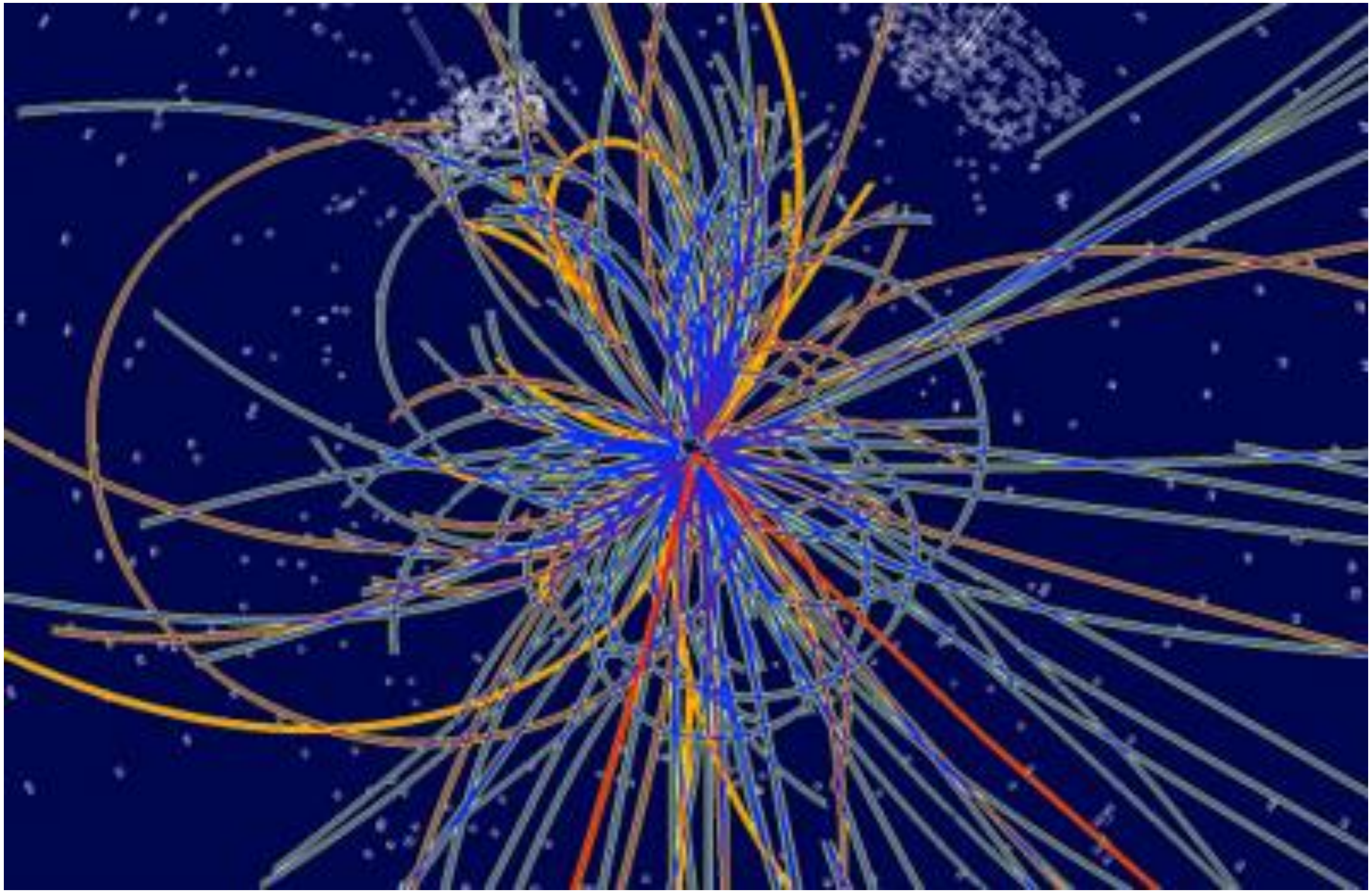
Final Exam

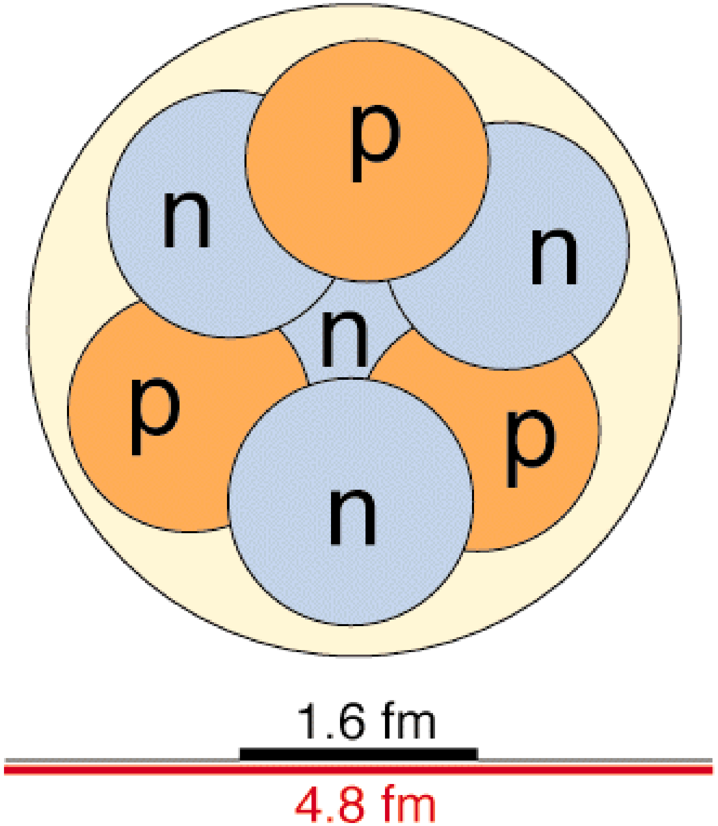
- Exam is on May 10, 12:00 – 3:00 PM.
- Physics Lecture Hall.
- Exam is "closed book".
- Please bring a laptop with webcam. (ipad should work but computer is recommended.)
- (If no webcam, we can work around it.)
- Bring photo ID.
- Make sure you have Lockdown Browser installed.
- Before the exam: Go to Assignments/Exam and do the "Lockdown Browser Practice" quiz to check your setup.
- Good Luck!!

Elementary Particle Physics



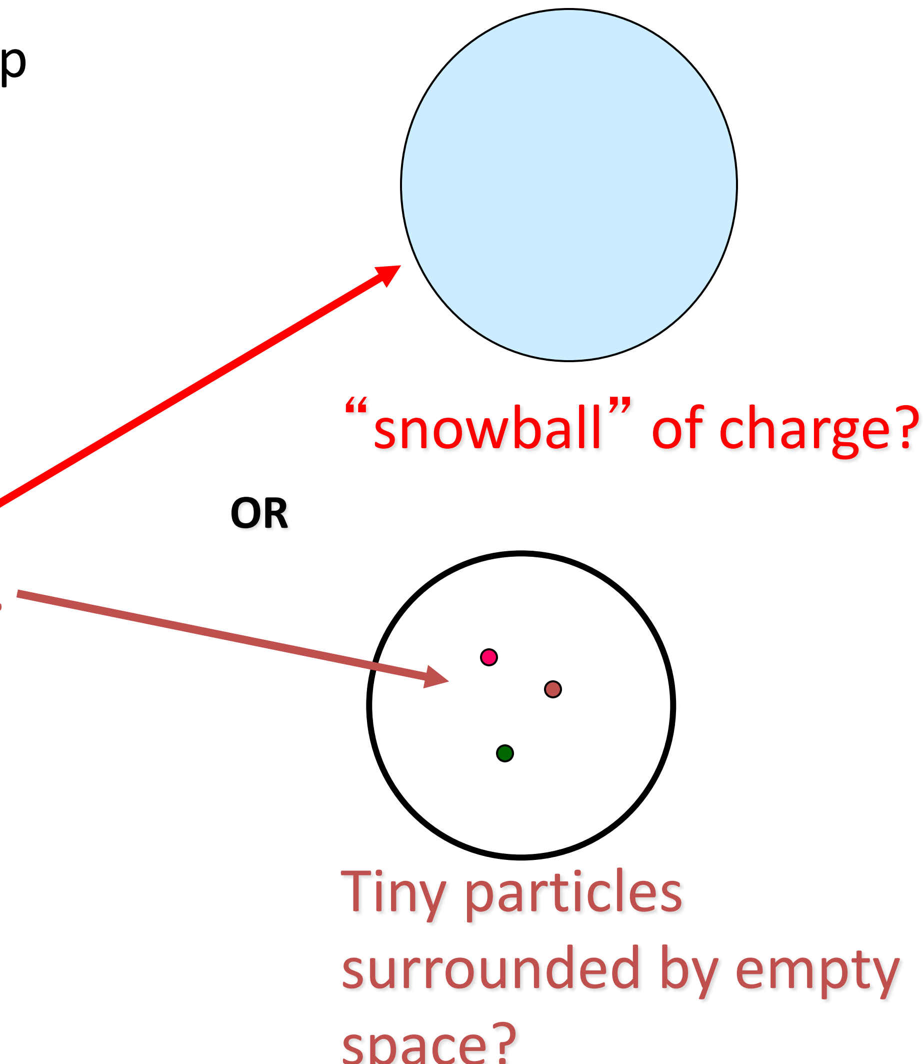
The Nucleus

- The nucleus is very small: 1fm = 10^{-15} m!
- What keeps the protons from flying apart?
  - **The STRONG force.**
- Some combinations of neutrons+protons are happy (*stable*)…but some are not (*unstable*).
  - Radioactivity! α, β, γ decays.
- Some disintegrations of unstable nuclei can cause their unstable neighbors to disintegrate.
  - Fission, **chain reaction**.



What's Inside a Proton or Neutron?

- Protons, neutrons making up the nucleus with orbiting electrons completed the atom.
  - *But are these particles the final layer of matter?*
- Two competing theories:
  - **Proton is fundamental.**
  - **Constituents within proton.**
- Electron is fundamental as far as we know.



Why is this hard to answer?

- Rutherford: looked inside atom.
  - Needed energy equivalent to an electron **~10 million volts**.
  - He saw nucleus.

  Less than 10^{-8} m, or 0.0000004 inches.

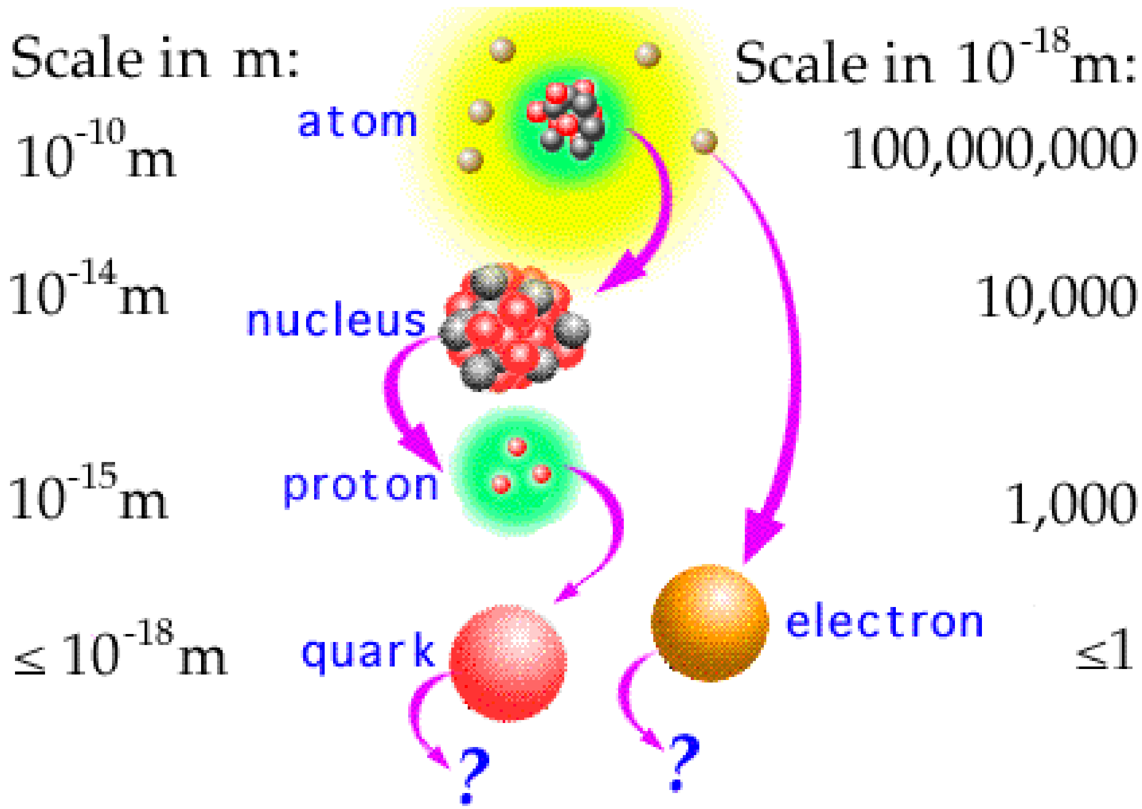
- Kendall, Friedman, Taylor: looked inside proton.
  - Energy needed was ~**10 billion volts.**

  Less than 10^{-15} m, or 0.00000000000004 inches.

- By contrast:
  - A TV accelerates electrons by ~10 volts.
  - X-ray tubes by ~1000 volts.

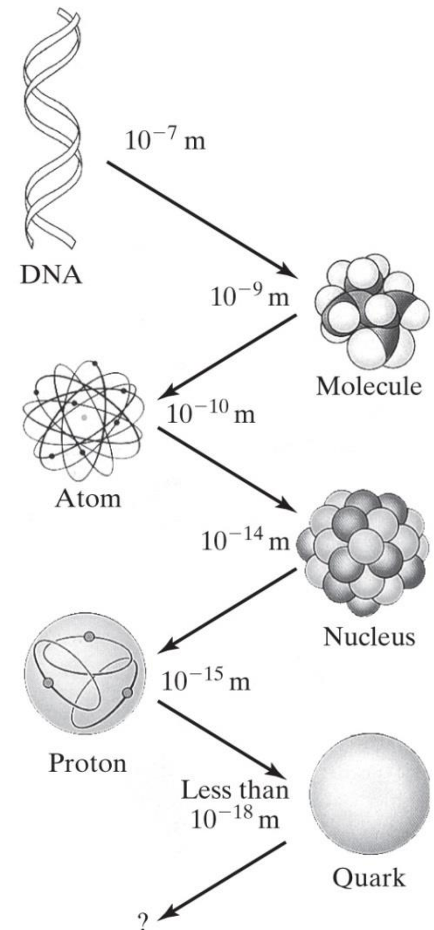
Visible light microscope limit is ~0.0001 inches

Are protons and neutrons the smallest bits of matter?



Scattering to find Structure of Matter

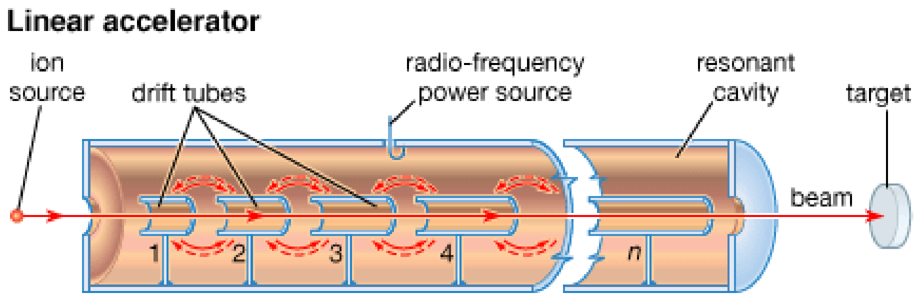
- To look at smaller things, go to higher energy projectiles. Need accelerators.
    - Atom is 1/ (10 billion) meters. Need hard x-rays.
    - Nucleus is 1/ (100,000 billion) meters. Need gamma rays.
    - Proton, neutron is 1/ (1 million-billion) meters. Need cyclotrons.
    - Quarks are pointlike (as far as we know). Need massive, huge, mile long accelerators.



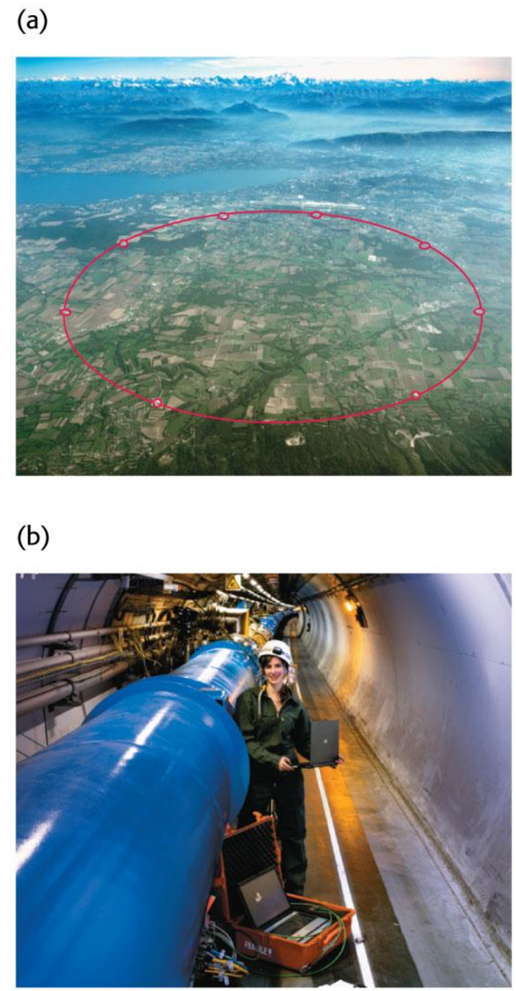
Accelerators

Elementary particles are studied by slamming high-energy particles into other particles.

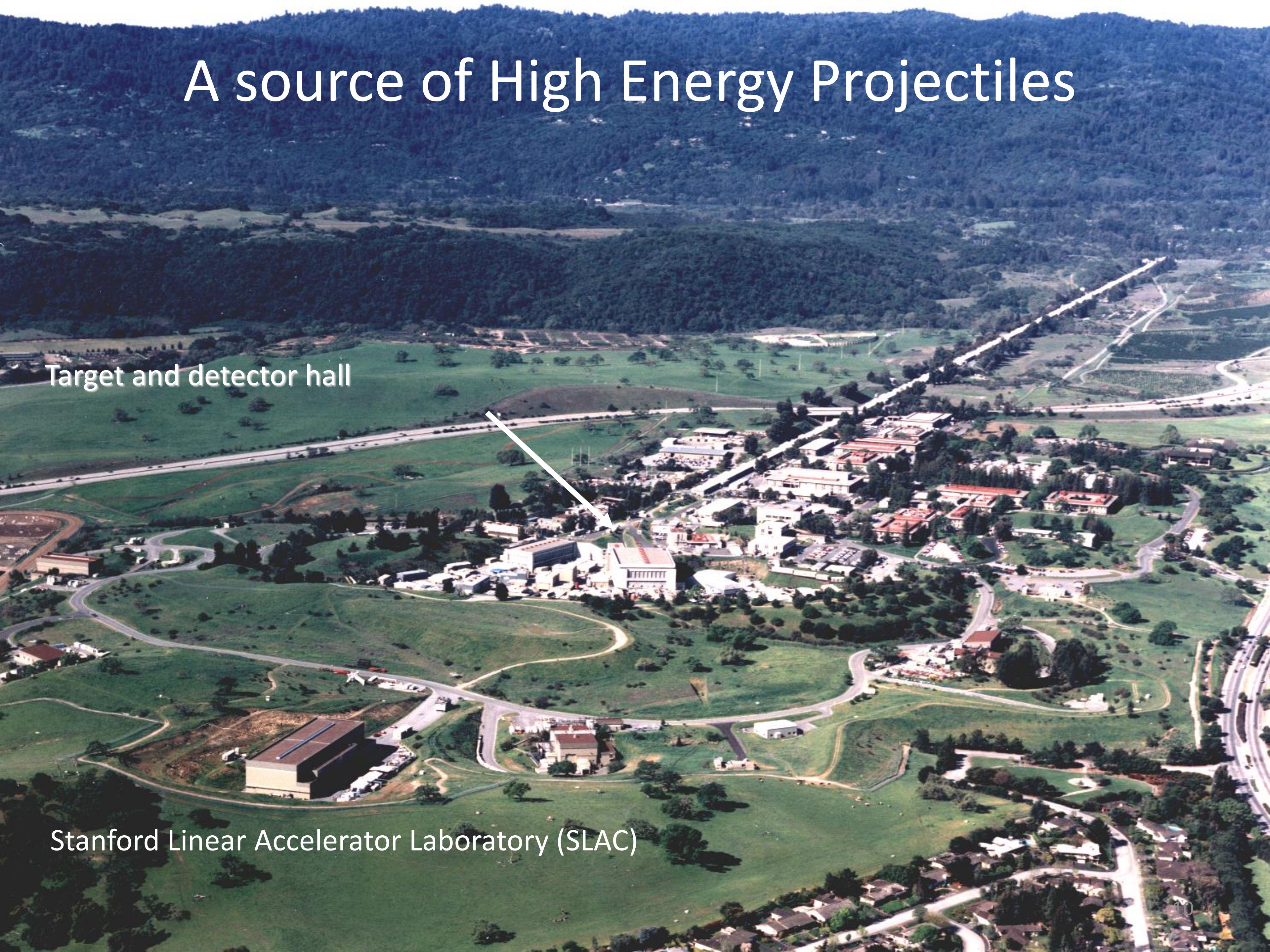
High-energy particles are produced in particle accelerators.



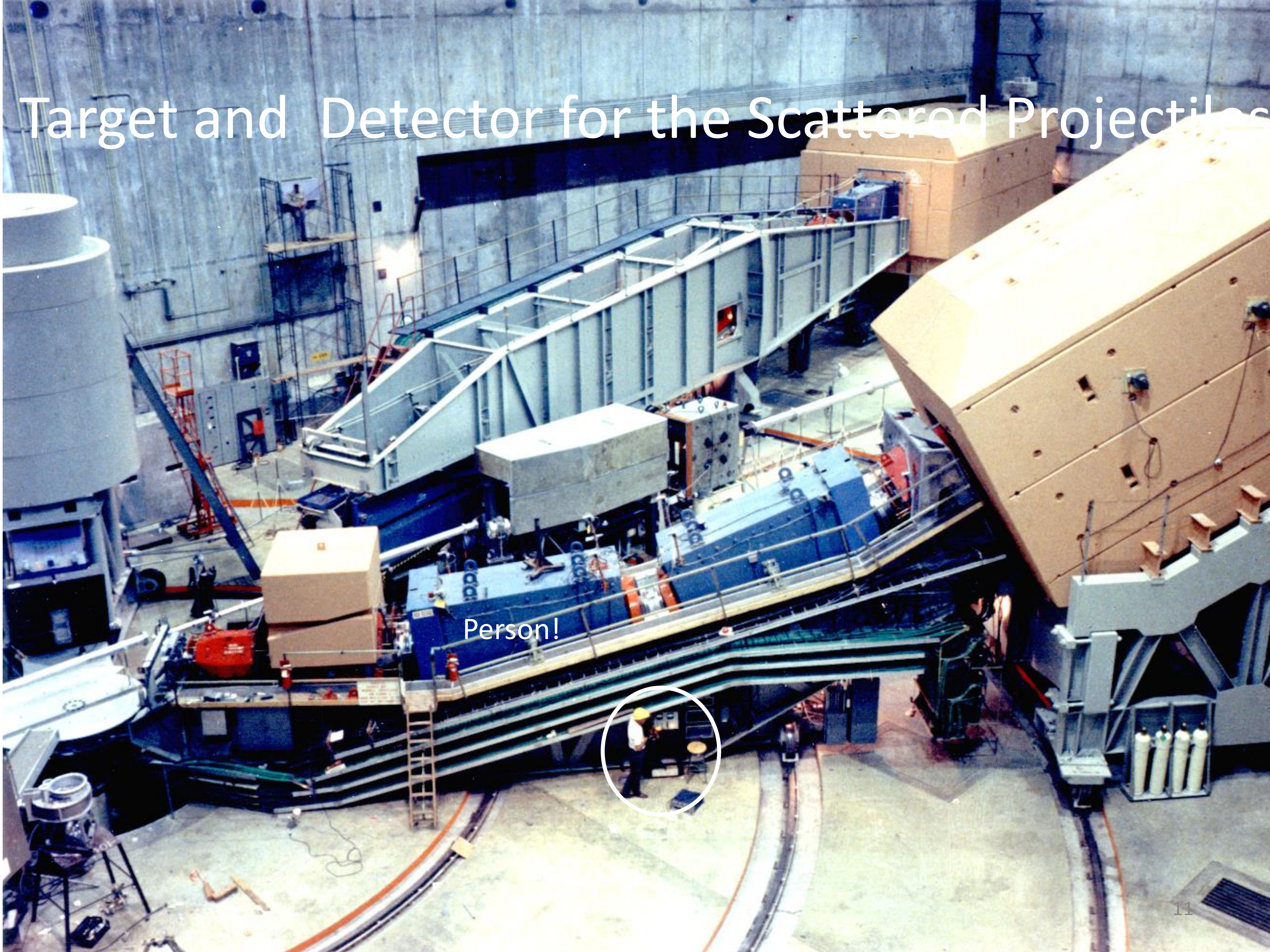
Synchrotron: Large Hadron Collider at CERN accelerates protons to 7 TeV (7 million MeV). Circumference: 17 miles!



A source of High Energy Projectiles



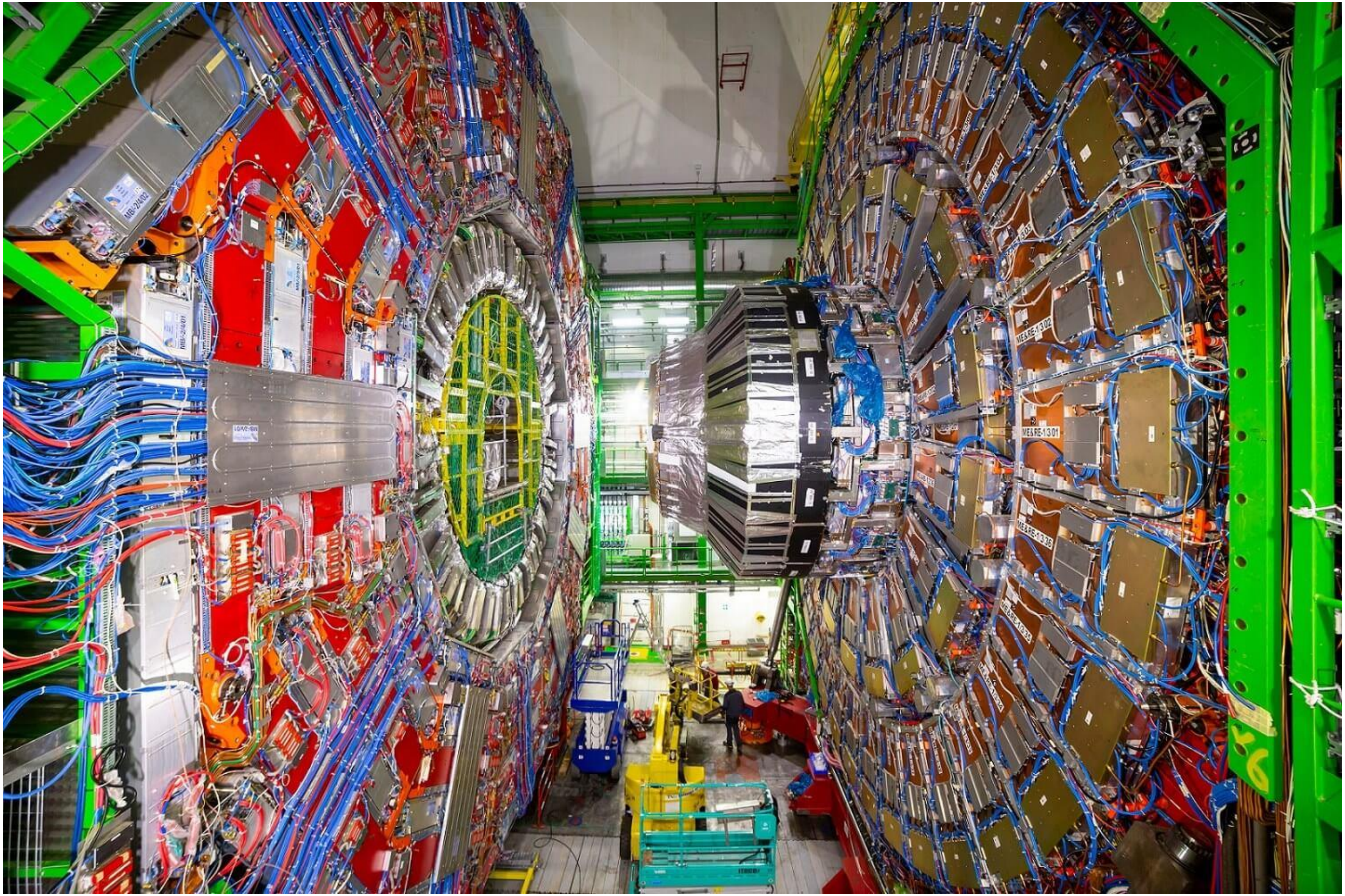
Target and Detector for the Scattered Projectiles



Large Hadron Collider

Large Hadron Collider

Large Hadron Collider



Clicker

Alpha particles are held together by:

A. The strong nuclear force.
B. The weak nuclear force.
C. The electrostatic force.
D. Magnetic forces.
E. Gravitational forces.

Clicker

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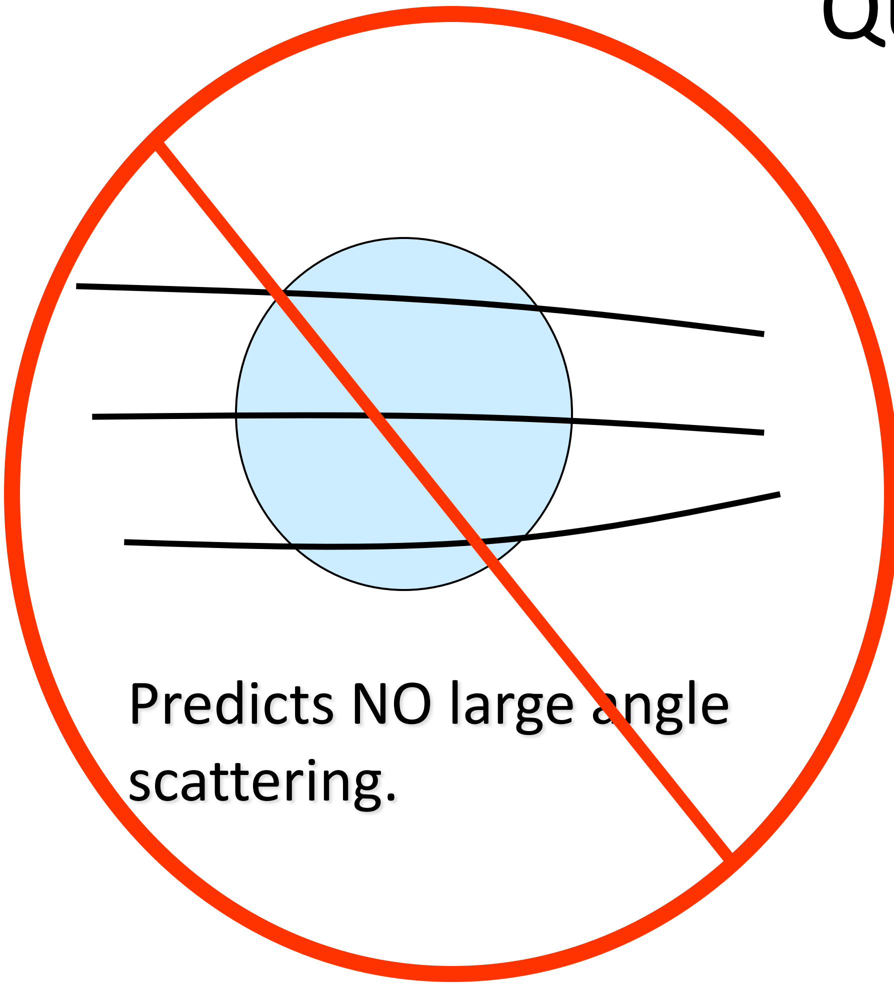
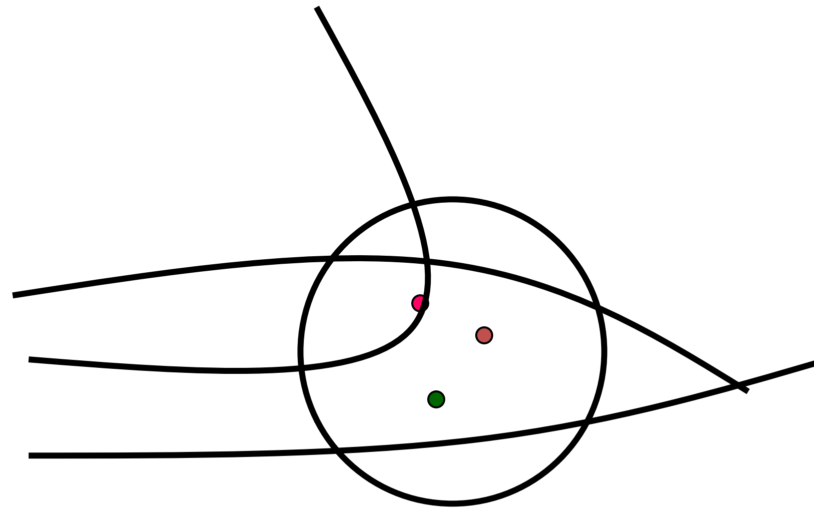
Quarks!

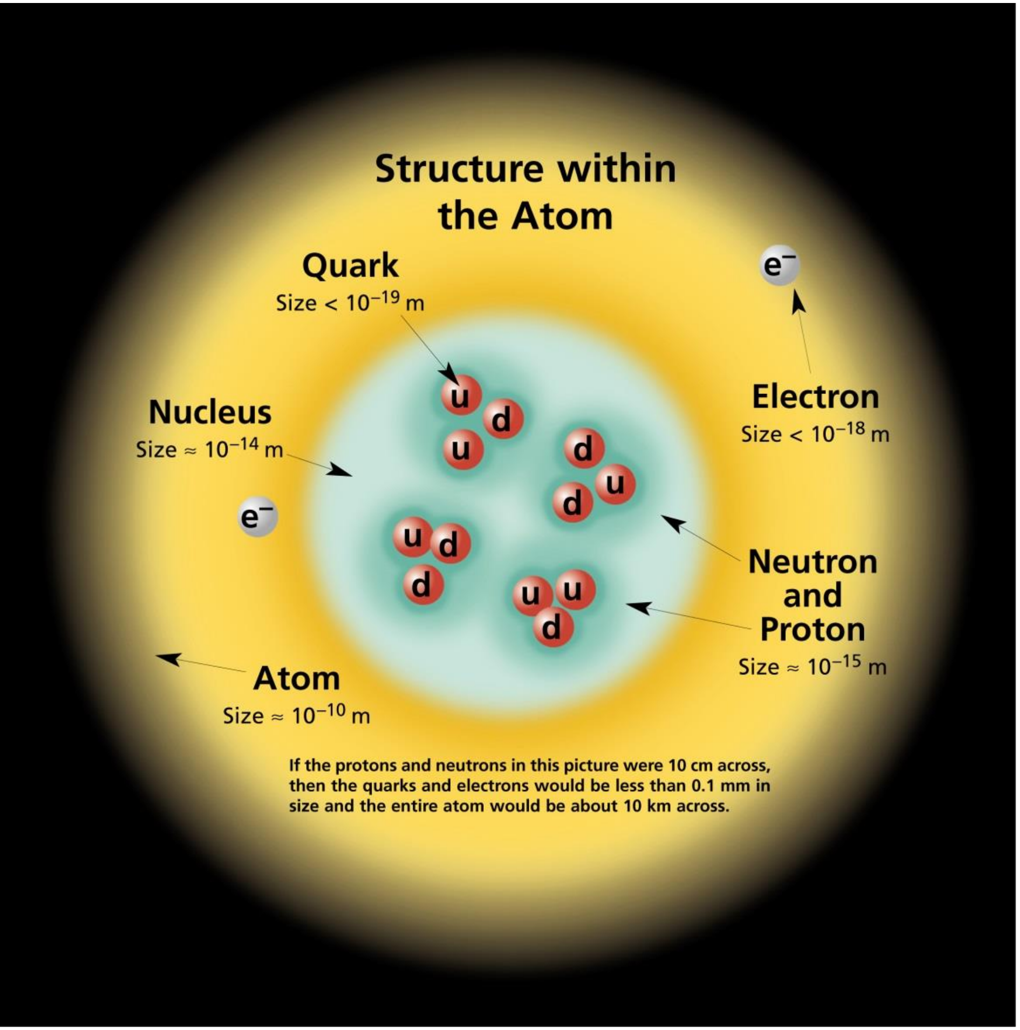


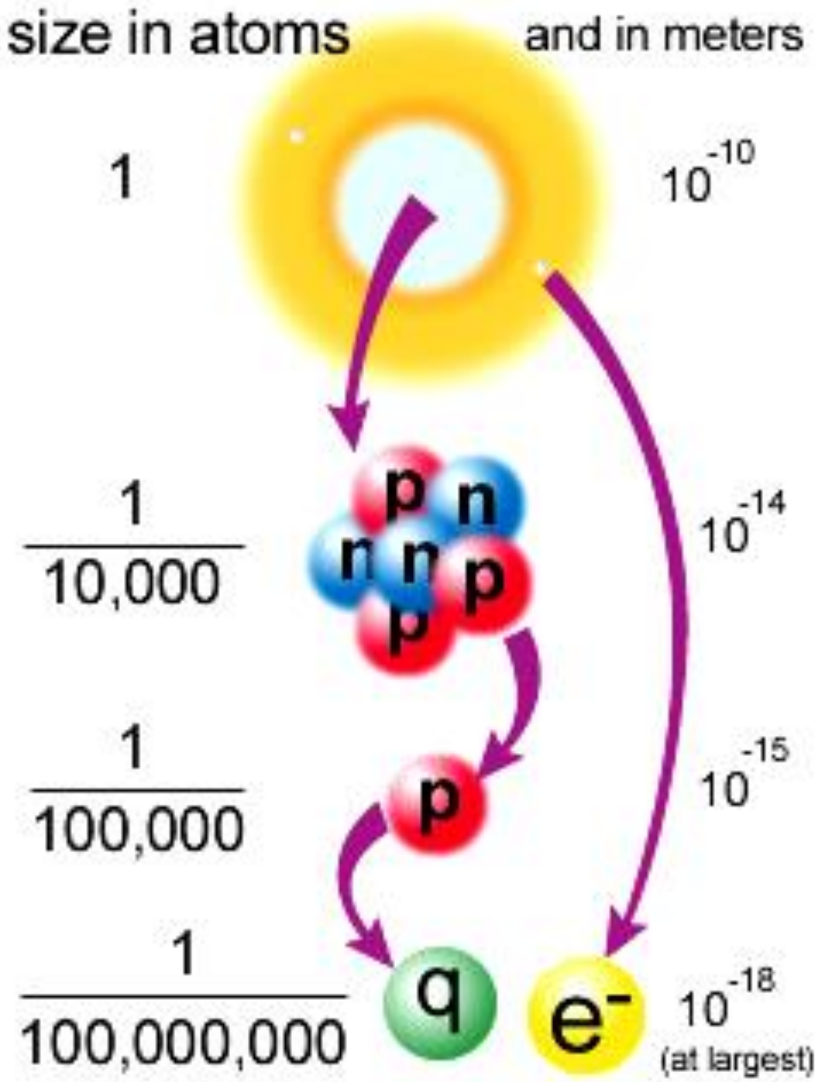


Large angle scattering can happen:

Protons and neutrons consist of ultra-small constituents!

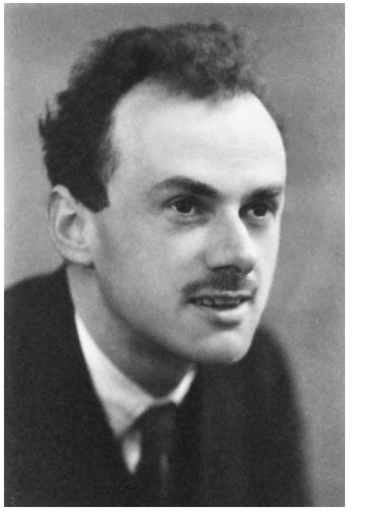
Structure of Matter





Antimatter

- Predicted in 1928 by Paul Dirac.
- Positron discovered in 1932 by Carl Anderson.
- Positron is an electron with positive charge.
- Positron and electron can annihilate each other in a flash of energy (gamma rays).

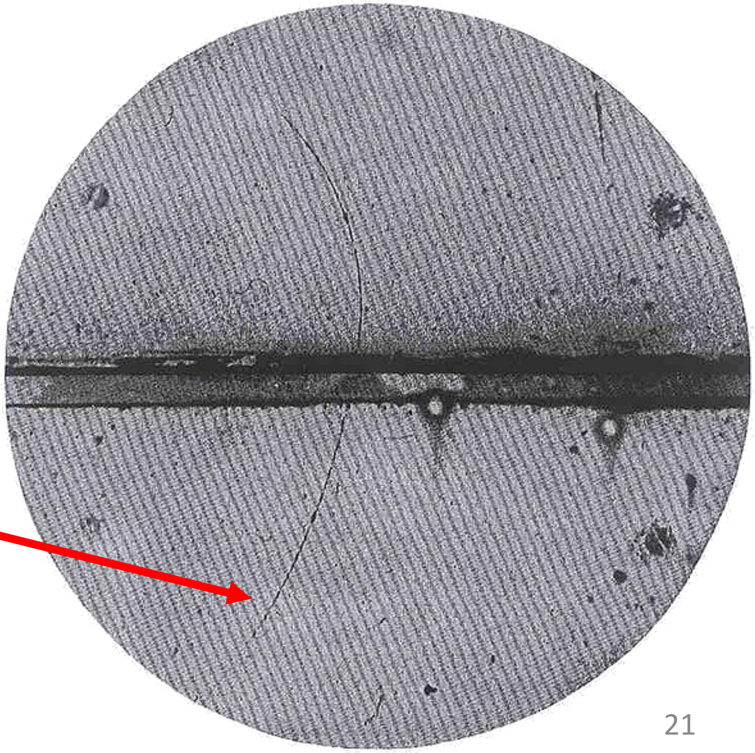


Positrons

- Discovered in nuclear decays (beta +)
- Also in cosmic rays

  – Exactly the same mass as e^-
  – But positively charged !
  – Call it "e^+" or "positron"

Track curves "wrong way" in magnetic field



Carl Anderson

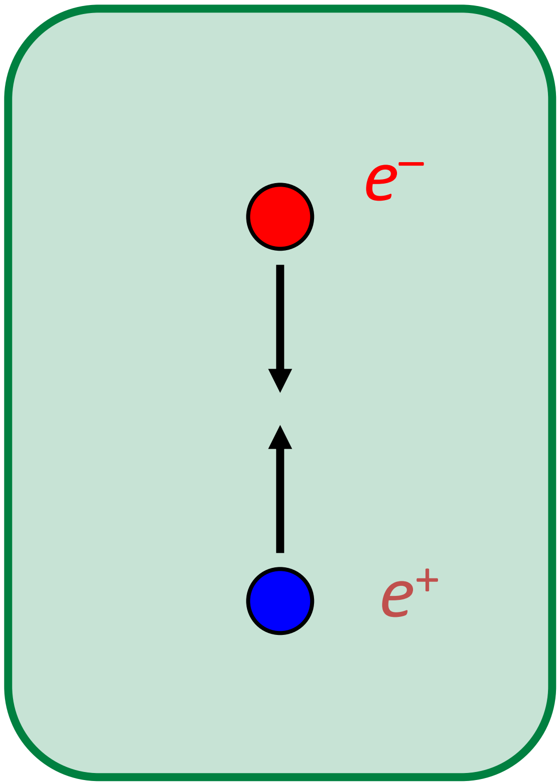
Antiparticles

Every matter particle has an antiparticle:

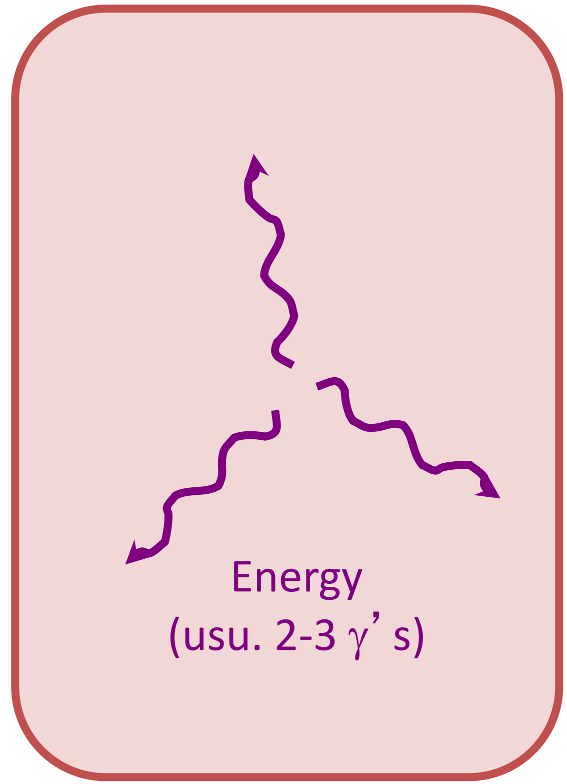
- electron (e^-) and positron (e^+)
- proton (p) and antiproton ($\bar{p}$)
- neutron (n) and antineutron ($\bar{n}$)
- neutrino (ν_e) and antineutrino ($\bar{\nu}_e$)
- etc.

Antiparticles can annihilate!

Before

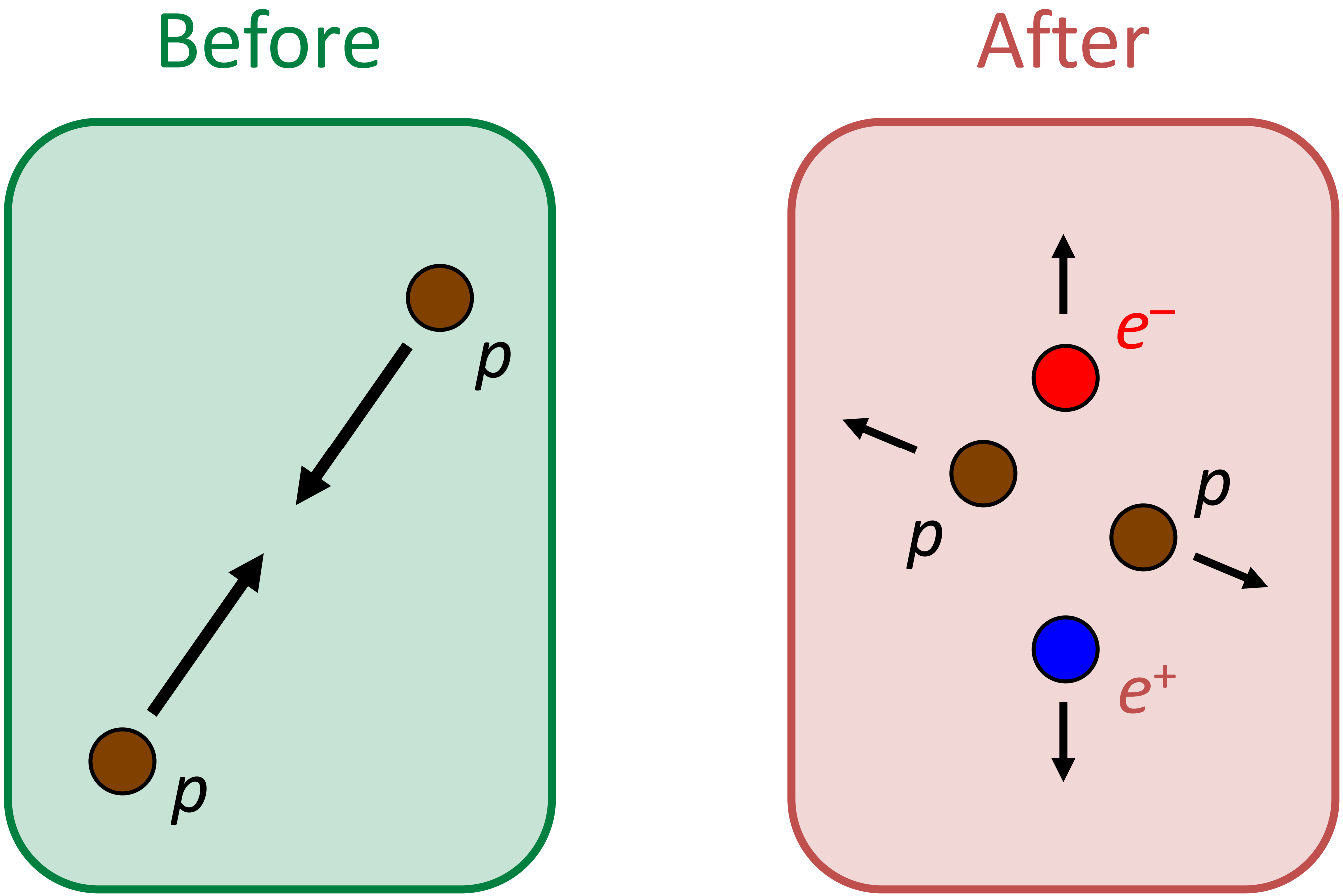


After

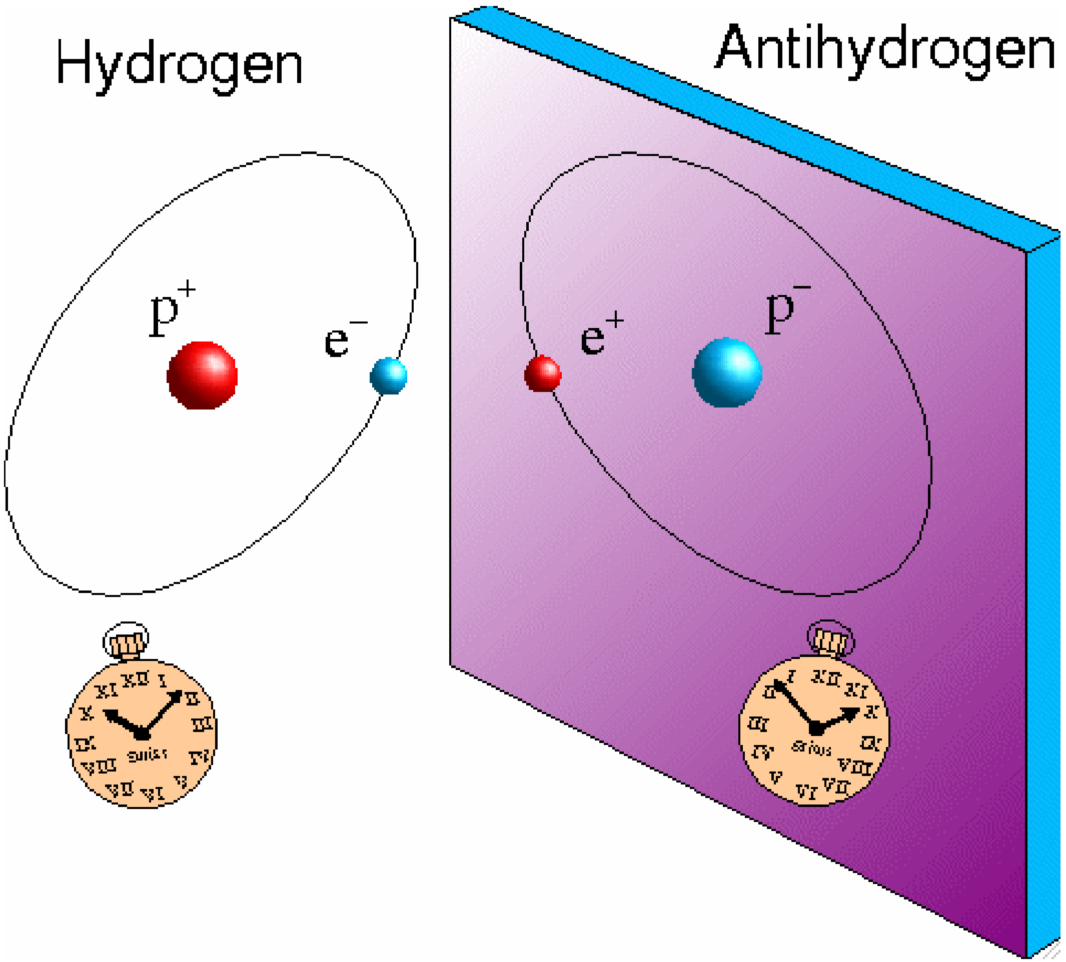


Energy released = $2m_e c^2$

Antiparticles can be created!



Antimatter



Are there antimatter stars and galaxies?
No.

Origin of matter

Big bang produced:

- 50.001% matter
- 49.999% antimatter

After annihilation, we were left with:

- 0.002% matter
- **No antimatter**

That small 0.002% is all that remains today

Origin of matter

Big bang produced:

- 50.001% matter
- 49.999% antimatter

After annihilation, we were left w

- 0.002% matter
- **No antim**

T s all that remains today

The origin of this matter-antimatter discrepancy is one of the biggest mysteries in physics today

Clicker

An antiproton has

A) Positive charge and positive mass.

B) Positive charge and negative mass.

C) Negative charge and positive mass.

D) Negative charge and negative mass.

E) Zero charge and zero mass.

Clicker

An antiproton has

A) Positive charge and positive mass.

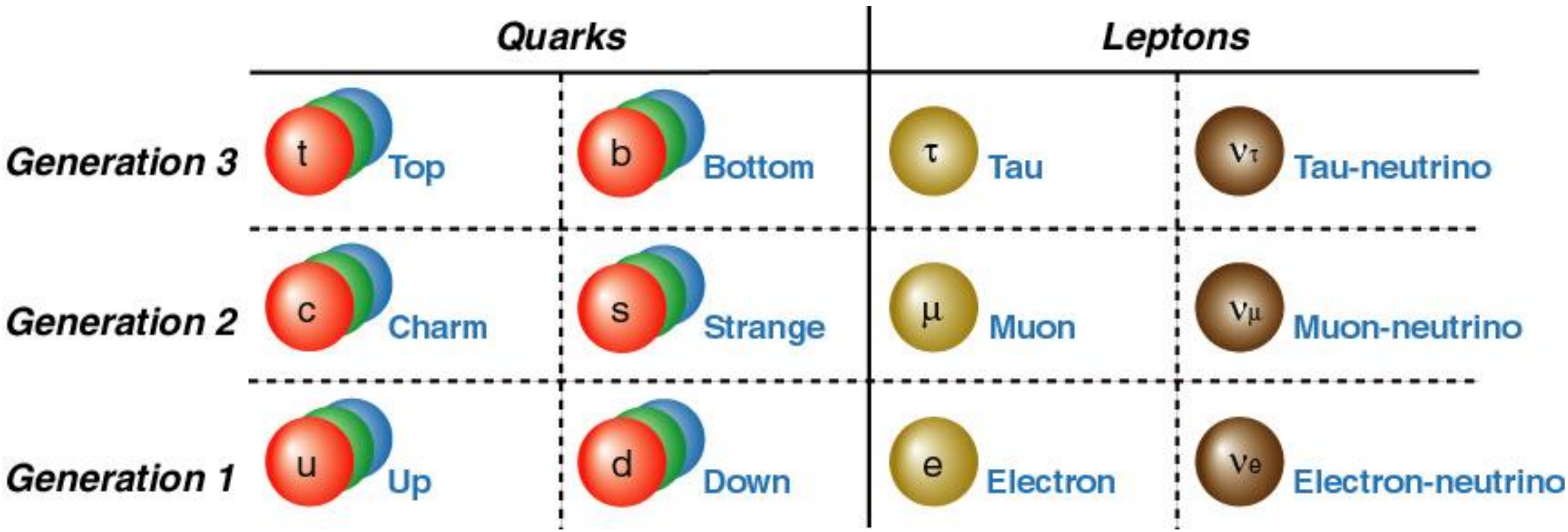
B) Positive charge and negative mass.

C) Negative charge and positive mass.

D) Negative charge and negative mass.

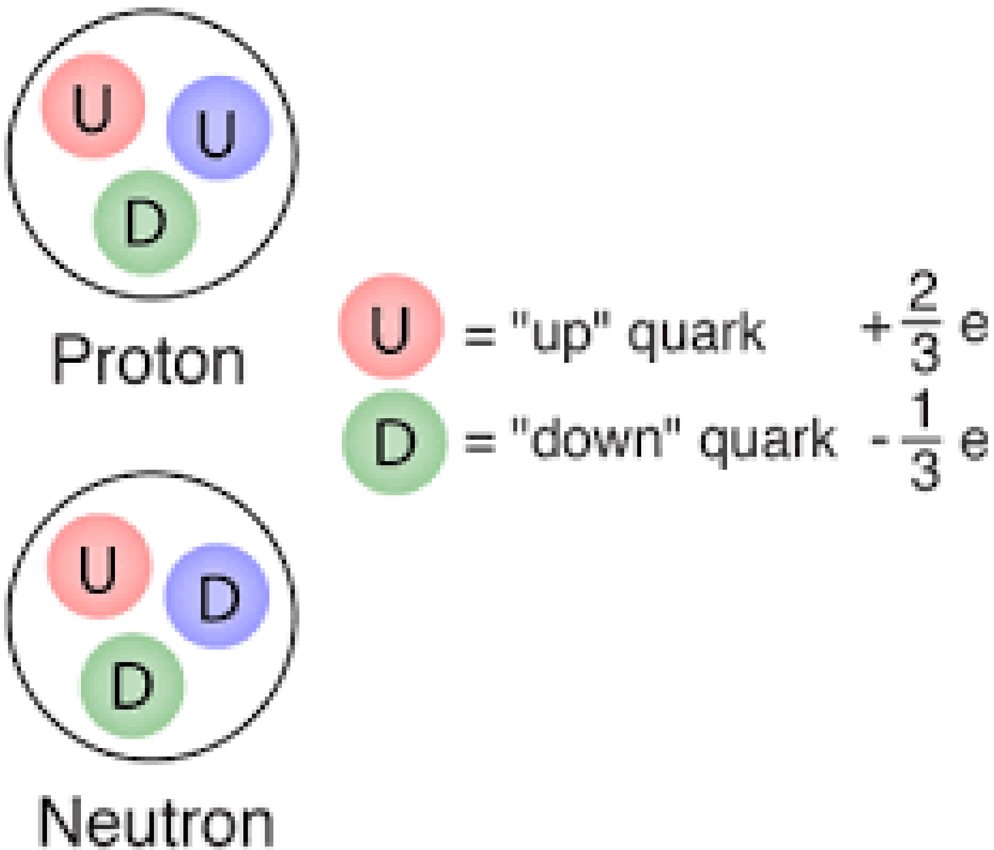
E) Zero charge and zero mass.

Standard model: Matter particles



plus antiparticles of all of these…

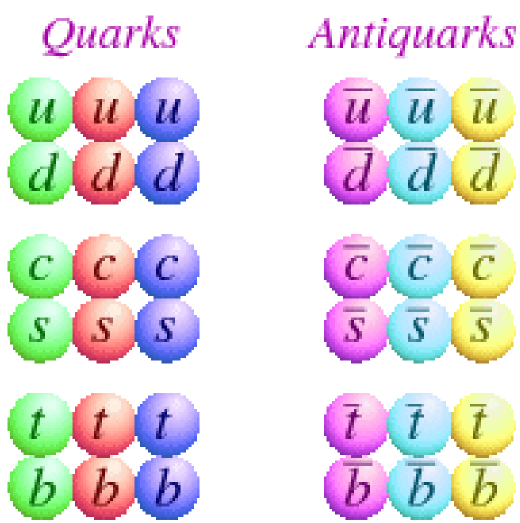
Nucleons Made of Quarks

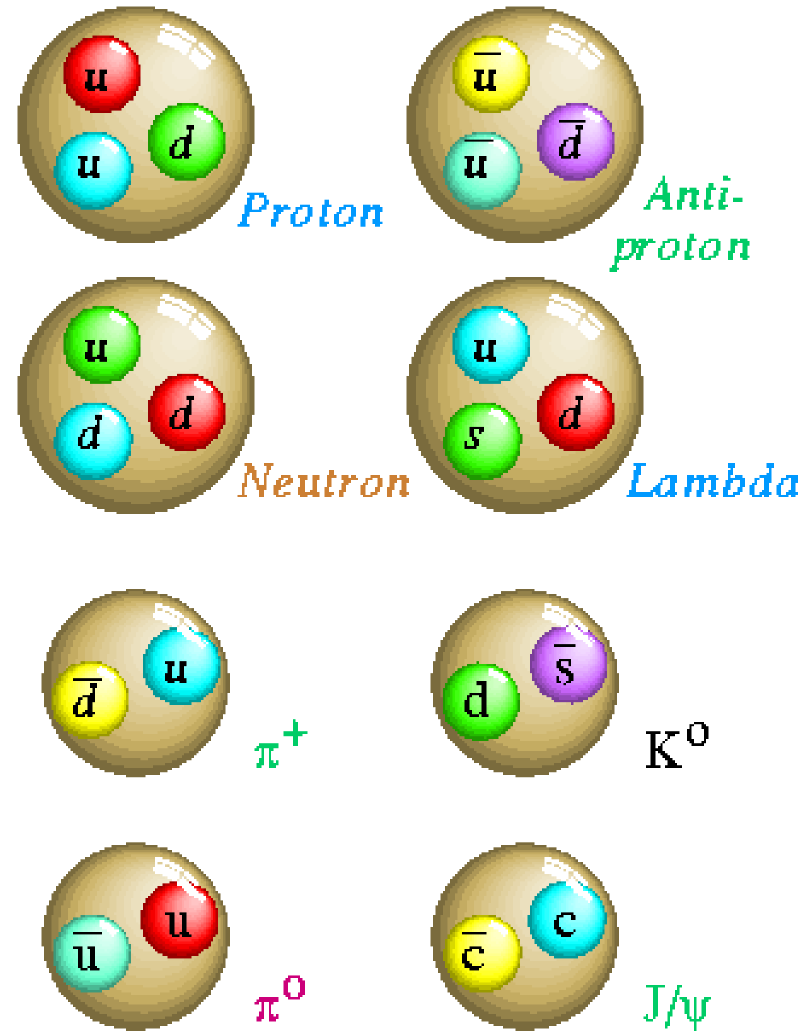


Hadrons are Made of Quarks

These are particles that act through the strong force. → Made up of quarks

Baryons: 3 quarks (or anti-quarks)

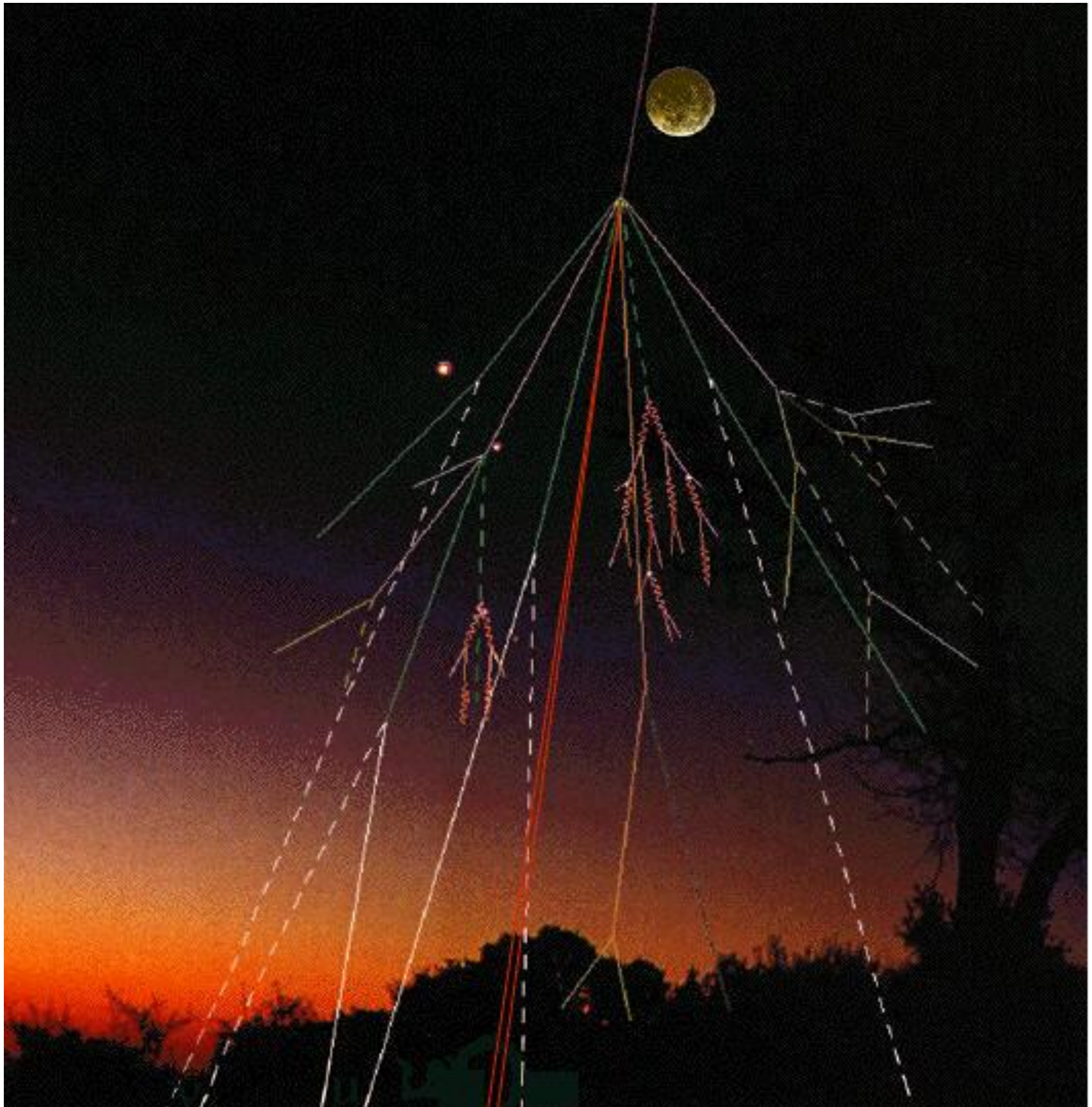


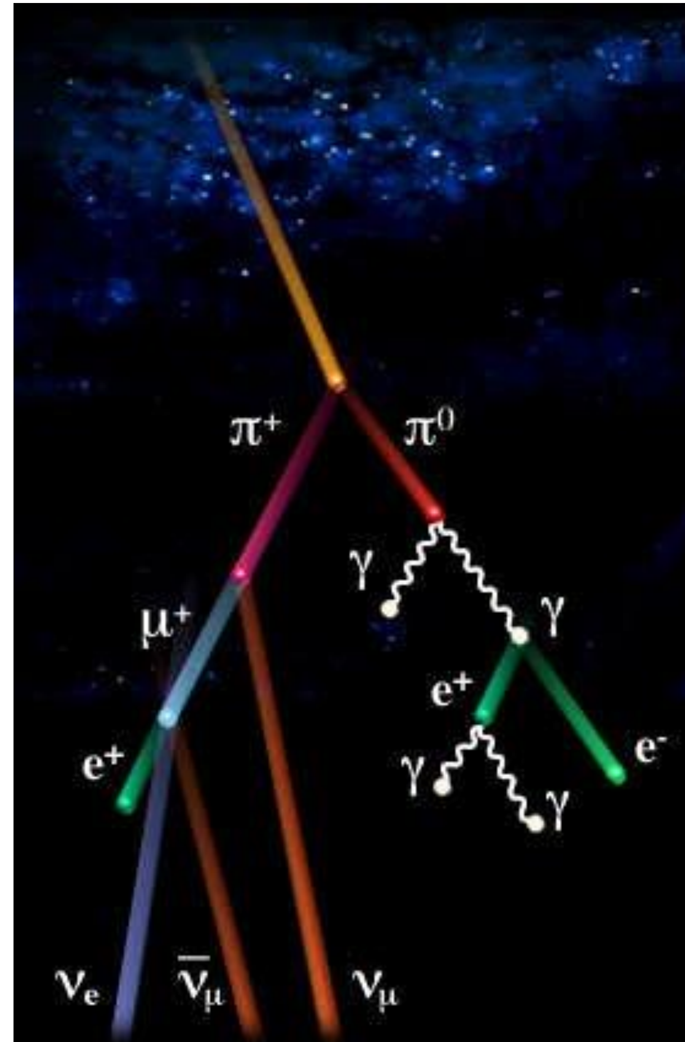


Mesons: quark + anti-quark

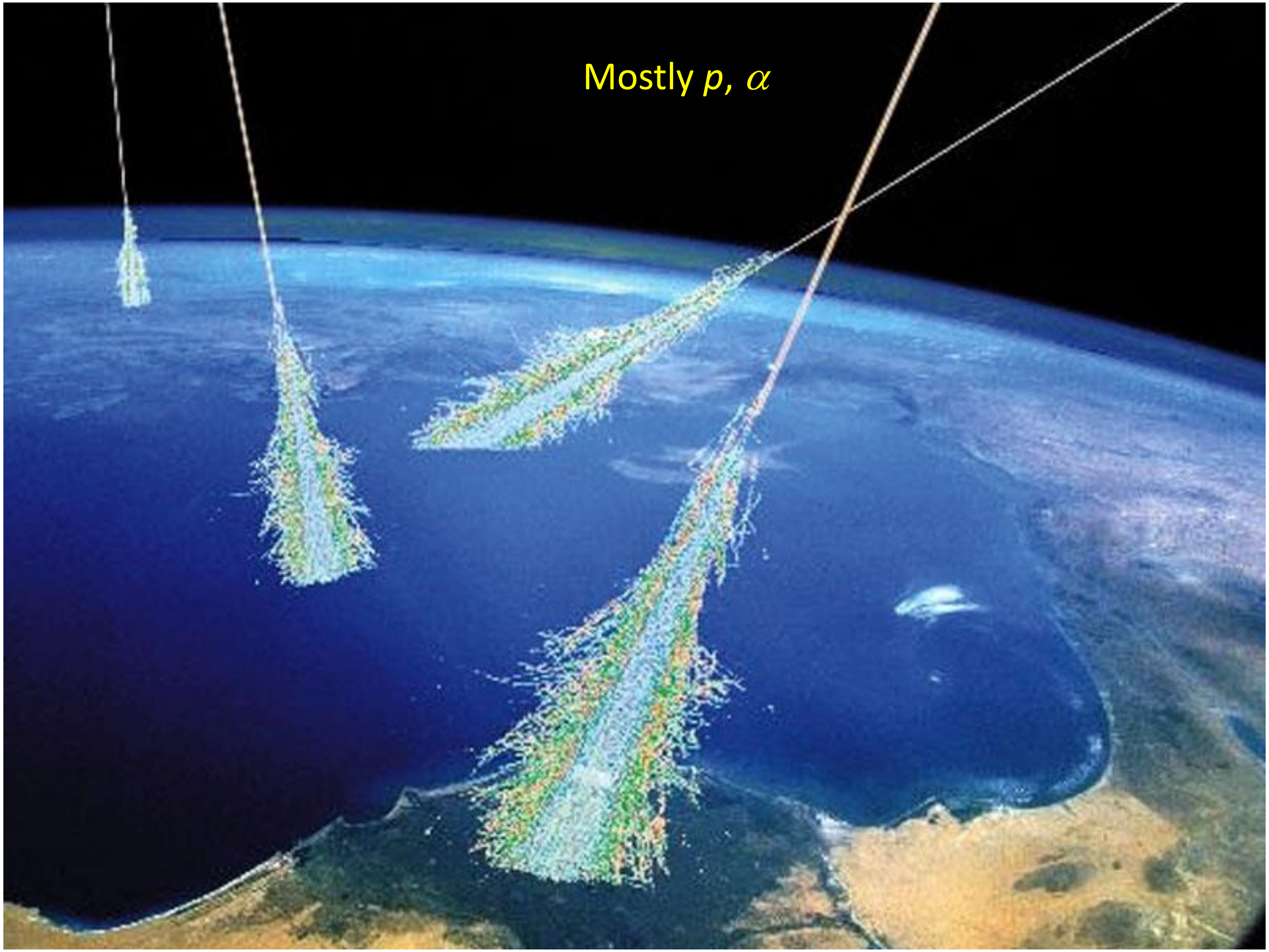
Except for the proton/antiproton, all of these are unstable (decay). Even the neutron!

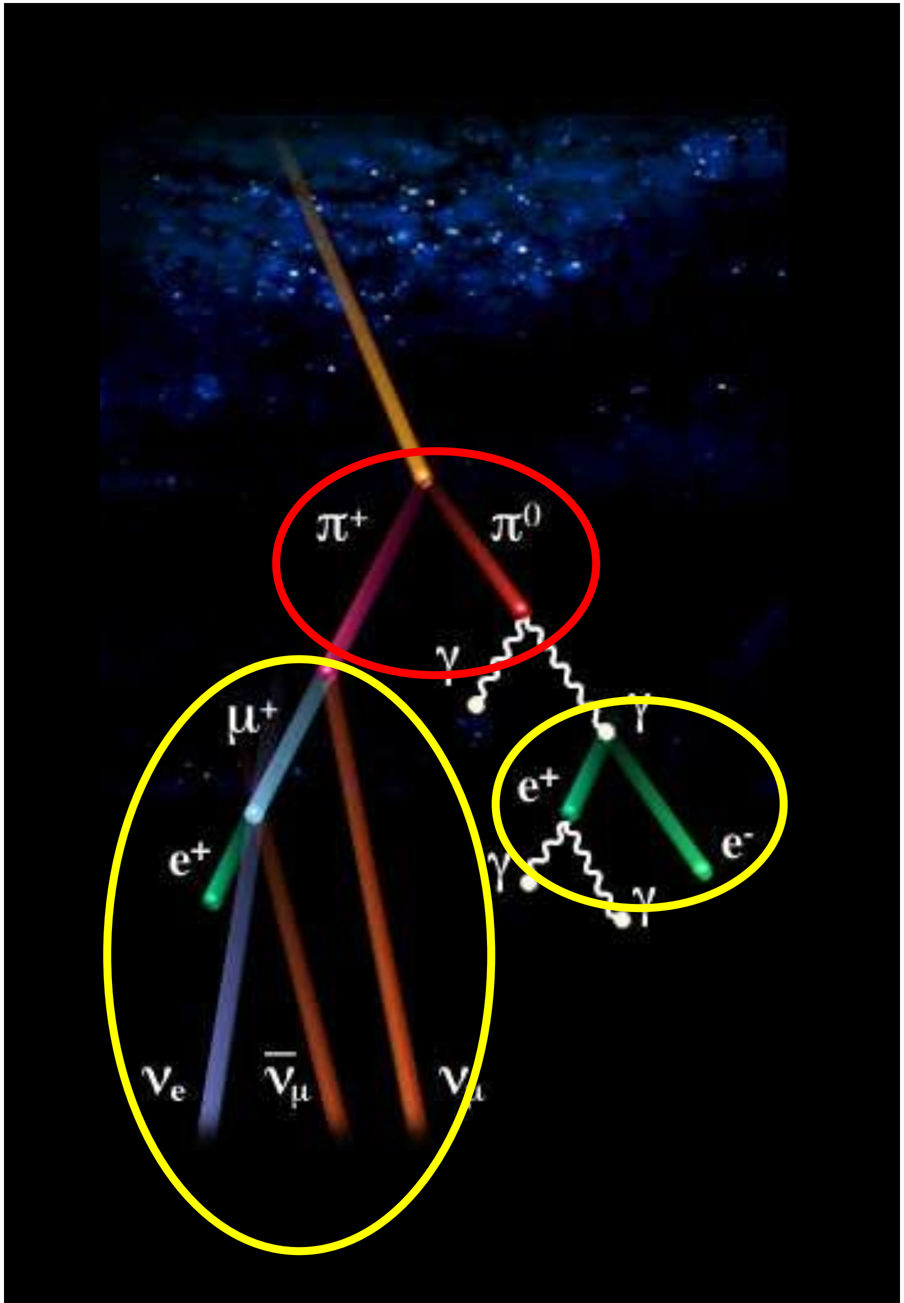
Cosmic Rays





Cosmic Rays





Hadrons

π^0, π^+, π^-, n, $\overline{n}$, p, $\overline{p}$, …

Leptons/Anti-leptons			
e^- Electron	e^+ positron	ν_e electron neutrino	$\overline{\nu}_e$ electron anti-neutrino
μ^- Muon	μ^+ Anti-muon	ν_μ muon neutrino	$\overline{\nu}_\mu$ muon anti-neutrino

Forces and their Fields

Electromagnetic fields/light

- Quantized particle: *photon*
- Rest mass: zero!

Weak-force fields (responsible for beta decay)

- Quantized particles: *W*, *Z*
- Rest mass: yes!

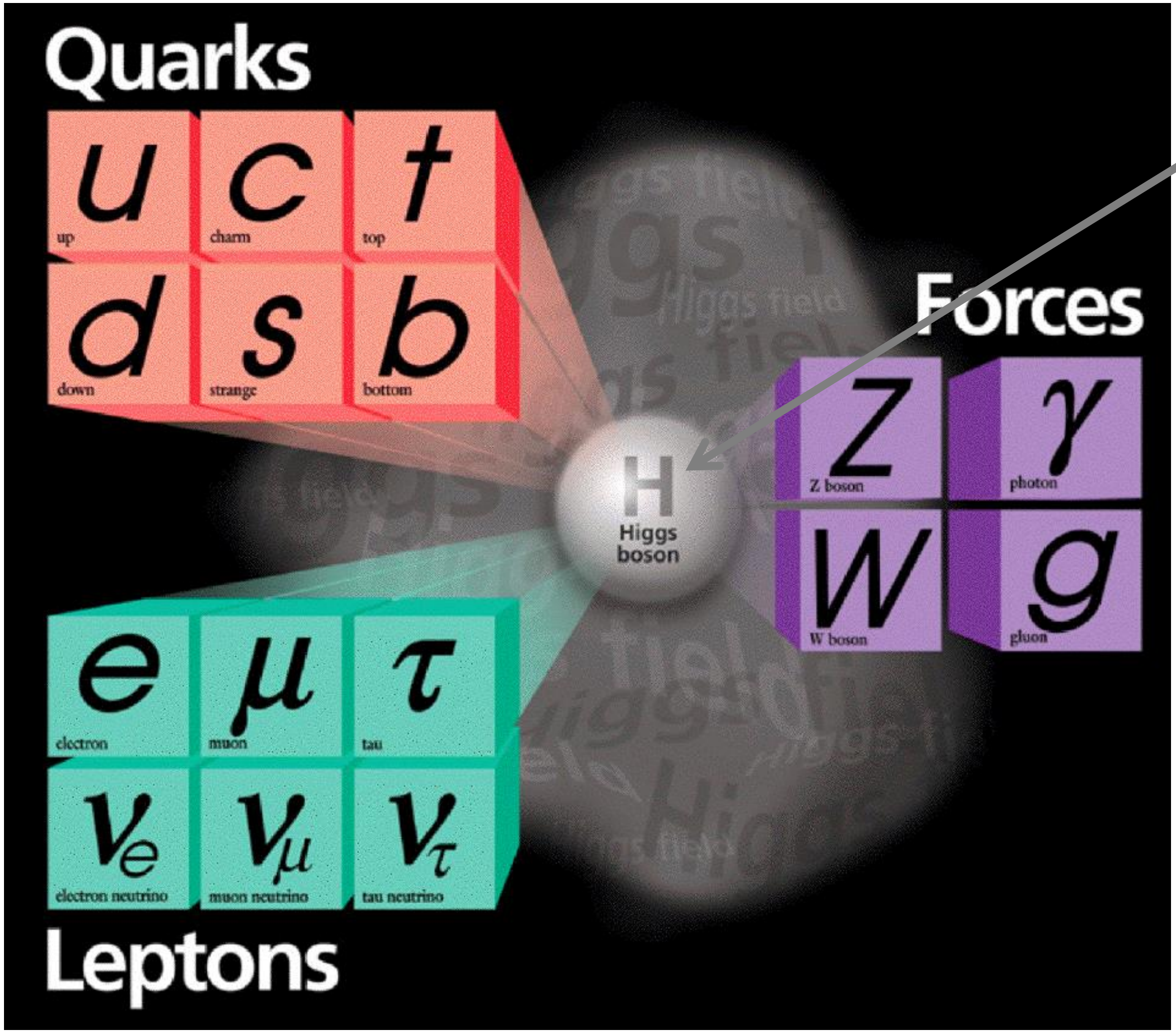
Strong ("color") fields:

- Quantized particles: *gluons*
- Rest mass: zero!

Gravity:

- Quantized particle: graviton ???
- Rest mass: zero.

Standard Model



Higgs Field (particle) Discovered 2012.

Rutgers group had major role in its discovery!

plus antiparticles of all of these…

Why don't we find isolated quarks?

In other word:
What happens if you try to pull apart two quarks?

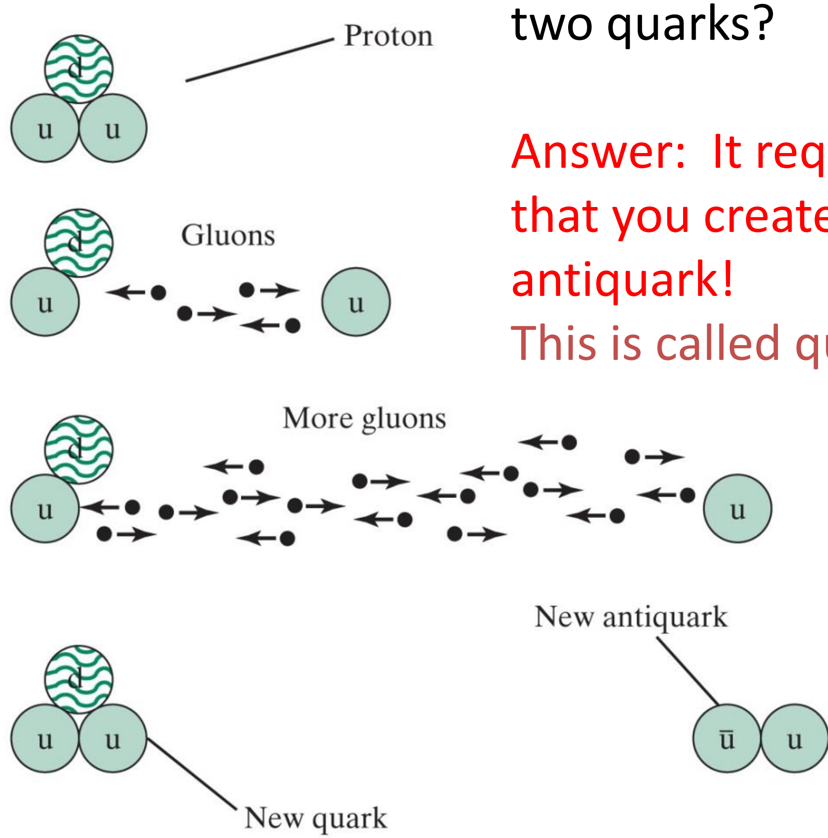
Answer: It requires so much energy, that you create another quark and antiquark!
This is called quark confinement.

Suppose you start with the three quarks in a proton—

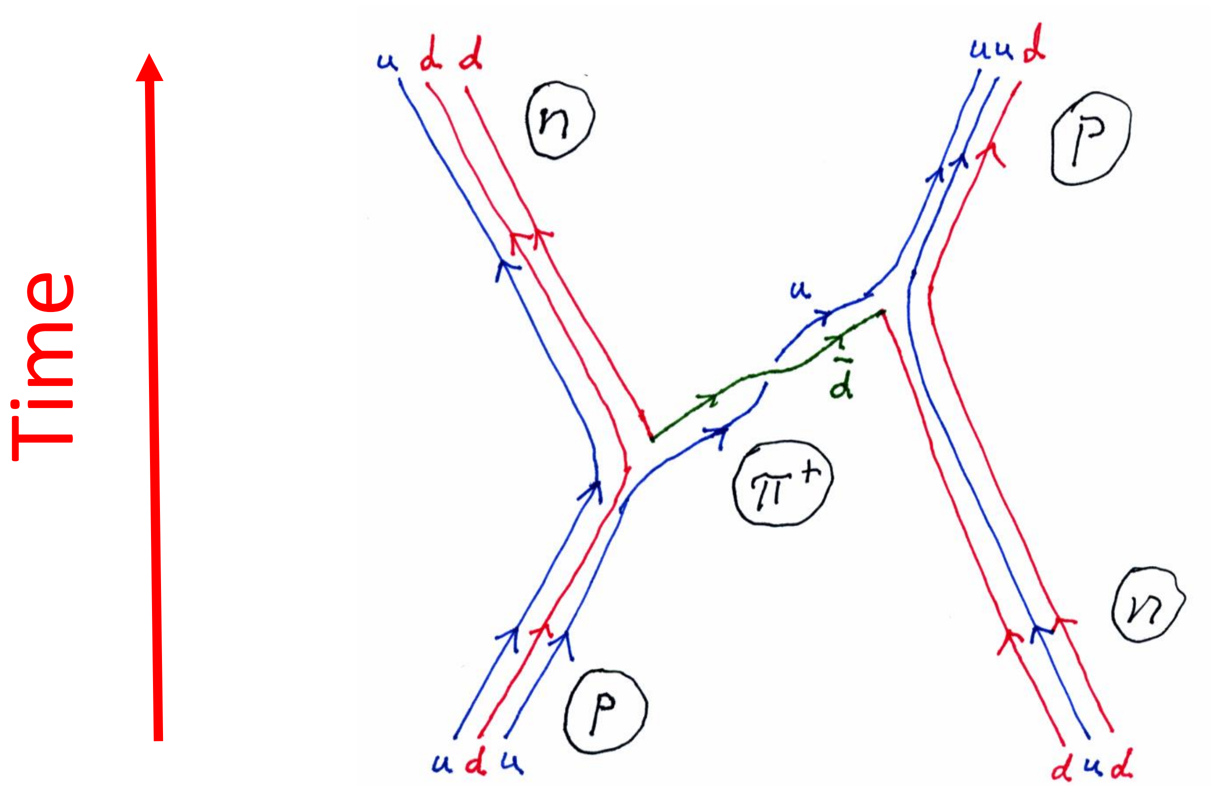
and begin pulling away one of the quarks. Gluons travel between the quarks.

As the quark is separated further, the gluons make more gluons, which makes the force between the quarks stronger.

Finally, all the gluon energy (strong field energy) creates a quark–antiquark pair, the new quark makes the proton whole again, and the new antiquark combines with the old quark to form an unstable quark–antiquark pair.

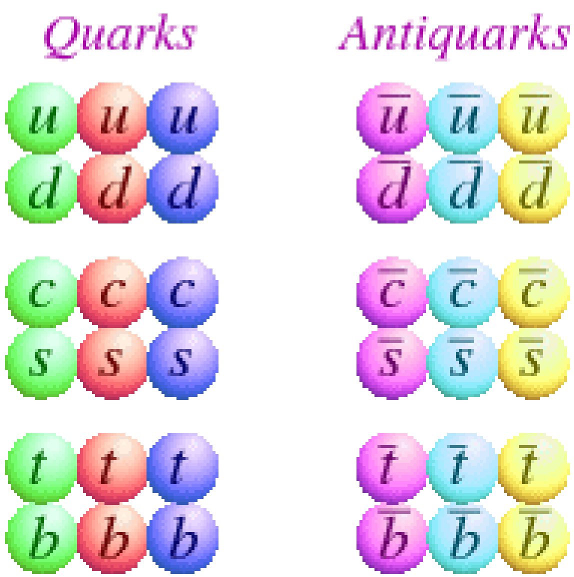


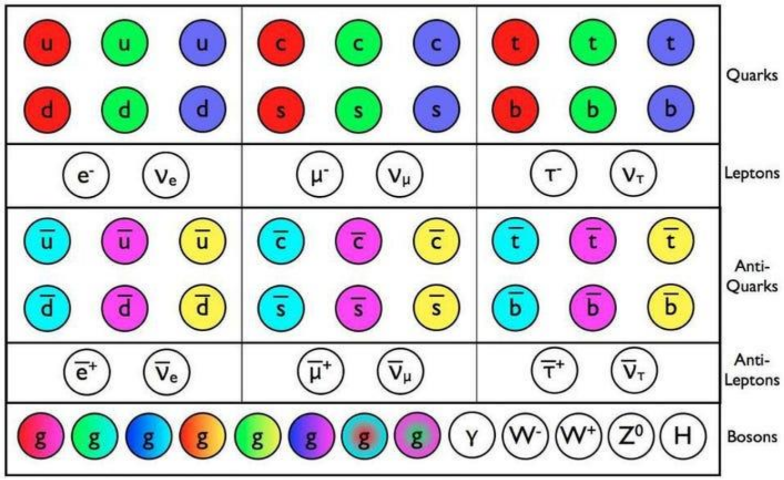
Scattering of Proton and Neutron



- This process “explains” the strong nuclear force.
- Nucleons inside nuclei are held together by exchange of pi mesons!
- Note that the anti-down quark can be considered a down quark traveling backwards in time!

“Color” Charge of Quarks/Gluons

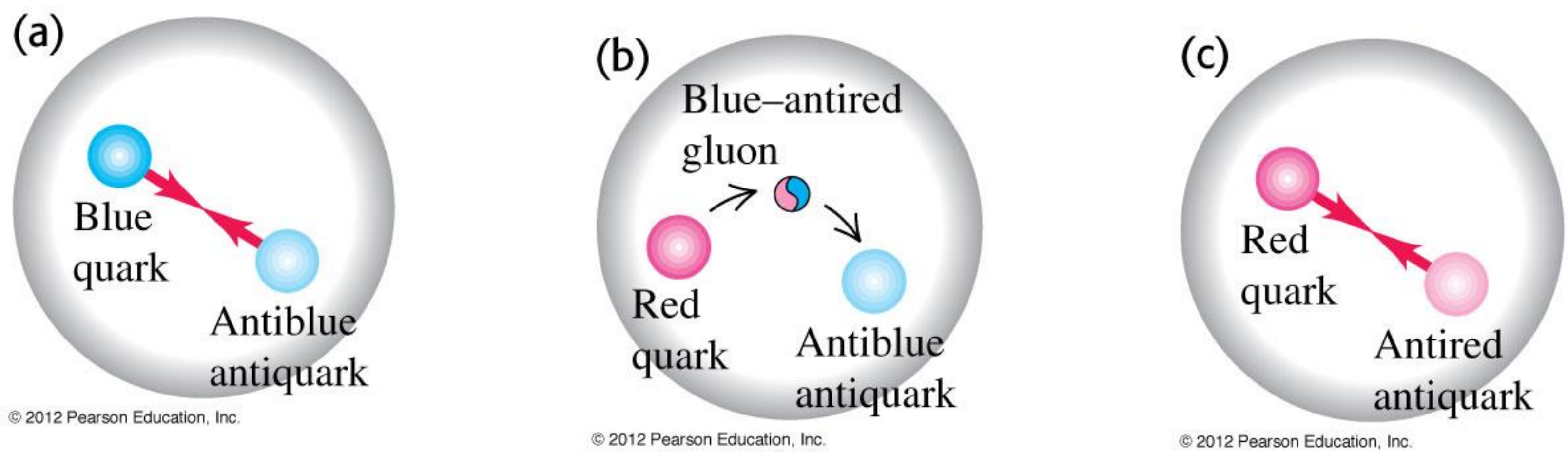




Color Charge and Strong Interactions

Quarks possess a type of charge which we call "color". Instead of two types (+/-), there are six types of strong-interaction charges, called "red/antired", "green/antigreen" and "blue/antiblue". Quarks interact by exchanging colored gluons.

Hadrons are colorless. Three-quark hadrons (baryons, like the proton and neutron) are made of 1 red + 1 green + 1 blue quark. Two-quark hadrons (mesons, like the π) are made up of, e.g., red + anti-red quarks.



Clicker

If we were to pull a single quark away from a proton,

A. we would end up with an isolated quark.
B. we would end up with a baryon and a meson.
C. No force is strong enough to do this.
D. we would end up with a black hole.

Clicker

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A. we would end up with an isolated quark.
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Clicker

According to our current understanding,

A) Muons are elementary particles.

B) Electrons are elementary particles.

C) Neutrons are made out of quarks.

D) Quarks are elementary particles.

E) All of the above.

Clicker

According to our current understanding,

A) Muons are elementary particles.

B) Electrons are elementary particles.

C) Neutrons are made out of quarks.

D) Quarks are elementary particles.

E) All of the above.

Clicker

If I turn an up quark upside down,

A. it becomes a down quark
B. it becomes an antiquark
C. it changes color charge
D. it remains an up quark

Clicker

If I turn an up quark upside down,

A. it becomes a down quark
B. it becomes an antiquark
C. it changes color charge
D. it remains an up quark

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