Mauro Mezzetto
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" Measuring neutrino mass hierarchy without beams or neutrino telescopes"

Reactor neutrinos and atmospherics in underground detectors

- Introduction
- The θ_{13} saga.
- Detecting neutrinos at Reactors.
- Measuring neutrino mass hierachy at reactors.
- Measuring neutrino mass hierachy with atmospheric neutrinos.

iCal export More

Restricted | Europe/Rome | M. Mezzetto

XV International Workshop on Neutrino Telescopes

Istituto Nazionale di Fisica Nucleare

11-15 March 2013 *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti*

Europe/Rome timezone

my home

Committees

Venue

Logistic

Accommodation

social events

poster session

Registration

Registration Form

List of registrants

Methods of Payment

Sponsor

Support

The "Neutrino Telescopes" is one of the most prestigious international event in the field of Physics. It takes place every two years and dates back to 1988 when Prof. Milla Baldo Ceolin conceived it and launched the first edition. It became soon a crucial event and it is now considered a consolidated appointment where to discuss the latest discoveries and the fascinating future scenarios in topics that range from Neutrinos to Astrophysics and Cosmology.

The program will be structured in plenary sessions with invited talks followed by discussions. There will be also a poster session, aiming at involving particularly, but not limited to, young researchers with new brilliant ideas on the workshop's topics of interest.

The Workshop will take place from March 12th to March 15th, 2013. Registration will open on March 11th. Secretariat desk will be available from 15.00 to 18.00

Leptons are VERY different from quarks. (I)

Neutrinos $U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$

Quarks $V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$

Solar+Atmospherics indicate a quasi bi-maximal mixing matrix, **VERY DIFFERENT from CKM matrix (almost diagonal)!**

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

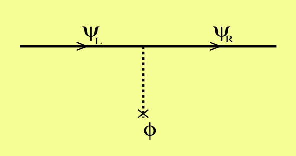
$\theta_{13} \to 0 \quad \Rightarrow \quad$ The 3x3 mixing matrix becomes a trivial product of two 2x2 matrixes.

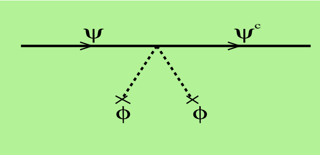
θ_{13} drives $\nu_\mu \to \nu_e$ subleading transitions $\Rightarrow$
the necessary milestone for any subsequent search:
neutrino mass hierarchy and leptonic CP searches.

Leptons are VERY different from quarks. (II)

$u \sim 5$ MeV	$c \sim 1$ GeV	$t \sim 175$GeV	$e \sim 0.5$ MeV	$\mu \sim 0.1$ GeV	$\tau \sim 2$GeV
$d \sim 8$ MeV	$s \sim 0.1$ GeV	$b \sim 5$GeV	$\nu_e \leq \mathcal{O}(1\ eV)$	$\nu_\mu \leq \mathcal{O}(1\ eV)$	$\nu_\tau \leq \mathcal{O}(1\ eV)$

How can the same model generate mass ratio so different?





$$\lambda_\nu \overline{\Psi}_R \Phi \Psi_L + h.c. \qquad m_f = \lambda_f v \qquad L$$

$$\frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c. \qquad m_f = \alpha_\nu \frac{v^2}{M} \qquad \not{L}$$

A new physics scale, M, can explain the new hierarchy (if at the GUT scale) and is associated to the breaking of a global symmetry of the SM: total lepton number L.

Shopping list for future experiments

δm^2_{12} ✓ SOLARS+KAMLAND $\delta m^2_{12} = (7.9 +/- 0.7)\ 10^{-5} eV^2$

θ_{12} ✓ SOLARS+KAMLAND $\sin^2(2\theta_{12}) = 0.82 +/- 0.055$

Addressed by accelerator neutrino experiments

δm^2_{23} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.4 +/- 0.4)\ 10^{-3}\ eV^2$

θ_{23} ✓ ATMOSPHERICS $\sin^2(2\theta_{23}) > 0.95$

θ_{13} ✓ $\sin^2 2\theta_{13} = 0.1$

LSND/Steriles ?

δ_{CP}

Mass hierarchy

Σm_ν BETA DECAY END POINT $\Sigma m_\nu < 6.6$ eV

Dirac/Majorana

θ_{13} measurement is a milestone in HEP

- θ_{13} was one of the few standard model parameters still unknown.
- It is one of the most discriminant parameters to select neutrino mass matrixes, a key ingredient to decide grand unified theories (if any).
- Non-zero θ_{13} is necessary to build-up leptonic CP violation. The value (order of magnitude) of θ_{13} is necessary to optimize new facilities to measure leptonic CP violation.

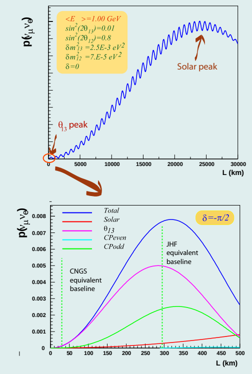
$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1 - 2s_{13}^2)\right] \qquad \theta_{13} \text{ dri}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{CPev}$$

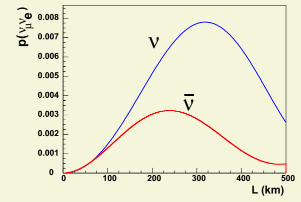
$$\mp 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin^2 \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar drive}$$

$$\mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \qquad \text{matter effect (CP odd)}$$



θ_{13} discovery requires a signal ($\propto \sin^2 2\theta_{13}$) greater than the solar driven probability



Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

Reactors vs Accelerators

Accelerators: ν_e appearance

$$P_{\nu_\mu \to \nu_e} = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2} (1 - 2 s_{13}^2) \right] \qquad \theta_{13} \text{ driven}$$

$$+ 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{CPev}$$

$$\mp 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4 s_{12}^2 c_{13}^2 \{ c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta \} \sin^2 \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

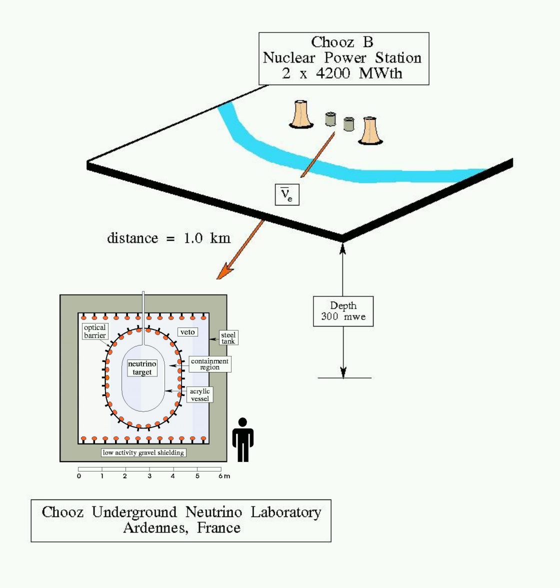
$$\mp 8 c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2 s_{13}^2) \qquad \text{matter effect (CP odd)}$$

Reactors: $\overline{\nu}_e$ disappearance

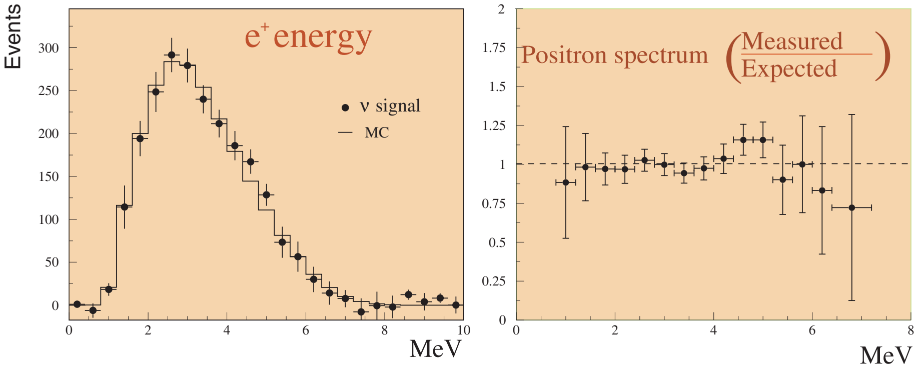
$$1 - P_{\overline{\nu}_e - \overline{\nu}_e} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m_{31}^2 L/4E) + (\Delta m_{21}^2 / \Delta m_{31}^2)^2 (\Delta m_{31}^2 L/4E)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

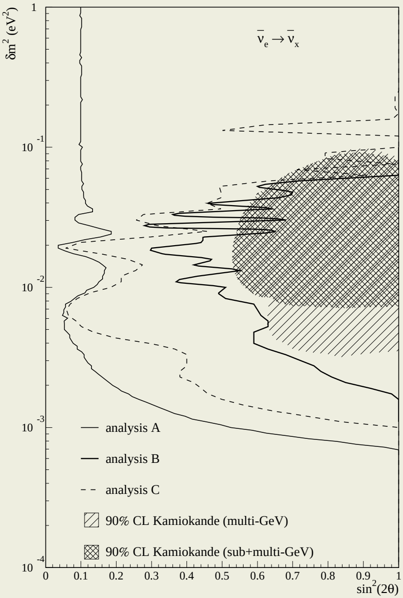
CHOOZ experiment (France-Italy-Russia-USA)

Took data in 1997-98



CHOOZ data

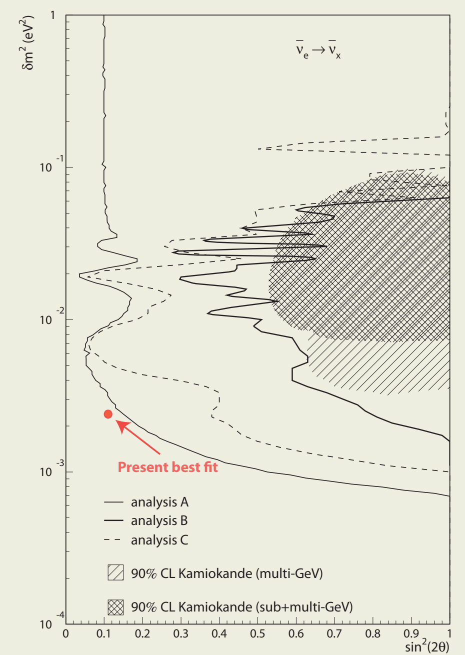

Events
e+ energy
ν signal
MC
MeV
Positron spectrum (Measured / Expected)
MeV



CHOOZ final results

- **Analysis A** $\overline{\nu}_e$ spectrum after background subtraction. Both the absolute rate and the spectrum are used.
- **Analysis B** Uses the different baseline ($\Delta L = 117.7\ m$) of the two reactors. Many systematic errors cancel, but statistical errors are bigger and the Δm^2 sensitivity is reduced by the shorter baseline.
- **Analysis C** Only spectrum information is used.

1450 citations:
the top cited null result in hep ever !



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1998 - 2011

Until 2011 no experiment had been able to improve the Chooz sensitivity.

Even if 3 neutrino oscillation long-baseline projects had been setup in 3 continents:

- **K2K**: KEK to SuperKamiokaNDE: the first check of the discovery of neutrino oscillation in atmospheric neutrinos by using an artificial neutrino beam. The proton intensity was not enough to achieve a competitive sensitivity to θ_{13}.
- **MINOS**: NuMI neutrino beam from Fermilab to the Minos detector. Aimed to improve the precision of the measurement of the atmospheric oscillation parameters θ_{23} and Δm^2_{23}. The iron magnetized Minos detector was not optimized for the detection of electrons. Recently achieved a sensitivity on θ_{13} similar to the CHOOZ sensitivity.
- **CNGS:** CNGS neutrino beam from CERN to the Opera and Icarus detectors at LNGS. The beam setup had been optimized for the ν_τ appearance searches and for this reason was not optimal for θ_{13} searches.

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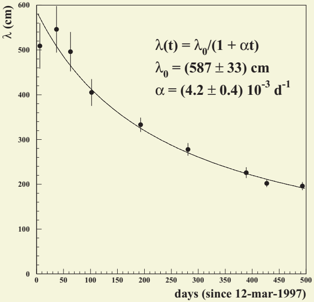

Fig. 26. λ_{Gd} versus time with best-fit function superimposed.

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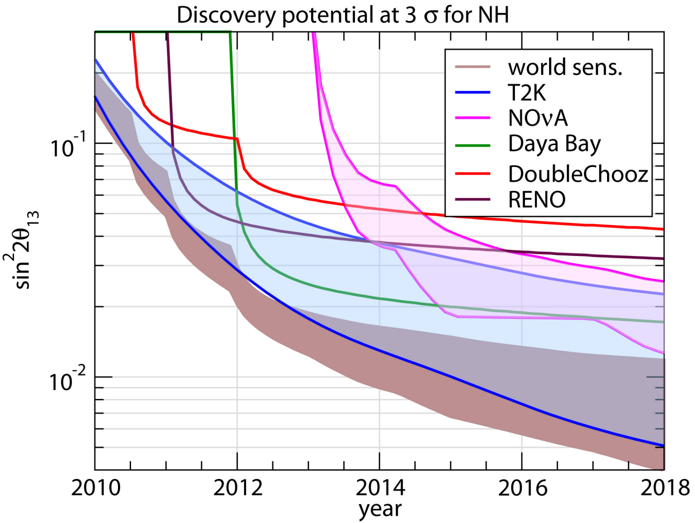
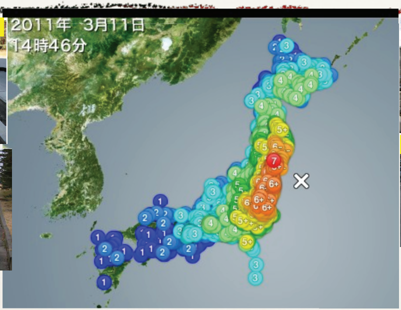
Predictions before exp. results

M.M. and T. Schwetz, J.Phys.G G37 (2010) 103001



The T2K Experiment

T2K/J-PARC recovery after the BIG earthquake in March 11, 2011



09:30 Key was on.

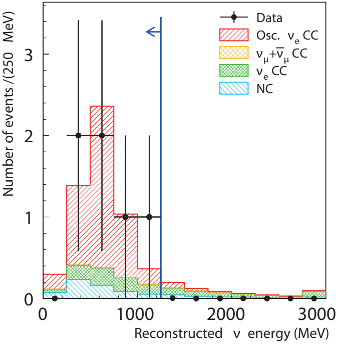
On Dec.9, 2011, J-PARC LINAC operation restarted!!!
On Dec.24, 2011, Neutrino events were observed at T2K-ND280!!

- ***Heartfelt gratitude to the tremendous supports to J-PARC and T2K from all over the world.***

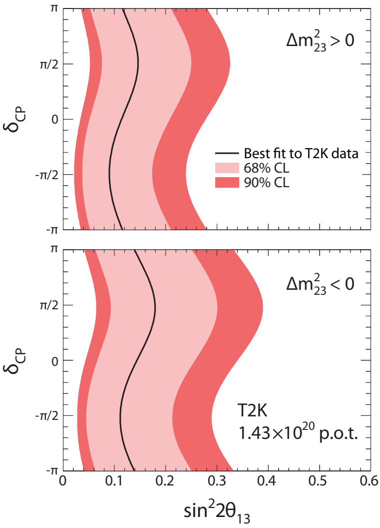
3

12年6月5日火曜日

T2K result, PRL 107 (2011) 041801



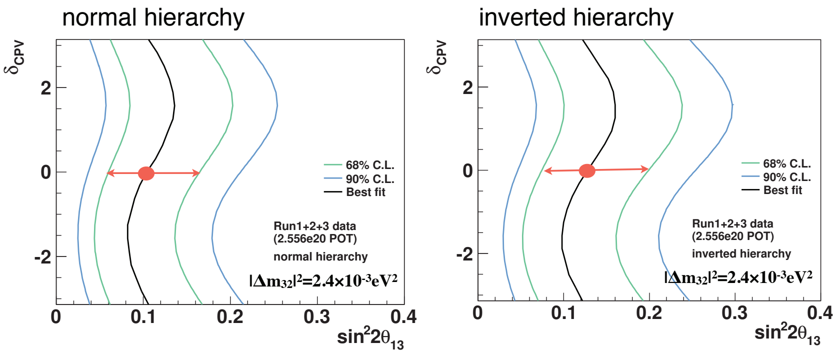
Expected: 1.5 +/- 0.3
Measured: 6



Systematic errors

Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N^{exp}_{SK}/N^{exp}_{SK}$	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Final Results: ν_e appearance evidence at 3.2 σ



$\sin^2 2\theta_{13}=0.104\ ^{+0.060}_{-0.045}$ @$\delta_{CP}=0$ $\sin^2 2\theta_{13}=0.128\ ^{+0.070}_{-0.055}$ @$\delta_{CP}=0$

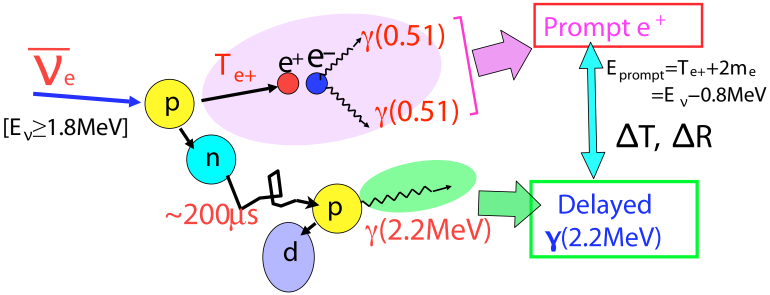
Detecting $\overline{\nu}_e$ in liquid scintillator

prompt positron signal, energy range.

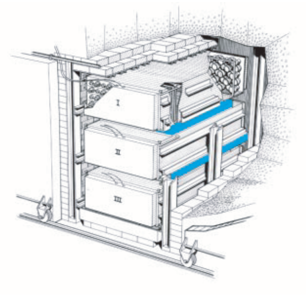
$$\overline{\nu_e} p \rightarrow e^+ n$$

$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma(2.2\ MeV)$$

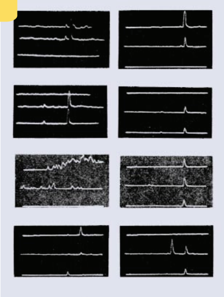
delayed correlated photon.



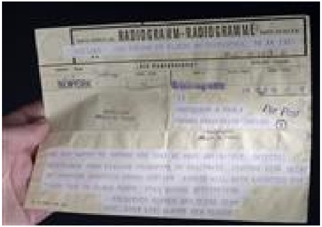
Used by Reines, Cowan et al 1956 to discover neutrinos



Nobel Prize 1995



14/6/1956, cable to 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"



Neutrinos from nuclear reactors

Nuclear reactors are a very intense source of $\overline{\nu}_e$ from β decays of the fission fragments.

Every fission reaction emits about 200 MeV of energy and 6 $\overline{\nu}_e$.

$$\Downarrow$$

Flux $\sim 2 \cdot 10^{20}\ \overline{\nu}_e\ s^{-1}\ \mathrm{GWatt}^{-1}$, isotropic, $\langle E(\overline{\nu}_e)\rangle \simeq 0.5\,MeV$.

Latest oscillation experiments look for $\overline{\nu}_e$ disappearance at different baselines:

- $L = \mathcal{O}(2\mathrm{km})$ $\Rightarrow$ atmospheric regime: Chooz, Double Chooz, Reno, Daya-Bay.
- $L = \mathcal{O}(150\mathrm{km})$ $\Rightarrow$ solar regime: Kamland

Neutrino flux

Detect absolute number of neutrino interaction and distortions of their spectrum

prompt positron signal, energy range.

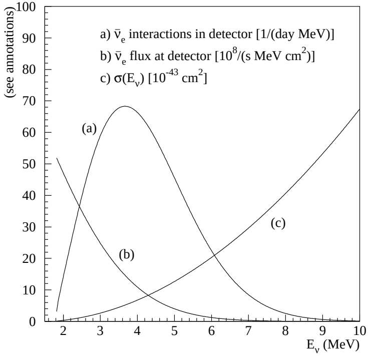
$\overline{\nu_e} p \rightarrow e^+ n$

$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma(2.2\ MeV)$$

delayed correlated photon.

To determine neutrino flux:

1. **Measure of the reactor thermal power**
2. **Determination of the neutrino spectrum**
3. **Definition of the experimental observable: positron momentum spectrum.**

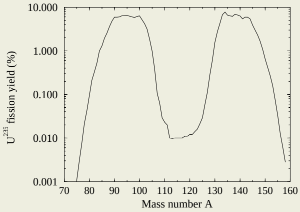


Thermal power of the reactor

The leading reaction is ^{235}U fission:

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

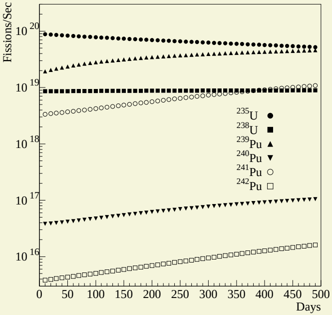
The lightest fragment have on average $A \simeq 94$, the heavier: $A \simeq 140$. Stable nuclei with $A = 94$, 140 are $_{40}Zr^{94}$ e $_{58}Ce^{140}$. ^{235}U has 98 protons and 142 neutrons $\Rightarrow$ to reach the stability, on average it needs 6 neutron β decays $\Rightarrow$ 6 $\overline{\nu}_e$.



The interaction process $\overline{\nu}_e + p \rightarrow n + e^+$ has a threshold of $\sim 1.8\,MeV \Rightarrow$ only $\sim 25\%$ of neutrinos can be detected.

All the neutrinos from low Q-value processes, as nuclear fuel stored in the reactors and radioactivity induced in the nuclear plant structures, don't produce detectable neutrinos.

The fuel composition of the reactor core changes with the time, it's under monitor (reactor power depends from its composition).



From fission rate to the $\overline{\nu}_e$ spectrum

The $\overline{\nu}_e$ spectrum of three of the four principal fission nuclei: (^{235}U, ^{239}Pu, ^{241}Pu), has been derived by measuring the electron spectrum. The fourth: ^{238}U, has been computed from nuclear models, as well all the processes in the decay chain. Systematic error: $\sim 1\%$.

From $\overline{\nu}_e$ to positrons

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

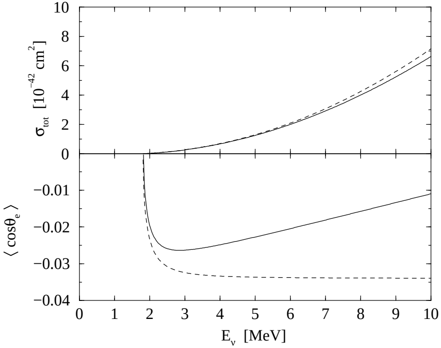
$$\sigma_{tot}^{(0)} = \sigma_0 \, (f^2 + 3g^2) \, E_e^{(0)} p_e^{(0)} = 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1 \ \mathrm{MeV}^2} \right) \times 10^{-42} \ \mathrm{cm}^2 \qquad (1)$$

$E_e^{(0)} = E_\nu - (M_n - M_p)$: positron energy (neglecting neutron recoil, marginal effect) $p_e^{(0)}$ momentum,

$f = 1, g = 1.26$ vector and axial coupling constants

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R) \ , \qquad (2)$$

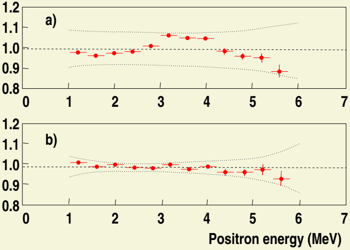
radiative corrections: $\Delta_{inner}^R \simeq 0.024$.



Solid lines: predictions at $\mathcal{O}(1/M_n)$, dashed $\mathcal{O}(1)$.

Experiment Bugey 3 (years 80', the very recent reanalysis of reactor antineutrino flux yields interprets its result as a $\sim$ 3% deficit): expected and measured $\overline{\nu}_e$ spectrum.

Curve b) is the most updated prediction.



Systematic errors summary (from `hep-ph/0107277`) Origin and magnitude of systematic errors in PALO VERDE and CHOOZ. Note that the two experiments offer different breakdowns of their systematics. For simplicity we do not show the systematics for the PALO VERDE ON-OFF analysis. The PALO VERDE results are from the analysis of the full data set (Boehm *et al.* 2001).

Systematic	CHOOZ (%)	P.V. (%)
$\sigma(\overline{\nu}_e + p \to n + e^+)$	1.9	-
Number of p in target	0.8	-
W_{th}	0.7	-
Energy abs. per fission	0.6	-
Total rate prediction	2.3	2.1
e^+ trigger eff.	-	2.0
n trigger eff.	-	2.1
$\overline{\nu}_e$ selection cuts	-	2.1
$(1-\epsilon_1)B_{pn}$ estimate	-	3.3
Total $\overline{\nu}_e$ efficiency	1.5	4.9
Total	2.7	5.3

ν spectrum emitted by a reactor

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector reactor neutrino experiments

Reactor data

Thermal power, $\delta P_{th} \leq 1\%$

Reactor evolution codes

Fraction of fissions from isotope k, δa_k=few % but large anti-correl @ fixed P_{th}

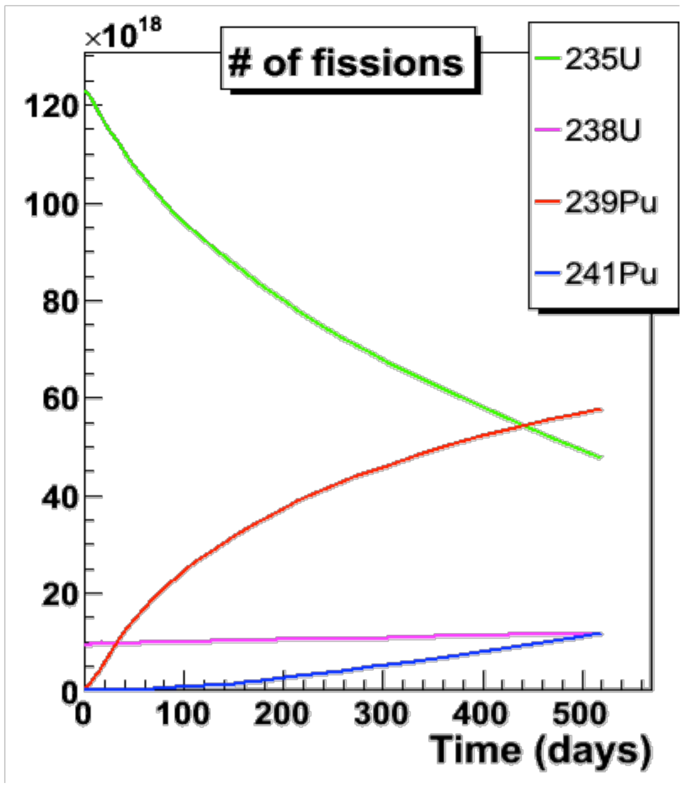
$$\Phi_{\nu}(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

Nuclear databases

E released per fissions of isotope k, $\delta E_k \approx 0.3\%$

ν spectrum per fission
This work !

$k = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$



The guts of $S_k(E)$

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branch of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

Theory of β-decay

$$S^b_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

$$\times \underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

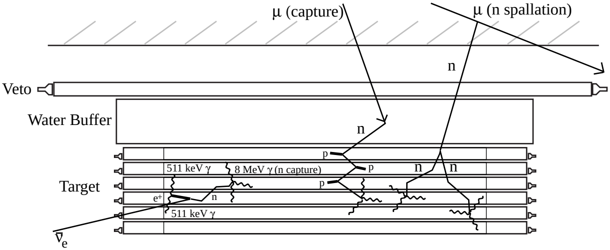
$$\delta^b_{fp}(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

Complementary approaches to compute the ν flux

	Ab initio	**Integral measurements**
Sum of all fission products' activities	fission product inventory (t)	fission rates (t)
	• Fission Yields (JEFF, ENDF, JENDL) • Life time	
Sum of all β-branches of each fission product	Build total spectrum from sum of β-branches	Reference spectrum per isotope
Theory of β-decay	• Complete β-decays schemes (ENSDF) • β-strength (Greenwood et al.) • Total β spectrum per nucleus (Rudstam et al.) • Masses (Q_b) • Nuclear models …	• ILL electron data

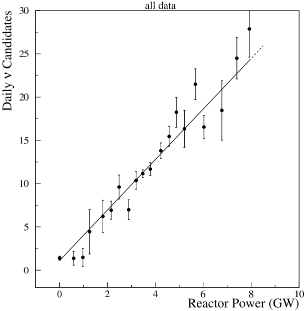
Full ab-inito — **Our mixed approach** — **Effective**

Experimental backgrounds



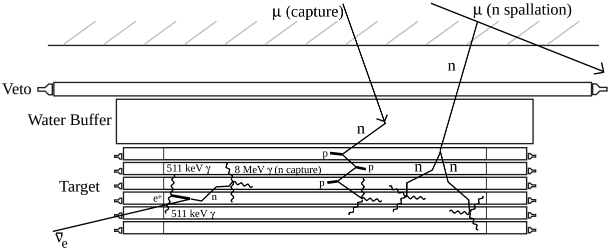
Two main categories:

- Accidental backgrounds from the random superposition of a “positron-like" and “neutron-like" signals. Directly estimated from the measured rates of the two processes.
- Backgrounds from neutrons induced by cosmic rays. They can be measured only if the reactor is off (impossible to pay to have a reactor shutdown).



Chooz counting rate as function of the reactors power.

Experimental backgrounds



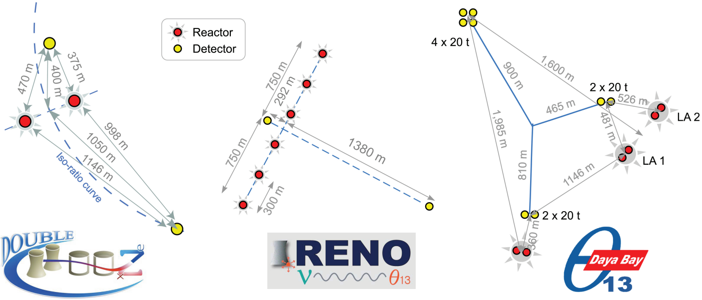
"The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos.
Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it.
We did record neutrino-like signals but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals.
We felt we had the neutrino by the cottails, but our evidence would not stand up in count."
Reines and Cowan, first trial at Savannah River

Two main categories:

- Accidental backgrounds from the random superposition of a “positron-like" and “neutron-like" signals. Directly estimated from the measured rates of the two processes.
- Backgrounds from neutrons induced by cosmic rays. They can be measured only if the reactor is off (impossible to pay to have a reactor shutdown).

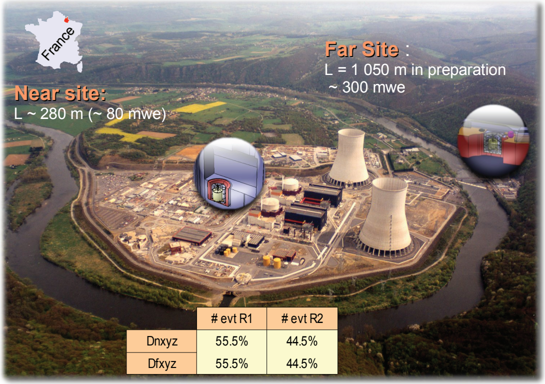
The three reactor players

Setup	P_{Th} [GW]	L [m]	m_{Det} [t]	Events/year	Backgrounds/day
Daya Bay	17.4	1700	80	$10 \cdot 10^4$	0.4
Double Chooz	8.6	1050	8.3	$1.5 \cdot 10^4$	3.6
RENO	16.4	1400	15.4	$3 \cdot 10^4$	2.6



Double Chooz

Talk by J. Dawson



	# evt R1	# evt R2
Dnxyz	55.5%	44.5%
Dfxyz	55.5%	44.5%

2 cores – 1 site – 8.5 GW_{th}

1 near position, 1 far

- target: 2 x 8.3 t

Civil engineering

- 1 near lab ~ Depth 40 m, Ø 6 m
- 1 available lab

Statistics (including ε)

- far: ~ 40 evts/day
- near: ~ 460 evts/day

Systematics

- reactor : ~ 0.2%
- detector : ~ 0.5%

Backgrounds

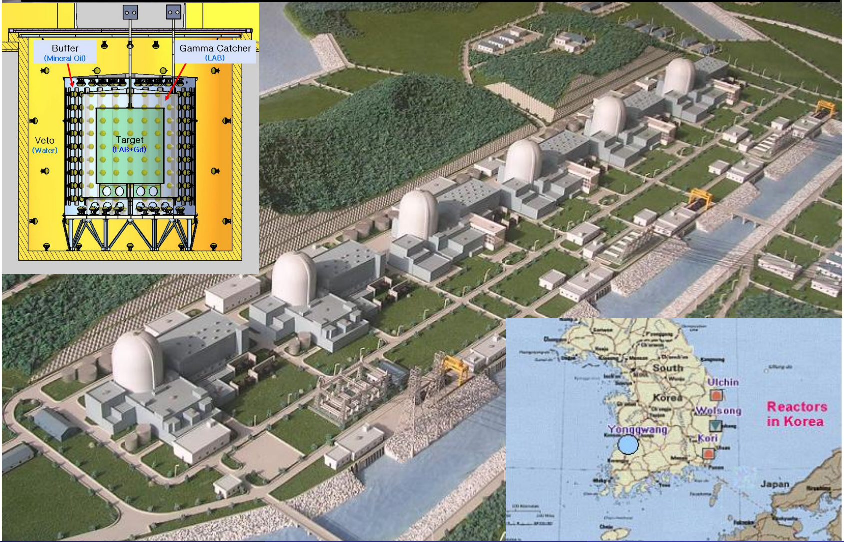
- σ_{b2b} at far site: ~ 1%
- σ_{b2b} at near site: ~ 0.5%

Planning

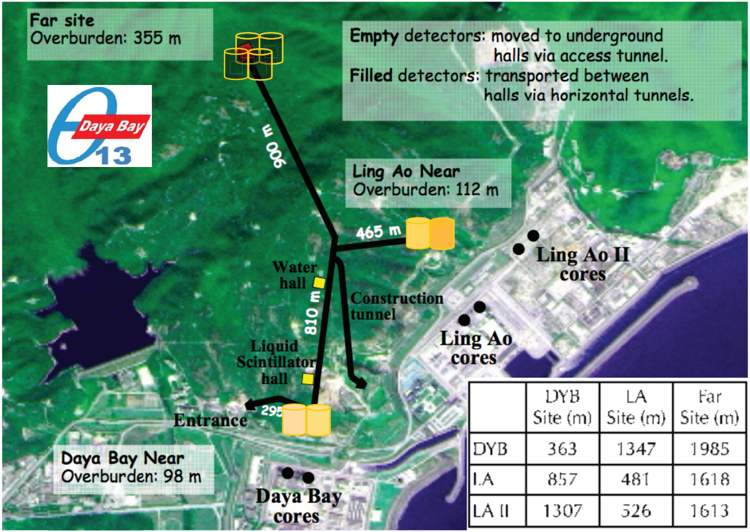
1. Far detector only
   - Sensitivity (1.5 ans) ~ 0.06
2. Far + Near sites
   - available from 2010
   - Sensitivity (3 years) ~ 0.025

RENO

	Location	Thermal Power	Distances Near/Far (m)	Depth (mwe)	Target Mass (tons)	Cost
RENO	Korea	17.3 GW	290/1380	120/450	16/16 ton	~10M$

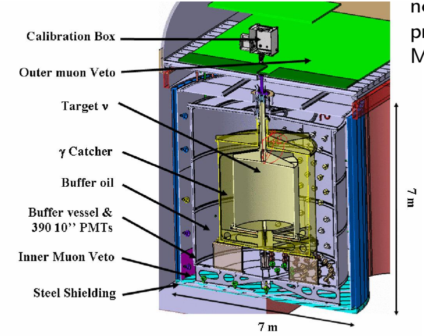


Daya Bay



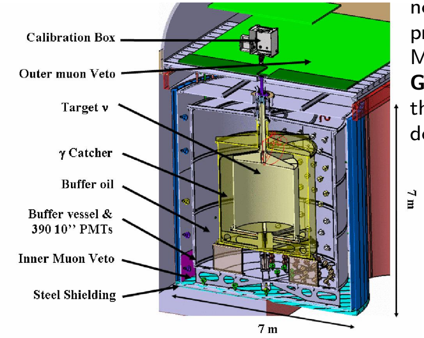
	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Design of a reactor neutrino detector



Inner detector Liquid scintillator doped with Gadolinium (0.1%) in a acrylic vessel. Gadolinium increases neutron capture cross section, reducing capture time from $\sim$ 170 μs to $\sim$ 27 μs $\Rightarrow$ with a reduction of not-correlated noise. Furthermore it increases the energy of the γs produced by the neutron capture, from $\sim$ 2 MeV to $\sim$ 8 MeV.

Design of a reactor neutrino detector



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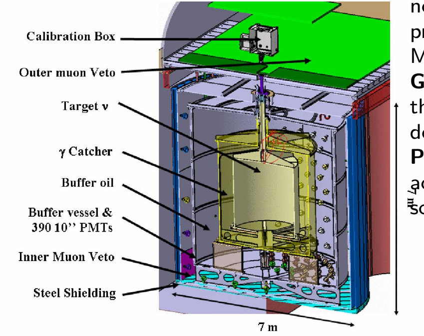
Gamma catcher: Not doped liquid scintillator to capture the γs emitted by the neutron capture. It allows a better definition of the fiducial volume.

Design of a reactor neutrino detector



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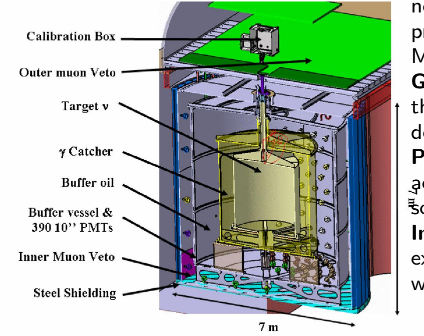
Phototubes shield: Not scintillating oil to separate the active volume from the phototubes, the most important source of radioactivity in the detector.

Design of a reactor neutrino detector



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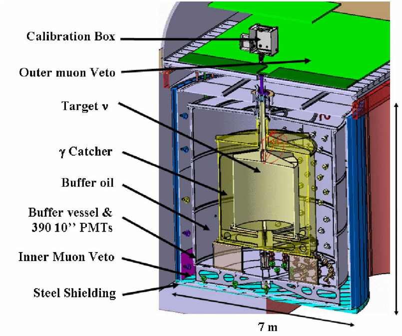
Gamma catcher: Not doped liquid scintillator to capture the γs emitted by the neutron capture. It allows a better definition of the fiducial volume.

Phototubes shield: Not scintillating oil to separate the active volume from the phototubes, the most important source of radioactivity in the detector.

Inner veto: To shield against Comptons induced by external radioactivity and by crossing muons. Equipped with phototubes.

Design of a reactor neutrino detector



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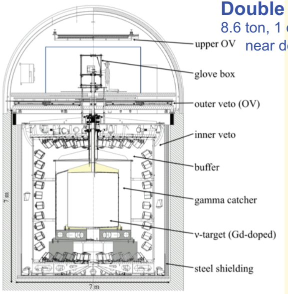
Inner veto: To shield against Comptons induced by external radioactivity and by crossing muons. Equipped with phototubes.

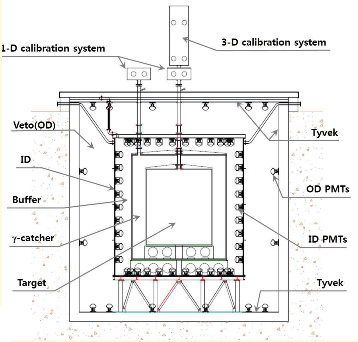
Outer veto: To veto crossing muons. It is required a minimum 100 m.w.e depth to keep dead times below 25%. Some ions produced by μs: ^{8}He and ^{9}Li, withd decaying times of 119 ms and 174 ms cannot be vetoed anyway.

Reactor detectors



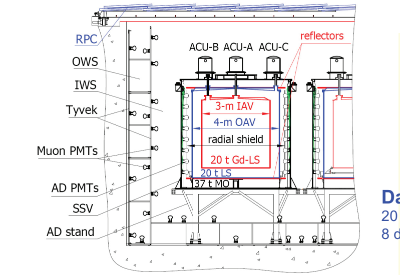
Double Chooz

8.6 ton, 1 detector (far)
near detector by 2013



RENO

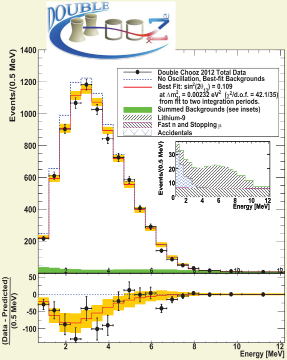
16 ton, 2 detectors (near + far)

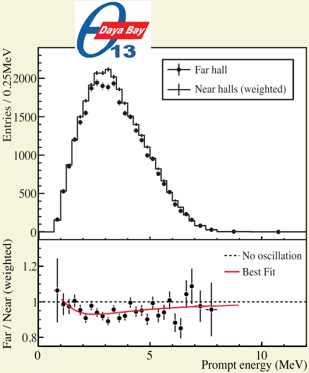


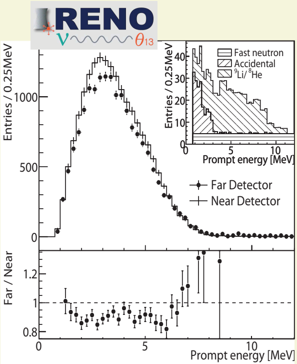
Daya Bay

20 ton, 6 detectors (3 far, 3 near)
8 detectors by 2013 (4+4)

Experimental Results







$\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

R=0.944 +/- 0.007 (stat) +/- 0.003 (syst)

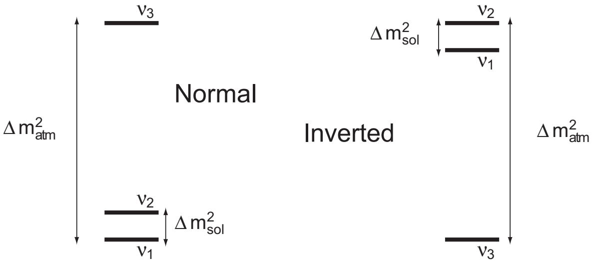
$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

R=0.920 +/- 0.009 (stat) +/- 0.014 (syst)

$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$

Mass hierarchy

An internal degree of freedom of neutrino masses is the sign of Δm^2_{31}: $\mathrm{sign}(\Delta m^2_{13})$.



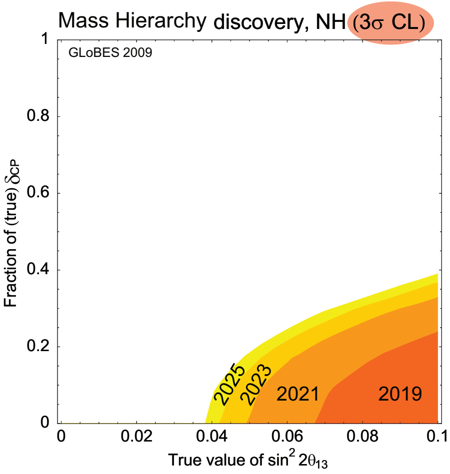
This parameter decides how mass eigenstates are coupled to flavor eigenstates with important consequences to direct neutrino mass and double beta decay experiments.

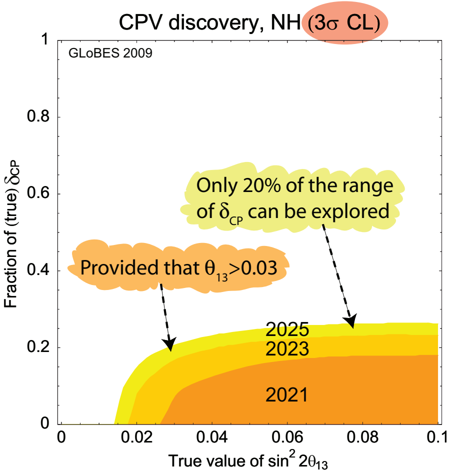
Large θ_{13} allows mass hierarchy searches using reactor and atmospheric neutrinos (accelerator neutrinos could measure MH even at small θ_{13}).

Status after accelerator upgrades

From P. Huber et al., JHEP 0911:044,2009.

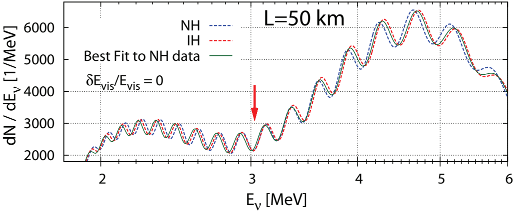
Prediction of sensitivity including a **fully optimized global run** (antineutrinos in T2K and NOνA) and **full upgrade of the accelerators**: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)





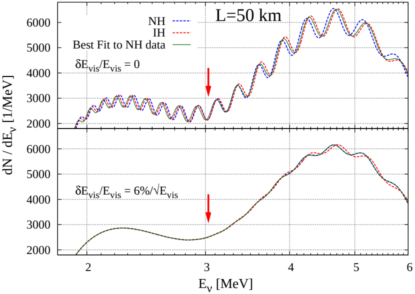
MH at reactors

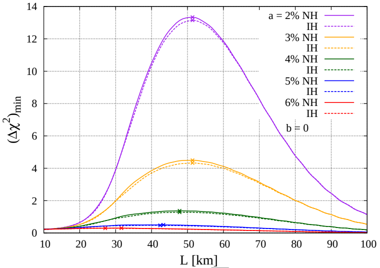
$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm\frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$



- The MH term $\propto \Delta m^2_{12}$, this explains why the 50 km baseline
- The MH term $\propto \sin^2 2\theta_{13}$ this explains why the interest on this technique revamped after the T2K result
- The MH term goes to zero at the max solar probability and changes sign crossing the zero point. An important feature for the MH fits
- Note the the mass hierarchy has just two possible, known values, +/- 1, this implies that the gaussian statistic is not adequate to discriminate among the two values (see arXiv:1210.3651)

MH at reactors:experimental challenges



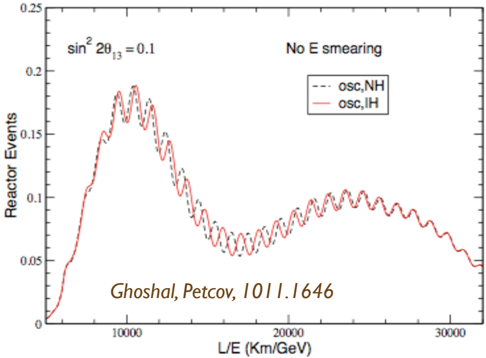


- Requires excellent energy resolution to keep the wiggles, goal: $3\%\sqrt{E}$: 2 × Kamland
- Requires excellent linearity: goal 0.1% 10 × Kamland
- Requires statistics: 20 kton liquid scintillator detector, 10 × Kamland
- "Far" reactors can spoil the wiggles, the effective optimal baseline is shorter than the optimal baseline according to oscillations (to increase the signal/noise ratio)
- Background rates induced by cosmics are more dangerous than Daya-Bay-I (longer distance from reactors), not too shallow depth mandatory.
- The distance of the detector from the reactors must be uniform (the wiggles correspond to 1 km baseline), not too much freedom on the choice of the location of the far detector

Hierarchy from a reactor experiment

Petcov, Piai, hep-ph/0112074

$\overline{\nu}_e$ disappearance at intermediate baseline (40~60 km)
interference term between solar and atmospheric oscillations

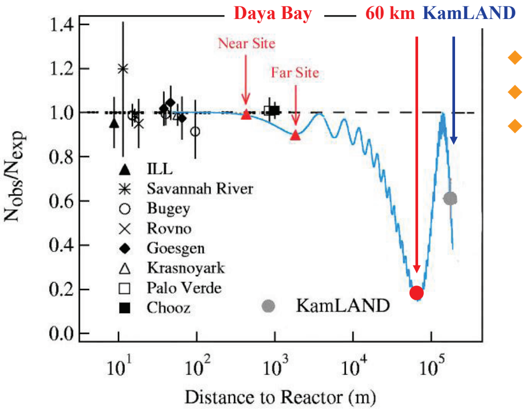


T. Schwetz

30

Daya Bay-II Experiment

Giant Detector located at 60 km from Daya Bay reactors, the 1st maximum of θ_{12} oscillation.



- **20 kton detector**
- **3% energy resolution**
- Rich physics possibilities
  - **Mass hierarchy**
  - **Precision measurement of 4 mixing parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Sterile neutrino**
  - **Abnormal magnetic moment**
  - **Possible CPV**

A Slide at NuTel 2009, Venice

We may not afford larger detector

If $\sin^2 2\theta_{13}$ is large

A **10k ton detector** at 60km, with **3%/sqrt(E)** energy resolution, can determine the mass hierarchy to 90% C.L. in 5 years.

still

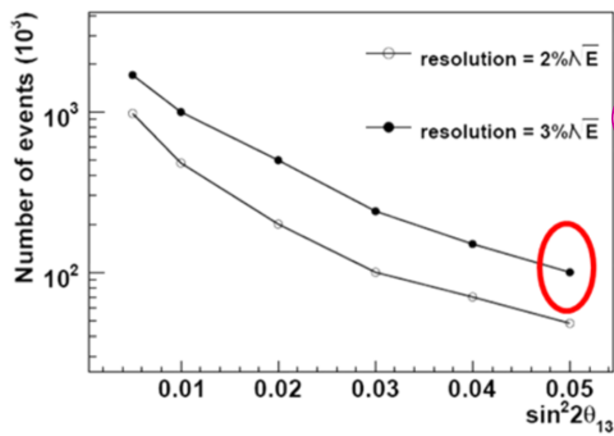


FIG. 6: Requirements to the number of events to determine the mass hierarchy at 90% probability as a function of $\sin^2(2\theta_{13})$.

[arXiv:0901.2976]

Each point represents 500 simulated Exp.

100k events = 10k ton • (2.9GWx8) • (300 days x 5) / (60 km)^2

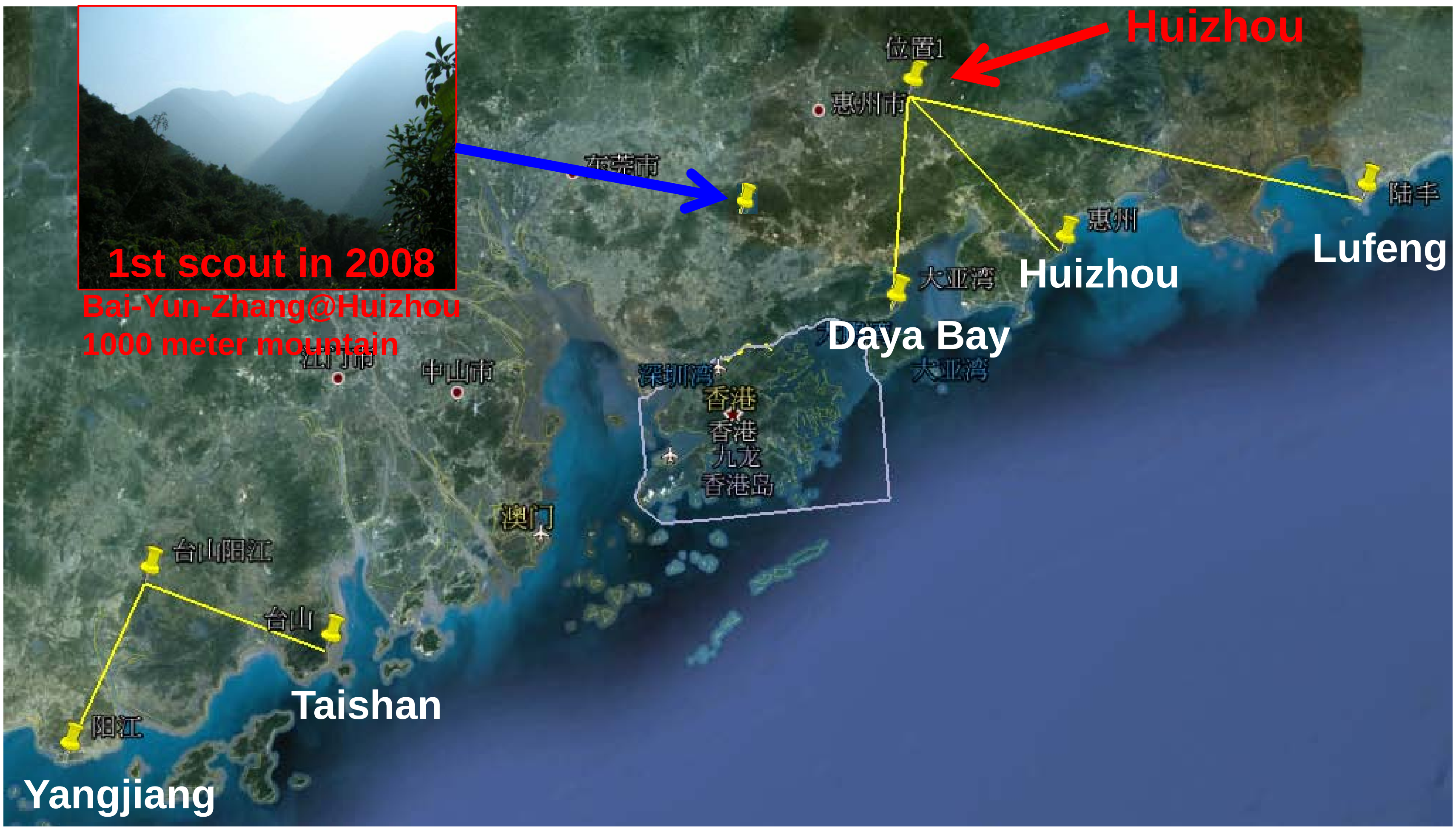
If we are lucky, $\sin^2 2\theta_{13}$ may be as large as 0.05

In general, neutrino exps were not precise.

8 cores planned @DYB

The reactors and possible sites

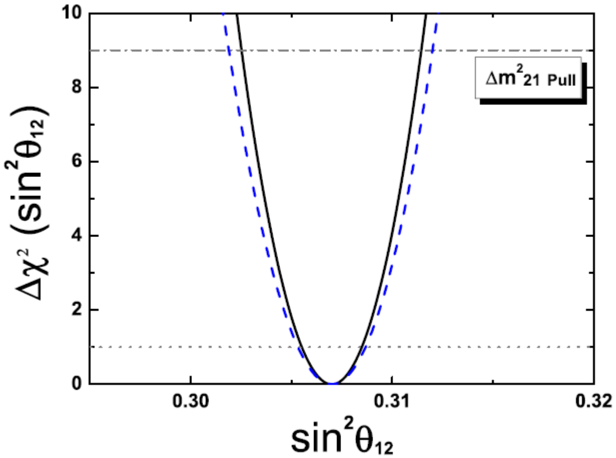
	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

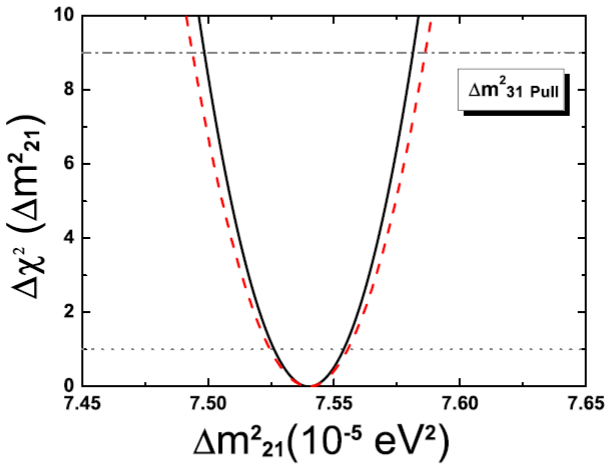


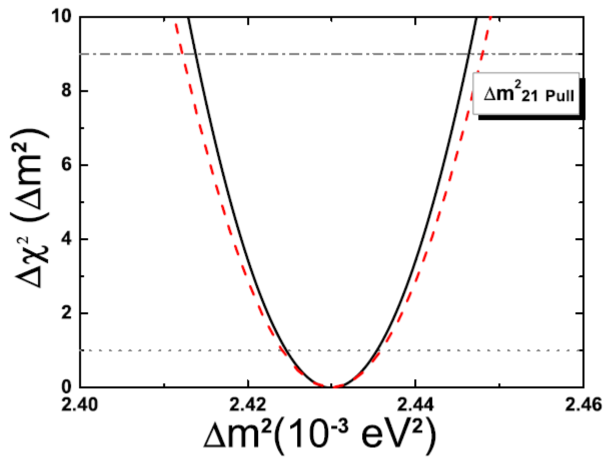
Precision Measurements

- **Fundamental to the Standard Model and beyond**
- **Probing the unitarity of U_{PMNS} to ~1% level !**

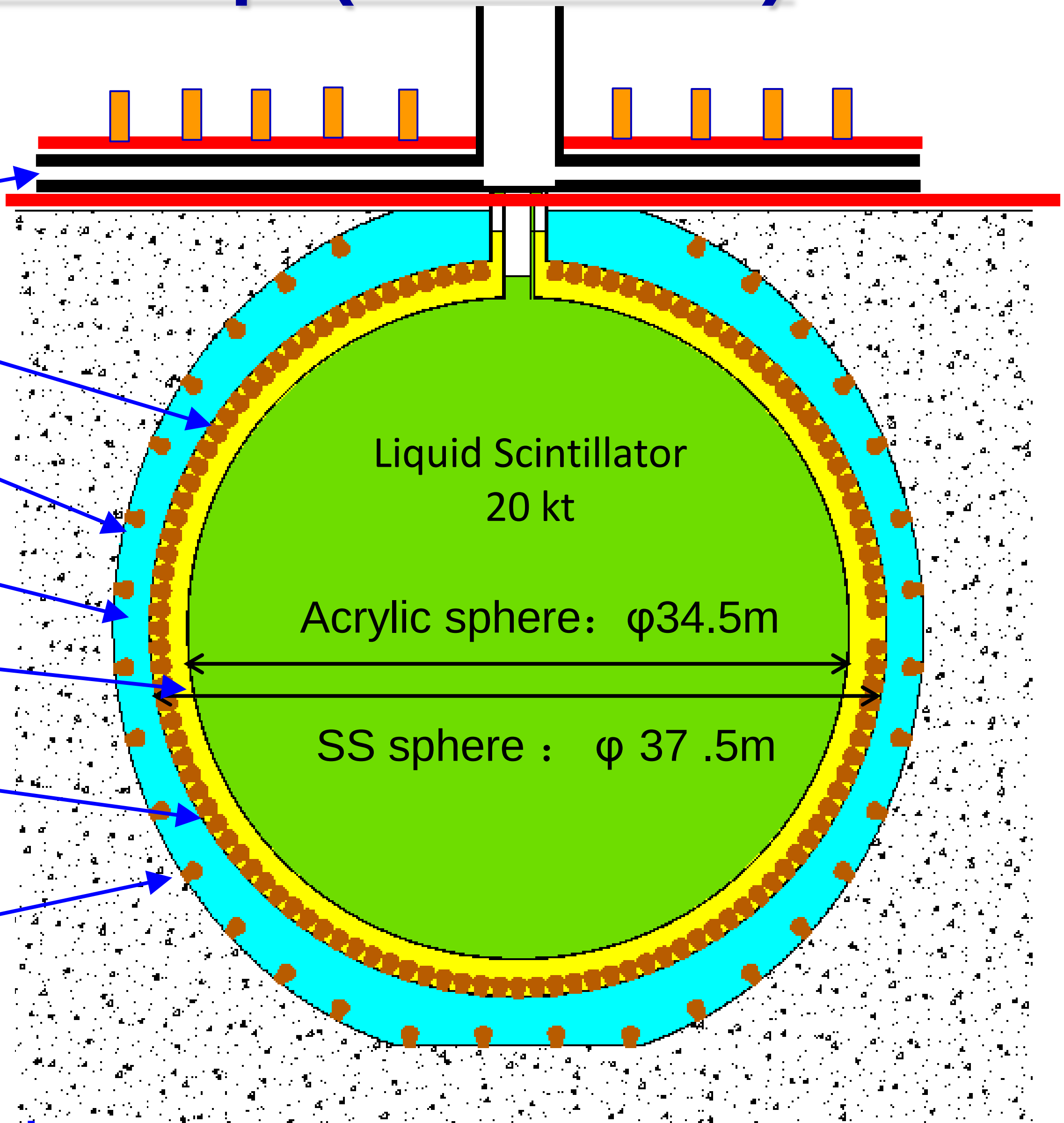
	Current	Daya Bay II
Δm^2_{12}	3%	0.26%
Δm^2_{23}	5%	0.30%
$\sin^2\theta_{12}$	6%	0.63%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14% ➔ 4%	~ 15%







Detector Concept (Traditional)



Alternate: acrylic -> ballon
Alternate: acrylic -> PET sphere

Summary

- **The large θ_{13} discovery accelerates the experiments on mass hierarchy and CP phase.**
- **Daya Bay II proposed in 2008-2009, now boosted by the large θ_{13}**
  - ⇨ **Science case is strong with significant technical challenges**
  - ⇨ **Very rich physics.**
  - ⇨ **Funding are promising.**
  - ⇨ **Possible time schedule:**
    - Proposal to government: 2015
    - Construction: 2016-2020

Thanks many colleagues for providing slides and materials

THREE-FLAVOR EFFECTS IN ATMOSPHERIC NEUTRINOS

- *Incomplete list of the literature:*

Petcov (1998), Chizov, Maris, Petcov (1998), Akhmedov (1999),Akhmedov,Dighe,Lipari,Smirnov (1999),Kim (1998),Peres,Smirnov(1999),Bernabeu, Palomares-Ruiz, Perez, Petcov, (2002), Gonzalez-Garcia, Maltoni (2003), Bernabeu, Palomares-Ruiz, Petcov (2003), Peres, Smirnov (2004), Indumathi, Murthy (2004), Gandhi, Ghoshal, Goswami, Mehta, Sankar (2004), Gonzalez-Garcia, Maltoni, Smirnov (2004), Palomares-Ruiz, Petcov (2005), Choubey, Roy (2005), Fogli, Lisi, Marrone, Palazzo (2005); Huber, Maltoni, Schwetz (2005), T. Kajita (2005); E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2005), Petcov, Schwetz (2006), S. Choubey (2006); Indumathi, Murthy, Rajasekaran, Sinha (2006), E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2007), R. Gandhi, P. Ghoshal, S. Goswami, P. Mehta, S. U. Sankar and S. Shalgar (2007), E. K. Akhmedov, M. Maltoni and A. Y. Smirnov (2008), Gandhi, Ghoshal, Goswami, Sankar (2008), Mena, Mocioiu, Razzaque (2008), Peres, Smirnov (2009), Gandhi, Ghoshal, Goswami, Sankar (2009), Samanta (2006 - 10), Samanta, Smirnov (2010), Conrad, de Gouvea, Shalgar (2010), Gonzalez-Garcia, Maltoni, Salvado (2011), Barger, Gandhi, Ghoshal, Goswami, Marfatia, Prakash, Raut, Sankar (2012), Blennow, Schwetz (2012), Akhmedov, Razzaque, Smirnov (2012), ...

- *My apologies if your name is missing here -*

Monolith

CERN-SPSC-2001-019, CERN-SPSC-M-657

See also T. Tabarelli de Fatis: "Prospects of measuring $sin^2 2\theta_{13}$ and the sign of iΔm^2 with a massive magnetized detector for atmospheric neutrinos." Eur.Eur.Phys.J. C24 (2002) 43-50

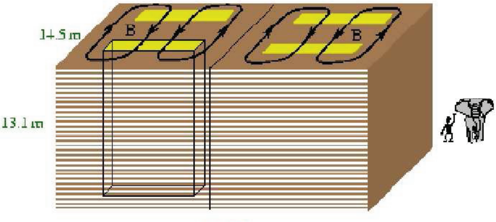
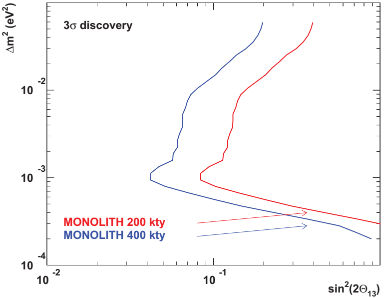
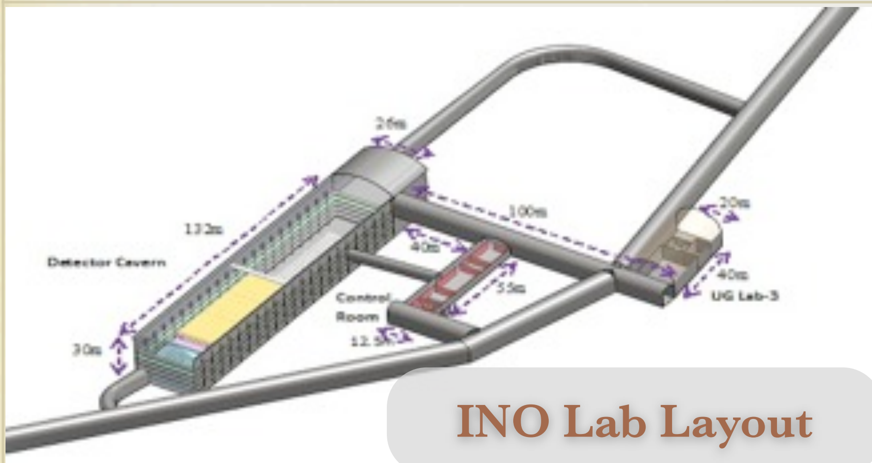


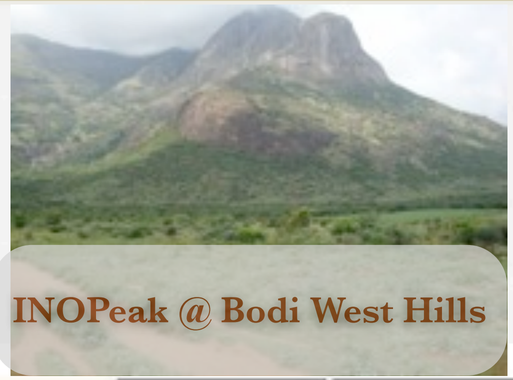
Fig. 3. Schematic view of the MONOLITH detector. The arrangement of the magnetic field is also shown.



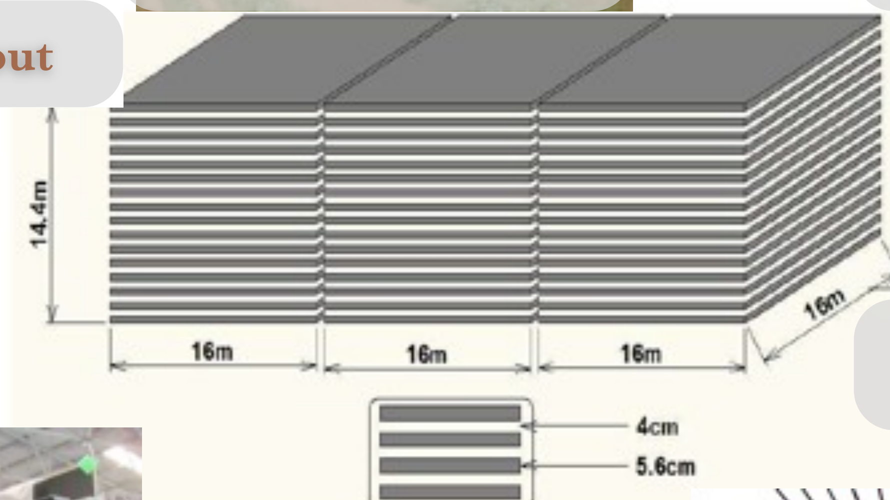
INDIA-BASED NEUTRINO OBSERVATORY (INO)



INO Lab Layout


INOPeak @ Bodi West Hills

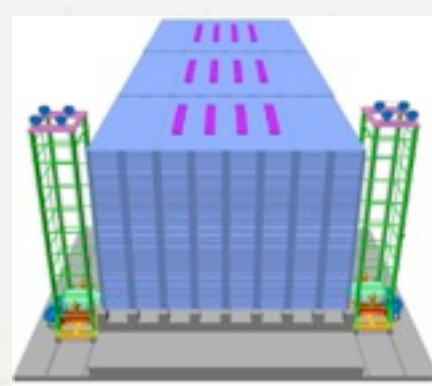

RPC Test stand at TIFR

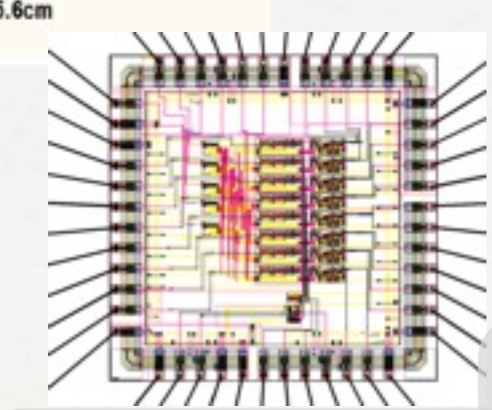



Prototype ICAL at VECC


RPC fabrication at TIFR


RPC fabrication at Asahi Glass Co.



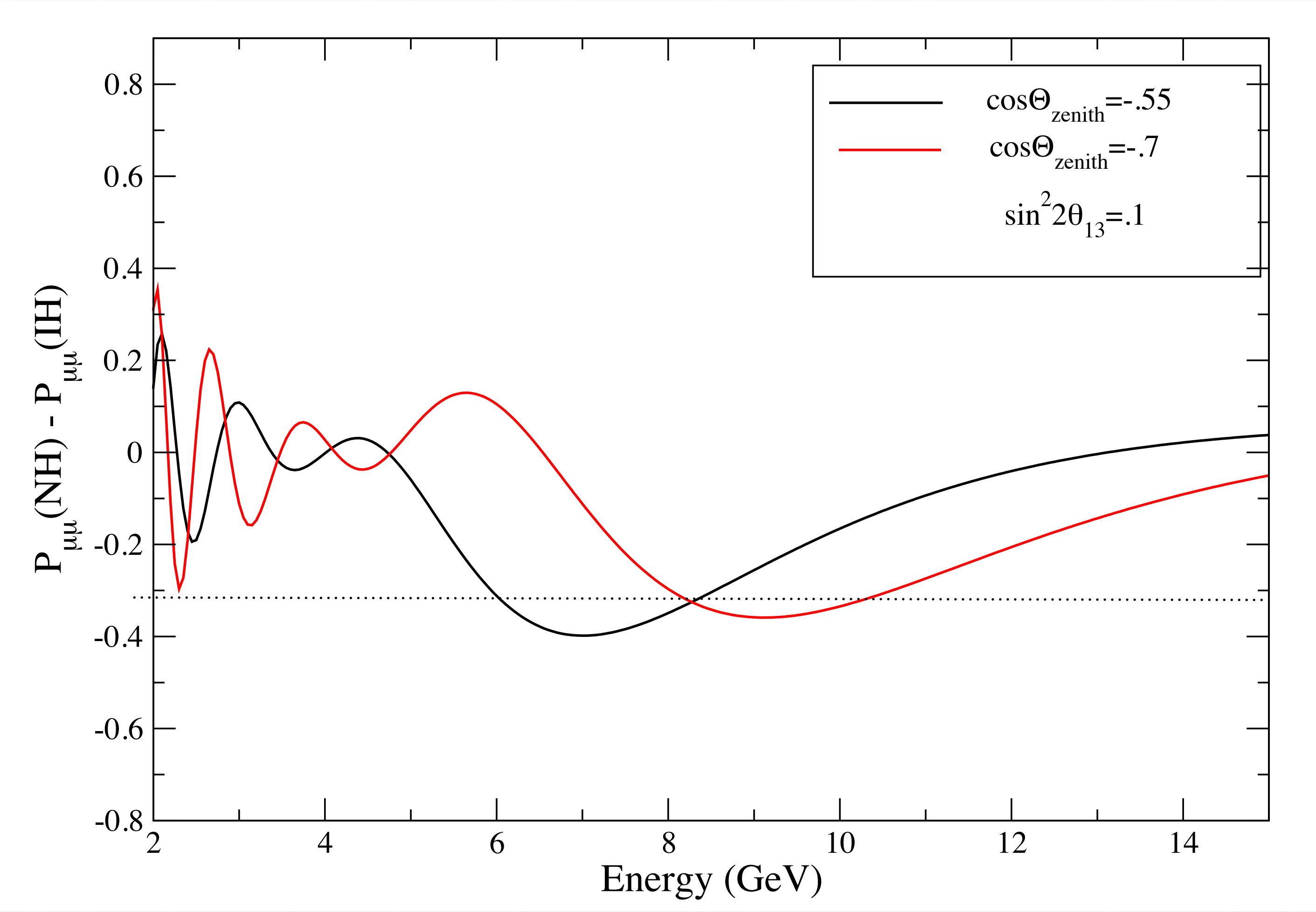

ASIC for RPC designed at BARC


2mx2m RPC stand at TIFR

PERT CHART

SN	Description of work	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17
	Civil work at Pottipuram						
1	Land acquisition and pre-project work						
2	Architectural and Engineering consultancy						
3	Tendering and award of contracts						
4	Mining of access portal						
5	Excavation of tunnel						
6	Excavation of caverns						
7	Installation of services, cranes, lifts etc.						
8	Civil work for magnet support bed						
9	Surface facilities						
	Magnet						
10	Procurement of steel plates						
11	Machining job for steel plates						
12	Transportation of machined plates at site						
13	Procurement of copper coils						
14	Assembly/erection of magnet (3 modules)						
	RPC						
15	Finalization of all design details, tendering						
16	Procurement of components						
17	Fabrication and assembly of 30000 pcs						
18	Transportation to site and tests						
19	Procurement of electronics, gas handling						
20	Installation and commissioning						

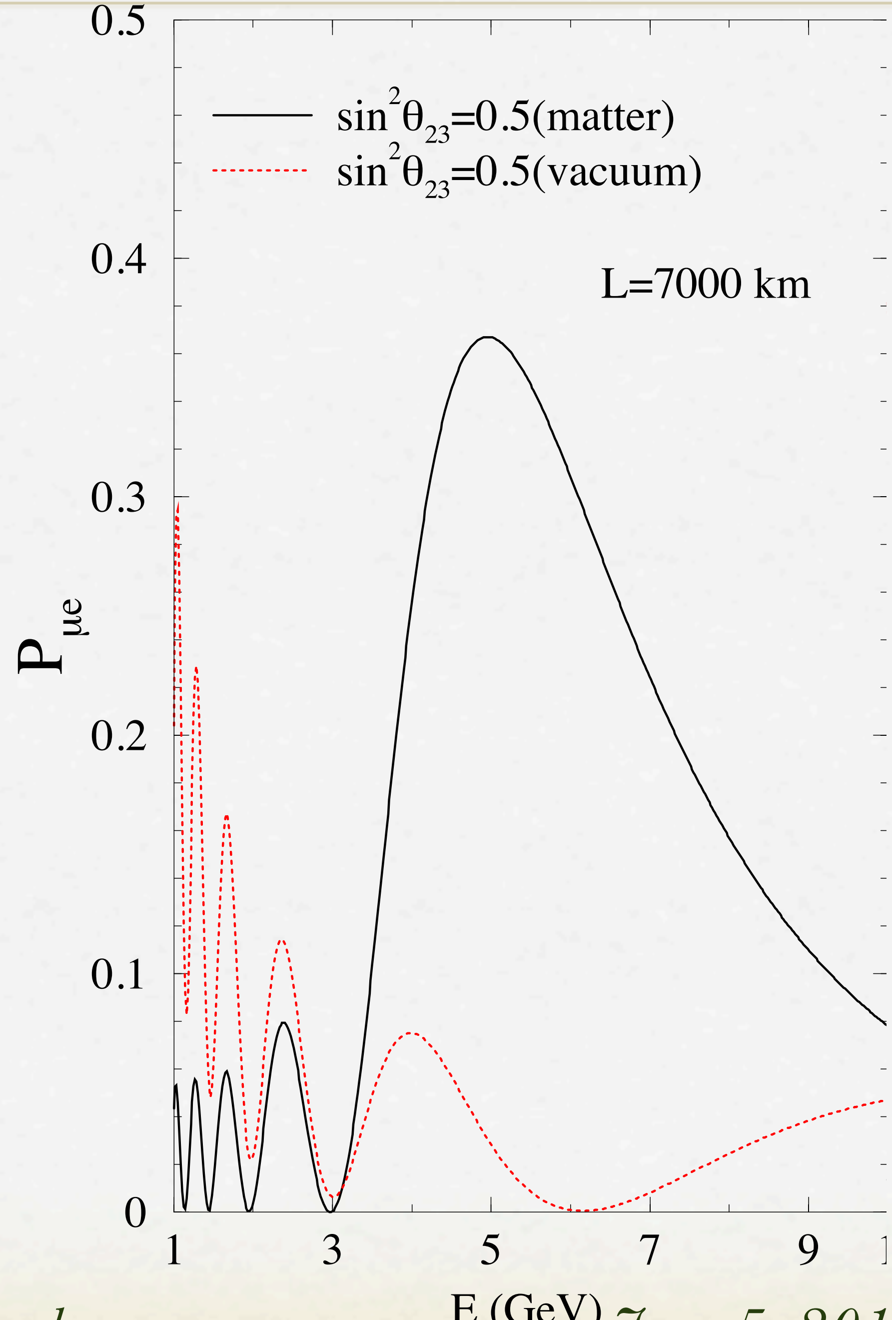
PHYSICS REACH OF ICAL@INO



- *Matter effects fluctuate rapidly with E and* $\cos\theta_{zenith}$
- *ICAL has good E and* $\cos\theta_{zenith}$ *resolution*
- *Effect will also be opp for nu and anti-nu...ICAL has charge id!*

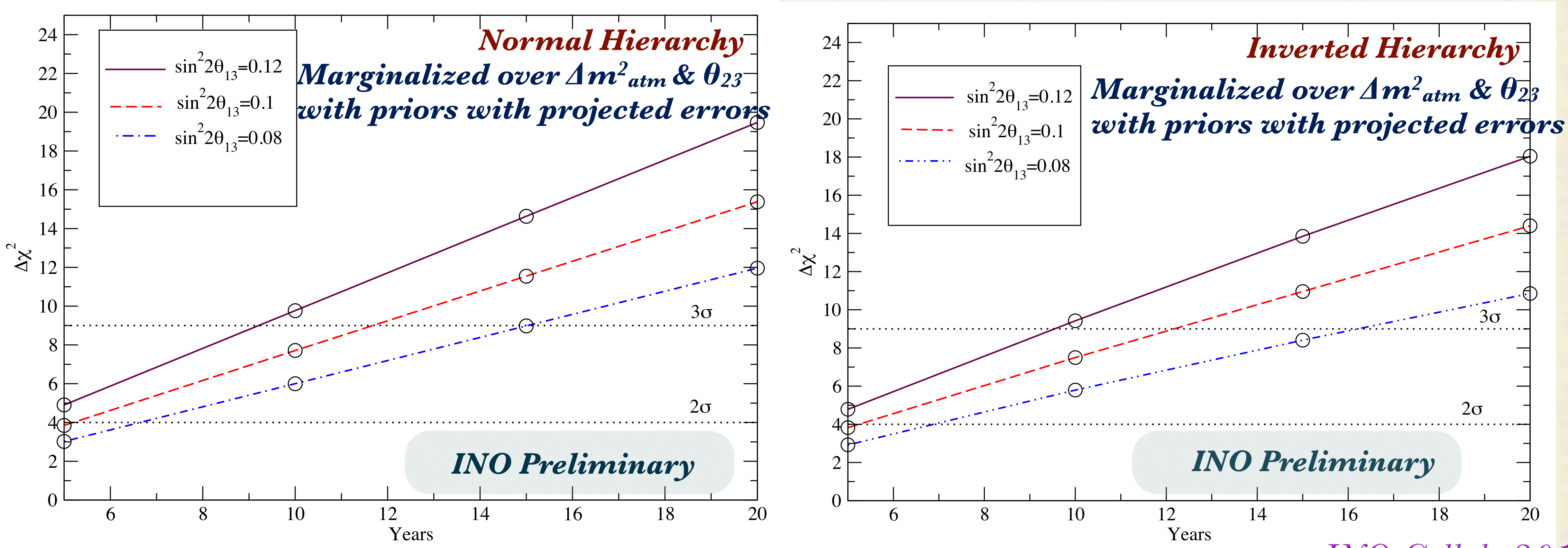
ATMOSPHERIC NEUTRINOS IN HYPER-KAMIOKANDE

- *Matter effects in muons demands good resoln in both E and L*
- *Matter effects in electrons does not vary so fast with E and L*
- *In WC detectors subdominant effects mainly in electron events*



MASS HIERARCHY @ INO

- *Events generated using Nuance and ICAL resoln in E and $\cos\theta_{zenith}$*



INO Collab, 2012

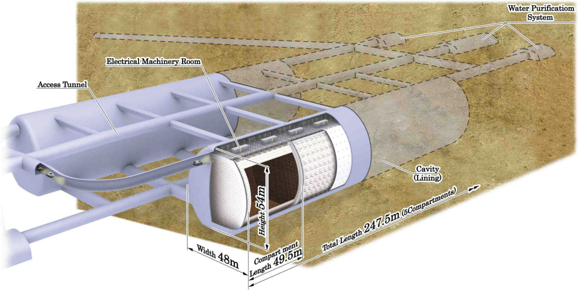
- *~2σ sensitivity for $\sin^2\theta_{23}$=0.5, $\sin^2 2\theta_{13}$=0.1 by 2022 (5 yrs)*
- *~2.7σ sensitivity for $\sin^2\theta_{23}$=0.5, $\sin^2 2\theta_{13}$=0.1 by 2027 (10 yrs)*

HyperKamiokaNDE

Letter of Intent: arXiv:1109.3262

J-Parc 30 GeV proton accelerator upgraded at 1.66 MW

540 kton water Cerenkov detector built at the same distance and off-axis angle as Super Kamiokande.

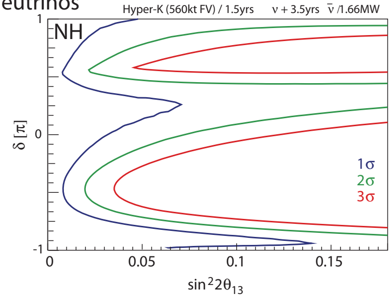


Challenge: push systematic errors at 5% (T2K first result published with 16% systematic errors)

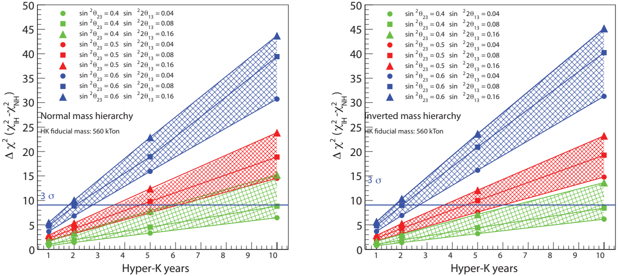
Outstanding performances for proton decays, solar neutrinos, supernova neutrinos etc.

HyperKamiokaNDE: mass hierarchy sensitivity

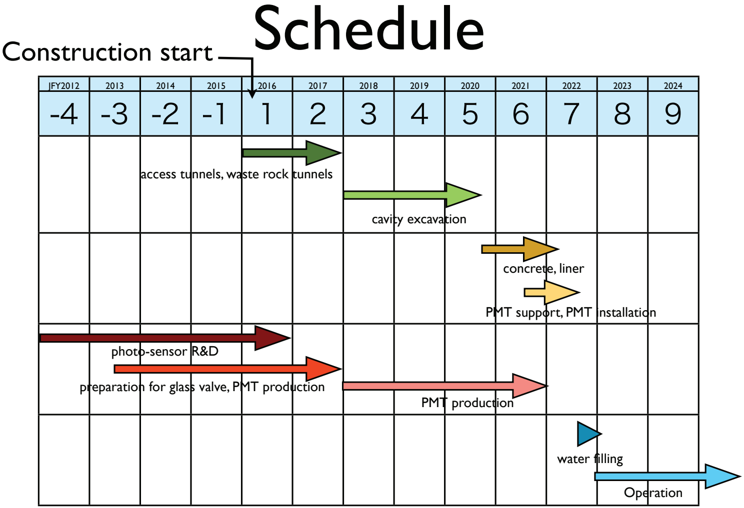
Beam neutrinos only



Atmospheric neutrinos only



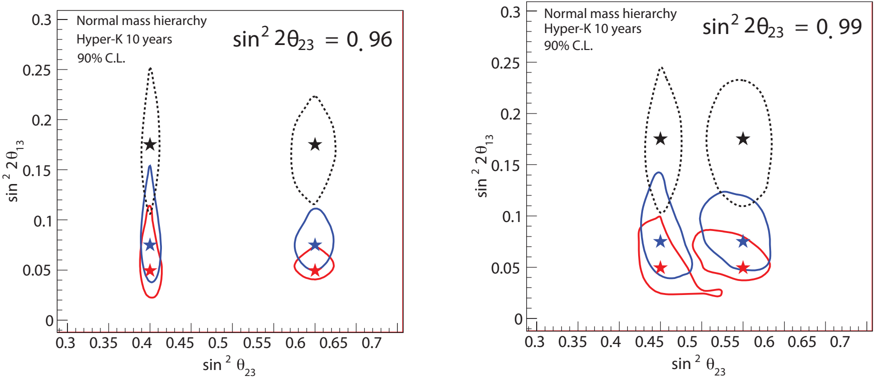
HyperKamiokaNDE schedule



assuming budget being approved from JPY2016

HyperKamiokaNDE: θ_{23} octant sensitivity

θ_{23} octant with atmospheric neutrinos



Conclusions

- The unexpected large value of θ_{13} allows for sensitive searches of mass hierarchy with many different methods.
- Running beam experiments, T2K and Nova, will have little chance in measuring MH
- Reactor experiments can achieve a 3σ sensitivity if they manage to overcome challenging experimental limitations. In any case reactor experiments at the solar baseline have a great physics case independently from MH.
- Atmospheric neutrinos could allow INO to approach a 3σ sensitivity in a 10 years run
- HyperKamiokaNDE, if build, would have an excellent oppurtunity of measuring MH both with atmospheric and beam neutrinos

iCal export More Restricted Europe/Rome M. Mezzetto

XV International Workshop on Neutrino Telescopes

11-15 March 2013 *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti*

Europe/Rome timezone

- **my home**
- Committees
- Venue
- Logistic
- Accommodation
- social events
- poster session
- Registration
  - Registration Form
- List of registrants
- Methods of Payment
- Sponsor

Support

The “Neutrino Telescopes” is one of the most prestigious international event in the field of Physics. It takes place every two years and dates back to 1988 when Prof. Milla Baldo Ceolin conceived it and launched the first edition. It became soon a crucial event and it is now considered a consolidated appointment where to discuss the latest discoveries and the fascinating future scenarios in topics that range from Neutrinos to Astrophysics and Cosmology.

The program will be structured in plenary sessions with invited talks followed by discussions. There will be also a poster session, aiming at involving particularly, but not limited to, young researchers with new brilliant ideas on the workshop’s topics of interest.

The Workshop will take place from March 12th to March 15th, 2013. Registration will open on March 11th. Secretariat desk will be available from 15.00 to 18.00