Long-Baseline Neutrino Oscillations: Current Status and Future Challenges

Milind V. Diwan
Brookhaven National Laboratory
November 4, 2016

Frontiers in Electroweak Interactions of Leptons and Hadrons
Aligarh Muslim University
Aligarh, India

Outline

- **Neutrino fundamental parameters and their importance.**
- **Oscillation phenomenology brief introduction.**
- **Quick survey of the most important data.**
- **Reactor result on θ_{13} and its consequences.**
- **Future avenues of inquiry and their status.**

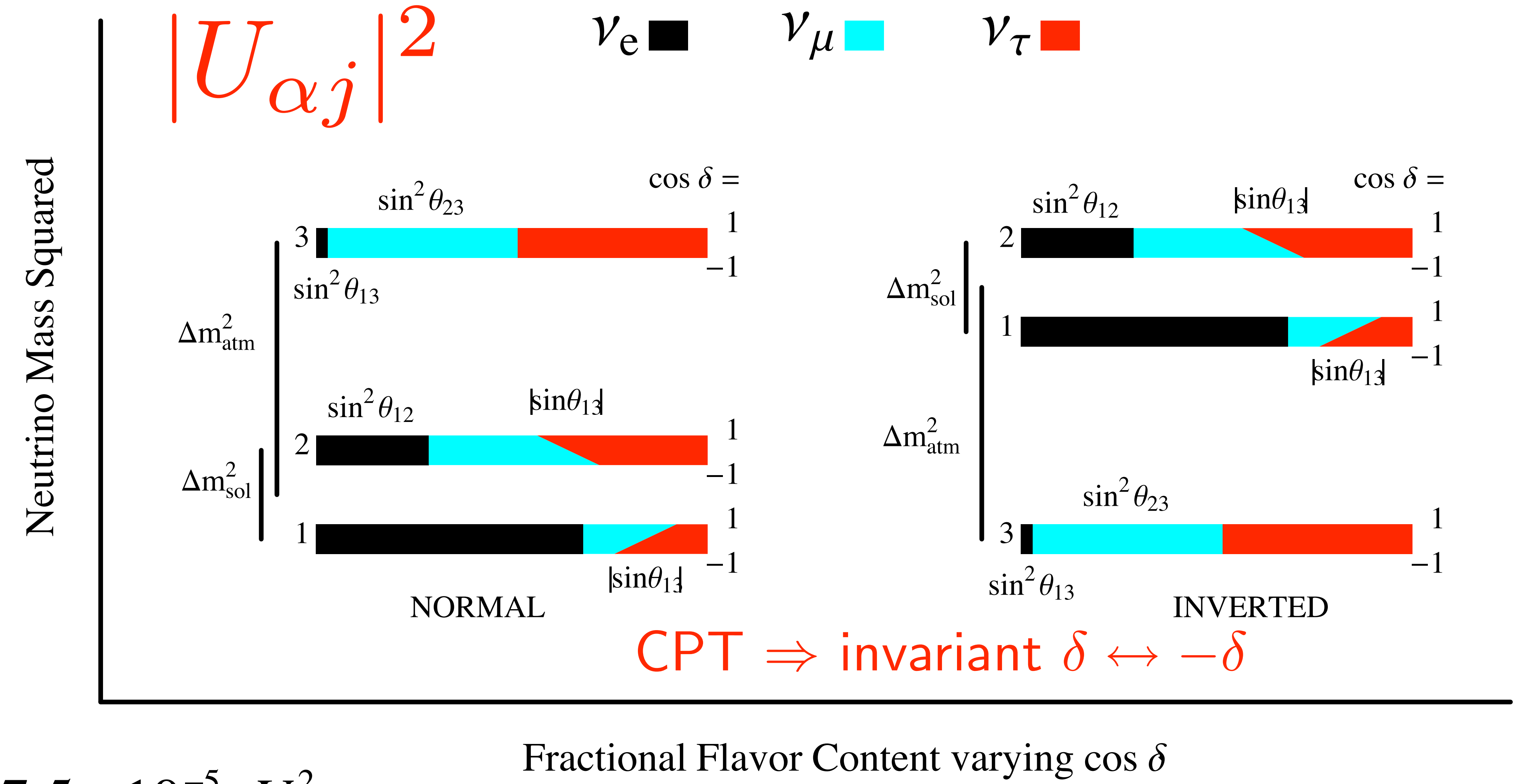
For a quick intro: MVD, Galymov, Qian, Rubbia, Annual Rev. Nucl Part. Sci. 2016. 66:47-71

3 neutrino picture.

$\theta_{23} \sim \pi/4$

$\theta_{12} \sim \pi/6$

$\theta_{13} \sim \pi/20$



CPT $\Rightarrow$ invariant $\delta \leftrightarrow -\delta$

$$\Delta m^2_{sol} = +7.5 \times 10^{-5}\, eV^2$$

$$\Delta m^2_{atm} = \pm 2.4 \times 10^{-3}\, eV^2$$

$$\frac{\Delta m^2_{sol}}{|\,\Delta m^2_{atm}\,|} \approx 0.03$$

$$\sqrt{\Delta m^2_{atm}} = 0.05 eV < \sum m_\nu < 10^{-6} m_e$$

CPT invariance: $P(\nu_l \to \nu_{l'}) = P(\bar{\nu}_{l'} \to \bar{\nu}_l)$

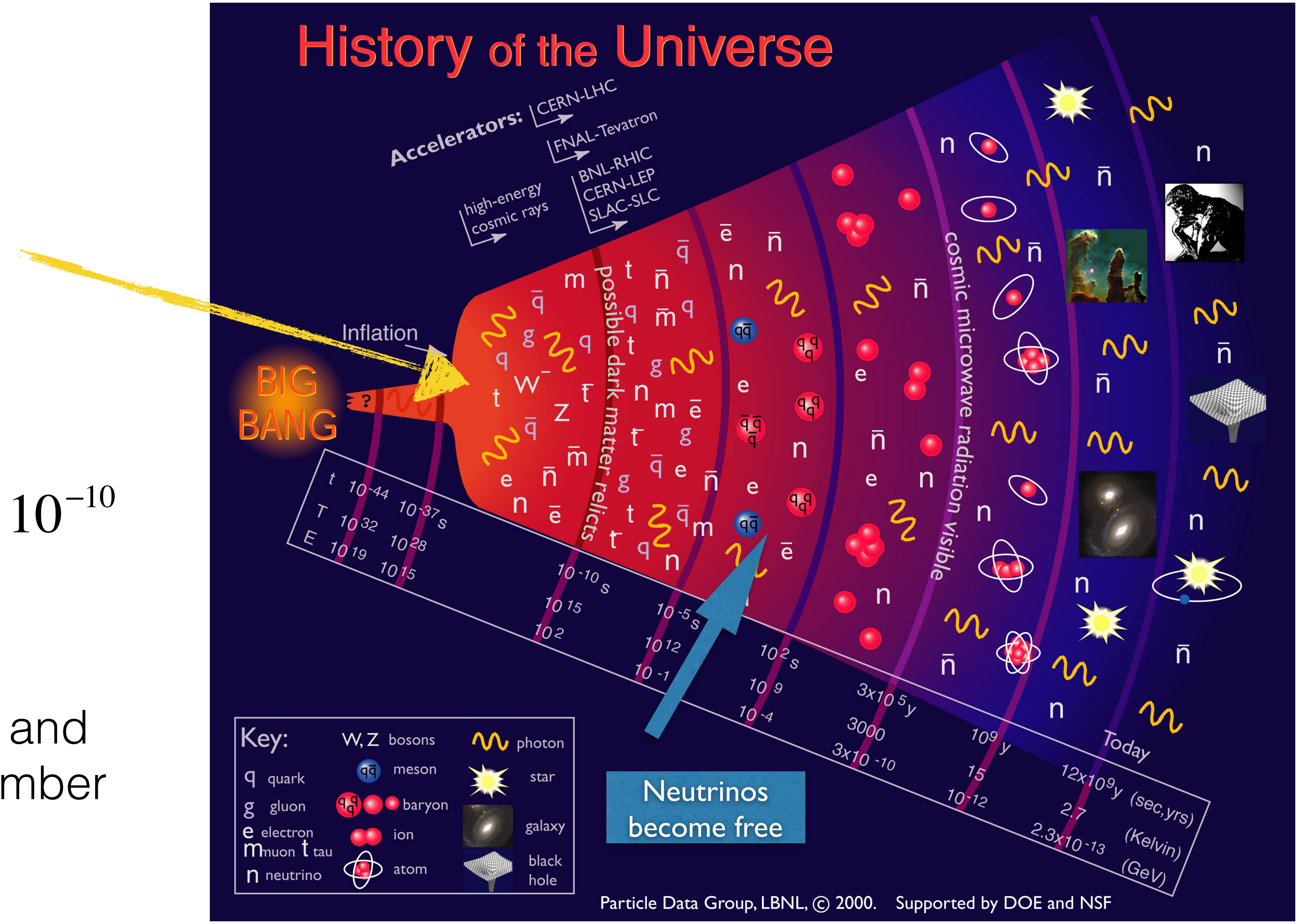
Why is this important ?

- **Such a small mass for a fundamental, electrically neutral spin 1/2 particle is a new problem. There must very heavy neutral state also (10^{12}GeV).**
- **For a massless Fermion, helicity states can be identified with particle/antiparticle states. Not possible if massive**
- **Mixing angles are very large giving a hint about how quarks and leptons melt into each other at very high energies.**
- **A new source of very large particle/antiparticle differences is possible (CP violation), giving us a handle on why the universe exists at all.**

Something happened here to make the universe more matter and much less anti-matter

$$\frac{N_B - N_{\bar{B}}}{N_\gamma} = 6\times10^{-10}$$

Calculable from nuclear physics and data. But the number should be ~0 !



Neutrinos become free

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

- **Small neutrino Majarona mass →Singlet heavy partner at ~10^{12} GeV (with lepton number and CP violation in its decay → natural explanation for leptogenesis →Baryogenesis.**
- **Must establish if neutrinos and antineutrinos behave differently or measure δ!**

A weakly interacting neutrino state could be a classic superposition of mass states.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \mathrm{Cos}\,\theta & \mathrm{Sin}\,\theta \\ -\mathrm{Sin}\,\theta & \mathrm{Cos}\,\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_\mu \to \nu_e) = \mathrm{Sin}^2\, 2\theta\, \mathrm{Sin}^2 \left(\frac{1.27(m_2^2 - m_1^2)}{E / L}\right)$$

For $\pi/2$ node

$$\Delta m^2 = 0.0025\, eV^2, E = 1 GeV \Rightarrow L = 494\, km$$

Although derived with plane waves, there are many subtleties behind this formula.One must imagine the production of a packet of neutrinos from the decay of a meson. See Akhmedov, Smirnov.

What happens through matter ?

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{2}\begin{pmatrix}-(\frac{\Delta m^2}{2E}\cos 2\theta-\sqrt{2}G_{\mathrm{F}}N_e) & \frac{\Delta m^2}{2E}\sin 2\theta\\ \frac{\Delta m^2}{2E}\sin 2\theta & (\frac{\Delta m^2}{2E}\cos 2\theta-\sqrt{2}G_{\mathrm{F}}N_e)\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

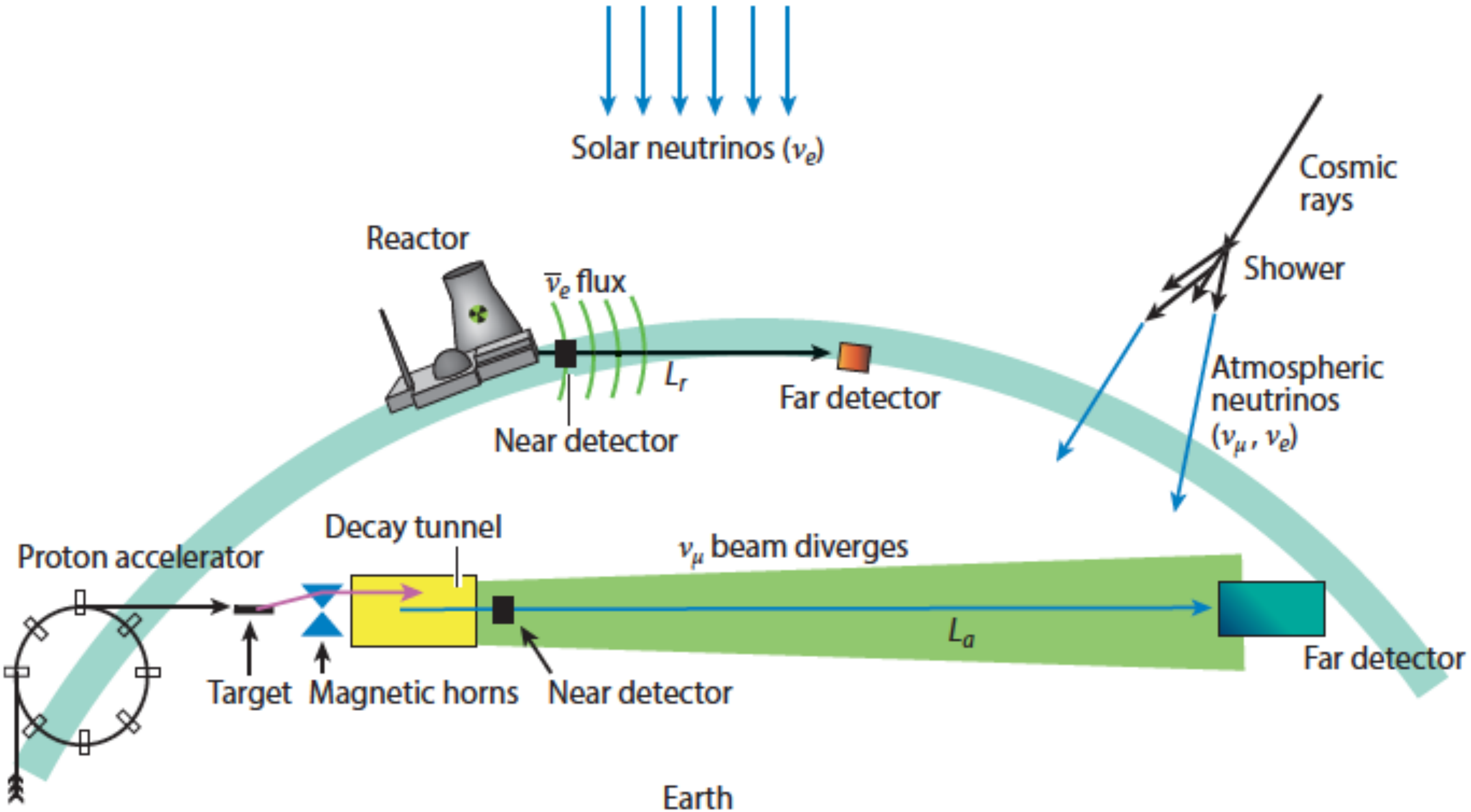
One must add a potential diagonal in the weak basis. For large N_e the weak basis is the coincides with mass basis.

$$N_e^{\mathrm{res}}=\frac{\Delta m^2\cos 2\theta}{2E\sqrt{2}G_{\mathrm{F}}}\approx 6.56\times 10^6\frac{\Delta m^2(\mathrm{eV}^2)}{E(\mathrm{MeV})}\cos 2\theta\cdot N_{\mathrm{A}}(\mathrm{cm}^{-3})$$

$$P(\nu_\mu\rightarrow\nu_e)=\frac{\tan^2 2\theta}{(1-N_e/N_e^{res})^2+\tan^2 2\theta}\times$$

$$\mathrm{Sin}^2\frac{1.27\Delta m^2((1-N_e/N_e^{res})^2\cos^2 2\theta+\sin^2 2\theta)^{1/2}}{E/L}$$

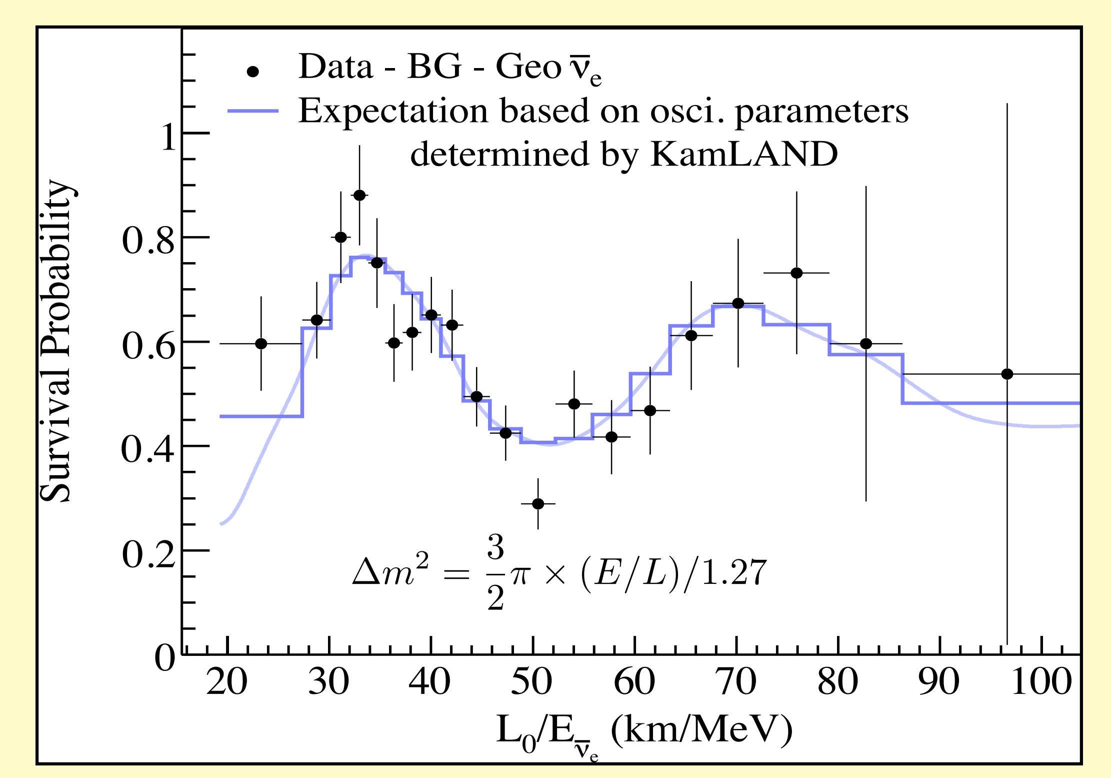
As Ne increases go from vacuum to matter enhanced



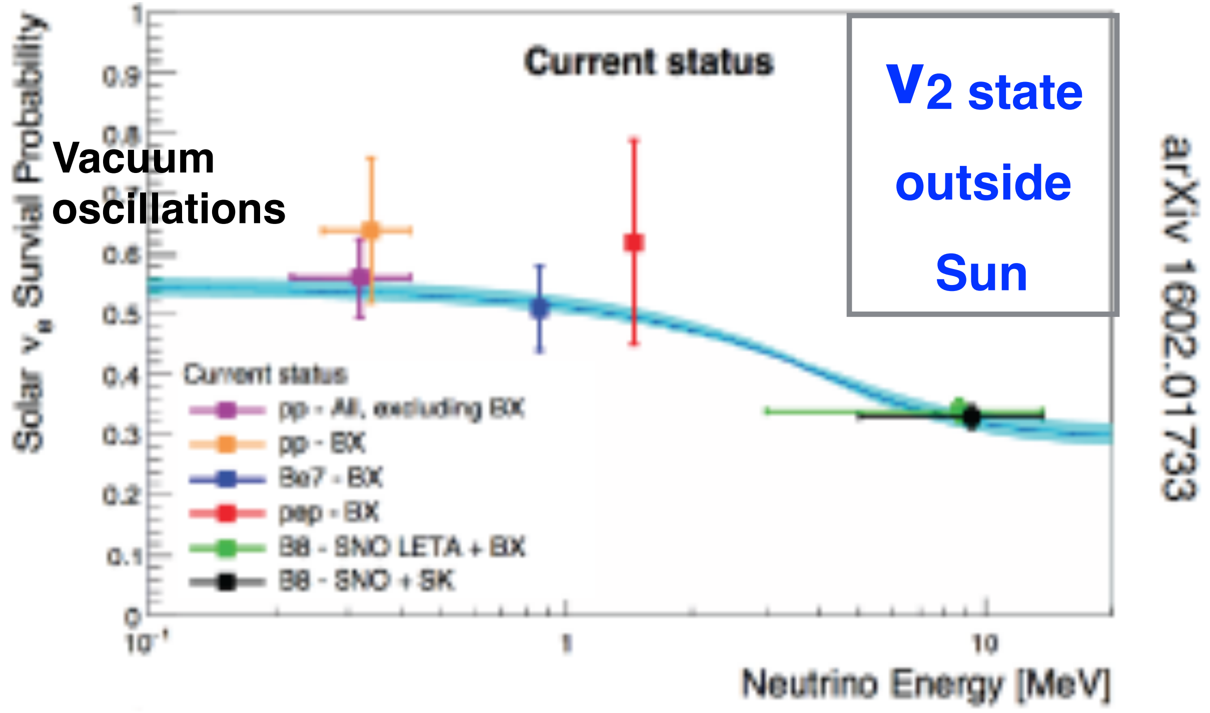
Sources of data for neutrino oscillations.
Atmosphere, Solar, Accelerator, Reactor.

The ν_e state at long distances

- $\nu_e = 0.82\nu_1 + 0.55\nu_2 + e^{-i\delta}0.15\,\nu_3$



$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta_{12} \qquad P_{ee} = \sin^2\theta_{12}$$



Vacuum oscillations

ν_2 state outside Sun

arXiv 1602.01733

Kamland reactor

Sun (SNO, Borexino, Gallium)

$\Delta m^2 = 7.5 \times 10^{-5} eV^2$

$$\theta_{12} = 34^o$$

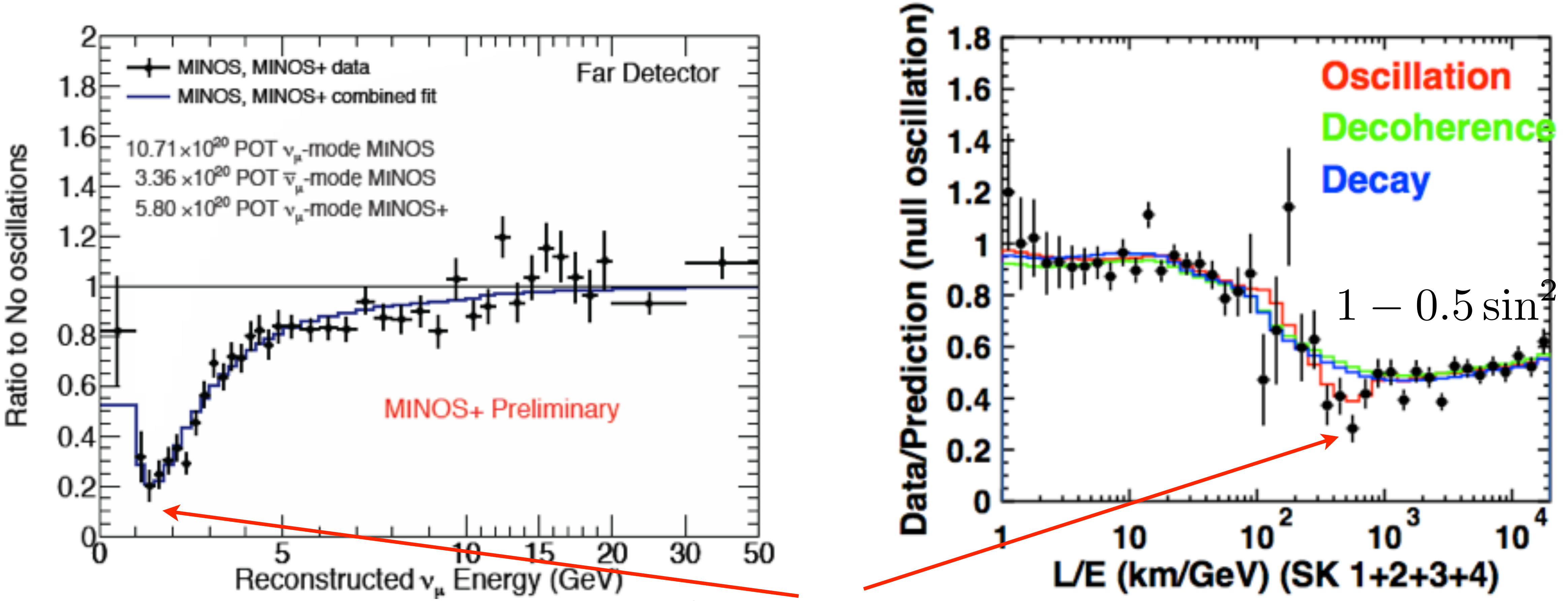
$$\Delta m_{21}^2 \, \mathrm{Cos}\, 2\theta_{12} > 0$$

Borexino has now measured pp neutrinos

The ν_μ state (ignore phases)

- $\mathbf{v}_\mu \sim -0.48\mathbf{v}_1 + 0.53\mathbf{v}_2 - 0.7\,\mathbf{v}_3 = 0.7(\boldsymbol{\nu}_m) - 0.7\mathrm{v}_3$

In addition - Important confirmation of tau neutrino mixing came from OPERA



SK2012

$1 - 0.5\sin^2 2\theta_{23}$

$\Delta m^2 = (\pi/2)(E/L)/1.27$

MINOS data

Super Kamiokande

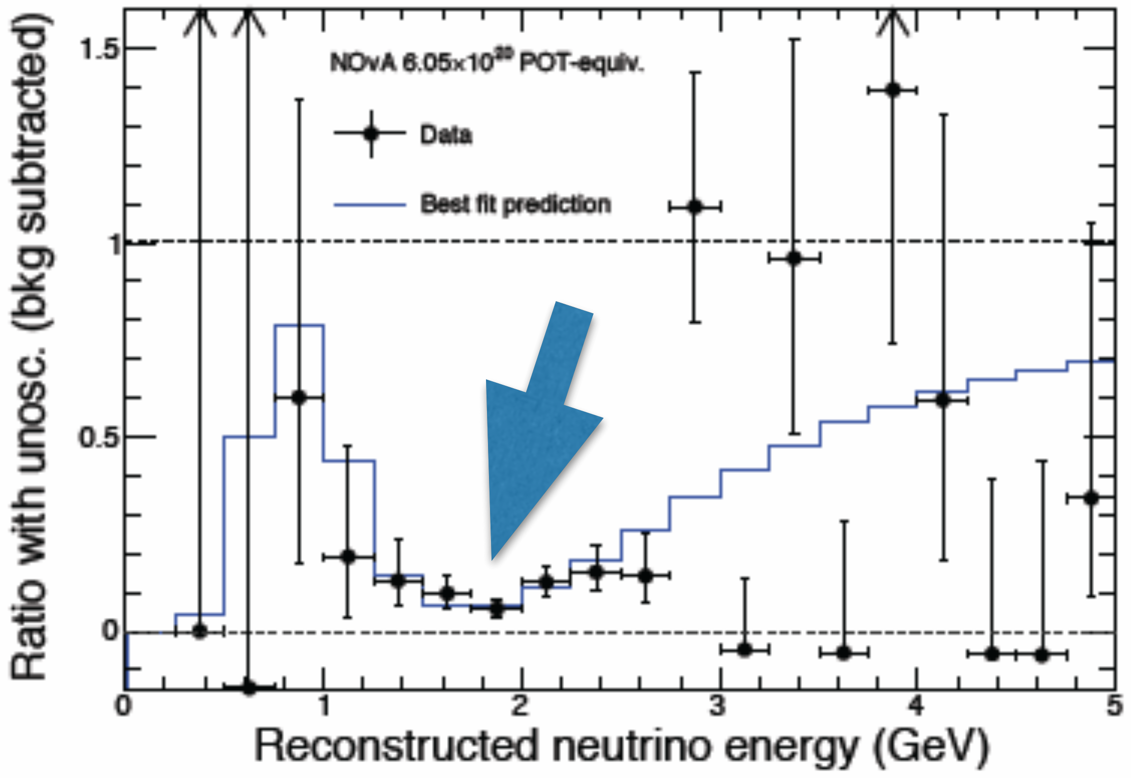
$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$

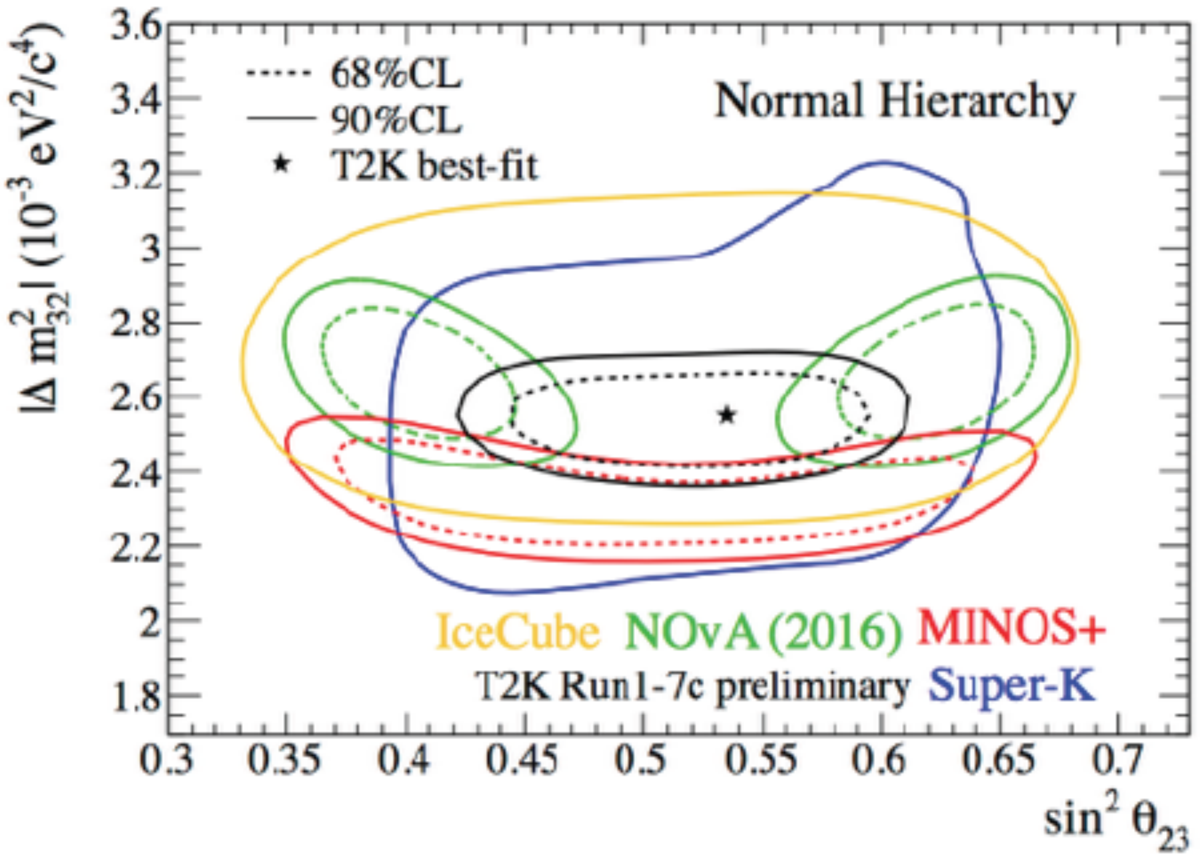
$\theta_{23} \approx 45^o$

Cannot determine sign of mass difference in disappearance

Important news regarding maximum mixing

NOVA collaboration nu2016 results



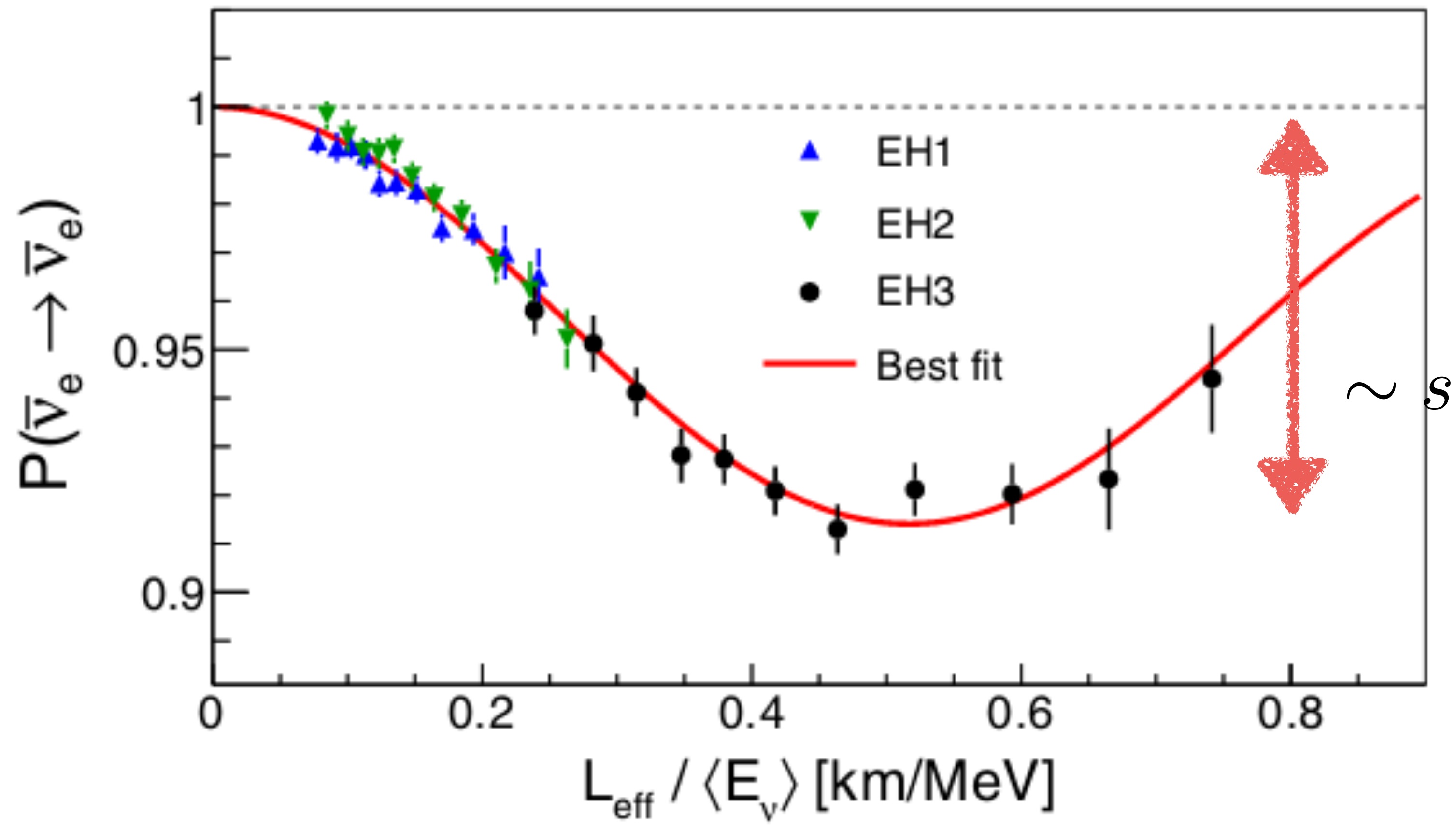


High energy resolution for NOvA ⇒ A small number of events are not disappearing at the node.

$$\text{NOvA: } 1-\text{Sin}^2 2\theta_{23} \approx 0.04$$

The ν_e state again !

- $\nu_e = 0.82\nu_1 + 0.55\nu_2 + 0.15\nu_3 = 0.99\nu_y + 0.15\nu_3$



Daya Bay

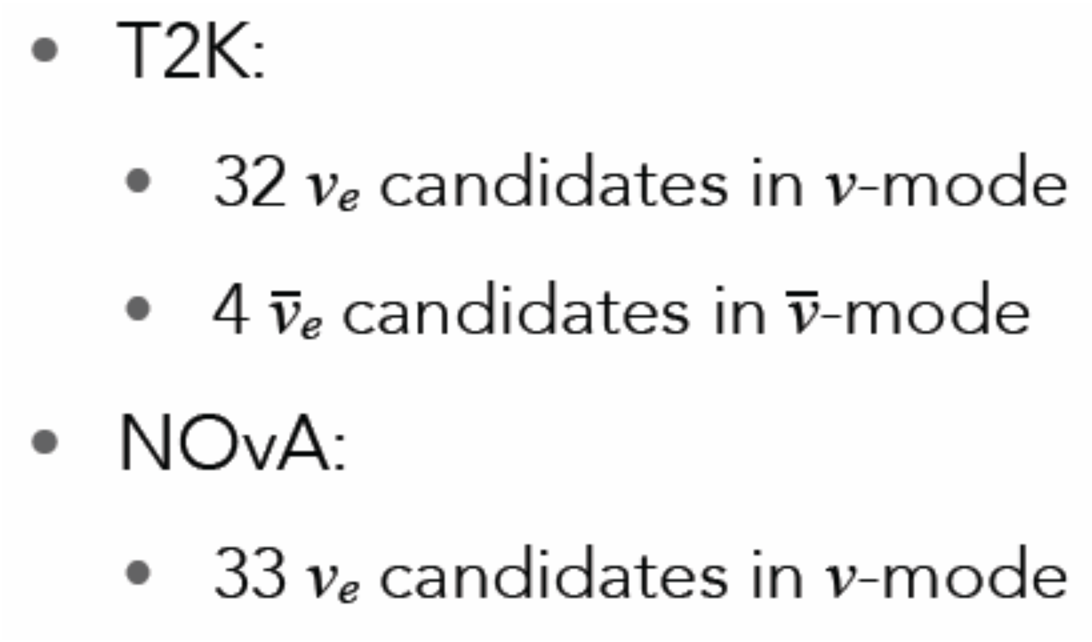
$\sim sin^2 2\theta_{13}$

$\Delta m_{ee}^2 \approx |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}$ eV^2 $\sim \pi/2(3.5MeV/1800m)/1.27$

$$\mathrm{Sin}^2 2\theta_{13} = 0.0841 \pm 0.0027 \pm 0.0019$$

Results from RENO and Double Chooz are consistent.

ν_e appearance



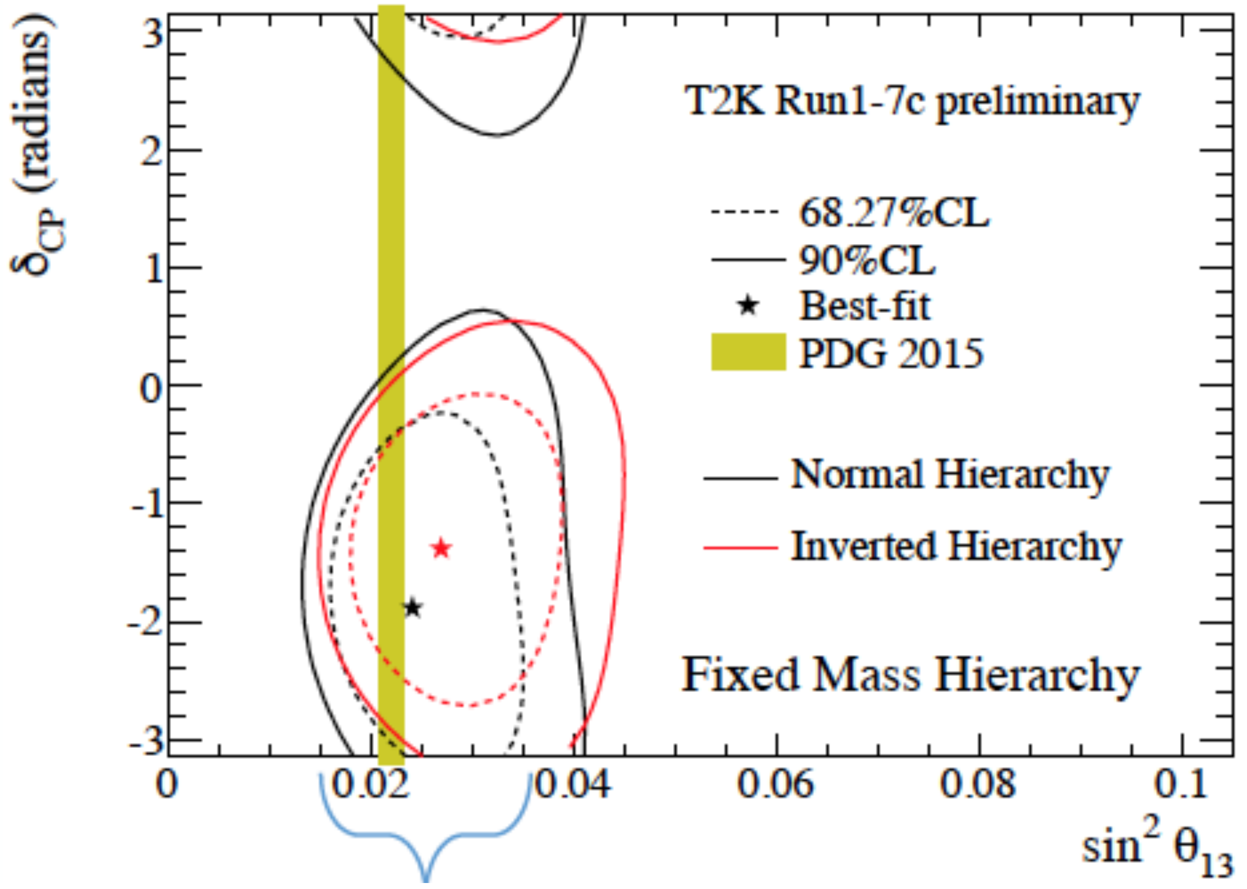
- T2K:
  - 32 ν_e candidates in ν-mode
  - 4 $\bar{\nu}_e$ candidates in $\bar{\nu}$-mode
- NOvA:
  - 33 ν_e candidates in ν-mode

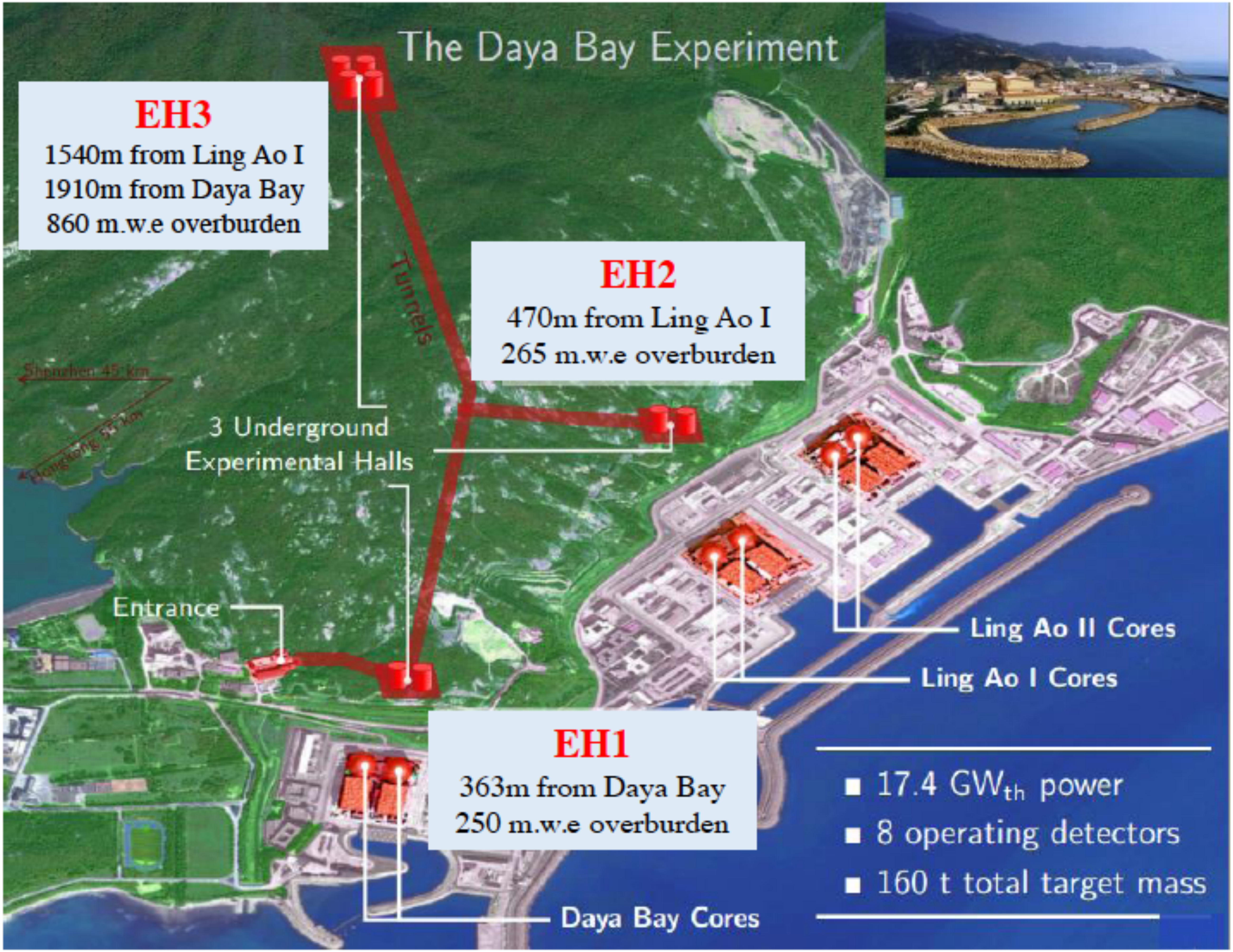
Both vaguely in the direction of

- Normal ordering
- CP phase ~ -90 deg.

The statistics for this plot improves slowly with data.

Significant correlations with θ_{23}



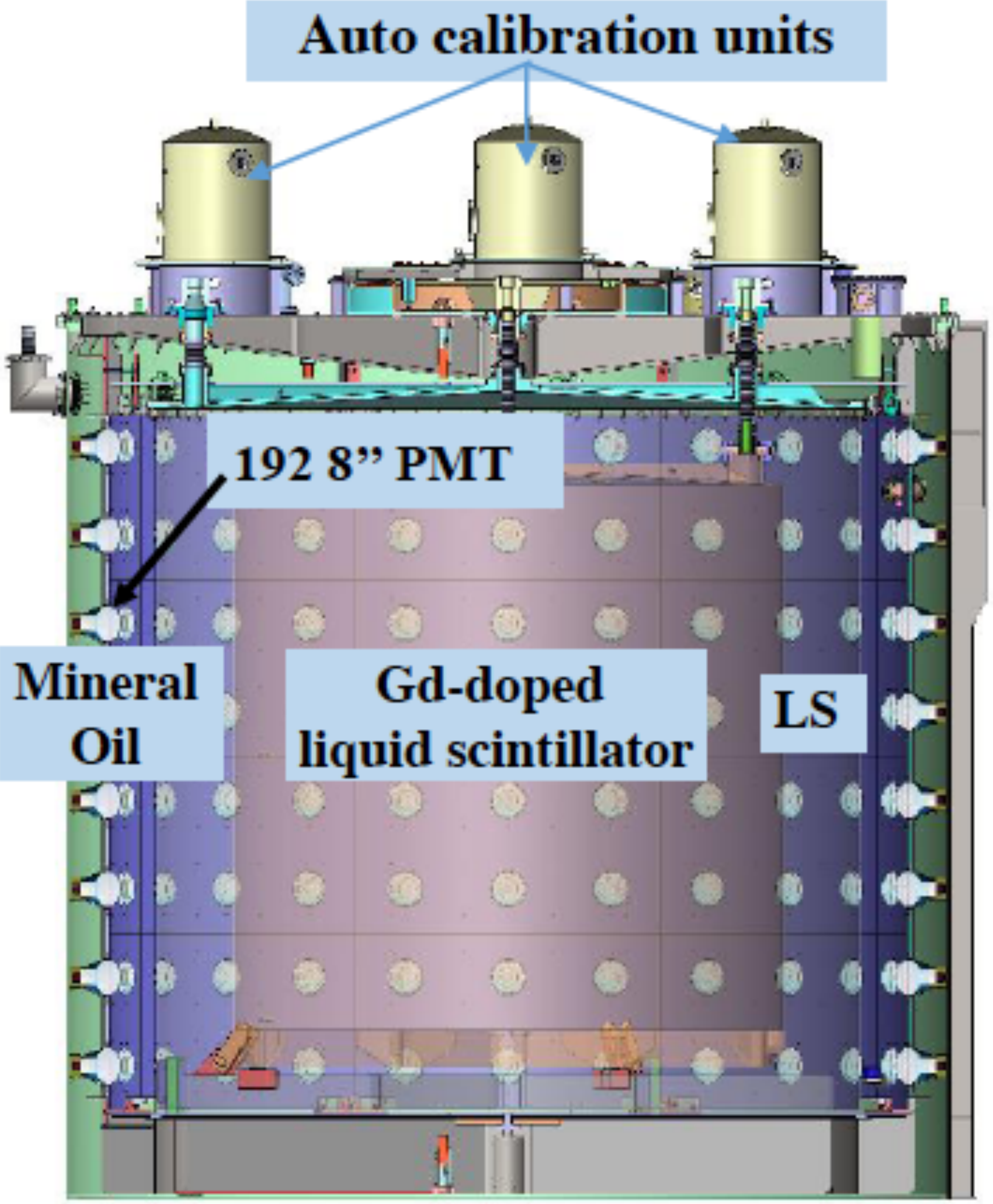

The Daya Bay Experiment
EH3
1540m from Ling Ao I
1910m from Daya Bay
860 m.w.e overburden
Tunnels
EH2
470m from Ling Ao I
265 m.w.e overburden
Shenzhen 45 km
Hongkong 55 km
3 Underground
Experimental Halls
Entrance
Ling Ao II Cores
Ling Ao I Cores
EH1
363m from Daya Bay
250 m.w.e overburden
17.4 GW_{th} power
8 operating detectors
160 t total target mass
Daya Bay Cores

Detector

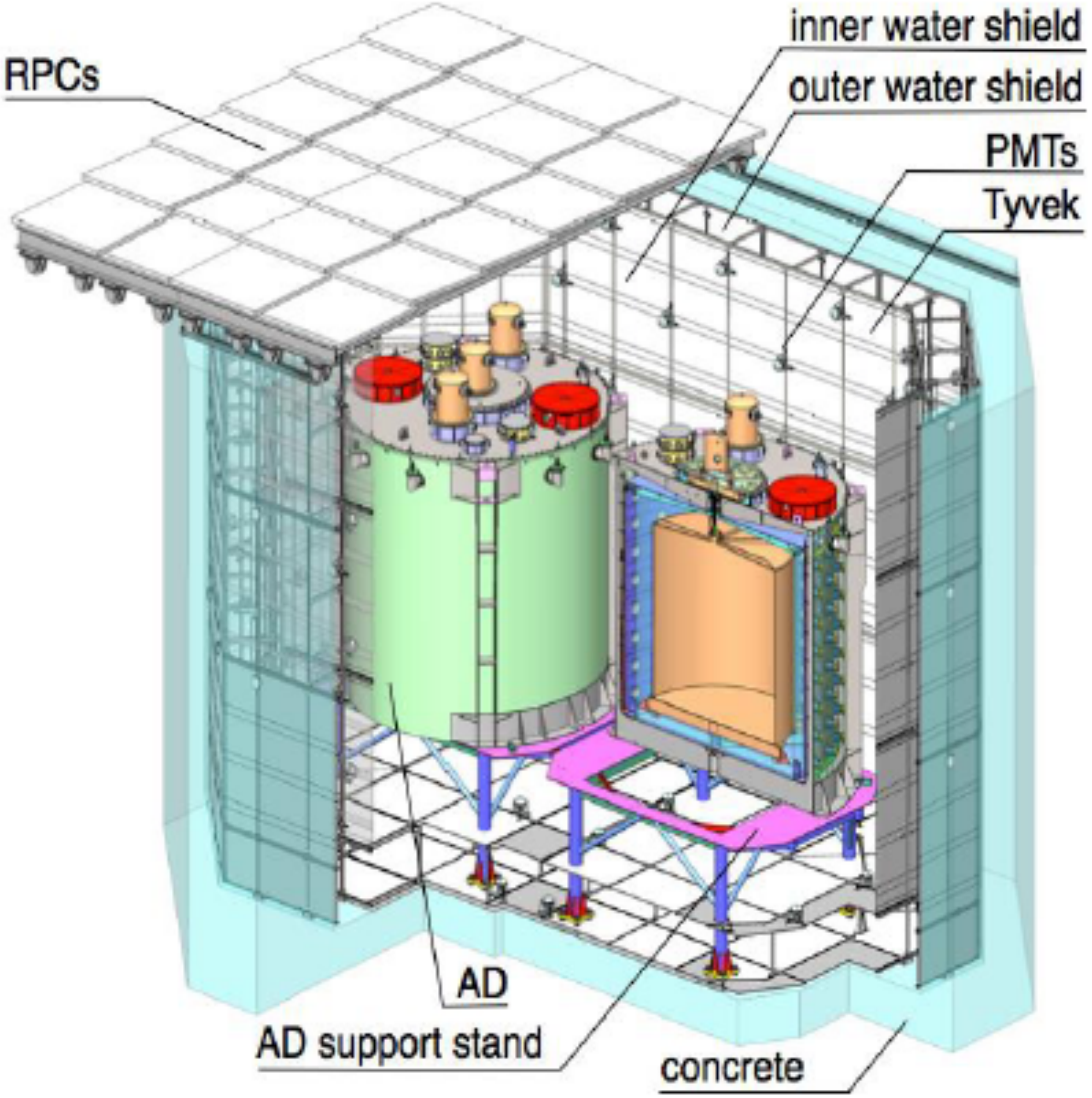
Eight functionally identical detectors

- **Study the near/far ratio and spectrum distortion**

$$\frac{N_{\rm Far}}{N_{\rm Near}} = \left(\frac{N_{\rm target,Far}}{N_{\rm target,Near}}\right)\left(\frac{L_{\rm Near}}{L_{\rm Far}}\right)^2\left(\frac{\varepsilon_{\rm Far}}{\varepsilon_{\rm Near}}\right)\left[\frac{P_{\rm survival}(E, L_{\rm Far})}{P_{\rm survival}(E, L_{\rm Near})}\right]$$



Nucl. Instrum. Meth. A 811, 133 (2016)



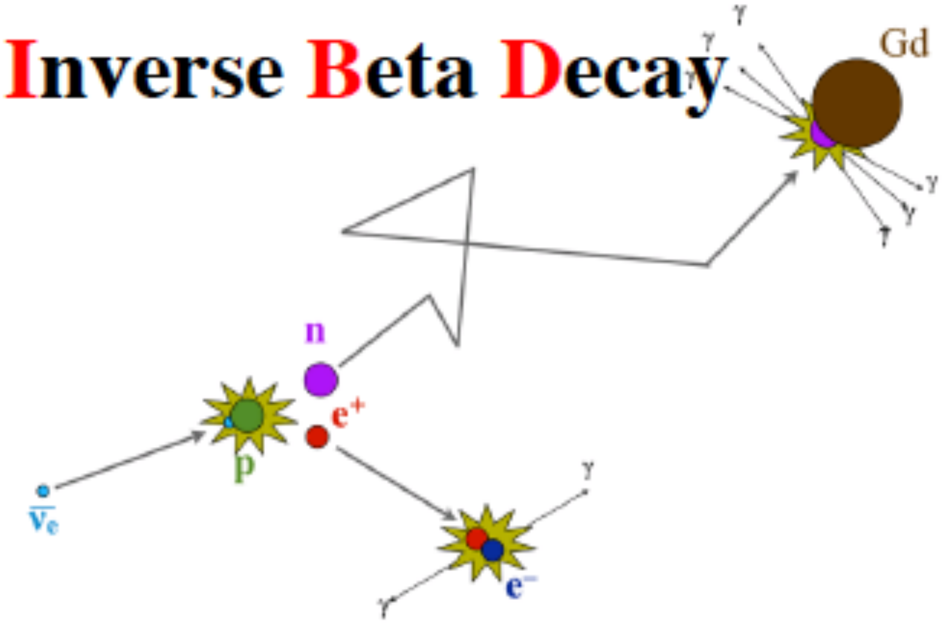
Nucl. Instrum. Meth. A 773, 8 (2015)

From Daya Bay collaboration
NU2016

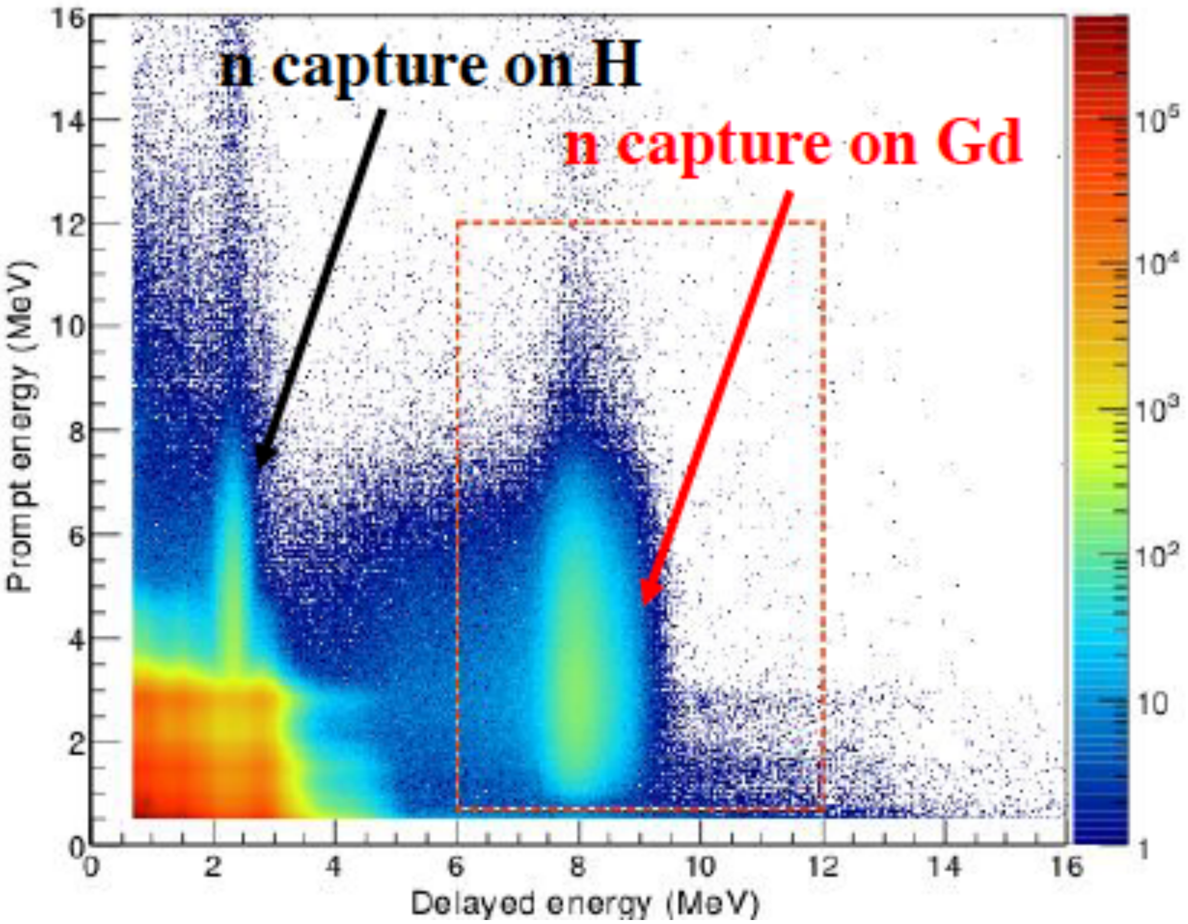
$\bar{\nu}_e$ selection

1230 days data

Inverse Beta Decay



- **Reject PMT flashers**
- **Muon veto**
- **Prompt and delayed energy cuts**
- **Neutron capture time cut**
- **Multiplicity cut**



Detection efficiencies

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%
Previous	80.6%	2.1%	0.2%

☐ : previous: 0.12%

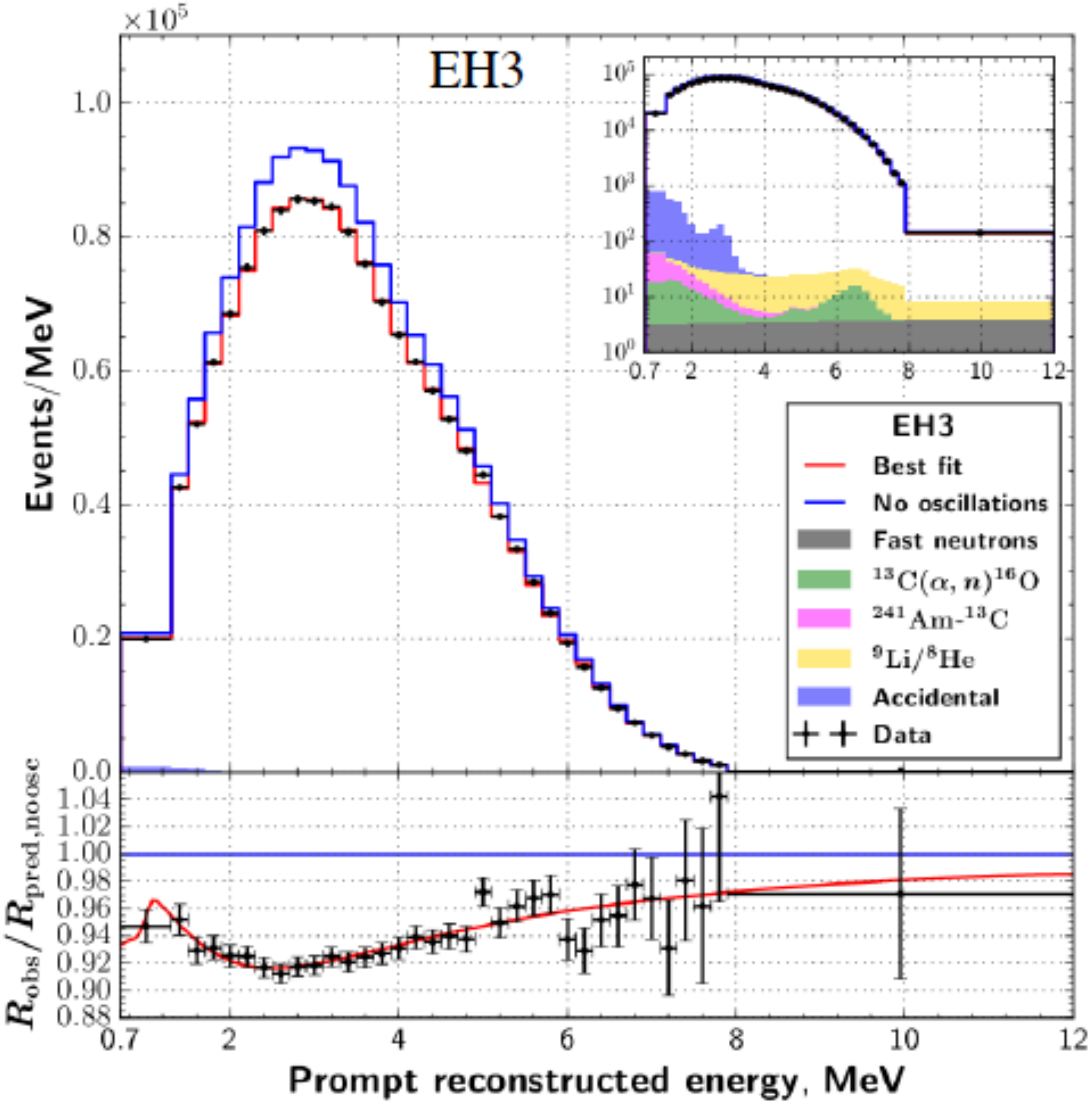
From Daya Bay collaboration
NU2016

Backgrounds

1230 days data

- **Accidentals:**
  - Uncertainty less than 0.02%
- **Fast neutron**
  - Uncertainty less than 0.05%
- **^{9}Li/^{8}He**
  - Uncertainty 0.1%~0.15%
- **From the ^{241}Am-^{13}C source**
  - Uncertainty 0.05%~0.1%
- **^{13}C(α,n)^{16}O**
  - Uncertainty less than 0.05%

Sites	B/S ratio	Background uncertainty
Daya Bay	1.8%	0.2%
Ling Ao	1.5%	0.15%
Far	2.0%	0.2%



Consequences of sizable θ_{13}

- Most important, each weak neutrino state is established to be a mixture of at least 3 massive states. $\mathbf{\nu_e} = 0.82\mathbf{\nu_1}+0.55\mathbf{\nu_2}+ e^{-i\delta}\, 0.15\mathbf{\nu_3}$

- $P(\nu_\mu \rightarrow \nu_e)$ with L/E=500km/GeV must exist (as discovered by T2K and NOVA) and CP violation could be very large compared to quarks.

- $P(\nu_\mu \rightarrow \nu_e)$ will show matter effects on Earth and allow determination of mass ordering.

    - Atmospheric neutrino experiments: INO, PINGU, KM3NET could see matter effects.

    - Large reactor experiment (JUNO) to measure mass hierarchy.

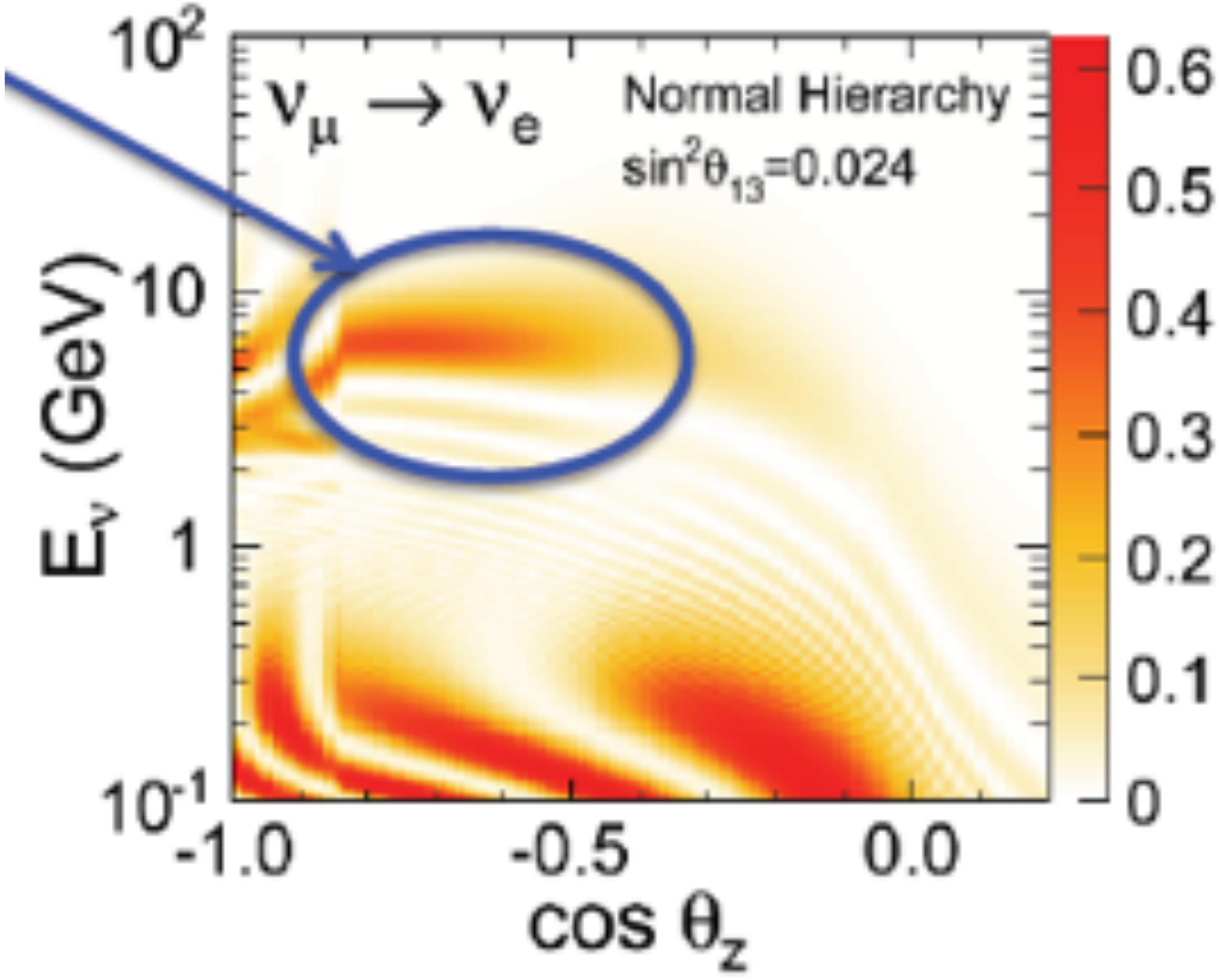
    - Huge CP violation signal possible in accelerator beams. But need ~1000 appearance events to establish it precisely.

Atmospheric effects

- **In NH (IH) a resonant nu (anti-nu) effect at 5 GeV, 60 deg below horizon (outer core Earth)**
- **Effect is measured through disappearance of muon neutrinos.**
- **Comparison of nu/antinu enhances.**
- **Event rates:**

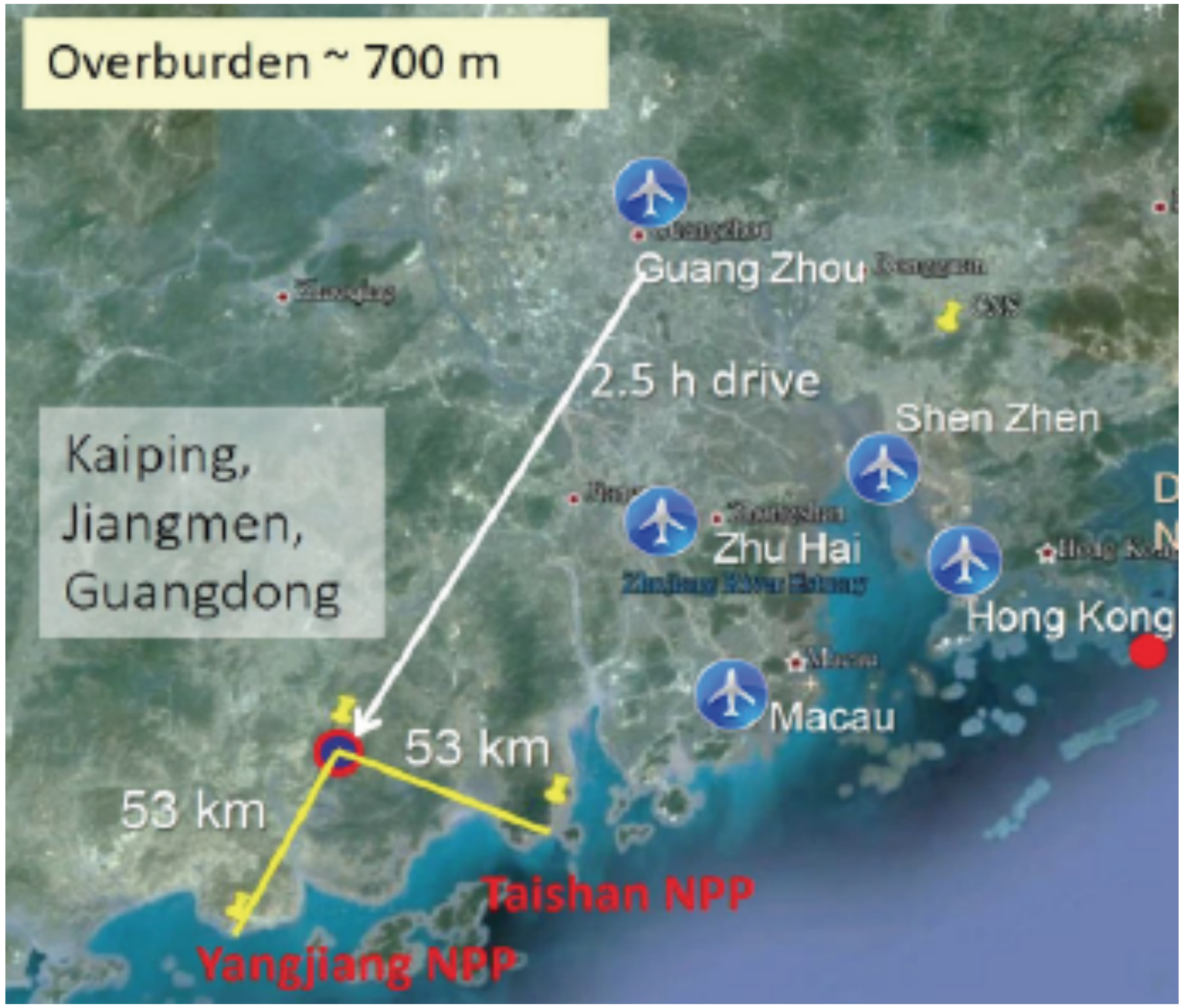
Total: 50k events/500kT*yrs

This only gets ~ 500 events in the 5 GeV bin.

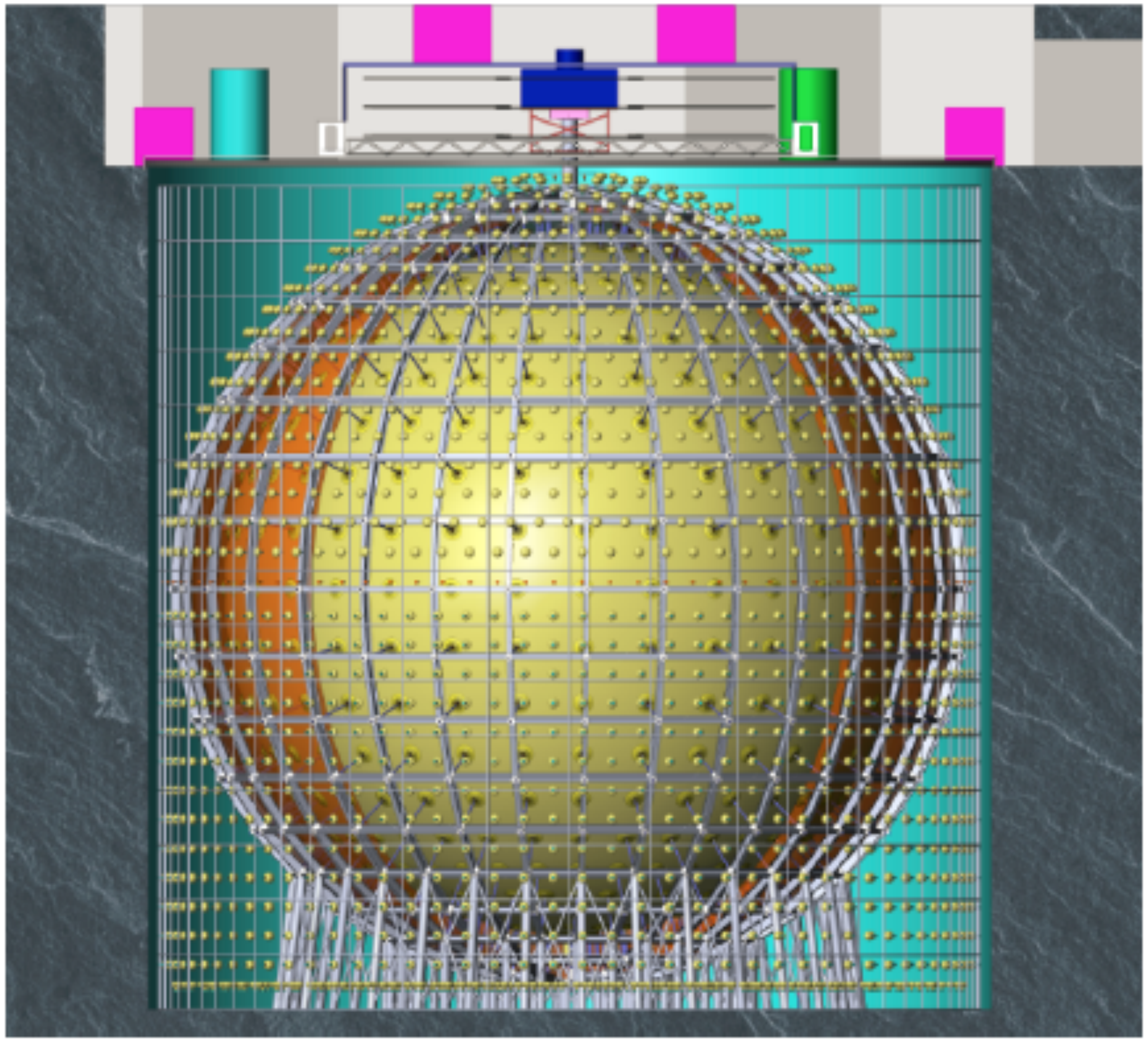


INO, PIngu, Orca strategy to measure mass ordering.
Key challenge: Huge detector, sufficient resolution.

Jiangmen Underground Neutrino Observatory (JUNO)

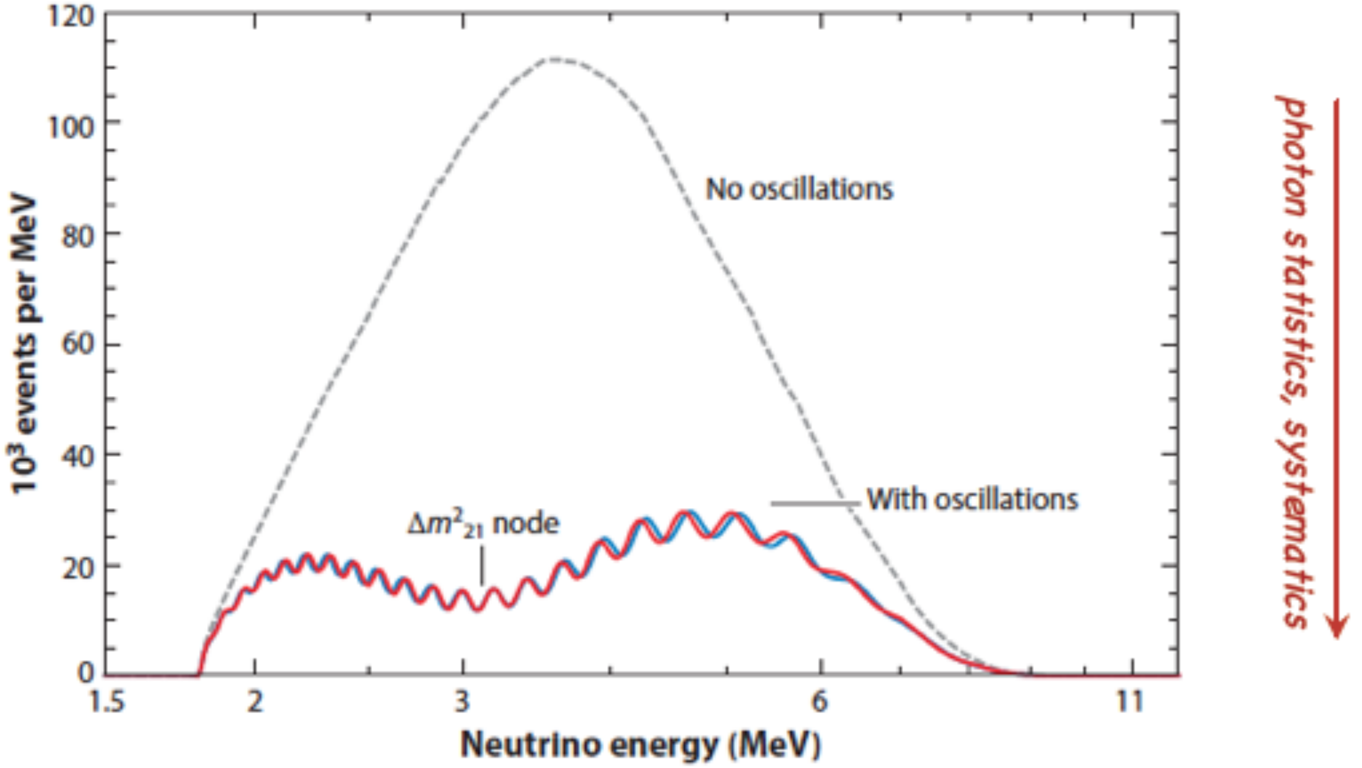


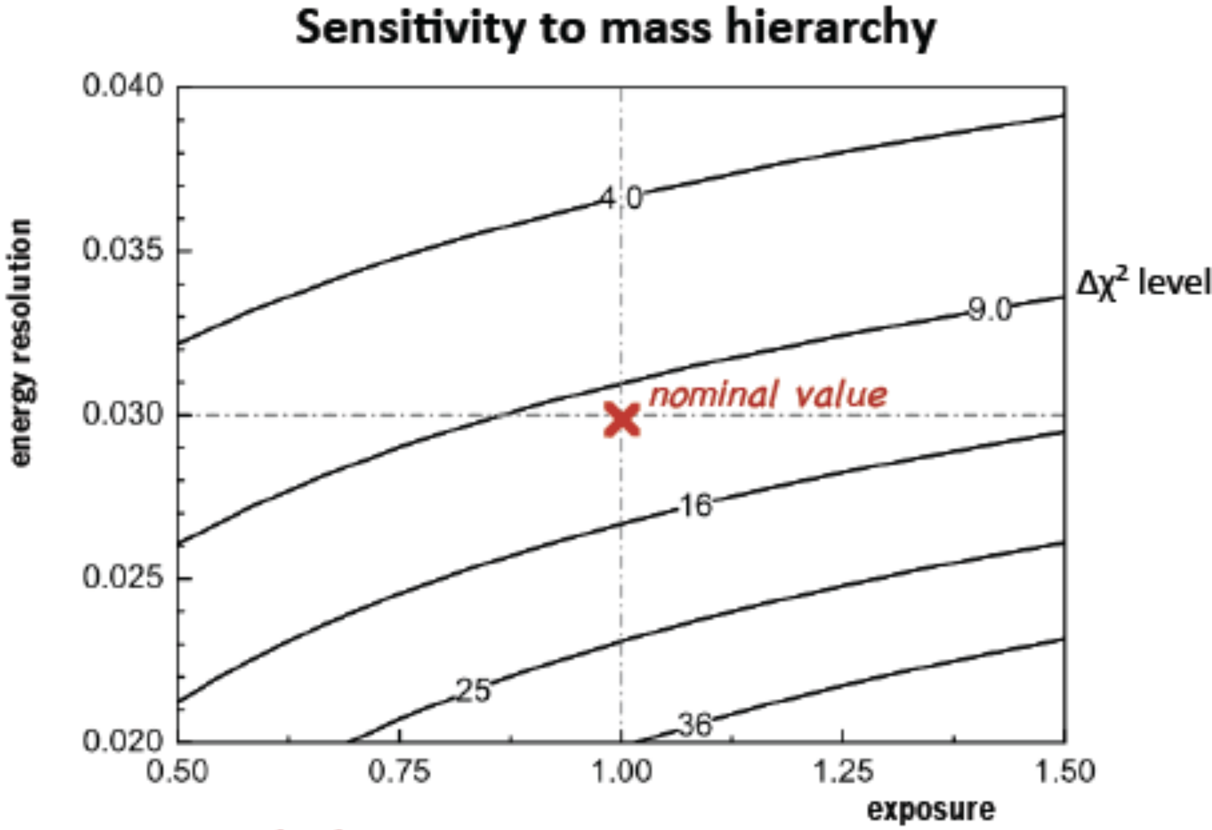
Reactor power: 26.6 GW.
Schedule goal: 2020



35 m diameter.
20 kton of LAB based scintillator. 80% PMT coverage.

JUNO technical challenges





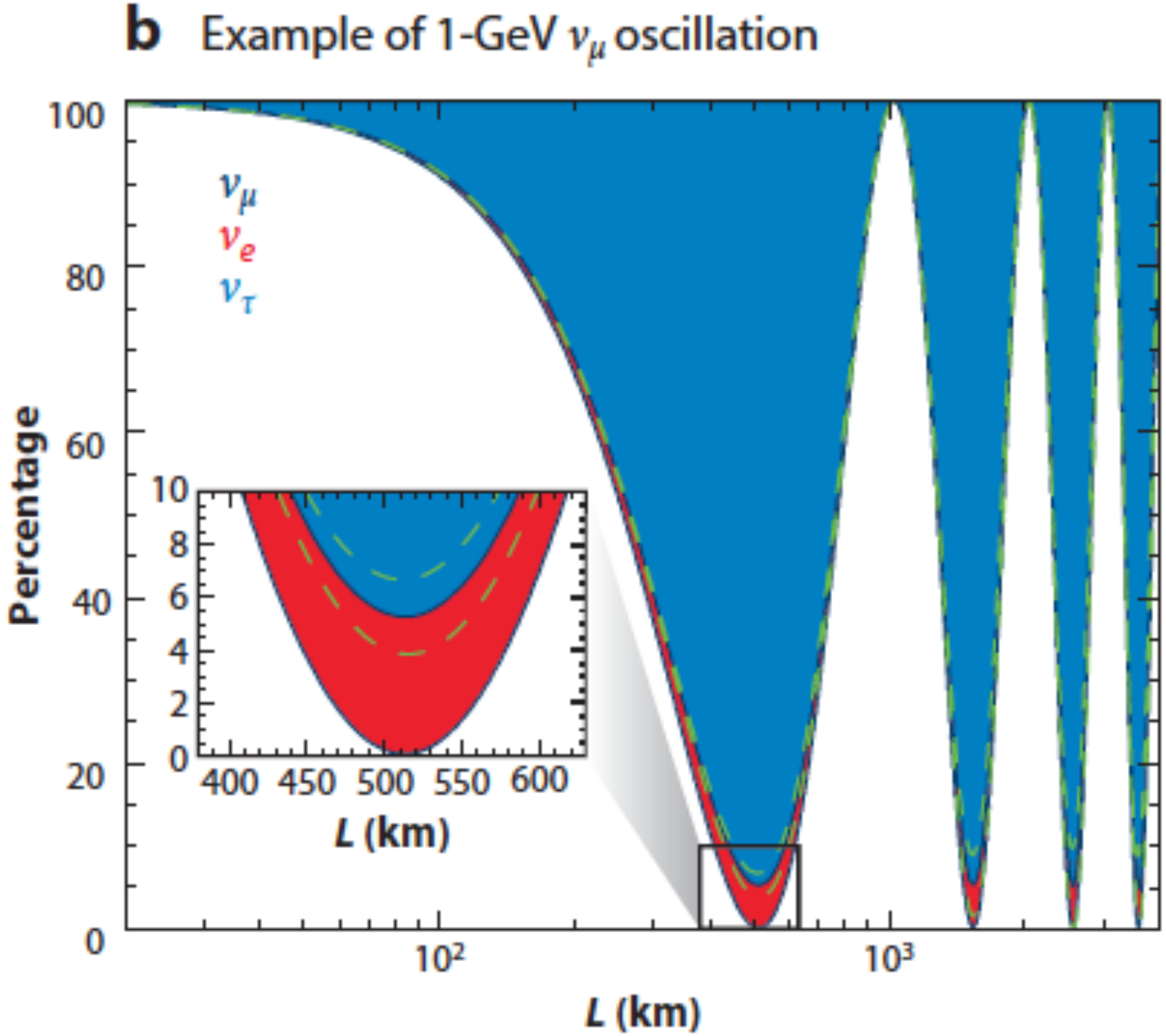
nominal exposure

- 36 GW x 6 years x 20kt
- 80% IBD efficiency

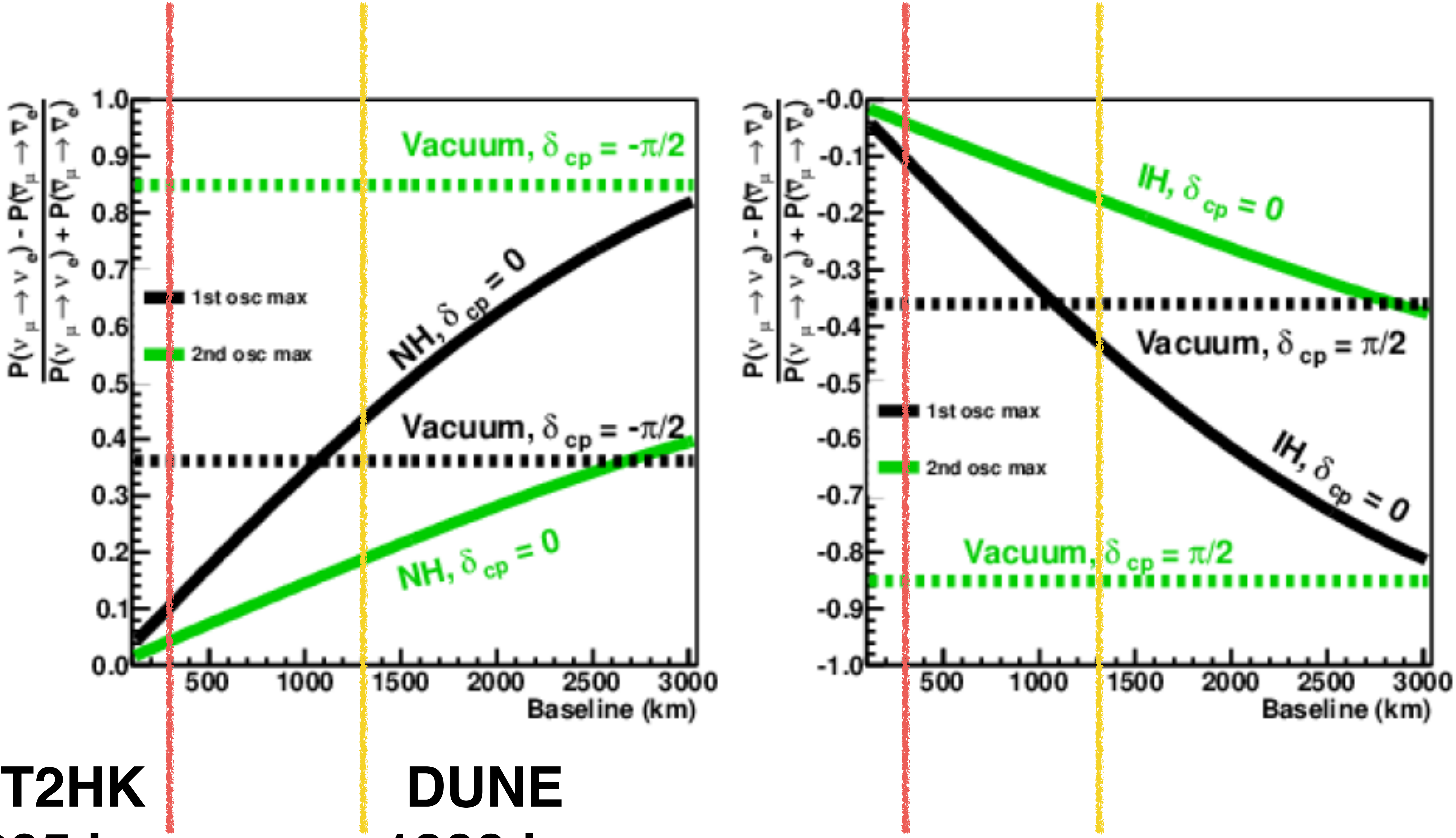
On two sides of the node, the oscillations shift inwards (NH) (red) outwards (IH) (blue)

- **Energy resolution**
- **Light yield**
- **Calibration**
- **PMT capability (18000 20inch + 36000 3 inch)**

Accelerator long-baseline



$$goal: P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

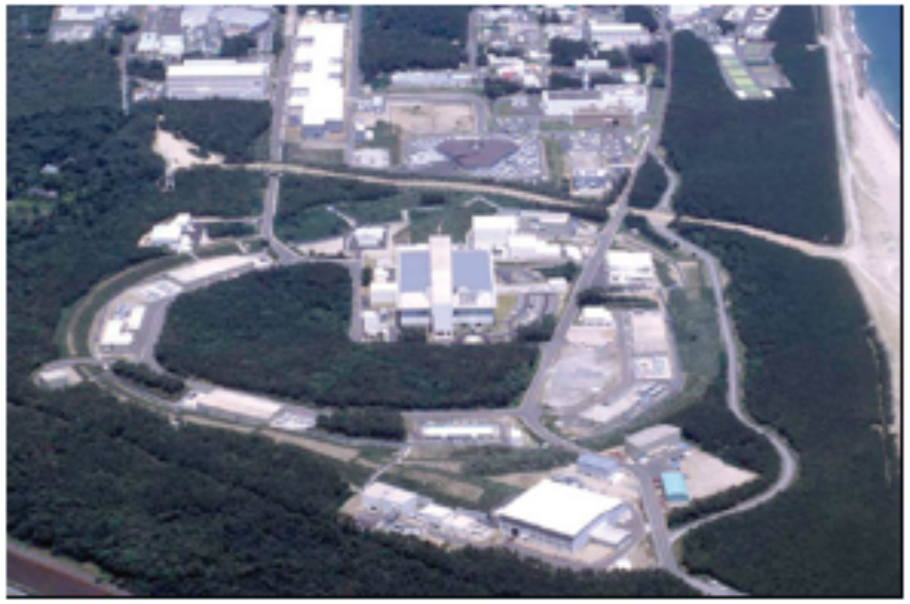


T2HK
295 km

DUNE
1300 km

- **Strategies:**
  - **T2HK: minimize matter effect focus on 1st max**
  - **DUNE: Resolve matter effects with broad-band data**
  - **Both: need >1000 events to measure CP asymmetry (<30%)**

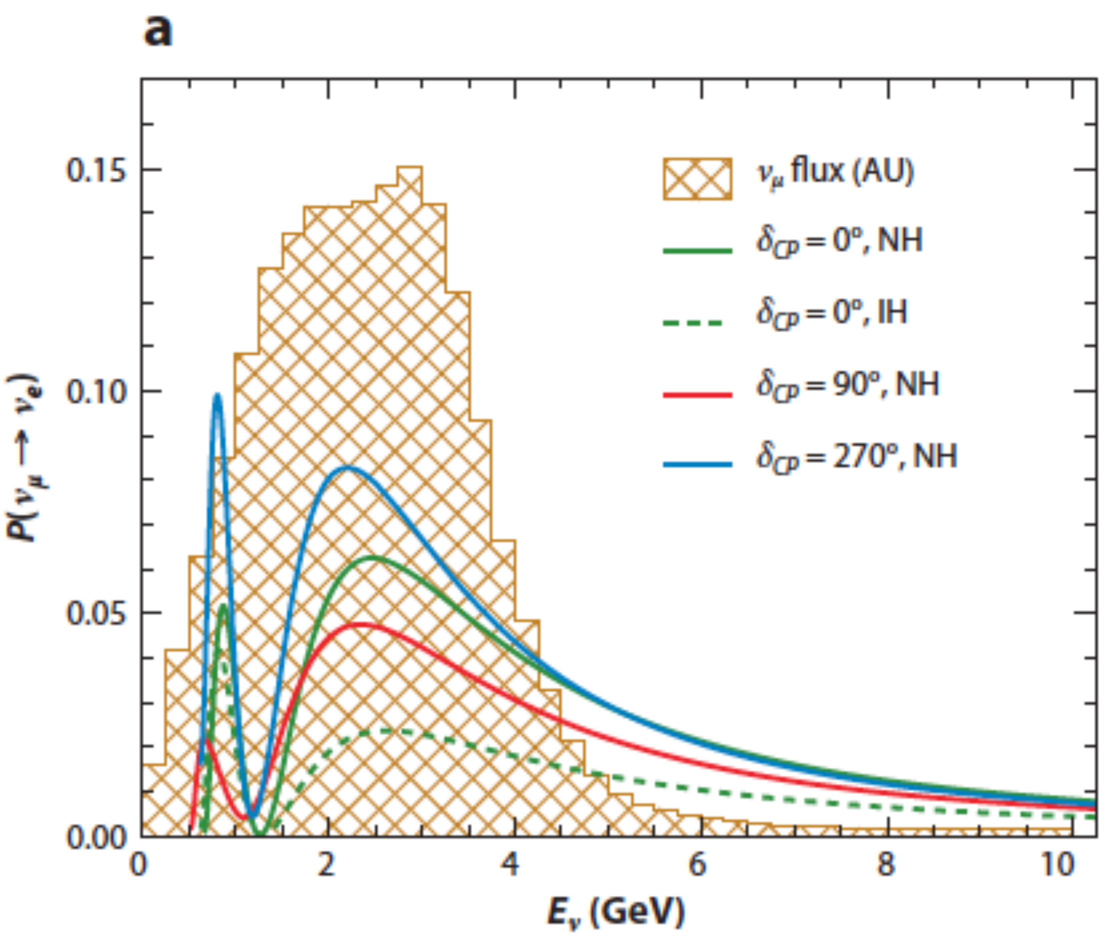
T2HK



- 420 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)

DUNE

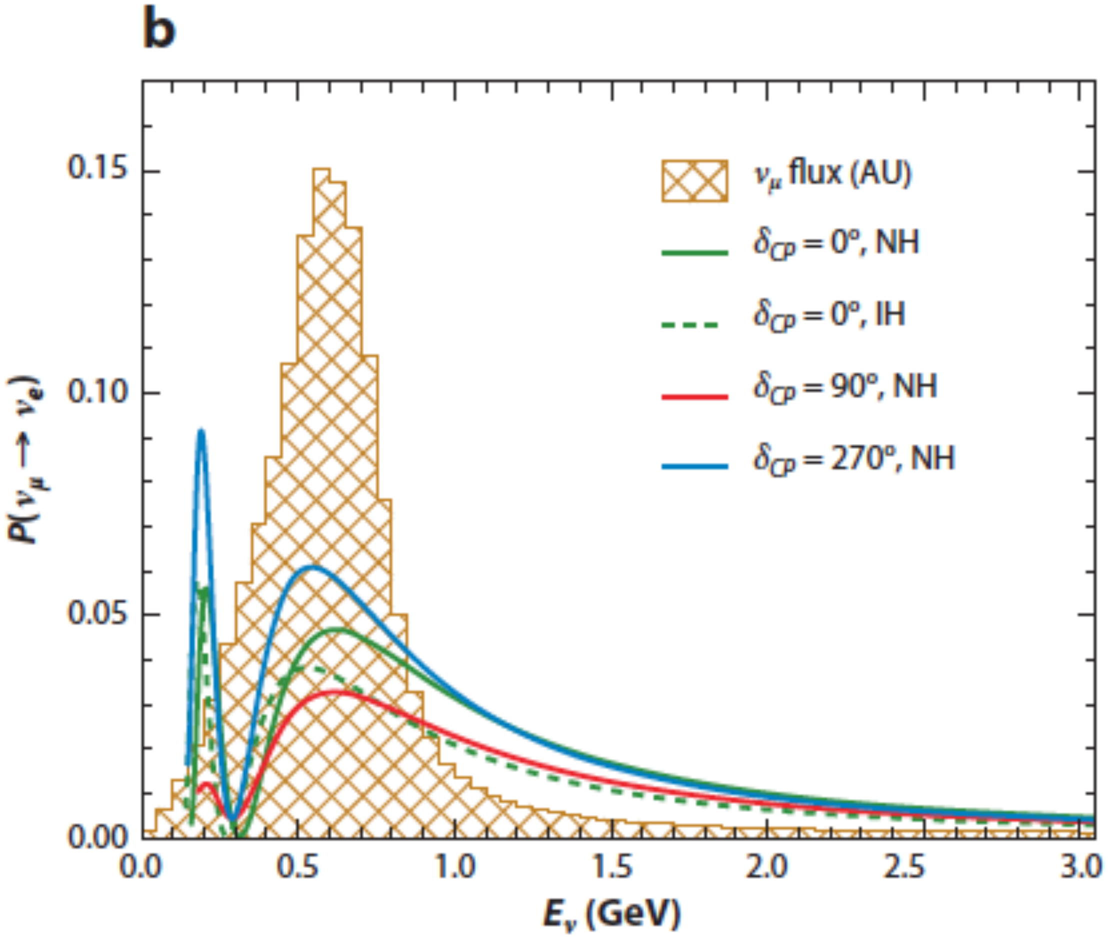
450 kW (today)
~700 kW (2020)
1.2 MW (future)



DUNE

Large Matter effects

Broad band beam



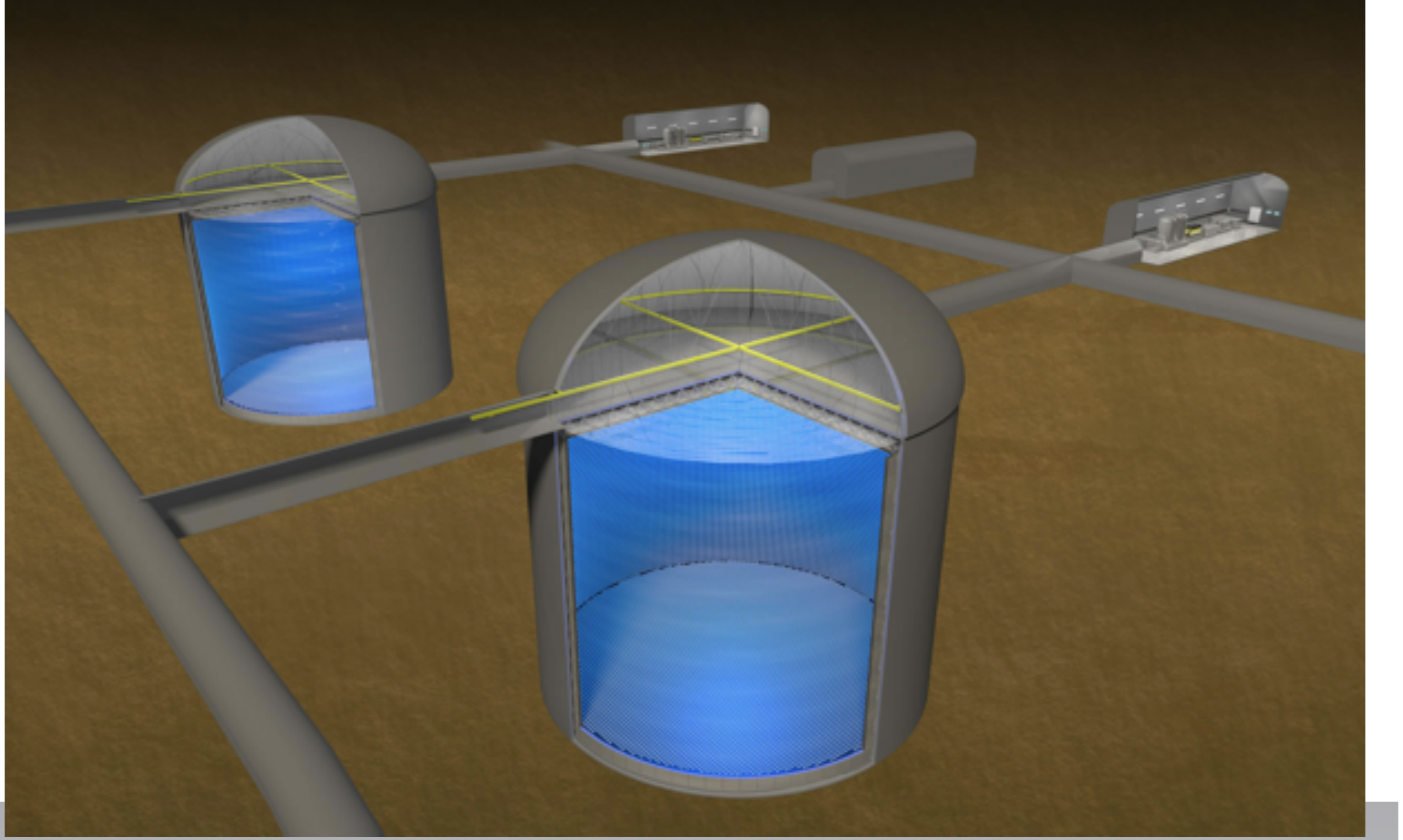
T2HK

Small Matter effects

narrow band beam

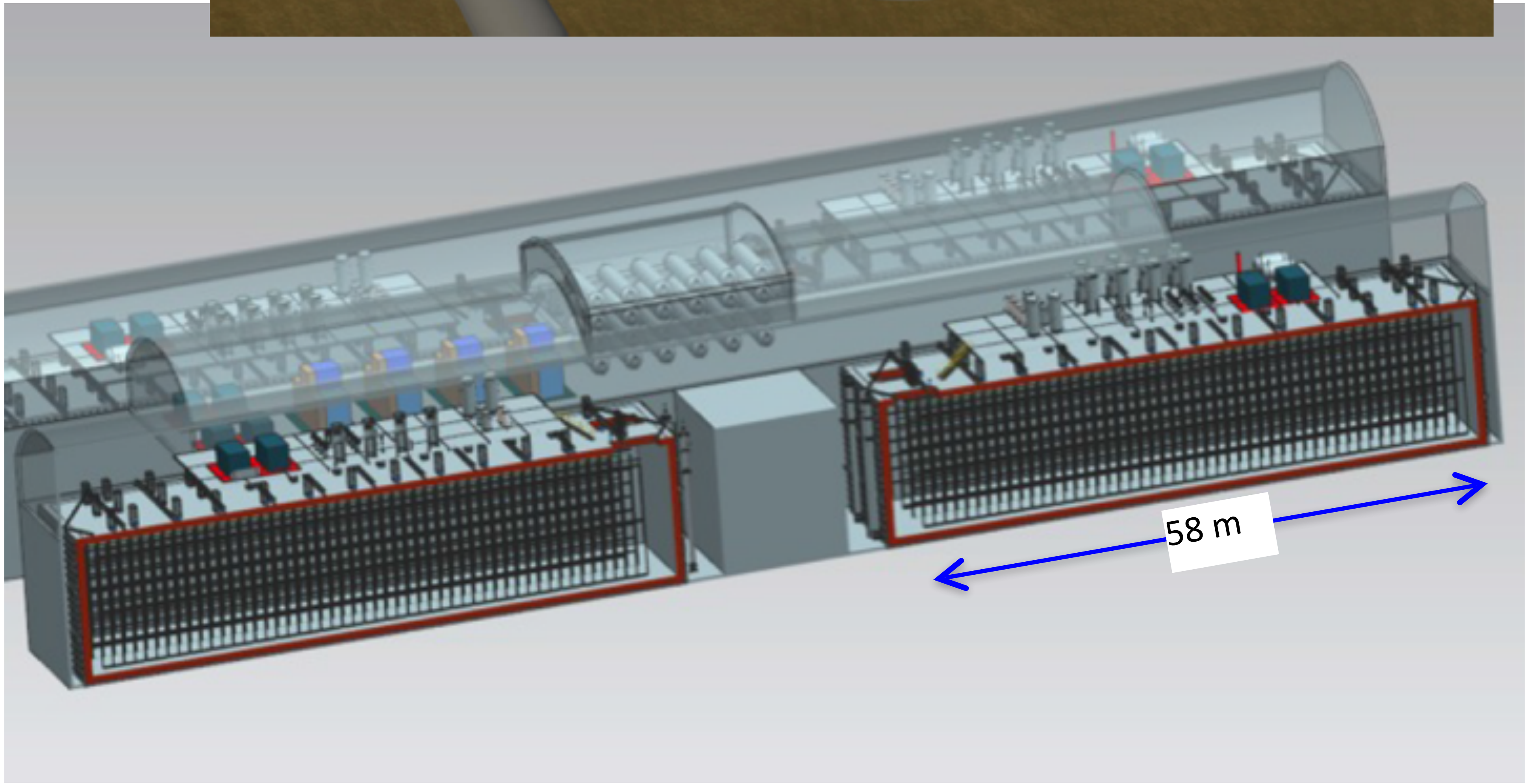
HyperK
~380 kT in two caverns.
~600 MWE

~100k PMTs



DUNE
40 kt Liquid argon TPC in 4 caverns.
~4200 MWE

~400k chs each



LBNF/DUNE and T2HK challenges

- **Both experiments face huge engineering challenges to construct the caverns and infrastructure. They must be international projects to attract the type of funding needed.**

- **DUNE faces the challenge of scaling up the liquid argon technology which uses extremely low noise cryogenic electronics.**

- **In either case, with event samples of ~1000-2000 expected, systematic errors of <2-3% will be needed using the near detectors.**

- **Both have a broad science program with proton decay and supernova. These will need to be considered for the detector requirements.**

Conclusion

- **Scientific motivation and scale of the next generation long-baseline neutrino oscillation experiment is well-known. LBNF design meets the requirements for a comprehensive experiment aimed towards CP violation in the neutrino sector.**
- **There will be a slow motion race to get to mass ordering and CP violation.**
- **There is potential to find new physics because the extraordinary sensitivity of oscillations which are due to interference effects.**

- **It is an opportunity to do something meaningful and permanent together.**