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*?

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

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

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:

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

and after a period of time *t* it evolves to:

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

where e^{-iE_it} 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

$$\nu_e(t) = A(t)\nu_e(0) + B(t)\nu_\mu(0) \tag{161}$$

where

$$\begin{aligned} A(t) &= e^{-iE_1t}\cos^2\alpha + e^{-iE_2t}\sin^2\alpha \\ B(t) &= \sin\alpha\cos\alpha[e^{-iE_2t} - e^{-iE_1t}] \end{aligned} \tag{162}$$

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

$$P(\nu_e \to \nu_e) = |A(t)|^2 = 1 - P(\nu_e \to \nu_\mu) \tag{163}$$

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

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

→ If neutrinos have equal (zero) masses ⇒ $E_1 = E_2$ ⇒ 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

$$\nu_e + n \rightarrow e^- + p$$

$$\nu_\mu + n \rightarrow \mu^- + p$$

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

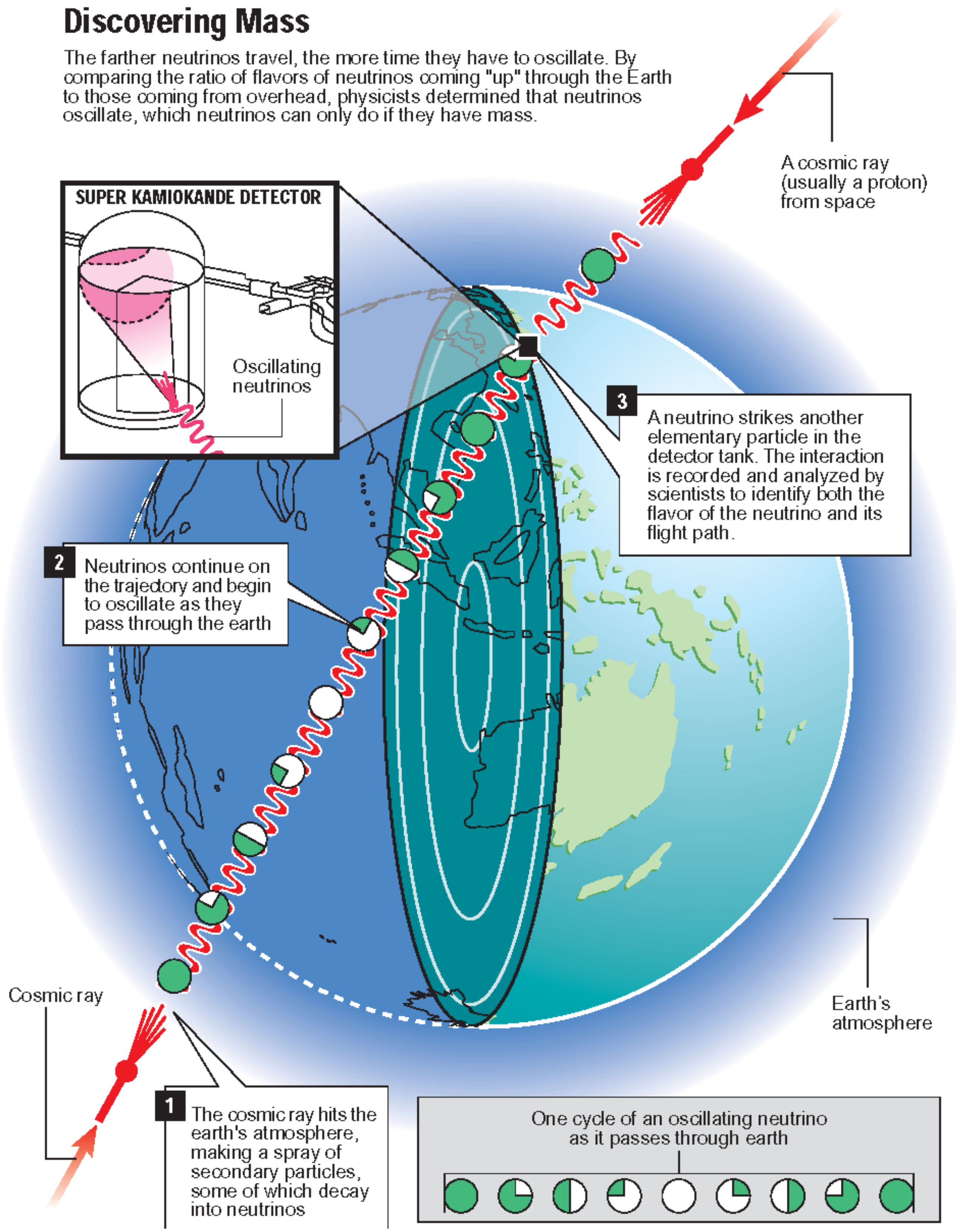
→ Several neutrino sources can be considered:
  - The sun
  - Cosmic rays (“atmospheric neutrinos”)
  - Secondary accelerator beams
  - Nuclear reactors
  - Natural radioactivity
  - Supernovas
  - The Big Bang

The atmospheric neutrino anomaly

→ This was first observed in the 1980's. Instead of having the predicted N(ν_μ)≈2N(ν_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 ⇒ it has no time to oscillate (proven by other experiments)
- A similar neutrino created on the other side of the Earth travels ≈13000 km ⇒ it has a good chances to oscillate
- If the ratio of ν_e and ν_μ is different in the two cases above ⇒ there are oscillations ⇒ 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.

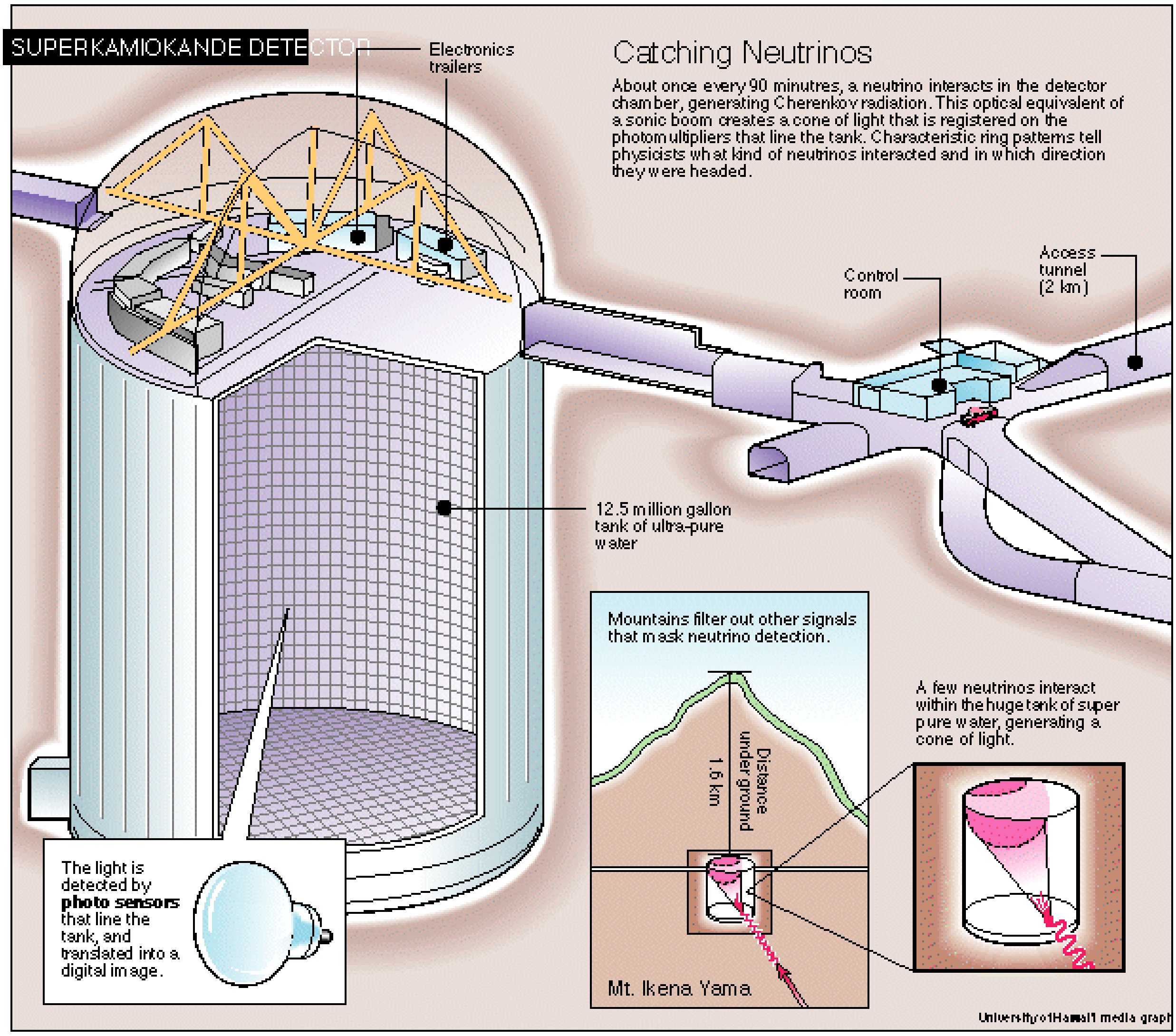
1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

One cycle of an oscillating neutrino as it passes through earth

Figure 134: Neutrino oscillations through Earth



About once every 90 minutres, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

Mountains filter out other signals that mask neutrino detection.

A few neutrinos interact within the huge tank of super pure water, generating a cone of light.

The light is detected by **photo sensors** that line the tank, and translated into a digital image.

Figure 135: Schematics of the Super-Kamiokande detector

– The detector is placed in a deep mine to reduce the background.

– 50 000 m^3 of water and 13 000 photomultipliers work as a Cherenkov detector.

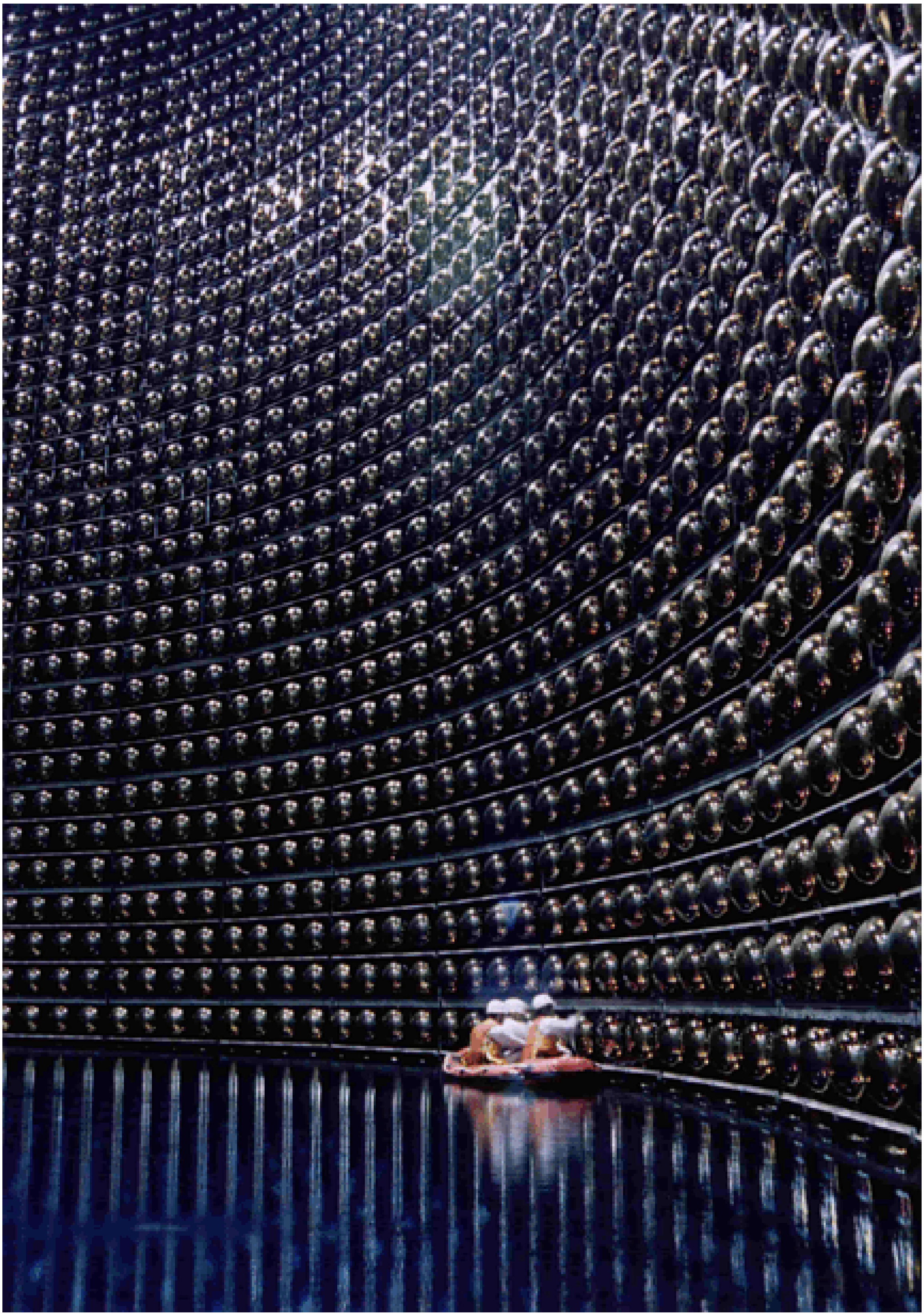


Figure 136: Interior of the Super-Kamiokande detector (during construction)

→ In 1998, the Super-Kamiokande Collaboration announced:

a) 4654 observed events – by far the largest sample in the world

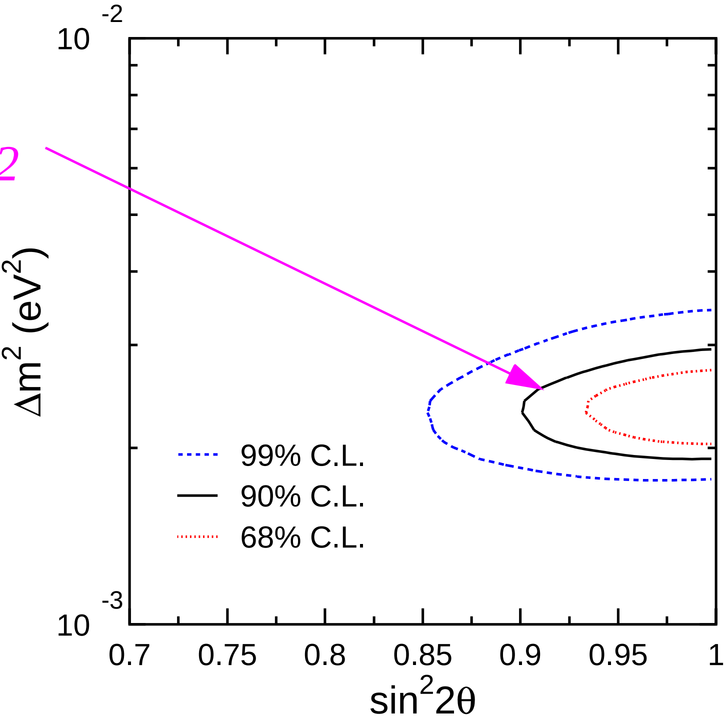
b) the ν_μ data exhibited a deficit with a zenith angle dependence

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

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

$$2\times10^{-3} < \Delta m^2 < 3\times10^{-3}\ eV^2$$



The solar neutrino problem

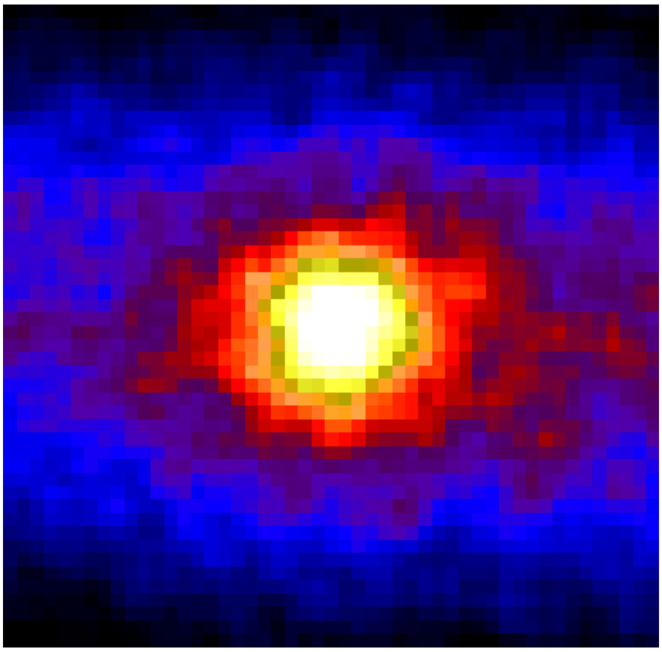


Figure 137: “Portrait” of the Sun made with neutrinos

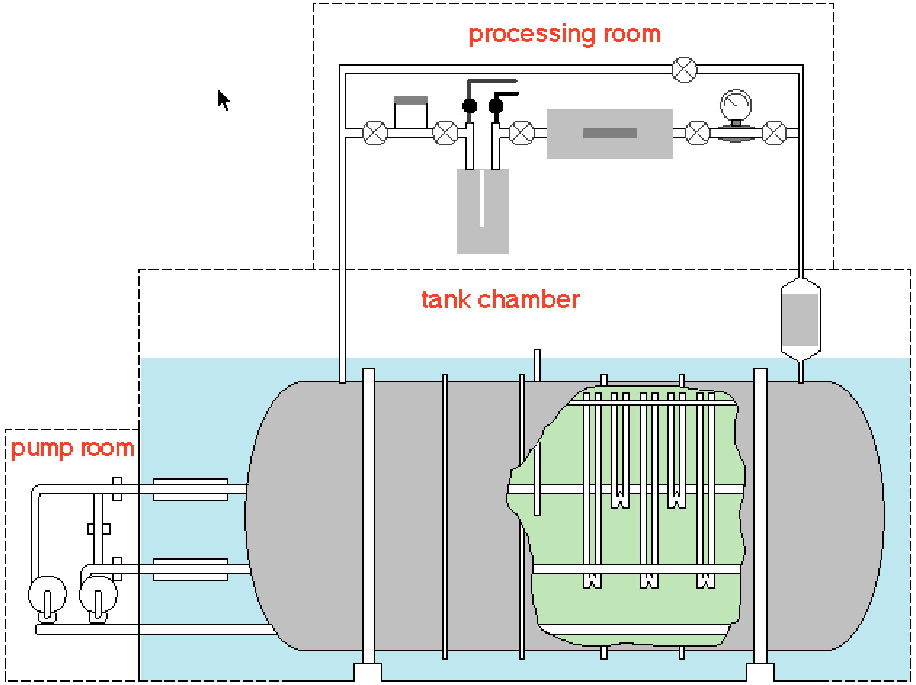
Several (similar) methods are used to detect solar neutrinos:

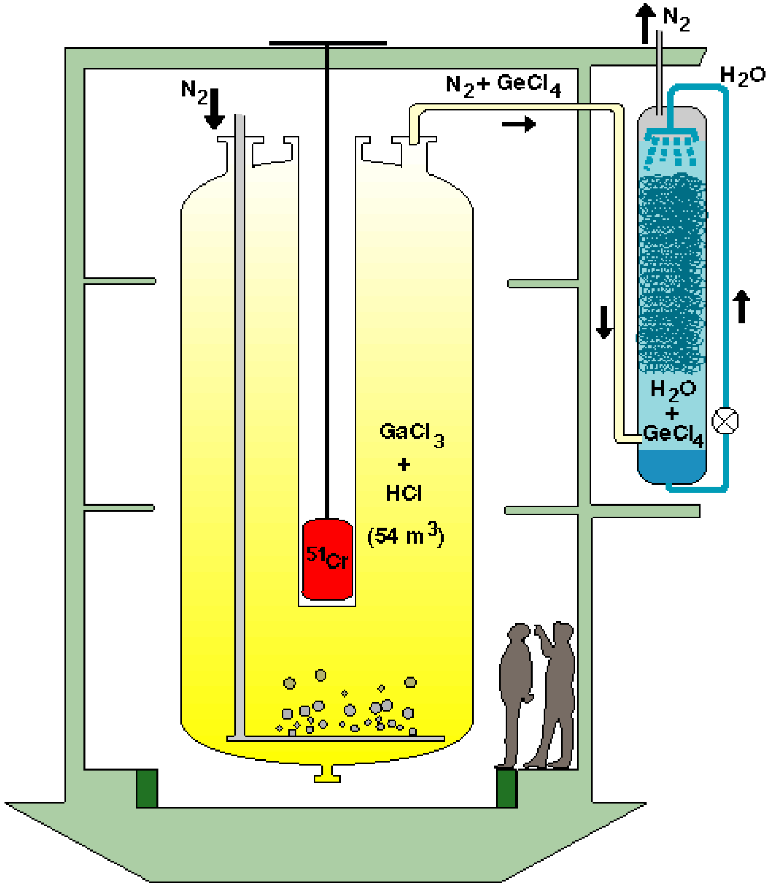
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

$$\nu_e + {}^{98}\mathrm{Mo} \rightarrow e^- + {}^{98}\mathrm{Tc}$$

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$$

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





The Homestake gold mine detector (USA).

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

GALLEX detector under the Gran Sasso mountain (Italy).

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

Figure 138: Typical layouts of solar neutrino detectors.

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

1 SNU = 1 capture / 1 second / 10^{36} 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:

1) $p + p \rightarrow {}^{2}H + e^{+} + \nu_{e}$ $E_{\nu,max}$=0.42 MeV (85%)

2) $e^{-} + {}^{7}Be \rightarrow {}^{7}Li + \nu_{e}$ $E_{\nu,max}$=0.86 MeV (15%)

3) ${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_{e}$ $E_{\nu,max}$=15 MeV (0.02%)

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_ν=10 MeV, Δt=10 s and $t_\nu=5\times10^{12}$s gives m_ν=20 eV.

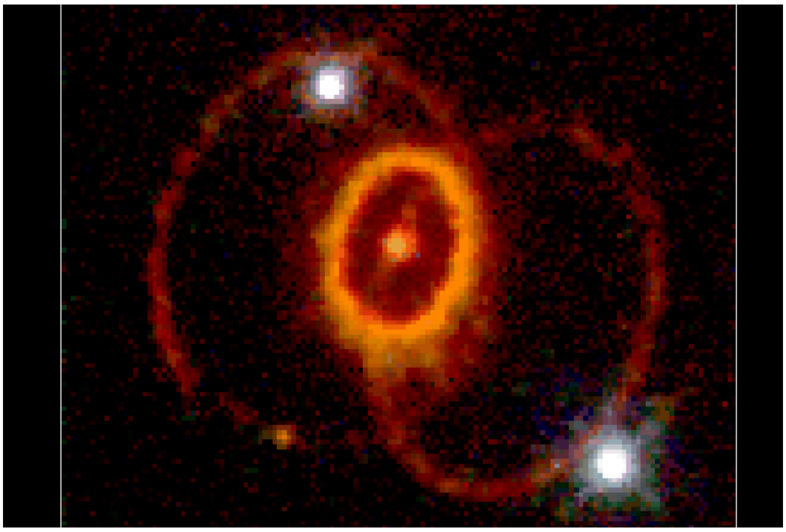


Figure 139: SN1987a as seen by the Hubble telescope.

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.

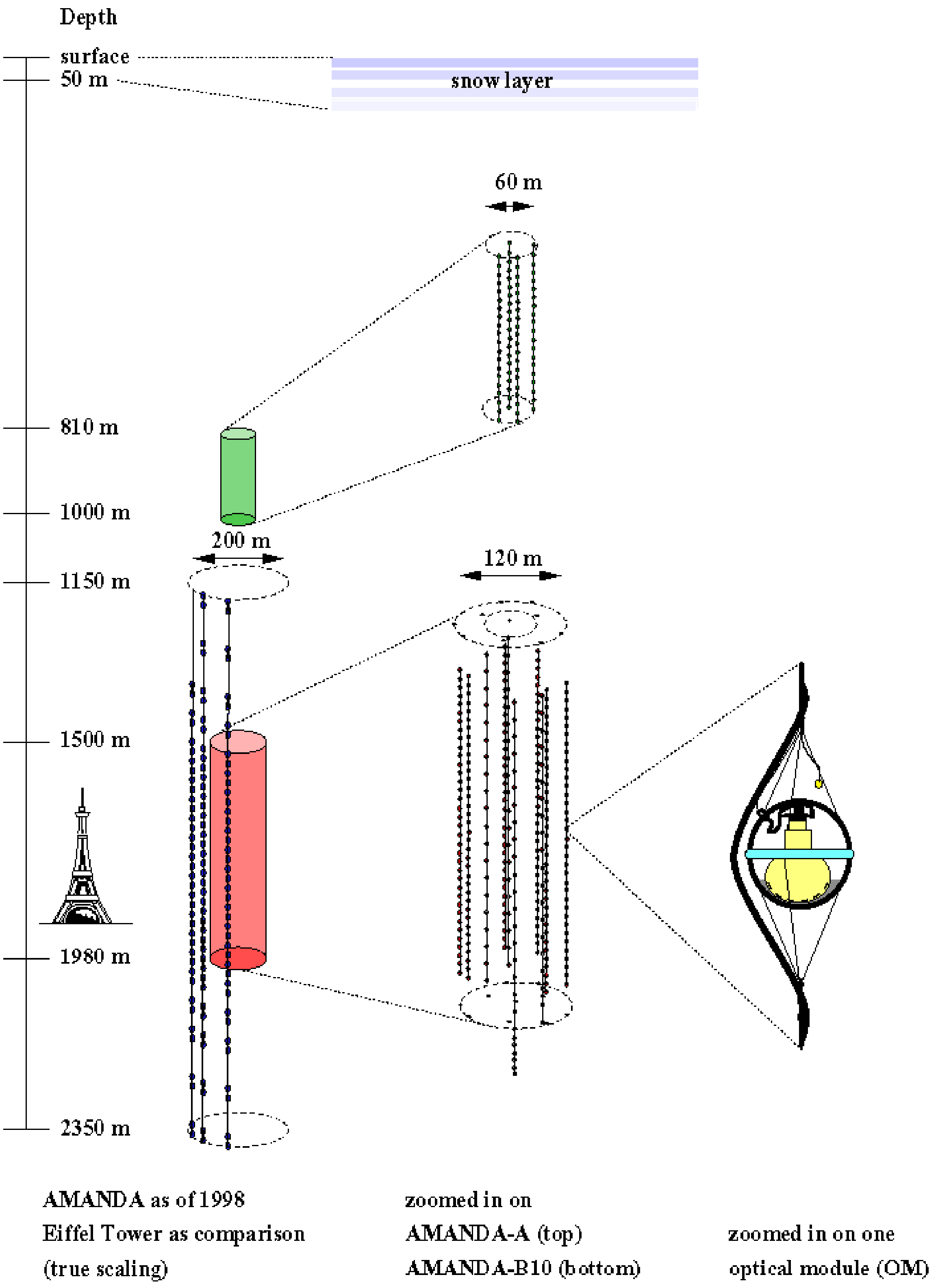
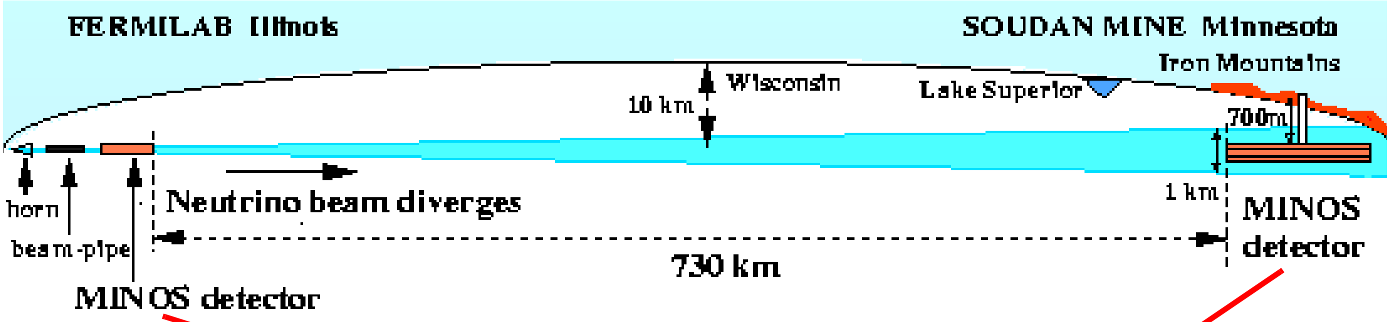


Figure 140: Schematics of the AMANDA neutrino telescope at the South Pole

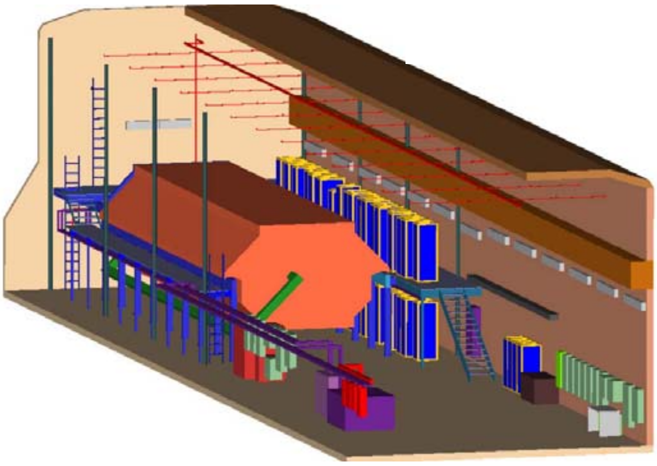
Long baseline neutrino experiments

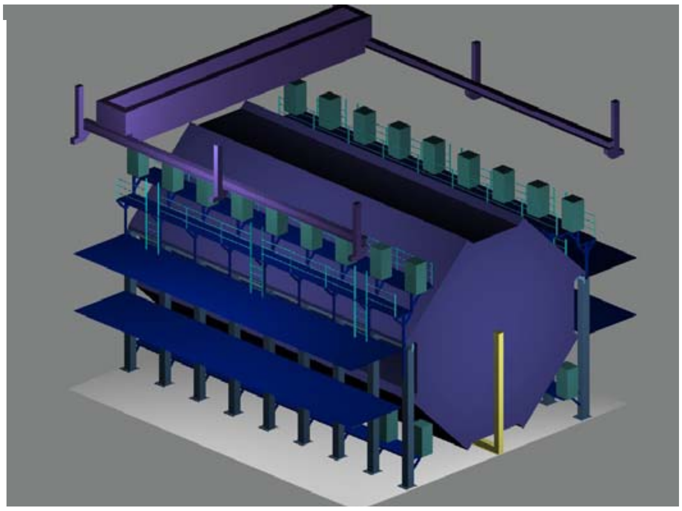
MINOS



Near detector:
980 tons magnetized iron + scintillators

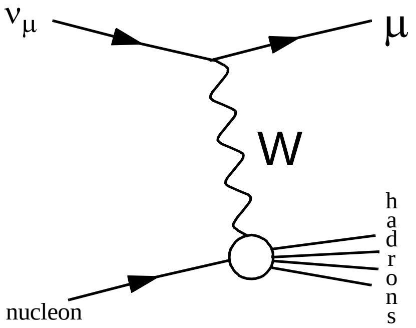
Far detector:
5400 tons magnetized iron + scintillators





❖ 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:



$$E_\nu = E_\mu + E_{hadrons}$$

→ 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.

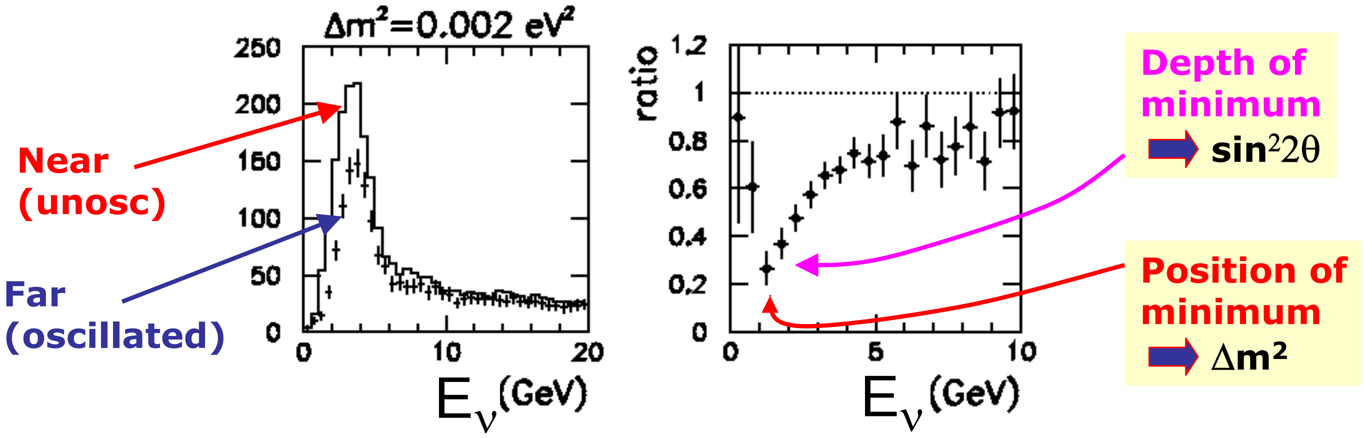


Figure 141: The simulated energy spectrum of the neutrinos in the near and far detector and the ratio of the two distributions.

Dark matter

Experimental evidence for the Big Bang model is:

- A nearly uniform distribution of matter in the universe.
- The universe expands.
- The cosmic background radiation which has a temperature of 2.7 K (0.0002 eV).
- An abundance of light elements (He, D, Li)

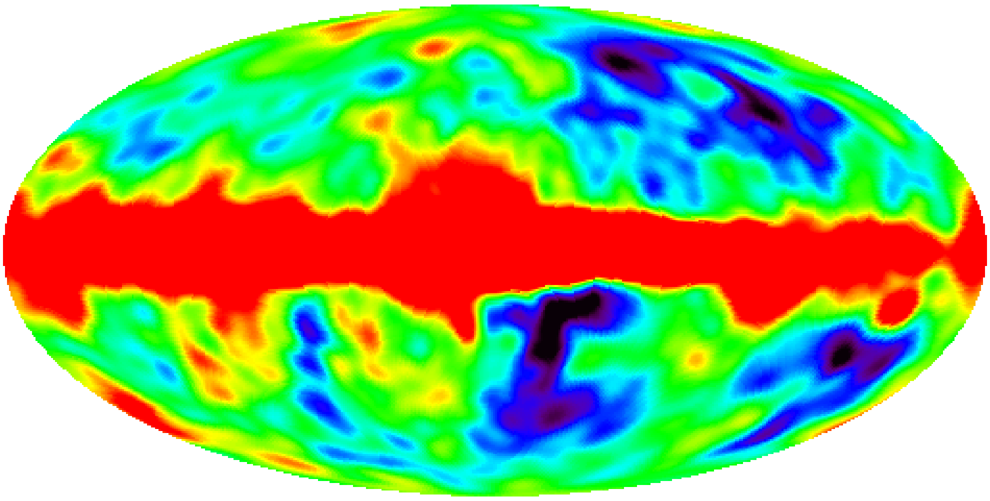


Figure 142: Sky as seen at microwave frequencies by the COBE satellite. Red (hottest) and blue (coldest) regions differ by only 0.0002 K while the overall temperature is 2.7 K

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

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

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. However, the observable (i.e. emitting electromagnetic radiation) matter in the Universe give only $\Omega_L \approx 0.01$

→ The rest is called “dark matter”

Possible components 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). There is evidence that $\Omega_B \approx 0.06$ only.

b) If neutrinos have a mass > 1eV 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.

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.

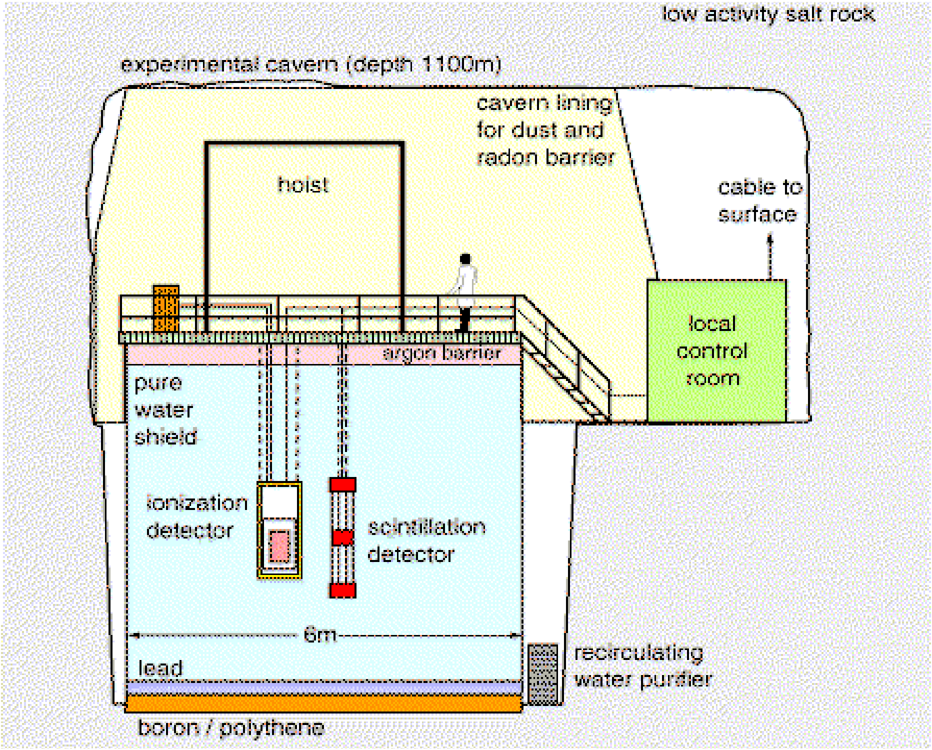


Figure 143: Layout of the Boulby experiment in the UK.

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

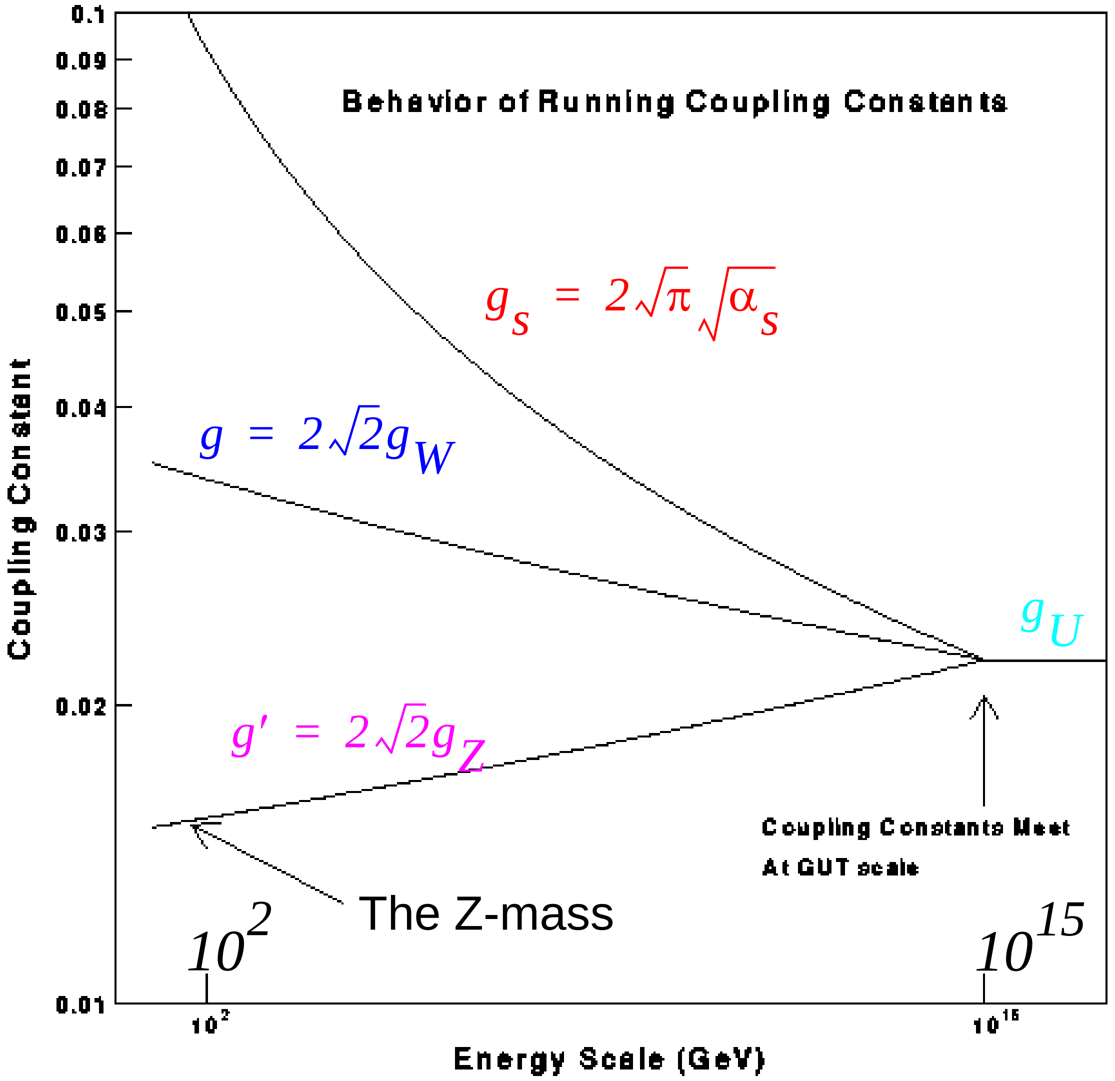


Figure 144: Behavior of the coupling constants in GUT

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, $M_X \approx 10^{15}$ GeV/c^2:

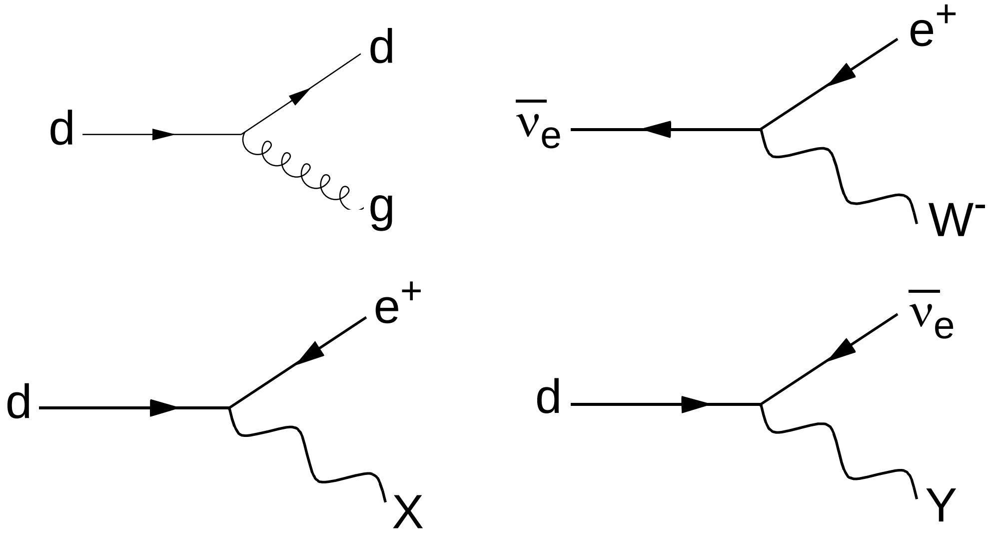


Figure 145: Standard processes together with new ones predicted by GUT

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 ⇒ $3Q_d + e = 0$ ⇒ 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:

$$\sin^2\theta_W = 0{,}21 \tag{166}$$

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

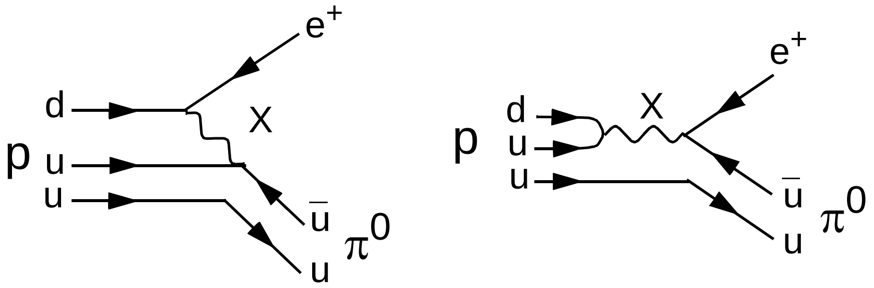


Figure 146: Proton decays in GUT

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

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

is conserved.

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

$$\tau_p = 10^{32} - 10^{33} \ years \tag{168}$$

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

$$p \rightarrow \pi^0 + e^+ \rightarrow \gamma\gamma + e^+$$

where the experiments looks 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:

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

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

The cosmic baryon asymmetry

❖ Why are there more baryons than antibaryons in the universe ?

Answer:

1. There was always an excess of baryons (the baryon number is conserved).

2. At the time of the Big Bang the universe had zero baryon number. The baryons were produced later (the baryon number is not conserved as suggested by GUT).

In the second case it is also necessary that C and CP are not conserved so that more antiparticles can be transformed to particles than vice versa.

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/c^2, and hence the lifetime of the proton increases:

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

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/c^2 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:

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

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

1) The cross section for producing selectron pairs is comparable with that of producing ordinary charged particles of the <u>same</u> 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:

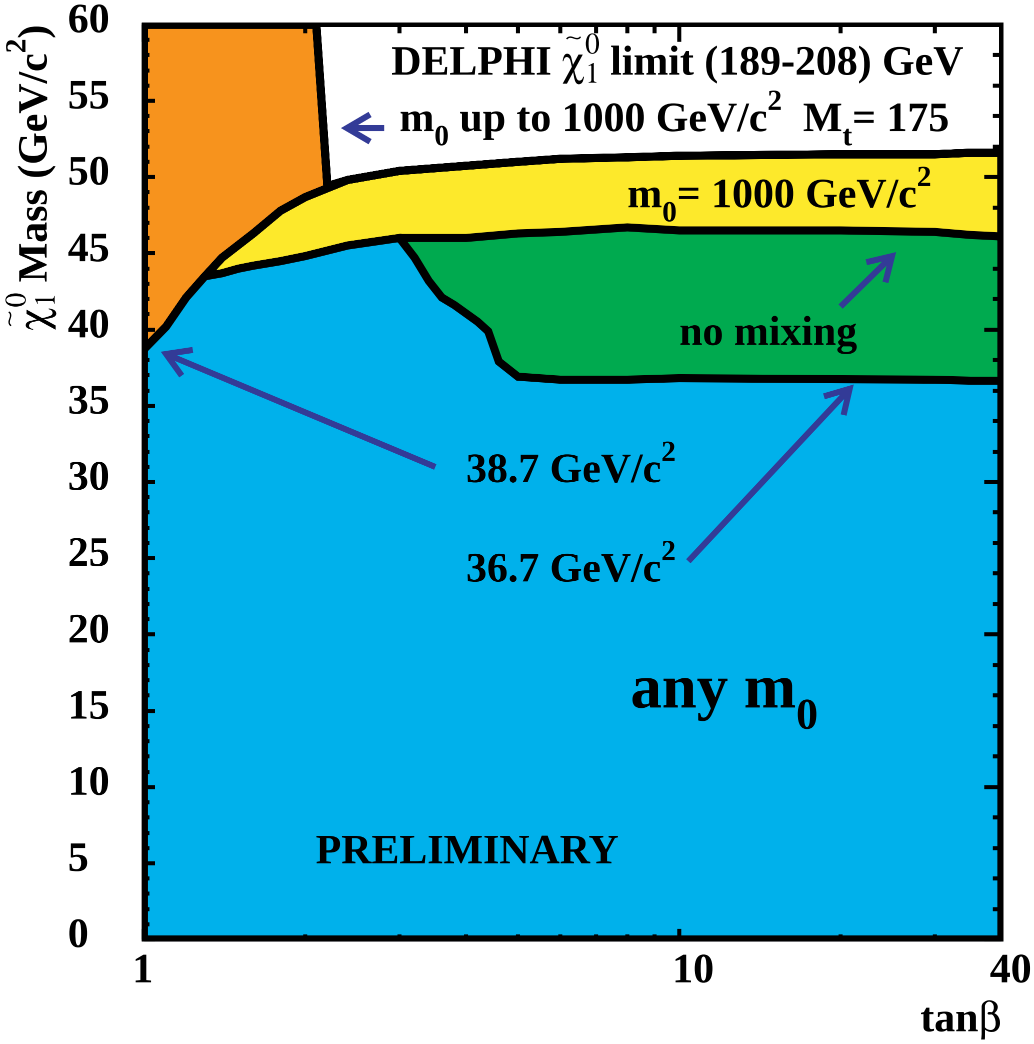


Figure 147: The lower limit on the mass of the lightest neutralino as a function of *tan* β (the ratio of the vacuum expectation values of the two SUSY Higgs doublets). m_0 is a universal SUSY mass parameter of the sfermions.

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.

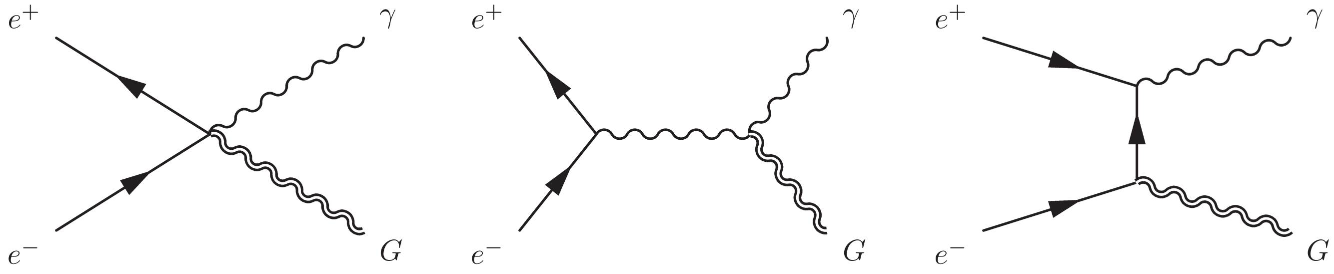
- Gravitation has only been studied at large distances (>1 mm) and it could be that it is stronger at shorter distances.

- 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).



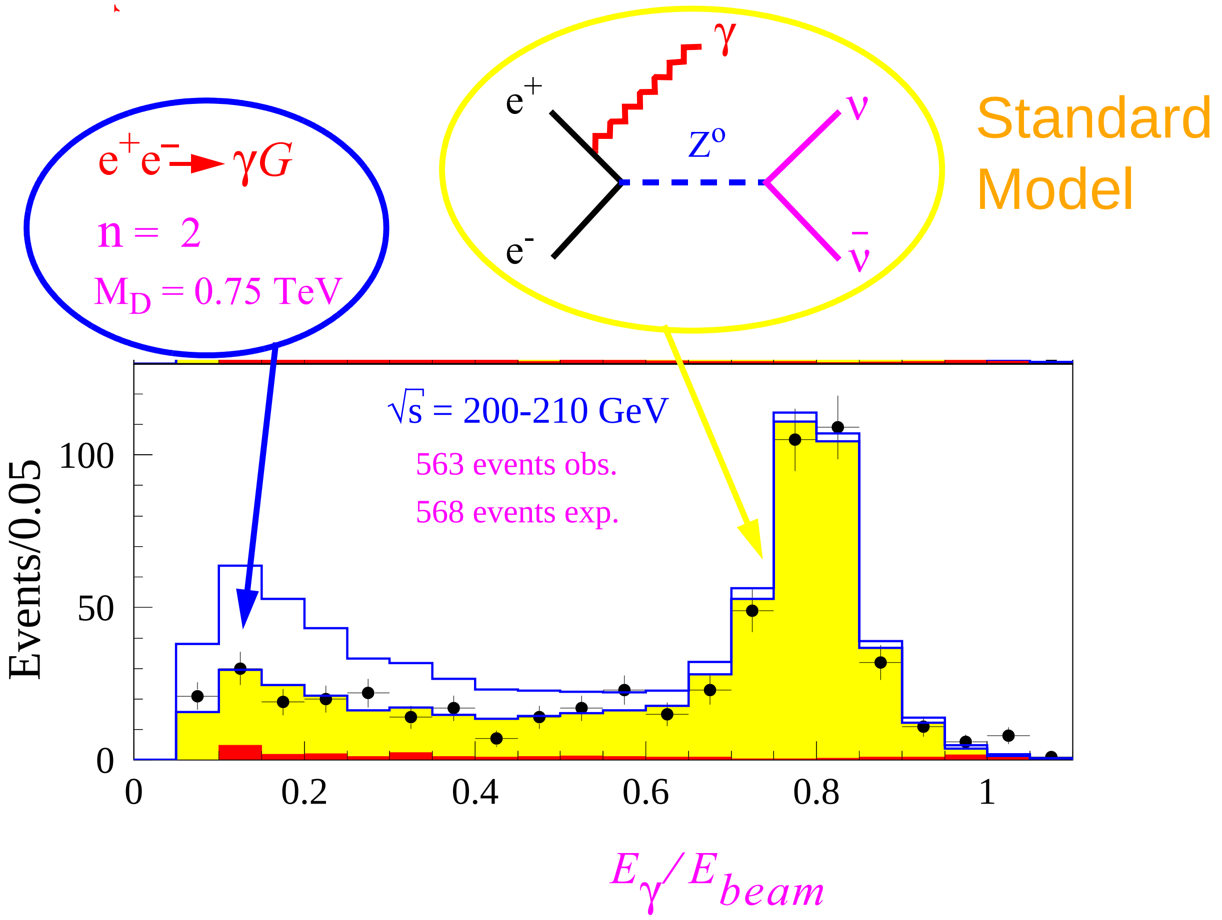


Figure 148: A search for graviton production at DELPHI.

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

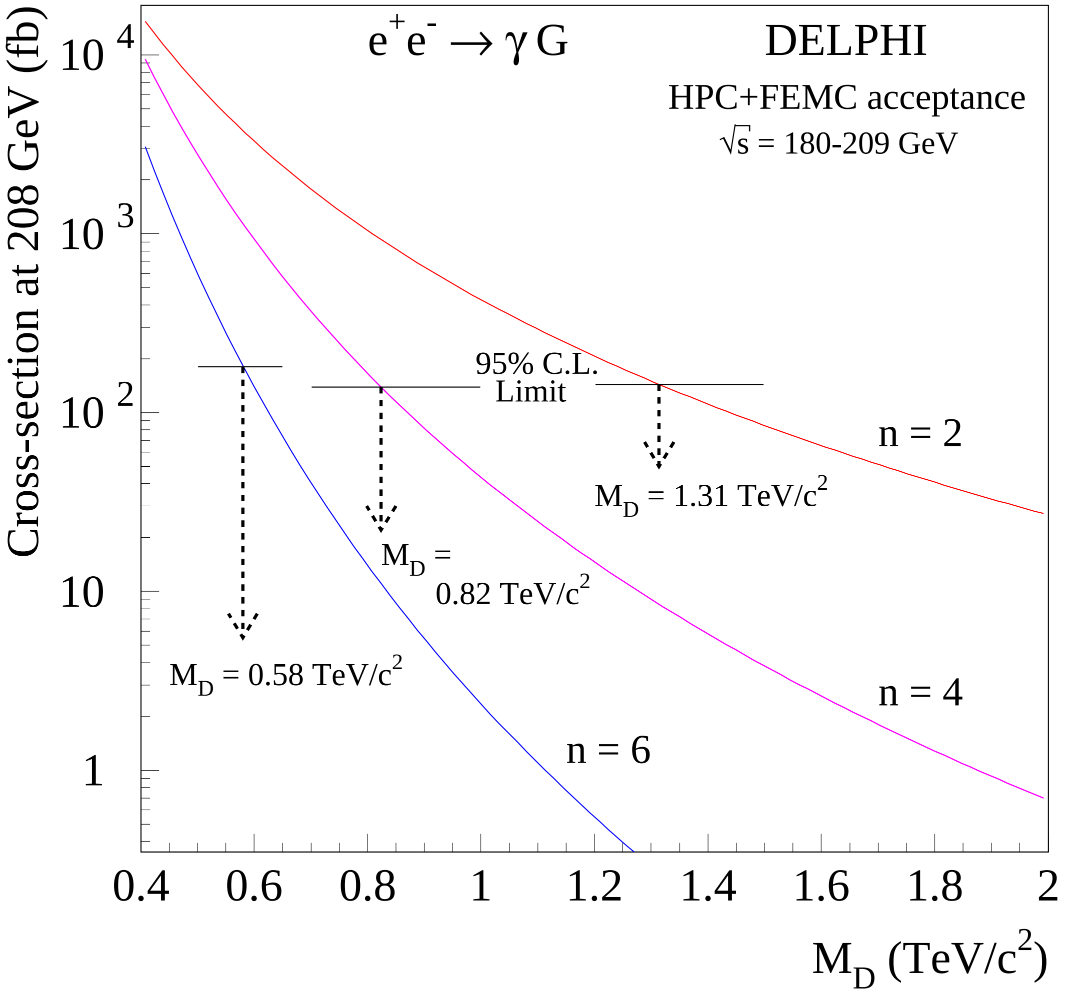


Figure 149: The expected cross section for graviton + photon production at LEP and the limits obtained by the DELPHI experiment.

→ The result from DELPHI is that $M_D > 1.3$ 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.