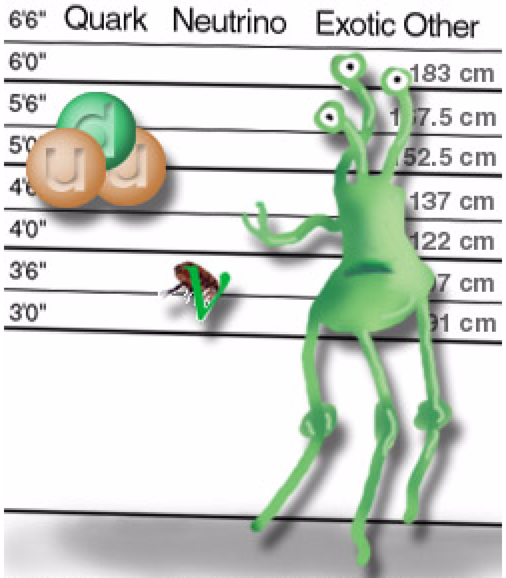
XI. Beyond the Standard Model

- 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 actually have masses?
  - What is the *Dark Matter*?
  - What is the *Dark Energy*?
  - What about the *Graviton*?
  - How come there is almost no antimatter?
  - Why there are *three* generations of quarks and leptons?



"All right... which of you punks is responsible for dark matter?"

Neutrino masses

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

Recall: quark mixing in weak interactions

$$d' = d\cos\theta_C + s\sin\theta_C$$
$$s' = -d\sin\theta_C + s\cos\theta_C$$

By analogy, neutrinos can be represented as linear combinations:

$$\begin{aligned} \nu_e &= \nu_1\cos\alpha + \nu_2\sin\alpha \\ \nu_\mu &= -\nu_1\sin\alpha + \nu_2\cos\alpha \end{aligned} \qquad (222)$$

that is, if neutrinos ν_1 and ν_2 have masses m_1 and m_2

- Mixing angle α must be determined from experiment; *neutrino oscillation* can be observed

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

In Dirac notation,

$$|\nu_e, \vec{p}\rangle = \cos\alpha|\nu_1, \vec{p}\rangle + \sin\alpha|\nu_2, \vec{p}\rangle \tag{223}$$

and after period of time t it evolves to:

$$e^{-iE_1t}\cos\alpha|\nu_1, \vec{p}\rangle + e^{-iE_2t}\sin\alpha|\nu_2, \vec{p}\rangle \tag{224}$$

– here e^{-iE_it} are oscillating time factors (recall strangeness oscillation in Section X.)

Form (224) is not a pure ν_e state anymore, but a mixture:

$$A(t)|\nu_e, \vec{p}\rangle + B(t)|\nu_\mu, \vec{p}\rangle \tag{225}$$

where the ν_μ states are, similarly to (223):

$$|\nu_\mu, \vec{p}\rangle = -\sin\alpha|\nu_1, \vec{p}\rangle + \cos\alpha|\nu_2, \vec{p}\rangle \tag{226}$$

The functions *A(t)* and *B(t)* hence are:

$$\begin{aligned} A(t) &= e^{-iE_1t}\cos^2\alpha + e^{-iE_2t}\sin^2\alpha \\ B(t) &= \sin\alpha\cos\alpha[e^{-iE_2t} - e^{-iE_1t}] \end{aligned} \qquad (227)$$

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

$$P(\nu_e \to \nu_e) = |A(t)|^2 = 1 - P(\nu_e \to \nu_\mu) \qquad (228)$$

$$P(\nu_e \to \nu_\mu) = |B(t)|^2 = \sin^2(2\alpha)\sin^2\frac{(E_2 - E_1)t}{2} \qquad (229)$$

- If neutrinos have equal (zero) masses ⇒ E_1=E_2 ⇒ no oscillations

Methods to detect neutrino oscillations:

- Appearance search
- Disappearance test

- ν_e and ν_μ can be distinguished by their interaction with neutrons: former produce electrons and latter - muons:

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

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

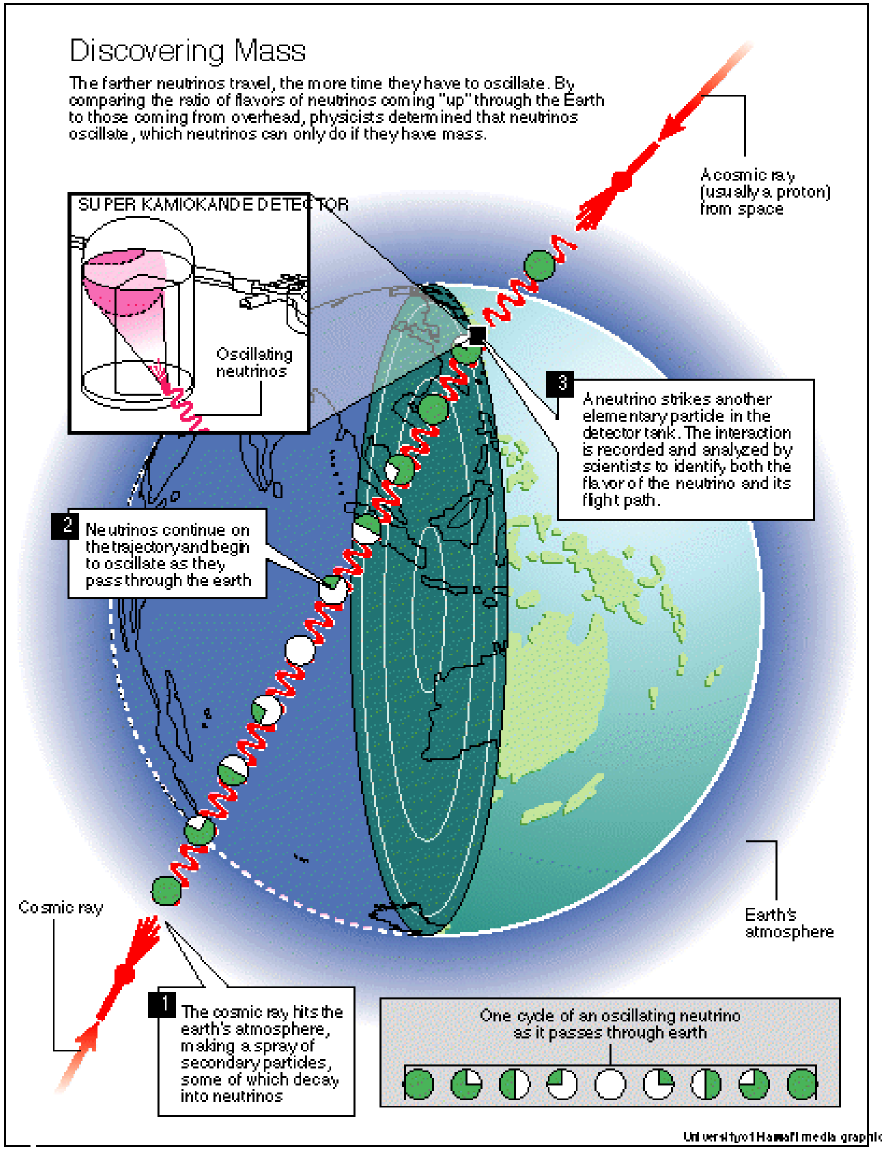
  - Time t in (229) is determined by the distance between the detector and the source of neutrinos

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

Atmospheric neutrino anomaly

Was first detected in 1980's: instead of predicted $N(\nu_\mu) \approx 2N(\nu_e)$, rates of both neutrinos were approximately equal.

- *Super-Kamiokande* detector: measures rates and flavours of neutrinos coming both from zenith and nadir
  - A neutrino created in cosmic rays travels ~15 km in the atmosphere ⇒ has no time to oscillate (proven by other experiments)
  - A similar neutrino created on the other side of the Earth travels ≈13000 km ⇒ has good chances to oscillate
  - If ratio of ν_e and ν_μ is different in two cases above ⇒ there are oscillations ⇒ at least one neutrino is massive.
- The detector is placed in a deep mine to reduce the background
  - 50 000 m^3 of water and 13 000 photomultipliers work at the Cherenkov detector



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.

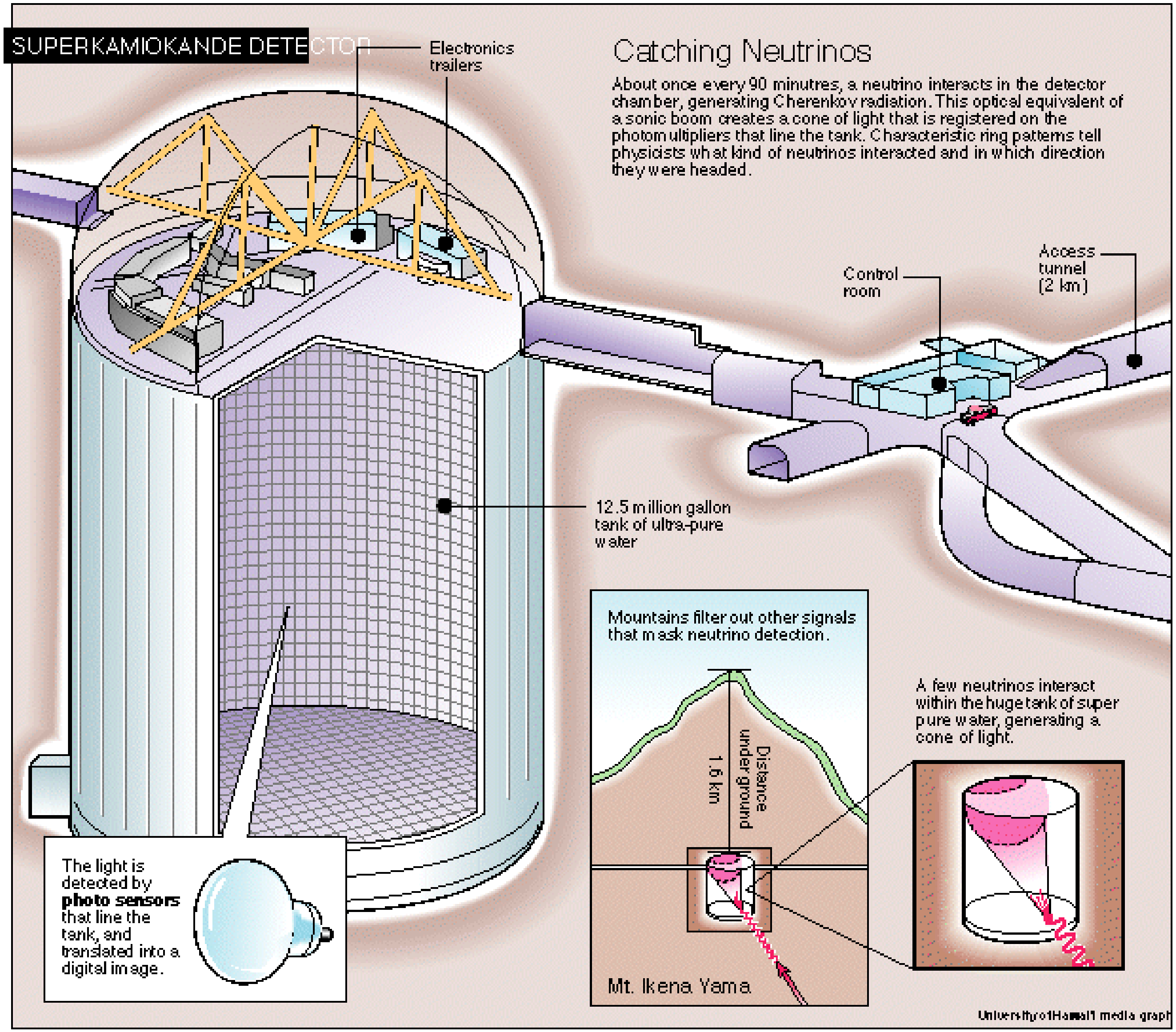
1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

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.

University of Hawaii media graphic

Figure 143: Neutrino oscillations through Earth



Catching Neutrinos

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.

University of Hawaii media graph

Figure 144: Schematics of the Super-Kamiokande detector

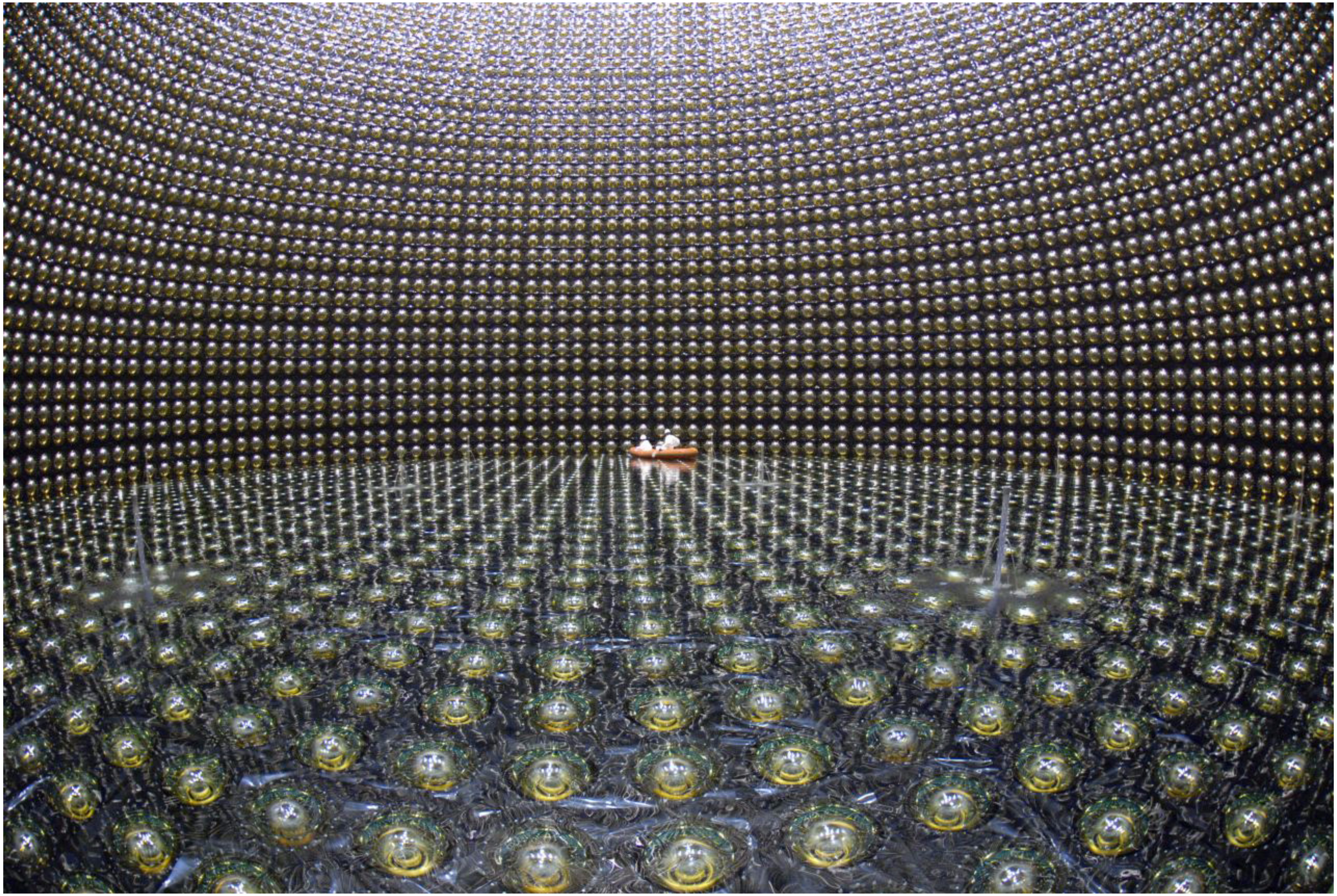


Figure 145: Interior of the Super-Kamiokande detector (April 2006, filling with water after full reconstruction)

- In 1998, the Super-Kamiokande Collaboration announced:

a) 4654 observed events – by far the largest statistical sample (more than doubled by now)

b) data exhibit zenith angle dependence of ν_μ deficit

c) hence the “atmospheric neutrino anomaly” can only be explained by oscillations $\nu_\mu \leftrightarrow \nu_\tau$, which leads to muonic neutrino deficiency in cosmic rays.

d) the mixing angle and neutrino mass difference Δm from athmospheric neutrino studies are currently estimated at

$$\begin{gathered} \sin^2(2\alpha) > 0.93 \\ 2\times10^{-3} < \Delta m^2 < 3\times10^{-3}\ eV^2 \end{gathered} \tag{230}$$

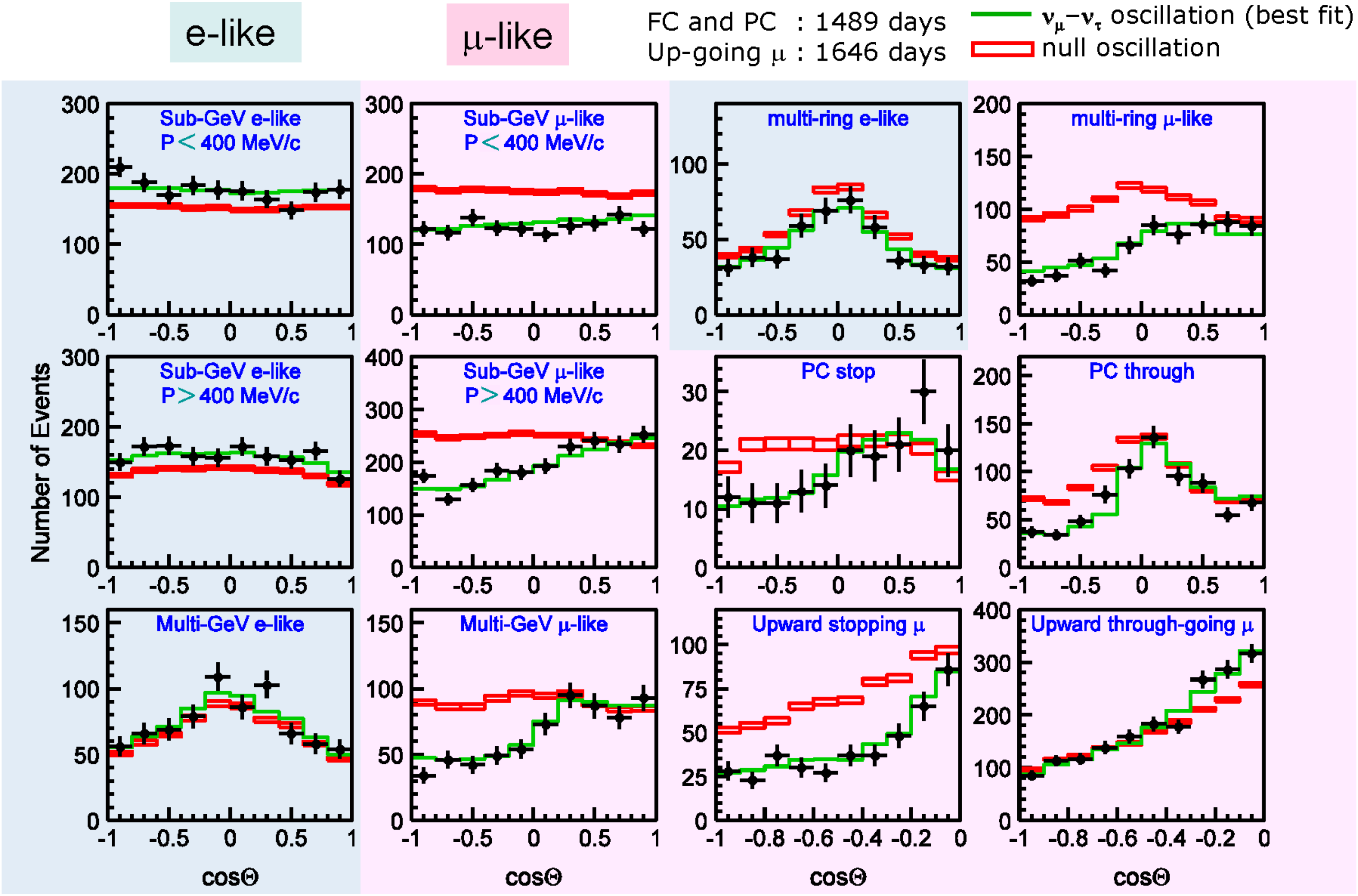


Figure 146: Zenith angle distributions, Super-Kamiokande I

Solar neutrino problem

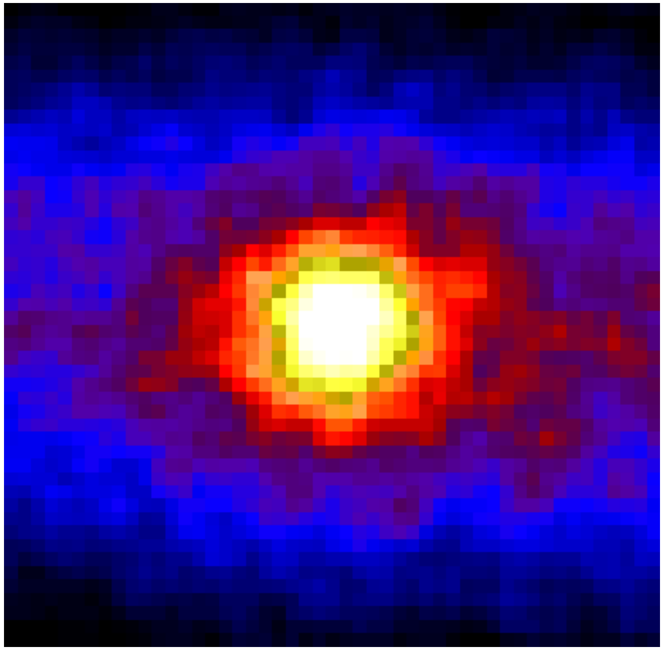


Figure 147: “Portrait” of the Sun in neutrinos (by Super-Kamiokande)

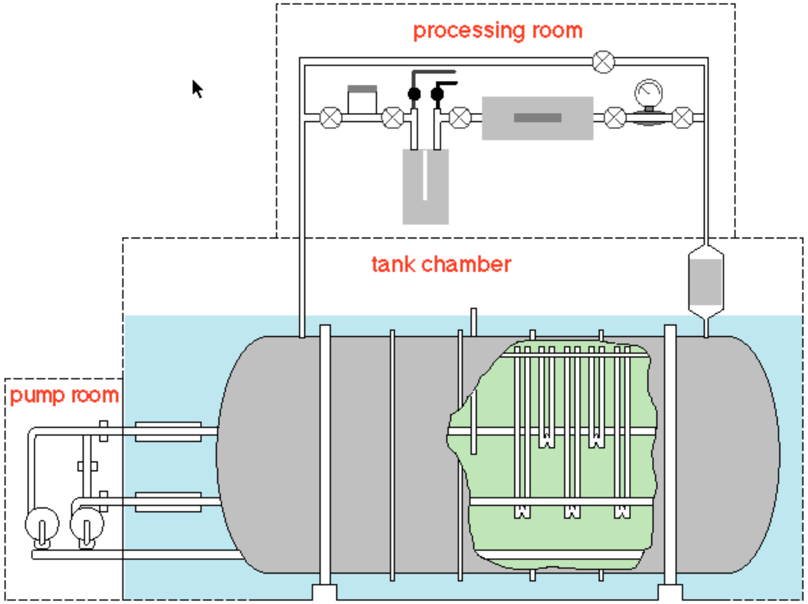
- Several (similar) methods are used to detect solar neutrinos:

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

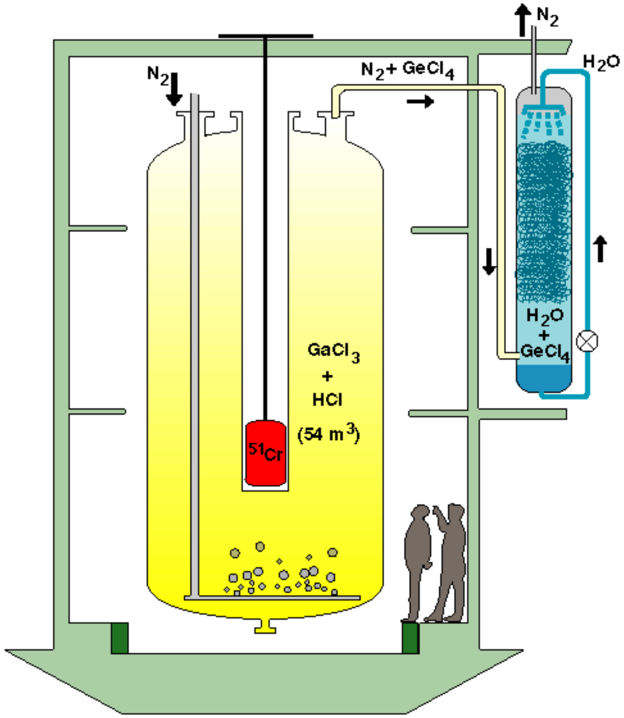
$$\nu_e + {}^{98}\mathrm{Mo} \to e^- + {}^{98}\mathrm{Tc}$$

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

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



Homestake gold mine detector (data taking since 1970, USA)



GALLEX detector under the Gran Sasso mountain (Italy), data taking in1991-1997

Figure 148: Typical layouts of solar neutrino detectors

Solar neutrino flux is measured in SNU ("solar neutrino unit"):

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

"Solar neutrino problem" (SNP):

- For the Homestake detector, predicted neutrino flux is 7.3 ± 2.3 SNU, measured 2.6 ± 0.2 SNU
- GALLEX: predicted 129 ± 8 SNU, measured 77.5 ± 8 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 seem to be the most appealing explanation, although there are many other hypotheses

Sudbury Neutrino Observatory (SNO)

- uses heavy water and can detect all three kinds of neutrinos
- Data taking since 1999
- In 2001, produced the first evidence of oscillations in solar neutrinos, which effectively solved the SNP

Figure 149: Sudbury Neutrino Observatory layout (2km underground)

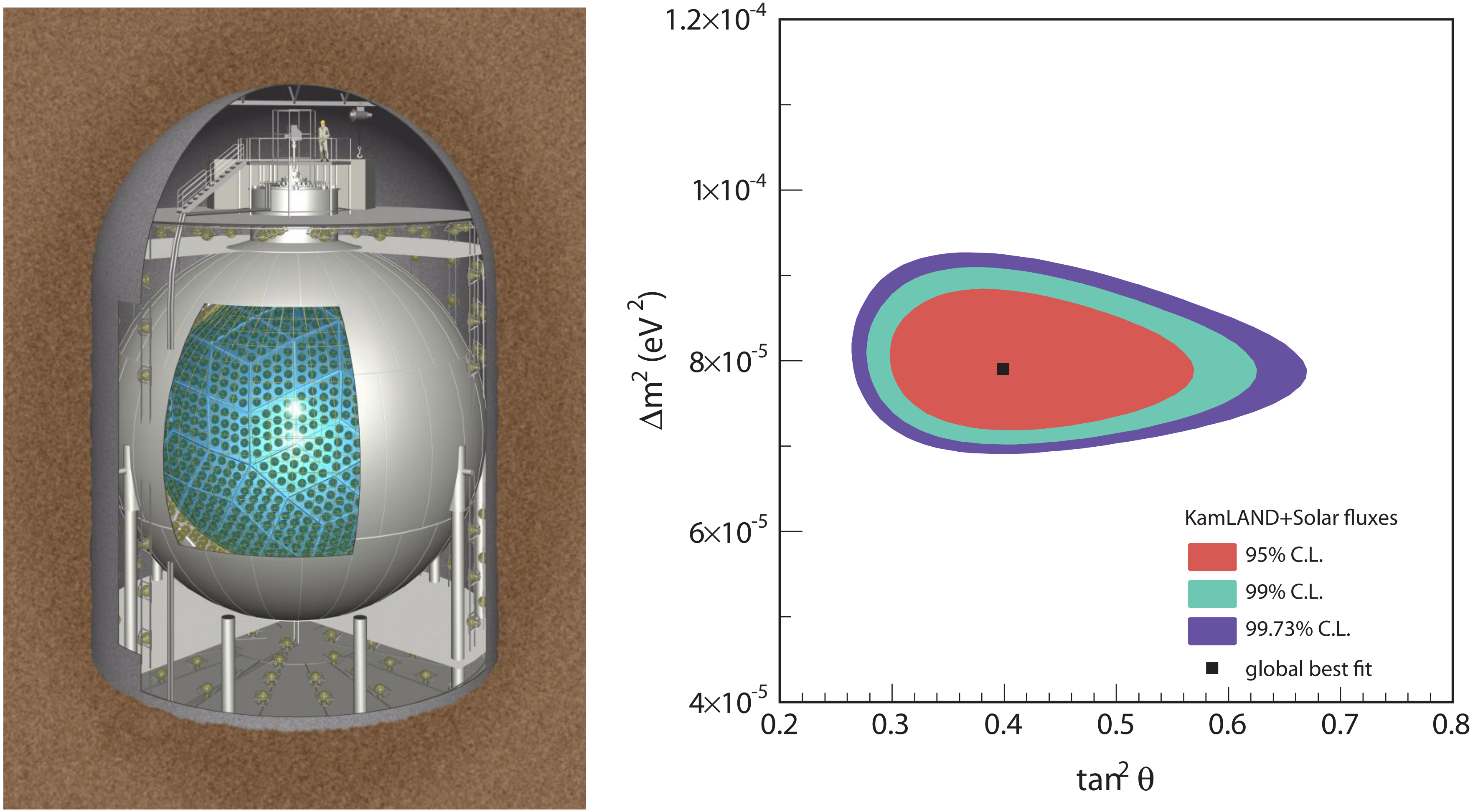


Figure 150: KamLAND detector and the combined SNO and KamLAND (neutrinos from a reactor) fit

- Detection of neutrinos from *supernovae* can provide information about neutrino mass

- Simultaneous observation of neutrinos from the SN1987a on February 23, 1987 by two experiments (IMB and Kamiokande) set the upper limit of neutrino mass at 20 eV

Figure 151: SN1987a as seen by the Hubble Space Telescope in 1994

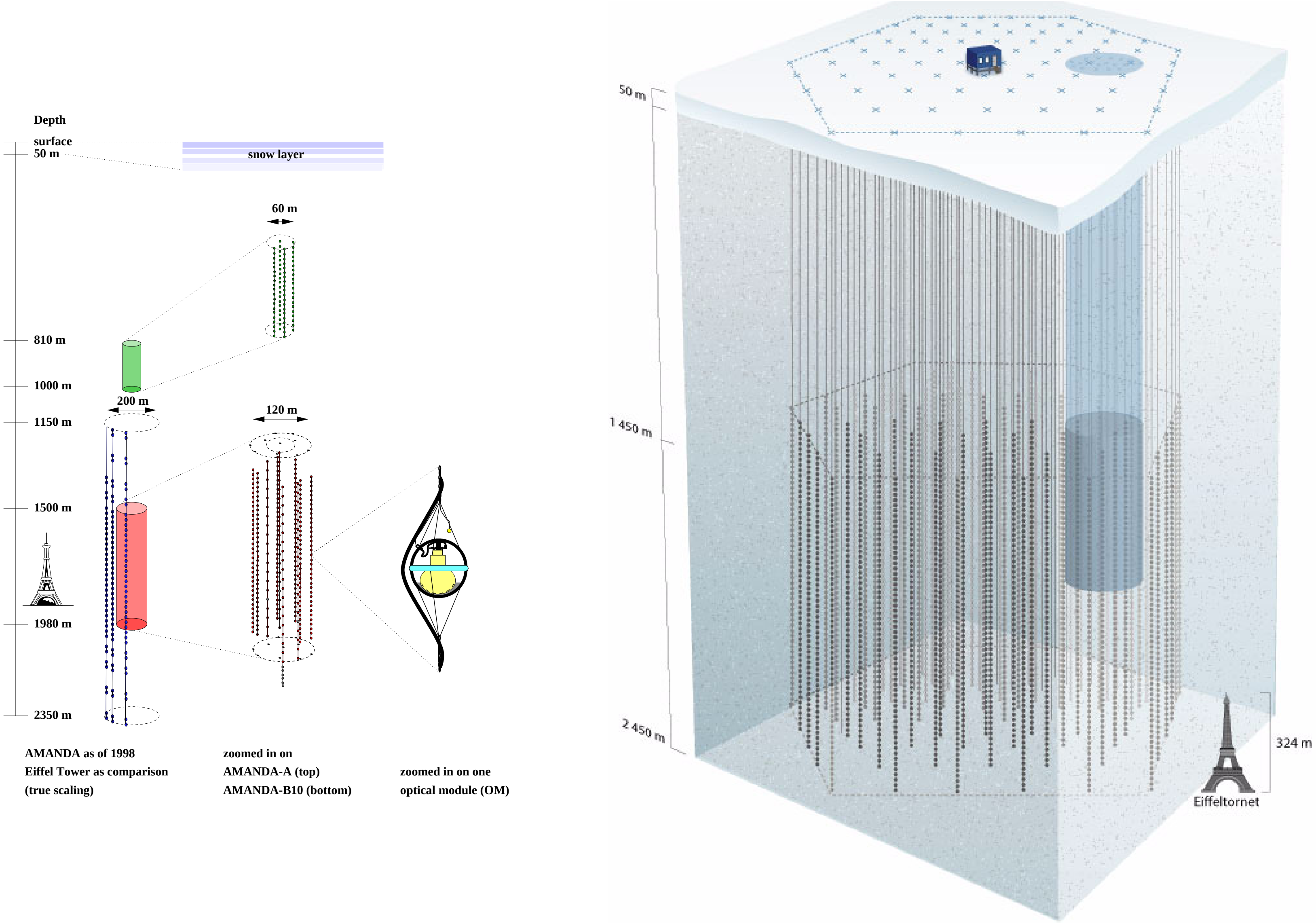
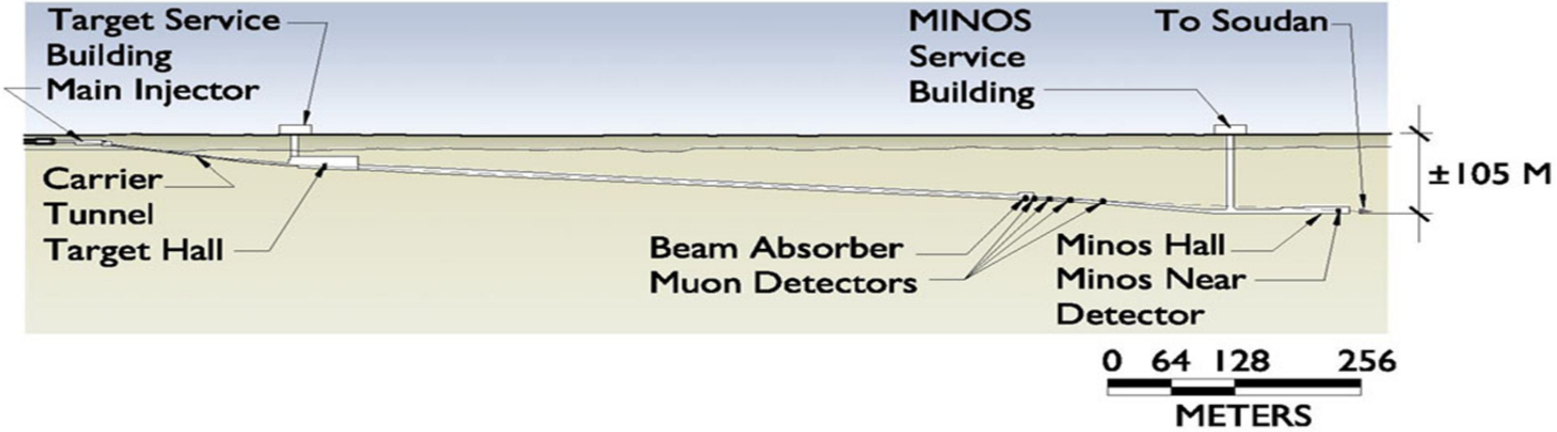
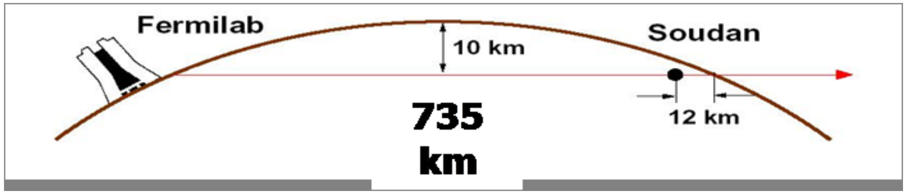


Figure 152: AMANDA (left) and IceCube (right) neutrino telescopes at the South Pole: looking for high-energy extra-gallactic neutrinos





- March 2006 results:

$$\Delta m^2 = 3.05 \pm 0.6 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta = 0.88 \pm 0.15$$

Figure 153: MINOS long-baseline experiment: shooting a ν_μ beam

Dark matter

Experimental evidence for the Big Bang model:

- Universe expands
- Cosmic background radiation
- Abundance of light elements

Expansion will halt at the critical density of the Universe:

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

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

The relative density is estimated to be close to 1:

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

- Relative density of the observable (i.e. emitting electromagnetic radiation) matter in the Universe is only $\Omega_L \approx 0.01$
- The rest is called the"*dark matter*" and the "*dark energy*"

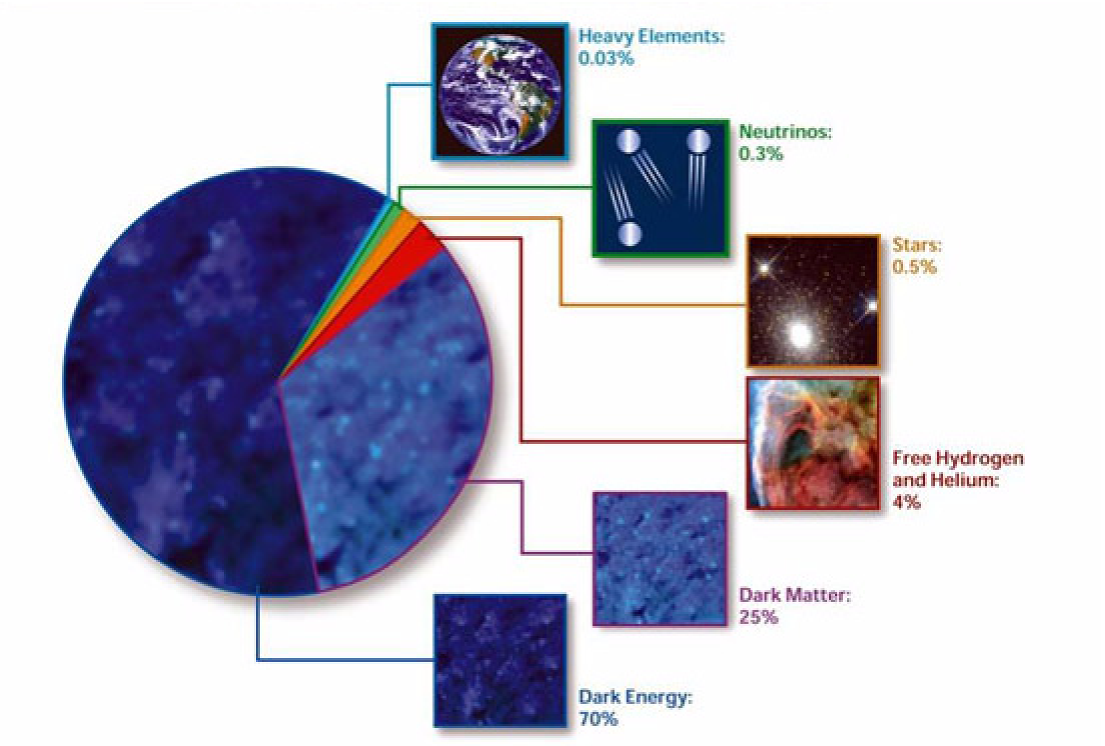


Figure 154: Composition of the Universe

- Possible components of the dark matter:
  - *Baryonic matter* that emits little or no e.m. radiation: brown dwarfs, small black holes – MACHO's (for MAssive Compact Halo Object). There is an evidence that $\Omega_B \approx 0.06$ only.
  - Massive neutrinos ("*hot dark matter*"): at the Big Bang, the rate of neutrino production is the same as of photons ⇒ knowing the density of photons and the expansion rate of the Universe:

    $$\sum m_\nu \leq 100\ eV/c^2$$

    Apparently, neutrinos can not be the dominant dark matter either.
  - "*Cold dark matter*": WIMP's (Weakly Interacting Massive Particles), non-baryonic objects, non-relativistic at early stages of the Universe evolution. Still to be detected...
- Dark energy: Universe's expansion is accelerating
  - While the Dark Matter produces attractive force, the Dark Energy is responsible for the repulsive force

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 may become equal

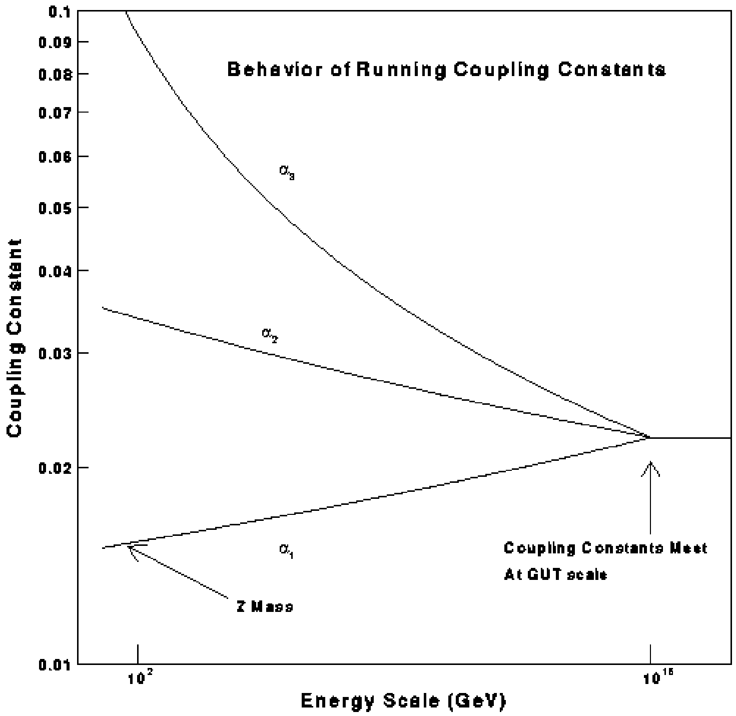


Figure 155: Coupling constants in GUT; α_1 and α_2 are couplings at Z and W

Grand unified theories can be constructed in many different ways.

- 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:

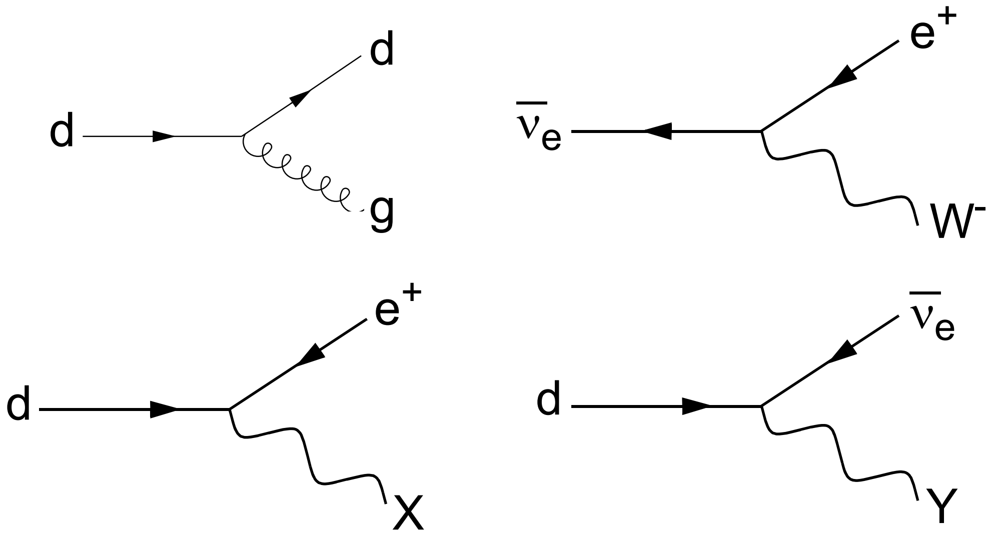


Figure 156: Standard processes together with predicted by GUT

The single unified coupling constant is g_U, and

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

- Georgi-Glashow model explains equal magnitudes of electron and proton charge

Sum of electric charges in any given family must be zero ⇒ $3Q_d + e = 0$ ⇒ down-quark has charge -e/3.

  – Factor of 3 arises simply from the number of colors

- This model also predicts the weak mixing angle using values of the coupling constants:

$$\sin^2\theta_W = 0.21 \qquad (231)$$

which is very close to experimental results, but not precisely.

- GUTs predict that the proton is unstable and can decay by a process involving X or Y bosons

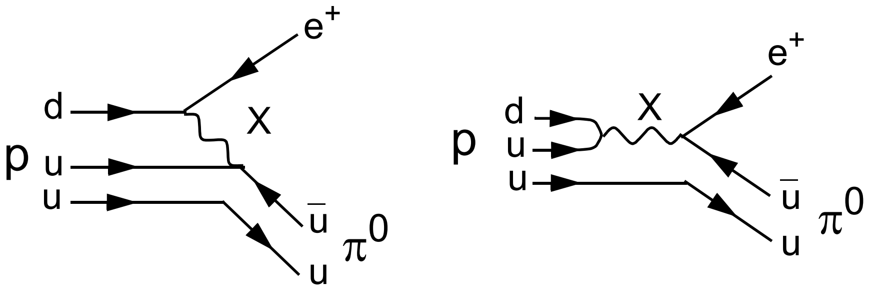


Figure 157: Proton decays in GUT

- In processes like those on Fig.157, baryon and lepton numbers are not conserved, but their combination is:

$$B - L \equiv B - \sum_{\alpha} L_{\alpha} \quad (\alpha = e, \mu, \tau) \qquad (232)$$

- From the simple zero-range approximation, lifetime of the proton is (from different GUTs):

$$\tau_p = 10^{29} \div 10^{30} \; years \qquad (233)$$

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

- Same detectors as those used for the neutrino physics (IMB, Kamiokande) are looking for the proton decays, but have not observed a clear example so far
  - The most interesting process is

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

  - The upper limit for the proton lifetime is > 5 × 10^{32} years, which disagrees with the Georgi-Glashow model; other GUTs can accommodate for it though
- Baryon number non-conservation allows explanation of excess of baryons in the universe as compared to antibaryons. However, CP-violation must be present as well.

Supersymmetry (SUSY)

- Most popular GUTs incorporate SUSY
  - 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 however have to be much heavier than their counterparts

- SUSY shifts the grand unification mass from 10^{15} to 10^{16} GeV/c^2, and hence the lifetime of the proton increases:

$$\tau_p = 10^{32} \div 10^{33}\ years \qquad (234)$$

which is more consistent with experimental (non)observations.

- SUSY also modifies the value of the weak mixing angle (231) to be closer to the experimental results.
- SUSY even attempts at unifying ALL forces, including gravity, at the *Planck mass* of the order of 10^{19} GeV/c^2 by replacing particles with *superstrings*

- Lightest superparticles can be candidates for the cold dark matter; most models introduce *neutralino* $\tilde{\chi}_0$, which is the mixture of photino, Higgsino and zino:

$$e^+ + e^- \rightarrow \tilde{e}^+ + \tilde{e}^- \qquad (235)$$

$$\tilde{e}^+ \rightarrow e^+ + \tilde{\chi}_0 \qquad \tilde{e}^- \rightarrow e^- + \tilde{\chi}_0 \qquad (236)$$

SUSY predictions for reactions (235)-(236):

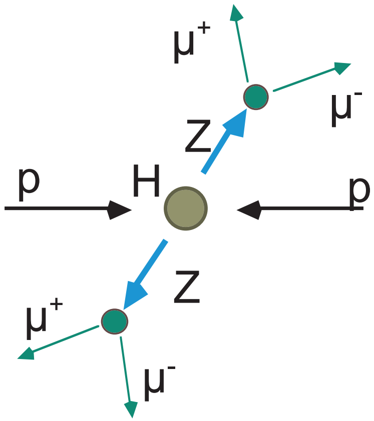
1) Cross-section of (235) is comparable with producing ordinary charged particles of the <u>same</u> mass
2) Selectrons decay before they can reach a detector
3) Neutralinos are virtually undetectable due to very weak interaction

Thus only the final state electrons in (236) can be detected, so that they:

(a) carry only half of the initial energy of the e^+e^- state,
(b) should not be emitted in opposite directions in CM frame

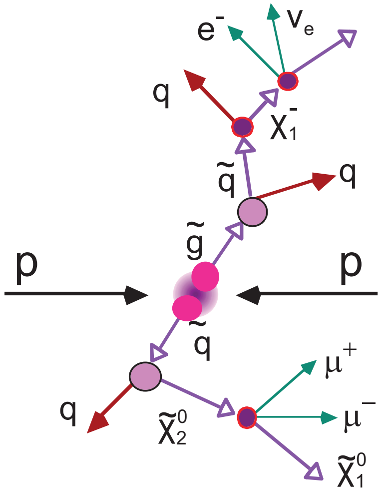
- No signature of this kind has been observed so far, tests at higher energies are needed

Minimal Supersymmetric Standard Model: target for LHC searches



- In MSSM, there are 5 Higgs bosons (h^0, H^0, A^0 and $H^\pm$). They decay to photons, lepton-antilepton or quark-antiquark pairs.

Figure 158: Possible Higgs signal at LHC



- Production of sparticles should be detectable via characteristic kinematical spectra, including e.g. missing transverse energy of more than 100 GeV

Figure 159: Possible supersymmetric particles at LHC