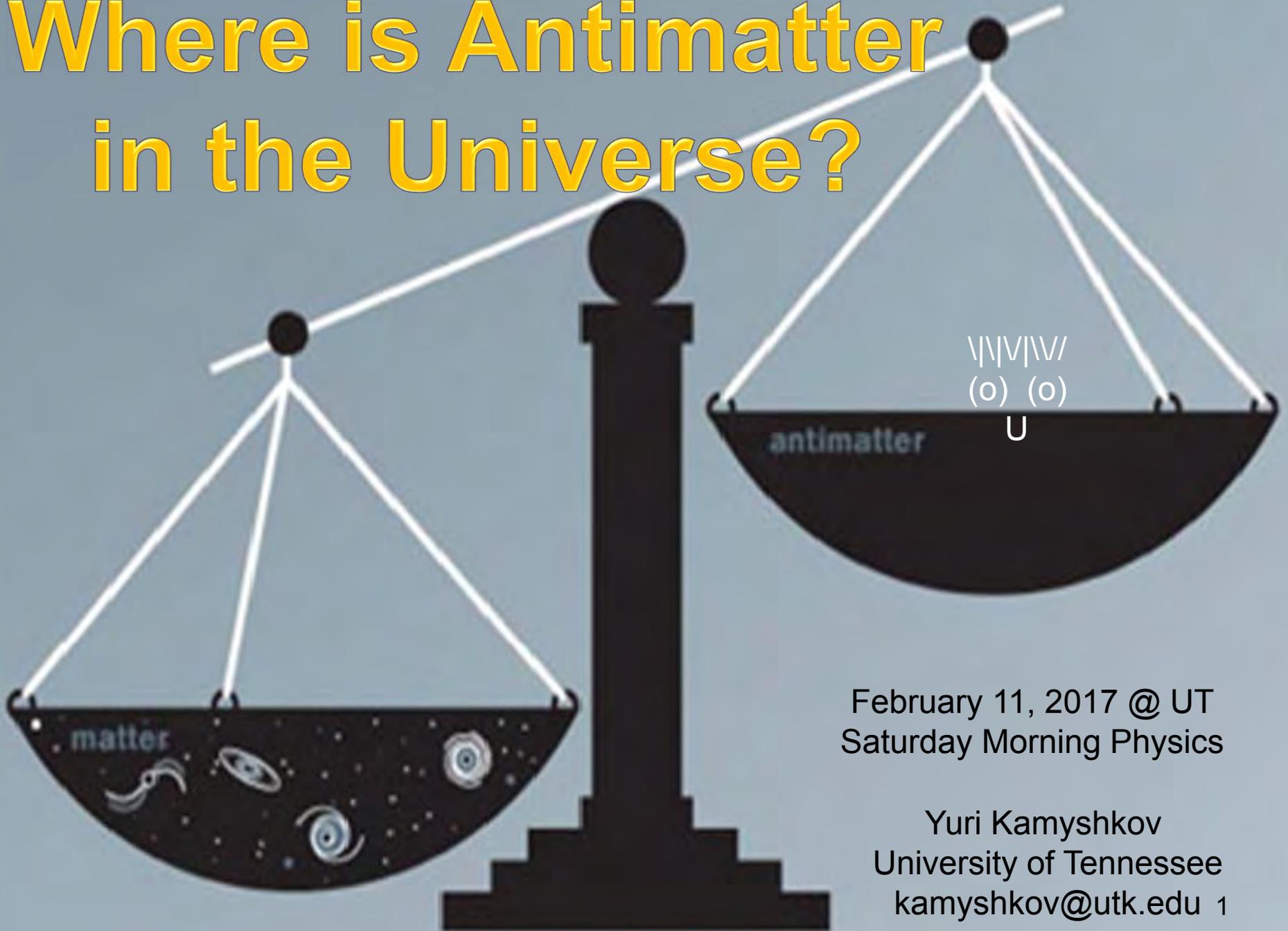


Where is Antimatter in the Universe?

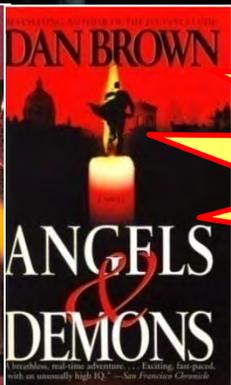
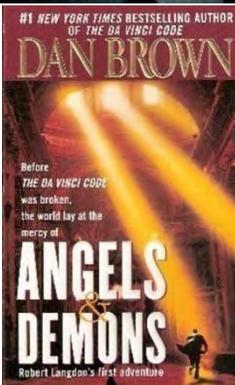
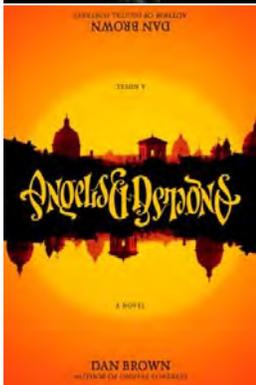


February 11, 2017 @ UT
Saturday Morning Physics

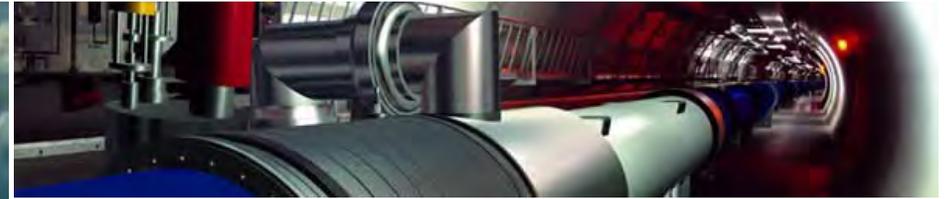
Yuri Kamyskov
University of Tennessee
kamyskov@utk.edu 1



Angels & Demons



Large Hadron Collider



CERN
European Centre
for Particle Physics
Geneva, Switzerland



<http://angelsanddemons.cern.ch/>



Antimatter stolen in the movie and exploded in Rome



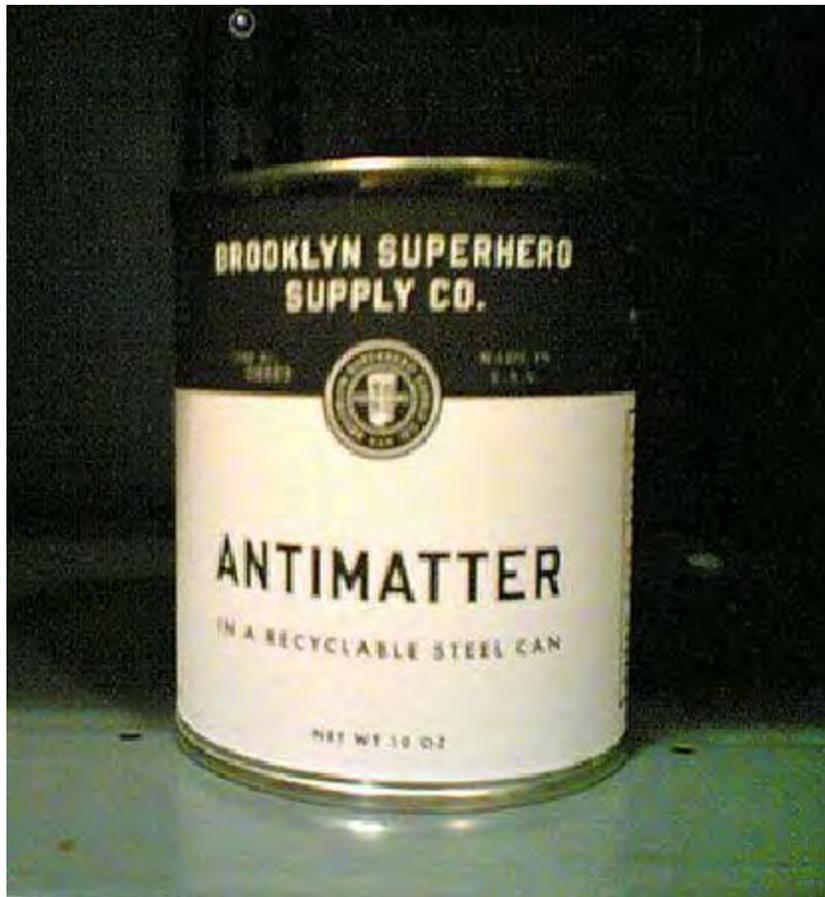
Can anti-matter be stored?

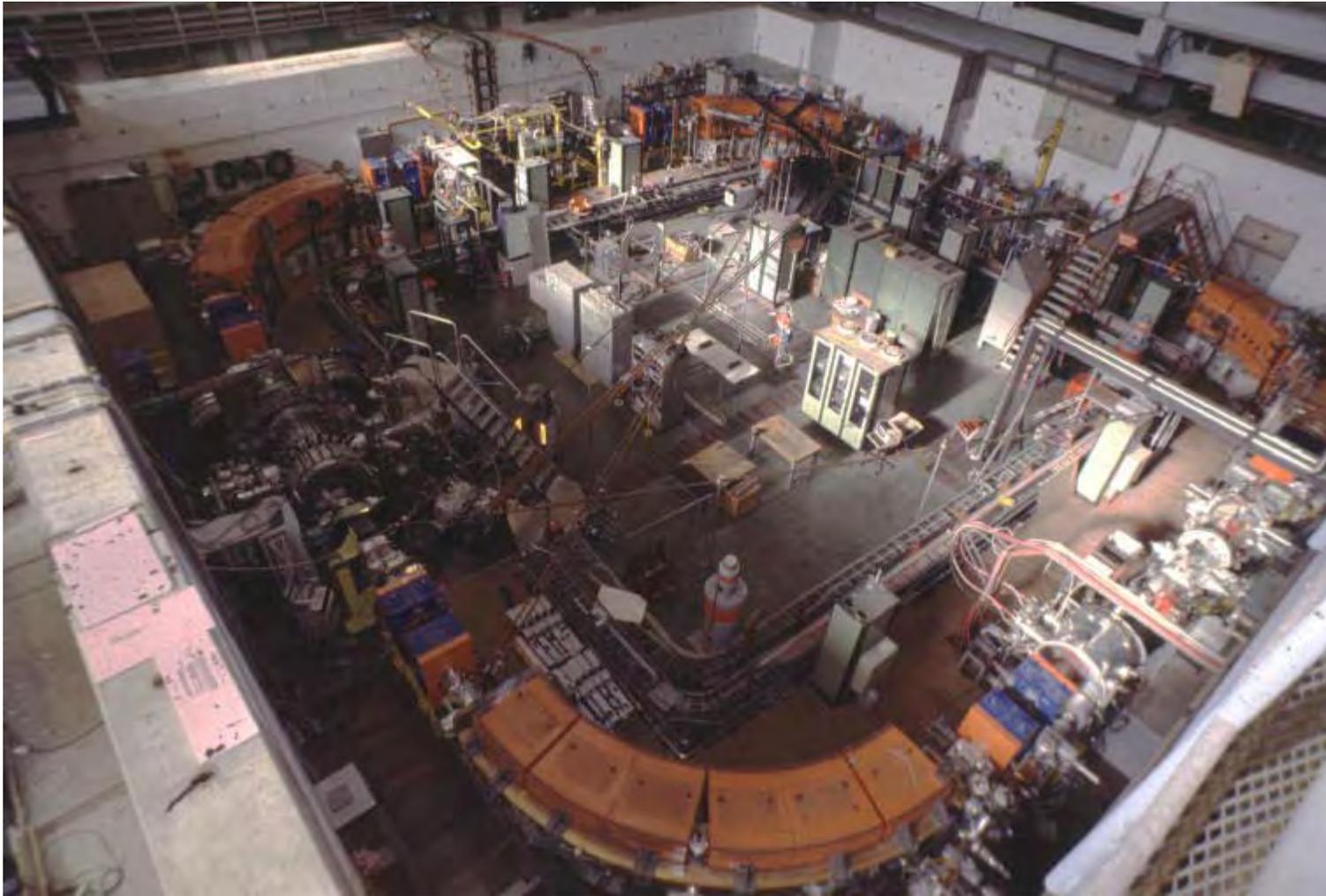


A poster encourages the effort at CERN's ATHENA experiment to create antimatter.

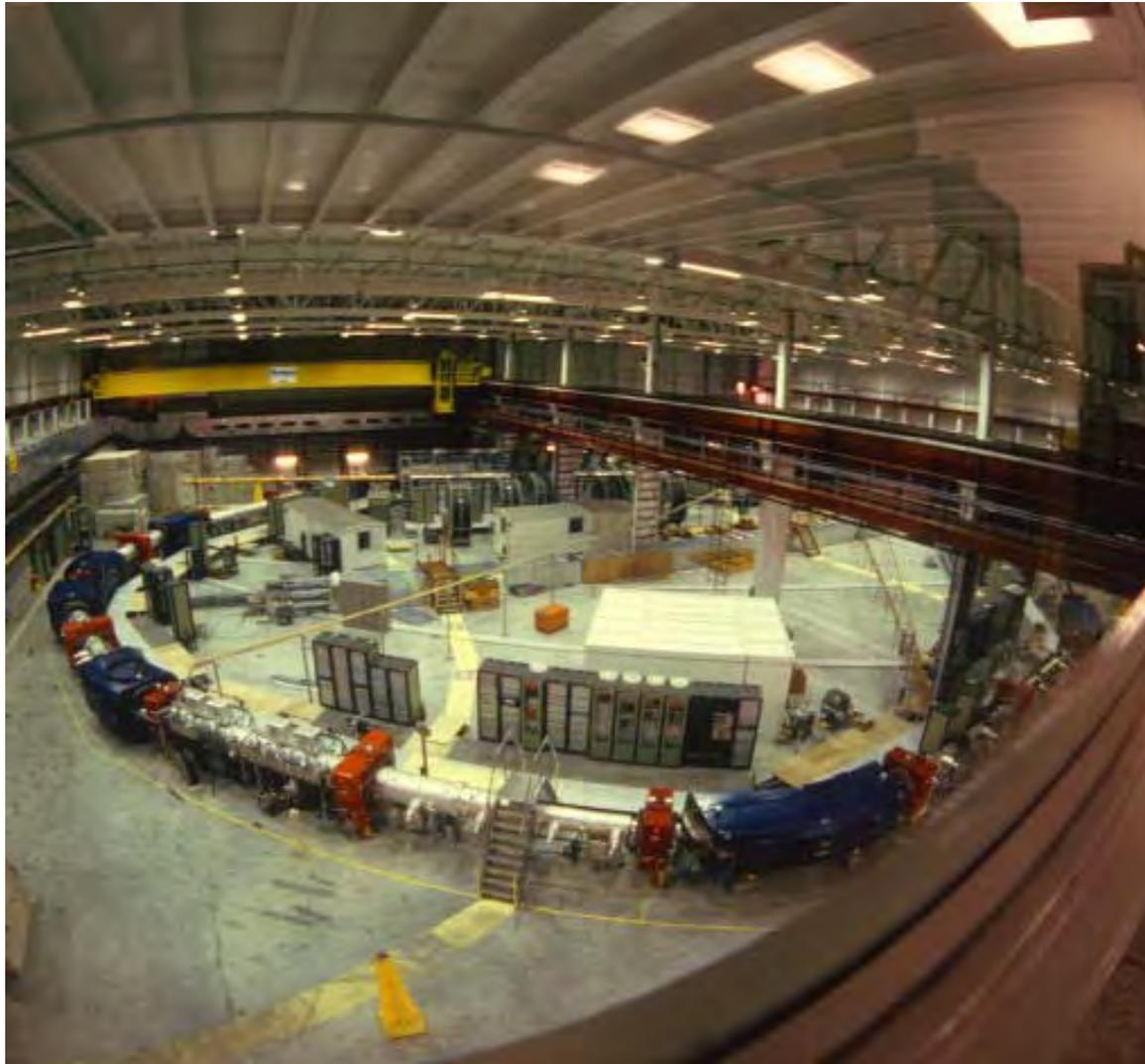
ATHENA/CERN

Can not be stored like that





The Low Energy Antiproton Ring (LEAR) at CERN (Geneva, Switzerland)

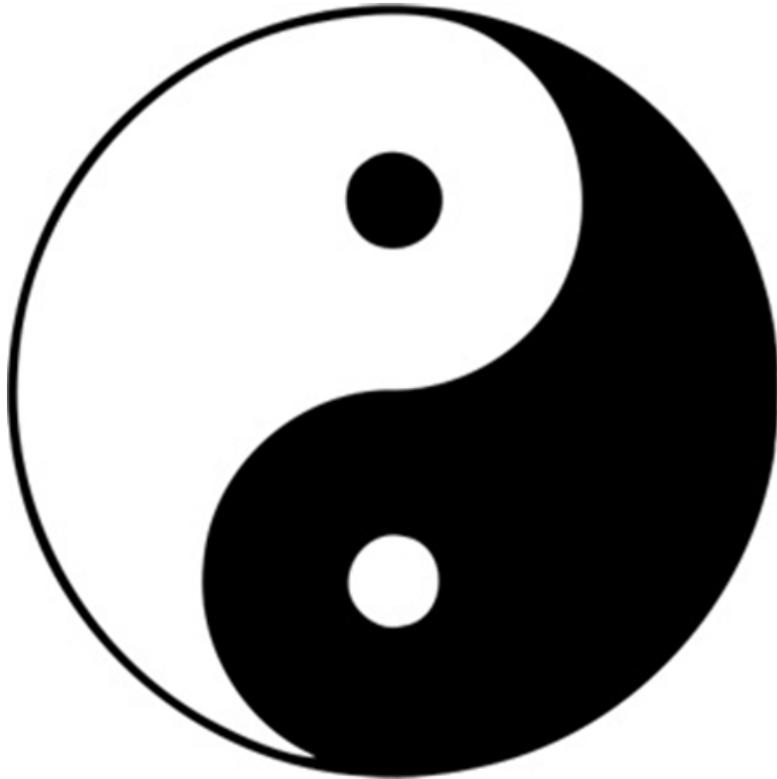


The Antiproton Accumulator (AA) which has been transformed into the Antiproton Decelerator (AD) in 1999

- 1 g of antimatter would produce an explosion equivalent to 40 kt of TNT.
- At CERN ~ 10,000,000 antiprotons per second can be produced.
- 1 g (~ 6×10^{23} protons) can be produced for ~ 2,000,000,000 years.
- Over the last 20 years, approximately 10 billionths of a gram of antimatter has been produced at CERN, whose explosive yield is equivalent to that of a firecracker, far less than is needed for it to be the threat depicted in the novel and movie.
- Antimatter production cost estimate: ~ \$62.5 trillion per gram (NASA).

What is Antimatter and how it is different from Matter ?

5,000 years old
concept of Nature



Yin and **Yang**

[Yin Yang is an active concept:](#)

Yin Yang are opposing

Yin Yang are rooted together

Yin Yang transform each other

Yin Yang are balanced

Yin-yang is not an actual substance or force, but it is a universal way of describing the interactions and interrelations of the natural forces that do occur in the world.

First Cosmological model:



"Book of Changes" created ~ 5,000 years ago "by first Chinese Emperor, Fu Hsi"

Concept of ☯ is represented by broken line (Yin) :  and continuous line (Yang) : 

Heaven 

Thunder 

Water 

Mountain 

Earth 

Wind 

Flame 

Lake 

Yin is usually characterized as slow, soft, insubstantial, diffuse, cold, wet, and tranquil. It is generally associated with the feminine, birth and generation, and with the night

Yang, by contrast, is characterized as hard, fast, solid, dry, focused, hot, and aggressive. It is associated with masculinity and daytime

| | | |
|---|--|---|
|  <p>Kuan</p> | <p>20. Contemplation WIND above, EARTH below</p> | <p><i>The immediate future is difficult, with you feeling 'blown around' and unable to achieve anything. Improvement will come.</i></p> <p><i>Be patient, and use this time to observe, examine (including yourself), gain wisdom, and plan. Improvement will come.</i></p> |
|---|--|---|



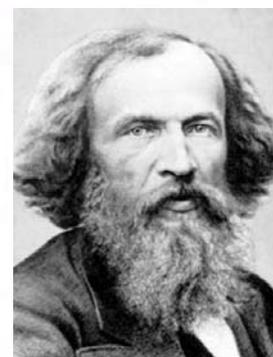
(c) Andy Brice 1998

For thousands years
we knew only matter

The Periodic Table

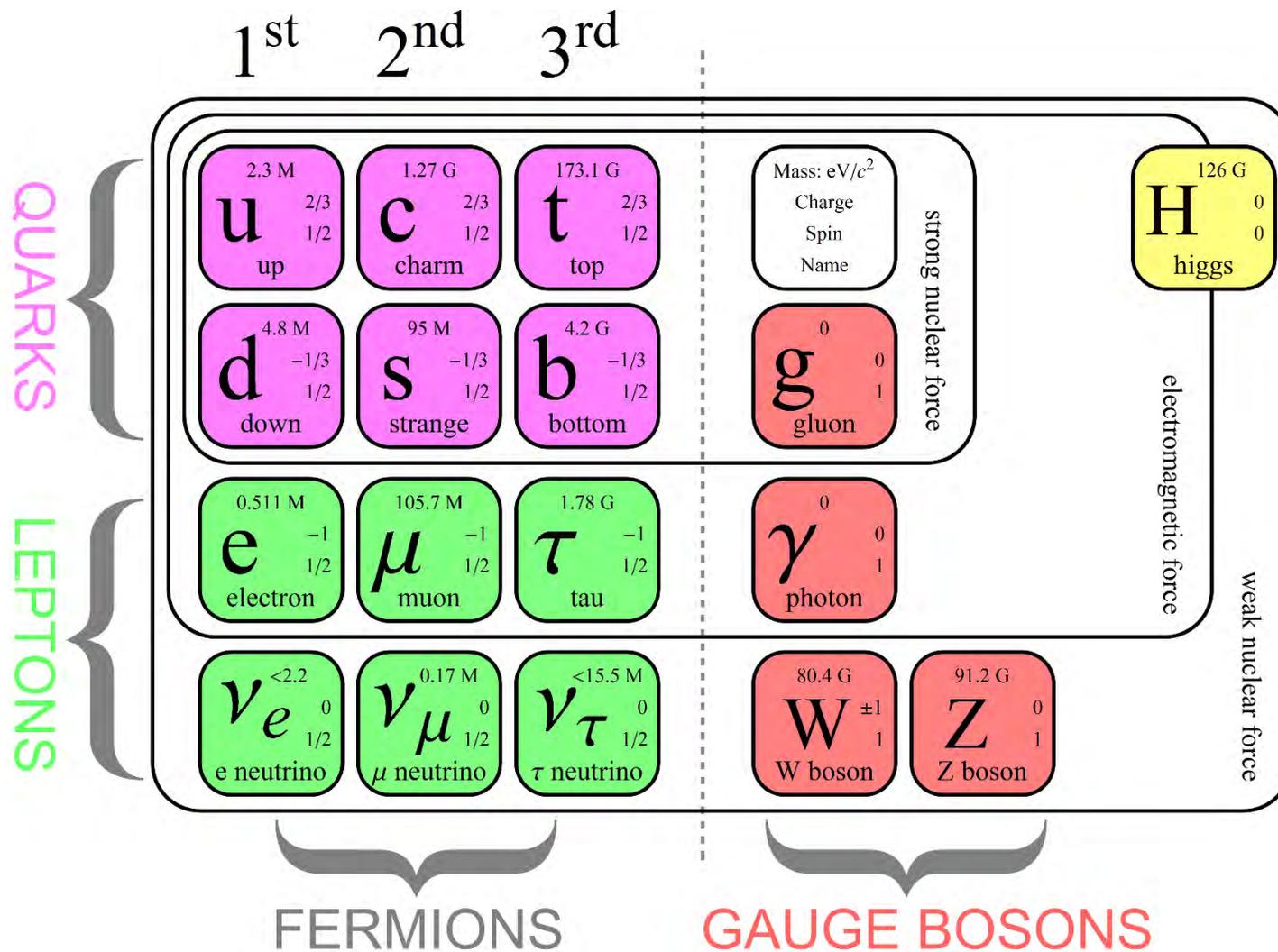
| | | | | | | | | | | | | | | | | | |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|---------|
| 1 H | | | | | | | | | | | | | | | | | |
| 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | |
| 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | |
| 19 K | 20 Ca | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | | | 33 As | 34 Se | 35 Br | | |
| 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | | | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I |
| 55 Cs | 56 Ba | | | 73 Ta | 74 W | | | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | | |

| | |
|----------|---------|
| 90 Th | 92 U |
|----------|---------|



Mendeleev 1869

Standard Model is Relativistic Quantum Field Theory of Fundamental Particles and Forces (without Gravity)



Standard Model Particles

Quarks



Up



Down



Charm



Strange



Top



Beauty

Leptons



Electron



Neutrino



Muon



Neutrino Muon



Tau



Neutrino Tau

Bosons



Photon



Gluon



Z^0



W^-



W^+



Higgs



Graviton

Greatest Discovery of XX century: anti-matter

*in 1928 Paul A.M. Dirac predicted **positron** (a particle like electron but with opposite electric charge) from unifying Einstein's special relativity with quantum mechanics.*

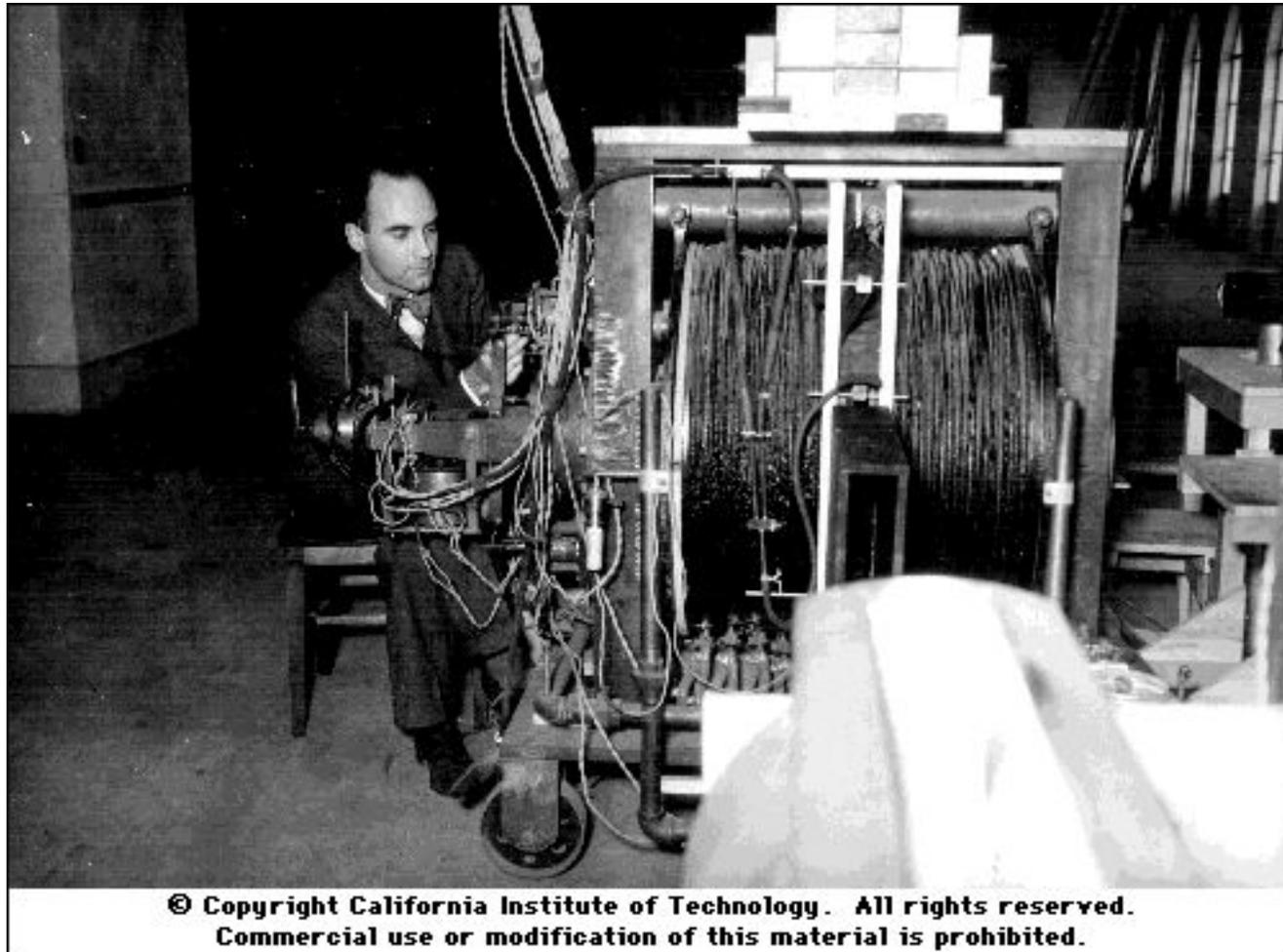
Solution of Dirac's equation for electron results in:

$$\mathcal{E} = \pm \sqrt{p^2 c^2 + m^2 c^4}$$



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

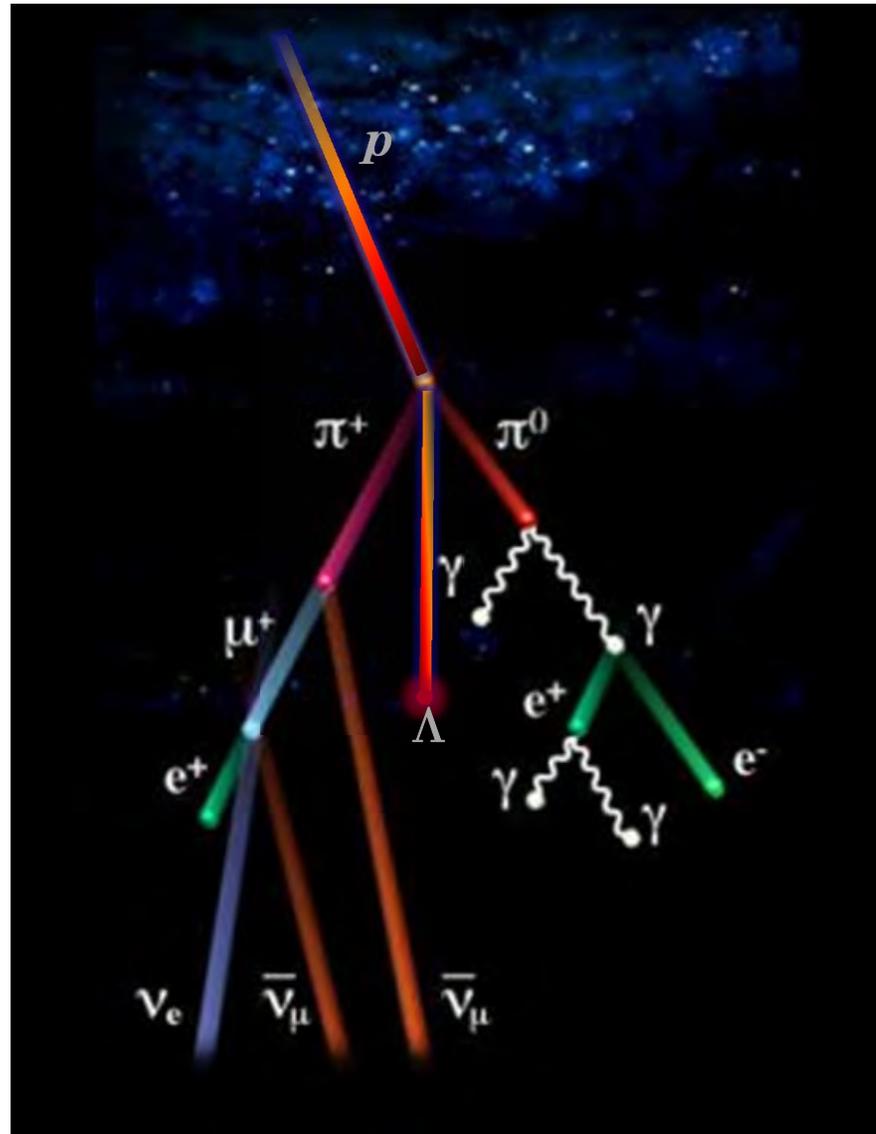
Nobel Prize in Physics 1933

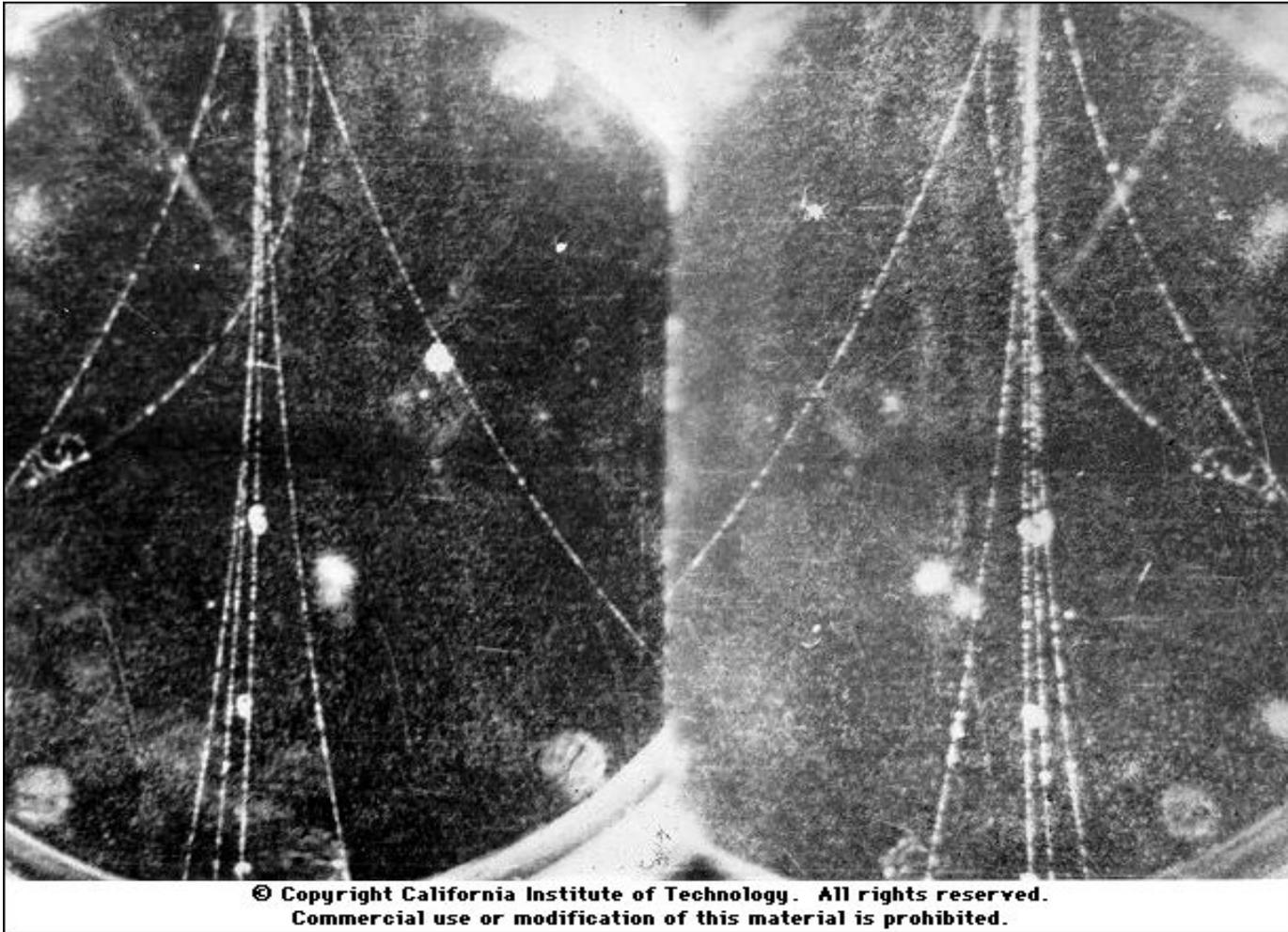


*in 1932 Carl David Anderson discovered **positrons**
produced in cosmic radiation*

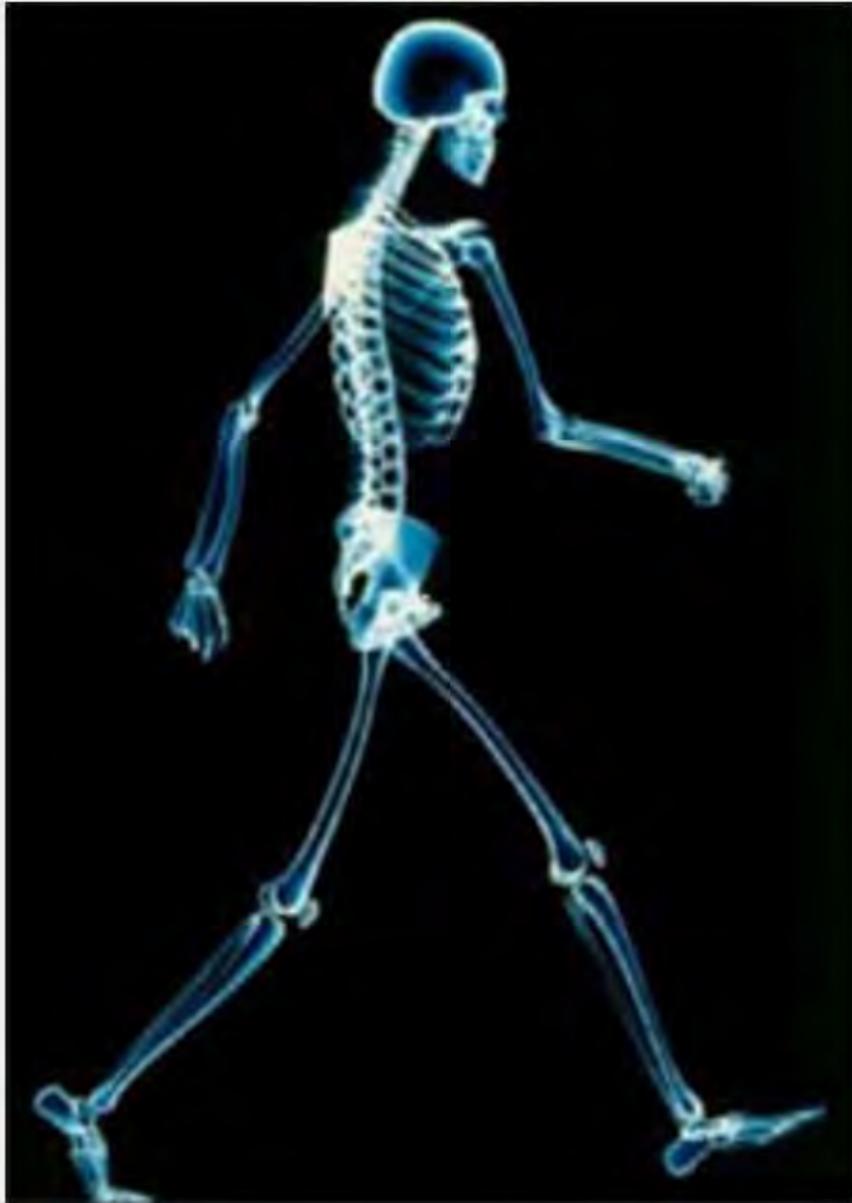
Nobel Prize in Physics 1936¹⁷

How positrons would appear in the cosmic rays?





Cloud chamber picture of a small cosmic-ray shower of positive and negative electrons in magnetic field

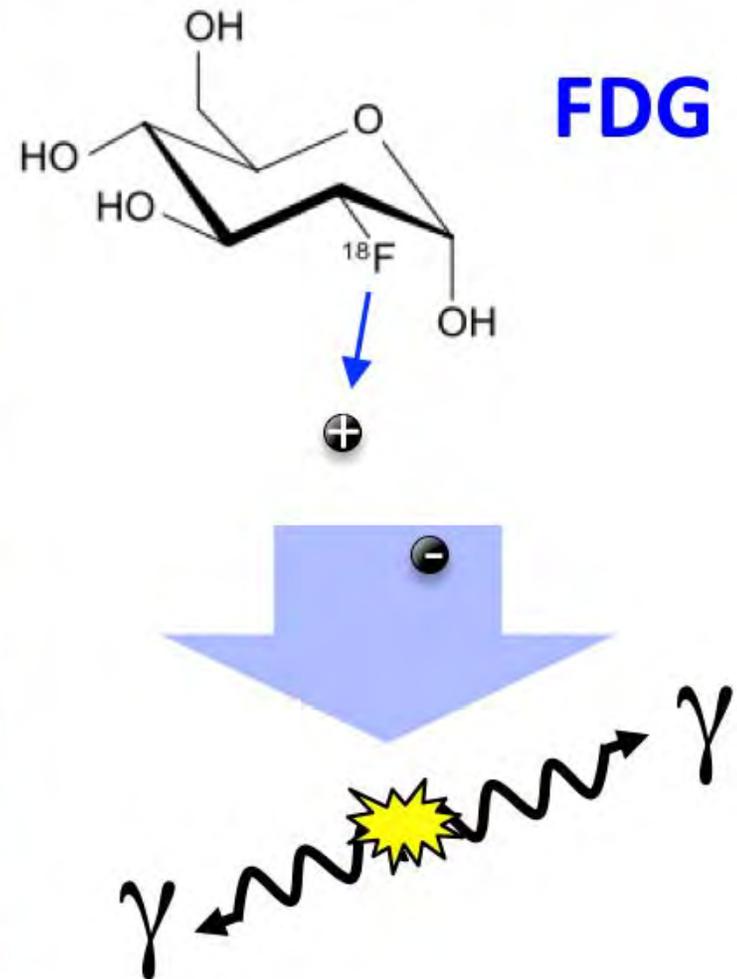


Your body emits antimatter!

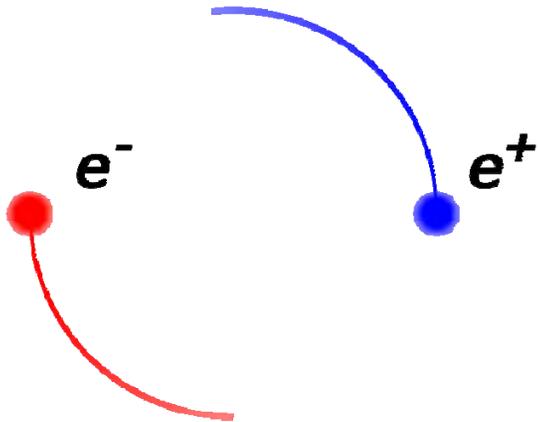
The body of a person weighing 80 kg emits 180 positrons per hour! This comes from the decay of potassium-40, a naturally occurring isotope that is ingested by drinking water, eating food and breathing.

Image: © sciencephoto.com, reproduced with permission.

Positron Emission Tomography



Positronium atom



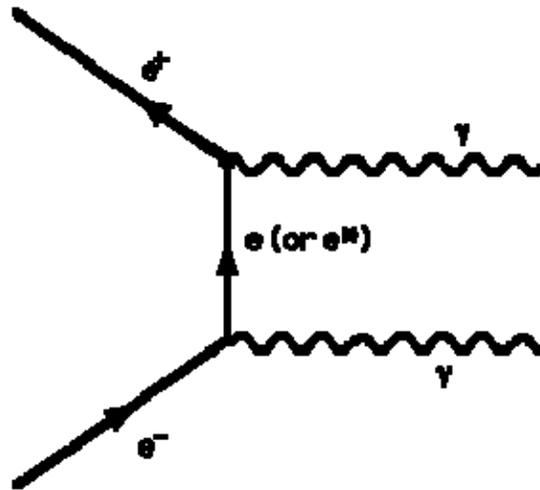
The Positronium Beam at University College London, a lab used to study the properties of positronium



Electron-Positron Annihilation

$$e^{-} + e^{+} \rightarrow \gamma + \gamma$$
$$m_{e^{-}}c^2 + m_{e^{+}}c^2 = 2\mathcal{E}_{\gamma}$$

$$\mathcal{E}_0 = mc^2$$



Two particles with masses (e^{+} and e^{-}) become two particles without masses (2γ) but with energy²³

Further discoveries of antimatter at accelerators:

in 1955 (O. Chamberlain, E. Segrè @ LBL)

anti-proton

in 1956 (B. Cork et al. @ LBL)

anti-neutron

in 1965 (D. Dorfan et al. @ AGS, Brookhaven)

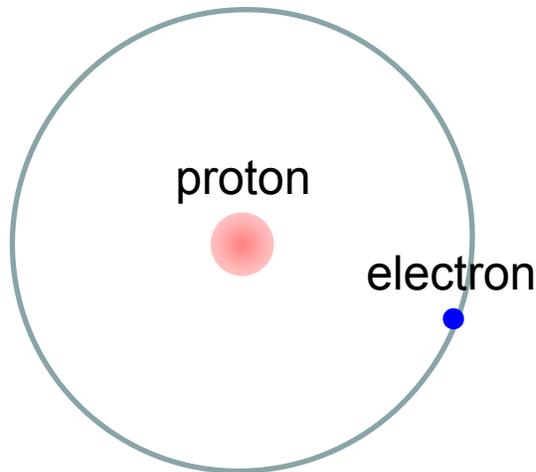
anti-deuteron

in 1995 (W. Oelert et al. @ LEAR, CERN)

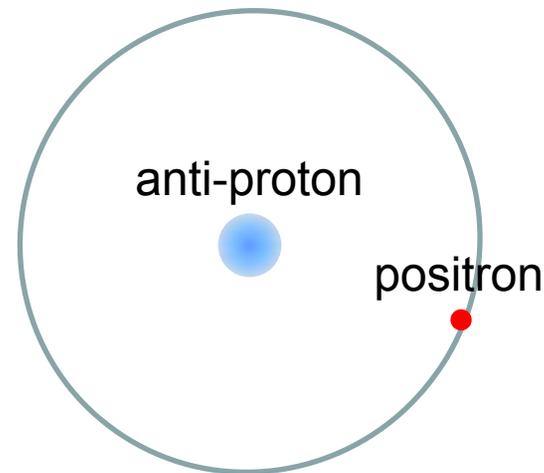
anti-hydrogen atom

in 2002 (R. Arsenescu et al. @ NA-52, CERN)

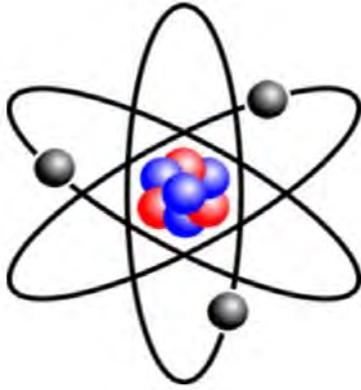
anti-³He



Hydrogen



Anti-Hydrogen



Matter is made of
protons + neutrons + electrons

If anti-proton, anti-neutron, and anti-electron exist, together with anti-hydrogen and anti-helium, then all anti-elements could be possible; and anti-stars, anti-galaxies, etc. might exist.

Are the properties of matter and antimatter different?

| | Mass (kg) | Charge (C) | Rest energy (Mev) |
|-------------|-----------|------------|-------------------|
| Electron | 9.1E-31 | -1.6E-19 | 0.51 |
| Positron | 9.1E-31 | 1.6E-19 | 0.51 |
| Proton | 1.67E-27 | 1.6E-19 | 938 |
| Antiproton | 1.67E-27 | -1.6E-19 | 938 |
| Neutron | 1.68E-27 | 0 | 939 |
| Antineutron | 1.68E-27 | 0 | 939 |

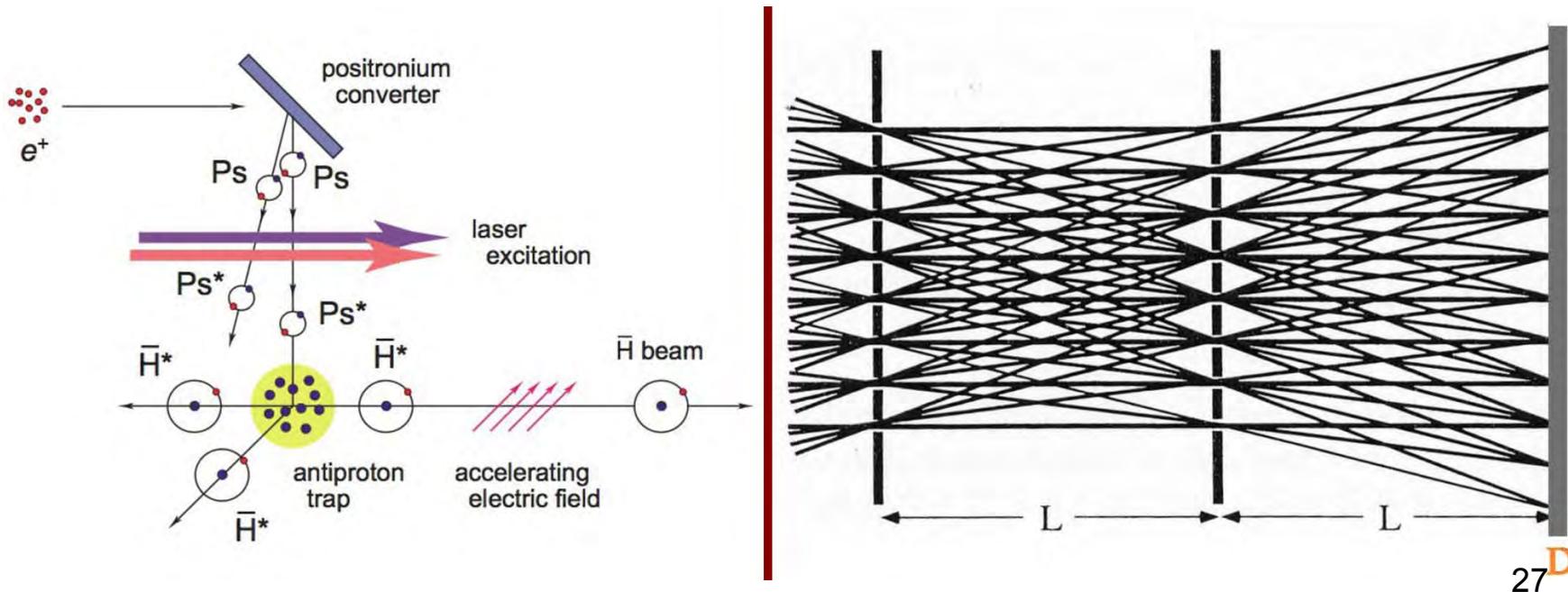
- If particle unstable (e.g. neutron) its antiparticle has exactly same lifetime.
- Magnetic moments of particle and antiparticle are opposite.

Does antimatter falls up?



AEGIS experiment at CERN

testing gravity interaction of antimatter



About CERN

Students & Educators

Scientists

CERN community

Accelerators

Experiments

Physics

Computing

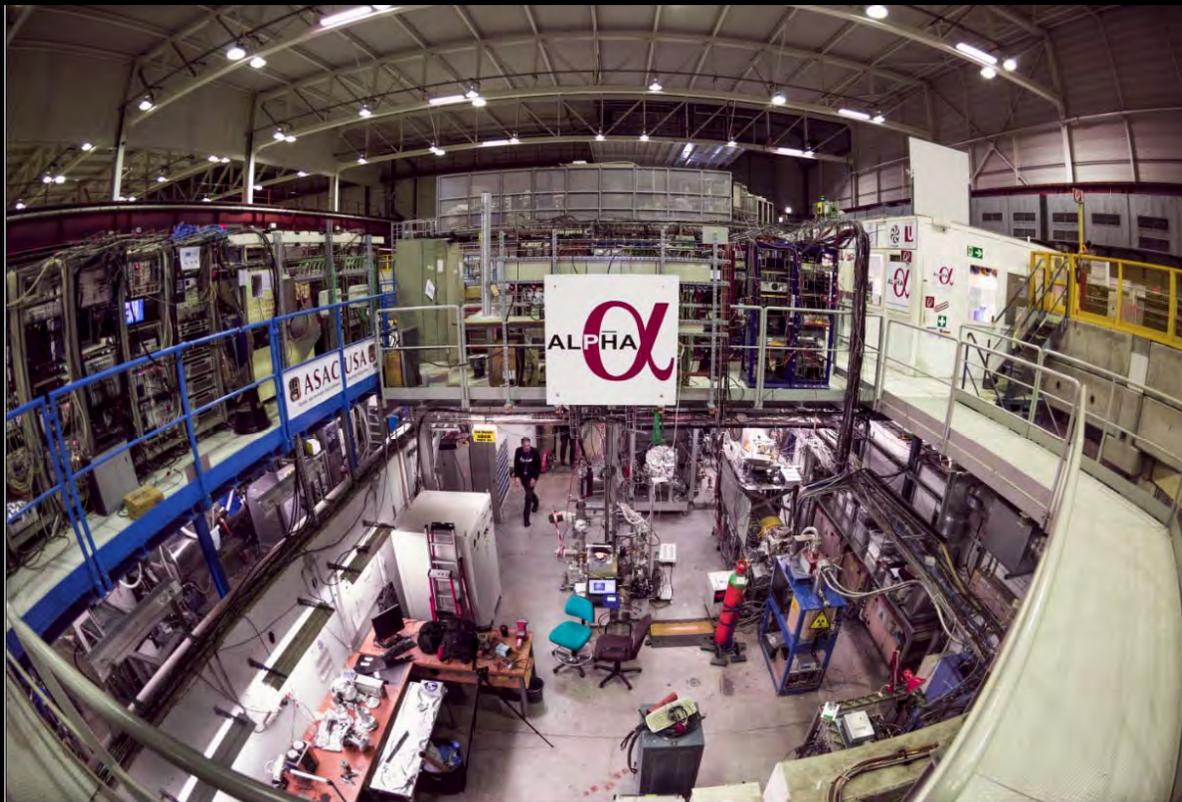
Engineering

Updates

Opinion

“One of the main physics results in 2016” ALPHA observes light spectrum of antimatter for first time

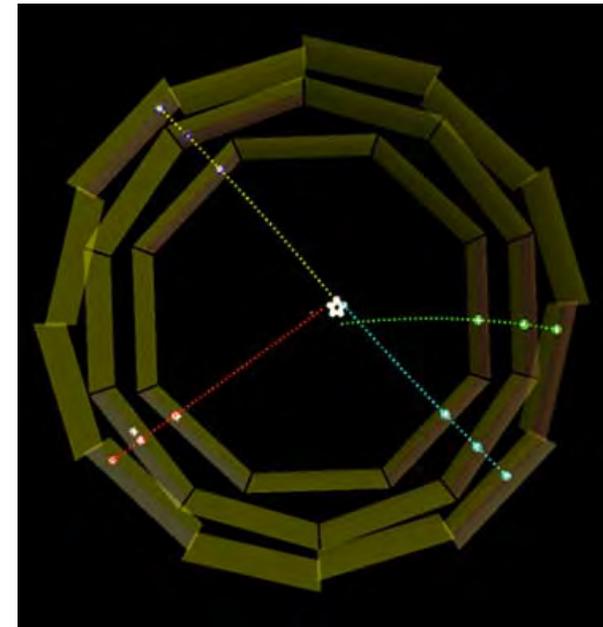
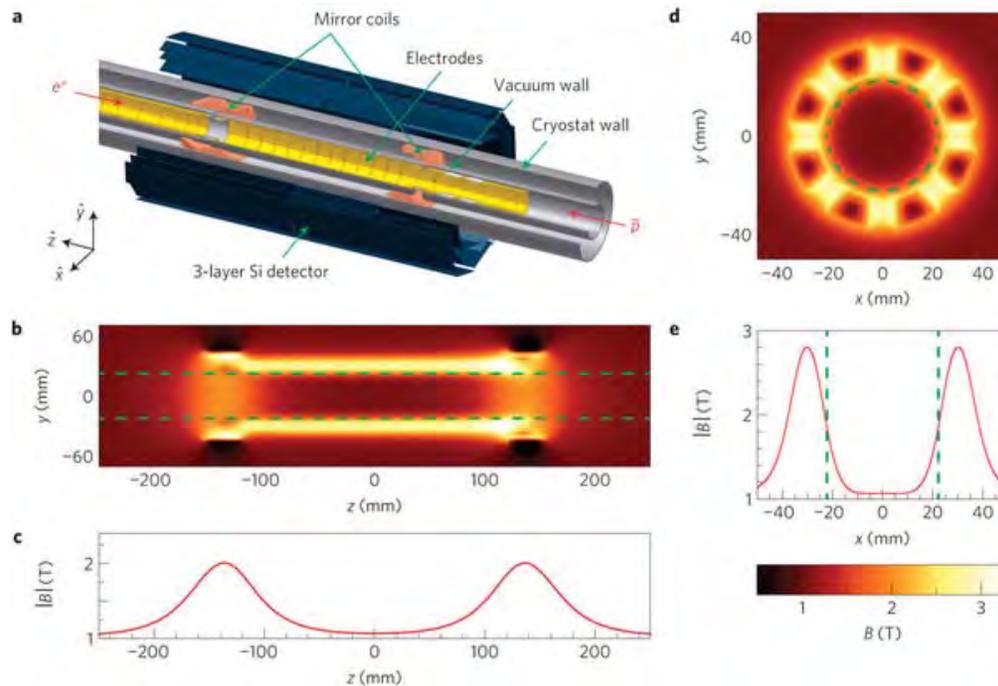
Read more at <http://alpha.web.cern.ch/>



Measuring the antihydrogen spectrum with high-precision offers an extraordinary new tool to test whether matter behaves differently from antimatter and thus to further test the robustness of the Standard Model (Image: Maximilien Brice/CERN)

<https://home.cern/about/updates/2016/12/alpha-observes-light-spectrum-antimatter-first-time>

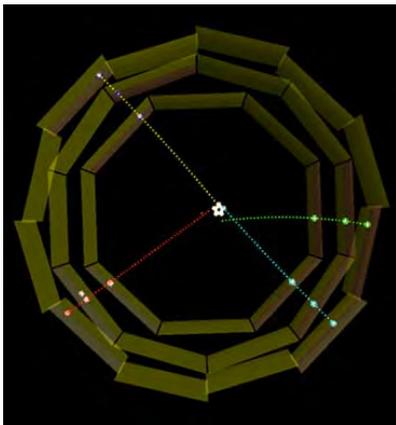
“Ioffe trap” of ALPHA experiment



Structure of energy levels of anti-hydrogen atom is exactly the same as for normal hydrogen

*What distinguishes anti-matter from matter is that they **annihilate** at contact*

E.g. electron and positron, if brought together, will form for a short while a positronium atom and then will annihilate into 2 or 3 photons



Anti-protons annihilate some different

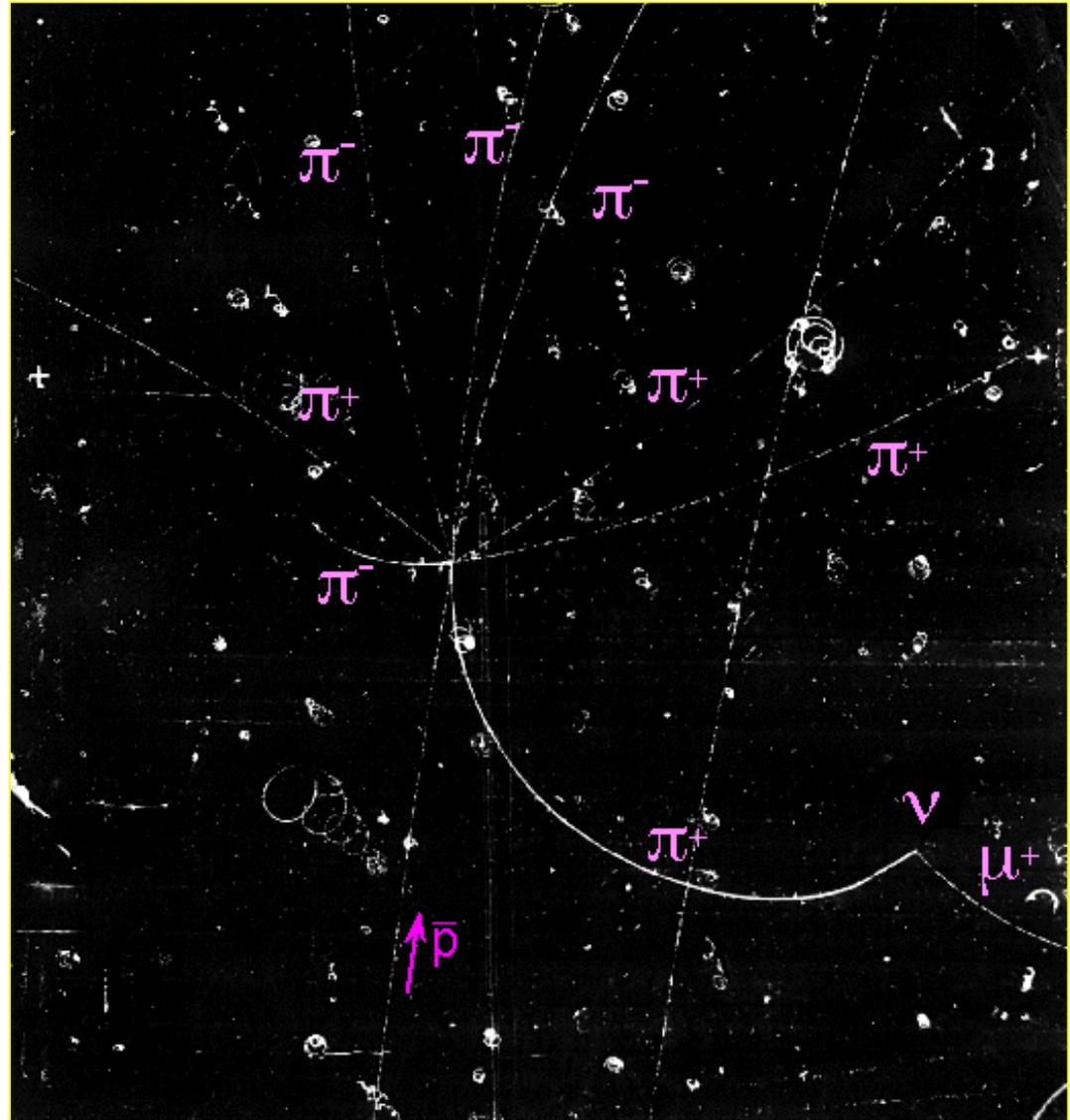
How will anti-proton and proton annihilate ?

Nucleon + anti-nucleon annihilate mostly into pions. Average number of pions = 5

Pions and muons eventually decay into stable particles: electrons, positrons, photons and neutrinos (~ 60% of energy ultimately is carried away by neutrinos).

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



31
Antiproton annihilation in hydrogen bubble chamber

View of annihilation



Clerc Romani, age 9



Important question

If e^+e^- and $p\bar{p}$ annihilate,
why e^- and p^+ in atom do not ?

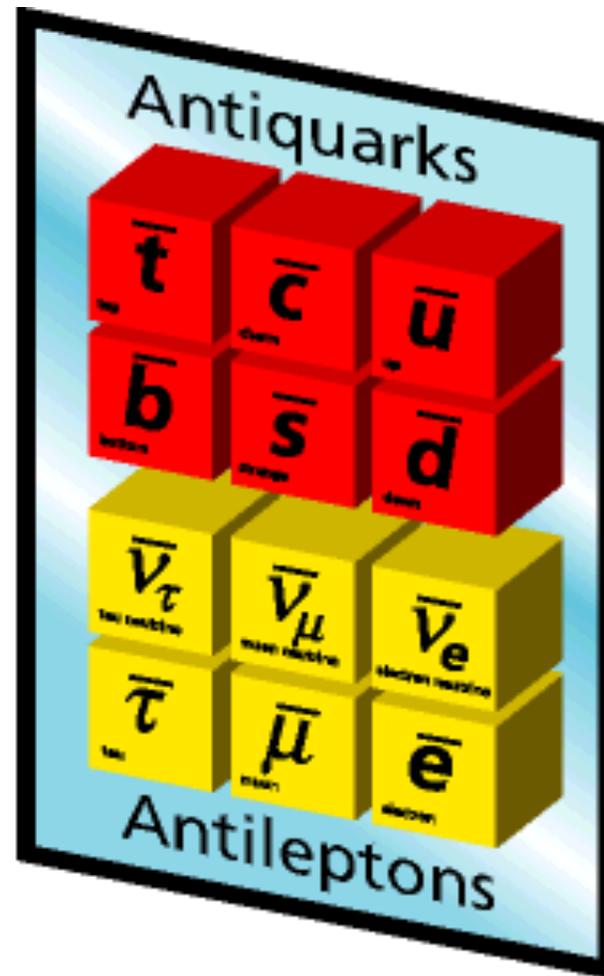
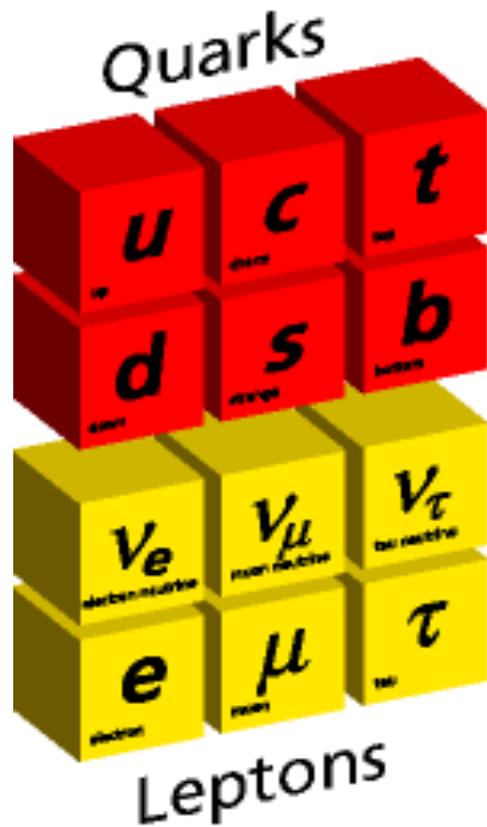
i.e. why hydrogen atom is stable
and there is no ${}^1H (e^-p^+) \rightarrow 2 \gamma$?
or why doesn't proton decay $p \rightarrow e^+ \gamma$?
If this would happen our matter will not
be stable.

Stability of Matter

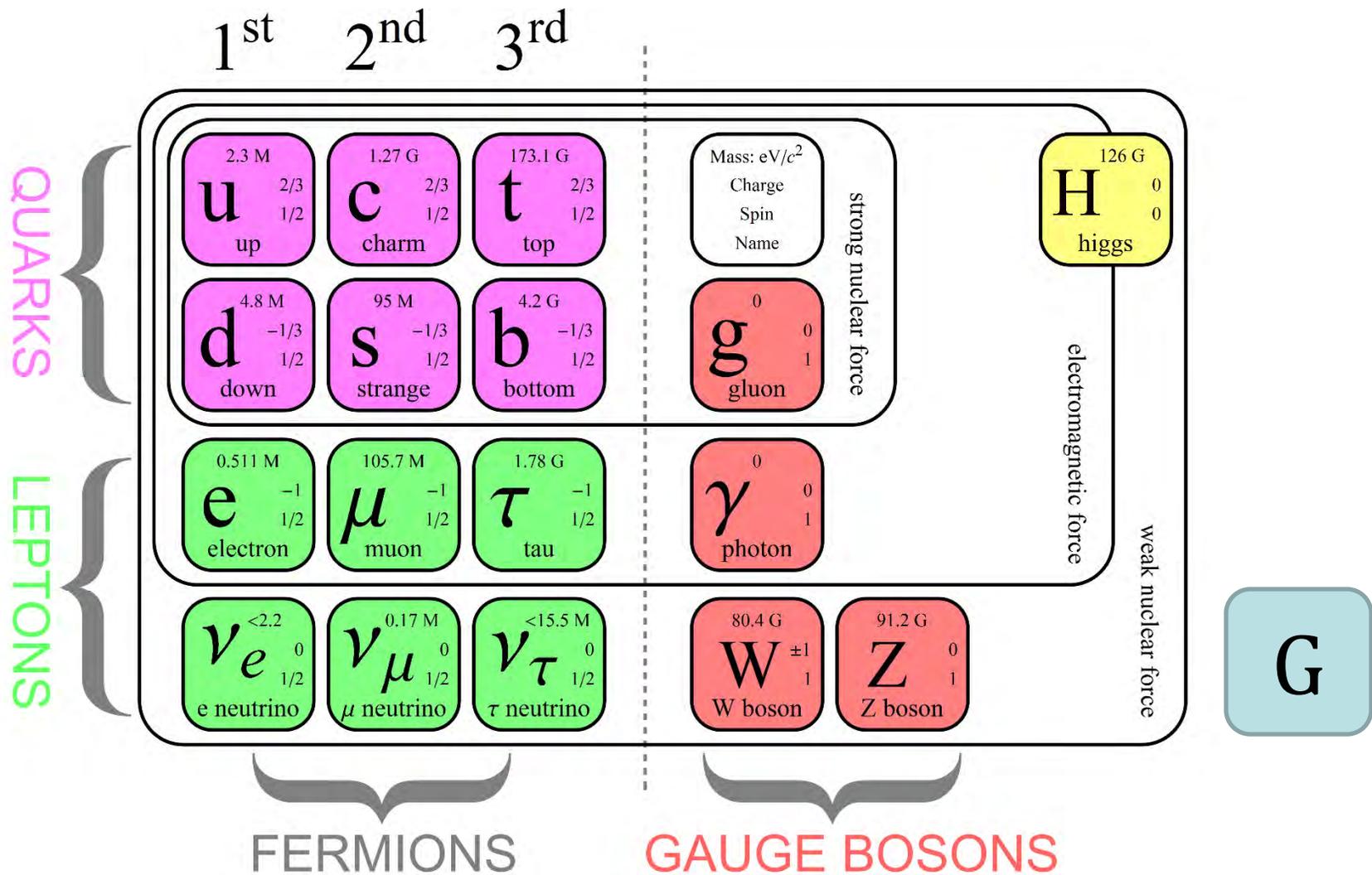
Nucleons (p , n) and other heavy 3-quark particles are called **Baryons**
 e , ν , and other particles with similar properties are called **Leptons**

Stability of the matter (at the level observed so far) can be explained as a conservation of the global quantum numbers called “*baryon charge*” and “*lepton charge*”.

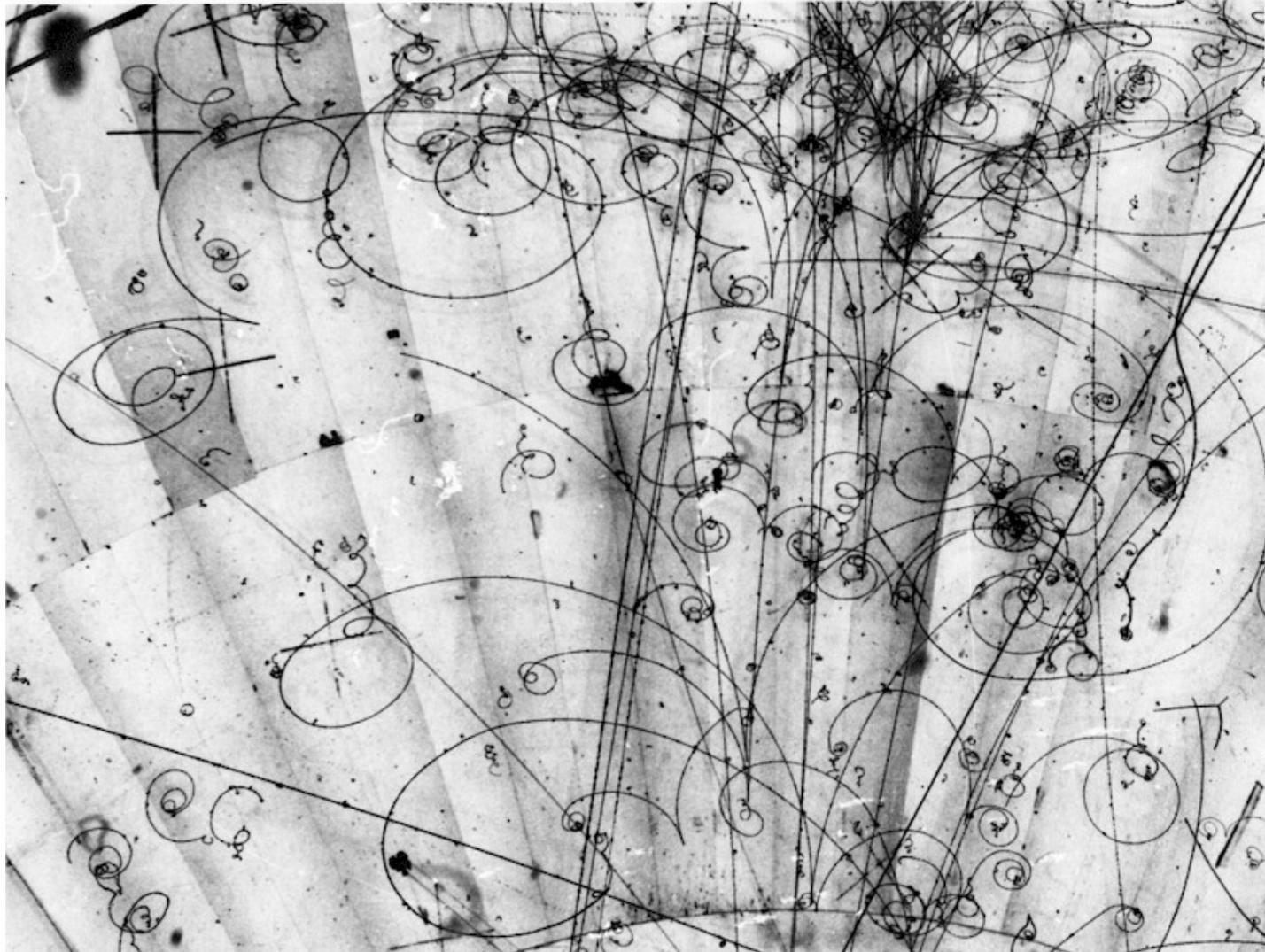
Matter and Antimatter



matter and anti-matter particles use the same forces for interactions



We have learned at accelerators that anti-matter and matter are always produced in equal amount



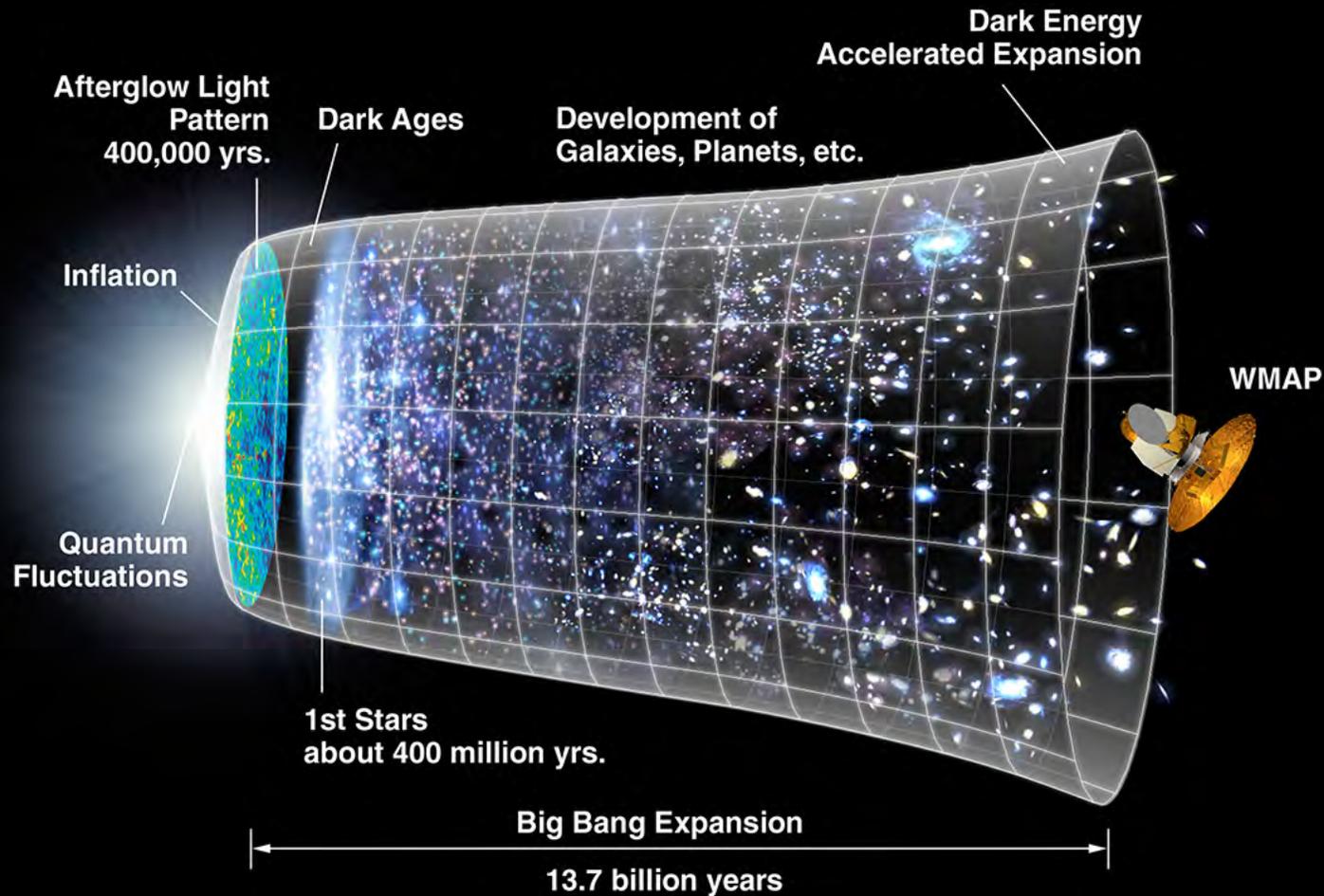
$$E.g. \ p + p \rightarrow p + p + p + \bar{p}$$

$$e^- + e^+ \rightarrow q + \bar{q}$$

$$e^- + e^+ \rightarrow \mu^+ + \mu^-$$

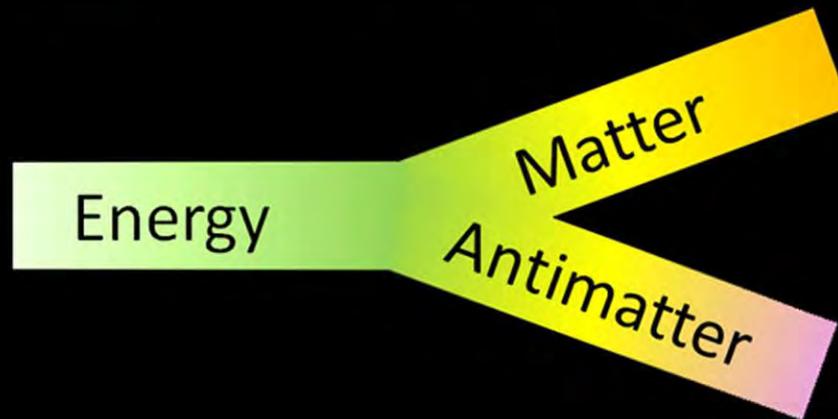
That is because “lepton number” and “baryon number” are conserved.

In the beginning was the... **Big Bang**



Big Bang is a broadly accepted and well justified theory of the origin and evolution of our Universe. The theory says that the observable universe started roughly 13.7 billion years ago from a singular point as a neutral state and underwent an extremely fast exponential expansion called "***inflation***". Initial state of the Universe was extremely dense and incredibly hot. Since then the Universe is cooling down.

$$E=mc^2$$



At Big Bang Matter and Anti-matter were produced in equal amounts.

Then our question should be
where is anti-matter in the universe?
It should be present in equal amount.

Why we were not annihilated out?



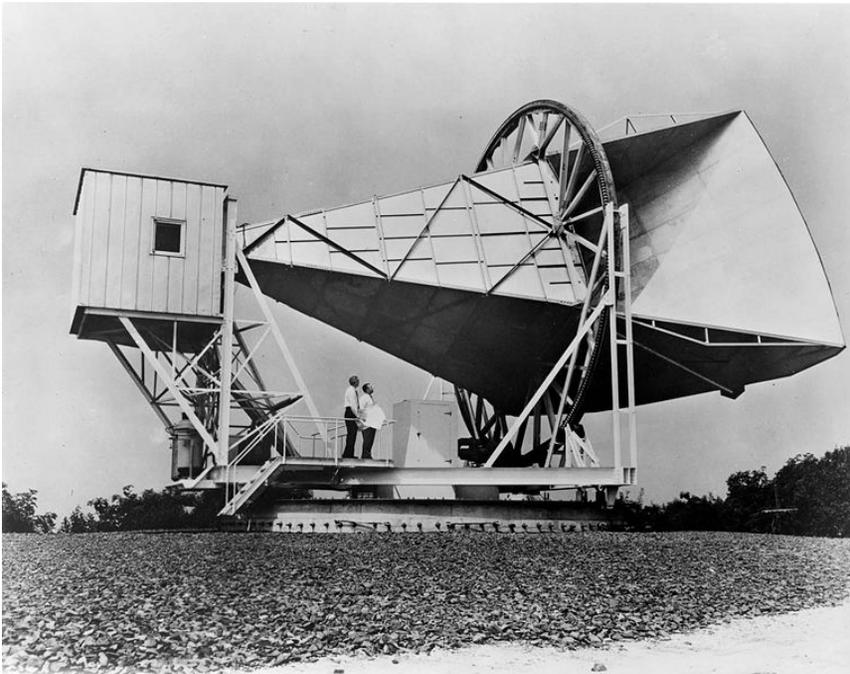
Matter-Antimatter Asymmetry

(Baryon Asymmetry of Universe)

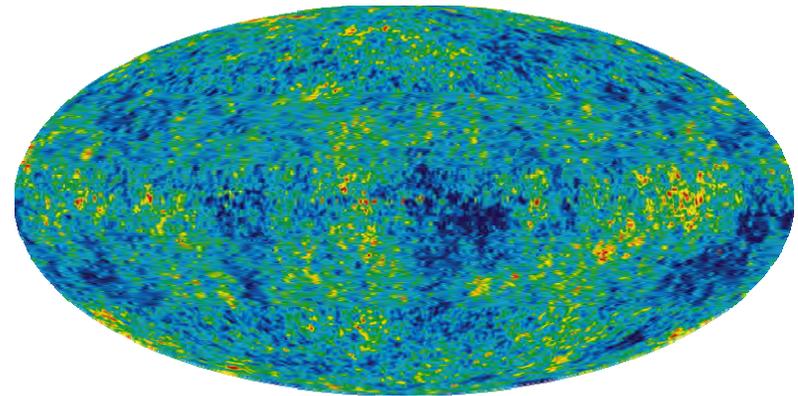
- No antimatter in the Solar system (direct probes)
- In cosmic rays measurements on Earth the Antimatter/Matter $\sim 1/10,000$, i.e. consistent with antiparticles production by high-energy matter particles in the Earth atmosphere.
- No significant amount of antimatter in the range of visible Universe (from spectrum of microwave background radiation)
- Signals for small amount of antimatter in our Galaxy are seen by AMS, Integral, Pamela
- Visible part of universe is made of Matter.

How do we know that there was an Antimatter in Big Bang?

Cosmic Microwave Background Radiation (Relic Radiation) discovered in 1964 by A. Penzias and R. Wilson



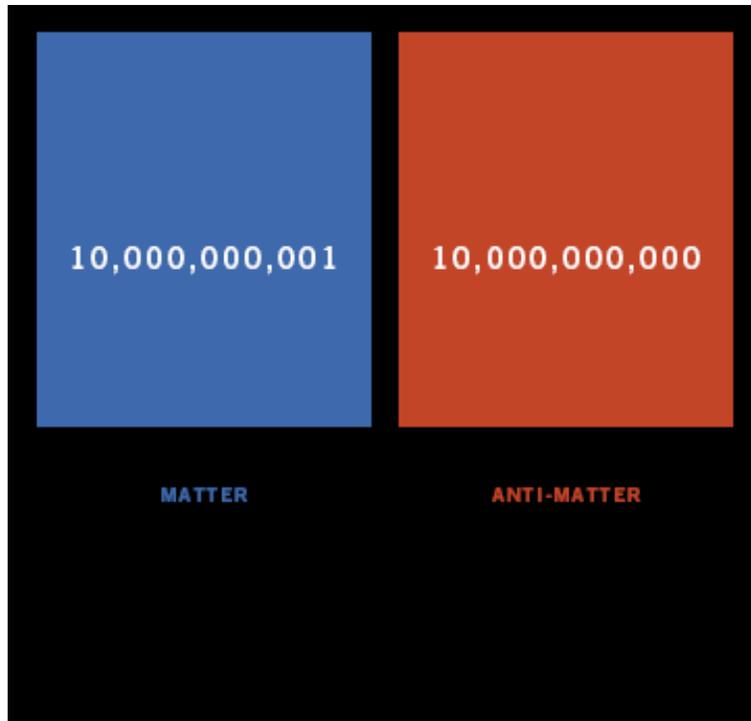
Radiation with $T=2.725\text{ K}$
and density of $\sim 400\ \gamma$ per cc



WMAP CMBR temperature anisotropy.

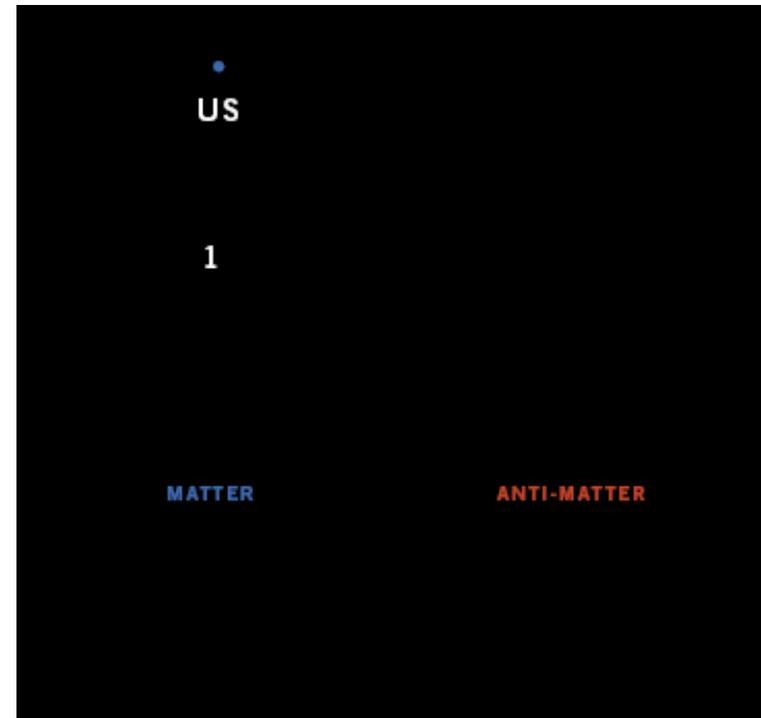
CMBR provides an evidence for massive annihilation in Early Universe

Early Universe



Equal amount of matter and antimatter followed by massive annihilation.

Present Universe



Only matter. No antimatter!

Generating a Matter-Antimatter Asymmetry

A. D. Sakharov, JETP Lett. 5, 24 (1967).

1. Very early in the Big Bang ($t < 10^{-30}$ s), matter and antimatter were in thermal equilibrium. There was exact balance between matter and antimatter and matter \leftrightarrow antimatter transitions took place.
2. At some point, there was a symmetry breaking process that led to a small imbalance between the number of Baryons and Anti-baryons...i.e. a few more Baryons.
3. When the Universe cooled down, all the Anti-baryons annihilated leaving a few Baryons and lots of high-energy annihilation photons.
4. The photons are still around! They have been highly red shifted by subsequent expansion and are present now as the Cosmic Microwave Background.



In this scenario, the total “apparent” matter-antimatter asymmetry is given by the ratio of Baryons to CMB photons:

$$\frac{n_{Baryon}}{n_{\gamma}} = 10^{-10} \quad \text{and} \quad \frac{n_{Antibaryon}}{n_{Baryon}} = 0$$

As formulated by A. Sakharov, 3 conditions are needed for explanation of Matter-Antimatter asymmetry:

- (1) Violation of Baryon number (non-stability of matter)
e.g. observation $p \rightarrow e^+ + \gamma$ or $n \rightarrow \bar{n}$
- (2) Violation of Time Invariance (or CP-invariance)
i.e. rate of $M \rightarrow A$ not equal $A \rightarrow M$
- (3) Departure from thermal equilibrium