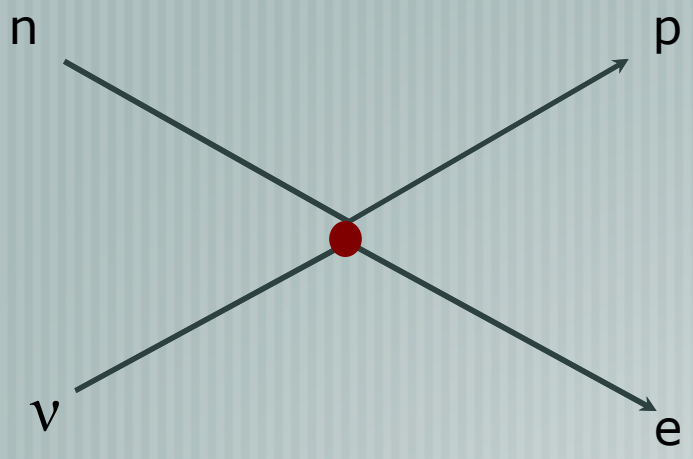
Fields

1958 Glashow

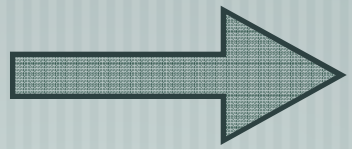
Back to the weak interaction: there was a big (theoretical) problem

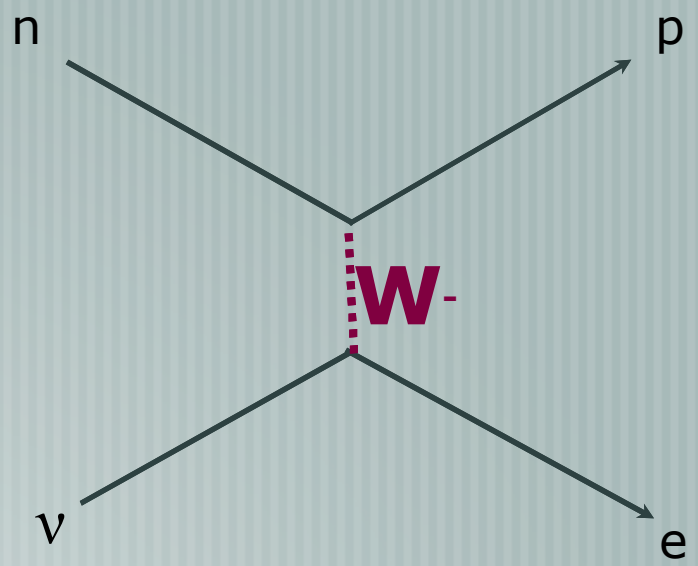
probability of this reaction > 100% for E > 300 GeV



Fermi model

New Idea





Glashow model

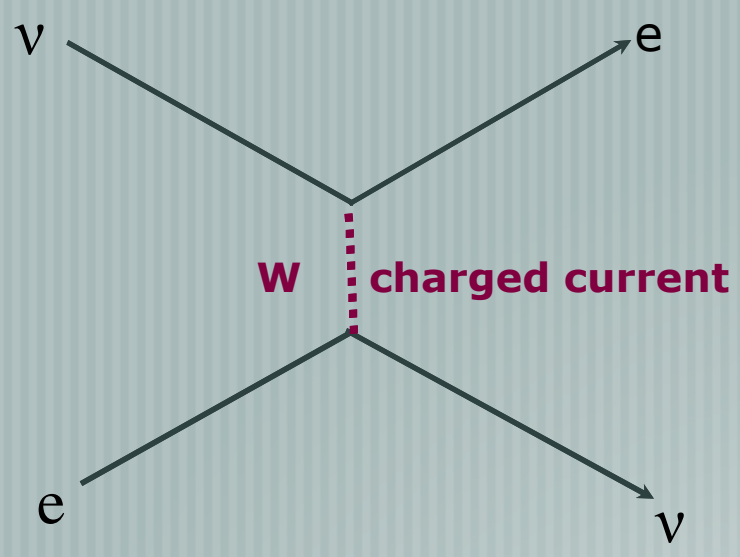
Weak interaction transmitted by massive vector bosons (in analogy to photon exchange!)

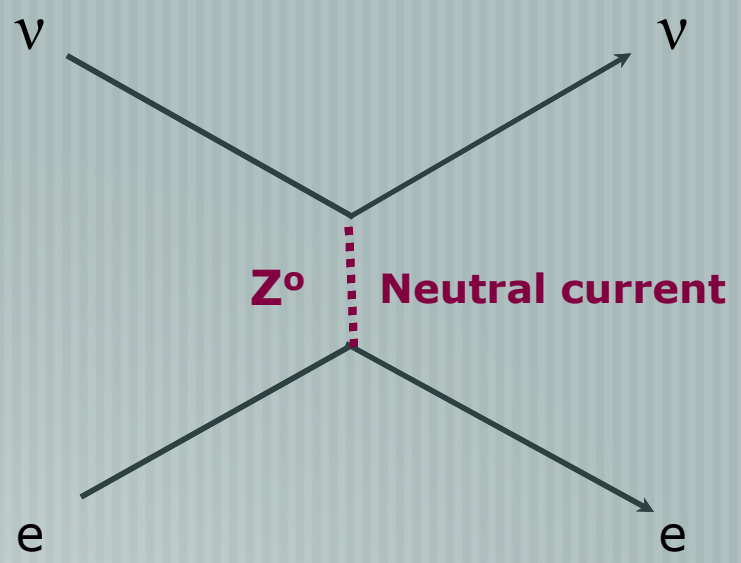
Large mass (80 GeV) explains short range ($2 \cdot 10^{-18}$ m) and small cross-sections

Fields

Electroweak Interaction

1968



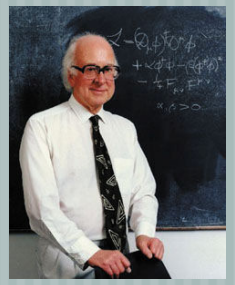


Glashow, Salam, Weinberg (1968) - Electroweak Force

- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge
- There should be a 'heavy photon' (Z^o) and two charged vector boson ($W^{\pm}$) of mass ~ 50-100 GeV
- **The W,Z bosons acquire their mass by interacting with the "Higgs field" (1964)**
- There are only 'left-handed' interactions

Fields

Interlude: The Higgs Field



Sir Peter Higgs

- it fills all of space since the ‘spontaneous symmetry breaking’ at Big Bang
- it is a new type of interaction giving their specific mass to all particles
- it is something like a ‘cosmic DNA’

QuickTime™ and a
GIF decompressor
are needed to see this picture.

QuickTime™ and a
GIF decompressor
are needed to see this picture.

QuickTime™ and a
GIF decompressor
are needed to see this picture.

♥David Miller

A cocktail party ...

.. a famous guest wants to cross the room...

.. but everybody wants an autograph - the guest is difficult to accelerate...

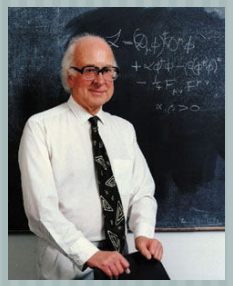
The Higgs field ...

... a new particle is created ...

... the Higgs field gives the particle its ‘inertia’ ...

Fields

The Higgs boson



Sir Peter Higgs

QuickTime™ and a
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are needed to see this picture.

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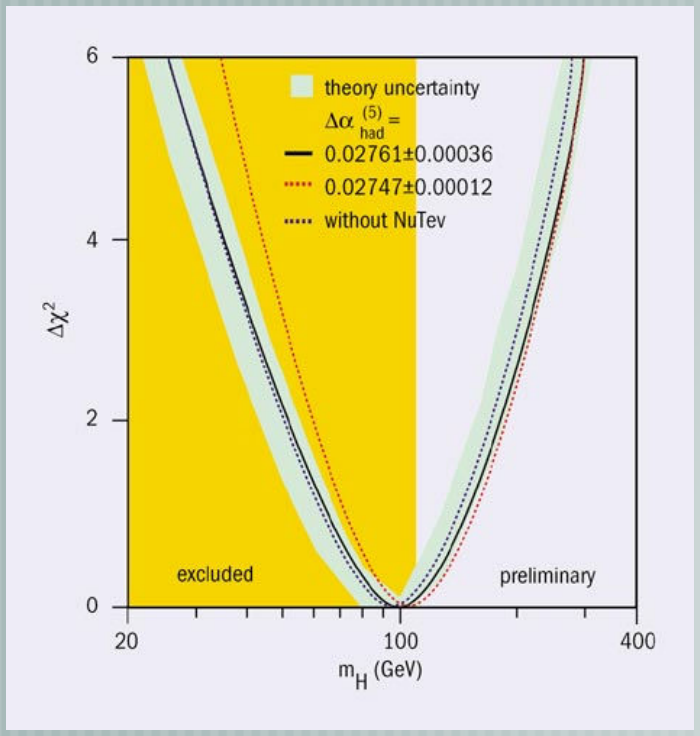


A rumour originates ...

.. many guest clump together
to discuss the rumour...

*The Higgs field is excited
and receives energy....*

*... which produces a
"real" field particle ...*

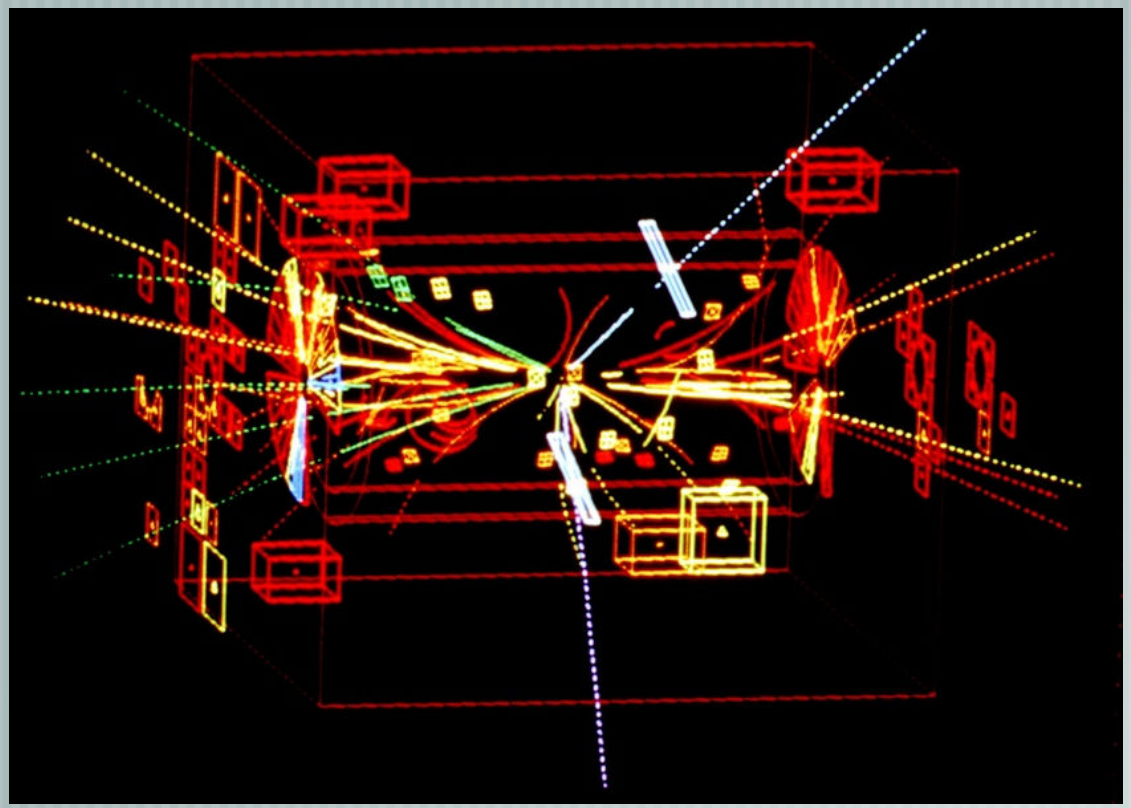
Indirect evidence ('vacuum fluctuations involving the Higgs particle') predicts that the mass of the Higgs particle should be less than ~200 GeV.

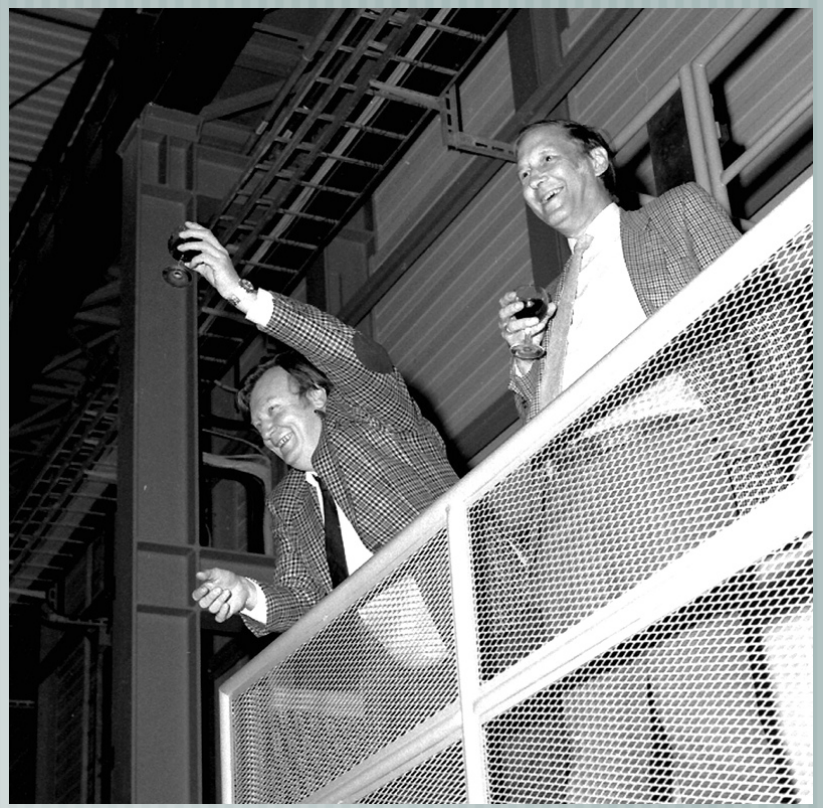
Fields

Electroweak Interaction 1983

“They really exist” : Discovery of the W, Z bosons at CERN (1983)

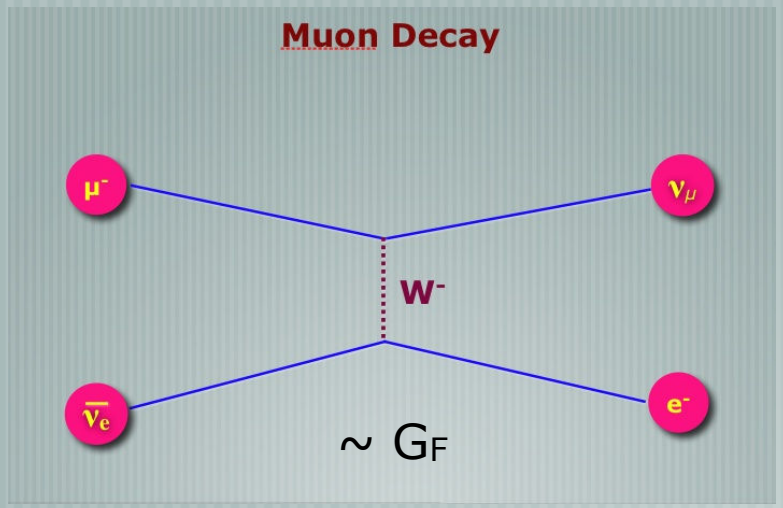
(Carlo Rubbia - leader of UA1 collaboration, and proponent of proton-antiproton collider in SpS)
(Simon van der Meer - inventor of stochastic beam cooling)

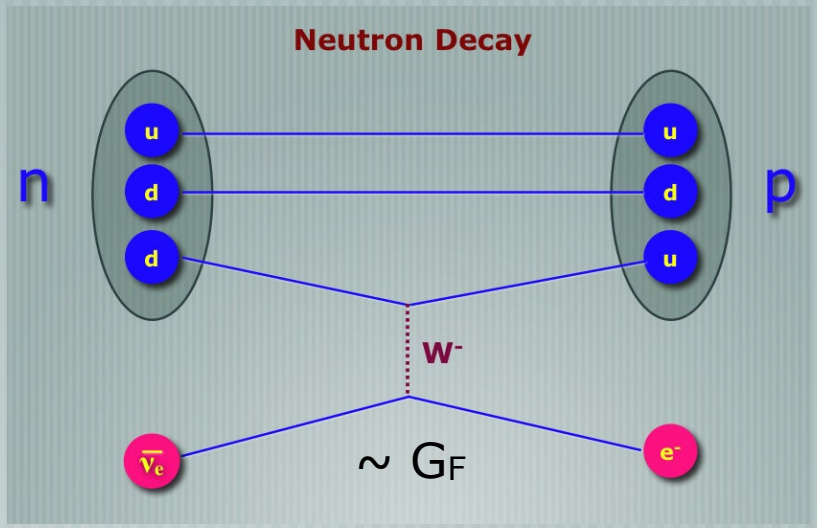




Fields

Electroweak interaction is the SAME for leptons and quarks





"Universality*" - transmitted by W, Z bosons, same strength!

*Assuming a little bit of 'quark' mixing

$$d' = d \cos\theta_c + s \sin\theta_c$$
$$s' = -d \sin\theta_c + s \cos\theta_c$$

θ_c = Cabbibo angle ~ 20°

Fields

1970

A legendary paper, predicting a new quark (Glashow, Iliopoulos, Maiani)

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

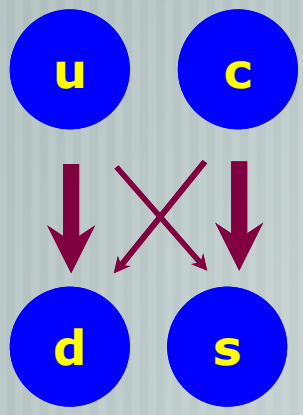
Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

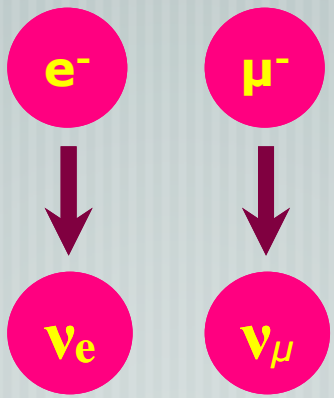
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Quarks



Leptons

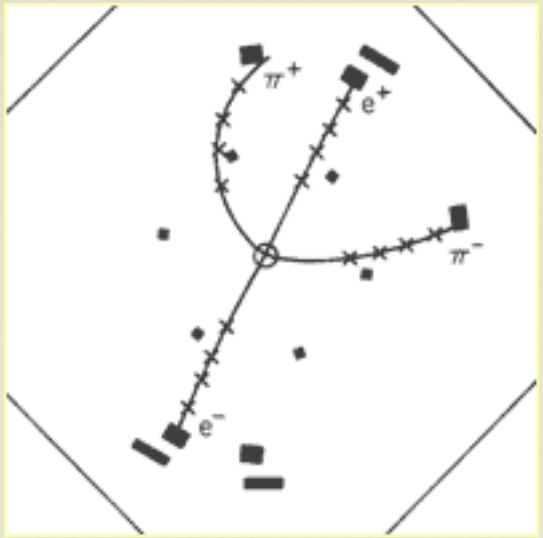


The "Standard Model" of 1970

Discovery of the ‘charm’ quark in 1974

NOVEMBER REVOLUTION (11 November 1974)

'Psi' am SLAC (Burt Richter)
'**J**' at Brookhaven (Sam Ting)
Compromise: J/Psi



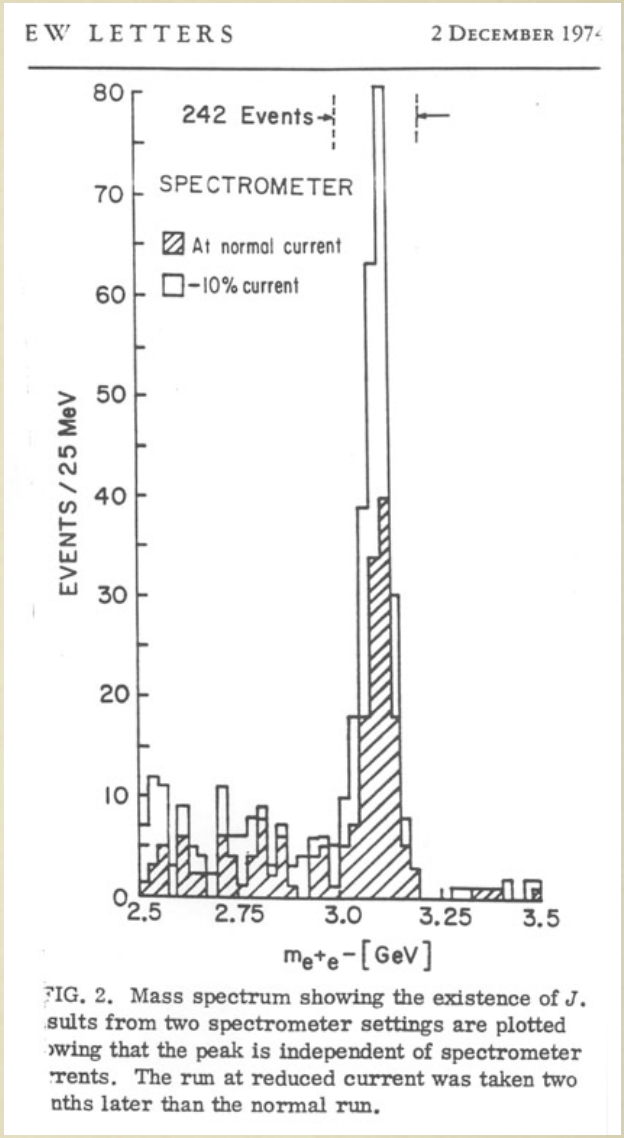
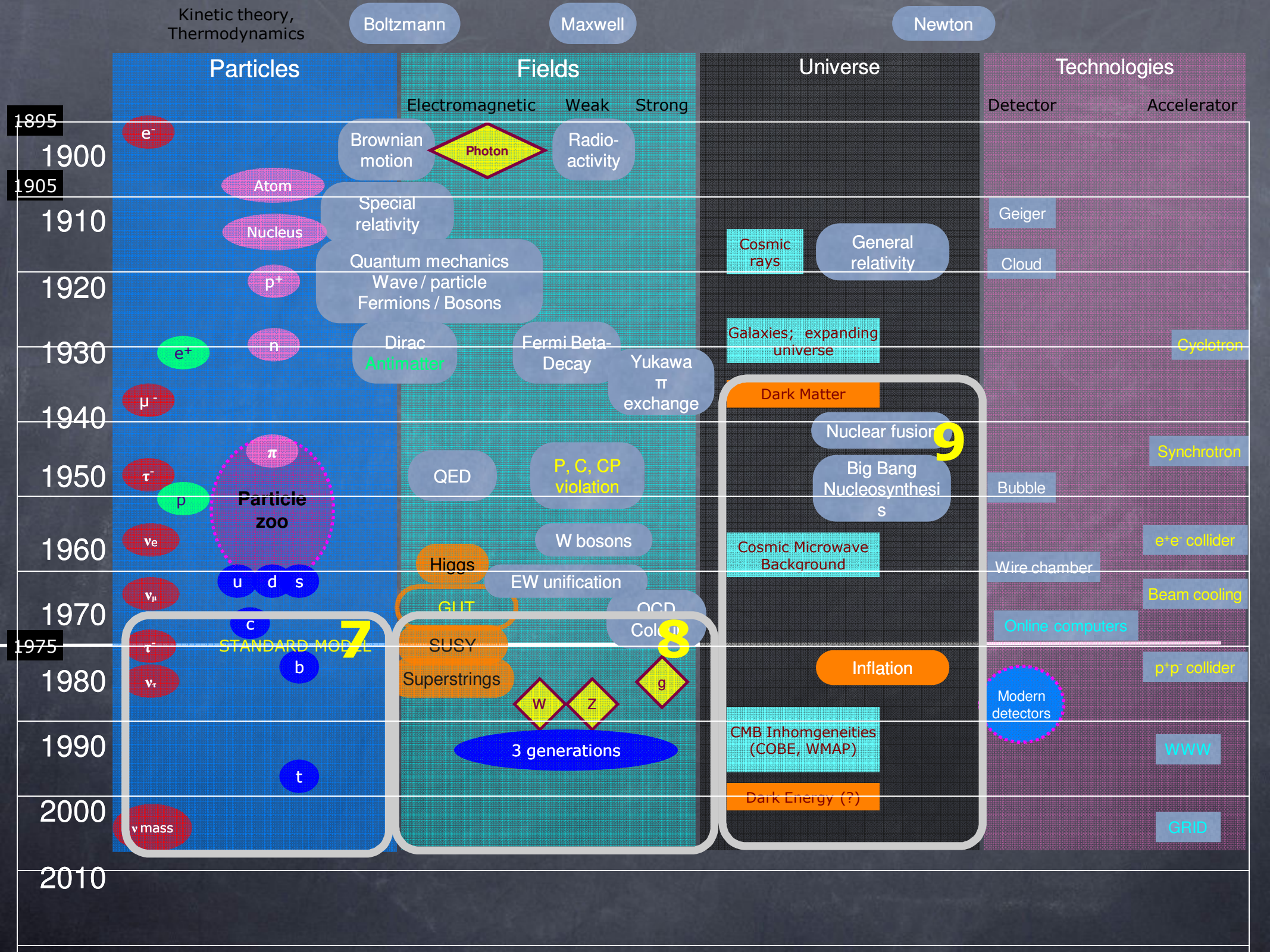


FIG. 2. Mass spectrum showing the existence of J. sults from two spectrometer settings are plotted owing that the peak is independent of spectrometer rents. The run at reduced current was taken two nths later than the normal run.

“Extremely” long lifetime (~10^{-20} sec)
Decay only possible through electroweak interaction


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

PARTICLE SPECTRUM

But a third family of particles was going to be discovered

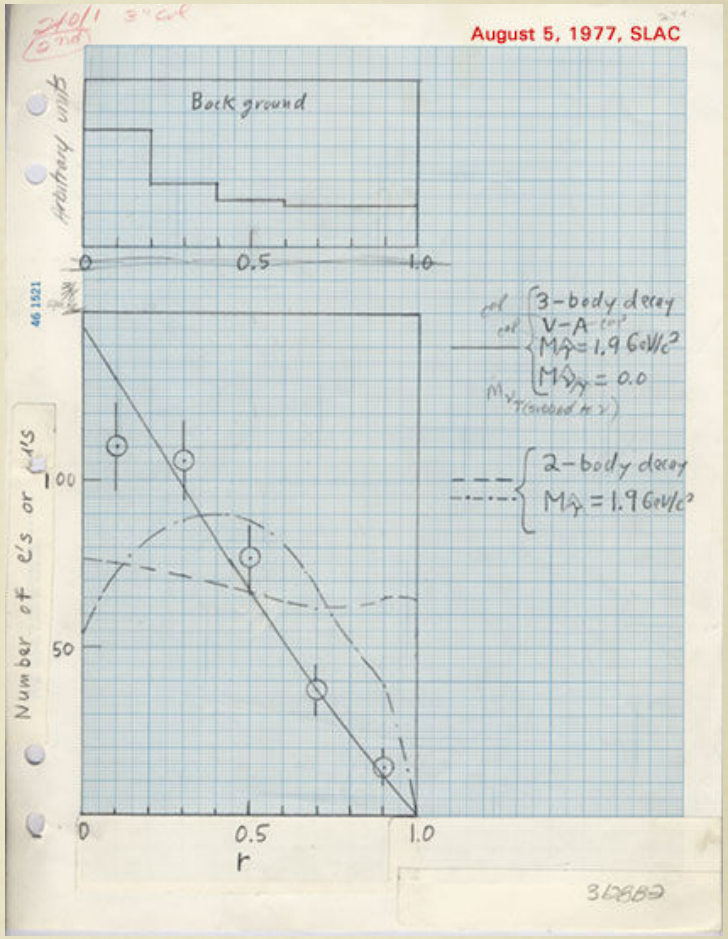
SLAC (Marty Perl)

A new 'heavy electron' with 3500 x m_e

... who ordered that?

THERE MUST BE A WHOLE NEW FAMILY

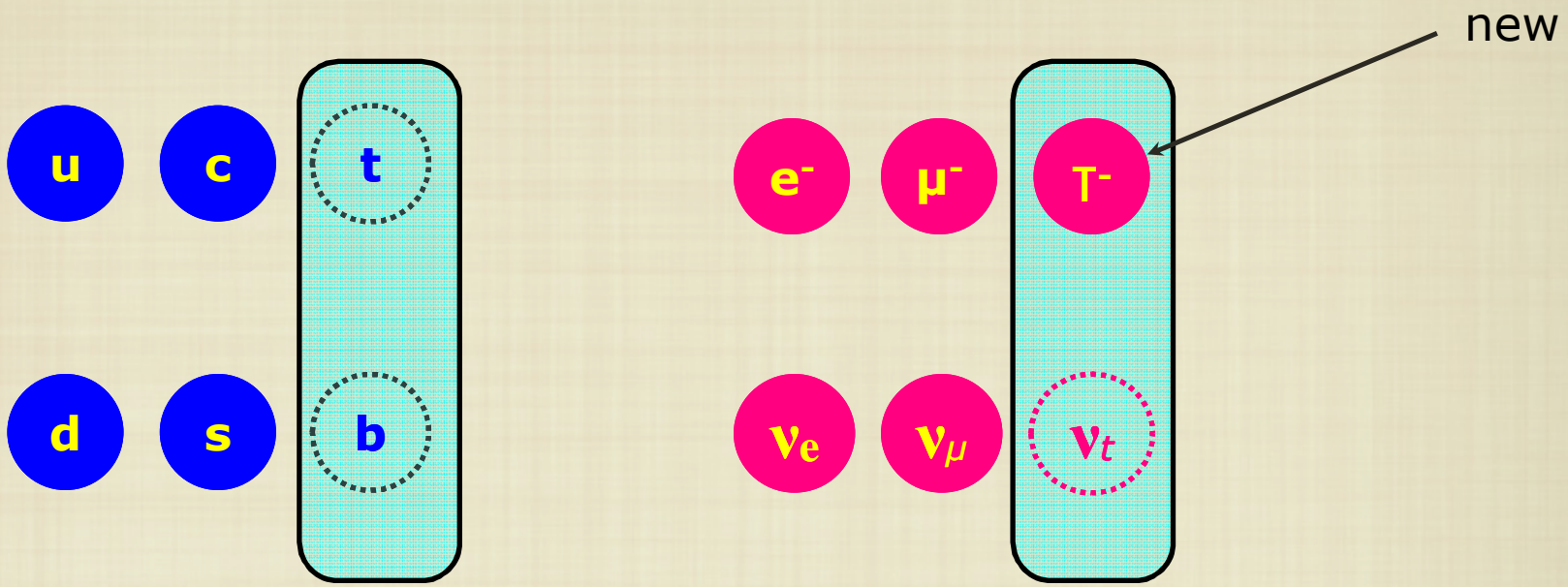
another neutrino (the 'tau neutrino'),
and two more quarks ('top' and 'bottom')



Marty Perl's logbook page

PARTICLE SPECTRUM

The search for the other family members started

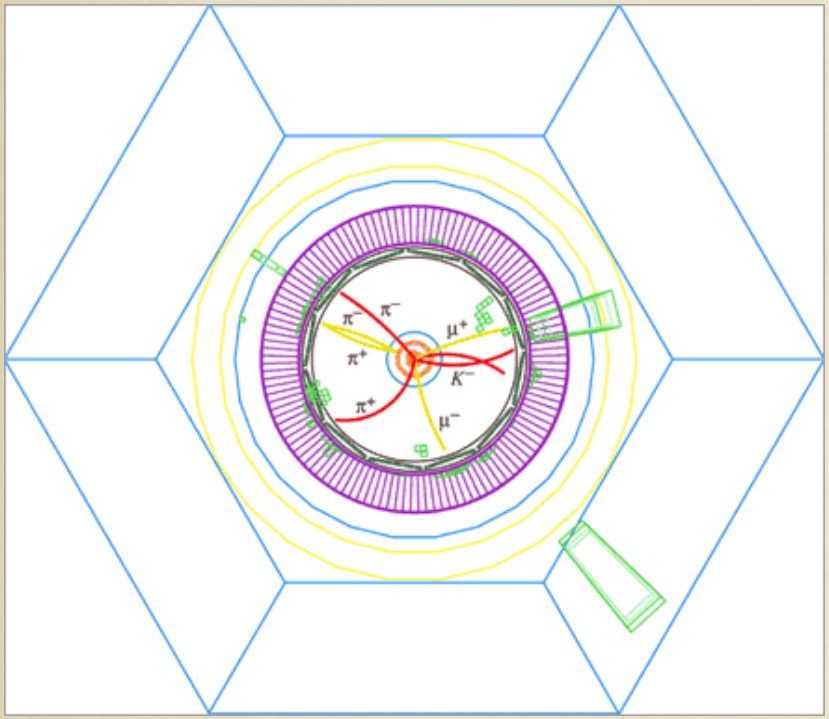


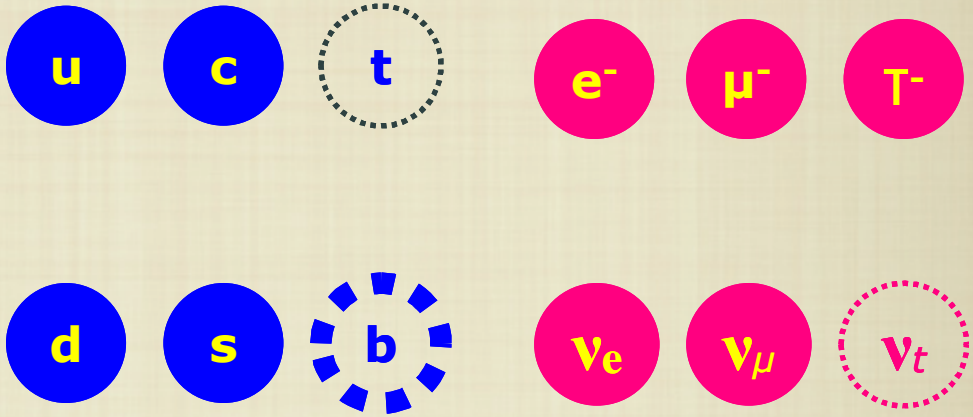
Quarks

Leptons

PARTICLE SPECTRUM

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





Quarks Leptons

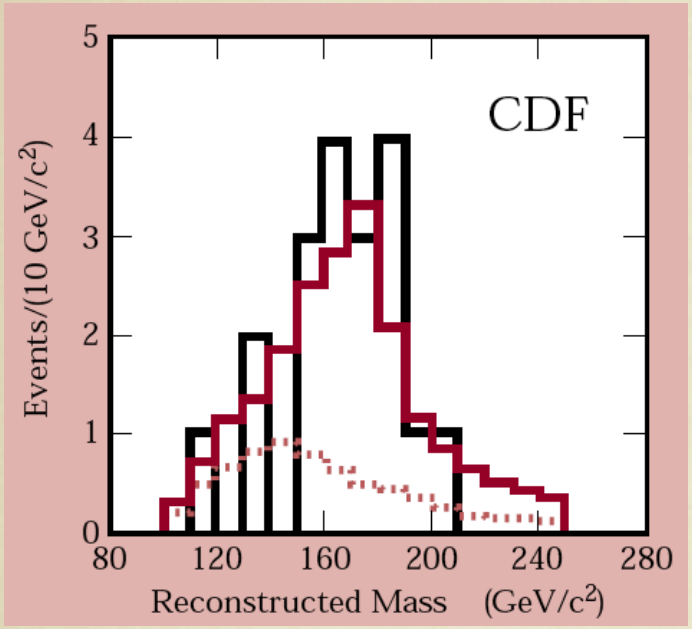
In 1977 physicists discovered a new meson called the Upsilon at the Fermi National Accelerator Laboratory.

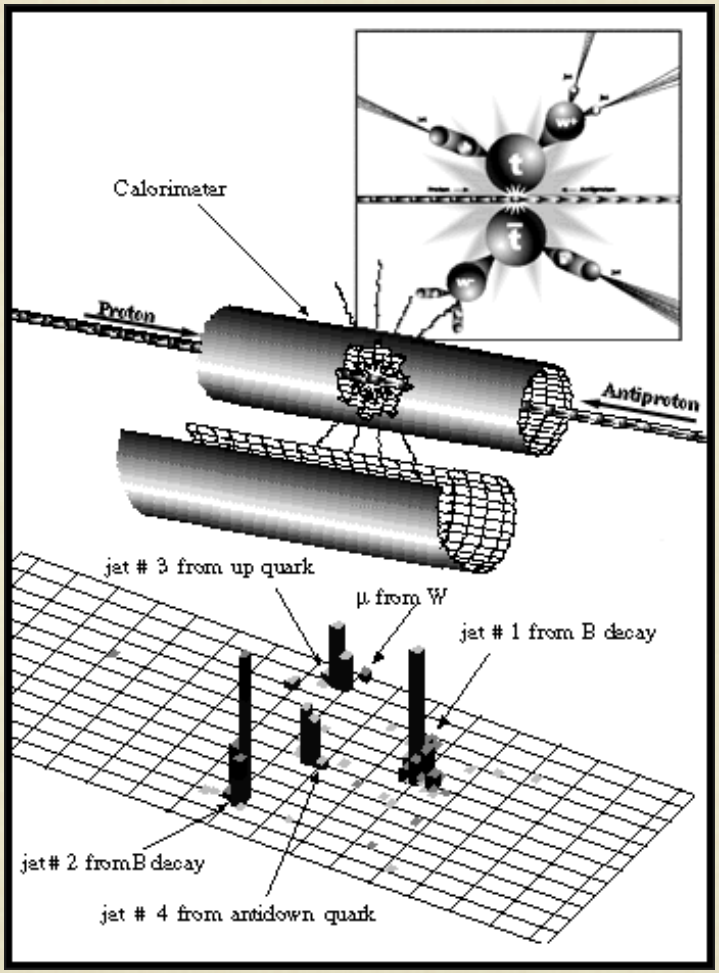
This meson was immediately recognized as being composed of a bottom/anti-bottom quark pair.

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

PARTICLE SPECTRUM

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





u c t

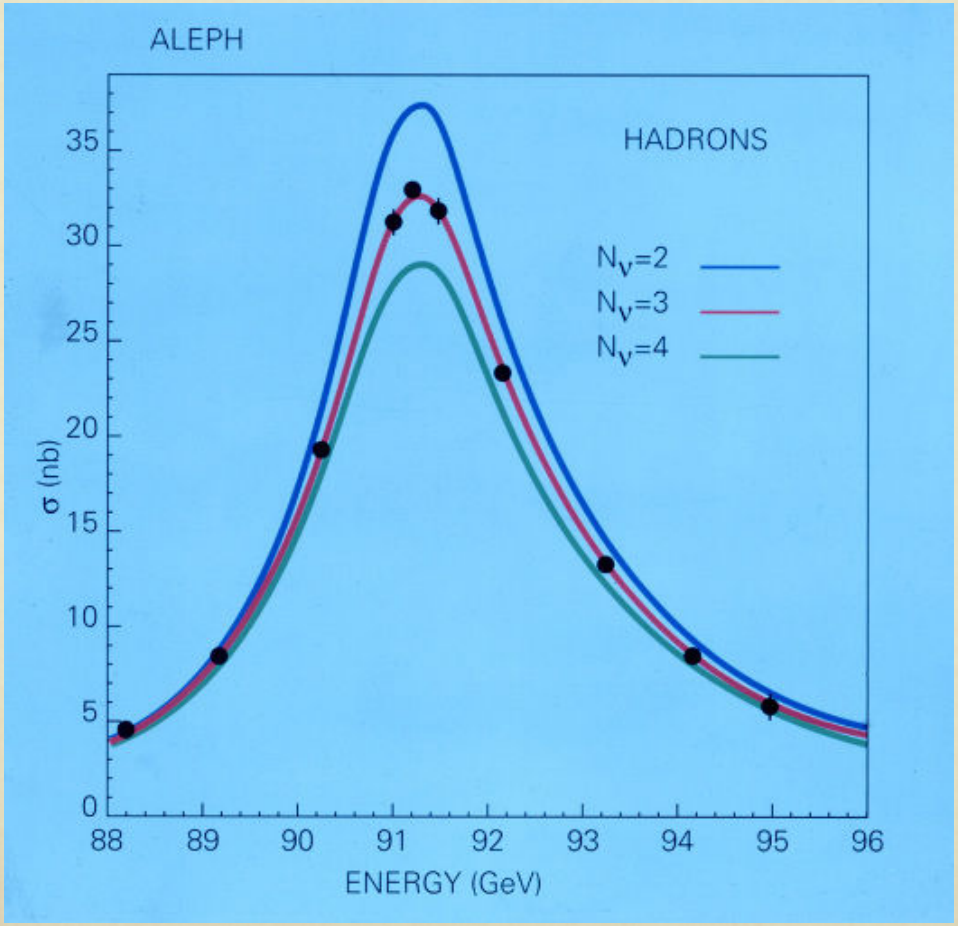
d s b

Quarks

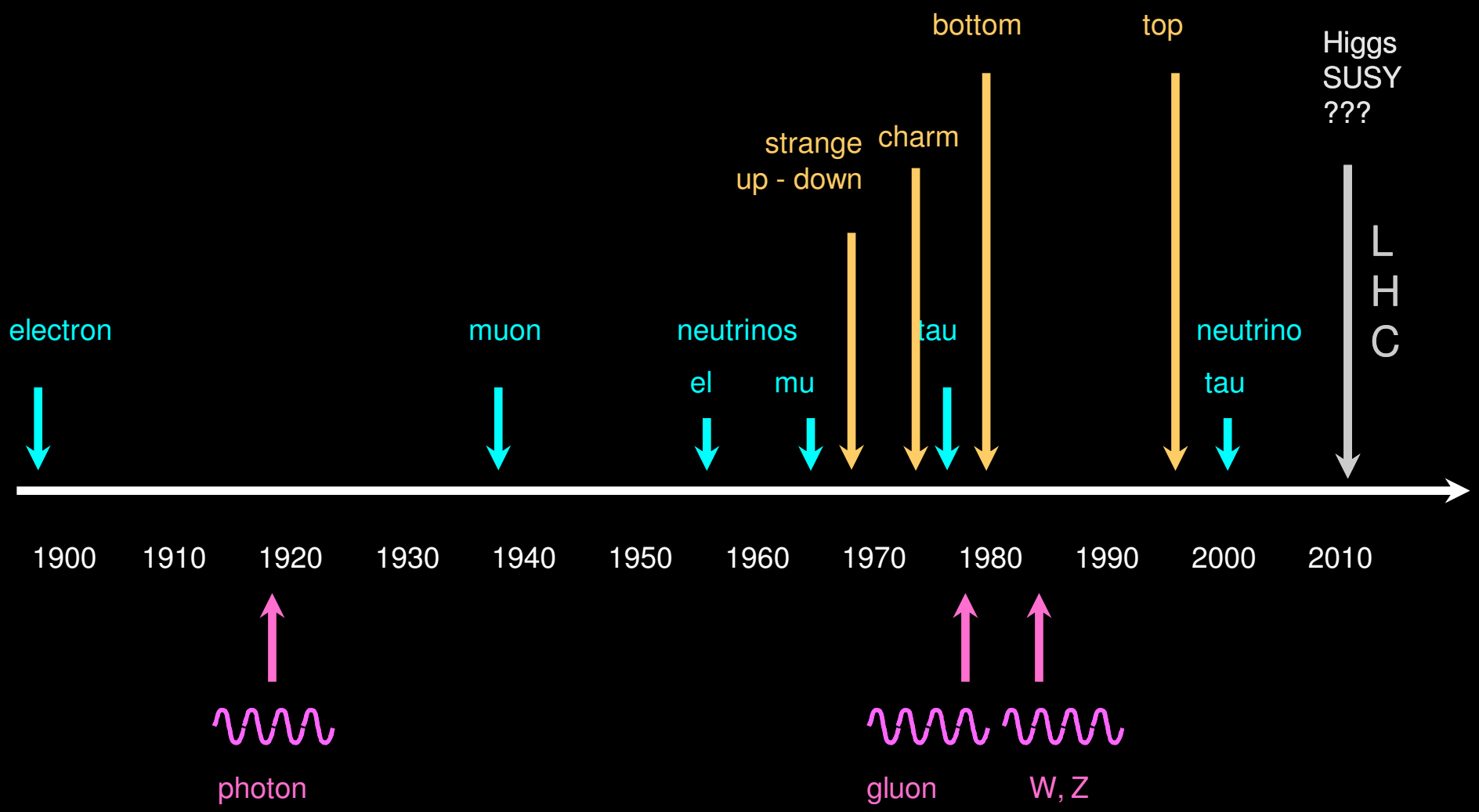
PARTICLE SPECTRUM

EXACTLY 3 families of particles

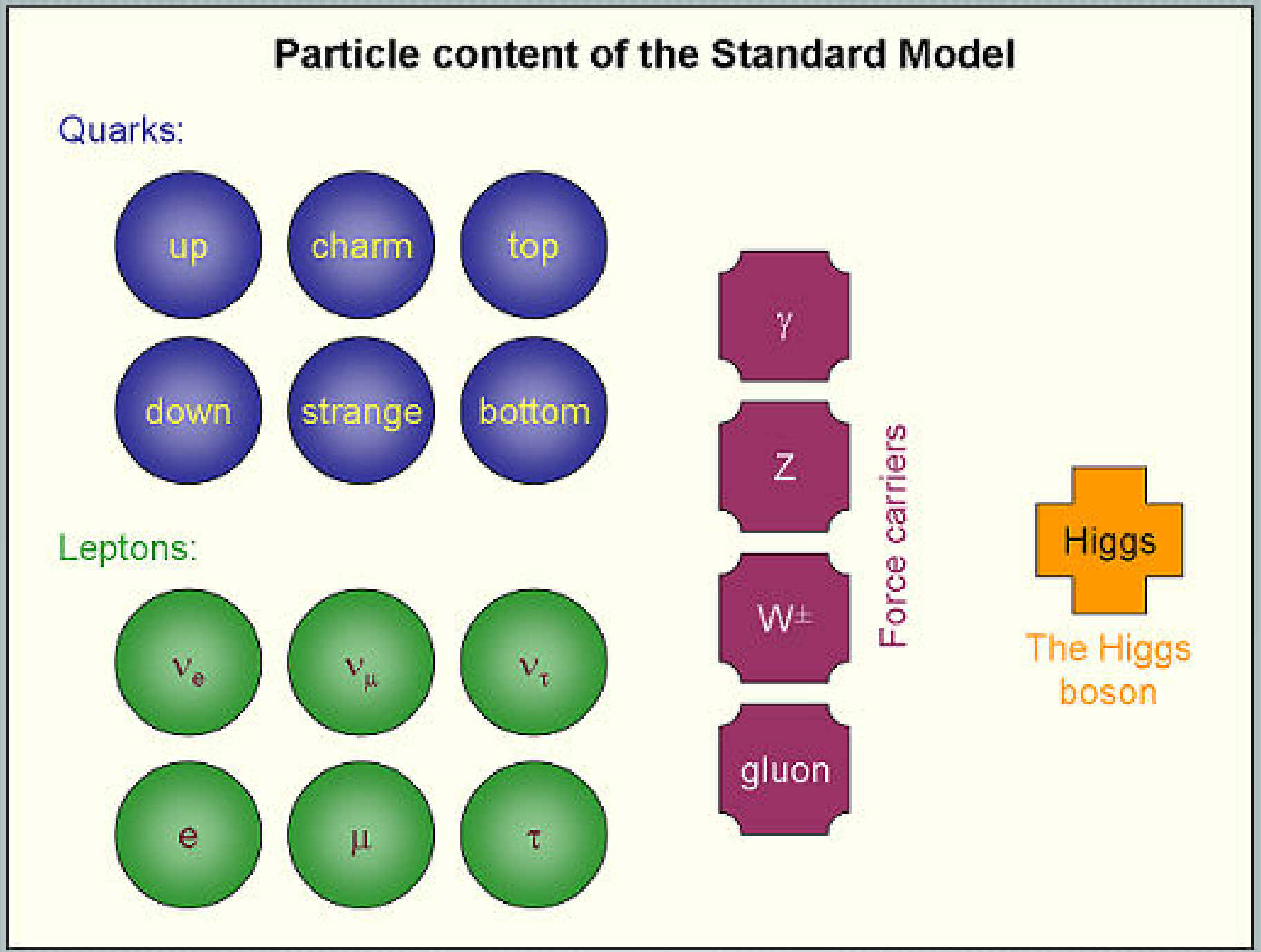
LEP measures the decay width of the Z^o particle

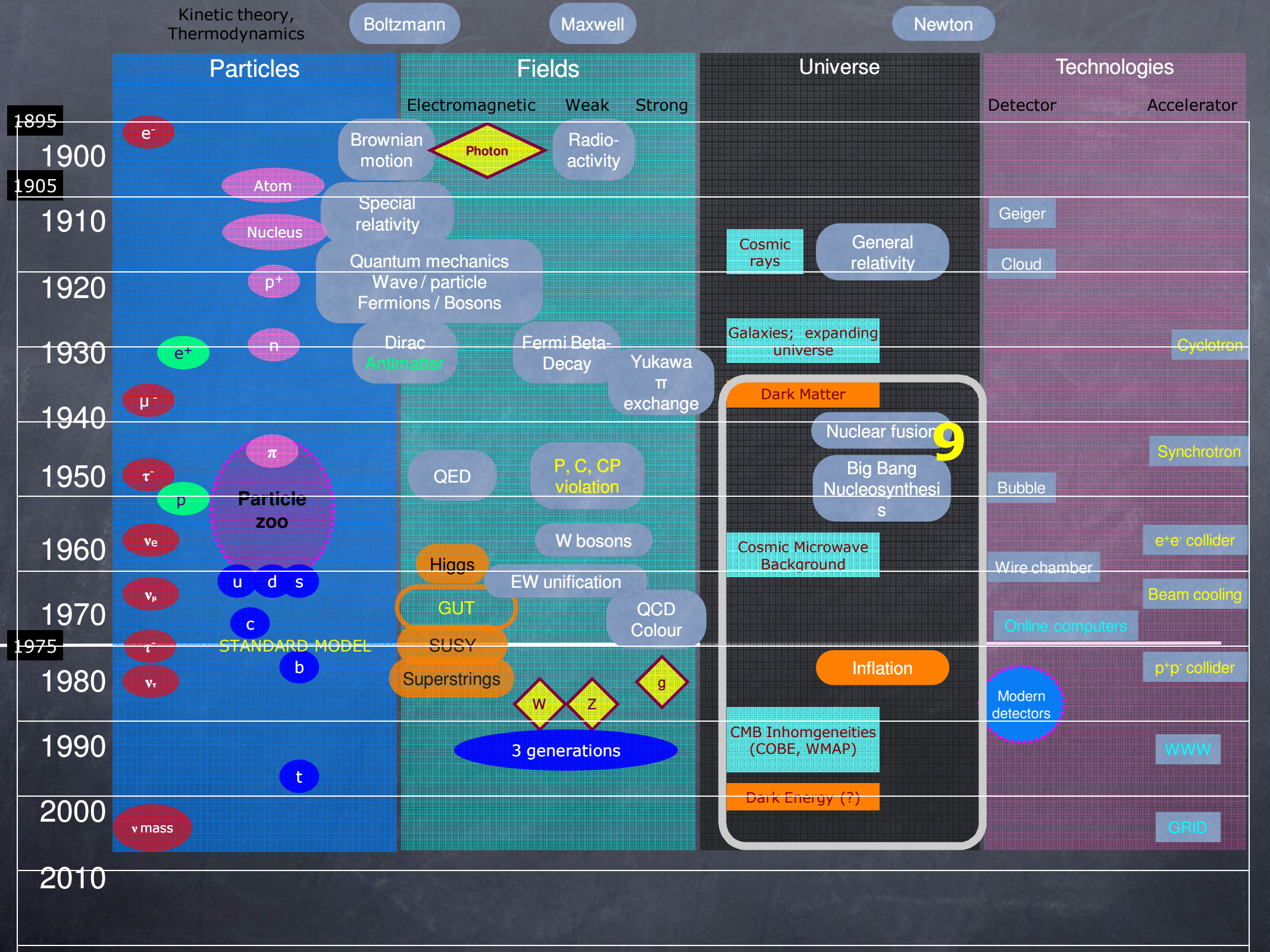


Experiments at accelerators have discovered the set of fundamental particles



THE STANDARD MODEL (2009)

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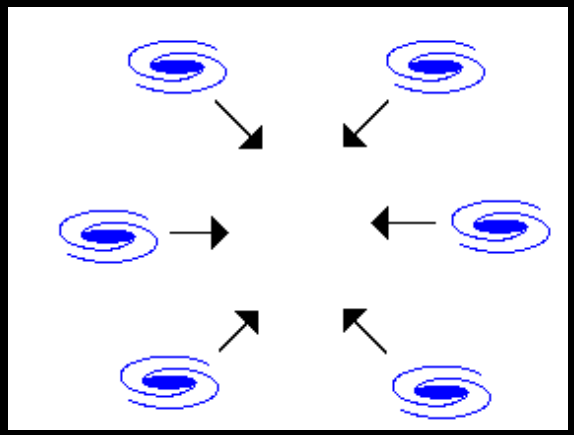
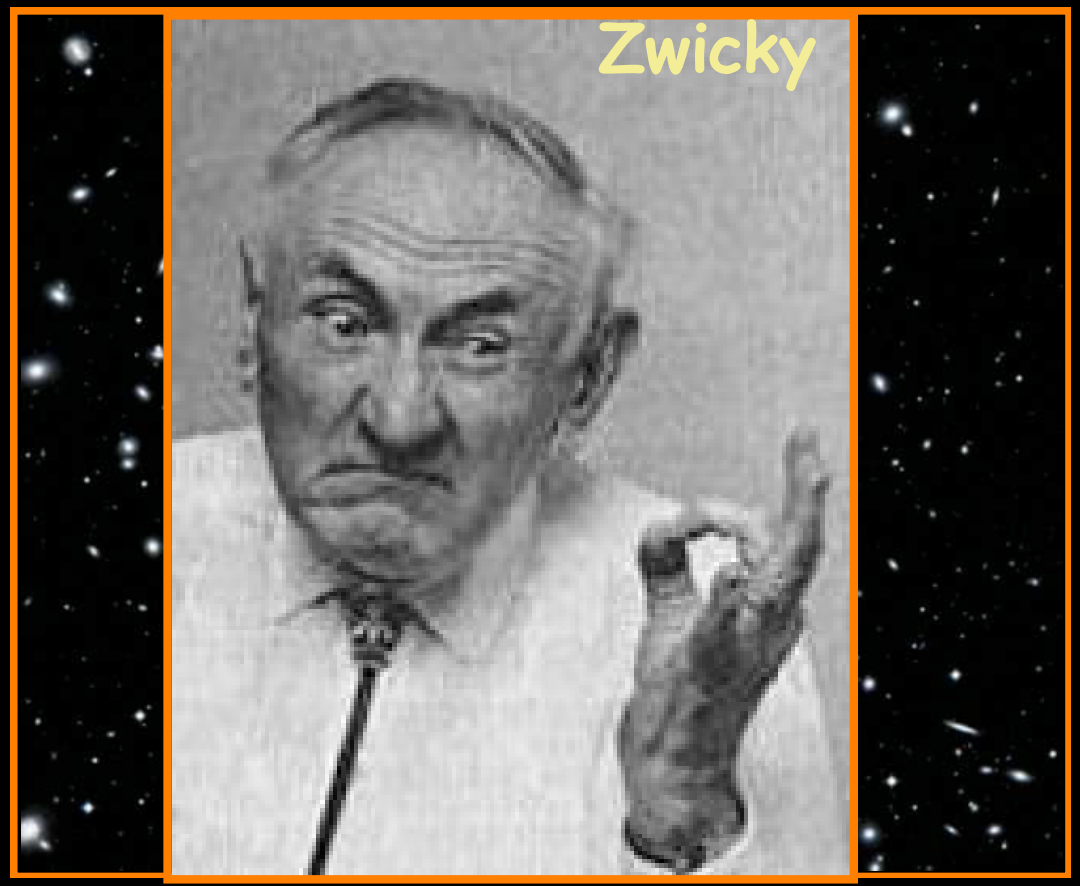
1970
1975
1980
1990
2000
2010
e-
Brownian motion
Photon
Radio-activity
Atom
Special relativity
Nucleus
Quantum mechanics
Wave / particle
Fermions / Bosons
p+
Cosmic rays
General relativity
Geiger
Cloud
e+
n
Dirac
Antimatter
Fermi Beta-Decay
Yukawa
π
exchange
Galaxies; expanding universe
Cyclotron
μ-
Dark Matter
Nuclear fusion
9
π
τ-
QED
P, C, CP violation
Big Bang Nucleosynthesis
Synchrotron
Bubble
p
Particle zoo
νe
W bosons
Cosmic Microwave Background
e+e- collider
Higgs
u
d
s
EW unification
Wire chamber
νμ
GUT
QCD Colour
Beam cooling
c
Online computers
τ-
STANDARD MODEL
SUSY
Inflation
p+p- collider
b
Superstrings
g
W
Z
Modern detectors
νt
3 generations
CMB Inhomgeneities (COBE, WMAP)
WWW
t
Dark Energy (?)
ν mass
GRID

Universe

Evidence for Dark Matter (1933)



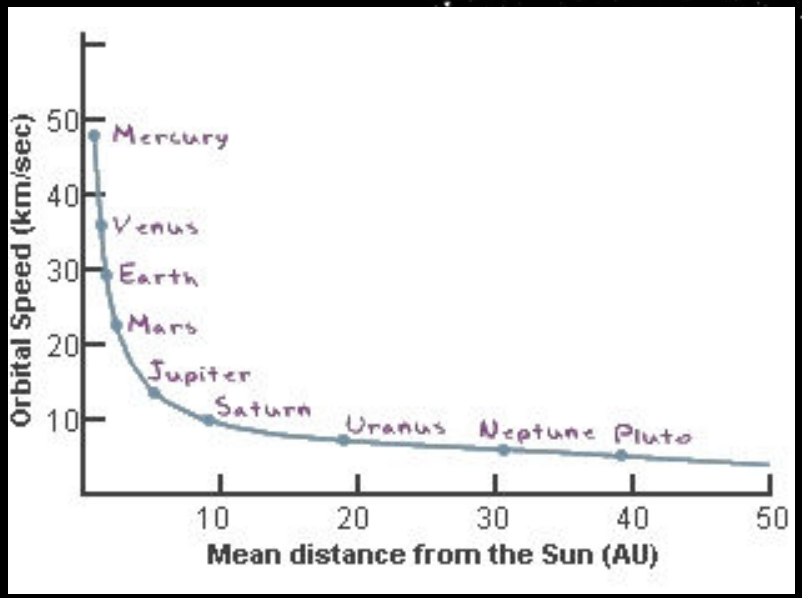


Mass of luminous matter
=
10%
Gravitational mass

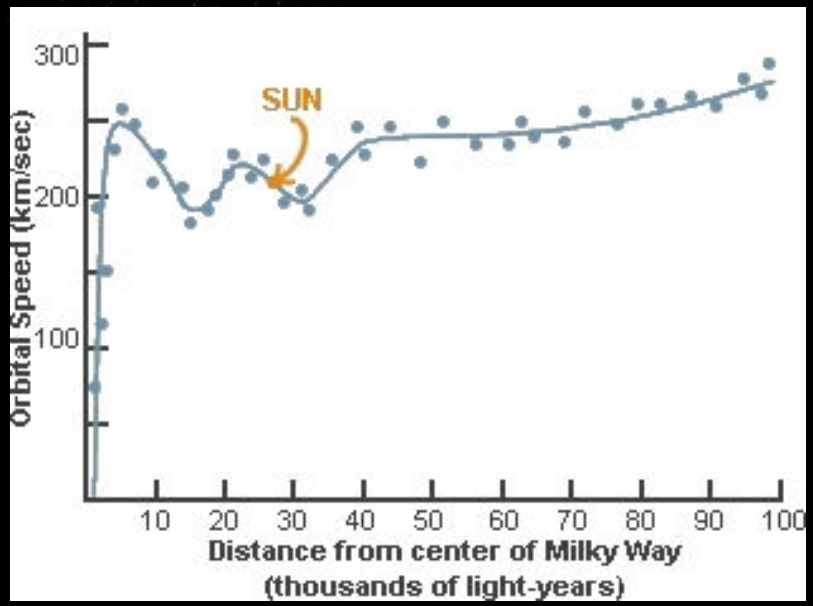
Universe

MORE EVIDENCE FOR “DARK MATTER”

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



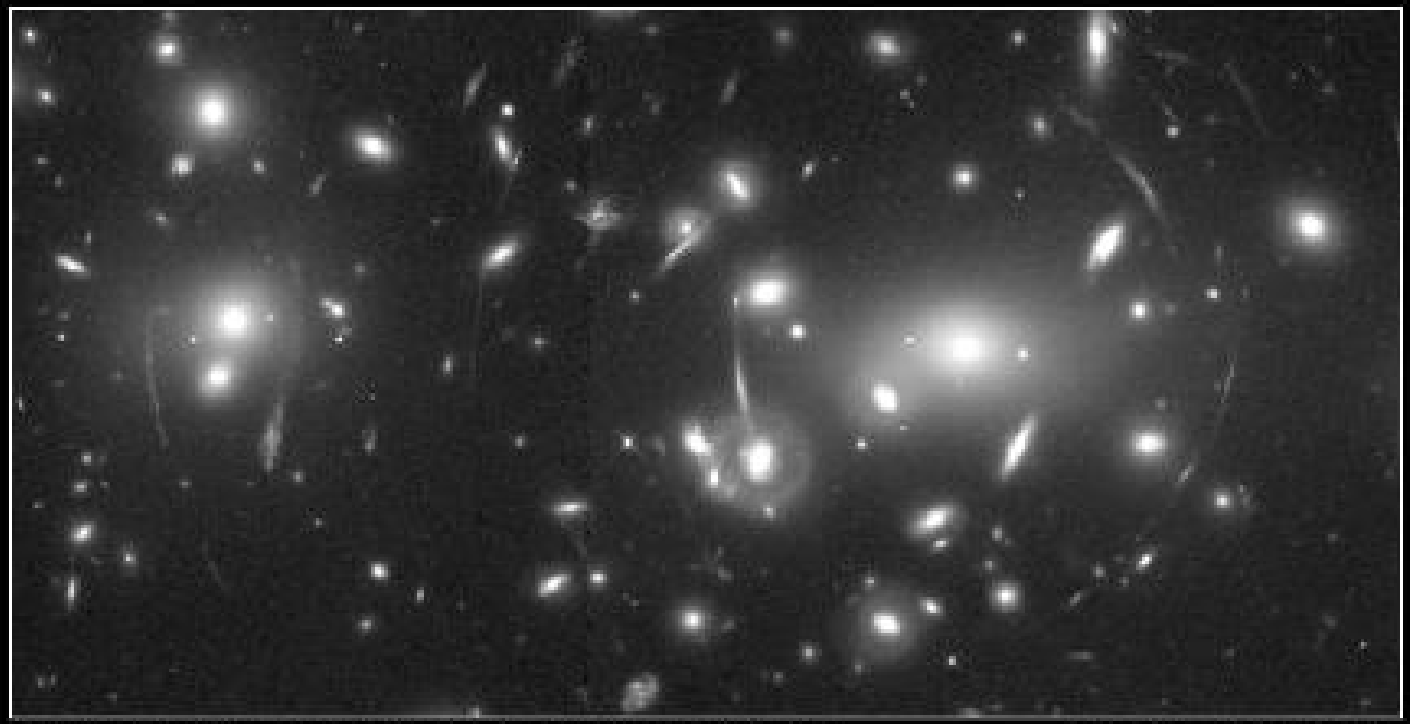
One central mass (Sun)



Milky Way

Universe

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

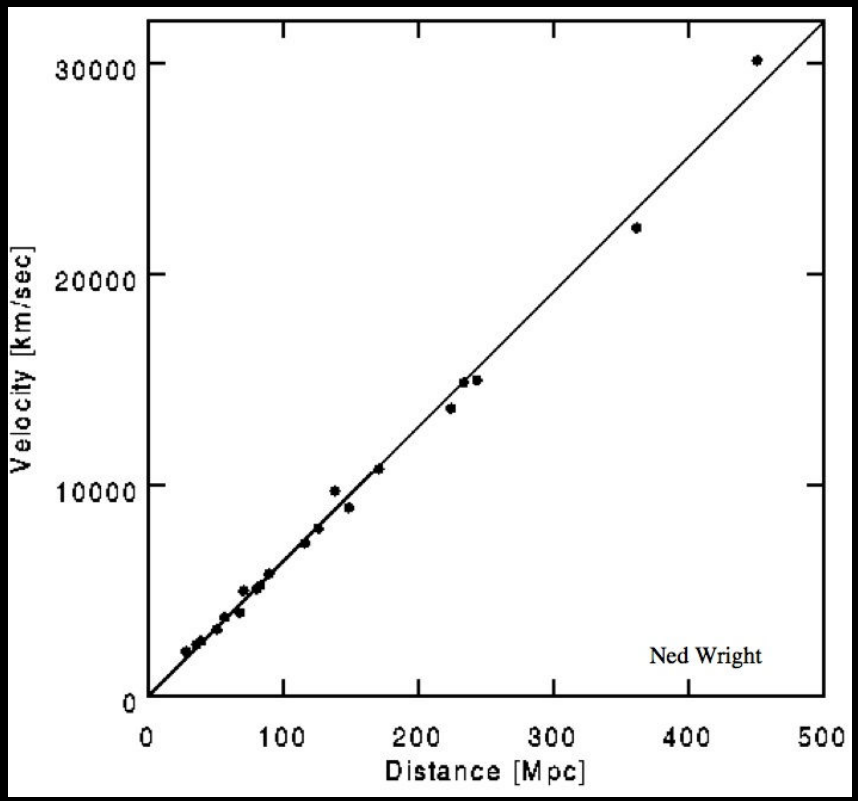
GRAVITATIONAL LENSING

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

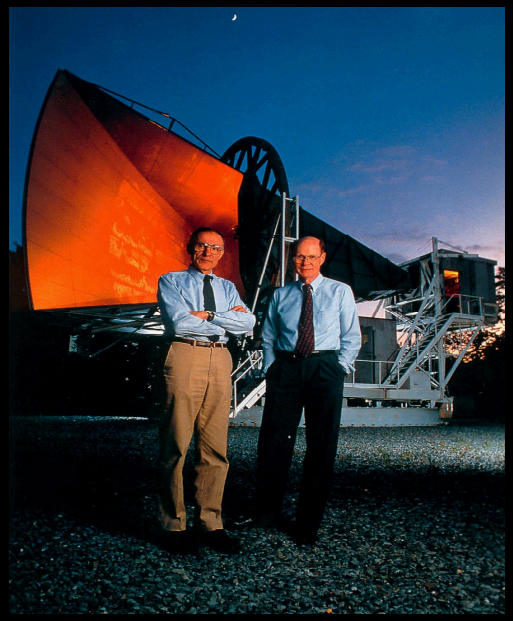


Today: $H = 70 \pm 3$ km s^{-1} Mpc^{-1}

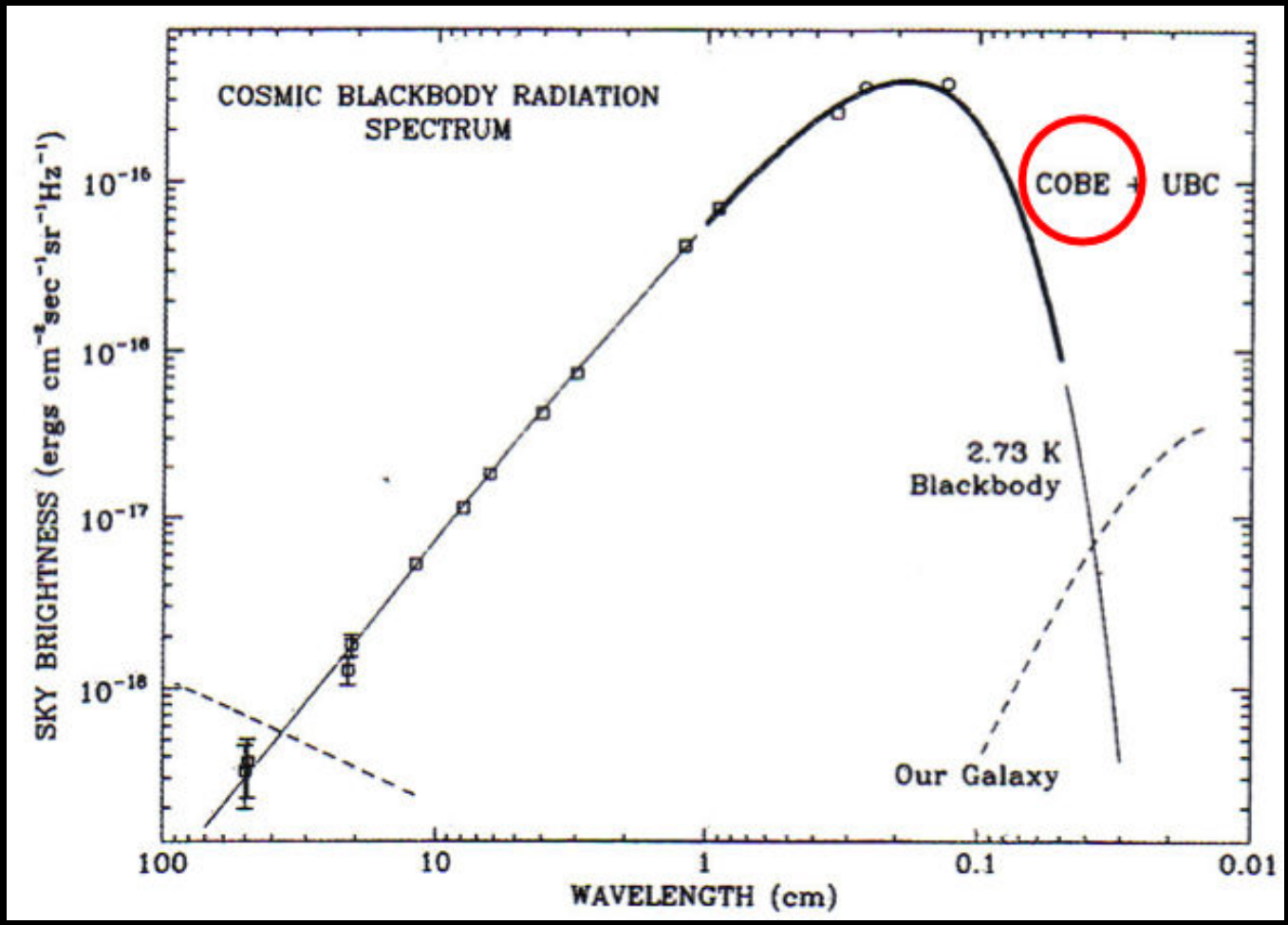
Hubble age (H^{-1}) ~ 13.4 billion years

Universe

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



Penzias and Wilson



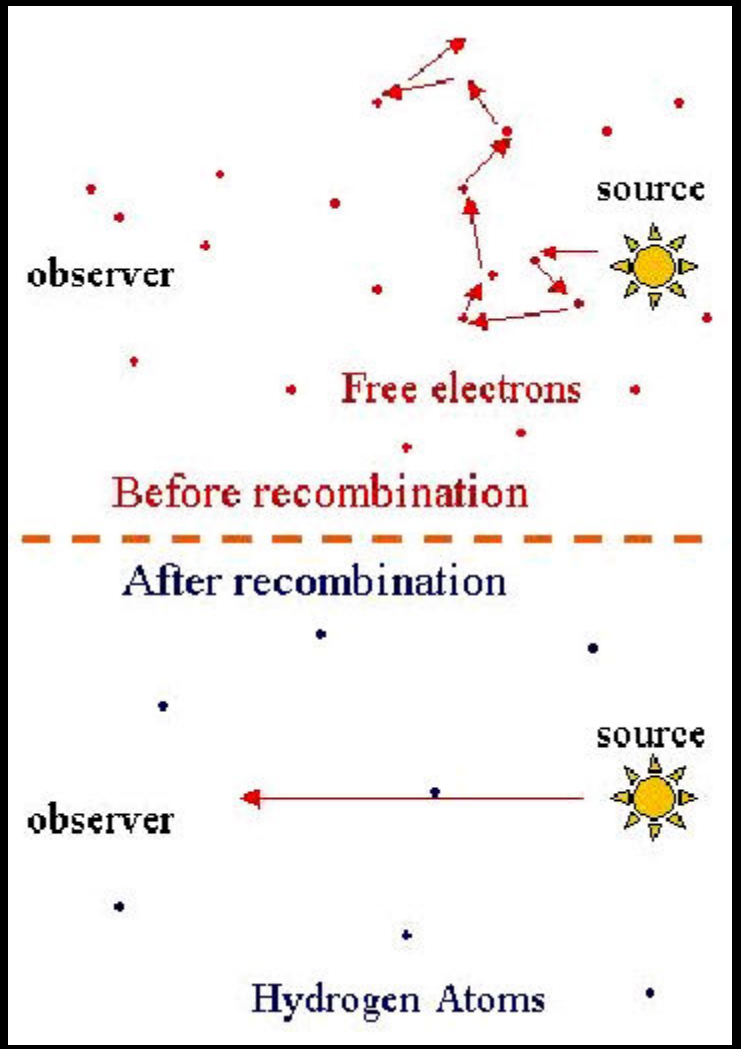
The Universe is a perfect ‘black body’ with T = 2.73 K

Universe

How was the cosmic background radiation produced?

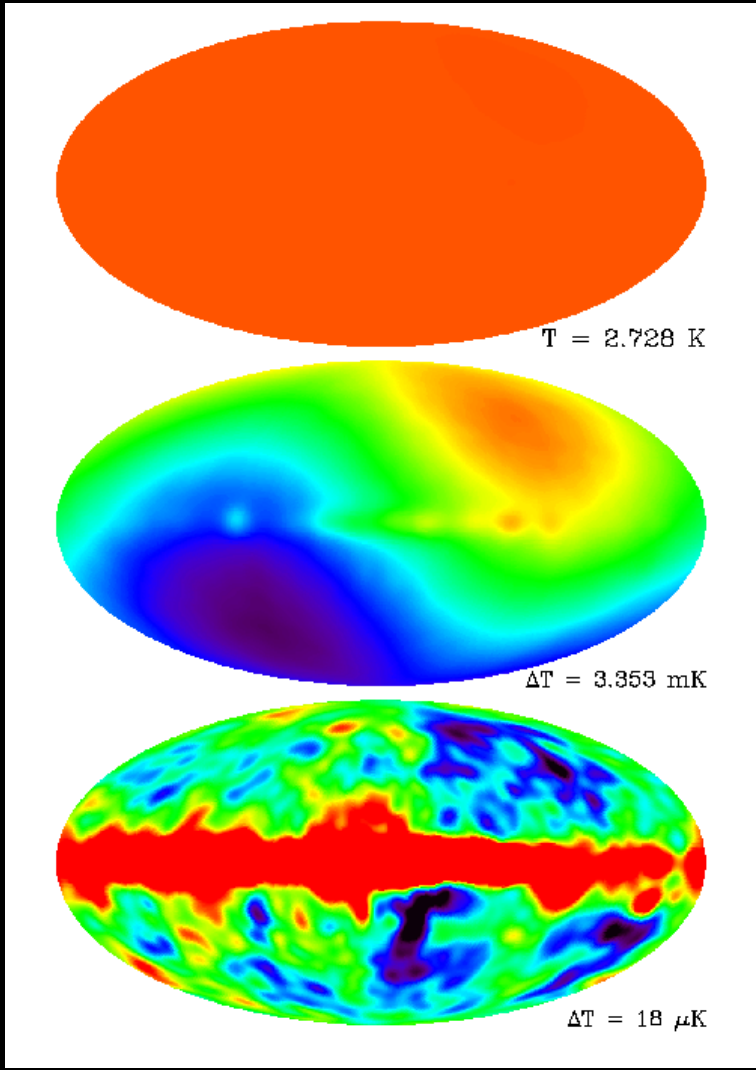
By the recombination of free electrons and nuclei

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



Universe

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



T= 2.7 K

Δελτα–T= 3.3 mK

(after subtraction of constant emission)

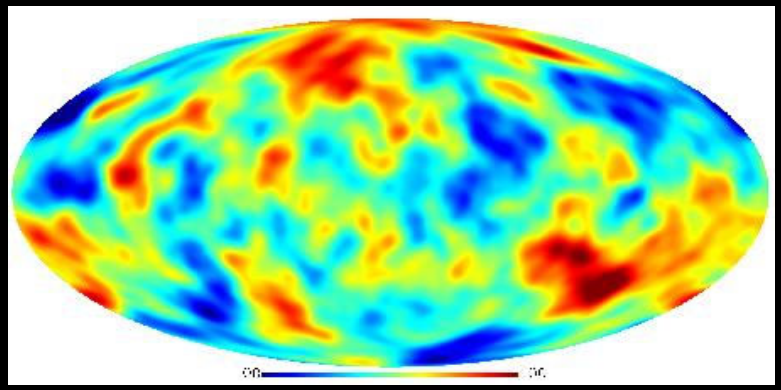
Δελτα–T= 18 μK

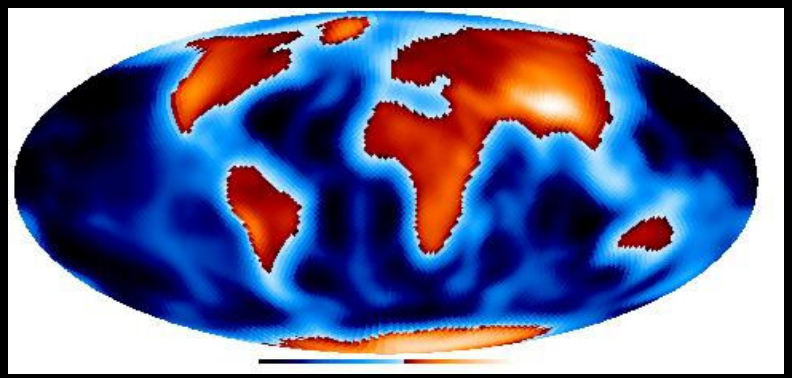
(after correcting for motion of Earth)

Universe

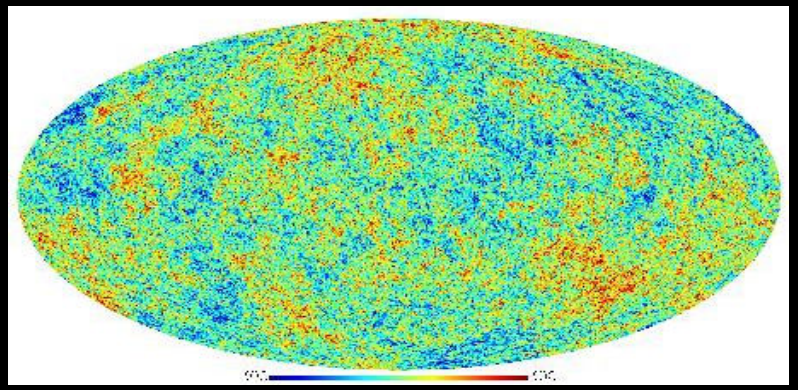
The most precise observation today (WMAP)

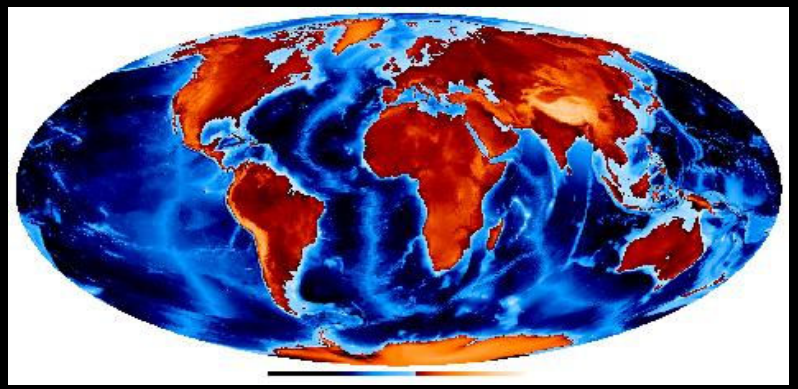
COBE
(7 degree resolution)





WMAP
(0.25 degree resolution)

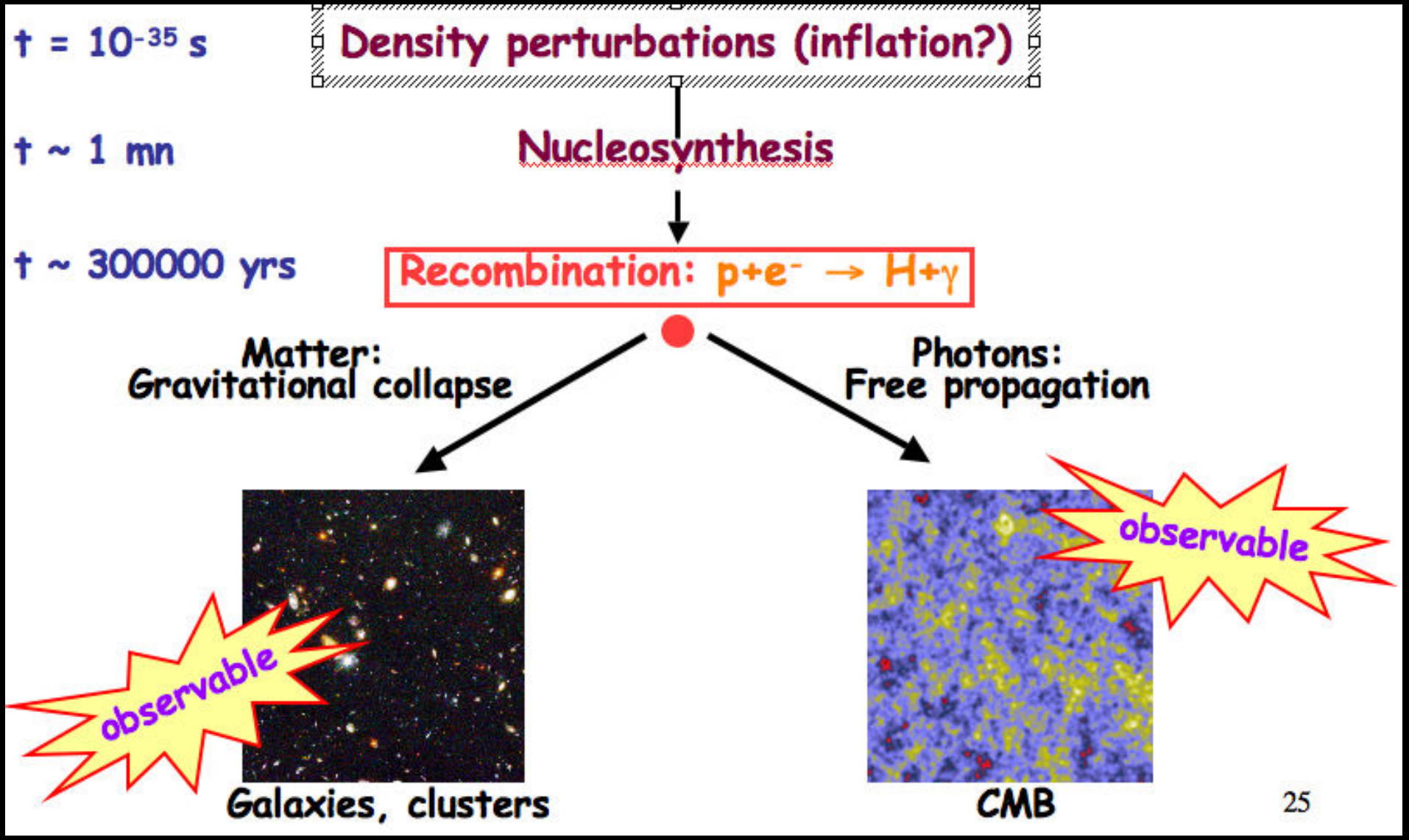




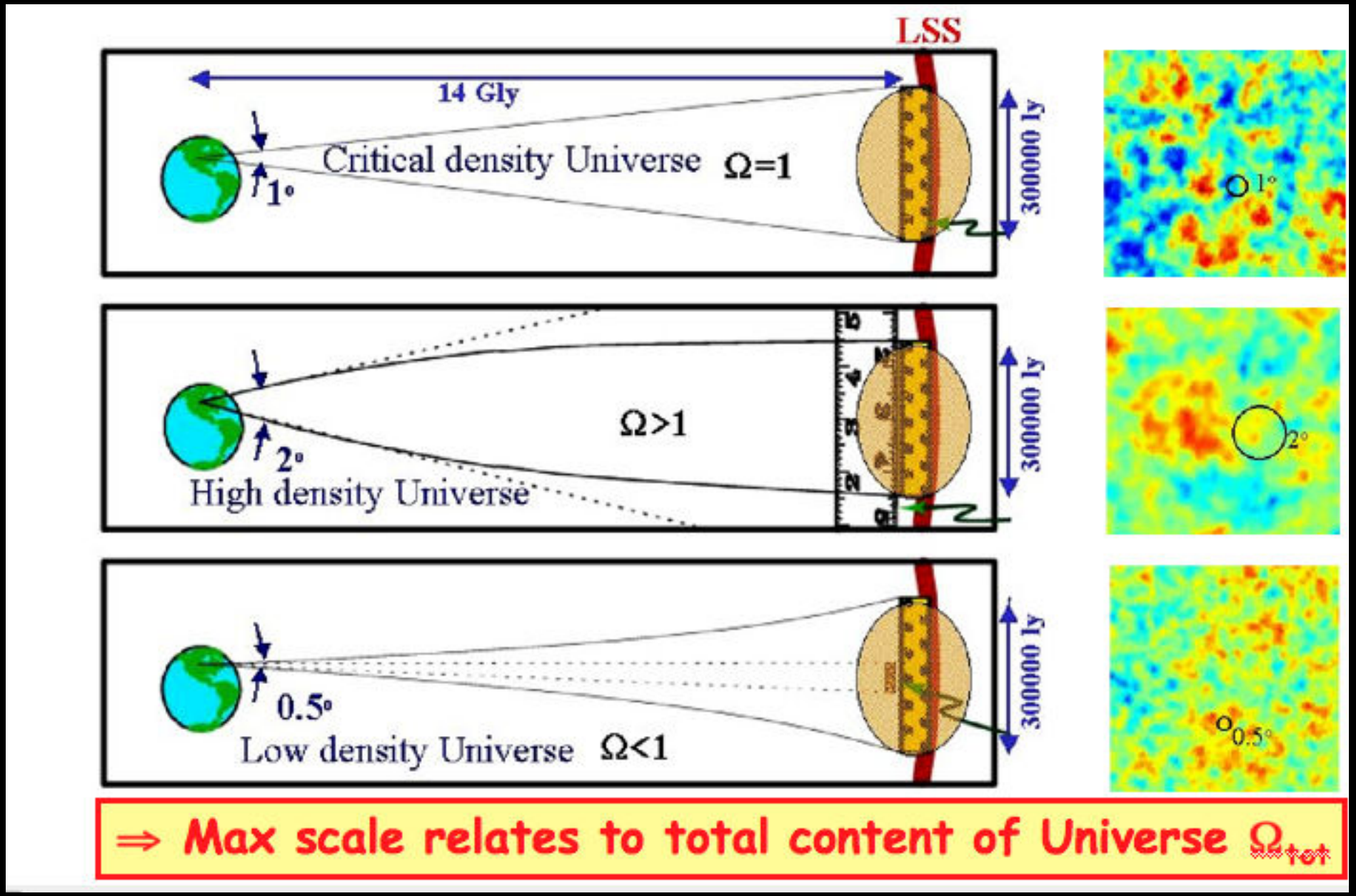
Universe

What WMAP measured

Back to the Beginning

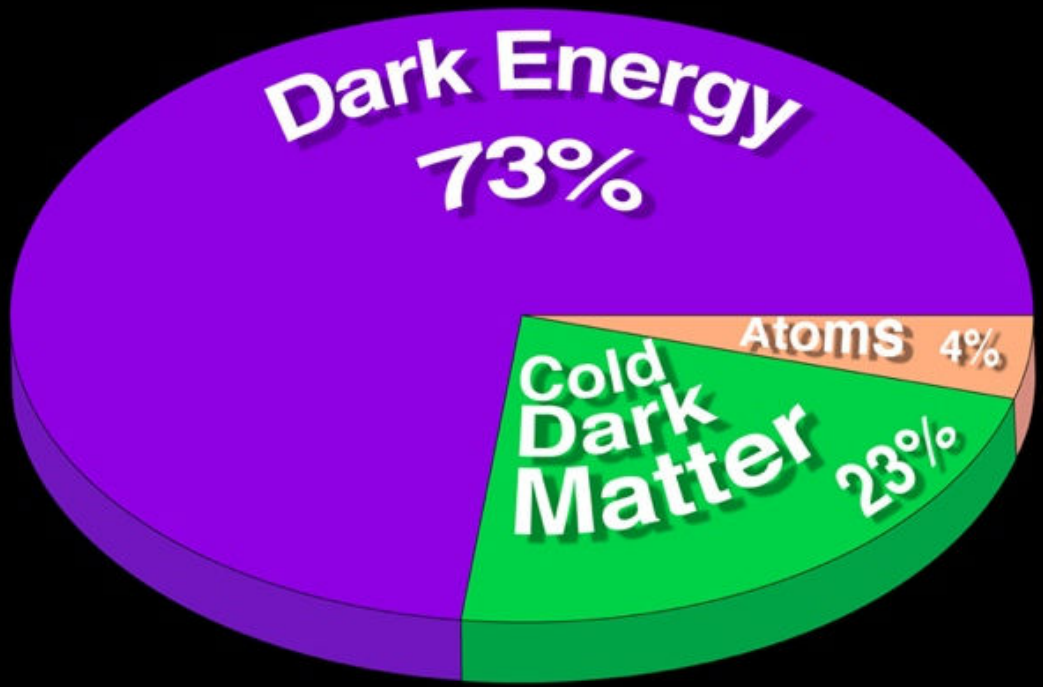


Analysis of inhomogeneities reveals the composition of the Universe

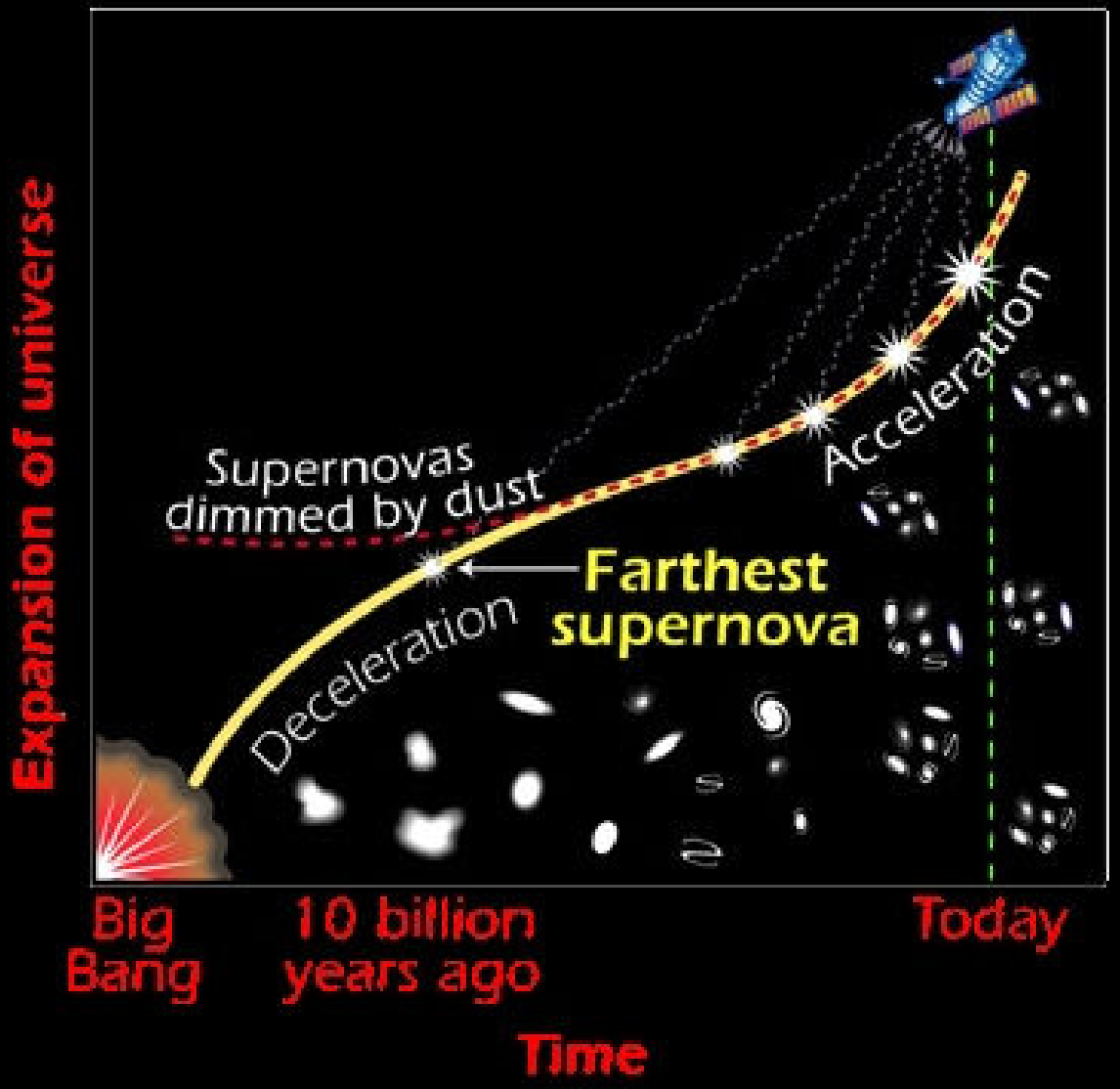


Universe

The strange composition of the Universe



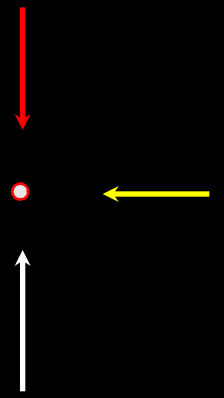
Evidence for Dark Energy



Universe

The beginning

Energy ~ 10^{72} J



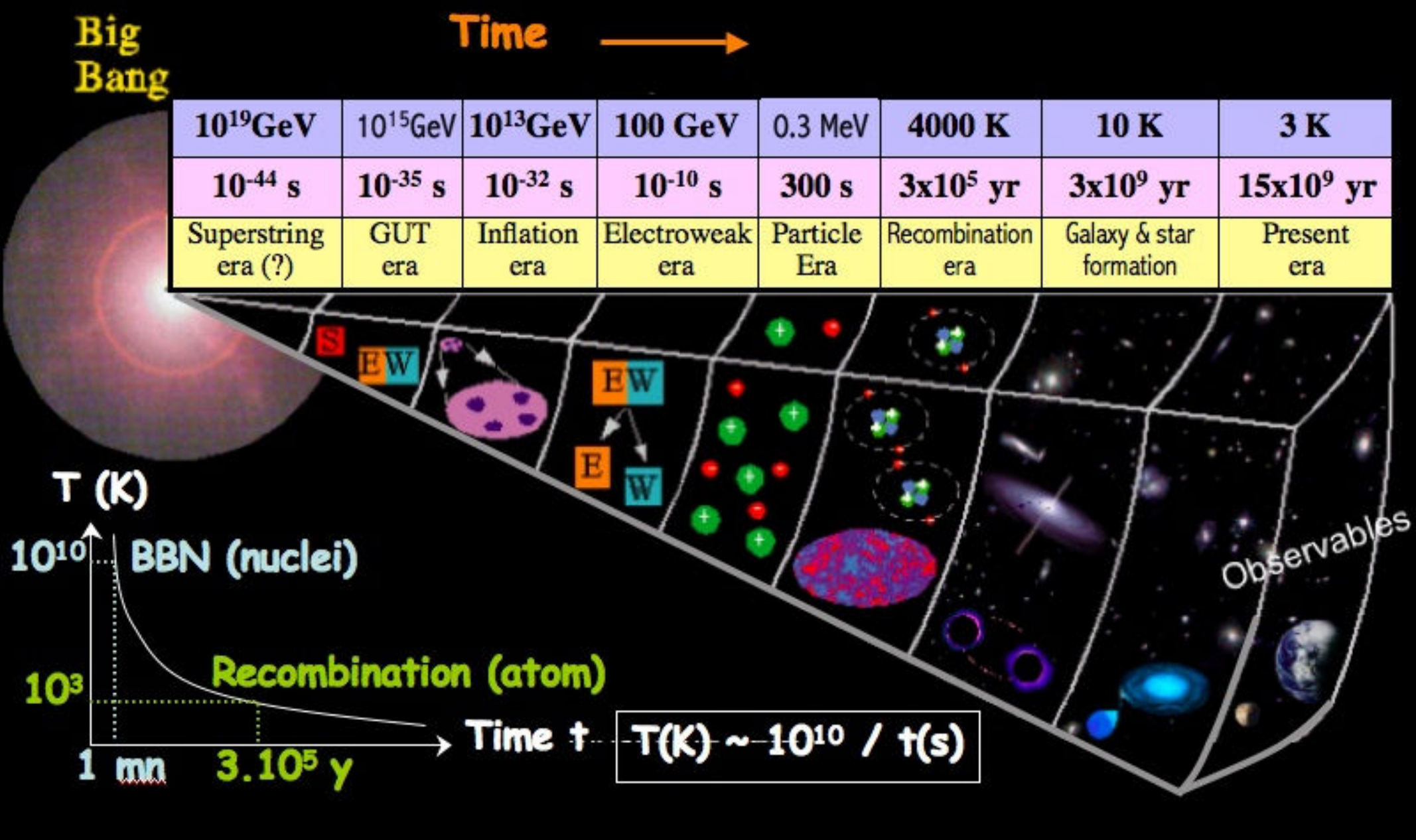
What are the Laws of Nature here?

Size of the visible Universe x 100

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

Universe

The reconstruction of the History of the Universe



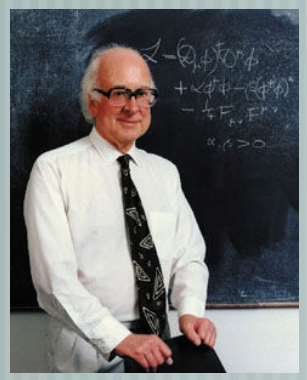
QUESTIONS FOR THE 21st CENTURY

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

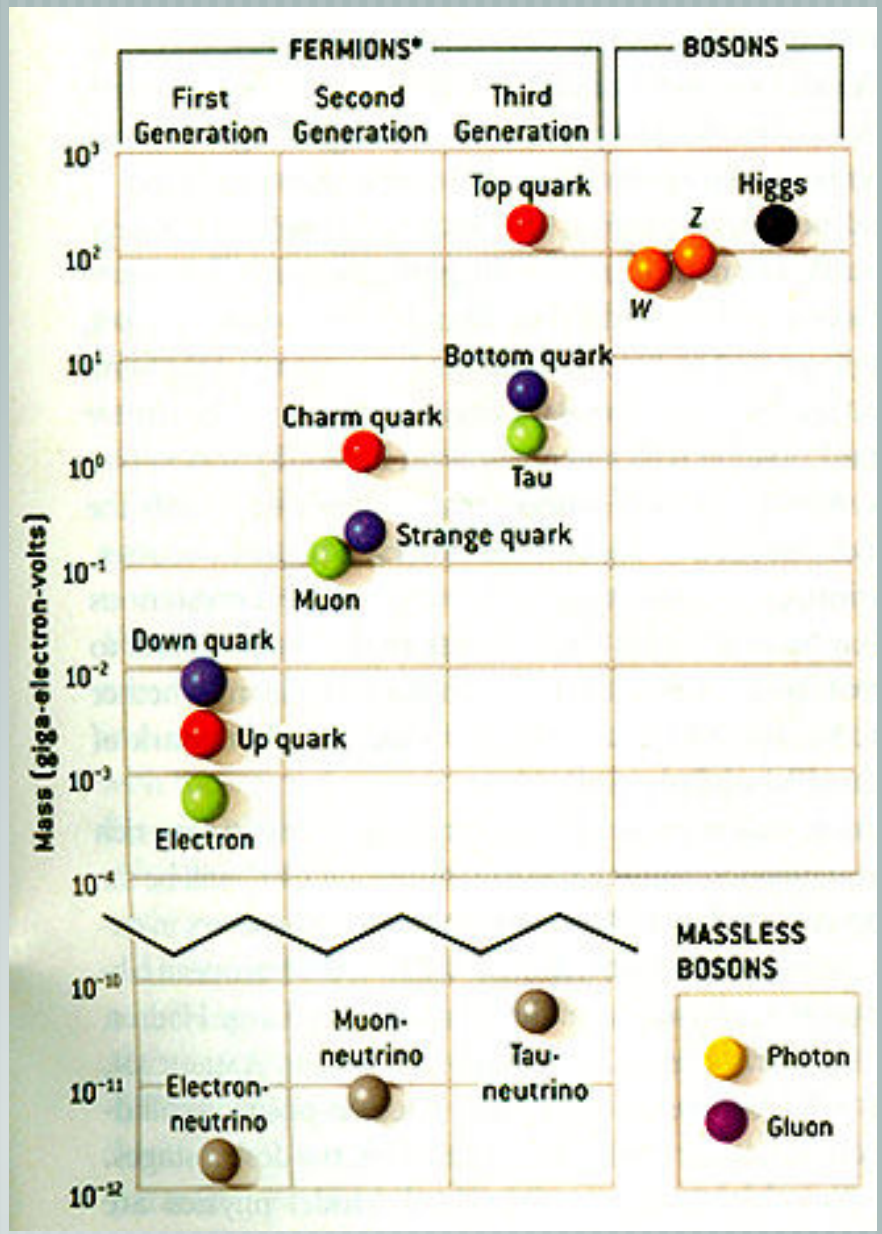
Problem

The Standard Model without the Higgs field does not make any sense

(either particles have no masses; or if they are given masses, the mathematics of the theory collapses)



Peter Higgs



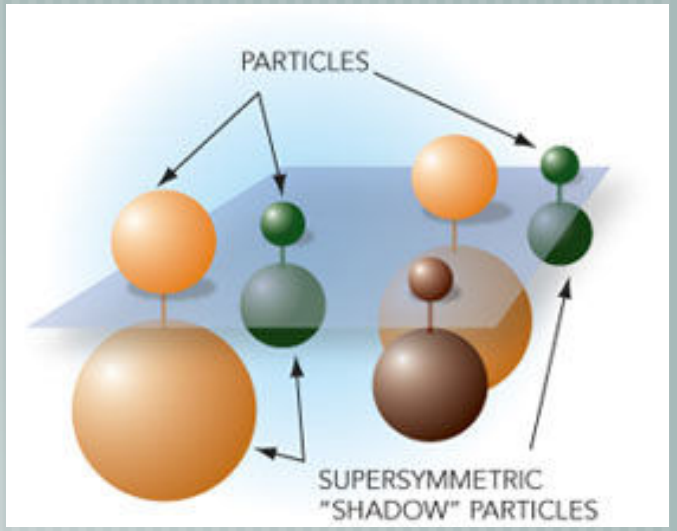
QUESTIONS FOR THE 21st CENTURY

2) Are particles and fields connected - Supersymmetry ?

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

Is there a deeper SUPERSYMMETRY between matter and fields? If yes:

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

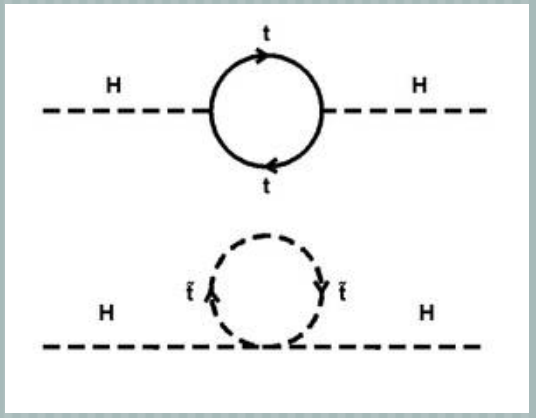


Spin 1/2	Integer spin
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)

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

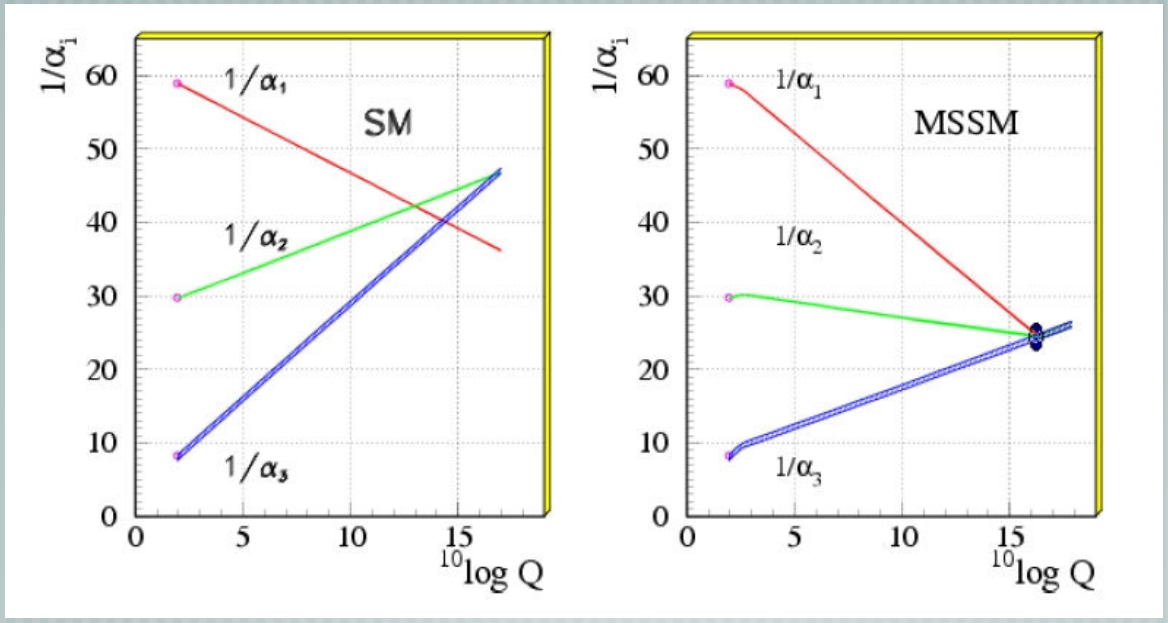
Good reasons for Supersymmetry

1) A fundamental symmetry of space and time



2) "Protection" of SM particle masses (< 10^3 GeV)
from vacuum fluctuations up to Planck Scale (10^{19} GeV)

3) Suggests unification of three forces at a single unification point (~10^{17} GeV)

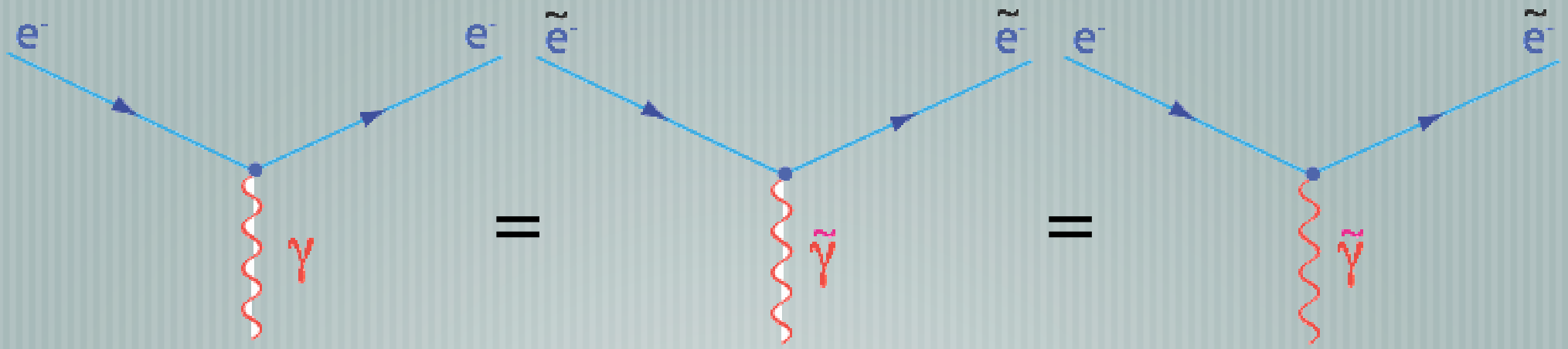


4) Possible explanation of cosmological matter-antimatter asymmetry

5) **Dark matter** ?

If Nature was supersymmetric, then:

Particles and their Super-Partners can be interchanged



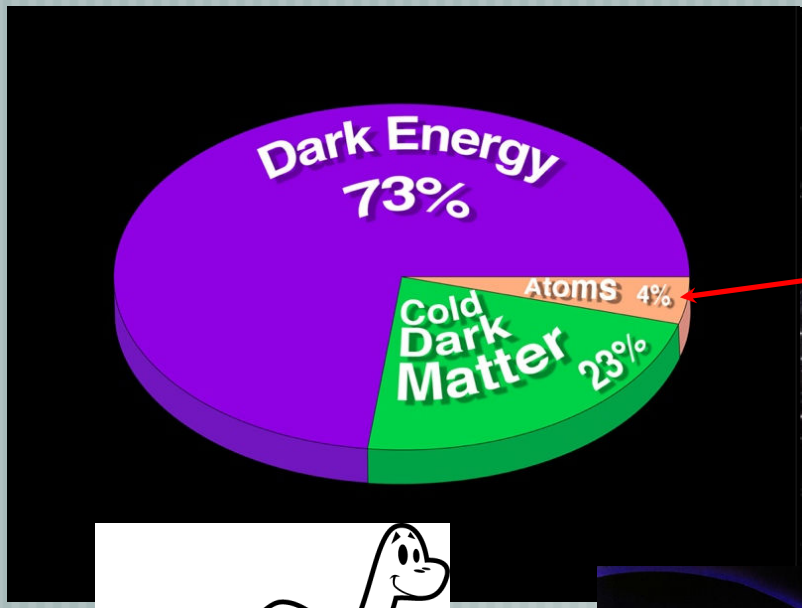
e = electron

$\tilde{e}$ = selectron

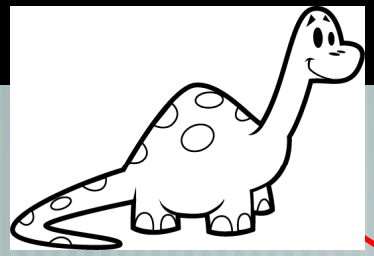
© = photon

$\tilde{©}$ = photino

QUESTIONS FOR THE 21st CENTURY



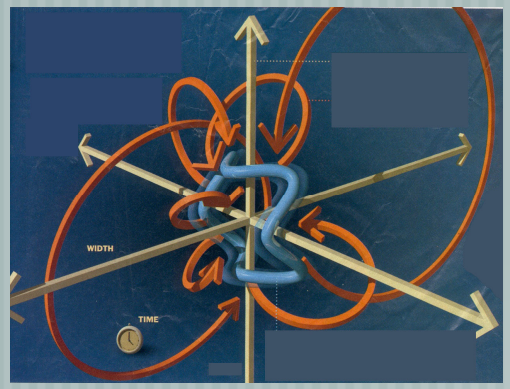
Our type of matter



Supersymmetric particles could be responsible for DARK MATTER

QUESTIONS FOR THE 21st CENTURY

What are particles?

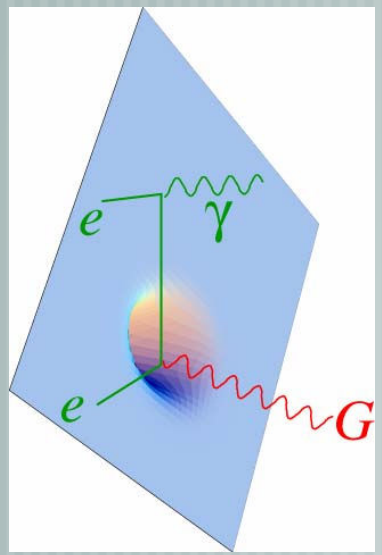


Superstrings in 9+1 dimensions?

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

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 !

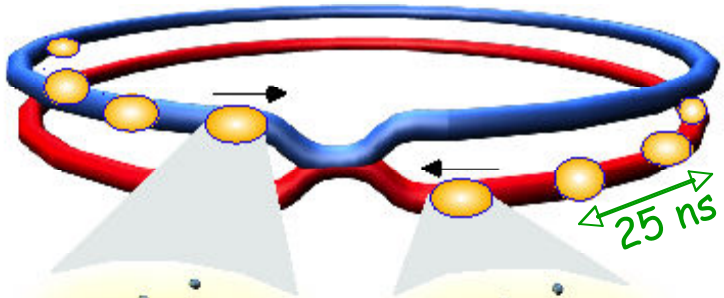
This is the physics of the 21st century !

QUESTIONS FOR THE 21st CENTURY

First LHC collisions in 2009

new answers !

Collisions at LHC



Proton-Proton

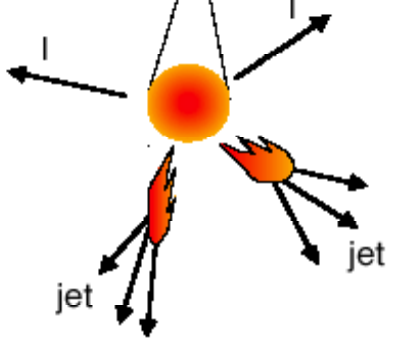
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

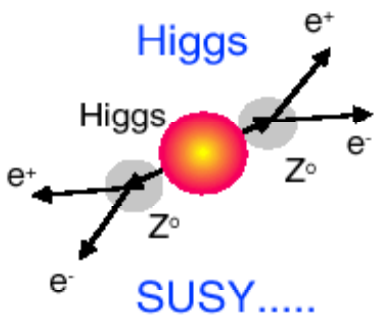
Bunch

Proton

Parton
(quark, gluon)

Particle





Event rate in ATLAS :

N = L x σ (pp) ≈ 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