Neutrino Physics: experimental status, theoretical aspects and perspectives

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… neutrinos induce courage in theoreticians and perseverance in experimenters
Maurice Goldhaber, 1974

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Charm physics with neutrinos

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Abstract

High energy neutrino interactions induce charmed hadron production at the level of a few percent and therefore they constitute a powerful tool to study charm physics. After 30 years of investigations with different neutrino beams and different detection techniques, important results have been achieved while other topics still need to be clarified. Recently, relevant results have been reported by several collaborations. We review the composite scenario of charm physics as it emerges from 30 years of investigations, including the latest results and pointing out possible future developments in this field.

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The potential for neutrino physics at muon colliders and dedicated high current muon storage rings

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Abstract

Conceptual design studies are underway for muon colliders and other high-current muon storage rings that have the potential to become the first true "neutrino factories". Muon decays in long straight sections of the storage rings would produce precisely characterized beams of electron and muon type neutrinos of unprecedented intensity. This article reviews the prospects for these facilities to greatly extend our capabilities for neutrino experiments, largely emphasizing the physics of neutrino interactions.

PACS: 13.15.+g

Keywords: Muon colliders; Muon storage rings; Neutrino factories

PHYSICS AT THE FRONT-END OF A NEUTRINO FACTORY: A QUANTITATIVE APPRAISAL

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Abstract

We present a quantitative appraisal of the physics potential for neutrino experiments at the front-end of a muon storage ring. We estimate the forseeable accuracy in the determination of several interesting observables, and explore the consequences of these measurements. We discuss the extraction of individual quark and antiquark densities from polarized and unpolarized deep-inelastic scattering. In particular we study the implications for the undertanding of the nucleon spin structure. We assess the determination of α_S from scaling violation of structure functions, and from sum rules, and the determination of $\sin^2\theta_W$ from elastic νe and deep-inelastic νp scattering. We then consider the production of charmed hadrons, and the measurement of their absolute branching ratios. We study the polarization of Λ baryons produced in the current and target fragmentation regions. Finally, we discuss the sensitivity to physics beyond the Standard Model.

Neutrino Physics is not ONLY oscillations, but MUCH more. For a review of past results, present status and future activities, we refer to the abovementioned reviews.

Outline

- Neutrino oscillation formalism
- Experimental status: solar, atmospheric, reactor and accelerator data
- Interpretation of all available data
- Key measurements with neutrinos
- Future projects
- Conclusion

The PMNS leptonic mixing matrix

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

Flavour e.s. Mass e.s.

For three neutrinos

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where c_{ij} $\cos$ $_{ij}$, *and* s_{ij} $\sin$ $_{ij}$

Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k=1}^{3} |U_{\alpha k}|^2 |U_{\beta k}|^2 + 2\,\mathrm{Re} \sum_{\substack{k=1 \\ k>j}}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E} \right)$$

Fixed by nature Tuned by experiments

The MSW effect

MSW is such a beautiful phenomenon that Nature would be well advised to use it. After all, it may eventually give us the unambiguous, incontrovertible, uncontestable, clear and definitive evidence we so eagerly seek that the neutrino has mass

S.P. Rose, 1986

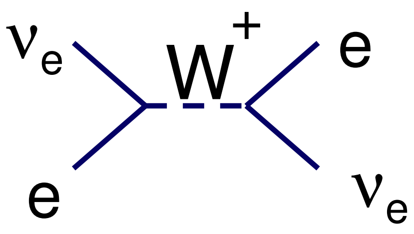
Mikheyev-Smirnov-Wolfenstein (MSW)

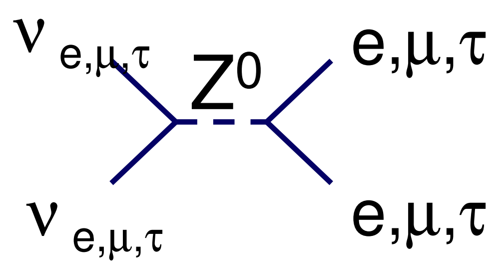
2-ν vacuum oscillation

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(1.27\ \Delta m^2[\mathrm{eV}^2]\ \frac{L[\mathrm{m}]}{E\,[\mathrm{MeV}]}\right) \text{ where } \Delta m^2 = m_2^2 - m_1^2$$

- In matter, ν_e and ν_μ/ν_τ have different "effective masses", flavor conversion can be a resonant effect ⇒

  Mikheyev-Smirnov-Wolfenstein (MSW)





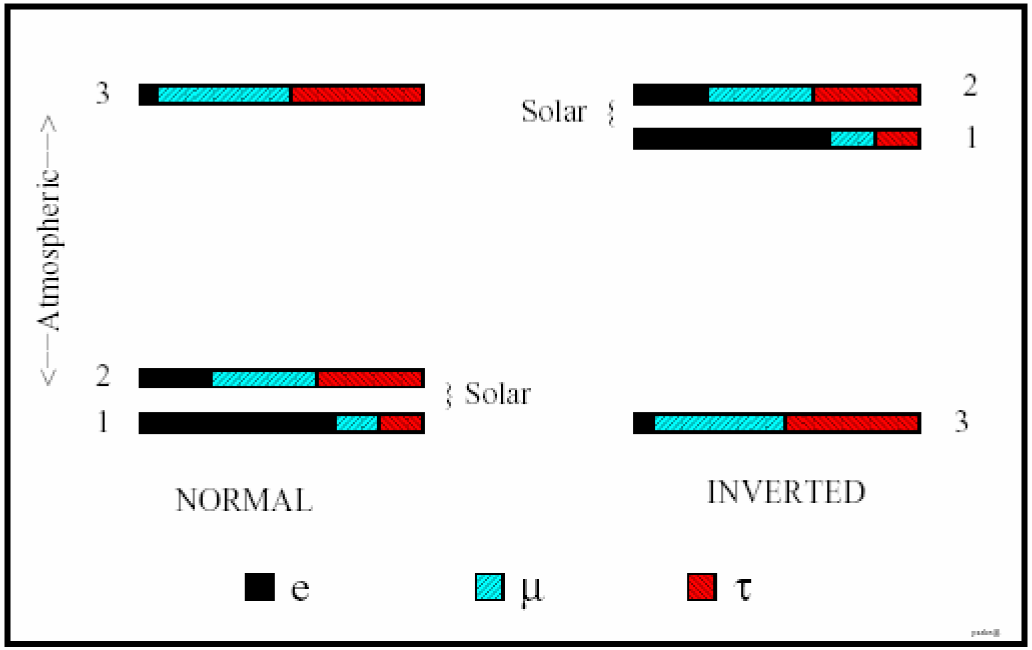
Mixing in matter

Effective Mixing Angle in Matter: $\tan 2\vartheta_M = \dfrac{\tan 2\vartheta}{1 - \frac{A_{CC}}{\Delta m^2 \cos 2\vartheta}}$

Resonance: $A_{CC}^R = \Delta m^2 \cos 2\vartheta \Longrightarrow N_e^R = \dfrac{\Delta m^2 \cos 2\vartheta}{2\sqrt{2} E G_F}$

Notation

- *Mixing parameters:* $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix
- *Mass-gap parameters:* $M^2 = \Delta m^2_{12}\ ,\ \pm \Delta m^2_{23}$



The absolute mass scale should be set by other measurements:

- β-decay
- 0ν2β-decay
- anisotropies in cosmic background radiation

Appearance channels: $\nu_\mu \to \nu_e$

$$
\begin{aligned}
P_{\text{app}} &\simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&\pm \alpha \sin 2\theta_{13}\, \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2},
\end{aligned}
$$

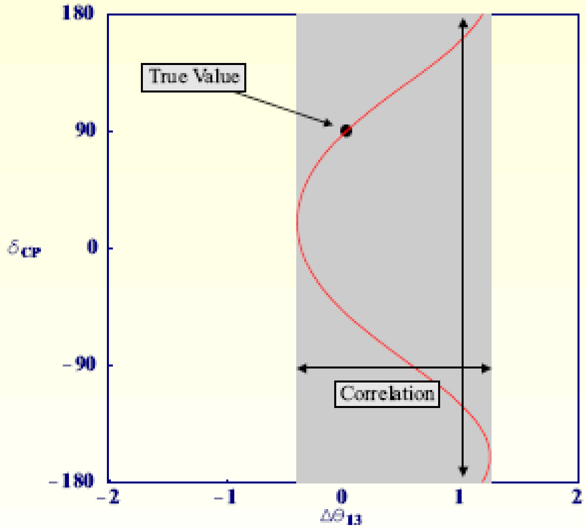
$$
\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \simeq \pm 0.03,\ \Delta \equiv \frac{\Delta m_{31}^2 L}{4E},\ \xi \equiv \sin 2\theta_{12} \sin 2\theta_{23},\ \hat{A} \equiv \pm \frac{2\sqrt{2} G_F n_e E}{\Delta m_{31}^2}
$$

- Complicated, but all interesting information there: θ_{13}, δ_{CP}, mass hierarchy (via A)

The intrinsic degeneracy

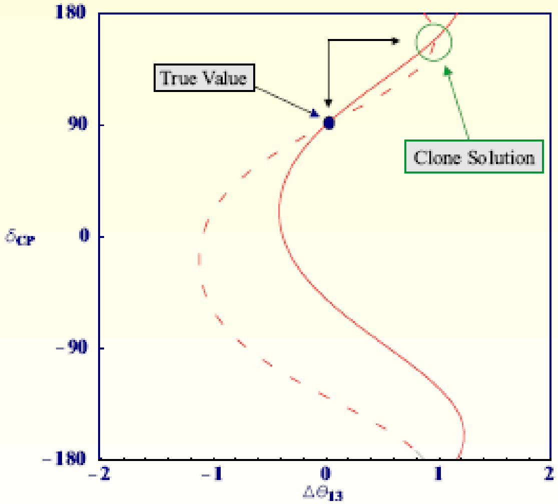
There is a strong correlation between θ_{13} and δ

$$P_+(\bar{\theta}_{13}, \bar{\delta}) = P_+(\theta_{13}, \delta)$$



There are infinite solutions!
Infinite degeneracies

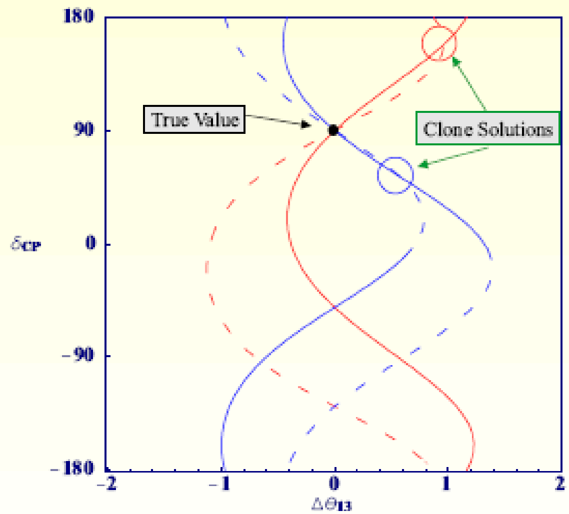
$$P_+(\bar{\theta}_{13}, \bar{\delta}) = P_+(\theta_{13}, \delta)$$
$$P_-(\bar{\theta}_{13}, \bar{\delta}) = P_-(\theta_{13}, \delta)$$



By using neutrinos and anti-neutrinos there are two solutions: the true and the clone

Measuring the $\nu_e \to \nu_\mu$ GOLDEN Appearance Channel;

Measuring the $\nu_e \to \nu_\tau$ SILVER Appearance Channel;



No clone solutions!

- **Degeneracies in (θ_{13}, δ) Measure: EIGHTFOLD DEGENERACY**

Besides θ_{13} and δ other two (discrete) quantities will be unknown in 5-10 years at the time of next generation neutrino experiments:

- The SIGN of the ATM mass difference $s_{atm} = \mathrm{sign}(\Delta m^2_{23})$
- The OCTANT of the ATM angle $s_{oct} = \mathrm{sign}(\tan 2\theta_{23})$

Consequently, for taking into account **ALL OUR IGNORANCE** on the neutrino masses and mixings one has to make a simultaneous fit to these 4 parameters, i.e. to solve the following equation:

$$N_i^{\pm} \underbrace{(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct})}_{\text{“true parameters”}} = N_i^{\pm} \underbrace{(\theta_{13}, \delta; s_{atm}, s_{oct})}_{\text{“guessed parameters”}}$$

One has to solve ALL the following FOUR systems of equations, each of them having in general two distinct solutions:

intrinsic degeneracy (Burguet01)

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = \bar{s}_{atm}, s_{oct} = \bar{s}_{oct})$$

sign degeneracy (Minakata01)

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = -\bar{s}_{atm}, s_{oct} = \bar{s}_{oct})$$

octant degeneracy (Fogli96, Barger01)

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = \bar{s}_{atm}, s_{oct} = -\bar{s}_{oct})$$

mixed degeneracy (Barger01)

$$N_i^{\pm}(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct}) = N_i^{\pm}(\theta_{13}, \delta; s_{atm} = -\bar{s}_{atm}, s_{oct} = -\bar{s}_{oct})$$

The Eightfold Degeneracy

The disappearance channels

$$1 - P_{ee} \cong \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right) + \underbrace{\sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{solar} L}{4E}\right)} + \ldots$$

Survival probability

negligible on the atm. peak ($\Delta m^2_{atm} \gg \Delta m^2_{solar}$)

- No sensitivity to CP phase, to θ_{23} and to the sign of Δm^2_{23}: the eightfold degeneracy is not an issue
- Drawback: only one parameter can be measured
- Difficult measurement: extremely sensitive to the knowledge of the flux, of the signal and of the background

$$P^{\pm}_{\nu_\mu \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right) + \mathcal{O}\left(\theta^2_{13} \sin^2\left(\Delta m^2_{23} L/4E\right)\right)$$
$$+ \quad \mathcal{O}(\cos\delta_{CP} \cdot \theta_{13} \cdot \Delta_{12} \cdot \sin(\Delta m^2_{23} L/4E)) + \mathcal{O}(\Delta^2_{12})$$

- Extremely sensitive measurement of θ_{23} and Δm^2_{23}
- No sensitivity at all to θ_{13} and to CP phase
- Difficult measurement: extremely sensitive to the knowledge of the flux, of the signal and of the background

SOLAR NEUTRINOS

Data taking: 1970 – 1995   108 solar runs.

Results:

ν interaction rate on ^{37}Cl: **2.56 +- 0.16 (stat) +- 0.16 (sys) SNU**

R (exp/SSM) = 0.34 +- 0.03 (exp) +- 0.05 (theo)

FIRST EVIDENCE FOR NEUTRINOS COMING FROM THE SUN

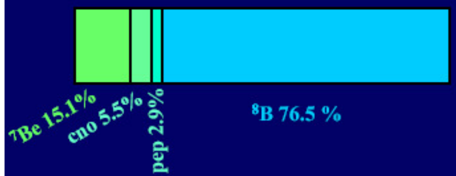
Neutrino interaction: $^{37}Cl\ (\nu_e\ , e)\ ^{37}Ar$

Threshold : 814 keV

Detection Technique: radiochemical

37Ar is extracted from the tank by He purging every two months, and then counted inside a gas proportional counter

Signal composition:



Results: (Runs 1-108) (May 91- Jan 02)

70.8 +- 4.5 (stat) +- 3.8 (sys) SNU

R (exp/SSM) = 0.55 +- 0.05 (exp) +- 0.03 (theo)

Results: (Runs 1 – 104) (Jan 90 – Jan 03)

70.5 +- 4.8 (stat) +- 3.5 (sys) SNU

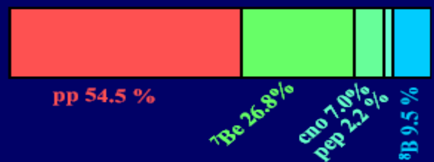
R (exp/SSM) = 0.55 +- 0.05 (exp) +- 0.03 (theo)

FIRST DETECTION OF PP SOLAR NEUTRINOS

SUPPRESSION OF INTERMEDIATE ENERGY SOLAR NEUTRINO FLUX

Neutrino interaction: $^{71}Ga\ (\nu_e\ , e)\ ^{71}Ge$ Threshold : 233 keV

Signal composition:



GALLEX/GNO

Location:
Laboratori Nazionali del Gran Sasso
Abruzzo (Italy)

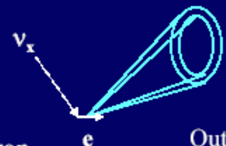
Target: 101 tons of $GaCl_3$ acidic solution
(30 tons of nat. Ga)

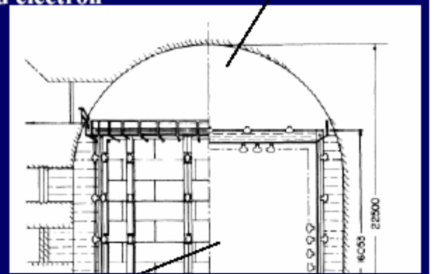
SAGE

Location:
Baksan Neutrino Observatory
Caucasus (Russia)

Target: 55 tons of metallic Ga

- **Location:** Kamioka mine, Japan, 2700 mwe depth
- **Target:** 4500 tons of pure water
  2150 tons (fid. Vol.)
- **Neutrino interaction:** $e + \nu_x \rightarrow e + \nu_x$ (CC+NC)
- **Detection Technique:** Cerenkov light of scattered electron





- **Signal composition:** 100% from $^8B\ \nu$
  Direction of recoil electron
  Energy spectrum of recoil electron
  Threshold : 7 MeV
- **Data taking:** 1987 → 1995
  2079 days of live-time.

Results : 597 ν events observed in 2079 days

$\Phi(^8B)$ = 2.80 +/- 0.19 (stat) +/- 0.33 (sys) $10^6\ cm^{-2}\ s^{-1}$

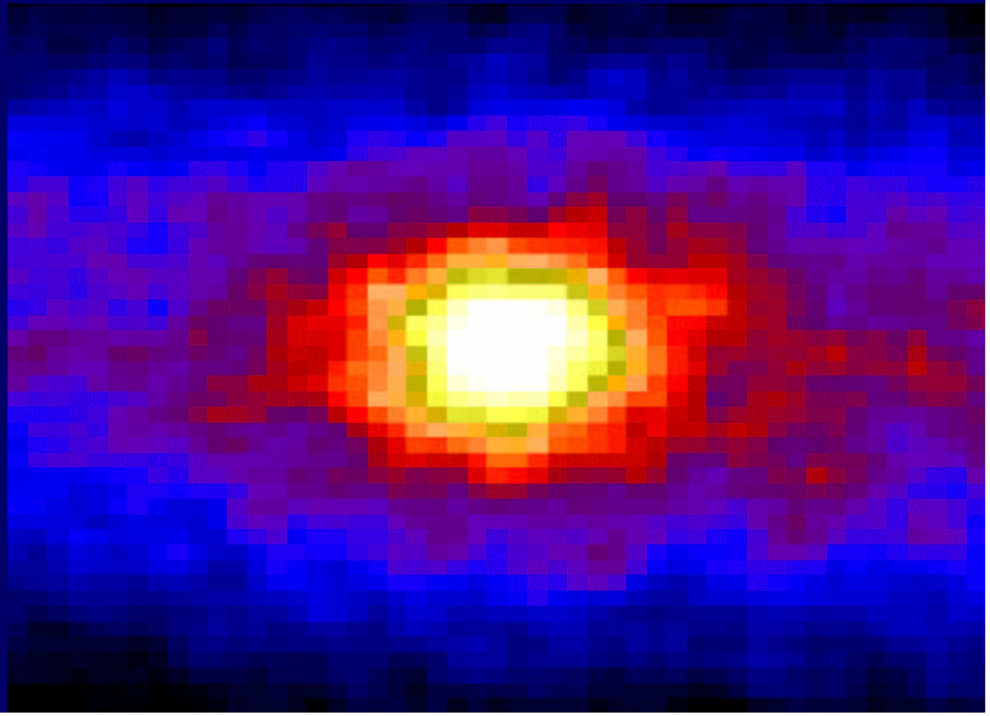
R (exp/SSM) = 0.37

Confirmation of the evidence for a "solar neutrino problem"

First evidence that neutrino signals are correlated with the Sun direction

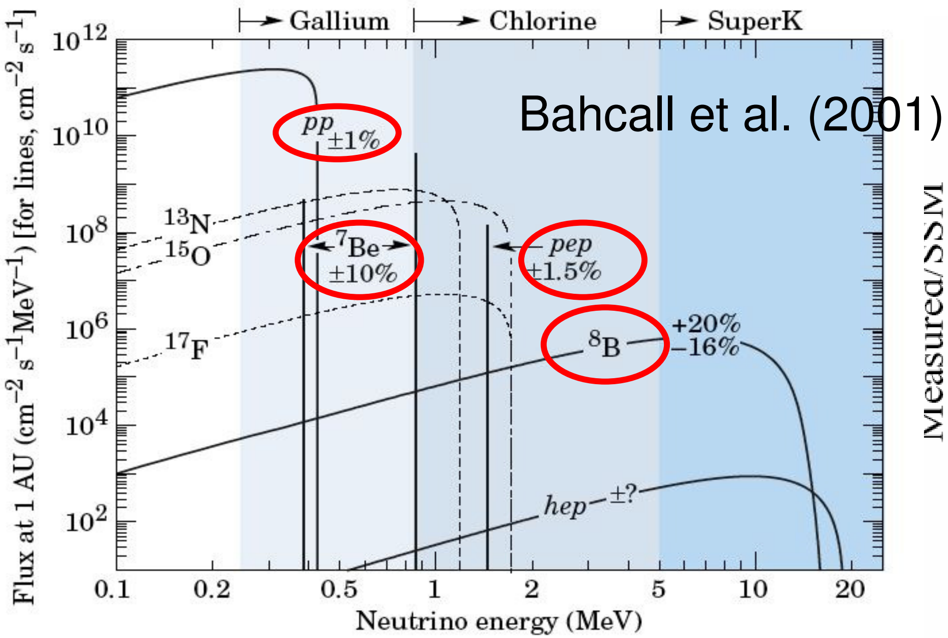
First test of the ^8B neutrino energy spectrum

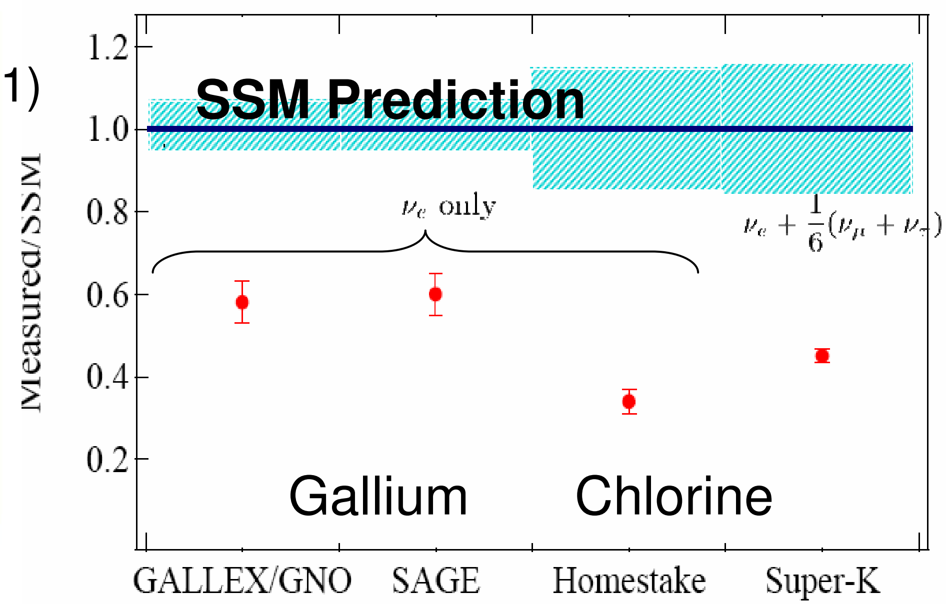
First measurement of solar neutrinos in real time



The old standing solar neutrino problem
(before year 2000)

Consistent predictions of ν_e flux from a number of Standard Solar Models (e.g. Bahcall *et al.*, and Turck-Chieze *et al.*)

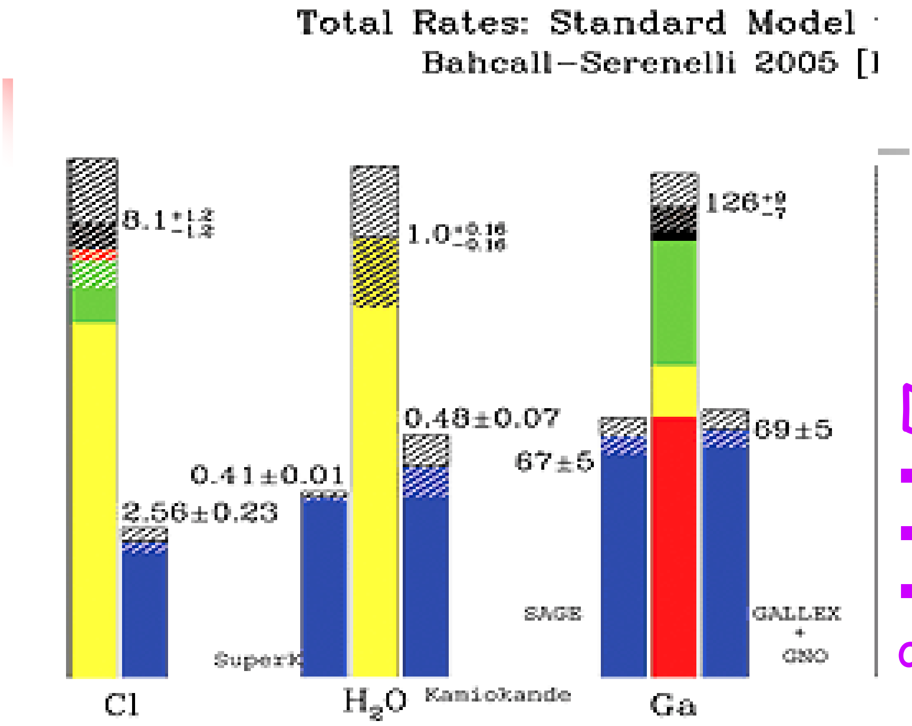


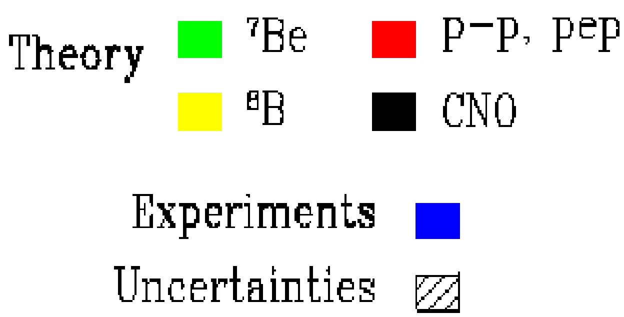


There is a strong deficit in the measured flux as well as an "energy" dependence of the deficit!!!

Although with a lower threshold Cl exp sees less ν than SK!!!

The Solar Neutrino Problem
(we don't get enough neutrinos)





Data are consistent with:

- Full ν_e flux from $p + p \rightarrow e^+ + \nu_e + d$
- ~50% of the ν_e flux from $B^8 \rightarrow Be^8 + e^+ + \nu_e$
- Very strong (almost complete) suppression of the ν_e flux from $e^- + Be^7 \rightarrow \nu_e + Li^7$

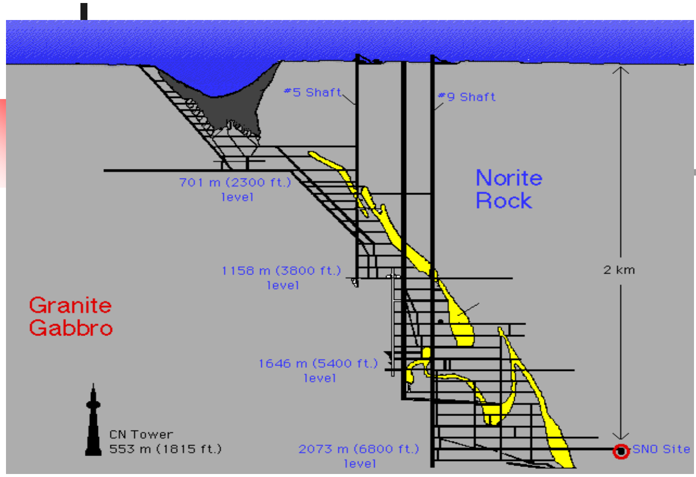
The real solar neutrino puzzle:

There is evidence for B^8 in the Sun (with deficit 50%), but no evidence for Be^7; yet Be^7 is needed to make B^8 by the fusion reaction $p + Be^7 \rightarrow \gamma + B^8$

Possible solutions:

- At least one experiment is wrong
- The SSM is totally wrong
- The ν_e from $e^- + Be^7 \rightarrow \nu_e + Li^7$ are no longer ν_e when they reach the Earth and become invisible $\Rightarrow \nu_e$ OSCILLATIONS

Sudbury Neutrino Observatory



1000 tonnes D_2O

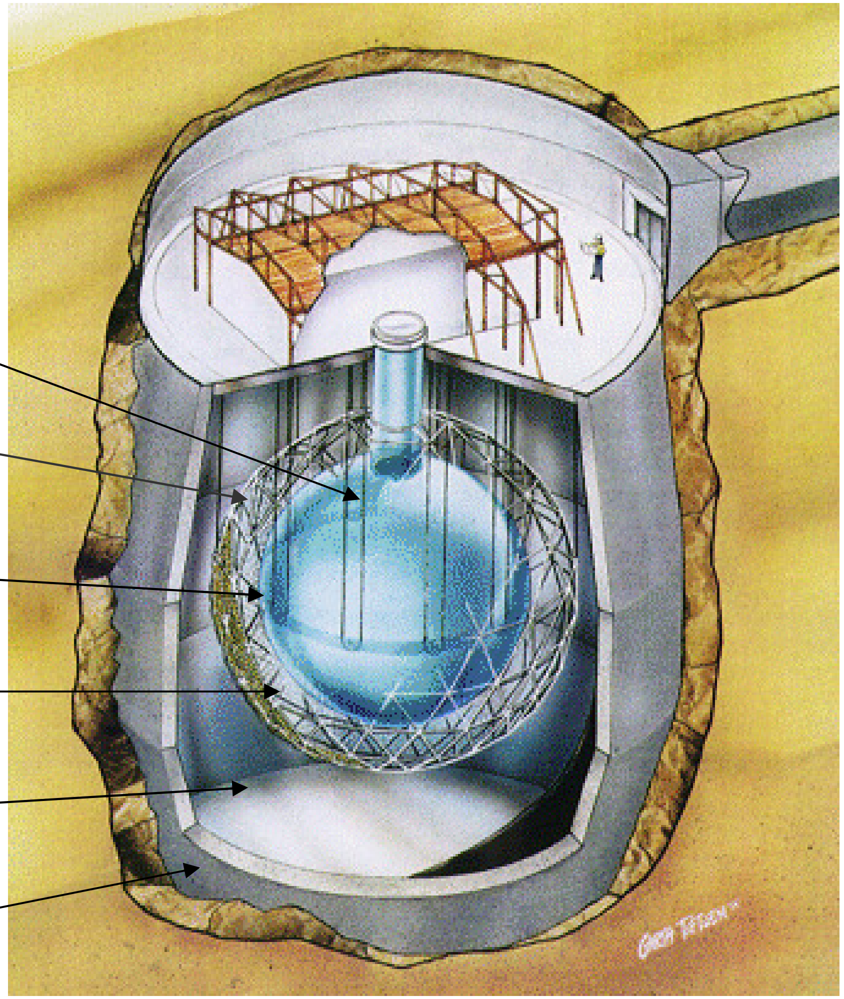
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



ν reactions in SNO

ES

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

- **Both SK, SNO**
- **Mainly sensitive to ν_e, less to ν_μ and ν_τ**
- **Strong directional sensitivity**

CC

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

- **Good measurement of ν_e energy spectrum**
- **Weak directional sensitivity $\propto$ 1-1/3cos(θ)**

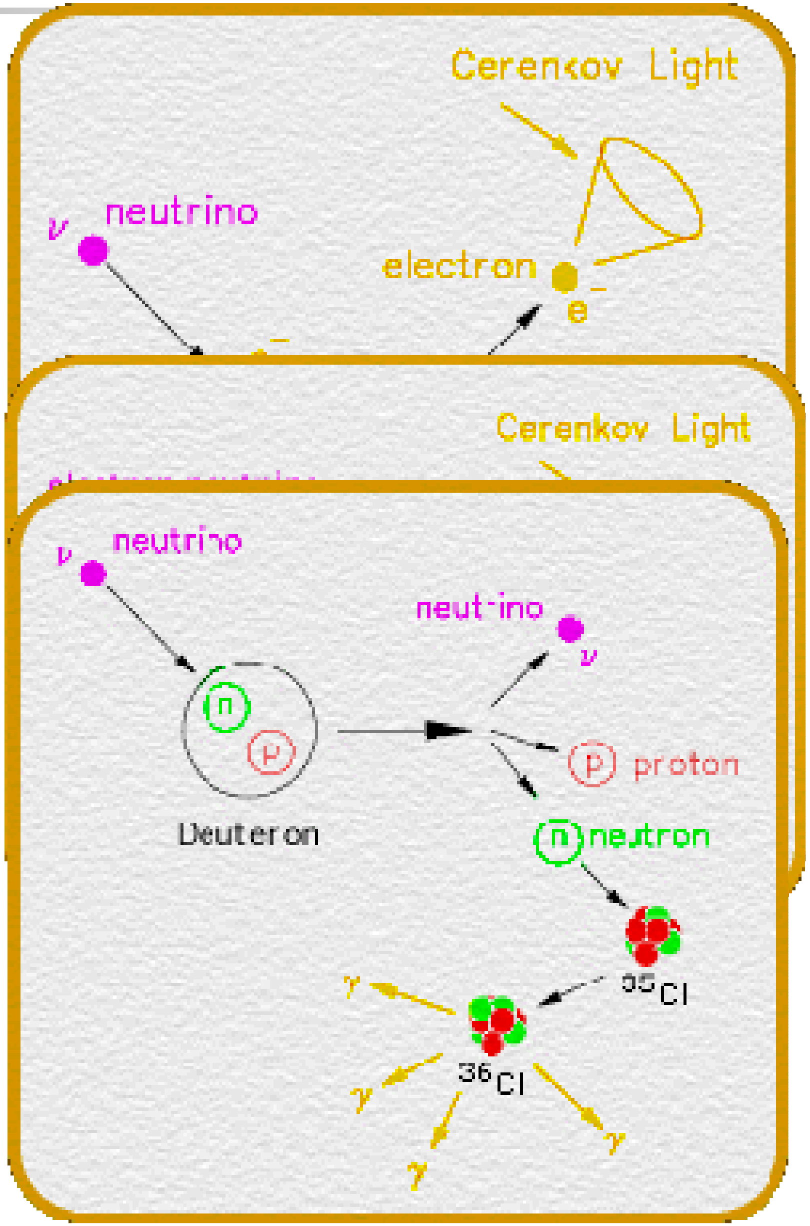
- ν_e ONLY

NC

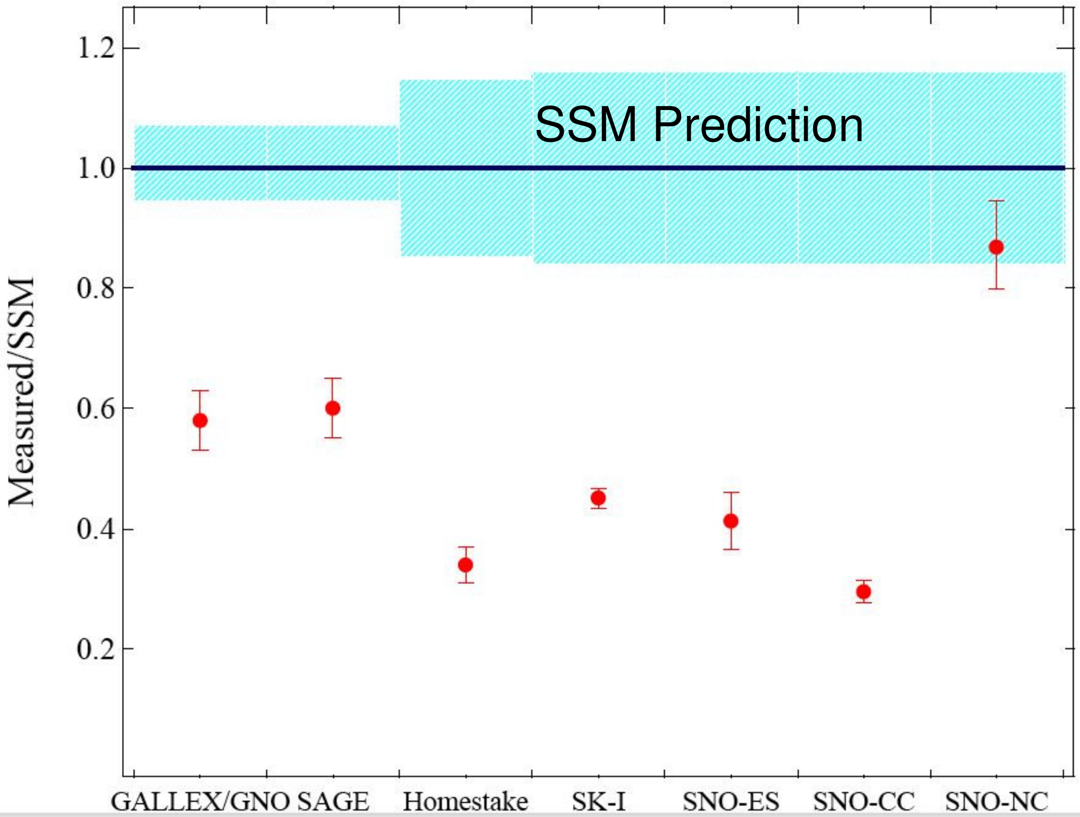
$$\nu_x + d \Rightarrow p + n + \nu_x$$

- **Measure total ^8B ν flux from the sun.**

- Equal cross section for all ν types



Resolution of the solar neutrino problem



SNO-measured "energy-unconstrained (no hypothesis on ^{8}B)" flux (Phase II) [x10^6 cm^{-2} s^{-1}]:

$$\phi_{CC}^{uncon} = 1.68^{+0.06}_{-0.06}(stat)^{+0.08}_{-0.09}(syst)$$

$$\phi_{ES}^{uncon} = 2.35^{+0.22}_{-0.22}(stat)^{+0.15}_{-0.15}(syst)$$

$$\phi_{NC}^{uncon} = 4.94^{+0.21}_{-0.21}(stat)^{+0.38}_{-0.34}(syst)$$

arXiv:nucl-ex/0502021

Standard Solar Model flux (x10^6 cm^{-2} s^{-1}):

$$\text{Bahcall-Pinsonneault 2000} = 5.05^{+1.01}_{-0.81}$$

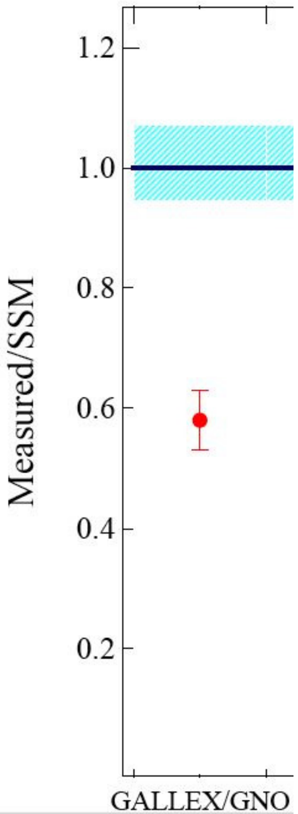
$$\text{Bahcall-Serenelli 2005} = 5.69 \pm 0.91$$

$$\text{Turck-Chieze 2004} = 5.31 \pm 0.60$$

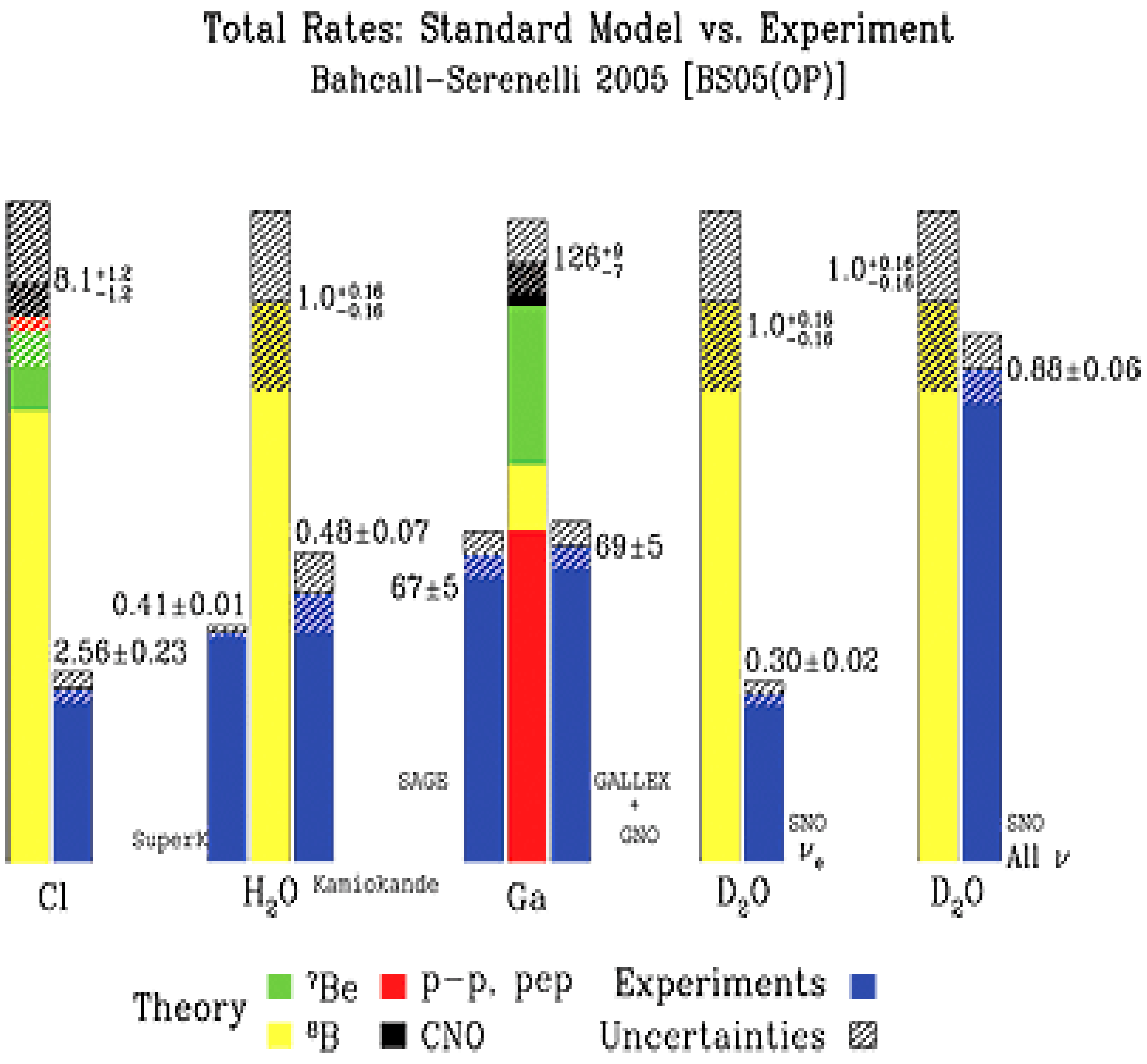
$$\frac{\phi_{CC}^{uncon}}{\phi_{NC}^{uncon}} = 0.340 \pm 0.023\ (stat)\ ^{+0.029}_{-0.031}\ (syst)$$

[BP2000]

Resolution of the solar neutrino problem



Standarc
(x10^6 cm



ergy-
ypothesis
II) [x10^6

tat) $^{+0.08}_{-0.09}$ (syst)

tat) $^{+0.15}_{-0.15}$ (syst)

tat) $^{+0.38}_{-0.34}$ (syst)

.01
.81

BP2000]

Indirect evidence for MSW effect

Study of the tolerance of the solar data for variations of standard MSW interaction energy

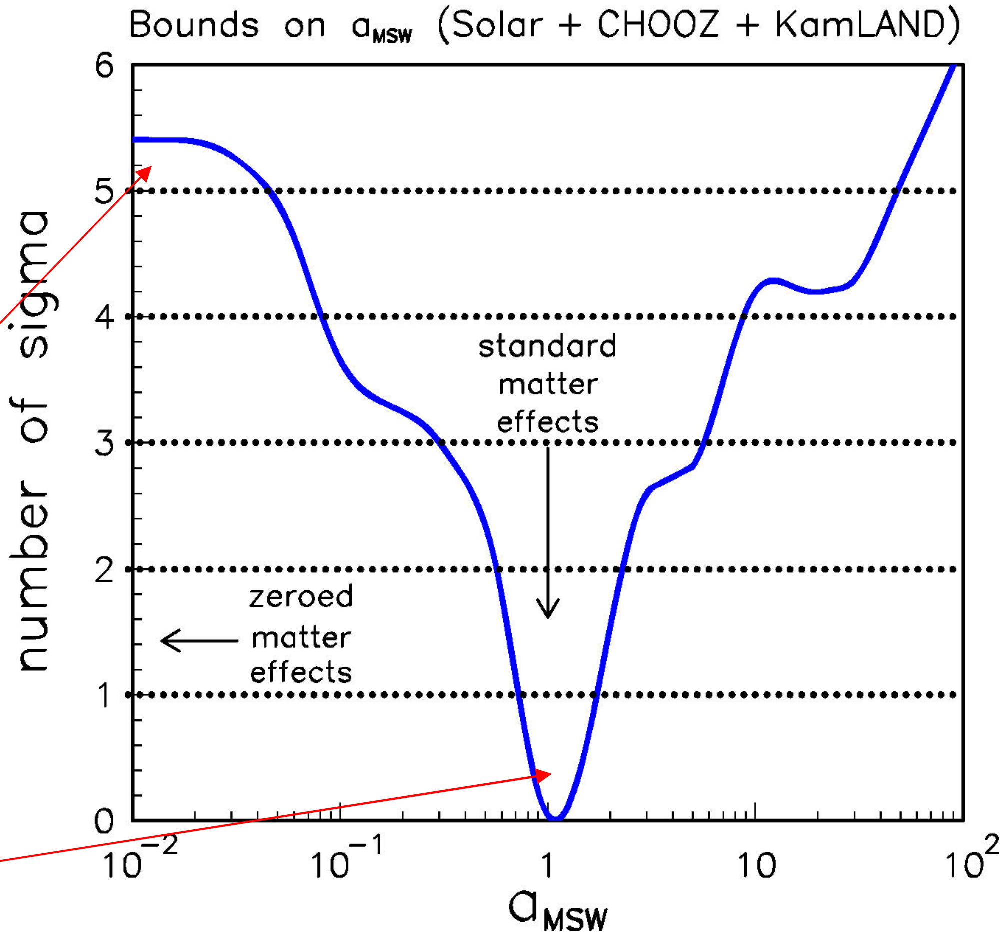
$$V = \sqrt{2}\, G_F\, N_e$$

through a shift

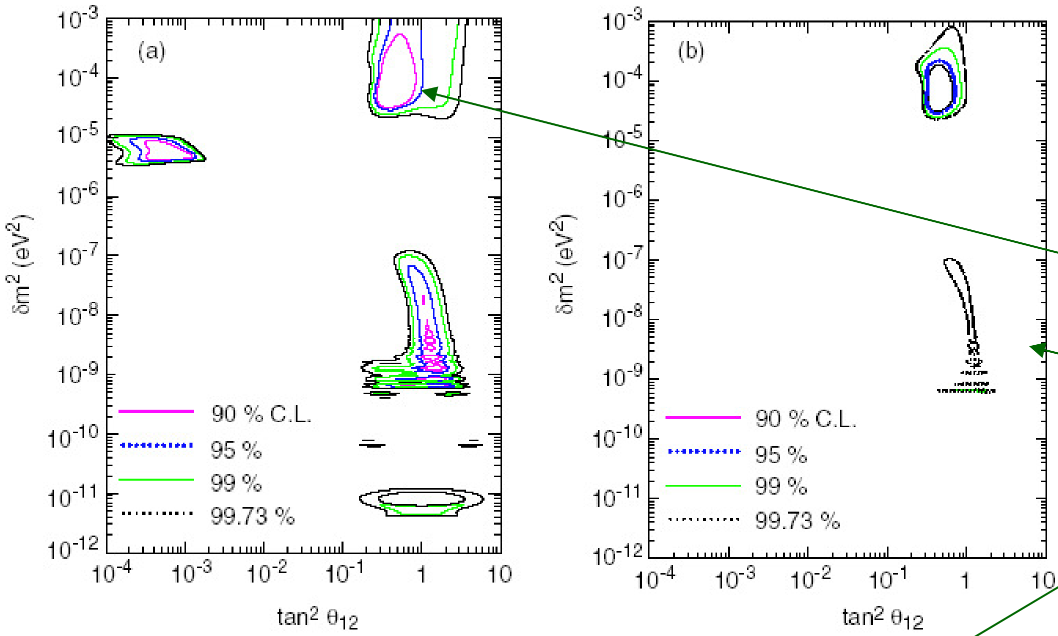
$$V \rightarrow V \cdot a_{MSW}$$

Case of no matter effects in the Sun is ruled out at >5 sigma.

Clear indication in favor of standard matter effects ($a_{MSW} = 1$).



What do we know about ν mixing from solar sector?

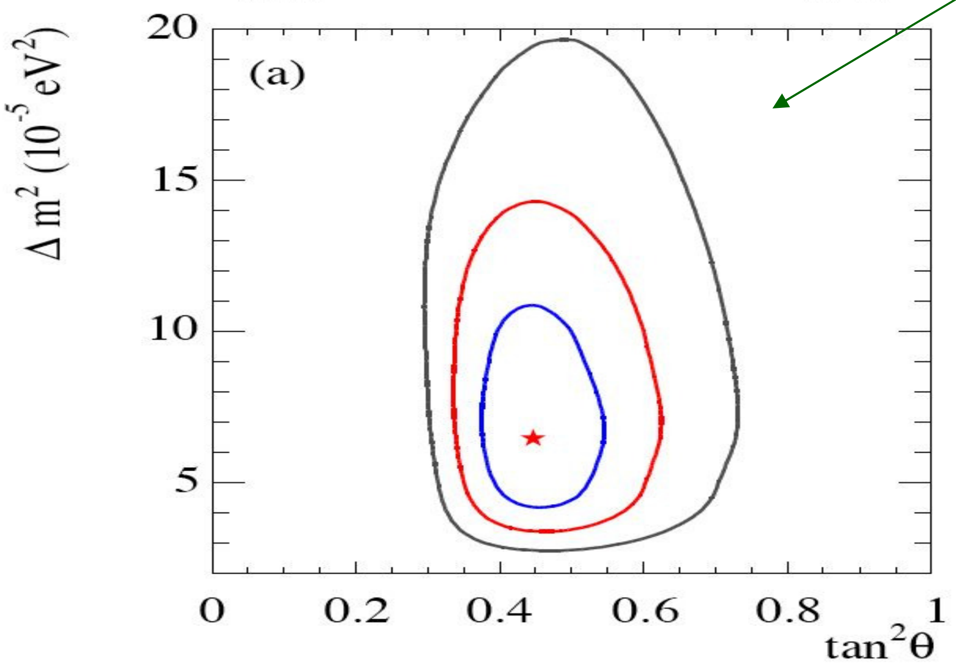


Dramatic reduction of the $(\delta m^2, \theta_{12})$ param. space in **2001-2003** (note change of scales)

Cl+Ga+SK (2001)

+SNO-I (2001-2002)

+SNO-II (2003)



(+ confirmation of solar model)

Direct proof of solar $\nu_e \to \nu_{\mu,\tau}$ in SNO through comparison of

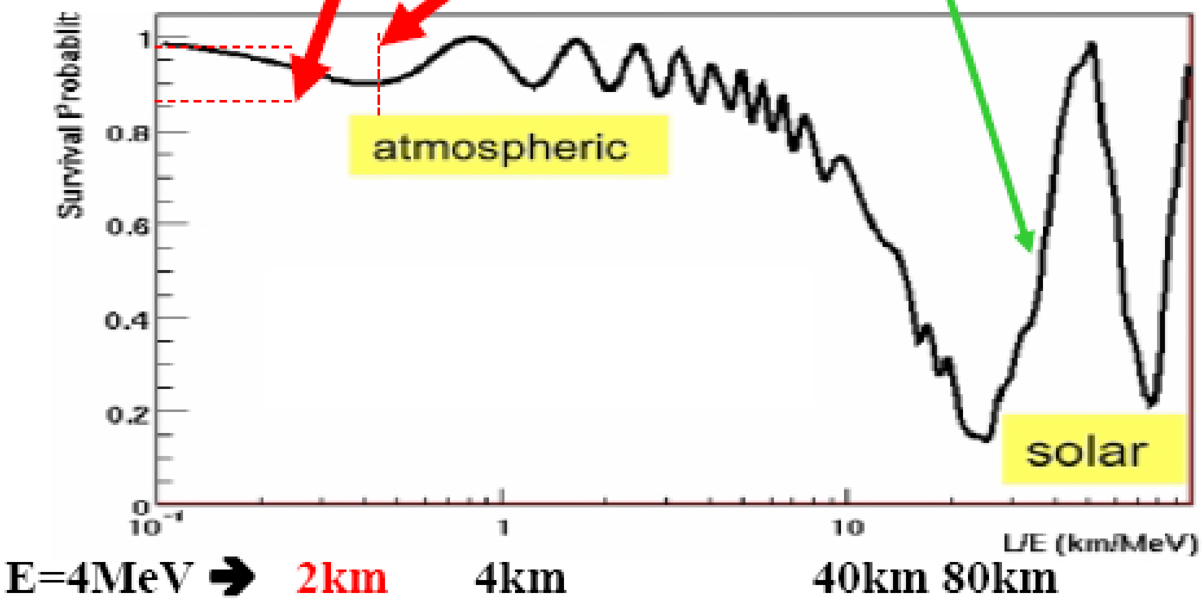
$$\begin{aligned} \mathrm{CC}: &\quad \nu_e + d \to p + p + e \\ \mathrm{NC}: &\quad \nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau} \\ \mathrm{ES}: &\quad \nu_{e,\mu,\tau} + e \to e + \nu_{e,\mu,\tau} \end{aligned}$$

From solar ν to reactor anti-ν?

CPT Theorem

Solar ν_e → Reactor $\bar{\nu}_e$

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$



To test the hypothesis of neutrino oscillation as the underlying mechanism for flavor transformation, we need a baseline of ~100-200 km for reactor anti-neutrino experiments

The KamLAND Detector

- 70 GW (7% of world total) is generated at 130-220 km distance from Kamioka. "Effective baseline" ~ 180 km

- Detects electron anti-ν by inverse β decay:

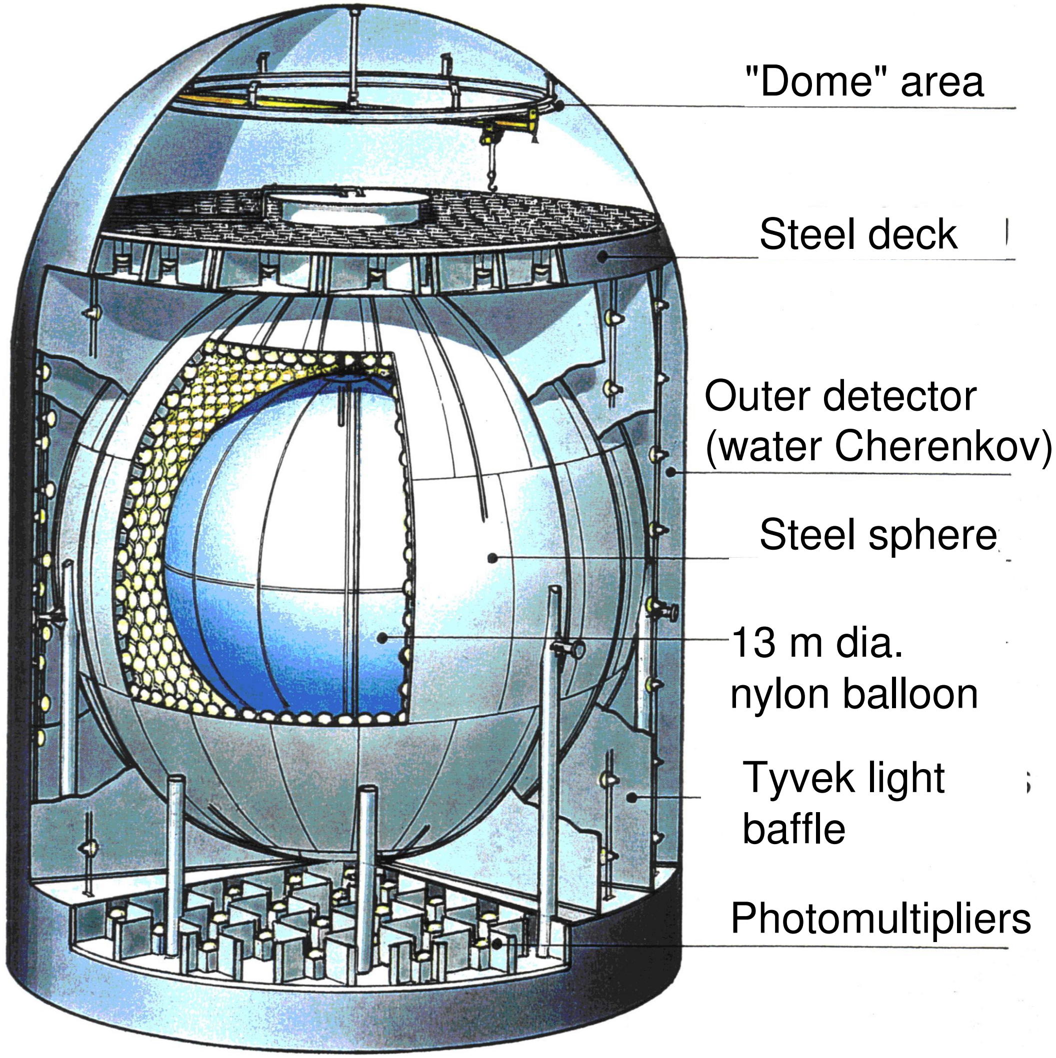
$$\overline{\nu}_e + p \rightarrow n + e^+$$

prompt

$$e^+ + e^- \rightarrow 2\gamma$$

delayed

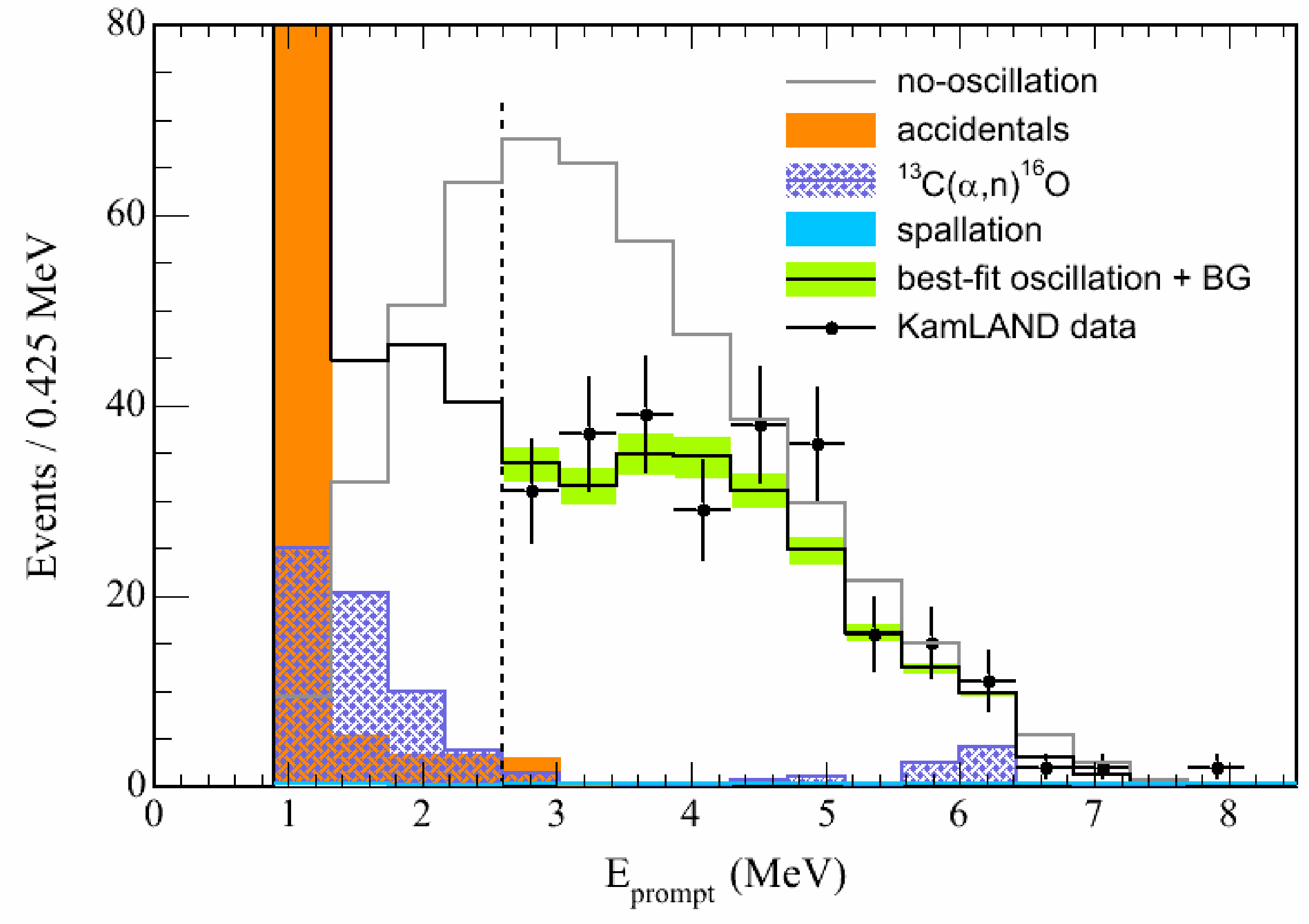
$$n + p \rightarrow d + \gamma\,(2.2\ \mathrm{MeV})$$



KamLAND: Signatures for Neutrino Oscillations

Energy spectrum Best-fit KamLAND only oscillation:

$$\tan^2\theta = 0.46$$
$$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

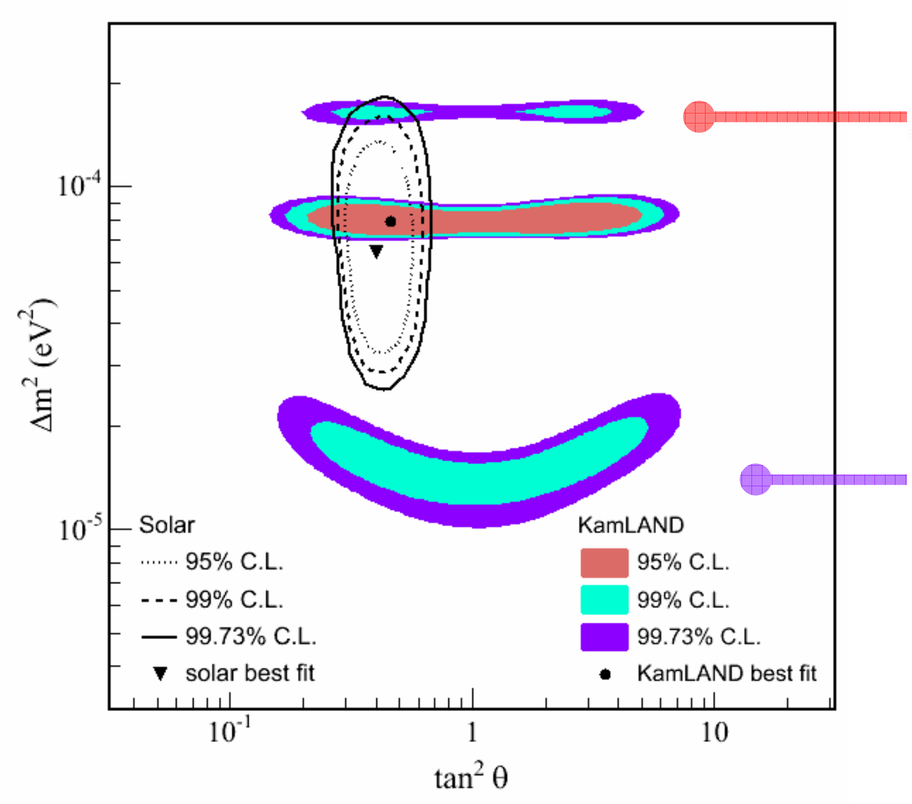


A fit to a simple rescaled reactor spectrum is excluded at 99.6% CL

PRL 94, 081802 (2005)

Solar+Reactor: What do we know about ν mixing now?

KamLAND-only

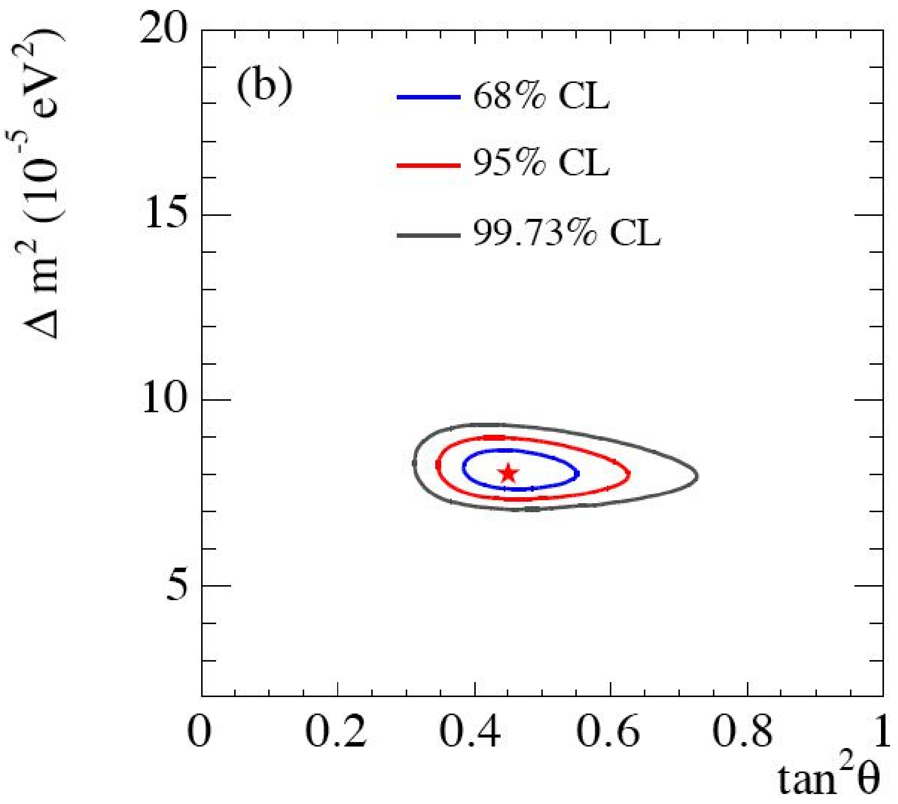


Best fit: $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$

$\tan^2\theta = 0.46$

KamLAND → Δm_{12}^2

Solar+KamLAND

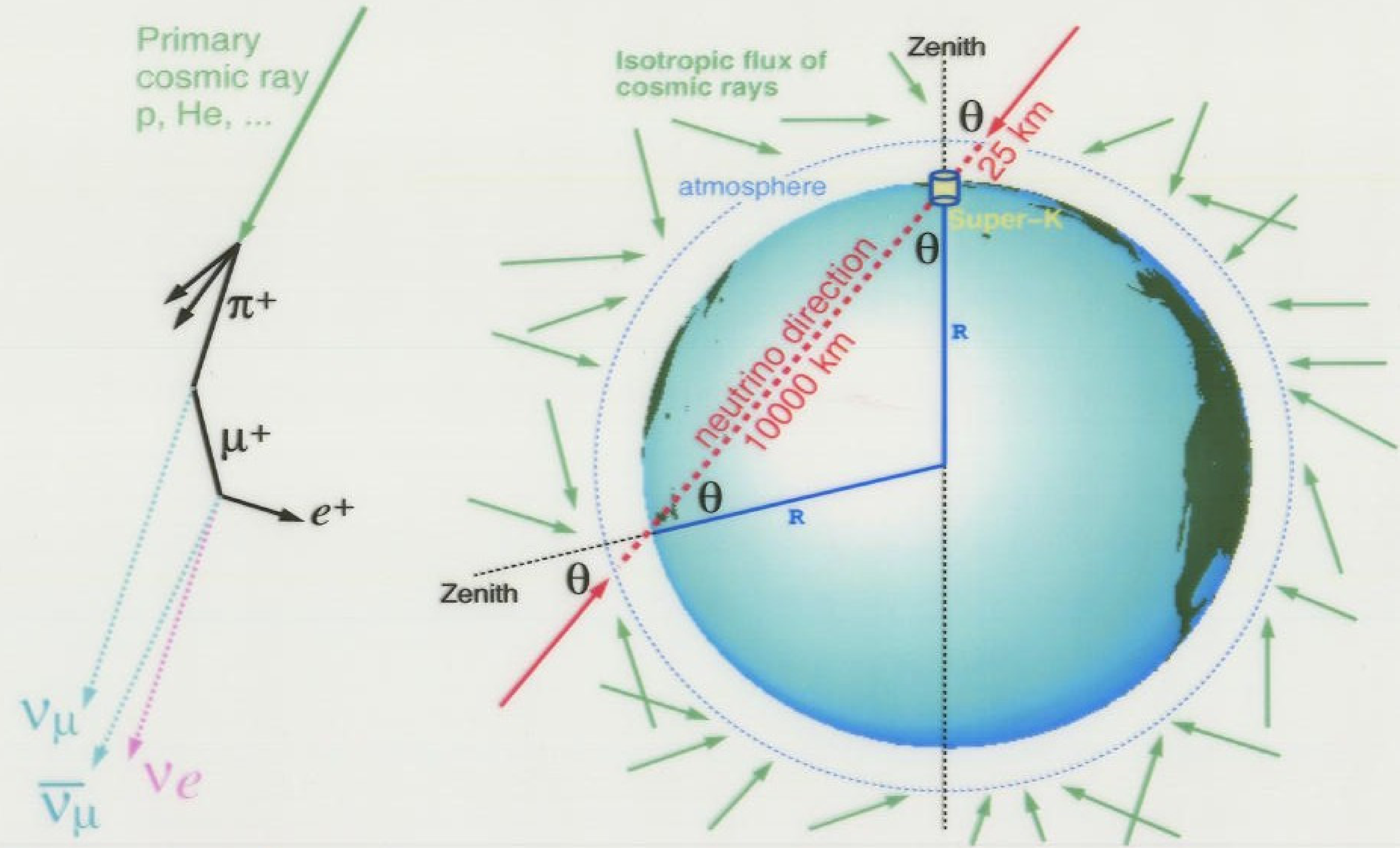


Best fit: $\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5} eV^2$

$\tan^2\theta = 0.45^{+0.09}_{-0.07}$

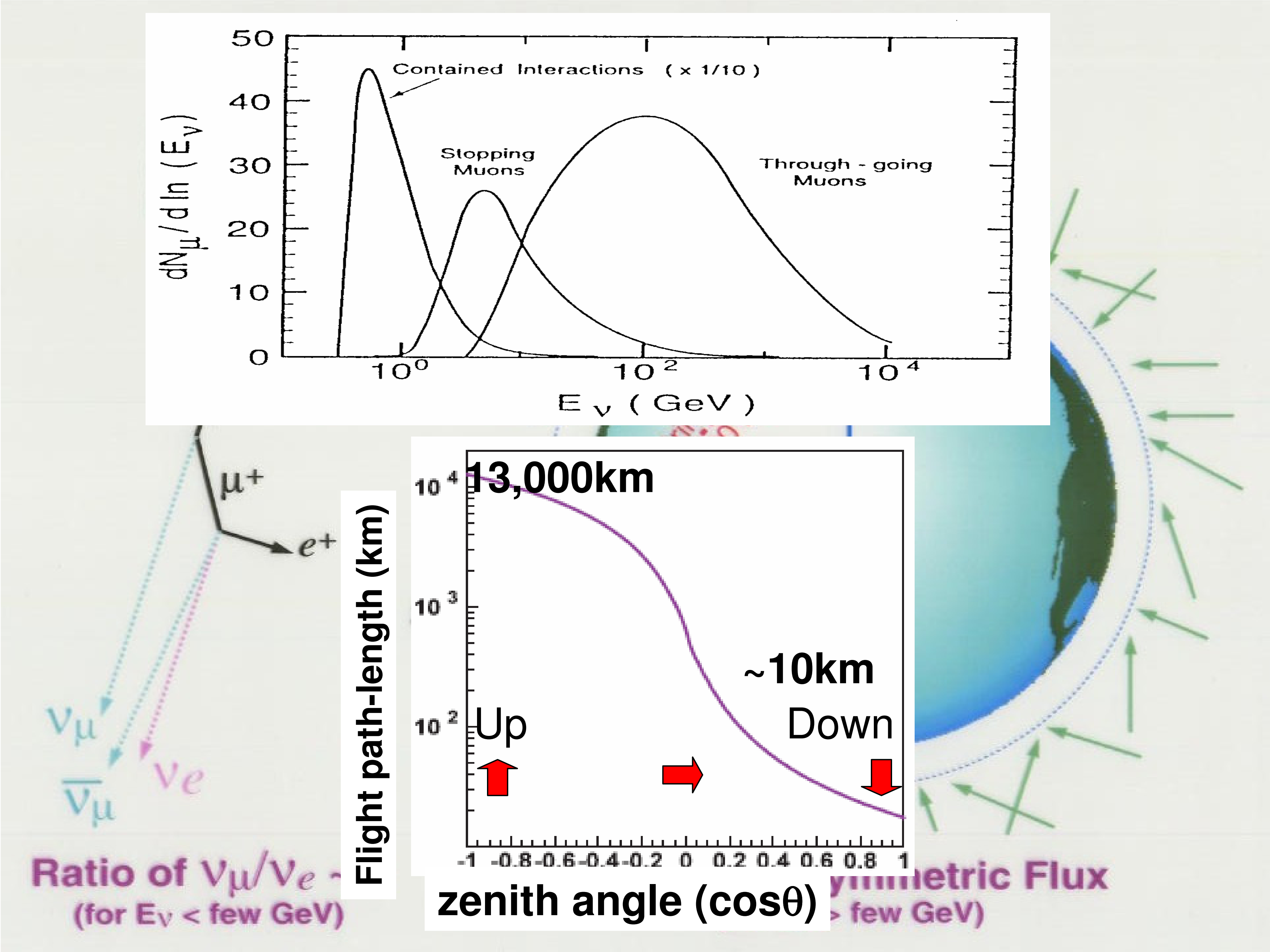
Solar → θ_{12}

ATMOSPHERIC NEUTRINOS



Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)

Up–Down Symmetric Flux
(for E_ν > few GeV)



50
40
30
20
10
0
Contained Interactions (x 1/10)
Stopping Muons
Through - going Muons
$dN_\mu/d\ln(E_\nu)$
10^0
10^2
10^4
E_ν (GeV)
μ^+
e^+
ν_μ
$\bar{\nu}_\mu$
ν_e
Flight path-length (km)
10^4
10^3
10^2
13,000km
~10km
Up
Down
-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
zenith angle (cosθ)
Ratio of ν_μ/ν_e ~
(for E_ν < few GeV)
ymmetric Flux
few GeV)

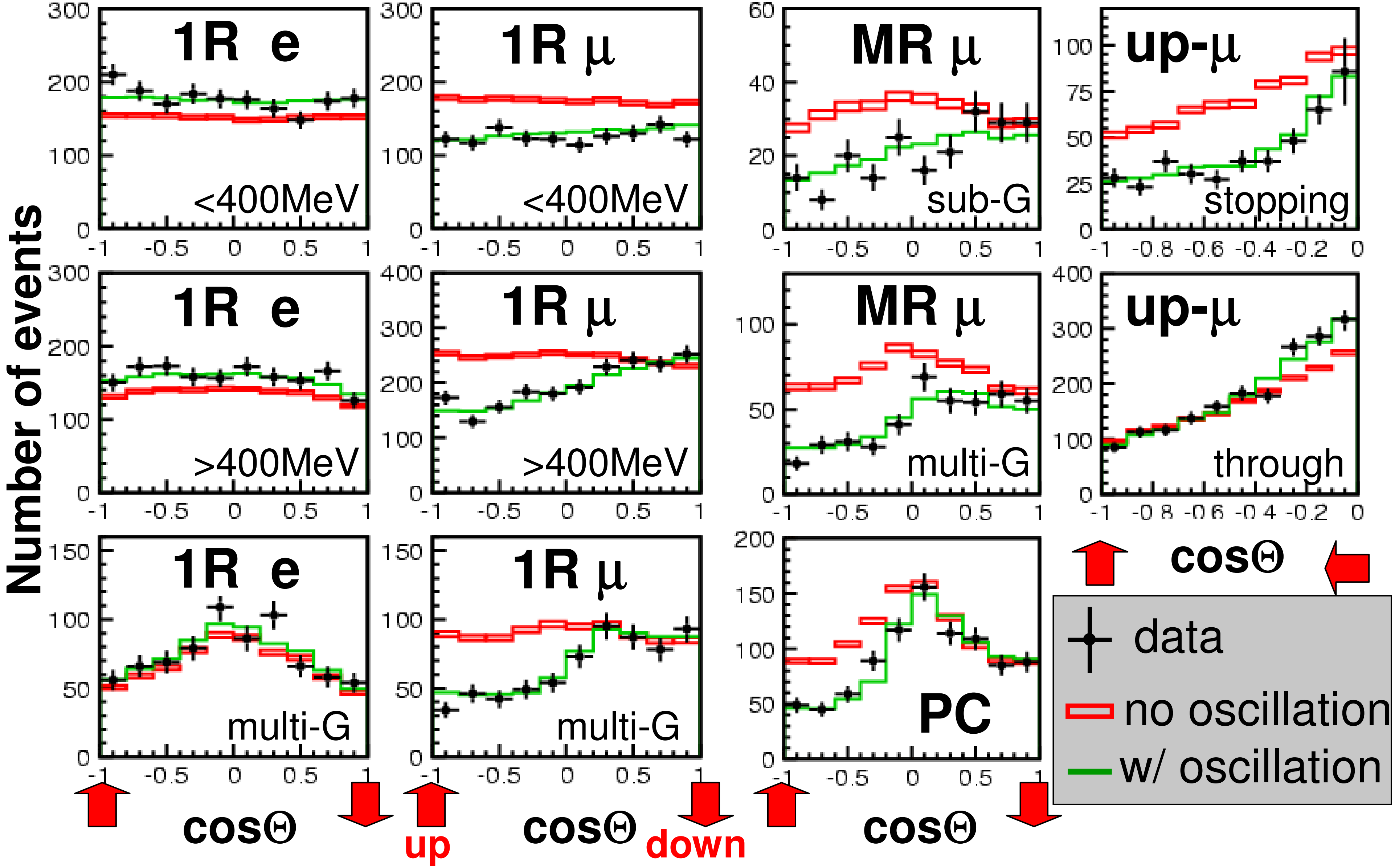
A bit of history

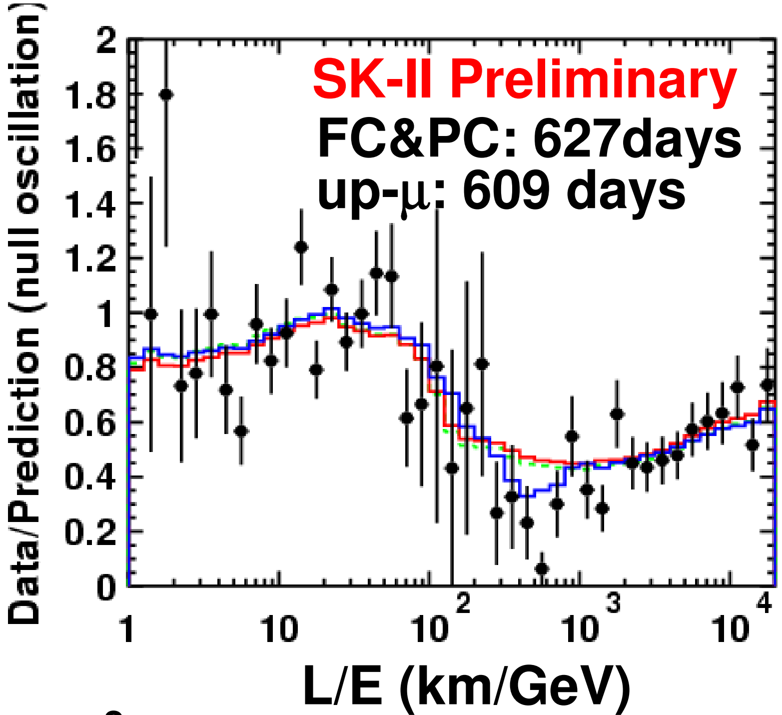
- In the '70 the most important problem in particle physics was the proton decay detection
- In this search the atmospheric neutrino interactions constituted the most tricky background: this is the reason why the study of atmospheric neutrinos started!
- The atmospheric neutrinos remained a "simple background" till when an anomalous results was obtained with Cerenkov detectors (Kamiokande, IMB) and lately confirmed with calorimeters (Soudan2)

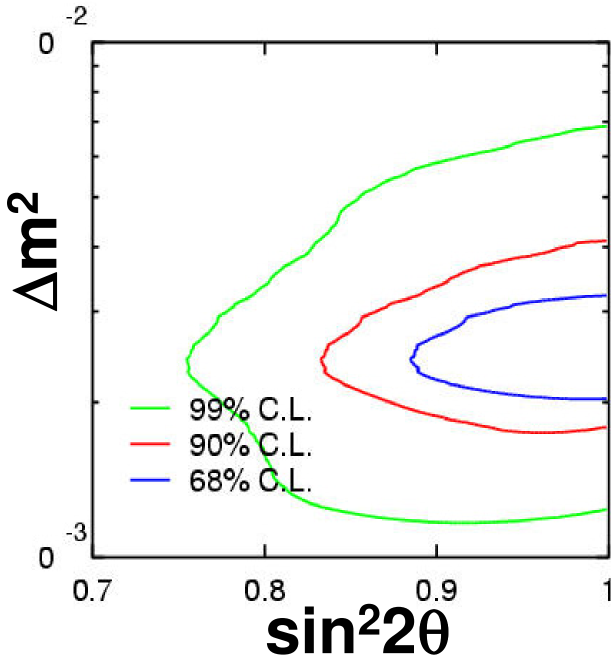
Since then atmospheric neutrinos became the "high-way" towards new physics beyond the Standard Model

SK-I Zenith angle distributions (w/ 100yr MC)

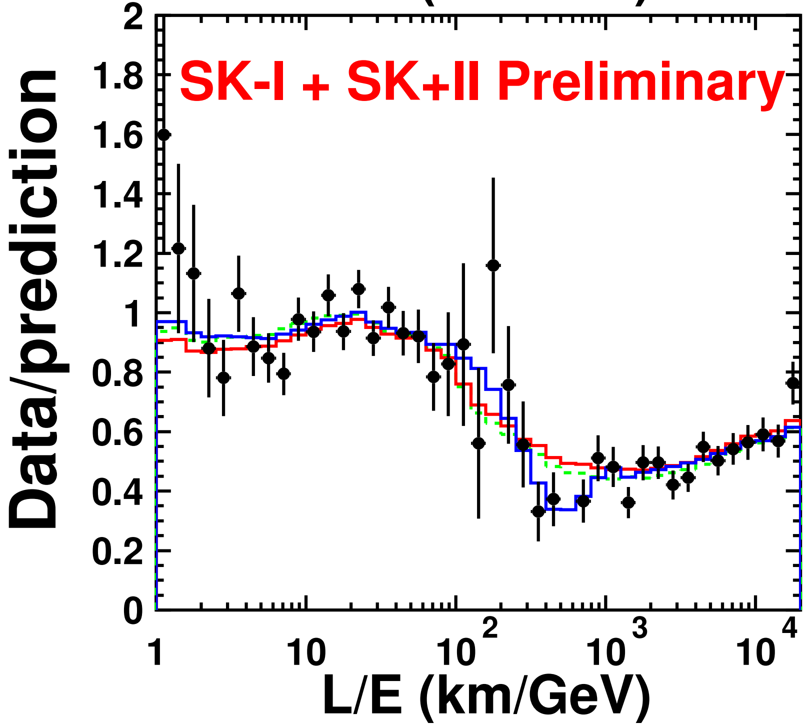
SK-I Atmospheric ν Full Paper hep-ex/0501064







Best Fit Results:
(physical region)
$\Delta m^2 = 2.6 \times 10^{-3}$ eV^2
$\sin^2 2\theta = 1.0$
$\chi^2_{min} = 54.8/40$ d.o.f.



Combined results from SK-I and SK-II will be shown.

Need correct treatment of different systematics of SK-I and II .

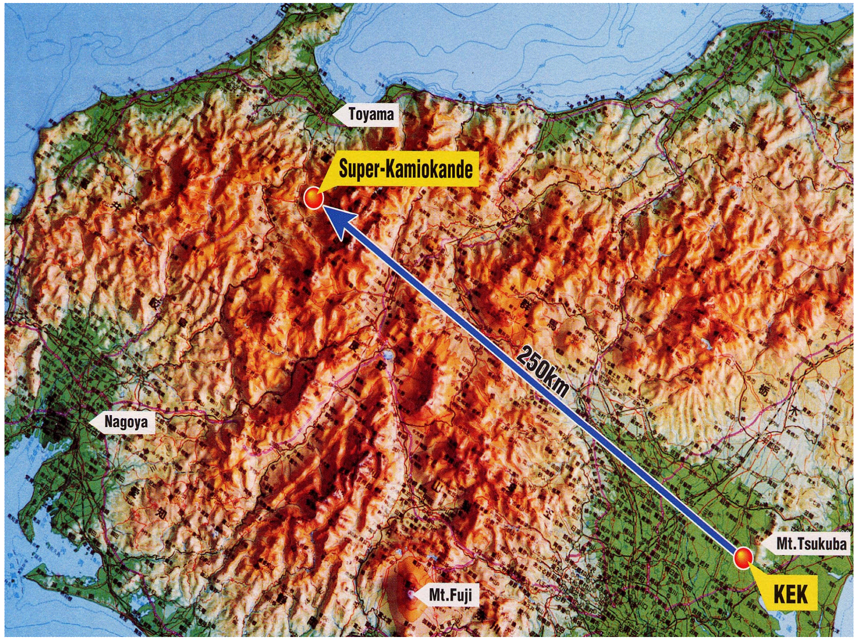
Guide Line χ^2

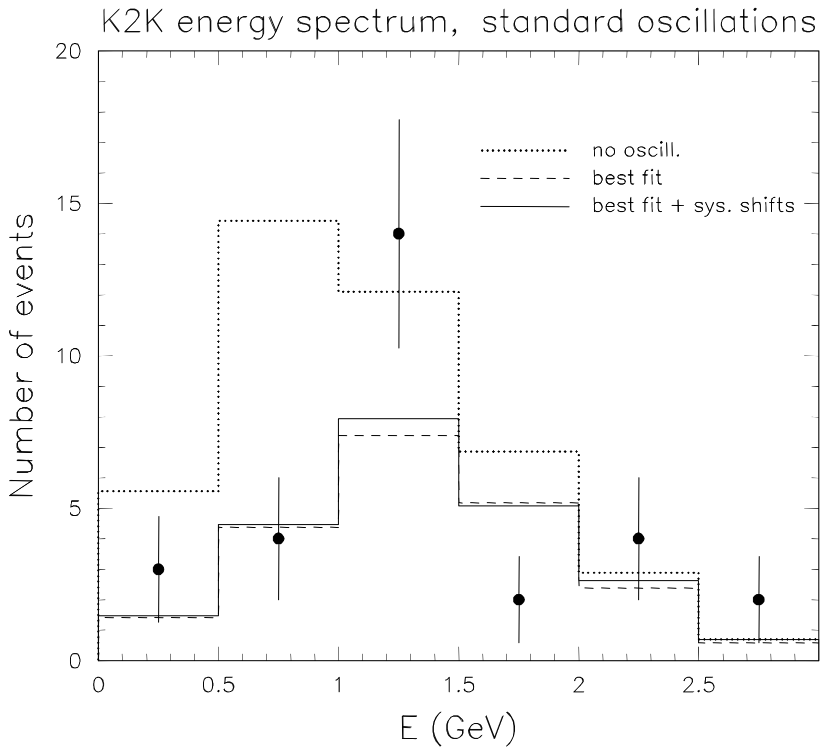
for $\Delta m^2 = 2.4\text{x}10^{-3}$ eV^2, $\sin^2 2\theta = 1.02$

$\chi^2_{osc} = 42.9/42$ d.o.f. (43%)

neutrino decay $\Delta\chi^2 = 16.5$ (4.1σ)
de-coherence $\Delta\chi^2 = 20.9$ (4.6σ)

First-generation LBL accelerator experiment: KEK-to-Kamioka (K2K)





Aimed at testing disappearance of accelerator ν_μ in the same range probed by atmospheric ν:

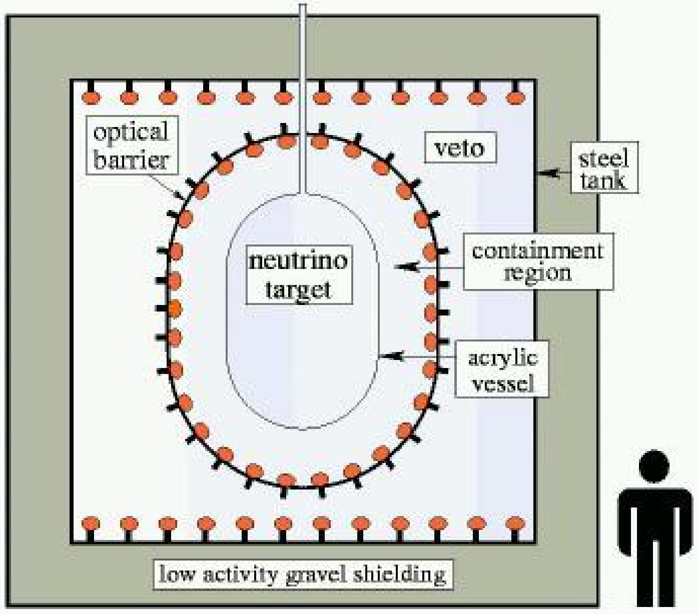
$(L/E)_{K2K} \sim (250\ \mathrm{km}/1.3\ \mathrm{GeV}) \sim (L/E)_{ATM}$

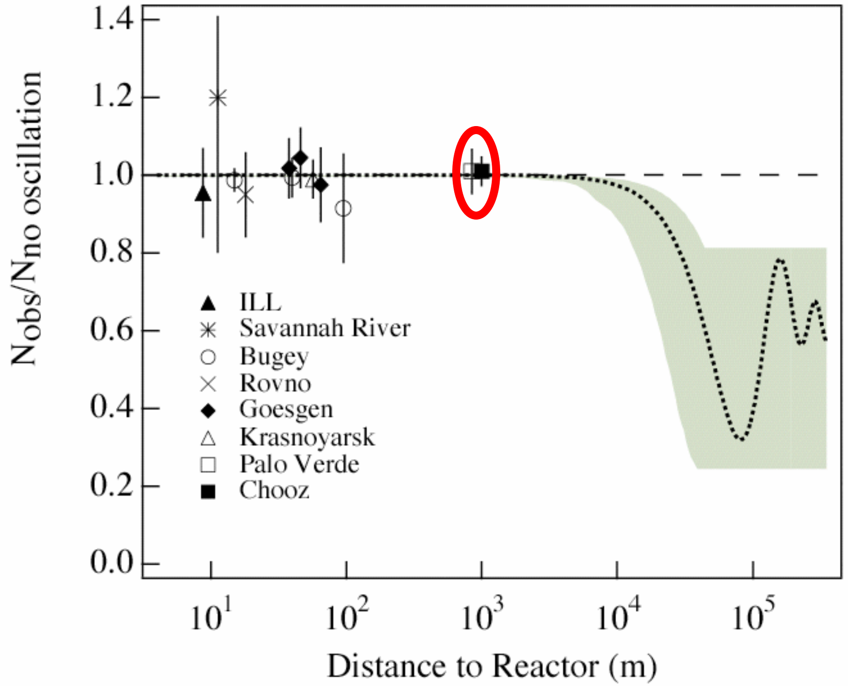
2002: muon disappearance observed at >99% C.L.

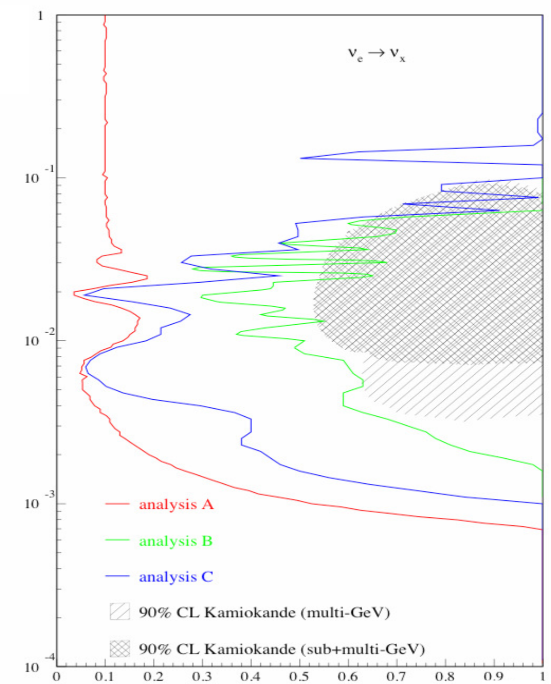
No electron appearance.

The CHOOZ reactor experiment and θ_{13}

- Searched for disappearance of reactor ν_e (E~few MeV) at distance L=1 km
- L/E range comparable to atmospheric ν $\rightarrow$ probe the same Δm^2
- No disappearance signal was found (1998) $\rightarrow$ Exclusion plot in (Δm^2, θ_{13}) plane
- Results also confirmed by later reactor experiment (Palo Verde)







Numerical ±2σ ranges (95% CL for 1dof), 2004 data:

$$\delta m^2 \simeq 8.0^{+0.8}_{-0.7} \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2 \simeq 2.4^{+0.5}_{-0.6} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} \simeq 0.29^{+0.05}_{-0.04} \quad (\mathrm{SNO}\ '05:\ \ 0.29 \to 0.31)$$

$$\sin^2\theta_{23} \simeq 0.45^{+0.18}_{-0.11}$$

$$\sin^2\theta_{13} <\sim 0.035$$

$$\mathrm{sign}(\pm\Delta m^2):\ \ \mathrm{unknown}$$

$$\mathrm{CP\ phase}\ \delta:\ \ \mathrm{unknown}$$

Note: Precise values for θ_{12} and θ_{23} relevant for model building

Probing absolute ν masses through non-oscillation searches

Three main tools (m_β, $m_{\beta\beta}$, Σ):

1) β **decay**: $m^2_i \neq 0$ can affect spectrum endpoint. Sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

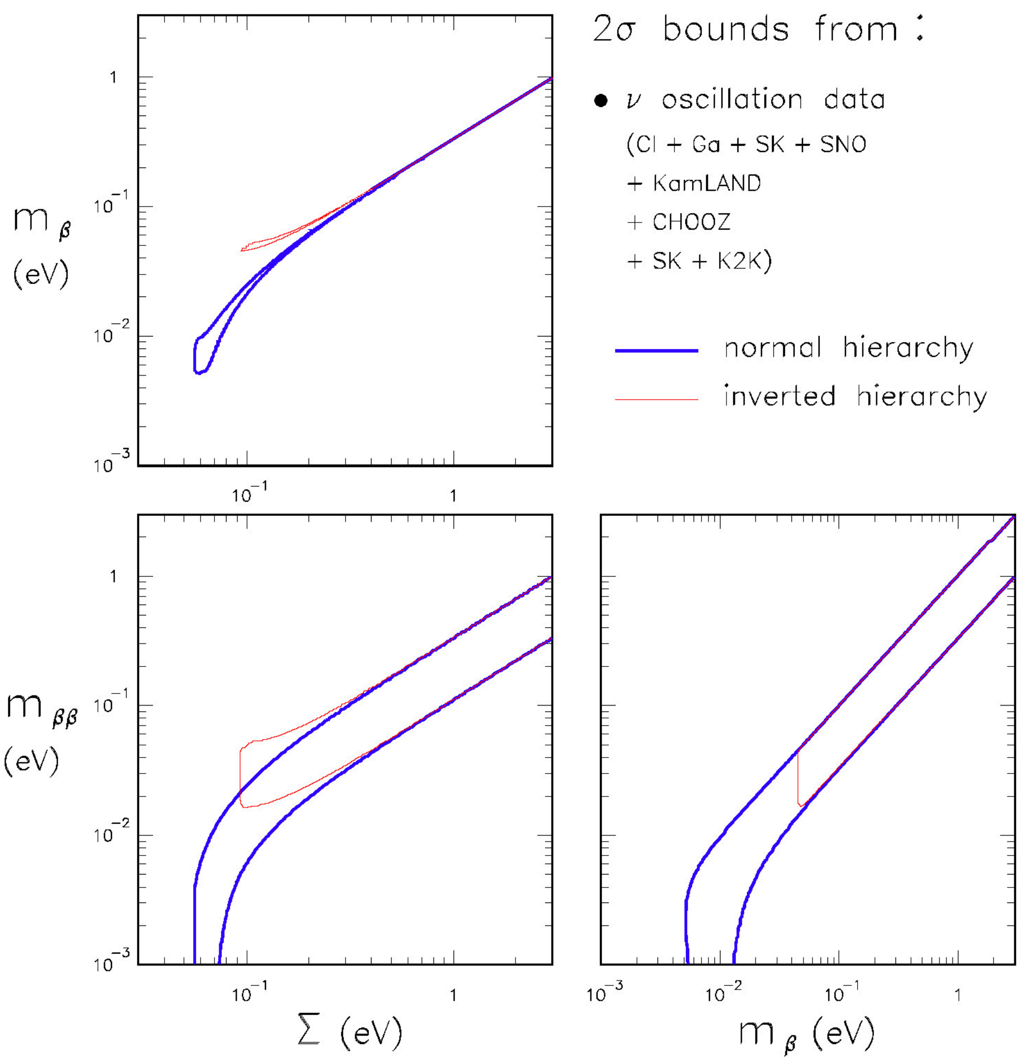
2) **0ν2β decay**: Can occur if $m^2_i \neq 0$ and $\nu=\bar{\nu}$. Sensitive to the "effective Majorana mass" (and phases):

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

3) **Cosmology**: $m^2_i \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB+other data. Probes:

$$\Sigma = m_1 + m_2 + m_3$$

Even without non-oscillation data, the (m_β, $m_{\beta\beta}$, Σ) parameter space is constrained by previous oscillation results



Partial overlap between the two hierarchies

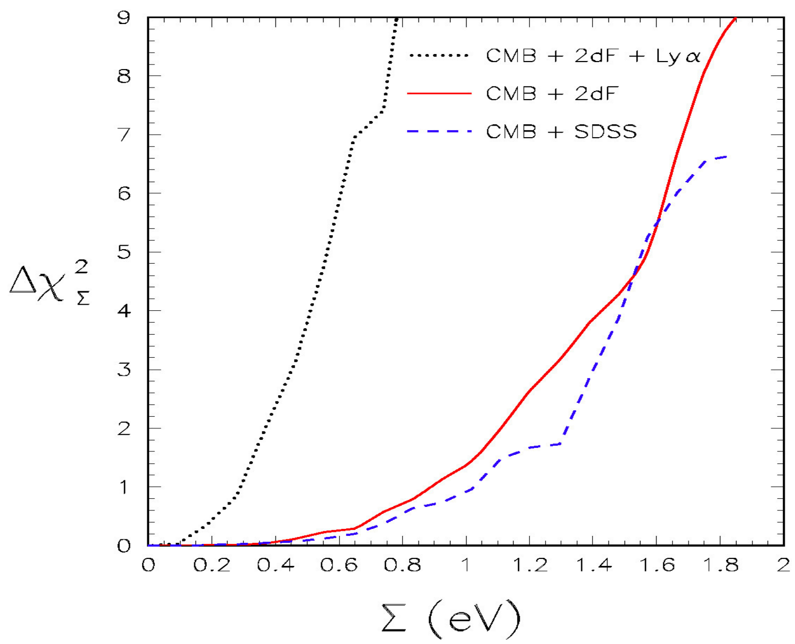
Large $m_{\beta\beta}$ spread due to unknown Majorana phases

But we do have information from non-oscillation experiments:

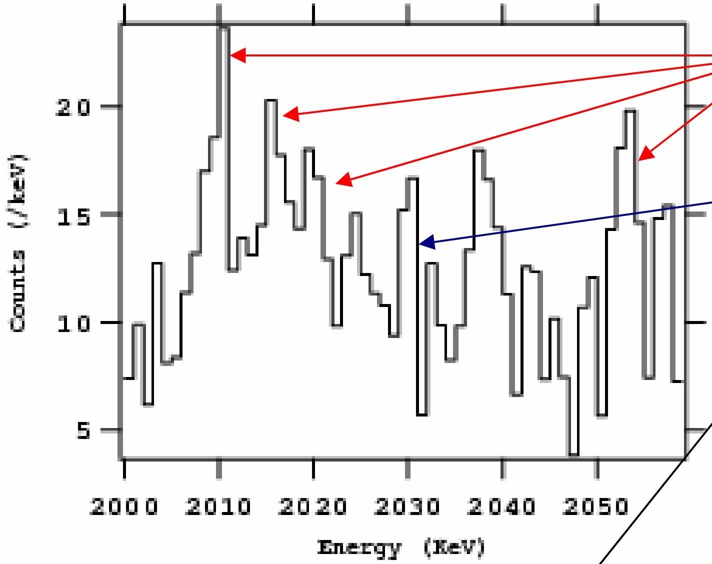
1) β **decay**: no signal so far. Mainz & Troitsk expts: m_β < O(eV)

2) 0ν2β **decay**, no signal in all experiment, except in the most sensitive one *(Heidelberg-Moscow)*. Rather debated claim.
   Claim accepted: $m_{\beta\beta}$ **in sub-eV range** (with large uncertainties)
   Claim rejected: $m_{\beta\beta}$ < O(eV).

3) **Cosmology**. Upper bounds:
   Σ < eV/sub-eV range,
   depending on several inputs and priors. E.g.,



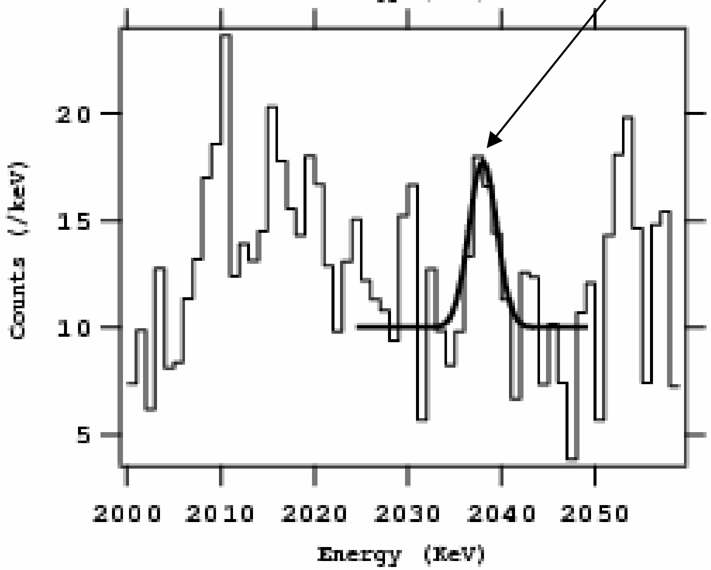
$0\nu 2\beta$ decay: Heidelberg-Moscow experiment final analysis (March 2004)



Four lines at 2010, 2017, 2022, 2053 keV are identified as due to ^{214}Bi decay

One possible line at 2030 keV is not identified

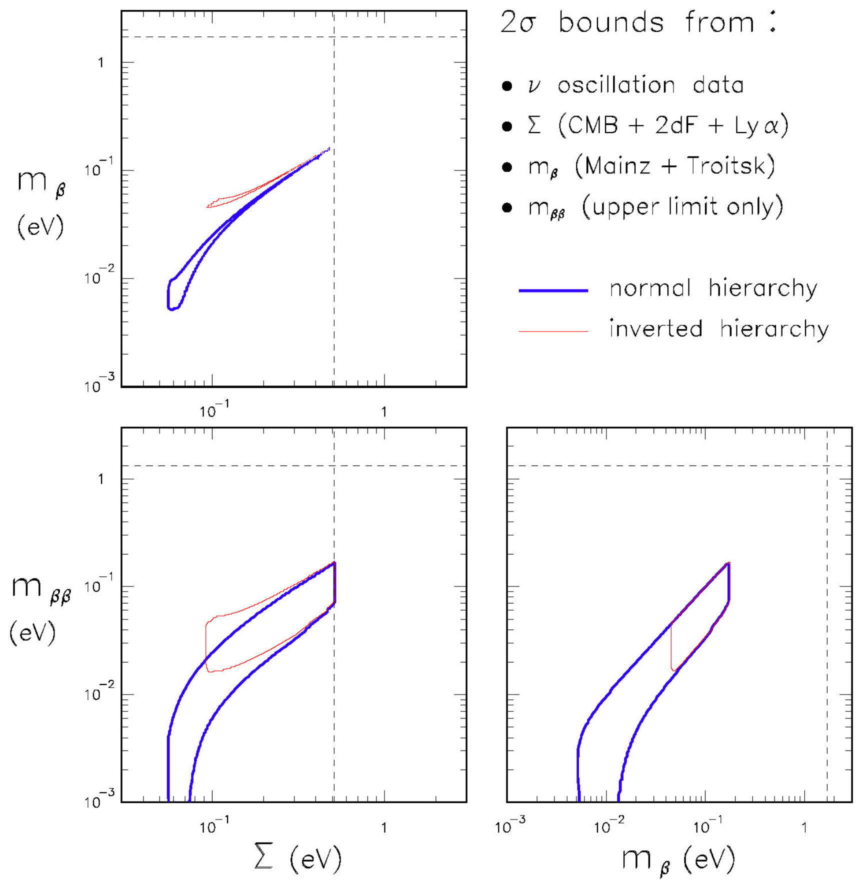
Claimed $0\nu\beta\beta$ line at ~2039 keV is now more clearly seen "by eye". Statistically, it emerges at about 4σ C.L. (~23 events)



We might have reached an "LSND-like" situation:

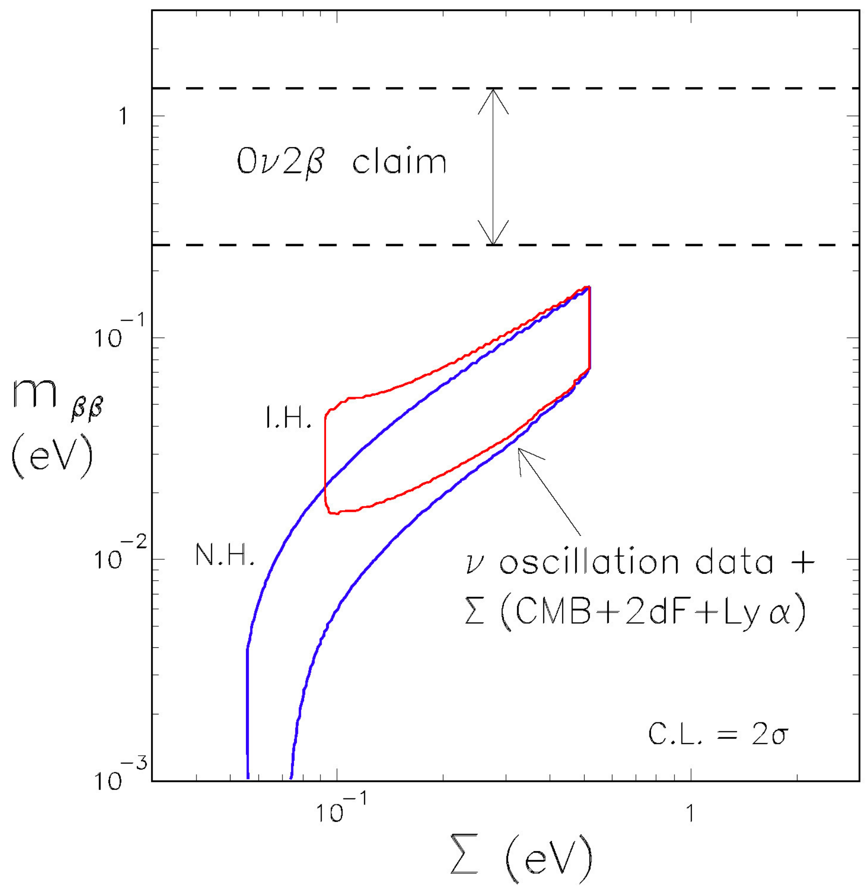
- Initial claim is rather controversial
- Then, further data/analysis strengthen it
- No current experiment can disprove it
- It will stay with us for a long time and will demand more sensitive expt. checks

0ν2β claim rejected



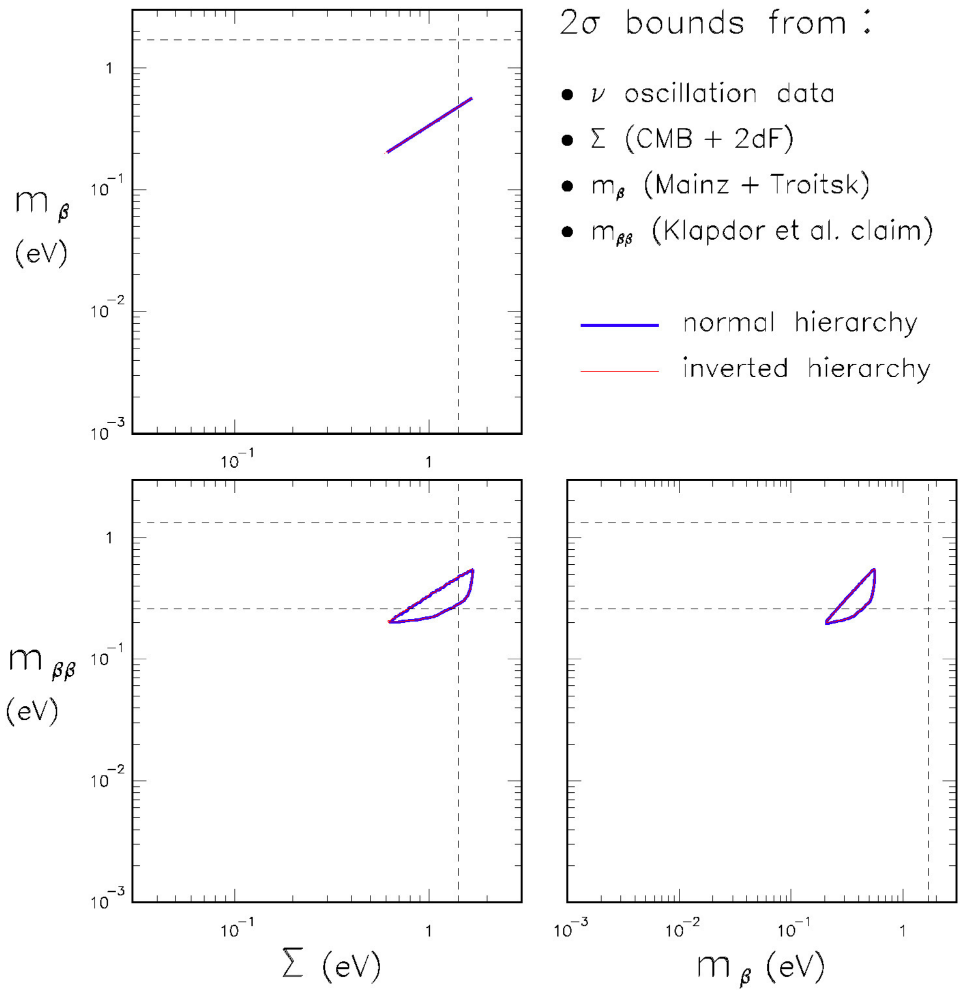
Cosmological bound dominates, but does not probe hierarchy yet

0ν2β claim accepted



Tension with cosmological bound (no combination possible at face value)
But: too early to draw definite conclusions

E.g., if 0ν2β claim accepted & cosmological bounds relaxed:



Combination of all data (osc+nonosc.) possible

Complete overlap of the two hierarchies (degenerate spectrum with "large" masses)

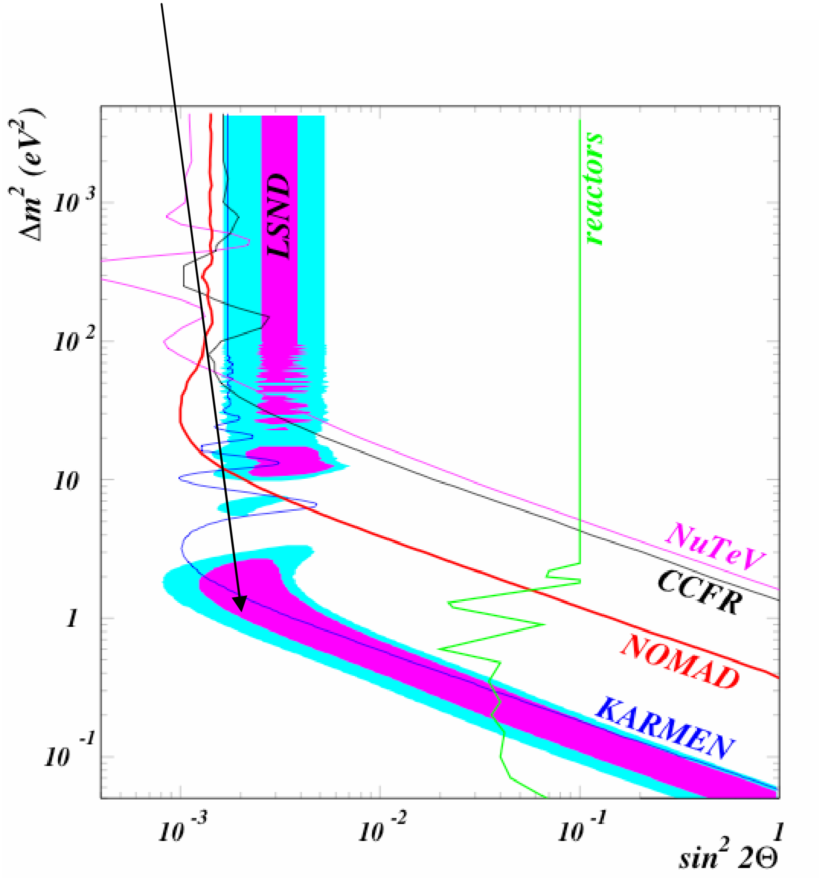
High discovery potential in future (m_β, $m_{\beta\beta}$, Σ) searches

Beyond three-neutrino mixing: LSND

Many theoretical reasons to go beyond the standard 3ν scenario

A purely experimental reason: the puzzling LSND oscillation claim

$\Delta M^2 \sim O(eV^2)$ with very small mixing?



Solutions invented so far (new sterile states, new interactions or properties) seem rather "ad hoc" and/or in poor agreement with world neutrino data

If MiniBoone confirms LSND this year (2005), many ideas will be revised,

Question raised by neutrino data I

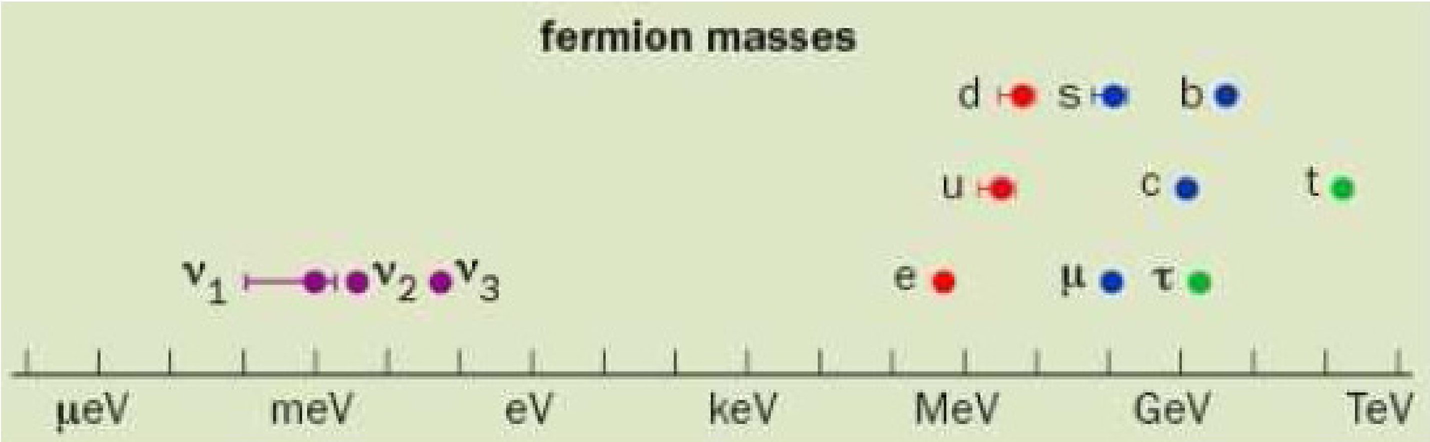
Quarks

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

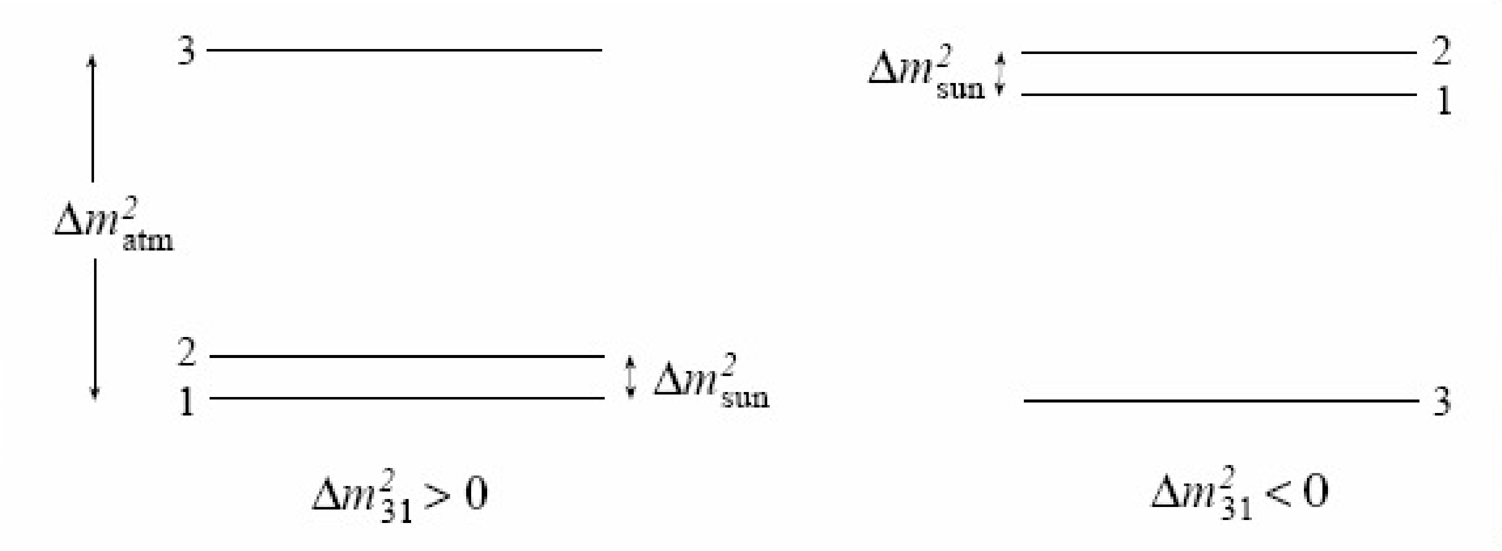
Why neutrino mixing are so large?

Question raised by neutrino data II

Mass hierarchy in the SM



What makes neutrinos so much lighter?



Question raised by neutrino data III

Origin of neutrino mass

- Neutrinos in the Standard Model (SM) are strictly massless, *ie.* there is no way to write a mass term for neutrinos with only SM fields which is gauge invariant and renormalizable
- Neutrinos are massive in reality – thus neutrino mass requires physics beyond the standard model
- One example of how to generate neutrino masses is the see saw mechanism: it introduces a heavy right handed neutrino (N_R), *ie.* a singlet under the SM gauge group

Question raised by neutrino data IV

Origin of baryons

- At the same time NR can provide a mechanism for creating the observed tiny surplus of matter over anti-matter
- Leptogenesis requires the temperature of the Universe to be high enough that there is a thermal population of N_R. Their subsequent out-of-equilibrium decays are a new source of CP violation and lepton number

$$\Gamma(N_R \rightarrow LH) - \Gamma(N_R \rightarrow LH^*) \neq 0$$

which later on is converted to baryon number by nonperturbative processes

Key measurements

In the context of GUT scale right handed neutrinos it is very difficult to establish a one-to-one correspondence between high and low-energy observables.

A given model, however, usually has generic predictions for low energy observables. Therefore studying neutrinos allows to gain considerable insight into phenomena which otherwise would be inaccessible.

Neutrinos provide a unique window of observation on the GUT scale! And complementary to the energy frontier (e^+e^- and hadron colliders)

What still we have to observe or measure with higher precision

- The source of atmospheric oscillations (detect τ appearance)
- Three angles (θ_{12}, θ_{13}, θ_{23})
- Two mass squared differences (Δm^2_{12}, Δm^2_{23})
- The sign of the mass squared difference Δm^2 ($\pm\Delta m^2_{23}$)
- One CP phase (δ)
- The absolute masse scale
- Are neutrino Dirac or Majorana particles (or both)?
- Are there more - sterile - neutrinos?

All the underlined items can be studied with LBL experiments

Discovery

Precision meas.

The accelerator/reactor based program

1st step: *transition era* — *Ongoing:* 2005-2010

- Improve the precision on the atmospheric parameters looking at ν_μ disappearance
- Confirm (atm. osc)=($\nu_\mu \rightarrow \nu_\tau$) and first look at $\nu_\mu \rightarrow \nu_e$

2nd step: θ_{13} era — *Approved/Proposed:* 2008-2015

- Demonstrate visibility of sub-leading transitions:
  $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_e$
- Explore θ_{13} down to 2^0 (today $<10^0$)

3rd step: *precision era* — *To be prepared:* 2015-2025

$\theta_{13} > 3^0$ —— Known by 2011 —— $\theta_{13} < 3^0$

- Existing facilities could reach it
- … but with very small sensitivity to δ_{CP} and mass hierarchy

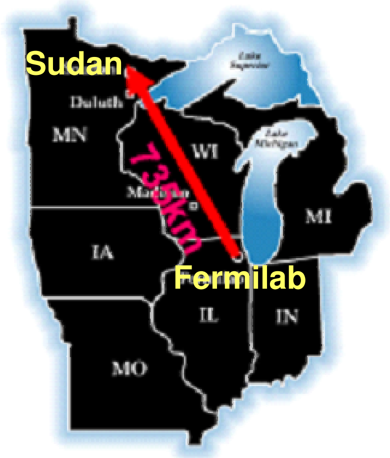
- No access for ongoing experiments at that time

Cleaner and more intense beams + bigger detectors

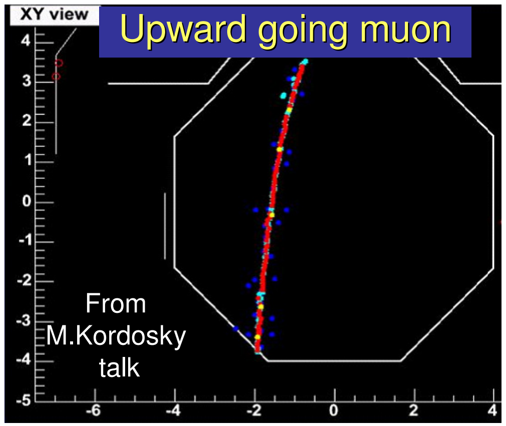
Transition era

- Conventional ν_μ beams from pion decay
- Long baseline experiments (such as K2K)
- Increased initial proton beam power: 0.01 (K2K) →0.4 MW

NUMI beam: MINOS (2005)



Magnetised iron calorimeter



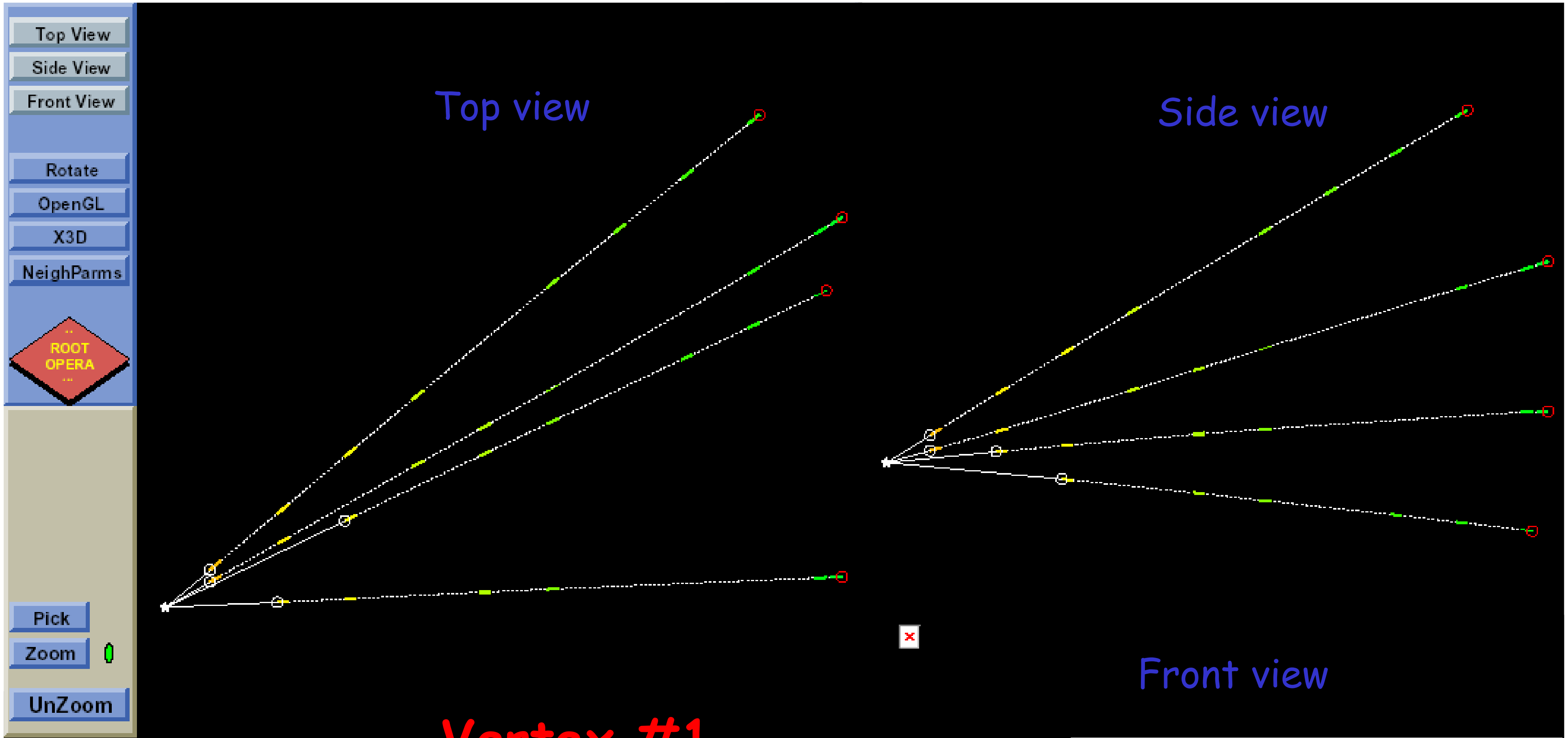
CNGS beam: OPERA (2006)

Hybrid emulsion detector

Improve atmospheric parameters

Confirm atm = $\nu_\mu \rightarrow \nu_\tau$

First look at ν_e appearance

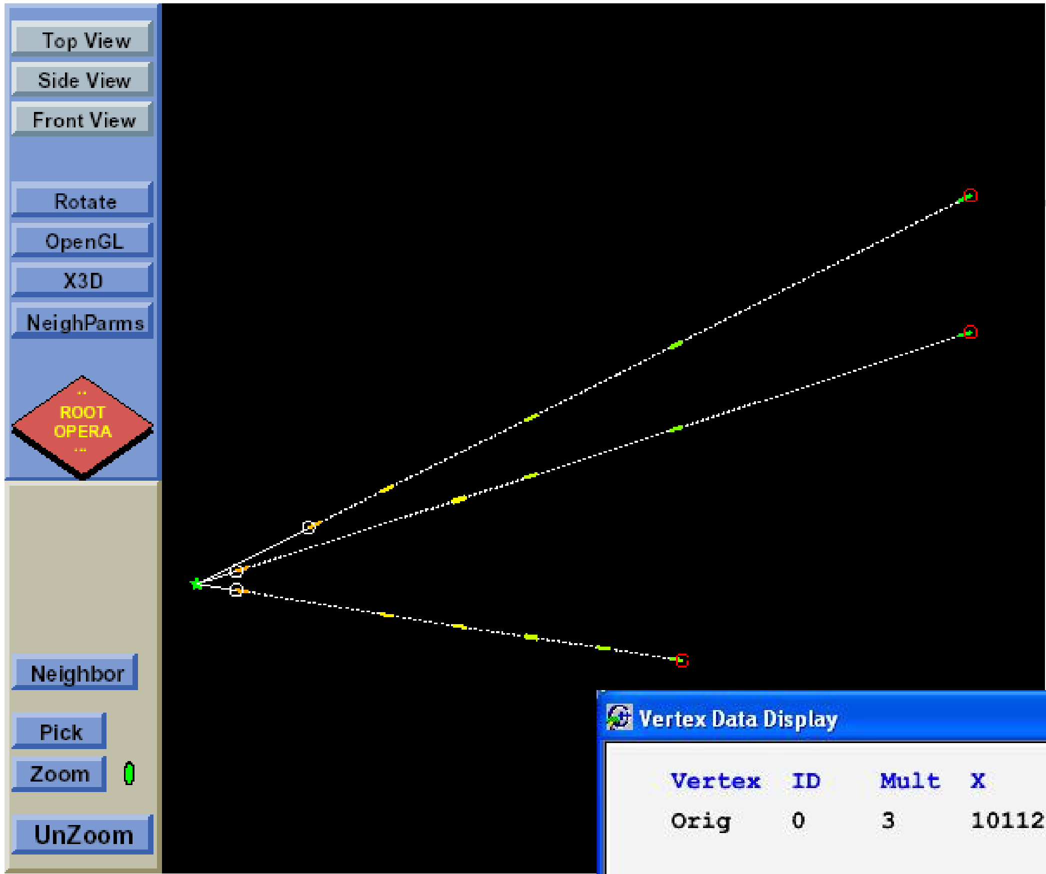


Vertex #1

Impact parameters: [4,4,7,11] μm

The "FIRST" neutrino interaction detected in an OPERA ECC has been found in Napoli Scanning Lab

D. Coppola, F. Di Capua, A. Marotta, C. Pistillo, L. Scotto Lavina, V. Tioukov



Vertex #2

Vertex Data Display

Vertex	ID	Mult	X	Y	Z	Dist	Chi2	Prob
Orig	0	3	10112.5	11555.9	-13879.3	5.9	0.2	0.92128

Tracks parameters for Original vertex

#	ID	Nseg	Mass	P	Chi2/ndf	Prob	Chi2Contrib	Impact	
0	986	5	0.1390	1.00	0.95	0.9970	0.000	1.23	Rem
1	1545	6	0.1390	1.00	0.71	0.9999	0.010	0.35	Rem
2	505	5	0.1390	1.00	2.03	0.8600	0.479	8.28	Rem

Vertex Data Display | VTX-Canvas-| | x=0, y=-9.45823

θ_{13} era: Reactors

- High rate $\bar{\nu}_e$ by inverse beta decay
- Unambiguous determination of θ_{13}
- … but cannot test mass hierarchy or CP violation

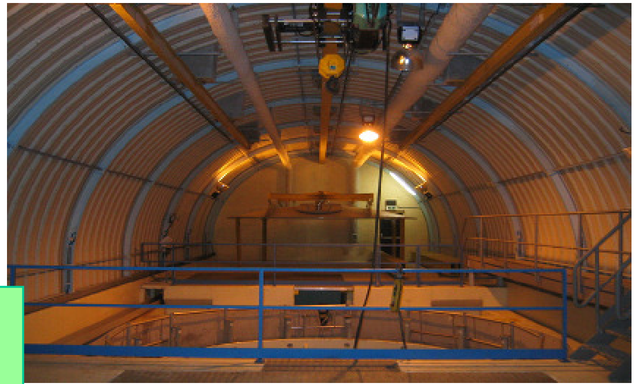
- Europe: Double-Chooz
- Others sites: Brazil, China, Japan, Russia, US, …

Can new reactor experiments achieve the required low level of systematic errors ?

Double-Chooz (2008)

Collaboration

- France, Germany, USA, Russia
- Approved in France
- LOI's: hep-ex/0405032 & hep-ex/0410081
- http://doublechooz.in2p3.fr



go down to θ_{13}~4-5^0
With $\bar{\nu}_e$ disappearance

- Reduce systematic errors by a factor 5 with two identical detectors
- Still pending for full funding

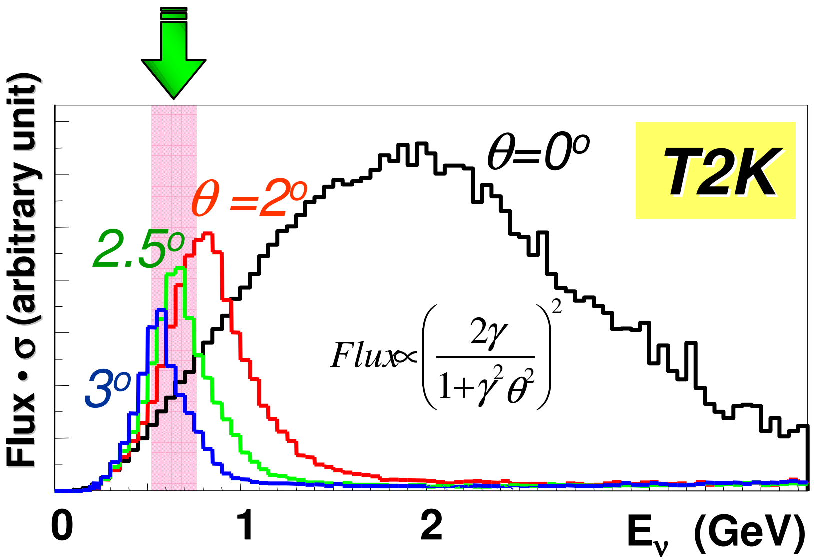
Chooz site (France)

- Agreement with EDF in 2005
- *Far site*: ready for integration (2007)
- *Near site*: 40 m shaft to build (2009)

θ_{13} era: Super-Beams

- Conventional ν_μ beams from pion decay
- Increased proton beam power: 0.4 →0.8 MW
- Off-axis technique: narrow band beam with purer composition
- Tune L/E to the oscillation maximum (L/E~ 500 Km/GeV)

Oscillation peak at 295 Km



JPARC beam: T2K (2009)
- 0.4% ν_e
- L=295 Km
- Water Čerenkov (SK)

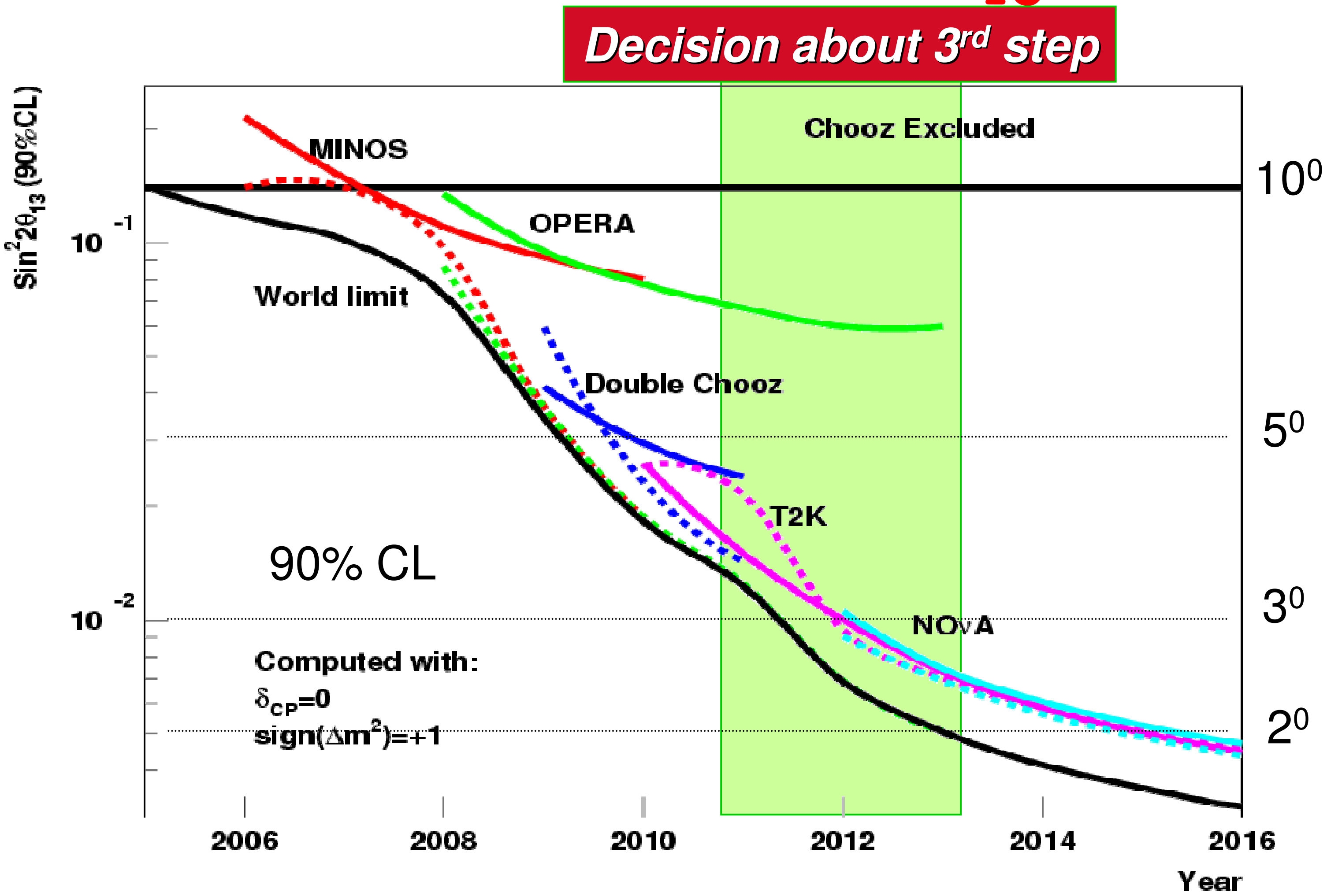
NuMI off-axis: NOνA (2011 ?)
- 0.5-1% ν_e
- L=810 Km
- Fully active calorimeter

Further improve atmospheric parameters with ν_μ disappearance

go down to θ_{13}~2-3^0 with ν_e appearance

A first look at mass hierarchy (NOνA only)

Results for θ_{13}

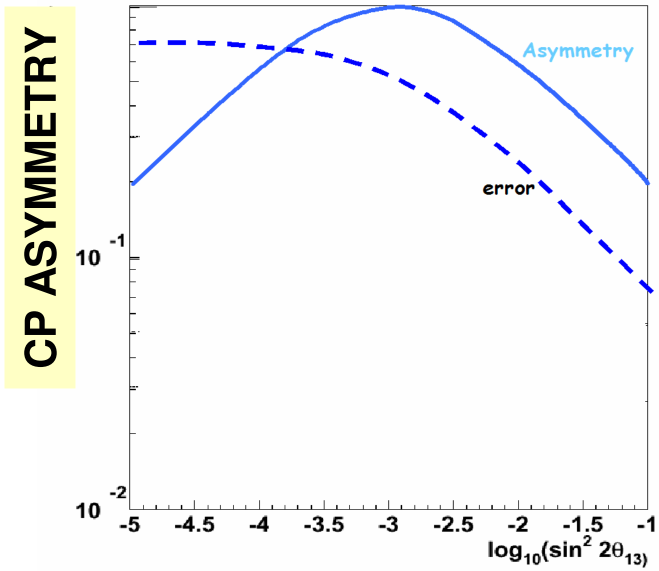


- If θ_{13} is not measured by ~2011, the probability to measure it with ongoing experiments would be very small
- Building new facilities will take more than 5 years

CP violation and mass hierarchy

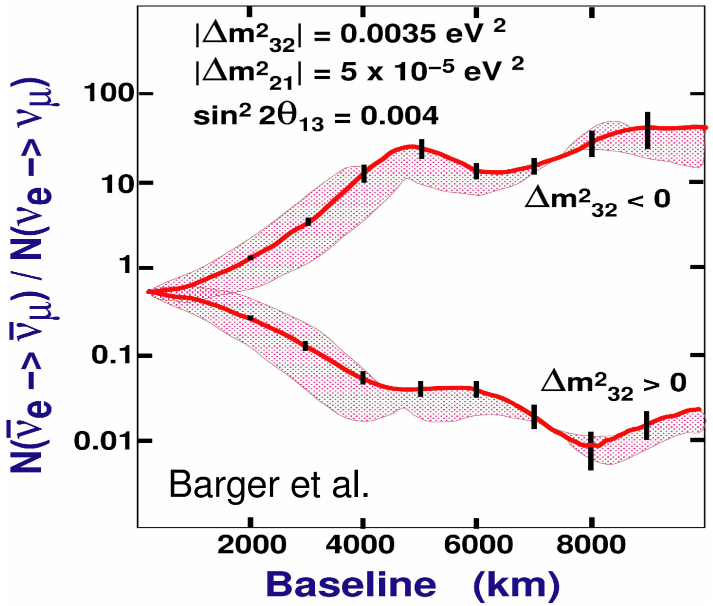
CP violating phase

$$A^{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \propto \sin\delta_{CP} \cdot f(\theta_{13})$$



Mass hierarchy: sign(Δm^2_{23})

- The oscillation probability depends on sign(Δm^2_{23}) through matter effects
- Sensitivity increases with L



Difficulties

Correlations

- Several unknowns in the same Eq.
  - θ_{13}
  - δ_{CP}
  - Sign (Δm^2_{23})

Degeneracies

- Ambiguities due to lack of knowledge on:
  - δ_{CP}
  - Sign (Δm^2_{23})
  - Octant: $\theta_{23}>\pi/4$ or $\theta_{23}<\pi/4$

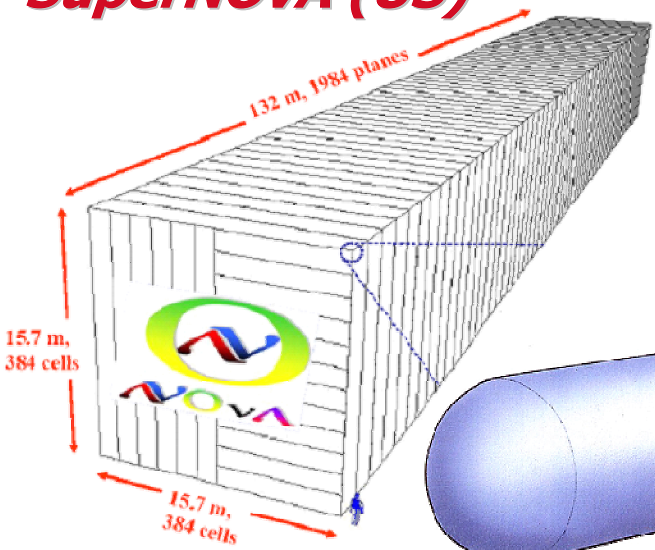
Improved Super-beams

- Increase by one order of magnitude
  - beam power: ~4MW
  - detector mass
- Three proposals:

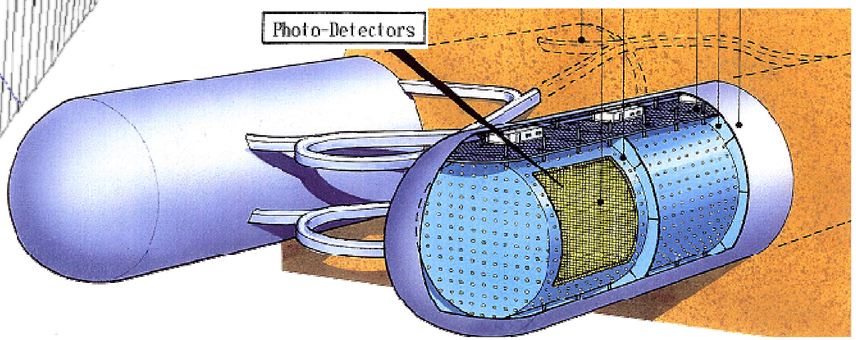
Systematics unchanged
- Beam contamination
- Cross section
- Detector efficiency

T2HK (T2K-II)	Japan	0.6 GeV	295 Km	1000 KT Water Čerenkov
SPL-Memphys	Europe	0.25 GeV	130 Km	440 KT Water Čerenkov
NuMI-SuperNOvA	US	2 GeV	890 Km	130 KT fully active calorimeter

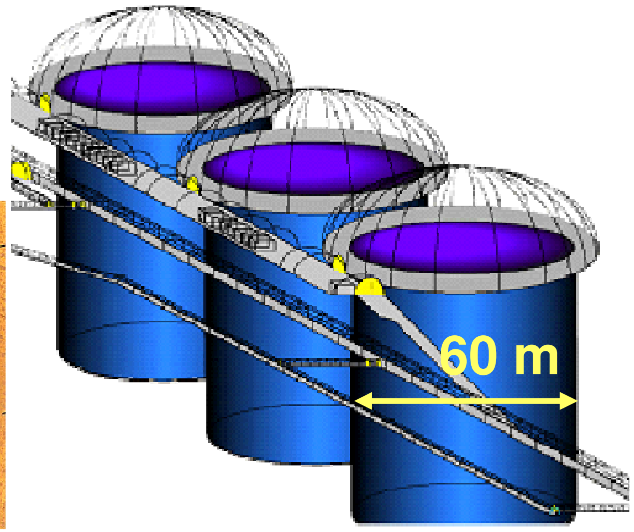
SuperNOvA (US)



Hyper-Kamiokande (Japan)



Memphys (Frejus)



Beta-beam

Pure ν_e or $\overline{\nu}_e$ beam ➡ small beam systematics and backgrounds

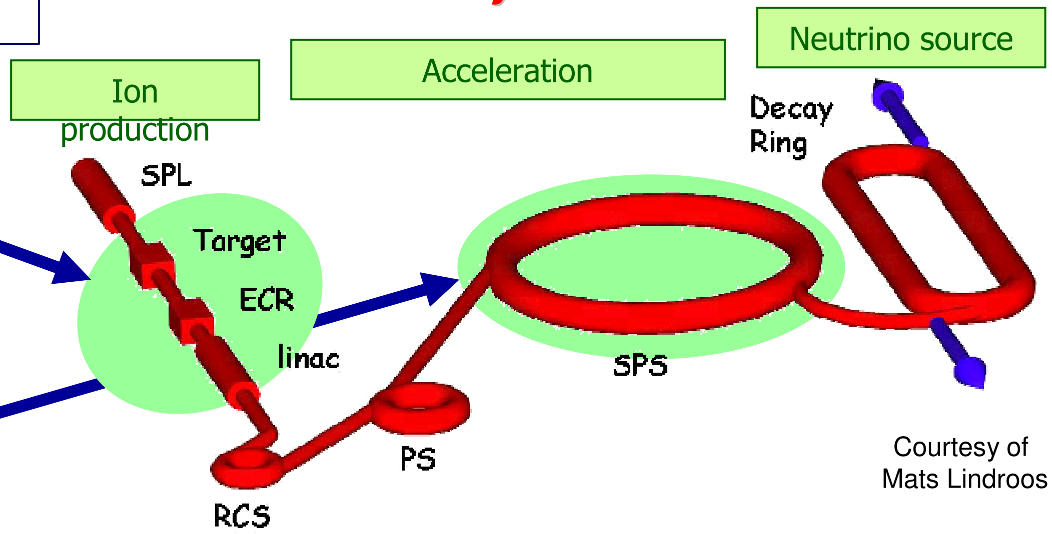
$${}^{6}_{2}He^{++} \rightarrow {}^{6}_{3}Li^{+++}\,\overline{\nu}_e\, e^{-}$$

$${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F\ \nu_e\, e^{+}$$

ongoing R&D for ion production
EURISOL design study

missing feasibility study
for high γ option

CERN layout



- Performance increases with beam energy if L/E is kept at oscillation max:
  - Higher flux and cross section. Better energy binning (no Fermi motion)
  - Smaller systematics from cross section and detector efficiency (Burget et al.)

Performace — High γ / Low γ

LHC	γ~1500	7 GeV	3000 Km	0.1 MT TC	CERN-Canarias
Tevatron or S-SPS	γ~350	1.5 GeV	730 Km	1 MT WČ orTC	CERN-GS/Canfranc
SPS (max energy)	γ~150	0.6 GeV	300 Km	1 MT WČ	?
SPS	γ~100	0.35 GeV	130 Km	1 MT WČ	CERN-Frejus

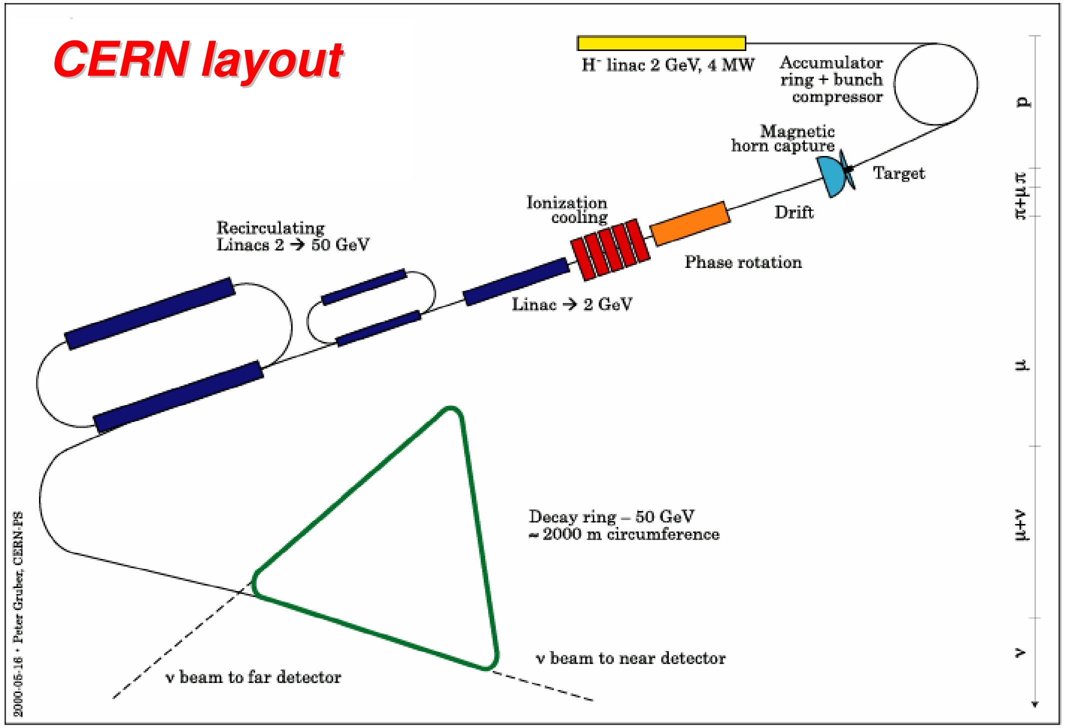
Neutrino factory

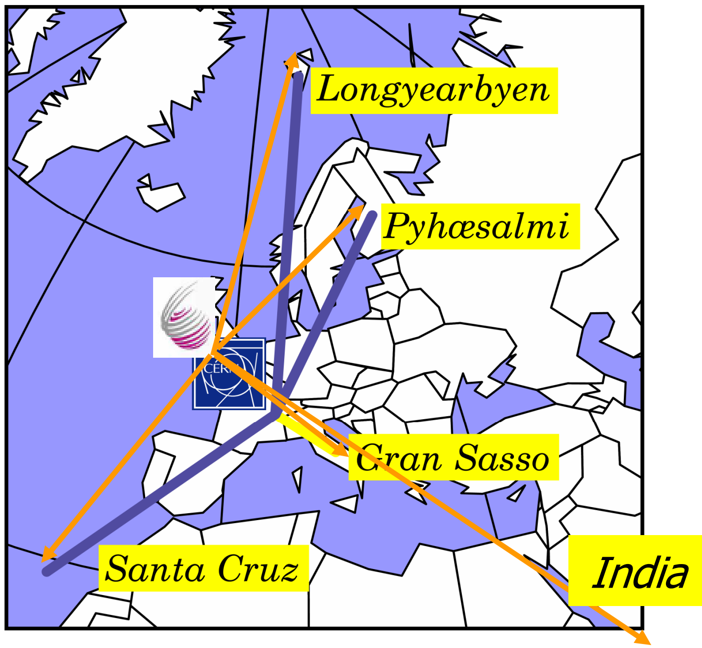
- 50% $\bar{\nu}_\mu$ 50% ν_e ➡ small beam systematics ... but charge required
- High energy beam ➡ small cross section systematics
- A wide variety of studies are possible:

unitarity	CP violation	T, CPT
$\nu_e \to \nu_\tau$	$\nu_e \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_e$
silver	golden	bronze

and also: $\bar{\nu}_\mu \to \bar{\nu}_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\tau$

Atmospheric osc.





Detectors

Neutrino Energy

High energy beams only: Nufact or high γ β-beam

Hybrid emulsion (4 KT)

- Experience from OPERA
- Silver channel $\nu_e \rightarrow \nu_\tau$

  Interesting to solve degeneracies

  CP asymmetry has opposite sign
- Golden and bronze also

Tracking Calorimeters (100 KT)

- Fully active with liquid scintillator: ~NOvA
- Or sampling iron calorimeter: ~MINOS
- Muon charge is crucial: B field !!!
- Golden channel $\nu_e \rightarrow \nu_\mu$

Both

Liquid Argon TPC (100 KT)

- 3D active detector: Imaging, calorimetry, Čerenkov
- Challenging: ongoing R&D strategy
- GLACIER conceptual design
- … also with magnetic field
- Could explore all channels

Low energy beam only:

- $\gamma<350$ β-beam
- Super-beam

And also:

- *Proton decay*
- *Supernovae neutrinos*

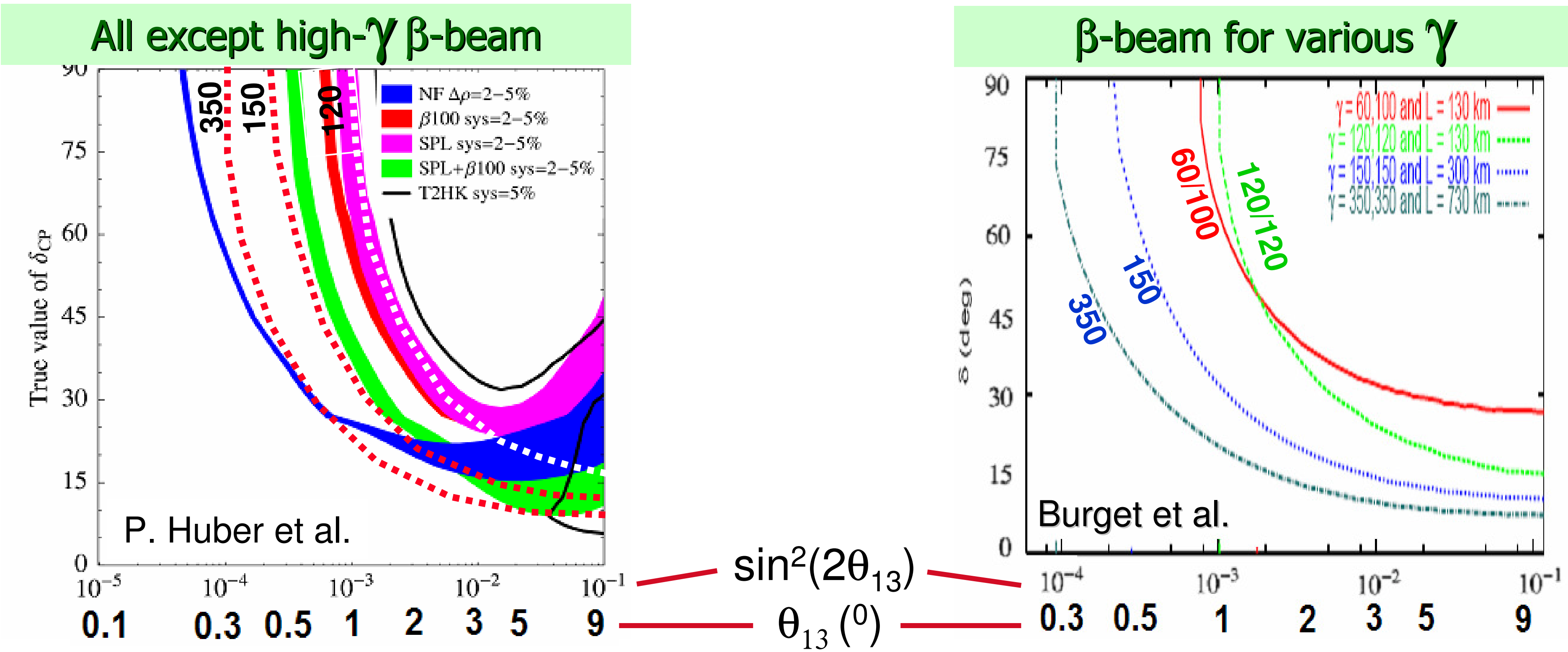
Water Čerenkov (0.5-1 MT)

- Well known technique from Super-K
- Interesting for e/μ separation

$\nu_\mu \rightarrow \nu_e$ **super-beam**

$\nu_e \rightarrow \nu_\mu$ **β-beam**

Comparisons: δ_{CP}-θ_{13}



- The Nufact study is old (5 years). It should be revisited in order to make a fear comparison with β-beam

- *For large θ_{13}* systematic errors dominate. The picture is not clear yet: ongoing studies by several groups
- *For small θ_{13}* Nufact and High γ β-beam (350) outperforms all others
- The third option should be Low γ β-beam + Super-beam

Physics reach

	Systematic errors	E bins	B field	WČ	channels	Sensitivity to oscillation parameter	$\theta_{13}<3^0$	$\theta_{13}>3^0$	R&D	Others
Nufact	Matter eff.	yes	yes	no	Golden Silver Bronze Atmos.	CP phase Mass hierarchy maximal θ_{23} ?	Good Good Good	Good Good Good	High	T violation Muon physics Muon collider
β-beam γ>1000	Matter eff.	yes	no	no	Golden Silver	CP phase Mass hierarchy	Good Good	Good Good	Med. ?	
β-beam γ~350		yes	no	yes	Golden Silver	CP phase Mass hierarchy	Good Small	Good Med.	Small	Supernovae Proton decay Atmos.
β-beam γ<150	x-section Efficiency	poor	no	yes	Golden Silver	CP phase Mass hierarchy maximal θ_{23} ?	Med. None Med.	Good Small Med.	Small	Supernovae Proton decay Atmos.
Super beam	x-section Efficiency Beam	poor	no	yes	Bronze Atmos.					

Some open questions

Facilities

- *Neutrino Factory* and *high γ β-beam* are the best options for osc. physics, but we do not understand yet all the elements, including their cost, feasibility and time scale
- *Low γ β-beam* and improved *Super-Beams* are not separated options, they form a package. Their combined physics reach should be better understood in terms of neutrino fluxes and systematics uncertainties

Detectors

- The different options should be understood at the same level
- Detectors are not yet optimised for all possible θ_{13} values

Systematic errors

- For $\theta_{13}>3^0$ systematic errors dominate for all scenarios
- Can we control them?

THE QUESTION

What is the best realistic scenario one could build in a reasonable time scale (10-15 years) to address CP violation and mass hierarchy ?

Outlook

Physics

- The CP violating phase and the mass hierarchy are crucial elements for the understanding of the leptonic sector
- Next generation neutrino facilities are required to assess these issues

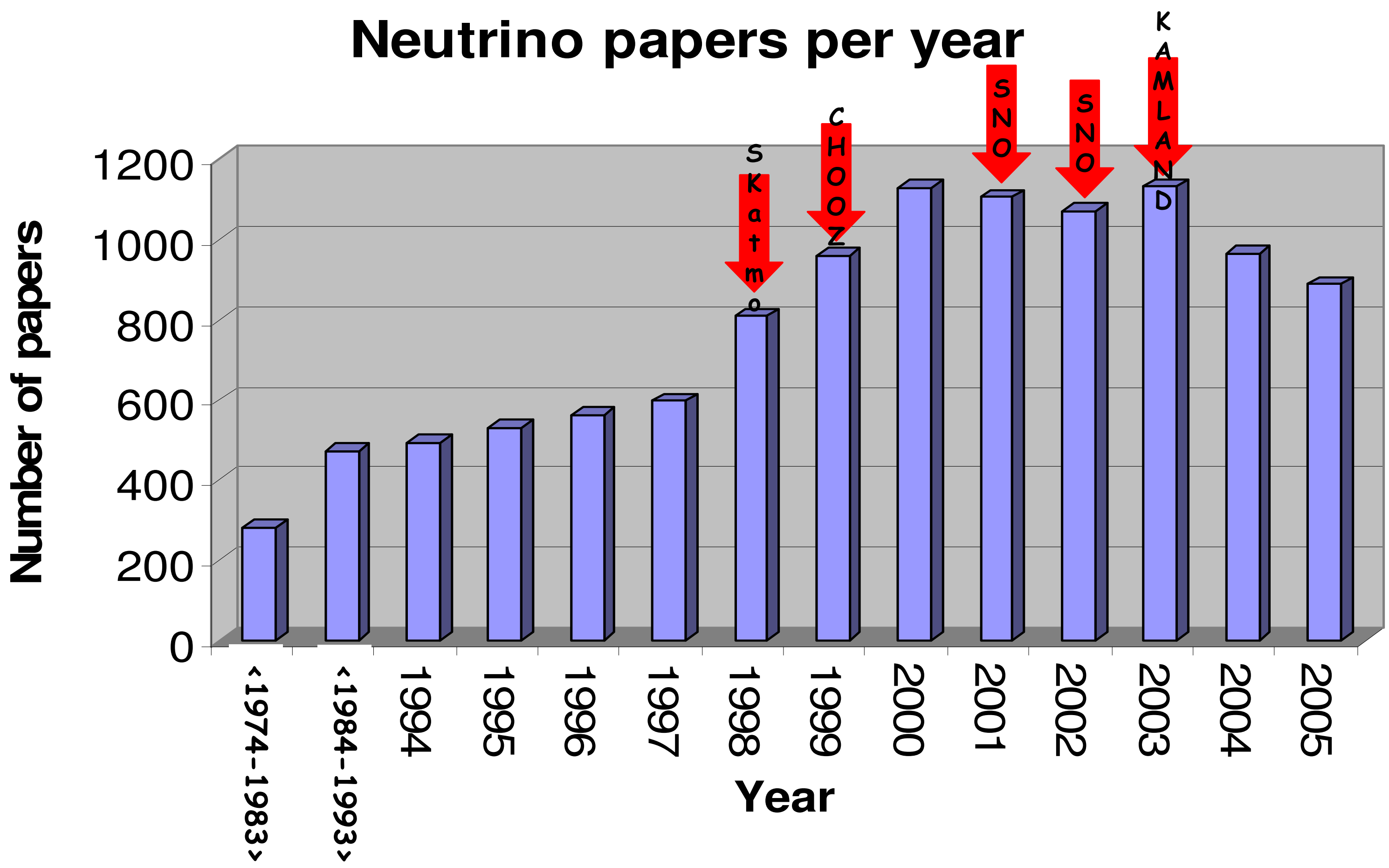
Low γ β-beam + Super-Beam + Megaton detectors	High γ β-beam	Neutrino Factory

Time scale

- We should enter the precision era in the second half of the next decade
- Meanwhile **priority is to perform an "International Design Study"**
  - Conceptual design and realistic cost estimate
  - Hardware R&D on accelerator and detectors

~ G€

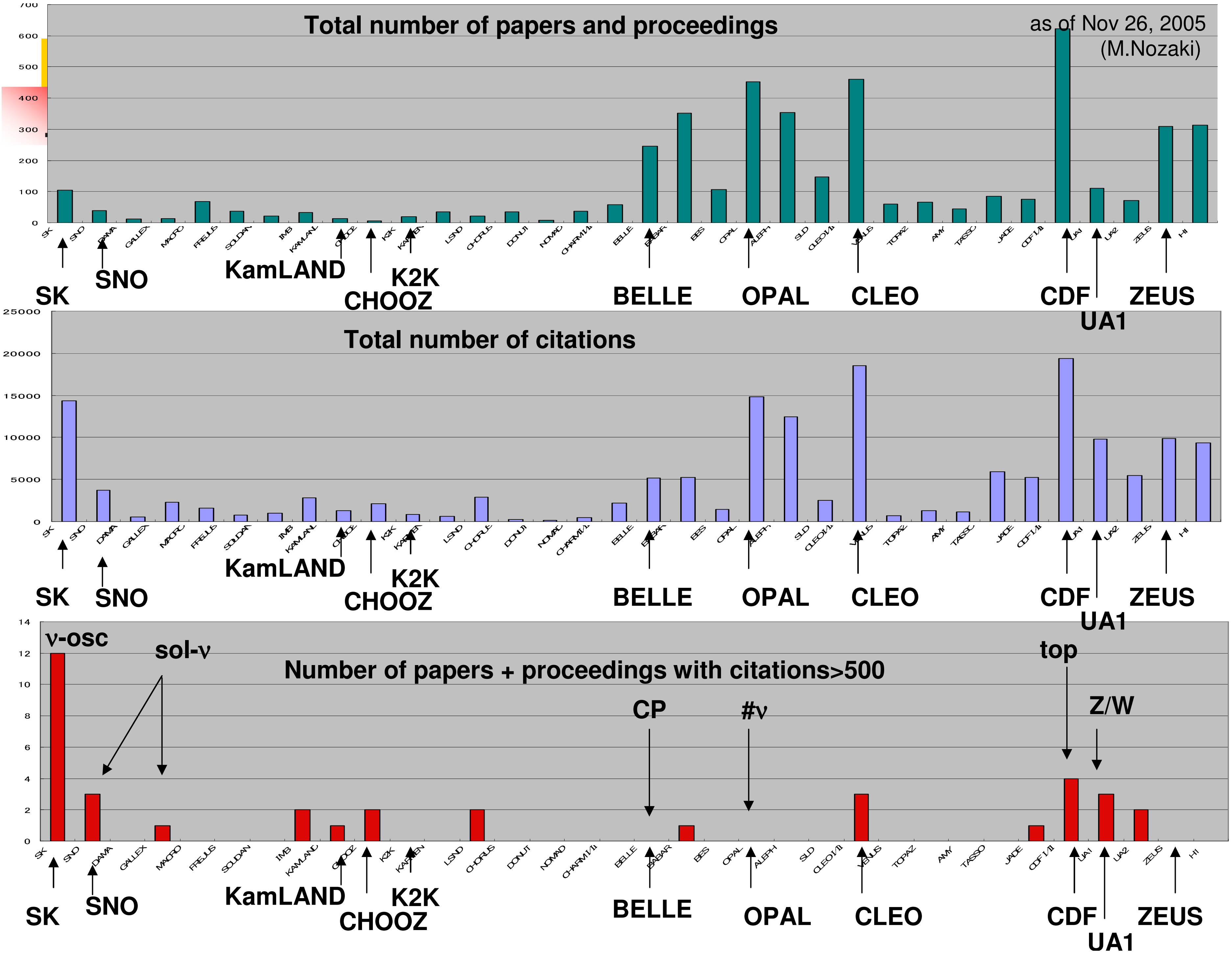
- … in order to be able to compare cost, feasibility and performance
- … to make the best choice by ~2011



In HEP from 1997 on:

19 papers are topcite 1000+ ⇨ 6 (32%) involve neutrinos

73 papers are topcite 500+ ⇨ 16 (22%) involve neutrinos



Total number of papers and proceedings
as of Nov 26, 2005
(M.Nozaki)
SK
SNO
KamLAND
CHOOZ
K2K
BELLE
OPAL
CLEO
CDF
UA1
ZEUS
Total number of citations
SK
SNO
KamLAND
CHOOZ
K2K
BELLE
OPAL
CLEO
CDF
UA1
ZEUS
ν-osc
sol-ν
Number of papers + proceedings with citations>500
CP
#ν
top
Z/W
SK
SNO
KamLAND
CHOOZ
K2K
BELLE
OPAL
CLEO
CDF
UA1
ZEUS

Conclusion

All the places where we have looked for new physics we haven't found anything, but with neutrinos the first searches already were successful - it just took us a long time to believe it. Still, neutrinos are the least known of all fundamental Fermions and therefore even the most exotic things could be just around the corner