Latest results from neutrino oscillations

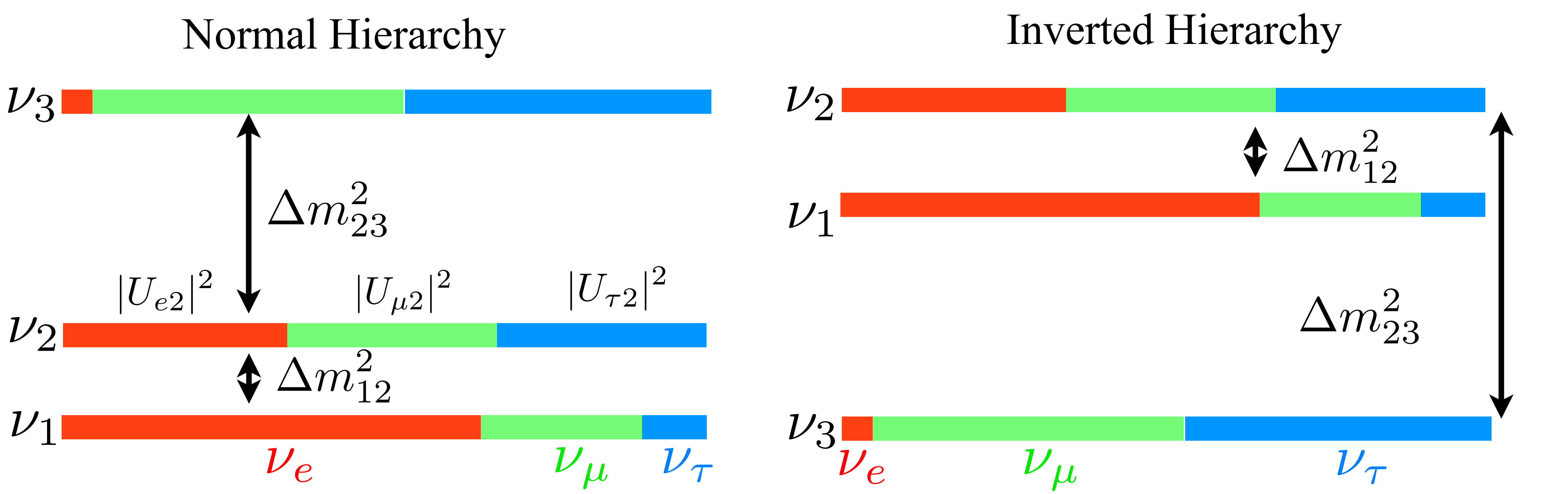
Melody Ravonel Salzgeber

outline

- What we know from current experiments
- What we don't know
    - Future oscillation experiments

Status of the neutrino physics: what we know

- Neutrino flavor eigenstates are superposition of neutrino mass eigentsates $\nu_\alpha = \sum_i U_{\alpha i}\nu_i$



- All mixing angles and mass square differences are now known with good precision

$\Delta m_{21}{}^2 = (7.6 \pm 0.2)\ 10^{-5}\ \mathrm{eV}^2$

$\theta_{12} \sim 34°$ ~4.6% error

$\theta_{13} \sim 9°$ ~11-15% error

$\Delta m_{31}{}^2 = (2.5 \pm 0.1)\ 10^{-3}\ \mathrm{eV}^2$ NH

$\Delta m_{31}{}^2 = -(2.4 \pm 0.1)\ 10^{-3}\ \mathrm{eV}^2$ IH

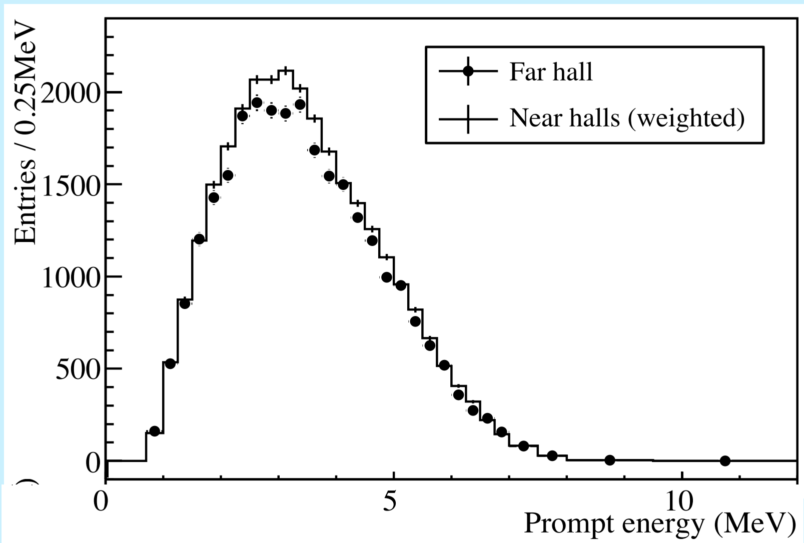
$\theta_{23} \sim 45°$ ~10-16% error

Big mixing angle
in comparison to the quark sector

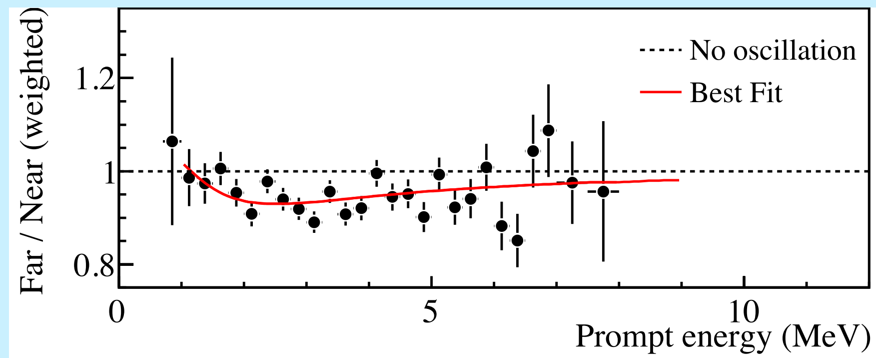
θ_{13}

$$\left.\begin{aligned}
\sin^2 2\theta_{13}|_{\text{Double-CHOOZ}} &= 0.109 \pm 0.030(stat) \pm 0.025(syst)\\
\sin^2 2\theta_{13}|_{\text{Daya Bay}} &= 0.089 \pm 0.010(stat) \pm 0.005(syst)\\
\sin^2 2\theta_{13}|_{\text{RENO}} &= 0.113 \pm 0.013(stat) \pm 0.019(syst)
\end{aligned}\right\}$$

Reactor experiments

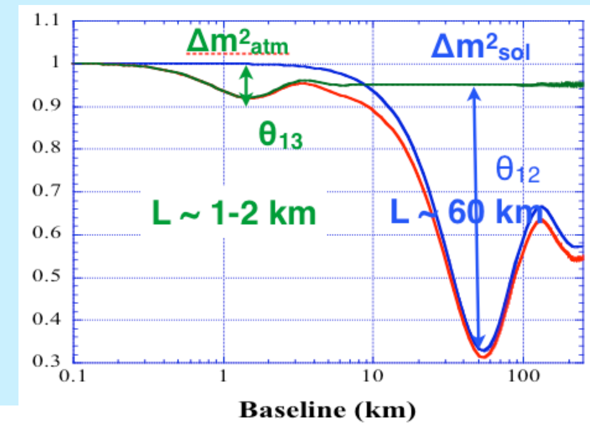


Daya Bay



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

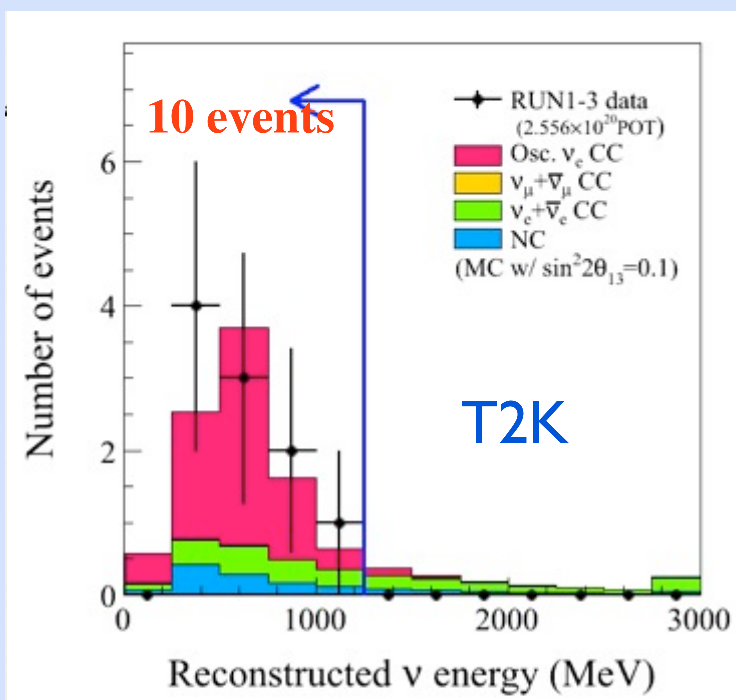
- anti-ν_e disappearance

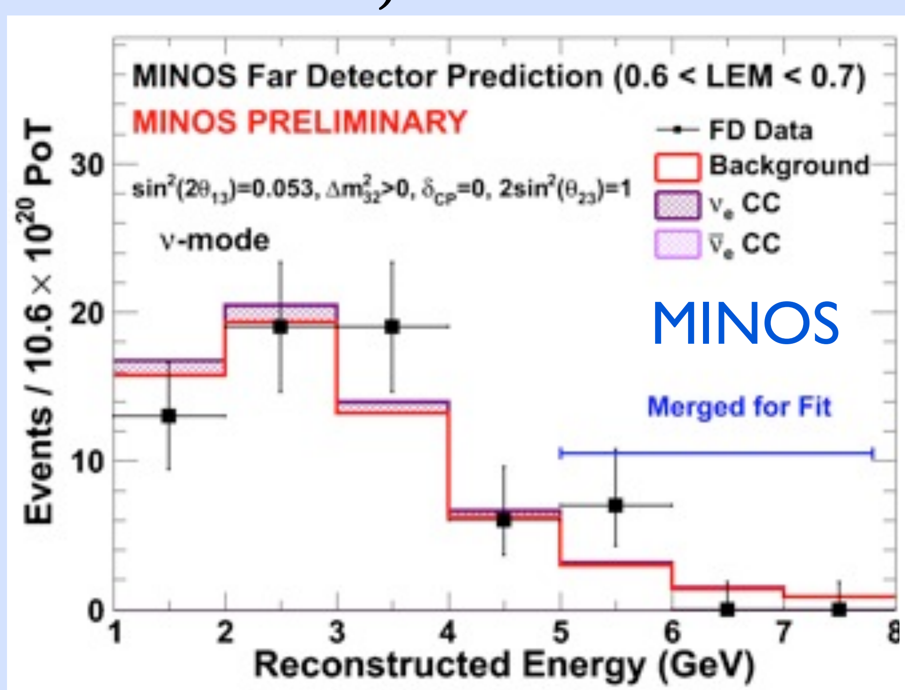


$$\left.\begin{aligned}
\sin^2 2\theta_{13}|_{\text{MINOS}} &= 0.094^{+0.04}_{-0.05}\\
\sin^2 2\theta_{13}|_{\text{T2K}} &= 0.104^{+0.060}_{-0.045}
\end{aligned}\right\}$$

Accelerator experiments

$P_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2(\Delta m^2 L/4E_\nu)$ + corrections

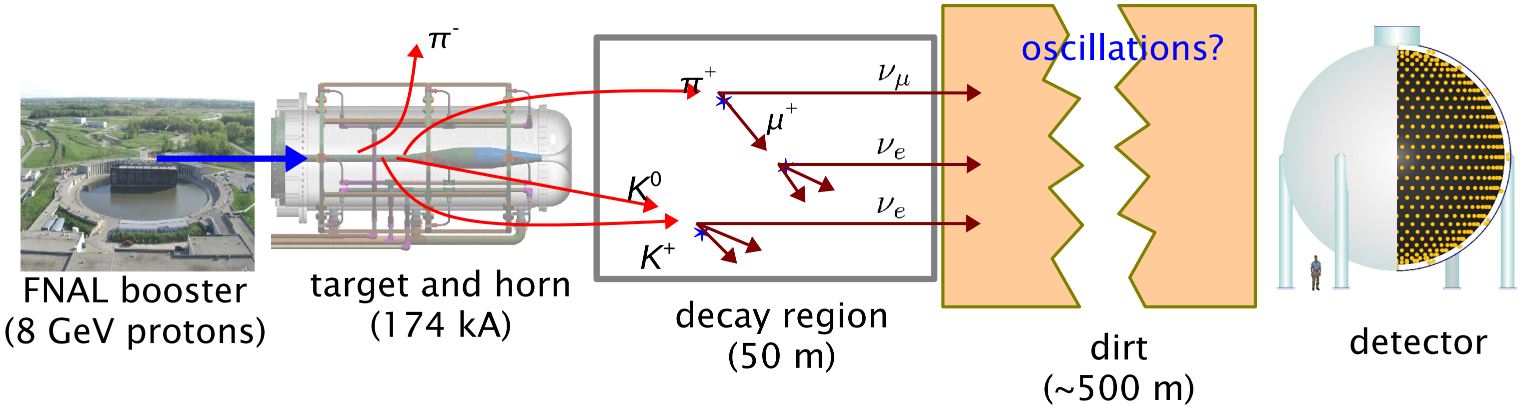




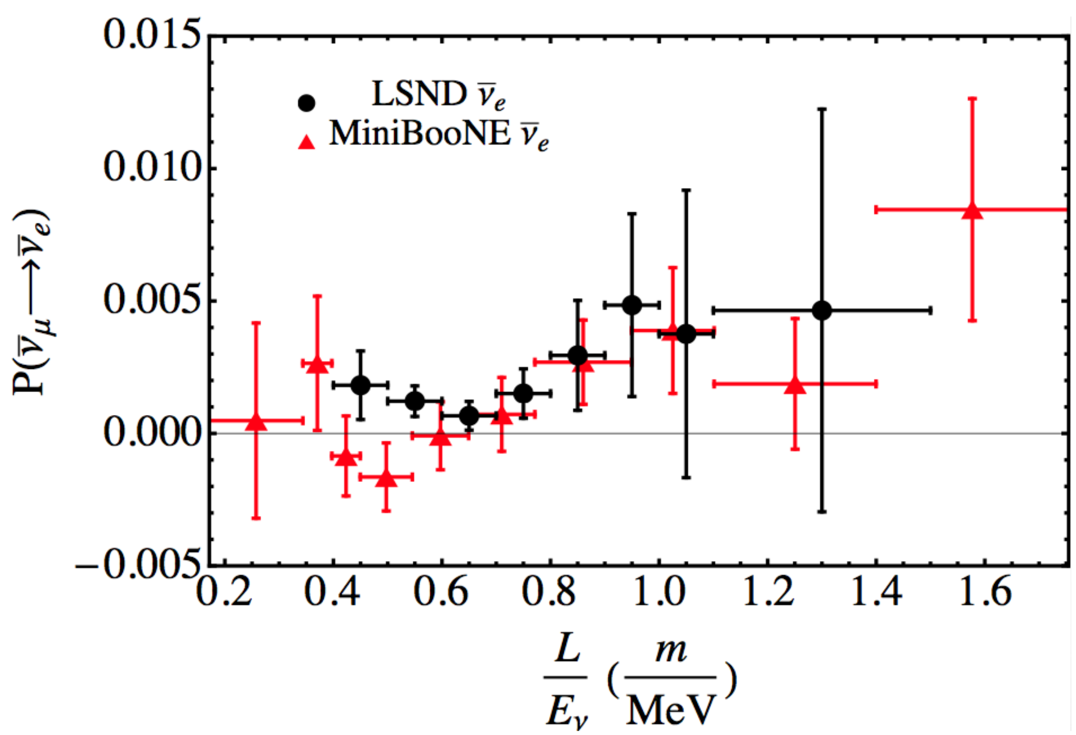
- ν_e appearance

MiniBOONE - LSND (short base line)

MiniBOONE

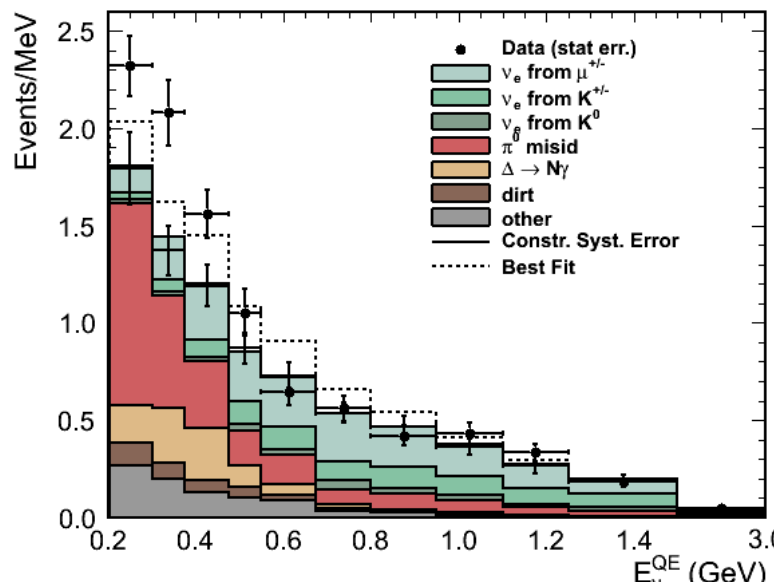


- MiniBOONE observe an excess at low energy.
- They observe comparable results than LSND



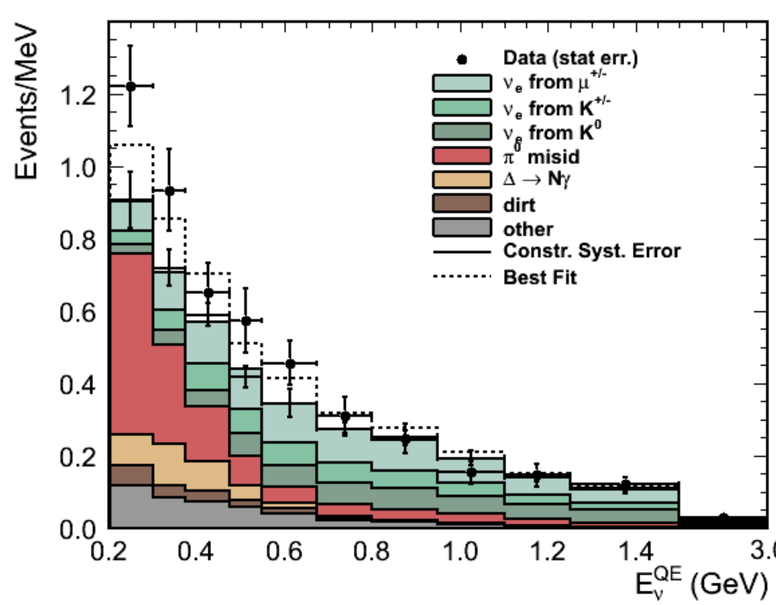
ν_μ

6.5e20 POT neutrino mode w/ 3+1 fit



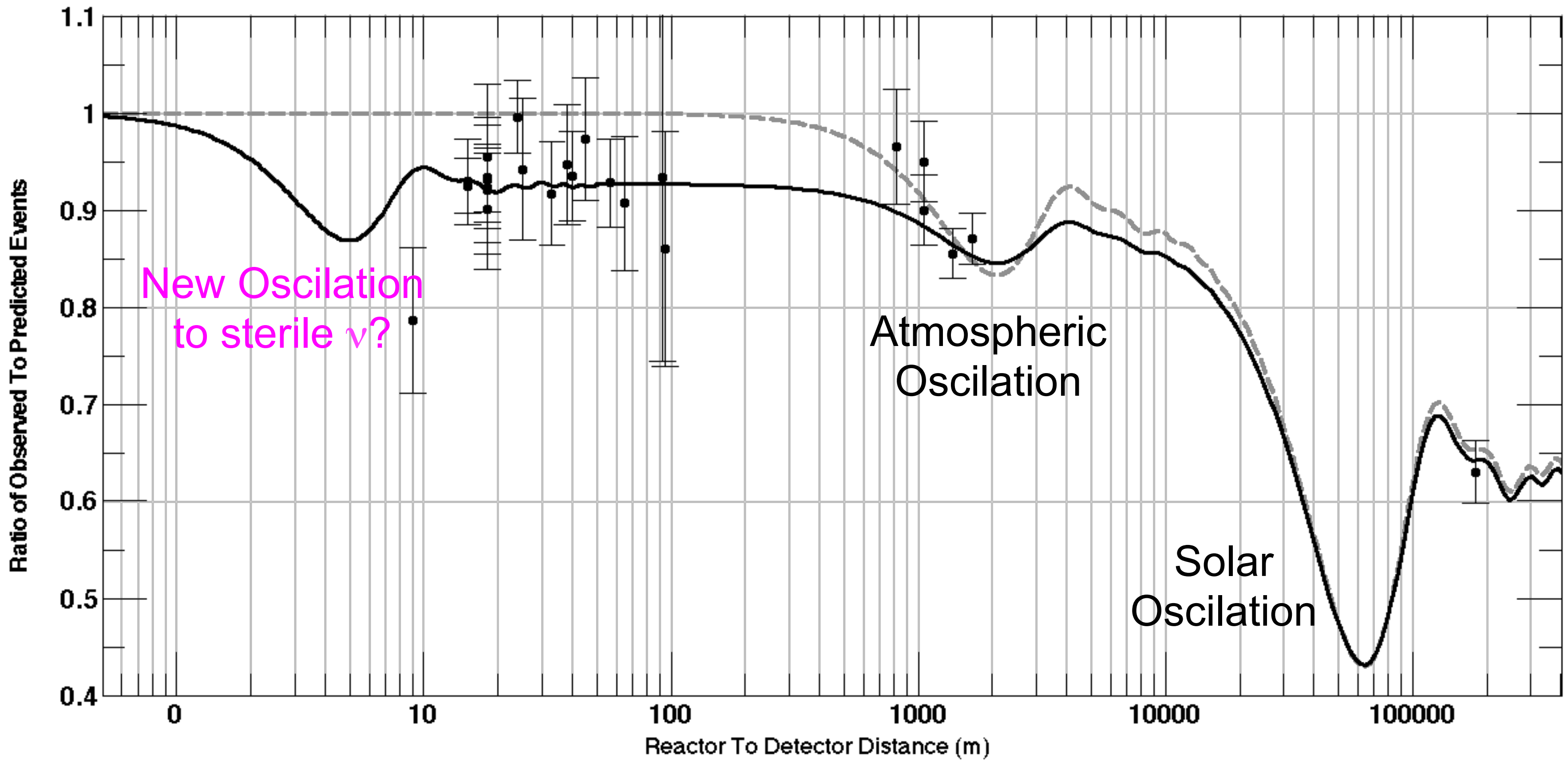
anti-ν_μ

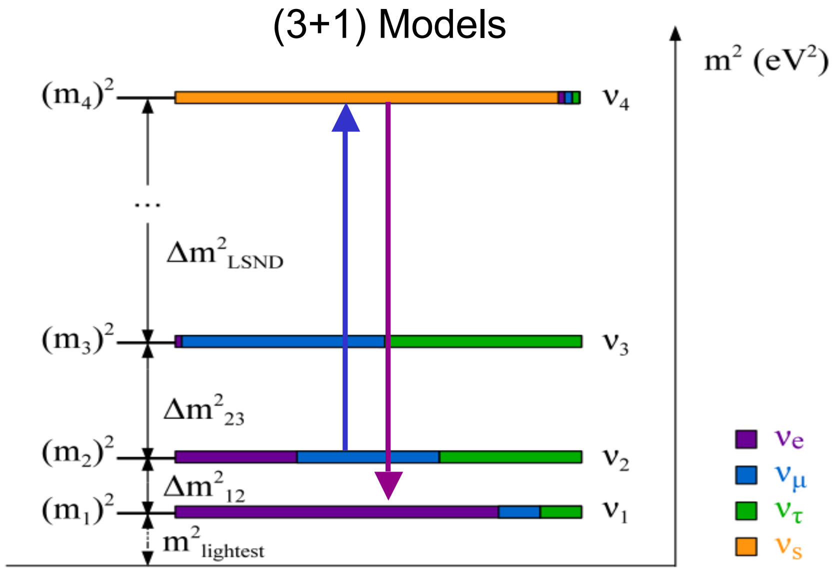
11.3e20 POT anti-neutrino mode w 3+1fit

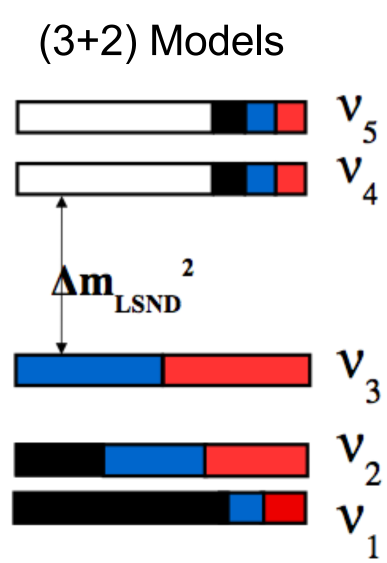


Reactor anomaly, sterile neutrinos?

G. Mention et al., Phys. Rev. D83, 073006, 2011







- Current measurements of appearance and disappearance are not very compatible with (3+1) models ⇒ (3+2) models
  - If $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ are different then (3+2) models can have CP violation
  - Still tension between appearance and disappearance

What we don't know

can be answered by neutrino oscillation studies

- The mass hierarchy
- Is θ_{23} maximal ?
- The CP phase (violation? can explain matter - anti-matter asymmetry)
- Absolute mass scale
- Type of neutrino (Dirac mass term or Majorana mass term or both => sterile neutrino)
    - Existence of sterile neutrino explaining the deficit of observed events or excess in MiniBOONE-LSND ➡ might be answered by oscillation experiment

Mass Hierarchy (reactors)

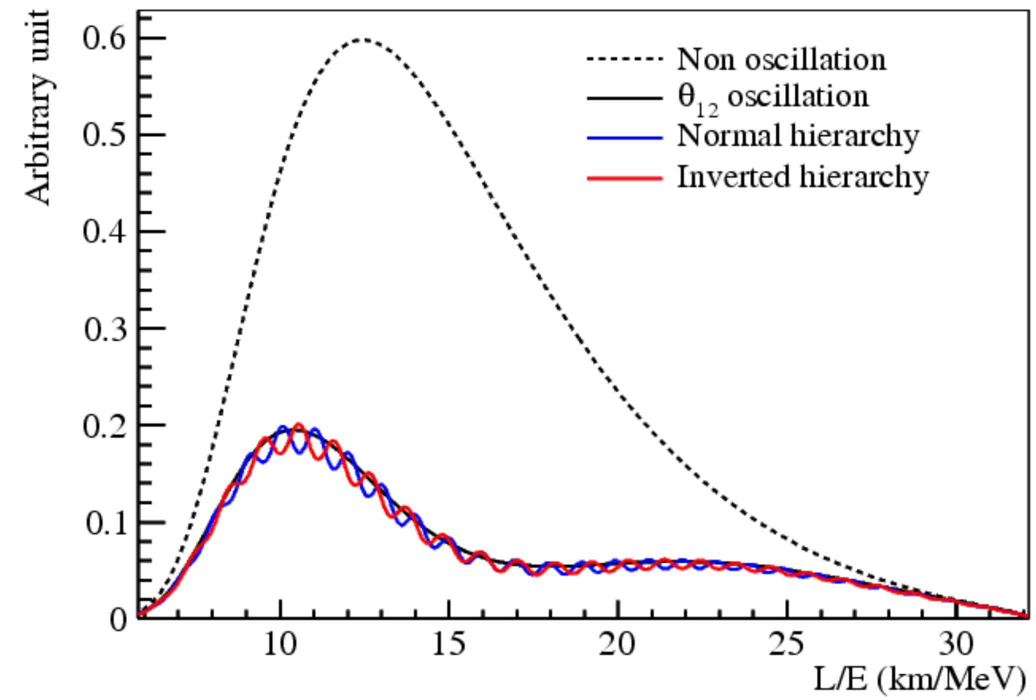
Reactor experiment sensitivity using Fourier transform

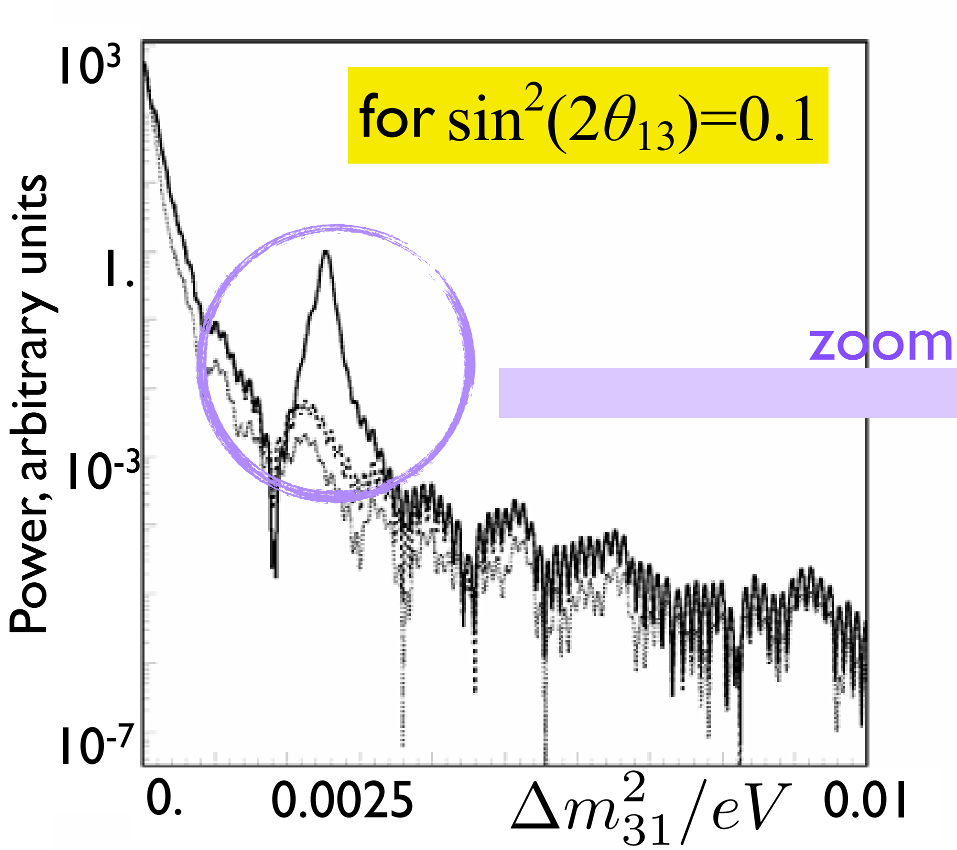
$$P_{ee} \approx 1 - \boxed{\sin^2 2\theta_{13}}\,\boxed{\sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

dominant term need to be sensitive to this term

=> Bigger detector,

at the right base line for a given energy

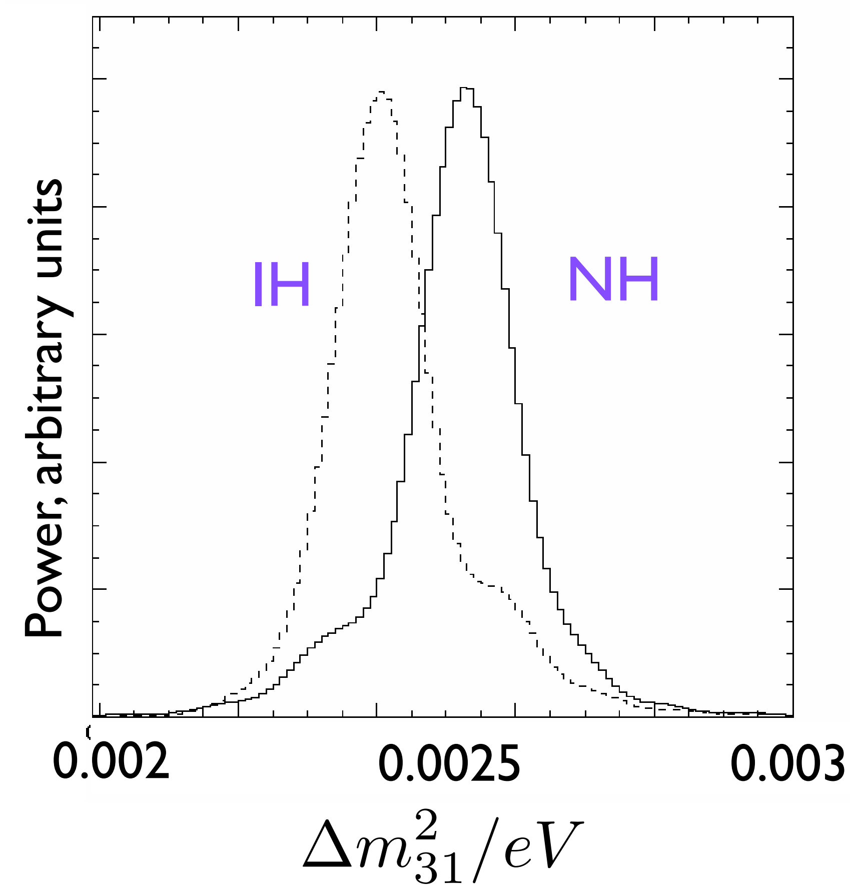




zoom of the peak

FIG. 2: Fourier power spectrum with modulation in units of eV^2 and power in arbitrary units on the logarithmic scale. The peak due to Δ_{31} with $\sin^2(2\theta_{13})$=0.1 is prominent.

zoom of the peak for the 2 hierarchies



Mass hierarchy + CP phase (accelerators)

Accelerator experiments use the matter effect in the ν_e appearance channel

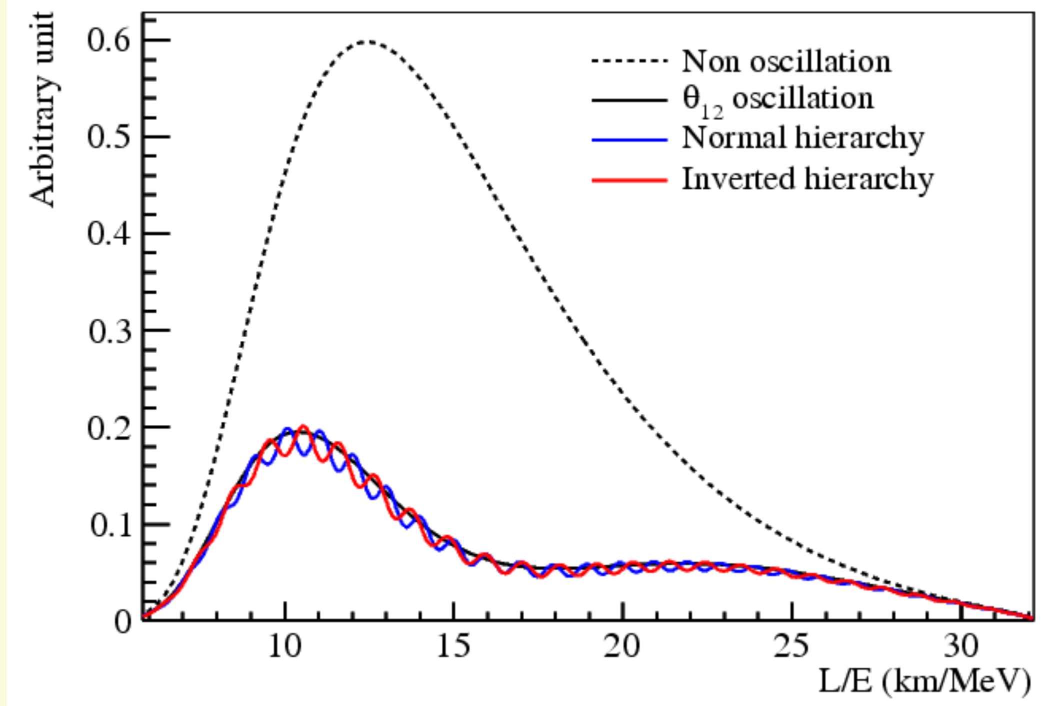
➡ need very long base line

see Alain's talk
and Mark's talk

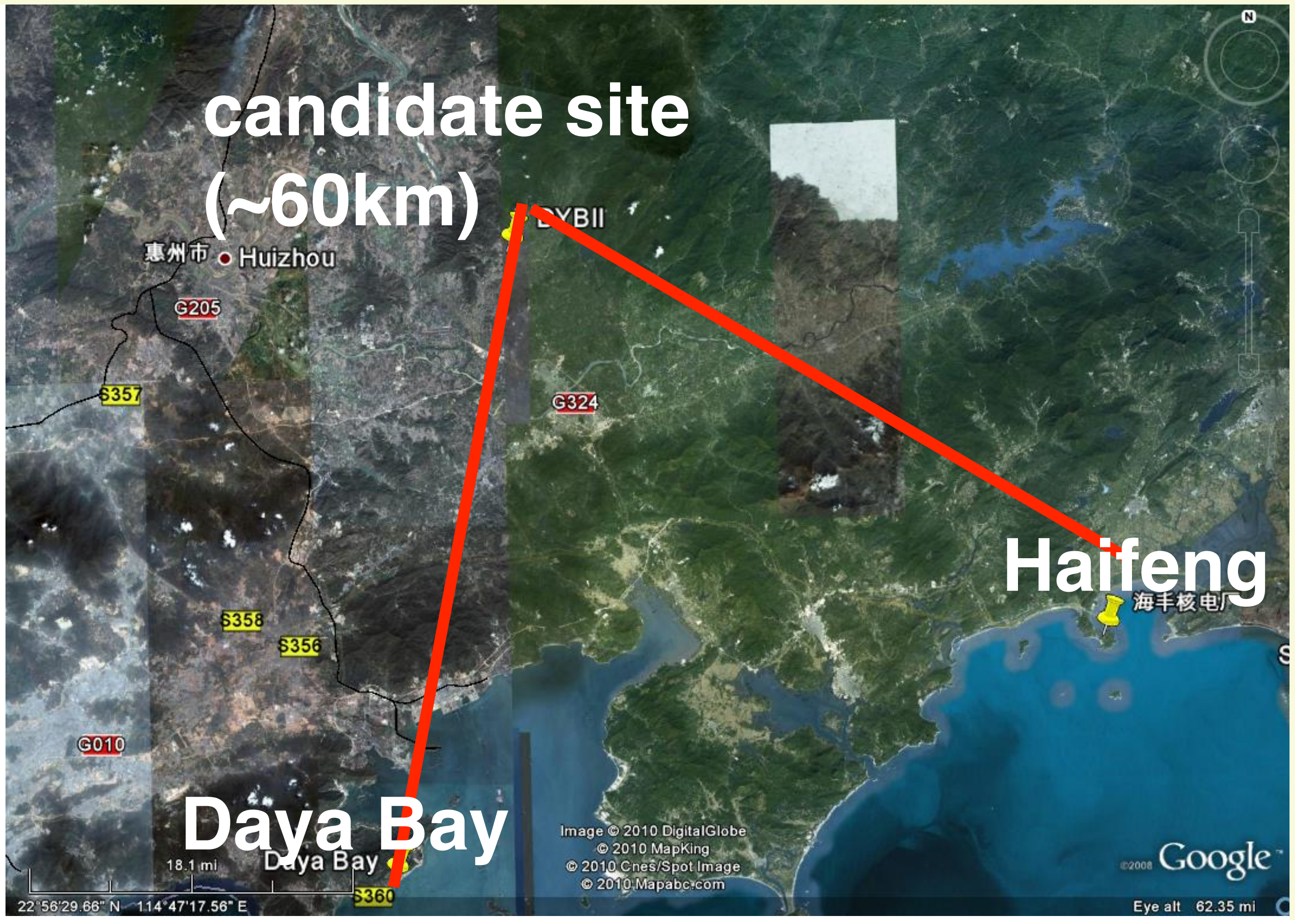
Future experiments

- Daya Bay II
  20 kton detector

50k events expected in 3 years
3 σ sensitivity (after 6 years)



- reactor experiment



- INO
- Hyper-Kamiokande
- PINGU (ICE CUBE)
- NOVA + T2K+
  REACTORS

Future experiments

- Daya Bay II
  20 kton detector

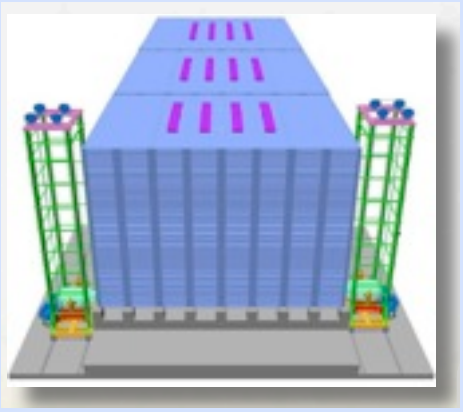
  ~3σ sensitivity for mass hierarchy, (6 years)
  - reactor experiment

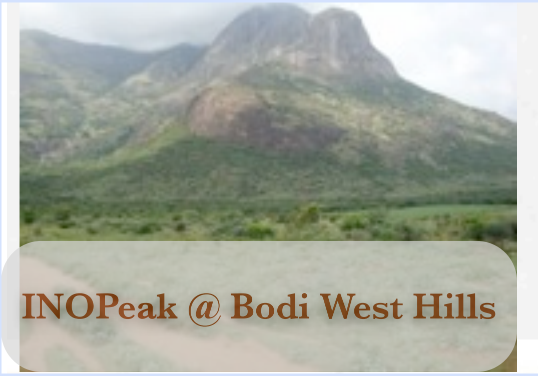
- INO
  50 kton detector
  - for atmospheric neutrinos

  ~2σ sensitivity for mass hierarchy for $\sin^2\theta_{23}= 0.5$, $\sin^2 2\theta_{13}= 0.1$, by 2022 (5 years)

  ~2.7σ sensitivity for mass hierarchy for $\sin^2\theta_{23}= 0.5$, $\sin^2 2\theta_{13}= 0.1$, by 2027 (10 years)

- Hyper-Kamiokande





- PINGU (ICE CUBE)

- NOVA + T2K+ REACTORS

magnetized iron detector (tracking calorimeter) → good energy resolution, good charge ID → Full oscillation pattern; → can distinguish ν_μ vs anti-ν_μ

Future experiments

- Daya Bay II
  20 kton detector

  ~3σ sensitivity for mass hierarchy, (6 years)
  - reactor experiment

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  50 kton detector
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  ~2σ sensitivity for mass hierarchy for $\sin^2\theta_{23}= 0.5$, $\sin^2 2\theta_{13}= 0.1$, by 2022 (5 years)
  ~2.7σ sensitivity for mass hierarchy for $\sin^2\theta_{23}= 0.5$, $\sin^2 2\theta_{13}= 0.1$, by 2027 (10 years)

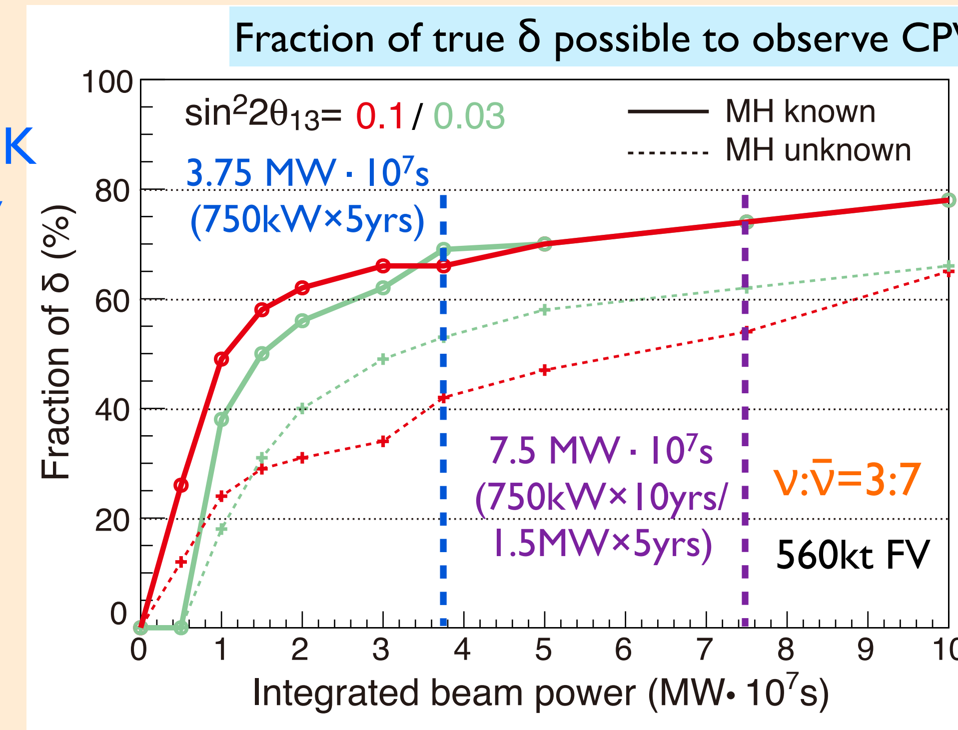
- Hyper-Kamiokande
  1 Mton (20x SK)
  - for atmospheric neutrinos
  - as far detector (T2HK)

  ~3σ sensitivity for mass hierarchy for $\sin^2\theta_{23}= 0.5$, $\sin^2 2\theta_{13}= 0.1$, by 2028 (5 years)
  ~4σ sensitivity for mass hierarchy for $\sin^2\theta_{23}= 0.5$, $\sin^2 2\theta_{13}= 0.1$, by 2033 (10 years)
  sensitivity to octant at 90 % C.L. up to $\sin^2 2\theta_{23}= 0.99$ (right plot)

- PINGU (ICE CUBE)

- NOVA + T2K+ REACTORS

750kW = designed T2K luminosity (2017)



For $\sin^2 2\theta_{13}=0.1$

Integ. power (MW× 10^7s)	Mass hierarchy known	Mass hierarchy unknown
3.75	69%	42%
7.5	74%	54%

Future experiments

• Daya Bay II 20 kton detector	~3σ sensitivity for mass hierarchy, (6 years) - reactor experiment
• INO 50 kton detector - for atmospheric neutrinos	~2σ sensitivity for mass hierarchy for $\sin^2\theta_{23}$= 0.5, $\sin^2 2\theta_{13}$= 0.1, by 2022 (5 years) ~2.7σ sensitivity for mass hierarchy for $\sin^2\theta_{23}$= 0.5, $\sin^2 2\theta_{13}$= 0.1, by 2027 (10 years)
• Hyper-Kamiokande 1 Mton (20x SK) - for atmospheric neutrinos - as far detector (T2HK)	~3σ sensitivity for mass hierarchy for $\sin^2\theta_{23}$= 0.5, $\sin^2 2\theta_{13}$= 0.1, by 2028 (5 years) ~4σ sensitivity for mass hierarchy for $\sin^2\theta_{23}$= 0.5, $\sin^2 2\theta_{13}$= 0.1, by 2033 (10 years) sensitivity to octant at 90 % C.L. up to $\sin^2 2\theta_{23}$= 0.99 (right plot) sensitivity to CP phase of 3σ
• PINGU (ICE CUBE) Multi-Mton ICE det. - for atmospheric neutrinos	20 additional string in the deep core, reduce the threshold to 1 GeV 3σ to 11σ sensitivity for mass hierarchy in 5 years
• NOVA + T2K+ REACTORS	

Future experiments

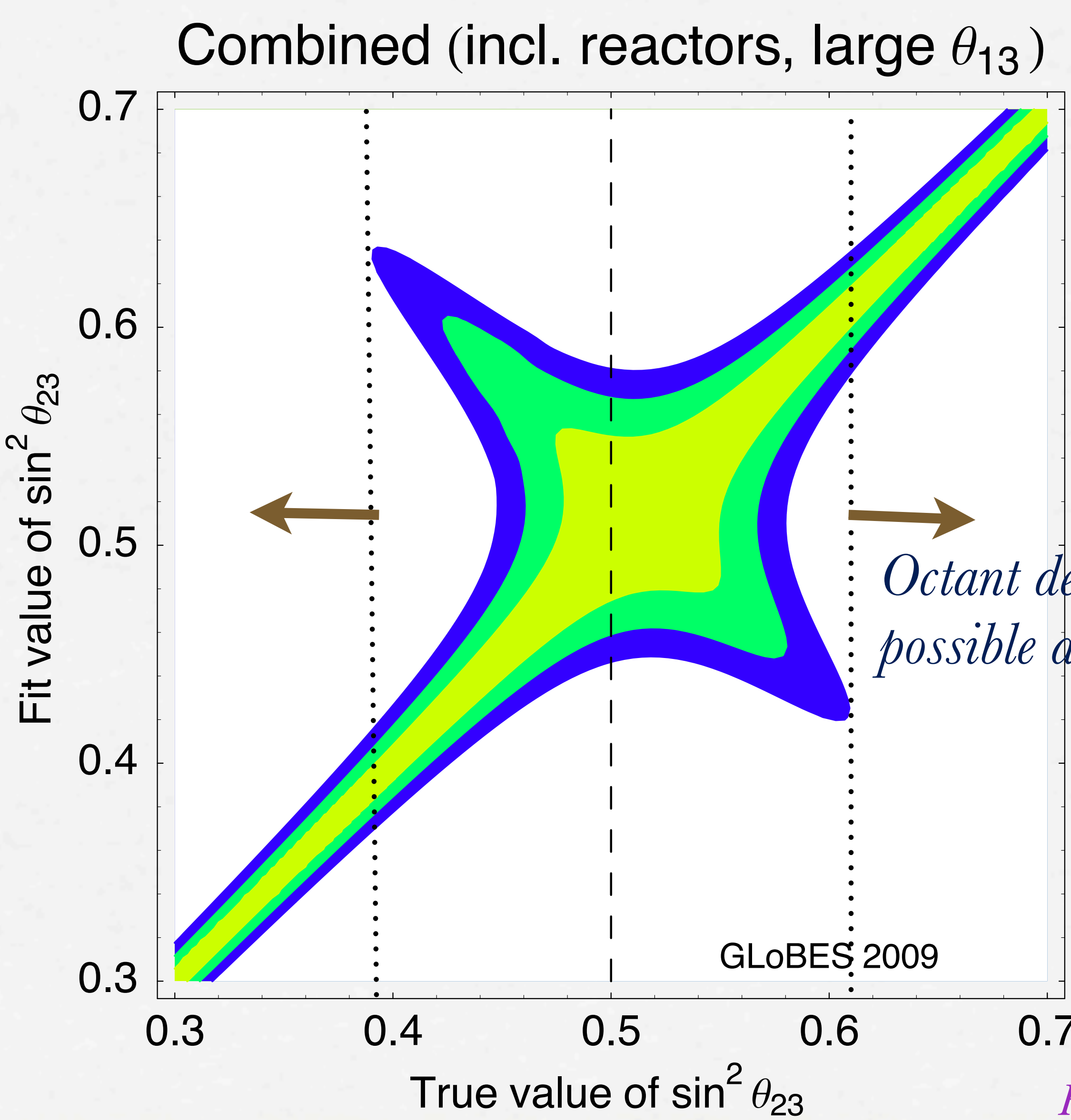
- Daya Bay II
  20 kton detector
  ~3σ sensitivity for mass hierarchy, (6 years)
  - reactor experiment

- INO
  50 kton detector
  - for atmospheric neutrinos
  ~2σ sensitivity for mass hierarchy for $\sin^2\theta_{23}$= 0.5, $\sin^2 2\theta_{13}$= 0.1, by 2022 (5 years)
  ~2.7σ sensitivity for mass hierarchy for $\sin^2\theta_{23}$= 0.5, $\sin^2 2\theta_{13}$= 0.1, by 2027 (10 years)

- Hyper-Kamiokande
  1 Mton (20x SK)
  - for atmospheric neutrinos
  - as far detector (T2HK)

- PINGU (ICE CUBE)
  Multi-Mton ICE det.
  - for atmospheric neutrinos

- NOVA + T2K+ REACTORS



Octant determination possible at 3 sigma

possibility of:
- mass hierarchy
- CP phase

see Mark's talk

Huber, Lindner, Schwetz, Winter, 0907.1896

Conclusions

- All mixing angles are now known
- A high θ_{13} (~ 9°) allows better sensitivity for mass hierarchy
- There are some hints that θ_{23} is not maximal ($\sin^2 2\theta_{13}$) =0.99 (latest result from SK)
- Mass hierarchy discovery can be achieved with improvements of some current experiments, or the experiments currently being built.
- Octant sensitivity can be achieved with current and near future experiments
- CP phase can be achieved by long base line experiments
  - ➡ can be achieved by Hyper-K, using the T2K beam
  - ➡ There are other proposition in Europe (LAGUNA/LBNO see Alain's talk) and USA (LBNE) with relative big liquid argon detector (which is a challenging technology providing a very good tracking quality)
- Some anomalies are still not explain. New experiments need to be built to verifiy the measurements of the MiniBOONE experiment.

BACK-UP

Numerical 1σ, 2σ, 3σ ranges:

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.34 – 2.50	2.26 – 2.58	2.15 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.32 – 2.49	2.25 – 2.56	2.14 – 2.65
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.45	2.14 – 2.79	1.81 – 3.11	1.49 – 3.44
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.46	2.15 – 2.80	1.83 – 3.13	1.50 – 3.47
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.98	3.72 – 4.28	3.50 – 4.75	3.30 – 6.38
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.08	3.78 – 4.43	3.55 – 6.27	3.35 – 6.58
δ/π (NH)	0.89	0.45 – 1.18	—	—
δ/π (IH)	0.90	0.47 – 1.22	—	—

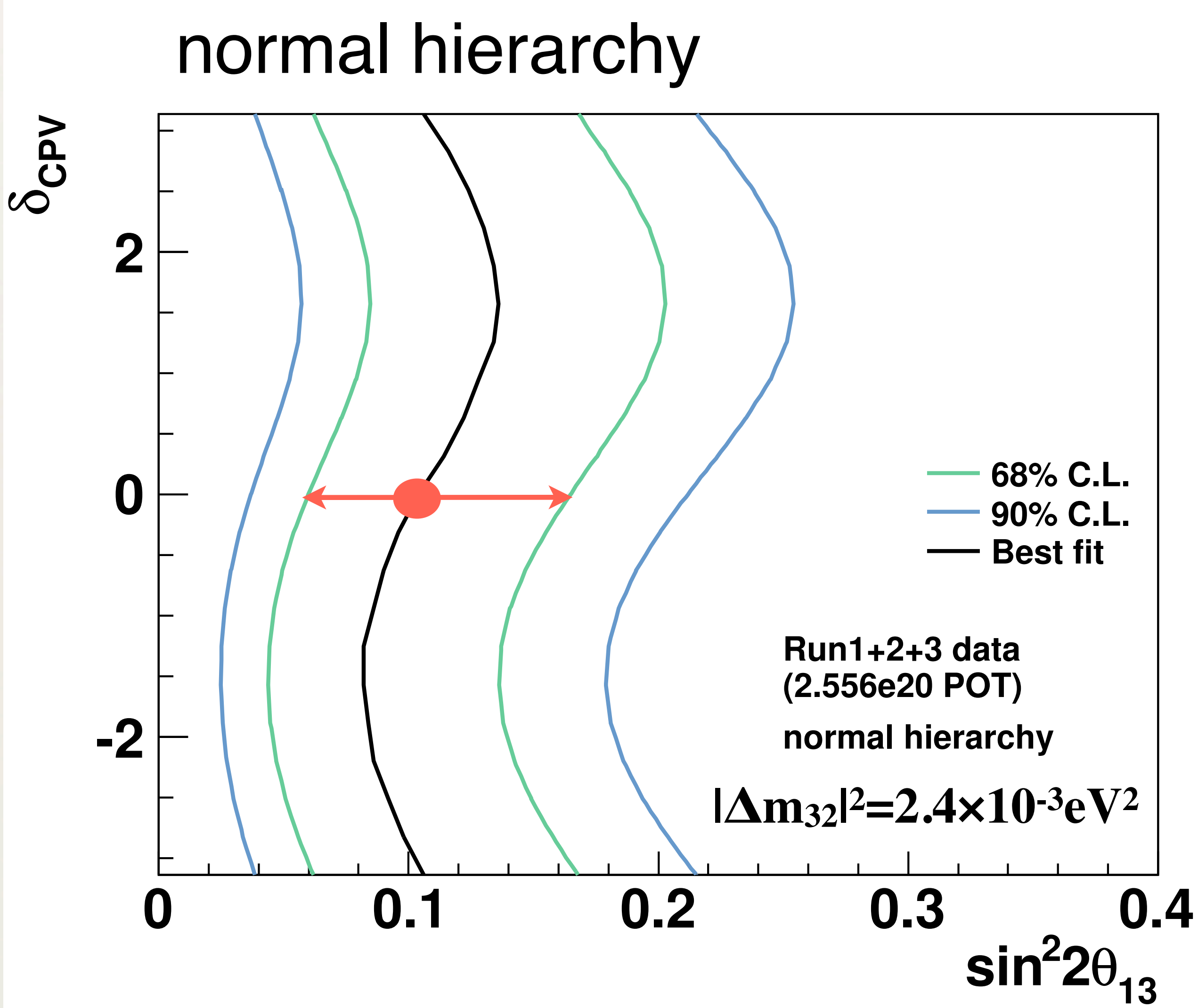
Note: above ranges obtained for "old" reactor fluxes. For "new" fluxes, ranges are shifted (by ~ 1/3 σ) for two parameters only: $\Delta\sin^2\theta_{12}/10^{-1} \simeq +0.06$ and $\Delta\sin^2\theta_{13}/10^{-2} \simeq +0.10$

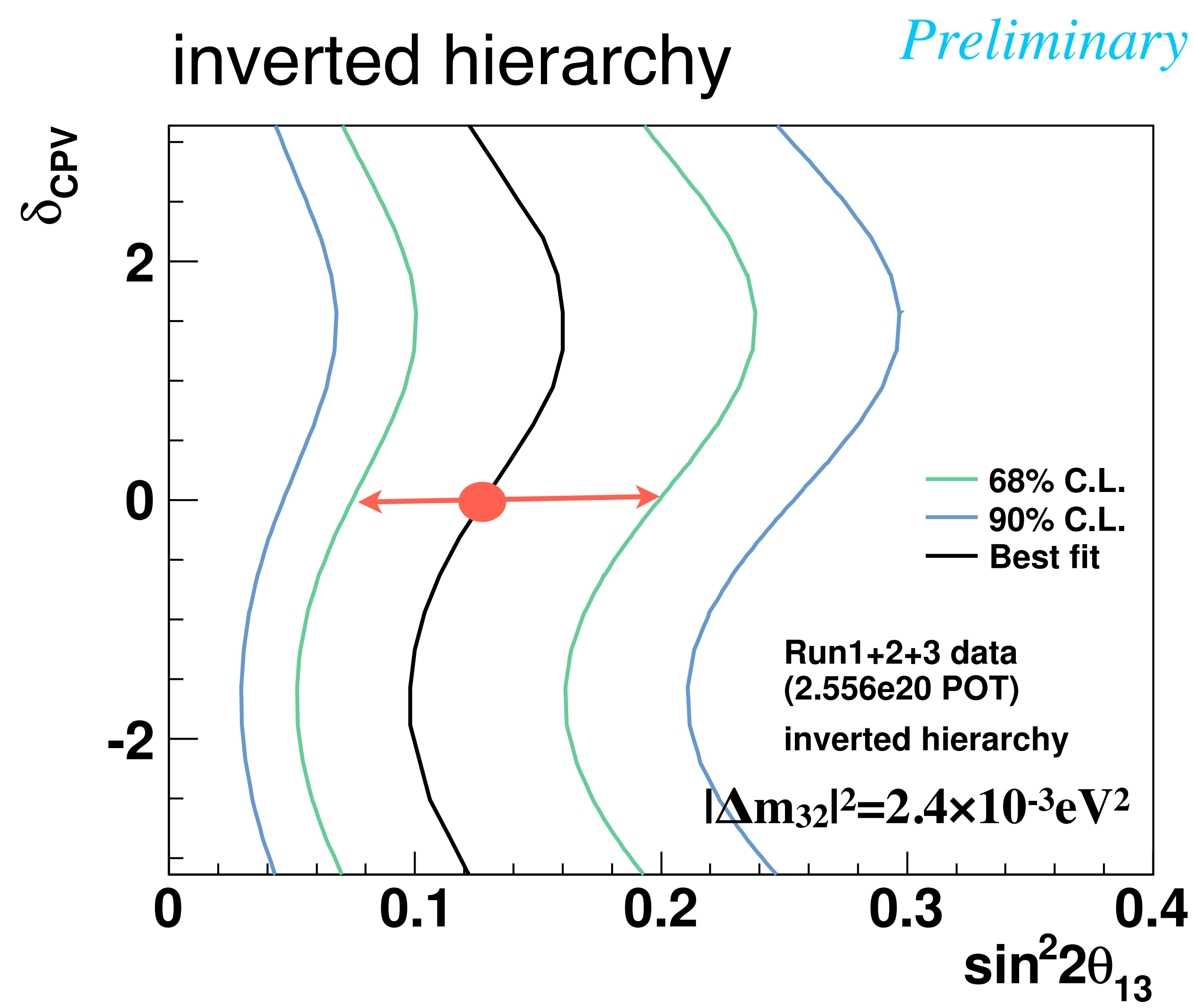
Fractional 1σ accuracy [defined as 1/6 of $\pm 3\sigma$ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	13%	13%	3.5%

We were already in the precision era for ν physics!

T2K





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

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

Neutrino sterile (1)

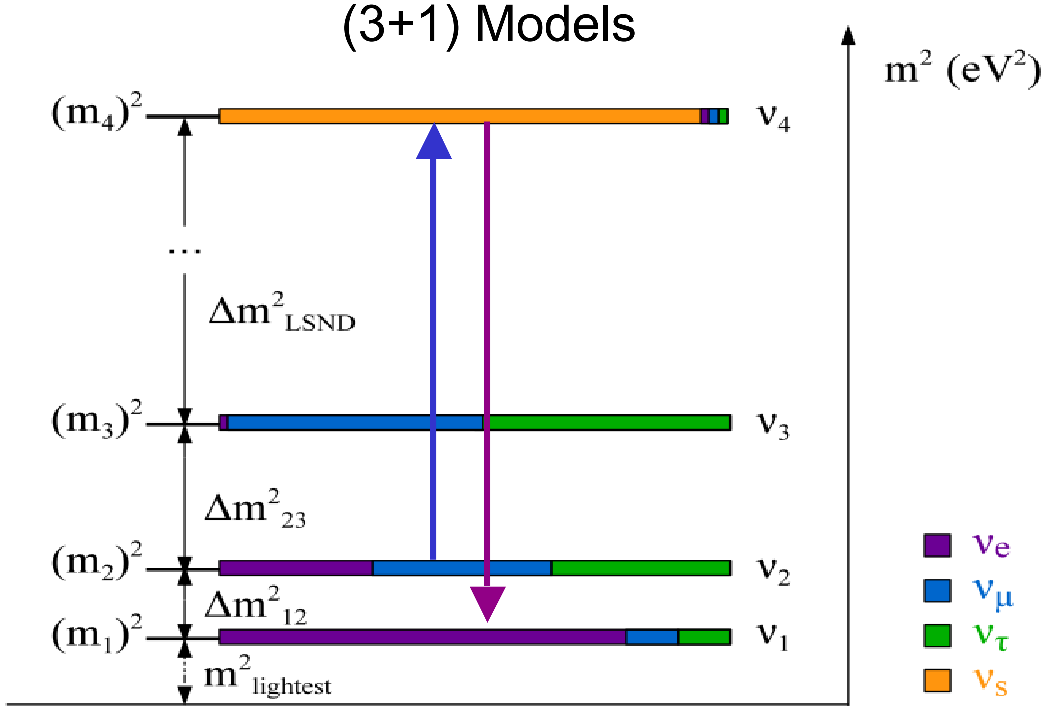
Phenomenology of Oscillations with Sterile Neutrinos

- In sterile neutrino (3+1) models, appearance comes from oscillation through ν_s
  - $\nu_\mu \to \nu_e = (\nu_\mu \to \nu_s) + (\nu_s \to \nu_e)$

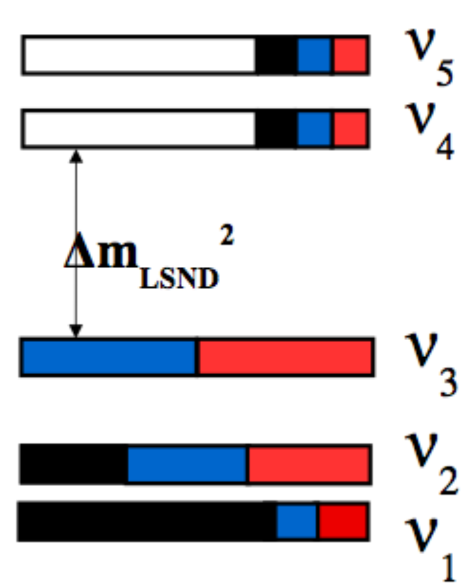
- (3+1) models require ν_μ and ν_e disappearance oscillations
  - $\nu_\mu \to \nu_s$ and $\nu_e \to \nu_s$
  - Constraints from disappearance restrict application of (3+1) fits

- Current measurements of appearance and disappearance are not very compatible with (3+1) models $\Rightarrow$ (3+2) models
  - If $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ are different then (3+2) models can have CP violation
  - Still tension between appearance and disappearance

(3+1) Models



(3+2) Models



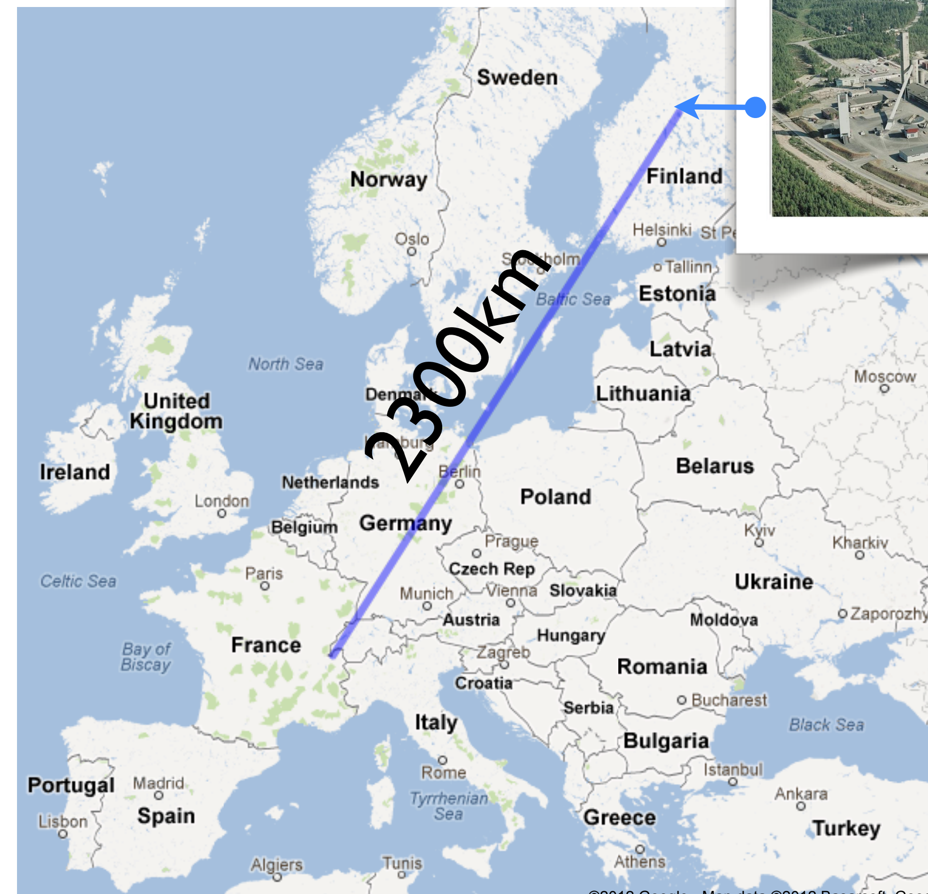
CP violation allowed in 3+2

Future Experimental Oscillation Proposals

Type of Exp	App/Disapp	Osc Channel	Experiments
Reactor Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	See K. Heeger Talk
Radioactive Sources	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$ $(\nu_e \to \nu_e)$	See T. Lasserre Talk
Isotope Source	Disapp	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator $\overset{(-)}{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$, $\nu_e \to \nu_e$	νSTORM at Fermilab

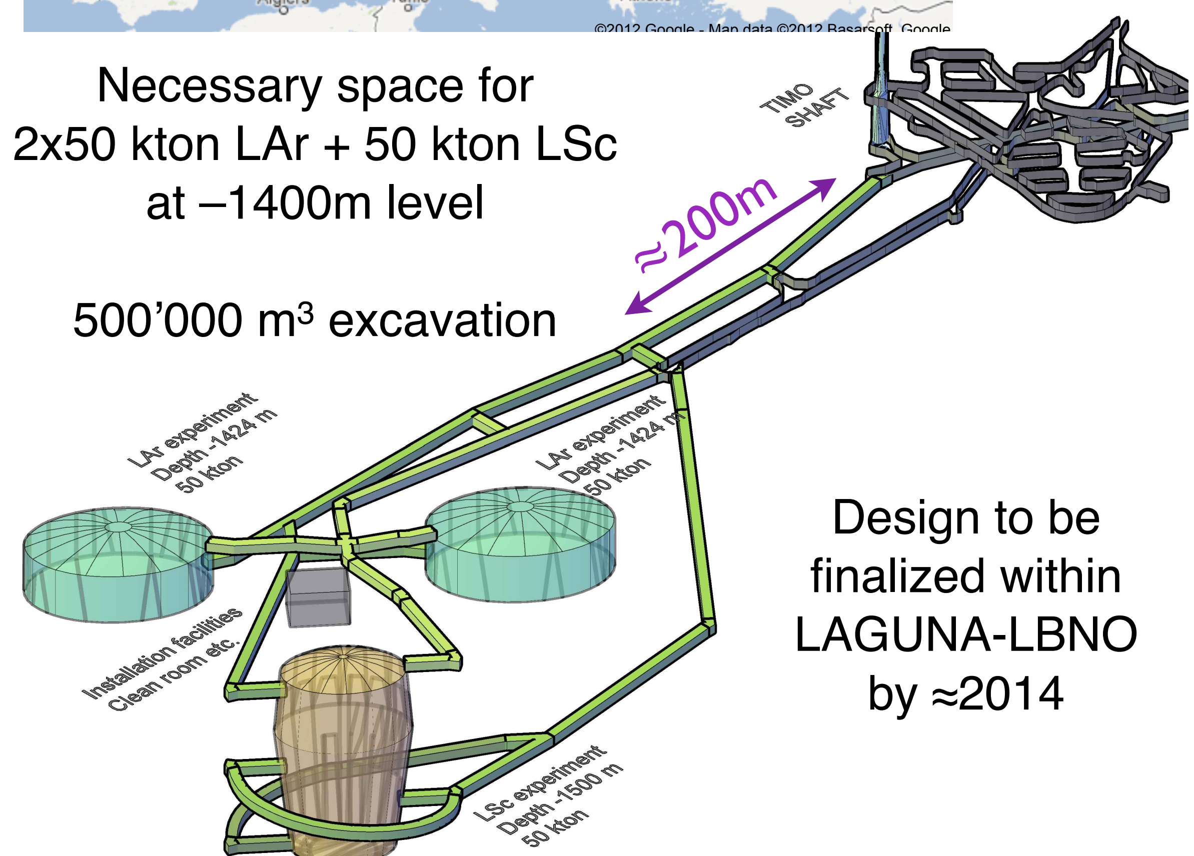
In Europe: LAGUNA/LAGUNA-LBNO

- ★ LAGUNA-LBNO = Large Apparatus for Grand Unification and Neutrino Astrophysics - Long Baseline Neutrino
- ★ Search for the optimal site in Europe for next generation deep underground neutrino detector (since 2008)
  - Detailed investigations of seven potential sites with three different detector technologies: WCD, LAr and LSc
- ★ Down-selection to top priority site where several optimal conditions satisfied simultaneously: Pyhäsalmi, Finland
  - Infrastructure in perfect state because of current exploitation of the mine
  - Unique assets available (shafts, decline, services, sufficient ventilation, water pumping station, pipes for liquids, underground repair shop...)
  - Very little environmental water
  - Could be dedicated to science activities after the mine exploitation ends (around 2018)
  - One of the deepest location in Europe (4000 m.w.e.)
  - The distance from CERN (2300 km) offers unique long baseline opportunities
  - The site has the lowest reactor neutrino background in Europe, important for the observation of very low energy MeV neutrinos.
- ★ Second priority: Fréjus, France.
- ★ All other sites are presently considered as backup options for LAGUNA.



Necessary space for
2x50 kton LAr + 50 kton LSc
at –1400m level

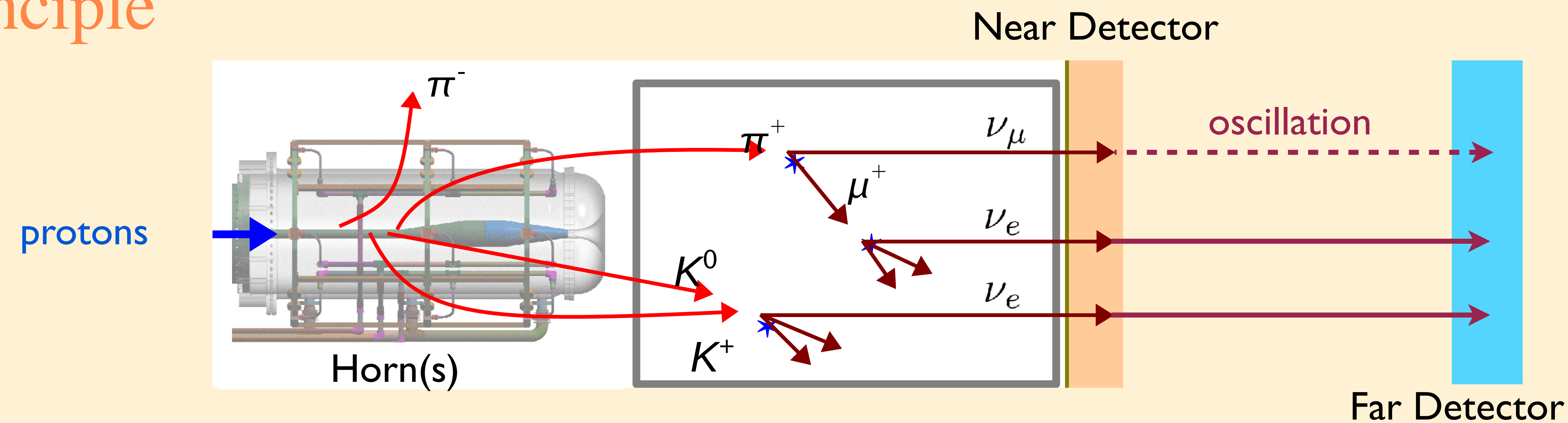
500'000 m^3 excavation



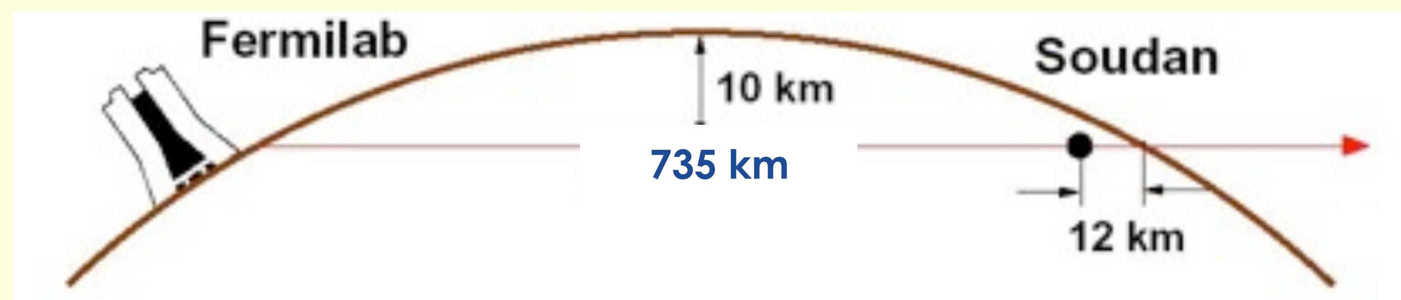
Design to be finalized within LAGUNA-LBNO by ≈2014

Accelerator Experiments Results

Principle

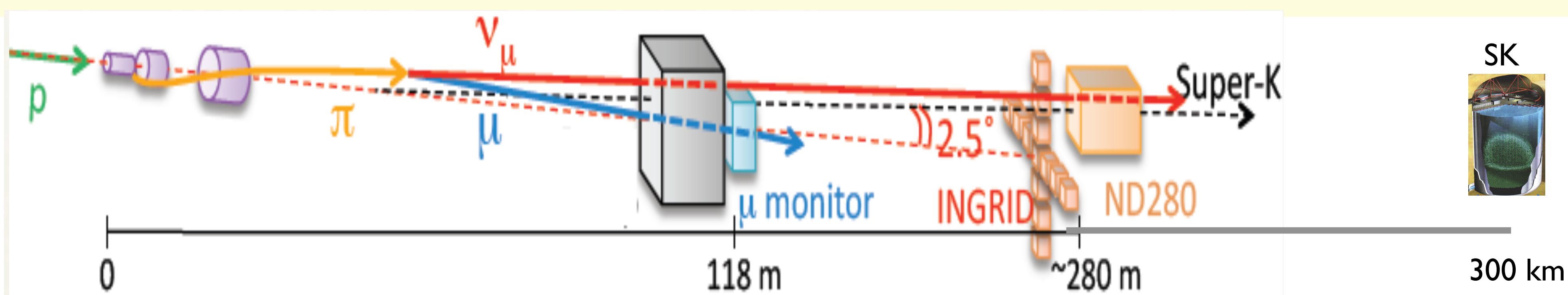


MINOS



T2K

see Mark's talk

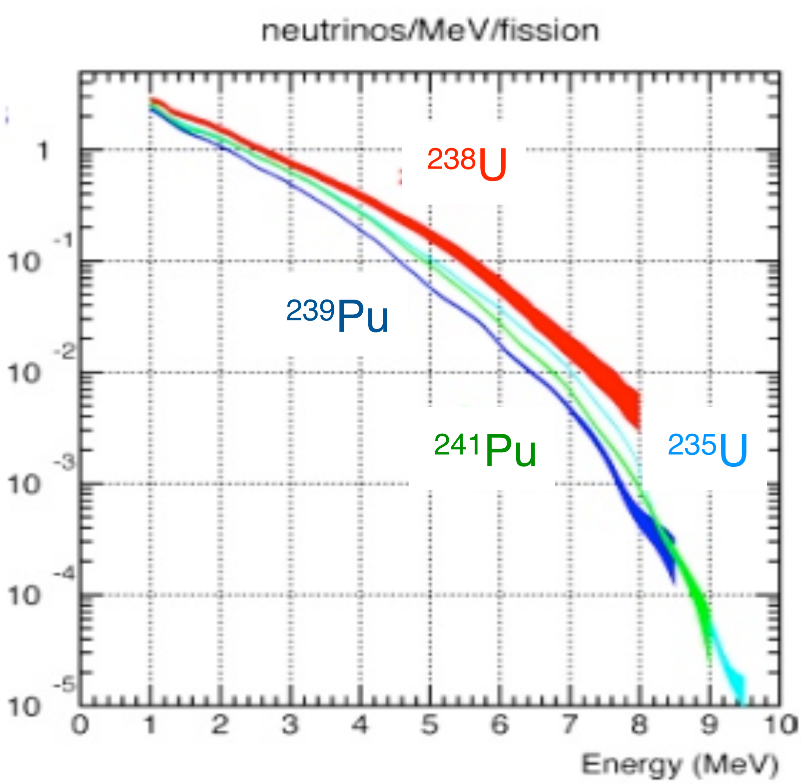


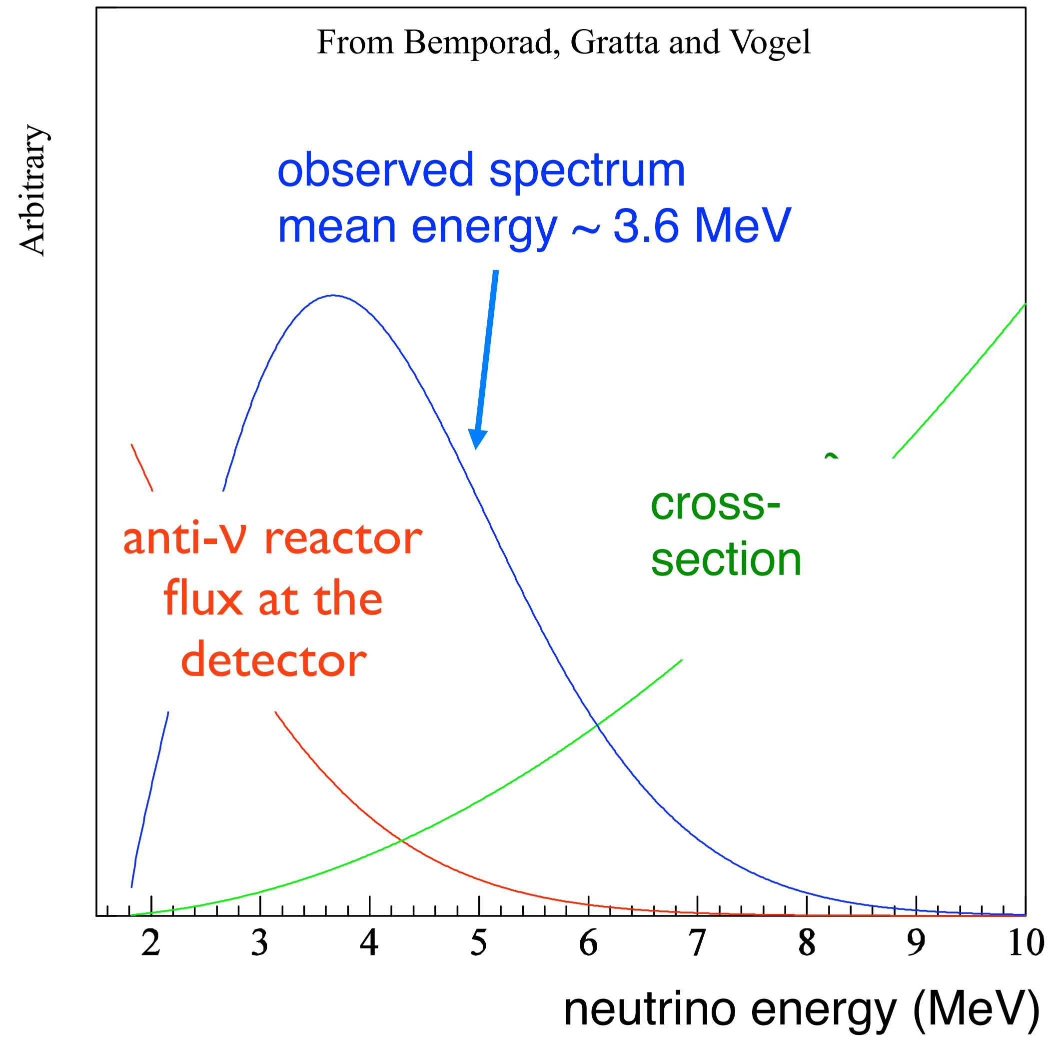
Principle

Source

$\bar{\nu}_e$ from β-decays

of n-rich fission products





For each fission, there are approximately 6 anti-neutrinos emitted.

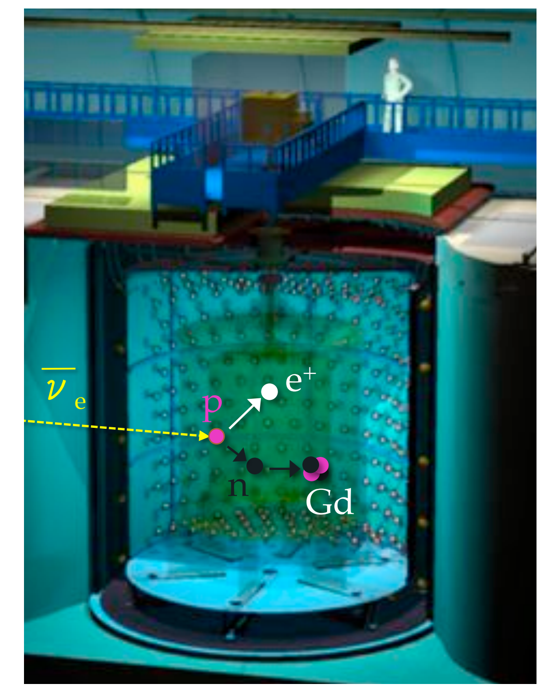
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Detection

inverse β-decay

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

Filled with liquid scintillator loaded with Gd.



Prompt signal

positron + annihilation γ's

1 ~12 MeV

Delayed signal

γ's from neutron capture on Gd: 8 MeV

Time interval

Δt ~ 30 μs

The Daya Bay Experiment

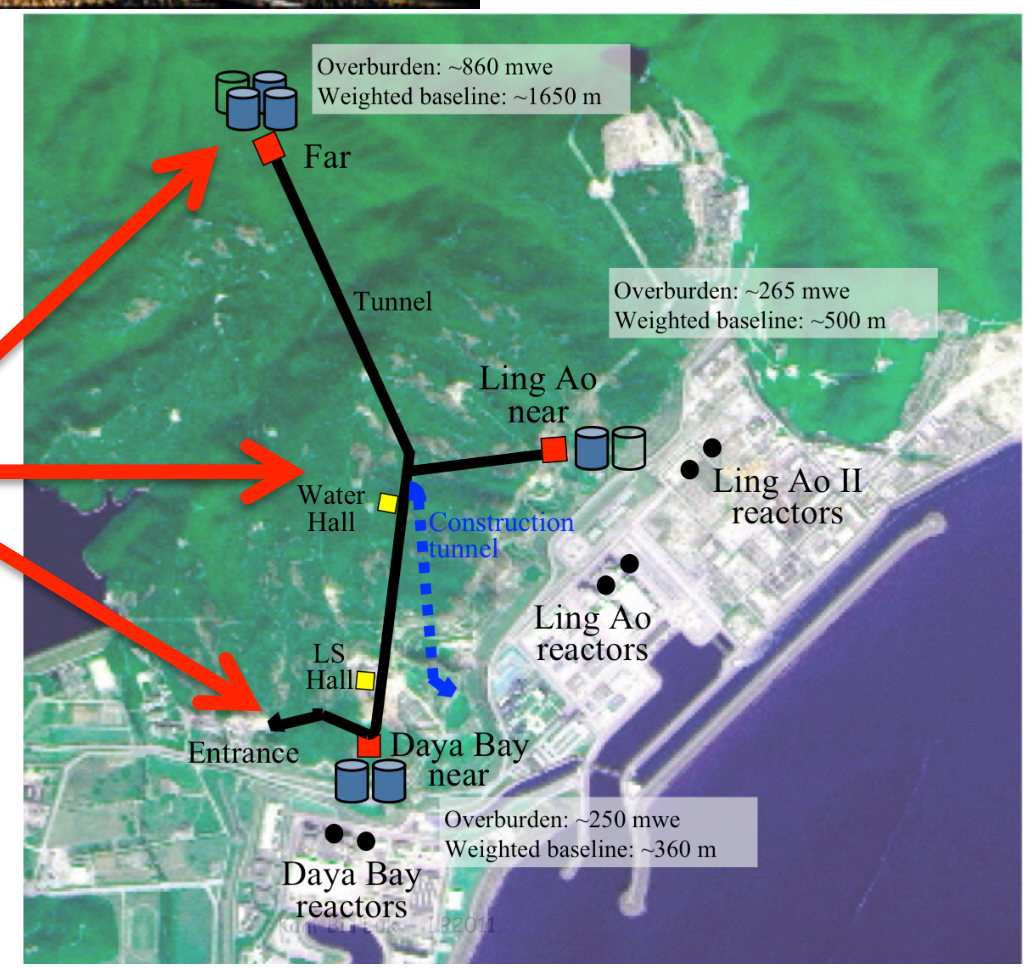
Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

Daya Bay   Ling Ao I + II

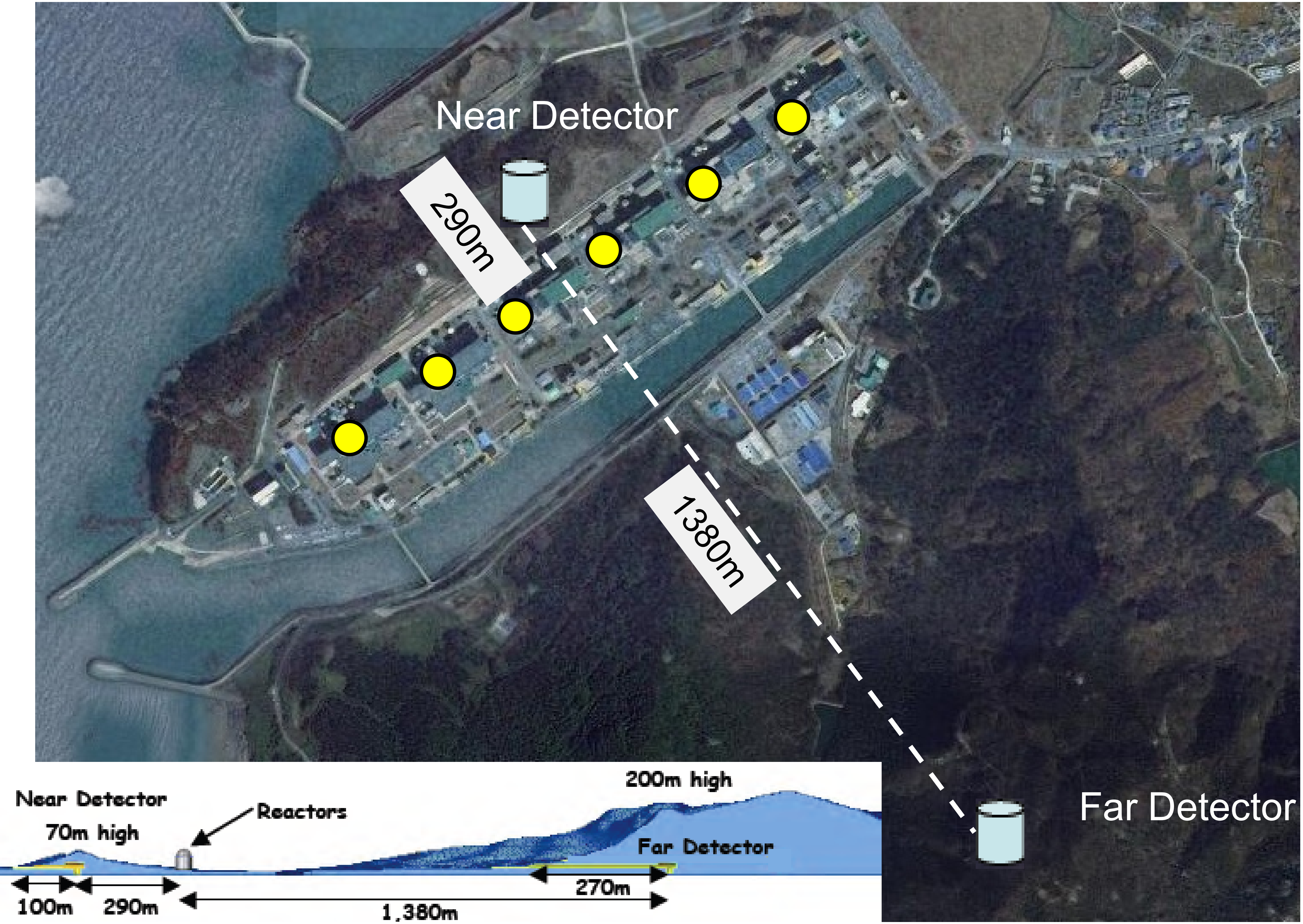
6 commercial reactor cores with 17.4 GW_{th} total power.

6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



RENO


Near Detector
290m
1380m
Far Detector
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
1,380m
270m

Mass Hierarchy (accelerators)

Accelerator experiments use the matter effect in the ν_e appearance channel

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$

$$B_\pm = |A \pm \Delta_{13}|$$ The $\pm$ is ν or anti-ν
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$