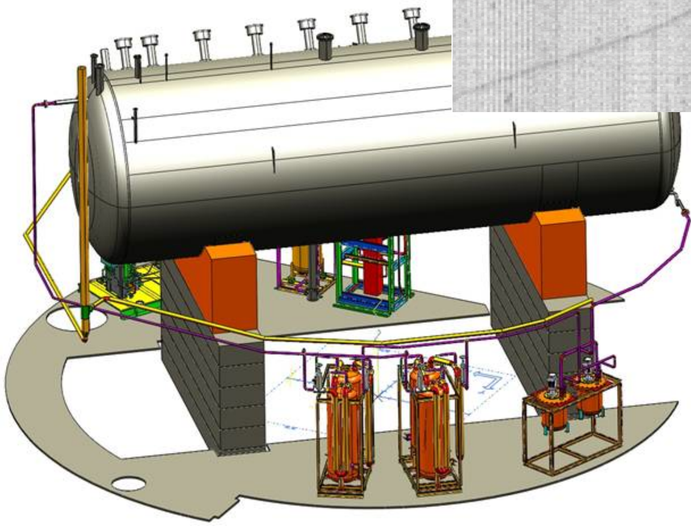
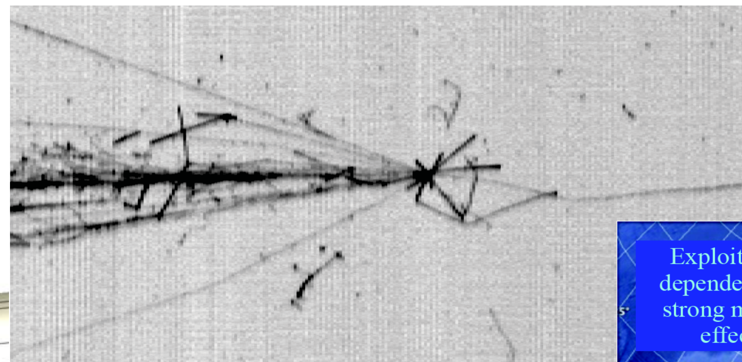
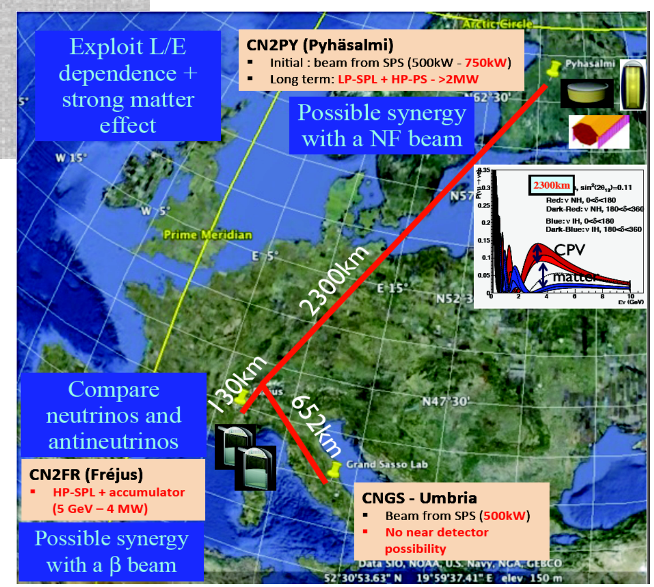
Justin Evans
University of Manchester

Future neutrino oscillation experiments







Oscillation parameters

Smallest mass splitting

- 'Solar' mass splitting

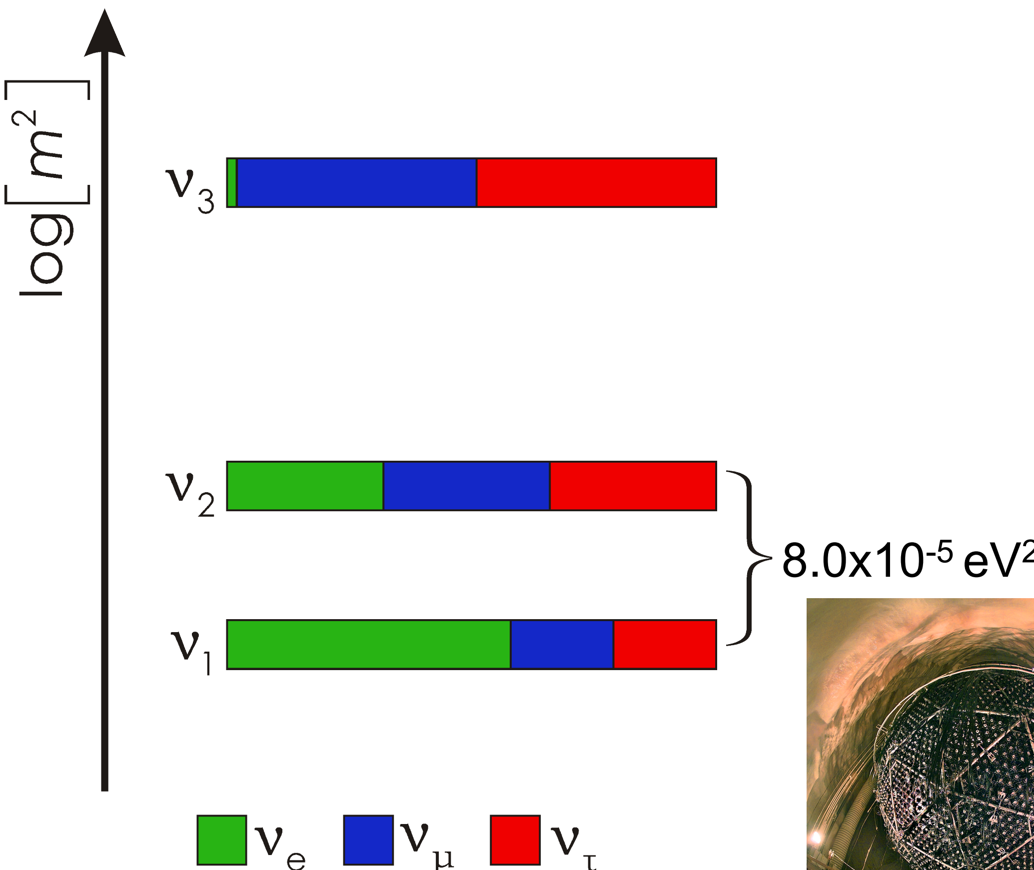
Require L/E ~ $\mathcal{O}(10^5$ km/GeV)

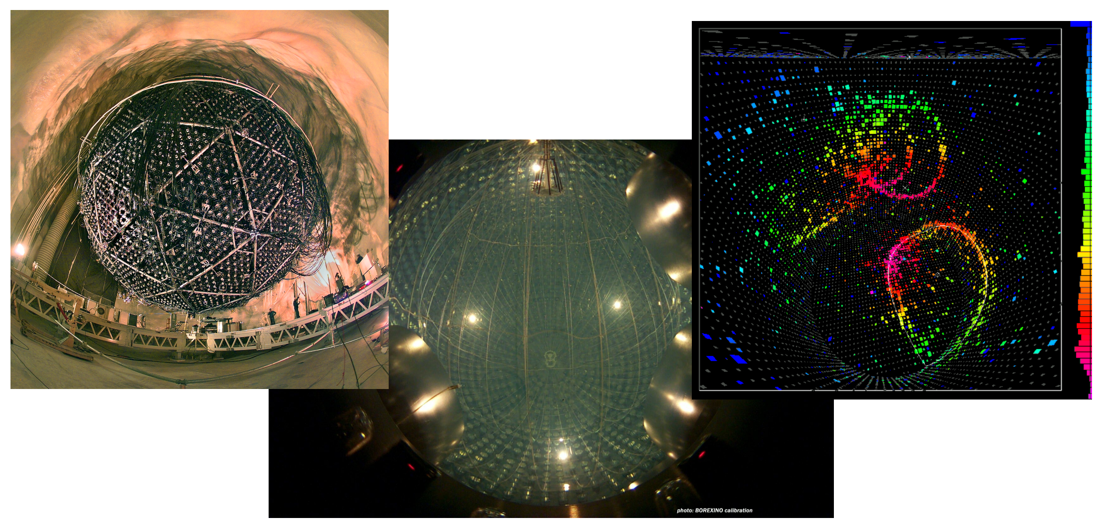
Solar neutrinos

- SNO, Borexino, etc

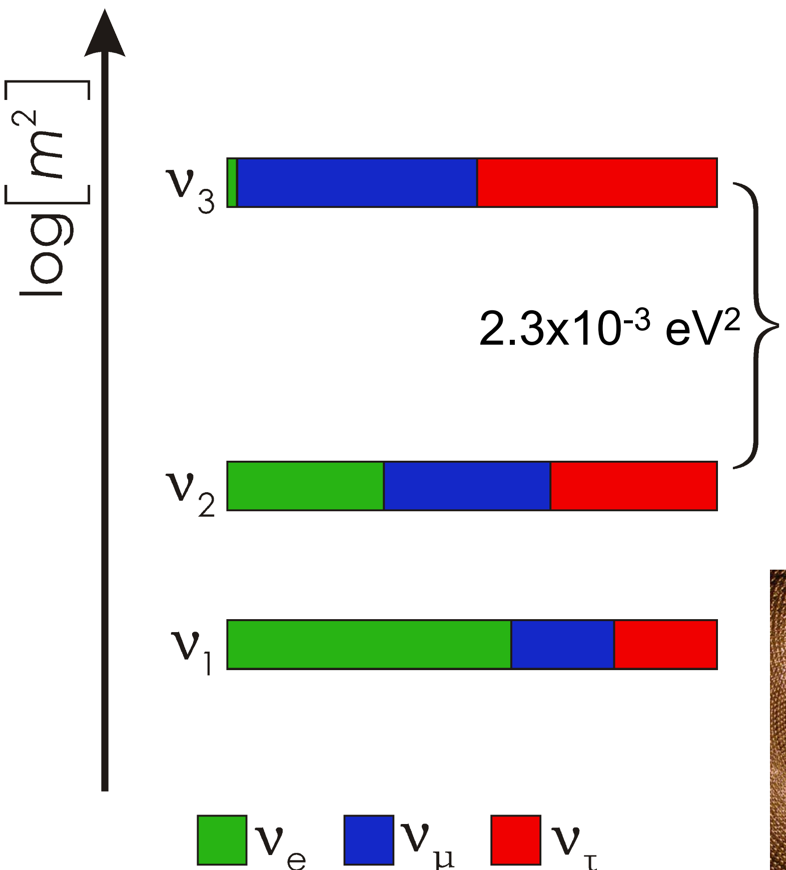
Reactor neutrinos over $\mathcal{O}$(100 km)

- KamLAND





Oscillation parameters



Largest mass splitting

- 'Atmospheric' mass splitting

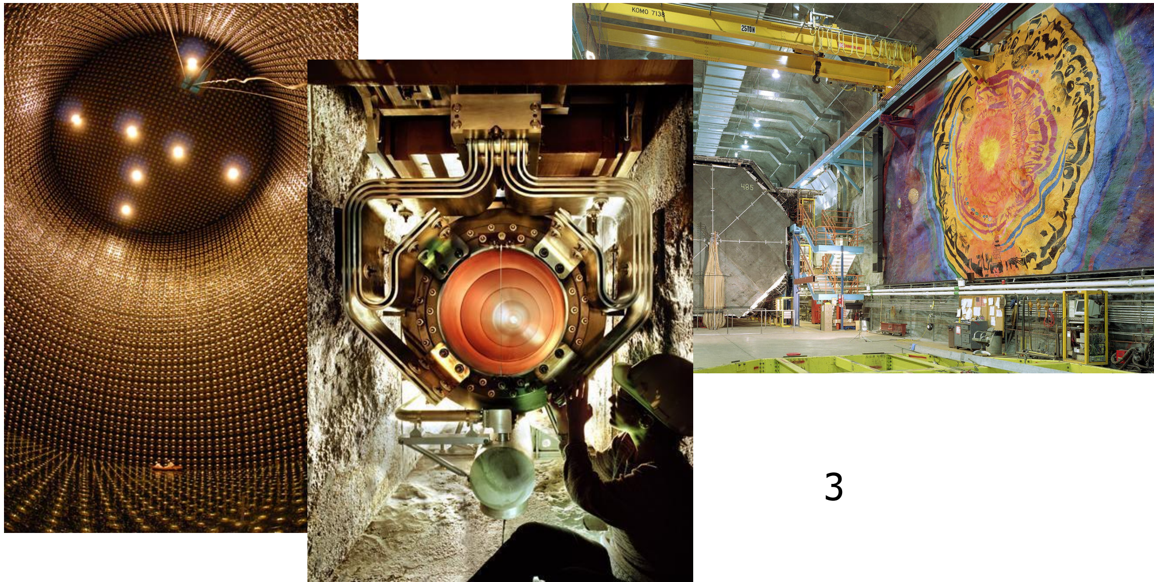
Require L/E ~ $\mathcal{O}(10^3$ km/GeV$)$

Atmospheric neutrinos

- Super-K, MACRO, Soudan2, etc

Accelerator neutrinos

- MINOS, T2K, Nova, etc



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The PMNS matrix

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

Atmospheric & accelerator
$\theta_{23} \sim 45^o$

Reactor & accelerator
$\theta_{13} \sim 9^o$

Solar & reactor
$\theta_{12} \sim 34^o$

θ_{13} was finally measured this year

- Daya Bay, Reno, T2K, Double Chooz, MINOS

Three unknowns remain

- CP violating phase δ
- Mass hierarchy: the sign of Δm^2_{32}
- Octant of θ_{23}: only $\sin^2(2\theta_{23})$ has been measured; $\theta_{23} < 45^o$ or $\theta_{23} > 45^o$?

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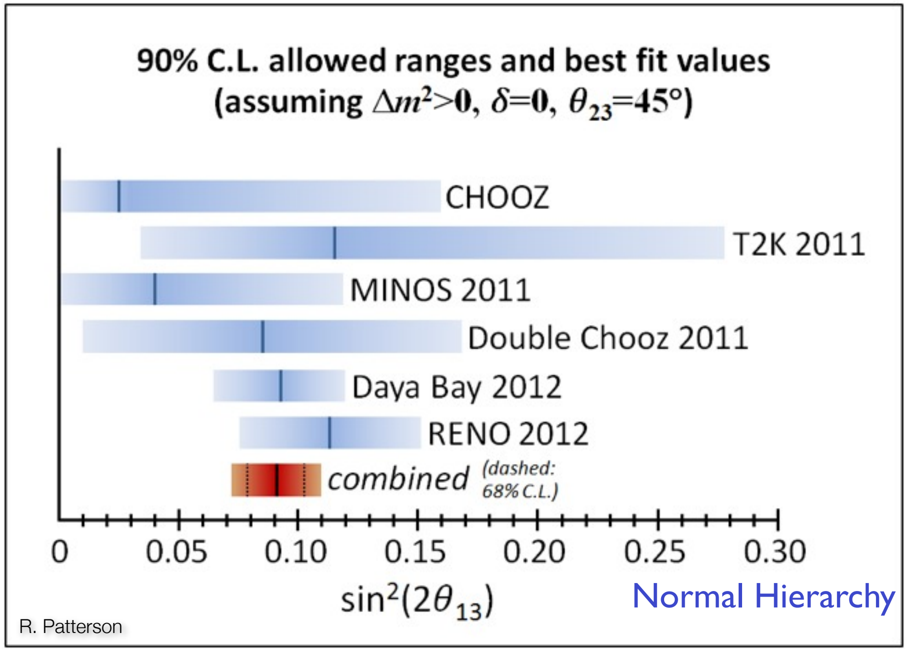
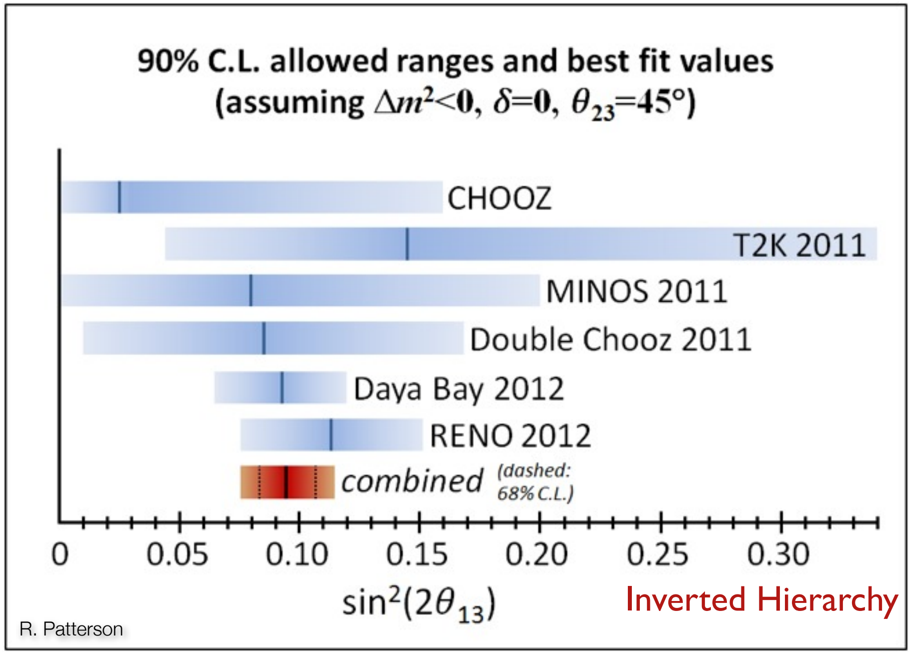
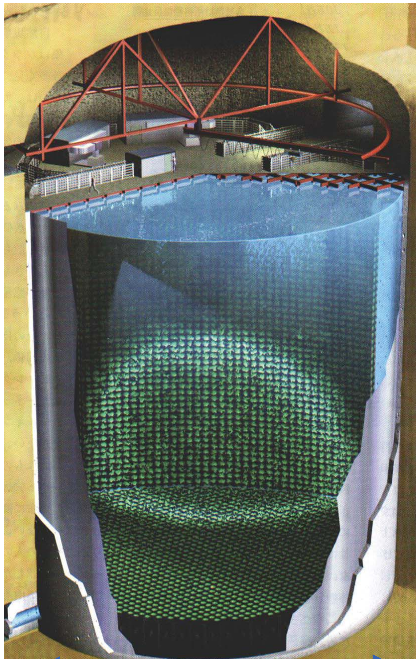
θ_{13} summary

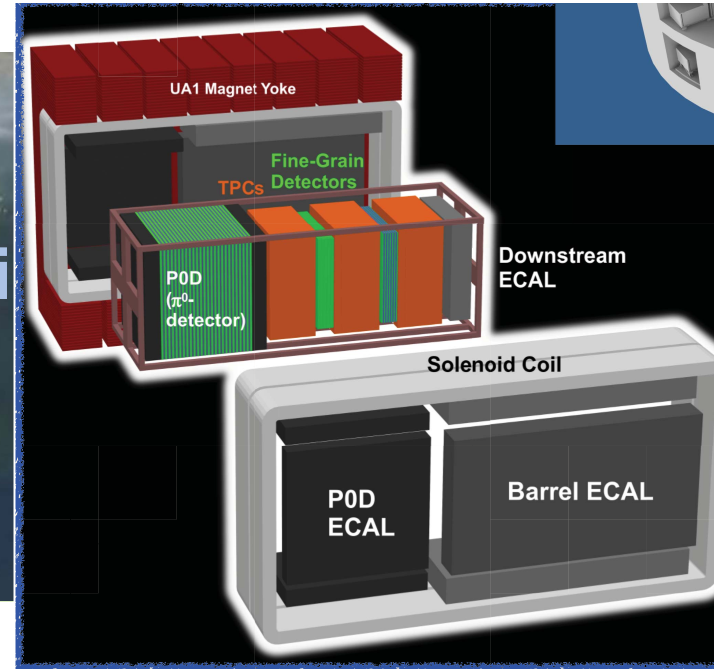




$\theta_{13} \sim 9^{\circ}$

T2K





Muon neutrino beam

- 2.5° off axis
- Search for ν_e appearance

High-resolution Near Detector

- π^0 identification

Super-Kamiokande Far Detector

NOνA

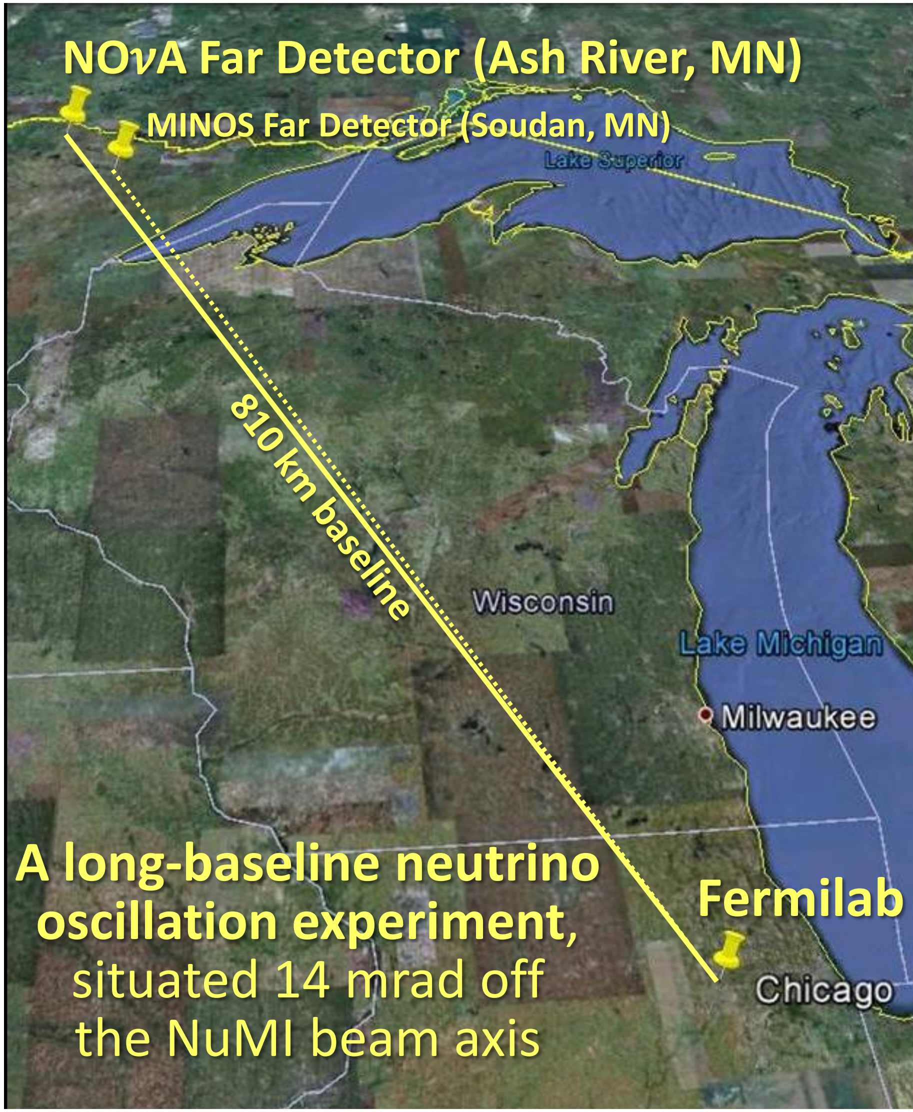
Upgrade the NuMI neutrino beam from Fermilab

- Previously used by the MINOS experiment

Totally active liquid scintillator detector

- 14 mrad off-axis

Search for electron neutrino appearance in the muon neutrino beam



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Measuring the unknowns

Now: Two-flavour approximation

$$P\left(\nu_\mu \rightarrow \nu_\mu\right) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.267 \, \Delta m^2(\mathrm{eV}^2) \, L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

No octant sensitivity

No mass hierarchy sensitivity

The future

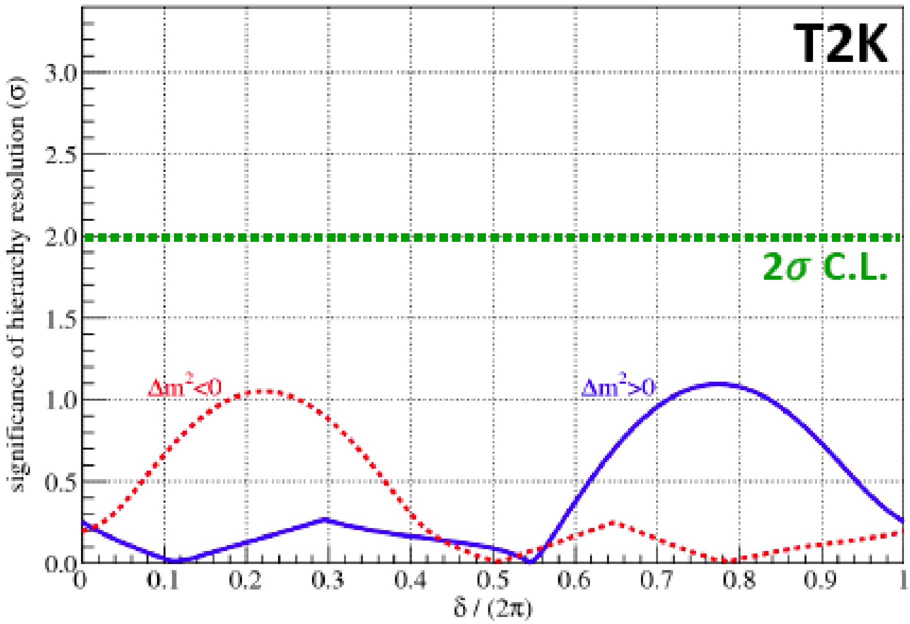
CP violation

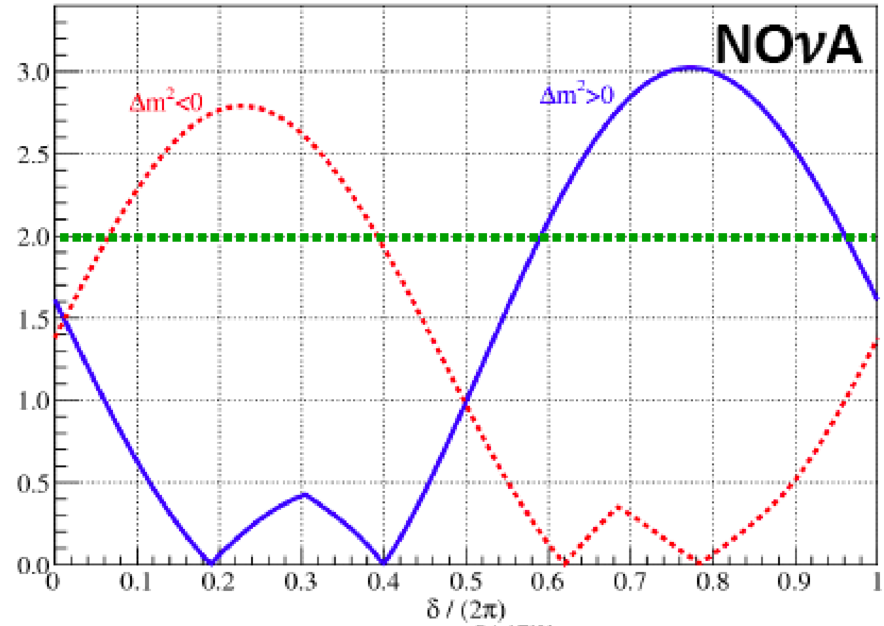
Octant

Mass hierarchy

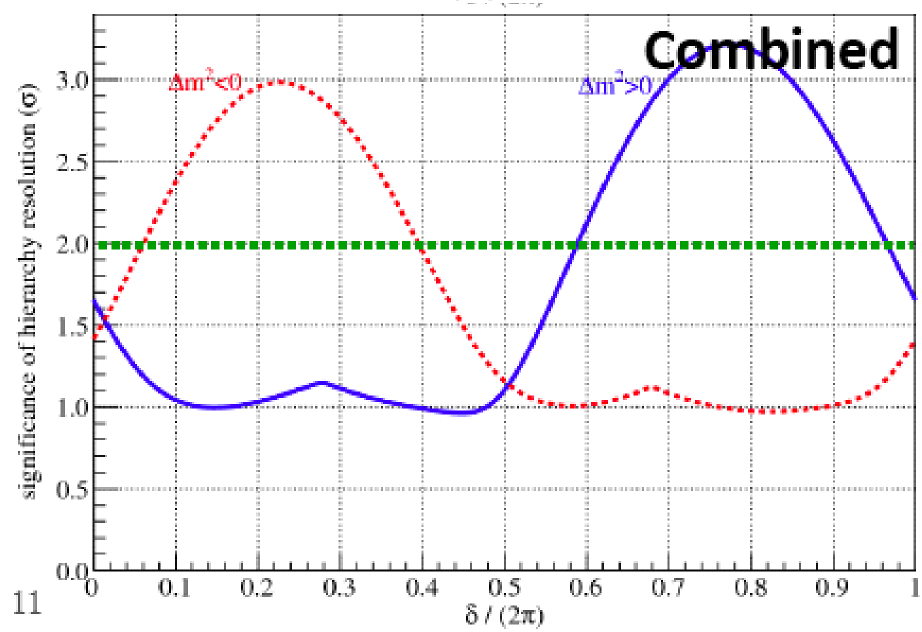
$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \approx \; & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \\ & + 2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta \\ & - 2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta \end{aligned}$$

T2K & NOvA mass hierarchy

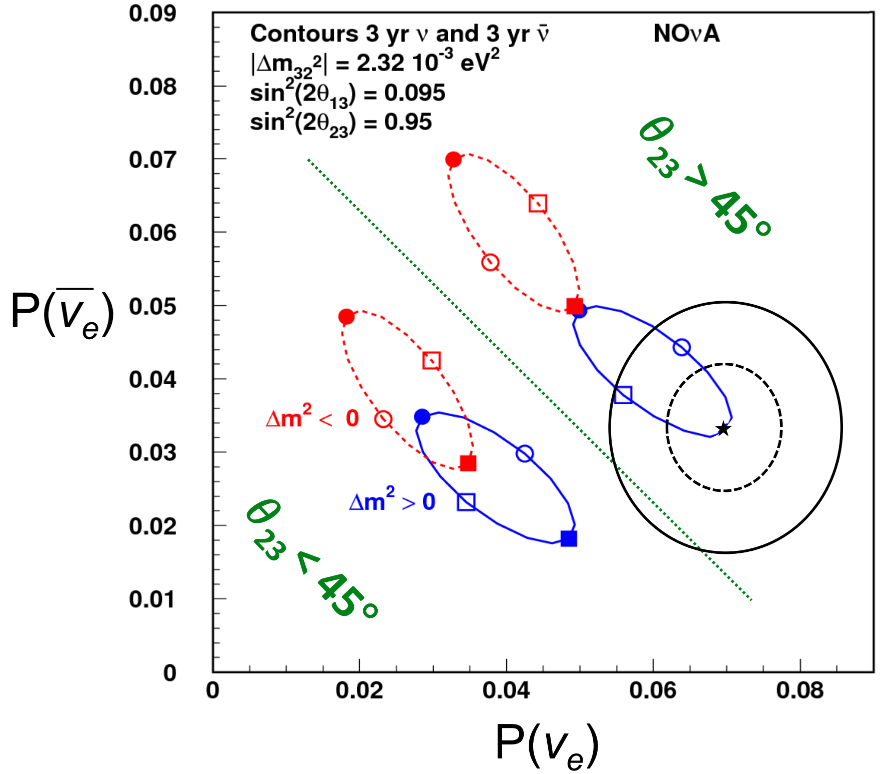




- NOvA: 3+3 years of neutrinos + antineutrinos
- Combination with T2K is important



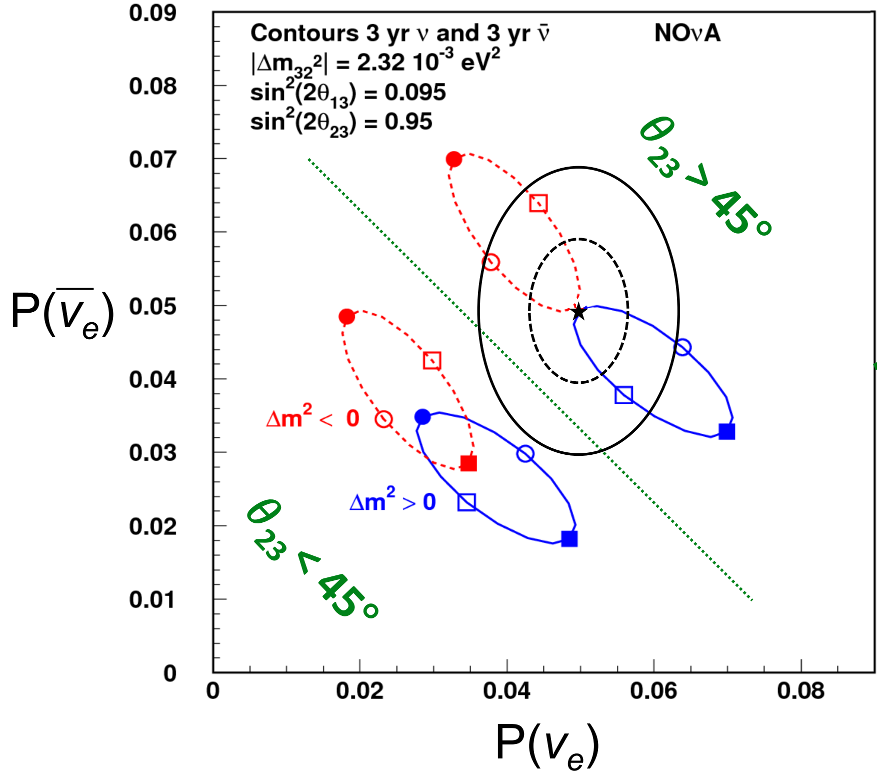
NOνA physics sensitivity



Black contours are 1σ and 2σ

- Simultaneous sensitivity to hierarchy, octant and CP phase
- Resolution ability depends on the values of δ and θ_{23}

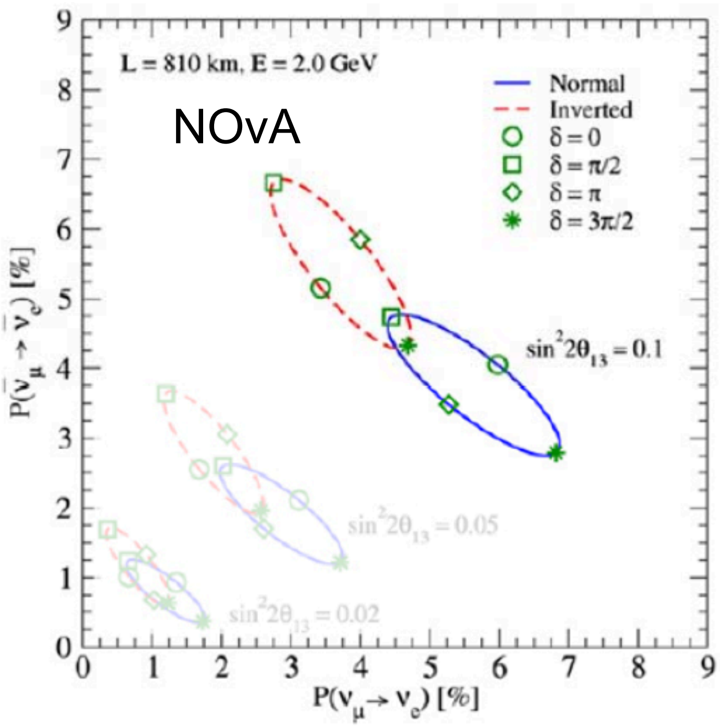
NOvA physics sensitivity

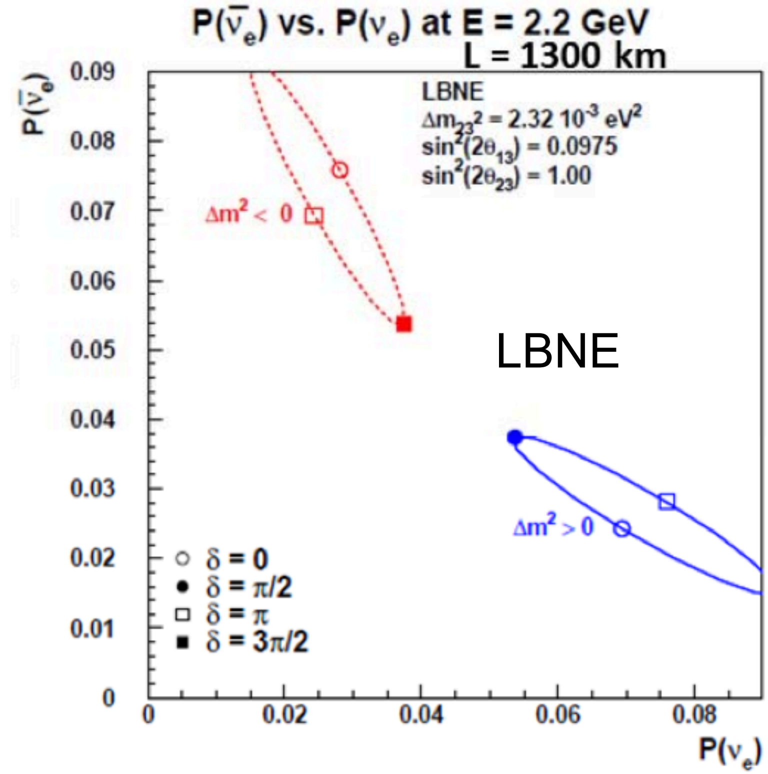


Black contours are 1σ and 2σ

- Simultaneous sensitivity to hierarchy, octant and CP phase
- Resolution ability depends on the values of δ and θ_{23}

Beyond NOvA





Increase the baseline beyond 810 km

- Increased matter effect allows mass hierarchy determination

But too long a baseline that CP-violation is hard to observe

- Matter effects conceal the CP violation
- Event rate drops off with distance

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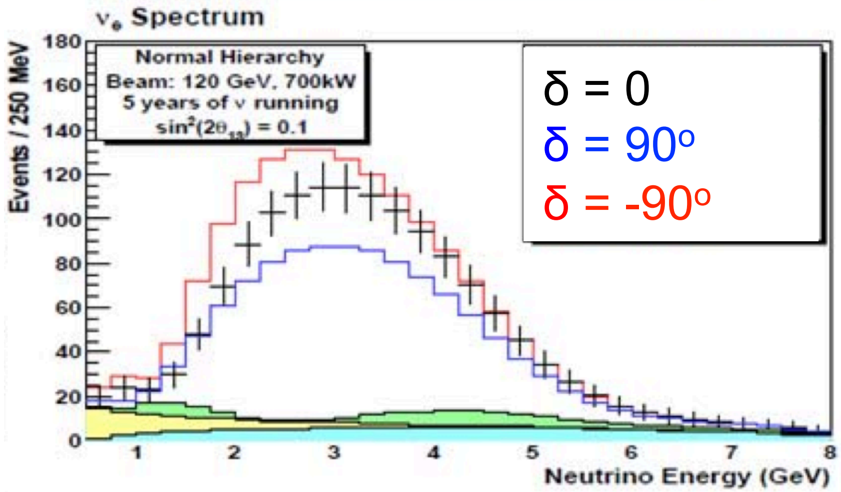
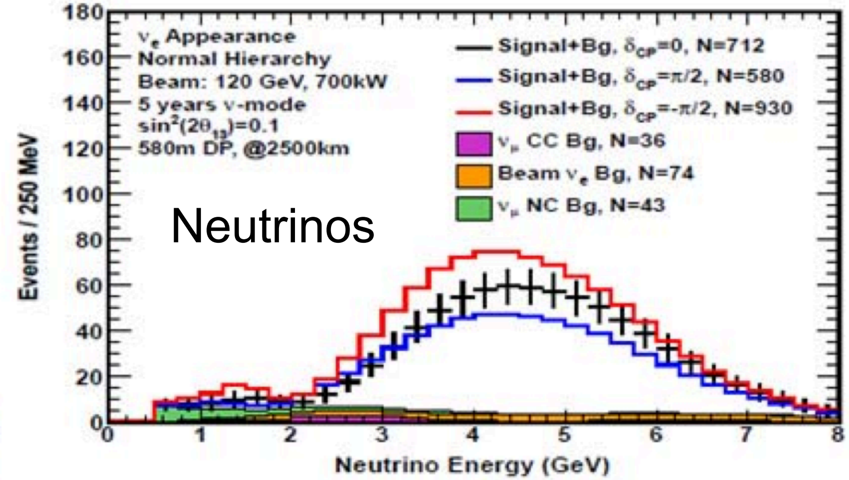
Long baselines

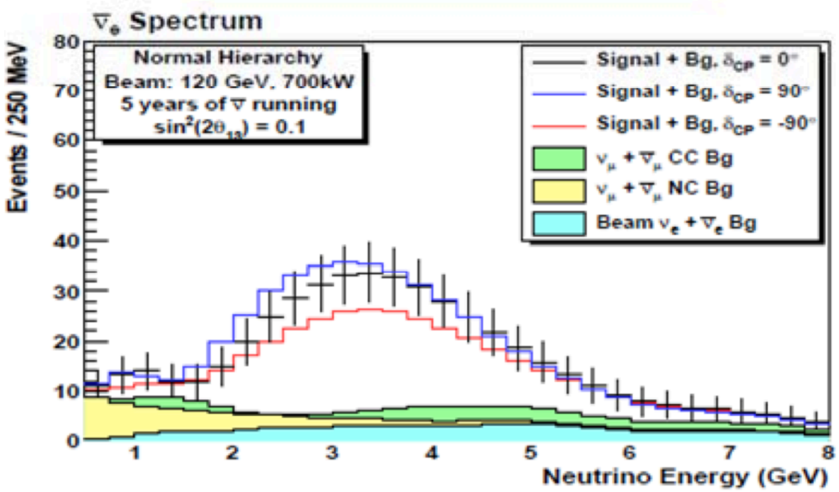
1300km, LBNE LE at Hmstk



2500km, LBNE pME (580m DP)



1300km, LBNE LE at Hmstk



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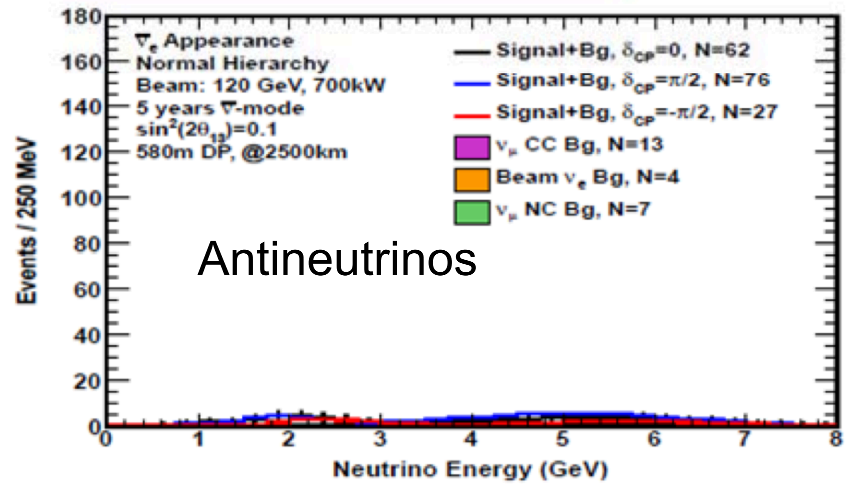
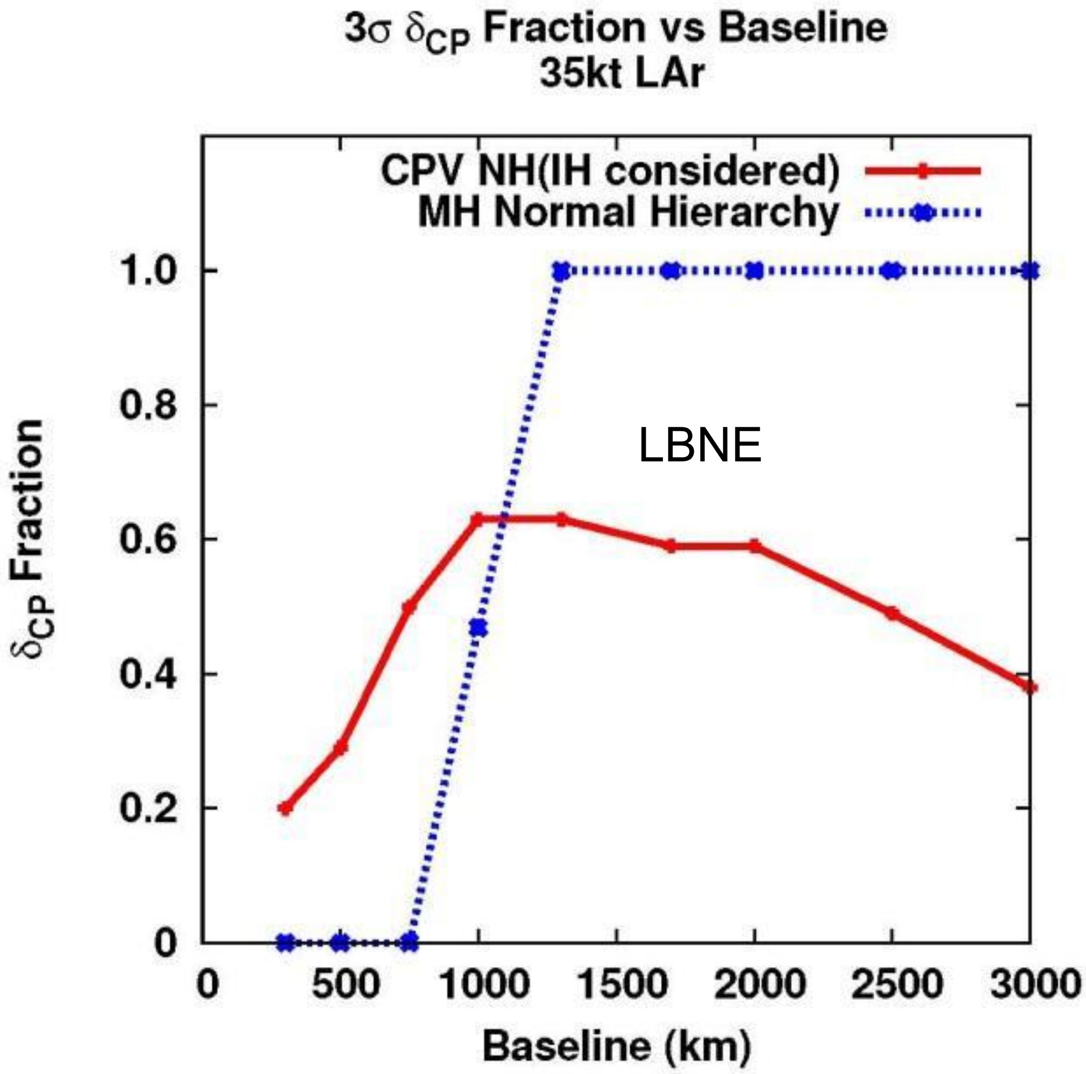
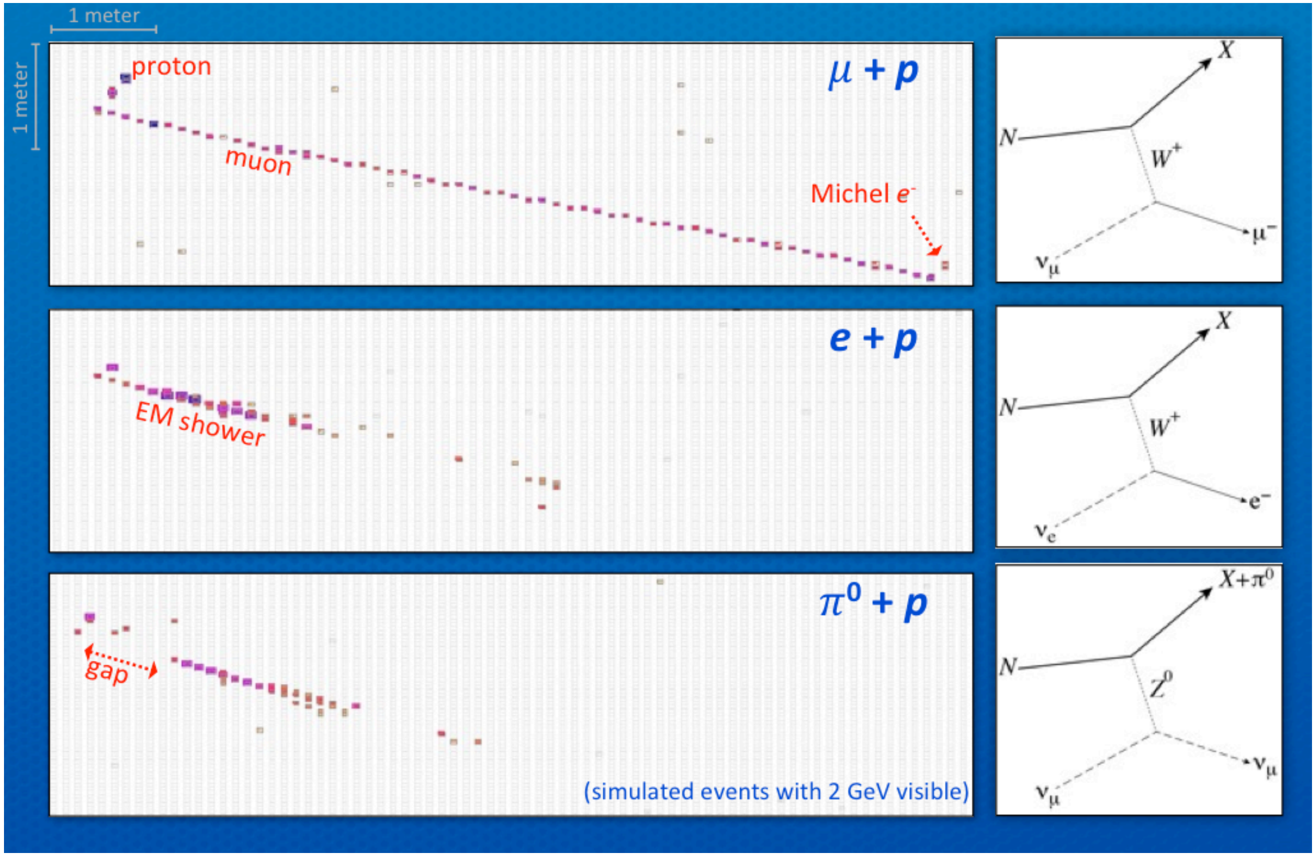


Opimising the baseline



Backgrounds in ν_e searches



The primary background to an electron neutrino search is π^0 production in neutral current interactions

- $\pi^0 \rightarrow \gamma\gamma$ produces an electromagnetic shower

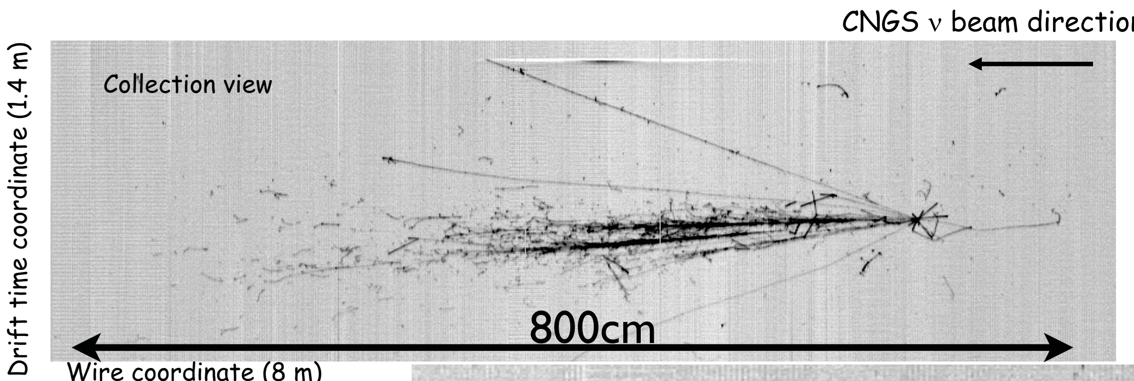
Liquid Argon TPCs

The ‘electronic bubble chamber’

- Bubble chamber-like imaging with electronic readout

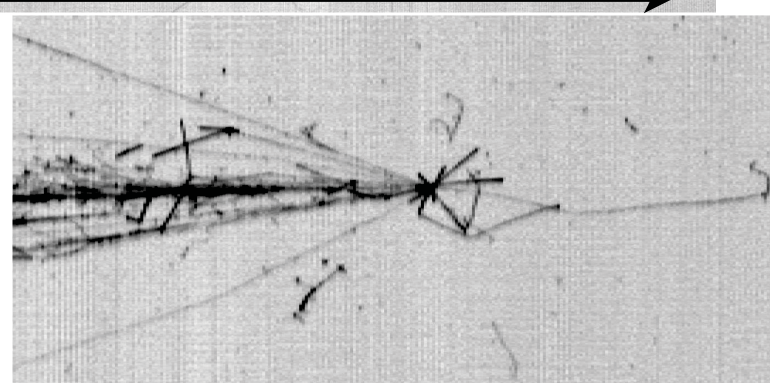
Millimetre-scale spatial resolution over a large fiducial mass

Aim to scale these detectors towards 100 kt

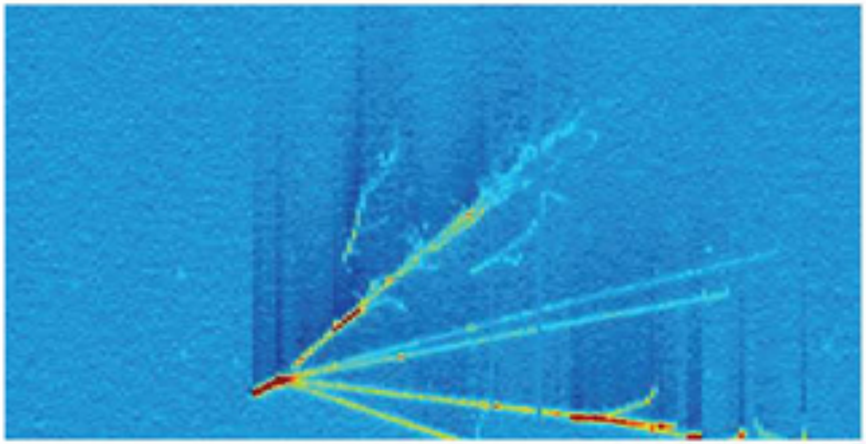


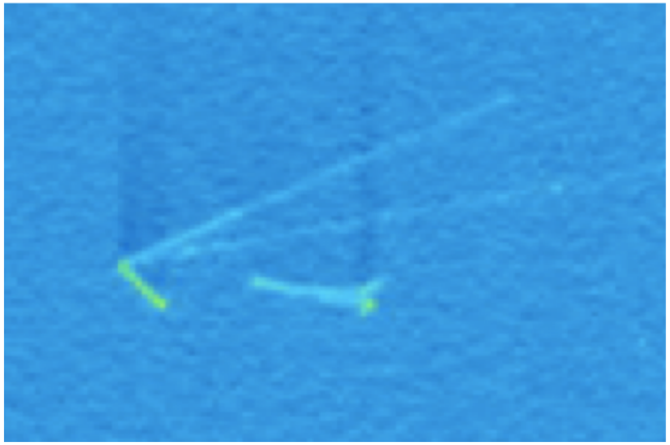
ICARUS T600 @ LNGS

Courtesy A. Guglielmi



Background rejection





Superb imagery of hadronic shower

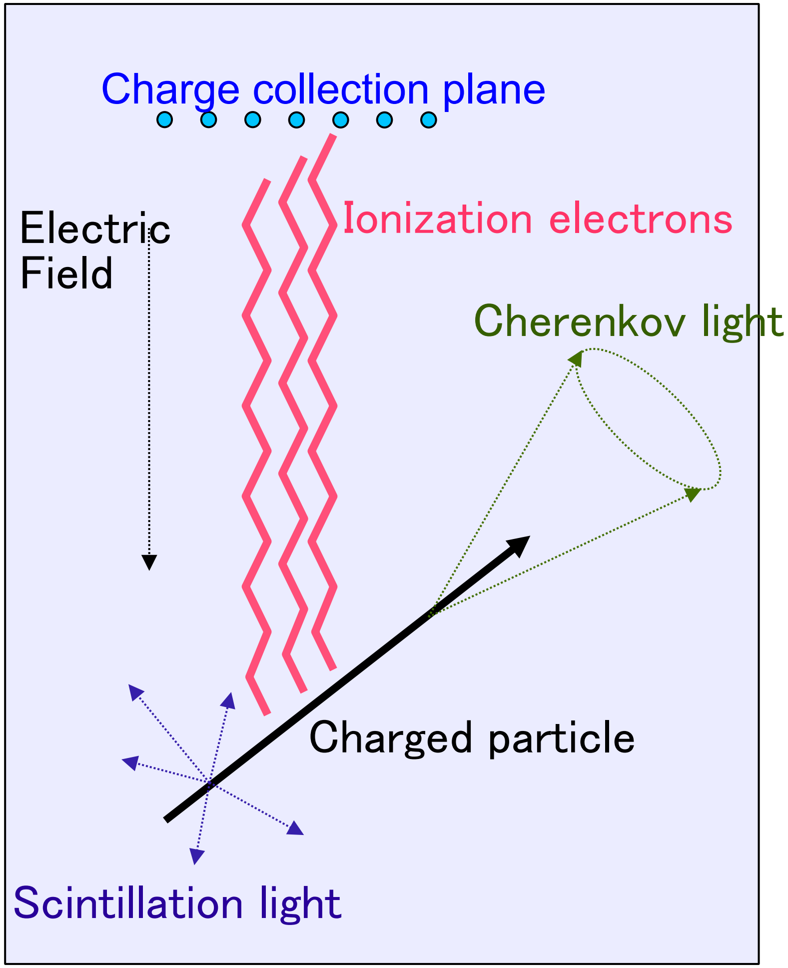
- Individual particles are visible

Excellent for rejecting π^0 backgrounds in ν_e searches

- ~3 times greater ν_e efficiency than existing technologies

Reconstruction software is very challenging

Liquid Argon TPCs



Liquid argon

- Scintillation light as well as ionization
- Cheap and dense
- Boiling point above that of nitrogen
- Electrons can drift over metres

Tracking

Calorimetry

dE/dx provides particle ID

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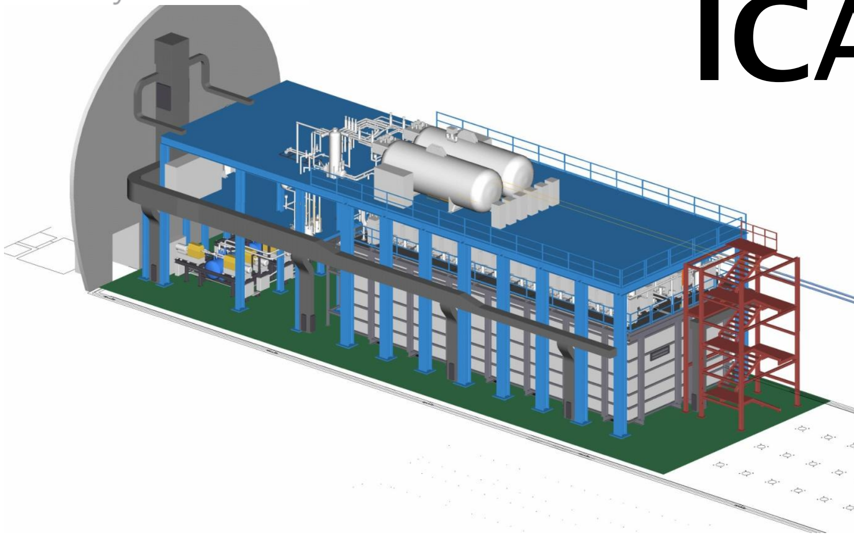
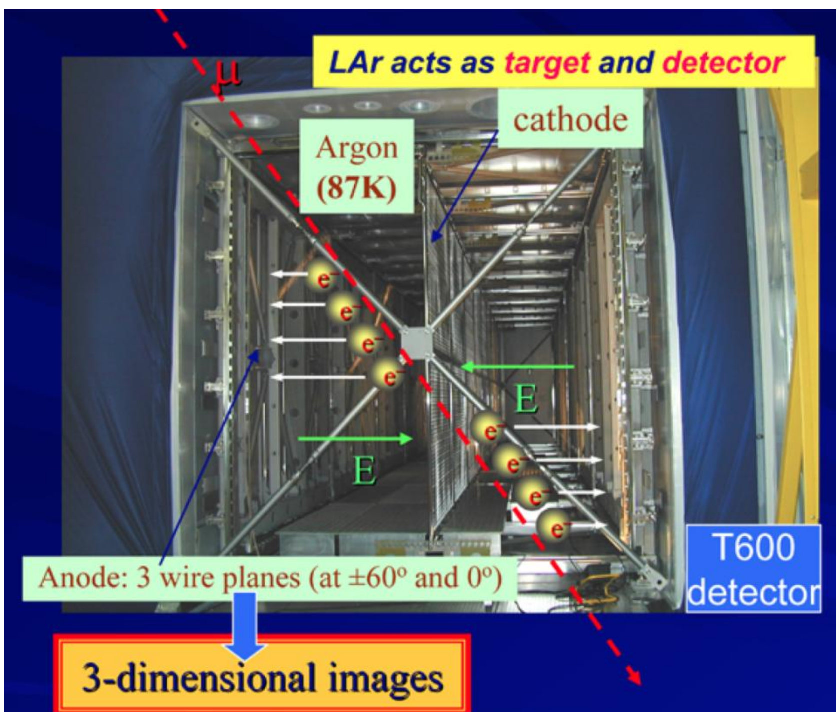
ICARUS





600 tons of liquid argon

- Divided between two detector modules

Drift length 1.5 m

- Electric field: 0.5 kV/cm
- Drift velocity: 1.55 mm / μs

Located at Gran Sasso laboratory

- Observed neutrino interactions from the CNGS beam

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Argon purity

Argon purity is vital for electron lifetime

- Better than part-per-billion levels of oxygen and water

Argon purity

Argon purity is vital for electron lifetime

- Better than part-per-billion levels of oxygen and water

Liquid argon purity demonstrator

- Aims to achieve this without evacuation

Argon purity

Argon purity is vital for electron lifetime

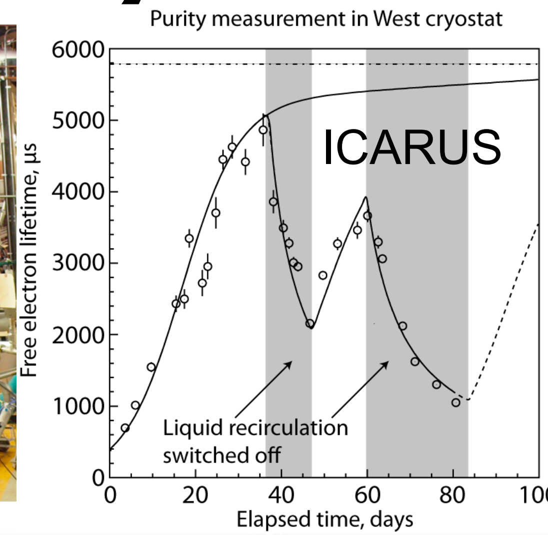
- ➢ Better than part-per-billion levels of oxygen and water

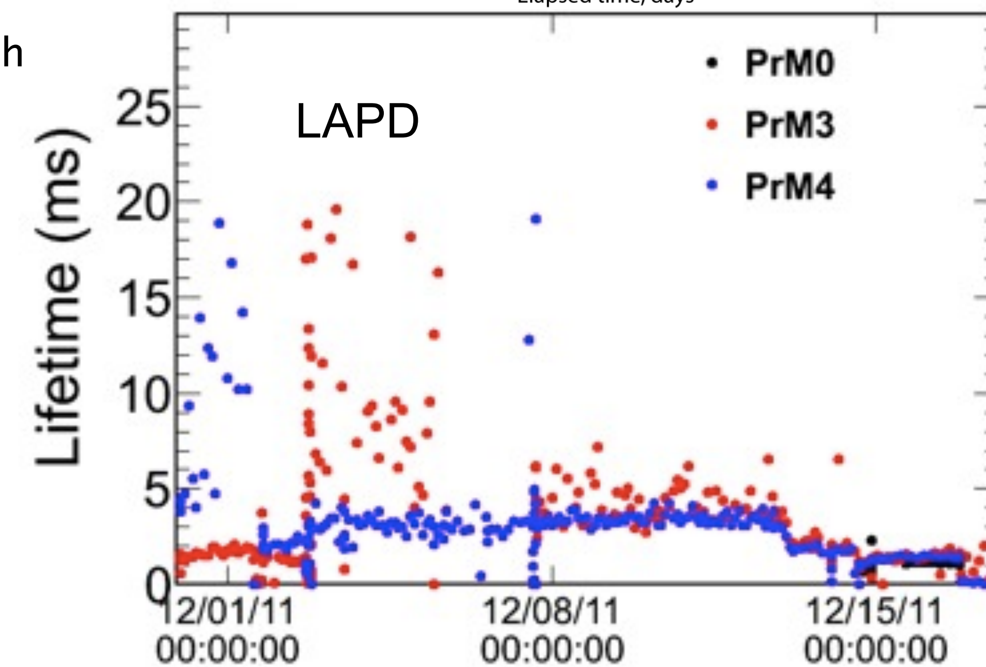
Liquid argon purity demonstrator

- ➢ Aims to achieve this without evacuation

Achieved lifetimes of 3 ms or better with an empty 30t vessel

- ➢ Kiloton-scale experiments require ~1.5 ms





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Argon purity

Argon purity is vital for electron lifetime

- Better than part-per-billion levels of oxygen and water

Liquid argon purity demonstrator

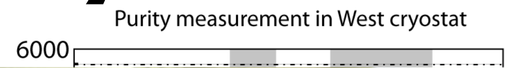
- Aims to achieve this without evacuation

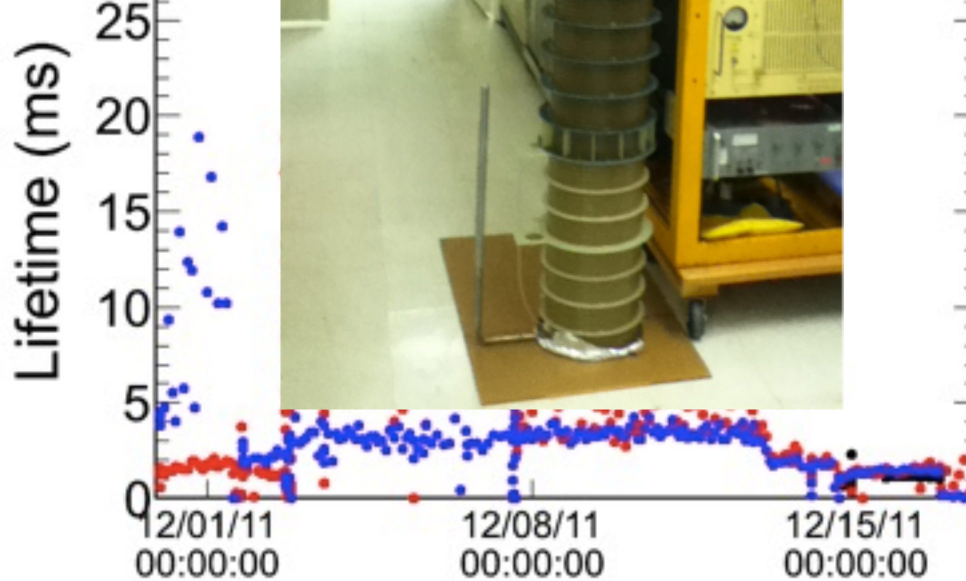
Achieved lifetimes of 3 ms or better with an empty 30t vessel

- Kiloton-scale experiments require ~1.5 ms

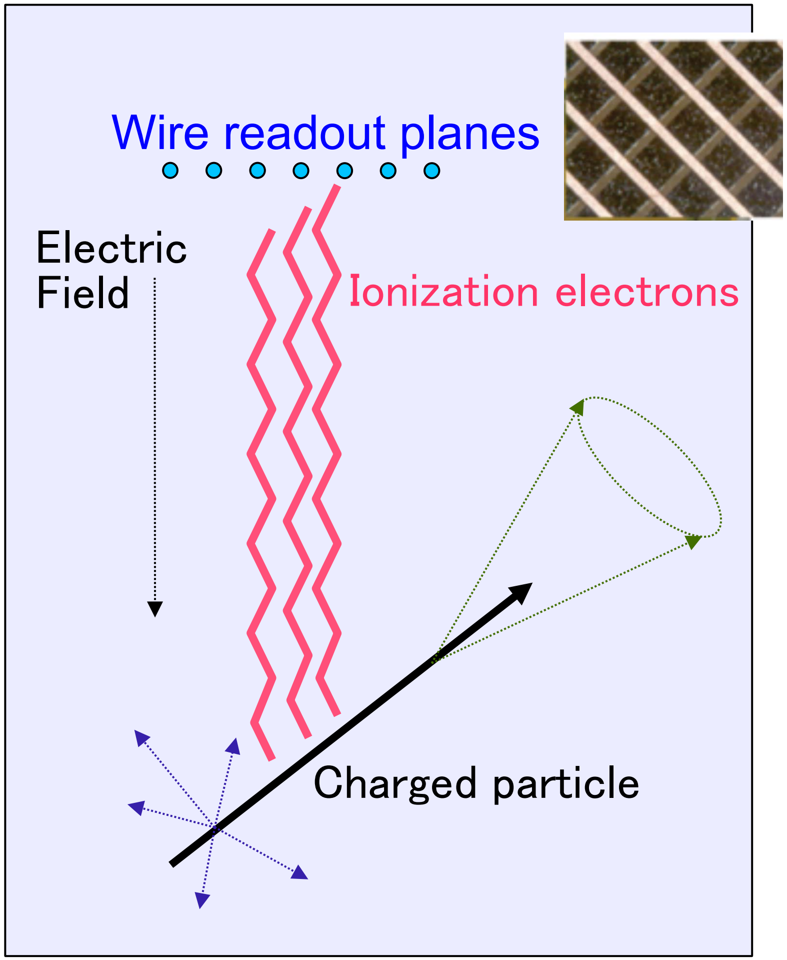
A TPC is about to be installed in the volume

- LongBo: 2 m drift





Single phase, wire-plane readout



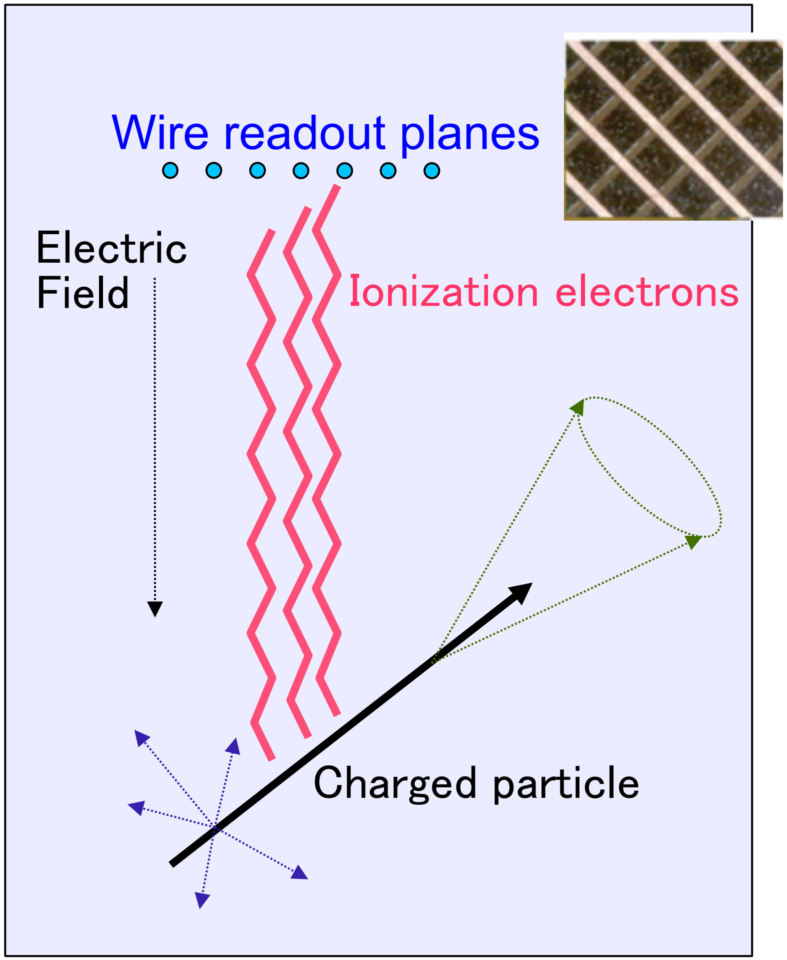
Most existing TPCs use wire-plane readout

- Anode planes consist of orthogonal planes of charge collection wires
- Anode planes sit in the liquid argon

No electron multiplication during drift

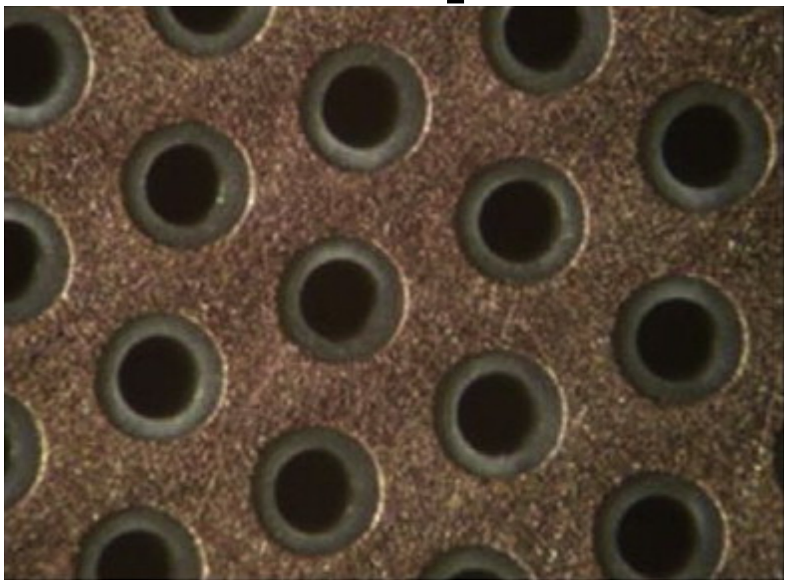
- Small, fC signals

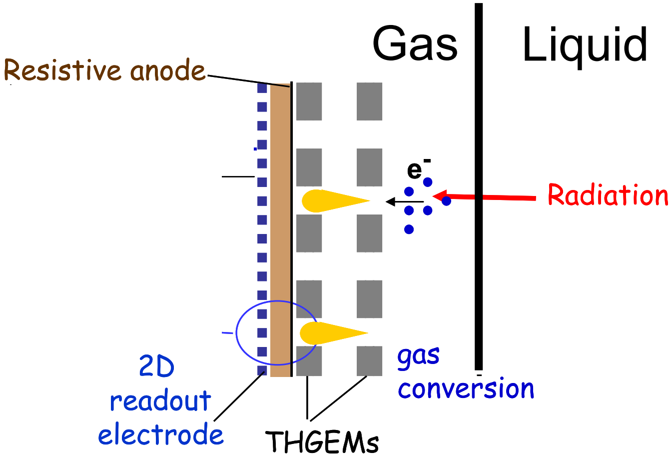
Single phase, wire-plane readout



Most existing TPCs use wire-plane readout

Dual-phase, GEM redout





Gas electron multiplier

- Holes, ~1 mm apart, etched in copper
- Strong electric field multiplies the electrons

Dual-phase TPC design

- GEMs located in a region of gas-phase argon, sitting above the liquid
- Electron multiplication in the gas increases signal / noise

Test beams

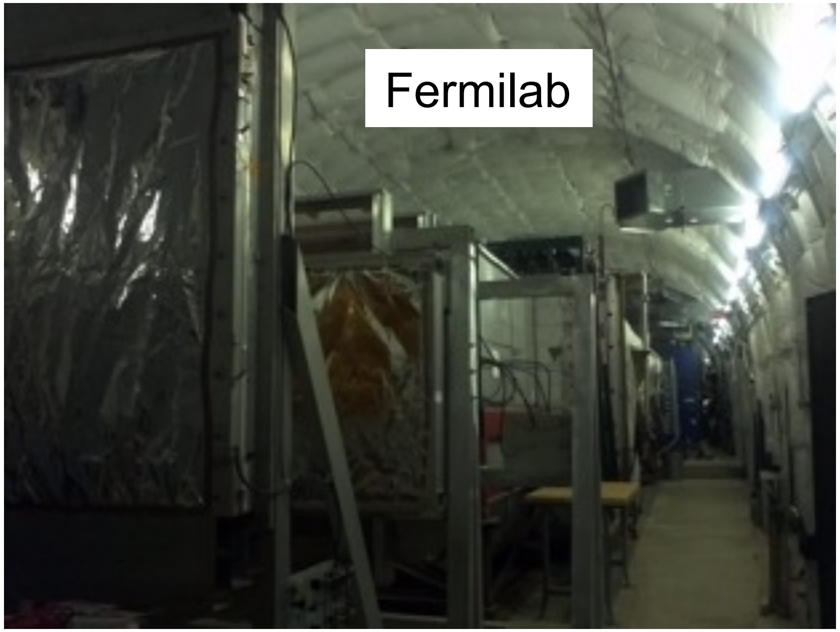
Plans to place O(6 m^3) TPCs in test beams

- LArIAT at Fermilab
- LAGUNA collaboration at CERN

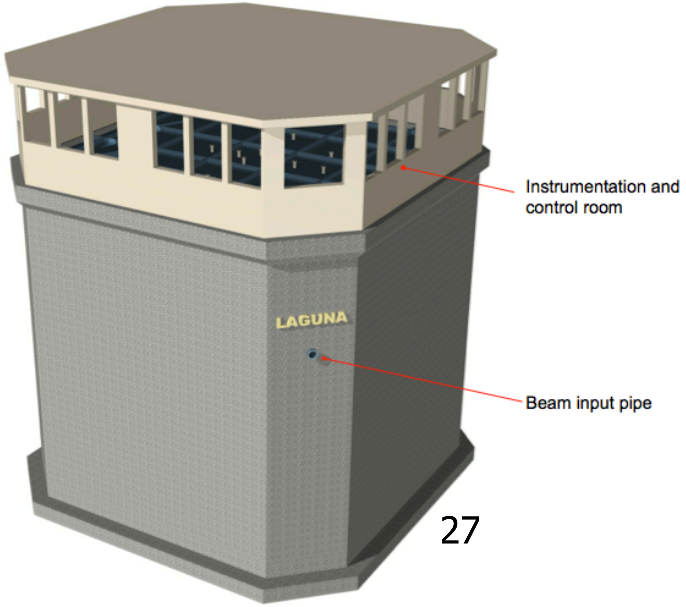
Characterise the response of a LArTPC to the particles and energies expected in neutrino interactions

- e, p, π, μ

- EM shower resolution
- Hadronic shower resolution
- Particle ID
- dE/dx
- Light collection efficiencies
- …



CERN



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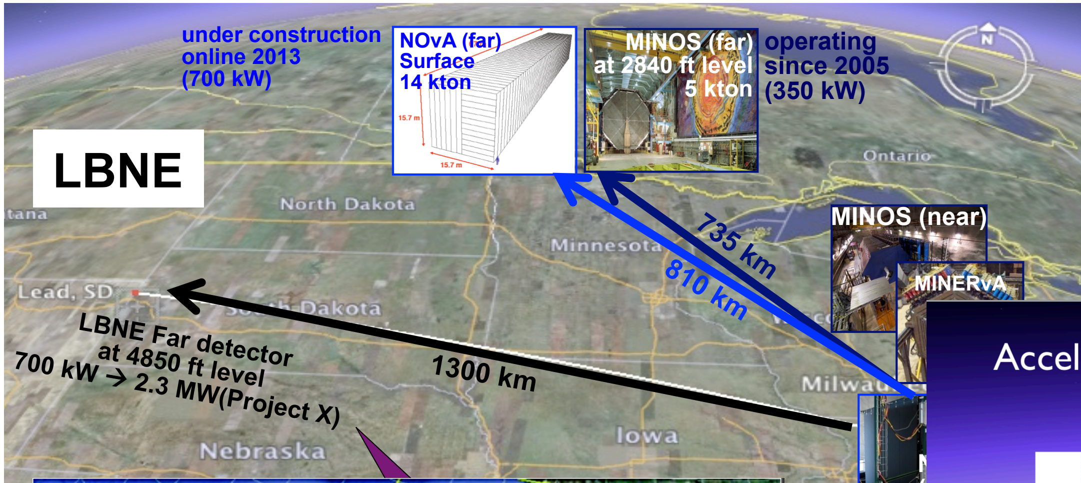
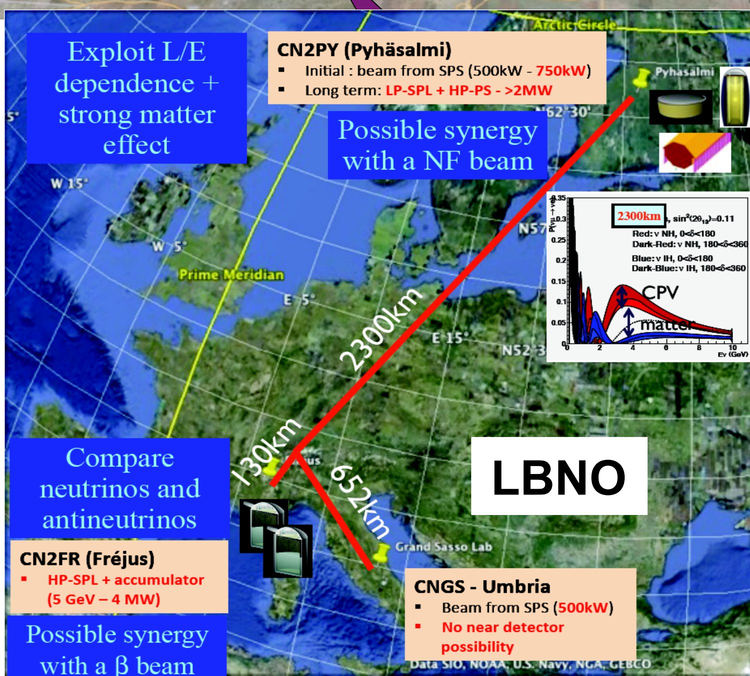
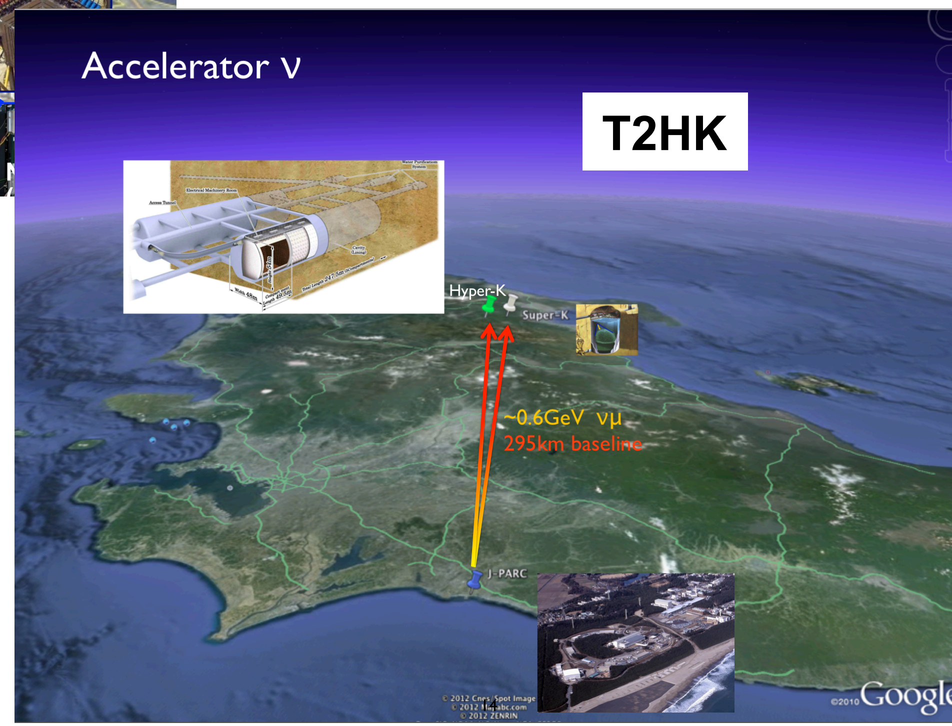
Long baseline proposals







LBNE: the original plan

Fermilab to Homestake (DUSEL)

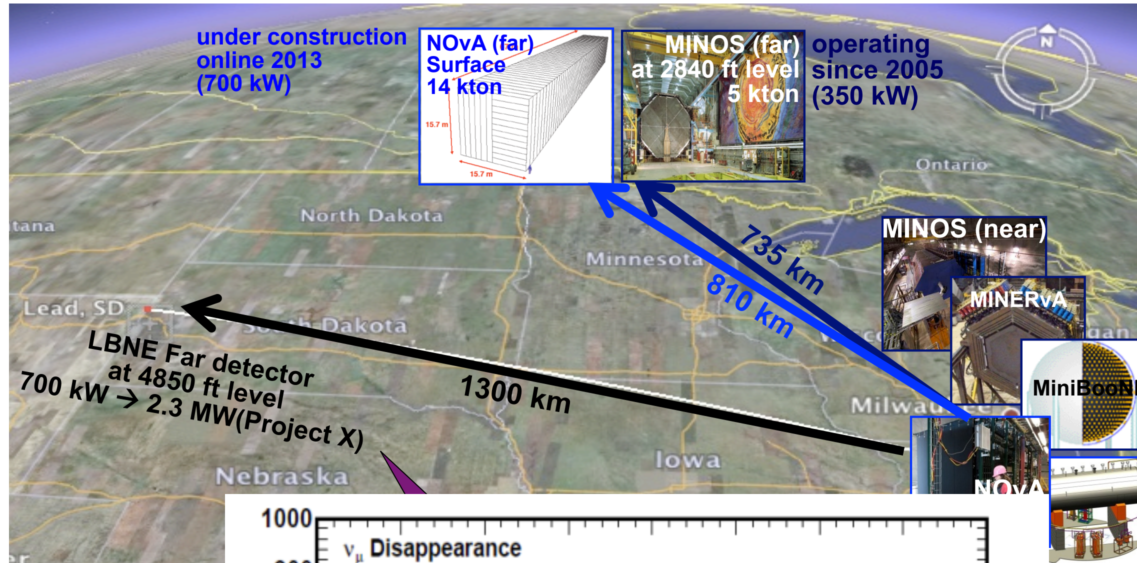
- 1300 km baseline
- 700 kW beam (up to 2.3 MW with project X)
- Original plan: 34 kt underground LArTPC

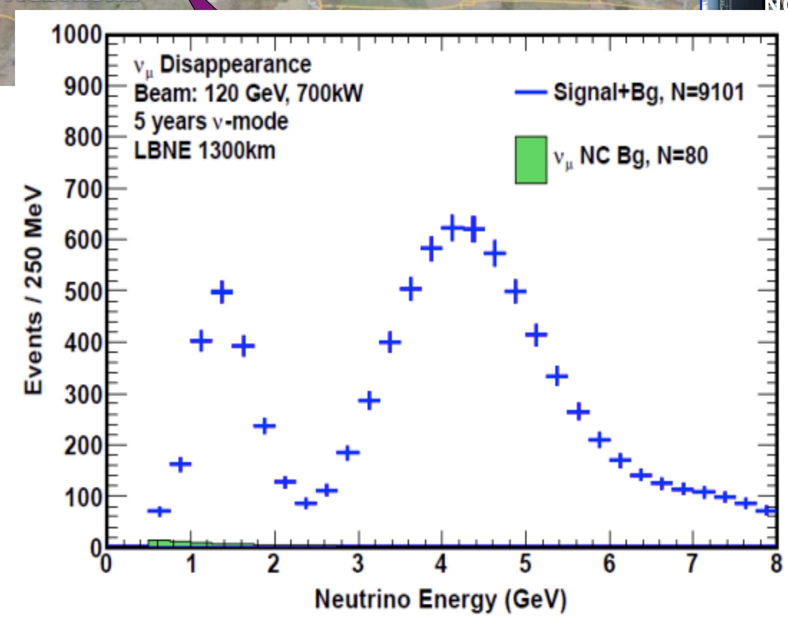
Broadband beam

- First two oscillation maxima at 2.5 GeV and 0.8 GeV

Underground physics programme

- Proton decay through p → $K^{+}\nu$
- Precisely measure ν spectrum from galactic supernova
- Measurements with atmospheric neutrinos





Staged LBNE

Politics and funding…

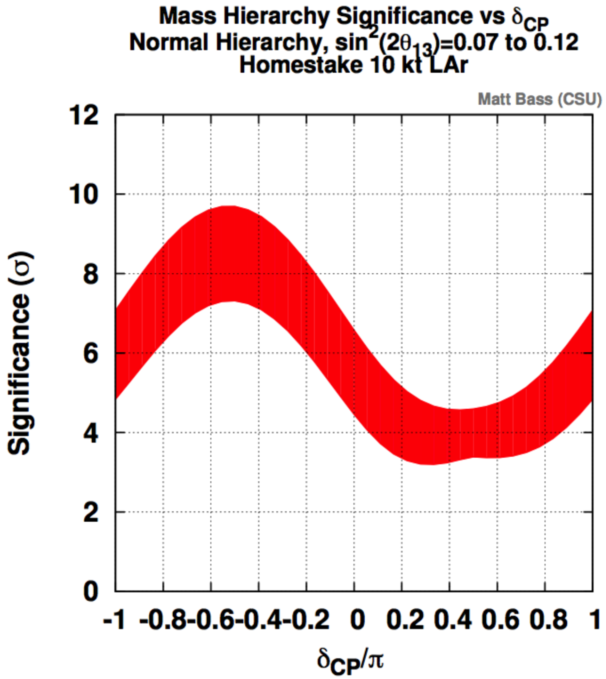
- NSF pulls out of DUSEL
- DoE must pay the bill
- DoE requests a phased programme

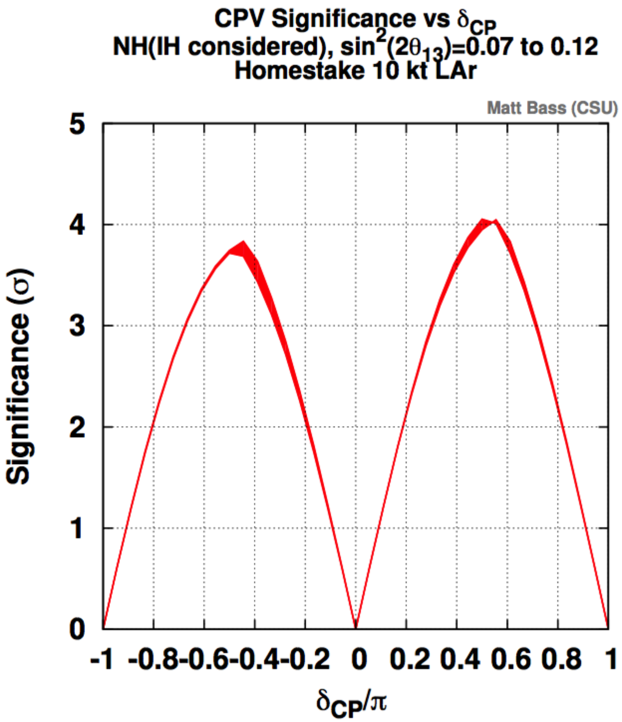
Phase 1

- 10 kt LAr TPC on surface at Homestake
- 700 kW beam
- No Near Detector

Reduced beam physics potential

No underground physics programme





LAGUNA-LBNO

2300 km baseline

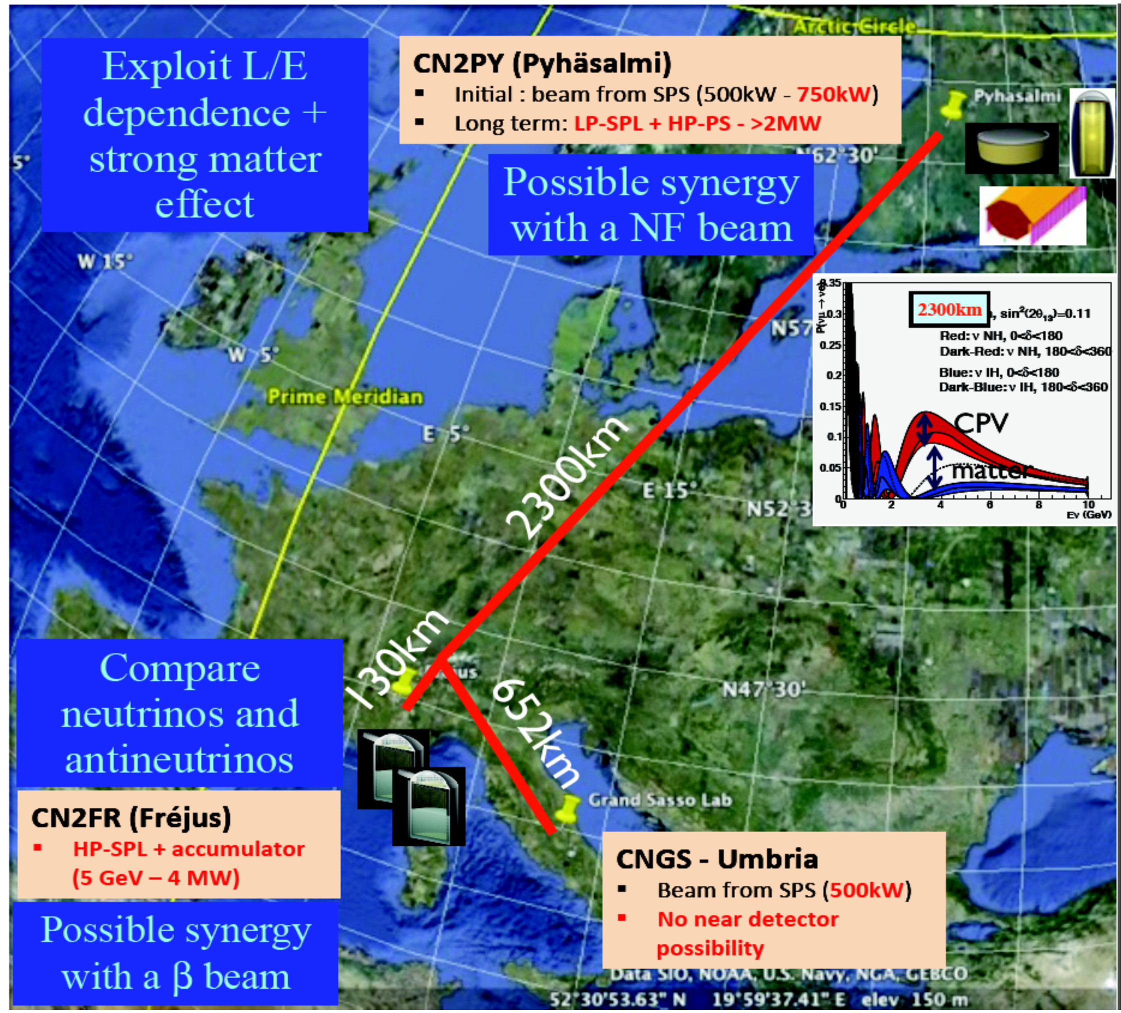
- Lots of matter effect

20 kt liquid argon TPC in Finland

- Possible upgrades to 100 kt

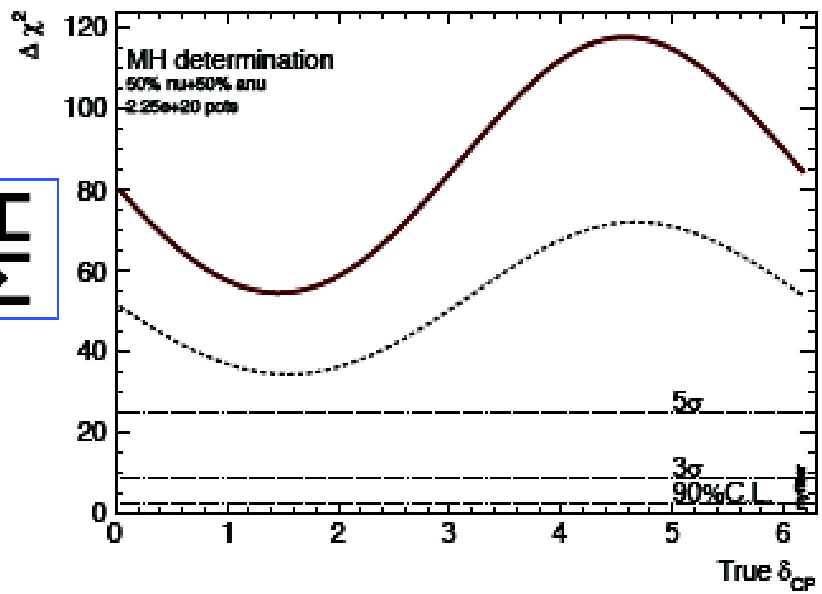
Wide-band muon neutrino beam

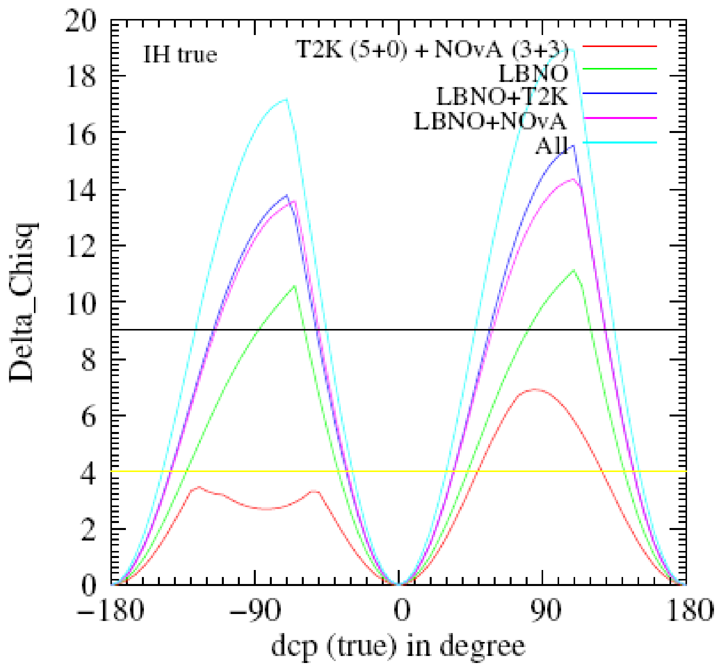
Good underground physics programme



LAGUNA-LBNO

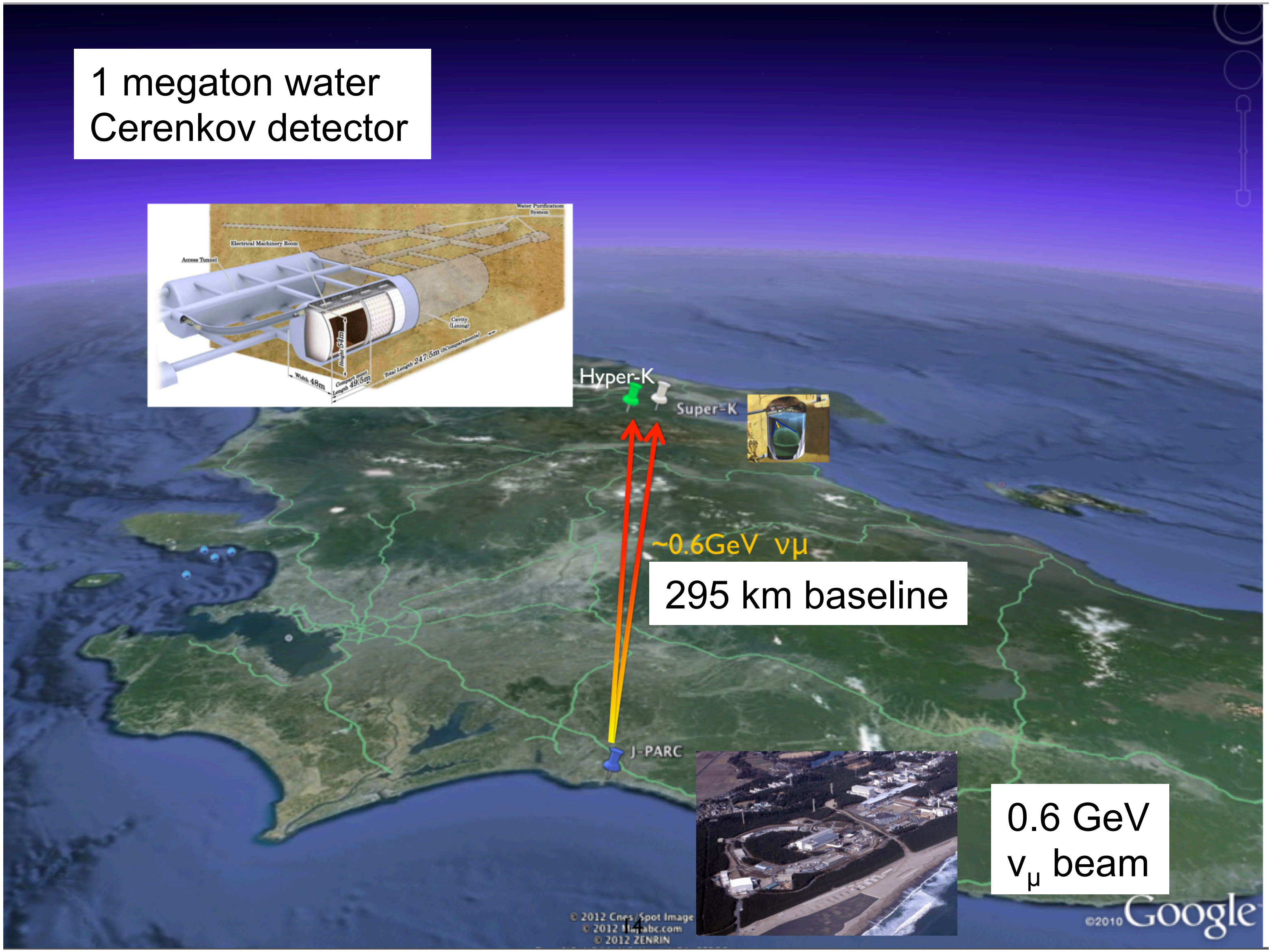
MH





- Excellent mass hierarchy determination
- CP violation: 44% coverage at 3σ in 10 years

T2HK


1 megaton water Cerenkov detector
Hyper-K
Super-K
~0.6GeV νμ
295 km baseline
J-PARC
0.6 GeV ν_μ beam
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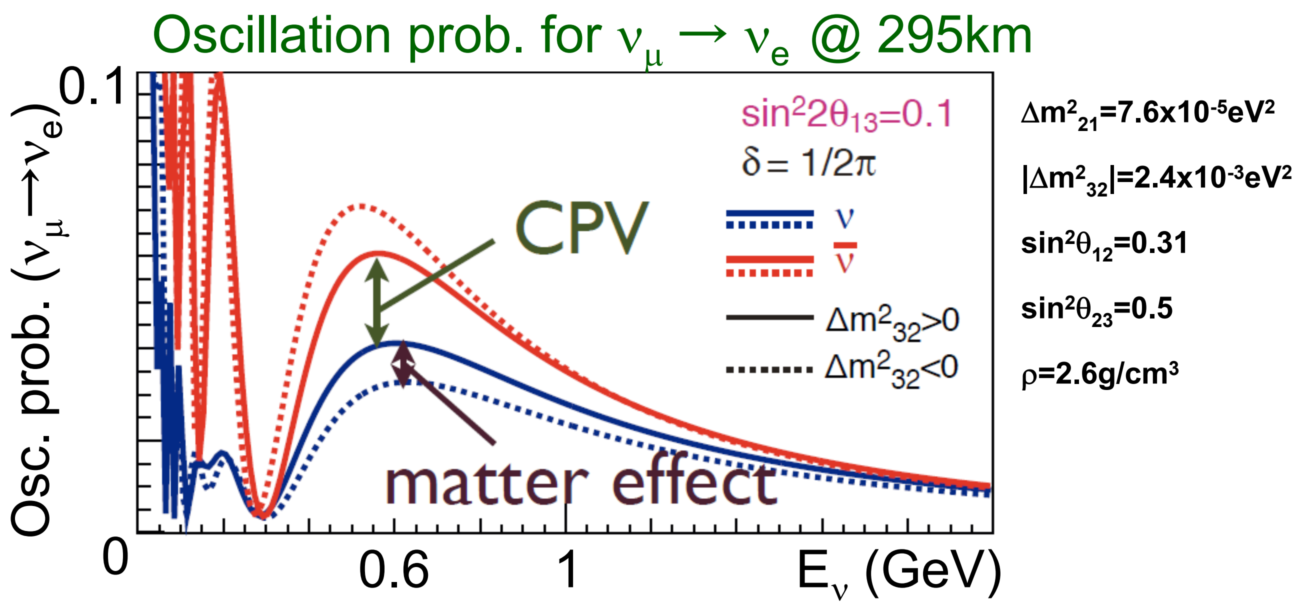
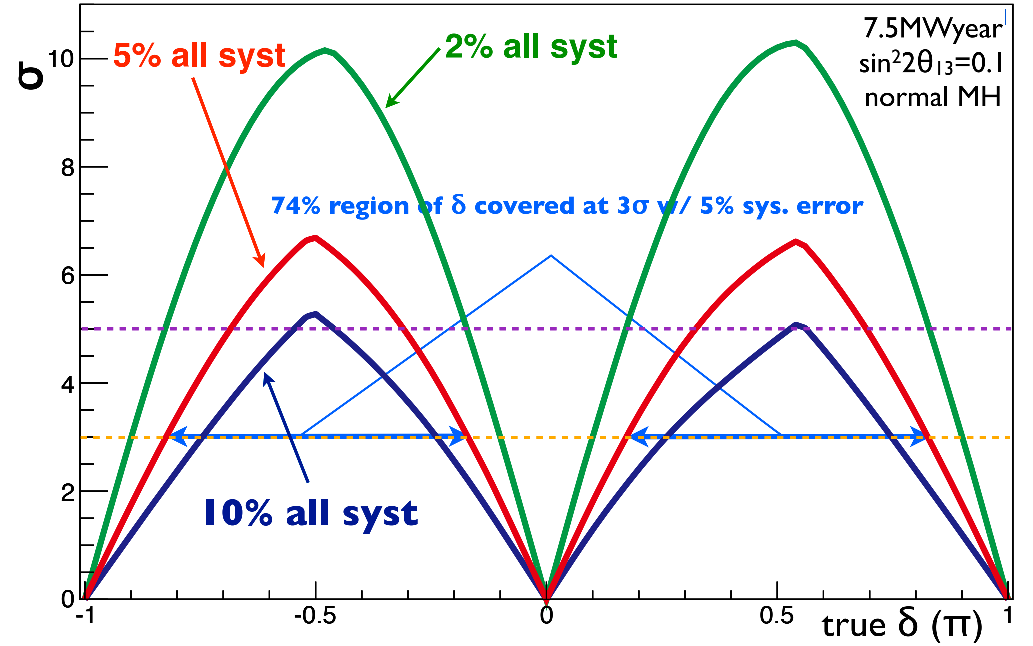
T2HK



- At the short T2HK baseline, CP violation dominates over matter effects

T2HK

Fraction of δ_{CP} space which can be distinguished from 0 at 3σ



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

T2HK has good CP violation determination potential

- But relies on the mass hierarchy already being known

MANCHESTER 1824
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Long baseline comparison

From M. Zito, European strategy meeting, Krakow

Project	Beam power MW	Fiducial Mass kt	Baseline km	MH	CPV 90%CL, (3σ)	Physics starts	Astrophysical program
LBNO	0.8	20->100	2300	Excellent	71 (44)	2023	Yes
T2HK	0.75	500	295	Little	86 (74)*	2023	Yes
LBNE	0.7	10	1300	OK	69 (43)	2022	No

*if mass hierarchy known

Summary

Three unknowns in neutrino physics

- Octant of θ_{23}, mass hierarchy, δ_{CP}

Future long baseline experiments will probe these

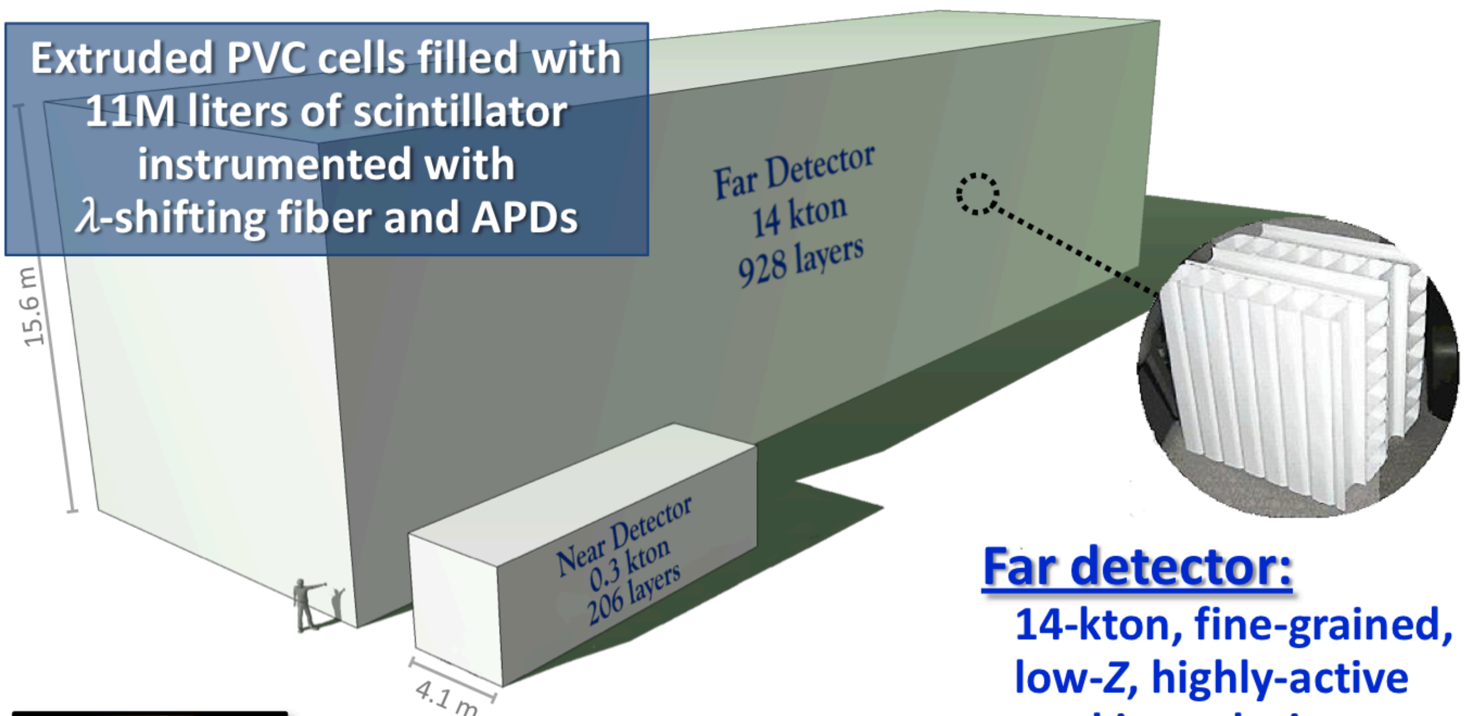
- T2K and NOνA have some sensitivity
- LBNE, LBNO and T2HK have much more sensitivity

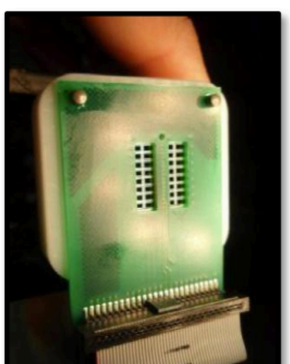
Liquid argon TPCs

- The electronic bubble chamber
- Excellent for separating ν_e from π^0 interactions
- The challenge is scaling these to >10 kt masses

NOνA

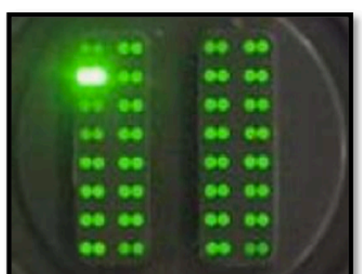
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs





32-pixel APD

Fiber pairs from 32 cells



Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

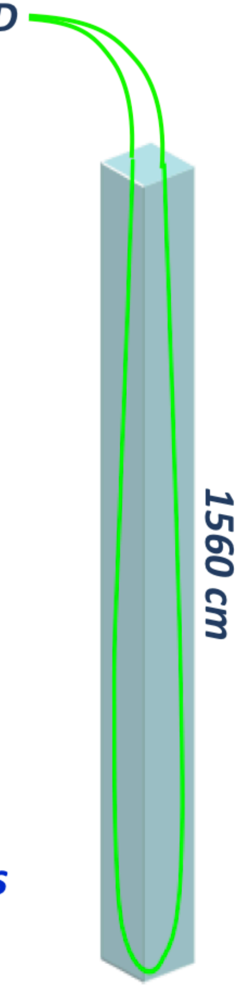
→ *360,000 channels*

→ *77% active by mass*

Near detector:

0.3-kton version of the same

→ *18,000 channels*



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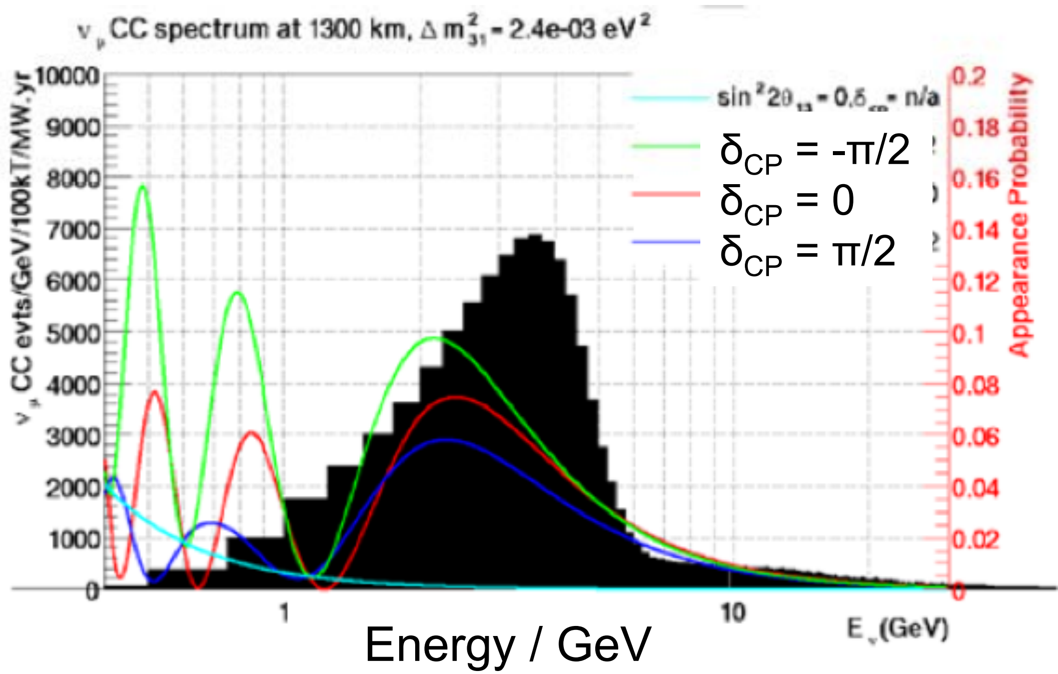
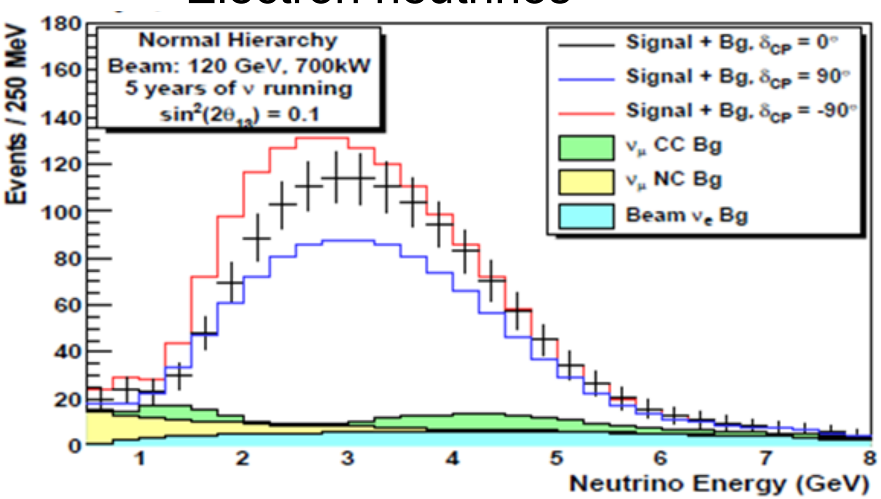
LBNE

Broadband beam

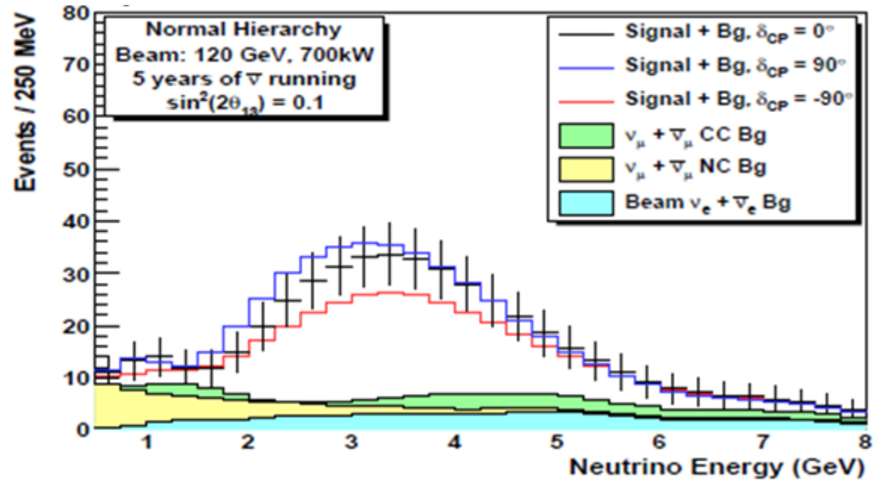
- First two oscillation maxima at 2.5 GeV and 0.8 GeV
- Low energy events vital for detecting CP violation



Electron neutrinos



Electron antineutrinos



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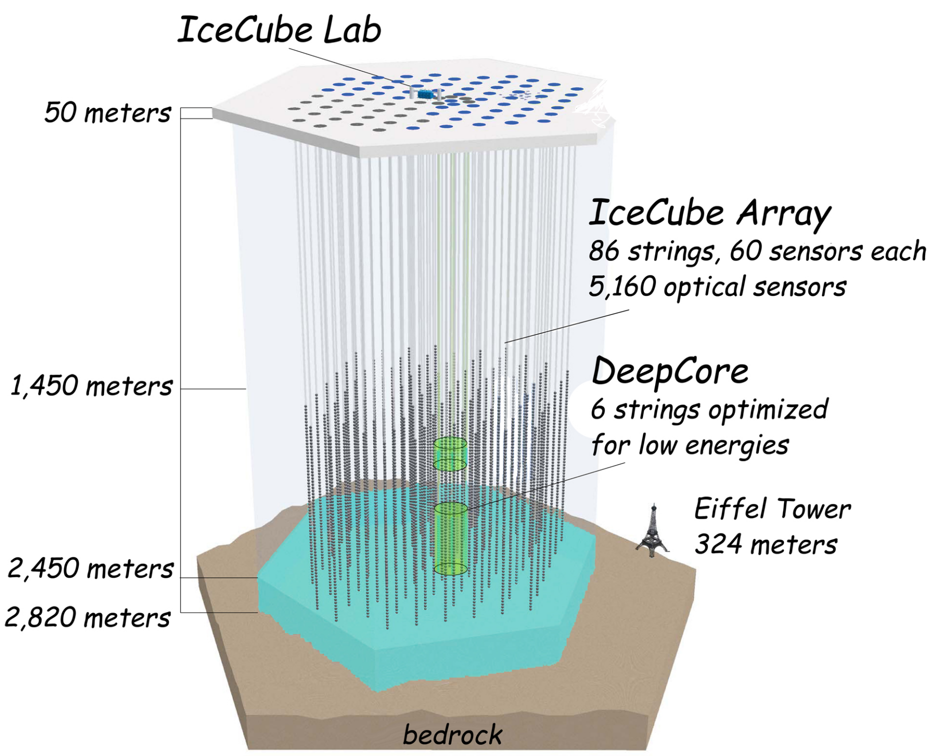
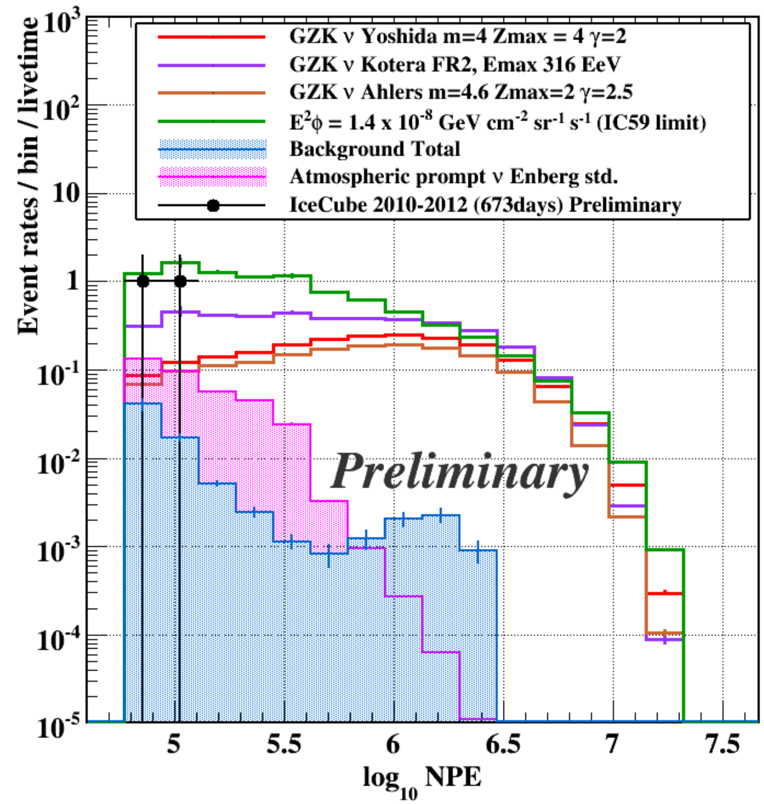
Antarctica





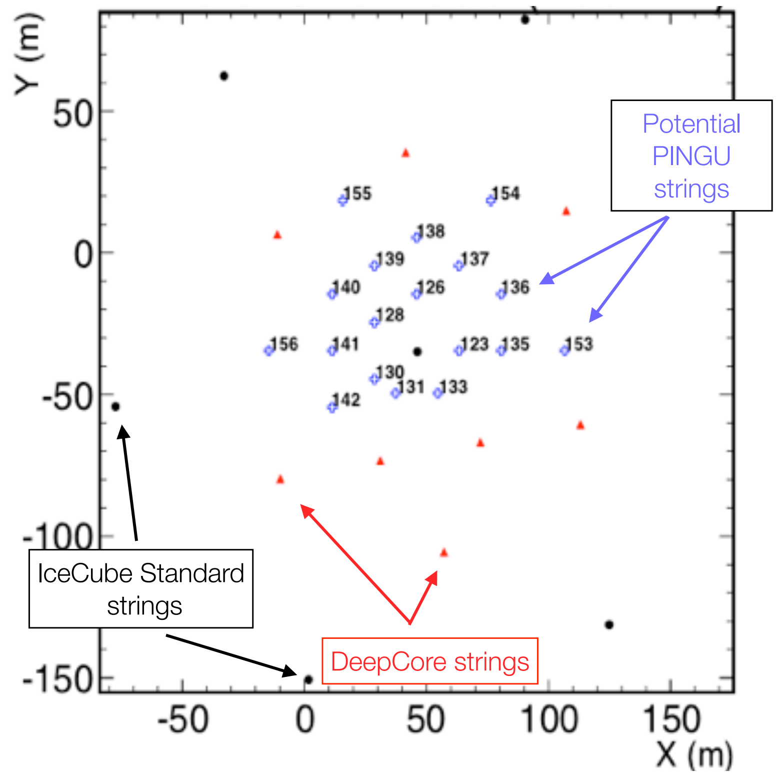
IceCube has turned the Antarctic ice shelf into the world's biggest neutrino detector

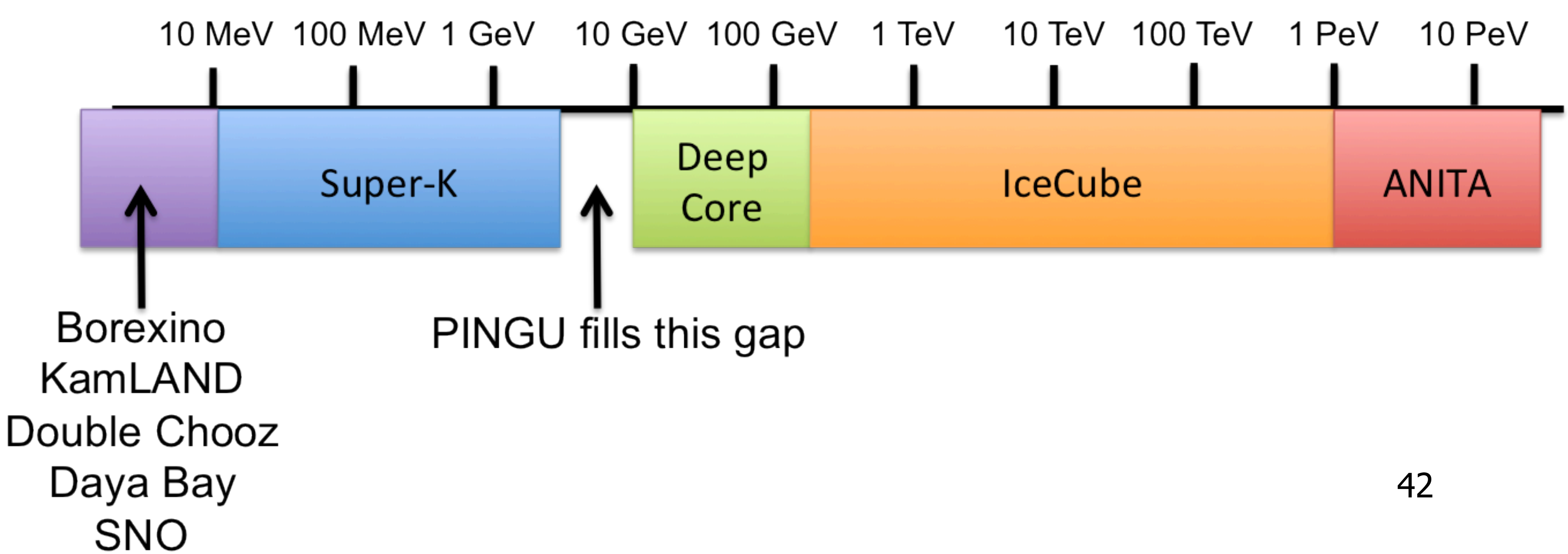
- Has seen the highest energy neutrinos ever observed

PINGU

Add 20 additional strings to the central region of IceCube

- Spaced by 6-7 m
- Take the neutrino energy threshold down to 1 GeV
- Measurements of atmospheric neutrino oscillations
- Searches for low-mass WIMPS

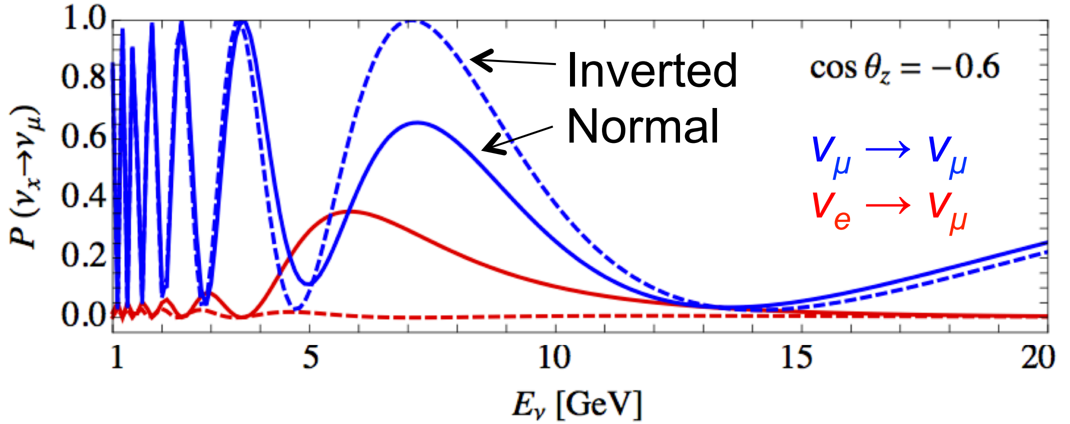




PINGU

5 GeV neutrinos traveling through the Earth are close to an MSW resonance

- Oscillations are enhanced
- The effect depends strongly on the mass hierarchy



A paper by Akhmedov et al. calculates PINGU's ability to determine the mass hierarchy

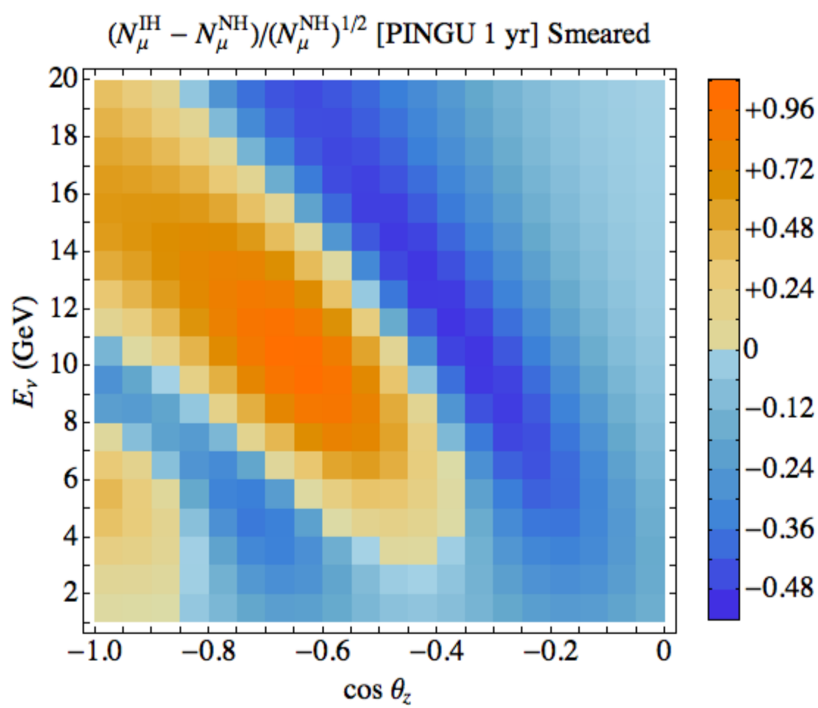
Assume a reasonable energy and angular resolution

- σ_E = 3 GeV, σ_φ = 15°

Mass hierarchy determination at 4.5σ – 7σ

- Assuming uncorrelated systematics at 5% – 10%

Fairly independent of δ_{CP}



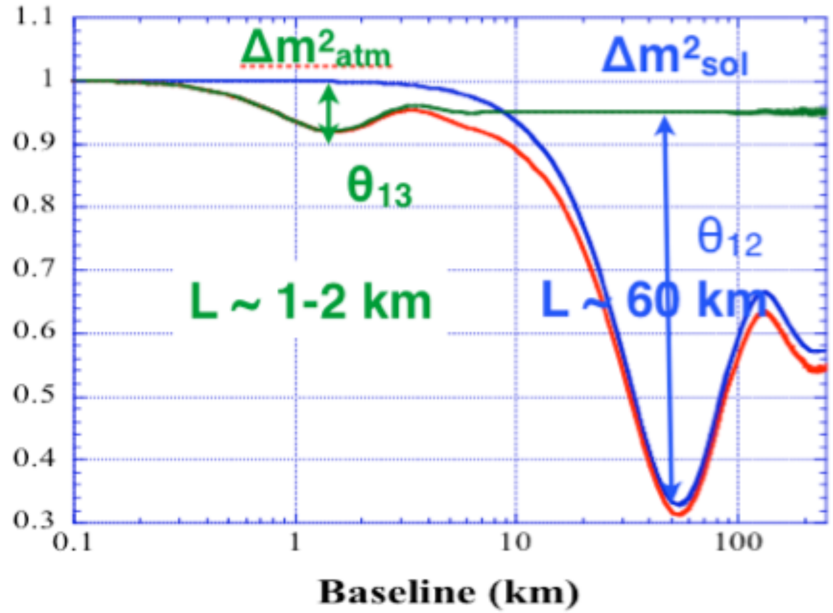
hep-ph/1205.7071

Reactor neutrinos

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

Slow oscillations (Δm^2_{21} is small)
Require >10 km to evolve (KamLAND)

Fast oscillations (Δm^2_{31} & Δm^2_{32} are large)
Oscillations seen after ~1 km
(Daya Bay, Reno...)



Reactor neutrinos at 60 km

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

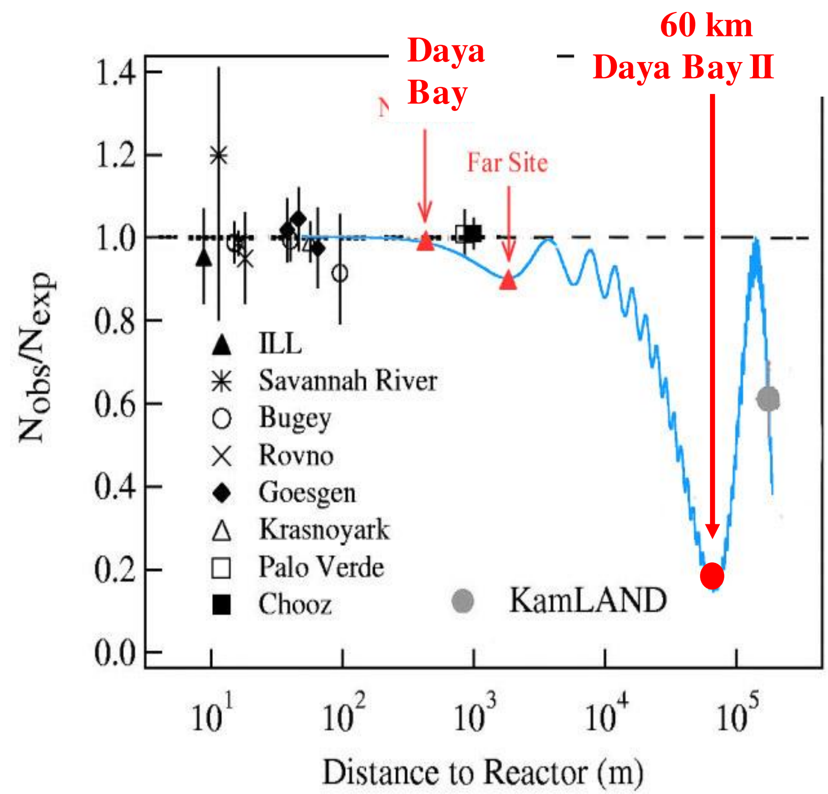
Dominant term at 60 km (θ_{12} is large)

Subdominant terms at 60 km (θ_{13} is small)

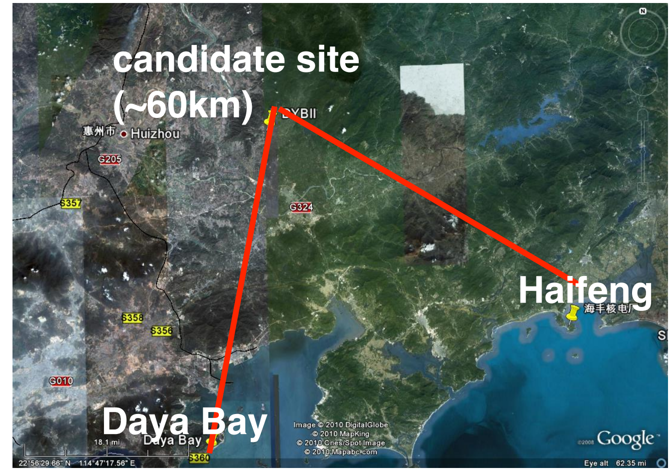
Subdominant terms produce a fast modulation to the ve disappearance probability

Modulation pattern depends on the hierarchy

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

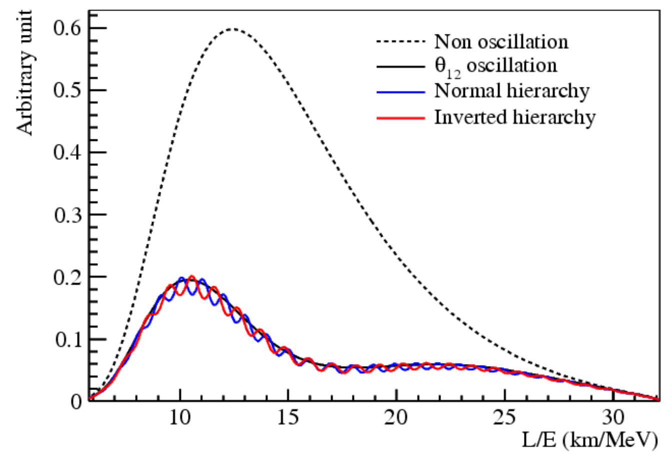


Daya Bay 60 km



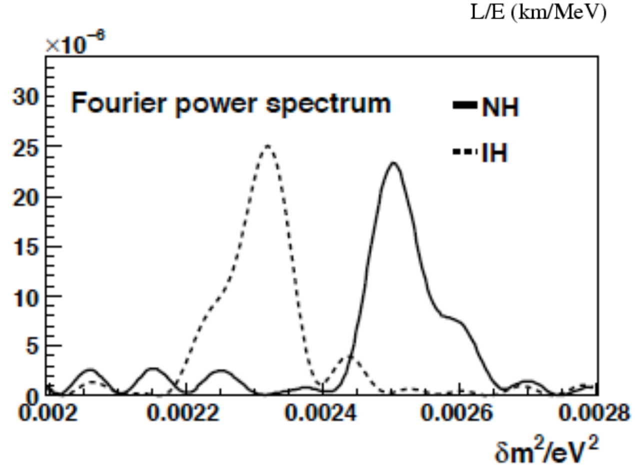
20 kt liquid scintillator detector

- Existing Daya Bay detectors are 120 tons total



Measure the subdominant, short-period oscillations

- Fourier transform



Require 3%/√E energy resolution

- Existing Daya Bay is ~10% / √E

3σ after 3 years

Summing up

Project	Mass hierarchy	CP violation (3σ coverage)	Comments
LBNE (stage 1)	OK	43	Robust physics studies Reduced by staging No near detector
LBNO	Excellent	44	Robust physics studies At least 10 years away >£1billion
T2HK	No	74	Robust physics studies Requires mass hierarchy from elsewhere
PINGU	>5σ	No	~£40 million, data within a decade, known technology Can it achieve the energy & angular resolution?
Daya Bay 60 km	>3σ	No	Can it achieve the energy resolution? Don't bet against the Chinese

Summary

Three unknowns in neutrino physics

- Octant of θ_{23}, mass hierarchy, δ_{CP}

Future long baseline projects

- Vital for determining δ_{CP}
- Expensive and long-timescale
- Optimization plays hierarchy against δ_{CP}

Other ideas

- PINGU or Daya Bay 60 km for mass hieararchy
- (Or NOvA if we're lucky!)
- Cheaper and faster
- But will they work? R&D needed.

Should we optimize the long baseline programme for hierarchy or δ_{CP}?

Neutrino disappearance

1970s

Homestake Mine

1970s onwards: Ray Davis looked for neutrinos from the Sun

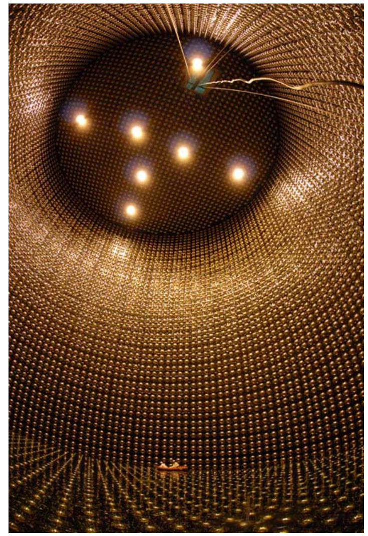
- Saw significantly fewer than predicted by solar models

Neutrino disappearance

1970s

Homestake Mine

1990s



Super-Kamiokande

1990s: Super-Kamiokande observed disappearance of muon neutrinos

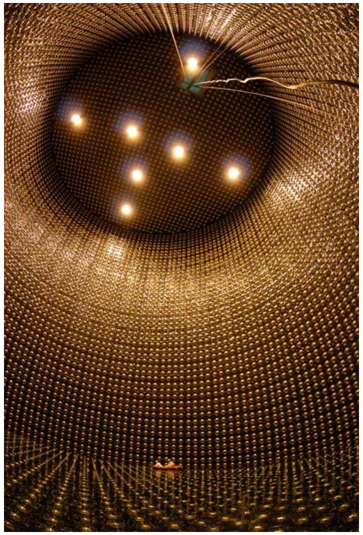
- As a function of L/E
- No disappearance of electron neutrinos

Neutrino disappearance

1970s

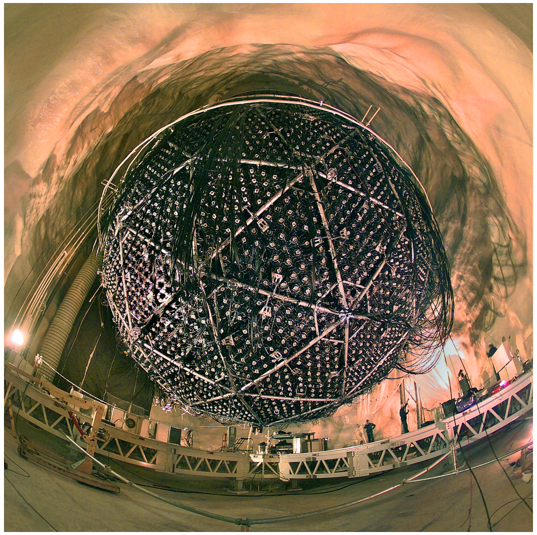
Homestake Mine

1990s



Super-Kamiokande

2000s



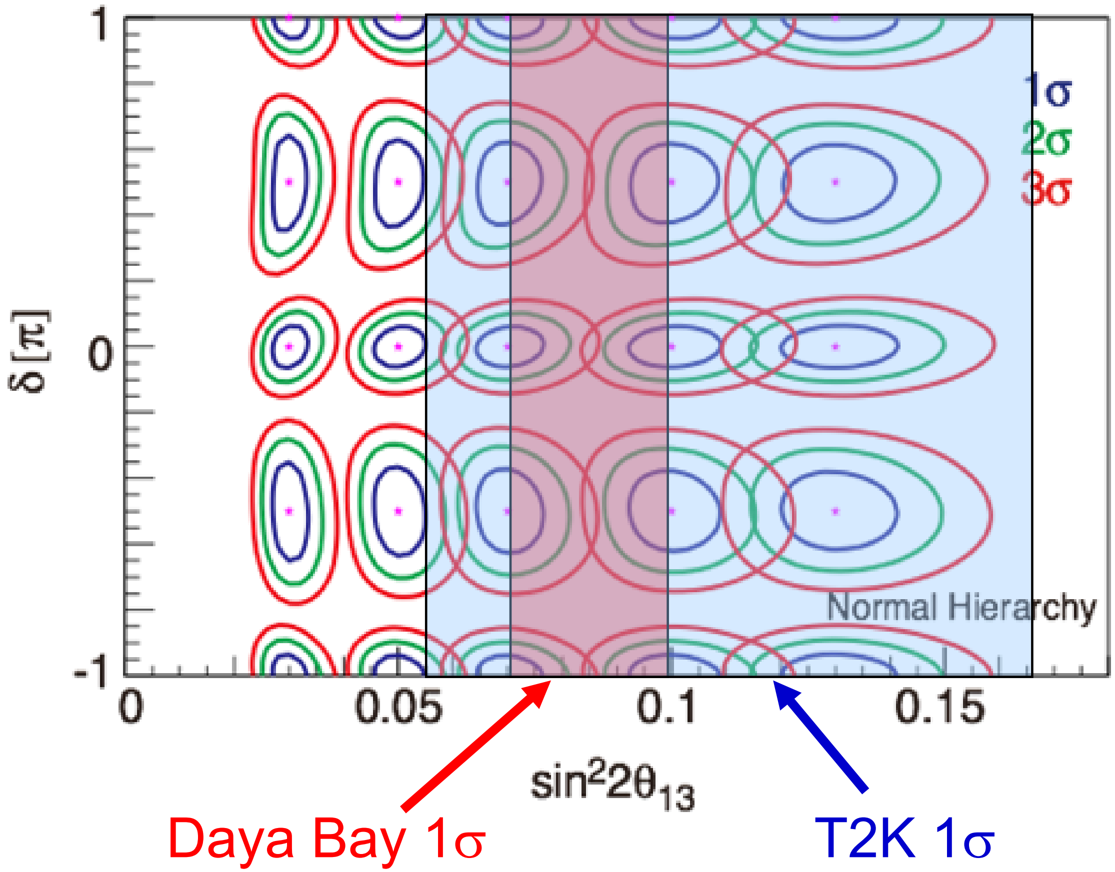
SNO

2000s: SNO sees disappearance of solar electron neutrinos

- No deficit in the neutral current event rate
- Confirms conservation of total neutrino number

T2HK

δ vs $\sin^2 2\theta_{13}$



7.5 MW years of data

NOvA schedule and status

Prototype near detector has been operated

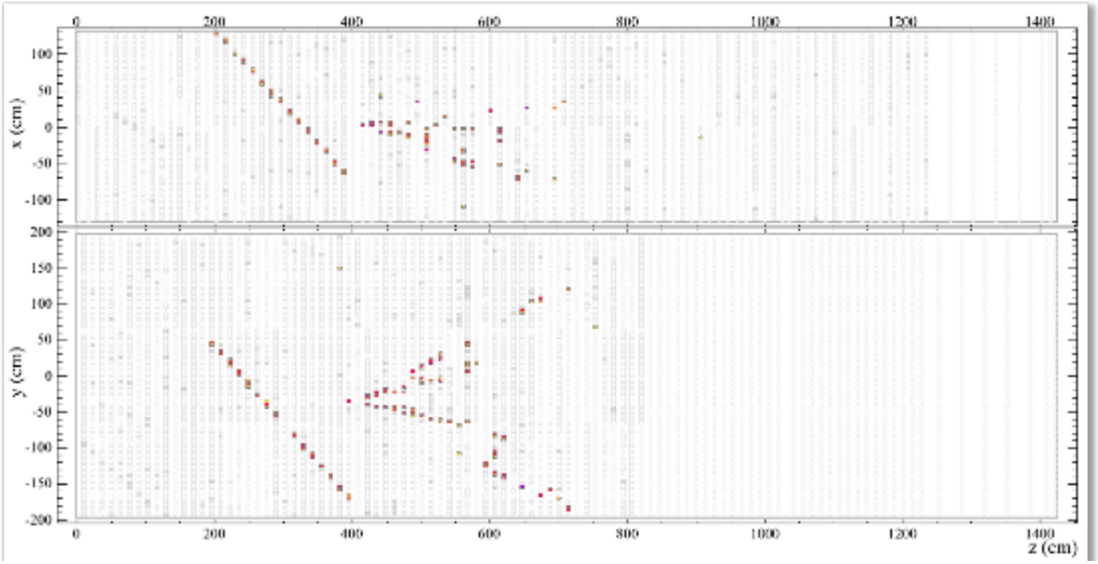
- DAQ development, calibrations, reconstruction, simulation…
- Detector assembly practice

Far detector assembly underway

- 5 kt when beam switches on
- 14 kt by May 2014

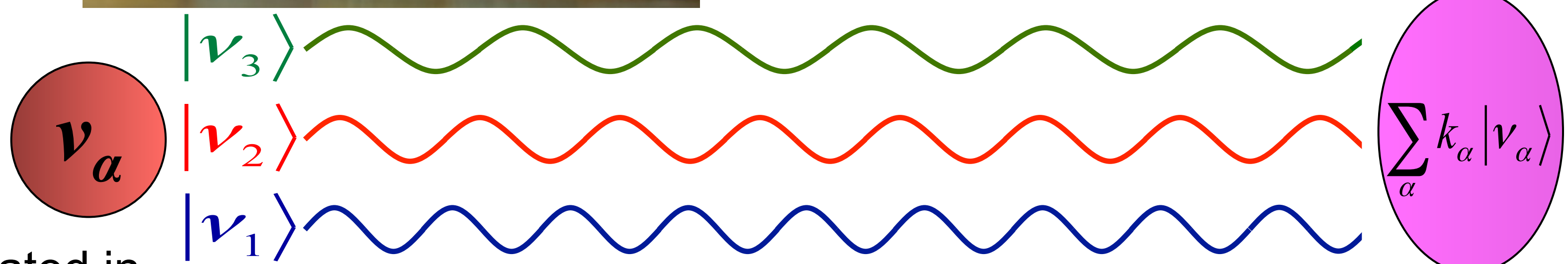
NuMI beam switches on in May 2013

- Reaches 700 kW by November 2013
- Baseline plan is 6 years of running



Neutrino flavour change – Oscillation

- Neutrino flavour states do not correspond to mass states



Created in a flavour eigenstate

Propagate as mass eigenstates

On detection, collapse back to flavour state: now not an eigenstate

Quantum mechanical interference on a macroscopic scale