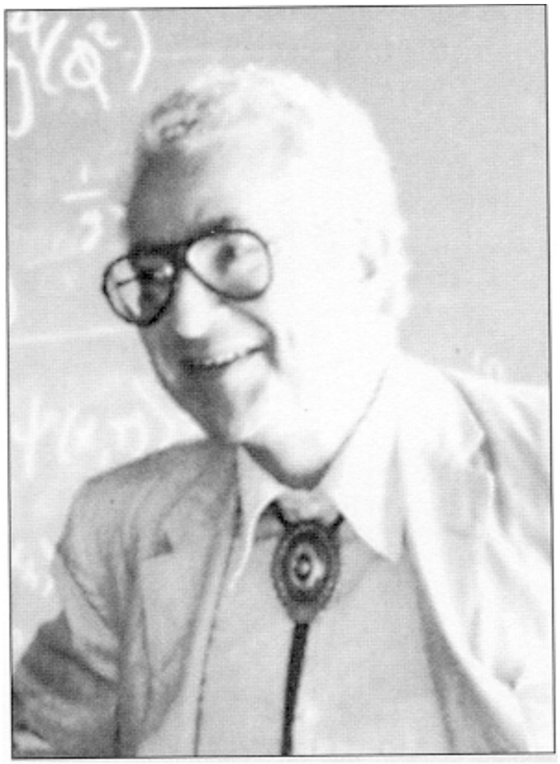
Announcements

- Help room hours (1248 BPS)
  - Ian La Valley(TA)
  - Mon 4-6 PM
  - Tues 12-3 PM
  - Wed 6-9 PM
  - Fri 10 AM-noon
  - I'll have office hours on Monday Dec. 10 from 2-5 PM
- Third hour exam Thursday Dec 6
- Review Tuesday Dec 4
  - since it's our last class, send me an email if there's a topic covered this year, you would like me to review
- Provide feedback for the course at https://sirsonline.msu.edu starting Nov. 26
- Final Exam Tuesday Dec 11 7:45-9:45 AM
  - please see me after class if you have a conflict for this time

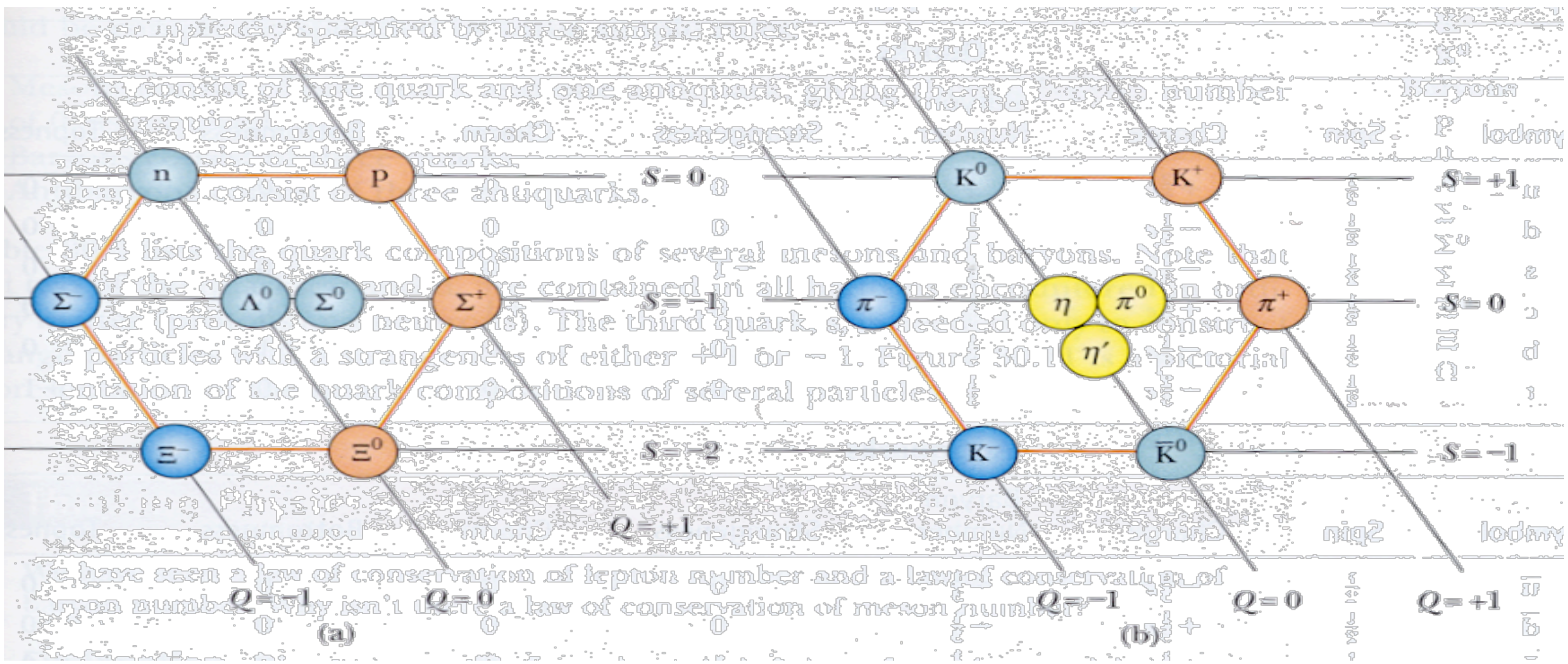
Murray Gell-Mann



Murray Gell-Mann,
American physicist (1929–)

- Starting in the early 1960s, Gell-Mann tries a variety of ways to organize the vast zoo of particles being discovered.

- He is guided by the example of the periodic table of elements.
- Eventually he hit upon the “Eight-fold Way”
- With the symmetry of the pattern, it was possible to discover “missing” particles, such as the Ω^- particle
- In addition, the pattern hinted at an underlying structure.

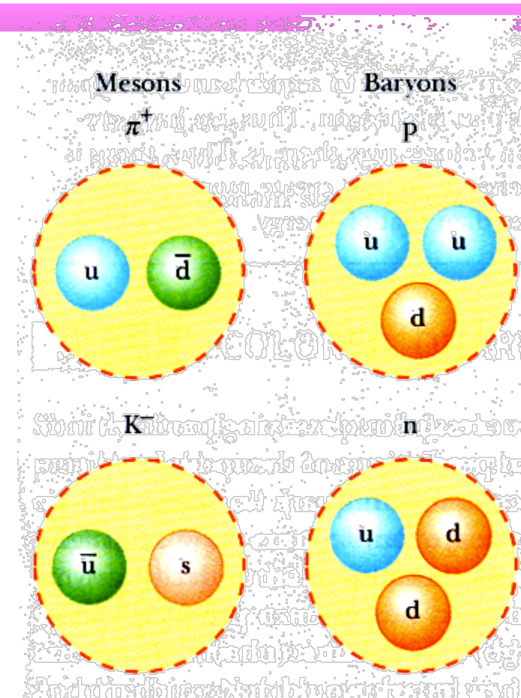


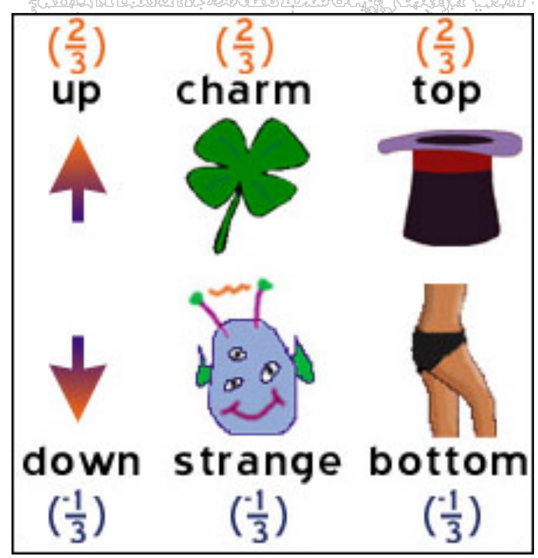
Quarks

- 1963: Gell-Mann and George Zweig independently suggested a more elementary structure for hadrons.
- The early model proposed that all hadrons are composed of two or three fundamental constituents, each with their own fractional charge, either 1/3e or 2/3e.
- Whimsically, Gell-Mann names them "*Quarks*" from a line in James Joyce's Finnegan's Wake
- "Three quarks for Muster Mark!"

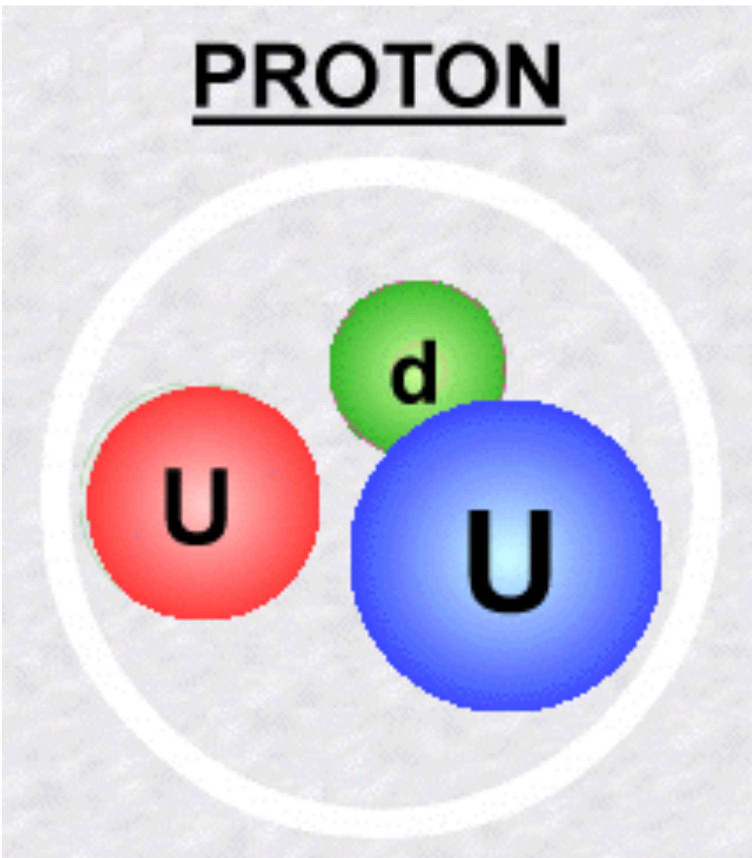
Quark flavors

- Simply put,
  - mesons consist of a quark and an antiquark.
  - baryons consisted of three quarks.
- Originally there were three (up, down, and sideways)
- Further research has led to 6

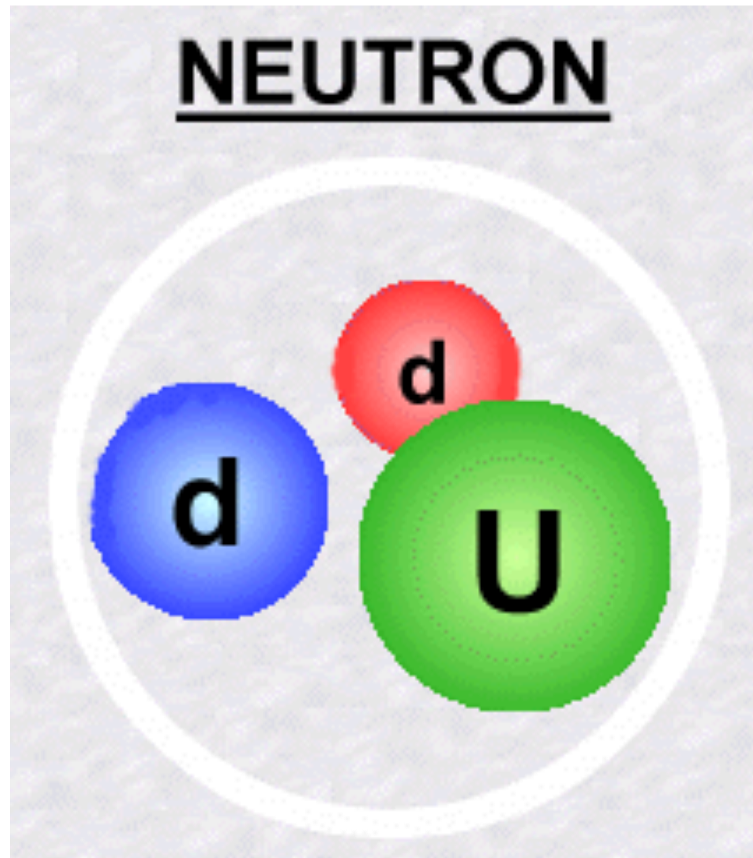




- So a proton is

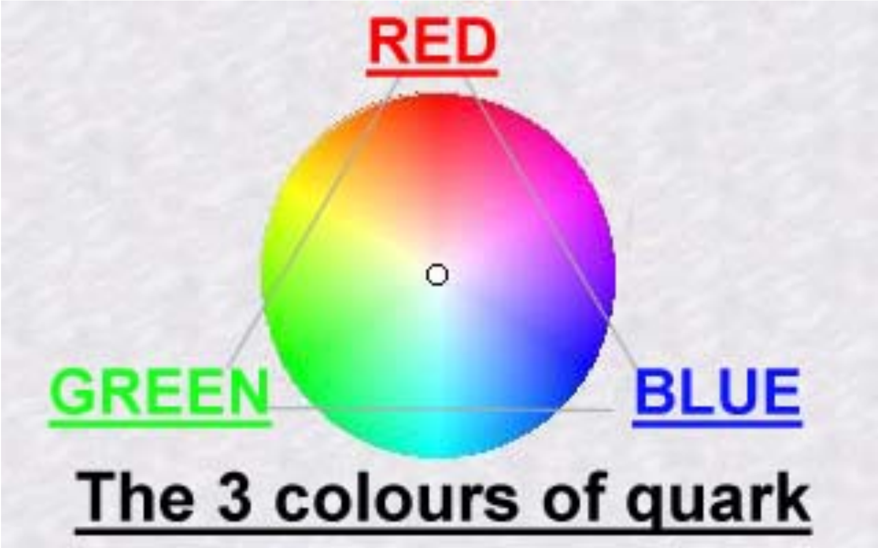


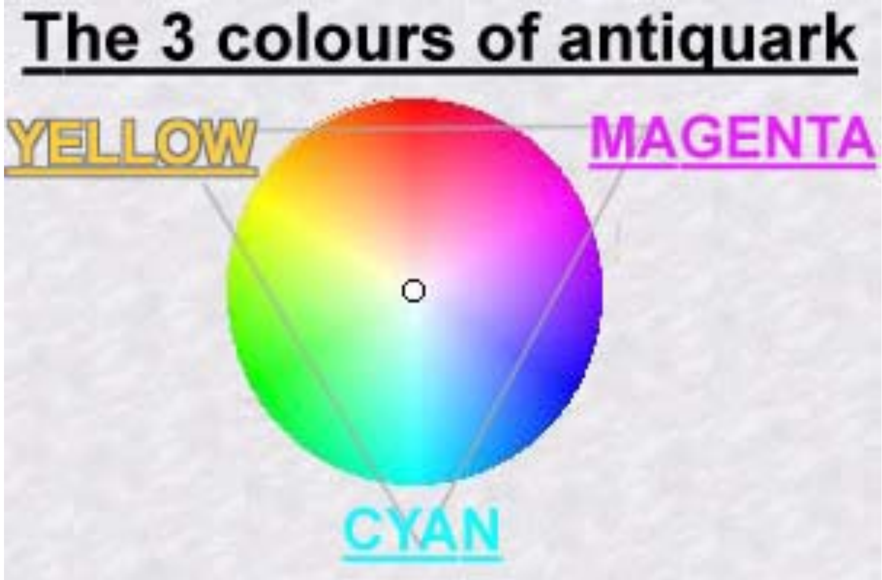
- ...and a neutron is



Quark colors

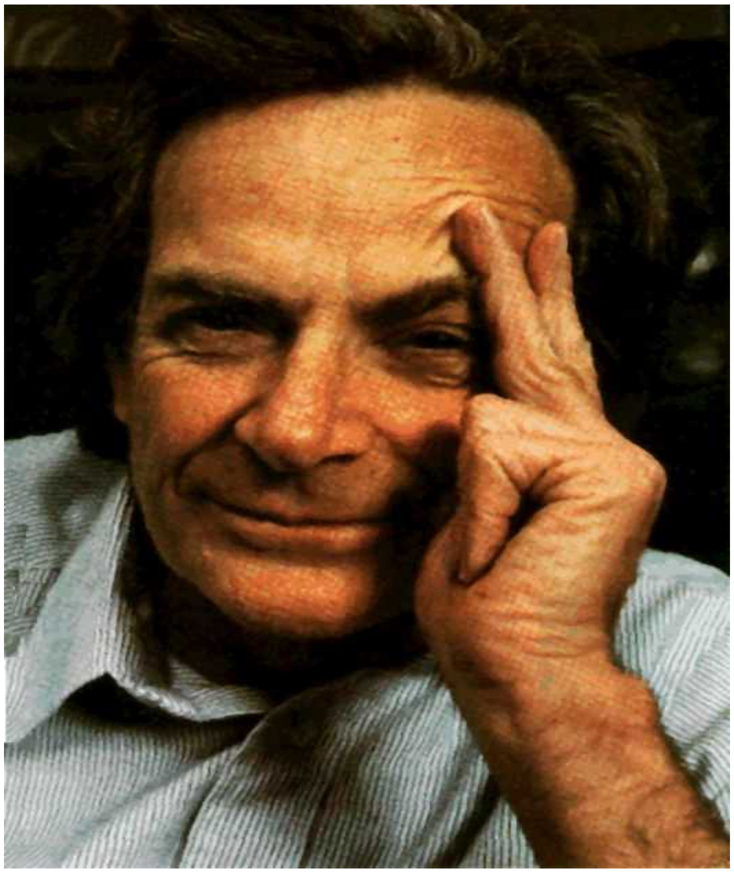
- There are 6 different flavors of quarks
- In addition, there are 3 different colors of quarks
  - red
  - green
  - blue
- Of course, quarks have neither flavor nor color as we know them
- We just use those names to distinguish the types of quarks from each other
- And of course, anti-quarks have 'anti-color'
- The theory of strong interactions is called Quantum Chromodynamics (or QCD)





Feynman and Field

- Feynman worked to develop QCD with Rick Field

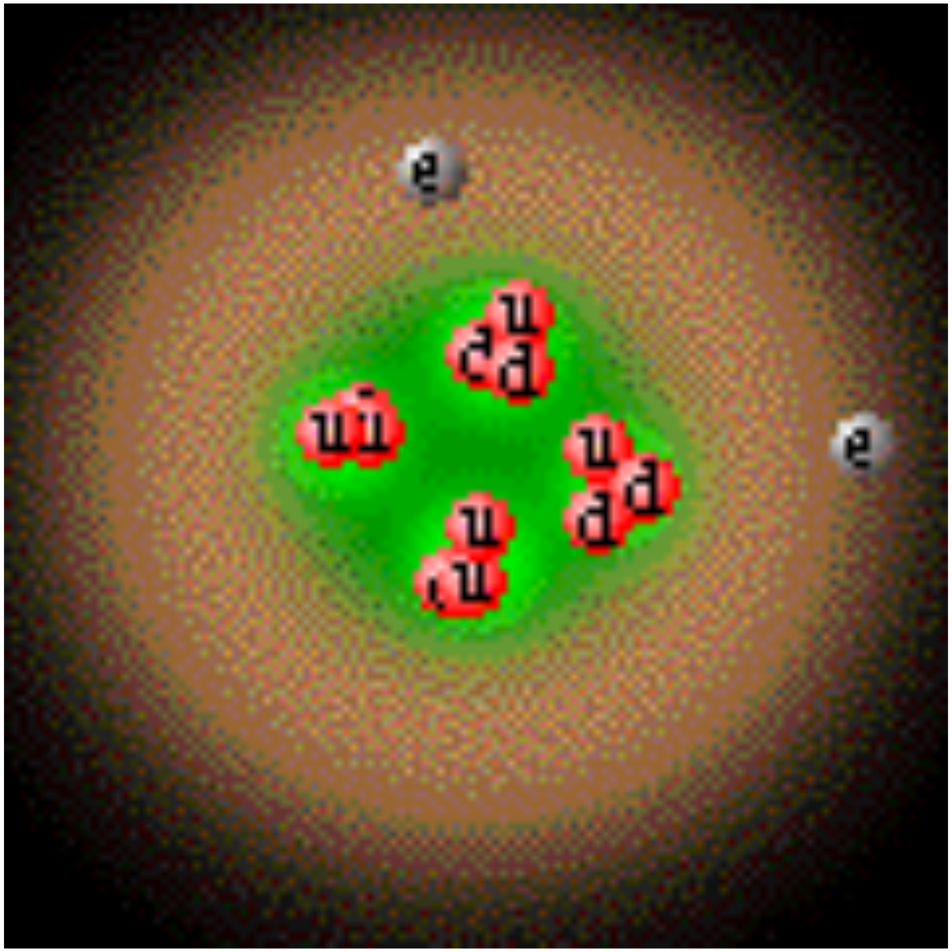


who now works on QCD with **me** and who has a famous sister…

Rick’s wife Rick’s famous sister Rick

Modern view of the atom

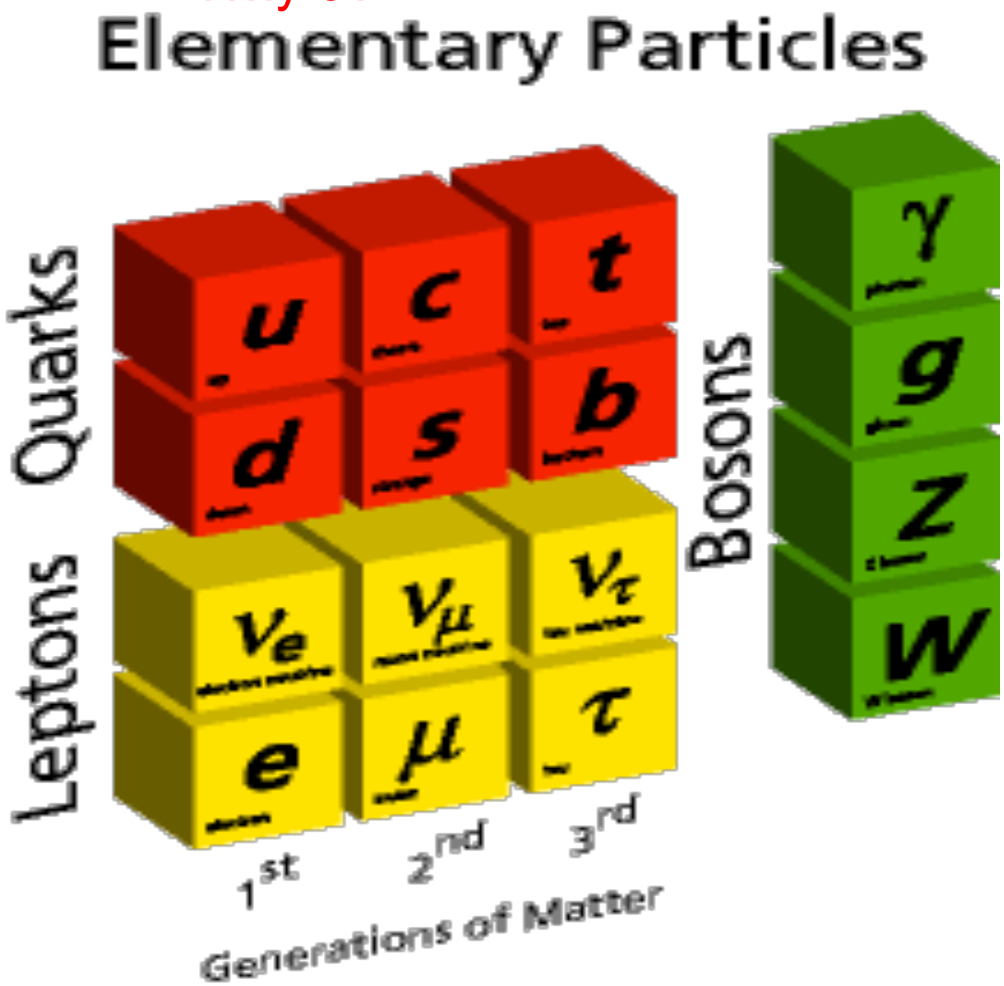
- Atoms consist of negatively charged electrons surrounding a positively charged nucleus
- The position of an electron can be described by a wave function giving its probability to be a particular location at a particular time
- The nucleus consists of protons and neutrons
- Both protons and neutrons are composed of quarks (up and down)



Standard Model

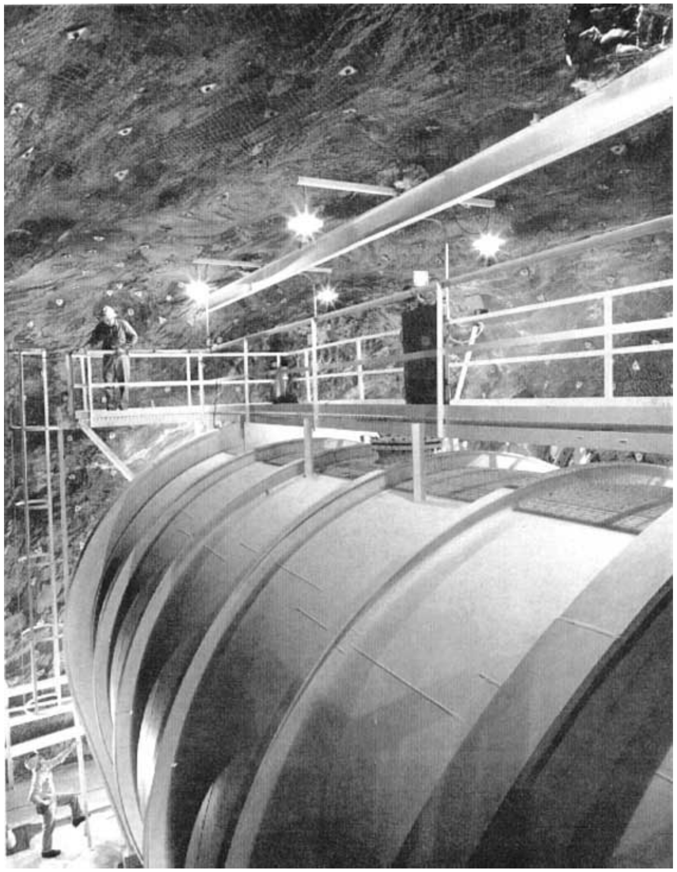
- While research was conducted on the particles- a new theory emerged that linked the electromagnetic force with the weak nuclear force-
- At a high enough temperature, both forces are actually the same.
- Combined with particle theory arises the concept of force particles or *carriers*.
- All force carriers are *bosons*.
- All of this constitutes the ***Standard Model***.

- Note 3 generations of quarks and leptons
- Why 3?



Neutrino mixing

- Note that there are 3 types of neutrinos
- If they have different masses, they can mix among each other, i.e. one type of neutrino can change into another type
- This solves an old mystery as to why the measurement of neutrinos coming from the Sun was too low by a factor of 2



100,000 gallons of perchloroethylene in the Homestake mine

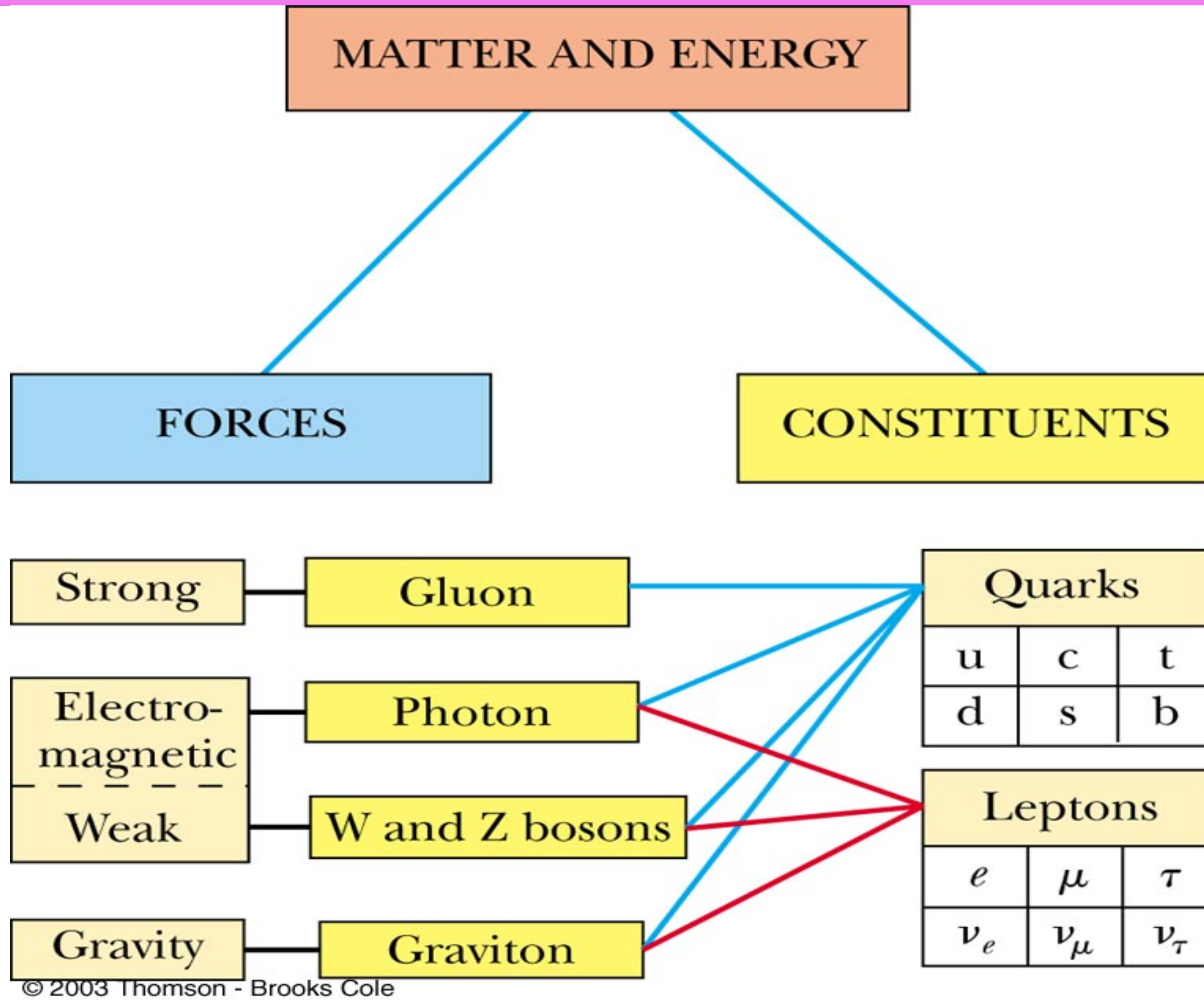
Forces in standard model

TABLE 30.1 Particle Interactions

Interaction (Force)	Relative Strength[a]	Range of Force	Mediating Field Particle
Strong	1	Short ($\sim$1 fm)	Gluon
Electromagnetic	10^{-2}	Long ($\propto 1/r^2$)	Photon
Weak	10^{-6}	Short ($\sim 10^{-3}$ fm)	$W^{\pm}$ and Z^0 bosons
Gravitational	10^{-43}	Long ($\propto 1/r^2$)	Graviton

[a] For two quarks separated by 3×10^{-17} m

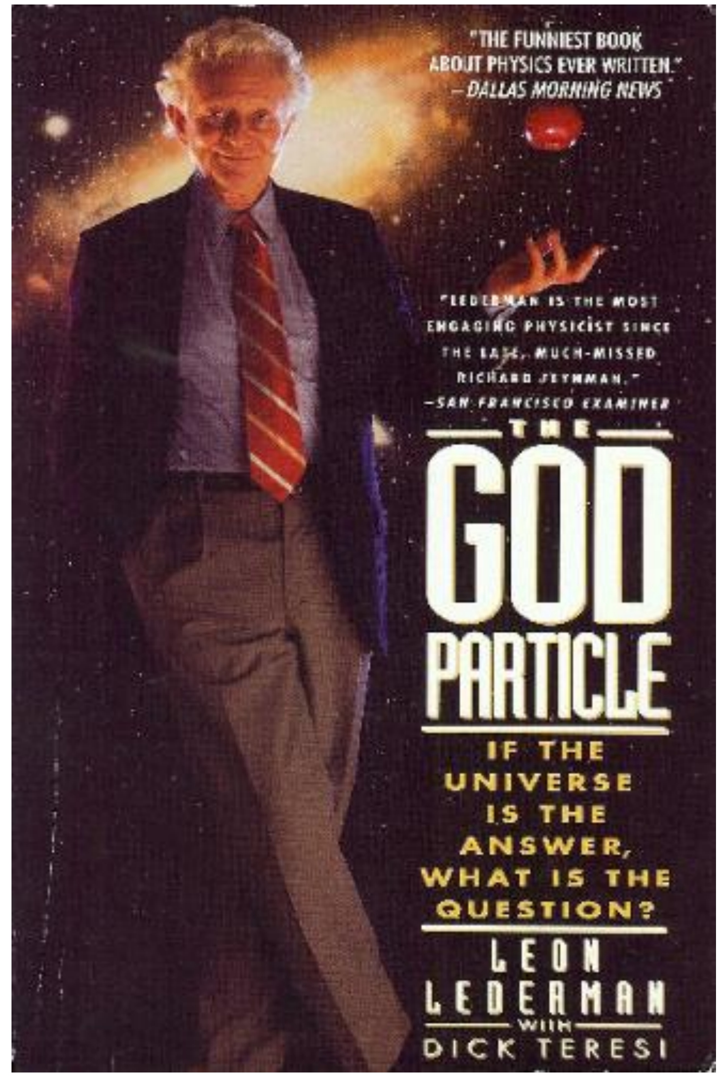
The standard model



works amazingly well

The Higgs particle

- The Higgs field fills all of space and is responsible for giving mass to all particles in the universe
  - the stronger the coupling of a particular type of particle to the Higgs field, the larger is its mass
  - it manifests as the Higgs particle
  - what Leon Lederman calls 'The God Particle'
- We found it, or at least something very much like it, at CERN on July 4

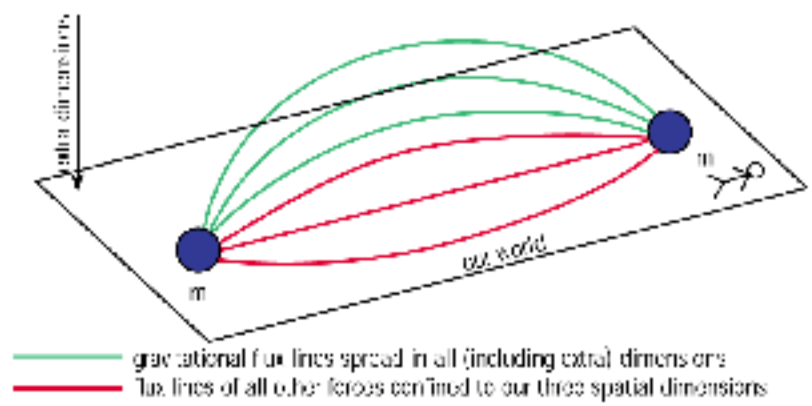


The standard model is incomplete

- Why do we see more matter than antimatter if there should be almost equal symmetry between the two in the Universe?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- Does the neutrino have mass? Yes
- Why can't the Standard Model predict a particle's mass?
- What is MASS? And why does the top quark have so much of it?
- How does gravity fit into all of this? Why is it so much weaker than the other 3 forces?
- Just how many dimensions does the universe have, anyway? And does this have something with to do with why gravity is so weak?
- Are there parallel universes? An infinite number?
- Why are there exactly three generations of quarks and leptons?
- What is all this extra matter (dark matter) in the universe that we can't explain using normal methods?
- What is all this extra energy (dark energy) in the universe that we can't explain using normal methods?

Gravity

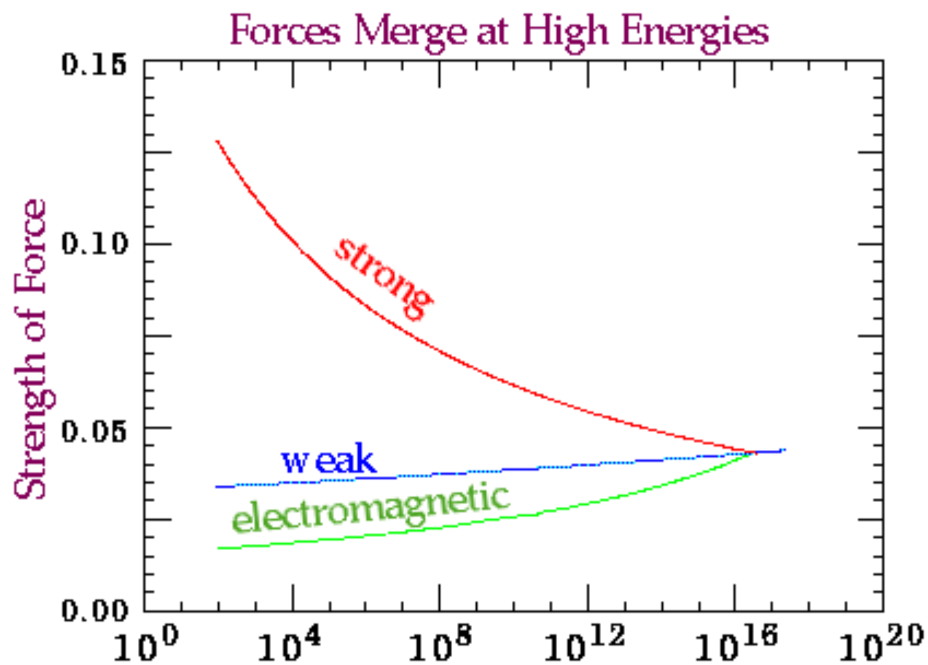
- How does gravity fit into all of this? And why is it so weak?
- Consider the experience of a person confined to a 2-D world
  - Seeing only the field lines that lay within the plane, he would measure the strength of gravity to be much less than someone who lived in the higher dimensional world
- These other dimensions must be small, i.e. rolled up
- The concept of extra dimensions could explain why gravity is so much weaker than the other forces; gravity exists in the other dimensions as well as our own 3 space + 1 time dimension, while the other 3 forces are confined to our dimensions

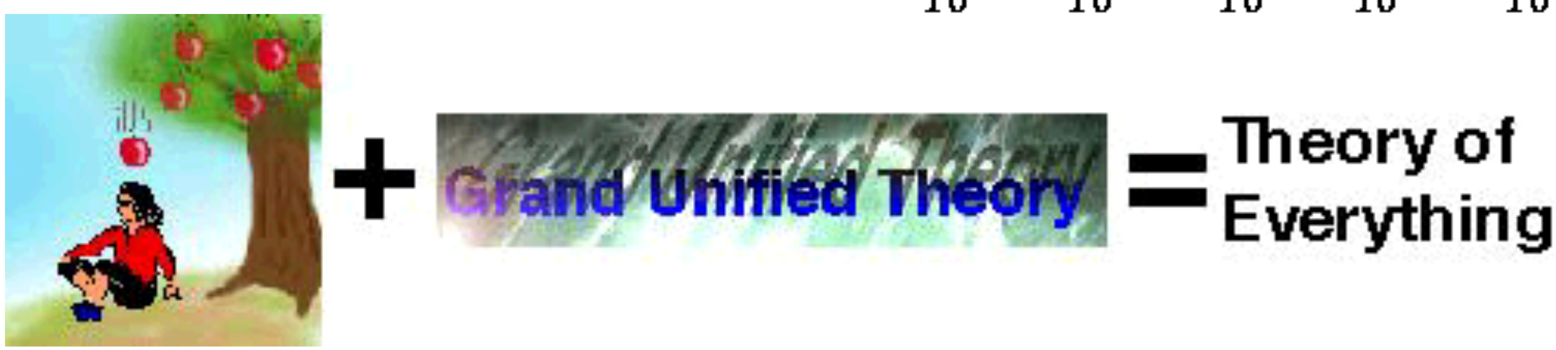


Theory of everything

How can gravitational interactions be Included in the standard model to form a 'theory of everything'?

Perhaps using string theory?

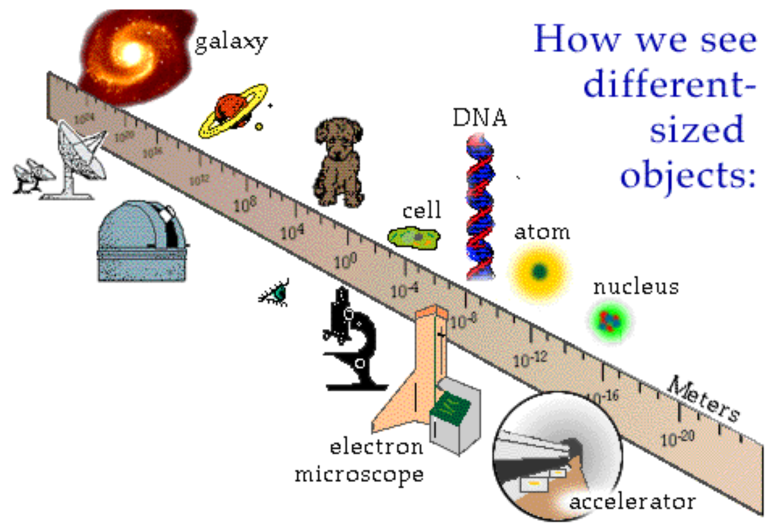




Elegant Universe

Strings

- Will often see instead of just m(eters)
  - mm (10^{-3} m)
  - μm (10^{-6} m)
  - nm (10^{-9} m)
  - pm (10^{-12} m)
  - fm (10^{-15} m)
- …or going the other way
  - km (10^{3} m)



The size of a superstring to an atom is the same as the size of a puppy to our galaxy.

Strings are down here, with a size of the order of 10^{-35} m

String theory

- Explains why gravity is so much weaker than other forces
  - it propagates into the extra dimensions, the other forces do no
- May provide a fundamental explanation/unification of all four forces, i.e. may be a Theory of Everything
  - although since it lacks concrete predictions, it is not universally accepted as a theory
  - we’ve learned that scientific theories must make testable predictions
- It predicts that the universe may have as many as 11 dimensions (10 space + 1 time)
  - a pretty neat idea, even if it turns out not to be true

Clicker question

- The Higgs mechanism

- A) explains how particles acquire mass
- B) explains why gravity is so weak
- C) explains why there are three generations of quarks and leptons
- D) all of the above
- E) none of the above

Clicker question

- The Higgs mechanism

- **A) explains how particles acquire mass**
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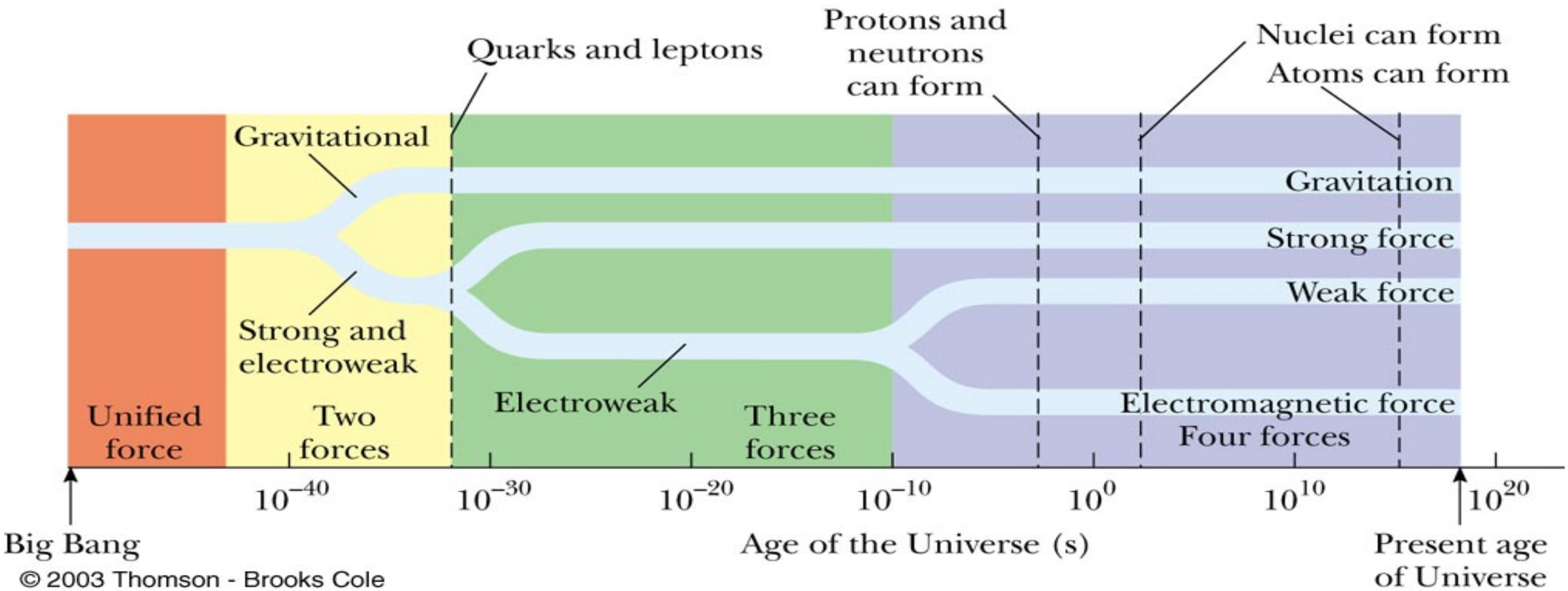
Looking back in time



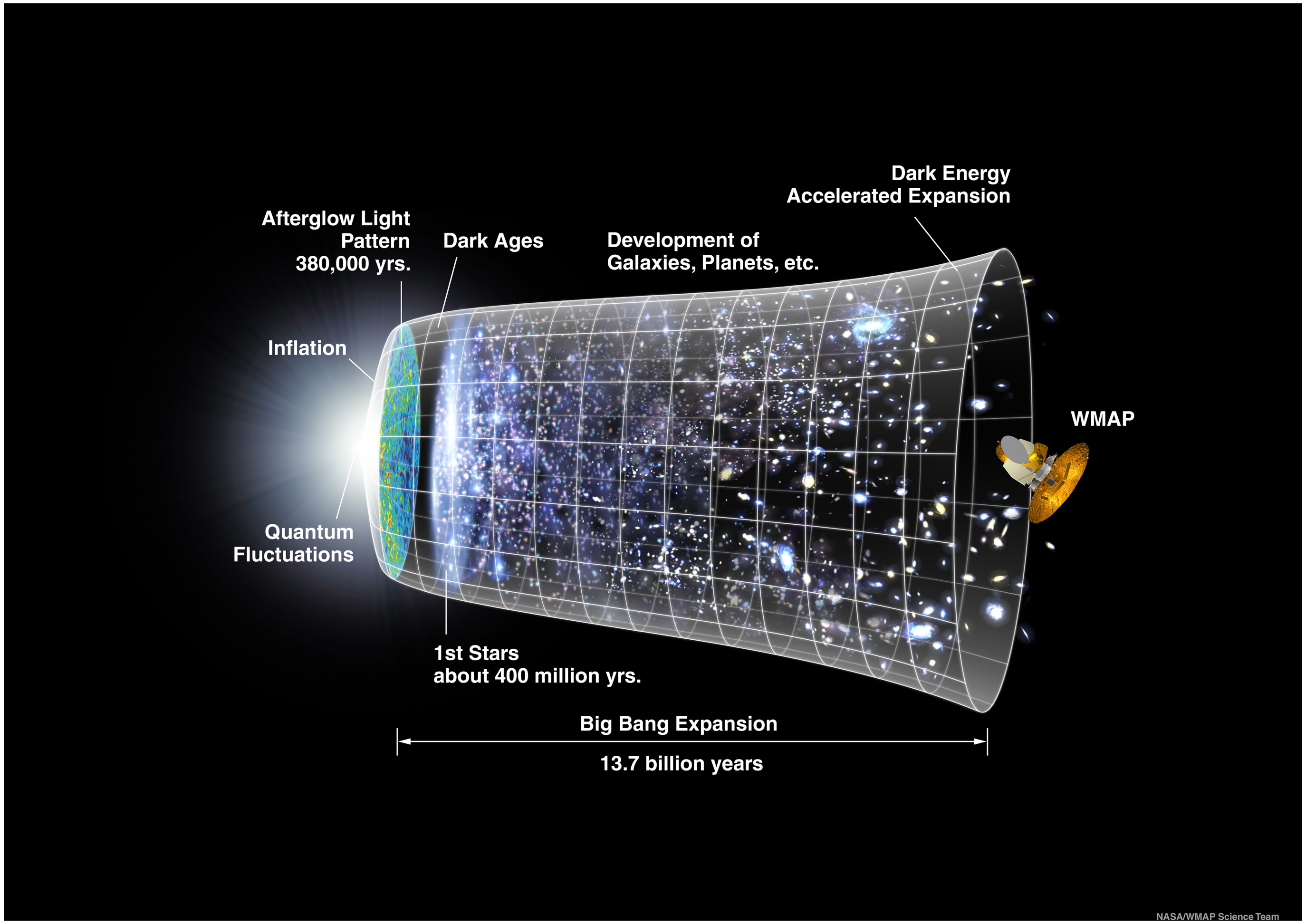
We would have to achieve these kinds of energies to directly probe strings.

I work here

you are here

WMAP

Wilkinson Microwave Anisotropy Probe

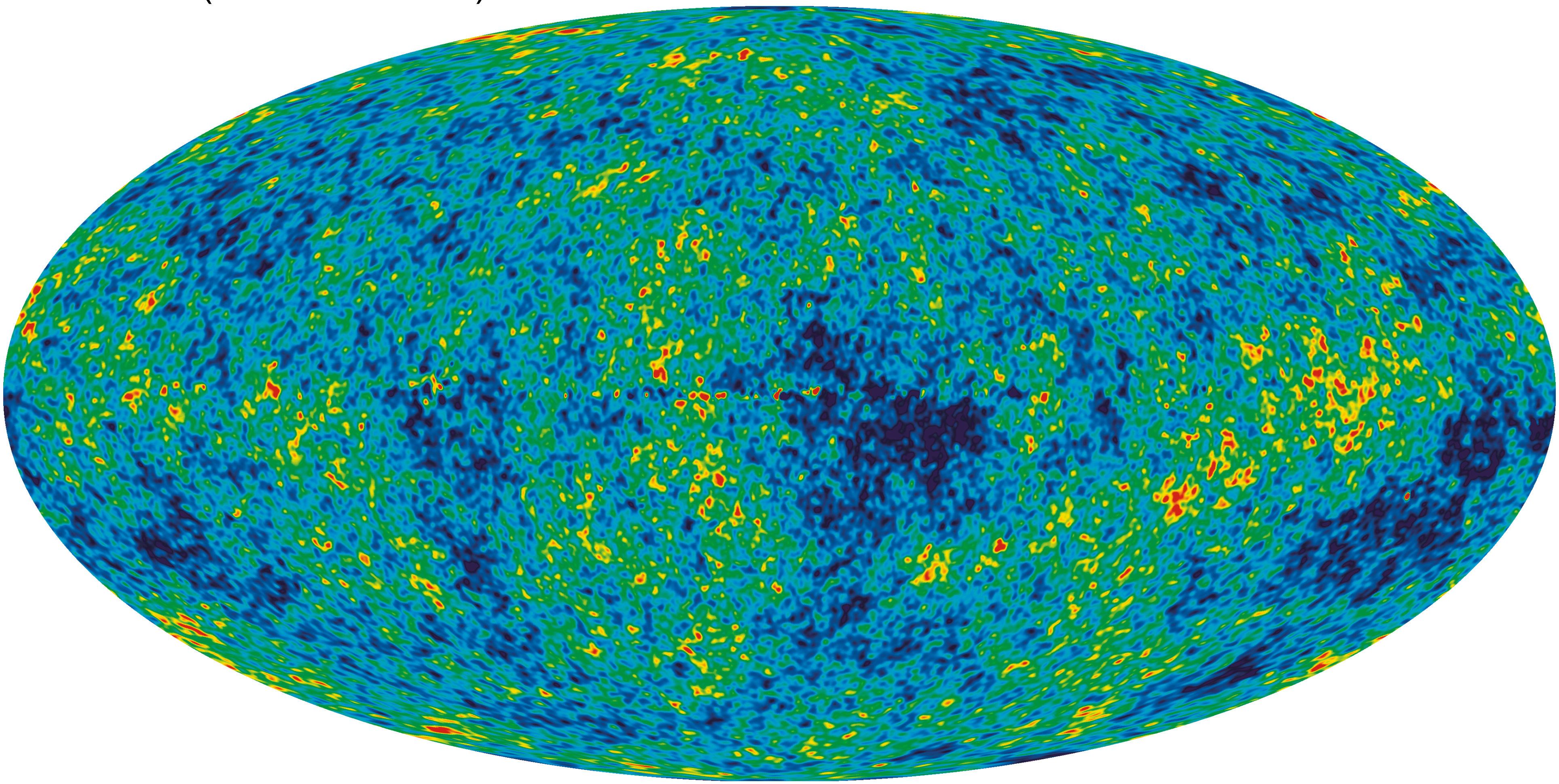


…in its mission, looked at the microwave radiation left over from the Big Bang

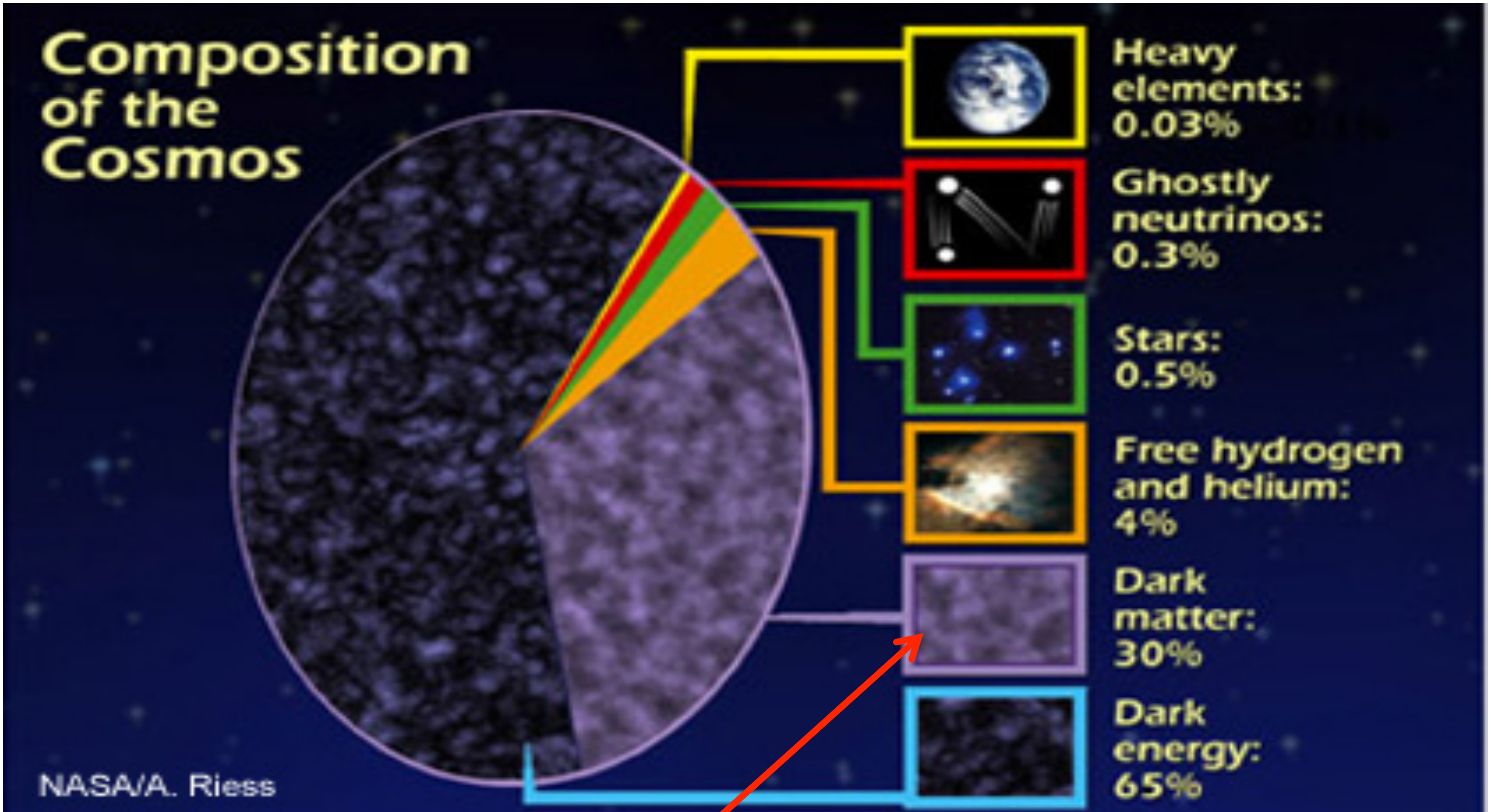
…this all started with Penzias and Wilson looking for problems with phone calls

The microwave sky

Our universe today is not uniform. So the early universe must not have been uniform either. We should see evidence of that in the map of the microwave sky and we do. The rest spots are slightly hotter (and thus denser); the blue spots cooler (and less dense).

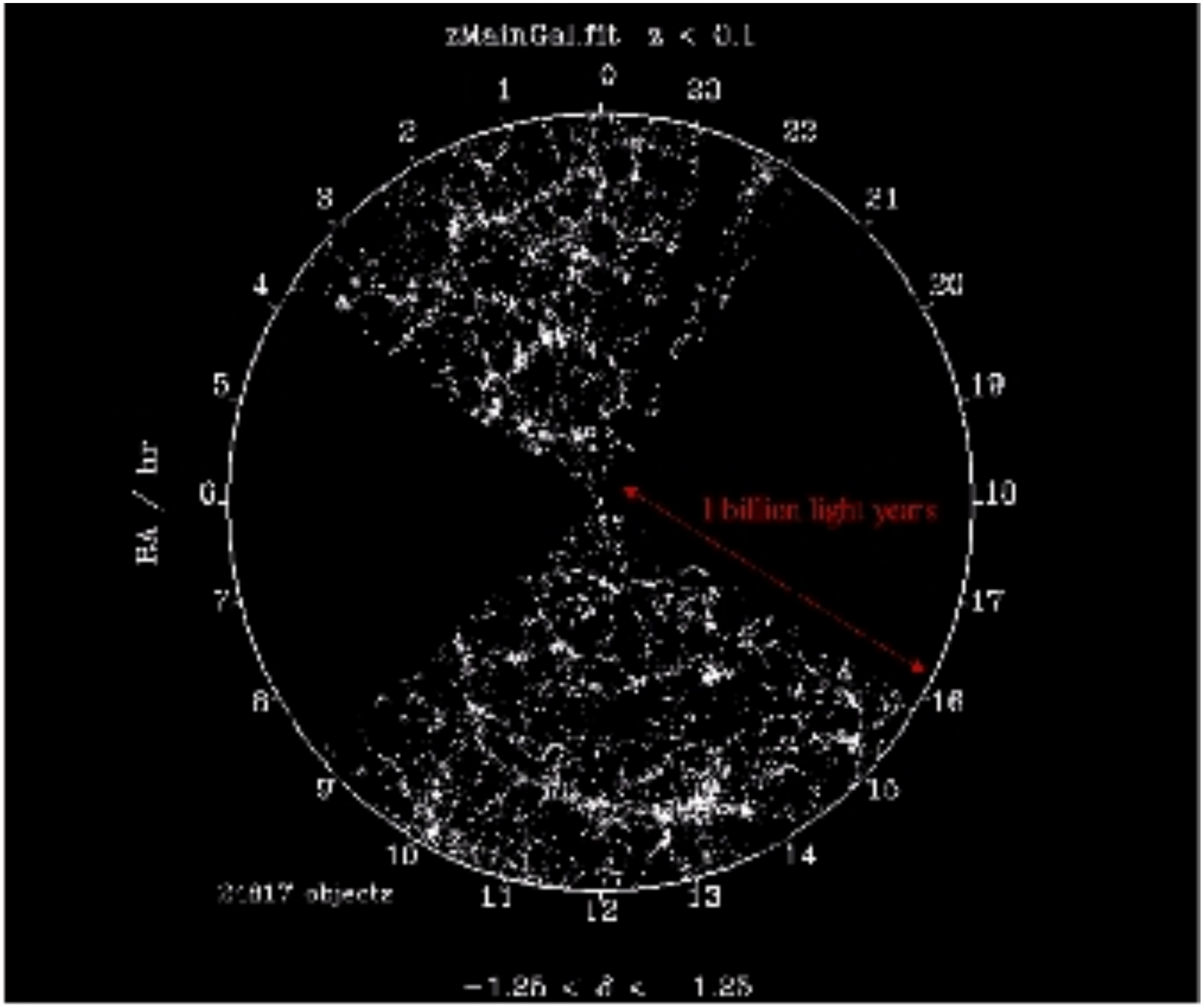


What the universe is made of



We may be able to produce dark matter particles at the LHC (cold dark matter).

…and what it looks like



our galaxy is a typical galaxy with 200 billion stars

each of the dots is a cluster of galaxies

note how non-uniform the structure is

lots of clumps and lots of voids

presumably because of dark matter