Neutrino Oscillations:
experimental triumphs, remaining puzzles

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What we do know: - Status of neutrino mixing

How did we learn it:
- Solar neutrino
- Atmospheric neutrino
- Reactor neutrinos
- K2K

Addressing remaining puzzles in neutrino mixing:
- LNSD/miniBoone → see Sam Zeller
- θ_{13} experiments
- Hierarchy/CP violation: ν-fact/β-beams
- Absolute m, Majorana/Dirac ν
  → see Steve Elliott

Impossible to be complete: I will just make an arbitrary -and hopefully interesting- selection

From LEP and SLC we know that there are 2.981±0.008 active, light ν flavors

We also know that 3 ν flavors were active in Big Bang Nucleosynthesis

If $m_\nu \neq 0$ then the 3 weak-interactions eigenstates $|\nu_j\rangle$ can be represented as superposition of mass eigenstates

$$|\nu_j\rangle = \sum_j U_{jl} |\nu_l\rangle$$

Neutrinos are produced and detected by weak interaction *but propagate in vacuum as mass eigenstates…*

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

→ Neutrino oscillations

A possible representation of the *Pontecorvo-Maki-Nakagawa-Sakata* matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

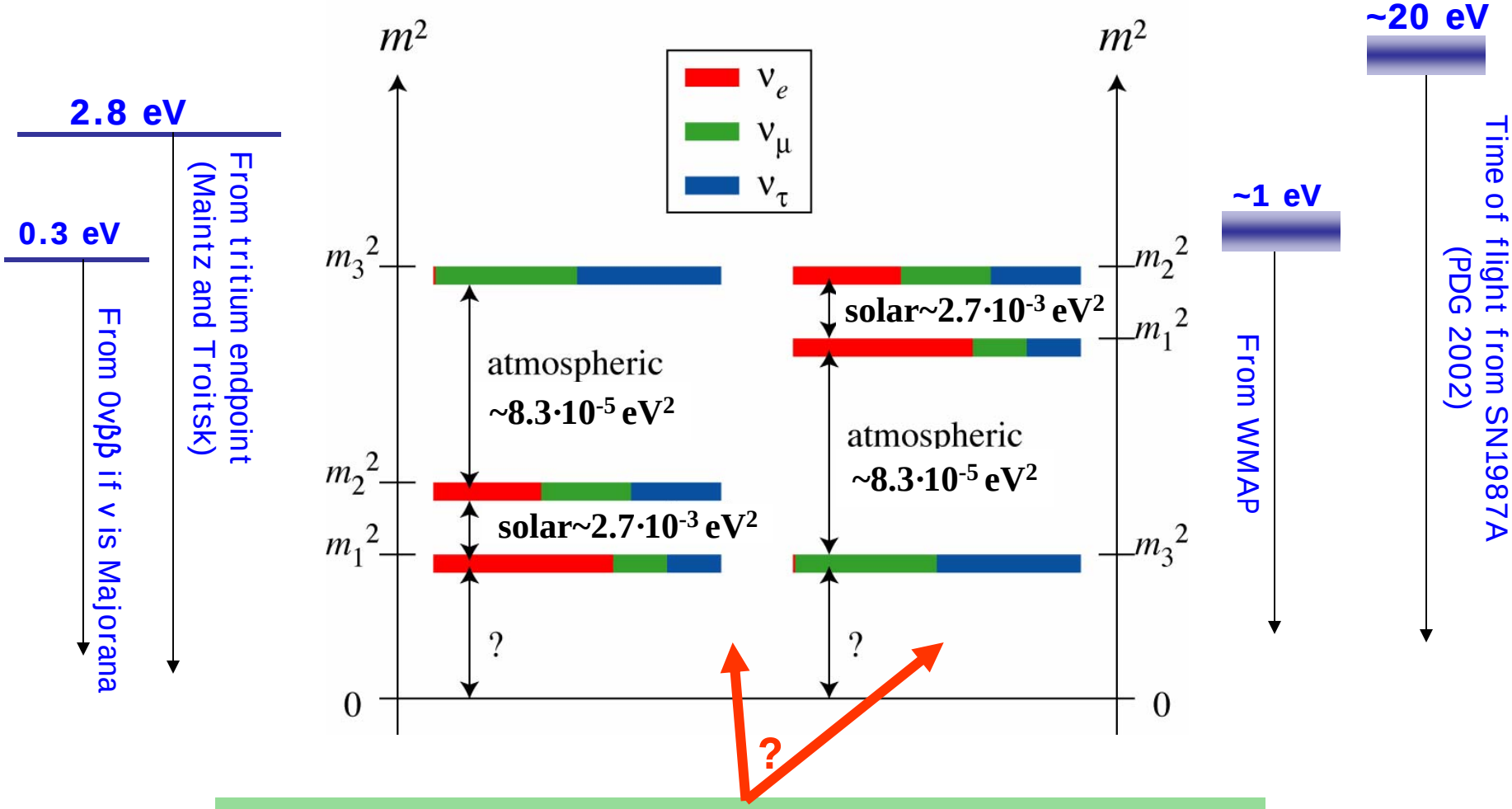
information on CP is here

Neutrino factory ?

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \bullet \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\alpha/2+i\beta} \end{pmatrix}$$

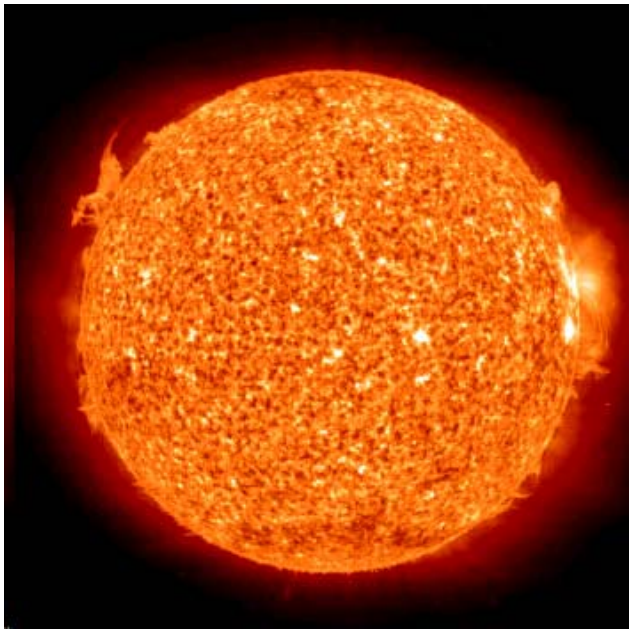
Solar ν KamLAND Future solar ν exp.	Chooz/Palo Verde Off axis Future reactors	Atmospheric ν K2K Minos et al	Neutrinoless double beta decay
θ_{12}~32°	θ_{13}<7° @ 90%CL	θ_{23}~45°	

Oscillations give the proof that neutrino masses are non-zero, but we still do not know the absolute mass scale and the hierarchy



Sign of Δm^2_{13} *(Future accelerator experiments)*

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" $2.4 * 10^{-5}$

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

"^{7}Be" 99.89%

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

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

0.11%

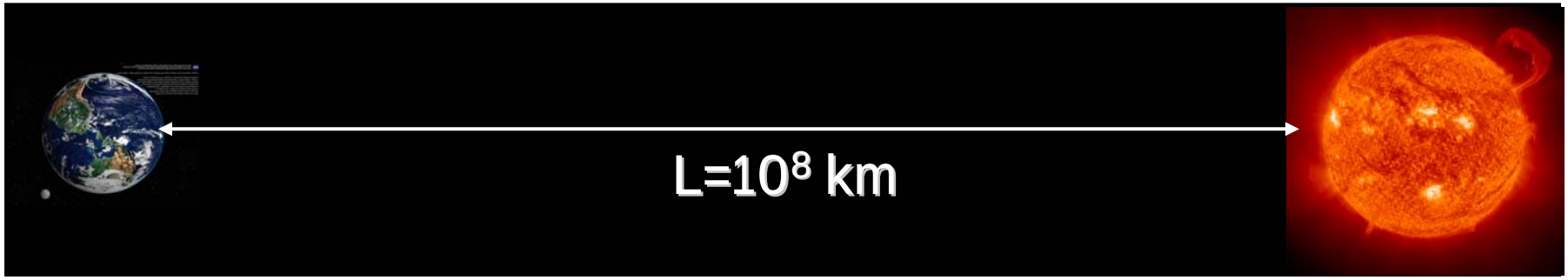
$${}^7Be + p \rightarrow {}^8B + \gamma + 0.14 MeV$$

"^{8}B" 0.11%

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

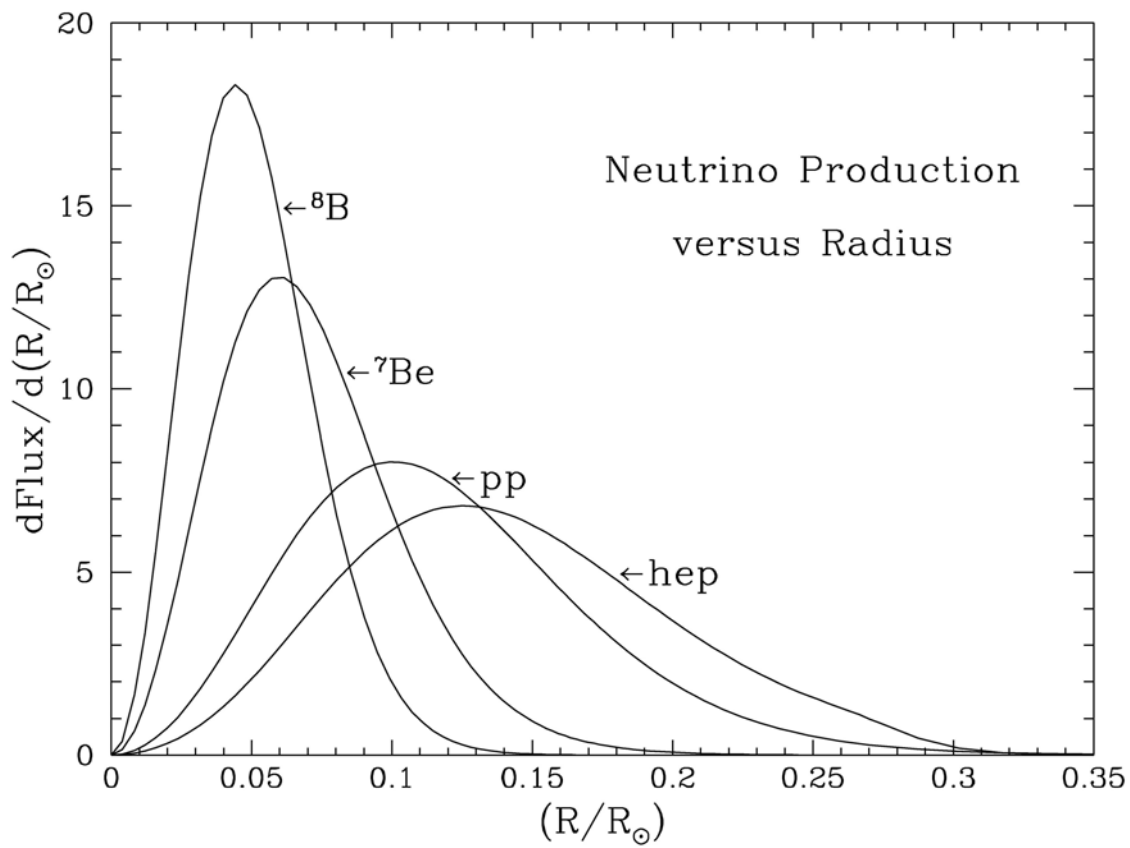
$${}^8Be \rightarrow \alpha + \alpha + 3 MeV$$

The detectors are located far away from the Sun



But neutrinos are produced deep inside the Sun, where most the fusion reactions take place

➔ Matter effects play an essential role



Several experiments detecting solar neutrinos

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

Homestake mine (US) Taking data from 1967-2002 (!)
The "father" of all solar neutrino experiments

Gallium: $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$

SAGE (Baksan, Russia), Gallex and GNO (Gran Sasso, Italy)
Lowest threshold
Calibrated with a neutrino source

Radiochemical,
no real-time information

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

Kamiokande and SuperKamiokande (Japan), SNO (Sudbury, Canada)

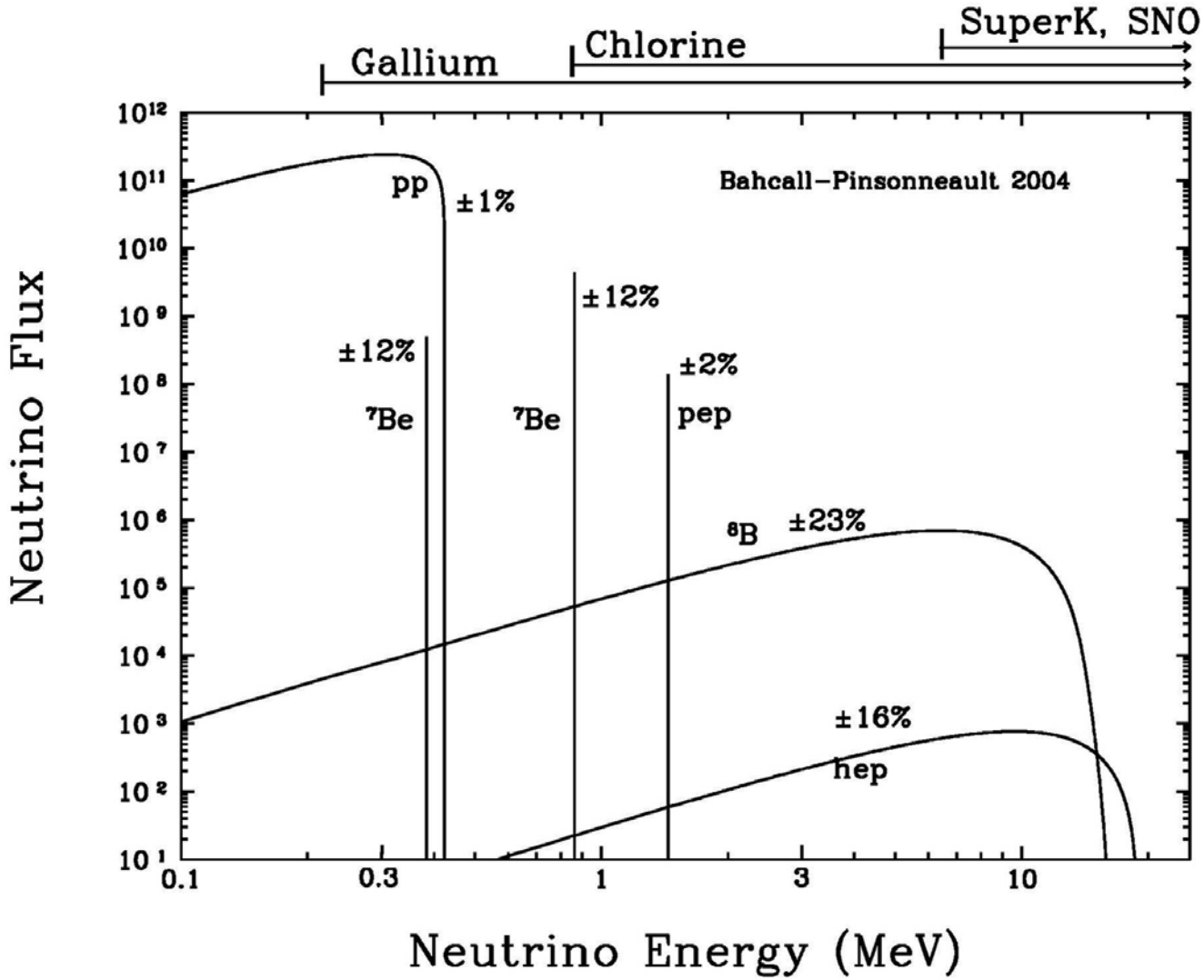
Largest statistics

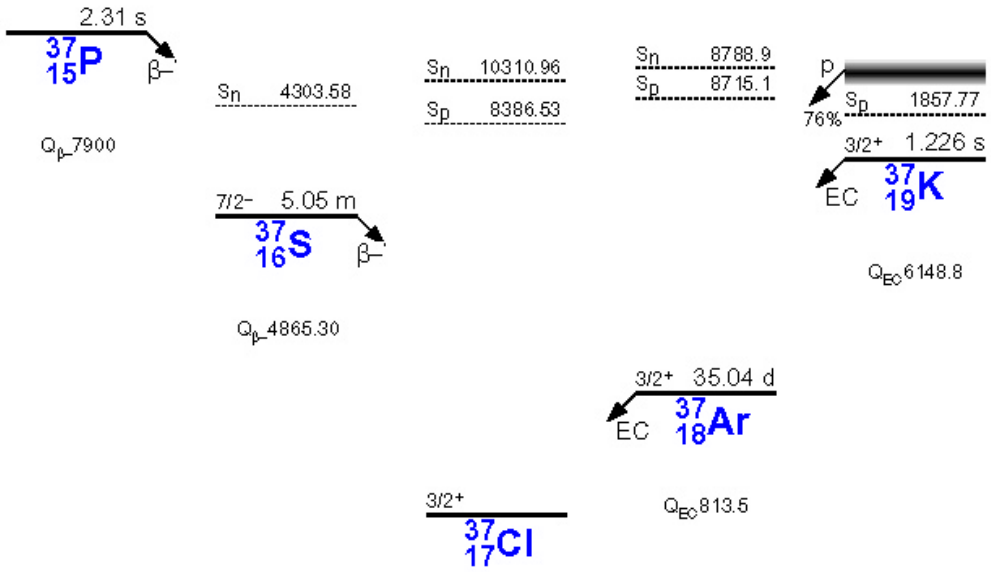
See D.Casper's talk

Cerenkov: Dν scattering

SNO (Sudbury, Canada)
For the first time measure ν_e and ν_X separately
See D.Waller's talk

Neutrino energy spectrum includes lines and continua

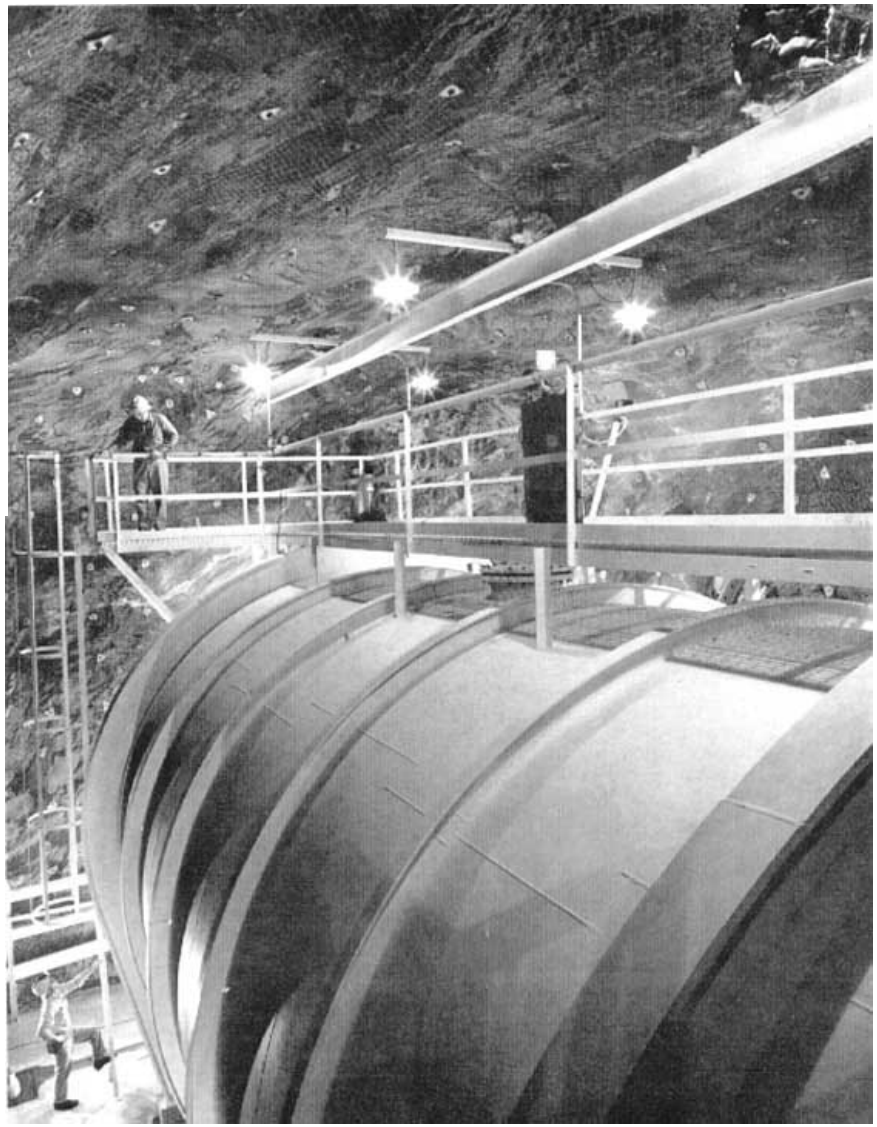




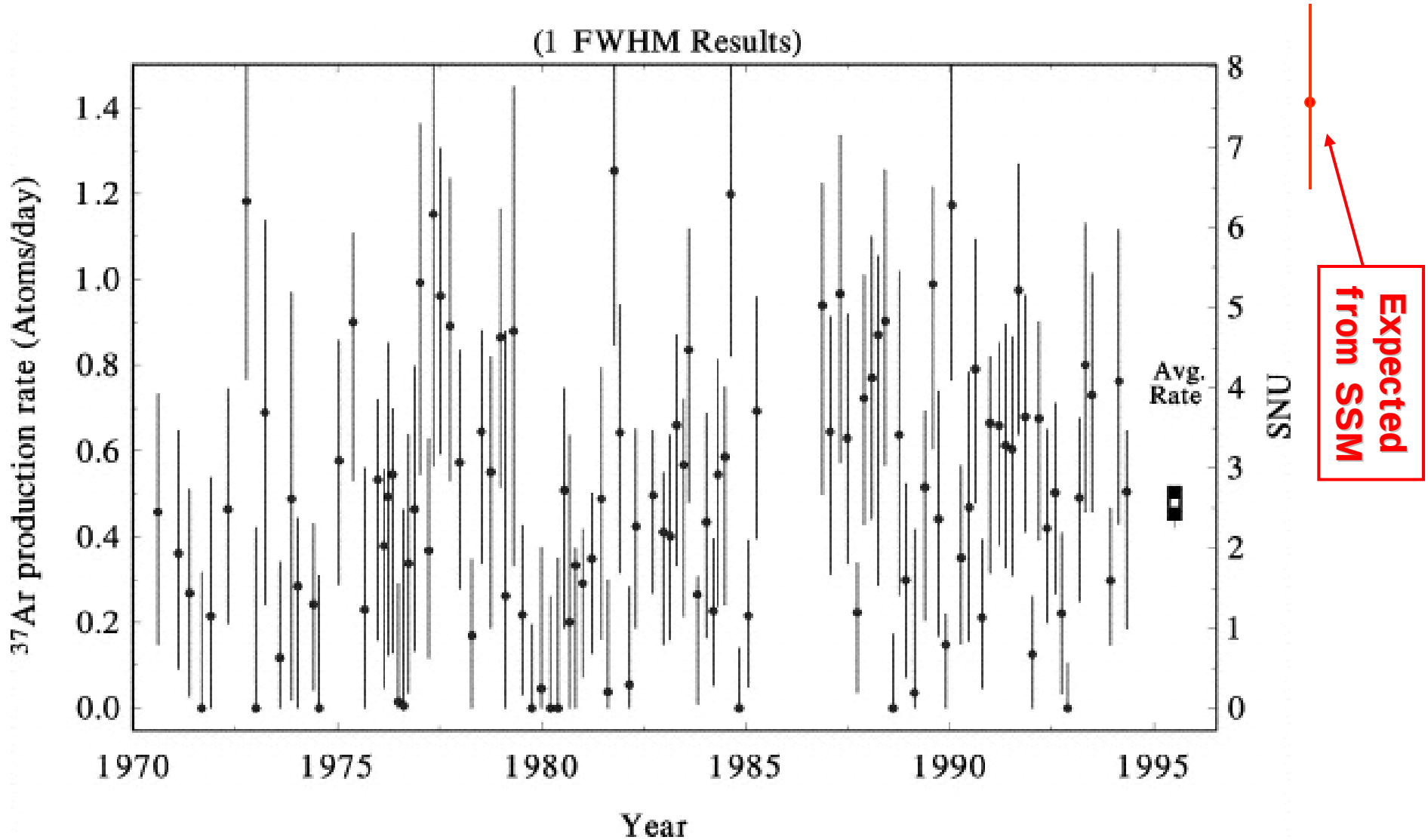
Homestake Mine, Lead SD
1400 m underground

615 tons of perchloroethilene (C_2Cl_4)

$2.2*10^{30}$ atoms of ^{37}Cl
^{36}Ar or ^{38}Ar added to the fluid as carrier gas

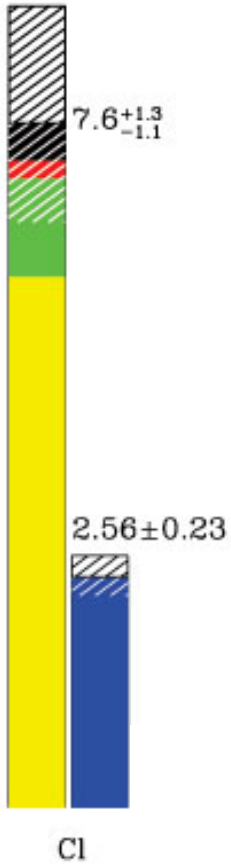


30 years of solar neutrinos with the Chlorine detector



Total Rates: Standard Model vs. Experiment

1 SNU = 1 ν interaction/sec per 10^{36} target atoms



ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/10 19 72

Prof. J.N.Bahcall
The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

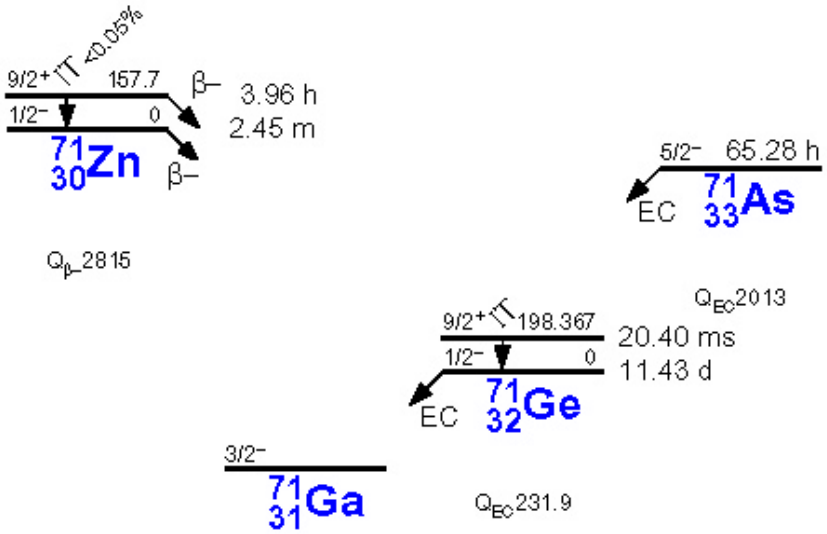
Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. 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 that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B.Pontecorvo



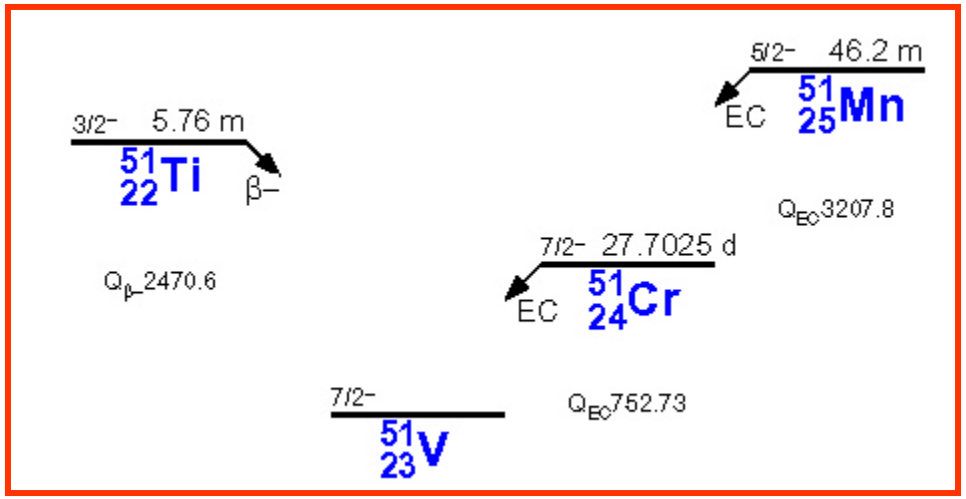
$Q_{EC}(4800)$

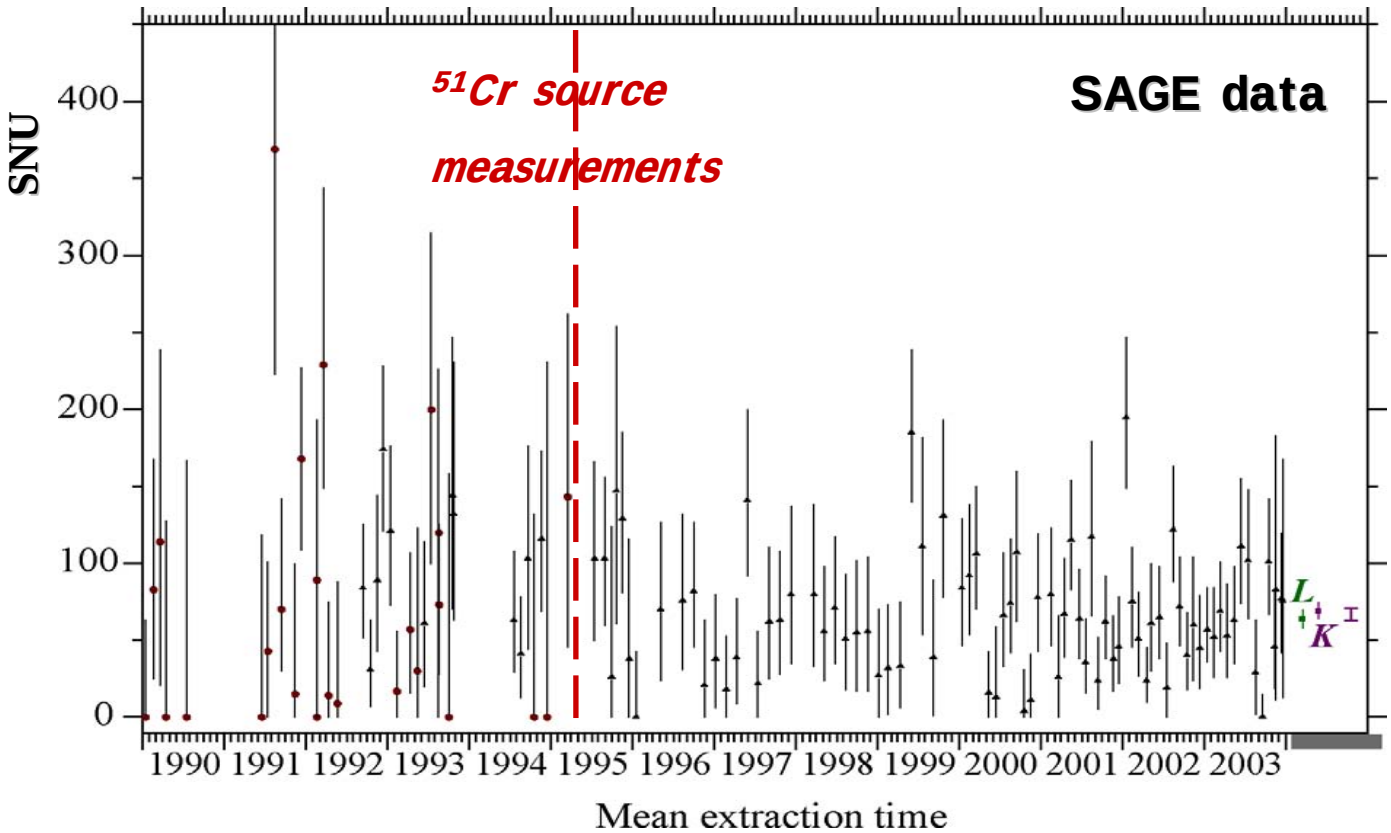
^{71}Ga has lower threshold: to date, only technique sensitive to pp neutrinos !

In Gallex/GNO 30.3 ton of Ga in aqueous solution of $GaCl_4$. $^{71}GeCl_4$ is volatile and is purged/counted

28 - 50 ton of metallic Ga kept liquid (>29.8 C) Extraction by HCl etch and GeCl4 and Ar purge

Both Ga experiments have been calibrated with a ^{51}Cr source of about 1 MCi

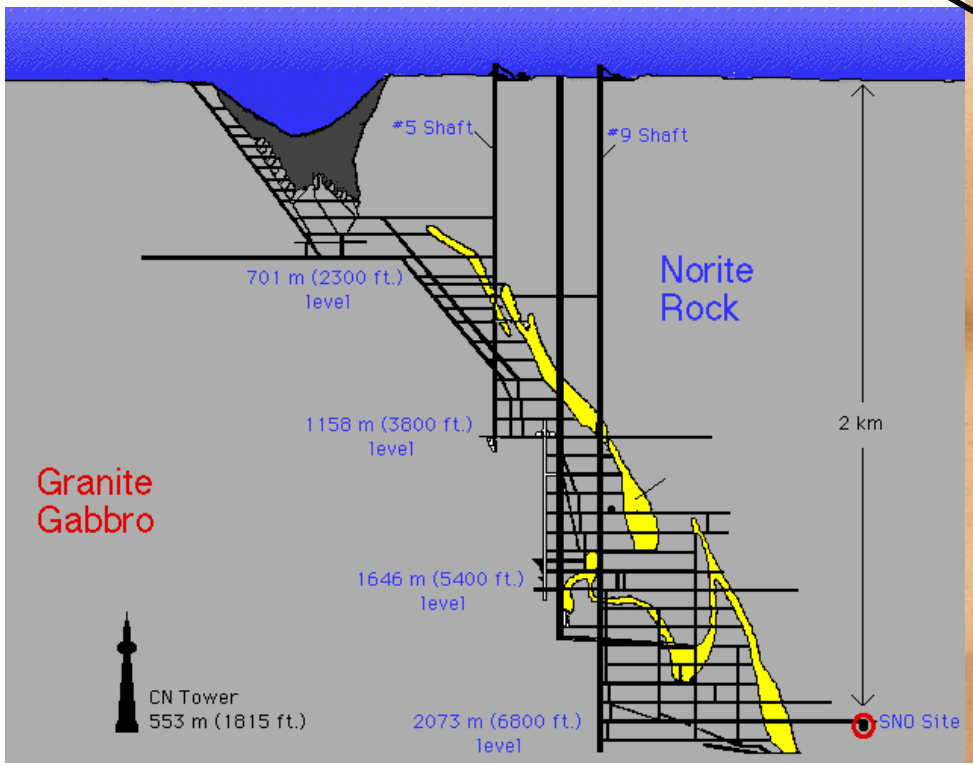


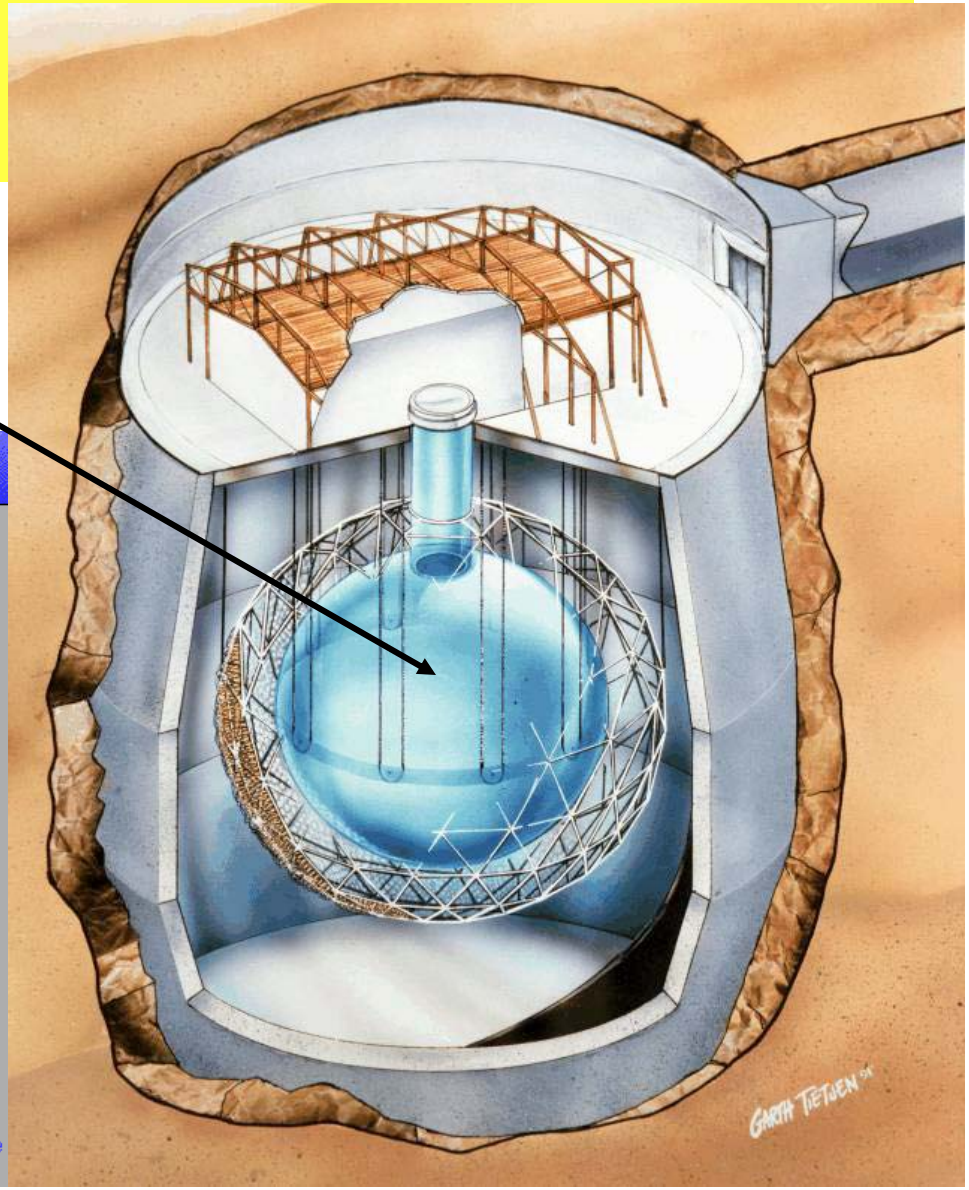


Expected from SSM

In order to better understand the situation it would be nice to also measure the *total* number of neutrinos from the Sun, all flavors together

The SNO detector:
1 kton of heavy water



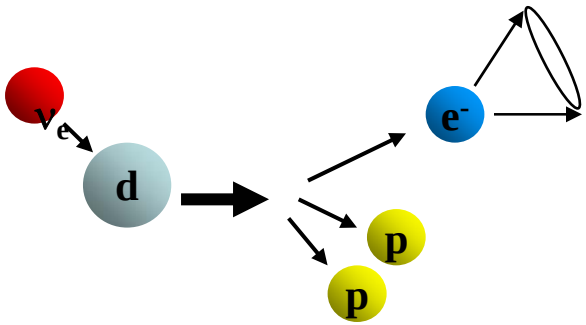


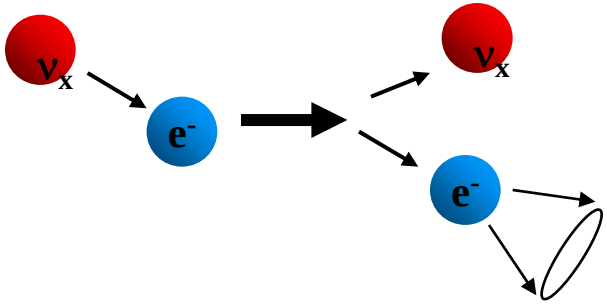
Neutrino interactions in D_2O

Charged Current (CC):

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

Electron neutrinos only





Elastic Scattering (ES):

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

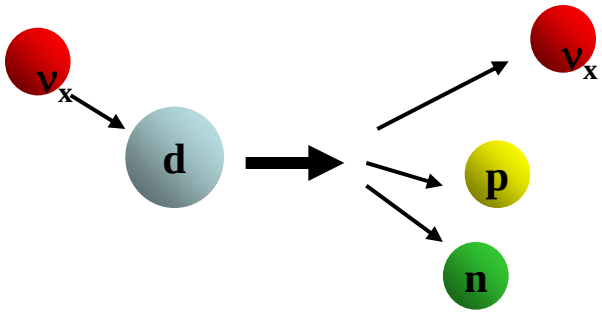
$0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

this is all SuperK sees

Neutral Current (NC):

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

Same for all neutrino flavors !

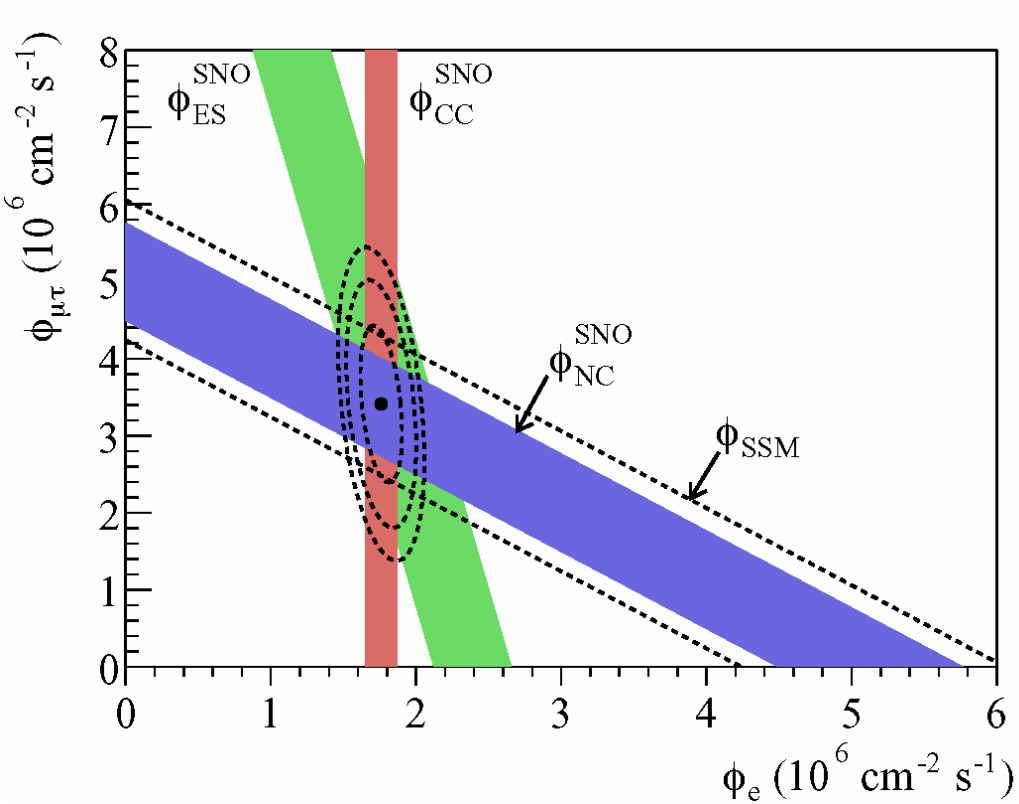


Remarkably the SNO measurement gives $\Phi_{NC} > \Phi_{CC}$

$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}),$$
$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(\text{stat})^{+0.12}_{-0.12}(\text{syst}),$$
$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}).$$

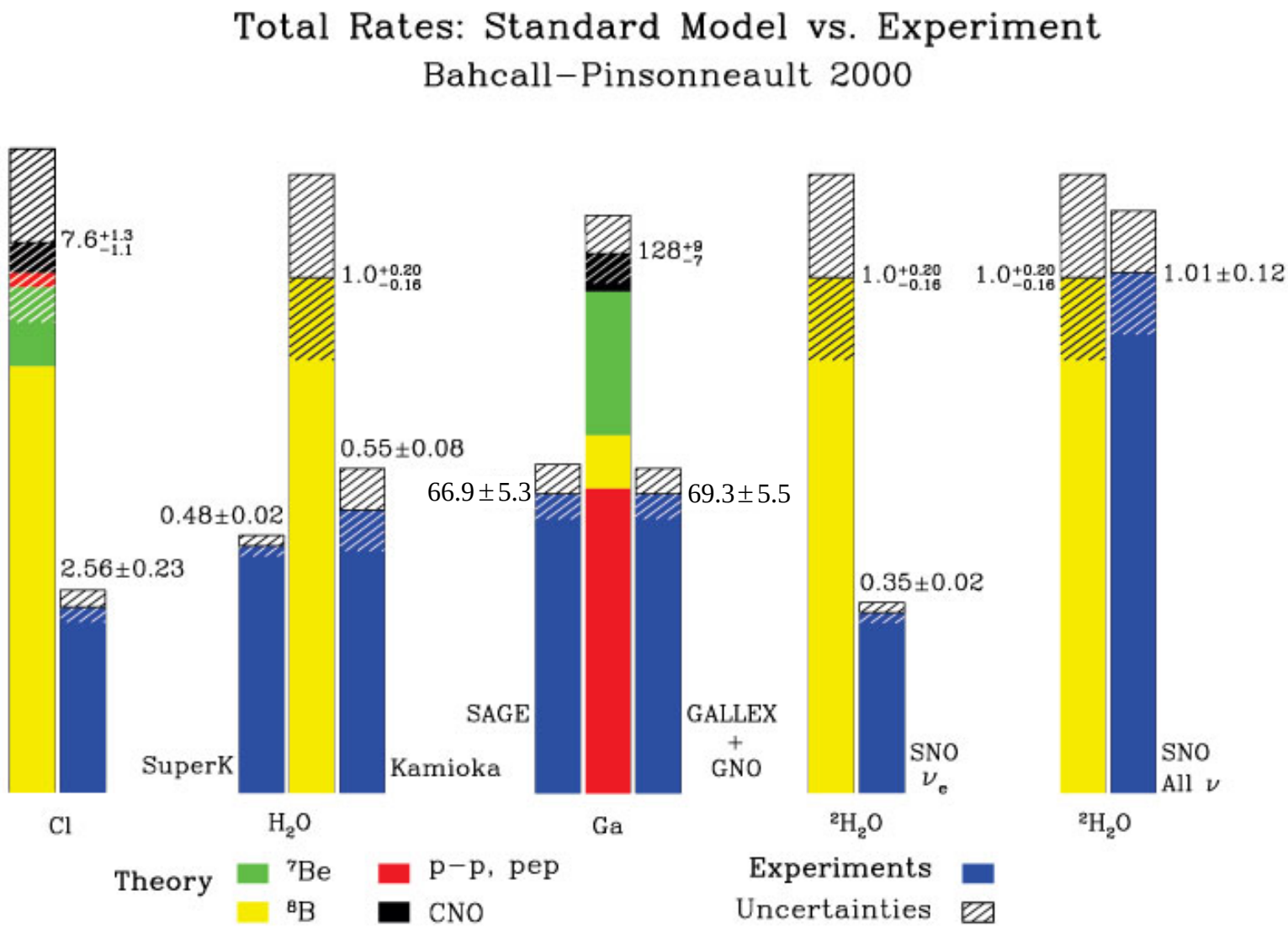
Phys. Rev.Lett. 89 (2002) 011301

For up-to-date results see Waller's talk

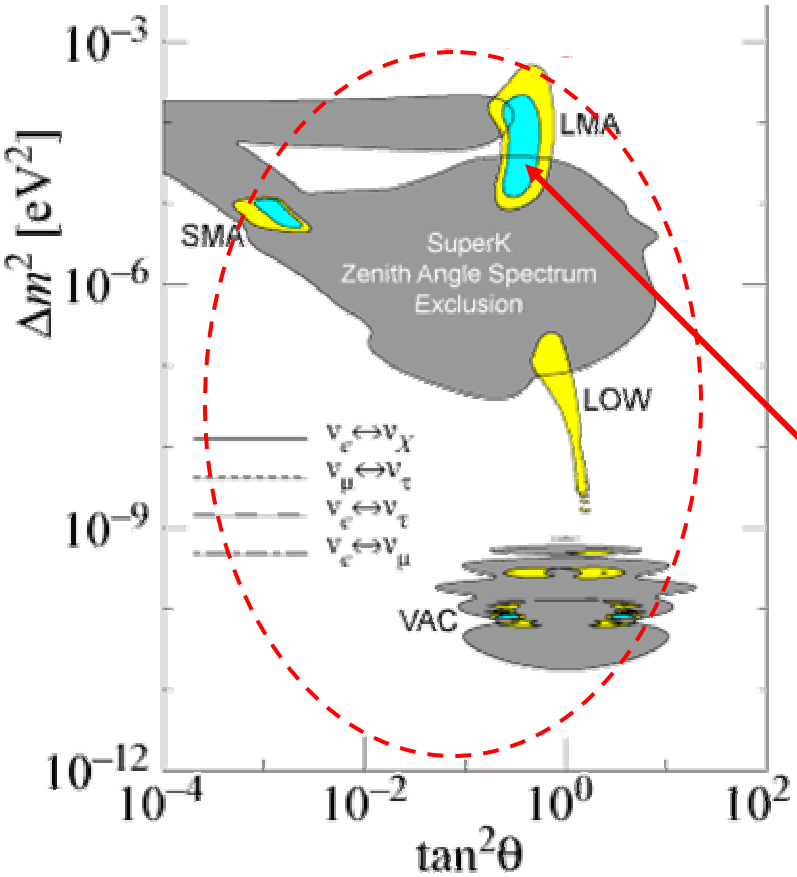


So ν_e are missing, but the total number of neutrinos is right !

1 SNU = 1 ν interaction/sec per 10^{36} target atoms



Clearly all this smells of flavor mixing…



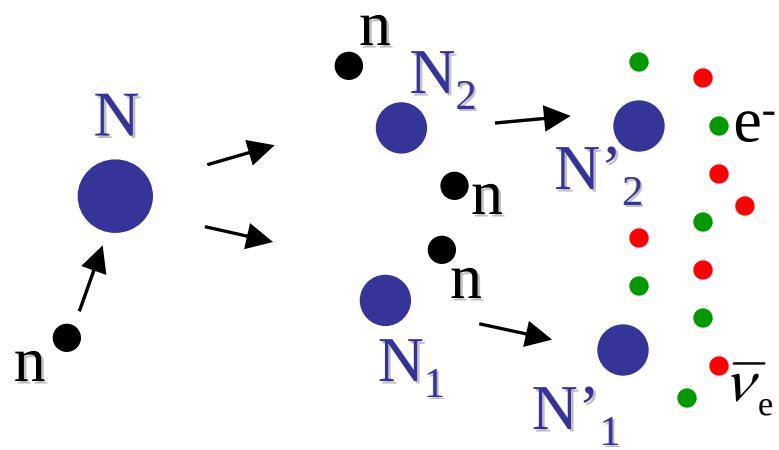
Global fit to all solar neutrino exps eliminates most of the solutions except for the MSW-LMA solution

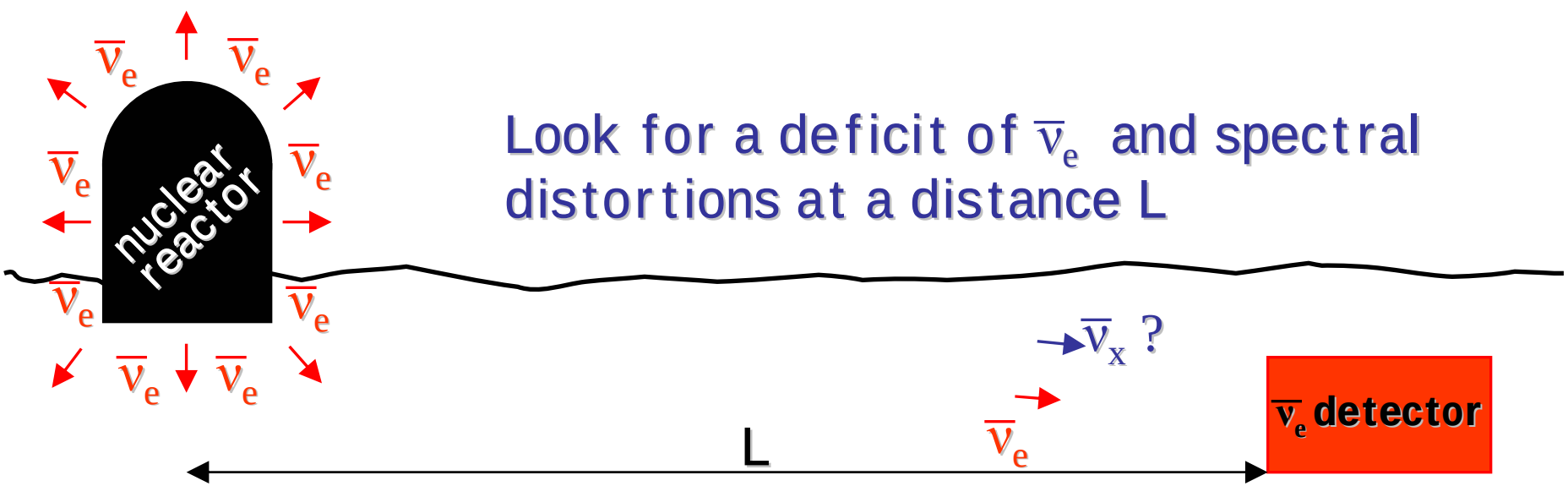
(The solar neutrino anomaly is a sort of neutrino-birefringence of dense matter occurring because neutrinos have finite masses -- see Boris Kayser' talk)

All of this is very interesting…

…but wouldn't it be great if we could reproduce it with artificial means ?

Nuclear reactors are very intense sources of $\bar{\nu}_e$ deriving from beta-decay of the neutron-rich fission fragments





Look for a deficit of $\bar{\nu}_e$ and spectral distortions at a distance L

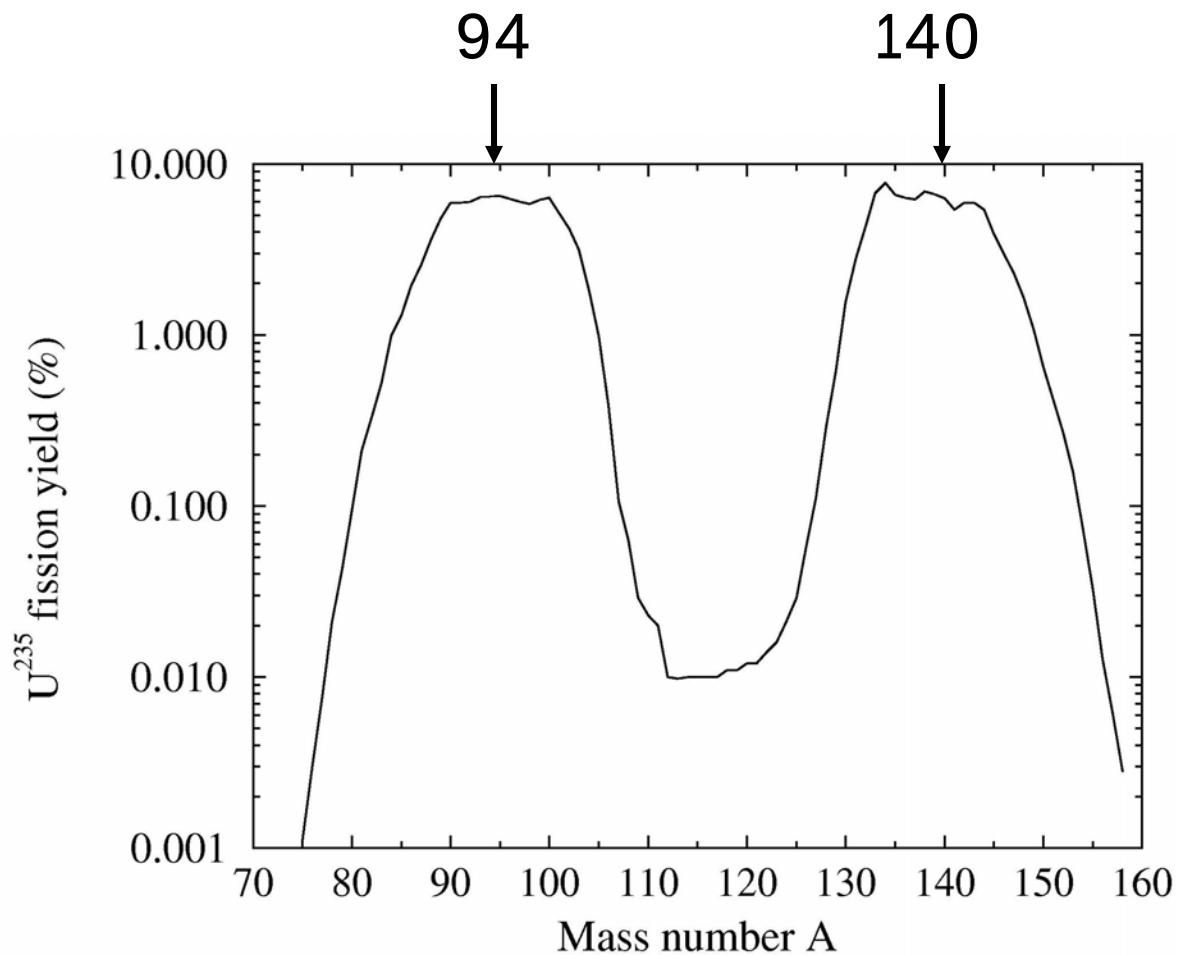
Example: ^{235}U fission

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

stable nuclei with A most likely from fission

$^{94}_{40}Zr$ $^{140}_{58}Ce$

together these have 98 protons and 136 neutrons



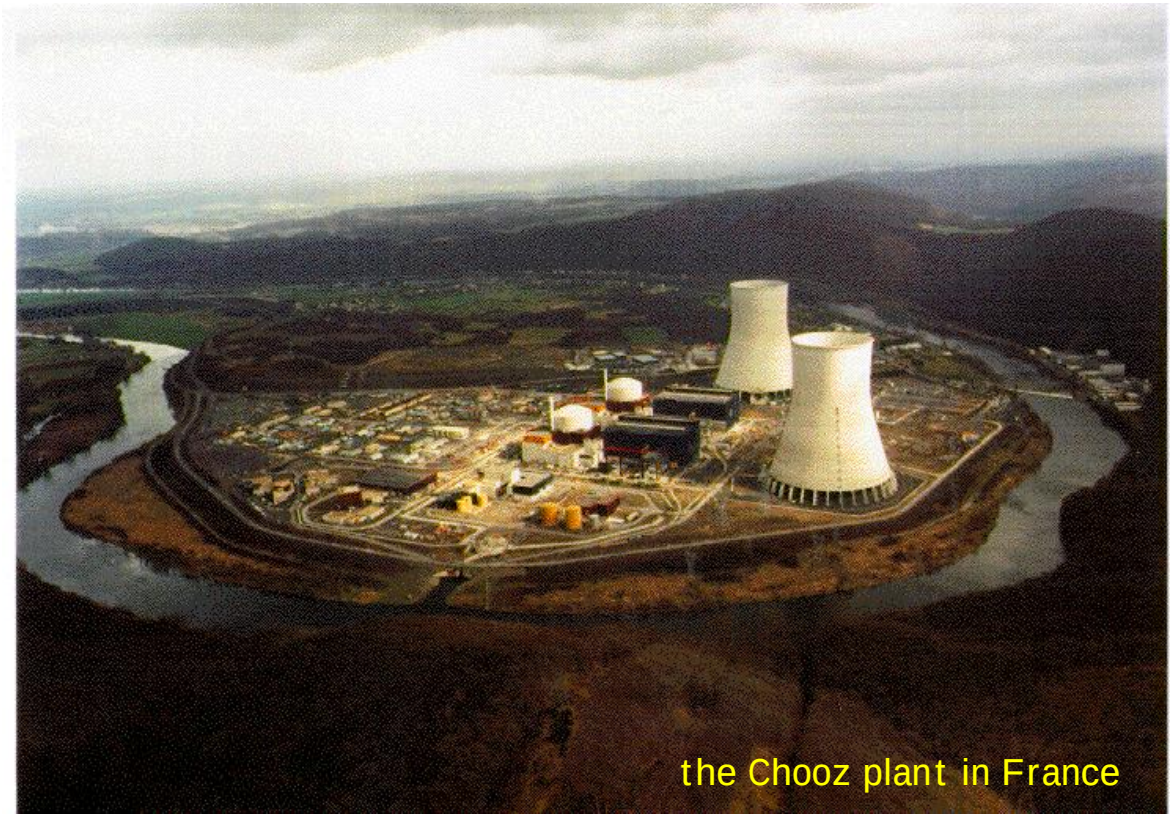
so, on average 6 n have to decay to 6 p to reach stable matter

Power/commercial reactors are generally used since only requirement is to have large power

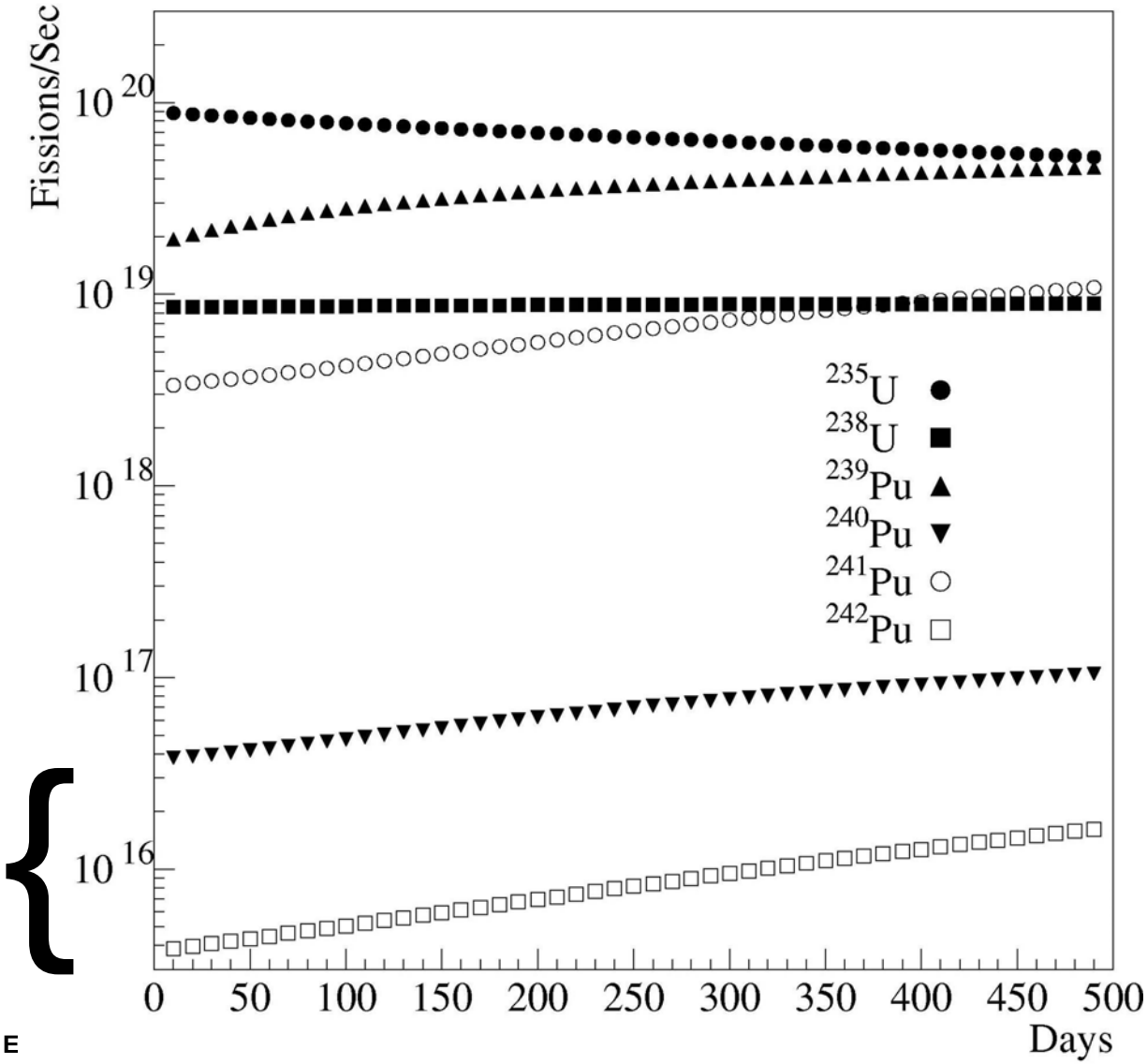
$$200 MeV / fission$$

$$6\bar{\nu}_e / fission$$

A typical large power reactor produces 3 $GW_{thermal}$ and $6 \cdot 10^{20}$ antineutrinos/s


the Chooz plant in France

>99.9% of $\bar{\nu}$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



contribution $<10^{-3}$ not taken into account for neutrino flux calculations

A specific signature is provided by the inverse-β reaction

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

$$\tau \approx 200\ \mu s$$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$

Event tagging by coincidence in time, space and energy of the neutron capture

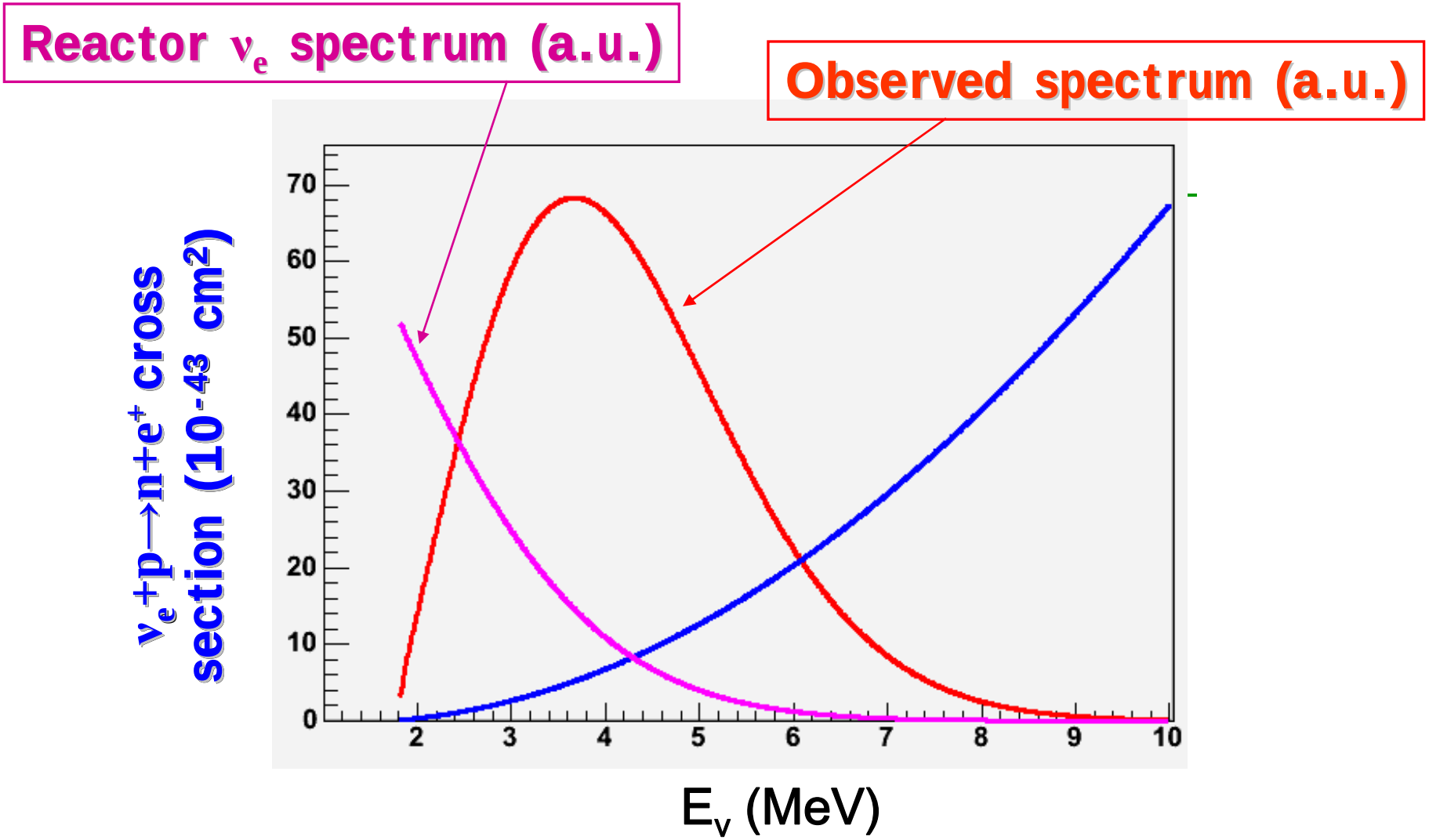
E_ν measurement

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$

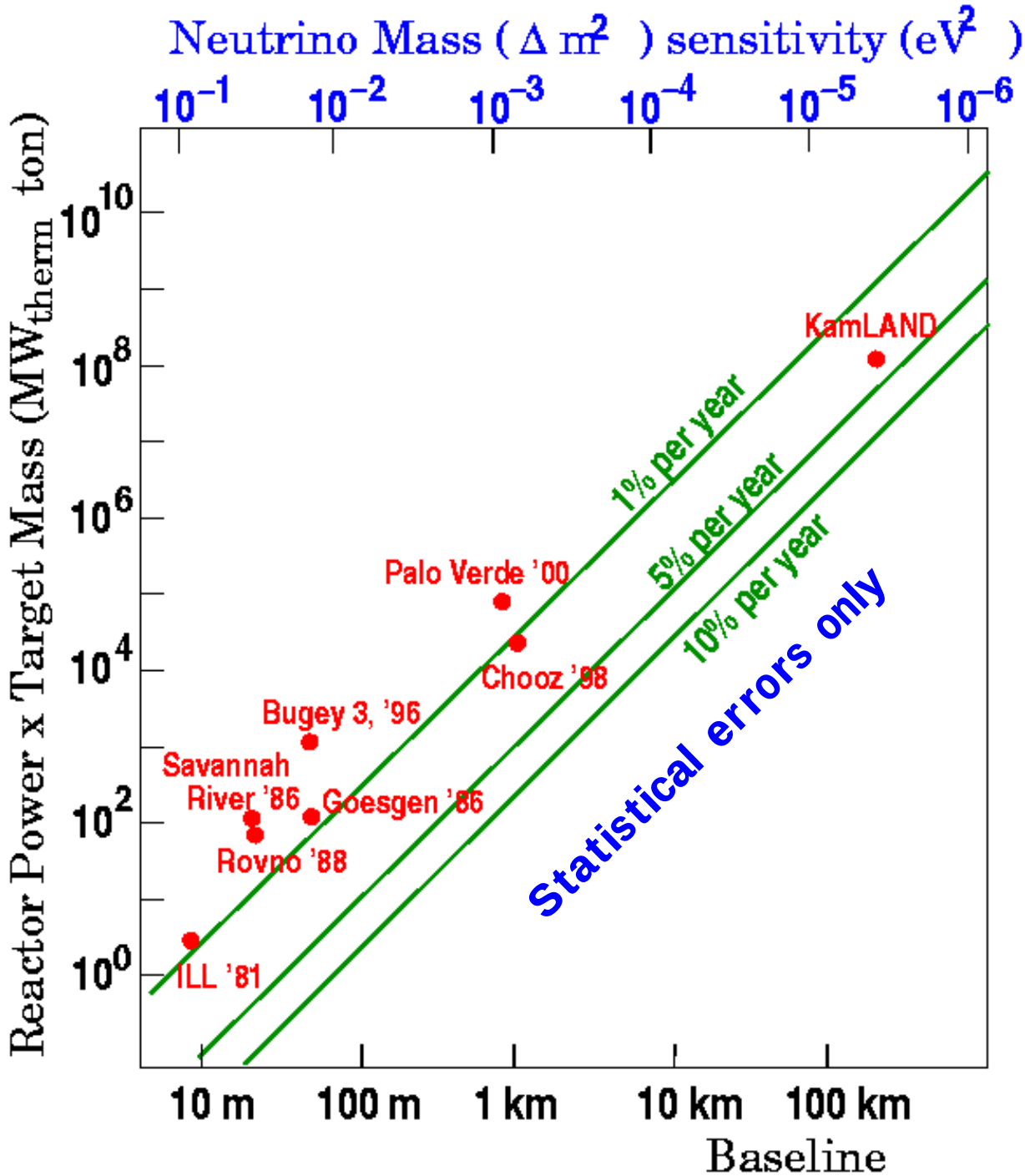
Threshold: $E_{\bar{\nu}} > 1.8 MeV$

→ **only ~1.5 antineutrinos/fission can be detected**

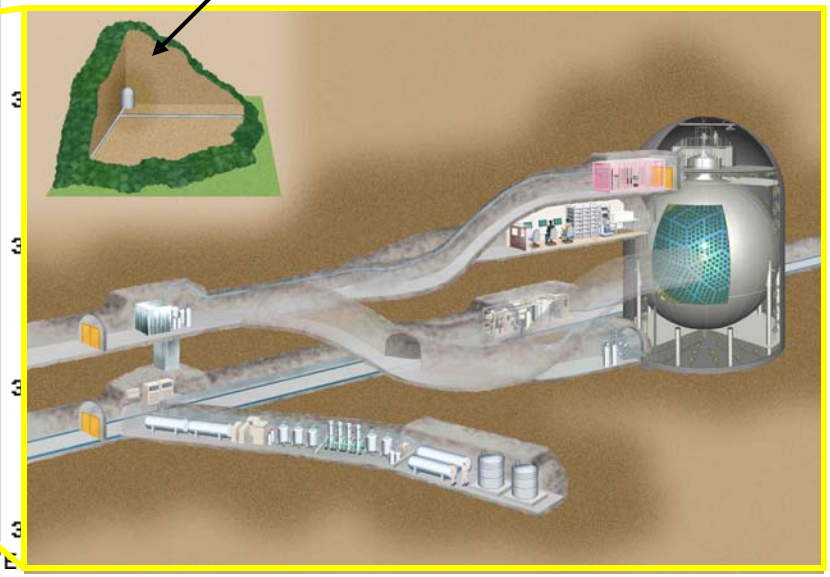
The $\bar{\nu}_e$ energy spectrum



An experiment relevant for solar ν will have ~100 km baseline and hence will need a huge detector and a "huge source"



~1 km high
Mt Ikenoyama



Many reactors contribute to the antineutrino flux at KamLAND

	Site	Dist (km)	Cores (#)	P_{therm} (GW)	Flux ($cm^{-2}\ s^{-1}$)	Rate noosc* ($yr^{-1}\ kt^{-1}$)
Japan	Kashiwazaki	160	7	24.3	$4.1 \cdot 10^5$	254.0
	Ohi	179	4	13.7	$1.9 \cdot 10^5$	114.3
	Takahama	191	4	10.2	$1.2 \cdot 10^5$	74.3
	Tsuruga	138	2	4.5	$1.0 \cdot 10^5$	62.5
	Hamaoka	214	4	10.6	$1.0 \cdot 10^5$	62.0
	Mihama	146	3	4.9	$1.0 \cdot 10^5$	62.0
	Sika	88	1	1.6	$9.0 \cdot 10^4$	55.2
	Fukushima1	349	6	14.2	$5.1 \cdot 10^4$	31.1
	Fukushima2	345	4	13.2	$4.8 \cdot 10^4$	29.5
	Tokai2	295	1	3.3	$1.6 \cdot 10^4$	10.1
	Onagawa	431	3	6.5	$1.5 \cdot 10^4$	9.3
	Simane	401	2	3.8	$1.0 \cdot 10^4$	6.3
	Ikata	561	3	6.0	$8.3 \cdot 10^3$	5.1
	Genkai	755	4	10.1	$7.8 \cdot 10^3$	4.8
	Sendai	830	2	5.3	$3.4 \cdot 10^3$	2.1
	Tomari	783	2	3.3	$2.3 \cdot 10^3$	1.4
South Korea	Ulchin	712	4	11.5	$9.9 \cdot 10^3$	6.1
	Yonggwang	986	6	17.4	$7.8 \cdot 10^3$	4.8
	Kori	735	4	9.2	$7.5 \cdot 10^3$	4.6
	Wolsong	709	4	8.2	$7.1 \cdot 10^3$	4.3
Total Nominal		**-**	**70**	**181.7**	**$1.3 \cdot 10^6$**	**803.8**

*E_ν>3.4MeV (E_{prompt}>2.6MeV)

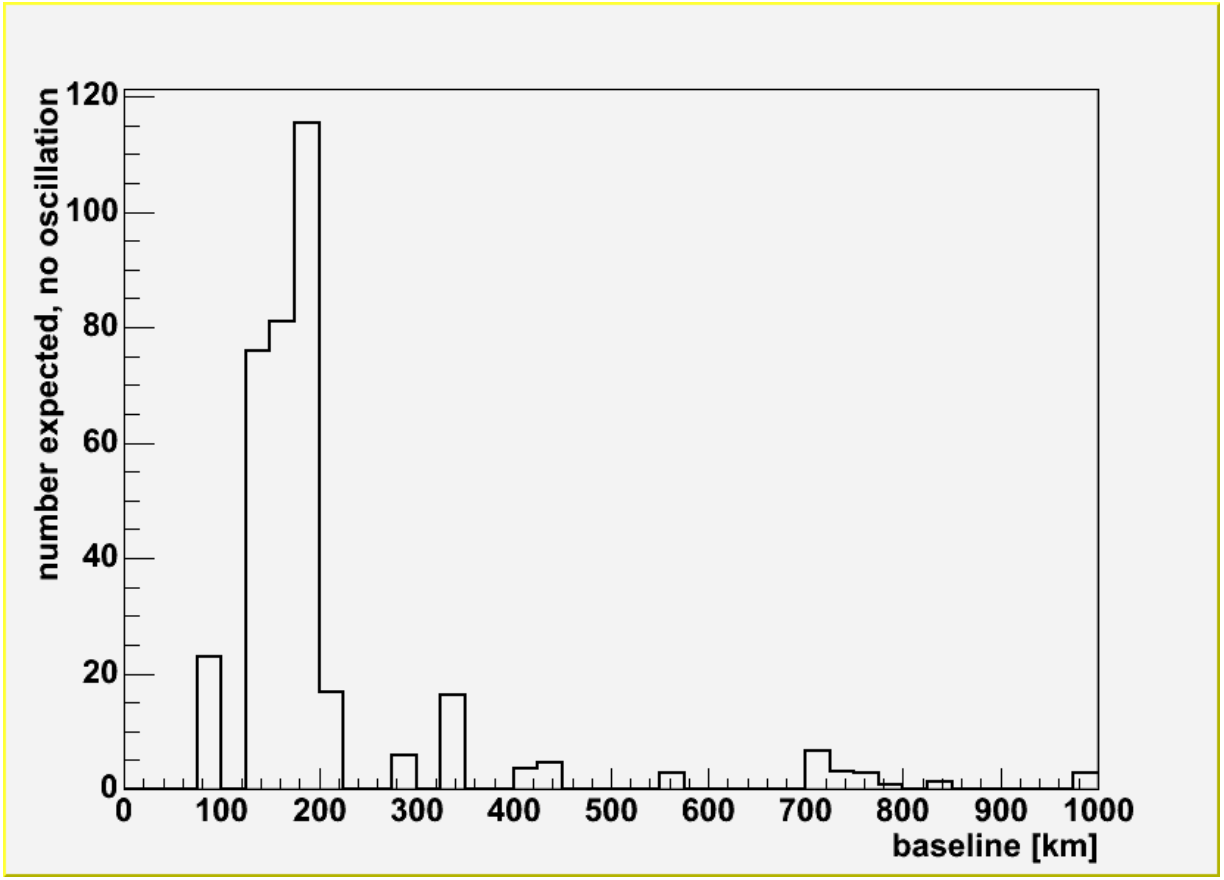
Detailed power and fuel Composition calculation used

From electrical power Japanese average fuel used

The total electric power produced "as a by-product" of the νs is:

- **~60 GW or…**
- **~4% of the world's manmade power or…**
- **~20% of the world's nuclear power**

A limited range of baselines contribute to the flux of reactor antineutrinos at Kamioka



Over the data period Reported here

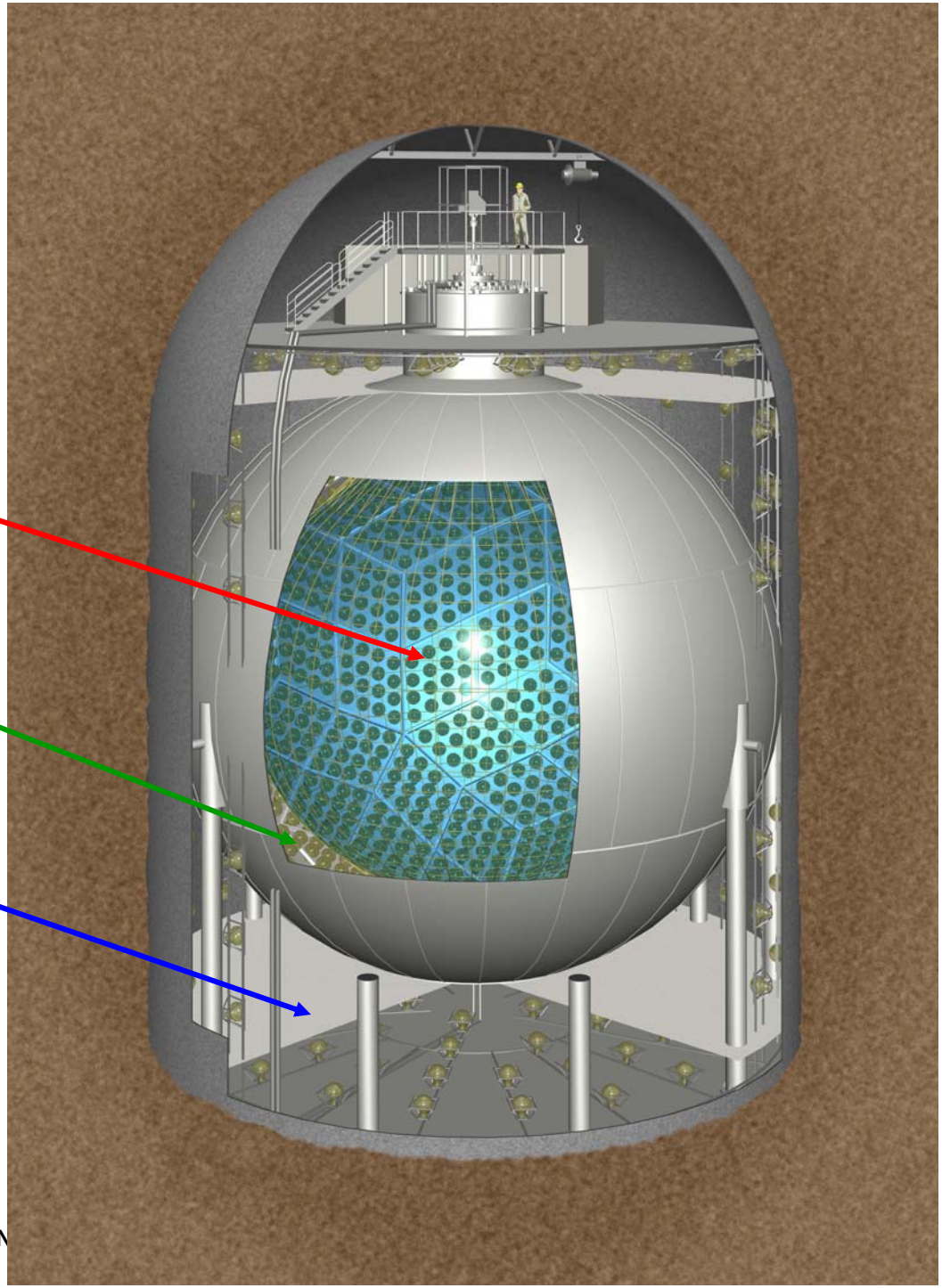
Korean reactors 3.4±0.3%

Rest of the world +JP research reactors 1.1±0.5%

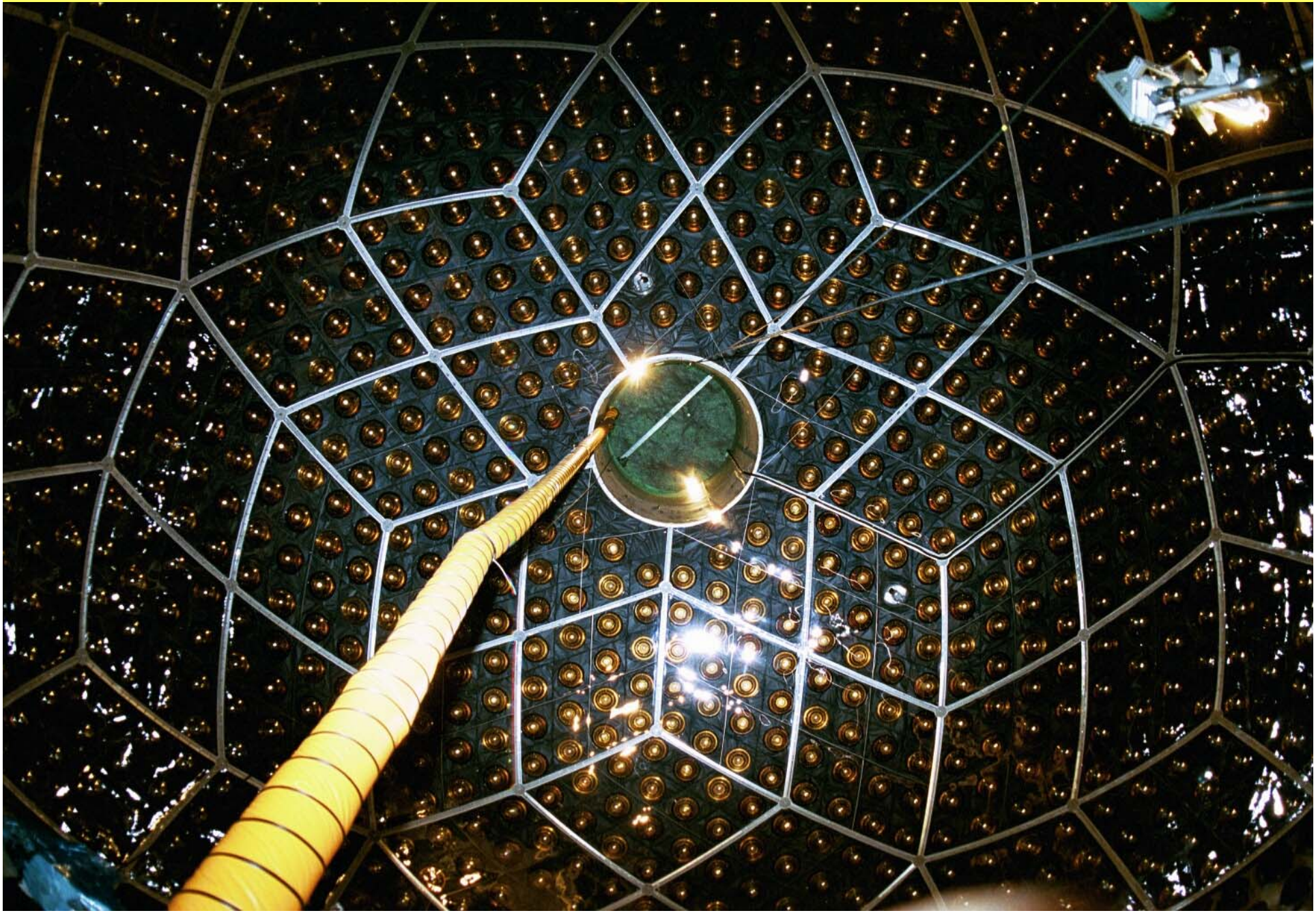
Japanese spent fuel 0.04±0.02%

KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17” fast PMTs
- 554 20” large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



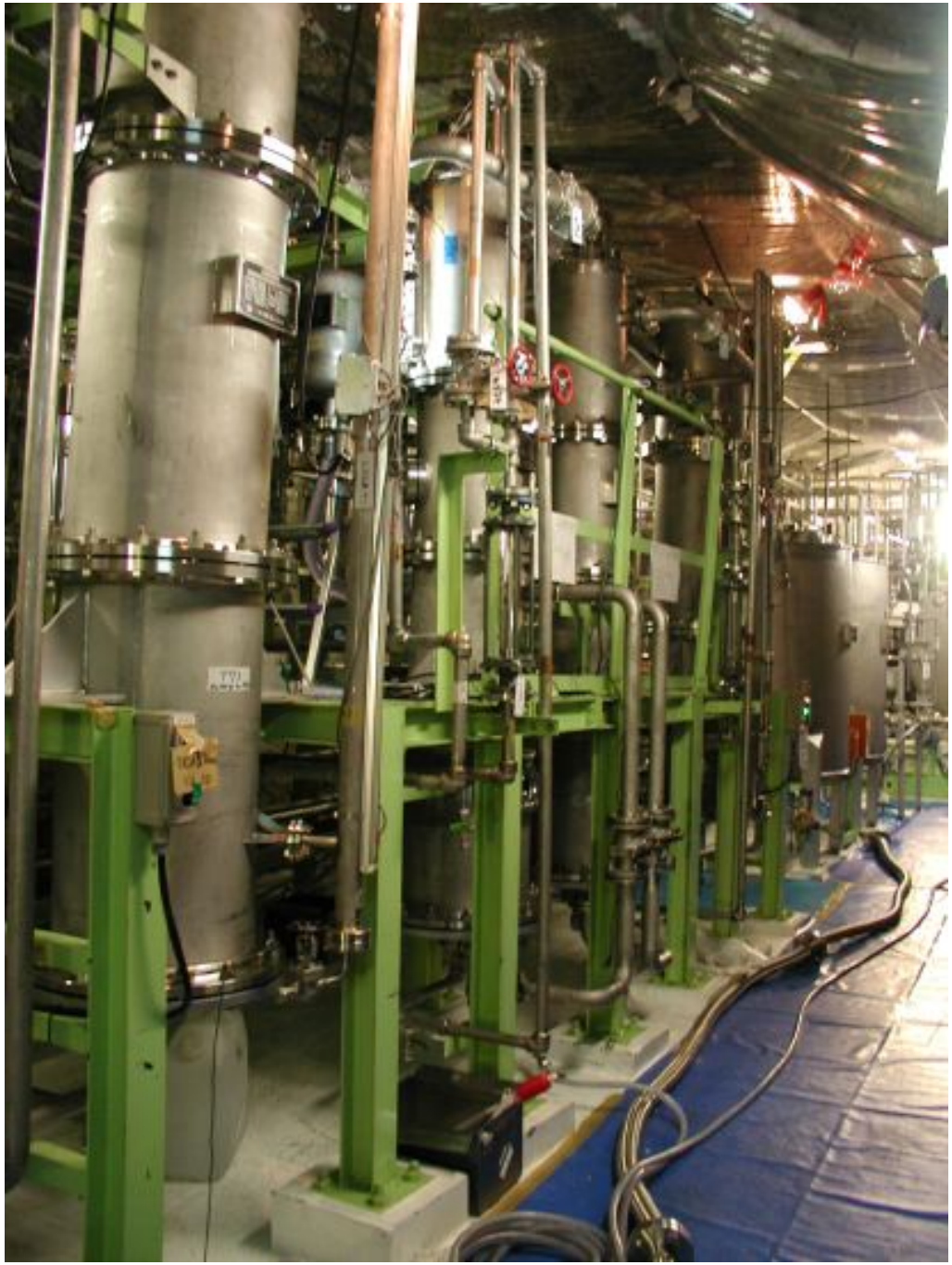
The completed detector, looking up



Scintillator is a blend of 20% pseudocumene and 80% dodecane

Different density paraffines are used to tune the density of buffer to $4 \cdot 10^{-4}$ of that of the scintillator

PPO concentration is 1.52 g/l in scintillator



Autoradiography of KamLAND

^{238}U : $^{214}Bi \xrightarrow{\beta+\gamma} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$

$\beta+\gamma$: $E = 3.27\ MeV$, $\tau = 28.7\ min.$

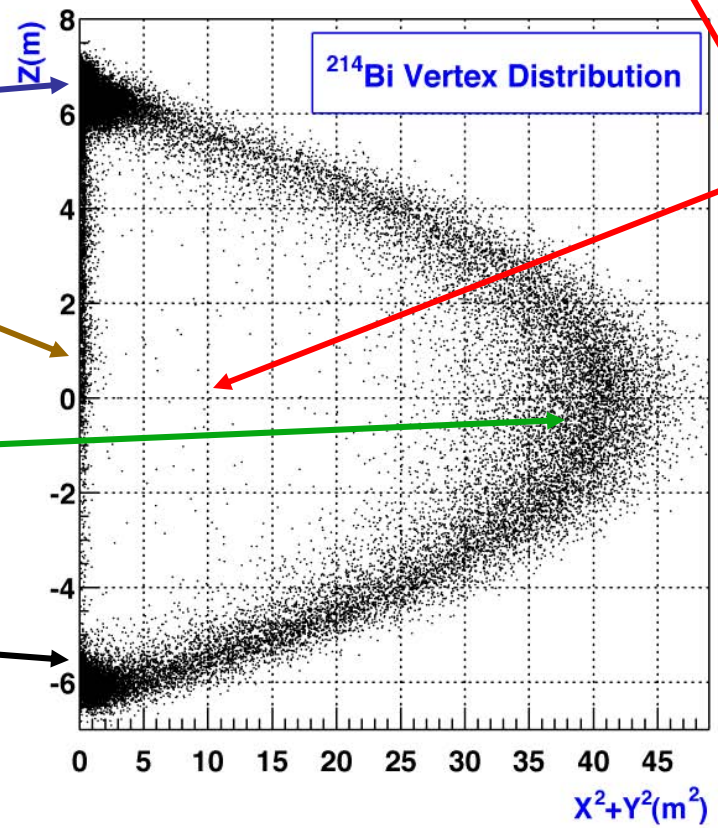
α: $E = 7.69\ MeV$, $\tau = 237\ \mu s$

Top flange and chimney region

Central thermometer

Balloon

Bottom flange and plumbing



In this region measure $^{238}U = (3.5 \pm 0.5) \times 10^{-18}$ g/g

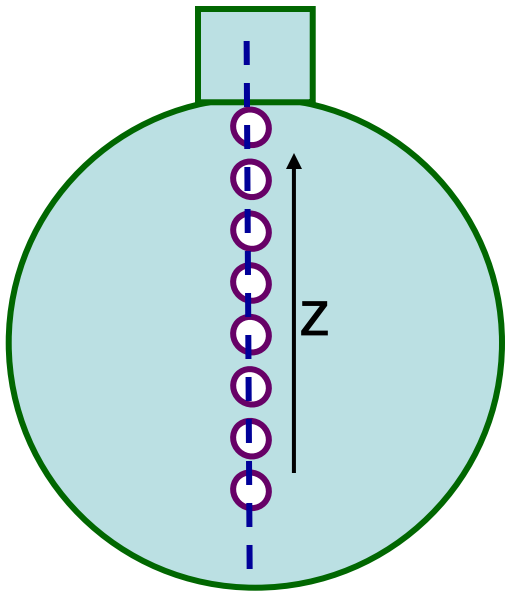
A brief history of KamLAND

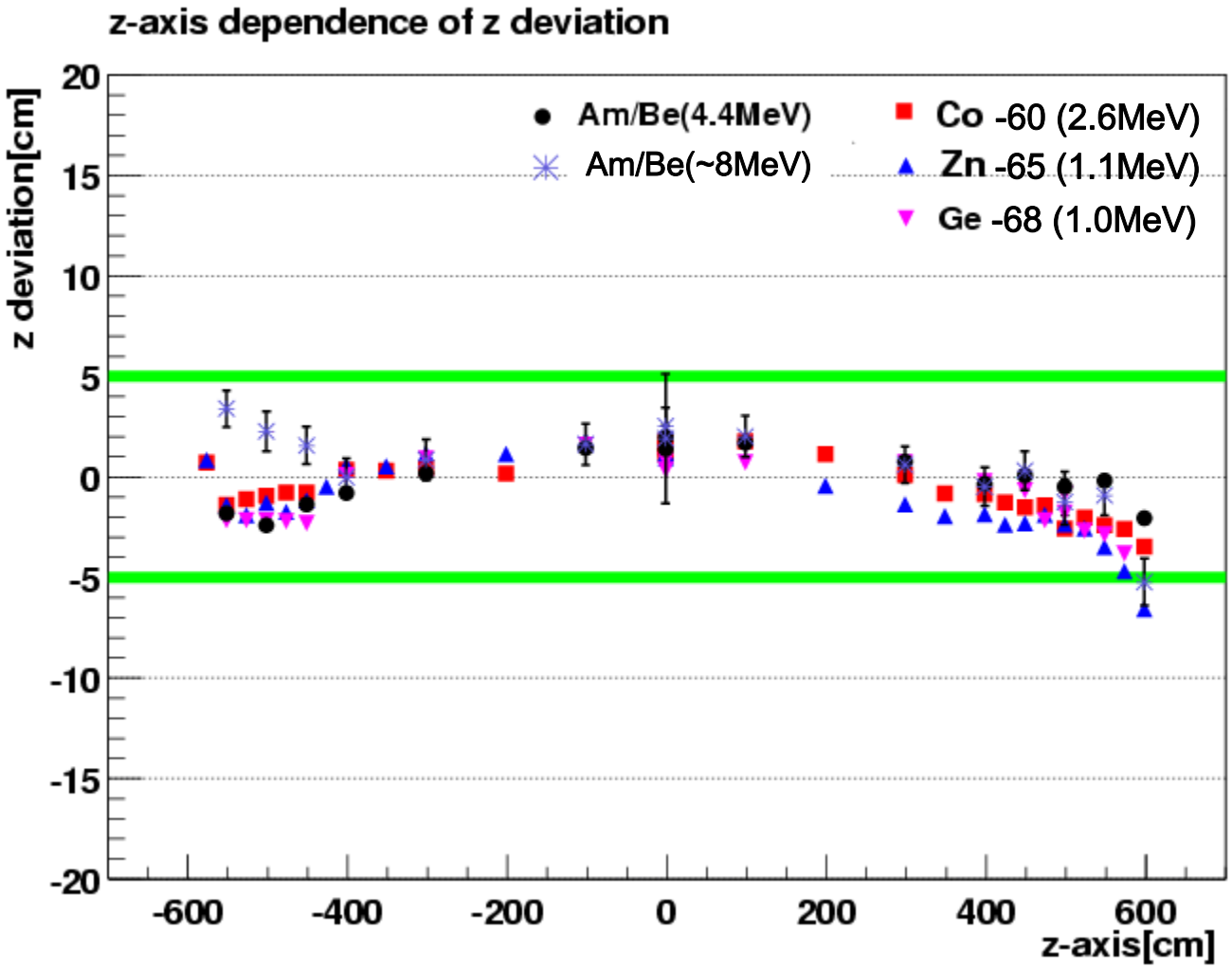
	Dates	Live time (days)
Start data taking	Jan 2002	-
Run A (data-set of 1st paper)	Mar 9 – Oct 6 2002	145.4*
Electronics upgrade & 20" PMT commissioning	Jan/Feb 2003	-
Run B	Oct - Jan 11 2004	369.7
Data-set presented here†	Mar 9, 2002 – Jan 11, 2004	515.1

*Was 145.1 with old analysis

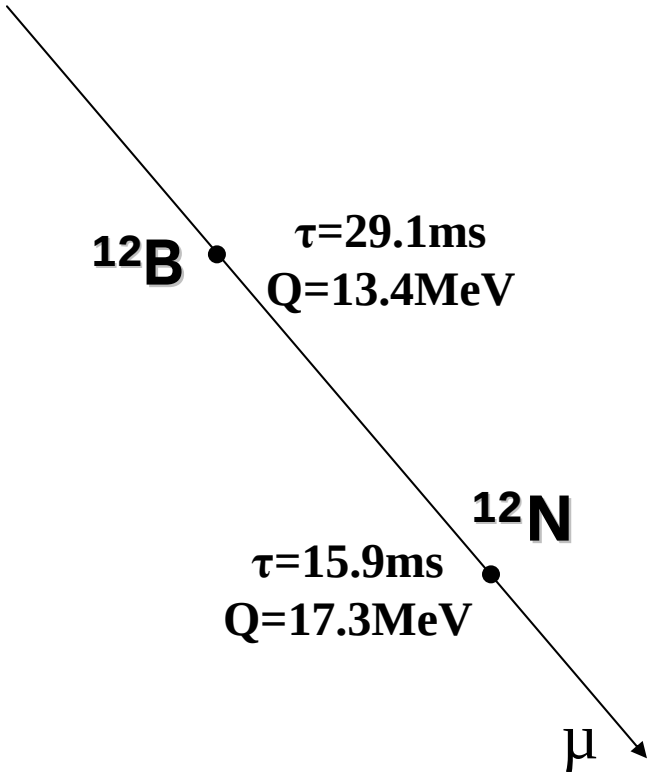
† T.Araki et al, arXiv:hep-ex/0406035 Jun 13, 04 submitted to Phys Rev Lett

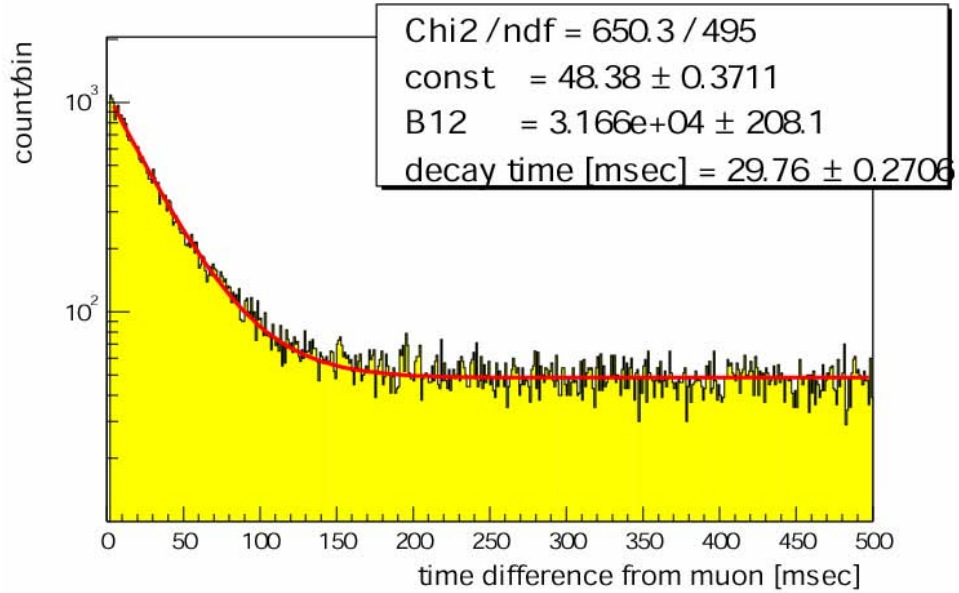
Vertexing is performed using timing from the 17" PMTs

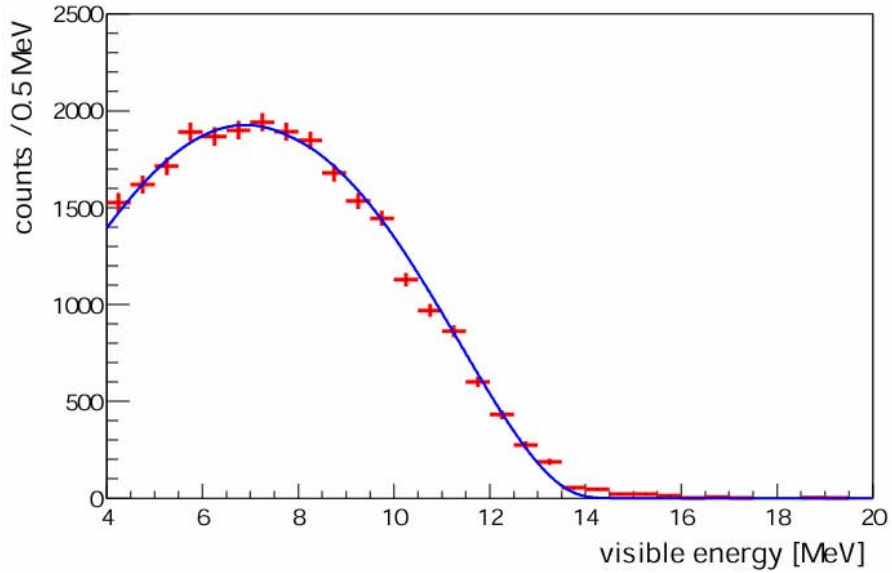




Tagged cosmogenics can be used for calibration

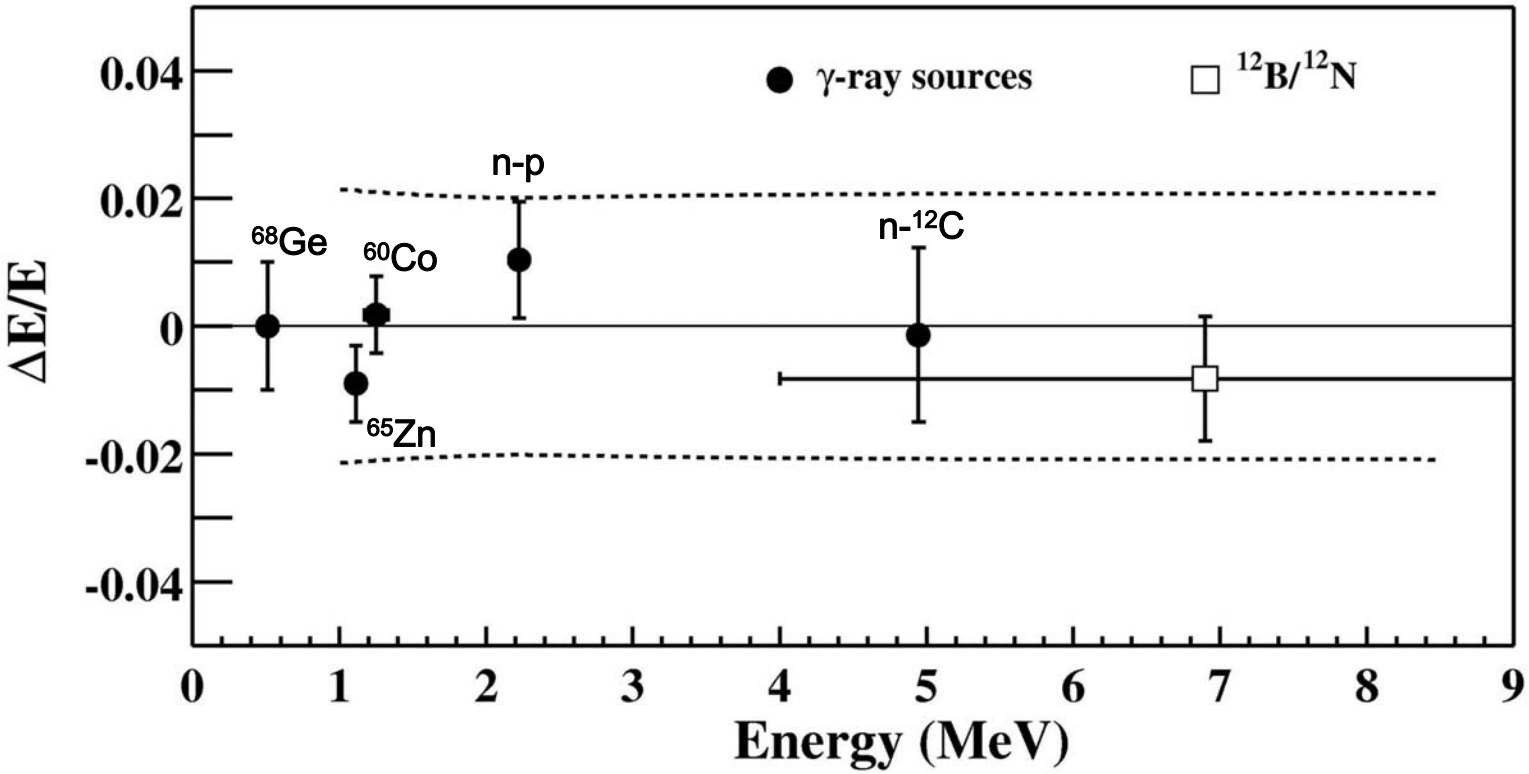






Fit to data shows that
^{12}B:^{12}N ~ 100:1

Energy calibration uses discrete γ and $^{12}B/^{12}N$



Carefully include Birks law, Cherenkov and light absorption/optics to obtain constants for γ and e-type depositions

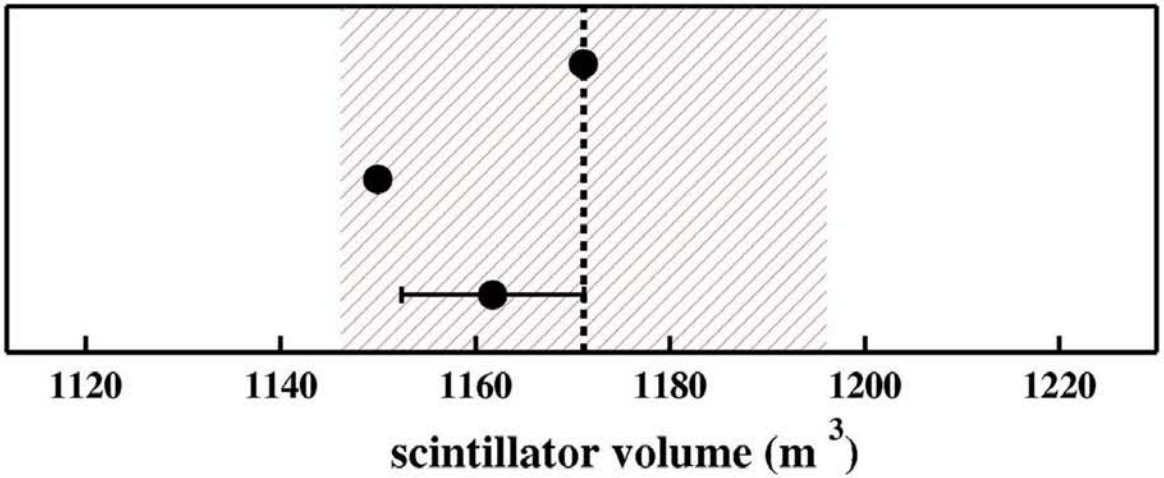
σ/E ~ 6.2% at 1MeV

Estimate of total volume and fiducial fraction

flow meter meas.

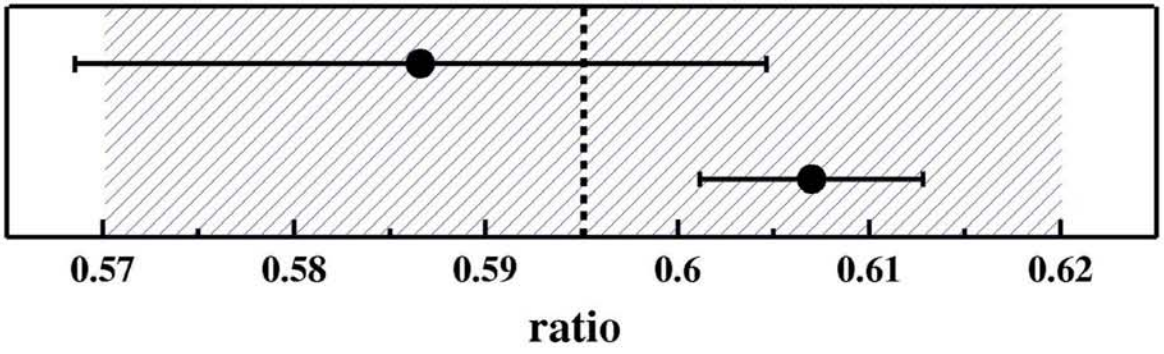
purification tank meas.

3,000 m^3 tank meas.



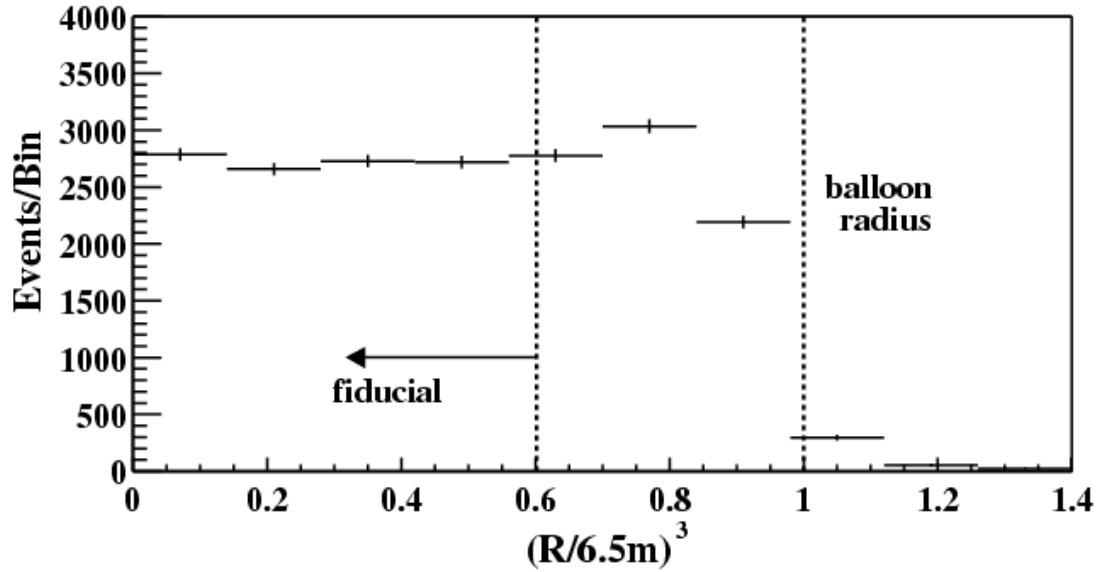
spallation neutrons

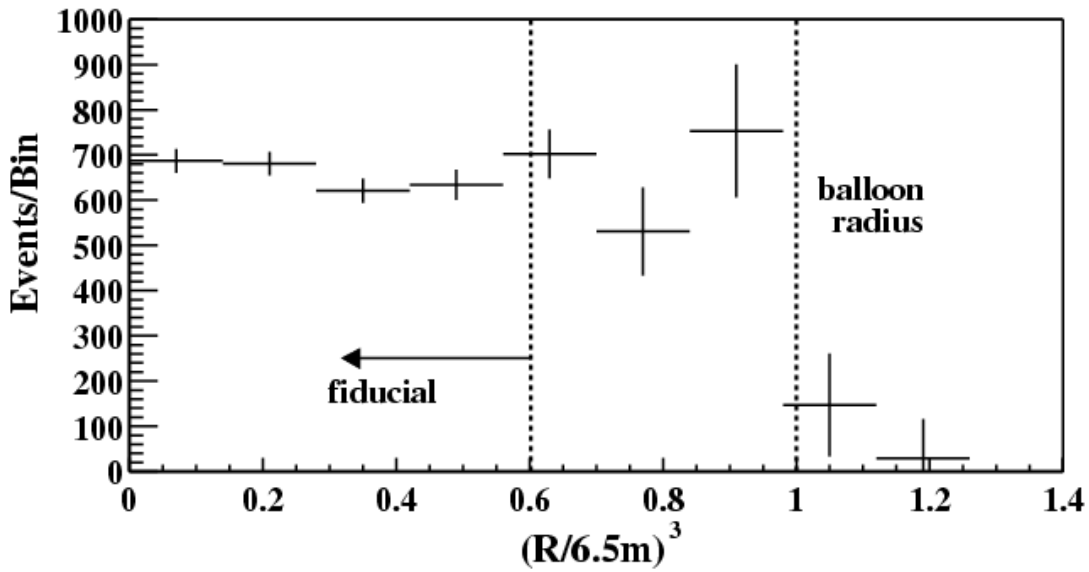
$^{12}B/^{12}N$



Fraction of volume *inside* the fiducial radius verified using μ-produced $^{12}B/^{12}N$ and n (assumed uniform)

$^{12}B/^{12}N$





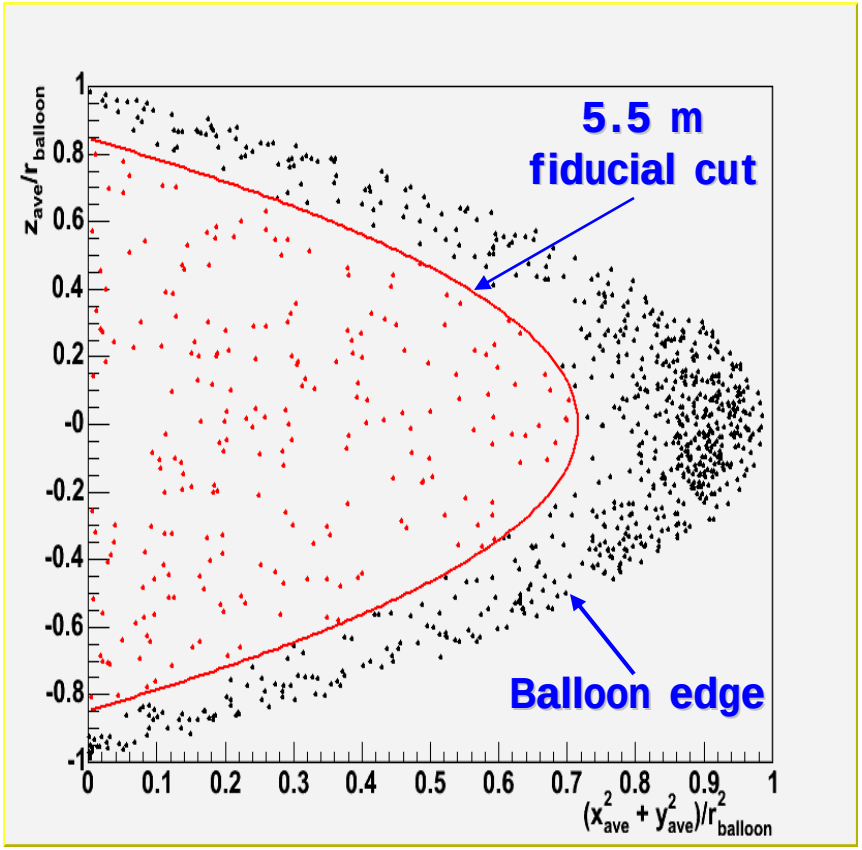
neutrons

Selecting antineutrinos, E_{prompt}>2.6MeV

543.7 ton

- $R_{prompt,\ delayed} < 5.5$ m
- $\Delta R_{e-n} < 2$ m
- $0.5\ \mu s < \Delta T_{e-n} < 1$ ms
- 1.8 MeV < $E_{delayed}$ < 2.6 MeV
- 2.6 MeV < E_{prompt} < 8.5 MeV

Tagging efficiency 89.8%



…In addition:

- 2s veto for showering/bad μ
- 2s veto in a R = 3m tube along track

Dead-time 9.7%

Systematic	%
Scintillator volume	2.1
Fiducial fraction	4.2
Energy threshold	2.3
Cuts efficiency	1.6
Live time	0.06
Reactor $P_{thermal}$	2.1
Fuel composition	1.0
Time lag	0.01
Antineutrino spectrum	2.5
Antineutrino x-section	0.2
Total	6.5

Results

766.3 ton·yr

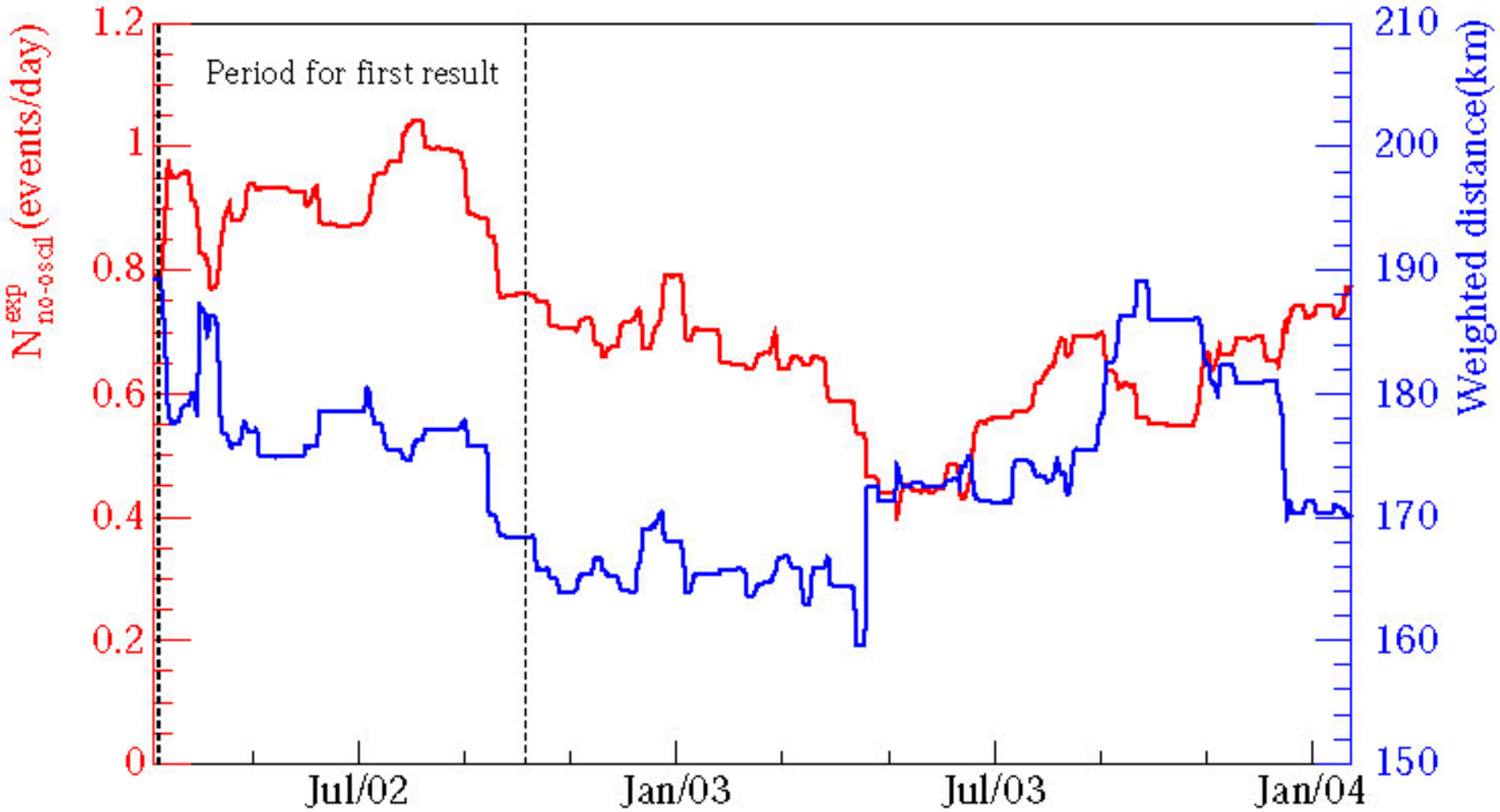
Observed events	258
No osc. expected	365±24(syst)
Background	7.5±1.3

Inconsistent with simple $1/R^2$ propagation at 99.995% CL

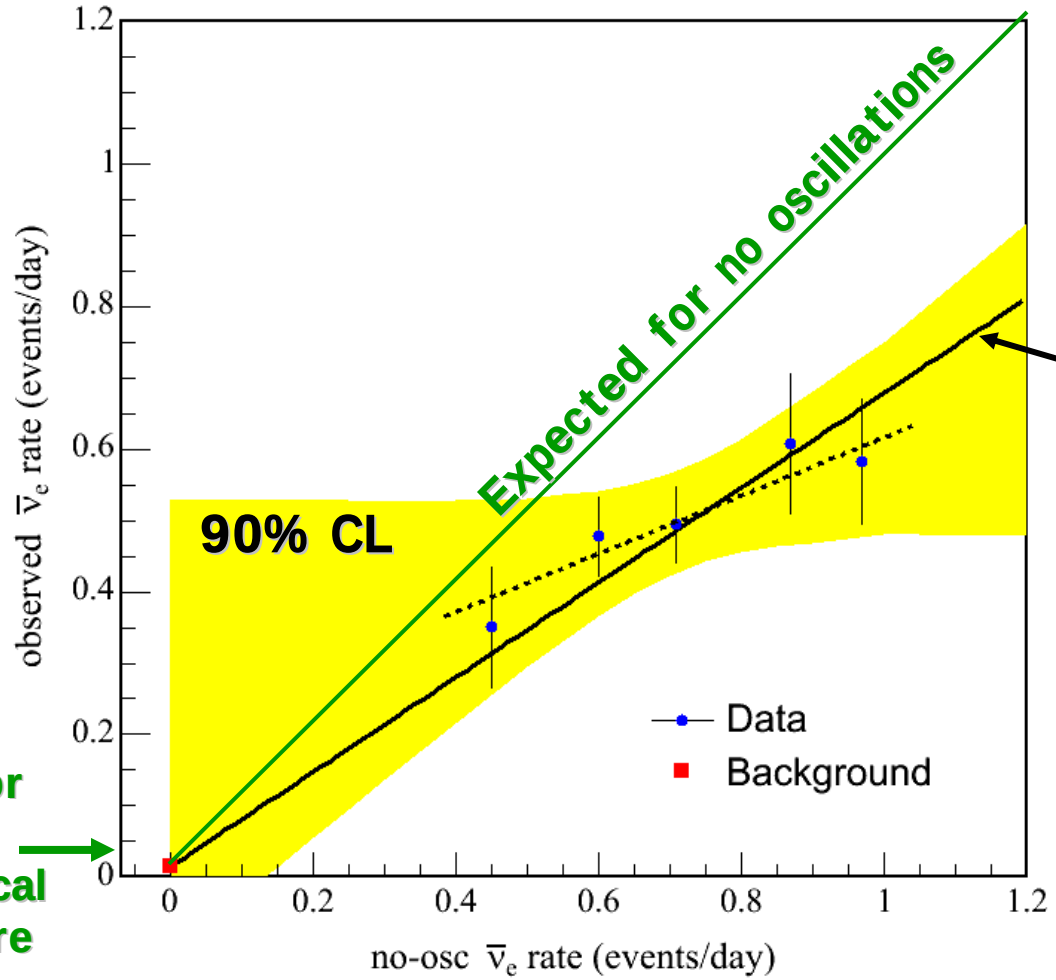
(Observed-Background)/Expected = 0.686±0.044(stat)±0.045(syst)

Caveat: this specific number does not have an absolute meaning in KamLAND, since, with oscillations, it depends on which reactors are on/off

2003 saw a substantial dip in reactor antineutrino flux



Good correlation with reactor flux

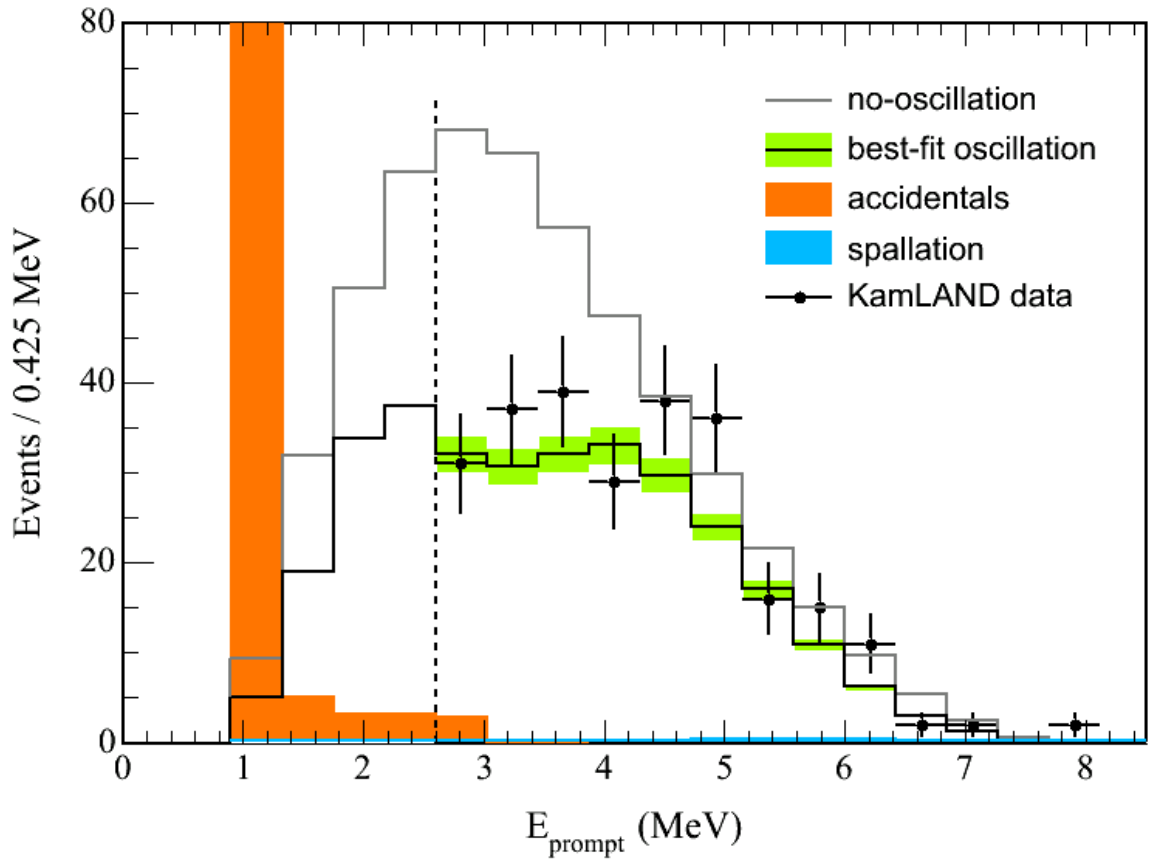


Fit constrained through known background
χ^2=2.1/4

~0.03 for 3TW hypothetical Earth core reactor

(But a horizontal line still gives a decent fit with χ^2=5.4/4)

Energy spectrum now adds substantial information



A fit to a simple rescaled reactor spectrum is excluded at 99.89% CL (χ^2=43.4/19)

Best fit to oscillations:

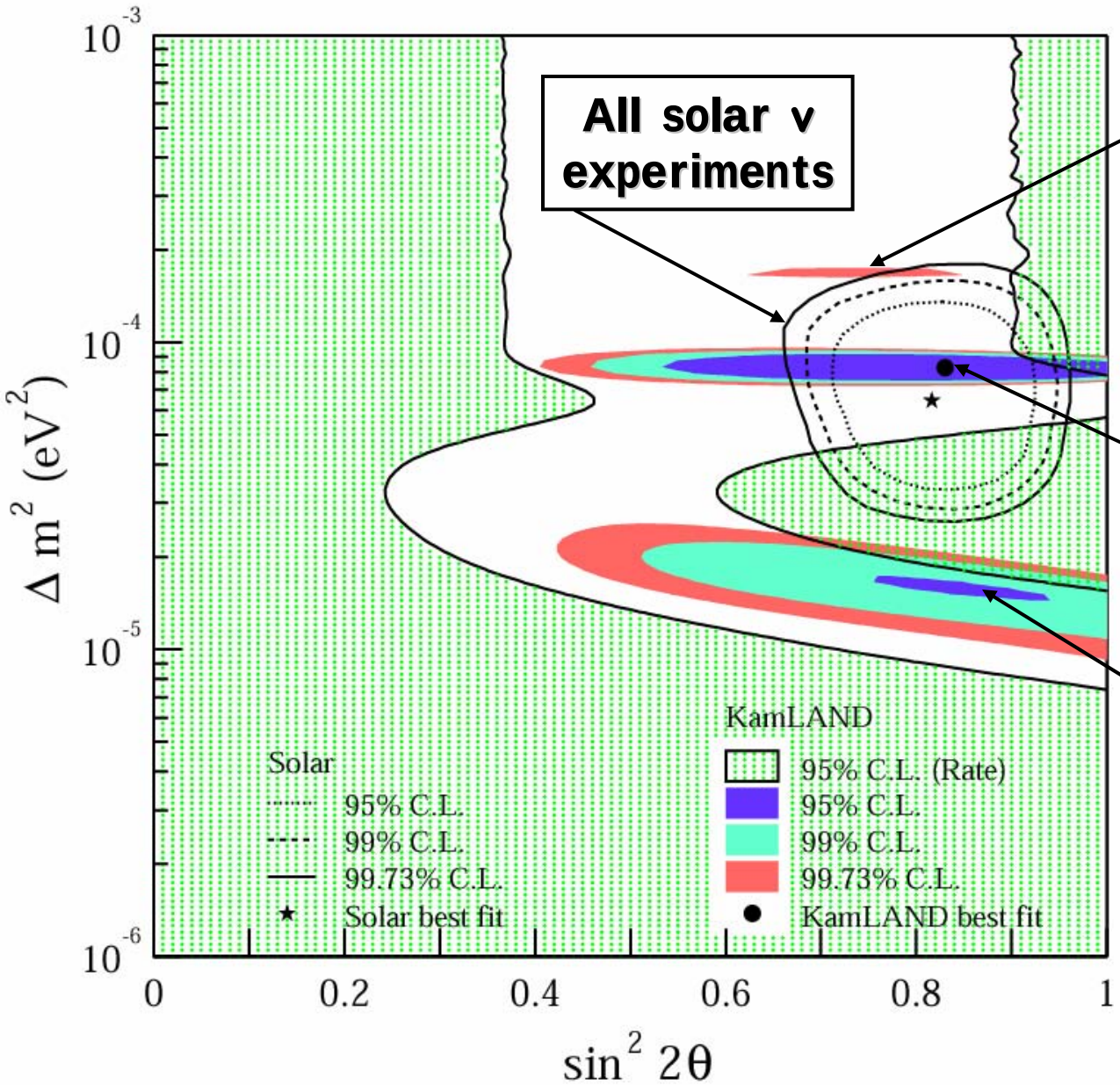
$\Delta m^2 = 8.3 \cdot 10^{-5}\ eV^2$

$\sin^2 2\theta = 0.83$

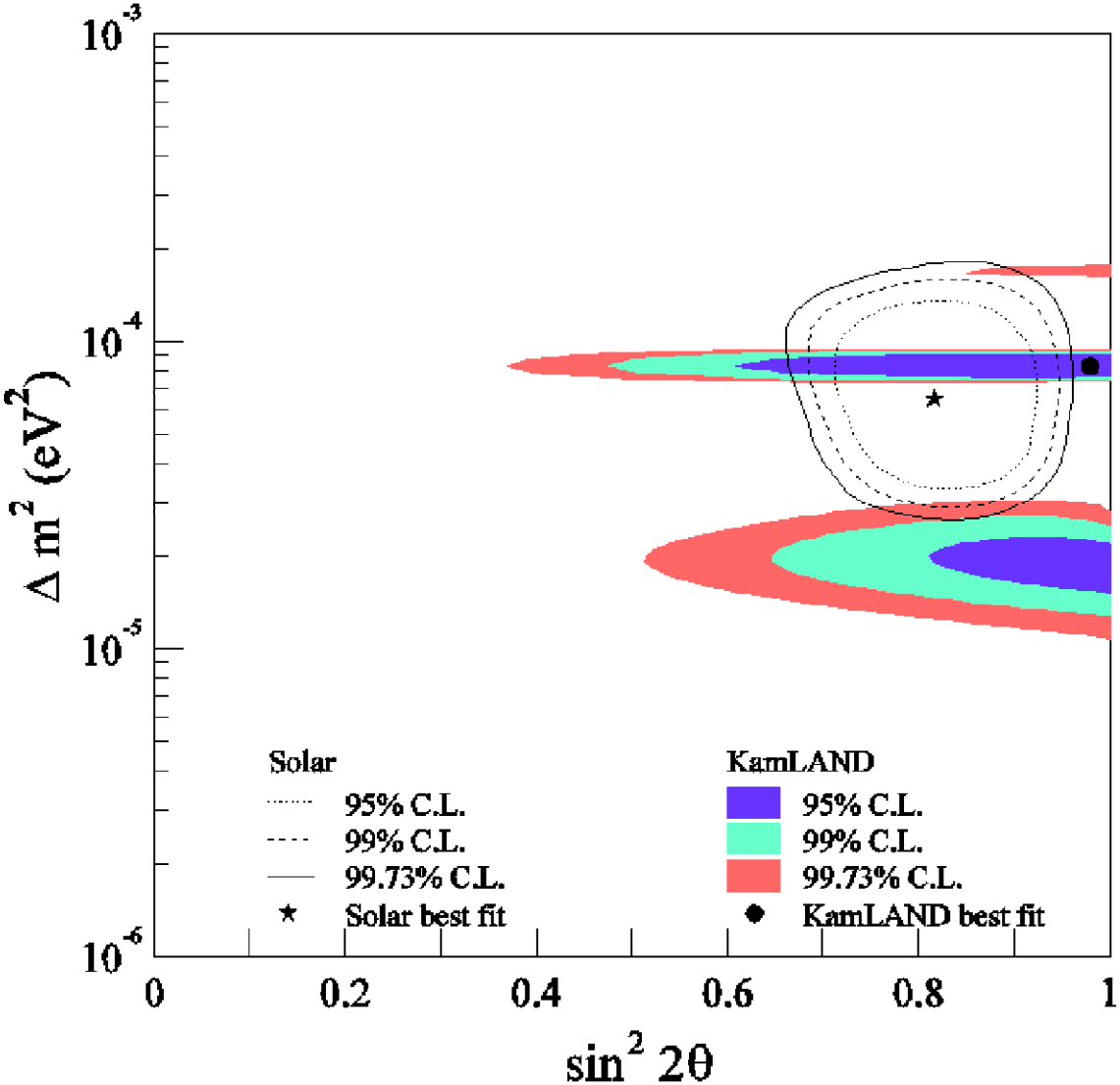
Straightforward χ^2 on the histo is 19.6/11

Using equal probability bins χ^2/dof=18.3/18 *(goodness of fit is 42%)*

Un-binned likelihood fit to 2-flavor oscillations



A shape-only fit gives similar results

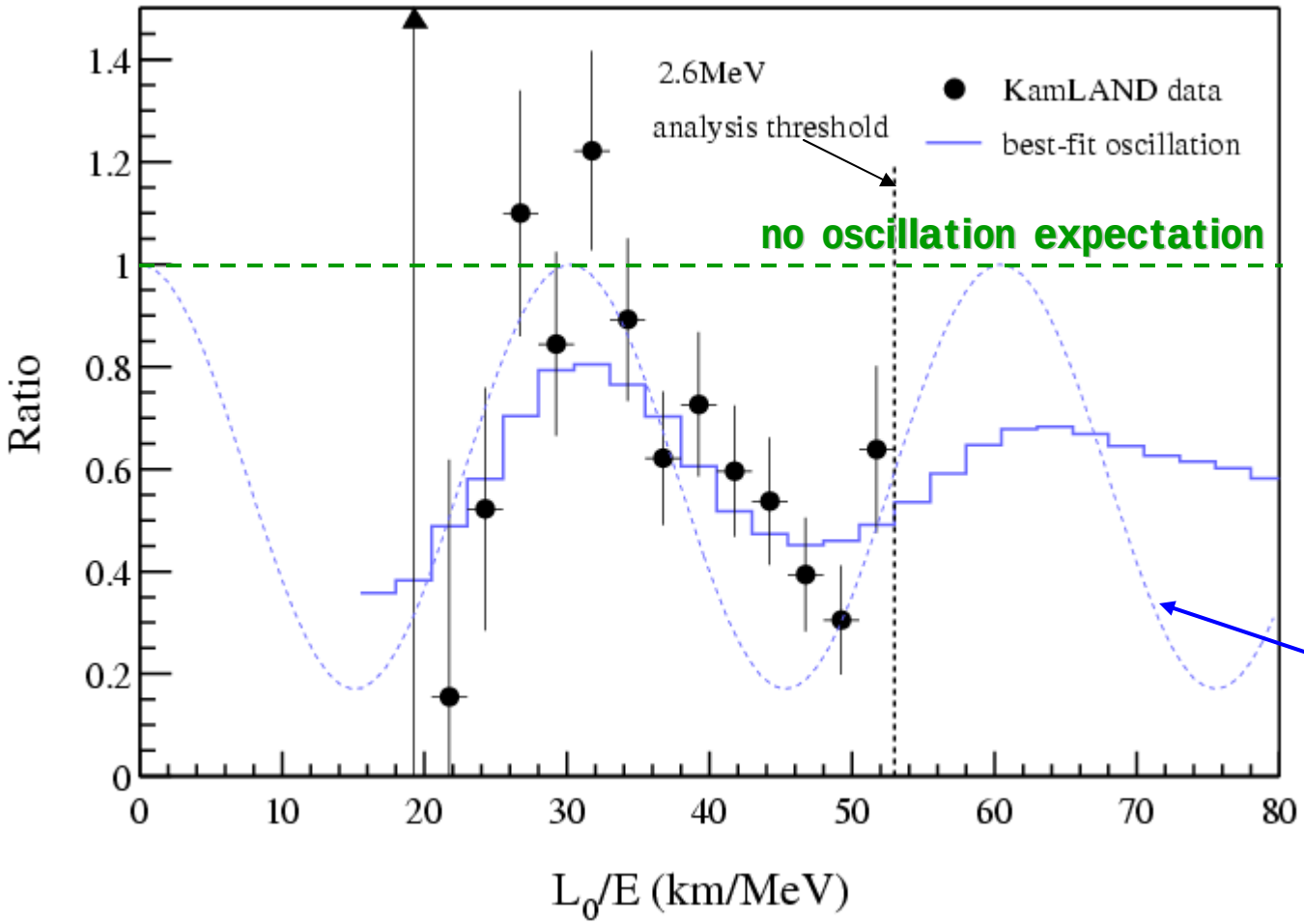


$\Delta m^2 = 8.3 \cdot 10^{-5}\ eV^2$

$\sin^2 2\theta = 0.98$

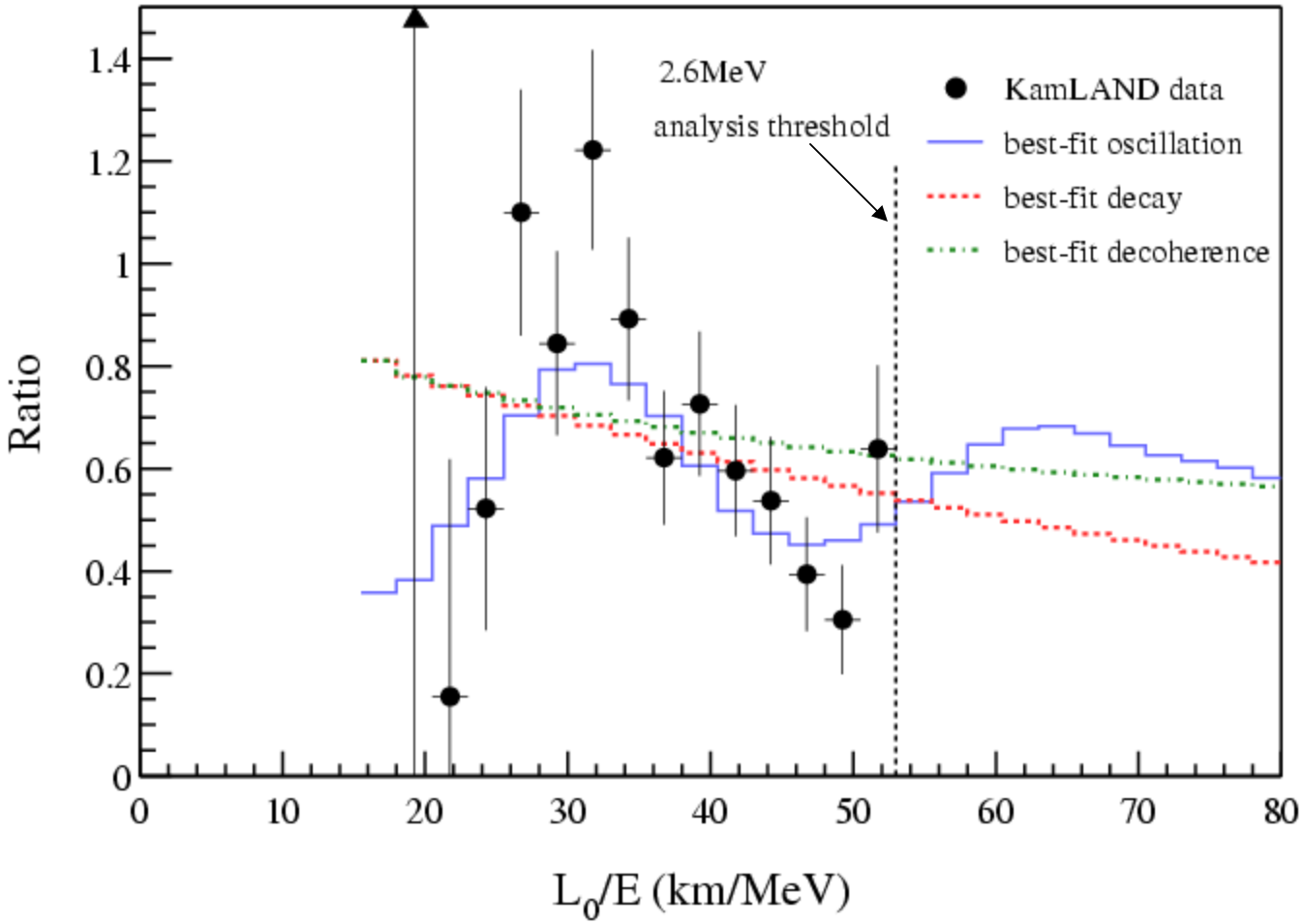
KamLAND uses a range of L and it cannot assign a specific L to each event

Nevertheless the ratio of detected/expected for L_0/E (or 1/E) is an interesting quantity, as it decouples the oscillation pattern from the reactor energy spectrum



Hypothetical single 180km baseline experiment

More exotic, non-oscillations models for the antineutrino channel start being less favored by data



Decay* excluded at 95% CL

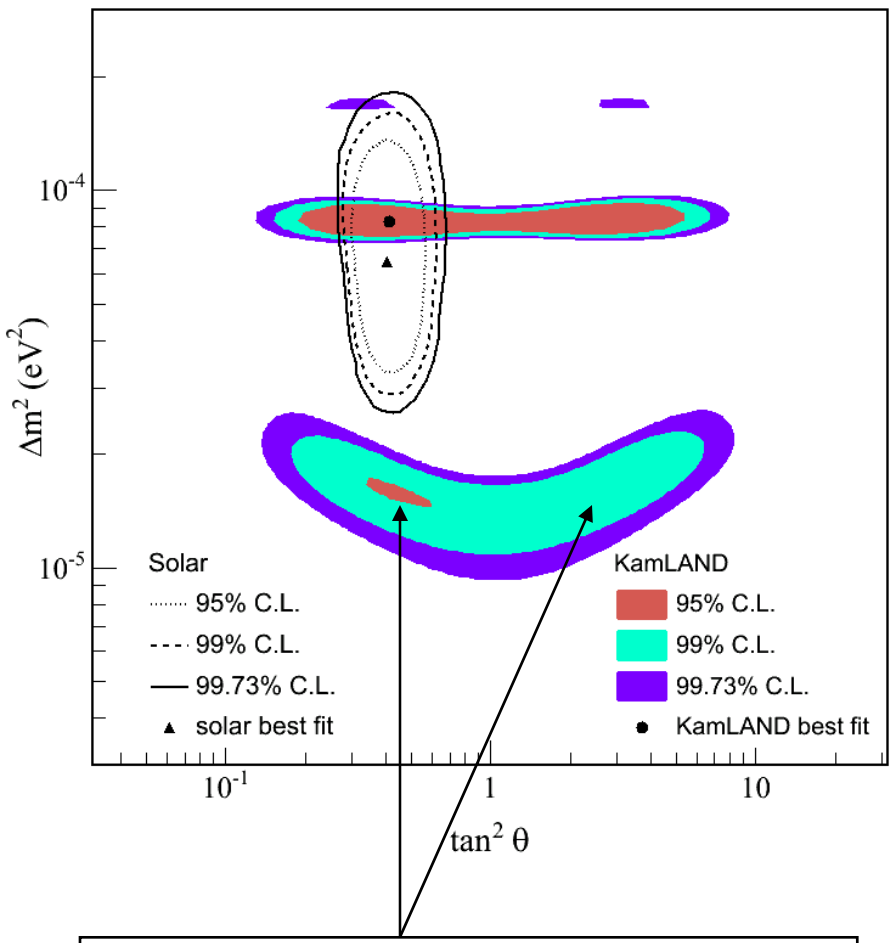
Decoherence† excluded at 94% CL

** V.Barger et al. Phys. Rev. Lett. 82 (1999) 2640*
† E.Lisi et al., Phys. Rev. Lett. 85 (2000) 1166

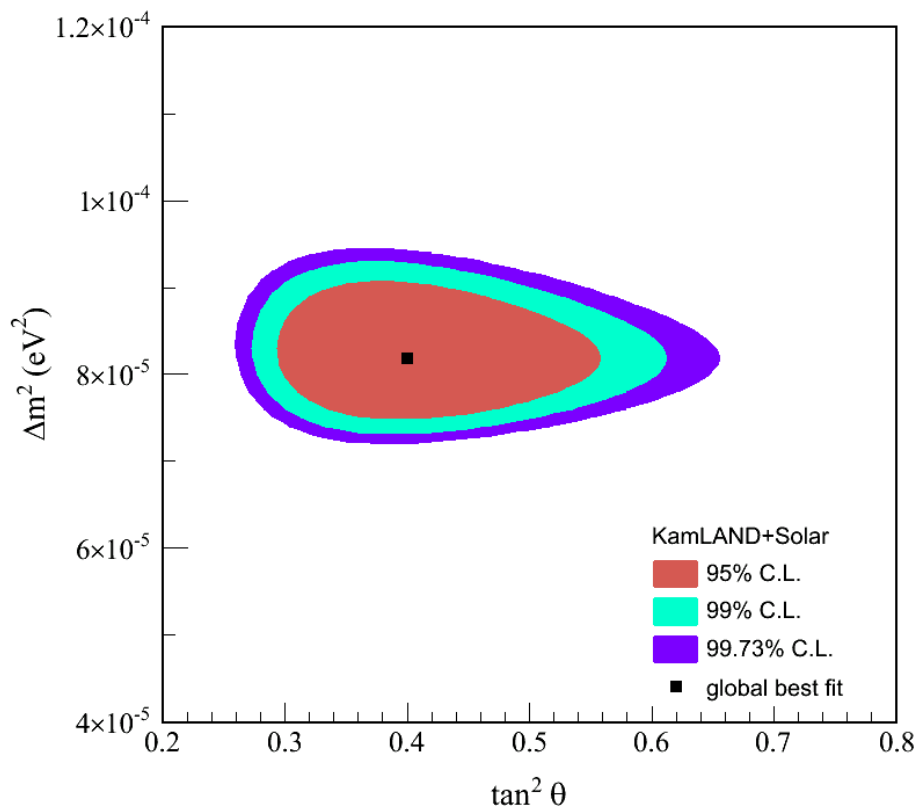
Combined solar ν – KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$

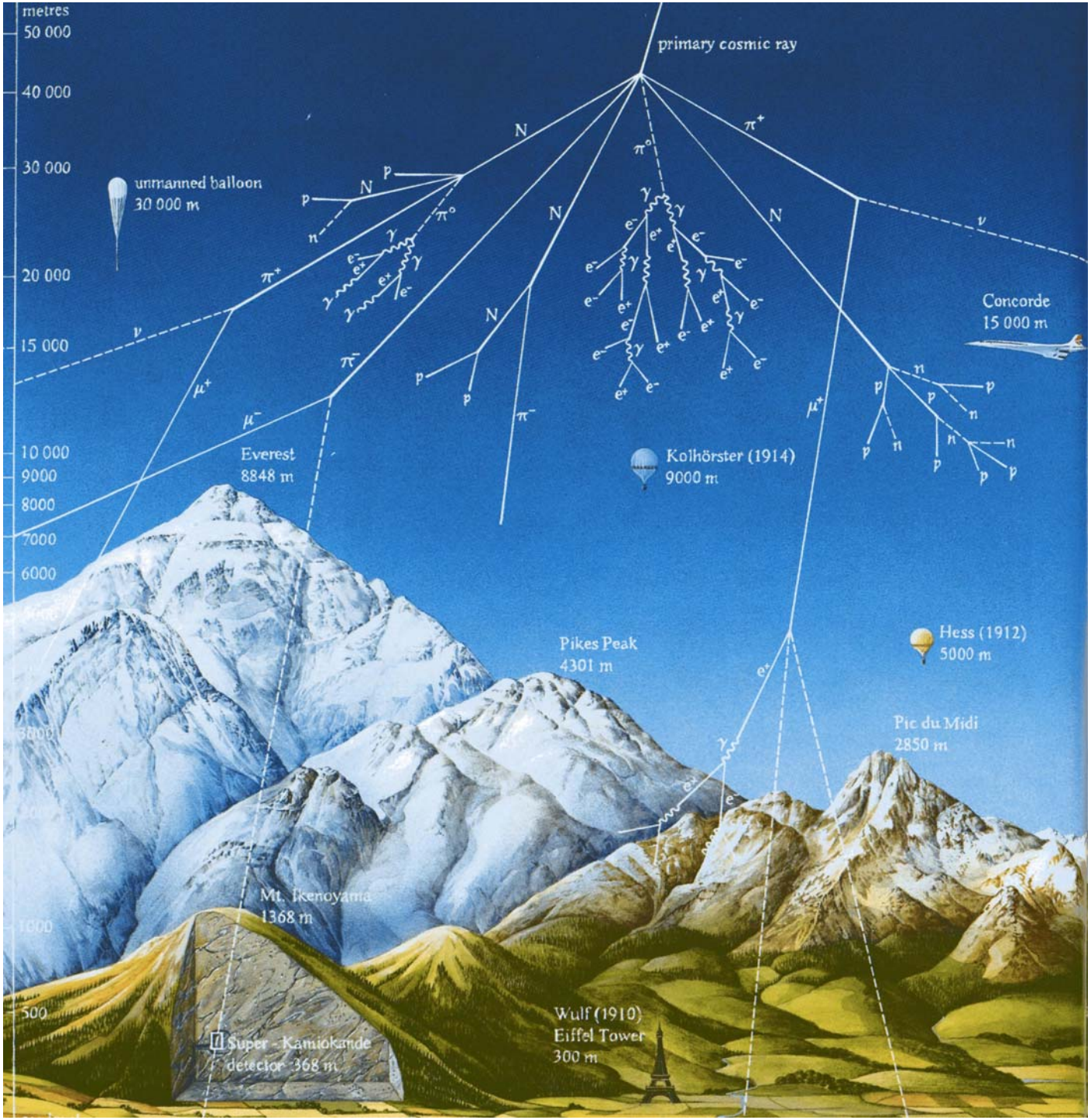


Includes (small) matter effects



…it took 35 years… but we have:

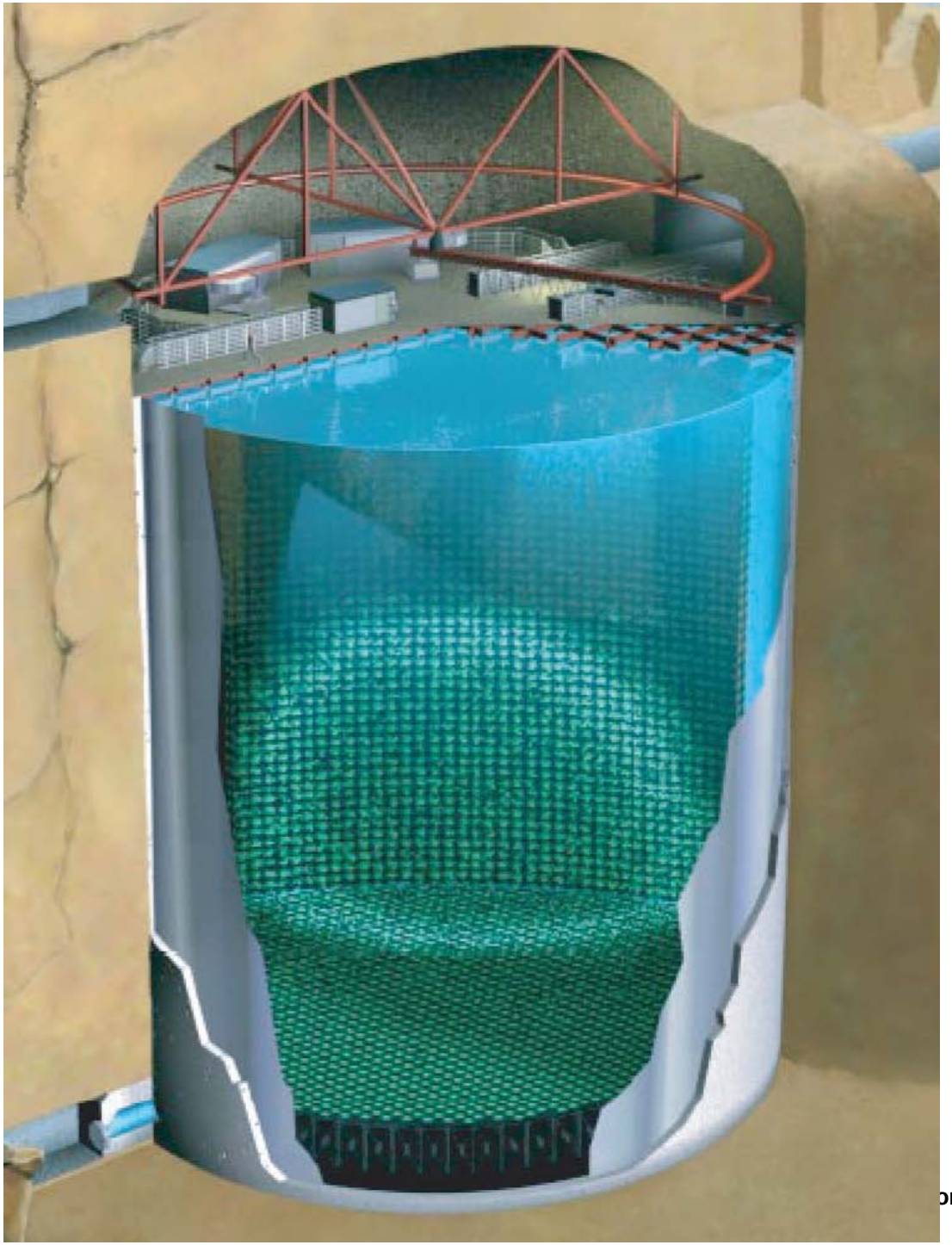
1) detected neutrinos from the sun
2) found that part of the neutrino flux is missing
3) found that only ν_e are missing
4) found that matter effects in the sun (MSW effect) are responsible for the deficit
5) found that neutrinos have finite masses (required for MSW)
6) identified mixing parameters Δm_{12}^2, θ_{12}
7) found that we can reproduce this effect artificially with vacuum oscillations with the same Δm_{12}^2, θ_{12}
8) found that ν and anti-ν behave the same way
9) found that flavor mixing works better than other scenarios (e.g. decay)
10) found that our model for the sun (SSM) works very well



The other oscillations: Atmospheric neutrinos

Higher energy phenomenon

Measurements dominated by SuperK



SuperKamiokande:
the largest "artificial" water Cerenkov detector ever built (50 kton)

SK1 1996-2001
>11146 50cm PMTs
40% photocathode
22.5kton fiducial mass

2003-2005
5182 PMTs recovered
19% photocathode
K2K beam

2006-…
Original PMT coverage
T2K beam

A composite data-set

~14000 events total from data reduction

	DATA	MC	C.C. Purity
Sub-GeV 1-ring e-like	3353	2978.8	88.0%
Multi-GeV 1-ring e-like	746	680.5	82.6%
Sub-GeV 1-ring μ-like	3227	4212.8	94.5%
Sub-GeV Multiring μ-like	208	322.6	90.5%
Multi-GeV 1-ring μ-like	651	899.9	99.4%
Multi-GeV Multiring μ-like	439	711.9	95.0%
Partially Contained μ	647	1034.5	97.3%
Stopping Upward μ	417.7	721.4	~100%
Throughgoing Upward μ	1841.6	1684.4	~100%

11530 events used (80%) in oscillation analysis

E.Kearns, Nu2004

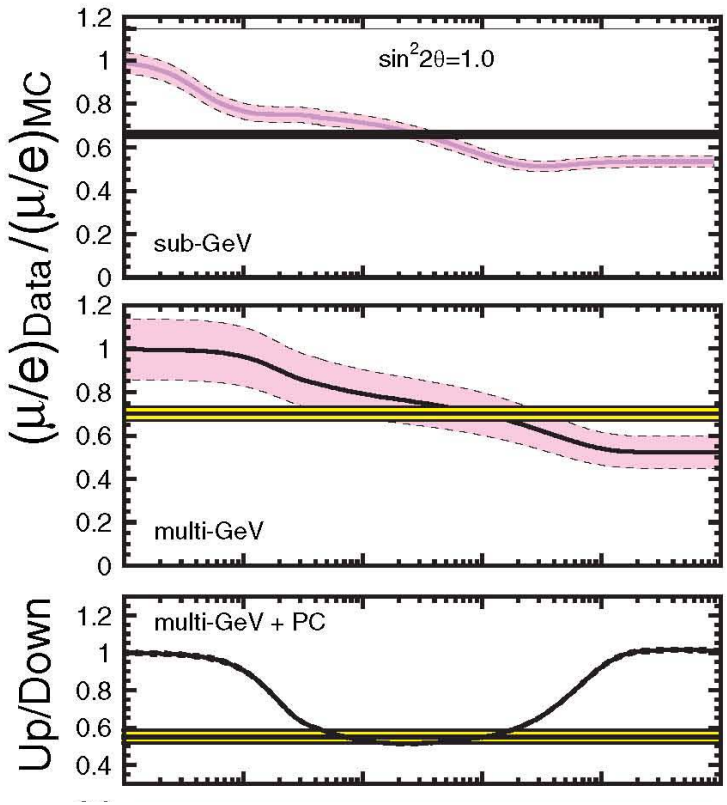
Ratios

$$R_{sub-GeV} = 0.658 \pm 0.016(stat) \pm 0.032(sys)$$

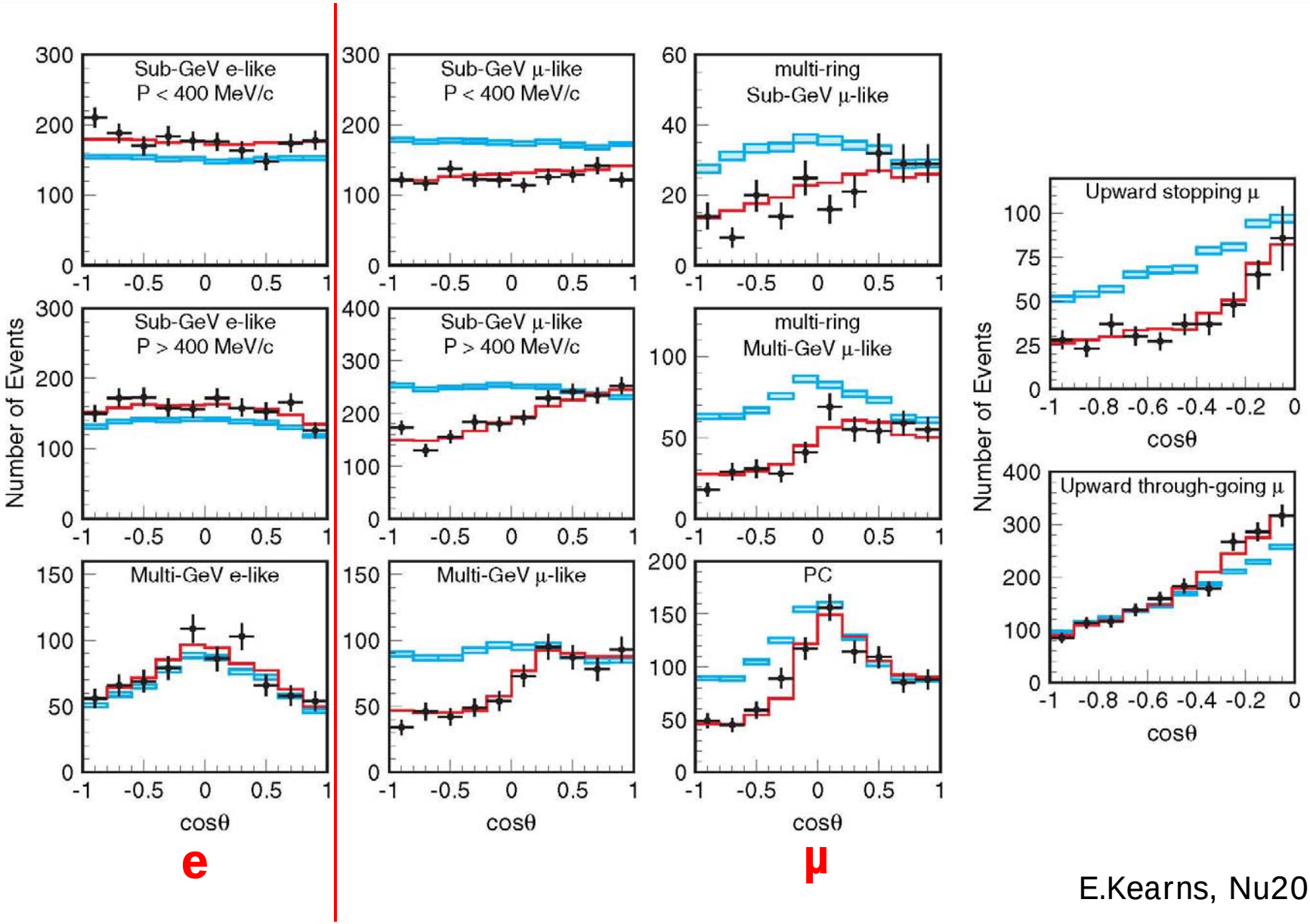
$$R \equiv \frac{(\mu/e)_{DATA}}{(\mu/e)_{M.C.}}$$

$$R_{multi-GeV} = 0.702^{+0.032}_{-0.030}(stat) \pm 0.099(sys)$$

$$\left(\frac{N_{UP}}{N_{DOWN}}\right)_{Multi-GeV+PC} = 0.55^{+0.035}_{-0.033}(stat) \pm 0.005(sys)$$

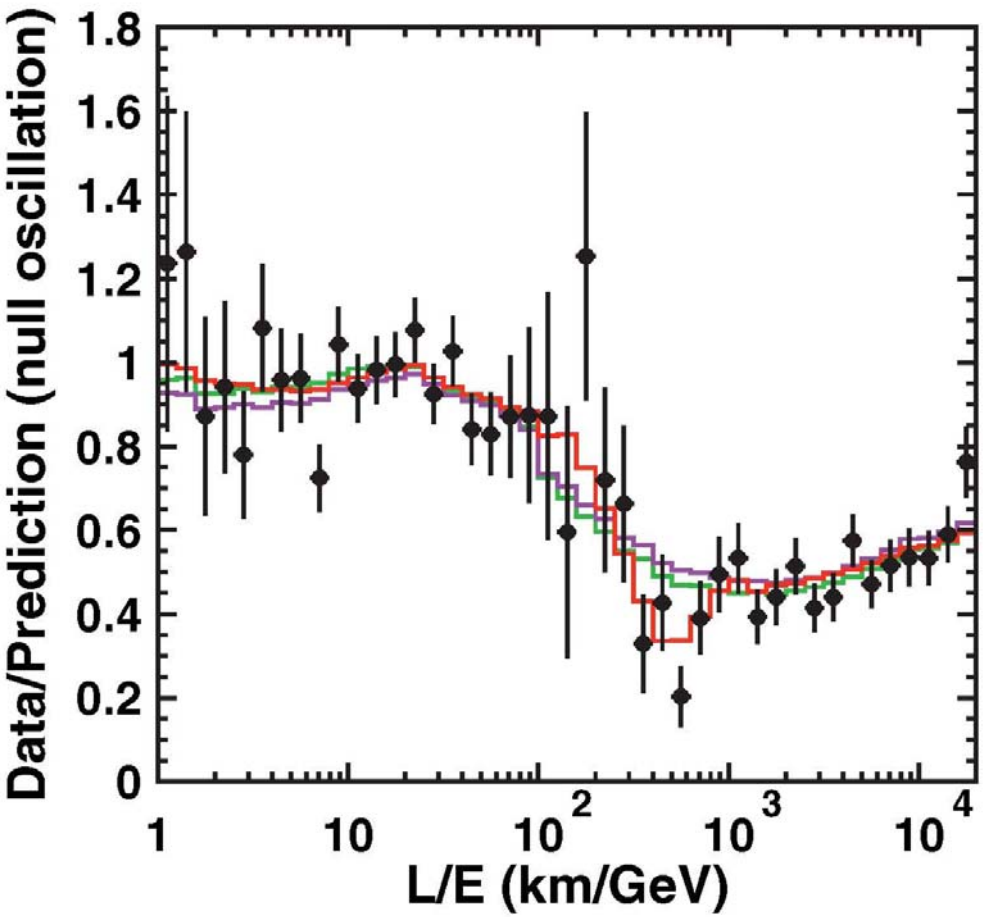


Zenith Angle Distributions



E.Kearns, Nu2004

The oscillatory pattern is now also visible with atmospheric neutrinos

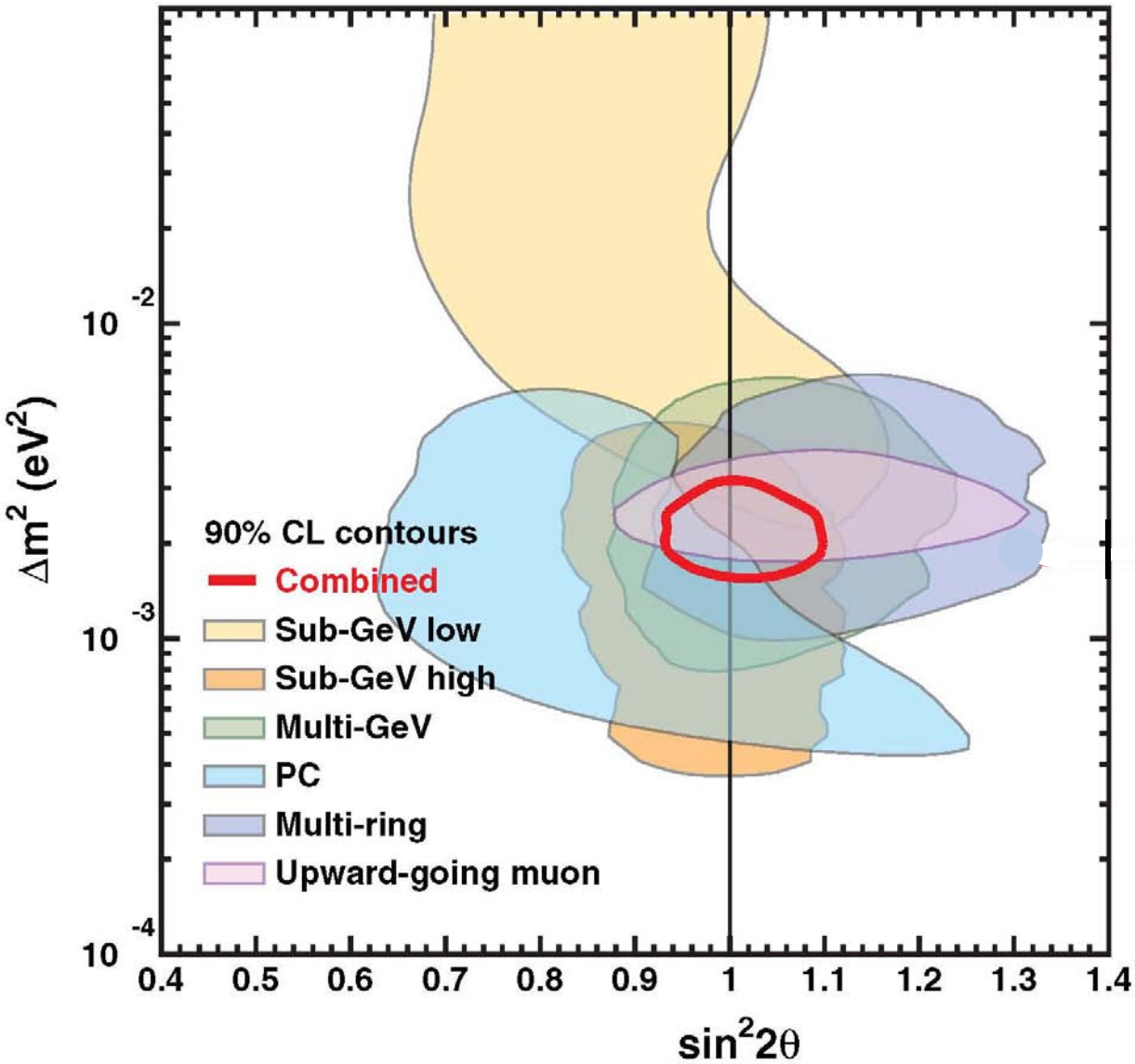


Decay rejected at 3.4σ
Decoherence rejected at 3.8σ

And flavor oscillation is favored over other models for disappearance

E.Kearns, Nu2004

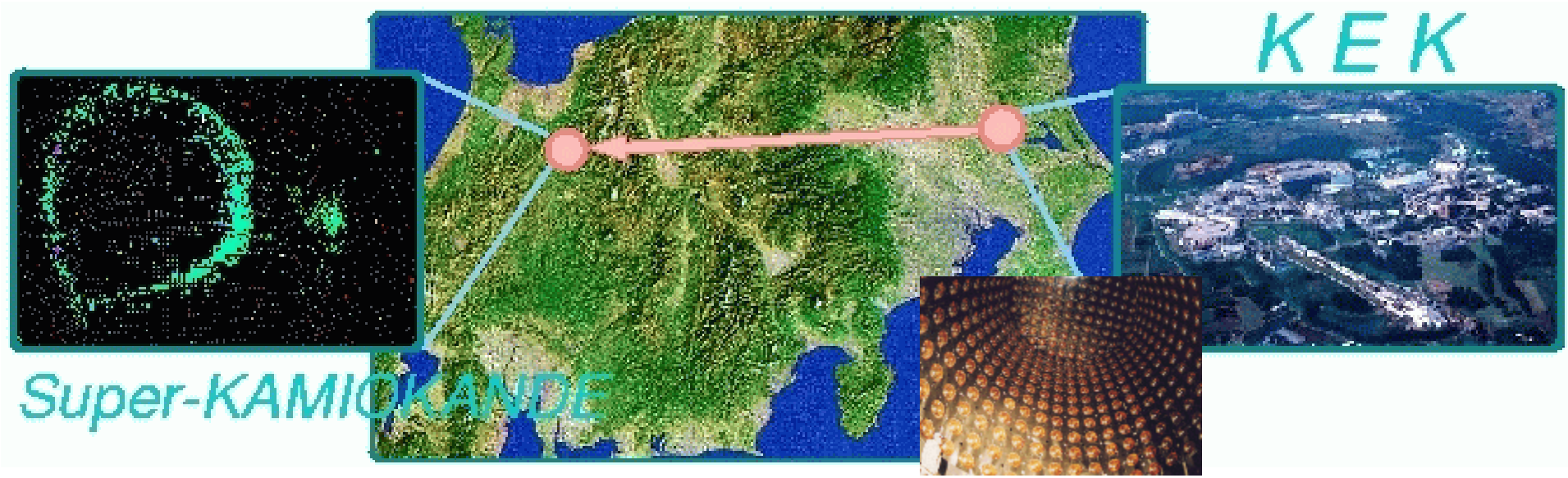
Parameter regions fit by different channels nicely overlap



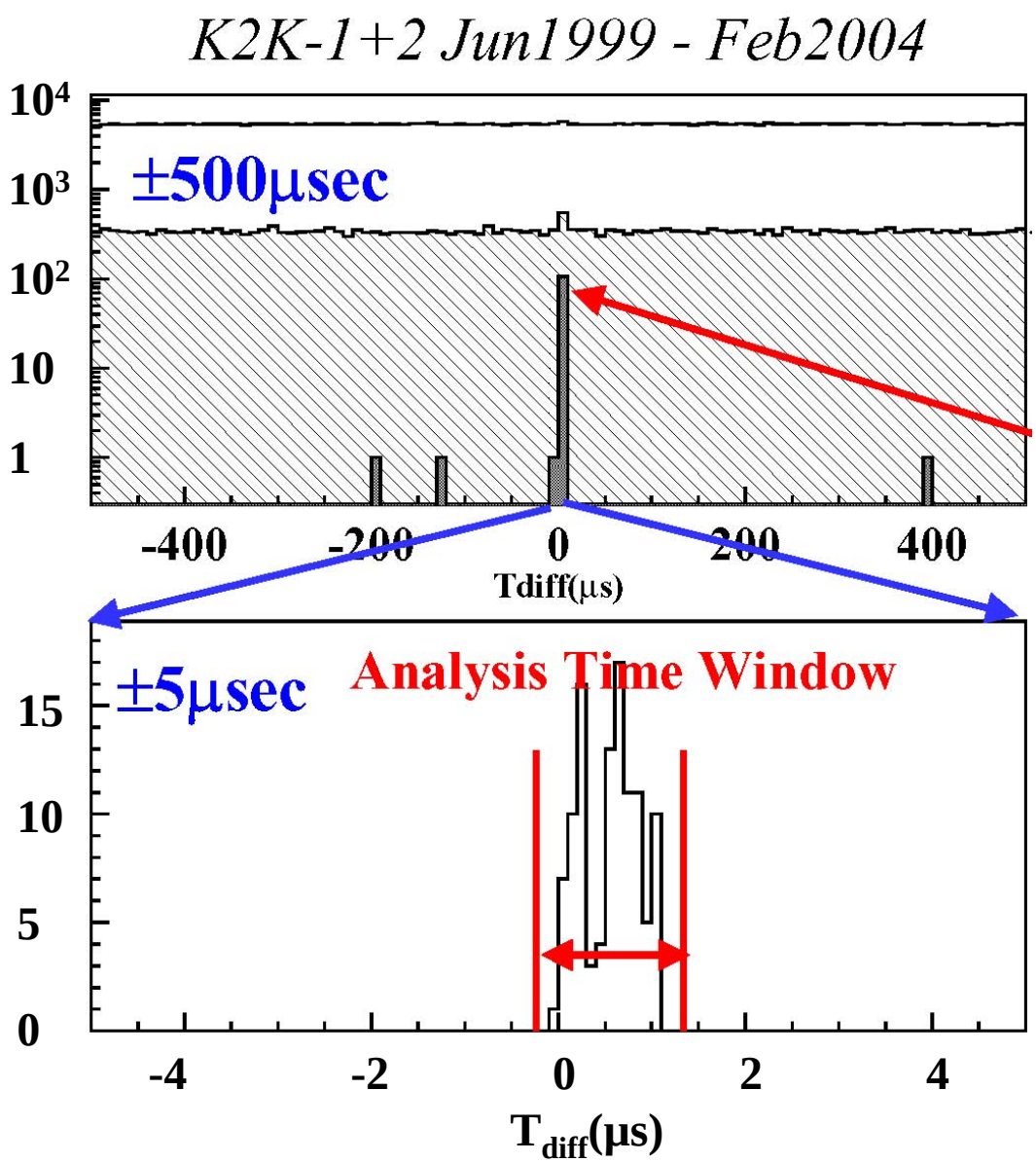
A 3 flavor analysis favors ν_μ-ν_τ oscillation as responsible for the atmospheric neutrino anomaly *(more on this later…)*

E.Kearns, Nu2004

Again, the quest is open to observe the oscillation phenomenon with artificial neutrinos



- 12 GeV KEK protons
- Mini-K (1kton water + other detectors)
  near detector (100m) 10^{11} ν_μ every 2.2s
- Super-K at 250km 10^6 ν_μ every 2.2s (detect ~1event/2days)
- $8.9 \cdot 10^{19}$ p.o.t. collected in ~3.5 yrs

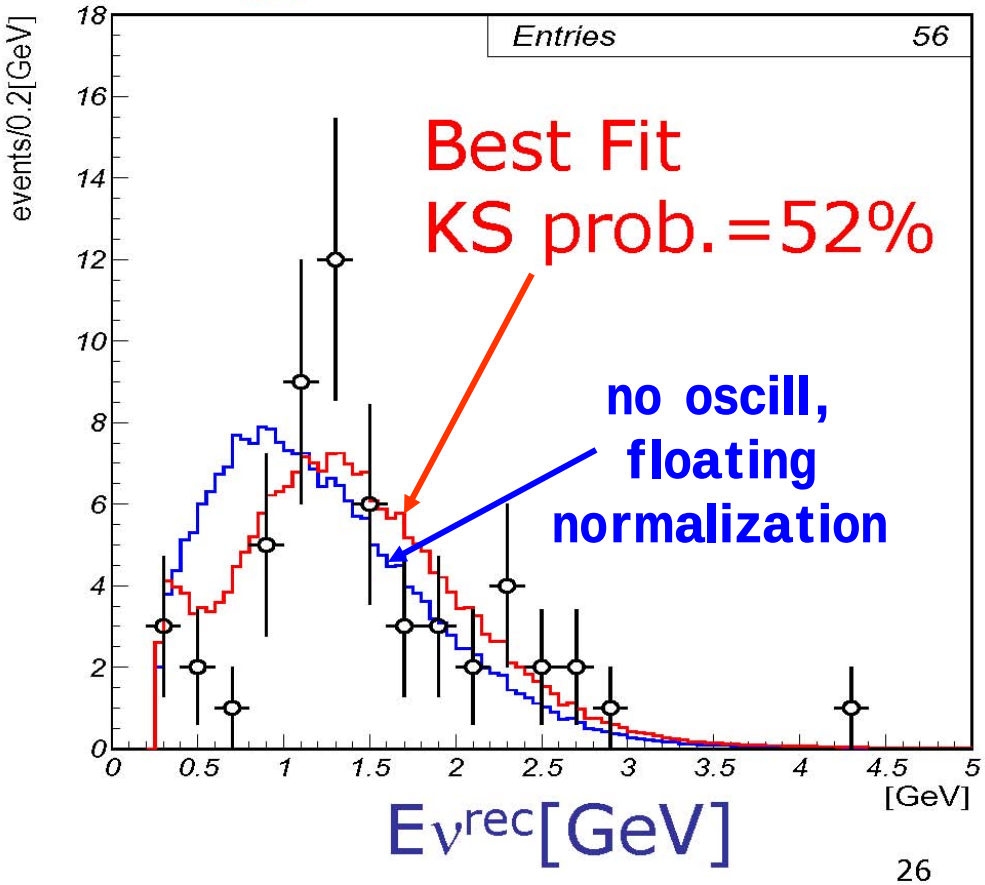


Although rate is low background greatly reduced by beam spill timing (0.83 ms delay, synchronized offline using GPS)

In the 3.5 yrs of data the atm nu background in the KEK beam spill window is 10^{-2} events

Expected no oscillation rate: $150.9^{+11.6}_{-10.0}$

- $N_{SK}^{obs}=108$
- N_{SK}^{exp} (best fit)=104.8

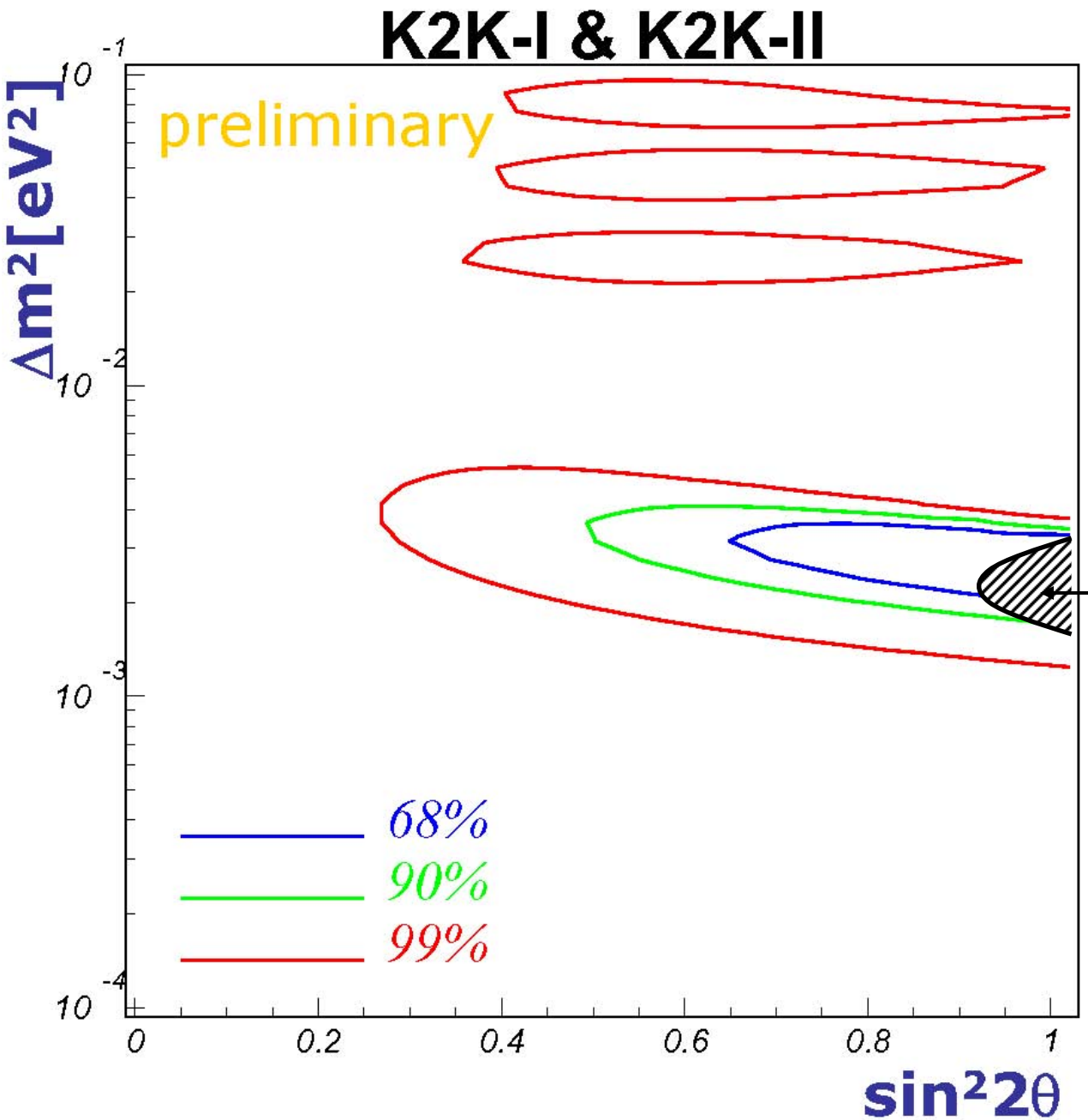


K2K establishes:

- **ν_μ disappearance at 2.9σ (standard physics has 0.33% CL)**
- **E_ν spectral distortion at 2.5σ (standard physics has 1.1% CL)**

Combined we have a 3.9σ effect (standard physics has 0.011% CL)

T.Nakaya, Nu2004



approximate 90% CL from global SK fit to atmospheric neutrinos

T.Nakaya, Nu2004

What we have discovered:

There is mixing involving νe with best fit at
$\Delta m^2 = 8.3 \cdot 10^{-5}$ eV^2 and $\theta = 32°$ ***(solar/KamLAND)***

There is also mixing involving ν_μ with best fit at
$\Delta m^2 = 2.7 \cdot 10^{-3}$ eV^2 and $\theta = 45°$ ***(atmospheric/K2K)***

If there are only 3 neutrino families, since the two mass differences are of different order of magnitude, we expect to find a third Δm^2 similar to the larger of the two above