three more historical things

1. **Feynman Diagrams**
2. **spin**
3. **beta decay**
4. **exchange forces**

1

"Feynman Diagrams"

actually, a shorthand for calculations

each diagram tells us how to skip about 20 pages of a calculation!

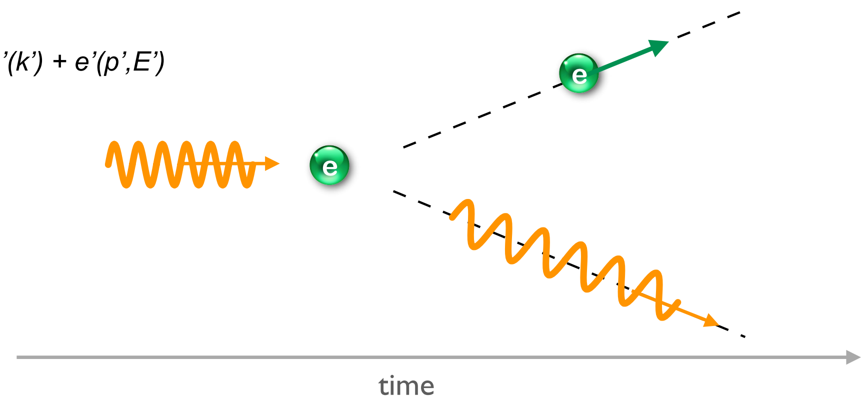
also, a marvelous "visualization" of any spacetime process

Compton Scattering

remember?

x-ray + electron -> x-ray + electron

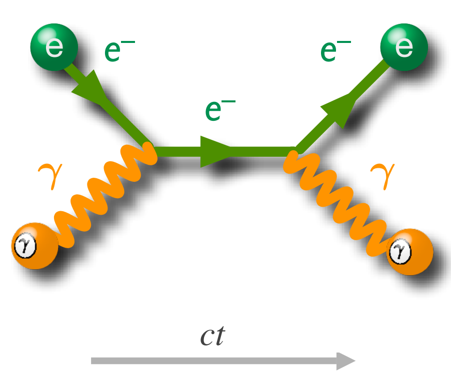
$\gamma(k) + e(p,E) \rightarrow \gamma'(k') + e'(p',E')$



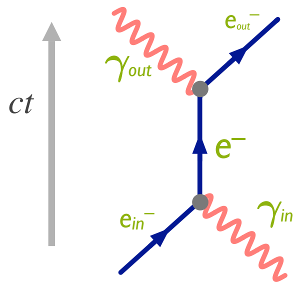
thought of as:

xray absorbed by electron...
then emitted later by electron

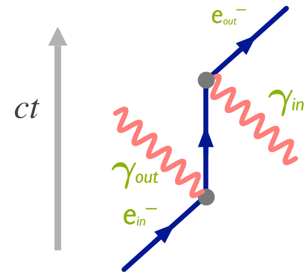
we draw them in a general frame



compton, revisited (it's $e\,\gamma \rightarrow e\,\gamma$)



In order to include all possibilities, it's necessary to also take into account:



the important thing is that the initial and the final states are indistinguishable between these two diagrams

As that's all we can measure, **we must include all ways of producing the same initial and final states, regardless of the direction of time.**

here's what I think of you:

the deal:

you come to class, do the work:

You'll learn some physics

and see science differently

and **you'll do okay.**

today:

think of it as Brian Greene

without the turtleneck or Star Wars bar characters

a little stuff, and a little entertainment.

three more historical things

1. **Feynman Diagrams**
2. **spin**
3. **beta decay**
4. **exchange forces**

2

"spin"

we actually define individual quanta by 3 quantities:

`mass, electrical charge, spin`

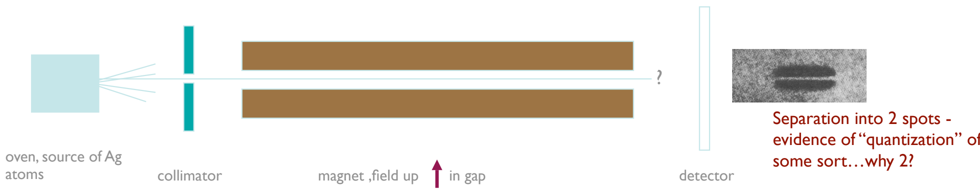
and other "quantum numbers"

but, spin has a history

Schrodinger could not explain:

From out of the blue: The Stern Gerlach Effect

In 1921, Otto Stern and Walter Gerlach managed to prepare a molecular beam of Silver atoms, which they passed through a magnetic field…



IF electrons were really orbiting the nucleus classically, then the magnetic field would spread the beam out depending on the orientation of the circulating currents - blur

IF electrons distributed themselves according to the Schrödinger model, then there would be many discrete spots at the detector…corresponding to all different directions of all of the many orbital angular momenta in the Silver atom

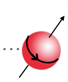
BUT this 2-line business was disconcerting

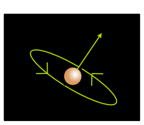
my head is spinning

Two young Dutch theoreticians had the nutty idea

In 1925, George Uhlenbeck and Sam Goudsmit speculated that the electron is like a spinning charge…

remember, a little current loop produces a little B field 

how about a little spinning sphere of charge? … also a little B field 



That's what they said an electron was like: BUT, there's no such current, and the electron has no size - this little "magnetic moment" is an inherent quality of an electron

But, since the electron has no apparent size – "spinning" is a weird notion!! …a metaphor

Their proposal was that to explain the Stern-Gerlach experiment, this spin-angular momentum, "S", is **also quantized** as ±1/2h - two states, "up" and "down"

It spins in only two orientations and there is a quantum number associated with them

*This quantum "number" is called "**Spin**" and is a property of the electron (and others).*

What's happening in the Stern-Gerlach experiment?

Silver happens to be an atom with a single valence electron in its most outer shell

The magnet was selecting those of the Silver atoms that had spin projection = +1/2 from those that had -1/2…two spots

another gift from Dirac:

Spin turned out to be required

when quantum mechanics was combined with Special Relativity…it naturally emerged as a natural part of that theory…quite amazing.

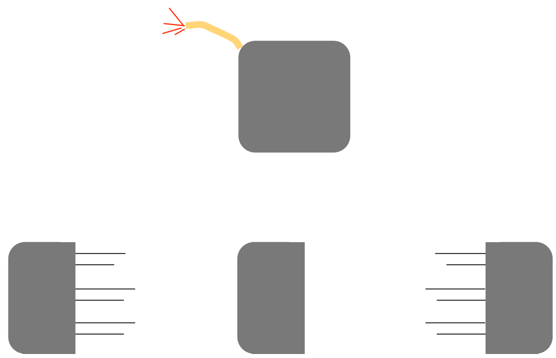
3

beta decay

was an embarrassment

strange firecracker

Suppose we have a firecracker exploding into two pieces



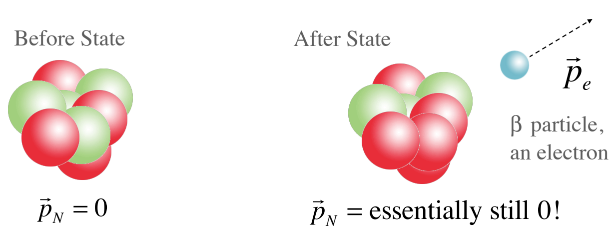
well, beta decay appeared to be the middle situation...it appeared to violate momentum and energy conservation

trouble with beta decay

Studies of the beta decay of various nuclei took a turn toward absurdity

The general reaction of interest was ${}_{Z}N^{A} \rightarrow {}_{Z+1}N^{A} + e^{-}$

nucleus adds a proton and emits an electron (so Q is conserved)



Momentum, and hence, energy… appeared to be imbalanced between the before and after states…

- By the late 1920's and early 1930's, measurement precision became quite good

all experiments agreed: **it behaved like a firecracker exploding into 1 moving piece**

…not conserving momentum or energy!

all searches for unseen radiation, like gamma rays, failed

conservation of energy was seriously called into question by, of course, Bohr

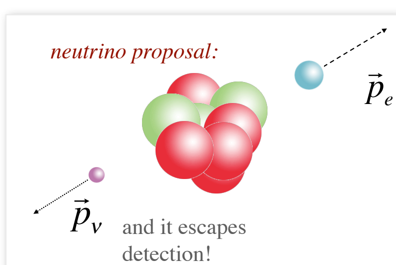
“I have come upon a desperate way out. To wit, the possibility that there could exist in the nucleus electrically neutral particles which I shall call neutrons[sic]…the mass…should not be larger than 0.01 times the proton…the continuous beta spectrum would then be understandable from the assumption that…a [neutrino] is emitted along with the electron…I admit that my way out may not seem very probable…But only he who dares wins…unfortunately I cannot appear personally in Tubingen since a ball which takes place in Zurich makes my presence here indispensable.”

Pauli, distressed at the crisis and unwilling to part with energy conservation–like Bohr suggested!–in 1930 made a bold proposal, in an off-hand way

the idea hung around for a few years -but the discovery of the actual neutron gave Enrico Fermi an idea.

the neutrino...little neutron

prediction of an elementary particle



Enrico Fermi

an unusual mixture of theoretician and experimentalist

…doesn't happen very often - he was simply the best

At an early age, he rewrote the statistical description of spin-1/2 particles

now called "fermions"

Discovered the first artificially produced nucleon excitation (called the "delta") and managed to create the first controlled nuclear fission reaction at Chicago

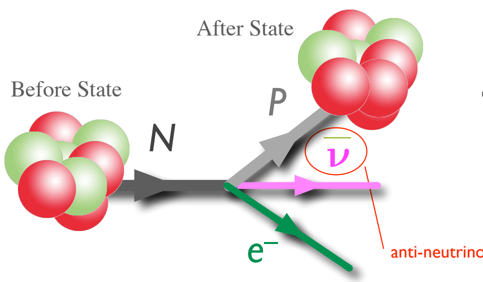
the beginning of the Manhattan Project

Enrico Fermi
1901-1954
(actually in a cafeteria in Ann Arbor, 1935)

In 1933 formulated the first workable model for beta decay

and heralded the beginning of the study of the "Weak Interaction"

neutrons aren't what they were cracked up to be



Fermi proposed:

the neutron is unstable and transmutes into a proton, electron, and neutrino

Dirac's ***creation*** and ***annihilation***, idea put to work

He recognized that the strength of the reaction - related to the lifetime of the state which decays under this reaction - is very small compared to the electromagnetic interaction

the electromagnetic interaction has a relative strength of 10^{-2}

the beta decay reaction has a strength of ~ 10^{-13}

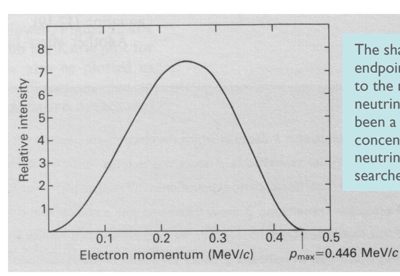
It's called the **Weak Interaction** for that reason…there are a whole class of interactions which fall into this category

any reaction involving a neutrino is weak.

So, the neutron would be a bit more massive than the proton

The neutrino carries away energy and momentum, balancing the electron energy, which can be a spectrum (since the proton is involved)

which Fermi predicted in a paper so audacious that it was originally rejected by *Zeitschrift fur Physik*…and so he had to publish it in Nuovo Cimento, a less prestigious Italian journal



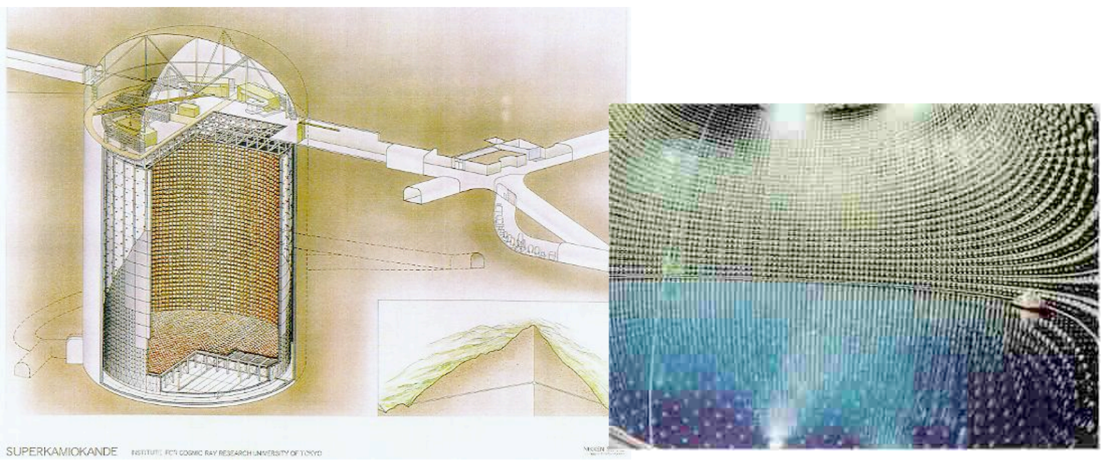
The shape of the endpoint is sensitive to the mass of the neutrino…and has been a feature of concentration in neutrino mass searches

The spectrum indicates that something else was taking away momentum/energy…it peaks at about 1/3 of the mass of the neutron, which is sensible.

neutrino's putting on weight

since Fermi's model

- neutrino has been presumed to be massless, but this has been tested for decades
  - now, after 50 years, it's clear that the neutrino has a tiny mass
  - *the mass difference among neutrinos is tiny fractions of an eV/c²*
  - discovered in Japan in 1998



they're everywhere, they're everywhere

The neutrino discovered in 1956 by Fred Reines and Clyde Cowan

- inexplicably, the Nobel Prize only awarded 1995
- Pauli did live to see the results
  - and he was right, they do not interact…very much
  - it takes lightyears of lead to stop a neutrino, on average

The neutrino is ubiquitous in the universe

- the nuclear reactions in the sun produce 10^{38} neutrinos per second
- the big bang is responsible for there being roughly 300 neutrinos/cm³ …a bath of neutrinos, everywhere in the universe
- the potassium 40 in our bodies beta decays: we are emitters of ~3×10^8 ν per day

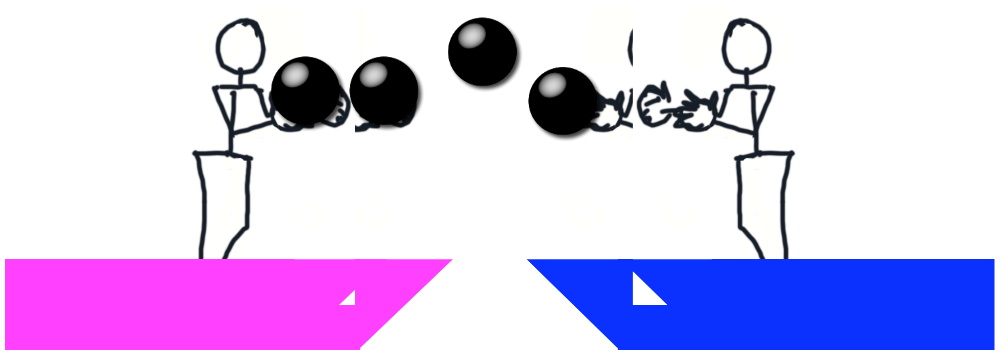
4

think about it.

what keeps the many protons large nuclei from repelling one another?

analogy:

a repulsive exchange force

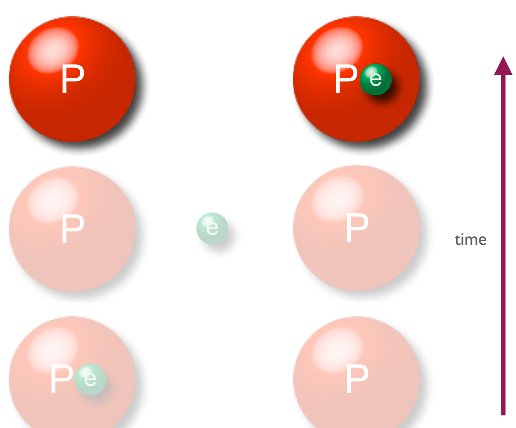


analogy:

an attractive exchange force

Heisenberg had an original idea

before the discovery of the neutron in 1932



this is wrong.

exchange forces

After the discovery of the neutron in 1932:

Heisenberg proposed a family relationship:

proton and neutron are very, very close in mass

He proposed that they can be thought of as

two sides of the same coin: a “nucleon”

one changing into another through the exchange of a third intermediate

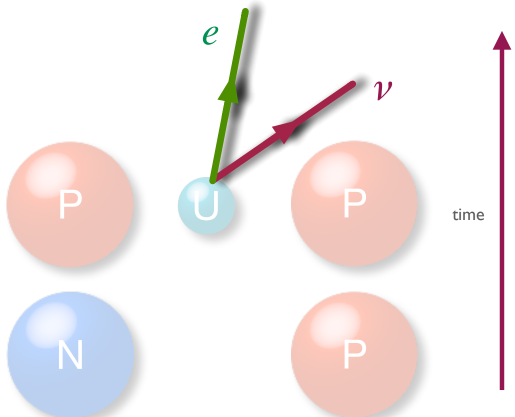
proposed a quantum number, “Isospin” of 1/2

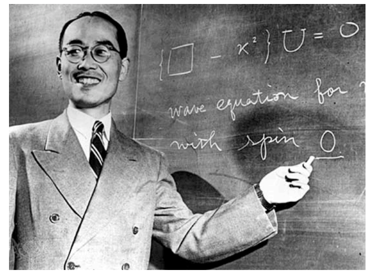
I of proton = +1/2

I of neutron = -1/2

changing p into n...requires the exchange of I = 1

a model for beta decay

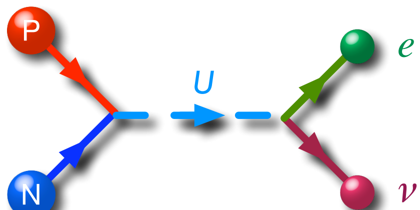




Hideki Yukawa in 1934

after the discovery of the neutron

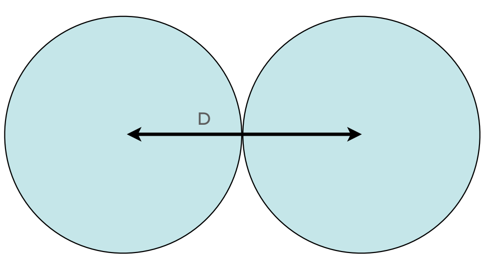
motivated by Fermi's theory of beta decay



Imagining the exchange particle being uncertain in position inside of the nucleon...and traveling at near the speed of light, he estimated the energy and hence, mass

range of strong force:

about the size of the proton...a rough concept



...can't travel faster than light, so the time across the proton would be: D/c
Yukawa's particle would violate energy in passing from one p to another

From uncertainty,

$$\Delta E \approx \frac{\hbar}{D/c}$$

$$m \approx \frac{\Delta E}{c^2} \approx 0.1 \times m_{proton}$$

So the hunt was on for a particle of a mass of about 0.1 times that of the proton ($\sim 200 \times m_{electron}$), or about 100 MeV/$c^2$...that would cause protons to stick together

Look, Ma…I'm on Top of the World

Cloud chambers: sophisticated & well-traveled

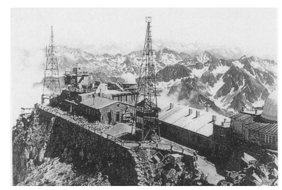
- Anderson and others took devices to the top of Pike's Peak, the Pyrenees…
  - By 1937, strange things were beginning to be seen…
  - tracks that looked like electrons…but would not slow down in Anderson-like plates
  - *They guessed that they had masses of around* ***200 x $m_{electron}$***

So…they were not protons and not electrons

- Could it be the Yukawa particle?
  - No…during WWII, Italians Conversi and Piccioni, working in Rome in basements at night fearing for their lives, built wholly electronic devices based on the Geiger-Mueller tubes
  - *They measured the lifetime of these penetrating particles: ~2×10^{-6} s*
  - *- too long-lived to be the Yukawa particle*

Named "mesotron" ('in the middle')

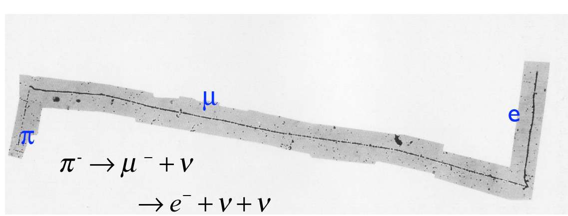
- now called the "muon"



muons and pions and electrons, Oh, my!

Robert Marshak figured it out:

- Other emulsion experiments observed, short, stopping tracks that were the Yukawa particle (dubbed the "pion")
  - they are unstable and decay into the muon
  - which in turn, is unstable, decaying into an electron and 2 neutrinos

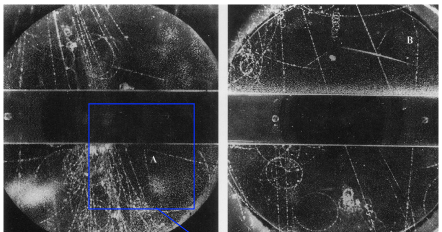


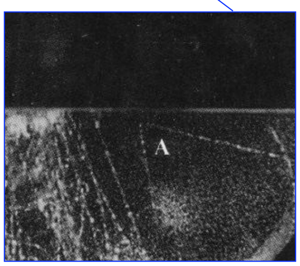
then, things went nuts...

Cosmic rays continued to produce surprises

In 1946 - in Manchester, pictures showed the presence of "Vee's"

the apparent production of a neutral particle that decayed into two charged particles





the reaction is the decay of what is now called the Kaon, or neutral version, K^0:

it has a mass of 0.496 MeV/c^2

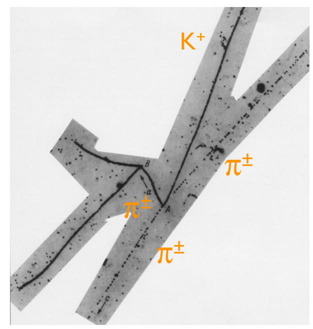
$K^0 \to \pi^+ \pi^-$

another V was found that decayed into a nucleon and a pion… called the "lambda"

it has a mass of 1.115 GeV/c^2

$\Lambda \to$ p π^- or n π^0

To add insult to injury… another Kaon was found that decayed into 3 pions



These were all "strange" things…so the particles were dubbed "Strange Particles" and the name stuck…thus beginning the tradition of naming the most fundamental bits of matter by whimsical and silly names

Eventually, forces categorized

By how strongly the forces act between particles

you can pick up one magnet with another magnet

so, you'd say that the magnetic force > the gravitational force, okay?

The four fundamental forces appear to be:

the **strong force** (strongest in Nature)

nuclear binding, originally thought to be propagated by the pion… the strongest force in nature

the **electromagnetic force**

between particles of electric charge - always involving a photon

the **weak force**

short decays like beta decay, any reaction involving neutrinos and other reactions that we'll come to realize involve new "photons"

the **gravitational force** (weakest in Nature)

particles of mass/energy…namely all particles

In all of nature, and for nearly the entire time of the universe, there appear to be only these 4

each force:

propagated by a quantum cousin of the photon:

strong force: the "gluon"
weak force: the "W"
electromagnetic force: the photon
gravitational force: the "graviton" (speculated)

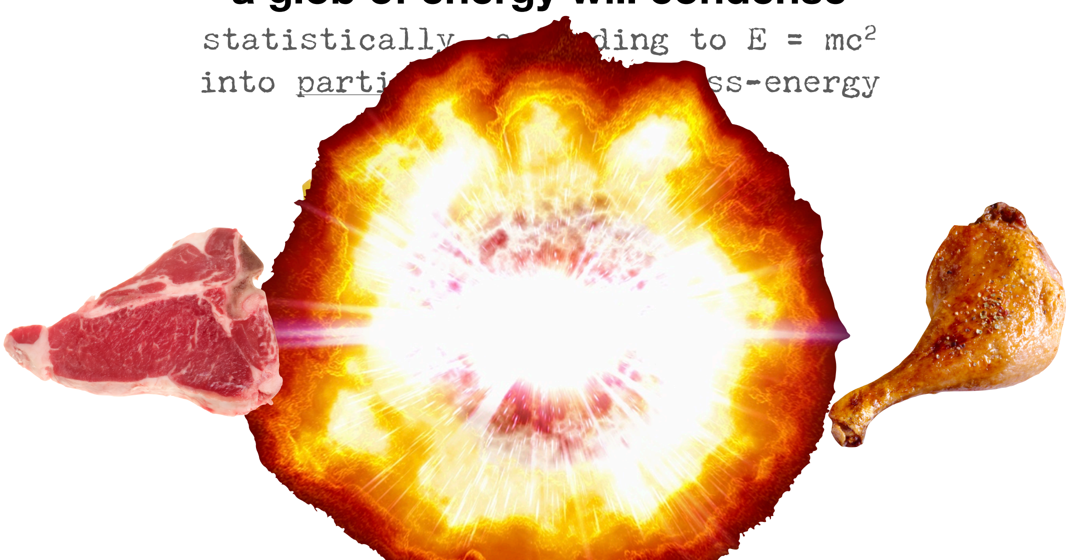
and a bonus: the weak and electromagnetic forces

are one in the same at very high energy densities
theory predicted: the "Z," directly related to photon

Nature is clumpy

a glob of energy will condense

statistically ... ding to $E = mc^2$
into parti ... ss-energy



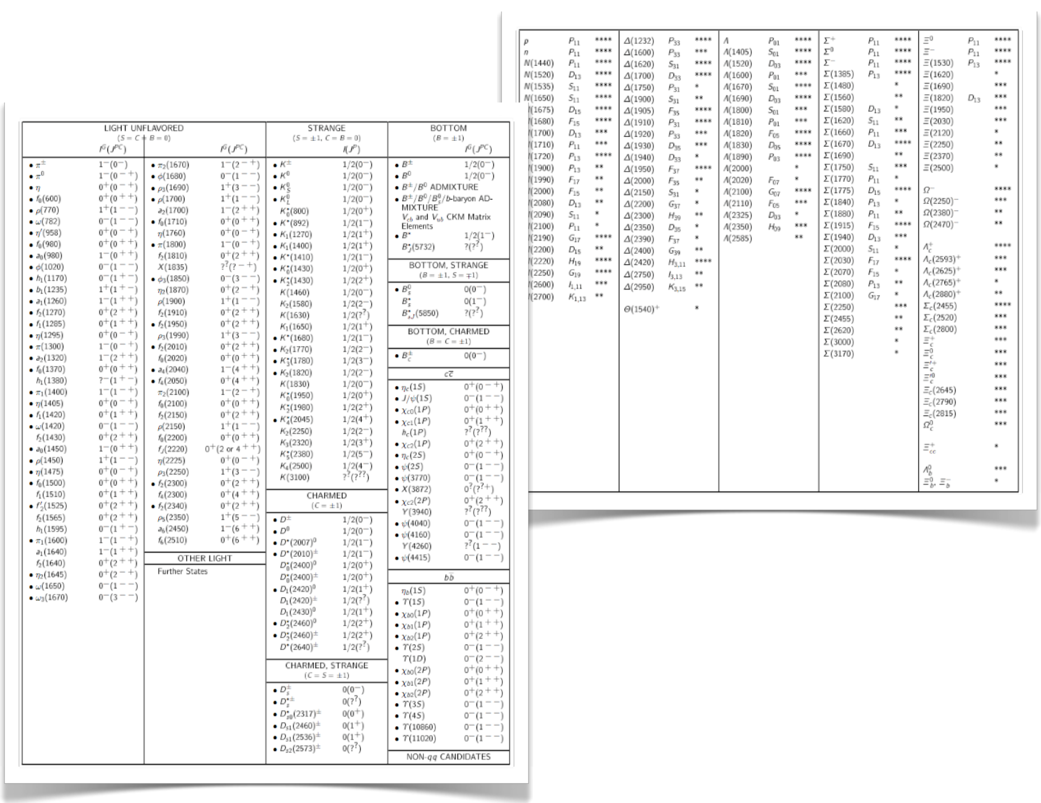
with family relationships among them...and different MASSES for their production

the clumps?
a menagerie of "particles".

subsequently, hundreds of them

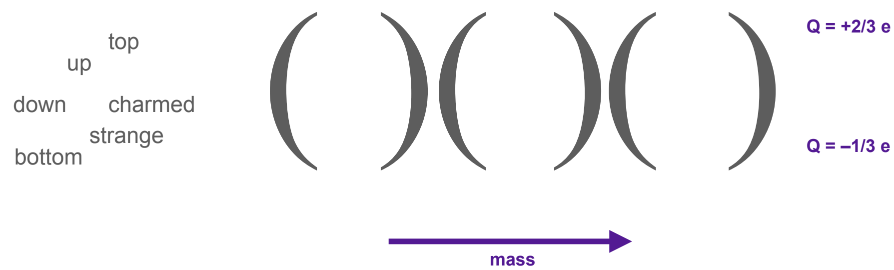
`produced artificially in accelerators`

sometimes, they don't live very long...



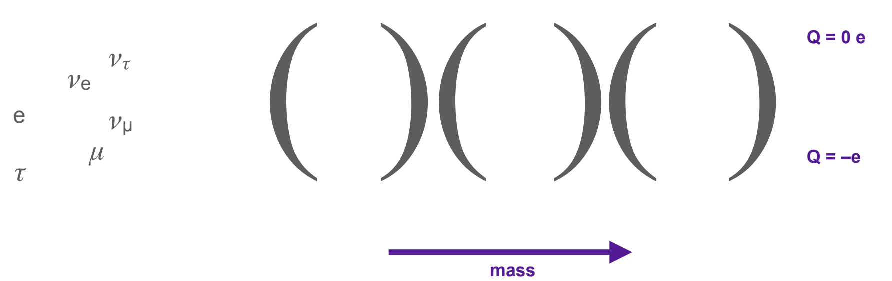
all can be described by patterns of 6 “quarks”

called “generations”



rest of matter described by patterns of 3 “electrons” and neutrinos

called “generations”



why?

are the quark patters like the lepton patterns?
are the masses arranged?
are the charges arranged?
are there 3 generations?

`dunno`

jargon

“Fermions”: n/2 spins; “Bosons”: integer spins

particles which interact via strong force:

- “Hadrons”
  - which can be spin n/2 (“baryons”) [proton, neutron, Δ, Σ, Ξ, Ω, ...] or spin 0, 1 (“mesons”) [pion, kaon, η, ρ,...]

particles which do not interact via the strong force:

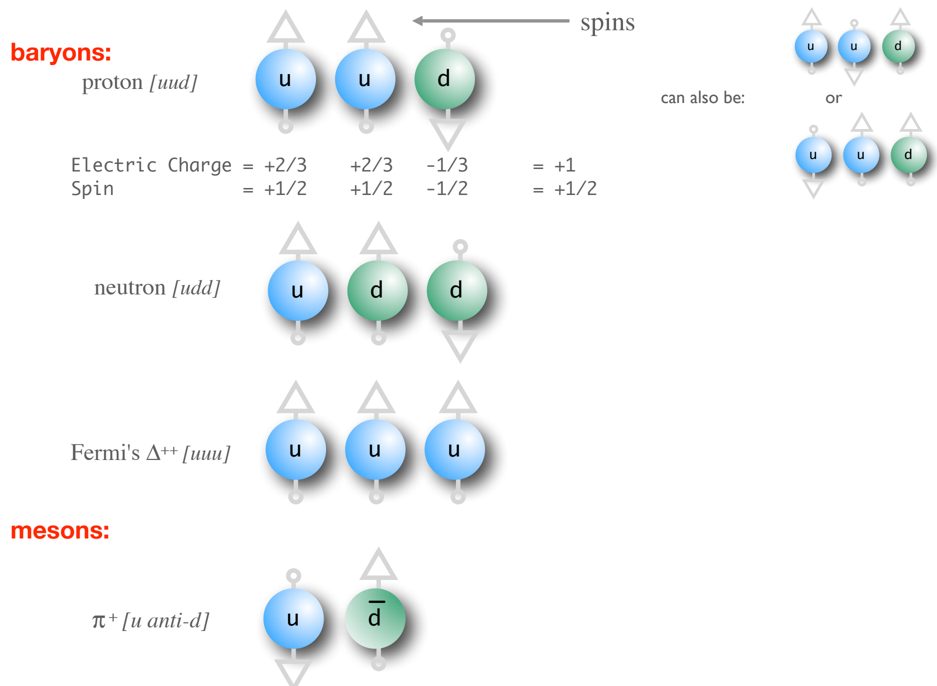
- “Leptons”
  - which are all spin 1/2 [e, μ, τ, ν_e, ν_μ, ν_τ]

And, fields which propagate the 4 forces:

- Electromagnetic: photon
- Weak: “W boson”
- Strong: “gluon”
- Gravity: “graviton”...speculated

And a surprise...conceived in 1967.

How to build a proton: *(originally) hypothetical building blocks of hadrons*



1969: Discovery of partons, Kendall, Freedman, and Taylor

Lo and behold: quarks were found rattling around inside of the protons and neutrons

an electron beam emits a photon with a wavelength inversely proportional to its energy

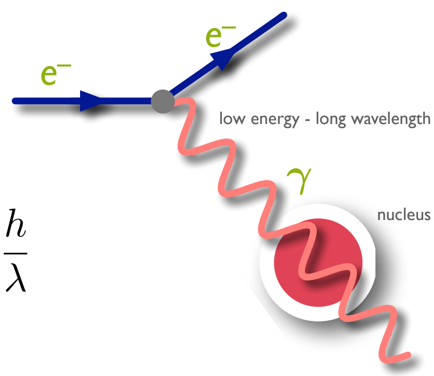
scattering from whole nuclei, required photons of wavelengths ~ nuclear sizes

INCREASE the energy of the electrons - *smaller sizes are resolvable*

$$p = \frac{h}{\lambda}$$

and an amazing thing happened:

individual protons and neutrons were broken up, and the pattern of Rutherford scattering emerged!



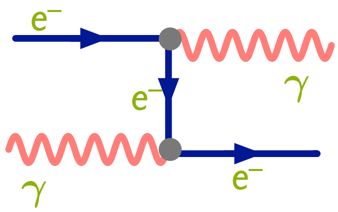
Something was inside and was much, much smaller than the proton, and the higher energy photons dug in and scattered directly from these point-like objects

called PARTONS by Feynman

They indeed turned out to be quarks.

quark language...describes it all:

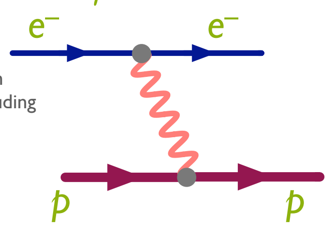
Compton scattering



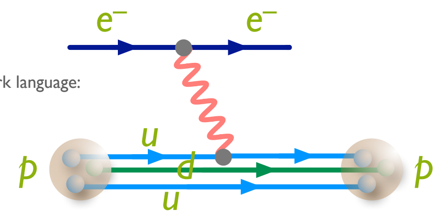
The electron and photon are fundamental objects, without any structure or constituents

That's how quarks are used...fundamental objects, without any structure or constituents:

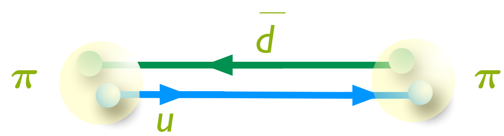
electron-proton scattering...including the atom

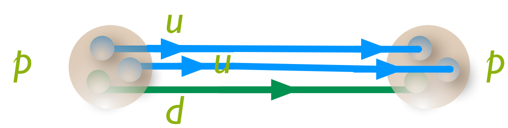


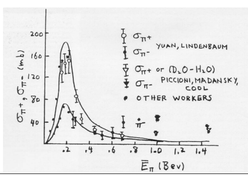
in quark language:



Δ^{++} production as a resonance







Connection with electrodynamics

In the late 1950's, Feynman and Gell-Mann put this idea on a mathematical footing for the Weak Interactions

...that the weak force also was propagated by a spin-1 boson but it was different from the photon.

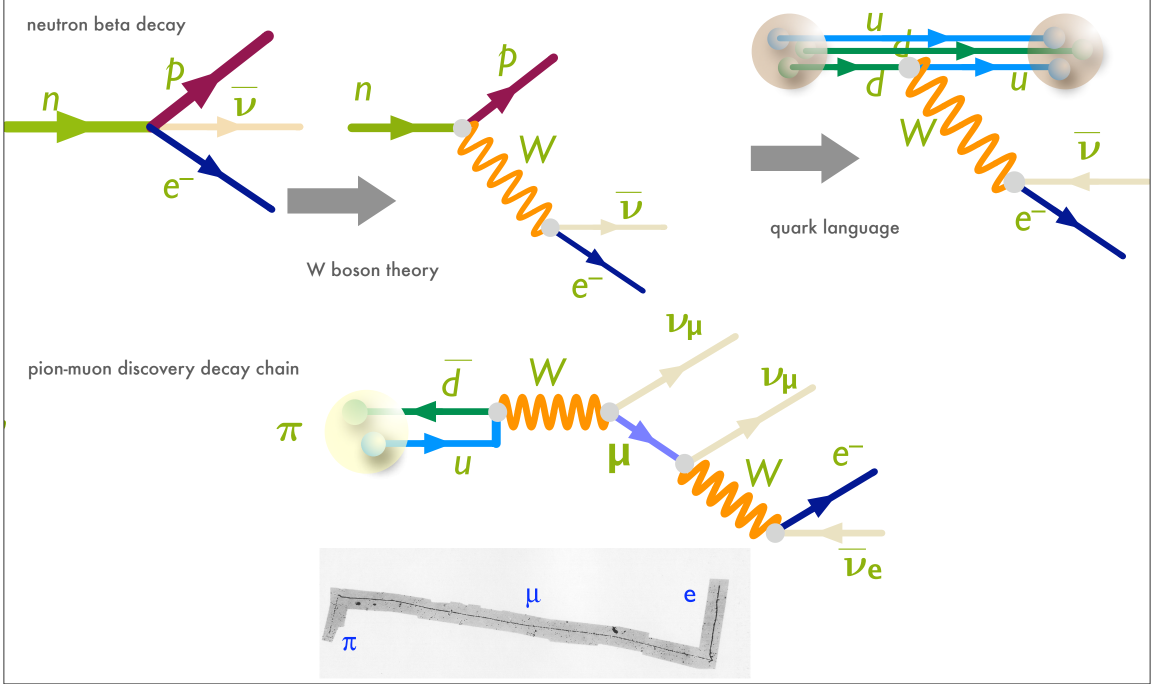
It had to be:

1. *electrically charged (it changes n → p, so Q goes from 0 to 1)*
2. *very massive (the weak force is propagated over short distances)*
3. *capable of changing isospin...ie, it can change one particle into another within isospin families (within other conservation requirements)*

dubbed the **"W Boson"**

Using the W boson

With W, reactions we have discussed look like this...



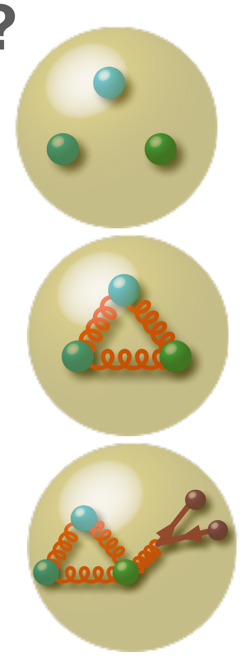
so: the force carriers:

connect the quarks and leptons to one another

according to strengths

strong interaction: the gluon

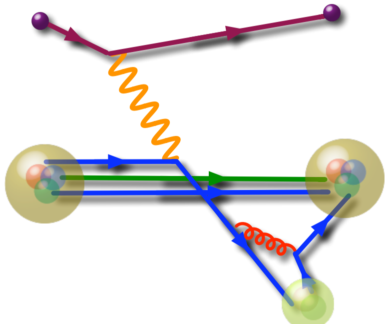
so, what's a proton?



A collection of three quarks...u, u, d...

What keeps the positive u quarks from repelling one another?

- the strong force...the one associated with Yukawa's particle: but not the pion, a new "photon" that transmits the strong force called the "gluon"
  - the gluons themselves are moving and spitting out new particles...quarks...



We scatter from all of these quarks with very high-energy particles...and produce the gluons all the time

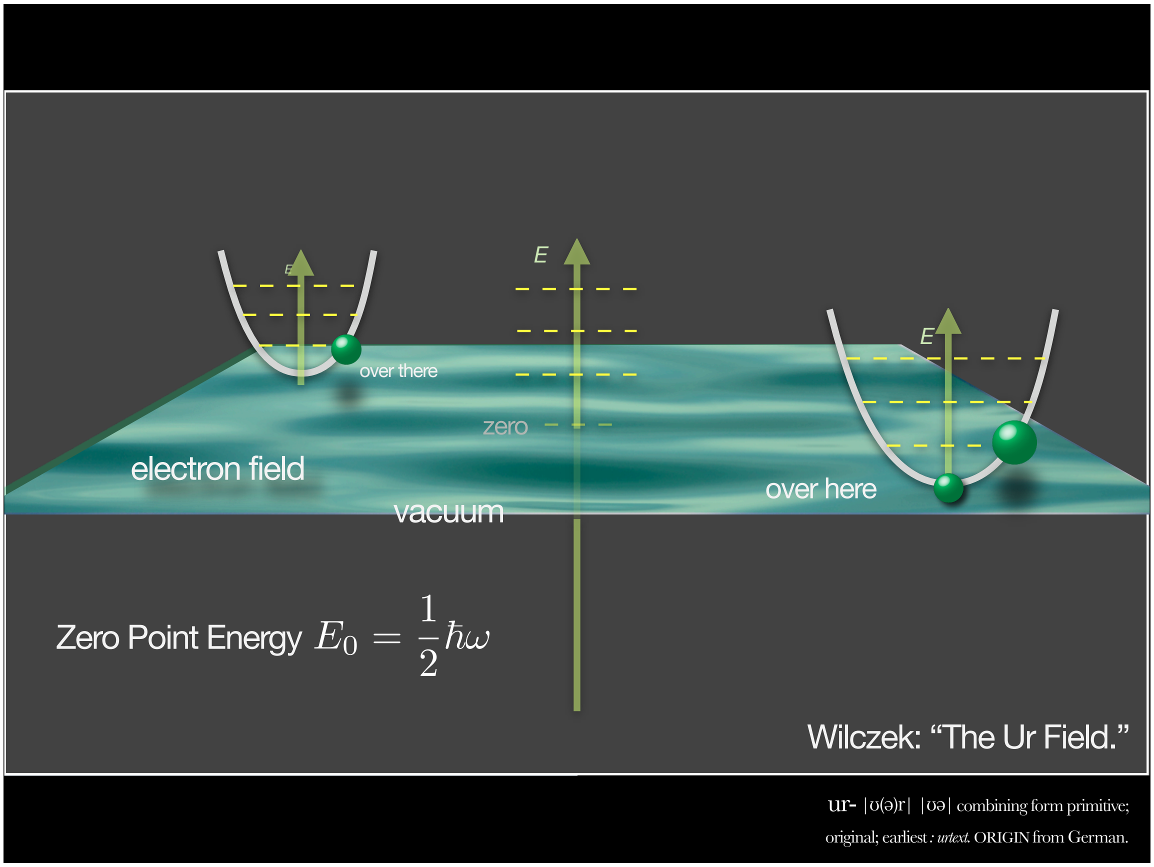
the issue:

mass.

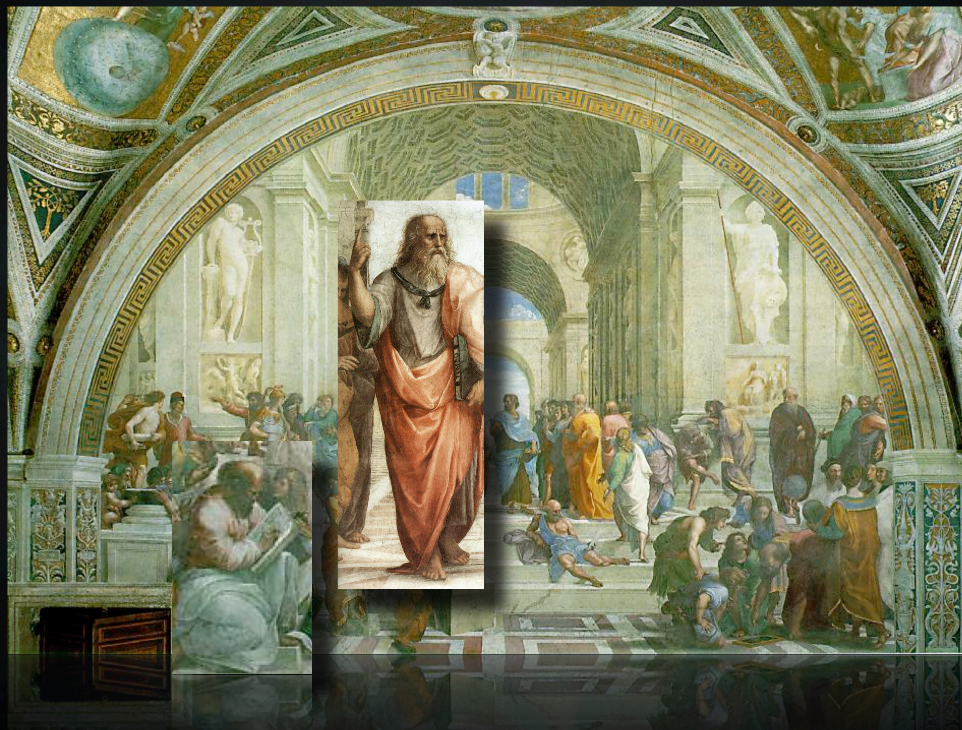
question:

what's a "particle"?

harmonic excitations of a

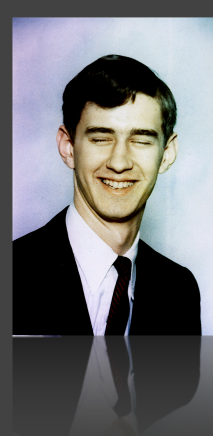

E
over there
E
zero
E
electron field
vacuum
over here
Zero Point Energy $E_0 = \frac{1}{2}\hbar\omega$
Wilczek: “The Ur Field.”
ur- |ʊ(ə)r| |ʊə| combining form primitive;
original; earliest : *urtext*. ORIGIN from German.

identity!



elementary particles are their own Platonic Forms

1967

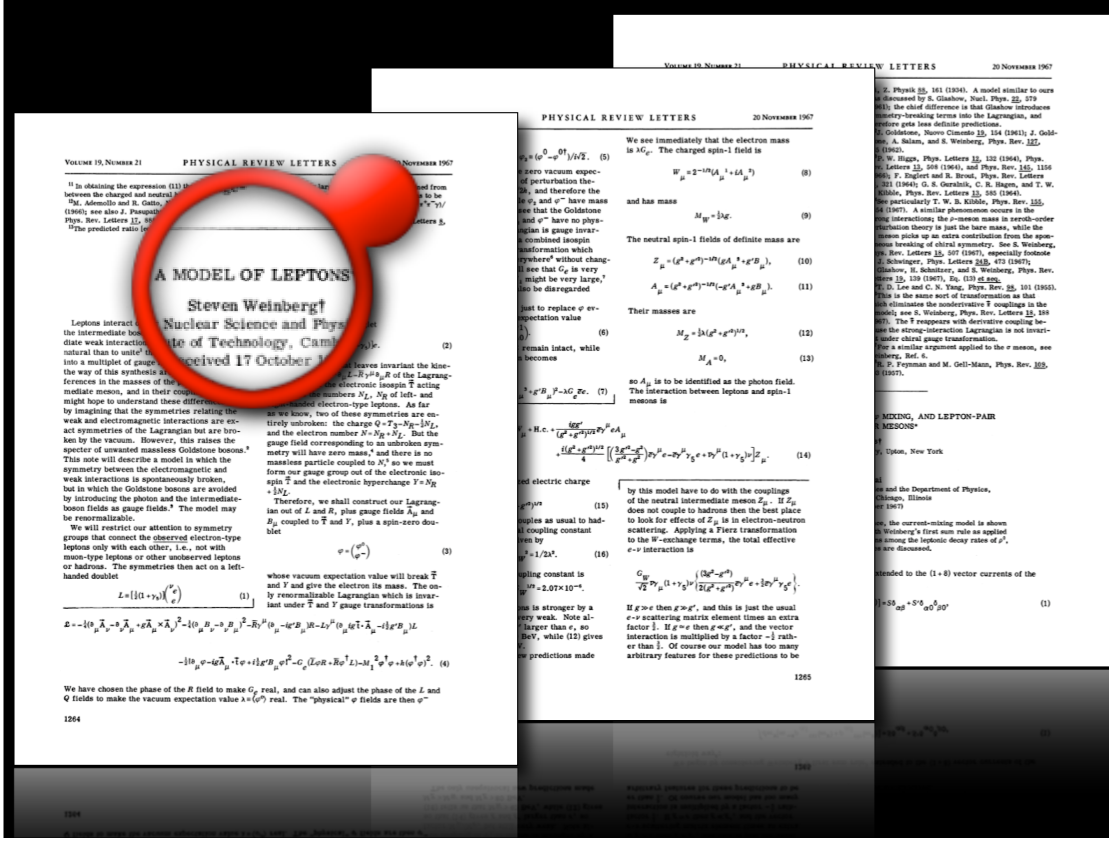


1967

http://www.mustangdreams.com/mdfastback.htm

http://nobelprize.org/nobel_prizes/physics/laureates/1979/weinberg-autobio.html

http://hacks.mit.edu/Hacks/by_year/2006



Standard Model

standard |ˈstandərd|

noun

1 a level of quality or attainment

model |ˈmädl|

noun

2 ...a simplified description, esp. a mathematical one, of a system or process, to assist calculations and predictions a model of leptons and quarks....

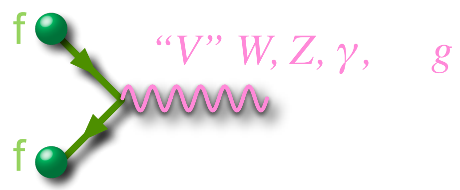
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \nu_{eR},\ e_R,\ \nu_{\mu R},\ \mu_R,\ \nu_{\tau R},\ \tau_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L u_R,\ d_R,\ c_R,\ s_R,\ t_R,\ b_R$$

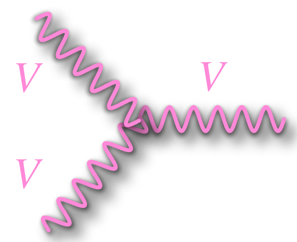
and forces....

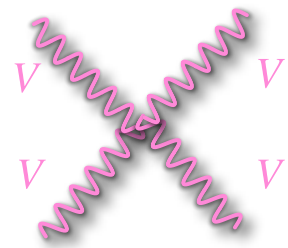
$W^\pm,\ Z^0,\ \gamma,\ g$

the weak, electromagnetic, and strong interactions



and dynamics....





astonishing level of understanding

$$\left.\begin{array}{lcl} Z^0 & \rightarrow & e+e;\ \mu+\mu,\ \tau+\tau,\ \nu+\nu \\ & \rightarrow & u+u,\ d+d,\ s+s,\ c+c,\ b+b \\ W^\pm & \rightarrow & e+\nu,\ \mu+\nu,\ \tau+\nu \\ & \rightarrow & u+d,\ u+s,\ u+b \end{array}\right\} +g, +2g... + \sum_{n=1}^{\infty} g$$

$$\begin{array}{lcl} d & \rightarrow & u, \ell, \nu \\ s & \rightarrow & d, u, \ell, \nu \\ c & \rightarrow & d, u, \ell, \nu \\ b & \rightarrow & d, u, \ell, \nu \\ t & \rightarrow & W+b \end{array}$$

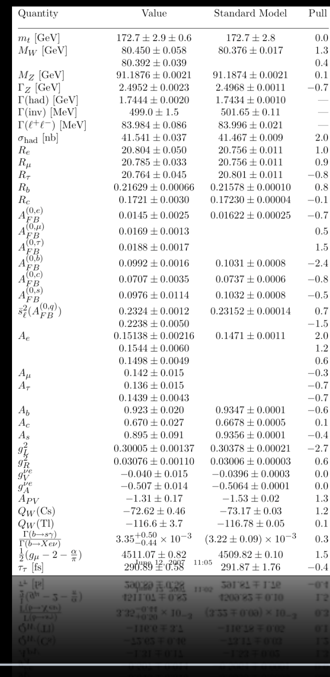
Including precise measurements of:
- masses,
- branching fractions,
- mixing
- production cross sections

$\nu \rightarrow \nu'$

Odd man out: neutrino sector

SM is an effective theory

pretty damn good.



Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		−1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
A_τ	0.136 ± 0.015		−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\text{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

June 12, 2007 11:05

The Review of Particle Physics
W.-M. Yao et al., Journal of Physics, G 33, 1 (2006)

a^0 0
B^0 0
B^+ +
B^- -
ϕ (+ , 0)
ϕ^* (- , 0)

γ
Z
$W^\pm$
H^0

t = the beginning 0 s — t = 10^{-12} s — t = 10^{+18}s

This...is:

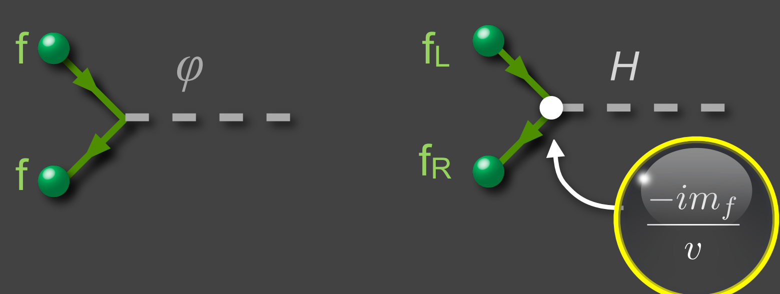
The “Higgs, Anderson, Mechanism, Guralnick, Kibble, Brout, Englert Mechanism”

H^0

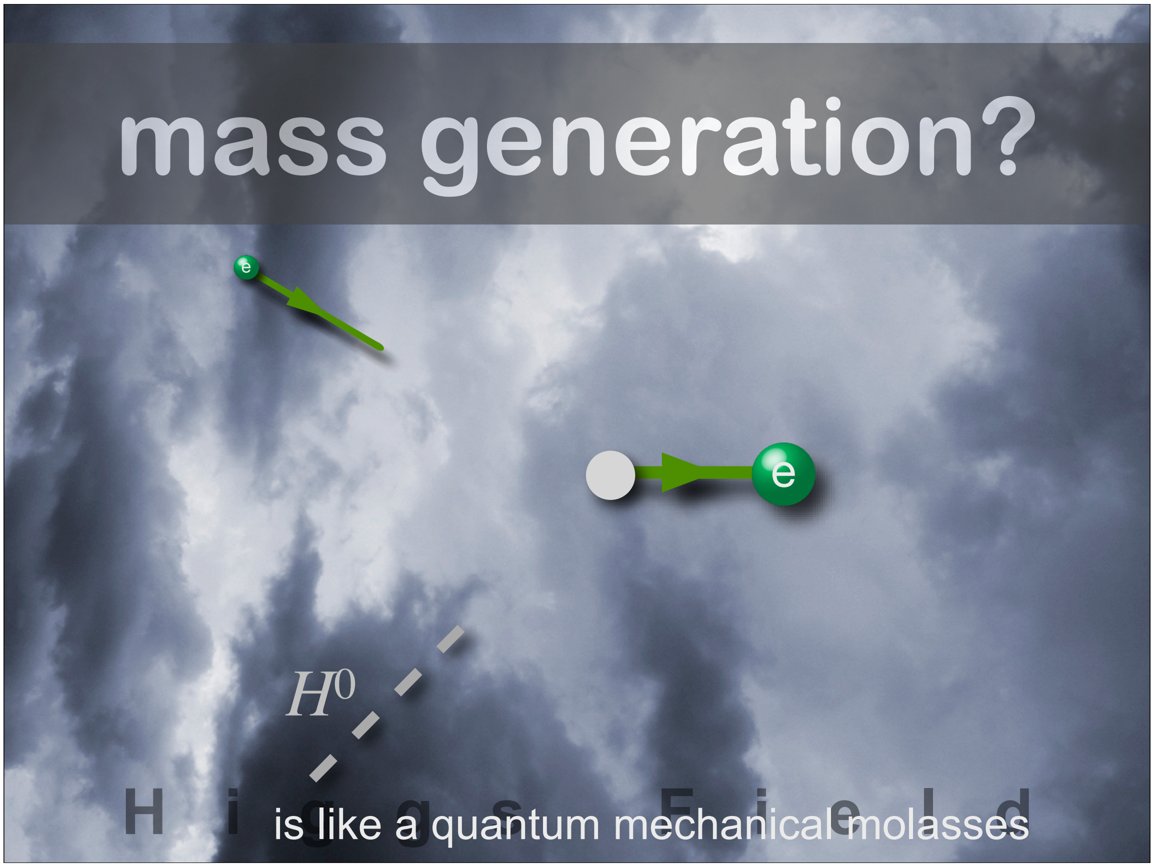
The remaining primordial scalar is the **Higgs Field.**

mass couplings

SM predicts:



coupling of L and R helicities...is mass



Masses come from the Higgs Mechanism. An analogy:

a room full of people, randomly oriented talking…

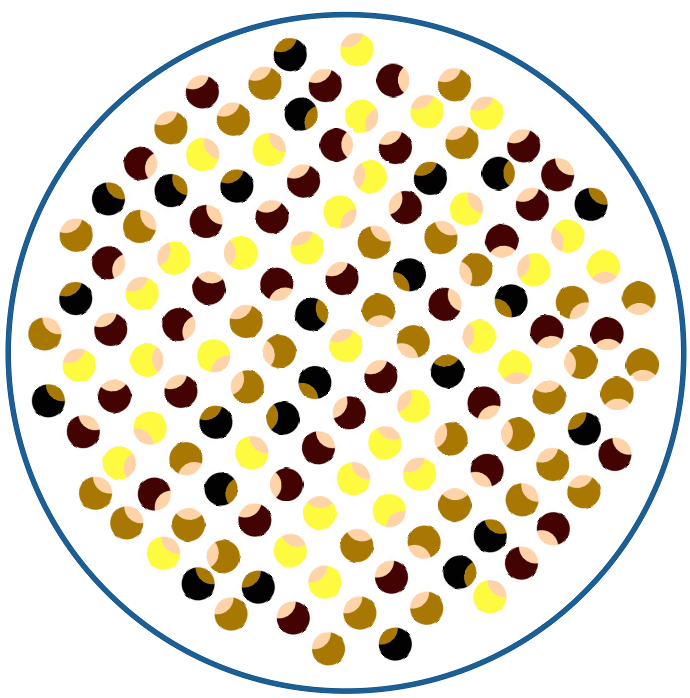
the noise (energy level) in the room is constant and forms a background (ground state) energy which is largely ignored by each member in his individual conversation

There is no ordering to the orientation of the people - a highly symmetric configuration

The room is the vacuum.
The people are collectively a **higgs field.**

…the ground state energy level is unimportant and tuned out

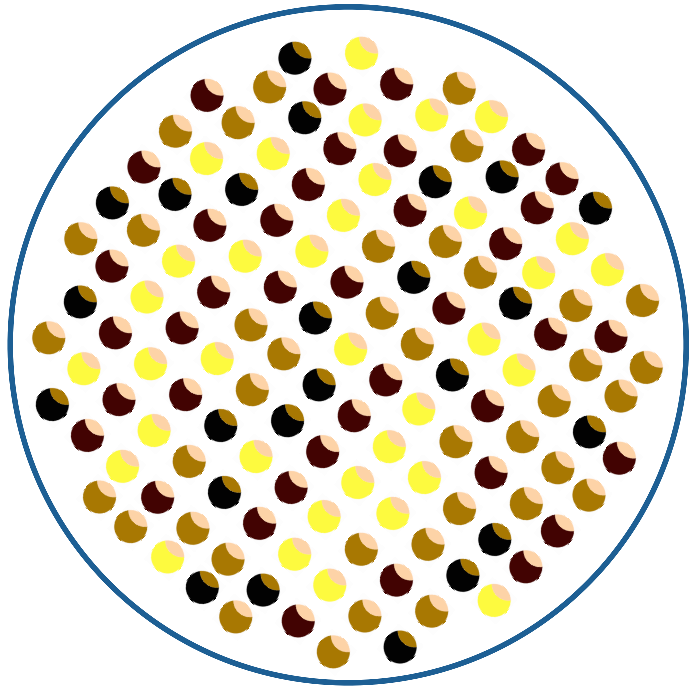
(after David Miller)



sleigh bells ring from the NE corner of the room…

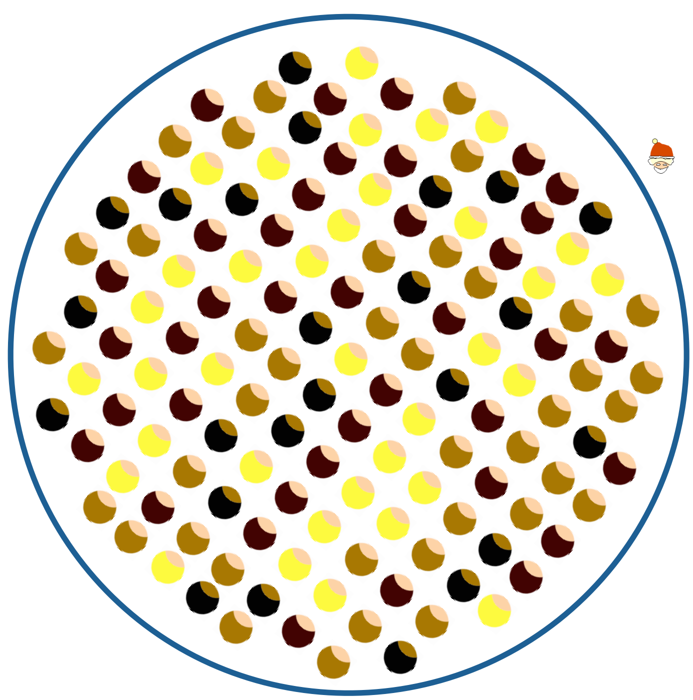
everyone turns to the sound
and is immediately silent - so,
the energy level in the room is
lowered when the randomness
is removed

The earlier symmetry is "broken"



Santa appears

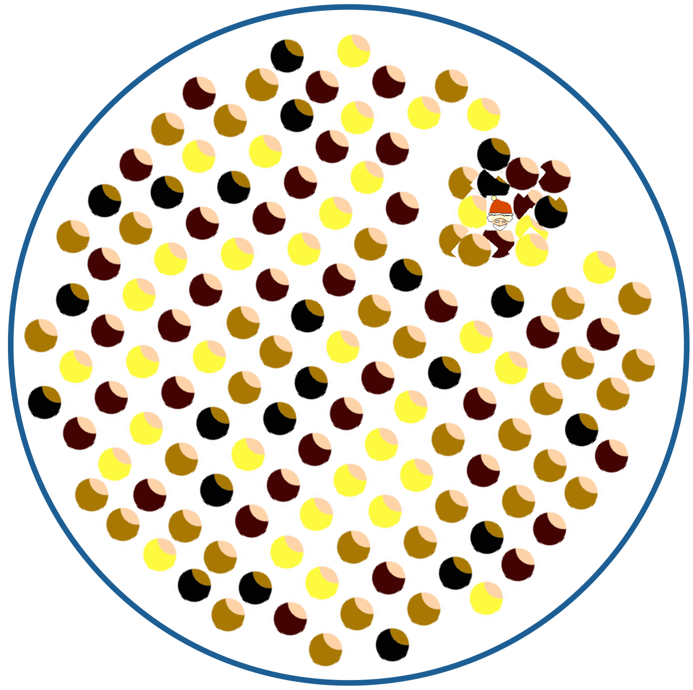
Santa is an electron.

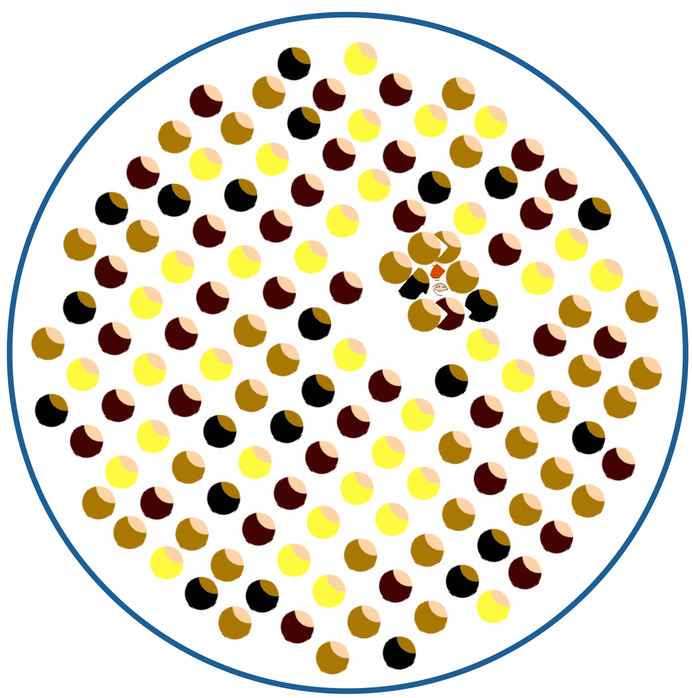


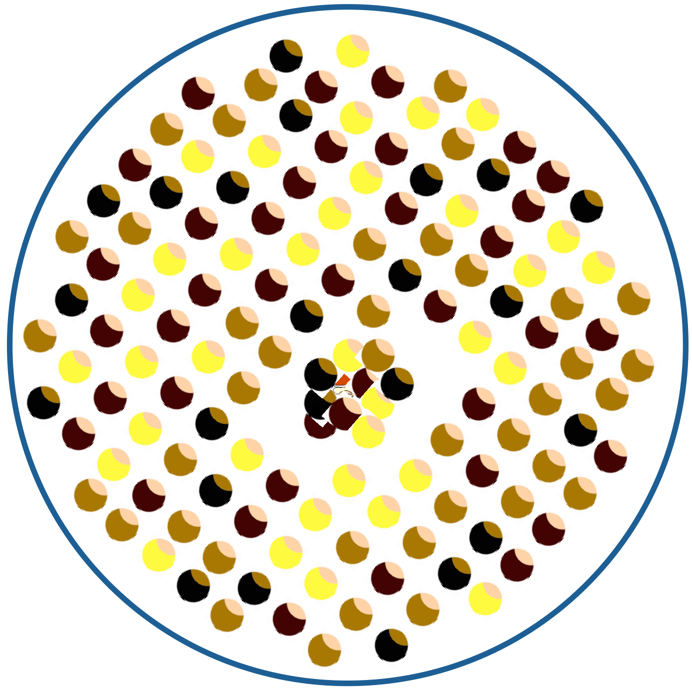
Santa enters the room and attempts to make it across…

his progress is impeded
as if his inertia has increased

ie, as if his *mass* has
increased by virtue of his
interaction with the people
around him.







This is the generation of mass.

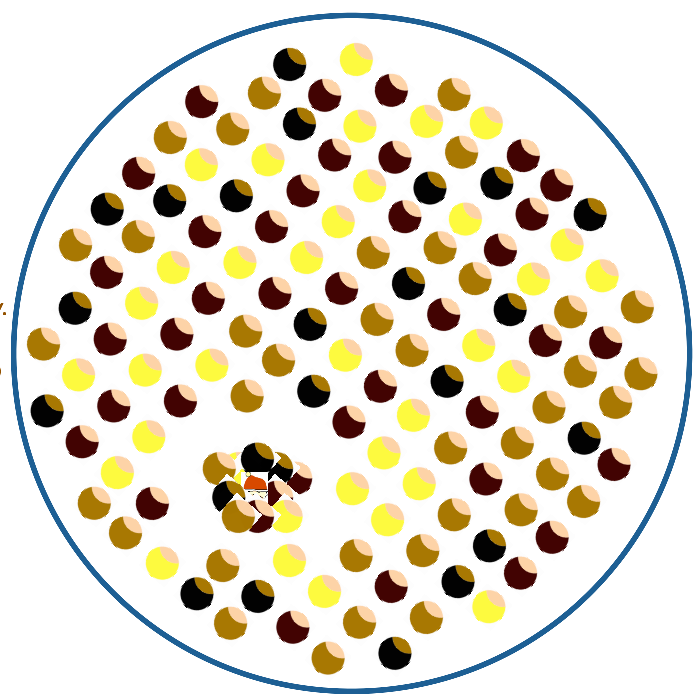
The circle is the Universe

The people are the analog of the Higgs field, triggered by the phase transformation inherent when they turned NE and lowered their energy.

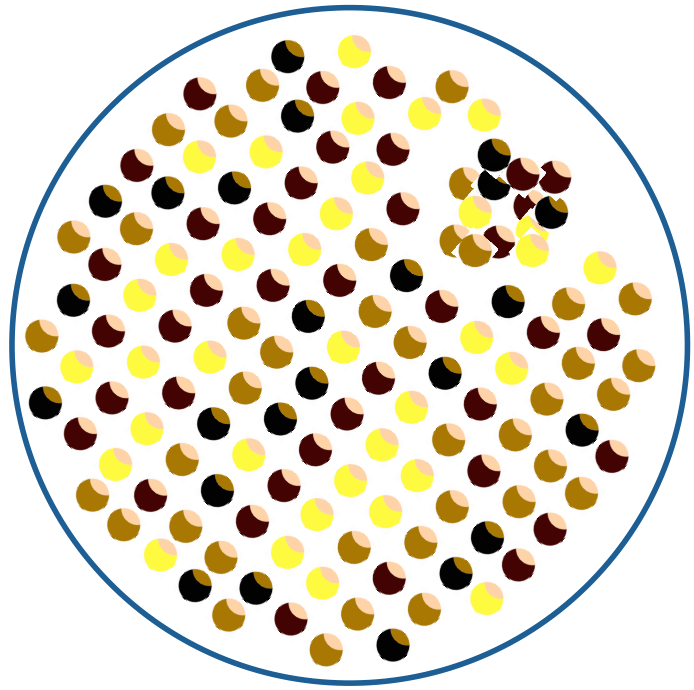
They give "mass" to Santa (particles) by interacting with him…

mass is generated by particle's interaction with the Higgs field

…in the vacuum.

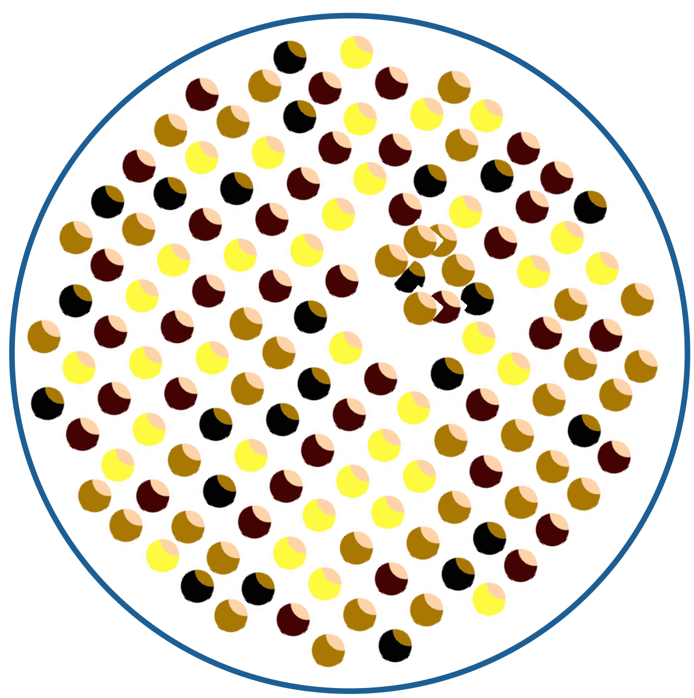


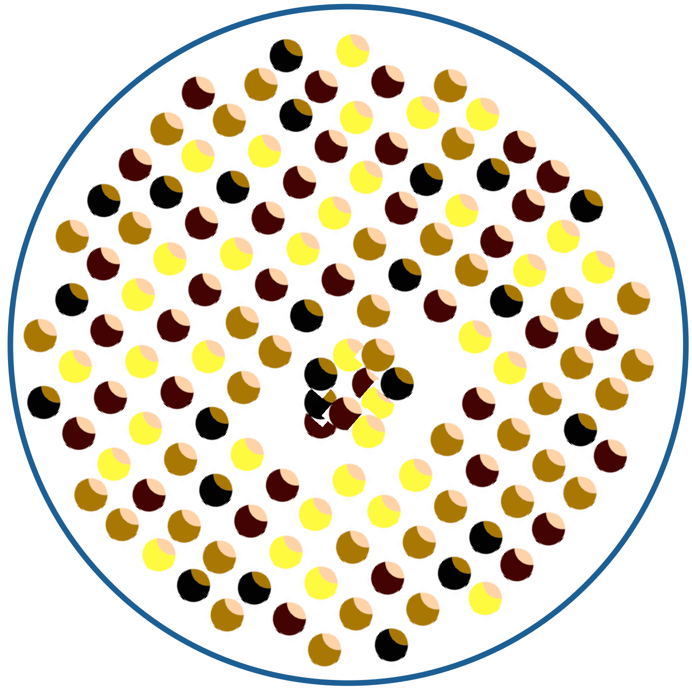
Suppose now, that only the rumor that Santa might arrive starts at the NE corner



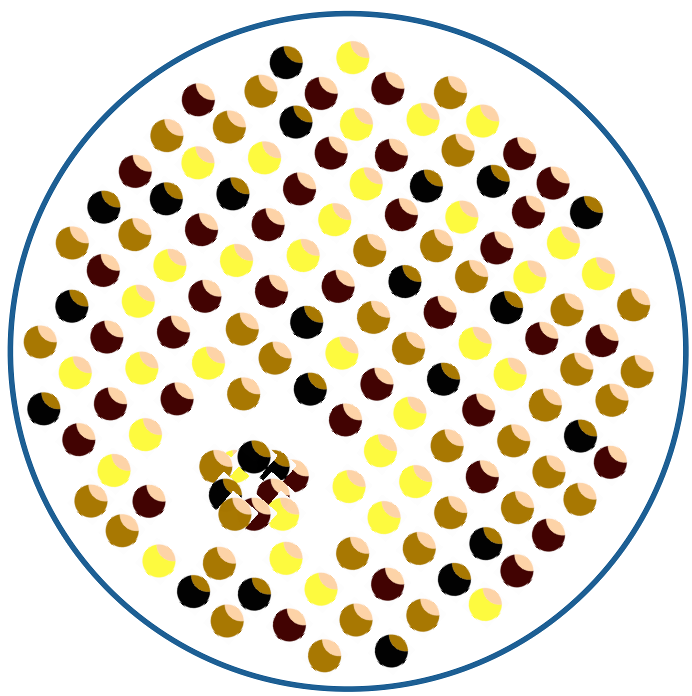
The rumor migrates across the room…

the clustering is the Higgs particle - the quantum of the Higgs field



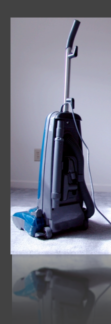


Finding the Higgs Boson is of fundamental importance to confirming the Standard Model and the veracity of the phase transition



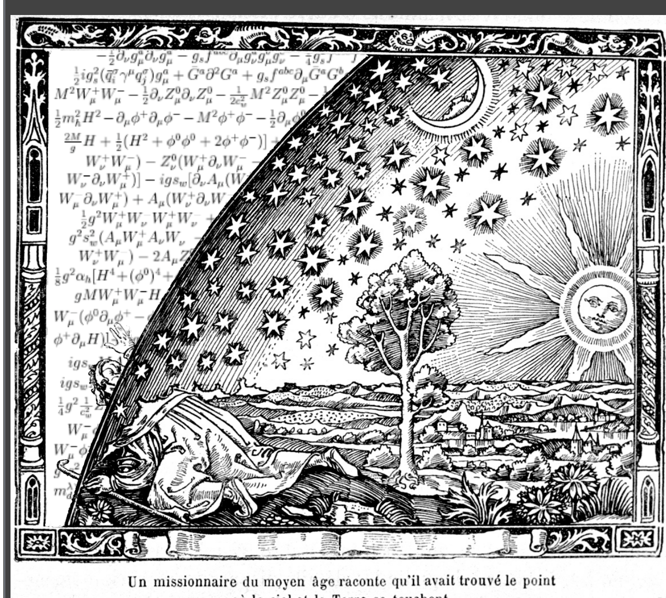
a Higgs boson would be a chip of the vacuum.

relativistic quantum field theory

says  is seething.

now like

that drawer you all have at home



the deeper...

the Standard Model fails...

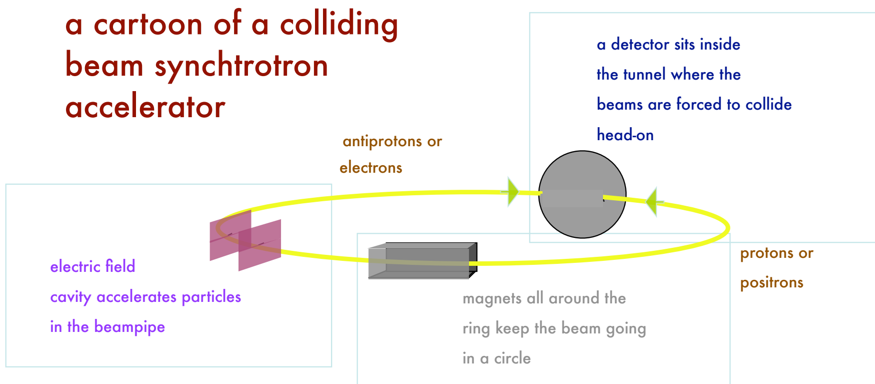
be there dragons?

after: Camille Flammarion, L'Atmosphere: Météorologie Populaire (Paris, 1888), p. 163.

accelerators

Synchrotron

a cartoon of a colliding beam synchtrotron accelerator



what is Fermilab?

it’s many things to me…

it’s a dedicated scientific community

made up of:

- 1200 physicists, engineers, and staff
- >1000 faculty, post docs, and students
- from > 80 US & ~20 foreign institutions

it’s an amazing scientific instrument

consisting of:

- A time machine
- A particle accelerator for antirotating beams of protons and antiprotons
- hand-made vehicles to explore the current and the very early universe
- A source of high energy/intensity beams of kaons and neutrinos

it’s a beautiful single-purpose DOE national lab

located at:

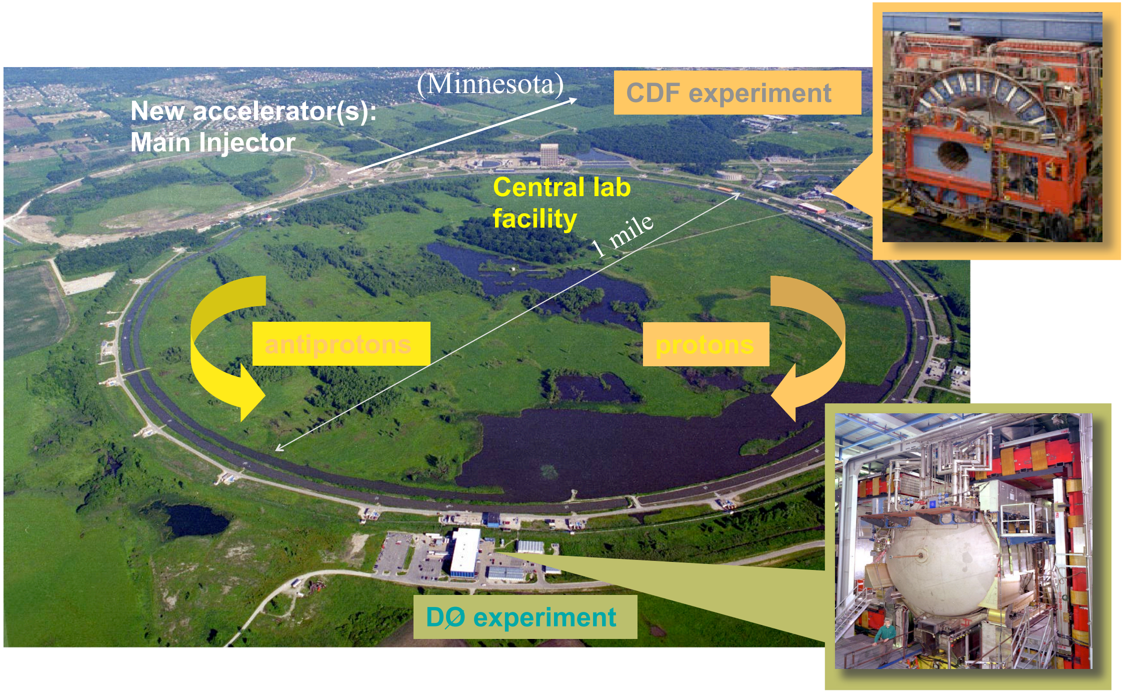
- real space: 60 mi west of Chicago
- cyberspace: `www.fnal.gov`

an inspiring place to work

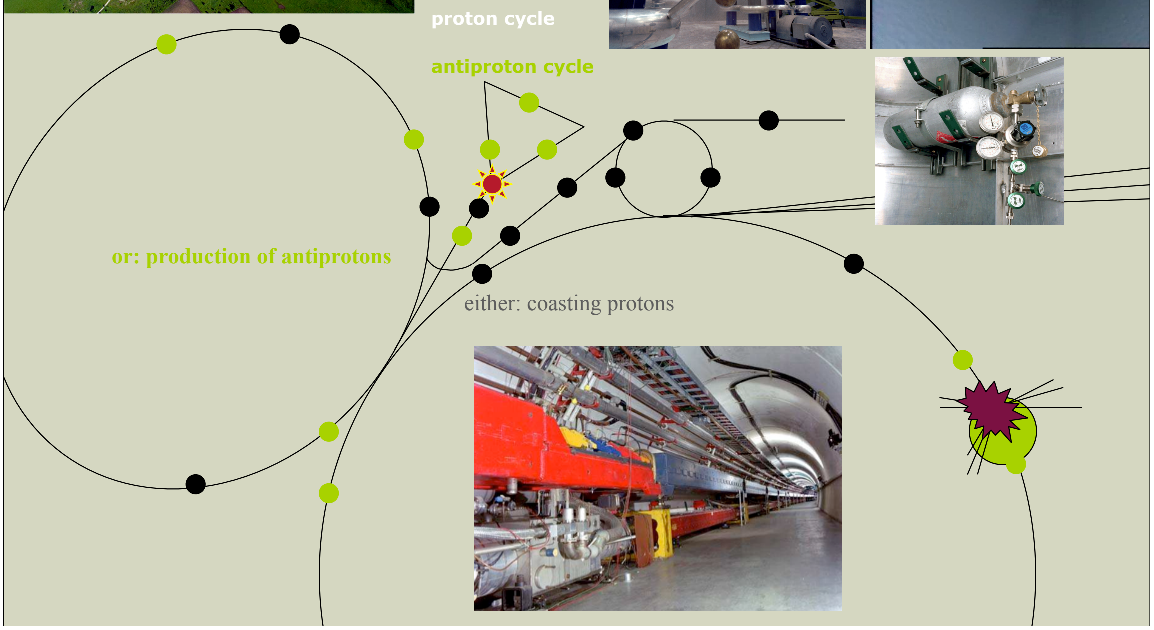
Wilson Hall

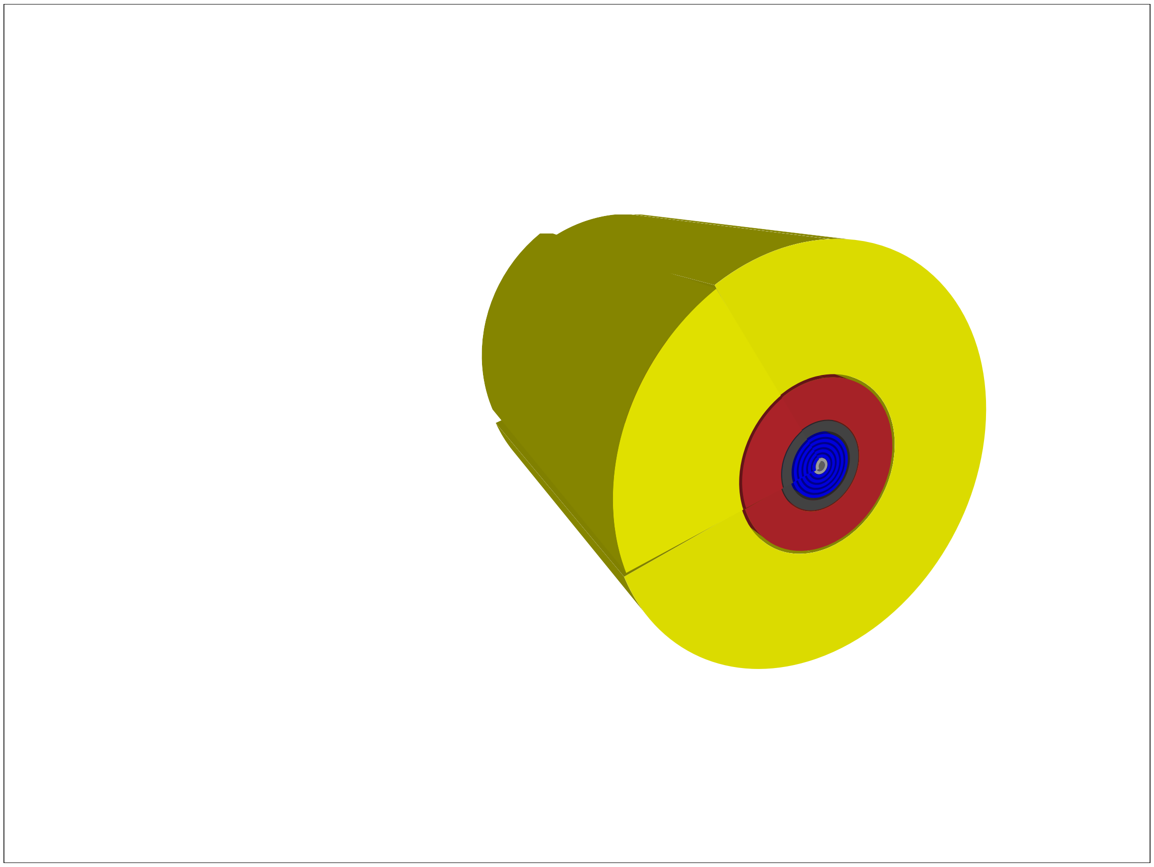
designed by the first director, Robert Wilson

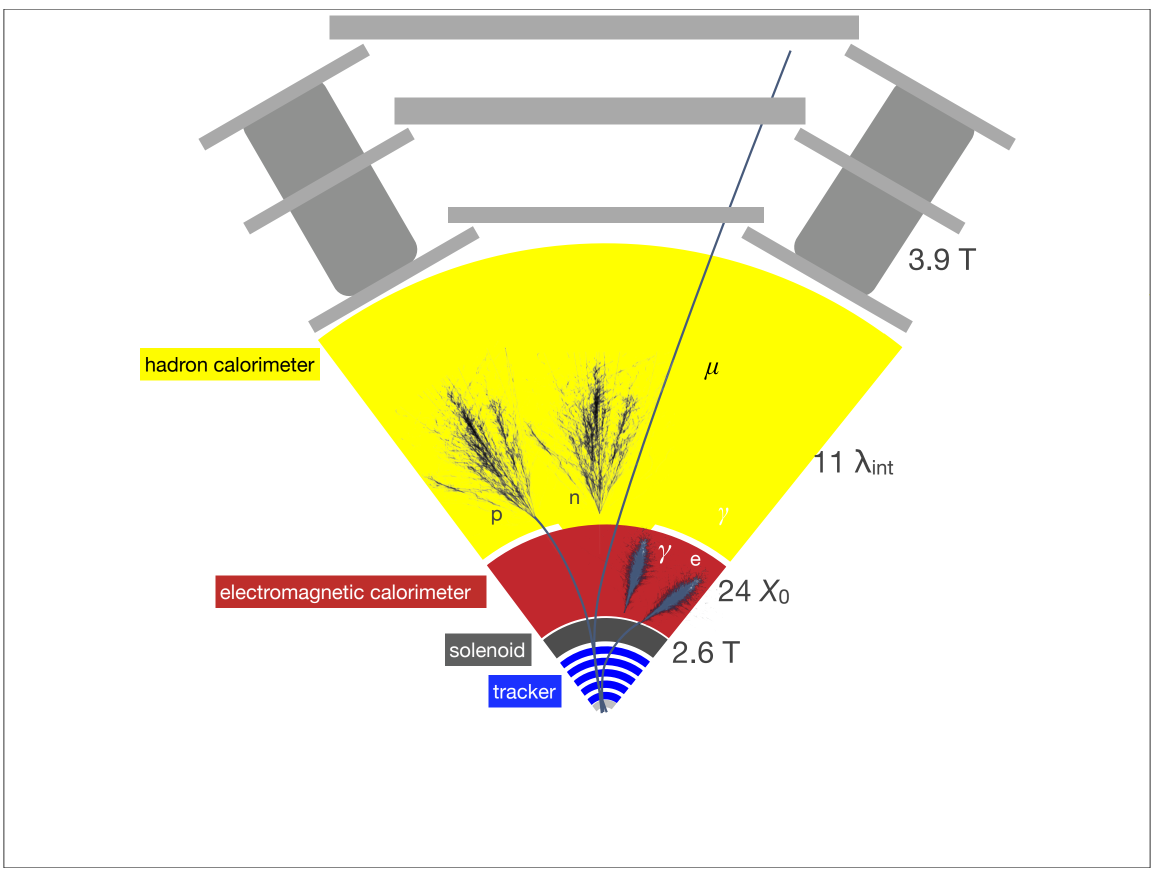
Fermi National Accelerator Laboratory



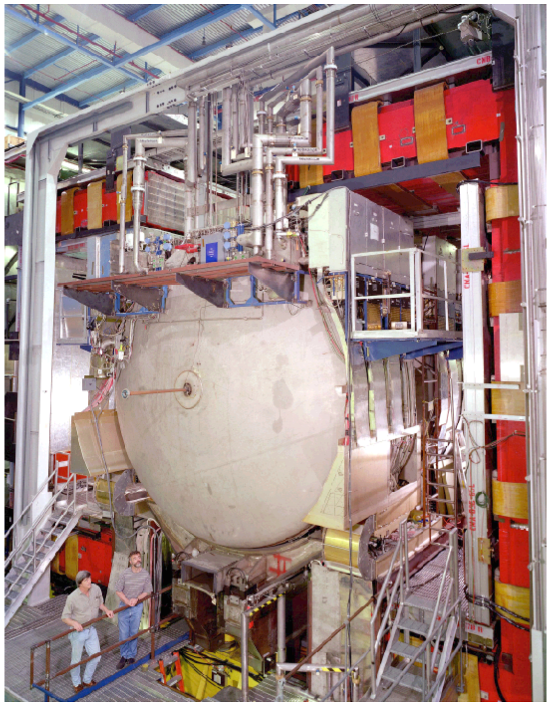
Accelerator Complex - the time machine



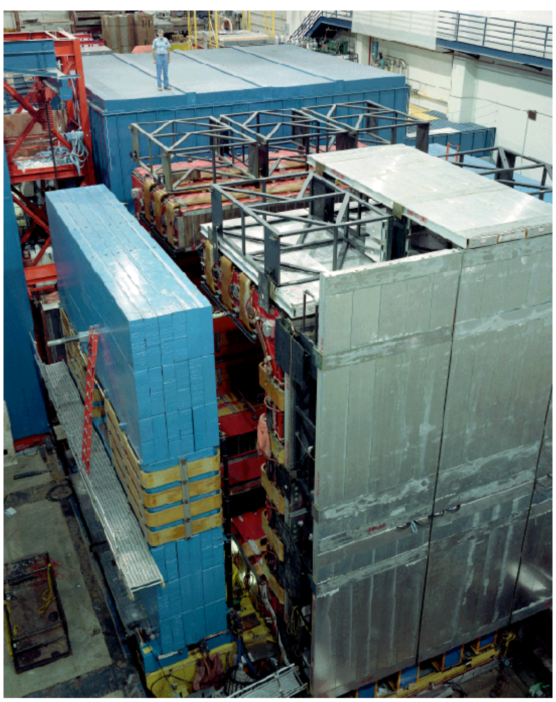



3.9 T
hadron calorimeter
μ
11 λint
p
n
γ
γ
e
electromagnetic calorimeter
24 X0
solenoid
2.6 T
tracker

the DØ detector: inside



the DØ detector: outside

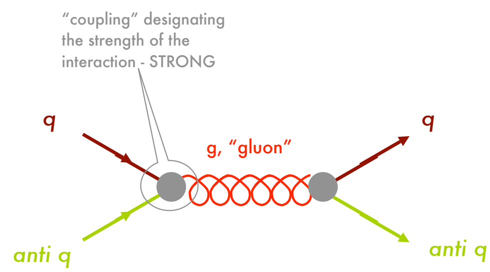


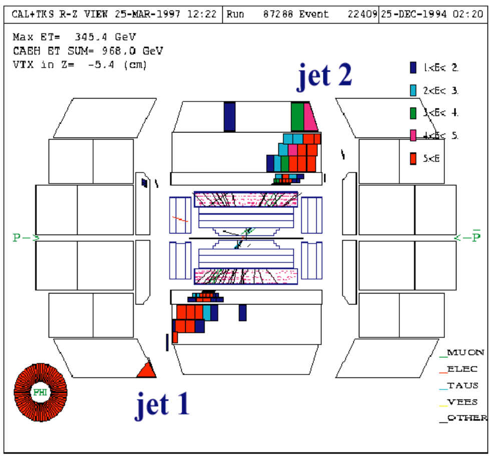

DETECTOR REMOVAL
03/12/96 M15 C15 07:56:49

most violent elementary particle collision produced on earth

Rutherford Scattering of one quark in the proton off of another quark from the antiproton

with the exchange of a "gluon" a photon-like particle that transmits only the STRONG force.





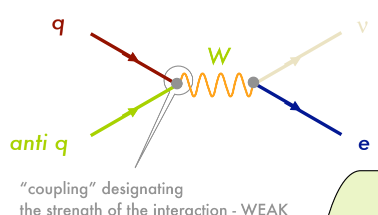
It required that
the quarks annihilated within 10^{-19} m of one another or
1/10,000 the size of a proton

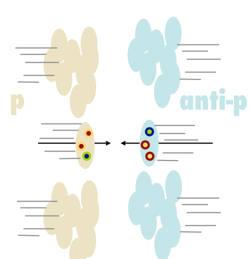
The energetics of this event is consistent with interactions in the early universe ~10^{-20} s after the big bang

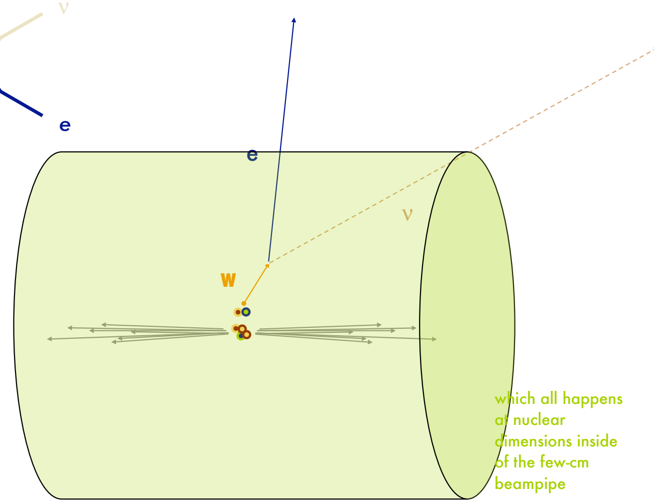
2 events: W boson production & detection

p + antip → W + uninteresting stuff

with W → e + ν







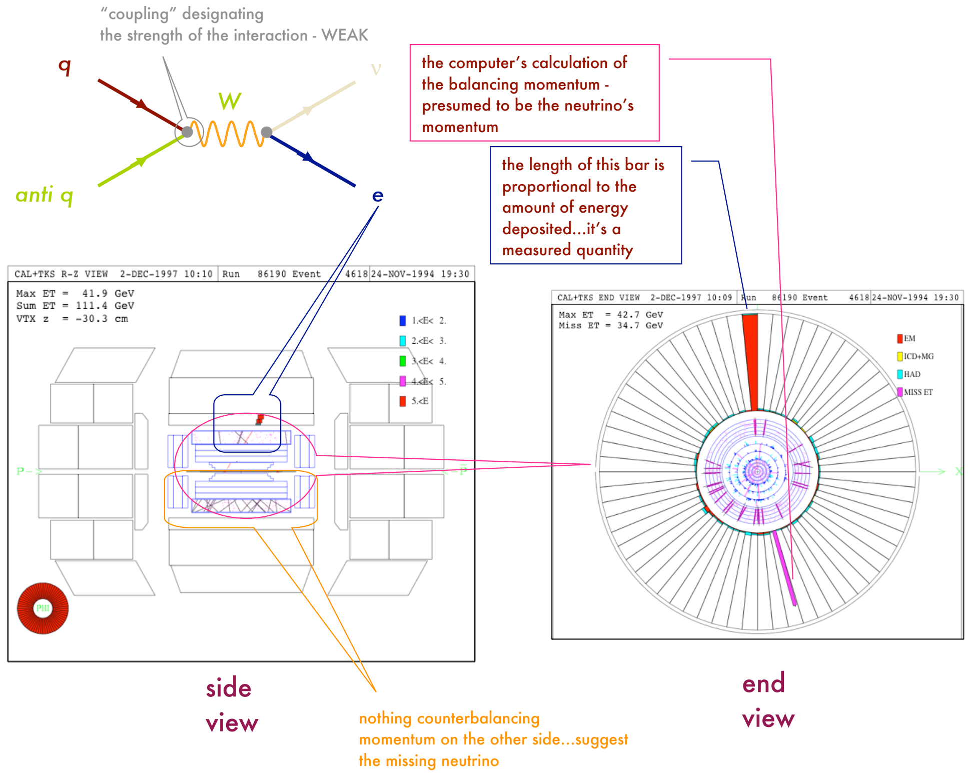
every few hundred nanoseconds - 10^{12} or so protons and antiprotons encounter one another

most go by without interacting

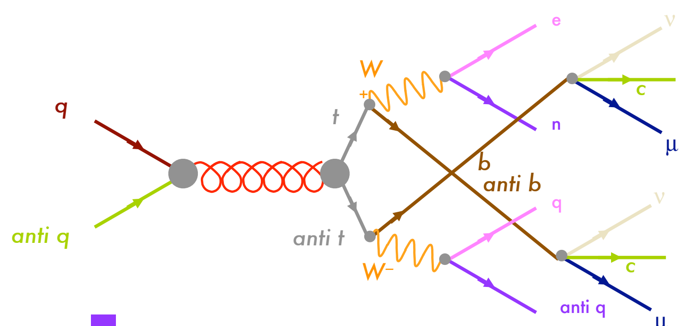
occasionally, a quark from the p and a quark from the anti-p are at particularly large momentum and annihilate, head-on with one another...

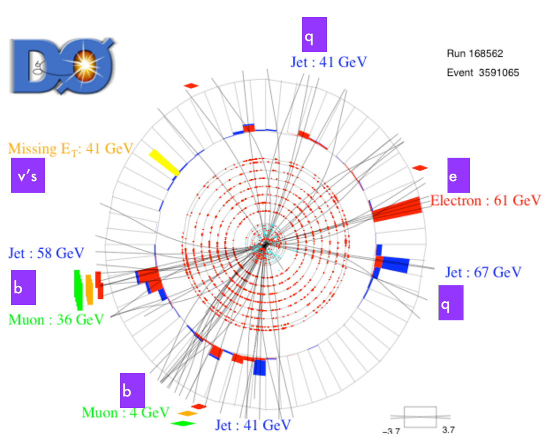
The other quarks interact, but with much lower initial momenta

what the detector "sees"



top quark production and decay

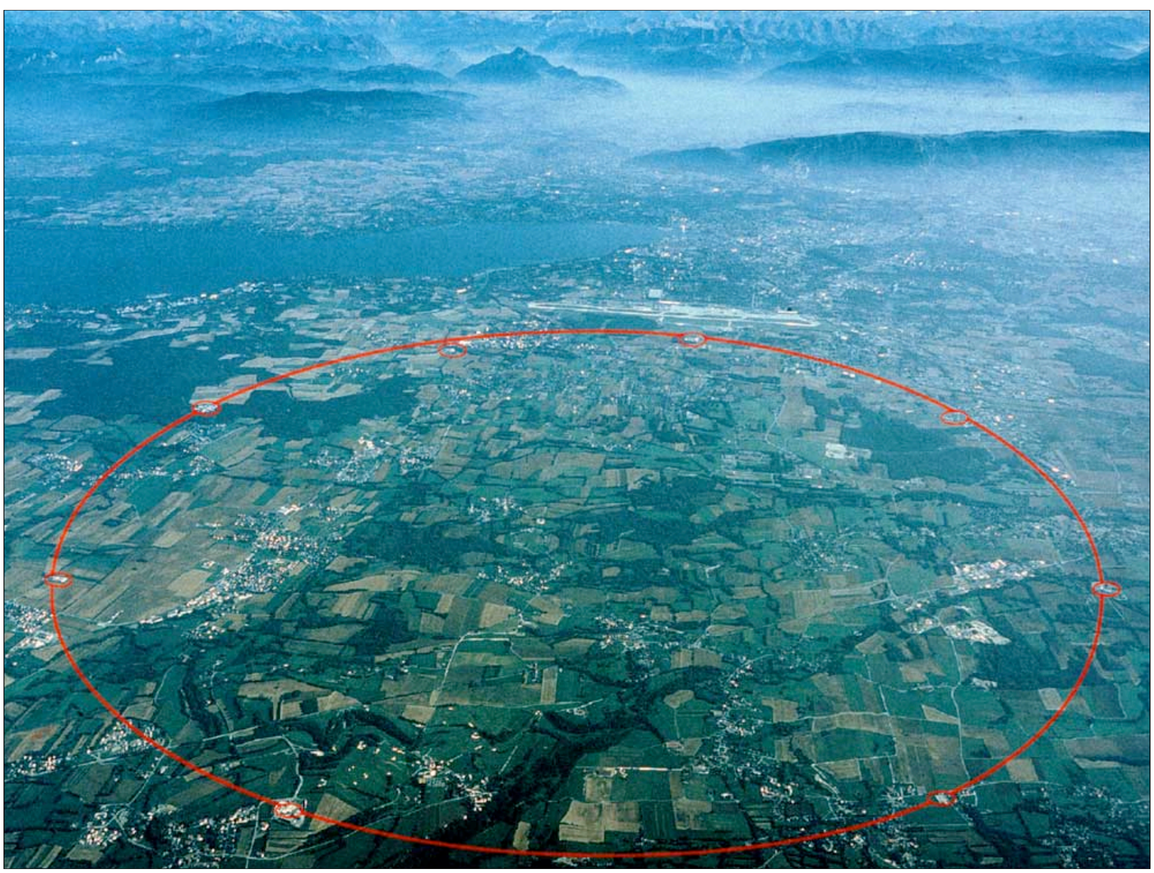


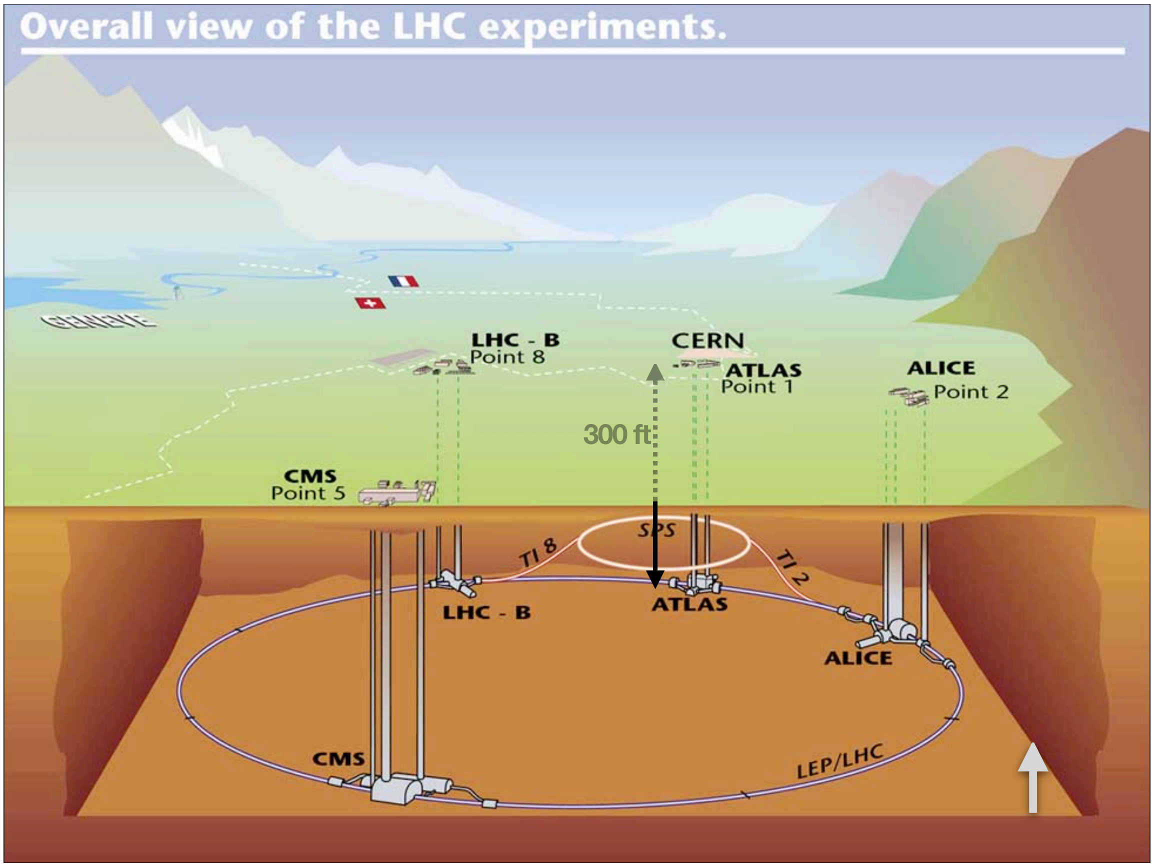


what's produced in the final state:

electron → electron shower neutrino → nothing, missing E/p	one W
quark → hadron jet antiquark → hadron jet	other W
c quark → hadron jet muon → track in iron magnet neutrino → nothing	one b
c quark → hadron jet muon → track in iron magnet neutrino → nothing	other b

the Large Hadron Collider





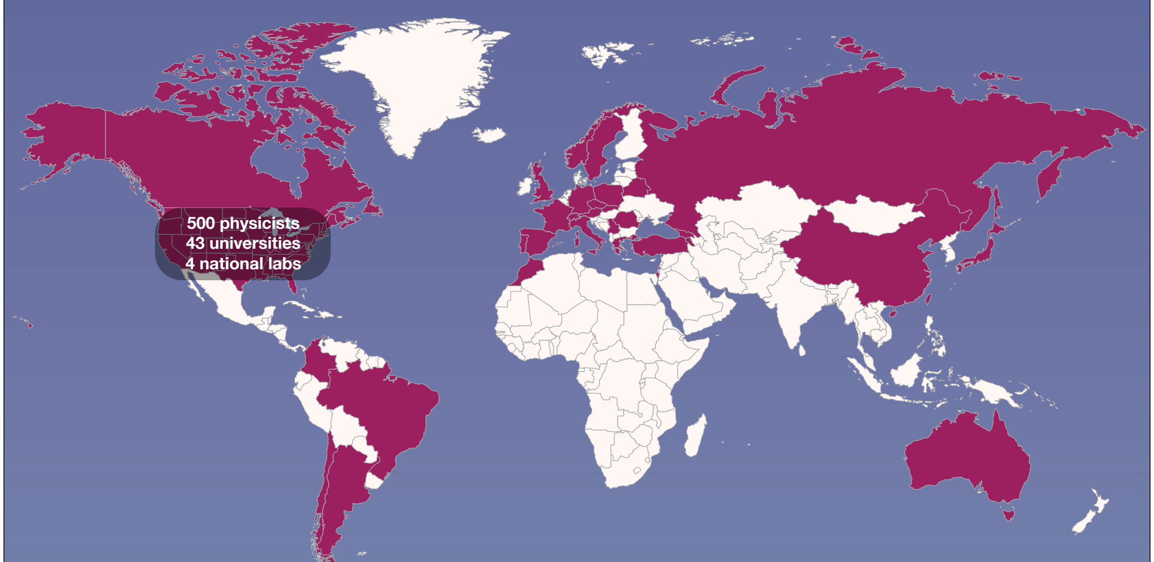
40 million times per second

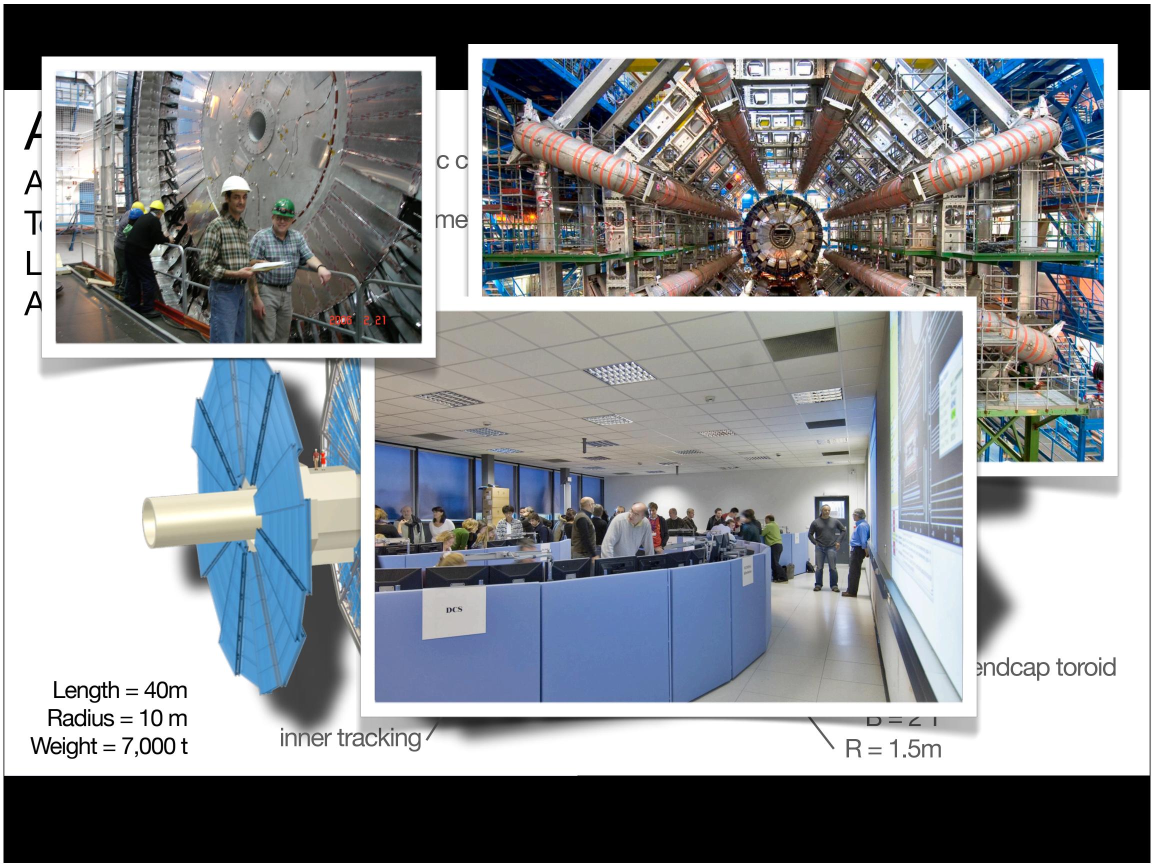
2835 bunches of protons
100,000,000,000 protons per bunch

ATLAS

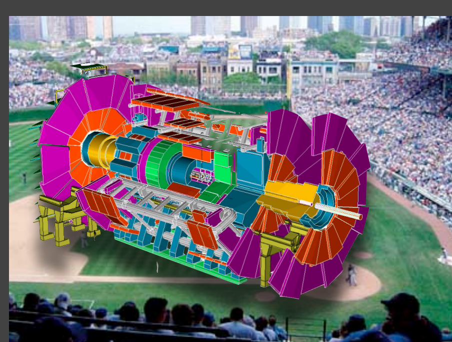
ATLAS Collaboration

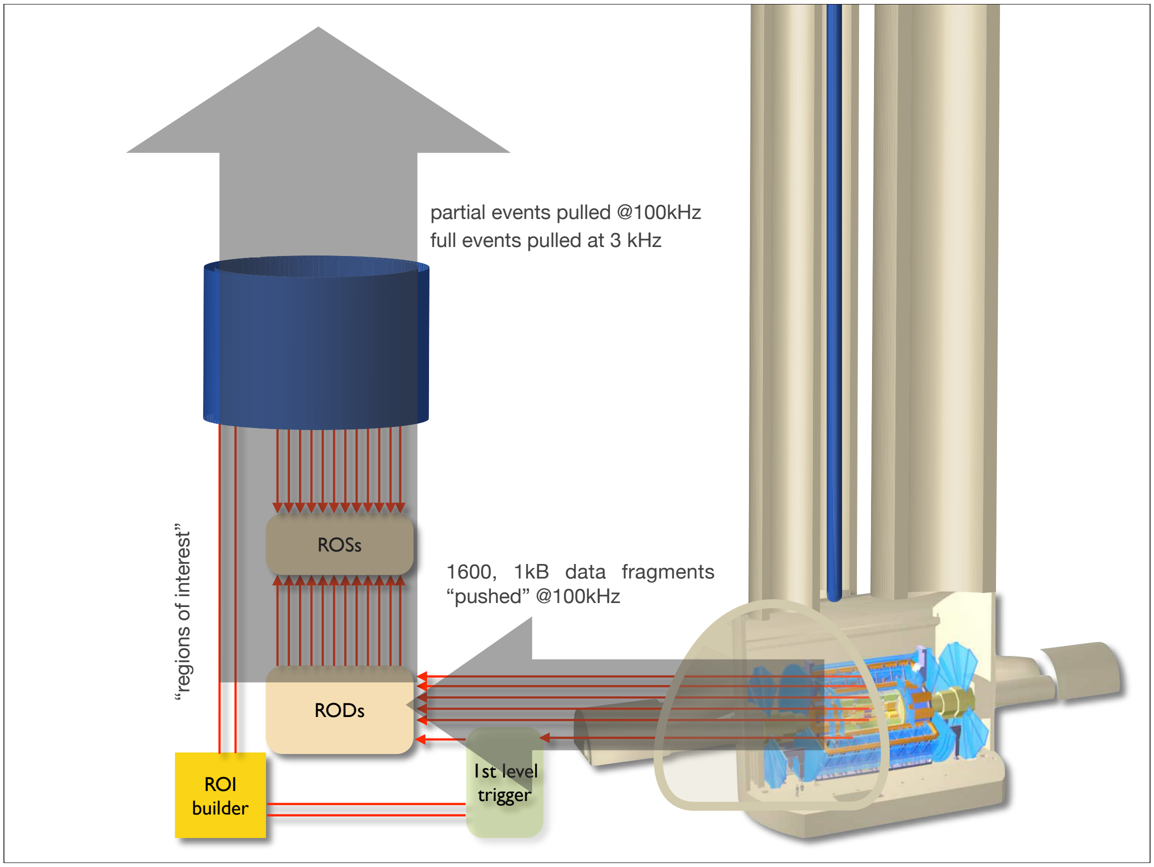
39 nations
164 institutions
1900 authors
400 PhD students

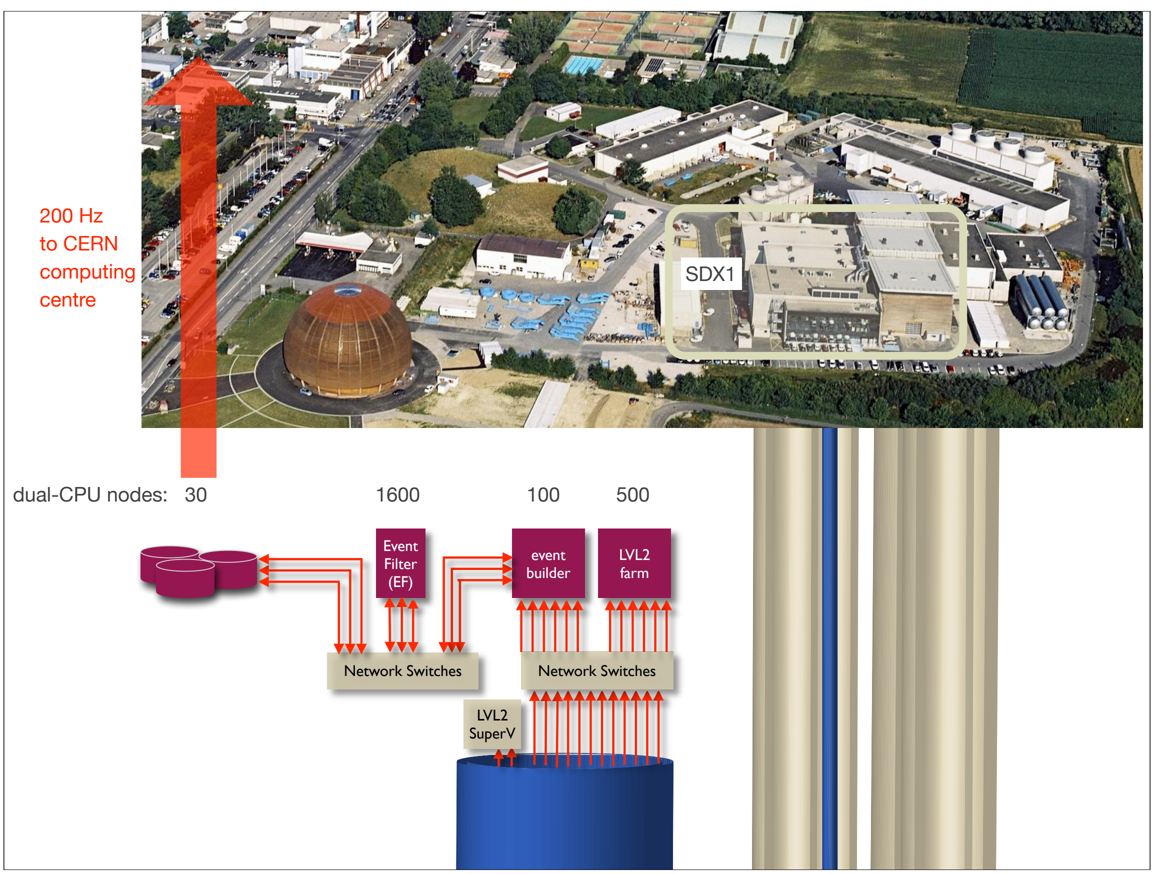




Length = 40m
Radius = 10 m
Weight = 7,000 t
inner tracking
endcap toroid
R = 1.5m



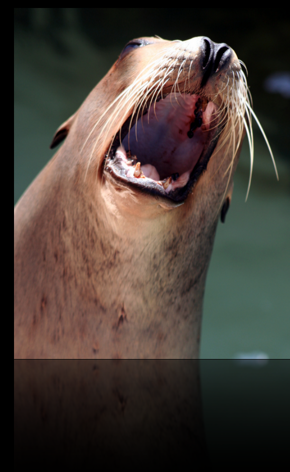

partial events pulled @100kHz
full events pulled at 3 kHz
"regions of interest"
ROSs
1600, 1kB data fragments
"pushed" @100kHz
RODs
ROI builder
1st level trigger


200 Hz
to CERN
computing
centre
SDX1
dual-CPU nodes: 30
1600
100
500
Event Filter (EF)
event builder
LVL2 farm
Network Switches
Network Switches
LVL2 SuperV

now what?

gotta store it.
gotta reduce it
gotta analyze it.

keep that up for 2 decades.



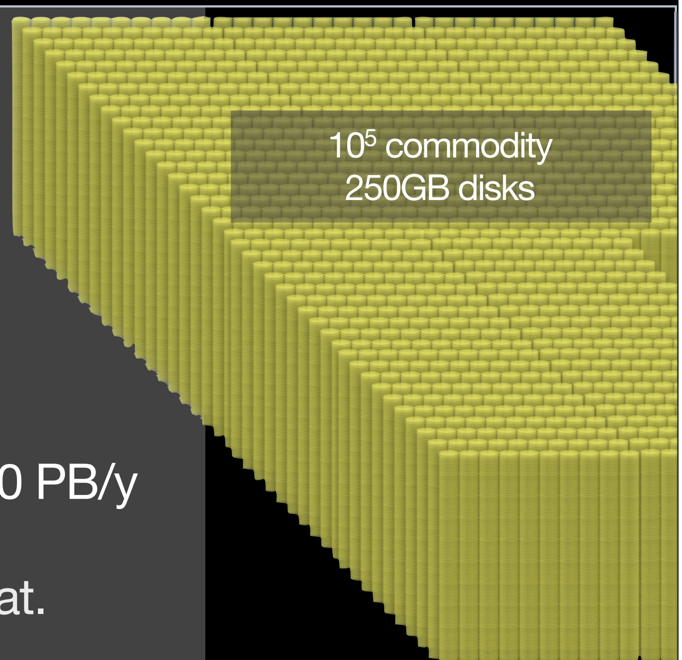
storage

10^{10} events per year

@ 1.6MB/event

~20PB/year + BU = 40 PB/y

yeah. we could do that.



1 GB = 1000MB
~ 2 CD's

1 TB = 1000GB
~ 200 DVD's

1 PB = 1000TB
~ 10^{11} books

1 EB = 1000PB
~ world annual information production

raw event reconstruction

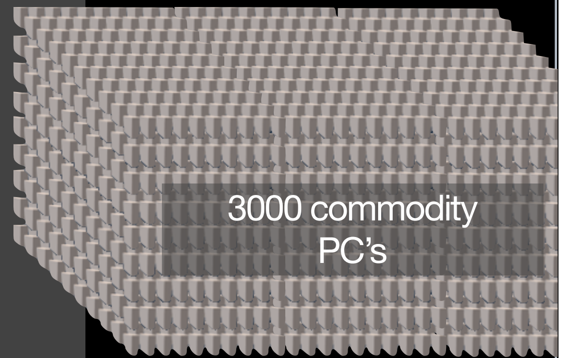
~15s per 1.6MB event per cpu

coming @ 200Hz

3000 cpu's to keep up

~400 nodes ~ 10 racks

yeah. we could do that.



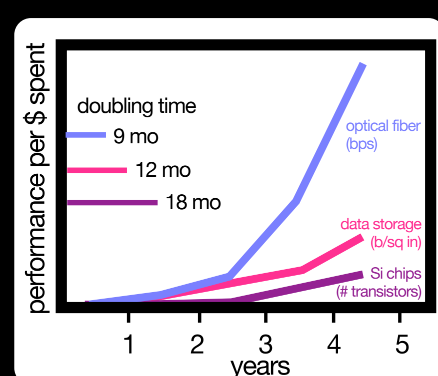
=> massively parallel systems...

physicist analysis?

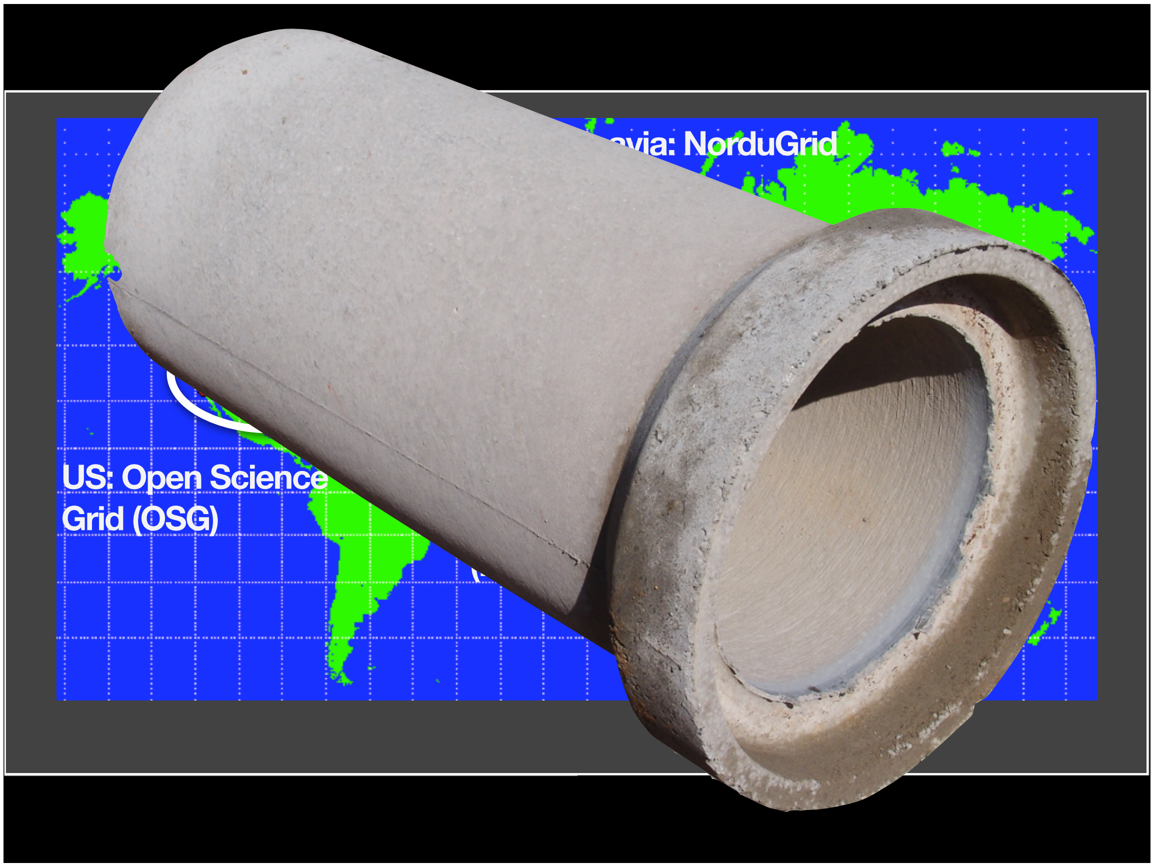
that's a toughy.

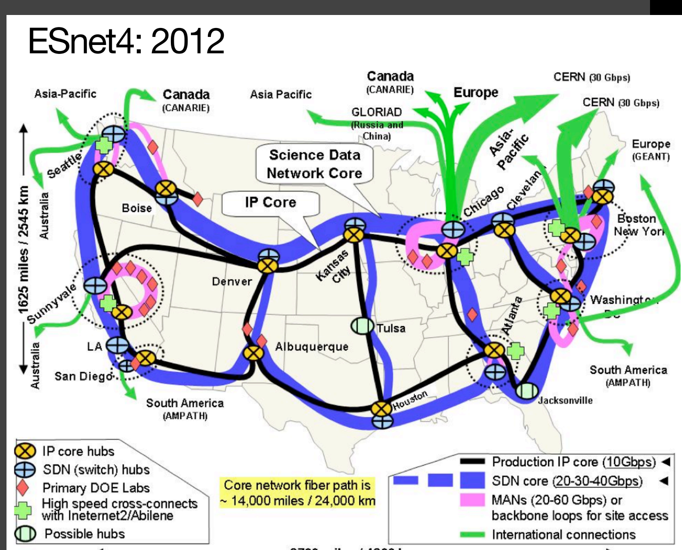
longer just to disk-access the data than collect it.

win with Moore's Law?
not any ...um...more.



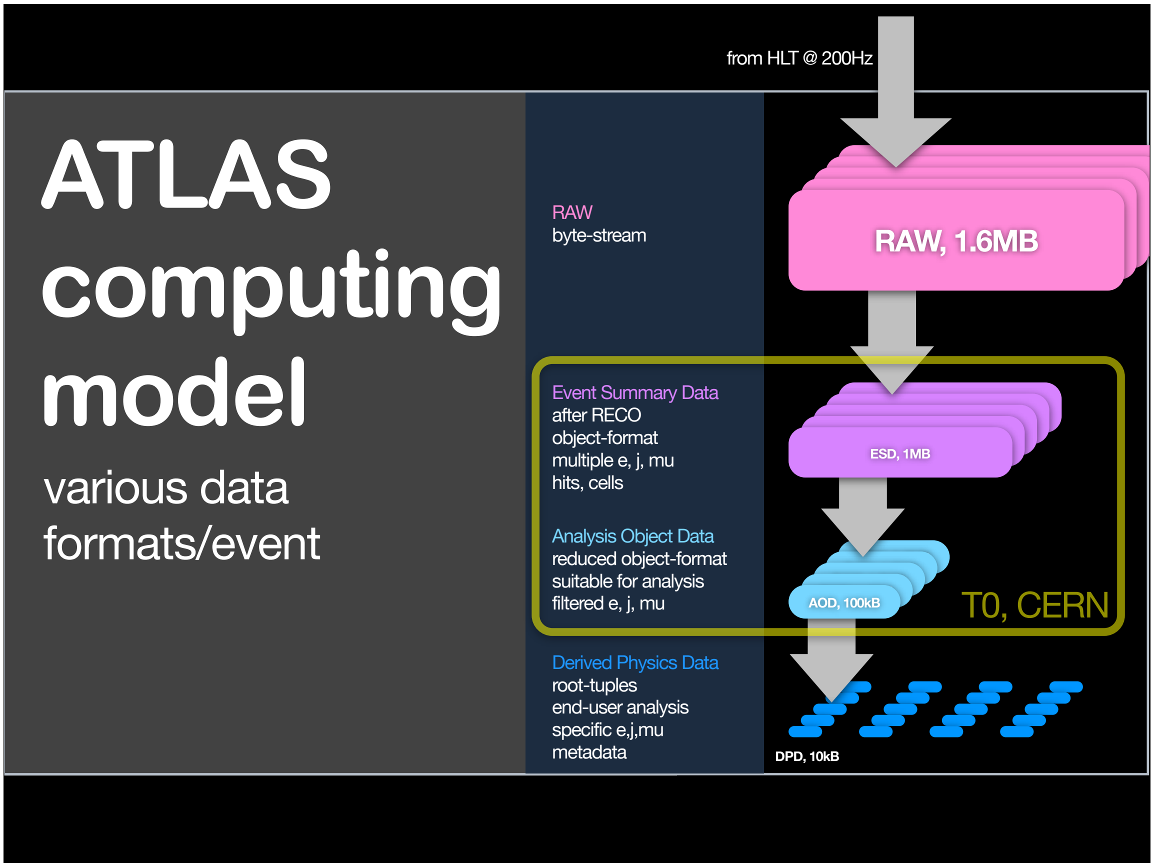
from: CLEO VILETT, SOURCE: Vined Khoslan, Kleiner, Caufield and Perkins.

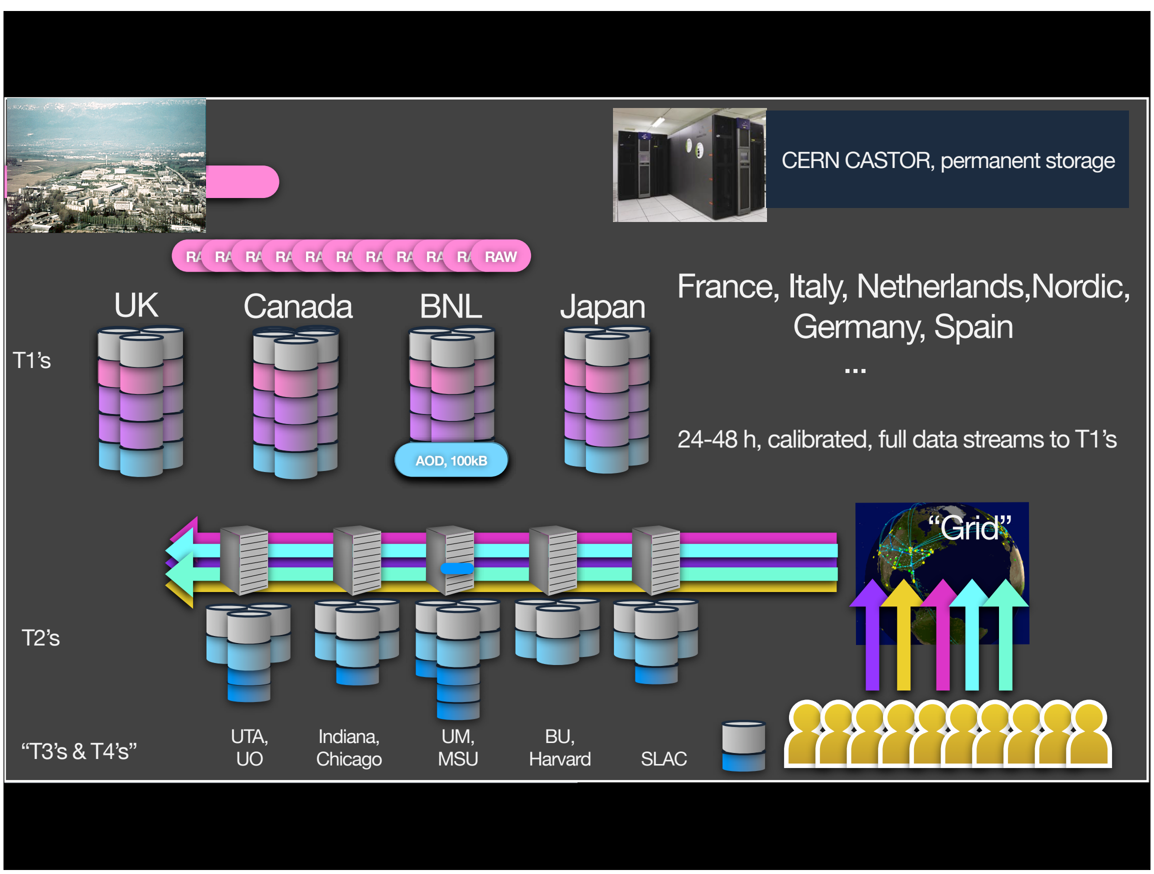


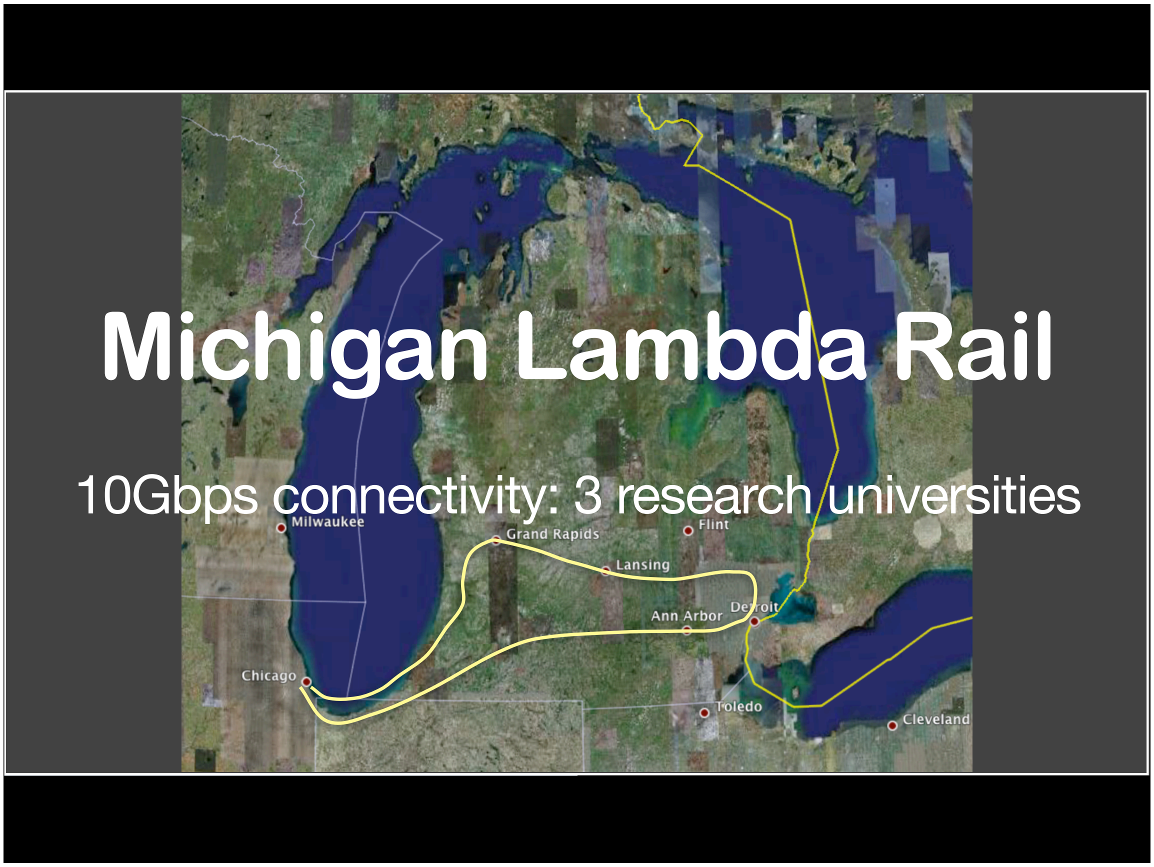


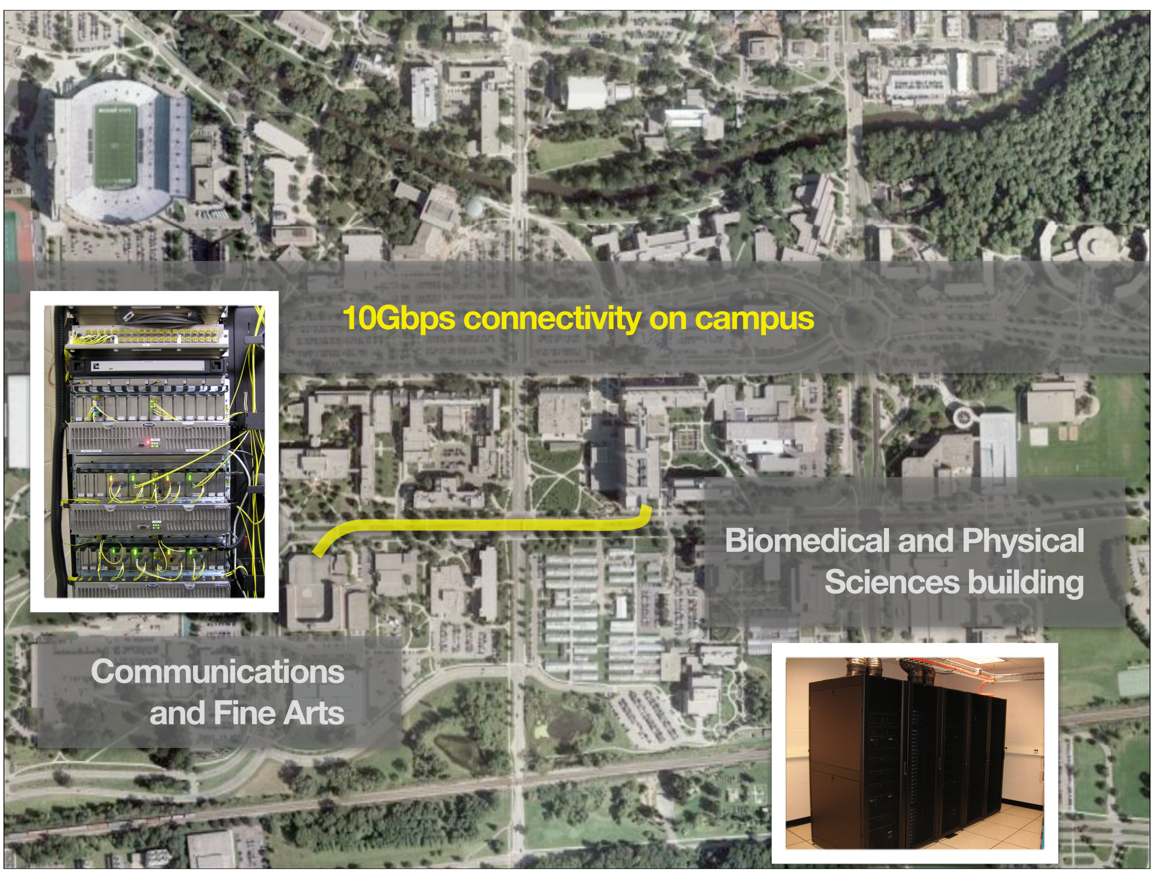
the infrastructure:

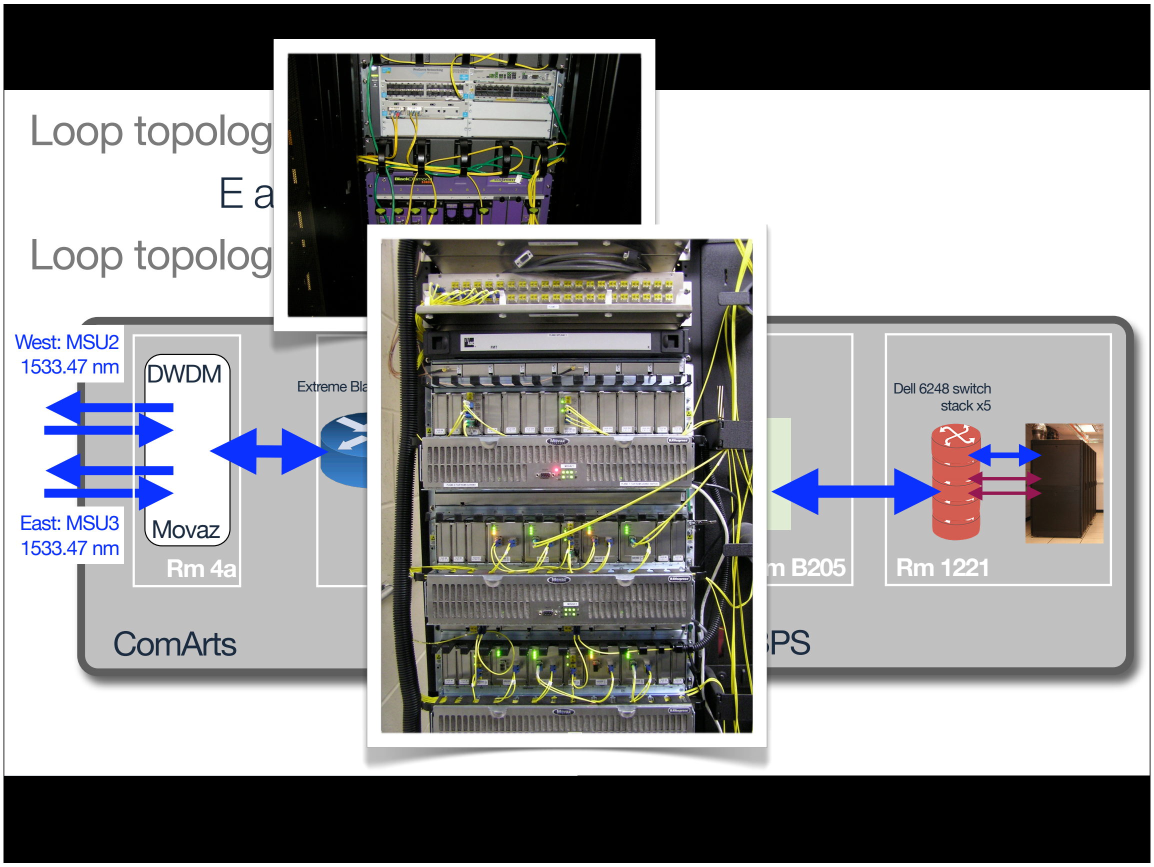
"Energy Science Network" (ESnet)

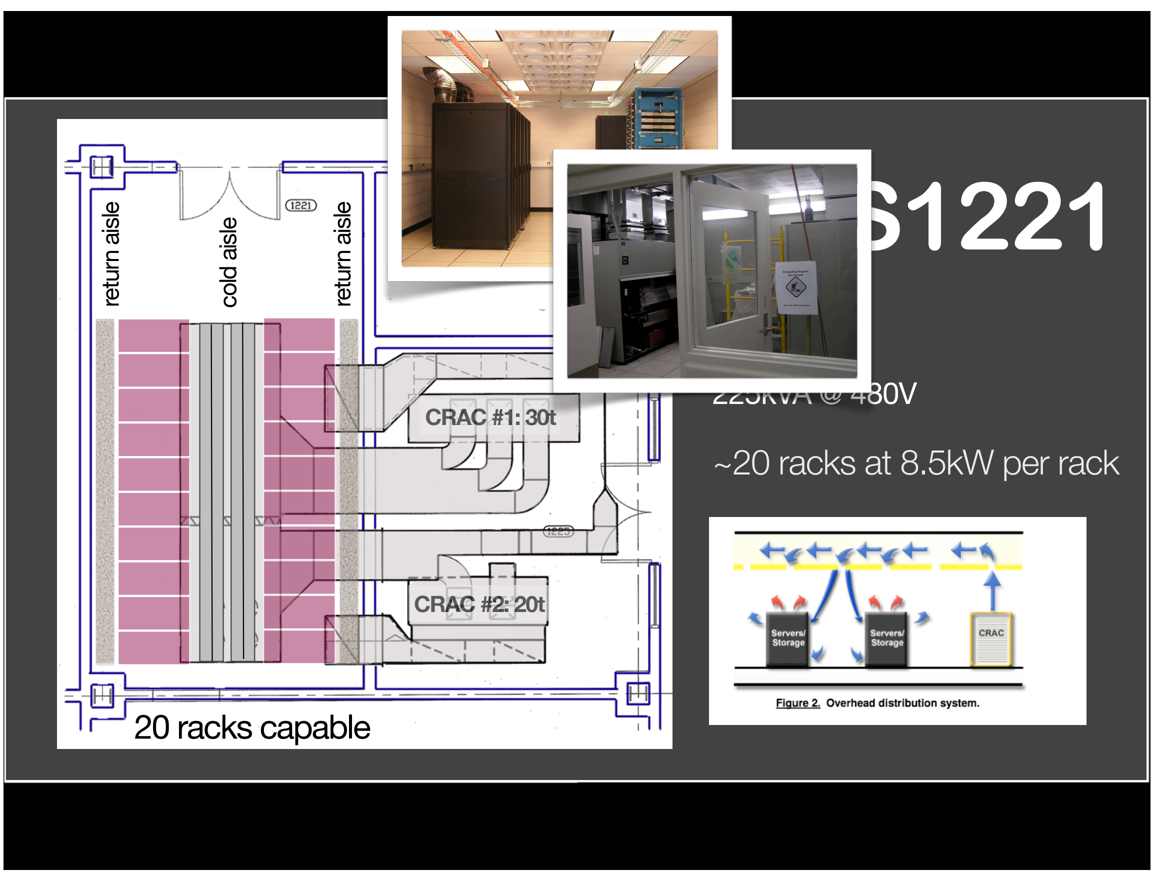

from HLT @ 200Hz
ATLAS computing model
various data formats/event
RAW
byte-stream
RAW, 1.6MB
Event Summary Data
after RECO
object-format
multiple e, j, mu
hits, cells
ESD, 1MB
Analysis Object Data
reduced object-format
suitable for analysis
filtered e, j, mu
AOD, 100kB
T0, CERN
Derived Physics Data
root-tuples
end-user analysis
specific e,j,mu
metadata
DPD, 10kB


CERN CASTOR, permanent storage
RAW
UK
Canada
BNL
Japan
France, Italy, Netherlands,Nordic, Germany, Spain
...
T1's
AOD, 100kB
24-48 h, calibrated, full data streams to T1's
"Grid"
T2's
"T3's & T4's"
UTA, UO
Indiana, Chicago
UM, MSU
BU, Harvard
SLAC


Michigan Lambda Rail
10Gbps connectivity: 3 research universities
Milwaukee
Grand Rapids
Flint
Lansing
Detroit
Ann Arbor
Chicago
Toledo
Cleveland


10Gbps connectivity on campus
Biomedical and Physical Sciences building
Communications and Fine Arts


Loop topolog
E a
Loop topolog
West: MSU2
1533.47 nm
East: MSU3
1533.47 nm
DWDM
Movaz
Rm 4a
Extreme Bla
Dell 6248 switch
stack x5
m B205
Rm 1221
ComArts
PS


S1221
225kVA @ 480V
~20 racks at 8.5kW per rack
return aisle
cold aisle
return aisle
1221
CRAC #1: 30t
CRAC #2: 20t
20 racks capable
Servers/ Storage
Servers/ Storage
CRAC
Figure 2. Overhead distribution system.

5 Racks running since December

Hardware:

computing:

Dell Poweredge 1950

54 nodes Intel Xeon 5355, 2.67 GHz dual, quad core

(SPECint_2000: ~2178/cpu => ~17,424/node => 940k SPECint2000)

so...432 cpus. will double by end of summer.

I plan for about 1500 cpu's

storage:

PowerVault MD1000

225,000GB storage in 5 shelves

just arrived for "T3":

40 nodes & 15TB

will it work?

probably

but not as designed

gridifying people is much harder than gridifying computers!

This'll keep us busy for 15 years.

- We have to find the Higgs Boson...or everything that's worked before crashes
- We have to find new physics... or everything that's worked before crashes

and wouldn't that be neat?

Cosmology

Big Bang
Microwave background
Measuring the Geometry of the Universe
uh oh

What about...The Universe?

The first, most remarkable thing perhaps is that it's expanding

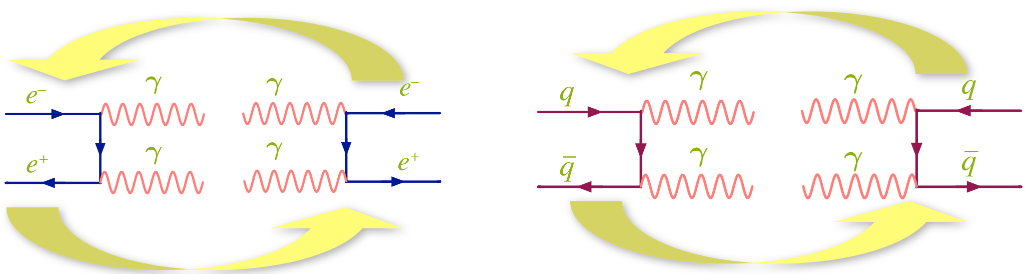
- We've seen Hubble evidence for that, but there's a trickier and more subtle piece of evidence
- If, by extrapolating backwards, everything in the universe started at a fixed time and from a tiny, even infinitesimal size - 10 Billion years ago

BUT, this is a state of the whole universe, spacetime and matter/energy

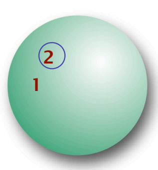
- **there is not an empty universe into which stuff expanded**
- rather, the **spacetime fabric of the universe expands** with matter/energy
- So, the conditions at that time must have been very hot.
  - *so hot, that only elementary particles and radiation could have existed*
    - a soup of energetic quarks, leptons, and the precursors to the photon, sibling massive particles, W and Z

These conditions

- fundamental interactions happen constantly...in equilibrium between radiation and matter
  - *things like:*



further... is earlier



t_1

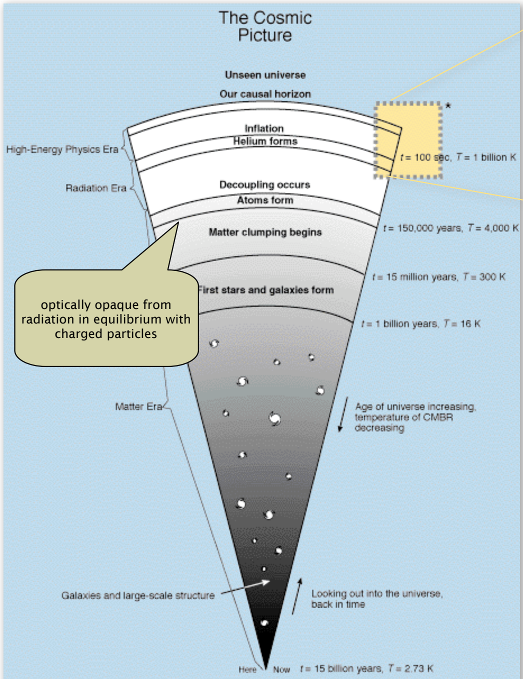
At an early time, two objects form

Light from 2 spreads out

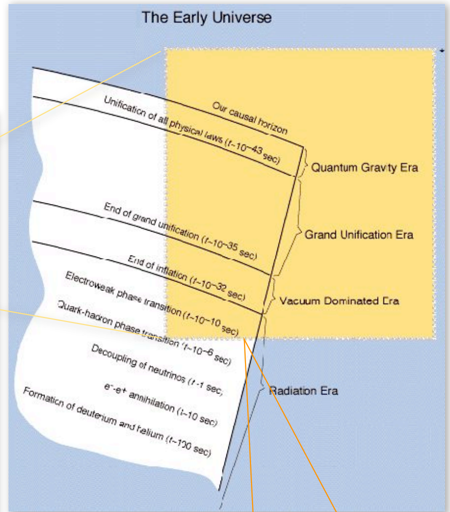
So, looking far away…is looking back in time

where the fastest objects are the earliest produced

and any radiation we get is from a much earlier time

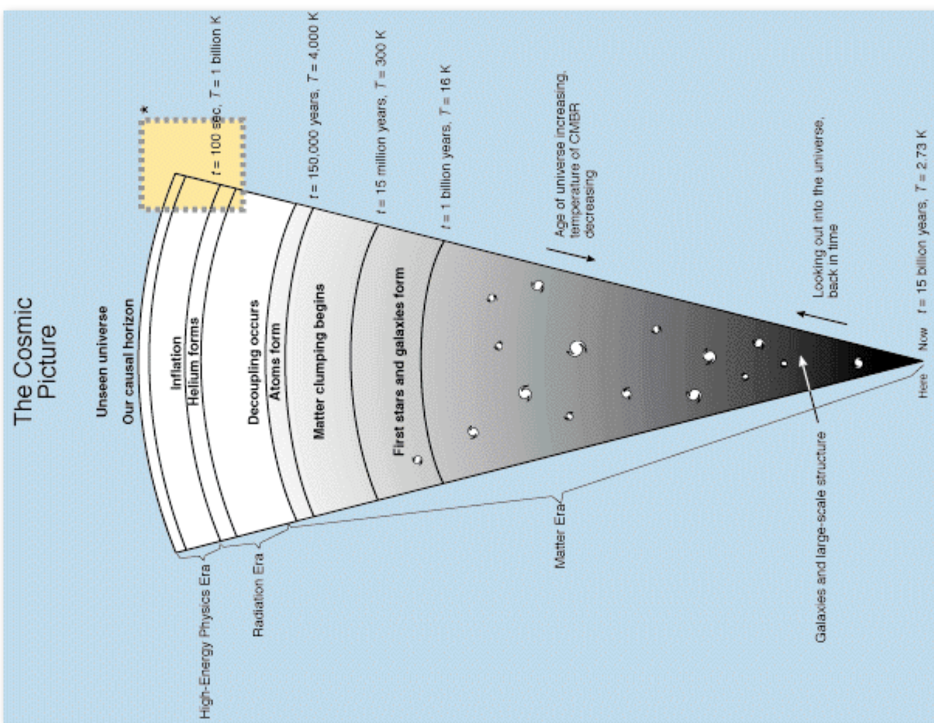


optically opaque from radiation in equilibrium with charged particles



It is in this region of the electroweak phase transformation where Fermilab works: We recreate through the high energy collisions I will describe the conditions which existed in the early universe at this point in

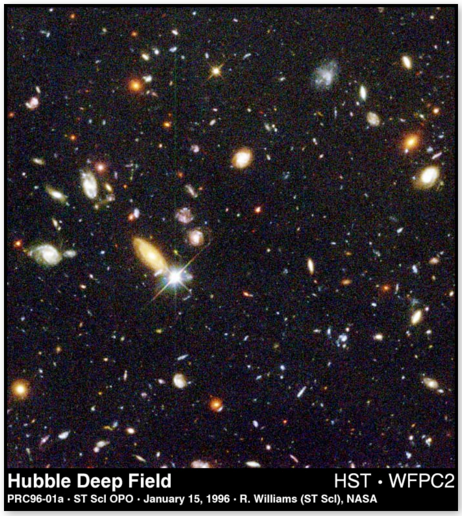
time…about 10^{-12} s after the Big Bang



the universe is bigger than…um.. anything else

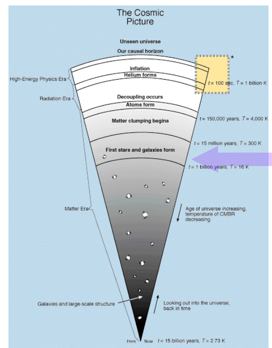
One of the more stunning results of the HST

- It was trained on a small patch of sky in the little dipper for 10 days
  - *previously cleared as not having any major, nearby galaxies that would be in the way*
  - *a patch of sky the size of a dime, seen from 75' away*
- This limit corresponds to looking back in time 10 billion years
  - *when the universe was 1/16 of its current age*
  - *to periods in which the galaxies were just starting to form, a billion y from the big bang*



Roughly 1500 galaxies in this patch, up to this distance.

100's of billions of galaxies in the universe as a whole



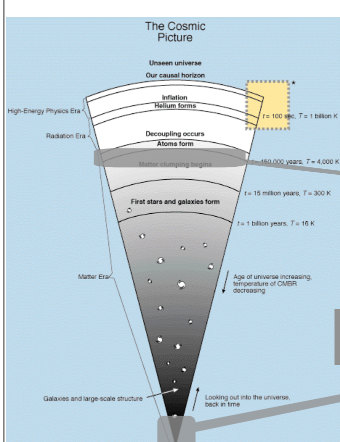
right about here

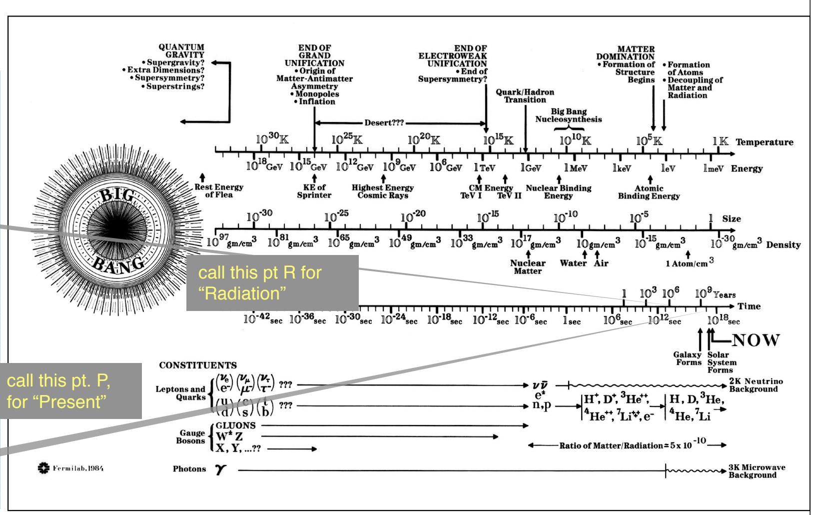
warm glow…actually, a cool glow

A little earlier

At some point the universe cooled enough that the equilibrium processes stop and the ratio of matter to radiation becomes fixed

We have a snapshot of the conditions when that happened and a test of expansion:





call this pt R for "Radiation"

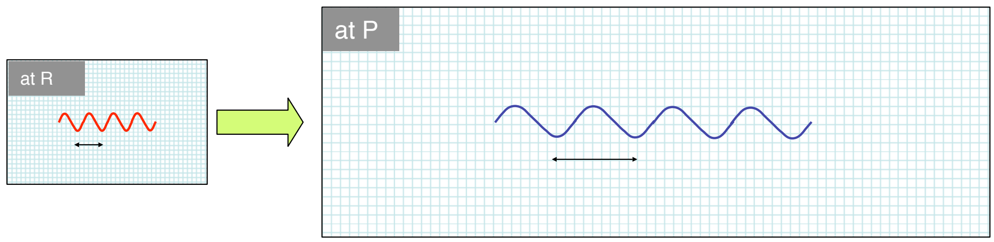
call this pt. P, for "Present"

Cosmic Microwave Background (CMB) Radiation

The radiation that is left has since cooled...a lot

- but it's not the kind of cooling that you might think of

  It's because the "measuring stick" for wavelength has stretched through the expansion of spacetime



lengths, short
so, wavelengths short,
or...frequency high,
or...energy high,
or...temperature high

lengths, longer
so, wavelengths longer,
or...frequency lower,
or...energy lower,
or...temperature lower

The **prediction** was:

the wavelengths should be about 7.35cm, which corresponds to a frequency of 4000MHz...or a temperature of ~3K

and that it should be everywhere...all directions.

seeing that and seeing as...

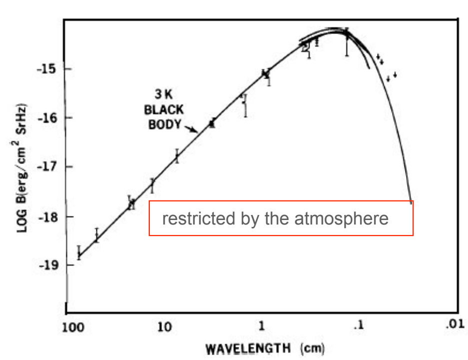
In 1965, Arno Penzias and Robert Wilson were trying to get rid of noise in a large radio telescope (designed to study satellite communications at AT&T)

- They couldn't and began to believe that it was coming from outer space, all day, all night, from all directions

  Rather quickly it was learned that this was precisely what he just been predicted at Princeton by James Peebles

In the 1940s, George Gamow had predicted

- that the big bang radiation would have indeed cooled and that it would have the characteristics of a black body



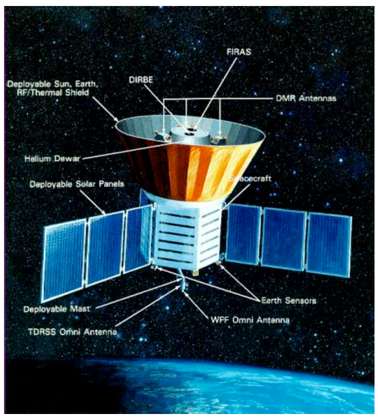
From Wilson's 1978 Nobel Lecture

The Cosmic Background Explorer (COBE)

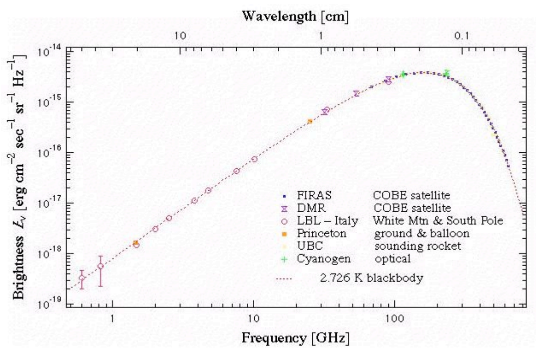
Specifically, a mission launched in 1989 to measure the CBM...and it's uniformity - the hot soup must start out uniform…BUT

- ...I mean, clumps do happen (us, Milky Way, etc)
- Now, it's incredibly precise...this plot has data points with error bars

  COBE measured E&M radiation as a function of frequency outside of the earth's atmosphere

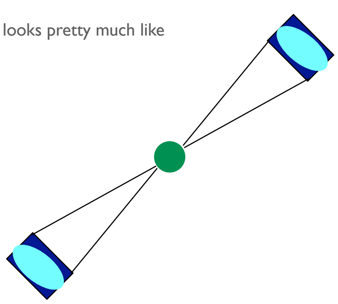


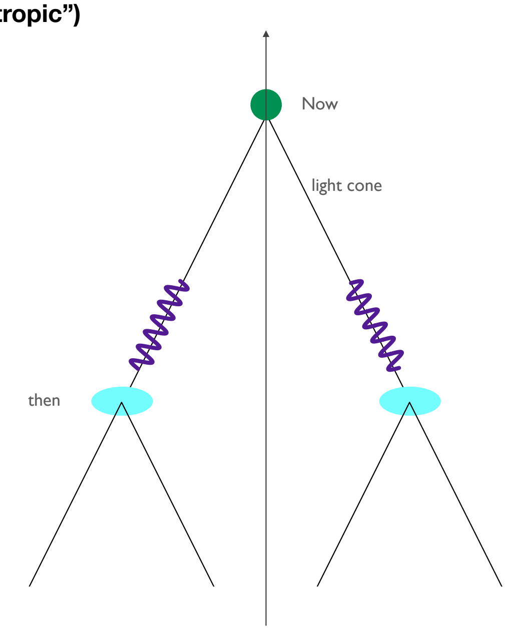
showing precisely the blackbody spectrum for a temperature of 2.726K



but wait...how come

the sky looks uniform? ("isotropic")



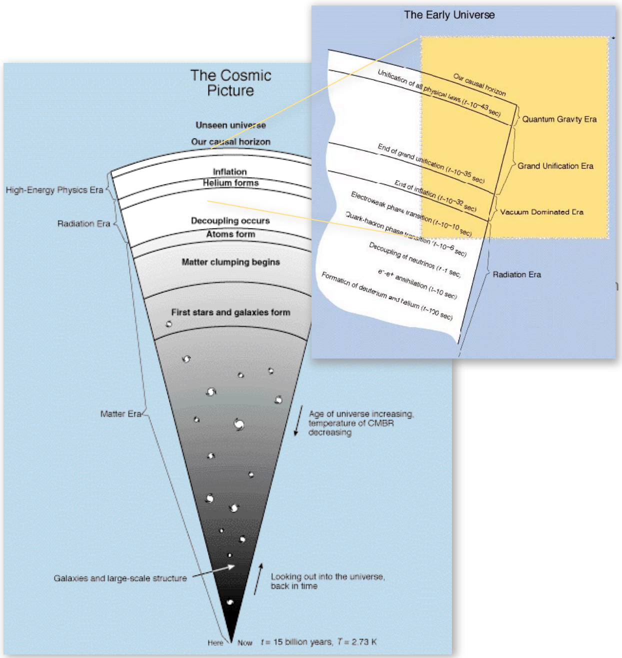


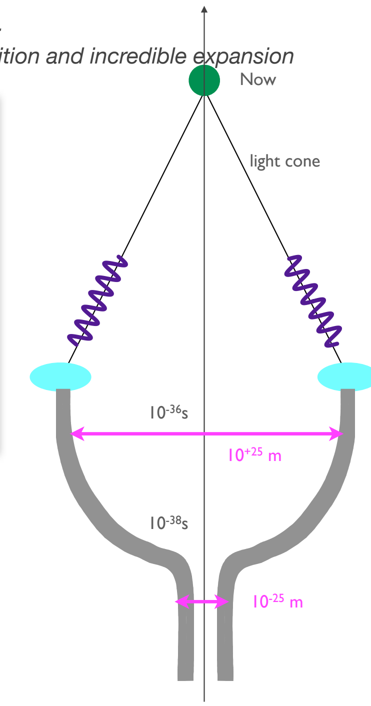
they would not have known about one another...neither would be in the other's Past

“Inflation”

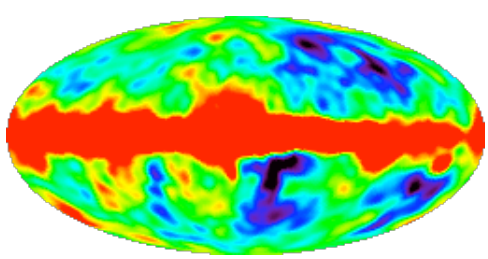
not an overheated economy...

- but a fluctuation in the vacuum state of the universe
  - *The vacuum state turned out to not be the lowest energy...*
  - *The universe “went there”...and that caused a phase transition and incredible expansion*





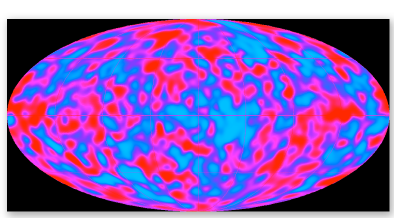
furthermore, we do exist



2.7279 (blue)-2.7281 (red) K x 25000Zoom

An all-sky image (like a Mercator projection) of the sky...notice the Galactic halo across the midline...

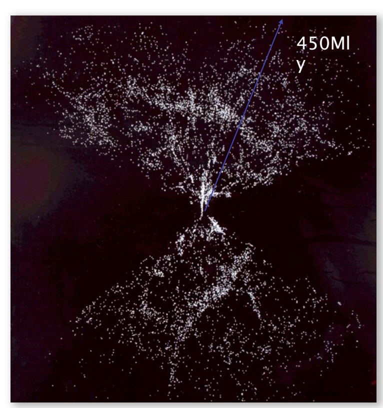
Then this large-scale structure is digitally removed...



fluctuations are 0.000030 K

This is incredible.

It is decisive evidence that the Big Bang model is correct and...the ripples are primordial density fluctuations consistent with that required to form galaxies.

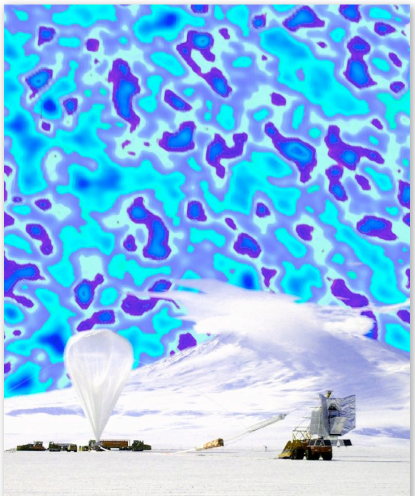


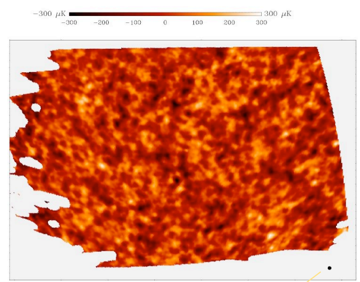
And, that’s true. There is non-random structure: These filament-like strands are combinations of 11,000 galaxies (MW at the center).

more measurements:

A balloon experiment, launched from the South Pole in 1998 has done even more precise measurements of the CMB

- BOOMERanG (Balloon Observations of Millimetric Extragalactic Radiation and Geomagnetics)





That's the moon's disk size for comparison

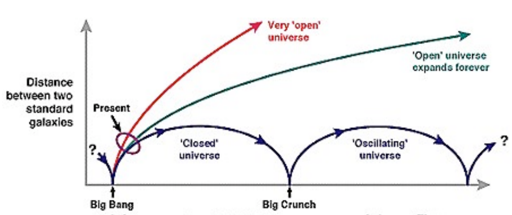
so, then if it started, does it end?

The evidence that the Big Bang occurred is overwhelming

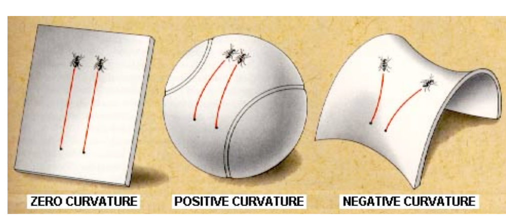
- Olber's Paradox

What is the future of the universe?

- Thought to depend on the balance between expansion and gravitation
  - *that depends on how much mass/energy there is*
- Two general ways to determine that
  - *count the stuff: how much stuff/light can we see and account for?*
  - *measure spacetime: what clues do we have to the geometry of the universe?*



These are the 3 extremes of geometries for spacetime: a totally closed (in which $C<2\pi r$) flat ($C=2\pi r$), and open ($C>2\pi r$)…parallel lines?



for the universe: density↔geometry

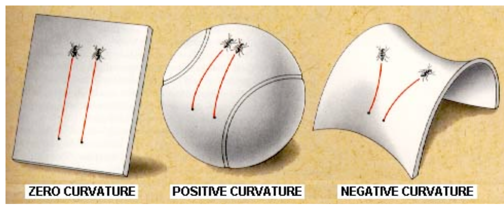
critical density...from General Relativity

$$\rho_c = \frac{3H^2}{8\pi G}$$

$\rho_{critical}$ = (0.97 ± 0.12) x 10^{-29} g/cc

$$\Omega = \frac{\rho_{measured}}{\rho_c}$$

Ω = 1 Ω > 1 Ω < 1



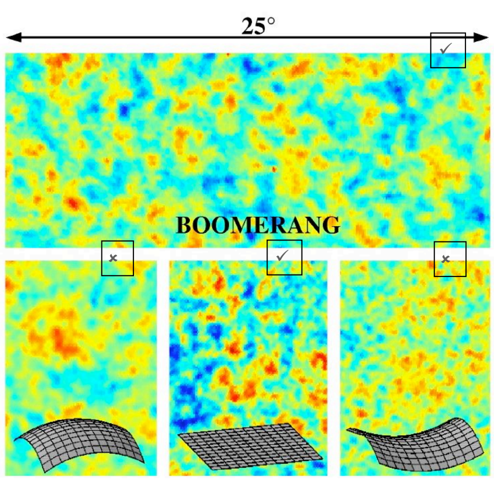
we can now measure the Geometry of the Universe

By comparing the anisotropy of the CMB to computer simulations

- the geometry of the universe is determined to be very close to F L A T

  (remember, in 4 spacetime dimensions)

  *The **characteristic quantity for flatness is** Ω **= 1 means flat.***



Lots is in play here...Spacetime will be bent and shaped by the amount of mass in the universe and how it's distributed

This is usually expressed in terms of Ω the deviation from flatness. If Ω = 1, then the universe is flat.

From these measurements,

$\Omega_{geometry}$ = 1

But, it gets worse.

a little short

Everything that has mass/energy would contribute to Ω

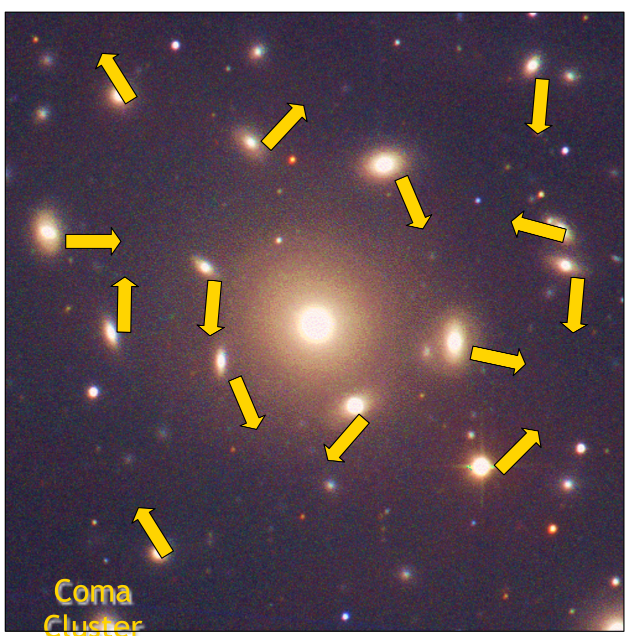
So, add up everything that's visible:

- The various **visible** contributions to the critical density $\Omega_{luminous\ matter}$ are:
  - *Visible stuff (stars, dust, gas) from telescopes $\Omega_{luminous\ matter} \approx 0.01$*
  - *Estimation of other regular matter..deuterium abundance & theory $\Omega_{luminous\ matter} \approx 0.05$*
- But: from measurements $\Omega_{geometry} = 1$

Meaning...that more than 94% of the mass/energy in the universe is unaccounted for by what we know as normal matter/radiation.

But, it gets worse.

galactic boogie



Galaxies are moving...should be consistent with their masses

it's not...

So, there is lots of stuff...

BUT, the universe is lacking in another way:

- Measurements of the motion of galaxies and other large-scale gravitational motions suggest

  there is not enough stuff that we can see with any telescope (optical, radio, microwave, infrared, etc) to account for the gravitational pulls that would account for these large scale motions. - the Coma Cluster is 400x too light to be consistent with its motions

There is something missing in the universe that specifically influences large-scale dynamics - The Missing Mass Problem

- Our paradigm: All manifestations of energy/mass are in the form of elementary "particles"

  So…We expect that there is some yet-to-be-observed elementary particle: **"Dark Matter"**

  created in large abundance in the Big Bang

  weakly interacting so as to have not scattered or interacted with "regular" matter, **so that it's still around**

- Trying to produce it in the laboratory, nor has it been possible to detect it passing through the earth - WIMP's
- The accounting suggests that there must be a contribution...$\Omega_{\text{dark matter}} \sim 0.25$

This means that there must be some large amount of mass/energy in the universe which will affect the way in which it expands

- So, adding it up: $\Omega_{\text{dark matter}} + \Omega_{\text{luminous matter}} \sim 0.3$
- **but** $\Omega_{\text{geometry}} = 1$

Will we end in a whimper? Or a big crunch?

That is, will the universe continue to expand, and not be slowed down by all of the mass?

Or, will the mass be sufficient to slow it down, bring it to a halt, and then cause contraction?

All of the observed and dynamically required matter lead to a poor accounting of Ω

But, it gets worse.

Supernovae

Remember, the determination of the Hubble Constant led to all of this:

- In order to make this measurement, one needs the ability to measure how far away something is and determine it's velocity

  This was done with a variety of "standard candles", such as Cepheid Variable Stars

Well, there's a new candle on the block:

- A particular kind of supernova

  A star is held together through two competing forces:

  the nuclear fuel in the core is "burned" in fusion reactions which tend to increase the mass of the center...and hence increase the gravitational pull

  Radiation from the nuclear reactions causes a pressure ***out*** stabilizing the gravitational forces ***in***

  A supernova is a star which has depleted its nuclear fuel & gravitationally collapses very quickly

  this results in an explosive release of neutrinos

  – *dramatically heating the outer shells to the point where they are explosively ejected*

  – *This super-heated shell is extremely bright*

  Not all stars will supernova, ours won't. Only especially large ones will and they are rather spectacular when they occur nearby (there are 100's catalogued per year in other galaxies)

  The bright 'star' appears, sometimes in the day (Tycho saw one and so did Kepler) and

  – *then the universe is bathed in a neutrino flux that's measurable on earth in elementary particle experiments, slightly preceding the visible explosion*

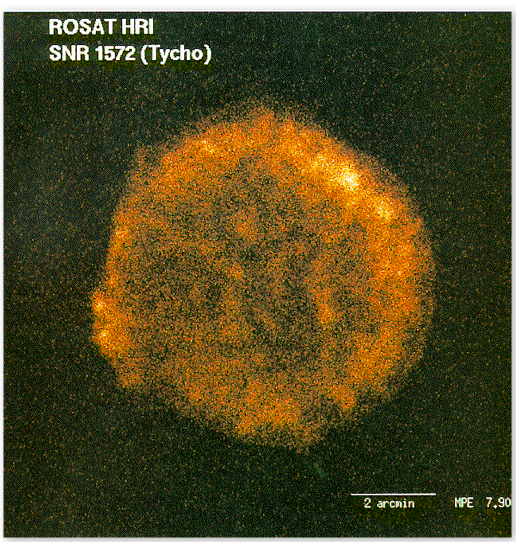
SN 1998S in NGC 3877

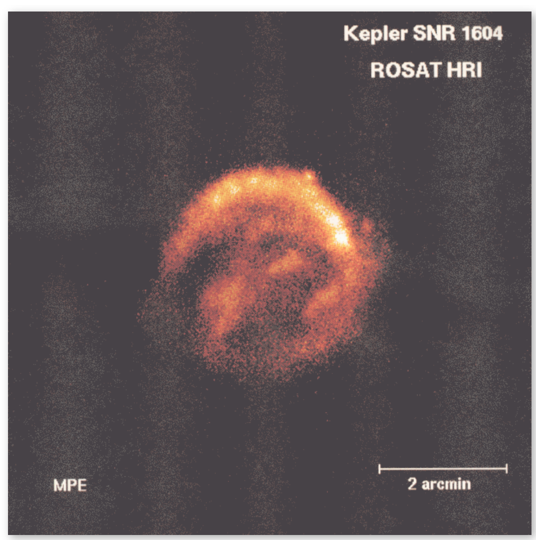
SN 1994D in NGC 4526

not very often...

The last supernovae to occur in the Milky Way:

- Tycho's in 1572 and Kepler's in 1604





a little excitement

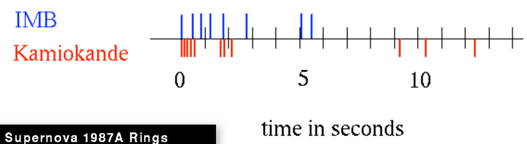
The first naked eye supernova in 400 years:

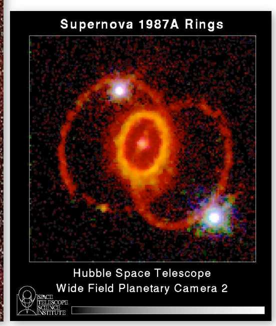
- SN1987a - a modest Blue Giant

  Large Megallanic Cloud (a companion galaxy 170,000 ly away, visible from the southern hemisphere)

  0736 23 Feb, neutrinos observed; 0930AM, nothing visible by amateur Aussie astronomer, but by 1030...it was visible

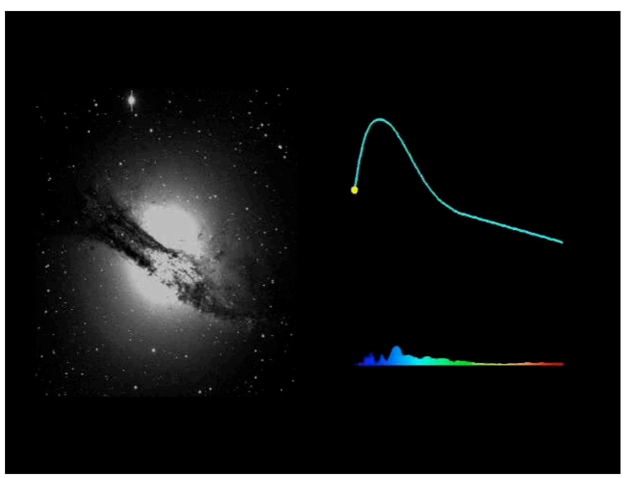
  According to the model of stellar collapse, it was expected that on earth there should be ~10 neutrino events, and in two very large "proton decay" experiments in Japan and Cleveland, detected 19





the remnant shell of SN1987a

smile, you're on candid camera



Three "representations" of a Supernova 1986G in the Centaurus A galaxy

Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

1a

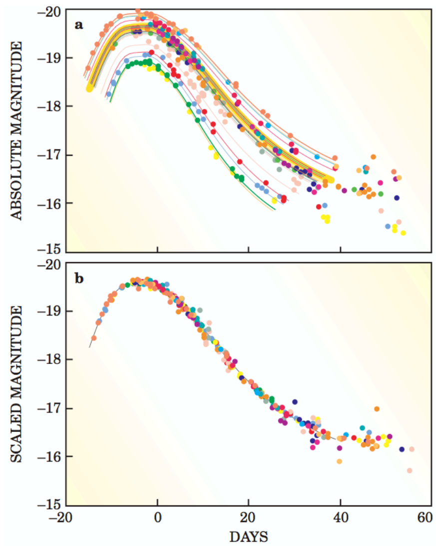
1a supernovae are different

- Typically stars not massive enough by themselves to nova

  but in close proximity to another star which it siphons matter from, enough to cause a supernova explosion after all

  *These are special as they stay bright for a period of time which is directly related to their magnitude - **So, like Cepheids, measure the time, deduce the brightness***

  with brightness, can determine the distance.



But, it gets worse.

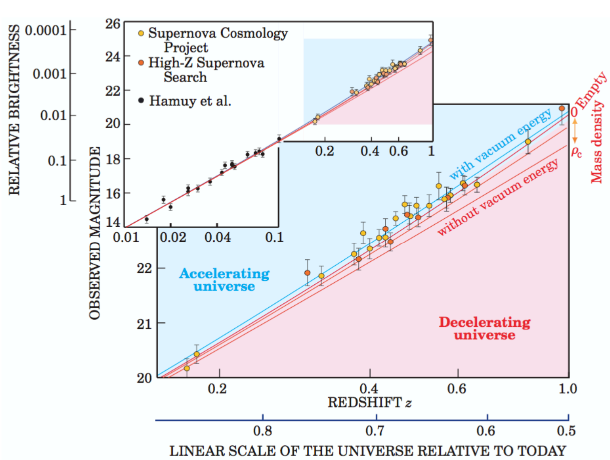
there are lots of them

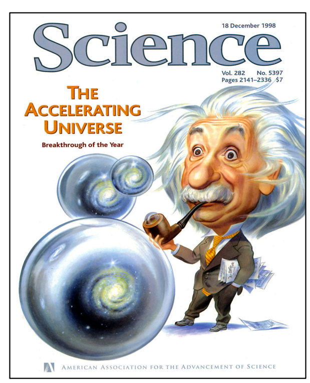
There are enough of these to have one about per second in deep galaxies

- So, by searching one gets a wide range of distances

  many, quite far away…at very "large redshifts"

An amazing thing happens:





The data require an interpretation that the Universe is Accelerating in its expansion

um...accelerating???

What would cause the universe to *accelerate*??

- Hubble data suggested maybe a constant expansion
- CMB data demand that the geometry of the universe is flat (an open geometry could account for this)

There has to be some "antigravity" kind of force at work to do this

- What's more, there has to be a lot of it
- The combination of all observables (only some of which have been mentioned), suggest a new contribution to Ω, called Ω_Λ

$$\Omega_{\text{lum matter}} + \Omega_{\text{dark matter}} + \Omega_\Lambda = \Omega(\text{total})$$

Ω_Λ could be due to the vacuum...

- Particles, fields in the vacuum that add a term of **Negative Pressure** to Einstein's equations!
- That is, it adds in essentially a quantum mechanical Cosmological Constant Term...back to the future.

Einstein's "blunder" may have been right after all!

Called the Missing Energy Problem

Understanding this is perhaps the biggest problem in science

- The world is mounting huge multiple-satellite Supernovae measuring missions

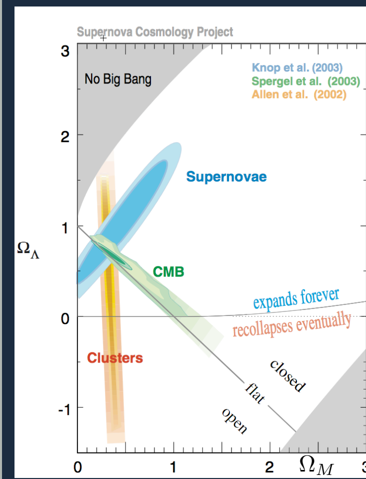
interpreting dark energy

as a vacuum energy:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda_{\text{eff}}\, g_{\mu\nu}$$

$$|\rho_{vac}(\text{cosmology})| < 10^{-9}\text{erg/cm}^3$$

Here, the vacuum energy absolute value matters!



uh oh.

THE 2 biggest problems in physical science

for High Energy Physics:

well...the vacuum belongs to us ;-)

it's energy density is: 10^{-43} erg/cc

cosmology suggests: 10^{-9} erg/cc

and any missing mass/energy is presumably quantum mechanical

that belongs to us also!

so, we are very aware of the possibility of producing such states in our collisions

we have to, for this to make any sense

It’s all great fun!