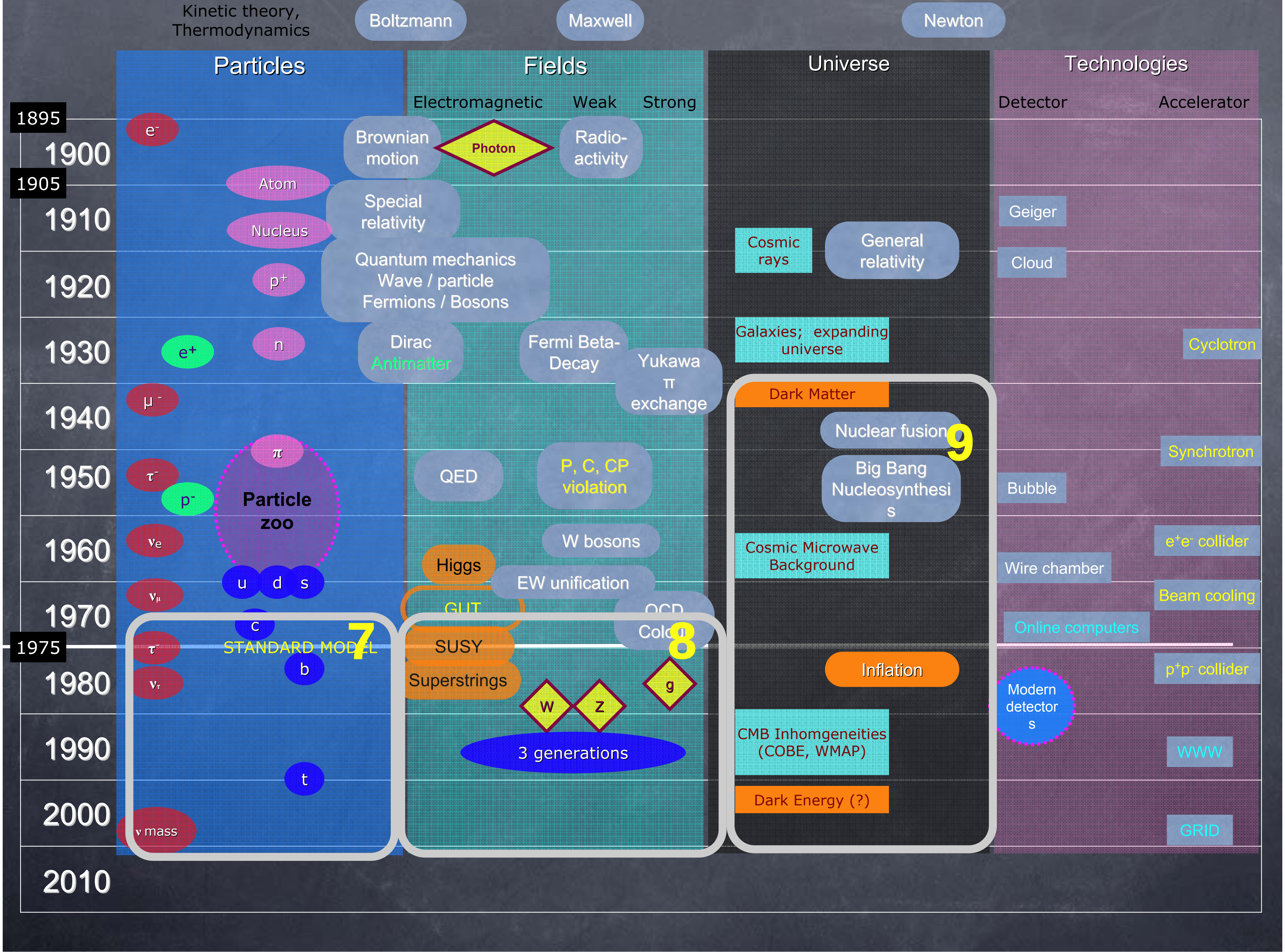

Kinetic theory,
Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Electromagnetic
Weak
Strong
Universe
Technologies
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e⁻
Atom
Nucleus
p⁺
n
e⁺
μ⁻
π
τ⁻
p⁻
Particle
zoo
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s
νμ
c
STANDARD MODEL
7
τ⁻
b
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ν mass
Brownian
motion
Photon
Radio-
activity
Special
relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
Antimatter
Fermi Beta-
Decay
Yukawa
π
exchange
QED
P, C, CP
violation
W bosons
Higgs
EW unification
GUT
QCD
Color
8
SUSY
Superstrings
W
Z
g
3 generations
Cosmic
rays
General
relativity
Galaxies; expanding
universe
Dark Matter
Nuclear fusion
9
Big Bang
Nucleosynthesi
s
Cosmic Microwave
Background
Inflation
CMB Inhomgeneities
(COBE, WMAP)
Dark Energy (?)
Geiger
Cloud
Cyclotron
Synchrotron
Bubble
e⁺e⁻ collider
Wire chamber
Beam cooling
Online computers
p⁺p⁻ collider
Modern
detector
s
WWW
GRID

PARTICLE SPECTRUM

But a third family of particles was going to be discovered

SLAC (Marty Perl)

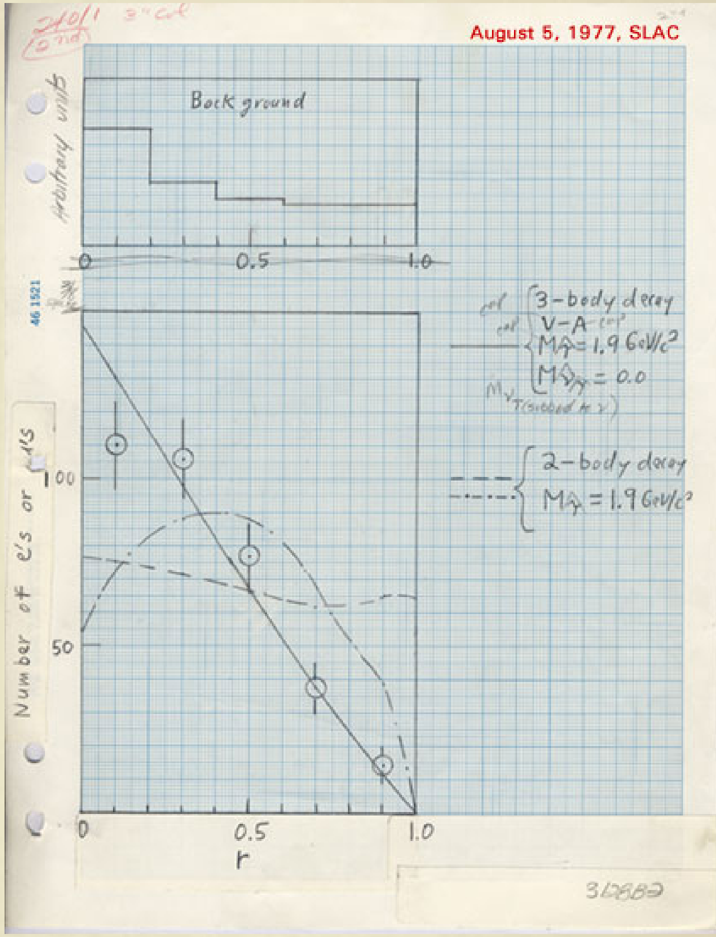
A new 'heavy electron' with 3500 x m_e

… who ordered that?

↓

THERE MUST BE A WHOLE NEW FAMILY

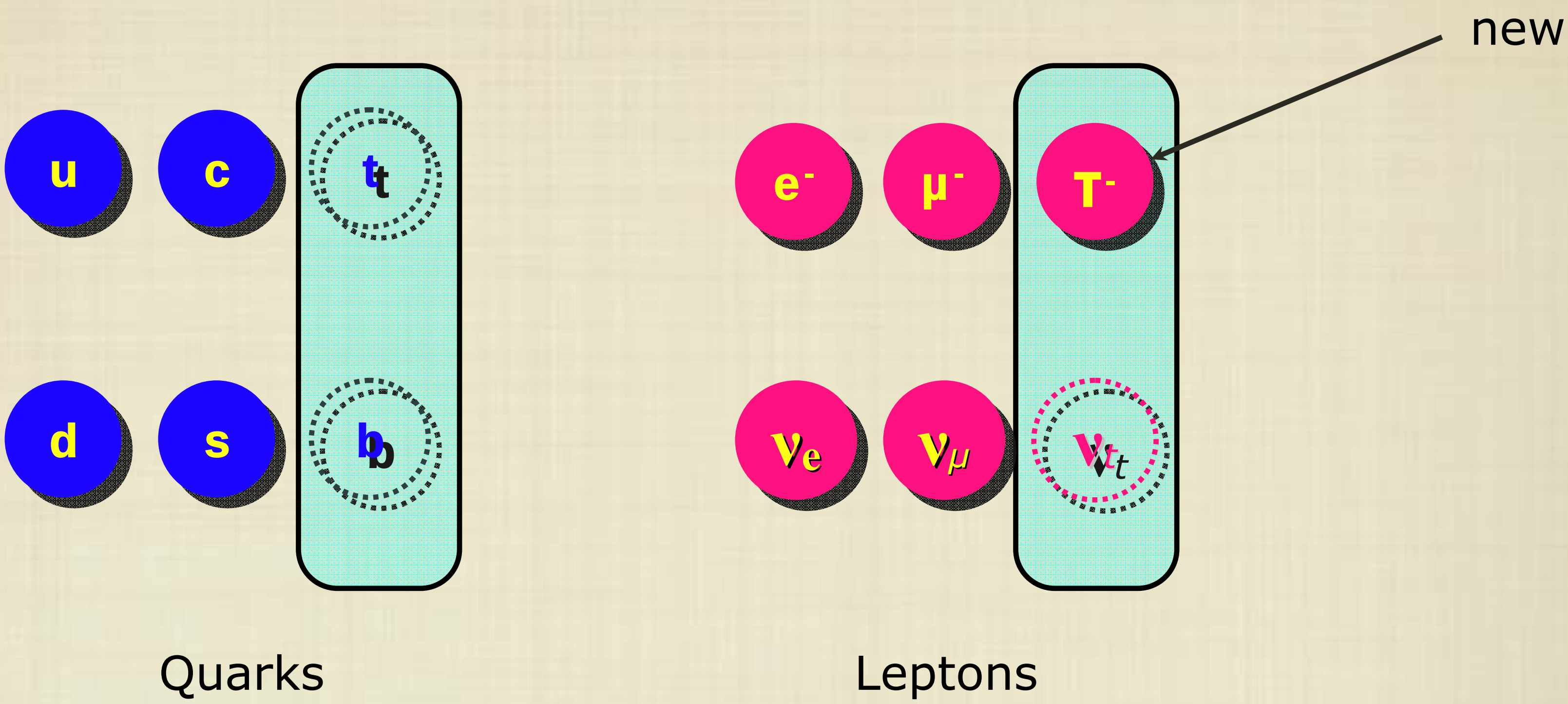
another neutrino (the ‘tau neutrino’),
and two more quarks (‘top’ and ‘bottom’)



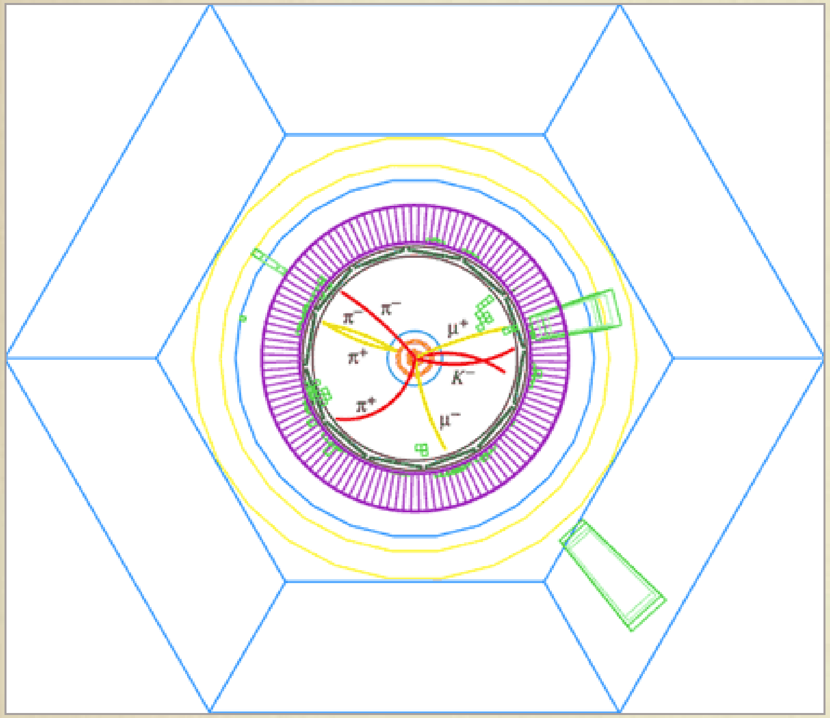
Marty Perl's logbook page

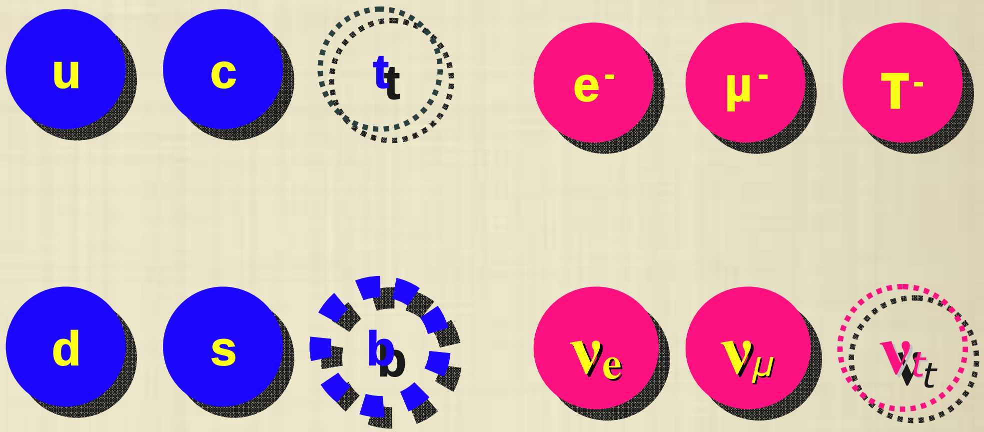
PARTICLE SPECTRUM

The search for the other family members started



Discovery of the **'Bottom' Quark (Fermilab)**





Quarks

Leptons

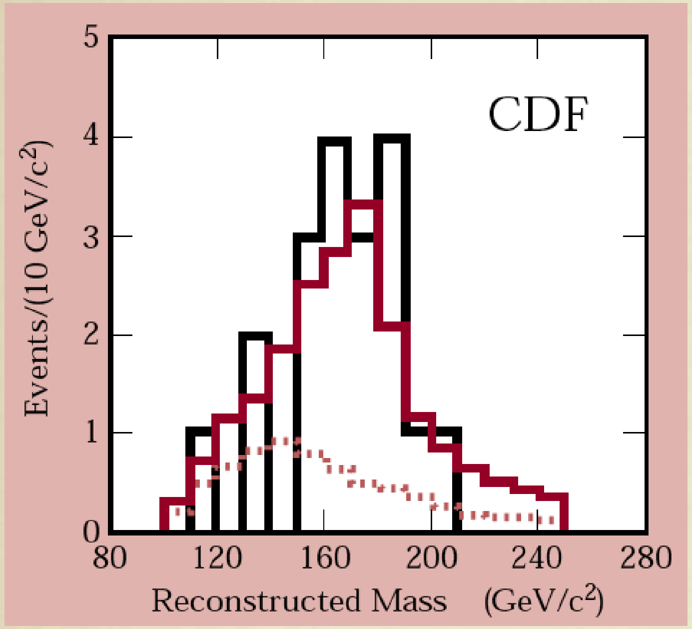
In 1977 physicists discovered a new meson called the Upsilon at the Fermi National Accelerator Laboratory.

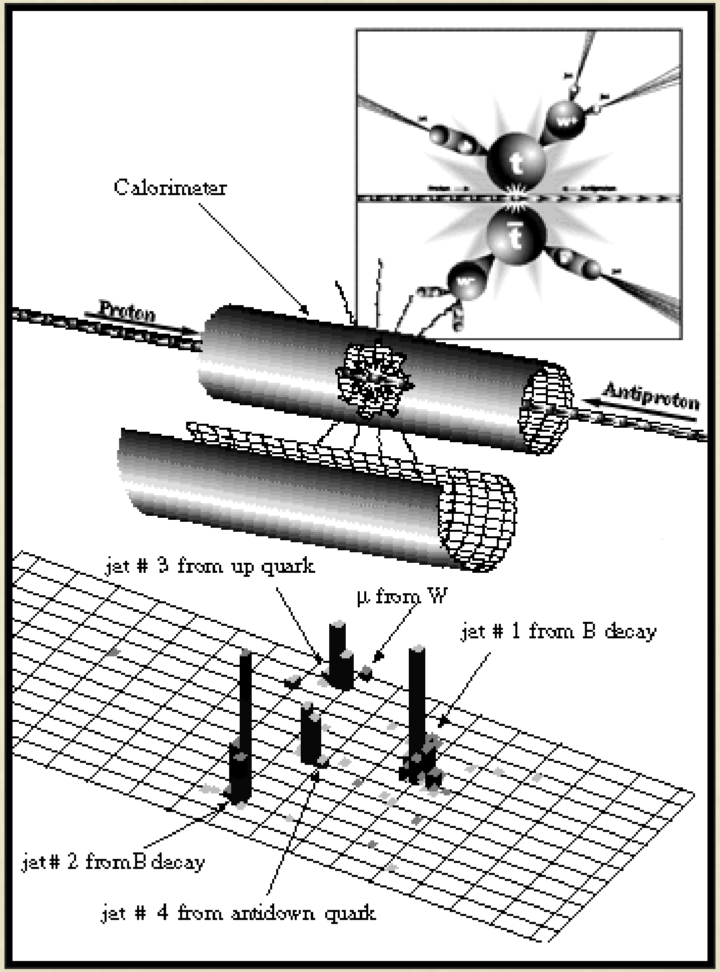
This meson was immediately recognized as being composed of a bottom/anti-bottom quark pair.

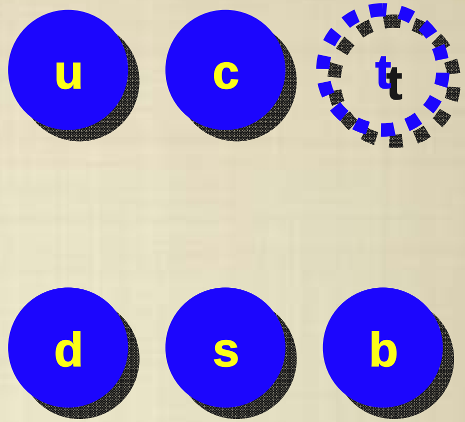
The bottom quark had charge -1/3 and a mass of roughly 5 GeV.

PARTICLE SPECTRUM

Discovery of the **'Top' Quark (Fermilab)**

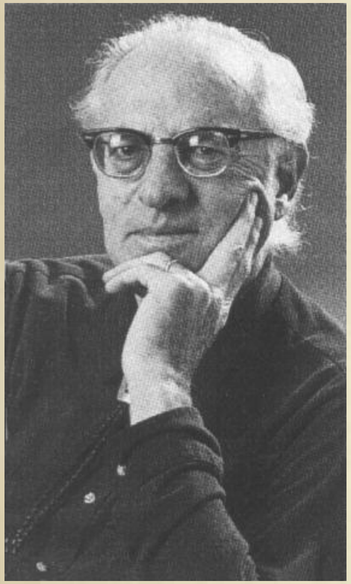






Quarks

The story of the neutrinos



Fred Reines

Discovery of the (electron) neutrino

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Nuclear reactors (n decay) are a strong source of (anti) neutrinos

Coincident signal from n capture and positron annihilation

PARTICLE SPECTRUM

Jack Steinberger, 1962

Jack Steinberger, HST 2002

"Muon" neutrino

Two different kinds of neutrinos exist: electron- and muon-neutrino

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

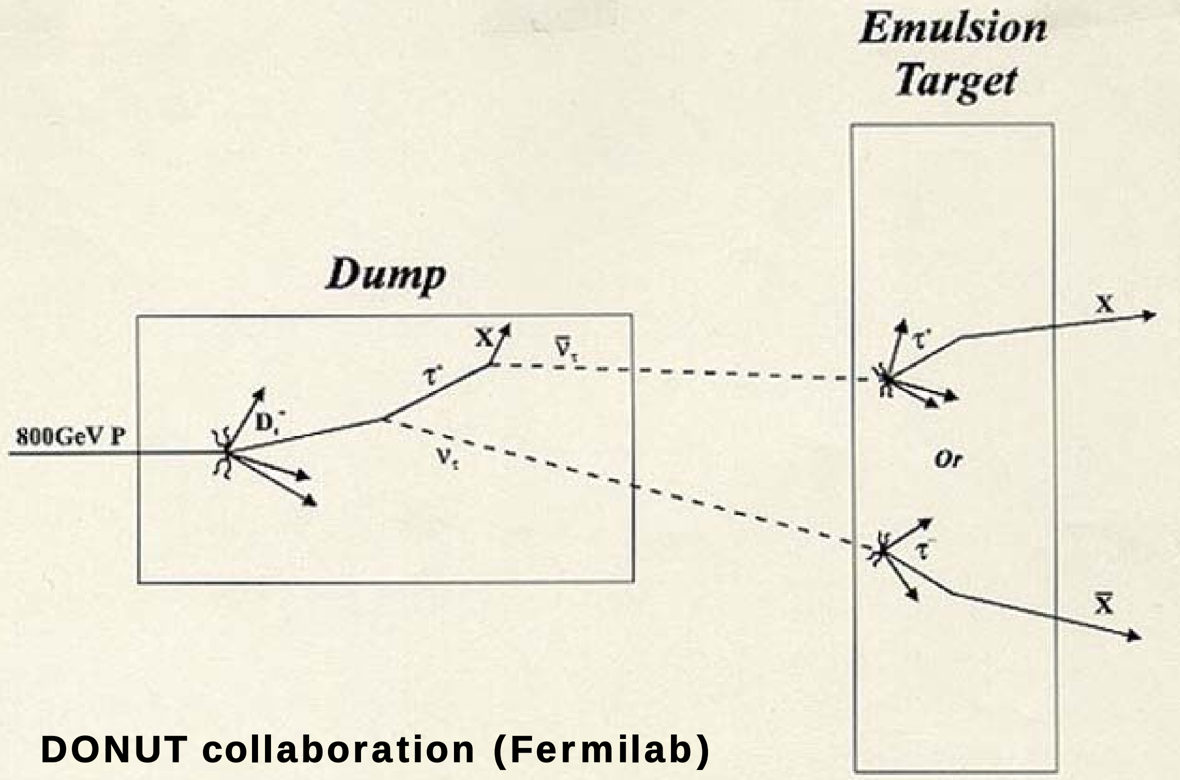
$$\pi^{\pm} \to \mu^{\pm} + (\nu/\bar{\nu}). \quad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

Do neutrinos have a mass? Can they transform into each other ('oscillations') ?

Discovery of the tau neutrino

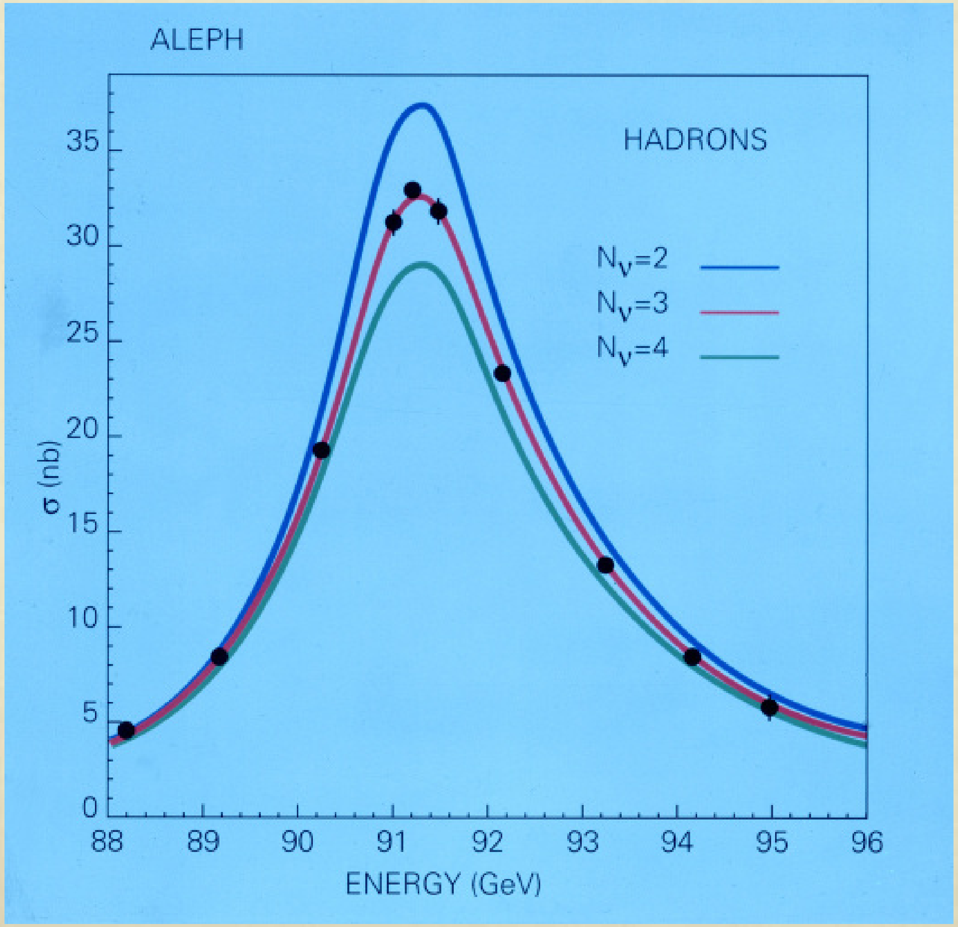


DONUT collaboration (Fermilab)

PARTICLE SPECTRUM

3 generations of neutrinos

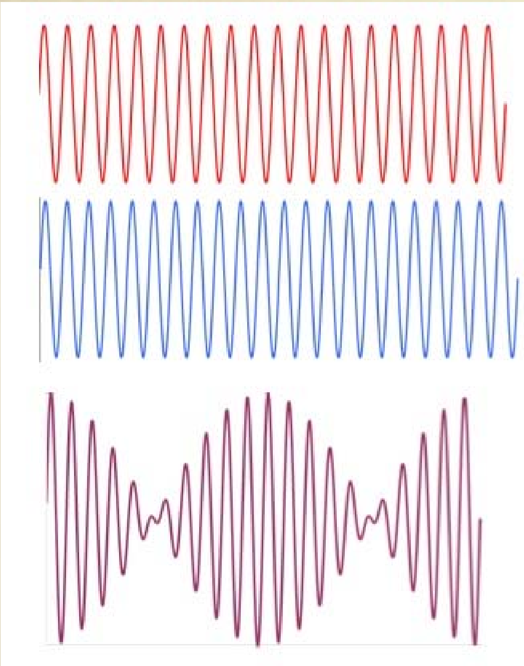
LEP measures the decay width of the Z^o particle



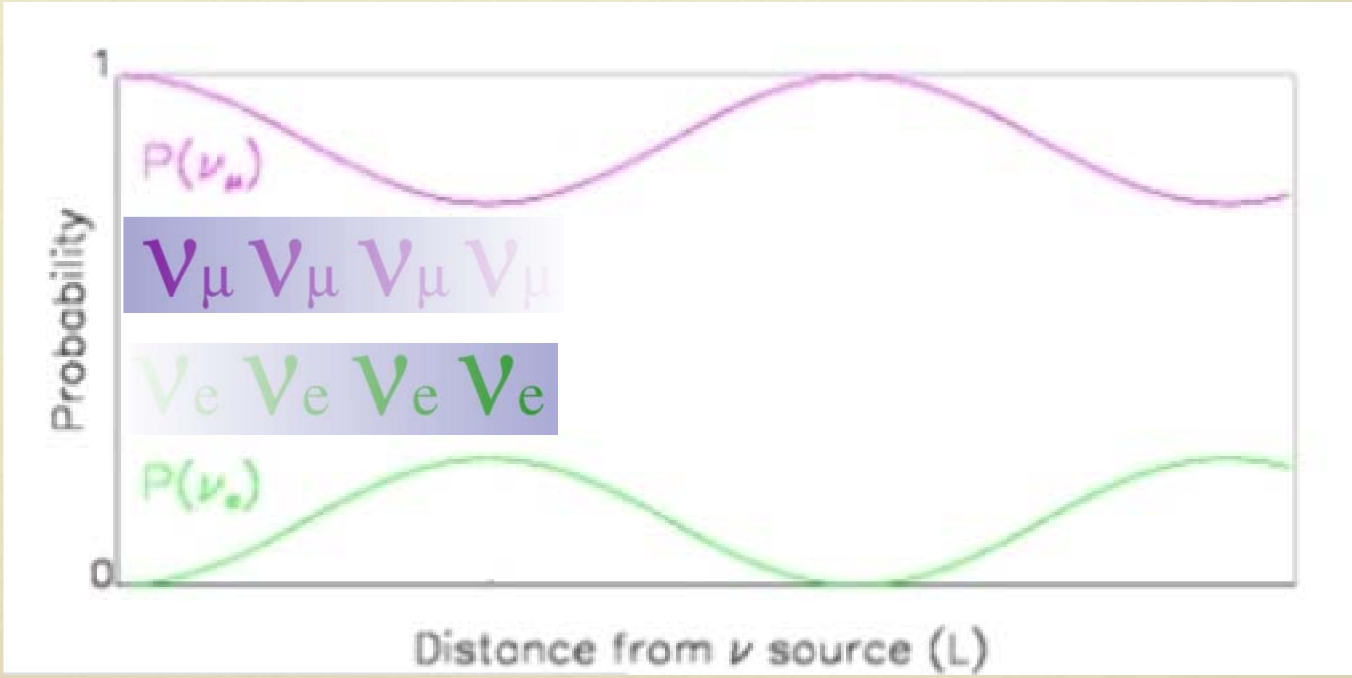
Do neutrinos have a rest mass ?

Neutrino oscillations

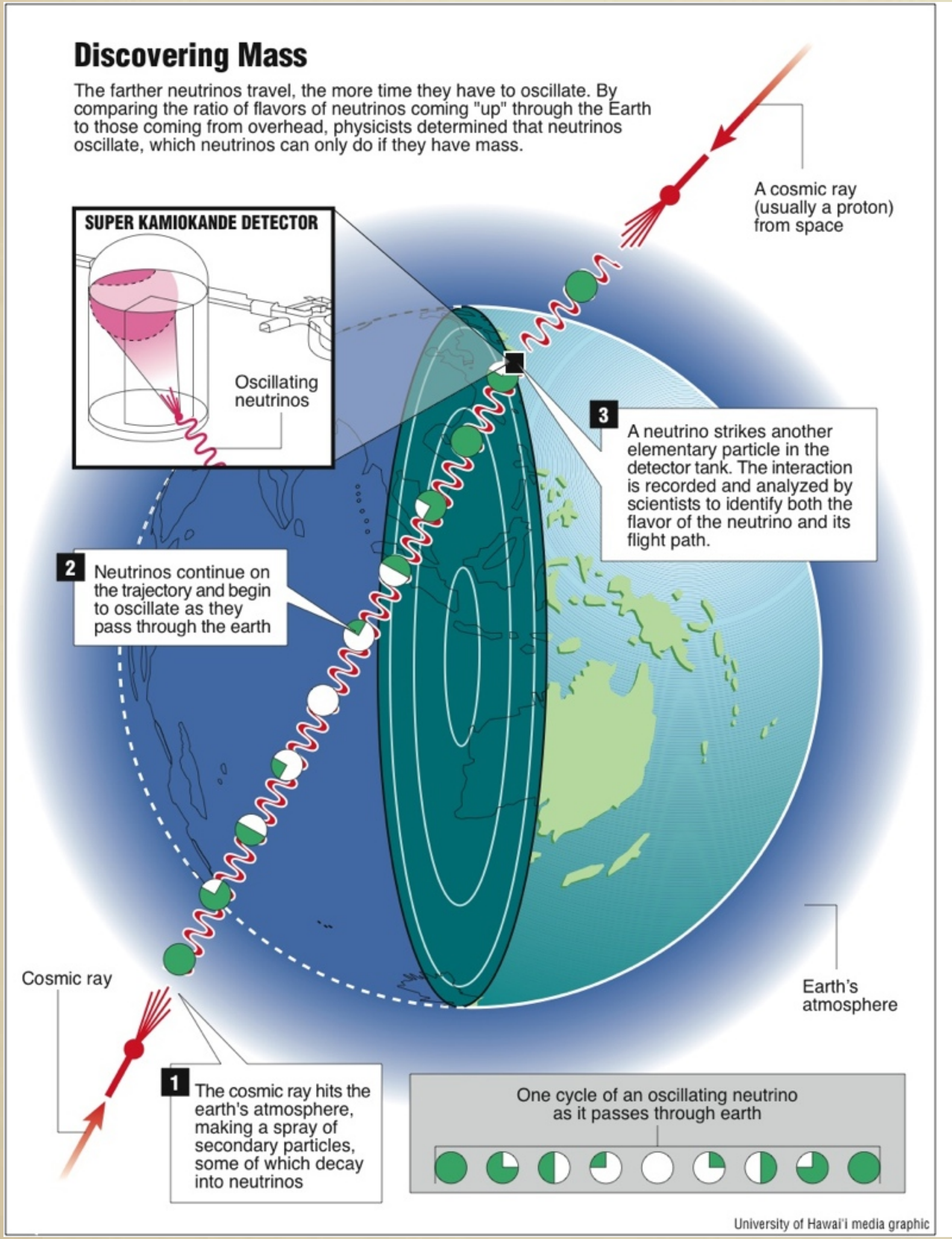
... like musical beats



If masses are not too different,
frequencies are quite similar



Neutrino oscillations discovery



Muon neutrinos are produced by cosmic rays in the upper atmosphere

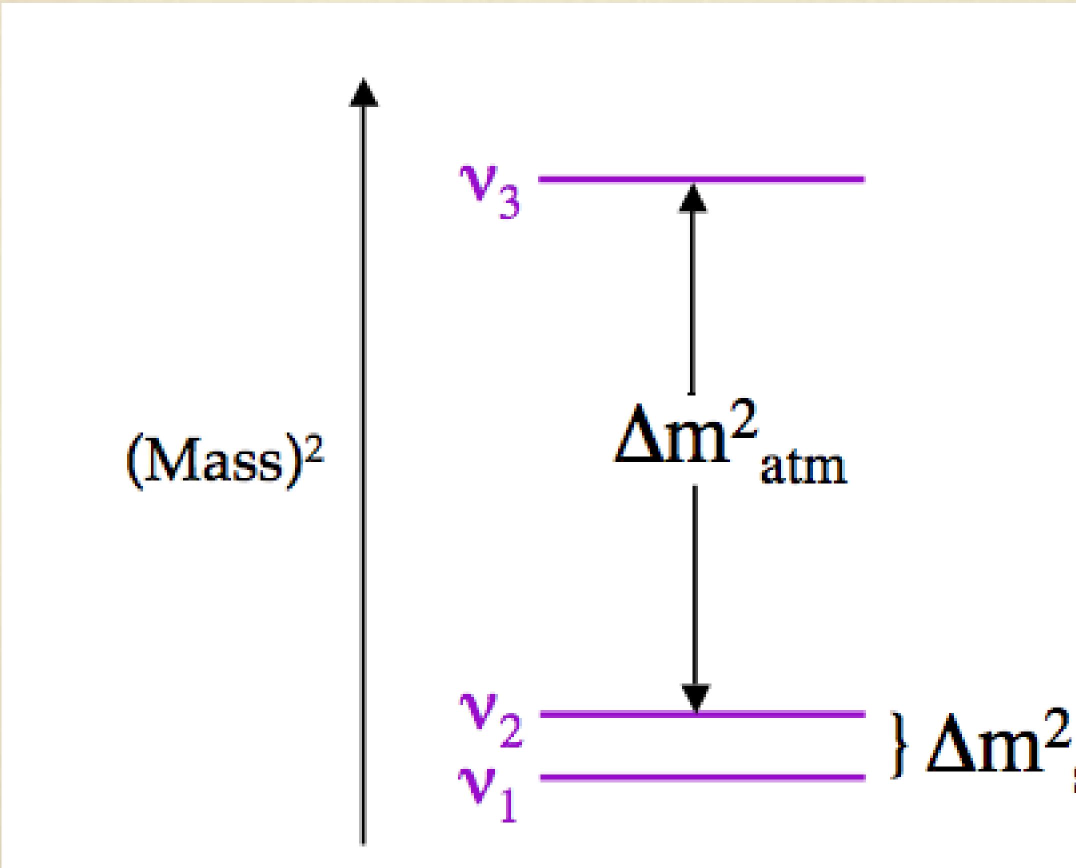
Deficit of muon neutrinos:

from 'below' - only about 1/2 expected
(and seen from 'above')

PARTICLE SPECTRUM

Neutrinos have mass !

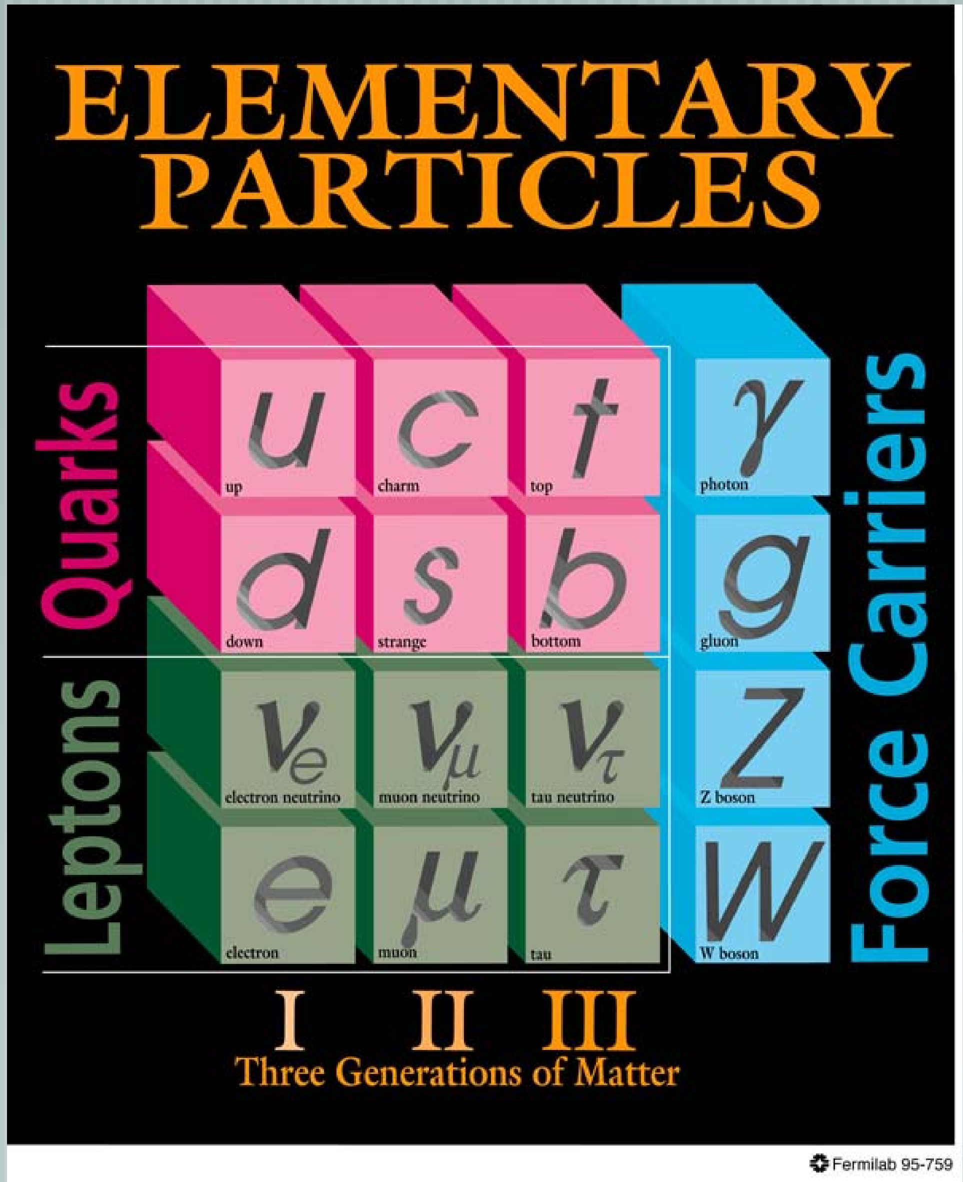
Today, only mass differences are known, but most models assume that the absolute masses are between ~ 0.01 - 0.1 eV



~ $2.5 \cdot 10^{-3}$ eV^2

~$8 \cdot 10^{-5}$ eV^2

THE STANDARD MODEL (2006)

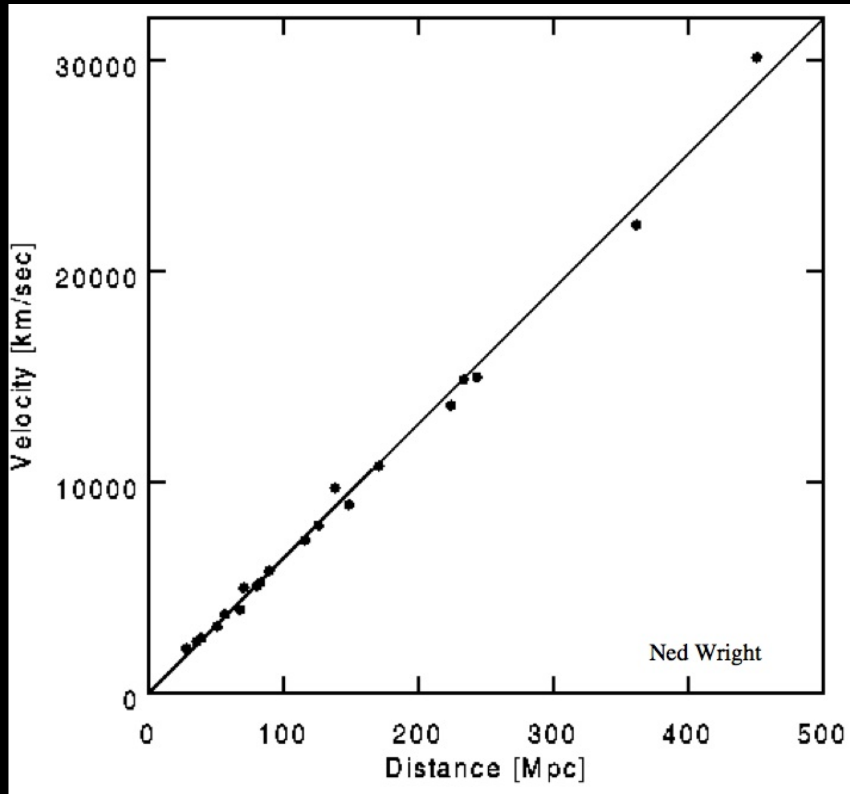


Universe (1960)

Age of cosmic objects
less than ~ 12-13 billion yr
Sun ~ 4.7 billion yr

Universal Ratio H:He ~ 3:1
Snapshot at t ~ 3 min

Cosmic Microwave Background ?
Predicted (Gamov), ~ 5 K

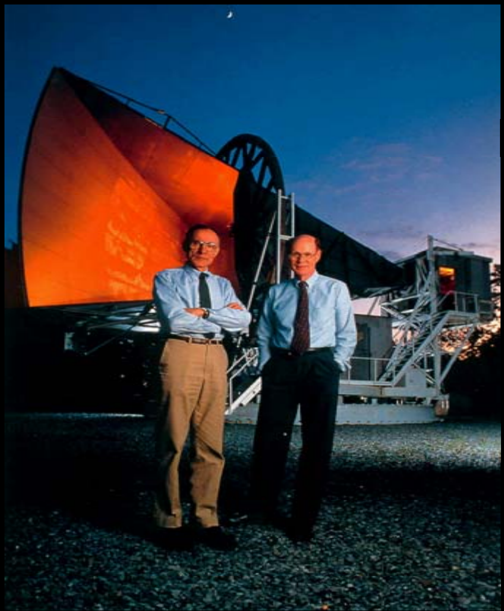


Today: H = 70±3 km s^{-1} Mpc^{-1}

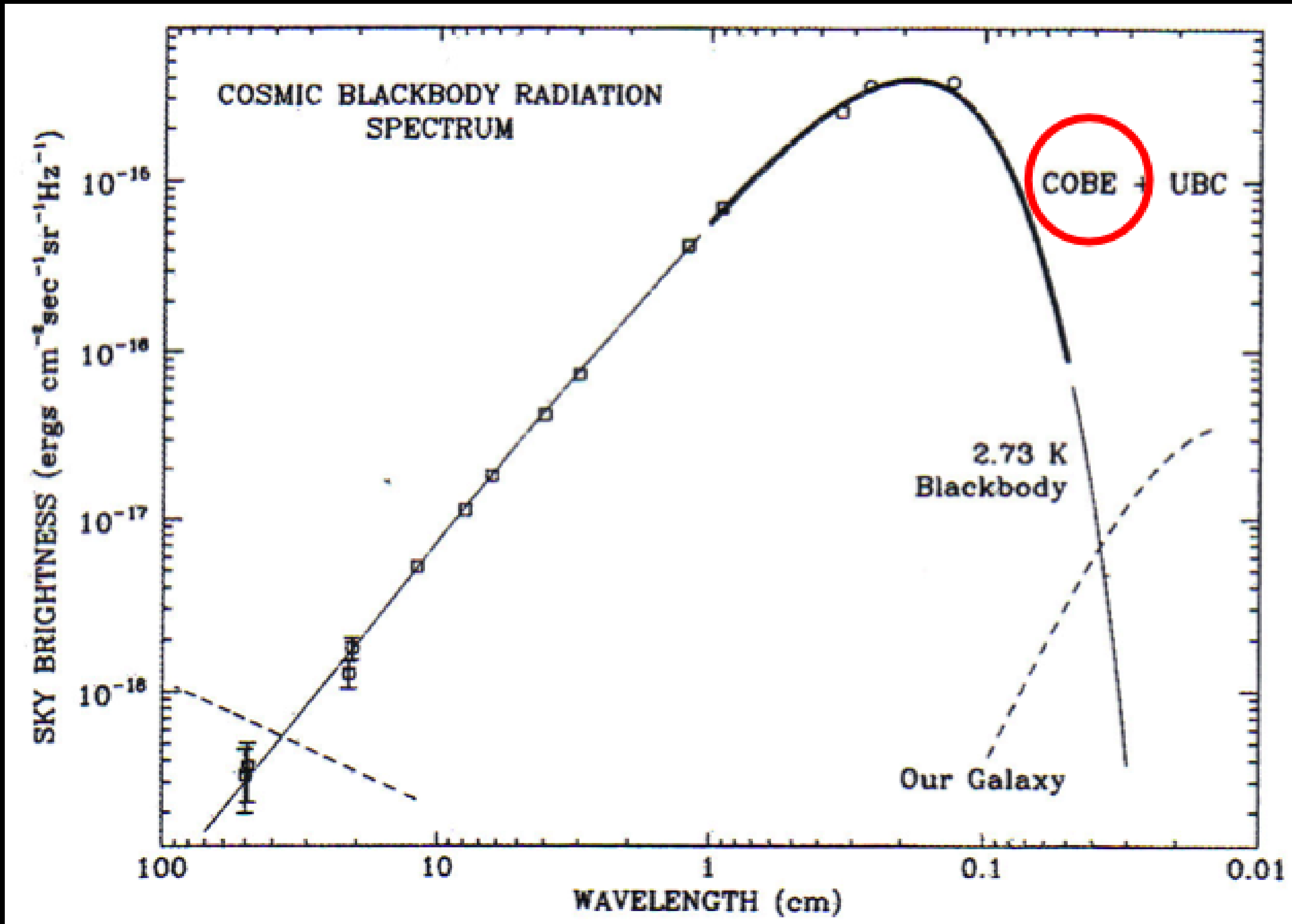
Hubble age (H^{-1}) ~ 13.4 billion years

Universe

The discovery of the 'Cosmic Microwave Background' (1963)



Penzias and Wilson



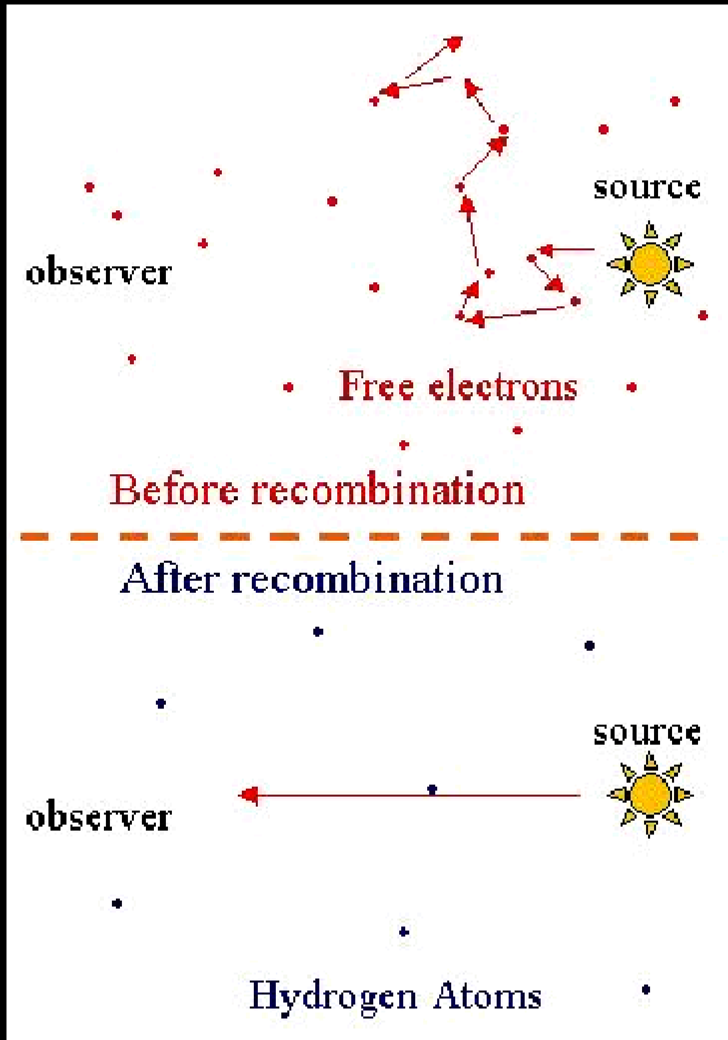
The Universe is a perfect 'black body' with T = 2.73 K

Universe

How was the cosmic background radiation produced?

By the recombination of free electrons and nuclei

(this was possible when the average energy per photon was smaller than the binding energy)



Universe

The beginning

Energy ~ 10^{72} J

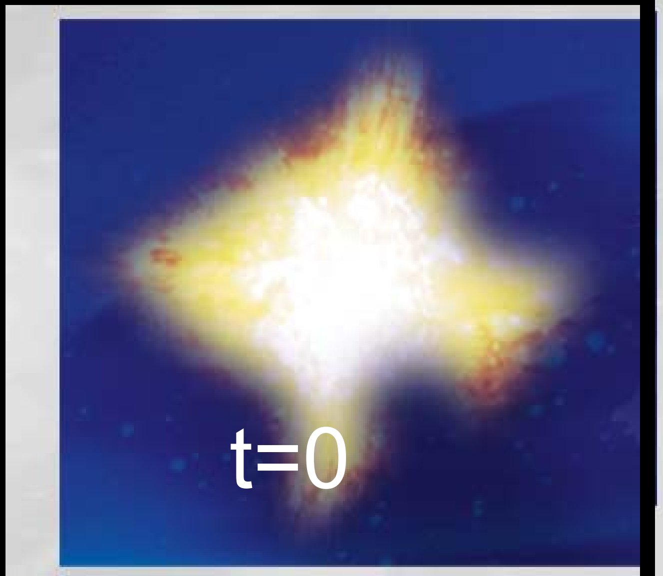
What are the Laws of Nature here?

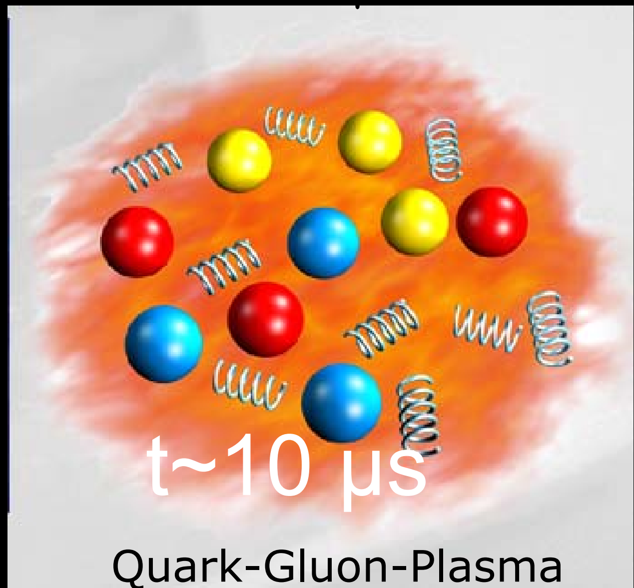
Size of the visible Universe x 100

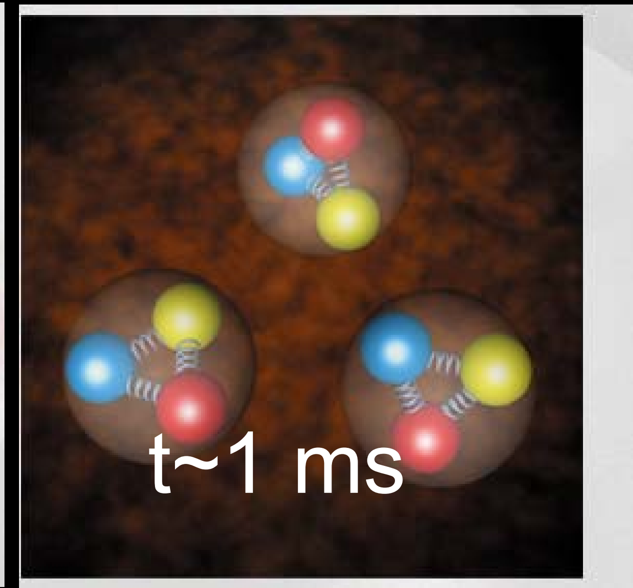
At t = 1/1,000 000 000 000 000 000 000 000 000 000 000 s

Universe

Particle Physics pushes the limit of knowledge towards shorter times







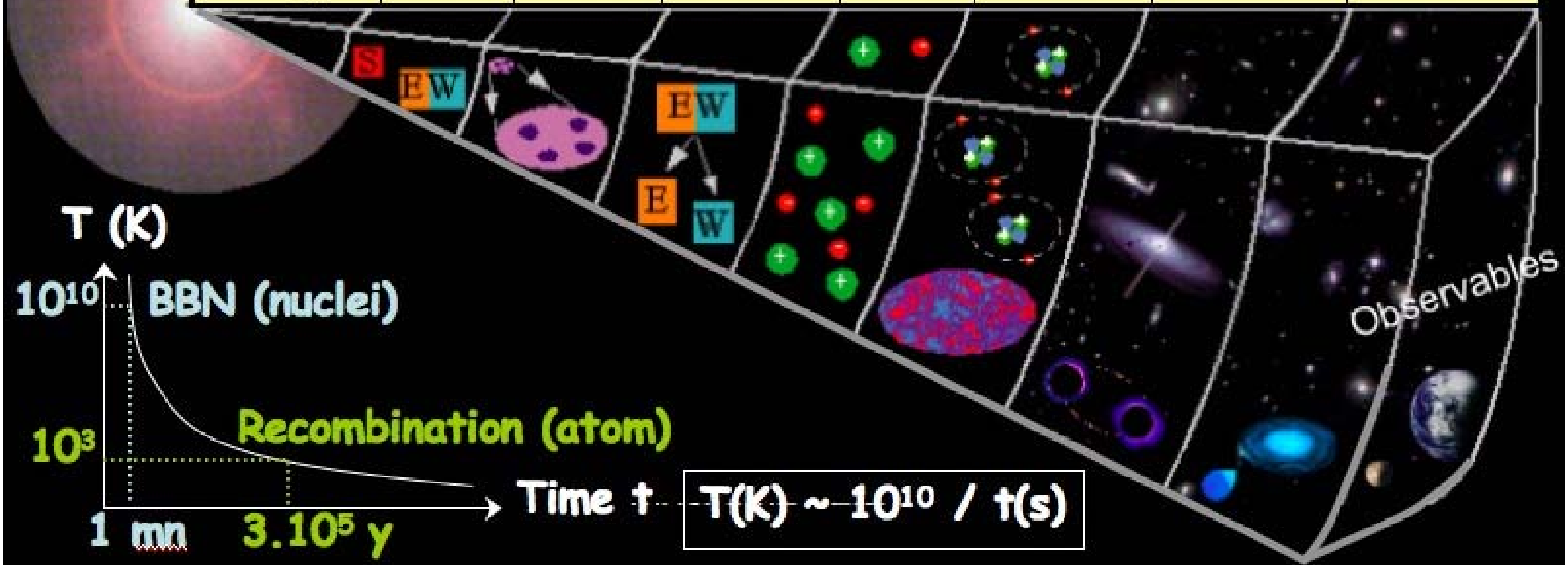
Universe

The reconstruction of the History of the Universe

Big Bang

Time →

10^{19}GeV	10^{15}GeV	10^{13}GeV	100 GeV	0.3 MeV	4000 K	10 K	3 K
10^{-44} s	10^{-35} s	10^{-32} s	10^{-10} s	300 s	$3x10^5$ yr	$3x10^9$ yr	$15x10^9$ yr
Superstring era (?)	GUT era	Inflation era	Electroweak era	Particle Era	Recombination era	Galaxy & star formation	Present era



Universe

Big Bang evolution

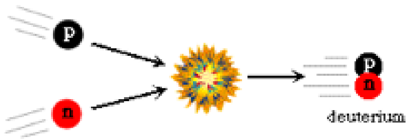
Time (sec)	Temperature (eV/K)	Phase
10^{-43} s	10^{19} GeV	Grand Unified Theory ?
10^{-35} s	10^{15} GeV	Inflation (GUT breaking) ?
10^{-10} s	10^{2} GeV	Electroweak symmetry breaking (W/Z mass)
10^{-5} s	300 MeV	Quarks form hadrons (neutrons, protons, etc)
1-3 min	0.3 MeV	Nucleosynthesis (H, He, Li)
10^{5} yrs	0.4 eV = 4000 K	Recombination of nuclei and electrons (transparent!)
10^{9} yrs	10 K	Stars, Galaxies; Supernovae produce heavy elements
10^{10} yrs	3 K	Today

Universe

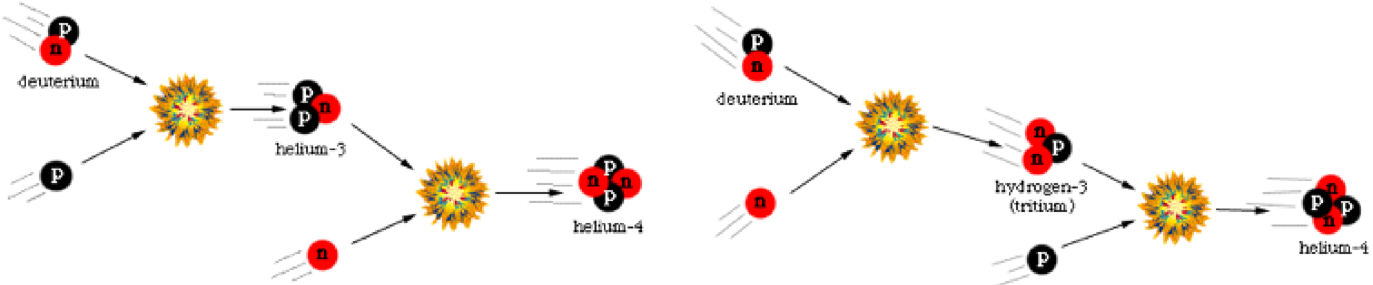
Big Bang Nucleosynthesis

t=1-3 mn, T=0.3-0.1 MeV

- neutron decay: n ⟶ p + e^- + $\bar{\nu}$ ⇒ n/p ~ 1/7
- Deuterium (all n):



- Helium (all D ie all n + equal number of p):



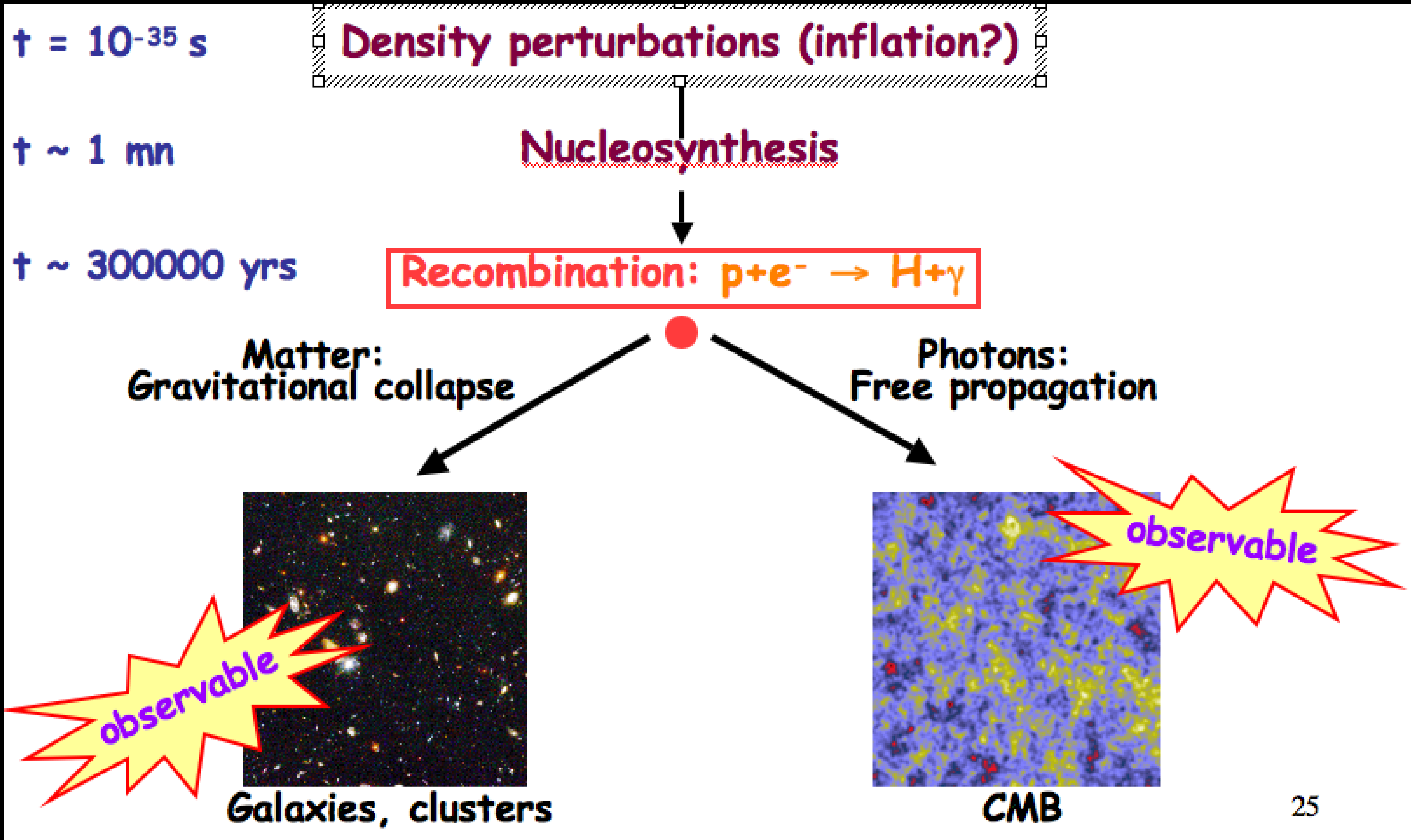
Helium abundance ~ $\frac{2n}{n+p}$ ~ 0.25

H abundance ~ 0.75

$\eta = n_B/n_\gamma$ | ⇒ D bottleneck lasts less ⇒ n/p | ⇒ He^4|

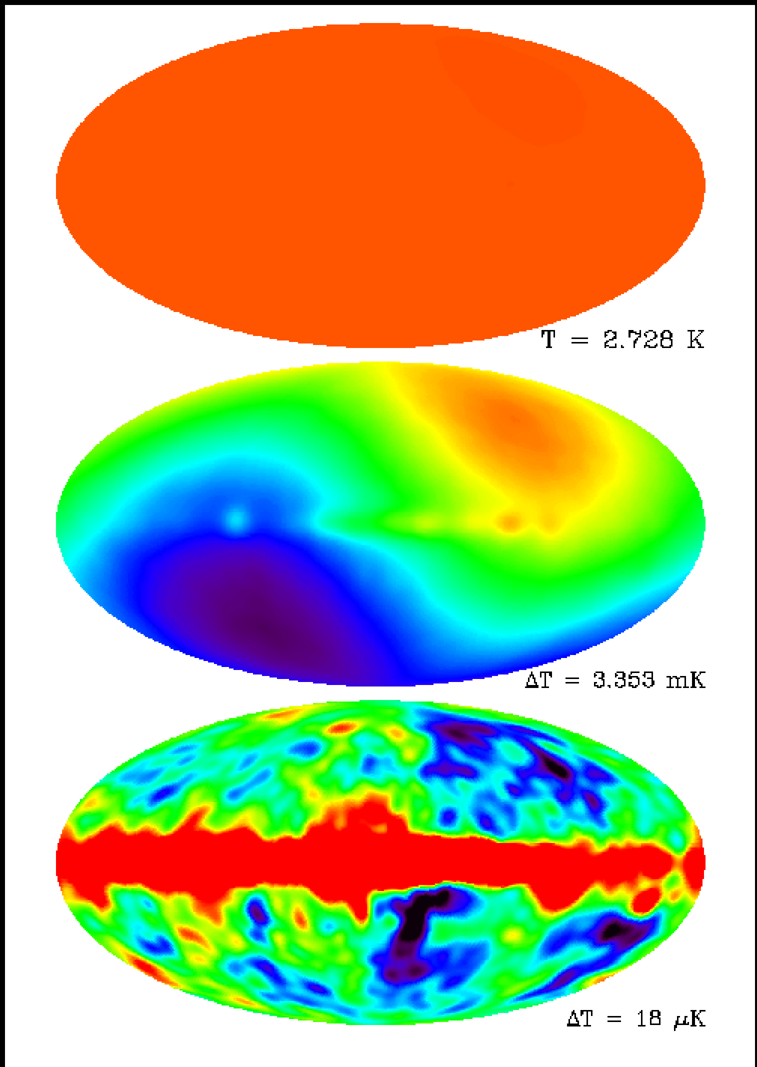
What WMAP measured

Back to the Beginning



Universe

Study of the Cosmic Microwave Background (COBE)
(Nobel prize 2006)



T= 2.7 K

Δελτα–T= 3.3 mK

(after subtraction of constant emission)

Δελτα–T= 18 μK

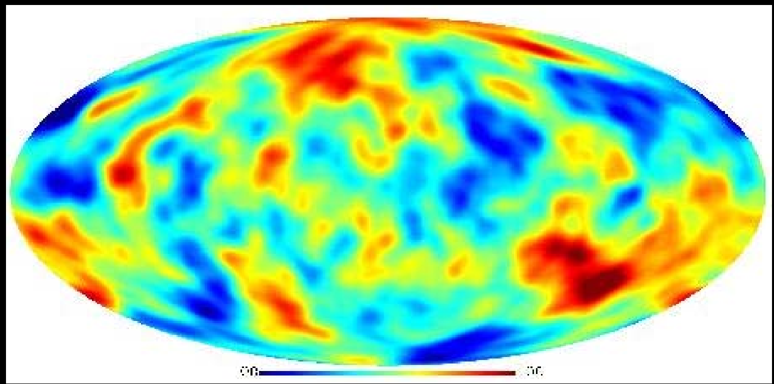
(after correcting for motion of Earth)

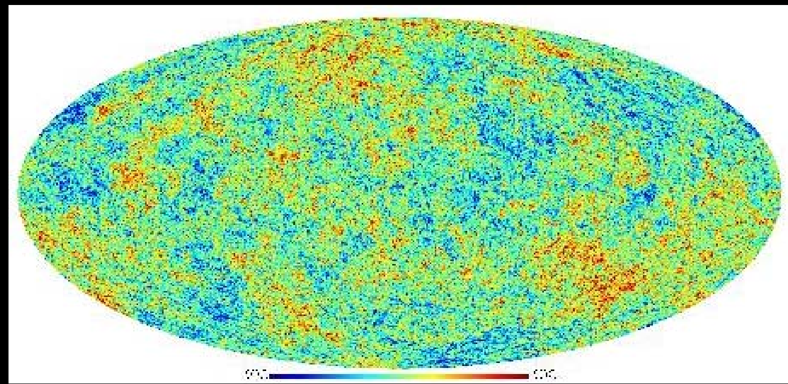
Universe

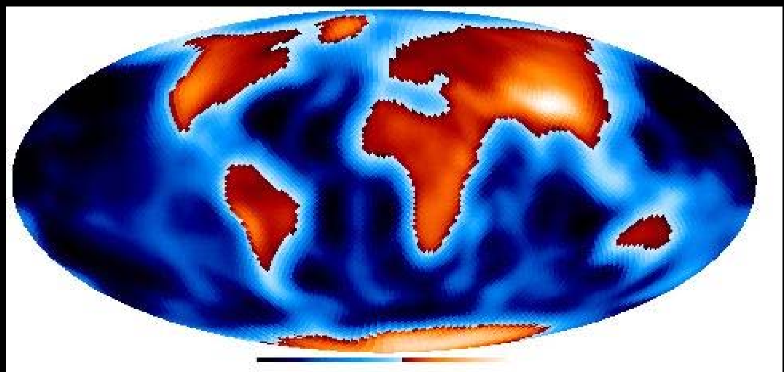
The most precise observation today (WMAP)

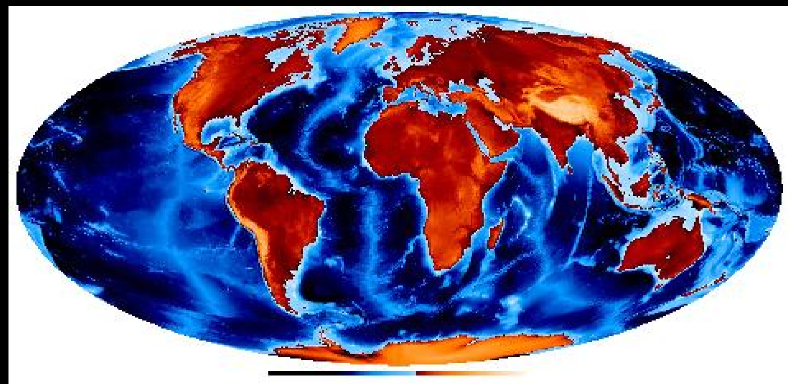
COBE
(7 degree resolution)

WMAP
(0.25 degree resolution)

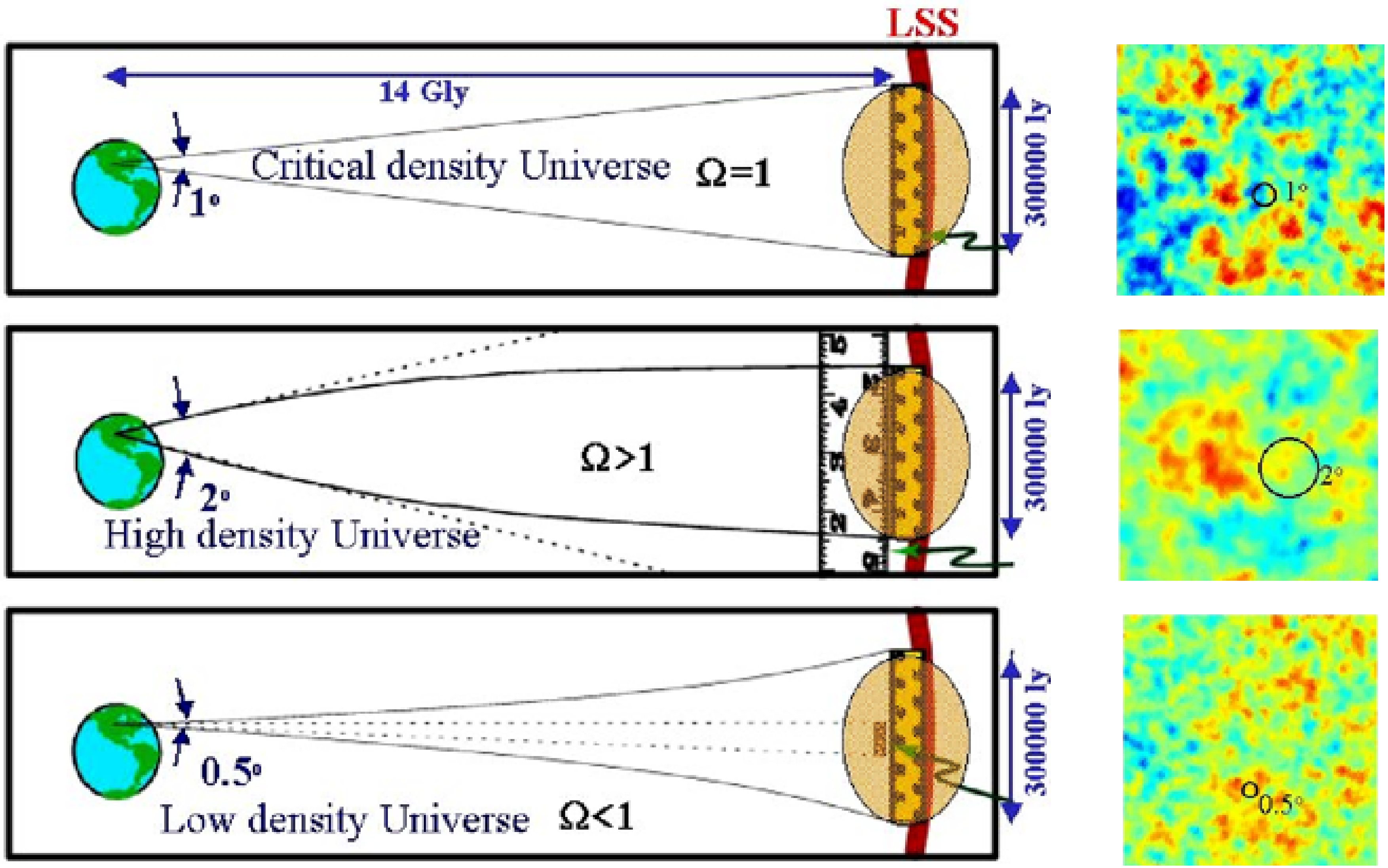








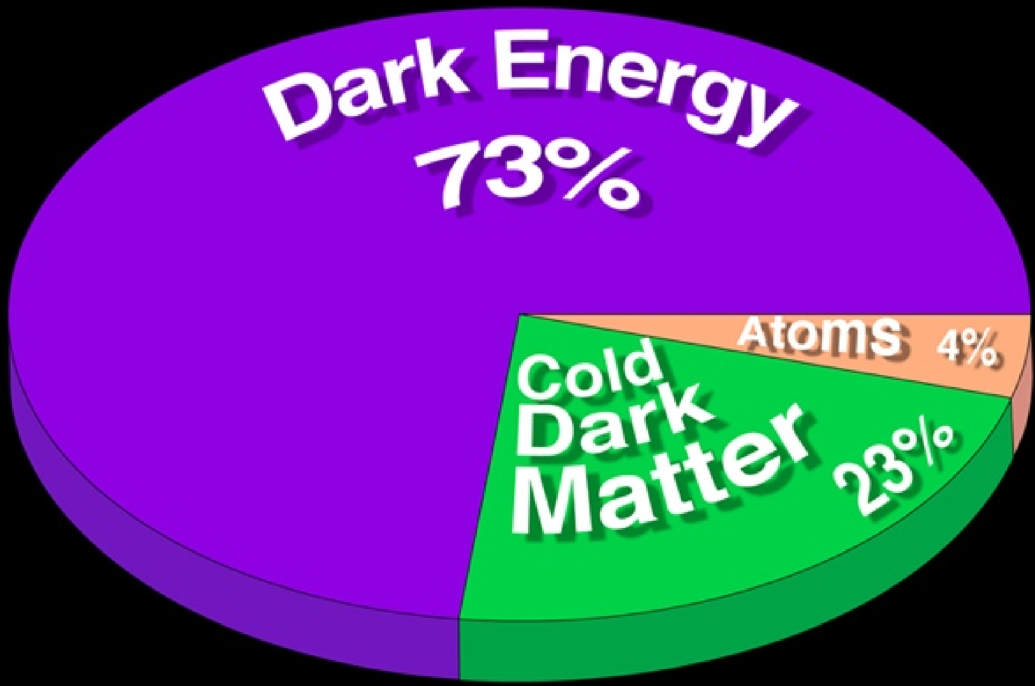
Analysis of inhomogeneities reveals the composition of the Universe



⇒ **Max scale relates to total content of Universe Ω_{tot}**

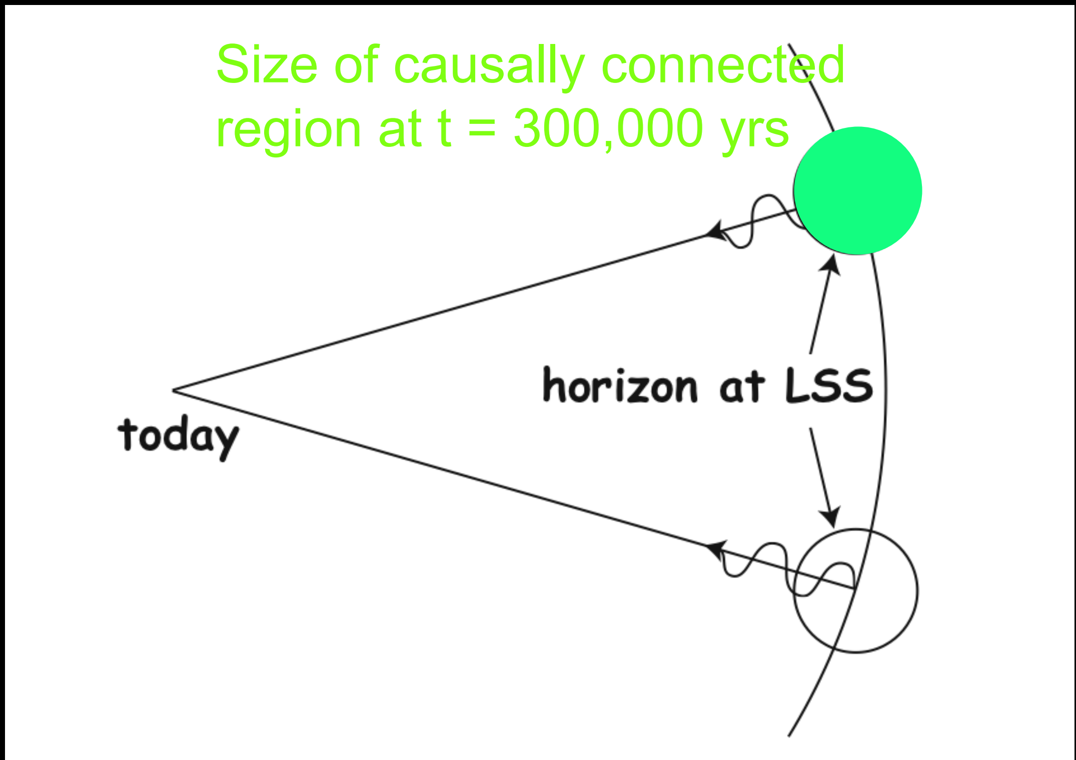
Universe

The strange composition of the Universe



The horizon problem :

How can the CMB radiation be so homogeneous when there are 10^{88} regions which have never been causally connected ?

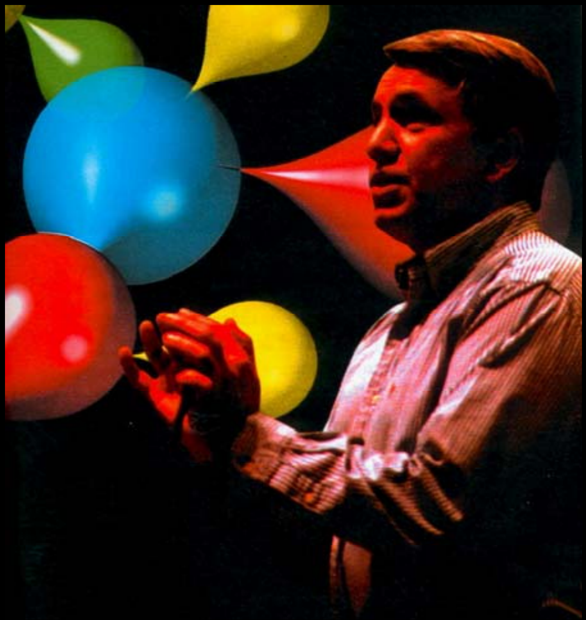


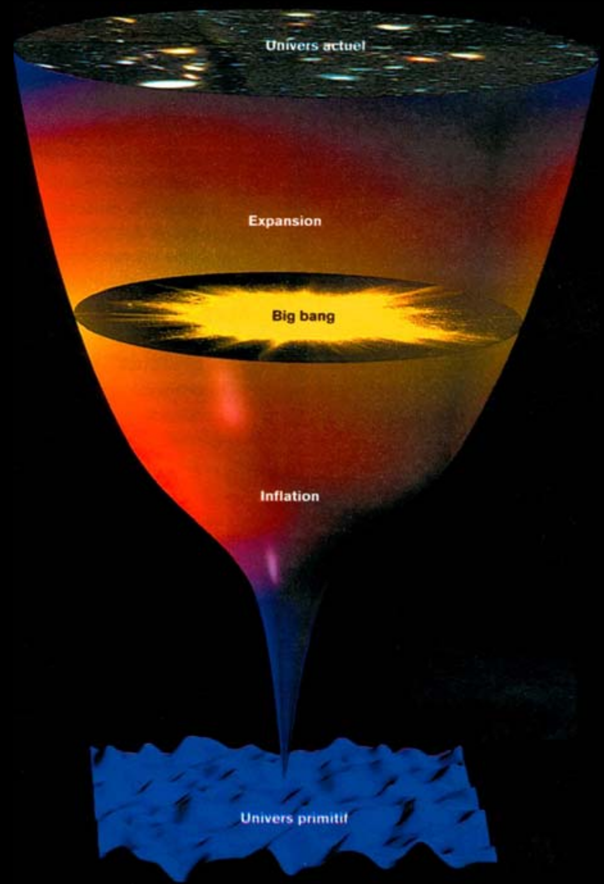
$$\text{Angle} \sim \frac{10^3 \times 3.10^5}{14.10^9} \text{ rad} \sim 1°$$

Universe

Guth/Linde (1980)

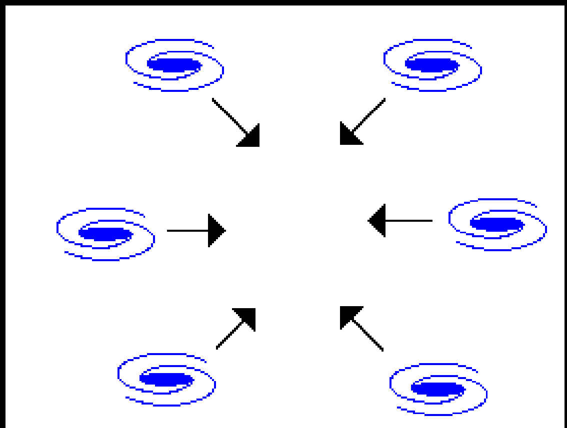
The Universe went through a phase of superluminal expansion,
driven by an 'inflaton' field

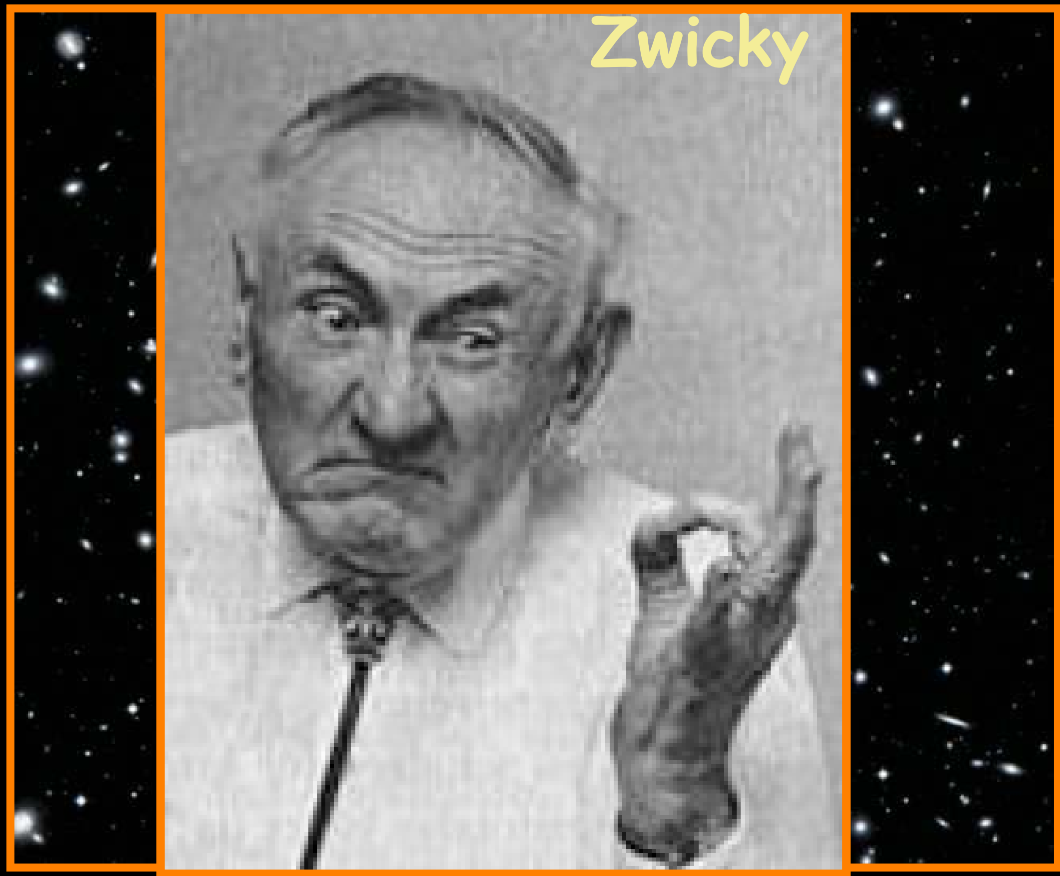




solves two big problems:
1) the flatness of the Universe
2) the horizon problem

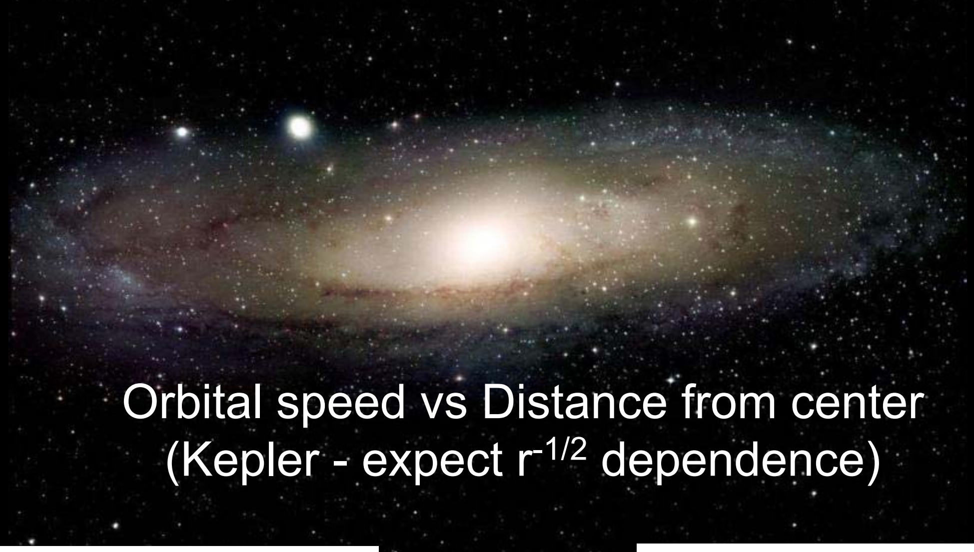
Evidence for Dark Matter (1933)



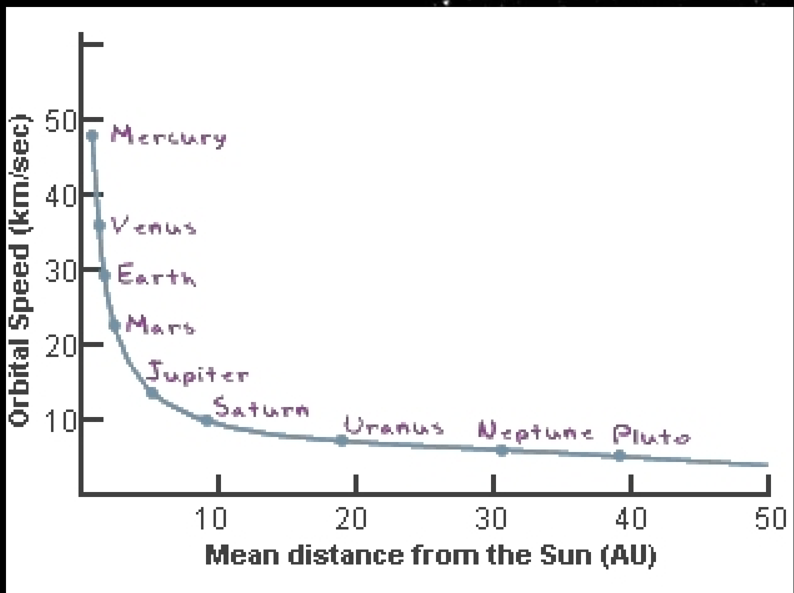


Mass of luminous matter
=
10%
Gravitational mass

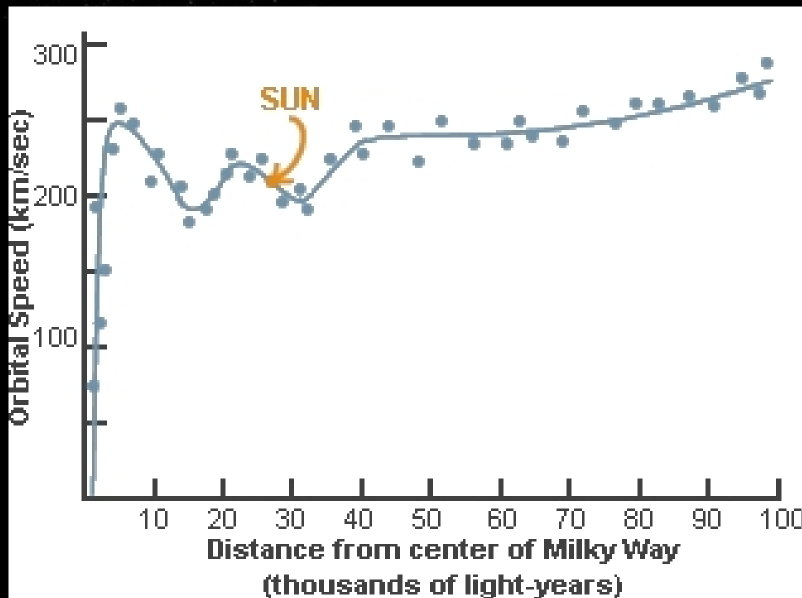
MORE EVIDENCE FOR "DARK MATTER"



Orbital speed vs Distance from center
(Kepler - expect $r^{-1/2}$ dependence)



One central mass (Sun)



Milky Way

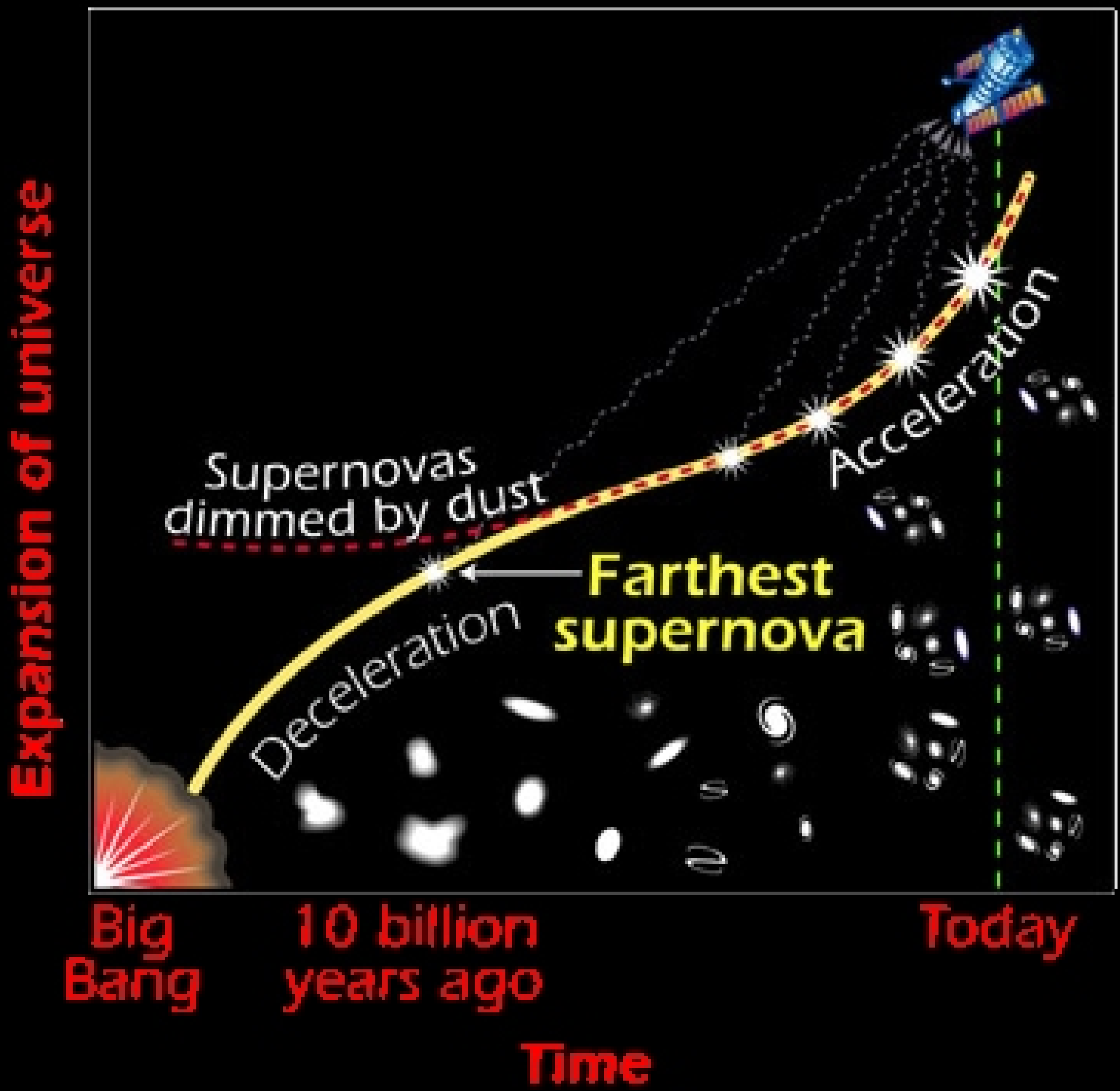
AND EVEN MORE EVIDENCE FOR "DARK MATTER"

Gravitational Lens in Abell 2218 HST · WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA

GRAVITATIONAL LENSING

Evidence for Dark Energy



QUESTIONS FOR THE 21st CENTURY

1) How do particles acquire their mass - the “Higgs” Field ?

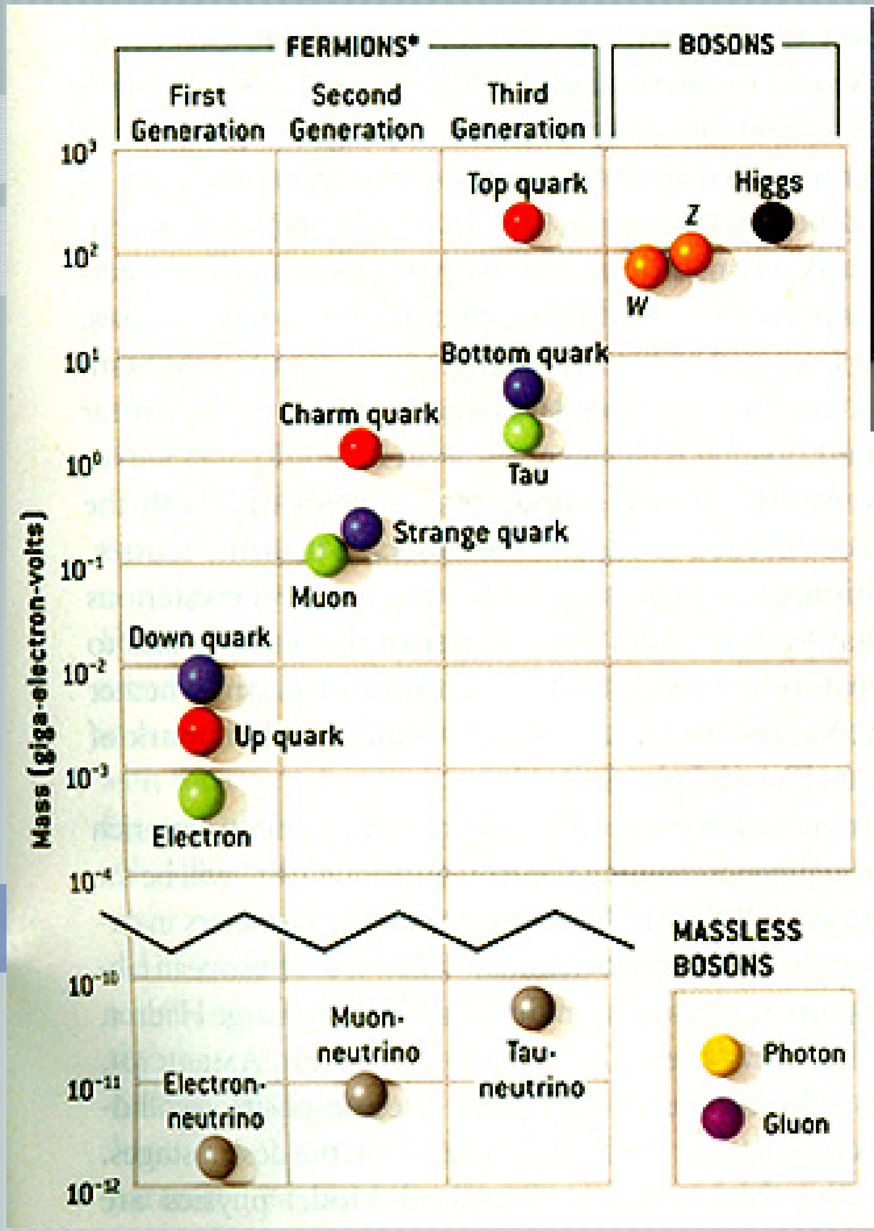
1 TeV →

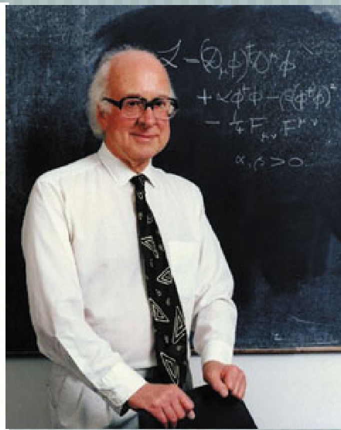
100 GeV →

1 GeV →

1 MeV →

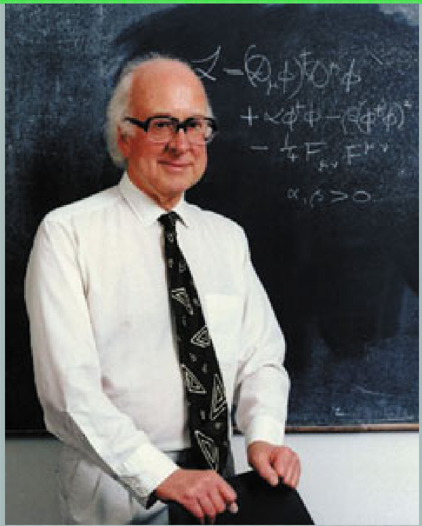
0.01 eV →





Peter Higgs

QUESTIONS FOR THE 21st CENTURY



Sir Peter Higgs

The Higgs Particle

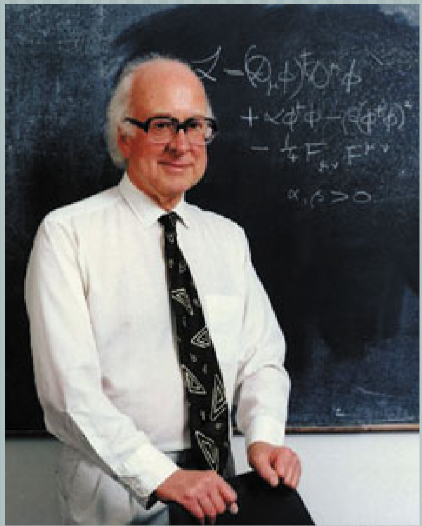
The 'Higgs' field gives mass (inertia) to particles
"friction with the vacuum "

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

How electrons and quarks acquire a mass

QUESTIONS FOR THE 21st CENTURY

The Higgs Particle



Sir Peter Higgs

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

The Higgs ‘particle’ is an excitation of the Higgs field
- if it exists, it will be found at CERN

QUESTIONS FOR THE 21st CENTURY

2) Are particles and fields connected - Supersymmetry ?

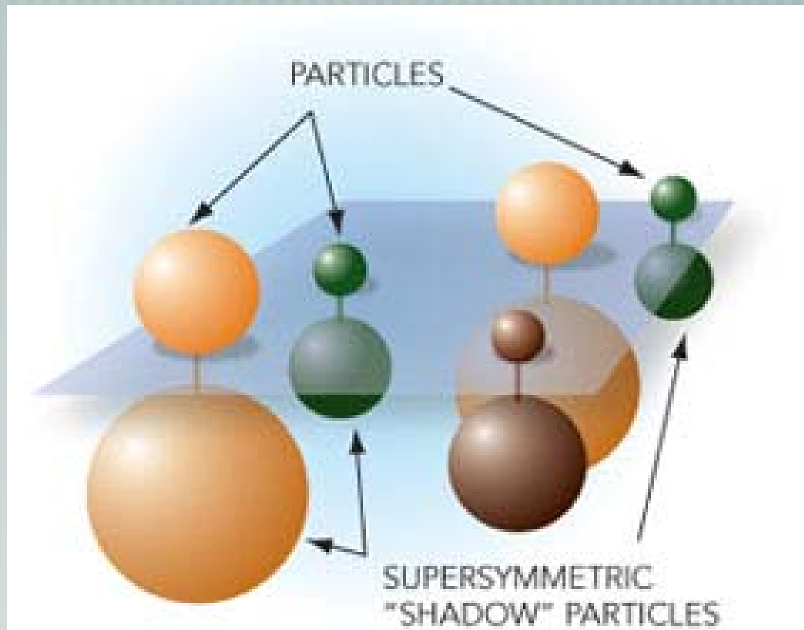
'Matter' particles (Spin 1/2=fermion)) interact by exchanging 'field' (Spin 1=boson) particles:

all particles (electrons, neutrinos, quarks) interact through 'gravitons' and W/Z fields
particles with electric charge (e.g. electrons, quarks) emit photons
particles with colour charge (quarks) emit gluons

Is there a deeper SUPERSYMMETRY between matter and fields?

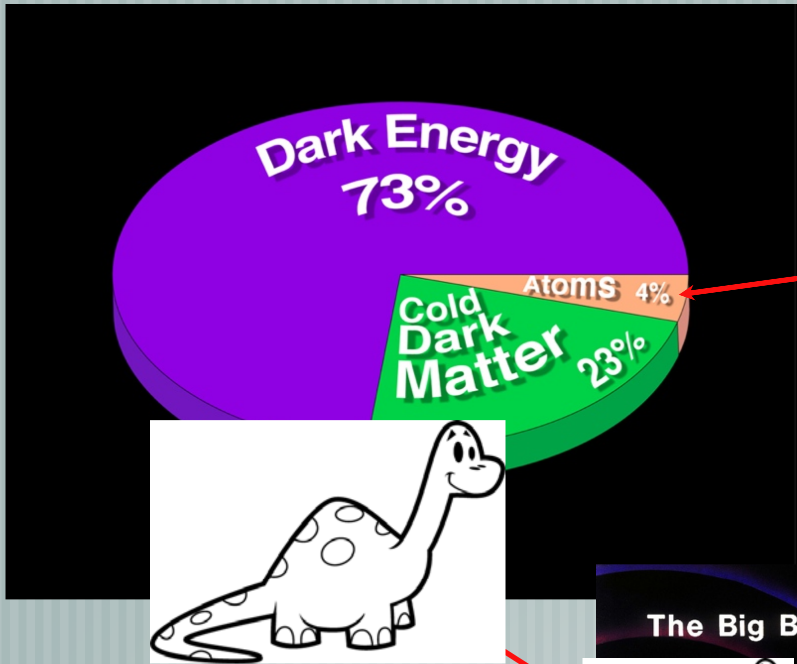
all matter particles have a field partner
all field particles have a matter partner

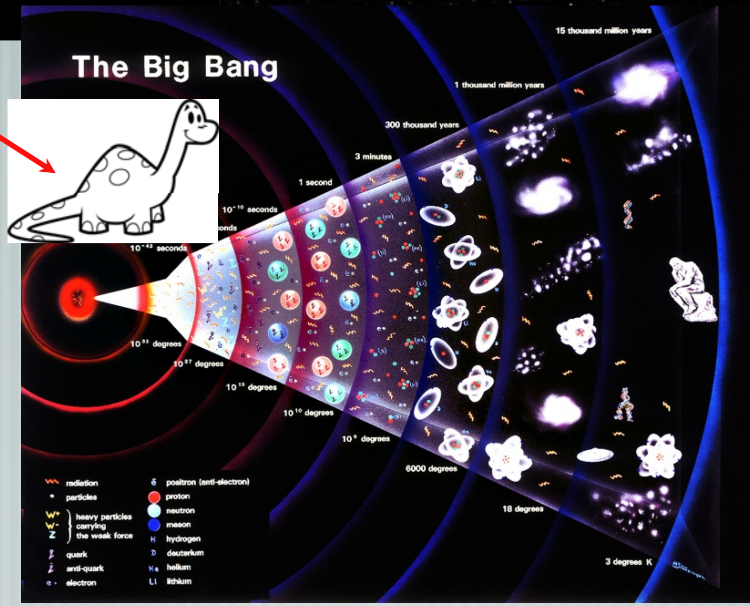
Spin 1/2	Spin 1
electron	selectron
quark	squark
photino	photon
gluino	gluon



If they exist - they must be VERY MASSIVE (> 200 GeV)

QUESTIONS FOR THE 21st CENTURY





SUSY = Dark matter particles
left over from Big Bang?

QUESTIONS FOR THE 21st CENTURY

What are particles?

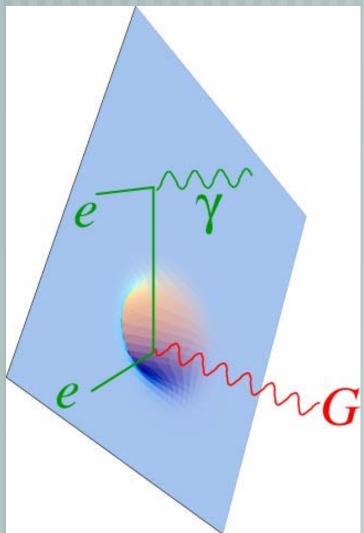
Superstrings in 9+1 dimensions?

Quantum theory of gravity only works in 9-dimensional space
Particles + fields are oscillating 'strings' (size ~10^{-35} m)
Different vibration patterns correspond to different particles

String theory 'contains' all known particles (including graviton) and fields
But: no prediction on how the additional dimensions are curled up
No prediction on the scale of the supersymmetry breaking

Quantum Gravity ?

Does gravity act in **more than 3 spatial dimensions?**



Is gravity so weak because 'gravitons' escape into the small extra-dimensions?

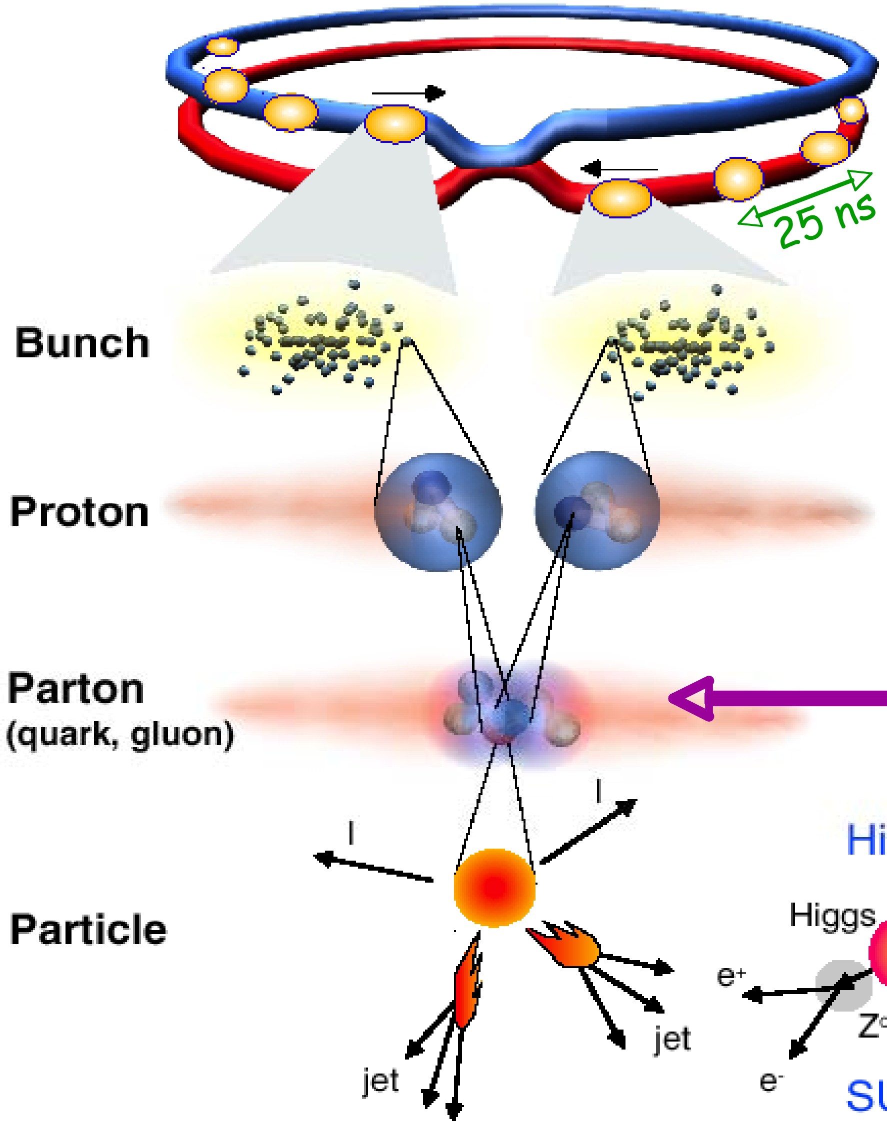
LHC collisions may produce 'mini' Black Holes

QUESTIONS FOR THE 21st CENTURY

LHC STARTUP IN 2008

new answers !

Collisions at LHC



Proton-Proton

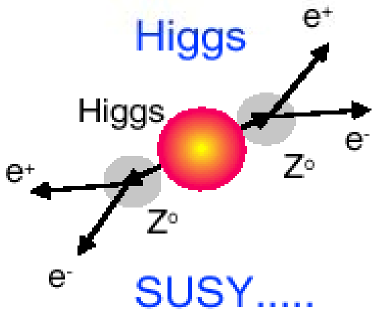
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate in ATLAS :

$N = L \times \sigma$ (pp) $\approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare



Selection of 1 in
10,000,000,000,000

Universe

1900 - 2000: Phantastic progress in understanding matter and the Universe

We know what matter is made of.
We know the principle steps in the evolution of the Universe.

Now we have a set of new, deeper questions:

Are quarks and leptons elementary?
Where is the link (remember: charge of proton + charge of electron =0)
Are there different kinds of matter? (Dark matter?)
Are there new forces of a novel kind?
What do generations mean? How many?
What is the origin and relation of the fundamental constants?
Is life in the Universe an accident? (“Anthropic principle”)
Where is the antimatter gone? (Matter-Antimatter asymmetry)
What caused inflation? (Connection cosmological constant?)
How and why did the initial symmetry break? (Unification of forces)
The worst understood part of the Universe: the VACUUM !

This is the physics of the 21st century !