Invisibles 15 workshop
June 2015, Madrid

Future Neutrino Oscillation Experiments

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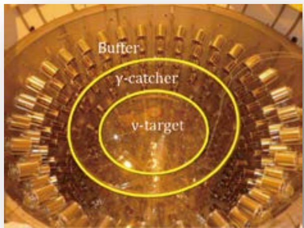
Outline

- Introduction
- Future neutrino oscillation experiments
  - Mass hierarchy
  - CP violation
- Other physics with future neutrino detectors
  - Proton decay
- Summary

Apologies: I cannot discuss all future neutrino osc. experiments. In particular, I will not discuss sterile neutrinos. I will discuss near future experiments only.

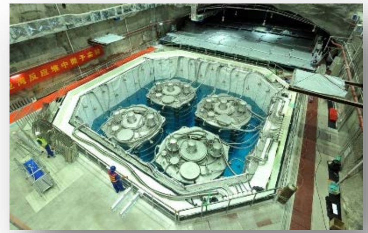
Introduction

Double CHOOZ



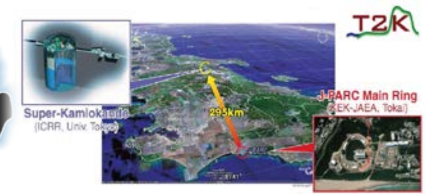
RENO

Daya Bay



MINOS

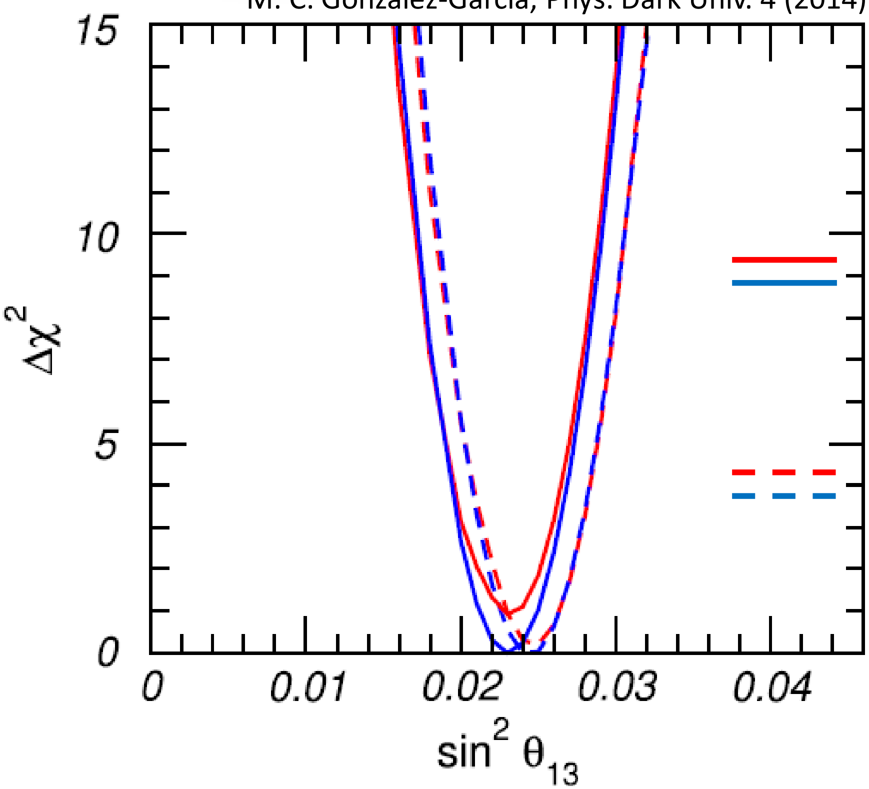
T2K



(Nova will come soon)

- ✓ θ_{13} has already been measured very accurately.
- ✓ θ_{12}, θ_{23}, Δm_{12}^2 and $|\Delta m_{23}^2|$ have also been measured accurately.

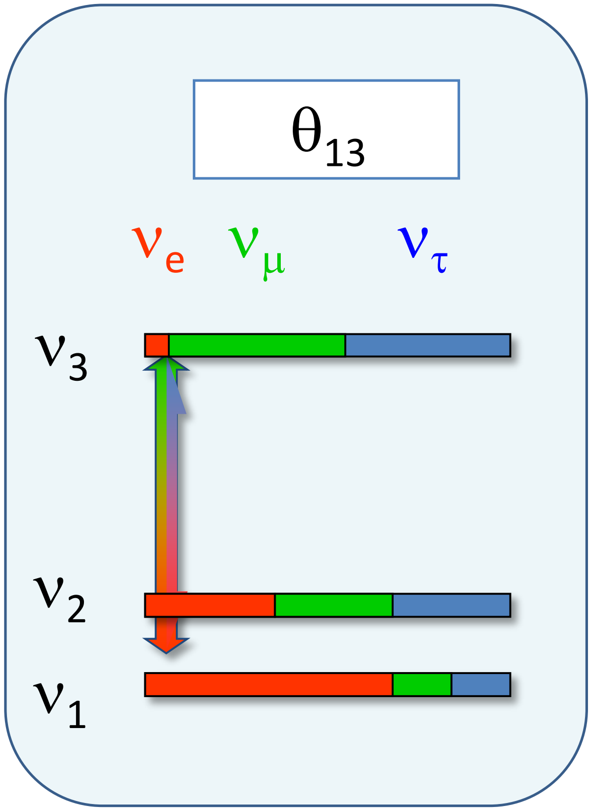
M. C. Gonzalez-Garcia, Phys. Dark Univ. 4 (2014) 1-5



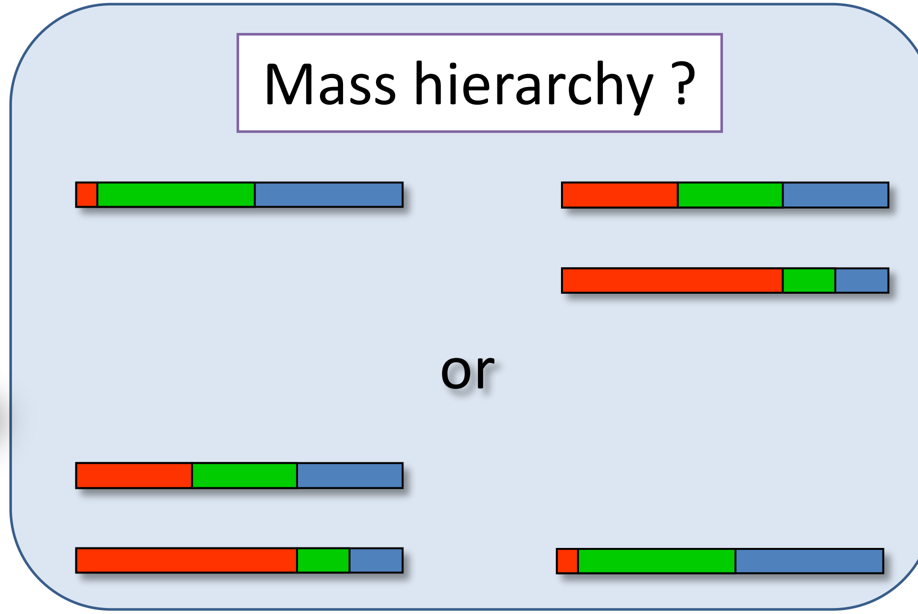
NH IH, Reactor flux = free, but short baseline data used.

NH IH, Reactor flux = recent calc.

Beyond θ_{13}



θ_{13} is not very small



Is the mass pattern of neutrinos similar to those of quarks and charged leptons?

CP violation ?

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

Future neutrino oscillation experiments

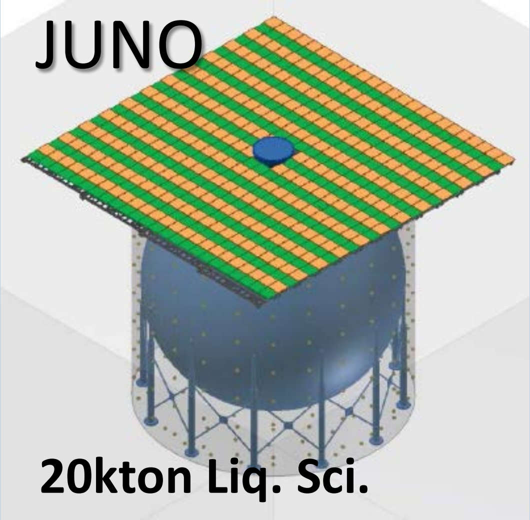
Mass hierarchy

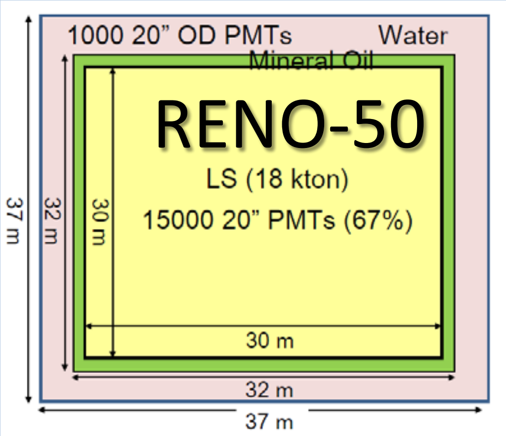
2 methods / 3 beams:

- Oscillation pattern
  - ✓ Reactor ν exp.
- Matter effect
  - ✓ Atmospheric ν exp.
  - ✓ LBL experiment

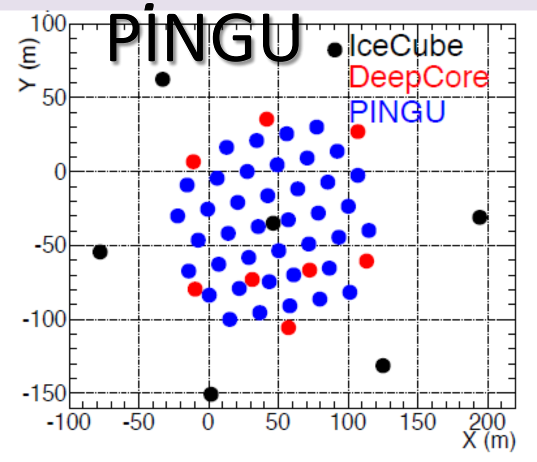
Future neutrino osc. exp's sensitive to mass hierarchy

Method 1: Reactor exp's

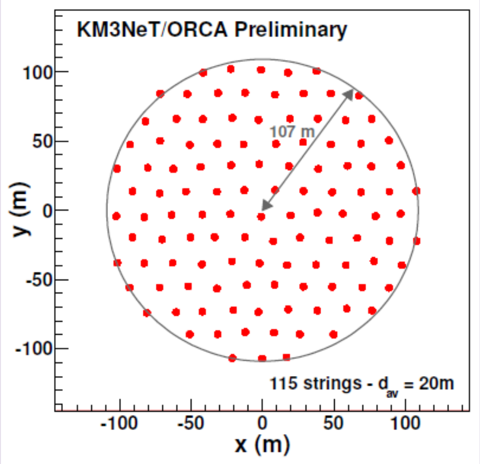


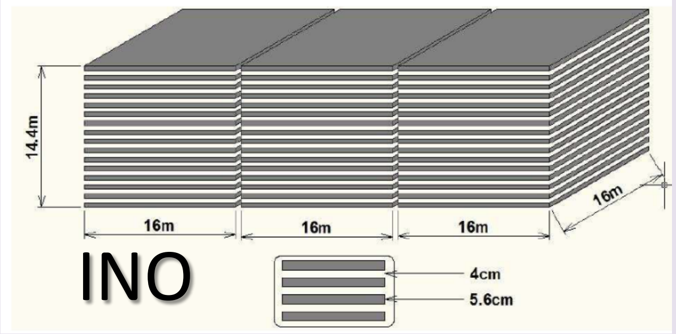


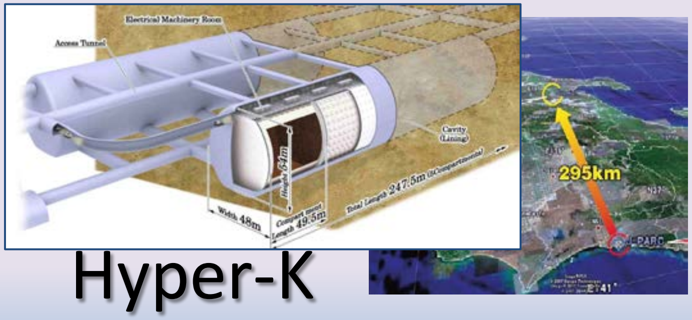
Method 2 (1): Atmospheric ν



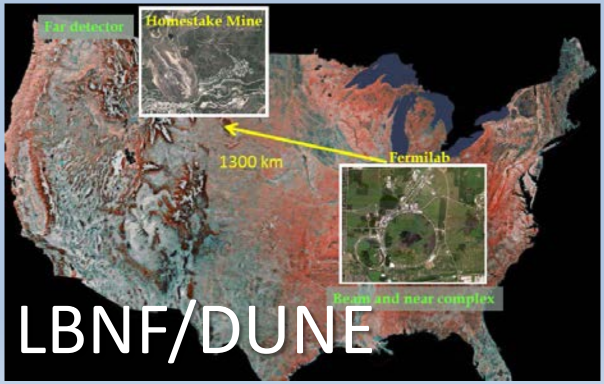
KM3NeT/ORCA



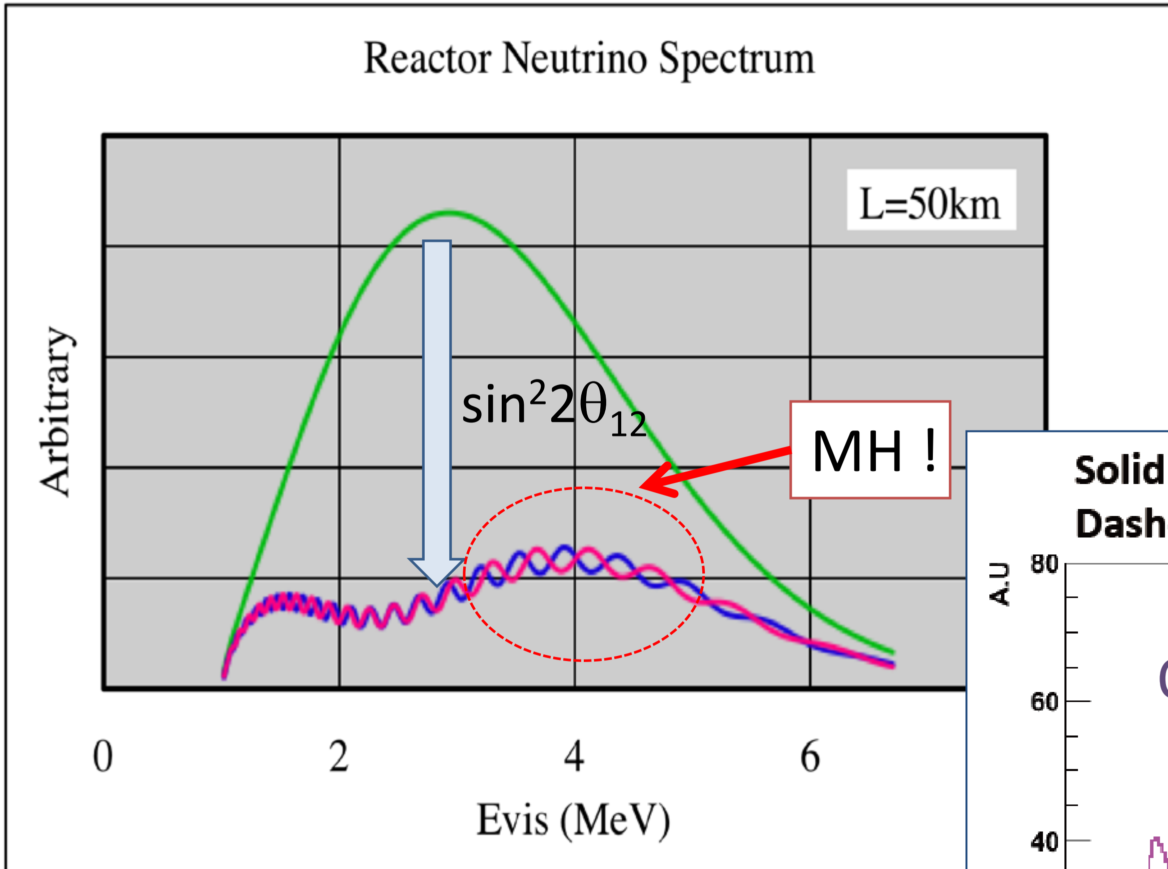




Method 2 (2): LBL ν exp's

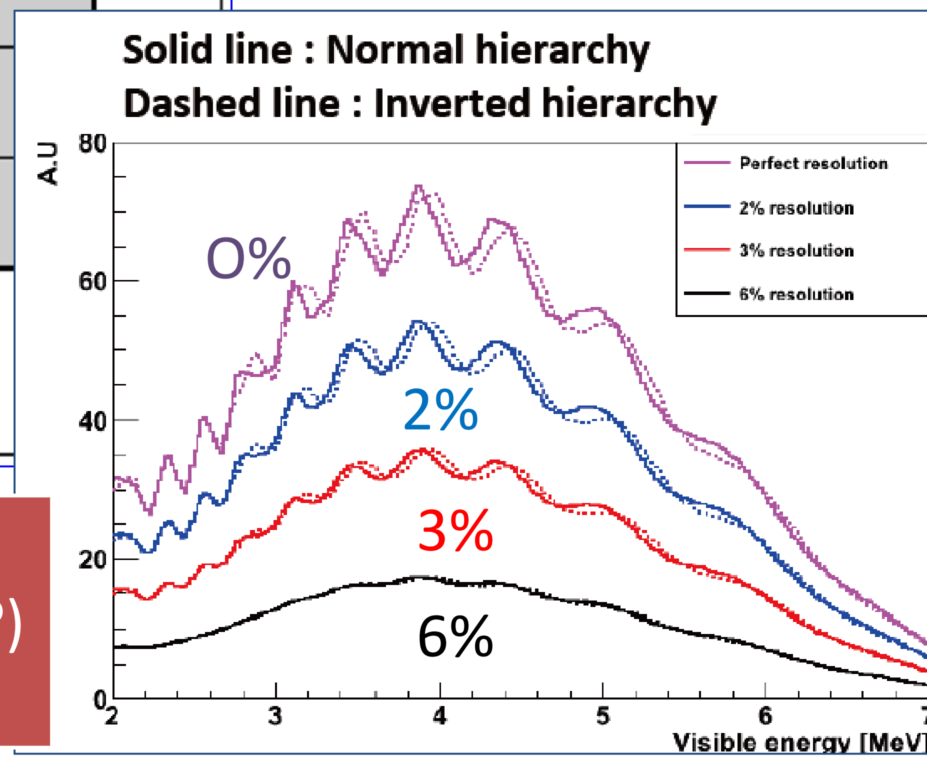


Method 1: Reactor MH experiments



Refs: RENO-50 workshop June 2013

Energy resolution



<u>Keys:</u>

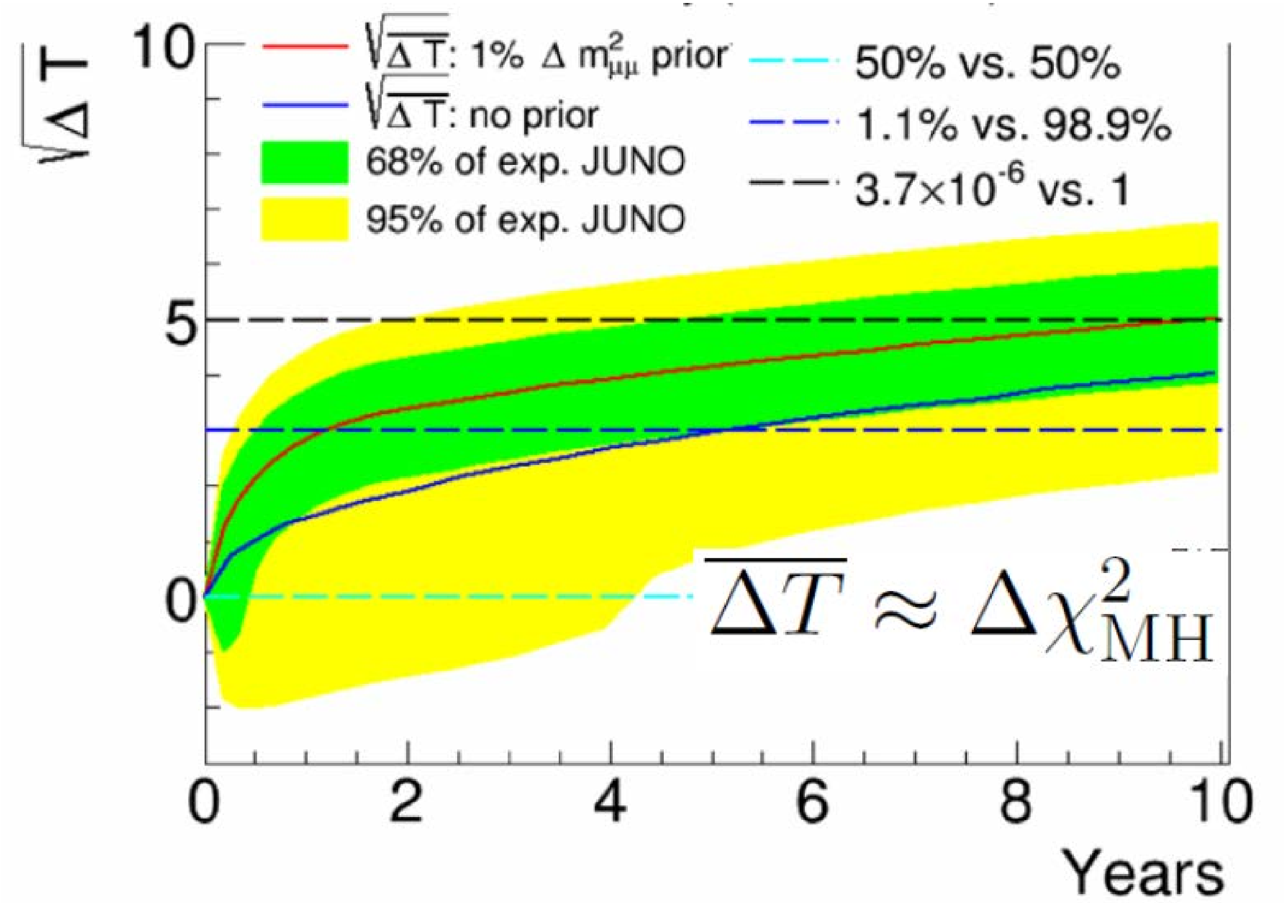
✓Good E. resolution (3% or better?)

✓High stat. (large detector)

Sensitivity to MH

Assume: JUNO (20kton, 3%/sqrt(E))

J. Cao, Neutrino Telescope 2015



Other physics: precise measurements of θ_{12}, Δm_{12}^2, Δm_{13}^2, supernova neutrinos, diffuse SN neutrinos …

Status of JUNO and RENO-50

JUNO

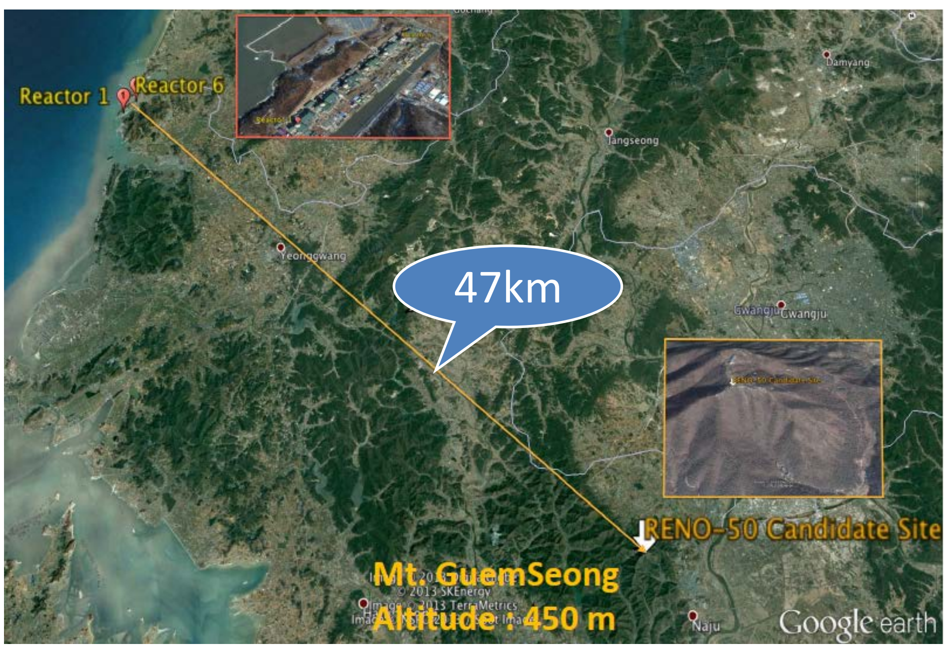
J. Cao, Neutrino Telescope 2015

- Approved in Feb. 2013, with ~300M$ budget
- Ground breaking in Jan. 2015. (Civil construction will be completed in 3 years.)
- Data taking in 2020.

RENO-50

S-H. Seo, Neutrino Telescope 2015

- Candidate site identified at the distance of 47km from the reactors.
- 2M$ grant from Samsung was awarded to RENO-50 R&D.

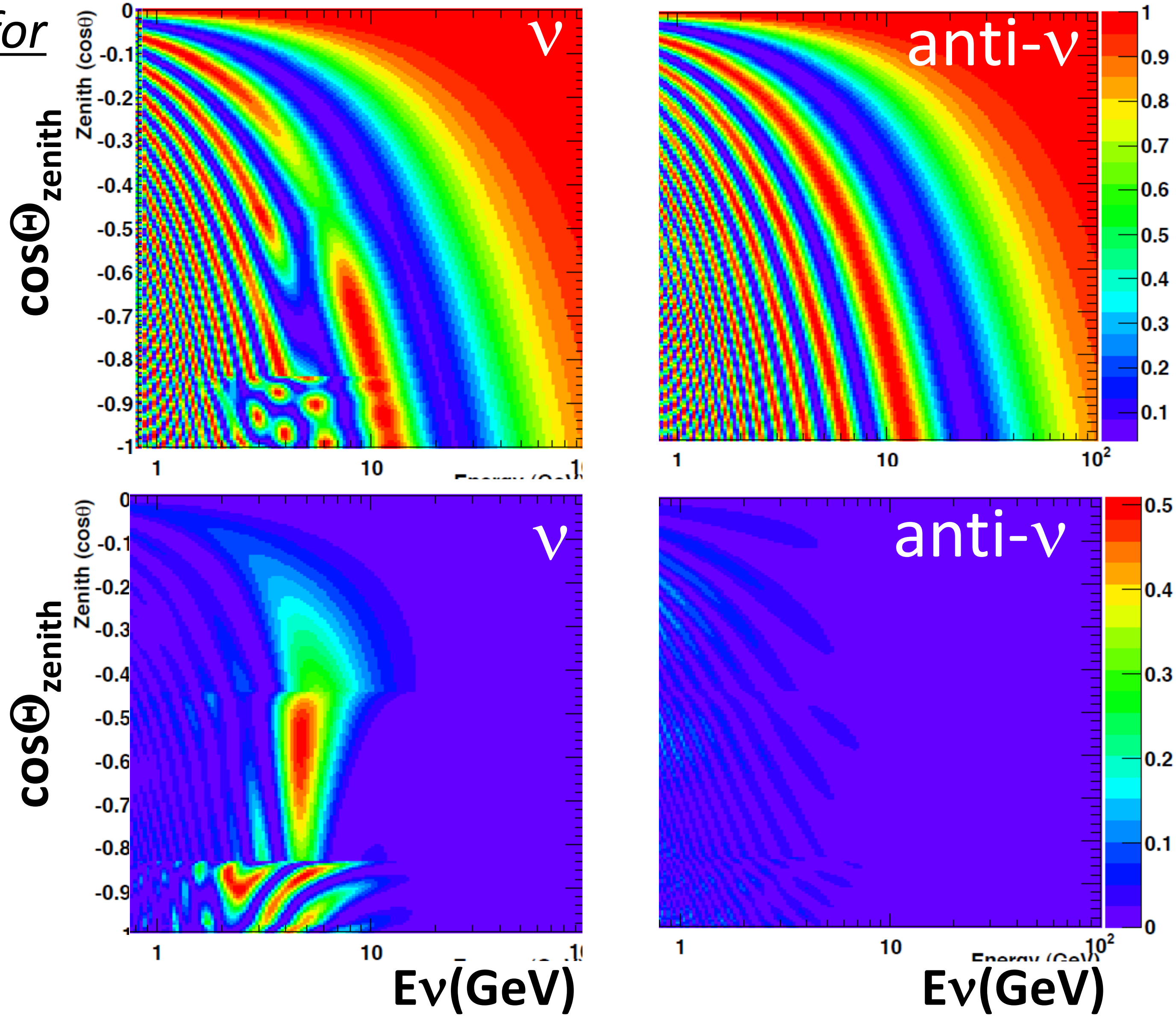


Method 2 (1): Atmospheric neutrino experiments

Osci. Probabilities for Normal Hierarchy

$P(\nu_\mu \rightarrow \nu_\mu)$

$P(\nu_\mu \rightarrow \nu_e)$



Atmospheric and LBL oscillation exp's use these features.

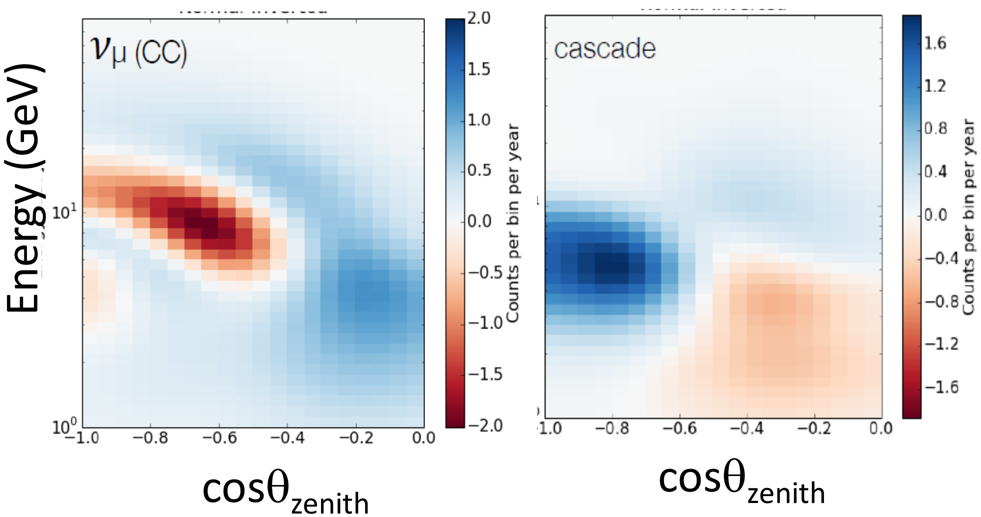
PINGU and KM3NeT/ORCA: Sensitivities to MH

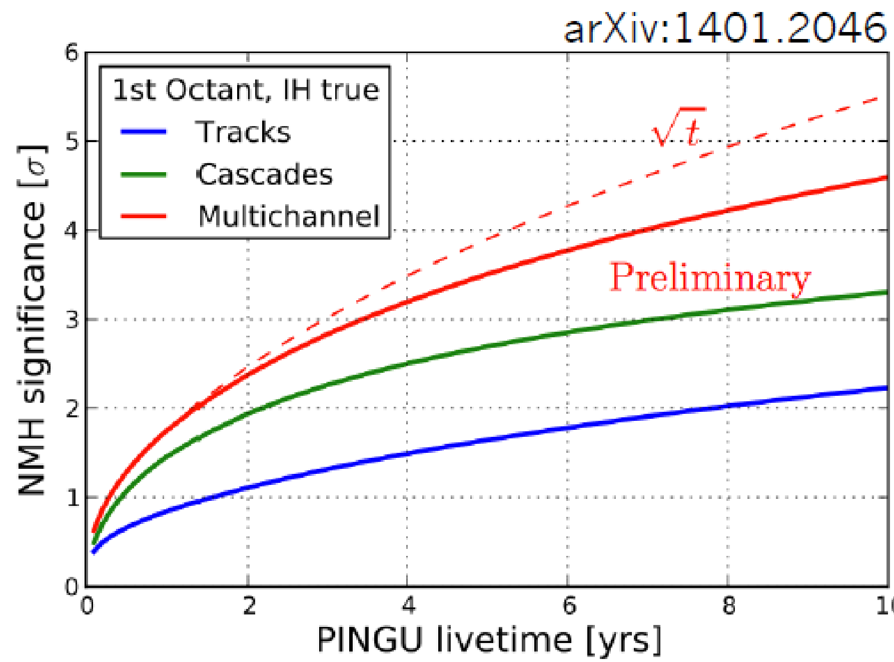
PINGU and KM3NeT/ORCA are low-energy extensions of Neutrino Telescopes. Both have multi-M ton volume and >2000 Optical Modules.

S. Boeser Neutrino Telescope 2015

PINGU (example)

Normal – Inverted





- ✓ Both cascade (ν_e enriched) and track (ν_μ enriched) used.
- ✓ Detector resolutions taken into account.

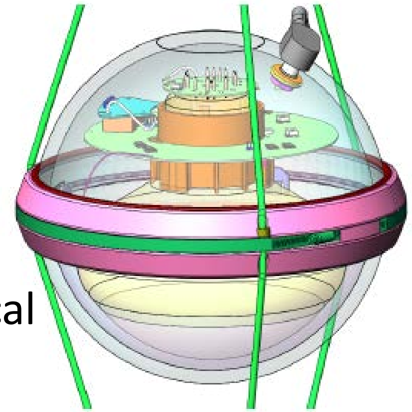
◆ KM3NeT/ORCA has very similar sensitivity.

In both experiments, ~3σ in 3 years is expected (systematic very important).

Plans of PINGU and KM3NeT/ORCA

PINGU

S. Boeser Neutrino Telescope 2015



PINGU optical module

- Deployment well understood with the experience of IceCube
- > 20 strings per season (40 strings in total (baseline design))
- Completion possible by early 2021 or 2022.

KM3NeT/ORCA

T. Eberl, Neutrino Telescope 2015

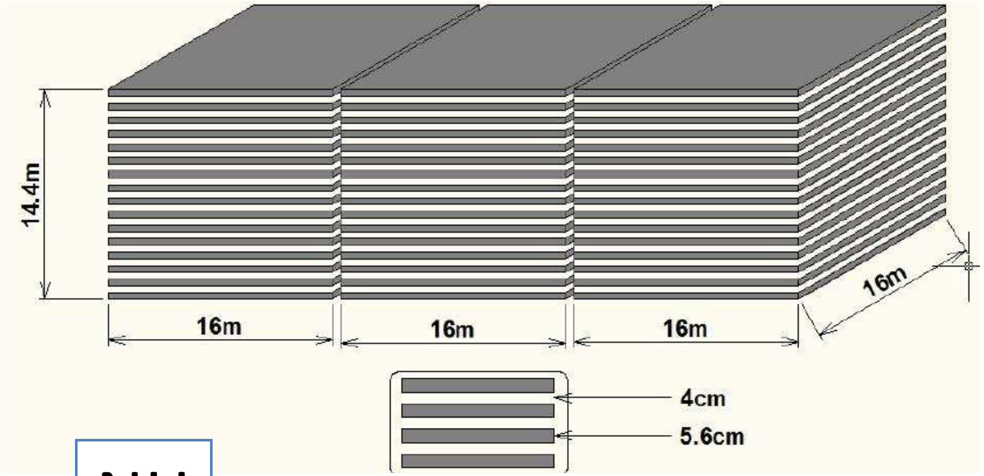
KM3NeT/ORCA optical module

- Deployment test with ORCA style string in Mid. 2015 (Phase 1)

- 6 strings deployed and operational by the end of 2016 (approved)
- Start construction 2017 (Phase 2.0)
- Completion possible in 2020

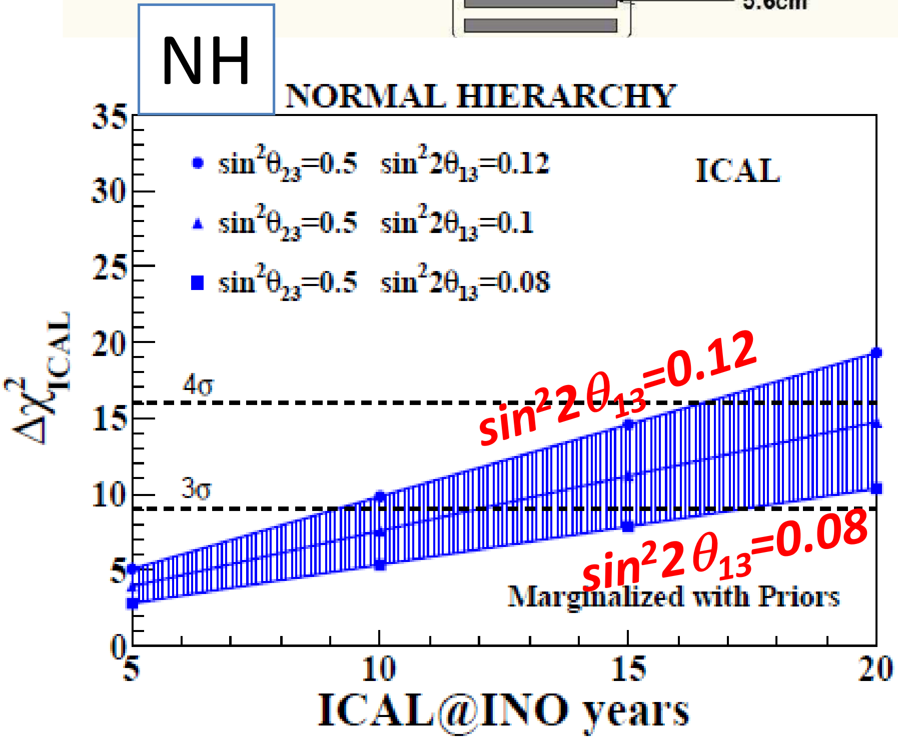
INO-ICAL

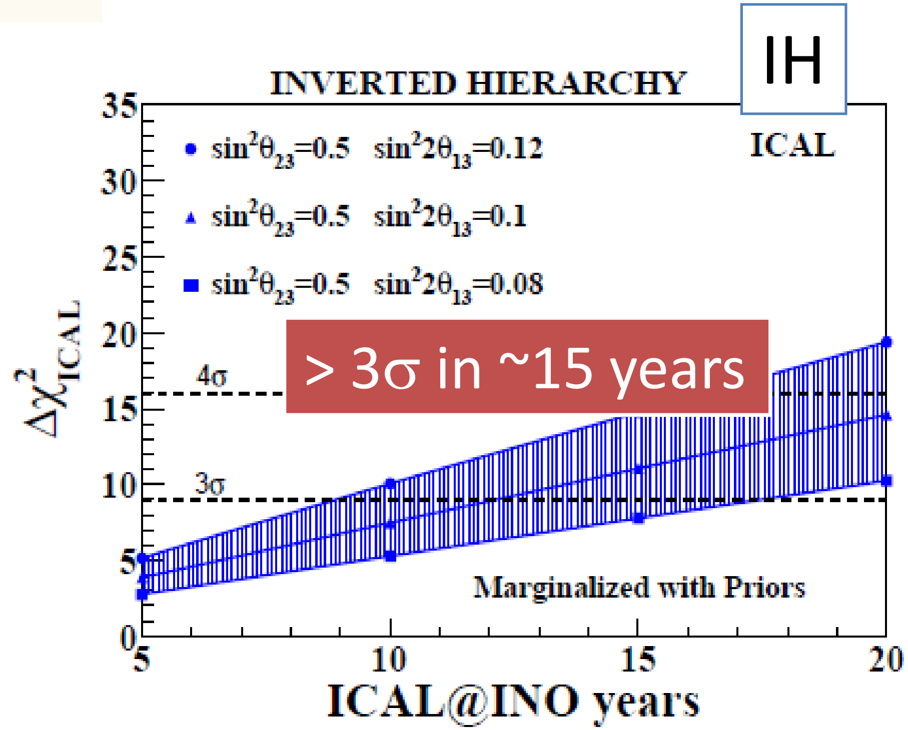
G. Majumder, Neutrino Telescope. March 2015
ICAL collab. arXiv: 1505.0738



- 50 kton magnetized (1.3T) detector
- Total number of RPCs = 28,800

➔ Will use ν_μ events



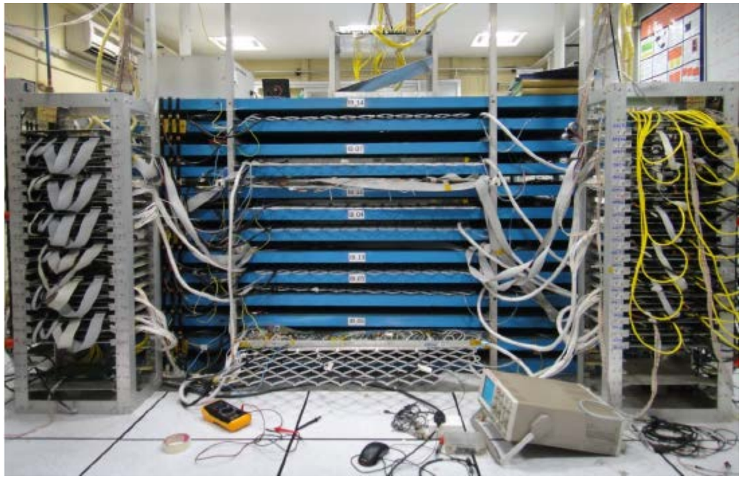


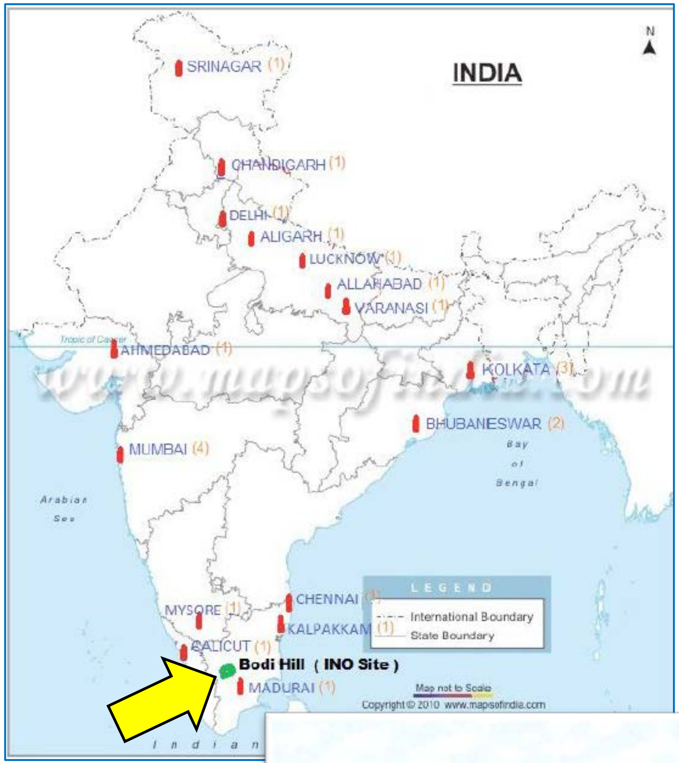
> 3σ in ~15 years

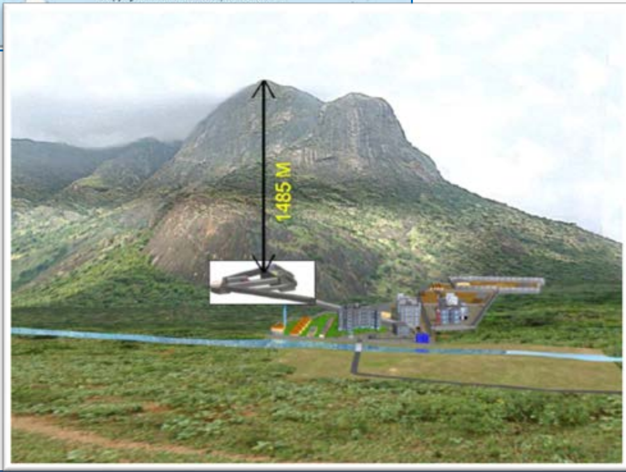
INO-ICAL status

G. Majumder, Neutrino Telescope. March 2015

- The site is Bodi West Hills.
- Civil works such as water, electricity, approach road have started.
- R&D works such as a 35 ton prototype with magnetic field are in progress.



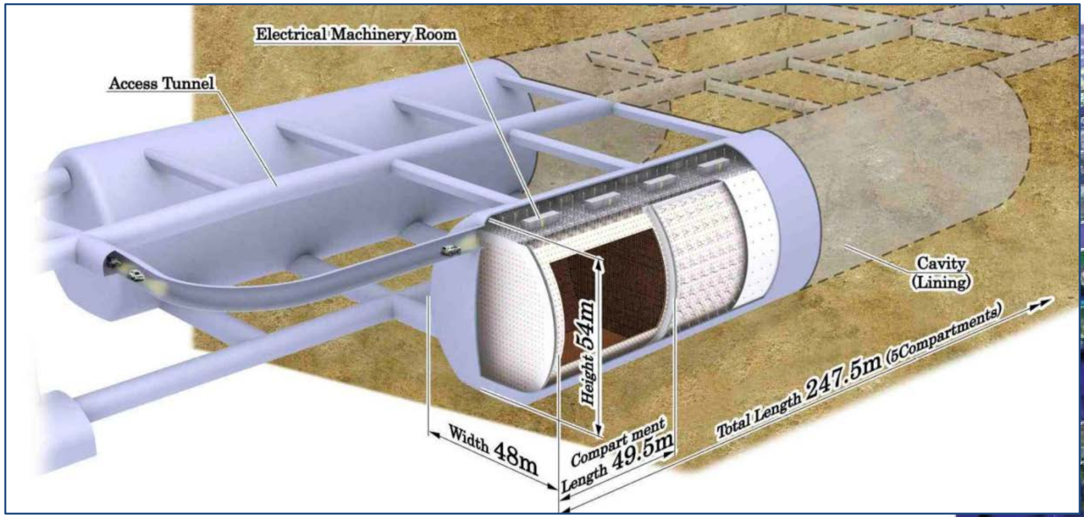




- Construction of the tunnel expected to begin by the end of 2015.
- Tunnel and experimental hall: 3-4 years.
- One module per year (total 3 years).

Hyper-Kamiokande

Hyper-K, PTEP (2015)



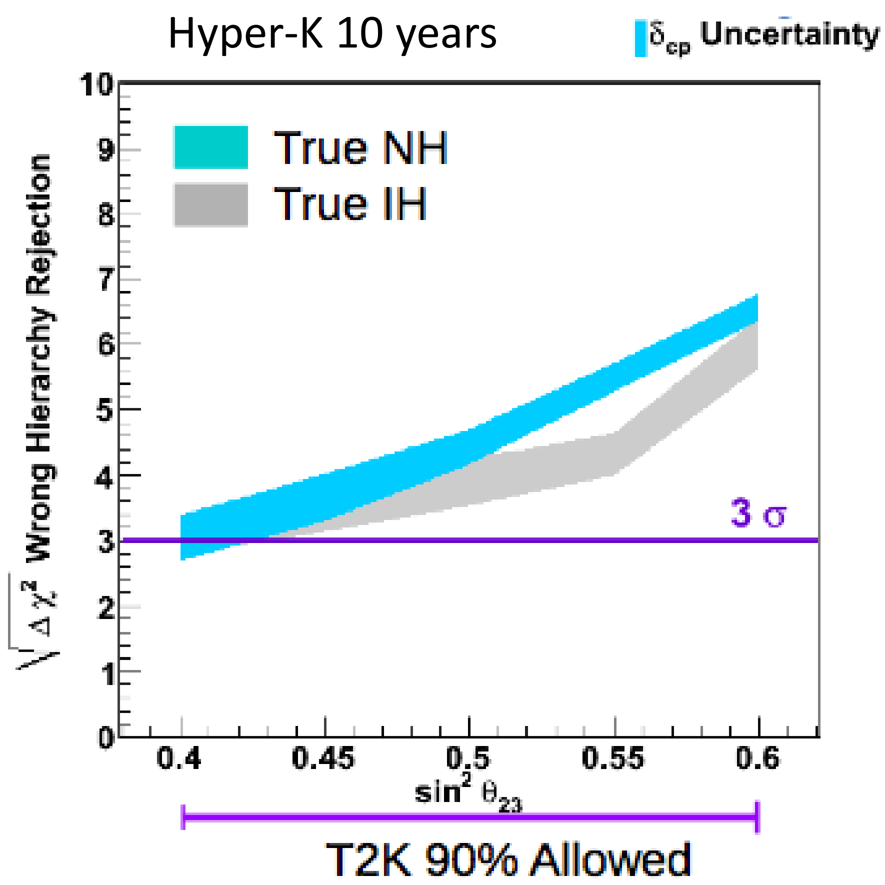
- Cavity : 48m(W) x 54m(H) x 250m(L) x 2
- Water volume :
  - Total : 0.496x2 = 0.99 Mton
  - Fiducial volume = 0.56 Mton (25x SK)
- Photo-detectors :
  - ID : ~99,000 20" PMTs, 20% photo-coverage
  - OD : ~25,000 8" PMTs, same coverage as SK

•750 kW (assumed)

2.5 degree off-axis beam from J-PARC
295km baseline length
and
Atmospheric neutrinos

Hyper-Kamiokande

MH determination with Atmospheric neutrinos

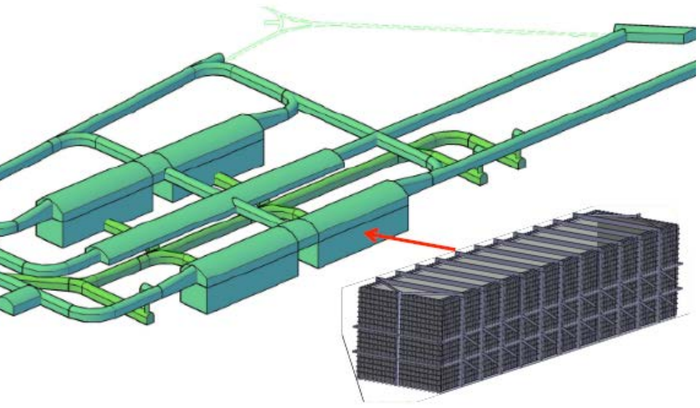


Hyper-Kamiokande status and plan

- proto-collaboration has been formed
- 240 people from 13 countries
- R&D funds have been granted in several countries
- Selected as one of the 25 top priority future projects by Science Council of Japan in 2014
- But was not included in the MEXT (Japanese funding agency) roadmap in 2014 → must wait for the next round (2017)
- If the construction begins in 2018, experiment ~2025

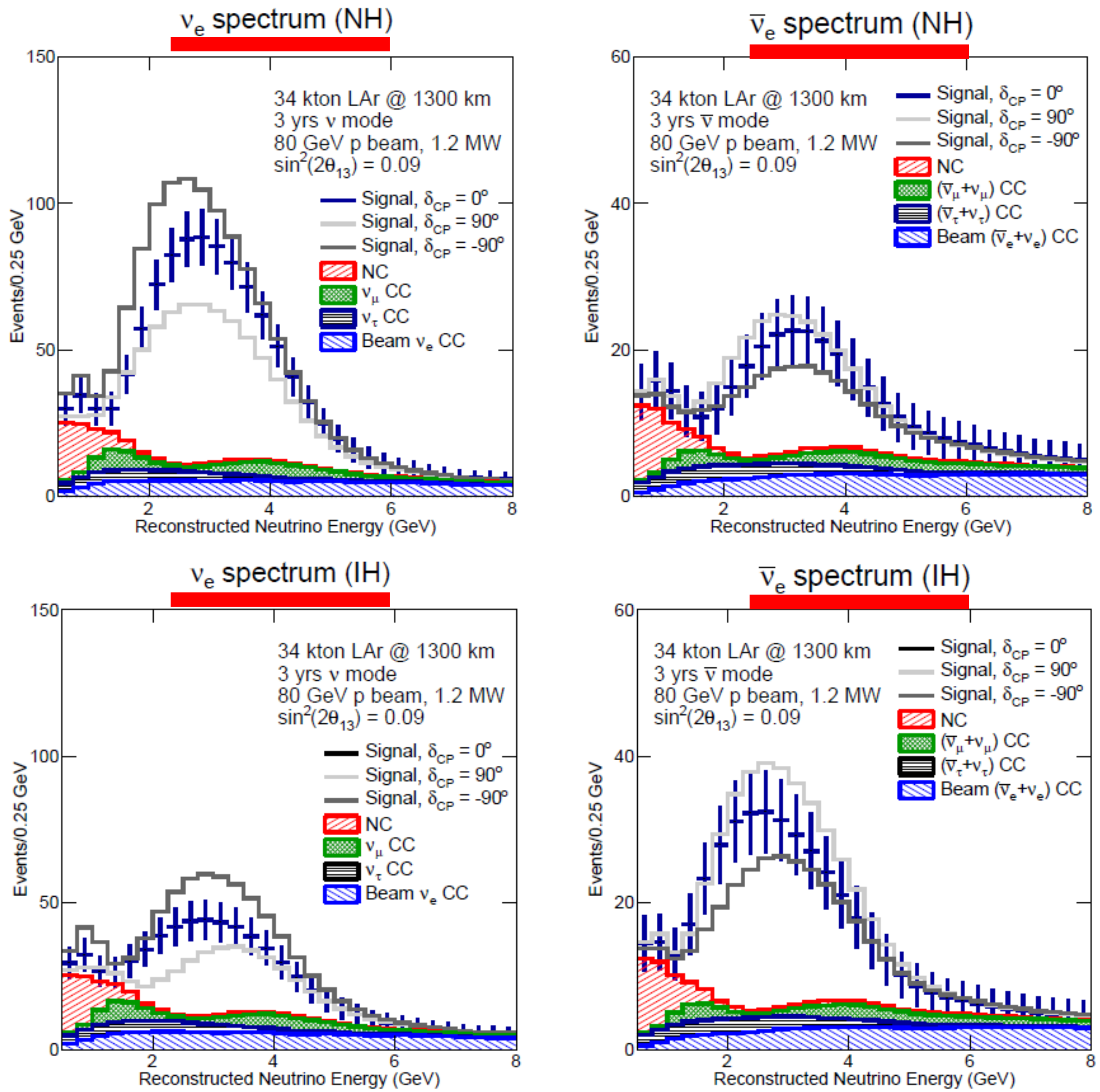
Method 2 (2): LBL experiment (LBNF/DUNE)

- ✓ 1.2 MW beam (➔ upgradable to 2.4 MW)
- ✓ 40kton Liq. Ar
- ✓ 1300km baseline length



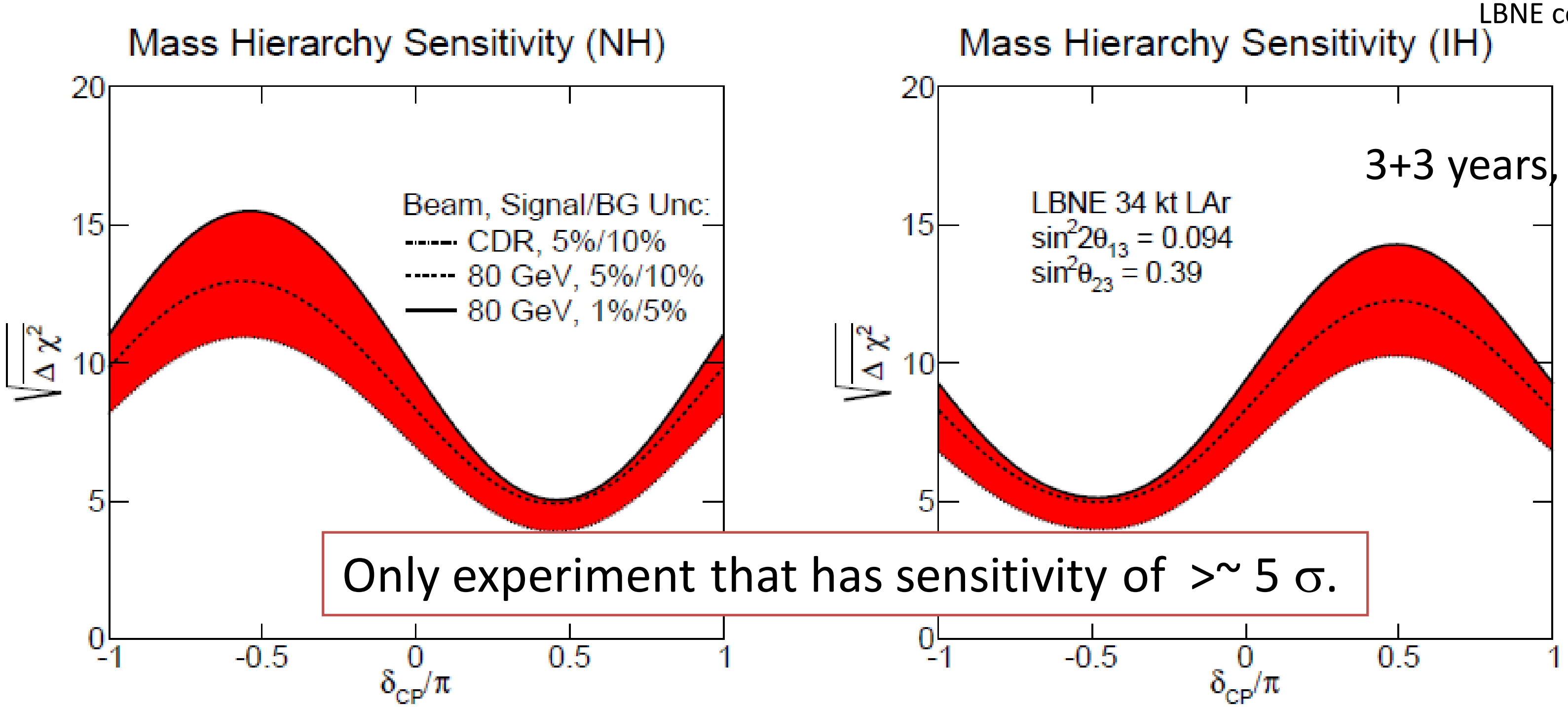
LBNE collab. arXiv: 1307.7335

J. Strait, 2nd International Meeting for Large neutrino Infrastructures, April 2015



LBNF/DUNE

LBNE collab. arXiv: 1307.7335



3+3 years, 1.2 MW

Only experiment that has sensitivity of >~ 5 σ.

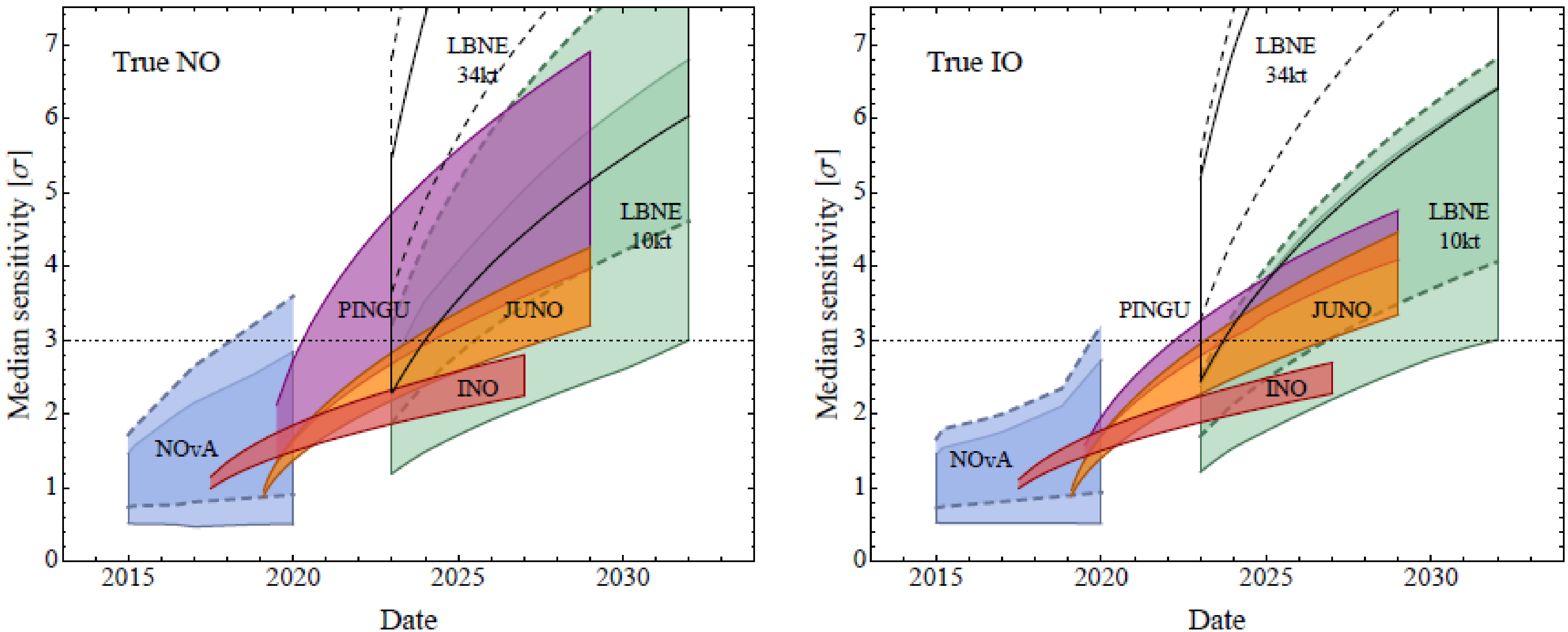
J. Strait, 2nd International Meeting for Large neutrino Infrastructures, April 2015

LBNF/DUNE status and plan

- 769 collaborators from 25 countries
- Huge progress in the last one year
- Schedule goals set in the LOI submitted to the Fermilab PAC:
  - development of the first 10-kt fid. mass detector on the time scale of 2021 followed by future expansion to the full size as soon as possible
  - 1.2 MW of power by 2024, … up to 2.4 MW of beam power by 2030

Mass hierarchy determination: Grand view

M. Blennow et al. arXiv: 1311.1822



With time, our knowledge on mass hierarchy will get certain…

Before 2020, we get some indication for MH

Before 2025, ~3 σ understanding

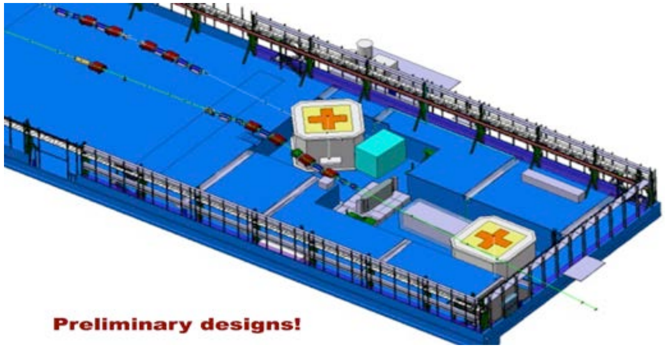
Before 2030, ~5 σ determination

Comment: CERN Neutrino Platform

- European Strategy (2013) : "CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments"
- In 2014, CERN has released an important amount of resources for a CERN Neutrino Platform, as part of its medium term plan (5 yrs)
- CERN will assist the EU neutrino community in their long term common plans.
- CERN Neutrino Platform activities:
  - ✓ Large scale demonstrators (Single- and Double-phase LAr TPC)
  - ✓ Generic neutrino detector R&D
  - ✓ Infrastructure (incl. cryogenics)
  - ✓ Beam component R&D

ICARUS detector at CERN to make it ready for SBL experiment at Fermilab

Test beam and test facility (EHN1 extension)



CP violation

- LBL experiment

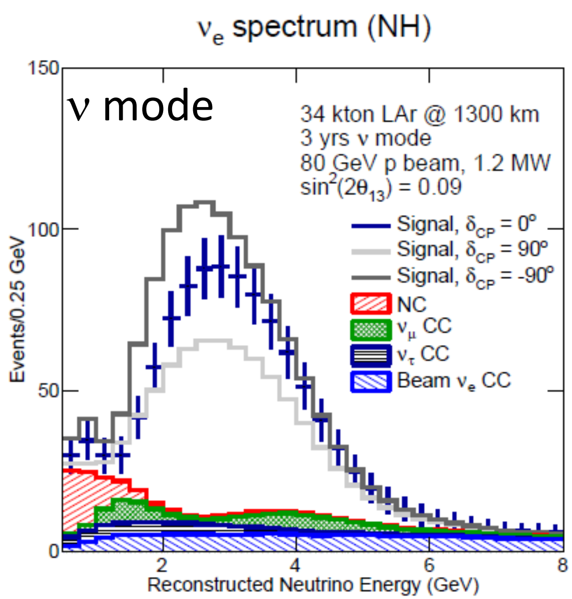
LBL experiments (LBNF/DUNE and J-PARC/Hyper-Kamiokande)

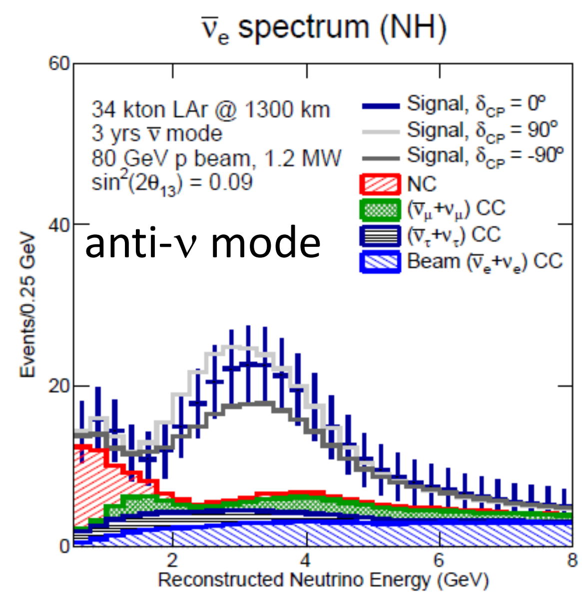
<u>*NH assumed*</u>

LBNE collab. arXiv: 1307.7335

◆LBNF/DUNE

(34kton in this fig.)

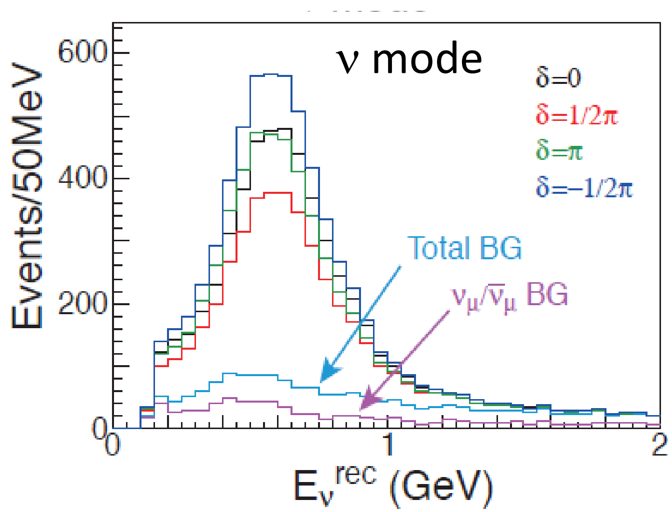


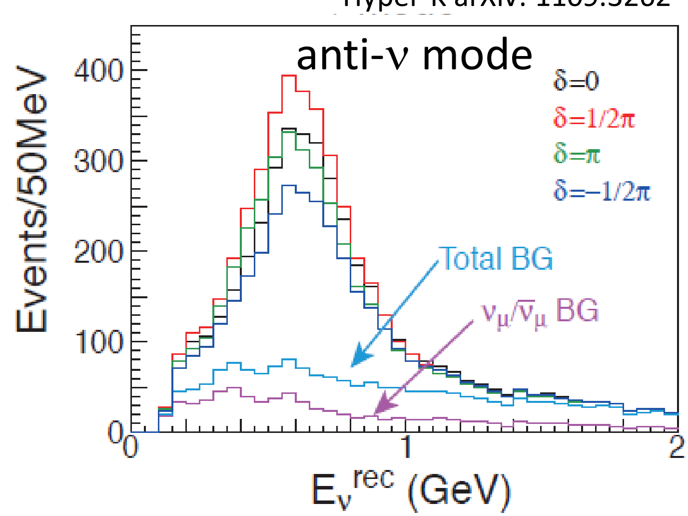


Hyper-K arXiv: 1109.3262

◆J-PARC/Hyper-K

(1.66MW with shorter run time in this fig.)

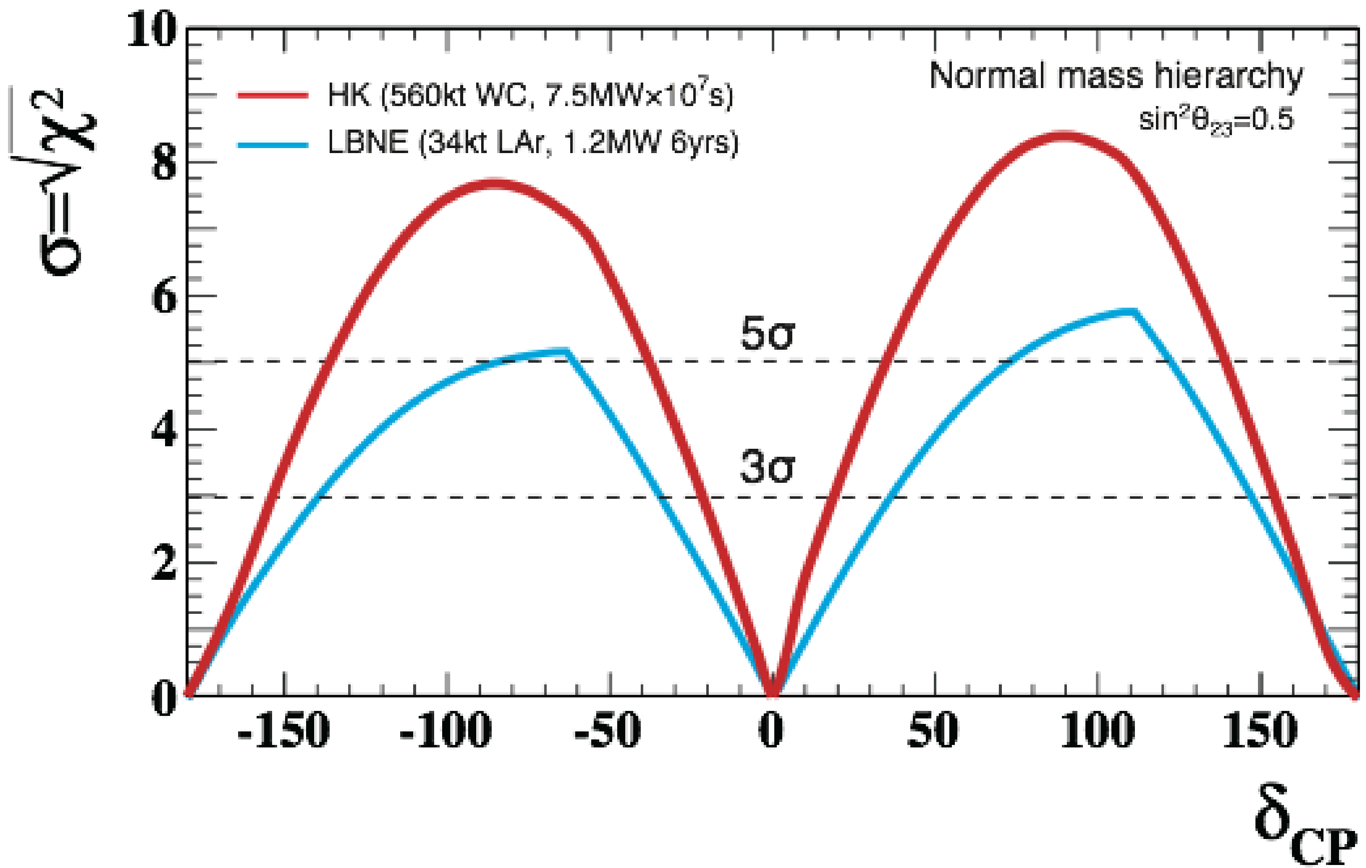




CP violation (LBNF/DUNE and J-PARC/Hyper-Kamiokande)

CP violation sensitivity (MH assumed to be known)

Plot by M. Shiozawa
K. Abe et al., arXiv: 1502.05199
M.Thomson, 2nd International meeting for Large Neutrino Infrastructure, April 2015



Hyper-K slightly better due to larger statistics
(➔ low E short BL is OK → other possibilities; Daeδalus and ESSnuSB)

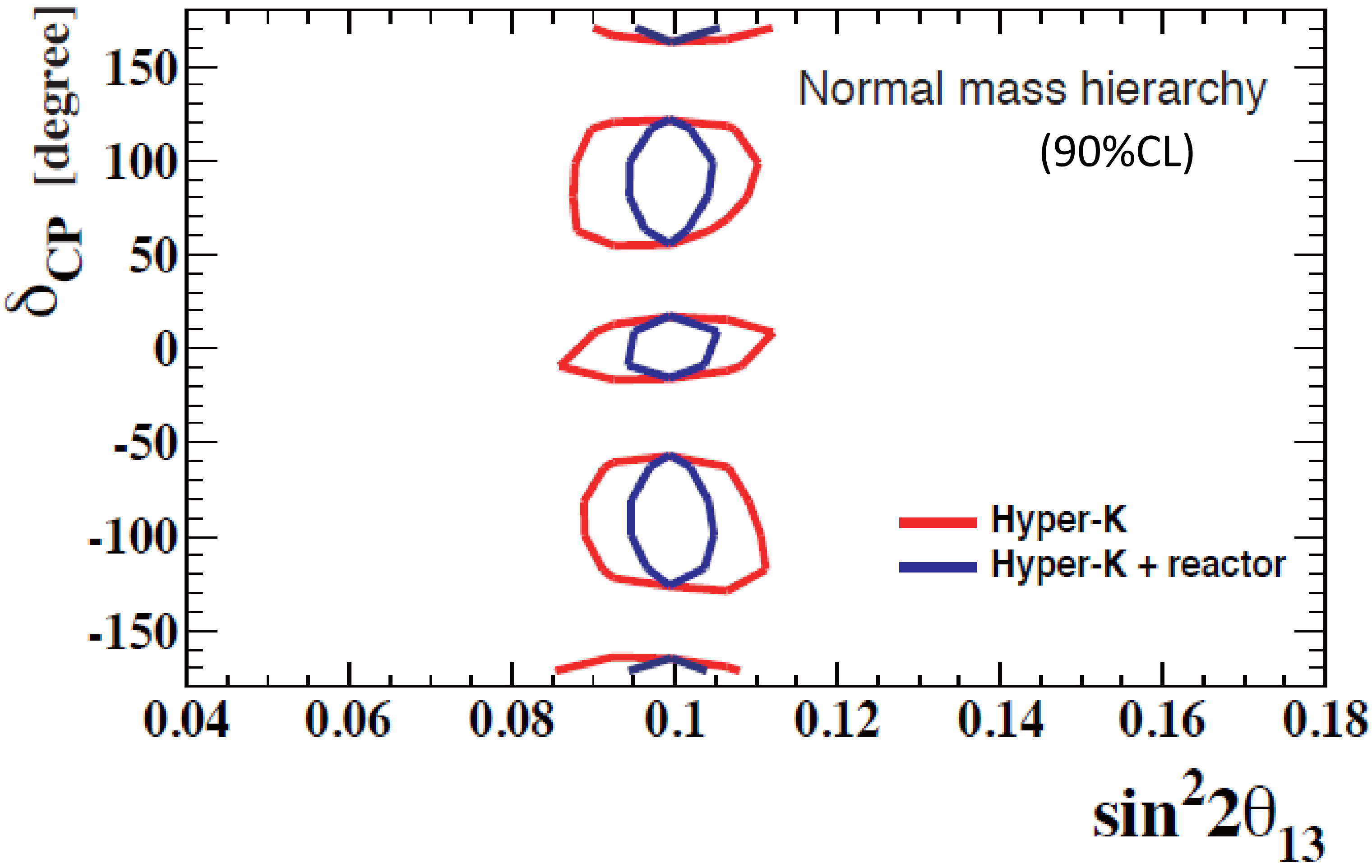
CP phase measurement

K. Abe et al., arXiv: 1502.05199

Measurement of δ_{CP}

(MH assumed to be known)

Hyper-Kamiokande

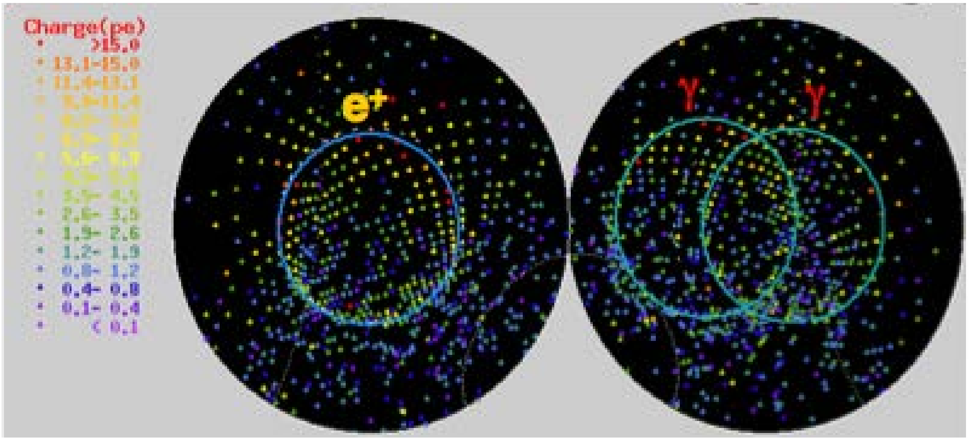


Other physics with future neutrino detectors

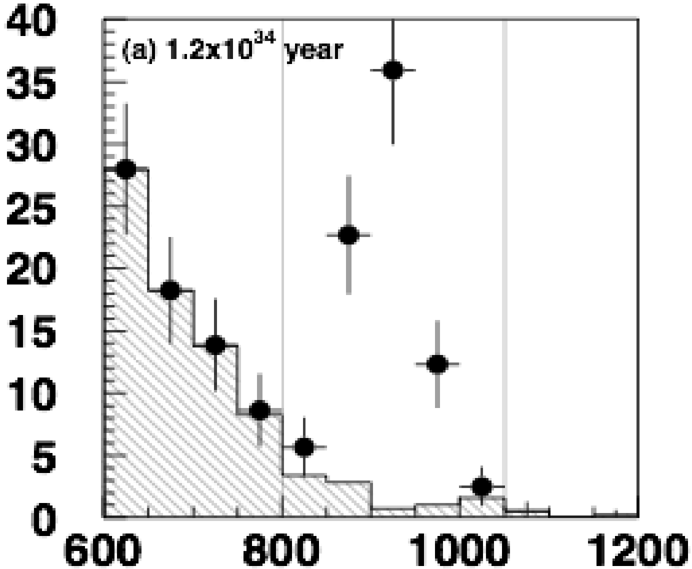
- Proton decay

Proton decays (1): $e^+\pi^0$

- *Because of the importance of proton decay, we should not forget about proton decay in the future (neutrino) detectors.*



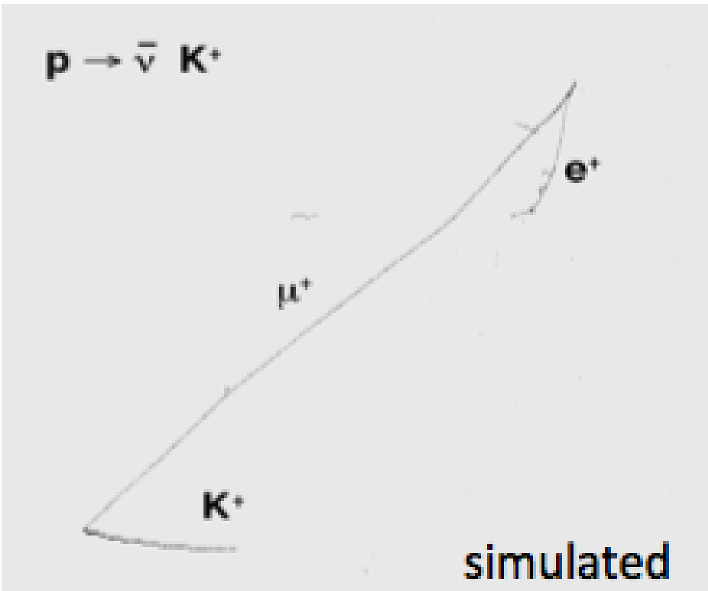
Water Cherenkov:
Simulation with 20% photocathode coverage.



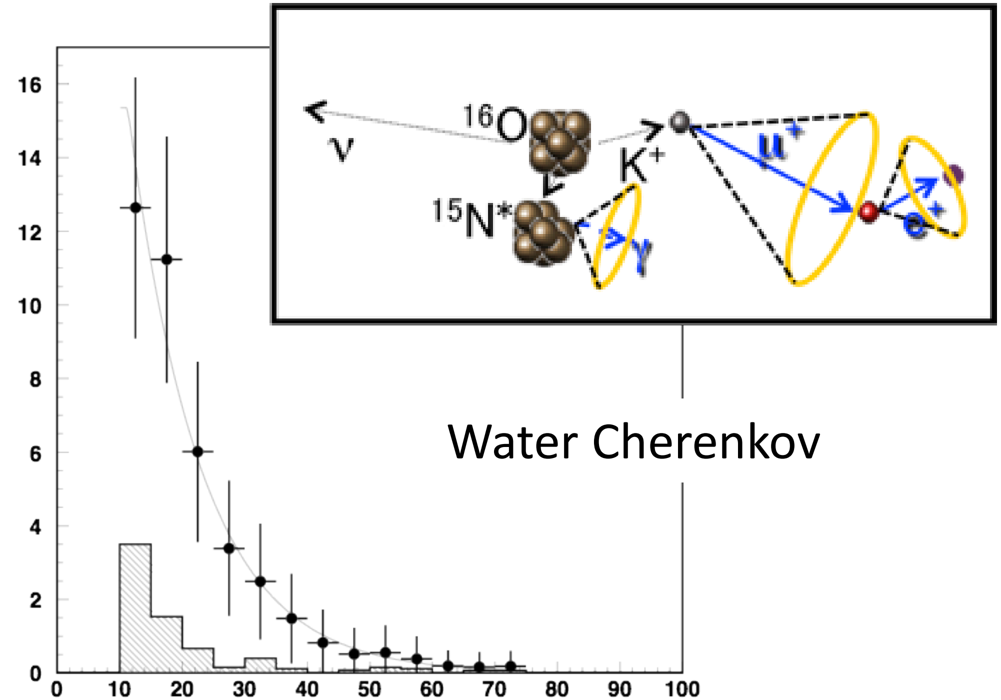
	Hyper-K		DUNE (LAr-TPC)	
$e^+\pi^0$	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)
	40	2.5	45	1

A. Bueno et al., hep-ph/0701101

Proton decays (2): $\bar{\nu}$ K^+



Liq. Argon: Simulation.



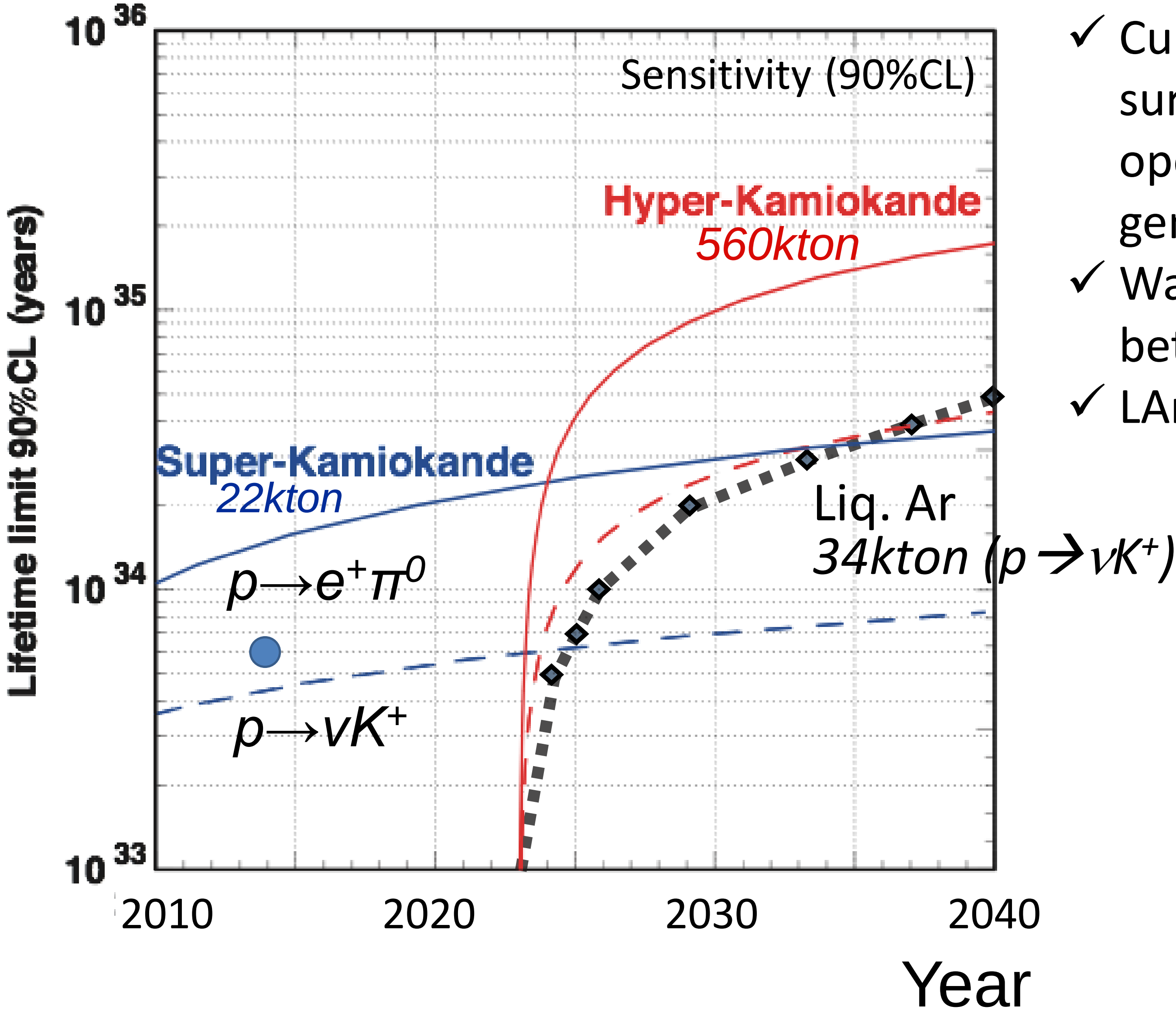
K^+ decay time (nsec)

	Hyper-K		DUNE (LAr-TPC)	
	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)
νK^+	13	6.2	97	1

Estimate from SK collab.
arXiv: 1408.1195 (w/ 20% coverage)

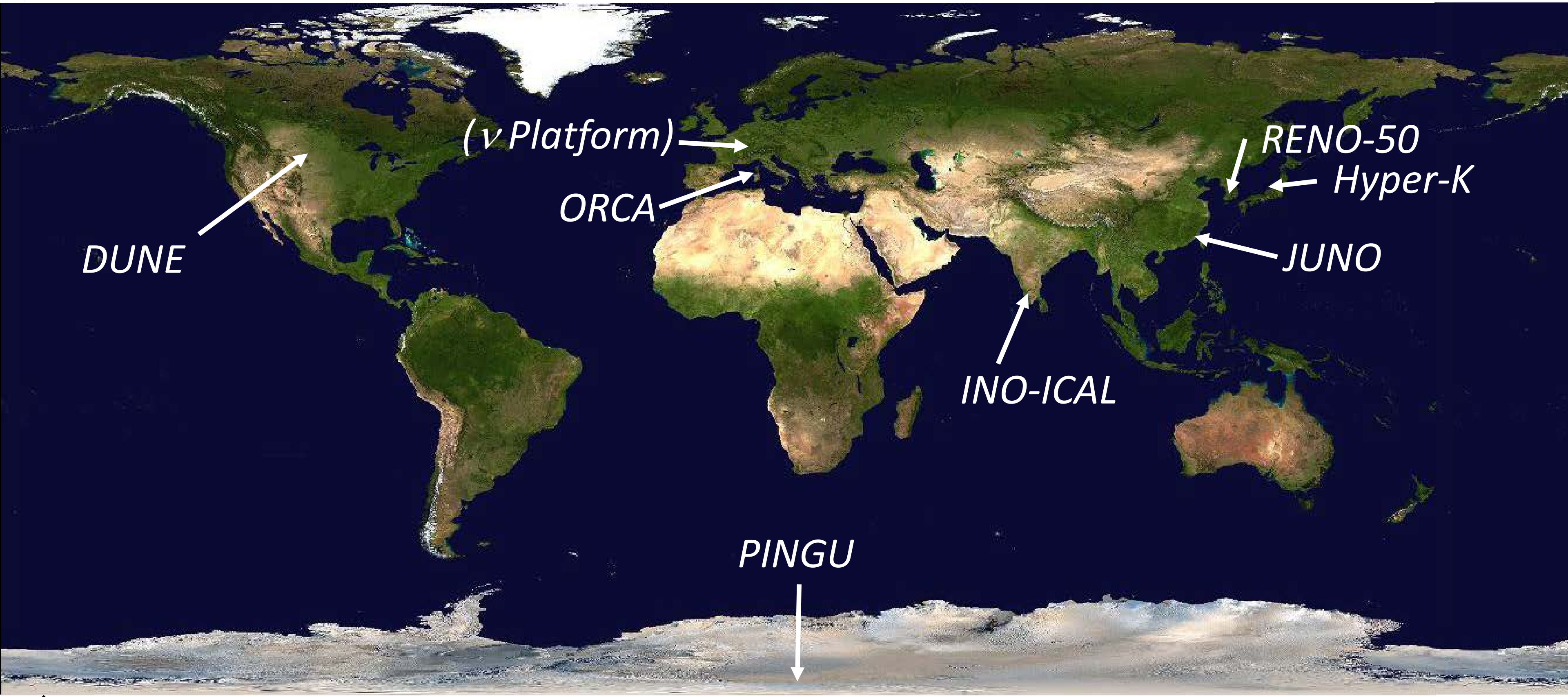
A. Bueno et al., hep-ph/0701101,
B. LBNE collab., arXiv:1307.7335

Proton decays: estimated limit…



- ✓ Current limited to be surpassed in ~1 year operation of the next generation detector(s).
- ✓ Water Ch. much better for $p \to e\pi^0$
- ✓ LAr better for $p \to \nu K^+$

Summary

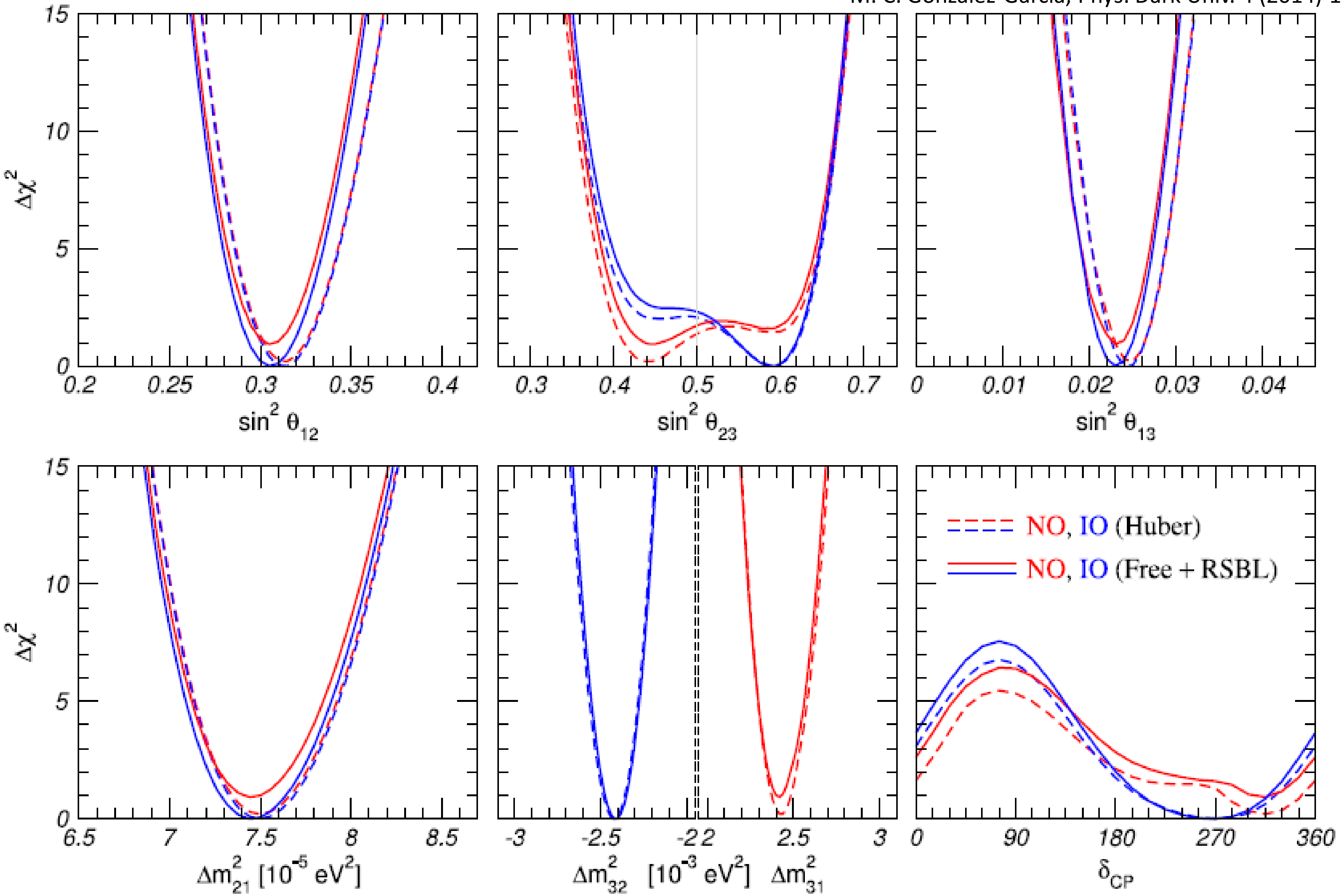


- The neutrino community has been planning many (and complementary) projects.
- In the last few years, many things have happened.
- Some "future experiments" already entered into the project phase!
- We will learn much more on neutrinos in the coming years!

Back ups

Global fit

M. C. Gonzalez-Garcia, Phys. Dark Univ. 4 (2014) 1-5

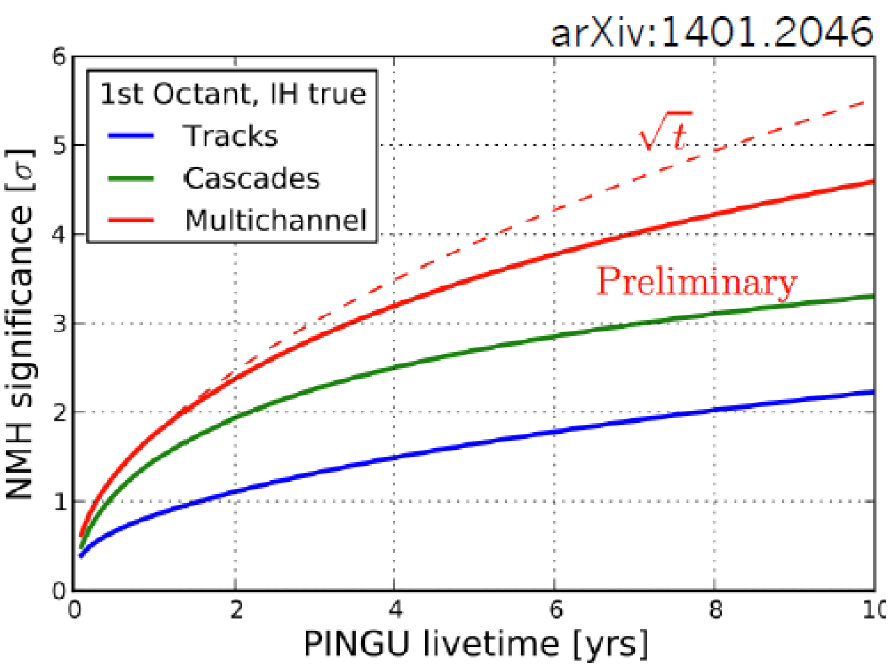


PINGU and KM3NeT/ORCA: Sensitivities to MH

Both cascade (ν_e enriched) and track (ν_μ enriched) used. Detector resolutions taken into account.

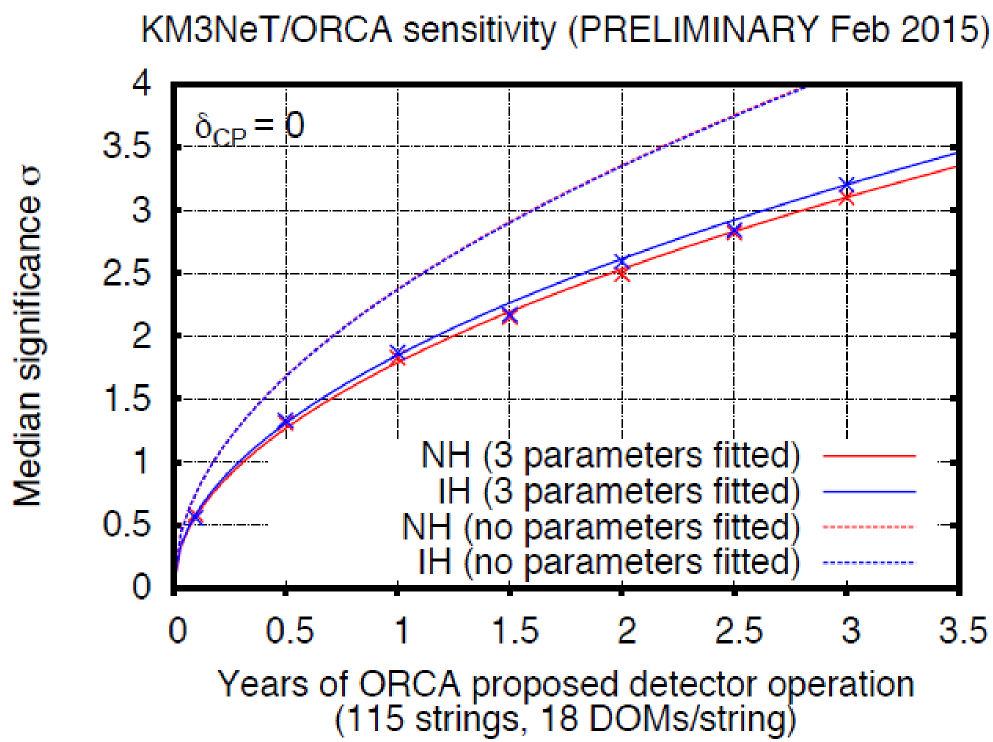
PINGU S. Boeser Neutrino Telescope 2015

Instrumented volume: ~5 M m^3
2400 Optical Modules.



KM3NeT/ORCA T. Eberl, Neutrino Telescope 2015

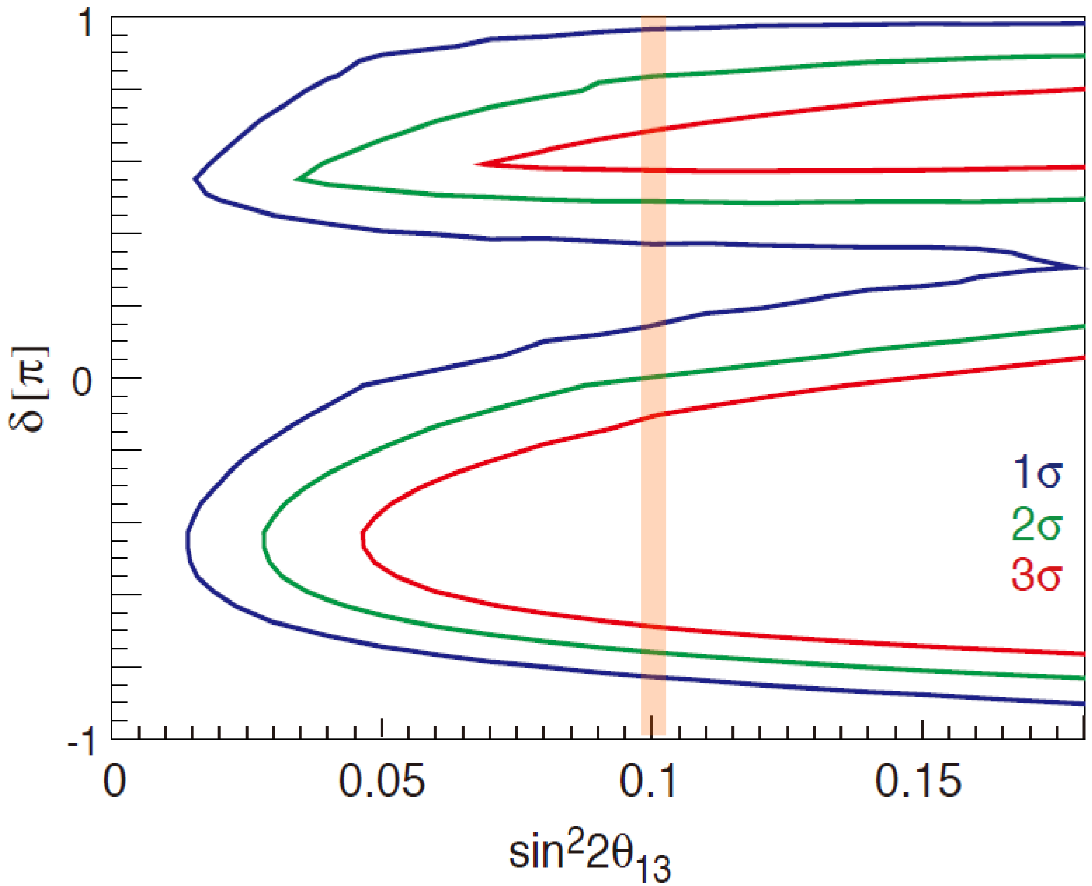
Instrumented volume: ~3.7M m^3
2070 Optical Modules



In both experiments, ~3σ in 3 years is expected (systematic very important).

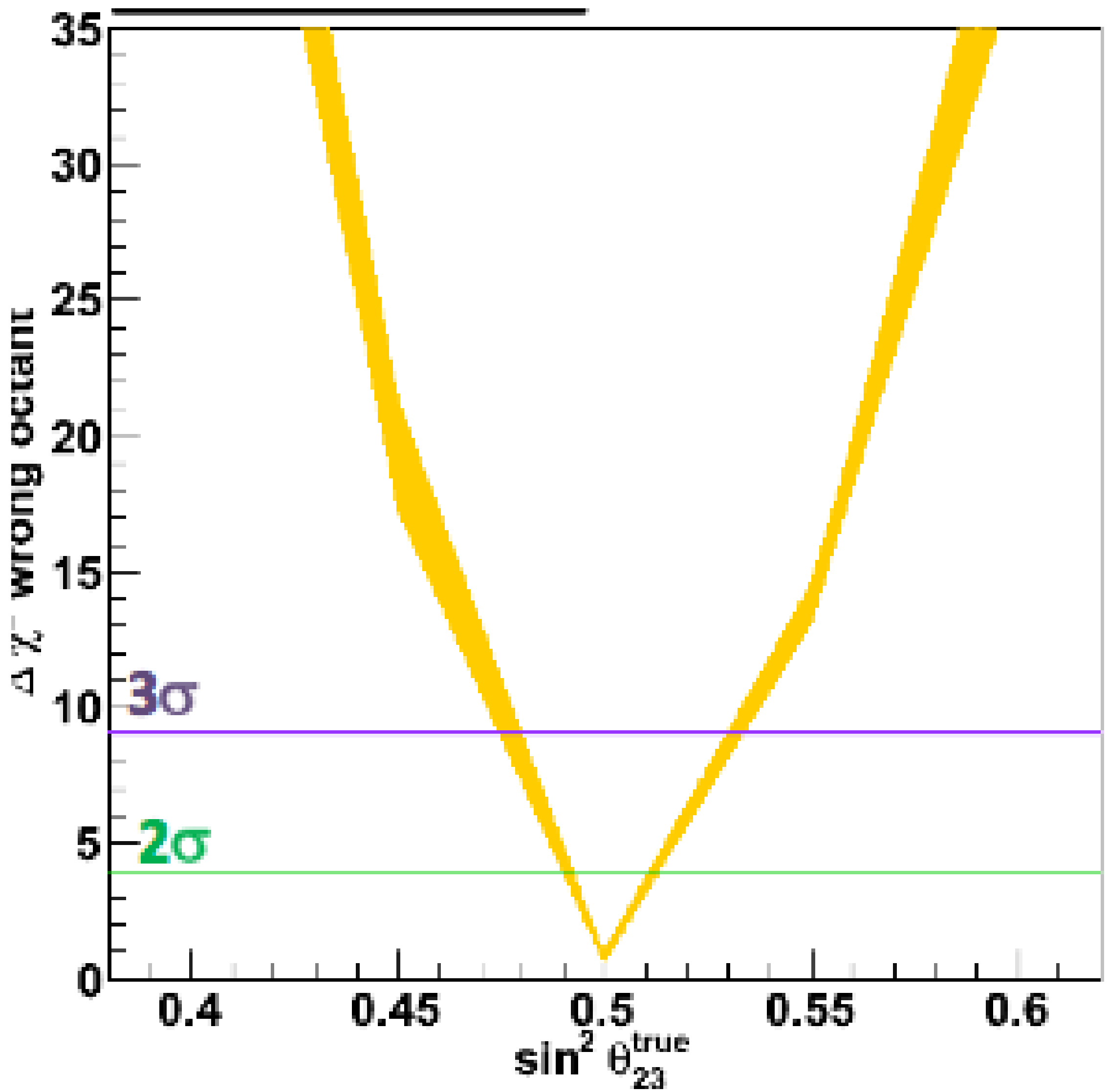
MH in Hyper-K

Beam only
(3yrs ν + 7 years anti-ν)



30～40% chance
(by J-PARC – Hyper-K beam ν only)

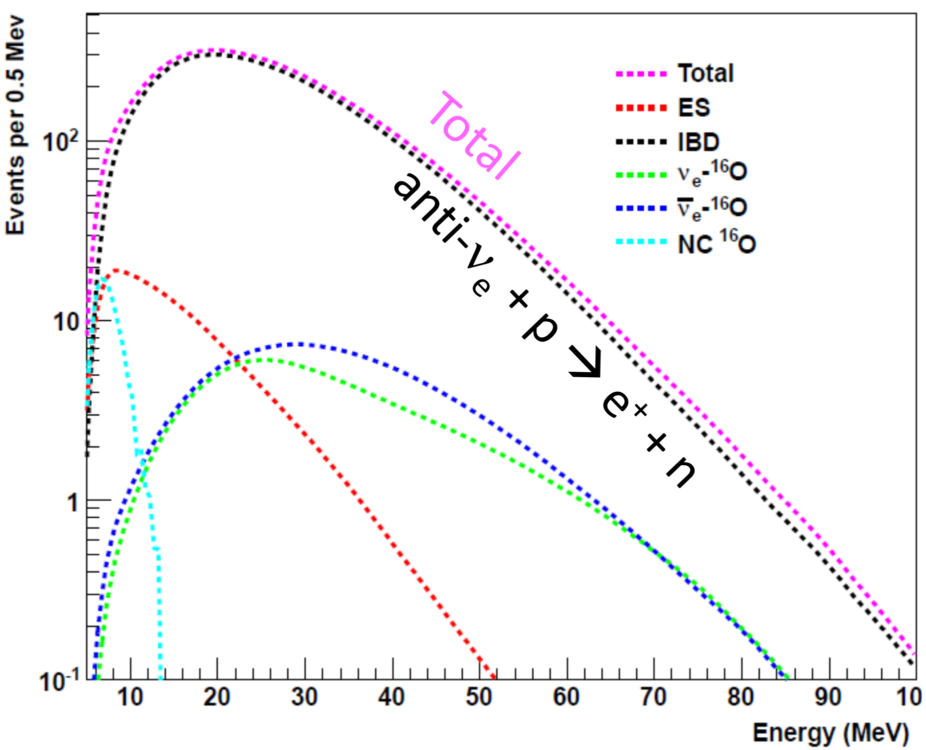
θ_{23} octant in Hyper-K based on atmospheric ν



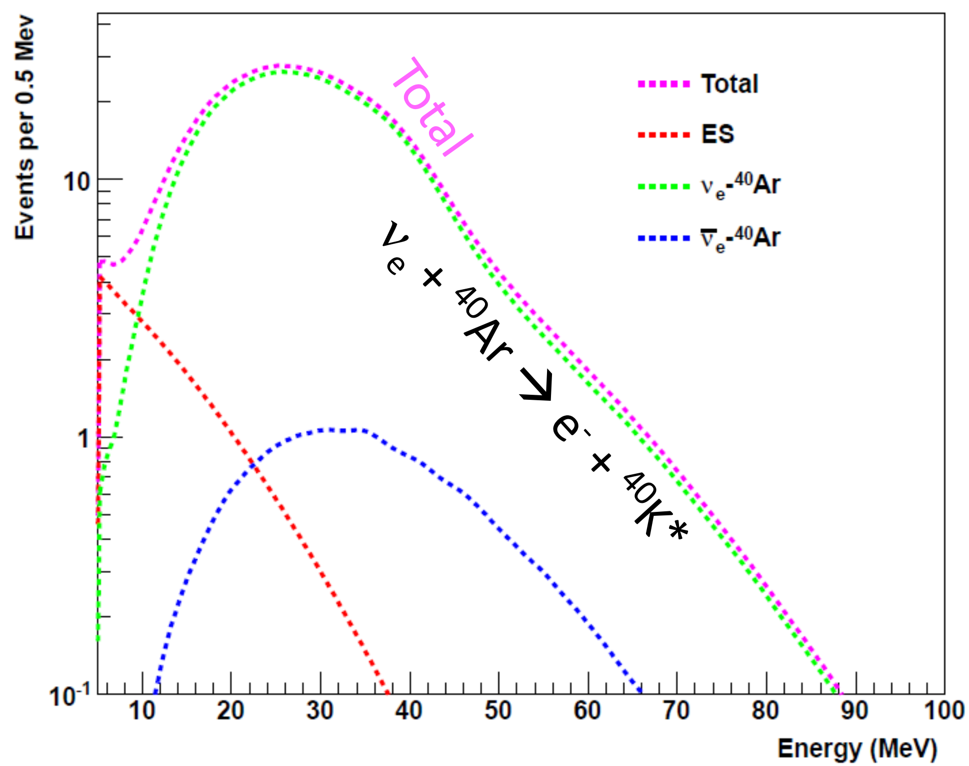
Supernova neutrinos

K. Scholberg, Ann. Rev. Nucl. Part. Sci. 62 (2012) 81-103.

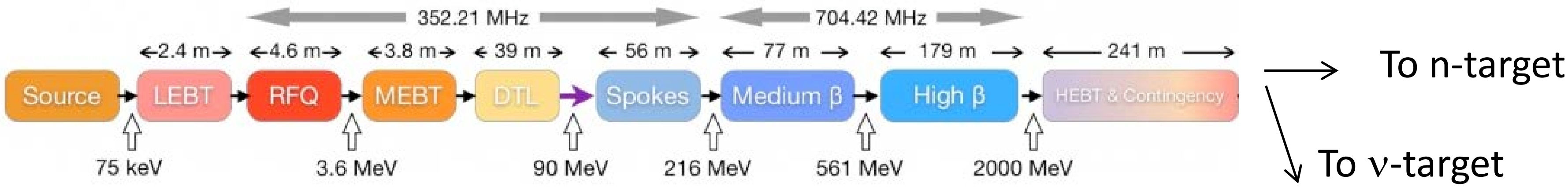
Water Ch. (100kton)



Liq. Ar (17kton)



European Spallation Source for neutrinos: ESSnuSB



- The ESS linac being built in Lund for neutron spallation: proton acceleration 5 MW
- Repetition rate can be increased to permit acceleration of
  - 5 MW protons for neutrons + 5 MW H- for neutrinos
- $>2.7\times10^{23}$ 2 GeV p.o.t/year
- Detector at 2nd oscillation max (2 GeV, 540 km)
- CPV: 5 σ could be reached over 60% of δ_{CP} range
- WC Detector 500 kt: MEMPHYS
- ESS ready by 2023
- If CDR ready by 2018, ESSnuSB ready by 2030