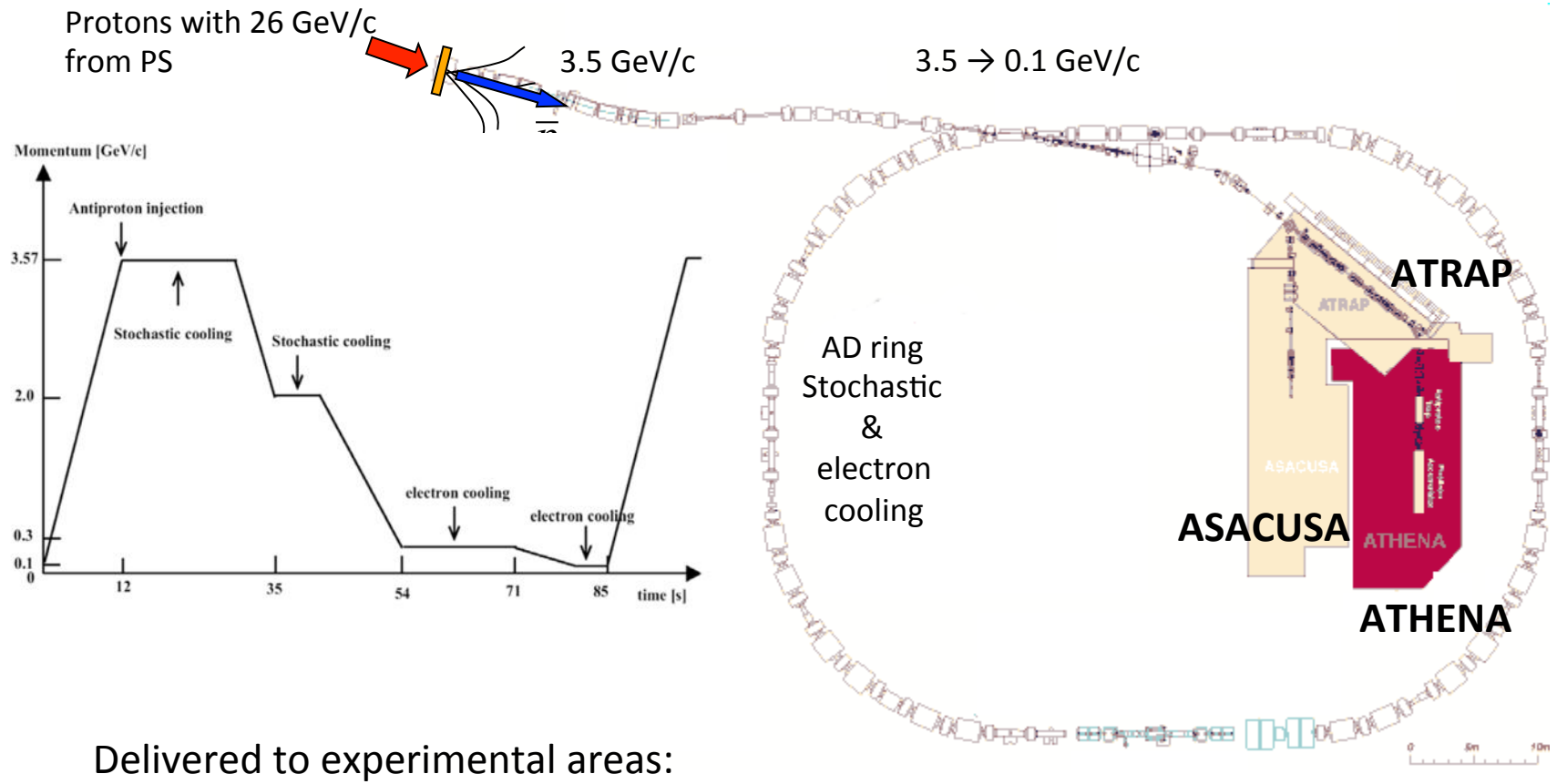
Erzeugung von Antiprotonen im Labor

Antiproton Decelerator (AD)
des CERN





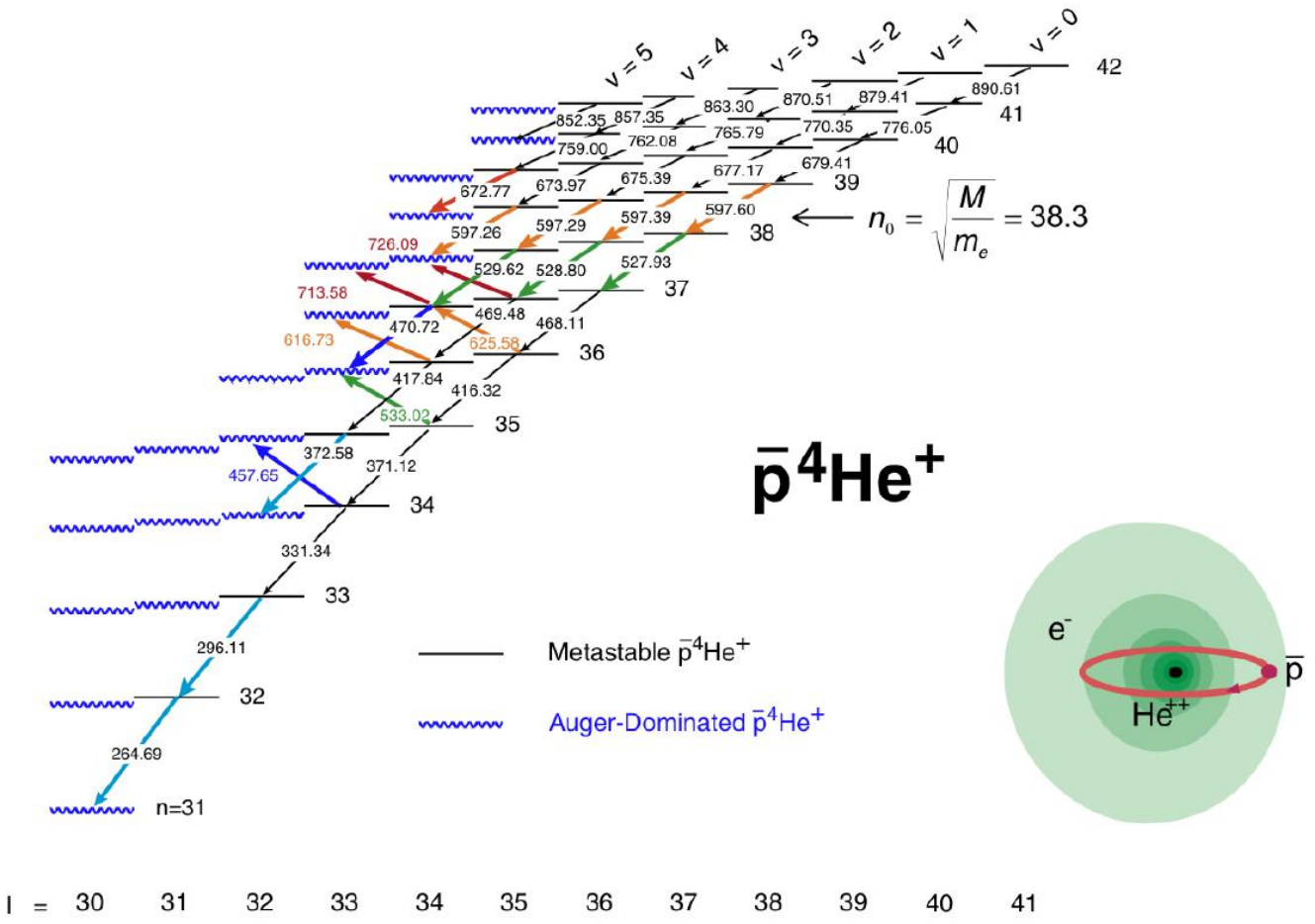
Antiprotons at AD/CERN



Delivered to experimental areas:

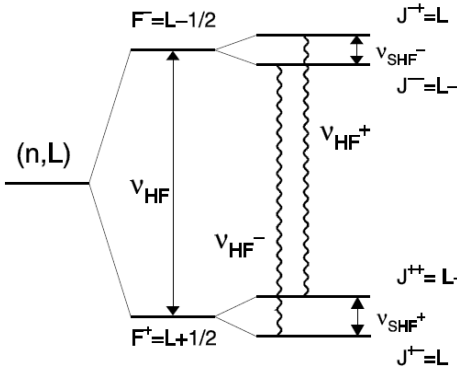
- 10^7 antiprotons delivered every ~85 s
- 0.1 GeV/c
- 200 ns bunches

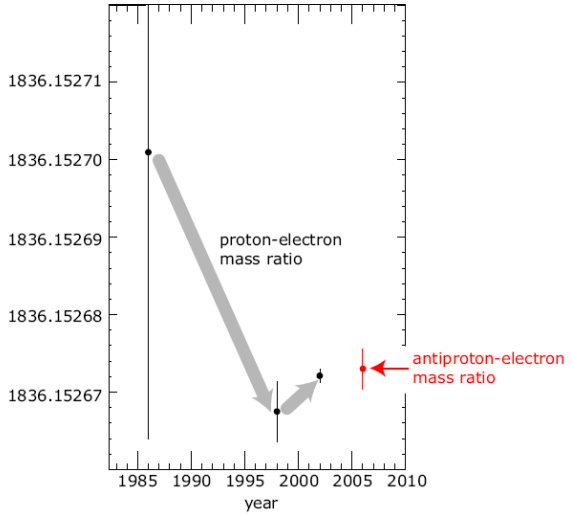
Antiprotonisches Helium

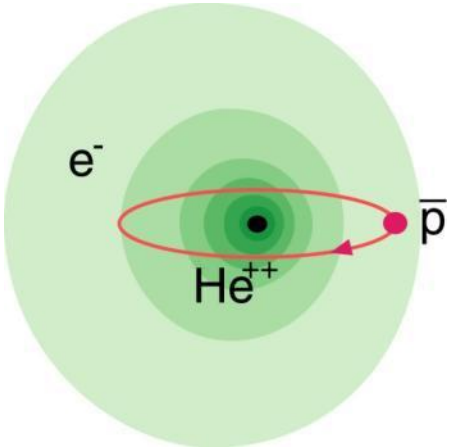


Antiprotonisches Helium

- Hyperfein-Struktur
  - Präzisionsmikrowellen-Spektroskopie
  - Antiproton magnetisches Moment QED/CPT Test
- Laser Spectroscopie
  - Antiproton Masse & Ladung → QED/CPT Test
  - 2-Photonen-Spectroscopie zur Steigerung der Präzision



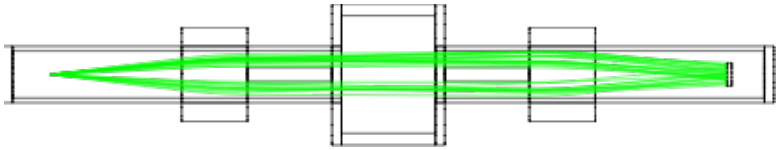


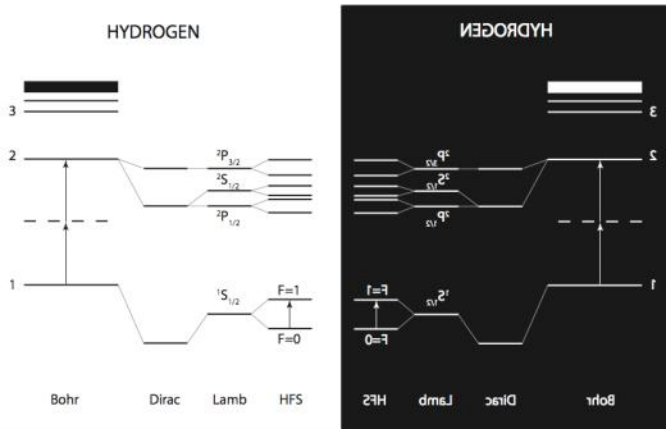


Hyperfeinstruktur von Antiwasserstoff im Grundzustand

- Komplementäre Studie zu 1S-2S Laser-Spektroskopie (ALPHA, ATRAP)
  - Spin-Spin Wechselwirkung
  - direkter CPT Test
- Genauigkeit in Wasserstoff 10^{-12}
- Atomstrahl-Methode (Rabi)
  - Keine Falle, 100 K Temperatur
- Neue Rekombinationsmethoden
  - Punktquelle

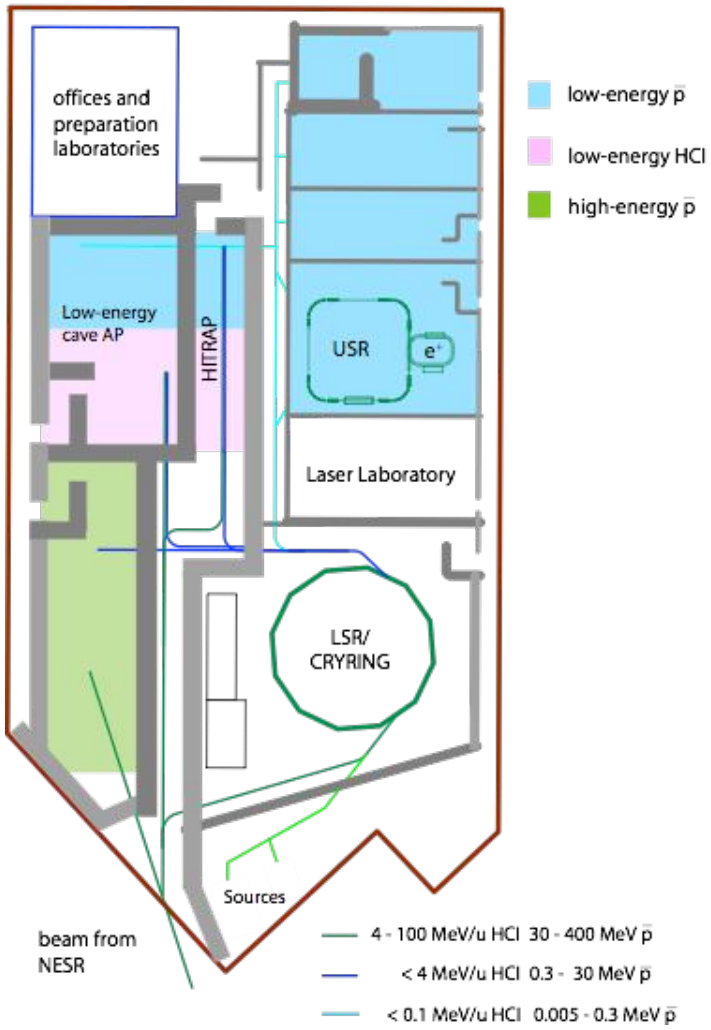
Sextupol-Magnete, 4T Feldstärke:
Effizienz $\sim 10^{-4}$

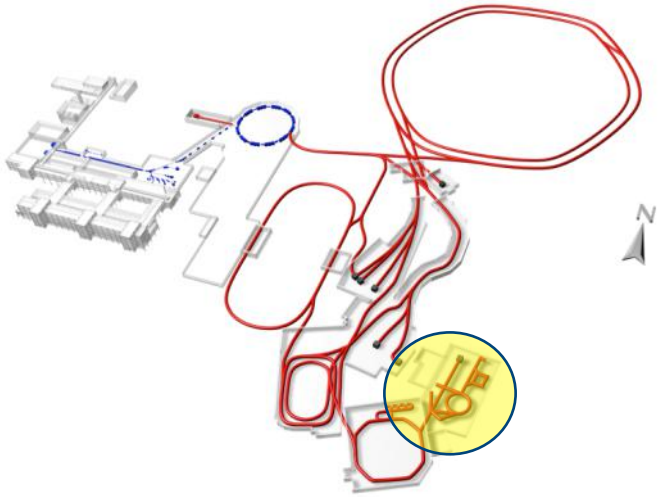




CPT Test mit Vergleich hfs H und. $\bar{H}$

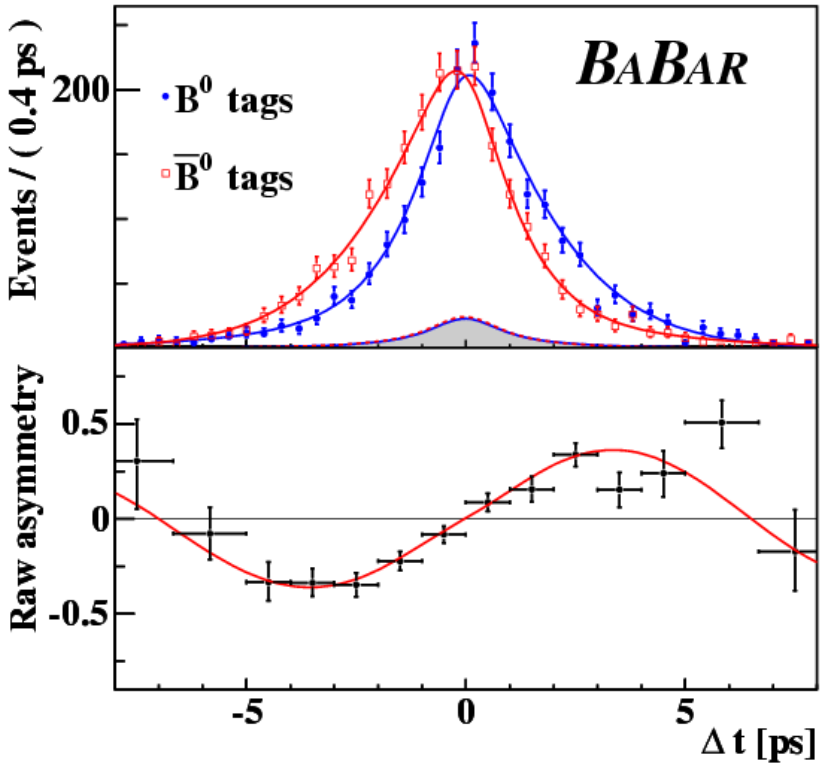
FLAIR





- Facility for Low-energy Antiproton and Ion Research
- Nächster Antimaterie-“Fabrik“ nach CERN-AD

CP Verletzung im K- und B-Meson System gefunden (Belle, Babar)



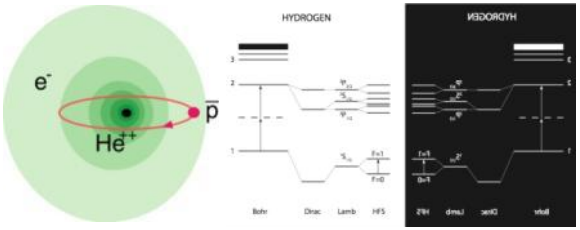
Ein Unterschied von Materie zu Antimaterie wurde gefunden, aber der Effekt erscheint zu klein um die Materie-Antimaterie Symmetrie im Universum zu erklären.

Physik mit Antimaterie an FLAIR

E.Widmann CAMOP, *Plans for a Next-Generation Low-Energy Antiproton Facility* , Physica Scripta 72 (2005) C51-C56

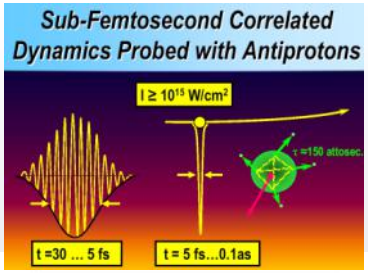
Spektroskopie für CPT and QED Tests

Antiprotonische Atome (pbar-He, pbar-p), Antiwasserstoff



Atomare Kollisionen

Sub-femtosekunden korrelierte Dynamik : Ionization, Energieverlust, Antimaterie-Materie Kollisionen



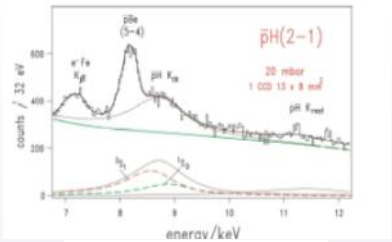
Antiprotonen als hadronische Testteilchen

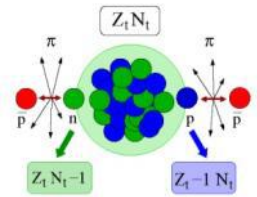
Röntgenstrahlung von leichten antiprotonischen Atomen:
Niederenergie QCD

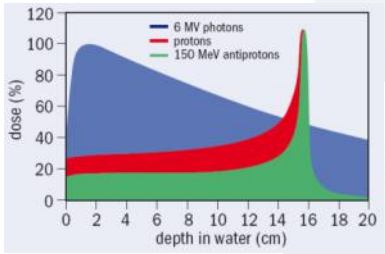
Röntgenstrahlung von neutronenreichen Kernen:
Kernstruktur (Halo)

Antineutron-Wechselwirkung

Strangeness –2 Produkion

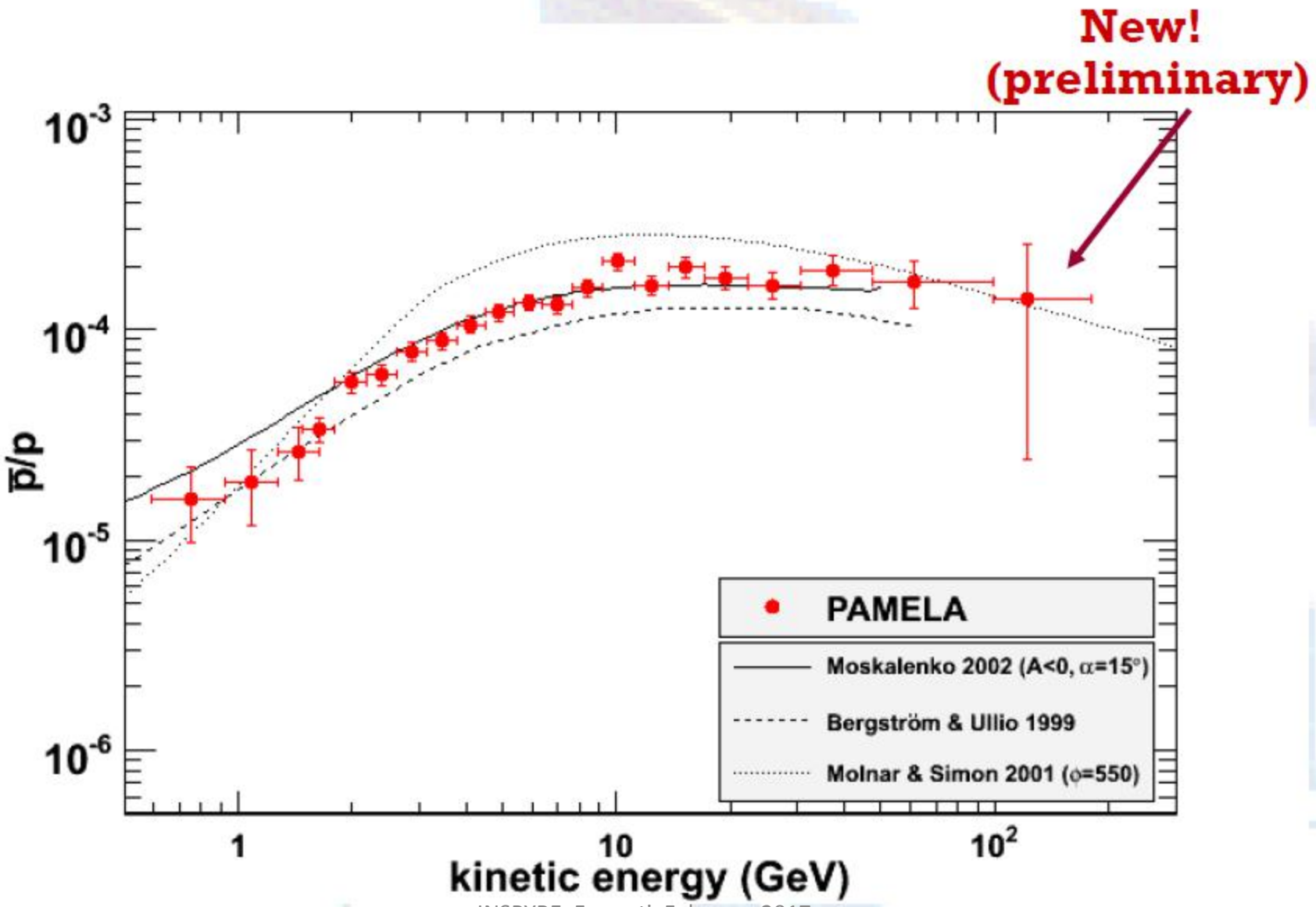




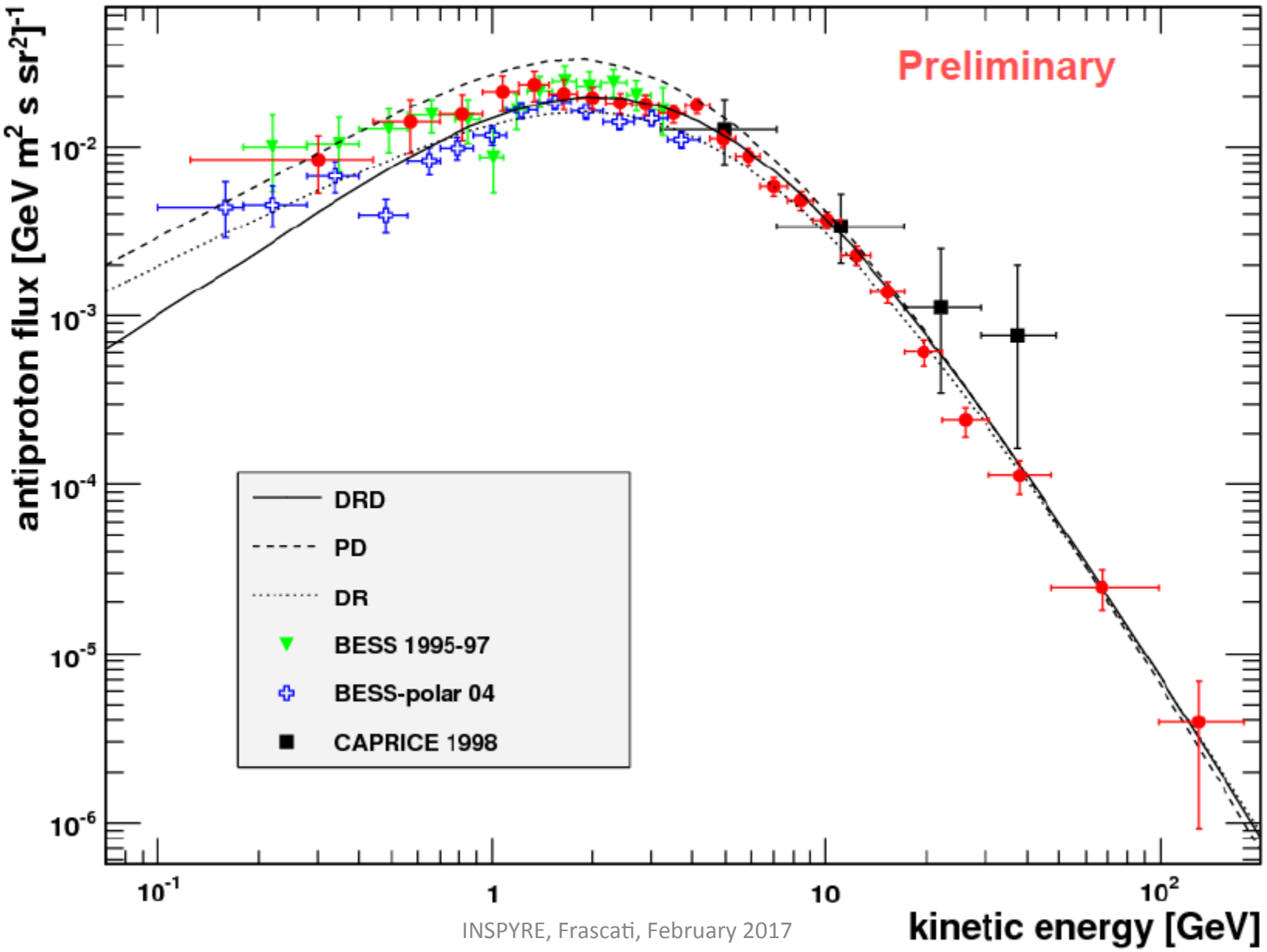


Medizinische Anwendung: Tumor Therapie

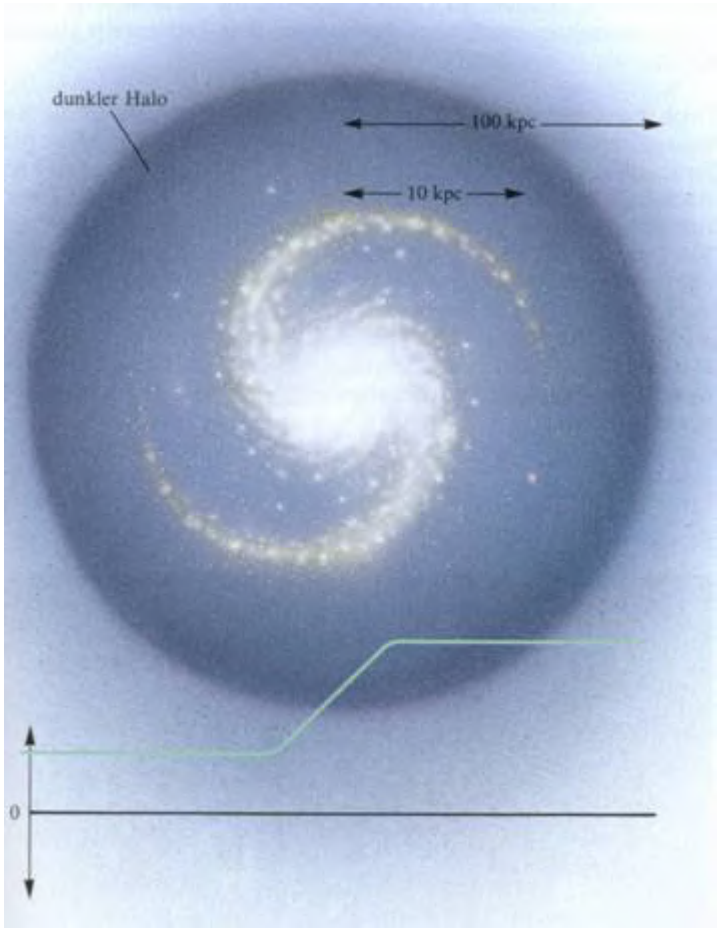
Antiproton to proton ratio



Antiproton Flux

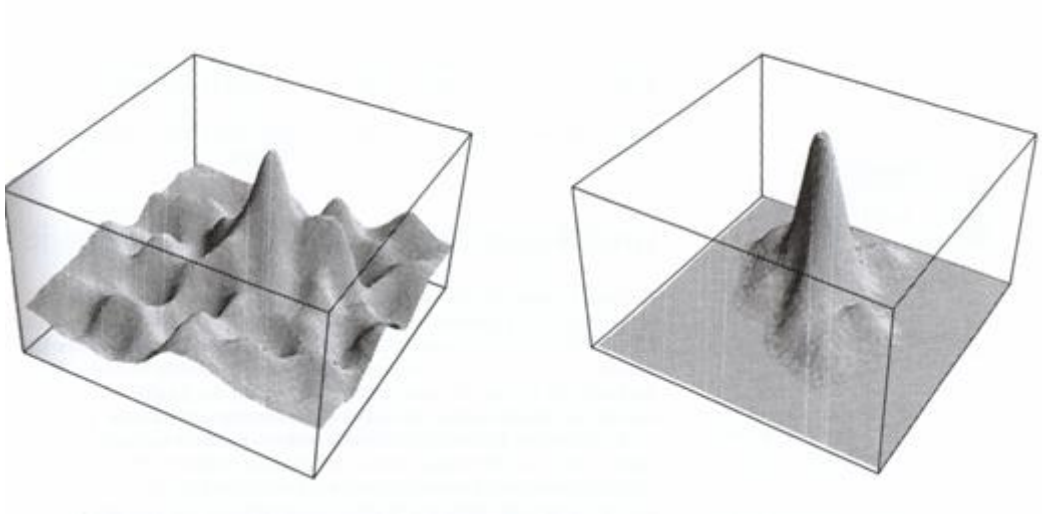


Dunkle Materie



Galaxien rotieren zu schnell in den Spiralarmen!

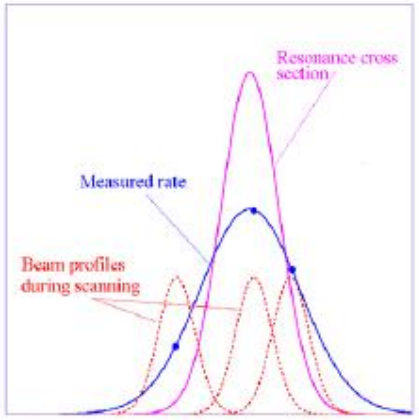
Verteilung der Materie



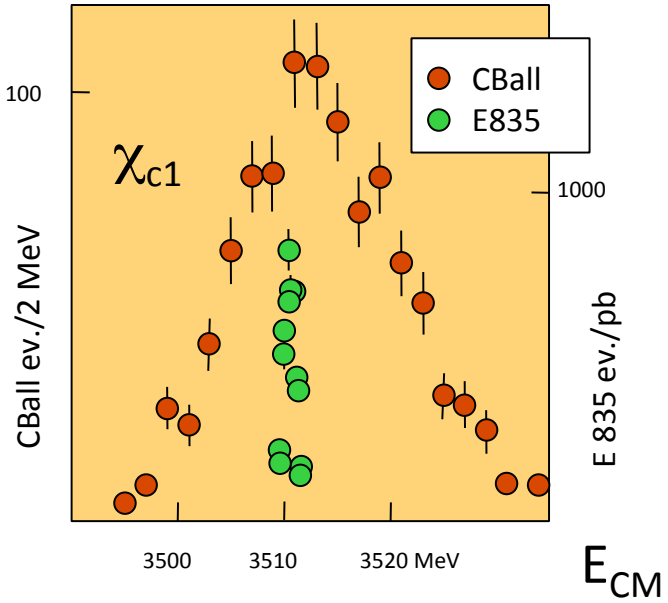
dunkel sichtbar

Hadronenphysik mit Antiprotonen

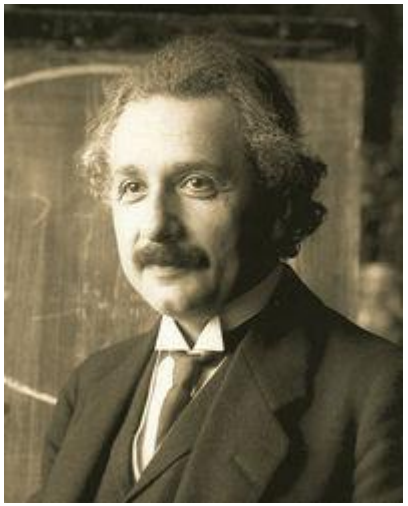
- Alle hadronischen Zustände mit Charm-Quarks können direkt gebildet werden.
- Gekühlte Antiprotonenstrahlen mit genau definiertem Impuls (10^{-5}) erlauben das Scannen von Resonanzen
- Erweiterter Energiebereich verglichen mit CERN bzw. Fermilab
- Optimiertes Detektorsystem



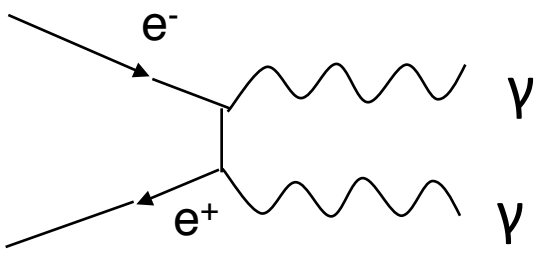
Präzision ist durch die Strahlqualität gegeben



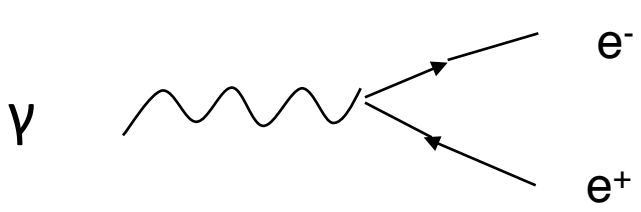
Materie-Energie



Einstein erkannte Äquivalenz
von Materie und Energie



Beim Aufeinandertreffen von
Materie mit Antimaterie tritt
Annihilation ein



Umgekehrt kann aus Energie
ein Teilchen-Antiteilchenpaar
Entstehen.

Mehr über Antimaterie

- Alle geladenen Leptonen und Quarks haben Antiteilchen
- Kombinationen von Quark-Antiquark (Mesonen) existieren ebenfalls

  – $\pi^+ = u\bar{d}$ $K^0 = d\bar{s}$

  – $B^0 = \bar{b}d$ $B^0 = b\bar{d}$