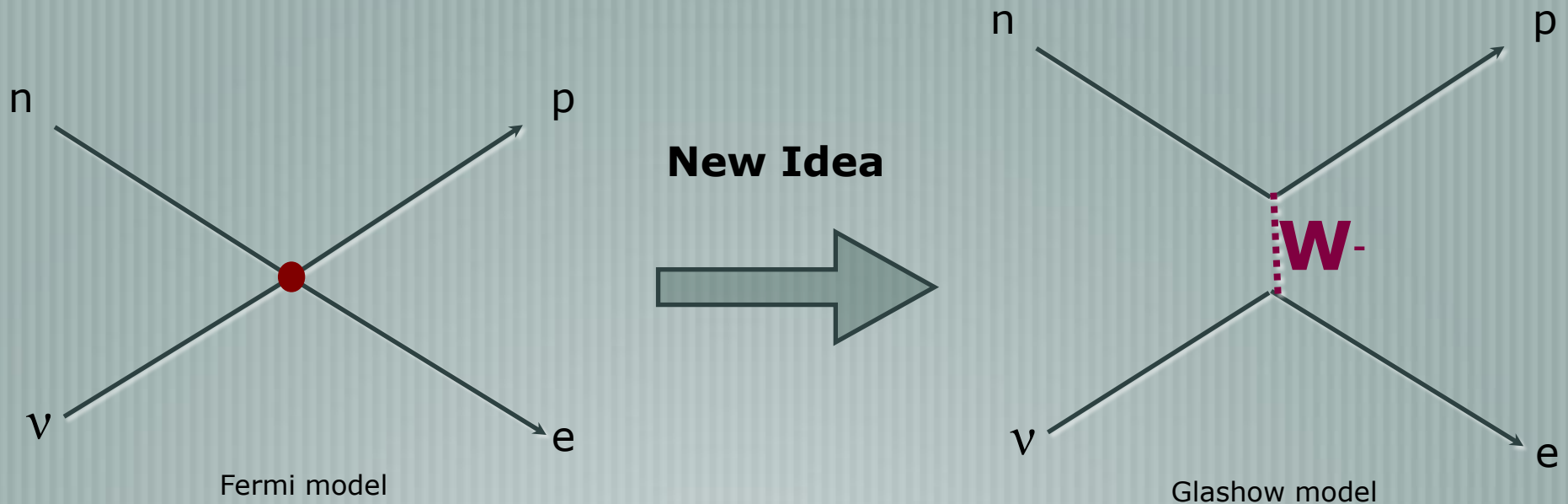


Fields

1958 Glashow

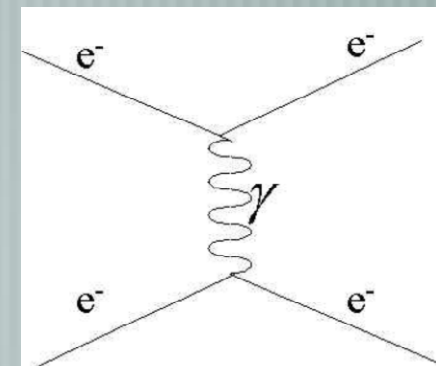
Back to the weak interaction: there was a big (theoretical) problem

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



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

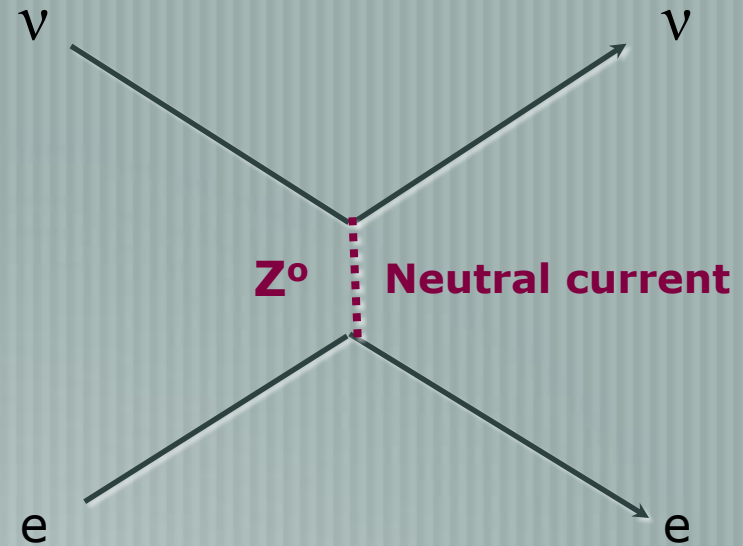
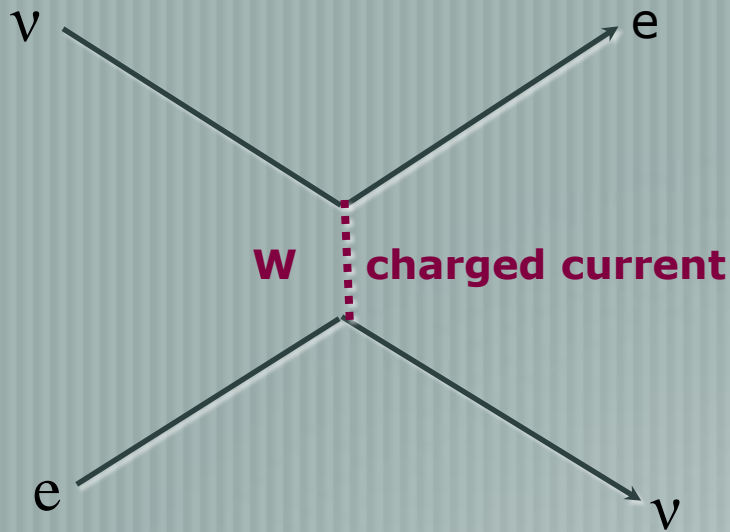
**Large mass (80 GeV) explains
short range ($2 \cdot 10^{-18}$ m) and small cross-sections**



Fields

Electroweak Interaction

1968

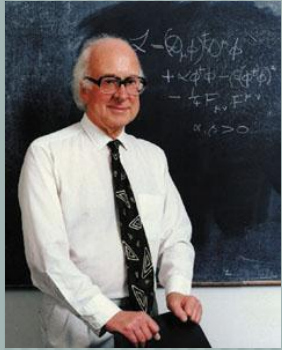


Glashow, Salam, Weinberg (1968) - Electroweak Force

- 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^0) 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’



A cocktail party ...

The Higgs field ...



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

... a new particle is created ...



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

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

♥David Miller

Fields

The Higgs boson



A rumour originates ...

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

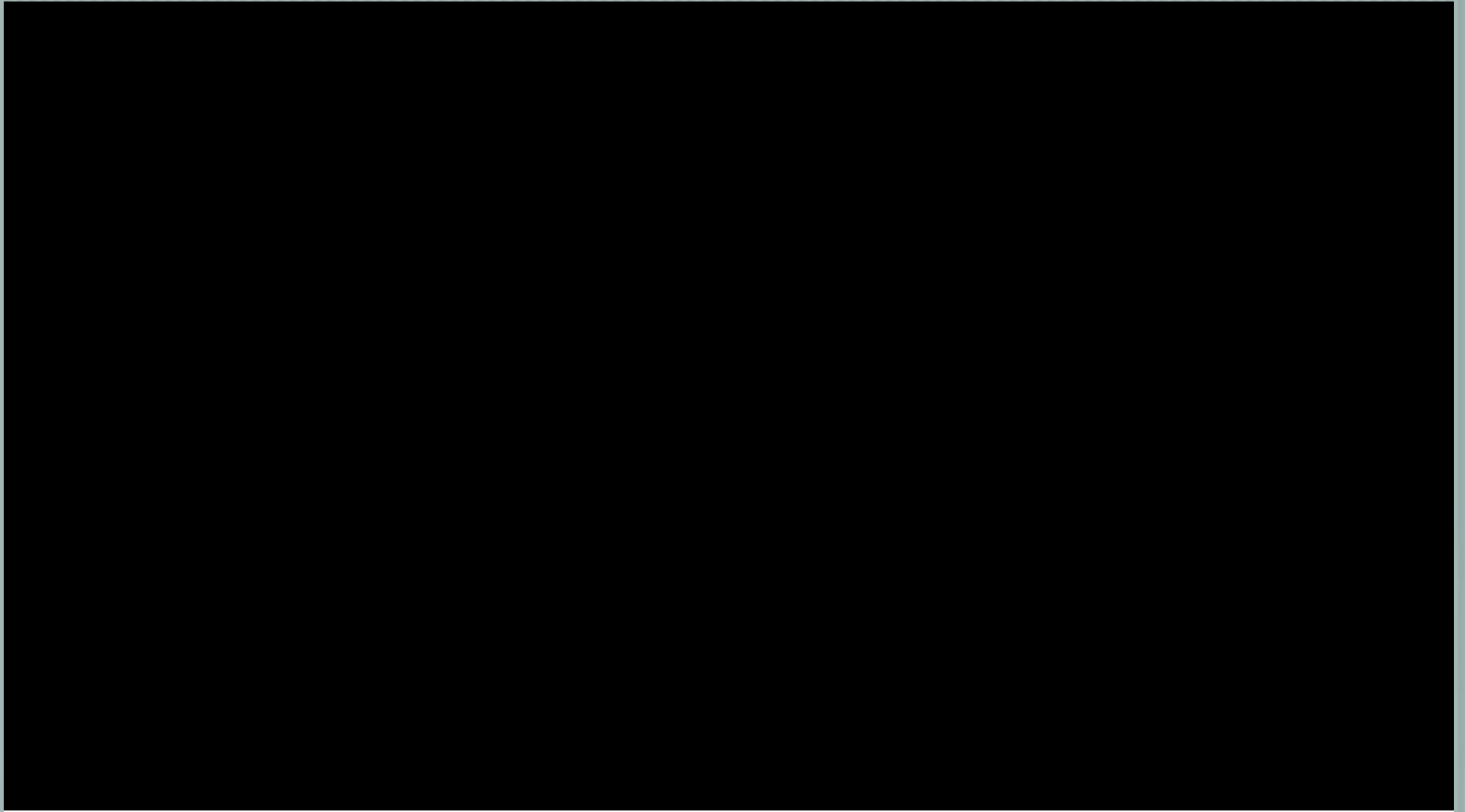


.. many guest clump together
to discuss the rumour..

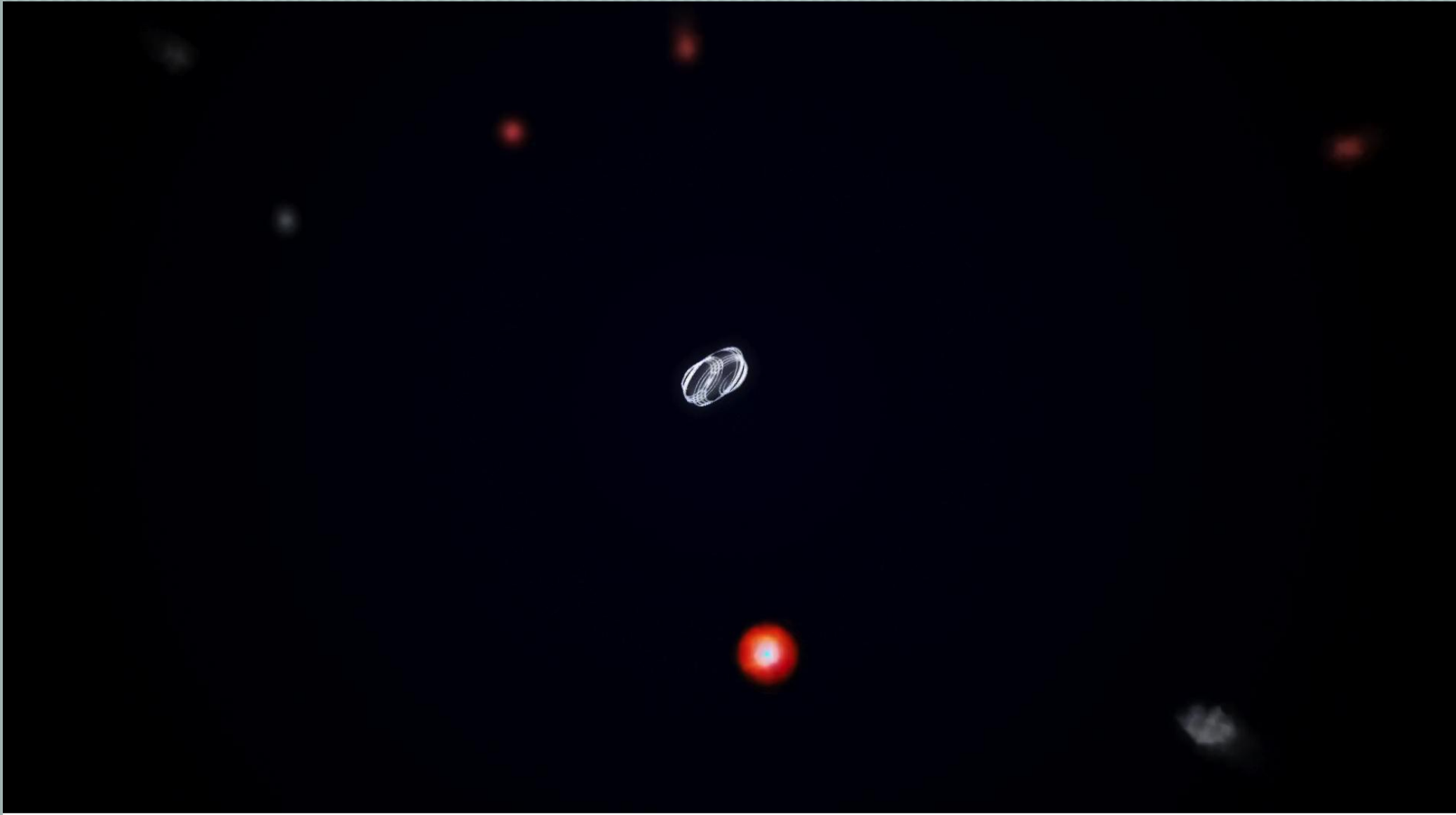
*... which produces a
"real" field particle ...*

A universe without the Higgs field

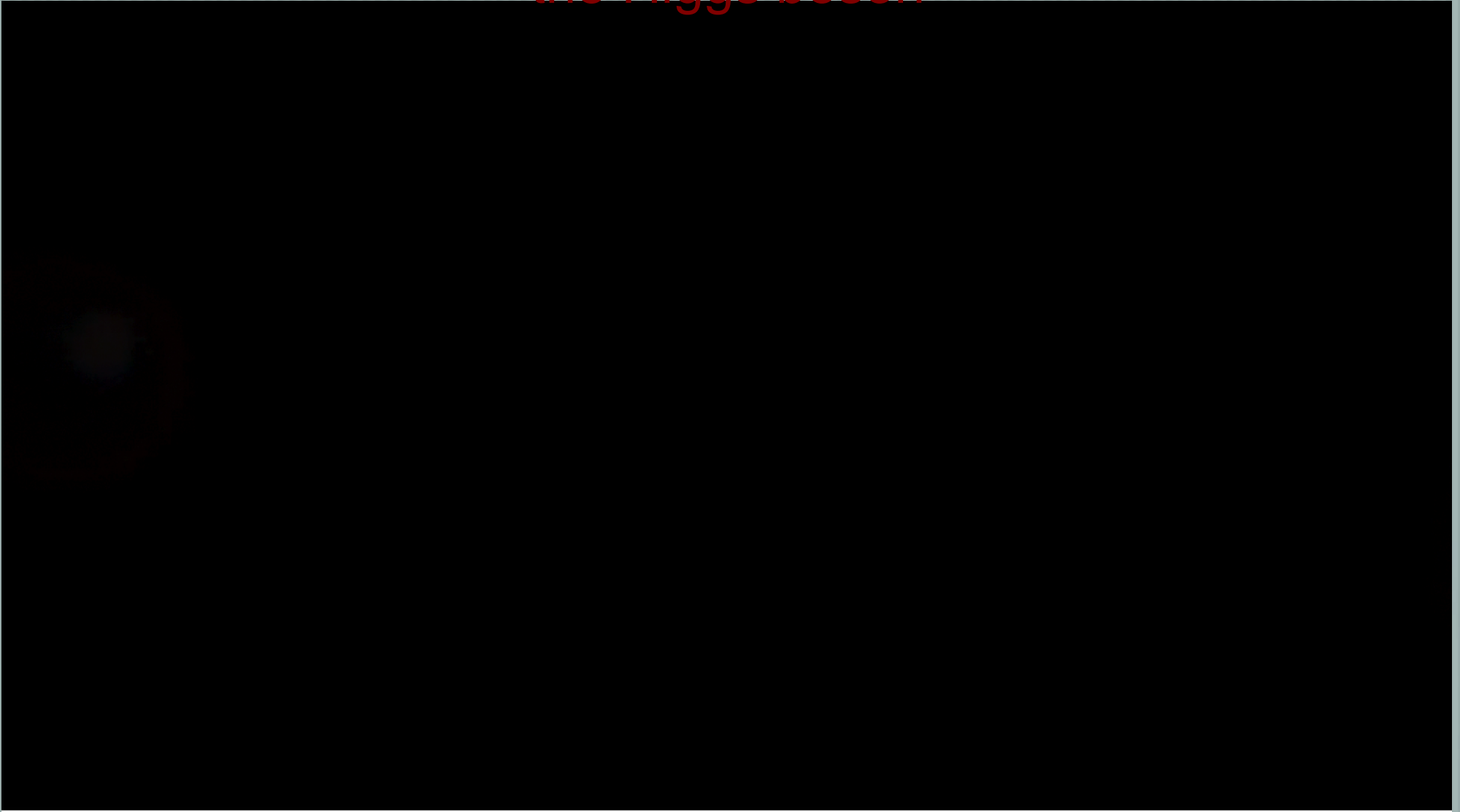
Everything moves with the speed of light



The Higgs field appears
Particles interacting with the Higgs field
acquire a mass and slow down

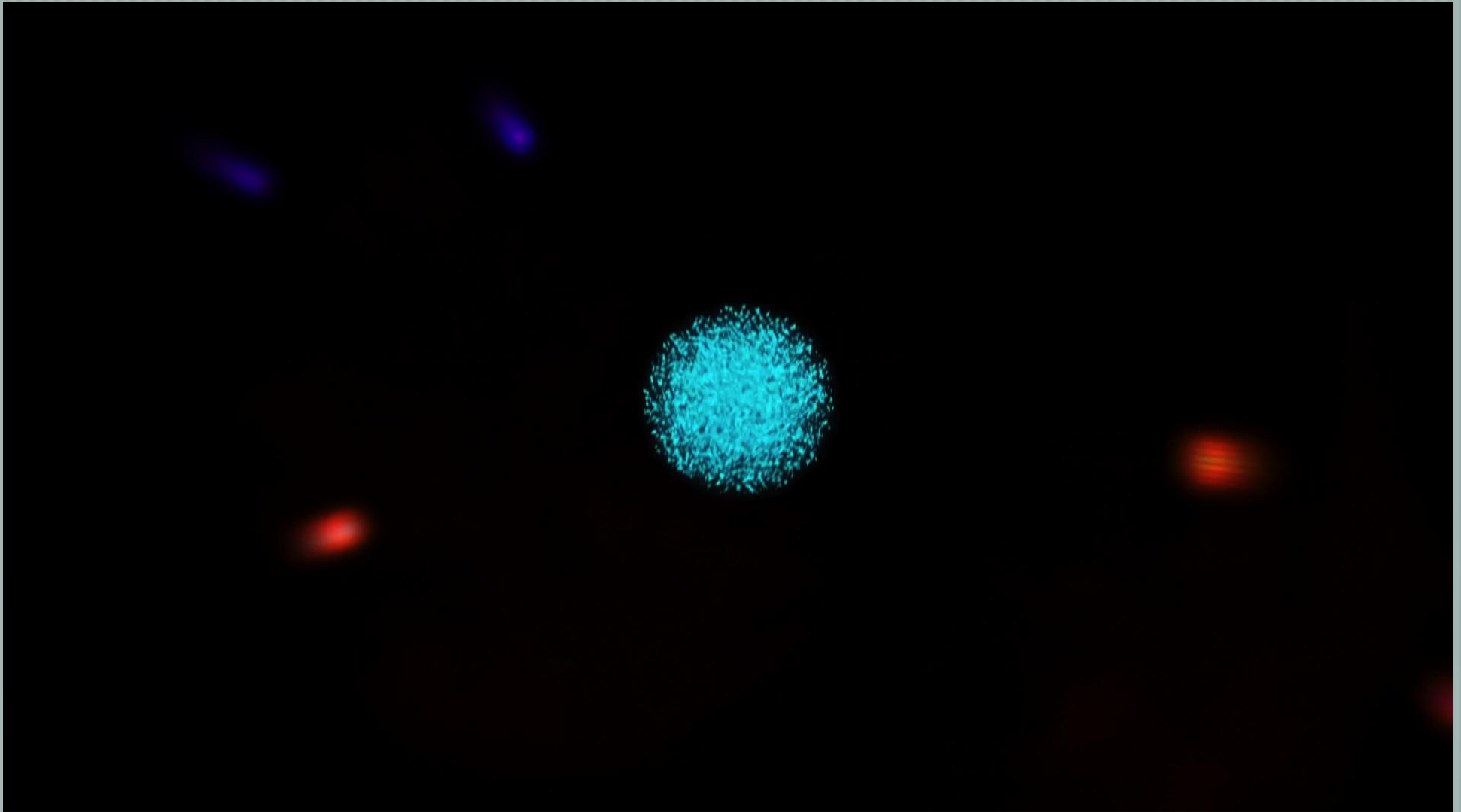


In collisions of two protons
an excitation of the Higgs field can be
produced:
the Higgs boson



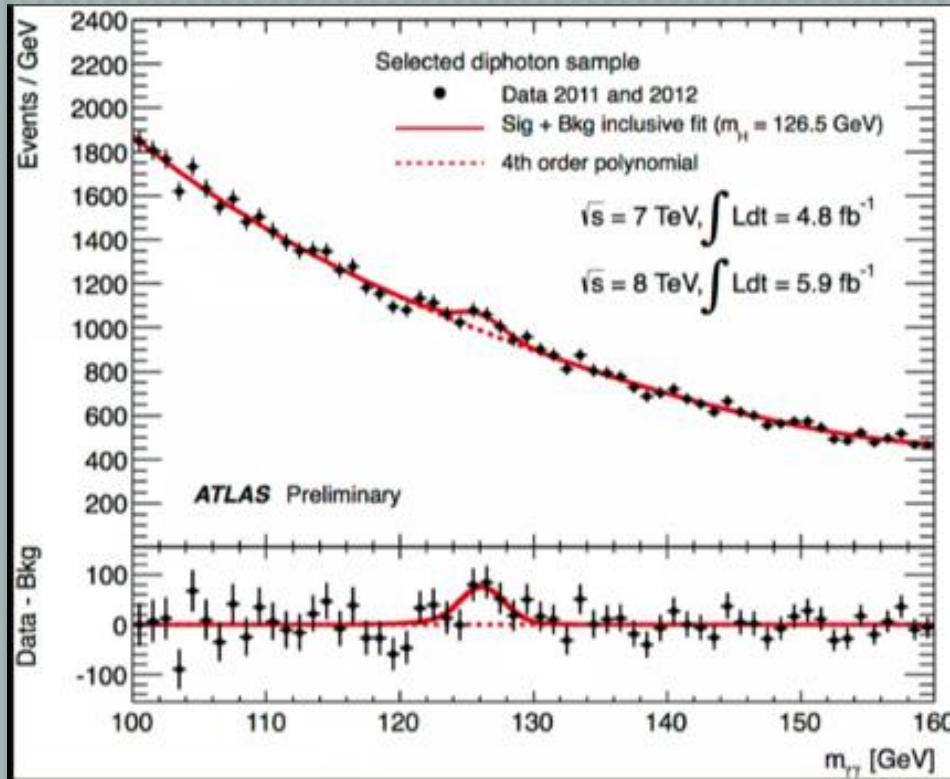
After a very short time (10^{-26} s)

the Higgs boson decays into other particles
with a probability related to their mass

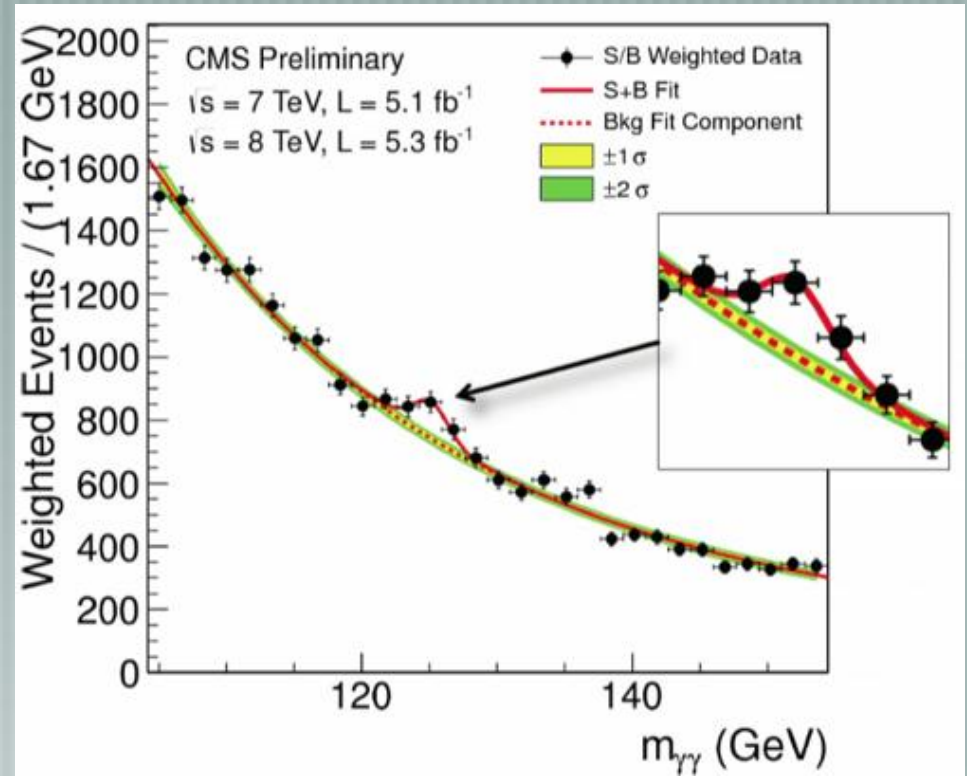


Fields

The Higgs boson evidence (2 photons)



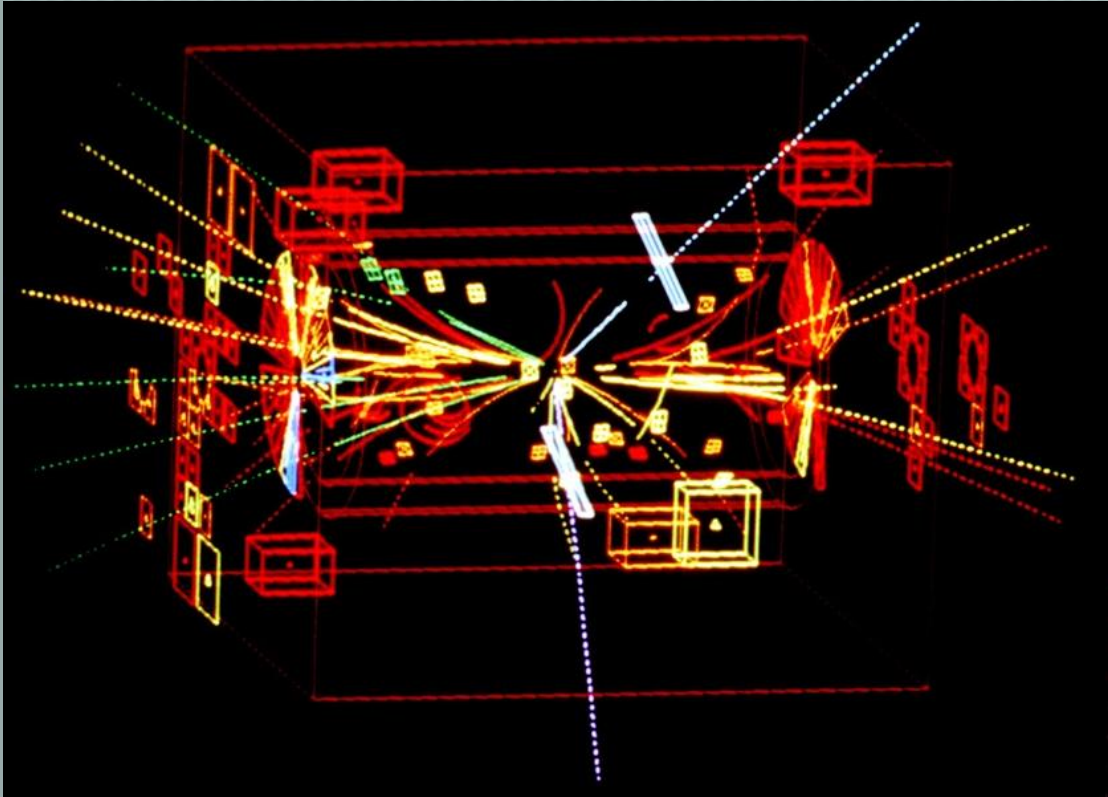
ATLAS



CMS

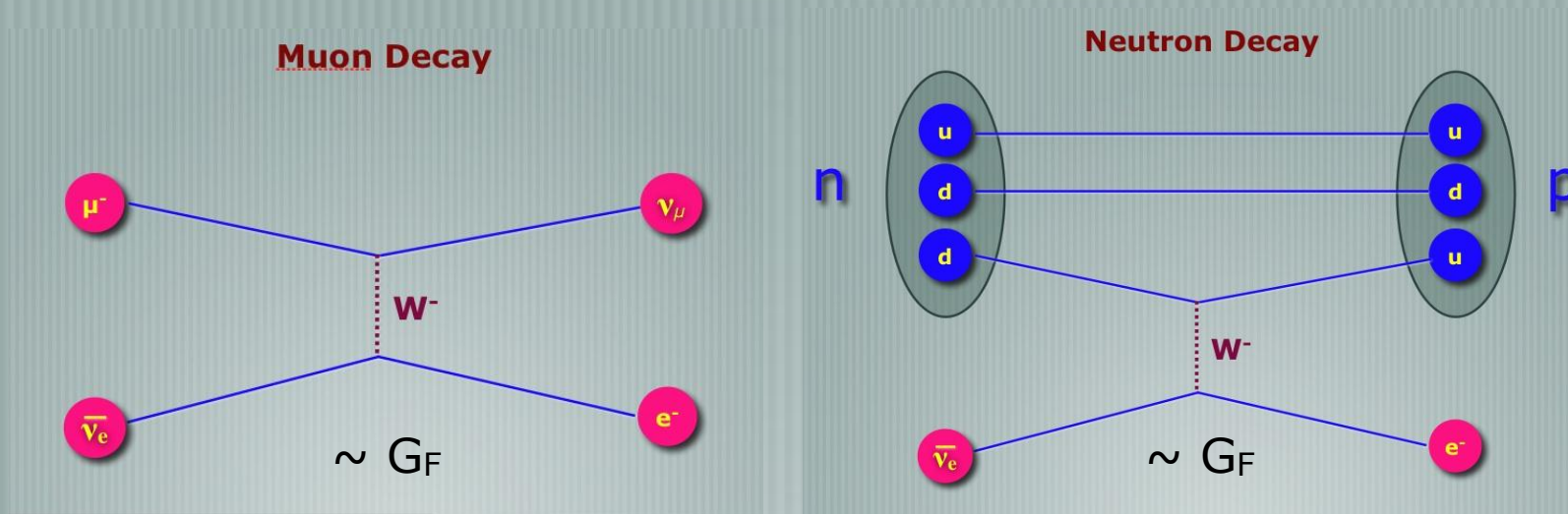
“They really exist” : Discovery of the W, Z bosons at CERN (1983)

(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

$$\begin{aligned}d' &= d \cos \theta_c + s \sin \theta_c \\s' &= -d \sin \theta_c + s \cos \theta_c\end{aligned}$$

$\theta_c = \text{Cabbibo angle} \sim 20^\circ$

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*

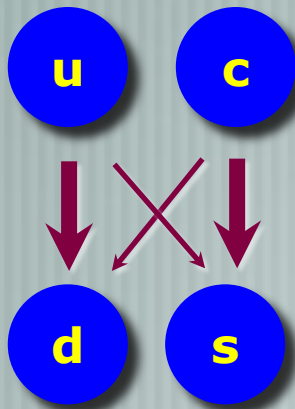
S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

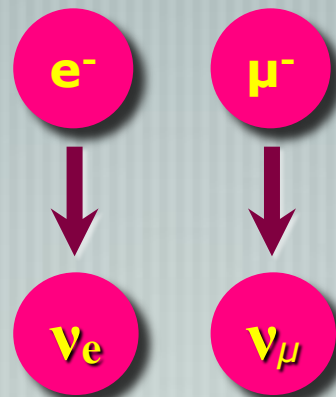
(Received 5 March 1970)

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-Mills theory is discussed.

Quarks



Leptons

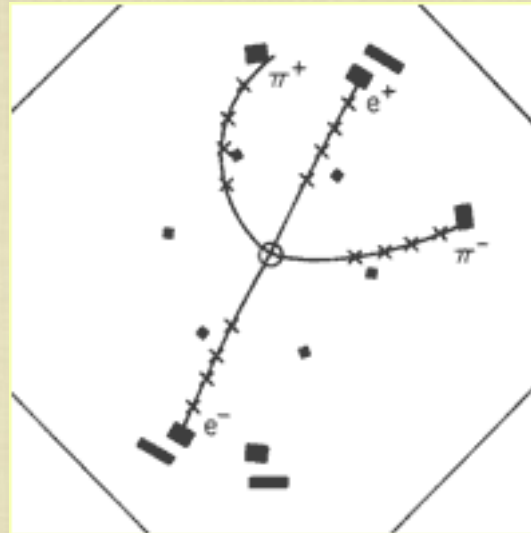


*The "Standard Model"
of 1970*

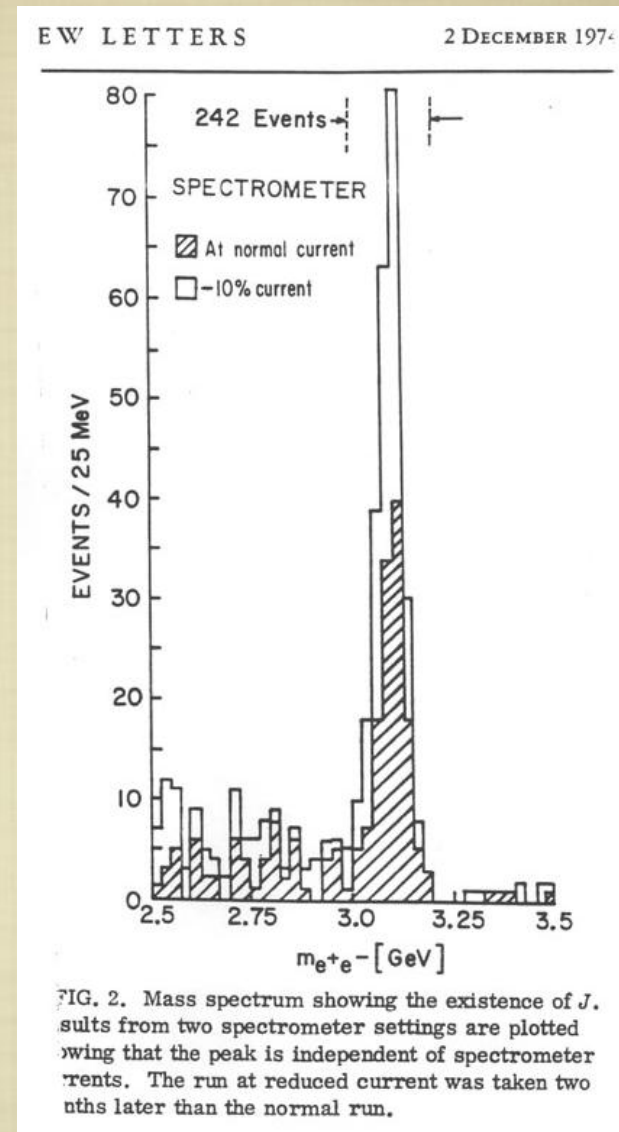
Discovery of the 'charm' quark in 1974

NOVEMBER REVOLUTION (11 November 1974)

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



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



PARTICLE SPECTRUM

Leptons

1975

But a third family of particles was going to be discovered

SLAC (Marty Perl)

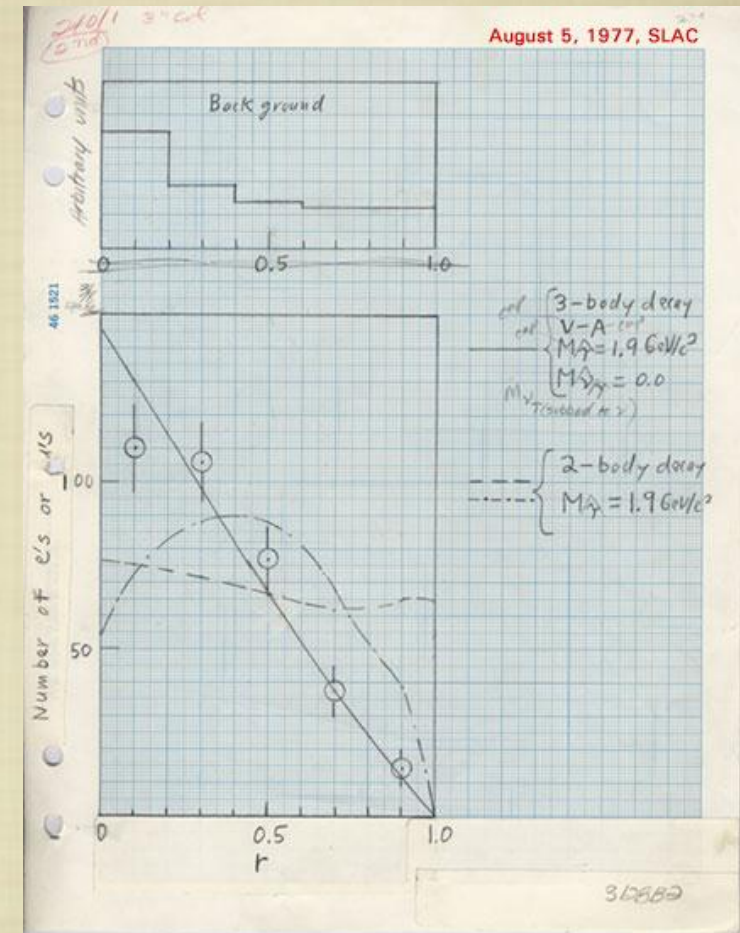
A new 'heavy electron' with $3500 \times m_e$

... who ordered that?



THERE MUST BE A WHOLE NEW FAMILY

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



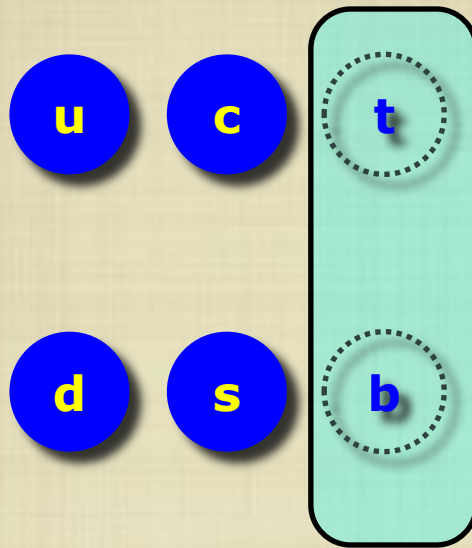
Marty Perl's logbook page

PARTICLE SPECTRUM

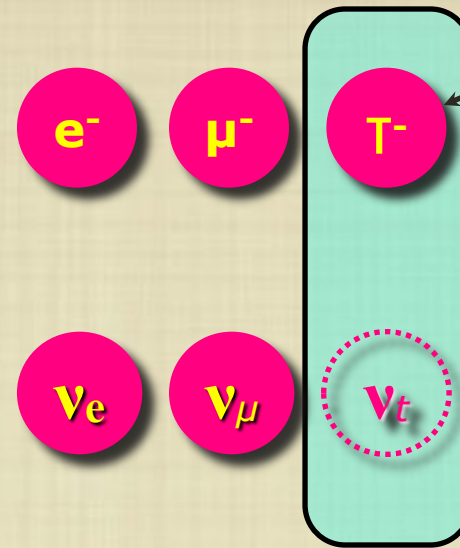
Quarks

1975

The search for the other family members started

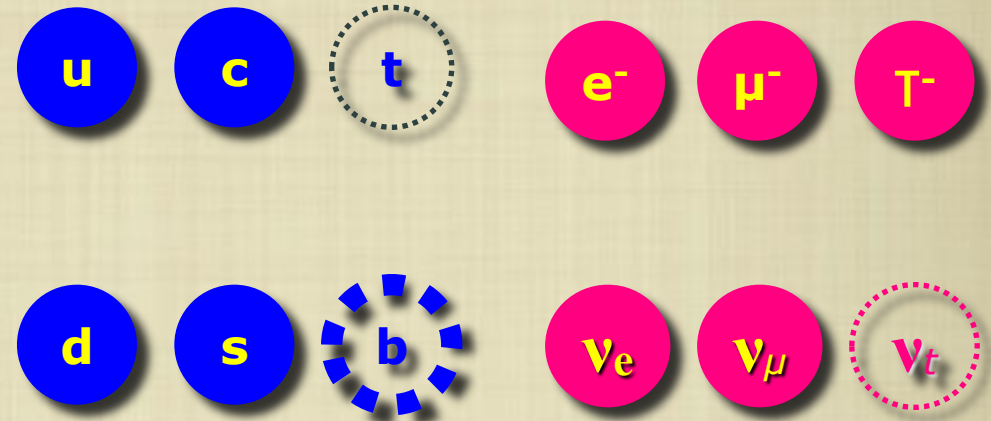
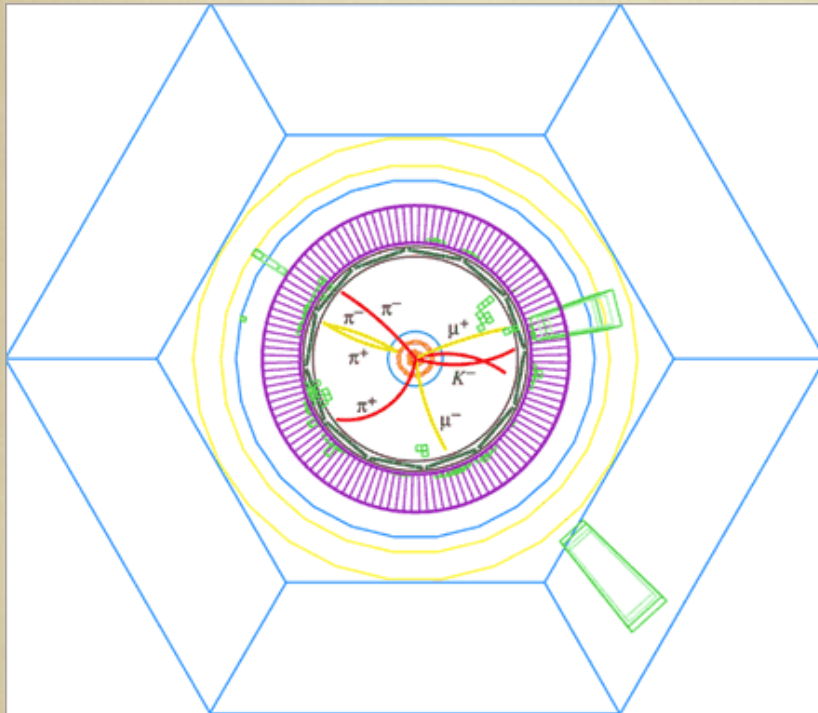


Quarks



Leptons

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.

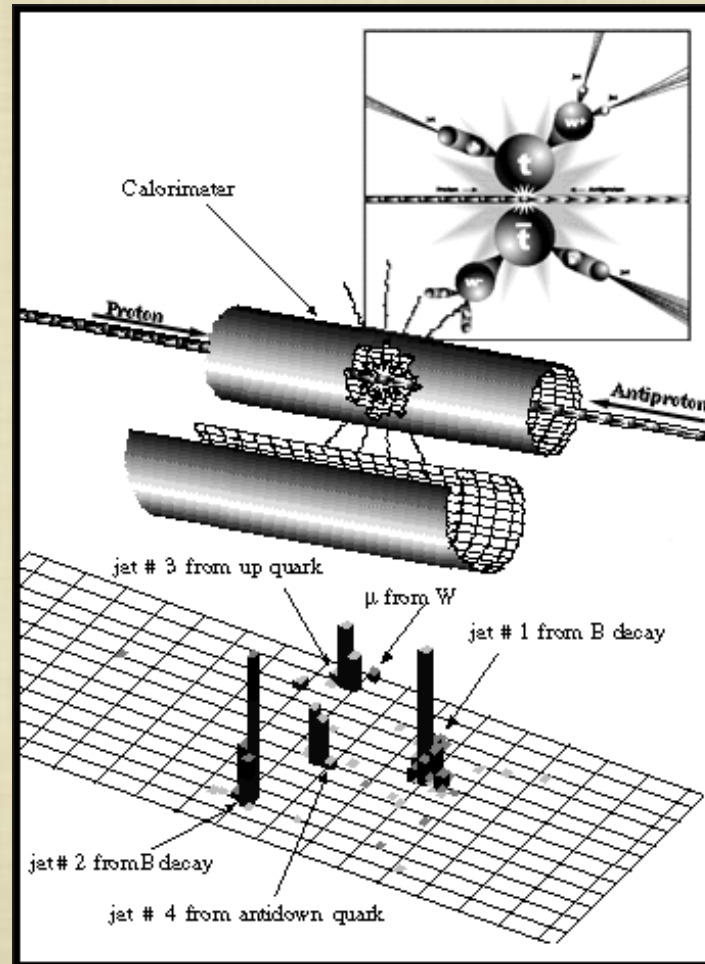
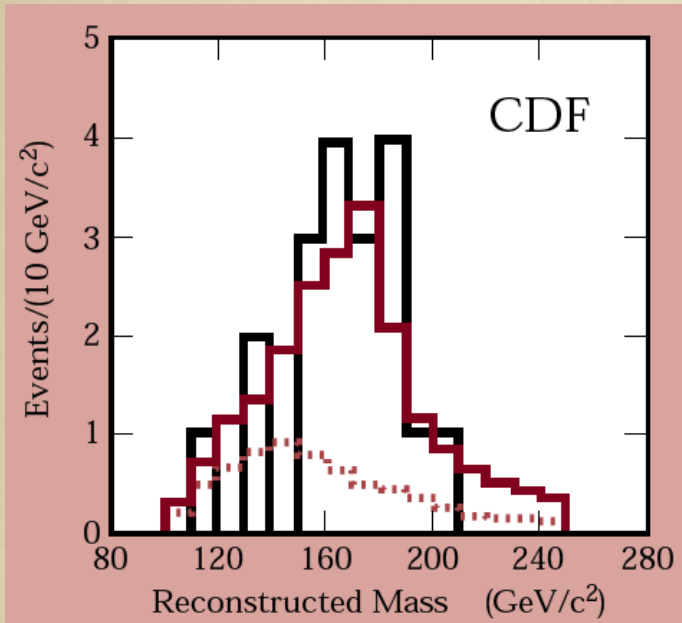
The bottom quark had charge $-1/3$ and a mass of roughly 5 GeV.

PARTICLE SPECTRUM

Quarks

1995

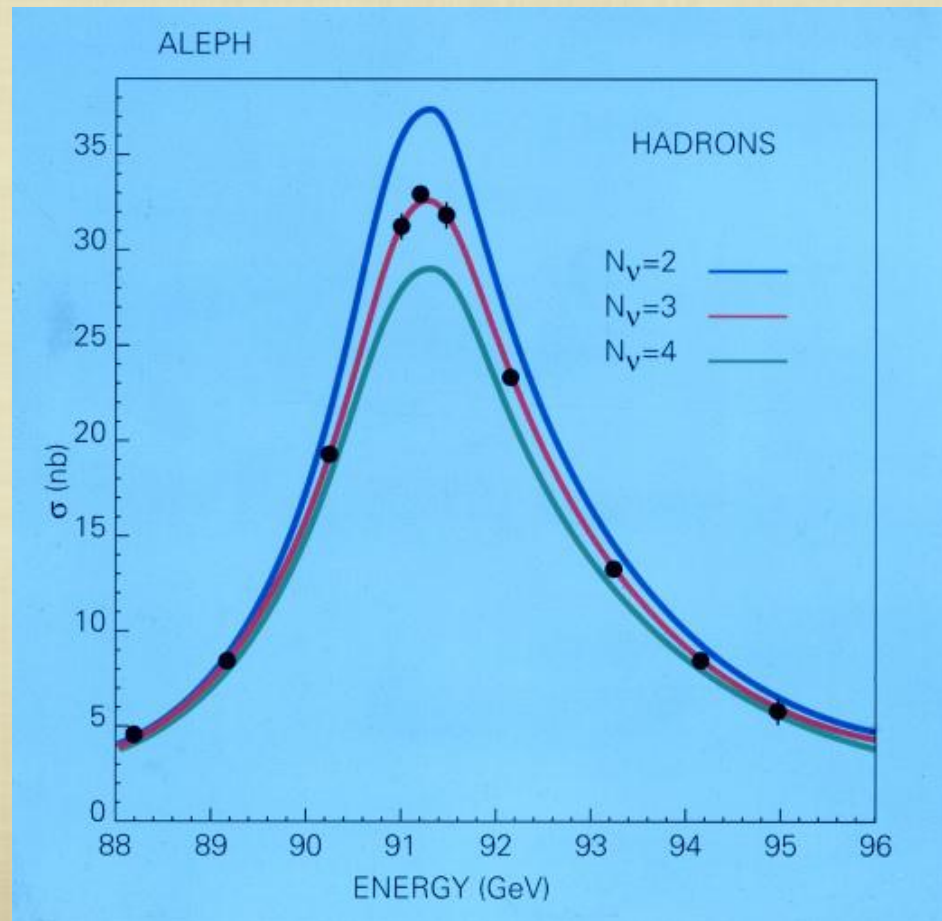
Discovery of the 'Top' Quark (Fermilab)



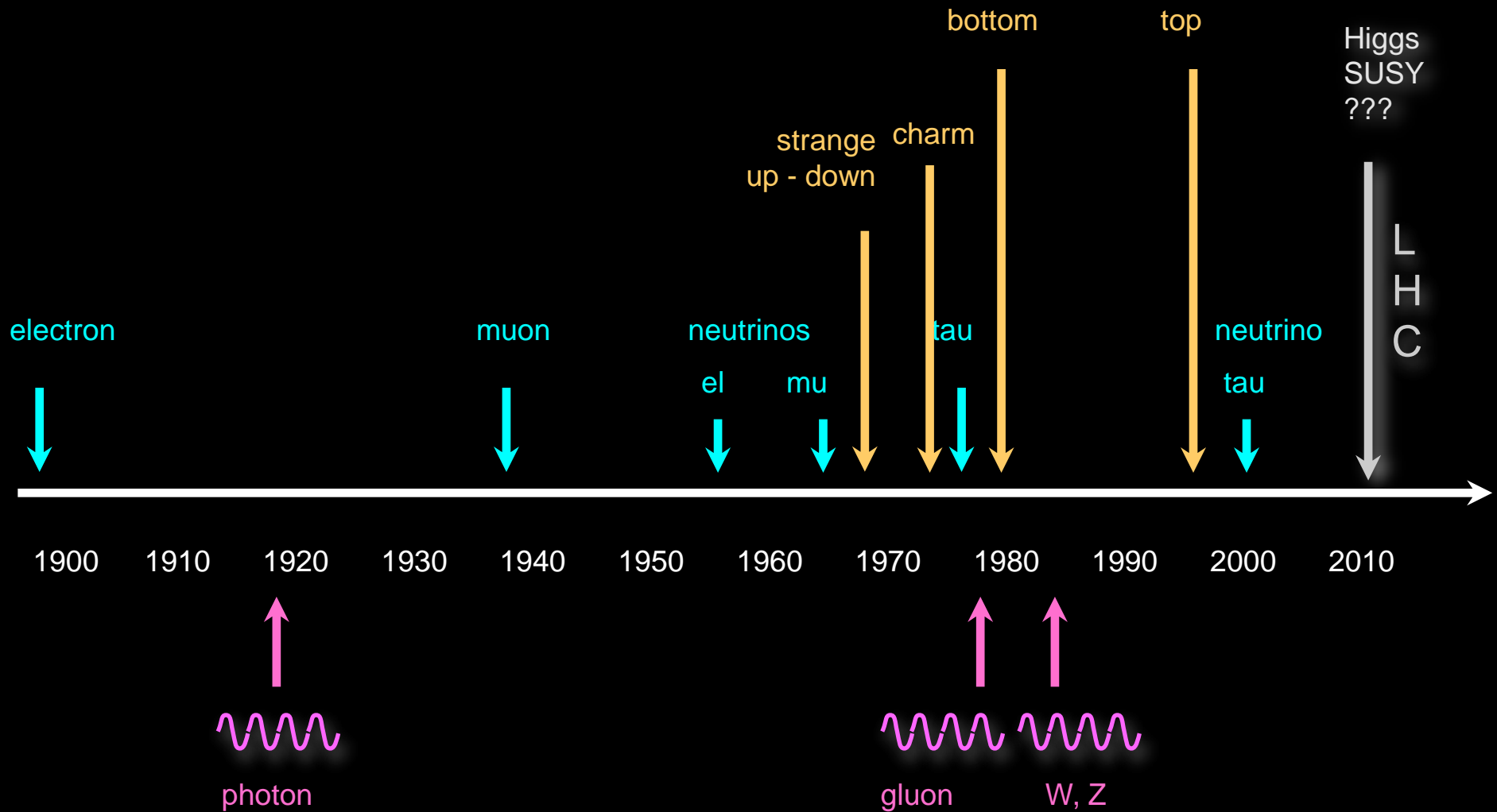
Quarks

EXACTLY 3 families of particles

LEP measures the decay width of the Z^0 particle



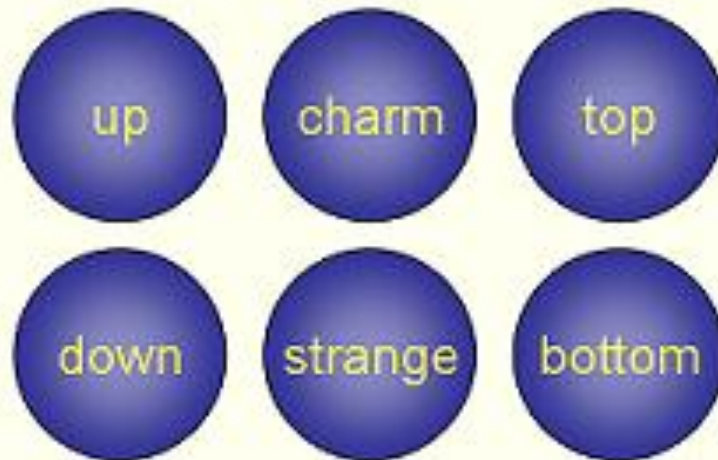
Experiments at accelerators have discovered the set of fundamental particles



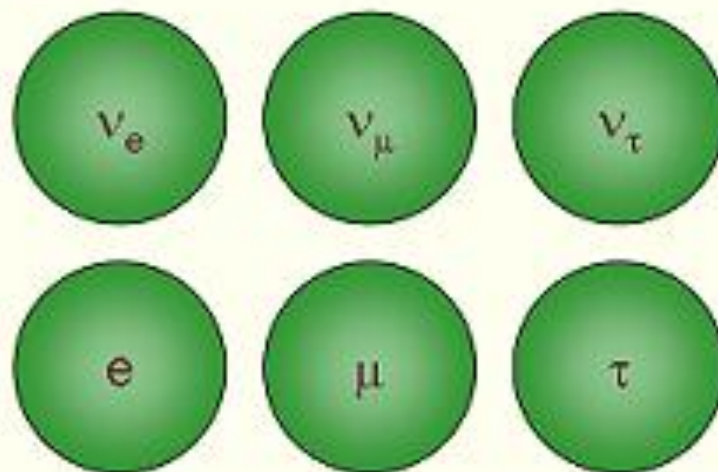
THE STANDARD MODEL (2012)

Particle content of the Standard Model

Quarks:



Leptons:



Force carriers



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^-

Atom

Nucleus

p^+

n

μ^-

π

τ^-

p^-

Particle zoo

ν_e

u d s

ν_μ

c

τ^-

b

ν_τ

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

Higgs

W bosons

GUT

EW unification

SUSY

QCD Colour

Superstrings

W

Z

g

3 generations

ν mass

Cosmic rays

General relativity

Galaxies; expanding universe

Dark Matter

Nuclear fusion

Big Bang Nucleosynthesis

Cosmic Microwave Background

CMB Inhomogeneities (COBE, WMAP)

Dark Energy (?)

Inflation

Geiger

Cloud

Cyclotron

Synchrotron

Bubble

e^+e^- collider

Wire chamber

Beam cooling

Online computers

p^+p^- collider

Modern detectors

WWW

GRID

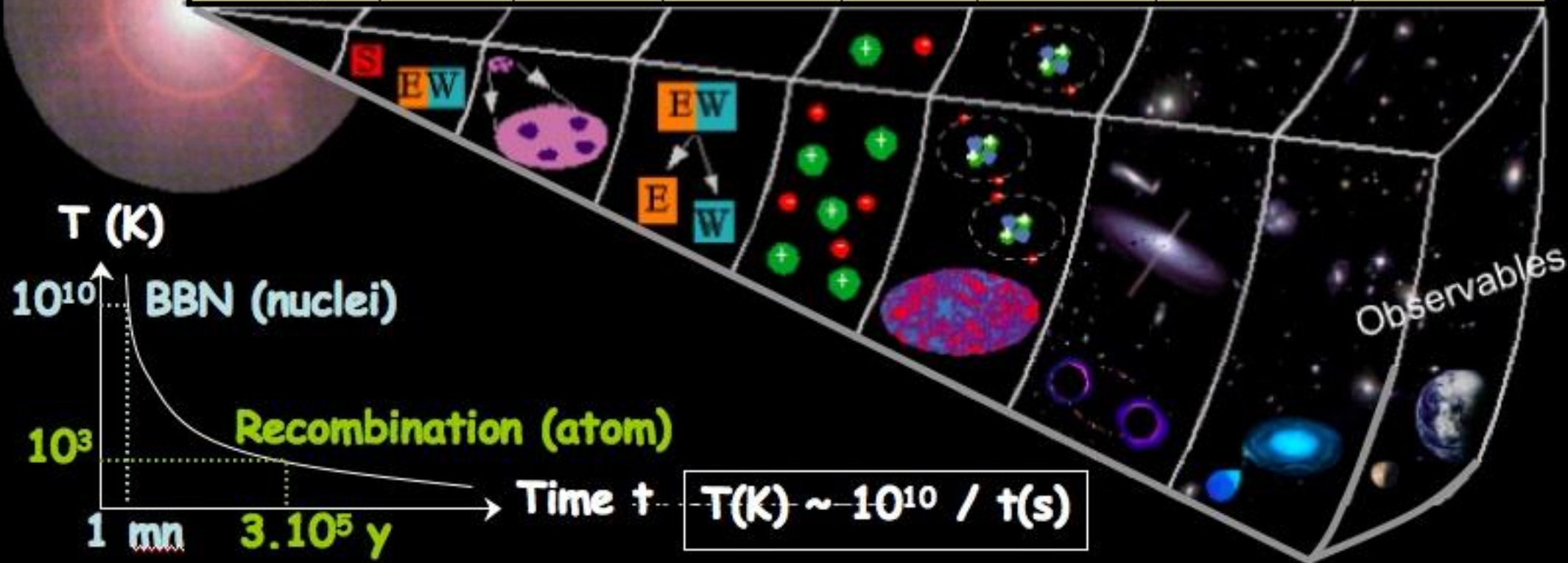
Universe

The reconstruction of the History of the Universe

Big Bang

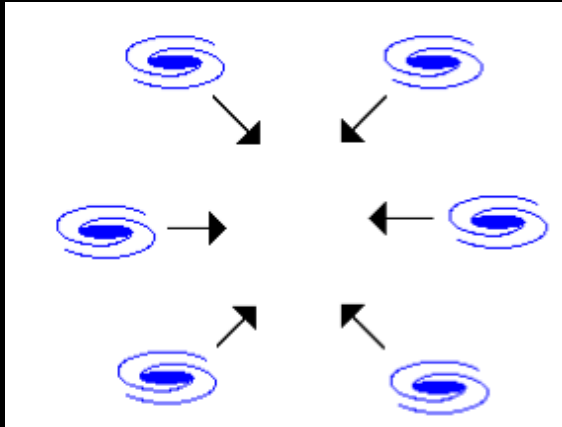
Time →

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	3×10^5 yr	3×10^9 yr	15×10^9 yr
Superstring era (?)	GUT era	Inflation era	Electroweak era	Particle Era	Recombination era	Galaxy & star formation	Present era



Universe

Evidence for Dark Matter (1933)

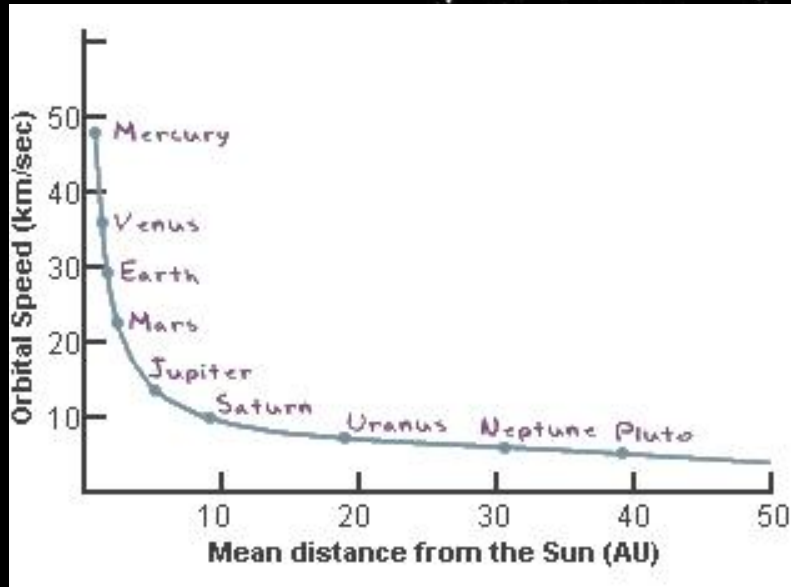


Universe

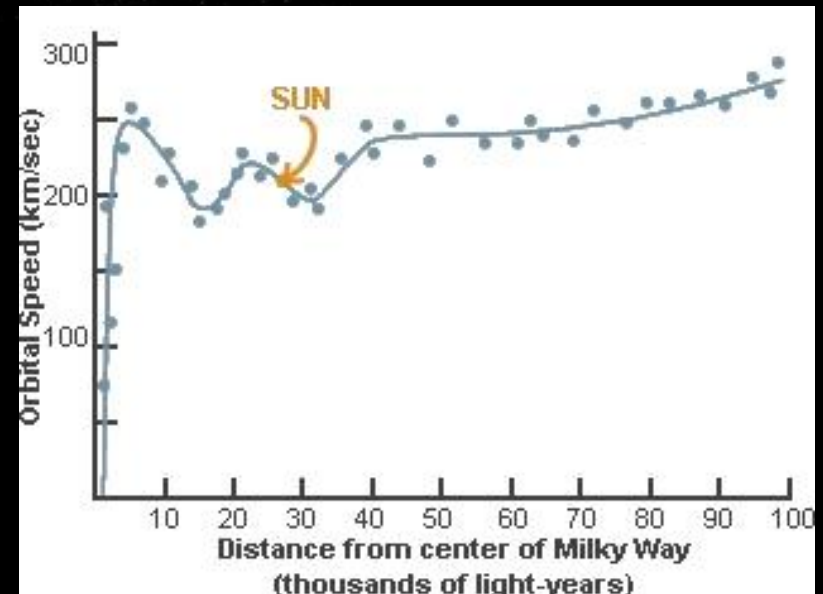
MORE EVIDENCE FOR “DARK MATTER”



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

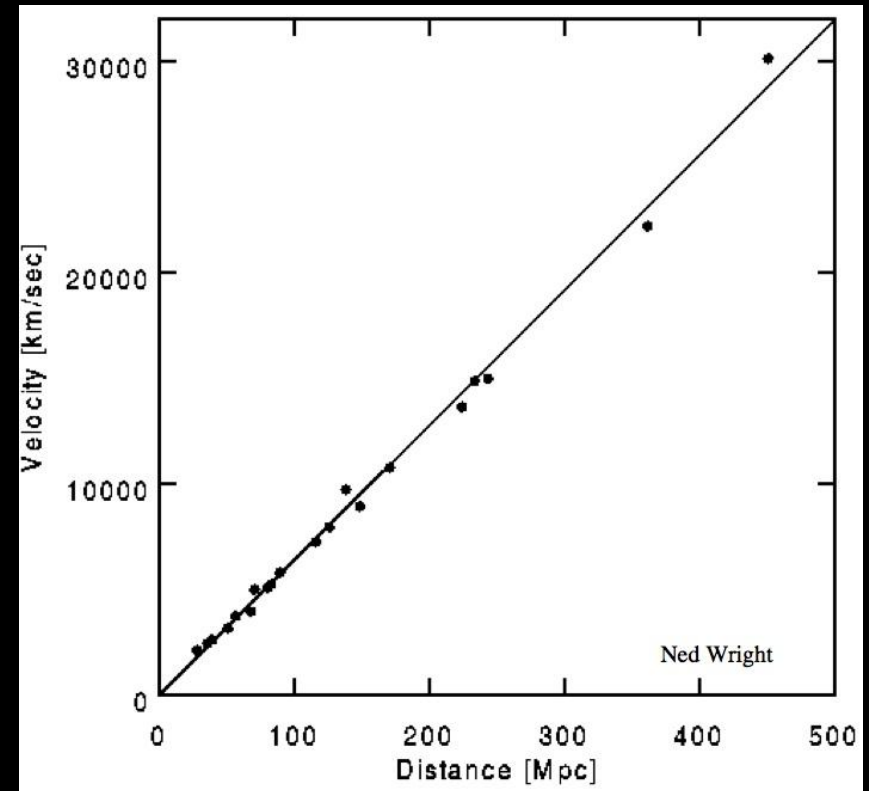
Sun ~ 4.7 billion yr

Universal Ratio H:He $\sim 3:1$

Snapshot at $t \sim 3$ min

Cosmic Microwave Background ?

Predicted (Gamov), ~ 5 K

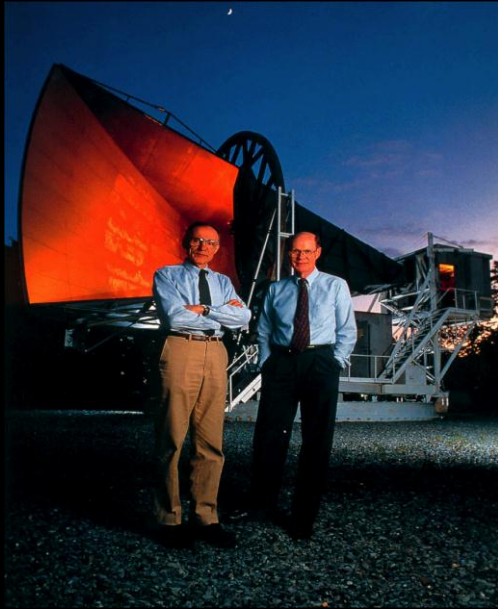


Today: $H = 70 \pm 3 \text{ km s}^{-1} \text{ Mpc}^{-1}$

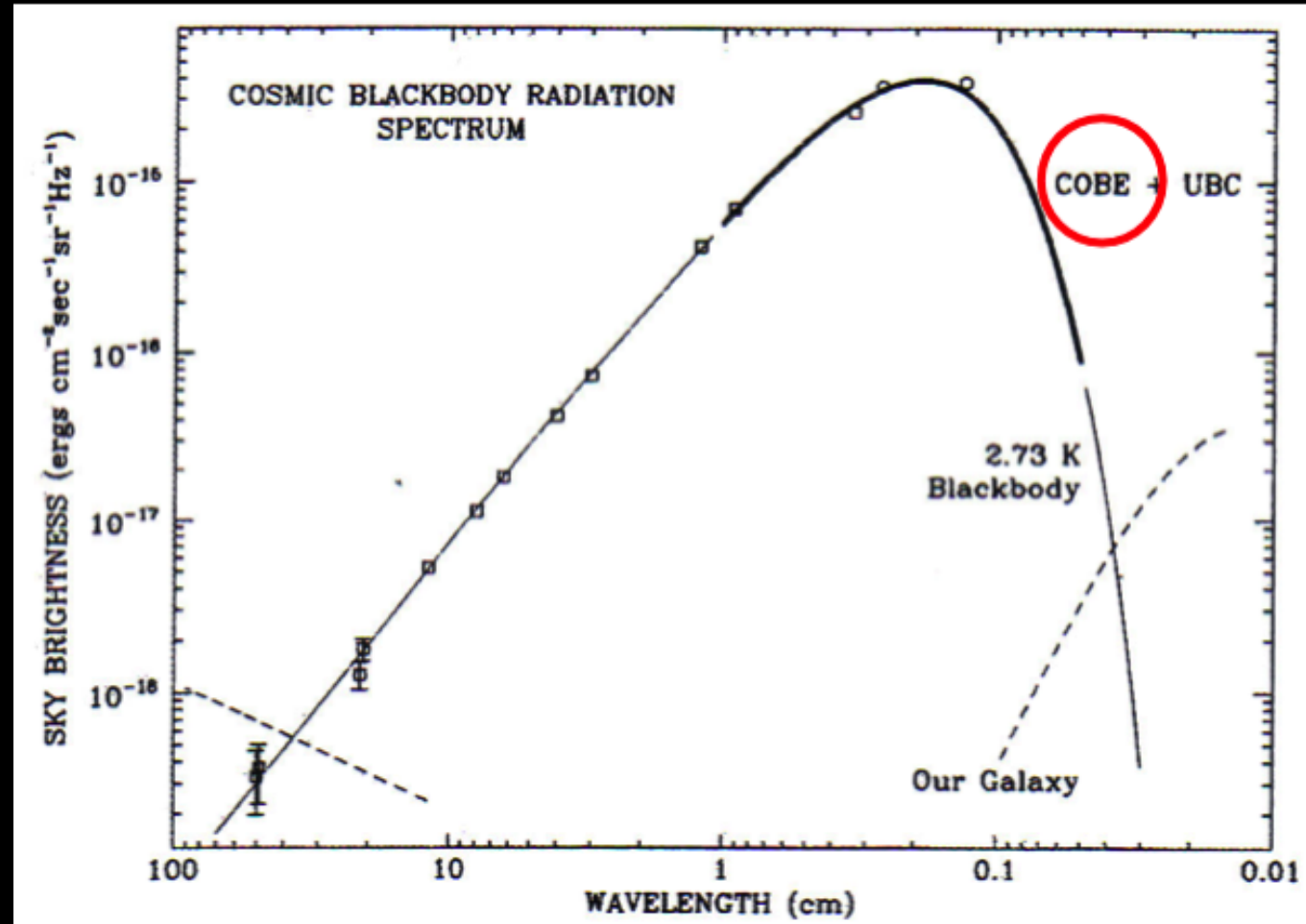
Hubble age (H^{-1}) ~ 13.4 billion years

Universe

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



Penzias and Wilson



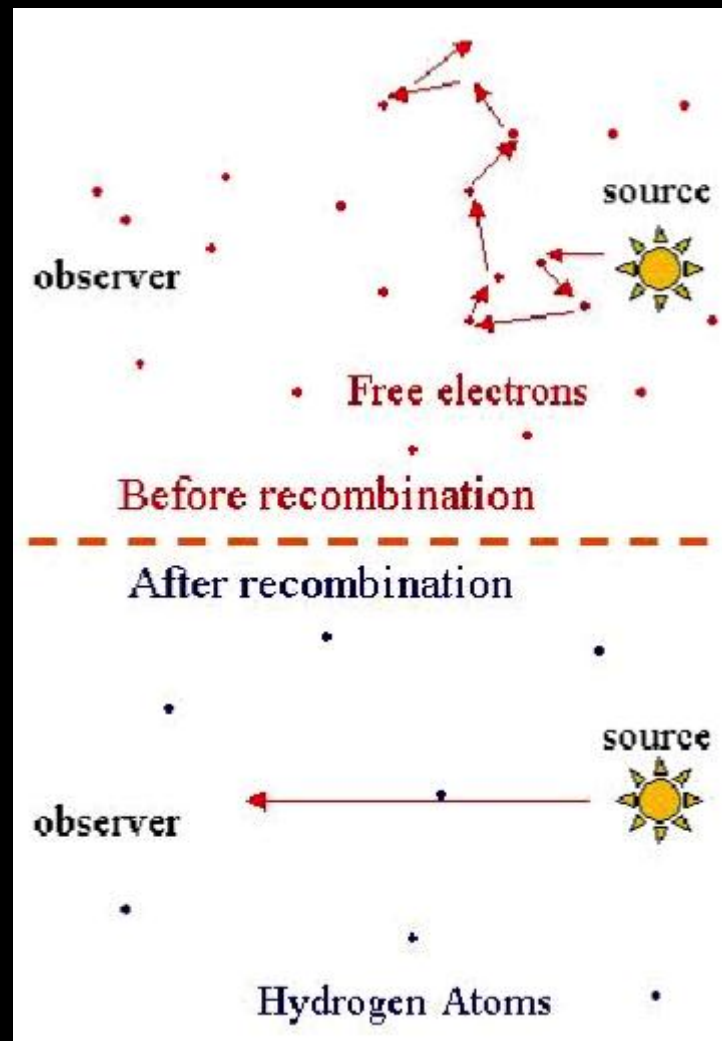
The Universe is a perfect 'black body' with $T = 2.73 \text{ K}$

Universe

How was the cosmic background radiation produced?

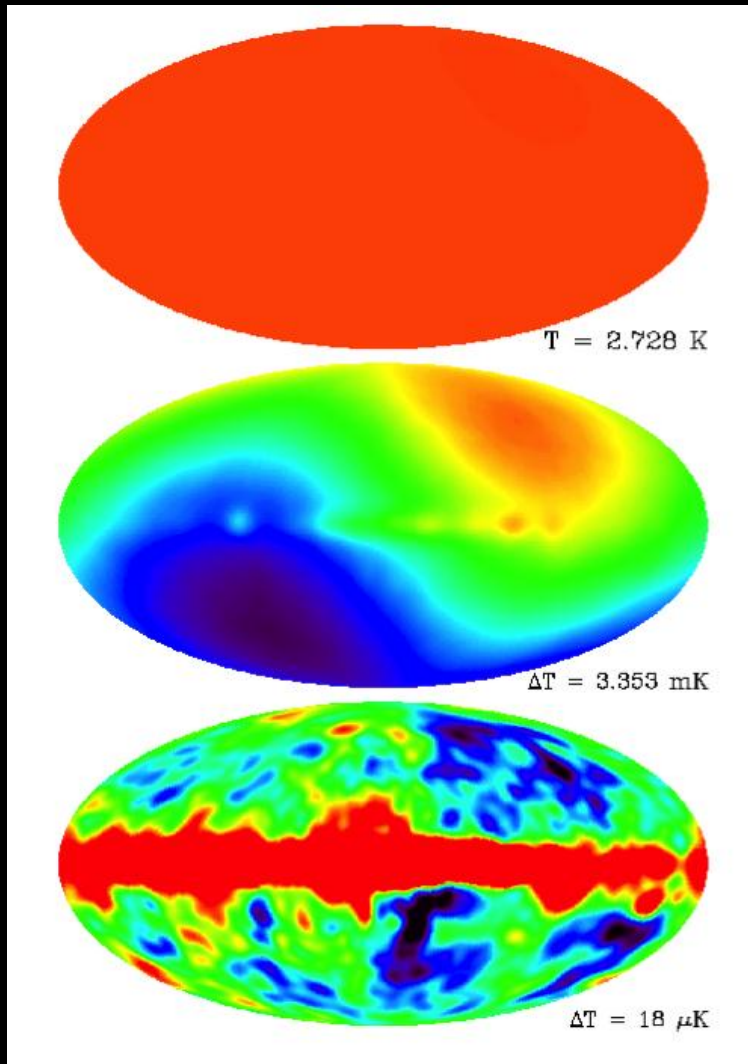
By the recombination of free electrons and nuclei

(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)



$$T = 2.7 \text{ K}$$

$$\Delta \epsilon_{\lambda\tau\alpha} - T = 3.3 \text{ mK}$$

(after subtraction of constant emission)

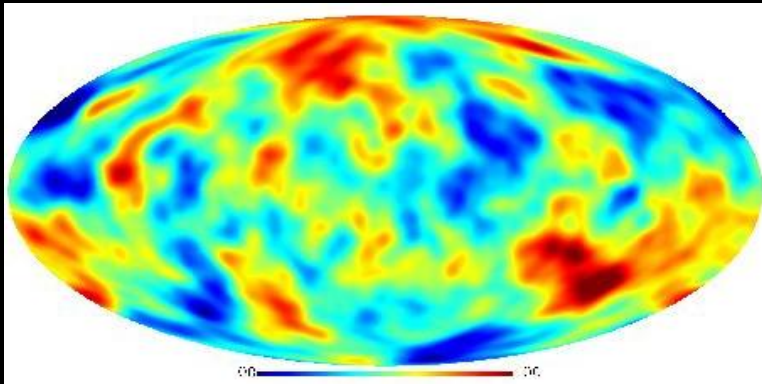
$$\Delta \epsilon_{\lambda\tau\alpha} - T = 18 \text{ } \mu\text{K}$$

(after correcting for motion of Earth)

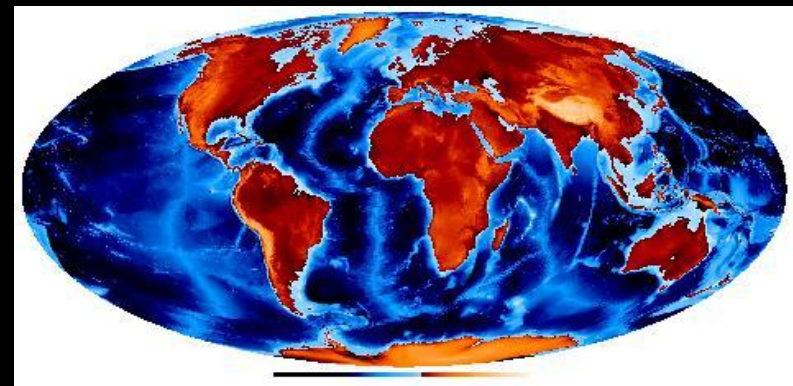
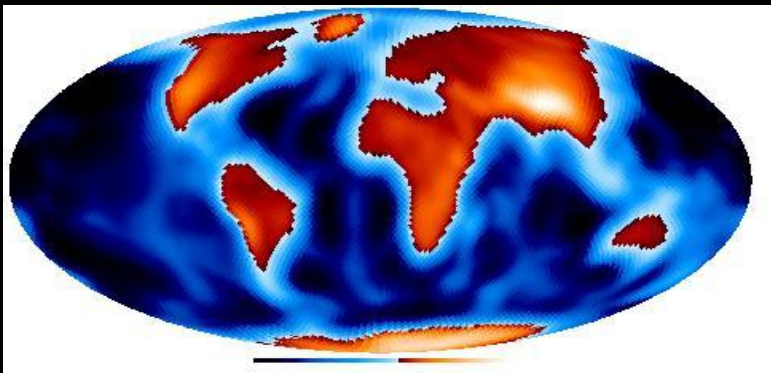
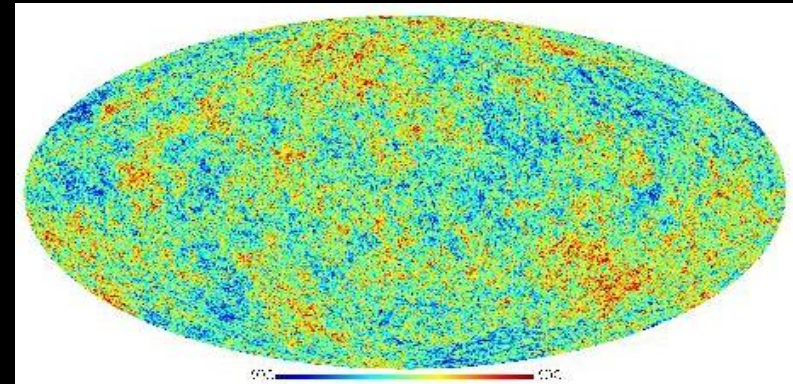
Universe

The most precise observation today (WMAP)

COBE
(7 degree resolution)



WMAP
(0.25 degree resolution)



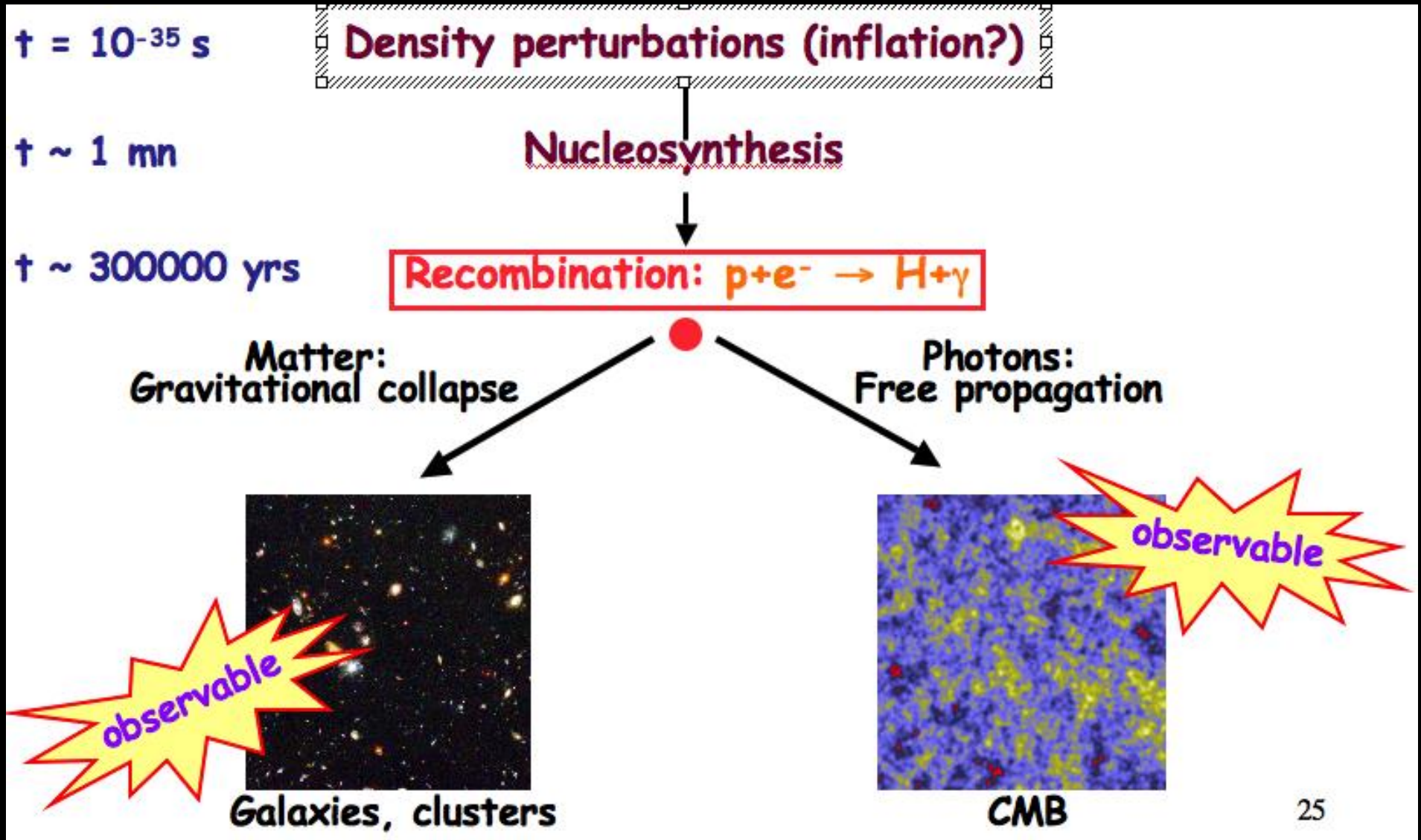
Universe

What WMAP measured

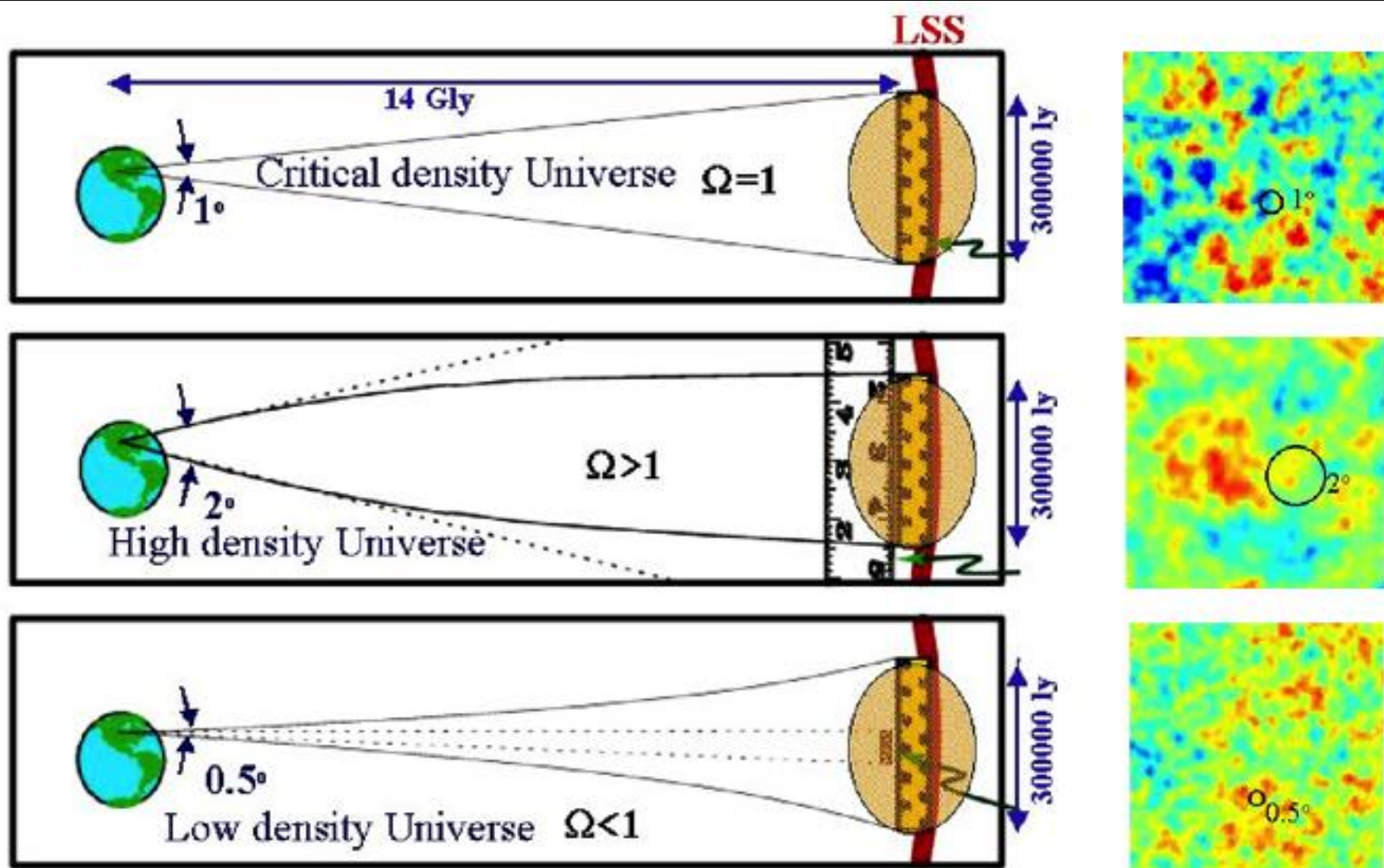


Universe

Back to the Beginning



Analysis of inhomogeneities reveals the composition of the Universe



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

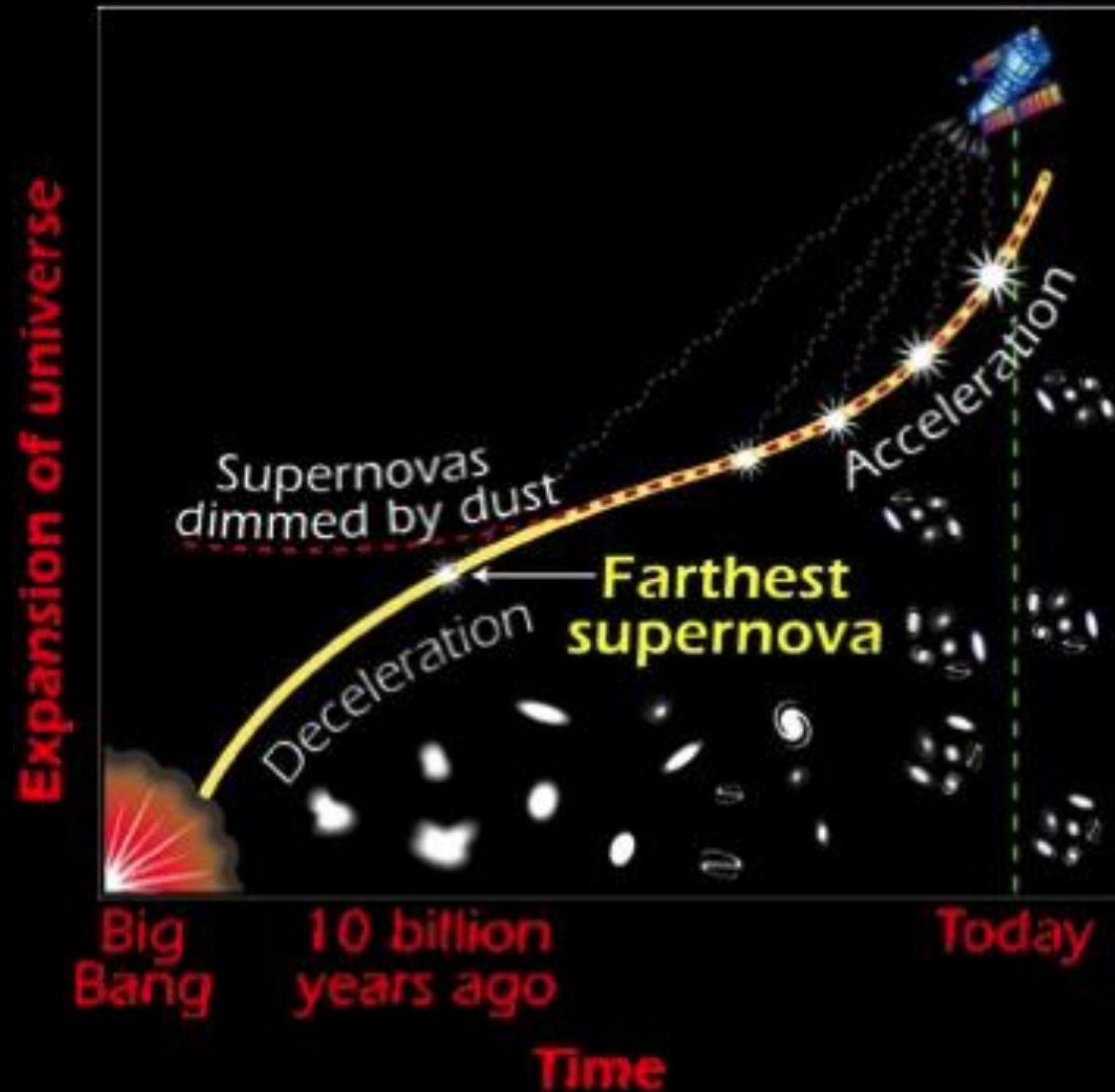
Universe

The strange composition of the Universe



Universe

Evidence for Dark Energy



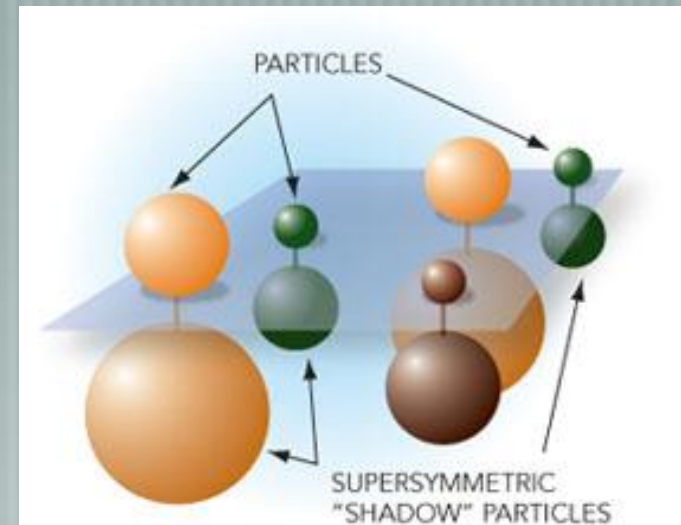
QUESTIONS FOR THE 21st CENTURY

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



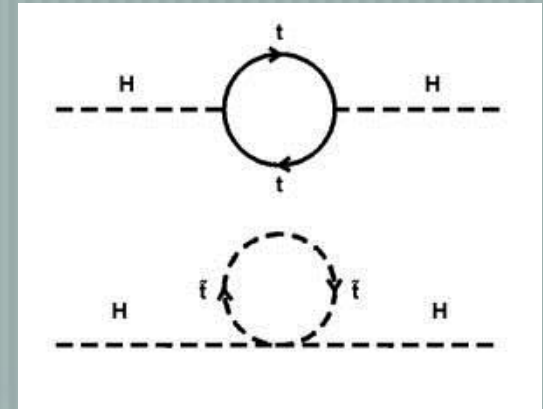
Spin 1/2	Integer spin
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)

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

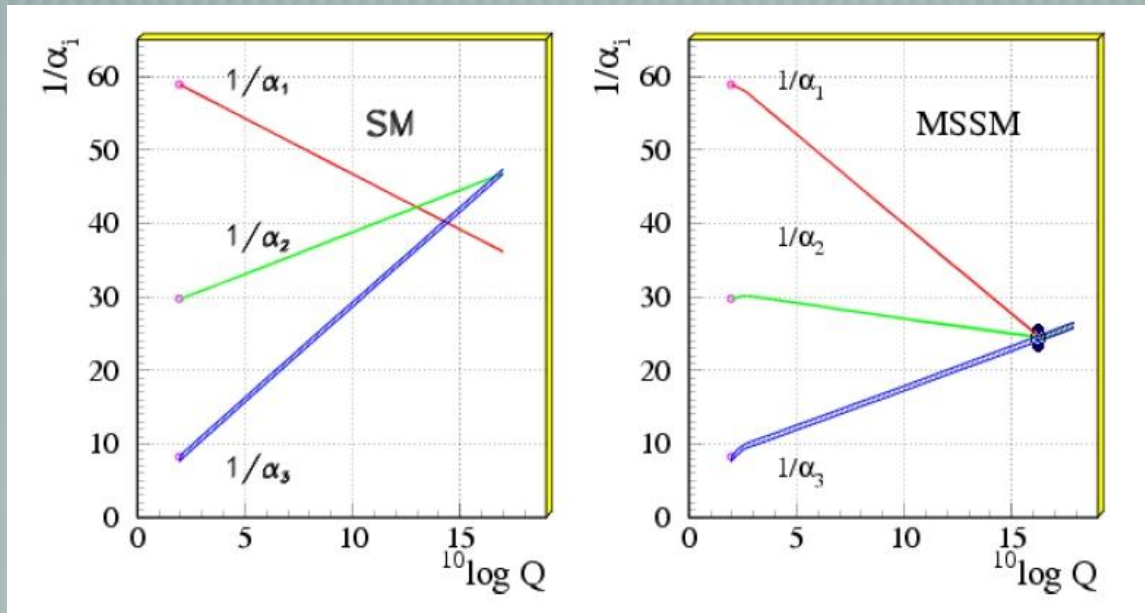
Good reasons for Supersymmetry

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 ($\sim 10^{17}$ GeV)

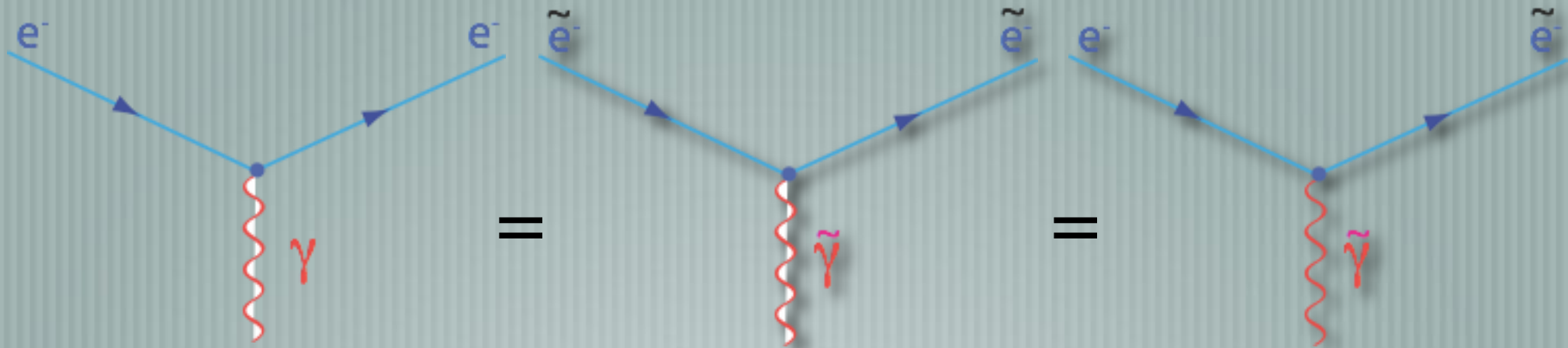


4) Possible explanation of cosmological matter-antimatter asymmetry

5) **Dark matter ?**

If Nature was supersymmetric, then:

Particles and their Super-Partners can be interchanged



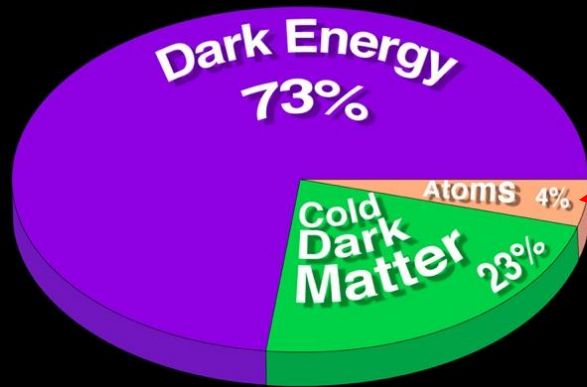
e = electron

γ = photon

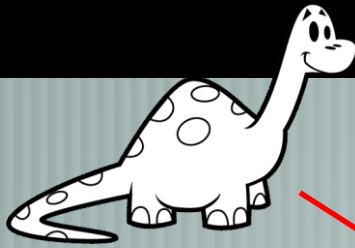
\tilde{e} = selectron

$\tilde{\gamma}$ = photino

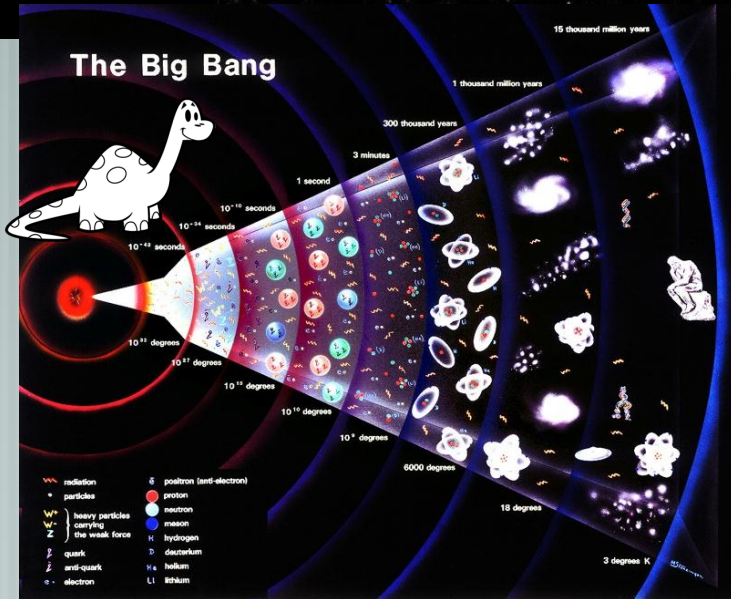
QUESTIONS FOR THE 21st CENTURY



Our type of matter



Supersymmetric particles could be responsible for DARK MATTER



QUESTIONS FOR THE 21st CENTURY

What are particles?



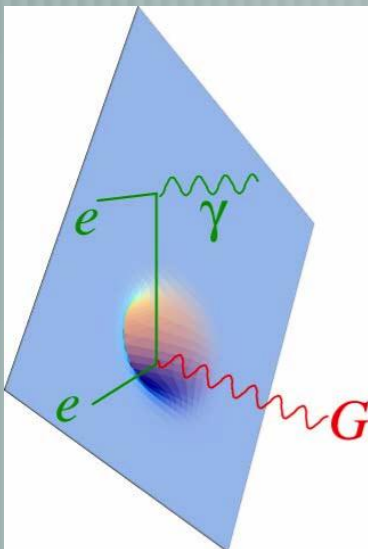
Superstrings in 9+1 dimensions?

Quantum theory of gravity only works in 9-dimensional space
Particles + fields are oscillating 'strings' (size $\sim 10^{-35}$ 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 at 7 TeV on 30 March 2010

Discovery of a new (Higgs?) boson 4 July 2012



a step forward to understanding the Universe