Lecture 16
Particle Physics

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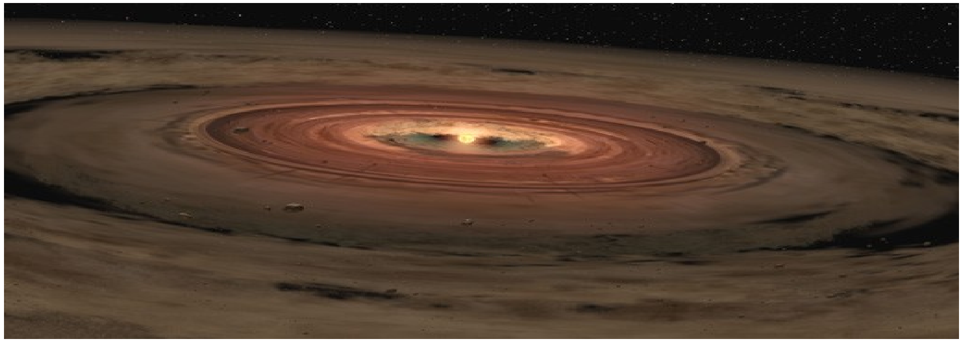
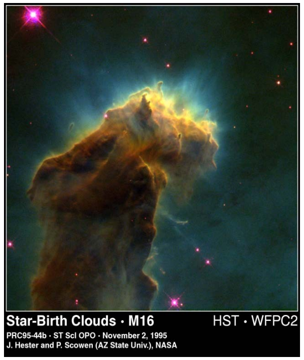
News

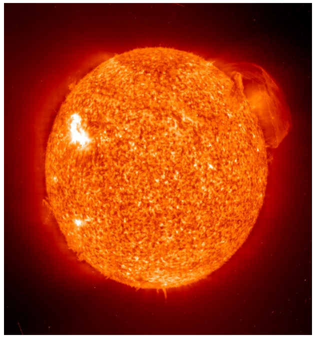
- Exam 2: Wednesday March 31 (next week!)
  - Hoyt at 2 pm
  - Bring a **calculator**
  - I will provide a formula sheet
  - Material: lectures 8 – 15 (up to nuclear physics, life of a star), recitations 5-7
- I want to meet with all groups before April 9.
  - Please contact me to set up a meeting during the week after the exam

Last time





- Stars are laboratories of the very big and very small at play
- Gravity pulls in, heat (radiation pressure) pushes out
- “Thermonuclear” **fusion** reactions in core
- Starts with H→He, then He→C,O (star then becomes **red giant**), small stars then become **white dwarfs**
- If star is very massive, it can synthesize up to ^{56}Fe
- Then explode into **neutron star** or **black hole**
- Heavier elements are formed in SuperNovae
- Next generation of stars form with heavier elements present from previous stars



Recap: big picture in PHY100

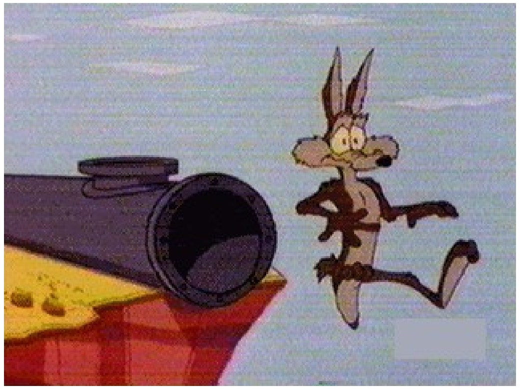
- We took the theory of gravity from the surface of the Earth and showed it applied to the solar system
- Then we looked at relativity
  - Objects moving fast must obey: speed of light is constant
  - Time is no longer fixed, but relative: spacetime
- Then we got introspective…
  - Quantum theory explained the atom, light, and the very small
  - No longer deterministic Universe: probability
  - Heisenberg: $\Delta x \Delta p \sim h$ ($\Delta E \Delta t \sim h$): cannot know things with arbitrary precision
  - Nucleus needed the addition of a "new force"

Our quest

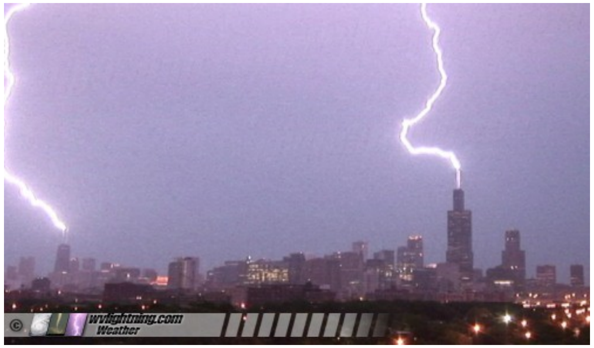
- Want to understand the "dynamics" of a theory, not just the "kinematics"
  - "Why" things move, not just "how"
  - Kinematics describe movement, Dynamics describe general forces and laws
- Want to understand the structure of matter at the smallest scales
  - Are there ultimate constituents of matter?
  - What lies beyond the nucleus?
  - What makes the matter we see in the Universe?
  - How do they interact?
  - What forces exist in Nature?
  - What is a force?

Forces in Nature

- **Gravity**: attractive force between particles with mass or energy
  - long range but very weak
  - holds planets, galaxies, etc. together
  - makes road runner happy



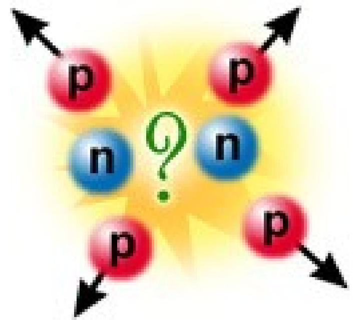
- **Electromagnetism**: attractive or repulsive force between particles with charge
  - long range, stronger than gravity
  - holds atoms together
  - keeps matter from collapsing under the force of gravity: shockingly important!



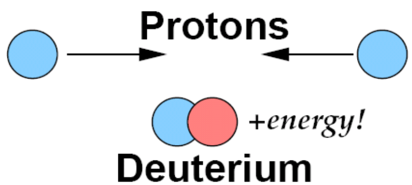
Forces in Nature: the very small

Strong Nuclear Force

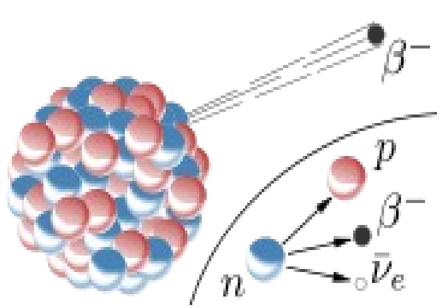
- the nucleus of an atom contains lots of protons that all repel each other electromagnetically
- the strong force binds them
- it's a force that is short-range (10^{-15}m) because it is so strong!



Weak Nuclear Force



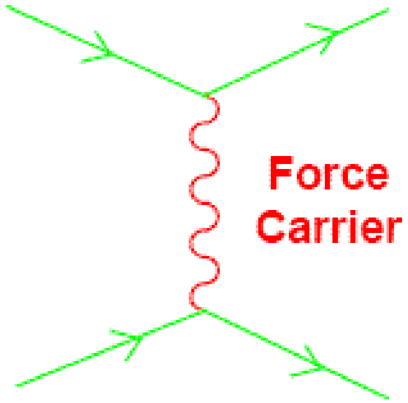
- its exciting role is to, well, make β-decays
- Not very exciting.... Who cares? We all do!
- Fusion in the sun requires that a proton turn into a neutron. Inverse of β-decay!
- Without β-decay, we are stuck with a sun that doesn't shine...



Four forces explain everything!

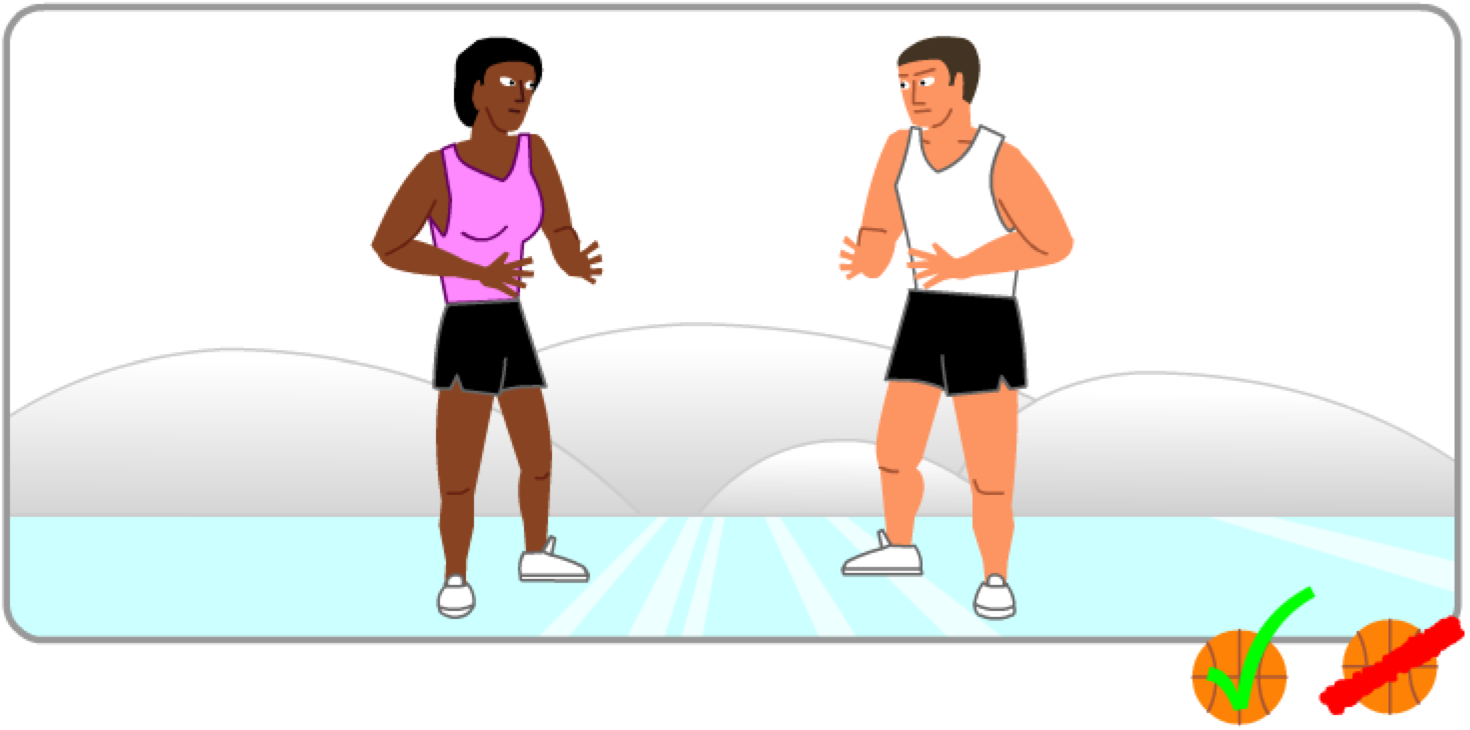
Force	Source	Range	Strength
Gravitation	Mass	Infinite	10^{-39}
Weak nuclear	Weak charge	10^{-18} m	10^{-5}
Electromagnetism	Electric charge	Infinite	10^{-2}
Strong nuclear	Color charge	10^{-15} m	1

- But what is our dynamical quantum theory of the atom?
- Theory of **force carriers**
  - All 4 forces above are “mediated” by an exchange of force carrying particles
- Symbolically: Feynman diagram
- The world is made of two kinds of particles:
  - Matter particles
  - Force carrying particles



How does this work?

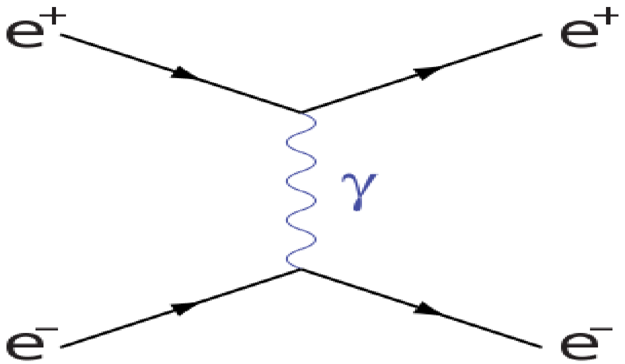
- Imagine a game of basketball on ice....

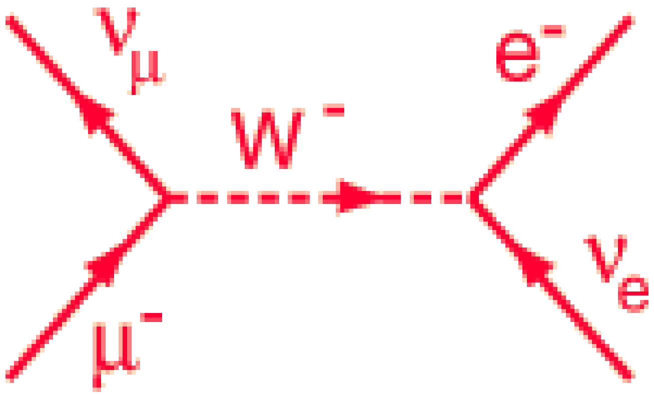


- By exchanging basketballs, players also exchange momentum. Definition of a force!
  - $p = mv \Rightarrow \Delta p = m\Delta v$ But: $a = \Delta v/\Delta t$
  - $F = ma \Rightarrow F = \Delta p/\Delta t$

This is Quantum Electrodynamics!

- Yicky name…
- But all it means is a **quantum**…
  - Think uncertainty principle, wave/particle duality
- … **electro**…
  - Electricity and magnetism. Like charges repel, etc.
- …**dynamical** theory
  - Finally an explanation for WHY!
- Developed by Richard Feynman and Julian Schwinger 1940's



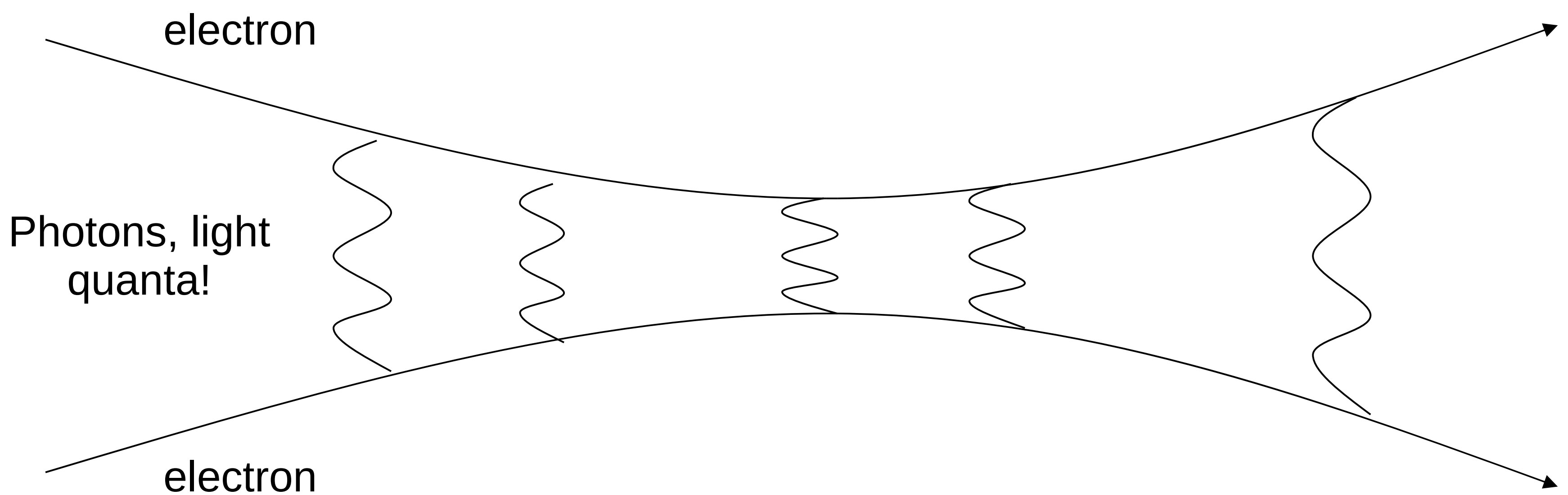


Electromagnetism:
Massless photon
Range: infinite

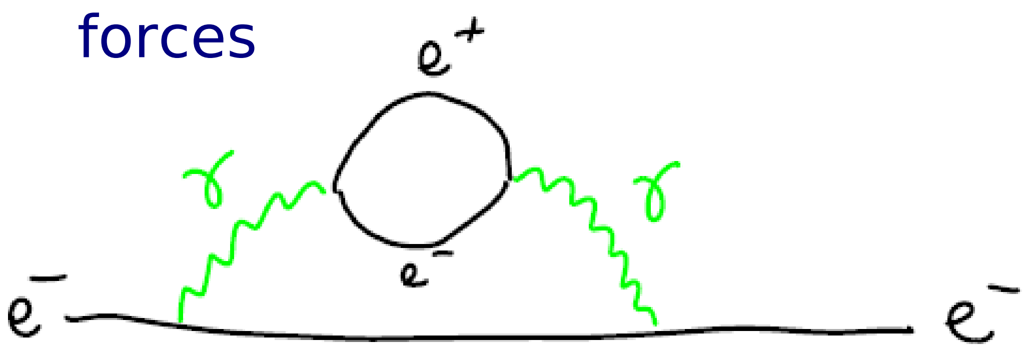
Weak interaction:
W boson (Mass=80 GeV) 1GeV=1000MeV
Range: 10^{-18}m

Electrostatic repulsion of two e^-

- Now might exchange many photons (far apart)
- The photons are a “quantum fluctuation” allowed by the uncertainty principle...



Virtual particles are the quanta that describe the fields of fundamental forces

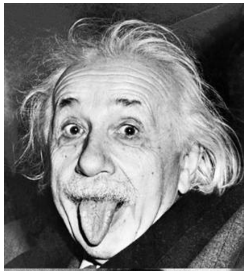


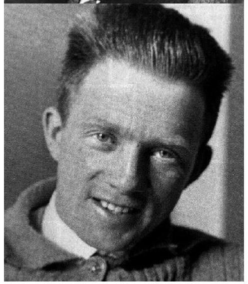
Einstein:

$E = mc^2$

Heisenberg:

$\Delta E \Delta t \sim h$

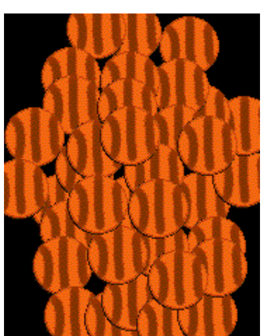


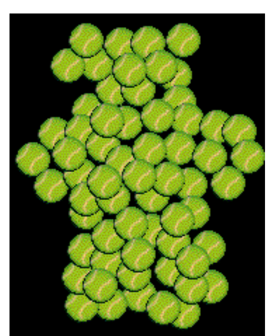


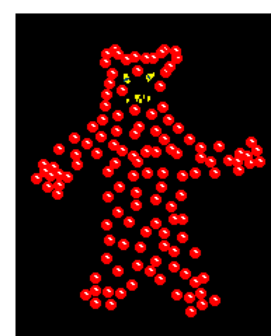
Seeing structure

- Imagine you fell in a dark cave and your hear ominous snorting noises. Is it a bear?

- Easier to see a bear with marble-sized probes than basketball-sized probes

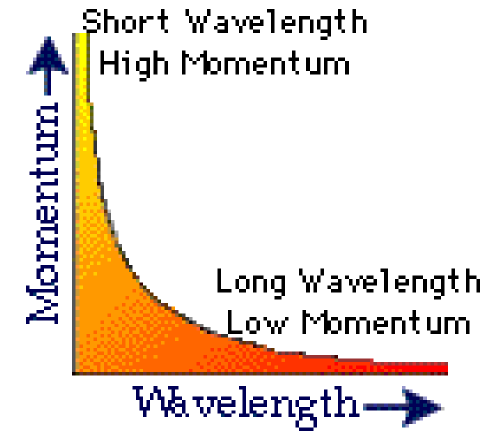


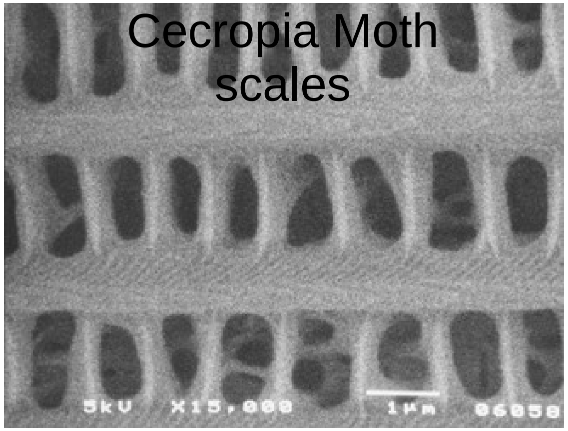


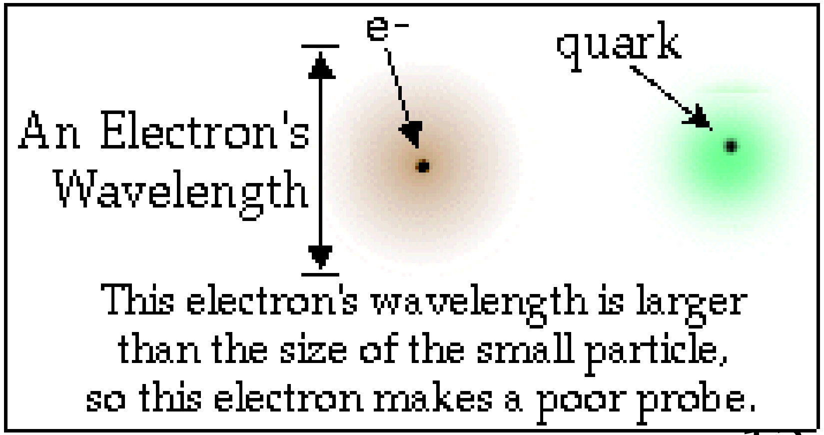


Microscopes and beyond

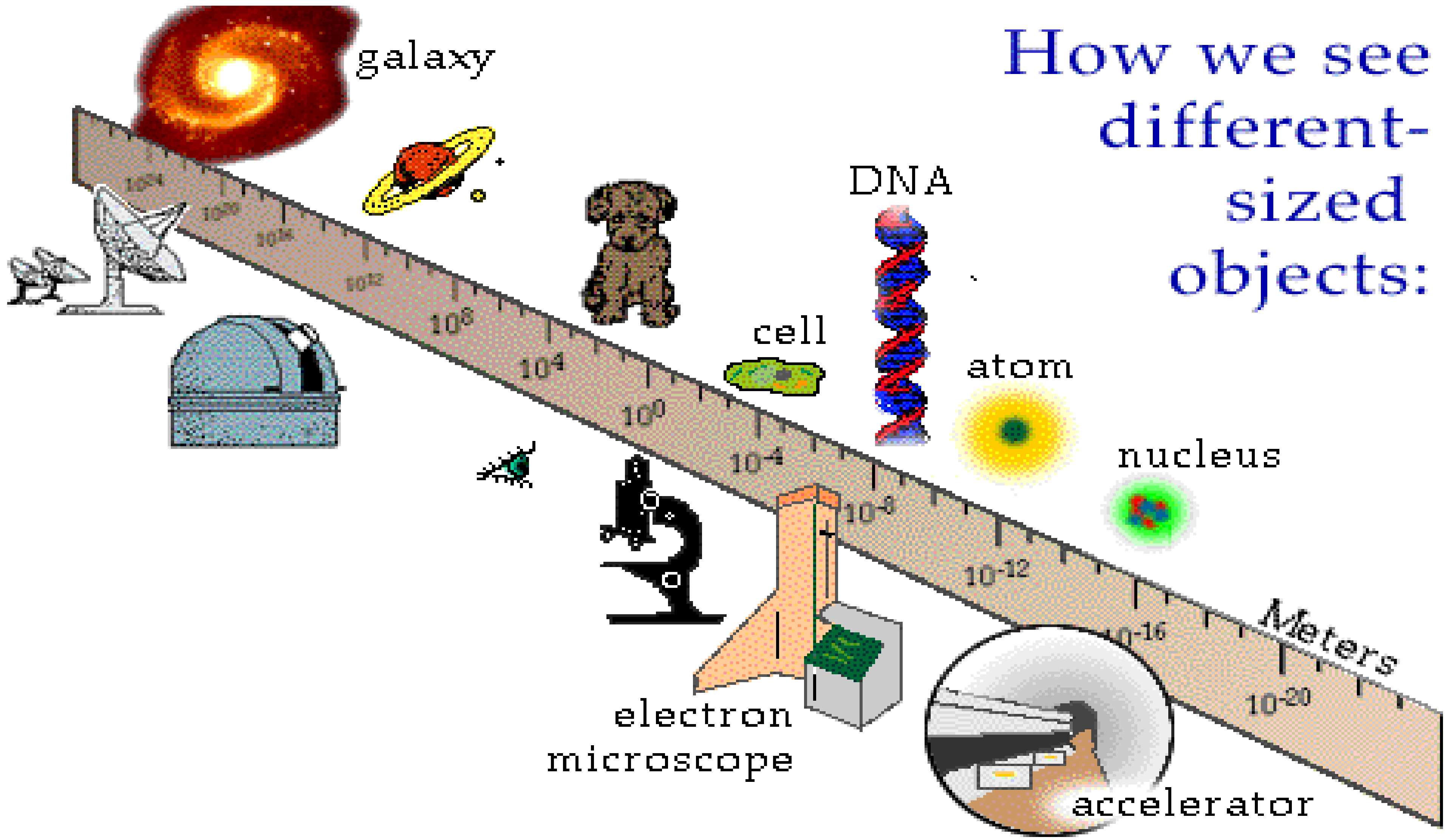
- So probes must be small if we want to see small structures.
- Use wave-particle duality to think of the "size" as the wavelength. Long wavelength waves can't be scattered by small things…
  - deBroglie says: $\lambda = h / mv$
  - Visible light limits microscopes $\lambda \sim 3\text{x}10^{-7}\text{m}$
  - Electron microscope can have smaller wavelength
- But electron microscopy doesn't work for subatomic structure!
  - Need smaller electron wavelength
  - Which implies higher speed or momentum
- Modern particle physics is stuck using large accelerators!





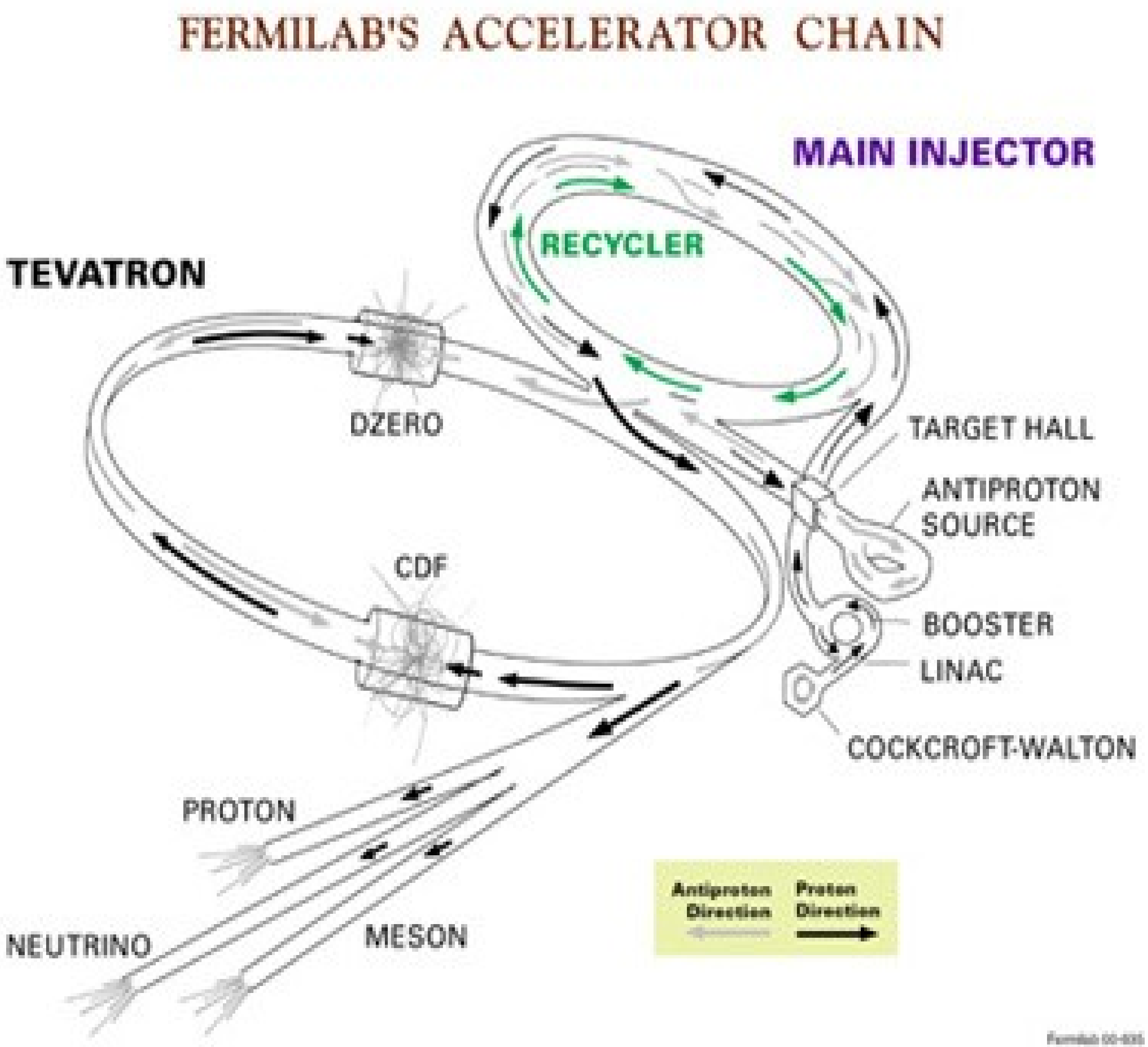


How we see things

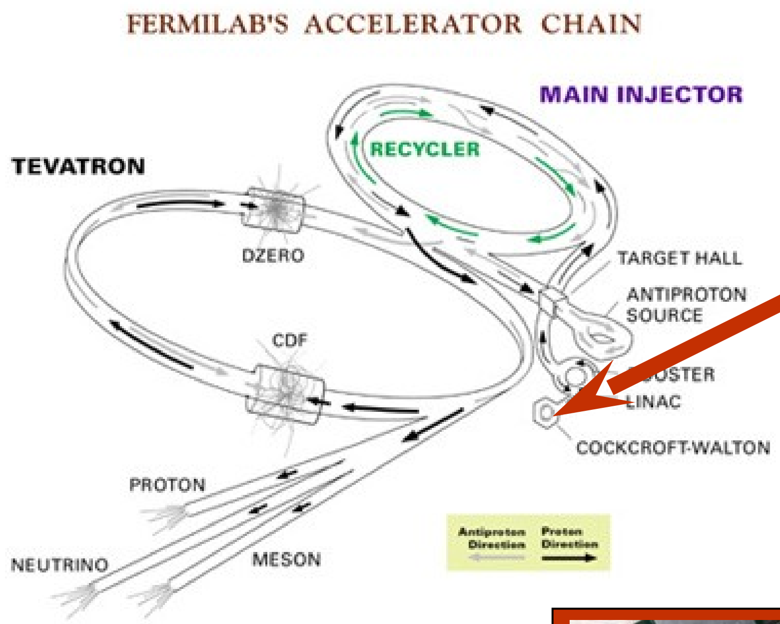


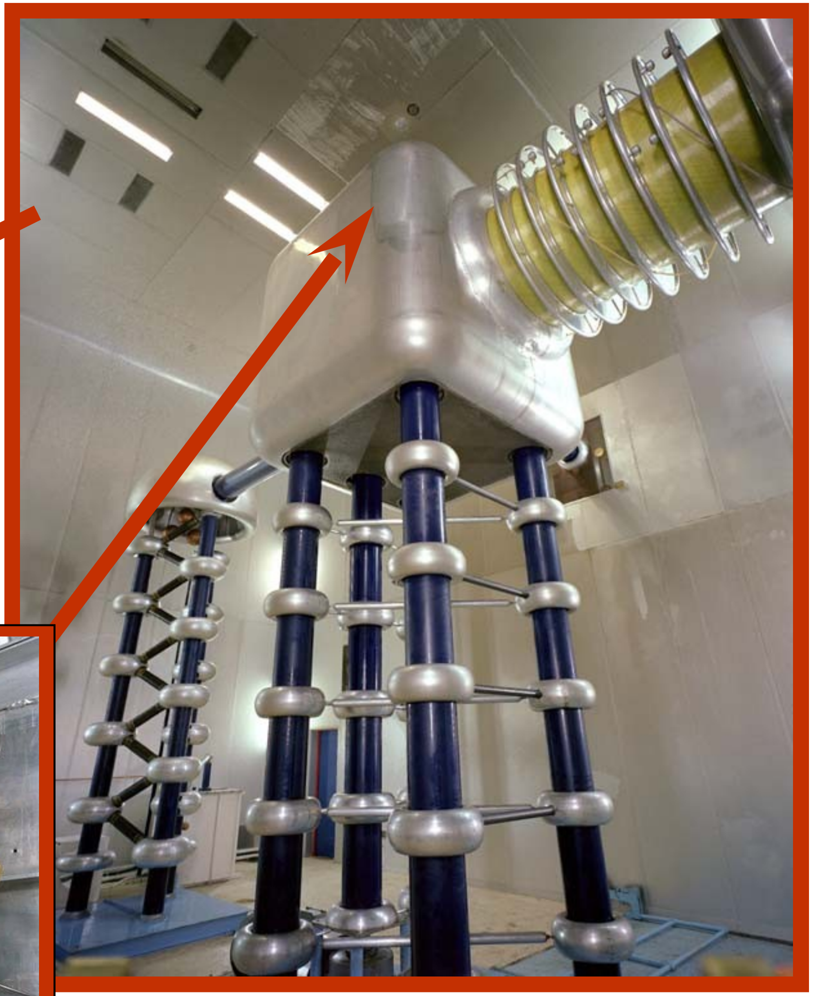
- Different technology for different scales
- Accelerators probe the smallest structure

Accelerators



Accelerators

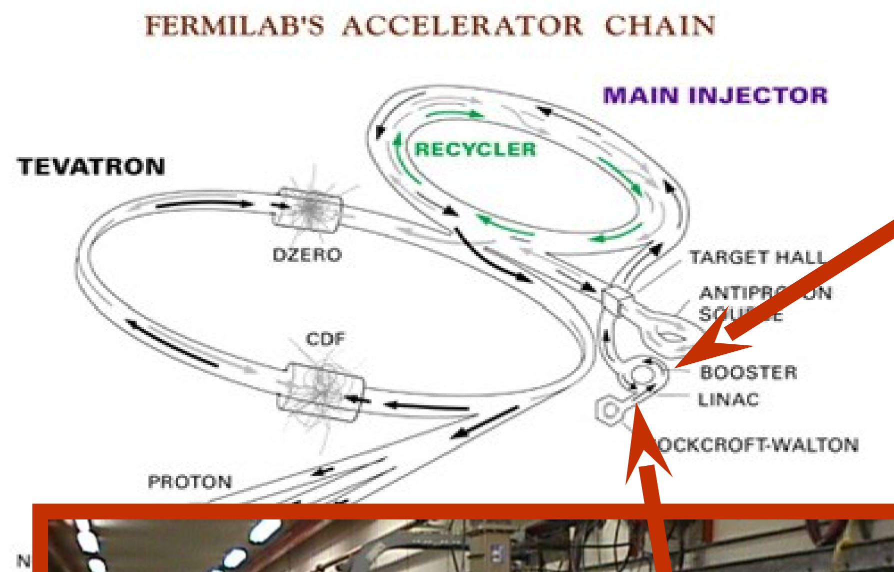




A small bottle of hydrogen is the source of protons to be accelerated.

Ions leaving here have 750 keV of kinetic energy.

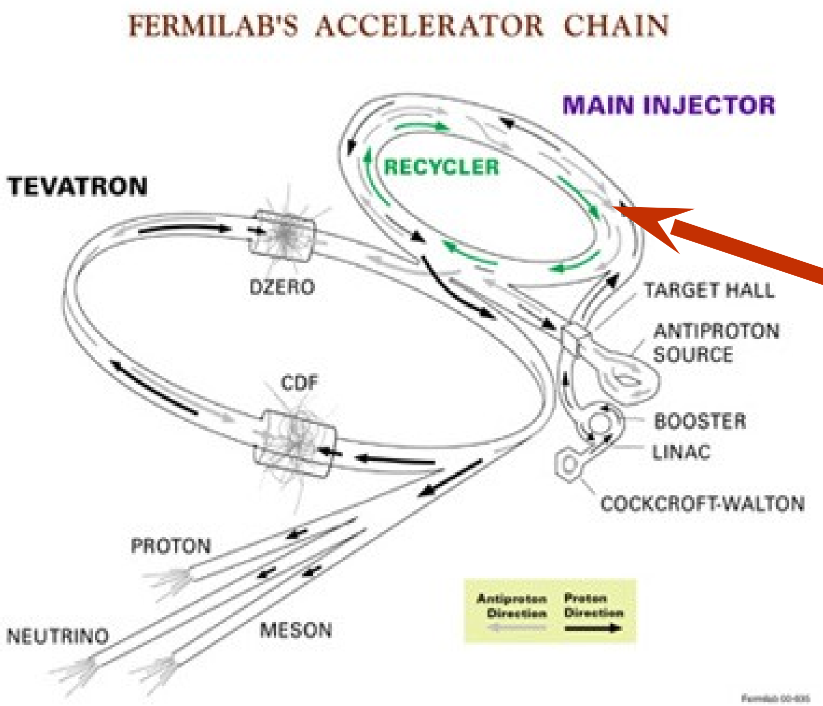
Accelerators



...and 8 GeV here

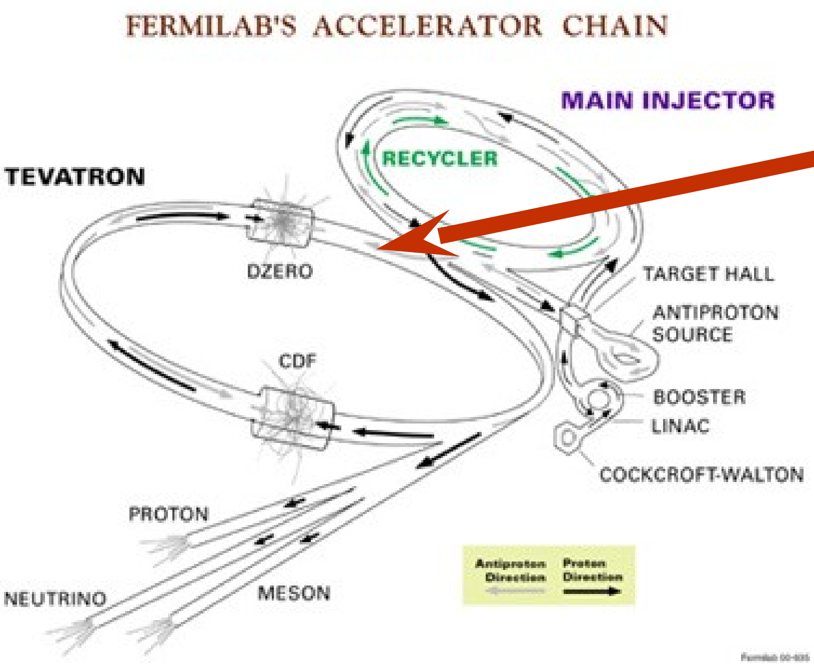
protons leaving here have 400 MeV of kinetic energy...

Accelerators



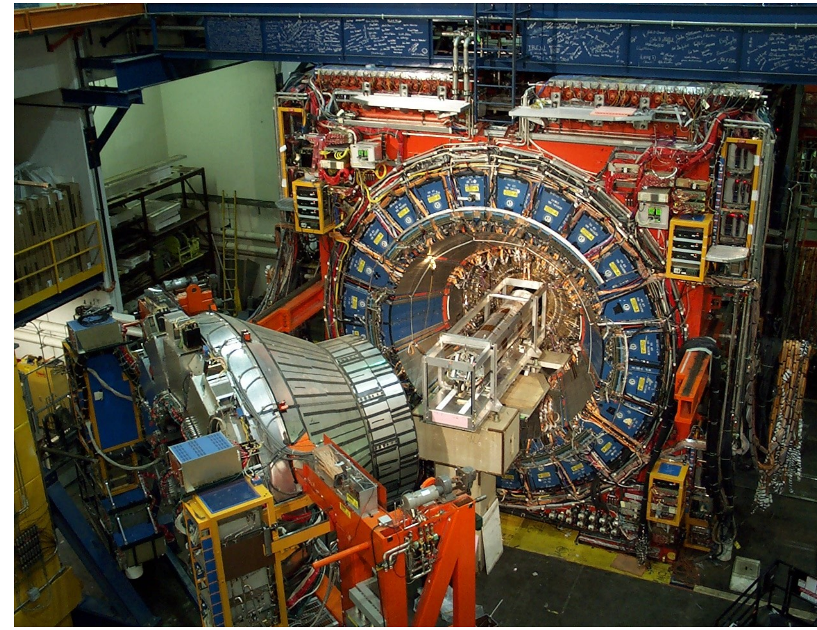
protons leaving here have
120 GeV of kinetic energy

Accelerators



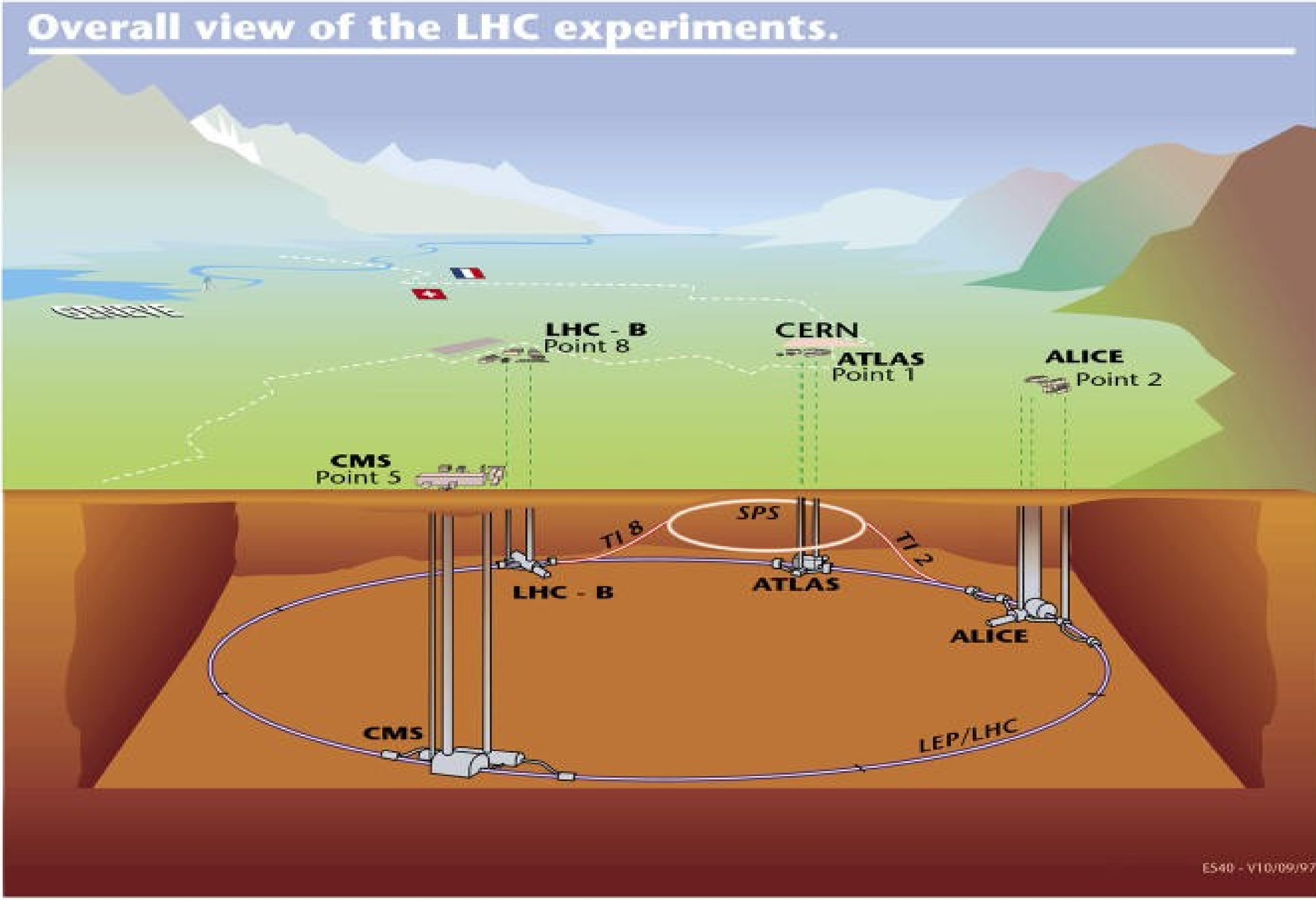
protons accelerated to
~980 GeV of kinetic energy

Accelerators: Fermilab



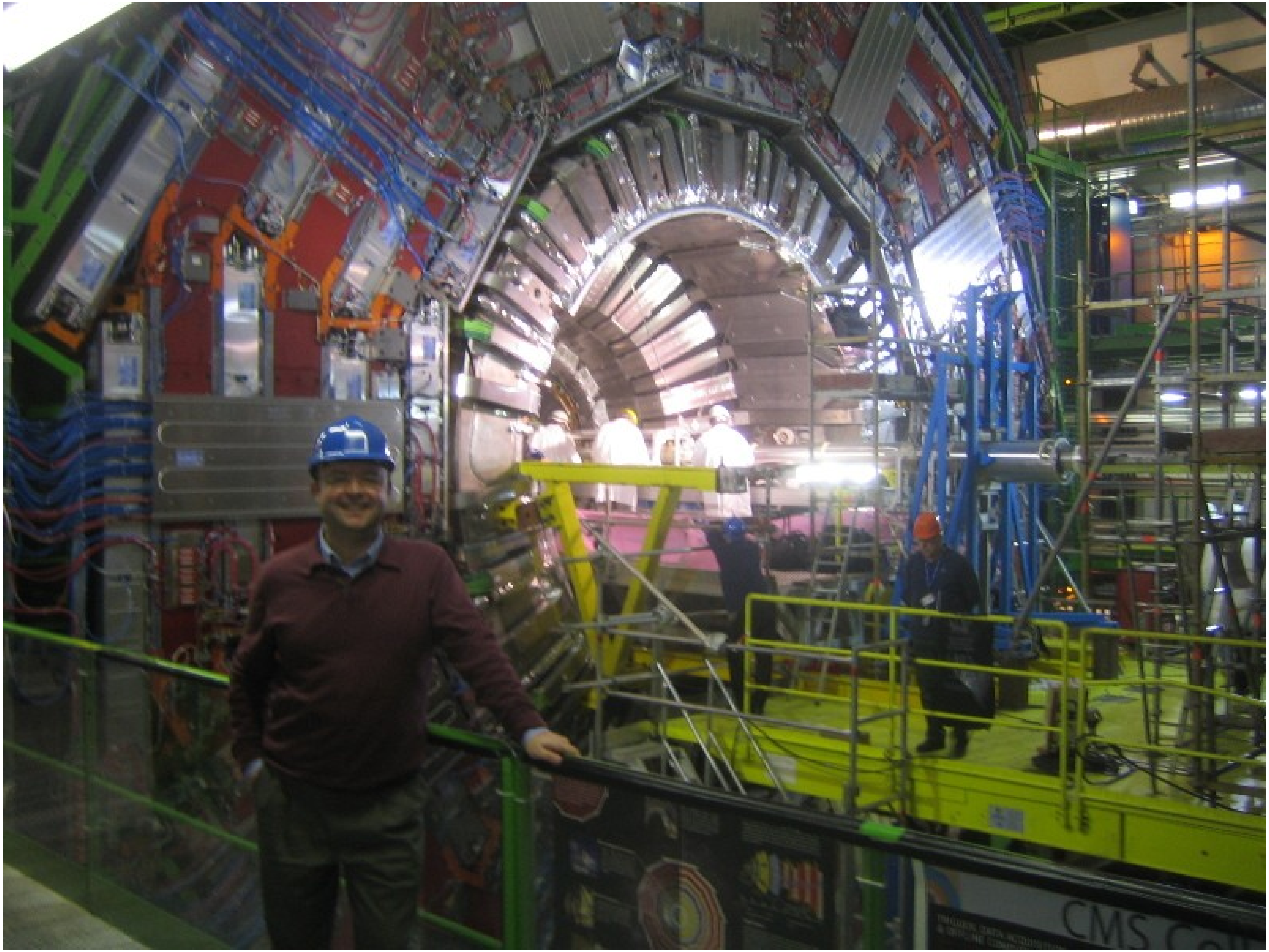
So the whole thing sits in a site the size of a moderate Chicago suburb... no problem!

But wait, there's bigger and better

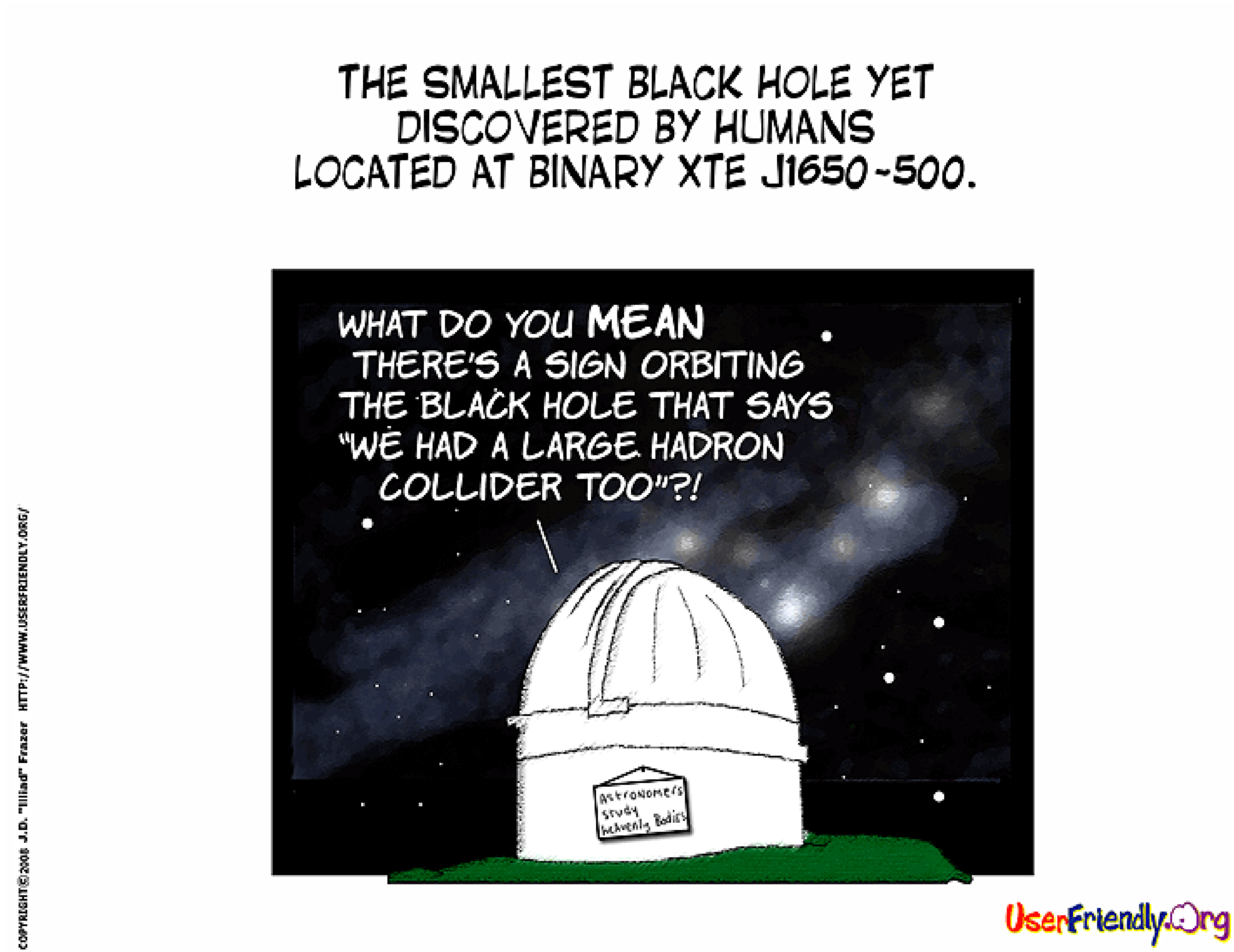


CERN's LHC

CMS detector: March 2009

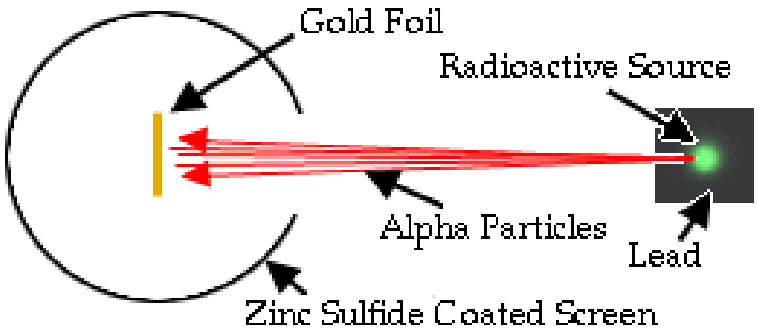


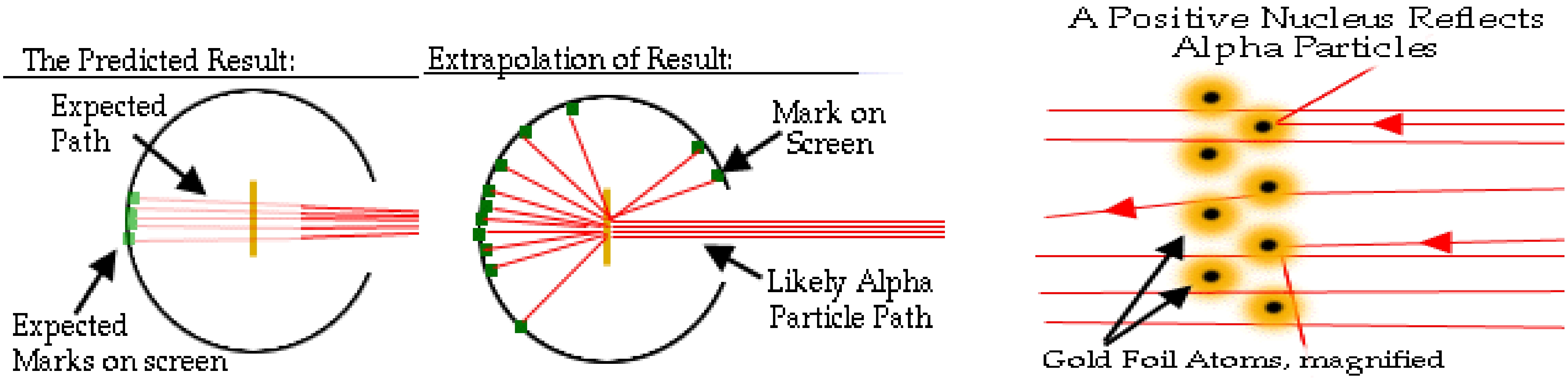
Relax, Earth will survive it!



Remember Rutherford

- Rutherford found the nucleus by scattering of alpha particles
  - Found unexpected large deflections
  - Interpreted these as more structure
  - “A hard center” to the atom

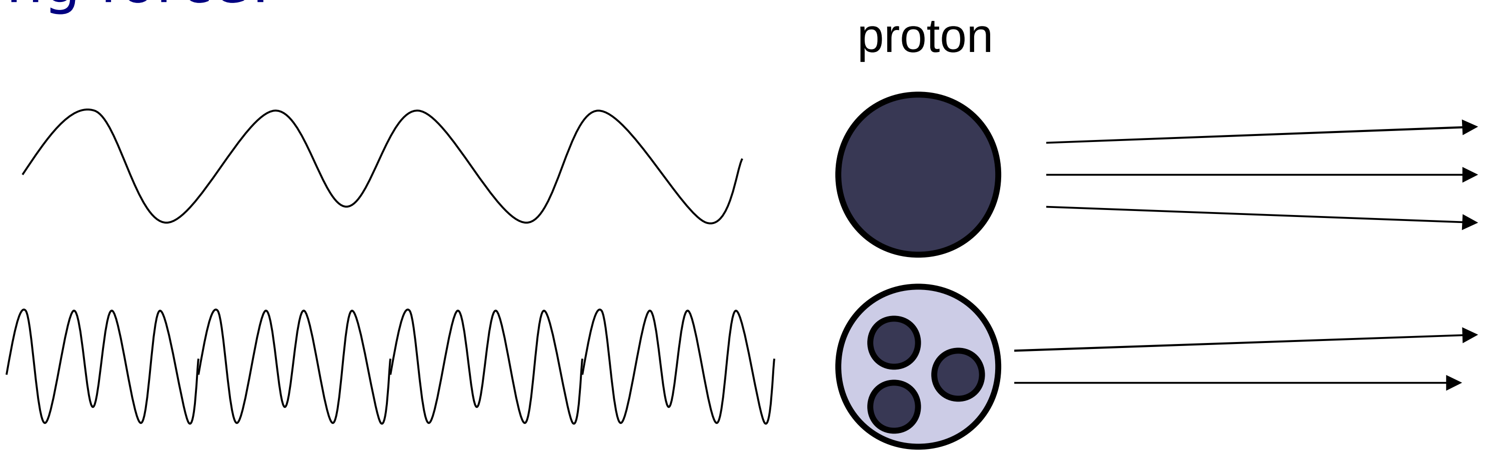


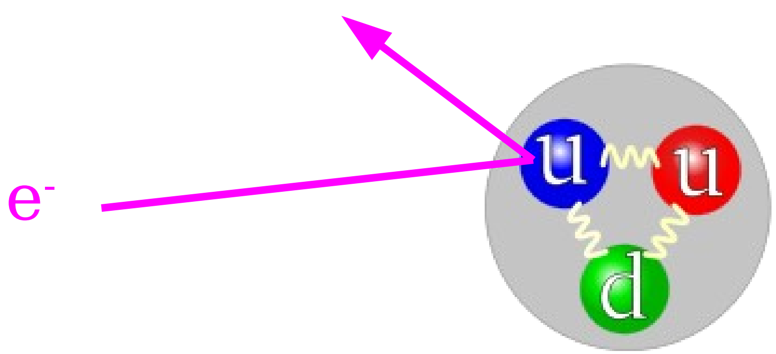


- Rutherford’s alpha particle had a mass of 6.7×10^{-27}kg and a speed of about 1×10^{7} m/s
- So the wavelength is about $\lambda = h / mv = 10^{-14}$ m
  - Good for resolving structure inside 10^{-10} m atoms
  - Lousy for resolving structure inside 10^{-14} m nucleus
- Need higher momentum (smaller wavelength)

Inside protons/neutrons

- Discovered smaller structure inside protons at Stanford Linear Accelerator
- Just as with Rutherford, essentially found unexpected backward scattering
- There are “quarks” inside the proton, bound together by the strong force!





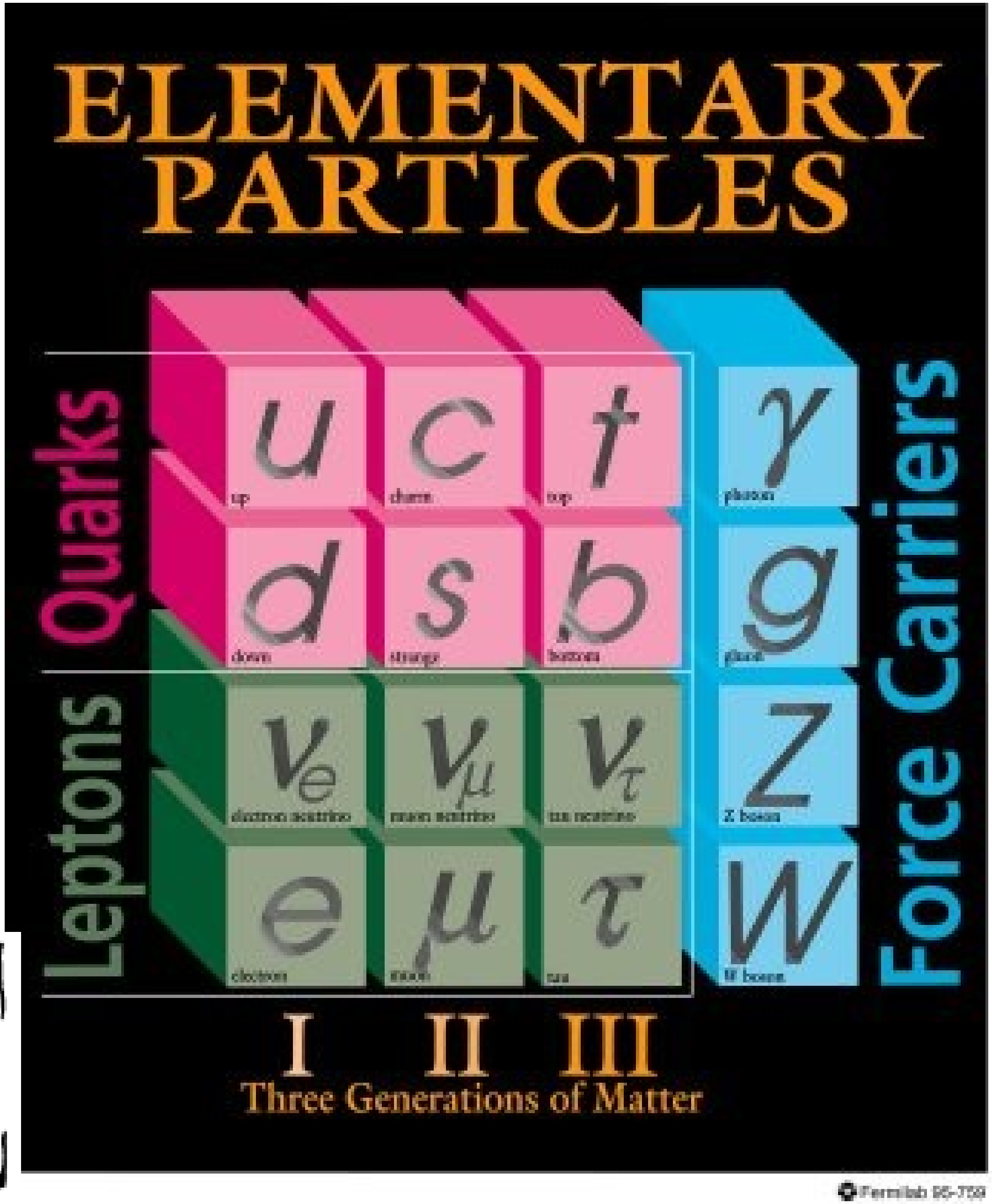
u = up quark (q=+2/3e)

d = down quark (q=-1/3e)

Quarks come in colors (red, green and blue) which are “strong-force” charges.... nothing to do with real colors!

Standard Model

- Three “families” of matter + forces
- Ordinary matter is made only with 1^{st} family: p=uud ; n=udd ; e
- W boson can convert u into d, or e into ν (mix different families)
- Gluons are responsible for the strong interaction
- Particles with “color” cannot be isolated: bound in **hadrons:**
- **Baryons**: qqq, like p and n
- **Mesons**: $q\bar{q}$, like K=$u\bar{s}$ or $\bar{u}s$; π=$u\bar{d}$ or $\bar{u}d$



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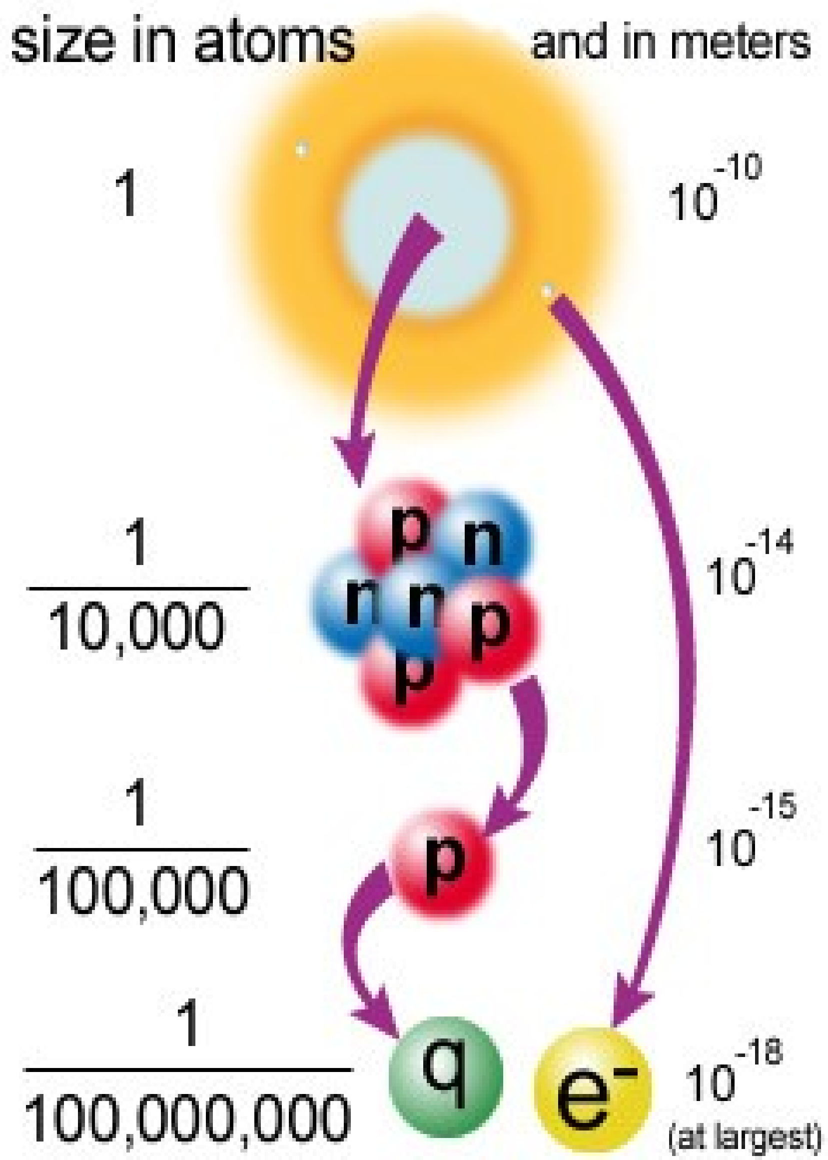
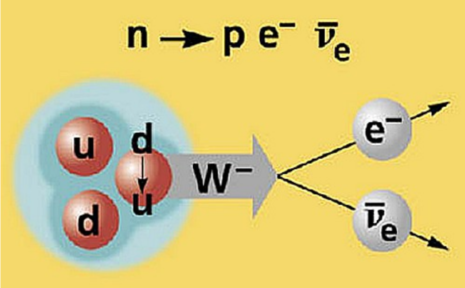
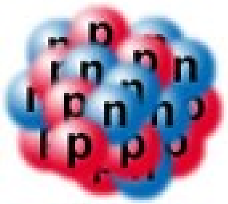
Summary

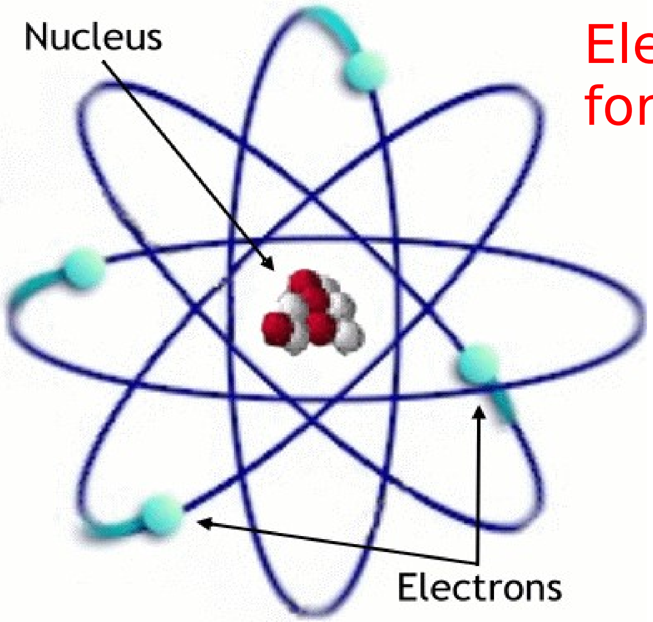




Weak force



Strong force



Electromagnetic force

Links

- http://www.interactions.org
- http://particleadventure.org
- http://pdg.lbl.gov
- http://public.web.cern.ch/public/
- http://www.fnal.gov/
- http://www.er.doe.gov/production/henp/np/index.html
- http://www.science.doe.gov/hep/index.shtml