Nuclear Physics School 2013

Scuola
di Fisica Nucleare
Raimondo Anni

Neutrino Physics

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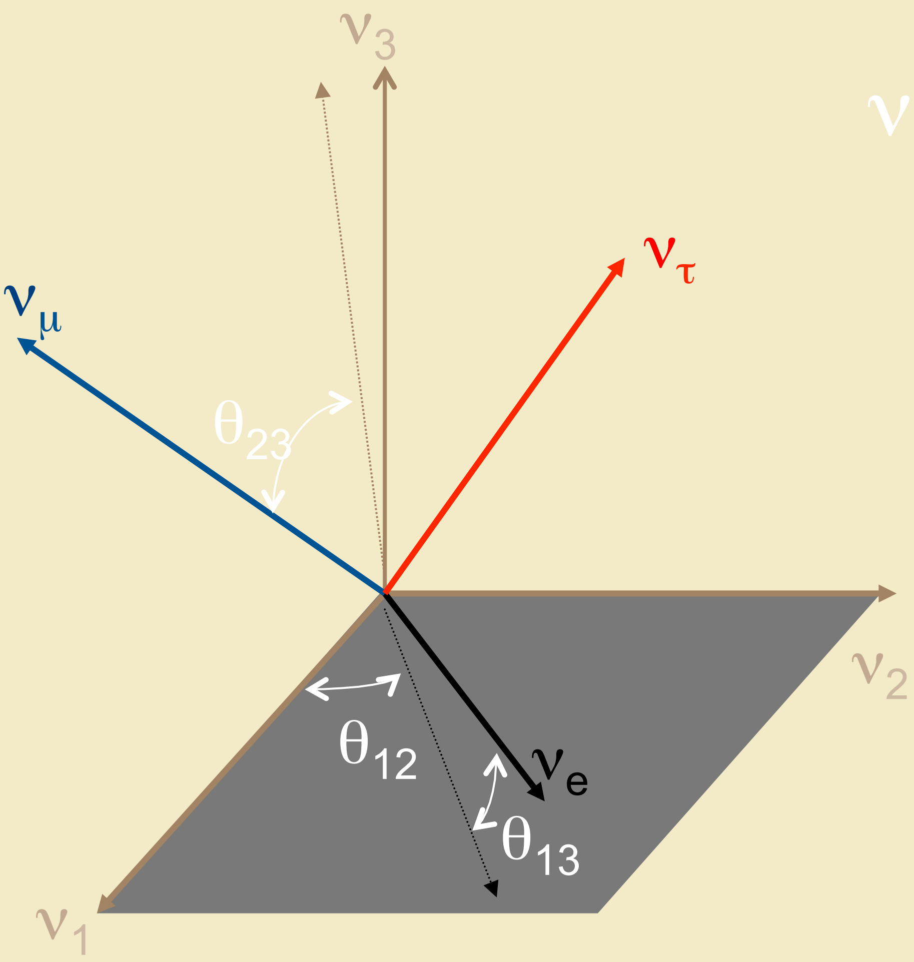
Part Two: Oscillation Phenomenology

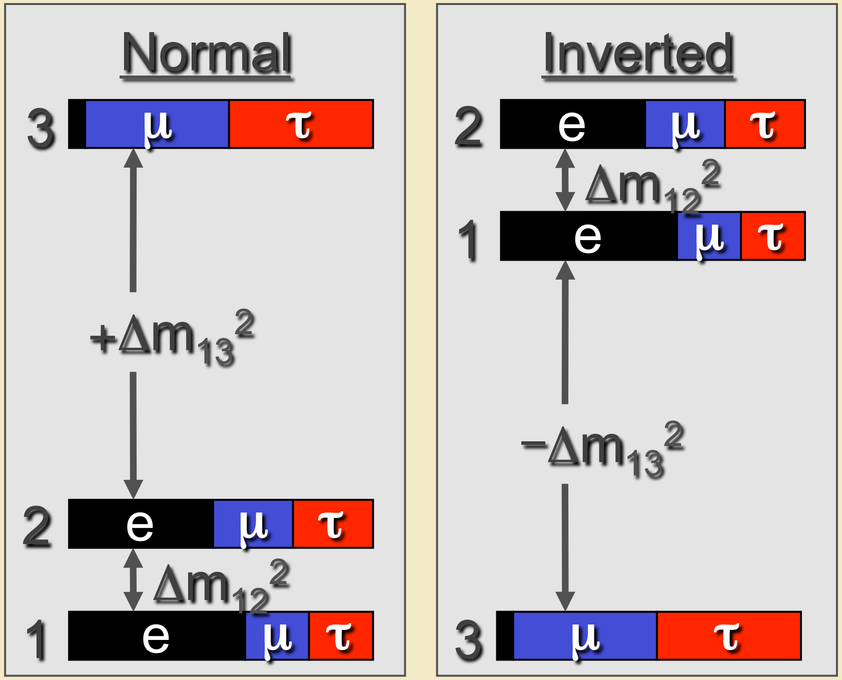
Notice: I strongly acknowledge Eligio Lisi for allowing me to use part of his presentations done in CHIPP PhD Winter School, Jan. 2013, Grindelwald, Switzerland

Neutrino mass spectrum and mixing

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}1 & & \\ & \cos\theta_{23} & -\sin\theta_{23}\\ & \sin\theta_{23} & \cos\theta_{23}\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_{13} & & -e^{i\delta_{CP}}\sin\theta_{13}\\ & 1 & \\ e^{i\delta_{CP}}\sin\theta_{13} & & \cos\theta_{13}\end{bmatrix}\cdot\begin{bmatrix}\cos\theta_{12} & -\sin\theta_{12} & \\ \sin\theta_{12} & \cos\theta_{12} & \\ & & 1\end{bmatrix}\cdot\begin{bmatrix}e^{i\varphi_1} & & \\ & e^{i\varphi_2} & \\ & & 1\end{bmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

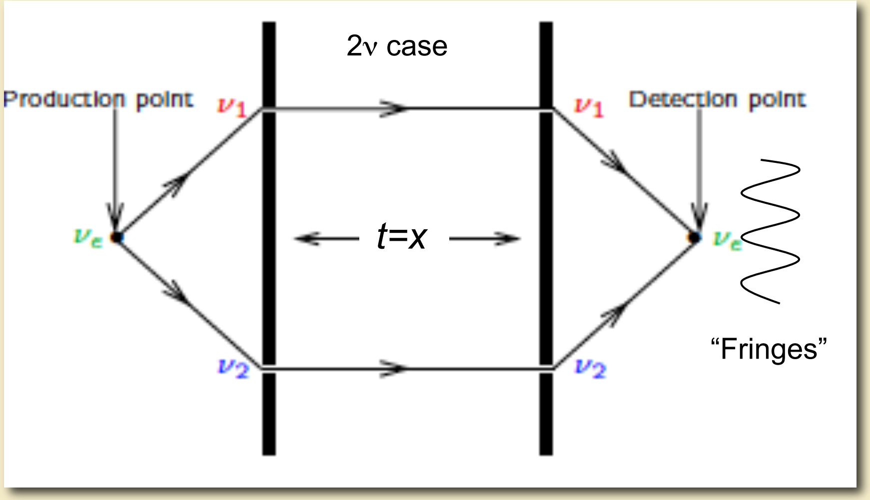


$\varphi_{1,2}$ are “physical” only if neutrinos are Maiorana particles. Anyway they are unobservable in oscillation experiments



Flavor oscillations

Each mass eigenstate propagates in a different way



$$i\frac{d}{dx}\nu_i = E_i\nu_i = \sqrt{p^2+m_i^2}\,\nu_i \cong \left(p+\frac{m_i^2}{2E}\right)\nu_i$$

$$i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{U_\theta M^2 U_\theta^T}{2E}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

2ν case:

$$P(\nu_\alpha \to \nu_\beta; x) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 x}{4E_\nu}\right)$$

≥3ν case:

$$P(\nu_\alpha \to \nu_\beta; x) = \delta_{\alpha\beta} - 4\sum_{k>j}\Re\left[U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}\right]\sin^2\left(\frac{\Delta m^2_{jk}x}{4E_\nu}\right)$$

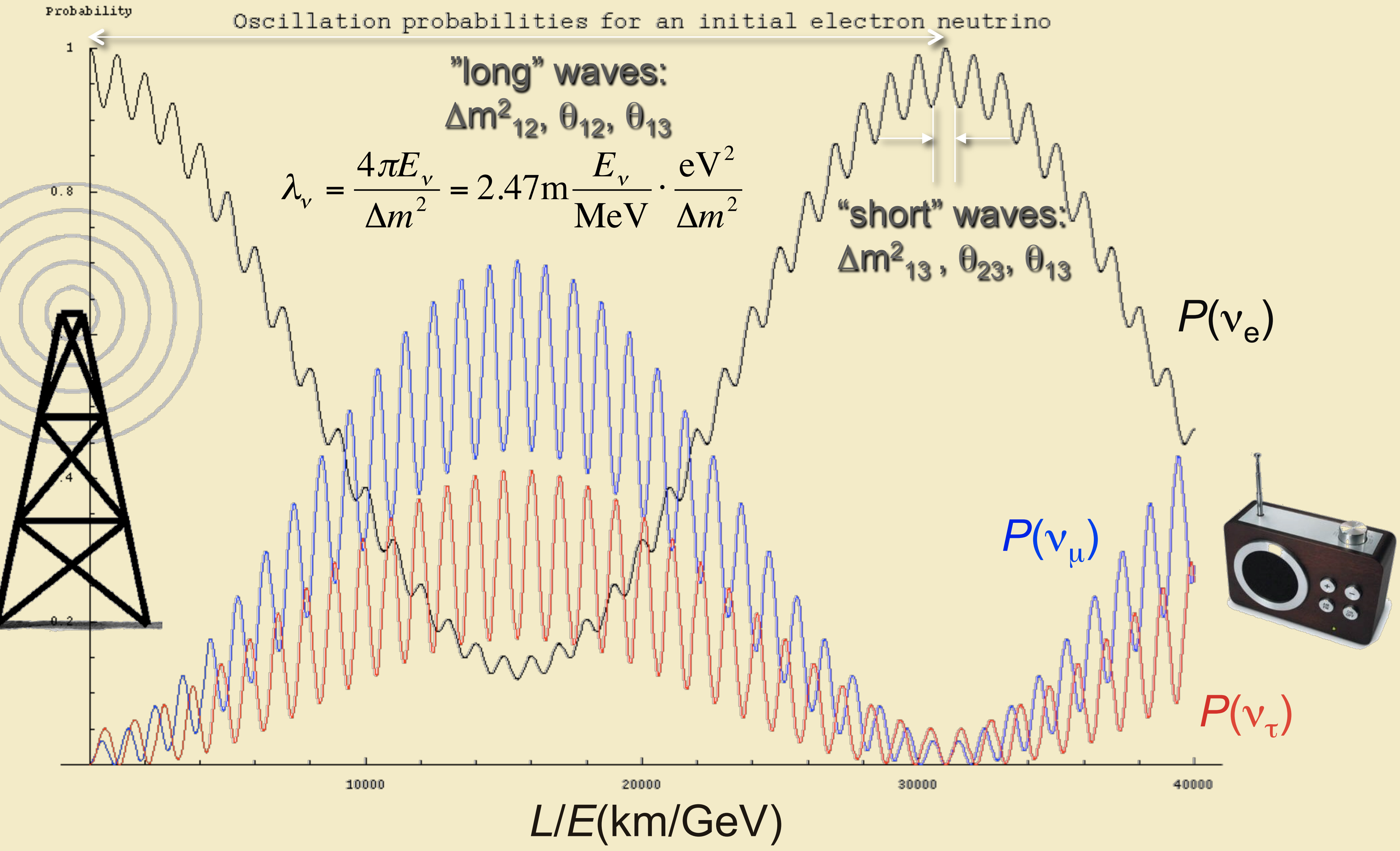
← CP even

$$+\,4\sum_{k>j}\Im\left[U_{\alpha j}U^*_{\beta j}U^*_{\alpha k}U_{\beta k}\right]\sin\left(\frac{\Delta m^2_{jk}x}{4E_\nu}\right)$$

← CP odd

reverse the sign for antiν

Flavor oscillations



"long" waves:
Δm^2_{12}, θ_{12}, θ_{13}

$$\lambda_\nu = \frac{4\pi E_\nu}{\Delta m^2} = 2.47\text{m}\frac{E_\nu}{\text{MeV}} \cdot \frac{\text{eV}^2}{\Delta m^2}$$

"short" waves:
Δm^2_{13} , θ_{23}, θ_{13}

One mass scale dominance

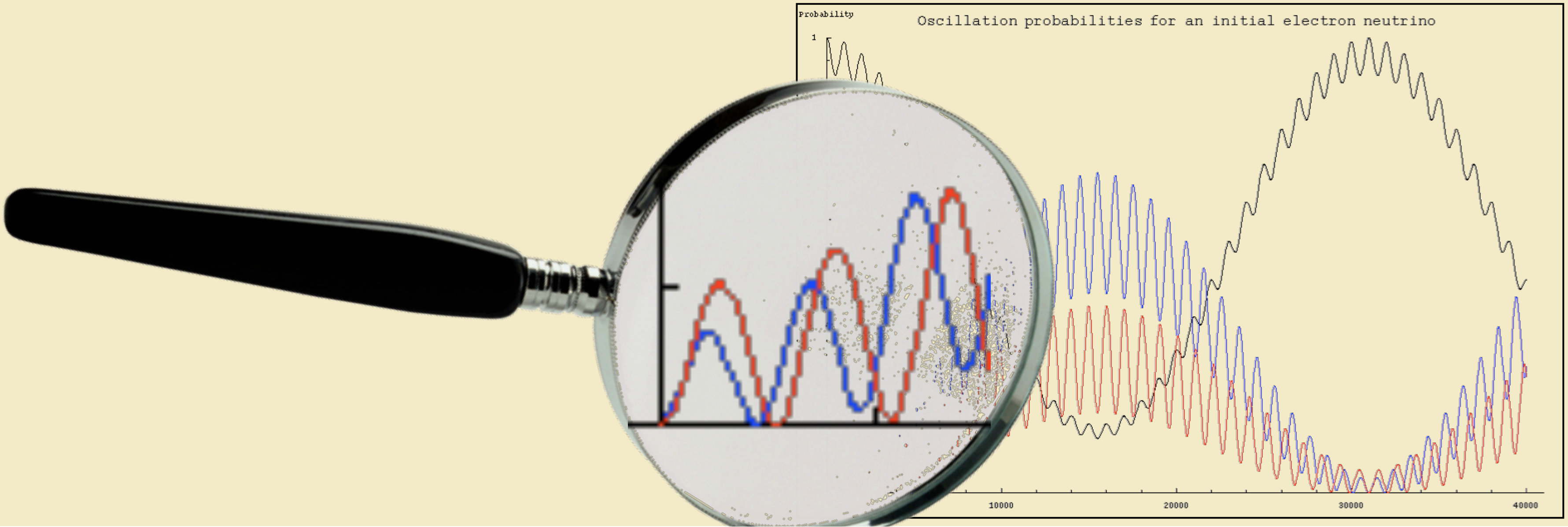
It is almost impossible to observe both “wavelength” in a single experiment. In practice for each experiment only one scale of mass is dominant. For example when (“short” waves)

$$\frac{\Delta m^2_{23} x}{4E} \sim O(1), \quad \frac{\Delta m^2_{12} x}{4E} \ll 1$$

(high energy and/or or short baseline) oscillation probability can be written as

$$P_{\alpha\alpha} \simeq 1 - 4|U_{\alpha 3}|^2 (1 - |U_{\alpha 3}|^2) \sin^2 \frac{\Delta m^2_{23} x}{4E}$$

$$P_{\alpha\beta} \simeq 4|U_{\alpha 3}|^2 |U_{\beta 3}|^2 \sin^2 \frac{\Delta m^2_{23} x}{4E} \quad (\beta \neq \alpha)$$



One mass scale dominance

Previous formulae is similar to those of 2ν case but with the identification

$$\sin^2\theta \equiv |U_{\alpha 3}|^2, \quad (\nu_\alpha \to \nu_\alpha)$$

$$\sin^2 2\theta \equiv 4|U_{\alpha 3}|^2|U_{\beta 3}|^2, \quad (\nu_\alpha \to \nu_\beta)$$

Oscillation experiments are often analyzed in term of two generations. However, with the previous identifications the results can be interpreted in term of 3 generations.

One mass scale dominance

Conversely, the opposite regime is (long waves)

$$\frac{\Delta m^2_{23} x}{4E} \gg 1, \quad \frac{\Delta m^2_{12} x}{4E} \sim O(1)$$

(low energy and/or long baseline). Normally this regime has interest only for low energy electron neutrinos (KamLand experiment). In this case the “fast” oscillations can be “averaged” yielding

$$P_{ee} = c^4_{13} \left[1 - \sin^2 2\theta_{12} \frac{\Delta m^2_{12} x}{4E} \right] + s^4_{13}$$

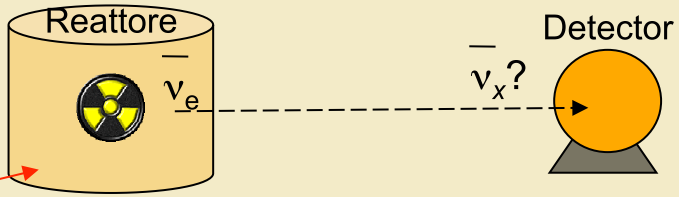
For (low energy) solar neutrinos, when matter effects are dominant, it can be shown that one mass scale dominance is also effective. In particular, the average on the “fast” oscillations yield

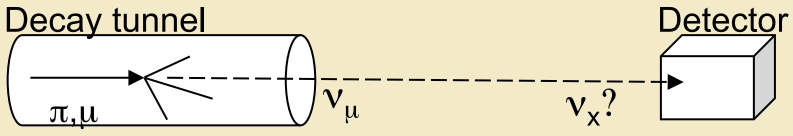
$$P_{ee} = c^4_{13} P^{2\nu}(\Delta m^2_{12}, \theta_{12})|_{N_e \rightarrow N_e c^2_{13}} + s^4_{13}$$

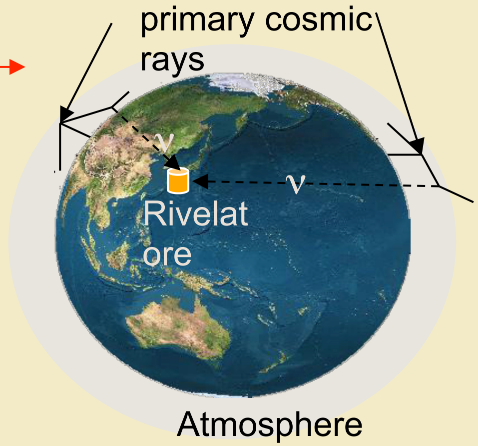
<u>hereafter</u> $\delta m^2 \equiv \Delta m^2_{12}, \;\; \Delta m^2 \equiv \Delta m^2_{13}$

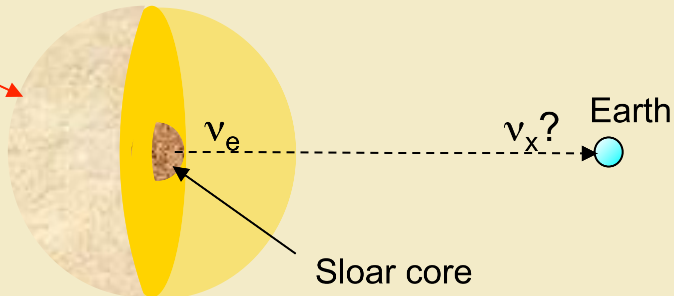
Sources of neutrinos

Main neutrino sources			
Origin	**Source**		E_ν
"Terrestrial"	**Artificial**	**Reactors**	~O(MeV)
		Accelerator	≥1GeV
	Atmspheric		1÷100GeV
	Geoneutrinos		≤2MeV
"Astrophysical"	**Solar**		0÷15MeV
	Type II supernovae		0÷30MeV
"Cosmic"	**Very High Energy (GRB's Blazars etc.)**		>>100GeV
	Primordial (Big Bang)		<<1eV

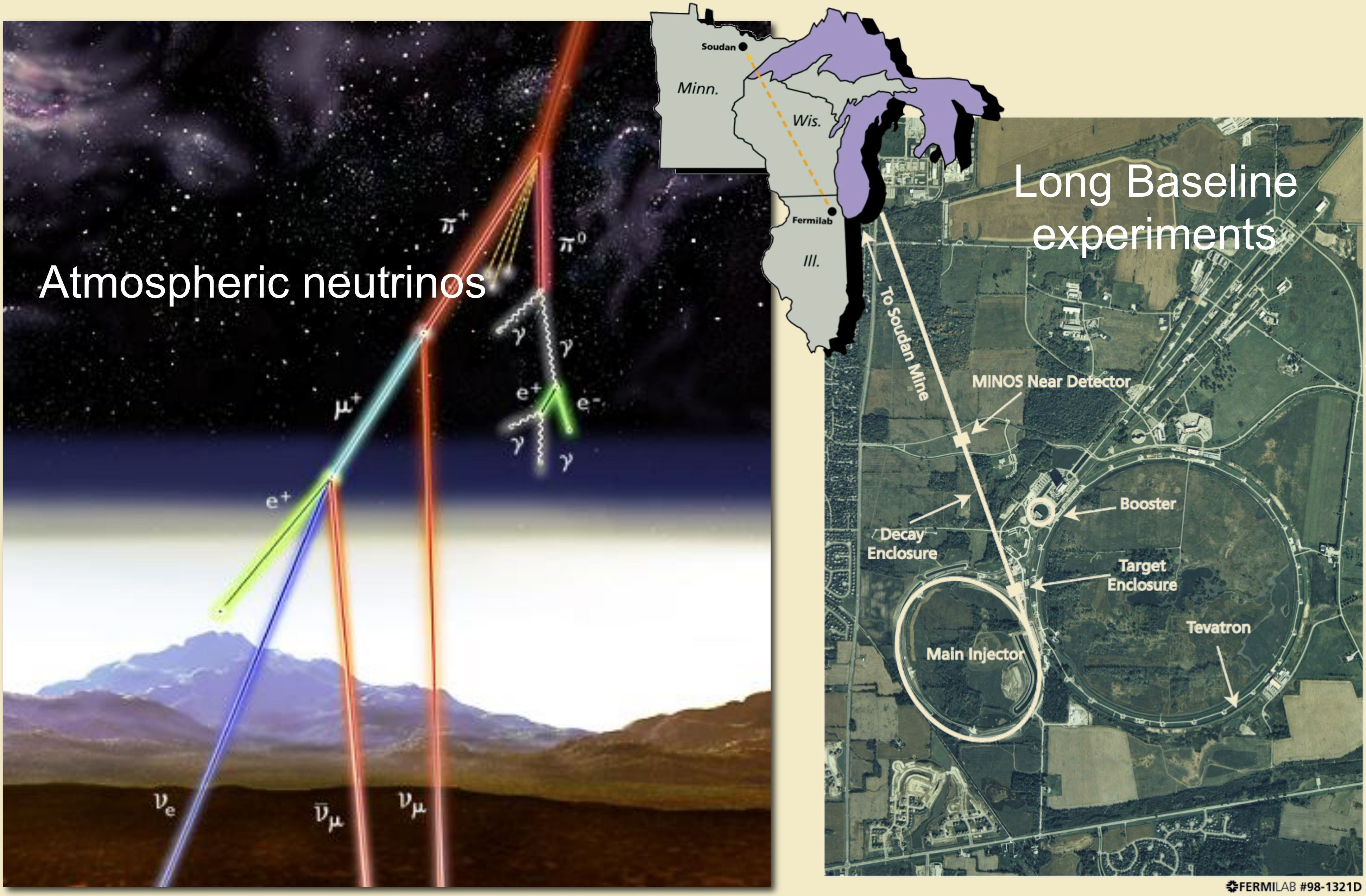








Tuning on short waves (E~GeV)…



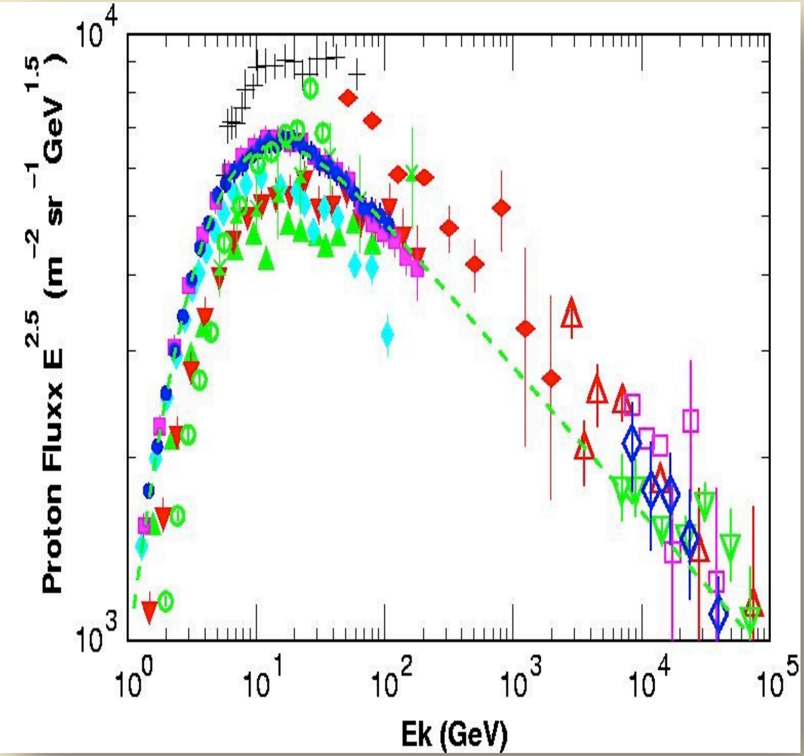
Atmospheric neutrinos

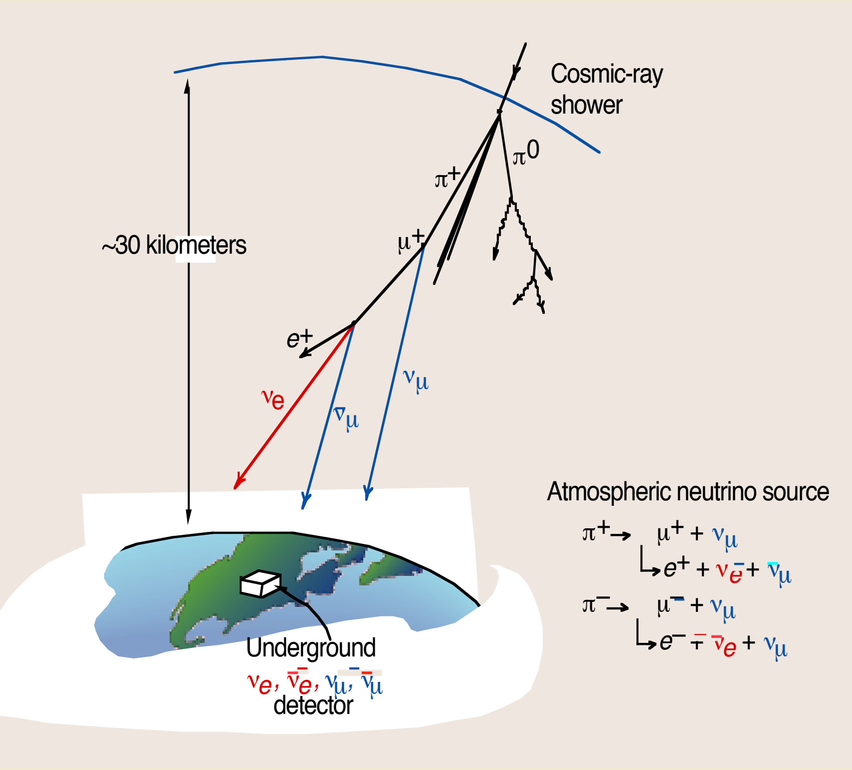
Long Baseline experiments

FERMILAB #98-1321D

Atmospheric neutrinos

Cosmic rays hitting the atmosphere can generate secondary (anti)neutrinos with electron and muon flavor via meson decays.

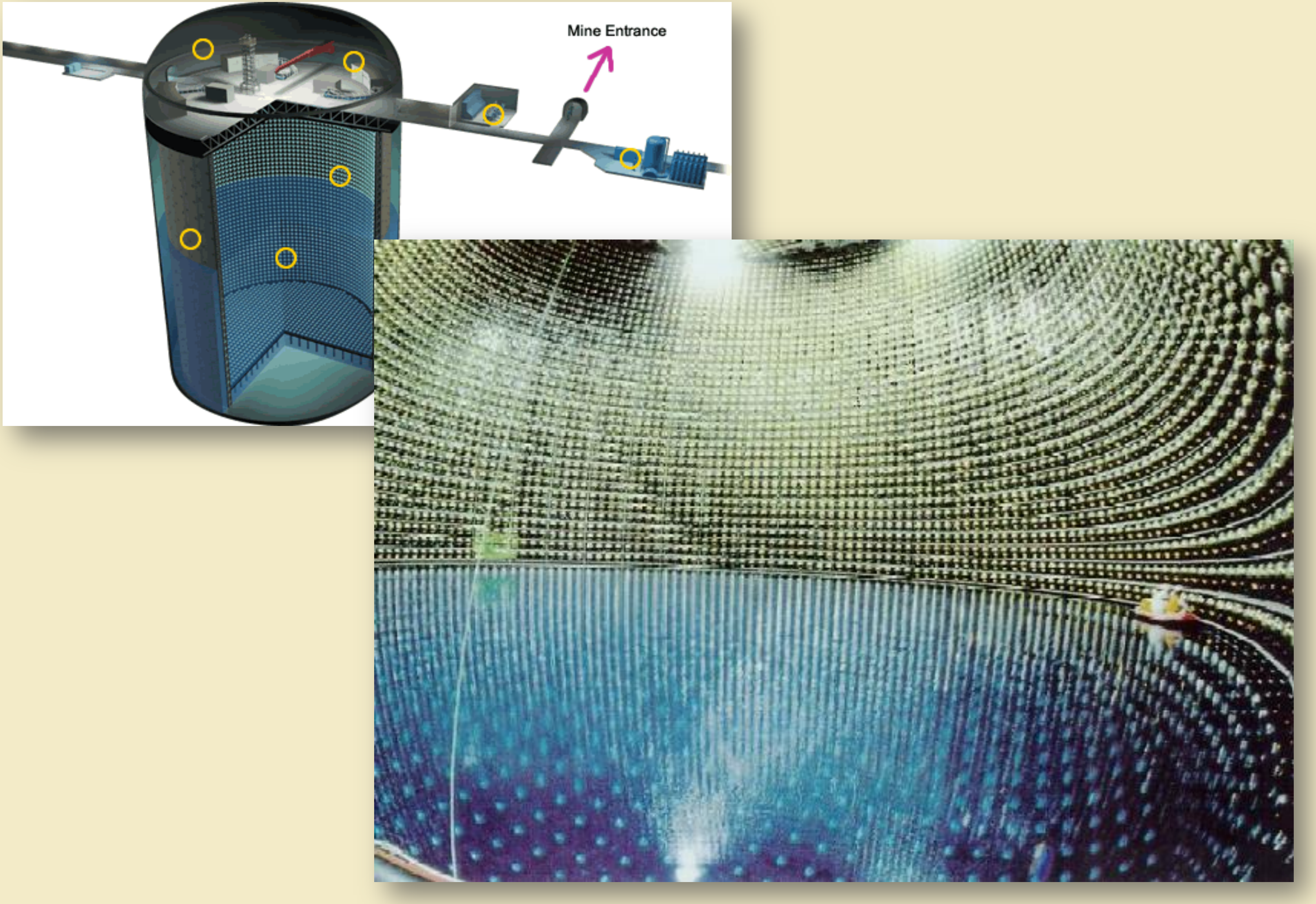




Primary flux affected by large normalization uncertainties…

… but (anti)neutrino **flavor ratio (μ/e ~ 2)** robust within few %

SuperKamiokande

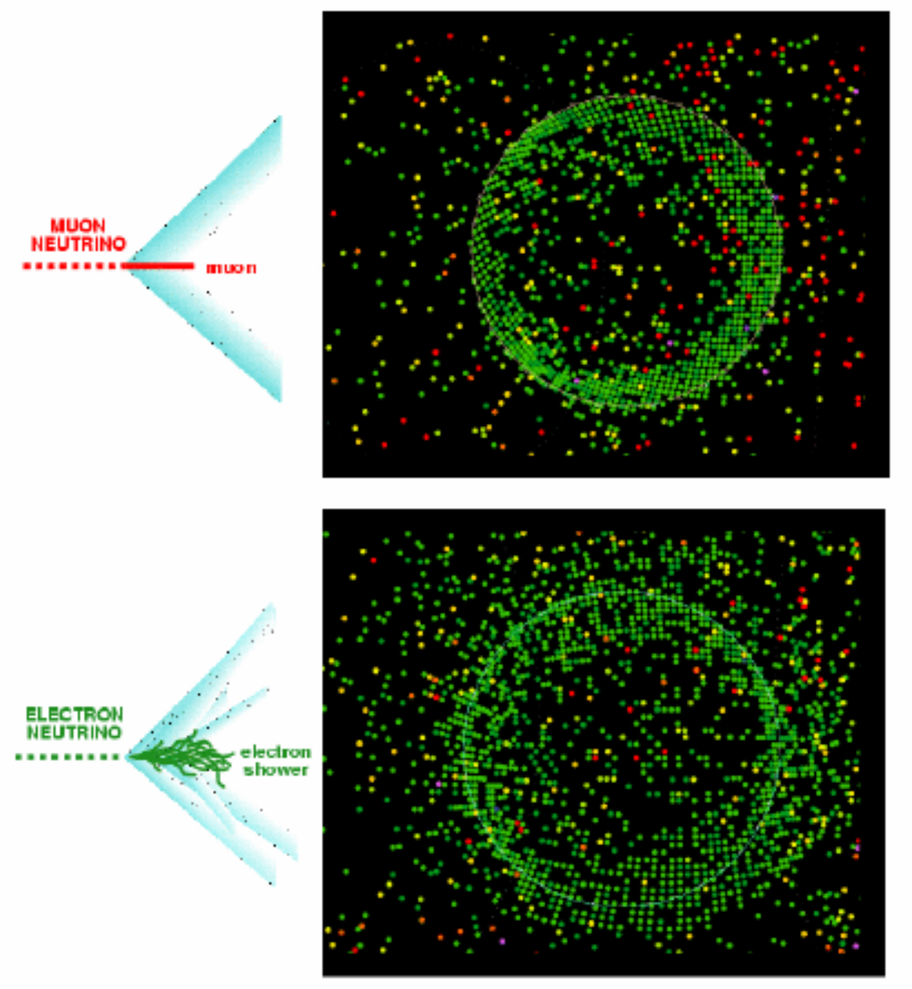


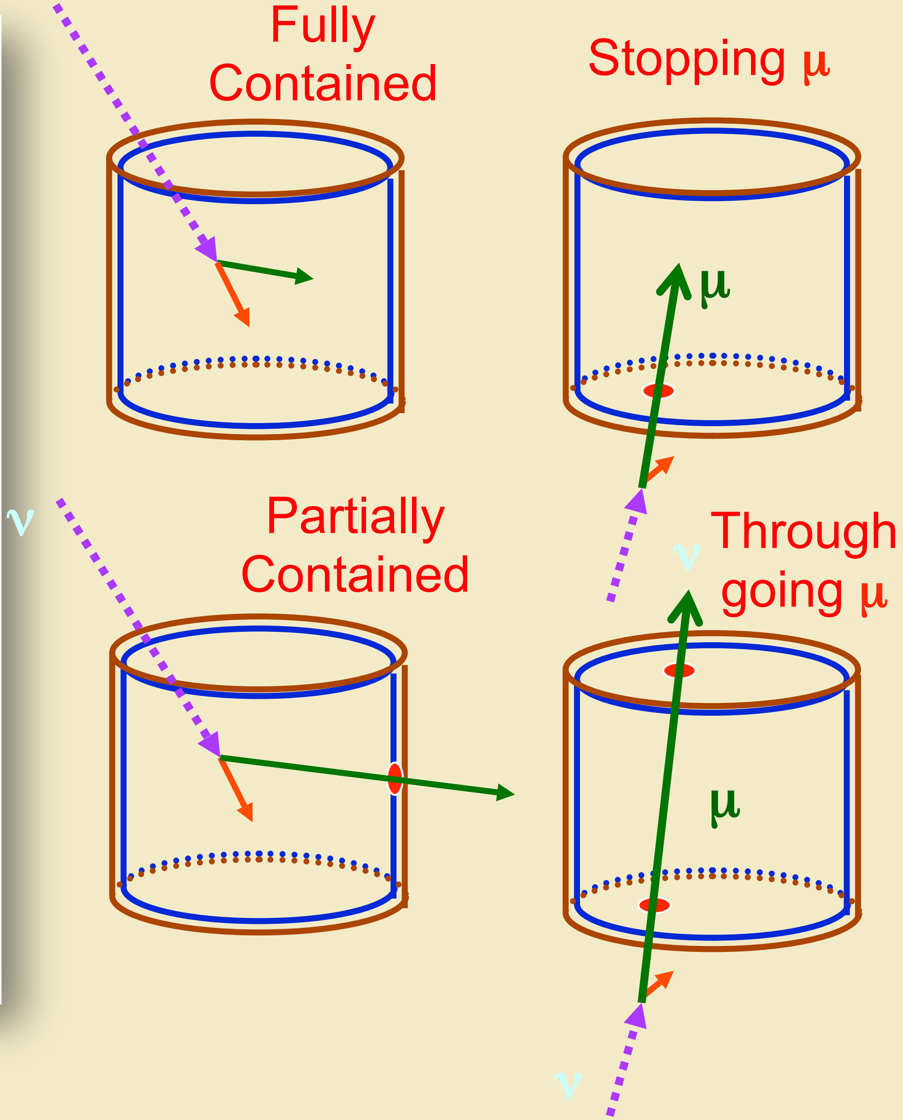
Detection in SK

Parent neutrinos detected via CC interactions in the target (water).

Final-state μ and e distinguished by ≠ Cherenkov ring sharpness.

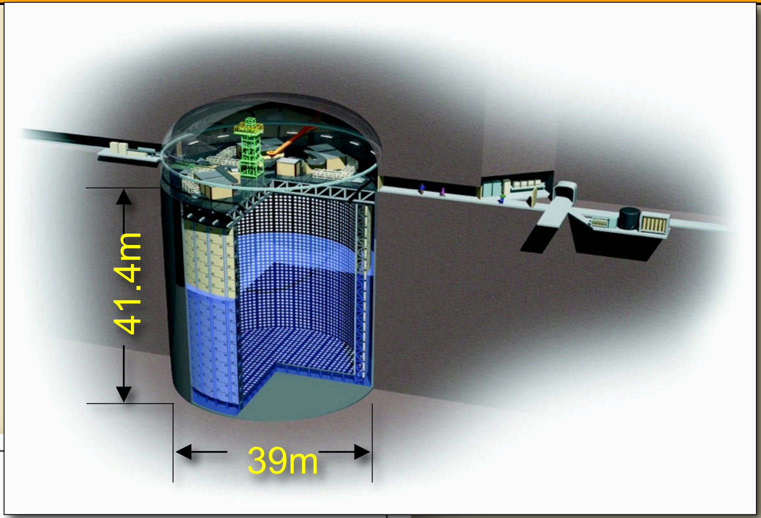
(But: no charge discrimination, no τ event reconstruction). Topologies:





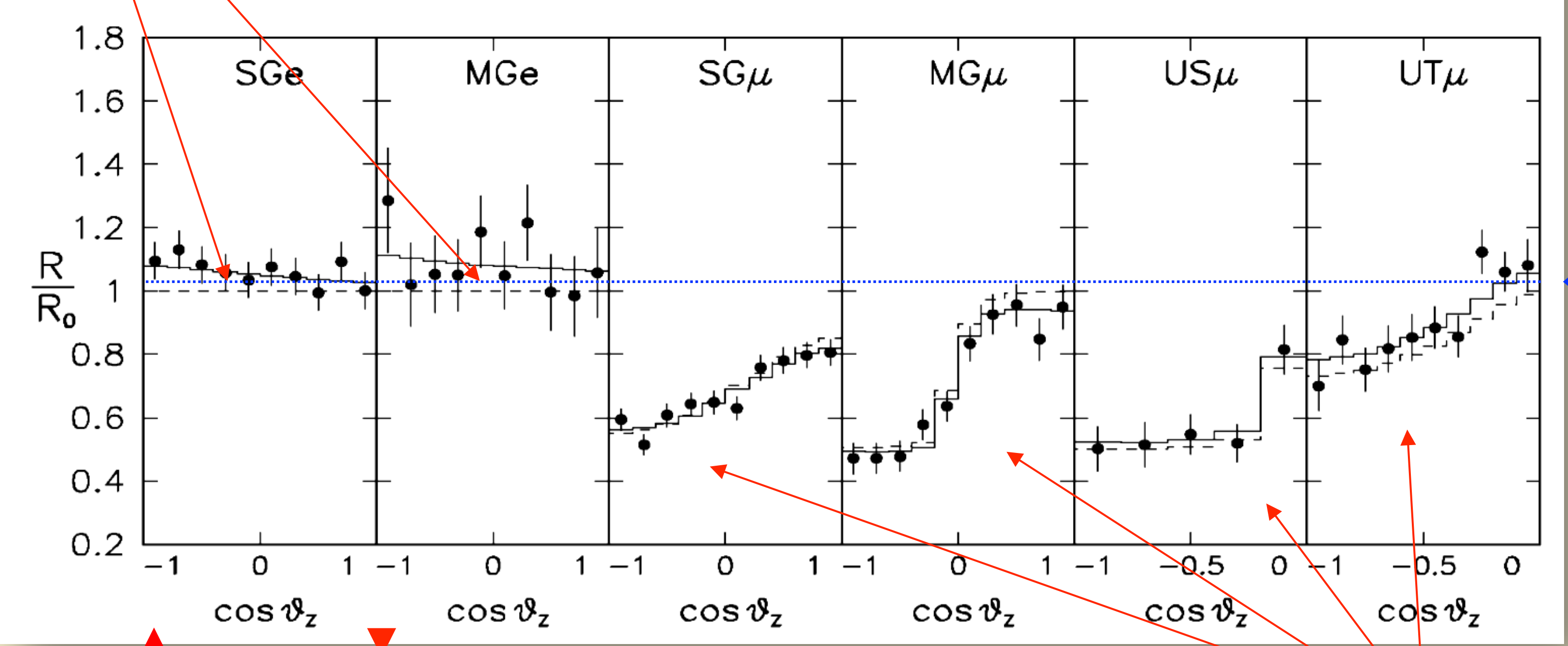
The SuperKamiokande atmospheric neutrino anomaly

SGe	Sub-GeV electrons
MGe	Multi-GeV electrons
SGμ	Sub-GeV muons
MGμ	Multi-GeV muons
USμ	Upward Stopping muons
UTμ	Upward Through-going muons



Super-Kamiokande (92 kTy)
e, μ zenith distributions
normalized to no oscillation

SK data
Best fit (standard oscillations)
Best fit + systematic shifts



ν_e ~OK

no osc.

up

down

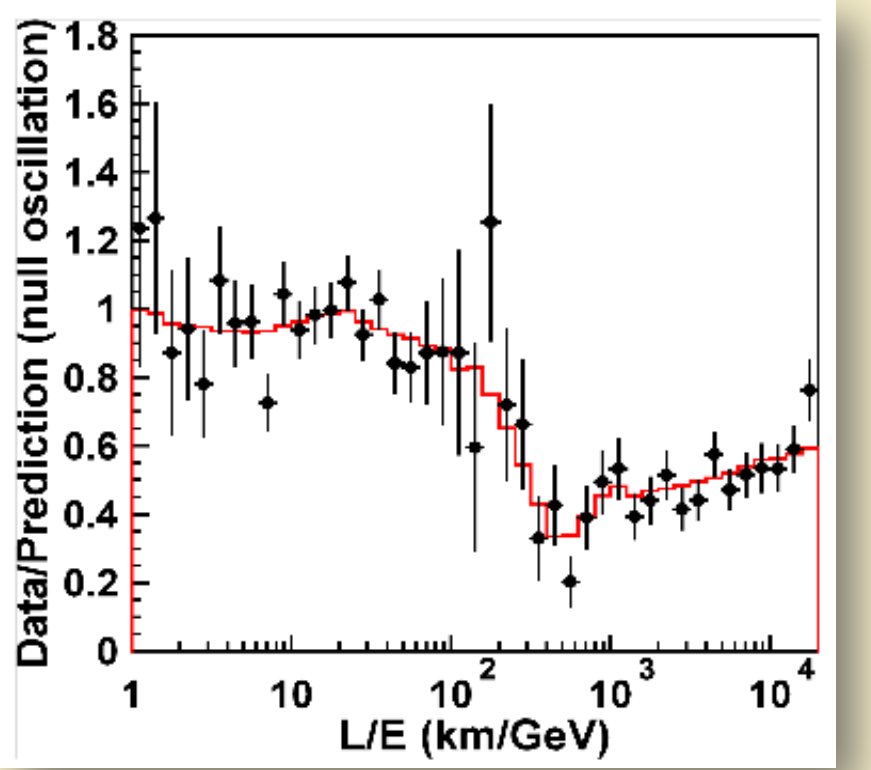
deficit of ν_μ from bottom

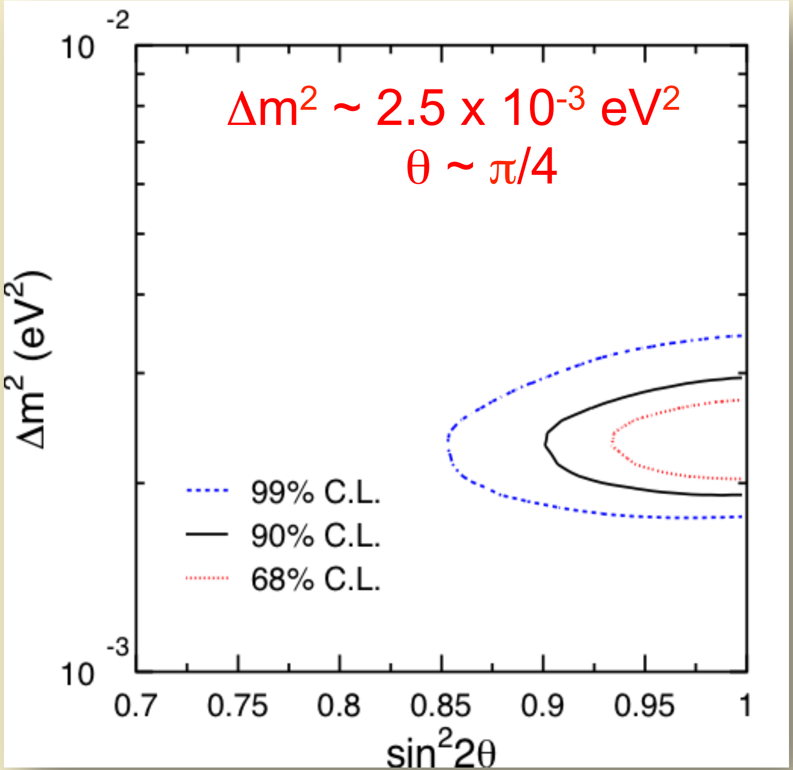
The SuperKamiokande atmospheric neutrino anomaly

Dedicated L/E analysis in SK “sees” half-period of oscillations

1st oscillation dip still visible
despite large L & E smearing

Strong constraints on the
parameters (Δm^2, θ)



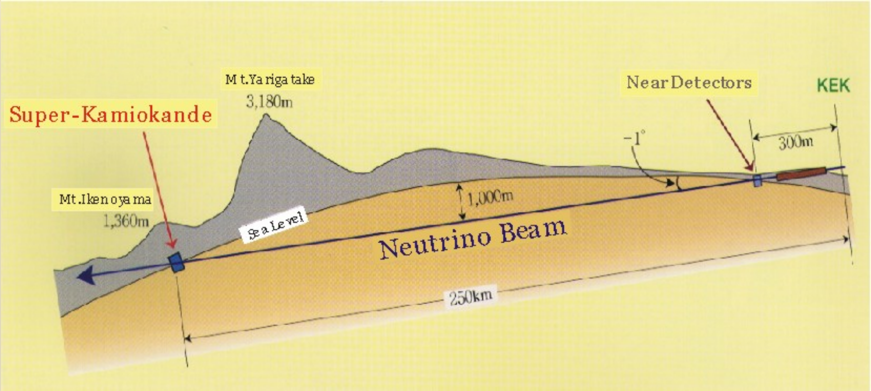


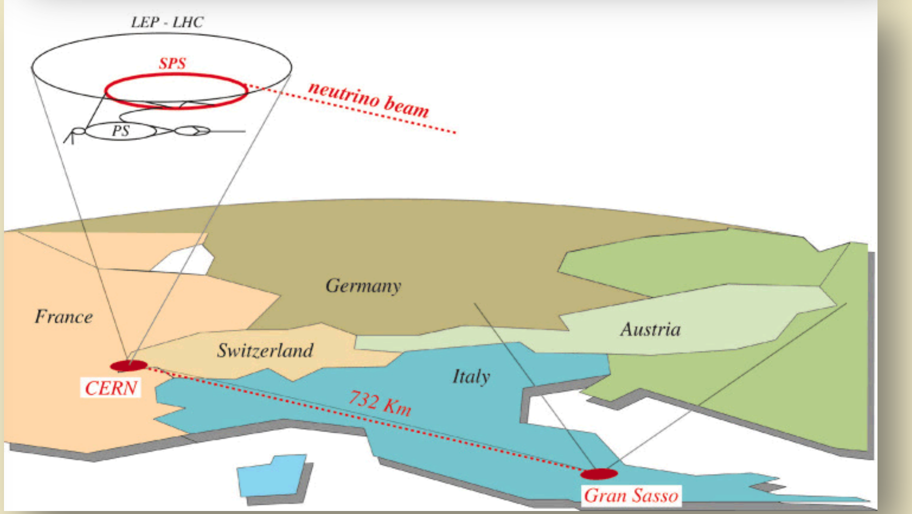
$\Delta m^2 \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\theta \sim \pi/4$

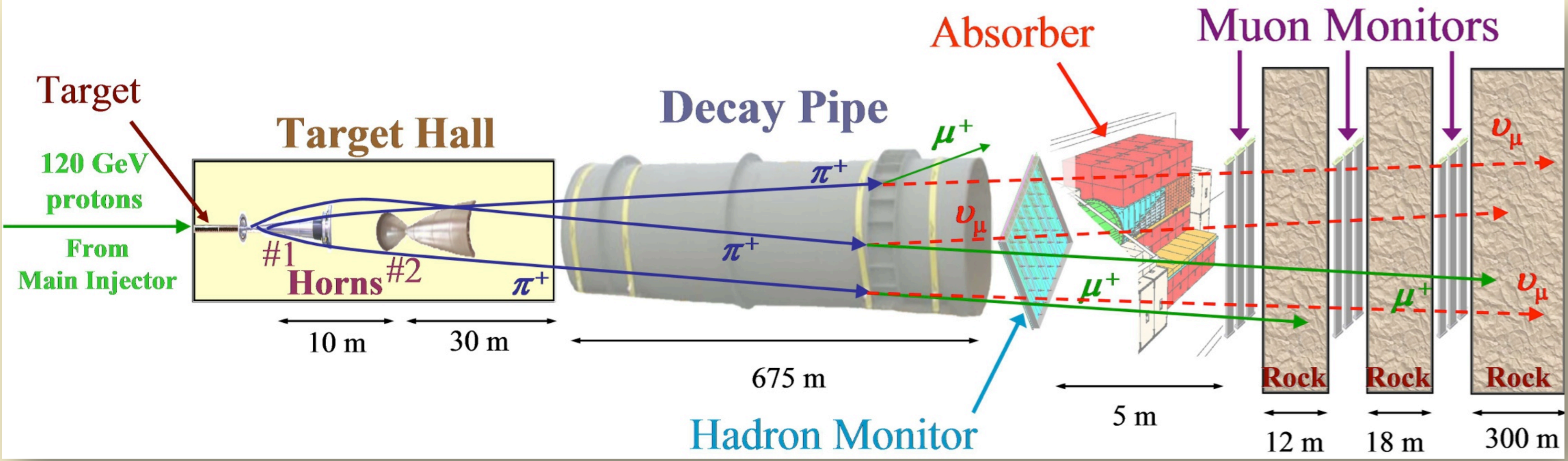
Long-baseline neutrino experiments

“Reproducing atmospheric ν_μ physics” in controlled conditions



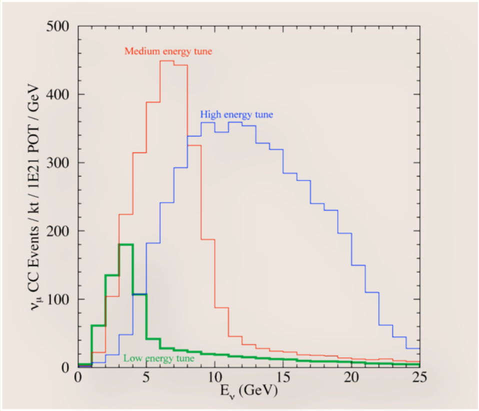


Production (e.g., MINOS)

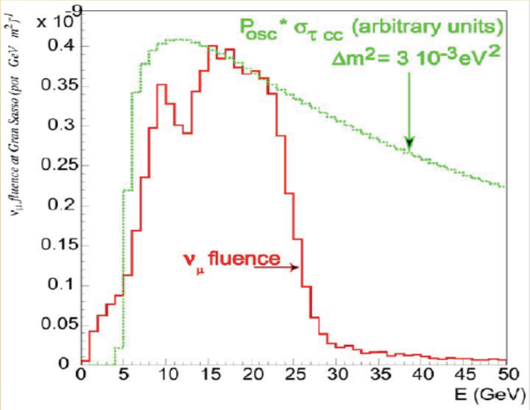


π decay: ν energy is only function of $\nu\pi$ angle and π energy

Spectra:



MINOS



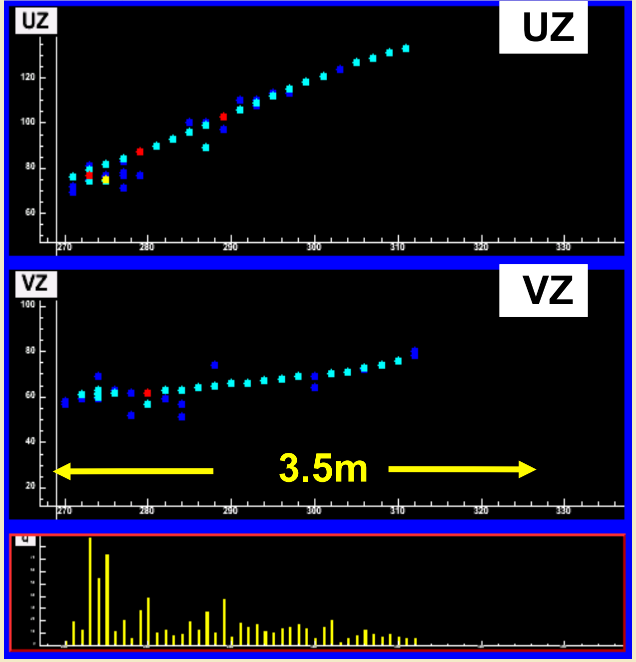
OPERA

(Far) Detection

K2K, T2K: Cherenkov technique in SK

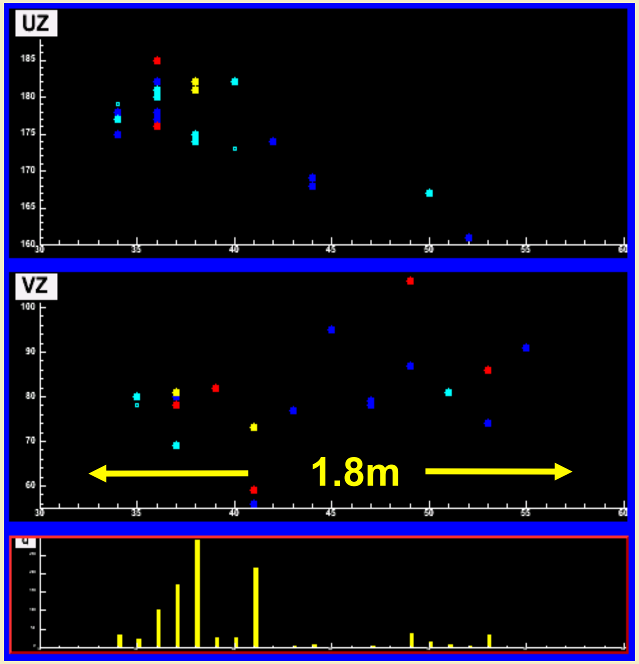
MINOS: Steel/Scintillator detector (+ magnetic field)

ν_μ CC Event



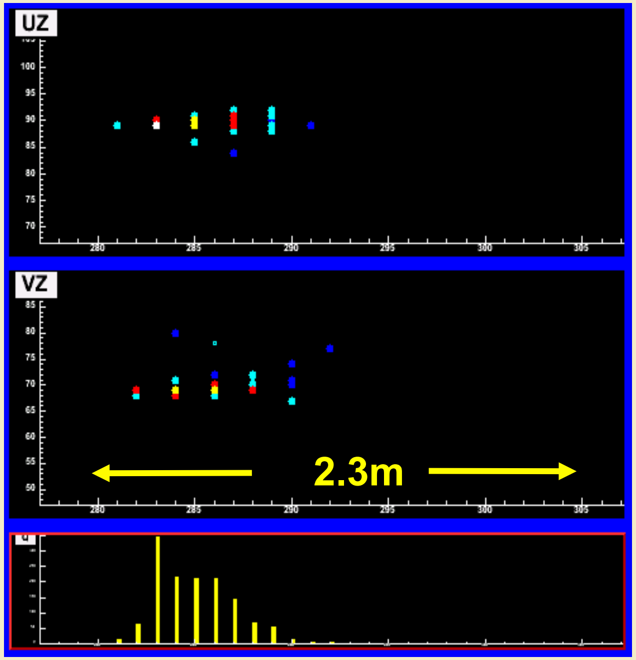
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

ν_e CC Event

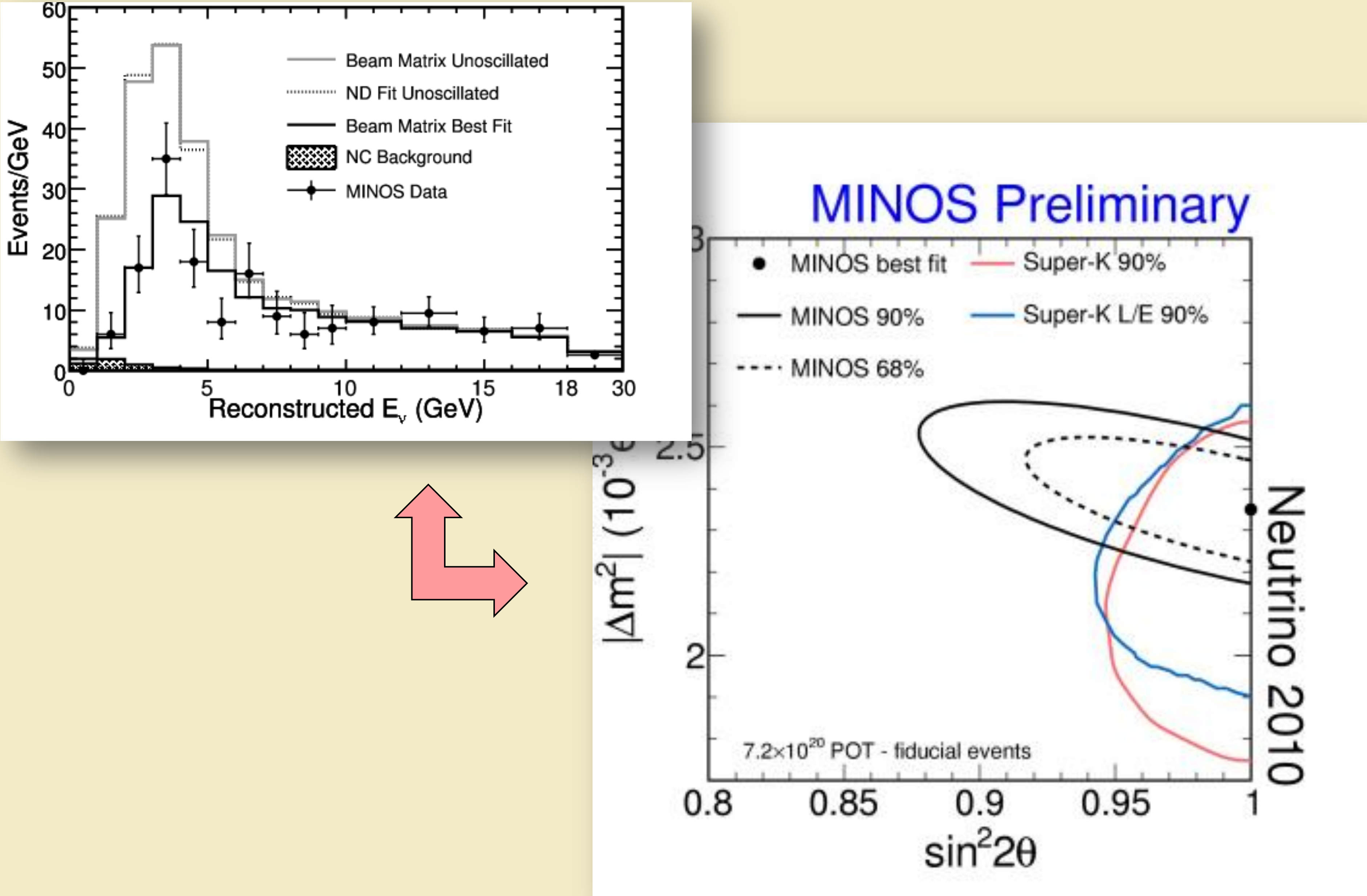


- Short event with typical EM shower profile

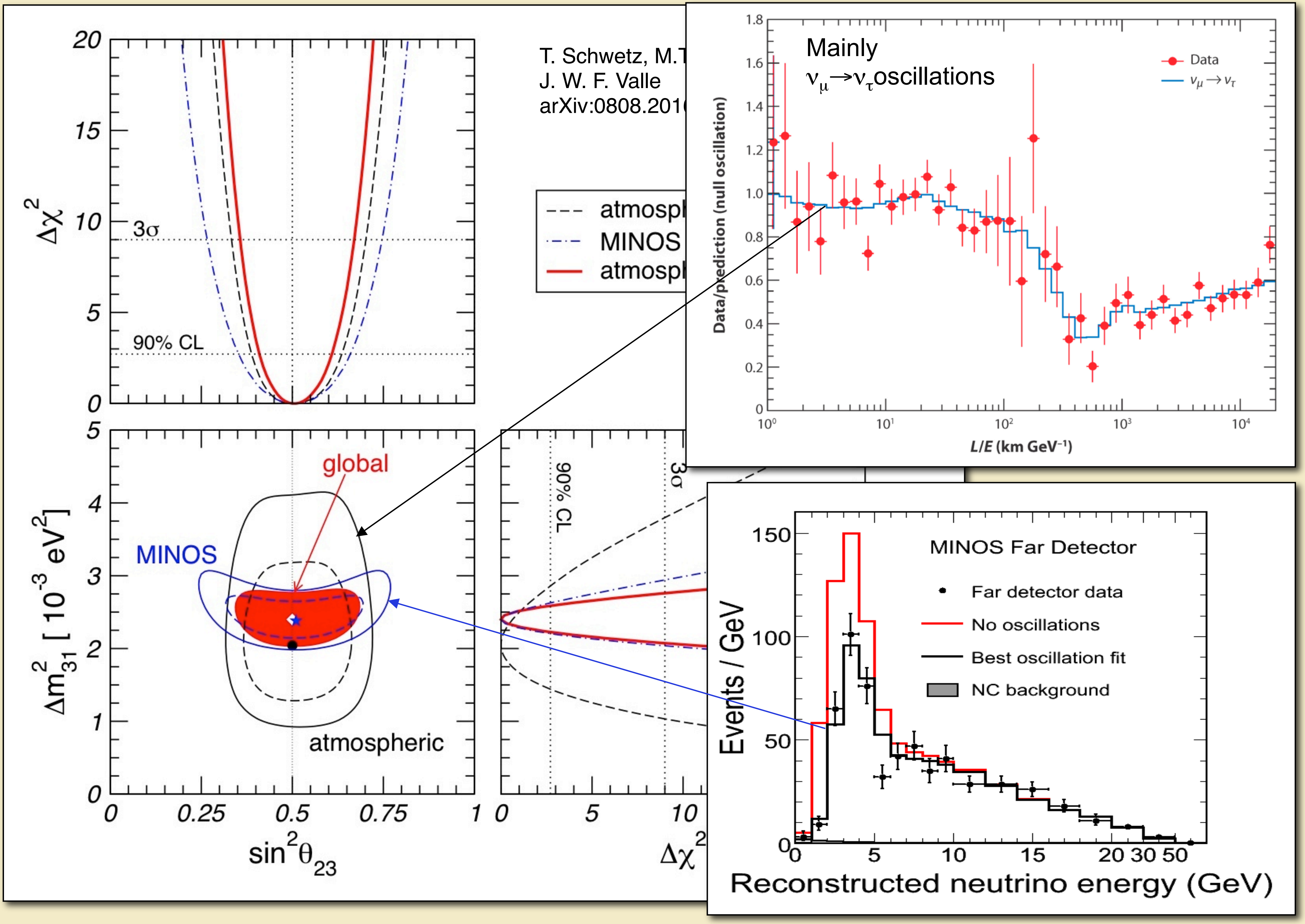
K2K, MINOS, T2K supplemented by near detectors to measure disappear. $P_{\mu\mu}$

MINOS results

Clear evidence of ν_μ disappearance

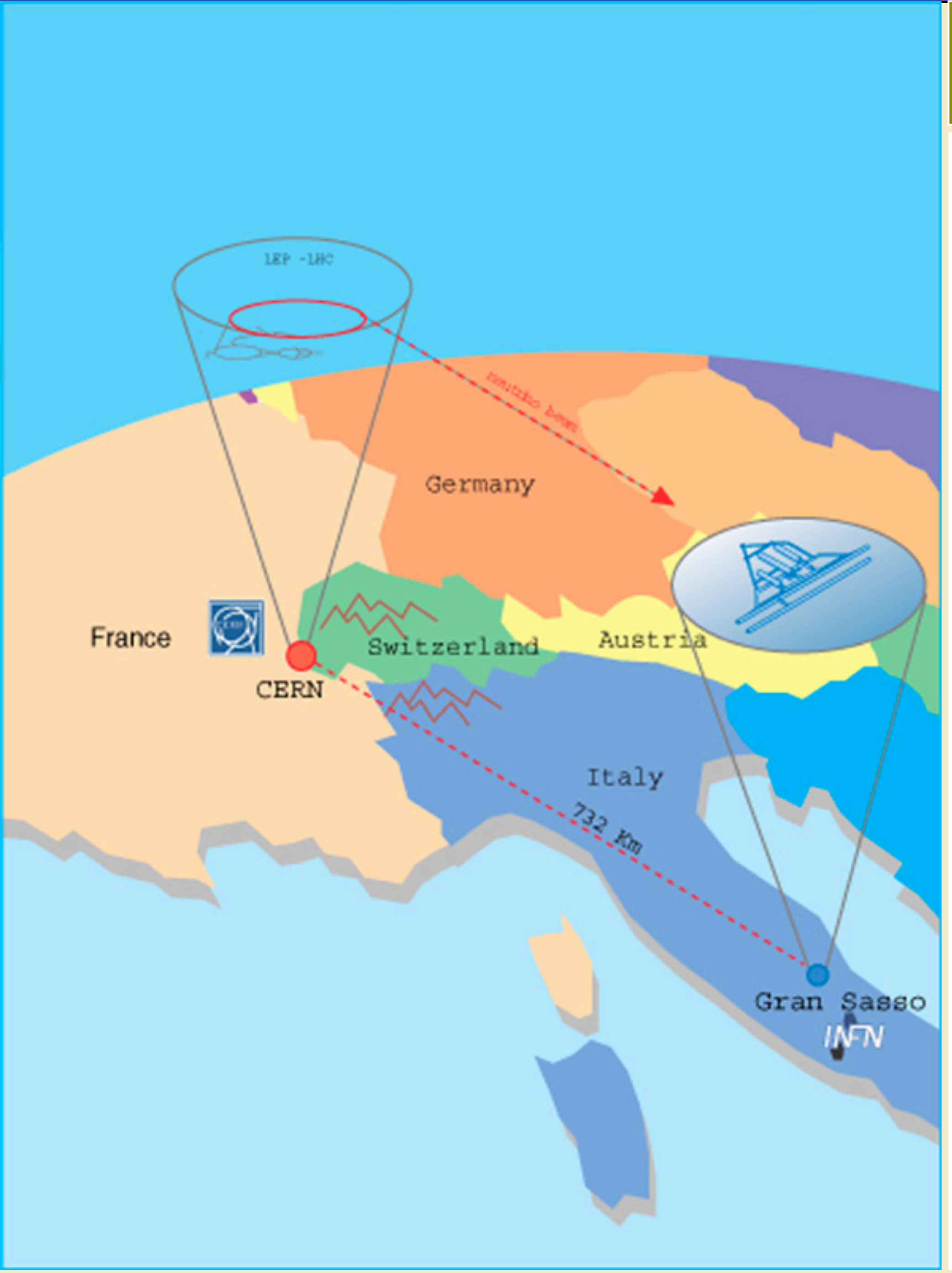


Tuning on short waves (E~GeV)…

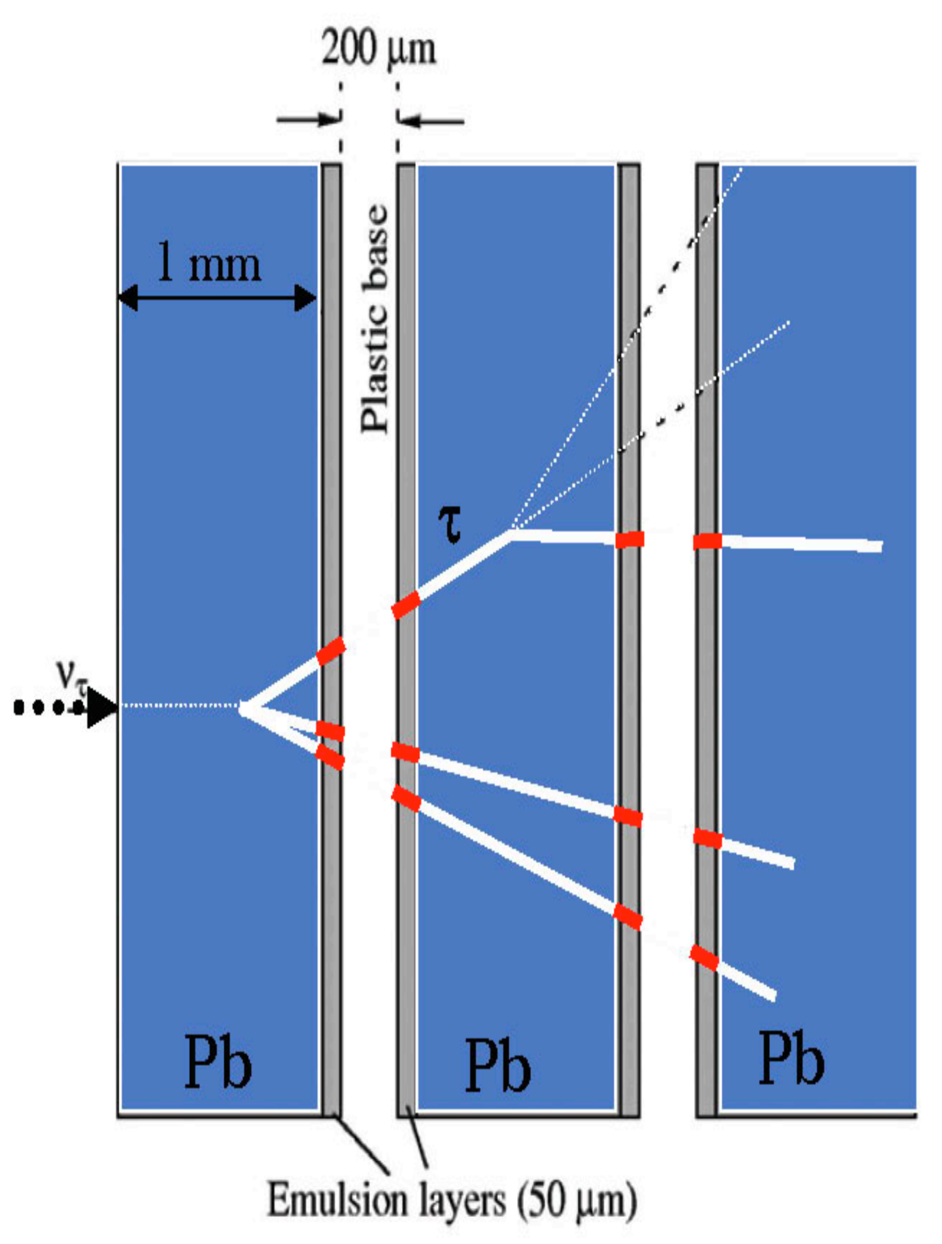


T. Schwetz, M.T
J. W. F. Valle
arXiv:0808.201

Testing ν_τ appearance

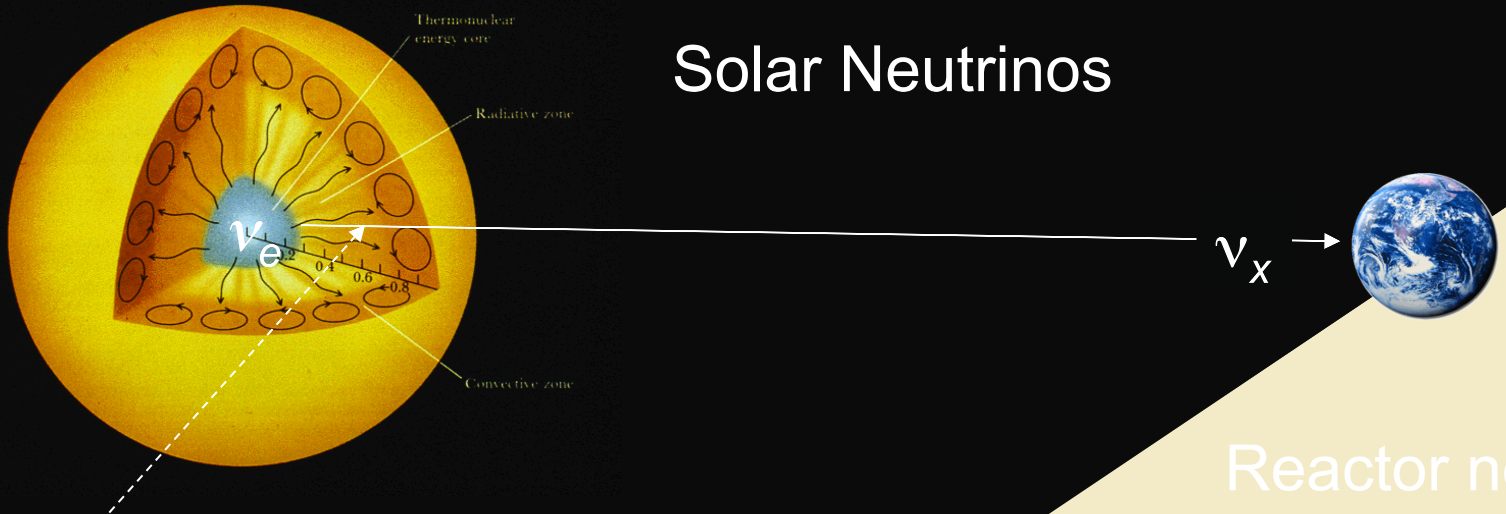


Two ν_τ have been seen in the OPERA experiment. Expected 5 in 5 years.

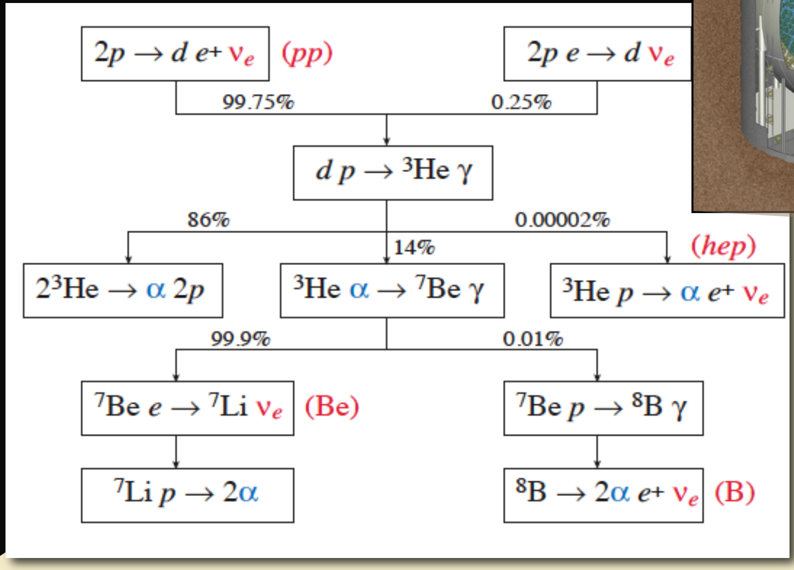


Tuning on long waves (E~MeV)...

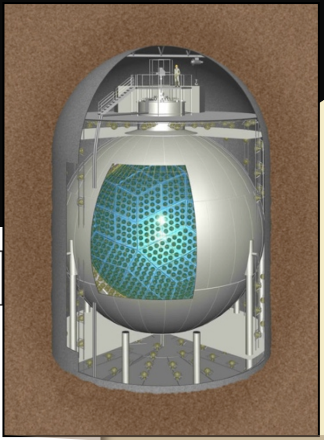
Solar Neutrinos

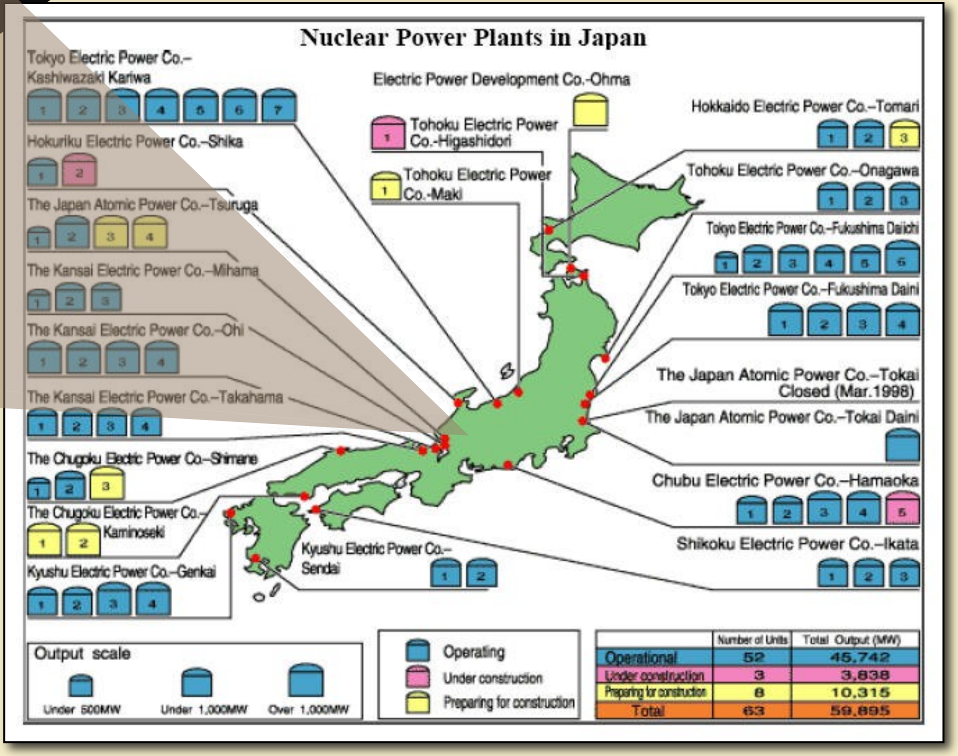


Coherent scattering of neutrinos modifies the evolution equation in matter (MSW effect)



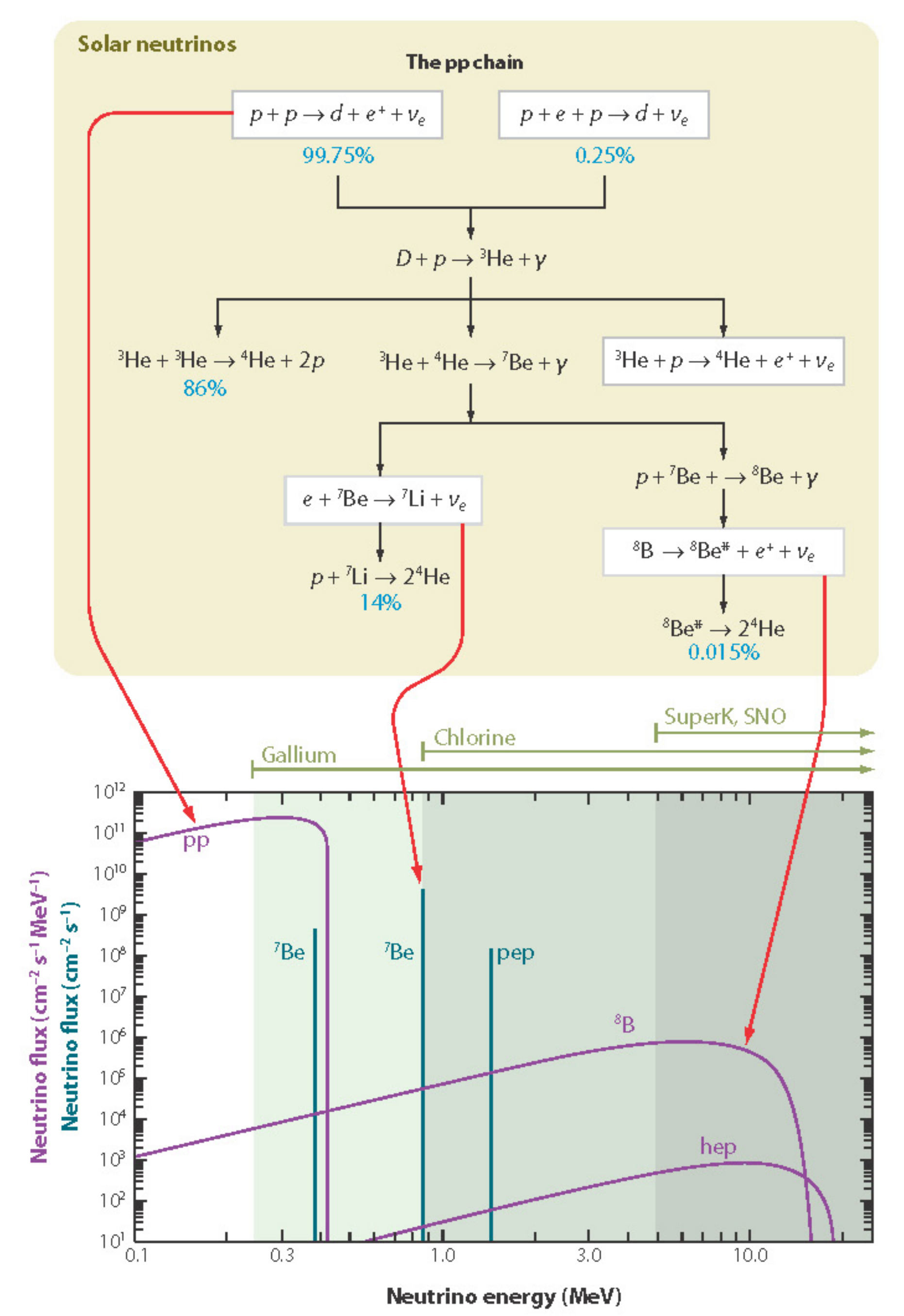
Reactor neutrinos (KamLand)





	Number of Units	Total Output (MW)
Operational	52	45,742
Under construction	3	3,838
Preparing for construction	8	10,315
Total	63	59,895

Solar neutrinos



Solar neutrinos

The pp chain

$p + p \rightarrow d + e^{+} + \nu_e$ 99.75%

$p + e + p \rightarrow d + \nu_e$ 0.25%

$D + p \rightarrow {}^{3}\mathrm{He} + \gamma$

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p$ 86%

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

${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{He} + e^{+} + \nu_e$

$e + {}^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li} + \nu_e$

$p + {}^{7}\mathrm{Li} \rightarrow 2\,{}^{4}\mathrm{He}$ 14%

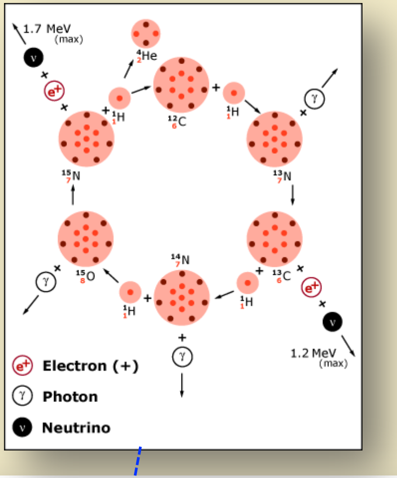
$p + {}^{7}\mathrm{Be} + \rightarrow {}^{8}\mathrm{Be} + \gamma$

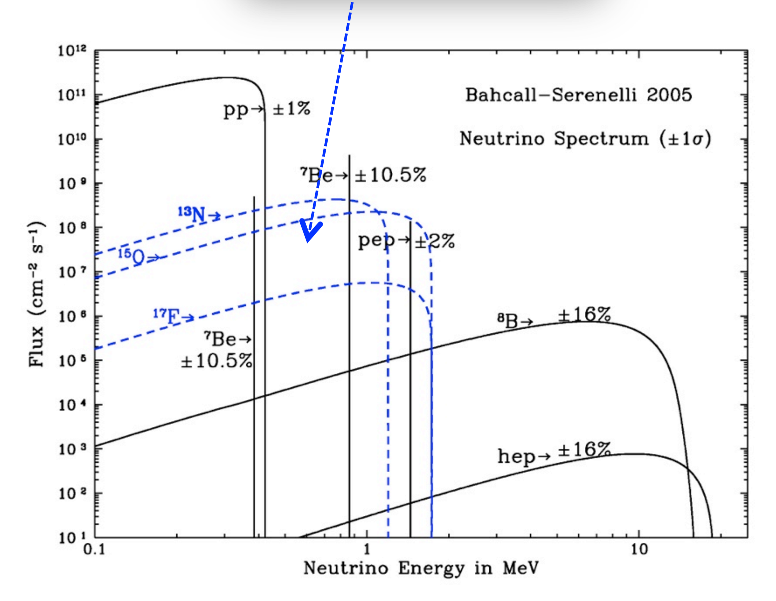
${}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{\#} + e^{+} + \nu_e$

${}^{8}\mathrm{Be}^{\#} \rightarrow 2\,{}^{4}\mathrm{He}$ 0.015%

Production

pp (+CNO) cycle





Detection of solar neutrinos

Radiochemical: count the decays of unstable final-state nuclei. (low energy threshold, but energy and time info lost/integrated)

$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^-$ (CC) Homestake

$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$ (CC) GALLEX/GNO, SAGE

Elastic scattering: events detected in real time with either "high" threshold (Č, directional) or "low" threshold (Scintillators)

$\nu_x + e^- \rightarrow \nu_x + e^-$ (NC,CC) SK, SNO, Borexino

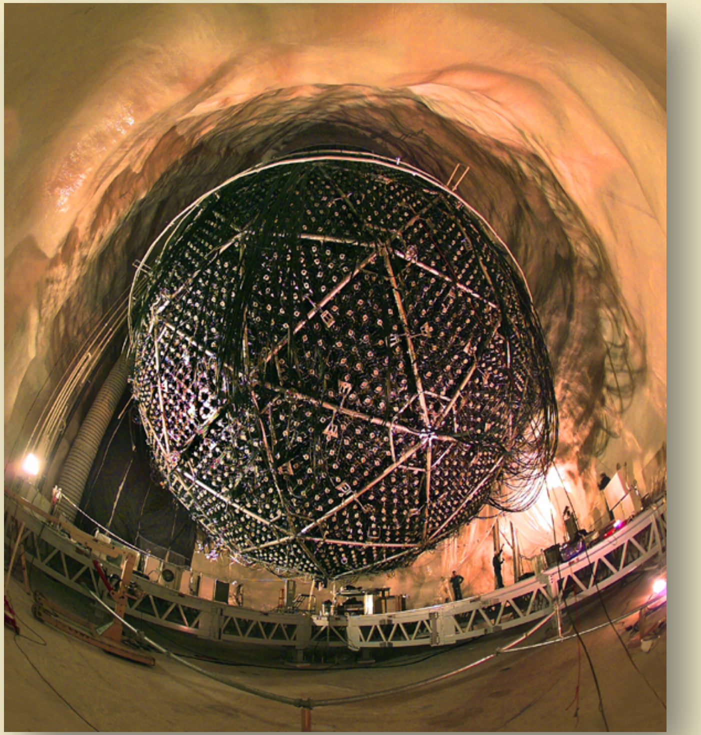
Interactions on Deuterium: CC events detected in real time; NC events separated statistically + using neutron counters.

$\nu_e + d \rightarrow p + p + e^-$ (CC)

$\nu_x + d \rightarrow p + n + \nu_x$ (NC)

SNO (Sudbury Neutrino Observatory)

The SNO experiment



The breakthrough: in deuterium one can separate CC events (induced by ν_e only) from NC events (induced by ν_e, ν_μ, ν_τ), and double check via Elastic Scattering events (due to both NC and CC)

$$\begin{aligned} \mathrm{CC}: &\quad \nu_e + d \to p + p + e \\ \mathrm{NC}: &\quad \nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau} \\ \mathrm{ES}: &\quad \nu_{e,\mu,\tau} + e \to e + \nu_{e,\mu,\tau} \end{aligned}$$

$$\frac{\mathrm{CC}}{\mathrm{NC}} \sim \frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})}$$

thus:

$$\frac{\mathrm{CC}}{\mathrm{NC}} < 1 \;\Rightarrow\; \phi(\nu_{\mu,\tau}) > 0 \;\Rightarrow\; \nu_e \to \nu_{\mu,\tau}$$

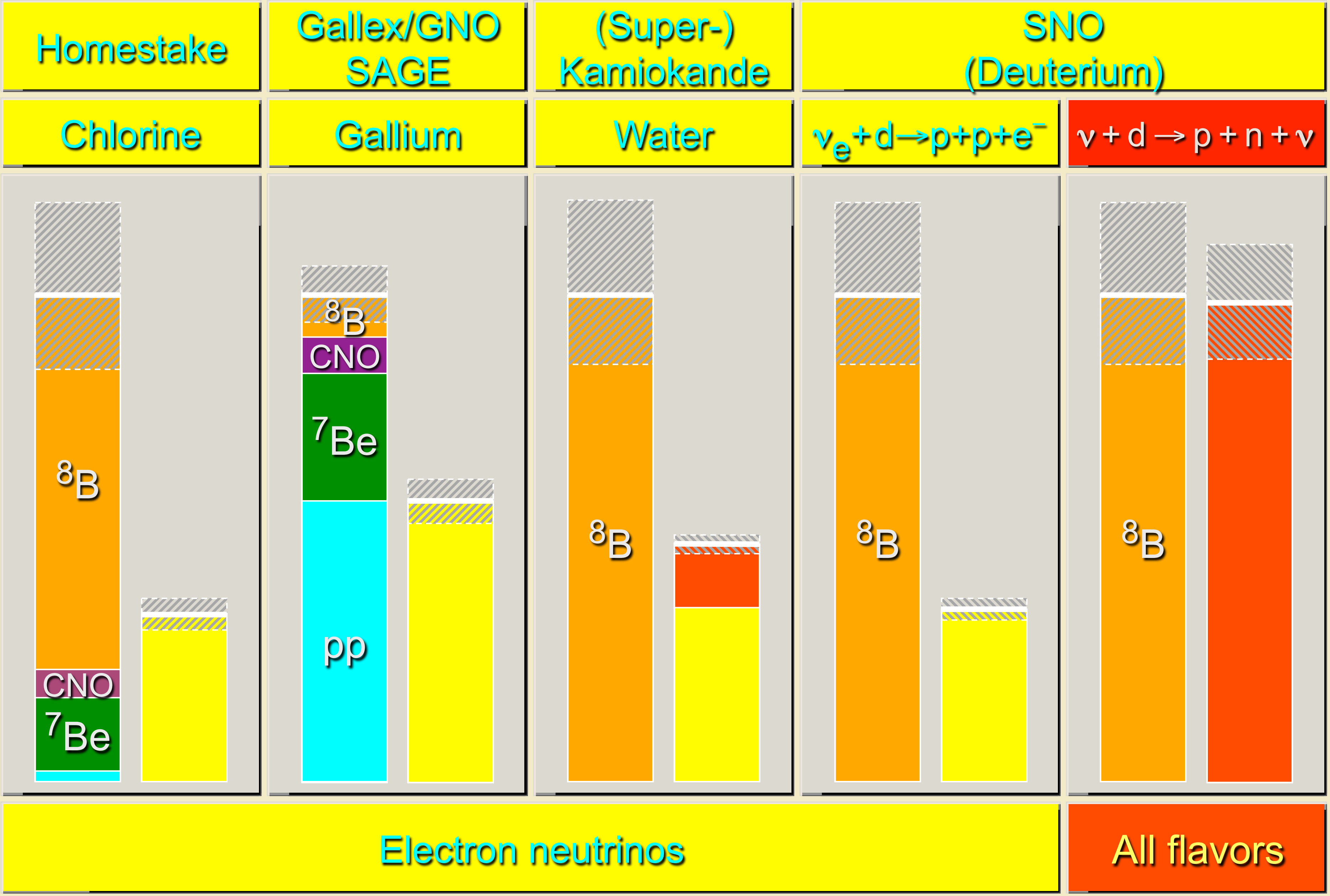
CC/NC ~ 1/3 < 1

“Smoking gun” proof of flavor change. Solar model OK!   Also:

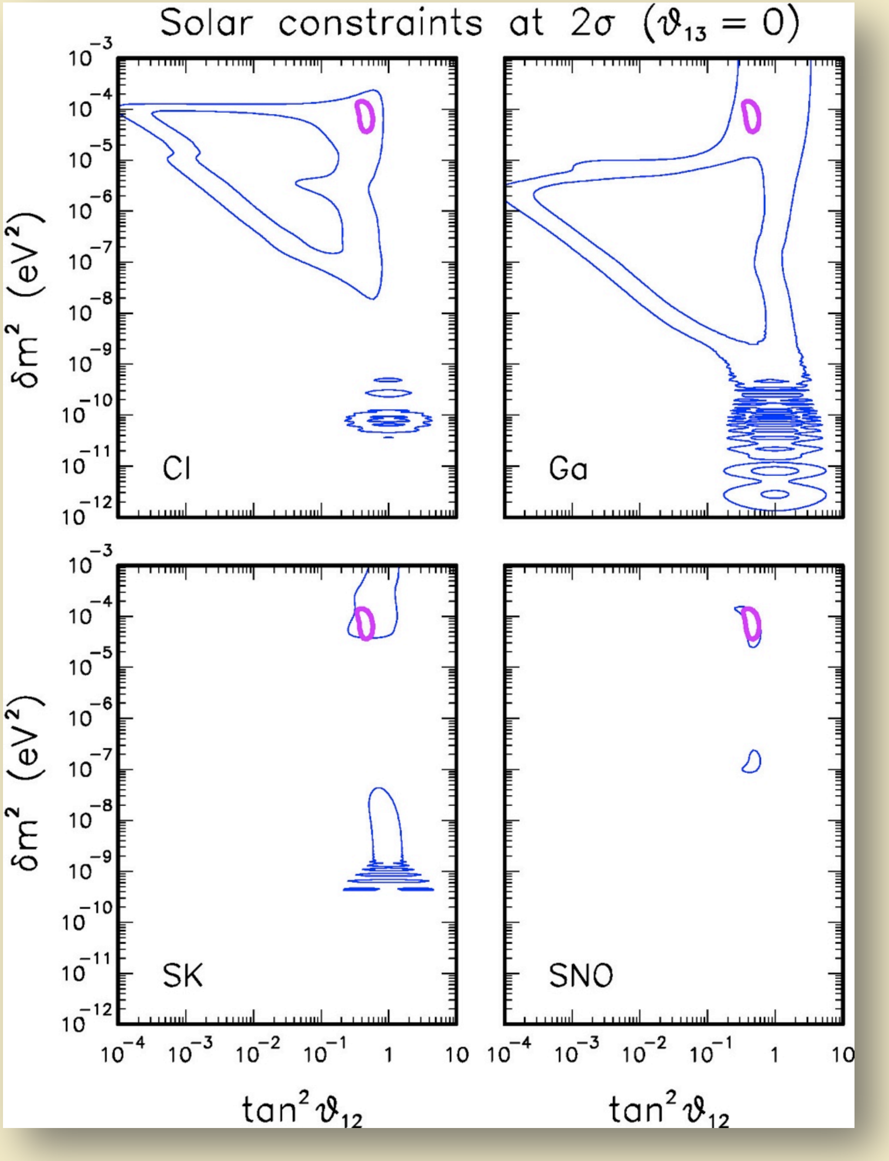
CC/NC ~ Pee ~ $\sin^2\theta_{12}$ (LMA) ~1/3 < ½

Evidence of: mixing in first octant + matter effects

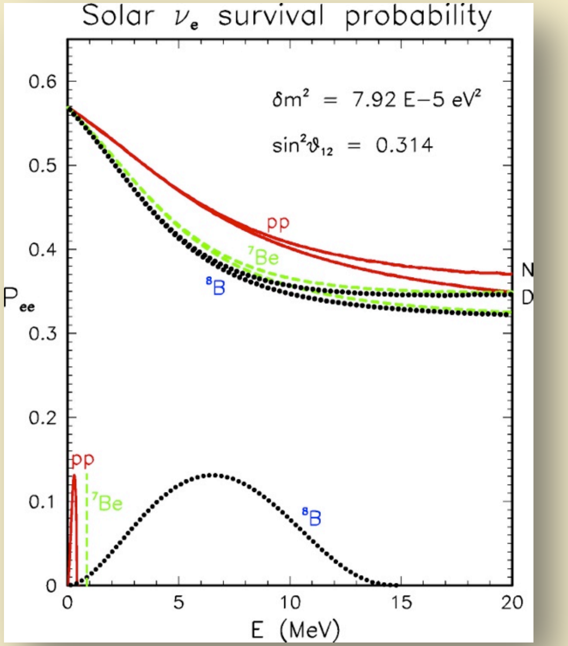
The solar neutrino deficit



The “oscillatory” solution



For LMA parameters, evolution is adiabatic in solar matter.

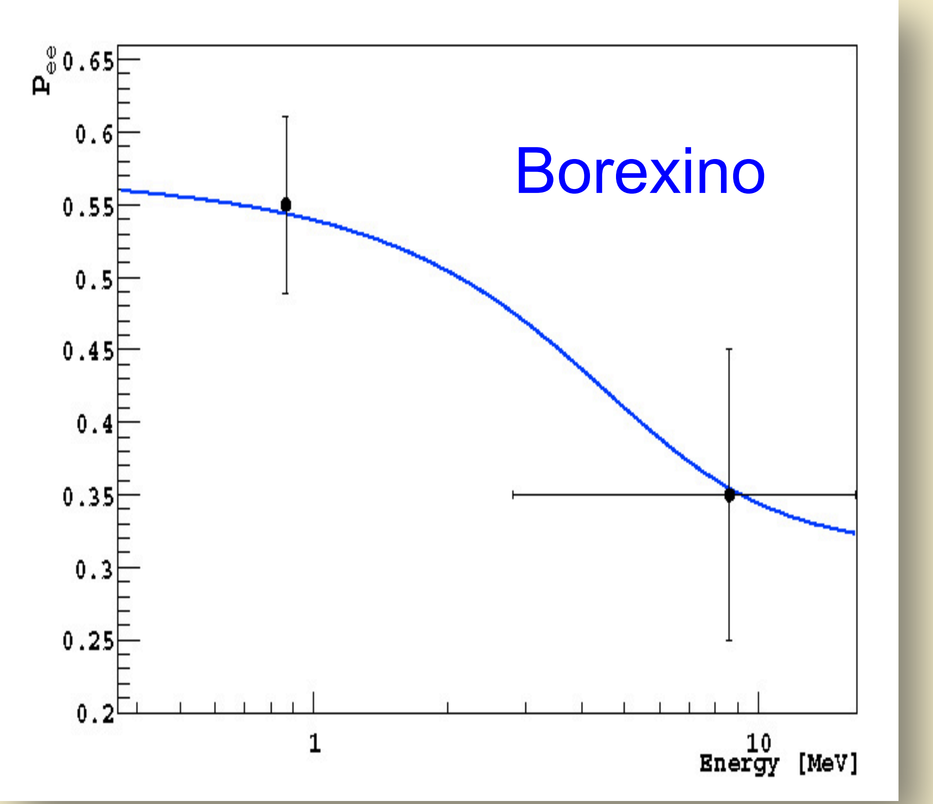


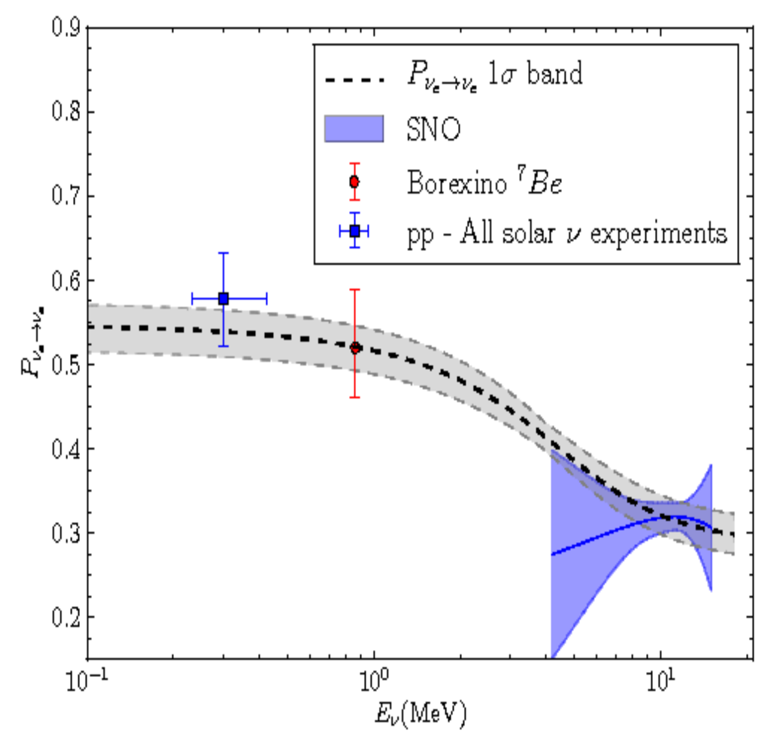
In the Earth: small day/night (D/N) effects, not yet seen.

The solar neutrino deficit

Recent, direct confirmation of adiabatic Pee pattern at LMA in a single solar ν experiment: BOREXINO at Gran Sasso

Overall picture including final SNO data [Spectral rise at low energy not yet directly observed – anomaly?]





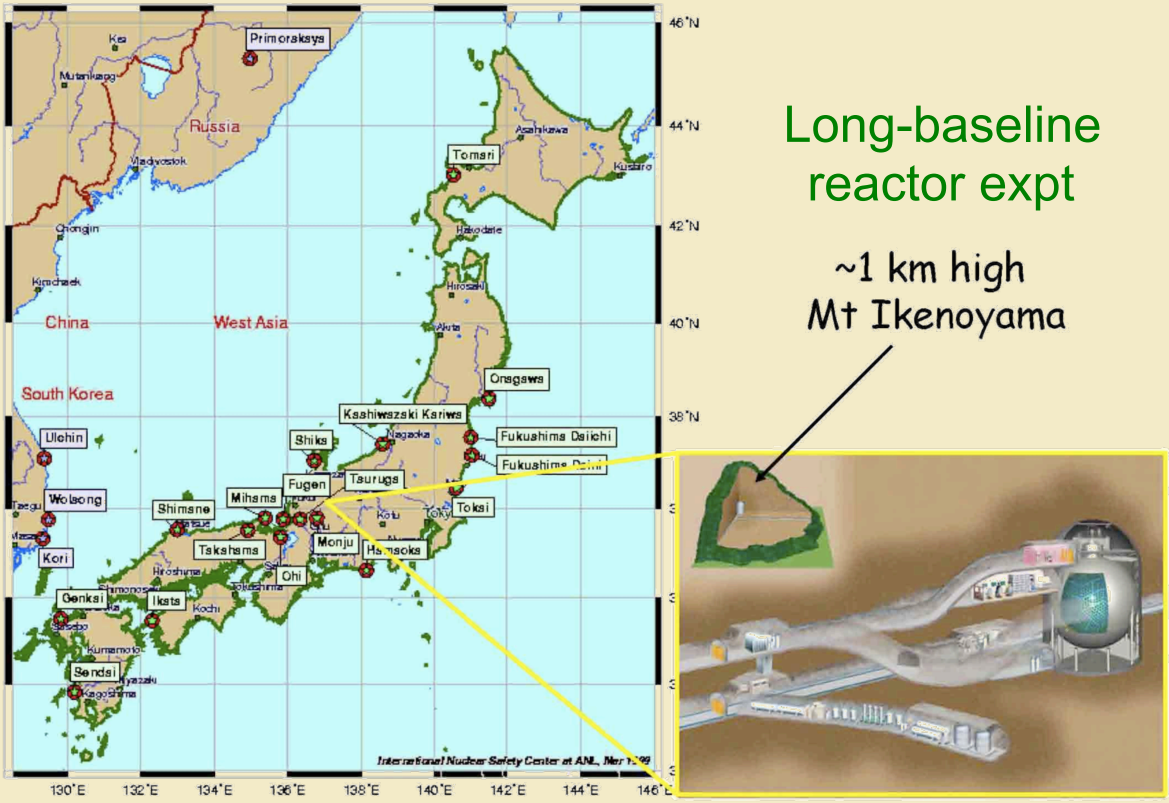
The KamLand Experiment

KamLAND: 1000 ton mineral oil detector, “surrounded” by nuclear reactors producing anti-ν_e. Characteristics:

$VE/\delta m^2 \ll 1$ in Earth crust
(vacuum approxim. OK)
L~100-200 km
E_ν~ few MeV

⇨

With previous $(\delta m^2, \theta)$ parameters it is $(\delta m^2 L/4E) \sim O(1)$ and reactor neutrinos should oscillate with large amplitude (large θ)



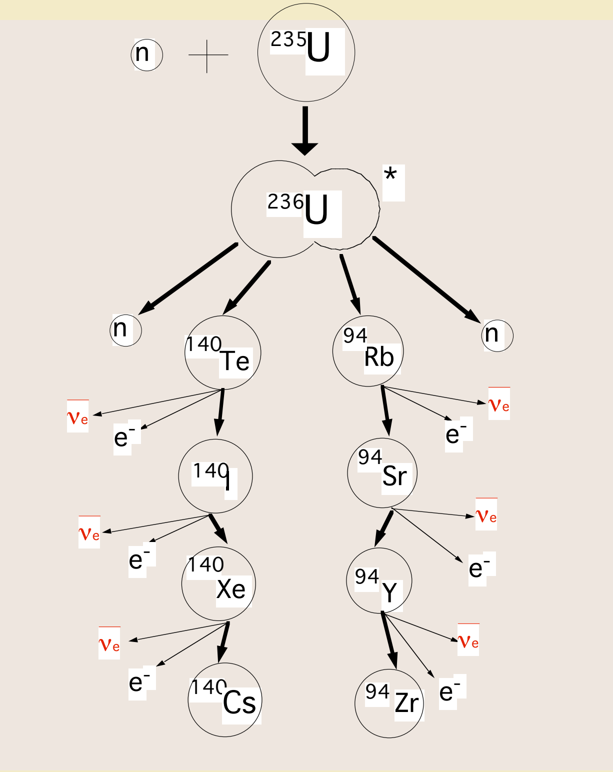
Long-baseline reactor expt

~1 km high
Mt Ikenoyama

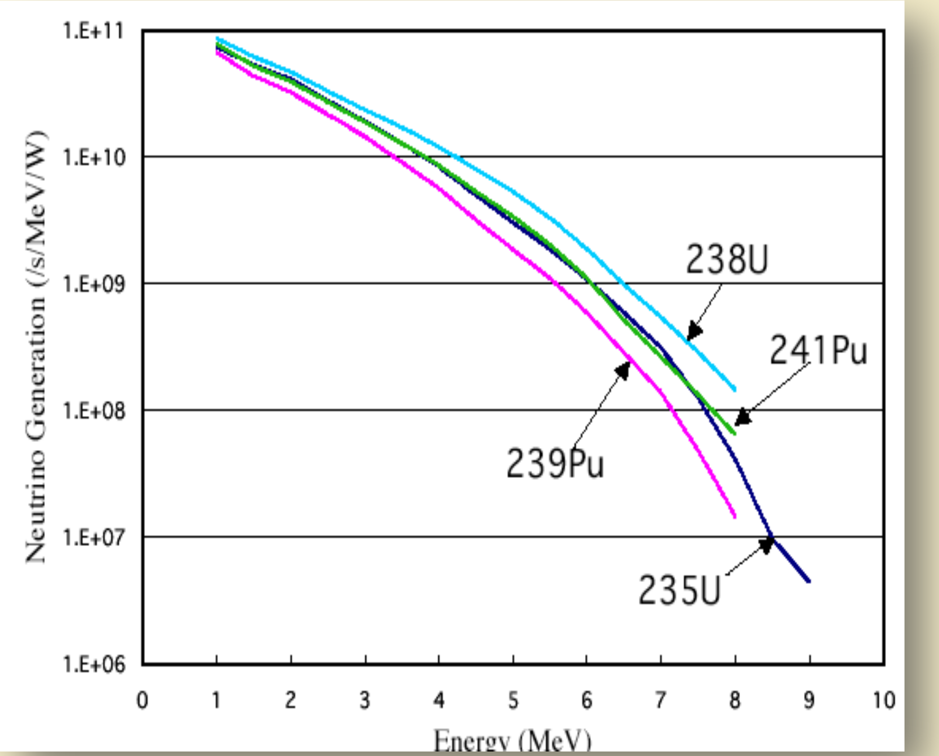
Reactor neutrinos

Reactors: Intense sources of anti-ν_e (~6×10^{20}/s/reactor)

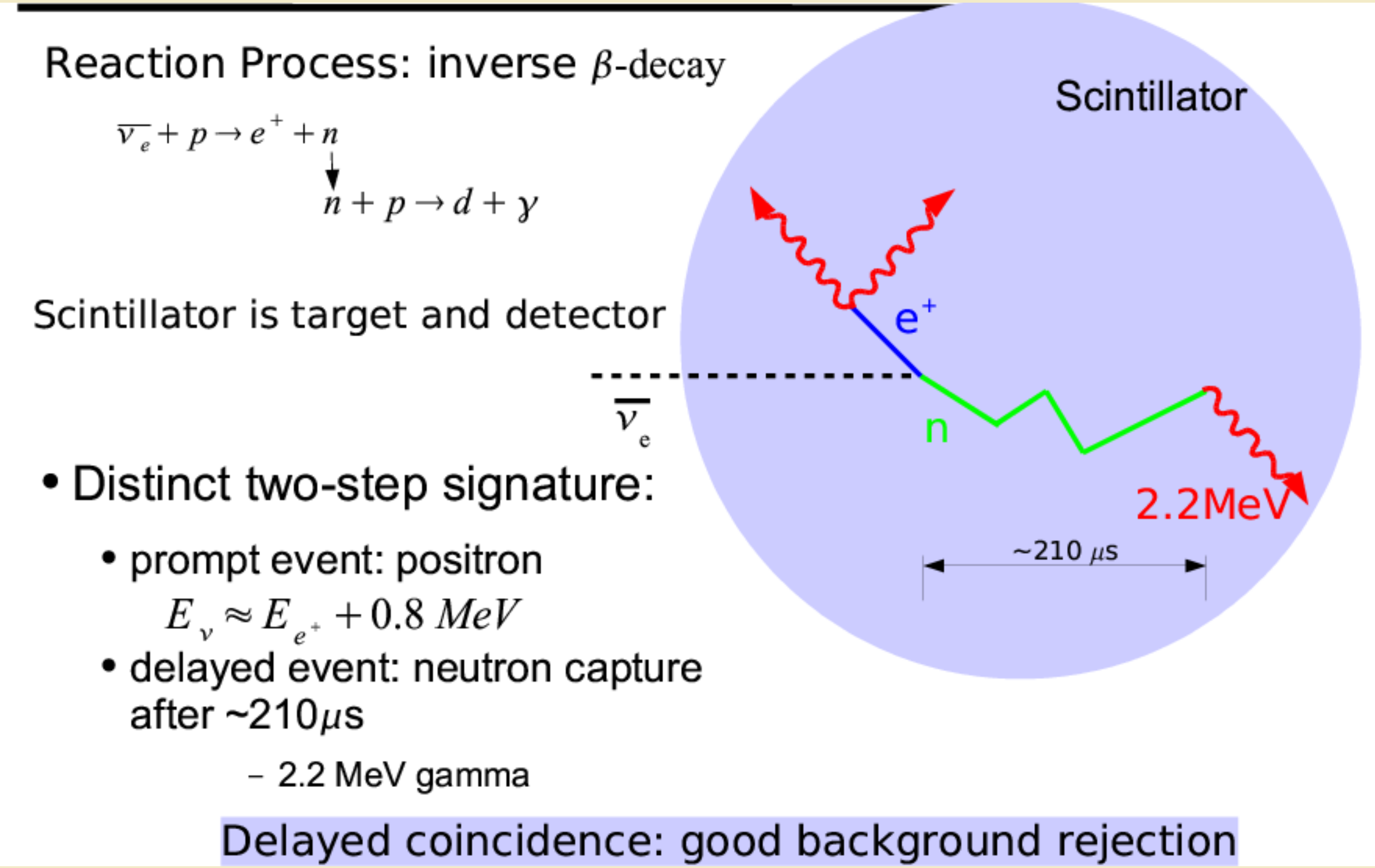
Typically, 6 neutron decays to reach stable matter from fission:



~200 MeV per fission / 6 decays:
Typical available neutrino energy is
E~ few MeV



Neutrino detection



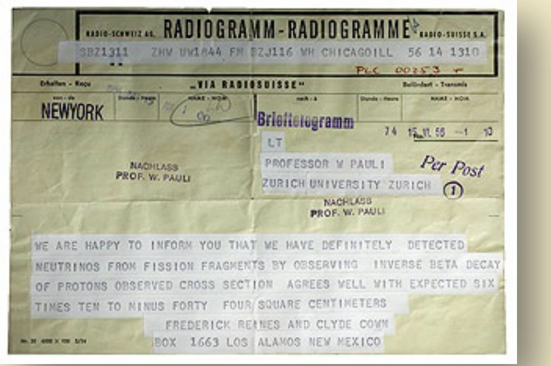
Reaction Process: inverse β-decay

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

Scintillator is target and detector

- Distinct two-step signature:
  - prompt event: positron
    $$E_\nu \approx E_{e^+} + 0.8\ MeV$$
  - delayed event: neutron capture after ~210μs
    - 2.2 MeV gamma

Delayed coincidence: good background rejection



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NEWYORK

Brieftelegramm

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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

①

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

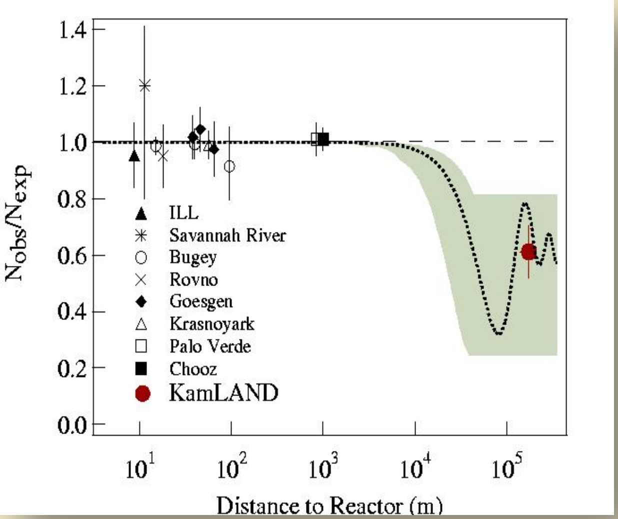
← This reaction allowed experimental neutrino discovery in 1956 (Reines & Cowan)

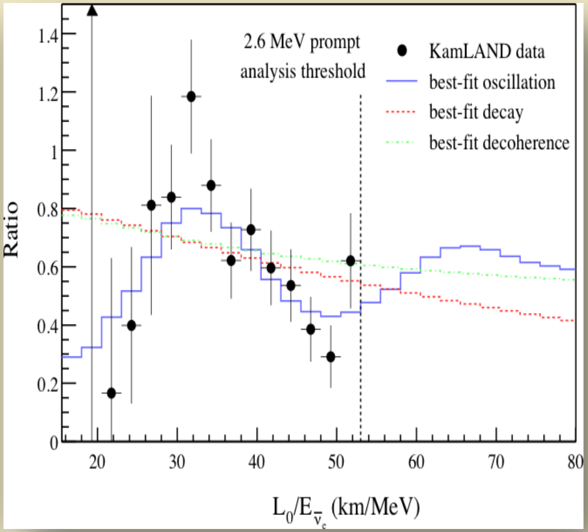
KamLand Results

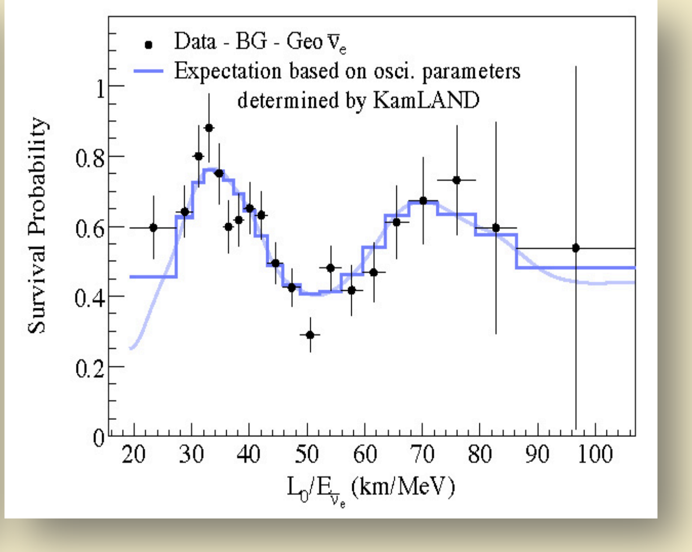
2002: electron flavor disappearance observed

2004: half-period of oscillation observed

2007: one period of oscillation observed

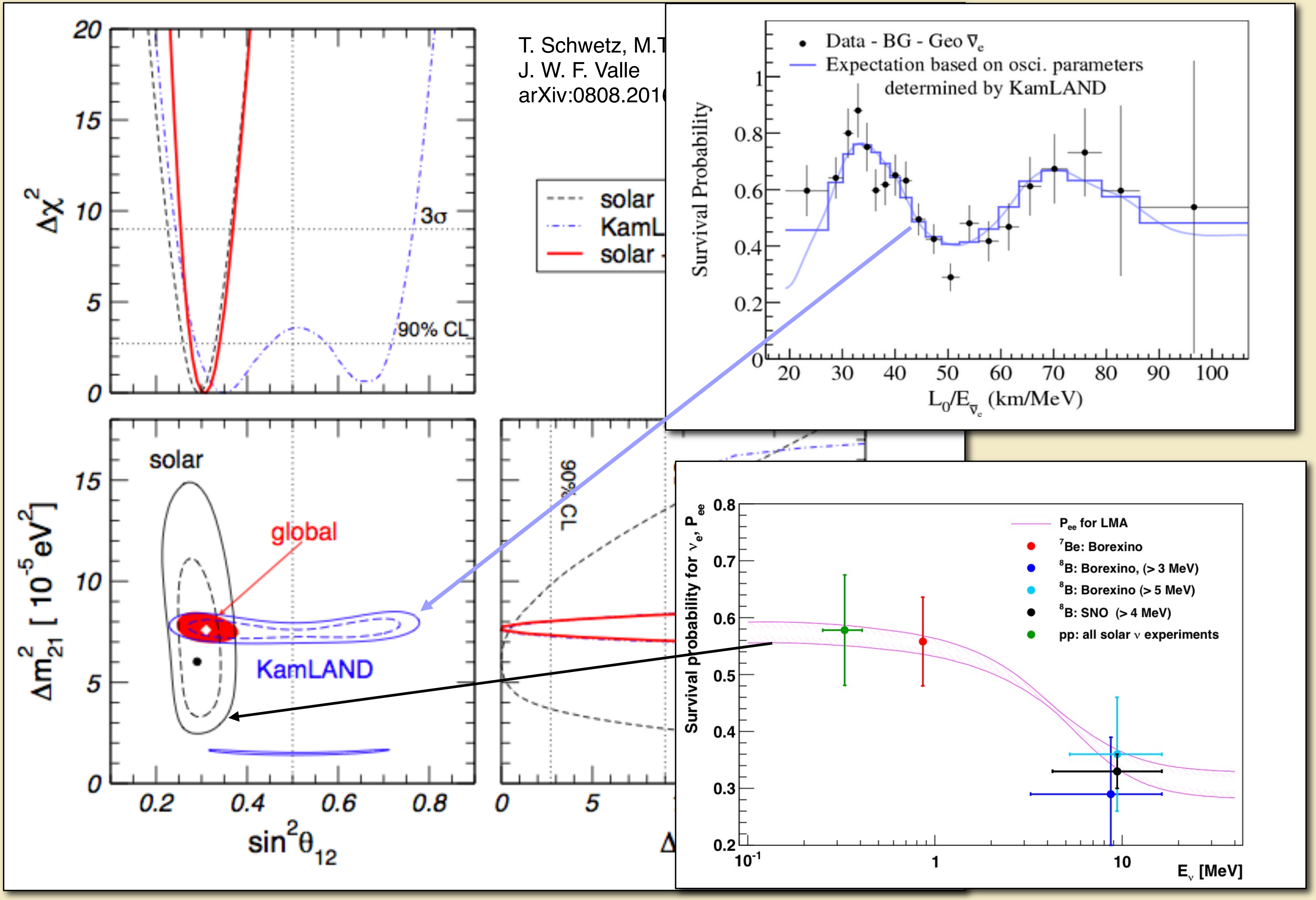






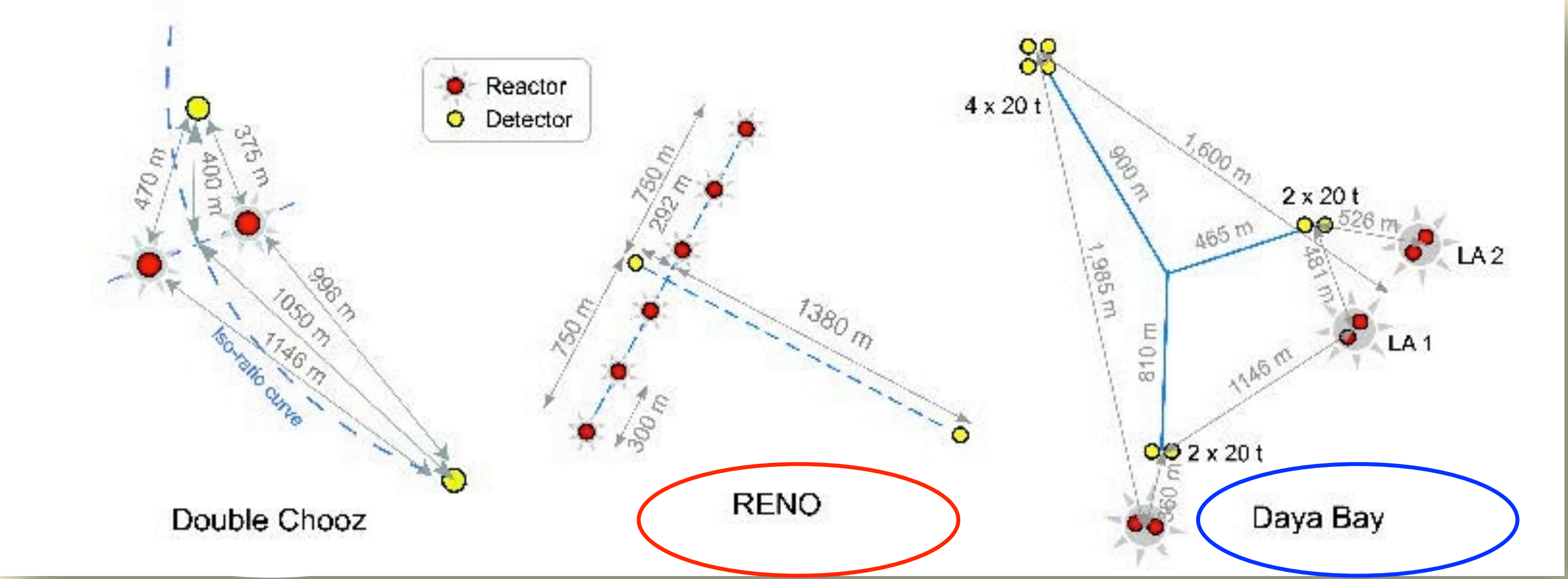
Direct observation of δm^2 oscillations!

Tuning on long waves (E~MeV)...



T. Schwetz, M.T
J. W. F. Valle
arXiv:0808.201

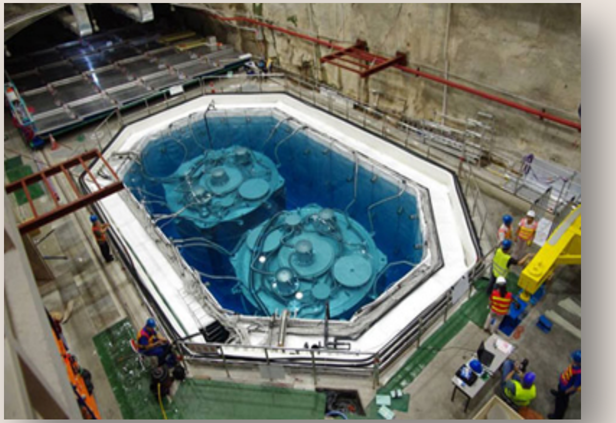
Short baseline neutrino experiments



Running with FD;
ND in construction

Running with
ND & FD

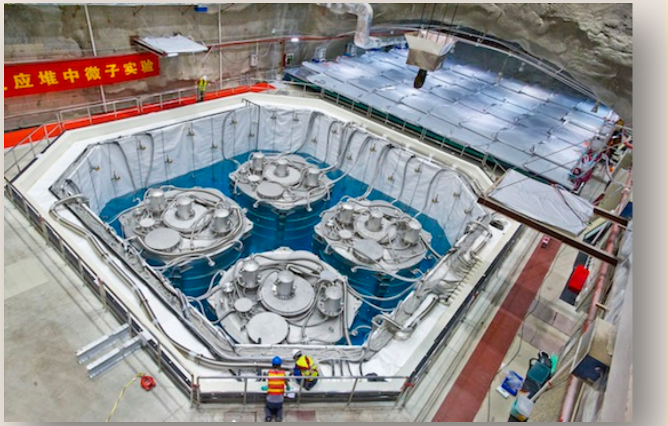
Running with
ND & FD



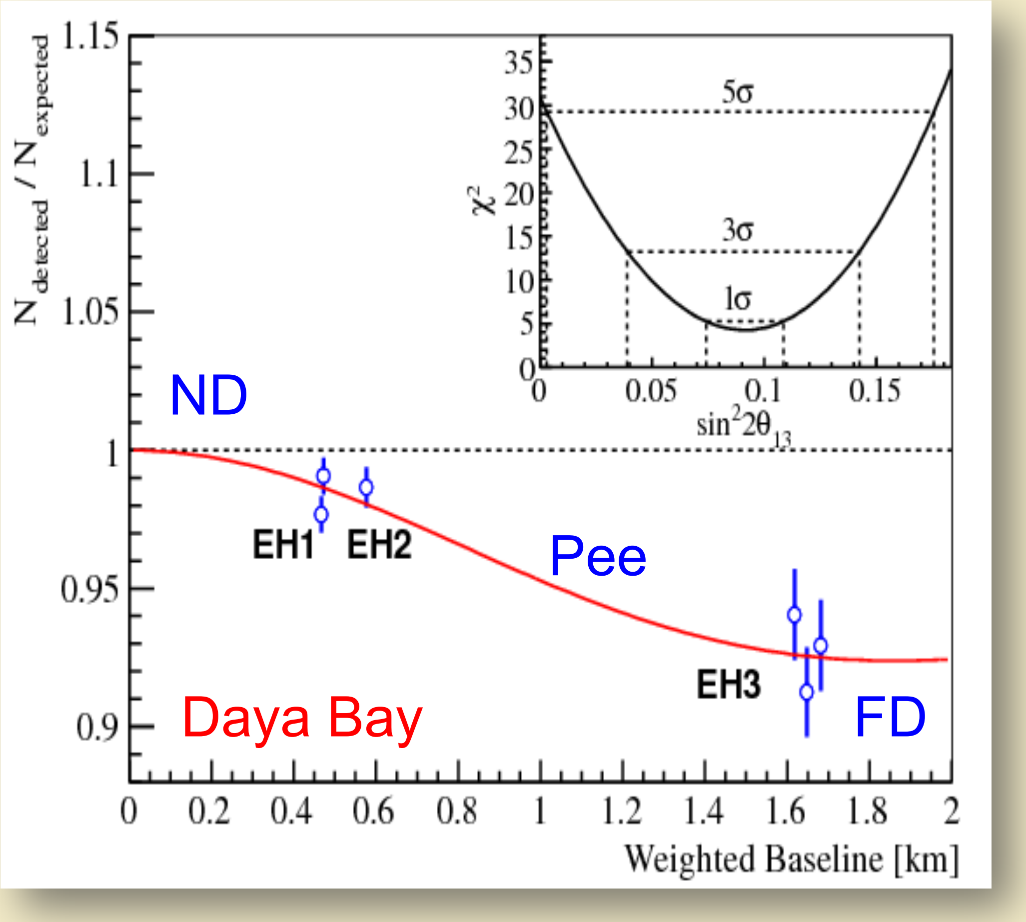
E.g, for
Daya Bay:

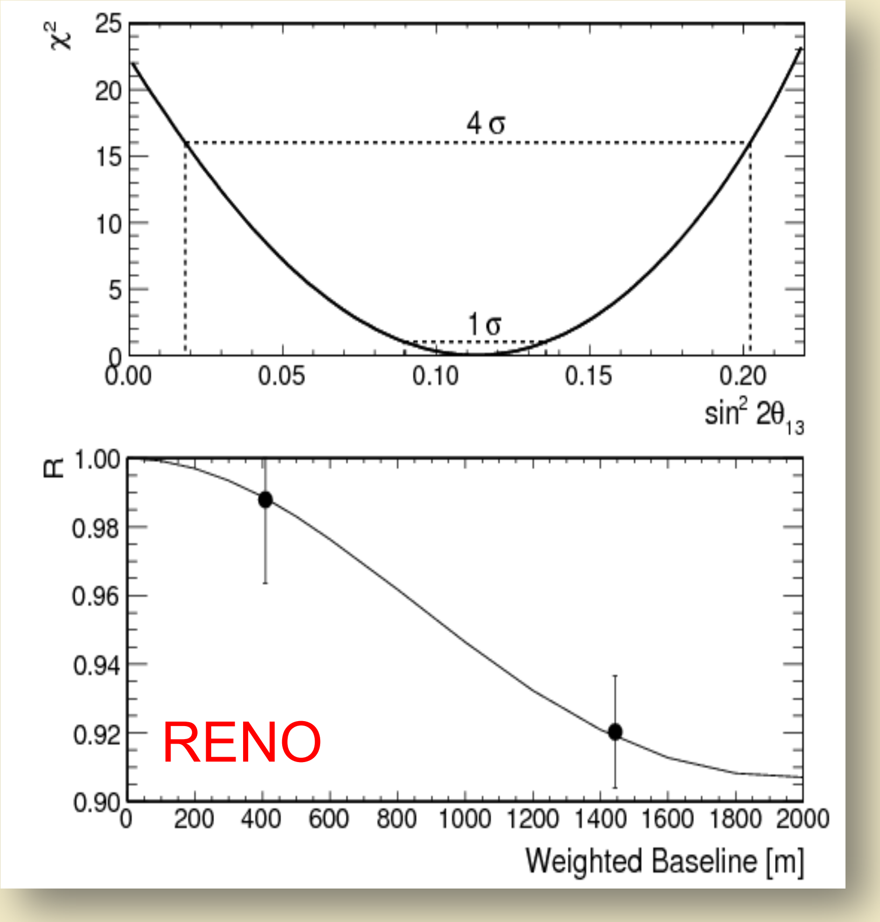
← ND

FD →



Neutrino disappearance on short distances





Results: disappearance at FD with respect to ~unoscillated at ND.

Double Chooz results (FD only) also consistent with Daya Bay & RENO.

Expect further data and spectral analyses in the near future.

Interpretation of Reactor results

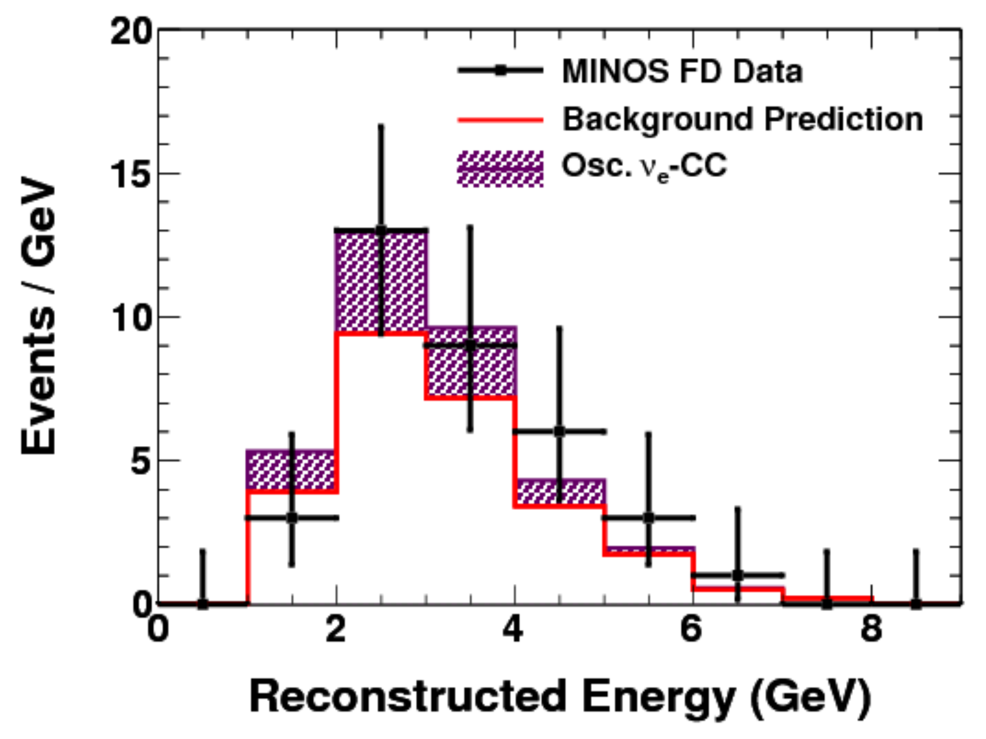
Reactor experiments show an (anti)neutrino disappearance, $P_{ee}<1$. In term of one mass scale dominance we have

$$P_{ee} = 1 - 4 s_{13}^2 c_{13}^2 \sin^2 \frac{\Delta m^2 x}{4E}$$

Since Δm^2 is known from atmospheric and accelerator experiments this can be interpreted by a nonzero value of θ_{13}.

ν_e appearance at LBL

excess of ν_e at MINOS and T2K: evidence for subleading $\nu_\mu \to \nu_e$ oscillations



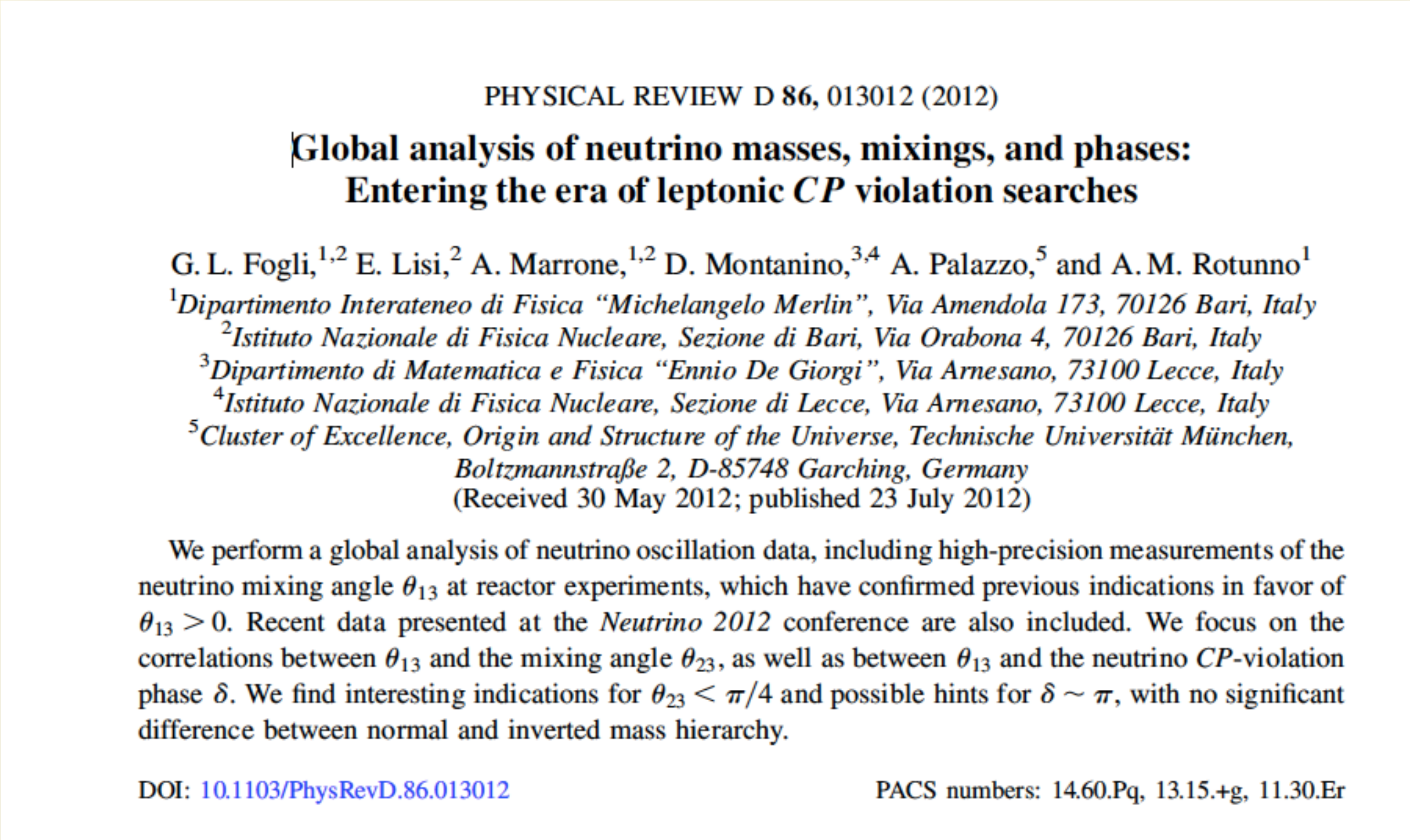
$$P_{\mu e} = 4|U_{e3}|^2|U_{\mu 3}|^2 \sin^2 \frac{\Delta m^2 x}{4E} = 4 s_{13}^2 c_{13}^2 c_{23}^2 \sin^2 \frac{\Delta m^2 x}{4E}$$

<u>Again: evidence for non zero</u> θ_{13}

Putting all togheter

Extracting oscillation parameters and their correlations from solar, atmospheric, accelerator and reactor neutrino data, as of summer 2012

Full 3ν probabilities included, no approximation.



PHYSICAL REVIEW D **86**, 013012 (2012)

**Global analysis of neutrino masses, mixings, and phases:
Entering the era of leptonic *CP* violation searches**

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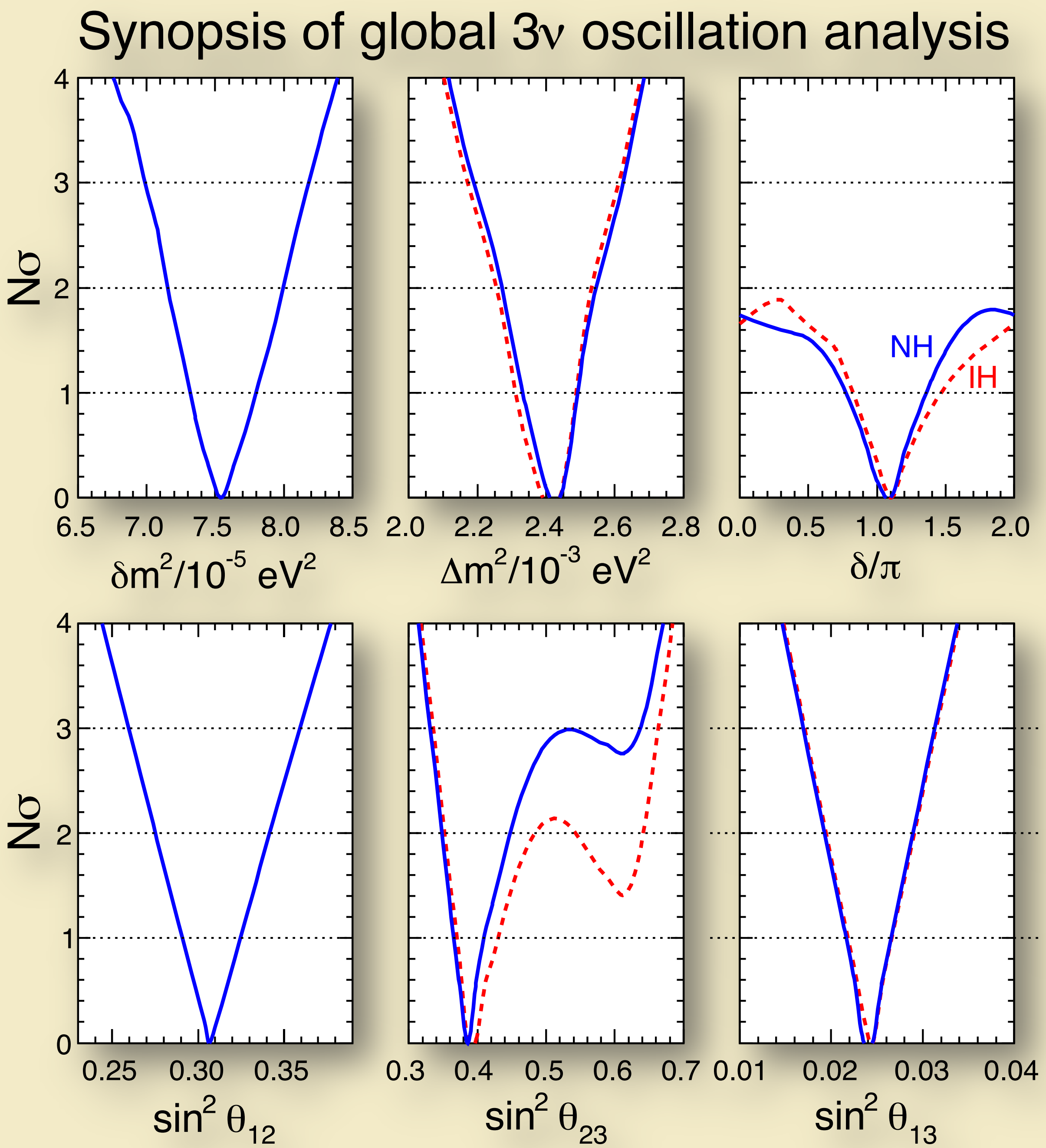
(Received 30 May 2012; published 23 July 2012)

We perform a global analysis of neutrino oscillation data, including high-precision measurements of the neutrino mixing angle θ_{13} at reactor experiments, which have confirmed previous indications in favor of $\theta_{13} > 0$. Recent data presented at the *Neutrino 2012* conference are also included. We focus on the correlations between θ_{13} and the mixing angle θ_{23}, as well as between θ_{13} and the neutrino *CP*-violation phase δ. We find interesting indications for $\theta_{23} < \pi/4$ and possible hints for $\delta \sim \pi$, with no significant difference between normal and inverted mass hierarchy.

DOI: 10.1103/PhysRevD.86.013012 PACS numbers: 14.60.Pq, 13.15.+g, 11.30.Er

Individual oscillation parameters from ALL data


Synopsis of global 3ν oscillation analysis

Previous hints of $\theta_{13} > 0$
are now measurements!
(and basically independent
of absolute reactor fluxes)

Some hints of $\theta_{23} < \pi/4$
are emerging at ~ 2σ ,
worth exploring by means
of atm. and LBL+reac. data

A weak hint of $\delta_{CP} \sim \pi$
emerging from atm. data
[Is the PMNS matrix real?]

So far, no hints for
NH ⟷ IH

Numerical 1σ, 2σ, 3σ ranges:

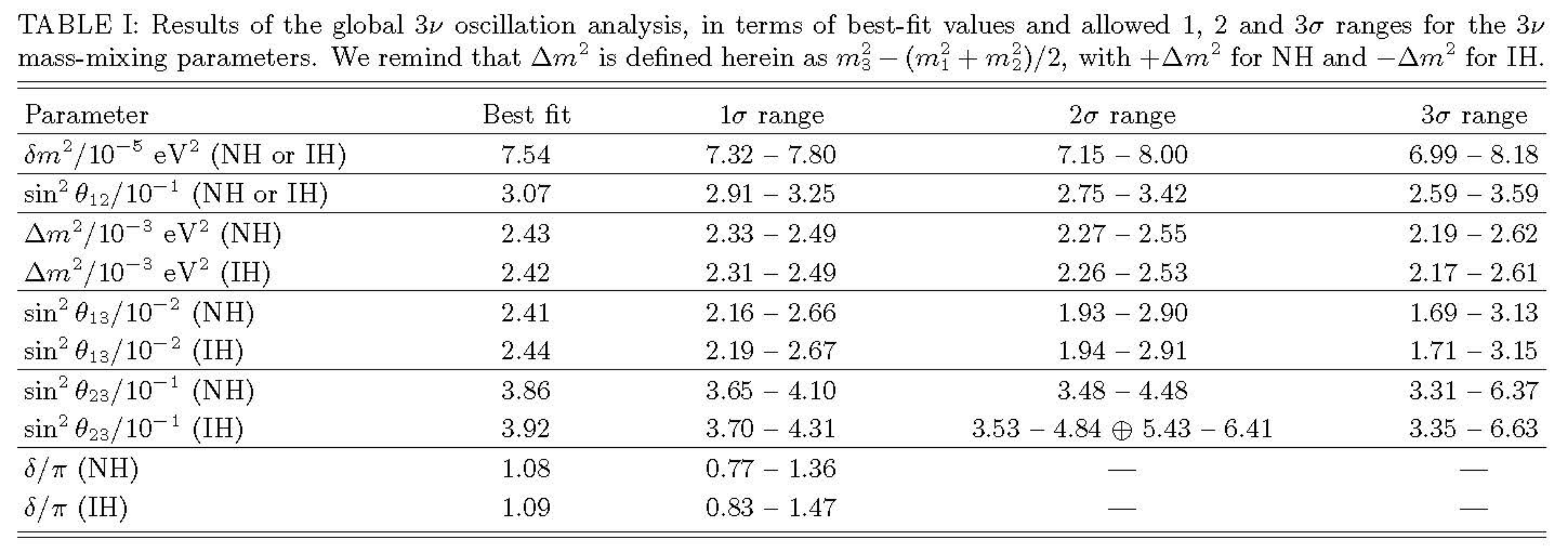


TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

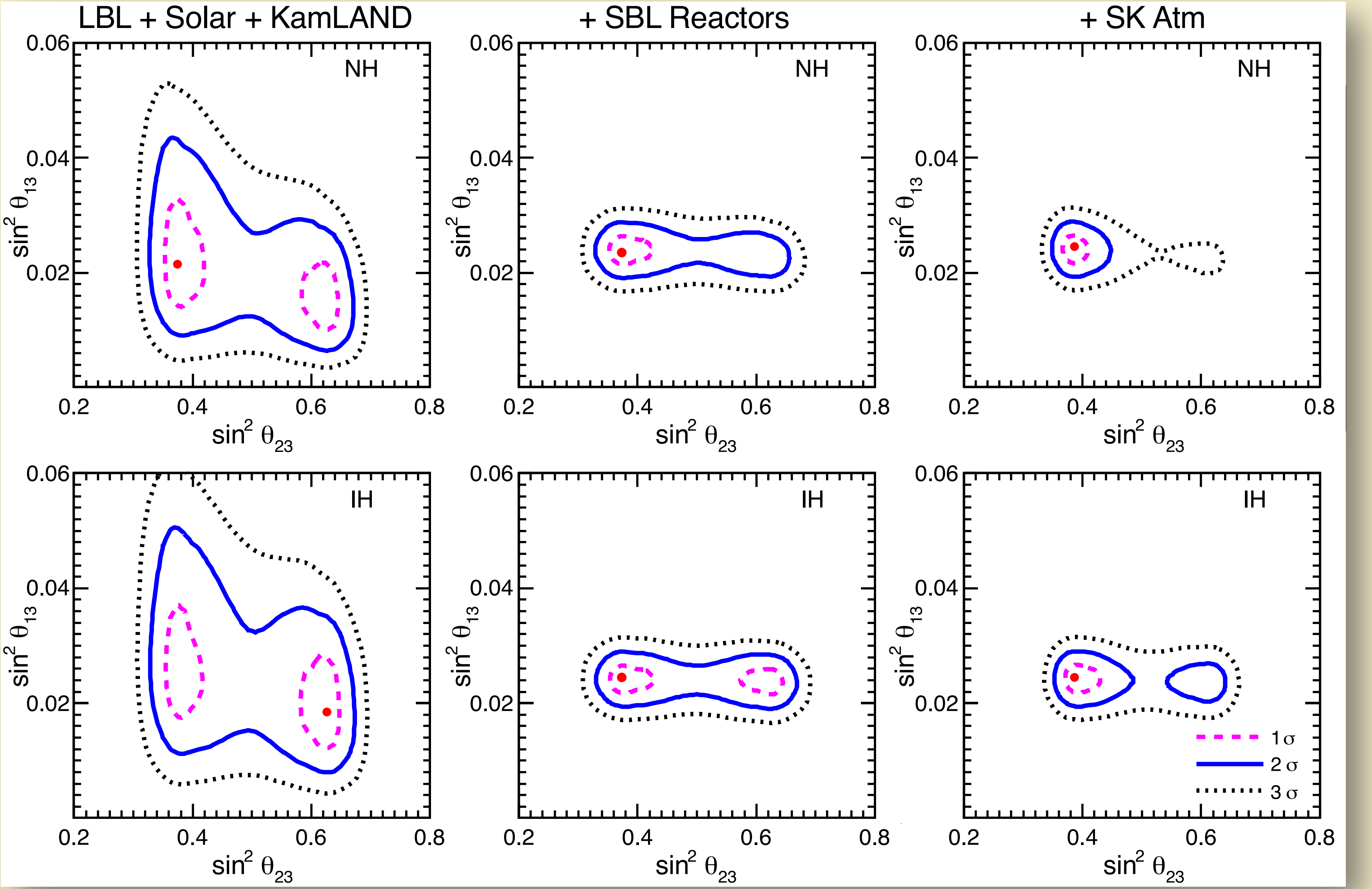
Fractional 1σ accuracy [defined as 1/6 of ±3σ range]

δm^2	Δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
2.6%	3.0%	5.4%	10%	14%

Hierarchy differences well below 1σ for various data combinations

Putting all togheter

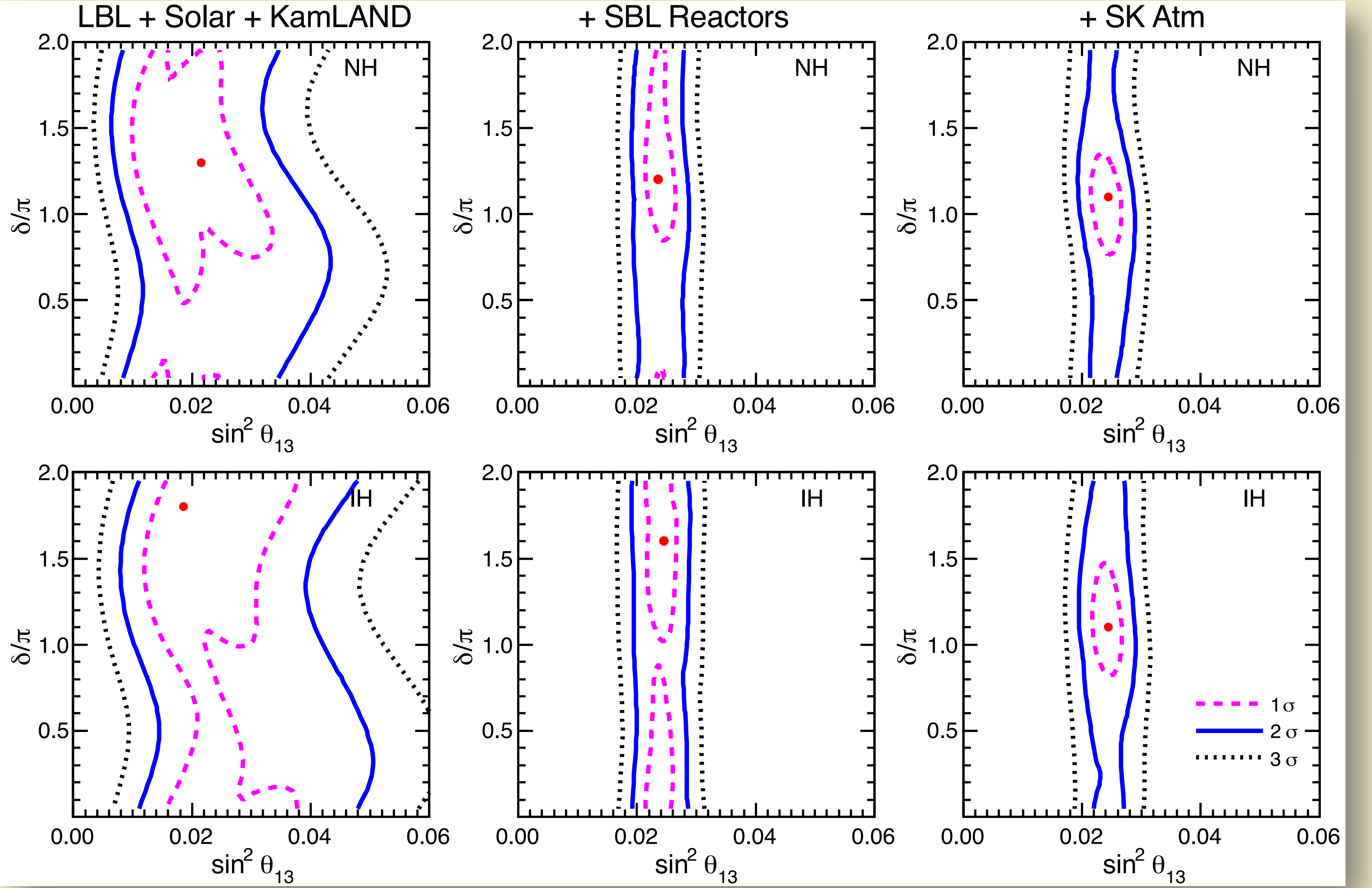
Adding 2012 SK atmospheric neutrino data:



Further hints for θ_{23} in 1st octant. But no significant hierarchy discrimination.

Putting all togheter

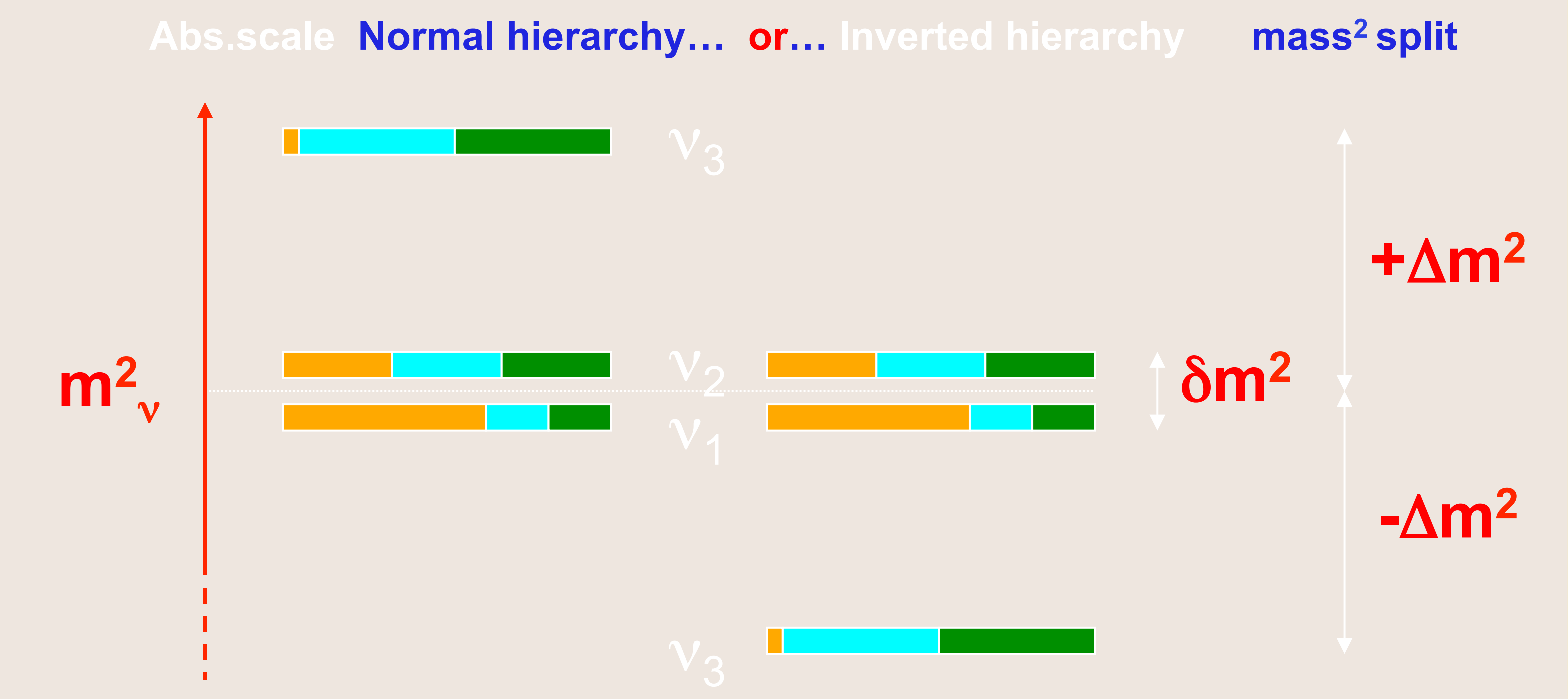
Adding 2012 SK atmospheric neutrino data:



We find a preference for δ ~ π (helps fitting sub-GeV e-like excess in SK)

Putting all togheter

Flavors = e μ τ



Knowns:

$\delta m^2 \sim 8 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Unkowns:

δ (CP)
sign(Δm^2)
octant($\sin^2\theta_{23}$)
absolute mass scale
Dirac/Majorana nature