Recent Developments in Neutrino Science:

A Whole Lot About Almost Nothing

Eric B. Norman
Nuclear Engineering Dept.
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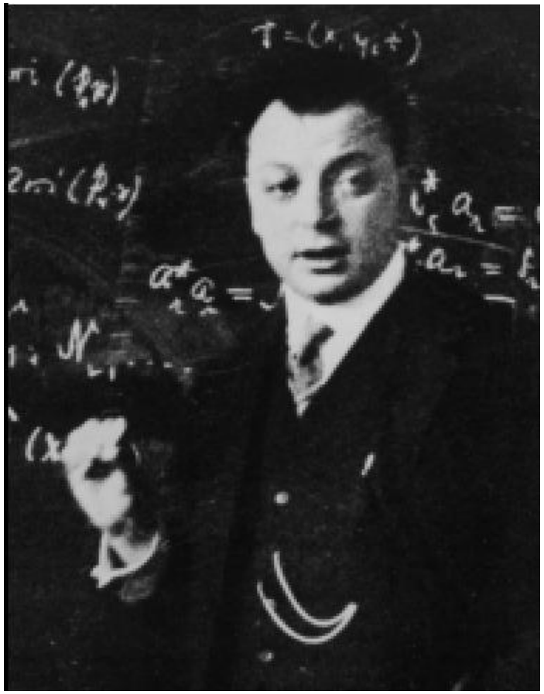
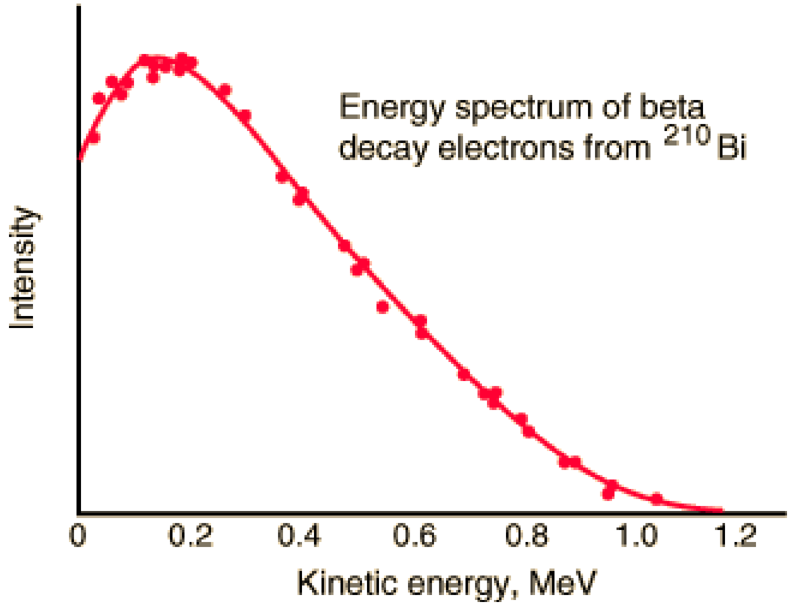
Berkeley, CA

Neutrinos are needed !



Pauli

1930



$$^{210}Bi \rightarrow {}^{210}Po + e^- + \bar{\nu}_e$$

Neutrino required to conserve energy, momentum, angular momentum

Neutrino must have no electric charge, little or no mass, and interact weakly with matter

Fred Reines

Clyde Cowan

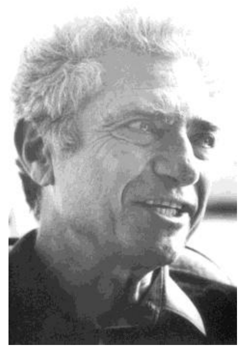
It took 25 years for the neutrino to be observed in the laboratory!

In 1955, at the Savannah River nuclear reactor, Reines and Cowan used the reaction $\overline{\nu}_e + p \rightarrow n + e^+$ to detect anti-neutrinos using a liquid scintillator detector

Nobel Prize in Physics
1995

Leon Lederman

Melvin Schwartz



Jack Steinberger

There are different kinds of neutrinos !

In 1962, using a high-energy accelerator at Brookhaven National Lab., Lederman, Schwartz, and Steinberger showed evidence for two kinds of neutrinos – one associated with the electron, and one associated with the muon (a heavy cousin of the electron)

Nobel Prize in Physics
1988

Neutrinos are produced by the "weak" interaction and are born with a "flavor"

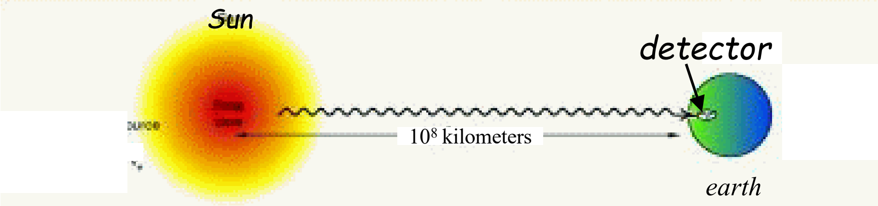
$n \rightarrow p + e^- + \overline{\nu}_e$

$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$

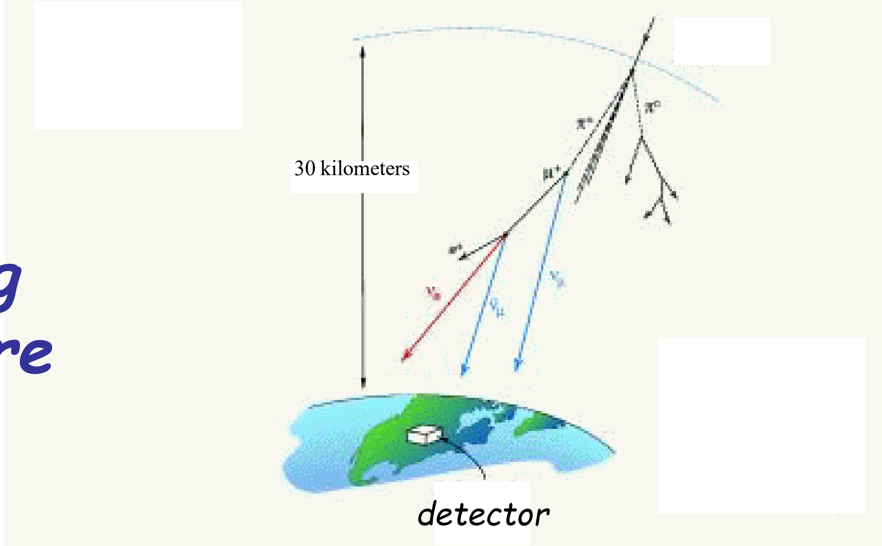
$B^- \rightarrow \tau^- + \overline{\nu}_\tau$

Sources of neutrinos

The Sun

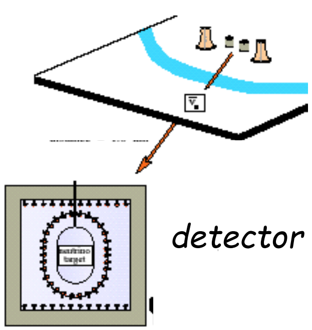


Cosmic Rays Interacting in the Earth's Atmosphere



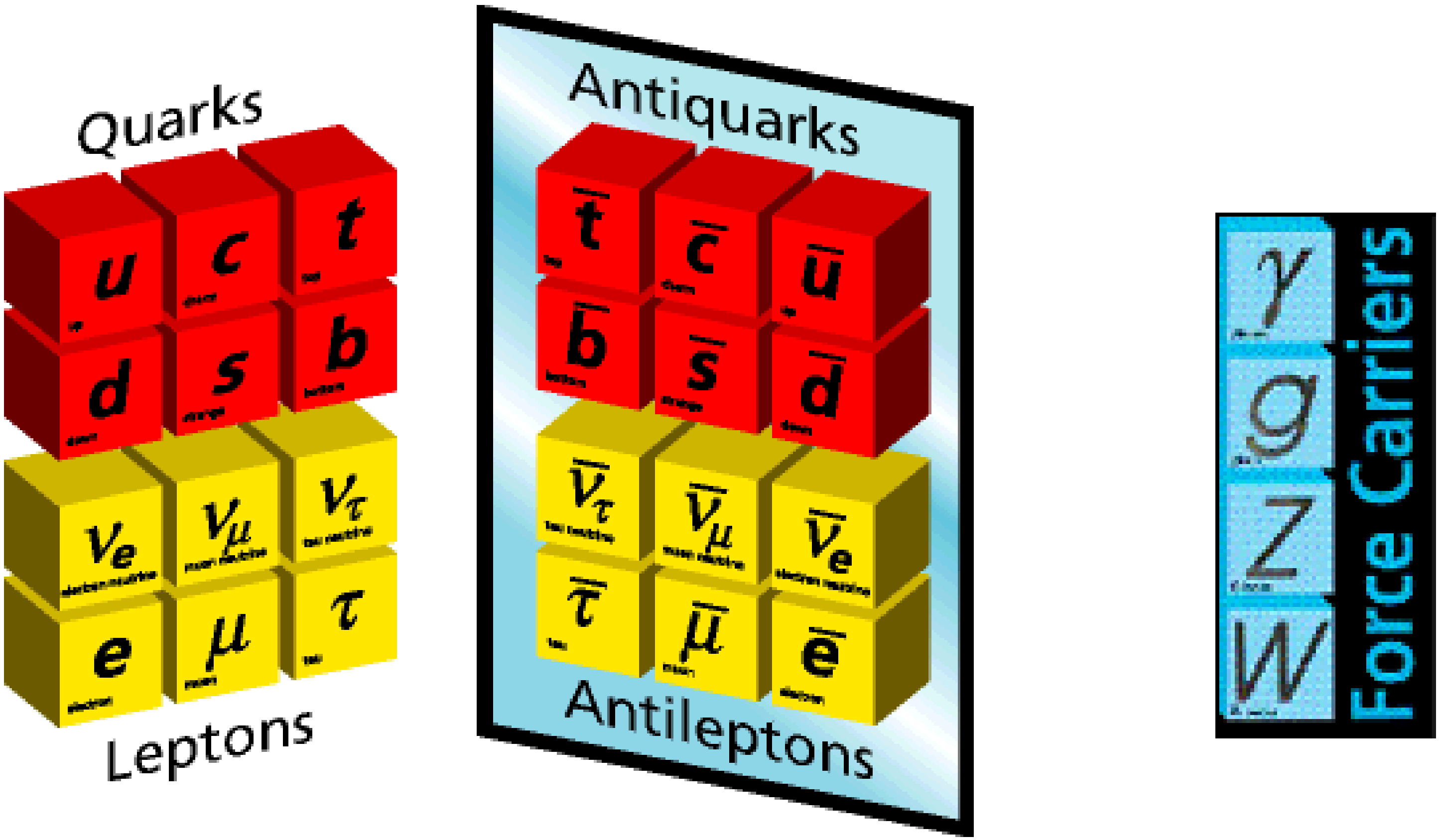
Accelerators

Nuclear Reactors

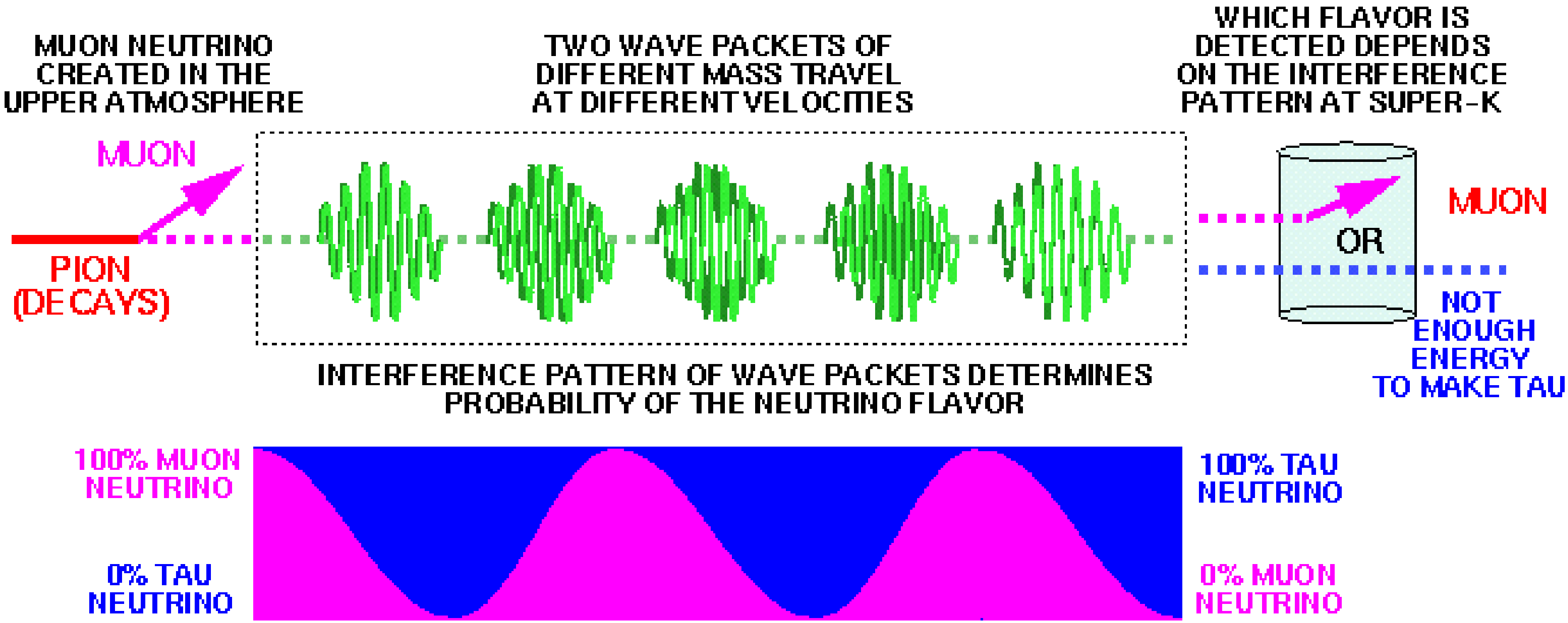


Neutrino interaction in a bubble chamber at a high energy accelerator

The "Standard Model"



Neutrinos do not have a well-defined mass, but are actually mixtures of 3 different mass states!



Neutrino Oscillations

Бруно Понтекорво

[j]M. Nakagawa, H. Okonogi, S. Sakata, and A. Toyoda, Prog. Theor. Phys. 30, 727 (1963); B. Pontecorvo, Zh. Eksp. Teor. Fiz. 53, 1717 (1967) [Sov. Phys. JETP 26, 984 (1968)]; V. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969).

$$E_i = \sqrt{p^2c^2 + m_i^2c^4} \approx pc + \frac{m_i^2c^4}{2pc}$$

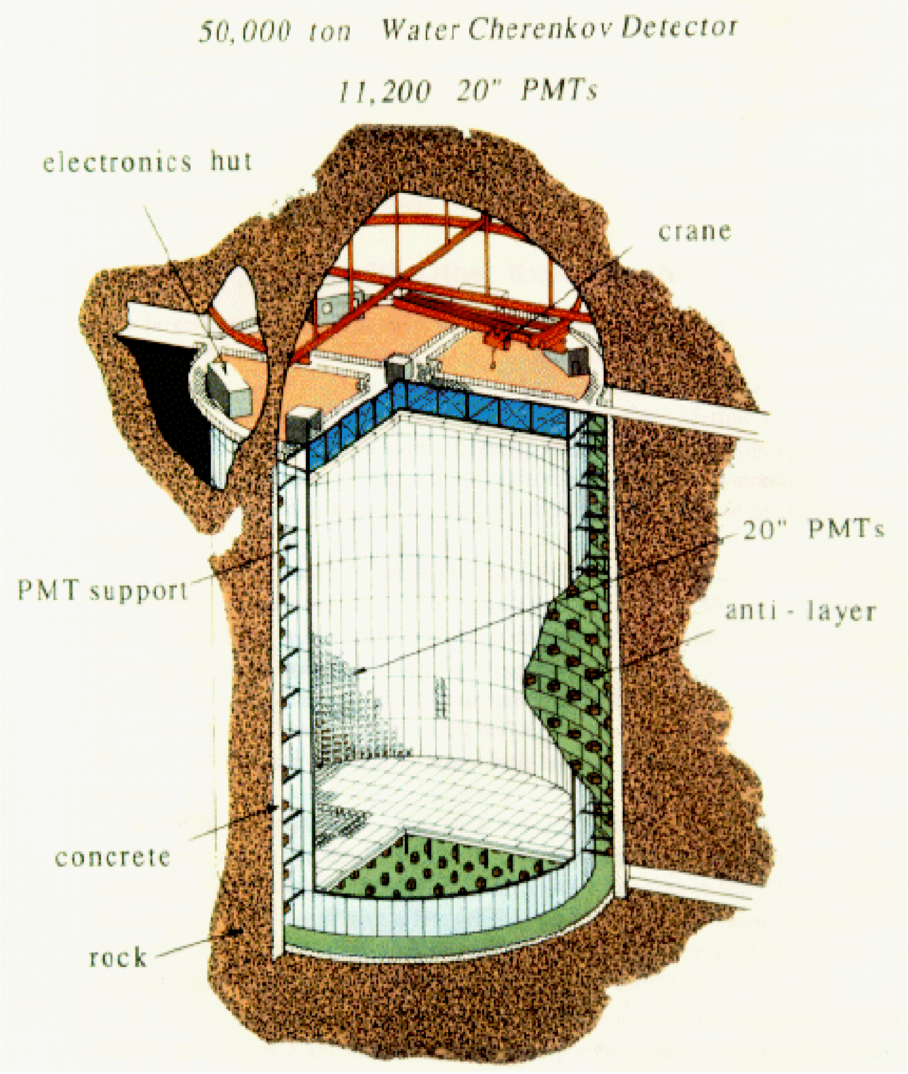
$$E \approx pc$$

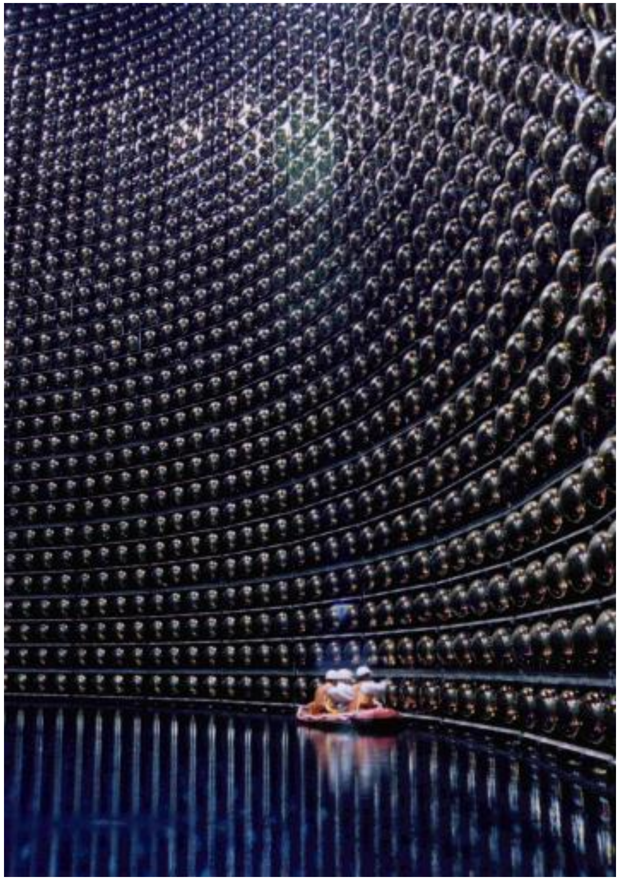
$$|\bar{\nu}_e, t\rangle = \cos\theta e^{-i\frac{m_1^2c^4}{2E}t}|\bar{\nu}_1\rangle + \sin\theta e^{-i\frac{m_2^2c^4}{2E}t}|\bar{\nu}_2\rangle$$

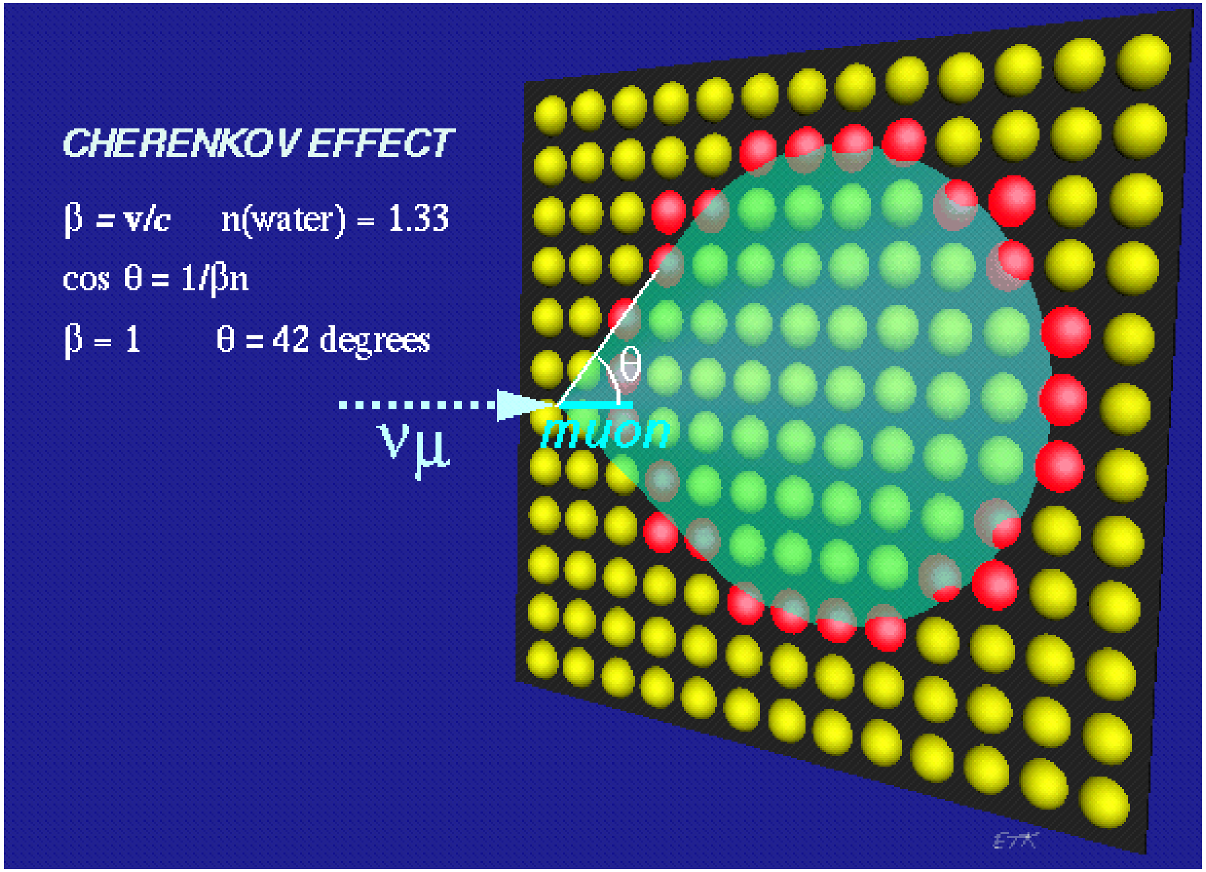
$$L \approx ct$$

$$P = |\langle \bar{\nu}_e, t | \bar{\nu}_e, 0\rangle|^2 = 1 - \sin^2 2\theta \sin^2[1.27\frac{\Delta m^2(eV^2)L(m)}{E(MeV)}]$$

SuperKamiokande







CHERENKOV EFFECT
β = v/c n(water) = 1.33
cos θ = 1/βn
β = 1 θ = 42 degrees
θ
muon
νμ

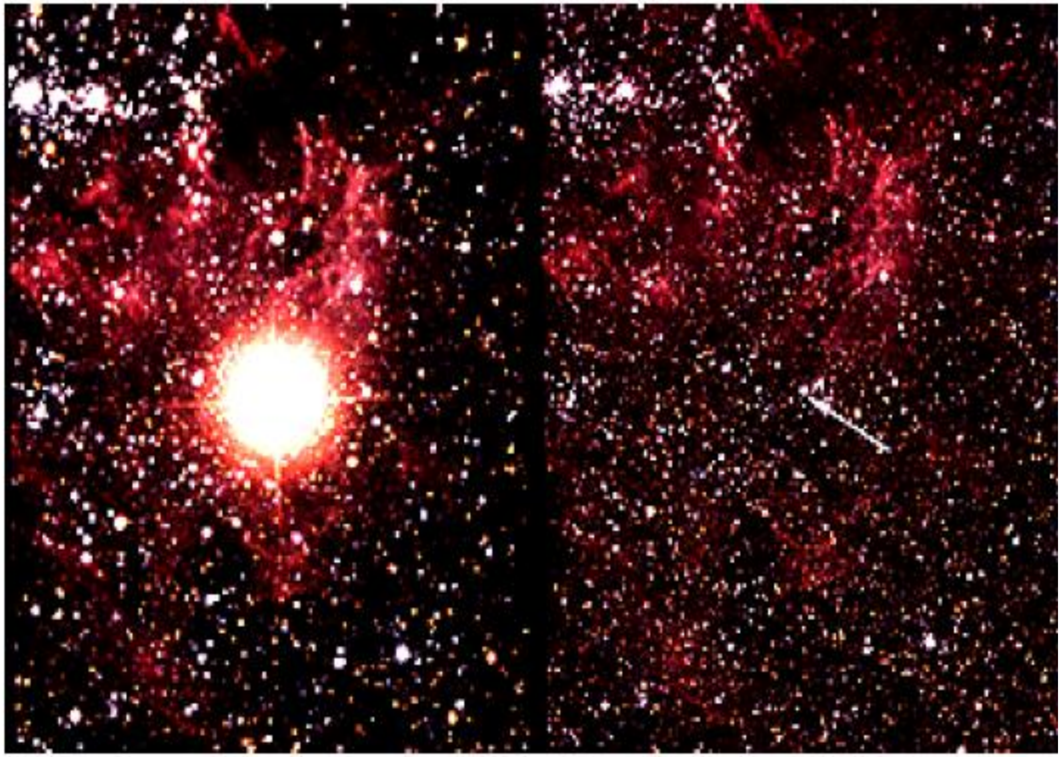
Core collapse of a massive star

Supernova Explosion

Temperature goes up
Density goes up

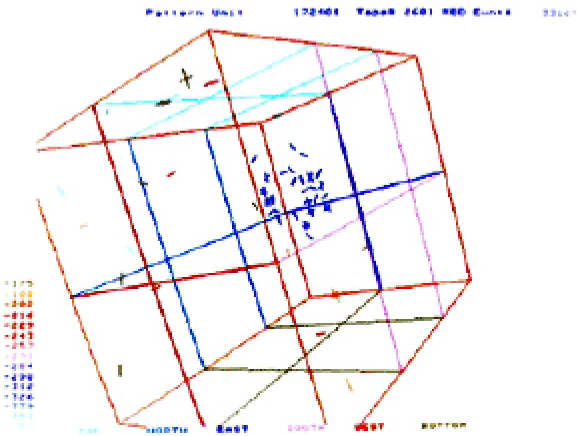
$$p + e^- \rightarrow n + \nu_e$$
$$e^+ + e^- \rightarrow \nu + \overline{\nu}$$

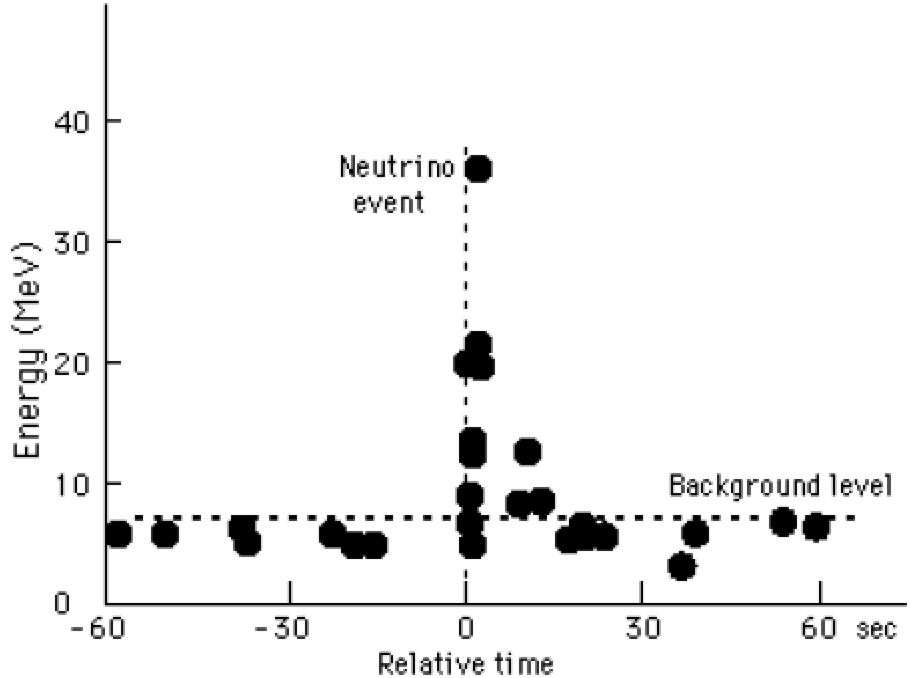
99% of SN energy comes off in neutrinos



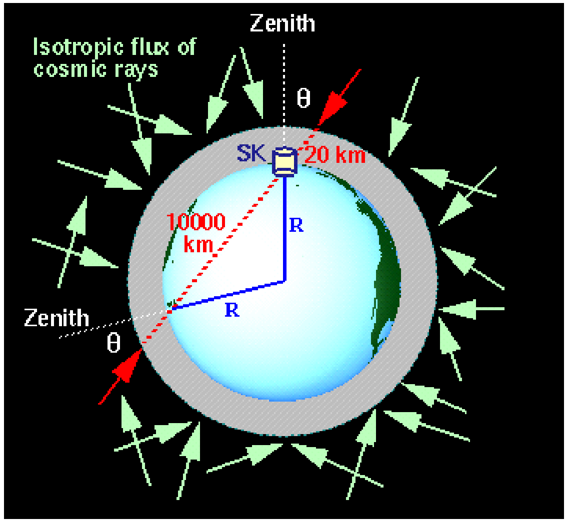
SN 1987a

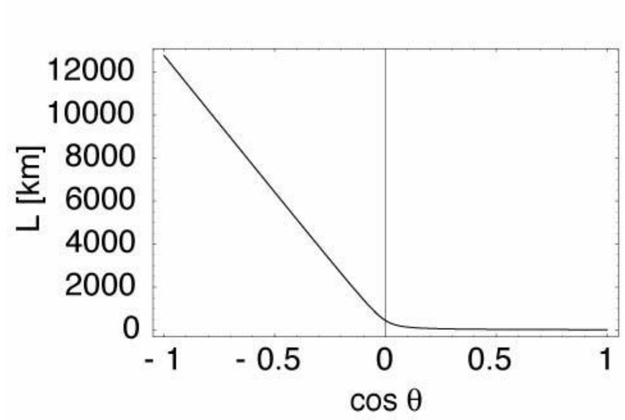
Neutrinos from SN1987a observed by Kamiokande and IMB underground telescopes

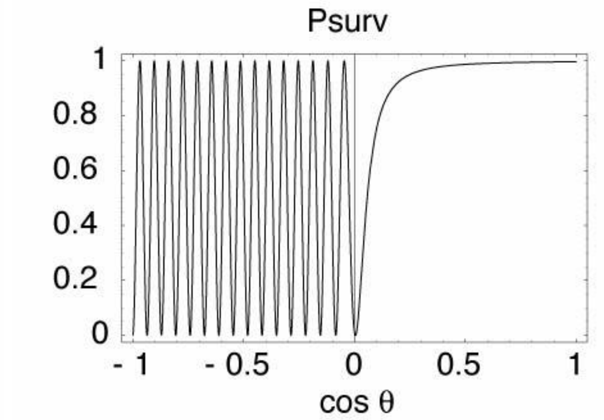


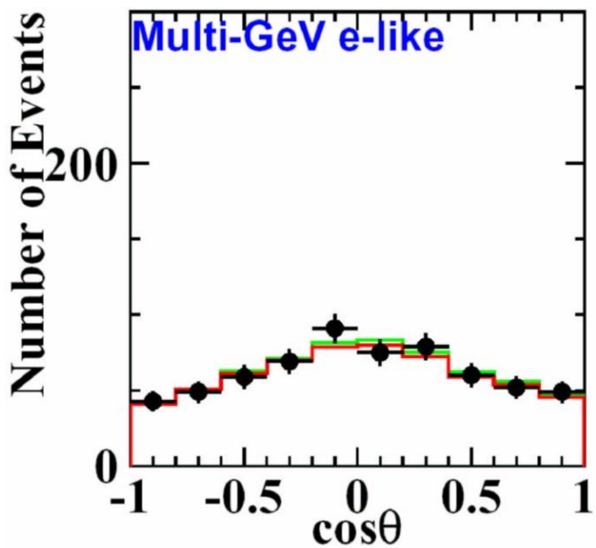


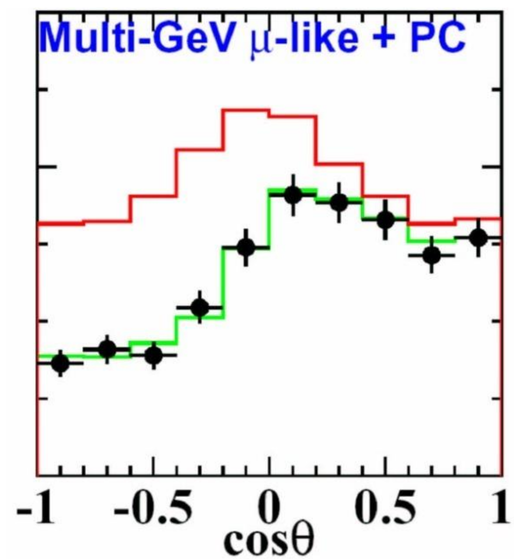
Atmospheric neutrinos









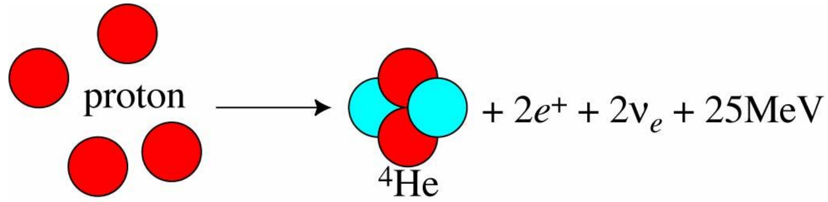


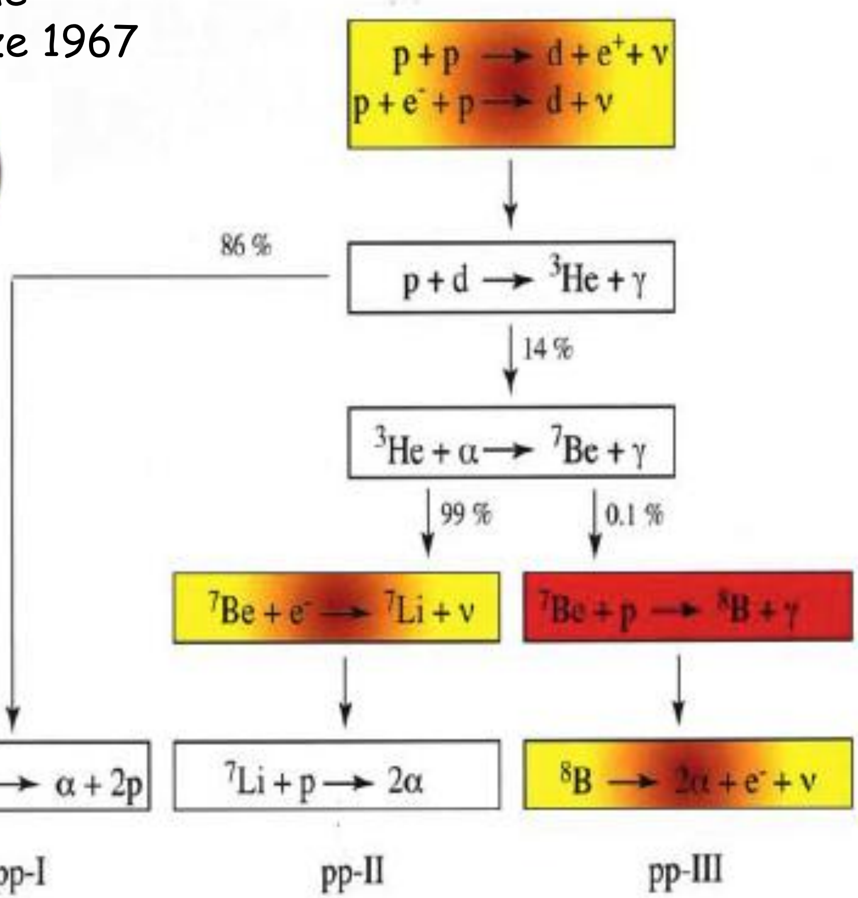
Evidence for neutrino oscillations from SuperK

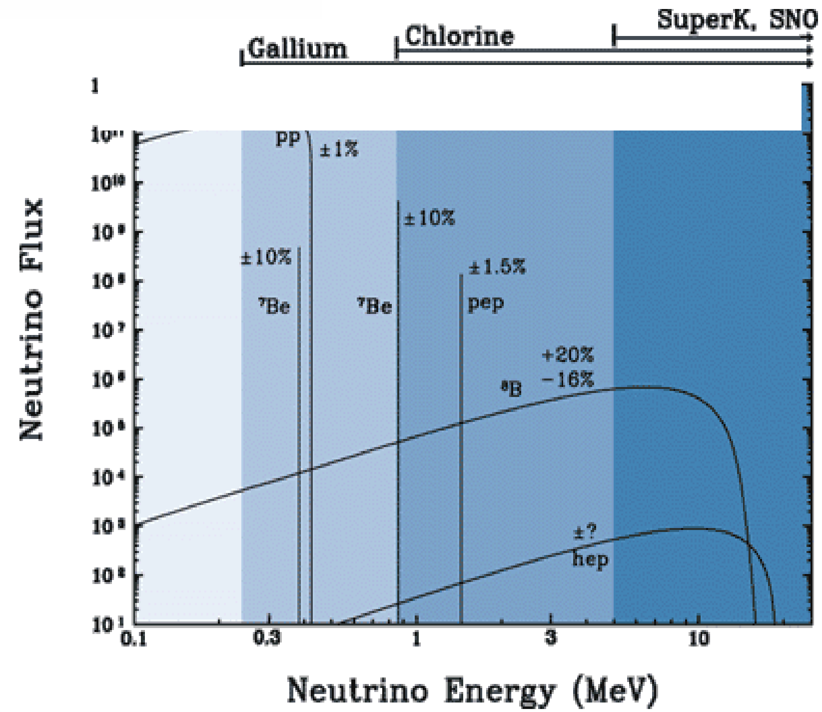
$\nu_\mu \rightarrow \nu_\tau$

The Sun shines by nuclear fusion reactions!

Hans Bethe
Nobel Prize 1967







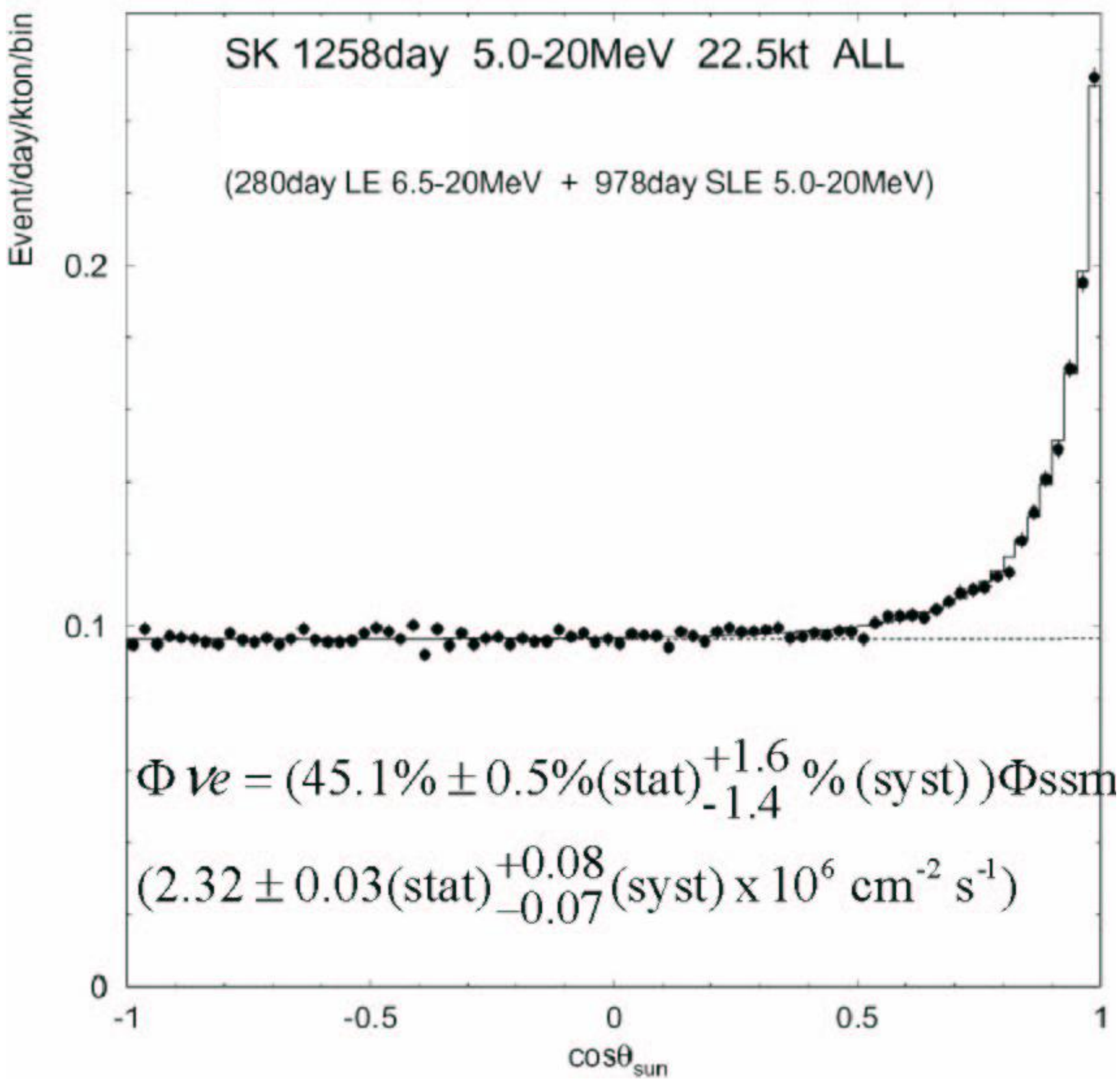
$\Phi_\nu = 2 \times L_{sun}/Q$
$L_{sun} = 1.2\ \text{kW/m}^2$
$Q = 25\ \text{MeV}$
$\Phi_\nu = 6\times10^{10}/\text{cm}^2/\text{sec}$

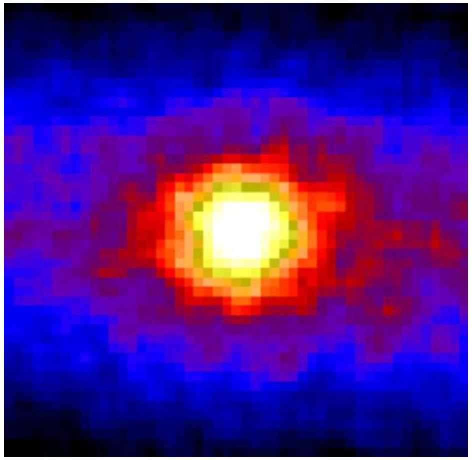
Pioneers in Solar Neutrino Science

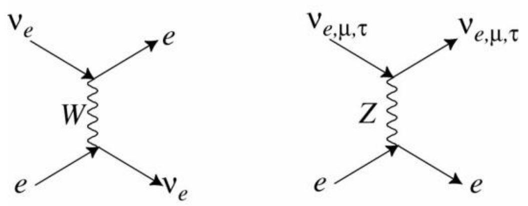
$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

1968 First Solar Neutrino Experiment

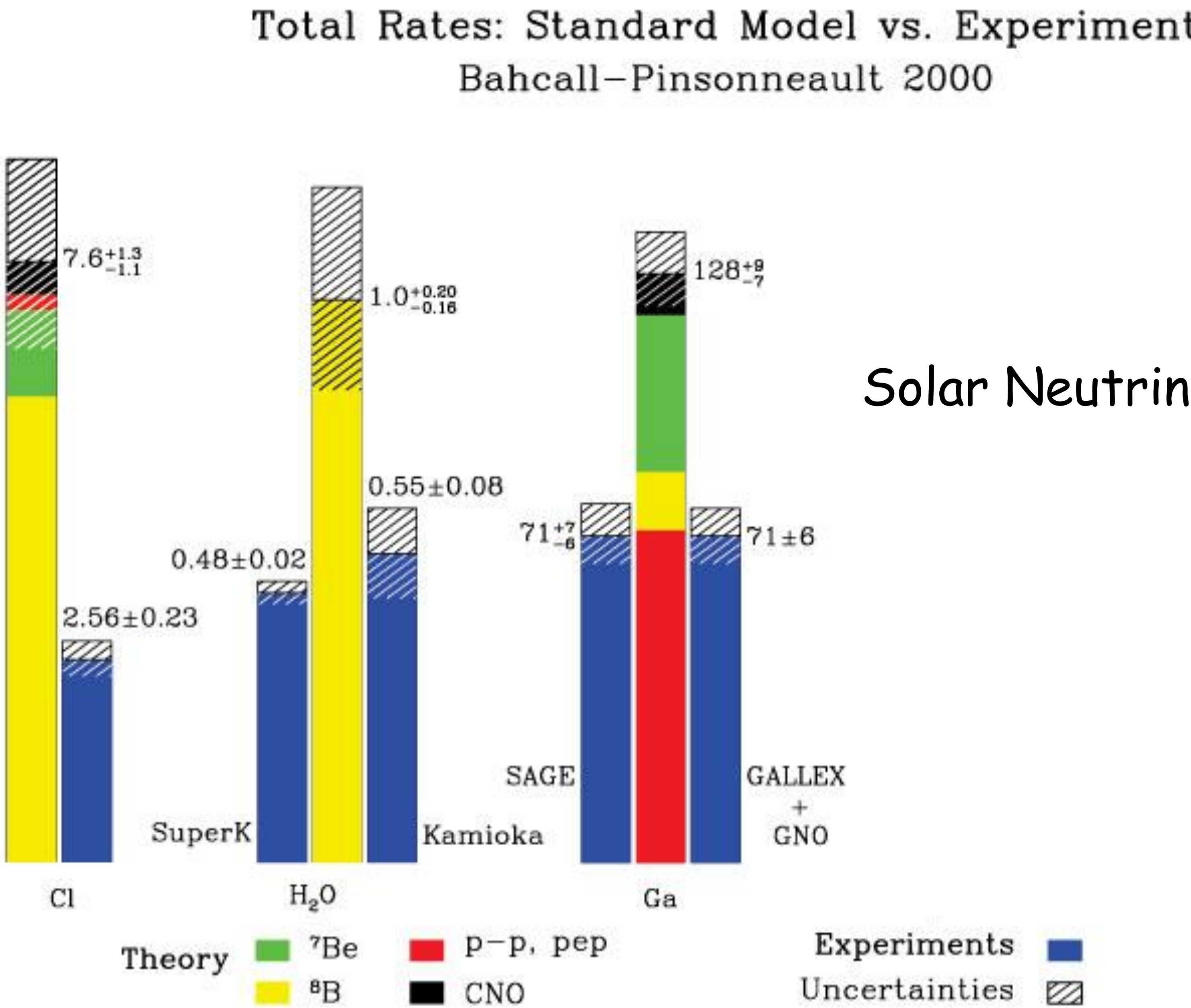
SuperKamiokande



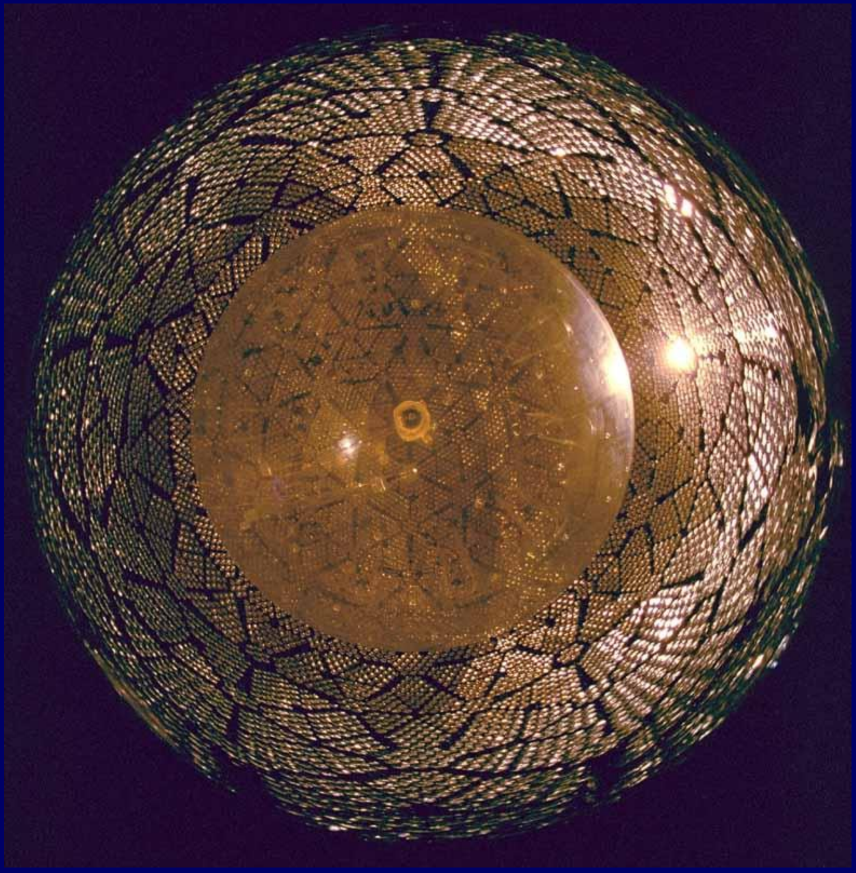




Solar Neutrino Problem

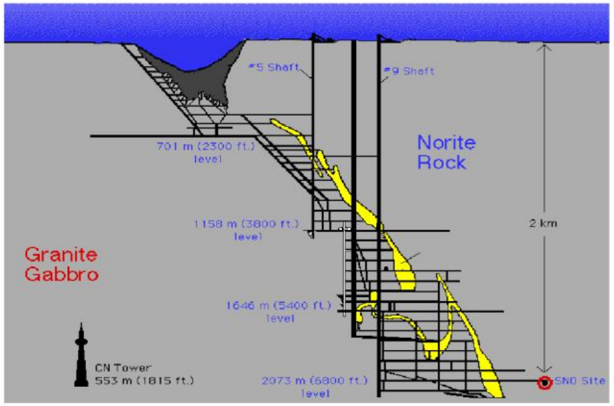


The Sudbury Neutrino Observatory



Nobel Prize in Physics
2015

Sudbury Neutrino Observatory



1000 tonnes D_2O

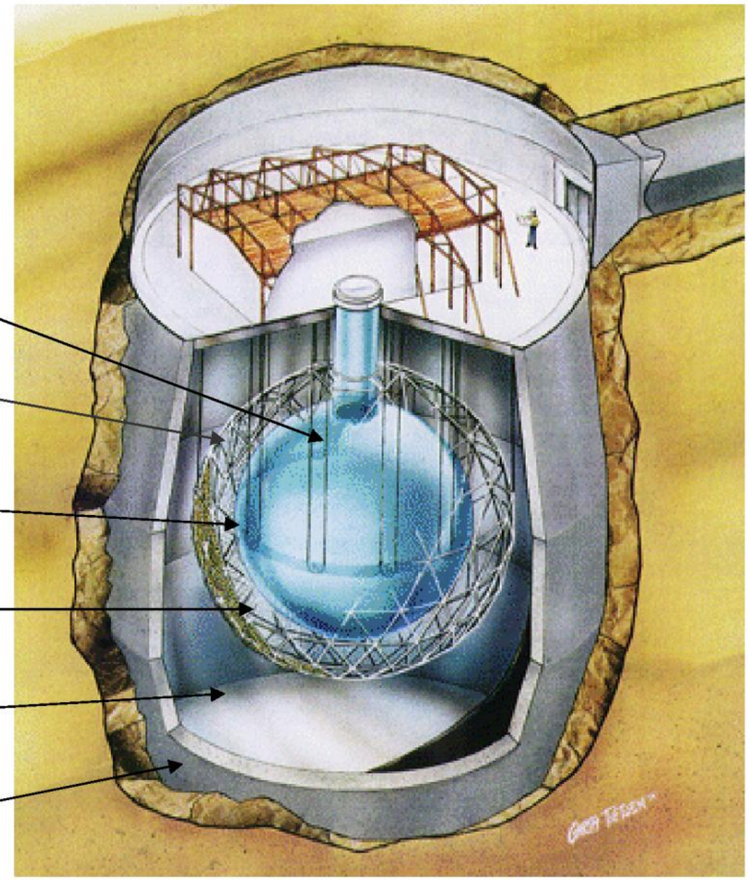
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

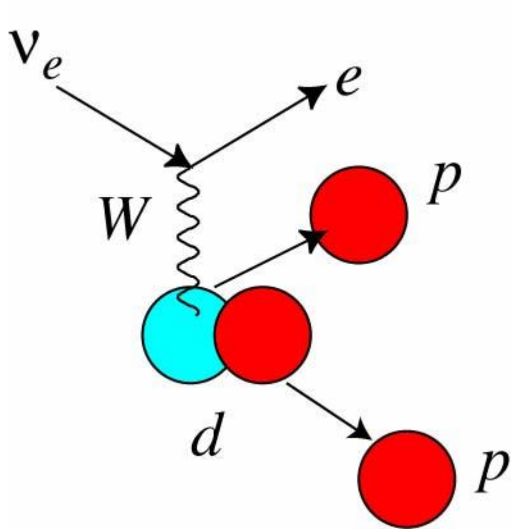
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

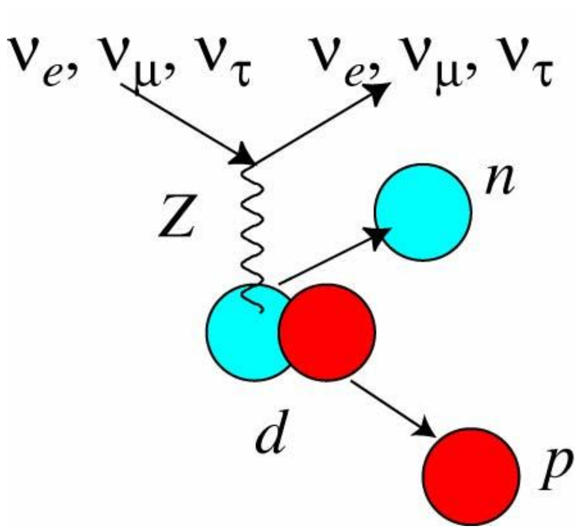
Urylon Liner and Radon Seal



Why did SNO use $300M worth of heavy water?



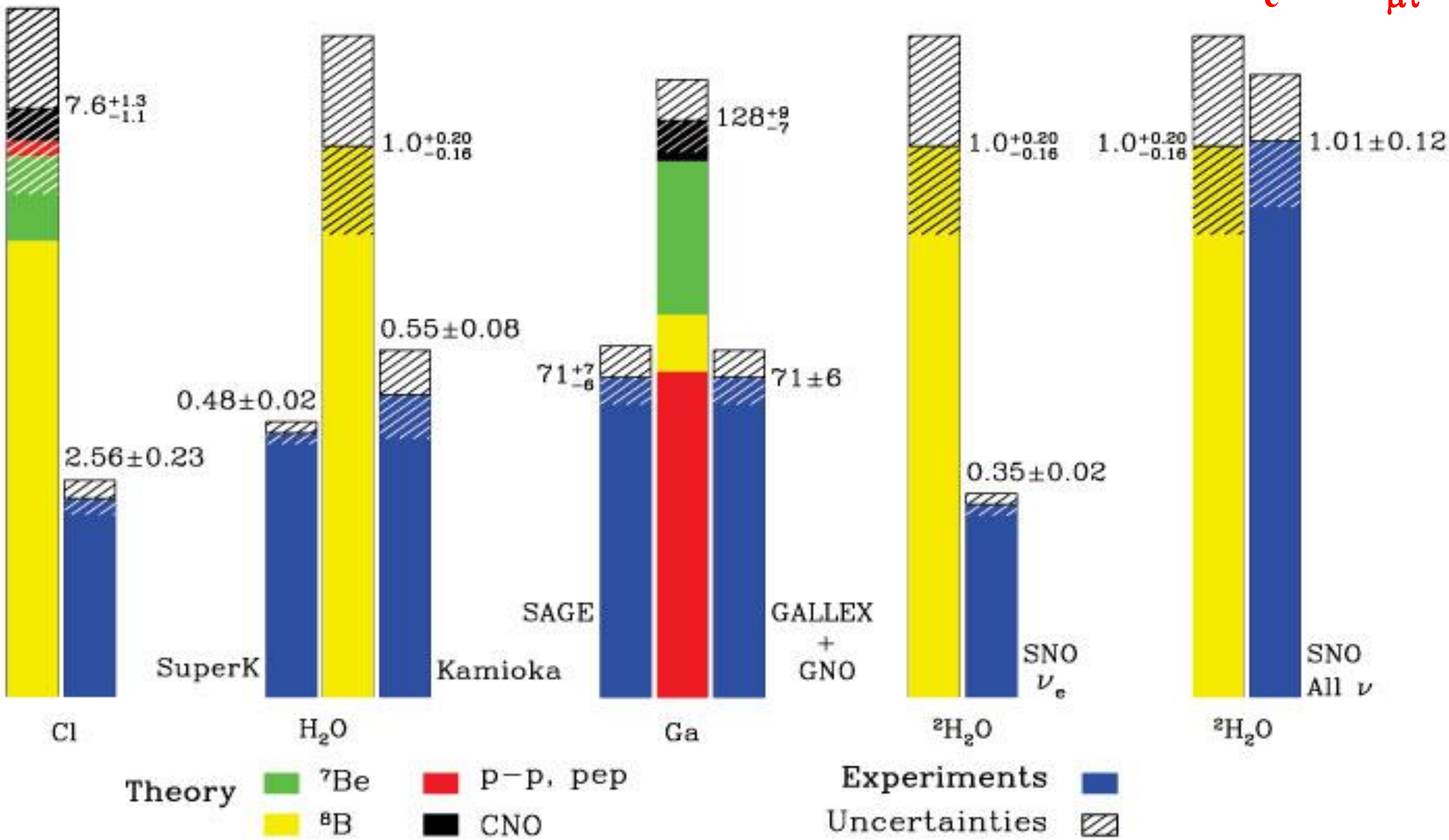
Charged Current



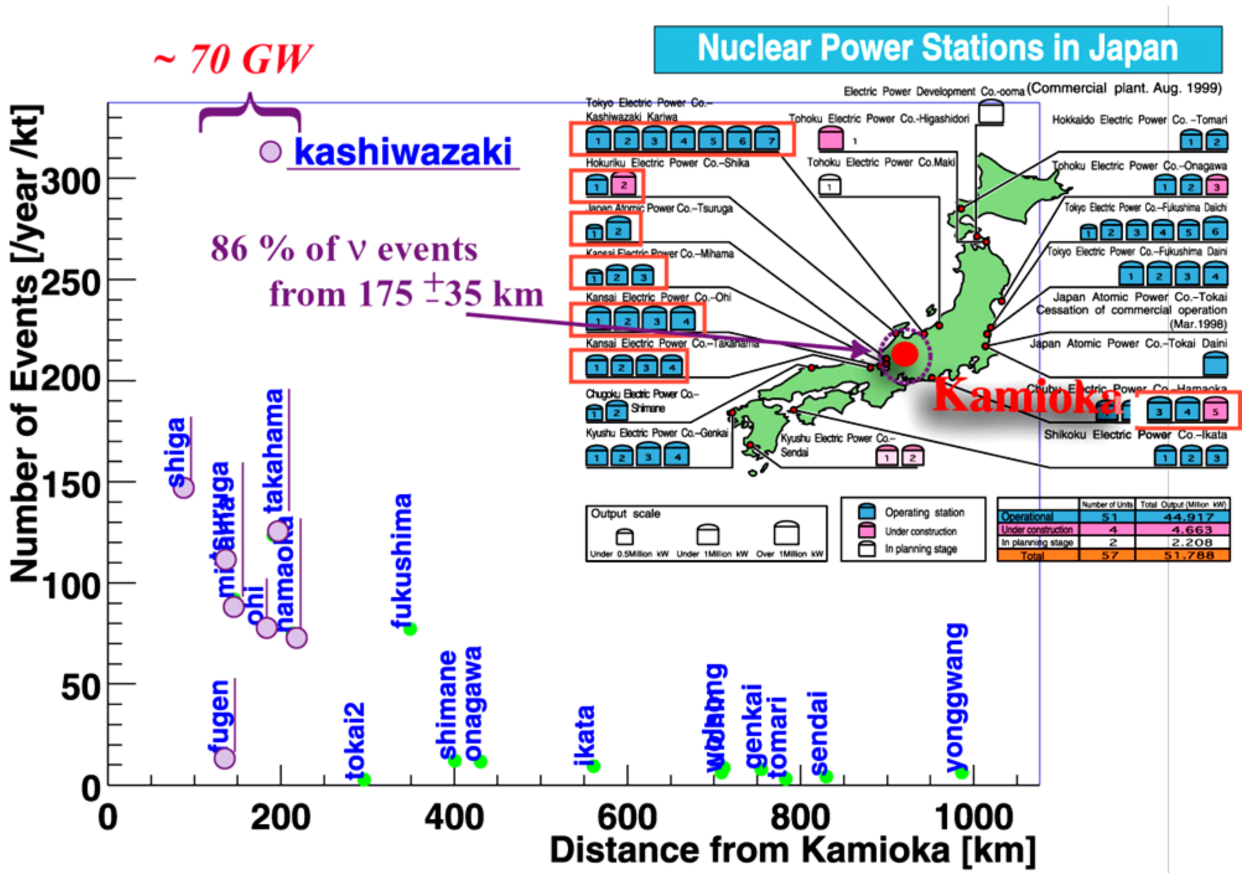
Neutral Current

Solar Neutrino Problem Solved !

Evidence for $\nu_e \rightarrow \nu_{\mu\tau}$



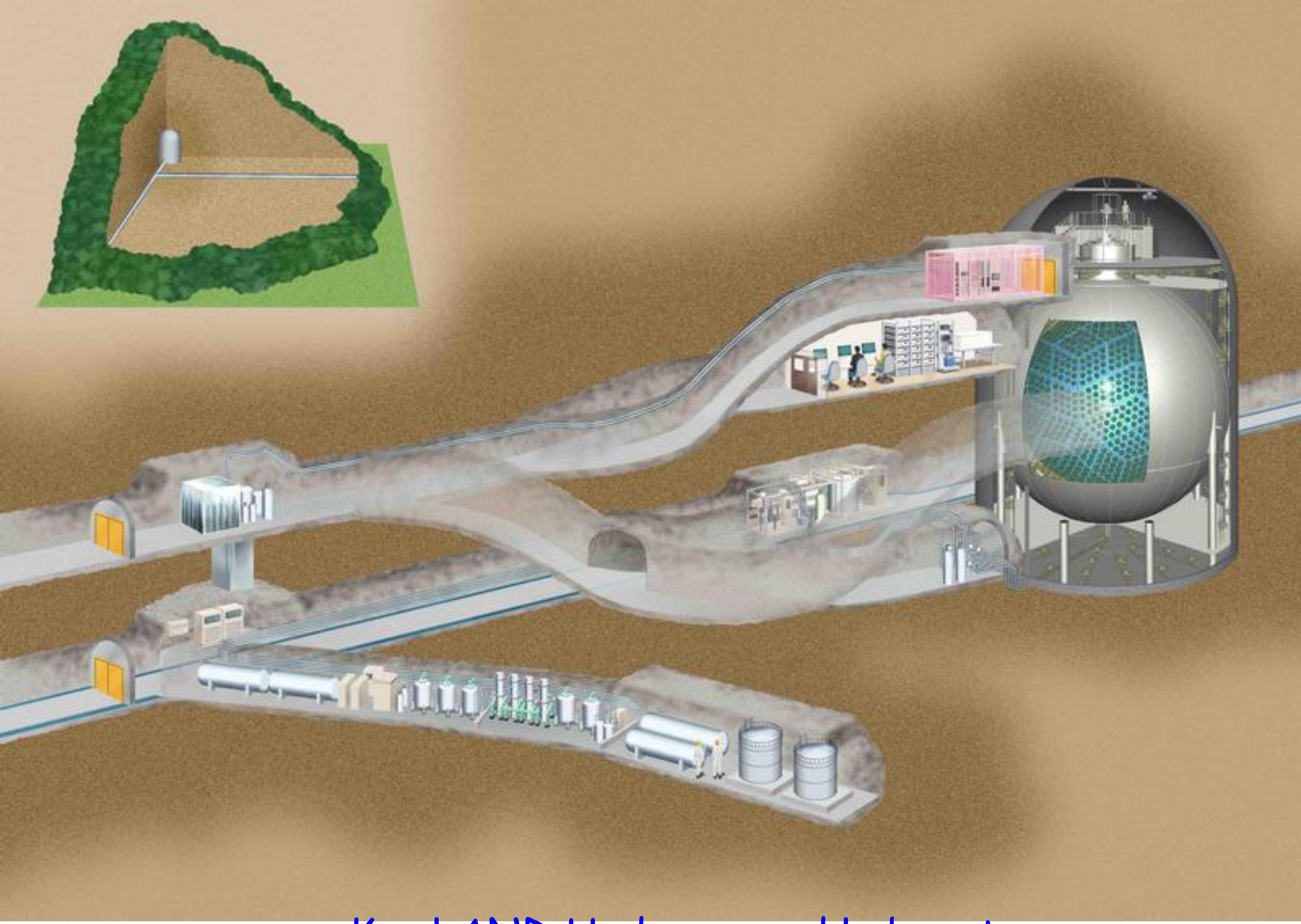
Kamland long baseline neutrino oscillation experiment



$^{235}U + n \rightarrow$ fission $\rightarrow$ $^{92}Rb + {}^{142}Cs + 2n$ (only one example)

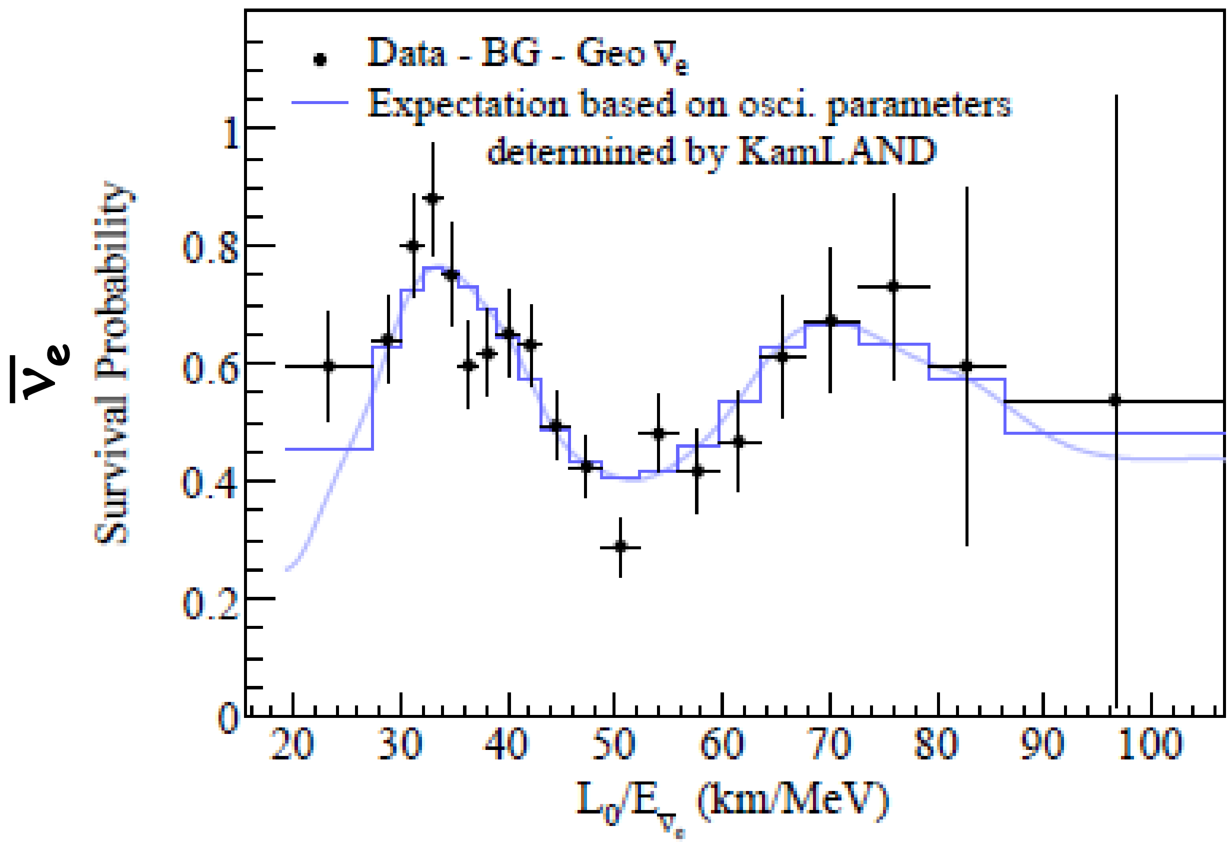
$^{92}Rb \rightarrow {}^{92}Sr + e^- + \bar{\nu}_e,$

$^{142}Cs \rightarrow {}^{142}Ba + e^- + \bar{\nu}_e$



KamLAND Underground Laboratory

KamLand

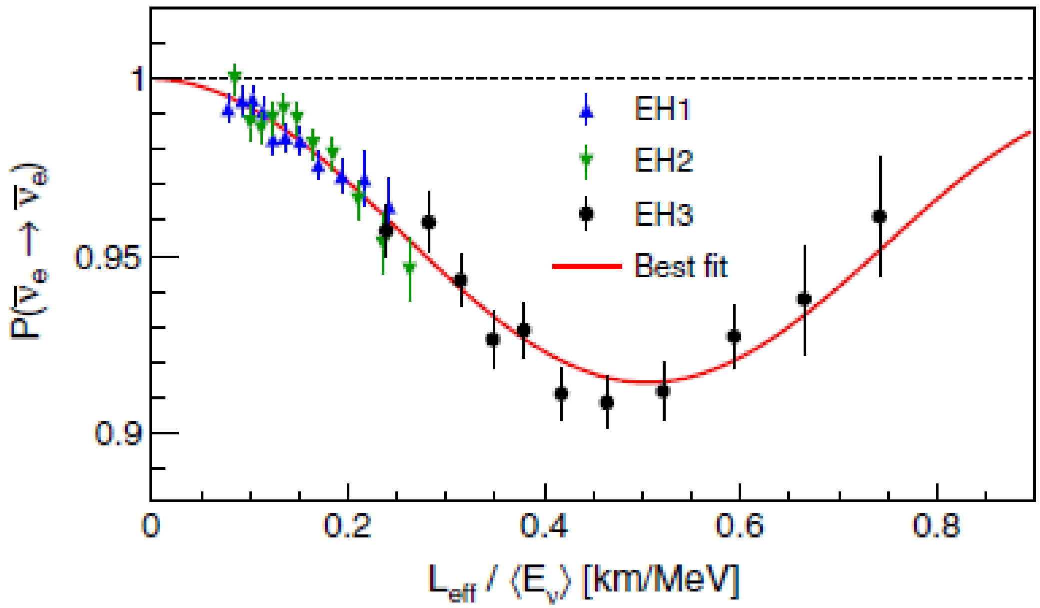


Evidence for $\bar{\nu}_e \rightarrow \bar{\nu}_{\mu\tau}$
over long distances

Daya Bay short baseline neutrino oscillation experiment

Daya Bay

$\overline{\nu_e}$ survival probability



Evidence for $\overline{\nu_e} \to \overline{\nu_{\mu\tau}}$
over short distances

SuperKamiokande, SNO, Kamland , Daya Bay have shown:

neutrinos have finite masses

neutrinos undergo flavor-changing oscillations

Neutrino mass hierarchy

Open Questions in Neutrino Physics:

What is the absolute scale of ν mass ?

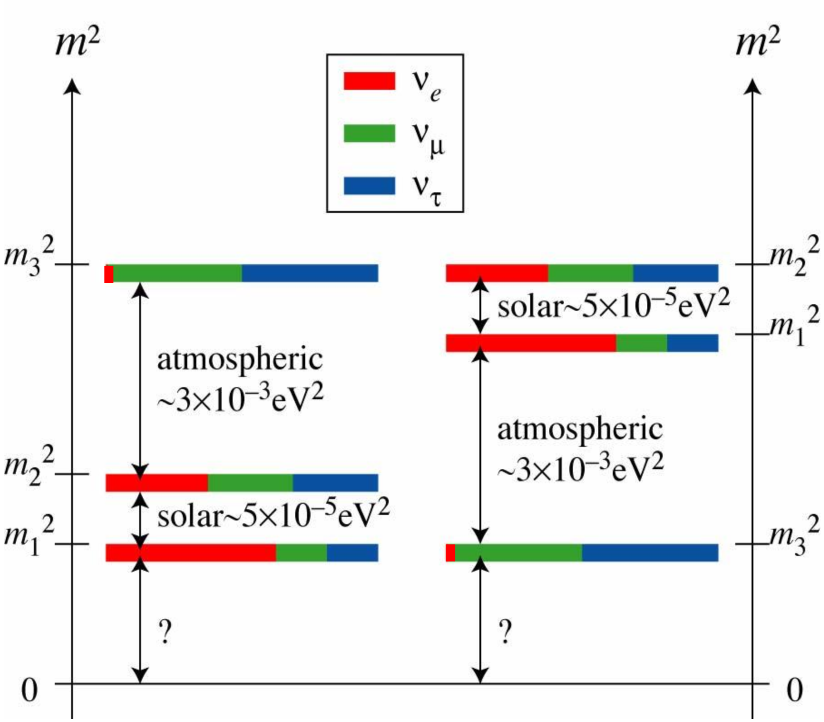
Are ν and $\bar{\nu}$ different particles ?

Alternative mass scheme:

$m_1 \sim m_2 \sim m_3$

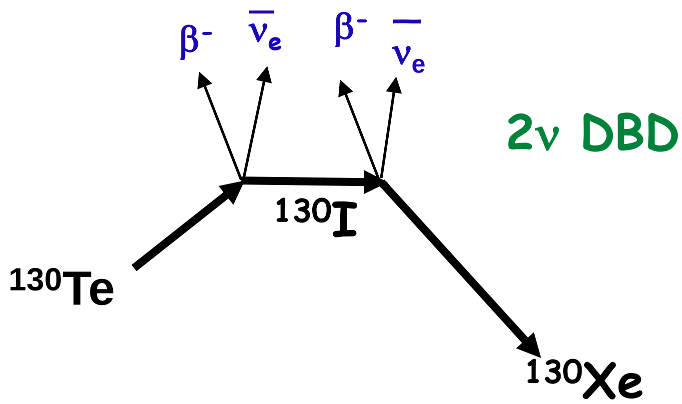
All splittings small

(degenerate)

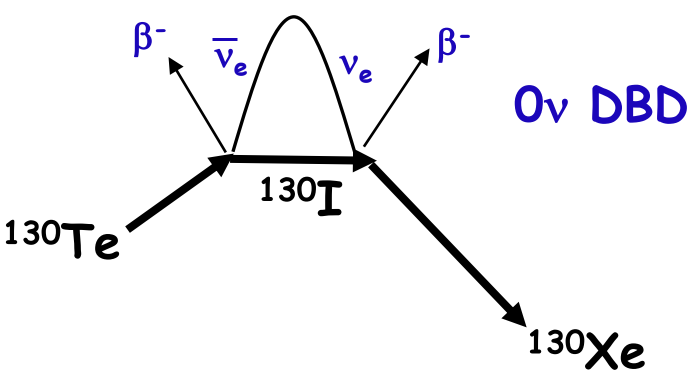


At least one ν has m > 55 meV

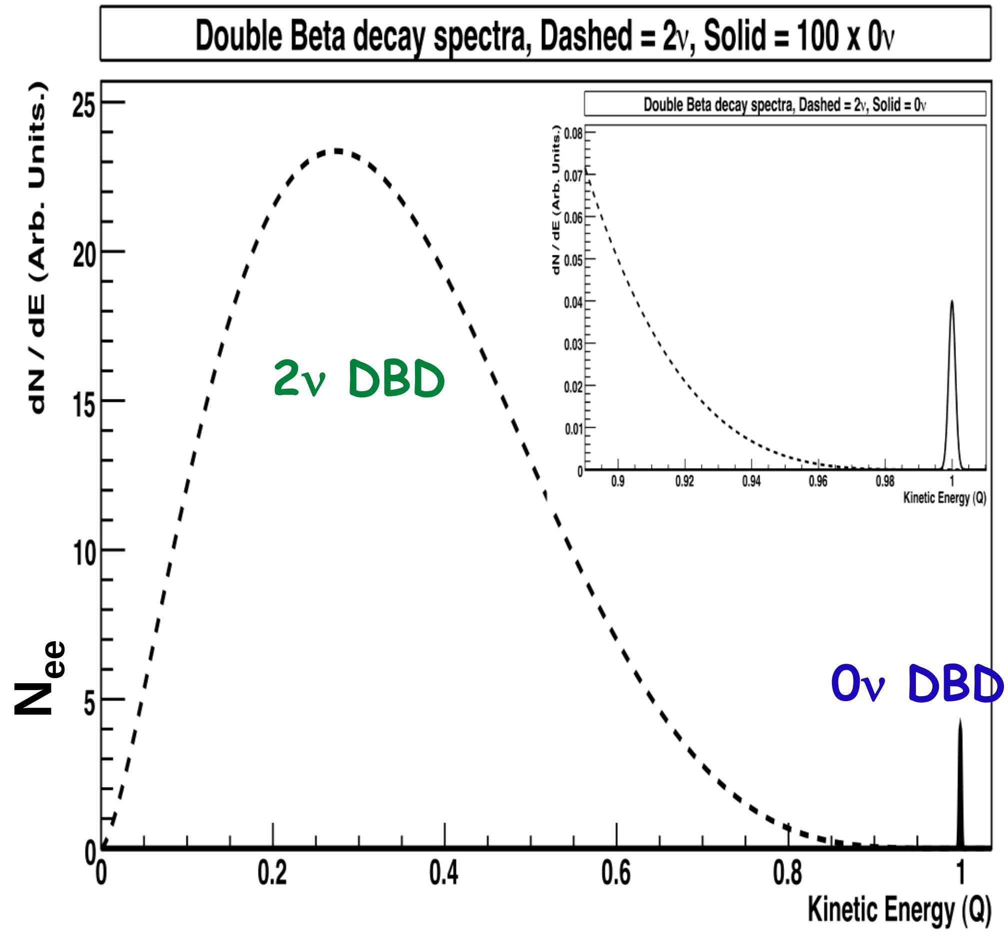
Double Beta Decay



Allowed by Standard Model



Only possible if ν is its own antiparticle and rate is proportional to m_ν^2



sum electron energy / Q

The CUORE experiment

Located at LNGS (Italy), ~3600 m.w.e. shield

Investigate: $^{130}Te \rightarrow {}^{130}Xe + 2e^-$

Array of 988 $^{nat}TeO_2$ detectors, arranged in 19 towers, 13 floors each. Total mass of ^{130}Te = 206 kg

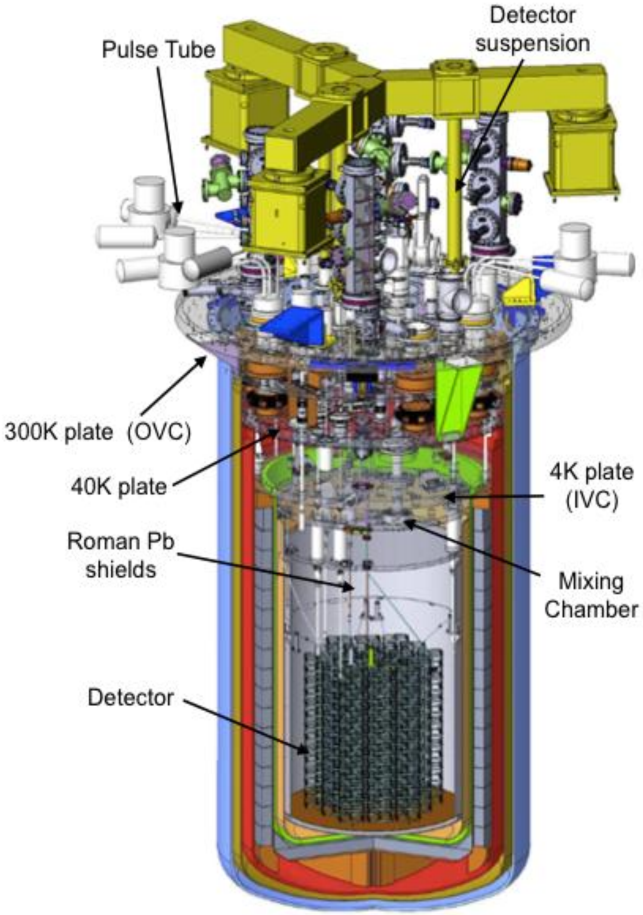
Operated at 10 mK

Energy resolution: 5 keV FWHM at $Q_{\beta\beta}$ (2527 keV)

Background goal: 10^{-2} c/keV/kg/year in the ROI.

Sensitivity on $m_{\beta\beta}$ (5y, 90% C.L.): 50 - 130 meV

Sensitivity on $0\nu\beta\beta$ $T_{1/2}$ (5y, 90% C.L.): 9.5 x 10^{25} y



CUORE location

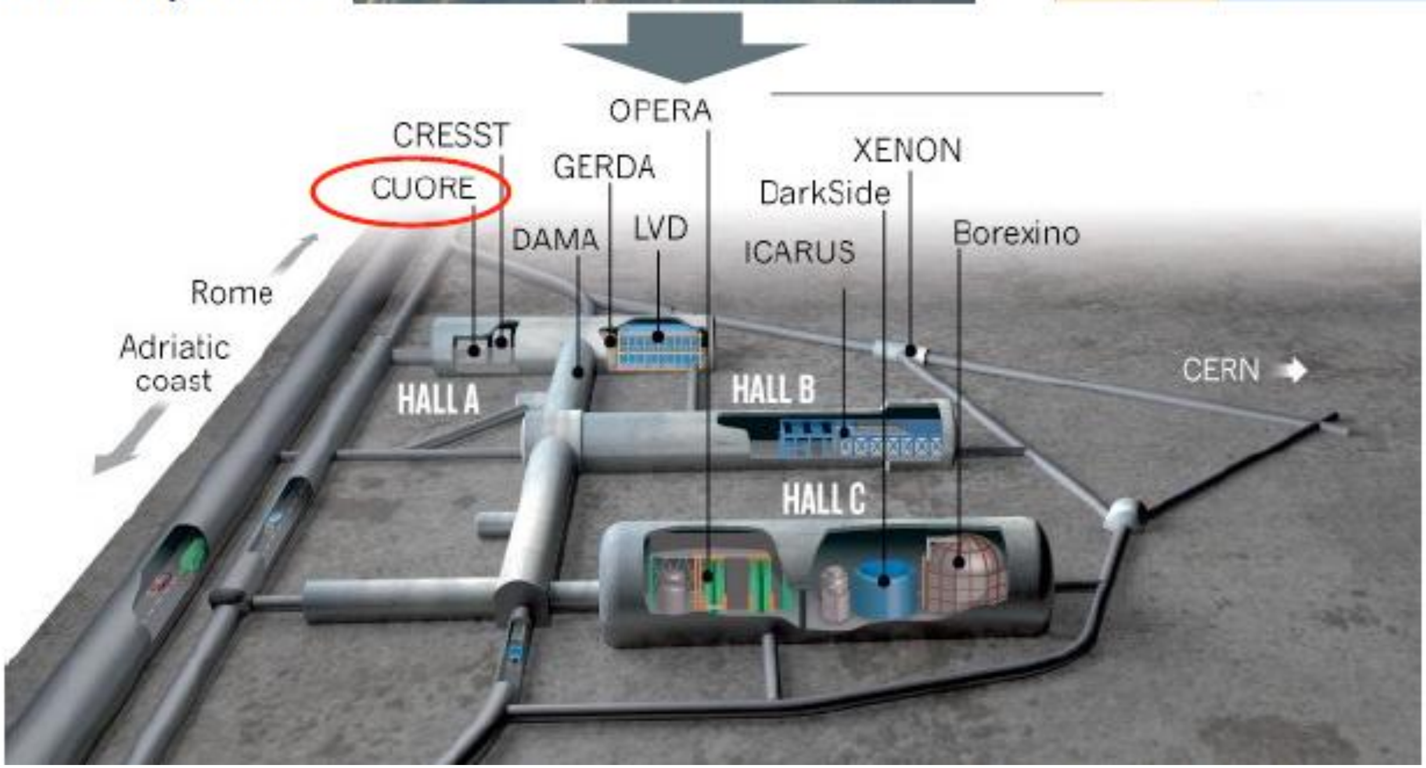
120 km from Rome

~ 3600 m.w.e. deep

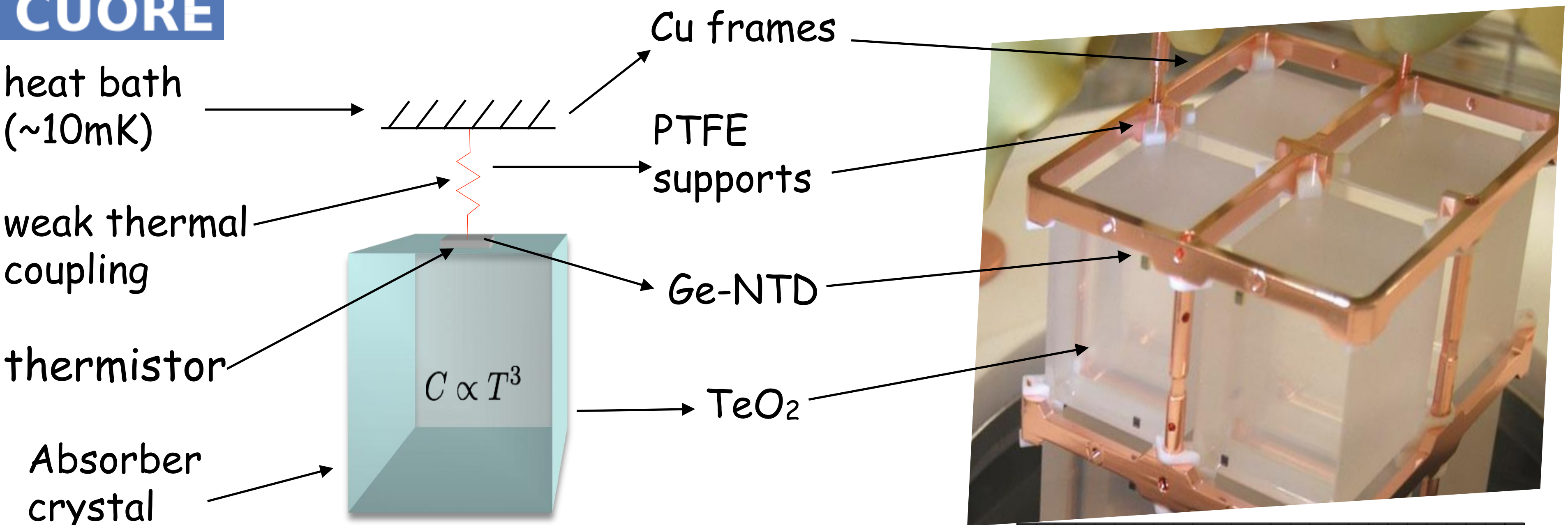
μ flux: ~ $3x10^{-8}$/(s cm^2)

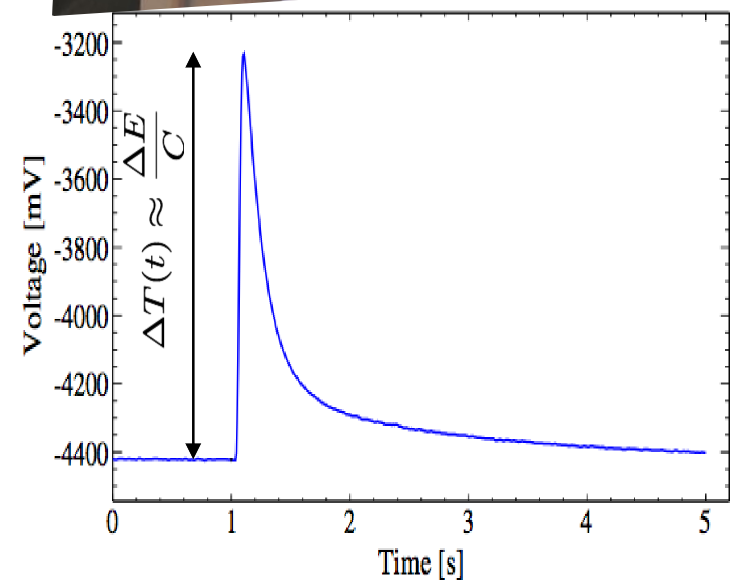
γ flux: ~ 0.73/(s cm^2)

neutrons: $4x10^{-6}$ n/(s cm^2)



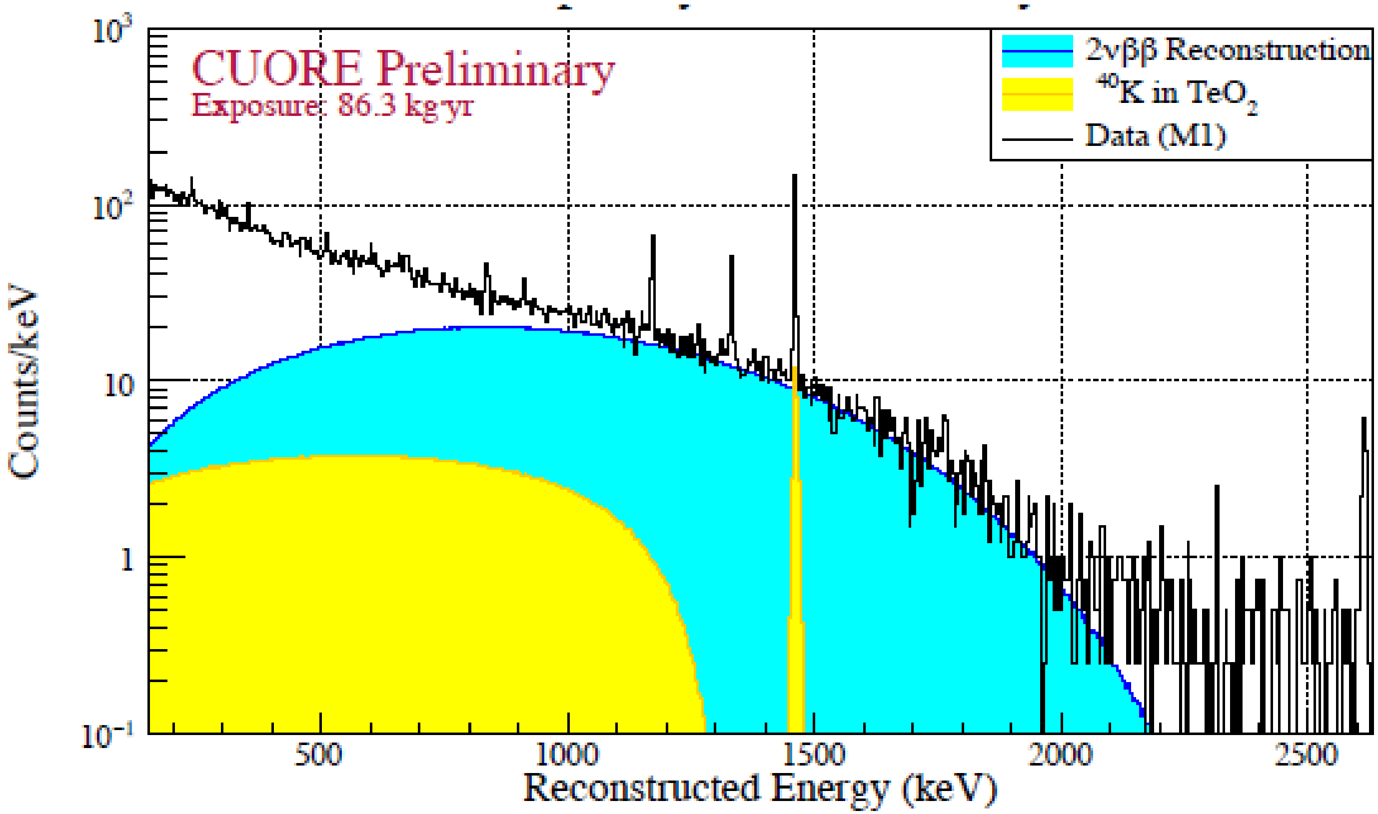
CUORE TeO_2 bolometers





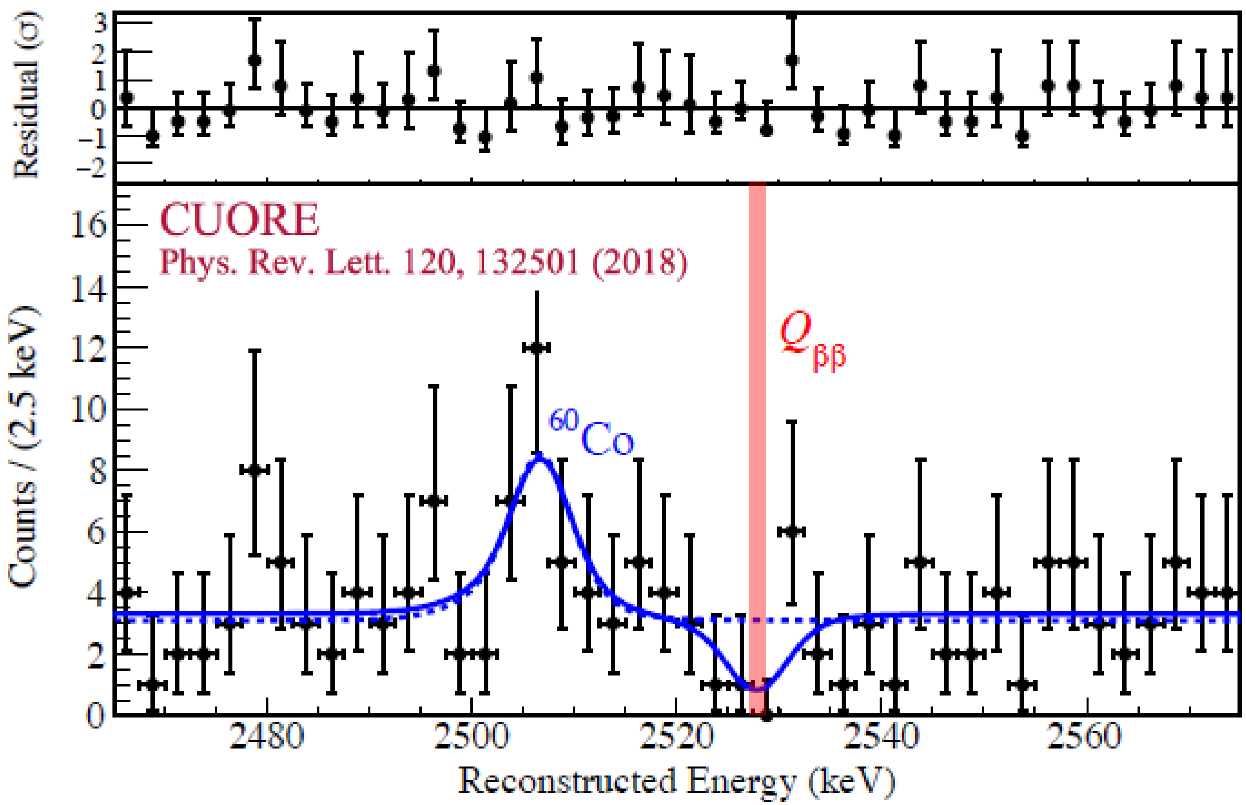
- operated in extreme conditions
- (low T, low noise environment)
- excellent energy resolution (~0.2% FWHM)
- no particle identification
- slow, but ok for rare event searches

$2\nu\ \beta\beta$ decay of ^{130}Te



- CUORE $T_{1/2}$ = [7.9 ± 0.1(stat) ± 0.2(syst)] · 10^{20} yr
- CUORE-0: [8.2 ± 0.2(stat) ± 0.6(syst)] · 10^{20} yr
- NEMO: [7.0 ± 0.9(stat) ± 1.1(syst)] · 10^{20} yr

Search for $0\nu\,\beta\beta$ decay of ^{130}Te

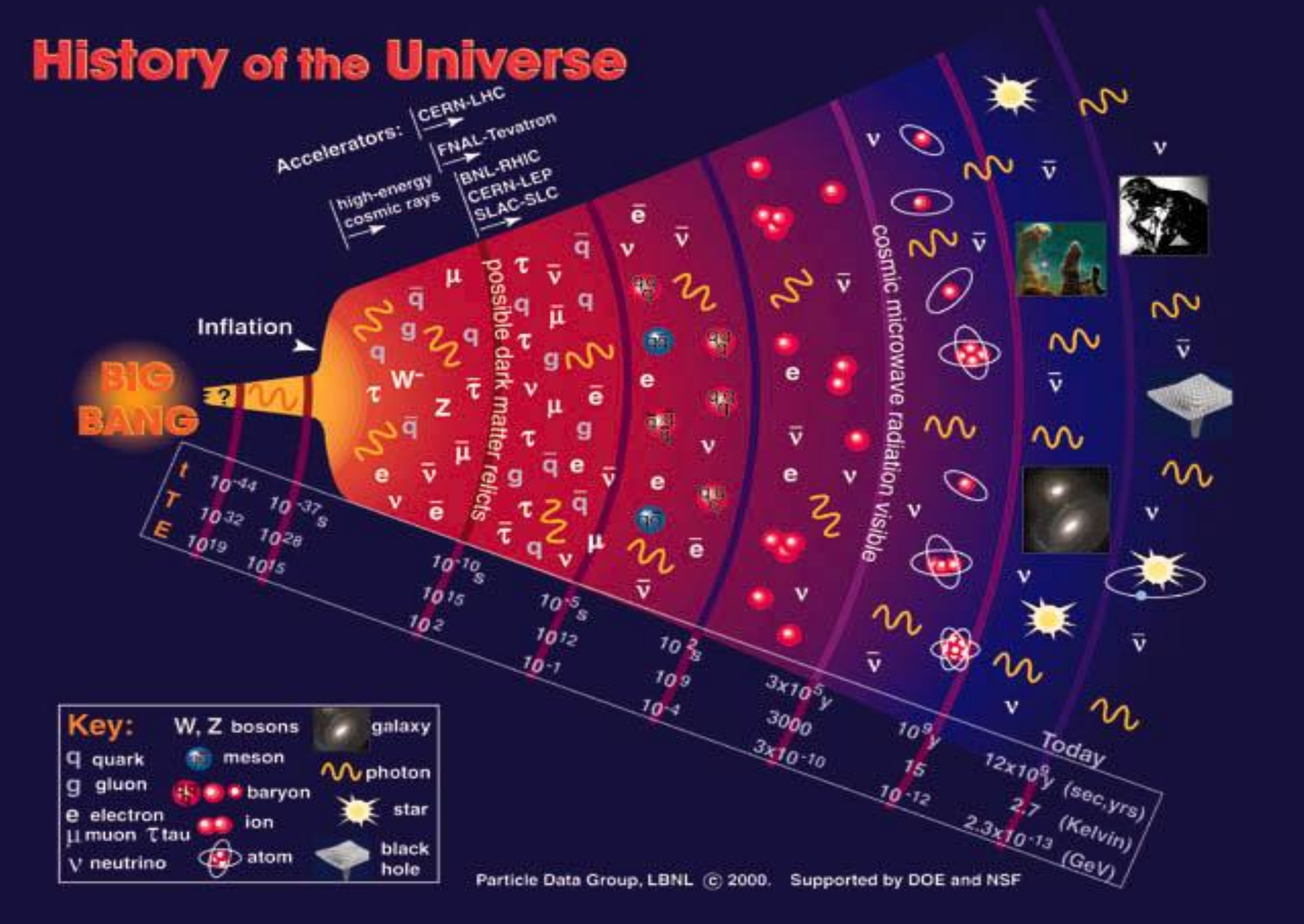


Fit components:

- Flat background
- ^{60}Co sum peak
- Peak at $Q_{\beta\beta}$
- $\Delta E = 7.7$ keV FWHM

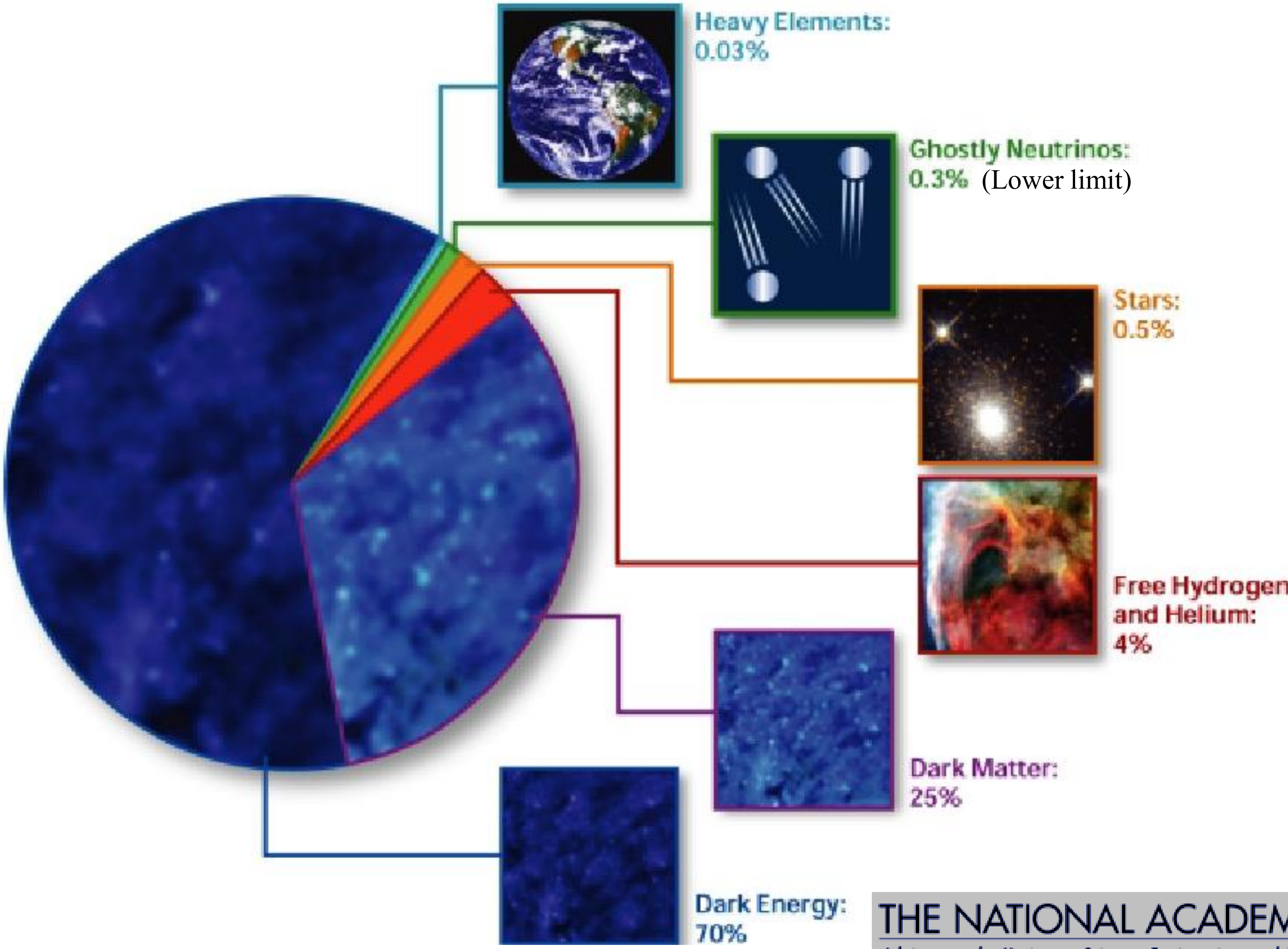
Half-life limit 90% CL:

- $T^{0\nu} > 1.3 \times 10^{25}$ yr



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t
T
E
10^-44
10^32
10^19
10^-37 s
10^28
10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole
Particle Data Group, LBNL © 2000. Supported by DOE and NSF

What's the matter?



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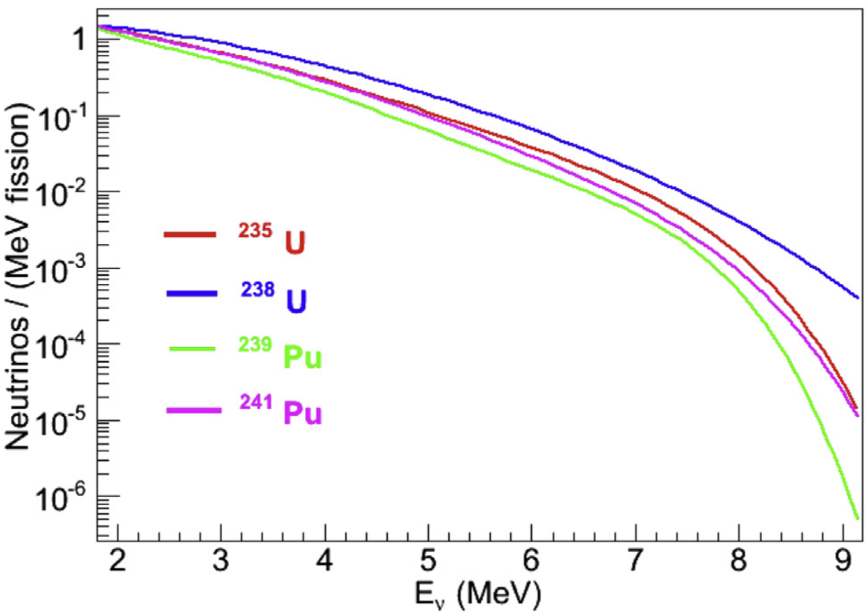
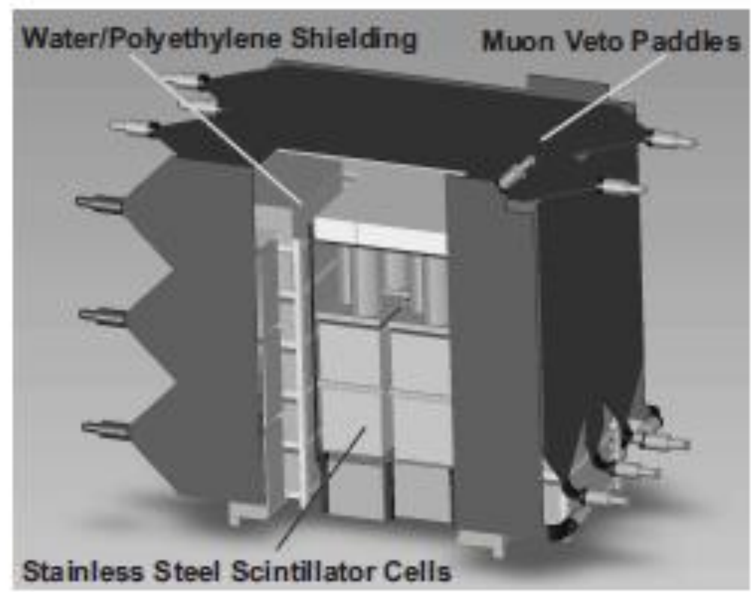
Advisers to the Nation on Science, Engineering, and Medicine

Q. But what are they good for?

A. Remote monitoring of nuclear reactors
(looking for diversion of plutonium !)

Reactor anti-neutrinos



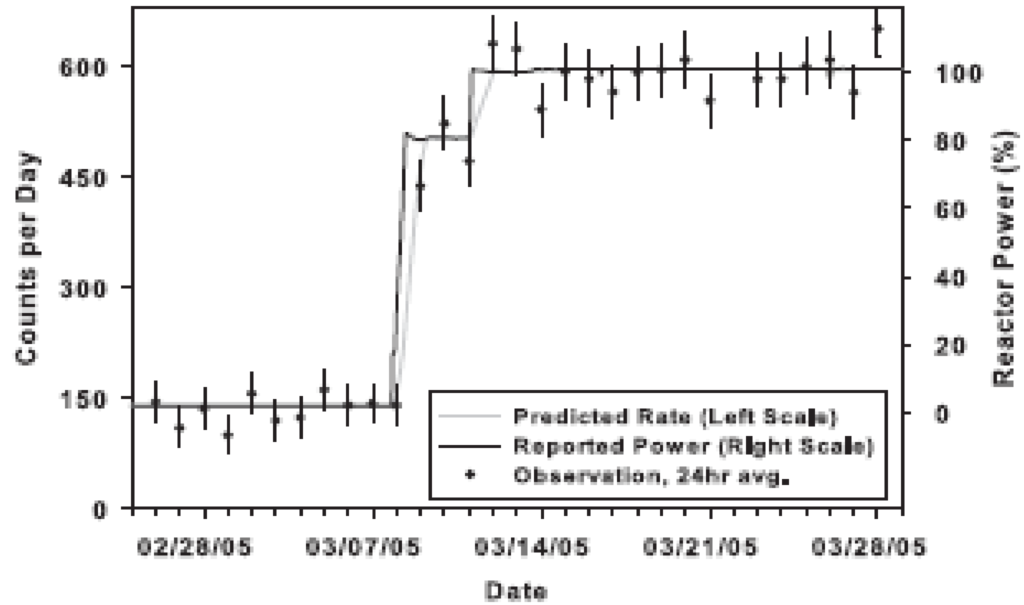


$\overline{\nu}_e + p \rightarrow n + e^+$

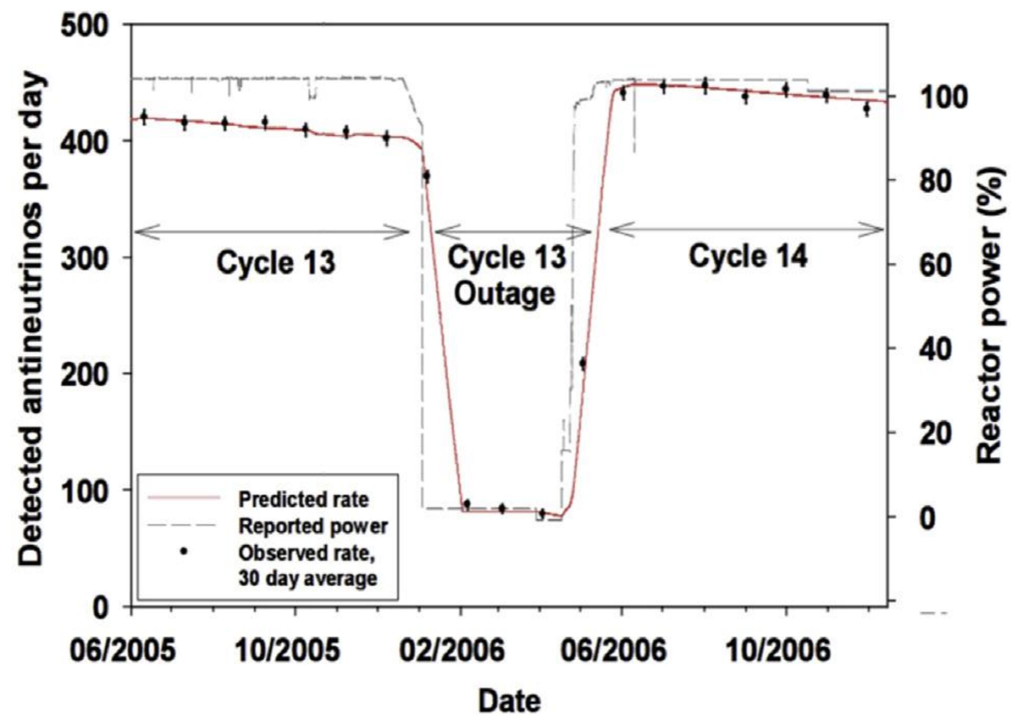
Composition of fuel changes with time: ^{235}U is destroyed, ^{239}Pu is produced

A. Bernstein *et al.*
SONGS reactor

Observed neutrino counting rate before and after reactor turns on



Observed neutrino counting rate during two reactor fuel cycles



Neutrinos in Popular Culture

Cosmic Gall
by John Updike (1960)

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.

***We now know neutrinos have very small masses**
***and do interact weakly**

Zak, The Neutrino