

XI. Beyond the Standard Model

❖ While the Standard Model appears to be confirmed in all ways, there are some unclear points and possible extensions:

- Why do the observed quarks and leptons have the **masses** they do?
- Do **neutrinos** have any **mass** ?
- If yes, are they the **Dark Matter**?
- Or is the missing matter due to **super symmetric WIMPs** ?
- And what is **Dark Energy** ?
- Do the **Graviton** exist ? If yes, does it live in **extra dimensions** of space ?

Neutrino masses

→ If neutrinos have non-zero masses, they must be subject to *neutrino-mixing*

Reminder: kaon mixing in weak interactions

$$K_s^0 = K_1^0 = \frac{1}{\sqrt{2}} \{K^0 + \bar{K}^0\}$$

$$K_L^0 = K_2^0 = \frac{1}{\sqrt{2}} \{K^0 - \bar{K}^0\}$$

By analogy, neutrinos can be represented as linear combinations

$$\begin{aligned} \nu_e &= \nu_1 \cos\alpha + \nu_2 \sin\alpha \\ \nu_\mu &= -\nu_1 \sin\alpha + \nu_2 \cos\alpha \end{aligned} \tag{158}$$

if neutrinos ν_1 and ν_2 have masses m_1 and m_2 .

→ The **mixing angle** α must be determined from experiment by studying *neutrino oscillations*.

→ **Neutrino oscillation**: a beam of ν_e develops a ν_μ component as it travels through space, and vice versa.

Neutrinos created at $t=0$ can be written as:

$$\begin{aligned} \nu_e(0) &= \nu_1(0)\cos\alpha + \nu_2(0)\sin\alpha \\ \nu_\mu(0) &= -\nu_1(0)\sin\alpha + \nu_2(0)\cos\alpha \end{aligned} \quad (159)$$

and after a period of time t it evolves to:

$$\begin{aligned} \nu_e(t) &= \nu_1(0)e^{-iE_1t}\cos\alpha + \nu_2(0)e^{-iE_2t}\sin\alpha \\ \nu_\mu(t) &= -\nu_1(0)e^{-iE_1t}\sin\alpha + \nu_2(0)e^{-iE_2t}\cos\alpha \end{aligned} \quad (160)$$

where $e^{-iE_i t}$ are oscillating time factors and E_1 and E_2 are the energies of neutrino ν_1 and ν_2 :

$$\begin{aligned} E_1 &= \sqrt{m_1^2 + p^2} \\ E_2 &= \sqrt{m_2^2 + p^2} \end{aligned}$$

If one starts with a pure ν_e state then after a time t one has a mixture of electron and muon neutrinos given by

$$\nu_e(t) = A(t)\nu_e(0) + B(t)\nu_\mu(0) \quad (161)$$

where

$$A(t) = e^{-iE_1 t} \cos^2 \alpha + e^{-iE_2 t} \sin^2 \alpha \quad (162)$$

$$B(t) = \sin \alpha \cos \alpha [e^{-iE_2 t} - e^{-iE_1 t}]$$

The squares of $A(t)$ and $B(t)$ are probabilities to find ν_e respective ν_μ in a beam of electron neutrinos:

$$P(\nu_e \rightarrow \nu_e) = |A(t)|^2 = 1 - P(\nu_e \rightarrow \nu_\mu) \quad (163)$$

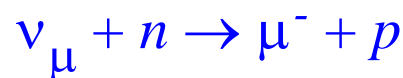
$$P(\nu_e \rightarrow \nu_\mu) = |B(t)|^2 = \sin^2(2\alpha) \sin^2 \frac{(E_2 - E_1)t}{2} \quad (164)$$

$$= \sin^2(2\alpha) \sin^2 \frac{(\sqrt{m_2^2 + p^2} - \sqrt{m_1^2 + p^2})t}{2}$$

→ If neutrinos have equal (zero) masses ⇒
 $E_1 = E_2 \Rightarrow$ no oscillations !

Ways to detect neutrino oscillations:

❖ ν_e and ν_μ can be distinguished by their **interaction with neutrons** since the former produce electrons and the latter muons



❖ The time t is determined by the distance between the detector and the source of neutrinos

→ Several **neutrino sources** can be considered:

- The sun
- Cosmic rays (“atmospheric neutrinos”)
- Secondary accelerator beams
- Nuclear reactors
- Natural radioactivity
- Supernovas
- The Big Bang

The atmospheric neutrino anomaly

→ This was first observed in the 1980's. Instead of having the predicted $N(\nu_\mu) \approx 2N(\nu_e)$ the rates of both neutrino types were approximately equal.

❖ The **Super-Kamiokande** detector measures rates and flavours of neutrinos coming both from zenith and nadir

- A neutrino created in cosmic rays travels at most **20 km in the atmosphere** \Rightarrow it has no time to oscillate (proven by other experiments)
- A similar neutrino created on the **other side of the Earth** travels ≈ 13000 km \Rightarrow it has a good chances to oscillate
- If the **ratio of ν_e and ν_μ** is different in the two cases above \Rightarrow there are oscillations \Rightarrow at least one neutrino is massive.

Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.

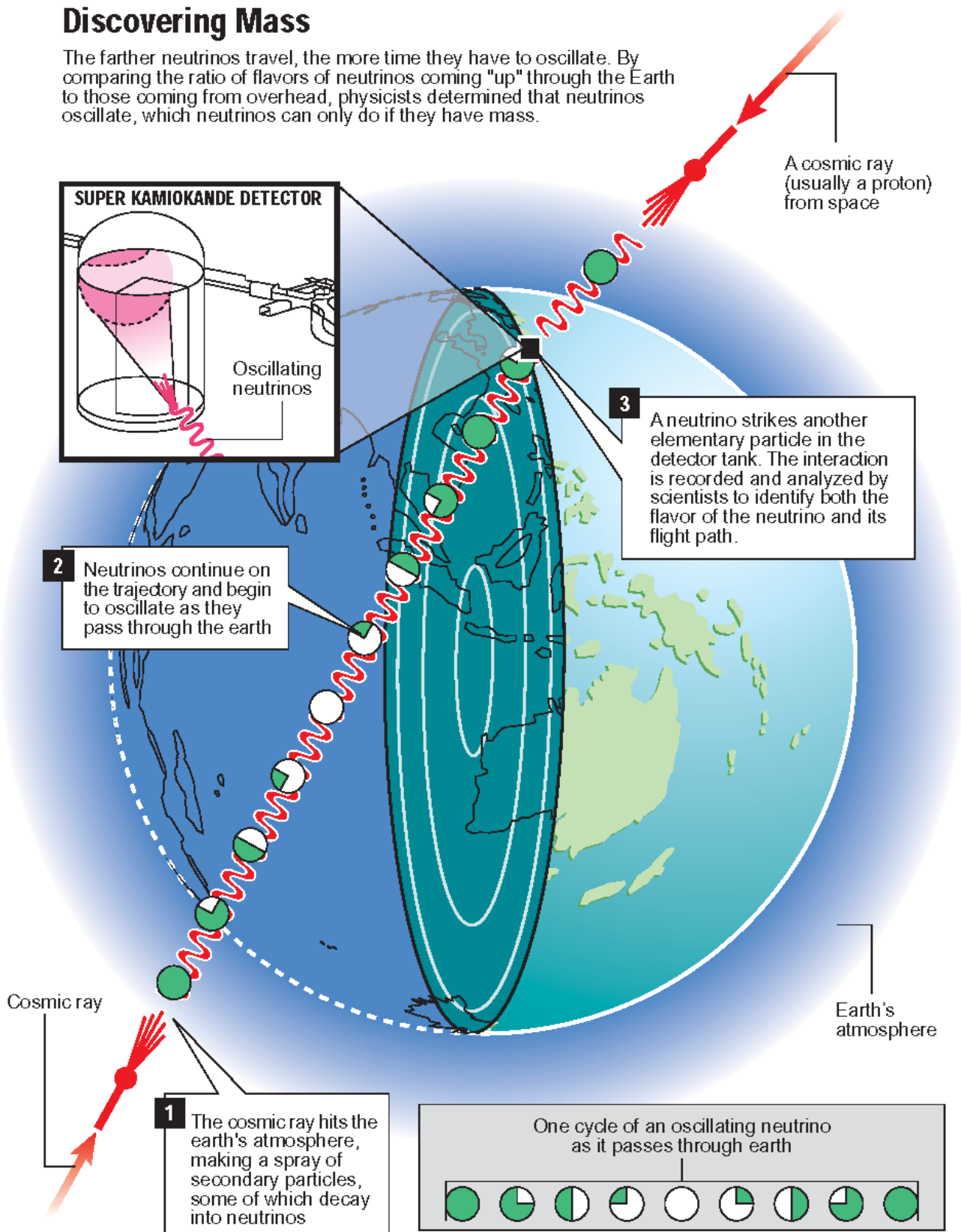


Figure 134: Neutrino oscillations through Earth

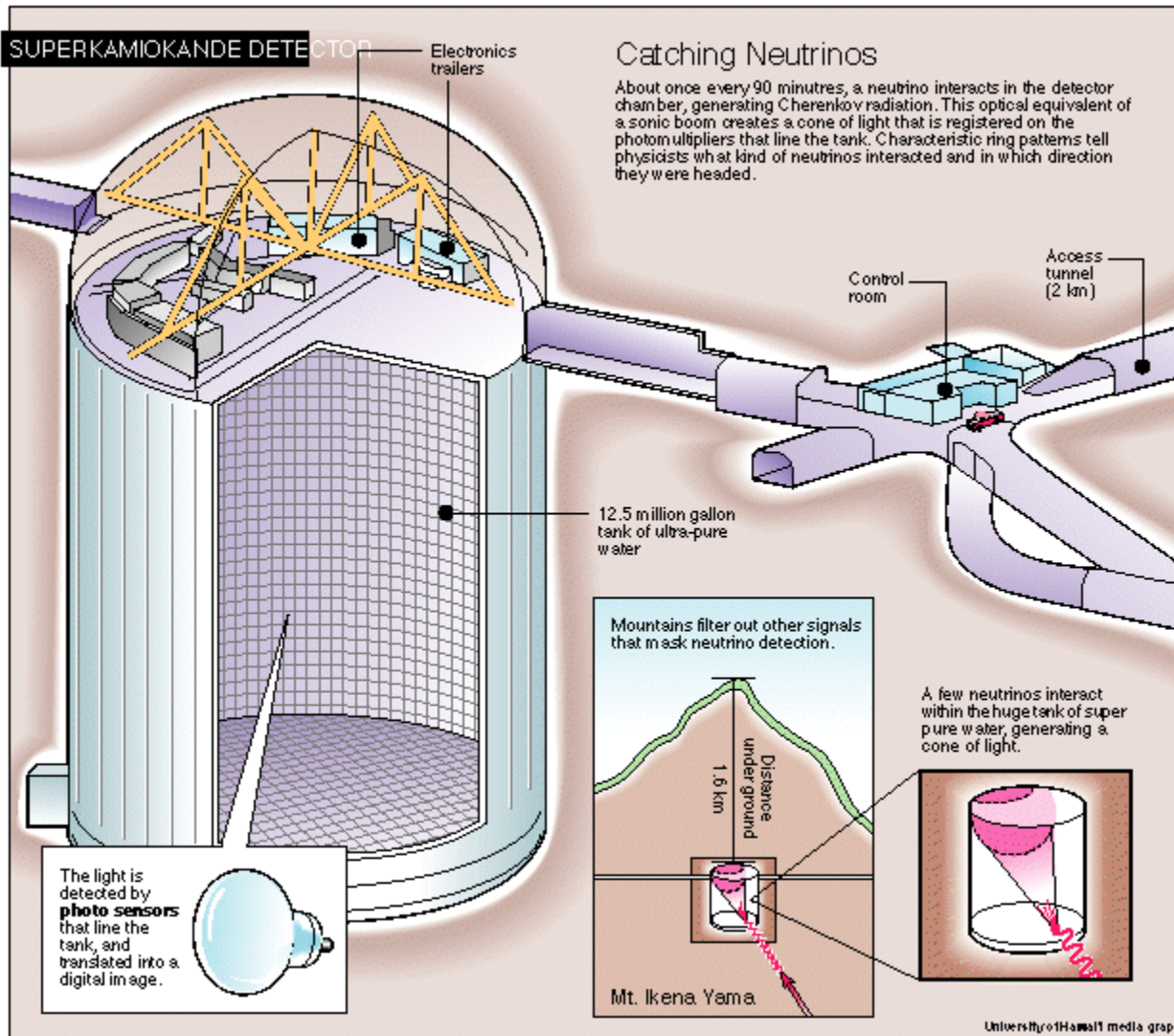


Figure 135: Schematics of the Super-Kamiokande detector

- The detector is placed in a deep mine to reduce the background.
- 50 000 m³ of water and 13 000 photomultipliers work as a Cherenkov detector.

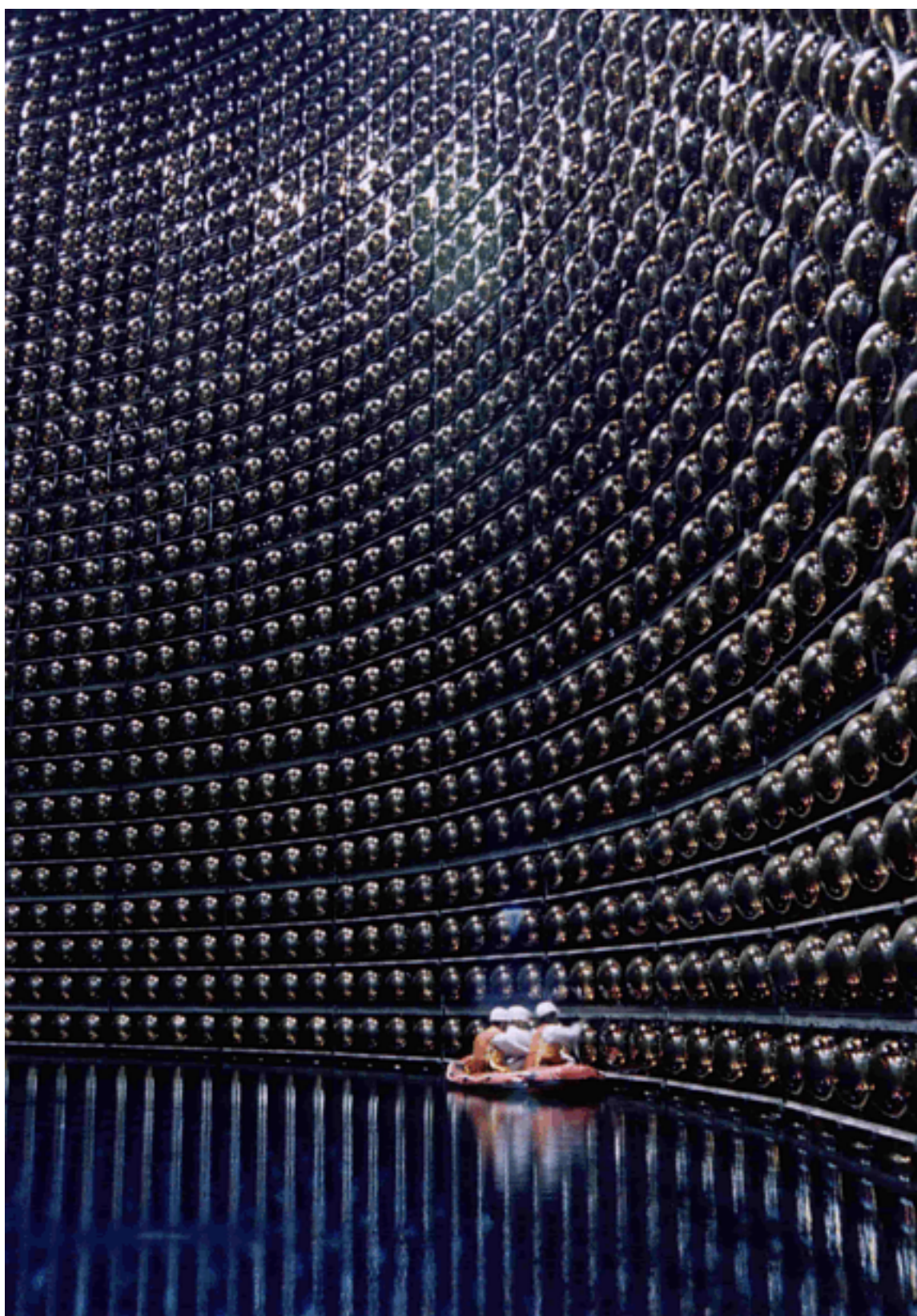


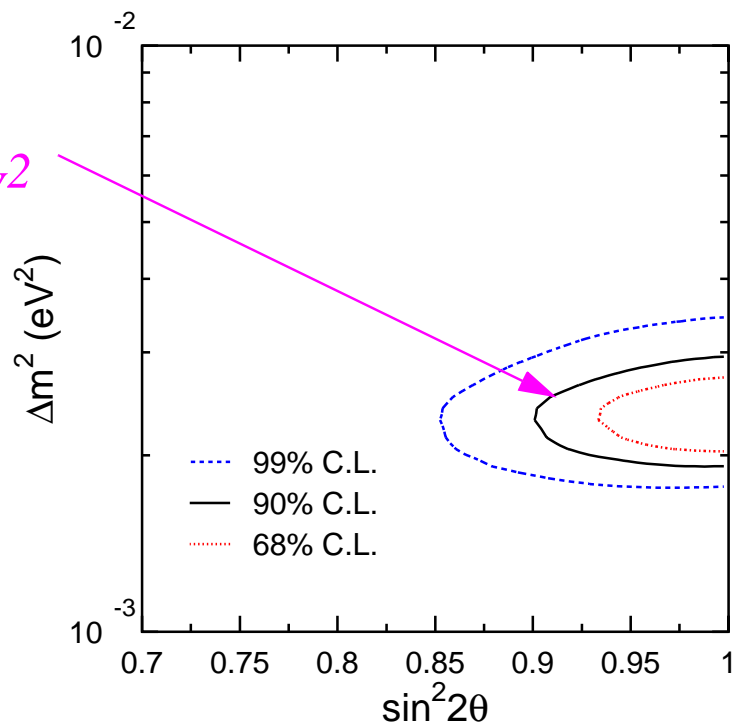
Figure 136: Interior of the Super-Kamiokande detector (during construction)

→ In 1998, the Super-Kamiokande Collaboration announced:

- a) 4654 observed events – by far the largest sample in the world
- b) the ν_μ data exhibited a deficit with a zenith angle dependence
- c) hence the “atmospheric neutrino anomaly” can only be explained by oscillations $\nu_\mu \leftrightarrow \nu_\tau$, which leads to a muonic neutrino deficiency in cosmic rays.
- d) the mixing angle and neutrino mass difference Δm are now (2004) estimated to be

$$\sin^2(2\alpha) > 0,90$$

$$2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-3} \text{ eV}^2$$



The solar neutrino problem

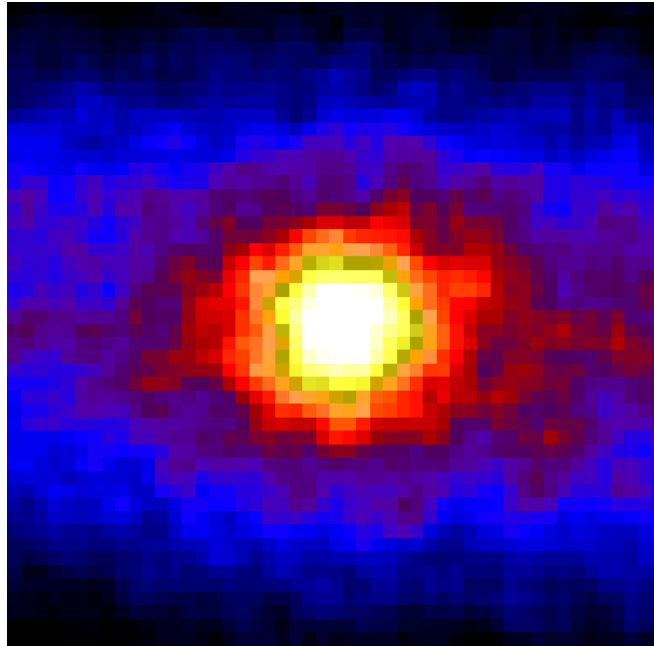
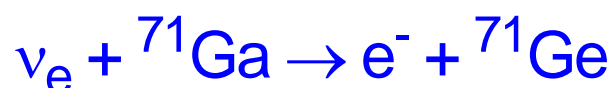
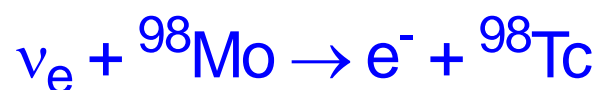
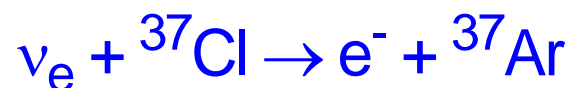
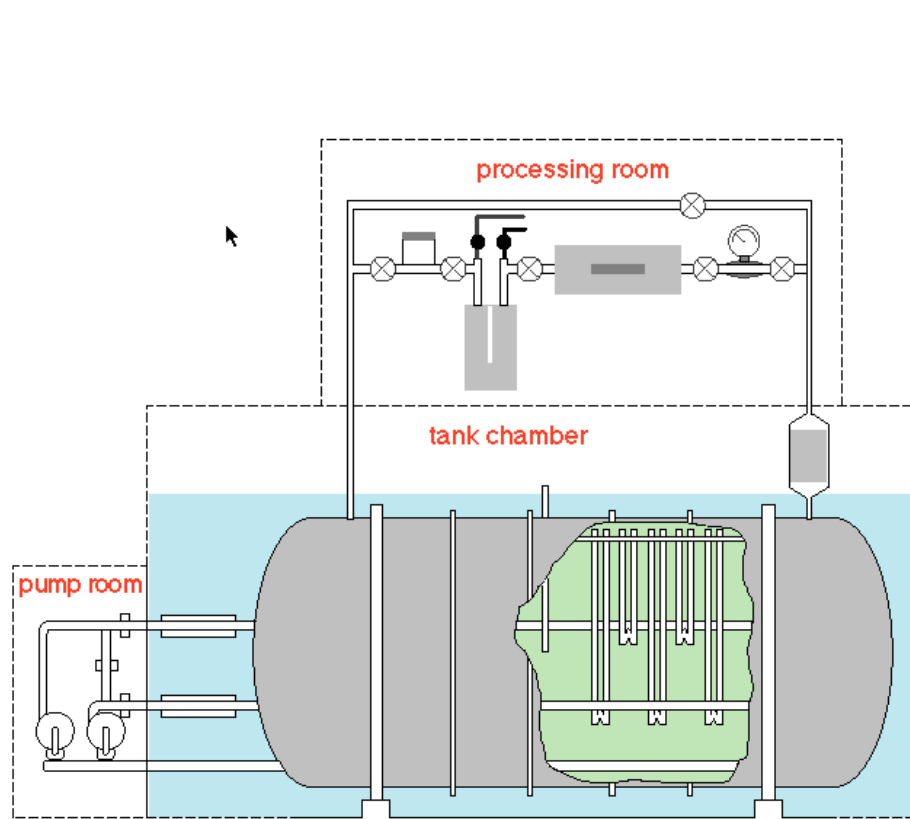


Figure 137: “Portrait” of the Sun made with neutrinos

Several (similar) methods are used to detect solar neutrinos:

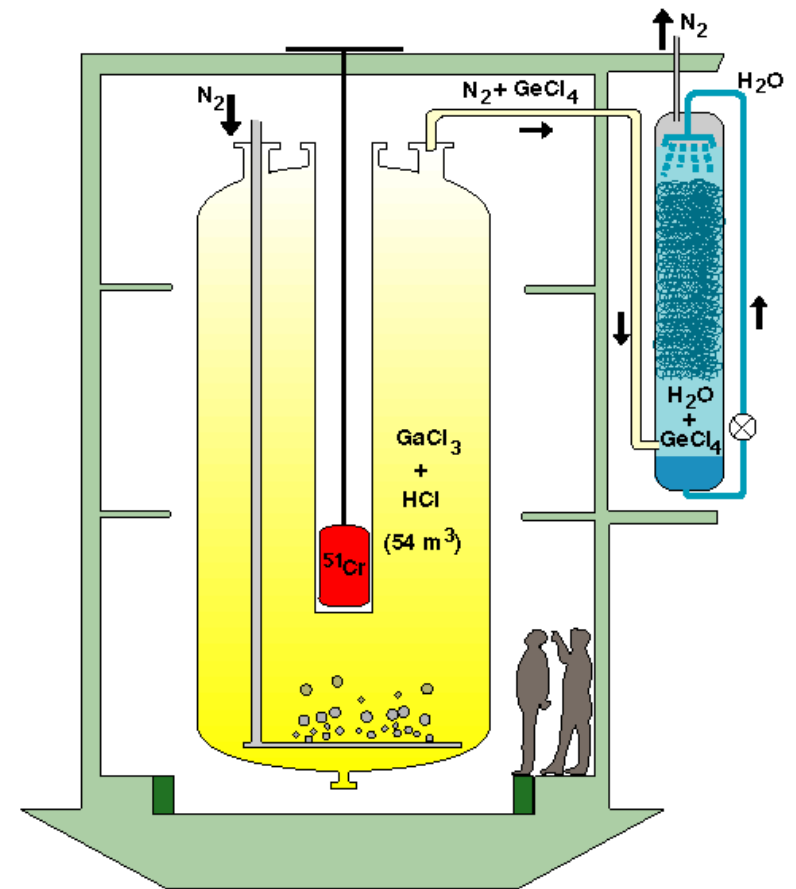


Experimental installations typically are tanks filled with corresponding medium and placed underground.



The Homestake gold mine detector (USA).

The reaction $\nu_e + {}^{37}\text{Cl} \rightarrow e + {}^{37}\text{Ar}$ is used.



GALLEX detector under the Gran Sasso mountain (Italy).

The reaction $\nu_e + {}^{71}\text{Ga} \rightarrow e + {}^{71}\text{Ge}$ is used.

Figure 138: Typical layouts of solar neutrino detectors.

The solar neutrino flux is measured in SNU (“solar neutrino unit”):

$$1 \text{ SNU} = 1 \text{ capture} / 1 \text{ second} / 10^{36} \text{ target atoms}$$

“The solar neutrino problem”:

- For the Homestake detector the predicted neutrino flux is 7.3 ± 2.3 SNU but the measured is 2.5 ± 0.2 SNU
- GALLEX: The predicted flux is 132 ± 9 SNU and the measured flux is 79 ± 11 SNU

Reactions producing solar neutrinos are:



GALLEX measures all of them, Homestake only the last one.

- Neutrino oscillations is one of the possible explanation for the lack of ν_e coming from the sun.

- During 15s on February 23 1987 the IMB and Kamiokande detectors recorded 20 neutrino interactions coming from a **supernova** explosion (SN1987a) only 160 000 light years away.

This was the first time extra-terrestrial neutrinos, not coming from the sun, was observed.

- From the energy (E_ν), the length of the burst (Δt) and the time of flight (t_ν) it is possible to estimate the neutrino mass (m_ν):

$$m_\nu = E_\nu \sqrt{\frac{2\Delta t}{t_\nu}}$$

- *Example:* $E_\nu=10$ MeV, $\Delta t=10$ s and $t_\nu=5 \times 10^{12}$ s gives $m_\nu=20$ eV.

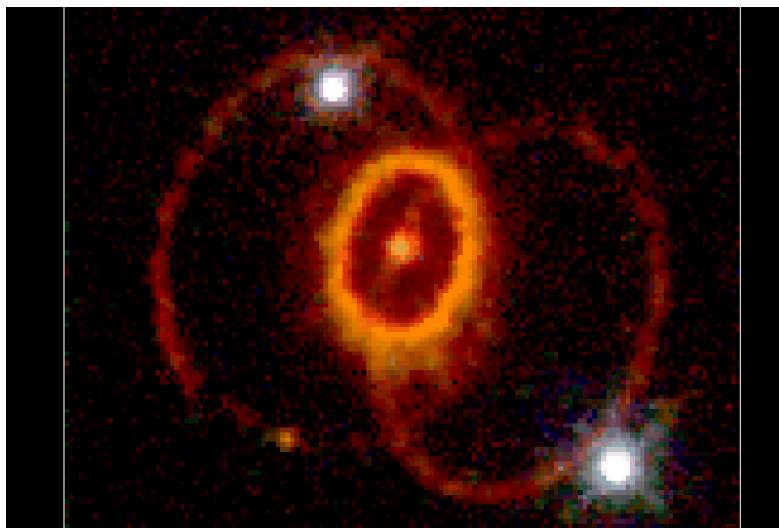


Figure 139: SN1987a as seen by the Hubble telescope.

Extra-galactic neutrinos

- ❖ Experiments have been built to look for **TeV neutrino** sources from outside of our galaxy.
- One of these experiments is called **AMANDA** and has Swedish participation.
- The experiments is situated on the **south pole** and consist of strings of photomultipliers drilled deep down into the ice.
- A neutrino interaction will give rise to **Cherenkov light** in the ice which is detected by the photomultipliers.
- So far **no extra-galactic neutrinos** have been observed.

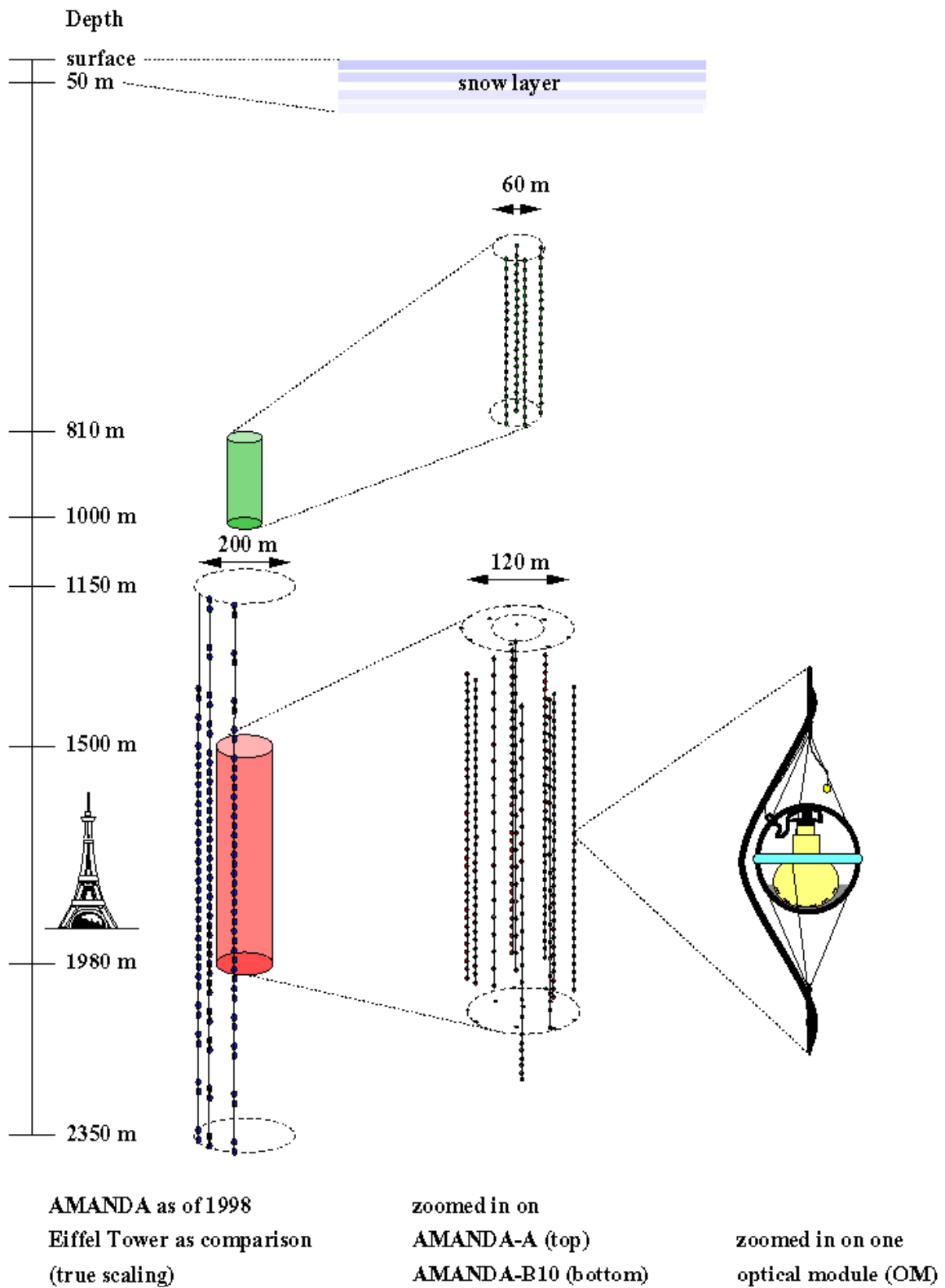
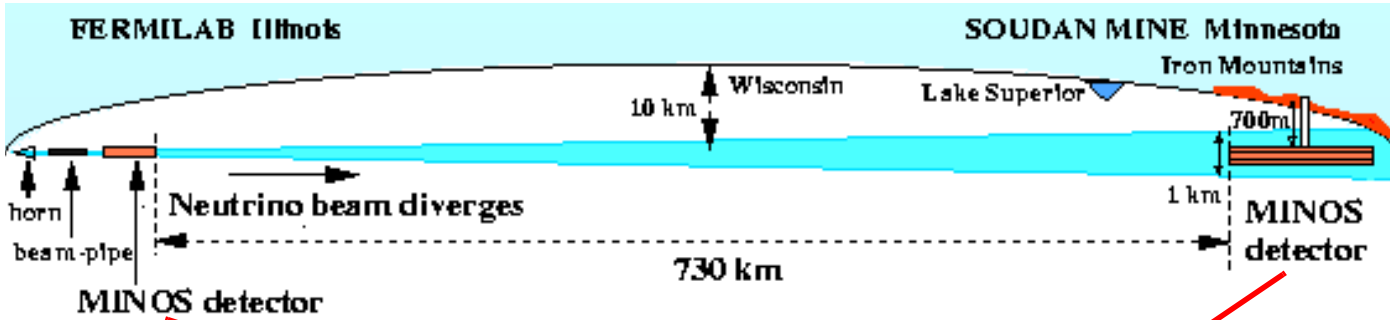


Figure 140: Schematics of the AMANDA neutrino telescope at the South Pole

Long baseline neutrino experiments

MINOS

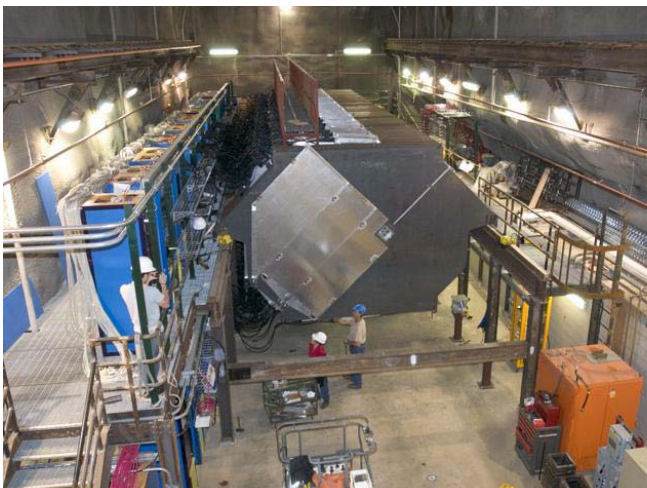
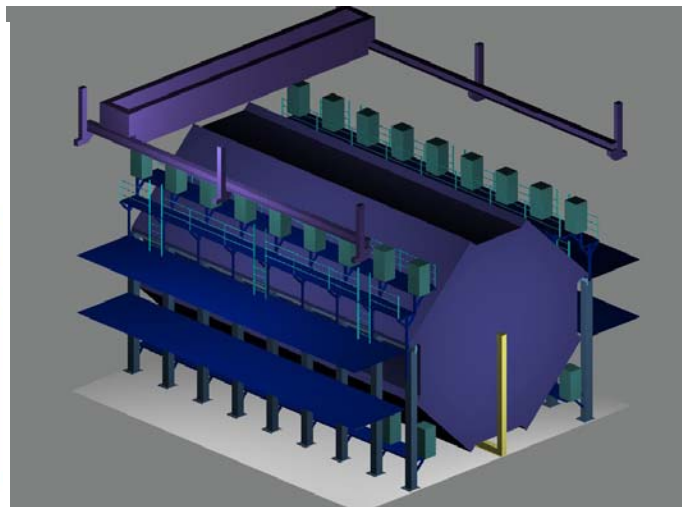
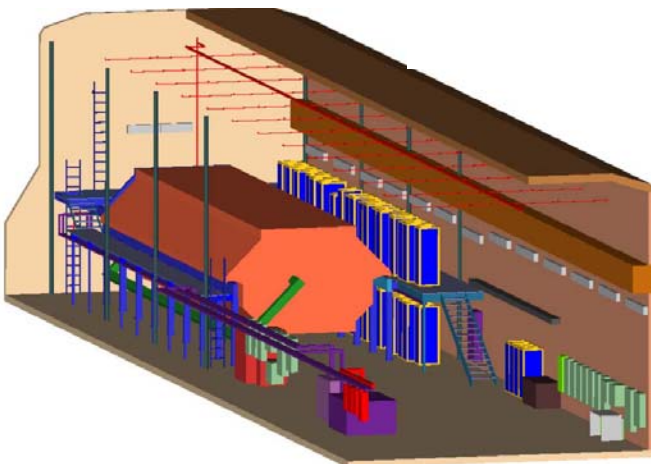


Near detector:

980 tons magnetized iron + scintillators

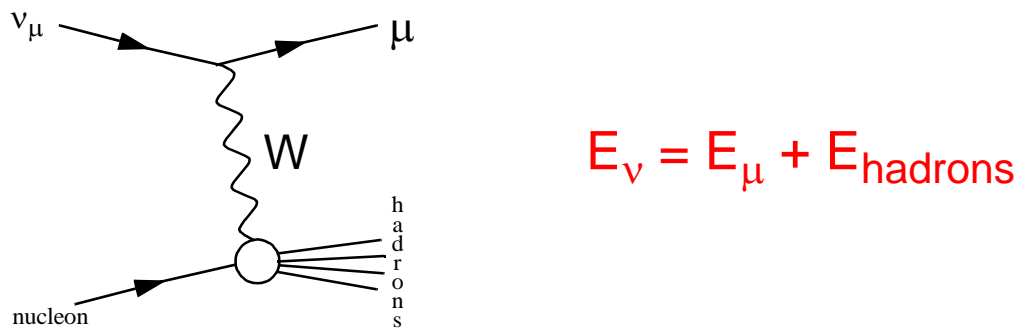
Far detector:

5400 tons magnetized iron + scintillators



❖ The proton accelerator at Fermilab will produce a **pure ν_μ beam** that will be detected in the near detector.

➔ The charged current reaction can be used to measure the **energy of the neutrinos** from the energy of the muons and the hadrons:



➔ If some of the ν_μ beam oscillate to ν_e or ν_τ the **energy spectrum** of the beam will be **different** in the far detector.

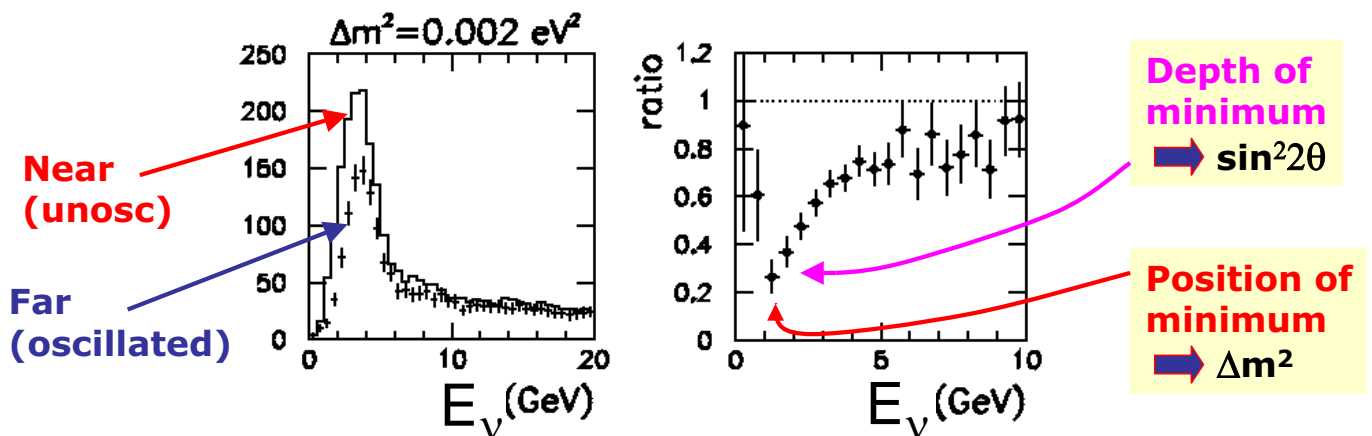


Figure 141: The simulated energy spectrum of the neutrinos in the near and far detector and the ratio of the two distributions.

Dark Matter

Experimental evidence for the **Big Bang** model is:

- A nearly uniform distribution of matter in the universe.
- The universe expands.

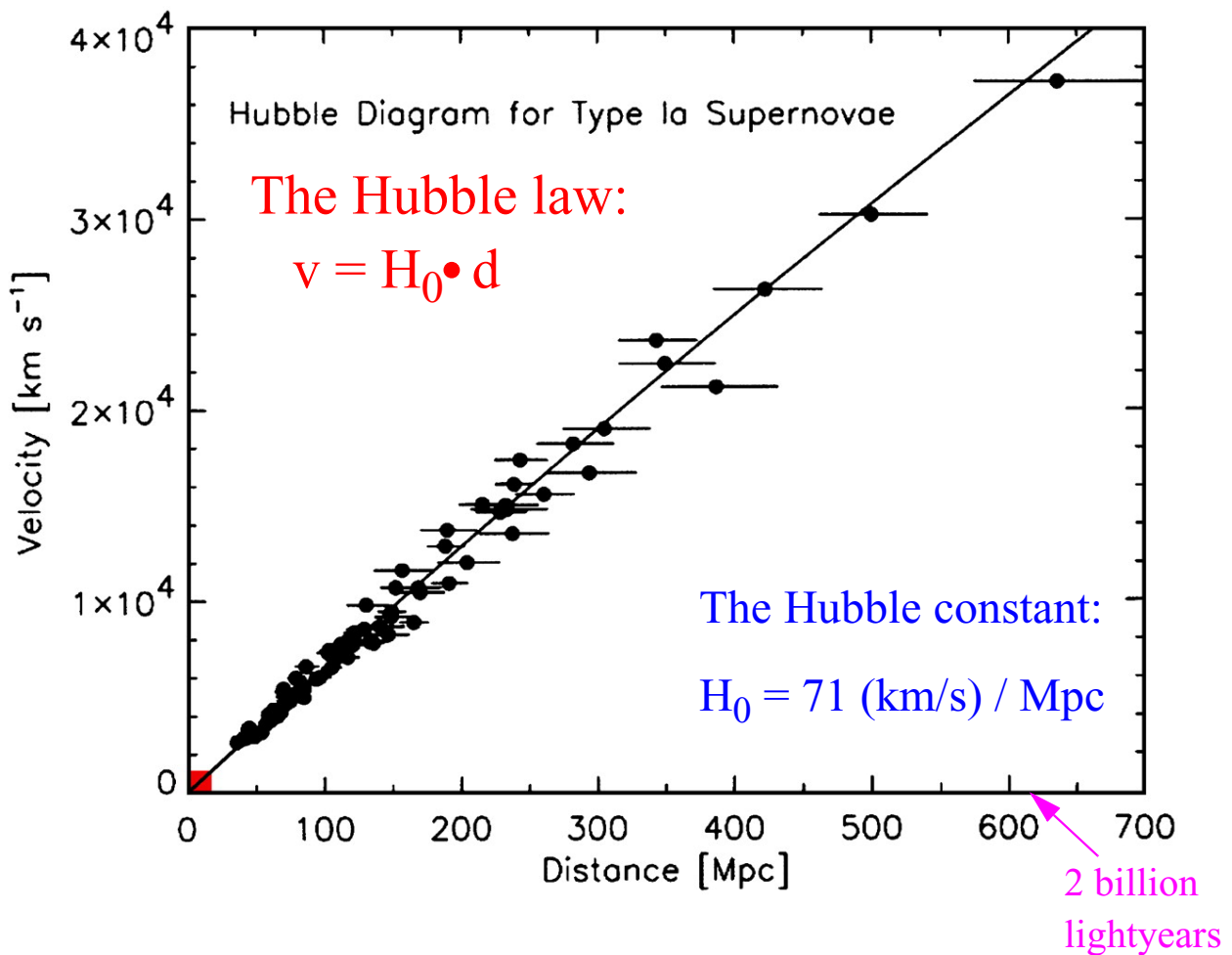


Figure 142: The velocity of supernovas increases with the distance to earth.

- The cosmic background radiation which has a temperature of 2.7 K (0.0002 eV).
- An abundance of light elements (He, D, Li)

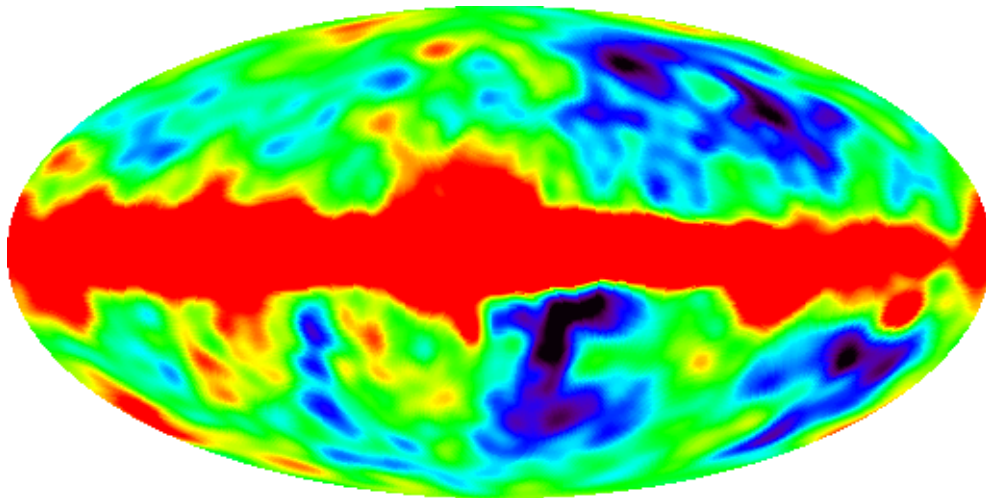


Figure 143: Sky as seen at microwave frequencies by the COBE satellite. Red (hottest) and blue (coldest) regions differ by only 0.0002 K while the overall temperature is 2.7 K

❖ If the density of the universe is smaller than the critical density, the expansion of the universe will continue for ever.

The critical density: $\rho_c = \frac{3H_0^2}{8\pi G} = O(10^{-26}) \text{ kg m}^3$

where H_0 is the Hubble constant and G is the gravitational constant.

❖ In the **inflationary Big Bang model**, the density of the universe is estimated to be close to the critical density:

$$\Omega \equiv \rho / \rho_c = 1$$

where Ω is called the **relative density**. This is now believed to be divided up into a matter part (Ω_M) and an energy part (Ω_Λ) so that $\Omega = \Omega_M + \Omega_\Lambda$.

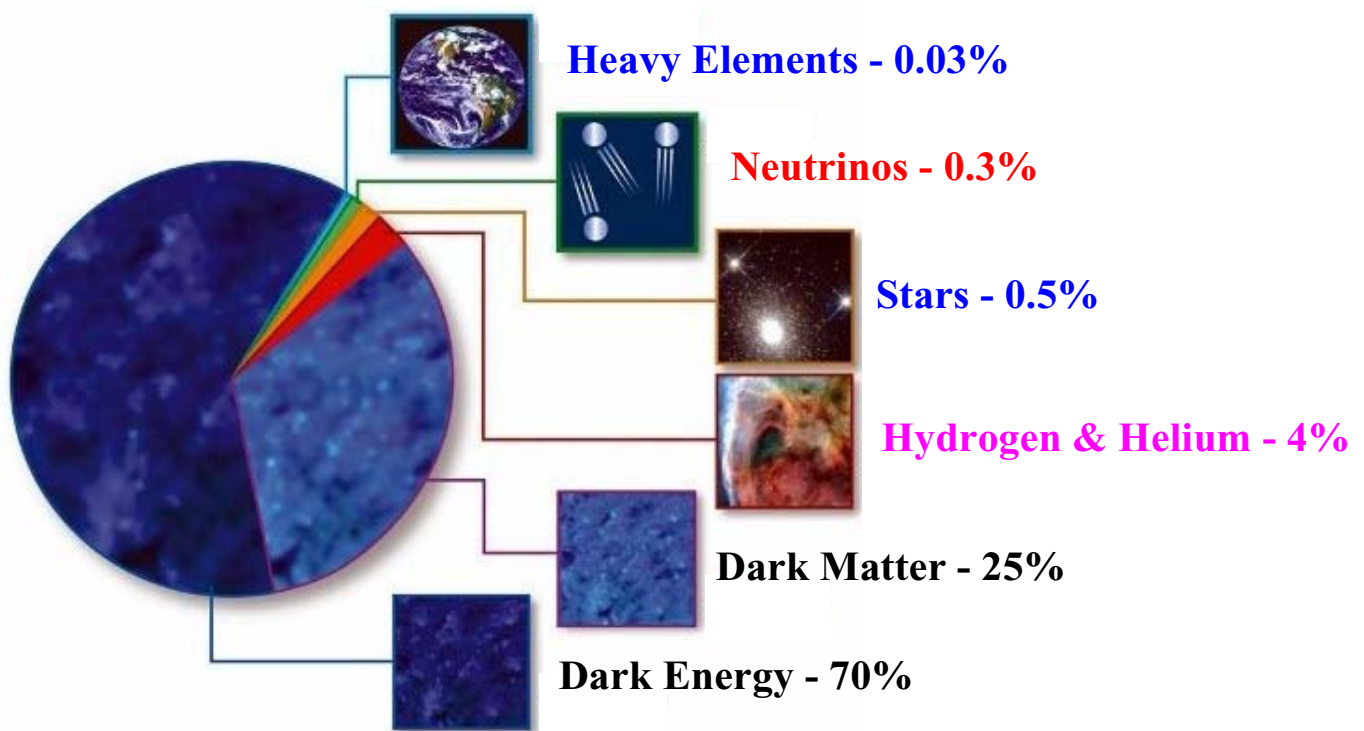


Figure 144: The present estimation of the matter and the energy in the universe.

❖ The evidence for dark matter came originally from measuring the rotation velocity of galaxies such as the Milky way.

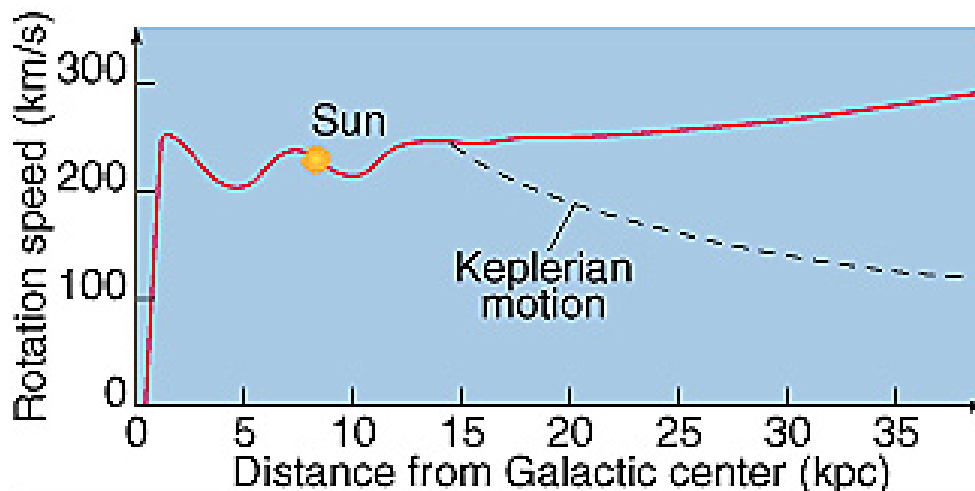
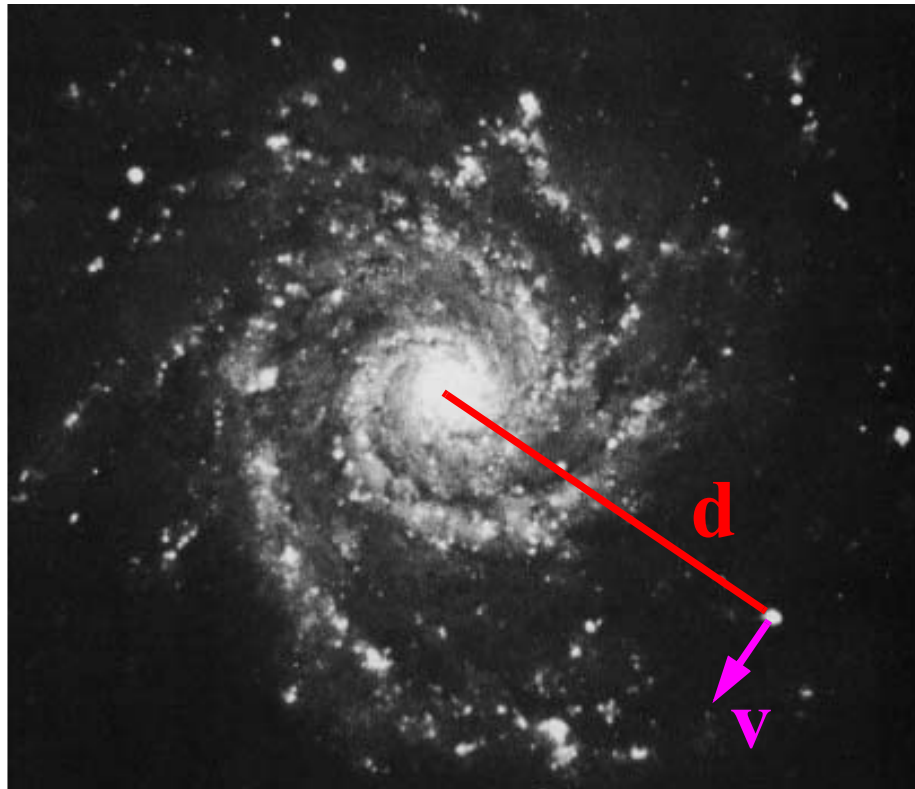
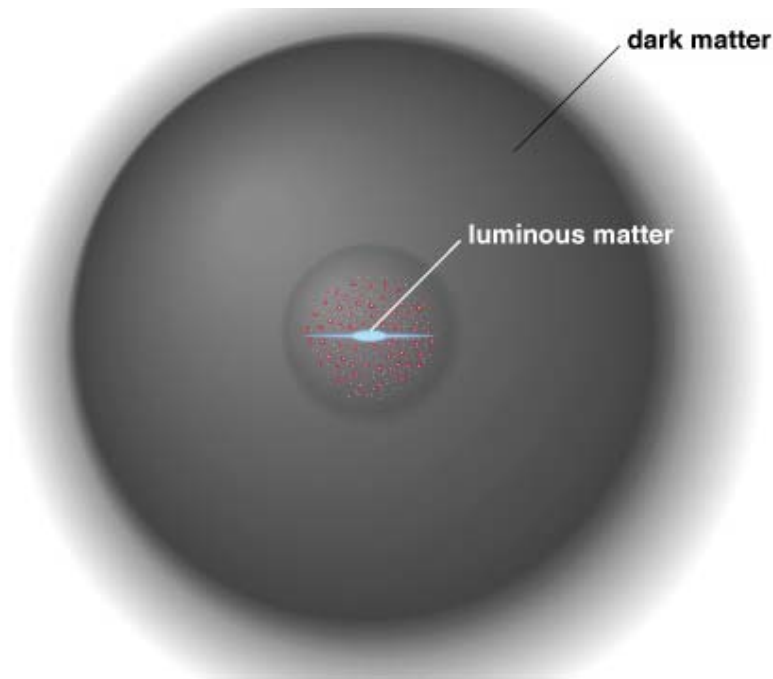


Figure 145: The rotational velocity of the stars in the Milky way is larger than what one would expect if the galaxy consists only of the known matter in the galaxy. The suggested explanation is called “Dark Matter”.



Possible explanations of the dark matter:

- a) *Baryonic matter* that emit little or no e.m. radiation: brown dwarfs, small black holes – **MACHO's** (for MAssive Compact Halo Object).
- b) If **neutrinos** have a mass $> 1\text{eV}$ they would make a significant contribution to the density of the universe (“*hot dark matter*”). It is, however, difficult to explain how the galaxies have formed if neutrinos are the dark matter.
- c) “*Cold dark matter*”: **WIMP's** (Weakly Interacting Massive Particles), non-baryonic objects, non-relativistic at the early stages of the evolution of the universe.

Dark Energy

❖ Studies of the brightness (magnitude) of remote supernovas and their redshift have indicated that **the expansion of the universe is not constant but accelerating**. Other evidence for this comes from the Cosmic Microwave Background and the motions of clusters of galaxies.

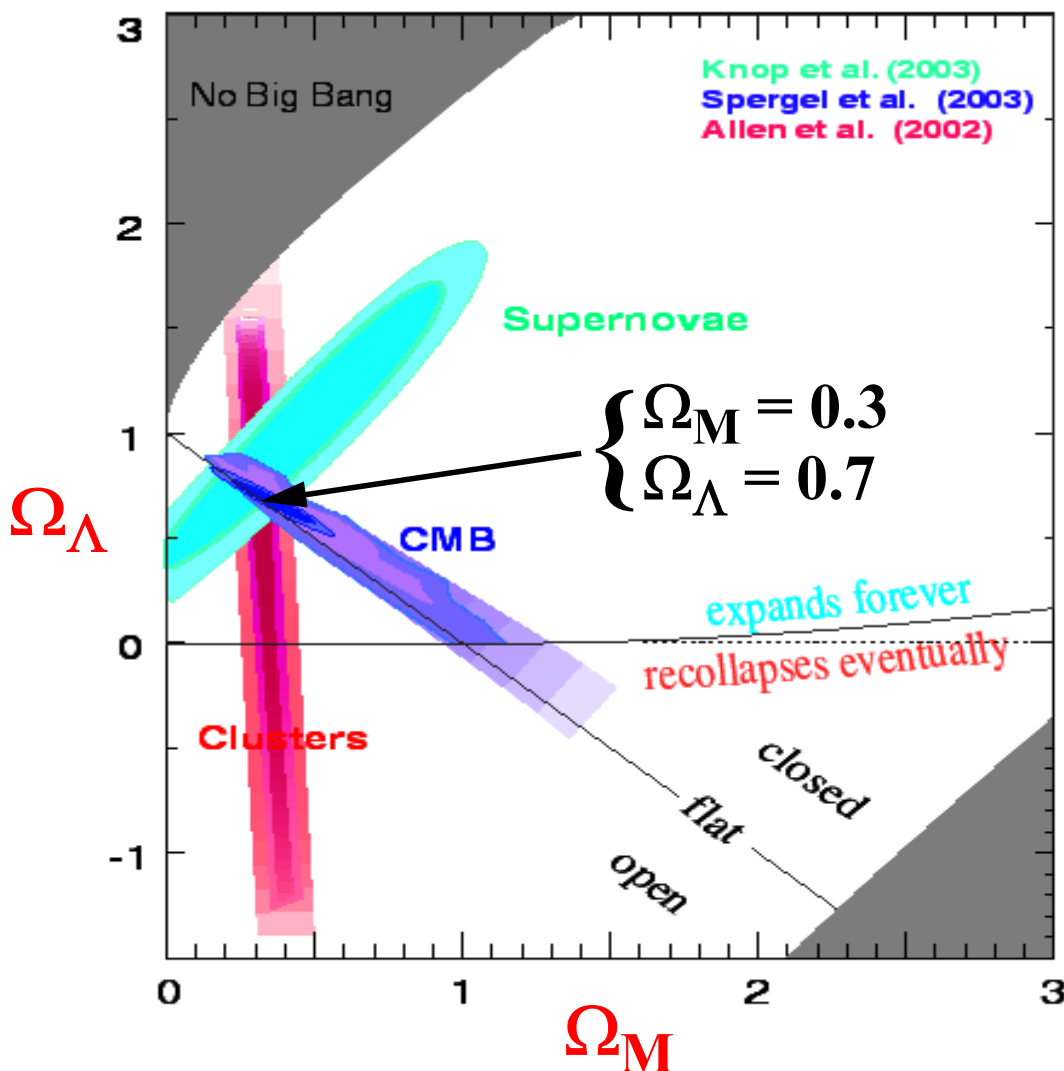


Figure 146: The allowed range of three measurements of Ω_M and Ω_Λ suggests that Ω_Λ should be about 0.7

❖ While Dark Matter is producing a gravitationally attractive force, the **Dark Energy** is producing a **gravitationally repulsive** force.

❖ Two main hypothesis have been suggested:

- a) **The Cosmological Constant:** A volume of space has an intrinsic constant fundamental energy (10^{-29} g/cm^3). Vacuum fluctuations in particle physics give rise to an energy density in vacuum but the calculated value do not agree with the astronomical observations.
- b) **Quintessence:** Particle-like excitations in a new dynamical field called quintessence. This field differs from the Cosmological constant in that it can vary in space and time.

The search for WIMPs

- ❖ **Interactions** between WIMPs and matter are very **rare**. About one WIMP per day is expected to interact in each kg of matter.
- ❖ To minimize the background, the WIMP detectors are installed **deep underground** and surrounded with shielding.
- ❖ The **Boulby experiment** uses a NaI detector which produces scintillation light if a WIMP interacts with an atom. 200 tons of ultra pure water is used as shielding.

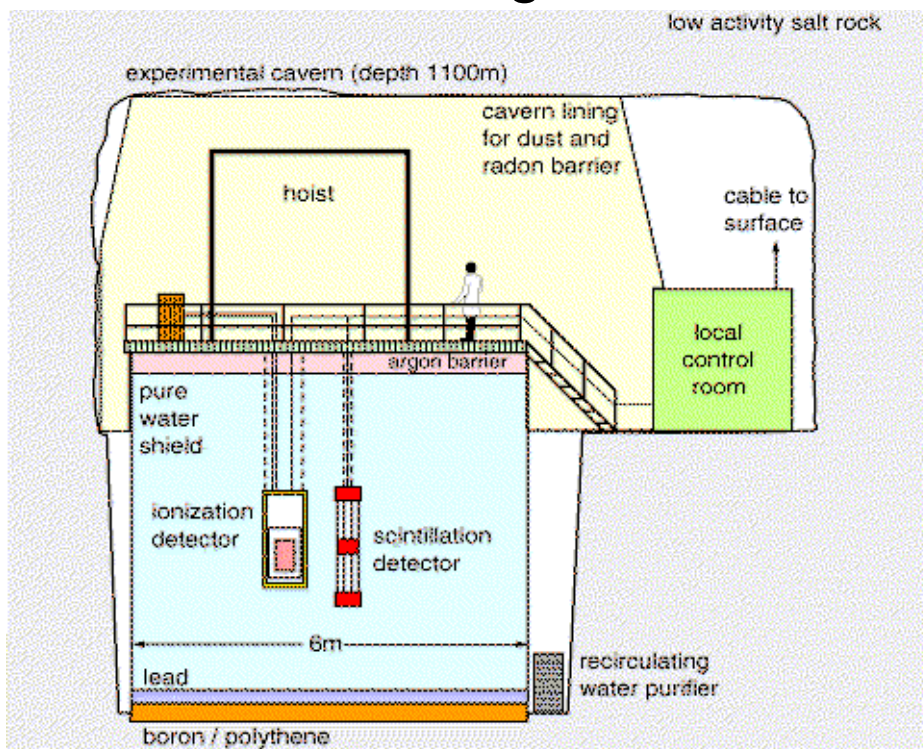


Figure 147: Layout of the Boulby experiment in the UK.

Grand Unified Theories (GUTs)

- ➔ Weak and electromagnetic interactions are unified, why not to add the strong one?
- ➔ At some very high “unification mass” electroweak and strong couplings might become equal

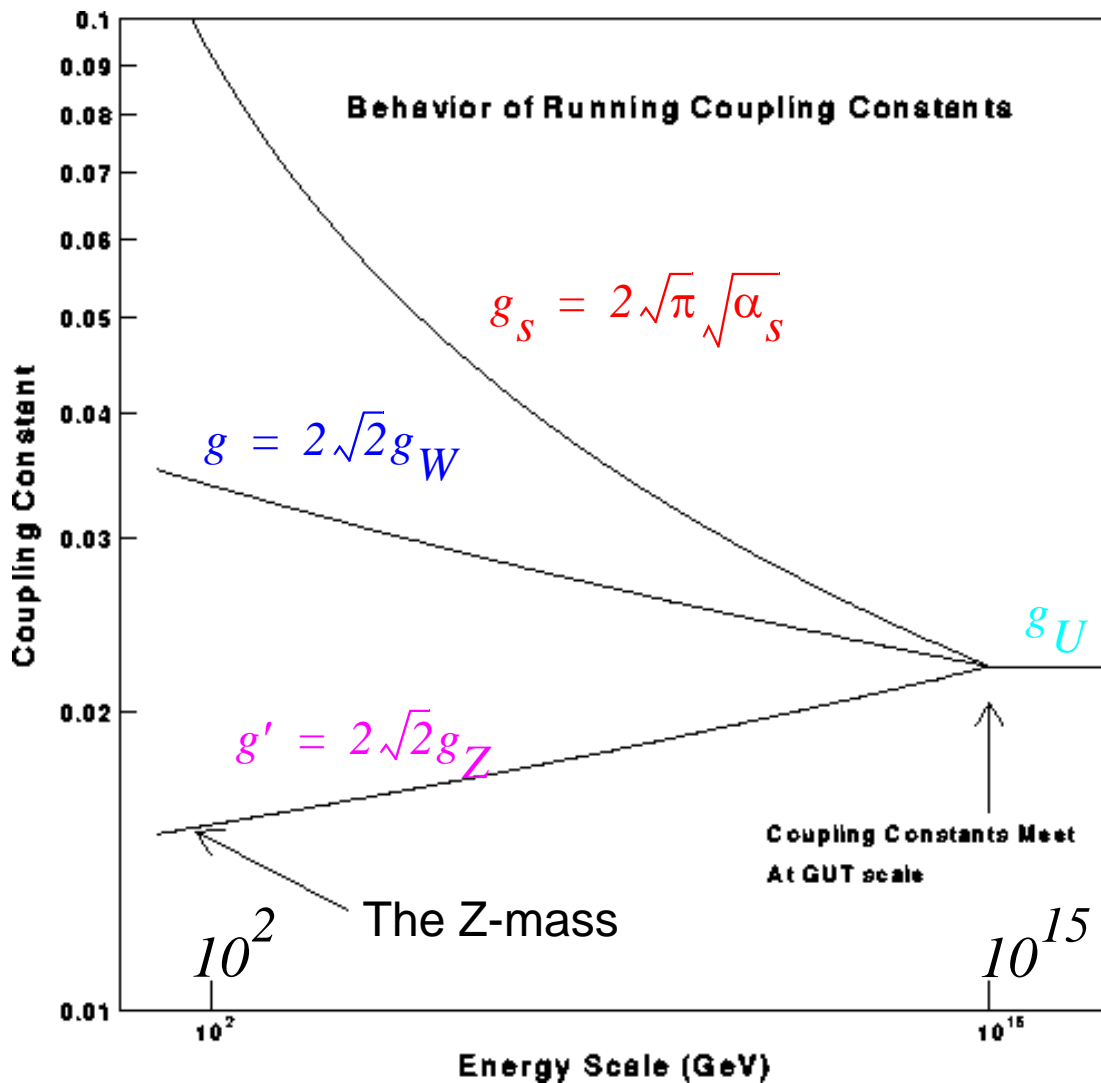


Figure 148: Behavior of the coupling constants in GUT

Grand unified theories can be constructed in many different ways.

❖ The **Georgi-Glashow model** combines coloured quarks and leptons in single families, like

$$(d_r, d_g, d_b, e^+, \bar{\nu}_e)$$

and hence new gauge bosons appear:

X with $Q=-4/3$ and **Y** with $Q=-1/3$, $M_X \approx 10^{15} \text{ GeV}/c^2$:

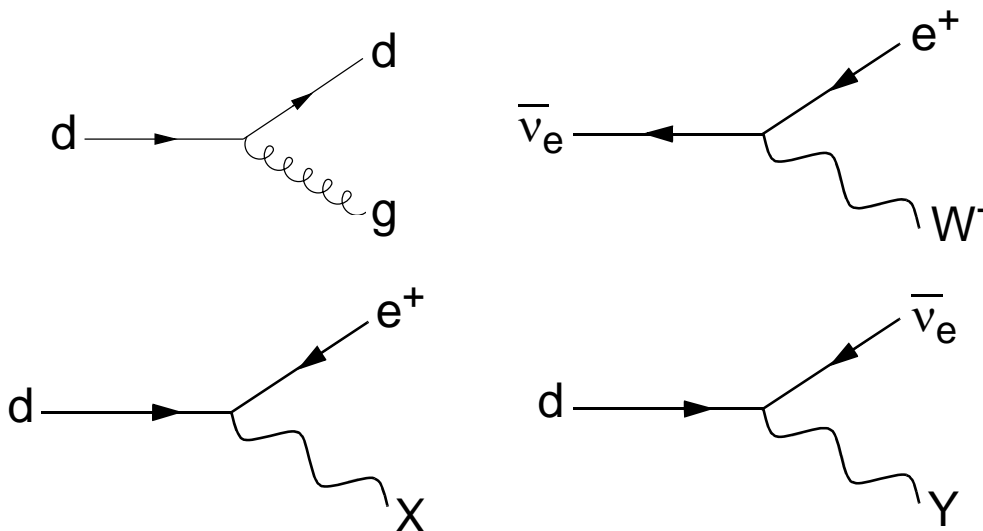


Figure 149: Standard processes together with new ones predicted by GUT

The single unified coupling constant is g_U , and

$$\alpha_U \equiv \frac{g_U^2}{4\pi} \approx \frac{1}{42} \tag{165}$$

→ The Georgi-Glashow model explains why the electron and the proton have the same charge

According to the model the sum of electric charges in any given family must be zero $\Rightarrow 3Q_d + e = 0 \Rightarrow$ the down-quark has charge $-e/3$.

❖ The factor of 3 arises simply from the number of colours

→ This model also predicts the weak mixing angle since it predicts the value of one of the three coupling constants:

$$\sin^2 \theta_W = 0,21 \quad (166)$$

This is close to the measured value of the weak mixing angle.

Proton decay

GUT predicts that the **proton** is **unstable** and that it can decay by a process involving X or Y bosons

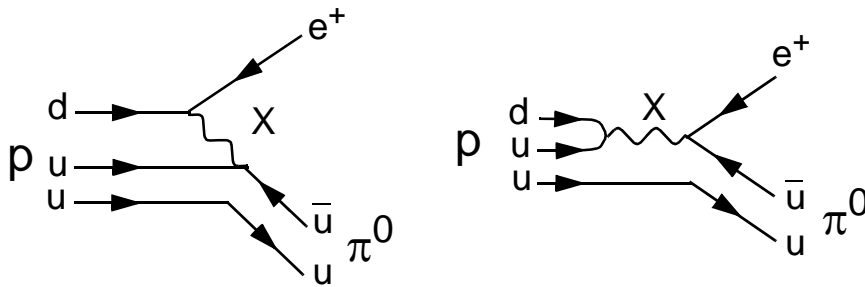


Figure 150: Proton decays in GUT

In processes like those above, baryon and lepton numbers are **not conserved**, but the combination

$$B - L \equiv B - \sum_{\alpha} L_{\alpha} \quad (\alpha = e, \mu, \tau) \quad (167)$$

is conserved.



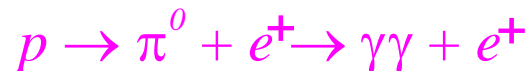
From a simple zero-range approximation, the lifetime of the proton can be estimated to be:

$$\tau_p = 10^{32} - 10^{33} \text{ years} \quad (168)$$

while the age of the universe is only about 10^{10} years...

❖ Some detectors which are used in neutrino physics (IMB, Kamiokande) are also looking for the proton decays.

❖ The most looked for decay mode is



where the experiments look for one positron and two electron-photon pairs from photon conversions.

❖ No clear examples of proton decays have been observed and the upper limit on the proton lifetime is now:

$$\frac{\tau_p}{B(p \rightarrow \pi^0 e)} > 5 \times 10^{32} \text{ years}$$

❖ The **Georgi-Glashow model** predicts this ratio to be only $0.003 \times 10^{32} - 0.03 \times 10^{32}$ years **in disagreement** with the experiments. Other GUT models, however, predict longer lifetimes.

Supersymmetry (SUSY)

❖ The most popular GUTs incorporate **supersymmetry** (SUSY) in which the interactions are symmetric under the transformation of a fermion to a boson.

➔ Every known elementary particle has a supersymmetric partner - "**superparticle**" - with different spin:

Particle	Symbol	Spin	Superparticle	Symbol	Spin
Quark	q	1/2	Squark	\tilde{q}	0
Electron	e	1/2	Selectron	\tilde{e}	0
Muon	μ	1/2	Smuon	$\tilde{\mu}$	0
Tauon	τ	1/2	Stauon	$\tilde{\tau}$	0
W	W	1	Wino	\tilde{W}	1/2
Z	Z	1	Zino	\tilde{Z}	1/2
Photon	γ	1	Photino	$\tilde{\gamma}$	1/2
Gluon	g	1	Gluino	\tilde{g}	1/2
Higgs	H	0	Higgsino	\tilde{H}	1/2

Supersymmetric particles have to be much heavier than their counterparts since they are not observed.

→ SUSY shifts the grand unification mass from 10^{15} to 10^{16} GeV/c², and hence the lifetime of the proton increases:

$$\tau_p = 10^{32} - 10^{33} \text{ years} \quad (169)$$

which is more consistent with experimental (non)observations.

→ SUSY also predicts a value of the weak mixing angle which is closer to the experimental results.

→ SUSY models even attempts to unify ALL forces, including **gravity**, at the *Planck mass* of order 10^{19} GeV/c² by replacing particles with *superstrings*

→ The lightest superparticles can be candidates for the cold dark matter. Most models introduce a *neutralino* $\tilde{\chi}_0$, which is a mixture of photino, Higgsino and zino.

→ One possibility to look for SUSY at LEP is to search for **selectron production** followed by a decay to electrons and neutralinos:

$$e^+ + e^- \rightarrow \tilde{e}^+ + \tilde{e}^-$$

$$\tilde{e}^+ \rightarrow e^+ + \tilde{\chi}_0 \quad \tilde{e}^- \rightarrow e^- + \tilde{\chi}_0$$

- 1) The **cross section** for producing selectron pairs is comparable with that of producing ordinary charged particles of the same mass
- 2) The **selectrons decay** before they can reach a detector
- 3) **Neutralinos** are virtually **undetectable** due to very weak interaction

The events one is looking for has only final state electrons and these

- a) carry only about half of the collision energy
- b) are not emitted in the opposite directions in the centre-of-mass frame

- ➔ No events with a neutralino signature have been observed.
- ➔ A measurement by DELPHI, using many more searches than slepton searches, set a lower limit on the neutralino mass of 37 GeV:

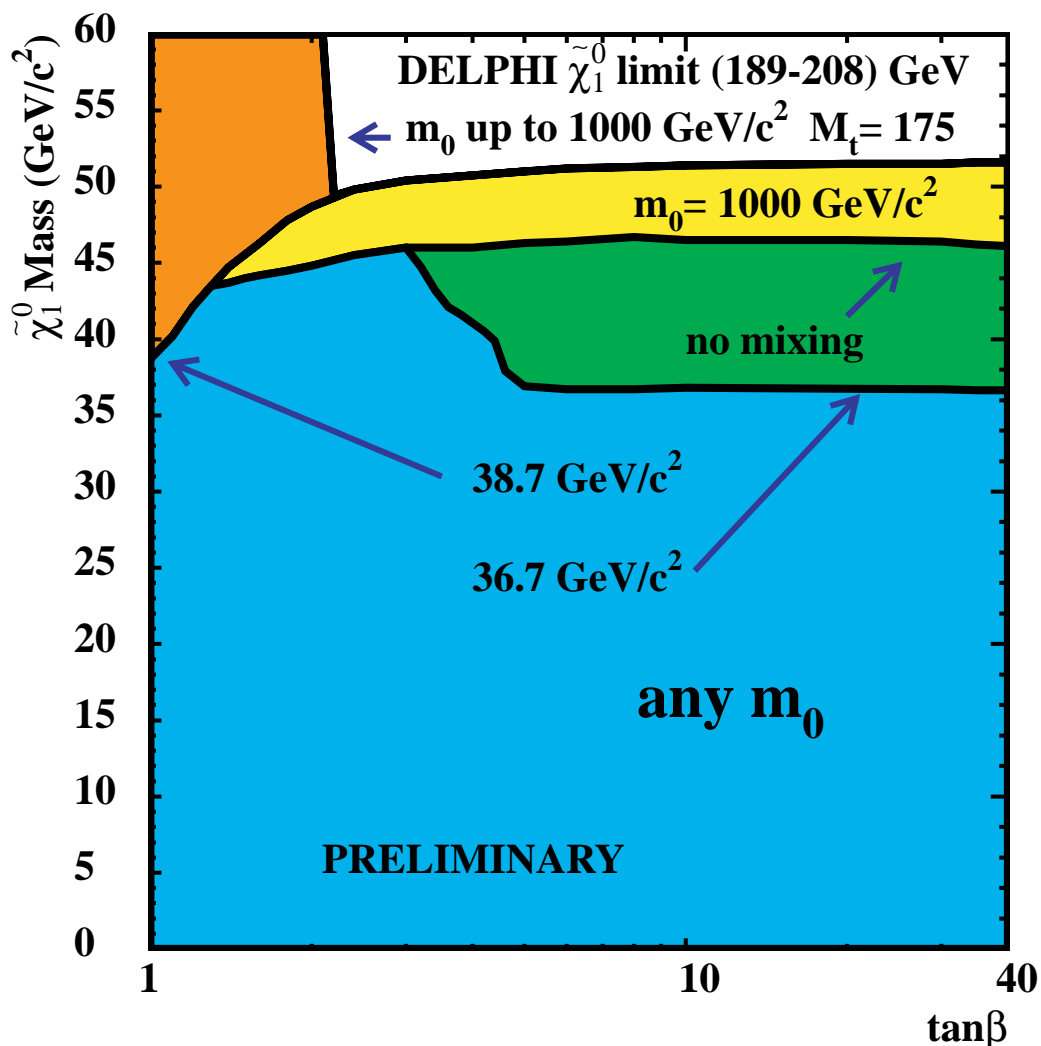


Figure 151: The lower limit on the mass of the lightest neutralino as a function of $\tan\beta$ (the ratio of the vacuum expectation values of the two SUSY Higgs doublets). m_0 is a universal SUSY mass parameter of the sfermions.

Gravitation and extra dimensions

❖ The **gravitational force** is much **weaker** than the electroweak and strong interactions and it has therefore not been studied in particle physics. One has, however, postulated that there exists gravitational force carriers (**Gravitons**) as for the other interactions.

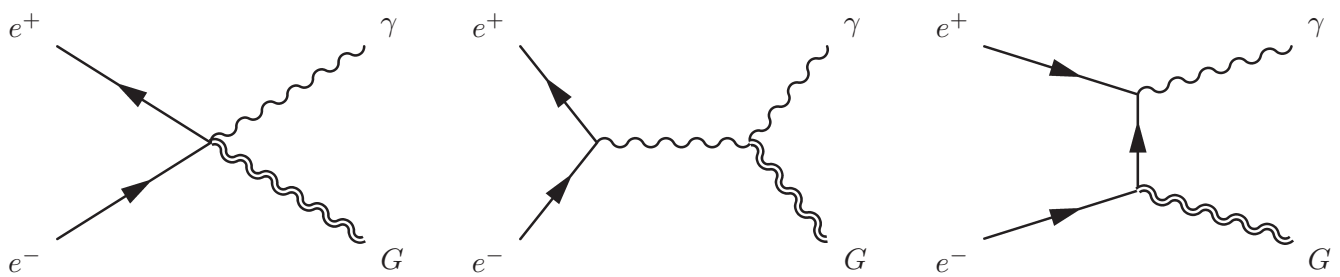
❖ Gravitation has only been studied at large distances (>1 mm) and it could be that it is **stronger at shorter distances**.

❖ In new theories it has been proposed that one can unify gravity with other interactions by introducing **new dimensions** of space (in addition to the normal 3 space + 1 time dimensions) in which **only gravity** can propagate.

❖ If our accelerators could reach the energy scale where gravity is unified with the other forces one could start to see **events** in which **gravitons** are **produced** that escape undetected into the extra dimensions.

❖ If this theory is correct + the unification energy is low then one should be able to produce **events with gravitons and photons** in e^+e^- collisions.

❖ The **cross section** for this process depends on the number of **extra dimensions (n)** and a **fundamental mass scale (M_D)**.



$e^+e^- \rightarrow \gamma G$
 $n = 2$
 $M_D = 0.75 \text{ TeV}$

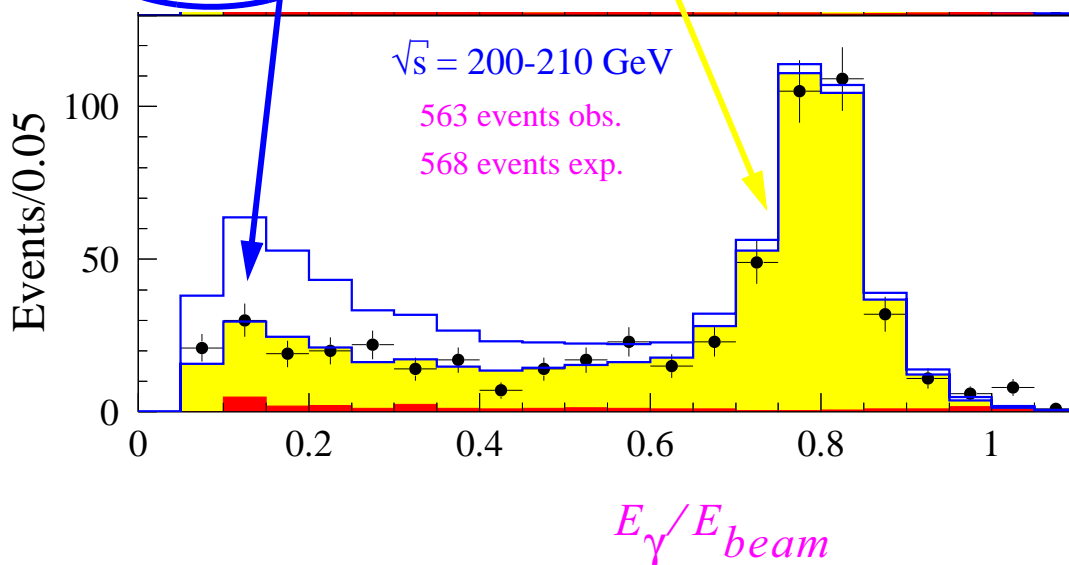
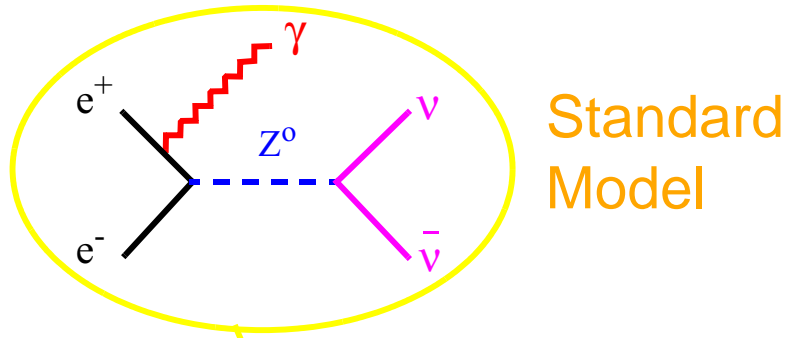


Figure 152: A search for graviton production at DELPHI.

❖ **No** single photon events have been found at LEP which could be interpreted as coming from **Graviton production**. This search for gravitons could, however, be used to set limits on the fundamental mass scale M_D .

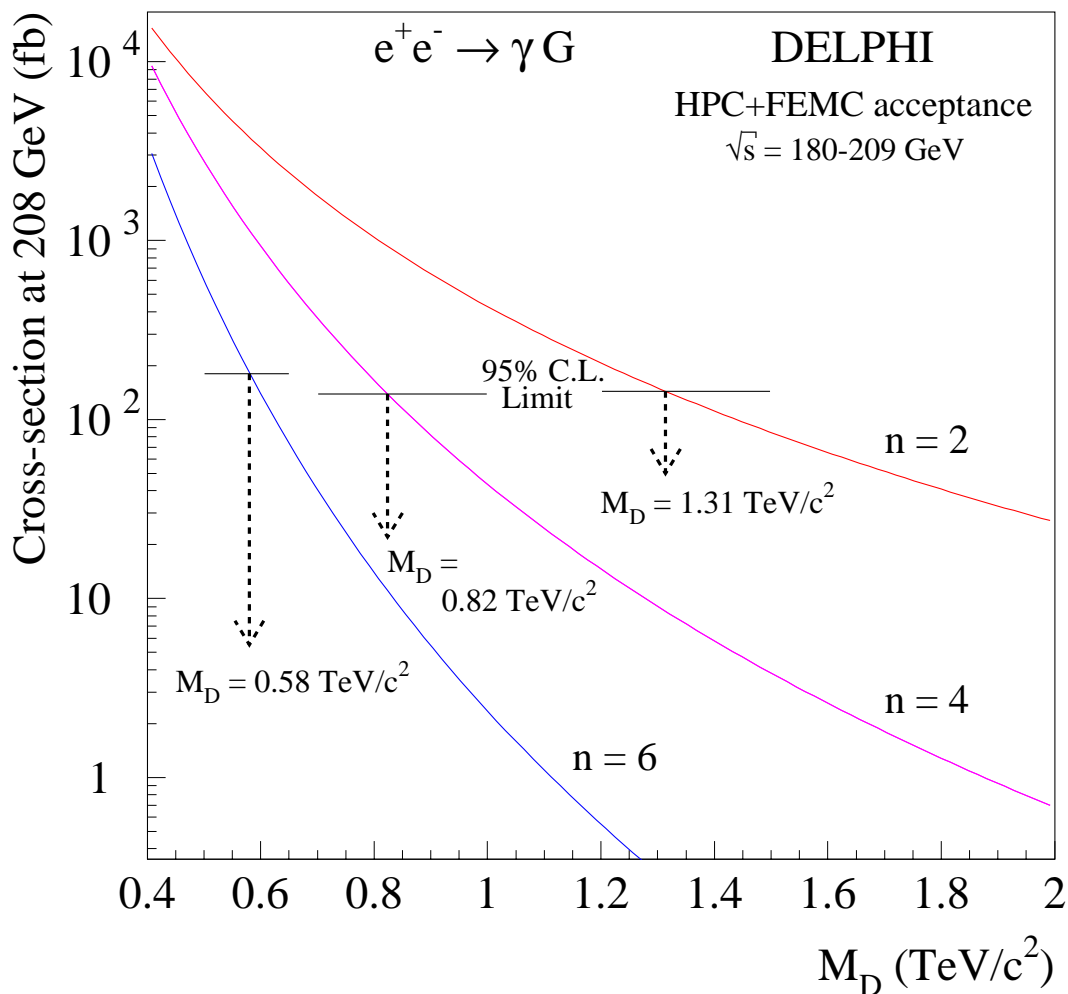


Figure 153: The expected cross section for graviton + photon production at LEP and the limits obtained by the DELPHI experiment.

➔ The result from DELPHI is that $M_D > 1.3 \text{ TeV}$ if there are two extra dimensions in nature.

Summary

• Neutrinos

- a) Neutrino mixing
- b) Neutrino oscillations
- c) Methods to detect neutrino oscillations
- d) The atmospheric neutrino anomaly
- e) The solar neutrino problem

• Dark matter

- f) What is dark matter ?
- g) Candidates for dark matter

• Grand Unified Theories

- h) All coupling constants equal
- i) The Georgi-Glashow model
- j) The importance of proton decay

- **Supersymmetry**

- k) Superparticles with different spin

- l) Unification of all forces including gravity

- m) The search for neutralinos

- **Gravitation and large extra dimensions**

- n) Predictions have been made that large extra dimensions exist in which only gravity can propagate.