Neutrini

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1. The invention of the neutrino

Chadwick Continuous β-spectrum, 1914, 1927

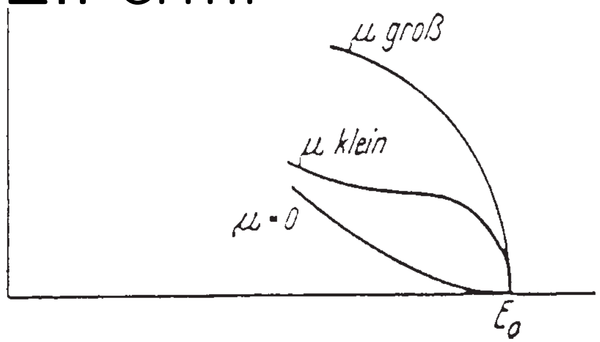
Bohr as late as '36 thought energy might not be conserved in nuclear physics

Pauli ν, 1930 (-1+3), Dear Radioactive Ladies and Gentlemen,

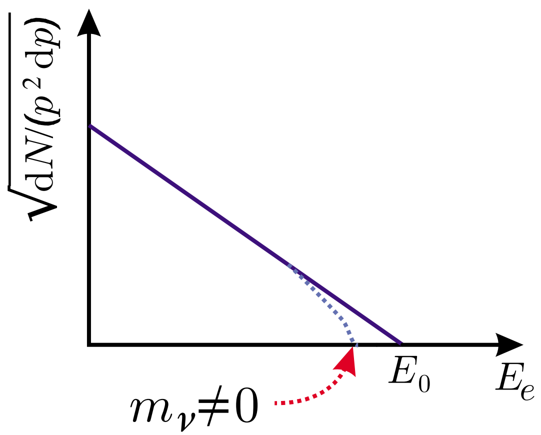
Fermi, in Zeitschrift fur Physik **88** 161 (1934) (16 January)

Emmy Noether, 1918, Noether's theorem

E.Fermi



Important papers were in German



Discovery

Bethe & Peierls 1934. $\lambda_{\nu-\text{abs}}$~10^{19} cm, 10 light-years for ρ=3, will never be observed.

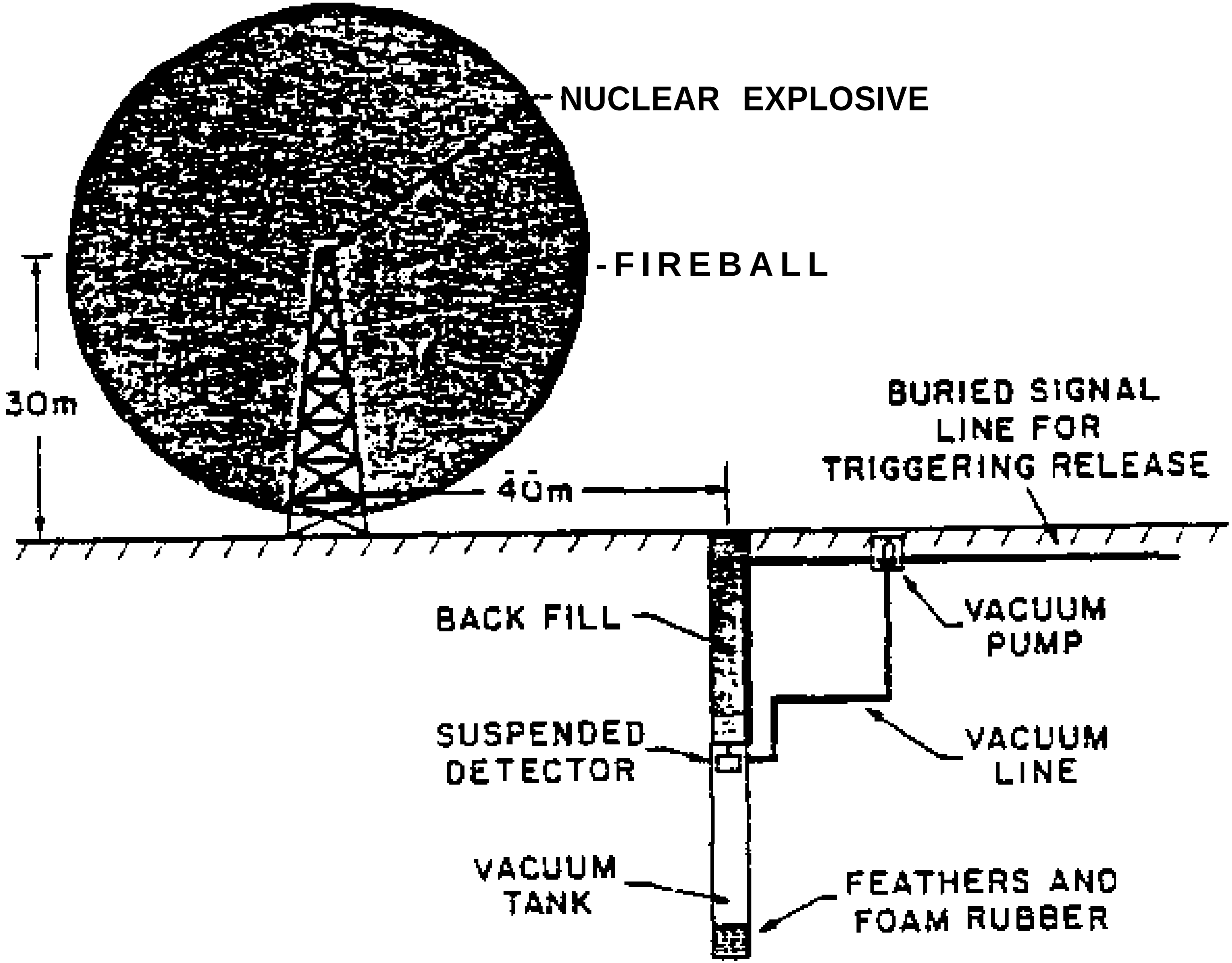
Reines & Cowan, try 100 m from an atomic bomb?... Attempt at small breeder, then at large power reactor. June '56 sent a telegram to Pauli to reassure him ν's exist. (24 y vs $>$? 40 y for Higgs)

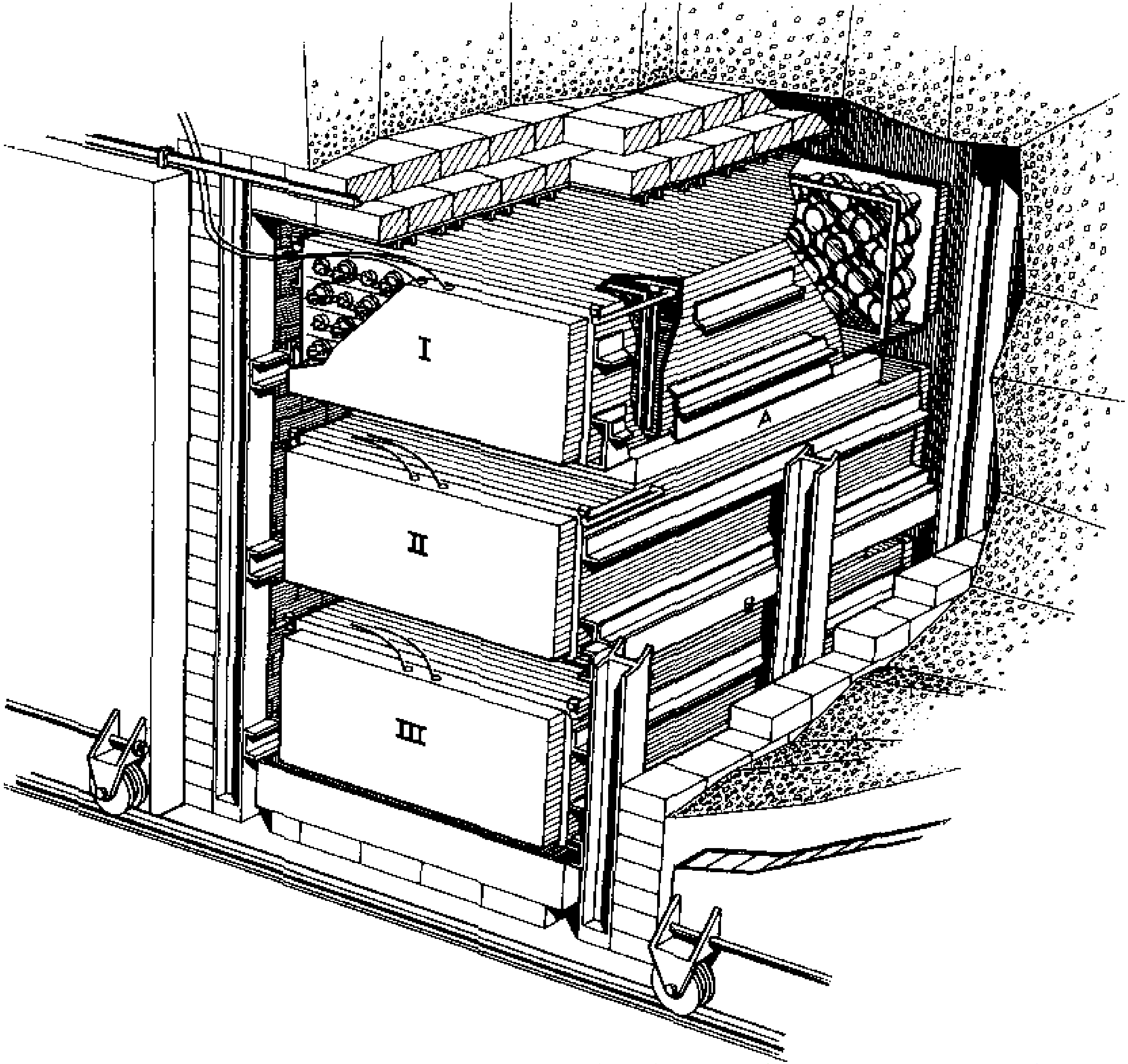
10^{13} ν/cm^2/s→3 events/h in ~1 ton detector

$$\bar{\nu} + p \to n + e^+$$

$$N_{\text{ev}}[/\text{s}] = f[/\text{cm}^2/\text{s}] \times \sigma[\text{cm}^2] \times V[\text{cm}^3] \times \rho_{\text{H}}[g_{\text{H}_2}/\text{cm}^3] \times N[p/g_{\text{H}_2}]$$

$$N = f \times \sigma \times N \times M$$


NUCLEAR EXPLOSIVE
FIREBALL
30m
40m
BURIED SIGNAL LINE FOR TRIGGERING RELEASE
BACK FILL
VACUUM PUMP
SUSPENDED DETECTOR
VACUUM LINE
VACUUM TANK
FEATHERS AND FOAM RUBBER


I
II
III
A

1957 to the 70's and on

Reactor: $\bar{\nu}$'s, not ν's; R. Davis, '55, chlorine (BMP)

Parity

$\mu \not\to e\gamma, \quad \nu_e \neq \nu_\mu$

ν_e and ν_μ helicity

Observation of ν_μ

All the way to the SM where neutrinos have zero mass

$m(\nu_e)$ <2.8 eV, $^3\mathrm{H} - \beta$ decay

Just 3 neutrinos

If m=0, helicity is L-invariant and $\mathcal{H} = \pm 1$ states are independent

$\nu_{\mathrm{right}}, \ \bar{\nu}_{\mathrm{left}}$ need not exist

Something different

1964 Look for solar ν's, just to peek inside the sun. 100,000 gallon of tetrachloroethylene - dry cleaning fluid - are enough to observe

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

as computed in SSM, from the reactions:

$$p + p \rightarrow d + e^+ + \nu \qquad E_{\text{max}} = 0.42\ \text{MeV}$$

$$p + p + e^- \rightarrow d + \nu \qquad E = 1.44\ \text{MeV}$$

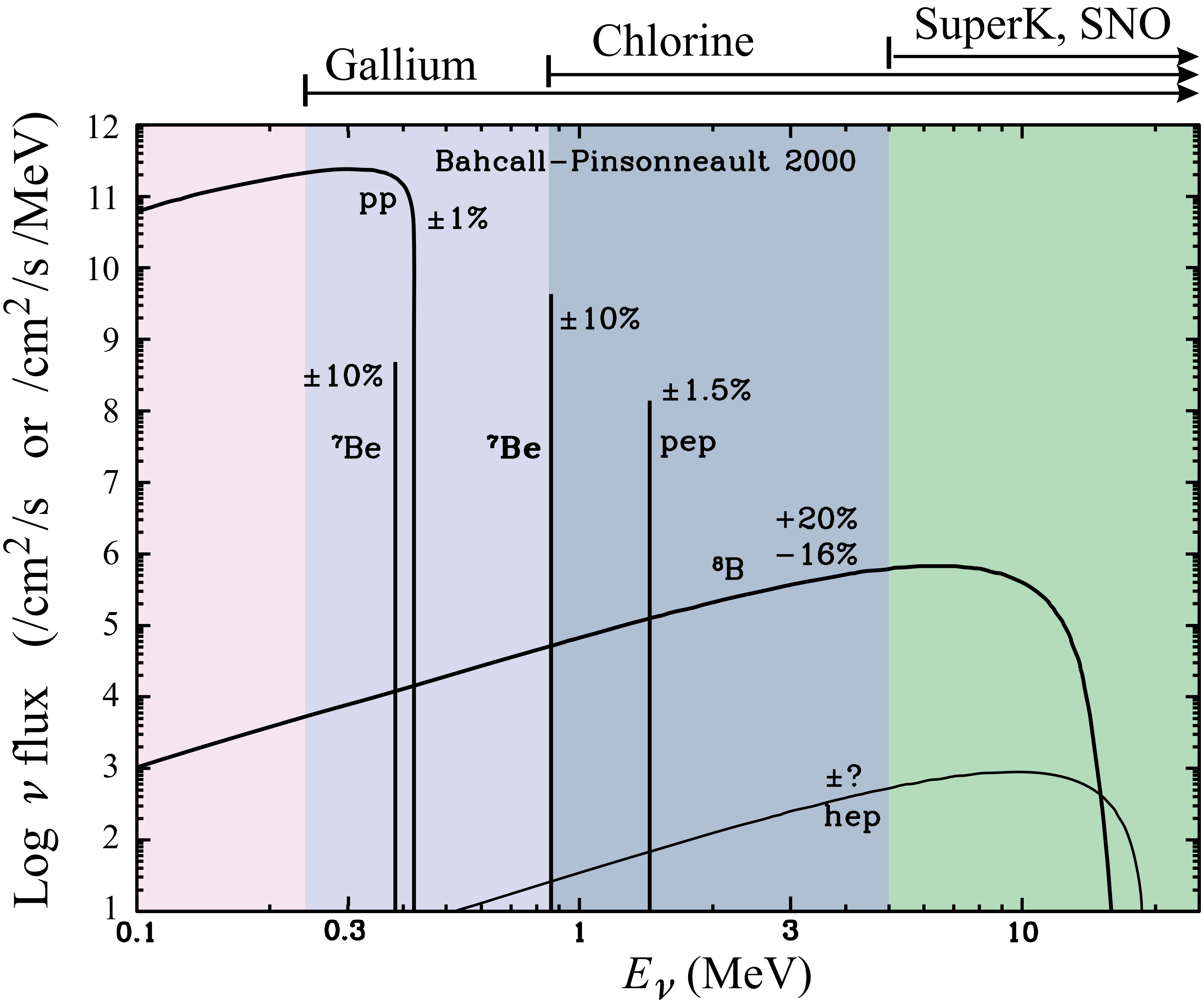
$$d + p \rightarrow {}^3\text{He} + \gamma \quad {}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p \quad {}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$$

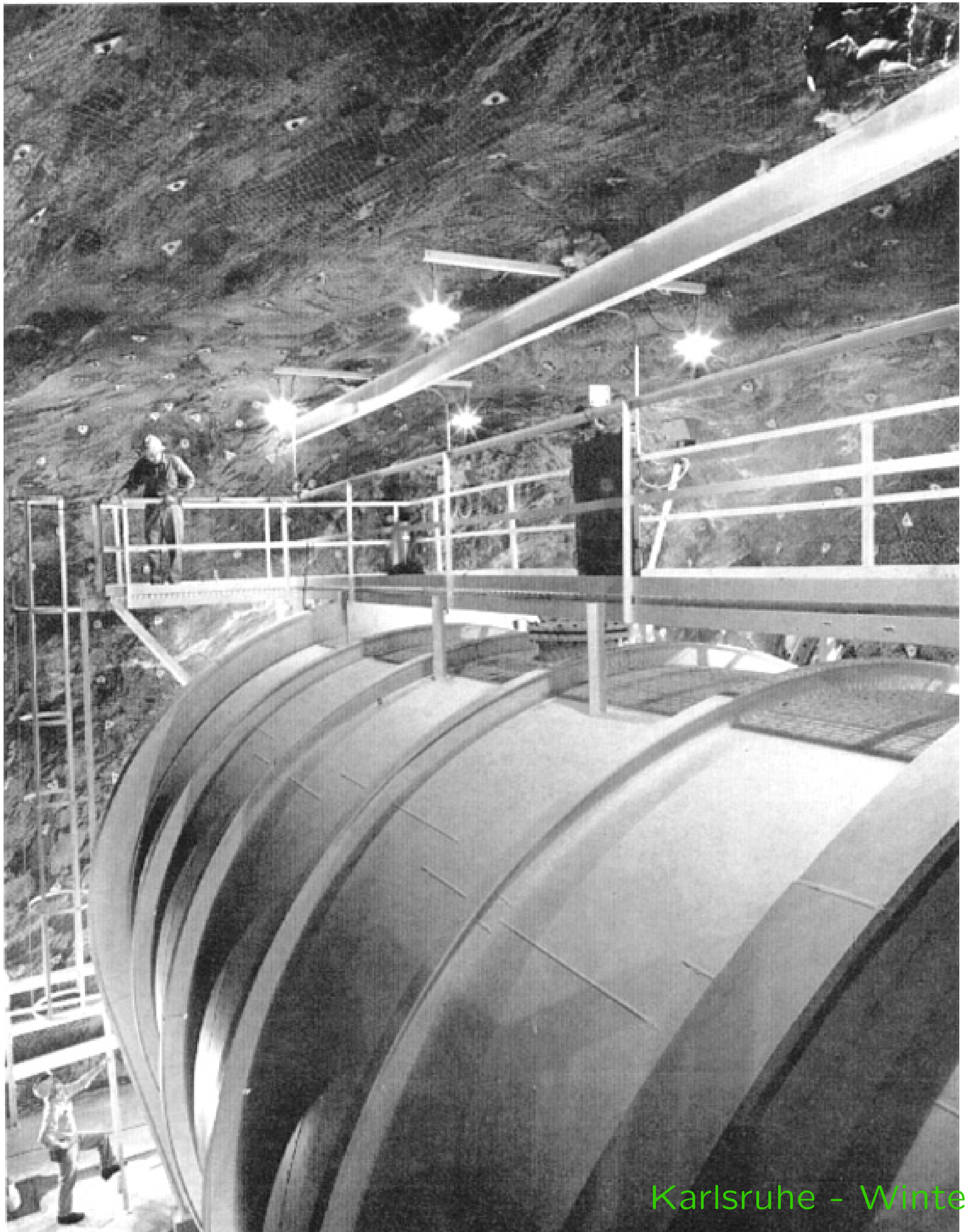
$${}^7\text{Be} + e^- \rightarrow \begin{matrix} {}^7\text{Li} + \nu & E = 0.86\ \text{MeV},\ 90\% \\ {}^7\text{Li} + \nu & E = 0.38\ \text{MeV},\ 10\% \end{matrix}$$

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

$$\text{Bo} \rightarrow \text{Be} + e^+ + \nu \qquad E_{\text{max}} = 15\ \text{MeV}$$

plus all return reactions without ν's.


Gallium
Chlorine
SuperK, SNO
Bahcall−Pinsonneault 2000
pp
±1%
±10%
⁷Be
±10%
⁷Be
±1.5%
pep
+20%
−16%
⁸B
±?
hep
Log ν flux (/cm²/s or /cm²/s /MeV)
1
2
3
4
5
6
7
8
9
10
11
12
0.1
0.3
1
3
10
E_ν (MeV)



400 ton $C_2H_2Cl_4$

Extract Ar

Count Ar decays

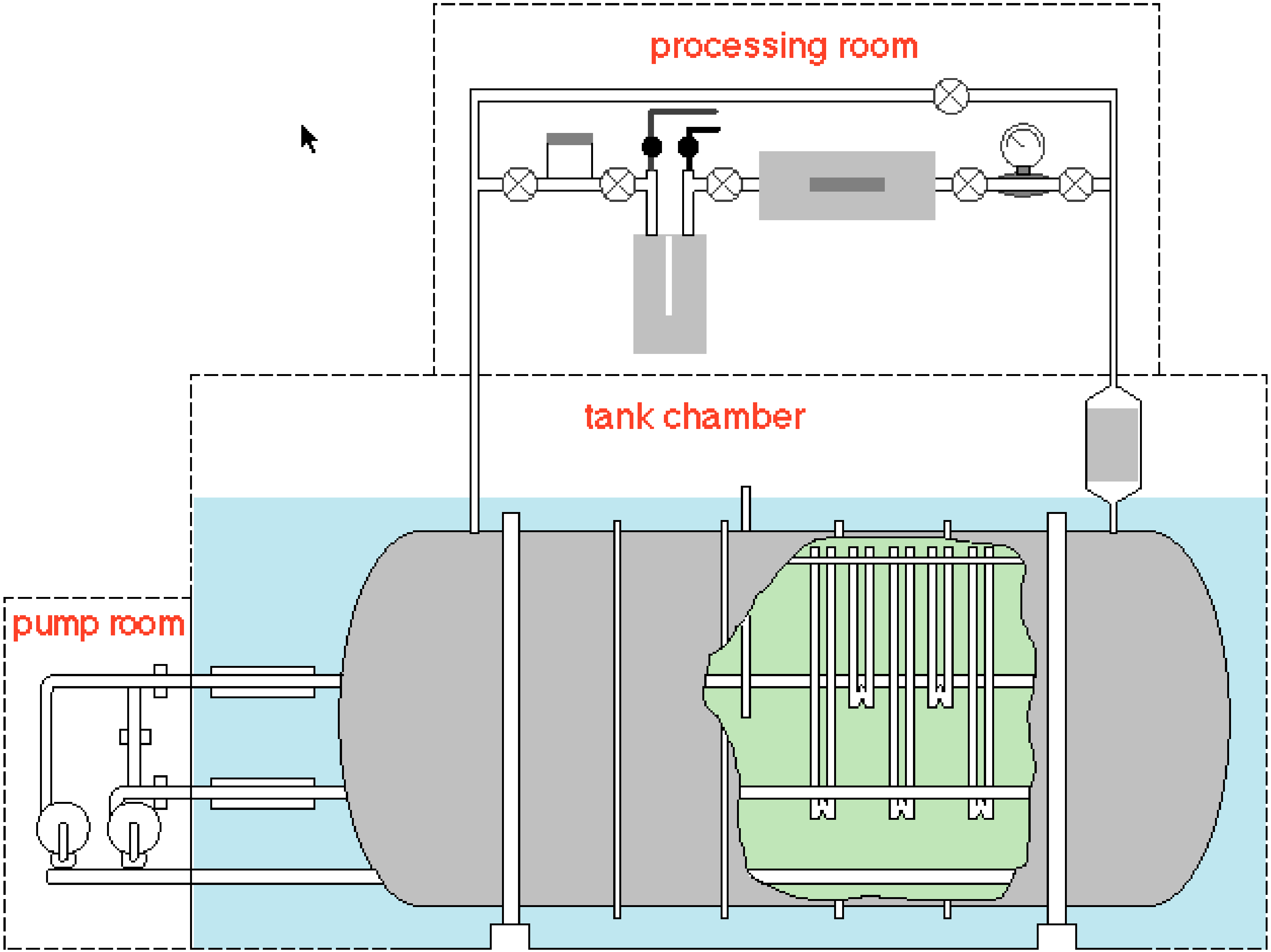
Add and recover Ar

(non radioactive)

Neutron source

check

30 Year Run


processing room
tank chamber
pump room

SNU≡1 interaction/sec/10^{36} atoms≈1 int./ton/year

Ray Davis, chlorine experiment, expected 7 SNU, gave upper limit of 2.5 by 1968. $E_\nu >$0.8 MeV

Is the experiment wrong? No, all checks OK!

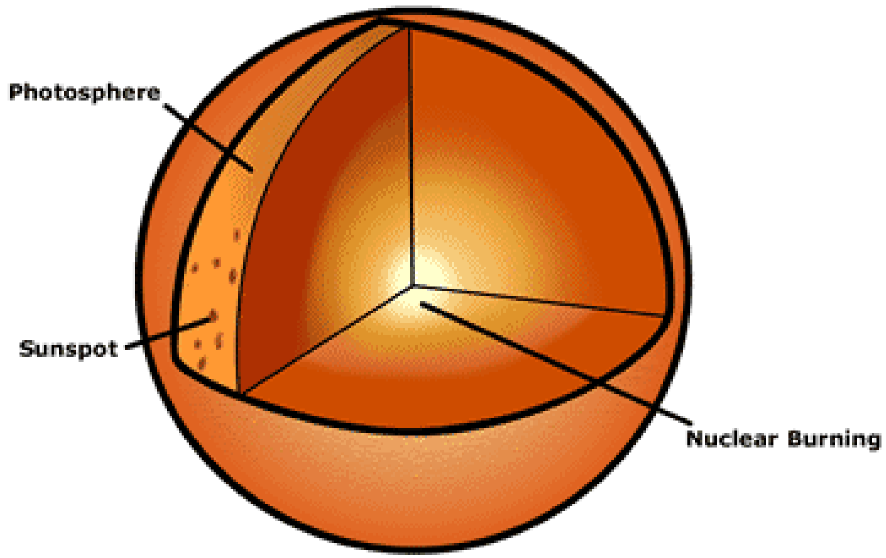
Is the SSM correct? Doubts but with help of Helioseismology and many checks had to be accepted.

New experiments: 1. K-SuperK, H_2O, $E_\nu >$6.5 MeV

2. Gallex-Sage, Ga, $E_\nu >$0.25 MeV

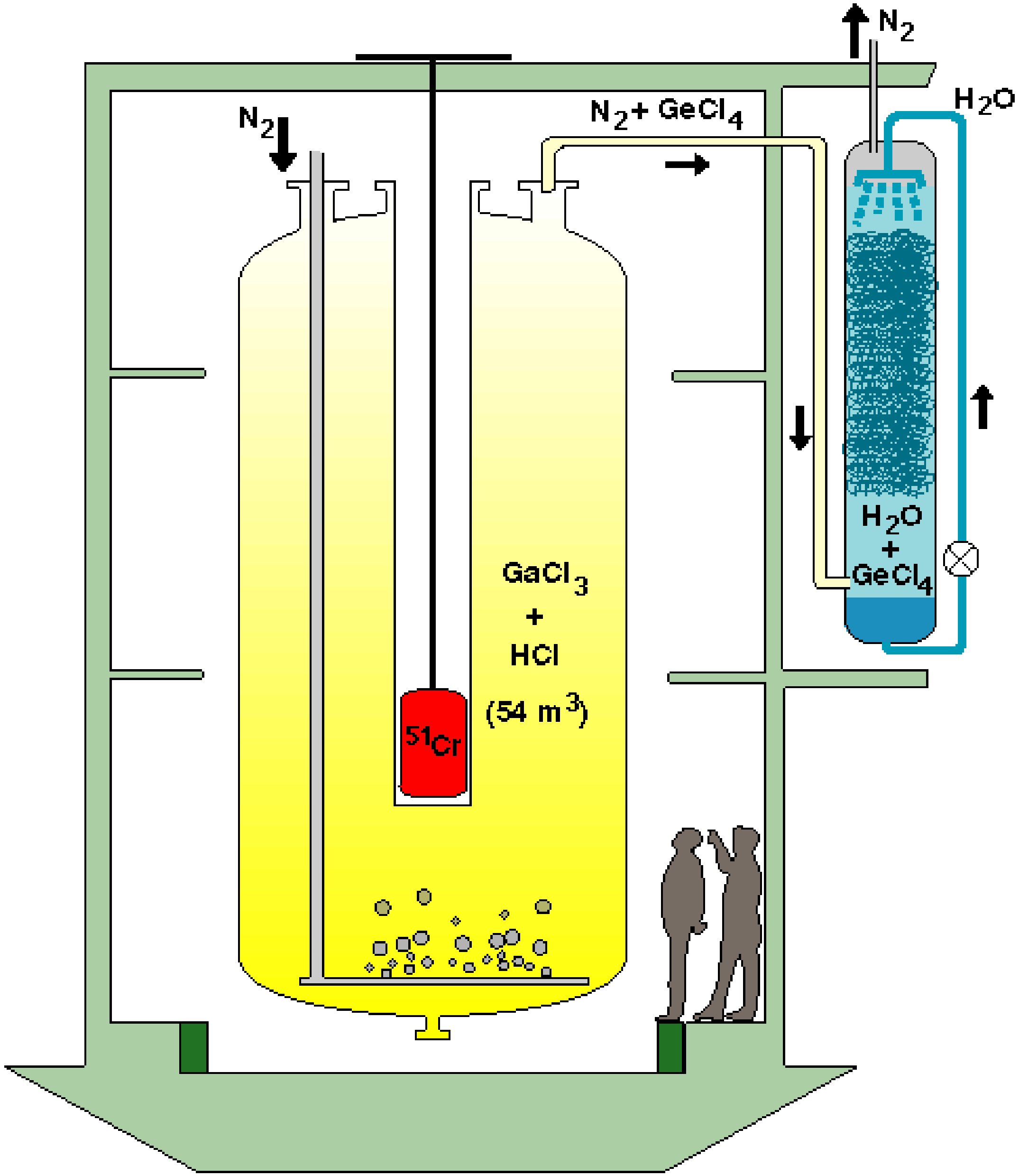
$v_{\text{sound}} \propto T^{1/2}$

$\phi_\nu(^7\text{Be}) \propto T^{10}$



Source	Flux $(10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$	Cl (SNU)	Ga (SNU)
pp	$5.94\left(1.00^{+0.01}_{-0.01}\right)$	0.0	69.6
pep	$1.39\times10^{-2}\left(1.00^{+0.01}_{-0.01}\right)$	0.2	2.8
hep	2.10×10^{-7}	0.0	0.0
^{7}Be	$4.80\times10^{-1}\left(1.00^{+0.09}_{-0.09}\right)$	1.15	34.4
^{8}B	$5.15\times10^{-4}\left(1.00^{+0.19}_{-0.14}\right)$	5.9	12.4
^{13}N	$6.05\times10^{-2}\left(1.00^{+0.19}_{-0.13}\right)$	0.1	3.7
^{15}O	$5.32\times10^{-2}\left(1.00^{+0.22}_{-0.15}\right)$	0.4	6.0
^{17}F	$6.33\times10^{-4}\left(1.00^{+0.12}_{-0.11}\right)$	0.0	0.1
Total		$7.7^{+1.2}_{-1.0}$	129^{+8}_{-6}
Observe		$2.6\pm.23$	73 ± 5

Gallium: $^{71}Ga \rightarrow ^{71}Ge$: Sage and Gallex



Are there any ν from the sun?

Super-Kamiokande

A H_2O Cerenkov detector. 41.4 m h × 39.3 m dia

50,000 tons of pure water

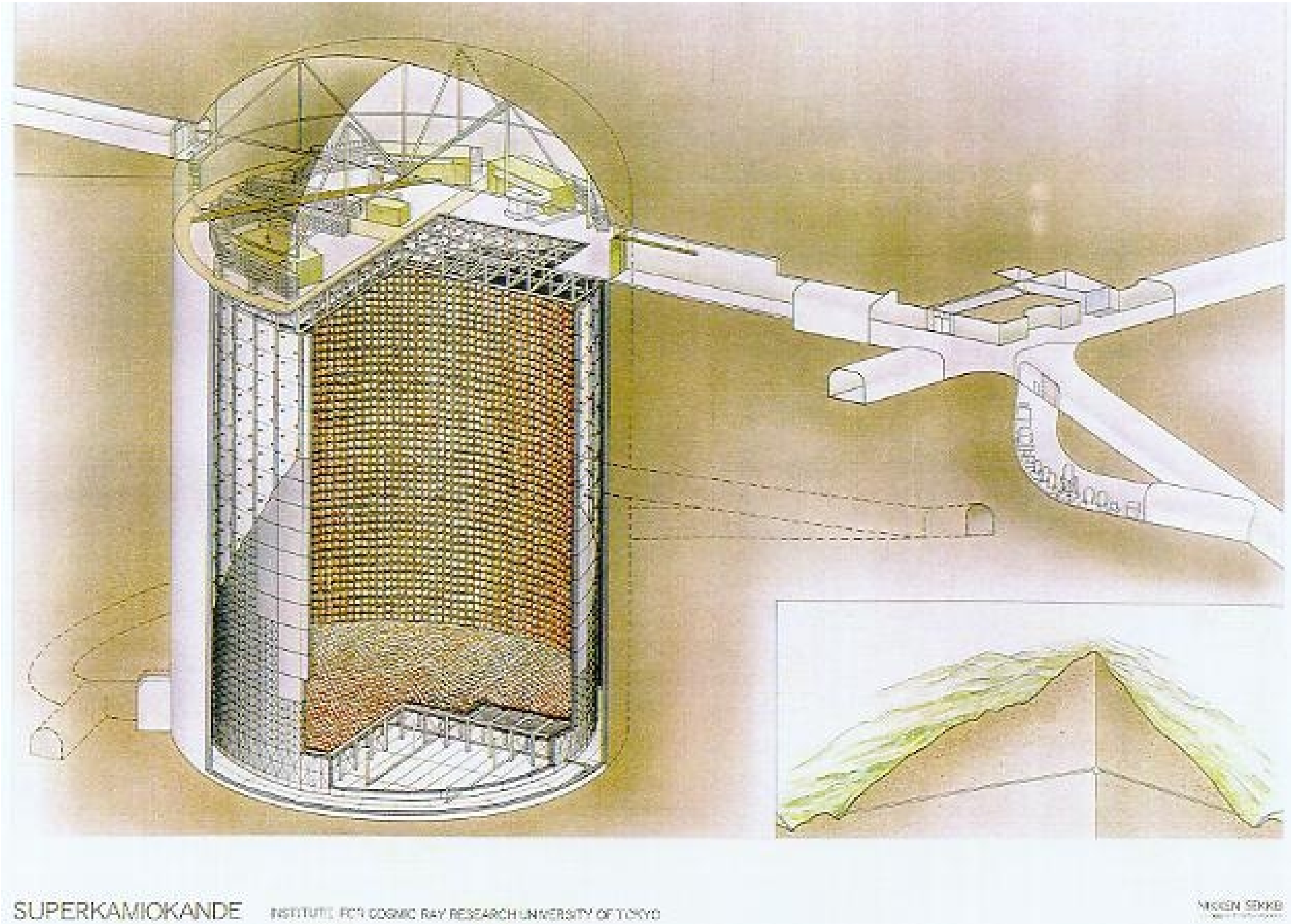
11,200 50 cm dia. PMTs, plus more, outer det.

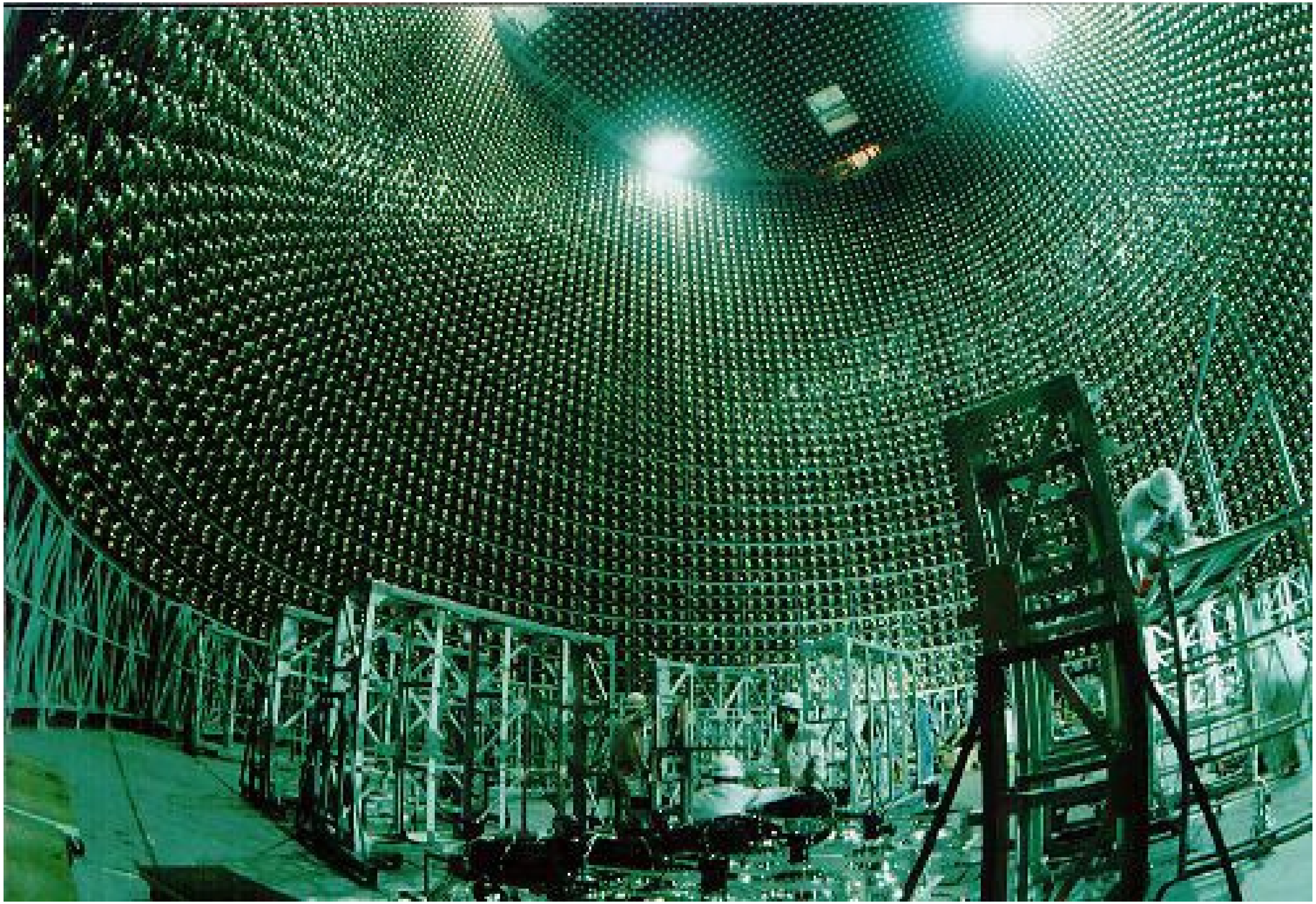
ν events point to the sun   ok

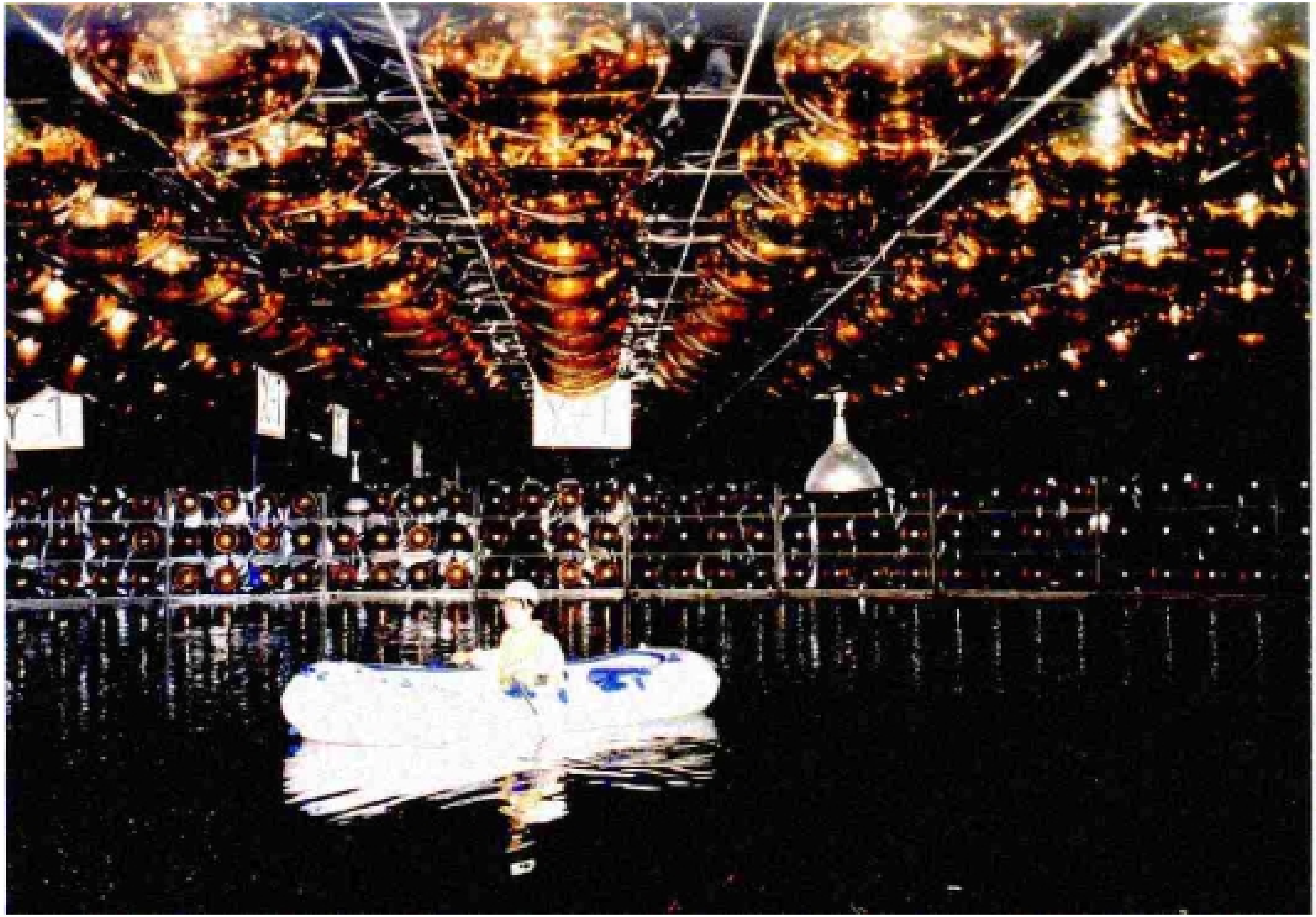
$E_{\text{max}} \leq$ 15 MeV   ok

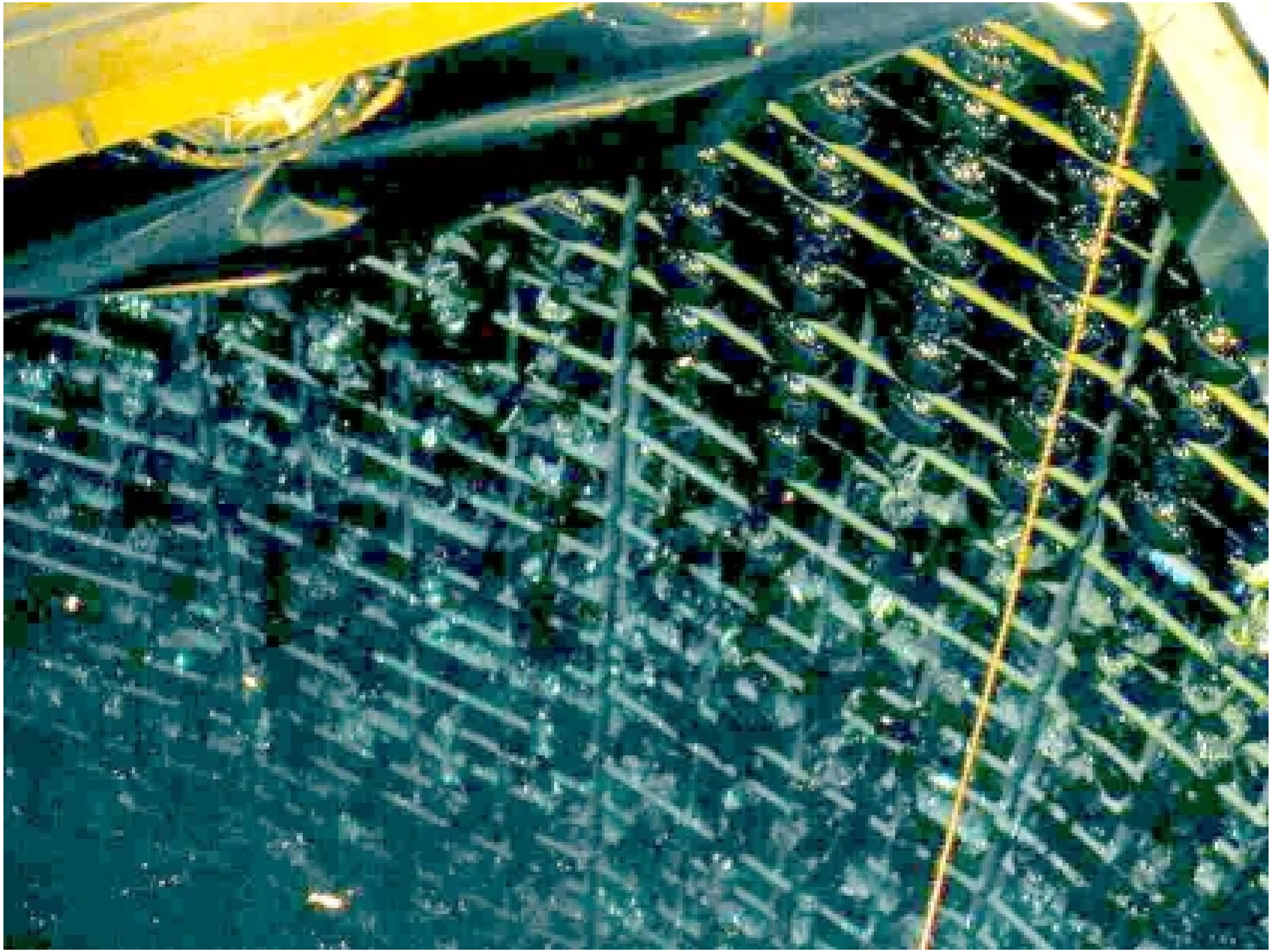
but

$$\frac{\text{SuperK } \nu}{\text{SSM}} = 0.44 \pm 0.03$$


SUPERKAMIOKANDE
INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO







Neutrinos disappear

In the E-W SM, neutrinos have no mass and $\nu_e \neq \nu_\mu \neq \nu_\tau$

Pontecorvo in '67 had speculated on what could happen if lepton flavor is not conserved and neutrino have mass.

Mass eigenstates are distinct from flavor eigenstates, and connected by a unitary mixing matrix.

$$\mathbf{V}_f = \mathbf{U}\mathbf{V}_m \qquad \mathbf{V}_m = \mathbf{U}^\dagger \mathbf{V}_f$$

where

$$\mathbf{V}_f = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \qquad \mathbf{V}_m = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

are the flavor and mass neutrino eigenstates.

Example. Two flavors, e, μ; two masses, 1, 2

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

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

If at time $t = 0$, $\Psi(t) = |\,\nu_e\,\rangle$ the state evolves as:

$$\Psi_e(t) = \cos\theta|\,\nu_1\,\rangle e^{iE_1 t} + \sin\theta|\,\nu_2\,\rangle e^{iE_2 t}.$$

Substitute and project out the e, μ amplitudes

$$A(\nu_e,\ t) = \cos^2\theta e^{iE_1 t} + \sin^2\theta e^{iE_2 t}$$

$$A(\nu_\mu,\ t) = -\cos\theta\sin\theta e^{iE_1 t} + \cos\theta\sin\theta e^{iE_2 t}$$

The intensities then are:

$$I(\nu_e,\ t) = \cos^4\theta + \sin^4\theta + 2\cos^2\theta\sin^2\theta\cos|E_1 - E_2|t$$

$$I(\nu_\mu,\ t) = 2\cos^2\theta\sin^2\theta(1 - \cos|E_1 - E_2|t).$$

more conveniently

$$I(\nu_e,\ t) = 1 - \sin^2 2\theta \sin^2\left(\frac{E_1 - E_2}{2}\, t\right)$$

$$I(\nu_\mu,\ t) = \sin^2 2\theta \sin^2\left(\frac{E_1 - E_2}{2}\, t\right).$$

or ($\Delta E = \Delta m^2/2E,\ t = l/c$, using $\hbar = c = 1$)

$$I(\nu_e,\ t) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \times \Delta m^2 \times l}{E}\right)$$

$$I(\nu_\mu,\ t) = \sin^2 2\theta \sin^2\left(\frac{1.27 \times \Delta m^2 \times l}{E}\right).$$

with E in MeV (GeV), Δm^2 in eV^2 and l in meters (km).

ν_e oscillate from 1 to 0 and back and forth...
ν_μ appear and then fade and so on...

That of course if

1. You are lucky
2. You are in control of the experiment

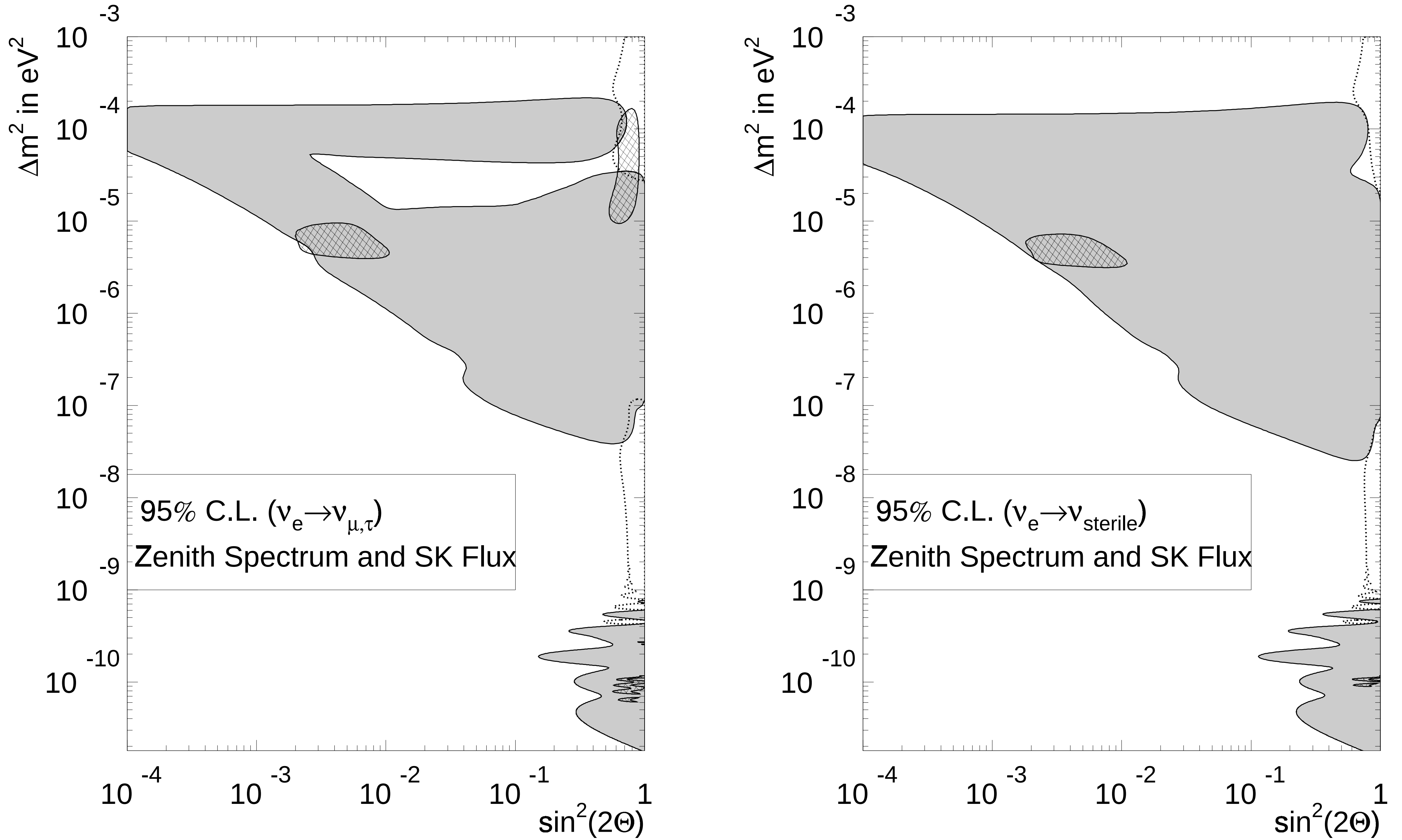
Typically, neutrinos have a continuous spectrum. Then in average some of the ν_e disappear and just as many ν_μ appear. For just two species, the limit is 1/2 disappearance and 1/2 appearance.

With solar neutrinos, $E < 15$ MeV, the muon (tau) neutrino are not positively observable because $\nu_\mu + X \rightarrow \mu + X'$ is energetically impossible.

1. This is encouraging but not quite enough...
2. No oscillation has ever been seen, except...
3. The missing neutrinos can be detected by scattering
4. There is more: atmospheric ν's

But, before that, what does one get from solar ν's?

In fact many solutions, must include oscillations in matter (MSW).
Wave length changes in matter.



Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
95% C.L. ($\nu_e \rightarrow \nu_{\mu,\tau}$)
Zenith Spectrum and SK Flux
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\Theta)$
Δm^2 in eV^2
95% C.L. ($\nu_e \rightarrow \nu_{sterile}$)
Zenith Spectrum and SK Flux
$\sin^2(2\Theta)$

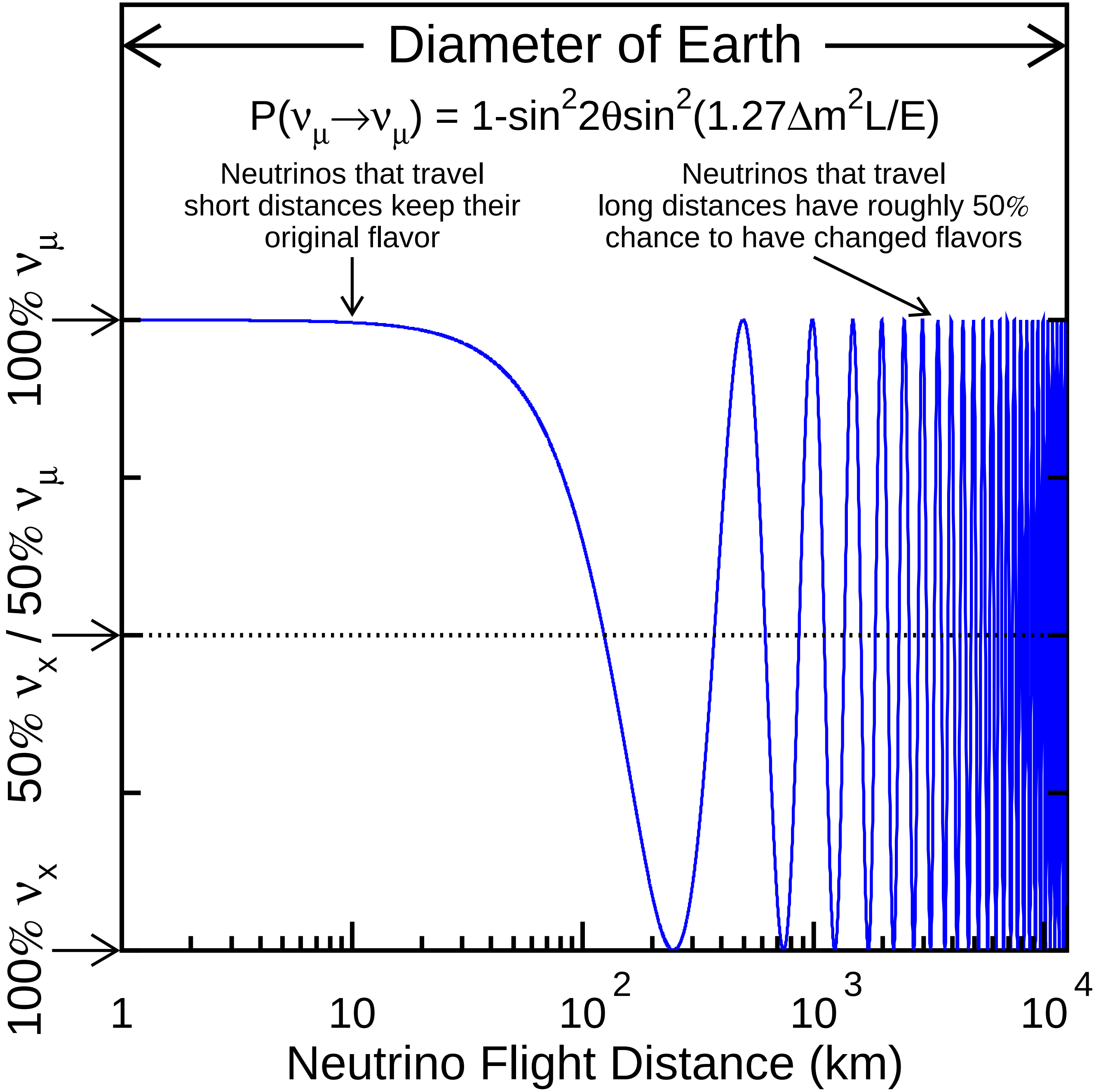
Atmospheric neutrinos

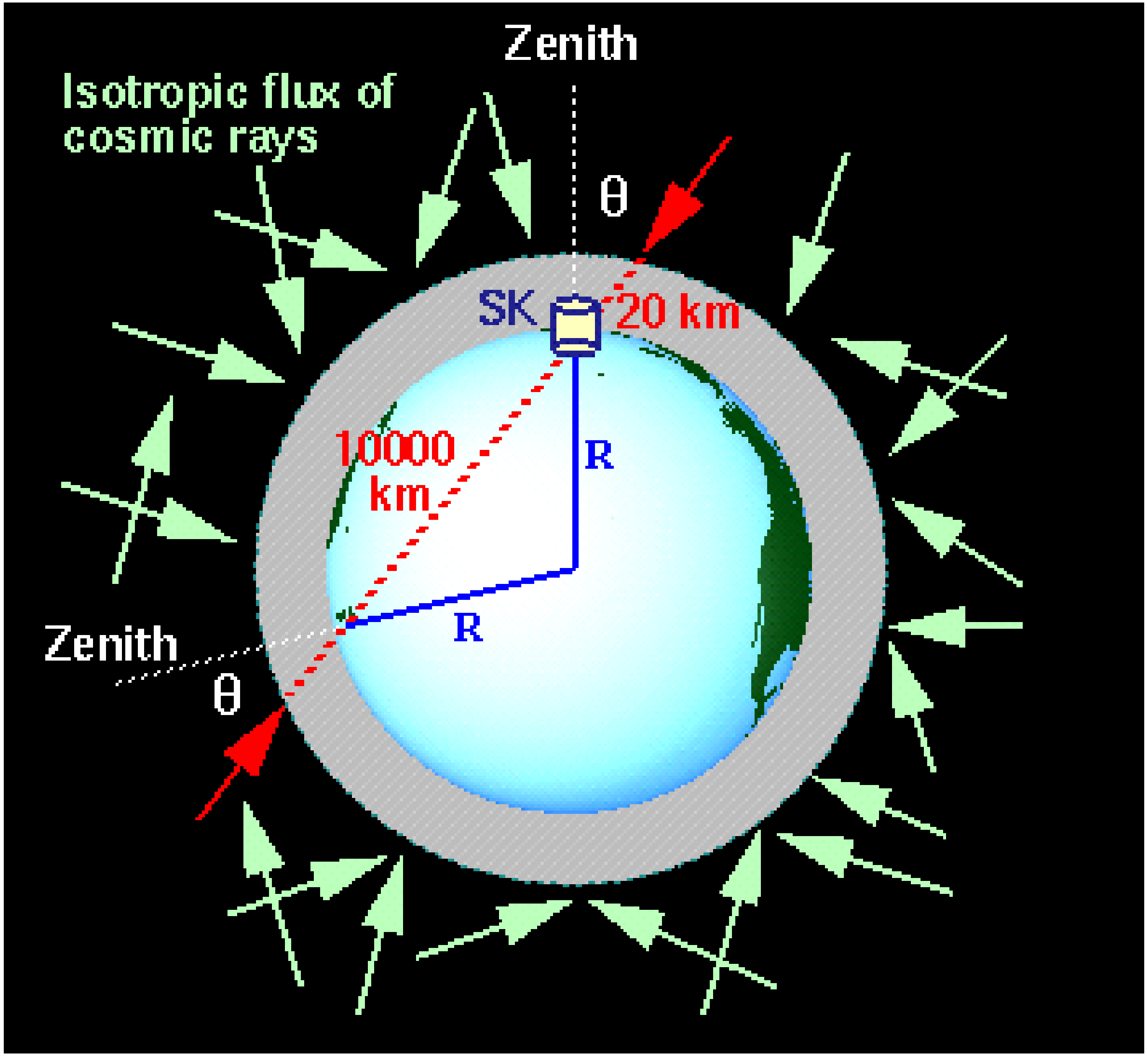
IMB, Kamiokande and **SuperK** find that high energy ν_μ are not twice ν_e. High energy ν's come from cosmic rays as:

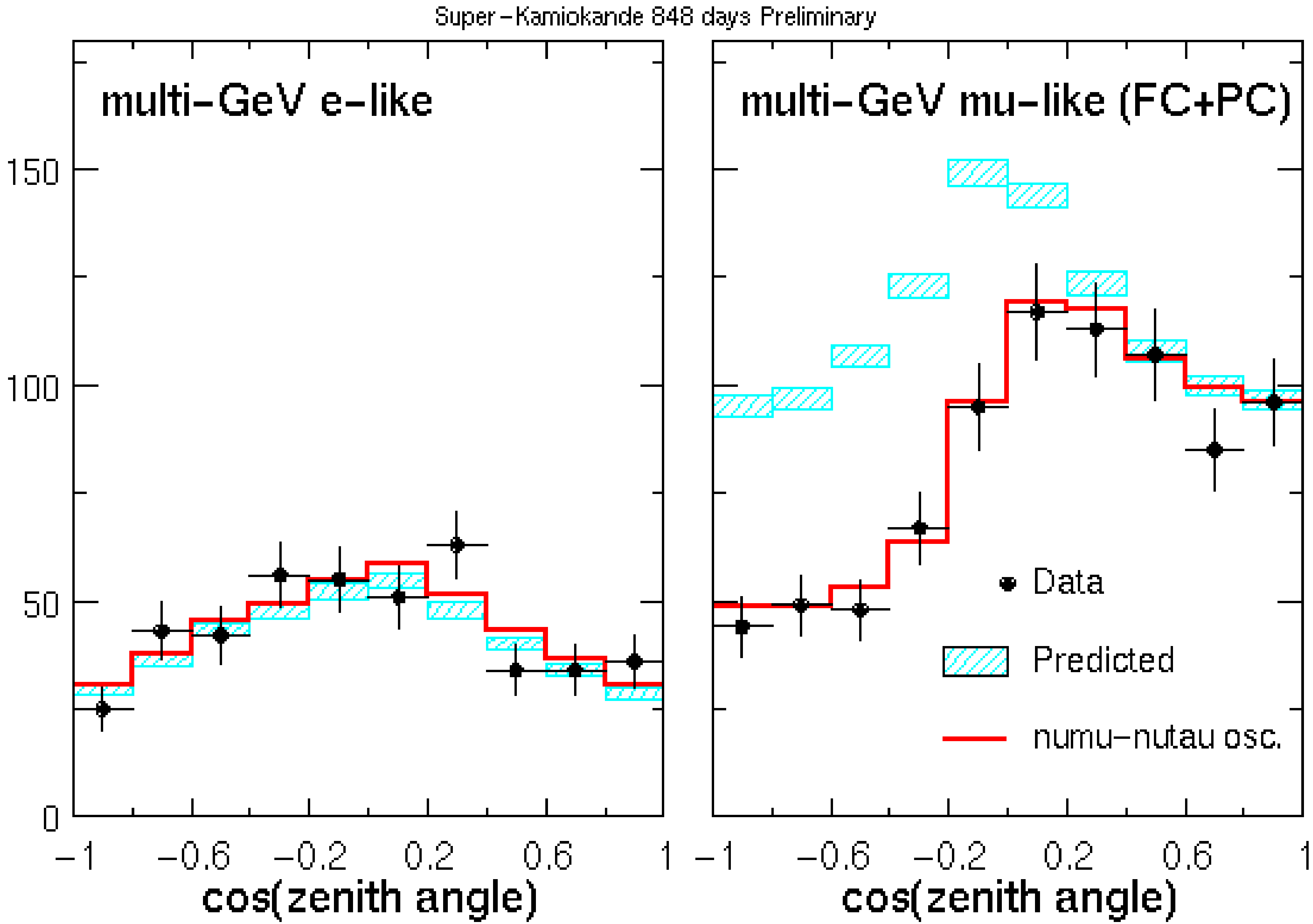
$$\left.\begin{array}{l}\pi \to \mu + \nu_\mu \\ \mu \to e + \nu_\mu + \nu_e\end{array}\right. \Rightarrow 2\nu_\mu + 1\nu_e$$

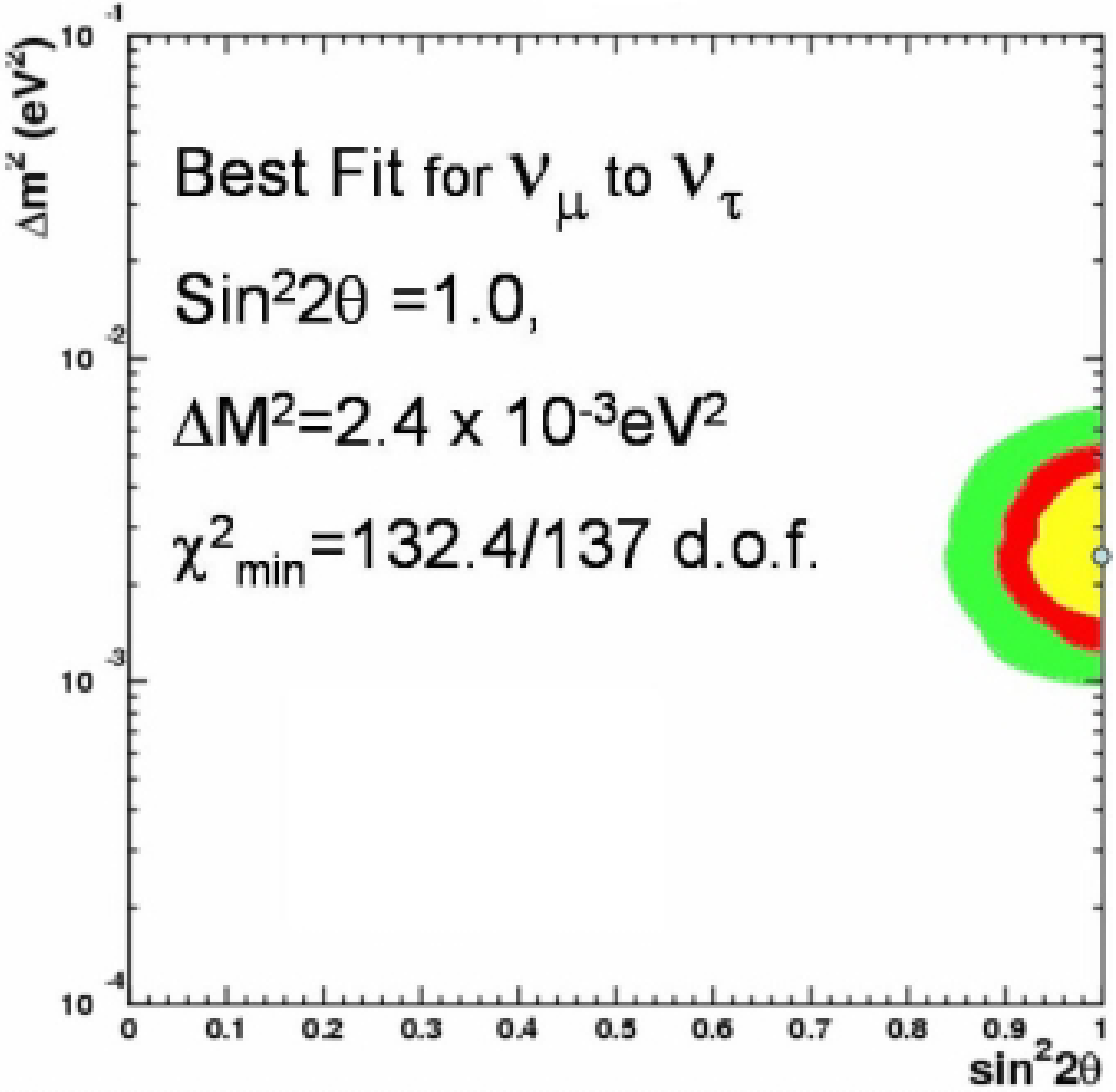
Super-K gives $(\nu_\mu/\nu_e)_{\text{obs.}}/(\nu_\mu/\nu_e)_{\text{SSM}}$=0.63. Striking for high E, upward ν's. Also seen in Macro at Gran Sasso.

The only hint for oscillation


Diameter of Earth
P(νμ→νμ) = 1-sin²2θsin²(1.27Δm²L/E)
Neutrinos that travel short distances keep their original flavor
Neutrinos that travel long distances have roughly 50% chance to have changed flavors
100% νμ
50% νx / 50% νμ
100% νx
1
10
10²
10³
10⁴
Neutrino Flight Distance (km)


Zenith
Isotropic flux of
cosmic rays
θ
SK
20 km
10000
km
R
R
Zenith
θ


Super-Kamiokande 848 days Preliminary
multi-GeV e-like
multi-GeV mu-like (FC+PC)
150
100
50
0
-1
-0.6
-0.2
0.2
0.6
1
cos(zenith angle)
Data
Predicted
numu-nutau osc.

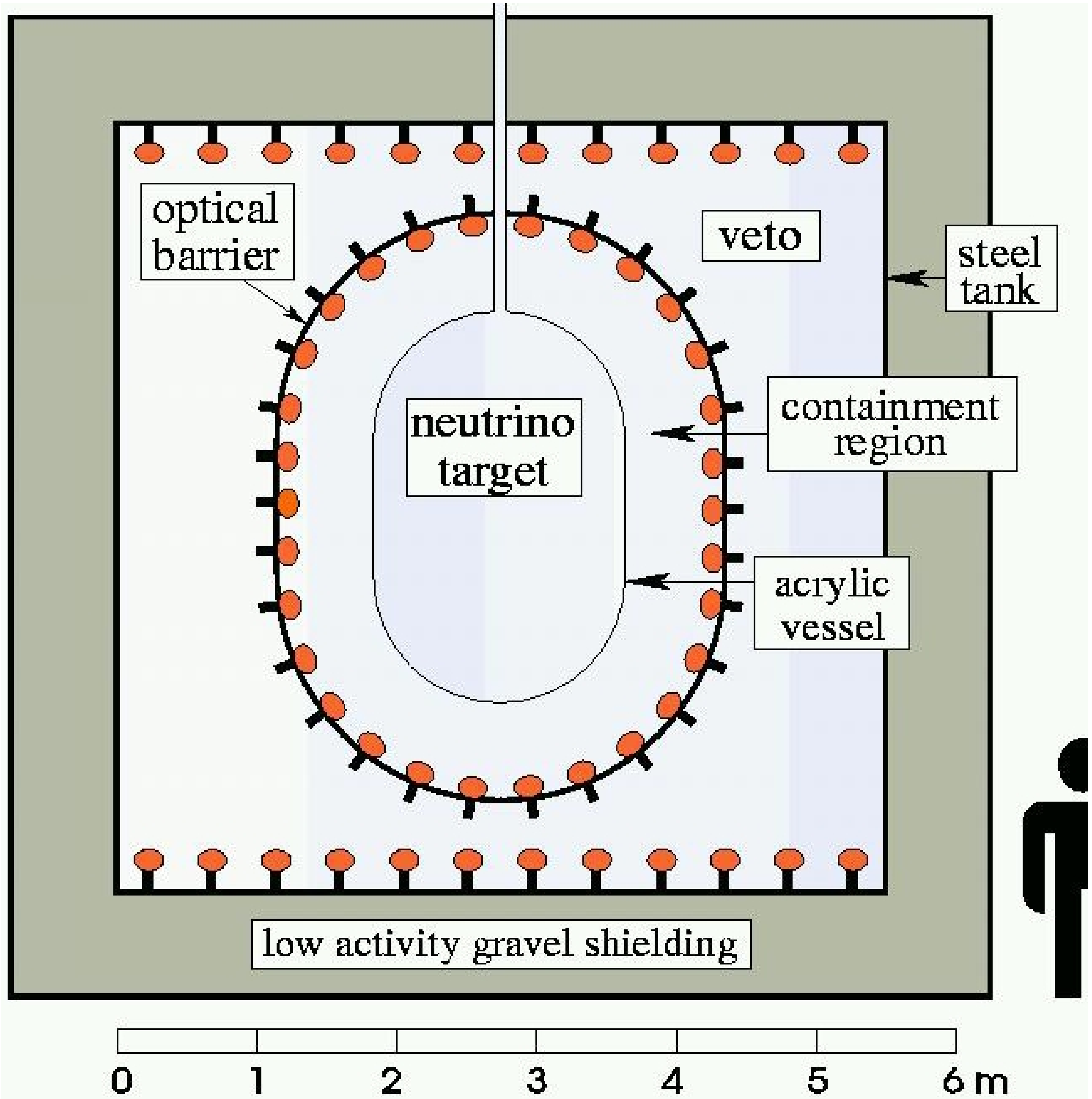

Best Fit for ν_μ to ν_τ
$Sin^2 2\theta = 1.0$,
$\Delta M^2 = 2.4 \times 10^{-3} eV^2$
$\chi^2_{min} = 132.4/137$ d.o.f.
$\Delta m^2 (eV^2)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\theta$

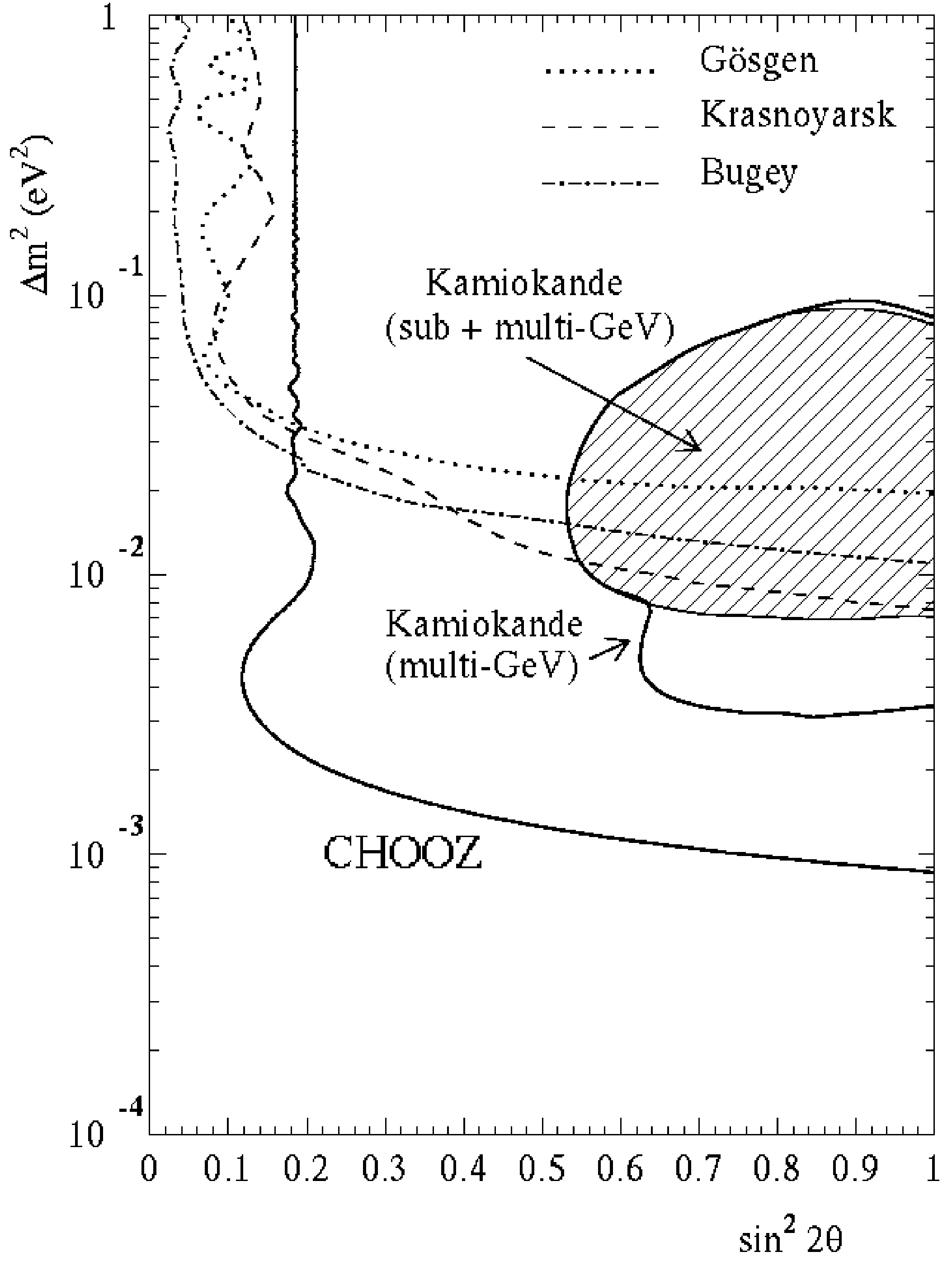
Reactor experiments. Example: Chooz

1 km to reactor

300 ℓ liq. scint.

Lots of $\bar{\nu}$'s

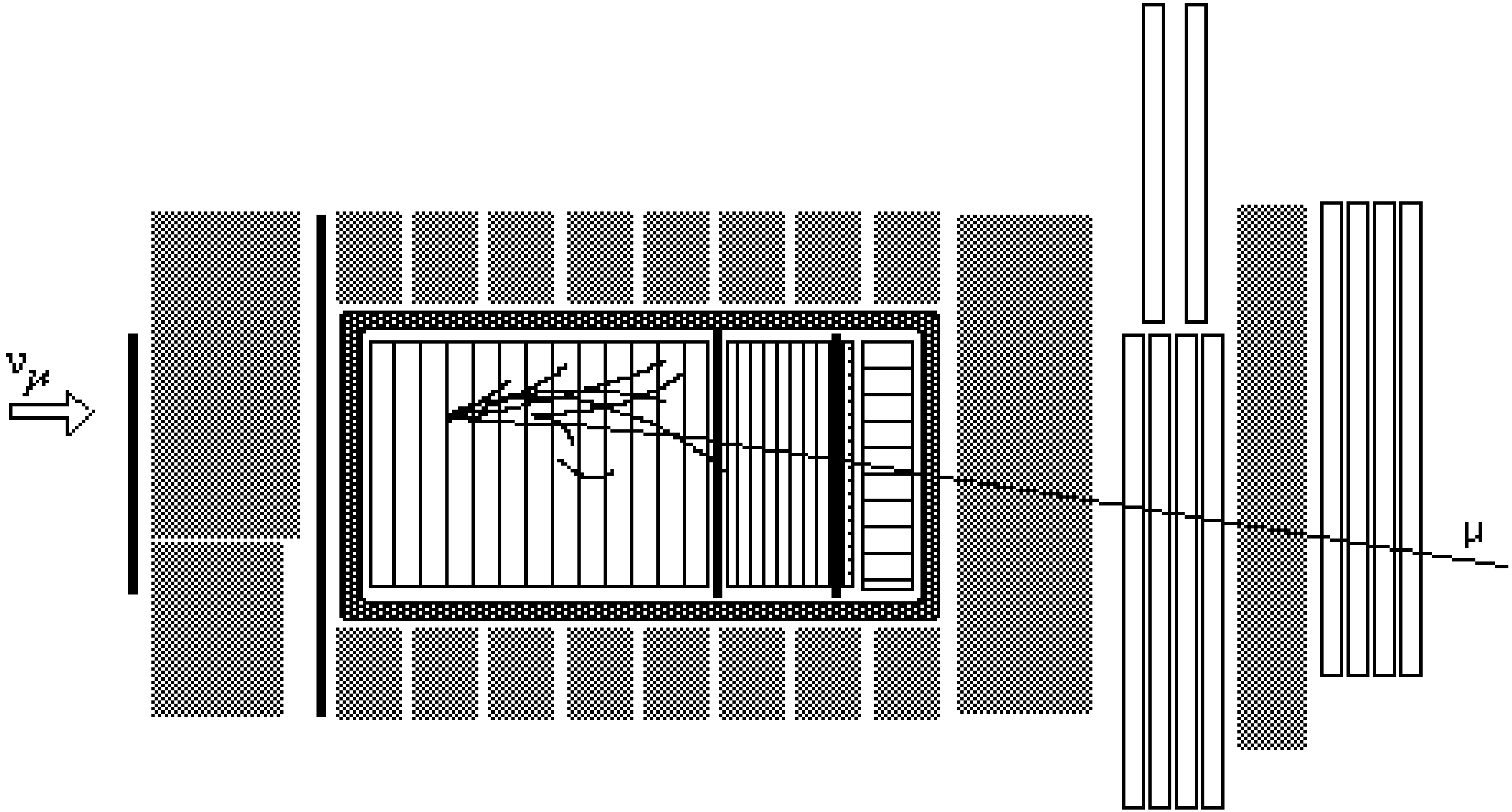


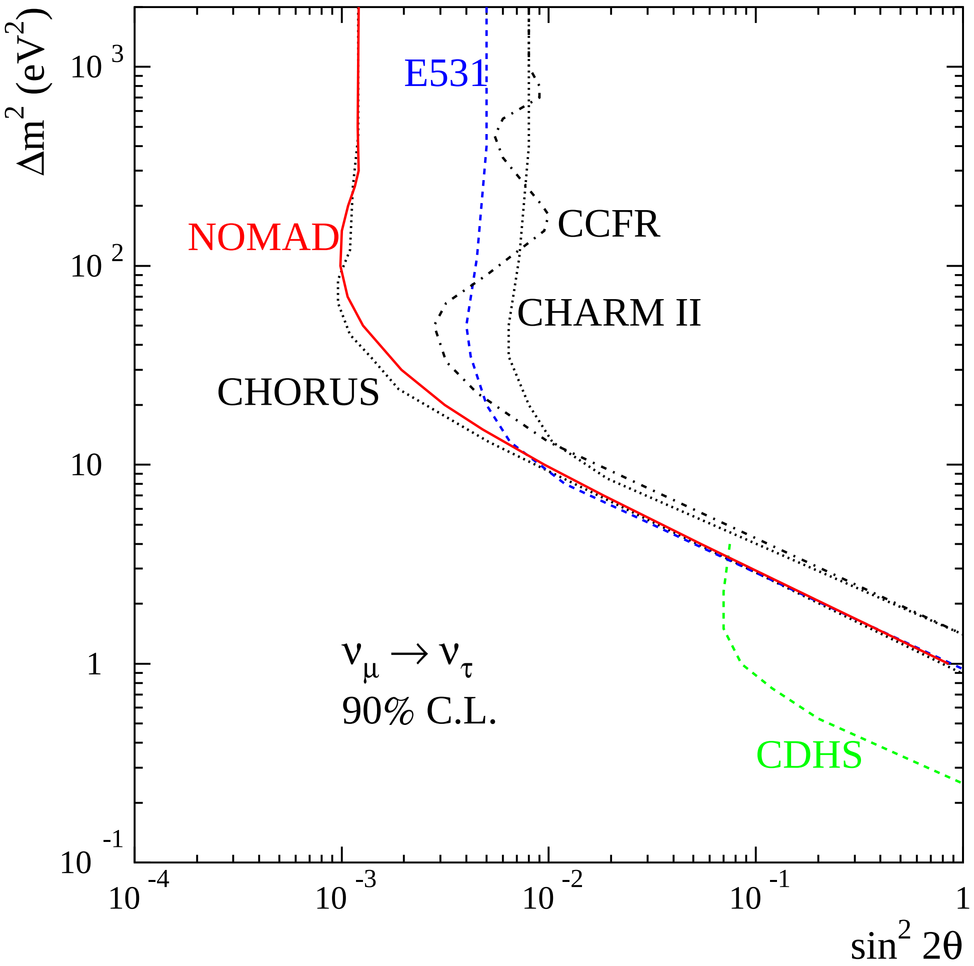

Gösgen
Krasnoyarsk
Bugey
Kamiokande
(sub + multi-GeV)
Kamiokande
(multi-GeV)
CHOOZ
Δm^2 (eV^2)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$\sin^2 2\theta$

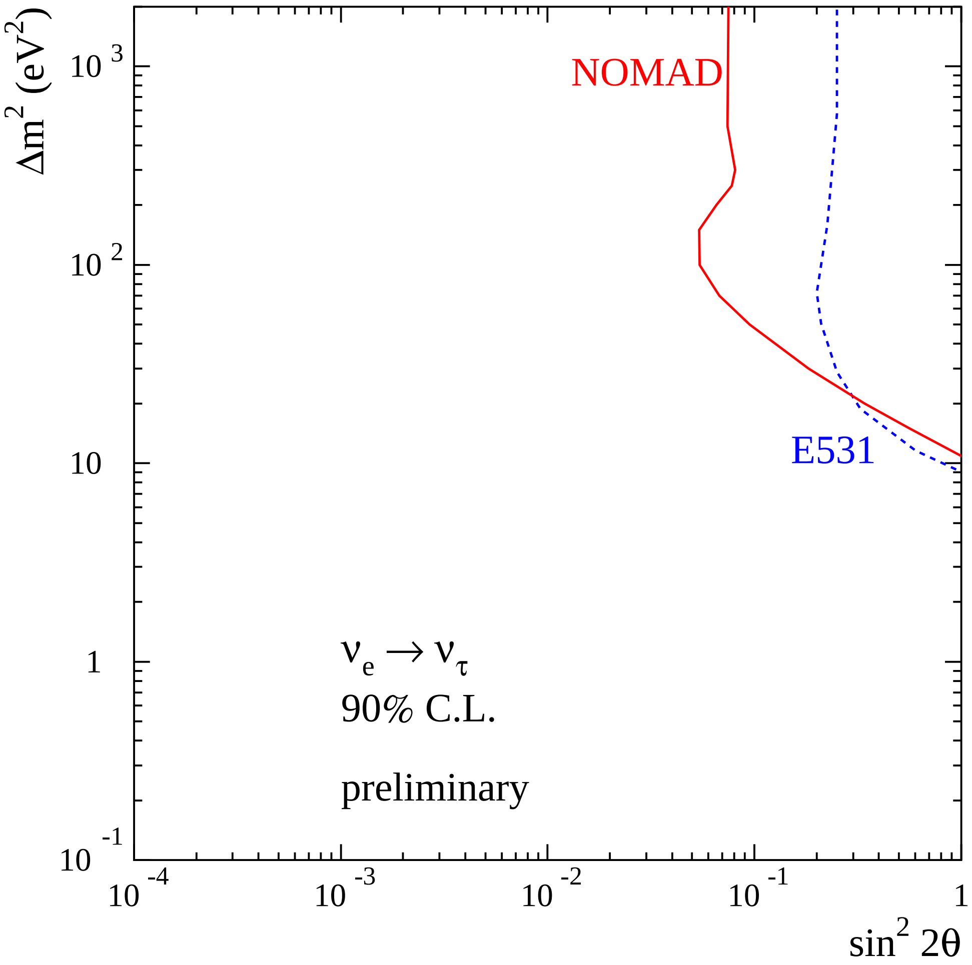
Conventional high energy ν beams

Recent example.

Nomad, closed. 450 GeV p produce 10^{13} ν_μ every 13 s







$$\Delta m^2 \lesssim 1 \text{ eV}$$

LSND - Karmen

The only appearance experiments

$$\pi^+ \to \mu^+ \, \nu_\mu$$

$$\hookrightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$$

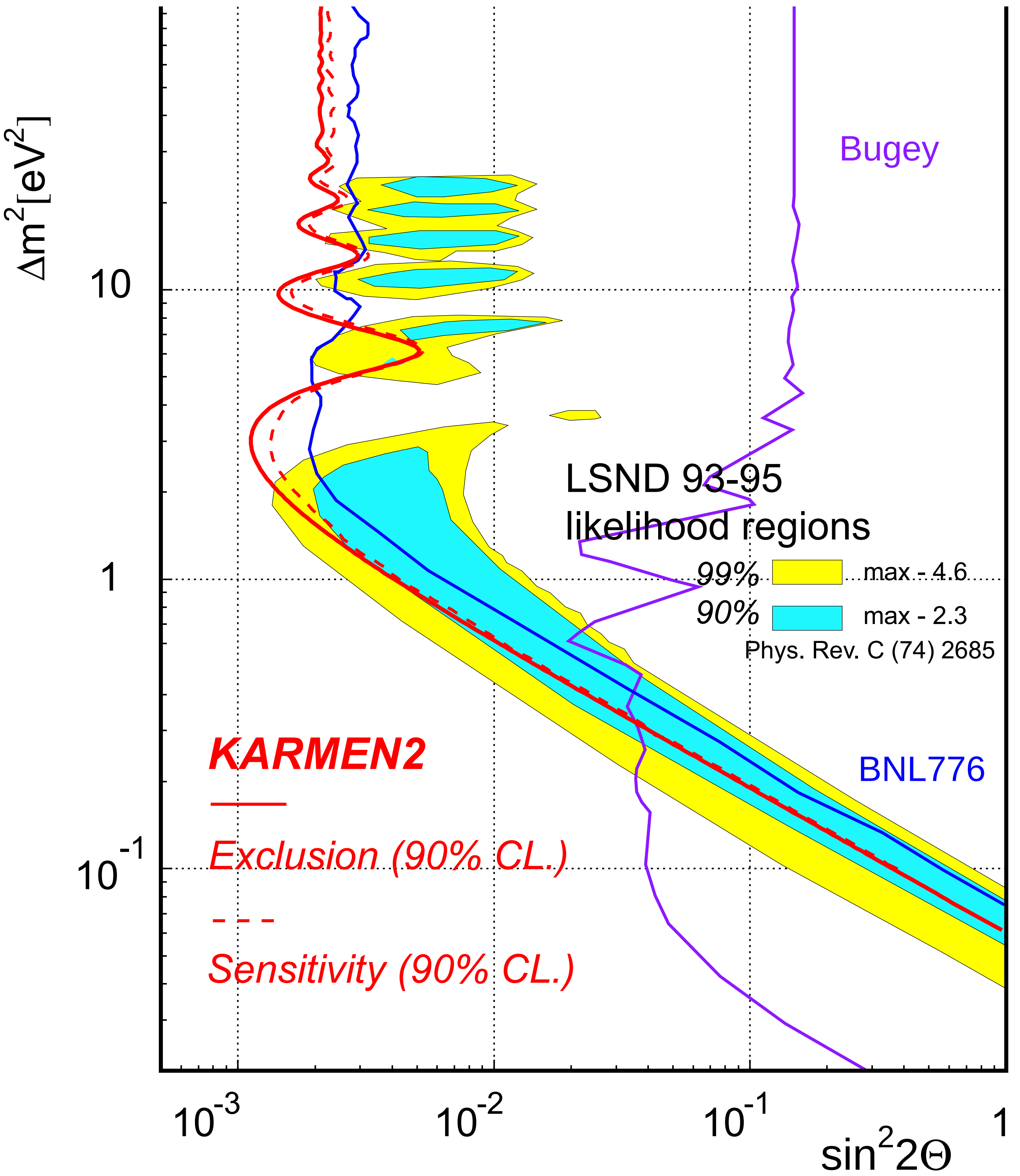
$$\hookrightarrow \bar{\nu}_e \text{ mixing}$$

$$\bar{\nu} + p \to n + e^+$$

Prompt e and delayed n $(n + p \to d + \gamma)$

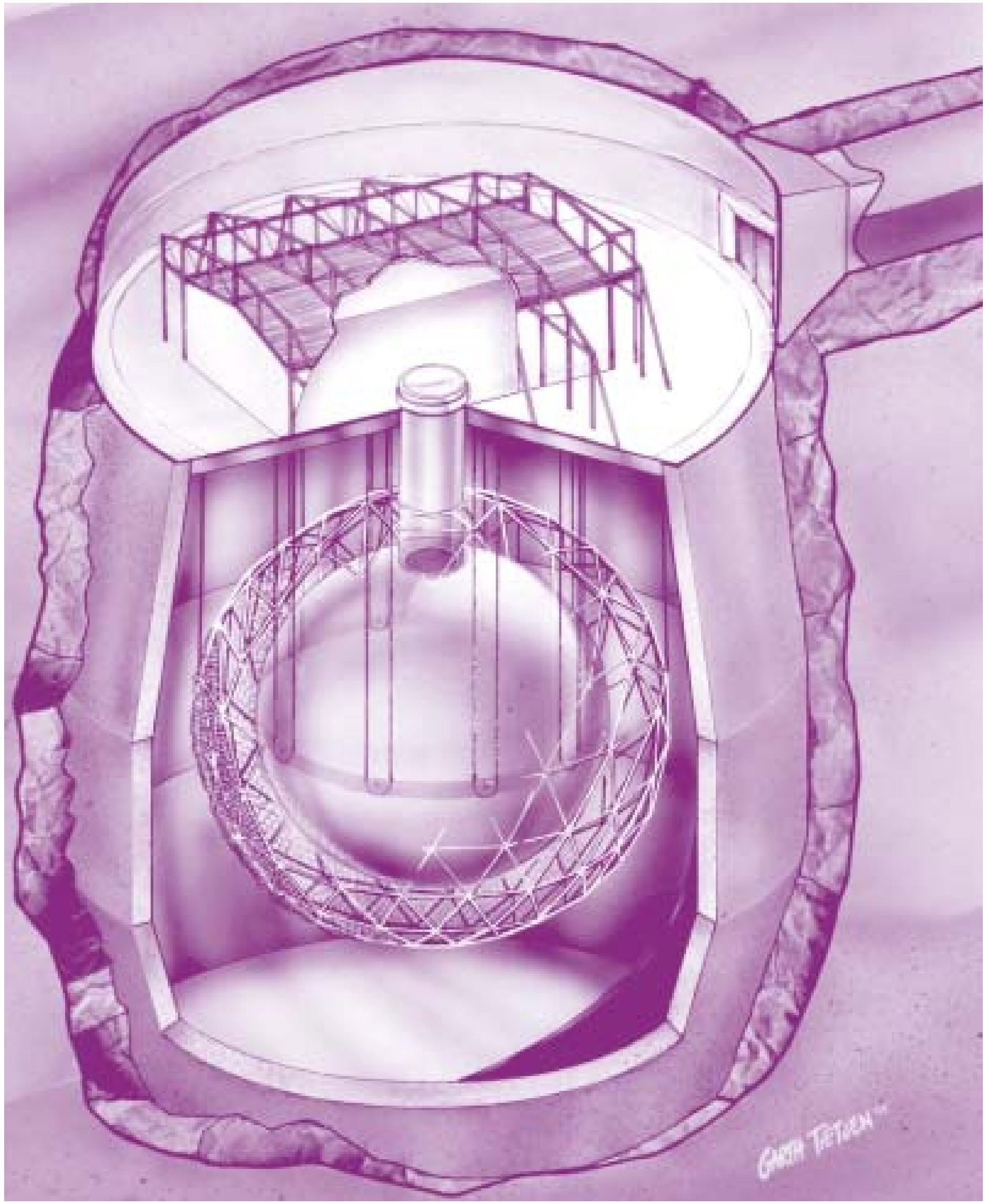
LSND $51 \pm 20 \pm 8$ events

Karmen No signal, lower sensitivity



Δm[2][eV[2]]
10
1
10[-1]
10[-3]
10[-2]
10[-1]
1
sin[2]2Θ
Bugey
LSND 93-95
likelihood regions
99% max - 4.6
90% max - 2.3
Phys. Rev. C (74) 2685
BNL776
KARMEN2
Exclusion (90% CL.)
Sensitivity (90% CL.)

SNO. A new kind of detector



D_2O Cerenkov

1000 ton heavy water inside

7000 ton water

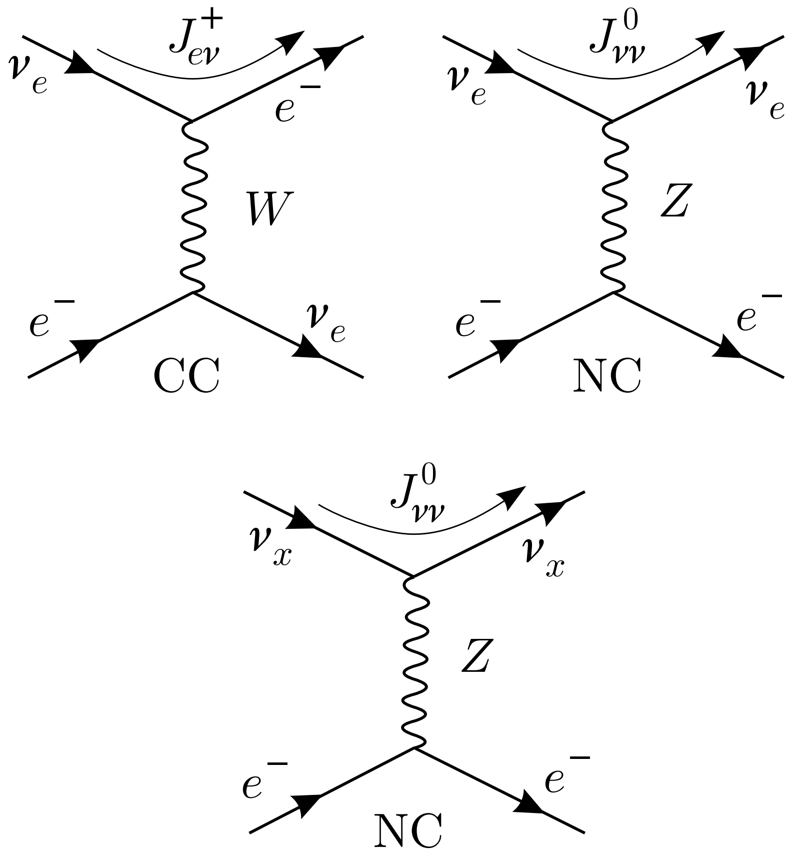
Reactions:

$\nu\, e \to \nu\, e$, El. scatt, ES

$\nu_e\, d \to p\, p\, e^-$, CC

$\nu\, d \to p\, n\, \nu$, NC

$\boldsymbol{\nu}_e$ / $\boldsymbol{\nu}_x$



$\sigma(\nu_e\, e \to \nu_e\, e) \sim 6.5 \times \sigma(\nu_x\, e \to \nu_x\, e)$

$\sigma(\nu_e\, d \to p\, p\, e) \sim 10 \times \sigma(\nu_e\, e \to \nu_e\, e)$

From measurements of CC and ES can find flux of ν_e and ν_x from sun to earth.

$$\phi^{\text{ES}}_{\text{SNO}}(\nu_x) = 2.39 \pm 0.34 \pm 0.15 \times 10^6 \ /\text{cm}^2/\text{s}$$

$$\phi^{\text{CC}}_{\text{SNO}}(\nu_e) = 1.75 \pm 0.07 \pm 0.11 \pm 0.05 \times 10^6 \ /\text{cm}^2/\text{s}$$

$$\Delta\phi = 1.6 \ \sigma$$

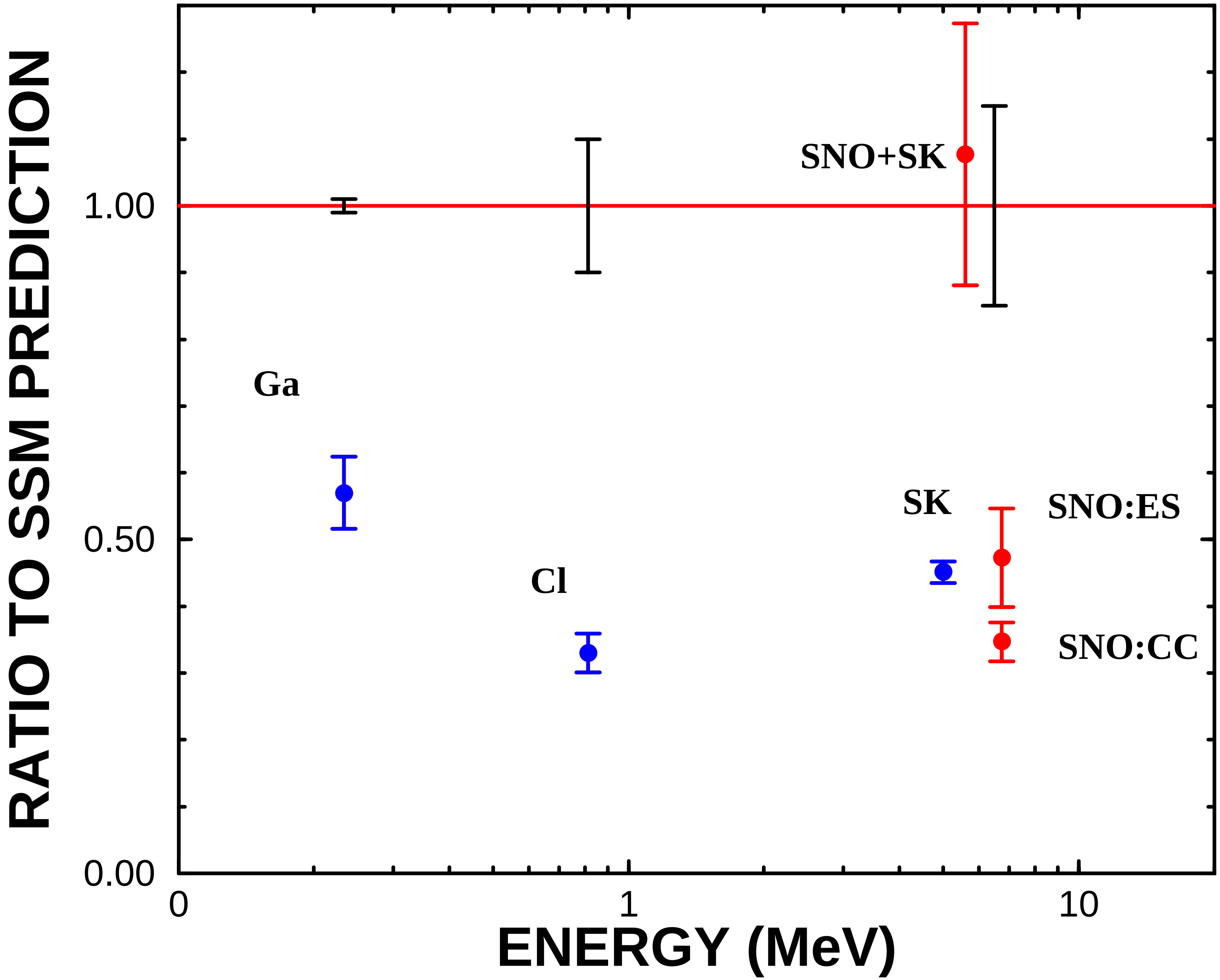
Therefore use SuperK result:

$$\phi^{\text{ES}}_{\text{SK}}(\nu_x) = 2.32 \pm 0.03 \pm 0.1.08 \times 10^6 \ /\text{cm}^2/\text{s}$$

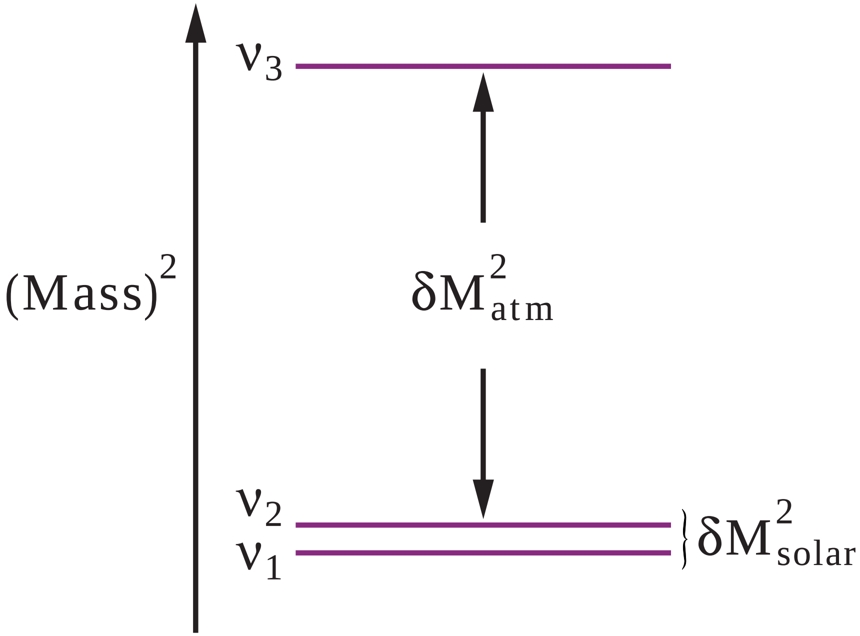
$$\Delta\phi = 3.3 \ \sigma$$

ES data contain all ν's (ν_e favored by 6.5 to 1) while CC data only due to ν_e. The difference is therefore evidence for non-e neutrinos from the sun.

SNO, LP01, summer 2001: found missing solar ν's



Neutrinos have mass



Consistent for solar, atmospheric, reactor data

LSND requires a fourth, sterile neutrino

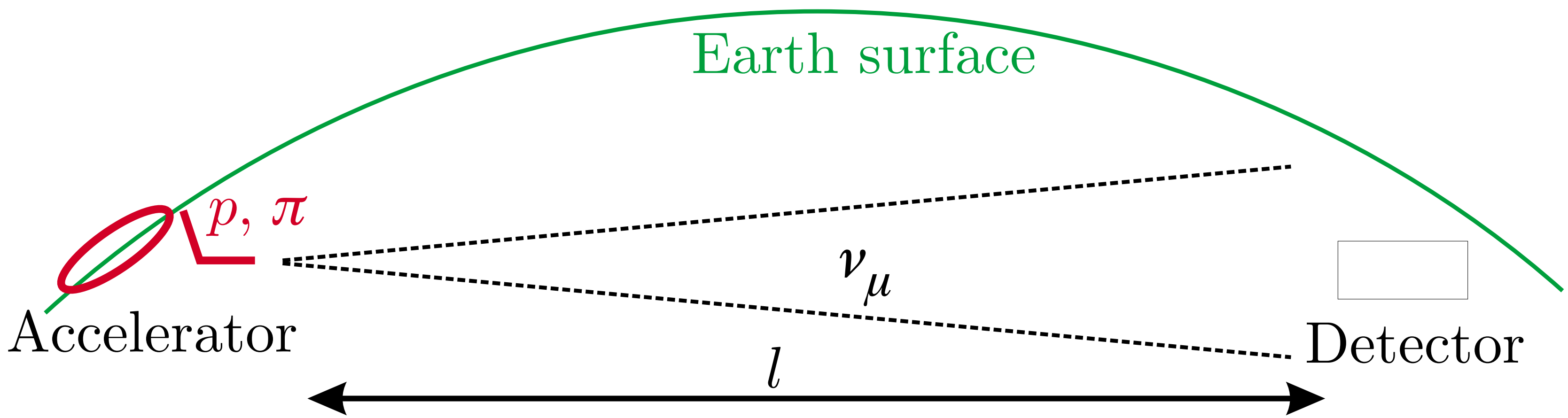
Most of the detector that led to the above results were not originally meant for measuring neutrino masses.

Reactor Experiments	Verify ν existence
Underground Experiments	Sun dynamics
	Proton decay
Accelerator experiments	Verify ν existence†
	Hadron structure
	E-W parameters

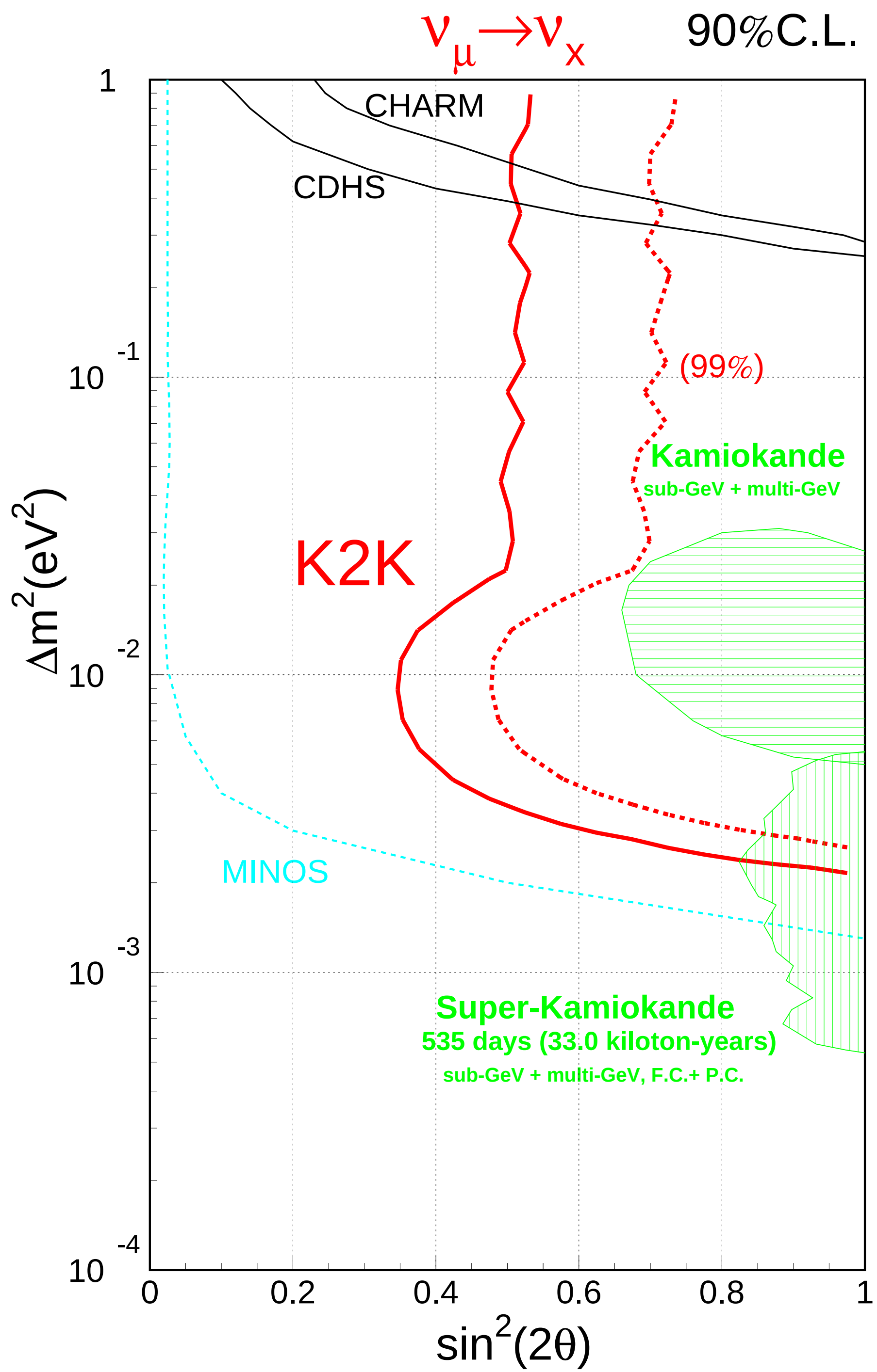
The results were surprising. What is still mostly missing are clear observations of oscillation and appearance of different flavors.

†Donut has reported observation of 4 $\nu_\tau \to \tau$ events.

The future will be dominated by the so-called long baseline experiments. If Δm is small one needs large l.



KEK has been sending ν's to SuperK, 250 km away. for a year and events have been observed.



$\nu_\mu \rightarrow \nu_x$
90%C.L.
CHARM
CDHS
(99%)
Kamiokande
sub-GeV + multi-GeV
K2K
MINOS
Super-Kamiokande
535 days (33.0 kiloton-years)
sub-GeV + multi-GeV, F.C.+ P.C.
$\Delta m^2(eV^2)$
$\sin^2(2\theta)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1

Two new projects are underway. MINOS in the USA, l=730 km to the Soudan Mine site. CERN-Gran Sasso, with l=732. Ultimately one would like to see the appearance of ν_τ.

MiniBooNE will begin data taking this year to confirm or otherwise the LSND claim, which seem to need a fourth neutrino.

More sensitive reactor experiments are on the way.

A real time experiment in Gran Sasso will measure the ^{7}Be flux in real time by $\nu - e$ elastic scattering.

There will also be experiments under water: Nestor, Baikal, Dumand. And also under ice, Amanda and over, RAND.

We will know more, but not very soon.

In the meantime we have to change the SM and possibly understand the origin of fermion masses.

Neutrinos have added a new huge span to the values covered.

Theories are around but which is the right way?