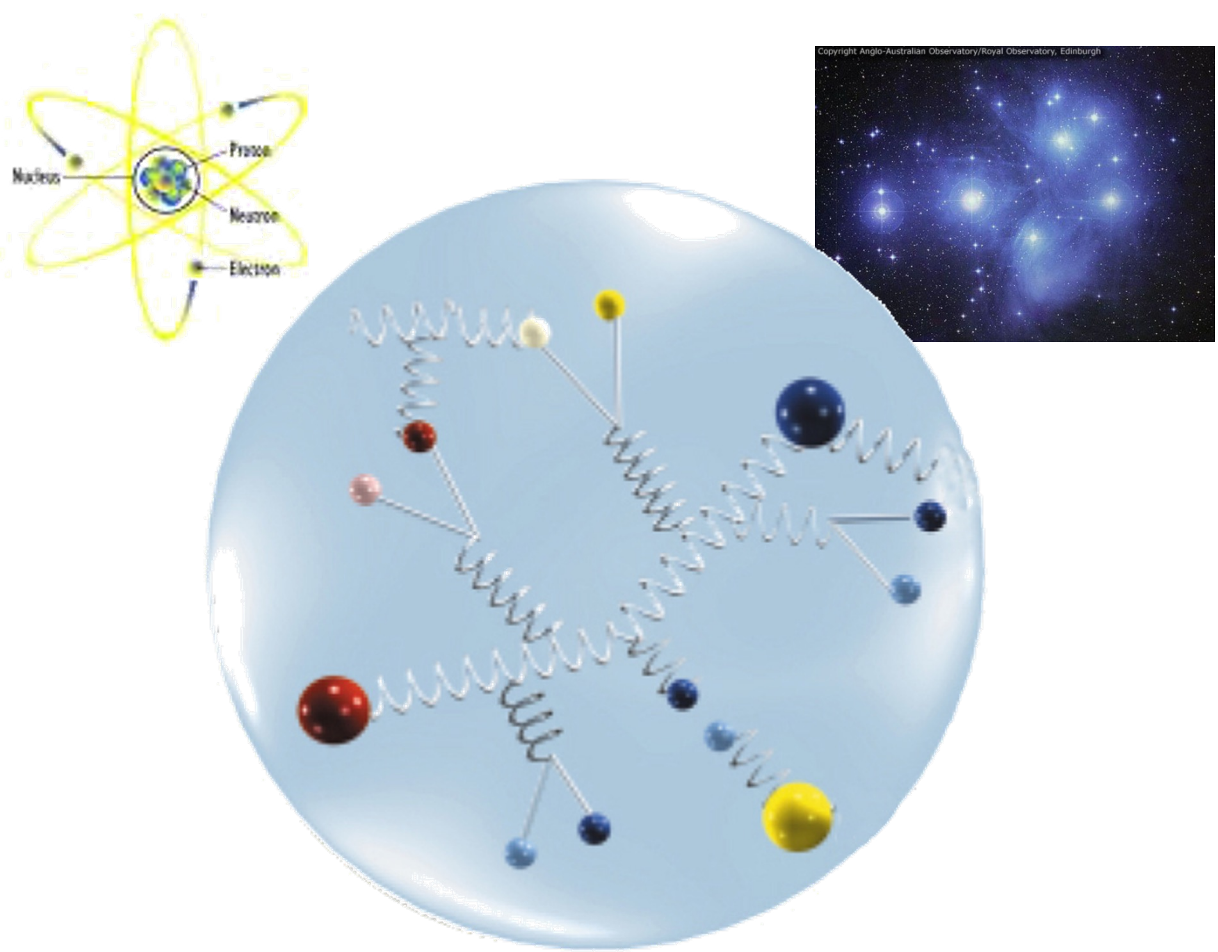
PH20016

Particles, Nuclei & Stars



Introduction

Contact details

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Moodle

Course schedule

Reading list

Problem class list

Particle Data Sheet

Always bring it with you!

You will have a copy at the exam…

Reading List

R.A. Dunlap; **Introduction to the Physics of Nuclei and Particles**,
Thomson-Brooks/Cole, 288 pp., 2004

B. Martin; **Nuclear and Particle Physics: An Introduction**,
Wiley & Sons, 428 pp., March 2006

M. Zeilik and S. Gregory; **Introductory Astronomy and Astrophysics**,
Harcourt Brace, 4/e, 1998

More references on the unit web page…

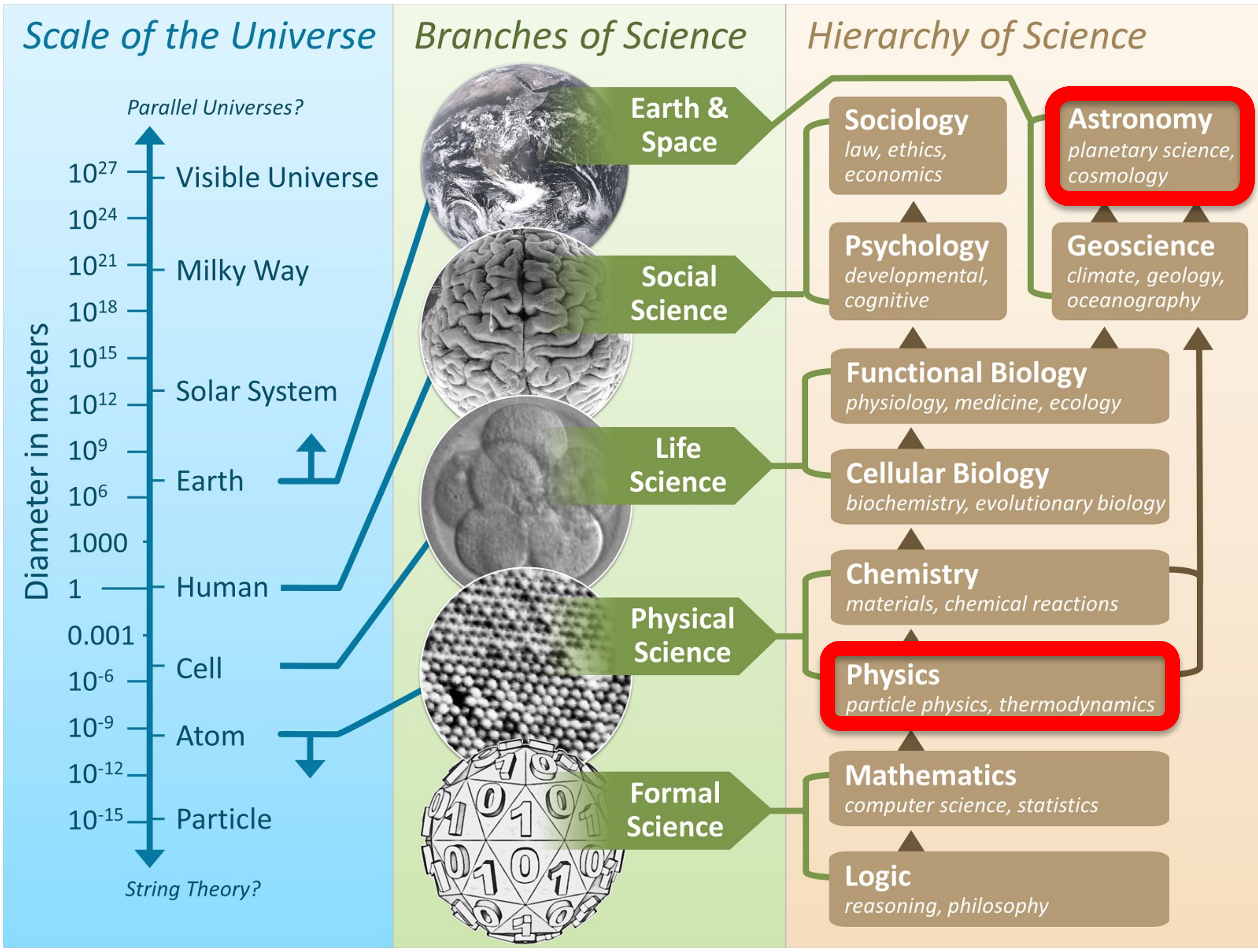
PH20016

The aims of this unit are to review our current picture of elementary particles and discuss the forces between them, to describe properties and reactions of atomic nuclei and to discuss how these enable us to understand the origin of the Universe and the elements, stars and galaxies within it.

After taking this unit the student should be able to:

- Describe the characteristics of the fundamental forces, and quote and use conservation laws to determine allowed particle reactions;
- Apply decay laws to problems in particle and nuclear physics, and define and perform simple calculations on cross section and centre of mass frame;
- Discuss binding in nuclei and explain the energetics and mechanisms of radioactive decay;
- Describe the liquid drop and shell models of nuclei and use them to calculate and interpret nuclear properties;
- Describe the physical processes involved in fission and fusion reactions and in stellar nucleosynthesis;
- Give a qualitative description of the early stages of the Universe, the condensation of particles, nuclei and the evolution of stars.

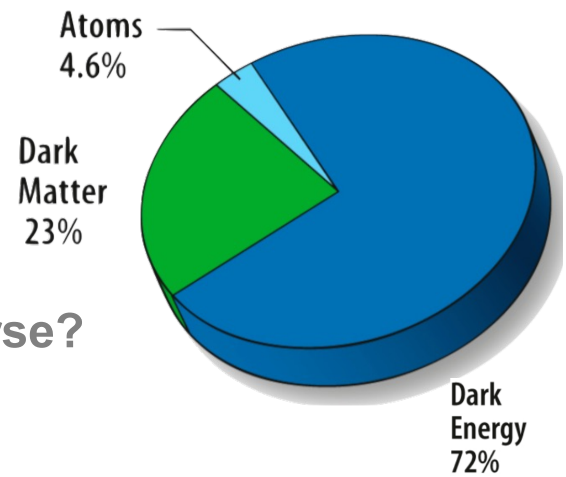
Assessment = 100% exam!



Why combine nuclear & particle physics with astrophysics in one course?

Key properties of astronomical objects and the chemical composition of stars and the universe can be understood on the basis of ***simple*** physics on the nuclear scale.

Key questions on the largest and smallest scales



- How did the universe begin?
- What is the fate of the universe?
- What is dark matter?
- What is the nature of dark energy?
- Why is there more matter than antimatter?
- Are protons unstable?
- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
- Is a new theory of matter and light needed at the highest energies? Do the forces really become unified at exceedingly high density and temperature?
- Can multiverse/string theories be empirically tested/falsified?

Many of these questions are still open. During this course we will learn the essential tools to address them.

PH20016 – Particles, nuclei & stars

I. Particle Physics

Conservation laws - Decays and reactions
Particle decay laws – Half life and mean lifetime
Unification of forces
Recent developments in particle physics (e.g., neutrino oscillations, the origin of cosmic rays, dark matter detections)

II. The nucleus

Nucleon interactions and binding energy
Nuclear size and mass (isotopes and isobars)
Radioactive decay:
- beta-decay
  - electron and positron emission
- K-capture
- alpha-decay
  - energetics and simplified tunnelling theory

The liquid drop model – Semi-empirical mass formula
The shell model
- Nuclear spin
- Excited states

III. Reactions, fission and fusion

Centre of Mass frame
Scattering
Spontaneous fission – Fission products
Induced fission – Chain reactions, delayed neutrinos
Nuclear fusion reactions – Principles of fusion reactions

IV. The cosmic connection

Stellar evolution – Stellar nucleosynthesis – Stellar death: neutron stars, supernova, cosmic ray bursts
The Big Bang – Hubble's Law – Cosmic background radiation and ripples therein – Inflation theory
Separation of unified forces
Formation of elementary particles – cosmic nucleosynthesis

Pre-Requisites

From PH10001 “Introduction to Quantum Physics”

Quarks, leptons and mediators

Antiparticles

Quark model of hadrons

Baryon and lepton number

The 4 forces

Classification of particles

Elementary particles can be grouped in several ways:

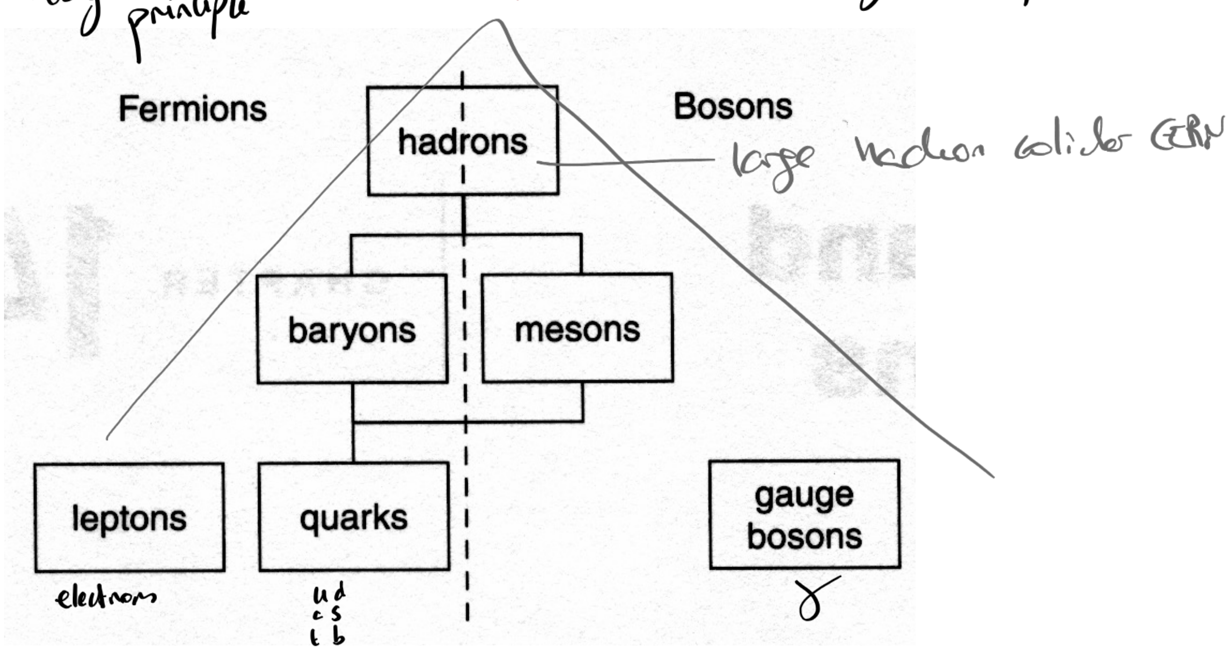
Fermions + Bosons

Quarks (baryons + mesons) + Leptons + Mediators

Fermions
- $\frac{1}{2}$ integer spin
- obey Pauli exclus° principle

V.S

Bosons
- integer spin
- don't obey P exclus° principle



This part is assumed known, and thus does not form part of the numbered sections. But a reminder never hurts …

Hadrons

Made of quarks (q) and antiquarks ($\bar{q}$)

6 quarks are known

ranking by increasing mass

	Quark flavour		Charge	
1st	up	u	$+\frac{2}{3}$	basic pair
	down	d	$-\frac{1}{3}$	
2nd	strange	s	$-\frac{1}{3}$	heavier
	charm	c	$+\frac{2}{3}$	
3rd	bottom	b	$-\frac{1}{3}$	heavier still
	top	t	$+\frac{2}{3}$	

↑
3 generations

Mesons

Quark – antiquark pair

Examples:

$$u\bar{d} \rightarrow \pi^+$$

$$\bar{u}d \rightarrow \pi^-$$

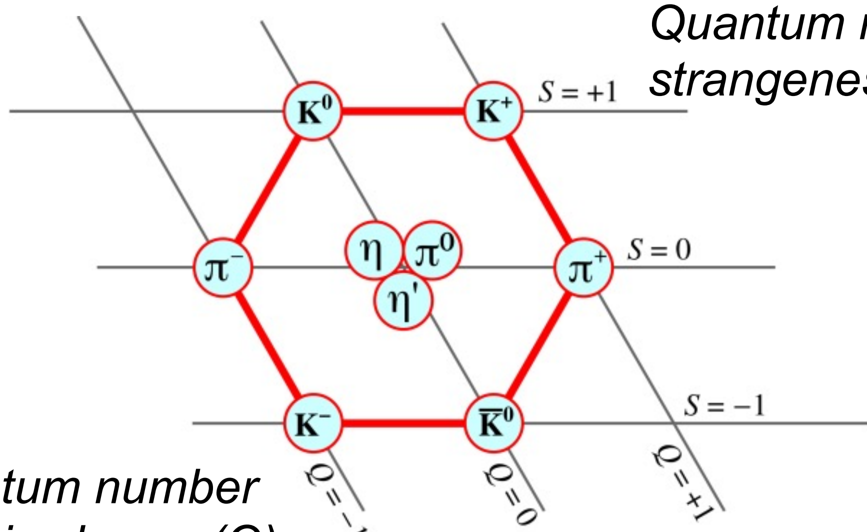
$$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}} \rightarrow \pi^0$$

Mixture of $u\bar{u}$ and $d\bar{d}$ states (can change into each other)

Mesons can be grouped into families: meson nonets

Example meson nonet of spin 0:

Quantum number strangeness (S)



Quantum number electric charge (Q)

Electric

charge

Baryons

Made of 3 quarks or 3 antiquarks

Baryons are composed of 3 identical quarks
&
aligned spin differ in color (RGB)

"hidden" quantum n° microscopic world in colorless

Examples:

$$uuu \rightarrow \Delta^{2+} \quad \left(\text{spin}\ \frac{3}{2}\right)$$

$$uud \rightarrow \begin{cases} p & \left(\text{spin}\ \frac{1}{2}\right) \\ \Delta^{+} & \left(\text{spin}\ \frac{3}{2}\right) \end{cases}$$

$$udd \rightarrow \begin{cases} n & \left(\text{spin}\ \frac{1}{2}\right) \\ \Delta^{0} & \left(\text{spin}\ \frac{3}{2}\right) \end{cases}$$

$$ddd \rightarrow \Delta^{-} \quad \left(\text{spin}\ \frac{3}{2}\right)$$

$$sss \rightarrow \Omega^{-} \quad (\text{3 quarks of distinct colours})$$

Baryons composed of 3 quarks of identical flavour and parallel spin do not violate Pauli exclusion principle because of a third 'hidden' quantum number, colour (RGB or $\bar{R}\bar{G}\bar{B}$). The macroscopic world is 'colorless'.

All hadrons are unstable in free space except the proton

Mesons $\xrightarrow[\text{(eventually)}]{\textit{decay into}}$ leptons & photons

Baryons $\xrightarrow[\text{(eventually)}]{\textit{decay into}}$ p (or $\overline{p}$), leptons & photons

Baryon number

$$\boxed{B = \frac{1}{3}\left(N(q) - N(\overline{q})\right)}$$

Conserved quantity

Leptons

Point-like or at least $< 10^{-18}$ m

Leptons are not composite

Most probably 6 leptons

electron	e^-	0.51 MeV/c^2	$L_e = +1$, $L_\mu = 0$, $L_\tau = 0$
e^- neutrino	ν_e	~ 0 (< 7 eV/c^2)	
muon	μ^-	105 MeV/c^2	$L_e = 0$, $L_\mu = +1$, $L_\tau = 0$
μ^- neutrino	ν_μ	~ 0 (< 300 eV/c^2)	
tau	τ^-	1800 MeV/c^2	$L_e = 0$, $L_\mu = 0$, $L_\tau = +1$
τ^- neutrino	ν_τ	~ 0	

They all have corresponding antiparticles

e^+ (positron) is the antiparticle of the electron e^-

Electrons and neutrinos are stable

μ^- and τ^- decay (eventually) into e^- and neutrinos

Lepton number

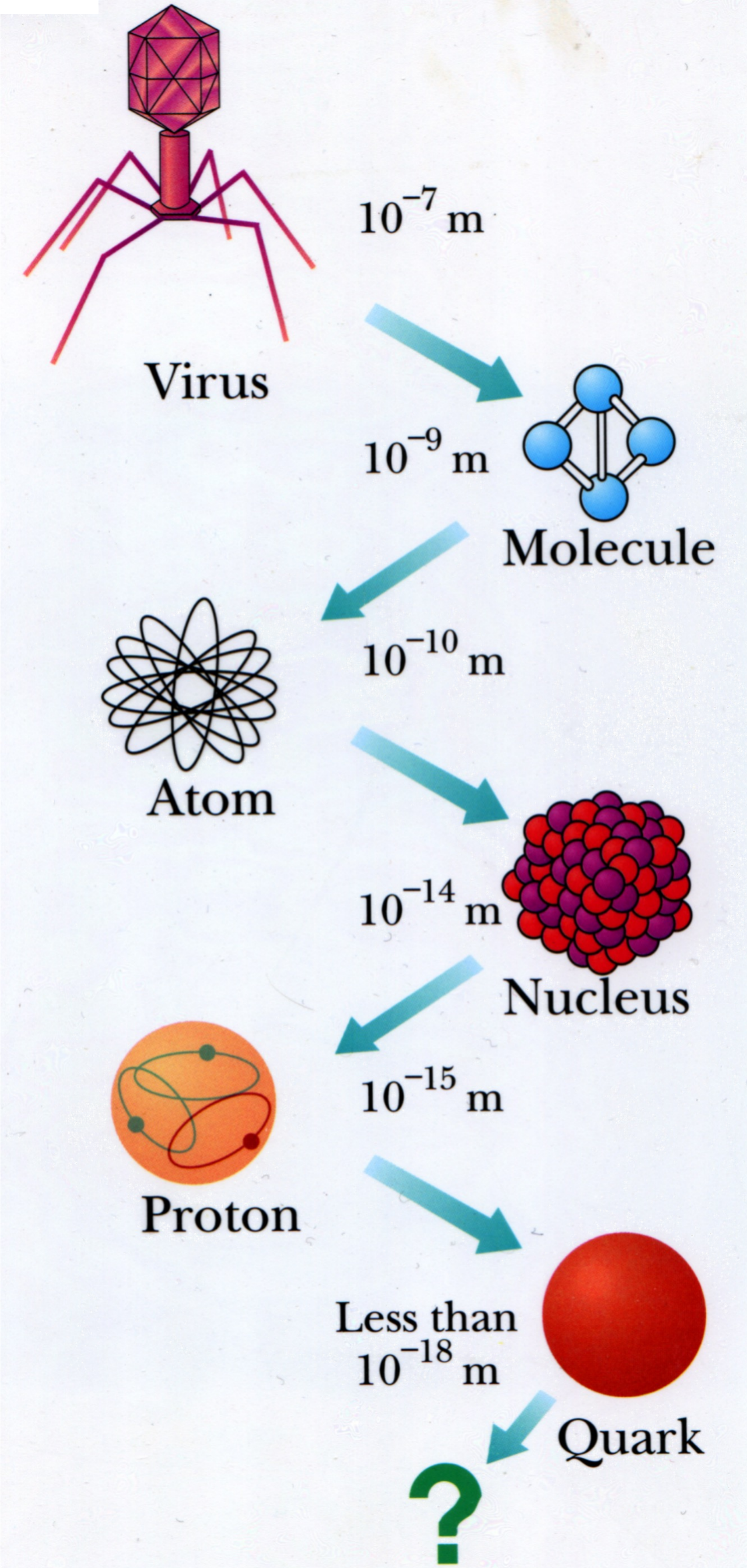
$$\boxed{L_e = N(e^-) - N(e^+) + N(\nu_e) - N(\bar{\nu}_e)}$$

and of course …

$$L_\mu = N(\mu^-) - N(\mu^+) + N(\nu_\mu) - N(\bar{\nu}_\mu)$$
$$L_\tau = N(\tau^-) - N(\tau^+) + N(\nu_\tau) - N(\bar{\nu}_\tau)$$

Dimensions

Atomic Physics		Nuclear Physics
1Å = 10^{-10} m	**LENGTH**	1 fm = 10^{-15} m
Shortest ~ 10^{-18} s (time for light to cross an atom)	**TIME**	Shortest ~ 10^{-23} s (light crossing a nucleus) Longest ~ 10^{17} s (age of the Universe)
m_e = 0.511 MeV/c^2	**MASS**	m_p = 938.3 MeV/c^2 m_n = 939.6 MeV/c^2 difference b/w p & n is important
10 – 1000 eV	**KINETIC ENERGY**	1 – 10 MeV (p's and n's will not be relativistic: KE << E_0) (but e^- will be …)



10^{-7} m
Virus
10^{-9} m
Molecule
10^{-10} m
Atom
10^{-14} m
Nucleus
10^{-15} m
Proton
Less than 10^{-18} m
Quark
?

particle info will be given in exam
(do not put it in the A4)

The 4 forces

(1) Gravity

Acts on all masses/energy

Always attractive

$\propto \frac{1}{r^2}$ Mediator: GRAVITON

↑ separation of 2 masses

Negligible in nuclear physics

(long range force: astrophysical scales)

(2) Electromagnetic force

Acts between all electrically charged particles

$\propto \frac{?}{r^2}$ Mediator: PHOTON (γ) γ

(3) Weak force

All hadrons/leptons experience weak force

Mediator: W^+, W^- Z^0 (BOSONS)

Seen in nuclear and particle decay

(4) Strong force

amplitude > weak force
does not apply to all particles

Acts on quarks/hadrons <u>but not</u> leptons

Mediator: GLUON (carries colour charge)

spring-like

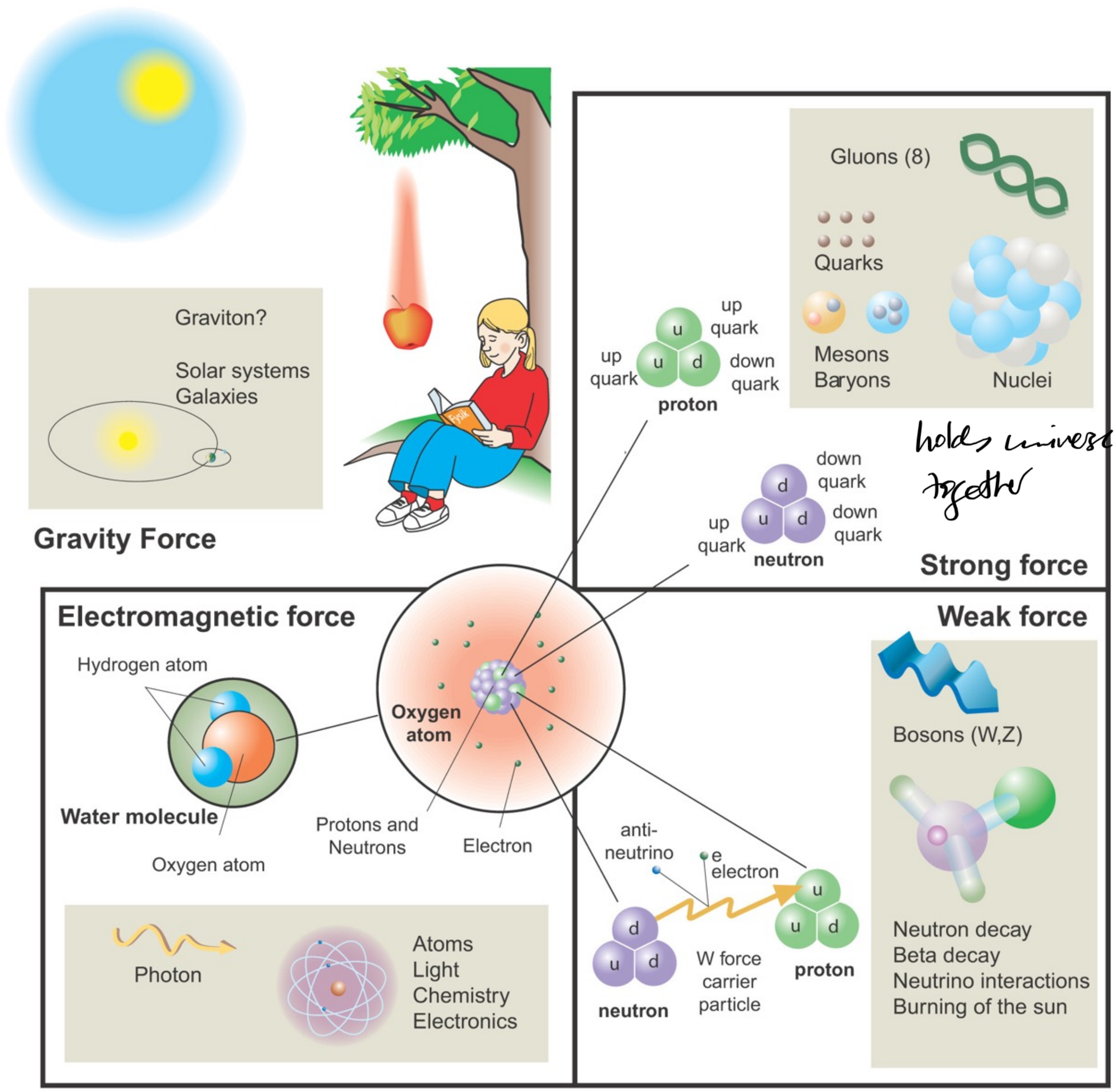
Holds hadrons and nuclei together

Force	*Range*	*Typical reaction time*	*Coupling constant*
E.M.	∞	$< 10^{-16}$ s	$\alpha = \frac{1}{137}$
weak	10^{-18} m	$> 10^{-12}$ s	$\alpha_w \approx 4\,\alpha$
strong	$\sim 10^{-15}$ m	10^{-23} s	$\alpha_s \approx 100\,\alpha$

Force	*"charge"*	*Exchange particle*	*Theory*		
gravity	mass	graviton	General Relativity		
E.M.	electric charge	photon	QED	electroweak	**G.U.T.**
weak	weak charge	W^+, W^-, Z^0			
strong	colour charge (r, g, b)	gluons	QCD		

$F r^2 \ll \hbar c \rightarrow$ force "weak"

$F r^2 \gg \hbar c \rightarrow$ force "strong"



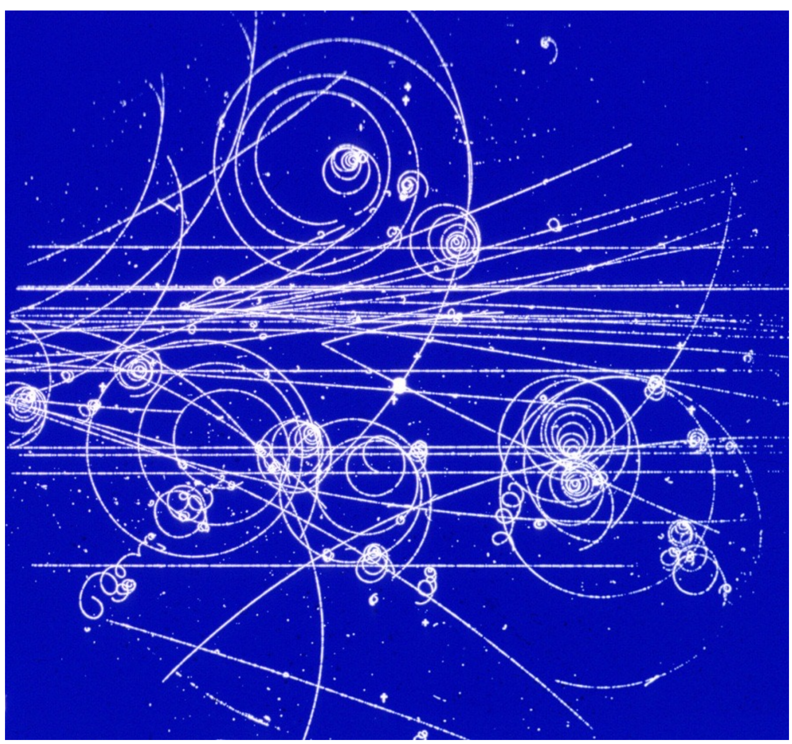
holds universe together

not sync bottom earth

nuclear decay

Conservation Laws

Decays and Reactions



must know all:

1.1. Conservation Laws

1. **Electric charge** is **always** conserved (including each vertex in a Feynman diagram)

2. **Momentum/angular momentum** are **always** conserved

3. **Energy** is **always** conserved (overall)

$E_{tot} = kE + E_e$

4. **Quark flavour** is conserved in strong and EM interactions but not in weak interactions

5. **Baryon number** is **always** conserved

6. **Individual lepton numbers** are **always** conserved

L_e : electron lepton n°
L_μ : muon lepton n°

Examples

Can this happen in nature?

Conservation law:

$\mu^- \rightarrow e^- + e^+ + e^-$

Charge	$-1 \rightarrow (-1) + (+1) + (-1)$ ✓	Yes
L_e (e lepton generation n°)	$0 \rightarrow (+1) + (-1) + (+1)$ ✗	No
L_μ (muon lepton generation n°)	$1 \rightarrow 0 + 0 + 0$ ✗	No

Not possible: violates conservation of L_e and L_μ

Conservation laws:

baryon, charges, electron ⇒ e lepton

$\Lambda \rightarrow \pi^{+} + e^{-} + \bar{\nu}_e$

Charge	$0 \rightarrow (+1) + (-1) + 0$	Yes
L_e	$0 \rightarrow 0 + (-1) + (+1)$	Yes
B	$1 \rightarrow 0 + 0 + 0$	No

Not possible: baryon number is not conserved

Heisenberg Uncertainty Principle

$\hbar$

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \, \Delta t \geq \frac{\hbar}{2}$$

Notes

look into rest mass origin

(i) “Energy is always conserved (overall)”

Energy can be uncertain to within ΔE for a time Δt when:

$$\Delta t \approx \frac{\hbar}{2\,\Delta E}$$

To create an extra particle of rest mass m_0:

$$\Delta E = m_0\, c^2 = E_0$$

∴ it can exist for

$$\Delta t = \frac{\hbar}{2\, m_0\, c^2}$$

∴ maximum range of this particle

$$= c\,\Delta t = \frac{\hbar}{2\, m_0\, c} = \frac{\hbar\, c}{2\, E_0}$$

Virtual photon → long-range force (m =0)

$L, m_0 = 0$

Virtual W can travel ~ 2×10^{-18} m = 0.002 fm (very short range ∴ weak force appears weak because particles rarely come this close at low energy)

(ii) “Energy is always conserved (overall)”

This applies to the conservation of mass/energy

We can convert: rest mass energy ↔ Kinetic Energy

Hence for a **decay**

$$A \rightarrow B + C$$

$M_A \geqq M_B + M_C$ (rest masses)

(for a decay: $M_B + M_C > M_A$ is not possible:
it would violate the conservation of energy)

However, for a **reaction**

$$A + X \rightarrow B + C$$

we can have

$$M_B + M_C \geqq M_A + M_X$$

The K.E. of A and X are converted into mass

(iii) Quark flavour is not conserved in weak interactions

∴ non-conservation of flavour => weak interaction

Conservation of flavour

may be possible by strong or E.M. interaction

both are much more likely than weak to occur!

If particles can decay by strong or E.M., they do so quickly

(iv) Conservation of baryon and lepton numbers <u>may</u> possibly breakdown

(in some Grand Unified Theories,
or at very high energies)

(v) There are 2 important transformations:

In QM, Particles ~ Wavefunct^ns

(P)arity $P(\psi(\vec{r})) = \psi(-\vec{r})$ $\underline{r} \rightarrow -\underline{r}$ mirror image of process

(C)harge conjugation

$$particle \leftrightarrow antiparticle$$

Symmetry under CP transformation means:
A process (e.g. decay) and its CP transform are equally likely to happen (i.e. same decay constant).

The weak interaction is **NOT** invariant under the combined CP transformation.

NOT symmetric

For example:

$$K_L^0 \rightarrow \pi^- + e^+ + \upsilon_e$$

occurs about 3 × 10^{-3} more often than

$$K_L^0 \rightarrow \pi^+ + e^- + \overline{\upsilon}_e$$

products = each other's anti-particle = each other's CP transform

(more likely verse)?

CP violation responsible for the dominance of matter over antimatter in the Universe.

$K_0 \longleftrightarrow \overline{K}_0$

but not in each direct^n as likely convergent

Recognising interactions

Weak interaction

neutrino/antineutrino involved

change of quark flavour

E.M. interaction

real photon is emitted or absorbed

lifetimes $10^{-16} – 10^{-20}$ s

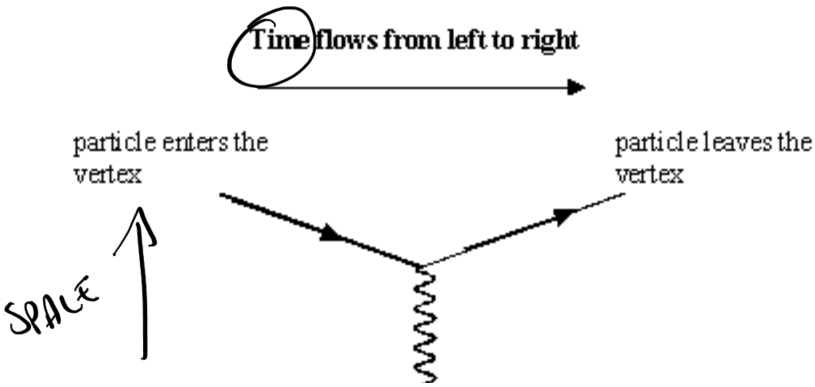
Strong interaction

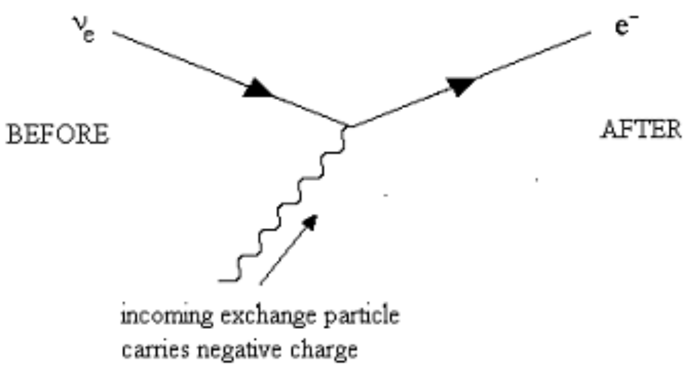
quark flavour is conserved

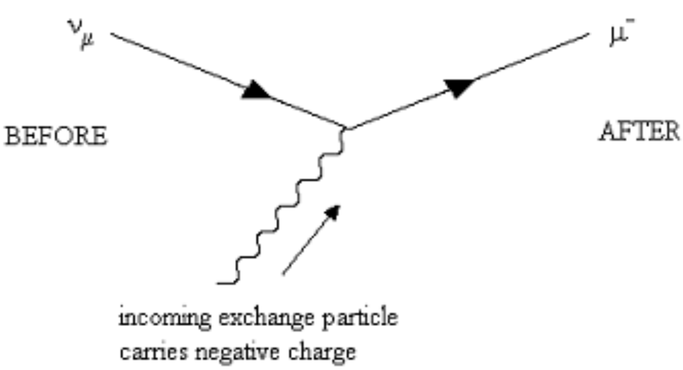
lifetimes $< 10^{-20}$ s

Feynman diagrams

Dimens: time, space







Feynman diagrams are schematic representations of particle interactions.
They DO NOT correspond to actual trajectories.

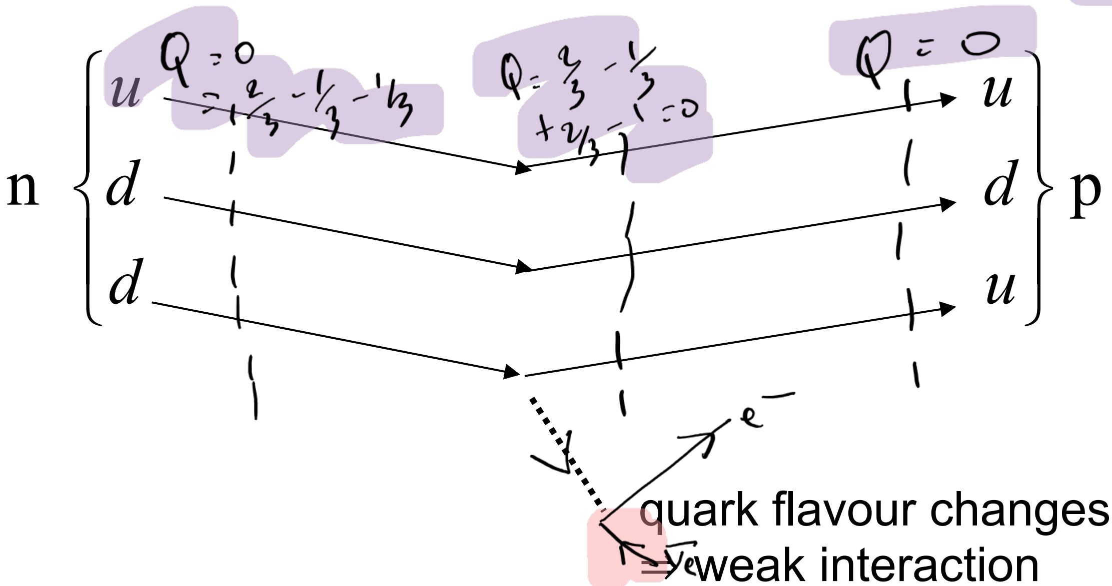
In more advanced applications, they can be used to calculate the probabilities of different interactions.

Particle decays (examples)

(1)) β⁻ decay

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

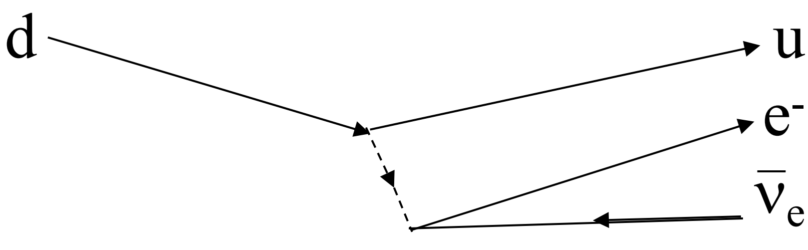
vertical line: all charge Σ = same value ← cons point



quark flavour changes
⇒ weak interaction

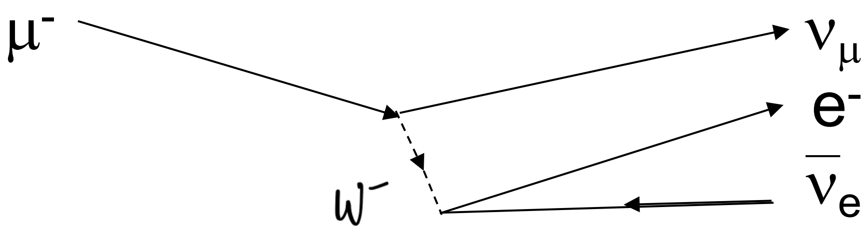
Opposite direction: notation saying opposite particle (neg)

~ 15 minutes



Charge is conserved (in both vertices)
L_e is conserved
Energy is conserved: $m_n > m_p + m_e$

(2) μ^- decay



$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

L_e : 0 $\rightarrow$ 0 +1 -1
L_μ : 1 $\rightarrow$ +1 0 0

weak interaction

~ 10^{-6} s

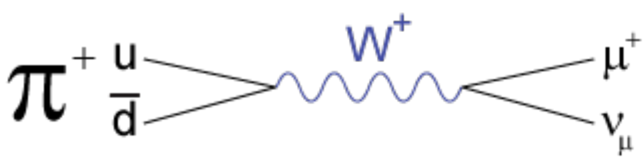
(3) π^+ meson decay

π^+ is made of quarks $u\bar{d}$

Typical decays:

$$\pi^+ \to \mu^+ + \nu_\mu \qquad (\text{probability} = 0.999877)$$

$$\pi^+ \to e^+ + \nu_e \qquad (\text{probability} = 0.000123)$$



weak interaction 2.6 × 10^{-8} s

(4) Σ^0 decay

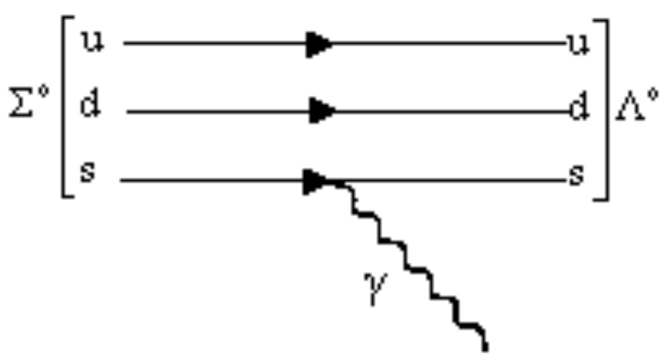
$$\Sigma^0 \rightarrow \Lambda^0 + \gamma$$
$$\{uds\} \quad \{uds\}$$

EM

Quark flavour is conserved

E.M. interaction (note the presence of a γ)

~ 10^{-20} s



One of the quarks in the Σ^0 emits a photon.

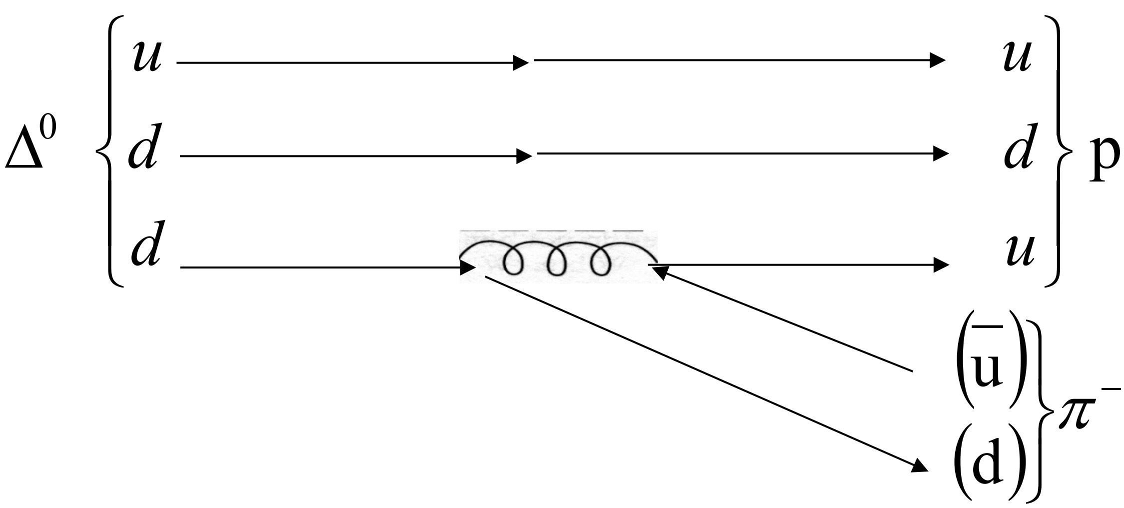
(5) Δ^0 decay

$$\Delta^0 \rightarrow p + \pi^-$$

$$\{udd\} \quad \underbrace{\{uud\} + \{\bar{u}d\}}_{udd}$$

Quark flavour is conserved

This can proceed via the strong interaction



(6) A reaction

$$\pi^- + p^+ \rightarrow K^0 + \Lambda^0$$

$$\{\bar{u}d\} + \{uud\} \rightarrow \{d\bar{s}\} + \{uds\}$$

Totals $\{udd\} \rightarrow \{udd\}$

Quark flavour is conserved

Charge $(-1) + (+1) \rightarrow 0 + 0$

Baryon number $0 + (+1) \rightarrow 0 + (+1)$

This can proceed via the strong interaction

Energy must be supplied:

mass (LHS) < mass (RHS)

1.2. Decay Laws

Two important values

λ decay constant

$t_{1/2}$ half-life

Probability of a nucleus or particle decay in time δt is proportional to this time: $\lambda\,\delta t$ ($\delta t \ll t_{1/2}$!)

Given N particles, in a time δt, we have $N\lambda\,\delta t$ decays

$$\therefore \quad \delta N = -N\,\lambda\,\delta t$$

$$\frac{dN}{dt} = -N\,\lambda$$

$$\Rightarrow N = N_0\, e^{-\lambda t} \qquad (1)$$

where $N_0 = N(t=0)$

The half-life is given by

$$e^{-\lambda t} = \frac{1}{2} \Leftrightarrow t_{1/2} = \frac{\ln 2}{\lambda} \qquad (2)$$

$$\text{mean life} = \frac{1}{\lambda}$$

Activity of source = number of decays per unit time

$$= \lambda\, N$$

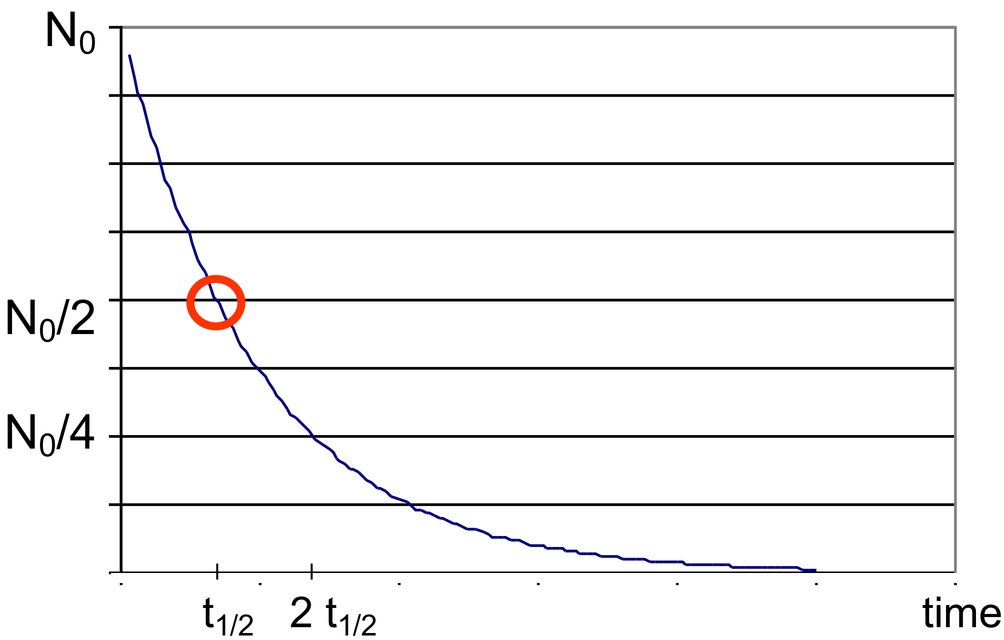
$$= \lambda\, N_0\, e^{-\lambda t}$$

1 Curie = 3.7 x 10^{10} decays s^{-1}

SI unit: Becquerel (Bq) = 1 decay s^{-1}

<u>Note:</u> activity decays with time

Number of particles



Initial activity = λN_0

Average activity over first half-life is:

$$A = \frac{N_0/2}{\ln 2/\lambda} = \frac{N_0\,\lambda}{2\ln 2}$$

This is not the same!

1.3. UNIFICATION OF FORCES

Are there really 4 distinct forces ?

FORCE

intrinsic strength   range

Perhaps forces only look different because of range

e.g. $W^{\pm}$ and Z^0 are heavy

$\therefore$ weak force range ~ 0.002 fm

Particles rarely get this close,

<u>except at high energies</u>

Particle motion is described by a wave

$\psi = e^{\mathrm{i}k\,x}$ with wavenumber $k = \frac{p}{\hbar}$

Wavefield only “sees” an object of size “a” when

$$\lambda \le a$$

A particle (e.g. p^+, e^-) beam with rest mass m_0 has the de Broglie wavelength $\lambda_B = \frac{h}{p}$

From special relativity:

$$E^2 = (pc)^2 + \left(m_0 c^2\right)^2$$

where $E = \text{total energy}$

$$= m_0 c^2 + KE$$ *(Kinetic Energy)*

So for extremely relativistic case:

$$\lambda_B \approx \frac{h\,c}{KE} \quad \left(KE >> m_0 c^2\right)$$

The De Broglie wavelength for a relativistic particle:

$$\lambda_B \approx \frac{h\,c}{KE}$$

Range of force mediated by exchange particle of rest mass energy E_0 is:

$$\frac{\hbar\,c}{E_0}$$

For large probability of interaction:

$\lambda_B \leq$ range of interaction

i.e. $$\frac{\hbar\,c}{KE} \leq \frac{\hbar\,c}{E_0}$$

occurs when Kinetic Energy $KE \geq E_0$

If $KE << E_0$,

weak interaction is really weak
(for W ~ 90 GeV)

For KE > 90 GeV,

weak and EM forces become
<u>equally strong</u>

They come equivalent

⇒ **UNIFICATION**

At lower energies, this symmetry is broken

Temperature/Energy equivalents:

1/40 eV ≡ 300 K

100 GeV ≡ 10^{15} K

$\left.\begin{array}{c}\text{Electroweak model} \\ + \\ \text{QCD model}\end{array}\right\}$ **STANDARD MODEL**

Electroweak theory predicted:

W^+ ✓ <u>found experimentally</u>

W^- ✓ <u>found experimentally</u>

Z^0 ✓ <u>found experimentally</u>

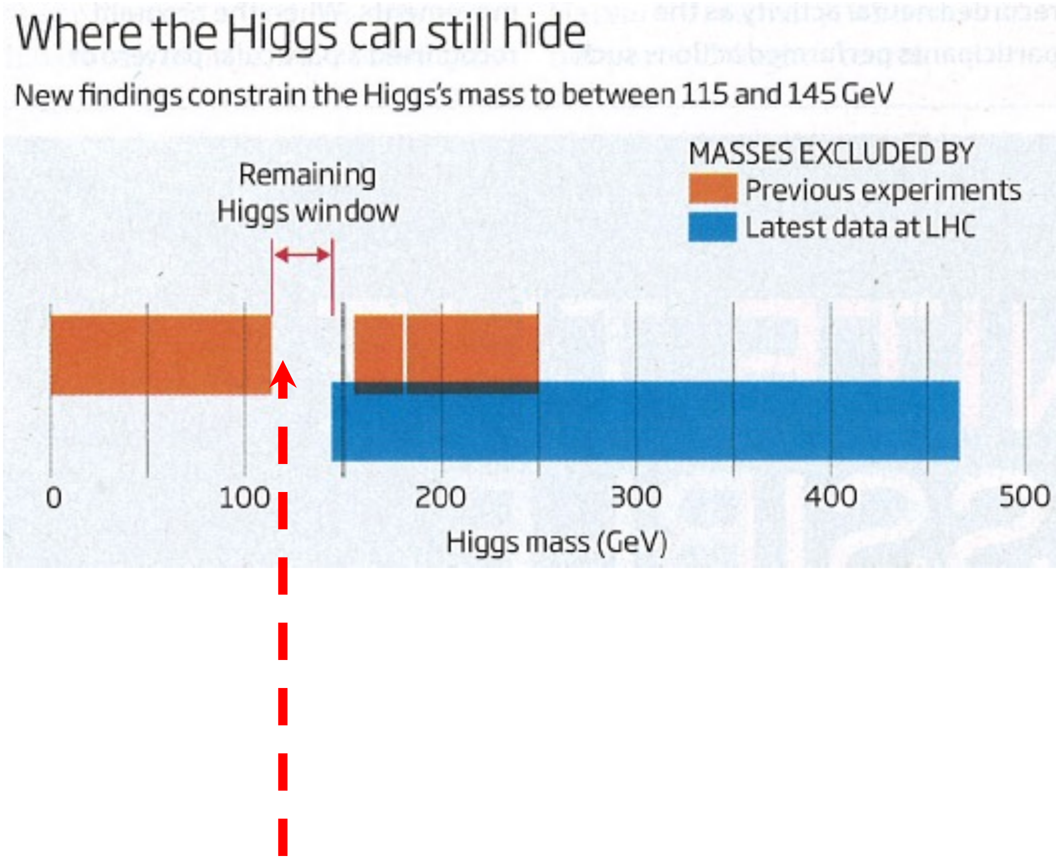
Theory also introduced:

Higgs mechanism/field

to give $W^\pm$, Z^0 mass

This implies the existence of the Higgs boson(s)

It should be neutral, with a spin of 0.



New Scientist, Sep. 2011

Theory: 1964. **Confirmed: July 2012 !!!**

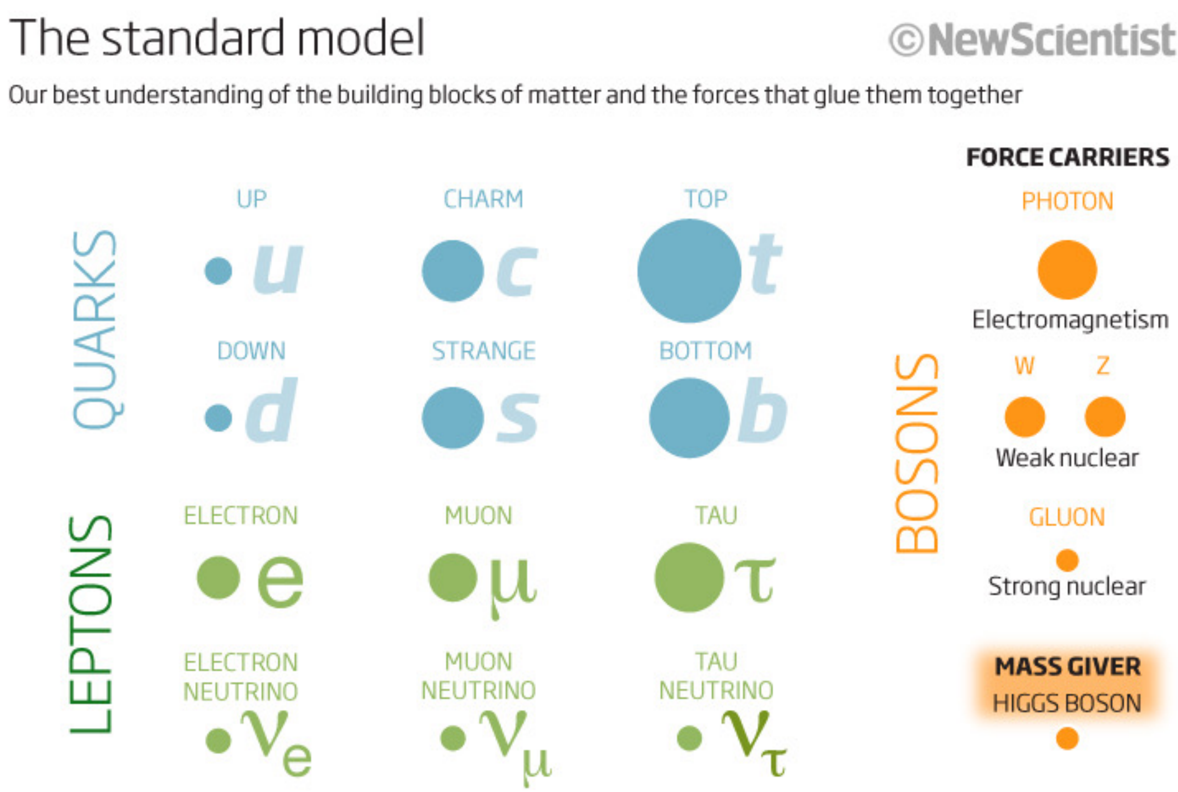
Mass: 125-126 GeV. Lifetime: 10^{-22} s. Seen from its decays.

1 Higgs expected per 10^{10} p-p collisions (10^{15} x 2 achieved by September)

Confidence level: 5 σ, i.e. 5-in-10^6 chance of being “a fluke”
Separate observations by the twin CMS and ATLAS detectors at the Large Hadron Collider (CERN). Confirmed by Tevatron results.

One property that needs to be investigated is the particle's spin (0 in standard model, 2 for more exotic theories). In July 2013, the ATLAS collaboration confirmed the spin was 0..

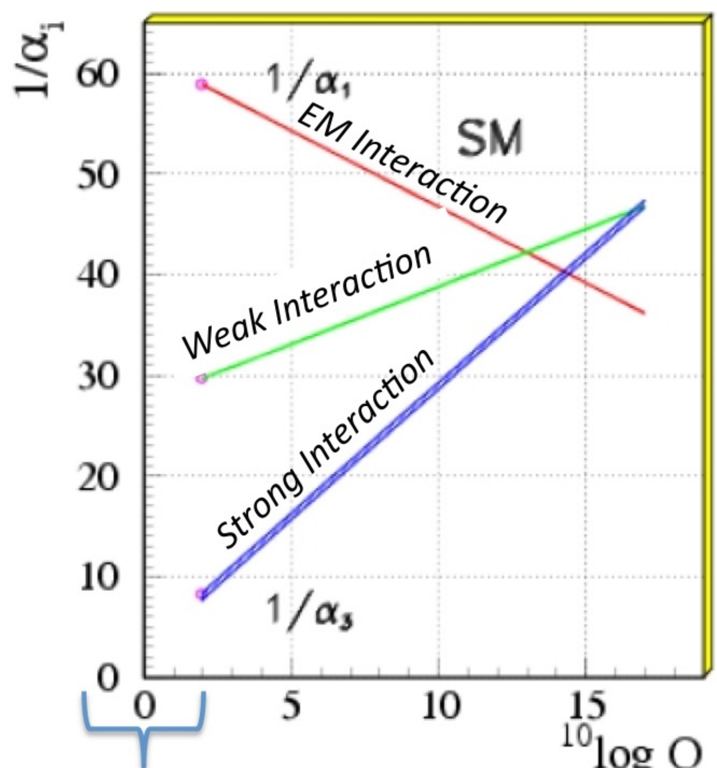
We know that the standard model is not complete – it does not contain dark matter or gravity, for a start – so a non-standard model Higgs could be very exciting.



Sep. 2012

Variation of interaction strength

(extrapolated from low energies)



The experimental domain: $Q \sim< 500$ GeV

10^{-31} m ≡ 10^{15} GeV

At even higher energies, strong interaction may possibly be unified:

⇒ G.U.T.s (Grand Unified Theories)

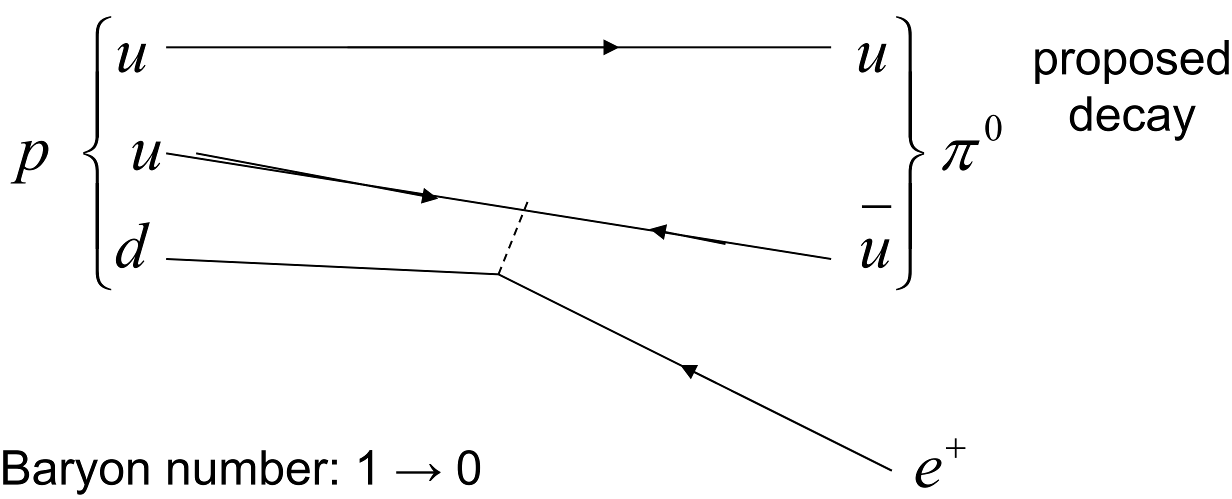
Quarks and leptons start to interact via new particles

(e.g. the X boson)

Mass (predicted) ~ 10^{15} GeV !

Range (predicted) ~ 10^{-31} m !

⇒ possibility of proton decay



Baryon number: 1 → 0

Lepton number: 0 → -1

(breakdown of conservation of baryon/lepton numbers)

Theory predicts a half-life ≥ 10^{32} years !!

(not yet observed)

What about gravity ?

Dimensional argument:

What are the important quantities in a quantum gravity theory ?

$\hbar$	G	c
$M\ L^2\ T^{-1}$	$M^{-1}\ L^3\ T^{-2}$	$L\ T^{-1}$

Planck length: $\left(\dfrac{G\,\hbar}{c^3}\right)^{1/2}$ $\sim 10^{-35}$ m

Planck energy: $\left(\dfrac{\hbar\,c^5}{G}\right)^{1/2}$ $\sim 10^{19}$ GeV

On these scales, we will need a quantum theory of gravity.

Research topics of current interest

- Neutrino oscillations
  - Neutrinos can change from one flavour to another during flight
- CP violation
  - responsible for excess of matter over antimatter (see 1.1 Conservation Laws)
- Mass of particles
  - ~~Search for Higgs boson~~ Ended: July 2012
  - Mass of photon ???
- Proton decay
  - Would give information on GUTs
- Supersymmetry
- Origin of cosmic rays
  - Cosmic rays are highly energetic charged particles. Breakthrough discovery in 2017 identifying blazars as the cosmic accelerators producing them.
- Dark matter
  - Indirect evidence for its existence and ongoing efforts to detect dark matter particles (e.g. WIMPS) directly.

Neutrino oscillations

Neutrinos can change from one flavour to another during flight

Experimentally proven using large neutrino detectors such as Super-Kamiokande by studying:

Solar neutrinos: less ν_e observed than expected from known fusion processes in the Sun

Atmospheric neutrinos: measuring changes in flux ratio of ν_e and ν_μ over a baseline of the radius of the Earth

Beam neutrinos: particle accelerator shooting muon beam at neutrino detector several 100km away

Implication: neutrinos have mass

(even though little ~0.05 eV)

Theory can explain neutrino mass and oscillation parameters with small changes to Standard Model. Neutrino flavour is superposition of eigenstates of different mass, which travel at slightly different speeds.

Origin of cosmic rays

Cosmic rays are **charged particles** (mostly protons) with the highest energies ever observed: up to 10^8 times the energies achievable with accelerators at CERN

Problem: Their paths are deflected and distorted by **magnetic fields** in extragalactic space, the Milky Way and surrounding the Earth
⇒ impossible to determine their point of origin

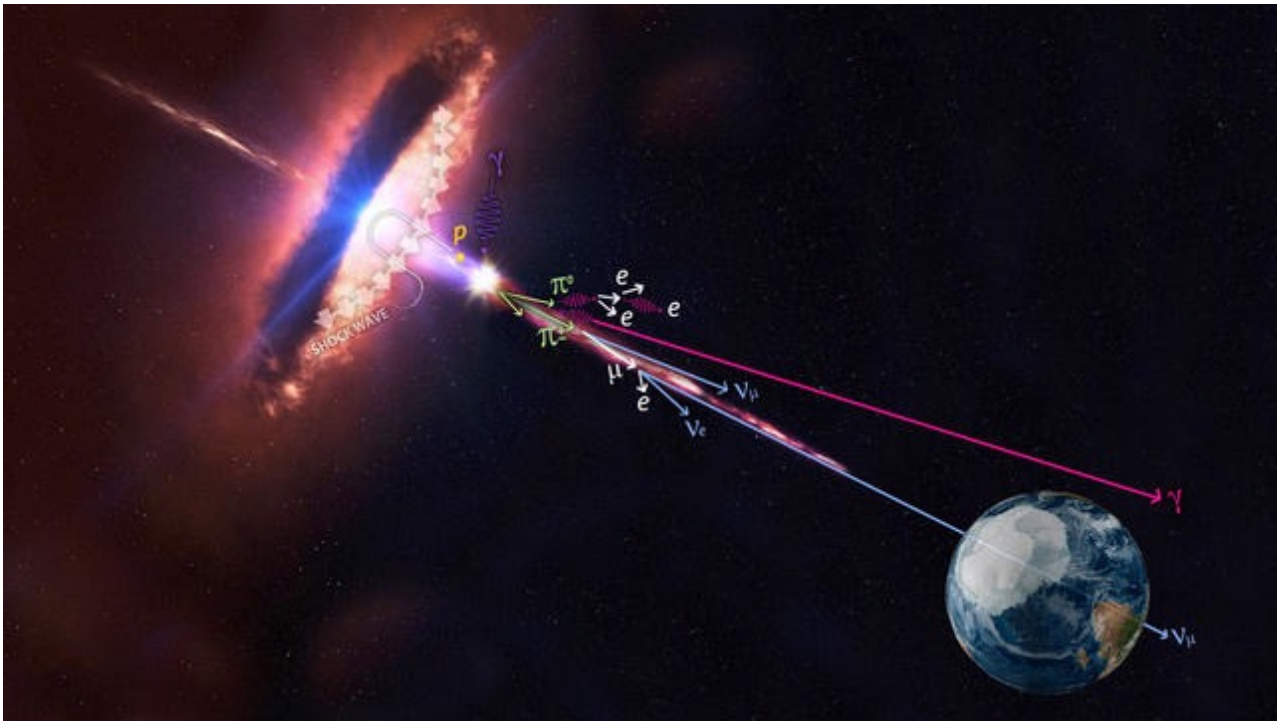
The sources responsible for accelerating cosmic rays have been a puzzle since their discovery over a century ago.

Solution: **High-energy neutrinos**, produced by the same same cosmic accelerators, are uncharged and thus preserve directional information.

Breakthrough: **Direction of a high-energy neutrino traced back to a well-known blazar** which at the same time showed enhanced gamma-ray emission.
Discovery by ICECUBE neutrino observatory in 2017!

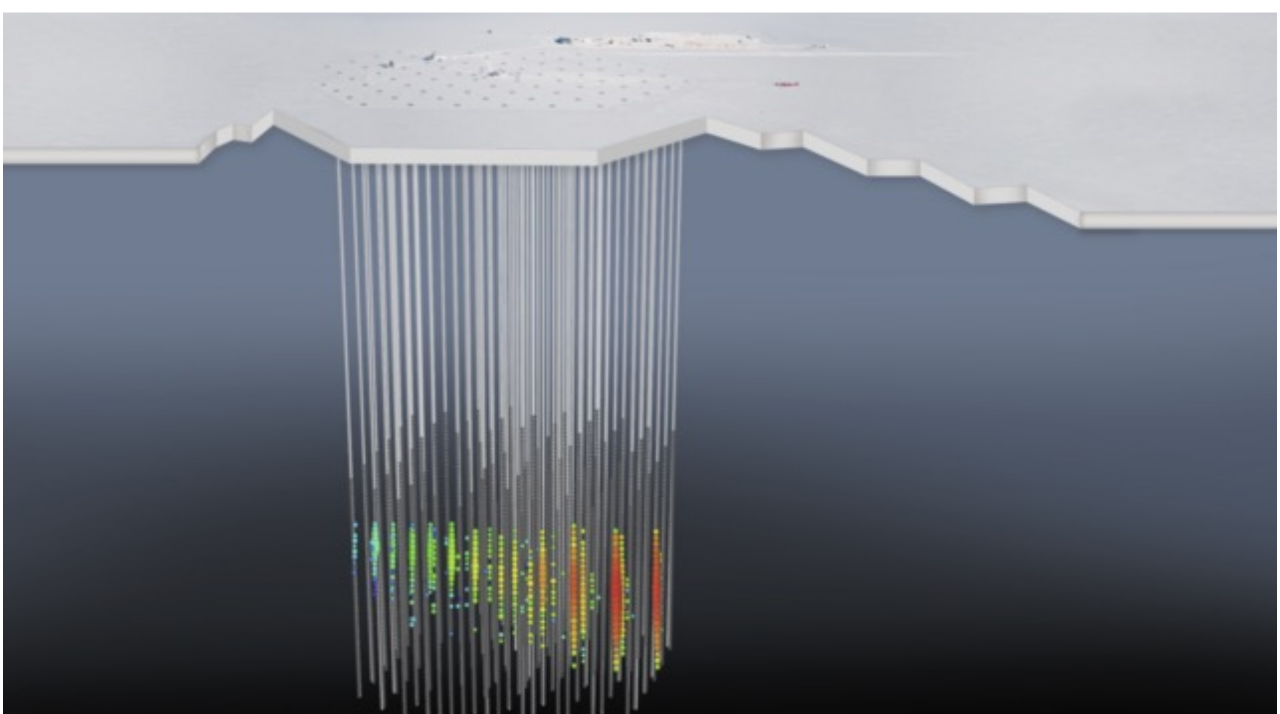
Theory: Feeding supermassive black holes at the centre of galaxies launch powerful jets which accelerate protons (i.e., produce cosmic rays). When this jet happens to be directed towards Earth we call the feeding black hole a **blazar**. Collisions between accelerated protons produce pions, which leave neutrinos and gamma rays as decay products moving in the jet direction.

Blazars as cosmic accelerators producing cosmic rays, high-energy neutrinos and gamma-rays



ICECUBE neutrino observatory detecting the trace of a high-energy neutrino

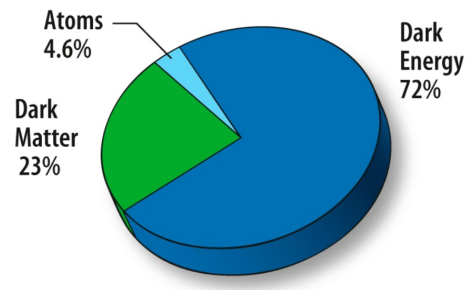
(color gradient shows time sequence)



Hunting for Dark Matter (DM)

Indirect evidence

Dynamical measurements of **galaxies in clusters** indicate there is more mass than can be accounted for by the visible mass. Similarly, **galaxy rotation curves** reveal more mass than present in stars.



Today's standard cosmology including dark matter and dark energy successfully reproduces observations of **large scale structure**, **expansion of the universe**, and fluctuations in the **cosmic microwave background**.

Candidates

Baryonic dark matter (e.g. planets) and light dark matter particles (e.g. neutrinos) ruled out as major contributor. Leading candidates are Weakly Interacting Massive Particles (WIMPS; ~100 GeV mass range)

Toward dark matter detection

- Attempts to **detect DM particles scattering** off atomic nuclei; dozens of detector experiments running / in development. This includes directional experiments (using Sun's motion in Milky Way).
- Attempts to **produce WIMPs in collisions** [LHC] ⇒ detect indirectly through apparent violation of conservation laws.
- High-energy telescopes and neutrino telescopes looking for signatures of **dark matter – anti dark matter annihilation** (e.g. look for signal from Milky Way center).
  [Ubath partner in Cherenkov Telescope Array]