Neutrino Basics

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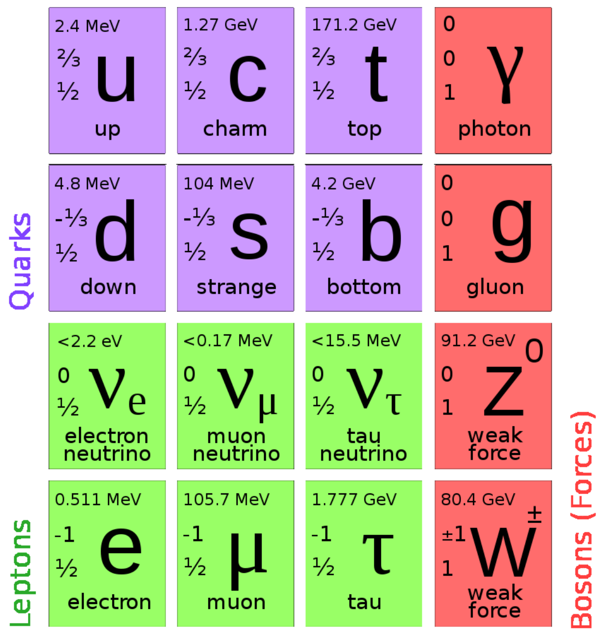


Neutrinos in Art

Neo-Swing

Cosmic Gall

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.

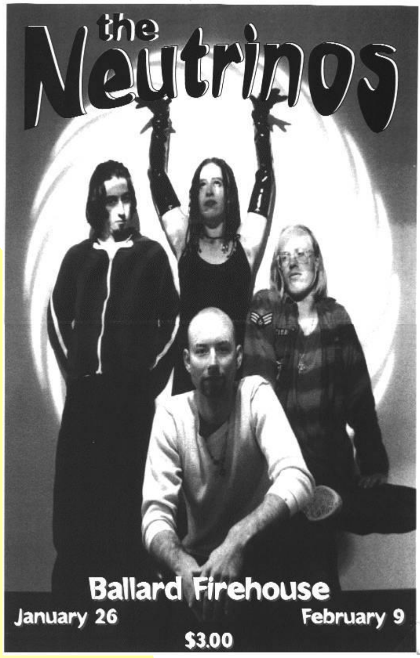
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

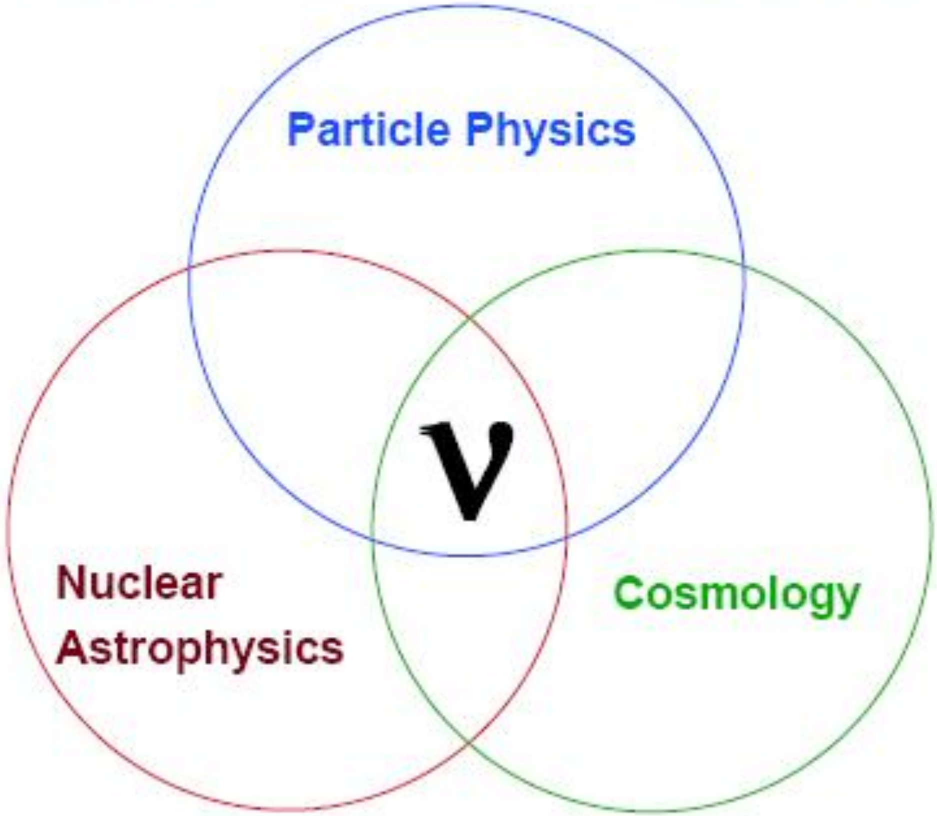
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.

John Updike
***Telephone Poles and Other Poems,* 1963**



Seattle Rock Band


Particle Physics
ν
Nuclear
Astrophysics
Cosmology

Neutrino Facts and Trivia

- What is a neutrino?
  - an elementary particle
    - » has no mass (in SM)

      travels at speed of light (for now)
    - » has no electric charge
    - » interacts little with any other matter (pure week interaction)

      ==> can pass through 50 billion miles of water without interacting

      ==> this in turn allows us see the interior of stars and provides us with information otherwise not obtainable by the traditional optical telescopes

      ==> neutrino telescopes

Neutrinos from Stars

- Solar Neutrinos
  - produced by nucleosynthesis inside the Sun : Fusion
  - Flux on the surface of the Earth: ~ 500 billion neutrinos /cm^2/sec
    - » Solar Neutrino Puzzle

      One of the most fascinating and longest running unsolved mysteries in physics Explained by neutrino oscillations
- Supernova Neutrinos
  - produced by the neutralization process at the core
  - carry 99% of the supernova energy
  - observed for the first time in 1987 (SN1987a): a total of 20 events by two detectors (IMB and Kamiokande) in about 10 second period of time ==> a triumph of supernova theory

Neutrinos from the Earth

- Atmospheric Neutrinos
  - produced by the cosmic rays bombarding on the atmosphere
  - first evidence for neutrino oscillation
    ==> discovery of non-zero neutrino mass
- Terrestrial Neutrinos
  - produced by natural radioactivity
  - ~ 6 million neutrinos /cm^2/sec
- Man-made Neutrinos
  - produced by particle accelerators, nuclear reactors
- Homo sapiens Neutrinos
  - produced by Potassium 40 decay in our body (~20 mg)
  - ~340 million neutrinos/day

Fermilab outside of Chicago is a source of accelerator neutrinos

Neutrinos from The Big-Bang

- Relic (thermal background) Neutrinos
  - produced 1 second after Big-Bang
  - a la 2.7° cosmic microwave background

  ~ 300 neutrinos/cm³ in our universe

  » if neutrino has mass, it can influence the ultimate fate of the Universe. (open? or closed Universe?)

  m_ν ~ 30 eV, closed universe ($\Omega >= 1$)

  m_ν ~ a few eV, "Dark Matter" candidate ($\Omega \sim 0.2$)

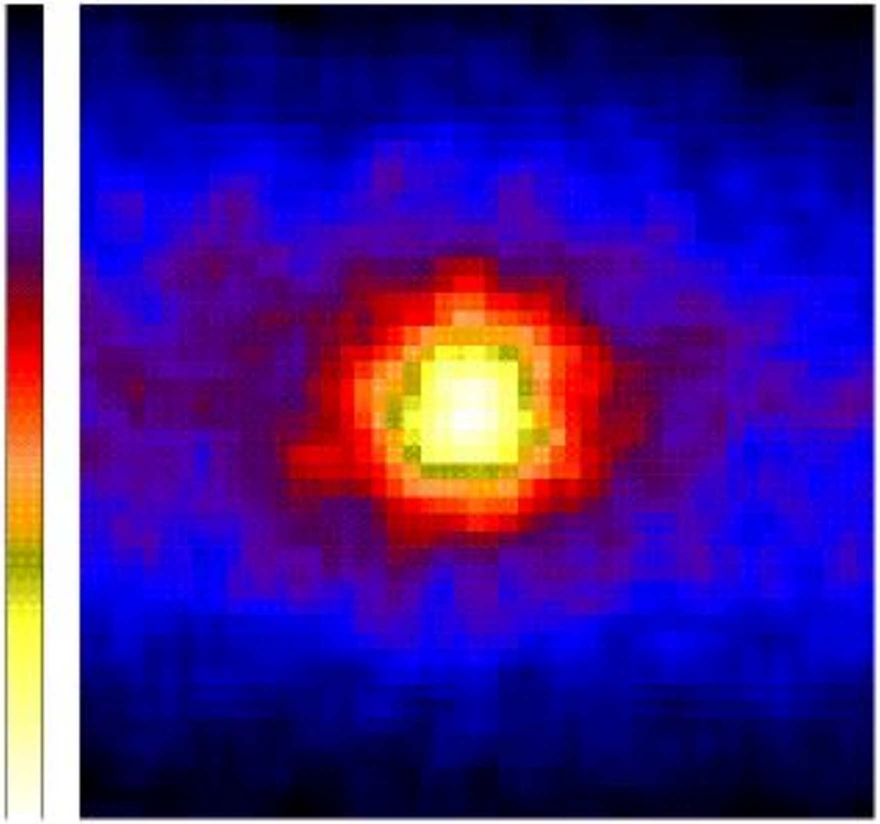
  m_ν ~ 1/20 eV, total neutrino mass in the Universe

  ~ total luminous matter mass ($\Omega \sim 0.003$)

  - never been directly detected (poses biggest challange to experimentalists, in fact observation has never been attampted.)

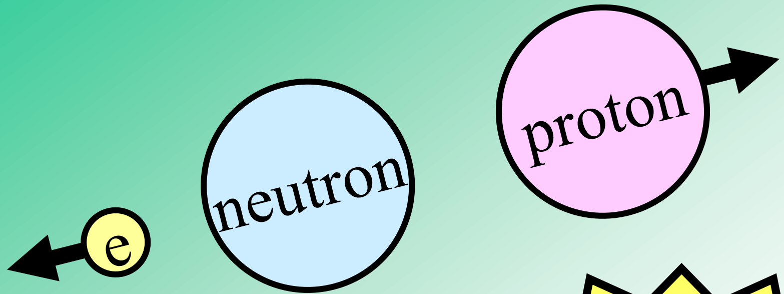
Neutrino experiments carried out deep underground

Super-Kamiokande Solar Image



Neutrino Image of the Sun
observed with the
Super-Kamiokande Neutrino Telescope

β decay



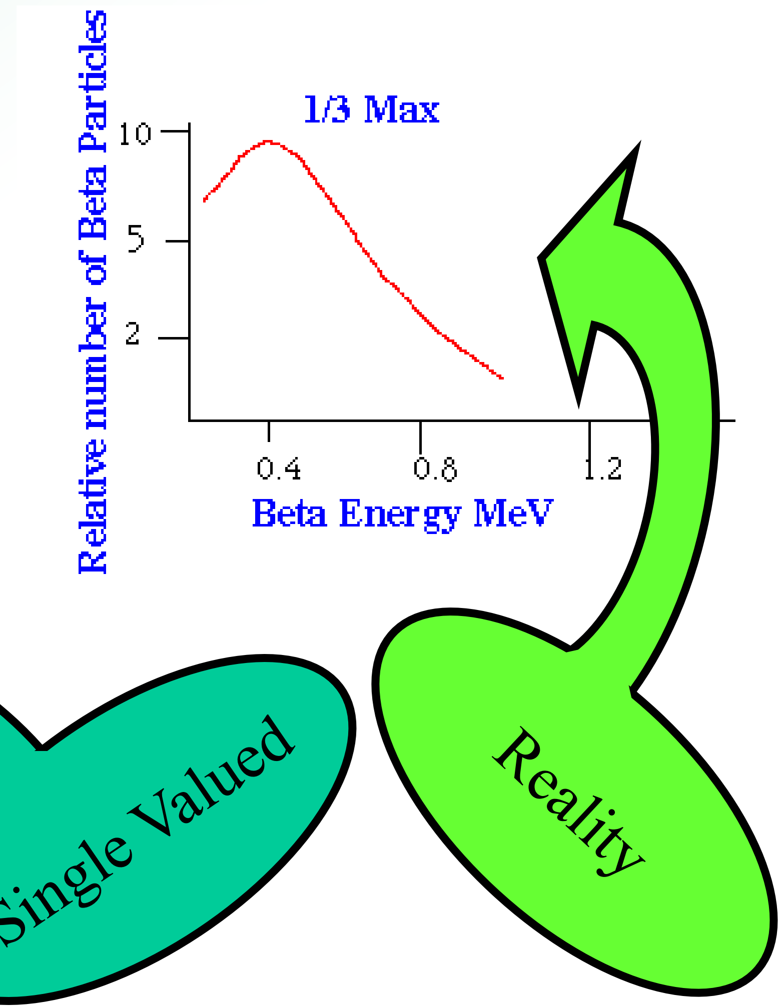
$$n_o \rightarrow p^+ + e^-$$

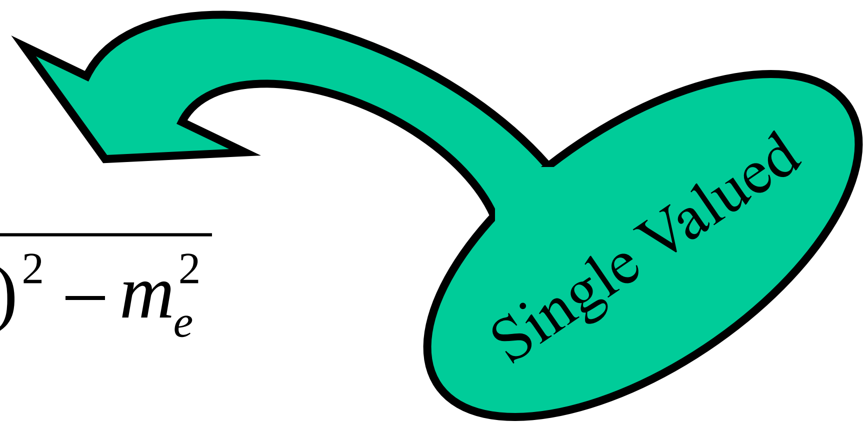
$$E_n = E_p + E_e$$

$$\vec{p}_n = \vec{p}_p + \vec{p}_e$$

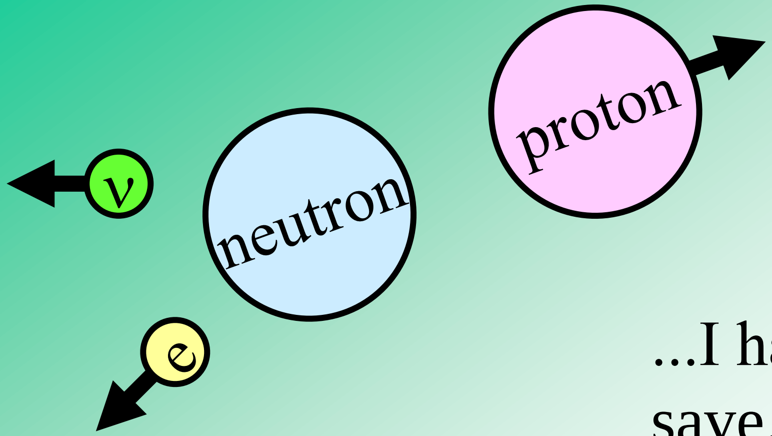
$$\vec{p}_p = -\vec{p}_e$$

$$p \approx \sqrt{(m_n - m_p)^2 - m_e^2}$$





β decay



December 4, 1930

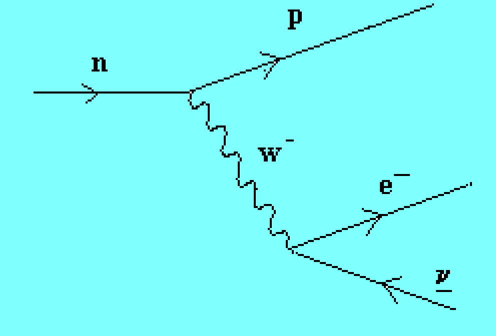
Dear radioactive ladies and gentlemen,

...I have hit upon a ‘desperate remedy’ to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli

Note: this was before the discovery of the real neutron

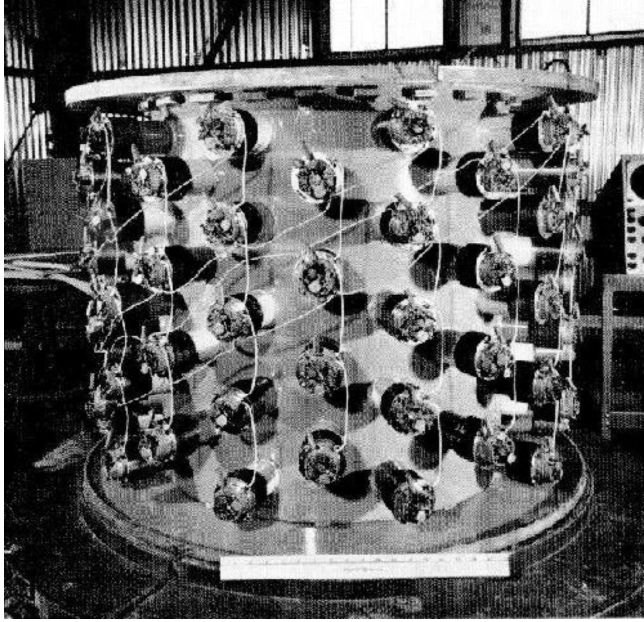


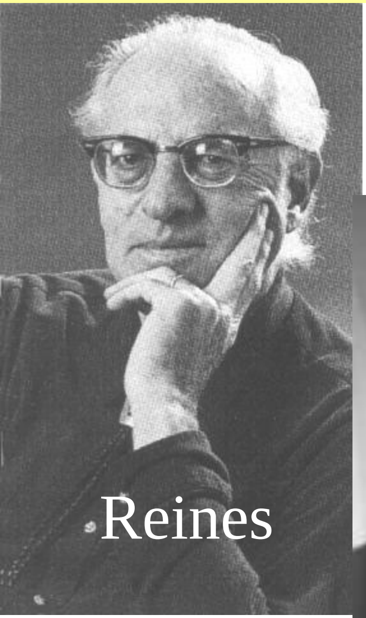
Project Poltergeist 1956

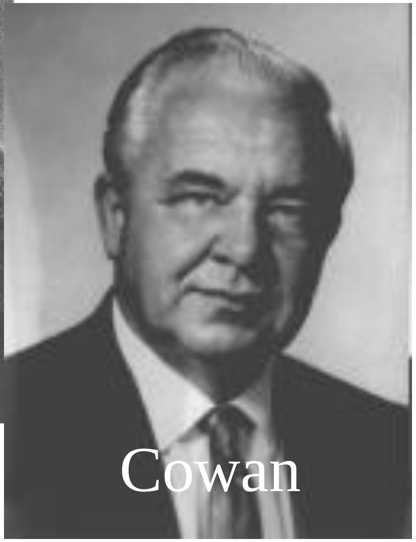
$$\nu + p^+ \rightarrow n^o + e^+$$

$$e^+ + e^- \rightarrow 2\gamma$$

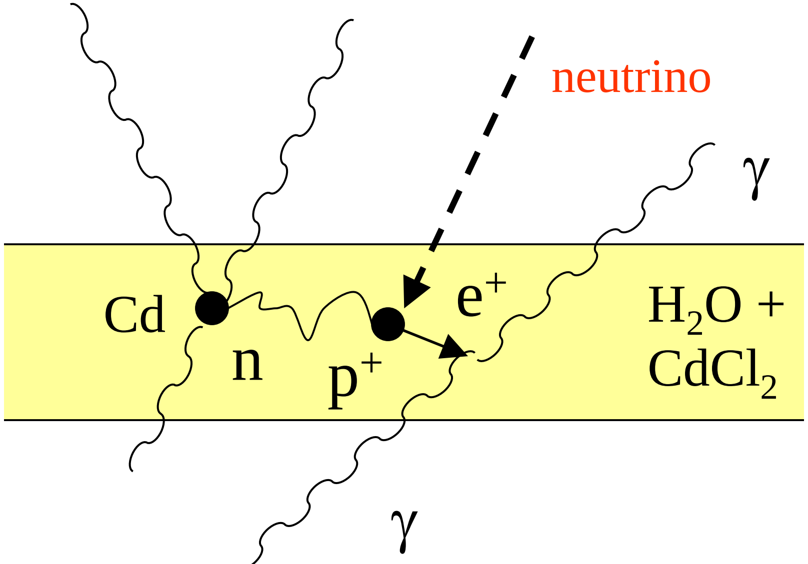
$$n^o + \text{Cd} \rightarrow (\text{several})\ \gamma$$





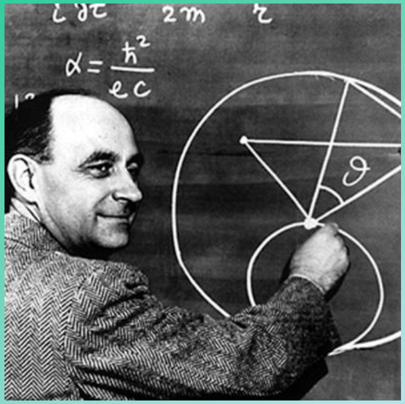


Signal 2γ, then several γ ~few μs later



Experiment attempted at Hanford in 1953, too much background. Repeated at Savannah River in 1955. [Flux: 10^{13} neutrinos/(cm^2 s)]

Neutrino Facts

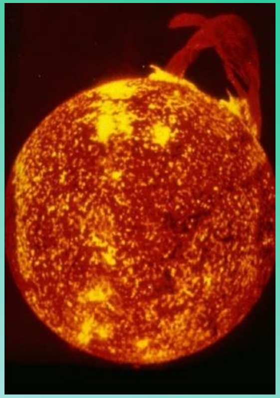


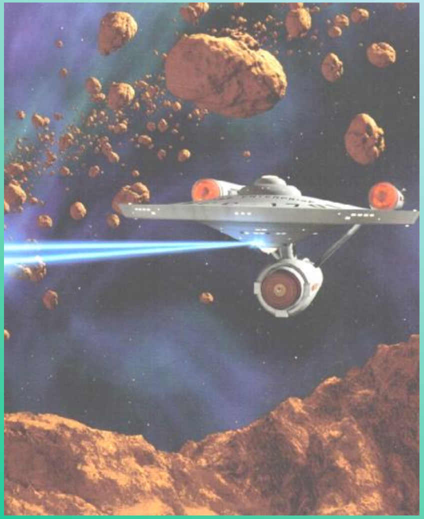
Neutrino from Enrico Fermi for “Little neutral one”

ν flux on Earth from Sun

$6.5\times10^{14}/(m^2\ s)$

<E> ~ 0.3 MeV





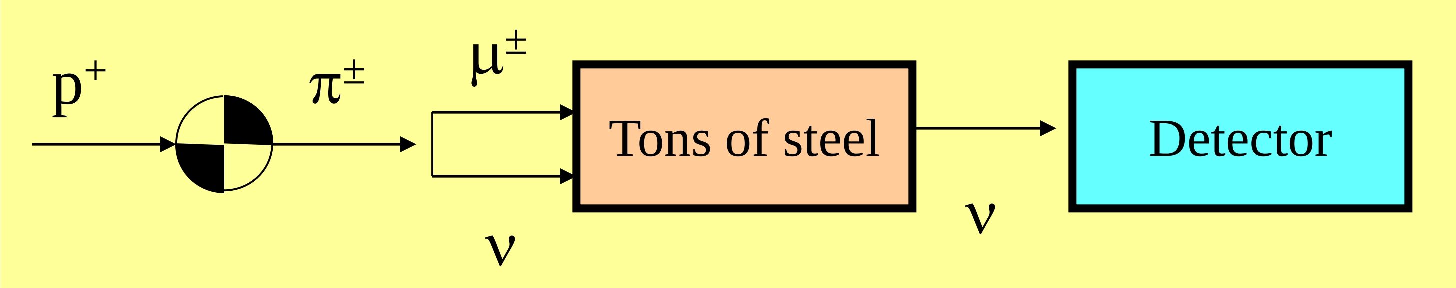
Neutrino from sun will pass through 5 LY of solid lead, with 50% chance of interacting

Average number of solar neutrinos interacting in a person per year

$\leq 30!$

≤ 1 with ‘real energy’

More than one kind of neutrino?



Date: 1962

Intent: Measure weak force at high energies

Expectation: Since neutrinos are created with muons and electrons, the neutrino beam should create both electrons and muons in the detector.

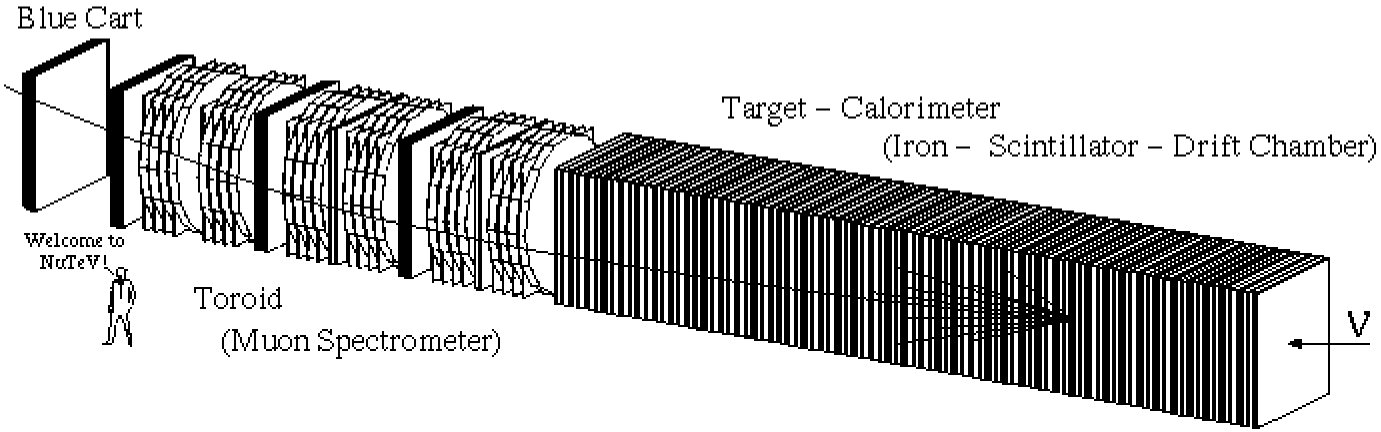
Result: No electrons produced, only muons

Conclusion: There must be two kinds of neutrinos.

Typical Experiment

Need lots of mass to force a neutrino to interact.

Beam-based experiments typically have weight of ~1000 tons

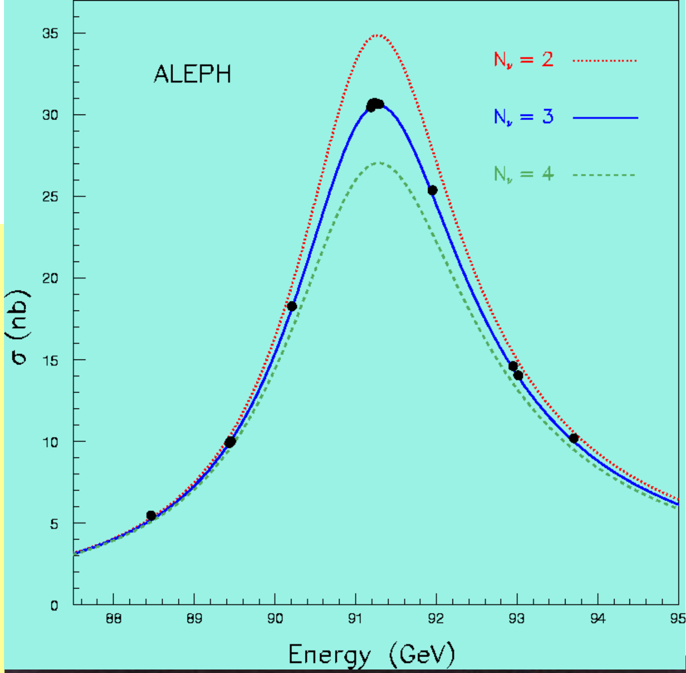


Neutrinos show number of generations

At LEP

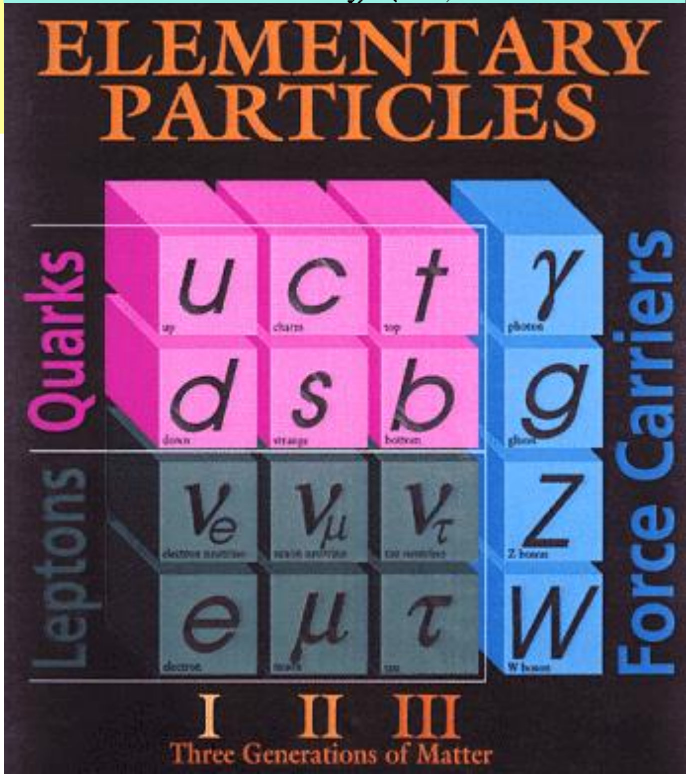
$$e^+ + e^- \rightarrow Z \rightarrow q\bar{q} \text{ or } e^+e^- \text{ or } \mu^+\mu^-$$

A *Z* can also decay into neutrino pairs. The width of the mass distribution of the *Z* boson is sensitive to the total number of neutrino generations into which it can decay.



Obvious Conclusion: There are 3 generations

Cautious Conclusion: There are only three flavors of low-mass neutrinos into which a Z can decay.



Neutrino Sources

Solar neutrinos

$p + p \rightarrow d + e^{+} + \nu_e$

$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$

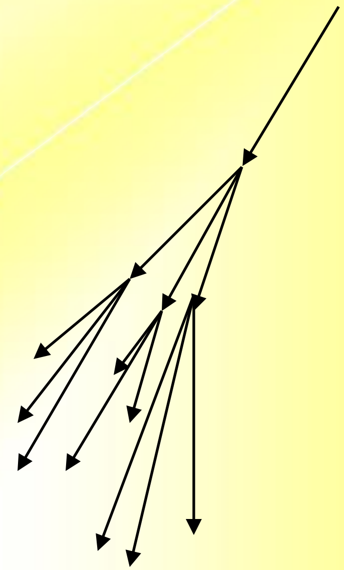
Sun emits ν_e

$2\times10^{38}\ s^{-1}$

Uranium and Thorium in the Earth's crust decay about 15 TW of energy.

Neutrino flux on Earth's surface (from Earth)

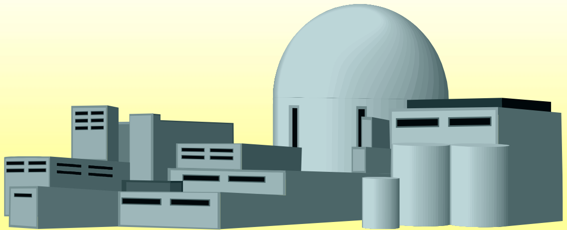
$\sim 5\times10^{10}\ s^{-1}\ m^{-2}$



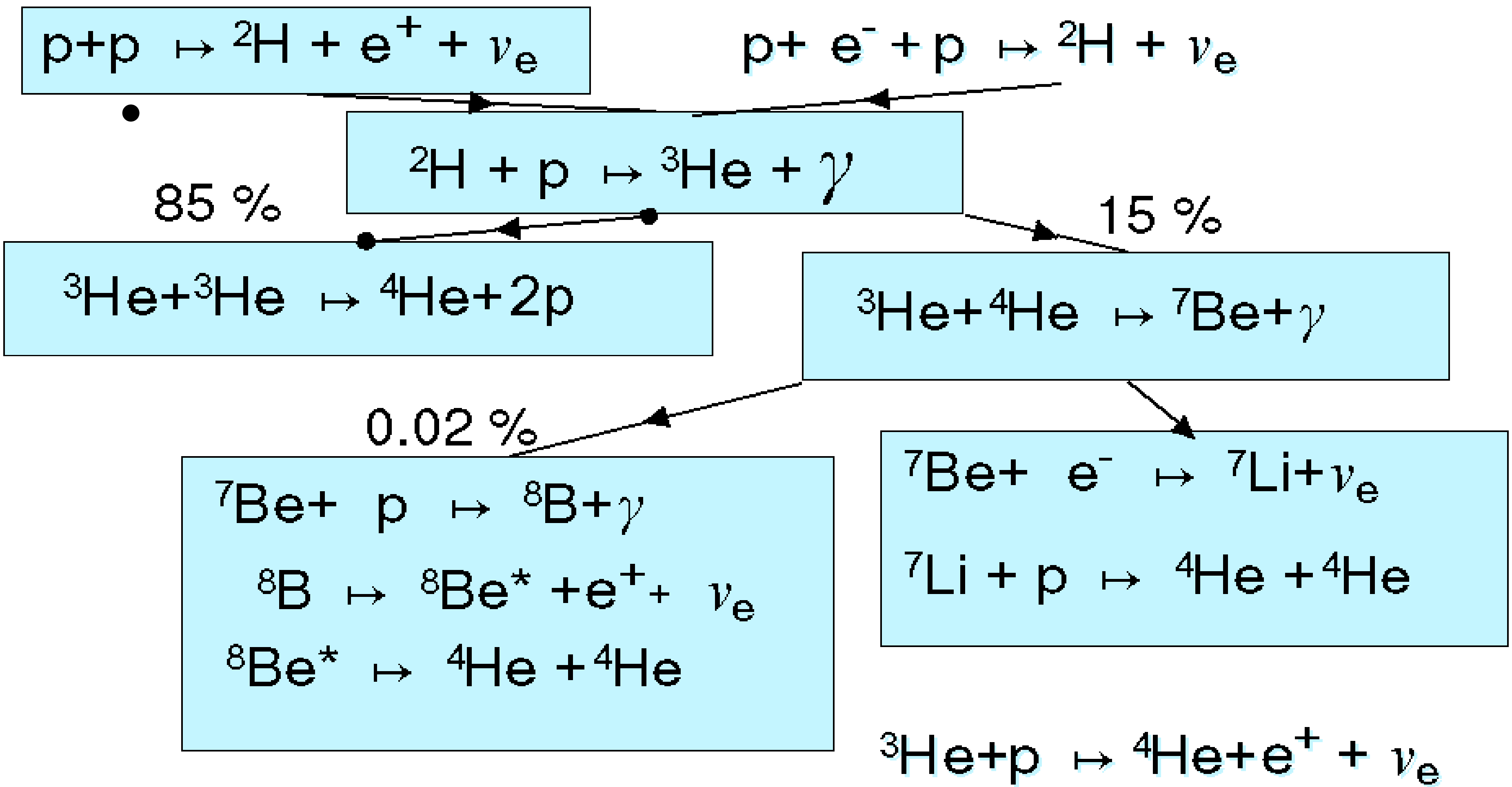
Neutrinos from cosmic rays

$\sim 100\ m^{-2}\ s^{-1}$

A 5-10 GW reactor complex has a neutrino flux of $\sim 10^{20}\ s^{-1}$



Solar Neutrinos



Homestake Gold Mine

100,000 gallons of cleaning fluid C_2Cl_4

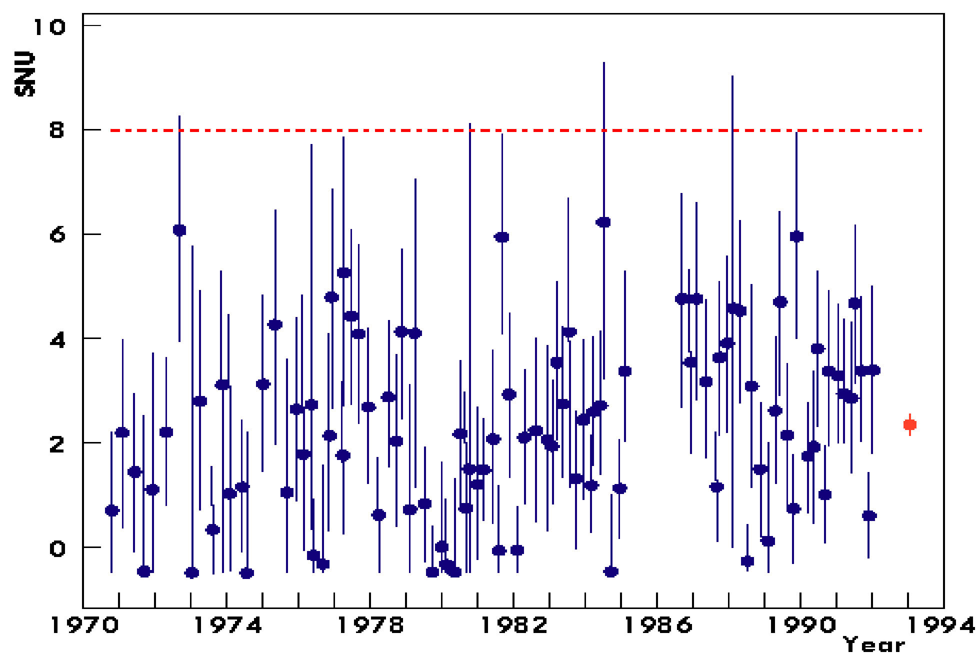
In South Dakota

Expected 1.5 interactions per day
Measured 0.5 interactions per day

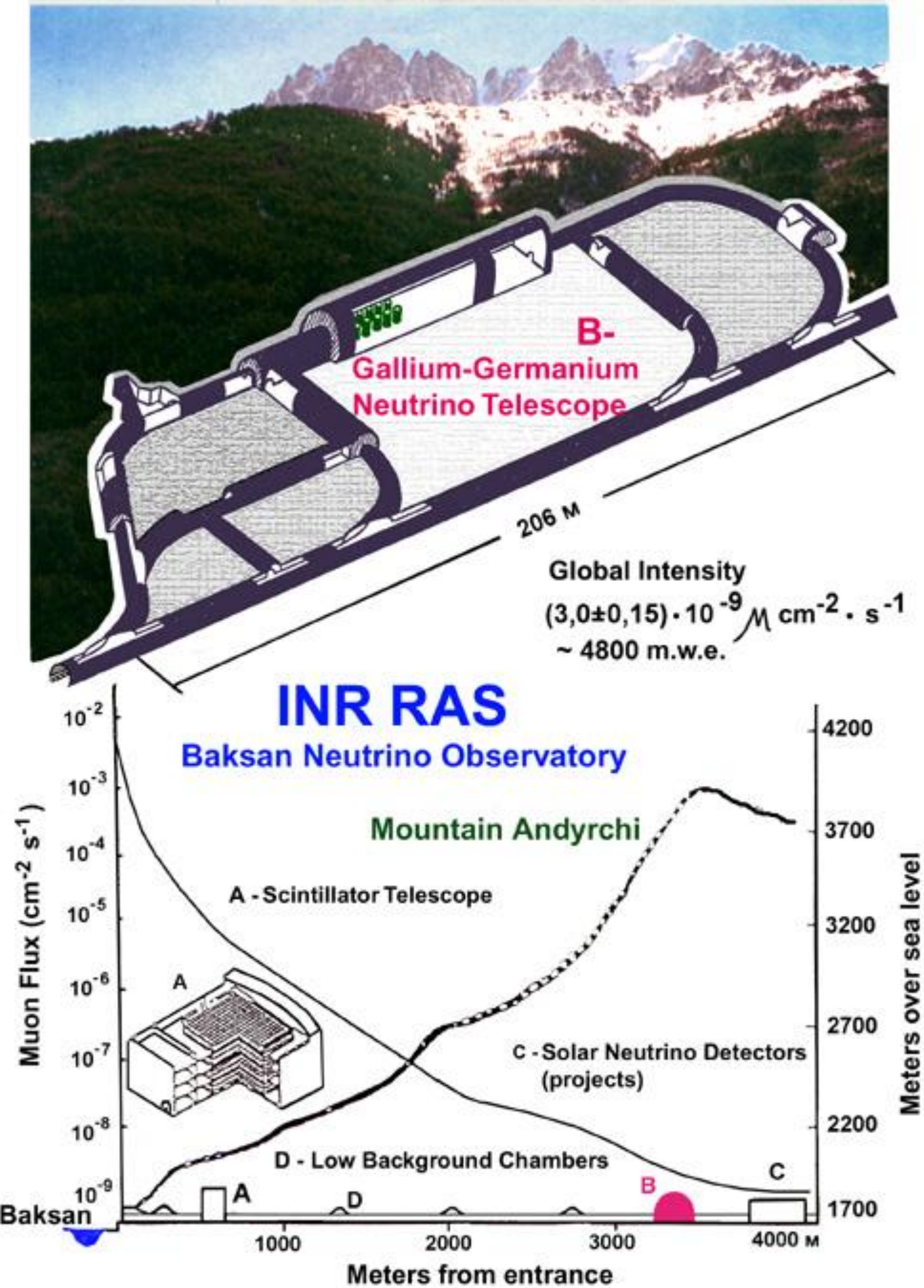
1968!

Sensitive to ^{8}B solar neutrinos only

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



SAGE Soviet-American Gallium Experiment

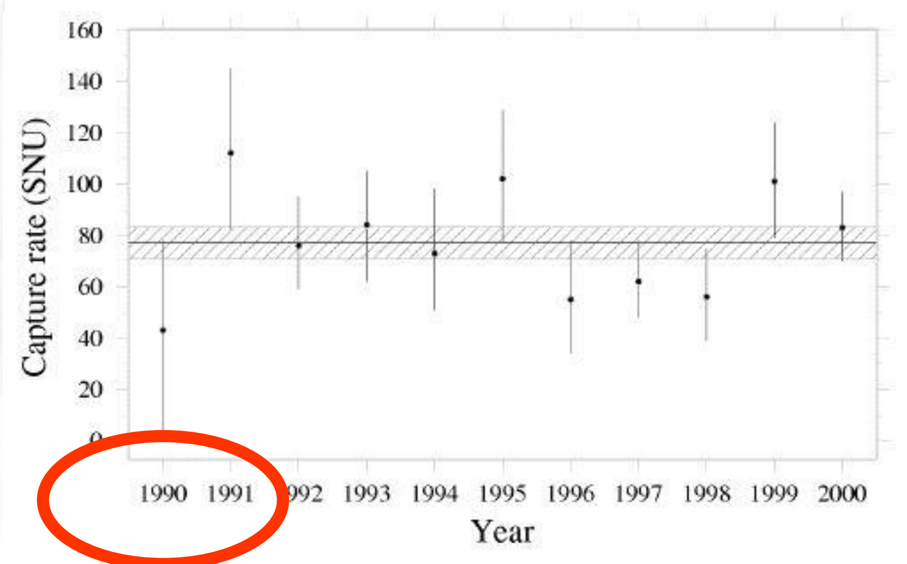


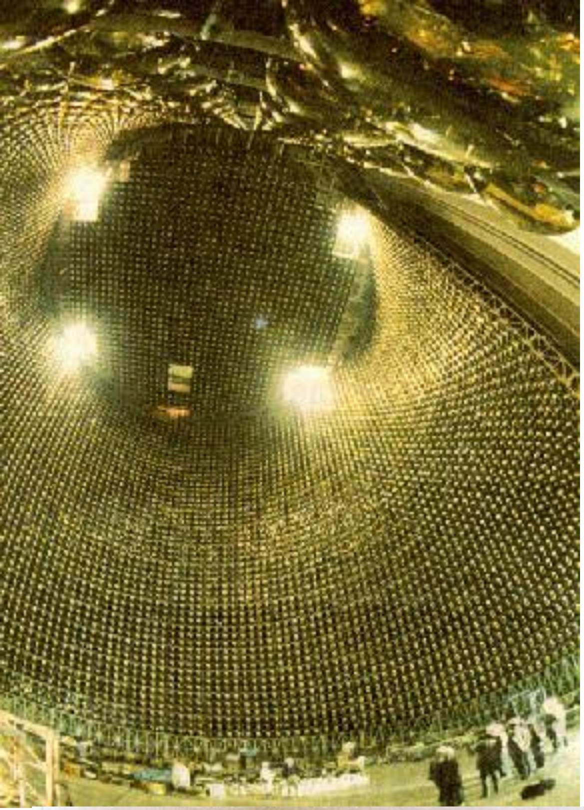
$^{71}Ga + \nu \rightarrow Ge + e^-$

Sensitive to pp fusion in sun.

50 metric tons of Gallium
They extract a *few tens of atoms* of Germanium

Measured: 77± 6 ± 3 SNU
Predicted: 123 + 9 -7 SNU

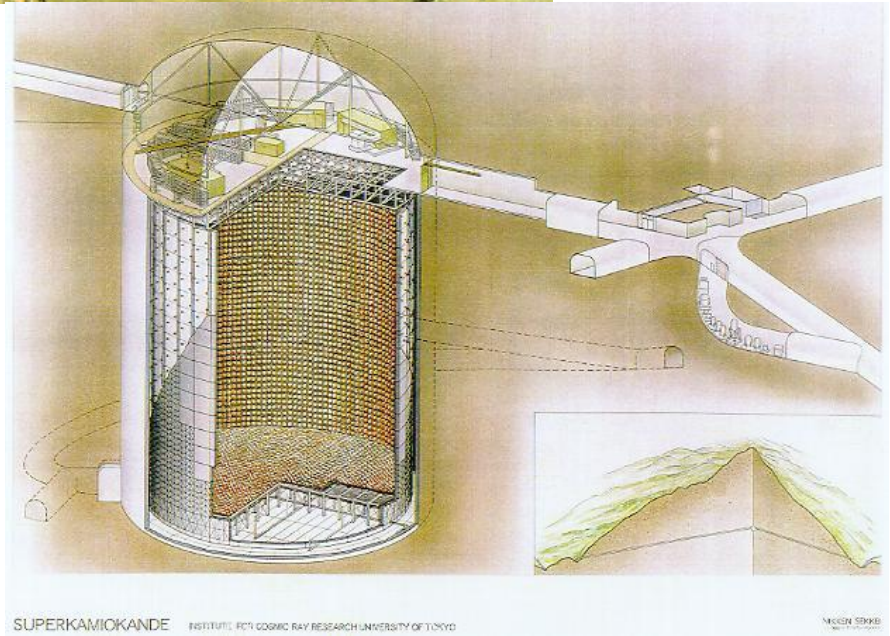


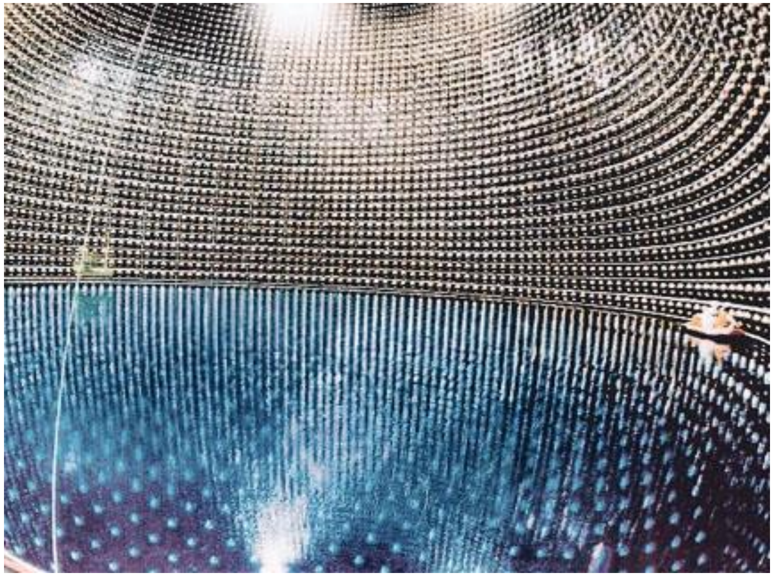


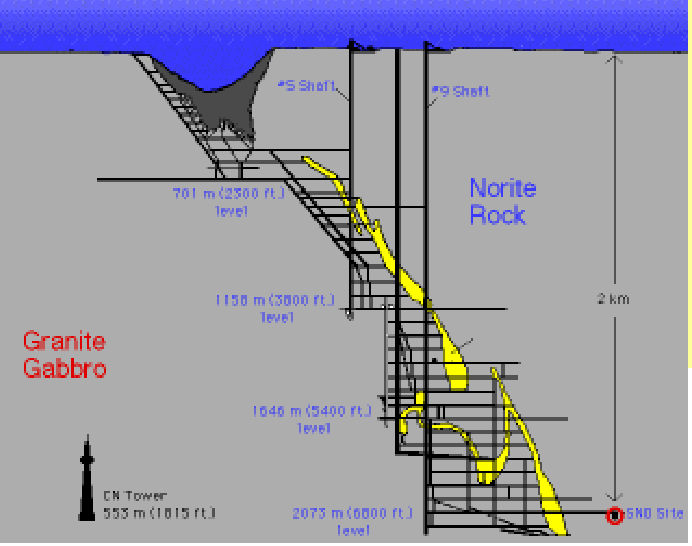
Super Kamiokande

11 stories high
1,000 meters underground
50,000 tons of water
22,500 tons fiducial volume
11,200 photomultipliers
0.5 meter photomultiplier diameter
Abandoned zinc mine

In Japan



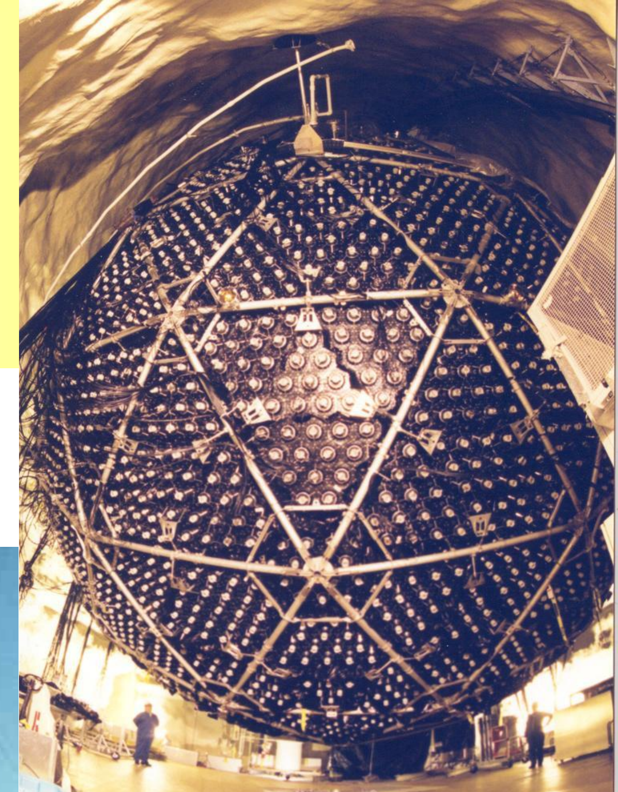


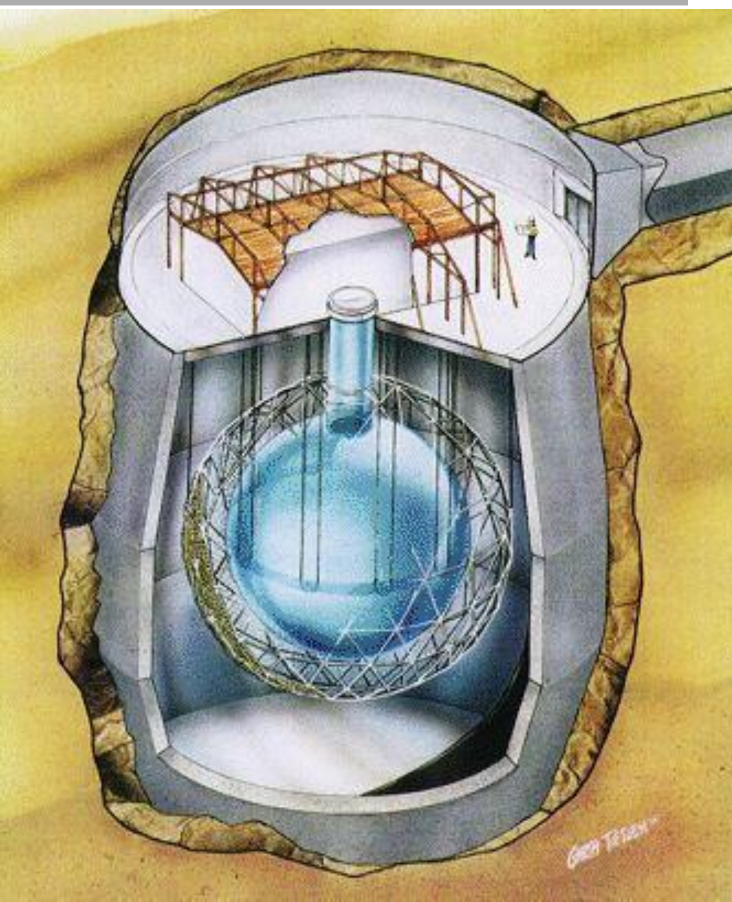


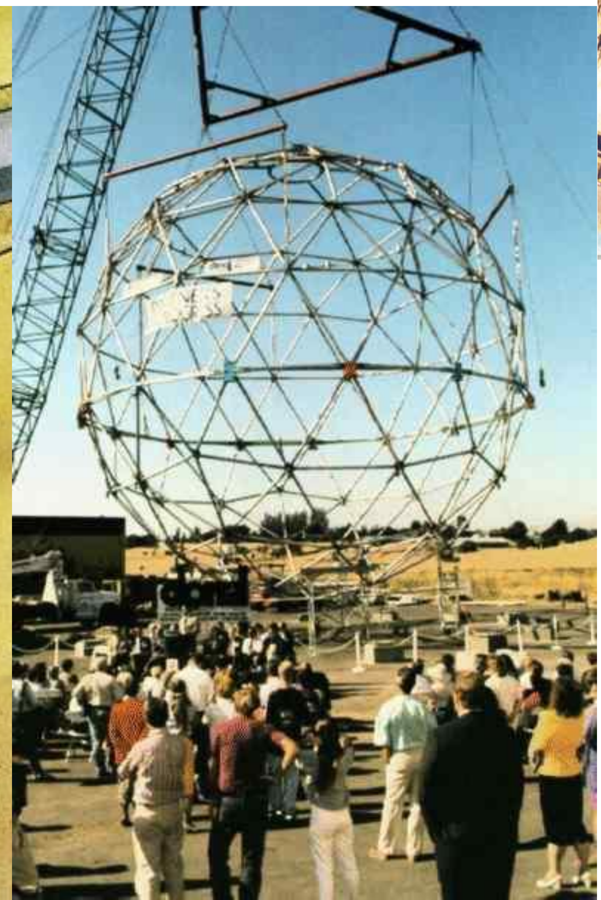
SNO

Sudbury
Neutrino
Observatory

In Sudbury, Ontario

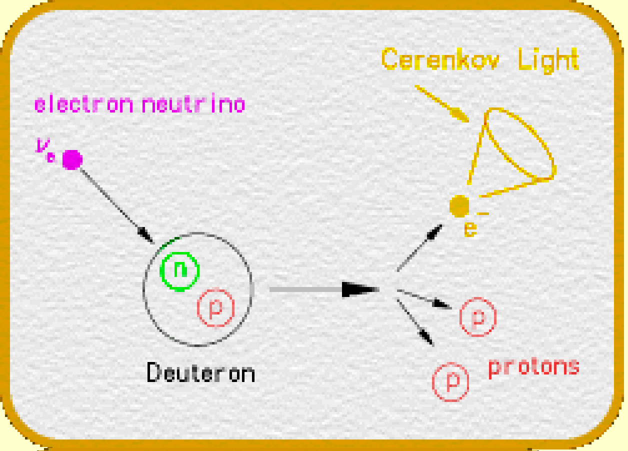




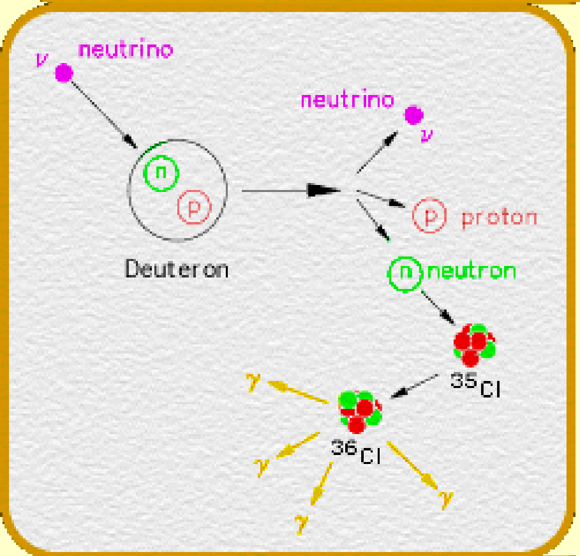


- Cerenkov detector
- Heavy water (can do solar model independent measurements)
- 6800 feet underground
- 9600 PMTs

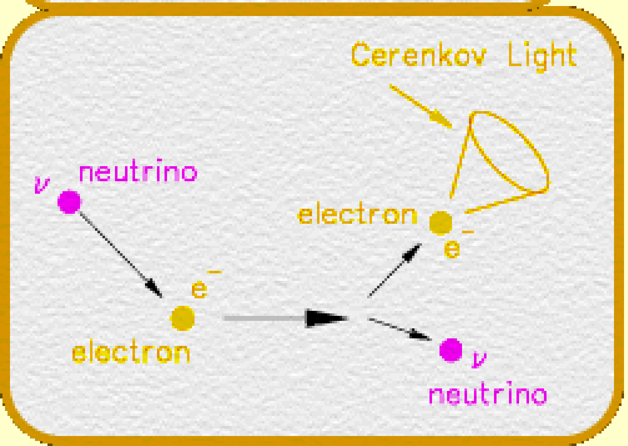
SNO Physics and Results



Charged interactions convert neutron to proton. Sensitive only to ν_e.
30 events/day



Neutral interactions disassociate deuteron into neutron and proton. Sensitive to ν_e, ν_μ, ν_τ.
30 events/day

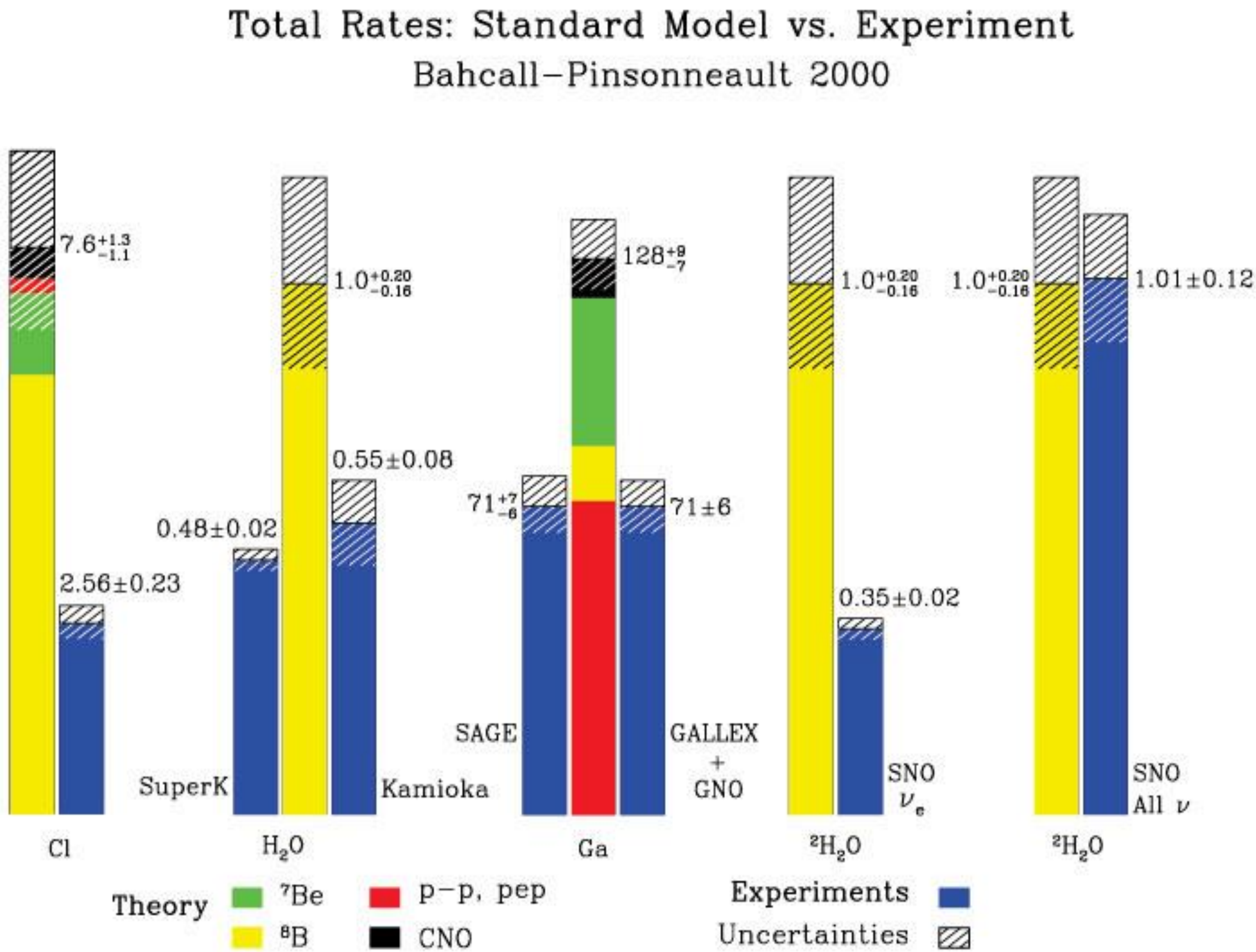


Electron scattering mostly sensitive to ν_e, with small contribution from ν_μ , ν_τ .
3 events/day

Announcement:

June 18, 2001

Comparison of SNO results with Super K indicates that the neutrino flux from the sun contains muon neutrinos, supporting neutrino oscillations.



Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
7.6$^{+1.3}_{-1.1}$
2.56±0.23
Cl
0.48±0.02
1.0$^{+0.20}_{-0.16}$
0.55±0.08
SuperK
Kamioka
H$_2$O
128$^{+9}_{-7}$
71$^{+7}_{-6}$
71±6
SAGE
GALLEX
+
GNO
Ga
1.0$^{+0.20}_{-0.16}$
0.35±0.02
SNO
ν_e
^{2}H$_2$O
1.0$^{+0.20}_{-0.16}$
1.01±0.12
SNO
All ν
^{2}H$_2$O
Theory
^{7}Be
^{8}B
p–p, pep
CNO
Experiments
Uncertainties

Daya Bay Reactor Antineutrinos

Observed disappearance of reactor antineutrinos (2012), measures the reactor angle of oscillations

Neutrino Flavor Oscillations

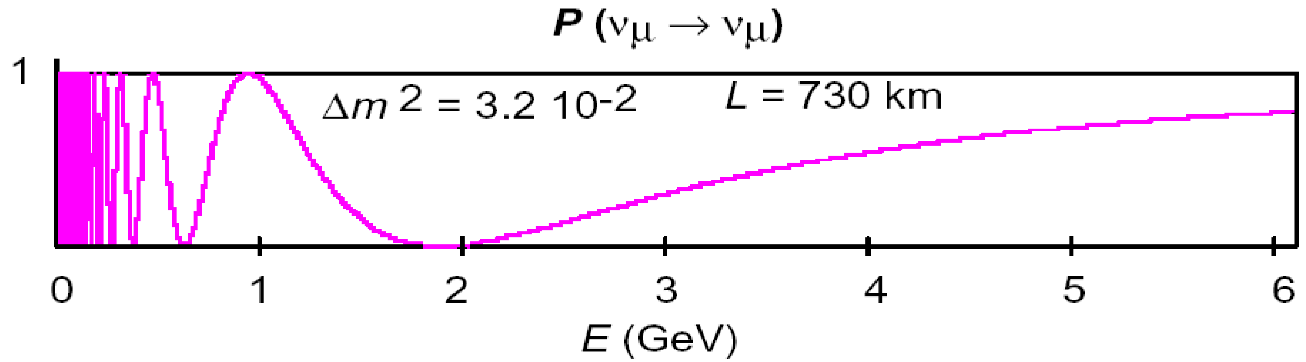
$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$|\nu_e(t)\rangle = |\nu_1(0)\rangle e^{-iE_1 t}\cos\theta + |\nu_2(0)\rangle e^{-iE_2 t}\sin\theta$$
$$|\nu_\mu(t)\rangle = -|\nu_1(0)\rangle e^{-iE_1 t}\sin\theta + |\nu_2(0)\rangle e^{-iE_2 t}\cos\theta$$

$$E_1 \simeq |\mathbf{p}| + \frac{m_1^2}{2|\mathbf{p}|}$$
$$E_2 \simeq |\mathbf{p}| + \frac{m_2^2}{2|\mathbf{p}|}$$

$$P(\nu_e \to \nu_\mu; L) = |\langle\nu_e(0)|\nu_\mu(t)\rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4|\mathbf{p}|}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

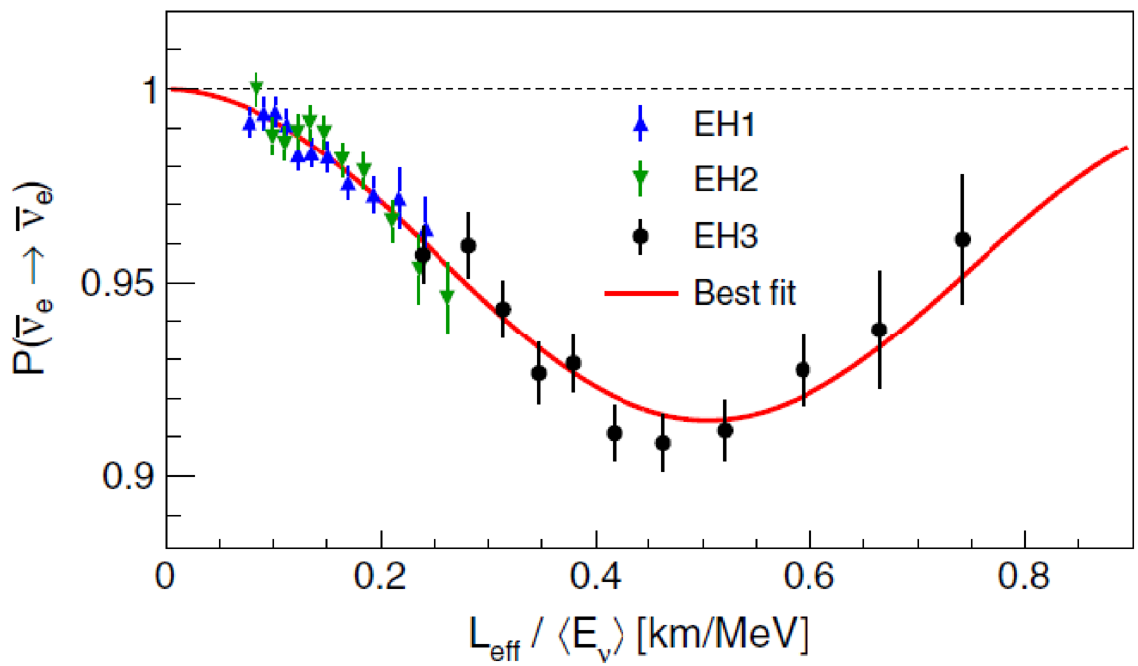


Oscillating Neutrinos Need Mass

- Neutrinos oscillate among flavors:

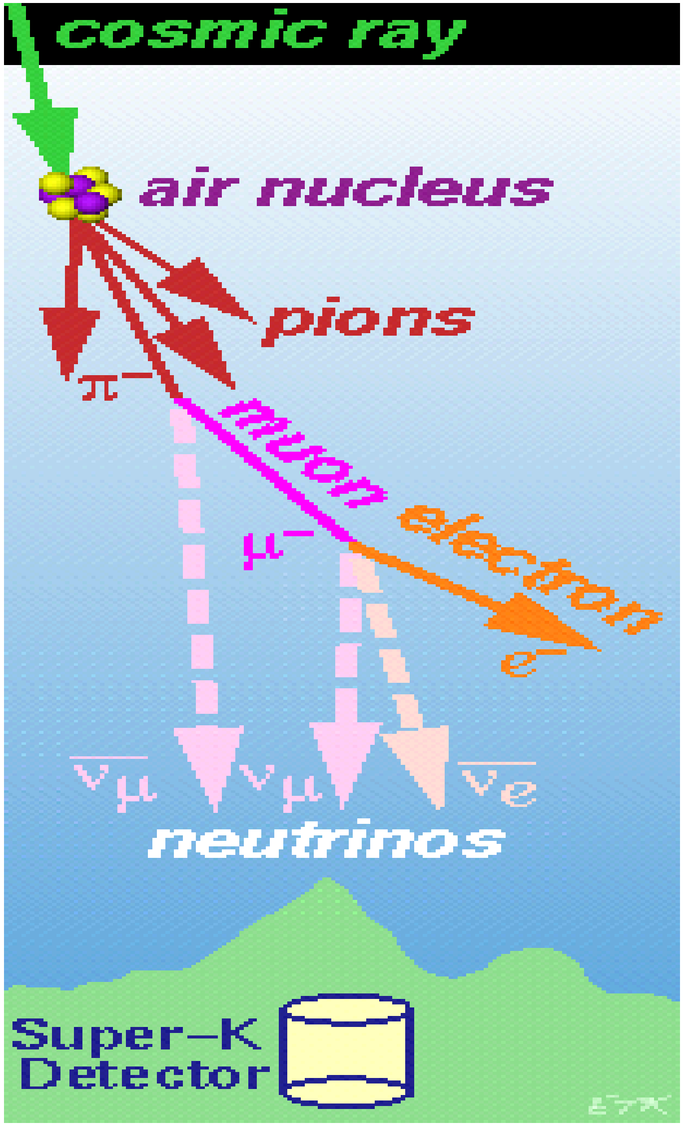
$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}, \quad \Delta m^2 \equiv m_{\nu_2}^2 - m_{\nu_1}^2$$

- Oscillatory behavior observed by Daya Bay $\overline{\nu}_e$, KamLand $\overline{\nu}_e$ and SuperKamiokande atmospheric ν_μ data



Daya Bay (2015)

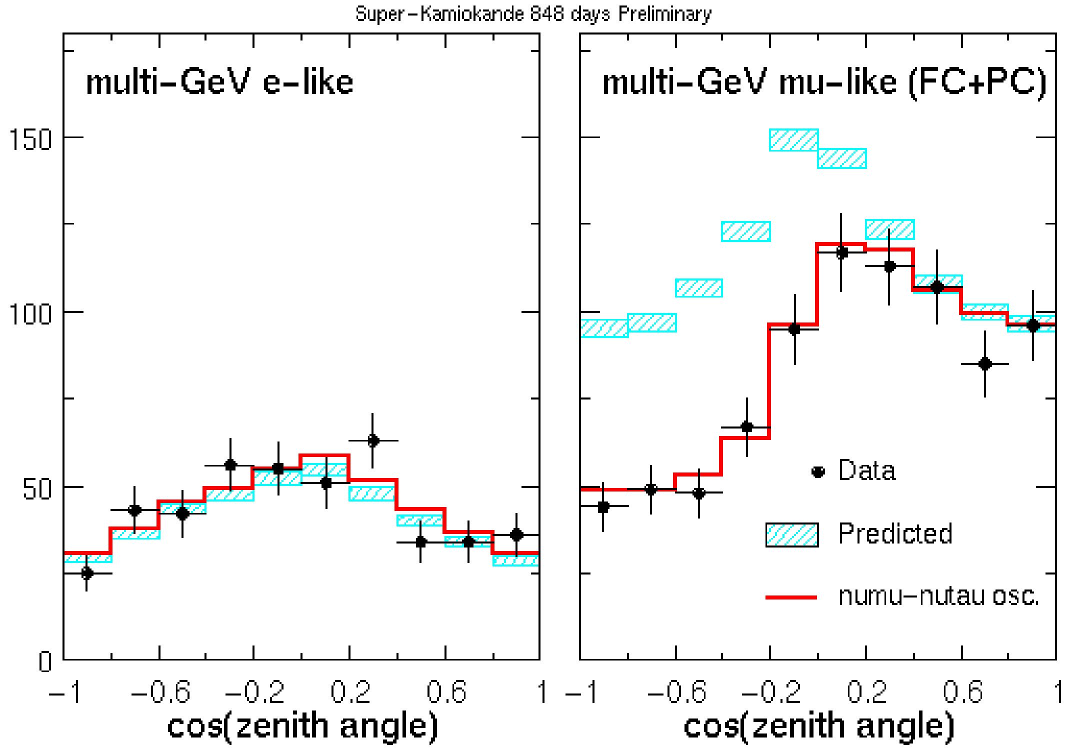
Atmospheric Neutrinos

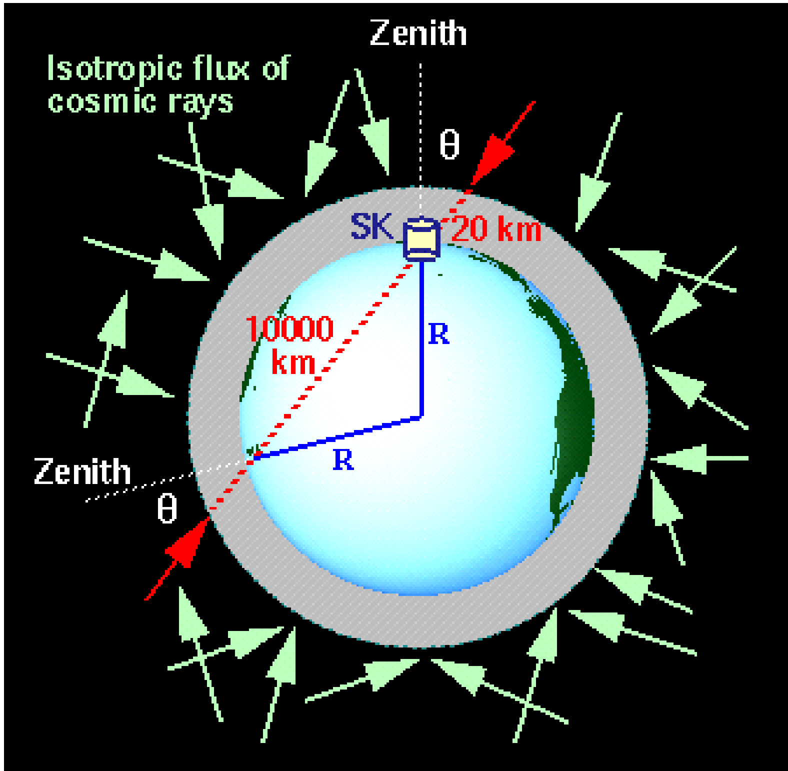


Super Kamiokande Discovery

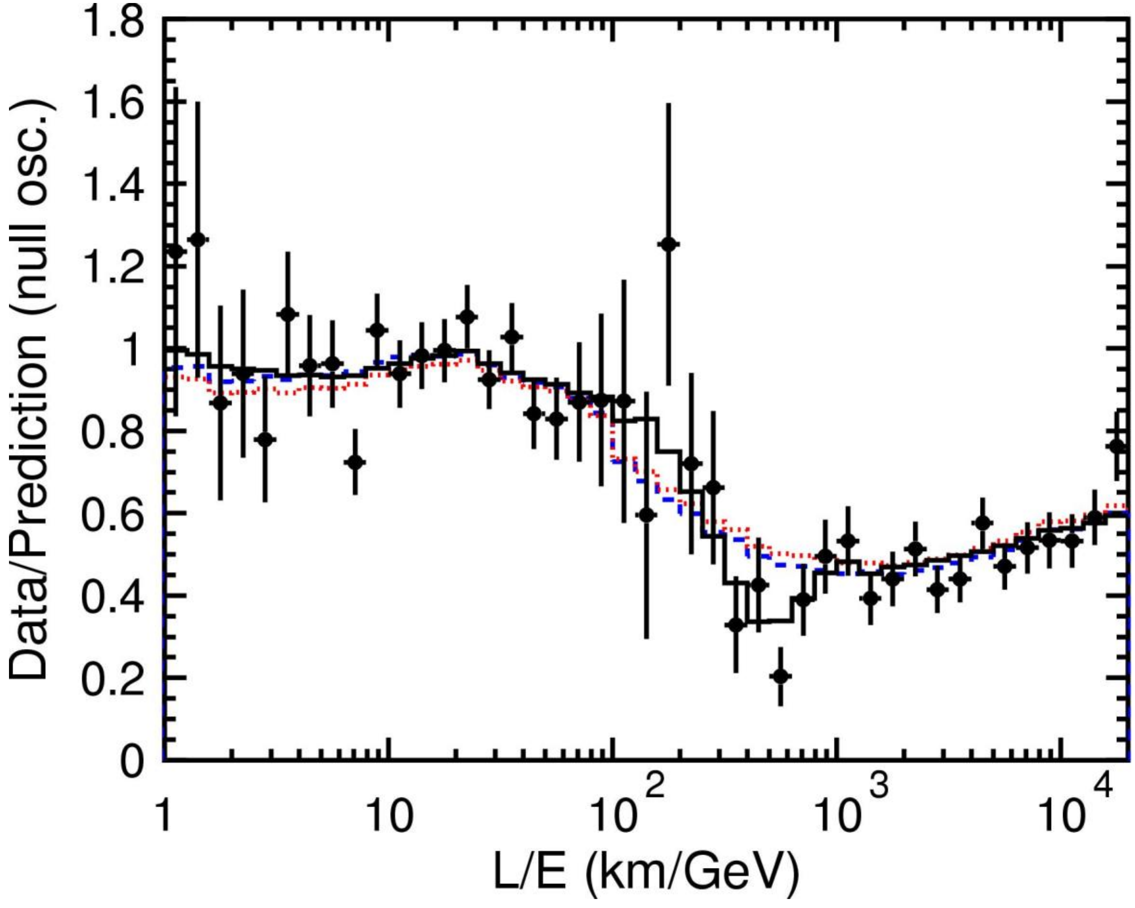
Announcement June 5, 1998

Gist: “There are fewer upcoming muon neutrinos than expected from down-going neutrino flux. Data consistent with neutrino oscillations.”





L/E Dependence of Atmospheric Neutrinos

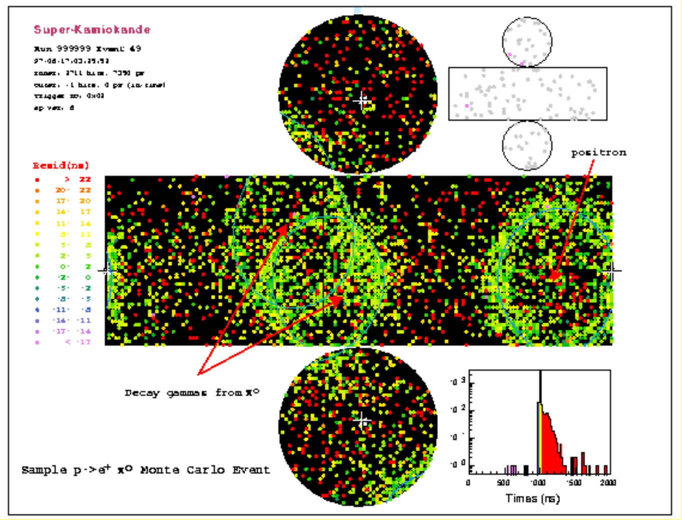


Accidental Evidence

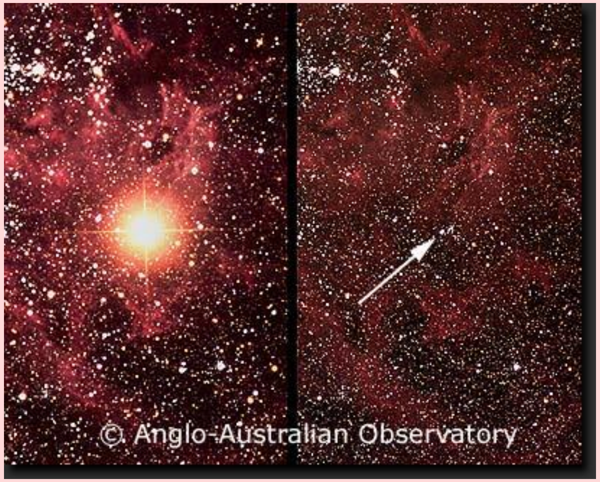
In the early 1980s, two experiments (IMB Irvine-Michigan-Brookhaven) and (Kamiokande) were built to look for proton decay.

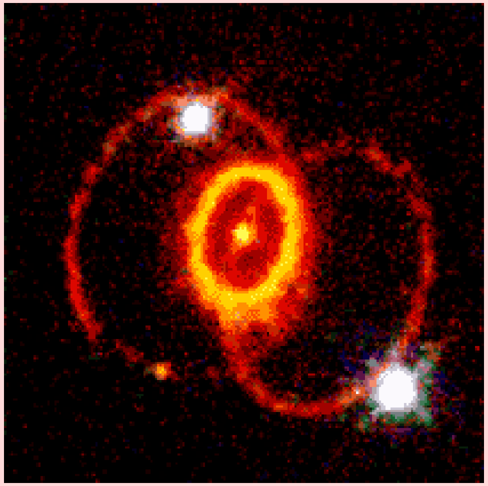
None detected. Proton lifetime > 10^{33} years.

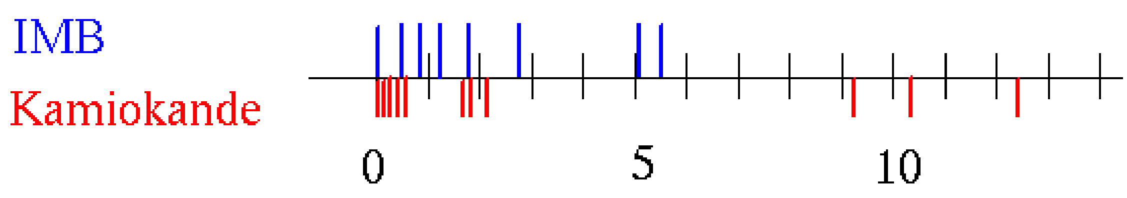
$$p^+ \rightarrow e^+ + \pi^o$$



Simulated Event







SN 1987A

time in seconds

7:36 neutrinos observed

9:30 amateur astronomer observes Tarantula Nebula in LMC. Nothing unusual.

10:30 LMC photographed, SN1987A observed.

~3 hours for shock wave to hit surface.

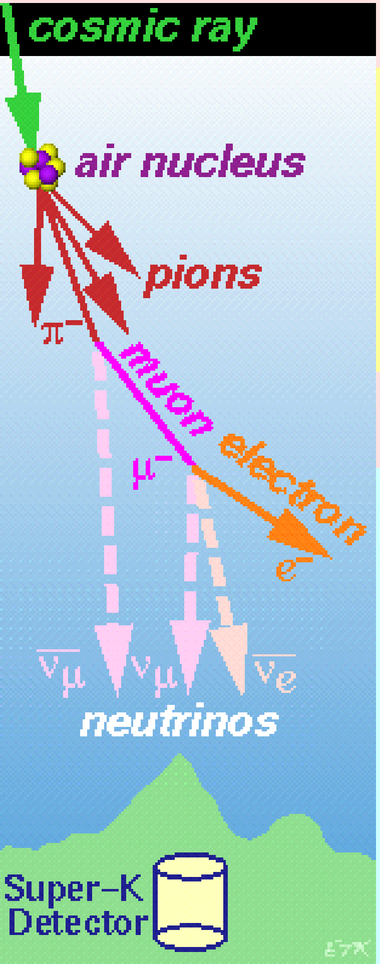
Background Becomes Signal

If proton decay goes as

$$p^{+} \rightarrow e^{+} + \pi^{o}$$

Signal is ring in detector. Anything that can make a ring is background.

Knowledge of detector response problematic. Compensate by double ratio:



$$R = \frac{N_{data}(\nu_e \text{ events}) / N_{data}(\nu_\mu \text{ events})}{N_{simulation}(\nu_e \text{ events}) / N_{simulation}(\nu_\mu \text{ events})}$$

Expected average ratio R = 1.

In cosmic ray showers, expect 2 ν_μ for each ν_e

Experiment	Value
Kamiokande (multi-Gev)	$0.57^{+0.08}_{-0.07} \pm 0.07$
Kamiokande (sub-Gev)	$0.60^{+0.06}_{-0.05} \pm 0.05$
IMB	0.54±0.05±0.12
Soudan 2	0.69±0.19±0.09

Cosmological Implications of Neutrinos

$\rho_\nu \sim 330\ /cm^3$ (from Big Bang)
<E> ~ 0.0004 eV (from Big Bang)

$R_{universe} \sim 10^{10}$ lightyears
$V_{universe} \sim 4\times10^{84}\ cm^3$

$N_\nu \sim 10^{87}$

$E_\nu(total) \sim 4\times10^{83}$ eV

$M_\nu(equivalent) \sim 7\times10^{47}$ kg

$M_{universe}(visible) \sim 4\times10^{52}$ kg

If neutrinos were massive objects, they could contribute significantly to the mass of the universe.

Neutrino	Mass
Electron	< 2.2 eV
Muon	< 170 keV
Tau	< 15.5 MeV

Are Neutrinos Massless?

$0.1\% < \Sigma M_\nu < 18\%$

Forthcoming Neutrino Experiments

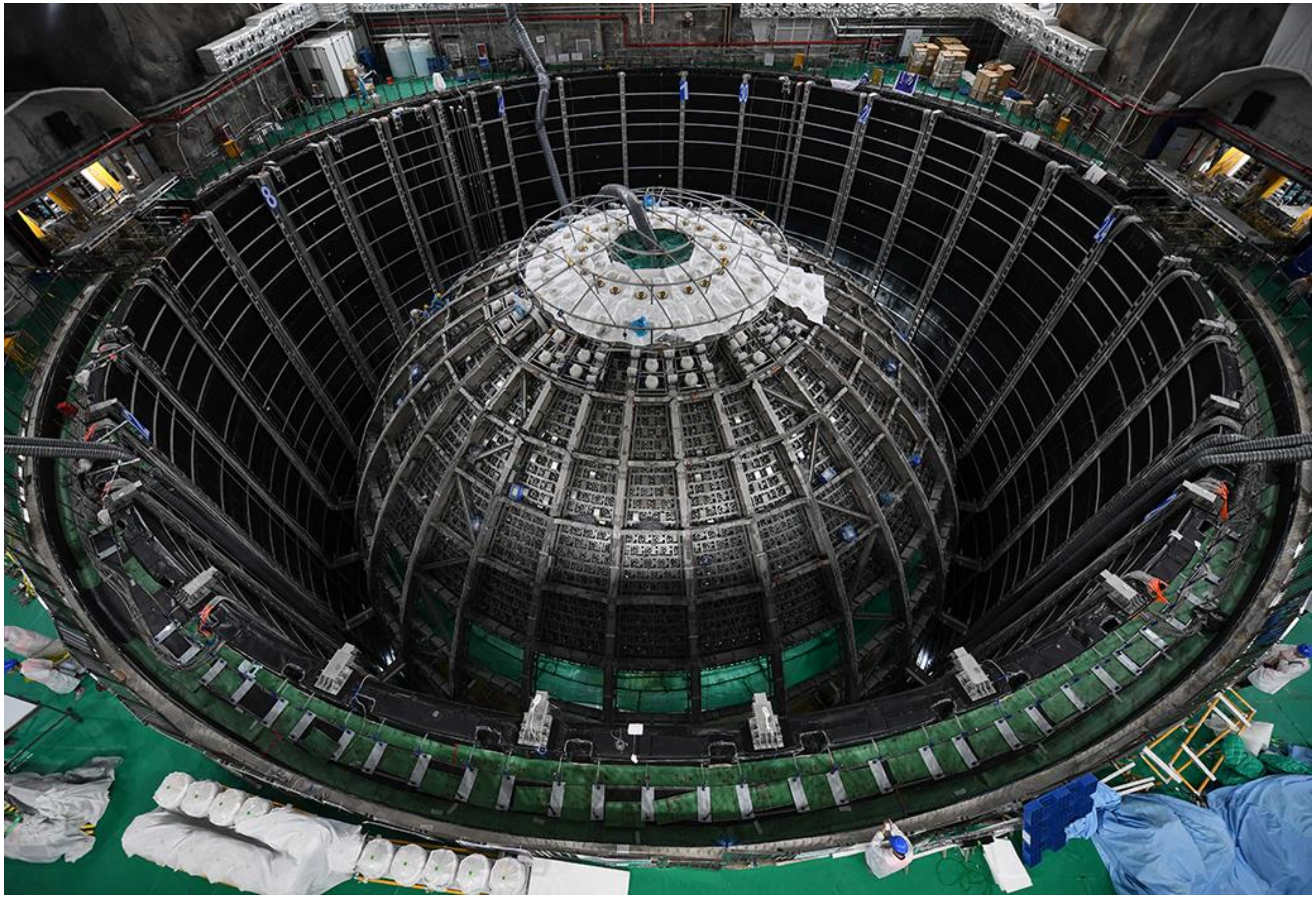
3 Large scale neutrino experiments are in the making

JUNO in China

DUNE in the US

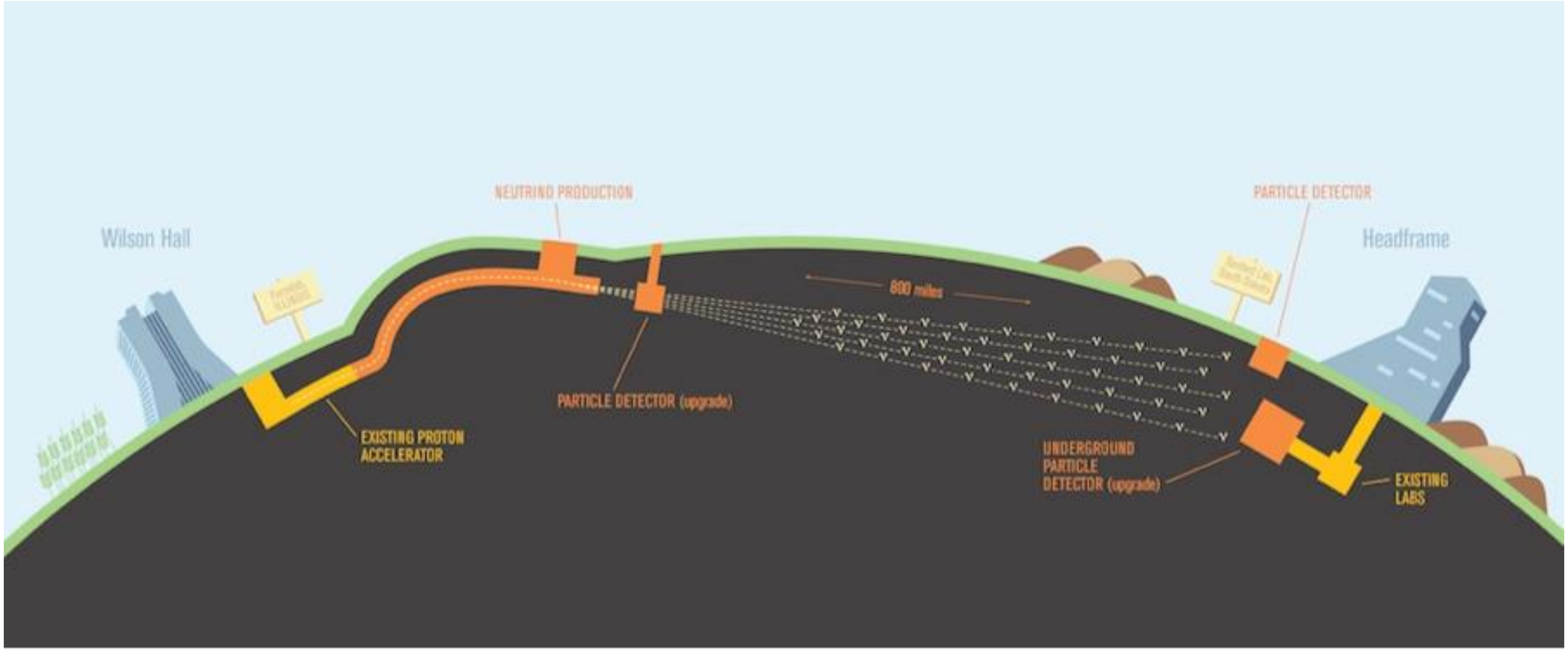
HyperKamiokande in Japan

JUNO: Multipurpose Detector (China)



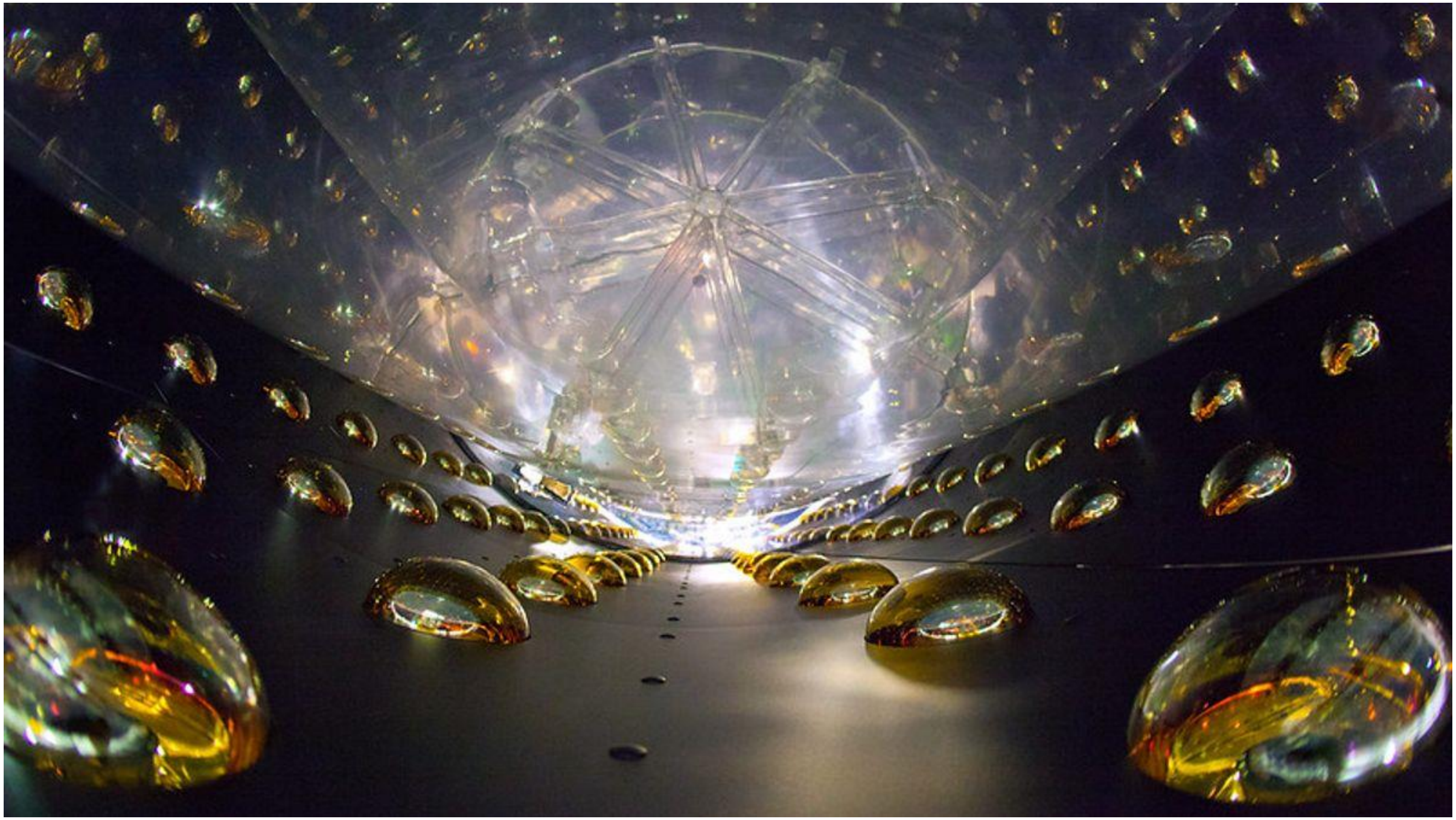
20,000 tons of liquid scintillator; reactor neutrinos, solar, atmospheric, supernova neutrino studies

DUNE: Fermilab-SURF (US)



70 kiloton of Liquid Argone at far detector in South Dakota; neutrino beam originates from Fermilab, travels 1300 km under ground!

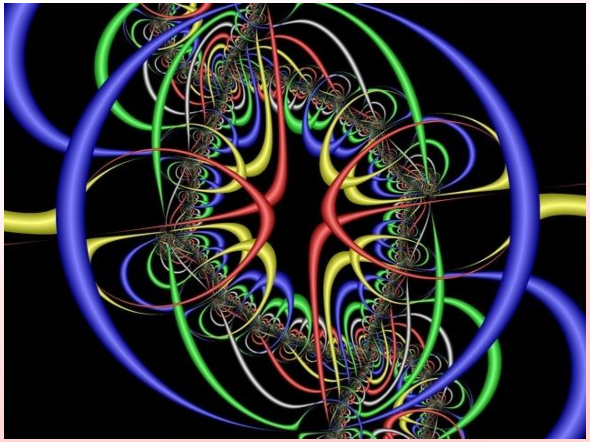
HyperKamiokande (Japan)



Successor of SuperKamiokande; 20 times larger, uses ultr-pure water as detector with PMTs

Neutrino Summary

- They interact with ordinary matter very weakly.



- Their behavior is highly complex and will need new physics to explain it.

- Many experiments not mentioned here are ongoing to unravel this rich behavior.