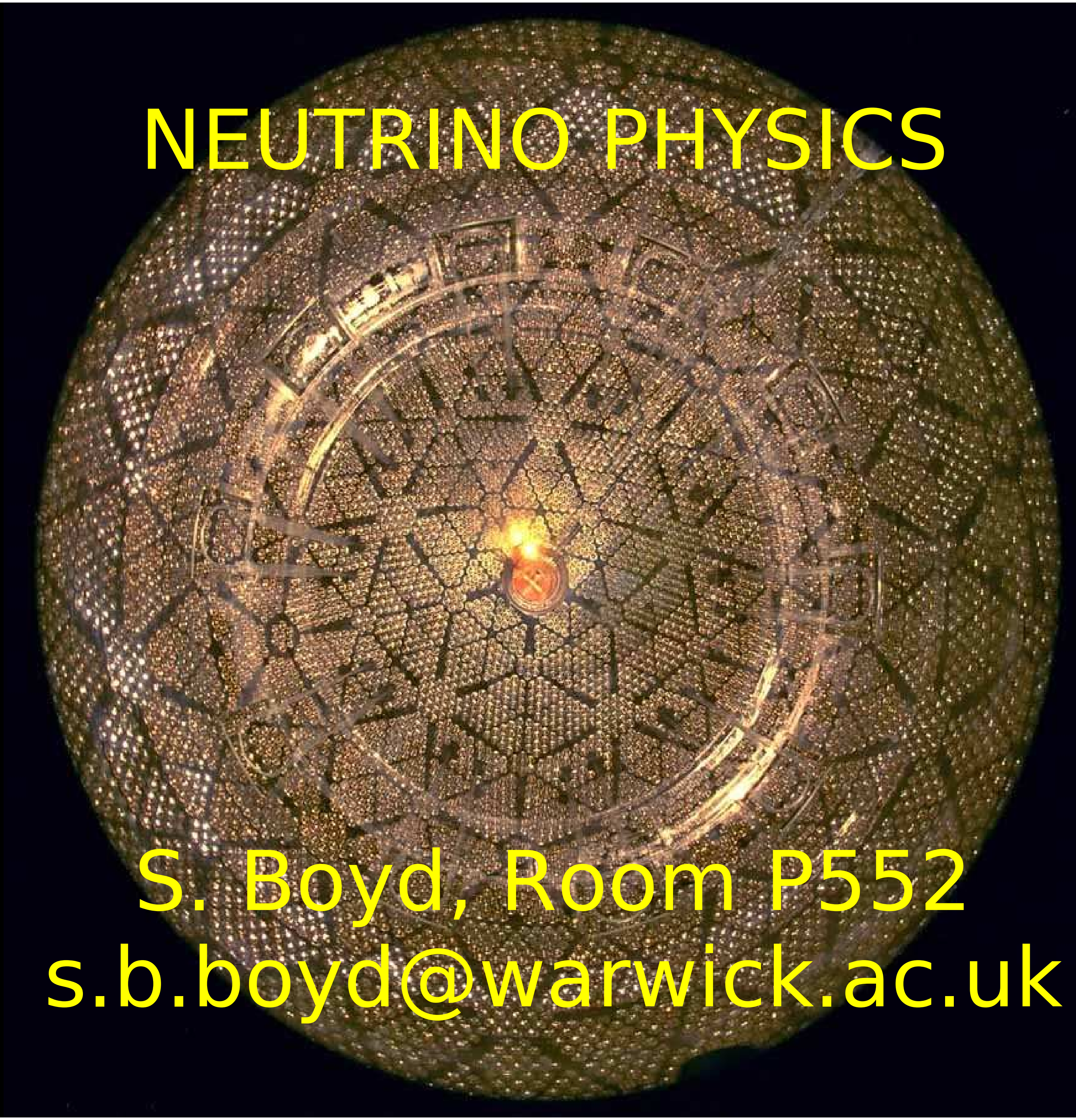
NEUTRINO PHYSICS



S. Boyd, Room P552
s.b.boyd@warwick.ac.uk

Course Plan

- Introduction (1)
- Some basic particle physics (3)
- History and motivation (1)
- Neutrino Properties and Interactions (2)
- Neutrino Sources and Detectors (2)
- Neutrino Mass (1)
- Neutrino Oscillations (4)
- Summary and Future (1)

Module homepage:
http://www2.warwick.ac.uk/fac/sci/physics/teach/module_home/px435

All Powerpoint presentations (in handout and normal format), Lecture writeups, interesting articles etc will be posted ahead of time (I hope)

Recommended texts:
K. Zuber, "*Neutrino Physics*", IoP Publishing (2004)
D. Griffiths, "*Introduction to elementary particle physics*", Wiley
B. Martin & G.Shaw, "*Particle Physics*", Wiley
F. Halzen & A. Martin, "*Quarks and Leptons*", Wiley
D. Perkins, "*Introduction to High Energy Physics*", Addison-Wesley

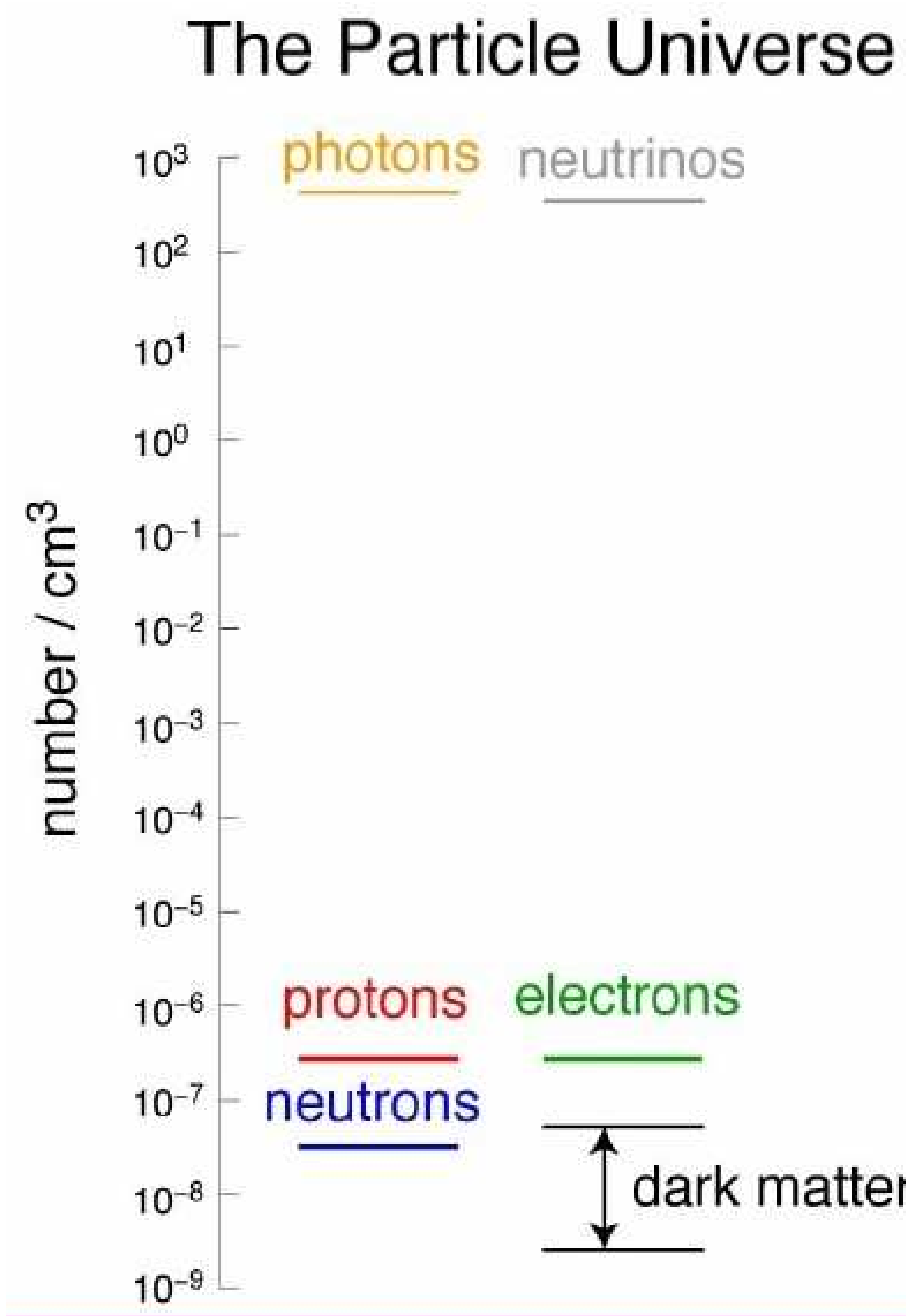
Assessment: 1.5 hour exam. 2 out of 3 questions.

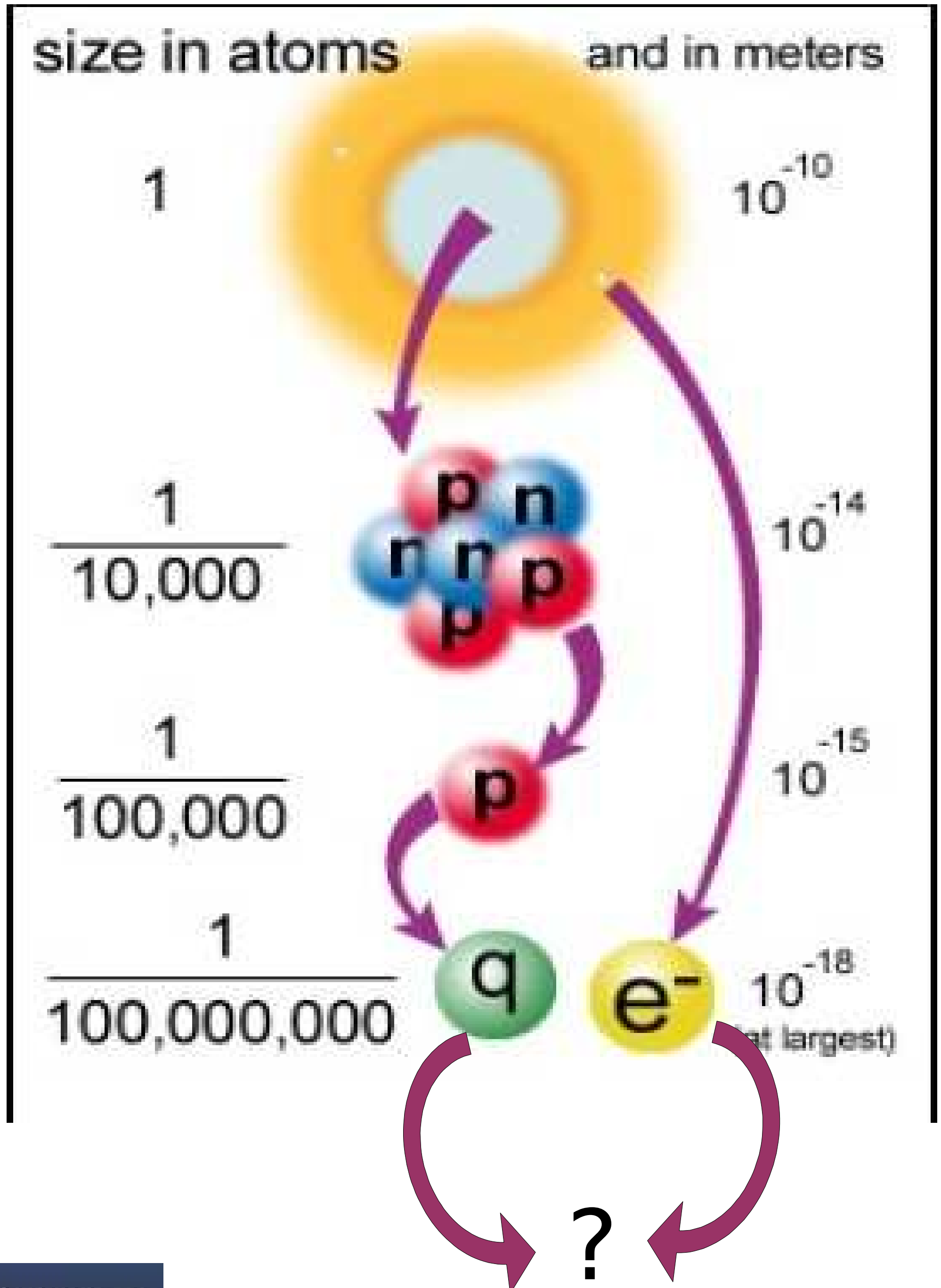
The Neutrino

Fred Reines : *... the most tiny quantity of reality ever imagined by a human being*

and yet

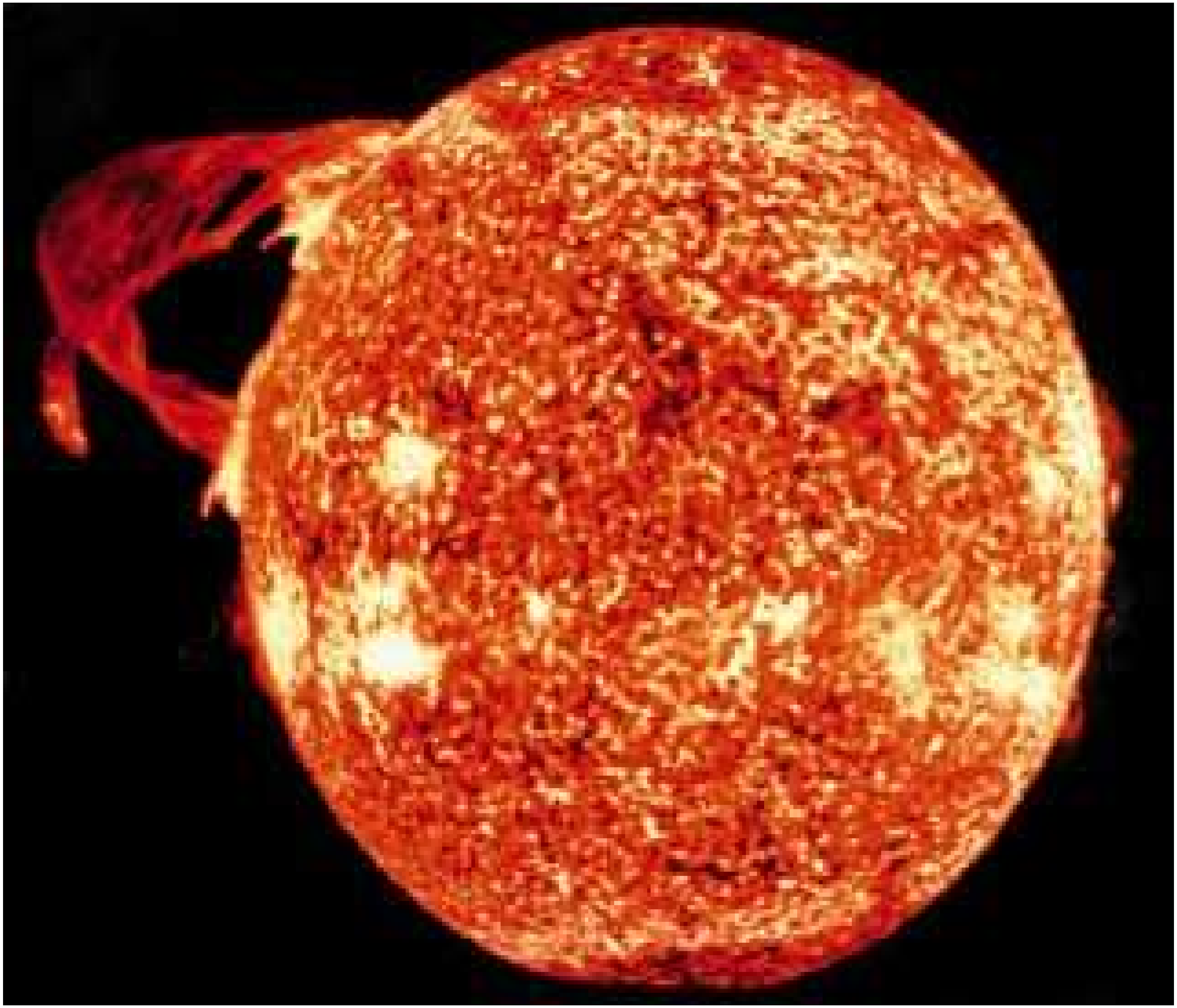
The Sun produces 2 x 10^{38} ν/s
The Earth receives > 5×10^{10} ν/s/cm^2
The Universe contains 300 ν/cm^3

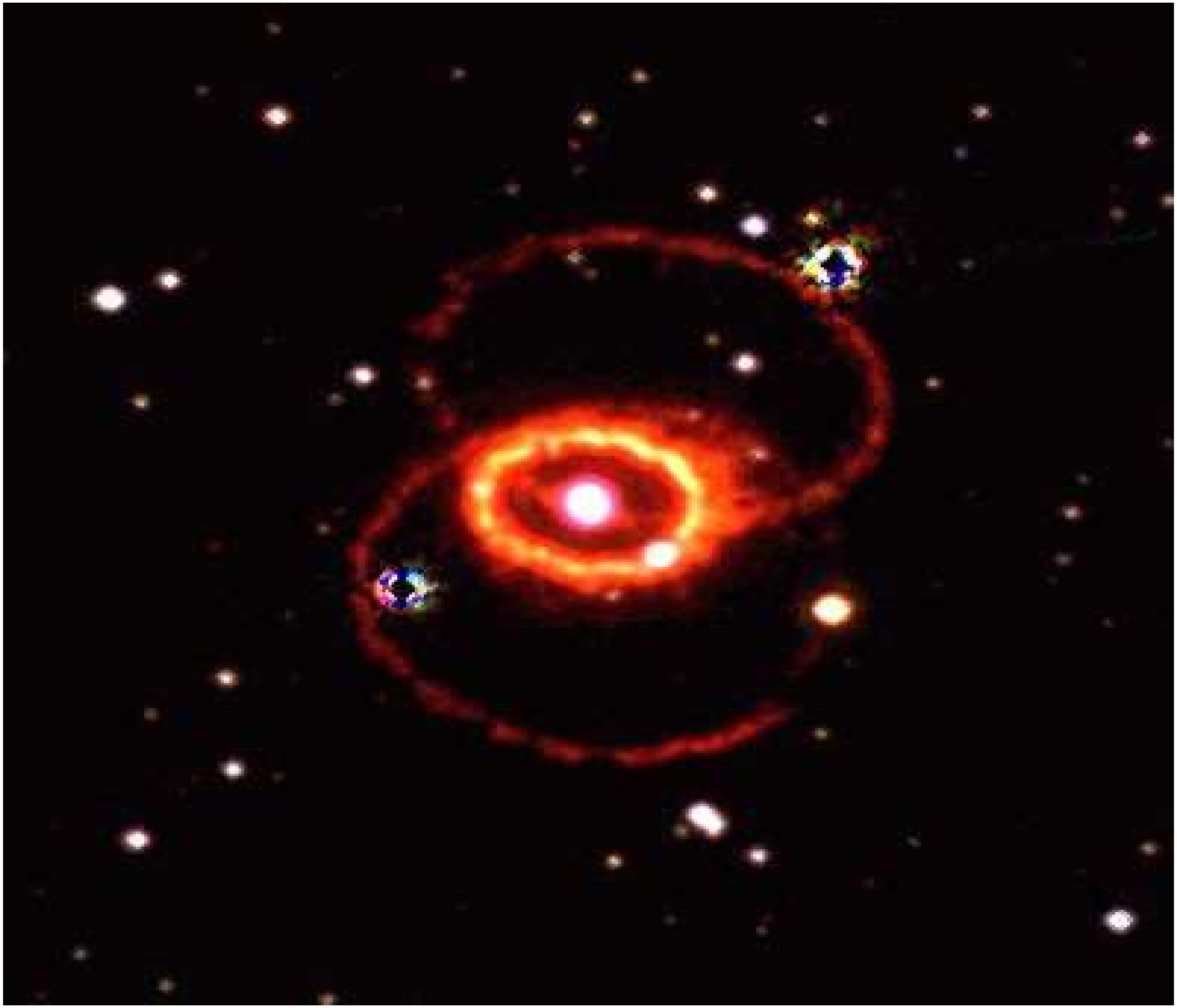

The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons
dark matter

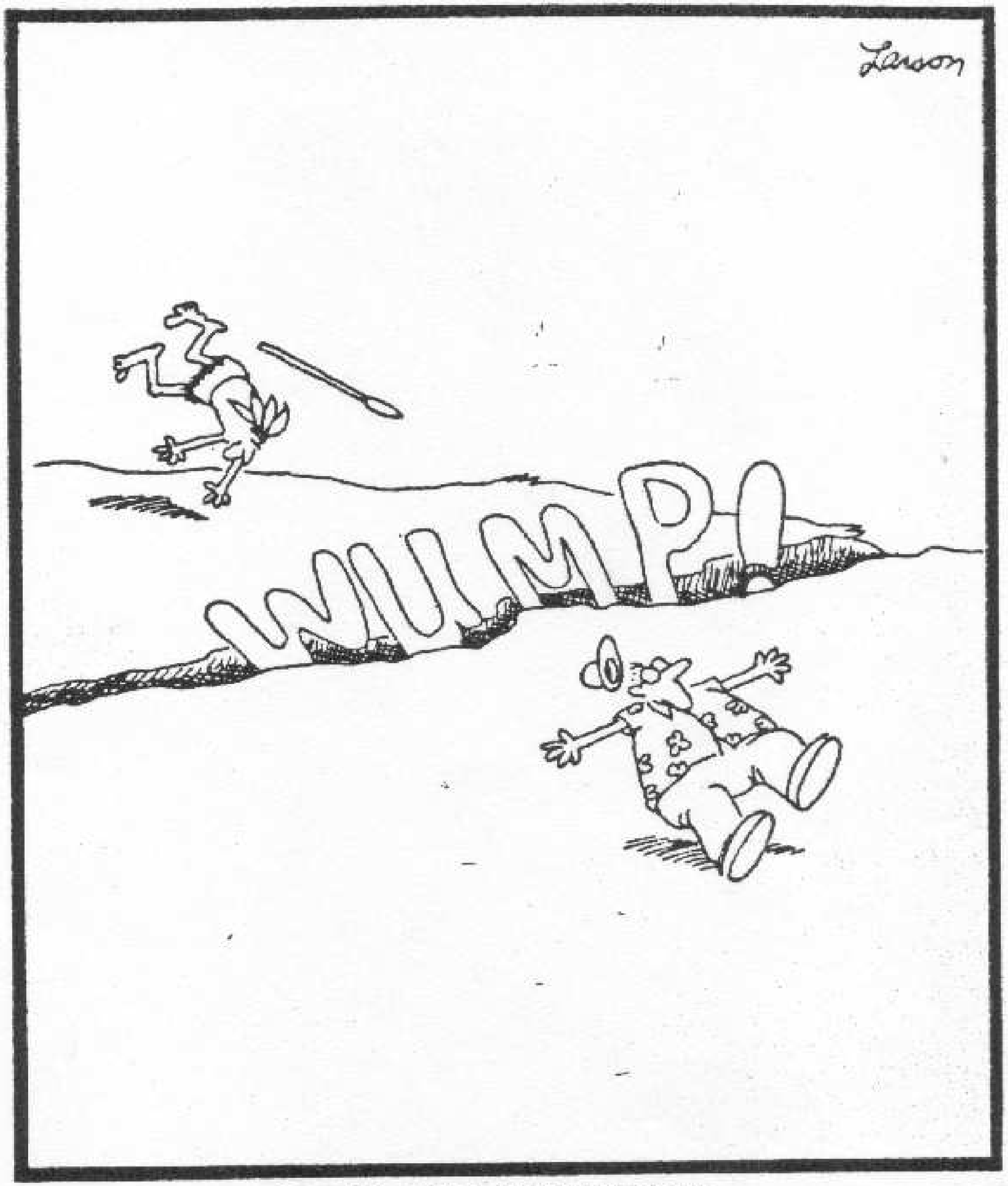


- Spin ½
- Massless (almost)
- Chargeless
- 3 Flavours
- Flavours mix

Neutrinos are responsible for.....

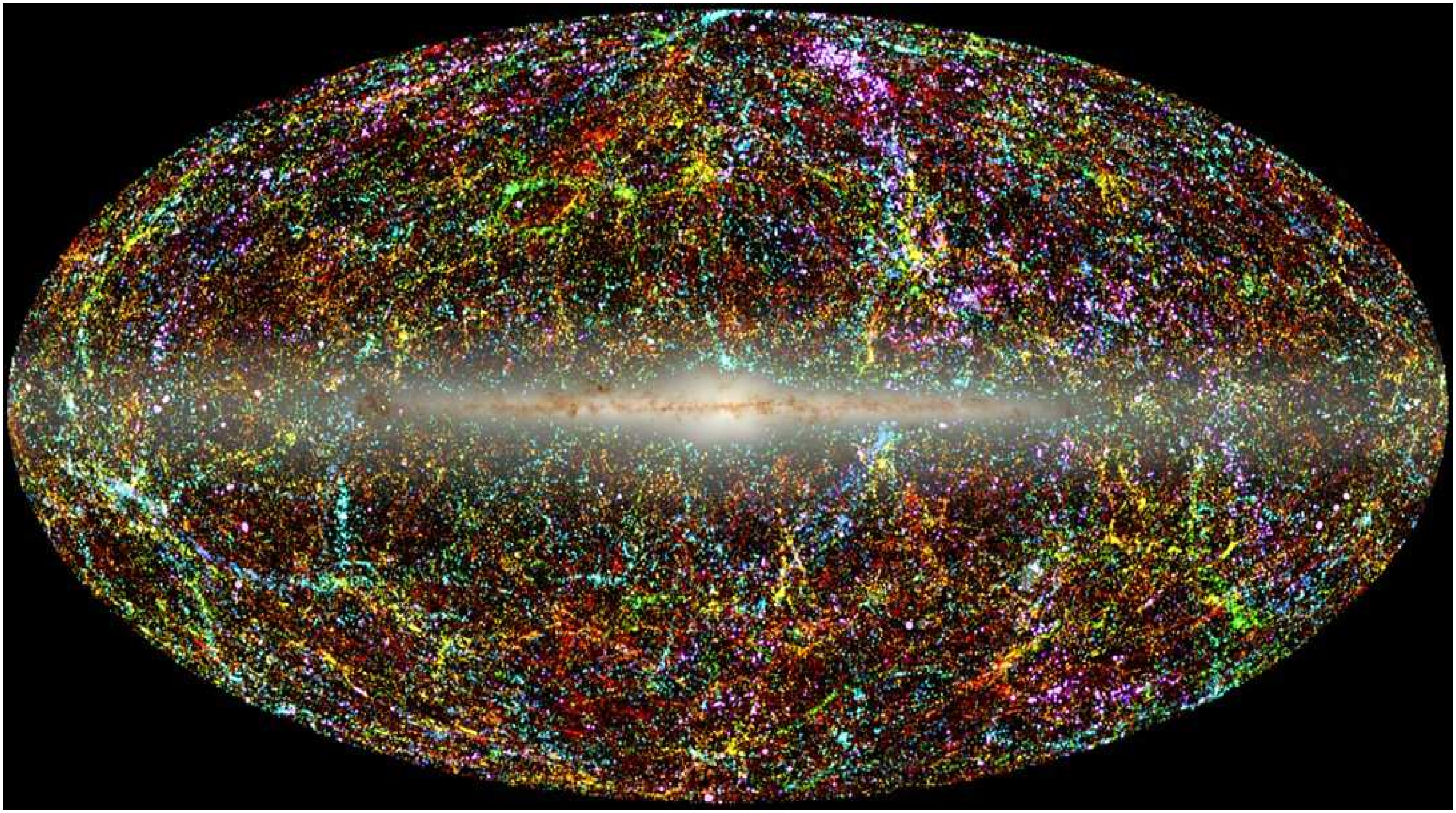




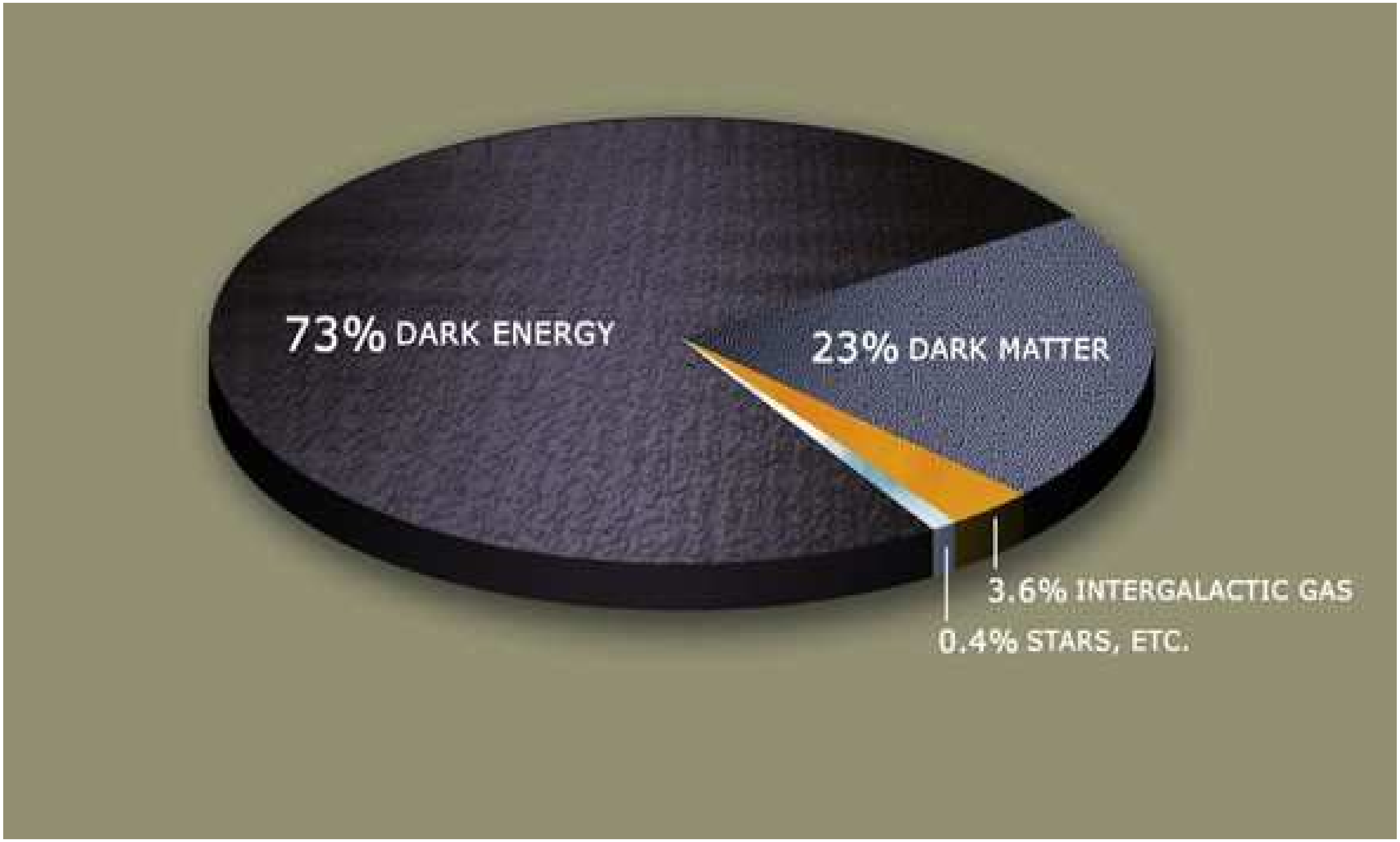


Continental drift whiplash

Neutrinos *might be* responsible for.....



Matter Anti-Matter


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Why study neutrinos?

- Could help explain the matter-antimatter asymmetry
- Could be a component of dark matter
- Can be a probe for environments that other techniques cannot.
- Knowing so little about a fundamental particle is just plain embarrassing

Basic Concepts

- Units and Relativistic Kinematics
- Basic Particle Physics
  - The Standard Model
  - Exchange forces
  - Decays, Cross-sections
  - Feynman Diagrams
- The Dirac Equation
- The Weak Interaction

Units

- kg, m and s are fine units up here in the macroscopic
- They get quite clumsy in the quantum
- Natural Units : $\hbar$, c and GeV

Energy	GeV	Time	$(\mathrm{GeV}/\hbar)^{-1}$
Momentum	GeV/c	Length	$(\mathrm{GeV}/\hbar c)^{-1}$
Mass	GeV/c^2	Area	$(\mathrm{GeV}/\hbar c)^{-2}$

- Particle physicist simplify even more by setting

$$\hbar = c = 1$$

Energy	GeV	Time	GeV^{-1}
Momentum	GeV	Length	GeV^{-1}
Mass	GeV	Area	GeV^{-2}

Relativity & 4-vectors

All energy-momentum relationships can be represented as 4-vectors

$$p^{\mu}=(E, p_x, p_y, p_z) \quad \text{contravariant}$$

$$p_{\mu}=g_{\mu\nu}p^{\nu}=(E,-p_x,-p_y,-p_z) \quad \text{covariant}$$

$$g_{\mu\nu}=\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & -1 & 0 & 0\\ 0 & 0 & -1 & 0\\ 0 & 0 & 0 & -1\end{pmatrix}$$

The two we will use most often are

$$4-space: x^{\mu}=(t, x, y, z)$$

$$4-momentum: p^{\mu}=(E, p_x, p_y, p_z)$$

In particle physics we require all quantities to be Lorentz invariant. These are usually formed from scalar products

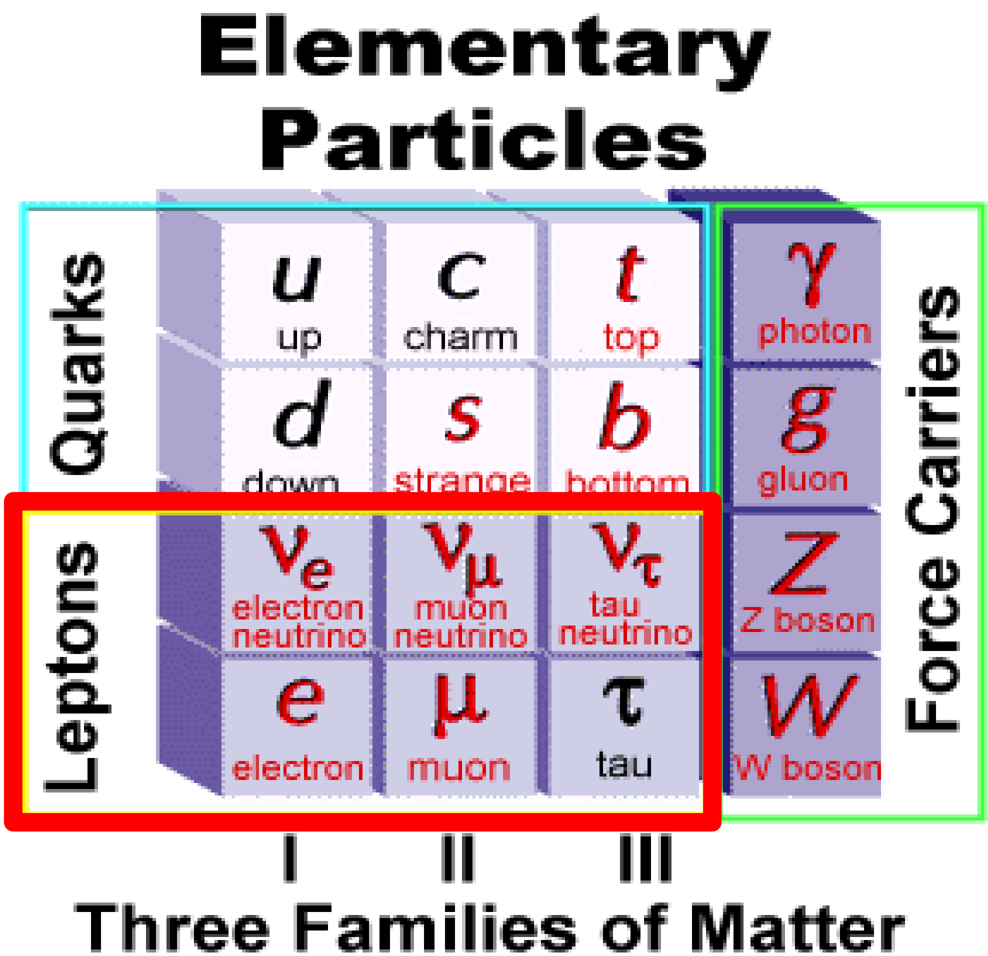
$$p_{\mu}p^{\mu}=p^2=g_{\mu\nu}p^{\nu}p^{\mu}=E^2-p_x^2-p_y^2-p_z^2=E^2-|p^2|=m^2$$

Example

A pion at rest decays into a muon and a muon neutrino. What is the momentum of muon?

The Standard Model

Leptons



Leptons

Particle	Lifetime (s)	Mass (GeV/c²)
e^+, e^-	stable	5.11×10^{-4}
μ^+, μ^-	2.2×10^{-6}	0.106
τ^+, τ^-	3.0×10^{-11}	1.784
$\nu_e, \bar{\nu}_e$	stable	$< 3.0 \times 10^{-6}$
$\nu_\mu, \bar{\nu}_\mu$	stable	$< 1.9 \times 10^{-4}$
$\nu_\tau, \bar{\nu}_\tau$	stable	$< 1.8 \times 10^{-2}$

- Spin $\hbar/2$ fermions
- Point-like
- Blind to the strong force
- Can be free

	L_e	L_μ	L_τ
e^-, ν_e	1	0	0
$e^+, \bar{\nu}_e$	-1	0	0
μ^-, ν_μ	0	1	0
$\mu^+, \bar{\nu}_\mu$	0	-1	0
τ^-, ν_τ	0	0	1
$\tau^+, \bar{\nu}_\tau$	0	0	-1

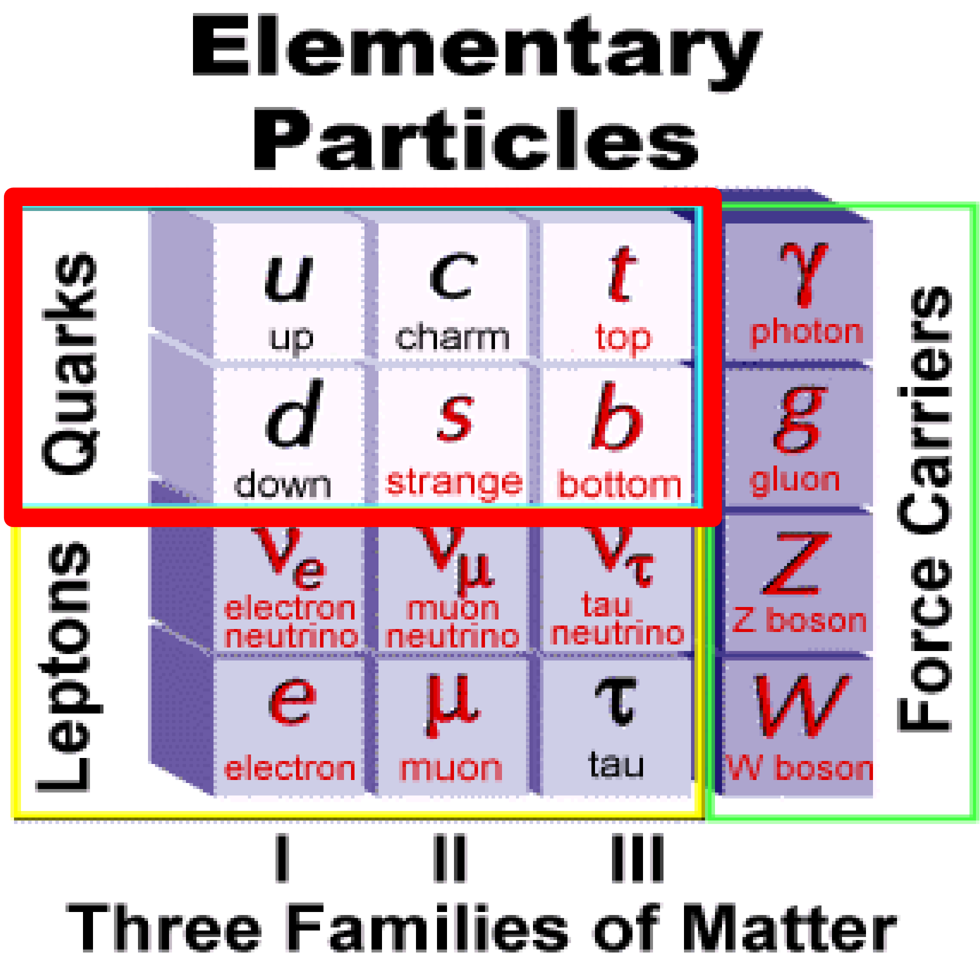
- Have a “Lepton Number”

Have 0 electric charge or ±e

- Come in 6 'flavours' +antiparticles

The Standard Model

Quarks



Quarks

- Spin $\hbar/2$ fermions
- Point-like
- Feel the strong force
- Are never free
- Have fractional charge
- Come in six 'flavours' + antiparticles
- Come in 3 colours – red, green and blue
- Do not have well-defined masses

Particle	Charge	Mass (GeV/c^2)
d	$-\frac{1}{3}$	$\sim 6 \times 10^{-4}$
u	$+\frac{2}{3}$	$\sim 3 \times 10^{-4}$
s	$-\frac{1}{3}$	~ 0.1
c	$+\frac{2}{3}$	~ 1.3
b	$-\frac{1}{3}$	~ 4.2
t	$+\frac{2}{3}$	~ 174

Hadrons

Quarks are always bound into colourless states called *hadrons*

Baryon Number

$$B = \frac{1}{3}(n_q - n_{\bar{q}})$$

Quarks	B	Name
qqq	$+1$	Baryon
$\bar{q}\bar{q}\bar{q}$	-1	Anti-Baryon
$q\bar{q}$	0	Meson
$q\bar{q}q\bar{q}$	0	Tetraquark?
$qqq\bar{q}q / \bar{q}\bar{q}\bar{q}\bar{q}q$	$+1/-1$	Pentaquark?

Baryons

Made from 3 quarks (or antiquarks)

- Spin $\hbar/2$ fermions
- Feel all forces
- Colourless
- $B = \pm 1$

Particle	Quarks	Mass (GeV/c^2)	Lifetime (s)
p	uud	0.938	stable
n	ddu	0.940	920
Λ	uds	1.116	2.6×10^{-10}
Δ^{++}	uuu	1.232	6.0×10^{-24}
Ξ^o	uss	1.315	2.9×10^{-10}
Ω^-	sss	1.672	8.2×10^{-11}

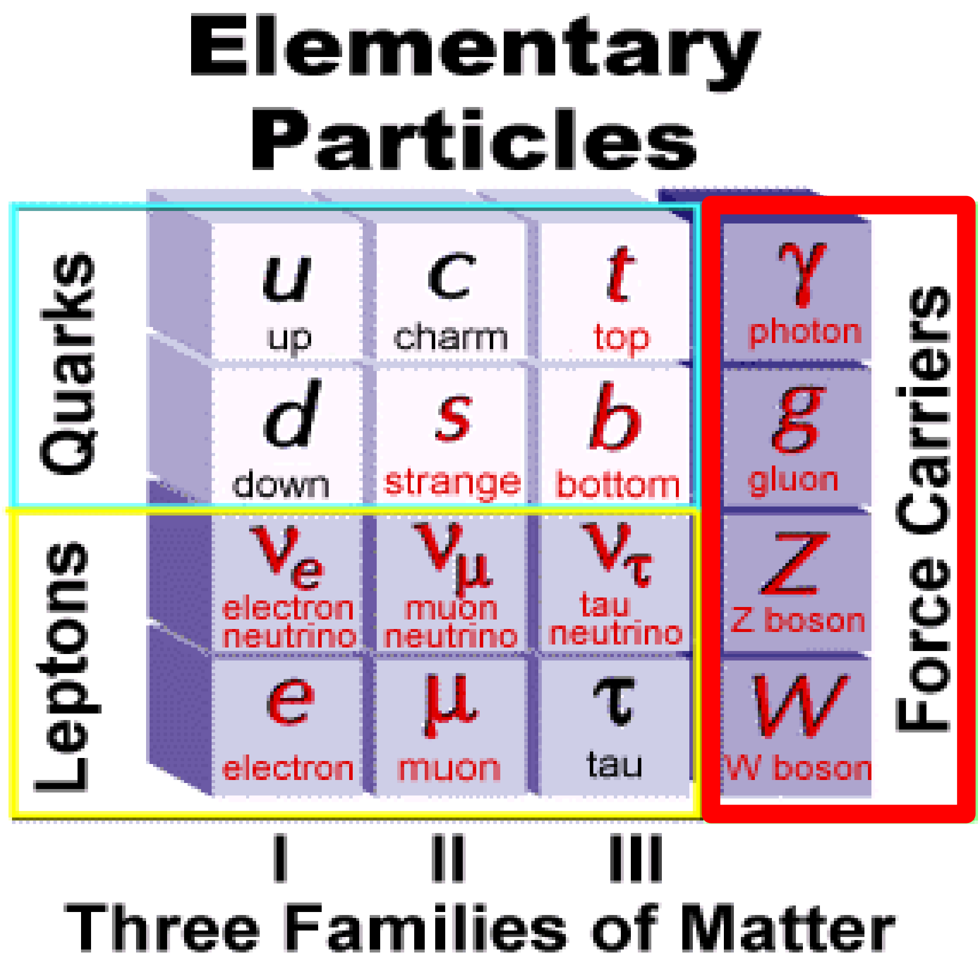
Mesons

Made from a quark and an antiquark

- Integral spin bosons
- Feel all forces
- Colourless
- B = 0

Particle	Quarks	Mass (GeV/c^2)	Lifetime (s)
π^+, π^-	$u\bar{d}, \bar{u}d$	0.139	2.6×10^{-8}
K^+, K^-	$u\bar{s}, \bar{u}s$	0.494	1.3×10^{-8}
J/Ψ	$c\bar{c}$	3.097	7.7×10^{-21}
Υ	$b\bar{b}$	9.460	1.3×10^{-20}

The Standard Model



Forces

Forces

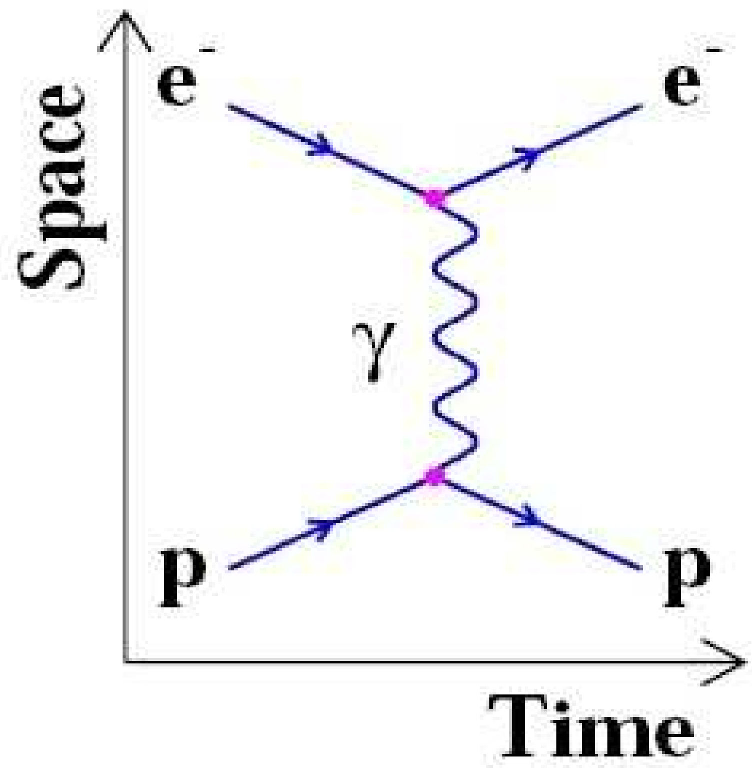
Particles interact (decay, scatter) through forces which we describe as the exchange of the gauge bosons

Particle	Life Time (s)	Mass (GeV/c^2)	Spin	Force	Range
γ (photon)	stable	massless	$1\hbar$	EM	∞
g (gluon)	stable	massless	$1\hbar$	Strong	10^{-15}
Z^o	2.7×10^{-25}	91.19	$1\hbar$	Weak	10^{-27}
$W^{\pm}$	3.1×10^{-25}	80.42	$1\hbar$	Weak	
graviton	stable	massless	$2\hbar$	Gravity	∞

Gravity does not fit into quantum theory yet

WARWICK

Modern Picture

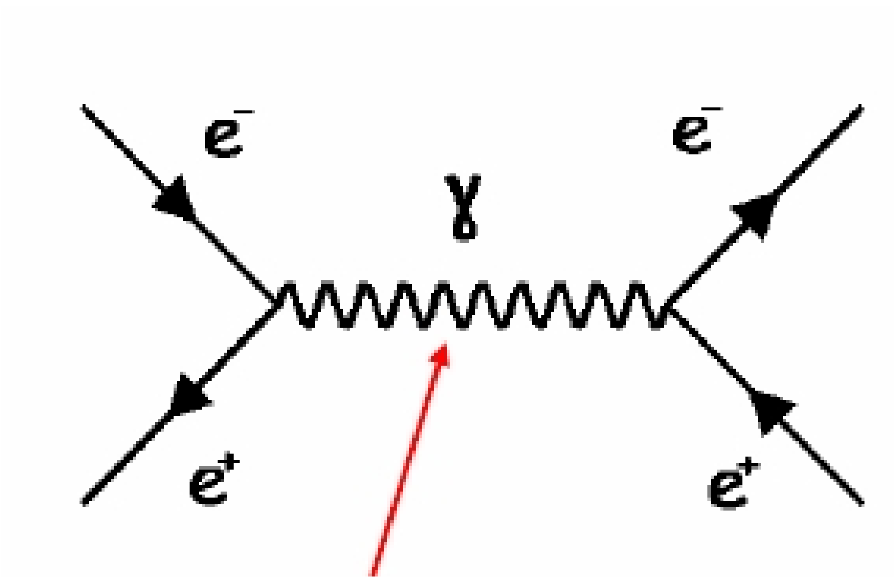


Gauge boson transfers information between particles (energy, momentum, charge, colour etc...)

How the gauge boson couples to the quarks and leptons determines the properties of the force

Gauge bosons are Virtual

i.e ($E^2 \neq p^2 + m^2$). Such particles are said to be *virtual* or *off mass-shell.* Fine as long as the particle isn't free.



energy and momentum must be conserved at *each* vertex

Photon must carry zero momentum and an energy of 2 E_e

$$m_\gamma = \sqrt{E_\gamma^2 - p_\gamma^2} = 2E_e \neq 0$$

Range of Forces

In general the range of
a force is inversely proportional
to the mass of the gauge boson

$$R \sim \frac{\hbar}{2m}$$

Uncertainty Principle

$$\Delta E \Delta t \sim \frac{\hbar}{2}$$

Virtual boson implies that $\Delta E \approx m$, so the gauge boson can only exist for a time $\Delta t \sim \hbar / 2m$. In this time the particle can travel at most $R \sim \Delta t$, so the range is around $\hbar/2m$.

Heavier exchange particles $\Rightarrow$ shorter range (weaker) forces

Conservation Laws

Particle physics is the physics of symmetries.
A symmetry implies something is conserved
(Noether's theorem)

Conserved Quantity	Electromagnetic	Strong	Weak
Kinematics	Yes	Yes	Yes
Electric Charge	Yes	Yes	Yes
Colour Charge	-	Yes	-
Baryon Number	Yes	Yes	Yes
Lepton Number	Yes	-	Yes
Quark Flavour	Yes	Yes	No

C, P and T

Charge conjugation $\hat{C}(particle) = (antiparticle)$

Parity: Spatial inversion $\hat{P}\psi(x, y, z) = \psi(-x, -y, -z)$

Time reversal $\hat{T}\psi(t, x, y, z) \rightarrow \psi(-t, x, y, z)$

Conserved Quantity	Electromagnetic	Strong	Weak
Kinematics	Yes	Yes	Yes
Electric Charge	Yes	Yes	Yes
Colour Charge	-	Yes	-
Baryon Number	Yes	Yes	Yes
Lepton Number	Yes	-	Yes
Quark Flavour	Yes	Yes	No
C	Yes	Yes	No
P	Yes	Yes	No
CP	Yes	Yes	No
CPT	Yes	Yes	Yes

Standard Model

- The Standard Model describes ALL experimental data
- Yet it's quite clunky and contains unanswered questions
  - There are 26 free parameters (15 are particle masses)
  - There are 3 generations of basically the same particle
  - The neutrino are orders or magnitude lighter than all the other particles.
  - Interactions aren't unified
- It's not the ultimate theory.