Physics 294H

- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
- Average on 3rd exam =77/120
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
  - **Are there any conflicts?**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

1930.

1.1 O.Klein 1.2 N.Bohr 1.3 W.Heisenberg 1.4 W.Pauli 1.5 G.Gamow 1.6 L.Landau 1.7 H.A.Kramers
2.1 I.Waller 2.2 P.Hein 2.3 R.Peirls 2.4 W.Heitler 2.5 F.Bloch 2.6 2.7 W.Colby 2.8 E.Teller
3.1 3.2 3.3 C.Møller 3.4 M.Pihl 3.5

Weak Nuclear Force

- Since the beta decay happened to free neutrons outside the nucleus, the Strong Nuclear Force could not be responsible.
- Thus physicists were led to consider another fundamental force- the Weak Nuclear Force.

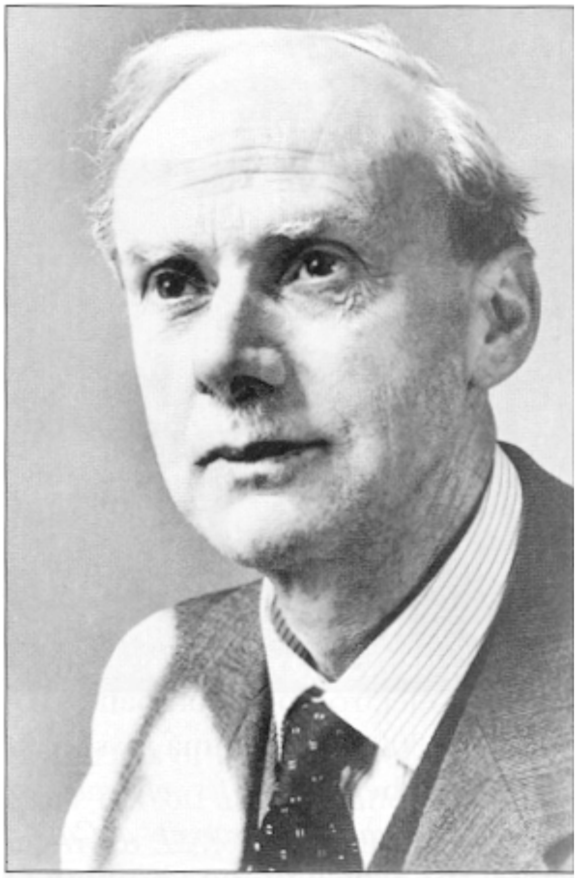
For Those Keeping Track

- At this point, there were
- Five Fundamental Particles: electron, proton, neutron, photon, and neutrino.
- And Four Fundamental Forces (or Interactions): Gravity, Electromagnetic, Strong Nuclear Force, and Weak Nuclear Force.

- Not until 1956, was there convincing experimental evidence that neutrinos really existed.
- Now generally accepted that the neutrino has mass, and the total mass of all neutrinos makes up a sizeable portion of the total energy of the universe

Fred Reines Nobel prize 1995

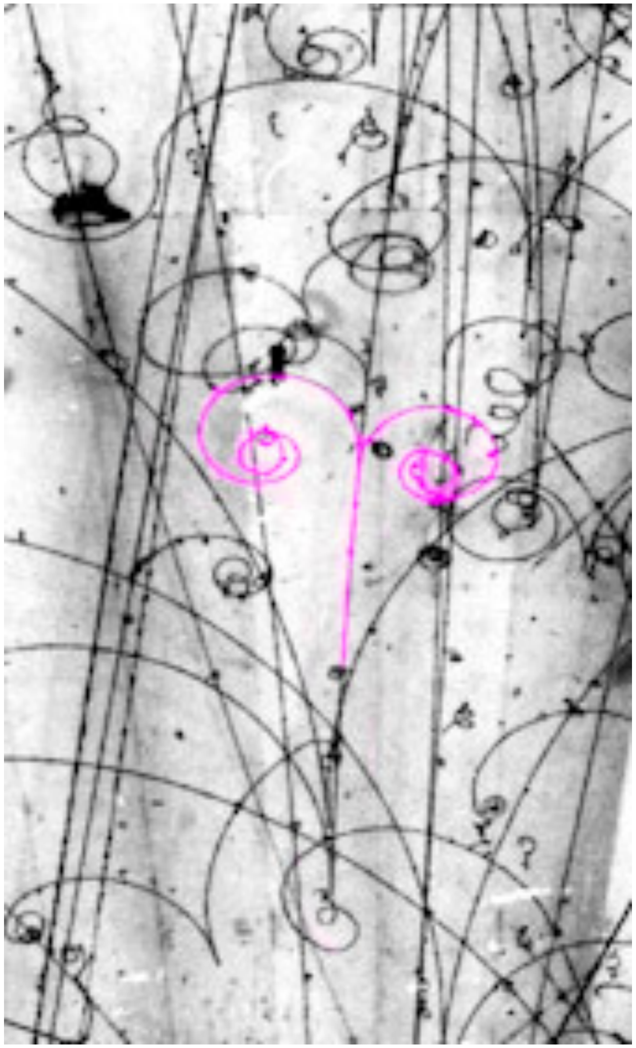
More Complications…



Paul Adrien Maurice Dirac (1902–1984)

- From 1927-1934, theoretical work by Paul Dirac on the existence of *antimatter* was proven experimentally.

- Charged particles such as electrons and protons have their oppositely charged counterparts, the *antielectron* (aka *positron*)and the *antiproton.*
- They curve the *wrong* way in a magnetic field, i.e. they have a positive charge



More Antimatter!

- In addition, the neutrino must have its own antiparticle, the *antineutrino*.
- It is currently believed that most particles have their own antiparticle pair (the photon is a major exception).

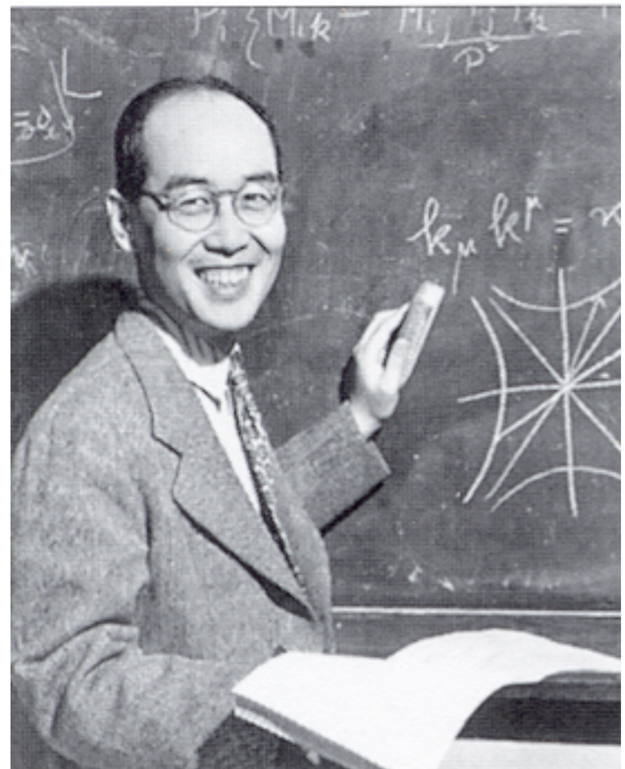
Fundamental Forces Interlude

- By mid 1930s, physicists thought they were close to figuring out the fundamental forces acting between particles.

- With the photon, a picture had arisen of the ElectroMagnetic Force as

"*charged particles interacting through the exchange of photons.*"

- Hideki Yukawa suggested a similar model to explain the strong nuclear force that was holding the protons and neutrons together inside the nucleus.



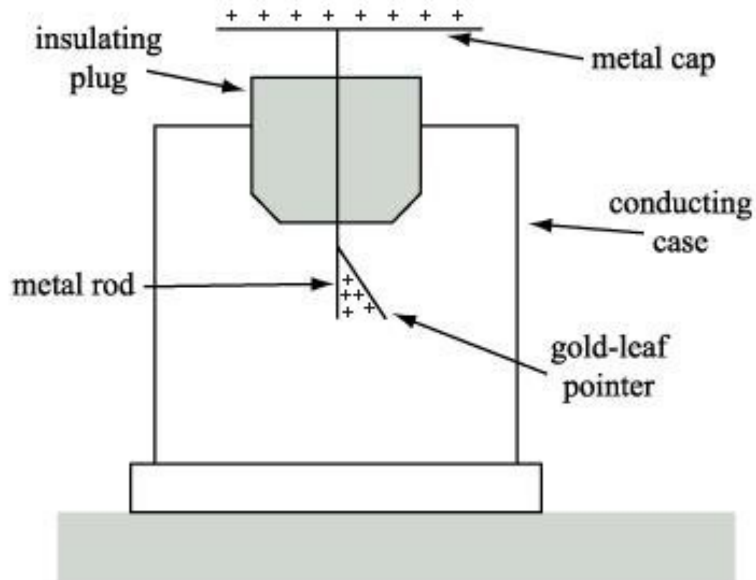
Hideki Yukawa, Japanese physicist (1907 – 1981)

- So, in his model, a new particle whose exchange between nucleons produces the strong force.
- Theoretically, the new particle would have a mass between that of an electron and a nucleon, (~200 m_e) thus it got the name

Meson, Greek for "middle."

Cosmic Ray Interlude

- The Earth is constantly bombarded by cosmic rays (mainly high energy protons) from beyond the earth.
- The earliest detector of cosmic rays was the electroscope.



- Looking at Cosmic Rays, physicists found in 1937 a particle that was similar to predictions, but did not match exactly. It did not interact strongly with matter.

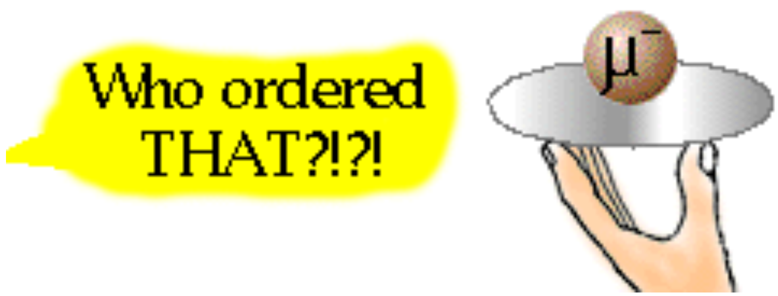
- Then World War II happened and most work on particle physics was put on hold.
- After WWII, physicists started to realize that the meson discovered in 1937 could not be the same as the one predicted by Yukawa.

Another Particle!

- The 1937 meson receives the name of *mu meson* or *muon* for short.

μ

- Realizing this was an "extra" particle, made I.I. Rabi comment "who ordered that?"
- The word *Lepton* is introduced to describe particles that do not interact strongly, electrons & muon become part of this family.



1946

- A meson that does interact strongly is found in cosmic rays, and is named the *pi meson* or *pion* for short.

π

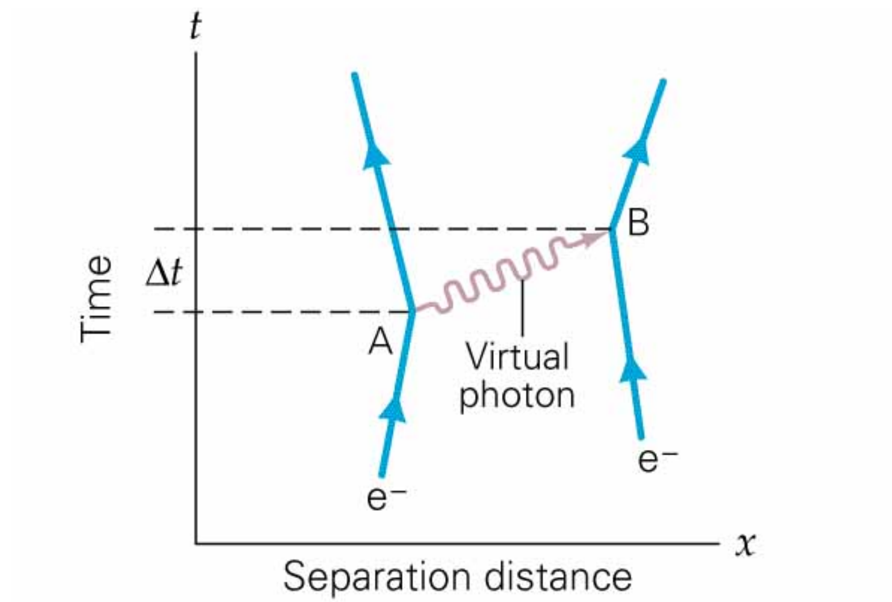
Richard Feynman

Richard Feynman (1918–1988) with his son, Carl, in 1965

- 1947: Feynman develops Quantum Electrodynamics (QED) and his Feynman diagrams.

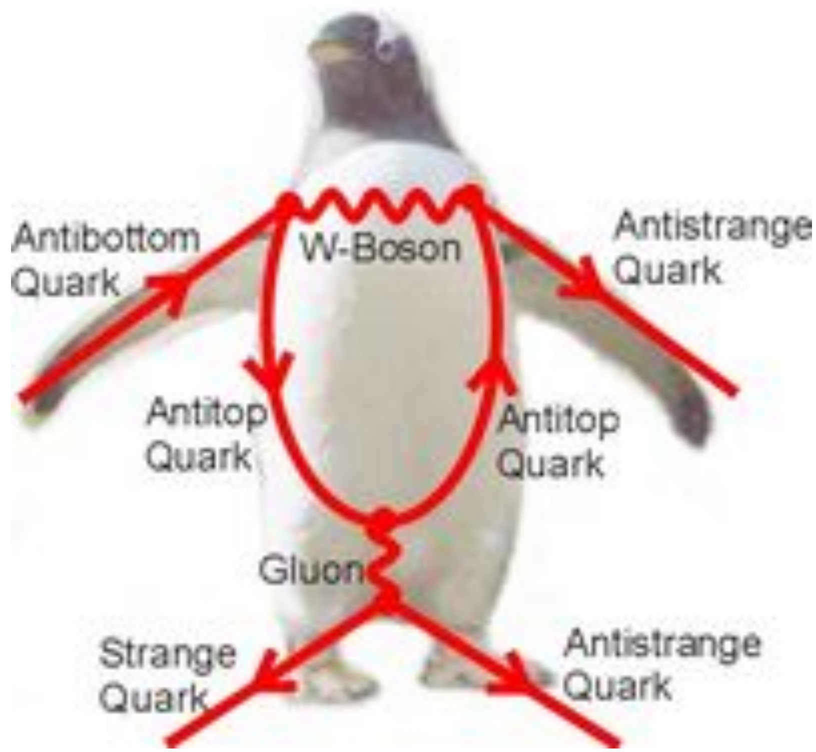
Feynman Diagrams

- Physicists now have procedures to calculate electromagnetic properties of electrons, positrons, and photons.



Including Penguin diagrams

- That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet."For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history."

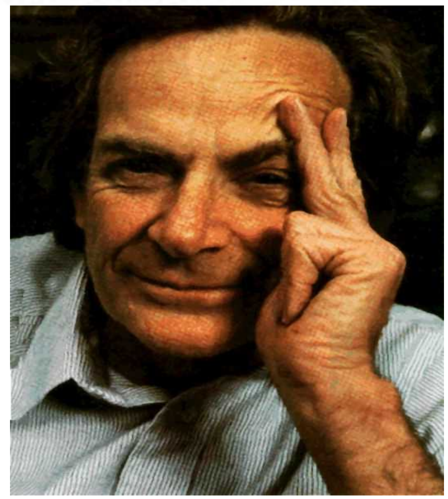


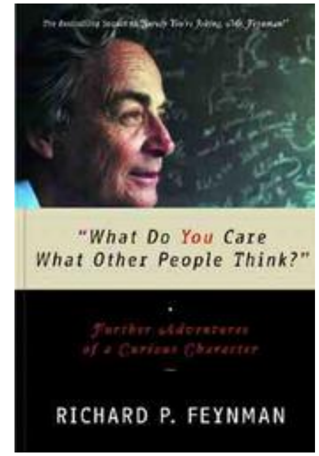
Either read the books…

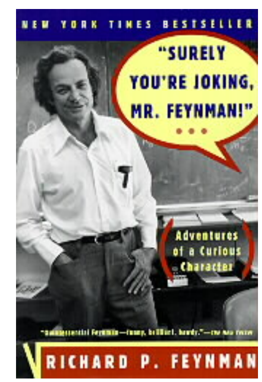
- Most of the public knows him fro the investigation of the Challeng disaster
- Also the father of nanotechnology

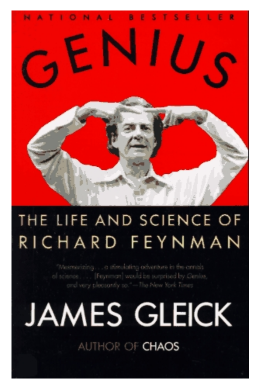
- Some quotes:

- “For those who want some proof that physicists are human, the proof is in the idiocy of all the different units which they use for measuring energy.”
- “I love only nature, and I hate mathematicians.”
- “Physics is like sex: sure, it may give some practical results, but that's not why we do it.”









…or see the movie

- Matthew Broderick as Richard Feynman in *Infinity*
- There is also a great new movie that appeared on the Science channel about Feynman and the Challenger disaster

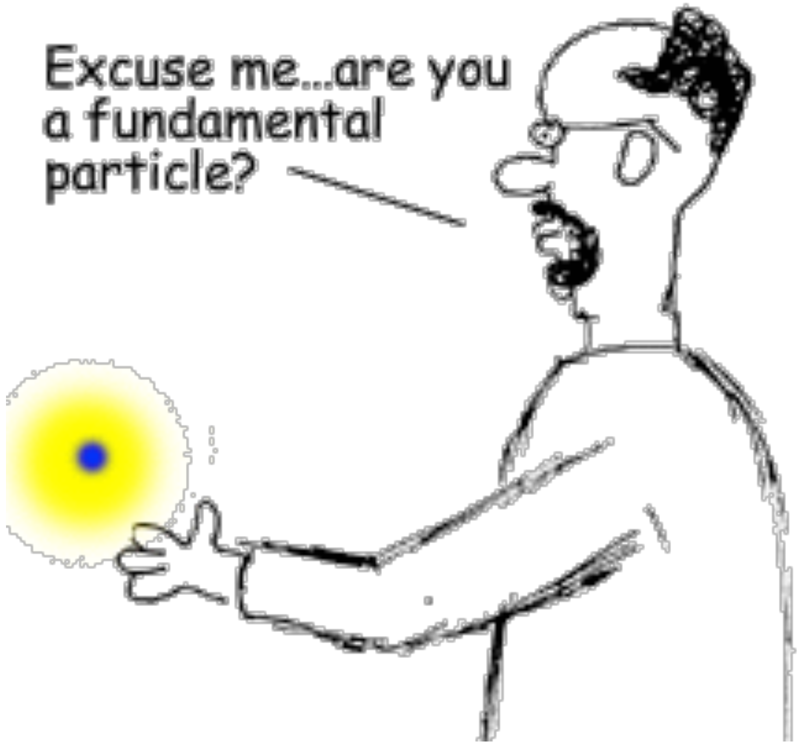
Accelerators

- In 1948, the Berkeley synchro-cyclotron produces the first artificial pions.
- Thus is launched the era of accelerators to produce and discover new particles- High Energy Physics.

It’s a Jungle Out There!

- Through the 1950s and on to the 1960s, a large assortment of particles were discovered.
- Currently the number of such particles is greater than 200!
- The large number prompted

- **Enrico Fermi to say:**
  "If I could remember the names of these particles, I would have been a botanist!"



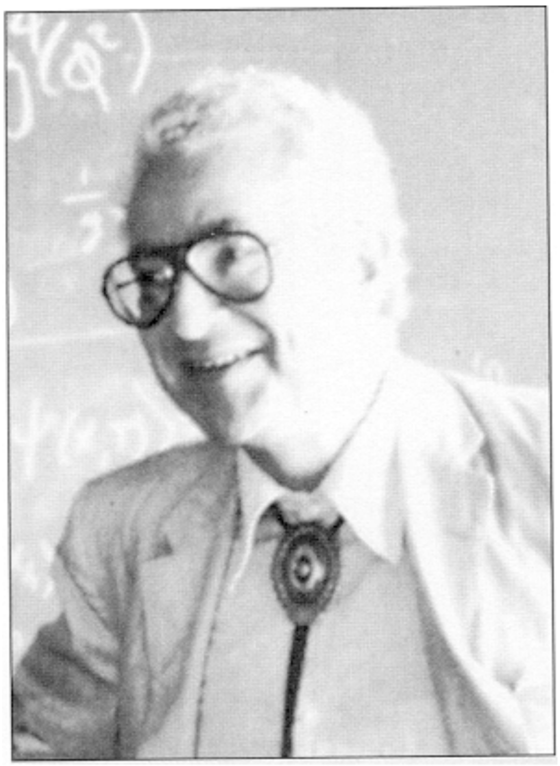
- The Lepton family seemed to be small- only 6 members (electron, muon and the tau; with each there was an associated neutrino)
- All the new particles being discovered were hadrons.

TABLE 30.2 Some Particles and Their Properties

Category	Particle Name	Symbol	Anti-particle	Mass (MeV/c^2)	B	L_e	L_μ	L_τ	S	Lifetime(s)	Principal Decay Modes[a]
Leptons	Electron	e^-	e^+	0.511	0	+1	0	0	0	Stable	
	Electron–Neutrino	ν_e	$\bar{\nu}_e$	$<7\ eV/c^2$	0	+1	0	0	0	Stable	
	Muon	μ^-	μ^+	105.7	0	0	+1	0	0	2.20×10^{-6}	$e^- \bar{\nu}_e \nu_\mu$
	Muon–Neutrino	ν_μ	$\bar{\nu}_\mu$	<0.3	0	0	+1	0	0	Stable	
	Tau	τ^-	τ^+	1784	0	0	0	+1	0	$<4 \times 10^{-13}$	$\mu^- \bar{\nu}_\mu \nu_\tau$, $e^- \bar{\nu}_e \nu_\tau$
	Tau–Neutrino	ν_τ	$\bar{\nu}_\tau$	<30	0	0	0	+1	0	Stable	
Hadrons											
Mesons	Pion	π^+	π^-	139.6	0	0	0	0	0	2.60×10^{-8}	$\mu^+ \nu_\mu$
		π^0	Self	135.0	0	0	0	0	0	0.83×10^{-16}	2γ
	Kaon	K^+	K^-	493.7	0	0	0	0	+1	1.24×10^{-8}	$\mu^+ \nu_\mu$, $\pi^+ \pi^0$
		K^0_S	$\bar{K}^0_S$	497.7	0	0	0	0	+1	0.89×10^{-10}	$\pi^+ \pi^-$, $2\pi^0$
		K^0_L	$\bar{K}^0_L$	497.7	0	0	0	0	+1	5.2×10^{-8}	$\pi^\pm e^\mp \bar{\nu}_e$, $3\pi^0$ $\pi^\pm \mu^\mp \bar{\nu}_\mu$
	Eta	η	Self	548.8	0	0	0	0	0	$<10^{-18}$	2γ, 3π
		η'	Self	958	0	0	0	0	0	2.2×10^{-21}	$\eta \pi^+ \pi^-$
Baryons	Proton	p	$\bar{p}$	938.3	+1	0	0	0	0	Stable	
	Neutron	n	$\bar{n}$	939.6	+1	0	0	0	0	920	$p e^- \bar{\nu}_e$
	Lambda	Λ^0	$\bar{\Lambda}^0$	1115.6	+1	0	0	0	−1	2.6×10^{-10}	$p\pi^-$, $n\pi^0$
	Sigma	Σ^+	$\bar{\Sigma}^-$	1189.4	+1	0	0	0	−1	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
		Σ^0	$\bar{\Sigma}^0$	1192.5	+1	0	0	0	−1	6×10^{-20}	$\Lambda^0 \gamma$
		Σ^-	$\bar{\Sigma}^+$	1197.3	+1	0	0	0	−1	1.5×10^{-10}	$n\pi^-$
	Xi	Ξ^0	$\bar{\Xi}^0$	1315	+1	0	0	0	−2	2.9×10^{-10}	$\Lambda^0 \pi^0$
		Ξ^-	$\bar{\Xi}^+$	1321	+1	0	0	0	−2	1.64×10^{-10}	$\Lambda^0 \pi^-$
	Omega	Ω^-	Ω^+	1672	+1	0	0	0	−3	0.82×10^{-10}	$\Xi^0 \pi^0$, $\Lambda^0 K^-$

[a] Notations in this column such as $p\pi^-$, $n\pi^0$ mean two possible decay modes. In this case, the two possible decays are $\Lambda^0 \to p + \pi^-$ and $\Lambda^0 \to n + \pi^0$.

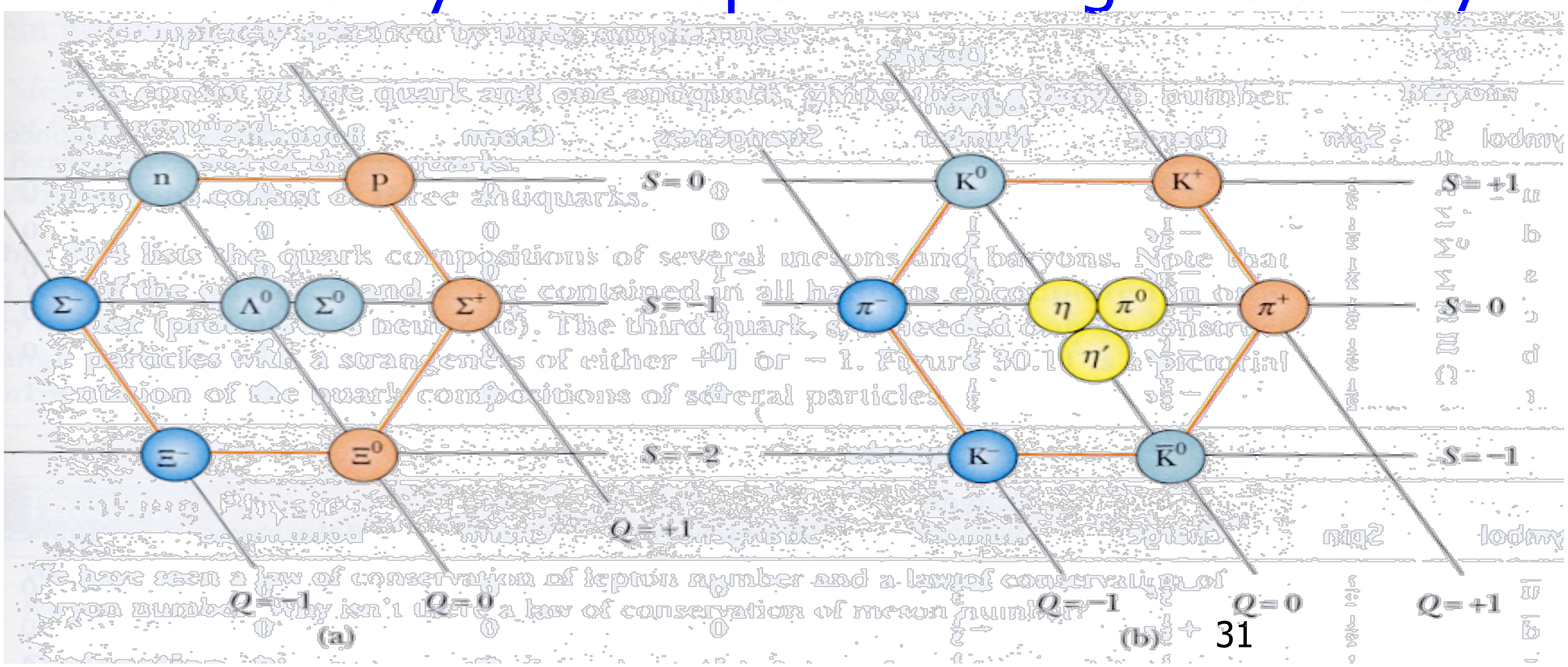
Murray Gell-Mann



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.
- In addition, the pattern hinted at an underlying structure.

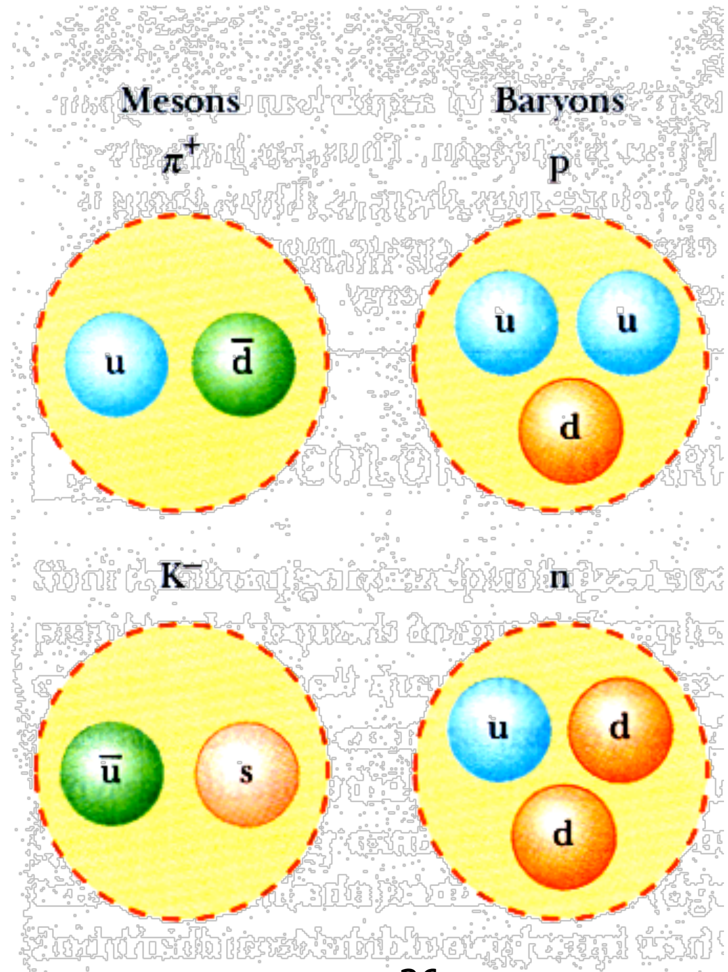
- Research at newer accelerators hinted at varying charge densities within nucleons.

- 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.

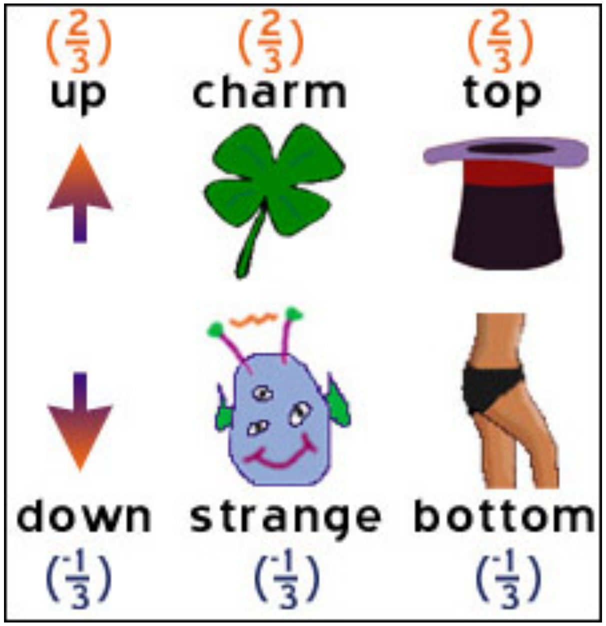
Finnegan's Wake

- Whimsically, Gell-Mann names them "*Quarks*" from a line in James Joyce's Finnegan's Wake
- "Three quarks for Muster Mark!"

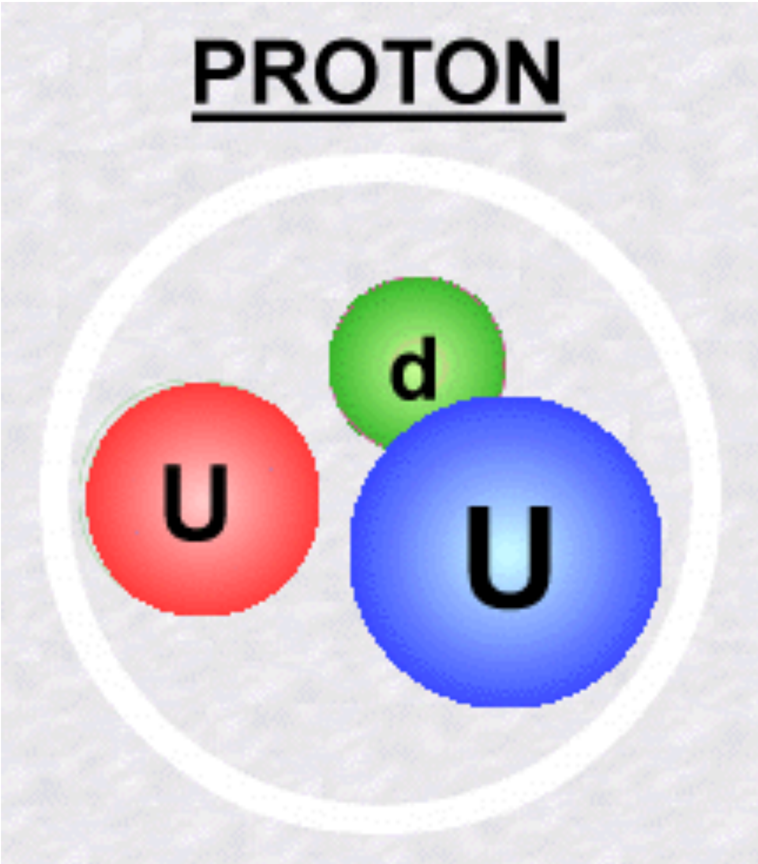
- Simply put,
- Mesons consist of a quark and an antiquark.
- Baryons consisted of three quarks.



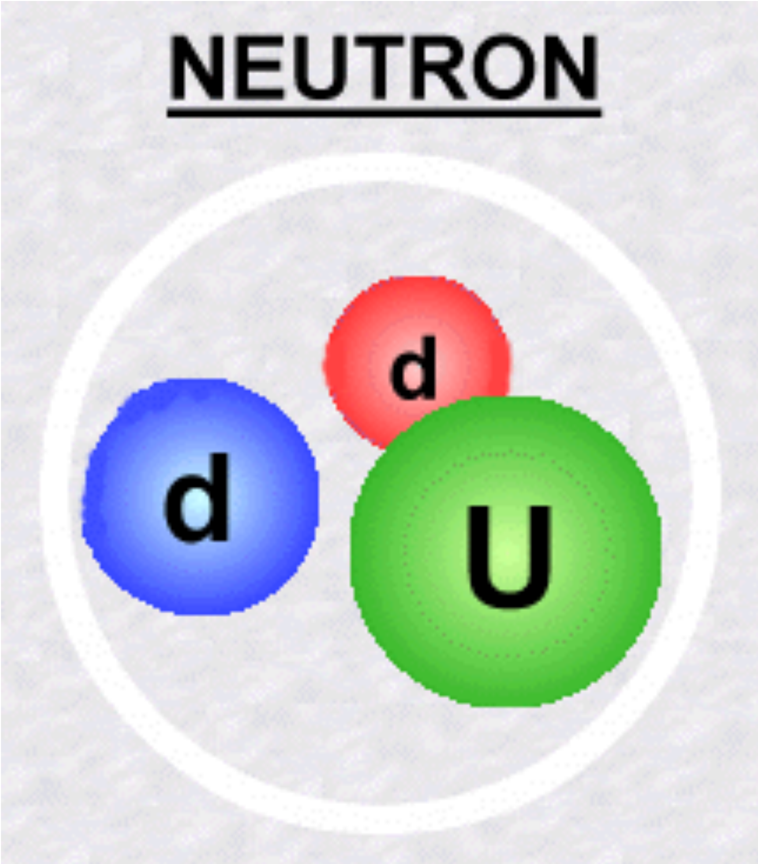
- Originally there were three (up, down, and sideways)
- Further research has led to 6



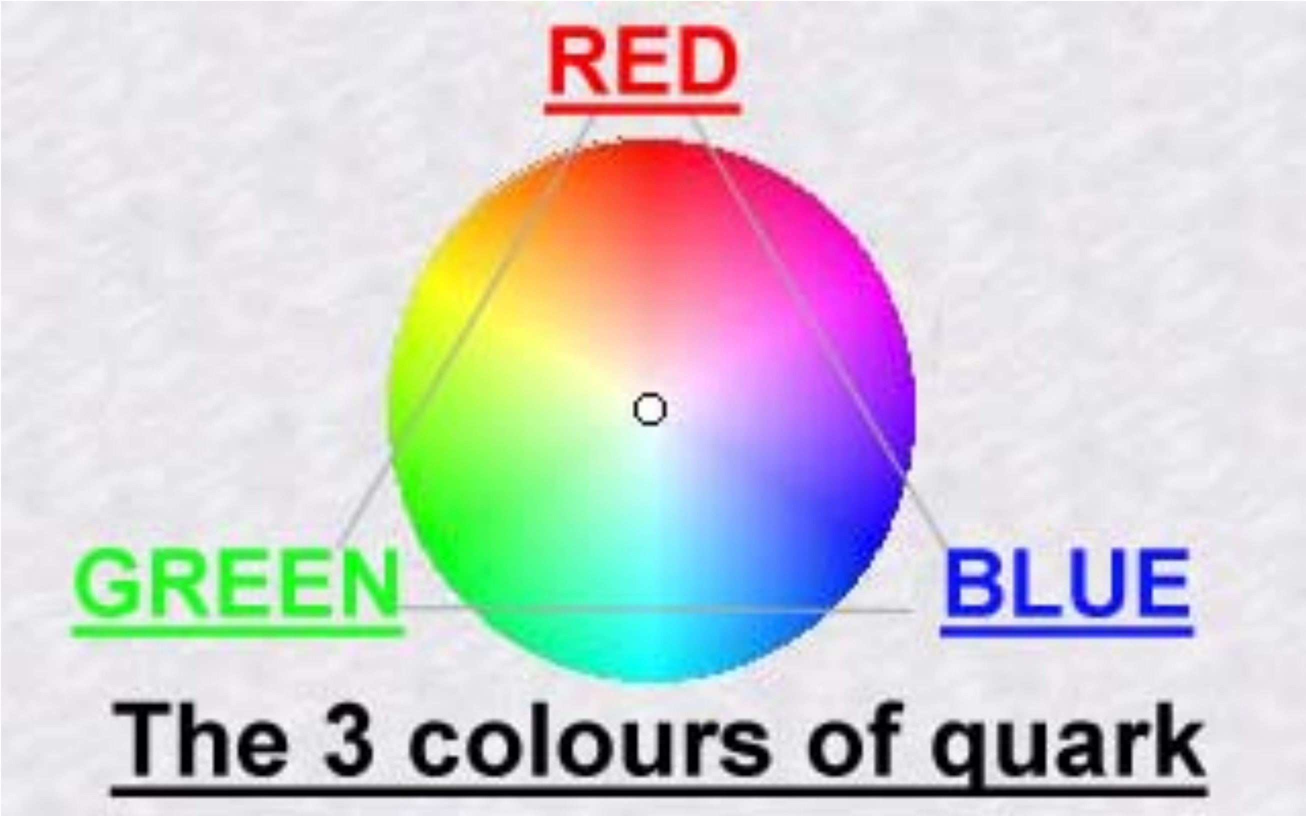
So a Proton is…



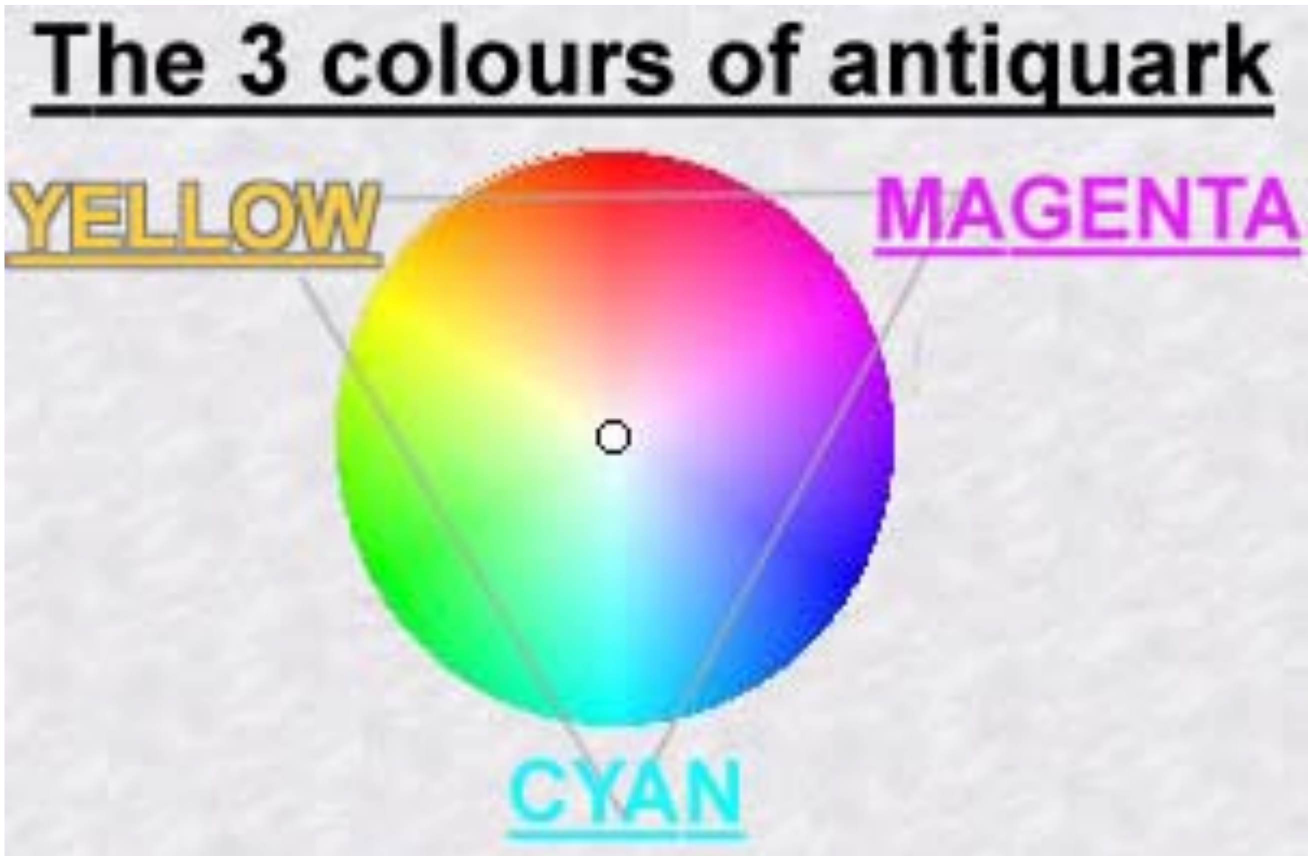
& a Neutron is…



In Case you were thinking this was getting simpler…

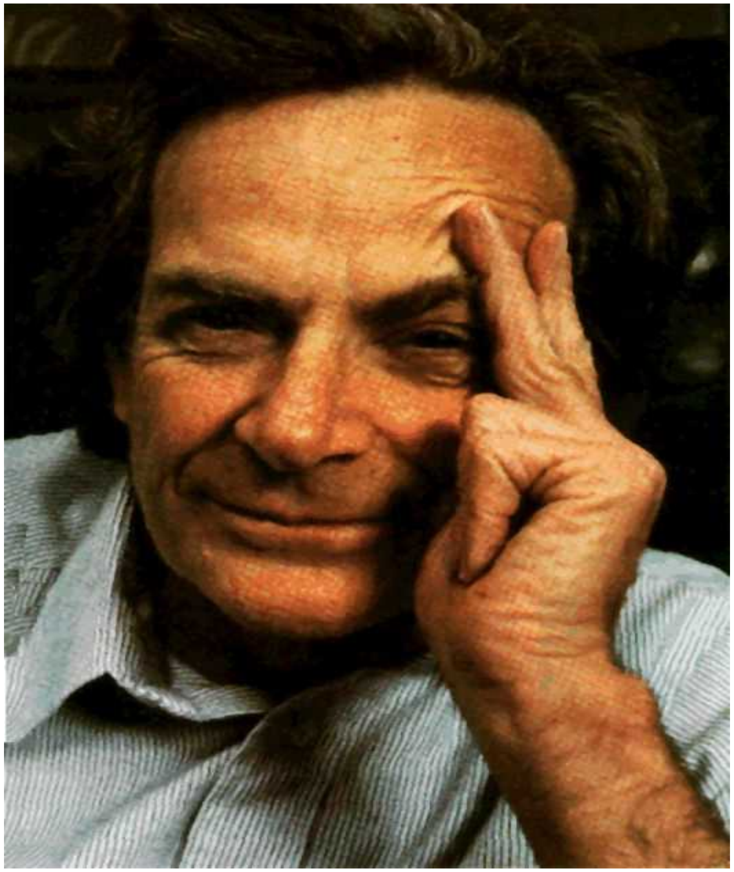


& Don't Forget...



The theory of the strong interaction is called Quantum Chromodynamics or QCD.

Feynman helped to develop QCD with Rick Field



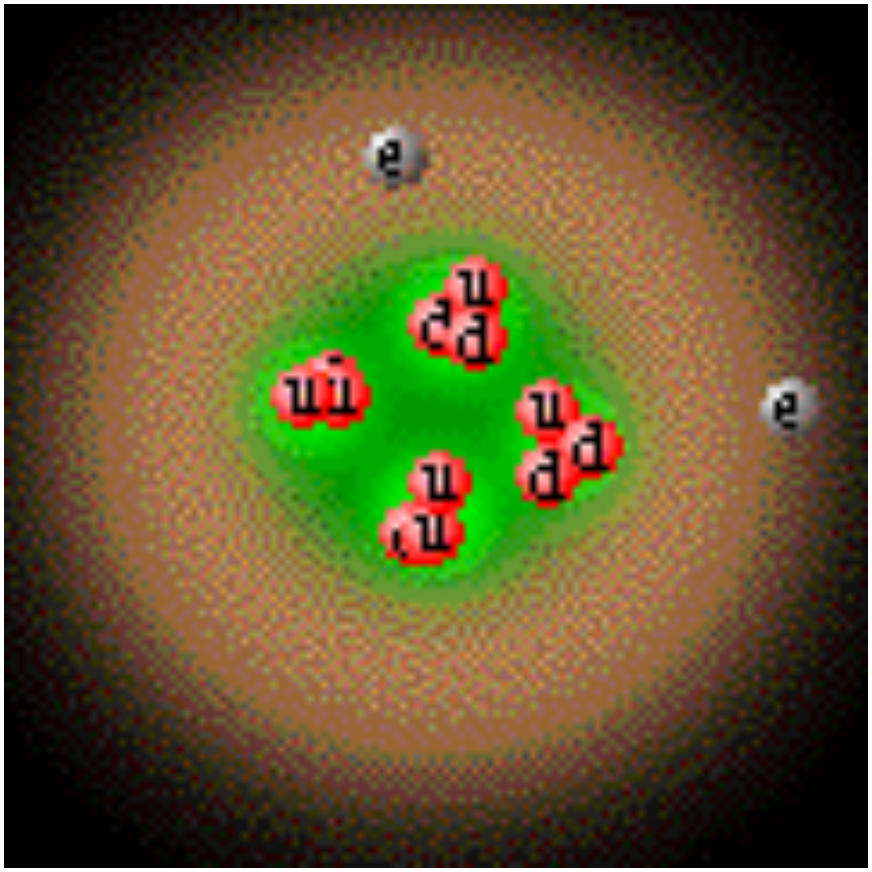
who now works on QCD with **me** and who has a famous sister…

Rick's famous sister

Rick's wife　　　Rick's famous sister　　　Rick

Me and Rick’s famous sister (at CERN)

Modern Atom

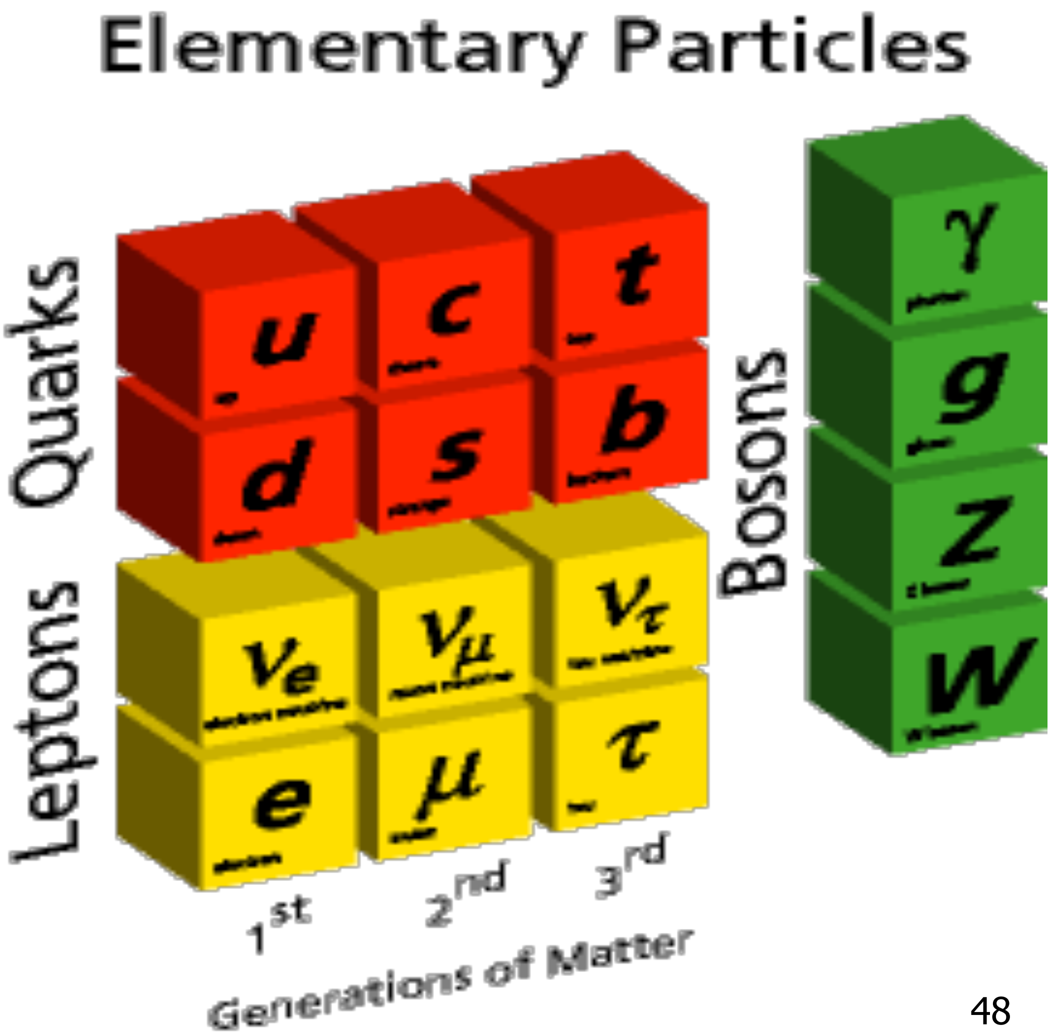


How about the Forces?

- 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* (don't obey the exclusion principle).
- All of this constitutes the ***Standard Model***.

The Standard Model



BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

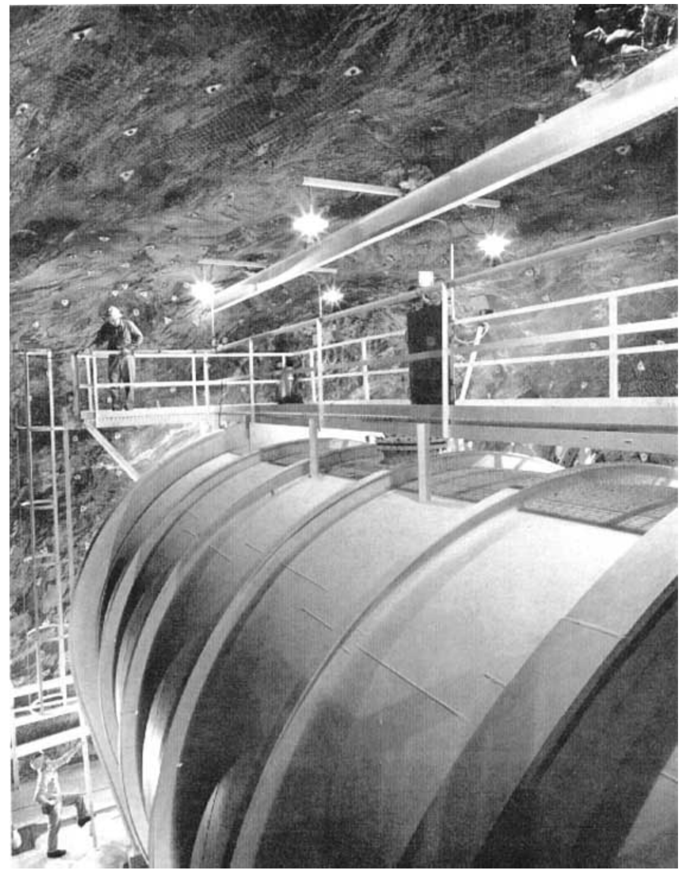
FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

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**

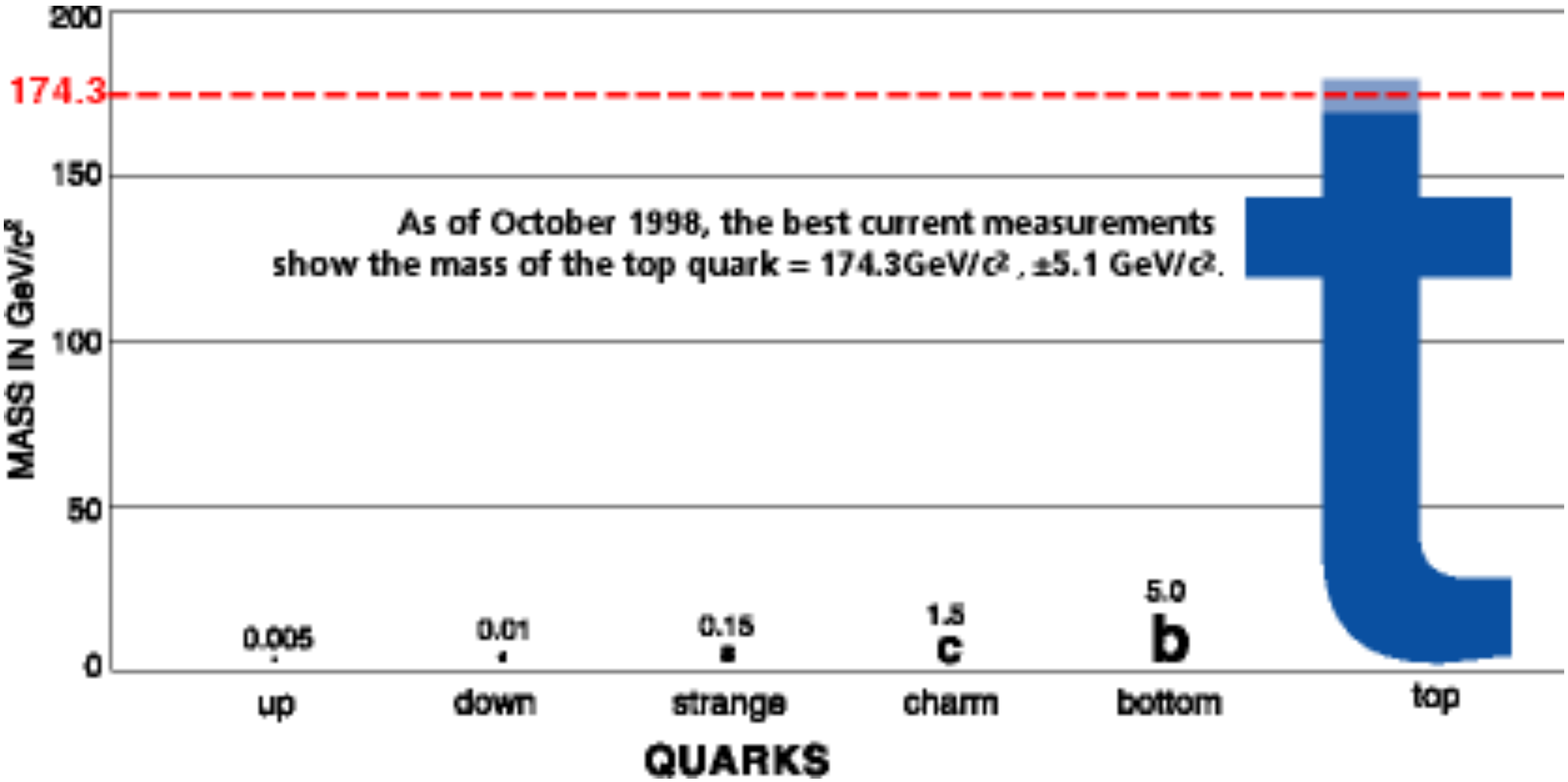
Interaction (Force)	Relative Strength[a]	Range of Force	Mediating Field Particle
Strong	1	Short ($\sim$1 fm)	Gluon
Electromagnetic	10^{-2}	Long ($\propto 1/r^2$)	Photon
Weak	10^{-6}	Short ($\sim 10^{-3}$ fm)	$W^{\pm}$ and Z^0 bosons
Gravitational	10^{-43}	Long ($\propto 1/r^2$)	Graviton

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

…but are we happy? NO

- 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?
- 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?

Top quark



200
174.3
150
100
50
0
MASS IN GeV/c²
As of October 1998, the best current measurements show the mass of the top quark = 174.3GeV/c², ±5.1 GeV/c².
0.005
0.01
0.15
1.5
c
5.0
b
t
up
down
strange
charm
bottom
top
QUARKS

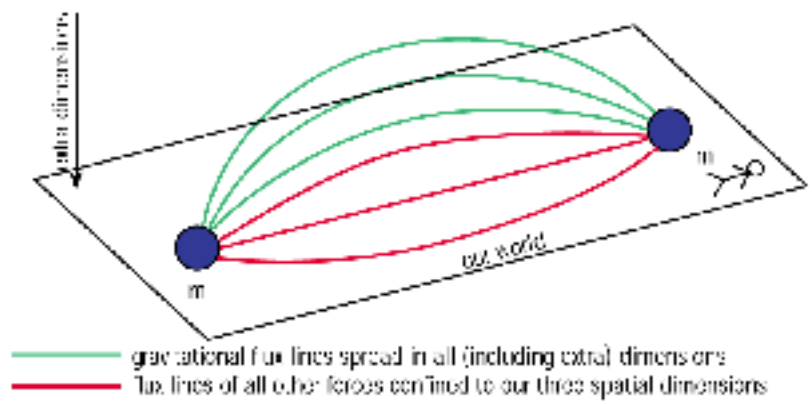
Gravity

- How does gravity fit into all of this?
  - and why is it so weak?

Extra Dimensions

- 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
  - …but if the 3rd dimension were infinite he would observe a deviation in the gravitational force from the 1/r law he expected in his two dimensions
    - …unless the extra dimension(s) were small
    - …in our case, they could be as large as 0.01 mm
- Tests consist of measuring G at the sub-millimeter scale and looking for graviton production in high energy collisions

The concept of extra dimensions could explain why gravity is so much weaker than the other forces; gravity lives in the higher dimensions while the other forces are confined to the 3+1 we know and love



Black holes (posting)

- Scientists at the European Center for Nuclear Research (CERN) want to use their atom smasher **to make mini-black holes to study Hawking Radiation.** I mean, how can anyone resist the urge to imagine future headlines like "Artificial Black Hole Escapes Laboratory, Eats Chicago" or some such thing? In reality, there is no risk posed by creating artificial black holes, at least not in the manner planned with the LHC. The black holes produced at CERN will be millions of times smaller than the nucleus of an atom; too small to swallow much of anything. And they'll only live for a tiny fraction of a second, too short a time to swallow anything around them even if they wanted to. I *really really really* hope they are right about the lack of danger involved in doing this. In James P. Hogan's science fiction novel **Thrice Upon A Time** his hero just happened to be working on a machine to send messages back thru time. Therefore his hero was able to save the planet Earth by sending a message back to warn a European physics research group that it would make a black hole if it conducted its planned experiment. But in reality we would have no such miraculous means to save us from a black hole eating away at the core of planet Earth.

Comments on claimed risk from metastable black holes

Steven B. Giddings[a,b,1] and Michelangelo L. Mangano[b,2]

[a] *Department of Physics, University of California, Santa Barbara, CA 93106*

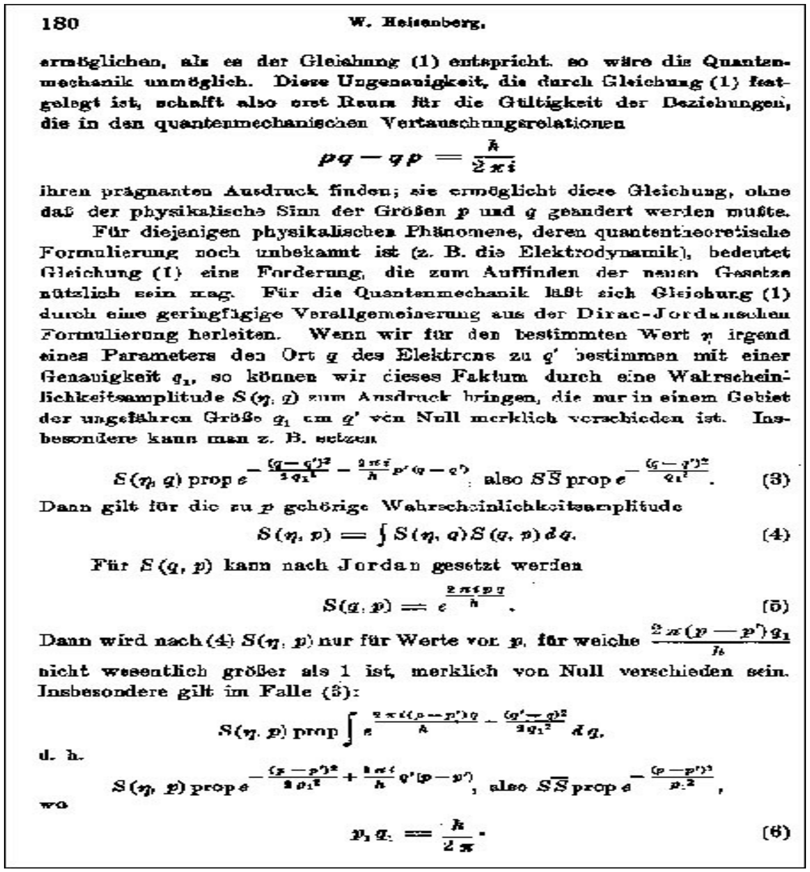
[b] *PH-TH, CERN, Geneva, Switzerland*

Abstract

Understanding Hawking radiation

- First, we have to go back to…
- Werner Heisenberg
- German physicist who in the 1920's was one of the founders of quantum mechanics
- Perhaps most famous for his uncertainty principle which related the precision with which you could measure *complementary* variables, like energy and time, or position and momentum

What is the Heisenberg Uncertainty Principle?


180 W. Heisenberg.

ermöglichen, als es der Gleichung (1) entspricht, so wäre die Quantenmechanik unmöglich. Diese Ungenauigkeit, die durch Gleichung (1) festgelegt ist, schafft also erst Raum für die Gültigkeit der Beziehungen, die in den quantenmechanischen Vertauschungsrelationen

$$pq - qp = \frac{h}{2\pi i}$$

ihren prägnanten Ausdruck finden; sie ermöglicht diese Gleichung, ohne daß der physikalische Sinn der Größen p und q geändert werden mußte.

Für diejenigen physikalischen Phänomene, deren quantentheoretische Formulierung noch unbekannt ist (z. B. die Elektrodynamik), bedeutet Gleichung (1) eine Forderung, die zum Auffinden der neuen Gesetze nützlich sein mag. Für die Quantenmechanik läßt sich Gleichung (1) durch eine geringfügige Verallgemeinerung aus der Dirac-Jordanschen Formulierung herleiten. Wenn wir für den bestimmten Wert η irgend eines Parameters den Ort q des Elektrons zu q' bestimmen mit einer Genauigkeit q_1, so können wir dieses Faktum durch eine Wahrscheinlichkeitsamplitude $S(\eta, q)$ zum Ausdruck bringen, die nur in einem Gebiet der ungefähren Größe q_1 um q' von Null merklich verschieden ist. Insbesondere kann man z. B. setzen

$$S(\eta, q) \text{ prop } e^{-\frac{(q-q')^2}{2q_1^2} - \frac{2\pi i}{h}p'(q-q')}, \text{ also } S\overline{S} \text{ prop } e^{-\frac{(q-q')^2}{q_1^2}}. \quad (3)$$

Dann gilt für die zu p gehörige Wahrscheinlichkeitsamplitude

$$S(\eta, p) = \int S(\eta, q) S(q, p)\, dq. \quad (4)$$

Für $S(q, p)$ kann nach Jordan gesetzt werden

$$S(q, p) = e^{\frac{2\pi i p q}{h}}. \quad (5)$$

Dann wird nach (4) $S(\eta, p)$ nur für Werte von p, für welche $\frac{2\pi(p - p')q_1}{h}$ nicht wesentlich größer als 1 ist, merklich von Null verschieden sein. Insbesondere gilt im Falle (3):

$$S(\eta, p) \text{ prop } \int e^{\frac{2\pi i(p-p')q}{h} - \frac{(q'-q)^2}{2q_1^2}}\, dq,$$

d. h.

$$S(\eta, p) \text{ prop } e^{-\frac{(p-p')^2}{2p_1^2} + \frac{2\pi i}{h}q'(p-p')}, \text{ also } S\overline{S} \text{ prop } e^{-\frac{(p-p')^2}{p_1^2}},$$

wo

$$p_1 q_1 = \frac{h}{2\pi}. \quad (6)$$

- …or
  - "The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa."
    --Heisenberg, uncertainty paper, 1927
- Mathematically, if I measure the position of a particle with a precision Δx and have a simultaneous measurement of the momentum with precision Δp_x, then the product of the two can never be less than $h/4\pi$
  - $\Delta x \Delta p_x > h/(4\pi)$
  - also, $\Delta E \Delta t > h/(4\pi)$

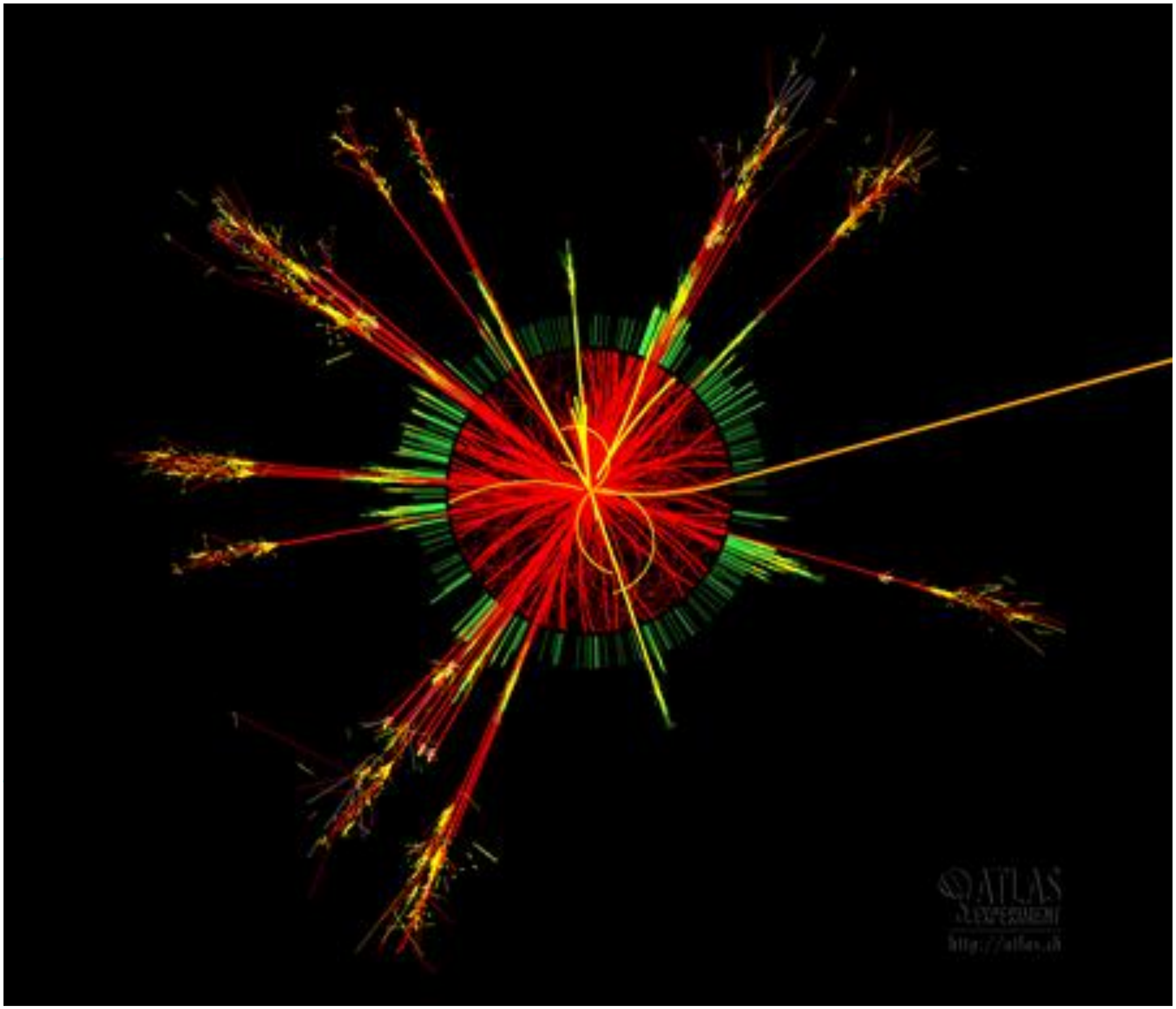
What does it mean?

- A careless summary would be that "all things are uncertain", but this is not really correct
- "In the sharp formulation of the law of causality-- if we know the present exactly, we can calculate the future-it is not the conclusion that is wrong but the premise."

  --Heisenberg, in uncertainty principle paper, 1927

- Einstein could not acept this inherent uncertainty to the universe for the rest of his life
- Famous debate in the 5th Solvay Conference with Niels Bohr

Black hole events (simulated) at the LHC

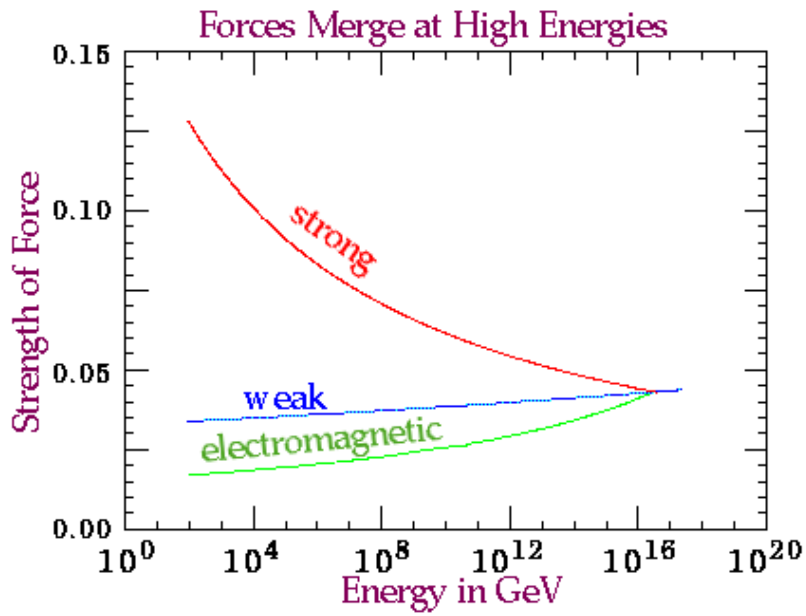


Steven Hawking

- His action figure is now available, and is sitting on my desk (with Sheldon and Einstein)

How can gravitational interactions be included in the Standard Model?

- Can the strong, electromagnetic and weak forces be described by one Grand Unified Theory?



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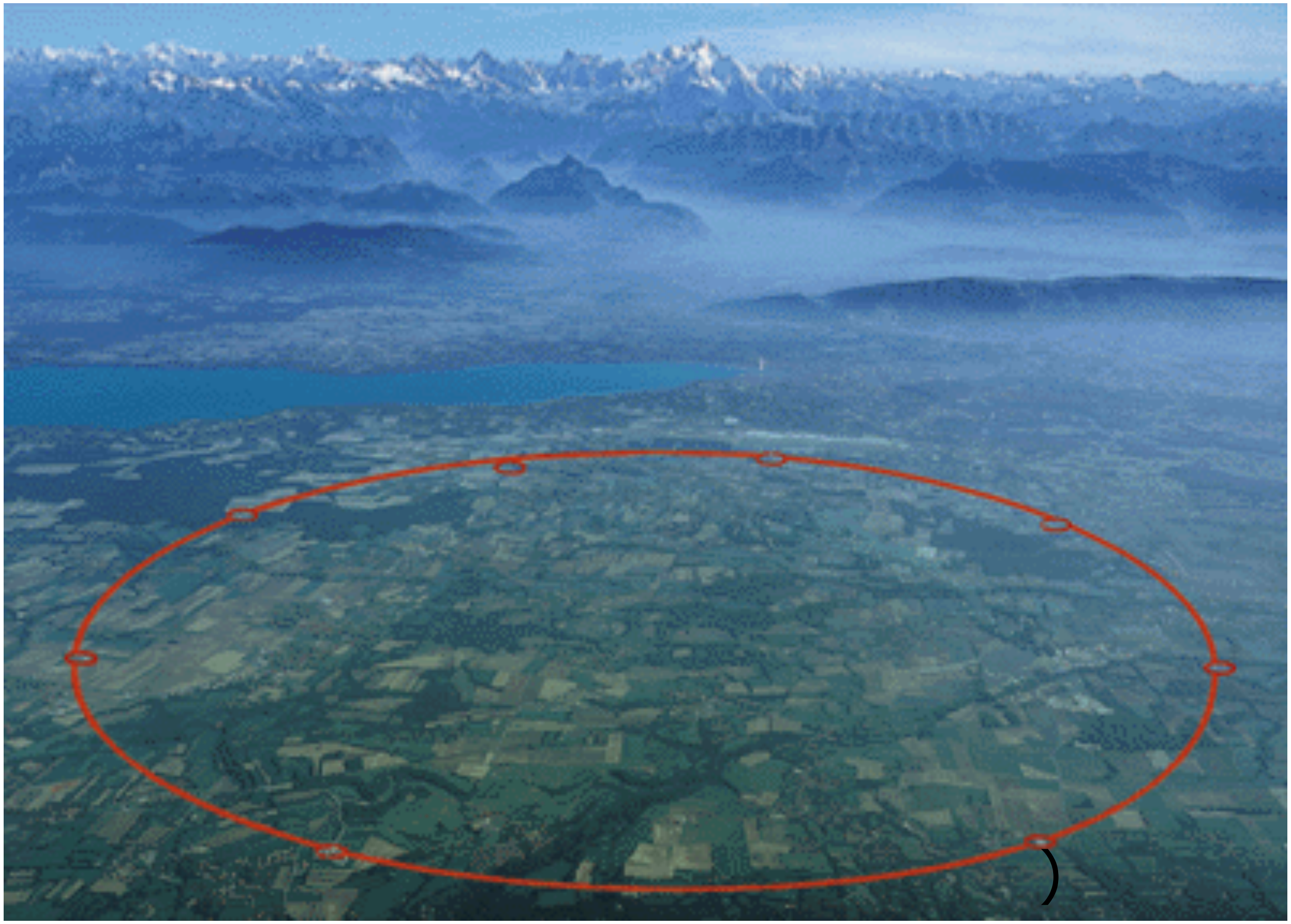
= Theory of Everything

Answers may come from…



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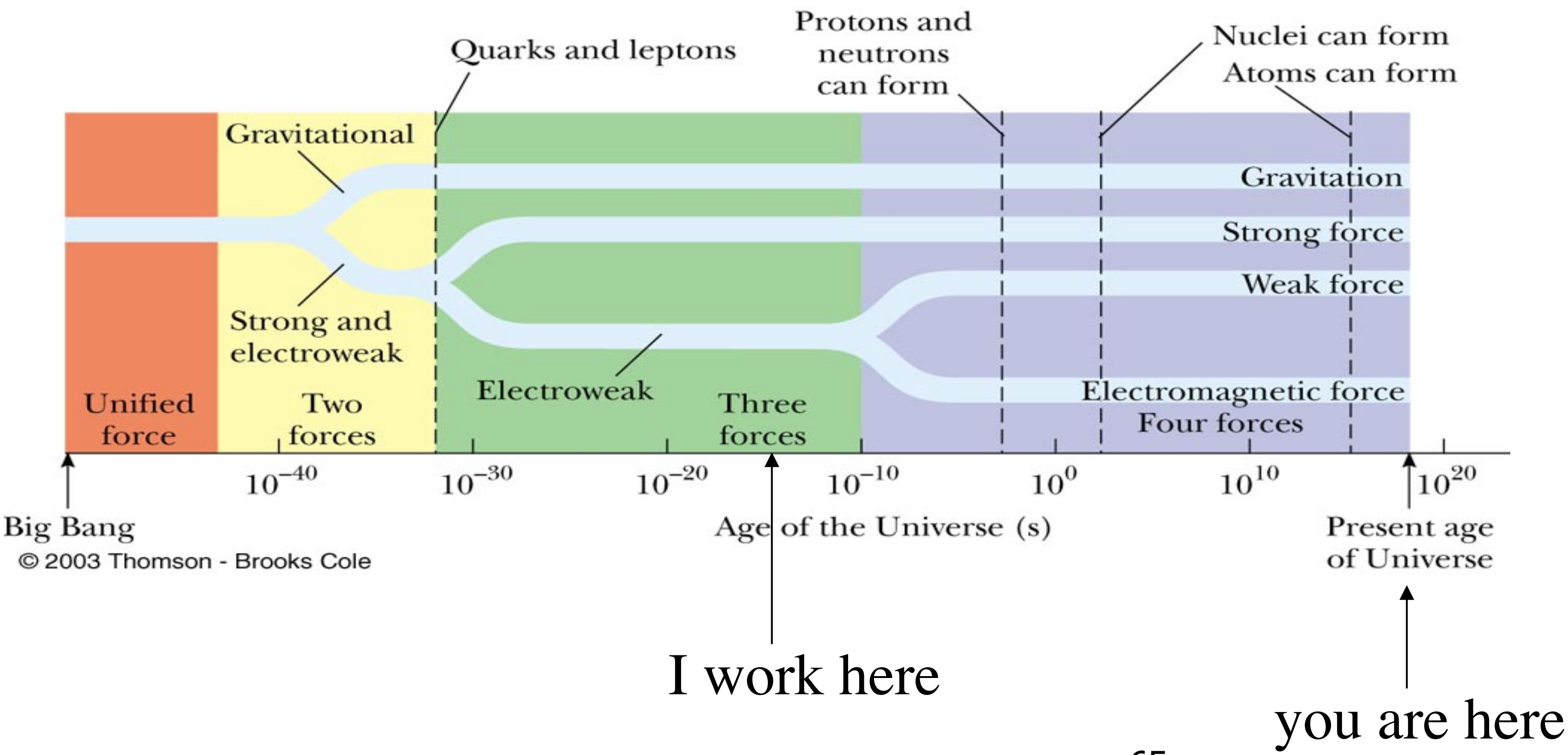
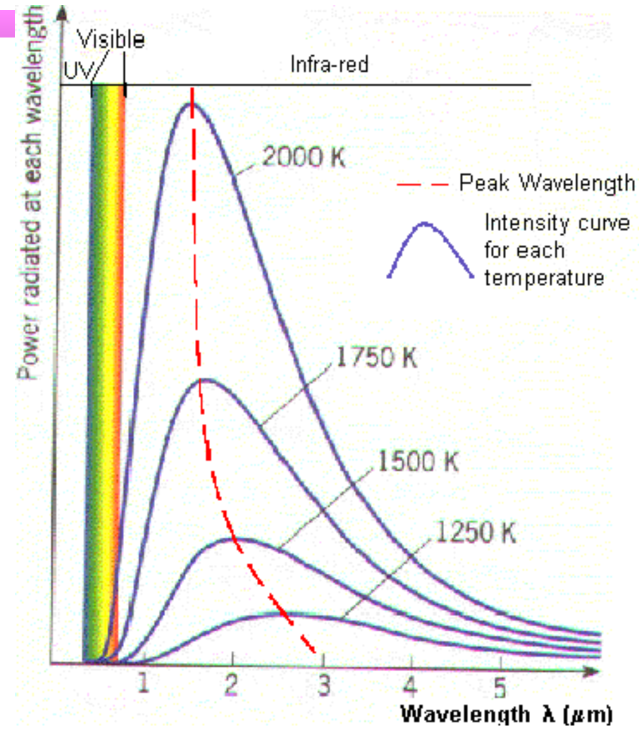
LHC at CERN

Looking back in time



Black-body radiation

- All bodies emit electromagnetic radiation characteristic of their temperature
  - black-body radiation
- The objects in this room are radiating mostly in the infra-red
- The universe is also radiating
  - in the 14 billion years since the Big Bang, it has cooled down to 3°K and is radiating in the microwave region



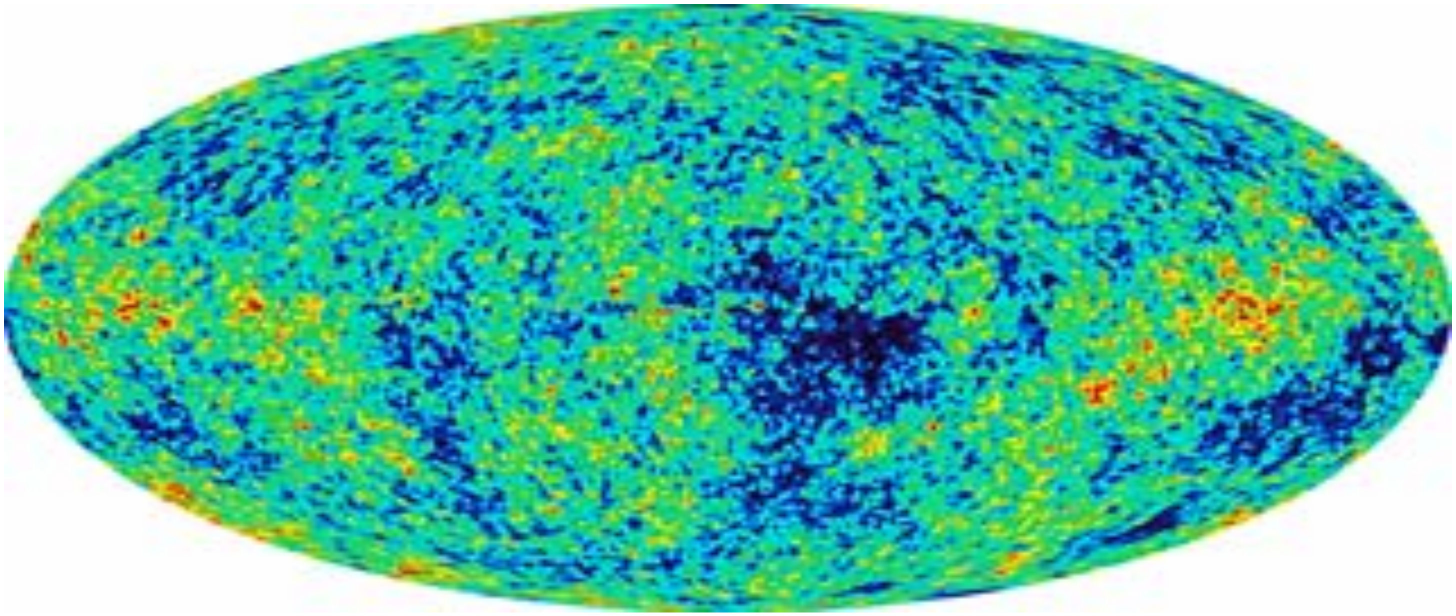
$$\lambda_{peak}(nm) = \frac{0.00290 m.K}{T(^oK)}$$

For body temperature, λ=9.35μm, or in the infra-red. Total power radiated by body =100 W.
The surface temperature of the sun is ~5800°K; λ_{peak}=500 nm (yellow).

Discovery

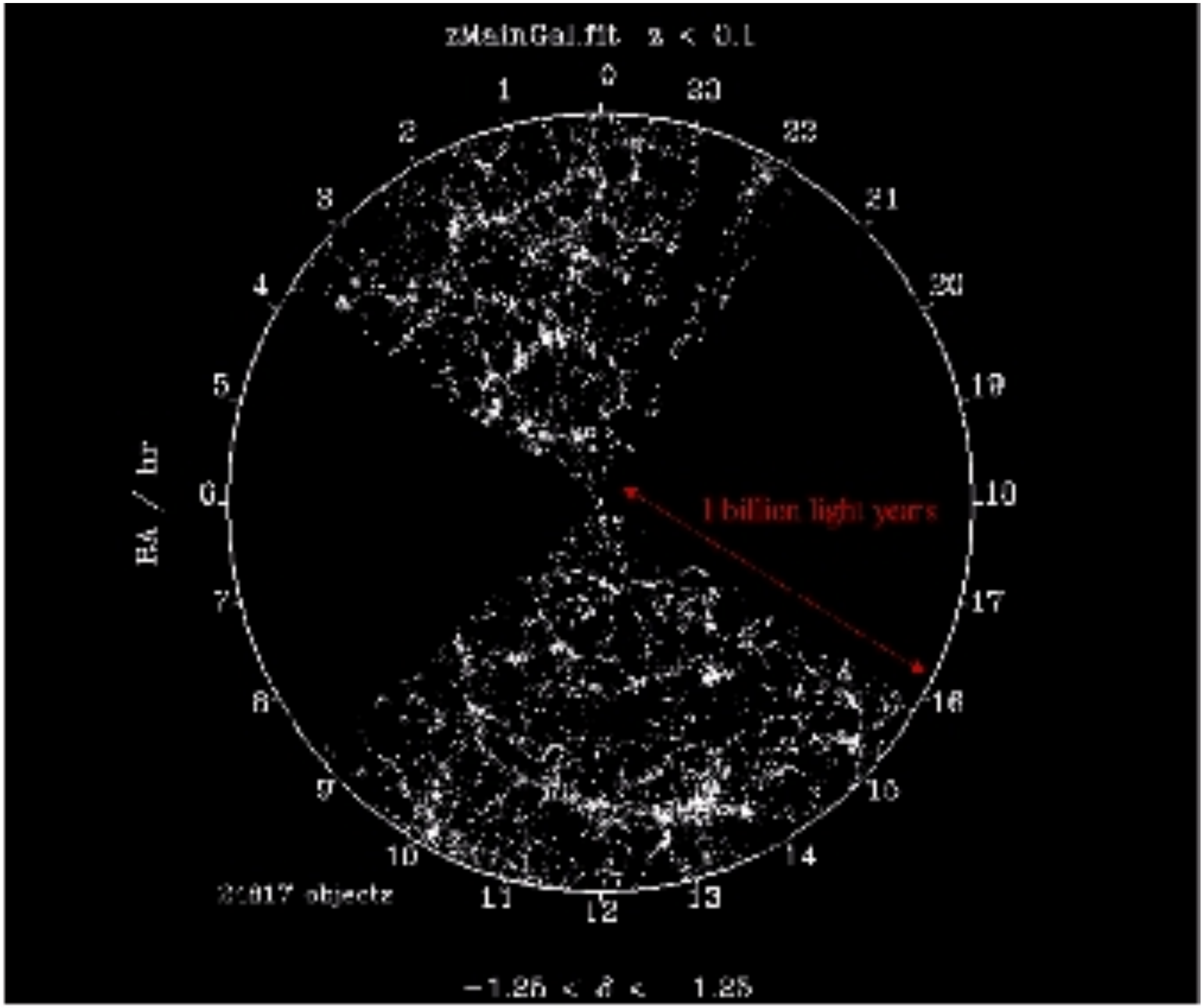
- Penzias and Wilson discovered the black-body radiation from the Big Bang in 1963 while working for Bell Labs
- What were they trying to do?

A microwave map of the early universe: colors indicate “warmer” (red) and “cooler” (blue) spots

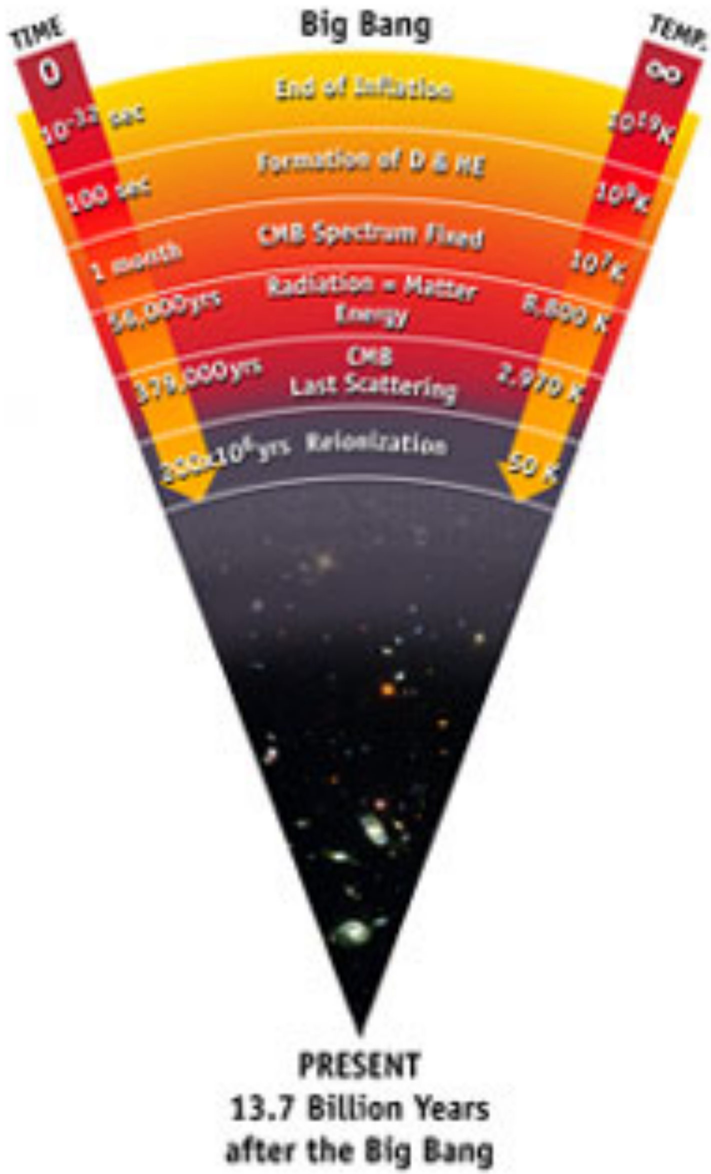


It’s these early differences that have caused the structure we see in the universe today

Map of the Univer

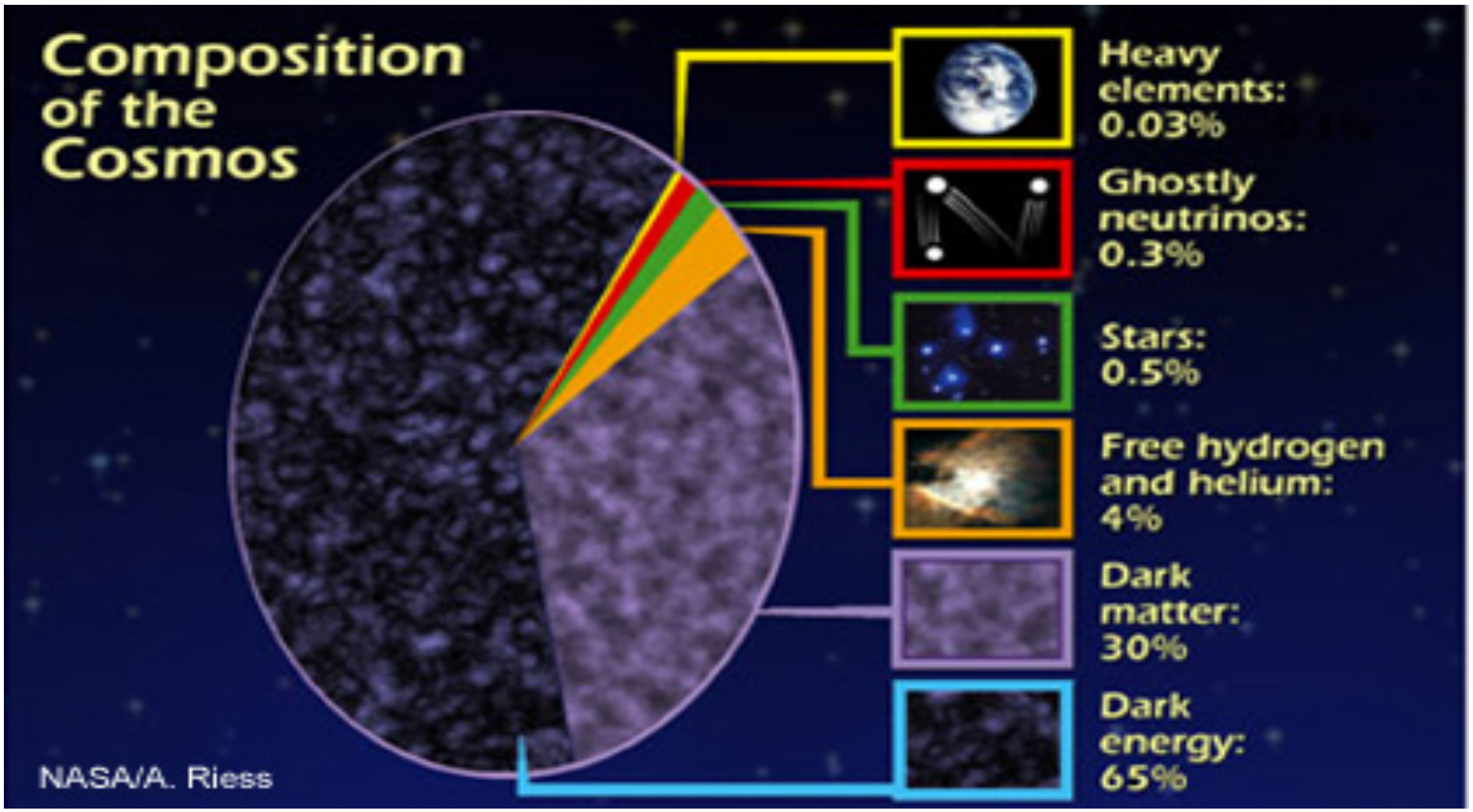


…and they' ve let us calculate the age of the universe



13.7 billion years
+/- 100 million

…and have helped to tell us what the universe is made of



It’s an interesting universe out there…and getting more interesting all the time.

- Thanks for putting up with me over the semester