1

Historial overview of topics that is relevant to us (Particle physics)

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Note

- The discussions are completely not vigorous, in terms of Facts and Timeline
- We focus more on the conceptual ideas and discoveries than technical details

- Obviously personally biased

Before 1900s

- Well established physics are
- Classical Mechanics
  - Newtons Law, Hamiltonian and Lagrangian mechanics
- Electromagnetism
  - Maxwell Equations
- Thermodynamics
  - Kinetic theory of gases

Particles here are characterised by
- Charge
- Mass
- (size)?
- Angular momentum / spin
- Position ($\vec{x}$)

Waves
- Wavelength
- Wave speed
- Frequency
- Interferences
- Diffraction

Special relativity 1905

- "Physics" is the same in inertial frames
  - Lorentz Invariances
- Inertial frames are related by Lorentz Transformation

See Appendix. Relativity, or any special realativity texts books for more details

- $$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\gamma\frac{v}{c} & 0 & 0 \\ -\gamma\frac{v}{c} & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix} \quad \text{or} \quad x'^{\nu} = \sum_{\mu} \Lambda^{\nu}_{\mu} x^{\mu} \equiv \Lambda^{\nu}_{\mu} x^{\mu} \ \text{ with } \ x^{\mu} = \begin{bmatrix} x^0 \\ x^1 \\ x^2 \\ x^3 \end{bmatrix} = \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$
- x^{μ} is an example of a 4-vector, which transforms according to Lorentz Transformation
- Length contraction
- Time dilation
- 4-momentum

We will use special relativity a lot in this course!

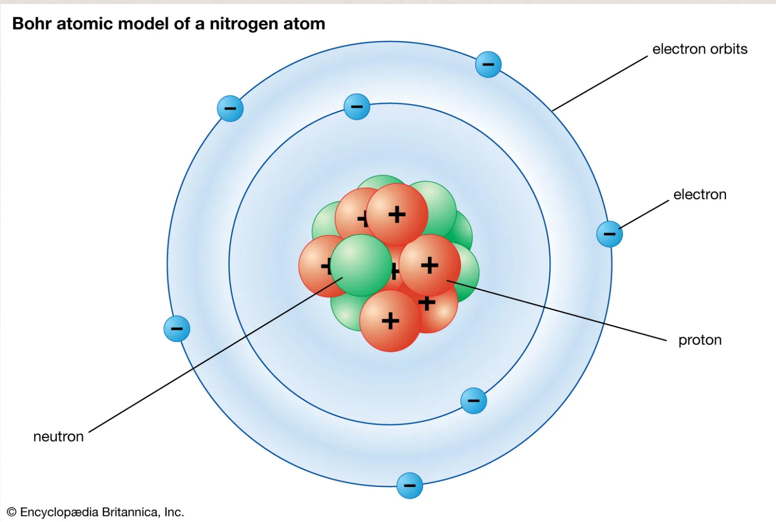
Special relativity 1905

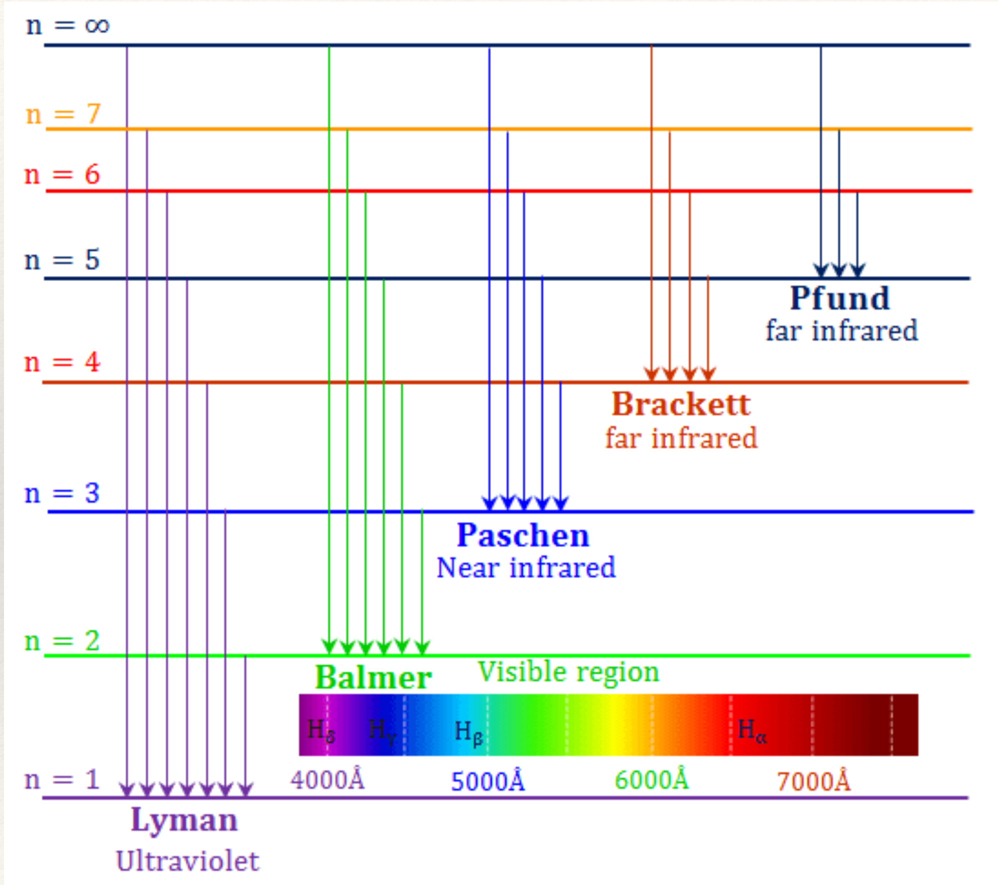
- Speed of light is a constant in nature
- $c = 299792458 m/s = 3 \times 10^8 m/s$
  - $=$ 1 if we define $1\text{m} = \dfrac{1}{3 \times 10^8}\,\text{s}$ ([L] = [T])
- Because $E = mc^2 = m$
- Units of Mass = Units of energy
- In high energy physics, mass is typically expressed in eV
- We will put "c" in and out of equations as we like, based on the situation
  - You should know what to do, based on the units

- Proton mass
  - 938.3 MeV$/c^2$ = 938.3 MeV
  - ($\simeq$ 1GeV)
- Neutron mass
  - 939.6 MeV ($\simeq$ 1 GeV)
- Electron mass
  - 511 keV

Atoms

- Protons (1917), electrons (1897), neutrons (1932)
- Bohr Model (1911-1918)
- Electron transitions in atoms produces atomic lines





Quantum Mechanics

- Planck distribution, Planck's Law (1900)

- $$\frac{dF}{d\Omega dE} = \frac{2cE^3}{(hc)^3}\frac{1}{e^{\frac{E}{kT}} - 1}$$
- Energy per area per time per solid angle per energy
- (We will come back to distributions like this many times)

- $E = hf$, were f is light frequency, and h is Planck constant
- $E = hf = \dfrac{hc}{\lambda}$. Now we define the reduced Planck constant $\hbar = h/2\pi$
- $E = \hbar\omega = \dfrac{2\pi\hbar c}{\lambda}$, were ω is the angular frequency

Quantum Mechanics

- Because (reduced) Planck constant is a fundamental constant, we can also choose to set it "1"
- Looking at the units
- $h = [E][T] = [E][L]$, from speed of light
- So we can define Energy as $[\text{Time}]^{-1}$ or $[\text{Length}]^{-1}$

- In particle physics convention,
- $\hbar c = 1$
- $\simeq 200$ MeV fm
- $\simeq 200 \times 10^{-15}$ MeV m

Planck constant	
Common symbols	h
SI unit	joule per hertz (J/Hz)
In SI base units	$\mathrm{kg \cdot m^2 \cdot s^{-1}}$
Dimension	$\mathsf{ML^2T^{-1}}$
Value	$6.626\,070\,15 \times 10^{-34}\ \mathrm{J \cdot Hz^{-1}}$ $4.135\,667\,696... \times 10^{-15}\ \mathrm{eV \cdot Hz^{-1}}$

Reduced Planck constant	
Common symbols	$\hbar$
SI unit	joule-second (J·s)
In SI base units	$\mathrm{kg \cdot m^2 \cdot s^{-1}}$
Derivations from other quantities	$\hbar = \dfrac{h}{2\pi}$
Dimension	$\mathsf{ML^2T^{-1}}$
Value	$1.054\,571\,817... \times 10^{-34}\ \mathrm{J \cdot s}$ $6.582\,119\,569... \times 10^{-16}\ \mathrm{eV \cdot s}$

electron charge magnitude	e	$1.602\ 176\ 634 \times 10^{-19}$ C	exact
conversion constant	$\hbar c$	197.326 980 4 . . . MeV fm	exact*
conversion constant	$(\hbar c)^2$	0.389 379 372 1 . . . $\mathrm{GeV^2}$ mbarn	exact*

PDG

- A list of use physical constants and their precision can be found in PDG
- https://pdg.lbl.gov/2024/reviews/rpp2024-rev-phys-constants.pdf
- PDG = Particle Data Group
- Publish the yearly review of particle physics
- Super concise, good as a starting point/dictionary

1. Physical Constants

Table 1.1: Revised 2024 by D. Robinson (LBNL) and P.A. Zyla (LBNL). Mainly from "CODATA Recommended Values of the Fundamental Physical Constants: 2018," E. Tiesinga, D.B. Newell, P.J. Mohr, and B.N. Taylor, NIST SP961 (May 2019) [1].[a] The electron charge magnitude e, and the Planck, Boltzmann, and Avogadro constants h, k, and N_A, now join c as having defined values; the free-space permittivity and permeability constants ϵ_0 and μ_0 are no longer exact. These changes affect practically everything else in the Table. Figures in parentheses after the values are the 1-standard-deviation uncertainties in the last digits; the fractional uncertainties in parts per 10^9 (ppb) are in the last column. The full 2018 CODATA Committee on Data for Science and Technology set of constants are found at `https://physics.nist.gov/cuu/Constants/archive2018.html`. The last set of constants (beginning with the Fermi coupling constant) comes from the Particle Data Group. See also "The International System of Units (SI)," 9th ed. (2019) of the International Bureau of Weights and Measures (BIPM), `https://www.bipm.org/utils/common/pdf/si-brochure/SI-Brochure-9-EN.pdf`.

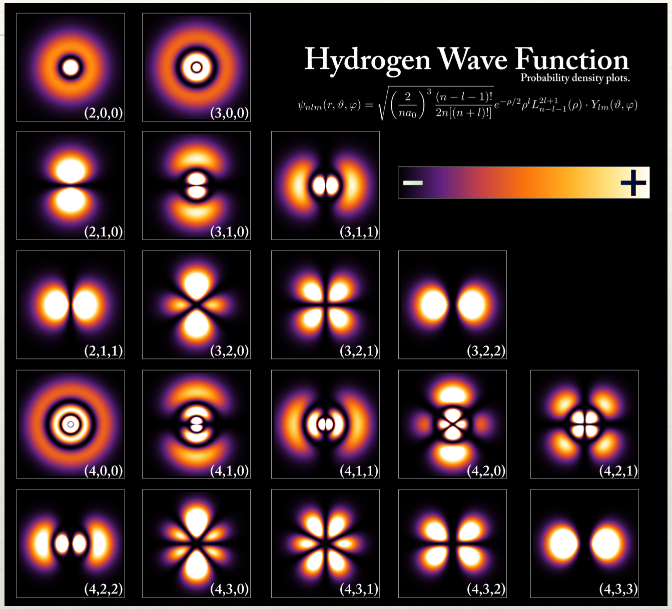
Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	$299\ 792\ 458$ m s^{-1}	exact
Planck constant	h	$6.626\ 070\ 15\times10^{-34}$ J s (or J/Hz) §	exact
Planck constant, reduced	$\hbar \equiv h/2\pi$	$1.054\ 571\ 817\ldots \times 10^{-34}$ J s	exact*
		$= 6.582\ 119\ 569\ldots \times 10^{-22}$ MeV s	exact*
electron charge magnitude	e	$1.602\ 176\ 634\times10^{-19}$ C	exact
conversion constant	$\hbar c$	$197.326\ 980\ 4\ldots$ MeV fm	exact*
conversion constant	$(\hbar c)^2$	$0.389\ 379\ 372\ 1\ldots$ GeV^2 mbarn	exact*
electron mass	m_e	$0.510\ 998\ 950\ 00(15)$ MeV/c^2 $= 9.109\ 383\ 7015(28)\times10^{-31}$ kg	0.30
proton mass	m_p	$938.272\ 088\ 16(29)$ MeV/c^2 $= 1.672\ 621\ 923\ 69(51)\times10^{-27}$ kg	0.31
		$= 1.007\ 276\ 466\ 621(53)$ u $= 1836.152\ 673\ 43(11)\ m_e$	0.053, 0.060
neutron mass	m_n	$939.565\ 420\ 52(54)$ MeV/c^2 $= 1.008\ 664\ 915\ 95(49)$ u	0.57, 0.48
deuteron mass	m_d	$1875.612\ 942\ 57(57)$ MeV/c^2	0.30
unified atomic mass unit**	$u = (\text{mass } ^{12}\text{C atom})/12$	$931.494\ 102\ 42(28)$ MeV/c^2 $= 1.660\ 539\ 066\ 60(50)\times10^{-27}$ kg	0.30
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	$8.854\ 187\ 8128(13)\ \times10^{-12}$ F m^{-1}	0.15
permeability of free space	$\mu_0/(4\pi \times 10^{-7})$	$1.000\ 000\ 000\ 55(15)$ N A^{-2}	0.15
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	$7.297\ 352\ 5693(11)\times10^{-3} = 1/137.035\ 999\ 084(21)$ †	0.15
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.817\ 940\ 3262(13)\times10^{-15}$ m	0.45
(e^- Compton wavelength)/2π	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$	$3.861\ 592\ 6796(12)\times10^{-13}$ m	0.30
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	$0.529\ 177\ 210\ 903(80)\times10^{-10}$ m	0.15
wavelength of 1 eV/c particle	$hc/(1\text{ eV})$	$1.239\ 841\ 984\ldots \times 10^{-6}$ m	exact*
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	$13.605\ 693\ 122\ 994(26)$ eV	1.9×10^{-3}
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	$0.665\ 245\ 873\ 21(60)$ barn	0.91
Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\ 381\ 8060(17)\times10^{-11}$ MeV T^{-1}	0.30
nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\ 451\ 258\ 44(96)\times10^{-14}$ MeV T^{-1}	0.31
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	$1.758\ 820\ 010\ 76(53)\times10^{11}$ rad s^{-1} T^{-1}	0.30
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	$9.578\ 833\ 1560(29)\times10^{7}$ rad s^{-1} T^{-1}	0.31
gravitational constant‡	G_N	$6.674\ 30(15)\times10^{-11}$ m^3 kg^{-1} s^{-2}	2.2×10^4
		$= 6.708\ 83(15)\times10^{-39}\ \hbar c$ (GeV/c^2)$^{-2}$	2.2×10^4
standard gravitational accel.	g_N	$9.806\ 65$ m s^{-2}	exact

Wavelengths

- We now know energy ~ 1/Length
- High energy means small length/wavelength, vice versa
  - Means we can see with higher resolution.

- Related length scales:
- De Broglie Wavelength $\lambda = h/p$
- Compton Wavelength $\lambda = h/mc$
  - Even particles that are not moving could have non-zero length scales

Quantum Mechanics



- Schrödinger Equation (1925)

$$i\hbar\frac{\partial}{\partial t}\Psi(x,t) = \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x,t)\right]\Psi(x,t).$$

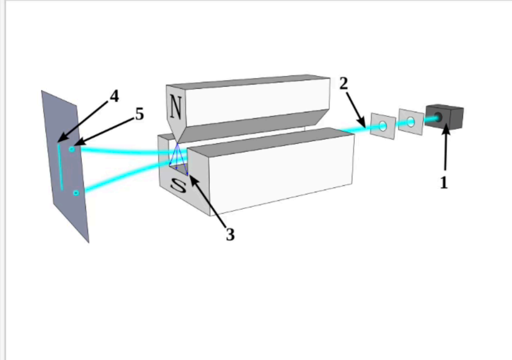
- Solving the hydrogen atom reveal that electrons does not behave like point-like particles.
- Instead, they behave like clouds around the nucleus, and the wavefunction is related to probability as
- $dP = |\Psi|^2 \mathrm{dx}$
- Particles are not just labeled just by (x, p), but also its "States"
- But Schrödinger Equation can not be used to describe Relativistic Equations! Obvious by looking at the derivative power of the operators.

Dirac equation

$$\boxed{(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi = 0}$$

Quantum Mechanics

- Dirac Equation (1928)
- μ = t, x
- And γ^{μ} are 4, 4x4 matrices.
- That is a lot of equations compared to Schrodinger!
- Turns out Dirac equation admits particles with equal masses but in opposite changes.
  - (There is much more than this, we will talk more when we talk about neutrinos)
- There are now interpreted as Anti-particles



Stern–Gerlach experiment: Silver atoms travelling through an inhomogeneous magnetic field, and being deflected up or down depending on their spin; (1) furnace, (2) beam of silver atoms, (3) inhomogeneous magnetic field, (4) classically expected result, (5) observed result

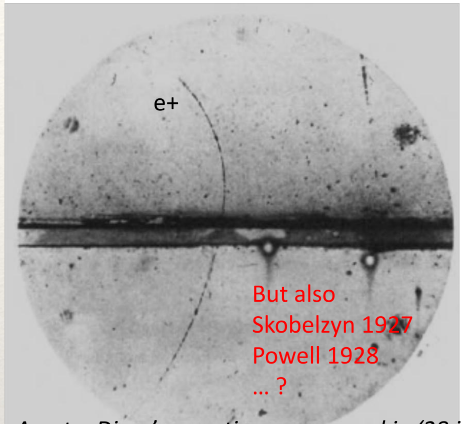
- Stern-Gerlach experiment 1921-1922
- Electrons (particles) have spins that can be half-integers

Anti-electrons

- Anderson (1932)
- Observations of particles that looks like electrons, but have opposite charge, from Cosmic Rays
- Interpreted as the positrons (anti-electrons) predicted from Dirac equation
- Antiparticles can annihilate with normal particles

Antimatter (the antielectron, or positron: Anderson 1933)

- *Consistent with Weil's interpretation of Dirac's equation (1927-28) …*

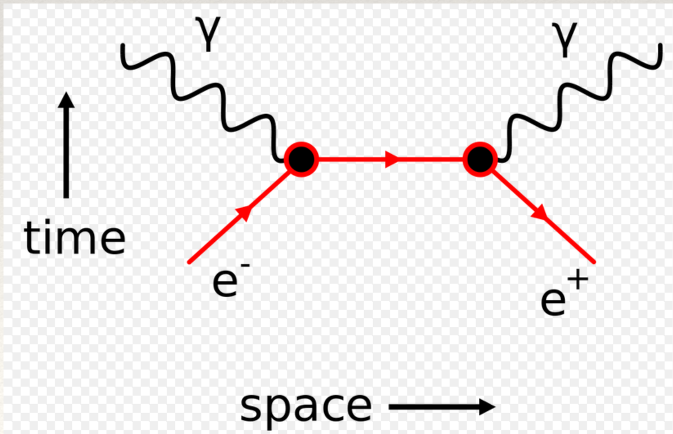


- Picture taken by Anderson in 1932 of a cloud chamber (Nobel to Wilson in 1927) in the presence of a magnetic field
- The band across the middle is a Pb plate, which slows down the particles. The momentum of the track after crossing the plate is smaller than before
- From the direction in which the path curves one can deduce that the particle is positively charged
- Mass can be deduced from the long range of the track - a proton would have come to rest in a shorter distance

=> It is a positive electron!

At the same time, gamma -> e+e- (Occhialini & Blackett)

A note: Dirac's equation announced in '28 in Cambridge; at the same conference Skobelzyn spoke about some unexplainable "wrong charge" events.



Quantum Statistics

The Formalism of Quantum Mechanics
Yehuda B. Band, Yshai Avishai, in
Quantum Mechanics with Applications to Nanotechnology and Information Science
, 2013

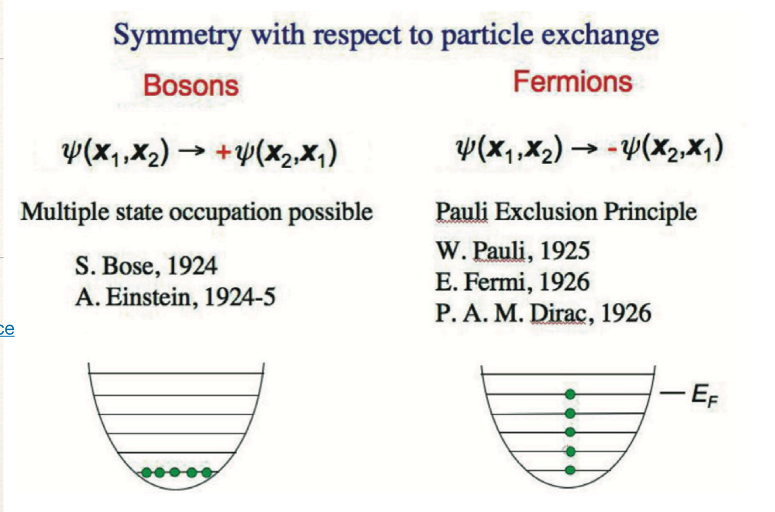


FIG 2.6 The zero-temperature occupation of single-particle states for bosons and fermions due to symmetry under particle interchange. The wave function for identical bosons must be symmetric under the interchange of any two particles, whereas for identical fermions, it must be antisymmetric. Therefore, bosons can occupy the same quantum state, whereas fermions cannot.

- From Quantum mechanics, you learn that if two particles are indistinguishable, then under particle exchange, the wavefunction can be **symmetric** or **anti-symmetric**
- **Symmetric: Bosons**
- **Anti-symmetric: Fermions**
  - Because of this, we have Pauli's exclusion principle for electrons (a Fermion)

Fermions, Bosons

- **Spin-Statistics Theorem**
- WIKI— The first proof was formulated[7] in 1939 by Markus Fierz, a student of Wolfgang Pauli, and was rederived in a more systematic way by Pauli the following year.[8]

- **Bosons** have integer spins (E.g., Photons, Higgs Boson, Graviton)
- **Fermions** have half-integer spins (quarks, leptons like electrons/ neutrinos)

Spins of particles

- Protons, neutrons, electrons: spin 1/2
- Photons, spin 1

Delta baryons

Particle name	Symbol	Quark content	Mass (MeV/c^2)	I_3	J^P	Q (e)	S	C	B'	T	Mean lifetime (s)	Commonly decays to
Delta[1]	$\Delta^{++}(1\,232)$	uuu	$1\,232 \pm 2$	$+\frac{3}{2}$	$\frac{3}{2}^+$	+2	0	0	0	0	$(5.63 \pm 0.14) \times 10^{-24}$[a]	$p^+ + \pi^+$
Delta[1]	$\Delta^{+}(1\,232)$	uud	$1\,232 \pm 2$	$+\frac{1}{2}$	$\frac{3}{2}^+$	+1	0	0	0	0	$(5.63 \pm 0.14) \times 10^{-24}$[a]	$\pi^+ + n^0$, or $\pi^0 + p^+$
Delta[1]	$\Delta^{0}(1\,232)$	udd	$1\,232 \pm 2$	$-\frac{1}{2}$	$\frac{3}{2}^+$	0	0	0	0	0	$(5.63 \pm 0.14) \times 10^{-24}$[a]	$\pi^0 + n^0$, or $\pi^- + p^+$
Delta[1]	$\Delta^{-}(1\,232)$	ddd	$1\,232 \pm 2$	$-\frac{3}{2}$	$\frac{3}{2}^+$	−1	0	0	0	0	$(5.63 \pm 0.14) \times 10^{-24}$[a]	$\pi^- + n^0$

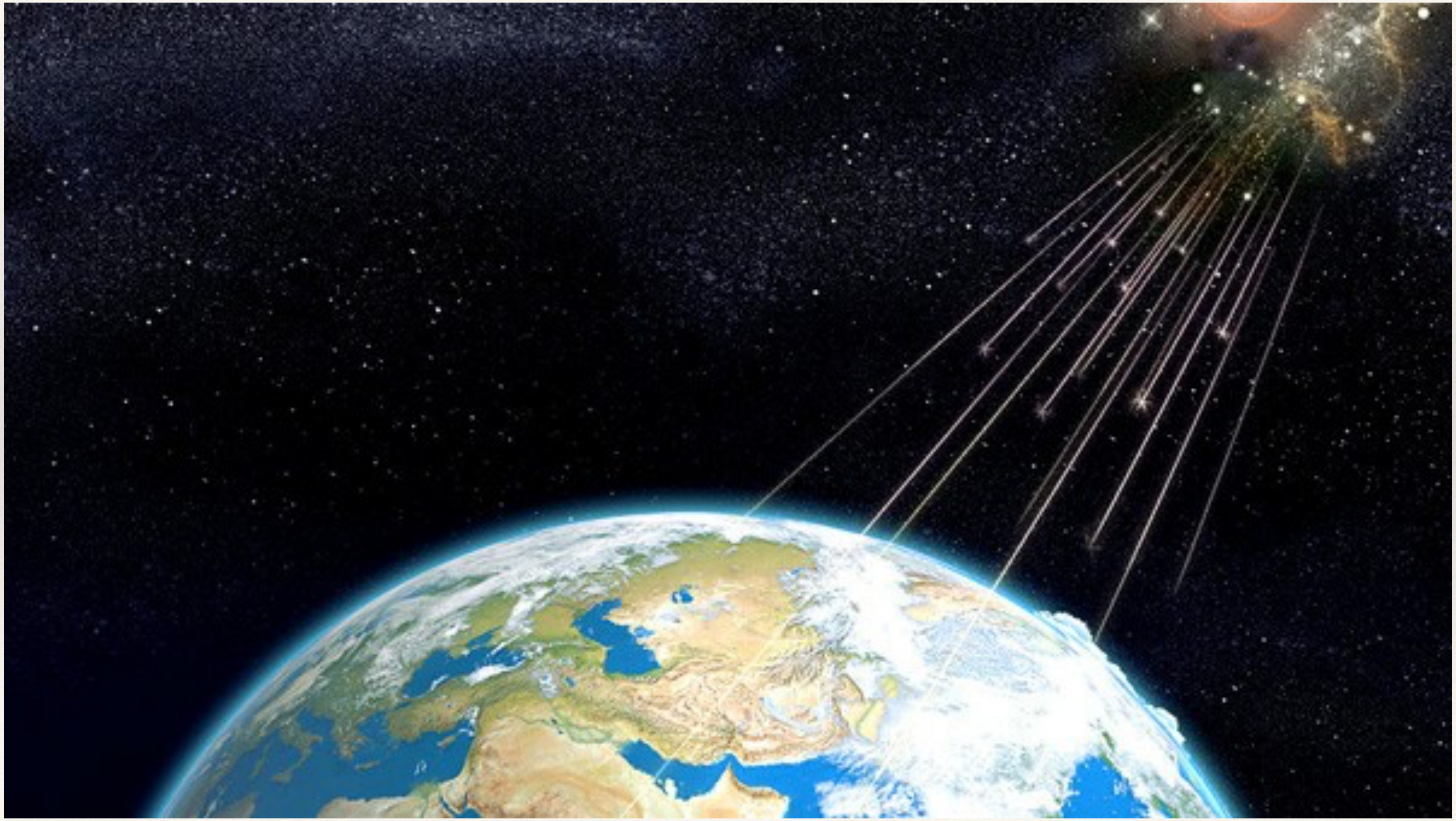
[a] ^ PDG reports the resonance width (Γ). Here the conversion $\tau = \frac{\hbar}{\Gamma}$ is given instead.

Connection between Statistics and Thermodynamics

- The Boltzmann entropy formula tells use that
- $S = k \ln W$, where k is the Boltzmann Constant
- The entropy is calculated by finding W, the number of "microstates"
- A microstate is a way to distribute a bunch of particles in the available states
- So, W is counting how many ways one can distribute particles
- We can also set Boltzmann constant to 1
  - $k = 1$ implies [E] = [Temperature]

Symbol:	k_B, k
Value in joules per kelvin	$1.380\,649 \times 10^{-23}$ J·K^{-1}[1]
Value in electronvolts per kelvin	$8.617\,333\,262 \times 10^{-5}$ eV·K^{-1}[1]

Cosmic rays



Electroscopes discharge spontaneously. Why?

- 1785: Coulomb found that electroscopes can spontaneously discharge by the action of the air and not by defective insulation
- 1835: Faraday confirms the observation by Coulomb, with better insulation technology
- 1879: Crookes measures that the speed of discharge of an electroscope decreased when pressure was reduced (conclusion: direct agent is the ionized air)

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Spontaneous Ionization to Subatomic Physics: Victor Hess to Peter Higgs
https://indico.cern.ch/event/197799/contributions/371924/attachments/291924/408037/12SpacepartDeangelis.pdf

100 years later: cause might be radioactivity

- 1896: spontaneous radioactivity discovered by Becquerel
- 1898: Marie (31) & Pierre Curie discover that the Polonium and Radium undergo transmutations generating radioactivity (radioactive decays)
  – Nobel prize for the discovery of the radioactive elements Radium and Polonium: the 2^{nd} Nobel prize to M. Curie, in 1911
  – In the presence of a radioactive material, a charged electroscope promptly discharges
  – Some elements are able to emit charged particles, that in turn can cause the discharge of the electroscopes.
  – The discharge rate of an electroscope was then used to gauge the level of radioactivity

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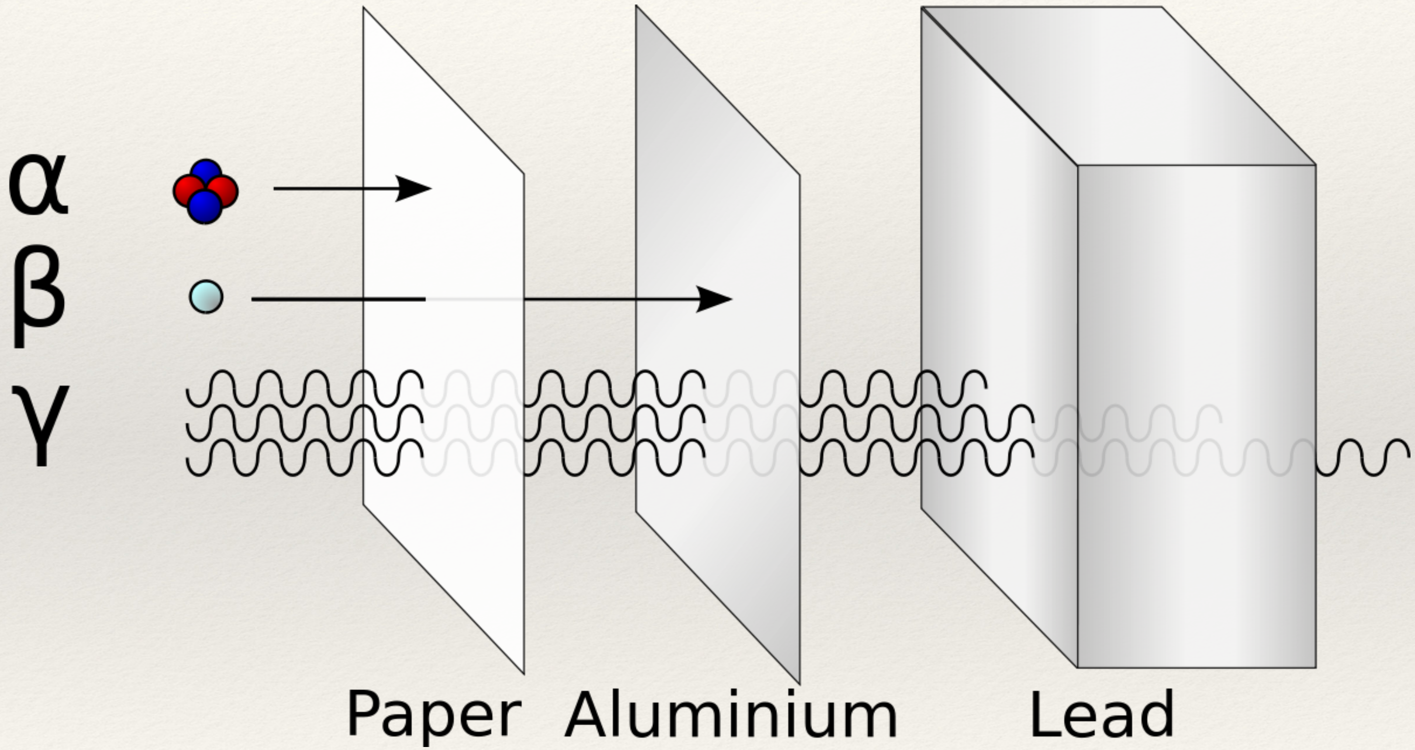
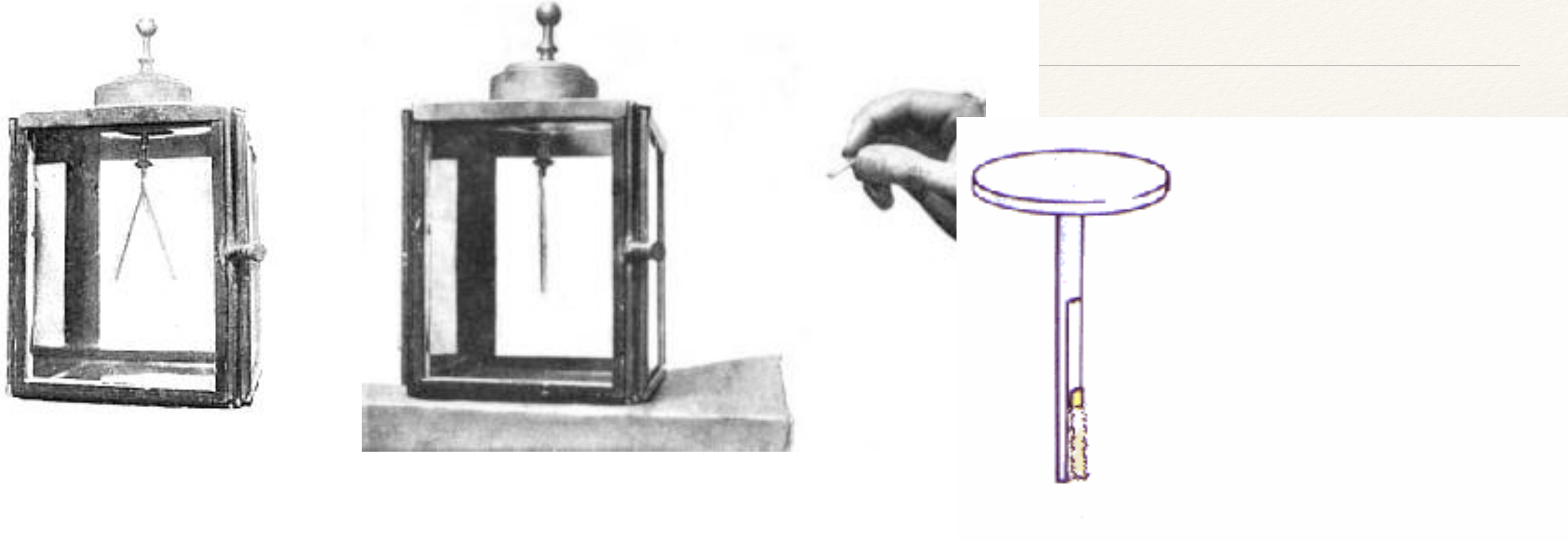
Radioactivity





Discharge of an electroscope by a radioactive material (Duncan 1902)

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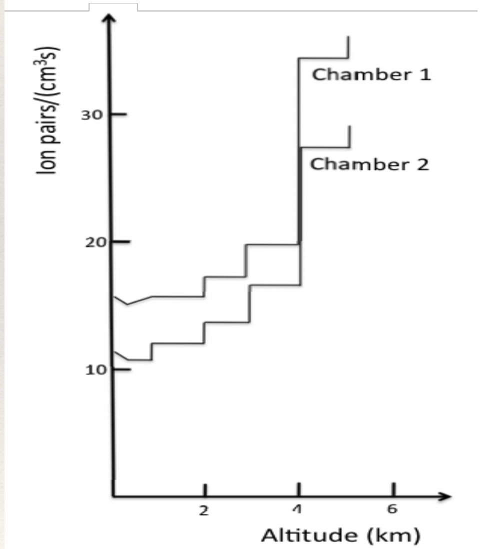

Hess' final balloon flights

- From April 1912 to August 1912 Hess had the opportunity to fly 7 times. In the final flight, on August 7, Hess, 29-y-old, reached 5200 m
  - His results showed that the ionization, after passing a minimum, increased considerably with height
  - He concluded that the increase of the ionization with height is due to a radiation coming from above, and thought that this radiation had extra-terrestrial origin

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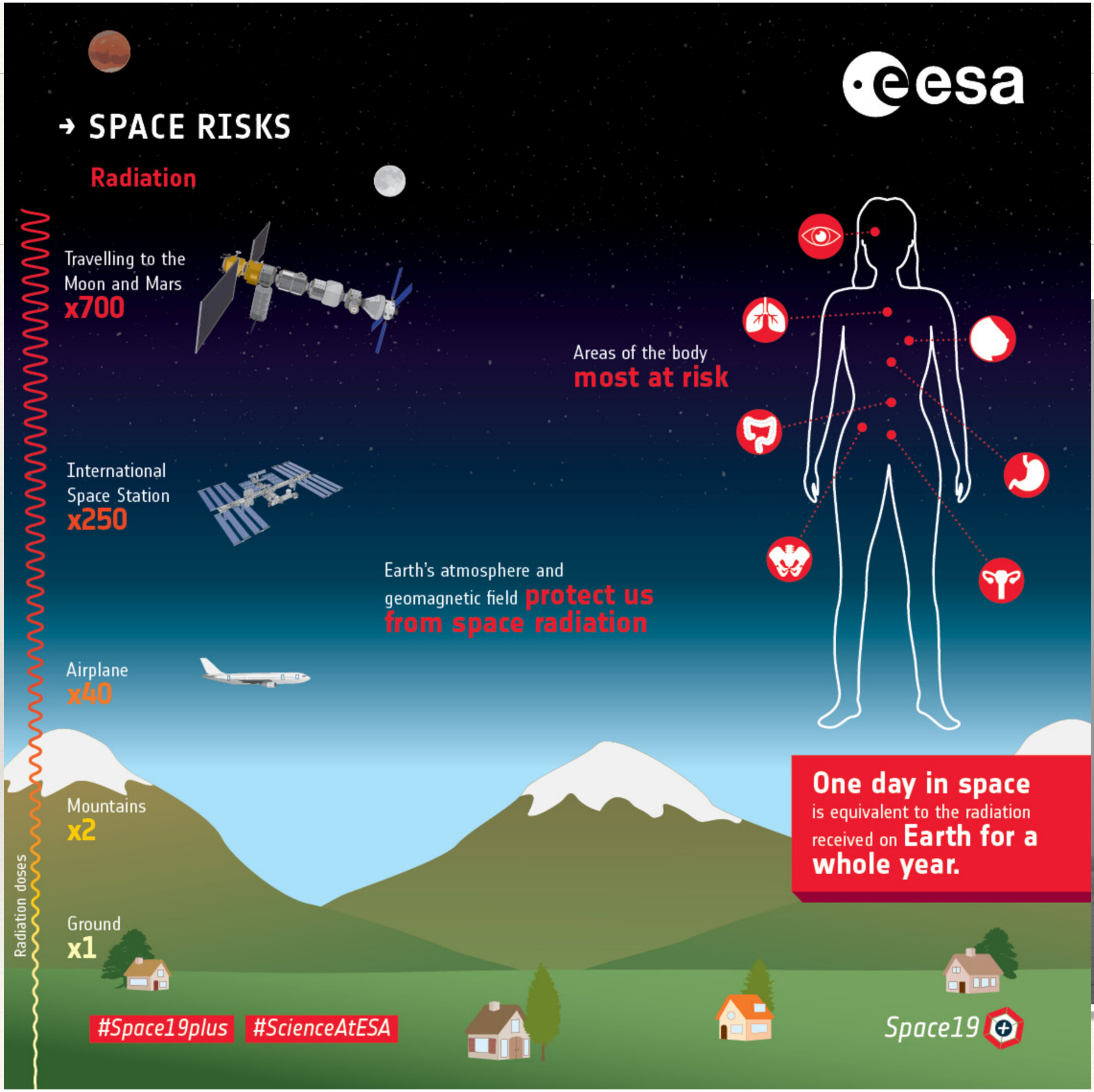
- Commercial plane
- 30000 feet, ~ 10000m



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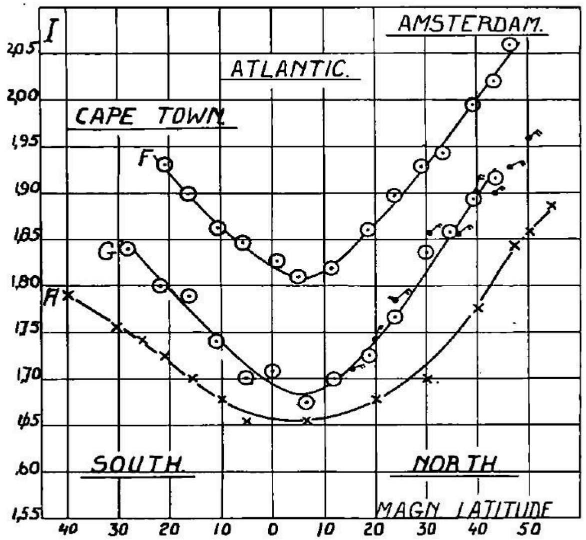
Charged or neutral?

- It was generally believed that the cosmic radiation was gamma because of its penetrating power (the penetrating power of relativistic charged particles was not known)
  - Millikan had put forward the hypothesis that the gamma rays were produced when protons and electrons form He nuclei in interstellar space
- The geomagnetic effect in CR (the CR flux depends on latitude) was discovered accidentally in 1927 by the Dutch researcher J. Clay
  - Clay was measuring radiation in Java; in 1927 he carried his detector in a trip from Java to Genova
- Confirmed by Clay himself in 1928 (Java to Amsterdam), by Kolhörster, by Rossi, by Compton+



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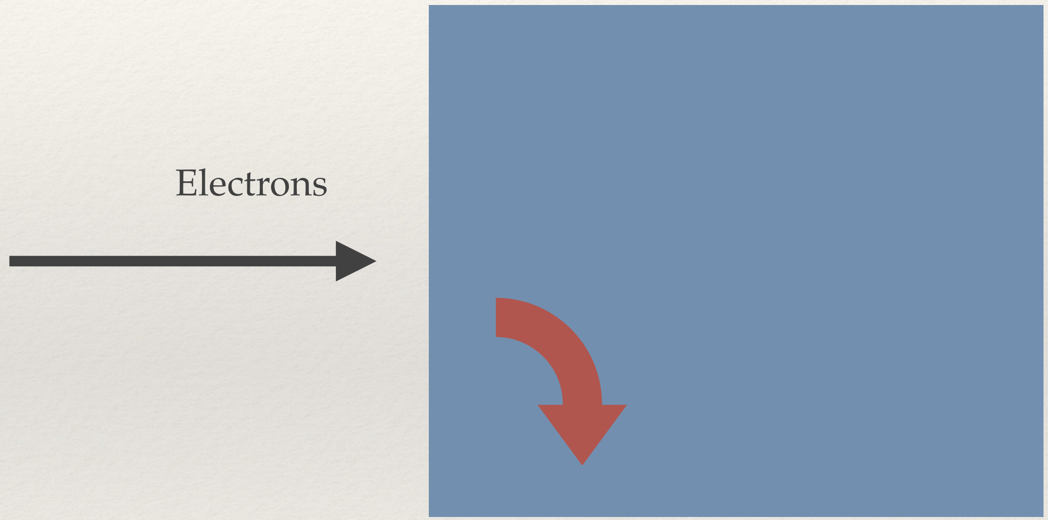
Charged particles in magnetic fields

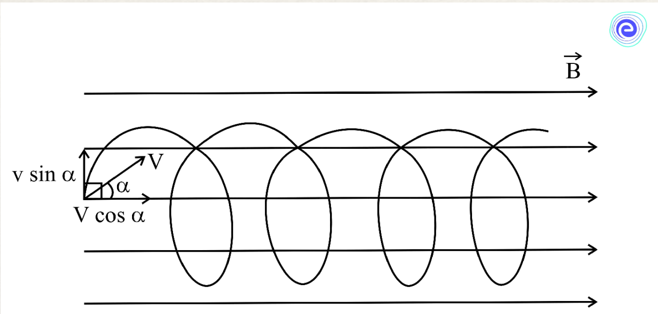
- $\frac{d}{dt}\vec{p} = q(\vec{E} + \vec{v} \times \vec{B})$

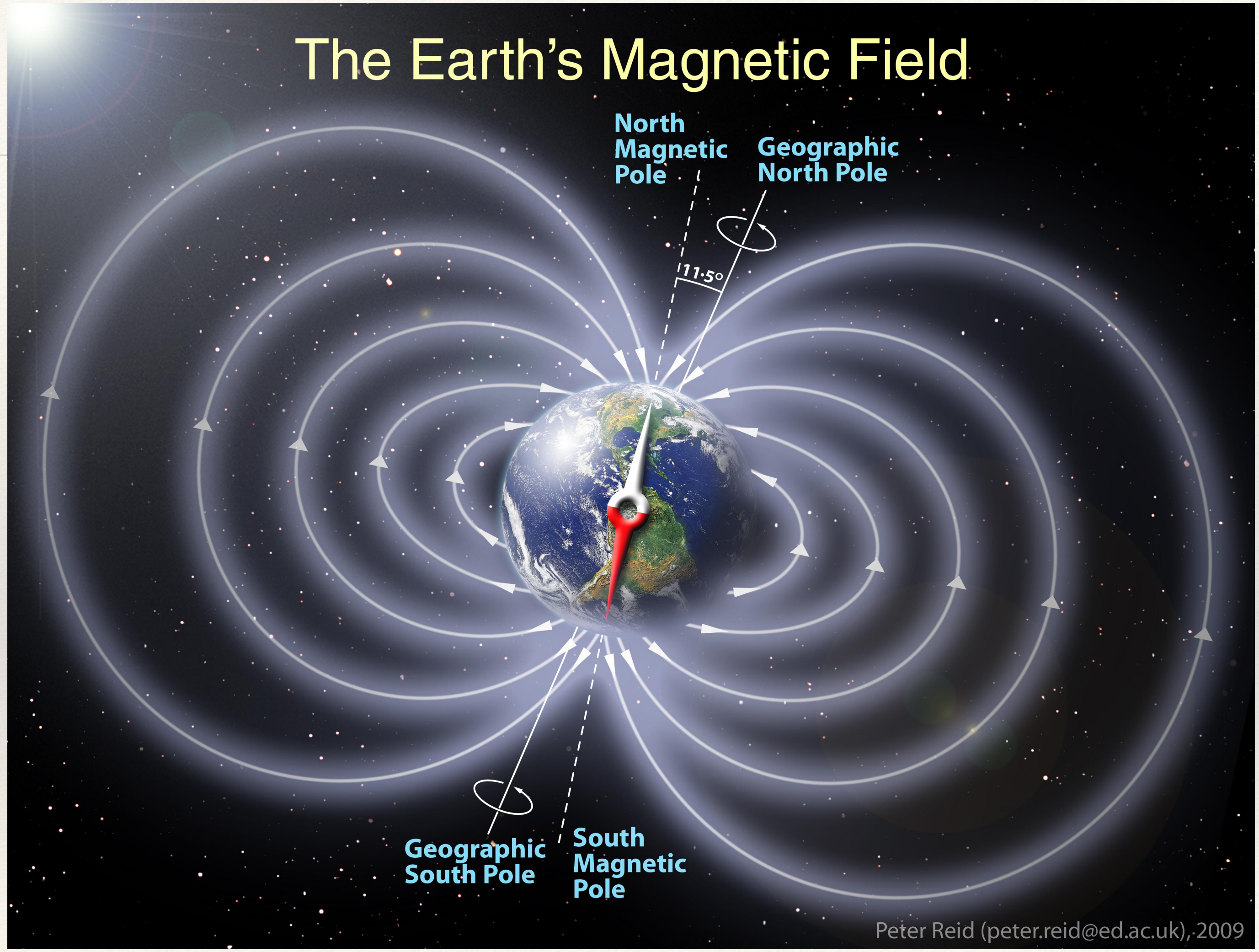
- $\vec{p}$: momentum
- q: charge
- $\vec{E}$, $\vec{B}$ electric and magnetic fields

- Gyro-radius or Larmor Radius
- $r_g = \frac{p_\perp}{|q|B}$, depends on
  - momentum, charge and Magnetic fields

B fields pointing into the screen




$\vec{B}$
v sin α
V
α
V cos α


The Earth's Magnetic Field
North Magnetic Pole
Geographic North Pole
11.5°
Geographic South Pole
South Magnetic Pole
Peter Reid (peter.reid@ed.ac.uk), 2009

Positive or negative?
The East-West effect

- 1933-34: three independent experiments (Alvarez & Compton, Johnson, Rossi) find that the intensity of CR is greater from the West than from the East => most primary cosmic rays are positively charged particles
  - In the course of his East-West experiment, Rossi (28 yr old) in Eritrea discovers cosmic-ray air showers, but does not study them in detail
    - Publication in Italian, again…
    - Auger will re-discover and study in larger detail in 1936

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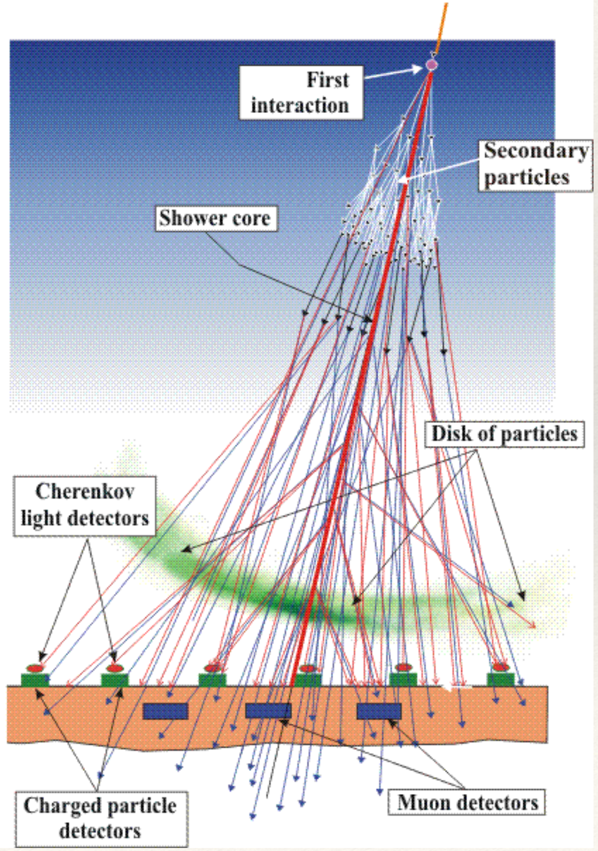
JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

low atmosphere. We have seen that we may take 10^6 as the total number of particles present. The energy of the majority of these particles is probably, the critical energy for air, that is 10^8 ev. We obtain in that way 10^{14} ev as the total energy of the shower particles, and have to add a factor 10 to account for the energy lost during the traversal of the atmosphere so that 10^{15} is likely to be the energy of the primary particle.

EAS of cosmic rays in atmosphere



1936: The Nobel prize to Hess (& Anderson)

Hess was awarded the 1936 Nobel Prize in physics, shared with Anderson. Hess was nominated by Clay, Compton:

- *The time has now arrived, it seems to me, when we can say that the so-called cosmic rays have their origin at remote distances from the Earth […] and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude. [...] It is, I believe, correct to say that Hess was the first to establish the increase of the ionization observed in electroscopes with increasing altitude; and he was certainly the first to ascribe with confidence this increased ionization to radiation coming from outside the Earth*

- Muon, a lepton (like a electron)
- Pions, Kaons are both Mesons

Later, many new discoveries in fundamental physics from cosmic rays

- 1937: The muon, or mu lepton, discovered by Neddermeyer+(mistaken for the pion until 1947: Conversi, Pancini, Piccioni)
- 1947: Pion (or π meson), the first meson, discovered by Lattes, Occhialini & Powell (predicted by Yukawa in 1935)
- 1947: Kaon (or K meson), the first strange particle, discovered by Rochester & Butler
- 1951: Λ, the first strange baryon, discovered by Armenteros+
- 1951-54: Parity violation (G-stack, the first European collaboration – mother of the modern HEP collaborations)

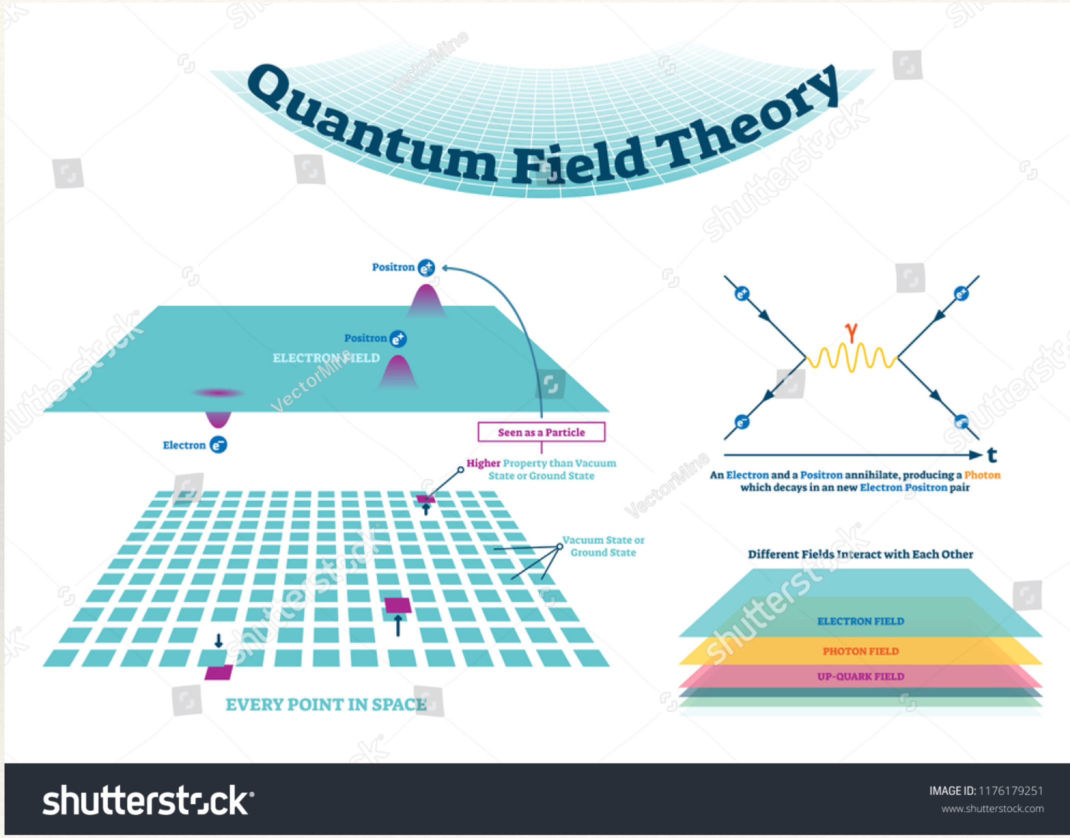
- CR physics is relatively cheap, which is important in the post-war conditions of European science (mountain-top labs, balloons…)

1950 Quantum Electrodynamics (A quantum field theory)

- Quantum mechanics (states)
  - Schrodinger equation is a "single-particle theory"
  - No particles are created and destroyed
- Relativity implies particle non-conservation.

- What is a QFT?
  - Fields are everywhere, e.g., $\psi_e(x^\mu)$ can be associated with electrons
  - A electron is an excitation of the field, that can propagate in space time (like a vibration)

- + Wavelike properties of particles
- + Why particles are "identical and Indistinguishable"
- Schwartz: QFT $\simeq$ QM with infinite set of harmonic oscillators



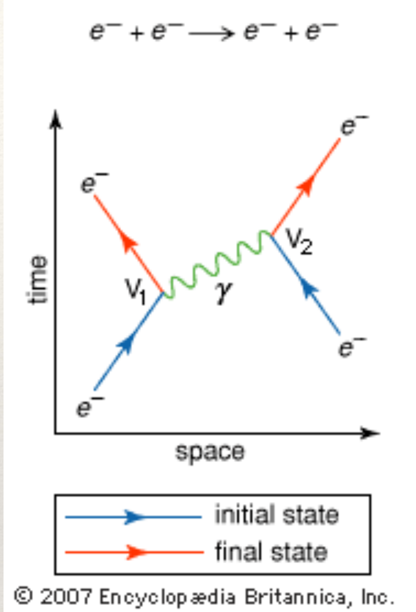
1950s Quantum Electrodynamics (A quantum field theory)

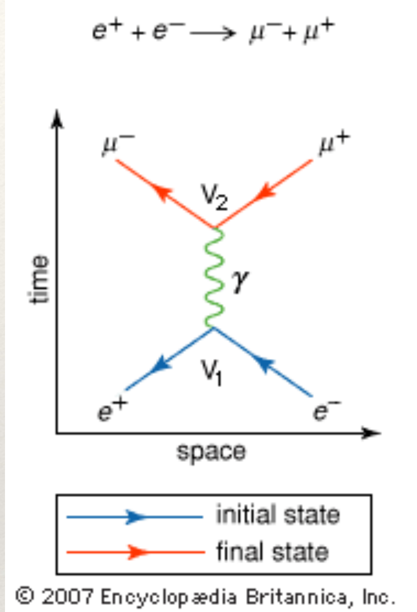
- QED = a theory of electrons interacting with photons

- Electron fields talk to each other (or anything with electric charge) via a (virtual) photon field
- Photons can be real and they are the light we see
- We call these particles the force "mediators"
- Photons mediates electromagnetic forces

- QED is the most successful theory in terms of testable numerical accuracy

- Yukawa potential for a mediator $V(r) \simeq \dfrac{e^{-\alpha m r}}{r}$
- EM and Gravity corresponds to massless mediators
  - We call these long range interactions





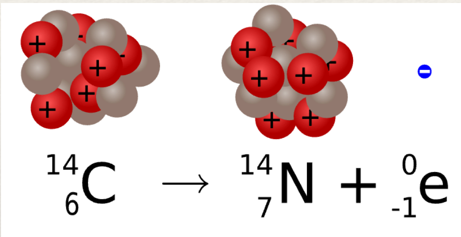
For the electron spin, the most accurate value for the spin g-factor has been experimentally determined to have the value

2.002 319 304 360 92(36).[4]

Note that this differs only marginally from the value from the Dirac equation. The small correction is known as the anomalous magnetic dipole moment of the electron; it arises from the electron's interaction with virtual photons in quantum electrodynamics. A triumph of the quantum electrodynamics theory is the accurate prediction of the electron g-factor. The CODATA value for the electron magnetic moment is

1956 Discovery of neutrinos

- What are neutrinos?
- It all started with beta decay

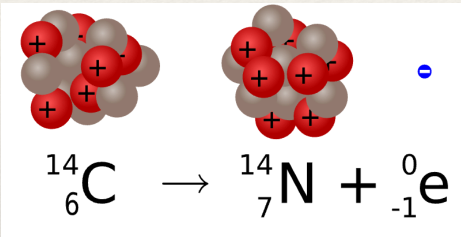


- $n \rightarrow p^+ + e^-$
- two conditions
  - energy conservation
  - momentum conservation

- $(m_n c^2, \vec{0}) = (E_p, \vec{p_p}) + (E_e, \vec{p_e})$
- Two equations
- Two unknown, E_p, E_e
- One should get 1 definite value for E_e

Neutrinos

- What are neutrinos?
- It all started with beta decay



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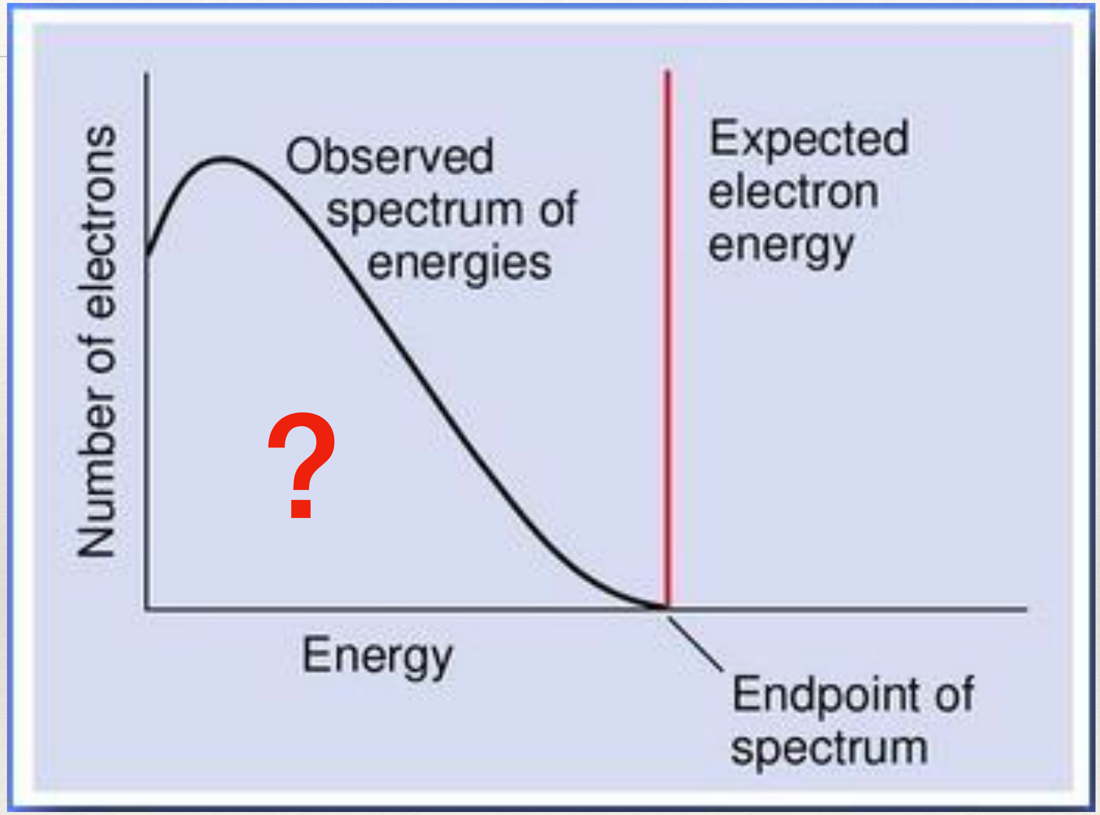


Energy not conserved???

Neutrinos (a new lepton)

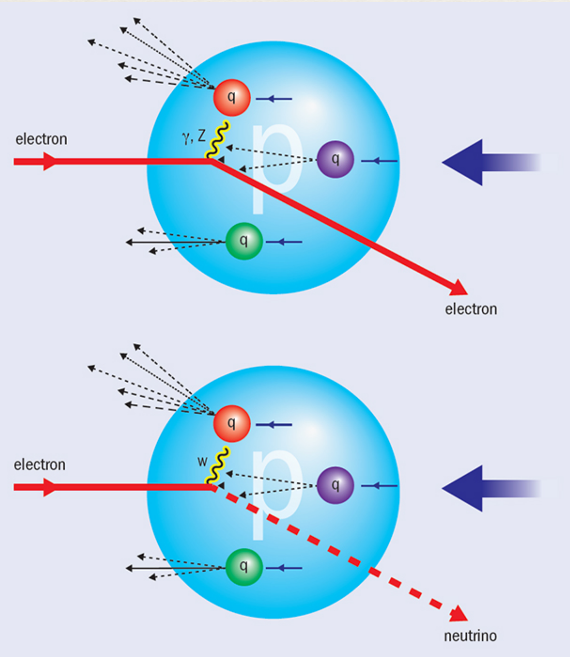
- Wolfgang Pauli (1930)
- $n \to p^+ + e^- + \nu$

I have done a terrible thing: I have postulated a particle that cannot be detected.

- Neutrino (little neutral one— Amaldi)
- (e / mu / tau neutrinos) 1956, 1962, 2000
- Defined using weak interactions
- $\bar{\nu}_e + p^+ \to n + e^+$
- $\nu_e + n \to p^+ + e^-$
- $\bar{\nu}_\mu + p^+ \to n + \mu^+$
- $\nu_\mu + n \to p^+ + \mu^-$
- $\bar{\nu}_\tau + p^+ \to n + \tau^+$
- $\nu_\tau + n \to p^+ + \tau^-$

Particle history

- Partons: inside ingredients of the Baryons
  - -> Quark theory



1962	**Muon neutrino** (or **mu neutrino**) shown to be distinct from the electron neutrino by a group headed by Leon Lederman[21]
1969	**Partons** (internal constituents of hadrons) observed in deep inelastic scattering experiments between protons and electrons at SLAC;[24][25] this was eventually associated with the quark model (predicted by Murray Gell-Mann and George Zweig in 1964) and thus constitutes the discovery of the **up quark**, **down quark**, and **strange quark**.
1974	**J/ψ meson** discovered by groups headed by Burton Richter and Samuel Ting, demonstrating the existence of the **charm quark**[26][27] (proposed by James Bjorken and Sheldon Glashow in 1964[28])
1975	**Tau** discovered by a group headed by Martin Perl[29]
1977	**Upsilon meson** discovered at Fermilab, demonstrating the existence of the **bottom quark**[30] (proposed by Kobayashi and Maskawa in 1973)
1979	**Gluon** observed indirectly in three-jet events at DESY[31]
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1995	**Top quark** discovered at Fermilab[34][35]
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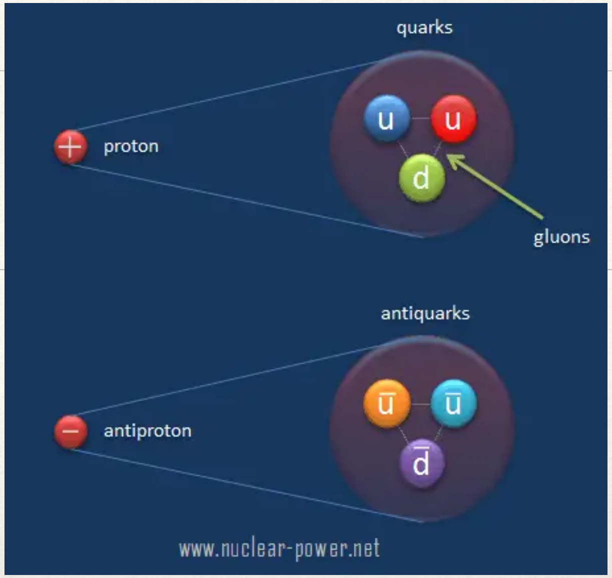
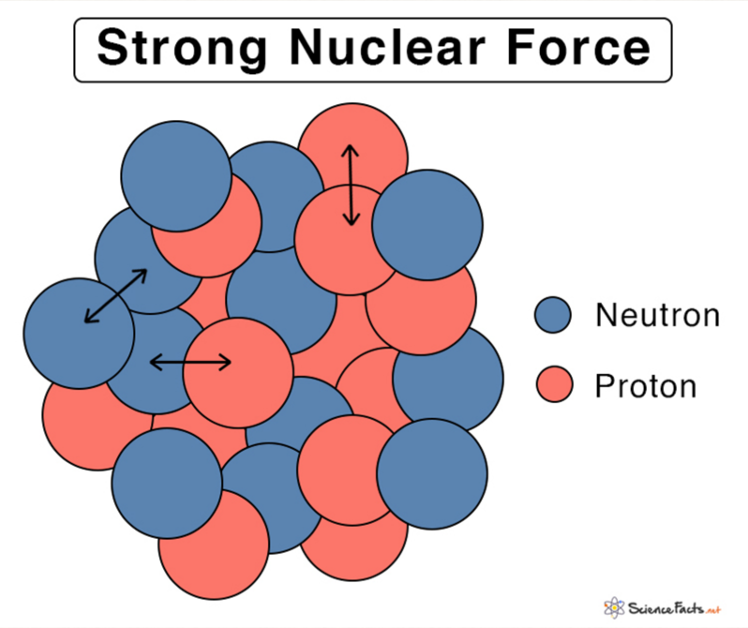
2012	A particle exhibiting most of the predicted characteristics of the **Higgs boson** discovered by researchers conducting the Compact Muon Solenoid and ATLAS experiments at CERN's Large Hadron Collider[39]

Quantum Chromodynamics 1970s

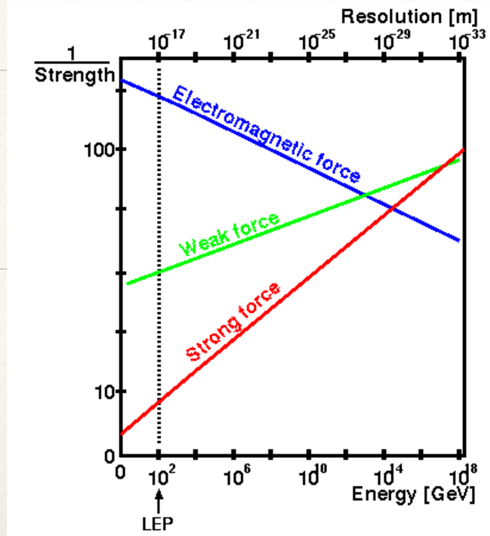
- Hadrons: things made with quarks
  - Baryons (things made with 3 quarks)
  - Mesons (things made with 2 quarks)

- QCD, a field theory with of the Yang-Mills type
- Describes the Strong force
  - Binds protons and neutrons together
  - Binds nucleus together (from EM repulsion)
  - Force is mediate by: Gluons
    - (Unlike photons, gluons also interacts with itself strongly!)

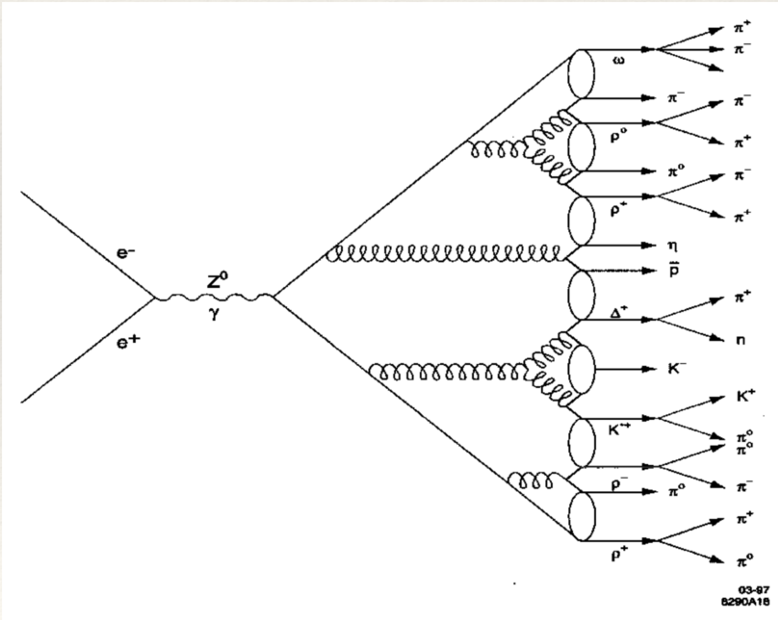




Quantum Chromodynamics 1970s



- Asymptotic freedom
  - Unlike QED, which becomes weaker as a function of energy
  - QCD becomes stronger at low energies (protons are tightly bounded)
  - No free quarks and gluons observed



- Scattering a hadron implies using the energy to produces many more hadrons
-

Weak interactions ~ 1970

- Weak forces is responsible for
- e.g., nuclear decays, neutrinos interactions (neutrino only has weak interactions)
- It is mediated by neutral Z, and $W^{\pm}$ bosons
- The mediator has mass!

$W^{\pm}$ and Z^0 Bosons

Composition	Elementary particle
Statistics	Bose–Einstein statistics
Family	Gauge boson
Interactions	W: Weak, electromagnetic Z: Weak
Theorized	Glashow, Weinberg, Salam (1968)
Discovered	UA1 and UA2 collaborations, CERN, 1983
Mass	W: 80.3692 ± 0.0133 GeV/c^2 (2024)[1][2] Z: 91.1880 ± 0.0020 GeV/c^2[3]
Decay width	W: 2.085 ± 0.042 GeV[1] Z: 2.4955 ± 0.0023 GeV[3]
Electric charge	W: ±1 e Z: 0 e
Spin	1 $\hbar$
Weak isospin	W: ±1 Z: 0
Weak hypercharge	0

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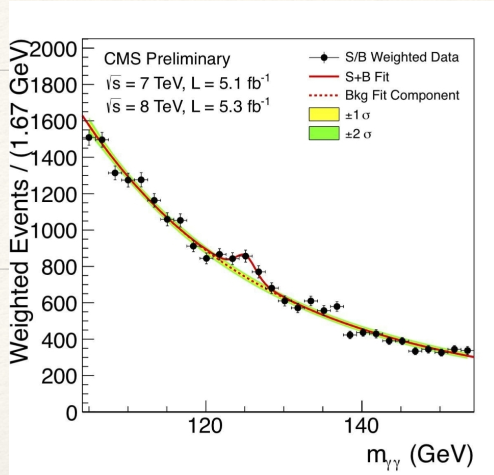
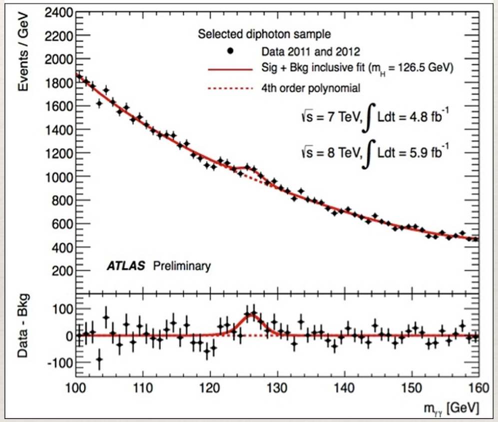
Electro-weak unification





- Actually the theory makes no sense if the mediators and the Fermions have mass!
  - All matter that we know are fermions, leptons and quarks
- Solution: Particle gains mass by interacting with a Higgs field
  - If there is a Higgs field, one can make a Higgs particle!
  - The only known fundamental Spin-0 particles
- The way that W and Z gains mass is called Spontaneous symmetry breaking. (SSB)
- Before SSB, we have 4 mediator for electro-weak interactions.
- B, W_1, W_2, W_3

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix}$$

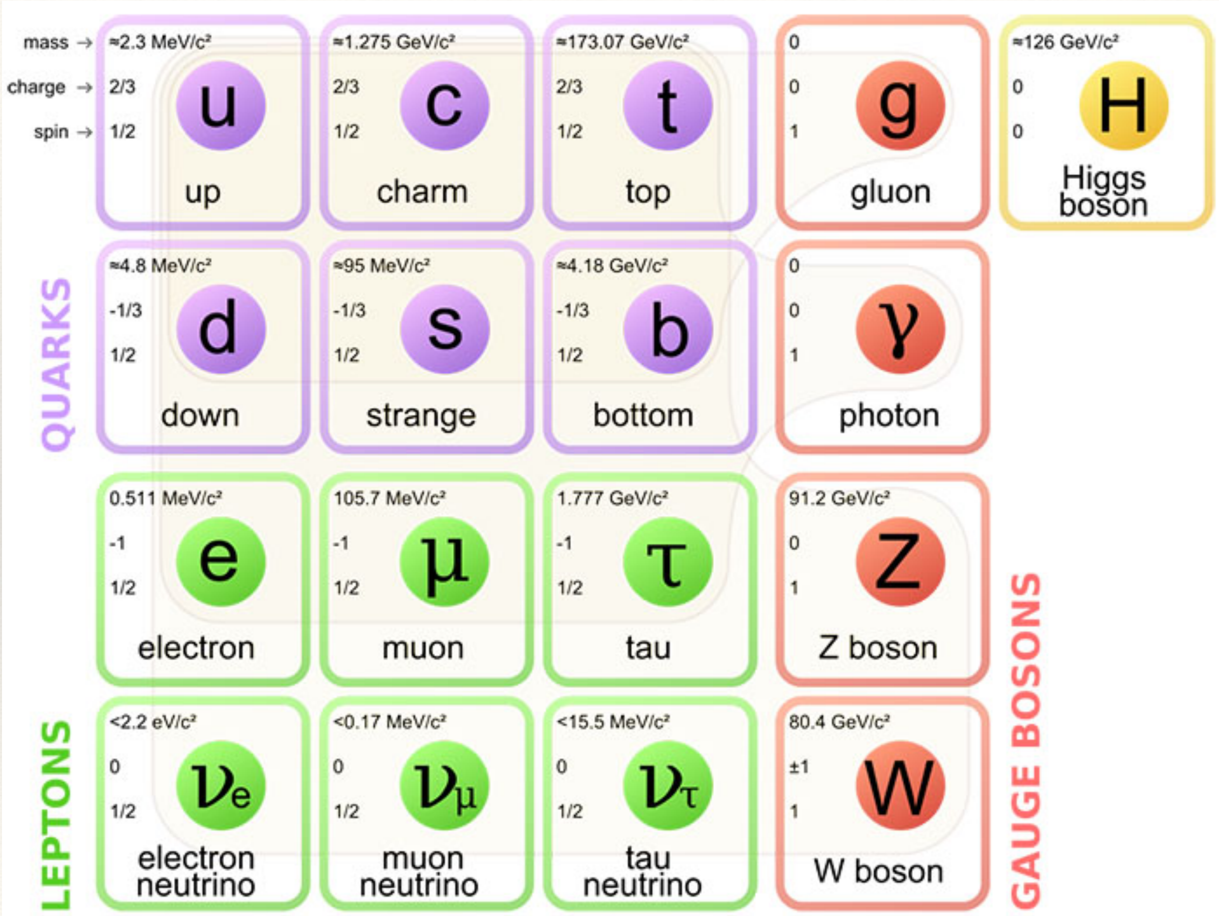
$$W^{\pm} = \frac{1}{\sqrt{2}} \left(W_1 \mp i W_2 \right)$$

- Photon and Z are actually mixtures of B, W_3 by the "Weak mixing angle"

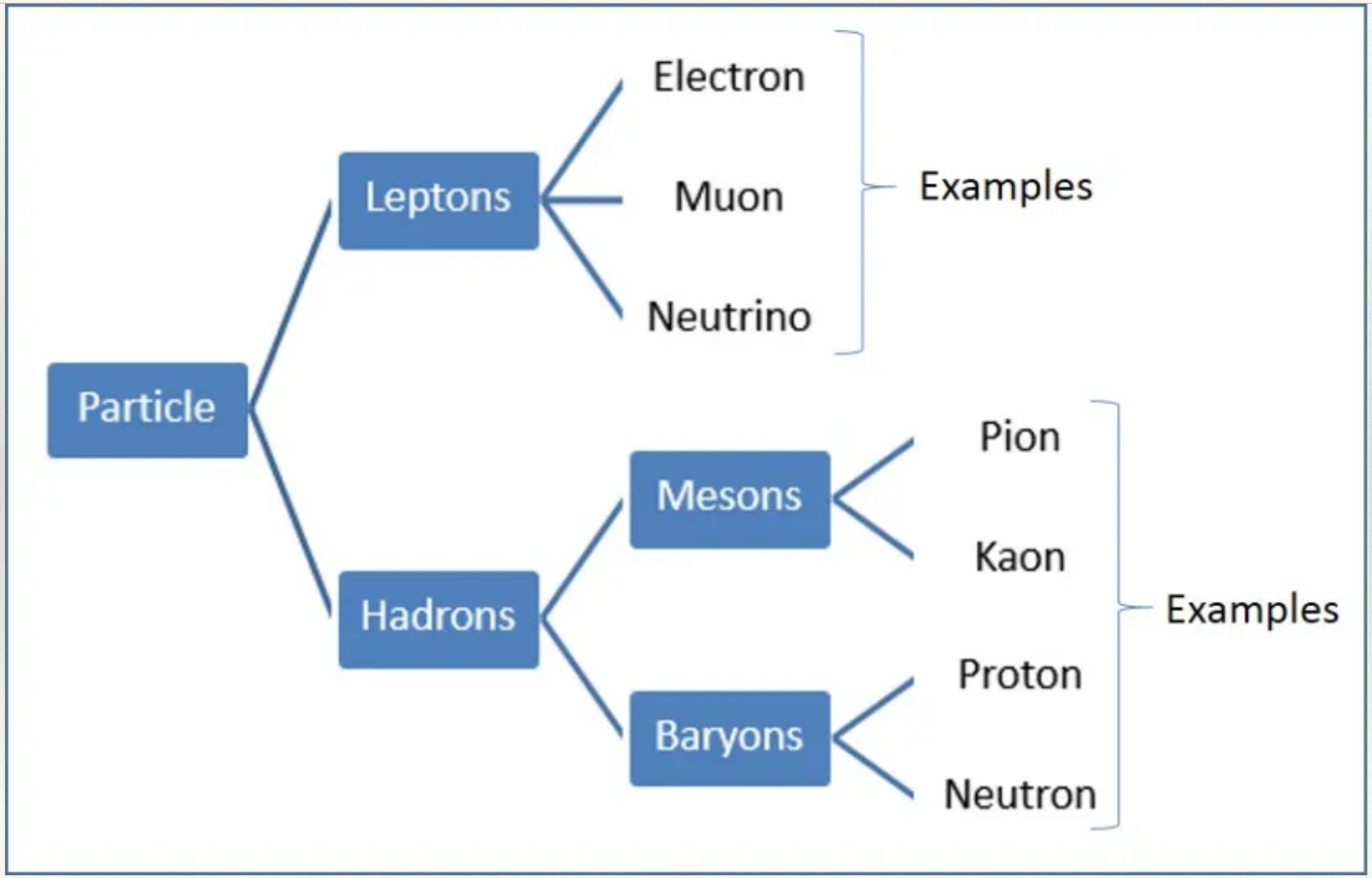
Standard Model of particle physics

- Extremely successful theory in predicting any known particle interactions.

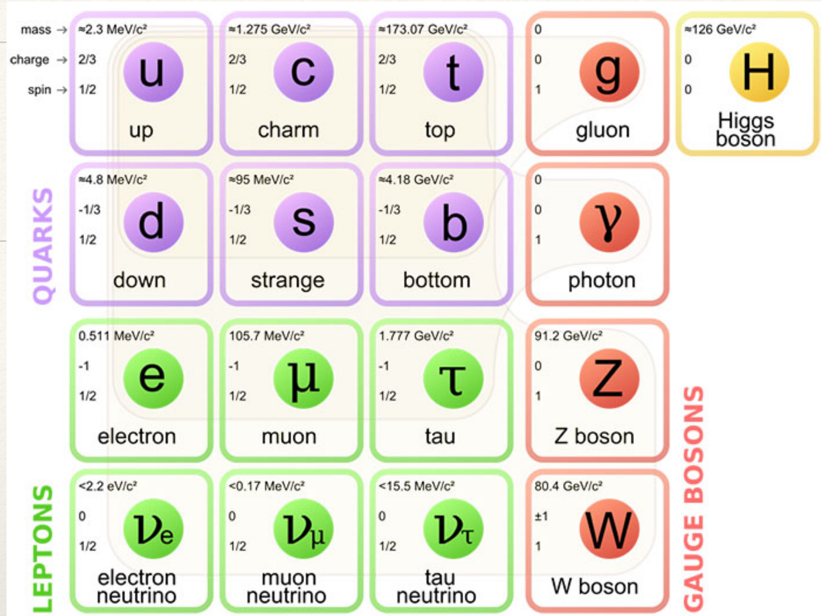
- 6 quarks (Strong interactions)
- 6 quarks + 3 charged leptons (EM)
- All 12 fermions (Weak interaction)



For particle physicists



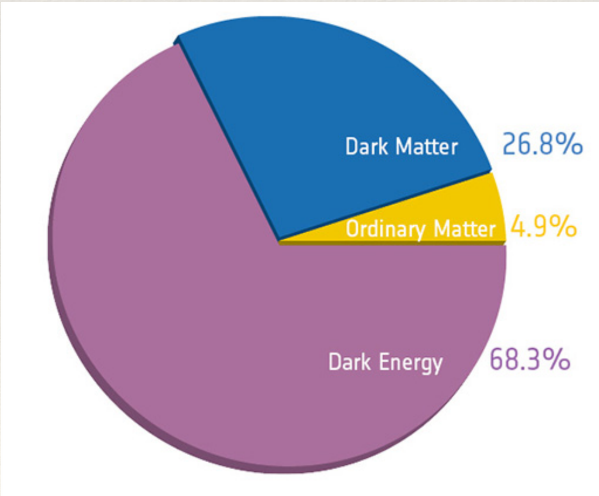
Problems

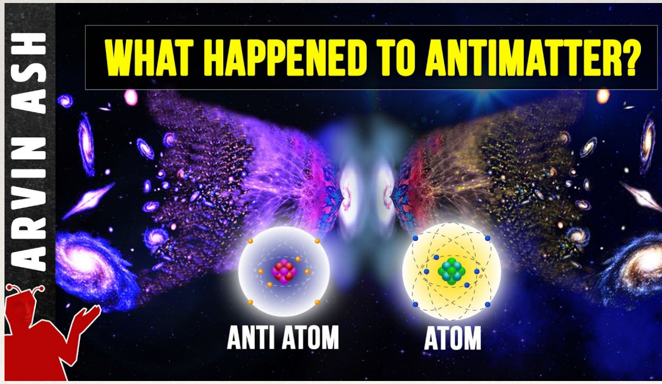


- Standard Model (SM) is extremely successful in laboratory particle physics.
- But still many problems

- Baryongenesis
  - SM is symmetric between matter and antimatter
  - We are now in an extremely not symmetric way (matter >> antimatter), why?
- Why there are 3 generations?
- Neutrino mass?
  - Why neutrinos have mass (old people)
  - Why neutrinos are so light?

- Dark matter, dark energy?? 95% of the universe is not in the SM!





- Solar Neutrinos
  - Nuclear reactions in the Sun
- Atmospheric Neutrinos
  - Cosmic ray interaction in Earth atmosphere

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Takaaki Kajita

Prize share: 1/2

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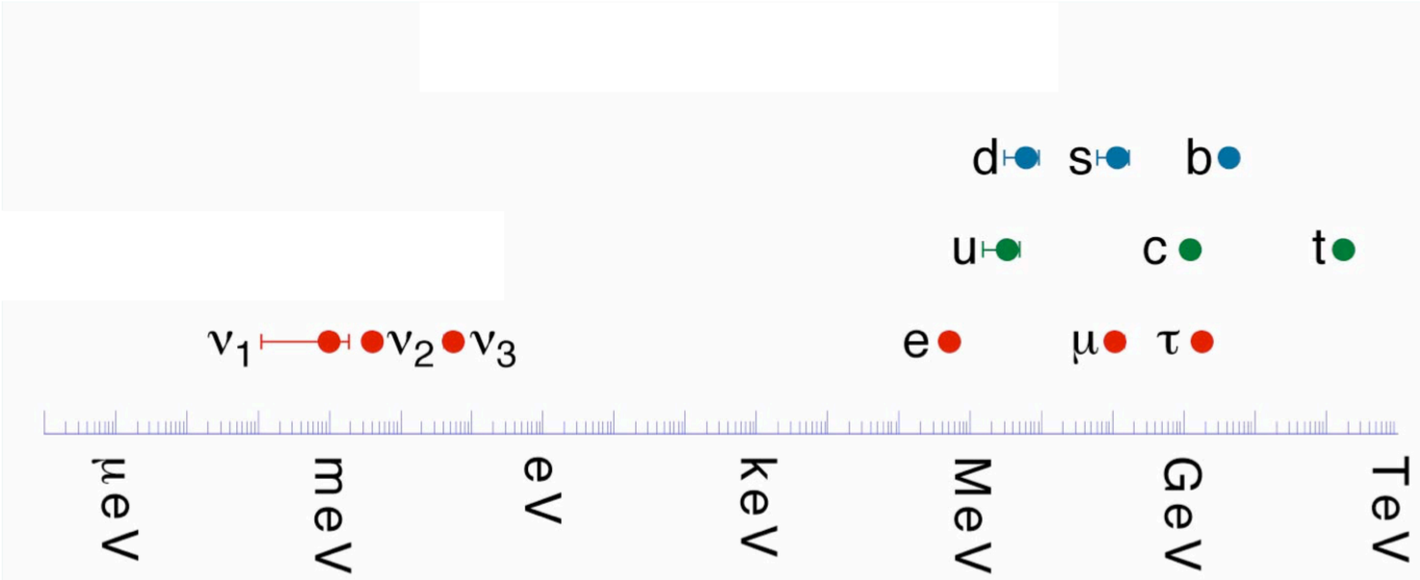
Arthur B. McDonald

Prize share: 1/2

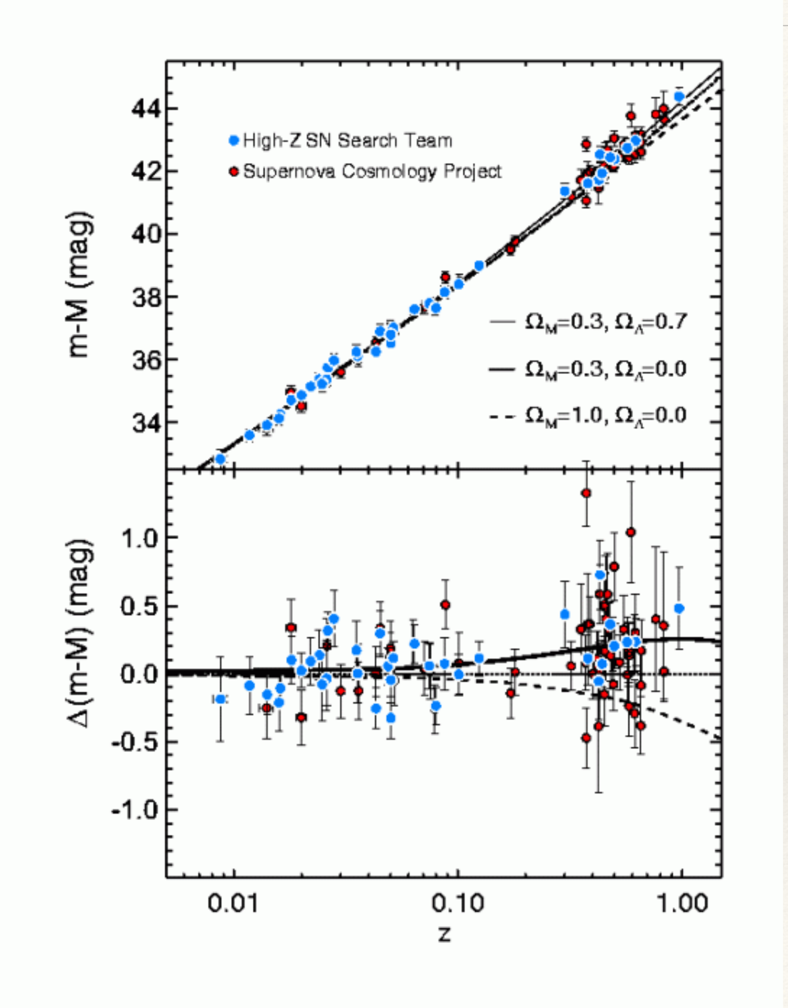
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass" why neutrino masses are so small, compared with the charged fermion masses?

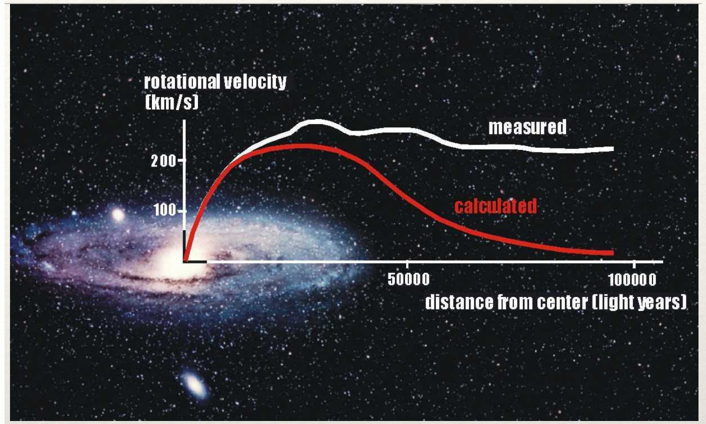


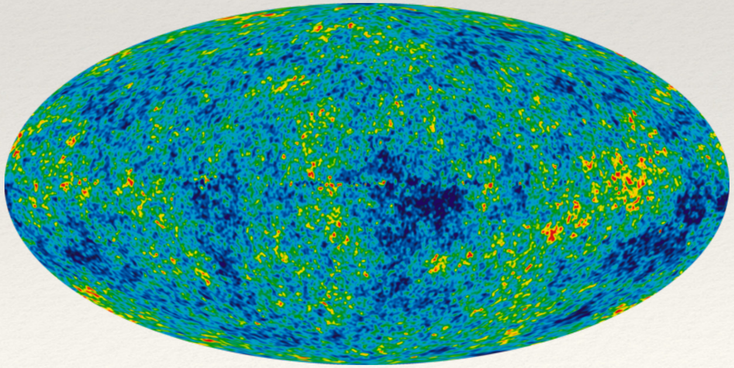
- Some considers Neutrino Mass “Beyond Standard Model”

The Standard Model of Cosmology

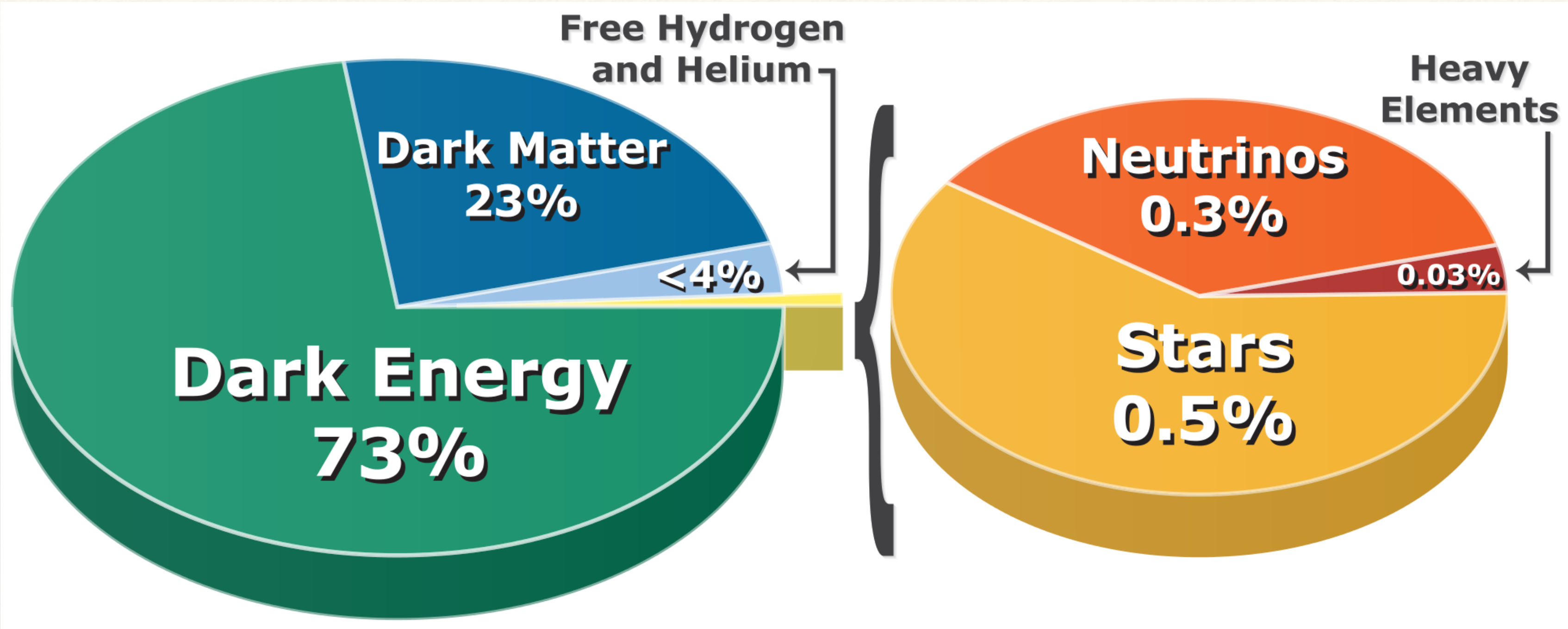
- Hubble's Law (~ 1930)
- CMB 1964
- Dark Matter (~ 1970)
- Dark Energy (~2000)







The Standard Model of Cosmology(Lambda-CDM)



- ~95% of the Universe is made with unidentified "stuff"
- *100% beyond standard model*

Quick Summary

- The most important things to remember today
- What it means when we say the following?
- $c = 1$
- $\hbar = 1$
- $k_B = 1$