NEUTRINO PHYSICS: NEW VISTAS

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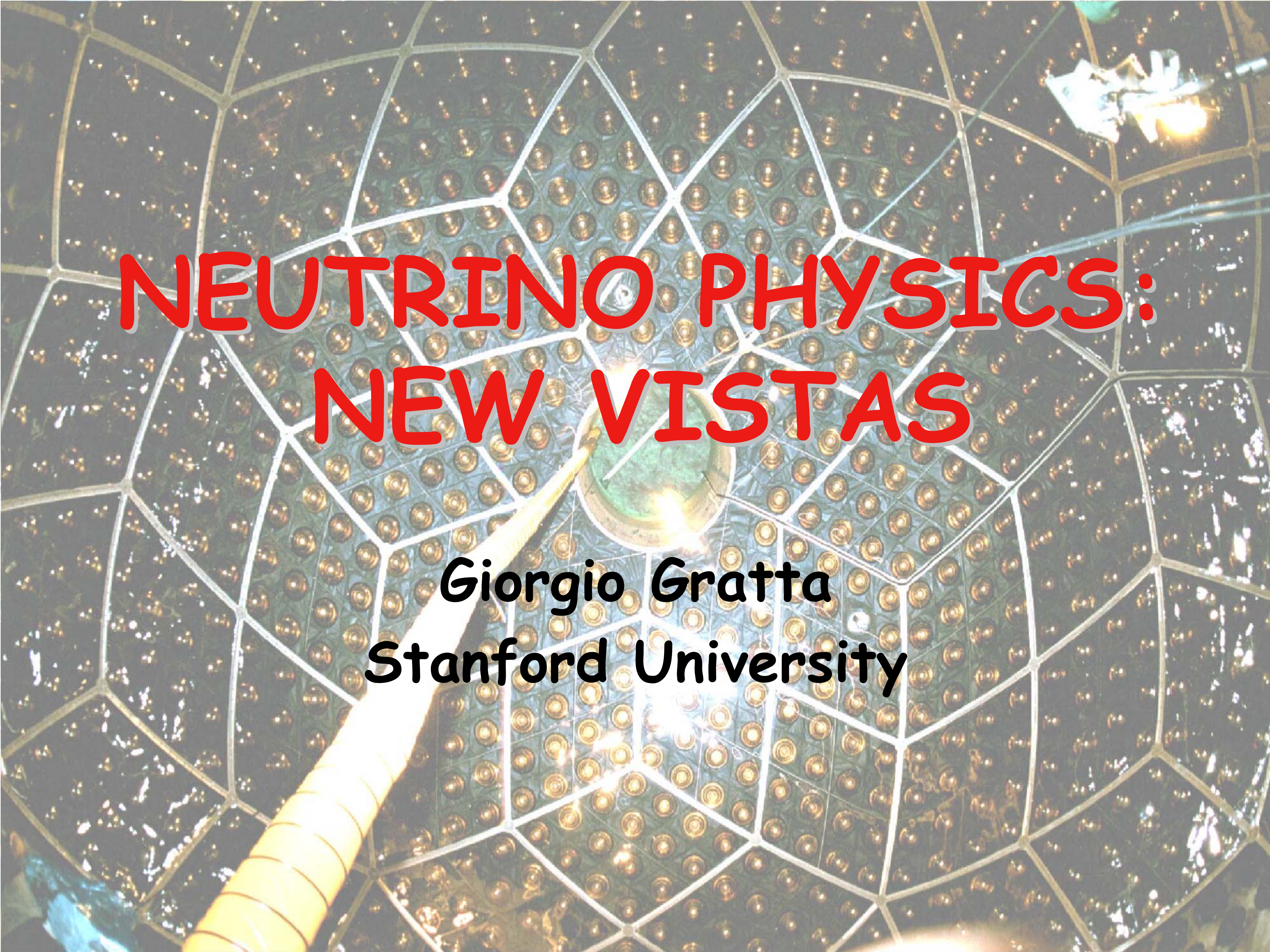


Neutrinos were "invented" in 1930 by W.Pauli to explain some features of nuclear beta decay

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a deseperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call *neutrons*, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the *neutrons* should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.........

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant
W. Pauli

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Today neutrinos occupy an important role in particle physics...

ν_e	ν_μ	ν_τ	Leptons
e	μ	τ	

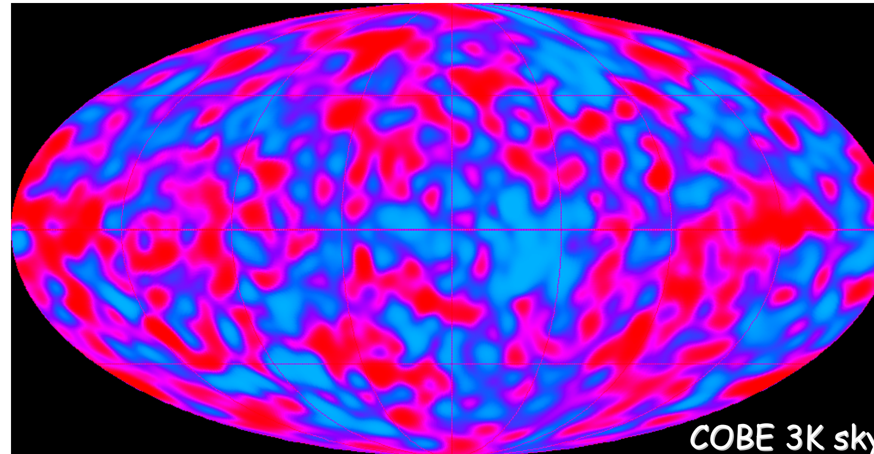
25% of elementary particles are neutrinos

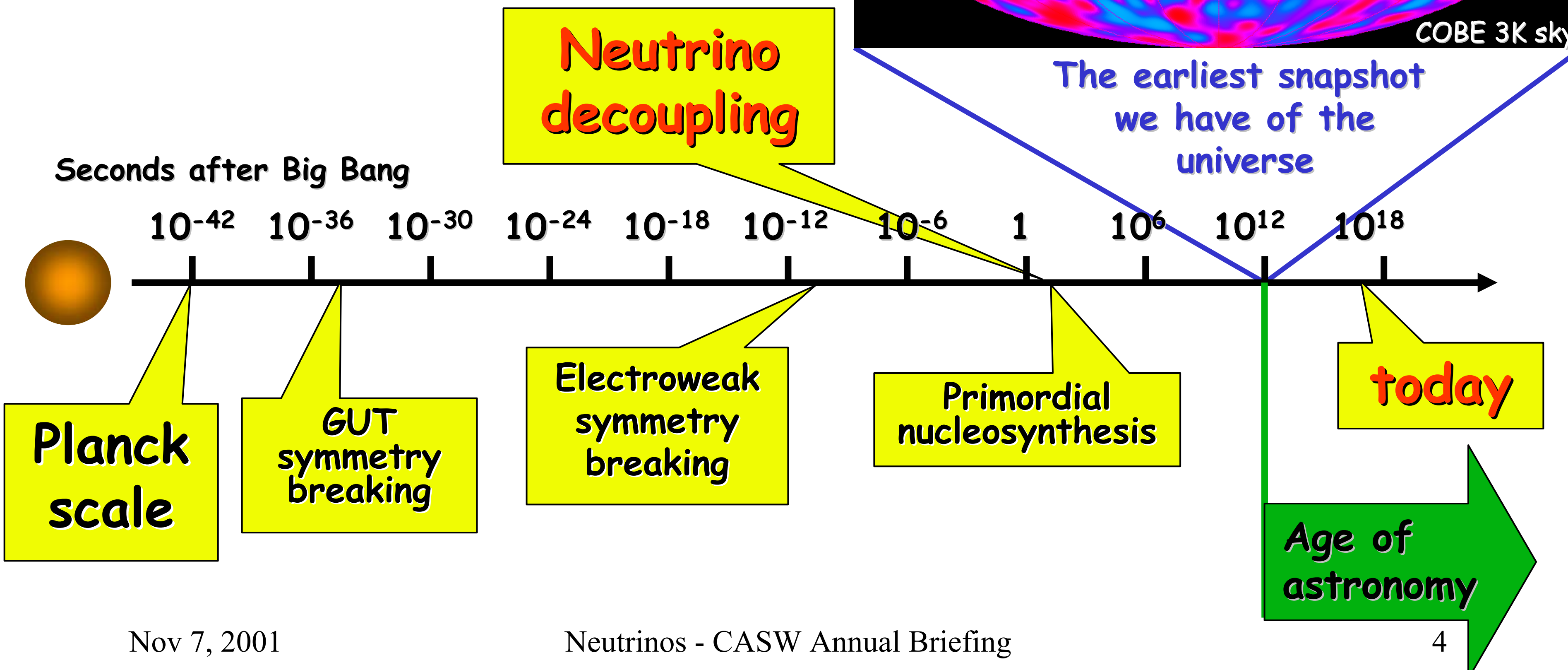
u	c	t	Quarks
d	s	b	

Neutrinos have been used as "projectiles" to study other particles and to establish the "Standard Model" of particle physics

...astrophysics and cosmology

Neutrinos are produced in great abundance in stars, supernovae and were produced in the primordial Big Bang





Experimental knowledge of neutrinos

"I have done a terrible thing. I have postulated a particle that cannot be detected." *W.Pauli*

- They exist — '50s
- They are left-handed — '50s
- $\nu_e \neq \nu_\mu$ — '60s
- $n_{light\ \nu} = 3$ — '90s
- $M_\nu \neq 0$ — '90s
- $\nu_\tau \neq \nu_{\mu,\ e}$ — '00s

What do we hope to learn studying ν masses ?

- More information on the "mass problem":
  after all the Standard Model does not really understand masses

- "Minimal Standard Model" usually constructed with $m_\nu=0$
  extensions with finite m_ν naturally give $m_\nu = m_l^2/M$
  where m_l is the lepton mass
  and M is the scale for new physics

- 300 ν/cm^3 in the universe from the Big Bang:
  non-zero ν masses have an impact on the problem of dark matter

If m_ν then leptons could behave like quarks

➡ the weak interaction eigenstate $|\nu_j\rangle$ is a superposition of mass eigenstates $|\nu_j\rangle = \sum_j U_{jl} |\nu_l\rangle$

U_{jl} is a 3×3 unitary matrix (like the CKM matrix for quarks)

What propagates is the mass eigenstate $|\nu_l\rangle$

Flight path

$$|\nu_l(t)\rangle = e^{-i(E_i t - p_i L)} |\nu_l(0)\rangle \cong e^{-i(m_j^2/2E)L)} |\nu_l(0)\rangle$$

What is produced and detected is $|\nu_j\rangle$

Assuming

$E_i = E >> m_i \qquad p_i >> m_i$

$$\left|\nu_j\right\rangle \cong \sum_l U_{lj} e^{-i(m_l^2/2E)L} \left|\nu_l\right\rangle \cong \sum_{j'} \sum_l U_{lj} e^{-i(m_l^2/2E)L} U_{j'l}^* \left|\nu_{j'}\right\rangle$$

…that is neutrinos "acquire" components from other flavors as they propagate

We can define a "transition probability"

$$P(\nu_{j'} \to \nu_j, L) = \left| \sum_l U_{lj} U_{j'l}^* e^{-i(m_l^2/2E)L} \right|^2$$

…a periodic function of the baseline L

For 2 flavors this simplifies:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Only one mixing parameter θ

$$P(\nu_e \to \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.3\Delta m^2 L}{E}$$

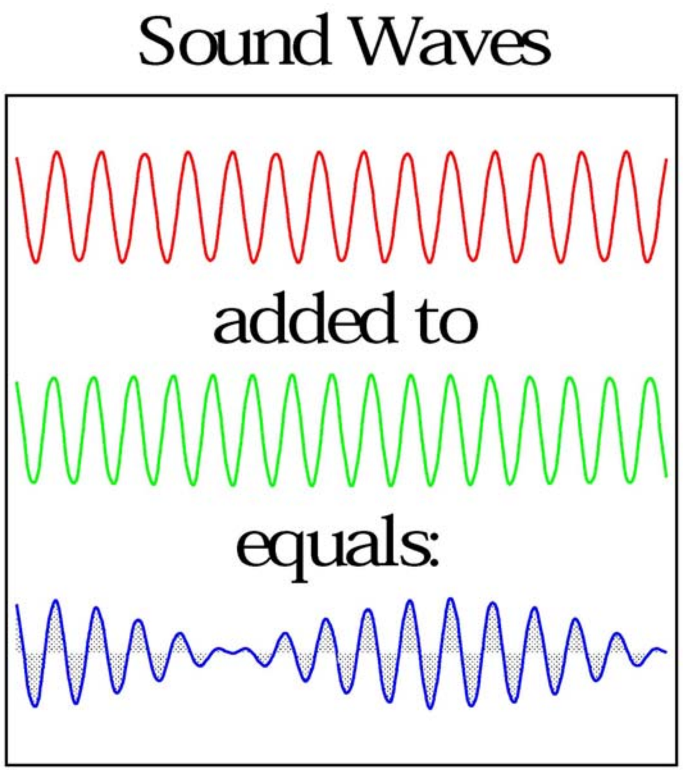
$\Delta m^2 = m_1^2 - m_2^2$ [eV²]

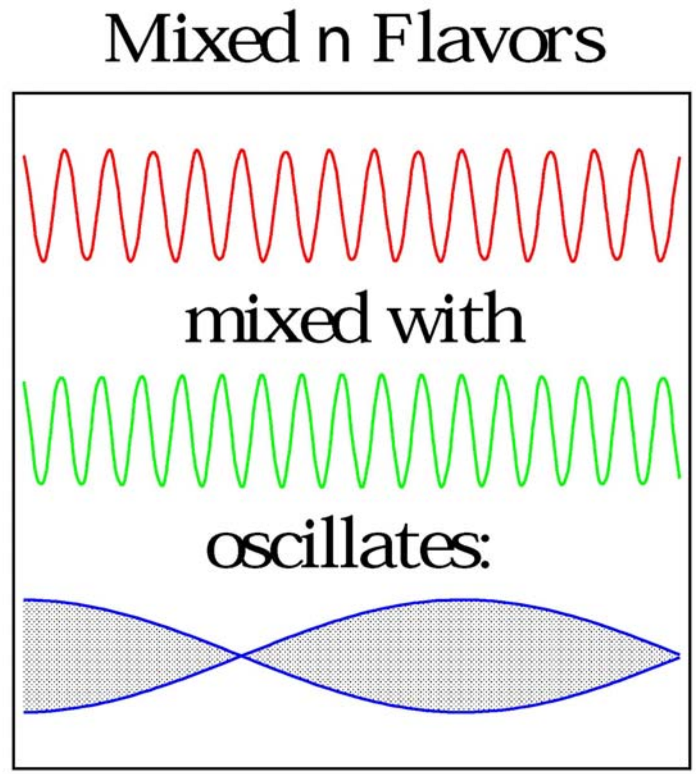
L [km]

E [MeV]

Neutrino oscillations ➡ $m_\nu \neq 0$

Neutrino oscillations are analogous to "beatings" in sound waves



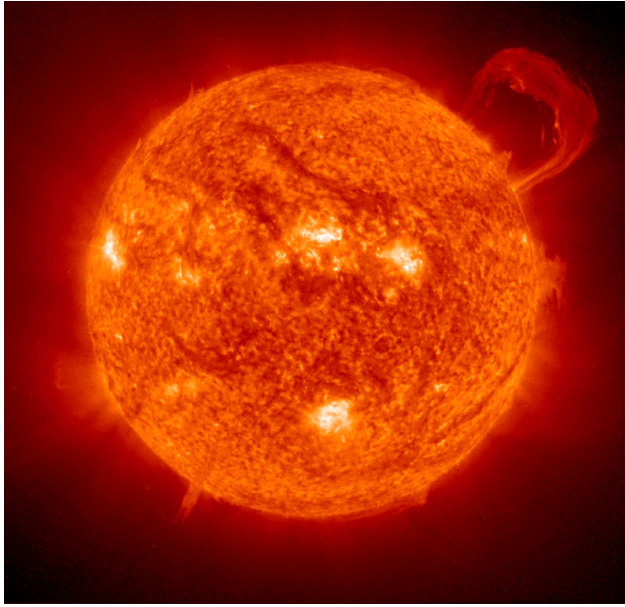


ν_1 wave-function

ν_2 wave-function

neutrino flux

ν_e are abundant by-products of nuclear fusion in the sun



$$p+p \rightarrow {}^2H + e^+ + \nu_e + 0.42 MeV$$

"pp" 99.75%

$$p+e^- + p \rightarrow {}^2H + \nu_e + 1.44 MeV$$

"pep" 0.25%

$${}^2H + p \rightarrow {}^3He + \gamma + 5.49\ MeV$$

86%

$${}^3He + {}^3He \rightarrow \alpha + 2p + 12.86 MeV$$

14%

$${}^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59 MeV$$

"hep" $2.4*10^{-5}$

$${}^3He + p \rightarrow \alpha + e^+ + \nu_e$$

"7Be" 99.89%

$${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e + 0.8617 MeV$$

$${}^7Li + p \rightarrow \alpha + \alpha + 17.35 MeV$$

0.11%

$${}^7Be + p \rightarrow {}^8B + \gamma + 0.14 MeV$$

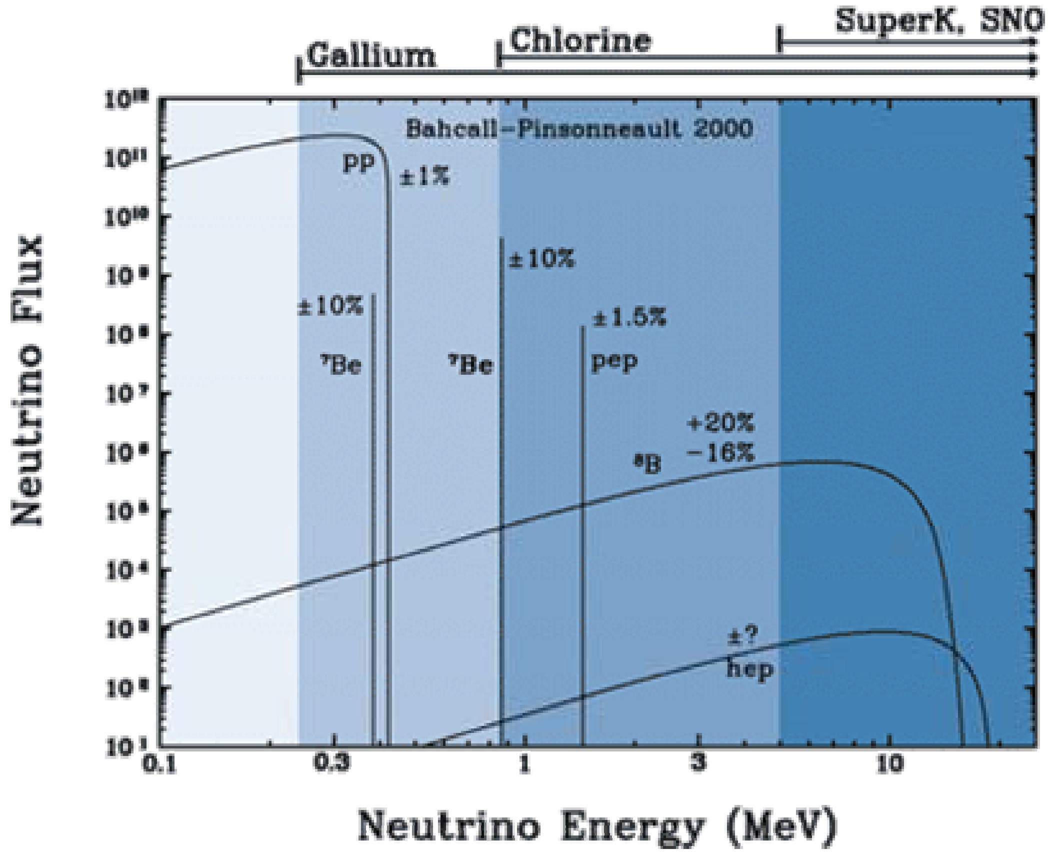
"8B" 0.11%

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6 MeV$$

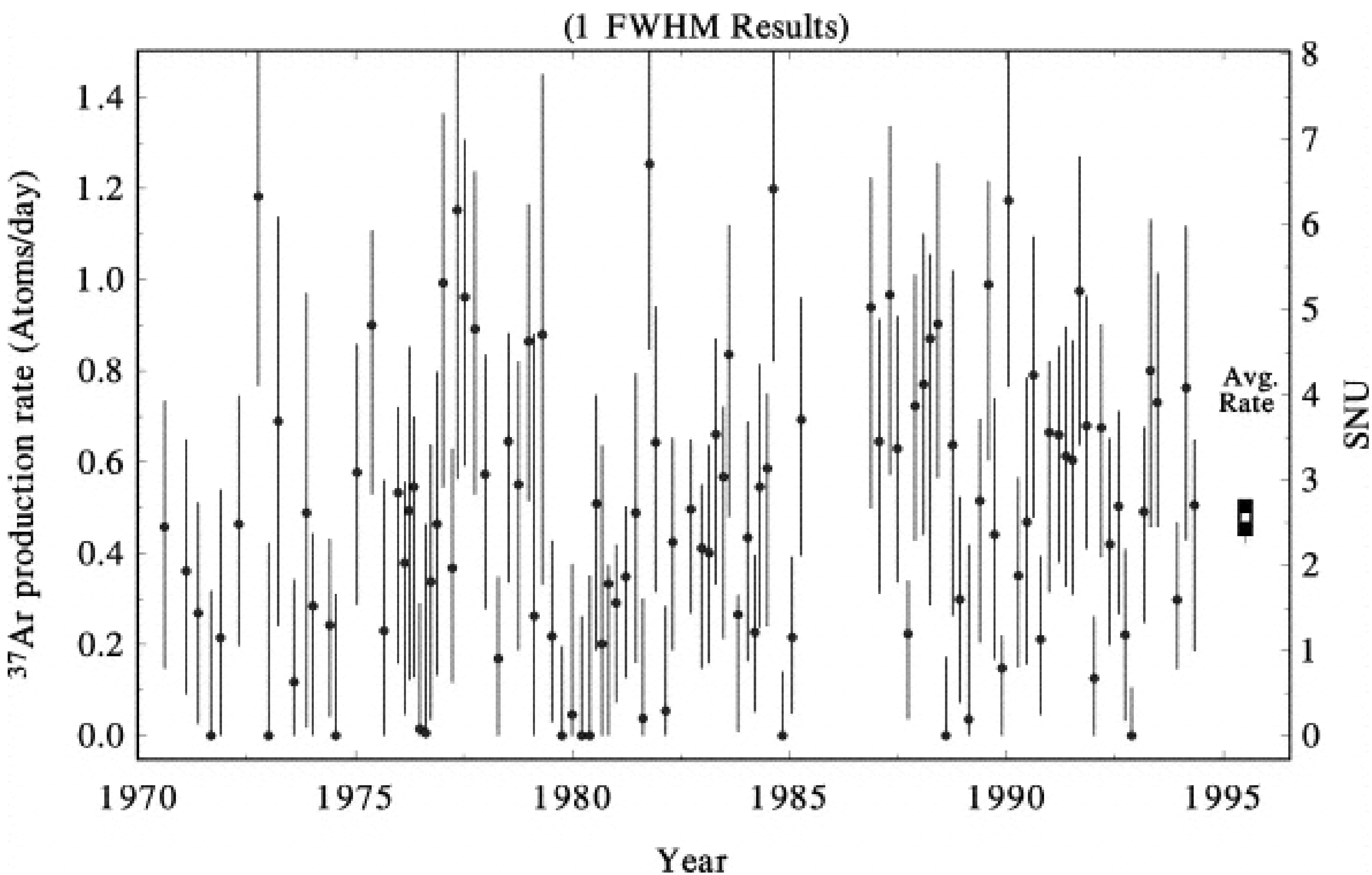
$${}^8Be \rightarrow \alpha + \alpha + 3 MeV$$

3 types of experiments detecting solar neutrinos

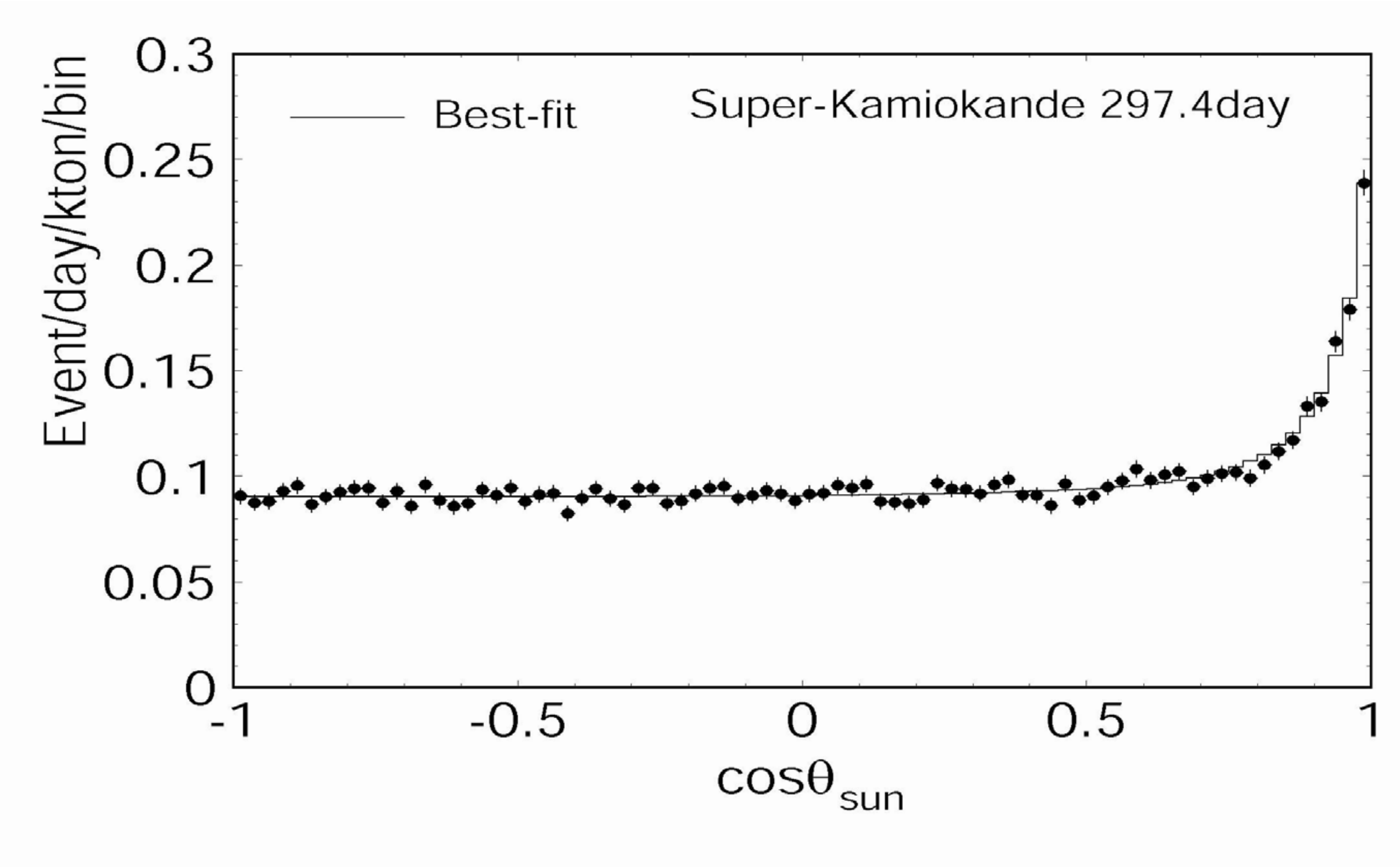
- Chlorine: $^{37}Cl + \nu_e = {}^{37}Ar + e^-$
  - 1 exp running >30 yrs (US)
- Gallium: $^{71}Ga + \nu_e = {}^{71}Ge + e^-$
  - 3 exp (Russia, Italy)
- Cerenkov: $e^- + \nu_e = e^- + \nu_e$
  - 3 exp (Japan, Canada)



30 years of solar neutrinos with the Chlorine detector



Neutrinos come from the Sun !

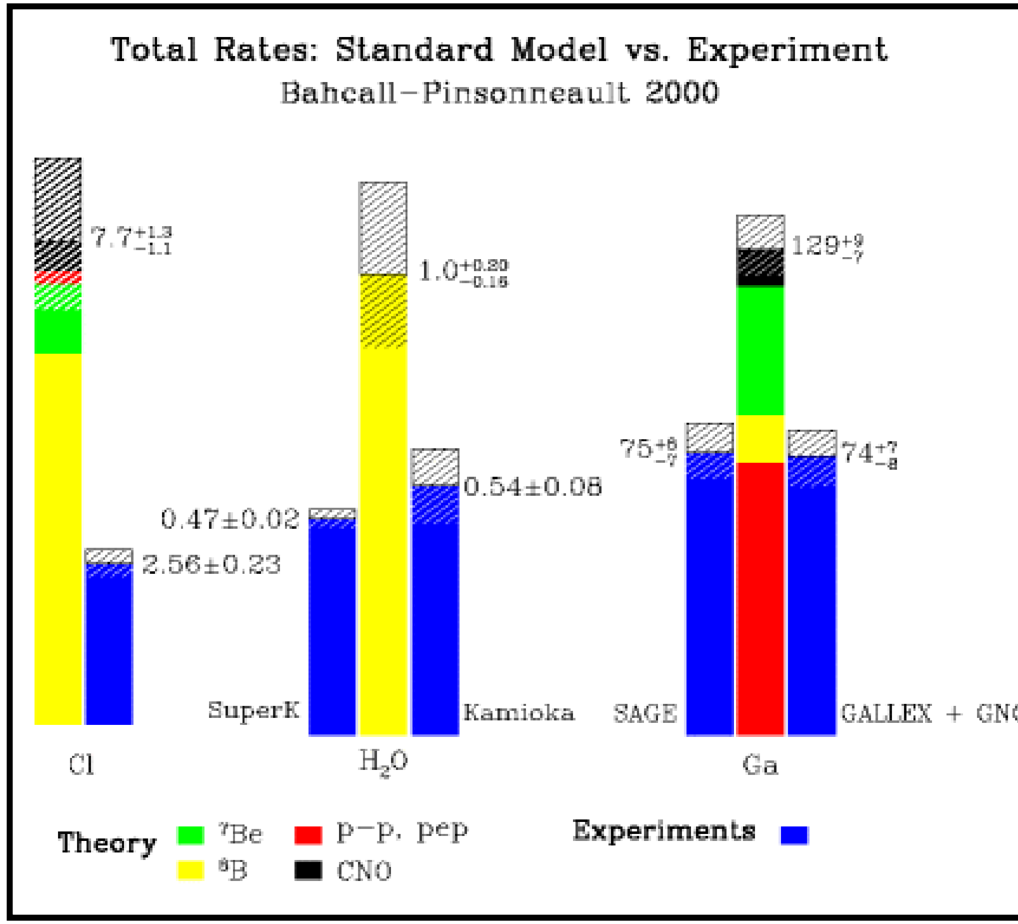


Conclusions:

1) We detect νs ! : nuclear fusion powers the sun

2) The sun is still shining (this is not trivial: it takes ~ 1Myr for a γ to emerge from the sun)

3) We do not see enough νs
   - do we understand the sun well enough ?
   - are νs playing tricks ?

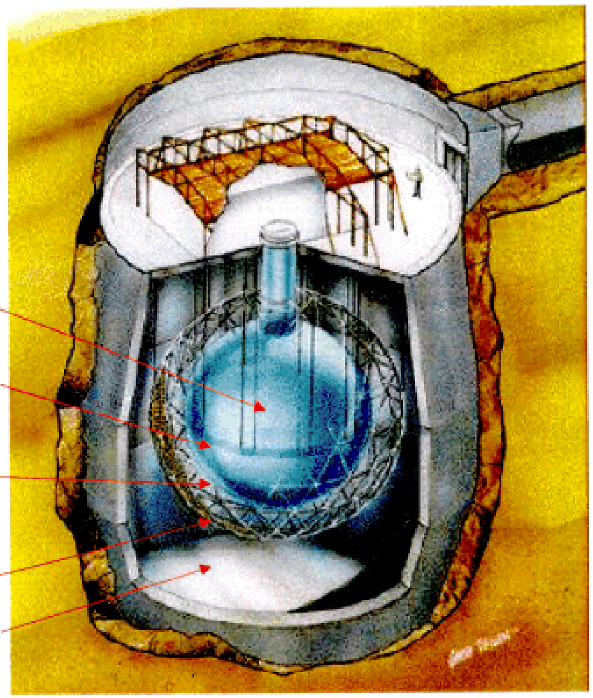


"It starts to be really interesting ! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately it will not be easy to demonstrate this, even if nature works this way…" B.Pontecorvo, 1972

J. Wilkerson, SSI 2000

SUDBURY, ONT.
46°28'30" N
81°22'4" W

SNO Description: nucl-ex/9910016



2039 meters to surface

1000t D_2O

12 m dia. Acrylic Sphere

1700t H_2O

9529 PMT's

5300t H_2O

Wilkerson, SSI 2000

SNO Measurements

Charged Current Reaction (D_2O):

CC | $\nu_e + d \rightarrow p + p + e^-$ $E_{thres} = 1.4$ MeV | (only ν_e)

- ν_e energy spectrum (distortion $\Rightarrow$ MSW effect)
- Some directional sensitivity ($1 - 1/3 \cos\theta_e$)

Neutral Current Reaction (D_2O):

NC | $\nu_x + d \rightarrow \nu_x + p + n$ $E_{thres} = 2.2$ MeV | (ALL ν types)

- Total solar ^{8}B neutrino flux (active neutrinos)

$$\text{Ratio} = \frac{CC}{NC} = \frac{(\nu_e)\ \text{flux}}{(\nu_e + \nu_\mu + \nu_\tau)\ \text{flux}}$$

Elastic Scattering Reaction (D_2O,H_2O):

ES | $\nu_x + e^- \rightarrow \nu_x + e^-$ $E_{thres} = 0$ MeV | (mostly ν_e)

- Low counting rate
- Directional sensitivity (very forward peaked)

$$\text{Ratio} = \frac{CC}{ES} = \frac{(\nu_e)\ \text{flux}}{0.86\,\nu_e + 0.14(\nu_\mu + \nu_\tau)\ \text{flux}}$$

The SNO detector recently started to produce data

SNO: 1kton D_2O

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

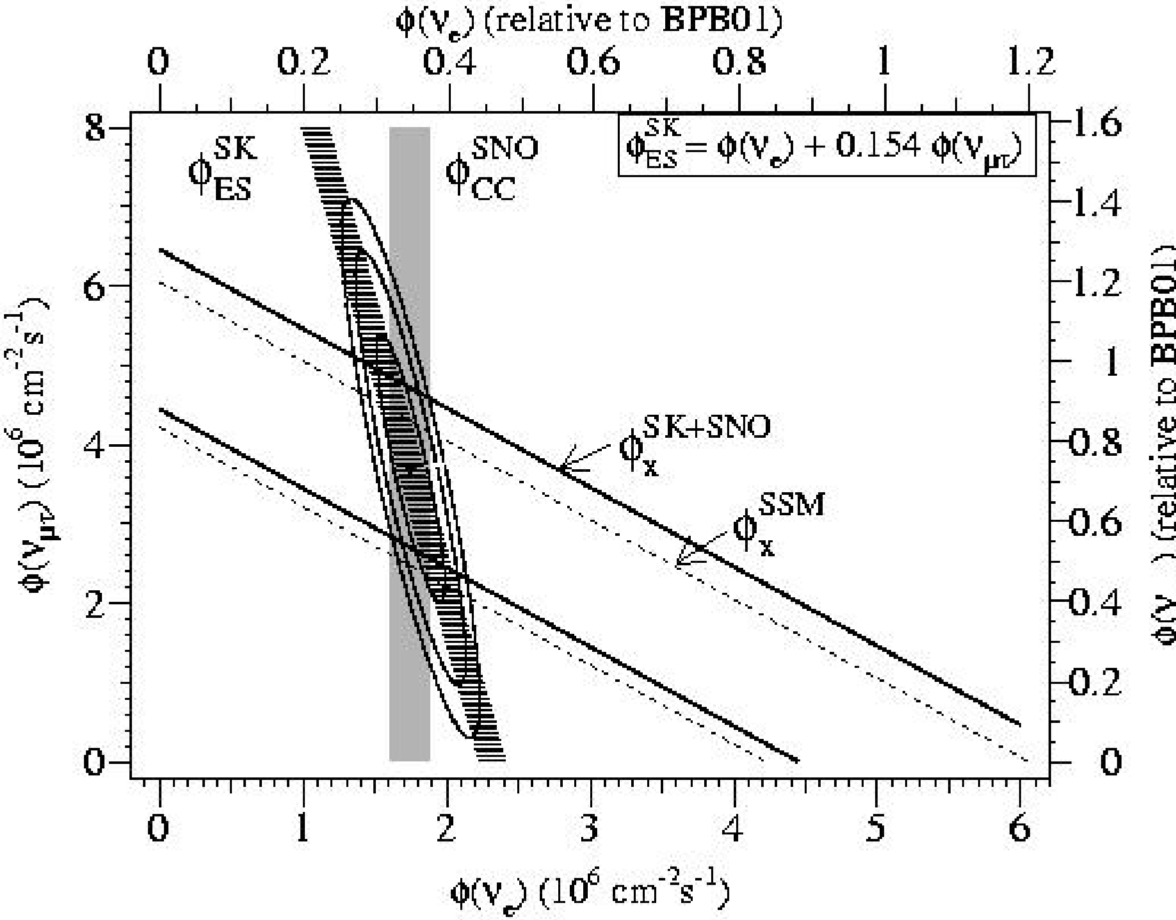
sensitive to ν_e only

SuperK:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

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

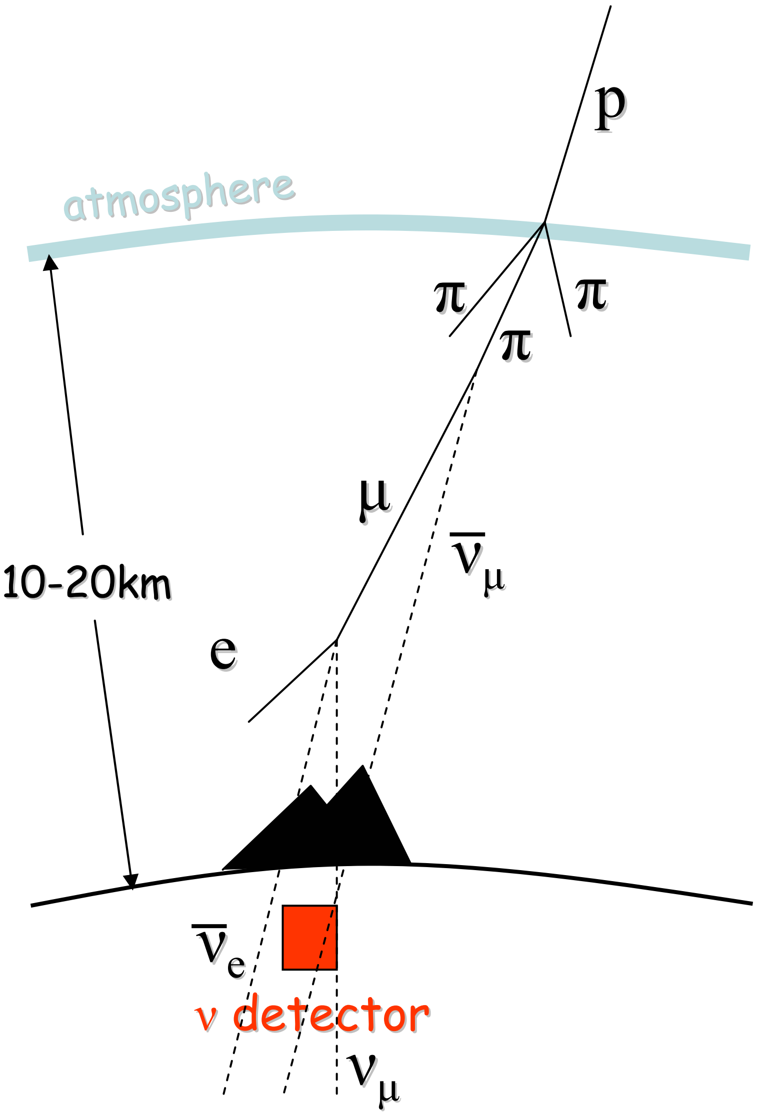
sensitive to a ν_e, ν_x mix

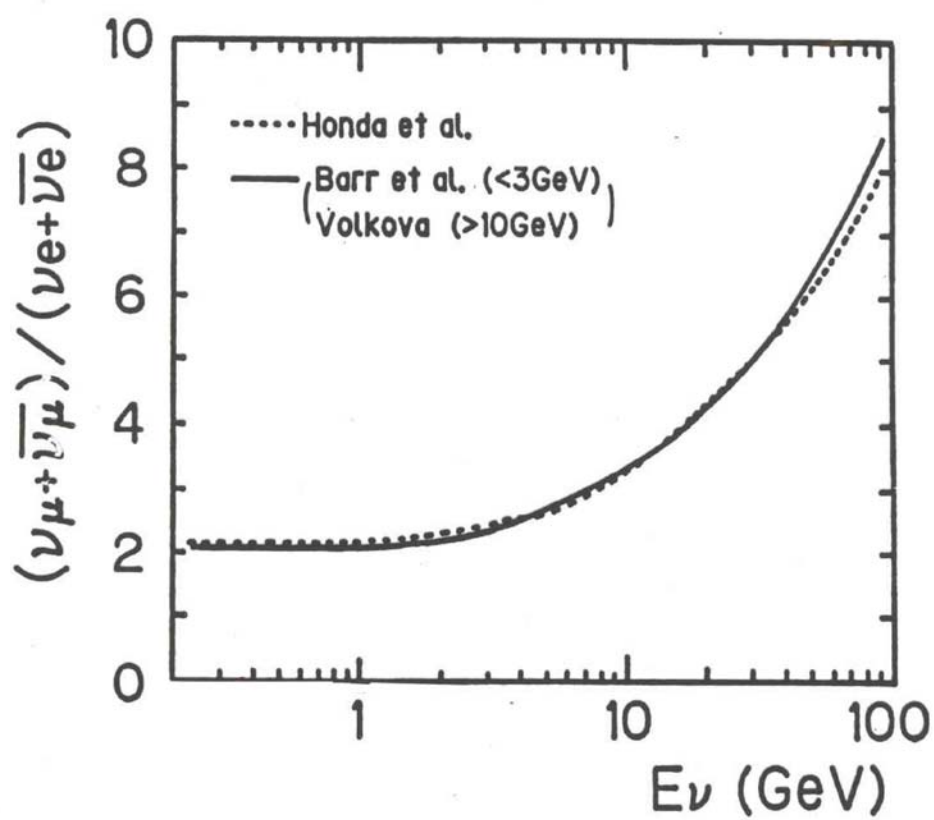


$$\begin{aligned}\phi(\nu_{\mu,\tau}) &= 3.69 \pm 1.13 \\ \phi(\nu_e) &= 5.44 \pm 0.99\end{aligned} \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

It appears like some ν_e change flavor !

More hints: Atmospheric Neutrinos



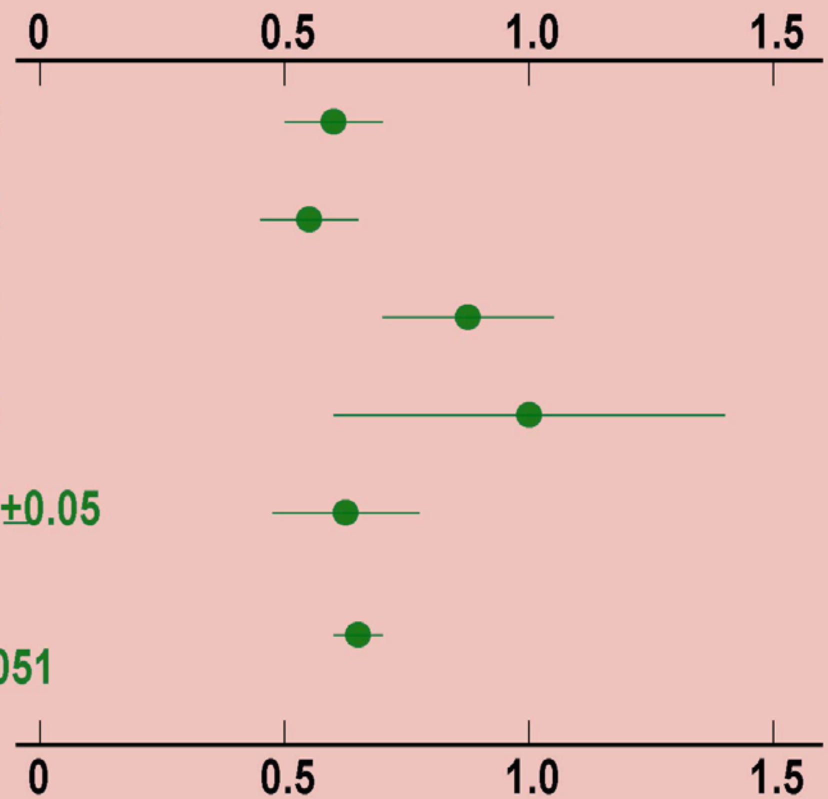


At low energy (~GeV) expect

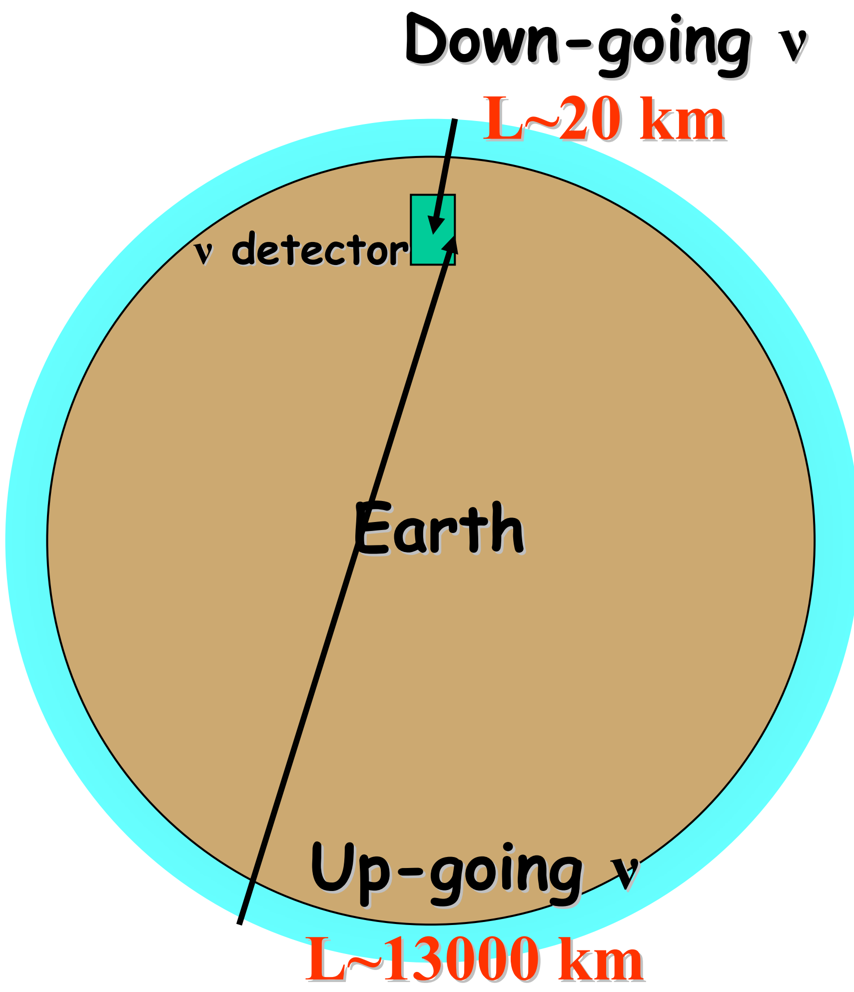
$$N_{\nu_\mu} \cong 2N_{\nu_e}$$

Atmospheric Neutrinos: Ratio of Ratios

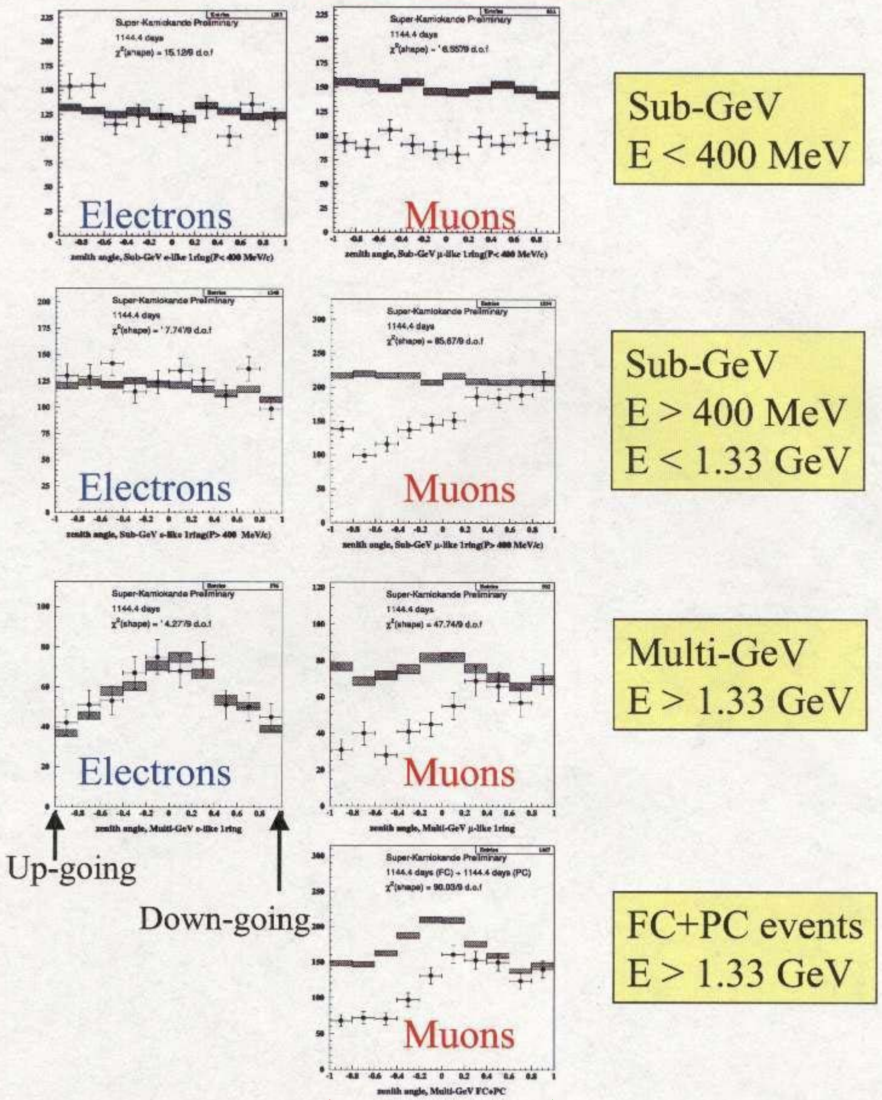
Experiment	Exposure (kton yr)	$\left(\frac{m}{e}\right)_{obs} \Big/ \left(\frac{m}{e}\right)_{theory}$
Kamiokande	6.1	0.60±0.08
IMB	7.7	0.54±0.09
Frejus	1.6	0.87+0.21
Nusex	0.4	0.99±0.40
Soudan 2	3.0	0.64±0.13±0.05
SuperK 2000, Sub GeV	70.5	0.652 ±0.019±0.051



Is there a way to tell if the effect is due to neutrino properties ?



What do we see?

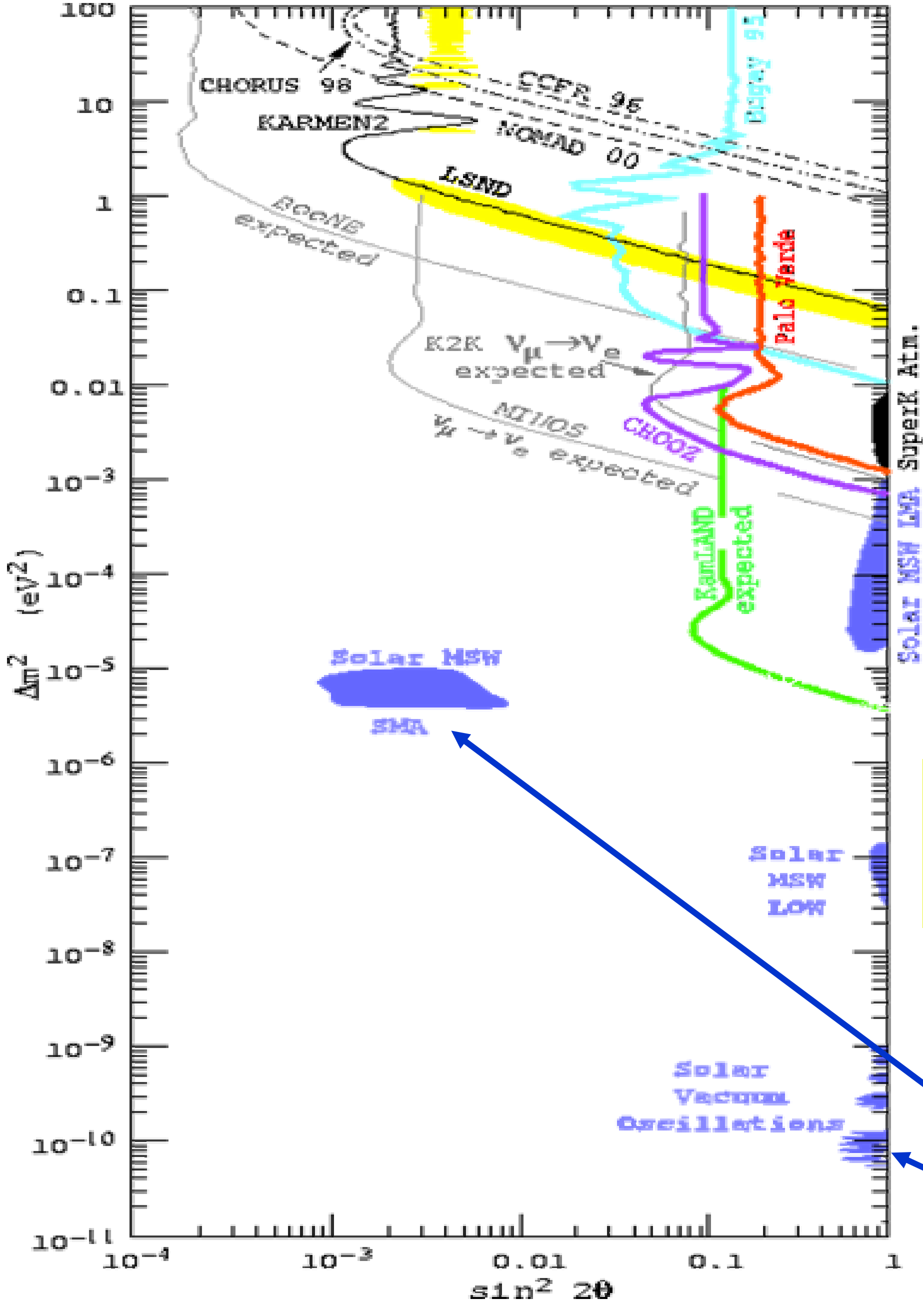


Up going — Down going

Indeed around 1 GeV the ν_μ flux depends on the angle !!

At higher and lower energies the angular behavior is consistent with oscillations

ν_e do not seem to have an oscillation pattern (more later)



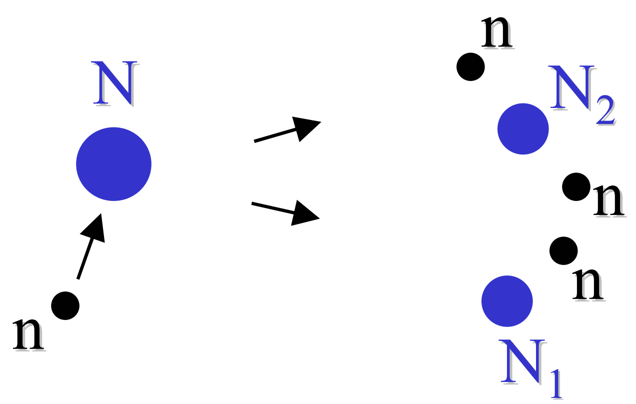
Interpreting solar and atmospheric neutrino anomalies as due to oscillations we can draw the parameters $\sin^2 2\theta$ and Δm^2 consistent with the experiments

$$P(\nu_e \to \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.3\Delta m^2 L}{E}$$

Mostly ruled out by the recent SNO results

How to check that neutrino oscillations occur without relying on extra-terrestrial sources ?

Nuclear reactors are very intense sources of ν_e deriving from beta-decay of the neutron-rich fission fragments

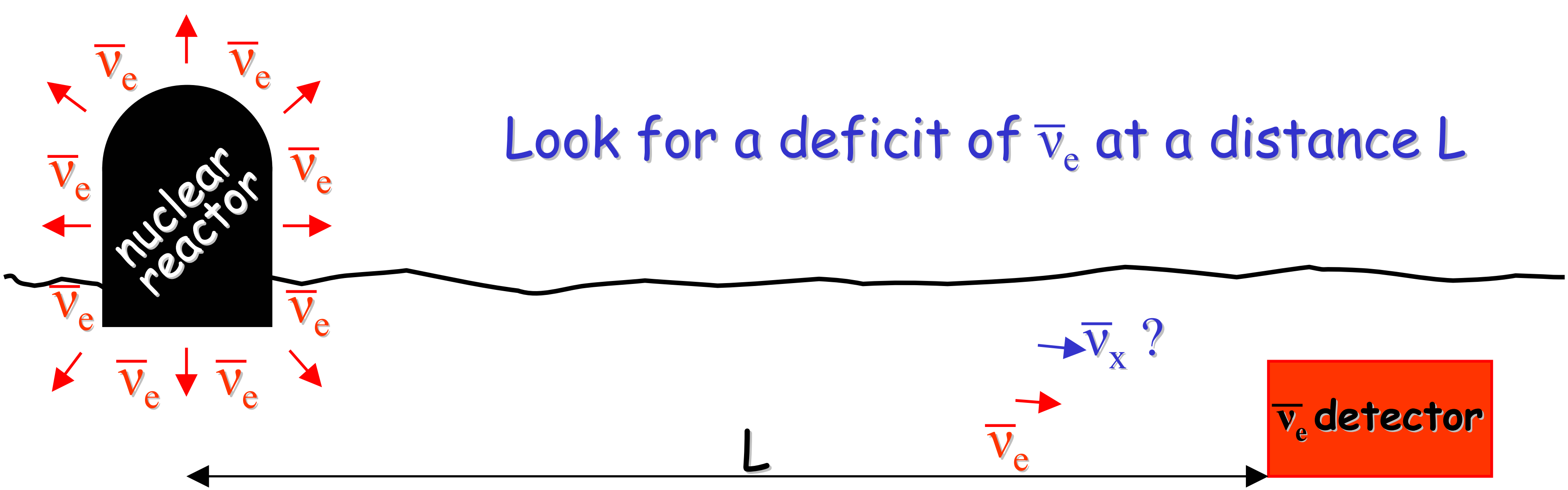


N_1 and N_2 still have too many neutrons and decay

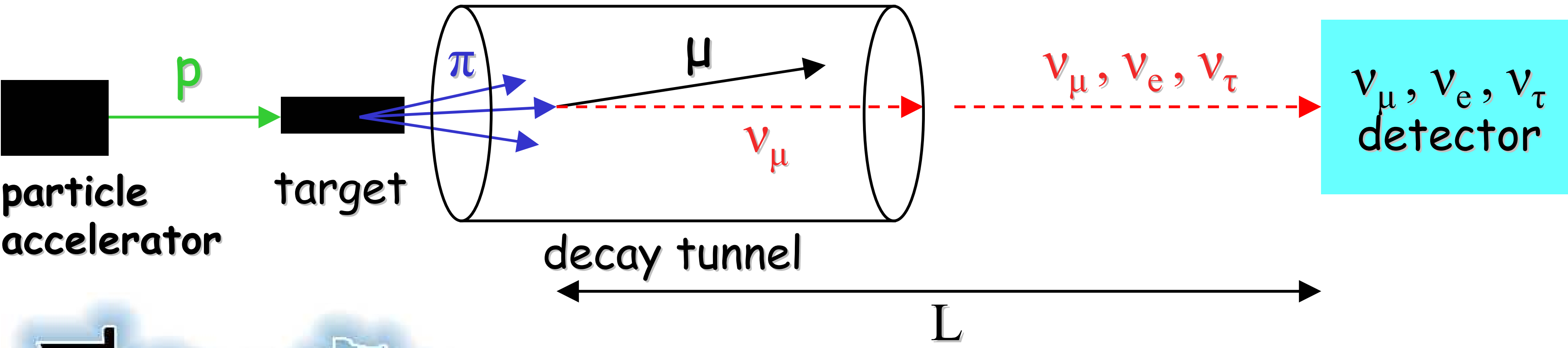
$$N_2 \rightarrow N_3 + e^- + \nu_e$$

(this is why reactor spent fuel is radioactive)

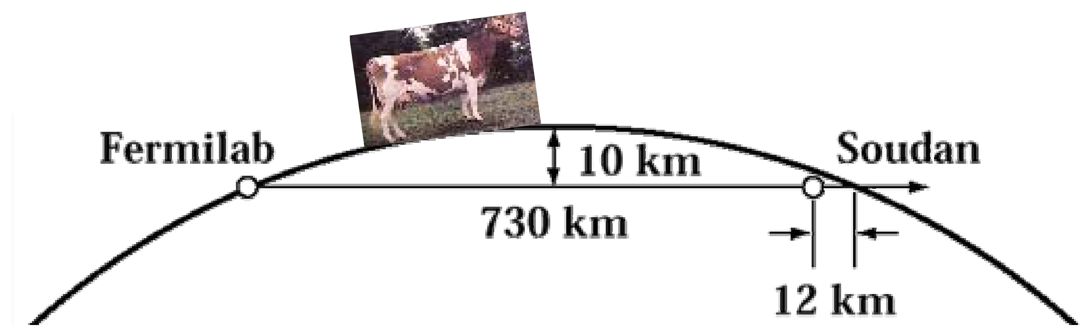
Look for a deficit of $\overline{\nu}_e$ at a distance L



Neutrinos can also be produced in particle accelerators



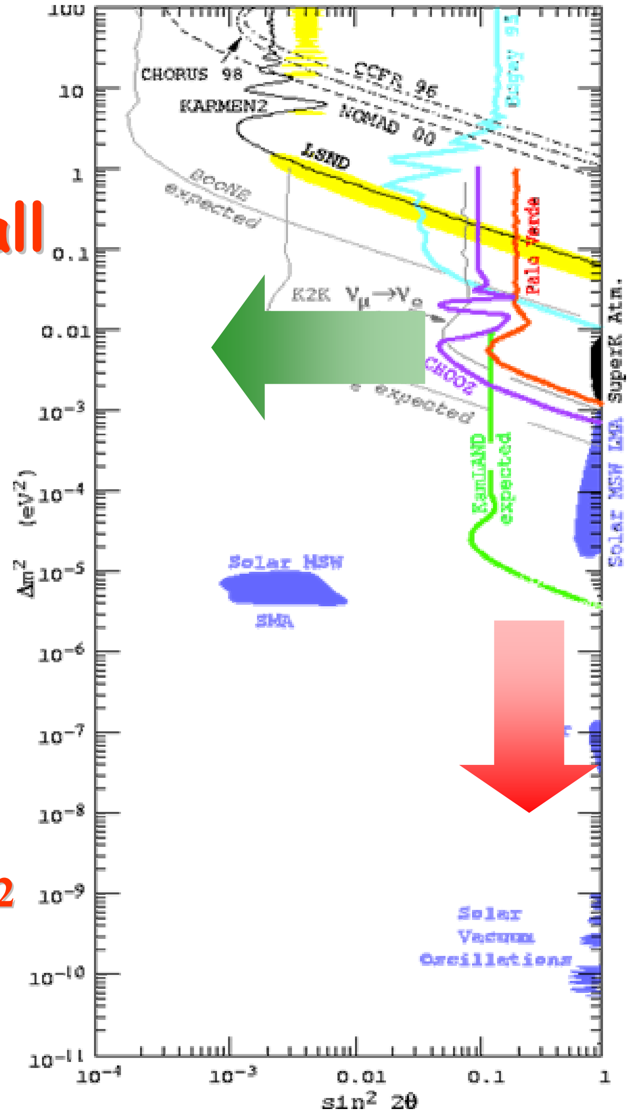
The MINOS experiment will study neutrino oscillations with neutrinos produced at FermiLab and detected in the Soudan mine in Minnesota



Complementary properties of Reactors and Accelerators

Reactors	Accelerators
E_ν~few MeV	E_ν~few GeV

- Can probe very small Δm^2
- Disappearance only
  → fair $\sin^2 2\theta$ sensitivity
- 4π source
  → detector mass grows with L^2



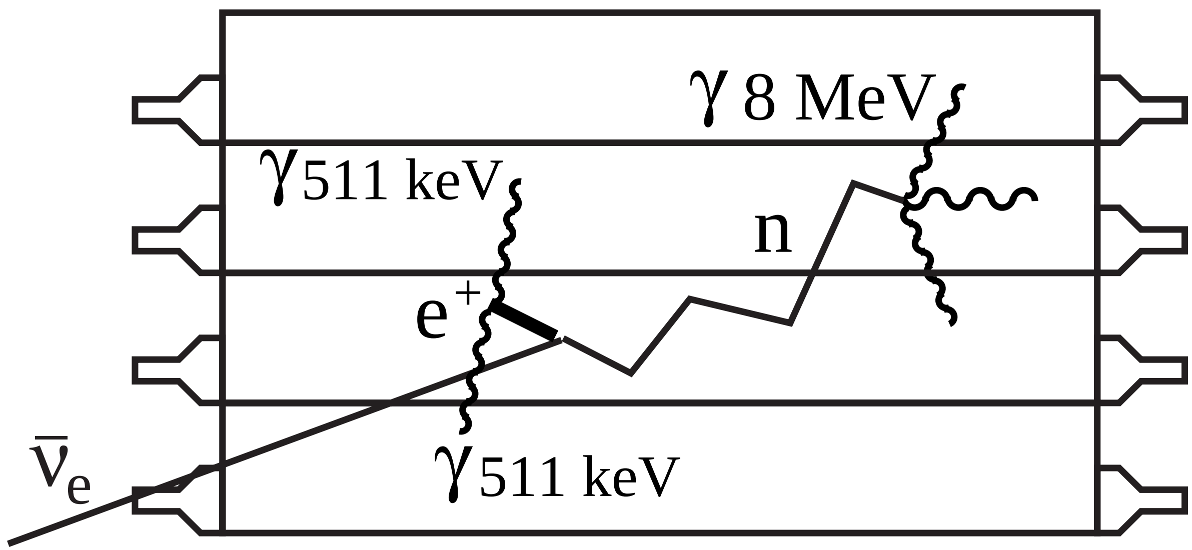
- Good mass sensitivity requires very large L
- Appearance possible (produce μ and τ)
- (More) collimated beam

Particle detection at low energy rather delicate: beware of backgrounds !

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

- Large(r) cross-section
- Specific signature

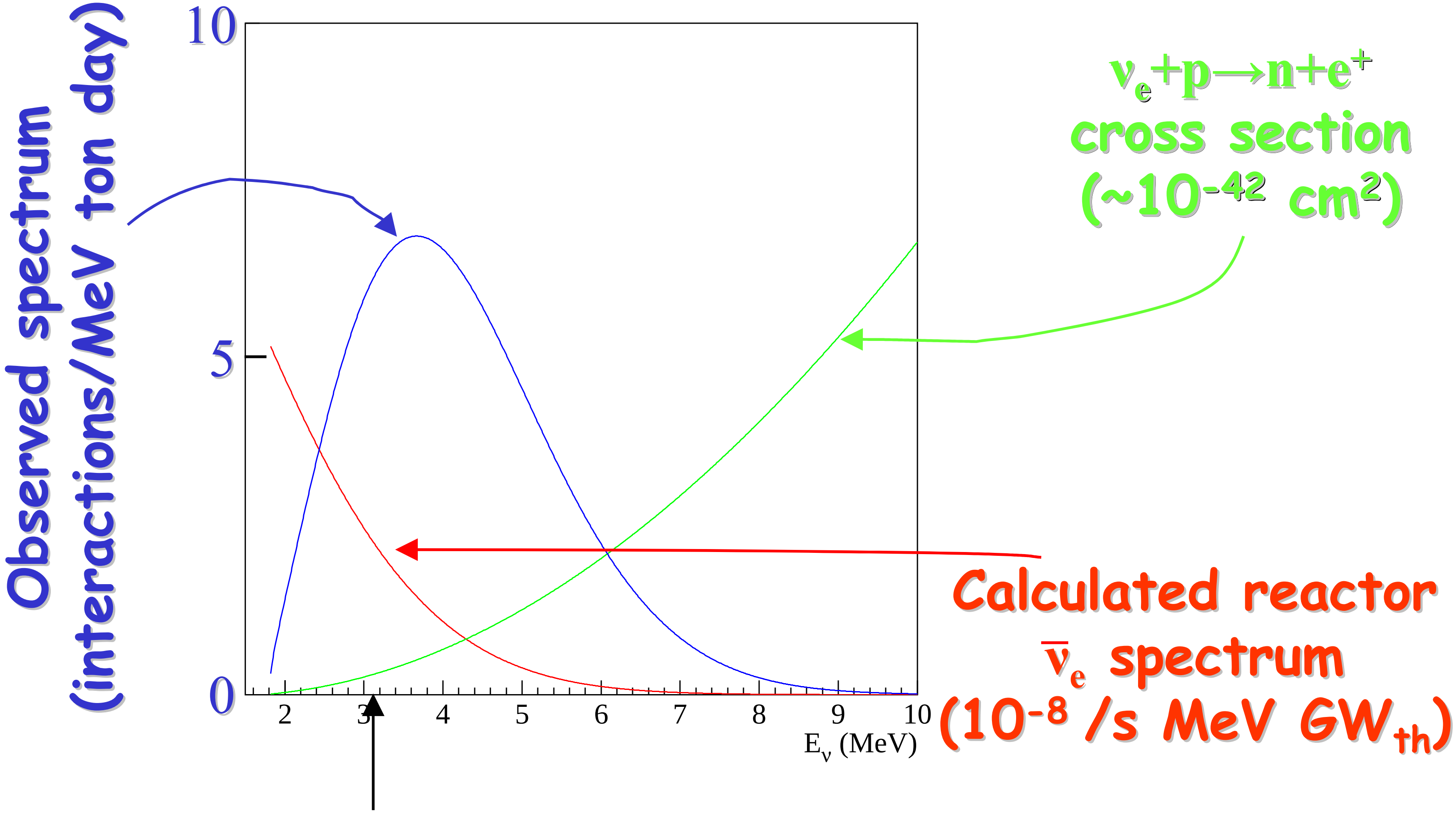
- e^+ kinetic energy (<8 MeV)
- 2 annihilation γs (0.5 MeV)
- neutron capture (2 to 8 MeV)



Neutrino energy measured from positron energy

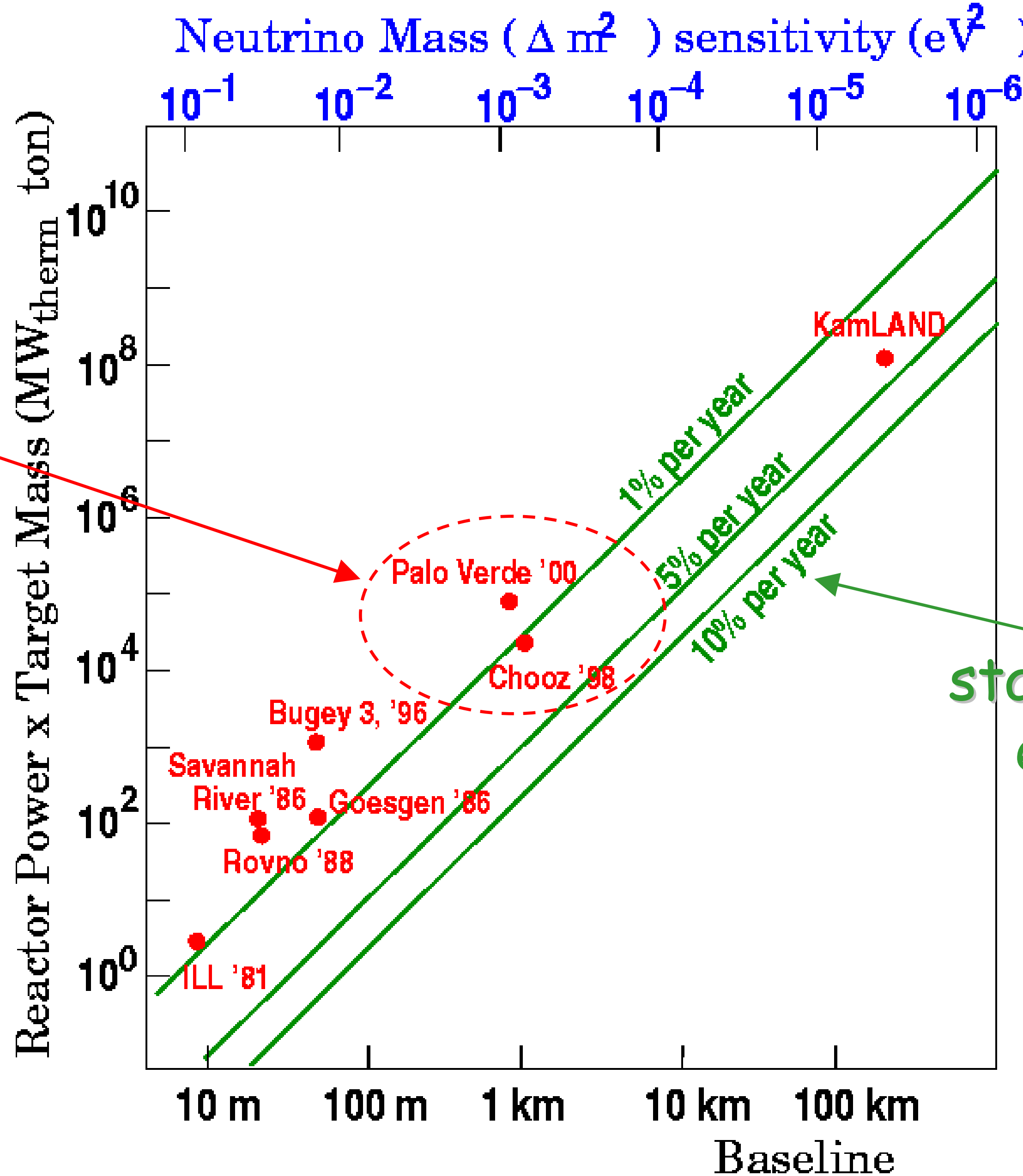
$$E_{\bar{\nu}} \cong E_{e^+} + (M_n + M_p) + m_{e^+}$$

The $\bar{\nu}_e$ energy spectrum



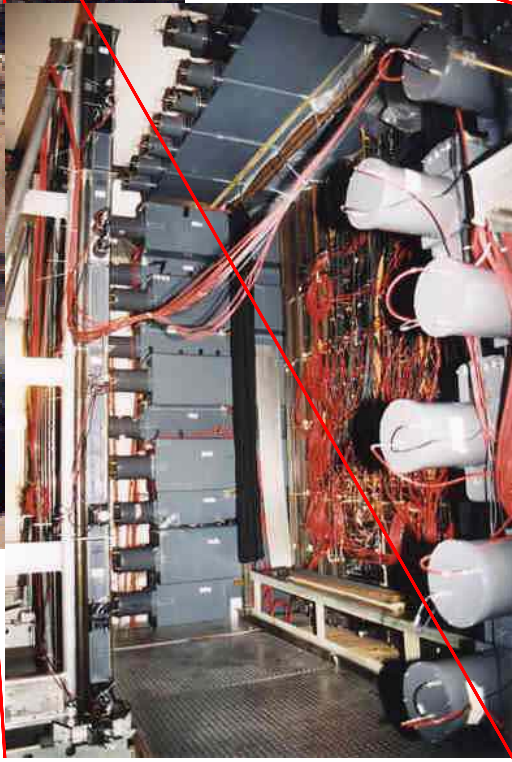
Neutrinos with E<1.8 MeV are not detected

2 detectors optimized to check if the atm. neutrino anomaly is due to ν_e-ν_x oscillations



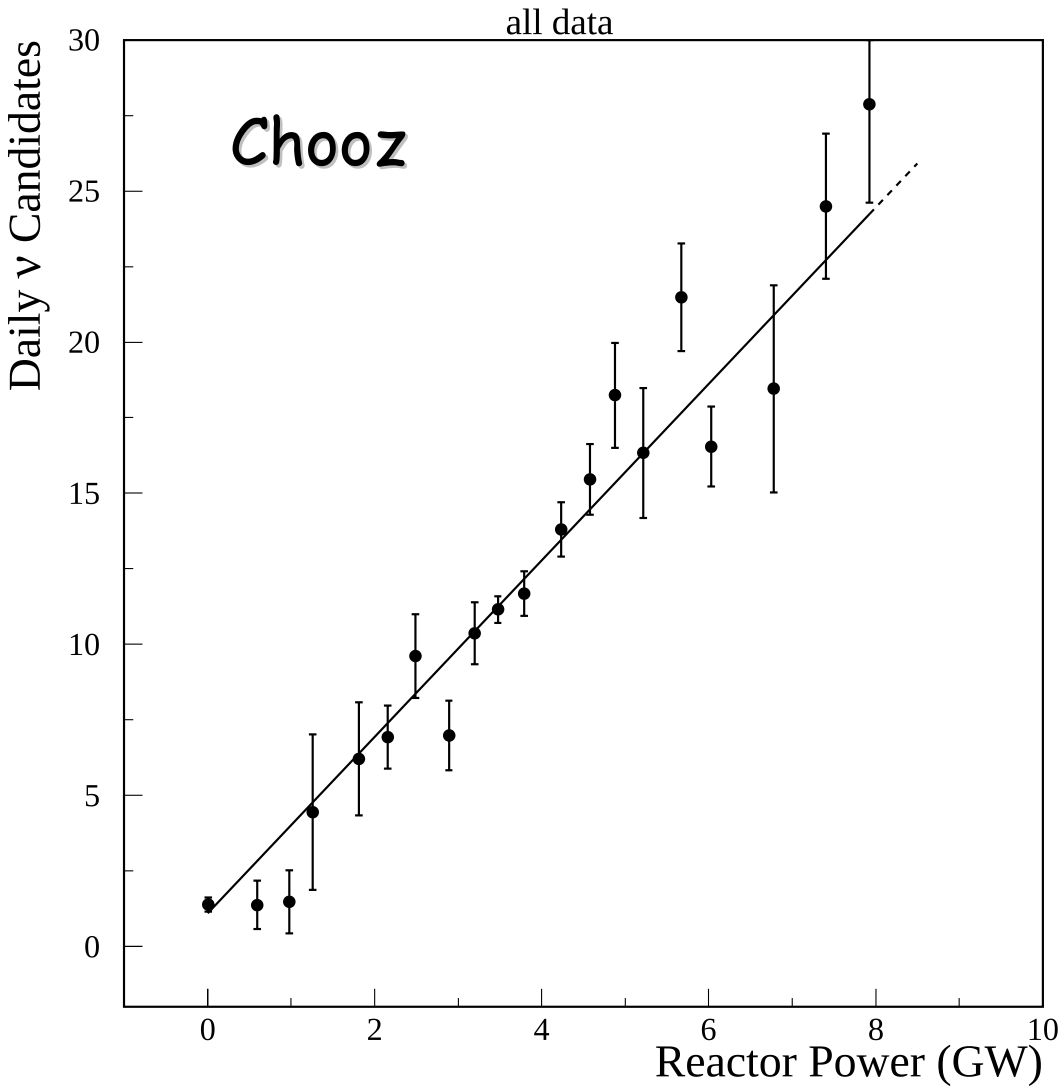
statistical error

The neutrino oscillation experiment at the Palo Verde Nuclear Generating Station (AZ)



U. of Alabama, <u>ASU</u> , Caltech, Stanford Collaboration
many thanks to APS !

The detected neutrino rate is proportional to the reactor's thermal power



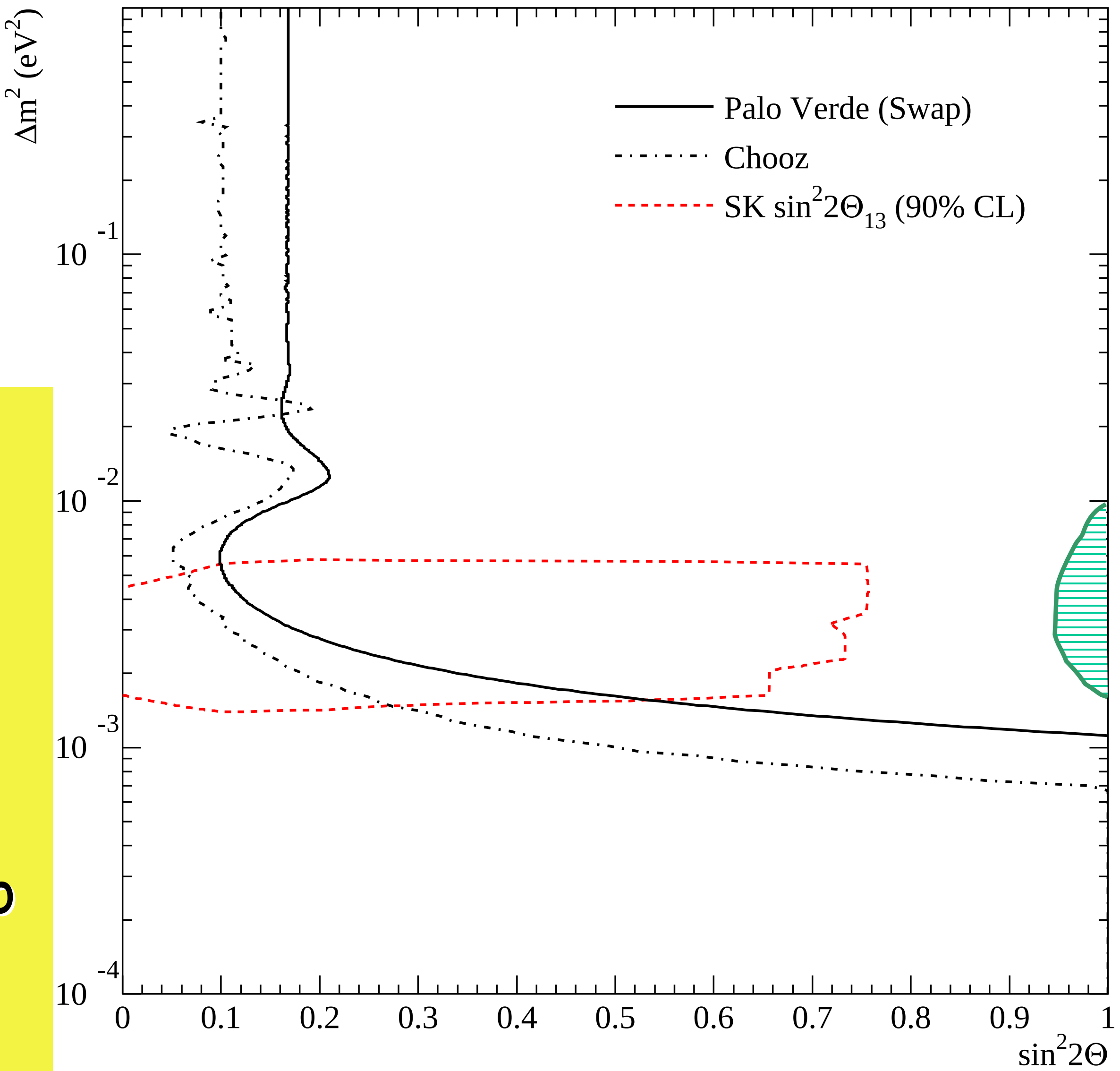
neutrinos detected / neutrinos expected

1.01±0.04 Chooz
1.04±0.08 Palo Verde

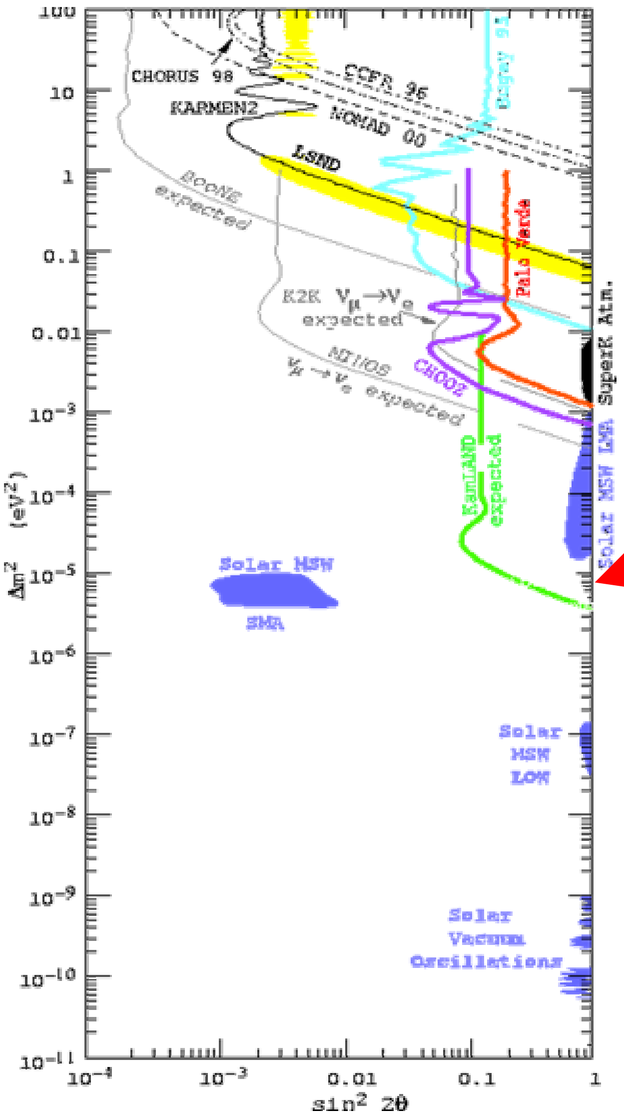
Conclusion:

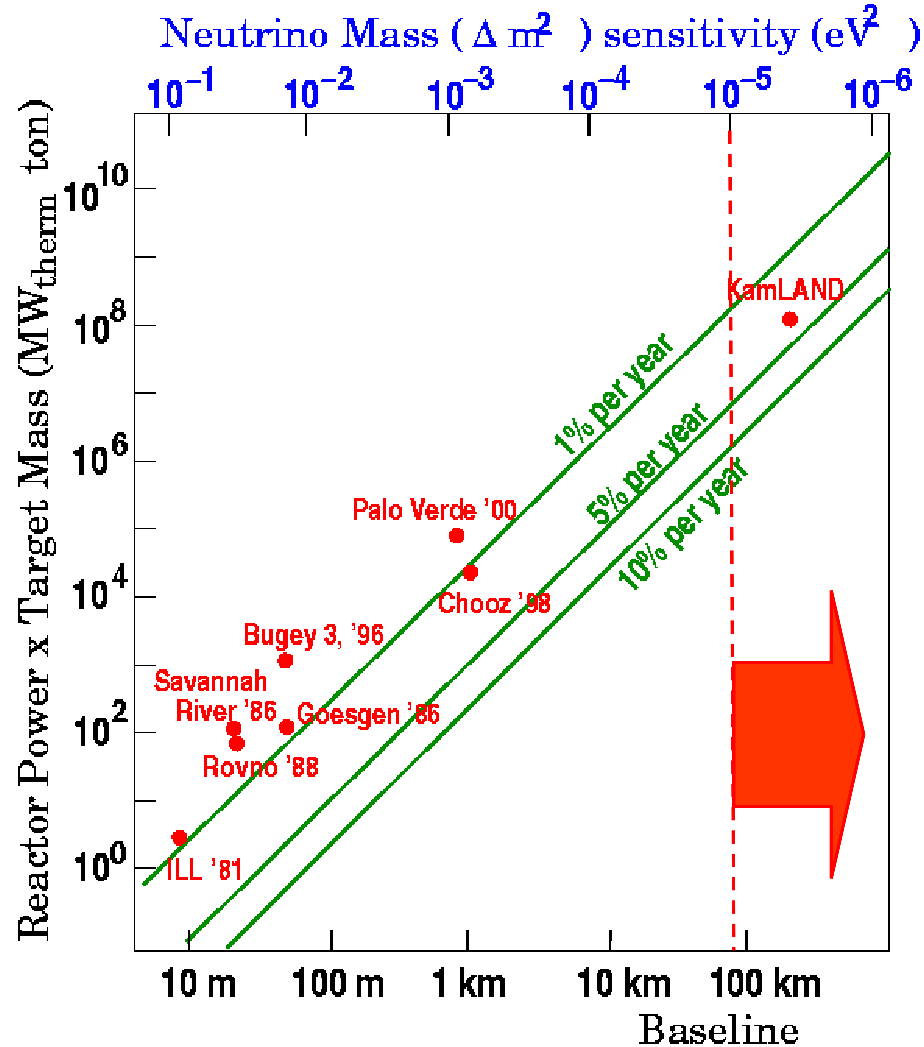
Chooz and Palo Verde saw no evidence for neutrino oscillations involving ν_e down to 10^{-3} eV^2

→ Atmospheric neutrino oscillations are mainly ν_μ-ν_τ

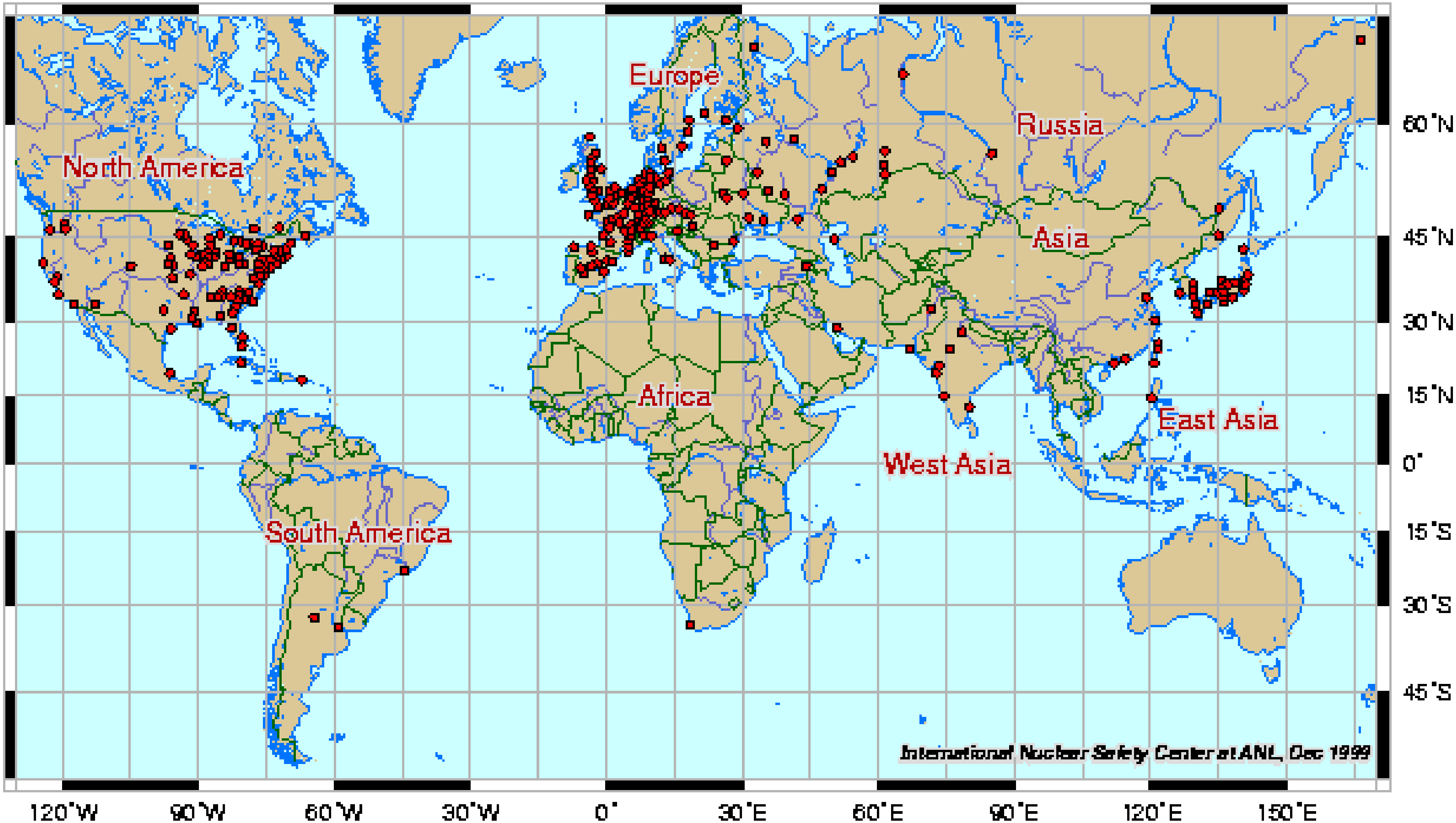


To access the region interesting for solar neutrino $\Delta m^2 < 10^{-5}$ eV^2 need 100 km baseline





Need to think regionally: large concentration of nuclear power plants exist in Europe, eastern US and Japan



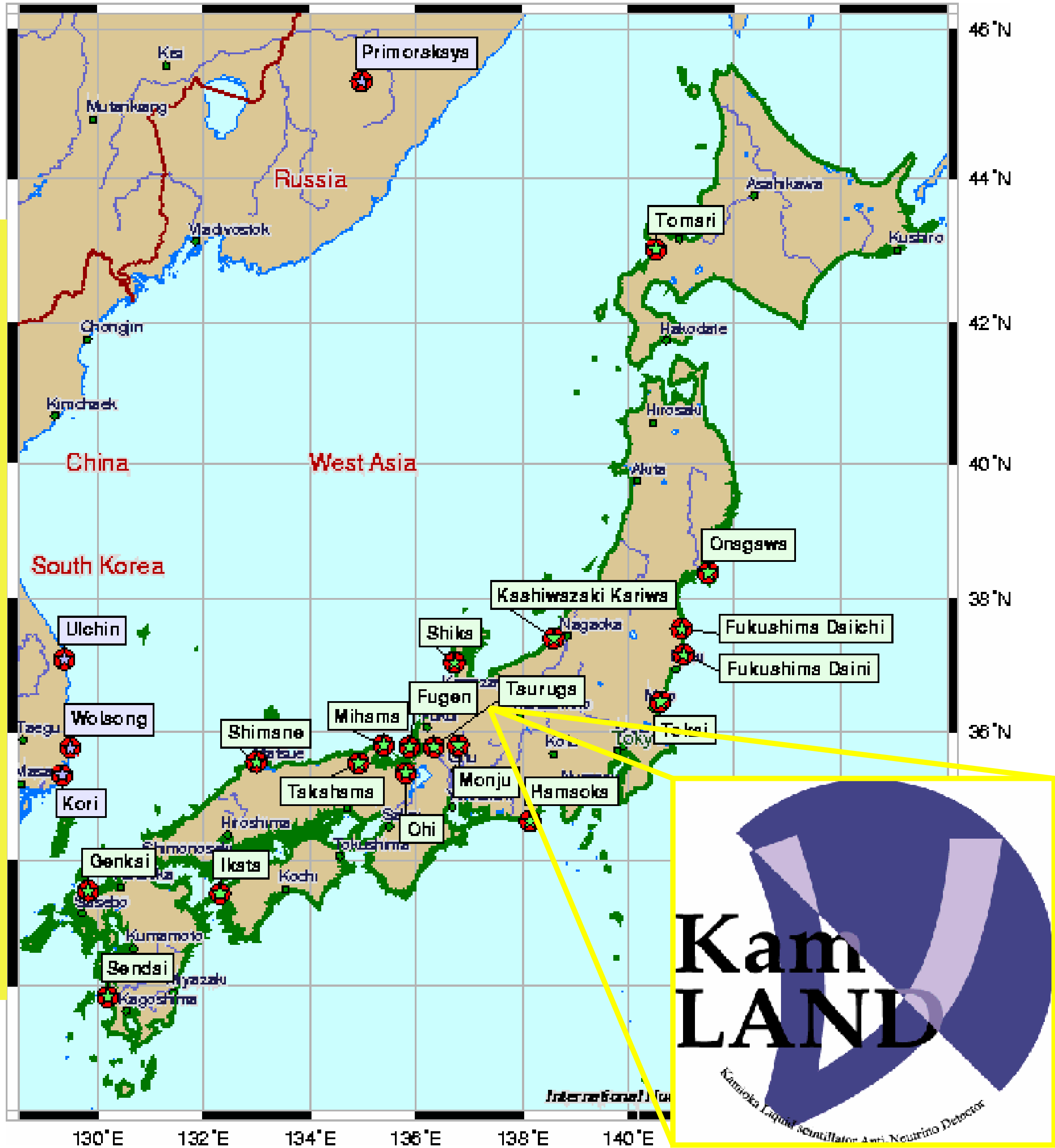
KamLAND is a collaboration between

Tohoku, KEK

Japan

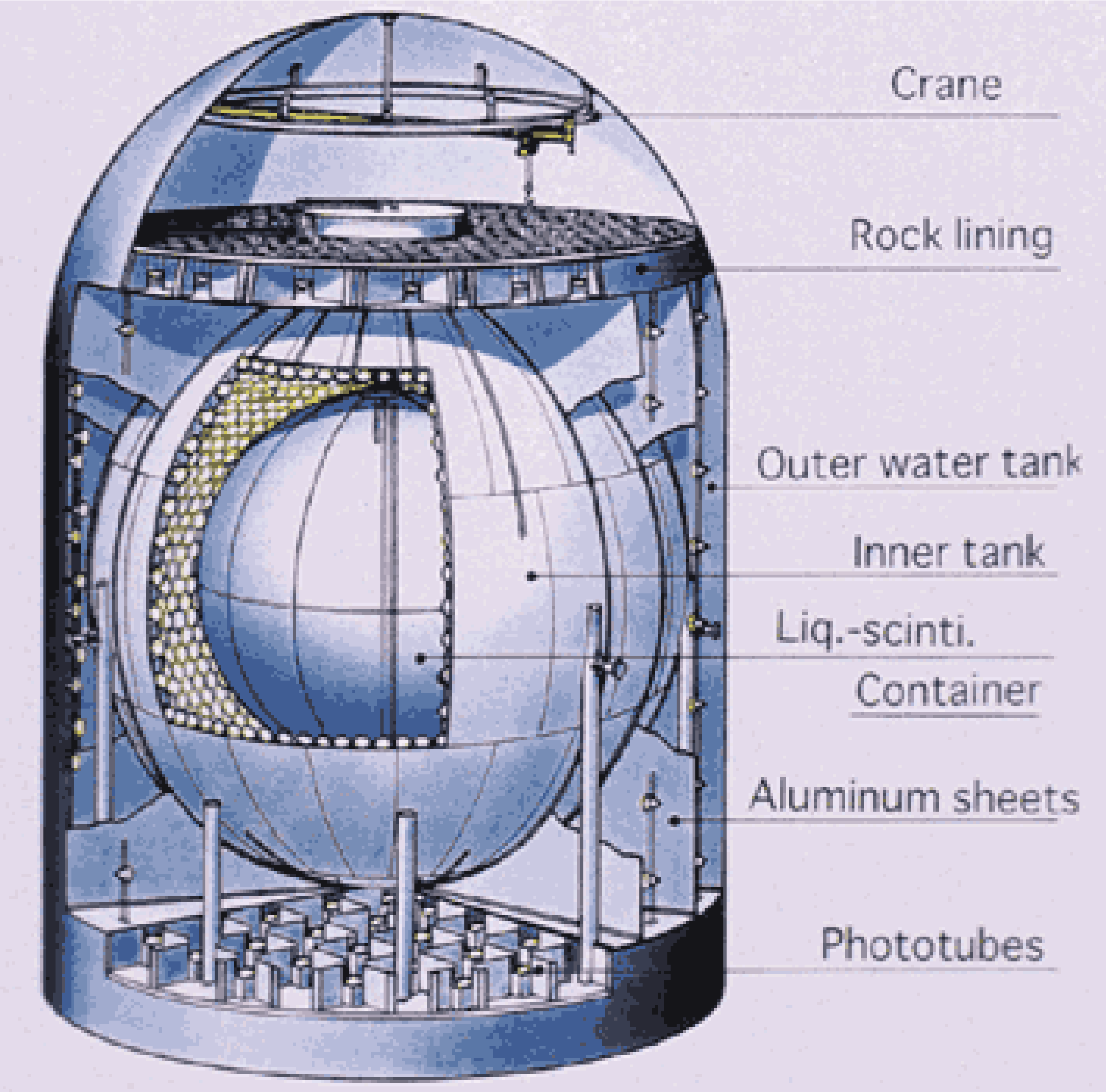
Alabama, Berkeley, Caltech, Drexel, Hawaii, New Mexico, Stanford, Tennessee, TUNL

USA



The KamLAND detector

- 1000 ton liquid scintillator detector in the Kamiokande cavern
- ~1300 17" fast PMTs
- ~700 20" large area PMTs
- 30% photocathode coverage
- H_2O Cerenkov veto counter
- Multi-hit deadtime-less electronics
- Δm^2 sensitivity $7*10^{-6}$ eV^2 LMA-MSW solution within reach on the earth !

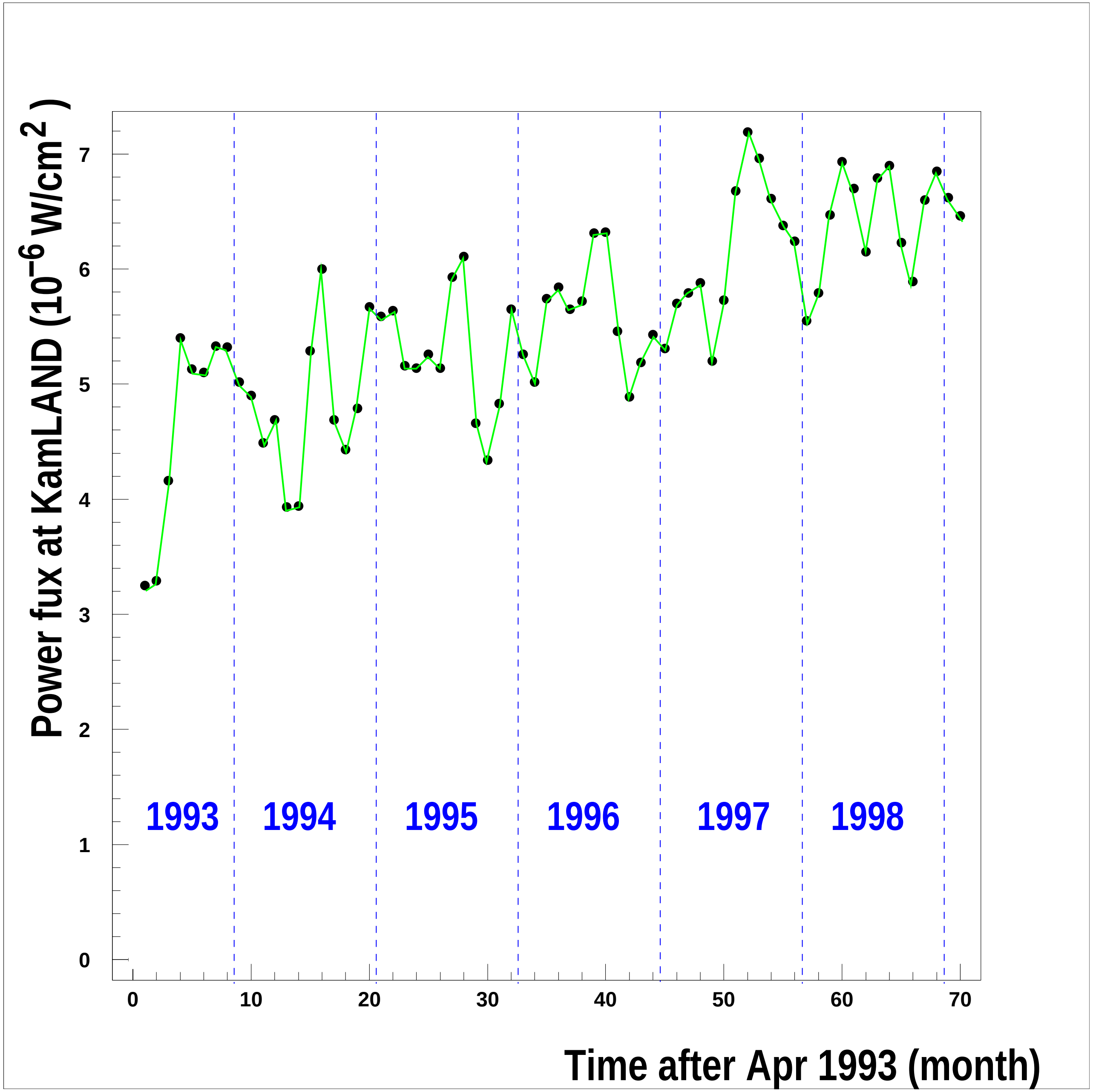


Baseline is limited: 85.3% of signal has 140 km < L < 344 km

- Signal from reactors is ~2 events/day
- Background from natural radioactivity and cosmic-rays expected to be 10 to 20 times smaller

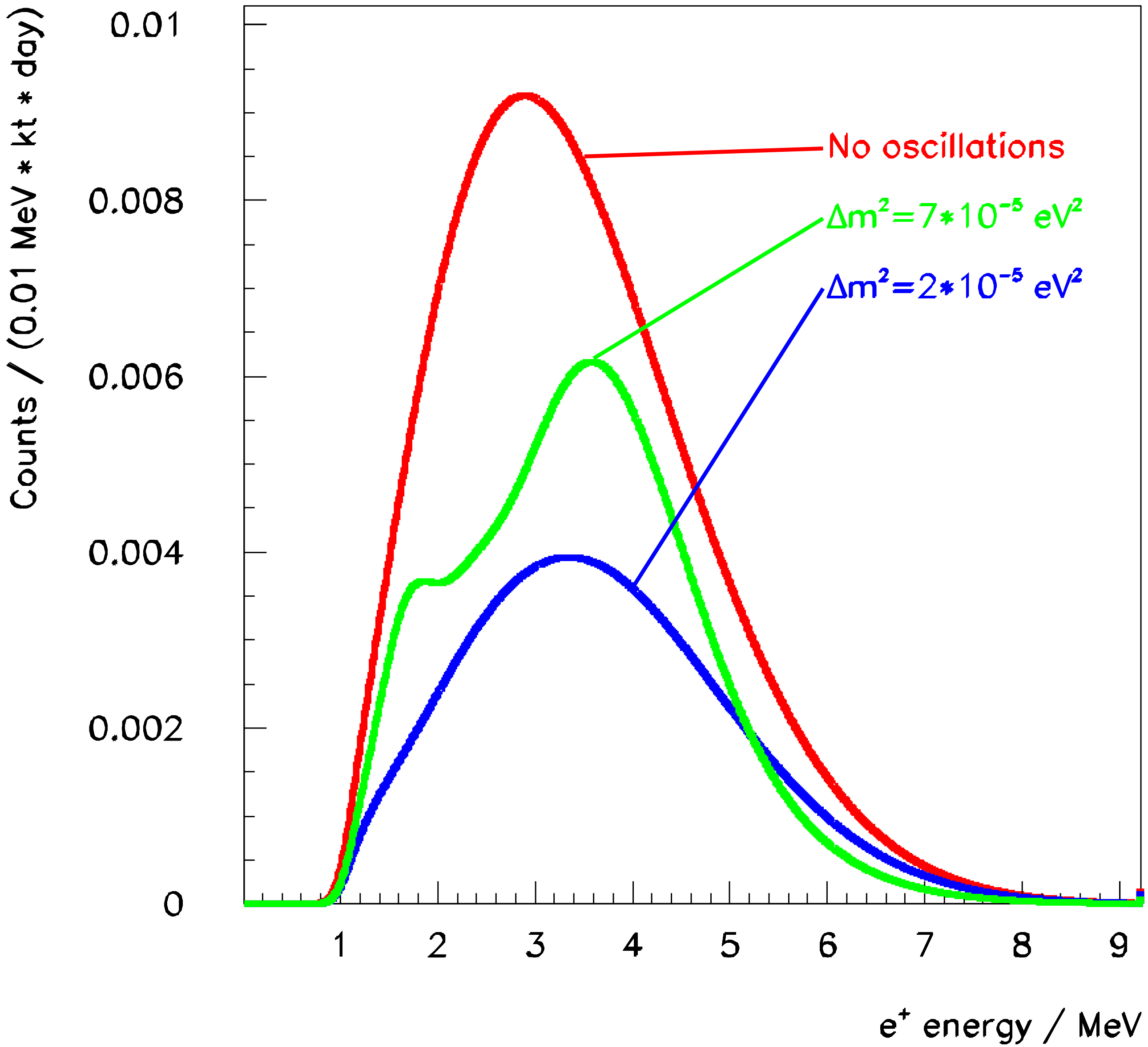
The total electric power produced "as a by-product" of the neutrinos is:
- ~60 GW or...
- ~4% of the world's manmade power or...
- ~20% of the world's nuclear power

An large nuclear submarine "parked with the engines running at full throttle" in Toyama bay would give a 10% excess in our signal
➔ not a problem

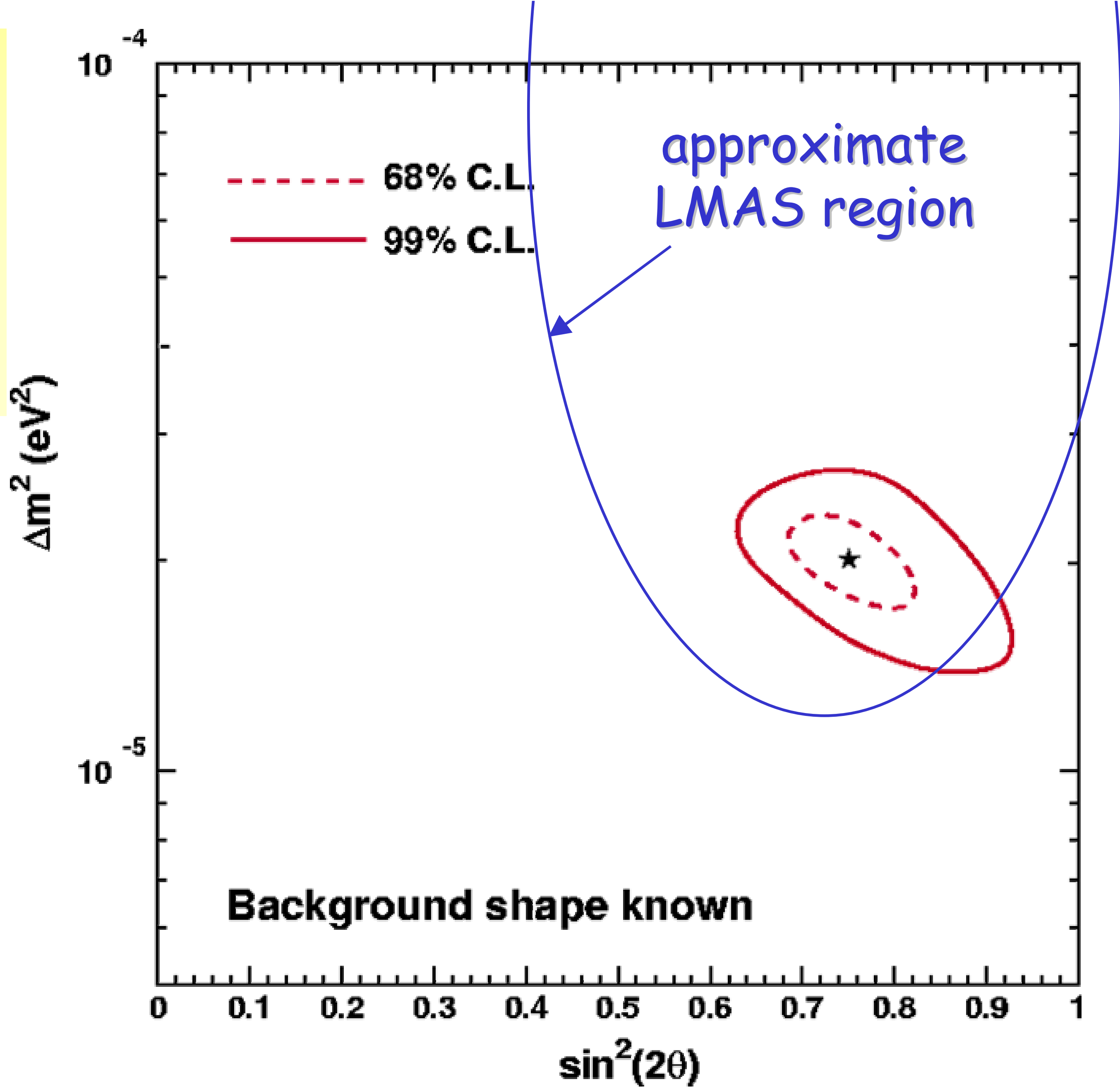


Power fux at KamLAND (10^-6 W/cm^2)
Time after Apr 1993 (month)
1993
1994
1995
1996
1997
1998
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70

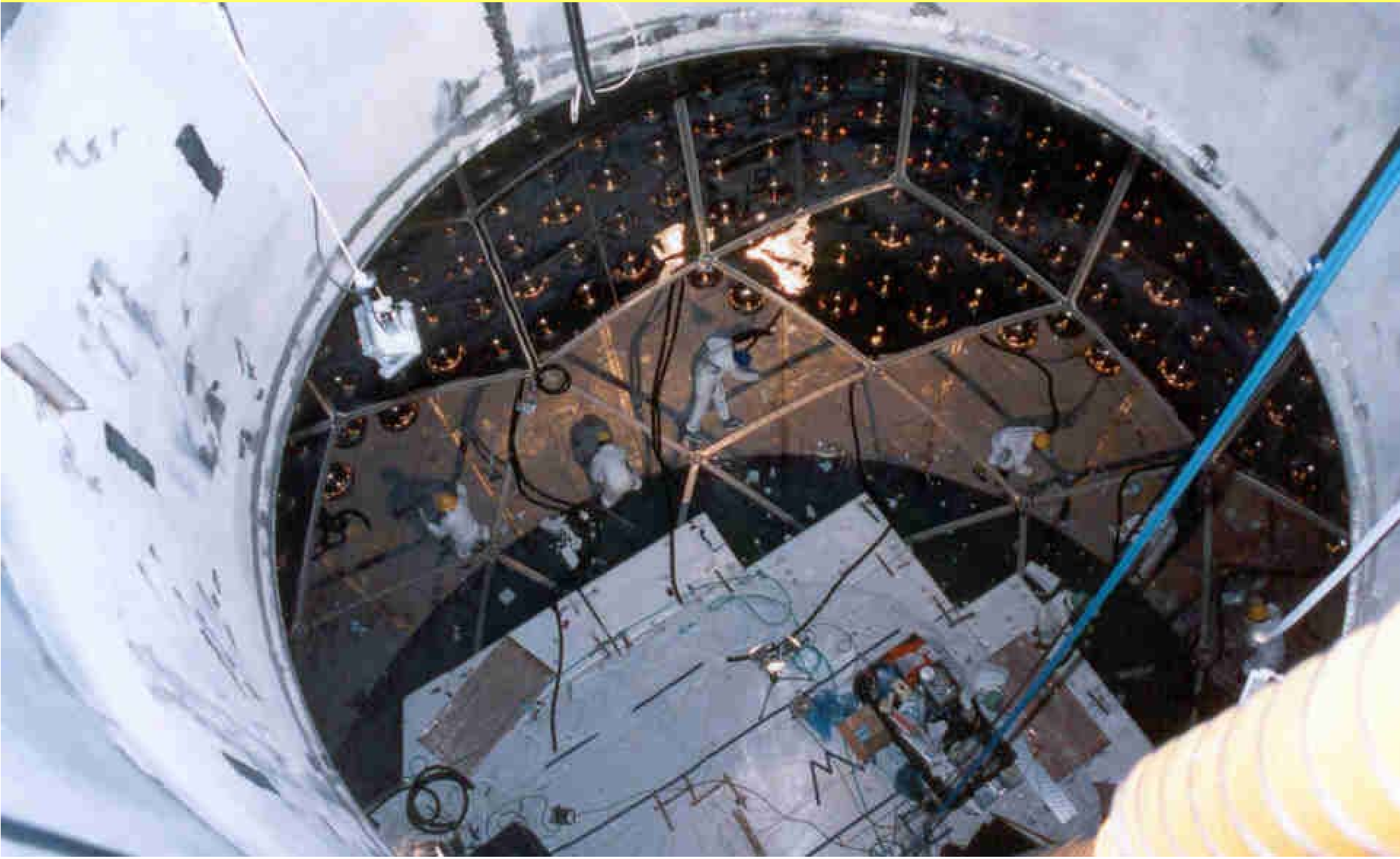
Neutrino oscillations in KamLAND could result in distortion of the energy spectrum along with a deficit of detected events



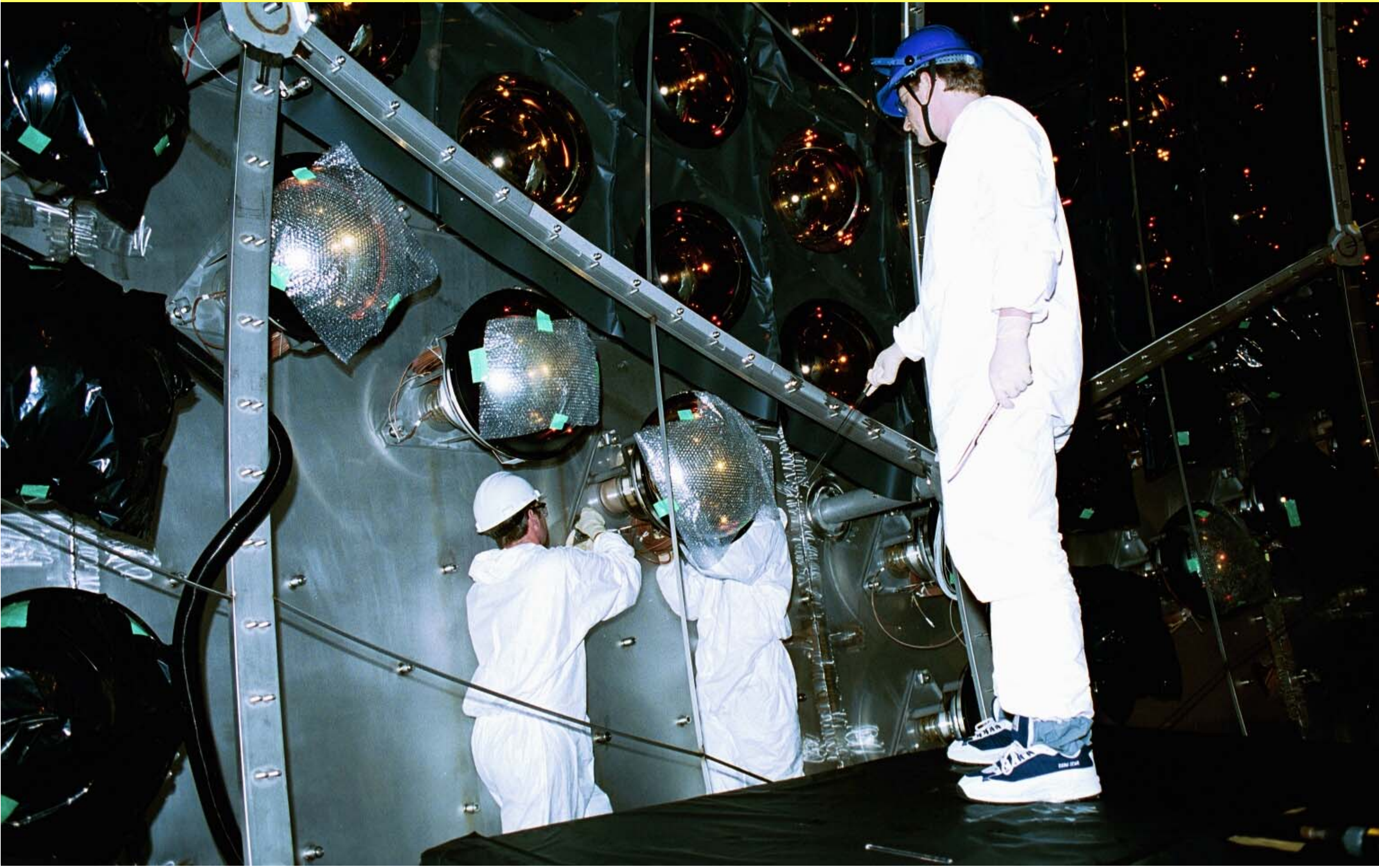
...if oscillations are detected very accurate measurement possible !



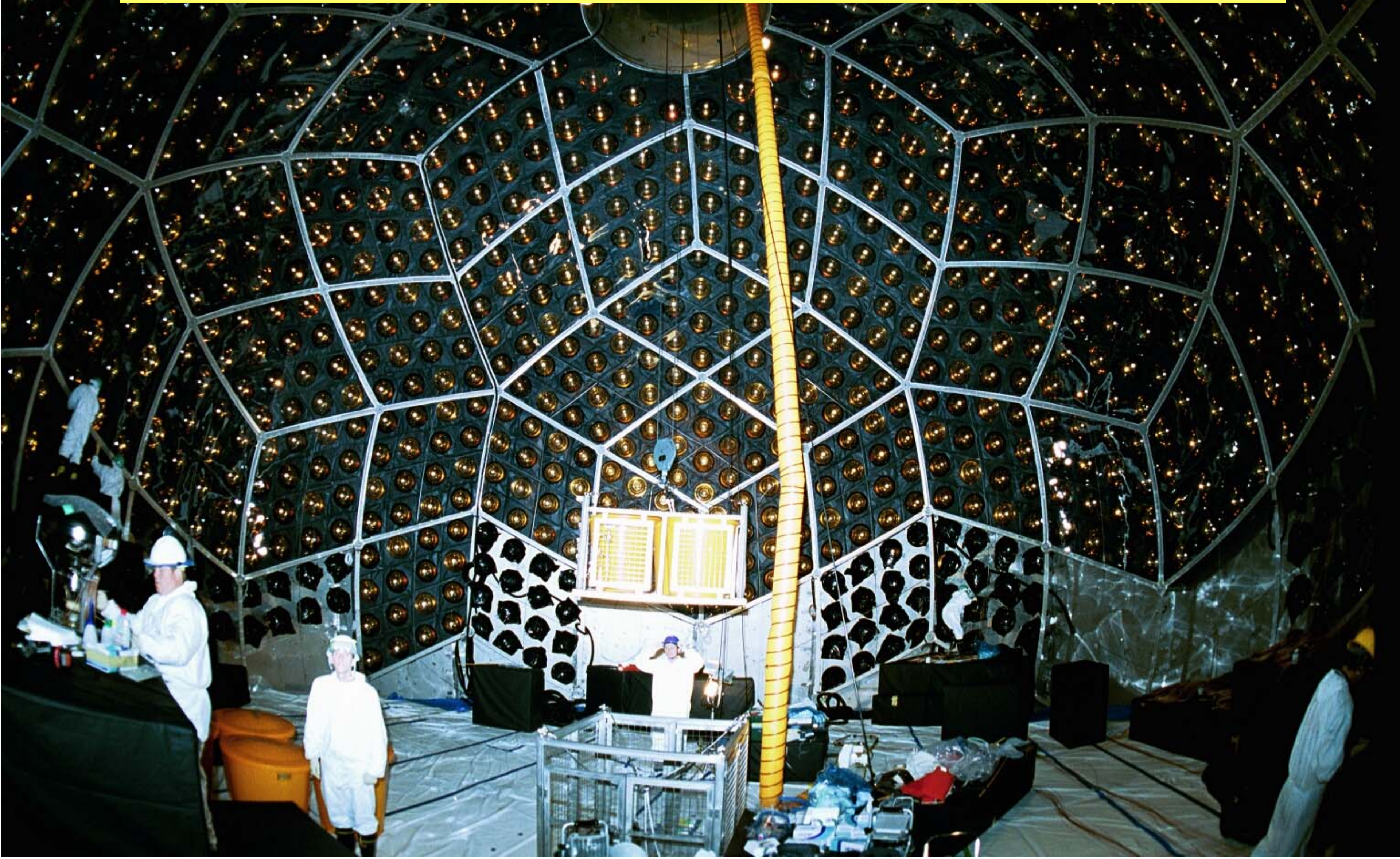
Cleaning the KamLAND sphere (Summer 2000)



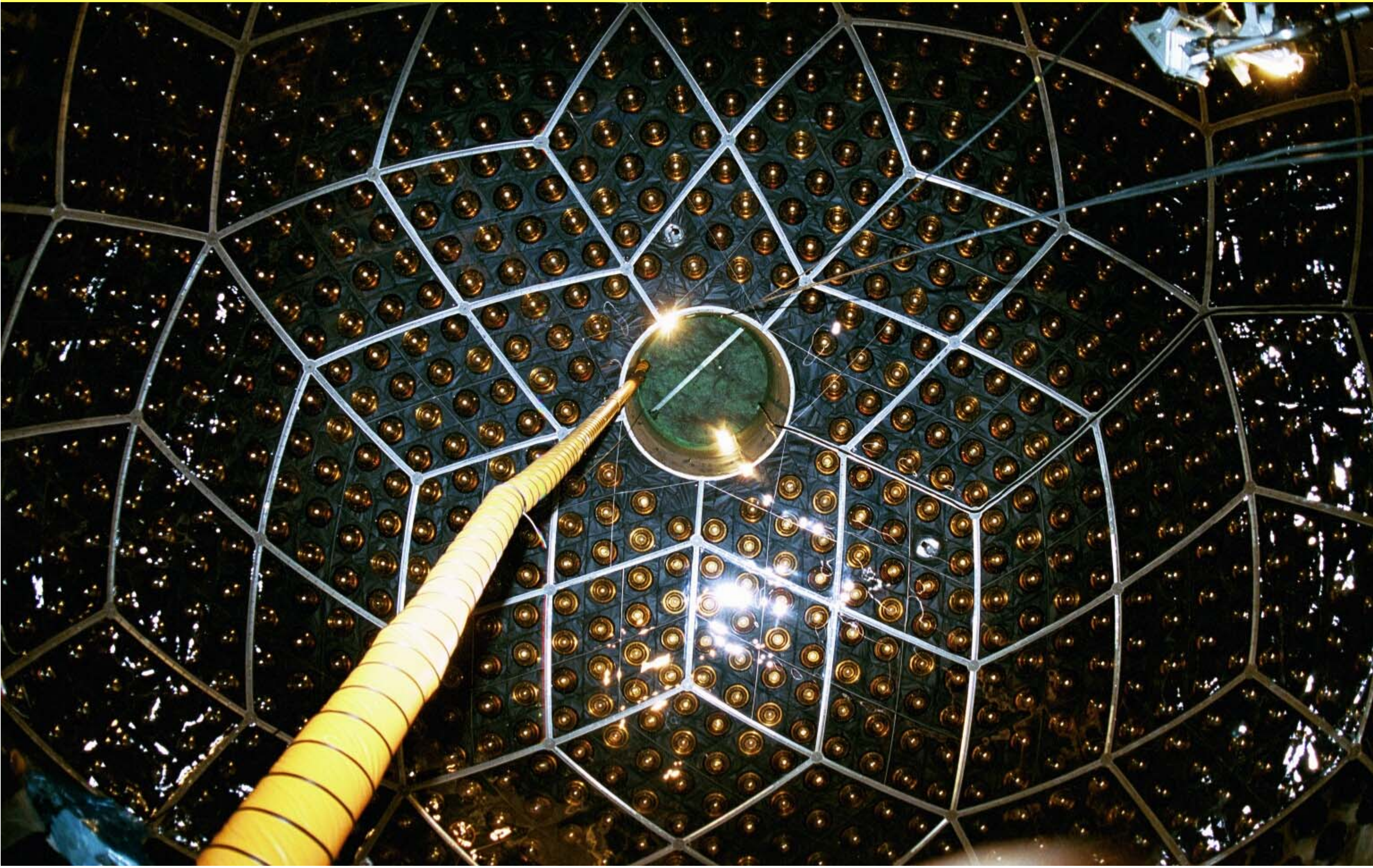
Installing PMTs in KamLAND (Summer 2000)



KamLANDers hard at work (Summer 2000)



The completed detector, looking up

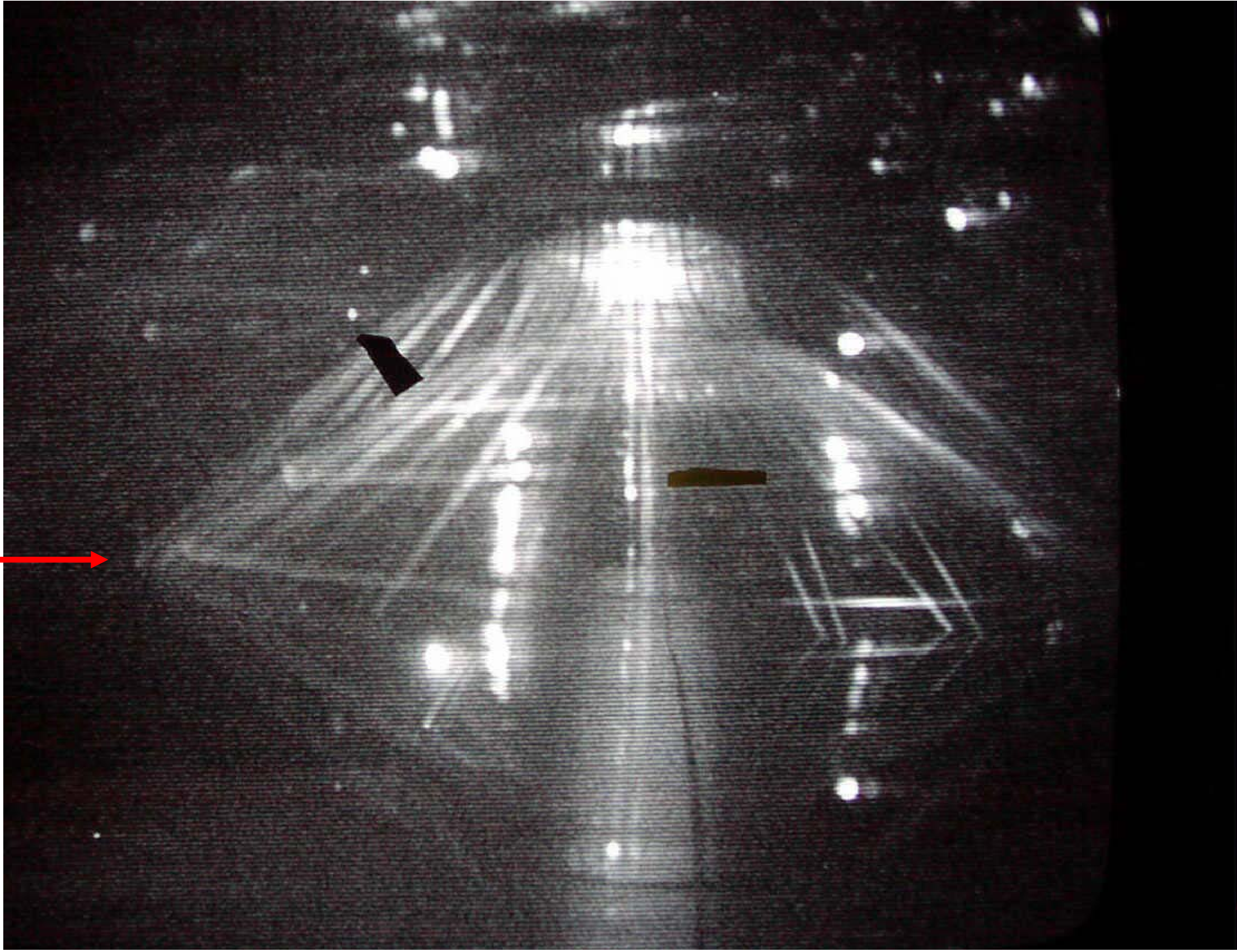


Balloon installed (Apr 2001)

Receiving a paraffine load in the mine

- Pseudocumene and paraffine oil of two different densities are blended to obtain 20% pseudocumene concentration inside the balloon and same density outside.
- PPO concentration is 1.5 g/l of the final blend.
- During blending the liquids are pre-purified, closed circulation and re-purification are started at the end of the fill.

Liquid level in KamLAND on Sept 11, 01



KamLAND is full since Sept 30, 2001

Now testing electronics, calibrating…

Stay tuned for results !

Allright, this is lots of fun but… can we use these neutrinos for something useful ?!

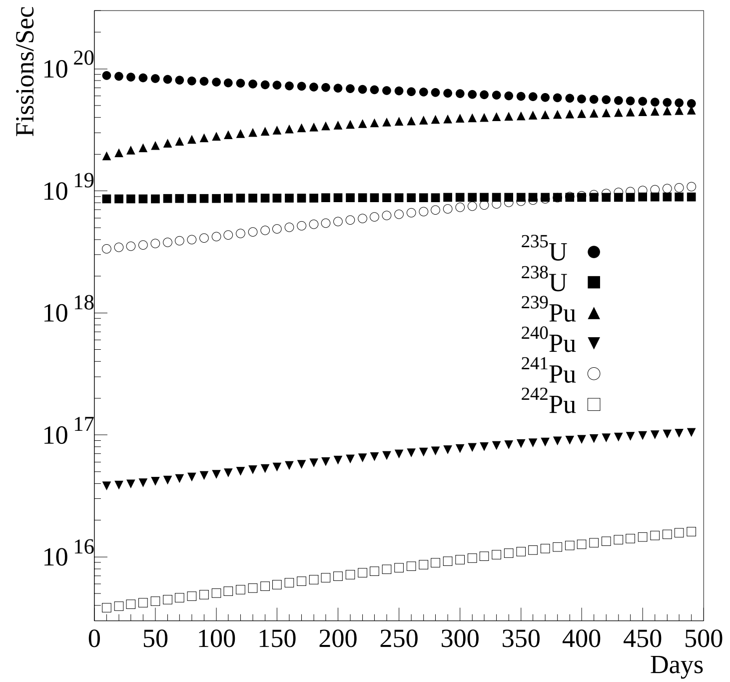
The answer is usually "no", among other things because neutrinos are so difficult to detect…

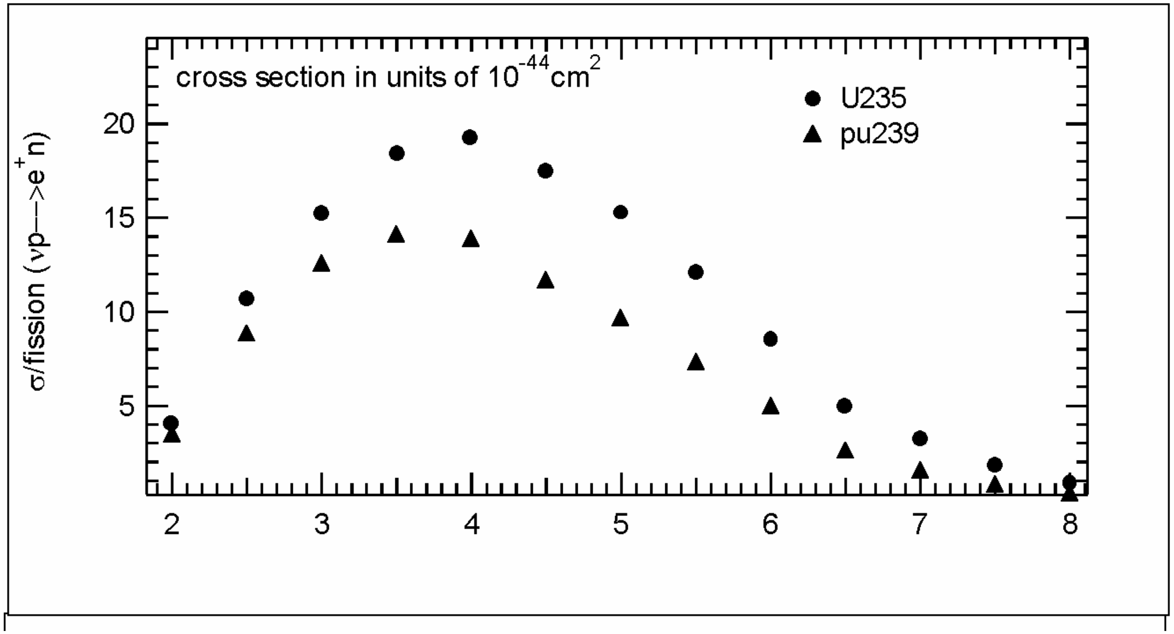
The mean free path in lead for a reactor antineutrino is about 0.1 light year !
(a good fraction of the distance to the closest star)

But lets go back to a device that makes LOTS of antineutrinos: a nuclear reactor

We can turn things around and use antineutrinos to "peek inside" the reactor's core
(neutrinos don't care that there are heavy walls !)

Most of the power and antineutrinos in a power reactor are produced by the fissions of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu





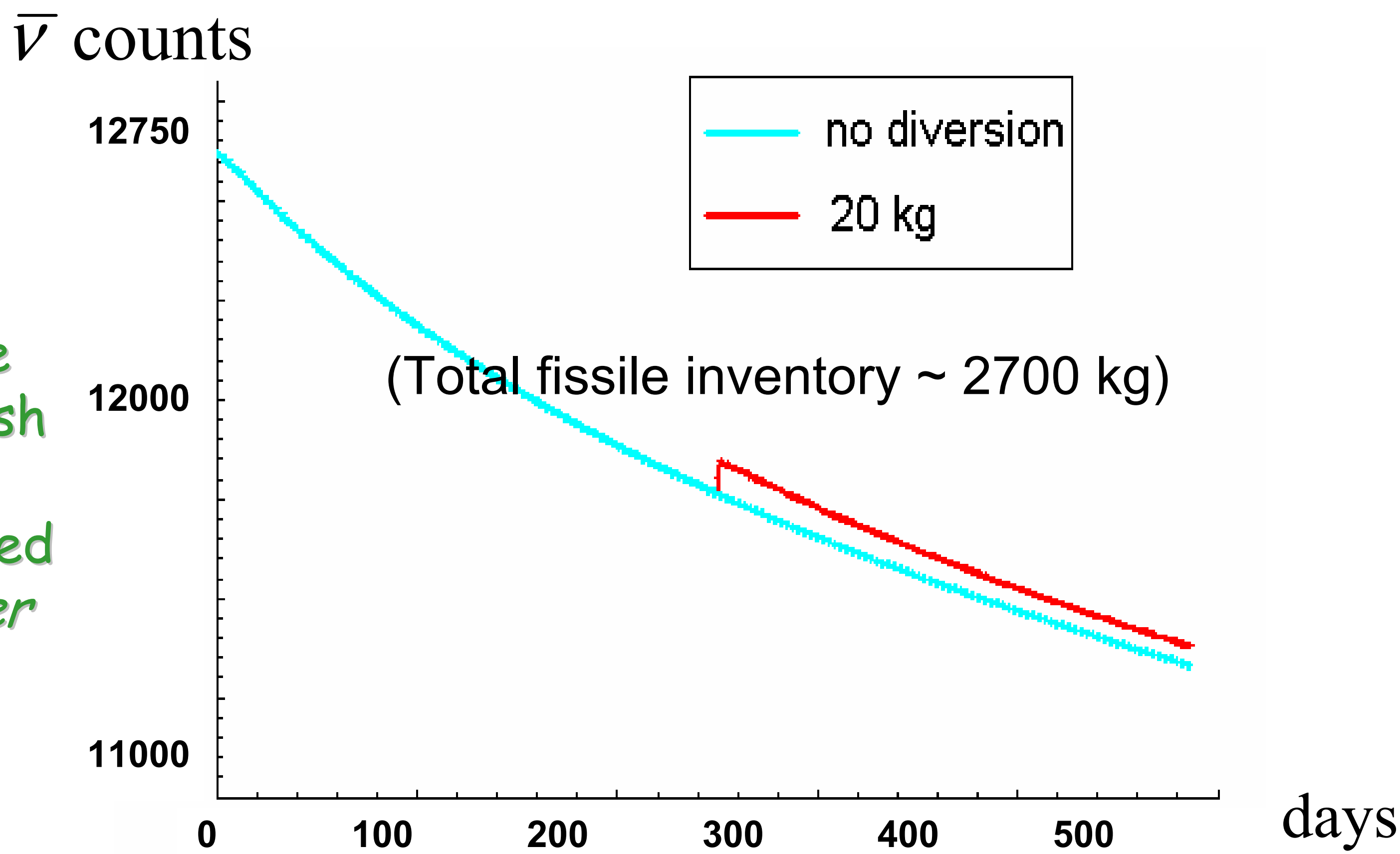
Antineutrino spectrum slightly different for the 4 main isotopes

The antineutrino count rate **varies** in a known way as Pu is produced even at constant power

- Deviations from the expected trajectory with known power may reveal improper reactor use
- ν rate is directly related to power with known U/Pu ratio

Example:

20 kg of fuel containing Pu are replaced with fresh U and then the reactor is restarted at the *same power level*

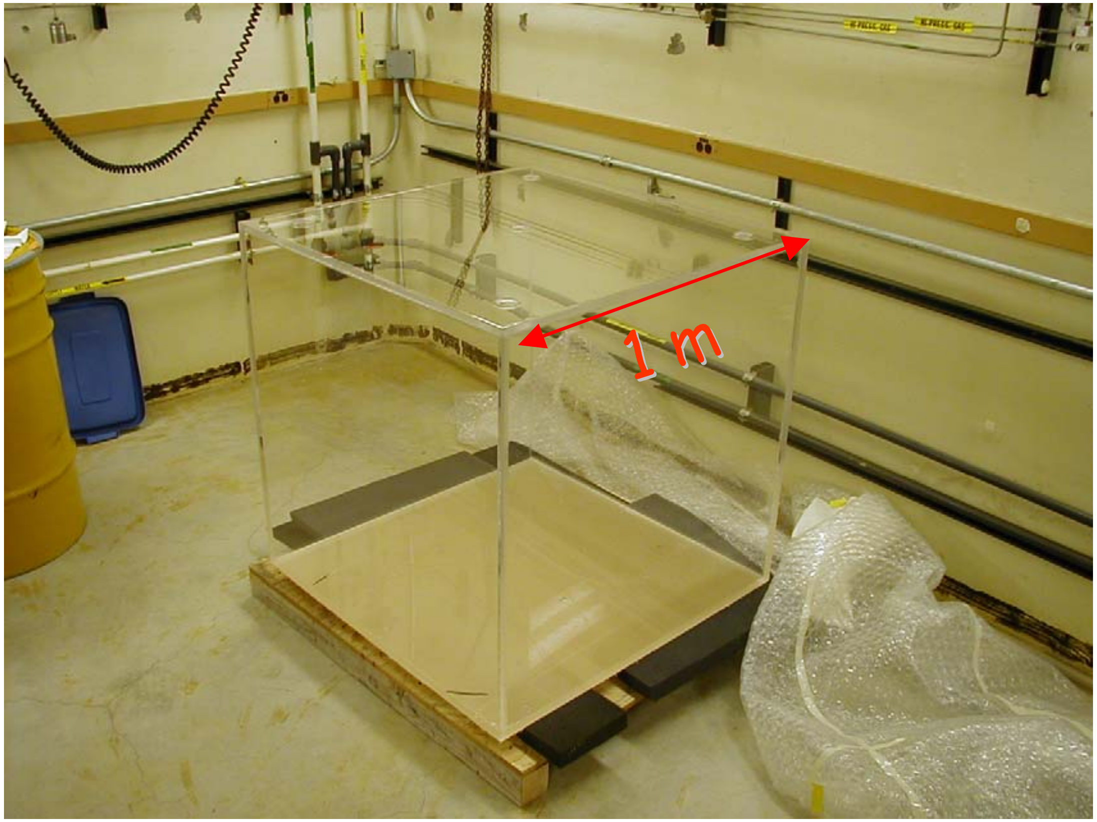


OK, but what about the 0.1 light year… how large is the detector ?

The detector needs to be very close to reactor core

For most reactors this is *not* a problem as space is available *outside* containment at distances of order 10 m from the core

Of course this can only work for cooperative facilities…



Sandia prototype detector is 1 m^3 of liquid scintillator (A.Bernstein et al.)

Still, there are many applications…

1) Detect diversion of Pu, probably in conjunction with thermal power measurements
   - Current: IAEA Nuclear Non Proliferation safeguards ~200 reactors
   - Future: Fissile Materials Cutoff Treaty safeguards ~435 reactors

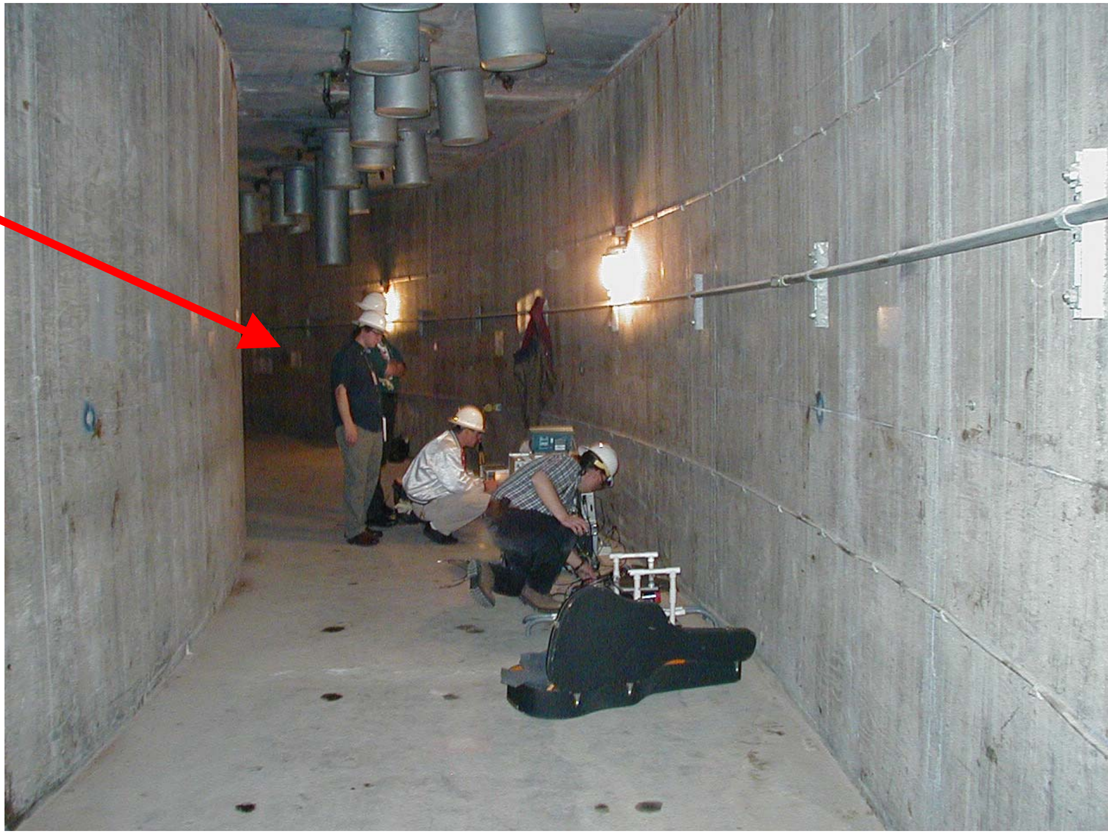
2) Detect abnormal reactor operations (atypical Pu buildup, reduced burnup levels)
   - Military reactor core reconversion verification
   - Pu production agreement verification

Possible advantages

- Continuous, real-time, quantitative information about core isotopics and/or power
- Non intrusive to reactor operation
- Reduction of manpower needed for inspections, cost effective
- Robust to many coutermeasures

Technology demonstration detector being prepared at the San Onofre Nuclear Generating Station (CA)

Set the 1m^3 detector in the "tendon gallery" 24.5 m from the core



Heavy reactor building provides shielding from cosmic rays

Expect 2600 ν/day with 40% detector efficiency

Should start data taking soon

Old backgrounds becoming KamLAND's signals...

Fred Reines preparing a neutrino detector (circa 1953)

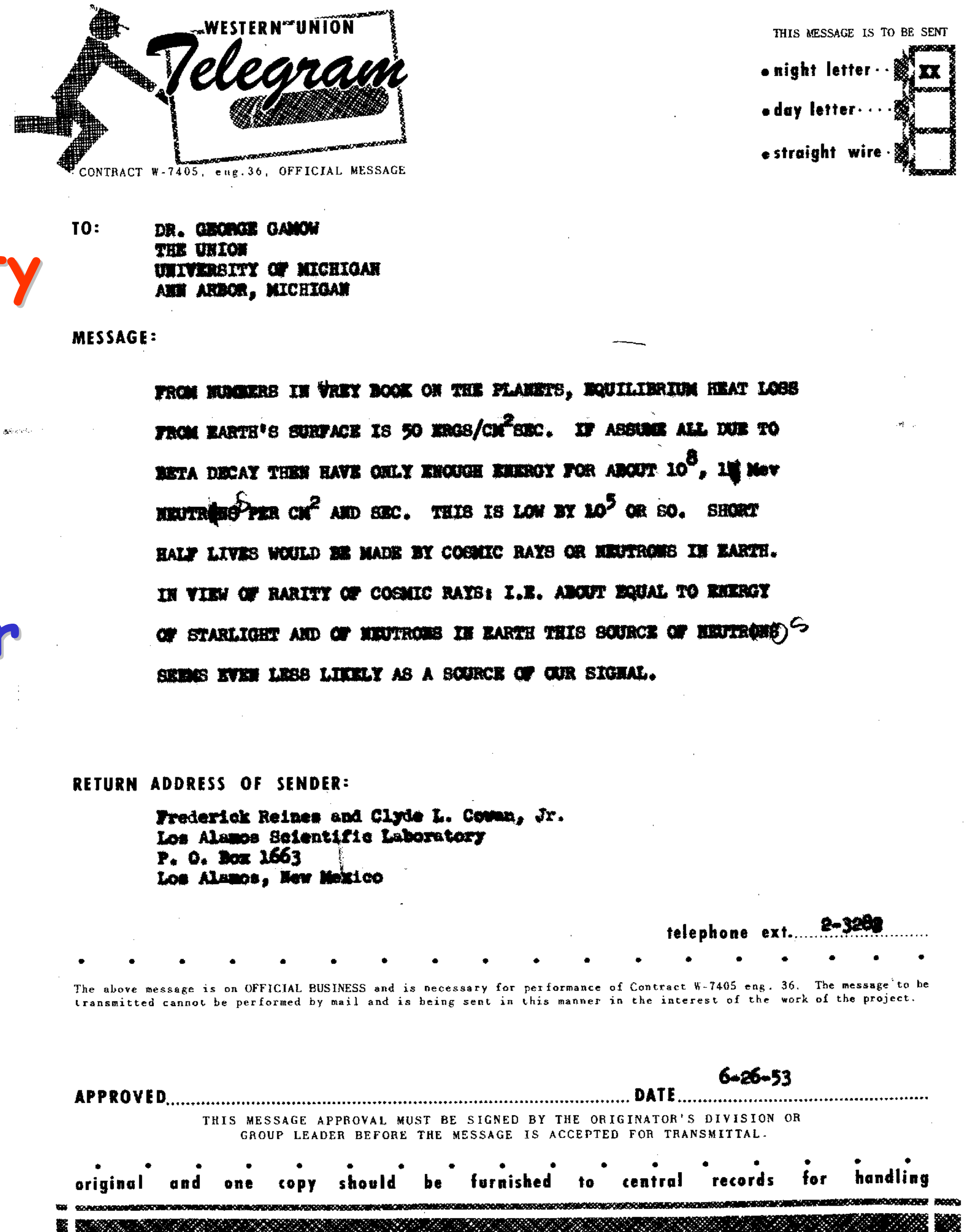
Santa Fe
The Chief

Dear Fred,
Just accured to me
that your background
neutrinos my just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. Do
not have on the train any
inform. to check it up, but it
seems the order of magn. is
resonable. In fact the total ~~energy~~
radioactive energy production
under one square foot of surface
may well be equal to the
energy of sollar radiation falling
on ~~earth~~ that surface...
What do you think?
Write to me at: The Union
Univ. of Mich. Ann Arbor. Mich

Yours Geo.

So… were neutrinos from natural radioactivity the cause of Reines' background ?

Not a chance, the detector was some 5 orders of magnitude too small to be sensitive to those…



WESTERN UNION Telegram

CONTRACT W-7405, eng.36, OFFICIAL MESSAGE

THIS MESSAGE IS TO BE SENT
- night letter XX
- day letter
- straight wire

TO: DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

MESSAGE:

FROM NUMBERS IN UREY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS FROM EARTH'S SURFACE IS 50 ERGS/CM^2 SEC. IF ASSUME ALL DUE TO BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT 10^8, 1 Mev NEUTRINOS PER CM^2 AND SEC. THIS IS LOW BY 10^5 OR SO. SHORT HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH. IN VIEW OF RARITY OF COSMIC RAYS: I.E. ABOUT EQUAL TO ENERGY OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRINOS SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.

RETURN ADDRESS OF SENDER:
Frederick Reines and Clyde L. Cowan, Jr.
Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, New Mexico

telephone ext. 2-3288

The above message is on OFFICIAL BUSINESS and is necessary for performance of Contract W-7405 eng. 36. The message to be transmitted cannot be performed by mail and is being sent in this manner in the interest of the work of the project.

APPROVED .... DATE 6-26-53

THIS MESSAGE APPROVAL MUST BE SIGNED BY THE ORIGINATOR'S DIVISION OR GROUP LEADER BEFORE THE MESSAGE IS ACCEPTED FOR TRANSMITTAL.

original and one copy should be furnished to central records for handling

…KamLAND is about 10^5 times larger than the early detectors of Reines

The earth radiates ~40 TW of heat from its surface

40% (~16 TW) radiogenic

↓

90% of it (~14 TW) from U and Th decays chains

Study of bulk U and Th concentrations is an important field of geophysics:

- Planet formation
- Heat production/planet dynamics

Traditional techniques:

•Heat-flow measurements (cannot separate different production mechanisms)

•U, Th sampling (difficult to sample on a global scale, difficult to sample very deep)

⇒ Result: very different models still plausible

General picture:

- 50% of U, Th in the crust
    - continental crust (~35 km thick) large concentration, ~ 1 ppm
    - oceanic crust (~6 km thick) lower concentration
- 50% of U, Th in the mantle and core, must lower concentration, 1 ppb in olivine

Antineutrinos are a way to make measurements in a truly global way (they essentially behave like gravity)

	Isotope	Endpoint (MeV)
U chain	^{234}Pa	2.29
	^{214}Bi	3.27
Th chain	^{228}Ac	2.08
	^{212}Bi	2.25

Total spectrum: 2 structures: ~2.1 MeV
~3.3 MeV

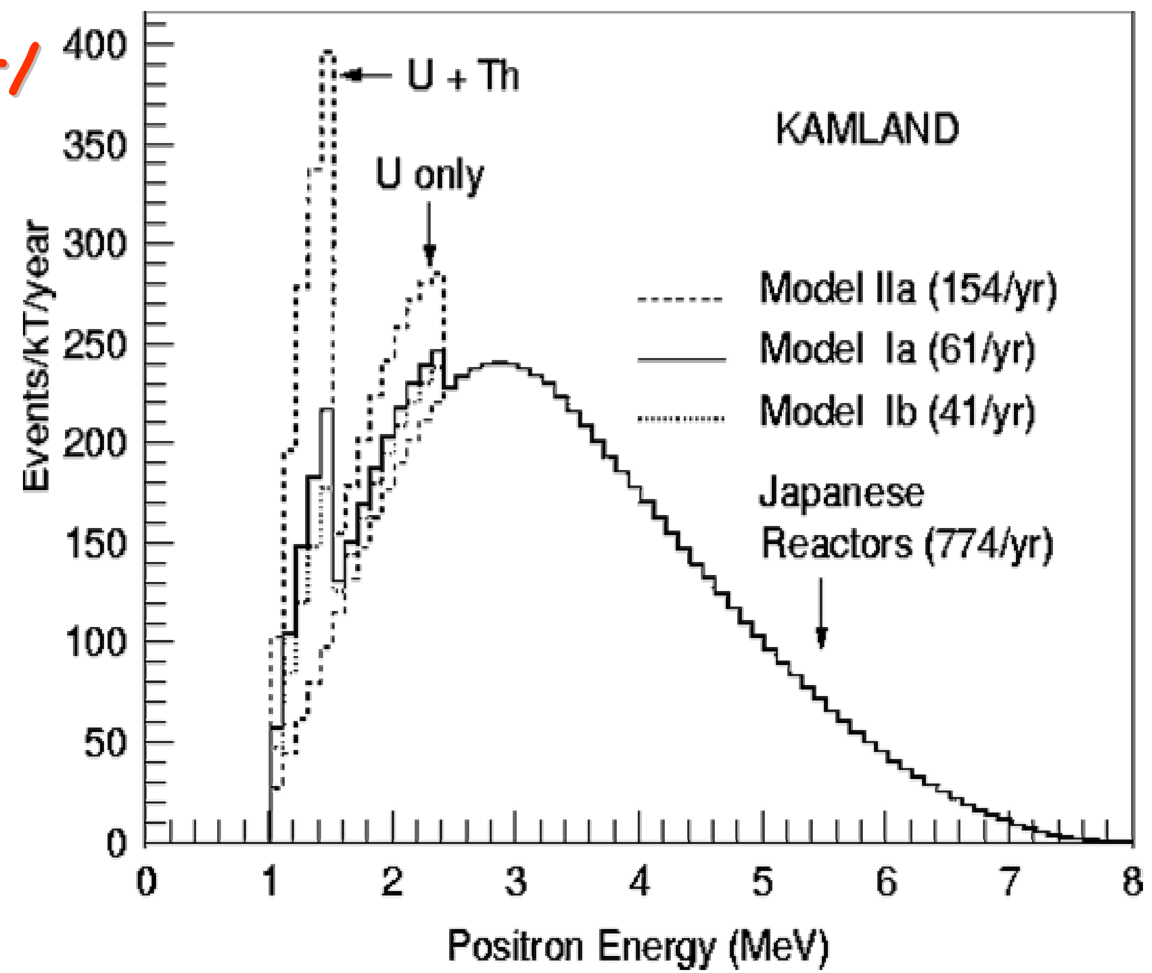
→ U and Th contributions can be separated-out

(^{40}K is below the detection threshold)

KamLAND: neutrinos from… hell

- High energy part: reactor measurement/ particle physics
- Low energy part: geophysics

If this first measurement is successful we may want to build a detector dedicated to geophysics at a non-nuclear location (Australia ?, North Canada ?....)



Supernovae and the neutrinos

Explosion of the “type II” supernova in the Crab; Jul 4, 1054 AD (as recorded by the Anasazi in Chaco Canyon, NM)

The Crab Nebula formed by the expelled outer shell of the star (as recorded by the VLT, Cerro Paranal, Chile)

Type II supernovae: explosive phase of a star with M>6 to 8 M_{sun}

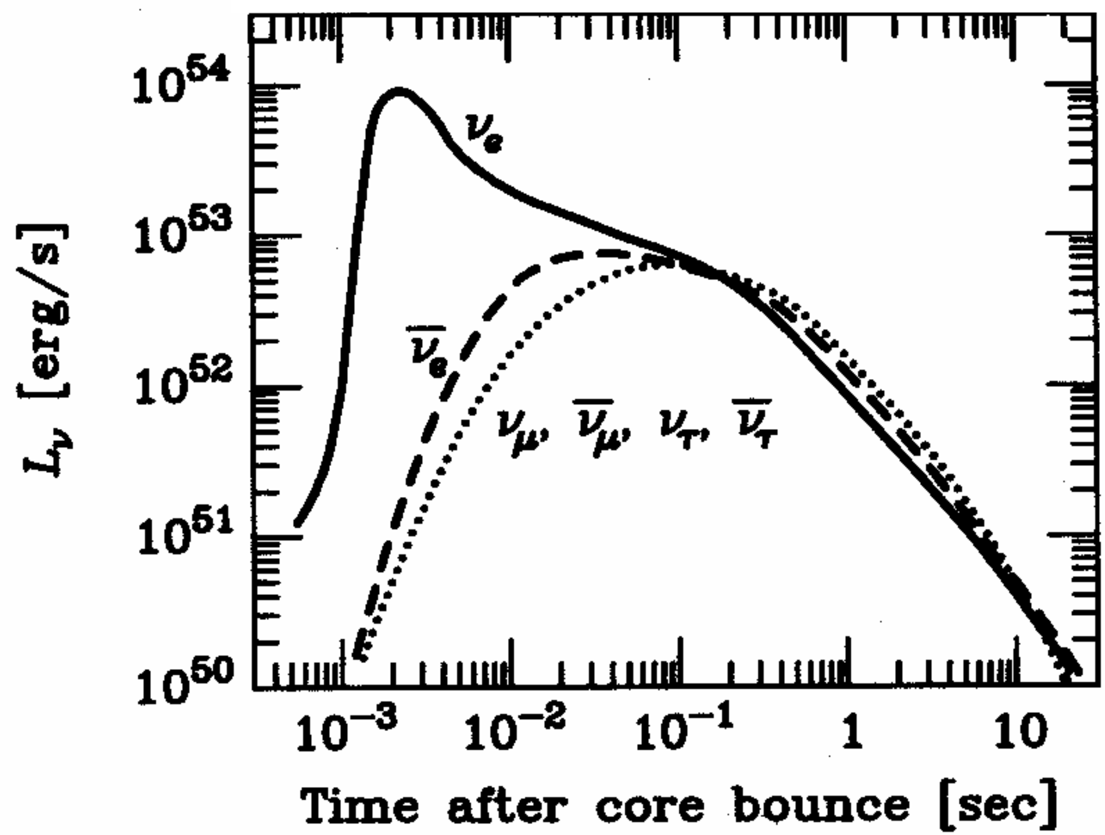
- Nuclear fuel burnt through Fe: no mechanism to hold further gravitational collapse
- $T=0.8*10^{10}$ K = 0.7 MeV
  $\rho=3*10^9$ g/cm^3 (this is a billion times the density of the earth, or the entire KamLAND in a teaspoon)
- The pressure causes the reaction $p+e^- \rightarrow n+\nu_e$

Very intense ν_e flash (~1 s duration)

- Neutrinos cool the star that collapses further
- The collapsing soup become so dense to be opaque to ν (!)
- Following mechanisms that we do not completely understand the fireball re-bounces blowing up the outer envelope (eventually like the Crab photo)
- ν of all flavors escape when density low enough (after ~10 s)

99% of the supernova explosive energy is carried away by neutrinos

*...~3.8*10^{33} erg, in 10 s it would take the sun 2000 billion years to produce that much energy !*

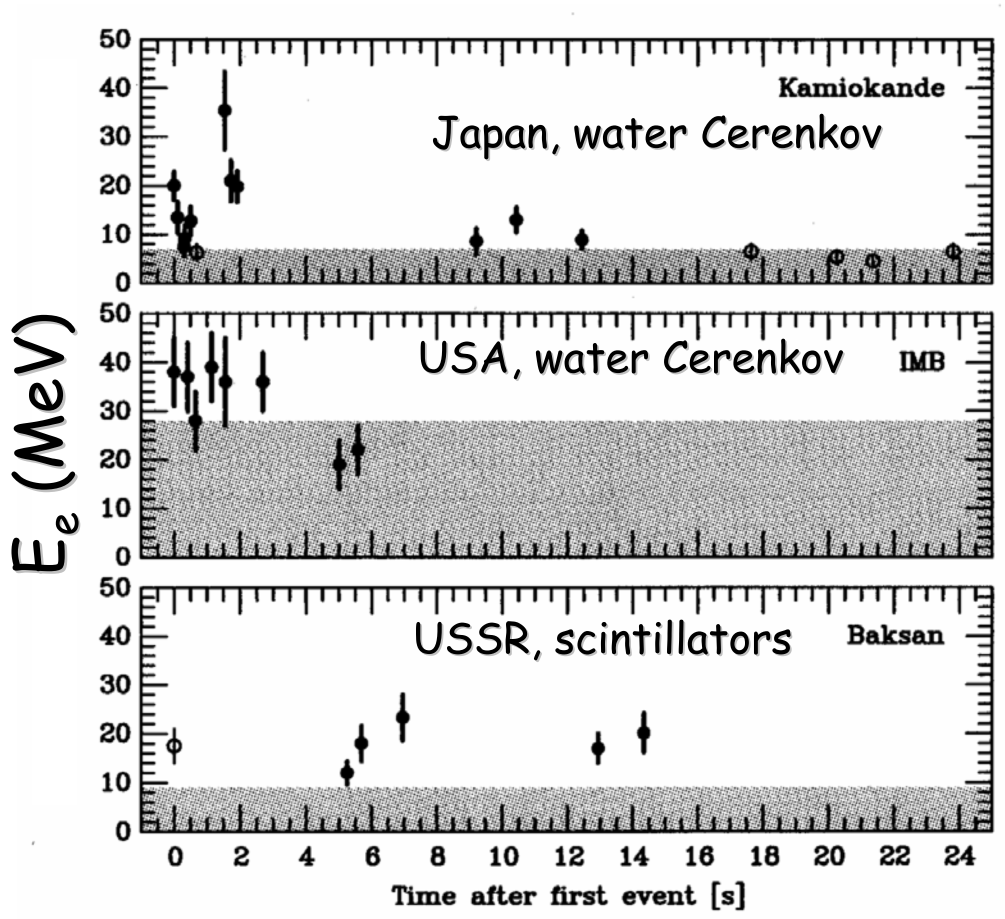


Only hours later the density is low enough for light to escape the star and the supernova flash appears

We have seen the neutrinos from a supernova only once

Feb 23, 1987 about 20 ν events were detected from an explosion in the Large Magellanic Cloud: SN1987A

The dawn of neutrino astronomy



Today there are several detectors ready to study neutrinos from supernovae

The number of events observed could be >10000 for a supernova in our galaxy

Observations could be used to explore:

- Neutrino masses (from the time of flight from the star)
- Neutrino oscillation (from the flavor composition)
- Explosion dynamics (from the duration of the flash and the temperatures (energy spectra) of different neutrino flavors)

From historical records there seem to be about 3 supernovae/century in the Milky Way…

Conclusions

I have covered a small fraction of the different ideas, experiments, theories connected to neutrinos

This is a fantastic field in rapid development

It is a very broad field with connections with particle physics, astrophysics, cosmology, geophysics and… who knows… technology !

…Keep an eye on it !