CHIPP School 2010 Ascona, Switzerland

Neutrino Oscillations: Current phenomenology

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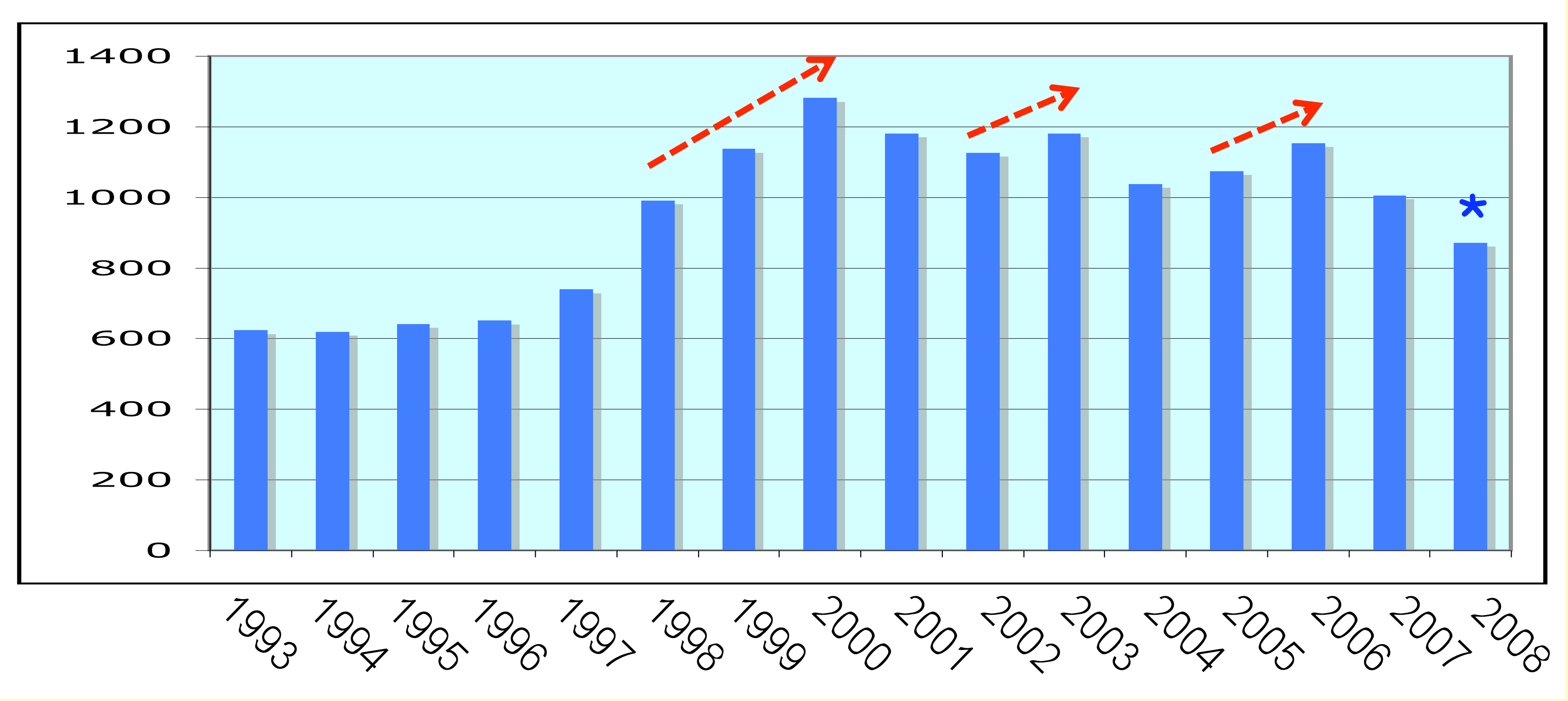
The discovery of flavor oscillations has raised the level of interest in neutrino physics, at the level of ~10^3 papers/year titled "…neutrino(s)…" on SPIRES

Peaks of interest:

Atmospheric ν oscillations, Limit from CHOOZ

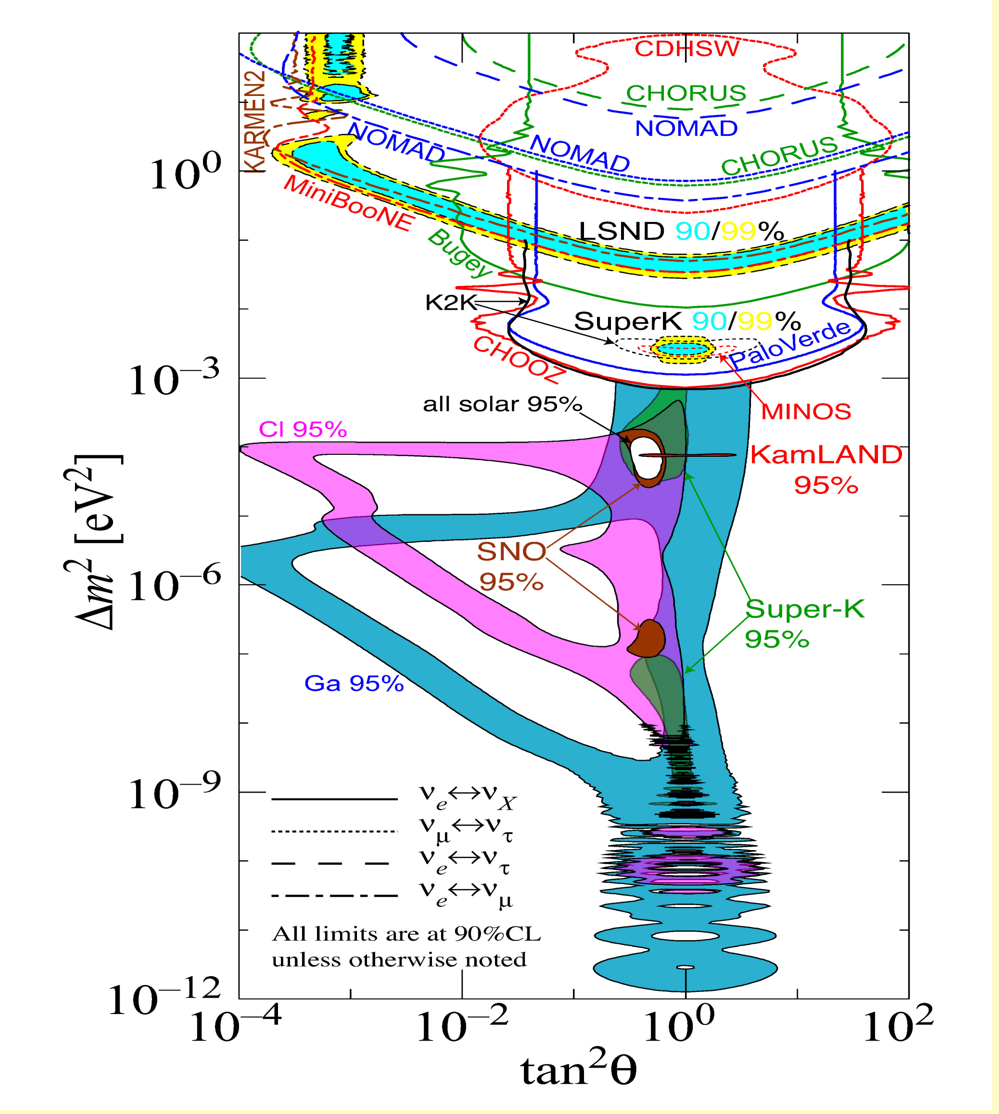
Solar and reactor ν oscillations, Nobel 2002 to Davis & Koshiba

Accelerator ν oscillations, Cosmological limits on absolute masses



* Apparent drop in 2008 is not really a sign of decline (SPIRES counts saturate only after ~2 yrs).

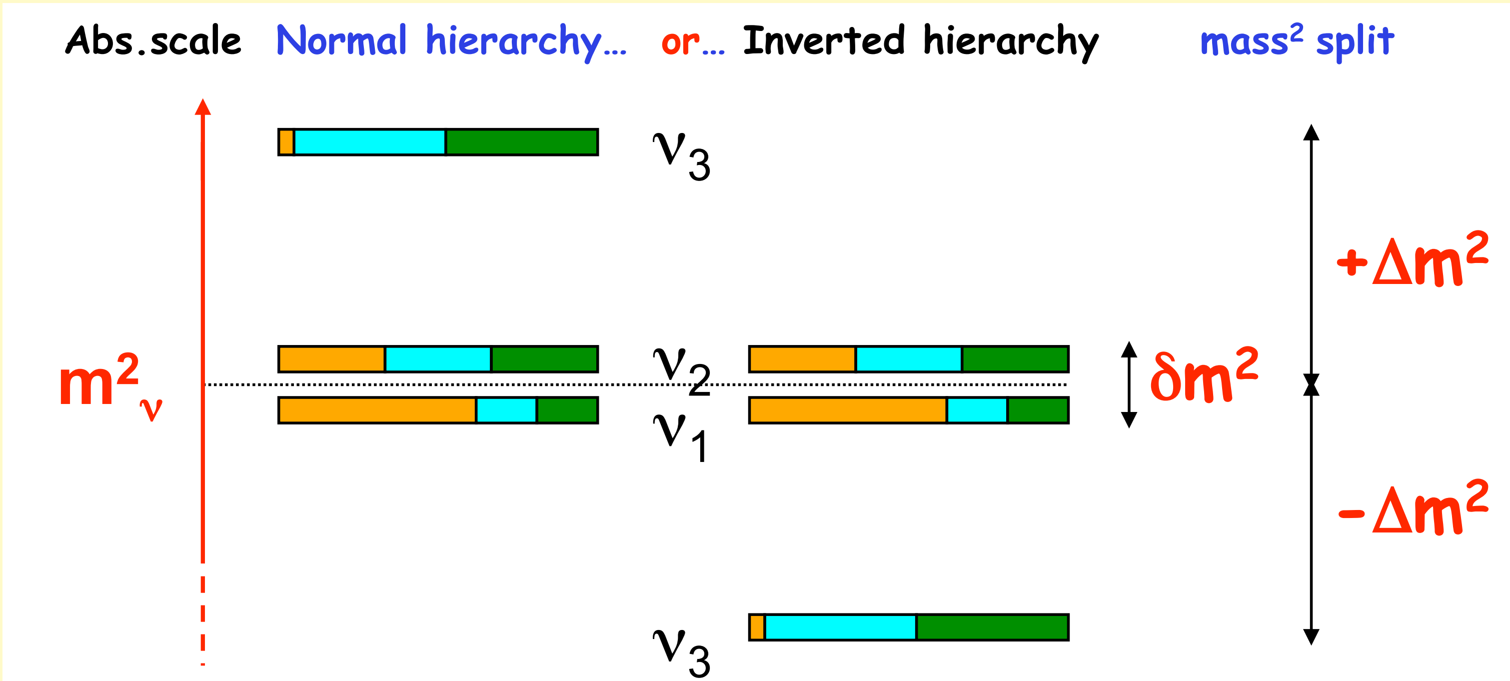
Many experiments contributed to a rich phenomenology



[Particle Data Group 2009]

Their 3ν interpretation can be summarized in just one slide

(here, with 1 digit accuracy). **Flavors** = e μ τ



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

$$m_\nu < O(1)\ \mathrm{eV} \qquad \sin^2\theta_{13} < \mathrm{few}\%$$

$$\mathrm{sign}(\pm\Delta m^2)\ \mathrm{unknown} \qquad \delta\ (\mathrm{CP})\ \mathrm{unknown}$$

We shall now examine how such information is (being) constrained from the following types of experiments:

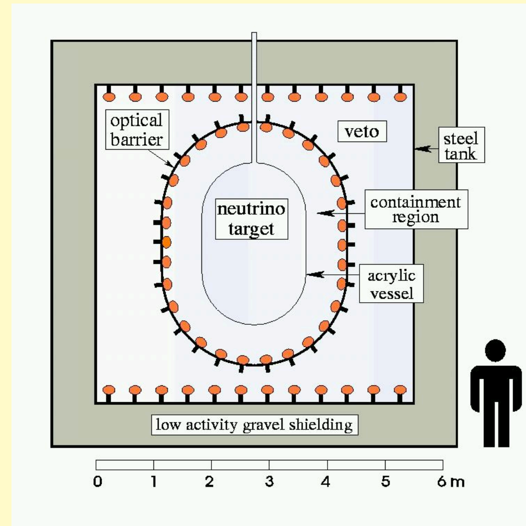
- **Short-baseline reactor**
- **Atmospheric**
- **Long-Baseline accelerator**
- **Solar**
- **Long-baseline reactor**
- **Short-baseline accelerator**

For each type of experiment we shall briefly discuss:

- **Production**
- **Detection**
- **Results**
- **Interpretation**

The short-baseline reactor experiment CHOOZ

~1 km →

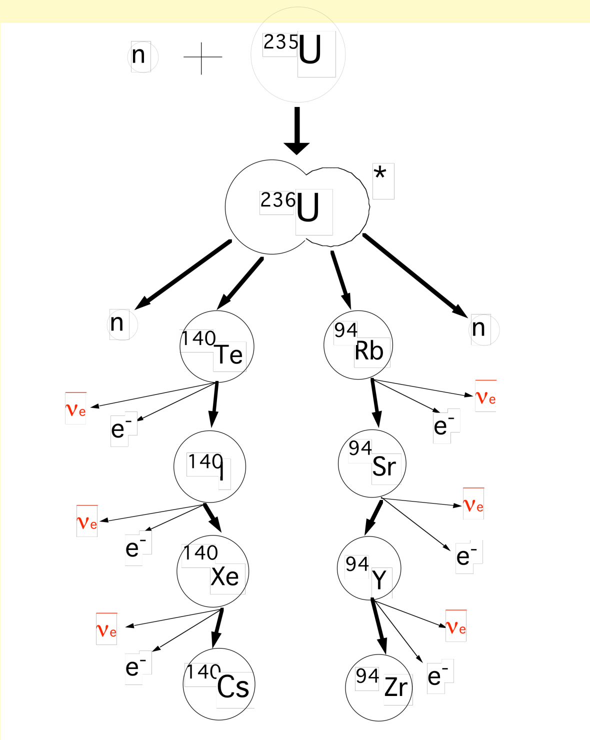


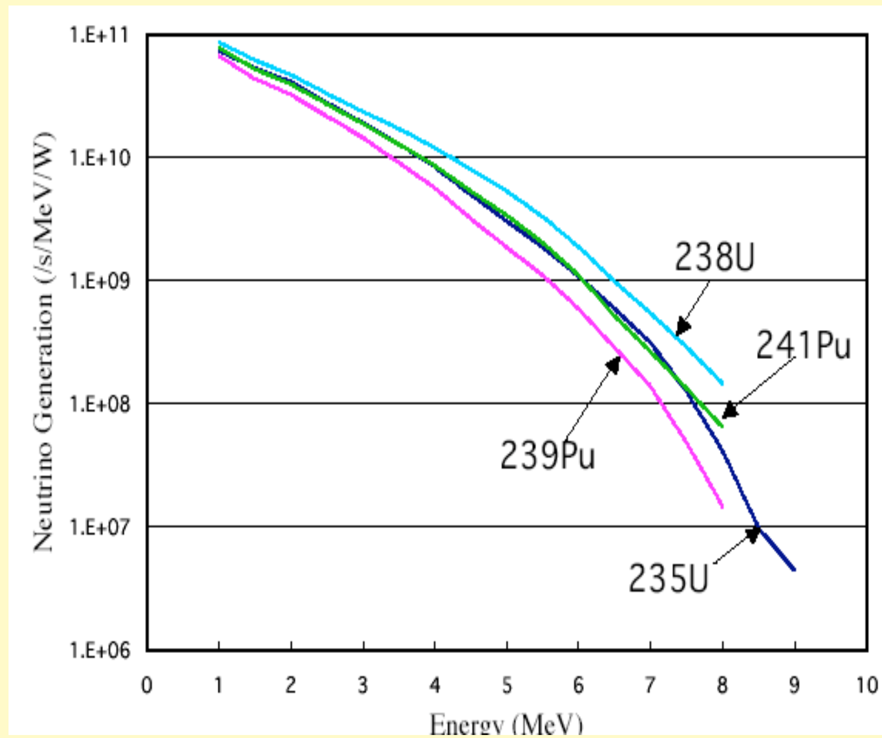
Production

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



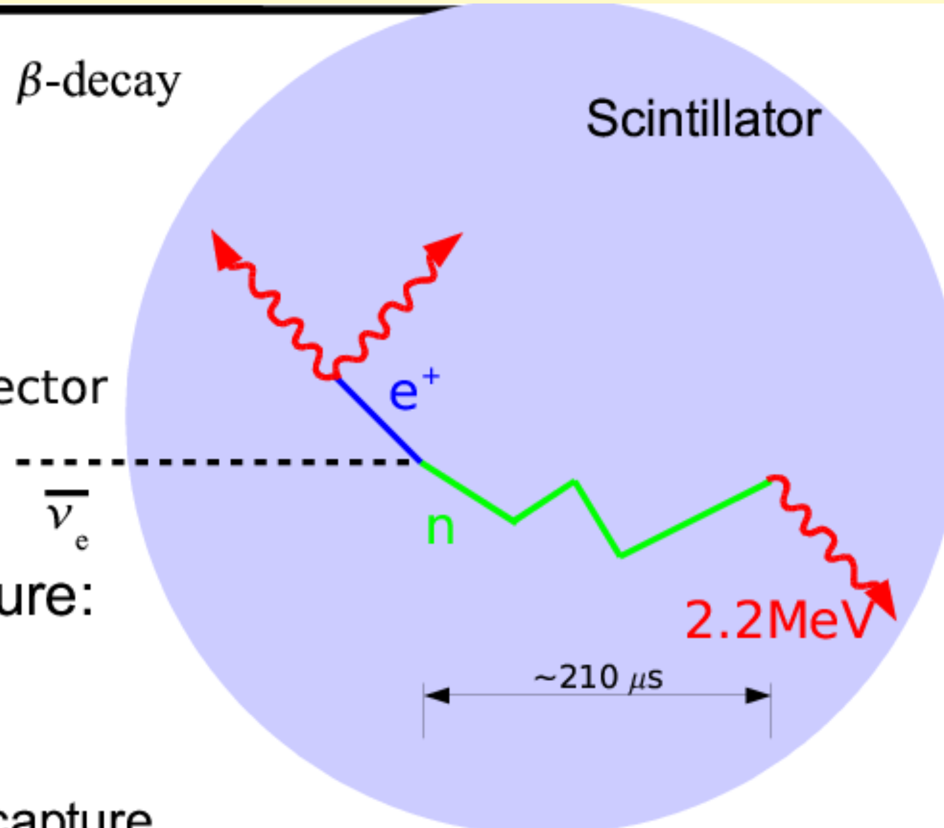


Detection

Reaction Process: inverse β-decay

$$\overline{\nu_e} + p \rightarrow e^+ + n$$
$$n + p \rightarrow d + \gamma$$

Scintillator is target and detector

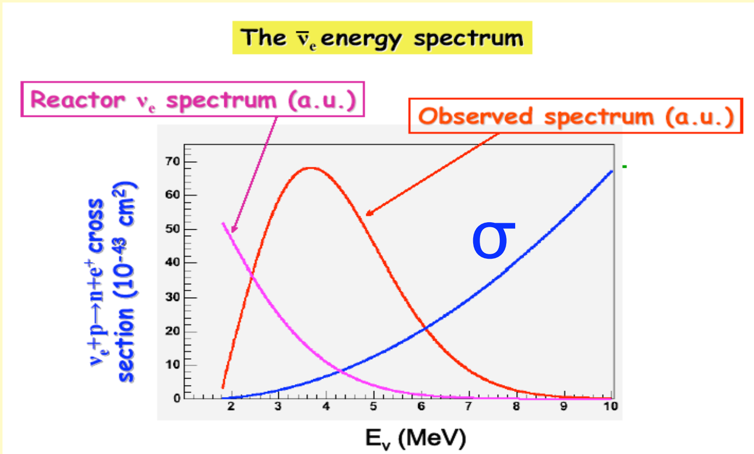


- Distinct two-step signature:
  - prompt event: positron
    $$E_\nu \approx E_{e^+} + 0.8\ MeV$$
  - delayed event: neutron capture after ~210μs
    - 2.2 MeV gamma

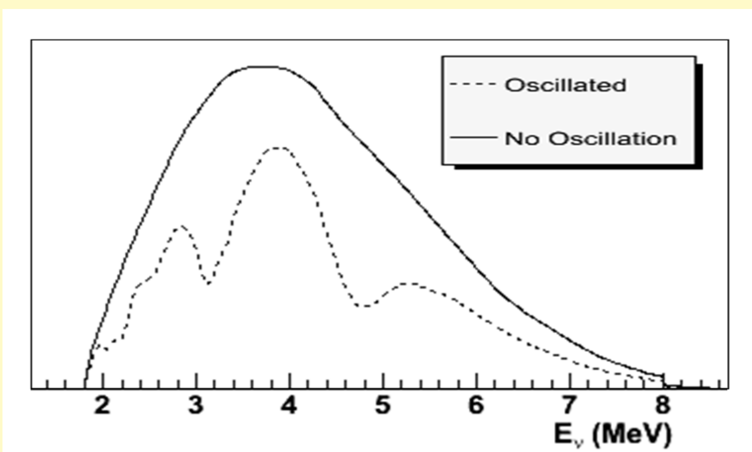
Delayed coincidence: good background rejection

Results

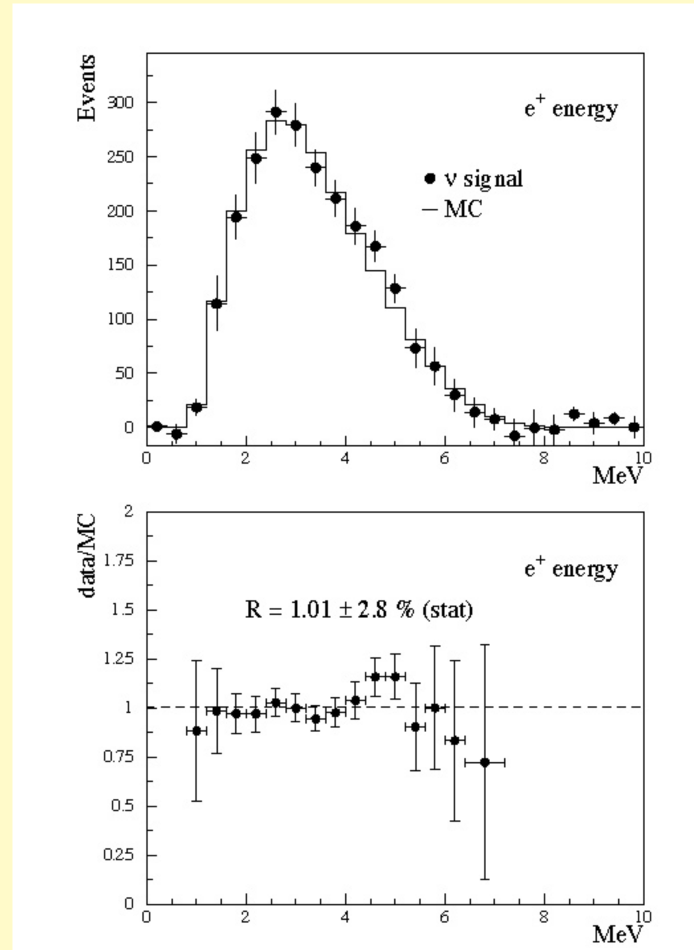
Expected spectrum (no oscill.):



With oscillations (qualitative):



CHOOZ: no oscillations within few % error



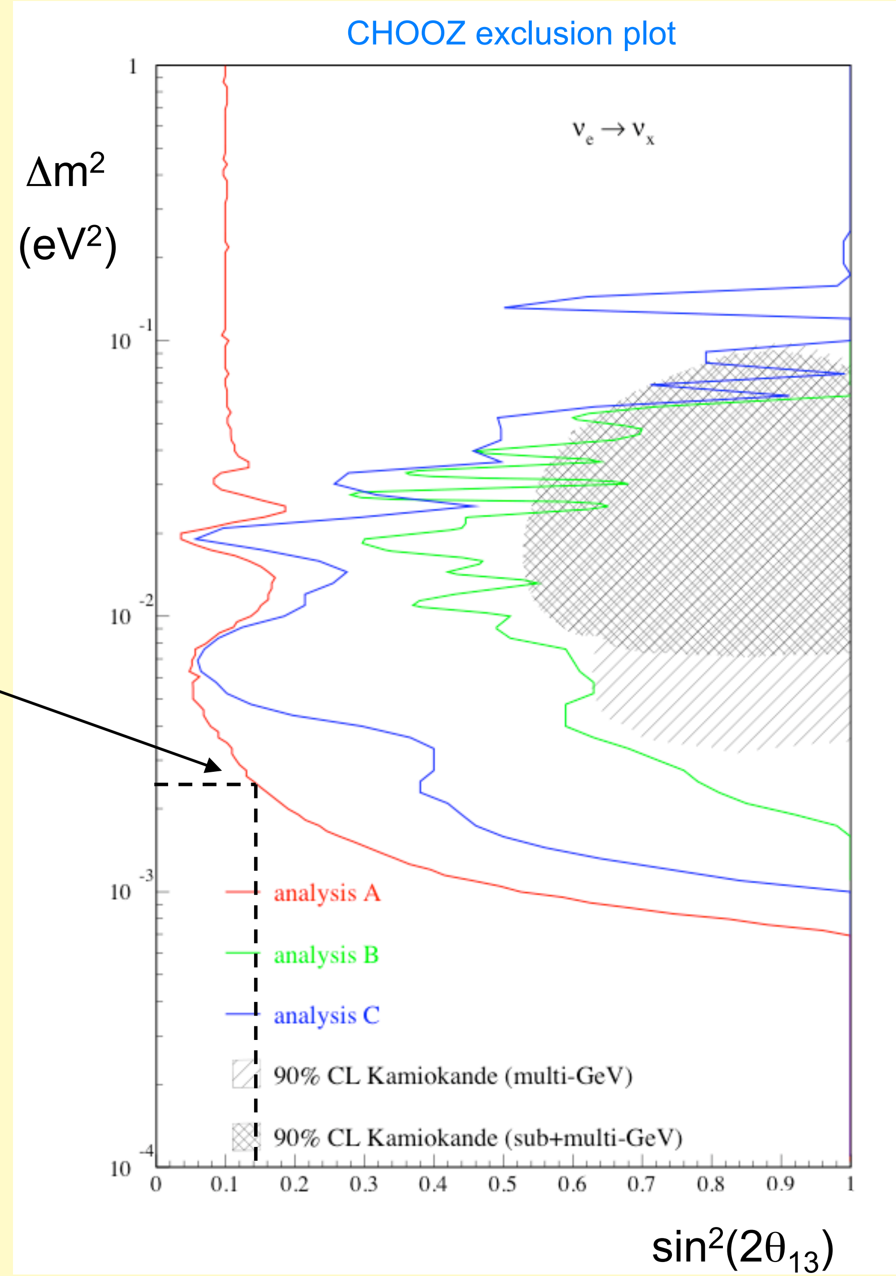
Interpretation

One mass scale dominance:

$P_{ee} = 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2 L/4E_\nu)$

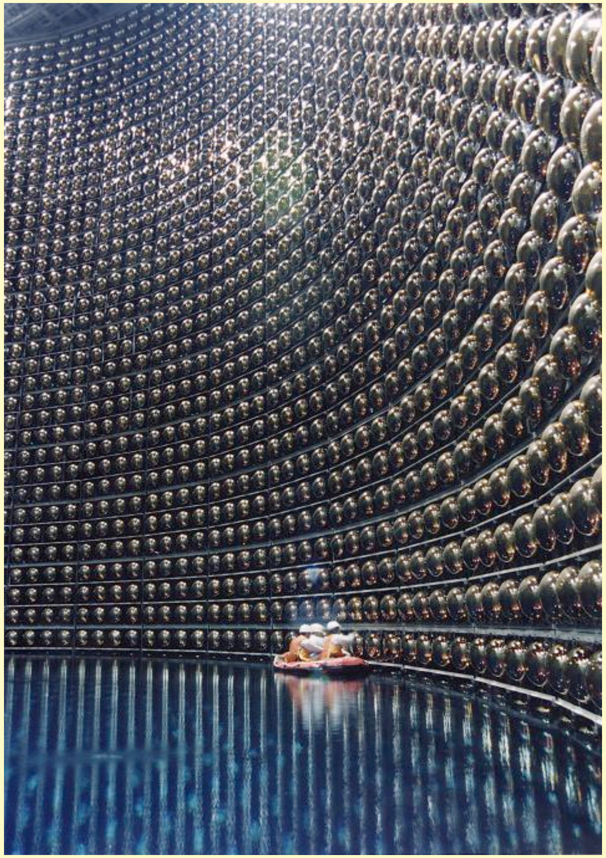
For any value of Δm^2 in the range allowed by atmospheric data (see next), get stringent upper bound on θ_{13}

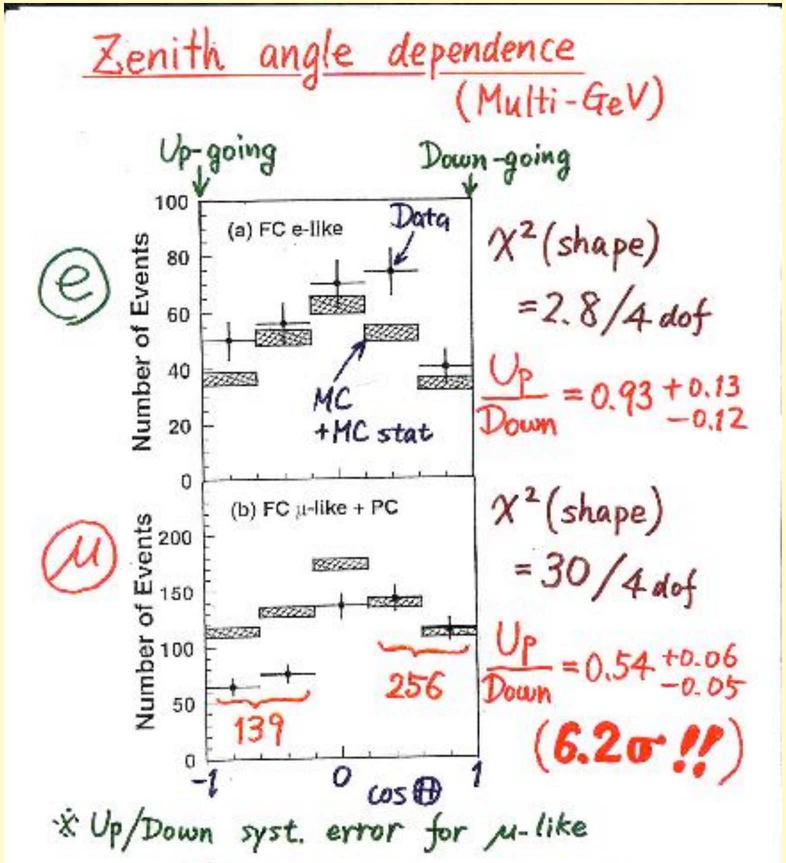
$\sin^2 \theta_{13} < \text{few } \%$



Feverish world-wide activity to build new reactor experiment with higher θ_{13} sensitivity → need to use a second (close) detector to reduce systematics

Atmospheric neutrinos: The Super-Kamiokande breakthrough

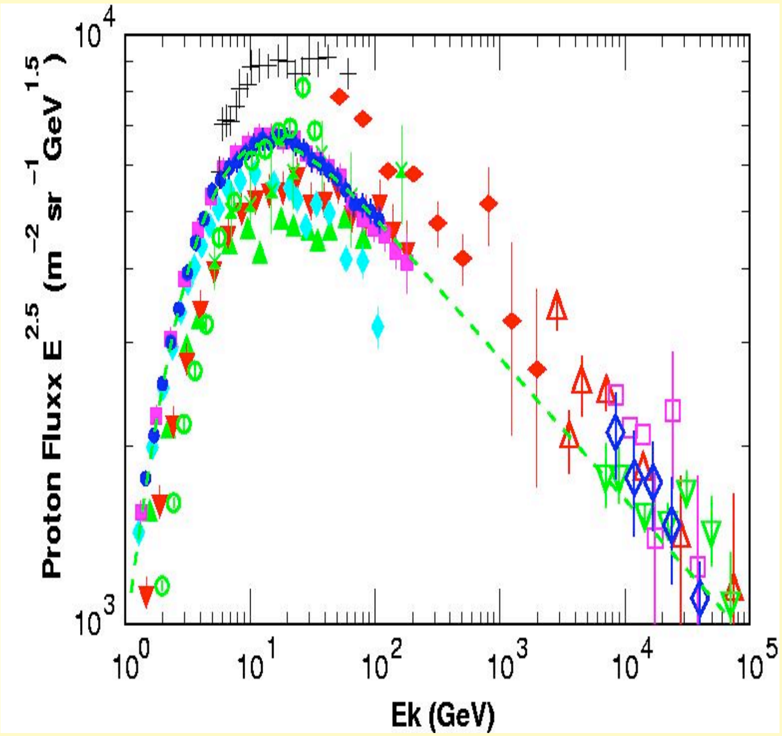


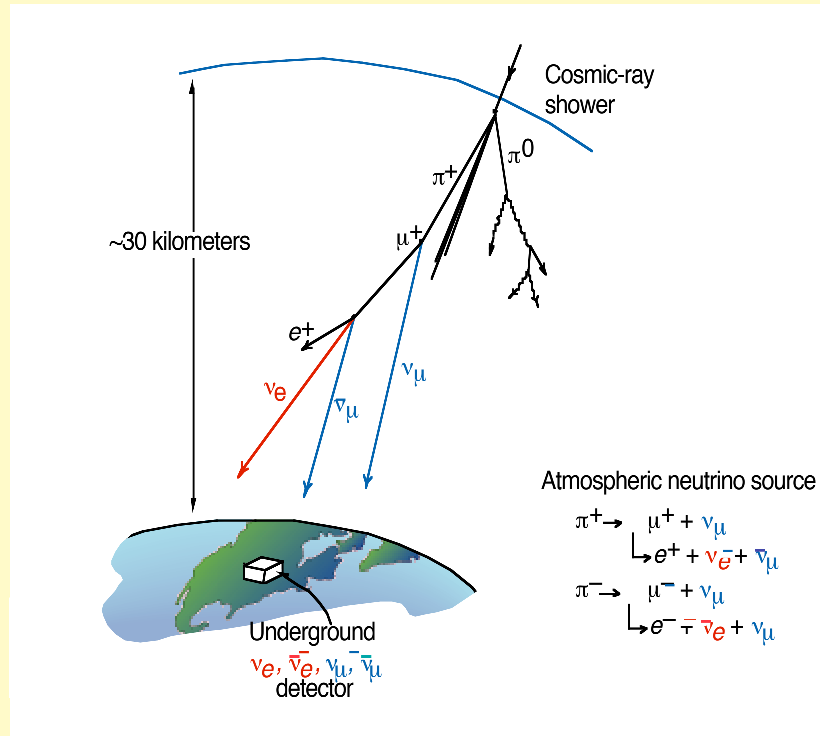


(T. Kajita at Neutrino'98, Takayama)

Production

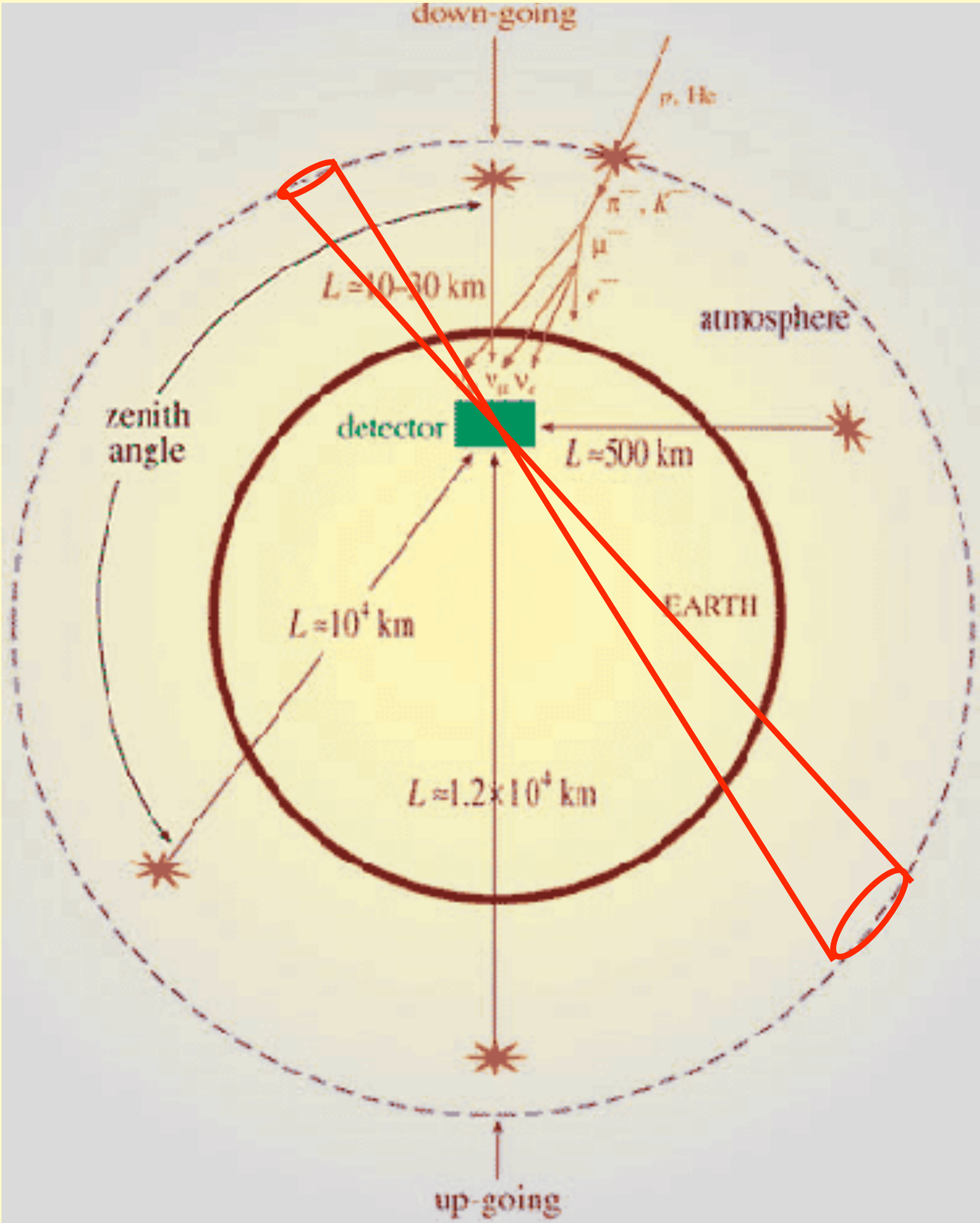
Cosmic rays hitting the atmosphere can generate secondary (anti)neutrinos with electron and muon flavor via meson decays.





Primary flux affected by large normalization uncertainties…

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



Moreover: same ν flux from opposite solid angles (up-down symmetry)

[Flux dilution (~1/r²) is compensated by larger production surface (~r²)]

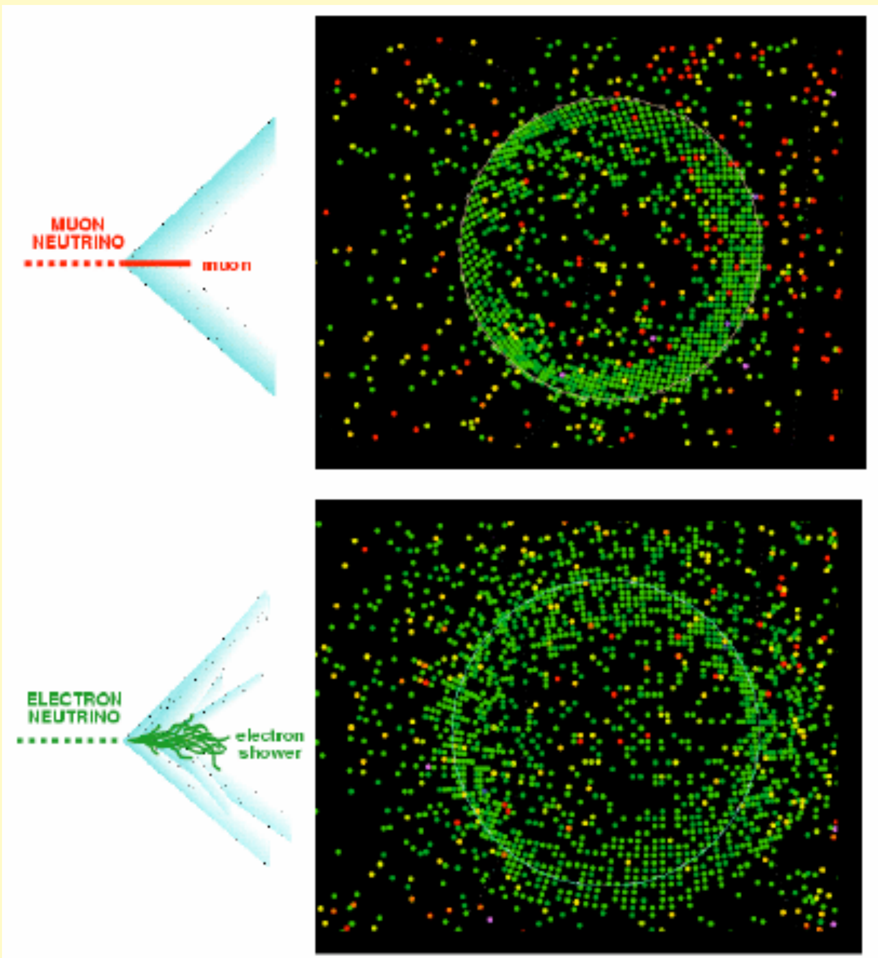
Should be reflected in symmetry of event zenith spectra, if energy & angle can be reconstructed well enough

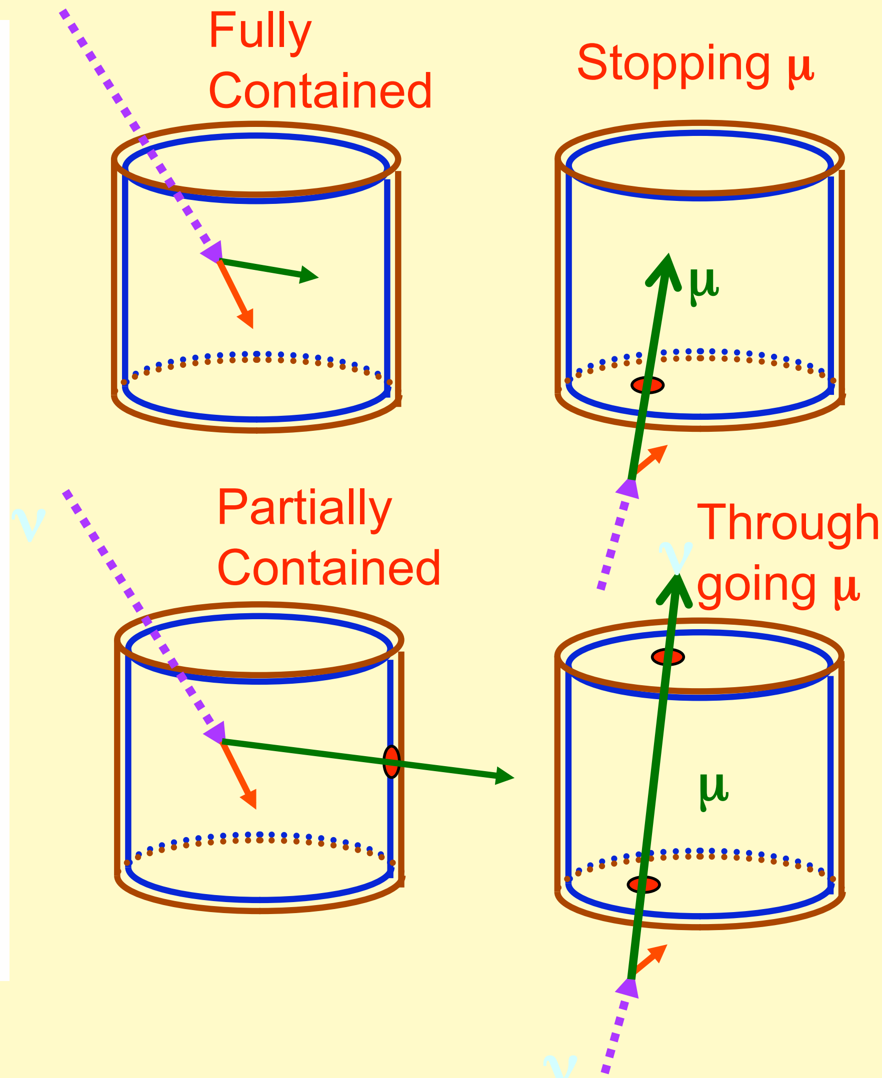
Detection in SK

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

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

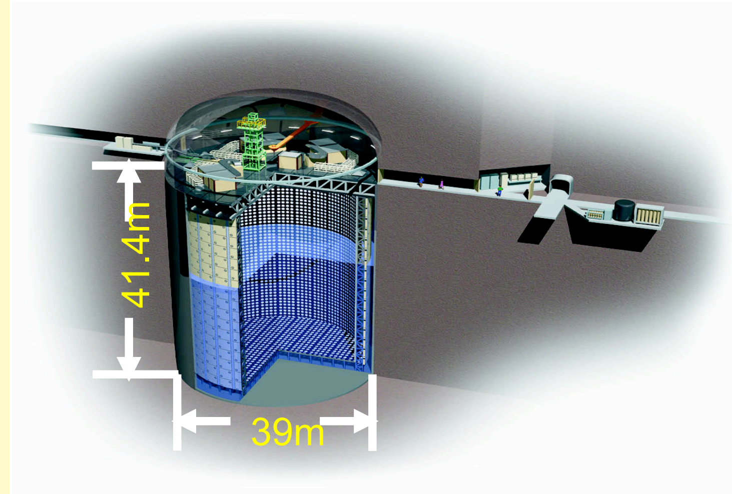
(But: no charge discrimination, no τ event reconstruction). Topologies:



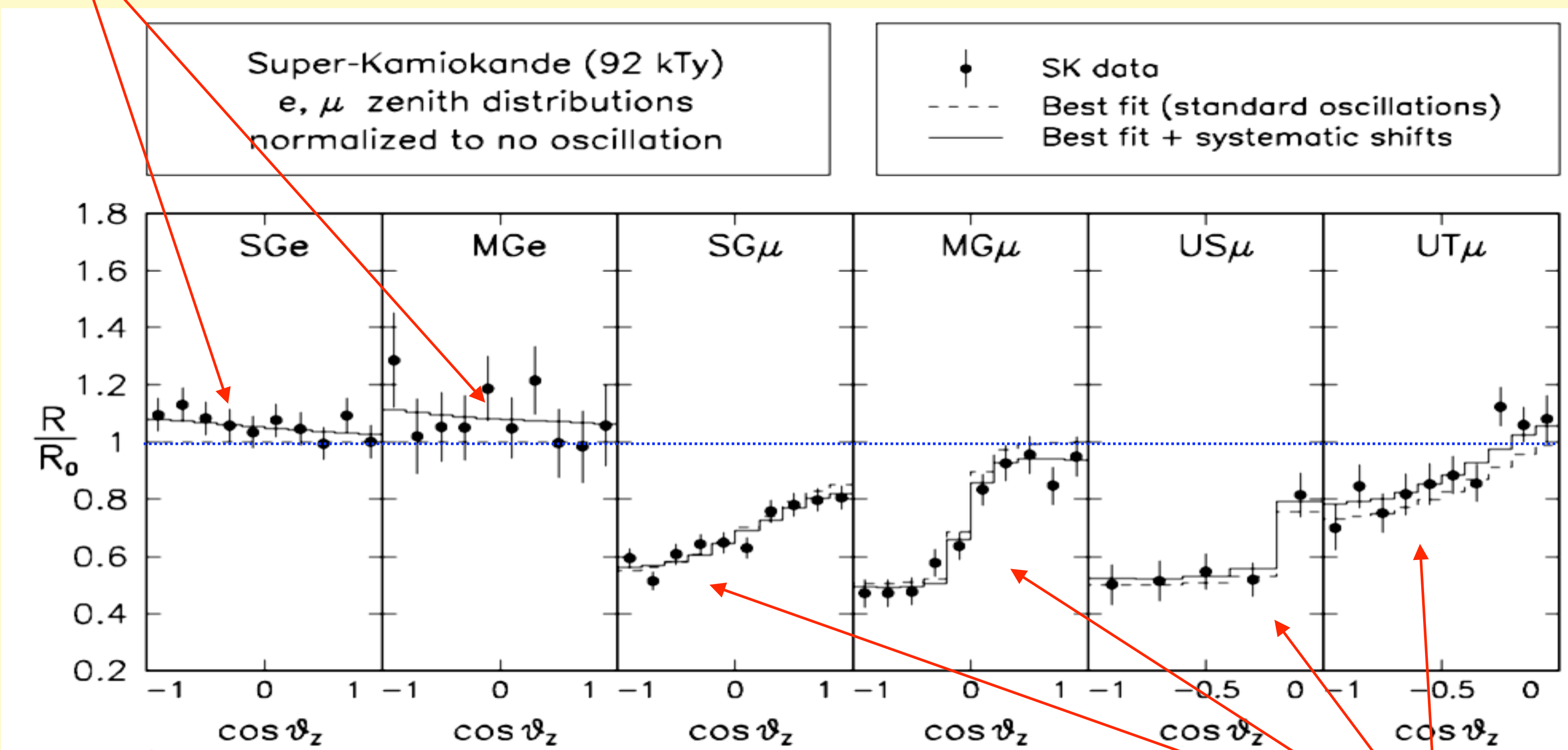


RESULTS SK zenith distributions

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



electrons ~OK



no osc.

up down

muon deficit from below

Observations over several decades in L/E:

ν_e induced events: ~ as expected

ν_μ induced events: disappearance from below

Interpretation in terms of oscillations:

Channel $\nu_\mu \rightarrow \nu_e$? No (or subdominant) ← CHOOZ OK!

Channel $\nu_\mu \rightarrow \nu_\tau$? Yes (dominant)

One-mass-scale approximation (for θ_{13}=0):

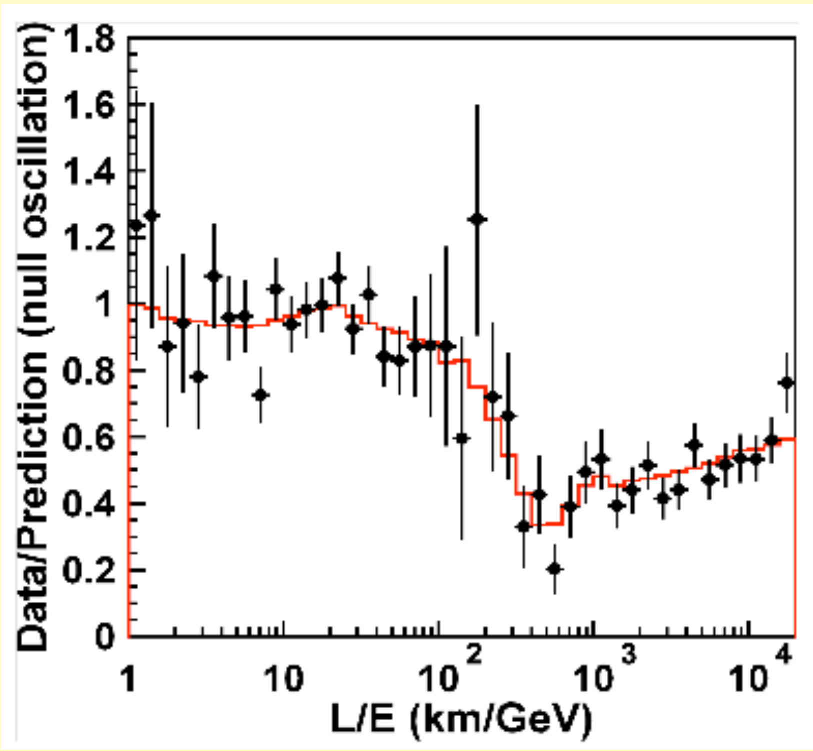
$$P_{\mu\tau} = \sin^2(2\theta_{23}) \sin^2(\Delta m^2 L/4E_\nu)$$

[In this channel, oscillations are ~vacuum-like, despite the presence of Earth matter]

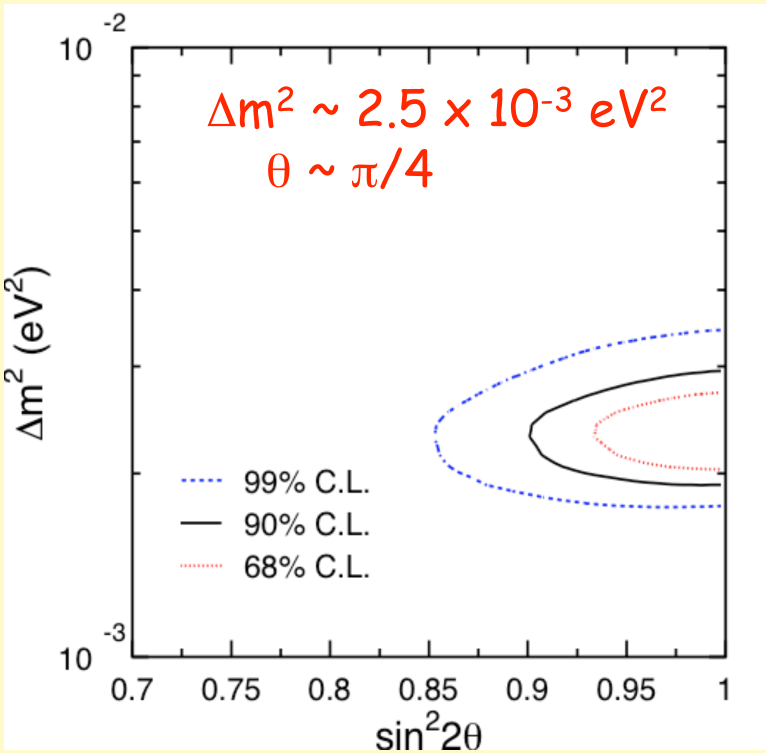
Results consistent with other atmos. expts. using different techniques (MACRO, Soudan2) but with lower statistics

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

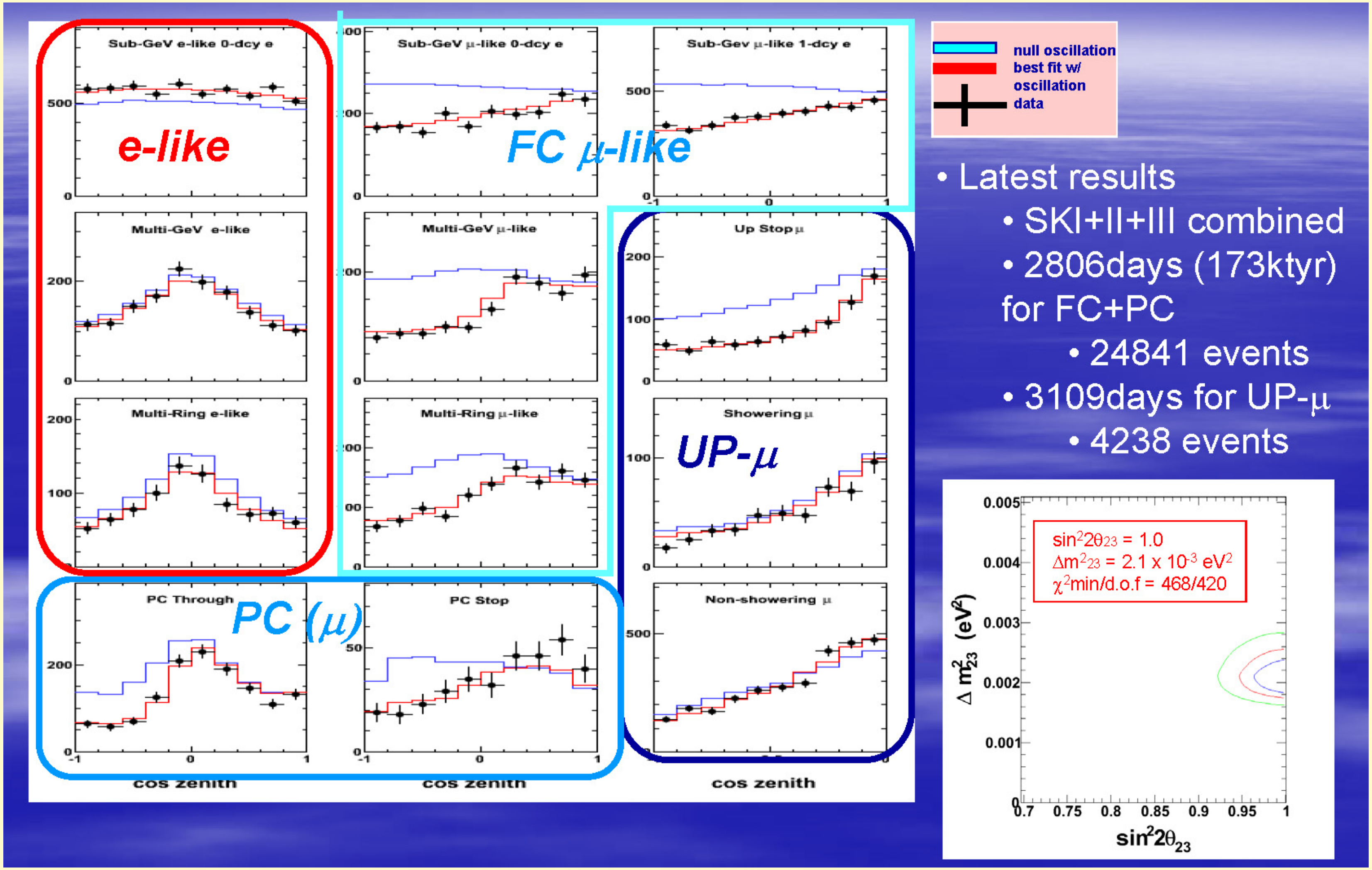
1st oscillation dip still visible despite large L & E smearing



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



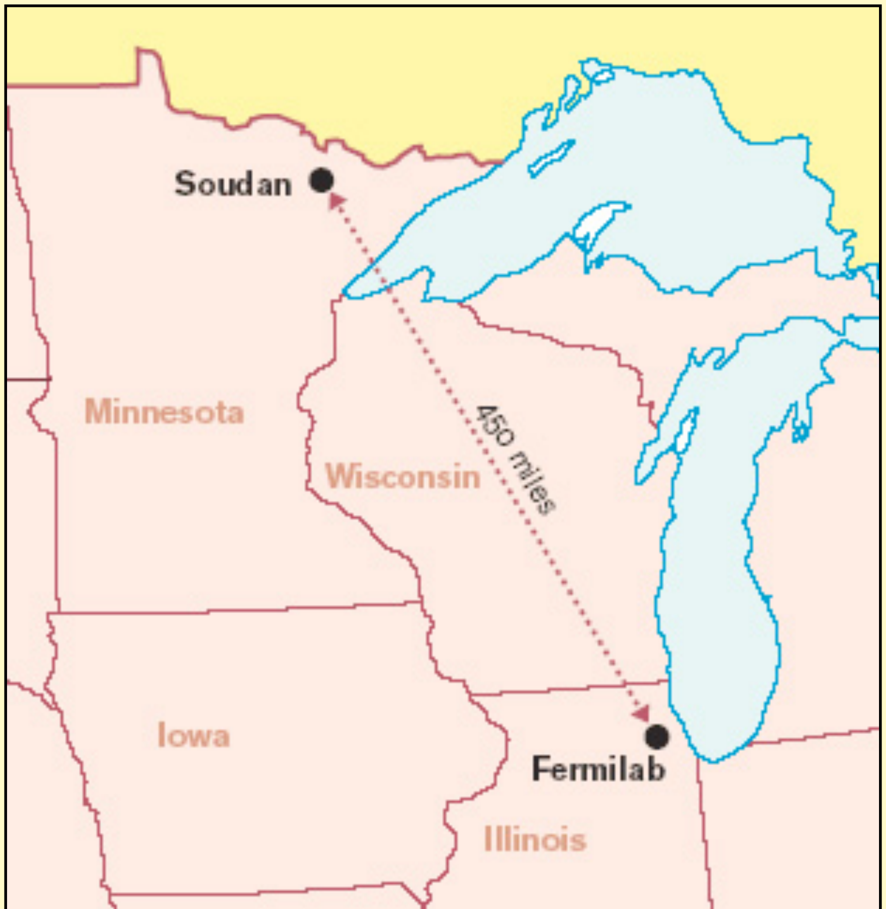
Latest SK dataset include hundreds of bins (Shiozawa, Erice 2009):

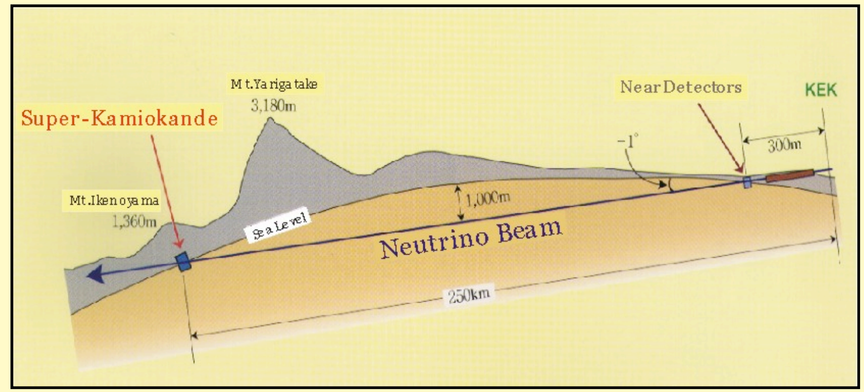


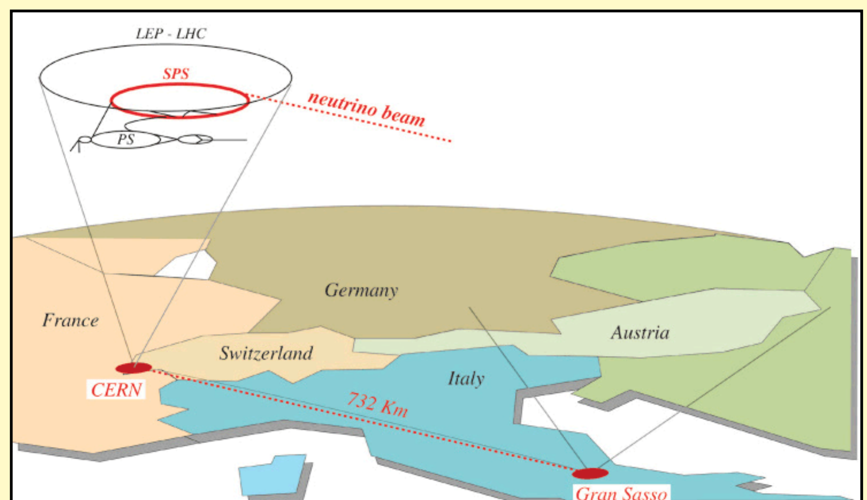
[L/E evidence for half-cycle also improved.]

Long-baseline neutrino experiments (K2K, MINOS, OPERA)

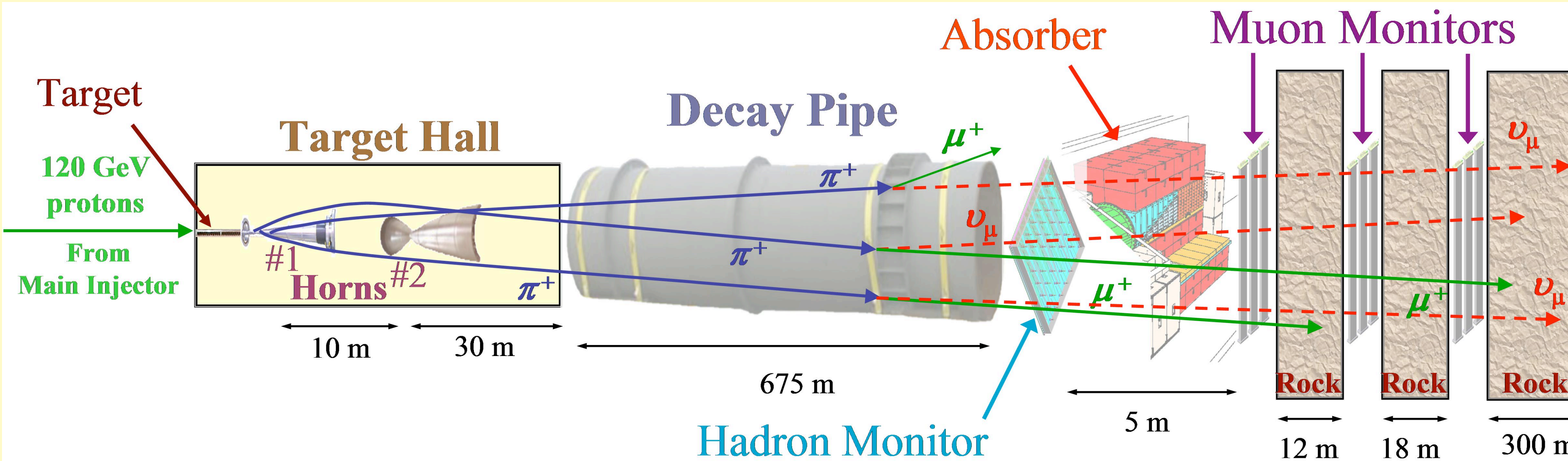
"Reproducing atmospheric ν_μ physics" in controlled conditions





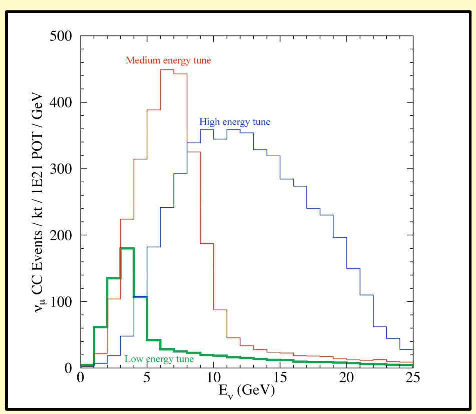


Production (e.g., MINOS)

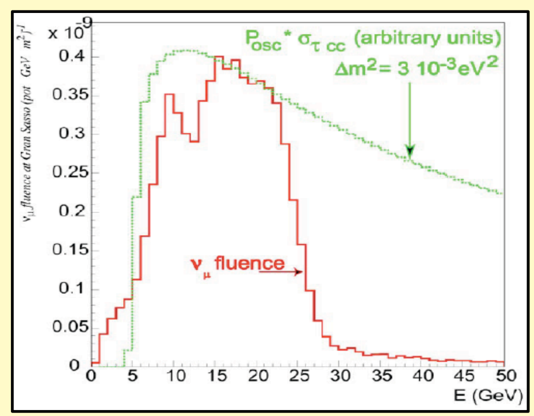


π decay: ν energy is only function of νπ angle and π energy

Spectra:



MINOS



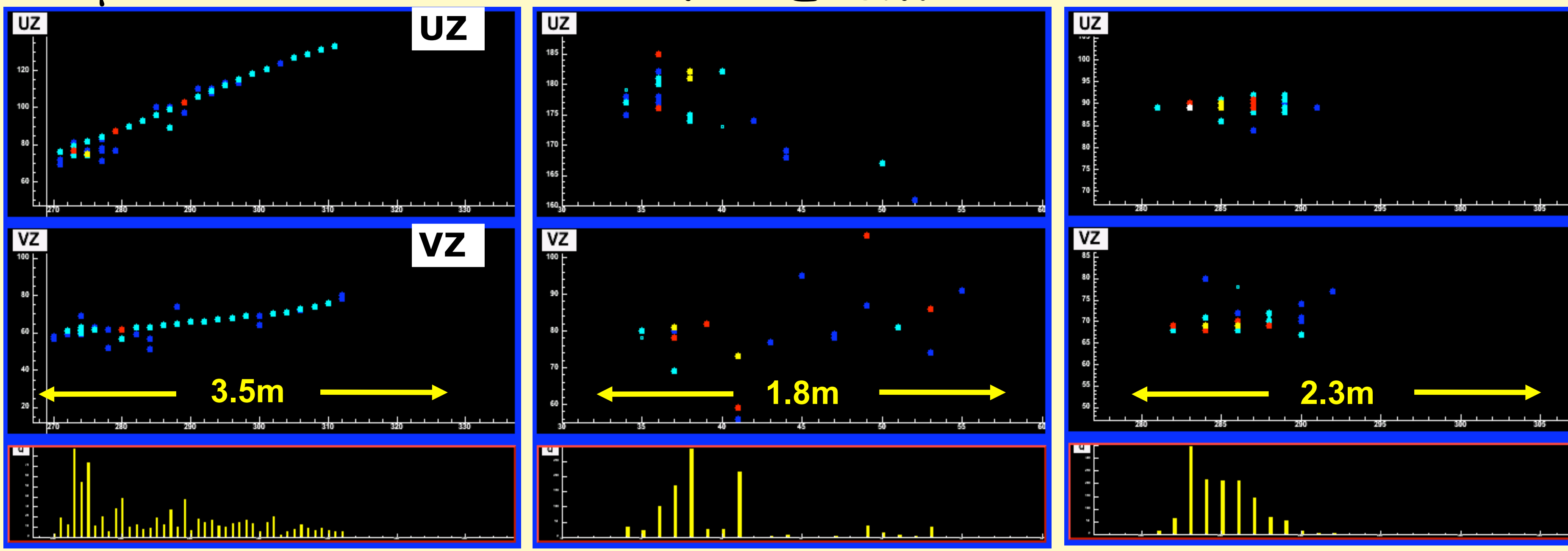
OPERA

(Far) Detection

K2K: Cherenkov technique in SK

MINOS: Steel/Scintillator detector (+ magnetic field)

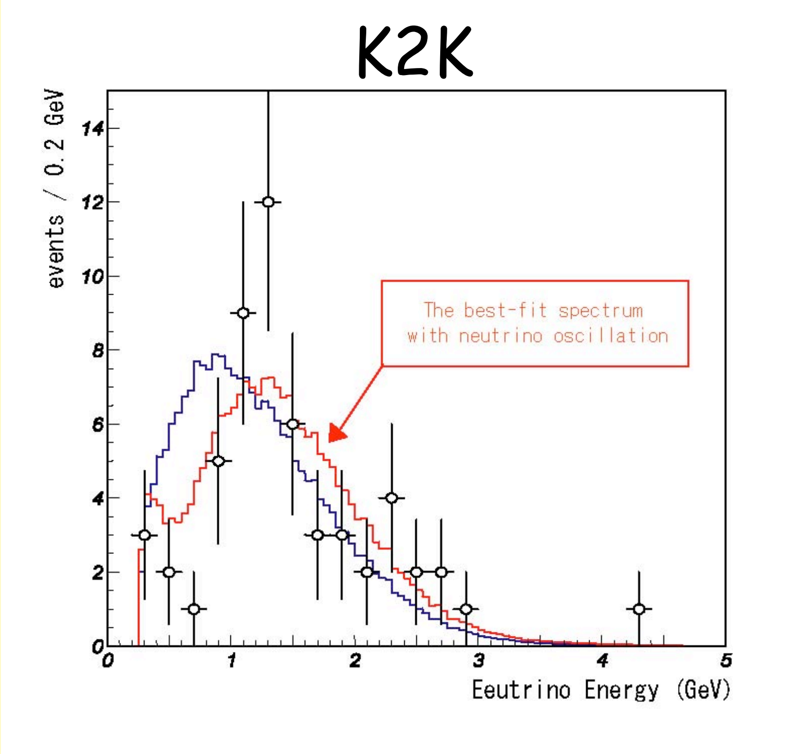
ν_μ CC Event | NC Event | ν_e CC Event

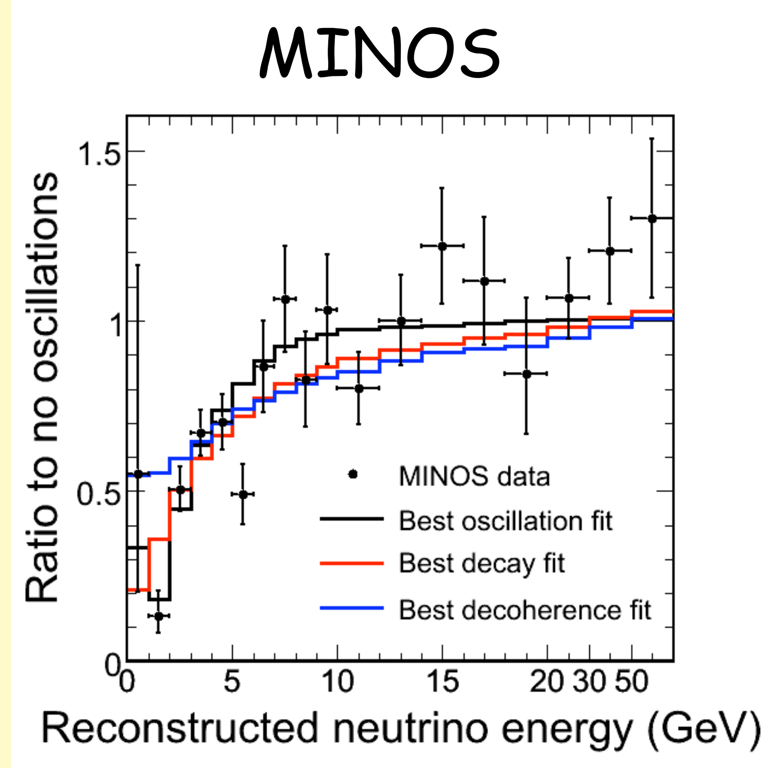


- Long muon track + hadronic activity at vertex
- Short showering event, often diffuse
- Short event with typical EM shower profile

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

Results (muon neutrino disappearance mode)





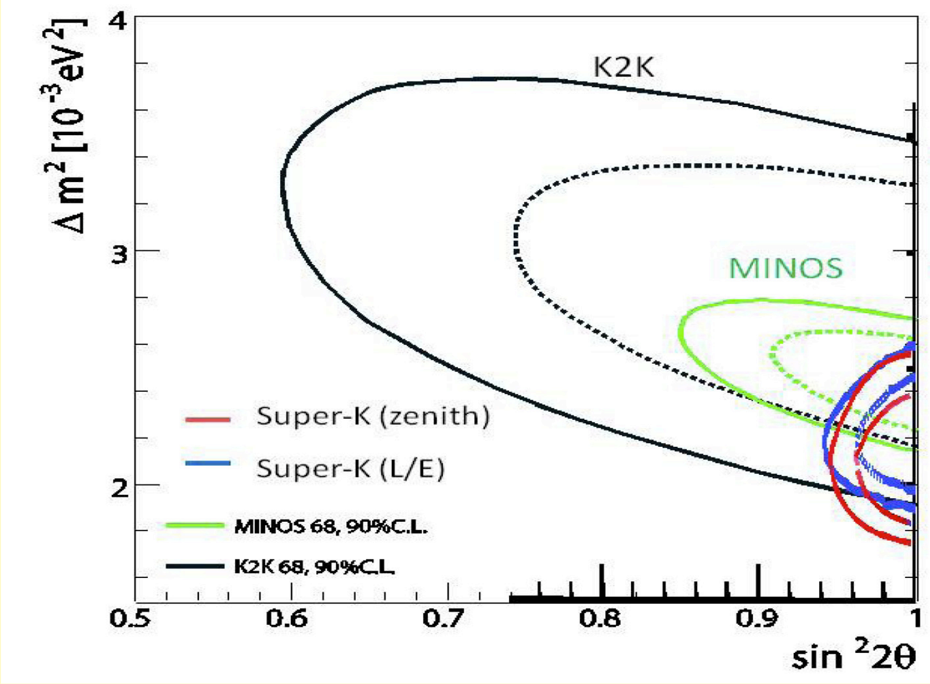
1st oscillation dip observed.

[Exotic explanations without dip (decay, decoherence) disfavored]

Interpretation

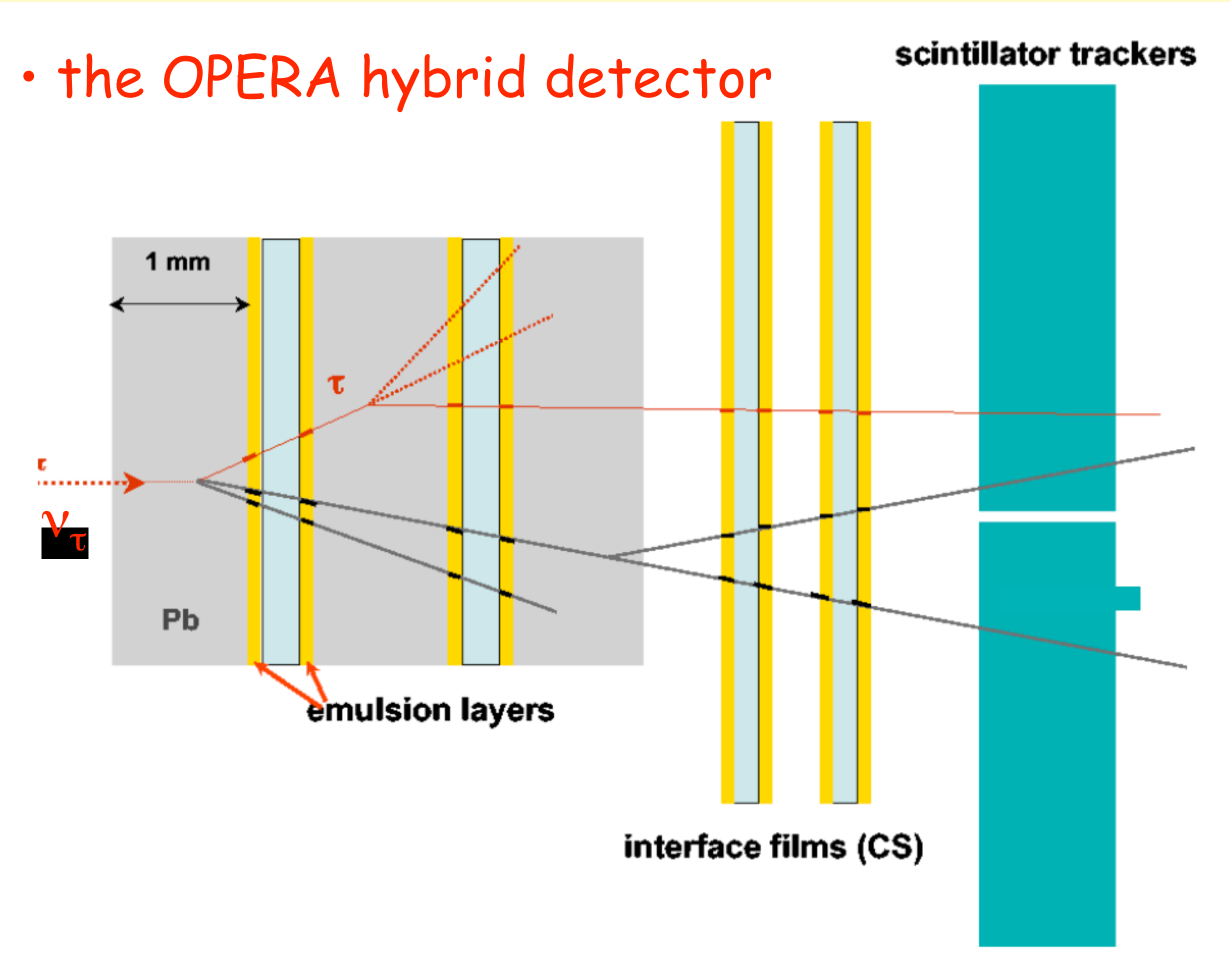
Once more… dominant $P_{\mu\tau} = \sin^2(2\theta_{23})\,\sin^2(\Delta m^2 L/4E_\nu)$

Oscillation parameters consistent among experiments

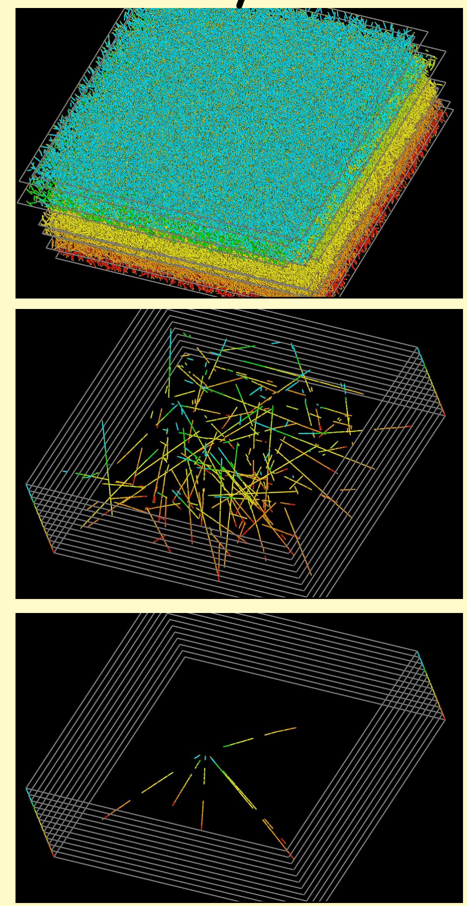


[But: lower-statistics muon <u>antineutrino</u> data in MINOS (2009) somewhat off.
Too early to claim CPT violation anyway…]

Testing dominant oscillations via τ appearance: **OPERA**



Finding needles in a haystack…

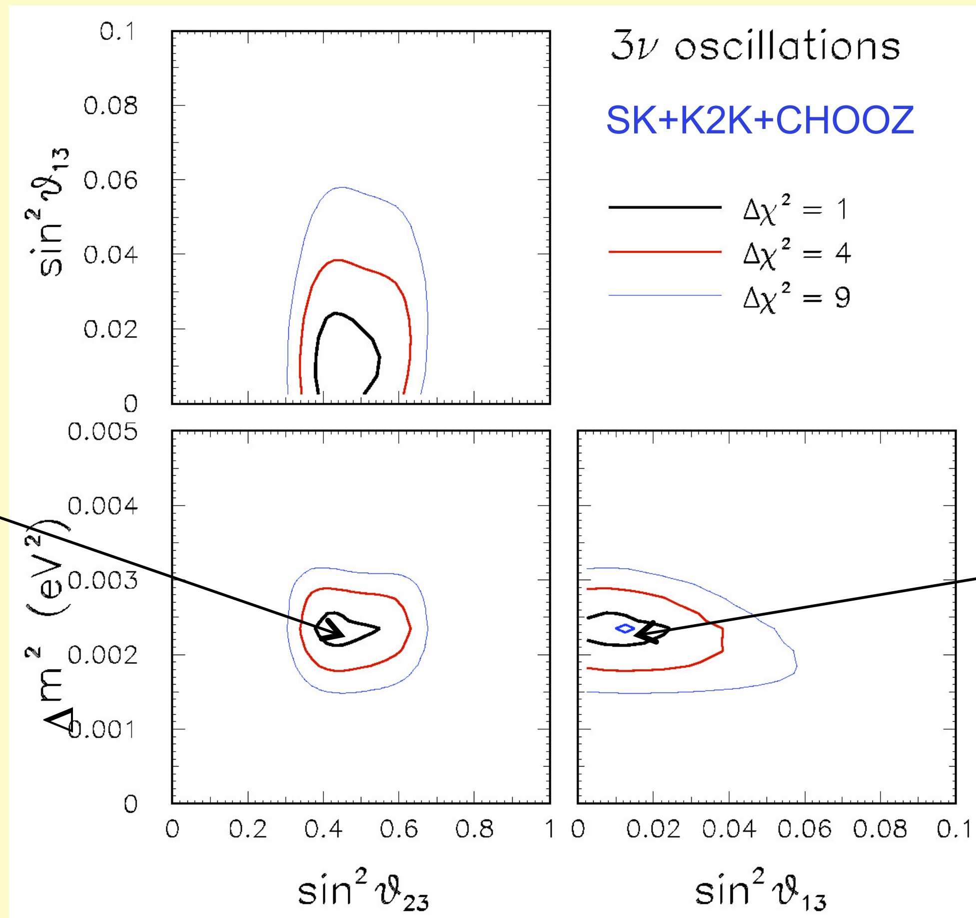


Best wishes for finding 1st "τ needle" in 2010 data analysis!

More refined (3ν) interpretation

Go beyond dominant $P_{\mu\tau} = \sin^2(2\theta_{23}) \sin^2(\Delta m^2 L/4E_\nu)$
Include subleading oscillations in vacuum and matter.
Interesting (small) effects emerge. [See e.g. hep-ph/0506083]

θ_{23} octant asymmetry?



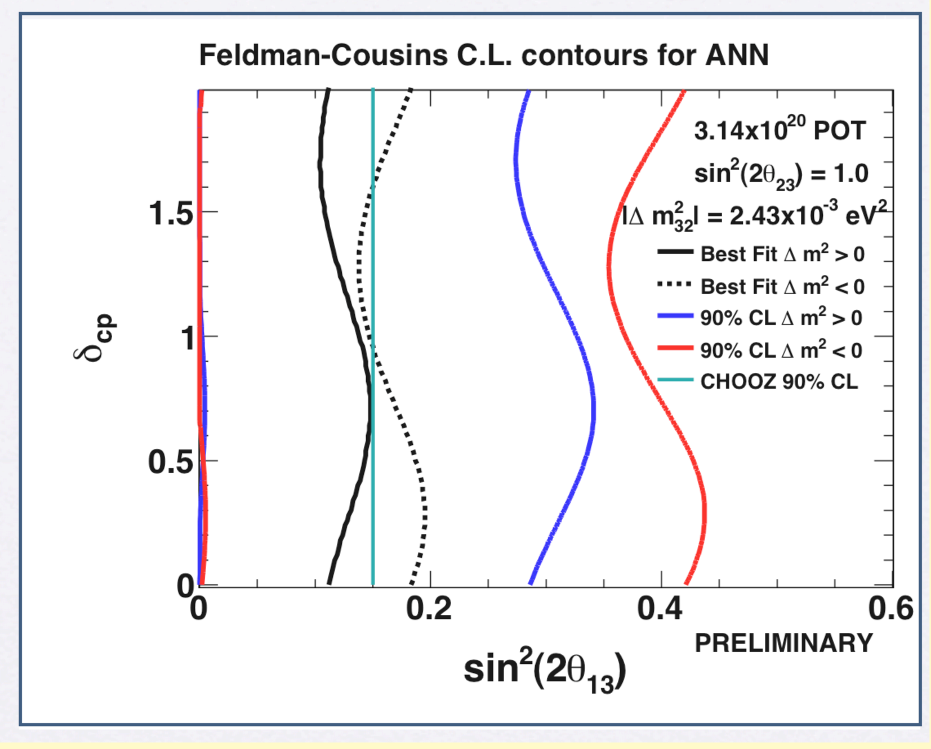
θ_{13} nonzero best fit?

Testing subdominant θ_{13} effects via e appearance: **MINOS**

Small electron excess found in $P_{\mu e}$ oscillation channel

Best fit for $\theta_{13} \neq 0$, but still low statistical significance.

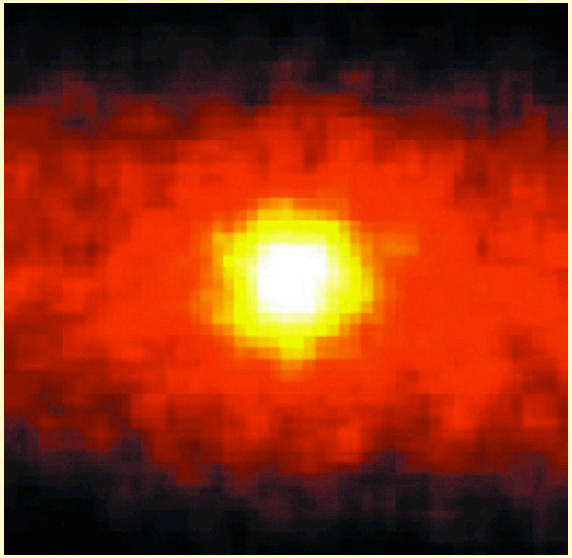
3ν probability: constraints depend on δ and hierarchy



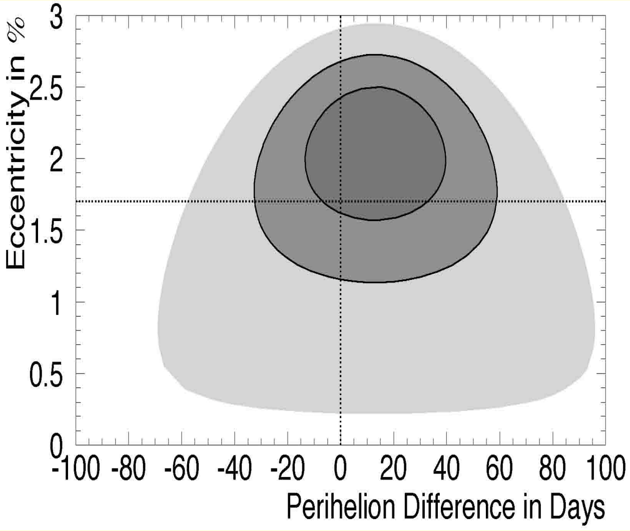
Expect interesting MINOS updates!

Experiments sensitive to the "small" δm^2:

Solar neutrinos



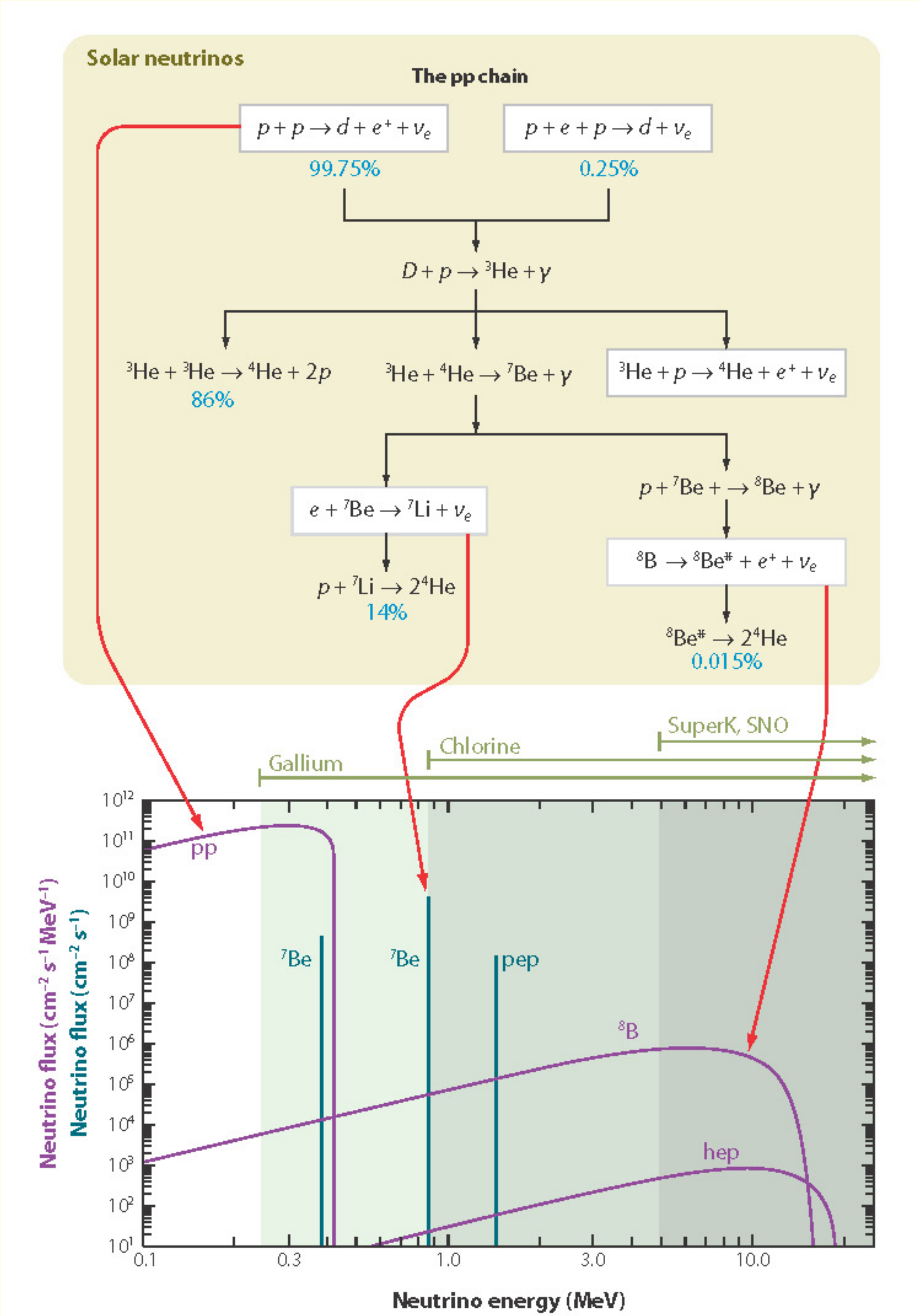
The Sun seen with neutrinos (SK)

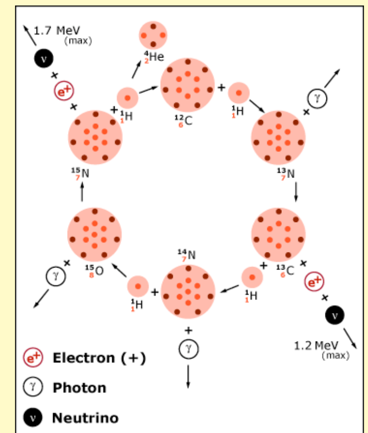


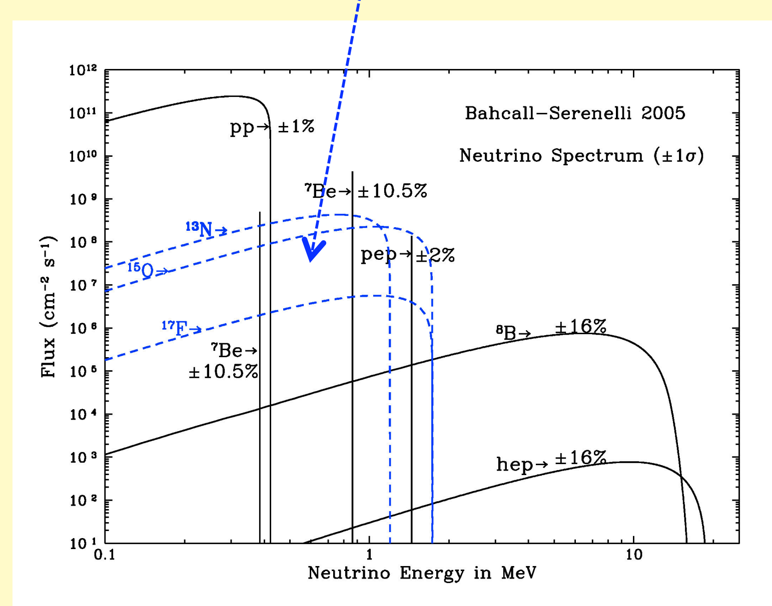
Earth orbit from solar ν (SK)

Production

pp (+CNO) cycle







Detection

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

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

Homestake

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^- \quad (\mathrm{CC})$$

GALLEX/GNO, SAGE

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

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (\mathrm{NC},\mathrm{CC})$$

SK, SNO, Borexino

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

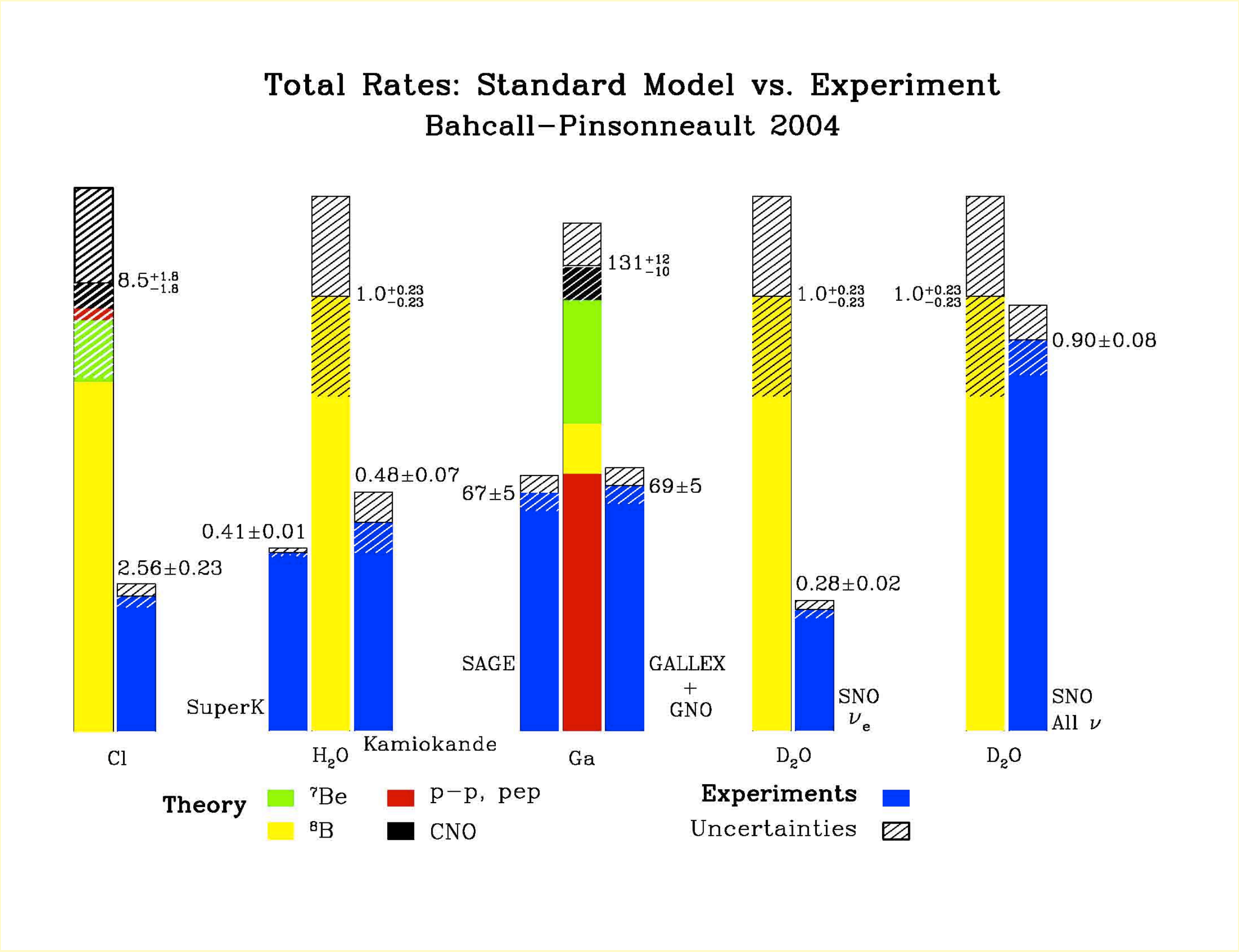
$$\nu_e + d \rightarrow p + p + e^- \quad (\mathrm{CC})$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad (\mathrm{NC})$$

SNO (Sudbury Neutrino Observatory)

Results

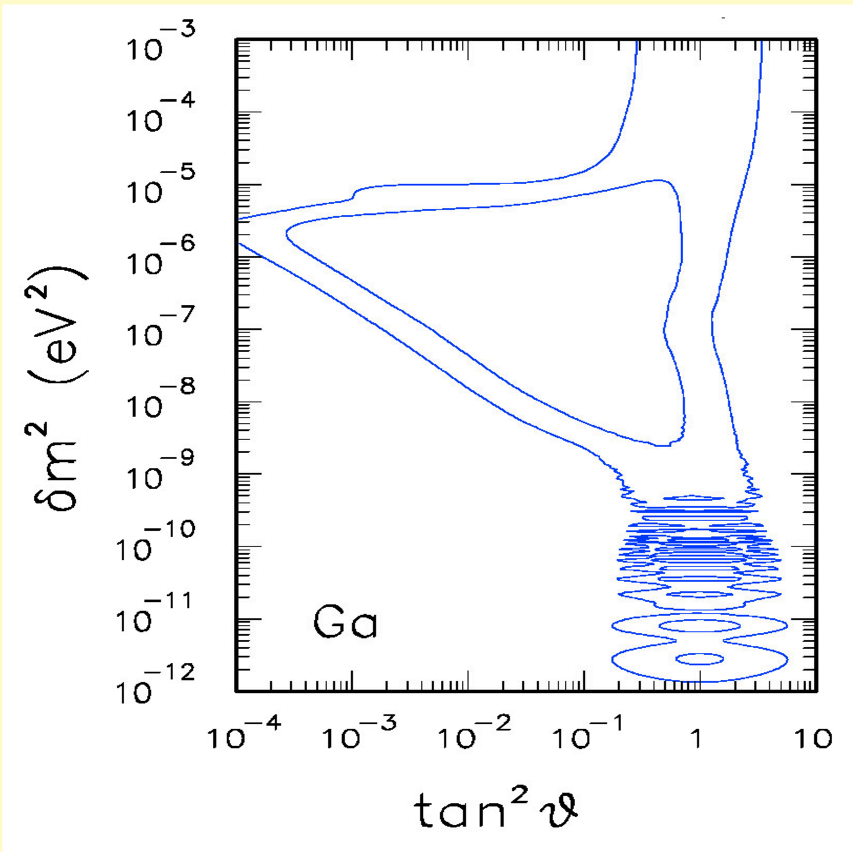
All CC-sensitive results indicated a ν_e deficit…



…as compared to solar model expectations

Interpretation

In the “past millennium”: Oscillations? Maybe, but…
- large uncertainties in the parameter space or solar model
- no unmistakable evidence for flavor transitions (“smoking gun”)



E.g., in Gallium expts:

“matter” (MSW) solutions

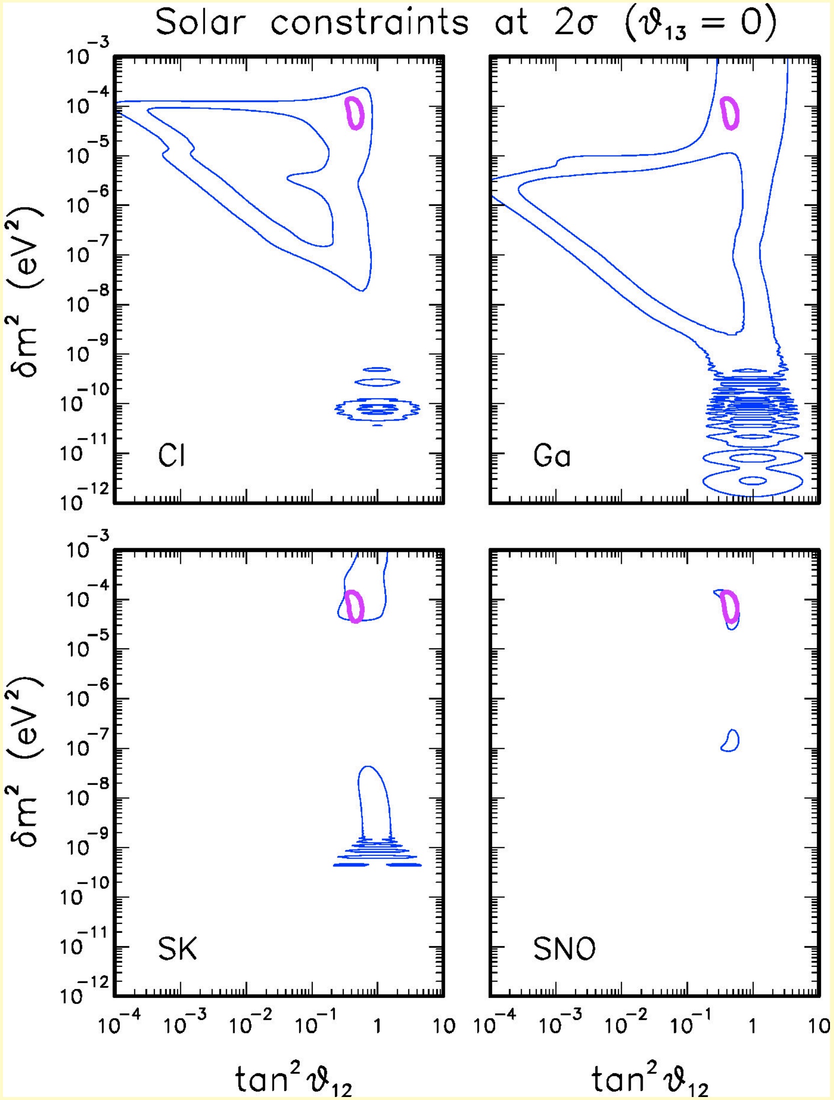
“vacuum” solutions

“small” mixing

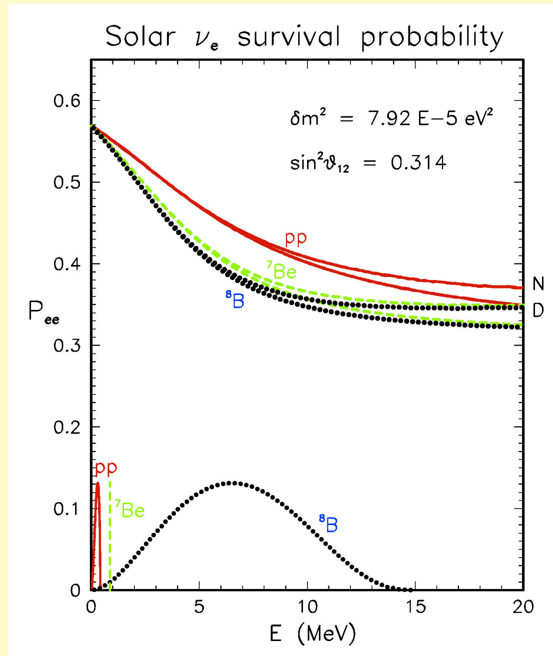
“large” mixing

+ many “exotic” or non-oscillatory solutions…

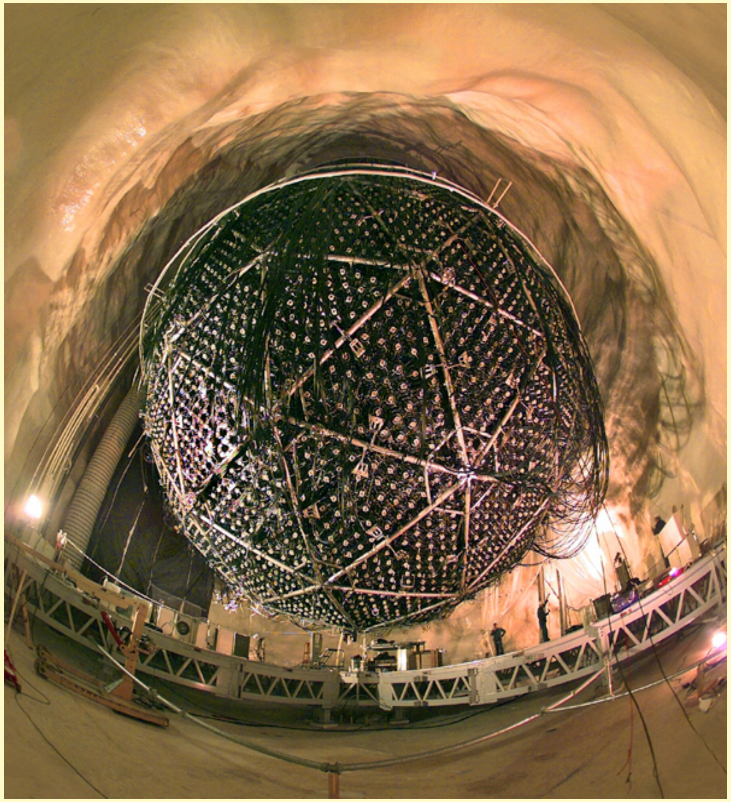
But, in 2002 ("annus mirabilis"), one global solution was finally singled out by combination of data ("large mixing angle" or LMA).



For LMA parameters, evolution is adiabatic in solar matter.



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



crucial role played by
Sudbury Neutrino Observatory:

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)

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

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

thus:

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

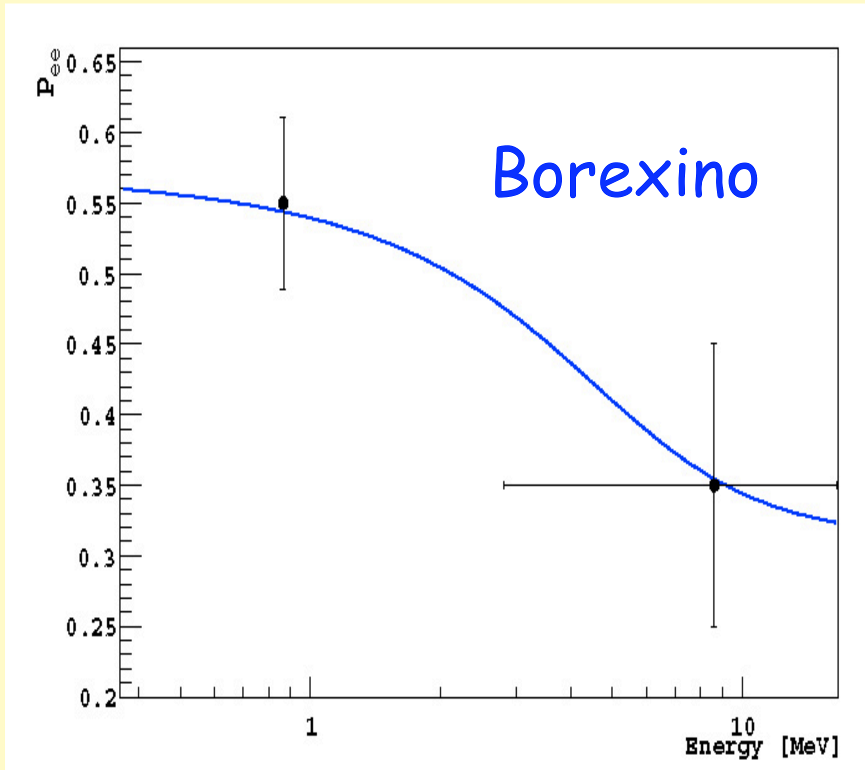
CC/NC ~ 1/3 < 1

"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

Very recent, direct confirmation of Pee adiabatic pattern of LMA solution in a single solar neutrino experiment: BOREXINO at Gran Sasso

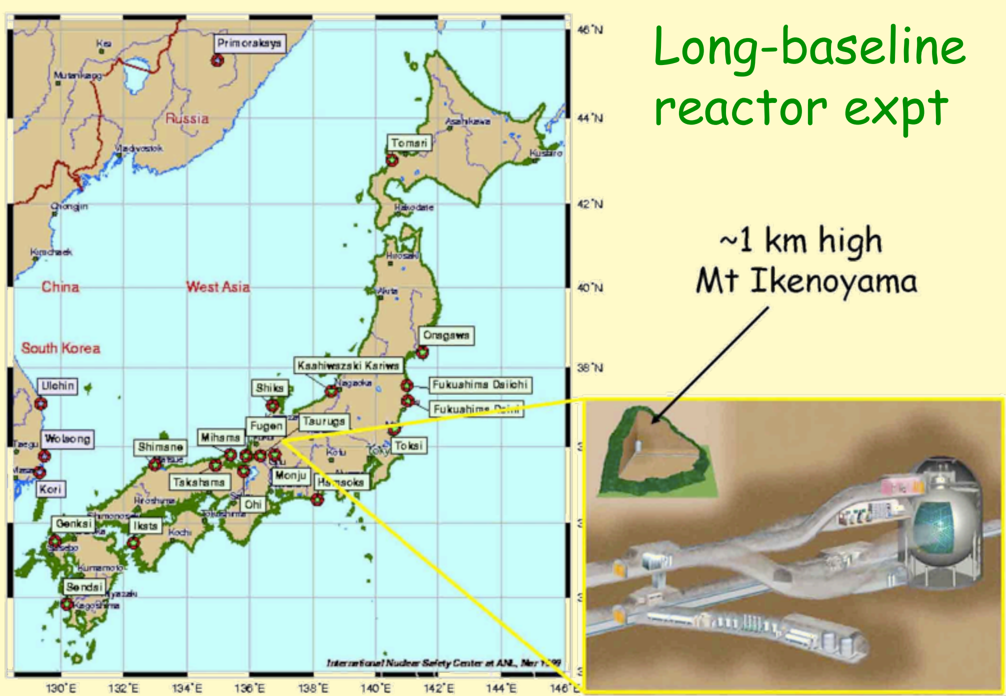


Also in 2002… KamLAND: 1000 ton mineral oil detector, "surrounded" by nuclear reactors producing anti-ν_e. Characteristics:

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

⇨

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

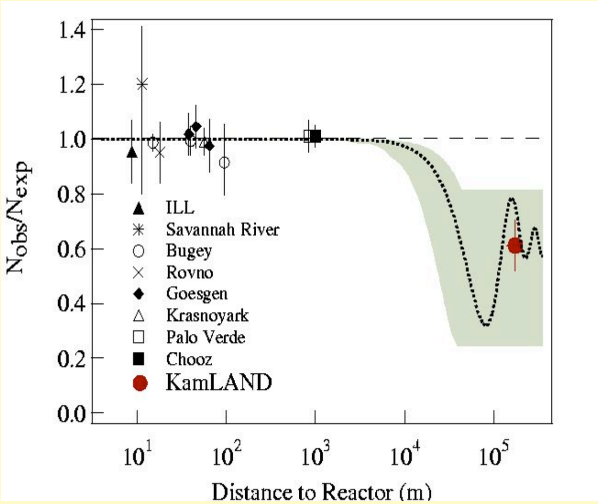


Long-baseline reactor expt

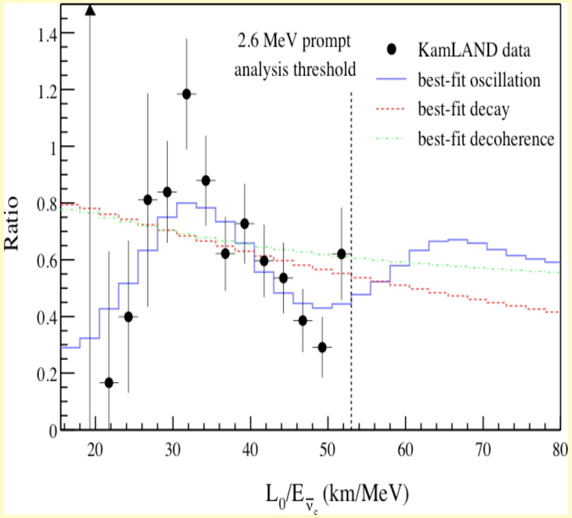
~1 km high
Mt Ikenoyama

KamLAND results

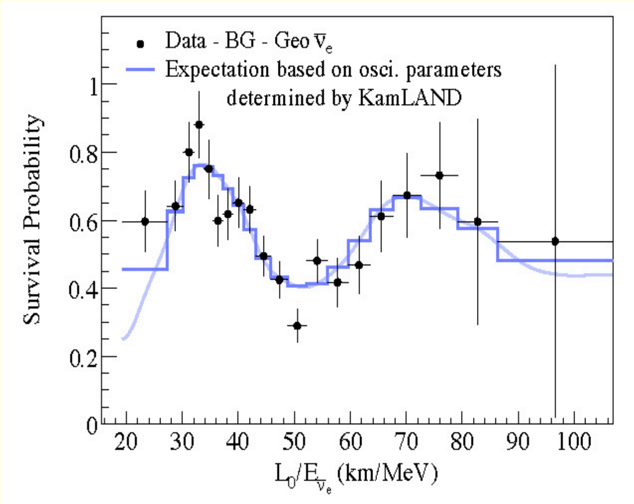
2002: electron flavor disappearance observed



2004: half-period of oscillation observed



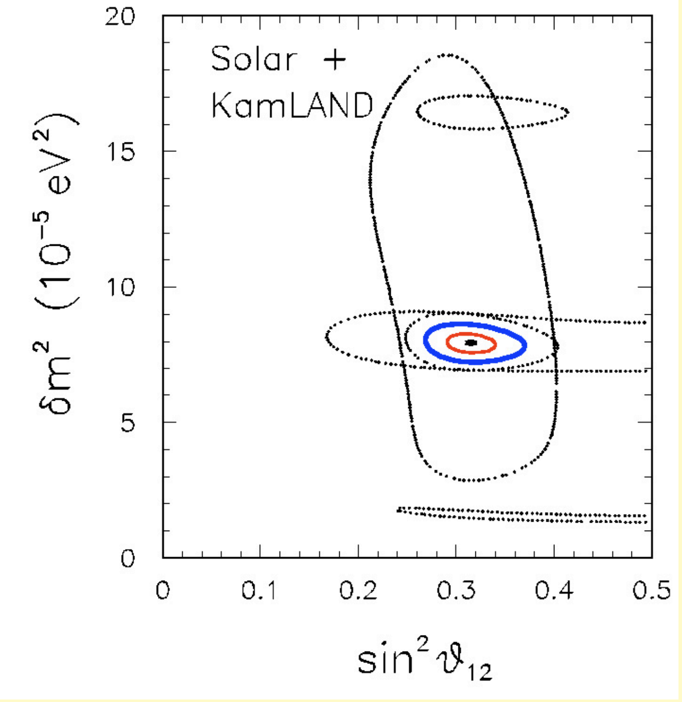
2007: one period of oscillation observed



Direct observation of δm^2 oscillations

Interpretation

(δm^2, θ_{12}) - complementarity of solar/reactor neutrinos



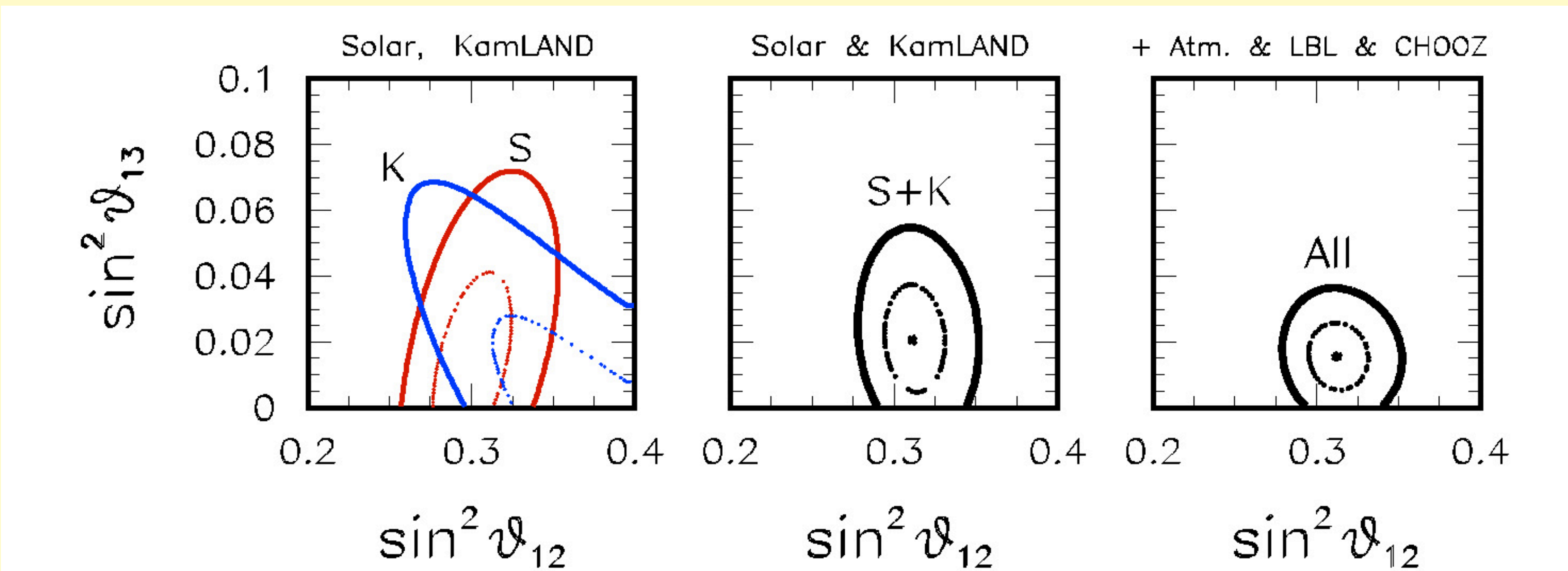
KamLAND

Solar

More refined (3ν) interpretation

Go beyond dominant 3ν oscillations. Include subleading effects due to θ_{13} and averaged Δm^2 oscillations in vacuum/matter.

Interesting (small) effects emerge. [See arXiv:0806.2649].



A hint of θ_{13}>0 arises from slight tension on θ_{12} (solar vs KamLAND) and from different correlation bewteen mixing angles, related to different relative signs in P_{ee} (survival probability) of solar vs KamLAND:

Solar, high energy (LMA MSW):

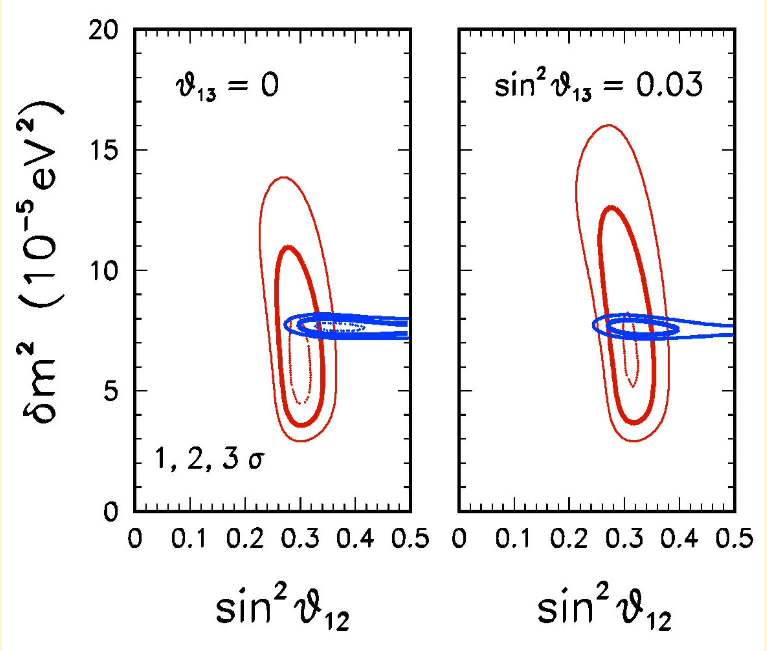
$$P_{ee} \simeq (1 - 2s_{13}^2)(+s_{12}^2)$$

$-$ $+$

Reactor (~vacuum): KamLAND

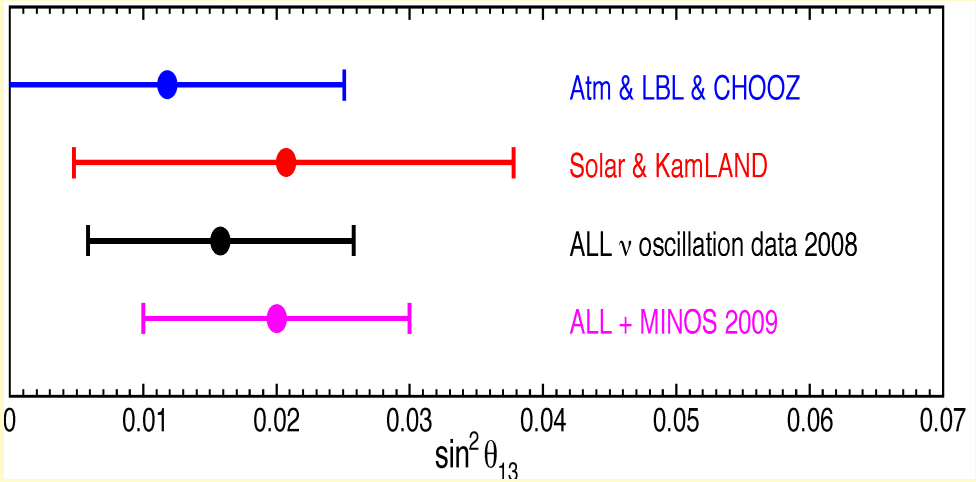
$$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2 c_{12}^2 \sin^2(\delta m^2 L/4E))$$

$-$ $-$



Slight "tension" on θ_{12} can be reduced for θ_{13}>0

Thus, there seems to be a few independent hints of $\theta_{13}>0$:



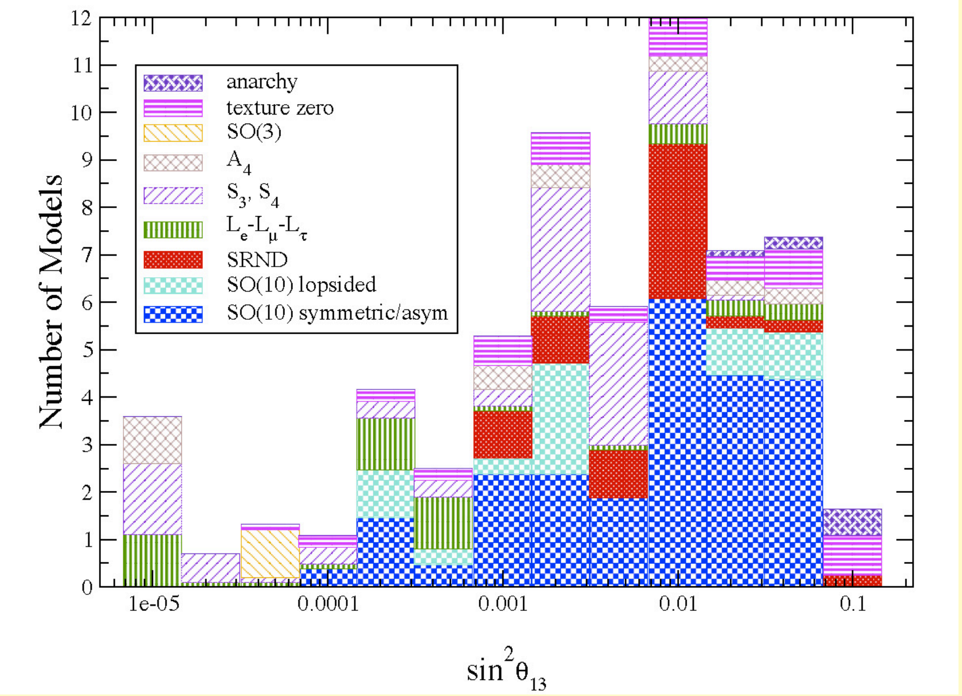
Combining all data (with some optimism), the grand total is:

$$\sin^2\theta_{13} \approx 0.02 \pm 0.01 \text{ (all data)}$$ arXiv:0905.3549

which is an encouraging 2σ indication, testable in the next few years.
(N.B.: MINOS, SK, SNO, KamLAND can still provide further improvements)

θ_{13} determination essential for further progress in terrestrial oscillation searches (CP violat., matter effects, mass hierarchy)

Also: very important to restrict theoretical models for ν masses



E.g.: CH Albright, 2008, “distribution” of published predictions

Synopsis of neutrino mass^2 and mixing parameters:
central values and n-σ ranges from global 3ν analysis

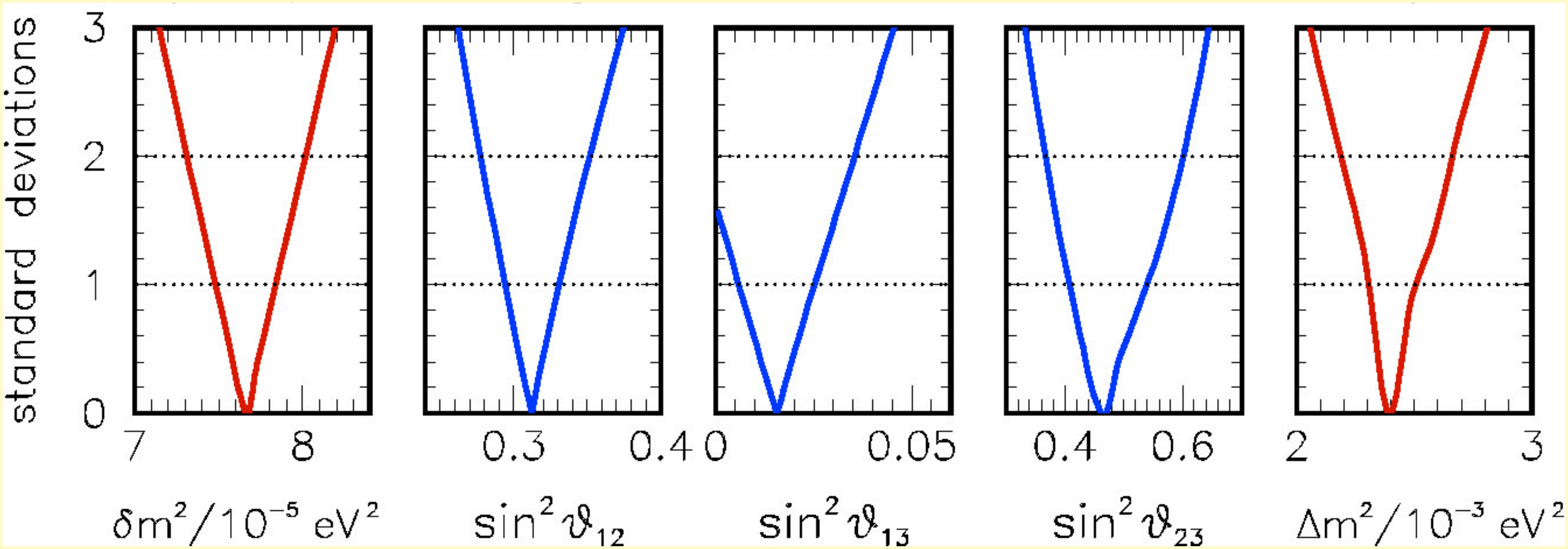


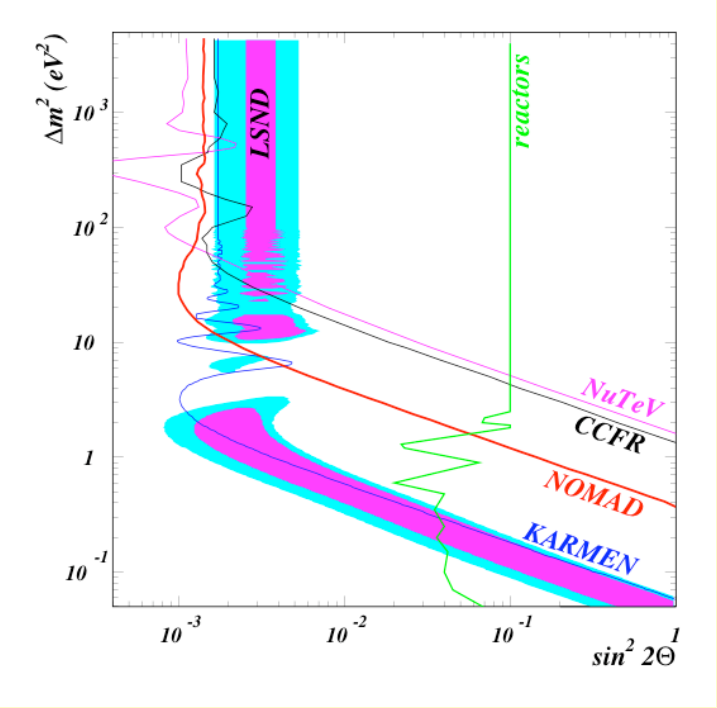
TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

arXiv:0805.2517

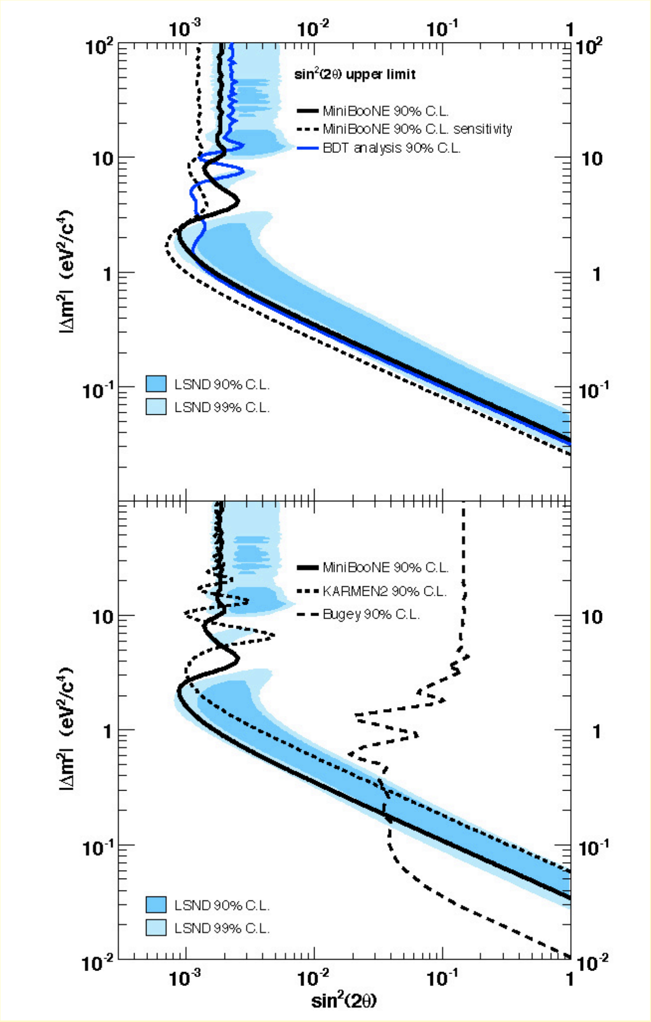
Short baseline accelerator expts: Beyond 3 neutrinos?

The LSND experiment found a signal of possible $\nu_\mu \rightarrow \nu_e$ oscillations at a relatively high ΔM^2 scale of O(0.1-1) eV^2



Large literature on attempts to reconcile LSND with other data, by using new (sterile) neutrino states and/or new neutrino interactions.
No satisfactory model emerged so far. Moreover…

… simplest LSND "oscillations" excluded by a dedicated test experiment, MiniBoone:

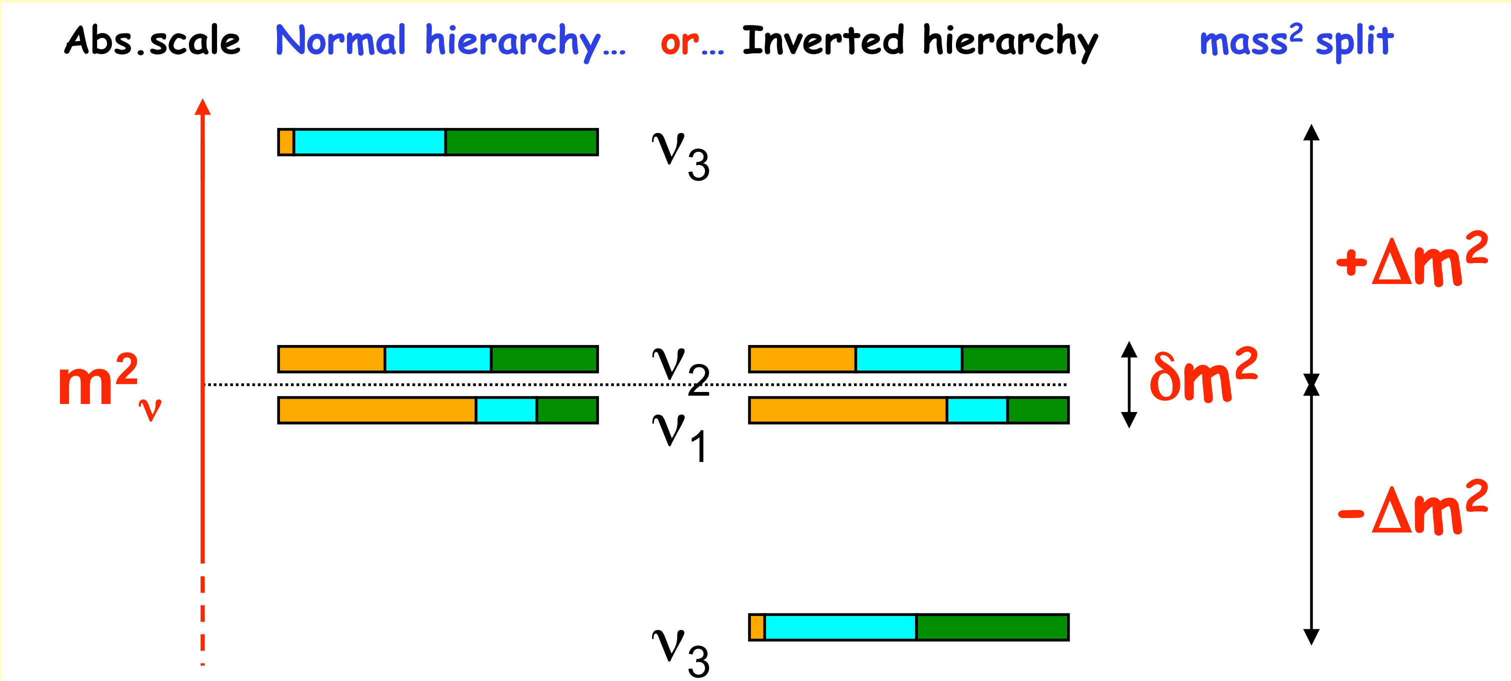


But, the MiniBoone data have some new, unexplained anomalies at low energy!

So the LSND/MiniBoone saga may have not yet ended …

Anyway, it's fair to say that there is no convincing indication of new neutrino states, oscillations or interactions beyond the standard 3nu scenario

SUMMARY (Flavors = e μ τ)



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

} established

$$m_\nu < O(1)\ \mathrm{eV} \qquad \sin^2\theta_{13} < \mathrm{few}\%$$

$$\mathrm{sign}(\pm\Delta m^2)\ \text{unknown} \qquad \delta\ (\mathrm{CP})\ \text{unknown}$$

} open issues