Long term* prospects in neutrino experiments

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Rencontres de Blois,
June 4 2015

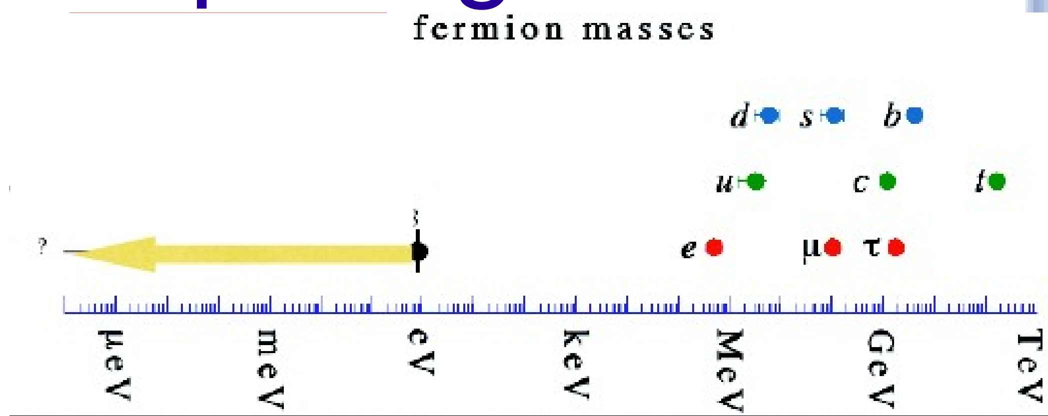
* Here long term means "in the next decade".

Outline

- The neutrino portal: a glimpse of physics beyond the Standard Model
- The PMNS 3 neutrino mixing paradigm
- CP violation: method and issues
- Mid-term experiment: mass ordering from atmospheric neutrinos and reactor neutrinos
- The quest for leptonic CP violation
- Conclusions

Thanks to the T2K, DUNE, Hyper-Kamiokande and other collaborations for providing input

Neutrino physics: surprising results

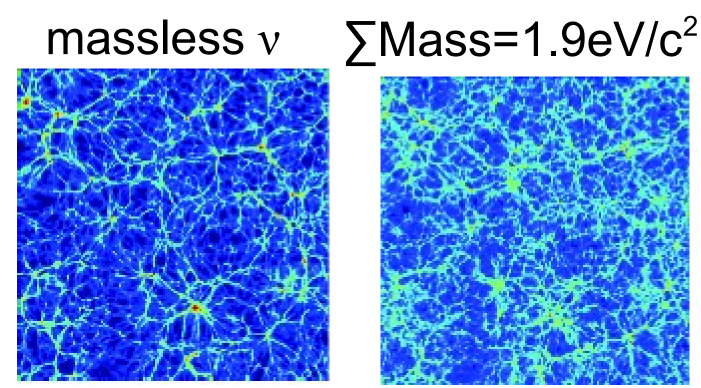


- The unbearable lightness of neutrino masses begs a compelling explanation

- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play a fundamental role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?



Baryon density

Agarwal, Feldman 2010

Baryon asymmetry in the Universe and leptonic CP violation

- To explain the Baryon Asymmetry in the Universe (BAU) (i) C and CP violation, (ii) B violation and (iii) processes out of thermal equilibrium are needed (Sakharov 1967)
- The observed CP violation in the quark sector is many order of magnitudes below what is needed to explain BAU
- The decay of heavy neutral leptons with CP violation may produce a lepton asymmetry first, later converted into a baryon asymmetry: leptogenesis model (Fukugita Yanagida 1986)
- Observing CP violation in the neutrino sector would be a supporting piece of evidence for leptogenesis (NB not a proof!)

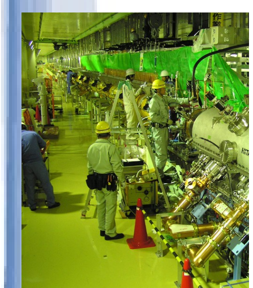
Neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

ν_μ = -sin θ ν_1 +cos θ ν_2

Source



W ν_μ μ

Propagation

$\nu_1 \rightarrow \exp(-ip_1 x)\,\nu_1$

$\nu_2 \rightarrow \exp(-ip_2 x)\,\nu_2$

$\Delta\varphi = \Delta m^2 L/(4E)$

ν_e e

Detector

L

Prob($\nu_\mu \rightarrow \nu_e$)= $\sin^2(2\theta)\ \sin^2(\Delta m^2 L/4E)$

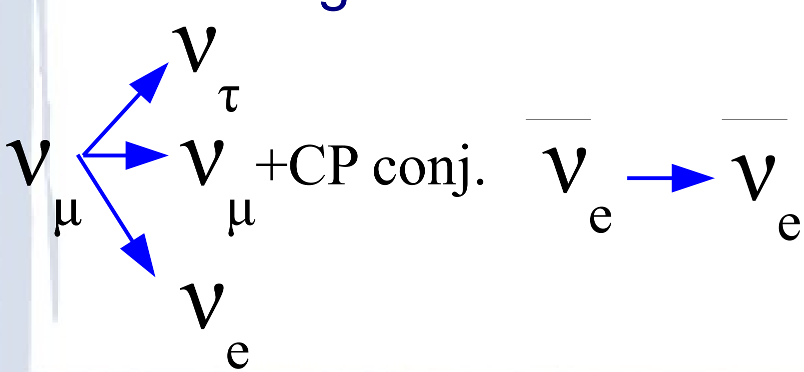
This is a simplified two neutrino scenario

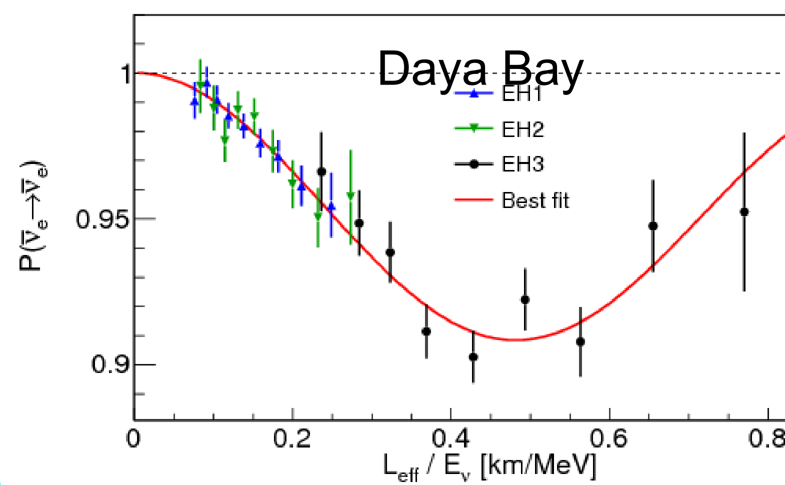
The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

$s_{ij}=\sin\theta_{ij}$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric, reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects





PRL 112, 061801

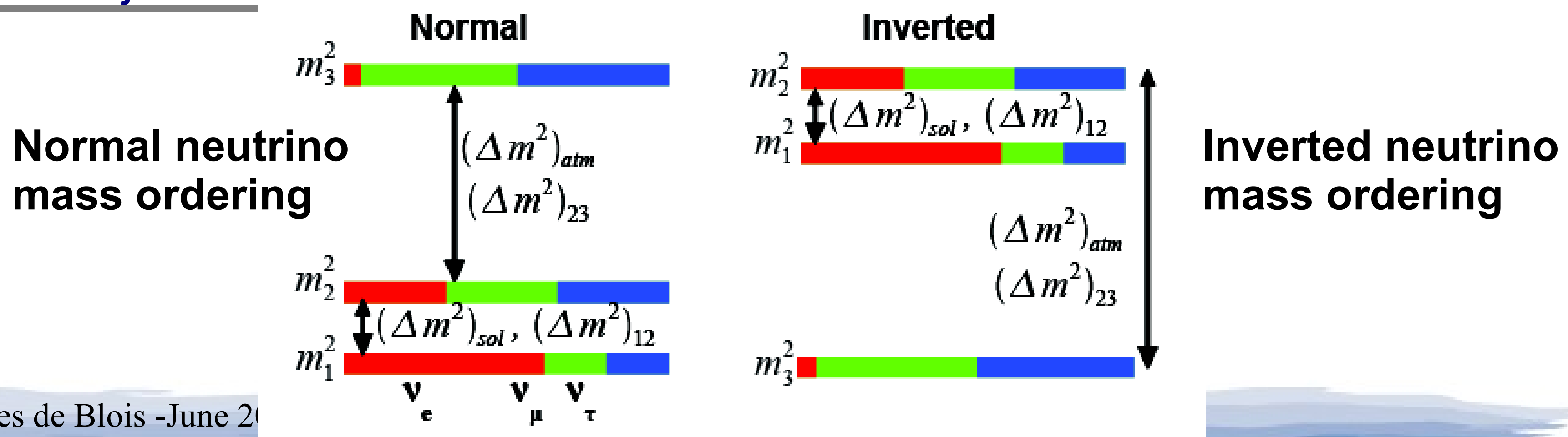
Parameter	Value	Precision (%)
Δm^2_{21}	$7.5\ 10^{-5}$ eV^2	2.6
θ_{12}	34°	5.4
Δm^2_{32}	$2.4\ 10^{-3}$ eV^2	2.6
θ_{23}	42°	~10
θ_{13}	9°	6 (Daya Bay 2014)

Capozzi et al.
ArXiv:1312.2878
Talk by M. Tortola

Next steps in neutrino studies

1) Is θ_{23} =45°? which octant ?
2) Determine the mass ordering
3) Measure the CP violation parameter δ
4) Precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)
5) Are there any new neutrino states ?
6) Dirac or Majorana ?

1) Is there a symmetry between ν_μ and ν_τ ?
2) Help model builders. Impact on cosmology.
3) Link with leptogenesis. Are we born out of (heavy) neutrinos ?
4) How different are neutrinos ?
5) Would require a new paradigm
6) Majorana mass term: major discovery



Neutrino oscillation physics from today to ~2030

2015 **2020** **2025** **2030** **T**

T2K NovA, Daya Bay, RENO, Double Chooz

Increased precision on θ_{13}, θ_{23}, limited sensitivity to CP and mass ordering

CESOX, STEREO, SOLID, MicroBoone, ...

eV mass sterile nu searches (source,reactor, short baseline)

JUNO, INO, PINGU, ORCA, RENO-50

Determination of neutrino mass ordering

Precision study of CP violation
Proton decay search
SN neutrinos

Hyper-Kamiokande DUNE

The road towards CP violation: $\nu_\mu \to \nu_e$: beyond the leading term

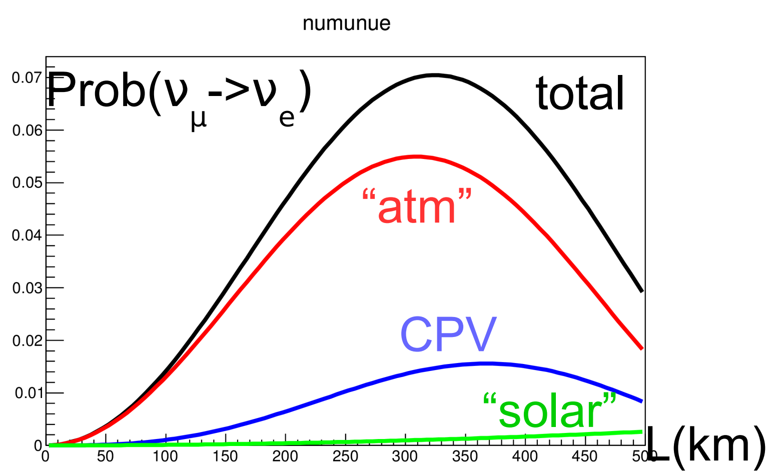
$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

$$\pm 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

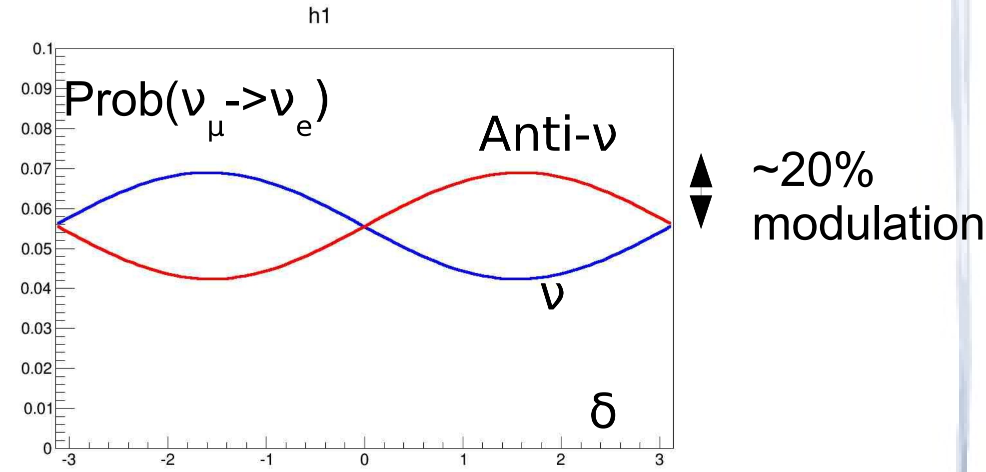
$$+4 S^2_{12} C^2_{13} (C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$ "Solar" term

$$C_{ij} = \cos(\theta_{ij})$$
$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from nu to anti-nu! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced



E=0.6 GeV

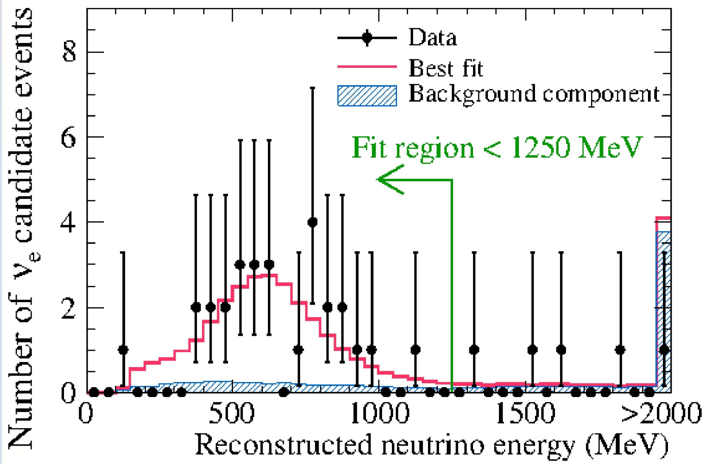


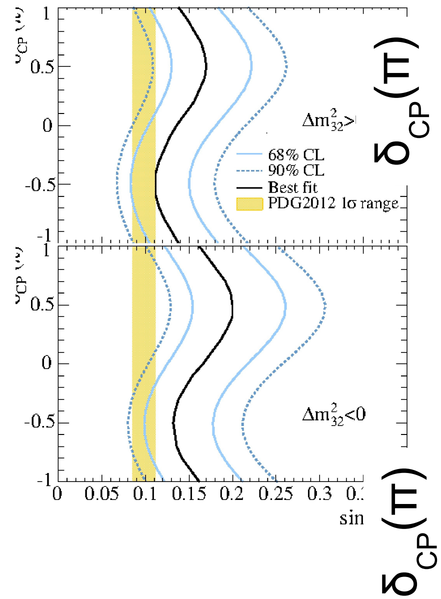
Caution: indicative plots !!

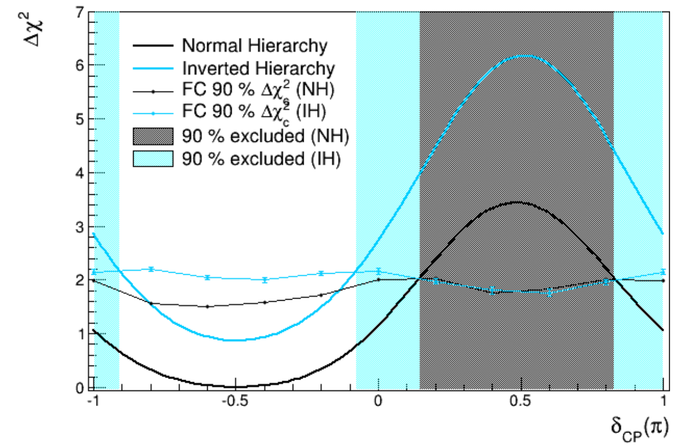
Phys. Rev. D 91, 072010

$\nu_\mu \to \nu_e$

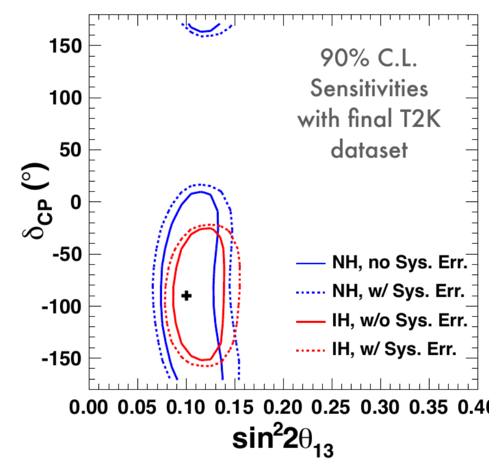
T2K first limits on CP violation







- Comparing the observed 28 ν_e events in T2K with θ_{13} measured at reactor experiments provides first hints of CP violation
- Full T2K data set (today ~15% of total) might provide ~2 σ evidence (if CP maximal)
- NOVA (data taking started in 2014) will provide additional sensitivity at a different L
- <u>However precision determination requires a new facility</u>



arXiv:1409.7469

Neutrino oscillation in matter

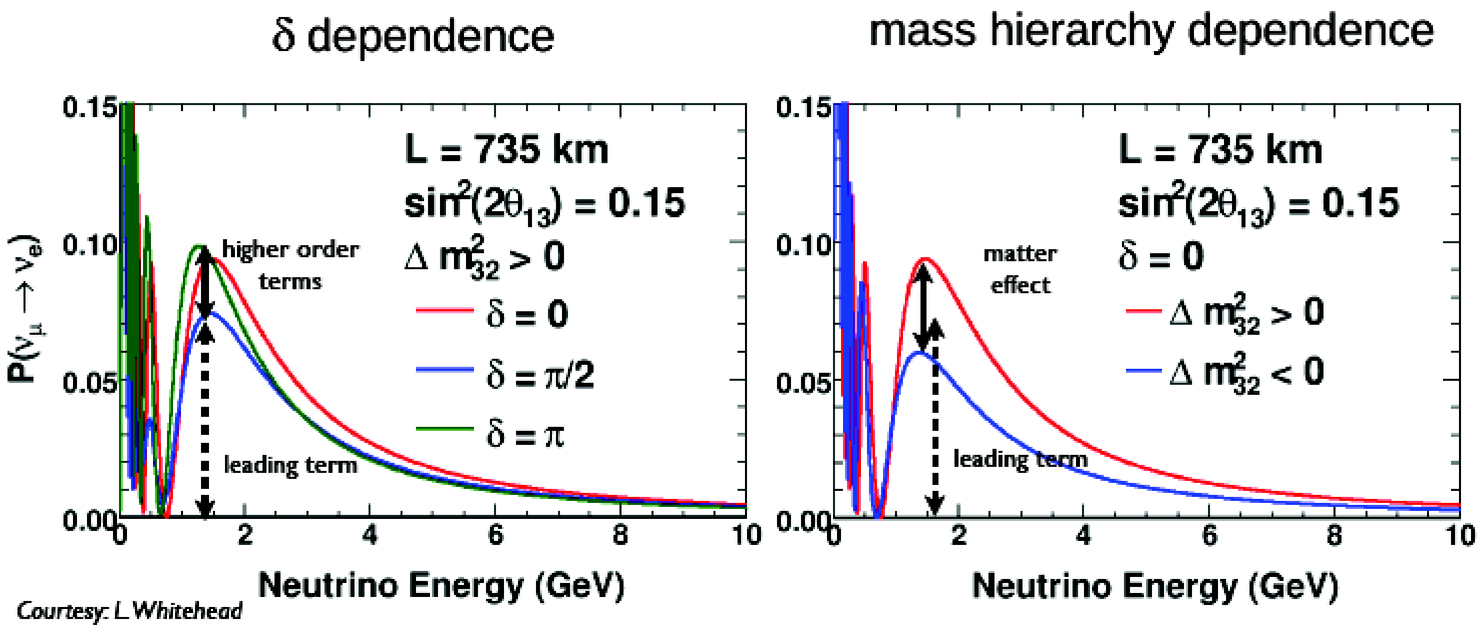
- Neutrino forward scattering on electrons, equivalent to light refraction index, proportional to $G_F\ N_e$
- Leads to oscillation enhancement (resonant behavior, MSW effect) for neutrino and normal ordering or antineutrinos and inverse ordering

$$\sin^2(2\theta_m)=\frac{(\Delta m^2/2E)^2\sin^2(2\theta_0)}{((\Delta m^2/2E)\cos(2\theta_0)-2\sqrt{2}G_F N_e)^2+(\Delta m^2/2E)^2\sin^2(2\theta_0)}$$

Constant density
2-ν case

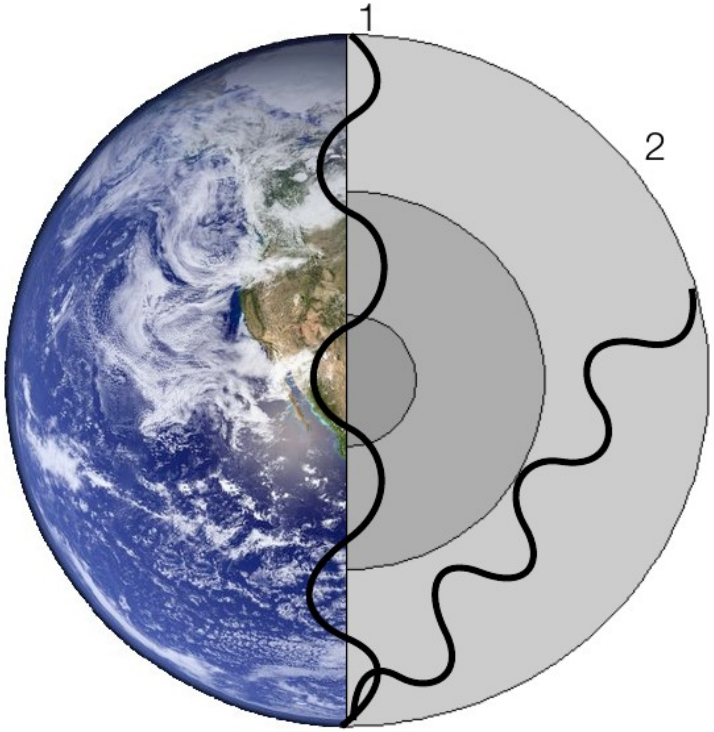
For the three neutrino case, for Normal Ordering matter effect enhance Prob ($\nu_\mu \to \nu_e$) and suppress it for antineutrinos. Viceversa for Inverted Ordering.

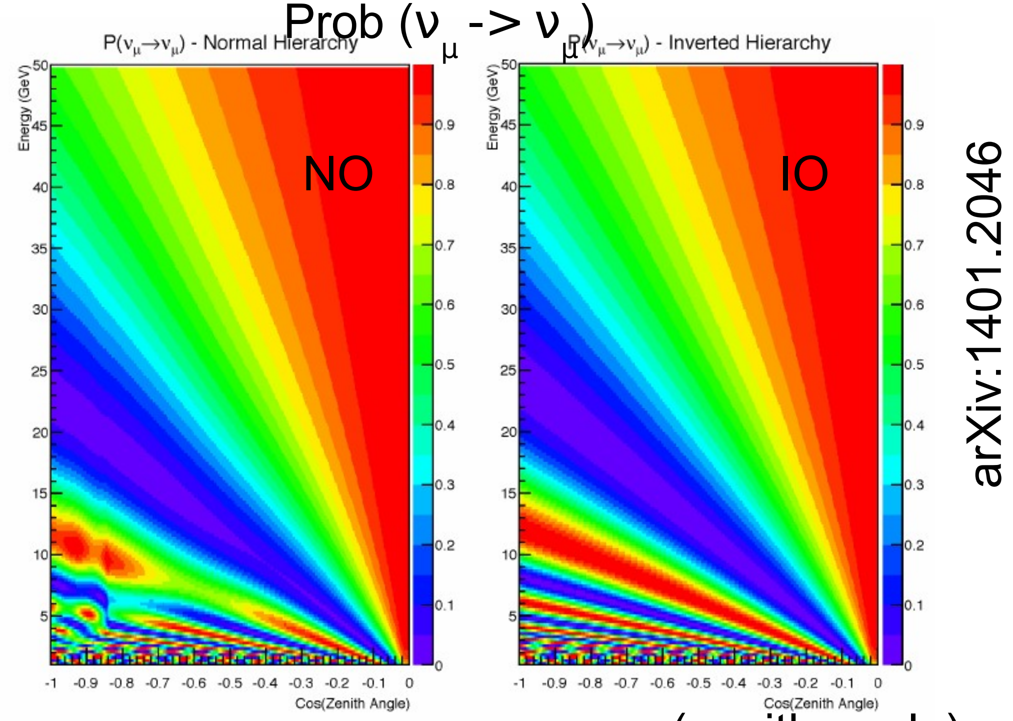
The matter with CP



- The study of the CP asymmetry is obscured (or enriched) by matter effects (interaction of ν with e in the traversed matter) that mimic a CP effect
- This complication can be seen as a challenge or an opportunity : clean measurement of mass hierarchy
- Solutions: go to a shorter baseline (~100km, little matter effects) or to a very long baseline (~1000km, decoupling of the two effects)
- The study of CP violation gets coupled to the determination of the neutrino mass ordering (MO)

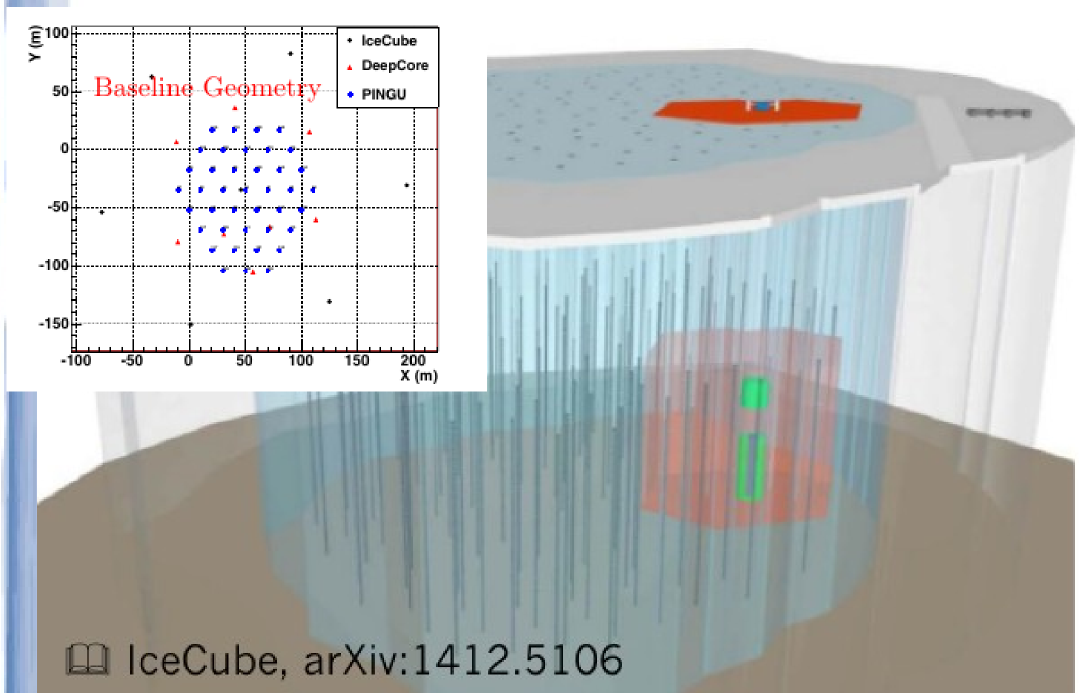
Matter effects for atmospheric neutrinos





- The matter effect can be seen with atmospheric neutrinos traveling in the mantle or the core (cos theta)<-0.8. Two channels are available: and Prob (ν_μ -> ν_μ) Prob (ν_μ -> ν_e). Max sensitivity below 20 GeV.
- These plots get smeared by angular and energy resolutions.
- Some detectors do not separate neutrinos from antineutrinos and rely on the difference in neutrino and antineutrino cross-sections (additional smearing).

Measuring the neutrino mass ordering with atmospheric ν: PINGU and ORCA

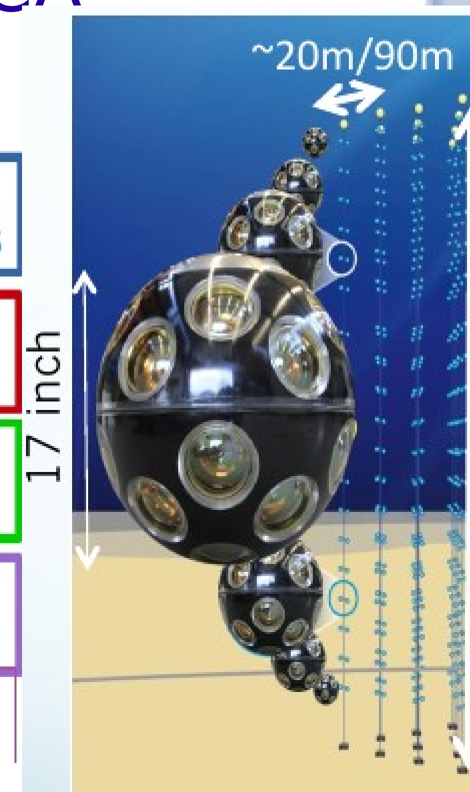


IceCube Gen2
→ +120 strings, 7,200 DOMs

IceCube
→ 86 strings, 5,160 DOMs

DeepCore
→ 8+7 strings, 500 DOMs

PINGU
→ +40 strings, 3,600 DOMs
10" R7081-02 High-QE
+ electronics upgrade

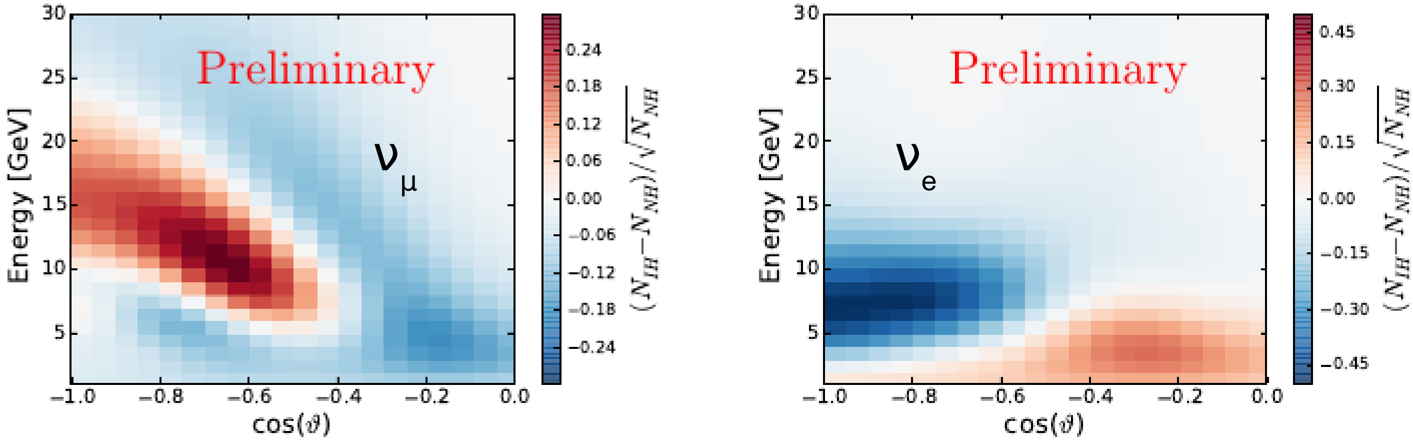


PINGU is a proposed low energy extension of the ICECUBE South Pole neutrino observatory. A much denser optical module array will provide a threshold at the few GeV level.

ORCA (based on Antares, KM3NET technology) is a similar project in the Mediterranean sea (Toulon site) with new optical modules (115 lines, 20m btw lines, 6m spaced OM, 2070 OM in total)

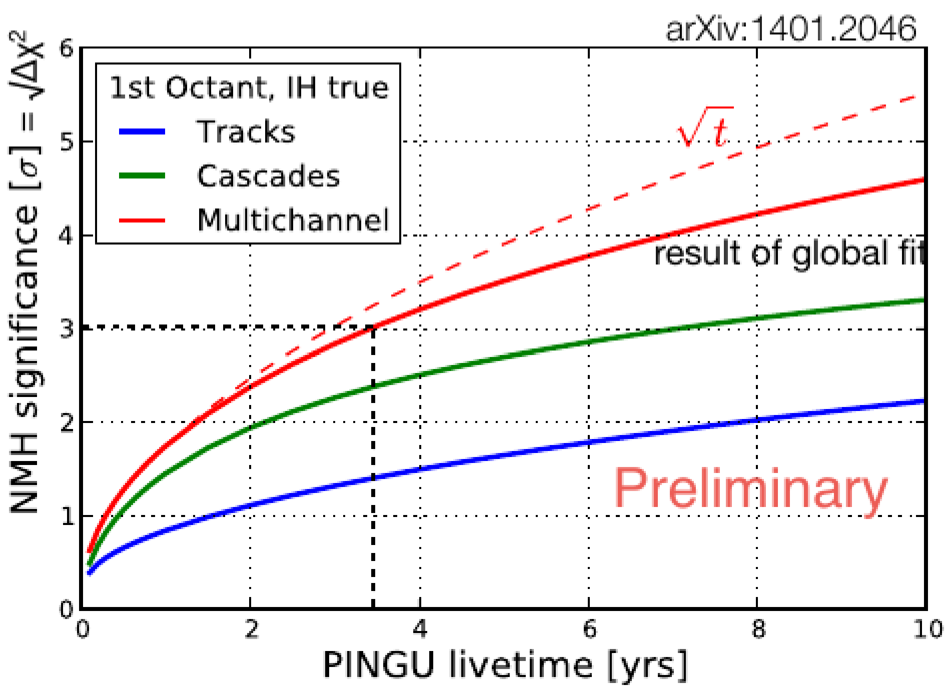
Multi Mt instrumented mass in both cases.

Measuring the neutrino mass ordering with atmospheric ν: PINGU and ORCA



(a) ν_μ CC events. (b) ν_e CC events.

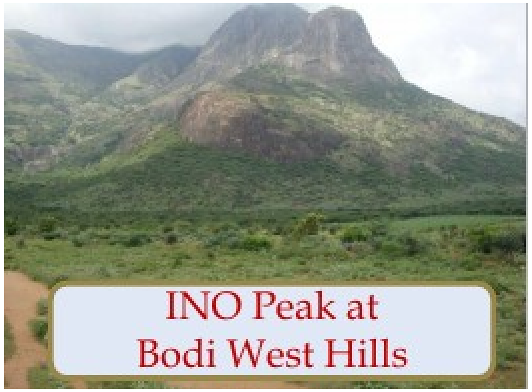
Sensitive regions in the energy-zenith angle plane



PINGU LOI (arXiv:1401.2046)
Main sensitivity from the ν_e channel
Normal and inverted mass ordering distinguished at 3 σ in 3.5 years.
Similar sensitivity for ORCA

The India-based Neutrino observatory

INO: located in Tamil Nadu (Southern India) 1289m (~3800mwe) vertical rock coverage

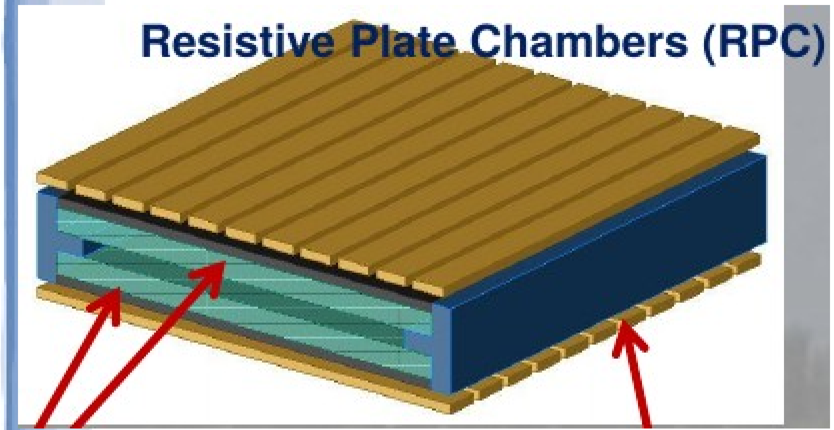


50 kton magnetized iron detector

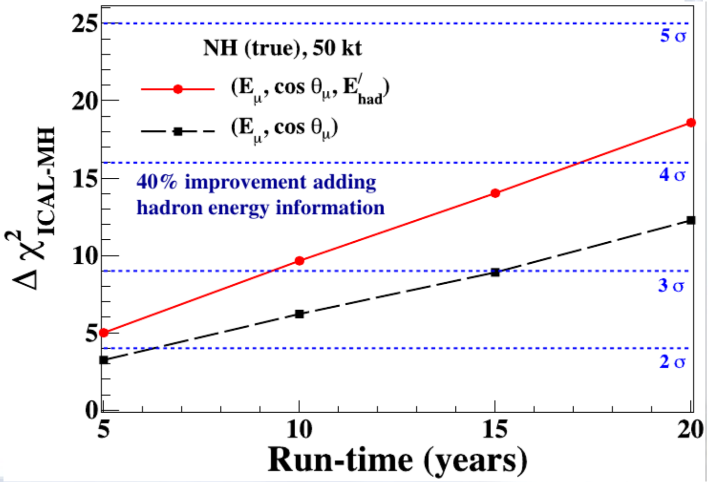
1.4 T magnetic field

Resistive plate chambers with 5.6 cm iron plates

Differentiate neutrinos from antineutrinos

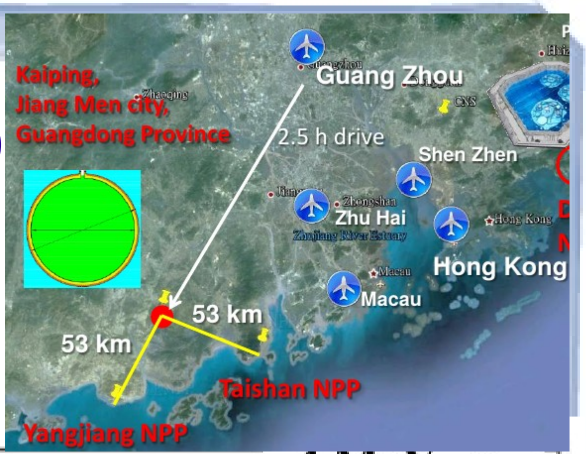


arXiv:1406.3689

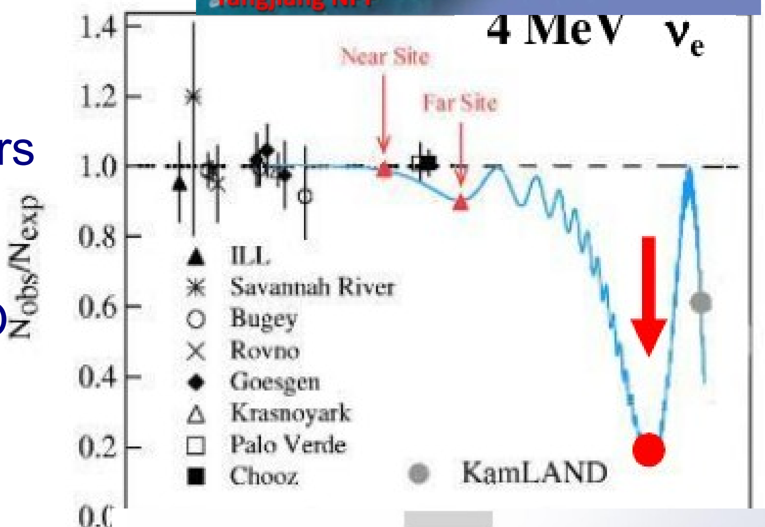


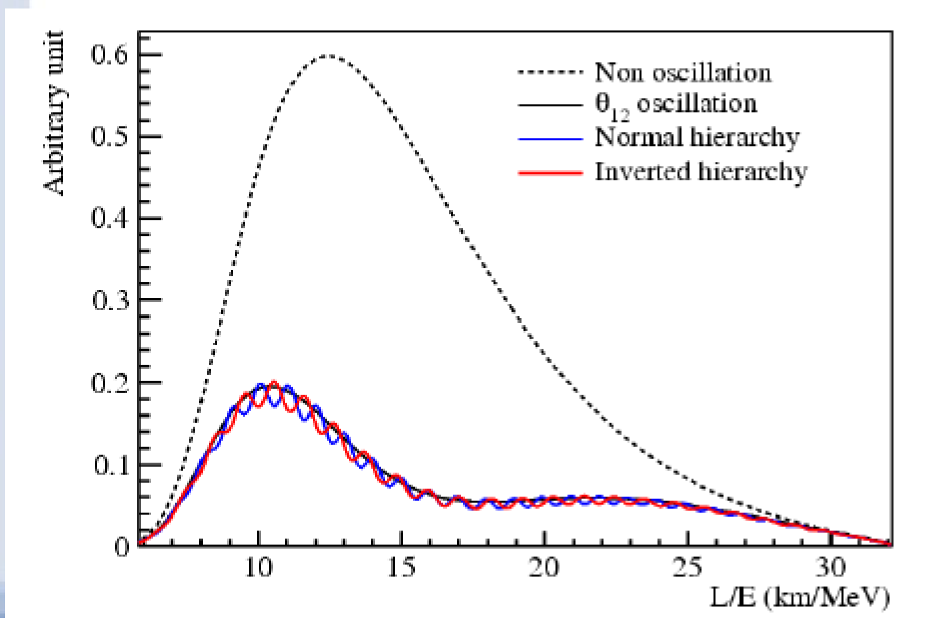
PRD78:111103, 2008; PRD79:073007,2009

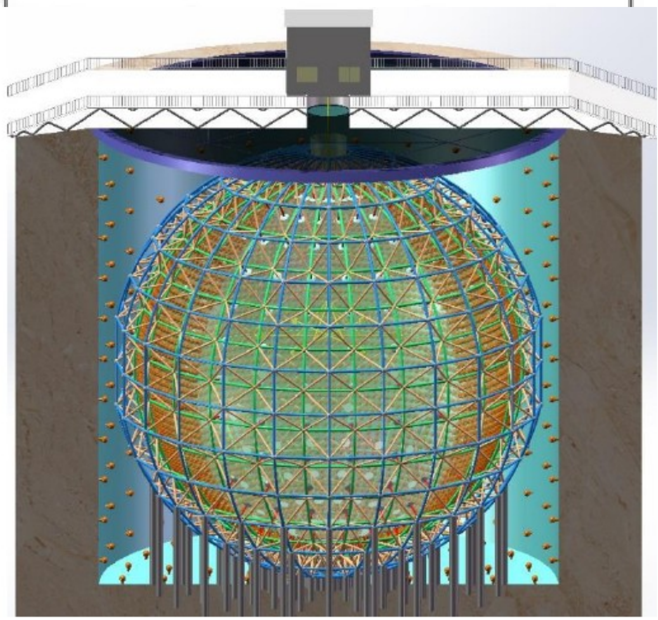
Measuring the neutrino mass ordering: JUNO



- 20kton Liquid Scintillator detector in southern China, 700m underground
- At 50 km from two nuclear reactors complexes
- Several other measurements: precision solar ν parameters Δm^2_{21}, θ_{12}, SN, ….
- Stringent requirements on energy (3% resolution) for MO
- Project approved, under construction, data taking 2020

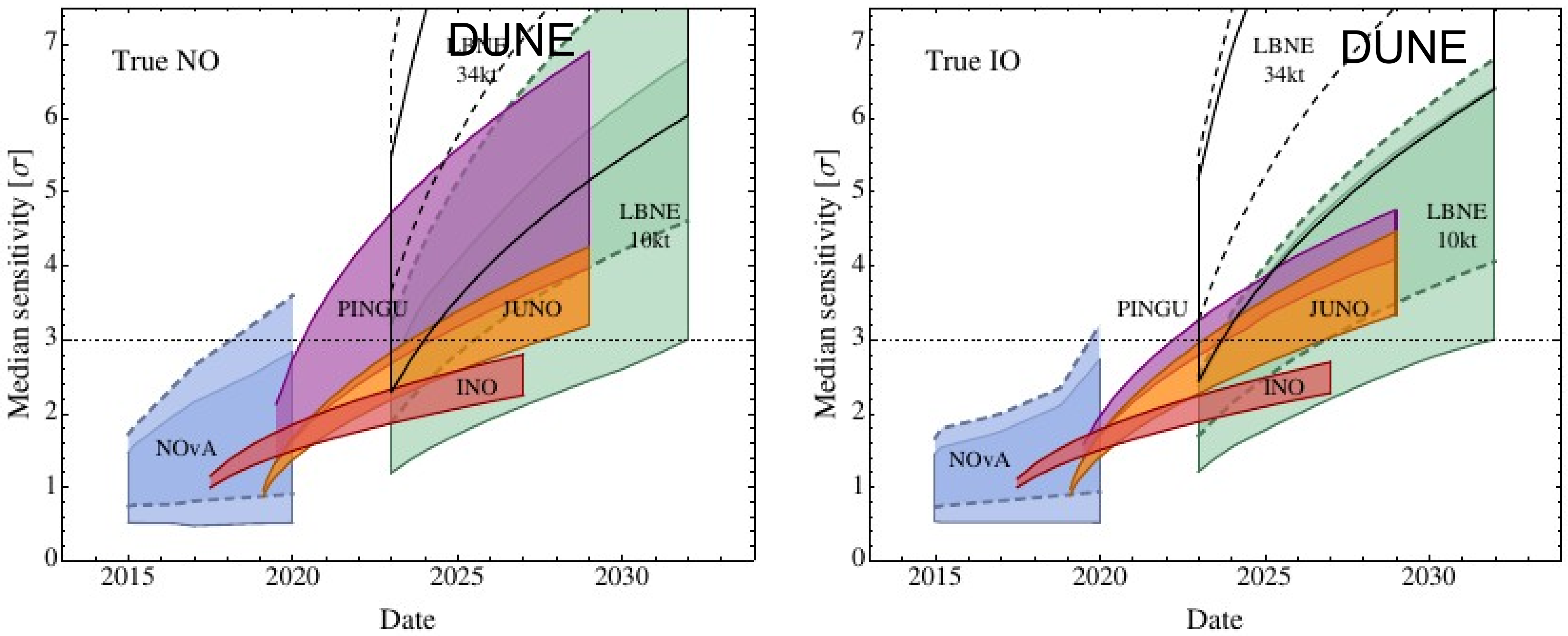






Blennow JHEP 1403 2014 028

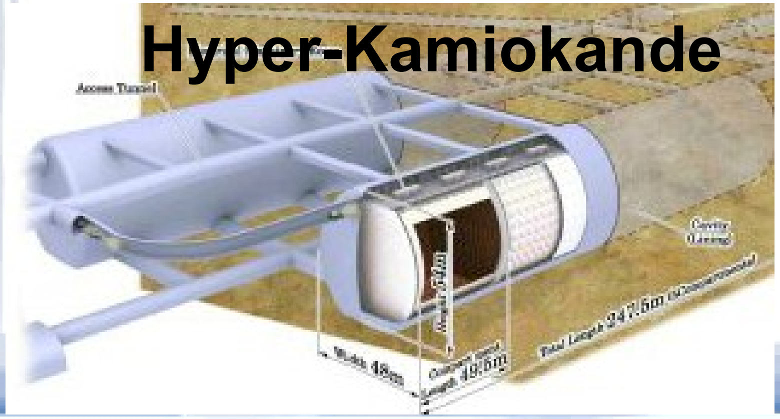
Mass ordering timeline

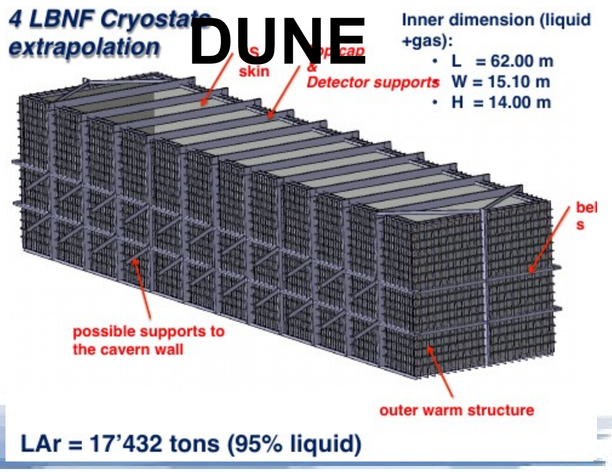


Caution: median sensitivity, starting dates indicative.

Strategies for CP

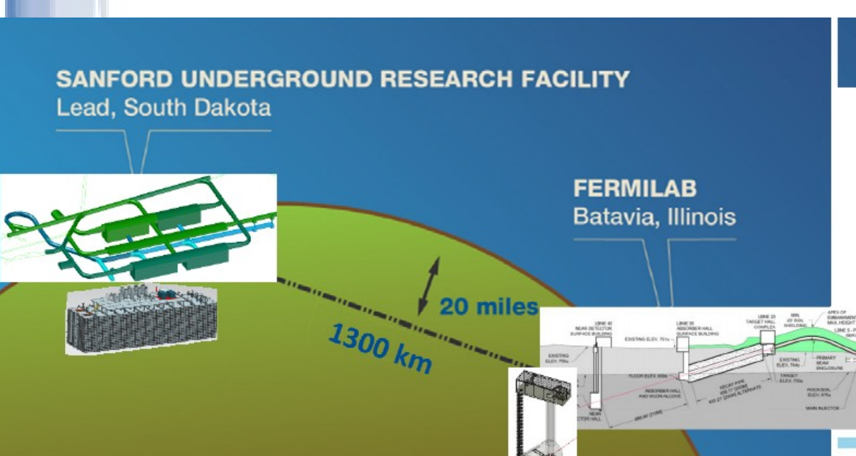
- Short baseline (~100-300 km), lower energy (<1 GeV), narrow beam, large Water Cherenkov (~500 kT). Concentrates on $\nu/\bar{\nu}$ asymmetry around the first oscillation max.
- Longer baseline (>1000 km), higher energy (>1 GeV), wide beam, Liquid Argon TPC. All final states accessible, E/L oscillation pattern and second maximum





The LBNF/DUNE project

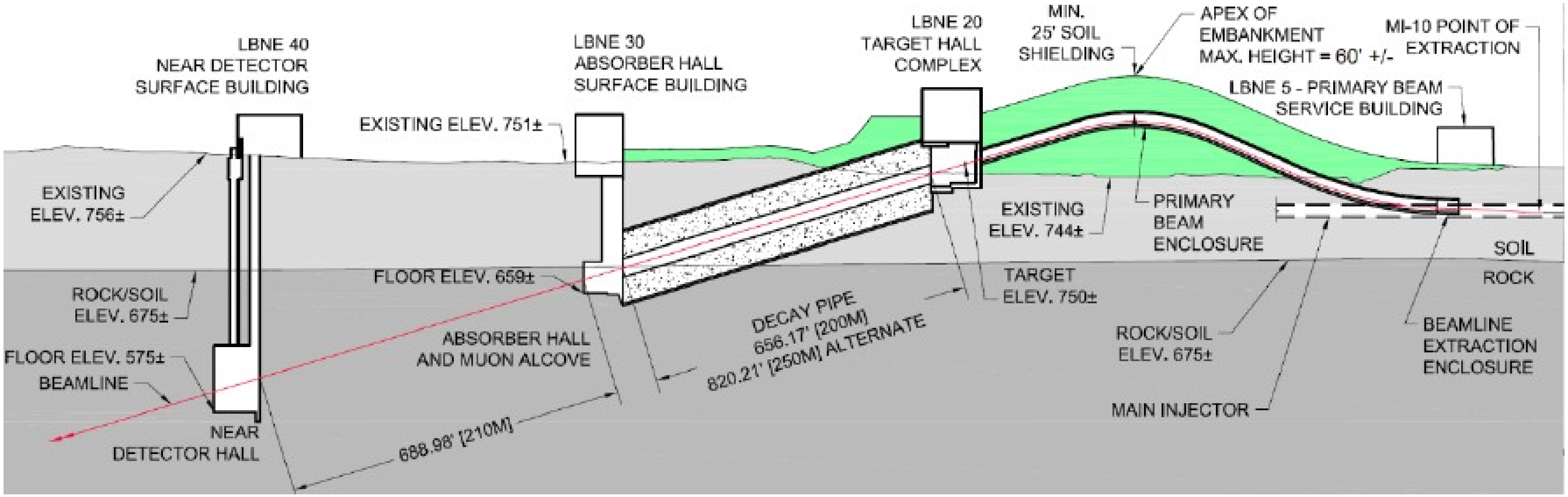
- LBNF DUNE: flagship particle physics project in the US (P5 recommendation)
- 1300 km baseline from FNAL to SURF (South Dakota)
- Based on PIP-II upgrade to FNAL accelerator complex: 1.2 MW at 120 GeV (ultimate beam power 2.4 MW)
- Sophisticated near detector on FNAL site
- SURF: 4 caverns with 4x10 kt fiducial mass far detector



Currently preparing CD-1 document (to be released in July)
LBNF LOI: deployment of first 10kt module in 2021
Collaboration strengthened (>700) and more international (India, CERN, Laguna-LBNO)

Fermilab Accelerator Complex

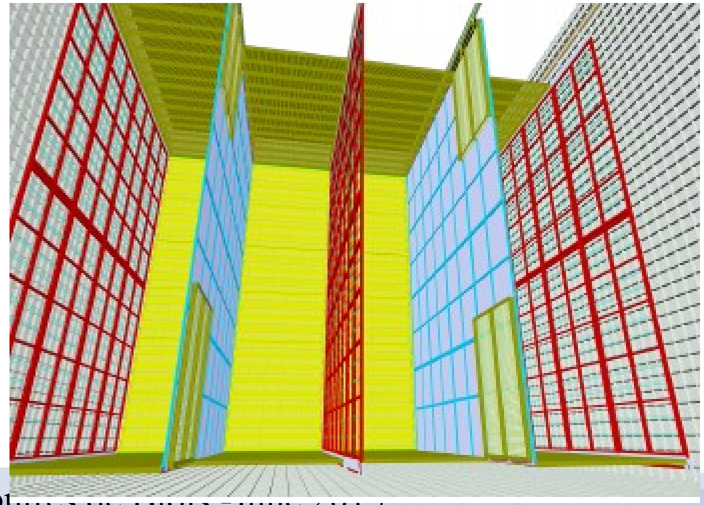
The LBNF beamline towards SURF

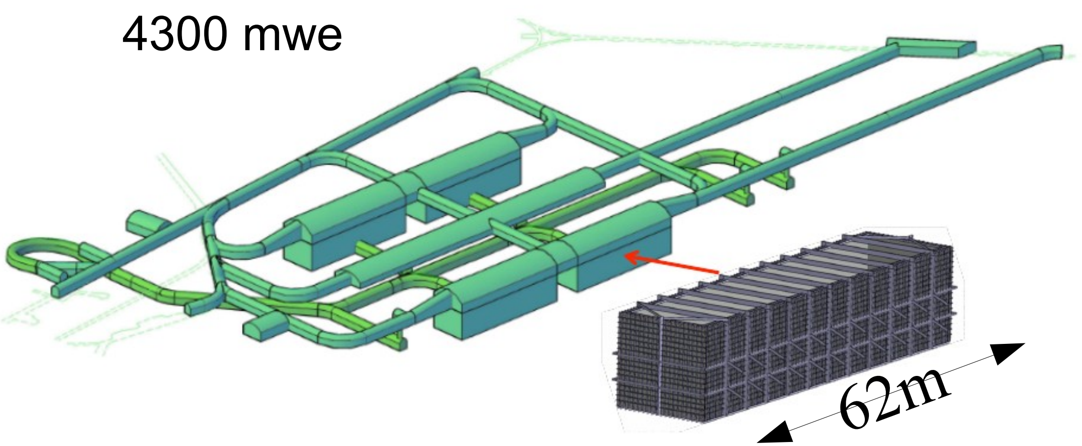


- Beam based on the Proton Improvement Plan II based on a SuperConducting Linac to provide 1.2 (up to 2.4) MW beam (at 60-120 GeV)
- The beamline includes a graphite target, an improved horn design, decay tunnel, hadron absorber and near detector hall

The Sanford Underground Research Facility (SURF)

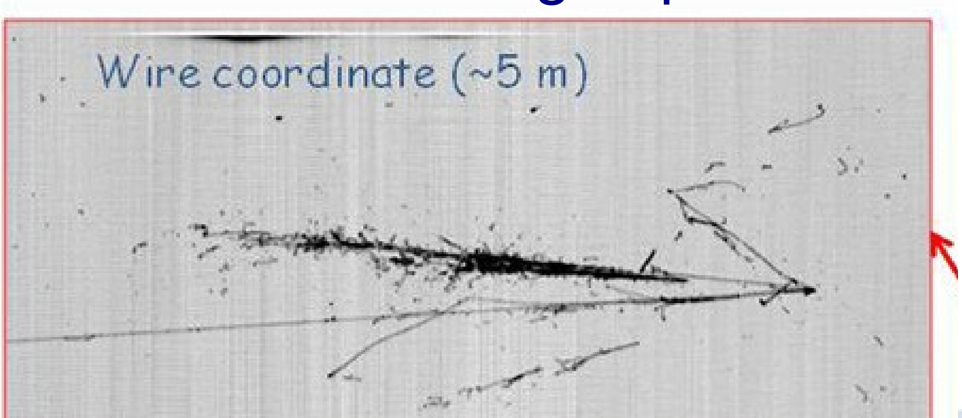
- Historical site for neutrino physics: laboratory of the Homestake Ray Davis solar neutrino experiment
- Today hosting dark matter experiments (LUX/LZ)
- Major refurbishing of the facility ongoing
- Underground lab includes four large caverns and other infrastructure
- Reference detector design : Liquid Argon TPC



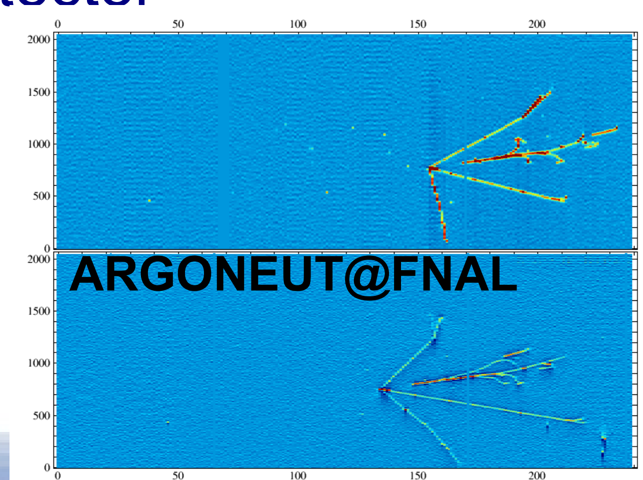


Why Liquid Argon TPC ?

- Technology pioneered by the ICARUS collaboration
- Fully active high granularity detector (voxel ~3x3x0.4mm^3): a modern bubble chamber
- PID (from range and dE/dx) and high resolution calorimetry
- Sensitive to ν_μ, ν_e and ν_τ
- Currently used by the MicroBoone short baseline exp.
- A full program with several prototypes and demonstrators will lead to a large optimized underground detector

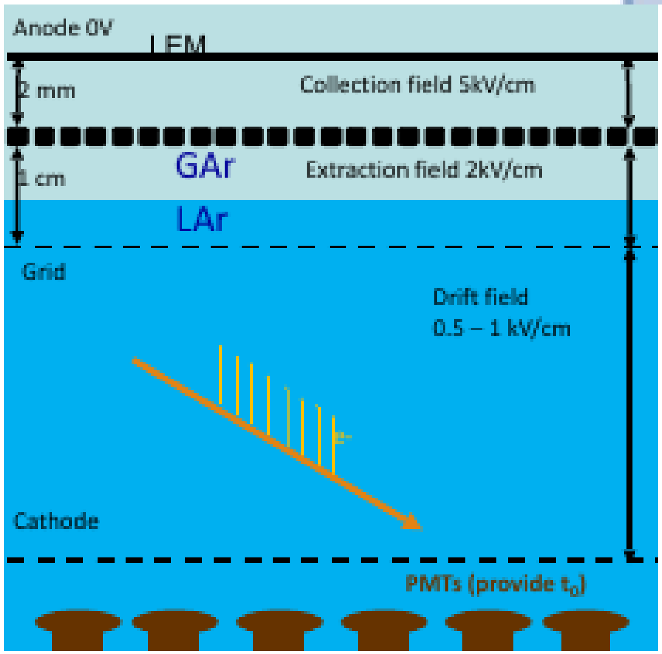


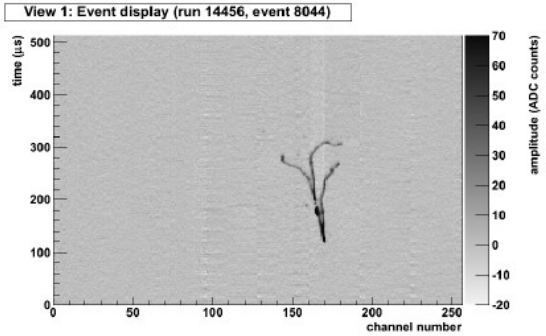
ICARUS CNGS neutrino interaction

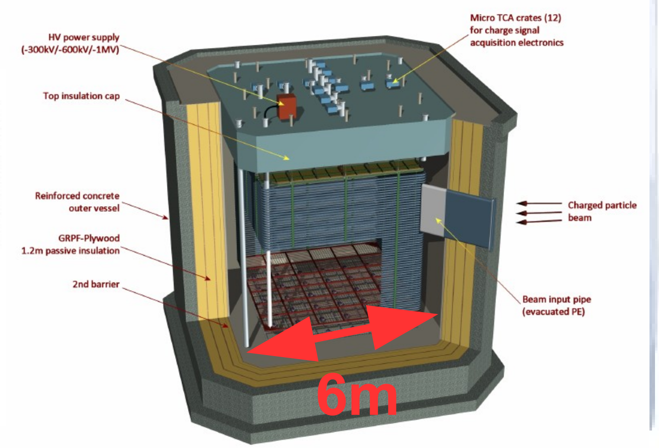


Double phase Liquid Argon TPC

- Development of the Liquid Argon TPC includes an amplification in the gas phase above the liquid argon volume: better S/N
- Solutions for large scale detector used in the 300 t WA105 demonstrator at CERN (beam test 2018)
- Alternate technology for the DUNE Far Detector

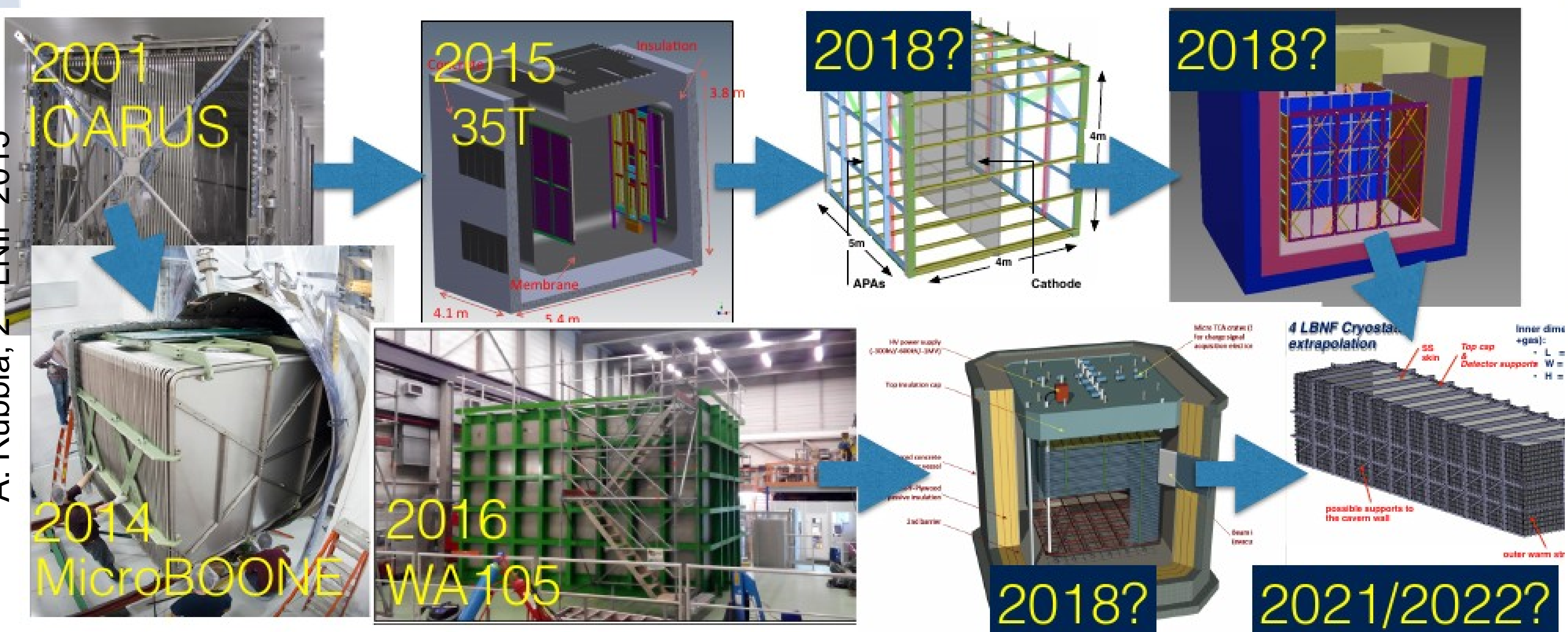






Path towards DUNE Far Detector

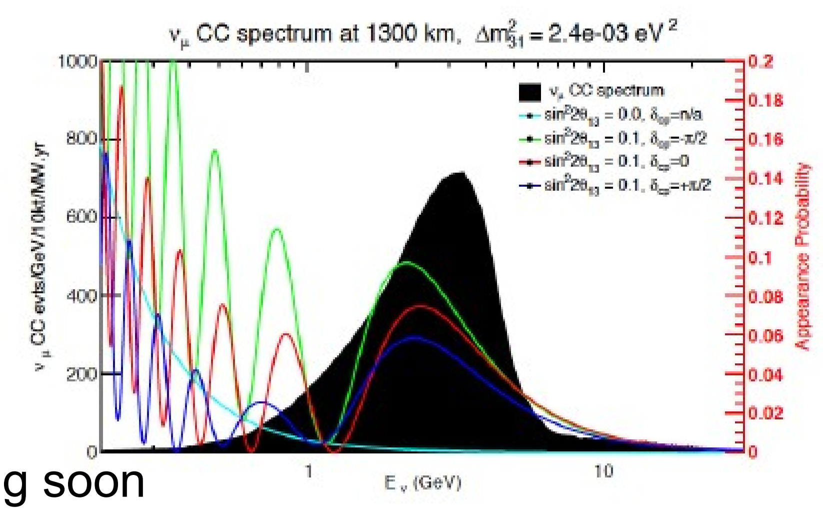
Crucial role played by the Fermilab prototypes and SB program and by the CERN Neutrino Platform towards providing the optimal cost-effective design for the Far Detector with proven solutions



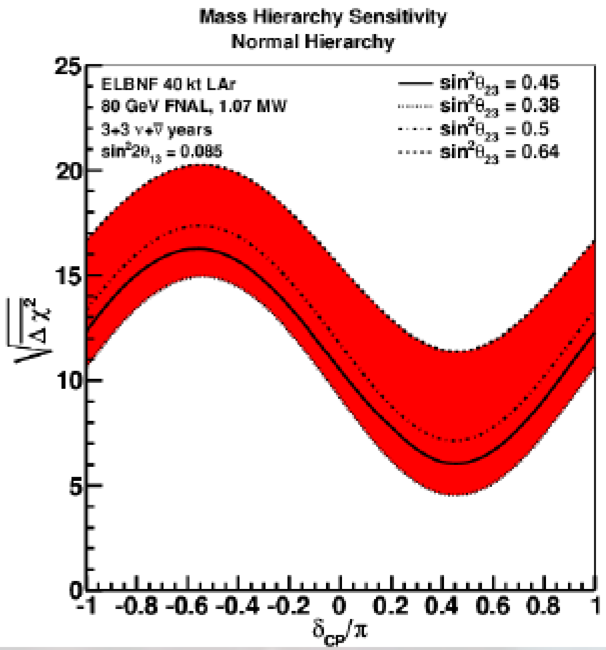
A. Rubbia, 2nd LNIF 2015

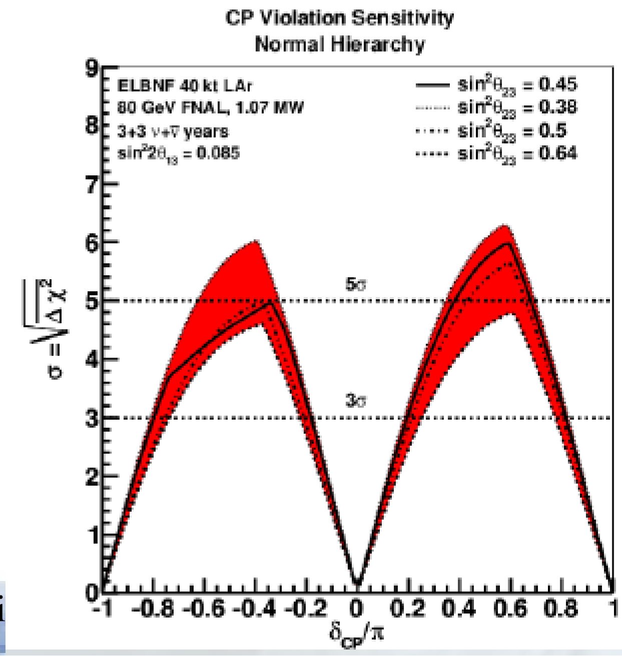
LBNF/DUNE sensitivity

- >3 σ for CP sensitivity over a large fraction of the phase space
- >5 σ for Mass Ordering



From ELBNF LOI (2015) DUNE sensitivities coming soon

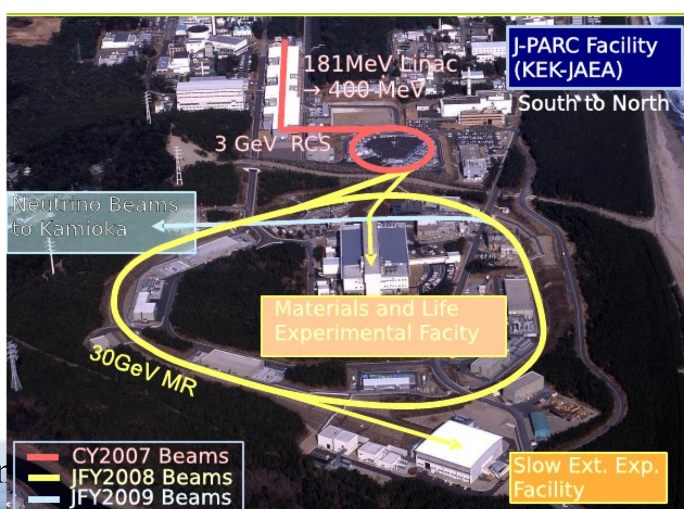


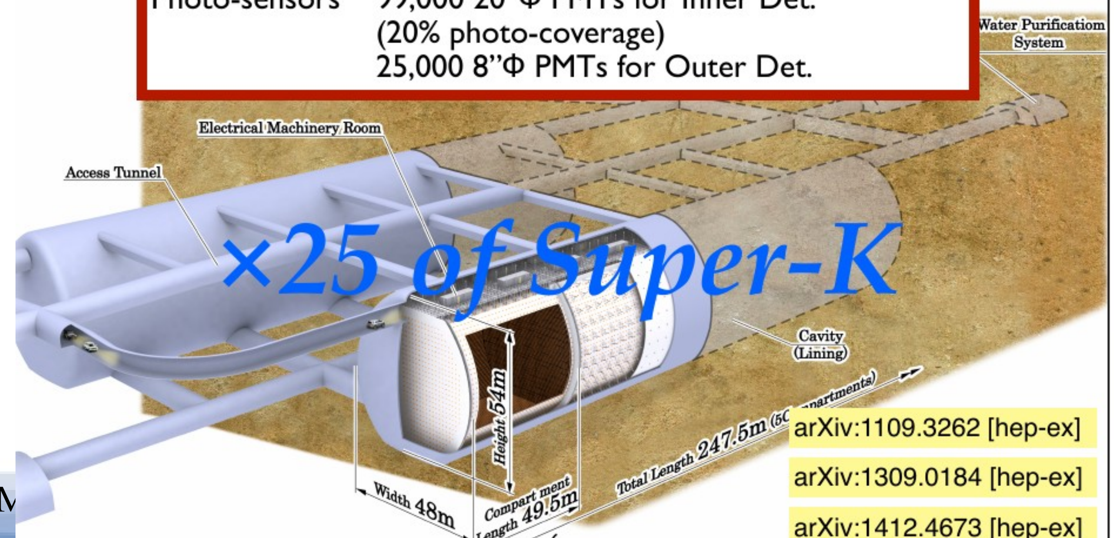


Hyper-Kamiokande

- Tokai to Kamioka 295 km baseline with the same beam as T2K (with possible upgrades)
- 0.56 Mt fiducial mass based on the Water Cherenkov technique
- Selected as top priority in Japanese Master Plan of Large Research Project
- Now preparing the Design Report
- Timescale: data taking in 2025

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.

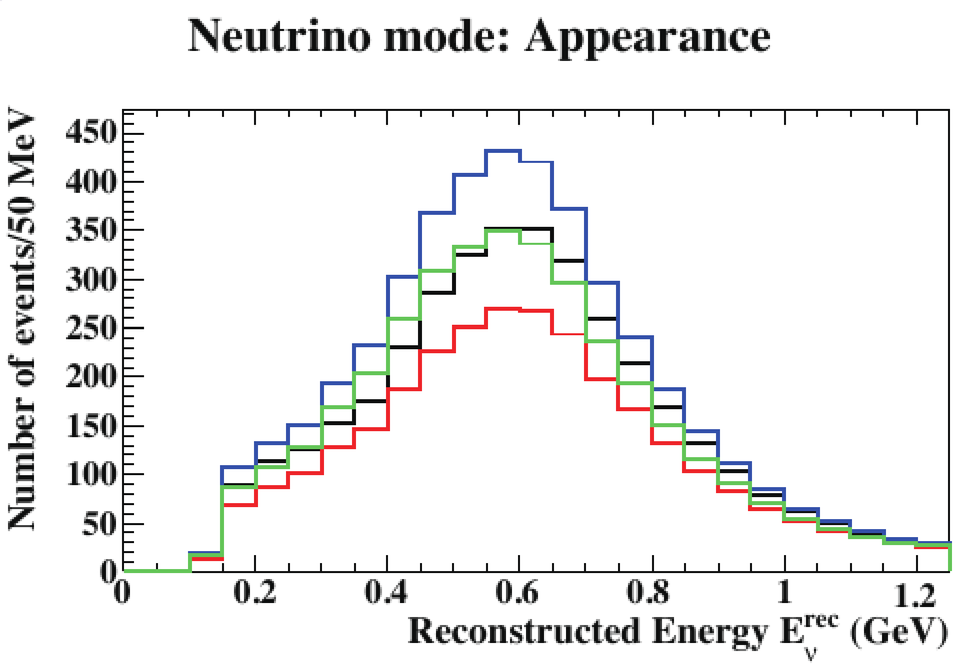


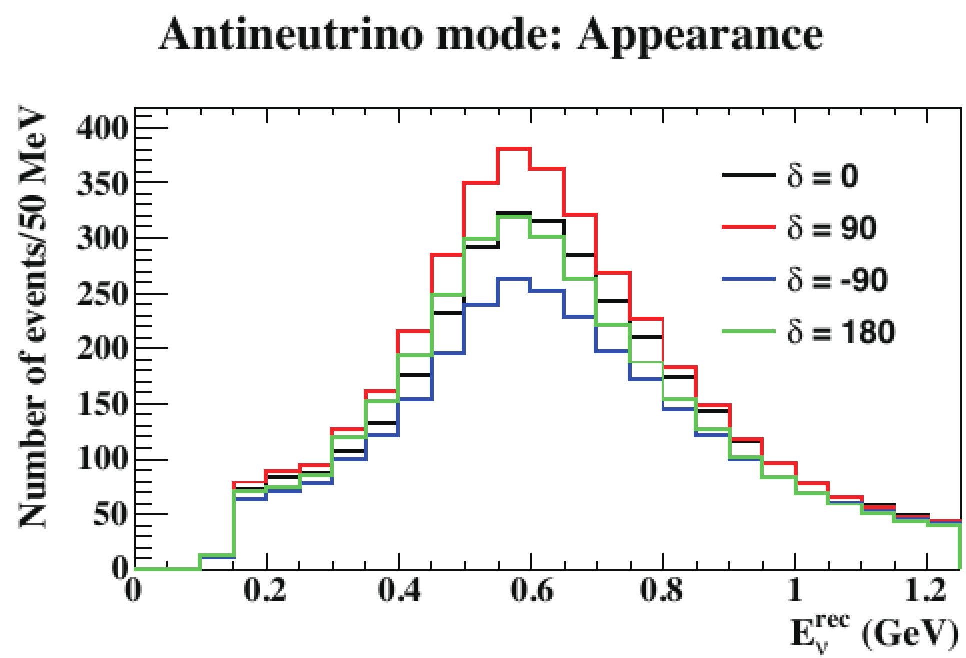


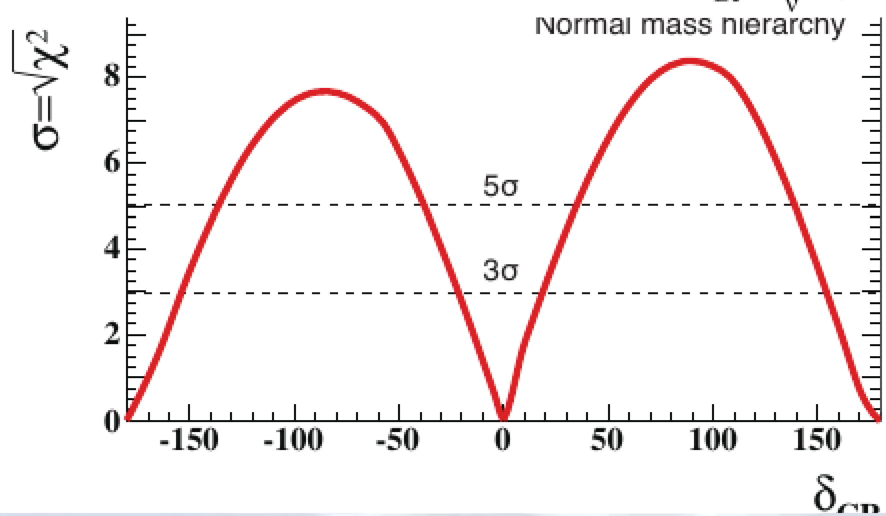
arXiv:1109.3262 [hep-ex]
arXiv:1309.0184 [hep-ex]
arXiv:1412.4673 [hep-ex]

Hyper-Kamiokande CP sensitivity

Arxiv:1502.05199





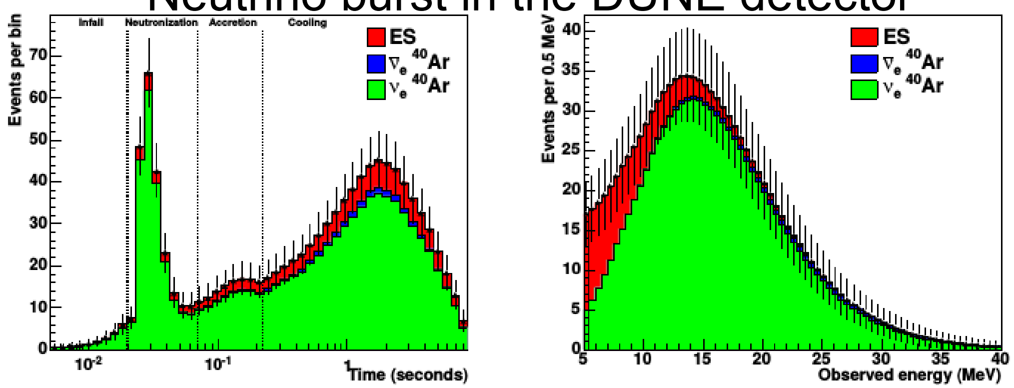


- >3000 ν_e appearance events (nu-mode) with ~700 bck
- Systematics extrapolated from T2K analysis (signal 3% nu mode)
- CPV >3 σ for 76% of δ values
-

Proton decay studies and neutrinos from the universe

- Large underground detectors like JUNO, DUNE and Hyper-Kamiokande are excellent observatories for a variety of non-accelerator physics studies
- Search for proton decay can attain limit of 10^{35} years
- Neutrinos from Supernova explosions : up to several 10^{5} (to be compared to 24 for SN1987A). Liquid argon: tag ν_e with $\nu_e\ {}^{40}Ar \rightarrow e^-\ {}^{40}K^*$
- 200 solar ν/day at HK
- Study of atmospheric neutrinos: mass ordering
- Large complementarity between different detection techniques

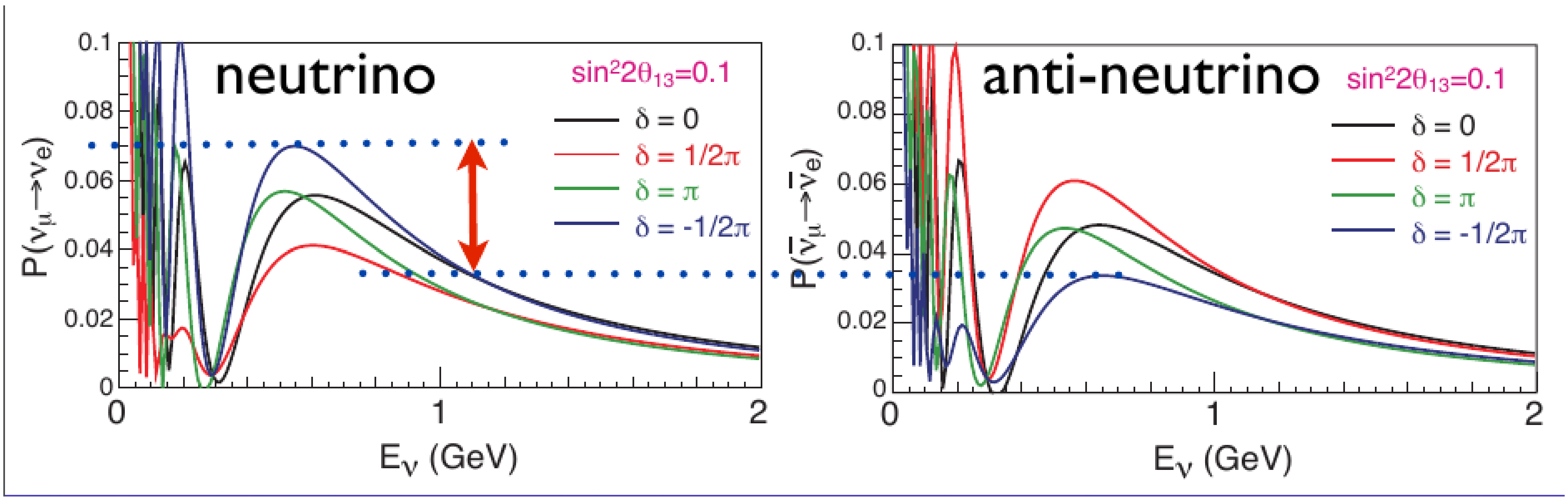
Neutrino burst in the DUNE detector



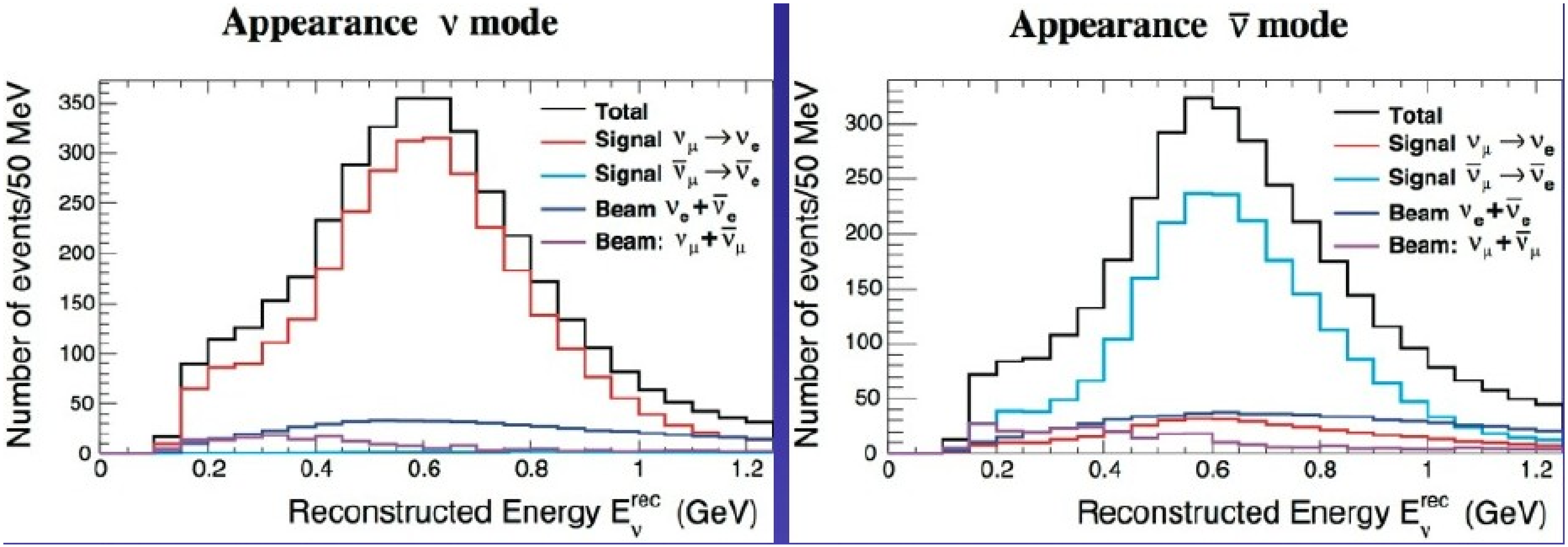
LBNF LOI

Conclusions

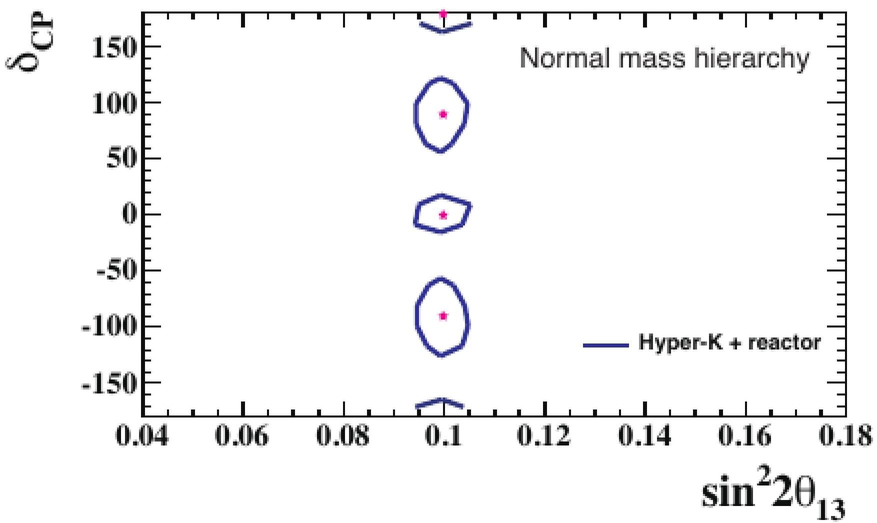
- The study of neutrino oscillations has provided many surprising discoveries in the last 15 years, establishing the three neutrino mixing paradigm, implying Physics beyond the SM
- The increased precision of experiments and the fact that θ_{13} is large opens a new era: sensitivities to sub-leading terms
- CP violation, neutrino mass ordering and θ_{23} octant, will be probed by several dedicated experiments and facilities in the next decade
- Proton decay and sensitivity to SN neutrinos from large underground observatories



neutrino
sin²2θ13=0.1
δ = 0
δ = 1/2π
δ = π
δ = -1/2π
P(νμ→νe)
Eν (GeV)
anti-neutrino
sin²2θ13=0.1
δ = 0
δ = 1/2π
δ = π
δ = -1/2π
P(ν̄μ→ν̄e)
Eν (GeV)

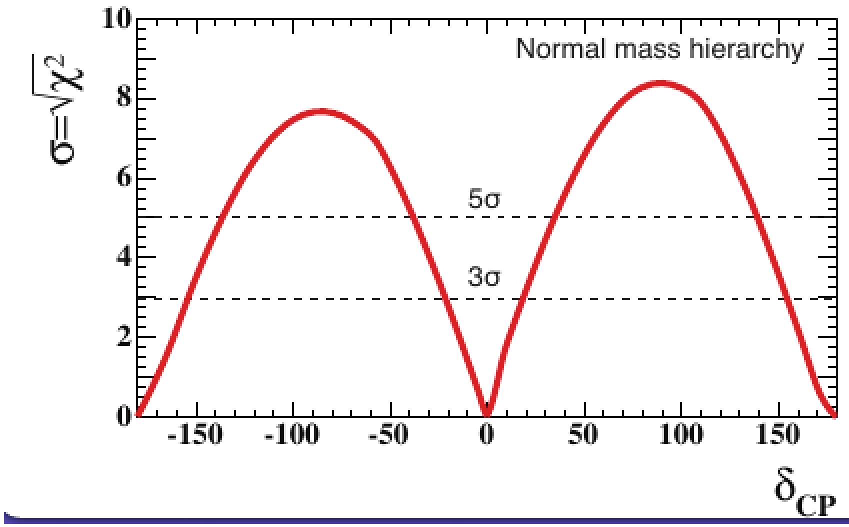

Appearance ν mode
Total
Signal $\nu_\mu \to \nu_e$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$
Beam $\nu_e + \bar{\nu}_e$
Beam: $\nu_\mu + \bar{\nu}_\mu$
Number of events/50 MeV
Reconstructed Energy E_ν^{rec} (GeV)
Appearance $\bar{\nu}$ mode
Total
Signal $\nu_\mu \to \nu_e$
Signal $\bar{\nu}_\mu \to \bar{\nu}_e$
Beam $\nu_e + \bar{\nu}_e$
Beam: $\nu_\mu + \bar{\nu}_\mu$
Number of events/50 MeV
Reconstructed Energy E_ν^{rec} (GeV)

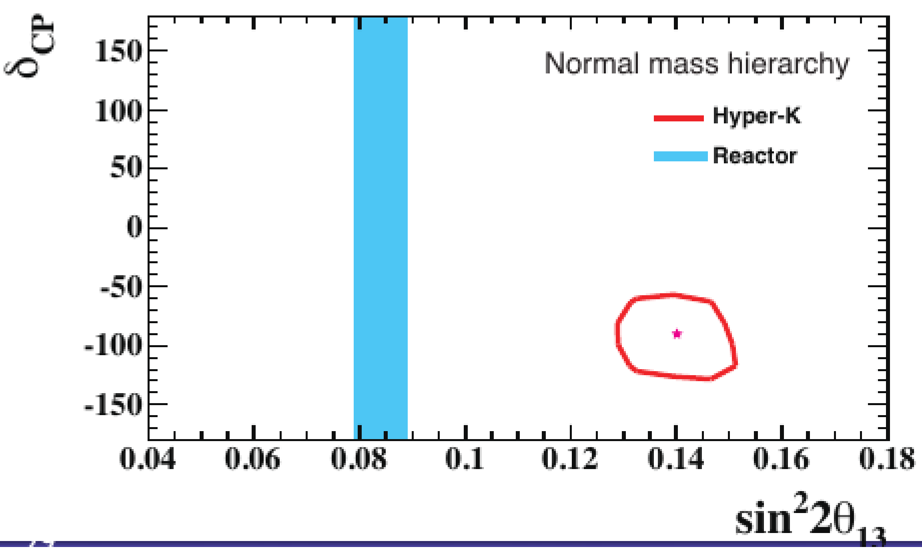
90% CL contour on $\sin^2 2\theta_{13}$-δ plane
(δ=0°, 90°, 180°, -90° overlaid)



- CPV establish ($\sin\delta \neq 0$)
  - 76% (58%) of δ for $>3\sigma$ ($>5\sigma$)
- δ resolution: 8°-19°

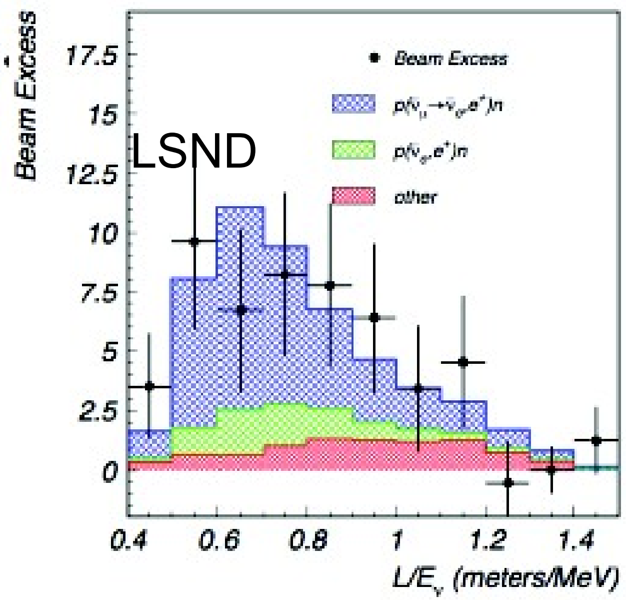
$\sin\delta \neq 0$ exclusion



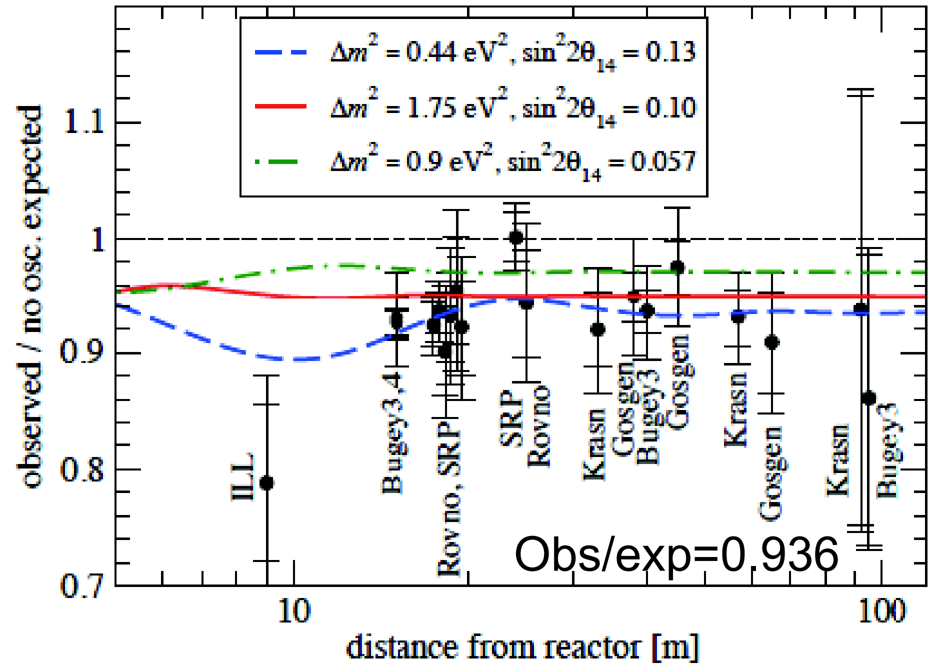


Short baseline neutrino anomalies

PRD64 (2001) 112007

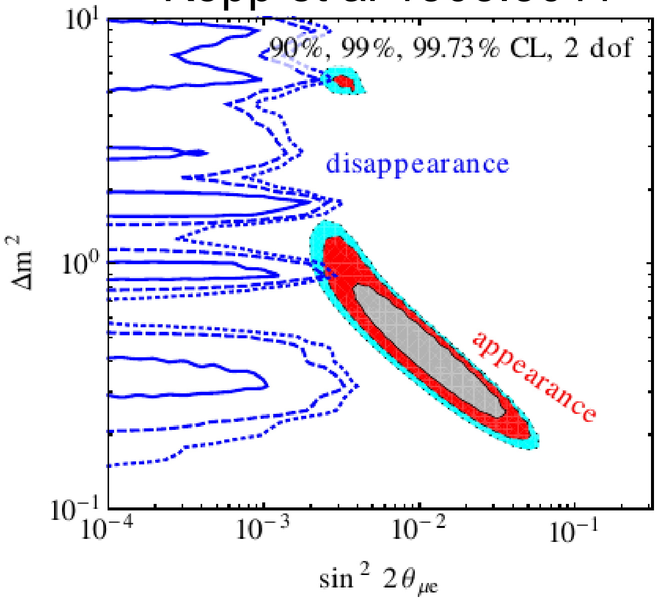


J. Kopp et al, arXiv:1303.3011v3



Original ref:G. Mention et al. PRD83:073006 (2011)

Kopp et al 1303.3011



- Short baseline experiments (LSND, MiniBooNE, reactors, Ga source) have revealed anomalies that could be interpreted as oscillations with Δm~eV
- No global satisfactory interpretation due to tensions within the data: numu->nue appearance vs numu disappearance

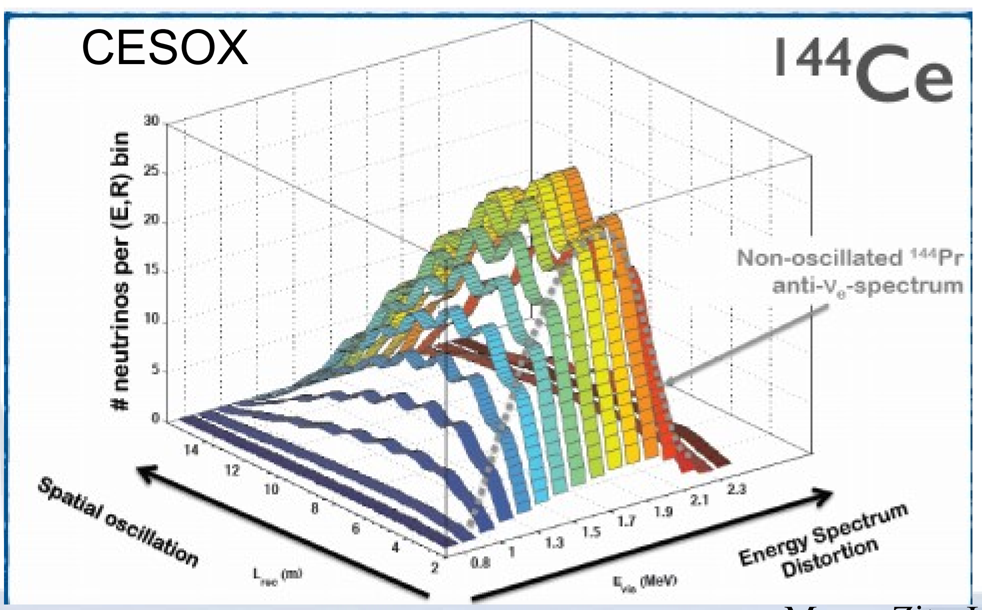
Testing the anomalies

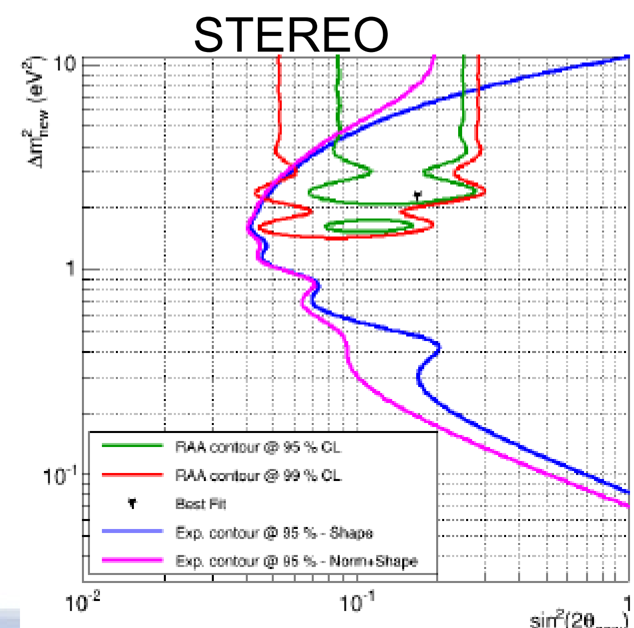
The eV**2 sterile neutrino anomalies will be tested in 2015-2020 with several approaches

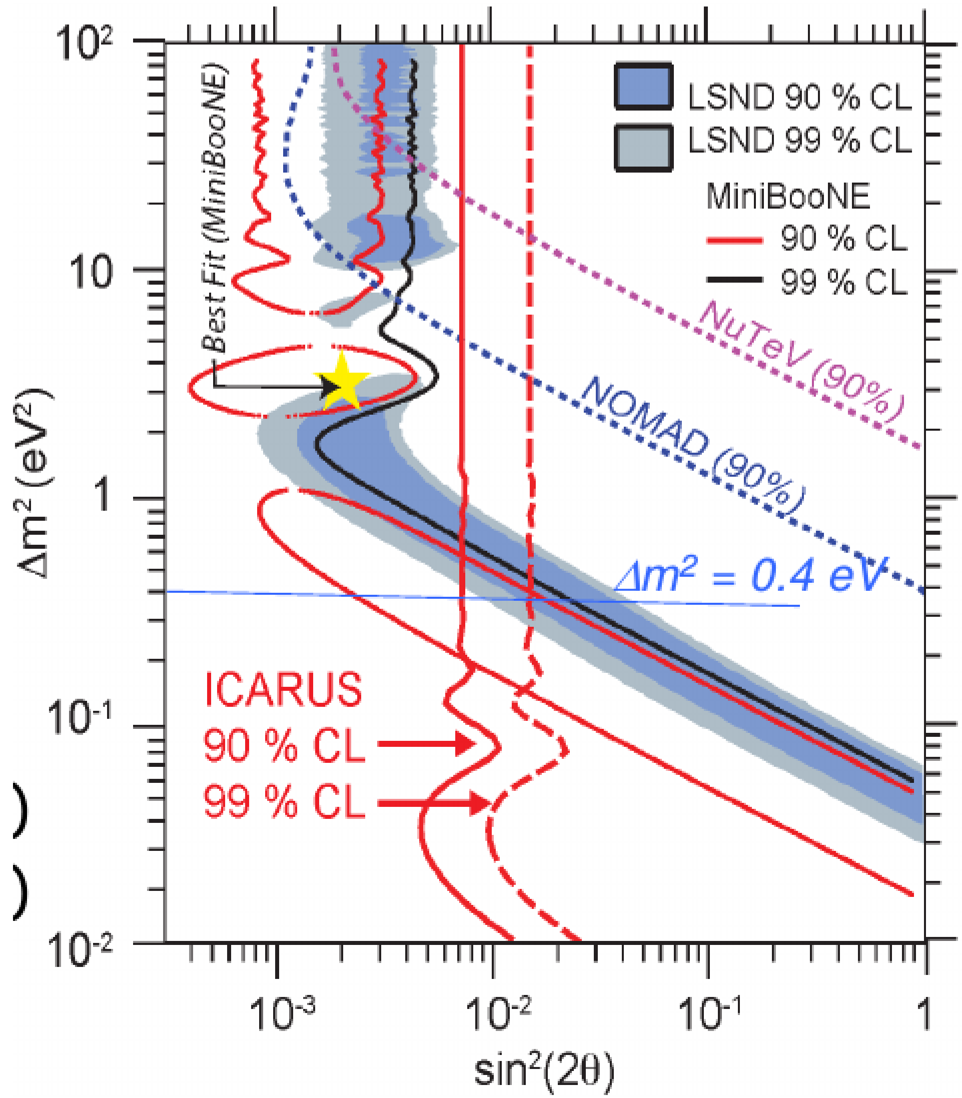
1) Detectors at nuclear reactors and very short baselines (5-10m) : STEREO, SOLID,...

2) An intense source close to the Borexino detector: CESOX

3) Short baseline neutrino program at FNAL: MicroBoone, SBN







LSND 90 % CL
LSND 99 % CL
MiniBooNE
90 % CL
99 % CL
Best Fit (MiniBooNE)
NuTeV (90%)
NOMAD (90%)
Δm² = 0.4 eV
ICARUS
90 % CL
99 % CL
Δm² (eV²)
sin²(2θ)
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻²
10⁻¹
1