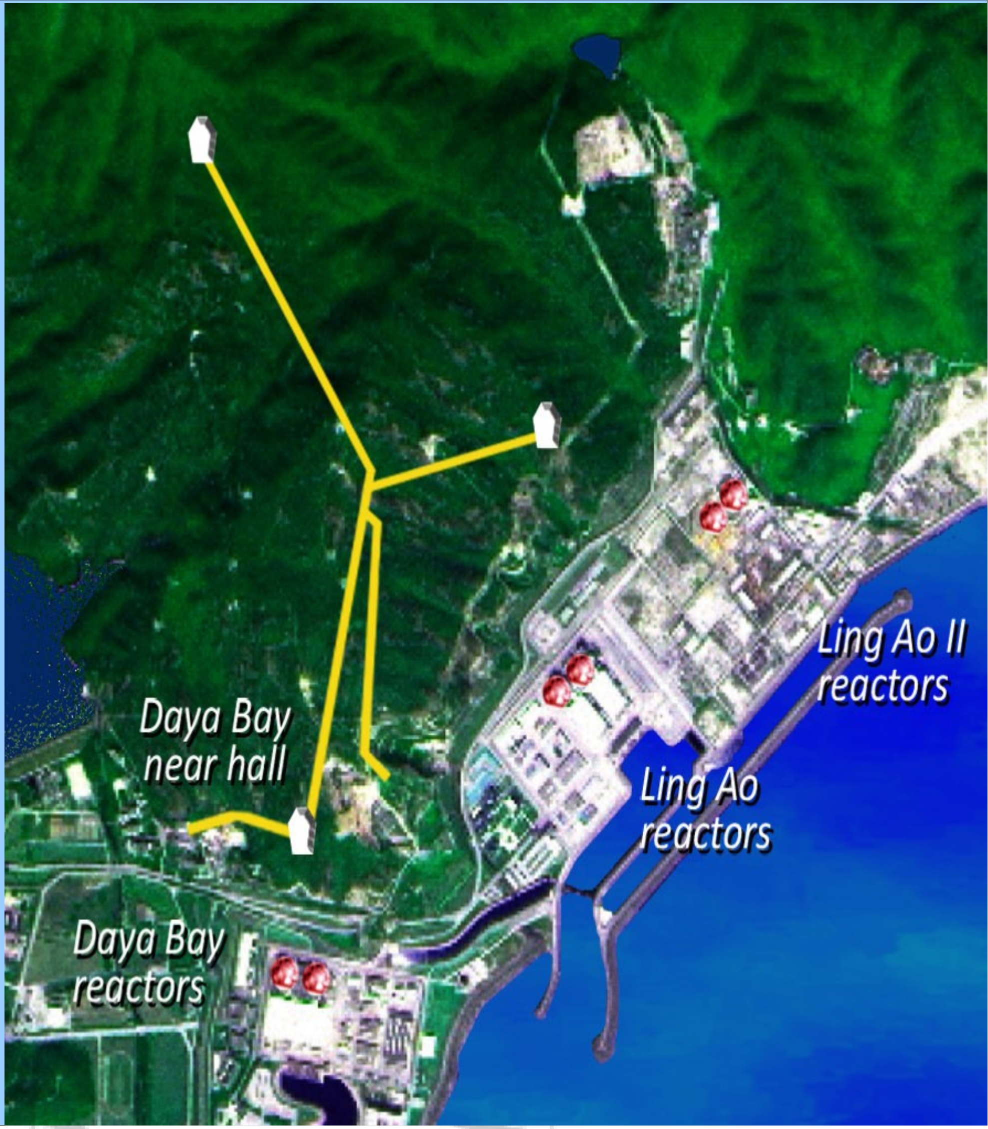
Latest Results on θ_{13}

Francesca Di Lodovico

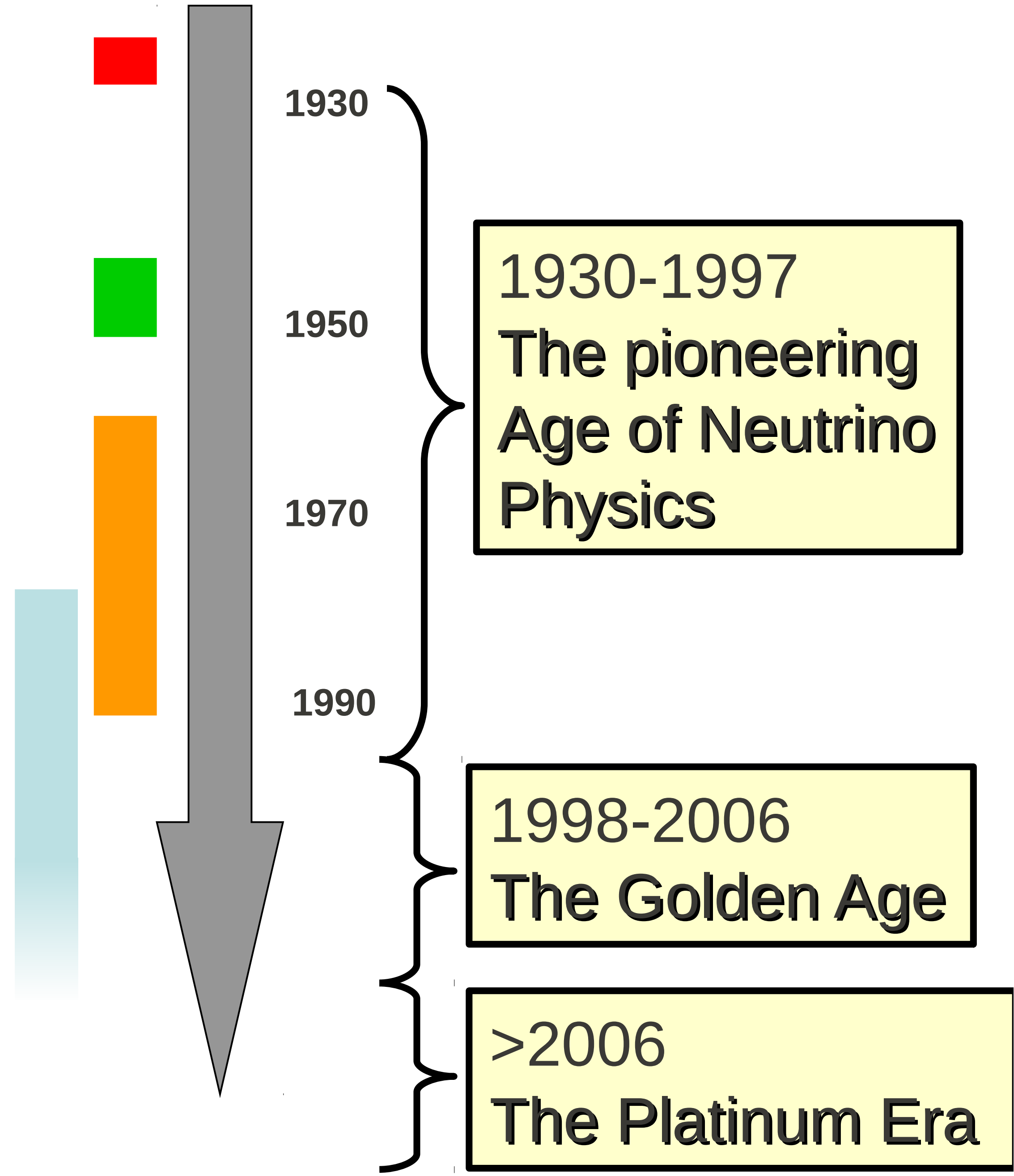
14th March 2012

NExT Meeting, Sussex



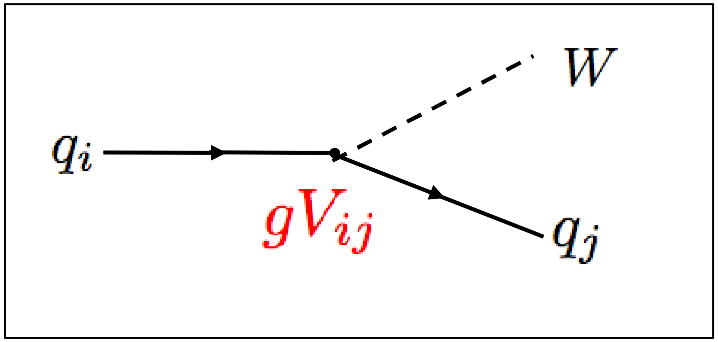
Our Timescale So Far...

- Pauli and Fermi (theory)
- to Reines and Cowan (discovery)
- to Davis (solar neutrinos)
- to Koshiba (supernova and oscillations)
- ????



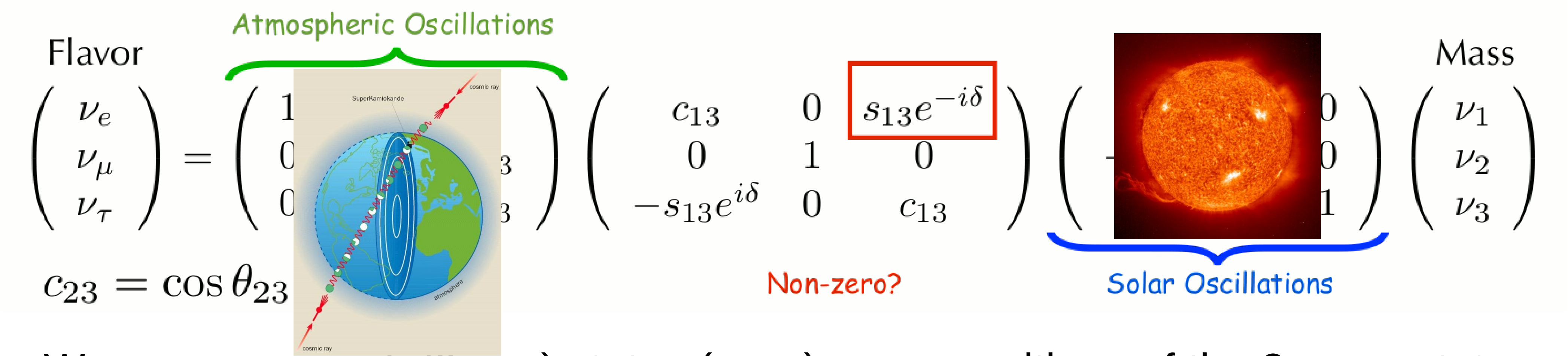
Neutrino Oscillation Review

- Evidence of solar and atmospheric neutrino oscillations in the 1960-1990.
- Similar mechanism as in the quark oscillation (CKM matrix) postulated.
- Free parameters: 3 angles, 1 phase



$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

- PMNS with “standard” parametrization (with c_{ij}= cosθ_{ij}, s_{ij}=sinθ_{ij}).



- We measure weak (flavor) states (e,μ,τ), superpositions of the 3 mass states.
- Three flavour effects suppressed b/c : Δm^2_{21} << Δm^2_{31} and θ_{31}<<1 ($\Delta m^2_{ij}=m^2_j-m^2_i$) → Dominant oscillations well described by effective 2 flavour oscillations

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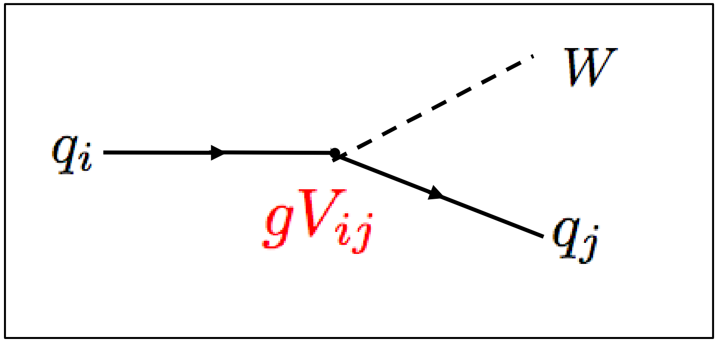

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Flavor | Atmospheric Oscillations | Mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{23} = \cos\theta_{23}$ etc...

Non-zero? | Solar Oscillations

- We measure weak (flavor) states (e,μ,τ), superpositions of the 3 mass states.
- Three flavour effects suppressed b/c : $\Delta m^2_{21} << \Delta m^2_{31}$ and $\theta_{31}<<1$ ($\Delta m^2_{ij}=m^2_j-m^2_i$) → Dominant oscillations well described by effective 2 flavour oscillations

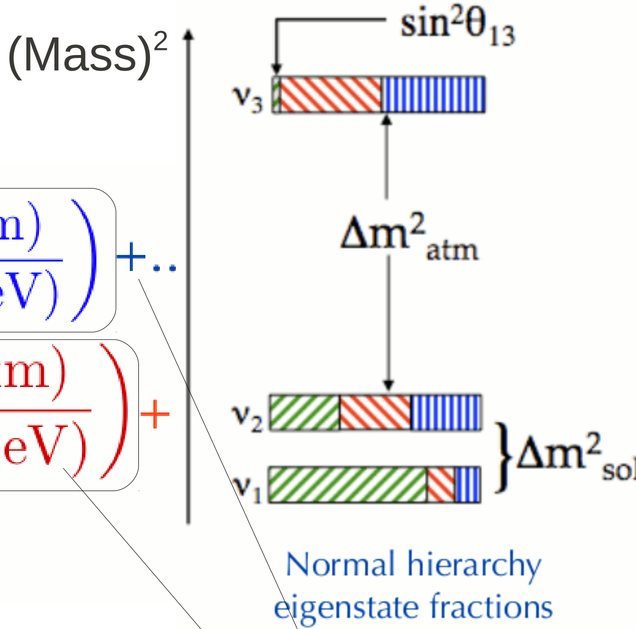
θ_{13}: two way to measure it

- Long Baseline neutrino experiments
- Use a human-made (anti) ν_μ beam shot from the accelerator to a “far” detector.
- Oscillation probability:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(1.27\Delta m^2_{\mathrm{atm}}(\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right) + ..$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \left(1.27\Delta m^2_{\mathrm{atm}}(\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right) +$$

1st order oscillation equations

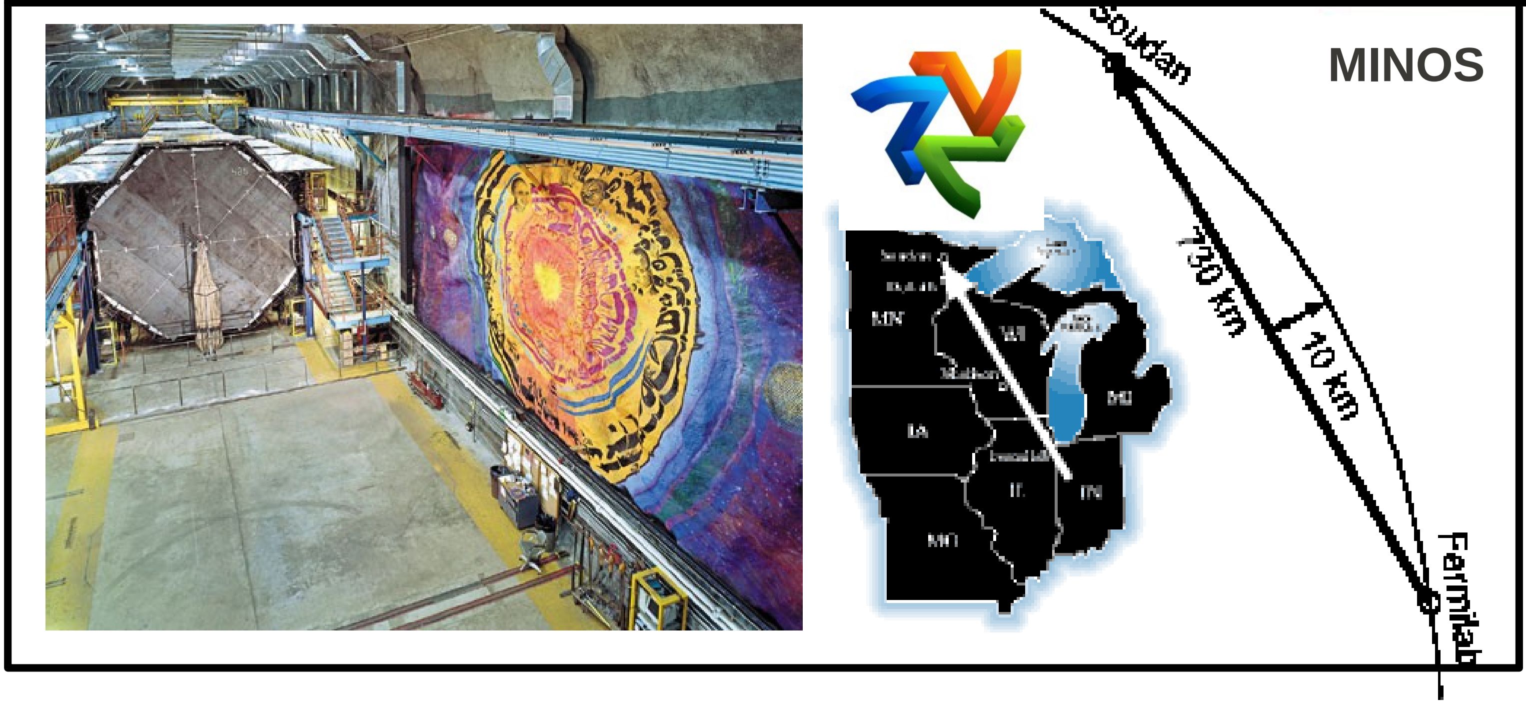


- Nuclear reactors
- Use the anti-ν_e flux from the core
- Oscillation probability:

$$P(\bar{\nu}_e \to x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Experimental Parameters. They depend on the experiment: be smart! Use “predicted“ oscillation maximum

2 Long Baseline Neutrino Experiments



3 Reactor Neutrino Experiments

Near and Far detectors

Two-detector experiments:

- Near detector
  - measure beam composition
- Far detector
  - measure oscillations

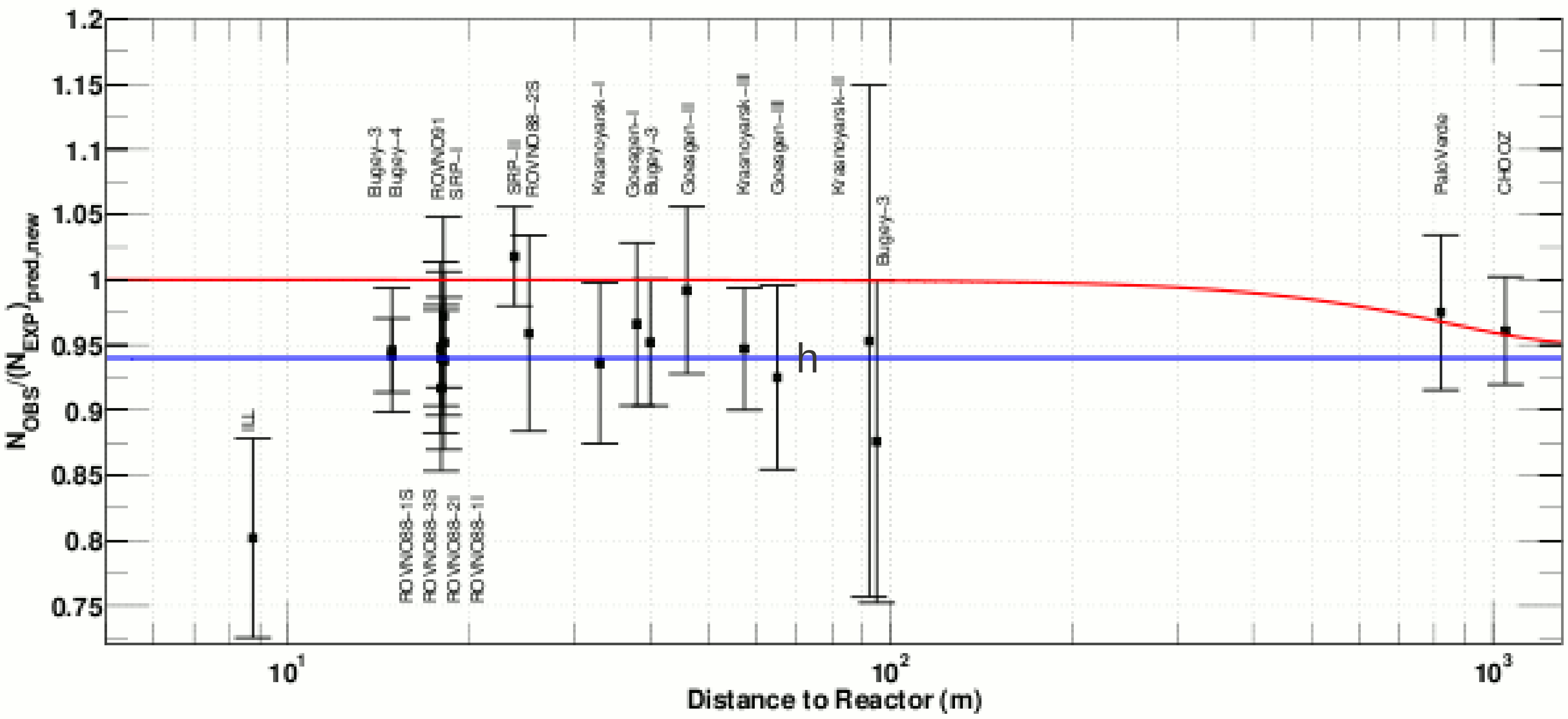
Comparing beam at the near and far detector allows to reduce the theoretical error due to the flux prediction from the source.

It is important for all the experiments to have a near detector.

The Reactor Neutrino Anomaly

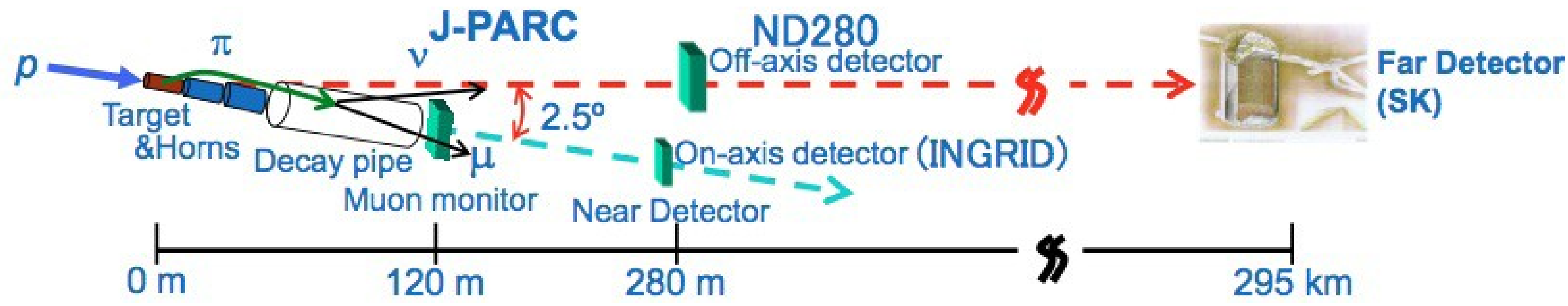
arXiv:1101.2755 [hep-ex]

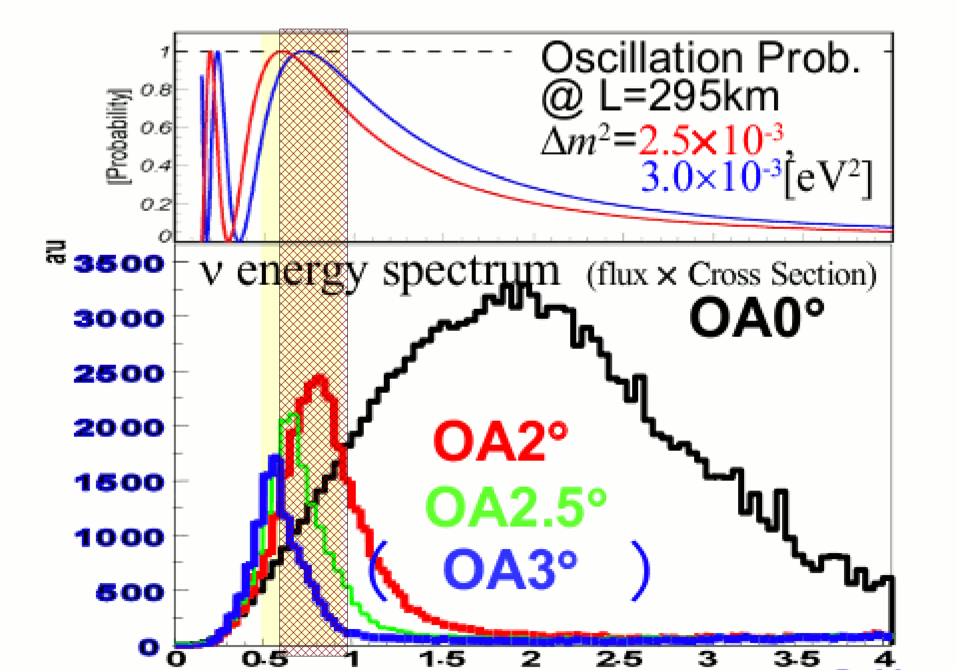
Illustration of the short baseline reactor antineutrino anomaly



- The experimental results are compared to the new predicted flux
- The mean averaged ratio, including possible correlations, is (0.943 ± 0.023)

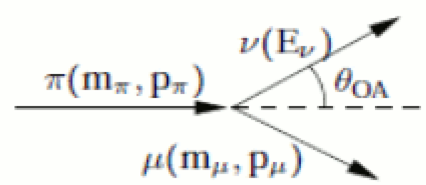
θ_{13} indications: T2K



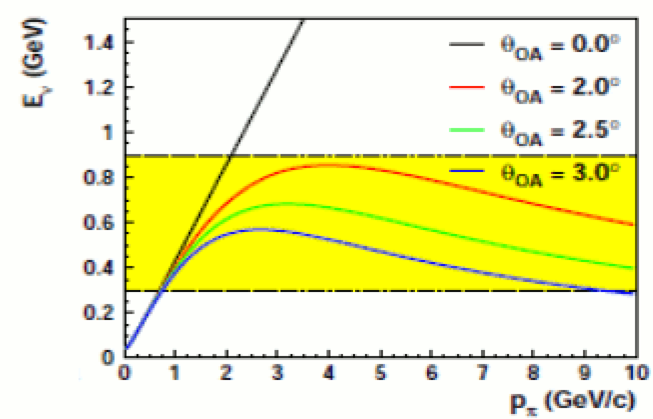


Concentrate ν_μ flux at one energy

Backgrounds lower: NC or other feed-down from high→low energy, ν_e (3-body decays)

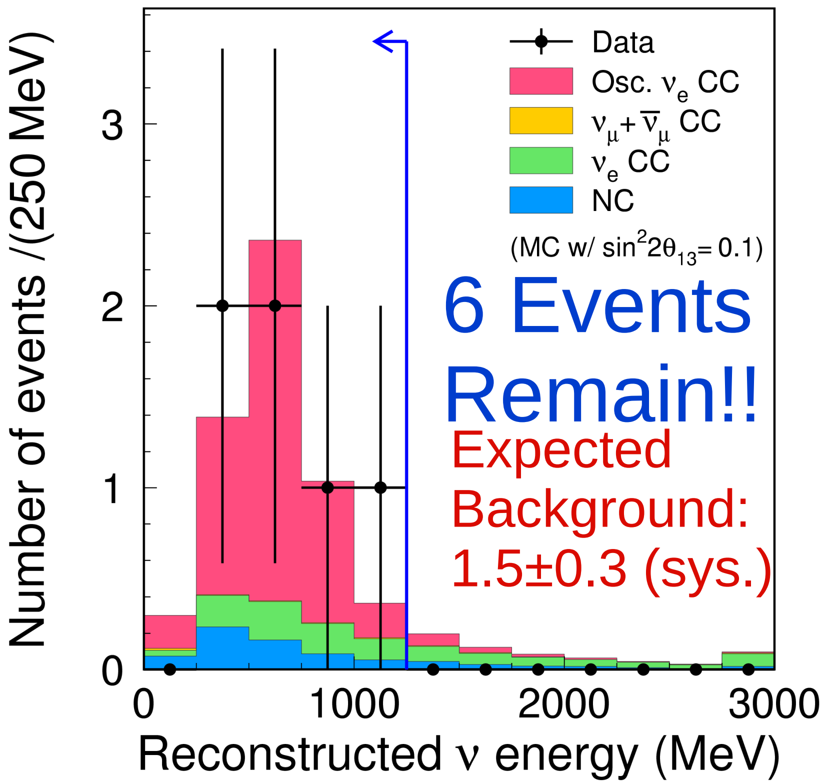


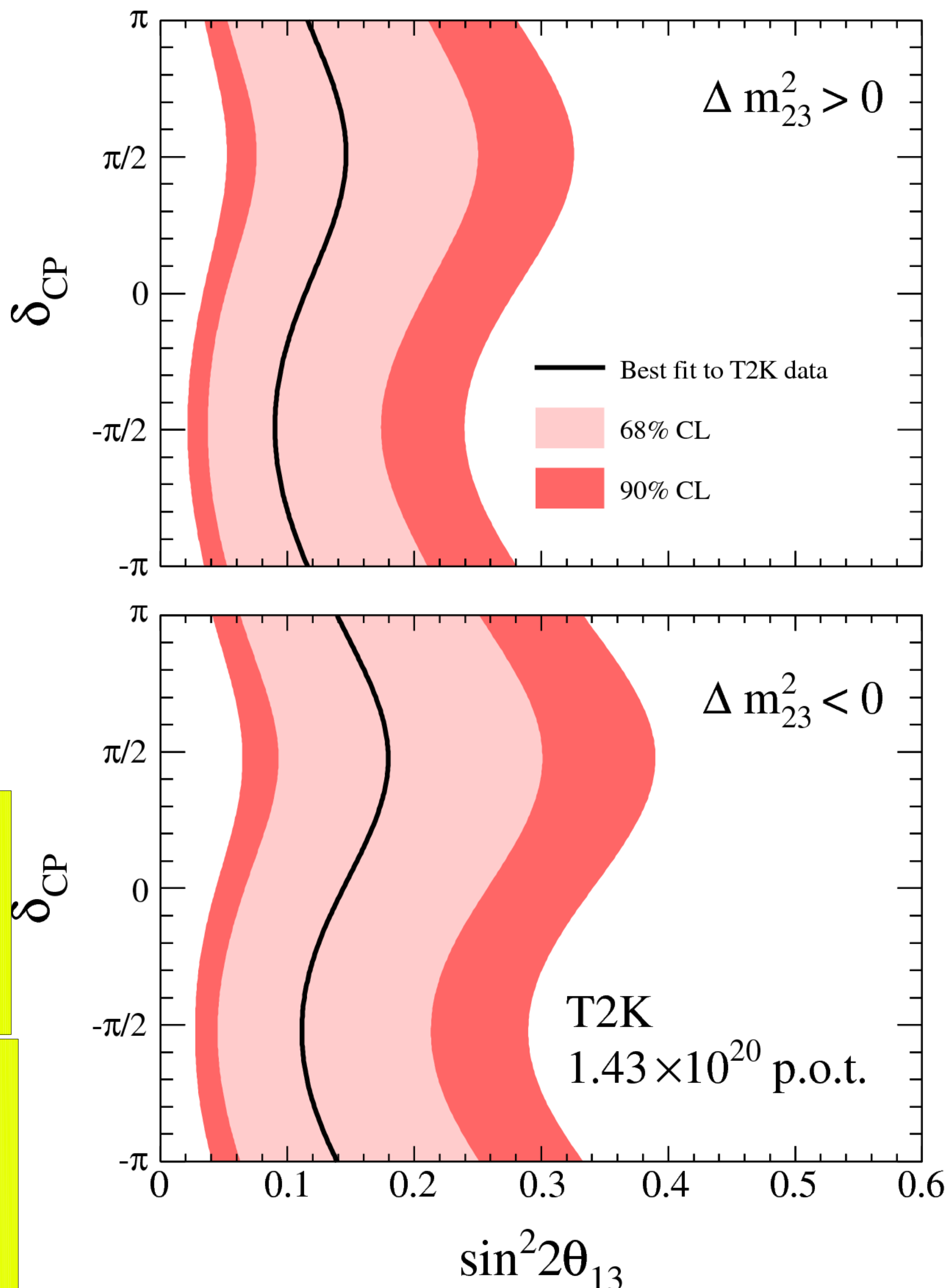
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$



θ_{13} indications: T2K

Phys. Rev. Lett. 107, 041801 (2011)





Normal hierarchy, δ=0:

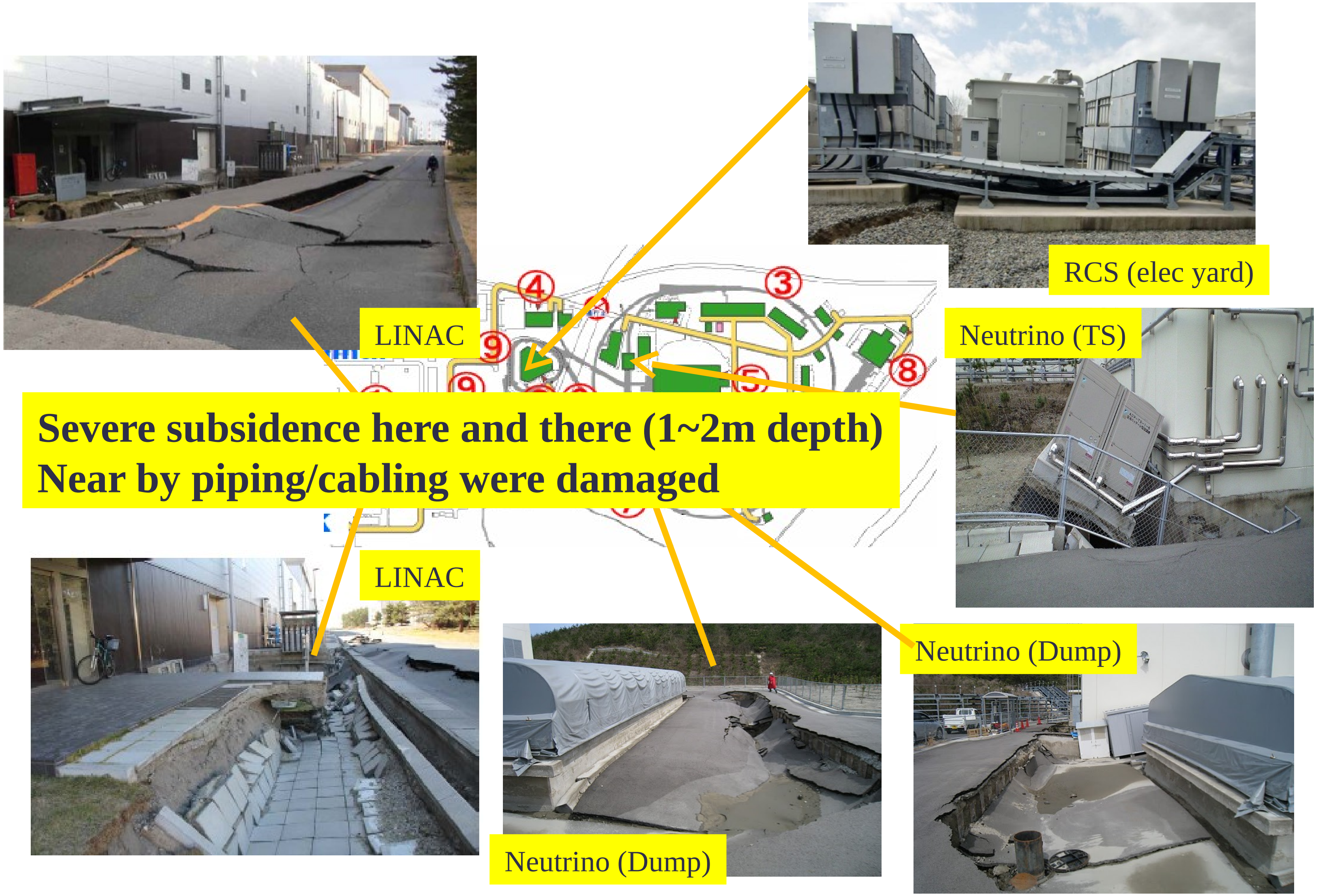
- Best fit: $\sin^2(2\theta_{13})=0.11$
- $0.03<\sin^2(2\theta_{13})<0.28$ @90% C.L.

Inverted hierarchy, δ=0:

- Best fit → $\sin^2(2\theta_{13})=0.14$
- $0.04<\sin^2(2\theta_{13})<0.34$ @90% C.L.

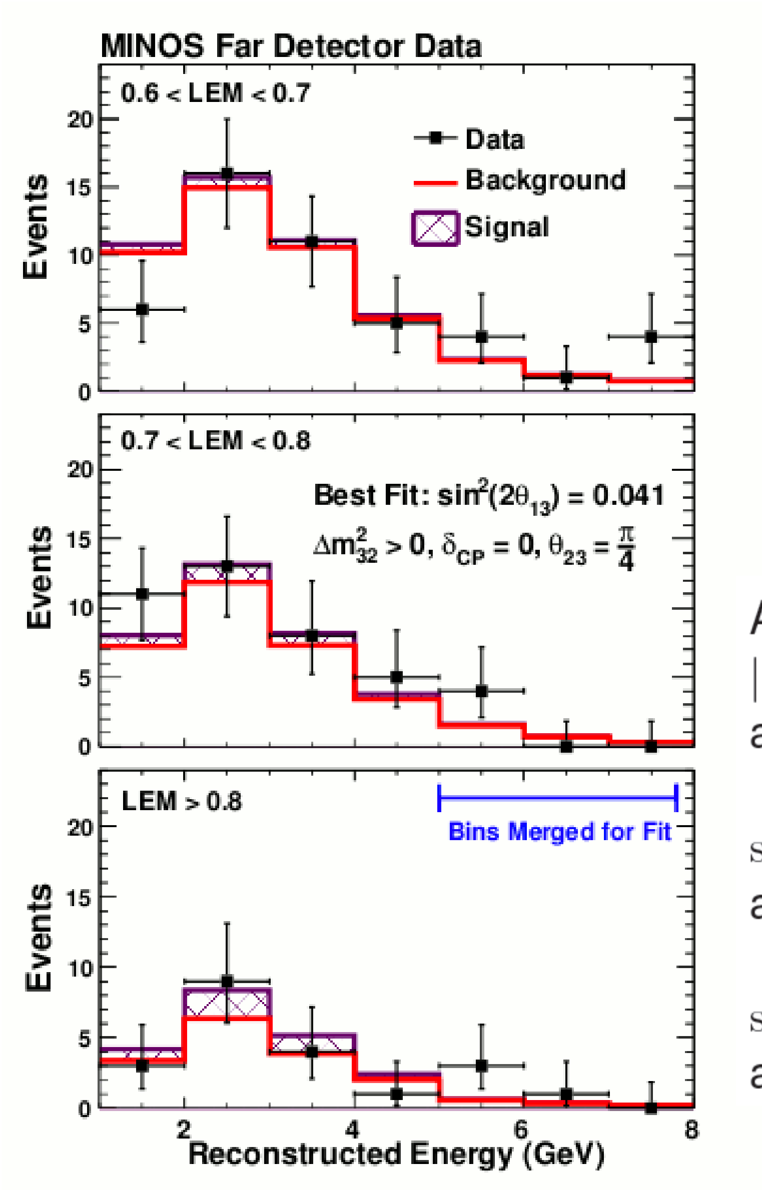
T2K Status

- Stalled for 1y due to the magnitude 9 earthquake in Japan
- Data taking restarted this month
- Next results at Neutrino 2012 in Kyoto



θ_{13} indications: MINOS

arXiv:1108.0015



- Based on Near Detector data, expect:

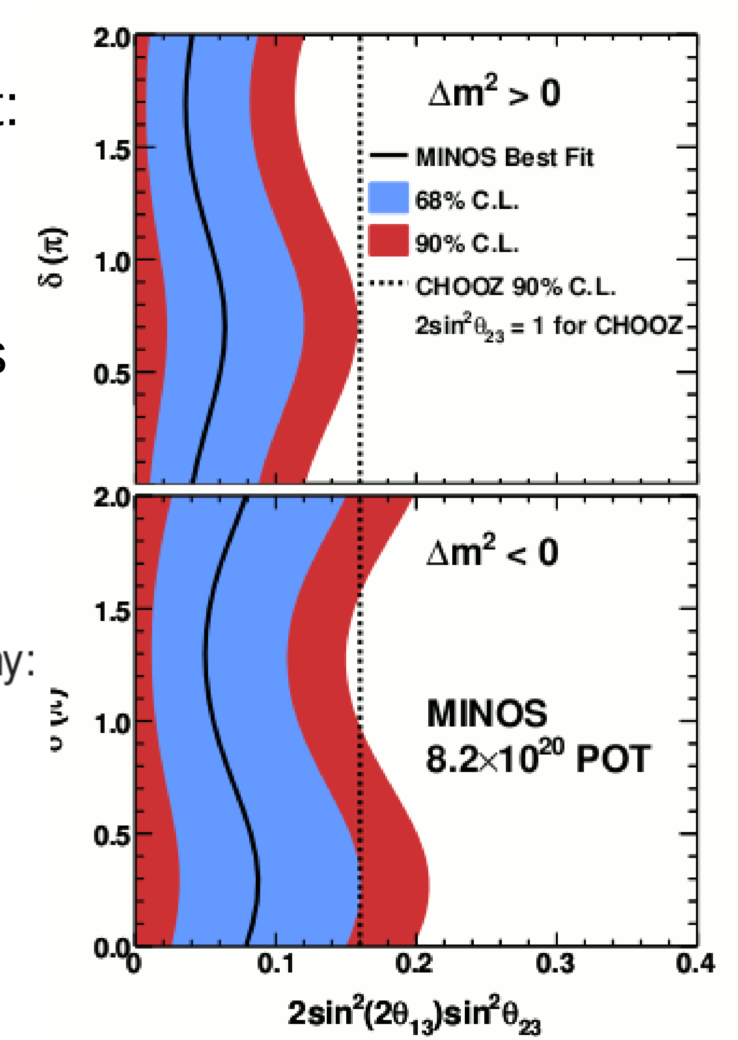
  49.6 ± 7.0(stat) ± 2.7(syst)

- Observe: **62** events in the Far Detector

Assuming $\delta_{CP} = 0$, $\theta_{12} = \pi/4$, $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2 and normal (inverted) hierarchy:

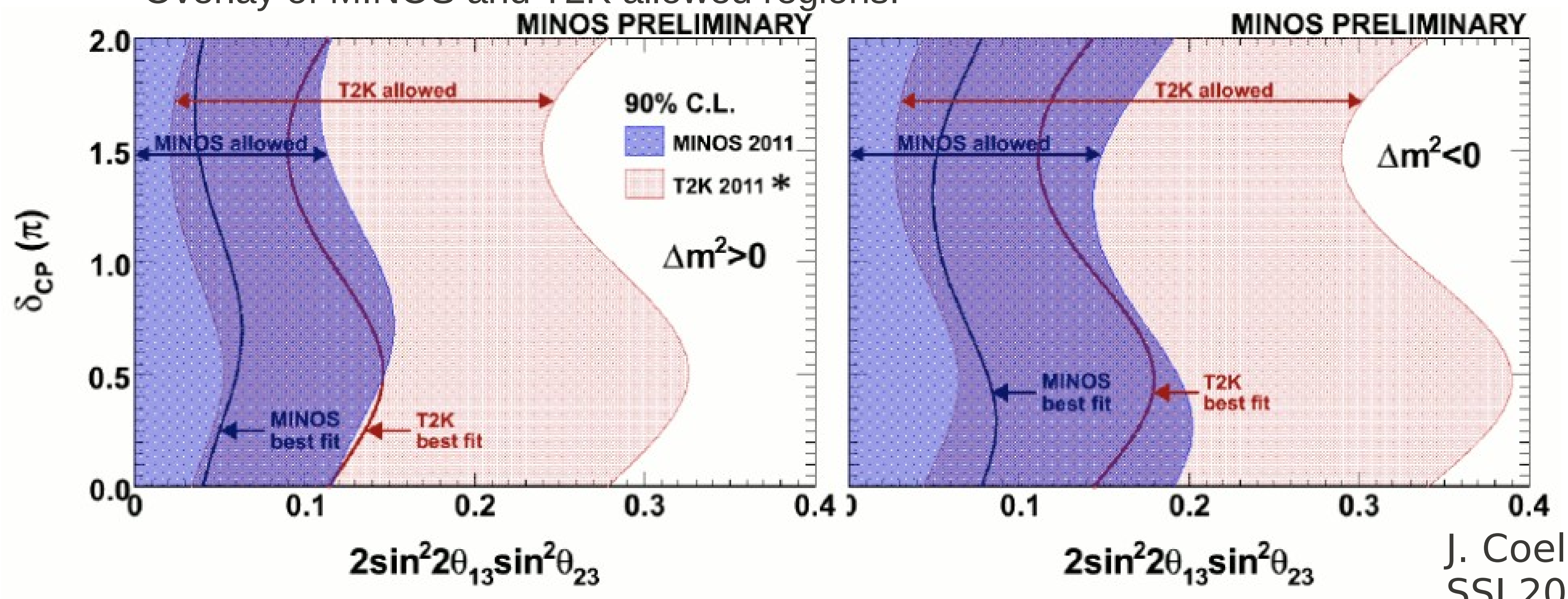
$\sin^2(2\theta_{13}) < 0.12\ (0.19)$ at 90% C.L.

$\sin^2(2\theta_{13}) = 0$ disfavored at 89% C.L.



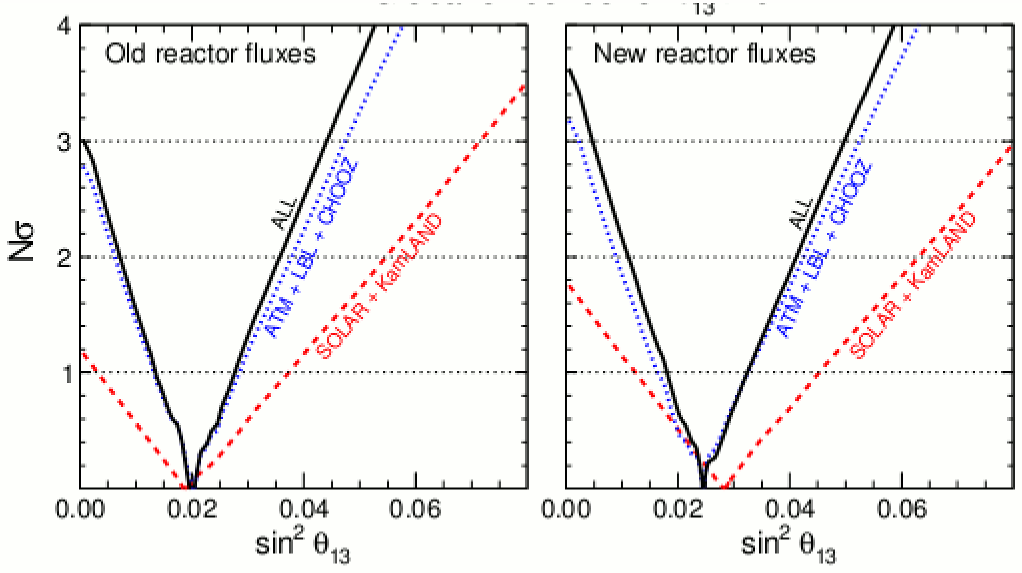
θ_{13} indications from Long Baselines

Overlay of MINOS and T2K allowed regions:



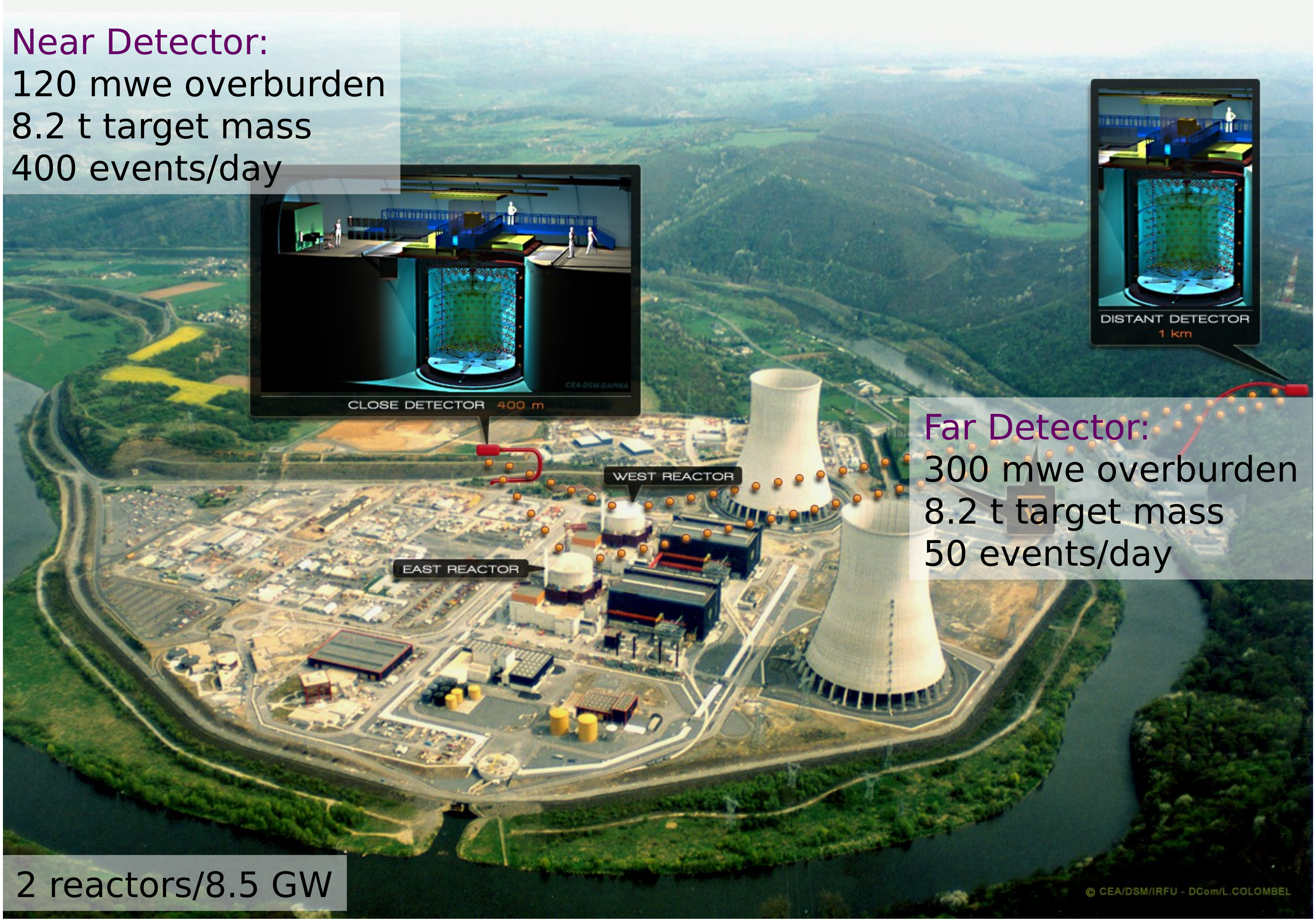
J. Coelho, SSI 2011

Global Neutrino Data Analysis
G.L. Fogli, at al
arXiv:1106.6028v2



θ_{13} indications: Double Chooz

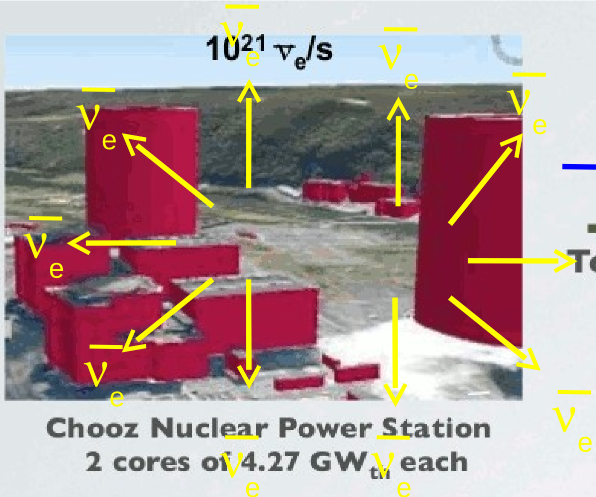
Near Detector:
120 mwe overburden
8.2 t target mass
400 events/day



Far Detector:
300 mwe overburden
8.2 t target mass
50 events/day

2 reactors/8.5 GW

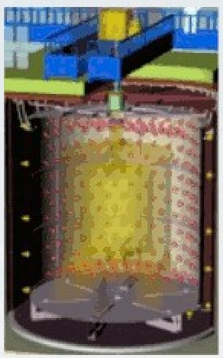
Reactor Experiments



Chooz Nuclear Power Station
2 cores of 4.27 GW_{th} each

$\bar{\nu}_e$

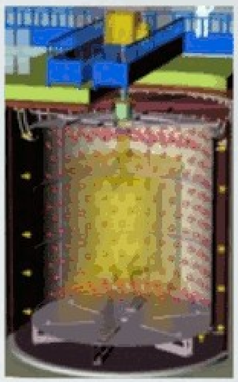
Total flux



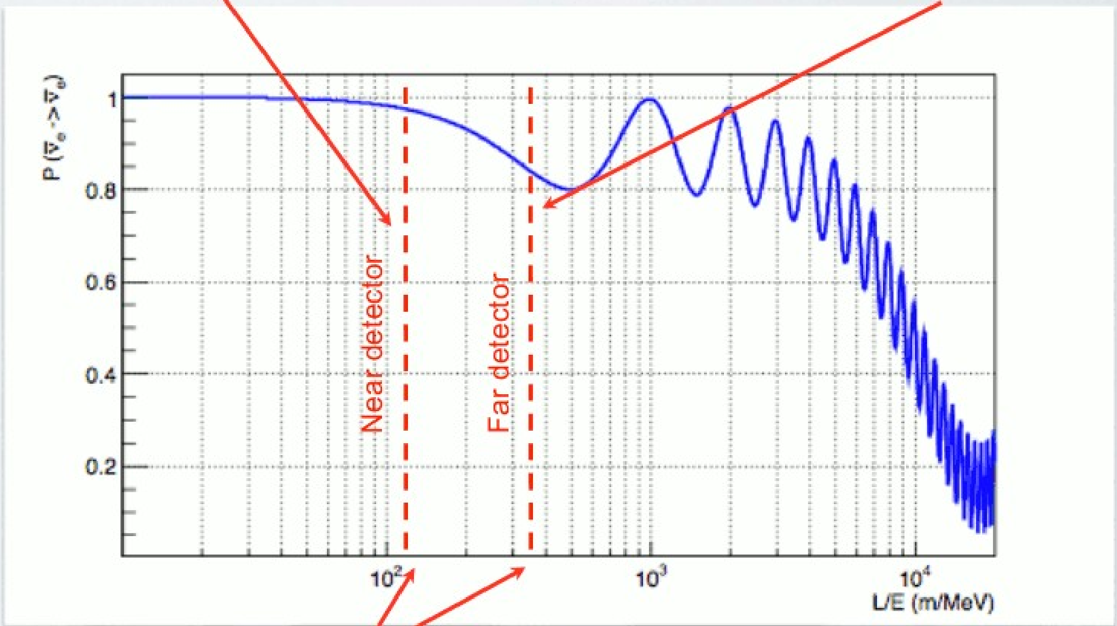
Near detector
400 m

$\bar{\nu}_{e,\mu,\tau}$

Oscillated flux

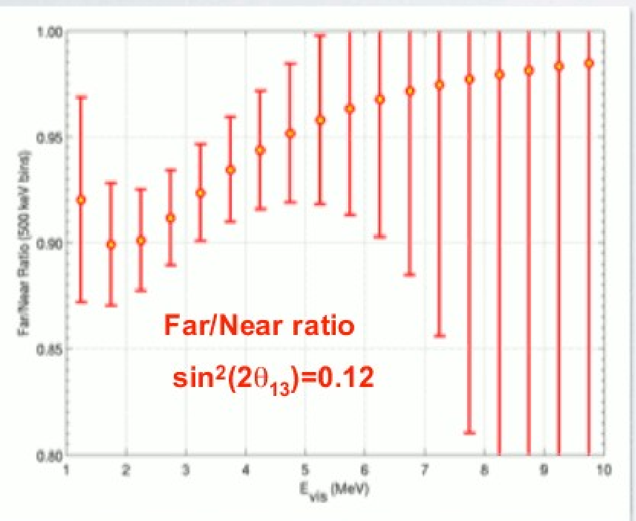


Far detector
1050 m



For <E> = 3 MeV

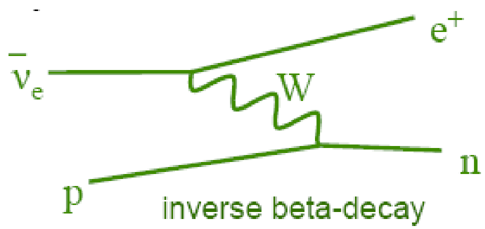
Prompt energy spectra comparison



$\Delta m^2_{12}=7\times10^{-5}$ eV^2 $\quad$ $\sin^2(2\theta_{13})=0.2$

$\Delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\quad$ $\cos^2(\theta_{12})=0.7$

Neutrino Detection: Gd-loaded LS

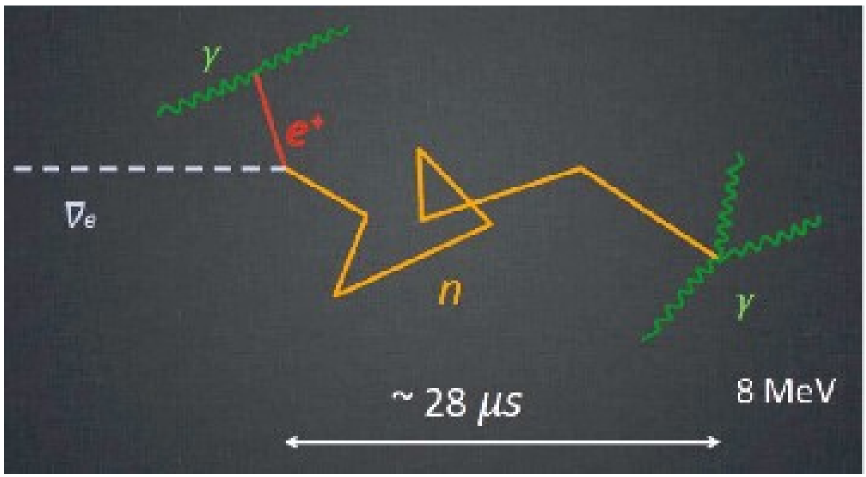


LS = Liquid Scintillator

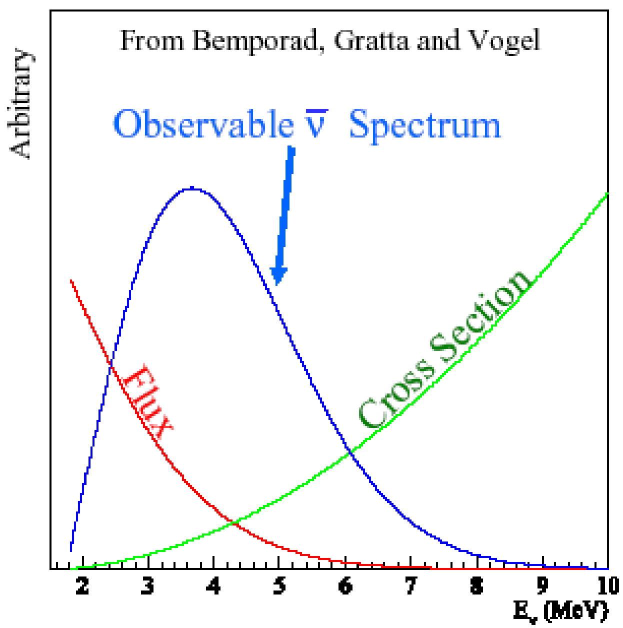
Inverse beta decay:
$\bar{\nu}_e + p \rightarrow n + e^+$

→ Prompt annihilation

→ $n + Gd \rightarrow Gd^* + \gamma s$ (8 MeV)
Delayed: $\Delta t \sim 30\ \mu s$



Neutrino event: coincidence in time, space and energy



Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + m_n - m_p + m_{e^+}$$

10-40 keV

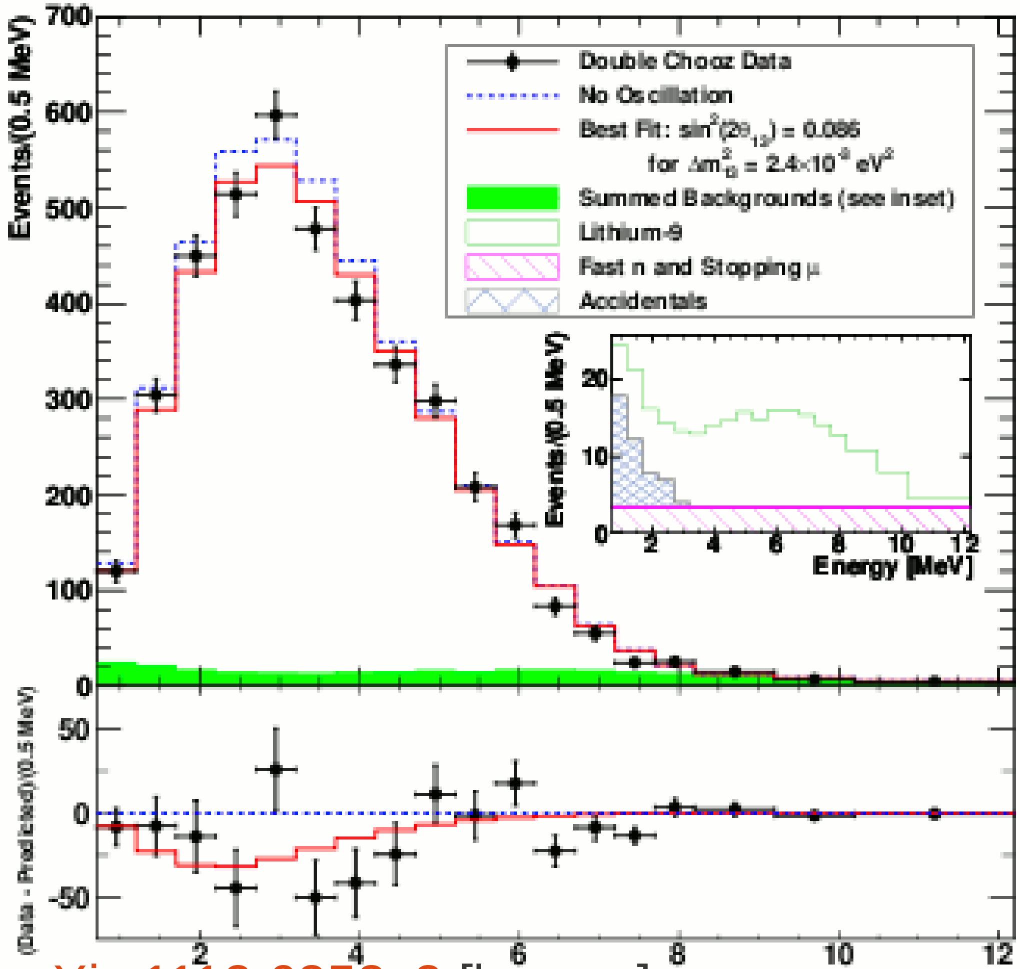
Threshold: 1.8 MeV

Double Chooz Results and Prospects

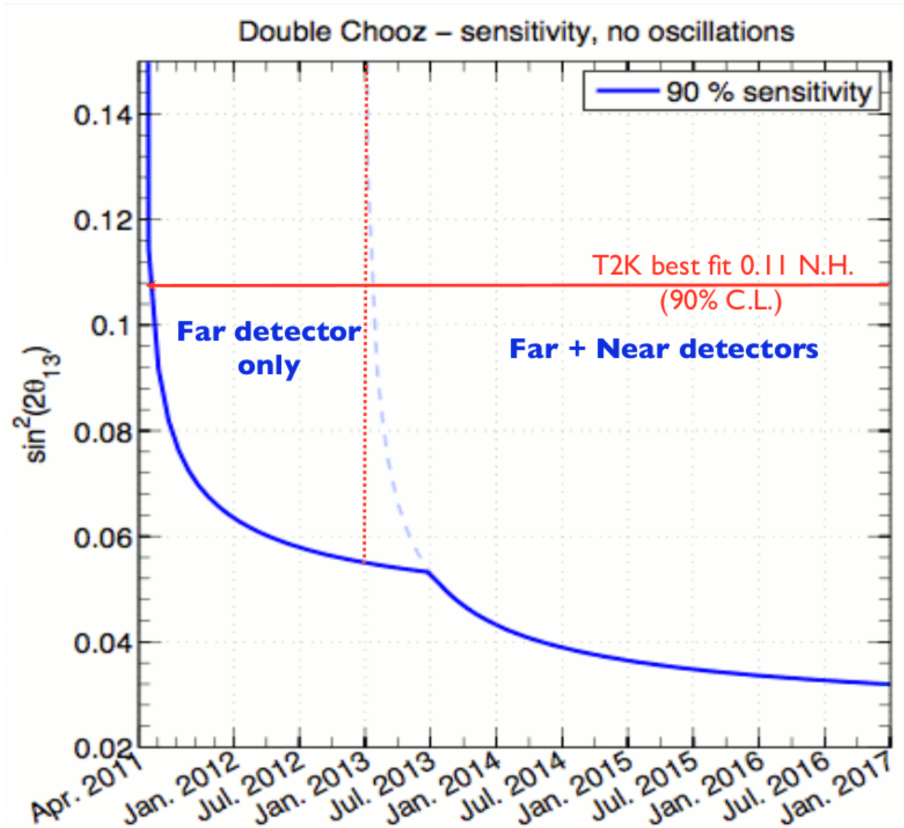
Rate + Shape Analysis:
$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(stat) \pm 0.042(syst)$
Rate Only:
$\sin^2(2\theta_{13}) = 0.093 \pm 0.029(stat) \pm 0.073(syst)$

Consistent results with T2K and MINOS

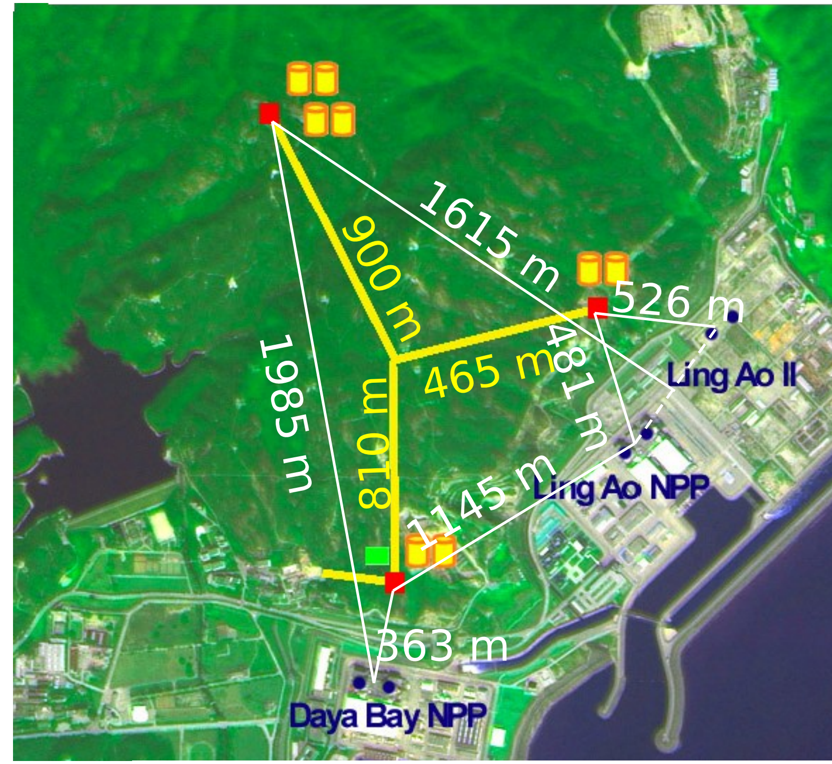
Planned addition of near detectors in 2013. Measurement will not be affected by the reactor neutrino anomaly.



arXiv:1112.6353v2 [hep-ex]



Daya Bay



Far site: *L* = 1615 m/1985 m
350 m overburden
~90 events/day/detector

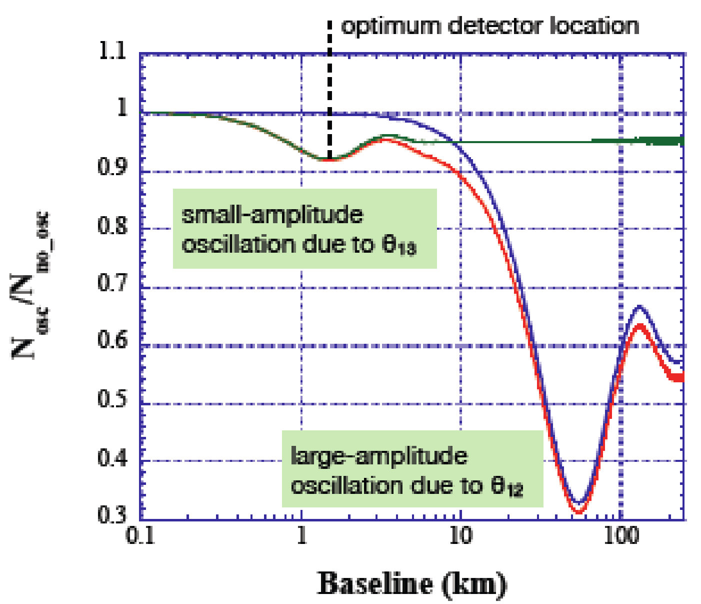
DB near site: *L* = 363 m/1145 m
98 m overburden
~930 events/day/detector

LA near site: *L* = 481 m/526 m
112 m overburden
~760 events/day/detector

Target mass 8 x 20 ton

Multiple near and far detectors
to reduce uncorrelated systematic errors

Optimum detector location:



θ_{13} Daya Bay Measurement

arXiv:1203.1669v1 [hep-ex]

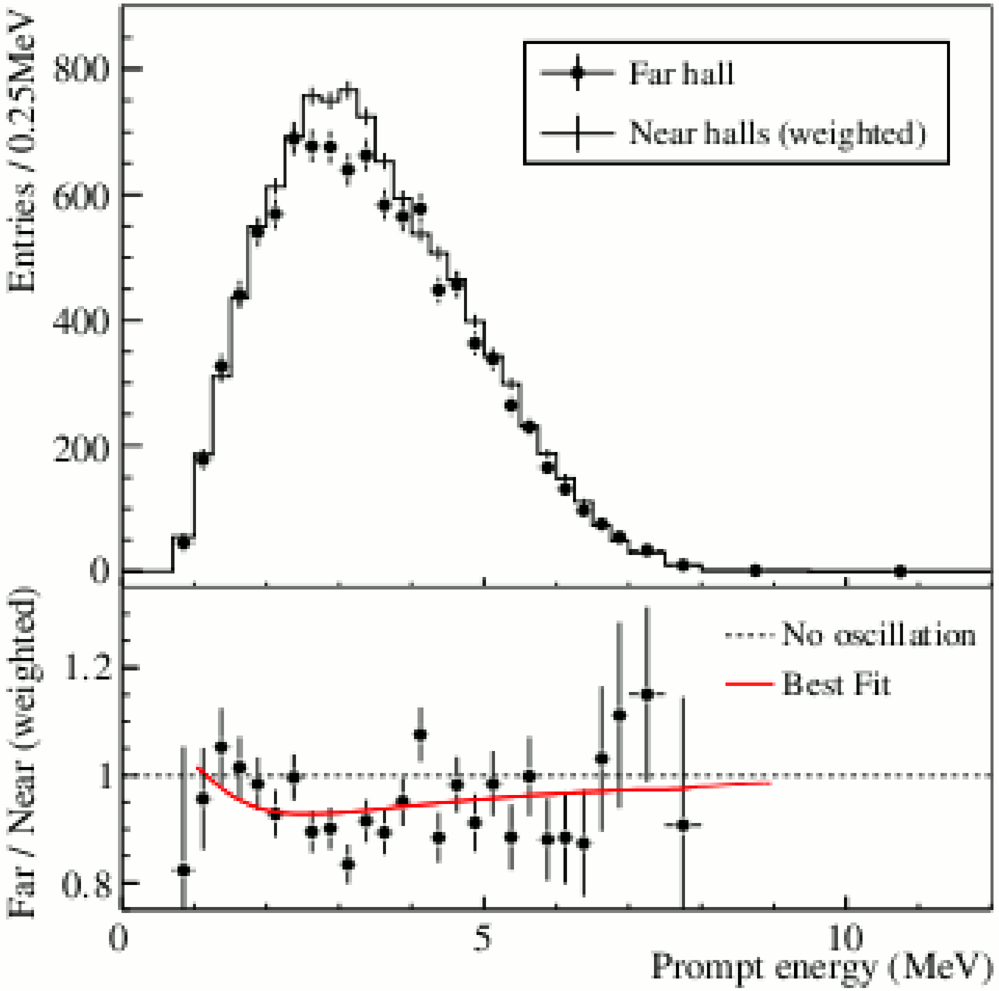
Using near to predict far

$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

$$M_i = \frac{IBD_i - B_i^{Acc} - B_i^{FNeutron} - B_i^{9Li/8He} - B_i^{AmC} - B_i^{\alpha-n}}{\epsilon_i^{muon}\epsilon_i^{multi} TMass_i}$$

Determination of α, β:

1) **Set R=1 if no oscillation**
2) **Minimize the residual reactor uncertainty**



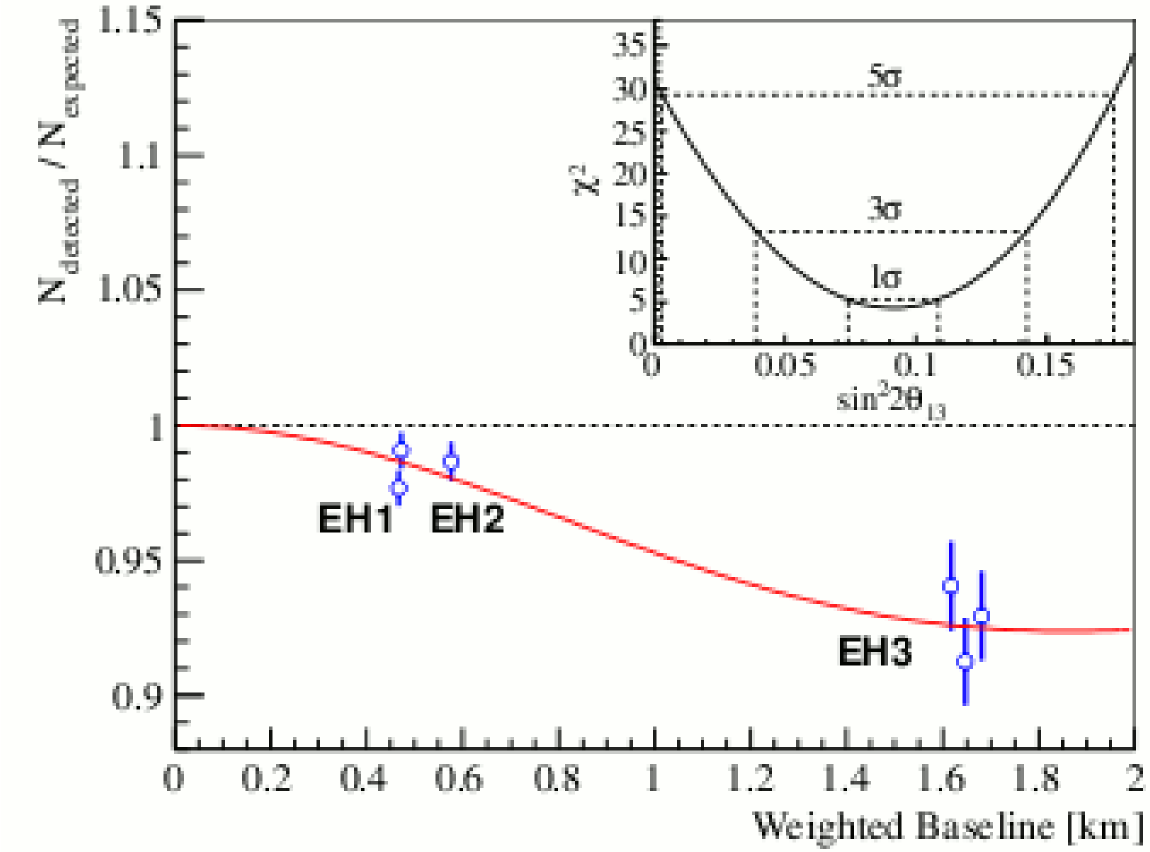
Observed: 9901 neutrinos at far site,
Prediction: 10530 neutrinos if no oscilla...

R = 0.940 ±0.011 (stat) ±0.004 (syst)

θ_{13} Daya Bay Measurement

$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

$\chi^2/NDF = 4.26/4$ 5.2σ for non-zero θ_{13}



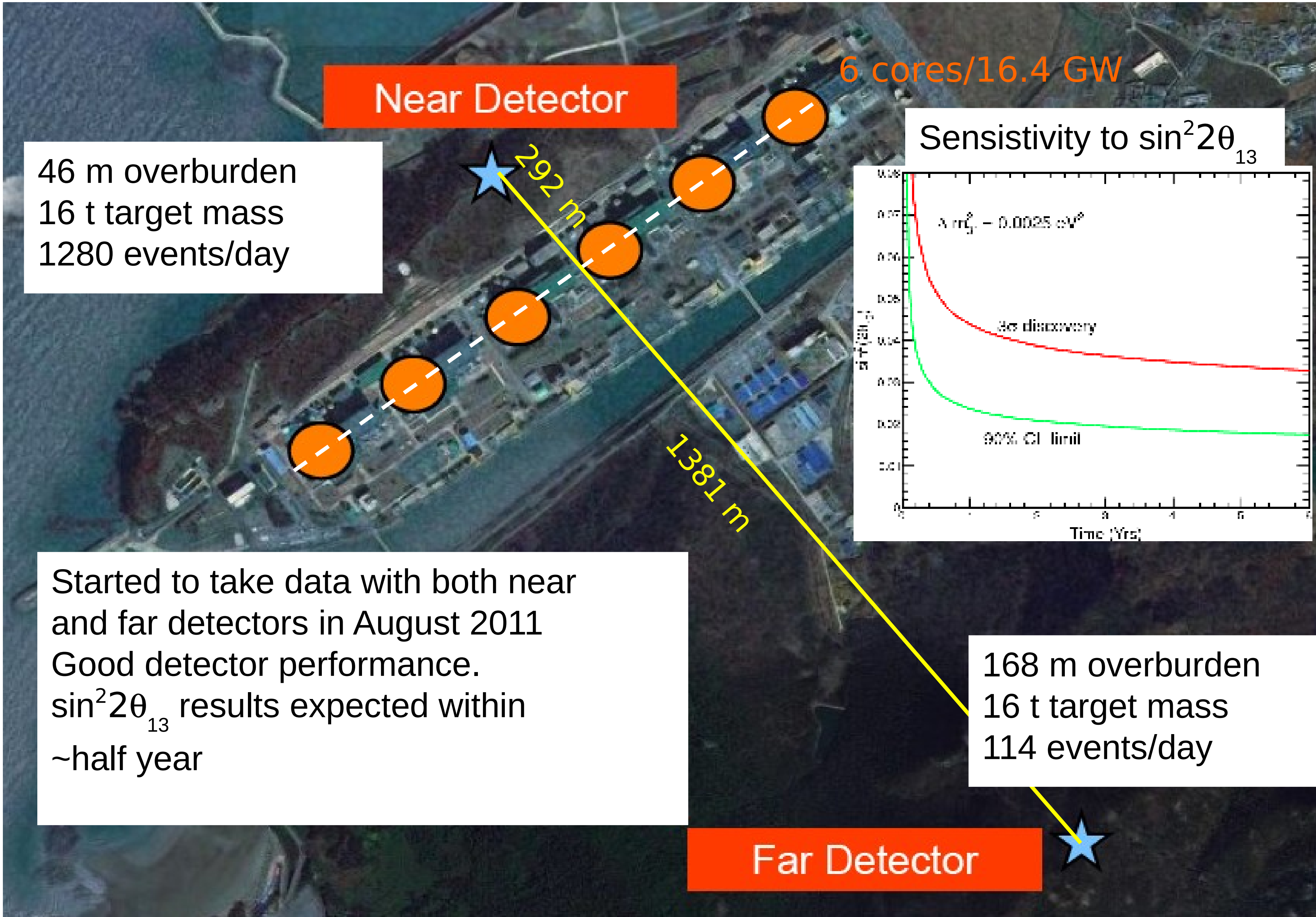
- Ratio of measured versus expected signal in each detector, assuming no oscillation.

- The oscillation survival probability at the best-fit value is given by the smooth curve.

θ_{13} Daya Bay Plans

- Assembly of AD7 and AD8, to be completed before the Summer
- Continue the data taking until the Summer
- Installation of AD7 & AD8 in Summer
- Detector calibration
- Re-start data taking after the Summer

RENO Status

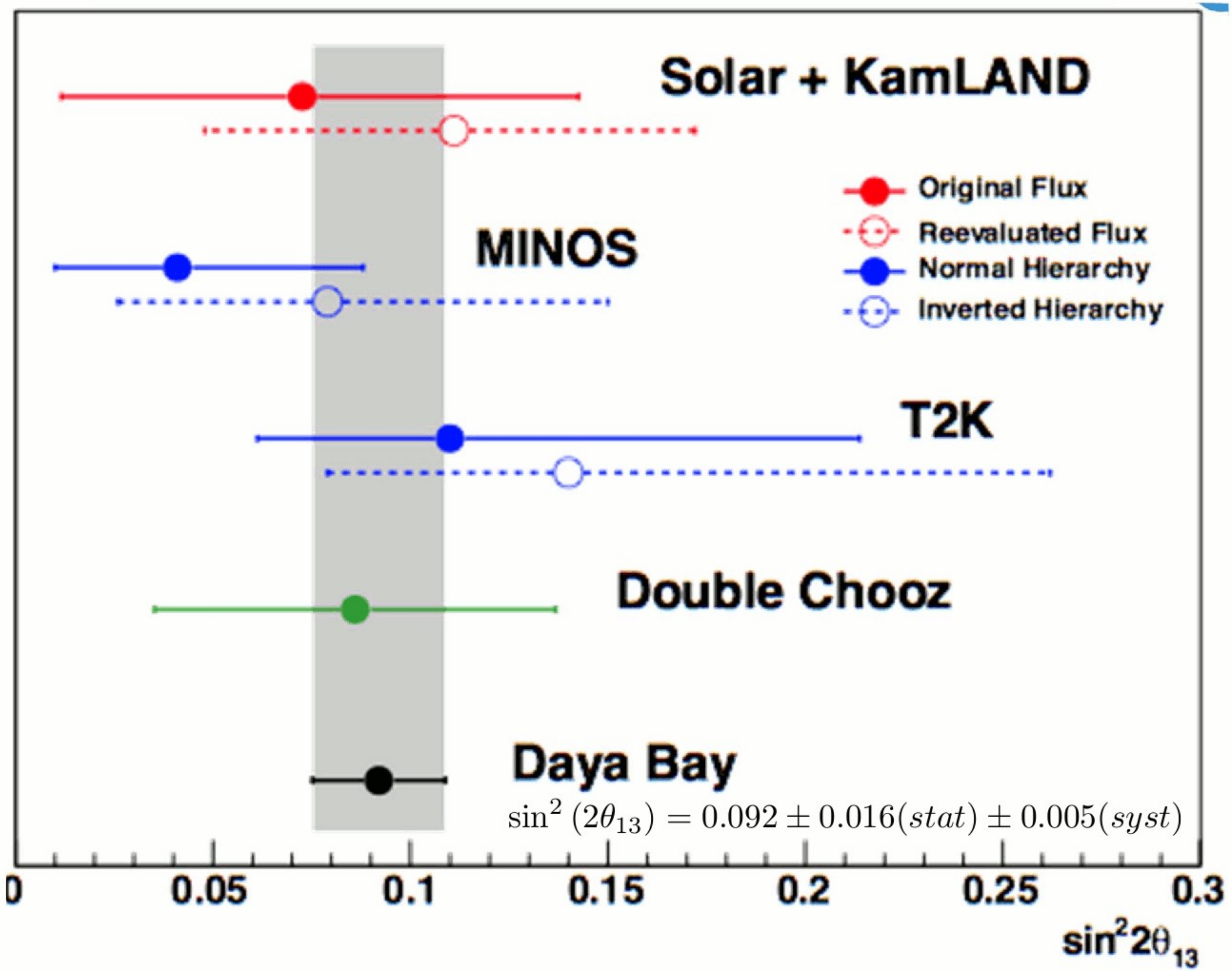


46 m overburden
16 t target mass
1280 events/day

Started to take data with both near and far detectors in August 2011
Good detector performance.
$\sin^2 2\theta_{13}$ results expected within ~half year

168 m overburden
16 t target mass
114 events/day

θ_{13} Overview



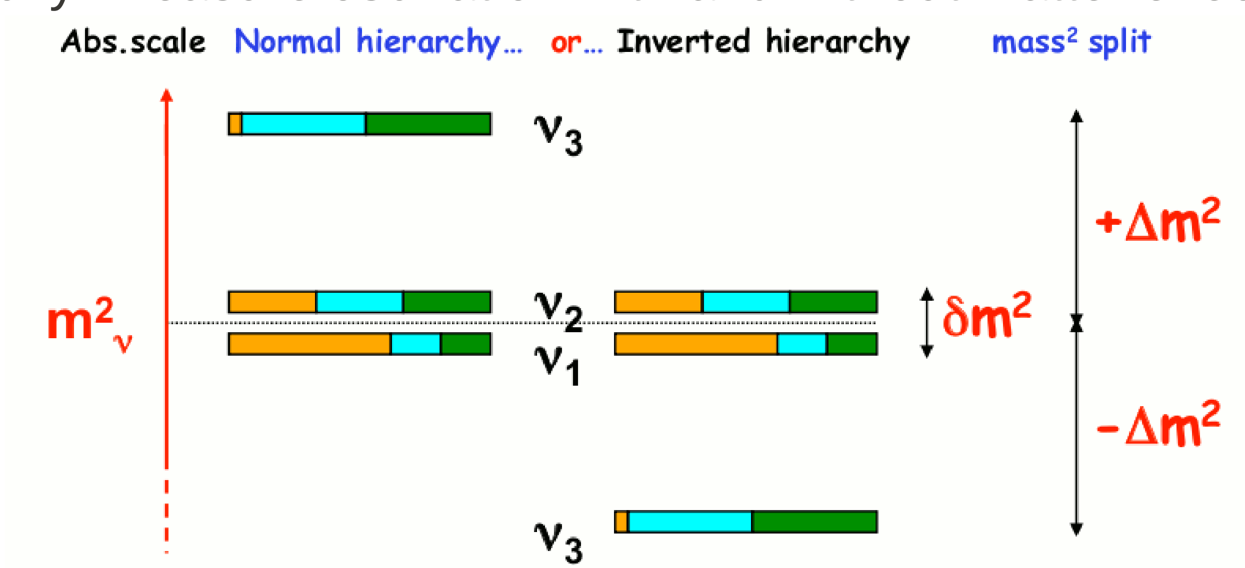
Focus of the Next Years

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

- $\sin 2\theta_{13} > 0 \rightarrow$ access to CP violation:

$$P_{\alpha\beta}(\nu) - P_{\alpha\beta}(\bar{\nu}) = 2 \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$
$$\times \sin\left(\frac{\Delta m^2 - \frac{\delta m^2}{2}}{4E} L\right) \sin\left(\frac{\Delta m^2 + \frac{\delta m^2}{2}}{4E} L\right) \sin\left(\frac{\delta m^2}{4E} L\right)$$

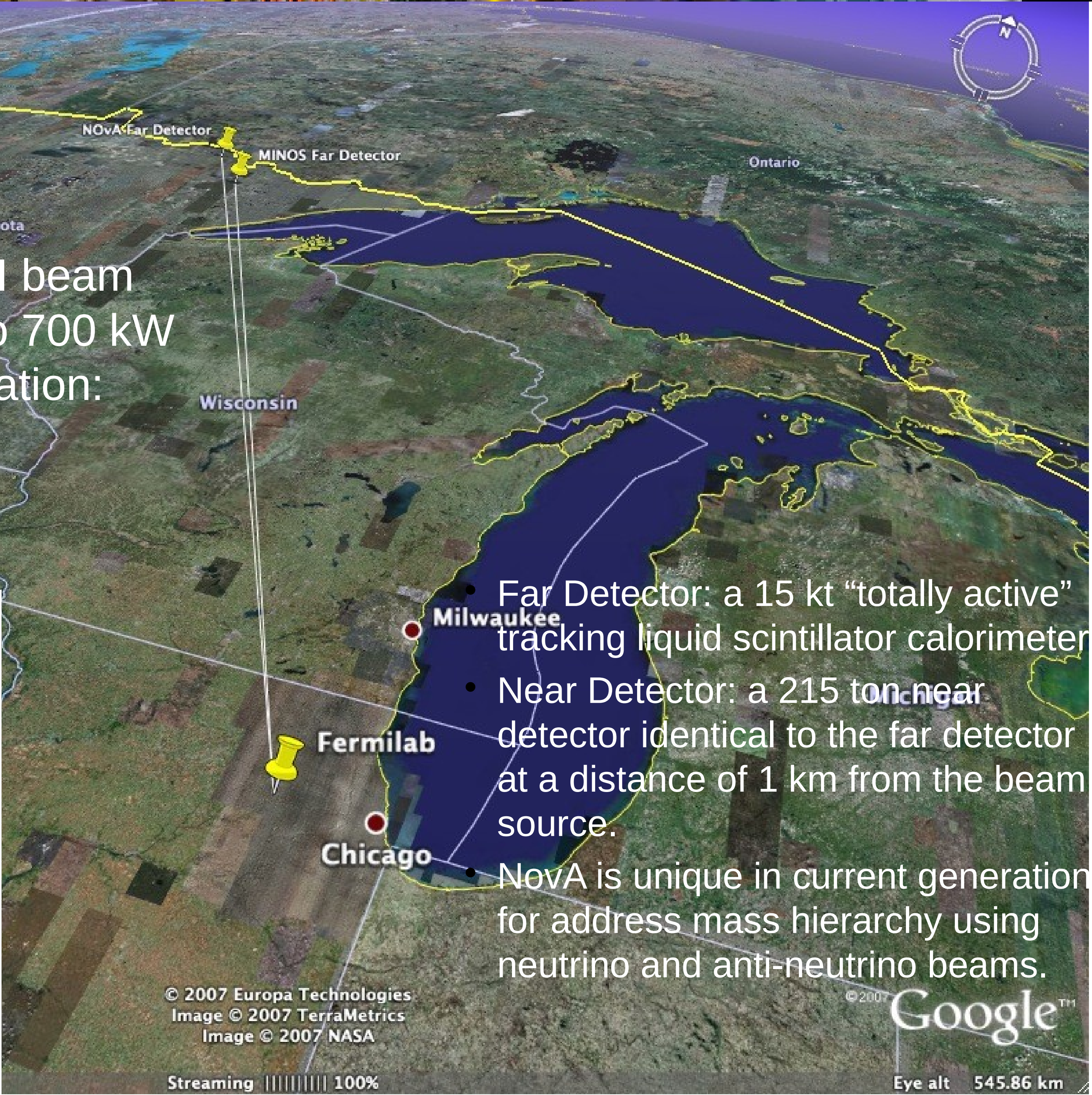
- Prob hierarchy: measure oscillation with and without matter effect:

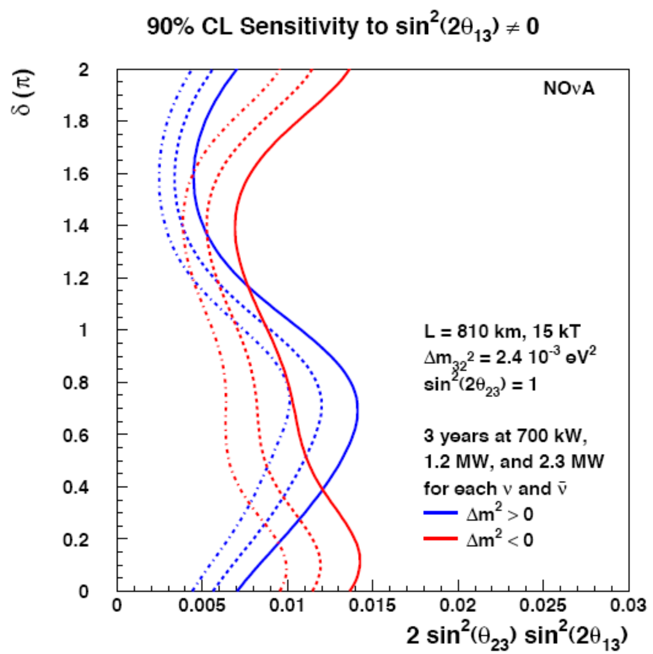


NOvA

- An upgrade of the NuMI beam intensity from 400 kW to 700 kW
- NOvA Far Detector Location:
  Ash River, MN
  810 km from Fermilab
  14.6 mrad off axis

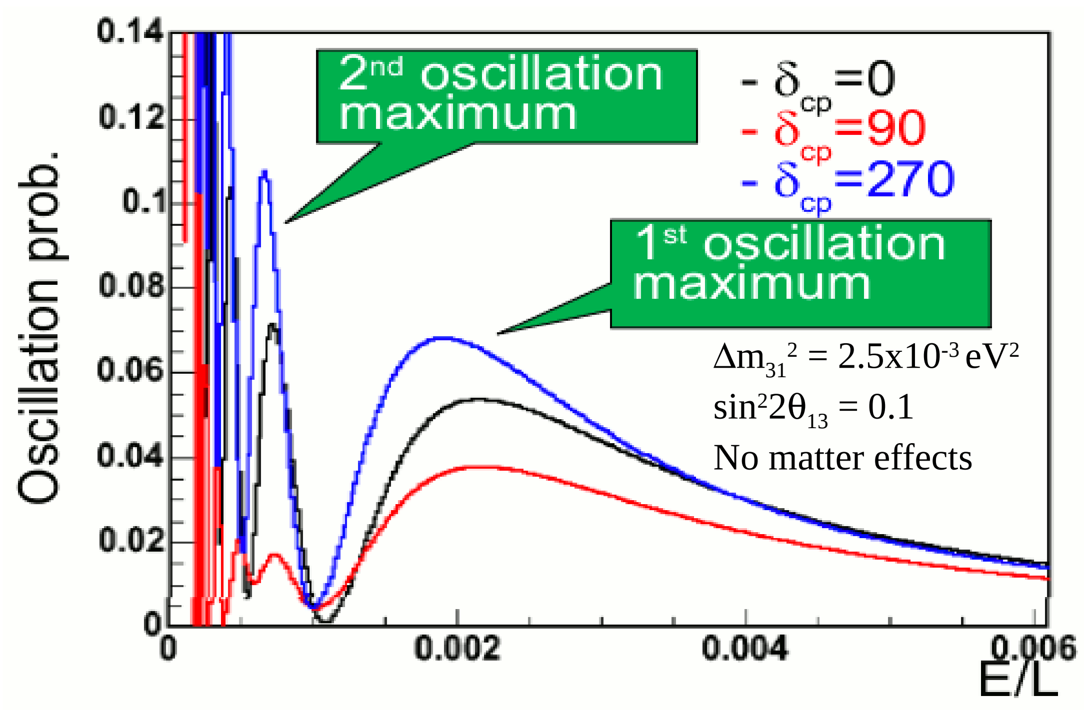
- Far Detector: a 15 kt “totally active” tracking liquid scintillator calorimeter
- Near Detector: a 215 ton near detector identical to the far detector at a distance of 1 km from the beam source.
- NovA is unique in current generation for address mass hierarchy using neutrino and anti-neutrino beams.





T2K Upgrade

Oscillation probabilities for $\nu_\mu \rightarrow \nu_e$ for different values of the oscillation parameter.



CP violation can be studied either:

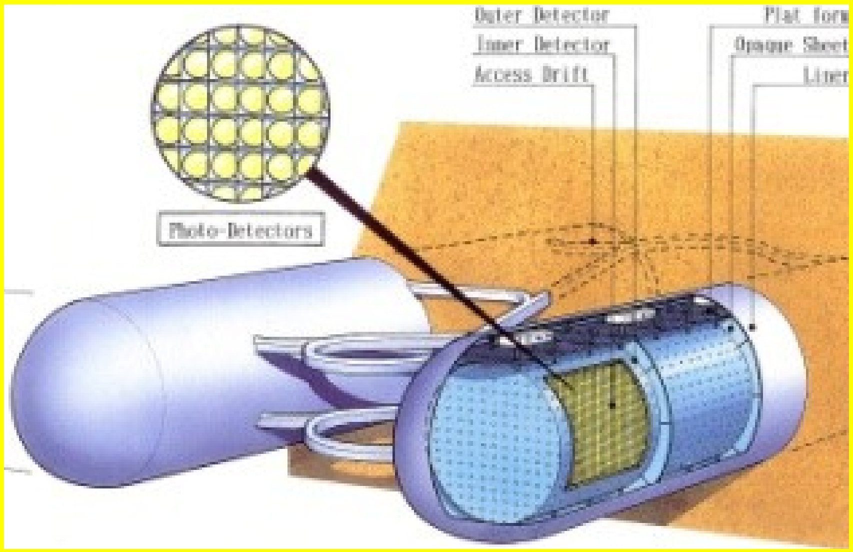
- comparing $P(\nu_\alpha \rightarrow \nu_\beta)$ versus $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$, where ν_α and ν_β are two neutrino flavours

or

- comparing the first and second oscillation peaks.

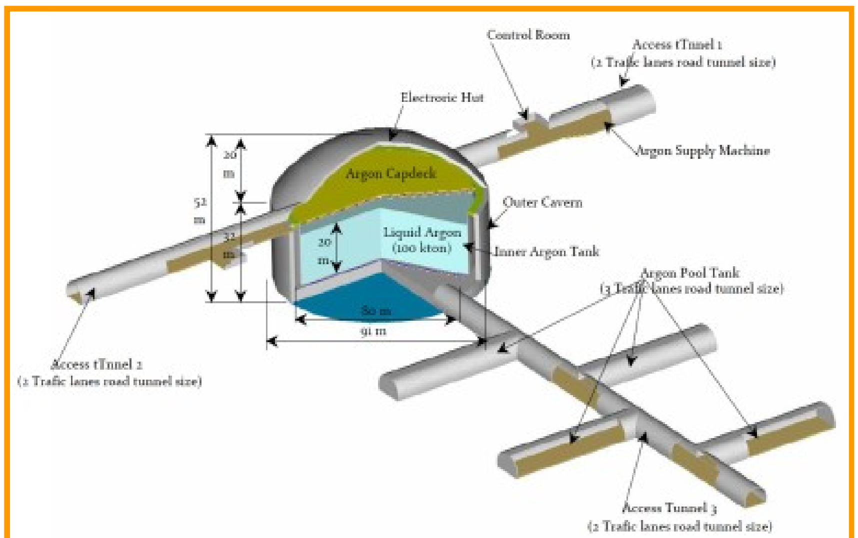
CP violation can't be observed in $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha$ as it is related to $\nu_\alpha \rightarrow \nu_\alpha$ by CPT.

T2K



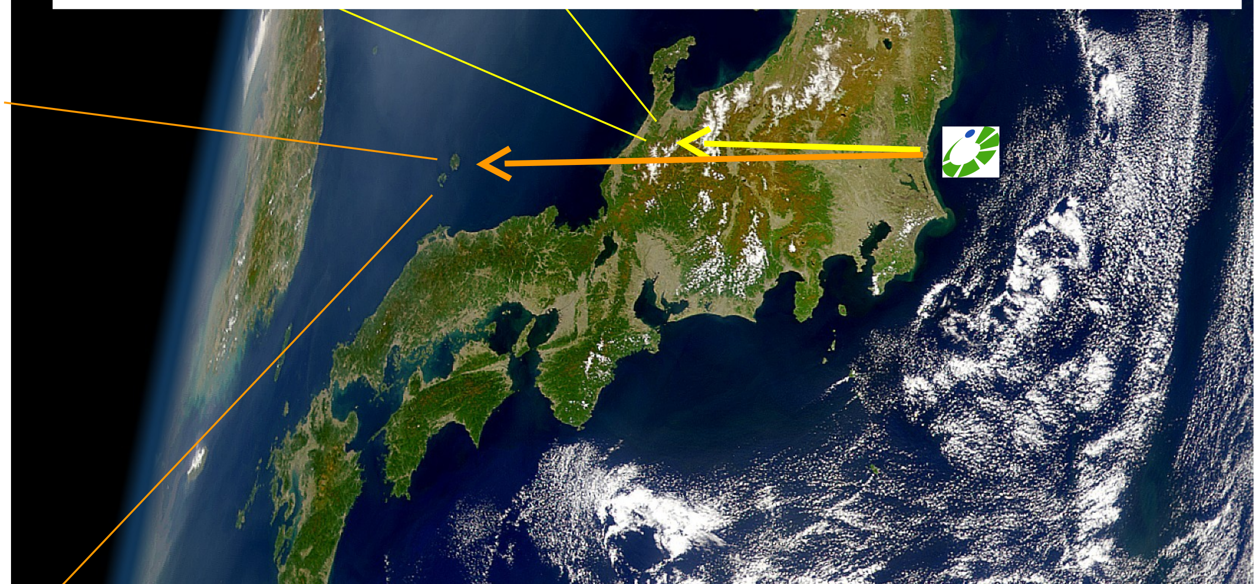
Kamioka L=295km OA=2.5deg

Okinoshima L=658km OA=0.78deg



P32 proposal (Lar TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111

- Baseline
  - Long:
    - ○ 2nd Osc. Max. at Measurable Energy
    - × Less Statistics
    - ? Large Matter Effect
  - Short:
    - ○ High Statistics
    - × 2nd Osc.Max.Too Low Energy to Measure
    - ? Less Matter Effect



DISCLAMER: the current configurations and technologies of the upgrade are under discussion within the community.

T2K Upgrade

Shiozawa, NNN 2011 conference

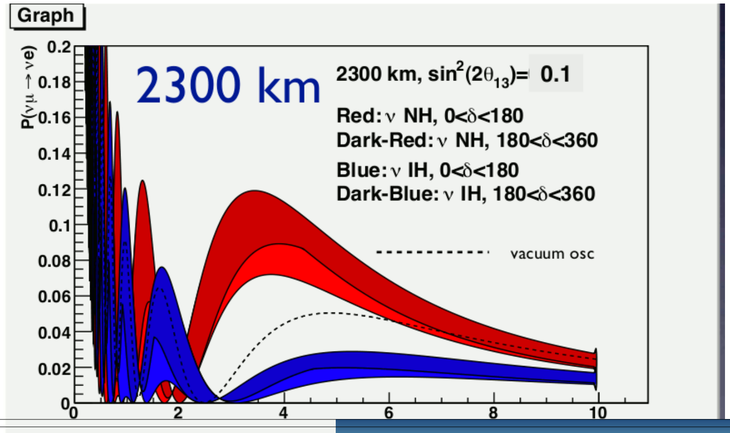
Hyper-K WG,
arXiv:1109.3262 [hep-ex]

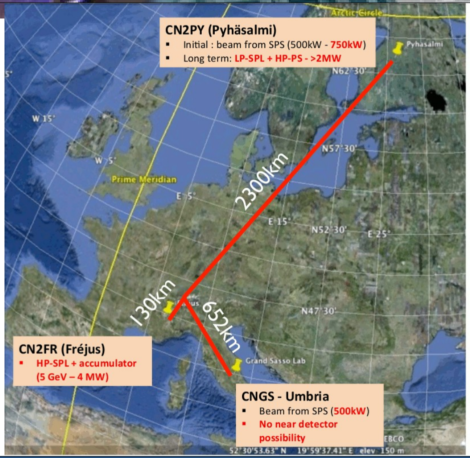
- Baseline design
- physics potential

Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		1.66 MW $\times$ 5 years (1 year $\equiv 10^7$ sec)
– CP phase precision	$< 18°$	@ $s^2 2\theta_{13} (\equiv \sin^2 2\theta_{13}) > 0.03$ and
		mass hierarchy (MH) is known
– CPV 3σ discovery coverage	74% (55%)	@ $s^2 2\theta_{13} = 0.1$, MH known(unknown)
	74% (63%)	@ $s^2 2\theta_{13} = 0.03$, MH known(unknown
	66% (59%)	@ $s^2 2\theta_{13} = 0.01$, MH known(unknown
Atmospheric neutrino study		10 years observation
– MH determination	$> 3\sigma$ CL	@ $0.4 < s^2\theta_{23}$ and $0.04 < s^2 2\theta_{13}$
– θ_{23} octant determination	$> 90\%$ CL	@ $s^2 2\theta_{23} < 0.99$ and $0.04 < s^2 2\theta_{13}$
Nucleon Decay Searches		10 years data
– $p \to e^+ + \pi^0$	1.3×10^{35} yrs (90% CL)	
	5.7×10^{34} yrs (3σ CL)	
– $p \to \bar{\nu} + K^+$	2.5×10^{34} yrs (90% CL)	
	1.0×10^{34} yrs (3σ CL)	
Solar neutrinos		
– ^{8}B ν from Sun	200 ν's / day	7.0 MeV threshold (total energy) w/ o
– ^{8}B ν day/night accuracy	$< 1\%$	5 years, only stat. w/ SK-I BG $\times 20$
Astrophysical objects		
– Supernova burst ν	170,000~260,000 ν's	@ Galactic center (10 kpc)
	30~50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	
– WIMP annihilation at Sun		5 years observation
	$\sigma_{SD} = 10^{-39}\text{cm}^2$	@ $M_{\text{WIMP}} = 10$ GeV, $\chi\chi \to b\bar{b}$ domina

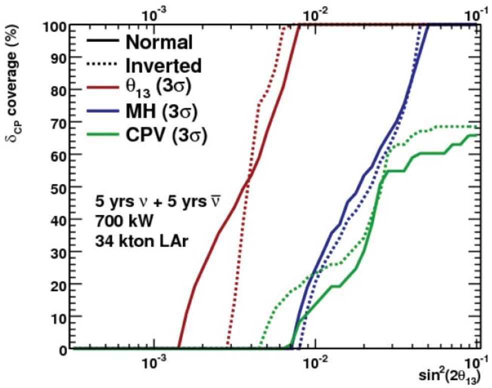
Experiments for CPV in 202x

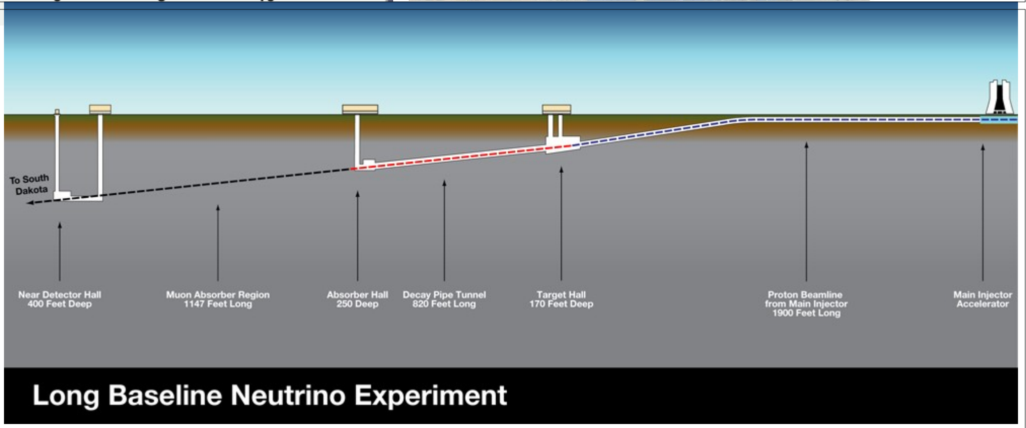
LAGUNA-LBNO (EU):
Long baseline experiment from CERN



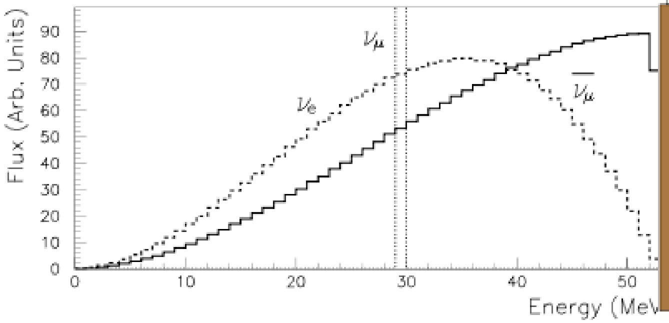


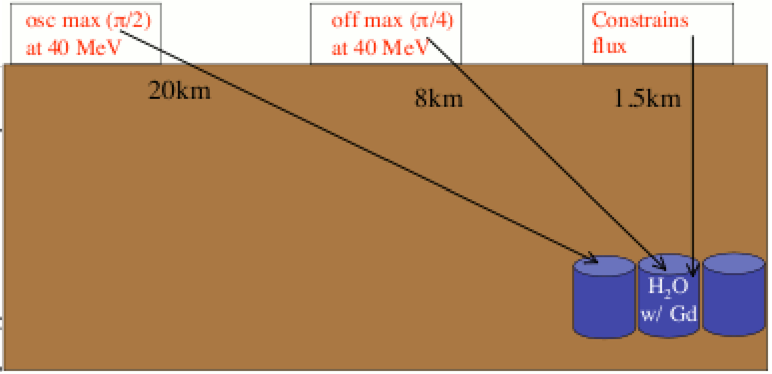
LBNE (US):
Long baseline neutrino experiment from Fermilab





DAEDALOUS (US):
neutrino from pion and muon decays at rest producted from proton accelerators





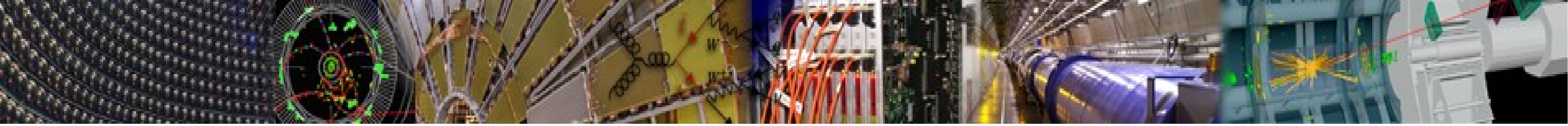
Conclusions

- Exciting last 9 months in neutrino physics
- After several indication of a non-zero value of θ_{13} (T2K, Minos, Double Chooz), it has been measured by Daya Bay:

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

$\chi^2/\mathrm{NDF} = 4.26/4$ 5.2σ for non-zero θ_{13}

- A breakthrough result: this will shape the preparation for the future neutrino experiments
- Current experiments will seek to validate this result in the short term future (T2K just restarted taking data after 1y from the earthquake)
- <u>This opens up the exciting prospective of measuring CP in the next future....</u>



Be Tuned!!

What's next for the Standard Model?

Nu's Weak

January 2013

$\nu_\mu \rightarrow \nu_e$ observed!

Can we now explain the Universe?

Backup Slides

Plans @ Fermilab

Draft 2012-15 Fermilab Accelerator Experiments' Run Schedule

Typically Revised Annually - This Version from January, 2012

Calendar Year		2012	2013	2014	2015
Neutrino Program	B	MiniBooNE	OPEN	OPEN	OPEN
	B		MicroBooNE	MicroBooNE	MicroBooNE
Muons	B		g-2	g-2	g-2
Neutrino Program	MI	MINERvA	MINOS+	MINOS+	MINOS+
	MI	MINOS	MINERvA	MINERvA	MINERvA
	MI	NOvA	NOvA	NOvA	NOvA
SY 120	MT	Test Beam	Test Beam	Test Beam	Test Beam
	MC	OPEN	OPEN	OPEN	OPEN
	NM4	SeaQuest	E-906/SeaQuest	E-906/SeaQuest	OPEN

This draft schedule is meant to show the general outline of the Fermilab accelerator experiments schedule, including unscheduled periods.

IMajor components of the schedule include shutdowns:

In Calendar 2012-2013, an 11 month shutdown for M&D scheduled to begin approximately May 1 to upgrade the proton source and change the NuMI beam to the Medium Energy (ME) configuration.

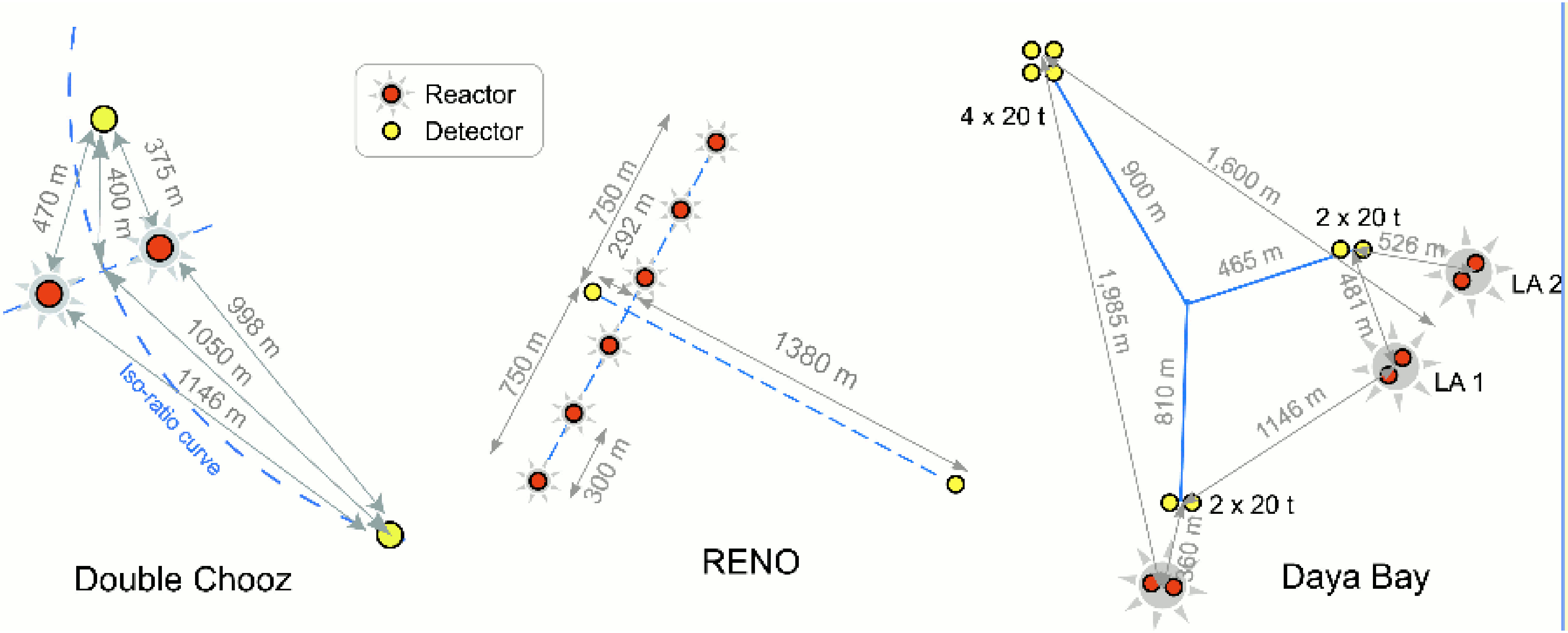
Later years are expected to have maintenance shutdowns of 4 to 6 weeks, typically in the summer months.

- RUN/DATA
- STARTUP/COMMISSIONING
- INSTALLATION
- M&D (SHUTDOWN)

31-Jan-12

http://www.fnal.gov/directorate/program_planning/schedule/

Reactor Neutrino Detectors



Comparisons

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	P_{Th} or P_{Target}	L [km]	Detector	m
Double Chooz	-	3	8.6 GW	1.05	L. scint.	8.
Daya Bay	-	3	17.4 GW	1.7	L. scint.	8
RENO	-	3	16.4 GW	1.4	L. scint.	15.
T2K	5	-	0.75 MW	295	Water	22.5
NOνA	3	3	0.7 MW	810	TASD	15