EXPERIMENTS STUDYING NEUTRINO OSCILLATIONS: NEWS AND FUTURE IDEAS

Paweł Przewłocki, NCBJ

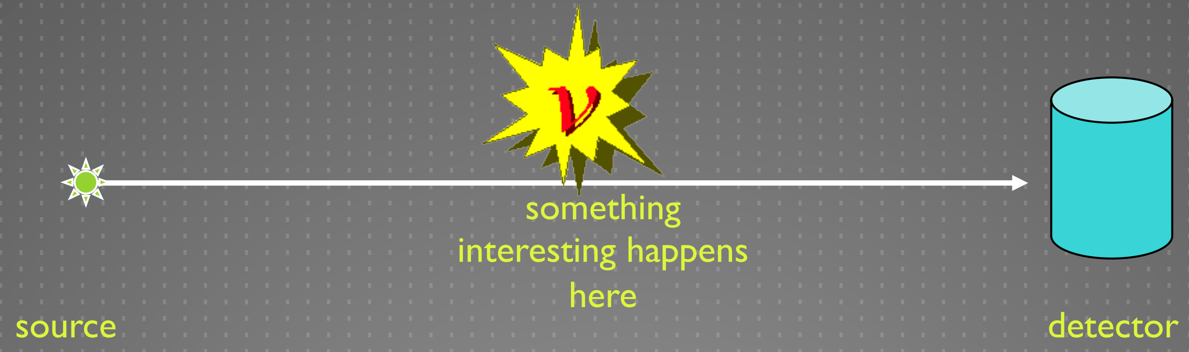
Warsaw Neutrino Group (FUW+NCBJ+PW)

OUTLINE

- Introduction: neutrinos and their sources
- Neutrino oscillations
- Current experimental status
- What we'd like to measure in near future
- Future experiments
  - Long-baseline: LBNF, T2HK, near detectors
  - Gadzooks!
  - km3net/Orca, IceCube/Pingu

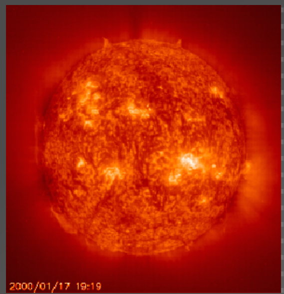
INTRODUCTION

- From sources to detectors (and in between)



NEUTRINOS AND THEIR SOURCES

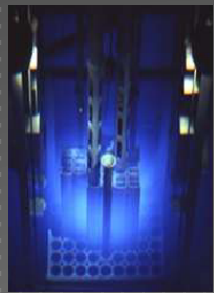
Solar



ν_e

A byproduct of nuclear thermofusion in the Sun
E<~10 MeV

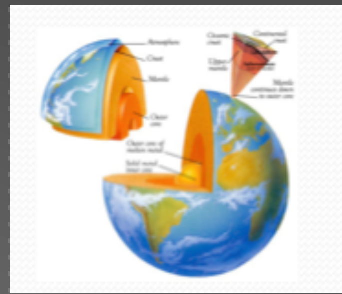
Reactor



$\bar{\nu}_e$

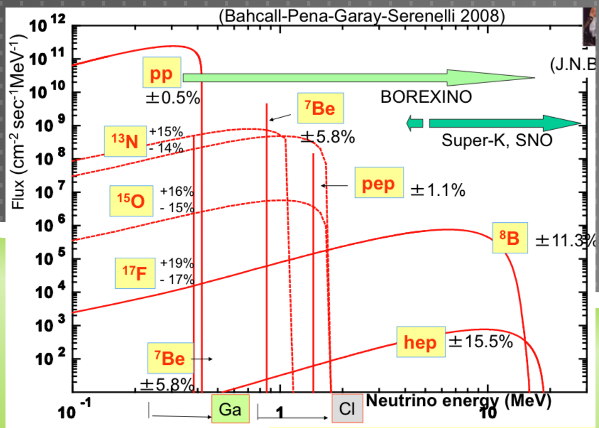
Beta decays in nuclear reactors
E<~6 MeV

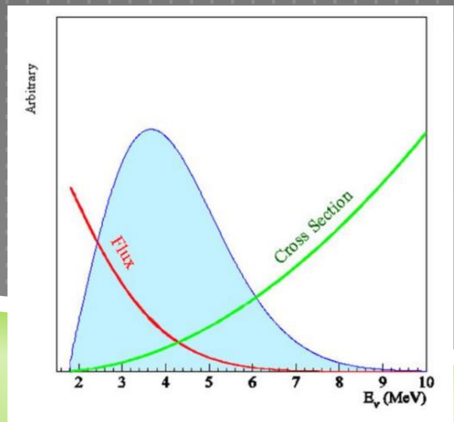
Geonus

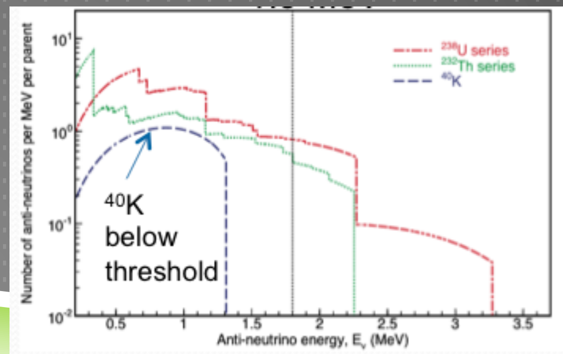


$\bar{\nu}_e$

Beta decay, mainly uranium and thorium series in the Earth's mantle
E<~3 MeV

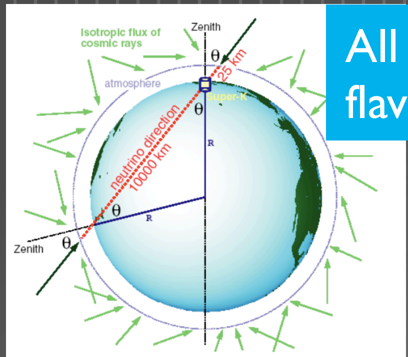






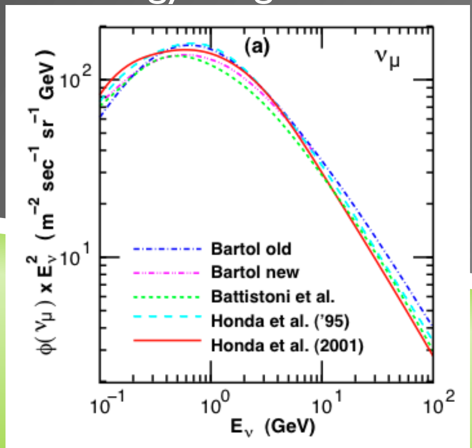
NEUTRINOS AND THEIR SOURCES

Atmospheric



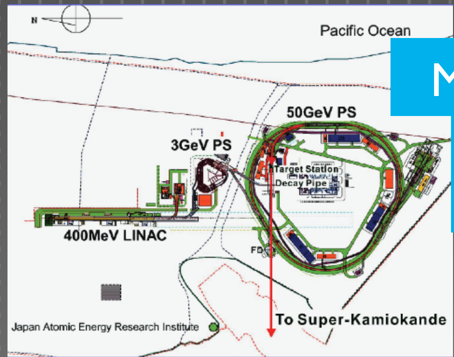
All flavors

Produced in cosmic ray interactions in upper layers of atmosphere
Wide energy range, max~ 1GeV



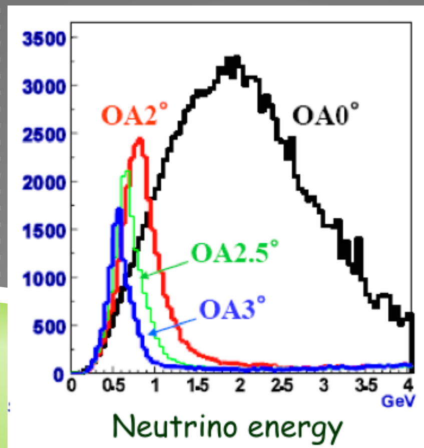
arXiv:hep-ph/0203272

Beam

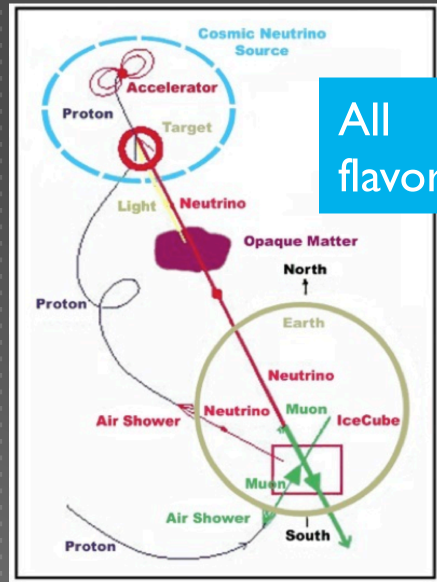


Mainly ν_μ

Artificial beams for long-baseline experiments
E<~ a few GeV

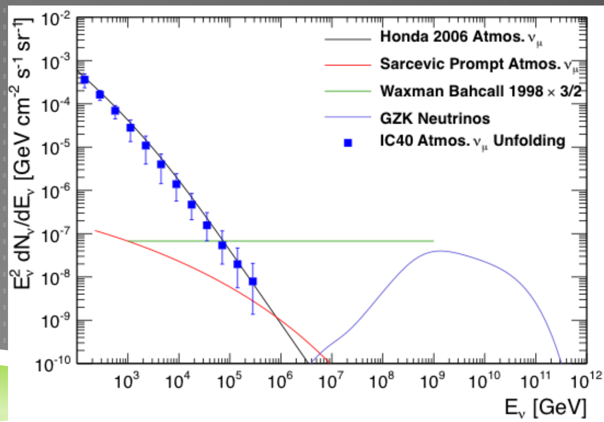


Cosmic

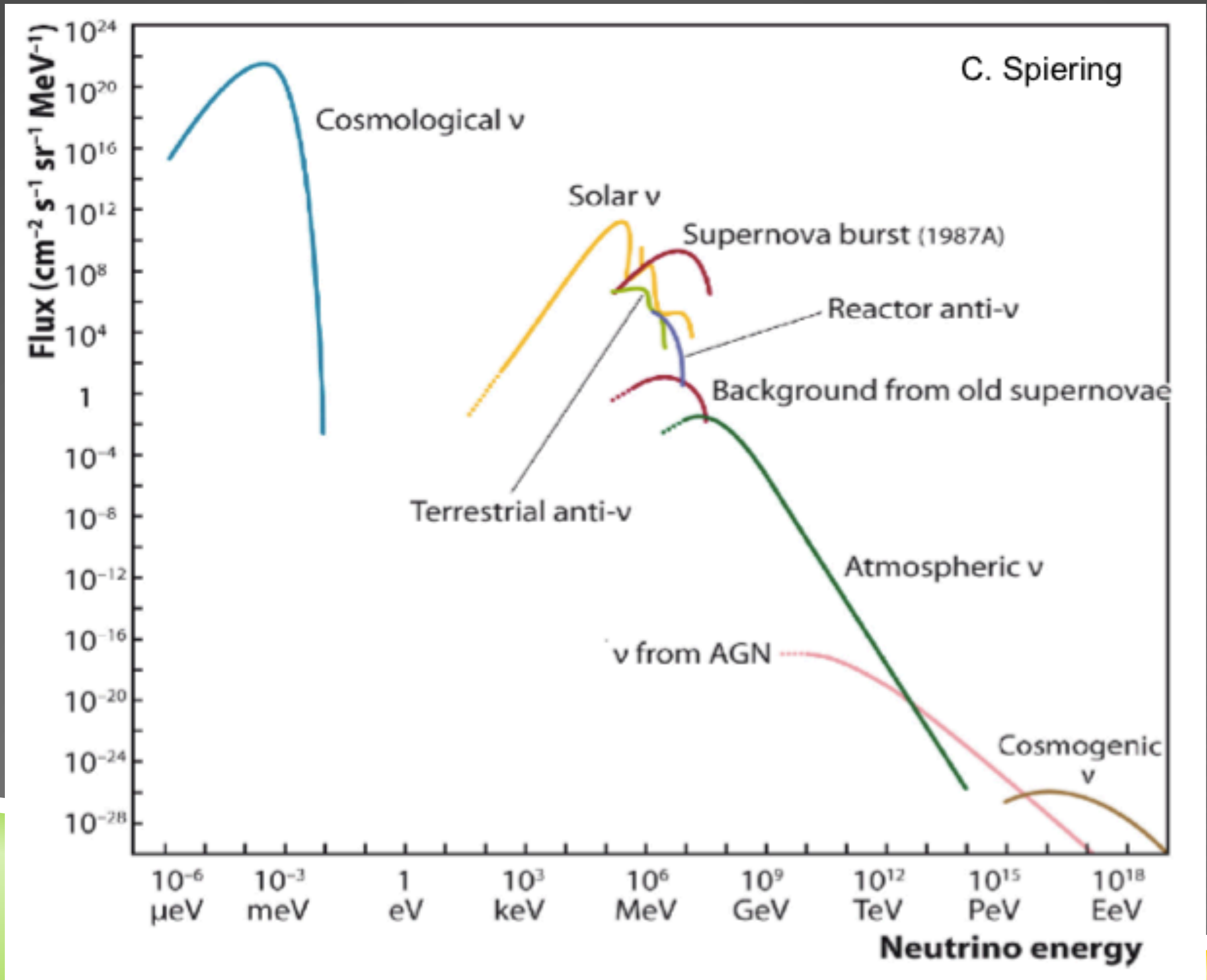


All flavors

Astrophysical, cosmogenic (GZK)
Very high E, TeV and above



NEUTRINOS FROM NATURAL SOURCES



OSCILLATIONS – EXCESSES AND DEFICITS

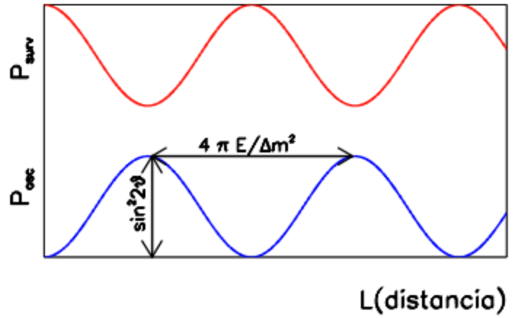
- **Two-flavor oscillations - two oscillation parameters** (mixing angle, difference of masses squared)

$$\begin{pmatrix} \nu_x \\ \nu_y \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P(\nu_x \to \nu_y) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

L – distance
E - energy

- To detect oscillations we can study the neutrino flavour as function of the Distance to the source

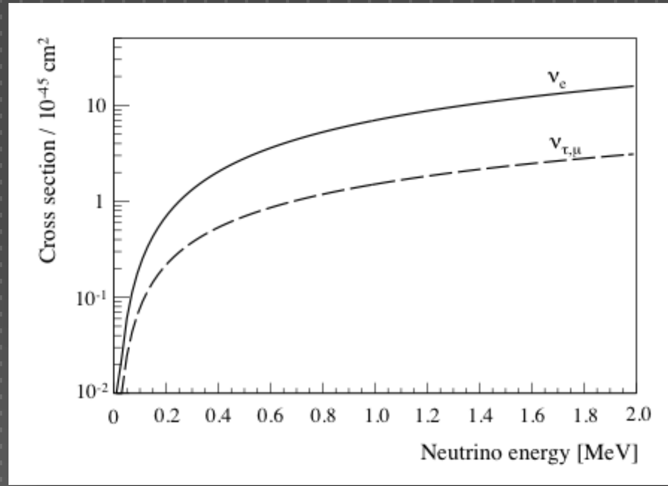


Studying the **survival** of original neutrinos – **disappearance** experiment – we are looking for a **deficit**

Studying the **oscillation** of original neutrinos into another flavour– **appearance** experiment – we are looking for an **excess**

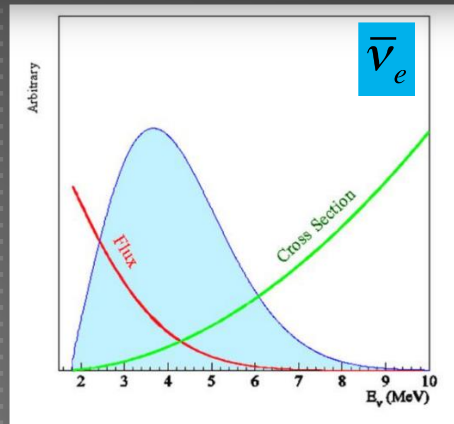
- If possible, it is worth to consider building a near detector in addition to a far one

DETECTING NEUTRINOS - INTERACTIONS



- elastic scattering on electrons
  E>60 keV

$$\nu_x + e \rightarrow \nu_x + e$$



- inverse beta decay (anti ν_e)
  E>1.8 MeV

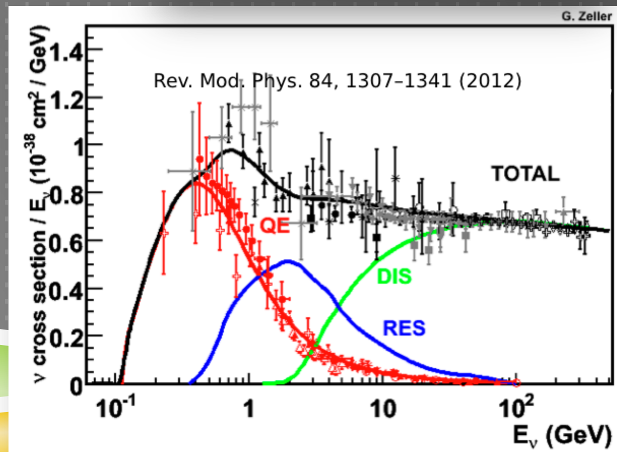
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

- scattering on nuclei (nucleons, quarks)

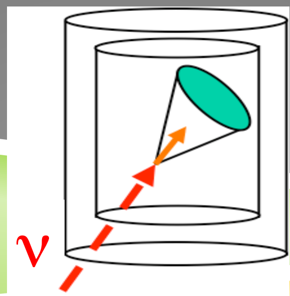
$$\nu + N \rightarrow l + N'$$

$$NC: \nu + N \rightarrow \nu + r^* \rightarrow \nu + N' + meson(s)$$

$$CC: \nu + N \rightarrow l + r^* \rightarrow l + N' + meson(s)$$



Detection techniques – we look for products of neutrino interactions (electrons, muons, hadrons) utilising scintillation, Cherenkov radiation, ionisation, etc.



Cherenkov cone

NEUTRINO OSCILLATIONS – FULL PICTURE

FLAVOR **PMNS mixing matrix** **MASS**

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

„atmospheric”
SK, K2K, T2K, MINOS

CHOOZ, DayaBay, Reno, DblChooz, T2K

„solar”
SNO, KamLand, SK, Borexino

atmospheric ν + K2K, MINOS	reactor ν + LBL	solar ν + KamLAND
$\sin^2 2\theta_{23} = 0.999 \pm 0.018$	$\sin^2 2\theta_{13} = 0.093 \pm 0.008$	$\sin^2 2\theta_{12} = 0.846 \pm 0.021$
$\theta_{23} \approx 45°$	$\theta_{13} \approx 9°$	$\theta_{12} \approx 33°$
$\Delta m^2_{32} = (2.44 \pm 0.06)\cdot 10^{-3} eV^2$		$\Delta m^2_{21} = (7.53 \pm 0.18)\cdot 10^{-5} eV^2$

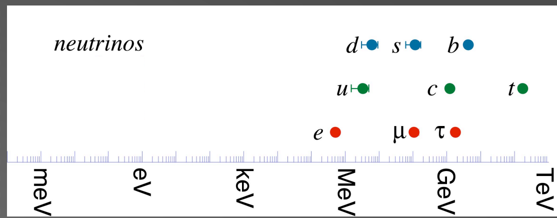
PDG2014

mixing angles, squared mass differences, CP violation phase - fundamental parameters of nature

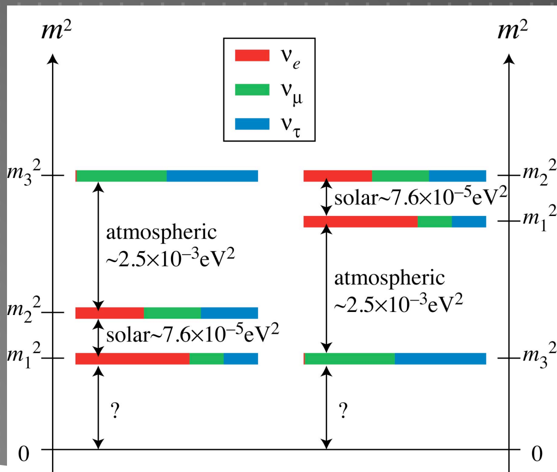
* $\Delta m^2_{ji} = m_j^2 - m_i^2$
Two free parameters for the three Δm^2's.
($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

INTERESTING QUESTIONS WE'D LIKE TO ASK

- **Is there a CP violation in neutrino sector?**
- **What is the neutrino mass ordering (hierarchy)**
- What is the absolute scale of masses?
- Are neutrinos Majorana or Dirac?
- Are there only three neutrino types?



- What are the exact values of neutrino oscillation parameters (mixing angles, mass squared differences)?



THINGS TO LOOK FOR IN OSCILLATION EXPERIMENTS

Unknown

CPV: $\delta \neq 0, \pi?$

MH: $m_3 \gtrless m_2?$

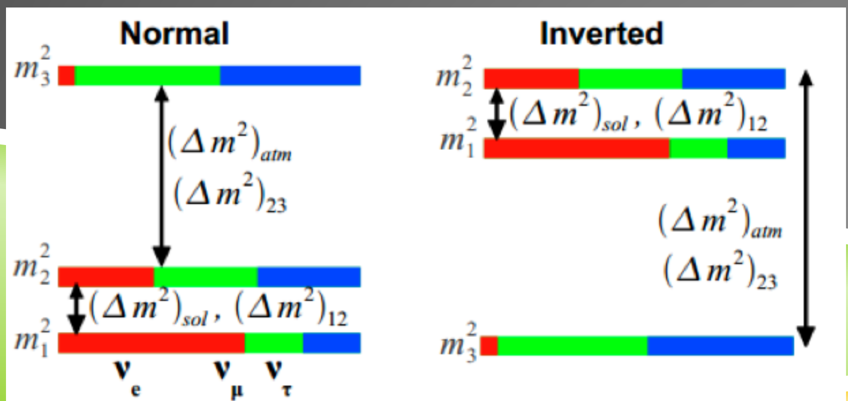
θ_{23} octant: $\theta_{23} \gtreqless 45°?$

Differences in **neutrino vs antineutrino** oscillation probabilities

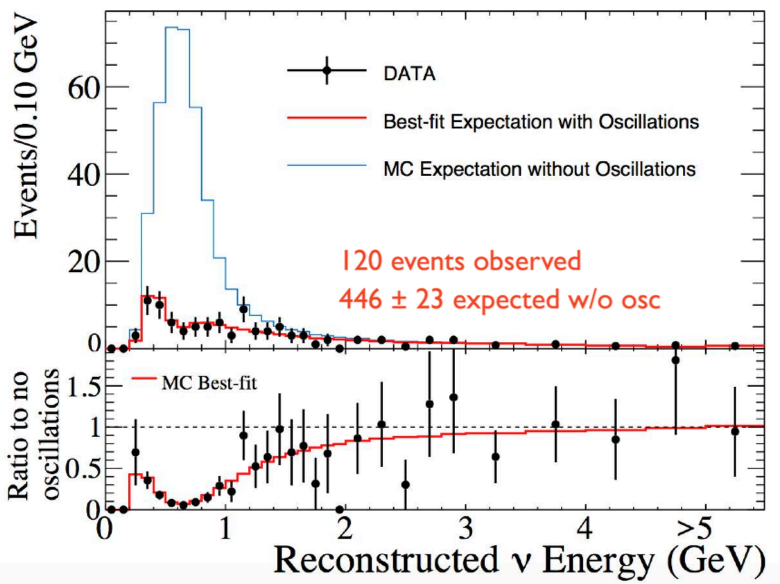
Changes the contribution from **matter effects** (important for neutrinos travelling through dense matter e.g through Earth)

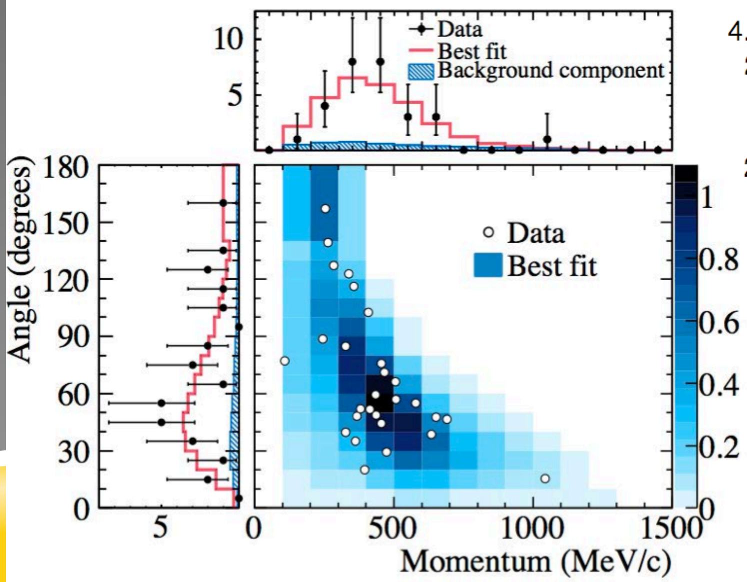
Additional source of degeneracies

An unknown hierarchy usually leads to a reduced ability to observe CP violation



T2K Experiment





4.92 ± 0.55 background

28 events observed

7.3σ observation

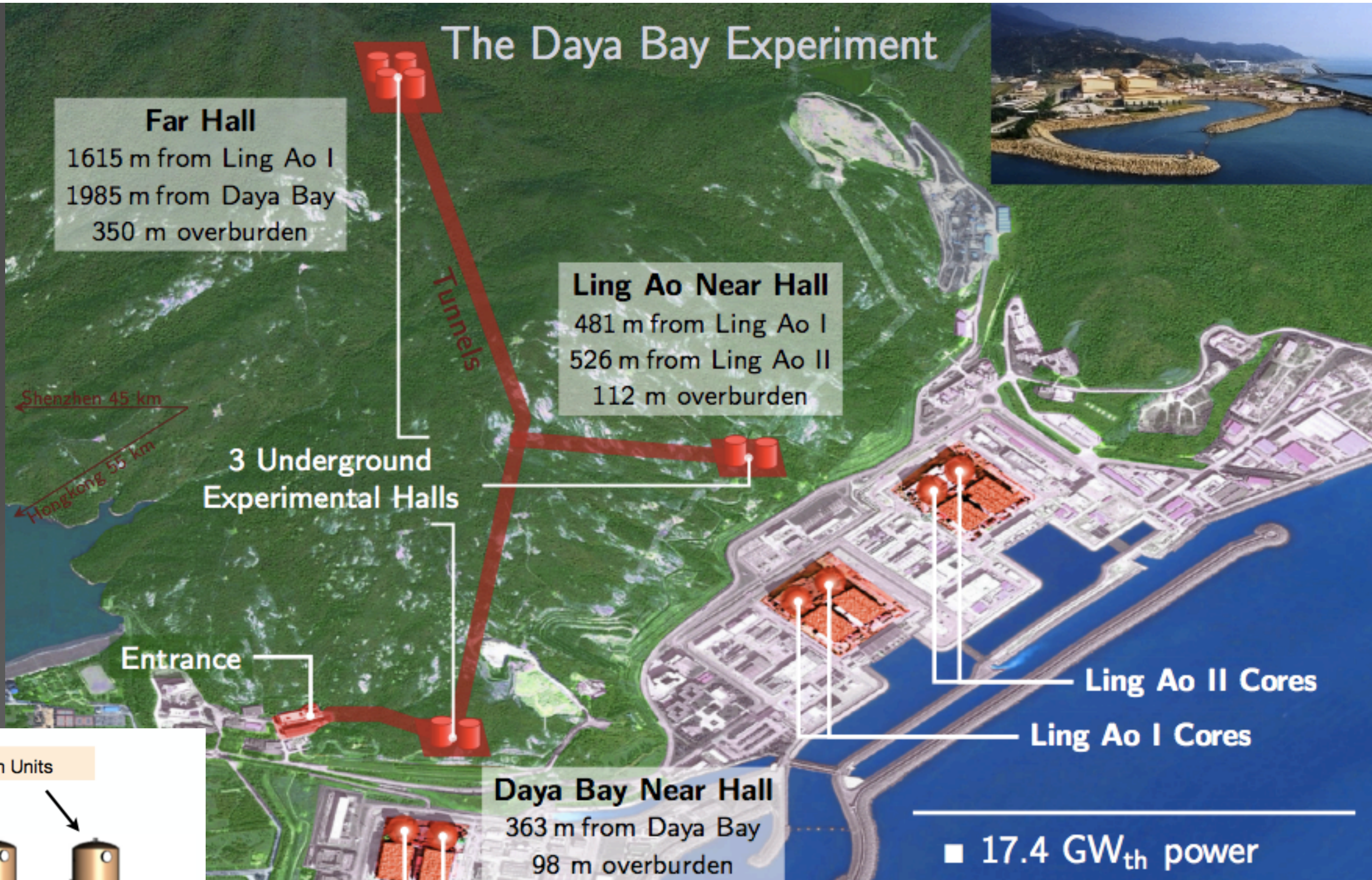
21.6 events expected

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

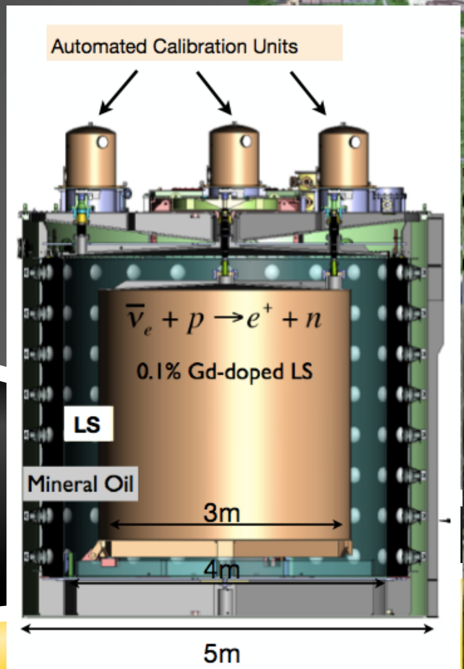
$\delta_{CP} = 0$

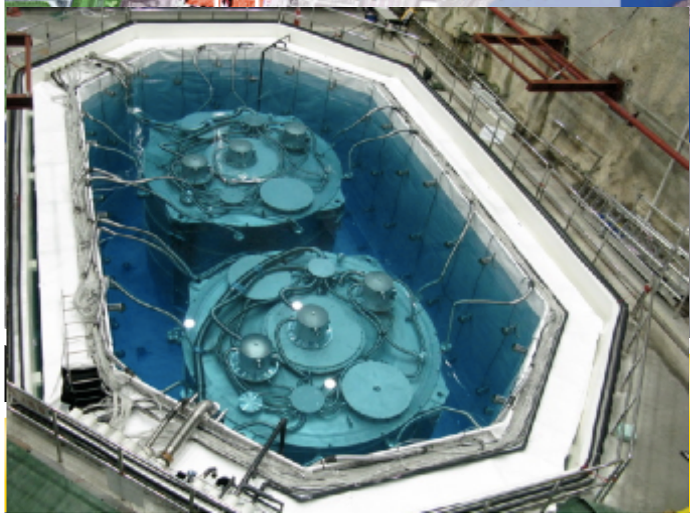
$\sin^2\theta_{23} = 0.5$

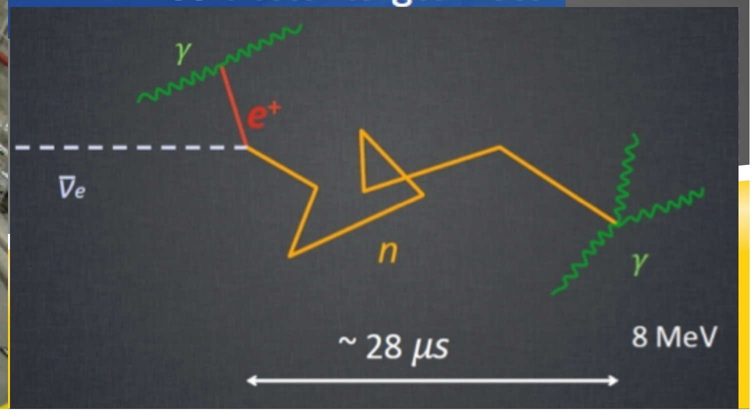
DAYA BAY



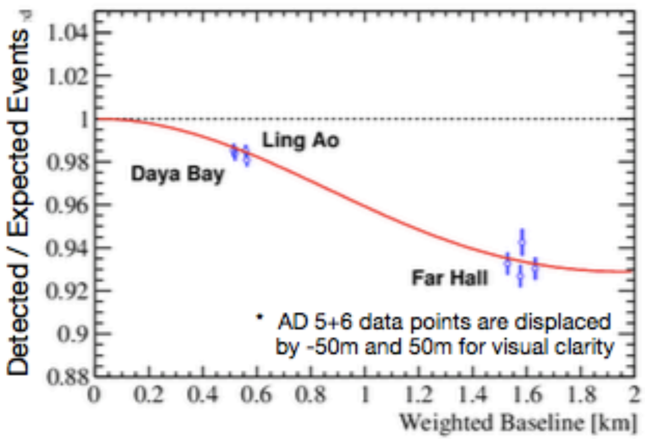
- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass



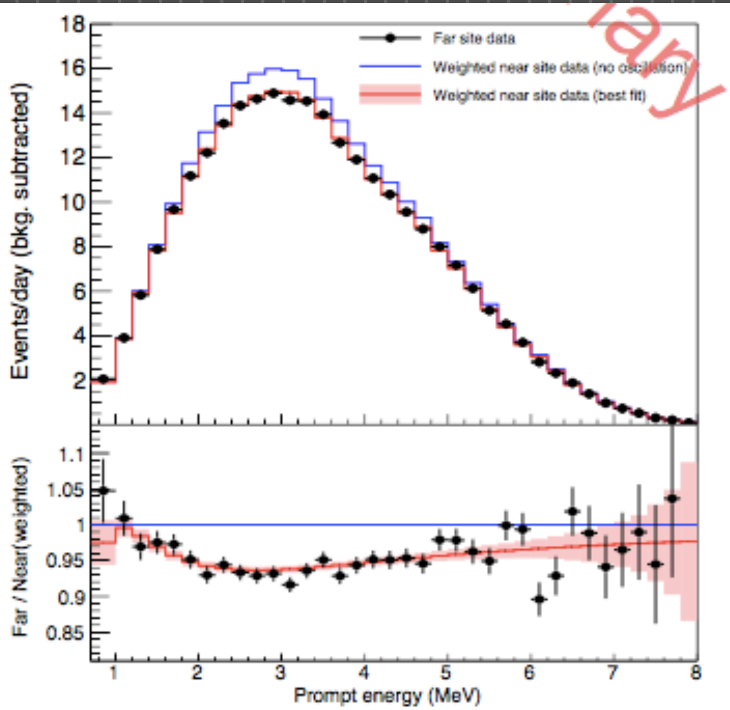




DAYA BAY



The observed relative rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation



- Daya Bay has measured

Taken from Chao Zhang (Neutrino 2014)

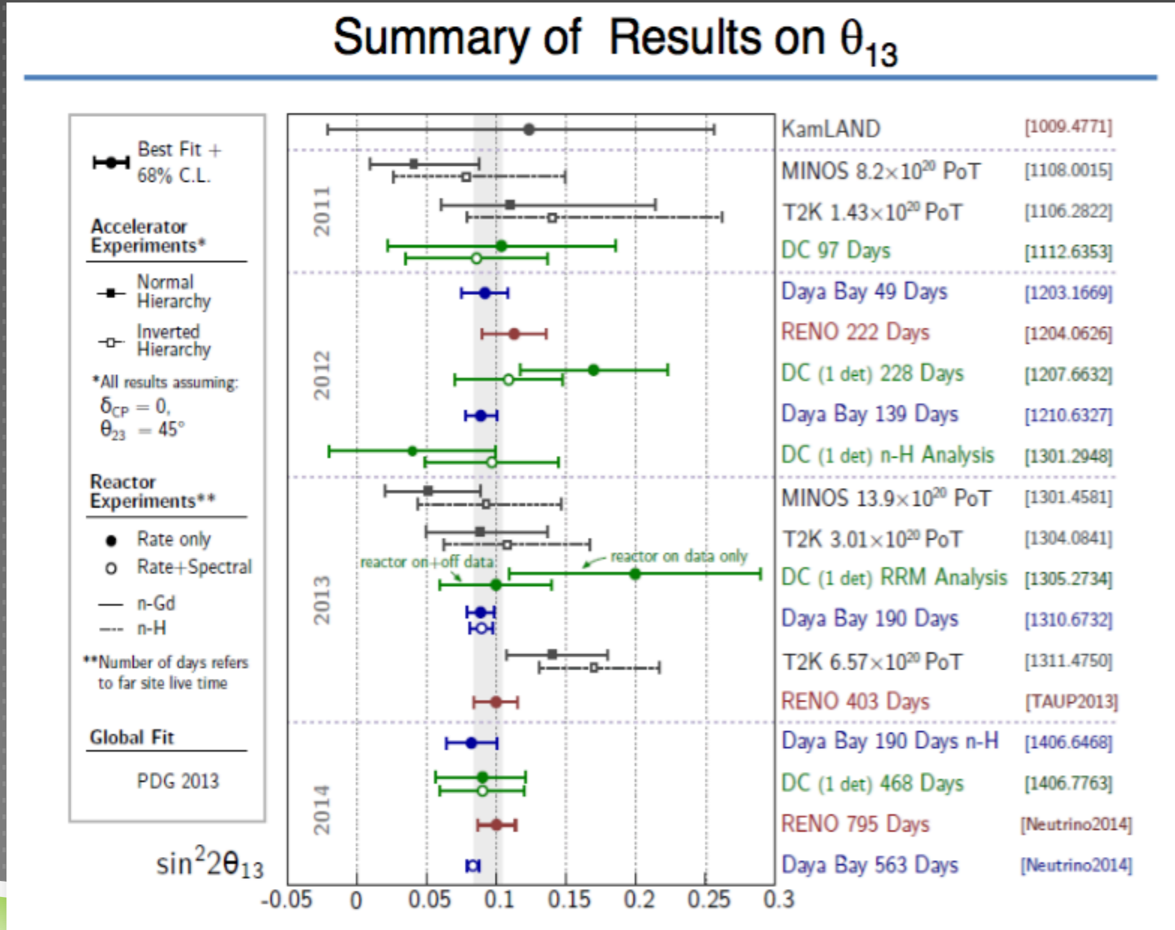
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$$

with 621 days of data. The precision measurement of θ_{13} opens the door for future experiments to study neutrino mass hierarchy and leptonic CP violation.

- Precision will be further improved in the coming years. By the end of 2017, we expect to measure both $\sin^2 2\theta_{13}$ and Δm^2_{ee} to precision below 3%.

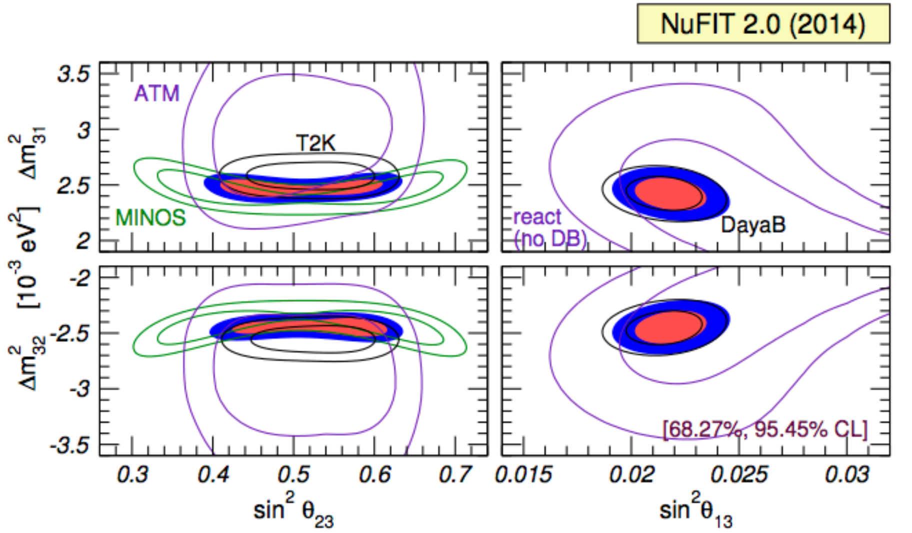
CURRENT STATUS

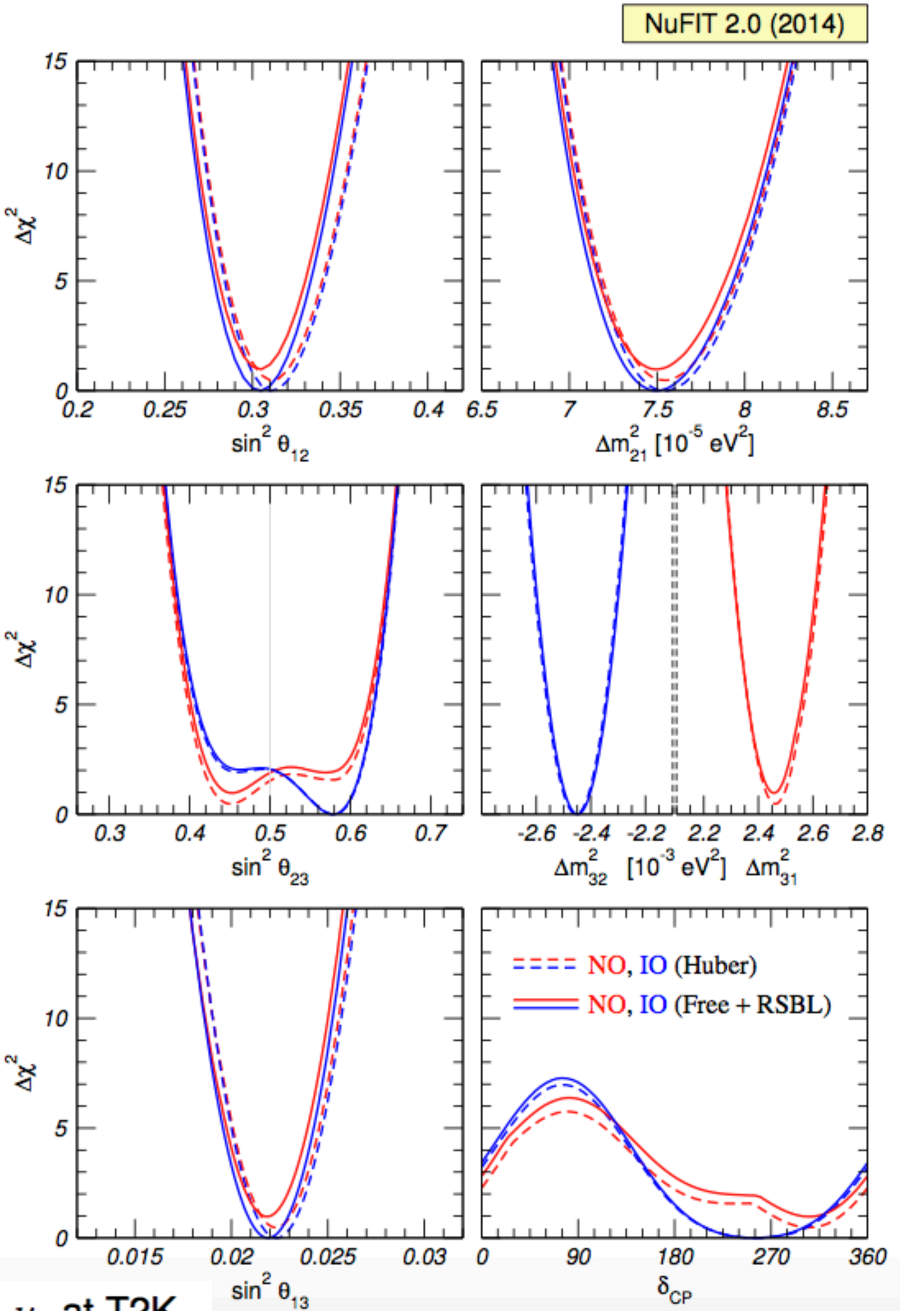
- Long-baseline experiments
  - T2K - Numu dissapearance, nue appearance
    - Anti numu expected this year!
  - Minos – Numu and anti-numu dissapearance
  - Minos+ - Numu dissapearance
  - Nova – just started
- Reactor experiments
  - Daya Bay, RENO, Double Chooz – nue dissapearance



GLOBAL FITS

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21}, θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}, θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}	$\|\Delta m^2_{3\ell}\|$
Atmospheric Experiments	θ_{23}	$\|\Delta m^2_{3\ell}\|$, θ_{13},δ
Accelerator LBL ν_μ Disapp (Minos, T2K)	$\|\Delta m^2_{3\ell}\|$, θ_{23}	
Accelerator LBL ν_e App (Minos, T2K)	δ	θ_{13}, θ_{23}, sign($\Delta m^2_{3\ell}$)





difference between best fit θ_{13} from reactors and $\nu_\mu \to \nu_e$ at T2K leads to best global fit value close to $\delta_{CP} = \frac{3}{2}\pi$

CPV & MH: LONG BASELINE EXPERIMENTS

- Electron neutrino appearance
- Studying neutrinos vs antineutrinos
- The longer the baseline the better (matter effects!)
- Study more than one oscillation maximum to disentangle the effects

$$P(\nu_\mu \to \nu_e) \quad vs. \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$ leading term

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CP conserving

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$ CP violating

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$ solar term

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

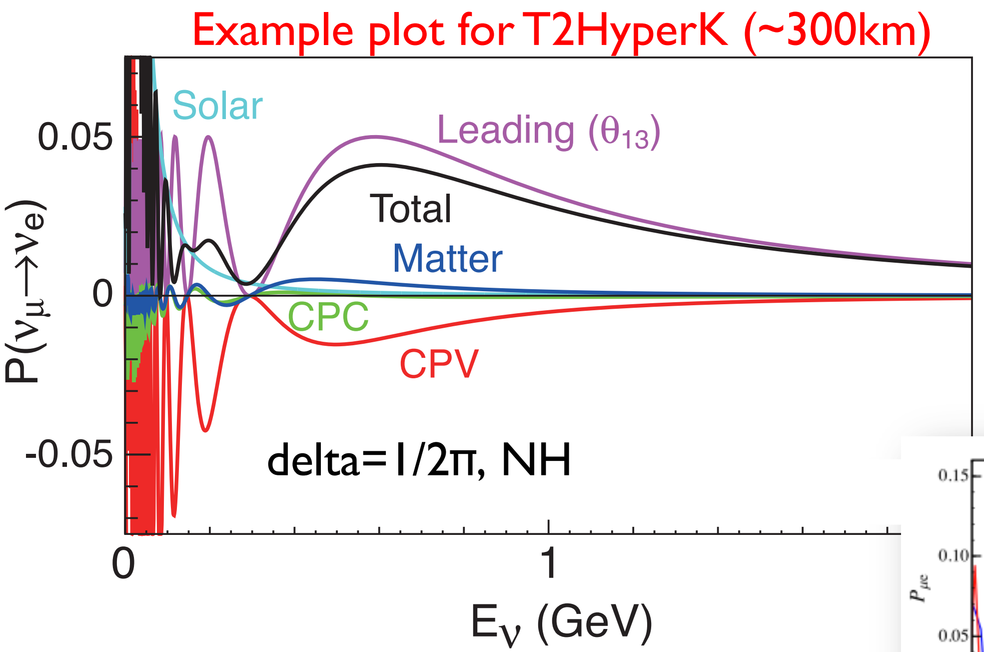
$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$ matter effects

$$P(\bar{\nu}_\mu \to \bar{\nu}_e): \ \delta \to -\delta \quad a \to -a.$$

$C_{ij}, \ S_{ij}, \ \Delta_{ij}$

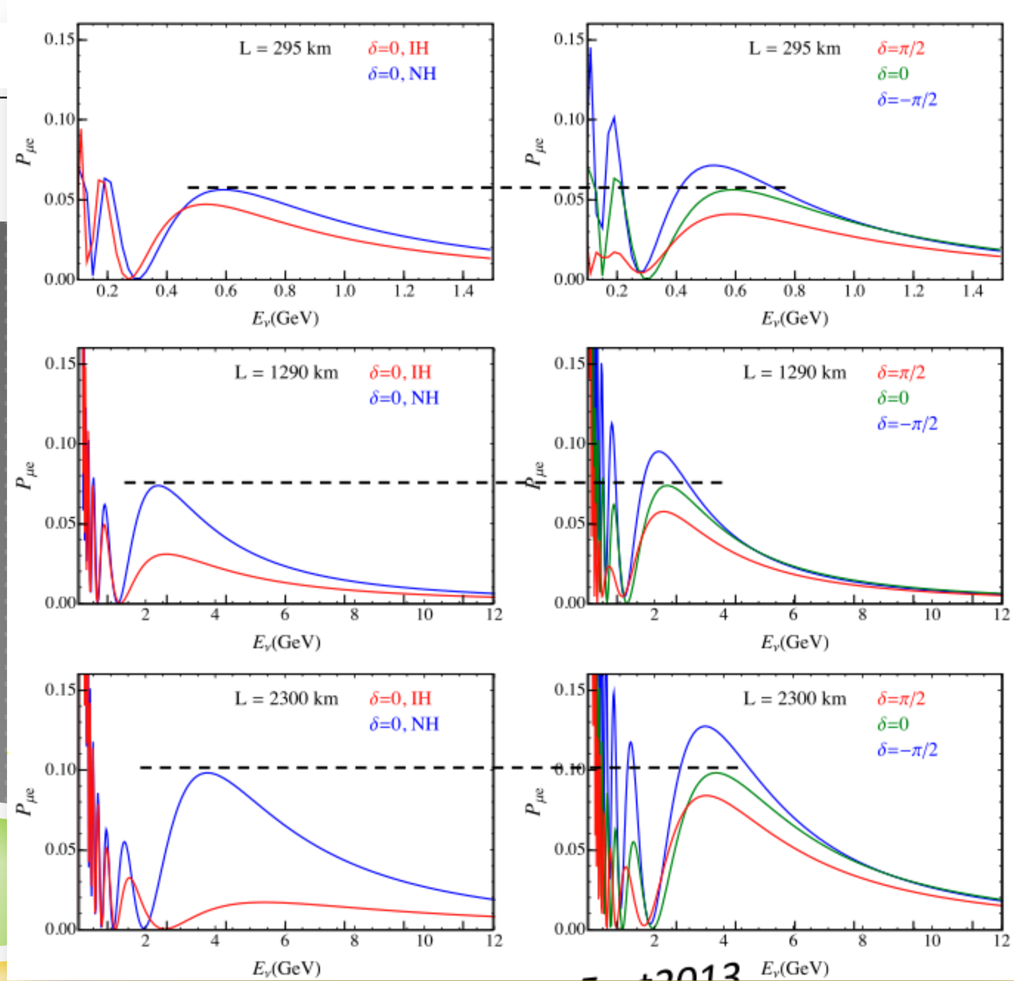
$\cos\theta_{ij}, \ \sin\theta_{ij}, \ \Delta m_{ij}^2 \, L/4E_\nu$ $\quad \alpha \sim \rho * E_\nu$

CPV & MH: LONG BASELINE EXPERIMENTS (2)

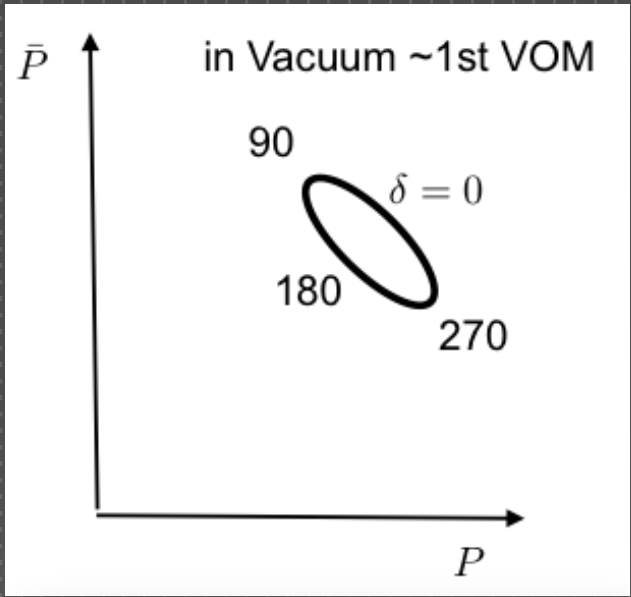


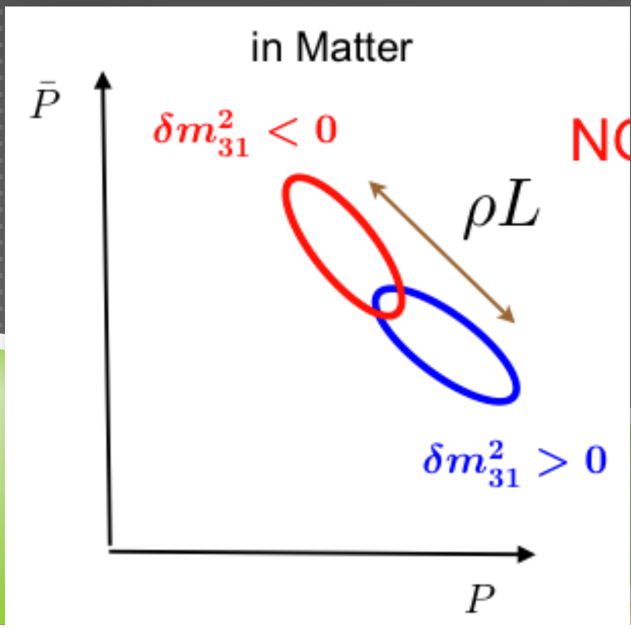
- Measurement by comparing oscillations of muon neutrinos and antineutrinos
- The contribution of some terms is different for neutrinos and antineutrinos, and the difference depends on CPV phase and MH
- More than one measurement needed to disentangle diffrent effects

Oscillation curves for different baselines (and neutrino energies)

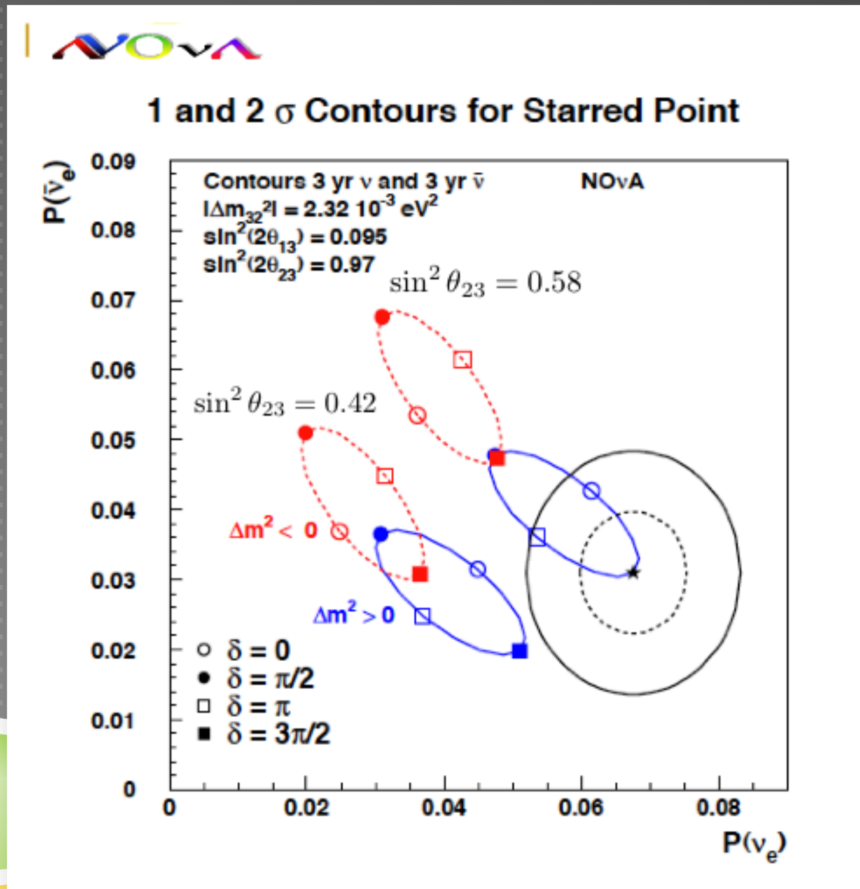


CPV & MH: LONG BASELINE EXPERIMENTS (3)



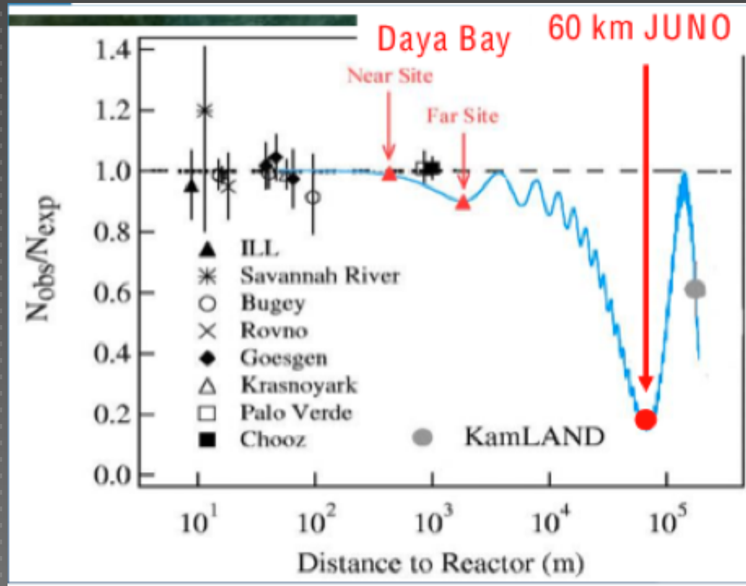


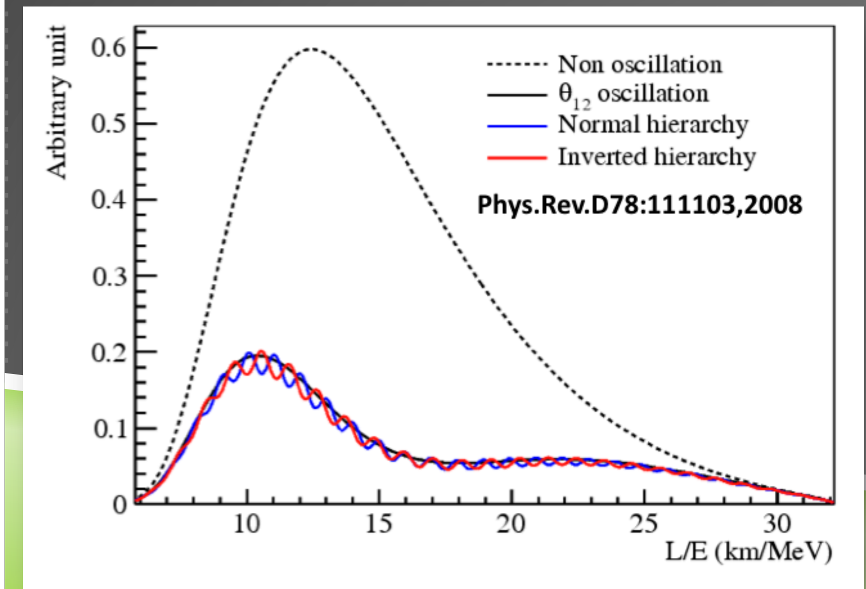
- Another way of looking at it
- Remember of experimental errors and that we could see something unexpected!



MH: REACTOR EXPERIMENTS

- Electron antineutrino dissapearance in the reactor flux („solar” dip)
- Θ_{13} is large, so we can look for small oscillations in the energy spectrum - interference between Δ_{31} and Δ_{32} terms
- They look different depending on the MH
- This is CP phase independent



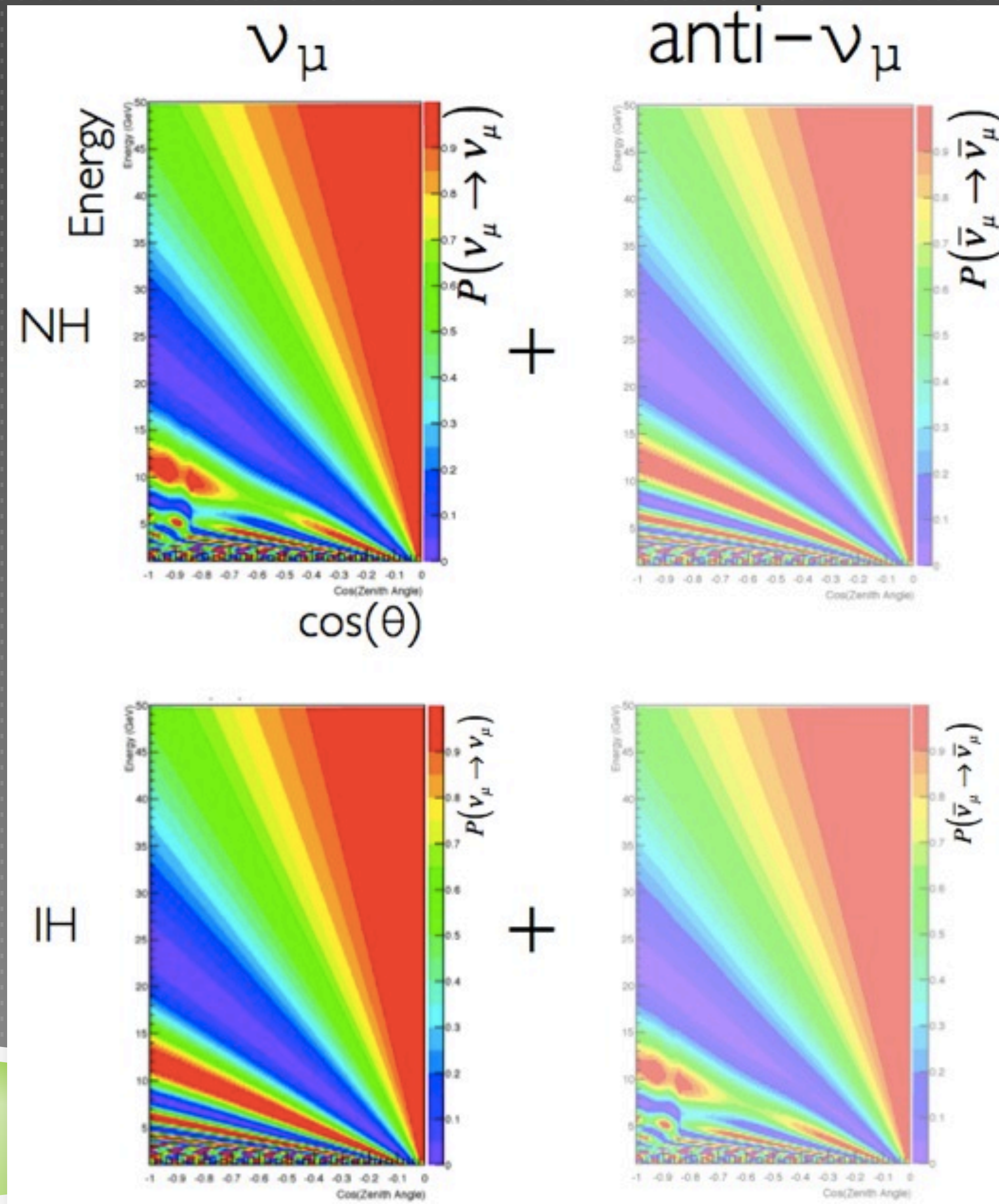


$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

MH: DISSAPEARANCE OF ATMOSPHERIC NEUTRINOS

- Difference in matter effect for neutrinos and antineutrinos
  - MSW effect that enhances oscillation probability for ν_μ ->ν_e: for neutrinos (NH) and antineutrinos (IH)
  - Additional effects coming from density transition on the border between core and mantle
- Can be studied in large future detectors



BEFORE WE BEGIN…

- (…) as we know, there are **known knowns**; there are things we know we know.
- We also know there are **known unknowns**; that is to say we know there are some things we do not know.
- But there are also **unknown unknowns** -- the ones we don't know we don't know.
- And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones.

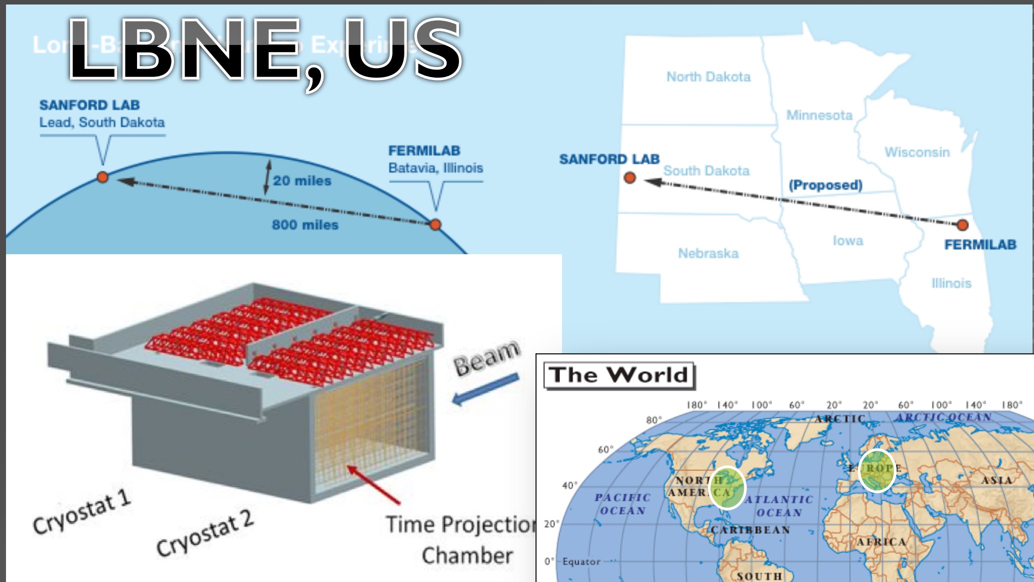
***Donald Rumsfeld**, 13th and 21st United States Secretary of Defense*

LBNF/LBNE/DUNE, T2HyperK

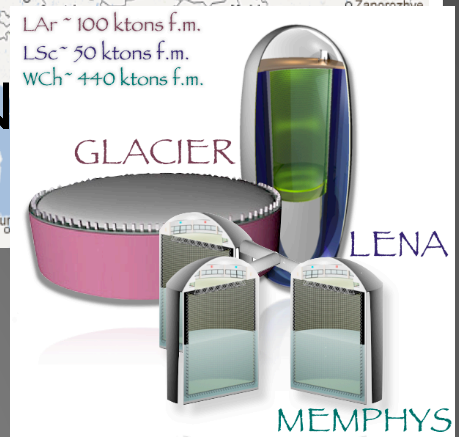
LONG BASELINE EXPERIMENTS

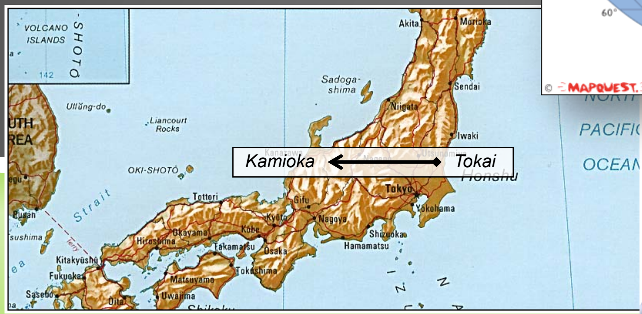
LONG BASELINE FUTURE

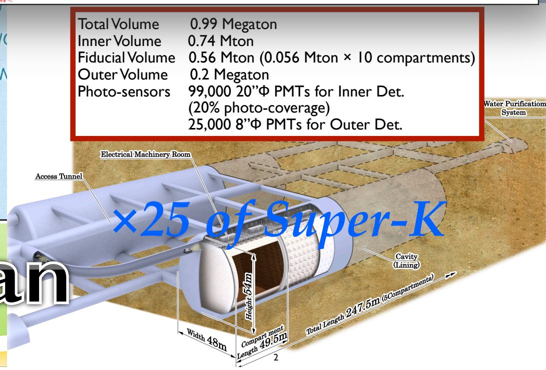
LBNE, US



Laguna-LBNO, Europe

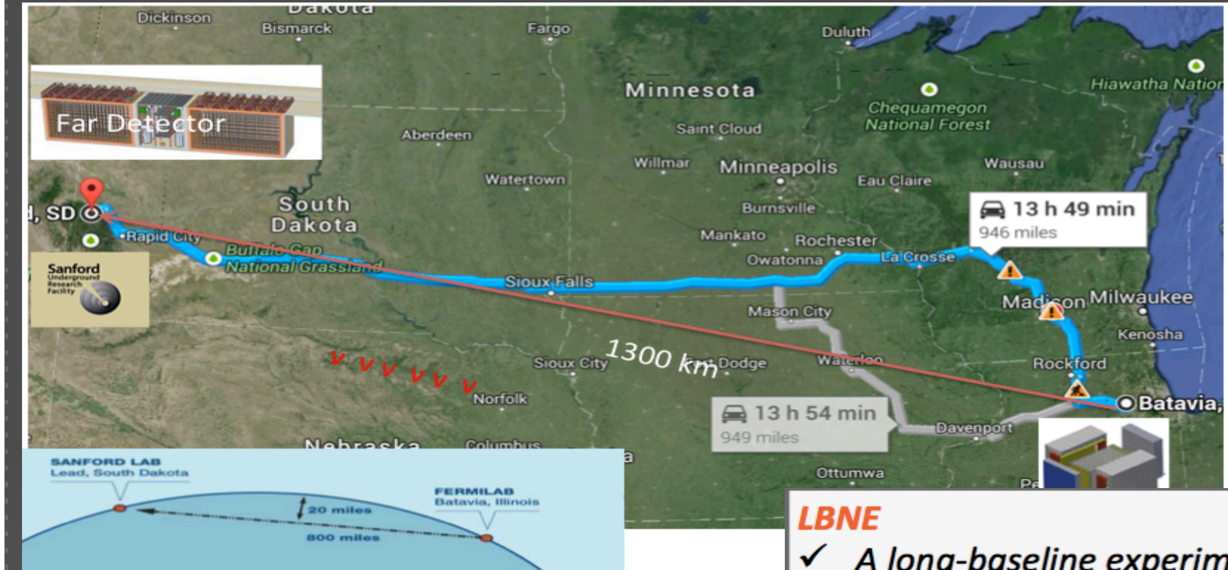






T2HyperK, Japan

LONG BASELINE NEUTRINO EXPERIMENT/ FACILITY -> DUNE



552 (~25% non-US) members,
90 (35 non-US) institutions,
9 countries

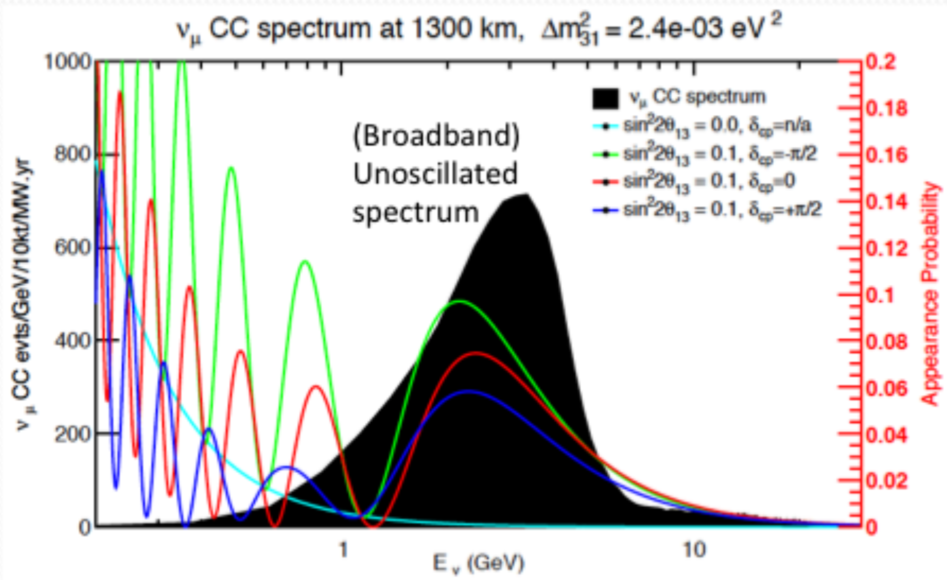
LBNE

- ✓ *A long-baseline experiment in USA with international participation*
- ✓ *34 kton LAr Far Detector underground at SURF (South Dakota)*
- ✓ *A Fine Grained Tracker as a Near Detector at Fermilab*
- ✓ *700KW to 1.2MW of beam from Fermilab*

LBNF and ELBNF – Facilities & Experiments separated

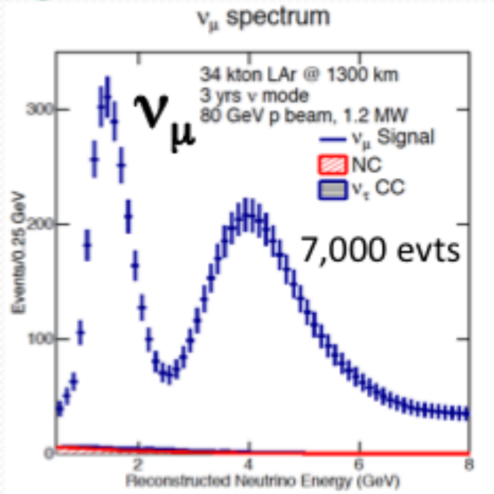
- ✓ ***LBNF*** *- Facility (Beam-line, target, horn, decay-pipe, Far & Near site for detectors & conventional infrastructures) owned and operated by Fermilab-DOE. In building the facilities, Fermilab will work with international partners including from the UK.*
  - ✓ *1.2MW (~2024) to 2.4MW (~2030) - beam from Fermilab*
- ✓ ***ELBNF*** *-* ***Long-baseline experiment "designed, built and operated" by physicists around the world***
  - ✓ *40 kton LAr Far Detector underground at SURF (Modular)*
  - ✓ *One or more Near Detectors (including Fine Grained Tracker)*
- ✓ ***International oversight***

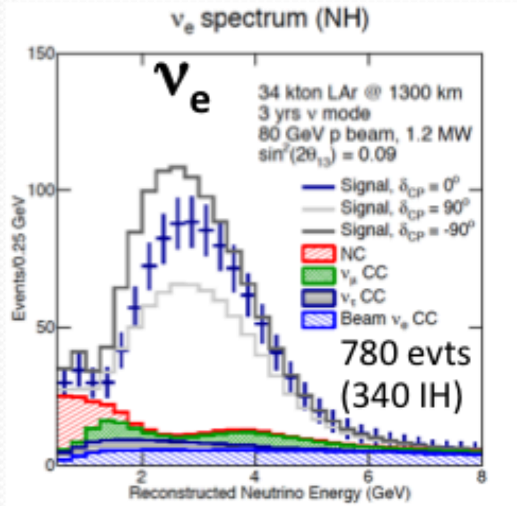
Essential Experimental Technique



disappearance

appearance





- Produce a pure ν_μ muon-neutrino beam with energy spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector

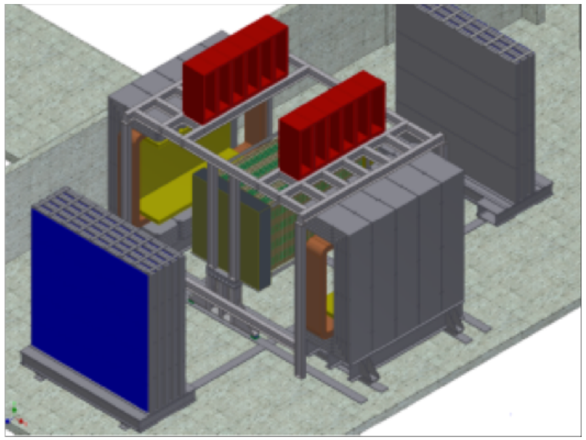
LBNE

- A new neutrino beam at Fermilab
  - 1.2 MW, 60-120 GeV proton beam, 2.3 MW capable
- A near neutrino detector
- An optimal 1300 km baseline: Fermilab-SURF

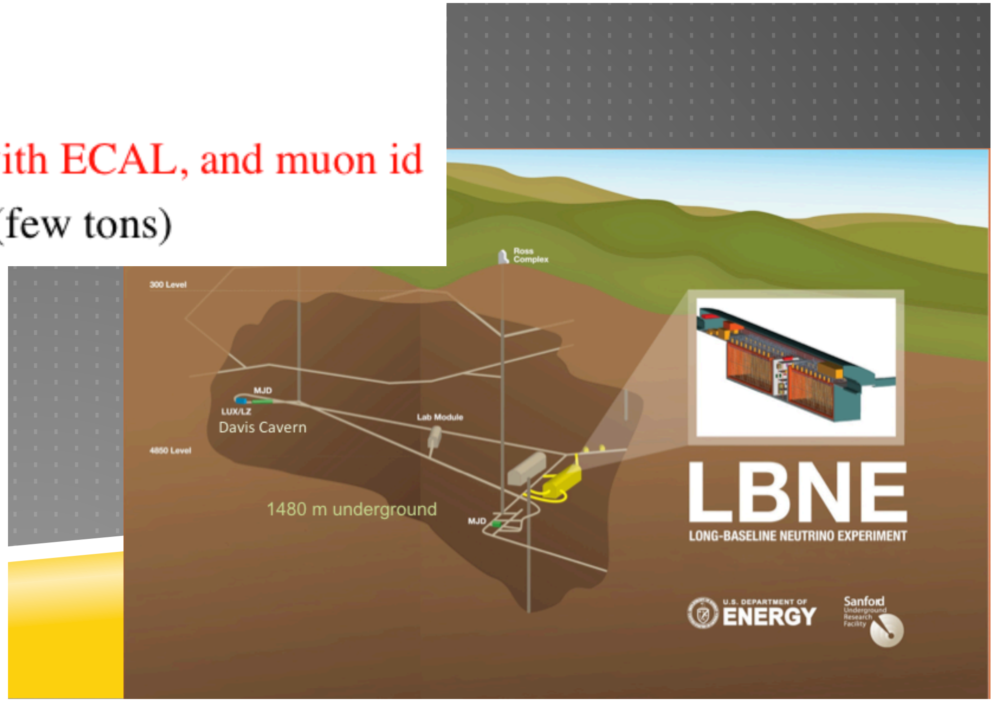
- A 34 kt Liquid Argon TPC with 4850' overburden
  - **Construction steps will depend on the new international collaboration.**
  - **Total excavated space for ~34 kton (fiducial) to be built.**
  - **The detector constructed in phases with >10kt at the start.**

Near detector parameters

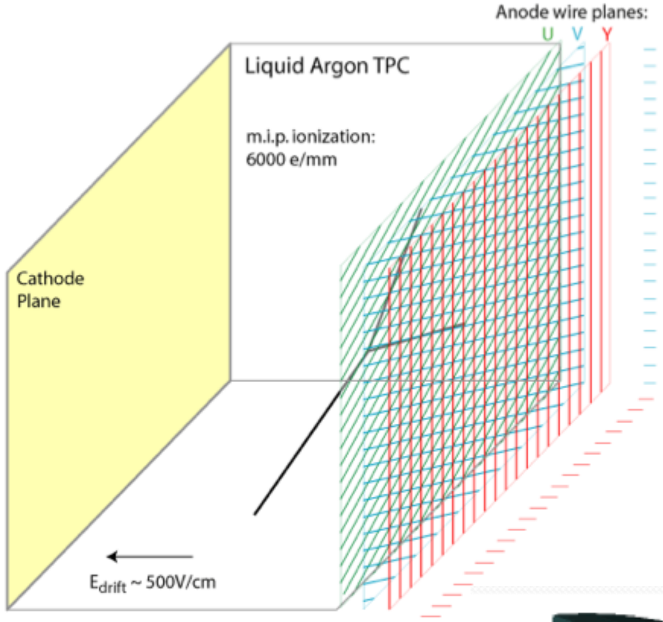
- distance ~450 m, ~3M events/ton/MW/yr
- Magnetized Fine Grained Tracker (8 ton) with ECAL, and muon id
- May be supplemented by a small LArTPC (few tons)

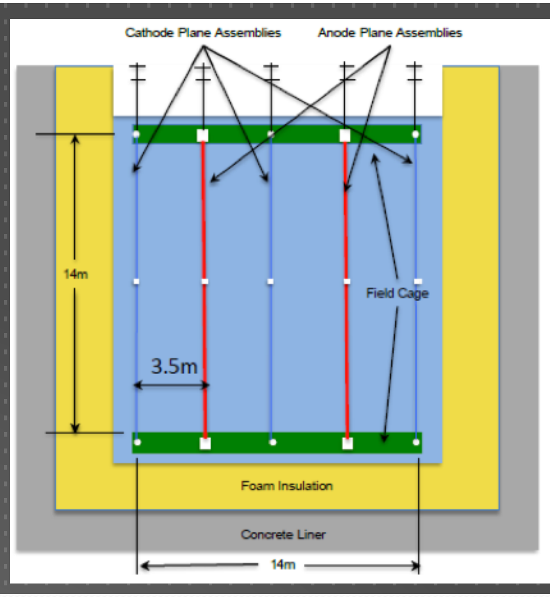


Fine-Grained Tracker - 460 m from target
- -Low-mass straw-tube tracker with pressurized gaseous argon target
- -Relative/absolute flux measurements
- -High precision neutrino interaction studies $\approx 10^7$ interactions/year
- -Additional target materials possible
- -May be supplemented by a small LArTPC (few tons)



FAR DETECTOR: LIQUID ARGON TPC

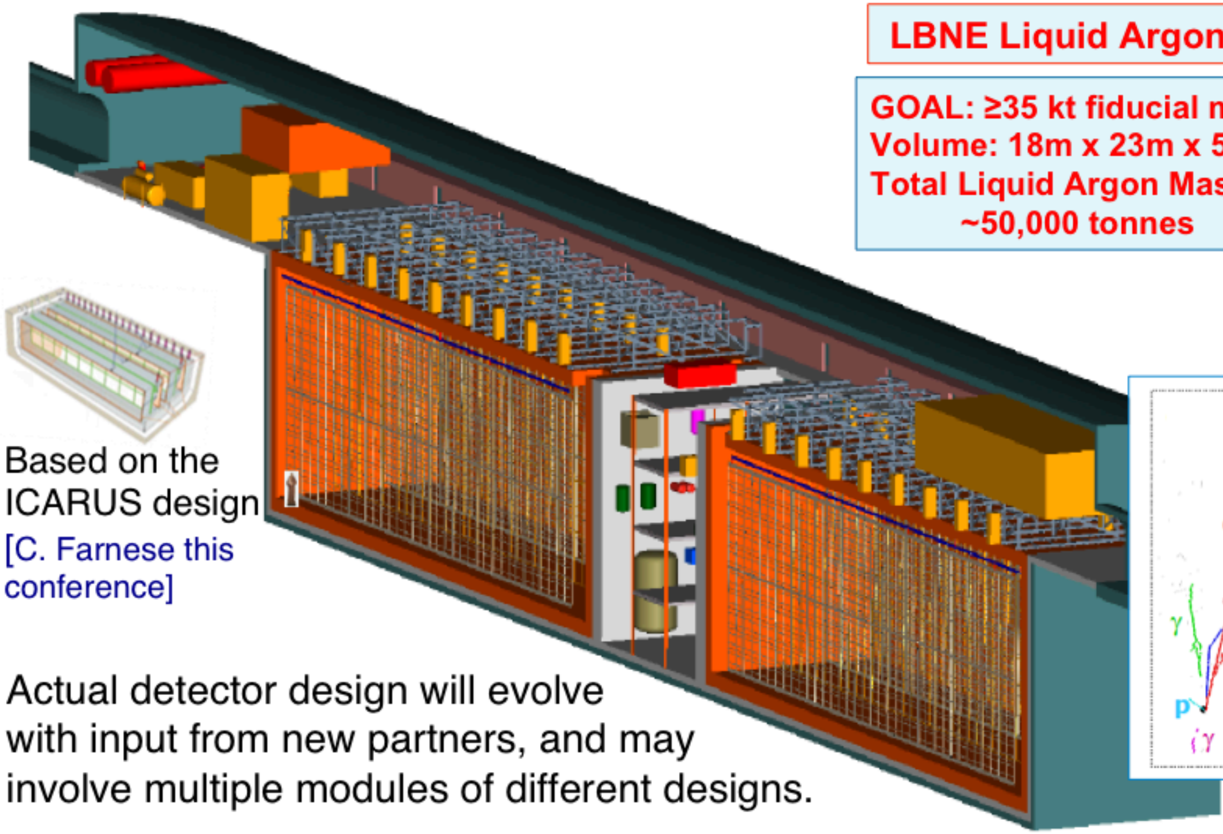




3.45m → 2.16ms

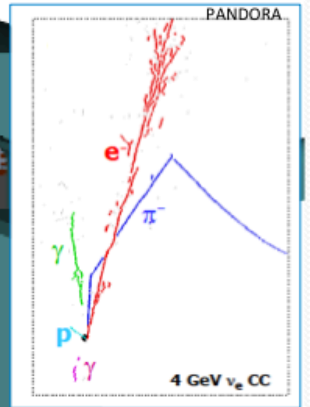
- 2 detector modules 5(9.4)kt fiducal(liquid) volume
- 2 anode plane assemblies (APA) wide
- 2 APA assemblies high
- 10*2.5m wide APAs long (~25m total length)
- Each module has 4 drift volumes 25m long
- Instrumented with Y,U,V planes

Based on the ICARUS design [C. Farnese this conference]



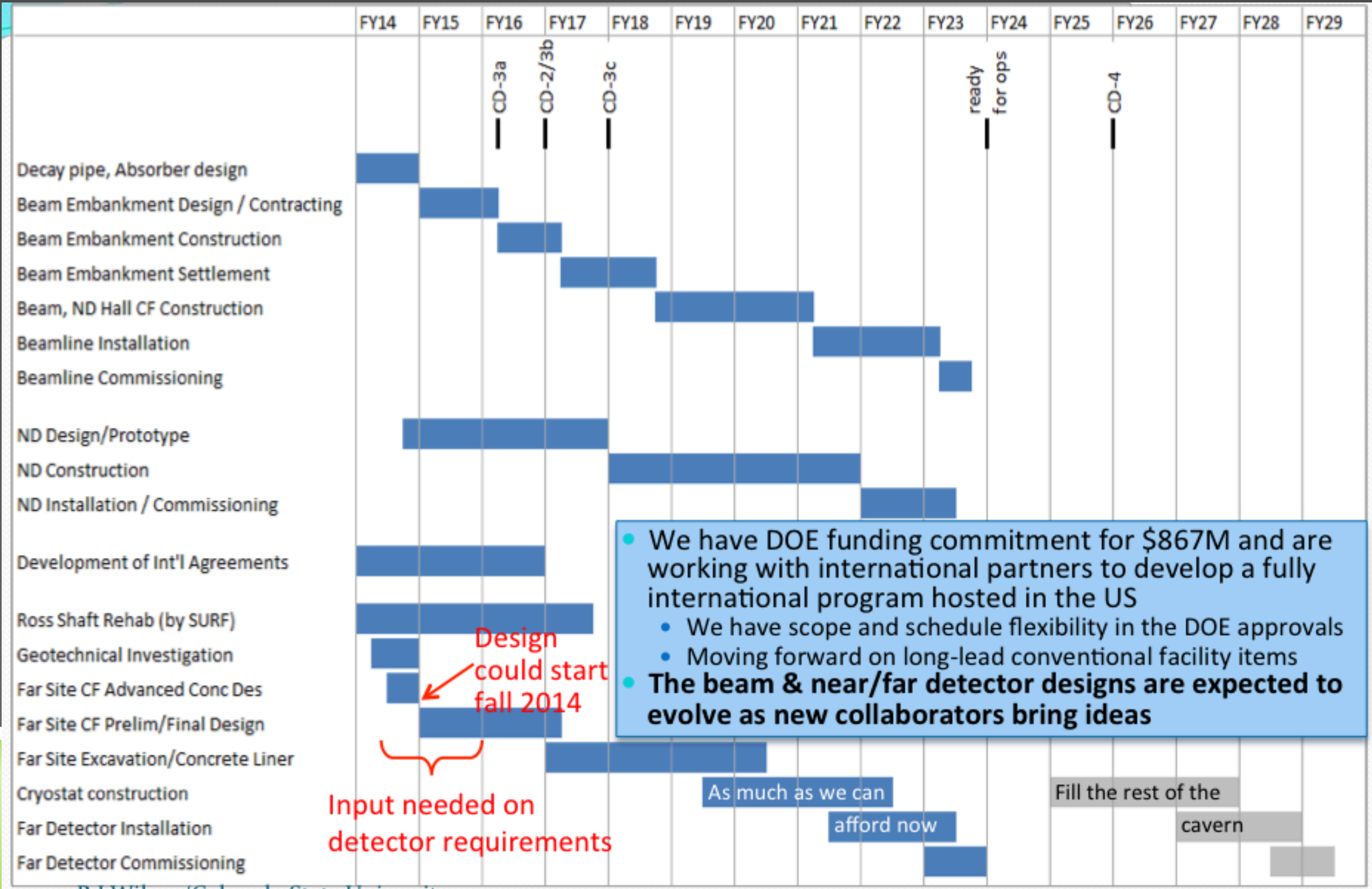
LBNE Liquid Argon TPC

GOAL: ≥35 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass: ~50,000 tonnes



Actual detector design will evolve with input from new partners, and may involve multiple modules of different designs.

LBNF – TIME AND MONEY



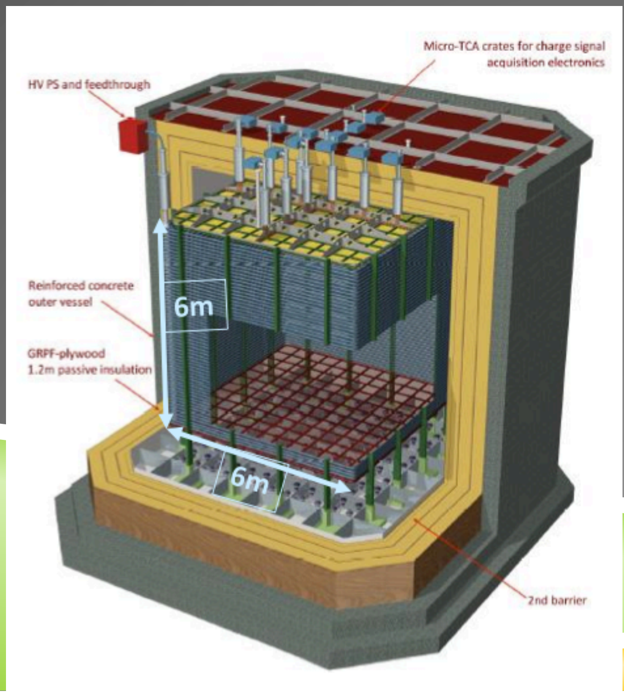
- We have DOE funding commitment for $867M and are working with international partners to develop a fully international program hosted in the US
  - We have scope and schedule flexibility in the DOE approvals
  - Moving forward on long-lead conventional facility items
- **The beam & near/far detector designs are expected to evolve as new collaborators bring ideas**

NEUTRINOS @ CERN (EUROPE)

CERN Neutrino Platform:

- ✓ CERN offers a platform for Neutrino detectors R&D. This platform is now part of the CERN MTP. We will support this platform in an active way and will help **WA104, WA105** and others proposals in this initial phase
- ✓ CERN will construct a large neutrino test area (EHN1 extension) with charged beams capabilities, available in 2016
- ✓ CERN will assist the EU neutrino community in their long term common plans. For the moment CERN is not committing to any neutrino beam at CERN, in view of an agreed road map between all partners

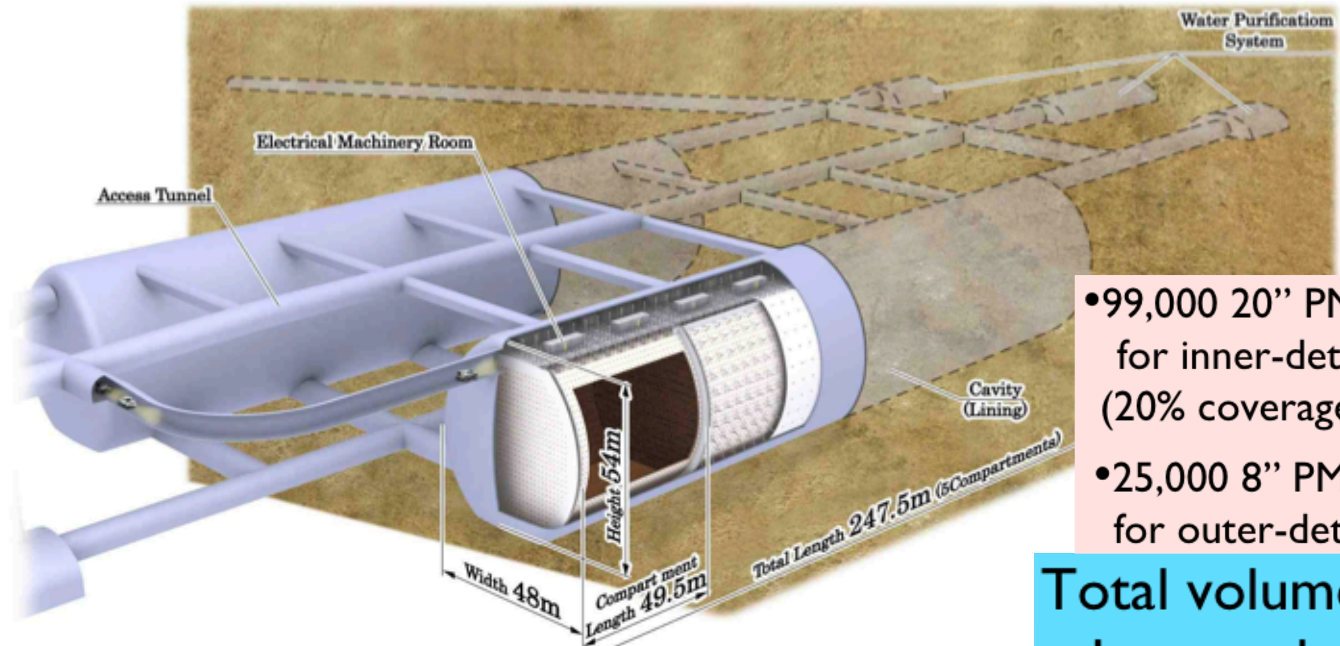
LBNO – DEMO:

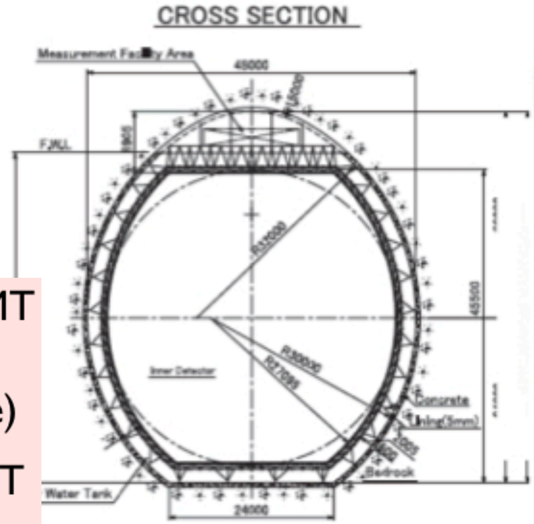


Preparation of 5 MOUs addenda in progress:

WA104: rebuild ICARUS T600 in bldg 185 and make it ready for a FNAL beam
WA104: R&D on an AIR core muon detector (NESSiE) or eventually integrate a solenoid in the main TPC
WA105: R&D on 2 phases large LAr TPC prototypes
MIND : R&D on muon tracking detectors
LBNF : Test of a LBNE module inside the WA105 cryostat

HYPER-KAMIOKANDE – A HUGE SUPER-KAMIOKANDE-LIKE DETECTOR





- 99,000 20" PMT for inner-det. (20% coverage)
- 25,000 8" PMT for outer-det.

Total volume:	0.99 Mton
Inner volume:	0.74 Mton
Outer volume:	0.2 Mton
Fiducial volume:	0.56 Mton

(0.056Mton × 10 compartments)

x25 of Super-K

Maximum utilization of resources and experiences in SK

~ Use established technology for the long term operation to achieve physics goal in timely manner.

T2K -> T2HK!

Hyper-Kamiokande with J-PARC neutrino beam

J-PARC neutrino beam line

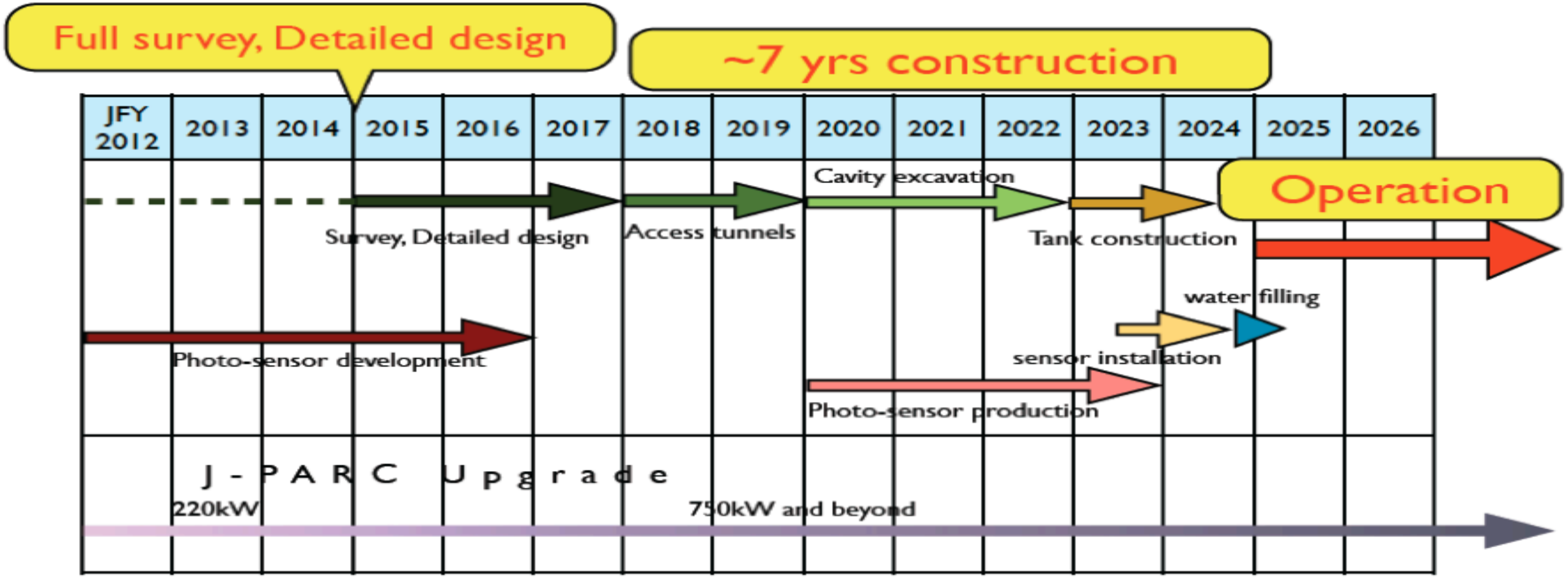
One of the most powerful beamlines in operation and further intensity upgrade (>750kW) is undergoing.

Hyper-Kamiokande

World largest water Cherenkov detector (fid. vol. 560 kt.)

Powerful combination to search for the lepton sector CP violation!

Hyper-Kamiokande project ~ Notional Timeline ~



-2015 Full survey, Detailed design (3 years)
-2018 Excavation start (7 years)
-2025 Start operation

(Optimistic) Timeline for anticipated results

-2022 ~2σ CPV indication (sinδ=1) by T2K+ Nova +reactors

-2025 *Start Hyper-K data taking*

-2028 Discovery of leptonic CPV w/ >5σ (MH at the same time or earlier)

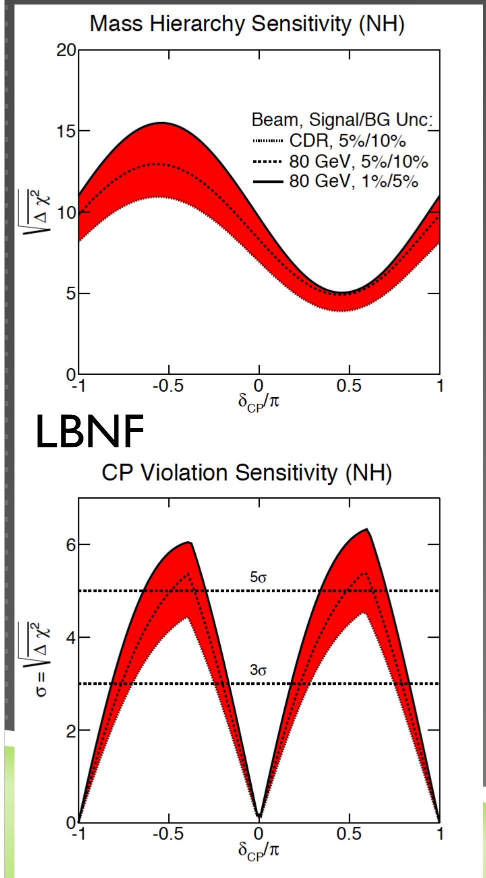
-2030 Discovery of proton decays

-20XX Always ready for Supernova neutrino burst

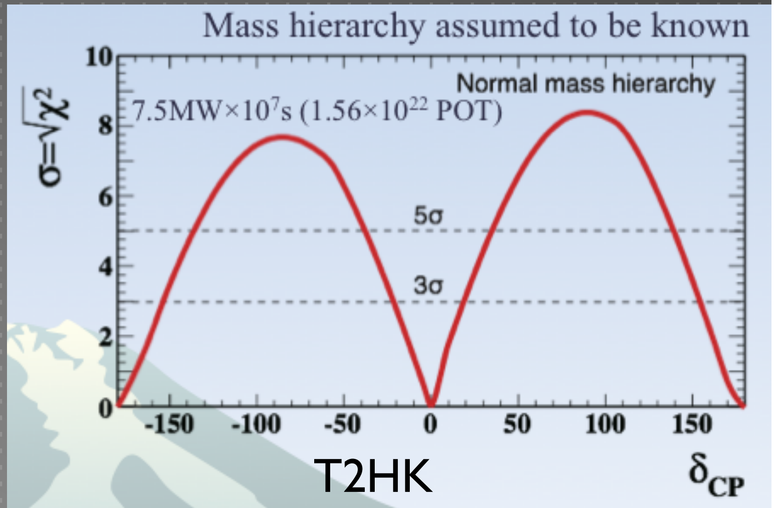
PHYSICS WITH LBNF AND T2HK

LBNE is a good choice of beam and distance for sensitivity to CP-violation, CP-phase, neutrino mass hierarchy, and other oscillation parameters within the same experiment.

- **Diff. btw. ν_e and $\bar{\nu}_e$ behavior** "T2HK"
  - Less-model dependent determination of CP symmetry
  - Less matter effect → relatively pure CPV measurement



- DUNE
  - Can study mass hierarchy (long baseline) as well as CPV
  - Promising Lar TPC technique but lots of problems to overcome
- T2HK
  - Short baseline – only CPV can be studied
  - But – no need to disentangle the two effects (MH/CPV)
  - Wery well known detection technique (SuperK!)

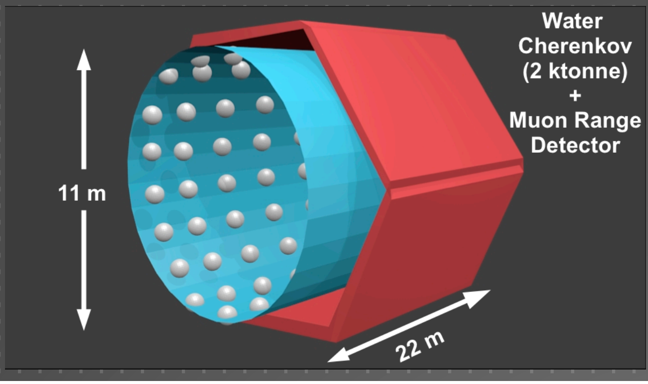


Exposure 245 kt.MW.yr
34 kt x 1.2 MW x (3ν+3$\bar{\nu}$) yr

We need both - two independent measurements!

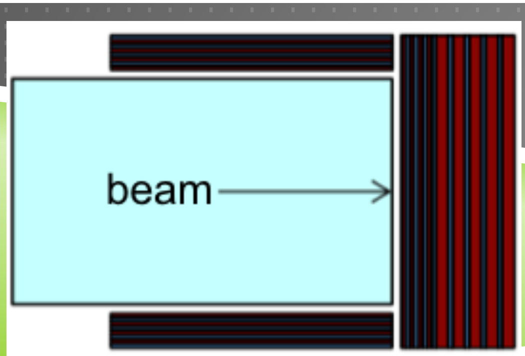
NEAR DETECTOR R&D

TITUS



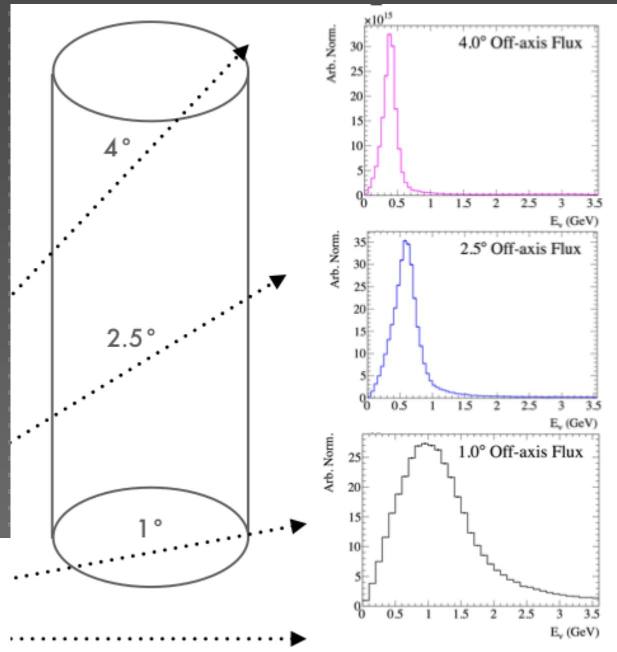
- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

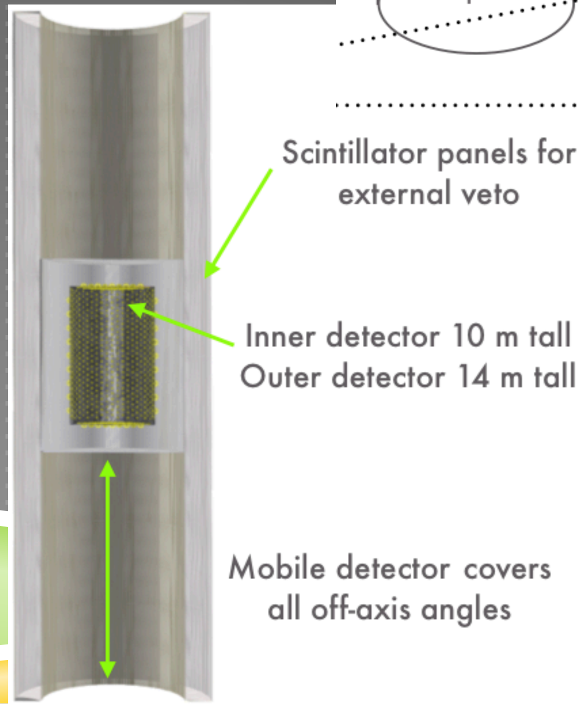
- Baseline design includes:
  - ~2 ktonne water Cherenkov tank
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector
    - Fe & plastic scintillator
      - End: 150 cm Fe
      - Side: 50 cm Fe (75% coverage)



Minimisation of systematic errors is crucial for future high-precision experiments!

NUPRISM

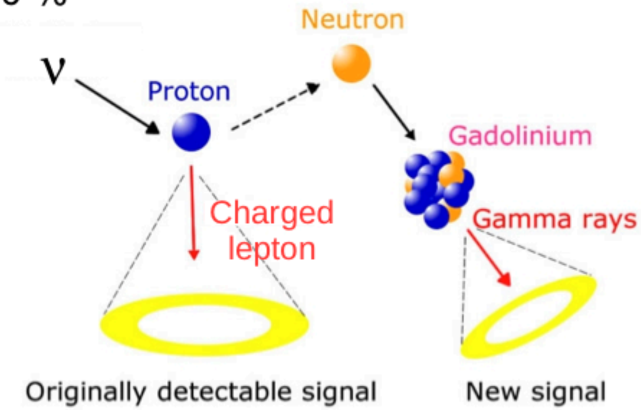




Gadolinium Doping

- **CCQE for ν:** ν + n → l^- + p (p is "invisible")

  CCQE for $\bar{\nu}$: $\bar{\nu}$ + p → l^+ + n
- In ordinary water: n thermalizes, then is captured on a free proton
  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK is ~20 %
- When n captured on Gd:
  - Capture time ~20 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - 100% detection efficiency



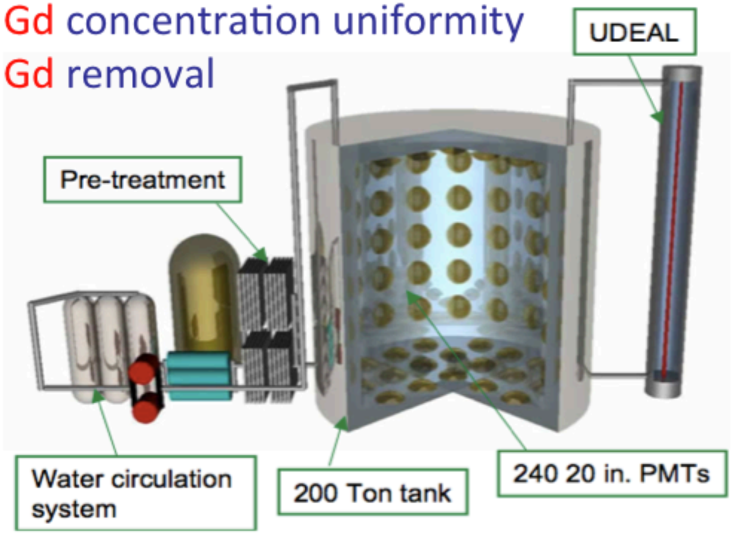
- "Wrong sign" neutrino discrimination
  - From T2K sensitivity studies, we know that running a mix of neutrino mode & antineutrino mode enhances δ_{CP} sensitivity
  - Antineutrino mode has greater contamination from neutrinos
  - With Gd-doping, can separate ν from $\bar{\nu}$ in TITUS to understand contamination, characterize beam, and reduce systematics for Hyper-K

EGADS – GADOLINIUM TEST

EGADS Evaluating Gadolinium's Action on Detector Systems

Facility for testing the effect of Gd in water-Cherenkov detectors:

- Selective filtration for Gd water
- $Gd_2(SO_4)_3$ "cleaning" and dissolving
- water transparency monitoring
- Gd concentration uniformity
- Gd removal



In the EGADS underground laboratory. From left to right: Roy Hall, Erin O'Sullivan, Masayuki Nakahata, Jeff Griskevich, Mark Vagins

Last summer it became an actual detector, instrumented with 240 PMTs

a *possible* timeline for EGADS & GADZOOKS!

06/2014 - 08/2014: EGADS 200-ton tank works
08/2014 - 11/2014: new EGADS test
05/2015: Make a decision among the SK collaboration

GADZOOKS! – SK WITH GADOLINIUM?

Diffuse Supernova Neutrino Background (DSNB)

One of our main motivation for this upgrade is to first detect DSNB, neutrinos from all the supernovae in the history of the universe

This would be detected through anti-neutrinos interacting inverse-β

The measurement is affected by large backgrounds that can be excluded with neutron tagging

At the moment SK can only put upper limits and they are 2- 4 times larger than the theoretical predictions

expected signal: **5 events/year/22.5kton**

Reactor Neutrinos

Improve sensitivity to solar sector oscillation parameters using reactor neutrinos

Although the future of japanese nuclear reactors is not clear, GADZOOKS! will detect a similar rate from korean reactors as KamLAND when all the japanese reactors were on

expected signal from 3.5 MeV: **200 events/day/22.5kton**

Galactic Supernova Burst

With neutron tagging, we can extract the $\bar{\nu}_e$ and ν_e spectra
Provides much more detailed information about the core-collapse process than that without neutron tagging

Others

Improve our knowledge of atmospheric and accelerator neutrino interactions and final states

Neutron tagging can help discriminating between ν and $\bar{\nu}$ at GeV scale

Neutron tagging also reduces background in proton decay searches by requiring final states with no neutrons

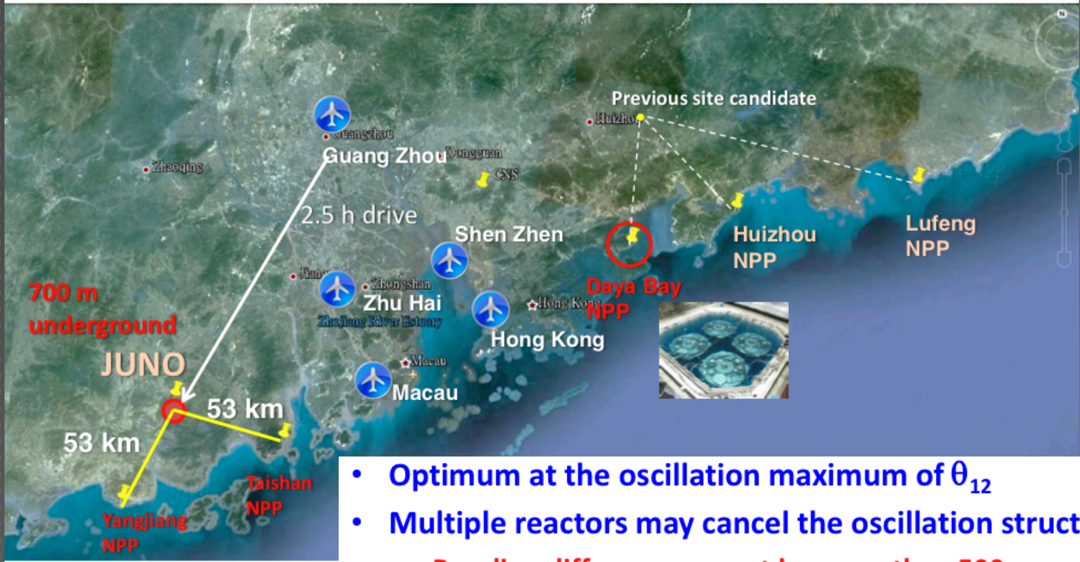
Decisions soon!

Juno, Reno 50

REACTOR EXPERIMENTS

JUNO & RENO 50

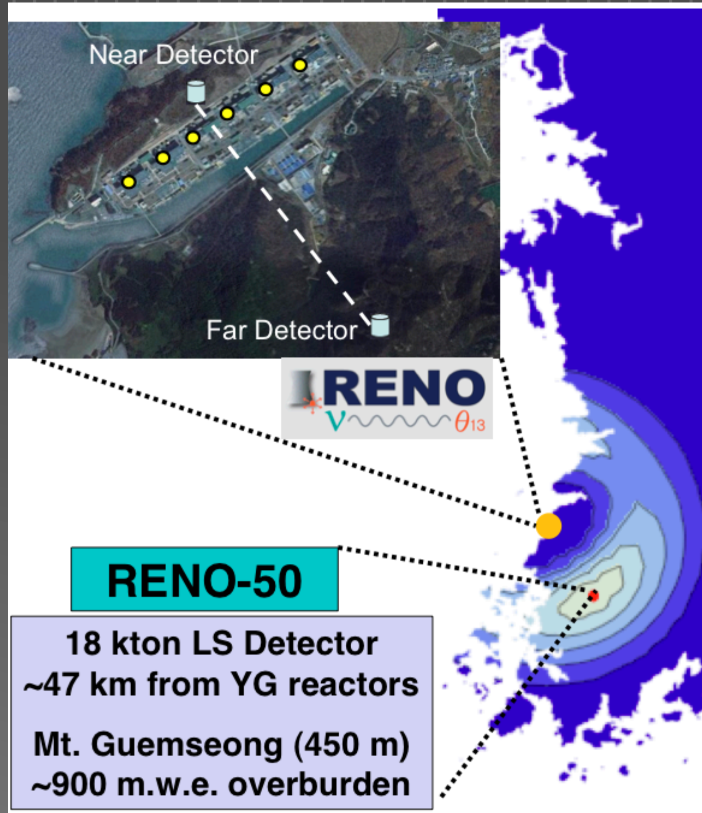
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



- Optimum at the oscillation maximum of θ_{12}
- Multiple reactors may cancel the oscillation structure
  - Baseline difference cannot be more than 500 m

JUNO Schedule:

Civil preparation: 2013-2014
Civil construction: 2014-2017
Detector component production: 2016-2017
PMT production: 2016-2019
Detector assembly & installation: 2018-2019
Filling & data taking: 2020

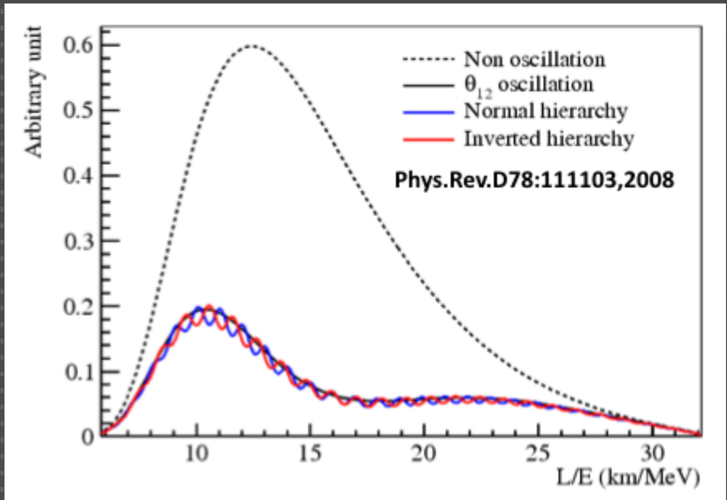


- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant
- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)
- **Schedule** : 2014 ~ 2019 : Facility and detector construction
  2020 ~ : Operation and experiment

We'll get the results faster than for long baseline!

REACTOR NEUTRINO MH MEASUREMENTS

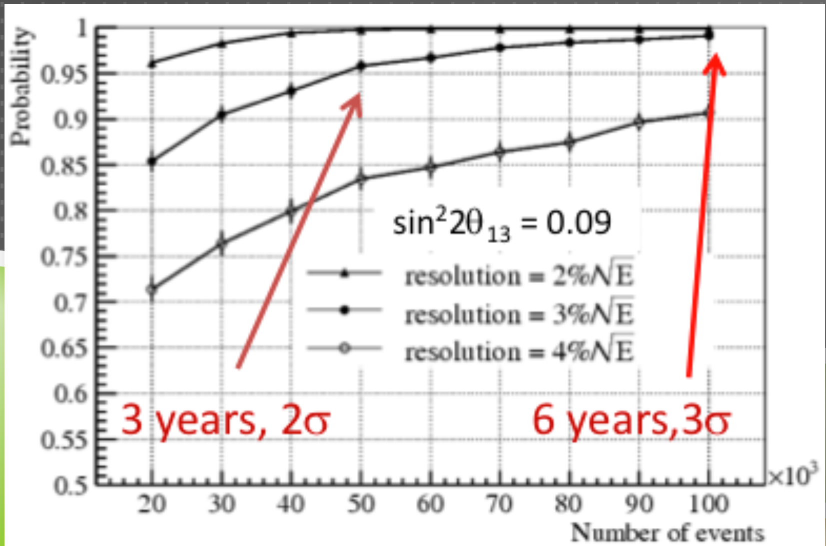
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

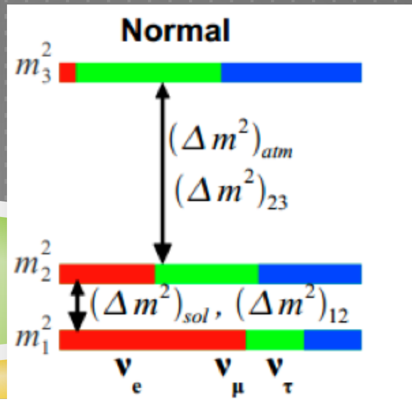


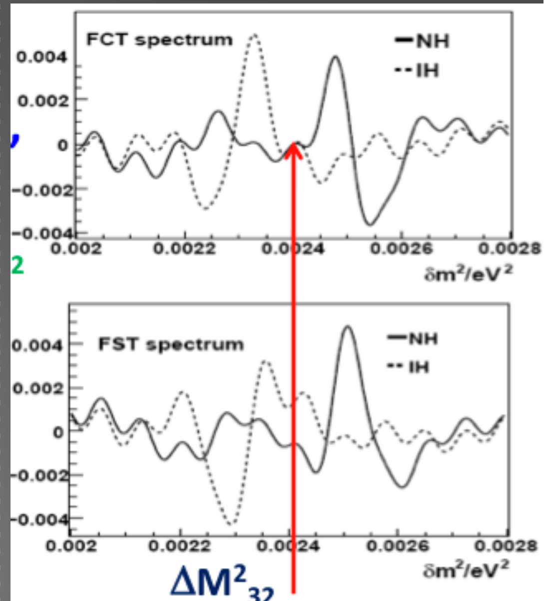
- Proposed method – Fourier transform analysis
- Fourier cosine and sine transforms are employed to find the oscillation frequency
  - Δm^2_{32} is a reference
  - Then, Δm^2_{31} peak at the left or right of Δm^2_{32}, depending on hierarchy

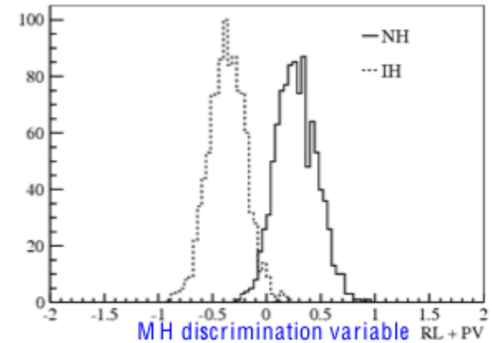
Experiment Concepts:
36GW reactors; 58km baseline
20 kton LS; $3\%/\sqrt{E}$ resolution;

Independent on CP phase and θ_{23} (Acc. & Atm. do)
Energy Resolution is the key

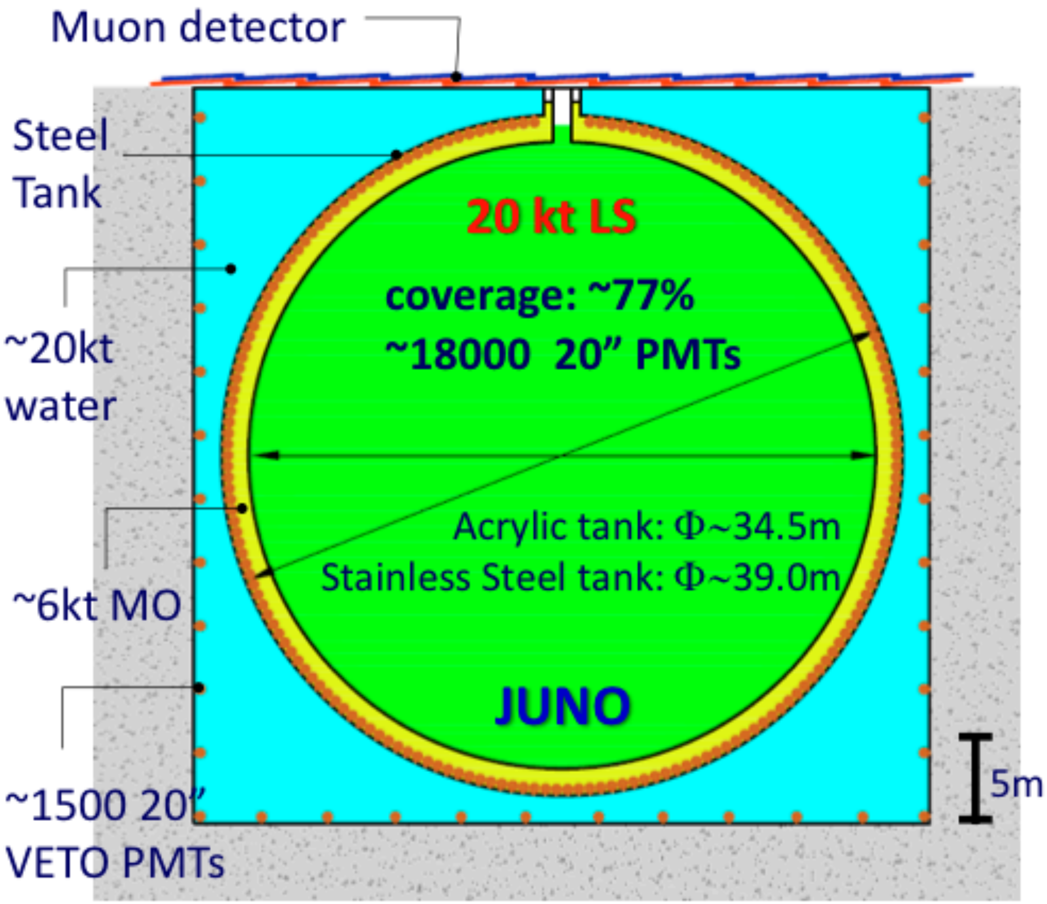


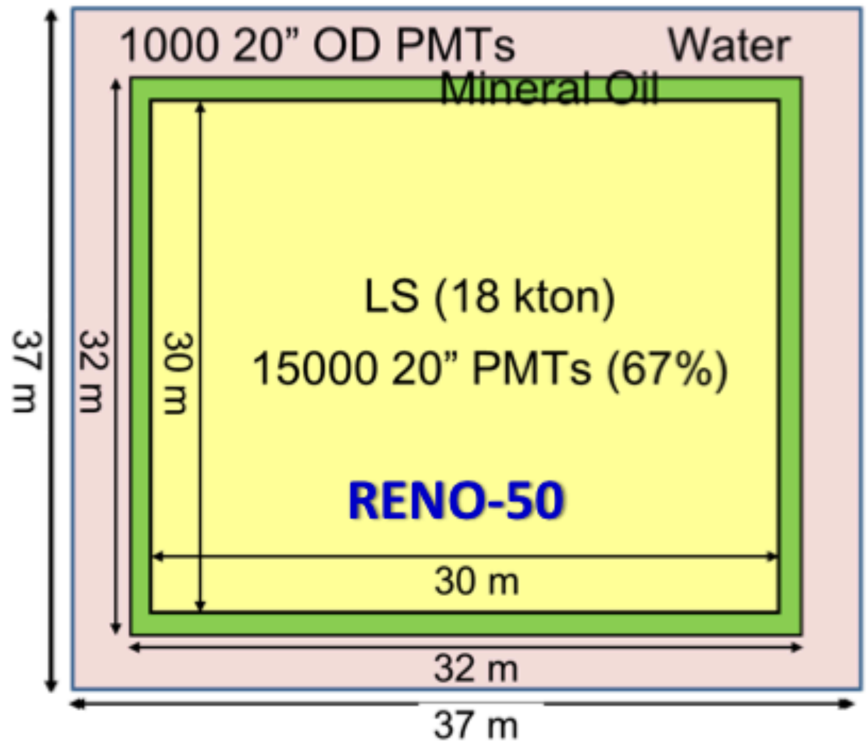






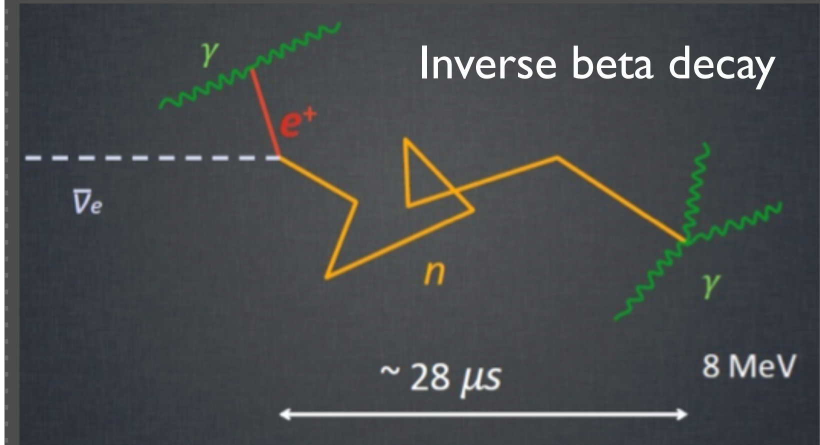
Challenge: high-precision, giant LS detector





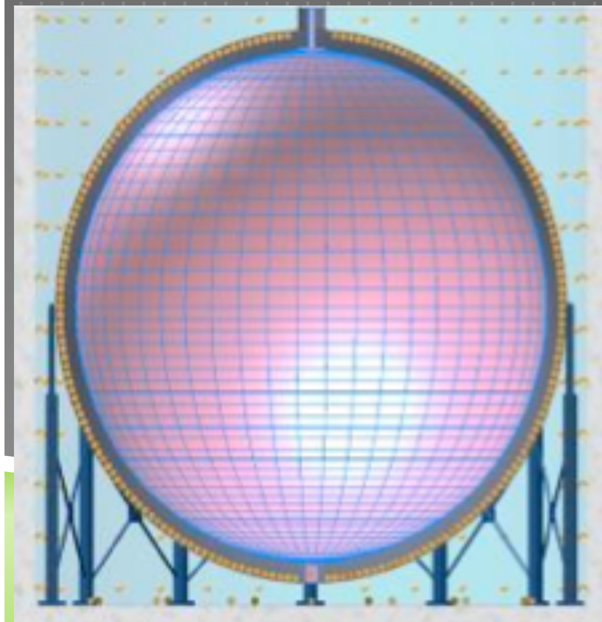
	KamLAND	JUNO	RENO-50
LS mass	~1 kt	20 kt	18 kt
Energy Resolution	$6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV

TECHNOLOGICAL ASPECTS



- Very high energy resolution required
  - Scintillator light yield and transparency improvements
  - High quantum efficiency photomultipliers
  - Scintillator's non-linear energy response corrections

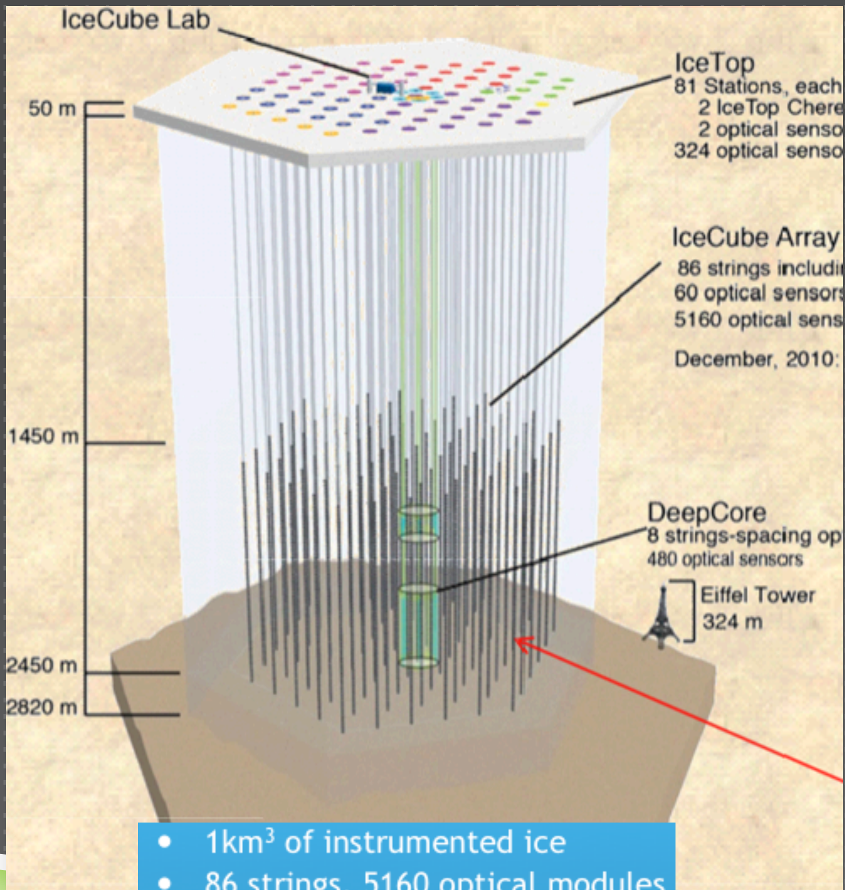
- **Some basic numbers:**
  - **Target: 20 kt LS**
  - **$\bar{\nu}_e$ Signal event rate: ~60/day**
  - **Backgrounds with 700 m overburden:**
    - **Accidentals(~10%), $^{9}Li/^{8}He$(<1%), fast neutrons(<1%)**
- **A huge detector in a water pool:**
  - **Default option: acrylic tank(D~35m) + SS structure**
  - **Backup option: SS tank(D~38m) + acrylic structure + balloon**
- **Issues:**
  - **Engineering: mechanics, safety, lifetime, …**
  - **Physics: cleanness, light collection, …**
  - **Assembly & installation**
- **Design & prototyping underway**



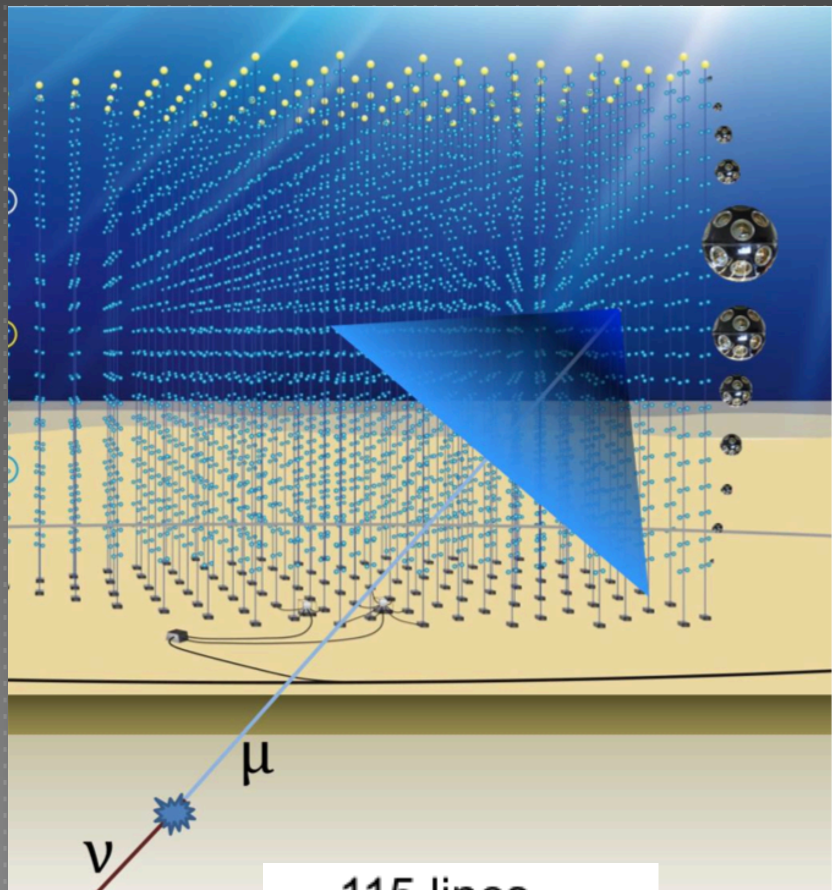
IceCube/Pingu, KM3Net/ORCA

SEA AND ICE EXPERIMENTS

ICECUBE VS KM3NET

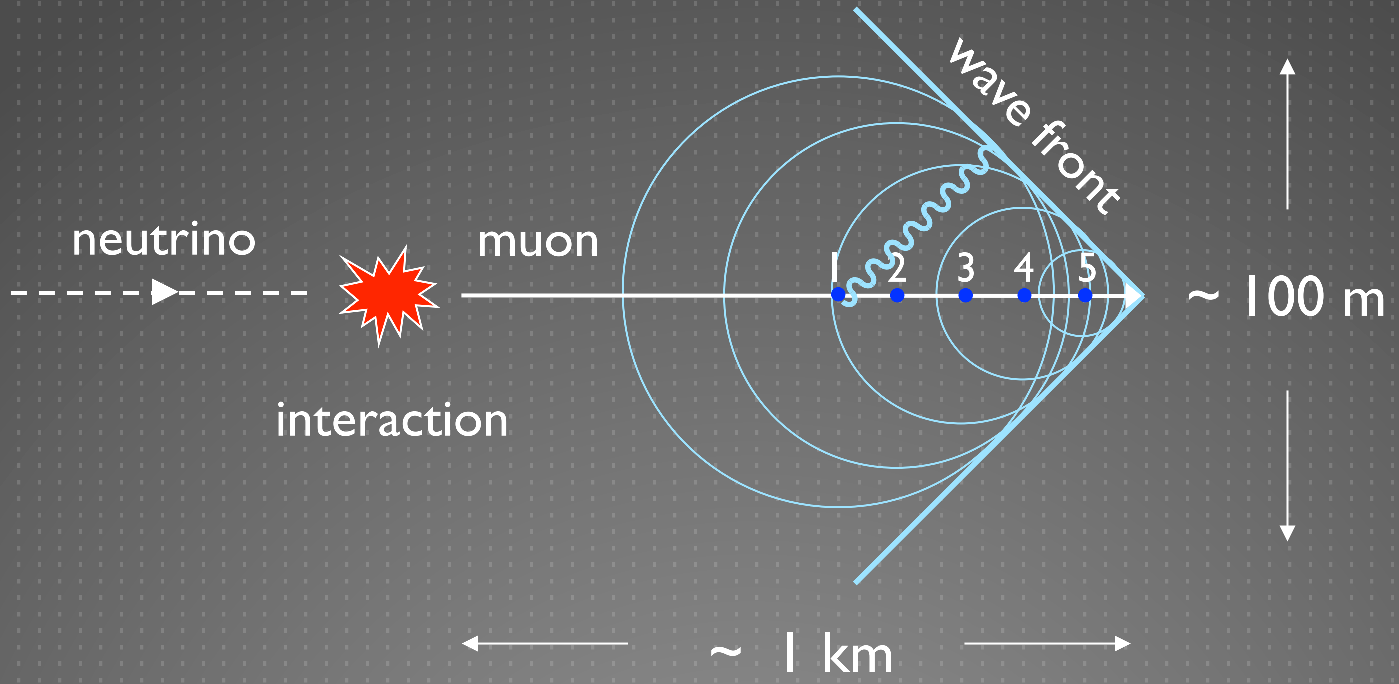


- $1 km^3$ of instrumented ice
- 86 strings, 5160 optical modules (PMTs)
- 125m interstring spacing, 17m between modules
- neutrinos of TeV energy
- started 2010

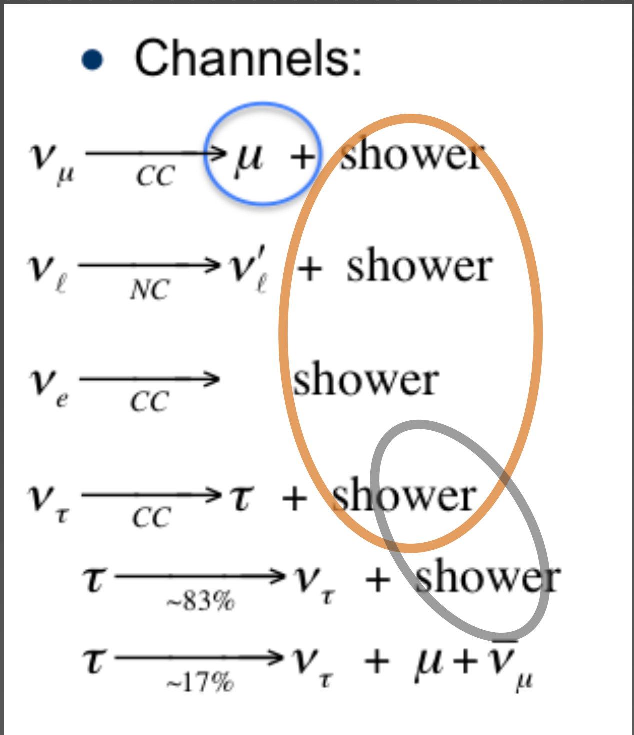


- 115 lines
- 90m spacing
- 64,170 PMTs

SIZE OF EVENTS



TYPES OF EVENTS



- Channels:

$$\nu_\mu \xrightarrow[CC]{} \mu + \text{shower}$$

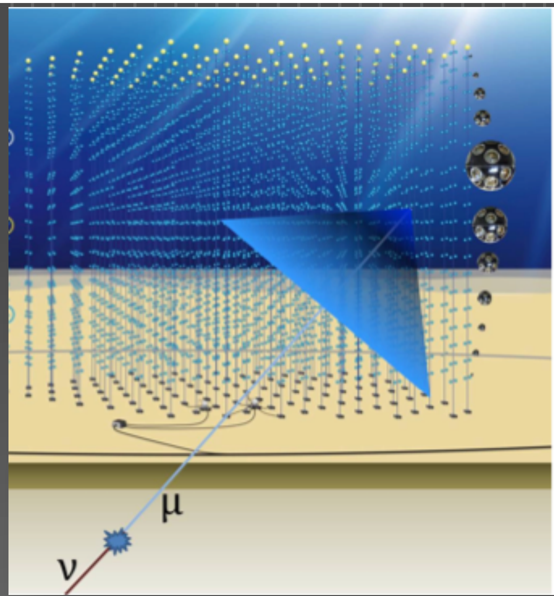
$$\nu_\ell \xrightarrow[NC]{} \nu'_\ell + \text{shower}$$

$$\nu_e \xrightarrow[CC]{} \text{shower}$$

$$\nu_\tau \xrightarrow[CC]{} \tau + \text{shower}$$

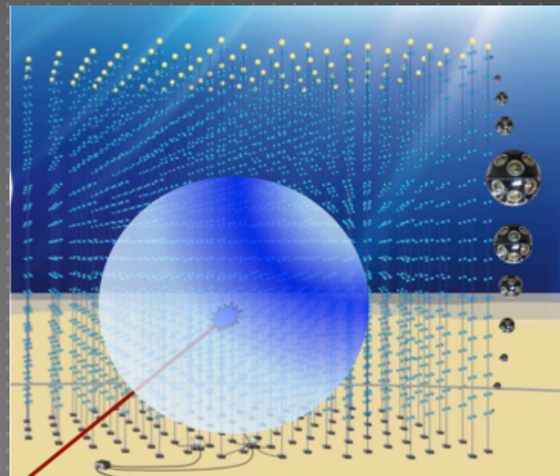
$$\tau \xrightarrow[\sim 83\%]{} \nu_\tau + \text{shower}$$

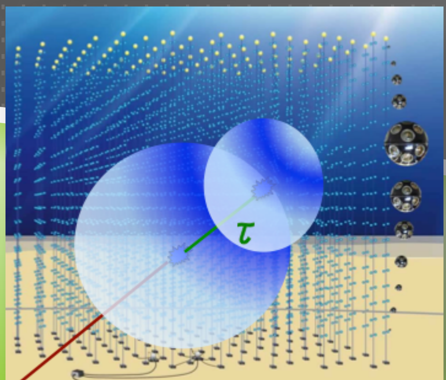
$$\tau \xrightarrow[\sim 17\%]{} \nu_\tau + \mu + \bar{\nu}_\mu$$



- **Track**
- Highest effective area, good angular resolution, but large cosmic muon background (look at events from below)

- **Cascade/ shower**
- Lower background, but worse directional resolution

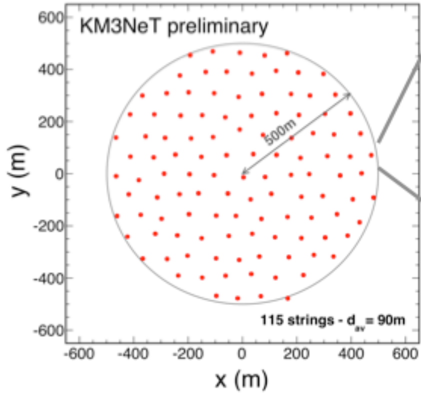




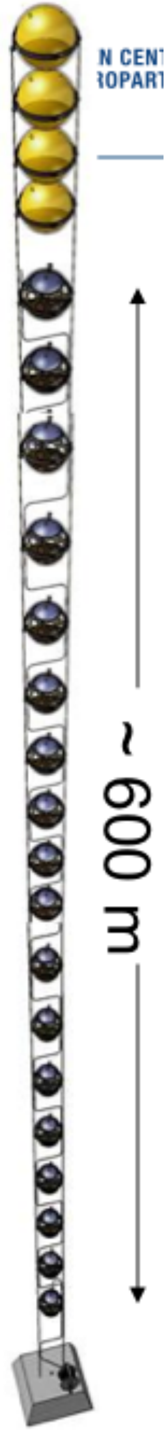
- **Tau double bang**
- No backgrounds, but very difficult to identify

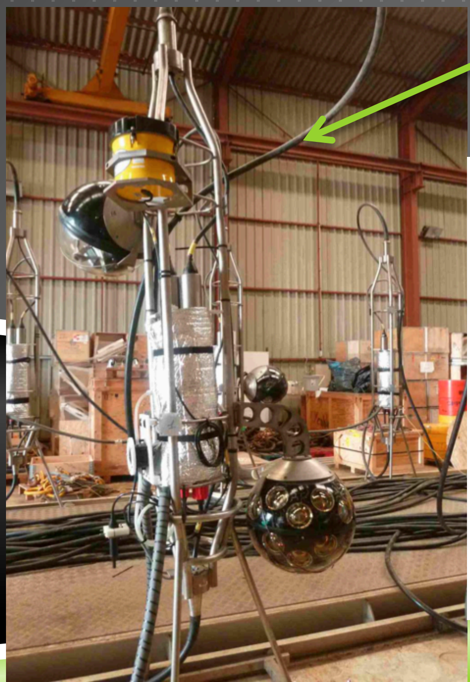
KM3NET DESIGN

- KM3NeT ‘detection unit’:
  - Line anchored to the sea floor
  - 18 optical modules spaced by 36m
- KM3NeT ‘block’ design (preliminary):
  - 115 lines
  - 90m spacing
  - 64,170 PMTs



Clancy James, KM3NeT TMEX 2014, Sep 3rd-5th





Km3Net@Antares

- Optical module:
  - 31 x 3” PMTs
  - Low-power HV
  - LED & piezo inside
  - FPGA readout
- Launcher vehicle:
  - rapid deployment
  - autonomous unfurling
  - recoverable

KM3NET: PLANS

- Fr: Toulon
- It: Capo Passero
- Gr: Pylos

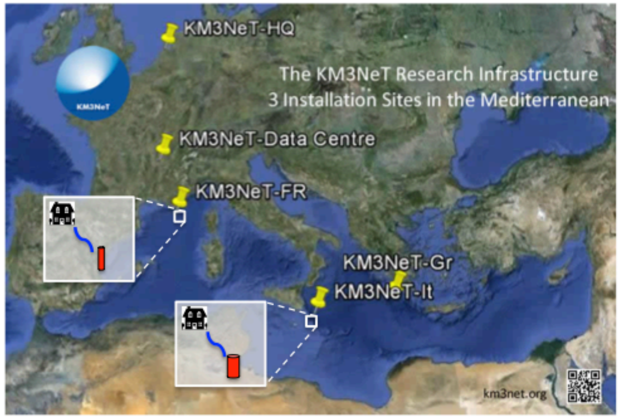
KM3NeT Phases: status

Phase	Total costs¶ [M€]	Primary deliverable	Status
1	31	Proof of feasibility of network of distributed neutrino telescope	***Funded***
1.5	80–90	Measurement of neutrino signal reported by IceCube	Letter of Intent
2	220–250	Neutrino astronomy	ESFRI road map

¶Total *cumulative* costs

KM3NeT Phase 1 (2013-2017)

- 24 lines (21% of a block) at KM3NeT-It (Capo Passero)
- 7 lines at KM3NeT-Fr (Toulon)

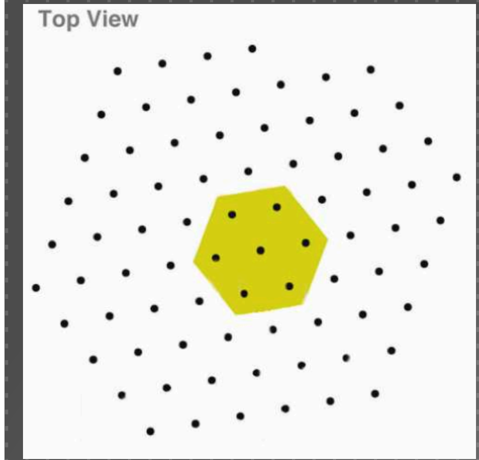


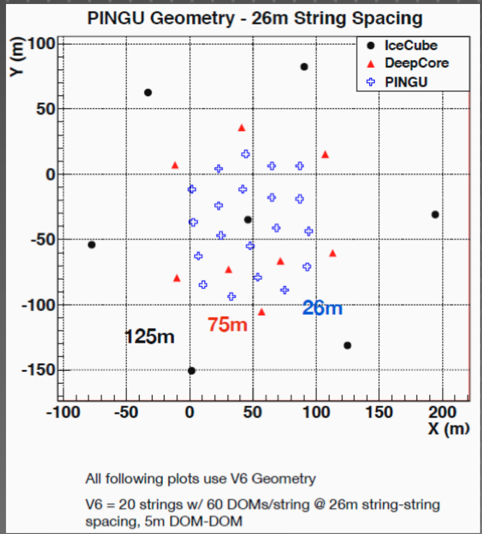
- Status:
  - Funded!
  - Construction begun
  - Completion: 2016
- Goals:
  - Proof of technology
  - Validation of distributed detector concept

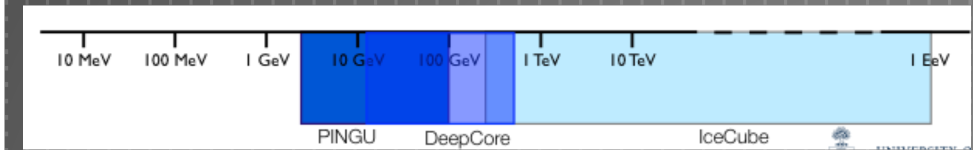
- Phase 1.5 – two full blocks, goal: study IceCube signal in the north
- Phase 2 – three full blocks, neutrino astronomy (search for galactic point sources)

MASS HIERARCHY–

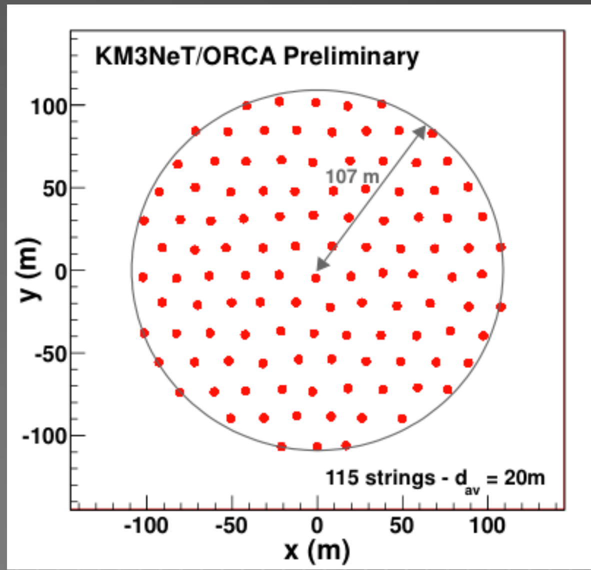
- Pingu@IceCube





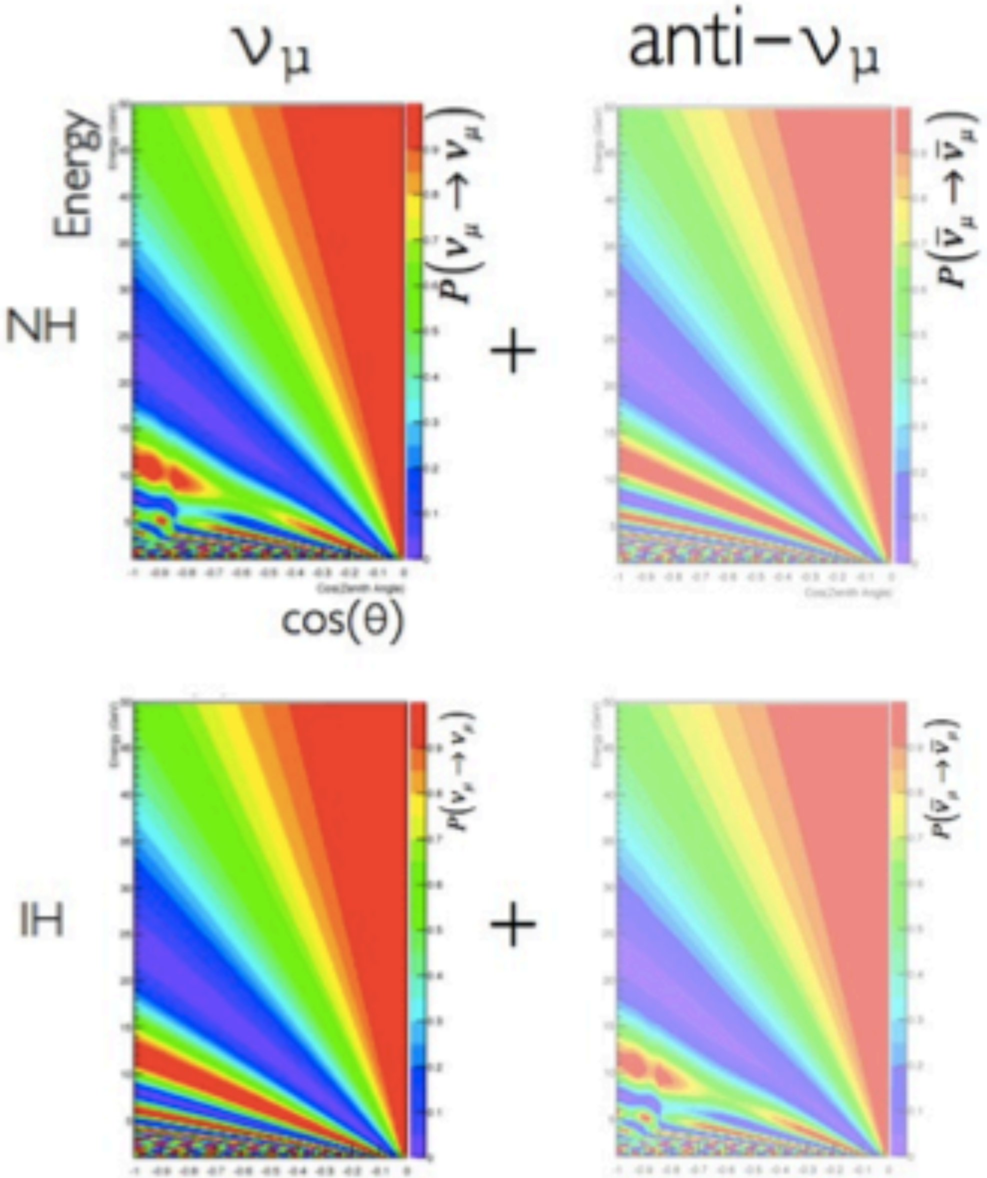


- Orca@Km3Net



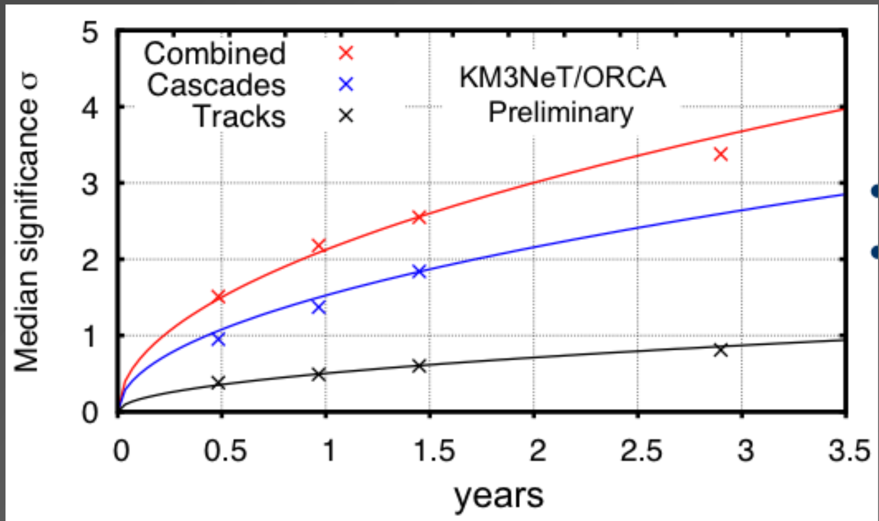
A denser network of sensors to study lower energies of atmosheric neutrinos

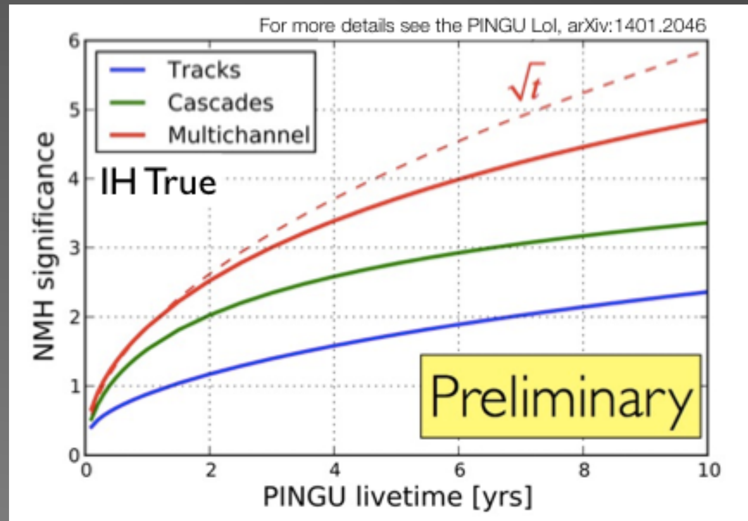
Neutrino Oscillograms



- The cross-section and flux are different for νμ and ν̄μ
- Counts will be derived from the essentially the addition of both graphs

WHO'S GOING TO BE THE FIRST ONE?





ALL THE CONTENDERS – MASS HIERARCHY

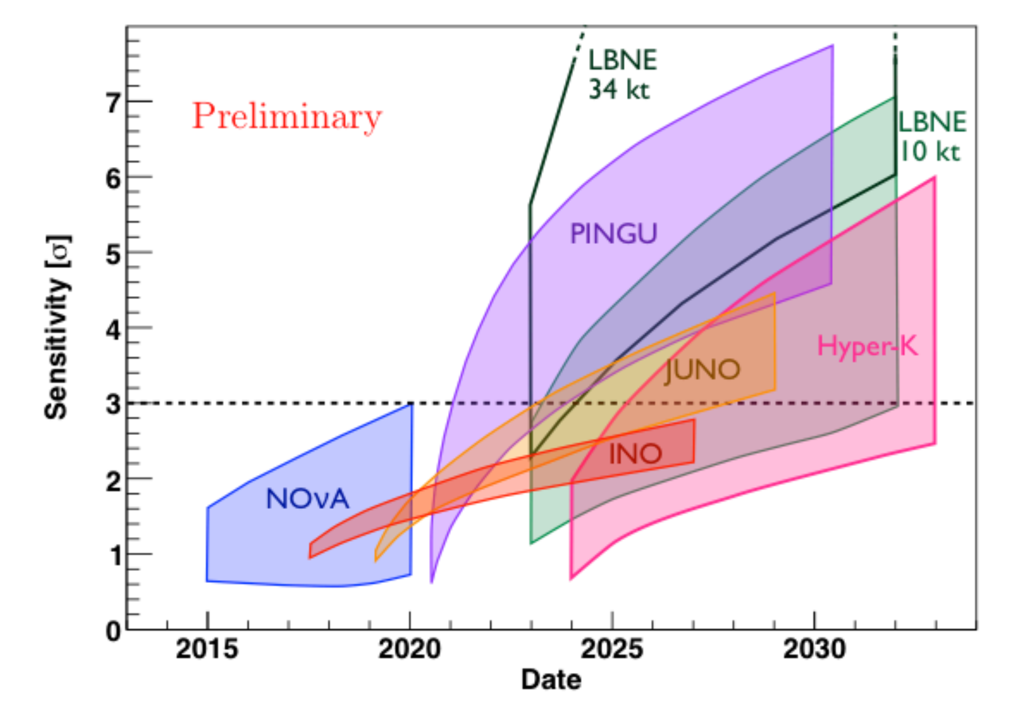


Figure 3: Comparison of the expected sensitivities (for rejecting the inverse hierarchy assuming the normal hierarchy) of different experiments with the potential to measure the neutrino mass hierarchy, following [24]. The widths of the bands cover the maximum sensitivity differences corresponding to the two hierarchy cases in combination with true values of the CP phase δ for NOvA and LBNE, different energy resolutions ranging from $3.0\%\sqrt{1\ \mathrm{MeV}/E}$ to $3.5\%\sqrt{1\ \mathrm{MeV}/E}$ for JUNO, and atmospheric mixing angles θ_{23} ranging from the first to the second octant for PINGU (38.7° to 51.3°) and INO (40° to 50°). The starting date and growth of sensitivity with time for PINGU are those presented in this letter, and all other curves are taken from [24] (Fig. 11), where the left and right plots of that figure have been merged to form the largest envelope from the curves for each experiment. Finally, the Hyper-K sensitivity is from [25].

SUMMARY

- A lot of competition in the neutrino oscillation world
- A few solid contenders for mass hierarchy and CPV measurements
  - Most of the experiments at the R&D stage, some of them not sure of funding
- Many interesting measurements expected in the next 10-15 years
- Stay tuned.

PRESENTATIONS USED

- All conferences in 2014, except where noted

- Nova: Musser/ICHEP, Coelho/Tau Workshop Aachen
- LBNE: Parke/TMEX, Nowak/ICHEP, Djurcic/HEP Valencia, Wilson/Neutrino
- LBL Europe: Bertolucci/TMEX
- T2HK: Kobayashi/TMEX, Hayato/Neutrino, Tanaka/ICHEP
- T2K, Titus, NuPrism: Wascko/Fermilab Wine&Cheese, Malek/TMEX, Kaboth/TMEX
- Gadzooks!: Fernandez/ICHEP
- Juno/RENO 50: Wen/Neutrino, Zhan/ICHEP
- Km3net, Orca, Pingu: James/TMEX, Bruner/IVICFA 2013, Clark/ICHEP
- Sterile: Caccianiga/Neutrino