A short review of Neutrino Physics

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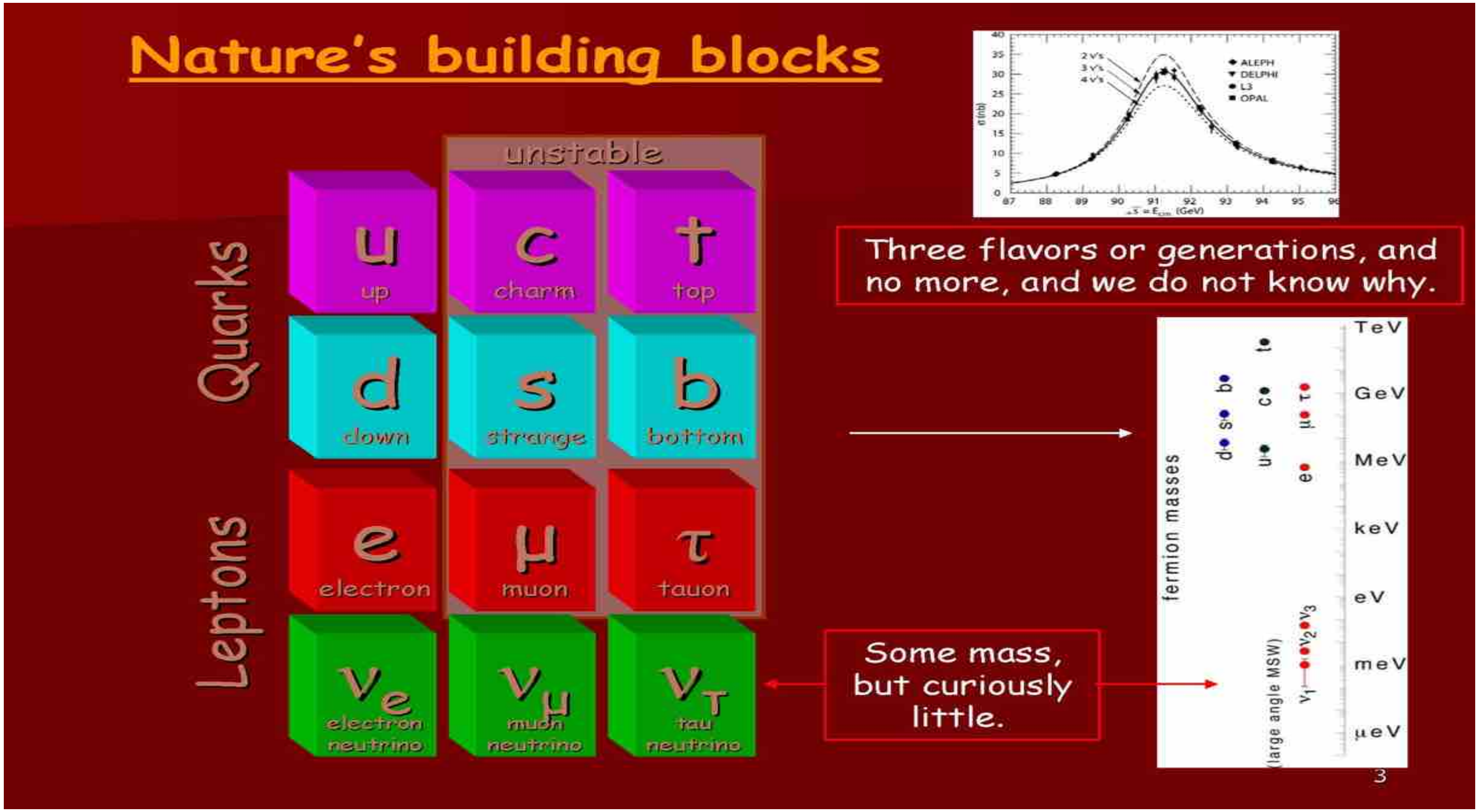
Roma Tor Vergata, March 23, 2016

What is a neutrino?

- **Stable Elementary Particle** – *3 over 6 constituents of (stable) matter*
- **No electric charge** – *cannot see it*
- **Very little interaction with matter** – *goes through the Earth unscathed*
- **Has very little mass** – *less than 1 millionth of electron's mass*
- **Lots of them throughout** – *100 million in your body any time!*



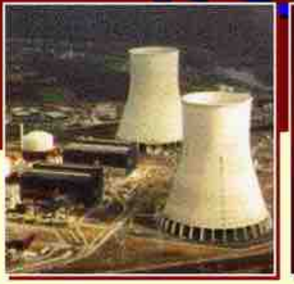
Nature's building blocks

Three flavors or generations, and no more, and we do not know why.

Some mass, but curiously little.

Where do Neutrinos come from?

✓ Nuclear Reactors
(power stations, ships)

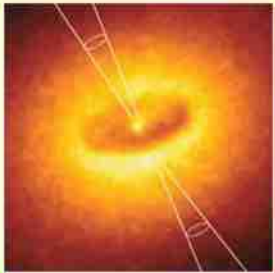


Sun ✓

✓ Particle Accelerator

Supernovae
(star collapse)
SN 1987A ✓

✓ Earth's Atmosphere
(Cosmic Rays)

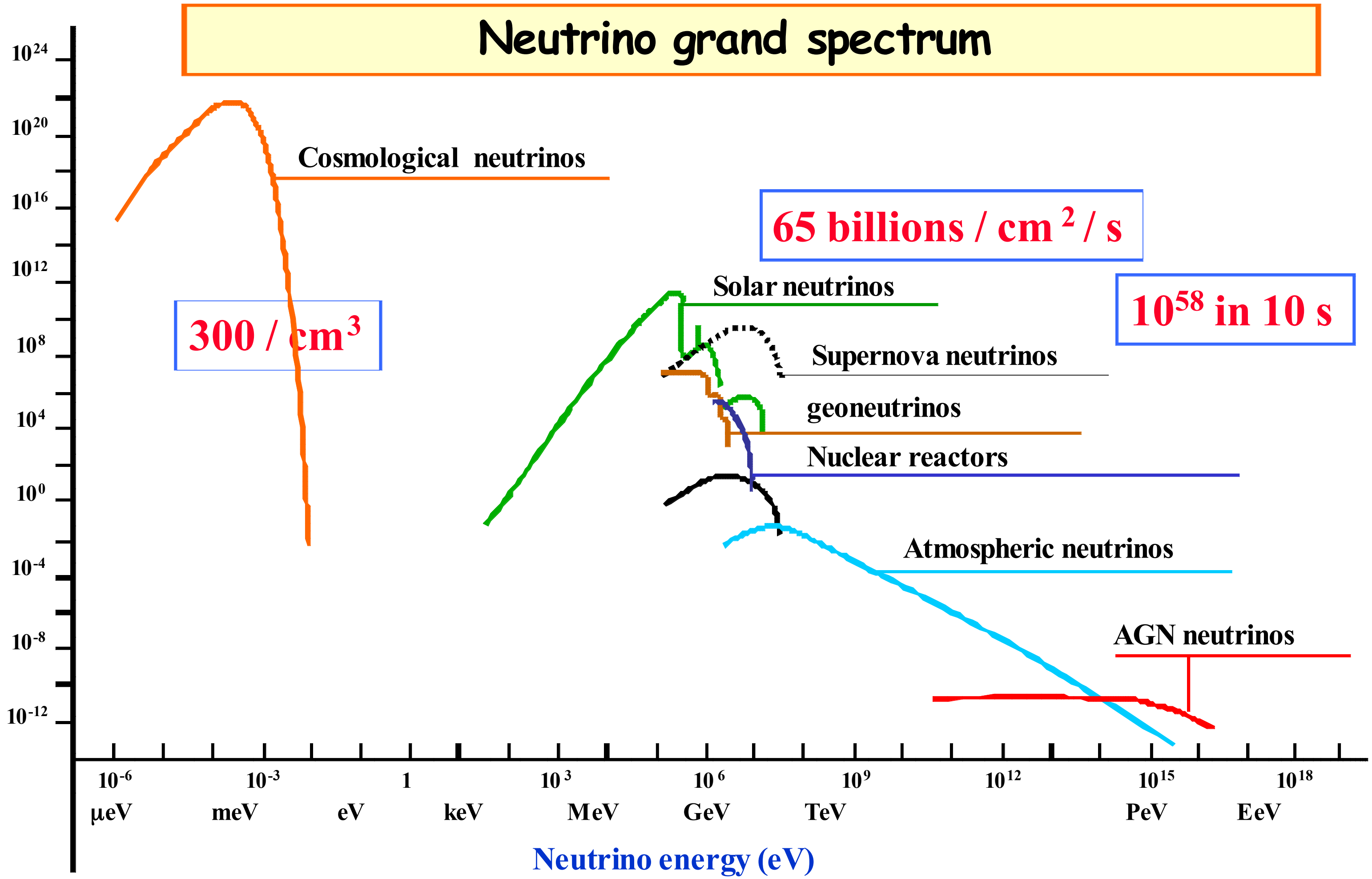


Astrophysical
Accelerators
Soon ?

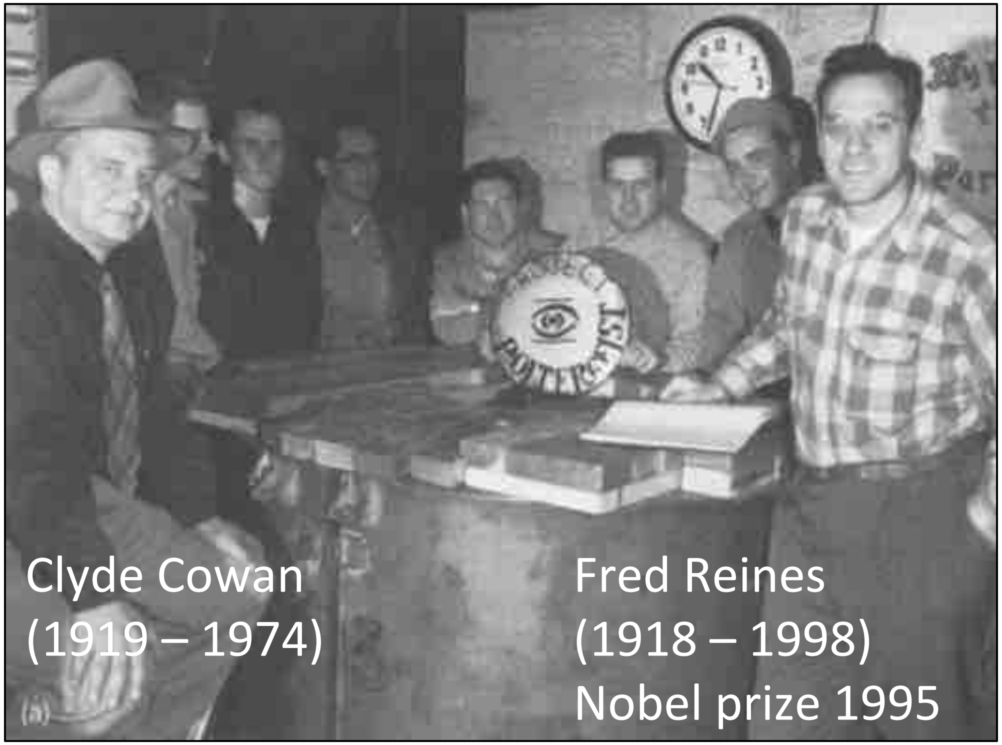
✓ Earth's Crust
(Natural
Radioactivity)

Big Bang
(here 330 ν/cm^3)
Indirect Evidence

Sources of ν

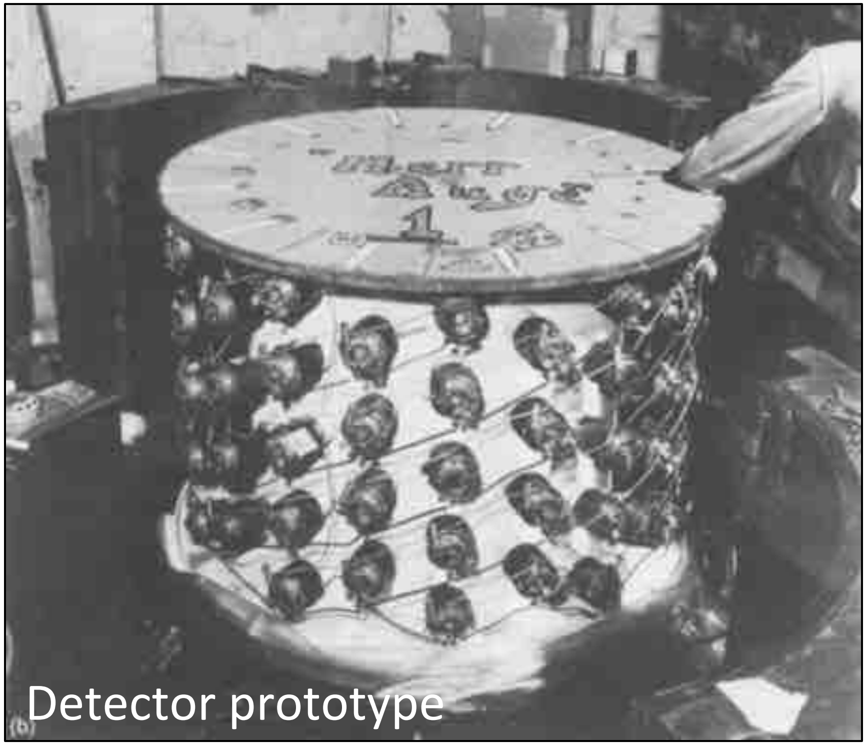


First Detection (1954 – 1956)



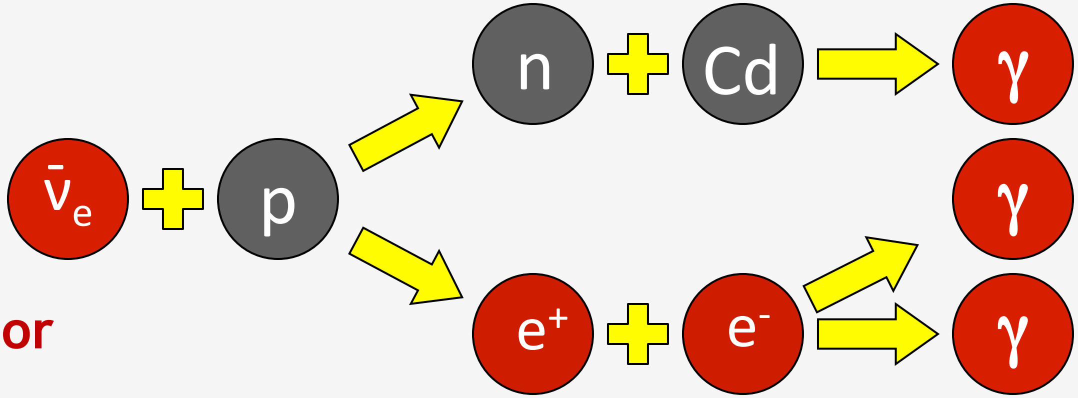
Clyde Cowan
(1919 – 1974)

Fred Reines
(1918 – 1998)
Nobel prize 1995



Detector prototype

Anti-Electron Neutrinos from Hanford Nuclear Reactor



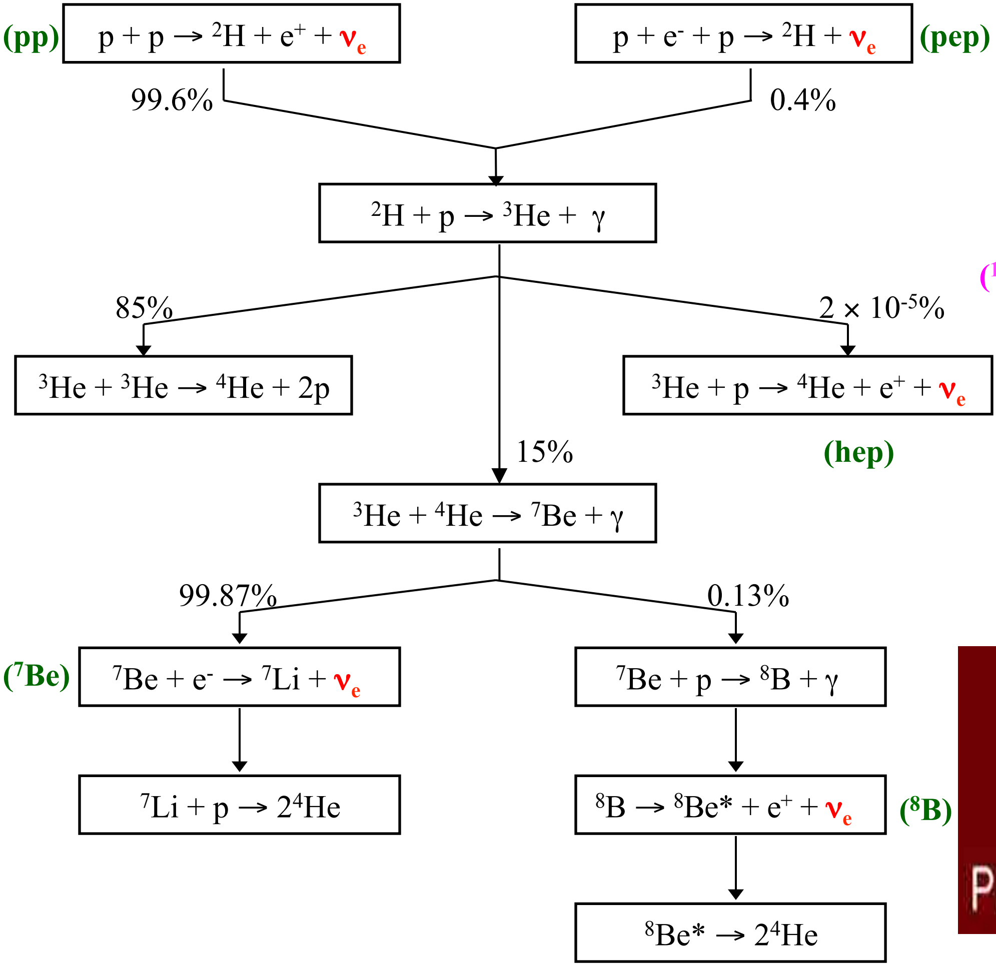
3 Gammas in coincidence

First evidences of anomalies in the neutrino field arrived from **solar neutrinos** (end of '60 and '70)

The solar ν are produced in the nuclear reactions in the solar core:

$$4p \rightarrow \alpha + 2e^+ + 2\nu_e + 26.7\ \text{MeV}$$

***pp* chain**



(pp) $p + p \rightarrow {}^2H + e^+ + \nu_e$

(pep) $p + e^- + p \rightarrow {}^2H + \nu_e$

99.6%

0.4%

${}^2H + p \rightarrow {}^3He + \gamma$

85%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

2 × 10⁻⁵%

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ (hep)

15%

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.87%

(⁷Be) ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Li + p \rightarrow 2\,{}^4He$

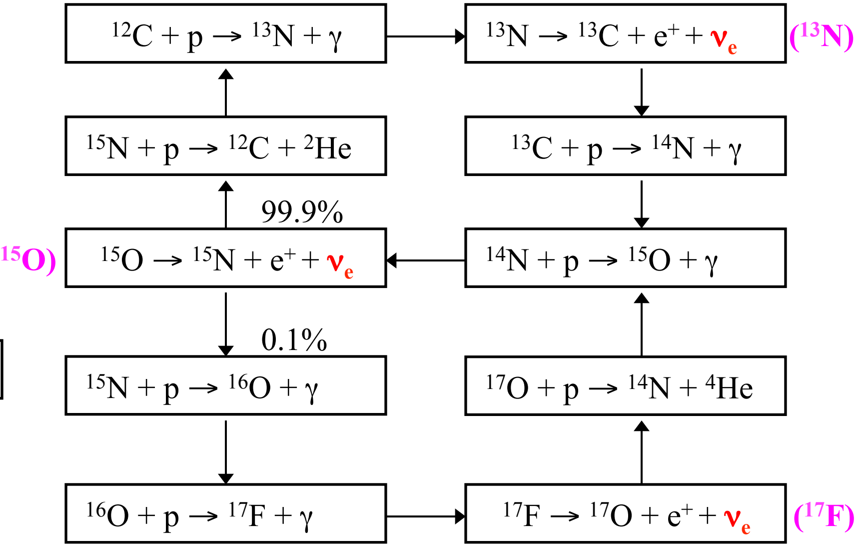
0.13%

${}^7Be + p \rightarrow {}^8B + \gamma$

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

${}^8Be^* \rightarrow 2\,{}^4He$

***CNO* cycle**



${}^{12}C + p \rightarrow {}^{13}N + \gamma$

${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$ (¹³N)

${}^{13}C + p \rightarrow {}^{14}N + \gamma$

${}^{14}N + p \rightarrow {}^{15}O + \gamma$

(¹⁵O) ${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

99.9%

${}^{15}N + p \rightarrow {}^{12}C + {}^2He$

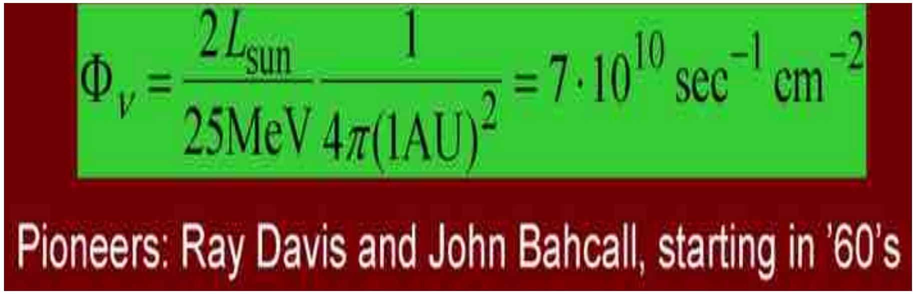
0.1%

${}^{15}N + p \rightarrow {}^{16}O + \gamma$

${}^{16}O + p \rightarrow {}^{17}F + \gamma$

${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$ (¹⁷F)

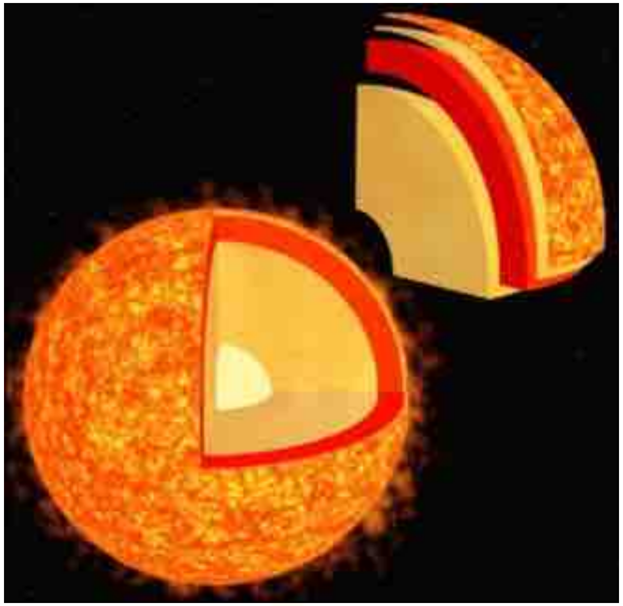
${}^{17}O + p \rightarrow {}^{14}N + {}^4He$

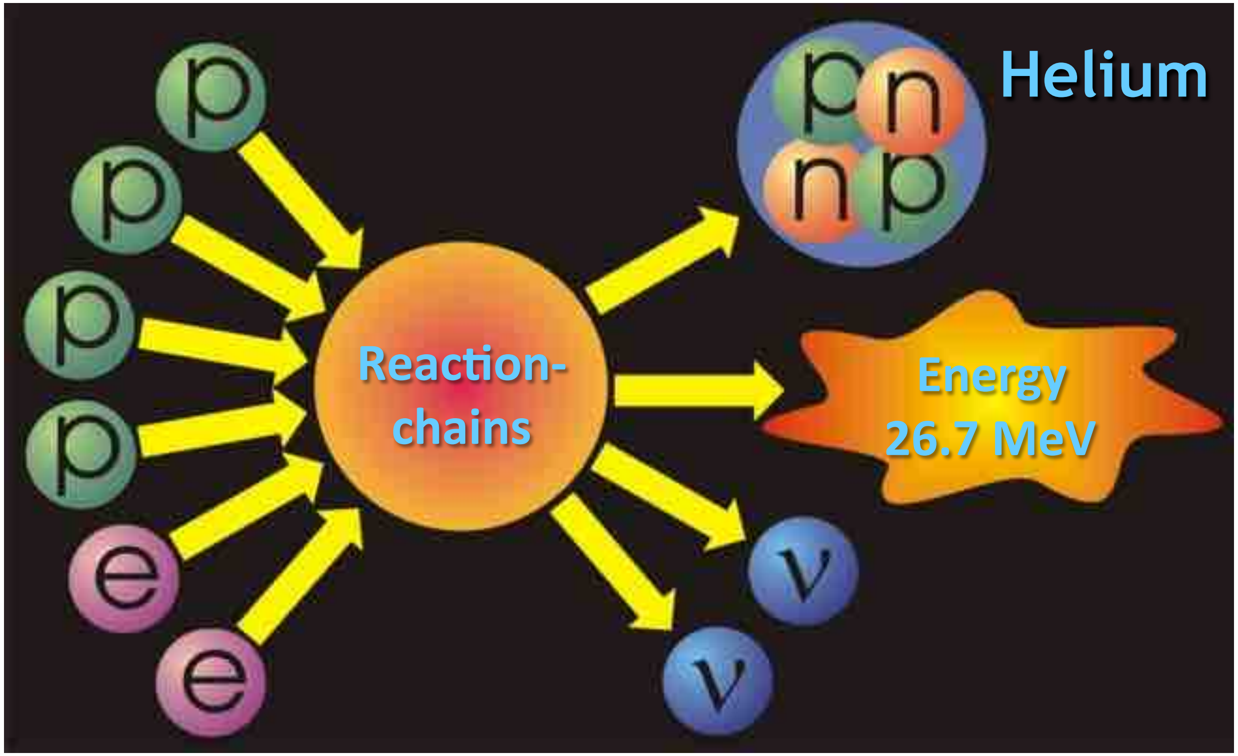


$$\Phi_\nu = \frac{2L_{sun}}{25\text{MeV}} \frac{1}{4\pi(1AU)^2} = 7 \cdot 10^{10}\ \sec^{-1}\ \text{cm}^{-2}$$

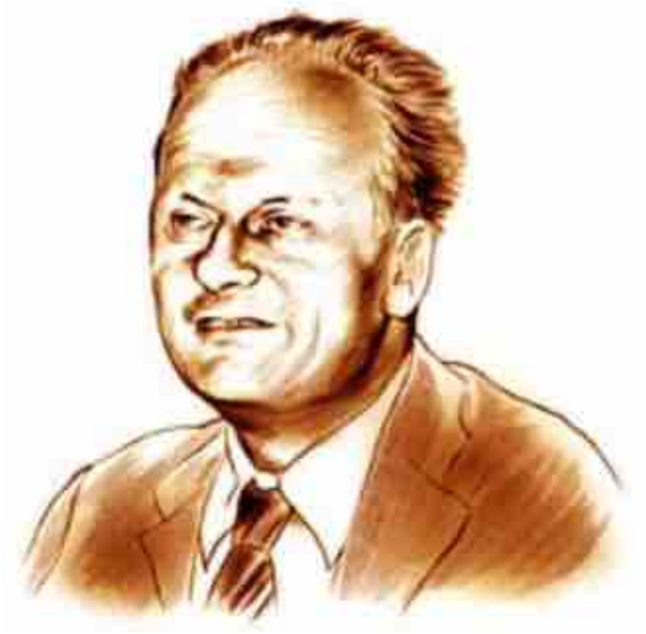
Pioneers: Ray Davis and John Bahcall, starting in '60's

Neutrinos from the Sun





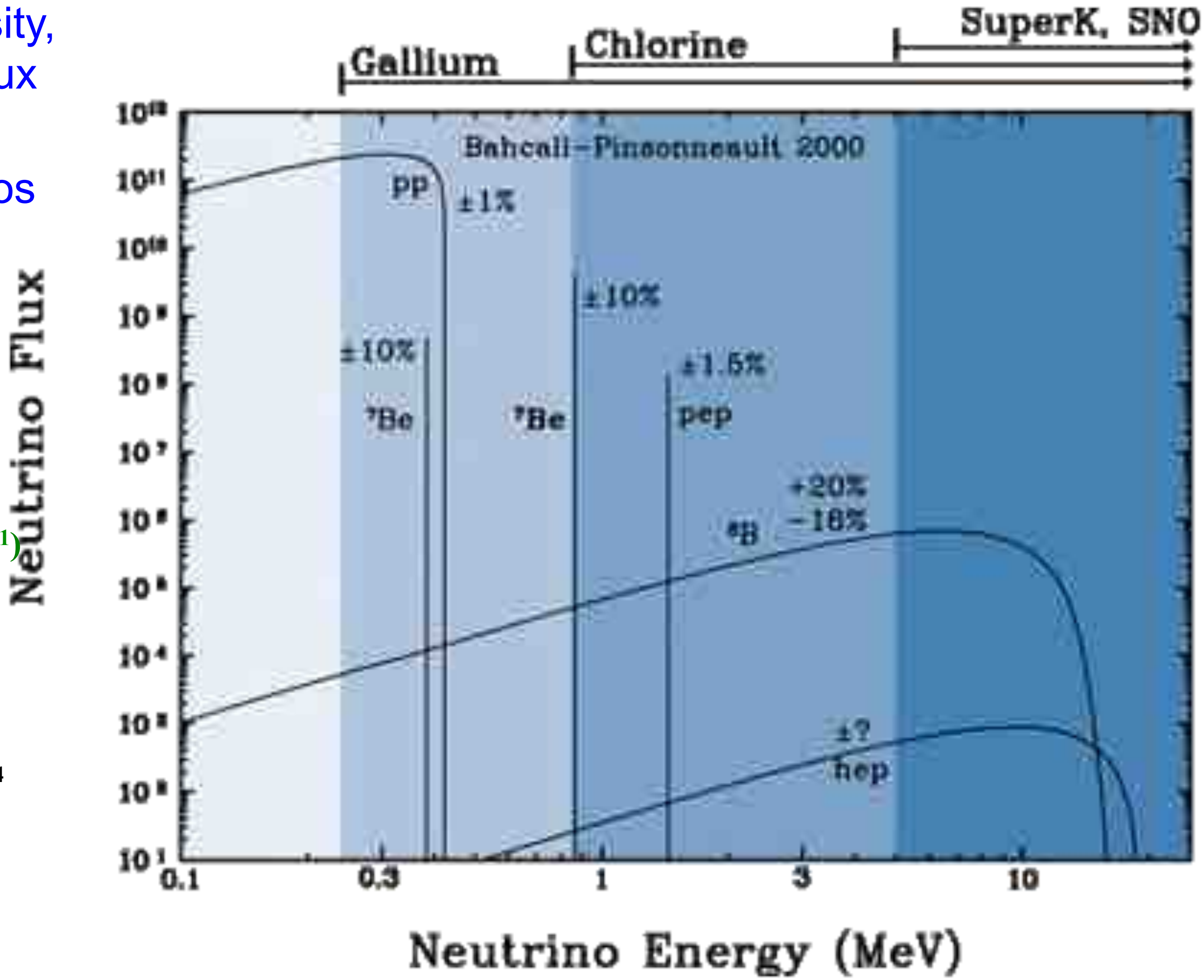
Solar radiation: 98 % light
2 % neutrinos
At Earth 66 billion neutrinos/cm² sec



Hans Bethe (1906–2005, Nobel prize 1967)
Thermonuclear reaction chains (1938)

Solar Neutrino Spectrum

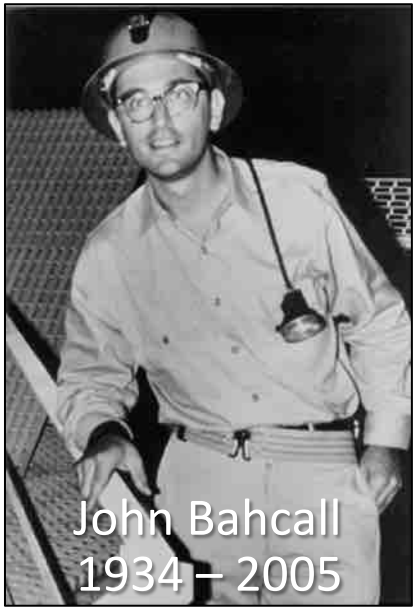
- Many fusion processes in the sun lead to ν's
- Solar model predicts flux
  - From solar luminosity, main pp neutrino flux known to 1%
  - ^{7}Be and ^{8}B neutrinos 10% to 20% uncertainties



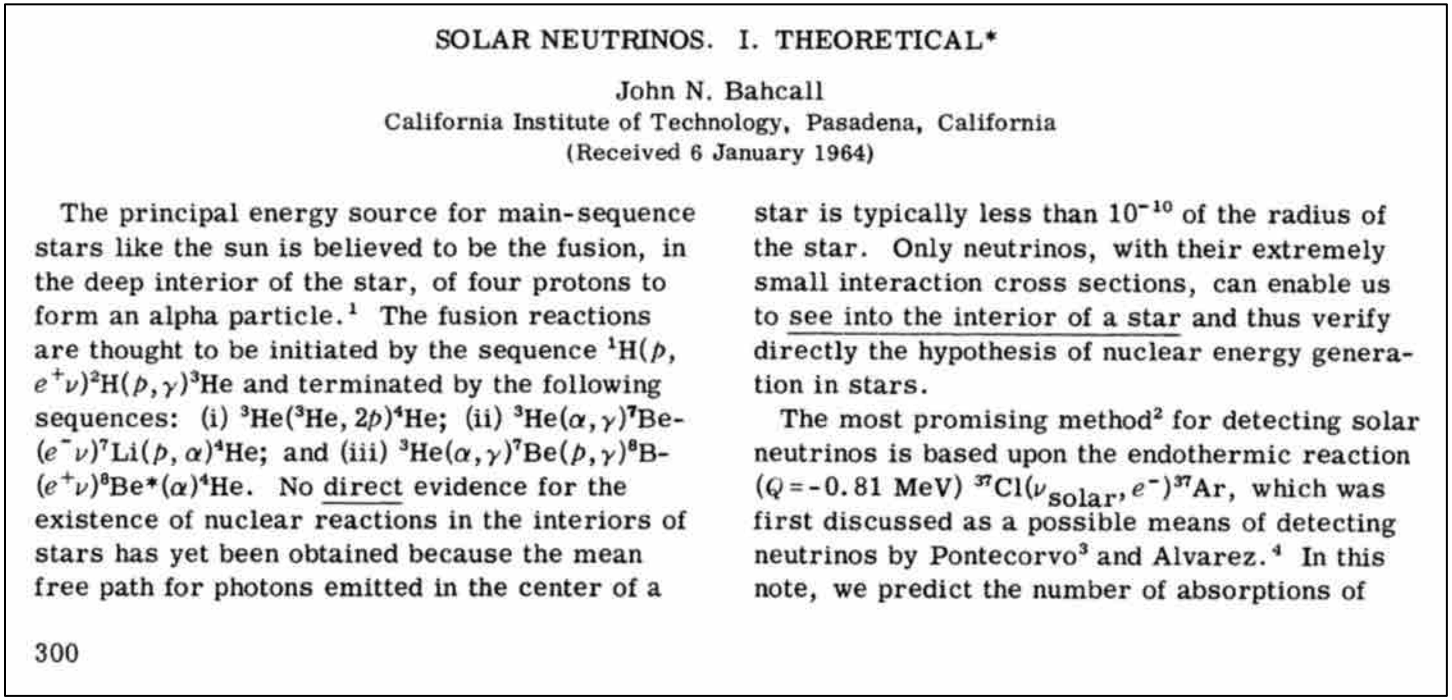
Solar neutrino flux in SSM

Source	Flux (10^{10} cm^{-2} s^{-1})
pp	6.0
pep	0.014
hep	8×10^{-7}
^{7}Be	0.47
^{8}B	5.8×10^{-4}
^{13}N	0.06
^{15}O	0.05
^{17}F	5.2×10^{-4}

Proposing the First Solar Neutrino Experiment



John Bahcall
1934 – 2005



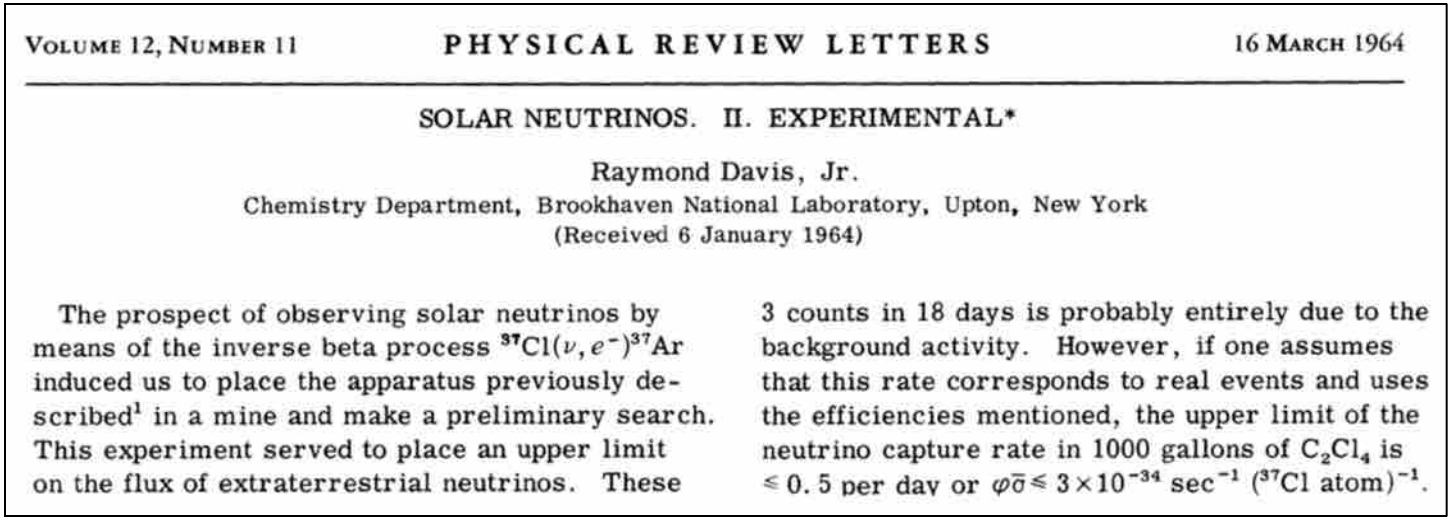
SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^1\mathrm{H}(p, e^+\nu)^2\mathrm{H}(p,\gamma)^3\mathrm{He}$ and terminated by the following sequences: (i) $^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$; (ii) $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}(e^-\nu)^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$; and (iii) $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}(p,\gamma)^8\mathrm{B}(e^+\nu)^8\mathrm{Be}^*(\alpha)^4\mathrm{He}$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) $^{37}\mathrm{Cl}(\nu_{\mathrm{solar}}, e^-)^{37}\mathrm{Ar}$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

Raymond Davis Jr.
1914 – 2006



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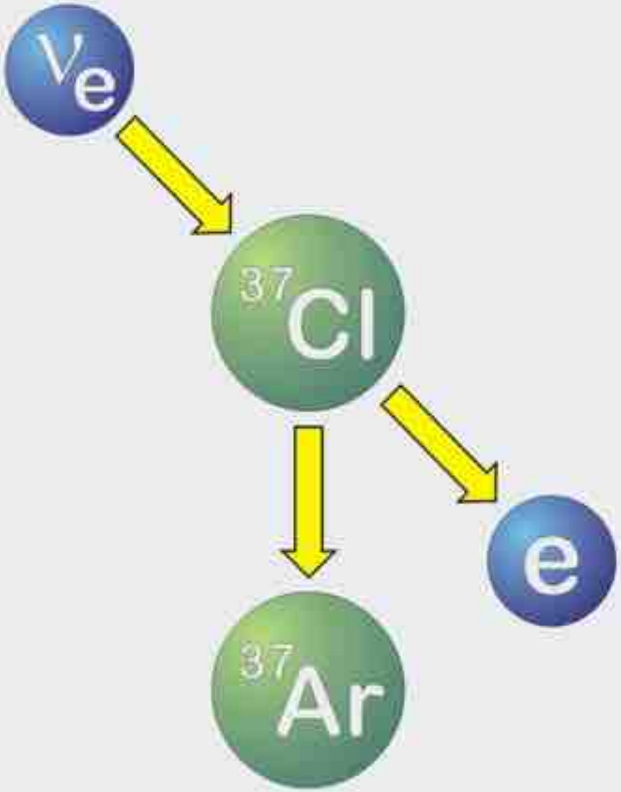
SOLAR NEUTRINOS. II. EXPERIMENTAL*

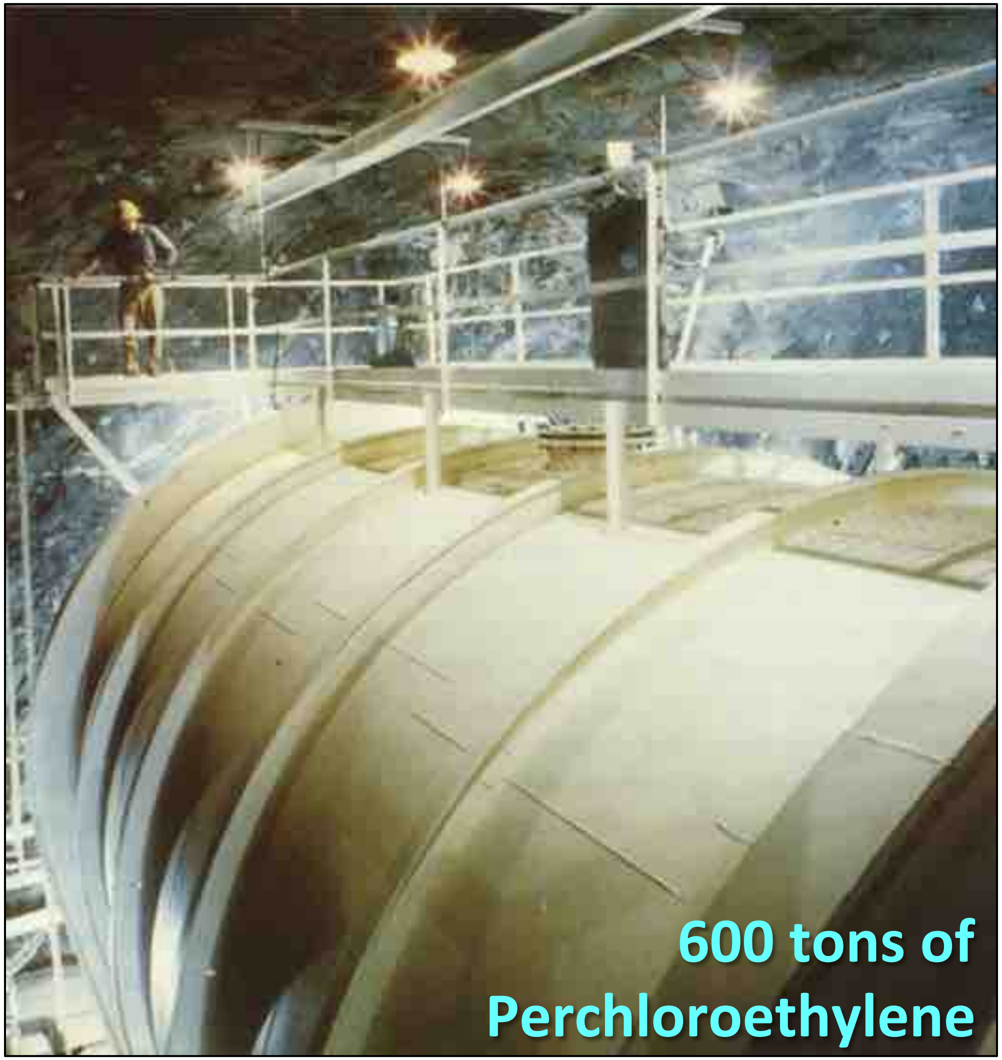
Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}\mathrm{Cl}(\nu, e^-)^{37}\mathrm{Ar}$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These 3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}$ sec^{-1} (^{37}Cl atom)$^{-1}$.

First Measurement of Solar Neutrinos

Inverse beta decay of chlorine




600 tons of Perchloroethylene

Homestake solar neutrino observatory (1967–2002)

2002 Physics Nobel Prize for Neutrino Astronomy

Ray Davis Jr.
(1914–2006)

Masatoshi Koshiba
(*1926)

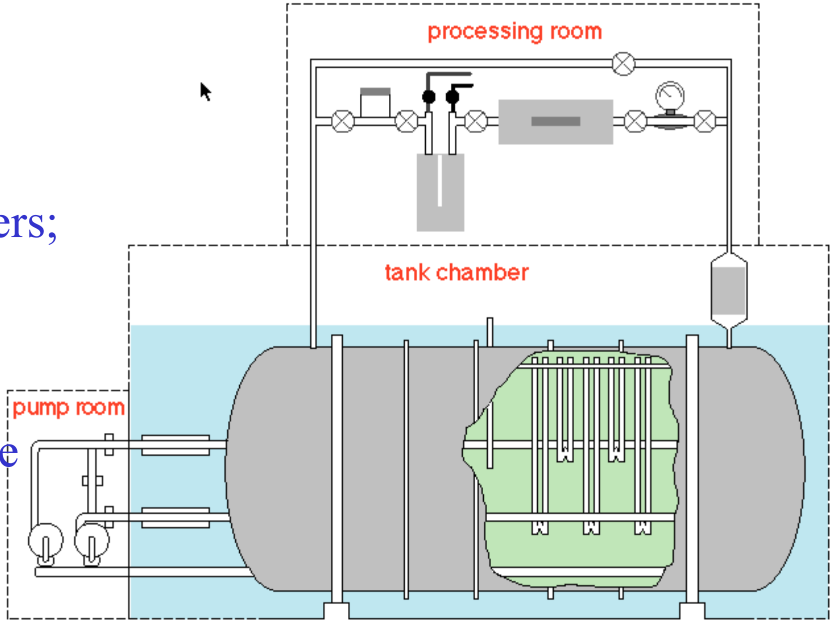
“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

The ^{37}Cl experiment

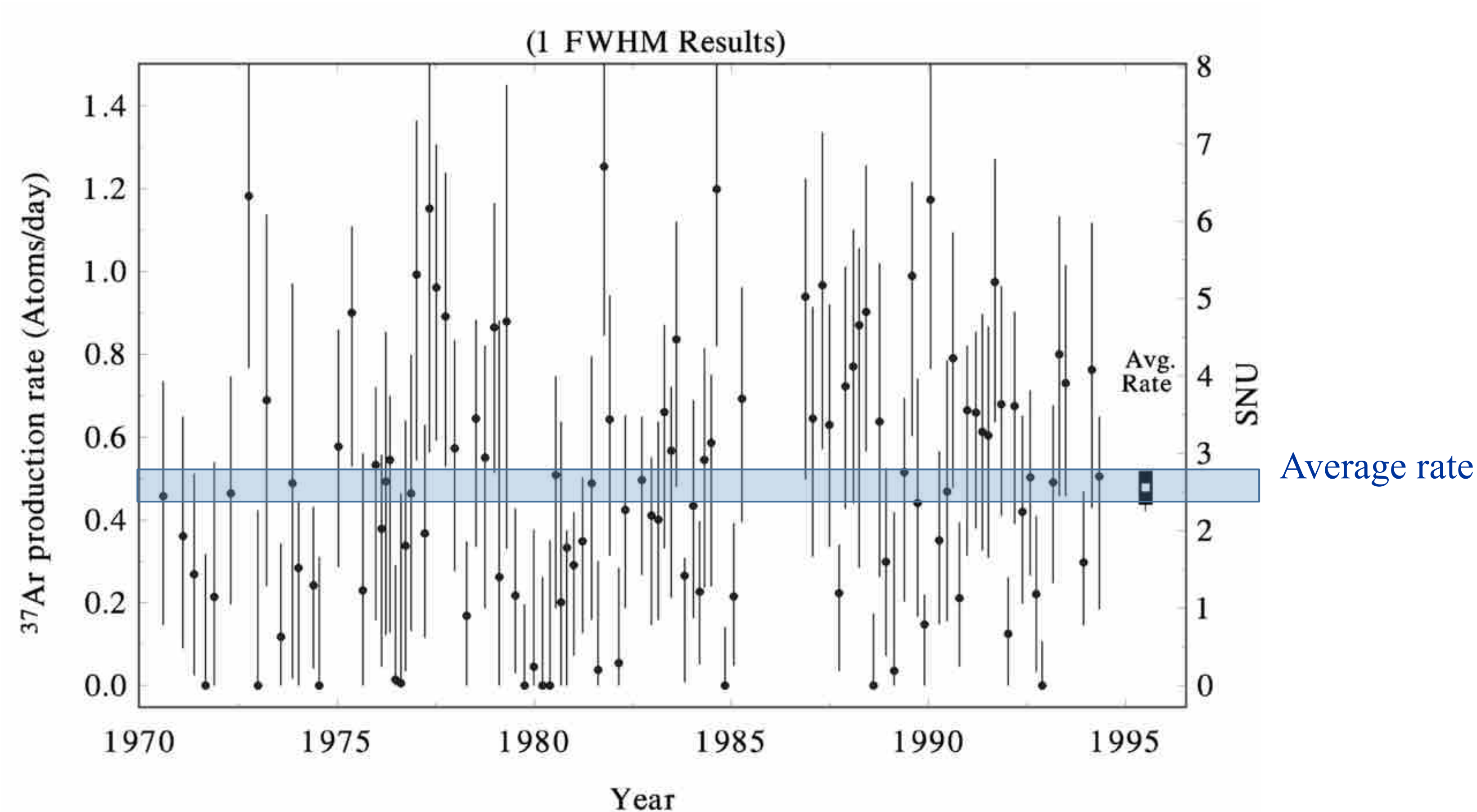
- Reaction : $\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$ $E_{thr} = 0.814$ MeV

It is not sensitive to ν_{pp} but to $({}^{8}\mathrm{B})\nu$

- Exp. site : gold mine of Homestake (4100 m.w.e.)
- Target : 615 tons of C_2Cl_4 , 2.2×10^{30} atoms of ^{37}Cl
- σ_c : 5×10^{-46} cm² @ 1 MeV
  10^{-41} cm² @ 15 MeV
- Procedure :
  - 35-150 days of exposition with 0.1 cm³ of STP of either ^{36}Ar or ^{38}Ar;
  - Ar removed by flushing He;
  - Ar purified by gaschromatography and getters;
  - ^{37}Ar inserted into proportional counters for measuring (EC decay of ^{37}Ar, $T_{1/2}$=35.04 days);
  - analysis with mass spectrometers to measure the amount of the extracted ^{36}Ar or ^{38}Ar



Results of Chlorine Experiment (Homestake)



Average (1970-1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

Theoretical Prediction 6-9 SNU

1 SNU = 10^{-36} capture/atom/s

“Solar Neutrino Problem” since 1968

Kamiokande

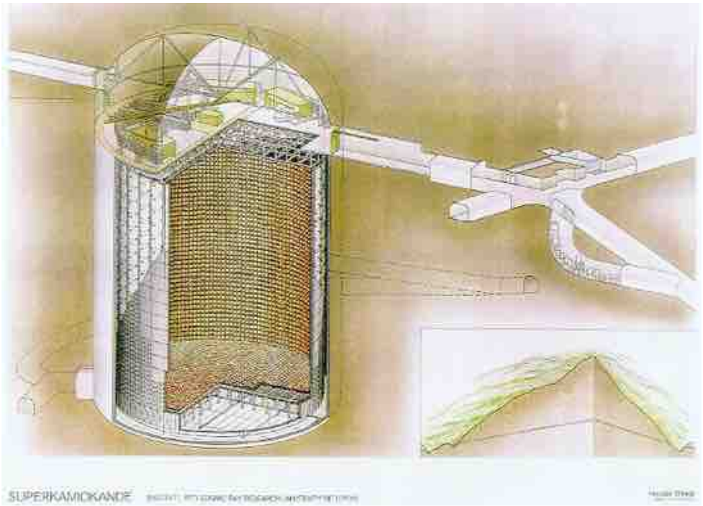
confirms the deficit of high energy solar ν

- Reaction : $\nu + e^- \rightarrow \nu + e^-$ exp. **Thr.:** E = 7.5 MeV
- Exp. site : Kamioka mine (2700 m.w.e.)

Sensitive to (^{8}B)**ν**

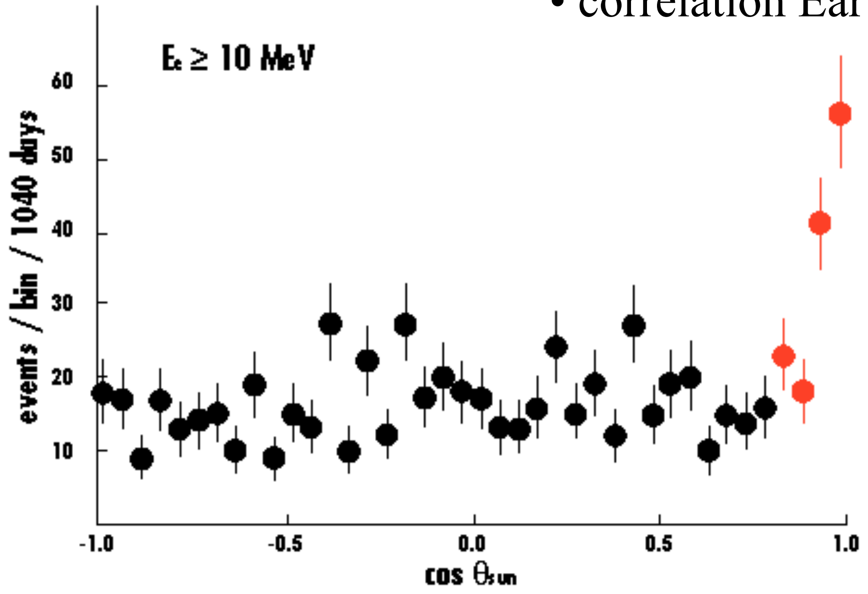
- Target : 680 tons of **H_2O** (fiducial volume) , 2.27×10^{32} e^-

→ charged particles detected by Cerenkov light



Identification of events due to ν_e:

- low energy events
- fiducial volume cut (γ,n)
- cosmic rays cut
- correlation Earth-Sun

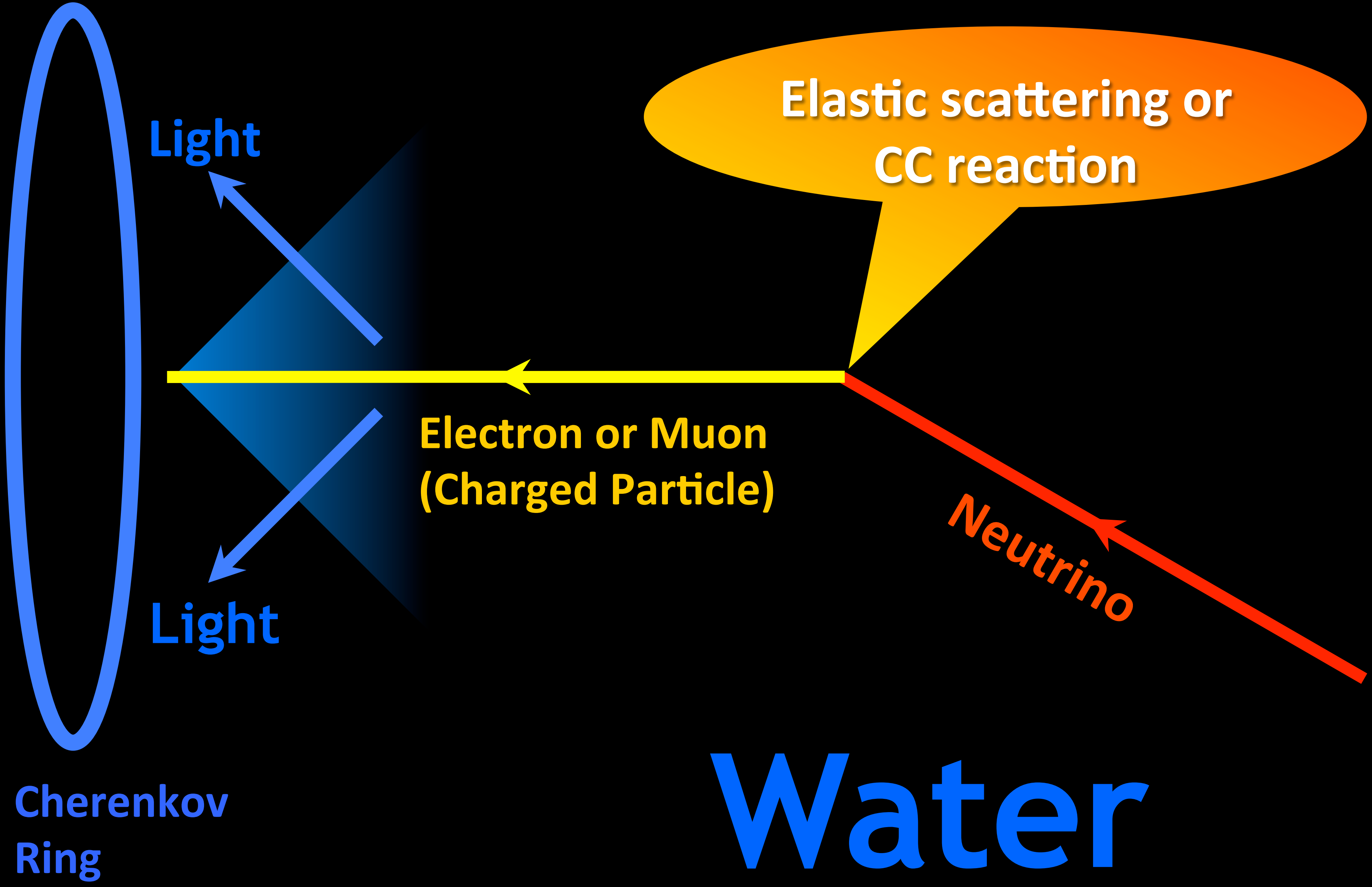


$R_{expected}$ = 0.3 events/days/680 tons (>10 MeV)

Kam. II and III:

Data/SSM = 0.50 ± 0.06 ± 0.06

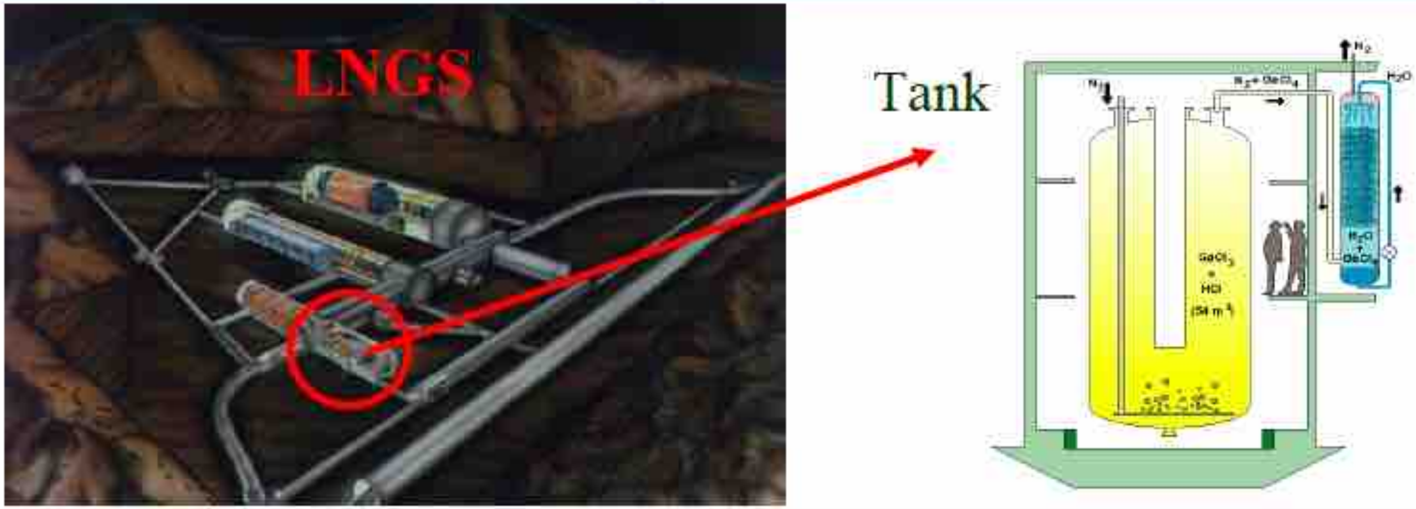
Cherenkov Effect



GALLEX/GNO

- Purpose: measurement of the low energy solar neutrino interaction rate which is related to the sun luminosity (i.e. *model-independent*), with an accuracy of 5 SNU (GNO) and investigation of its time dependence on a solar cycle with a sensitivity ~15% (GNO) .
- Basic interaction: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$ $E_{thr} = 0.233$ MeV ~ 1.2 capture/day expected by SSM

  $\rightarrow {}^{71}\mathrm{Ga}$ EC, τ=16.49 days $T_{1/2}$=11.43 days
- Exp. site: Gran Sasso underground laboratory (3300 m.w.e.)
- Target: 103 tons of $GaCl_3$ acidic solution ⇒ 30 tons of ^{nat}**Ga (12 tons of ^{71}Ga)** in $GaCl_3$ + HCl
- Technique: radiochemical, chemical extraction of ^{71}Ge every 3-4 weeks; detection of 71Ge decay with gas proportional counters
- Expected signal (SSM): ~ 9 ^{71}Ge counts detected per extraction



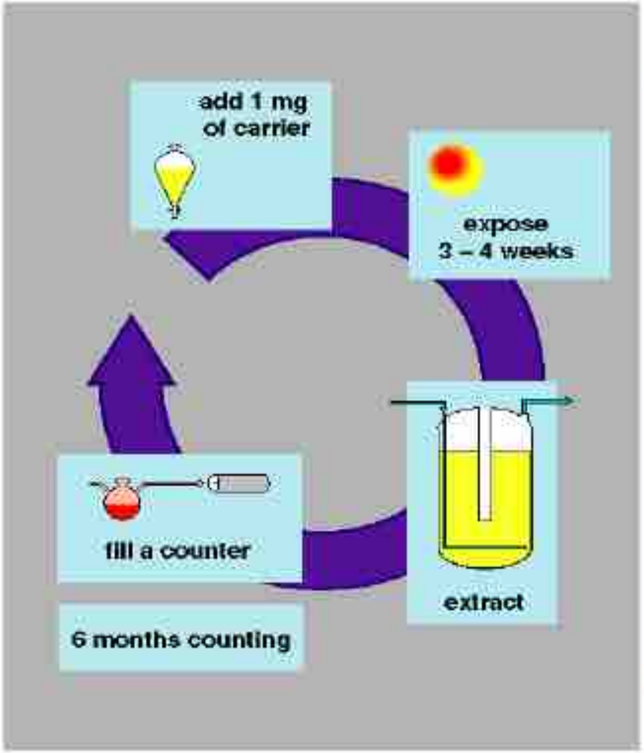
The columns

Proportional counter

The synthesis line

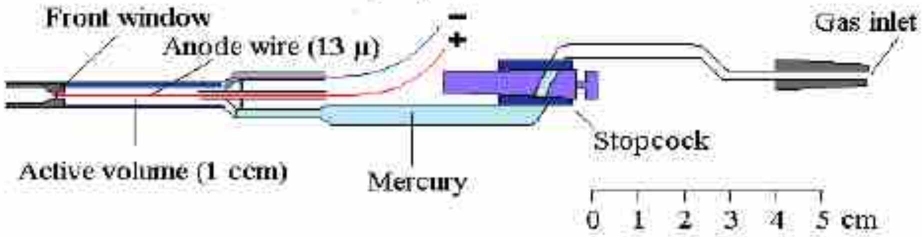
Shielding

Extraction and counting procedures - 1



- 3-4 weeks of exposure to the solar neutrinos (SR) or 1 day for *blank run* (BR).
- ^{71}Ge ($GeCl_4$) extracted in water fluxing ~ 3000 m^3 of nitrogen in the solution
- ^{71}Ge (~ 95%-98%) converted in GeH_4 (gas) and used together with Xe gas to fill a miniaturized proportional counter
- Counting of the ^{71}Ge nuclei through its decays $T_{1/2}$=11.43 days
- Expected signal (SSM): 1.2 n inter./day, but due to decay during exposure + ineff. ~9 ^{71}Ge counts detected per extraction

HD-II proportional counter



Miniaturized Proportional Counter

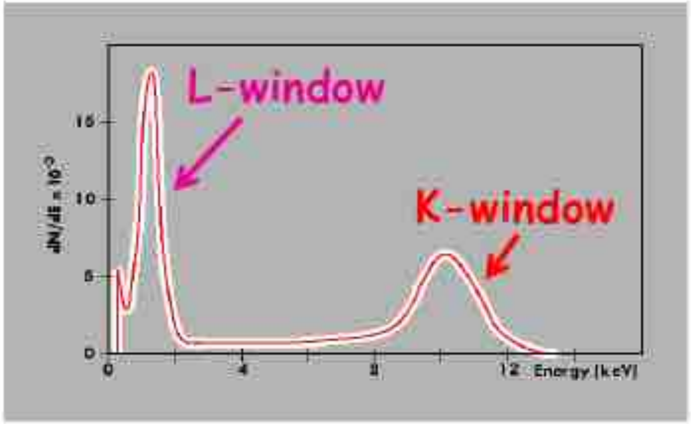
Extraction and counting procedures - 2

Decay processes for ^{71}Ge detection

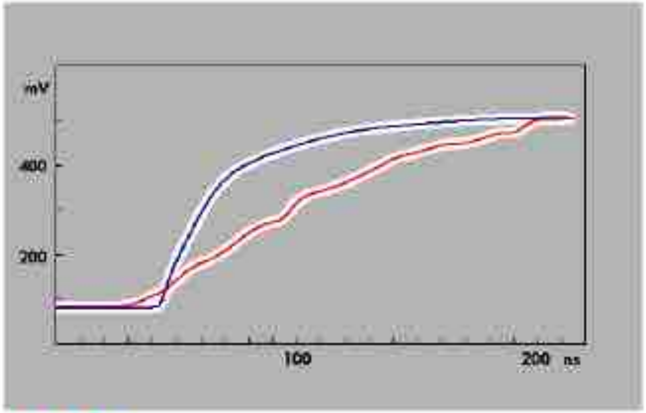
^{71}Ge (EC) → $^{71}Ga^* \rightarrow {}^{71}Ga$ ($t_{1/2}$ = 11.4 d)

	%	Auger (keV)	X-ray (keV)
K	41.5	10.37	-
	41.2	1.12	9.25
	5.3	0.11	10.26
L	10.3	1.30	-
M	1.7	0.16	-

→ fast pulses with the respect to those due to natural radioactivity



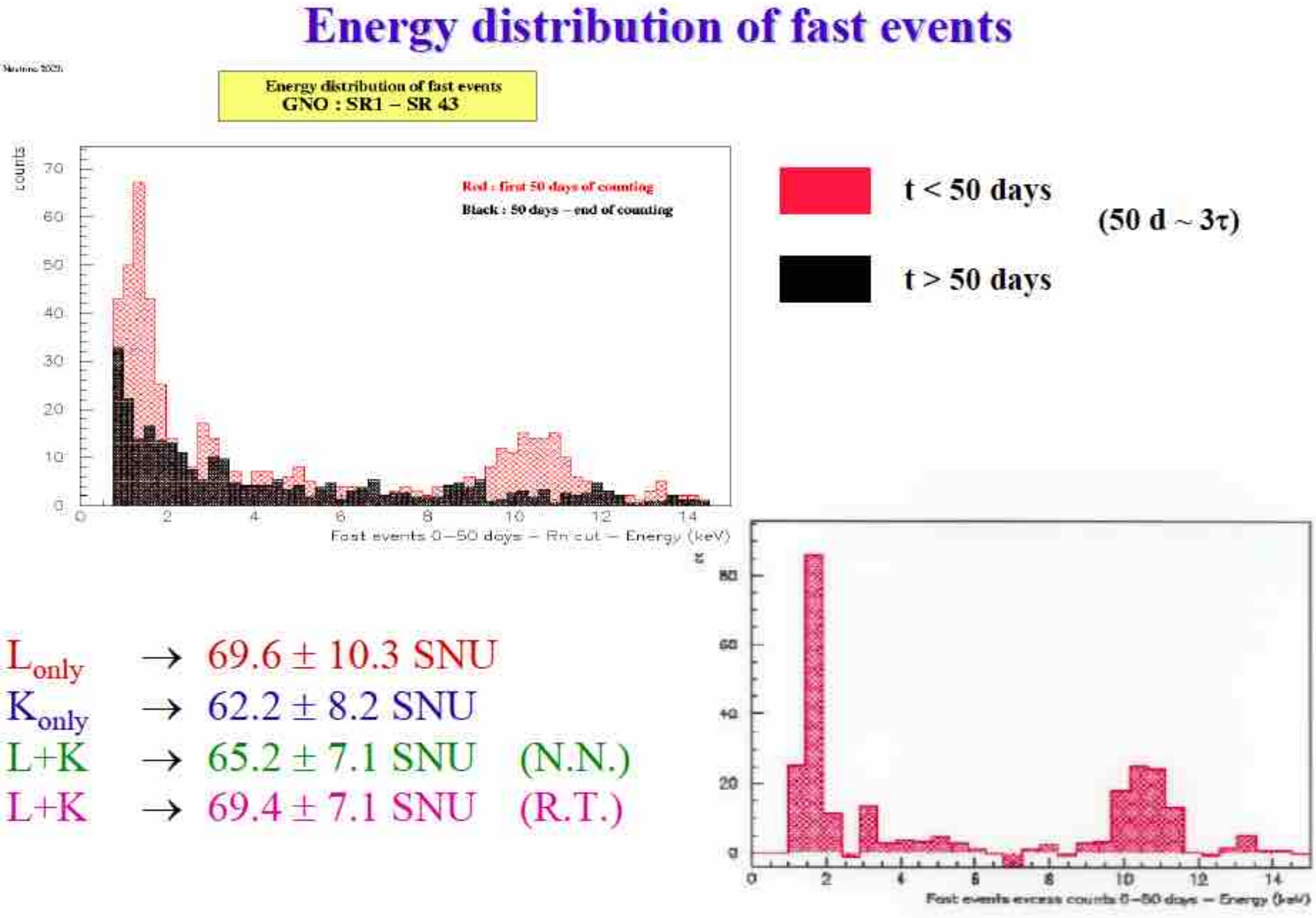
Expected energy distribution



RED: background pulse

BLU: fast event pulse of ^{71}Ge decay

Few hundred of events in several years of running



Energy distribution of fast events

Neutrino 2004

Energy distribution of fast events
GNO : SR1 – SR 43

🟥 t < 50 days

⬛ t > 50 days

(50 d ~ 3τ)

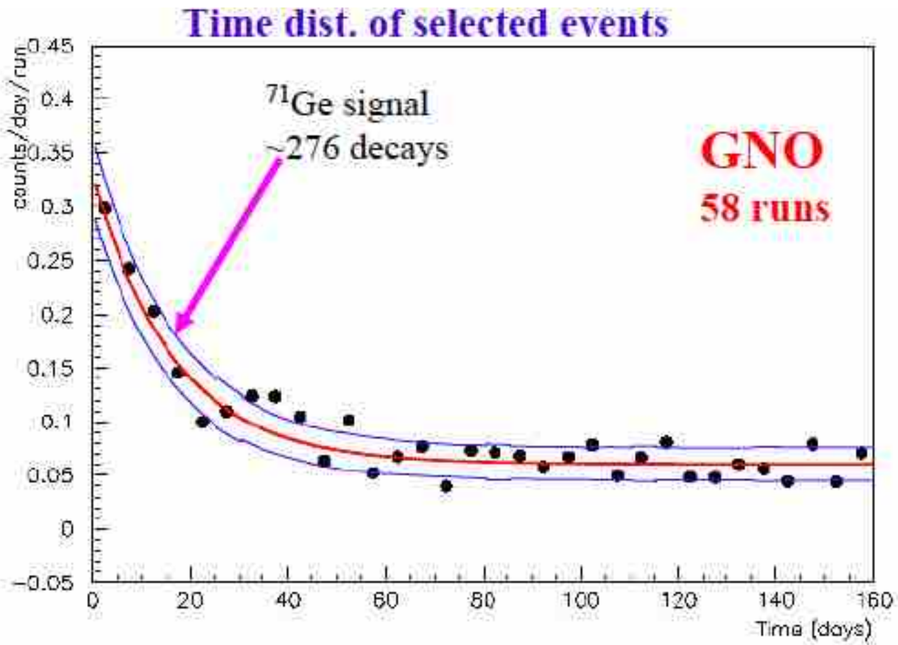
L_{only} → 69.6 ± 10.3 SNU

K_{only} → 62.2 ± 8.2 SNU

L+K → 65.2 ± 7.1 SNU (N.N.)

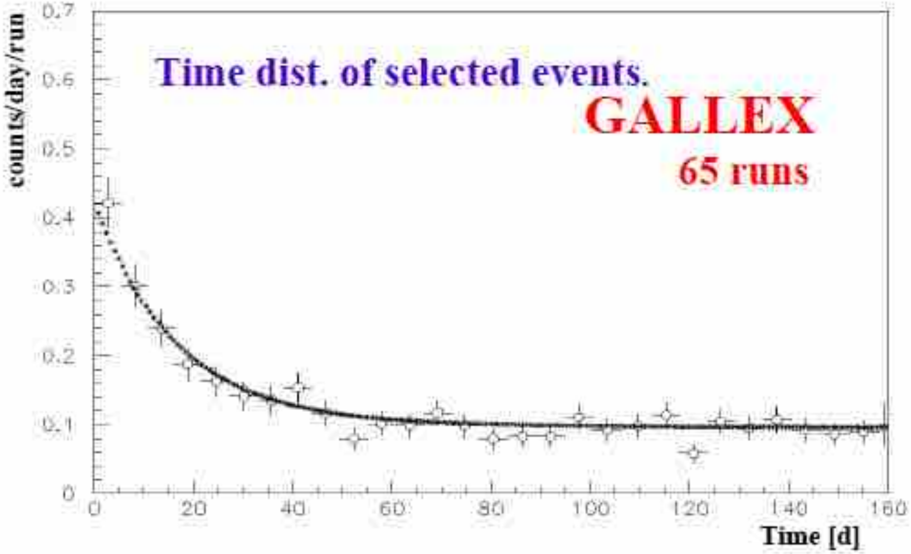
L+K → 69.4 ± 7.1 SNU (R.T.)

Few hundred of events in several years of running



$\tau\,(^{71}\mathrm{Ge}) = 16.6 \pm 2.1$ d

$\tau_{true}\,(^{71}\mathrm{Ge}) = 16.49$ d



Reduction of the bckg GNO vs Gallex 30%

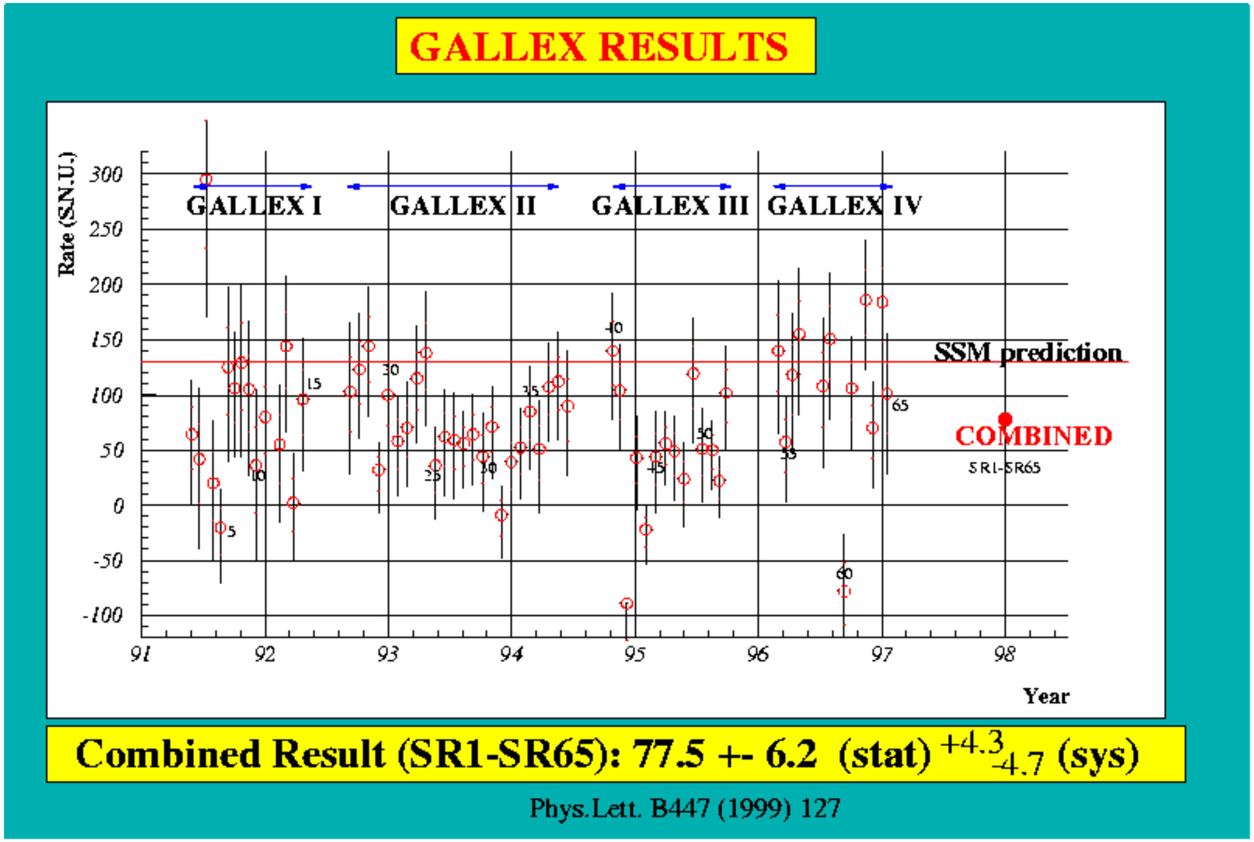
from 0.1 c/day/run to 0.07 c/day/run

GALLEX results

(Low energy ν measurements)

Capture Rate expected in
SSM for ^{71}Ga *

Source	Rate (SNU)
pp	70.8
pep	3.0
hep	0.06
^{7}Be	34.3
^{8}B	14.0
^{13}N	3.8
^{15}O	6.1
^{17}F	0.06
TOTAL	**132 SNU**



Combined Result (SR1-SR65): 77.5 +- 6.2 (stat) $^{+4.3}_{-4.7}$ (sys)

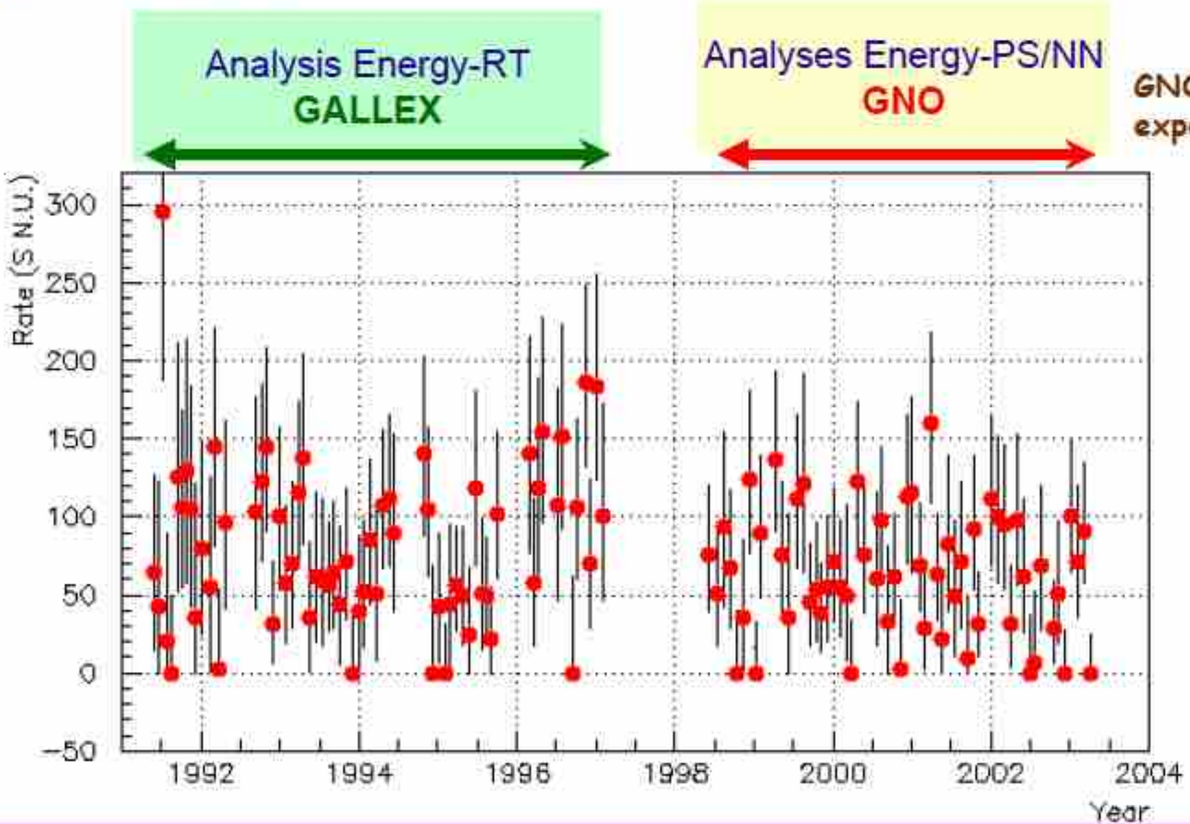
Phys.Lett. B447 (1999) 127

Data/SSM $= 0.59 \pm 0.06$

*Bahcall 1990

Gallex + GNO results: Davis plot

Total exposure time: 3307 d



GNO: 276 ^{71}Ge in 1713 d exposure time

GALLEX	65 SR	77.5 ± 6.2 (stat) ± 4.5 (sys) SNU
GNO	58 SR	62.9 ± 5.4 (stat) ± 2.5 (sys) SNU
GALLEX + GNO	123 SR	69.3 ± 4.1 (stat) ± 3.6 (sys) SNU

- observation of pp fusion in the solar core
- definitive deficit of ^{7}Be and pp ν not explainable by solar physics

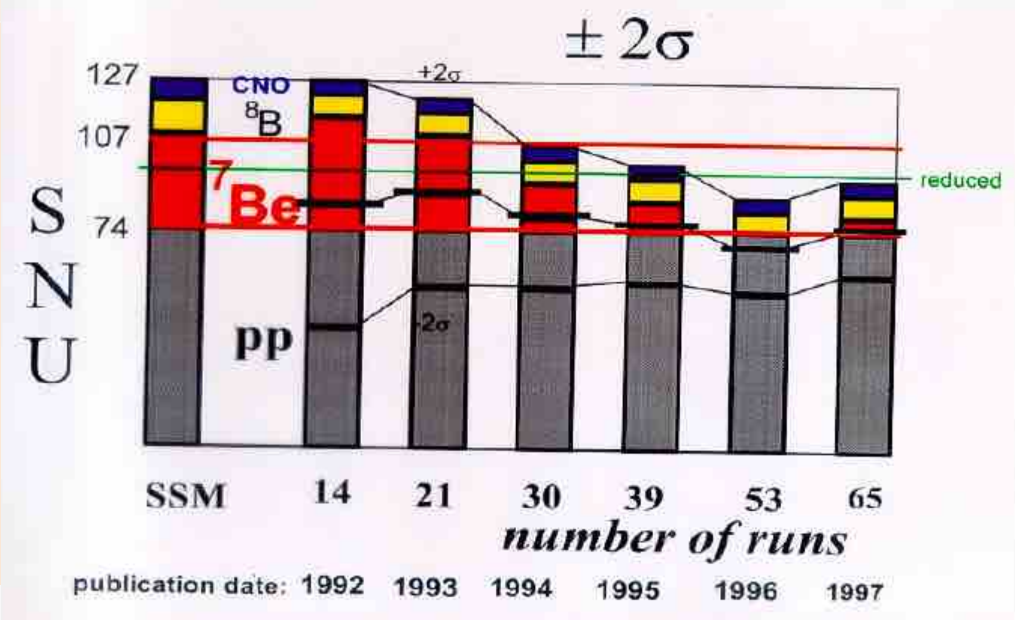
+ reliability of the radiochemical (solar-ν) experiments (ν-sources, As-test)

GALLEX and GNO legacy

- Construction of the detector: 1986-1990
- GALLEX runs: May 14, 1991 – Jan 23, 1997
- First ^{51}Cr ν source expt: Jun 1994 – Oct 1994
- Second ^{51}Cr ν source expt: Oct 1995 – Feb 1996
- Tests with ^{71}As: Feb 1997 – Apr 1997
- Improvements towards GNO: Apr 1997 – Apr 1998
- GNO runs: May, 20 1998 – Apr, 9 2003

GALLEX legacy:

- observation of pp fusion in the solar core
- definitive deficit of ^{7}Be (or pp) ν not explainable by solar physics
- reliability of the radiochemical (solar-ν) experiments (ν-sources, As-test)



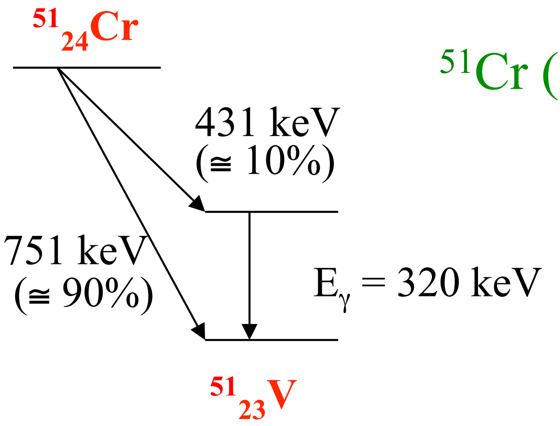
Why a ν source experiment?

To place trustworthiness of the experimental techniques (excluding unforseen effects)

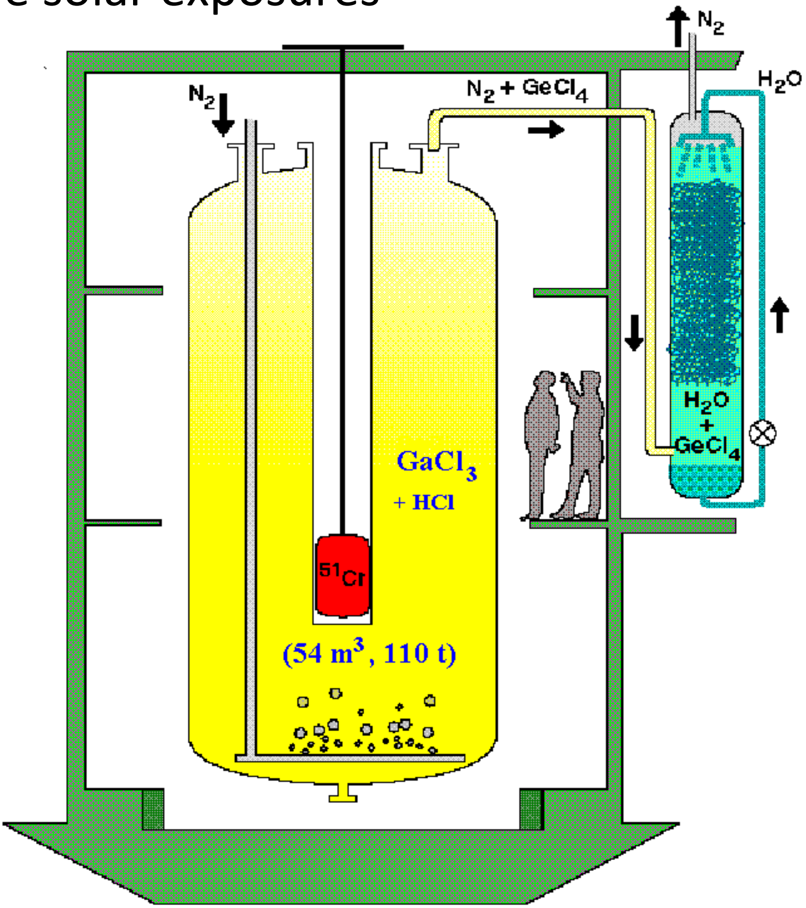
How? Exposing the target to ν's of suitable energy from source of known activity in the same condition than in the solar exposures

Needs

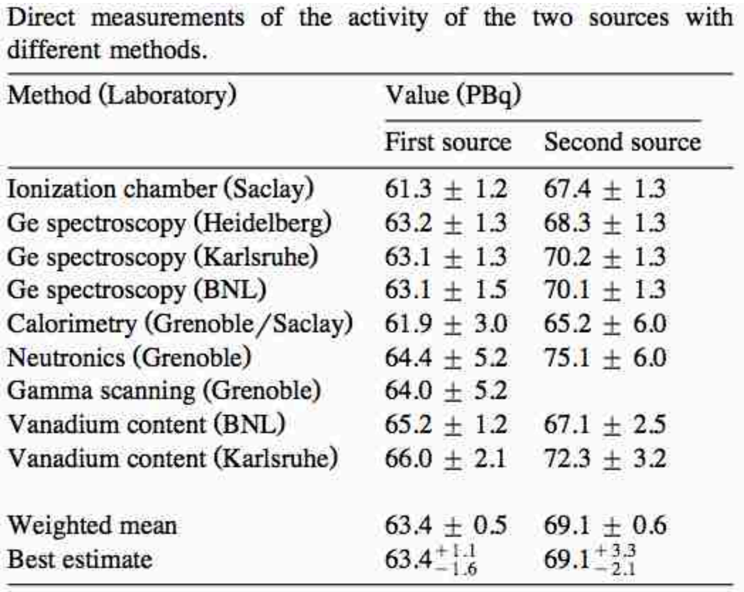
>50 PBq	build a ν source with activity allowing a precision on ≈9% in the measurements
^{51}Cr	ν energy close to solar ν detected in the experiments
(27.706 ± 0.007)	$T_{1/2}$ sufficient to transport the source and perform the experiment



$$^{51}Cr\ (EC) \rightarrow {}^{51}V + \nu_e$$



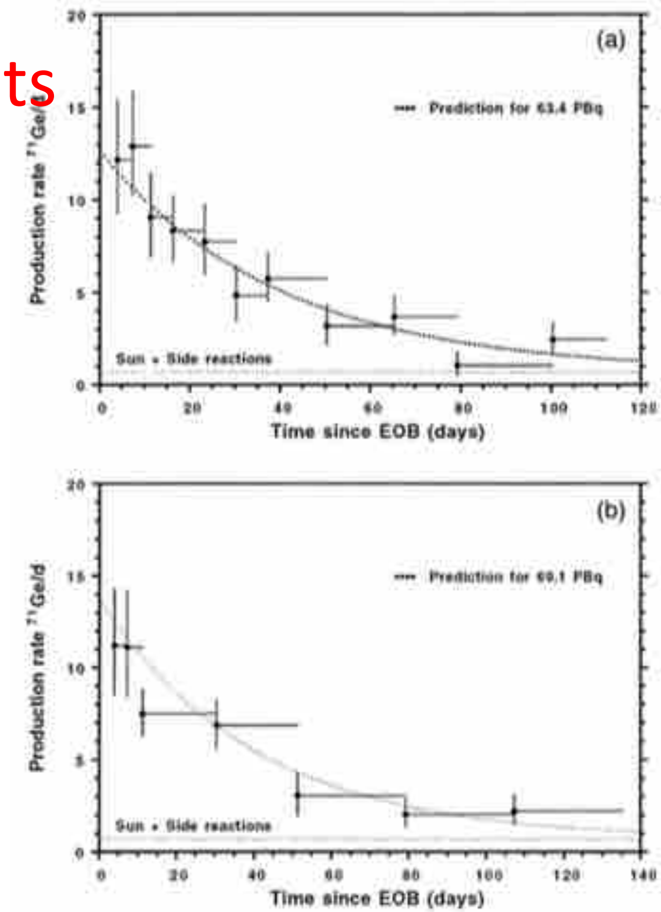
Response of GALLEX to ^{51}Cr source expts



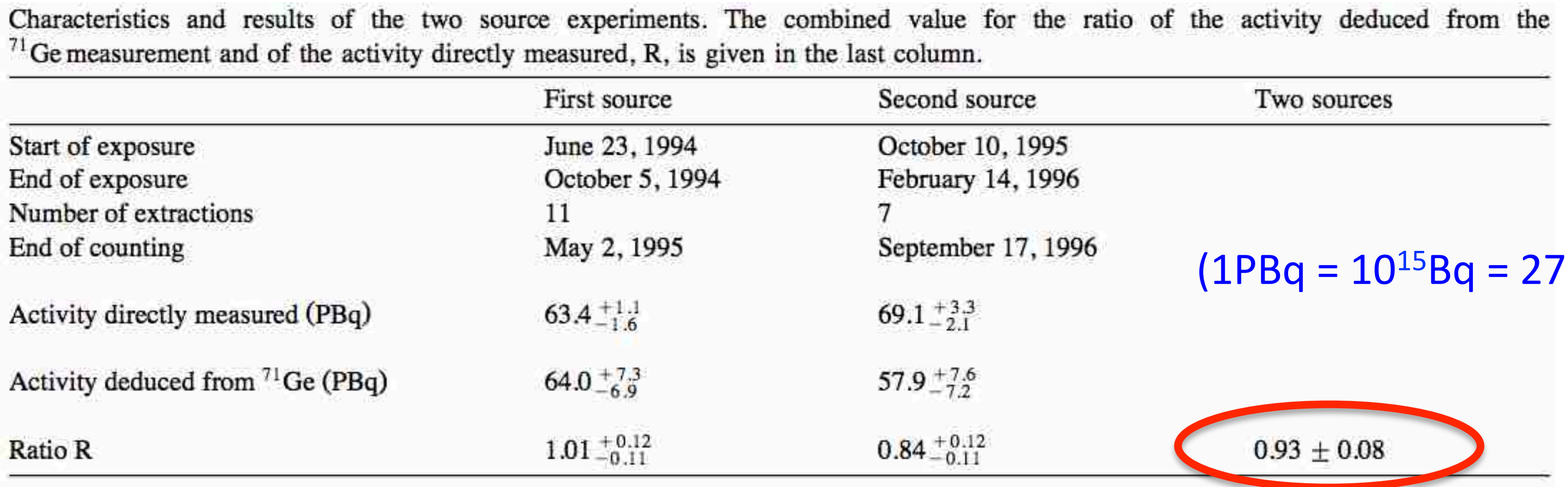
Direct measurements of the activity of the two sources with different methods.

Method (Laboratory)	Value (PBq)	
	First source	Second source
Ionization chamber (Saclay)	61.3 ± 1.2	67.4 ± 1.3
Ge spectroscopy (Heidelberg)	63.2 ± 1.3	68.3 ± 1.3
Ge spectroscopy (Karlsruhe)	63.1 ± 1.3	70.2 ± 1.3
Ge spectroscopy (BNL)	63.1 ± 1.5	70.1 ± 1.3
Calorimetry (Grenoble/Saclay)	61.9 ± 3.0	65.2 ± 6.0
Neutronics (Grenoble)	64.4 ± 5.2	75.1 ± 6.0
Gamma scanning (Grenoble)	64.0 ± 5.2	
Vanadium content (BNL)	65.2 ± 1.2	67.1 ± 2.5
Vanadium content (Karlsruhe)	66.0 ± 2.1	72.3 ± 3.2
Weighted mean	63.4 ± 0.5	69.1 ± 0.6
Best estimate	$63.4^{+1.1}_{-1.6}$	$69.1^{+3.3}_{-2.1}$

- First observation of low energy ν from artificial terrestrial source
- Confirmation of solar ν deficit
- General check of the experiment



- Radiochemical techniques are reliable: it is possible to extract few atoms from 30 tons and to count their decays

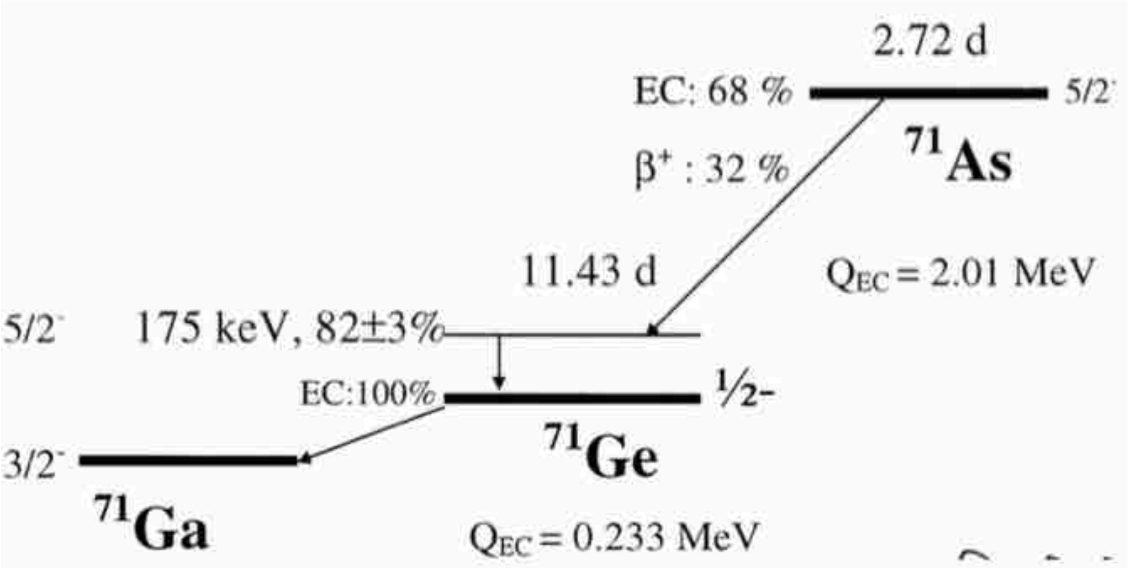


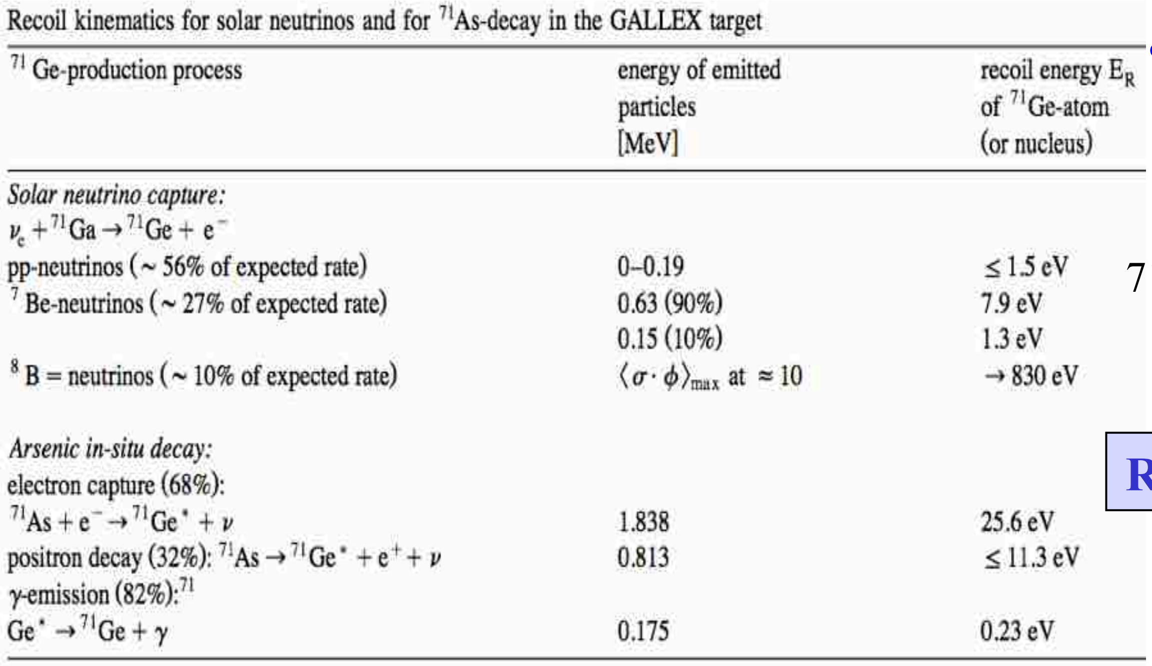
Characteristics and results of the two source experiments. The combined value for the ratio of the activity deduced from the ^{71}Ge measurement and of the activity directly measured, R, is given in the last column.

	First source	Second source	Two sources
Start of exposure	June 23, 1994	October 10, 1995	
End of exposure	October 5, 1994	February 14, 1996	
Number of extractions	11	7	
End of counting	May 2, 1995	September 17, 1996	
Activity directly measured (PBq)	$63.4^{+1.1}_{-1.6}$	$69.1^{+3.3}_{-2.1}$	
Activity deduced from ^{71}Ge (PBq)	$64.0^{+7.3}_{-6.9}$	$57.9^{+7.6}_{-7.2}$	
Ratio R	$1.01^{+0.12}_{-0.11}$	$0.84^{+0.12}_{-0.11}$	0.93 ± 0.08

(1PBq = 10^{15}Bq = 27.0 kCi)

^{71}As tests in GALLEX





Recoil kinematics for solar neutrinos and for ^{71}As-decay in the GALLEX target

^{71}Ge-production process	energy of emitted particles [MeV]	recoil energy E_R of ^{71}Ge-atom (or nucleus)
Solar neutrino capture:		
$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$		
pp-neutrinos (~ 56% of expected rate)	0–0.19	≤ 1.5 eV
^{7}Be-neutrinos (~ 27% of expected rate)	0.63 (90%)	7.9 eV
	0.15 (10%)	1.3 eV
^{8}B = neutrinos (~ 10% of expected rate)	$\langle \sigma \cdot \phi \rangle_{\max}$ at ≈ 10	→ 830 eV
Arsenic in-situ decay:		
electron capture (68%):		
$^{71}\text{As} + e^- \to {}^{71}\text{Ge}^* + \nu$	1.838	25.6 eV
positron decay (32%): $^{71}\text{As} \to {}^{71}\text{Ge}^* + e^+ + \nu$	0.813	≤ 11.3 eV
γ-emission (82%): $^{71}\text{Ge}^* \to {}^{71}\text{Ge} + \gamma$	0.175	0.23 eV

- Introduction of about 10^5 atoms of ^{71}As inside the tank in the solution
- Repeated tests under variable conditions with respect to:
  - Method and magnitude of carrier addition
  - Mixing and extraction conditions
  - Standing time
- To exclude withholdings (classical or "hot-atom" effects)

$$^{71}\text{As} \xrightarrow[T_{1/2} = 2.72\ \text{giorni}]{\text{EC}(68\%),\ \beta^+(32\%)} {}^{71}\text{Ge}$$

Recovery factor = (99.9 ± 0.8) %

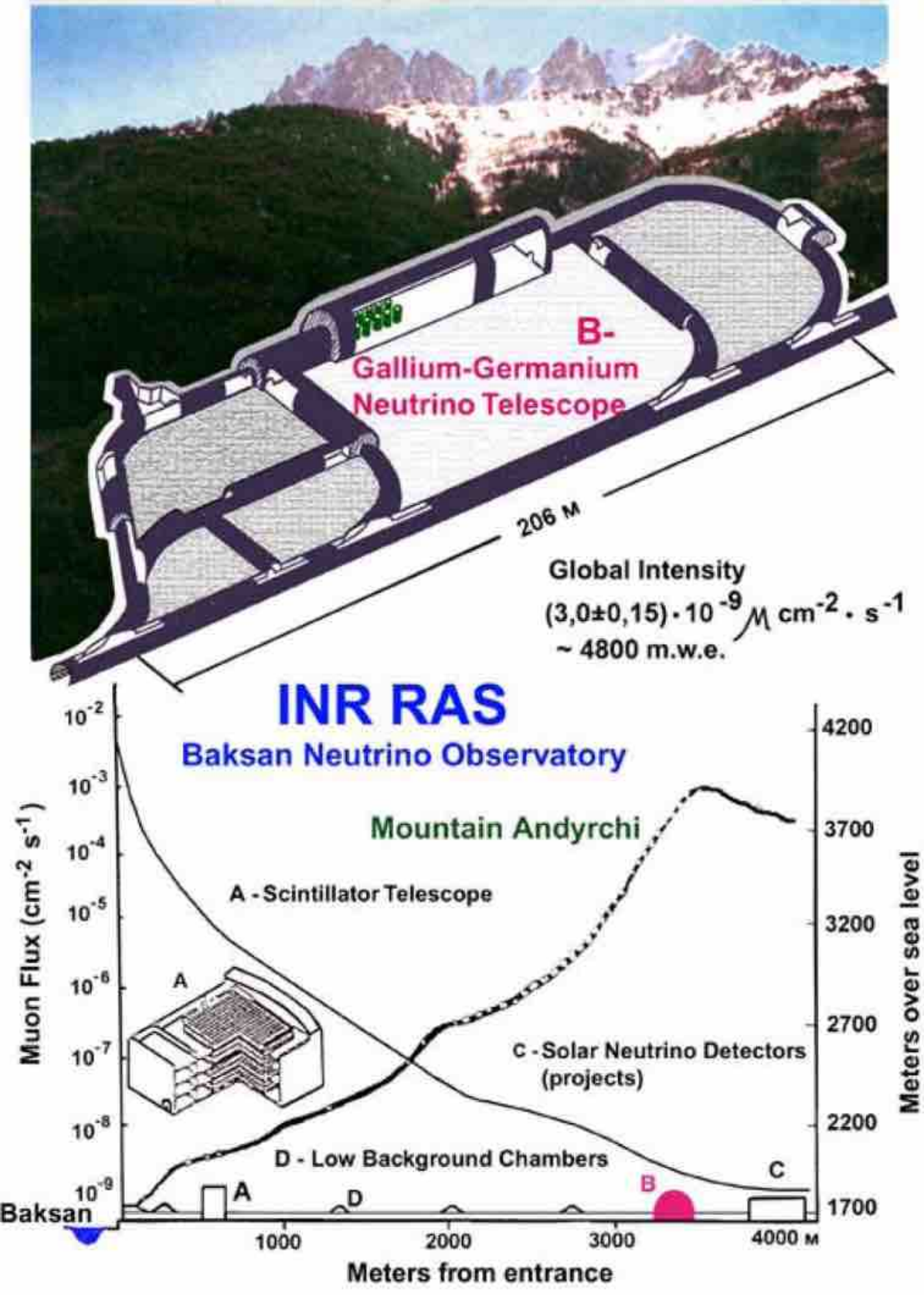
SAGE Soviet-American Gallium Experiment

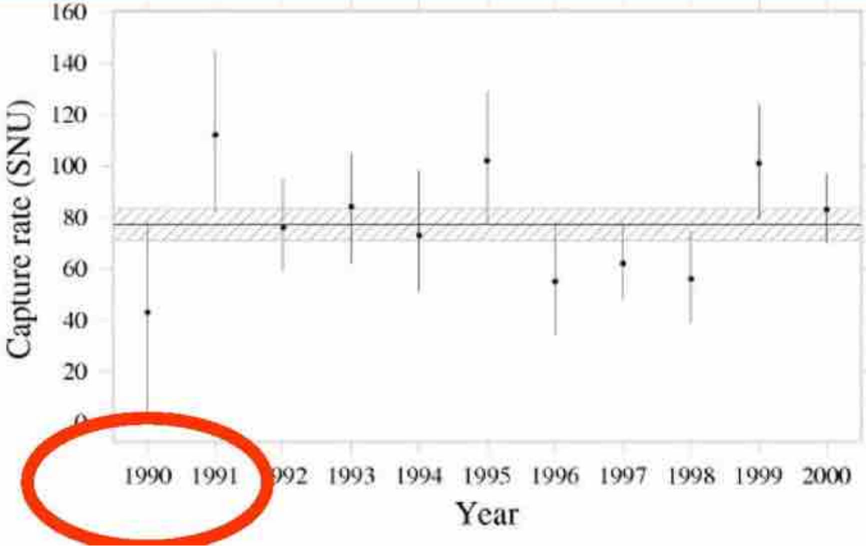
$^{71}Ga + \nu \rightarrow {}^{71}\Gamma\varepsilon + \varepsilon^-$

Sensitive to pp fusion in sun.

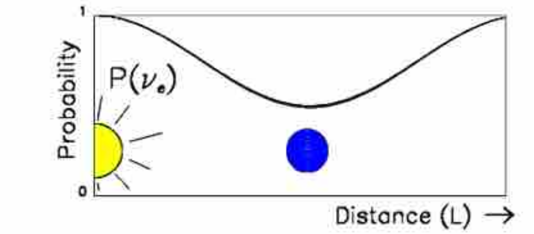
50 metric tons of Gallium
They extract a *few tens of atoms*
of Germanium

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





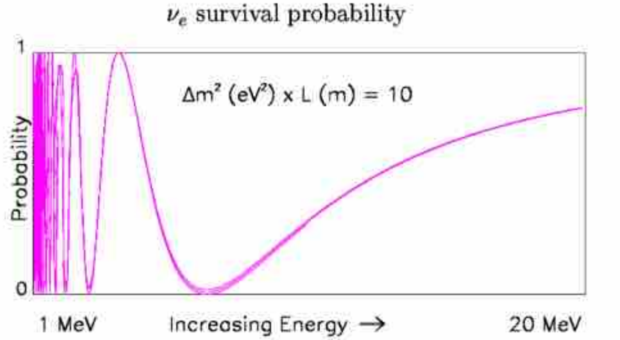
Vacuum neutrino oscillations



Interaction eigenstates are linear combination of mass eigenstates

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

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



An electron neutrino evolves in time into the state

$$|\nu_e(t)\rangle = \cos\theta e^{i E_1 t}\,|\nu_1\rangle + e^{i E_2 t}\sin\theta\,|\nu_2\rangle$$

Probability amplitude for e-nu to mu-nu conversion

$$A(\nu_e \rightarrow \nu_\mu) = \langle \nu_\mu | \nu_e(t) \rangle$$

$$= -\sin\theta\cos\theta e^{iE_1 t} + \cos\theta\sin\theta e^{iE_2 t}$$

$$= \sin 2\theta \frac{e^{iE_2 t} - e^{iE_1 t}}{2}$$

Probability of nu-e to convert into nu-mu

$$P(\nu_e \rightarrow \nu_\mu) = |A(\nu_e \rightarrow \nu_\mu)|^2$$

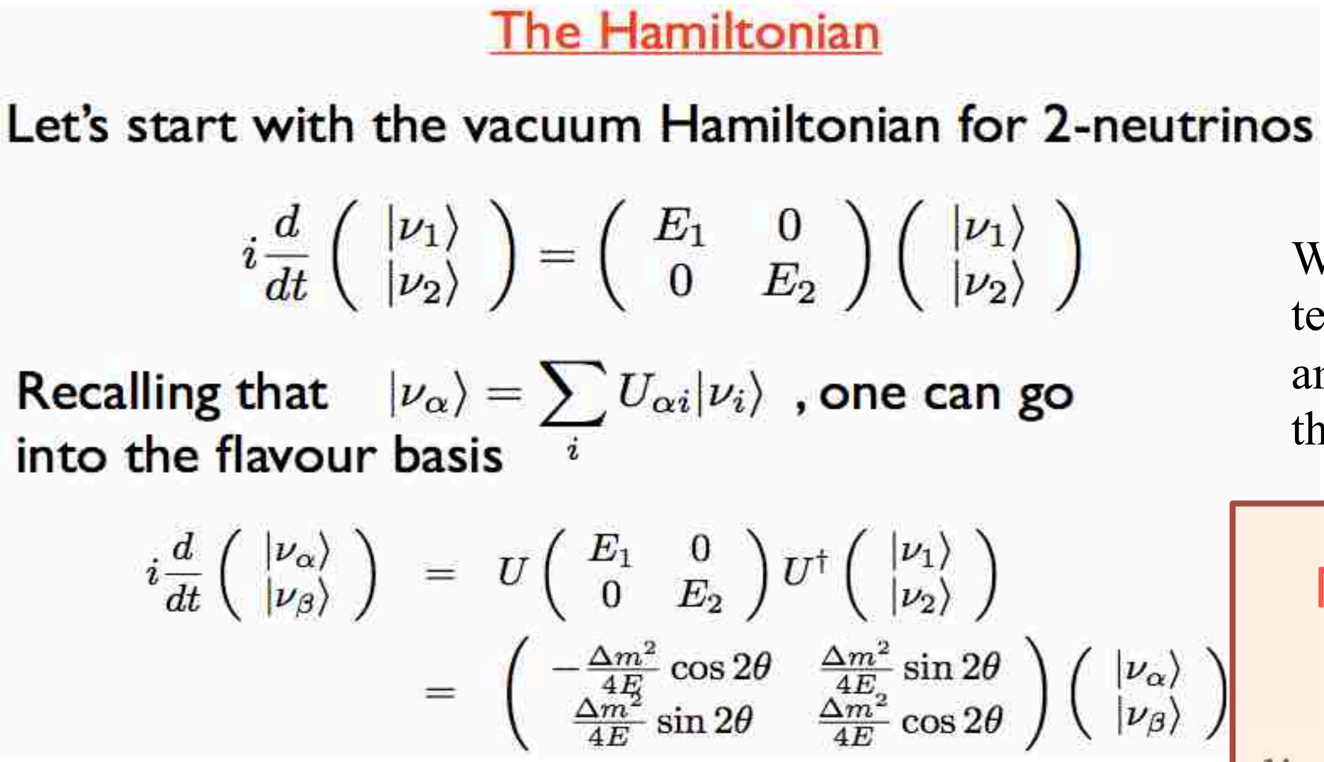
Δm^2 in eV^2; L in km; E in GeV

When neutrinos are relativistic

$$(E_2 - E_1) = \sqrt{(p^2 + m_2^2)} - \sqrt{(p^2 + m_1^2)} = \frac{\Delta m^2}{2p}$$

Neutrinos can change flavour during propagation with a probability

$$\boxed{P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)}$$



The Hamiltonian

Let's start with the vacuum Hamiltonian for 2-neutrinos

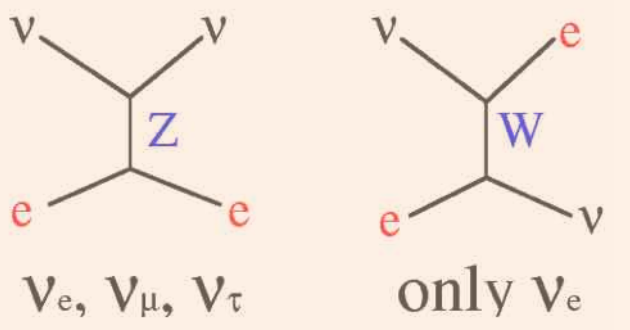
$$i\frac{d}{dt}\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix} = \begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

Recalling that $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$, one can go into the flavour basis

$$\begin{aligned} i\frac{d}{dt}\begin{pmatrix} |\nu_\alpha\rangle \\ |\nu_\beta\rangle \end{pmatrix} &= U\begin{pmatrix} E_1 & 0 \\ 0 & E_2 \end{pmatrix}U^\dagger\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix} \\ &= \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix} |\nu_\alpha\rangle \\ |\nu_\beta\rangle \end{pmatrix} \end{aligned}$$

We have neglected common terms on the diagonal as they amount to an overall phase in the evolution.

Neutrino oscillations in matter



The full Hamiltonian in matter can then be obtained by adding the potential terms, diagonal in the flavour basis. For electron and muon neutrinos

$$\boxed{i\frac{d}{dt}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}}$$

For antineutrinos the potential has the opposite sign.

In general, it is very difficult to find analytical solution to this problem.

Solar neutrinos: MSW effect

The oscillations in matter were first discussed in L. Wolfenstein, S. P. Mikheyev, A. Yu Smirnov.

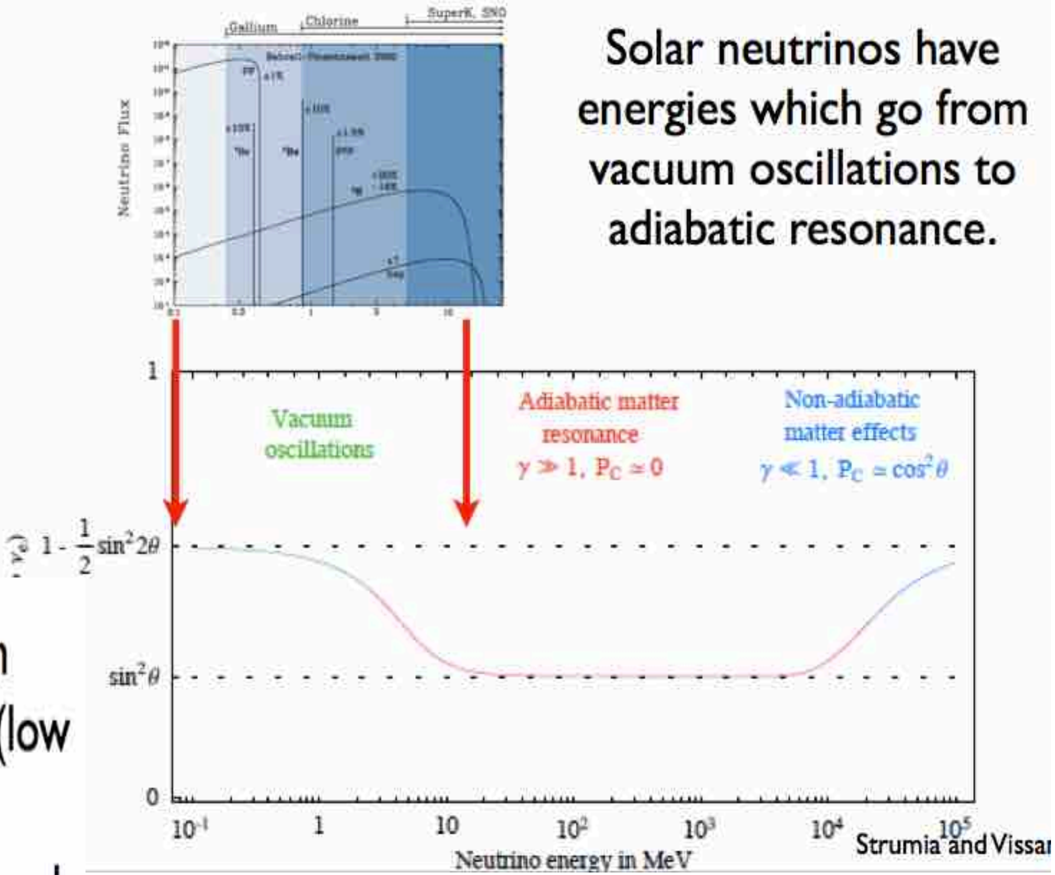
- Production in the center of the Sun: matter effects dominate at high energy, negligible at low energy.

The probability of ν_e to be

ν_A is $\cos^2\theta_m$
ν_B is $\sin^2\theta_m$

If matter effects dominate, $\sin^2\theta_m \simeq 1$

In presence of adiabaticity,
$\nu_e \rightarrow \nu_B \rightarrow \nu_2 \rightarrow P = \sin^2\theta$



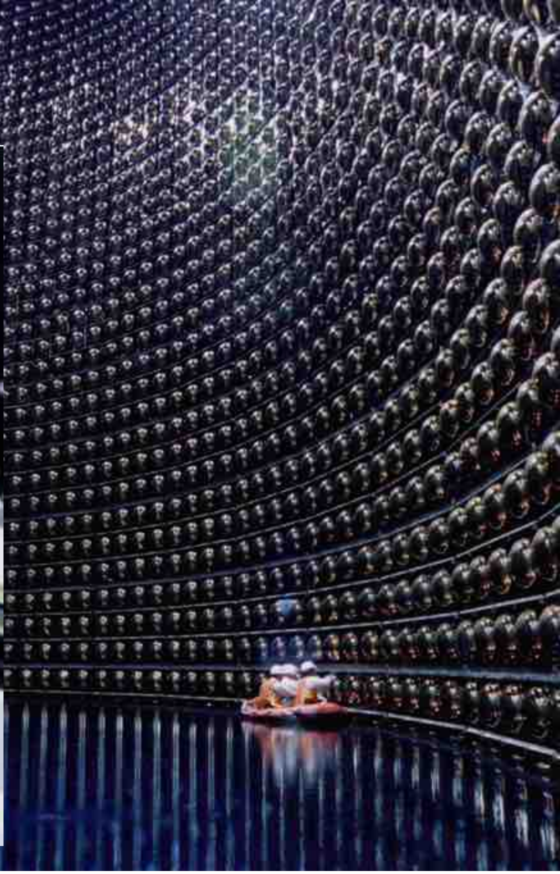
Solar neutrinos have energies which go from vacuum oscillations to adiabatic resonance.

Strumia and Vissar

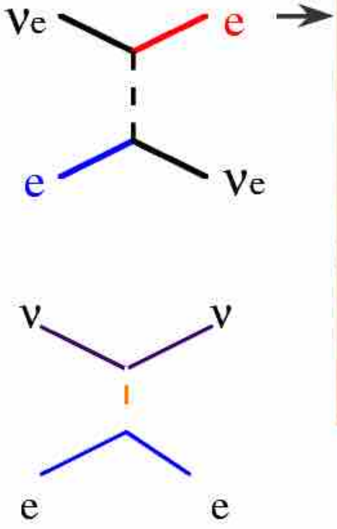
- $P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2}\sin^2(2\theta)$ (averaged vacuum oscillations), when matter effects are negligible (low energies)
- $P(\nu_e \rightarrow \nu_e) = \sin^2\theta$ (dominant matter effects and adiabaticity) (high energies)

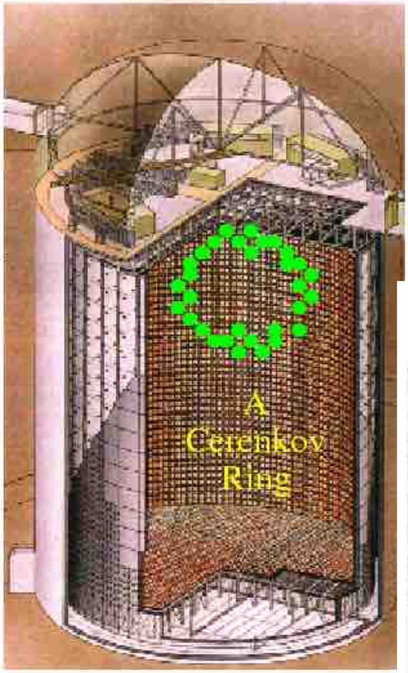
Super-K Experiment H_2O Cerenkov Detectors

- SuperK
  - 22.5 kton fiducial volume
  - 36 m high, 34 m diam.
  - 11,146 phototubes (50 cm)
  - Energy threshold: 6.5 MeV
  - Linac (5 – 16 MeV) for in-situ calibration

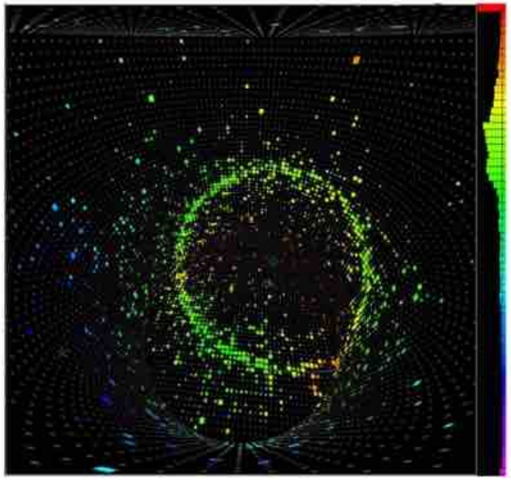


Both NC & CC scatters

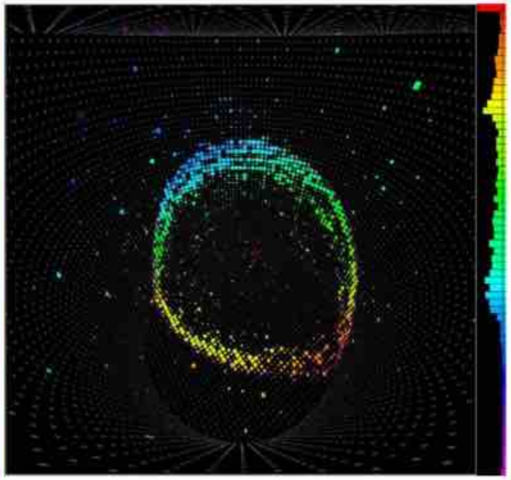




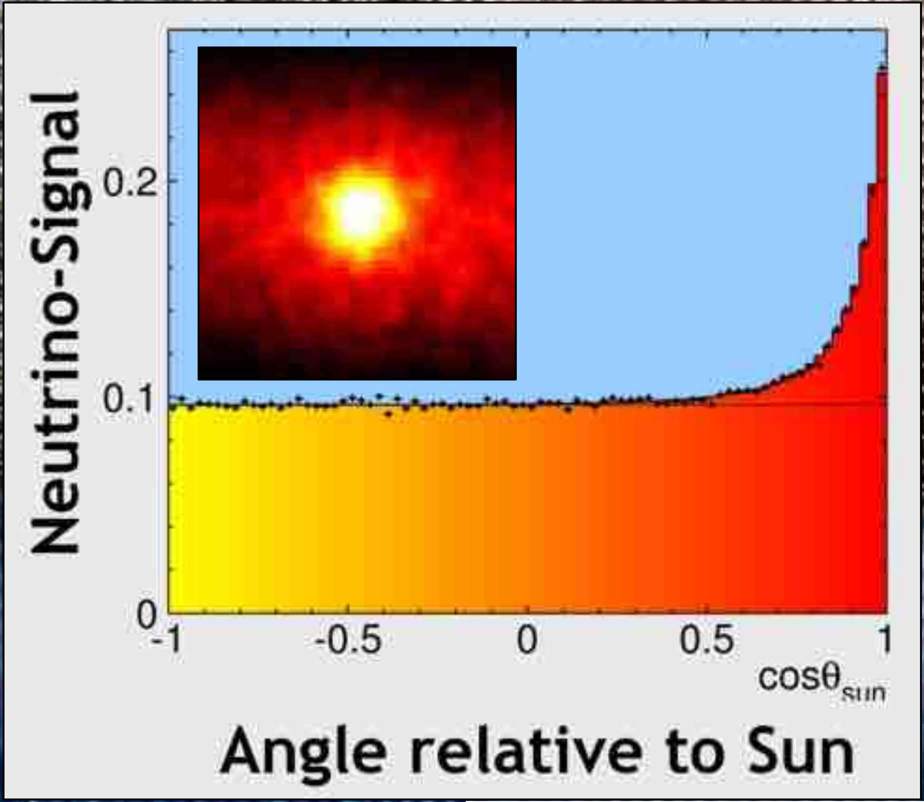
Elettrone

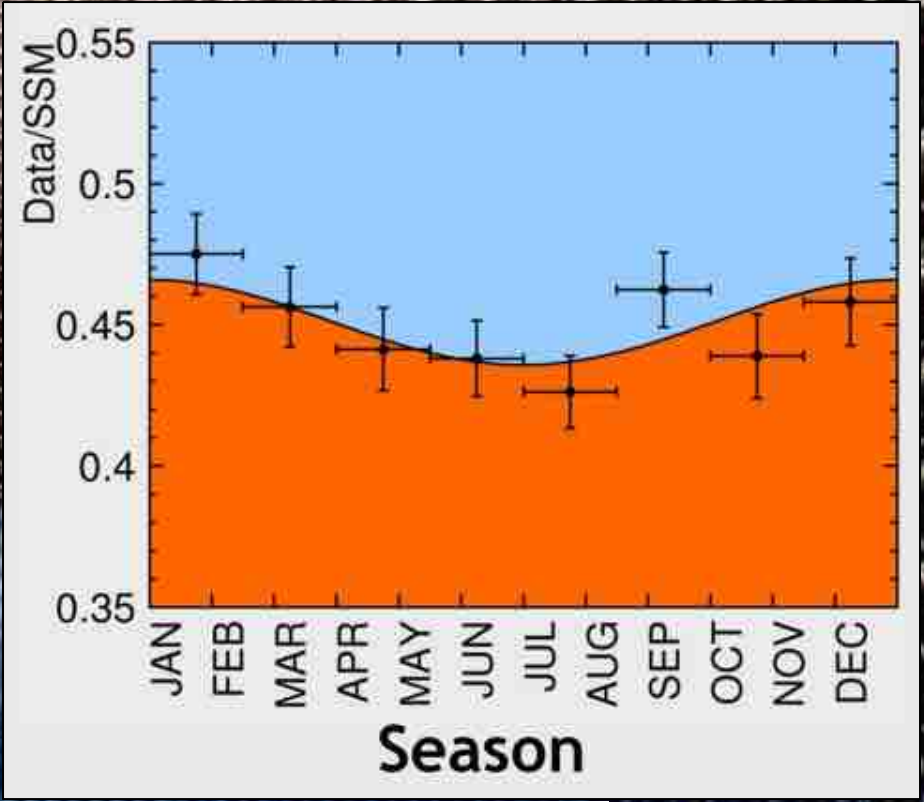


MUONE



Super-Kamiokande: Sun in the Light of Neutrinos (^{8}B ν, highest energy tail)



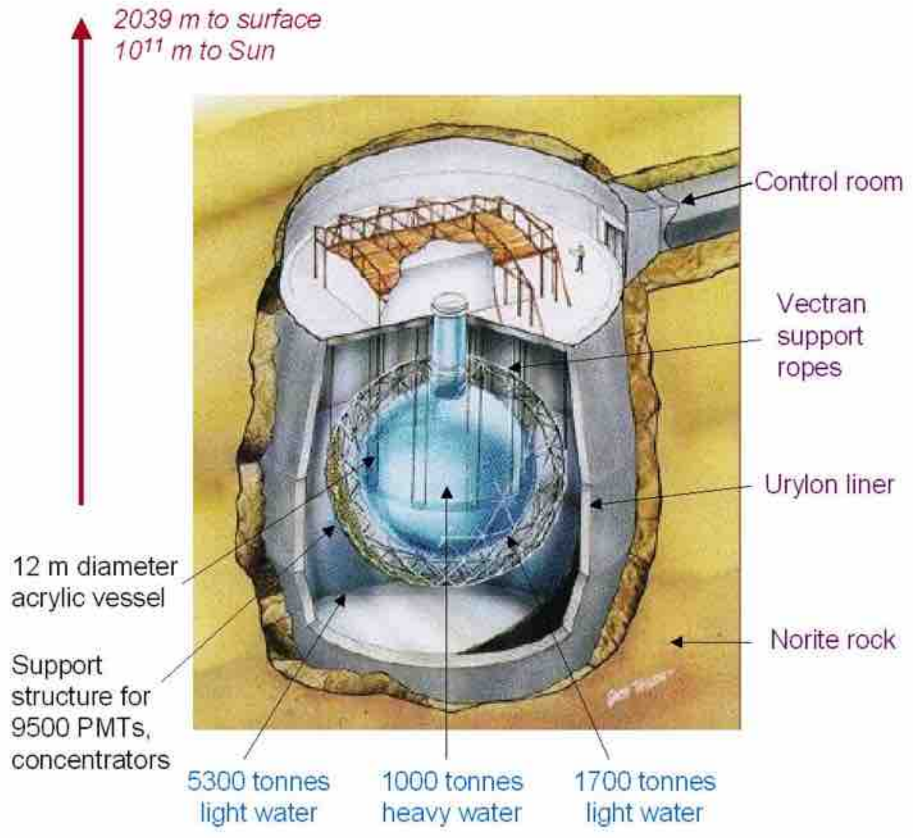


Measured flux (1117 days)
May ‘96 - April ‘00

$$\Phi = 2.40 \pm 0.03(stat.)^{+0.08}_{-0.07}(syst.) \times 10^6 / cm^2 / s$$

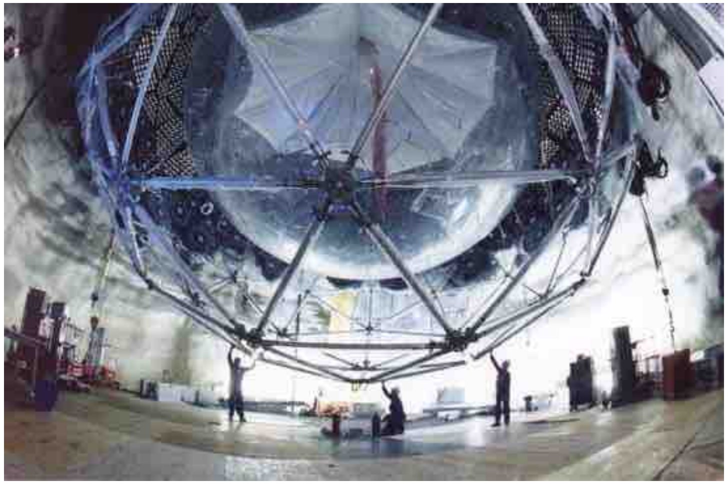
$$\text{Data/SSM} = 0.465 \pm 0.005(stat.)^{+0.015}_{-0.013}(syst.)$$

Sudbury Neutrino Observatory (SNO)



- **Location:** 6800 ft. level of INCO's Creighton mine near Sudbury, ON, Canada (~70 muons / day)
- **SNO Detector:** $9438_{\text{inward}} + 91_{\text{outward}}$ Hamamatsu 8" PMTs + concentrators = 64% coverage

1000 tons D_2O
(12m Inner Vessel)



- Advantages of Heavy vs Light Water
  - $\nu_e + d \rightarrow p + p + e^-$ (D_2O)
  - $\nu_e + e^- \rightarrow \nu_e + e^-$ (H_2O or D_2O)
  - Cross section $\propto (E_{cm})^2 = s$
    - $s = 2\, m_{target}\, E_\nu$
      $\Rightarrow s_N/s_{e-} = M_p/M_e \approx 2000$
  - But x5 more electrons in H_2O than n's

SNO (1kton) 8.1 CC events/day
SuperK (22ktons) 25 events/day

SNO Results

ν Reactions in Heavy Water

CC $\nu_e + d \Rightarrow p + p + e^-$

- "Charged Current"
- ν_e only.

30 events/day

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- "Neutral Current"
- Equal cross section for all active ν types

$E_{thr} = 2.225$ MeV

a) $n + d \rightarrow t + \gamma(6.26\ \text{MeV})$

b) $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma\ (8.5\ \text{MeV})$

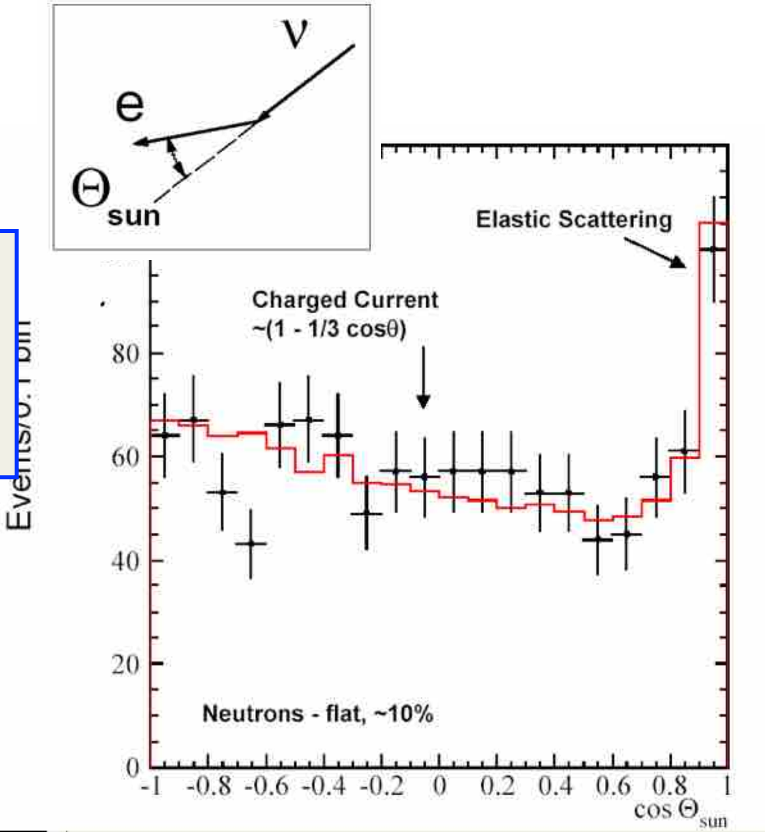
c) $n + {}^{3}He \rightarrow t + p$

3-9 events/day (for E_{th}=5 MeV)

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

- "Elastic Scattering"
- Mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ

3 events/day



Measure total flux of solar neutrinos vs. the pure ν_e flux

Charged-Current to Neutral Current ratio is a direct signature for oscillations

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

CC/ES Could also show significant effects

$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)}$$

ES = Elastic Scattering
ν_e = NC + CC
ν_μ or ν_τ = NC only

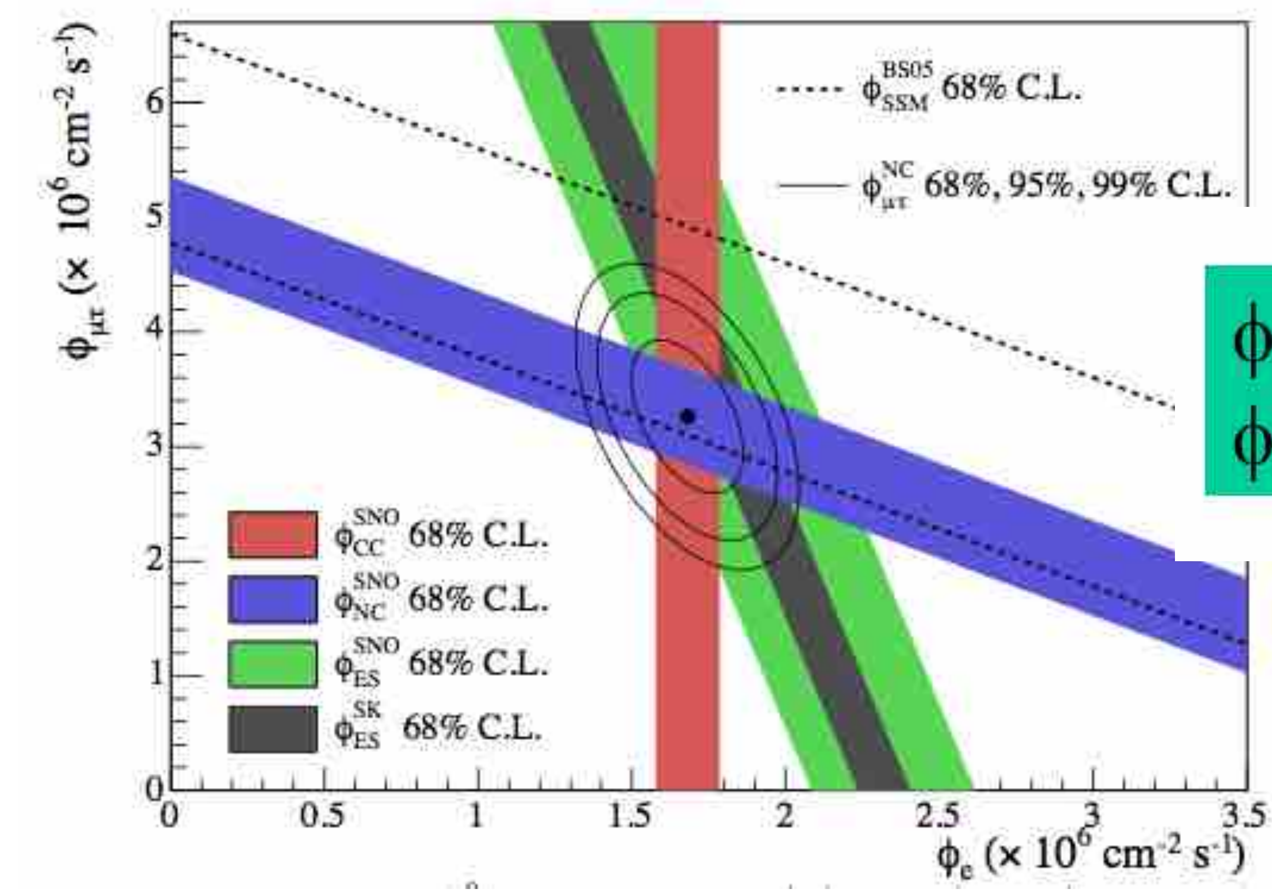
SNO Physics

- First measurement of the total flux of ^{8}B neutrinos:

$\phi_{total}(^8B) = 5.44 \pm 0.99 \times 10^6\ cm^{-2}\ s^{-1}$

Agrees well with solar models:

$\phi_{SSMI}(^8B) = 5.05 \pm 0.80 \times 10^6\ cm^{-2}\ s^{-1}$ (BPB01)



$$\phi_{CC} = \phi_e$$

$$\phi_{ES} = \phi_e + 0.154\ \phi_{\mu,\tau}$$

$$\Phi_{NC} = \Phi_e + \Phi_{\mu\tau}$$

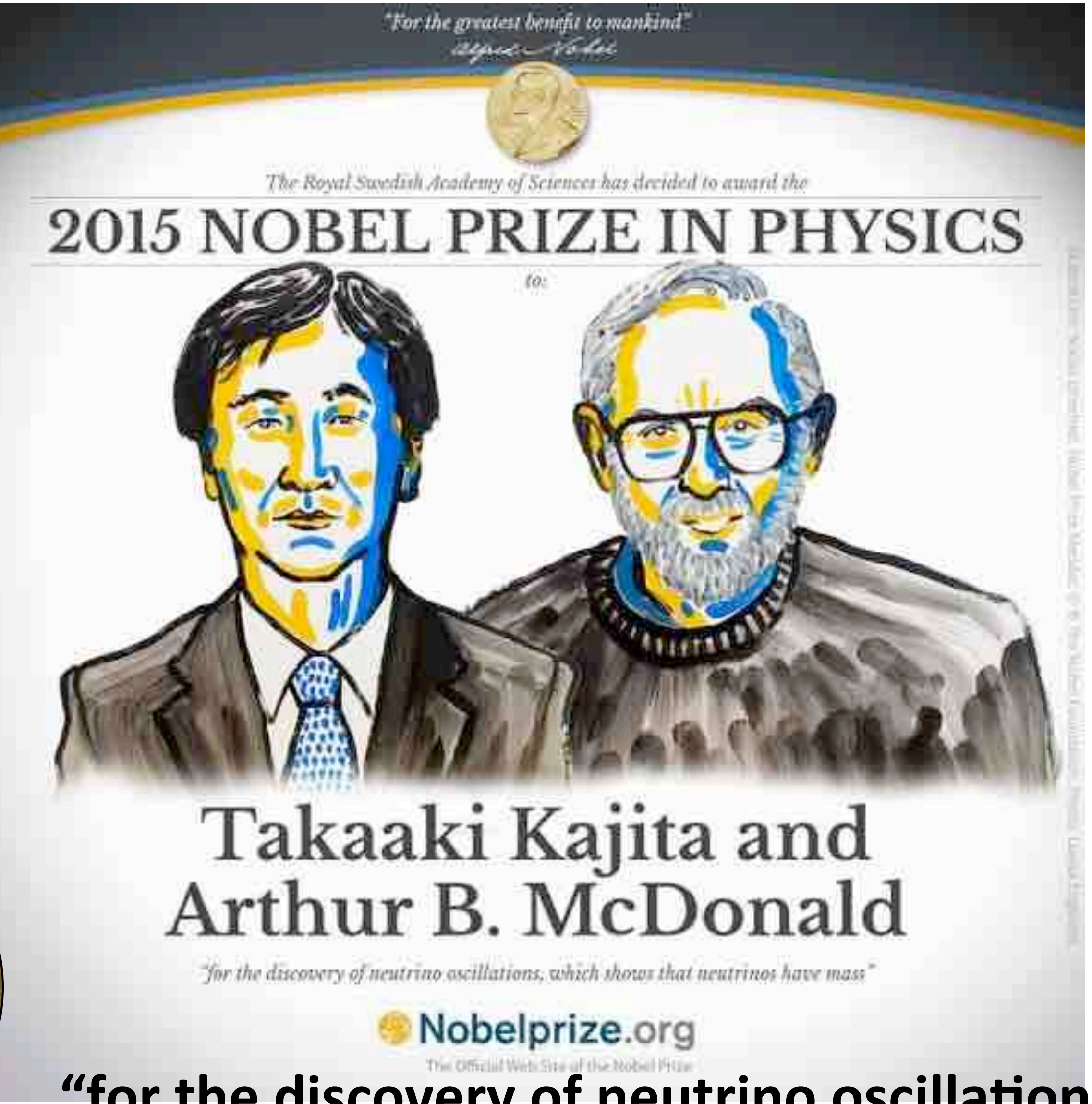
$$\phi_{SNO}^{CC} = (1.68 \pm 0.06^{+0.08}_{-0.09}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}\ ,$$

$$\phi_{SNO}^{ES} = (2.35 \pm 0.22 \pm 0.15) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}\ ,$$

$$\phi_{SNO}^{NC} = (4.94 \pm 0.21^{+0.38}_{-0.34}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}\ ,$$

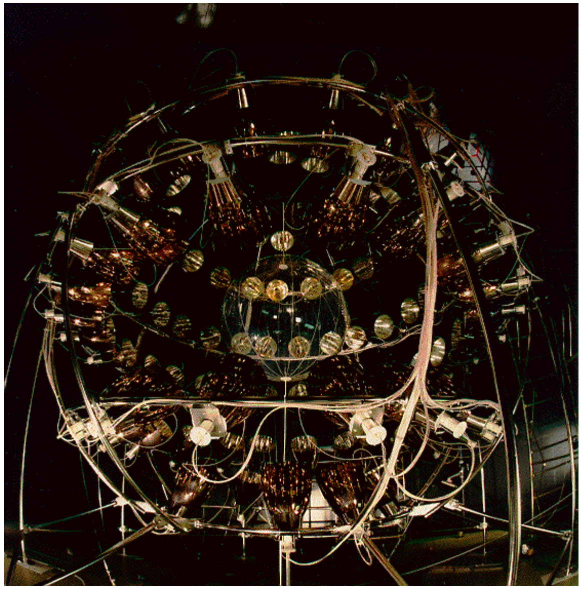
Ahmad et al. (SNO Collaboration), PRL 89:011301,2002 (nucl-ex/0204008)

2015 Physics Nobel Prize for Neutrino Astronomy



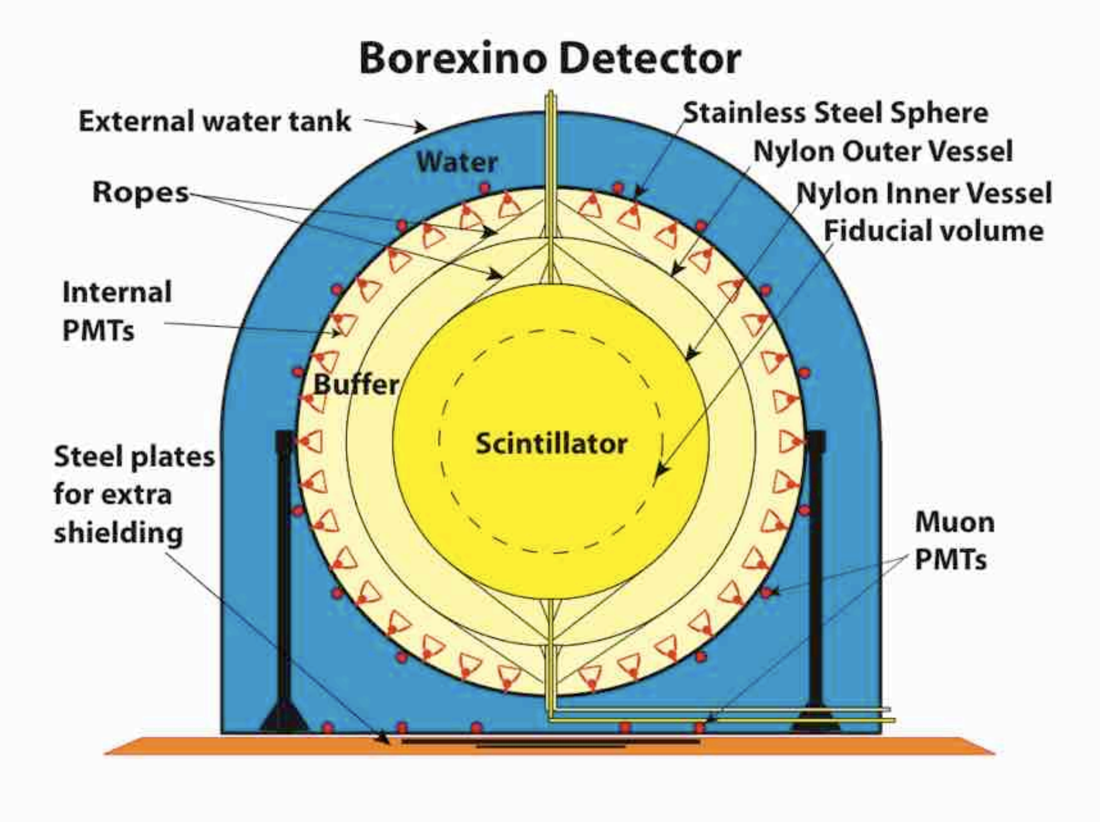
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

BOREXINO



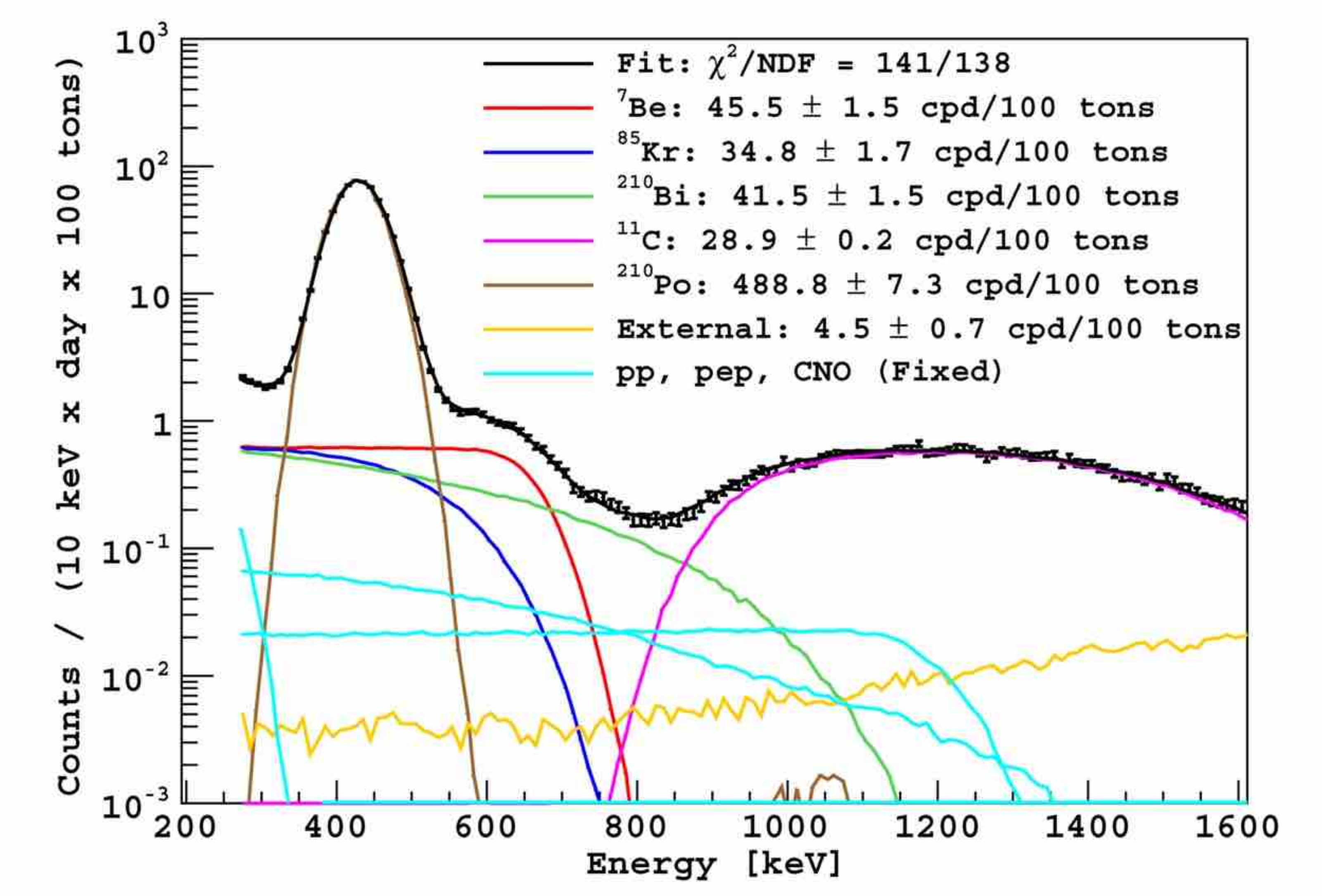
- Reaction : $\nu_e + e^- \rightarrow \nu_e + e^-$
- Exp. site : Laboratori del Gran Sasso (3300 m.w.e.)
- Target : 300 tons (fid.:100 tons) liquid scintillator
  Pseudocumen + PPO, sphere radius 18 m
- Goals : ^{7}Be neutrinos and neutrino spectroscopy.
  time behaviour; geo-neutrinos $\bar{\nu}$

$$\bar{\upsilon} + p \rightarrow n + e^+ \qquad n + p \rightarrow d + \gamma(2.2MeV)$$



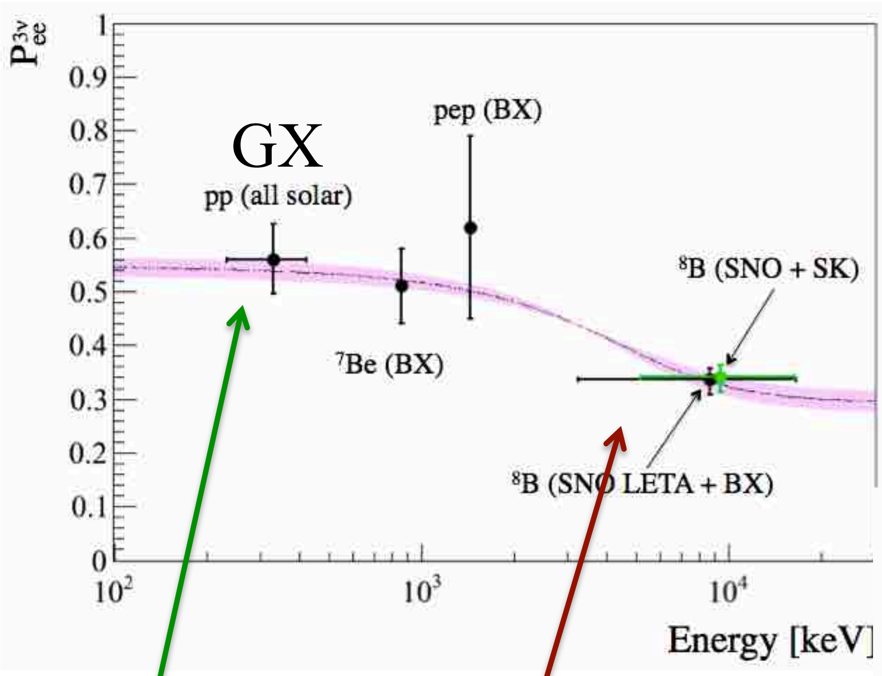
- Borexino
  Go after ^{7}Be ν's
  - 300 ton liquid scintillator
  - 2200 8-inch phototubes
  - $E_e > 250$ keV
- Detect $\nu_e + e^- \rightarrow \nu_e + e^-$
  - 55 events/day for SSM

Solar Neutrinos in Borexino



Borexino Collaboration, arXiv:1104.1816

Solar Neutrinos survival probability after Borexino



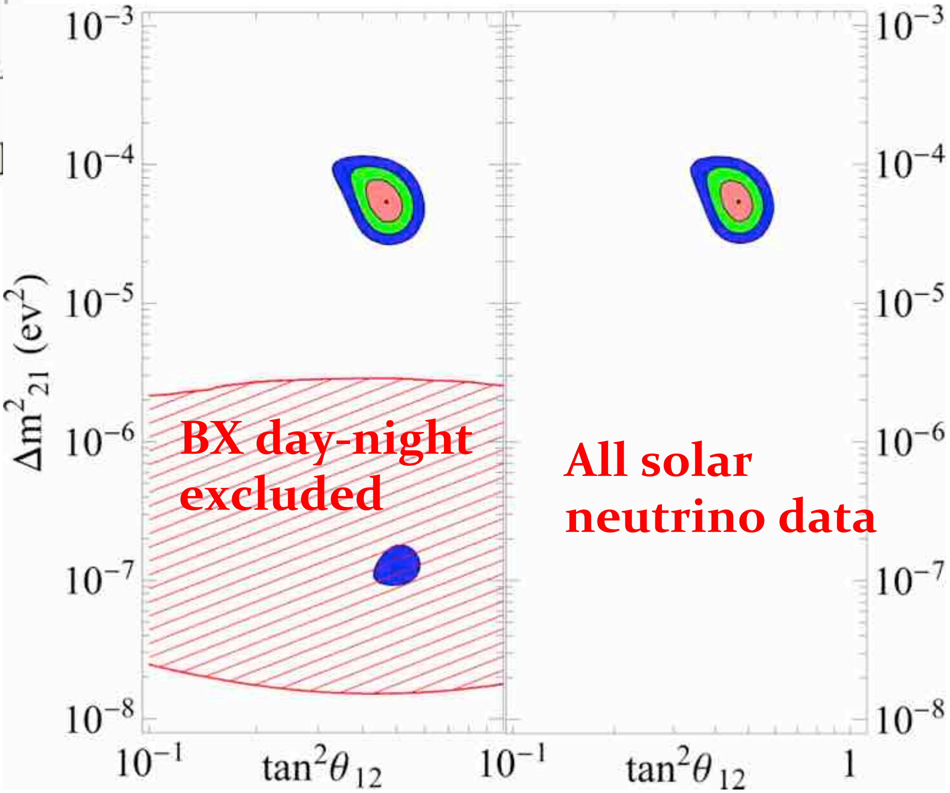
vacuum osc.

matter effect osc.

MSW effect

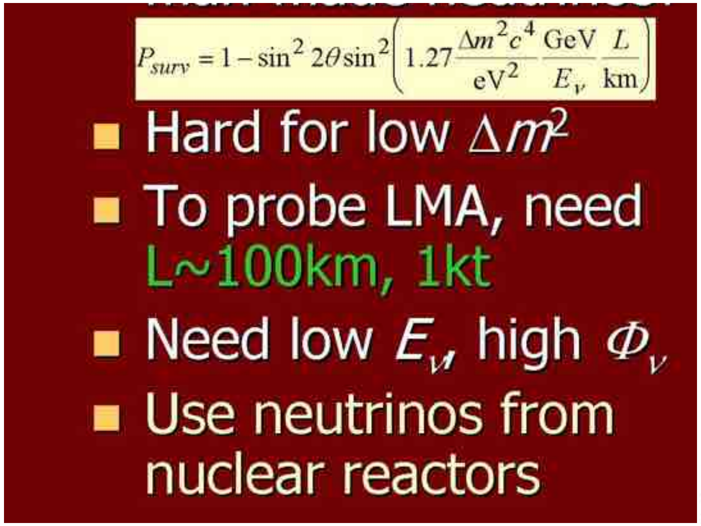
ν oscillation parameters' space:

Δm^2 vs tanθ



Terrestrial "Solar Neutrinos"

Can we convincingly verify oscillation with man-made neutrinos?



$$P_{surv} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\text{eV}^2} \frac{\text{GeV}}{E_\nu} \frac{L}{\text{km}}\right)$$

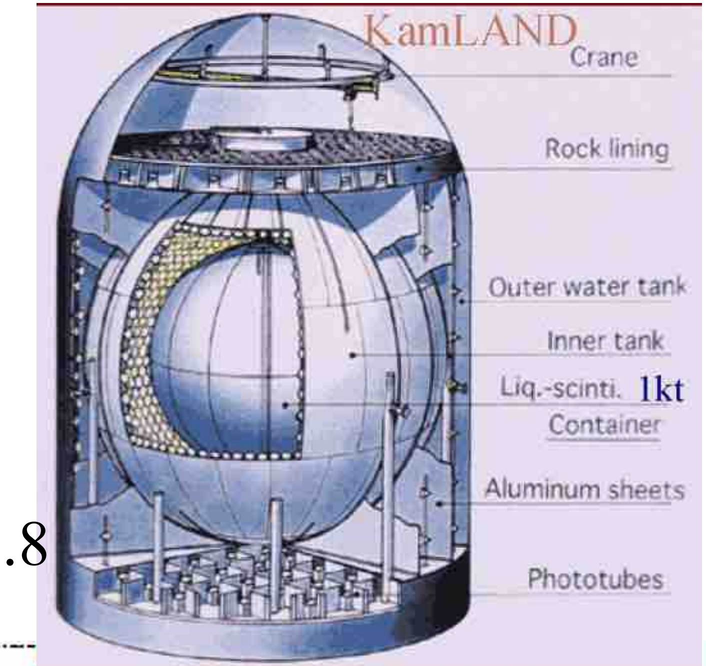
- Hard for low Δm^2
- To probe LMA, need L~100km, 1kt
- Need low E_ν, high Φ_ν
- Use neutrinos from nuclear reactors

$\Delta m^2 = 10^{-5}$ eV^2

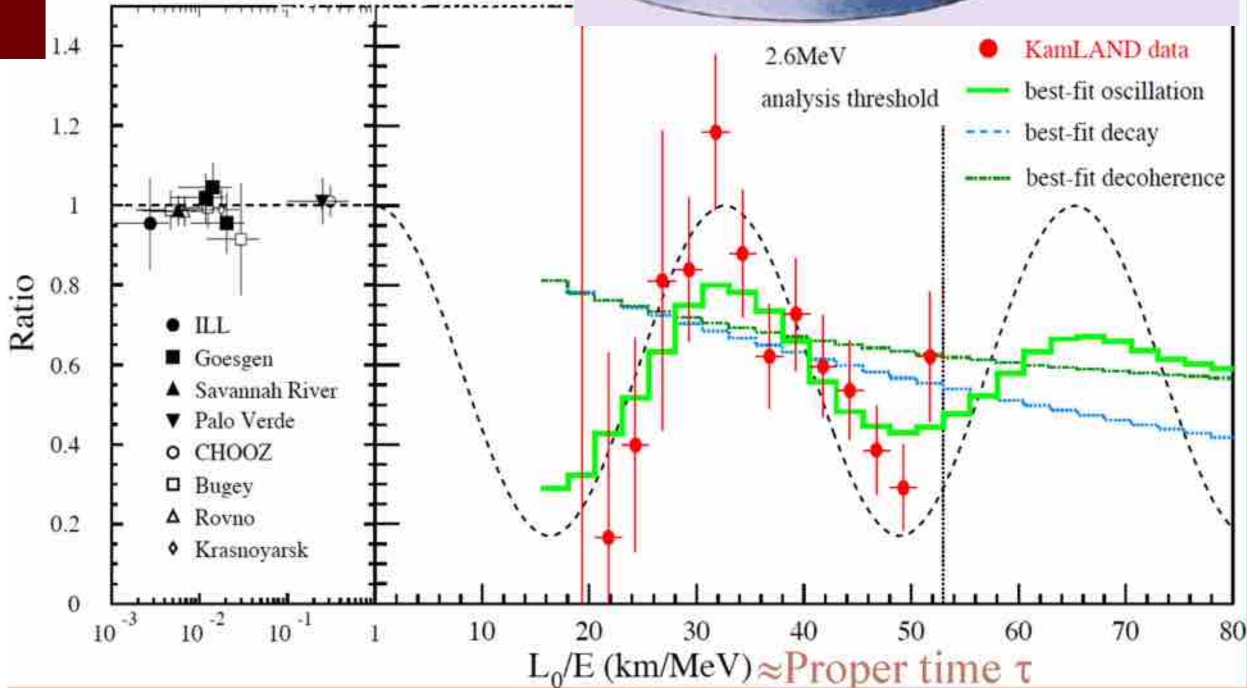
$E_\nu = 3$ MeV

$L = 180$ km

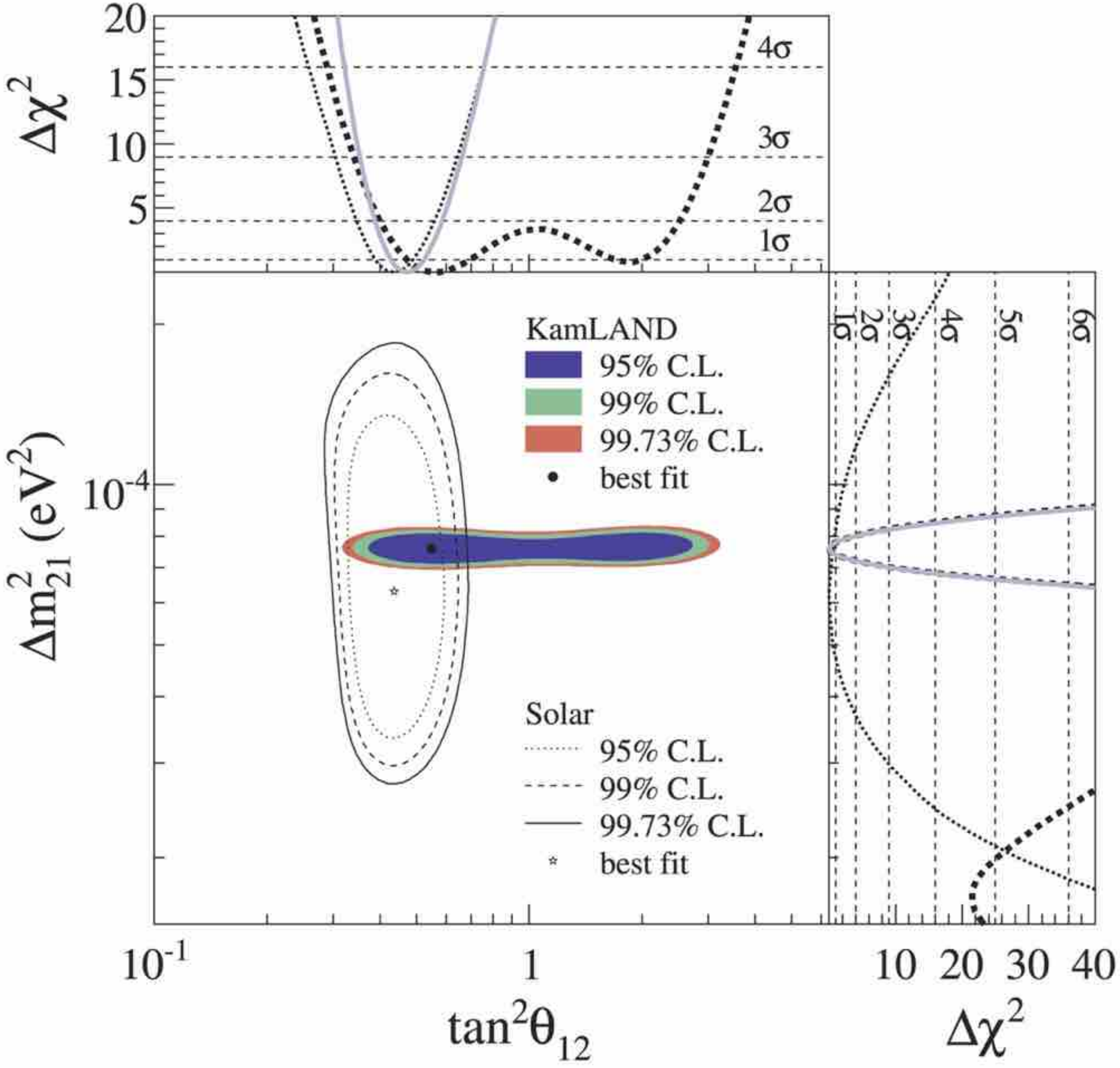
$\rightarrow 1.27\Delta m^2 L/E_\nu = 0.8$



KAMLAND: reactor anti-neutrino do oscillate!



Best-fit “solar” oscillation parameters

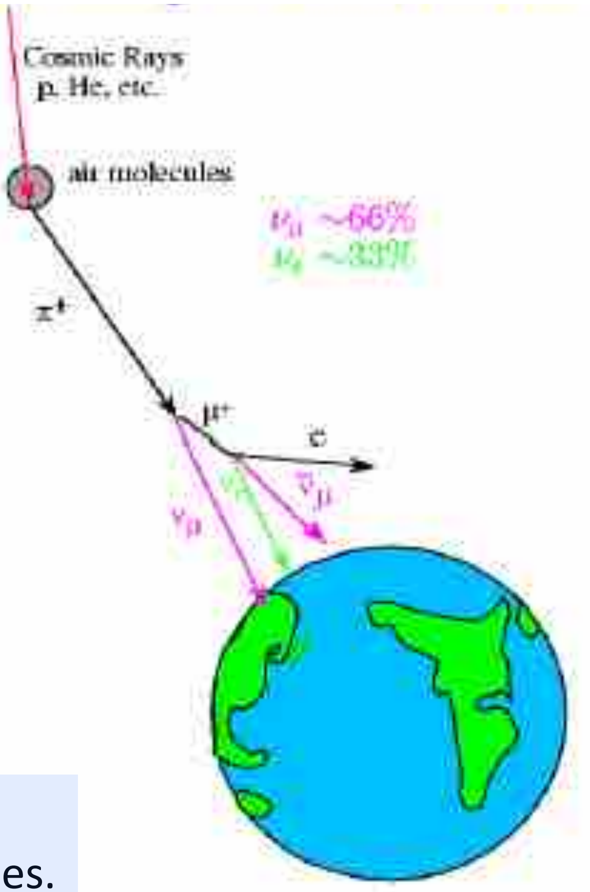


Atmospheric Neutrinos

- Another evidence for ν oscillations
- First atm. ν observations:
  - Kamiokande
  - Soudan
  - IMB

and then:

  - MACRO LNGS
  - SUPERKAMIOKANDE



Suppose neutrinos have non-zero masses.
Mass eigenstates are disctinct from weak interaction eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} .$$

“Atmospheric” neutrinos

Main sources of atmospheric neutrin

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\hookrightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

For energies $E < 2$ GeV most pions and muons decay before reaching the Earth:

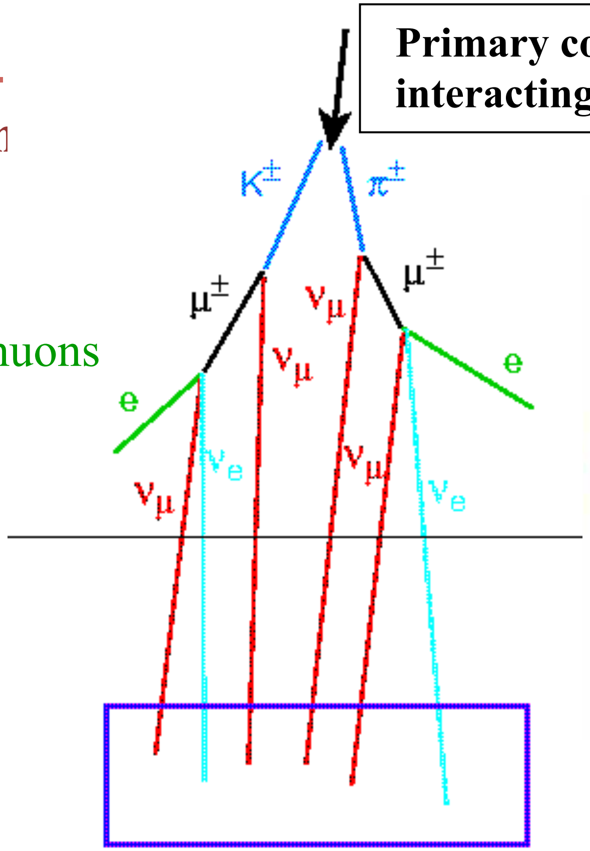
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

At higher energies most muons reach the Earth before decaying:

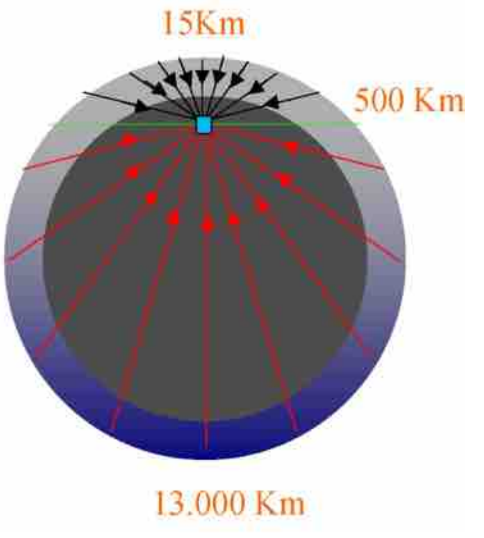
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} > 2$$

(increasing with E)

Primary cosmic ray interacting in the atmosphere



DETECTOR

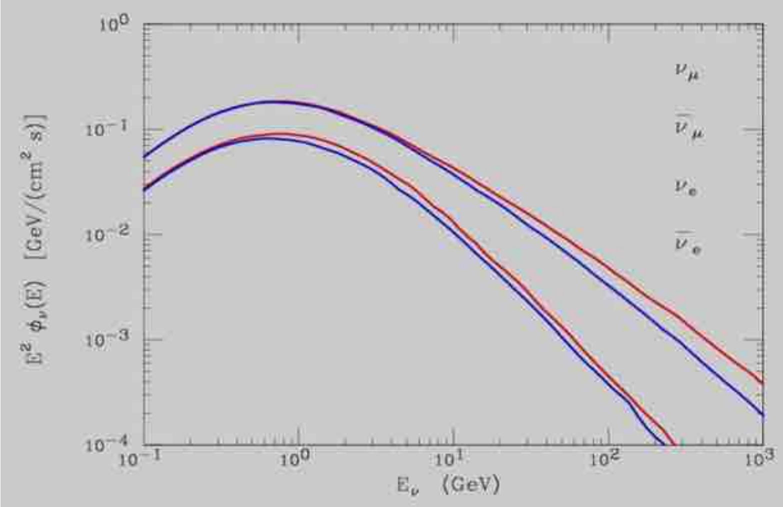


Atmospheric neutrino energies: 0.1 — 100 GeV

Very low event rates: ~100 /year for a 1000 ton detector

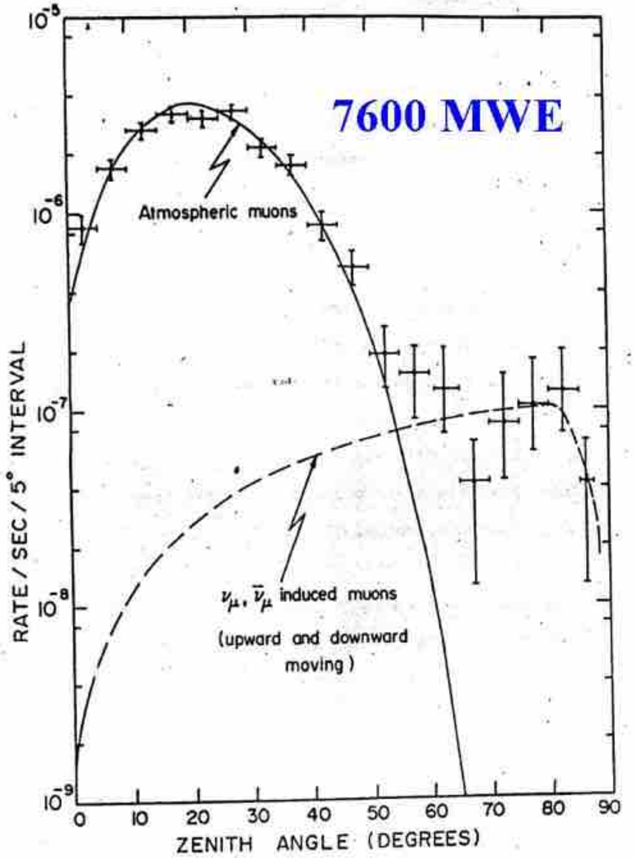
Typical uncertainty on the atmospheric neutrino fluxes: ± 30% (from uncertainties on the primary cosmic ray spectrum, on hadron production, etc.)

Uncertainty on the ν_μ / ν_e ratio : ± 5%

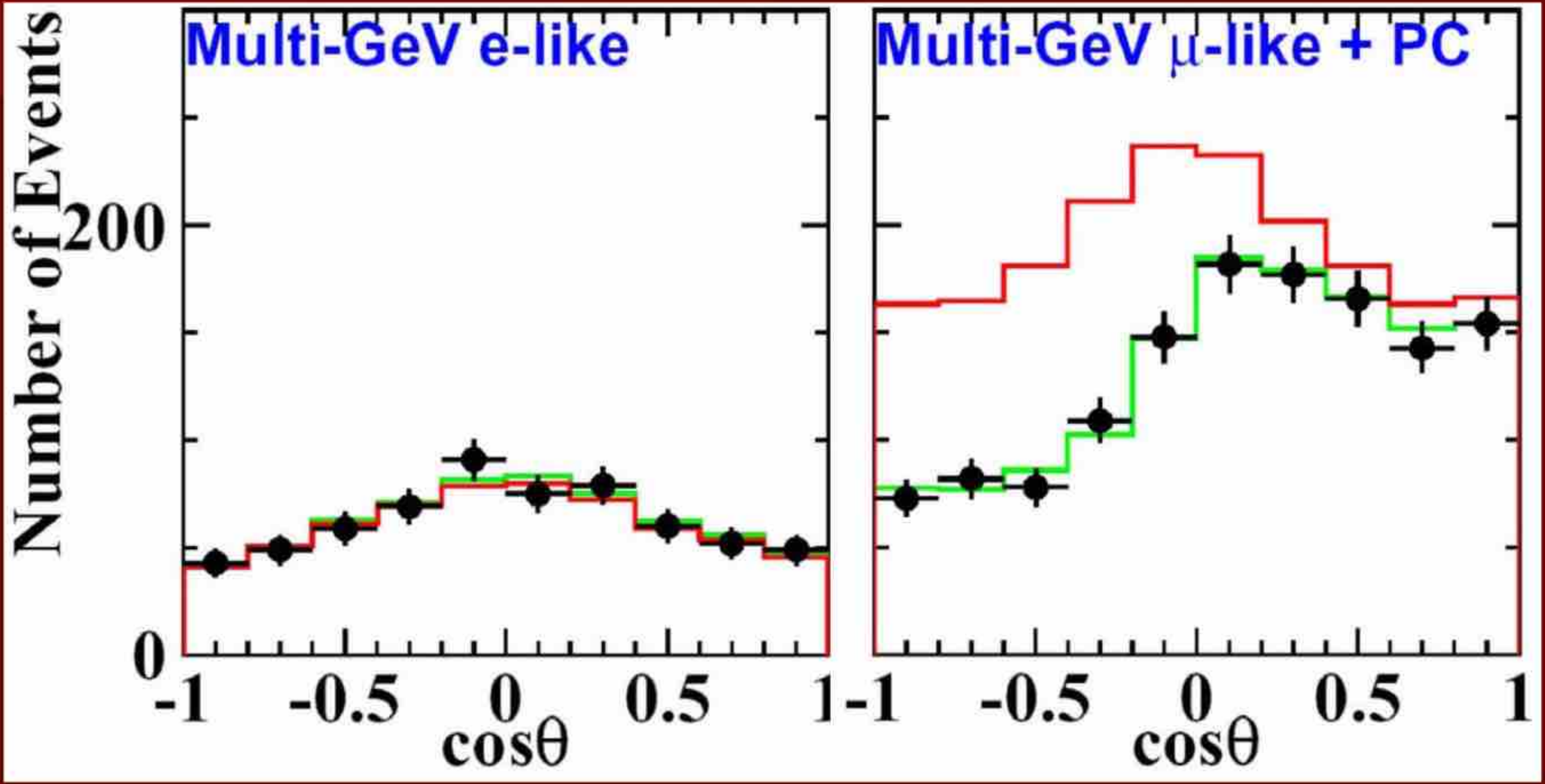


The first observations of Atmospheric Neutrinos made in Kolar Gold Fields near Bangalore, and in South Africa in 1965.

- The Indian team was led by
  M. G. K. Menon et al
- The South African team was led by
  F. Reines et al.



Half of ν_μ lost!



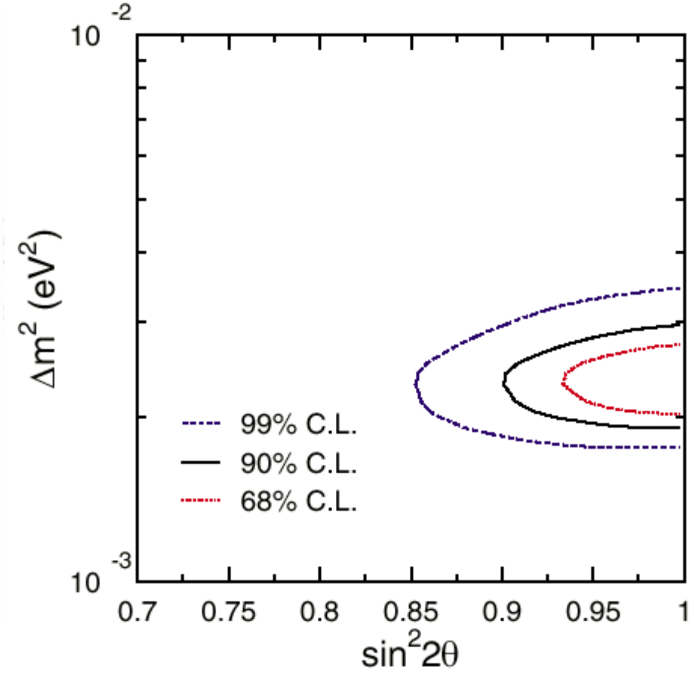
SUPERKAMIOKANDE

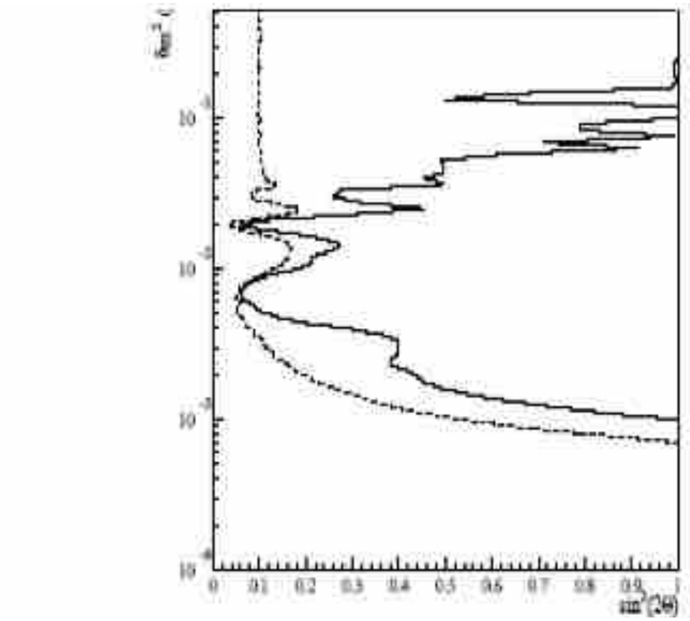
SK showed that at L/E of atmospheric neutrinos

1) ν_μ DO oscillate
2) ν_e DO NOT oscillate

Region of oscillation parameters (confidence level 90%):
$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2
$\sin^2 2\theta > 0.90$

This is confirmed by CHOOZ





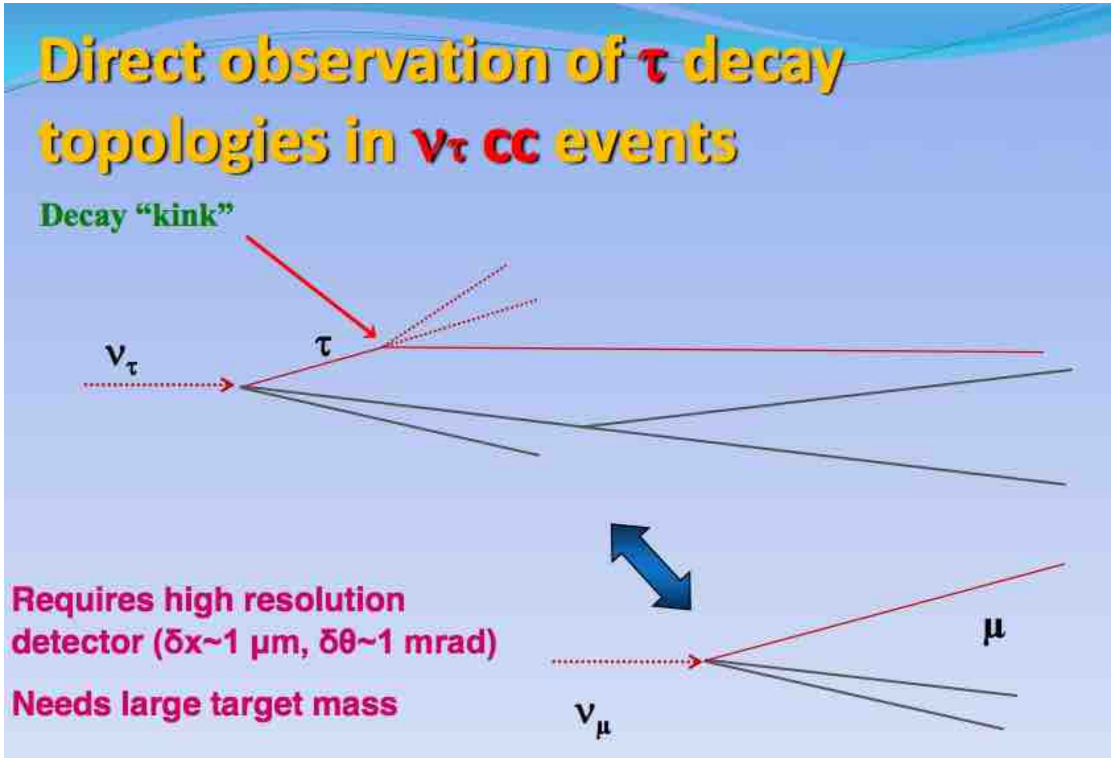
$\nu_\tau + N \rightarrow \tau + X$ requires $E(\nu_\tau) > 3.5$ GeV;
fraction of $\tau \rightarrow \mu$ decays $\approx 18\%$

- Atmospheric ν_μ do oscillate, but not to ν_e
- In a scenario with three neutrinos, ν_μ do oscillate to ν_τ
- Sterile neutrinos?
- Direct evidence of oscillation to ν_τ is from OPERA at LNGS (5 ν_τ observed)

OPERA: Oscillation Project with Emulsion tRacking Apparatus

- High-energy long baseline ν_μ beam
- Direct search for $\nu_\mu \to \nu_\tau$ oscillations by looking at the **appearance** of ν_τ in a pure ν_μ beam
- Search for the sub-dominant $\nu_\mu \to \nu_e$ oscillations for Θ_{13} measurement

OPERA
@ LNGS

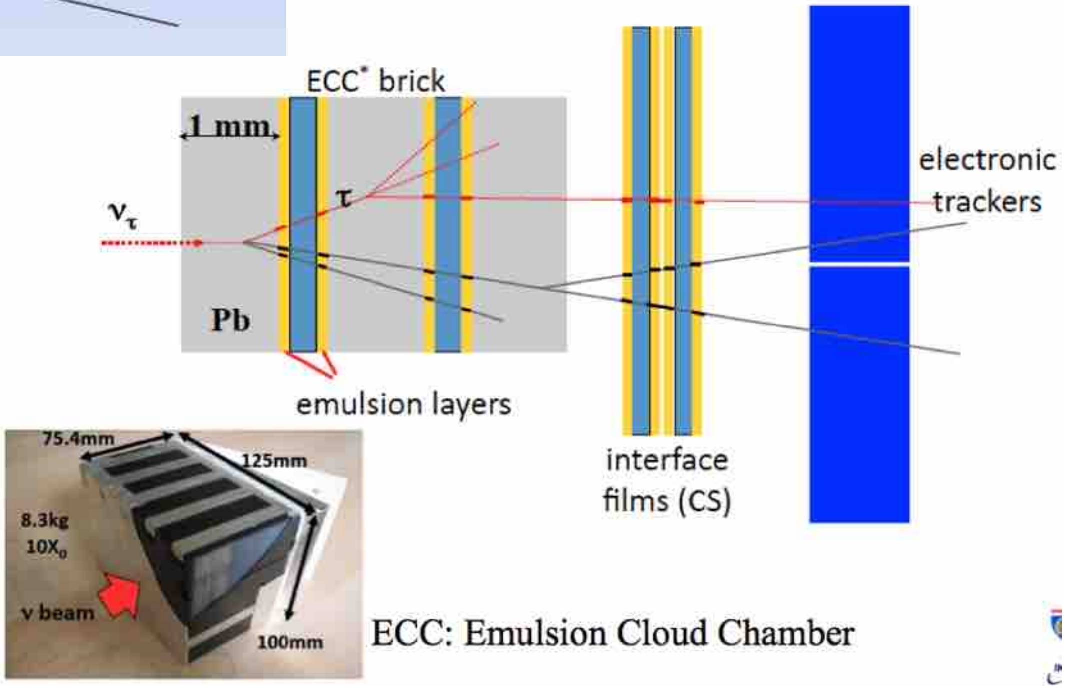


Direct observation of τ decay topologies in ν_τ cc events

Requires high resolution detector (δx~1 μm, δθ~1 mrad)

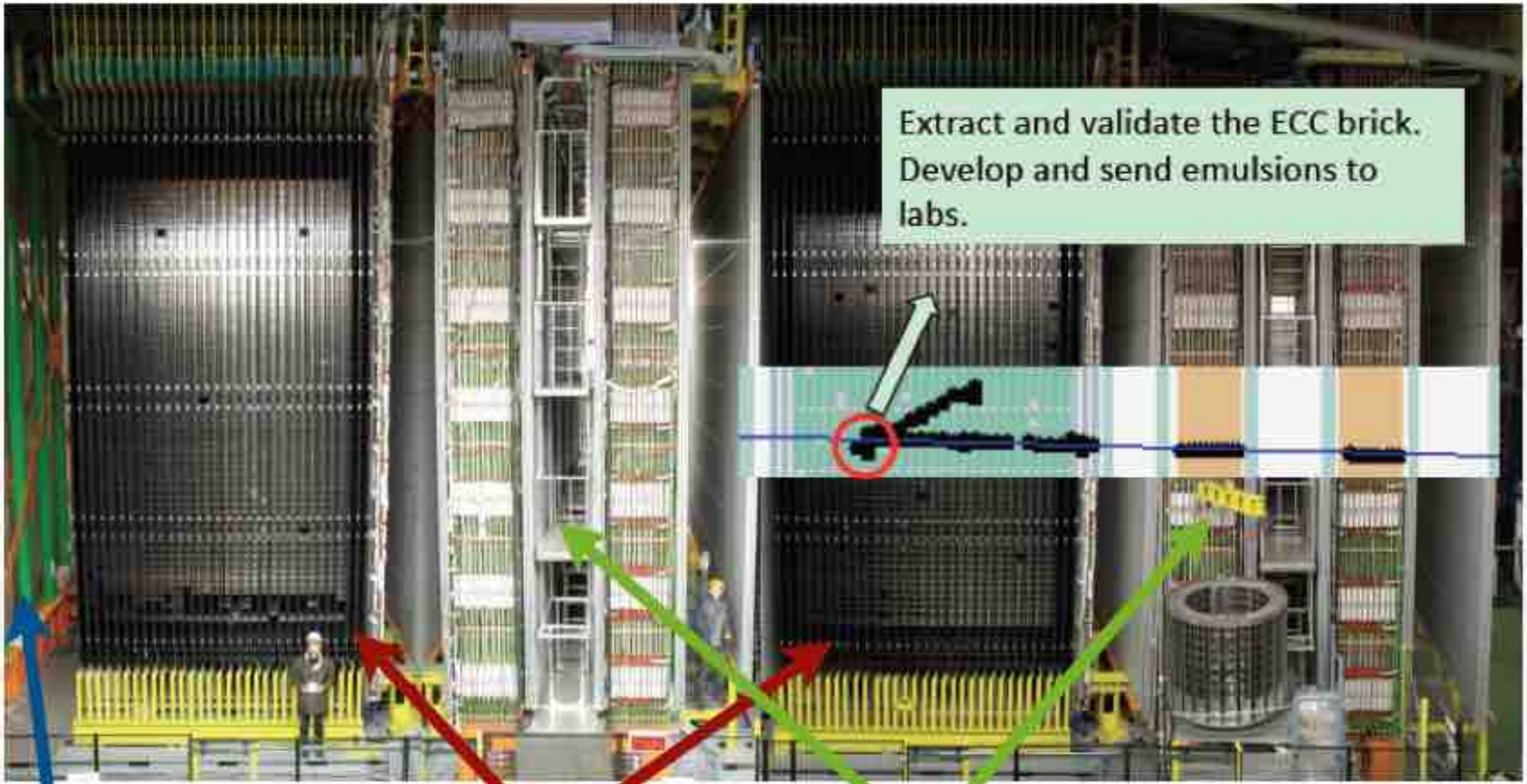
Needs large target mass

How to detect tau vertex



ECC: Emulsion Cloud Chamber

OPERA How to detect tau vertex



Extract and validate the ECC brick. Develop and send emulsions to labs.

Veto

Target:
- **Trackers (scintillators)**
- **Lead/Emulsion bricks**

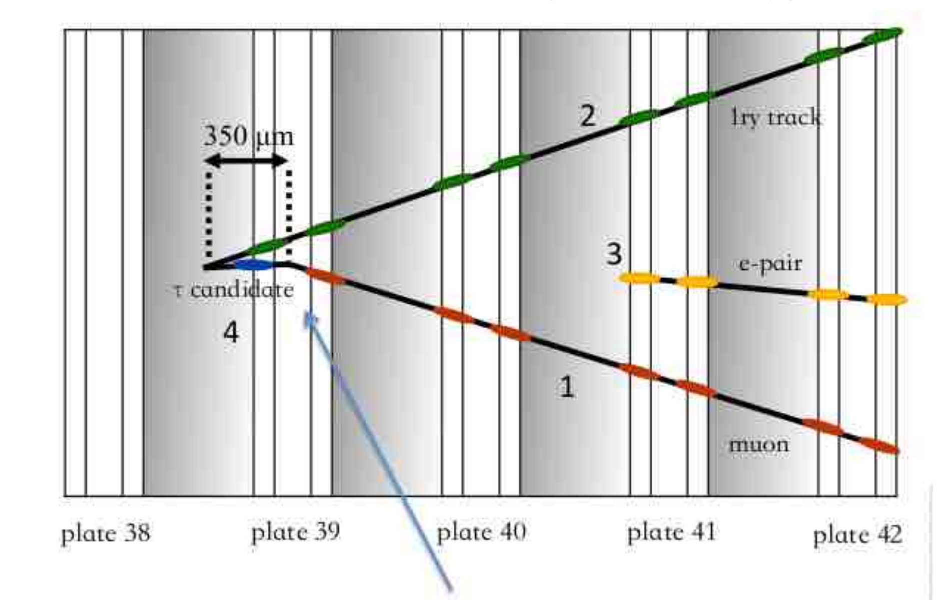
Spectrometers
- **Iron & RPC chambers**
- **6 planes of drift tubes for precision tracking**

Five ν_τ candidates observed until now

Examples:

PRL 115 (2015) 121802.

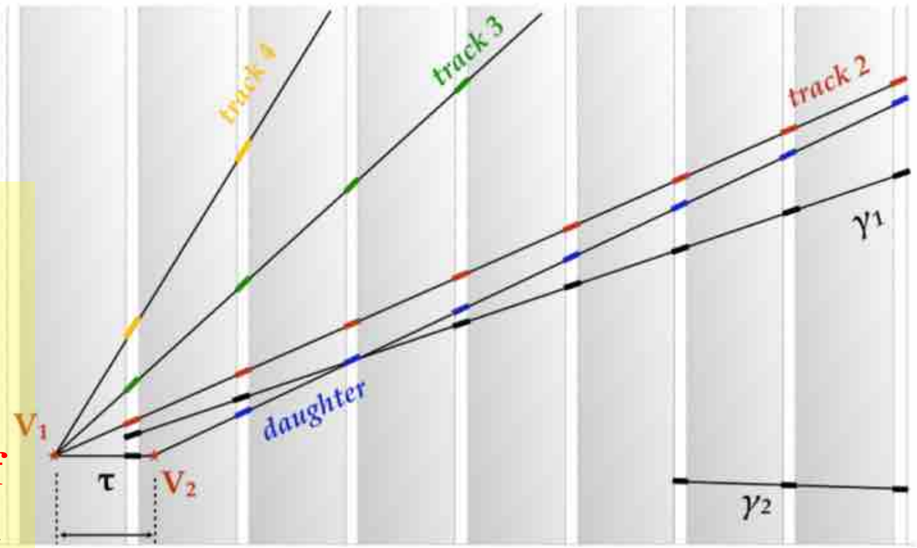
Third candidate (muon decay)



Decay in the plastic base

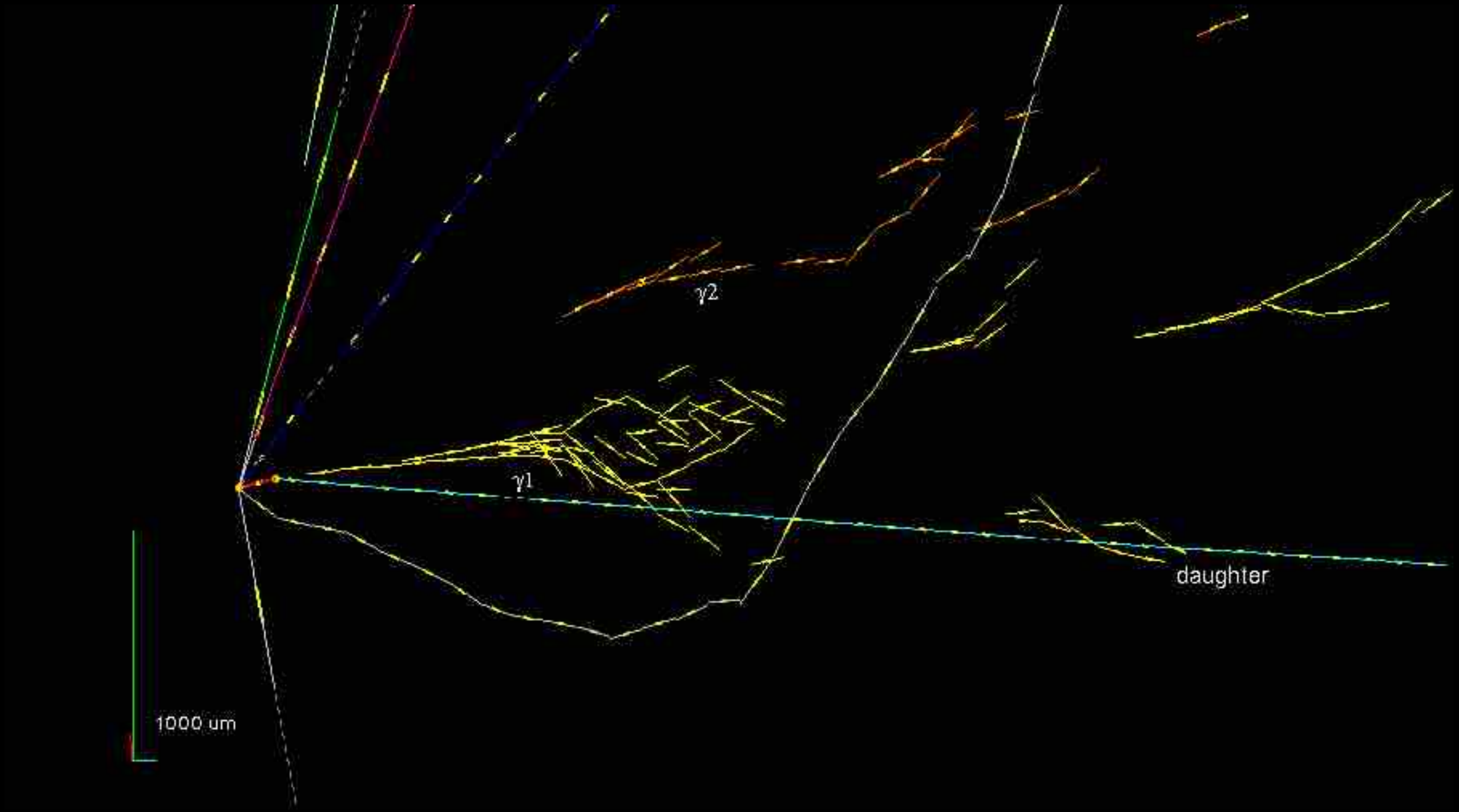
- OPERA was designed to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in **appearance** mode, i.e. by detecting the τ leptons produced in charged current ν_τ interactions.
- The experiment took data from 2008 to 2012 in the CERN Neutrinos to Gran Sasso beam.

Fourth candidate (hadronic decay, single prong)



- Observation of the $\nu_\mu \rightarrow \nu_\tau$ appearance, achieved with **five** candidate events.
- Together with a further reduction of the expected background, the candidate events detected so far allow to assess the **discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations** in appearance mode with a significance larger than **5 σ**

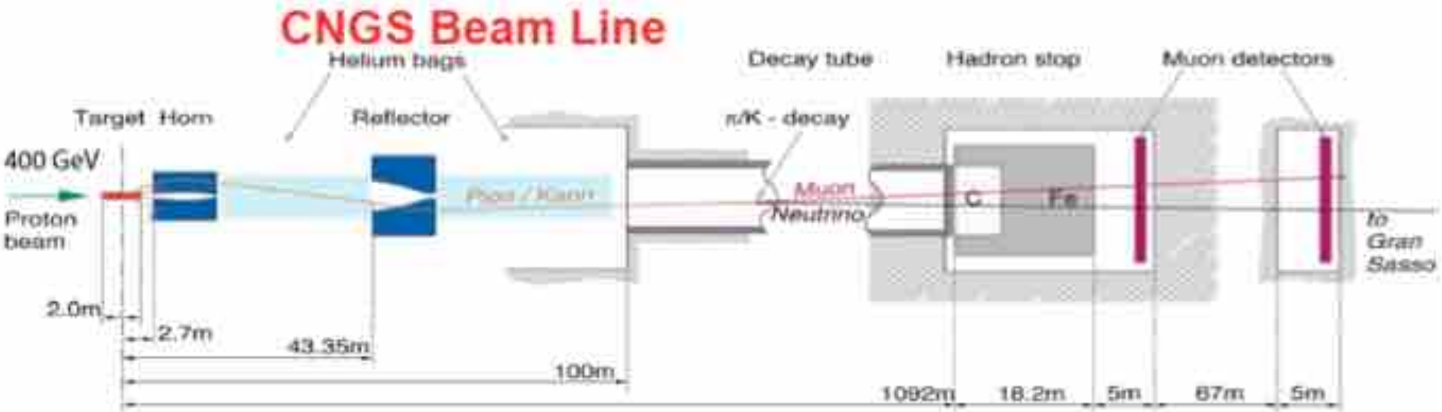
Event reconstruction (1)



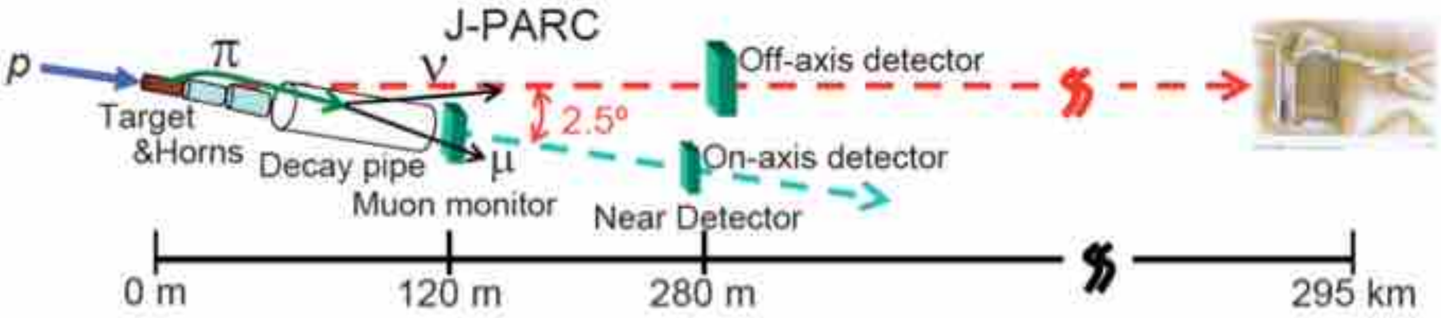
SK results for atmospheric neutrinos have been confirmed by “Long Baseline” expts

- neutrino beams in the world (at the end of their projects)

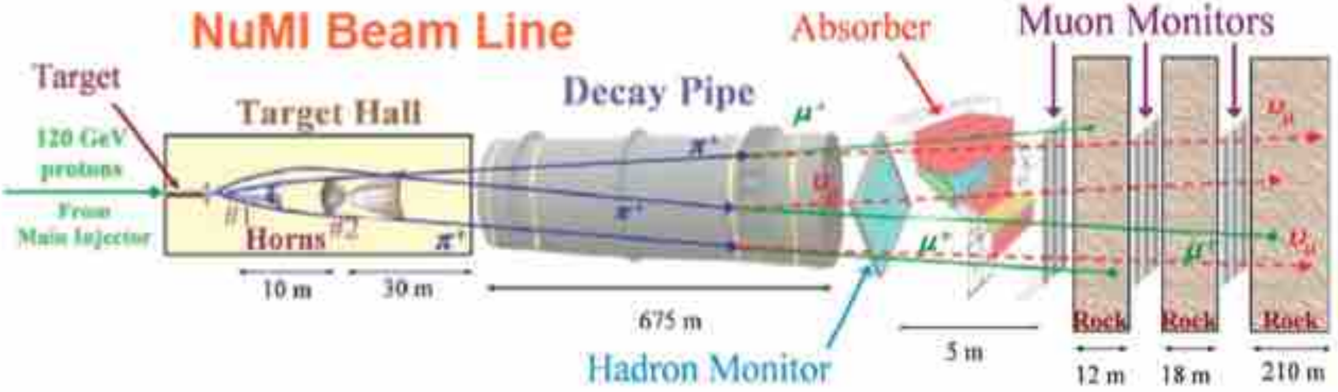
CERN-
Gran Sasso
~730 km
ν_τ appearance



KEK-
SuperK
~295 km
θ_{13}



Fermilab-
Minnesota
~730 km
ν_μ disappearance

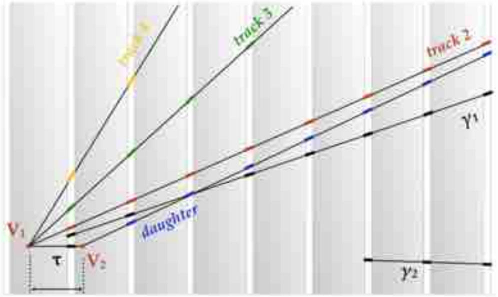


SK results for atmospheric neutrinos have been confirmed by “Long Baseline” expts

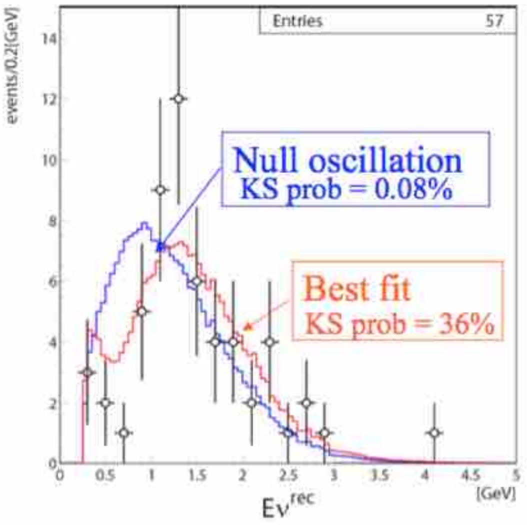
- neutrino beams in the world (at the end of their projects)

CERN-
Gran Sasso
~730 km
ν_τ appearance

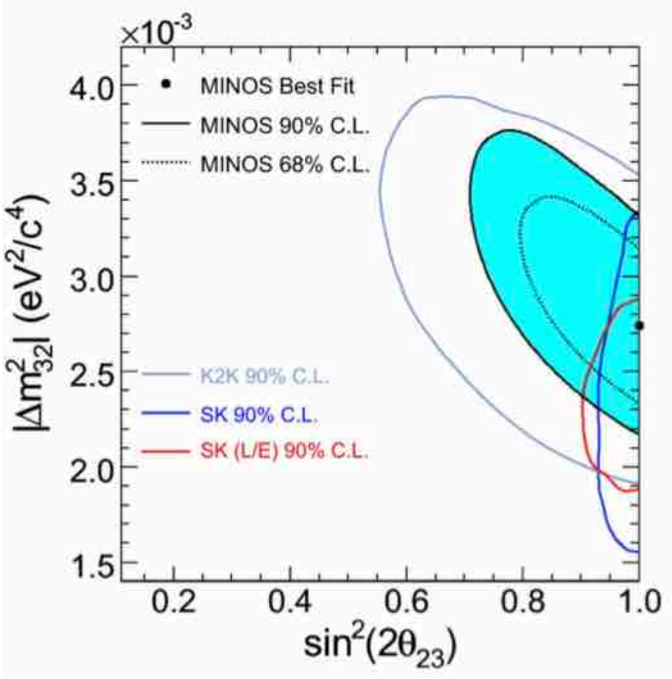
- Five ν_τ candidates observed
- Discovery of ν_τ appearence



KEK-
SuperK
~295 km
θ_{13}

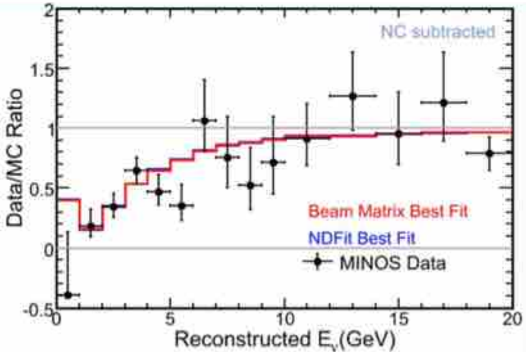


- Expected ν interactions with osc. is 104 (107 observed), 151 w/out.



Fermilab-
Minnesota
~730 km
ν_μ disappearance

- MINOS



3 flavor neutrino mixing

mixing matrix ***U**$_{MNSP}$* parametrized with 3 mixing angles θ_{ij}, CP phase δ

+ 2 mass differences Δm^2_{atm} , Δm^2_{sol}

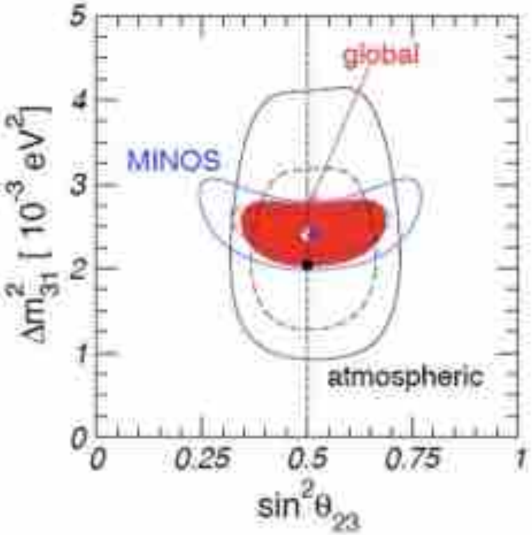
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}\, e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

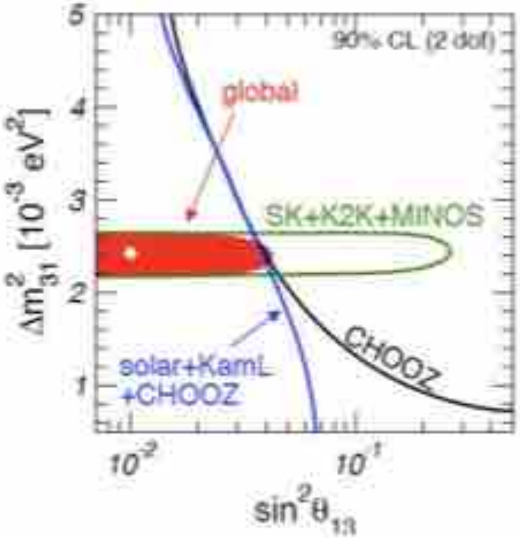
$s_{12} = \sin\theta_{12}$
$c_{12} = \cos\theta_{12}$

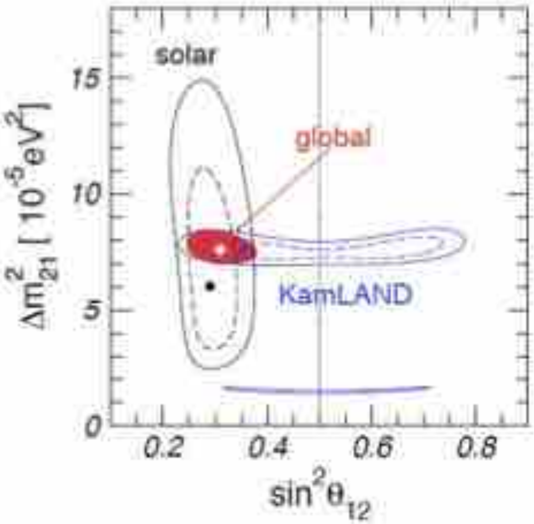
atmospheric ν
+ K2K, MINOS
$\Delta m^2_{atm} = 2.4 \cdot 10^{-3}$ eV^2
$\theta_{23} = (45 \pm 7)°$

reactor ν
(CHOOZ)
$\Delta m^2_{31} \approx \Delta m^2_{atm}$
$\theta_{13} < 13°$

solar ν
+ KamLAND
$\Delta m^2_{sol} = 7.6 \cdot 10^{-5}$ eV^2
$\theta_{12} = (34 \pm 3)°$







Search for θ_{13} at reactors

Antineutrino Signal

inverse beta decay:

$$Q_{thr} = M_n + m_e - M_p \approx 1.8\text{ MeV}$$

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

$$E_{vis} \cong E_\nu - E_n - 0.8\text{MeV}$$

$$\approx 1-8\text{ MeV}$$

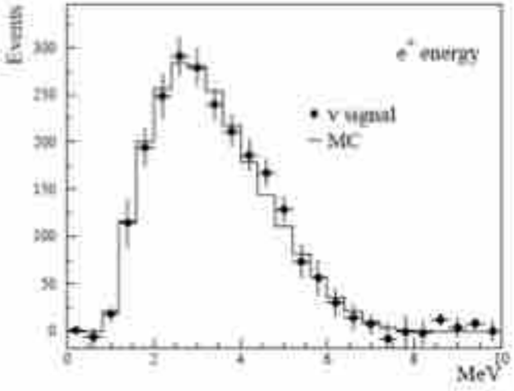
prompt event

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s } (\sim 8\text{MeV}), \tau \sim 30\mu s$$

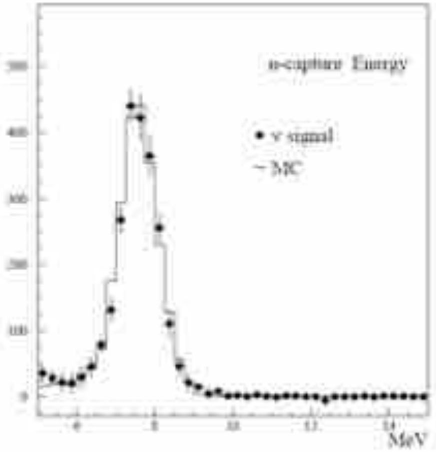
$$n + H \rightarrow d + \gamma\ (2.2\text{MeV}),\ \tau \sim 230\mu s$$

delayed event

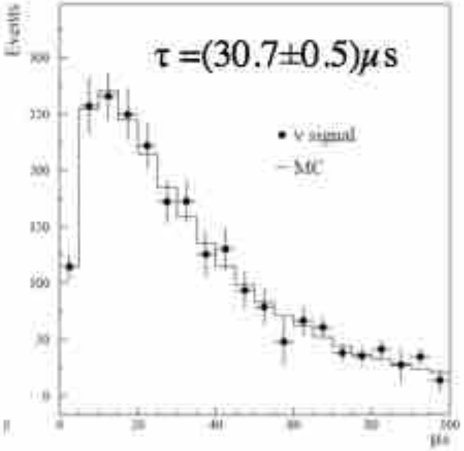
Detection in Gd-loaded liquid scintillator



e^+ energy



n capture energy

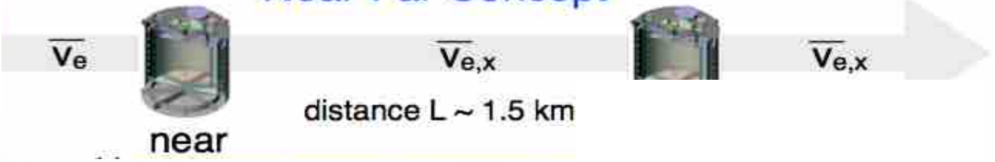


e^+-n time delay

Apollonio et al. (2003)

Daya Bay Anti-ν Detectors

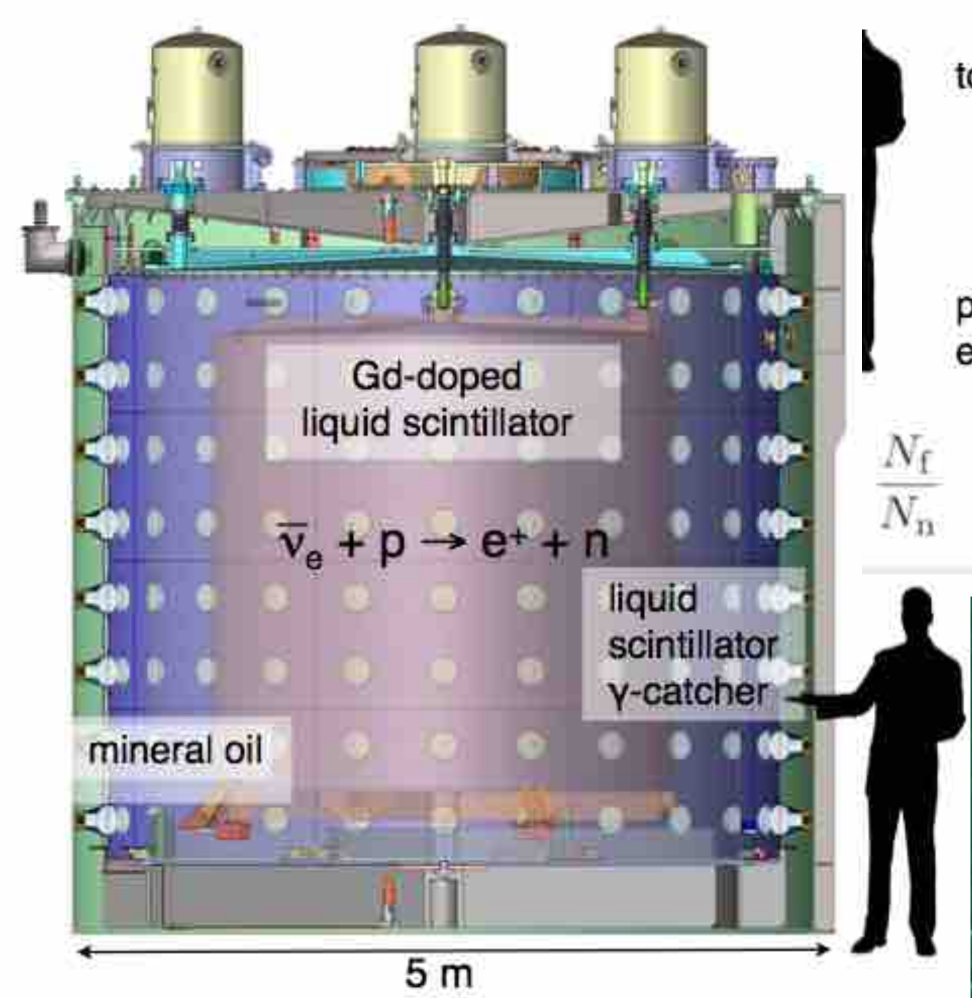
Near-Far Concept



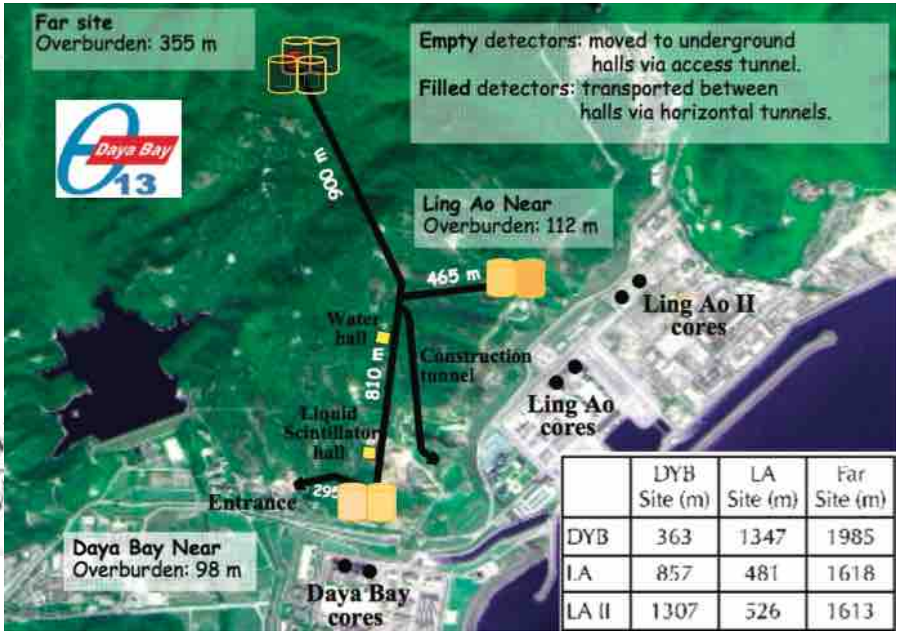
total detector mass: ~ 110t
inner: 20 tons Gd-doped LS (d=3m)
mid: 20 tons LS (d=4m)
outer: 40 tons mineral oil buffer (d=5m)

photosensors: 192 8"-PMTs
energy resolution: (7.5 / √E + 0.9)%

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

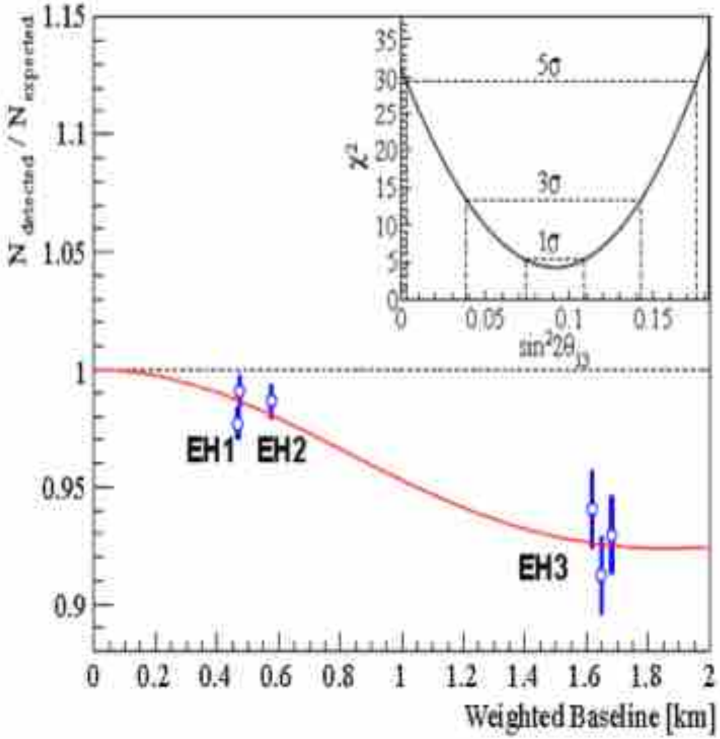


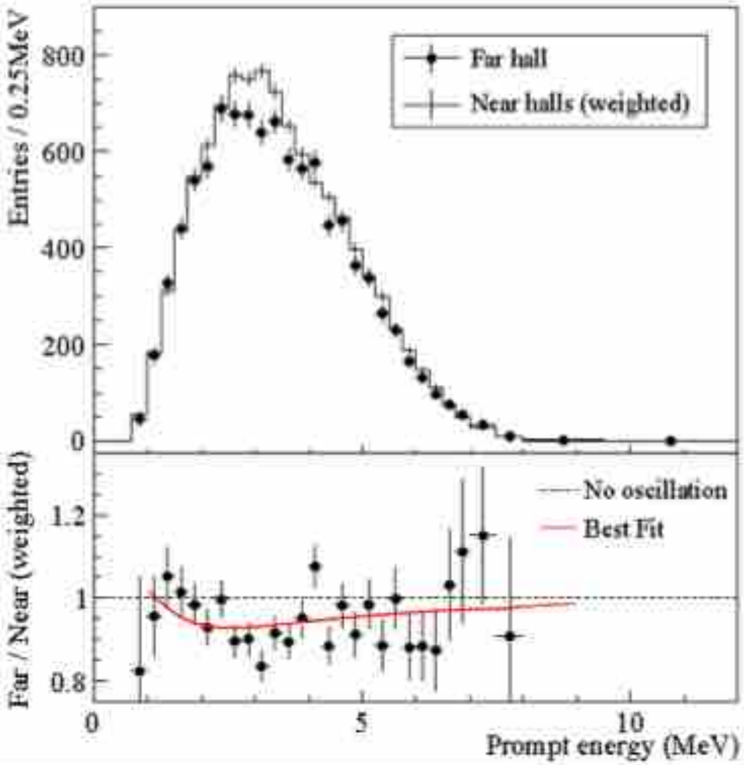
6 “functionally identical”, 3-zone detectors reduces systematic uncertainties



	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

March 8, 2012 : Daya Bay results





hall. Comparing with the prediction based on the near-hall measurements, a deficit of 6.0% was found. A rate-only analysis yielded $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$. The neutrino mixing angle θ_{13} is non-zero with a significance of 5.2 standard deviations.

Experimental Results

T2K ($\theta_{13} > 0$ @ 2.5σ)

Expected events: 1.5, Detected 6

Double Chooz (1.3σ)

Expected events: 4344, Detected 4101

$R_{DC} = 0.944 \pm 0.016(\mathrm{stat}) \pm 0.040(\mathrm{syst})$

Daya Bay (5.2σ)

Expected events: 85506, Detected 80376

$R_{DB} = 0.940 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst})$

RENO (4.9σ)

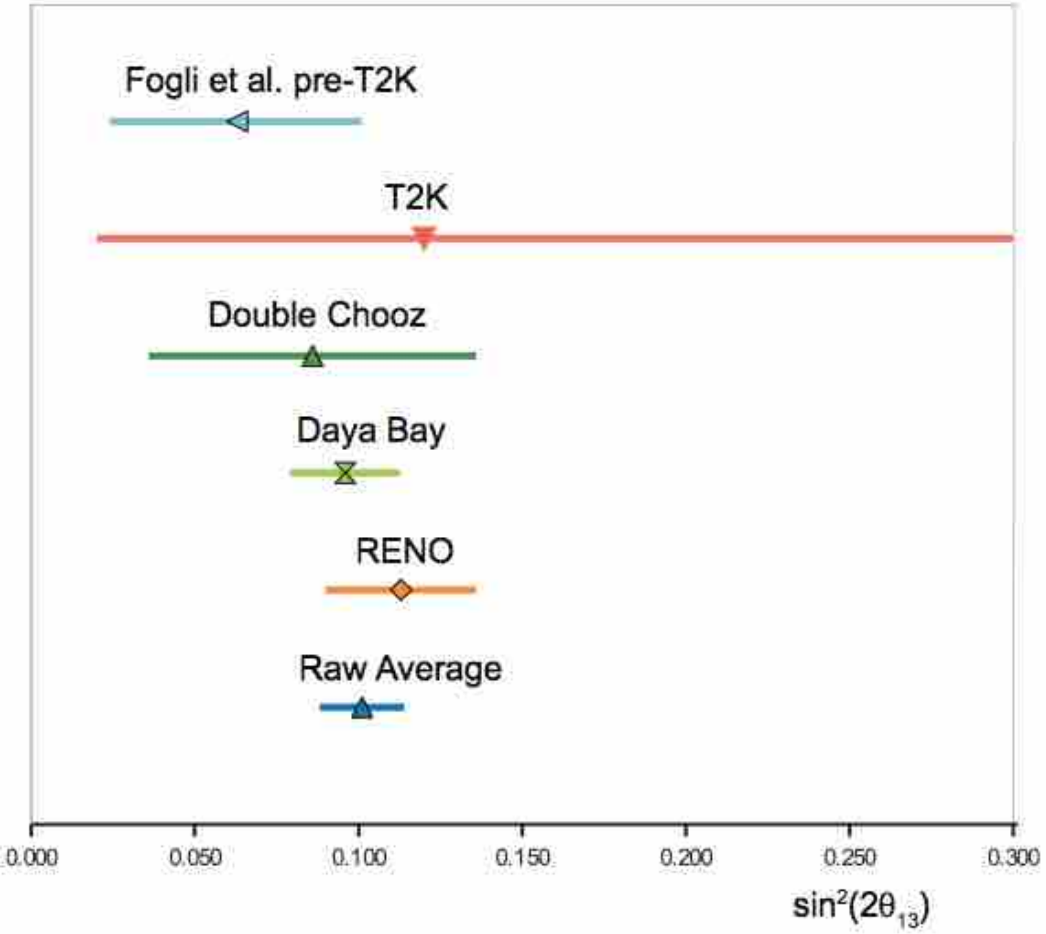
Expected events:149905, Detected 137912

$R_{R} = 0.920 \pm 0.009(\mathrm{stat.}) \pm 0.014(\mathrm{syst.})$

+ $\nu_\mu \rightarrow \nu_e$ appearance expt.:
T2K; OPERA
and then NOνA; LBNE; …

Summary of θ_{13} results

Computed for $\Delta m_{23}^2 = 2.4 \cdot 10^{-3}$ eV^2



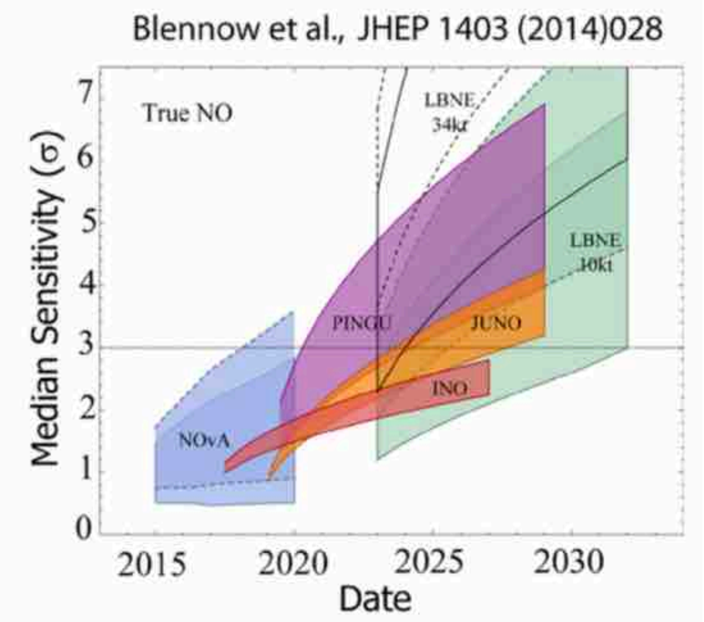
Critical Questions for Future Neutrino Physics Program

1) Are neutrinos their own anti-particles? Dirac or Majorana neutrinos (**$0\nu\beta\beta$**)

2) What are the scale of neutrino masses and the hierarchy of the neutrino mass ordering? (Oscillations indicate $\Delta m^2 \neq 0$, but unable to determine m_ν).

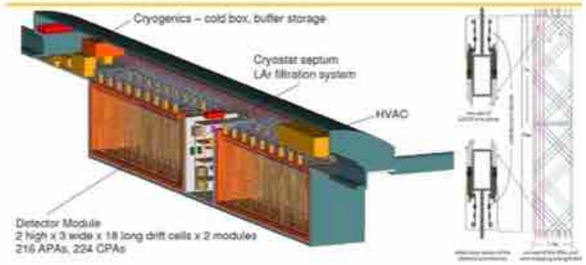
- Pure oscillation effects in ν_e disappearance: **Juno**
- Matter effects in ν_μ disappearance: **INO, Pingu, Orca, HyperKamiokande**
- Matter effects in ν_e appearance: **NOvA, Dune, T2HK**

Blennow et al., JHEP 1403 (2014)028



3) Do neutrinos violate the CP symmetry and contribute to the matter-antimatter asymmetry?

Mainly two players: Dune and HyperKamiokande



Is all discovered?

✓ A few experiments show (weak/not-strong) **deviations** (***anomalies***) from the 3 flavor ν-osc paradigma:

- **LSND** at Los Alamos observed excess of $\bar{\nu}_e$ events in the $\bar{\nu}_\mu$ beam
- **Mini-Boone** confirmed anomaly at low energy in anti-neutrino mode but not in neutrino mode
- **Gallium anomalies**: events from calibration sources in GALLEX and SAGE are less than expected (2.8σ)
- **Reactor anomalies**: reanalysis of reactor expts show a (small) deficit of ν_e

✓ It is too early to claim new physics. The only picture consistent with all data is the existence of ***sterile neutrinos***

✓ A short-term program includes MCi neutrino sources (SOX in Borexino at LNGS); SBL (short-baseline) expt probing GeV ν_e appearance at short distances (100m – 1 km)