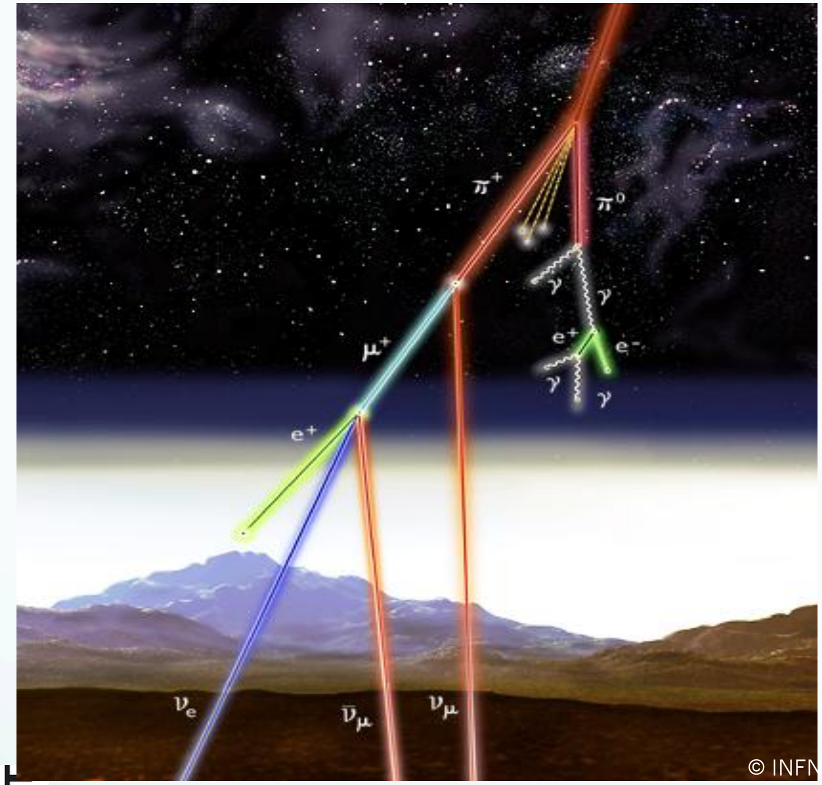
Status and prospects for atmospheric ν experiments

[in view of Mass Hierarchy determination]



I Atmospheric Neutrinos

The PMNS Matrix

Matter Effects

Fluxes and cross-sections

II Detectors

(latest achievements and prospects)

Water/Ice Cherenkov

Magnetized Trackers

Liquid Argon TPCs

Antoine Kouchner

University Paris 7 Diderot- AstroParticle and Cosmology

Credits - Acknowledgements

J. Brunner, A. Cabrera, A. de Gouvea, D. Grant, M. Nakahata, N. Mondal, A. Tonazzo, C. Walter, R. Wendell

Oscillations of Massive Neutrinos

- Neutrinos have distinct masses and mix (PMNS)

☞ E. Lisi

Neutrino oscillations can be described with 6 parameters (3 Dirac neutrinos):

- 3 mixing angles
- 2 mass-squared differences

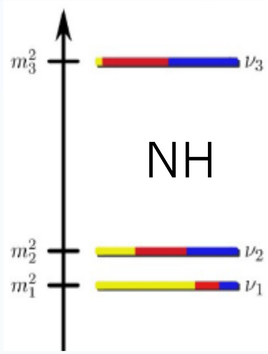
} <10%

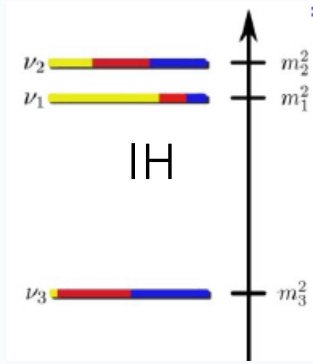
$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

MH

- CP phase





- Absolute mass scale
- Nature (Dirac vs Majorana)
- Origin of neutrino mass and flavor
- Core-Collapse Supernovae Physics

- « Standard approach » :probe $\nu_\mu \leftrightarrow \nu_e$ governed by Δm^2_{13}

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\, P_{2\nu} = \sin^2\theta_{23}\, \sin^2 2\theta_{13}^{\mathrm{eff}} \sin^2\left(\frac{\Delta m^{\mathrm{eff}\,2}_{31}\, L}{4E_\nu}\right)$$

- Insensitive to the sign of Δm^2_{13} at leading order.

- Matter effects (MSW) come to the rescue → Modify the oscillation probability

(Additional potential $A = \pm \sqrt{2}\, G_F N_e$ in the Hamiltonian)

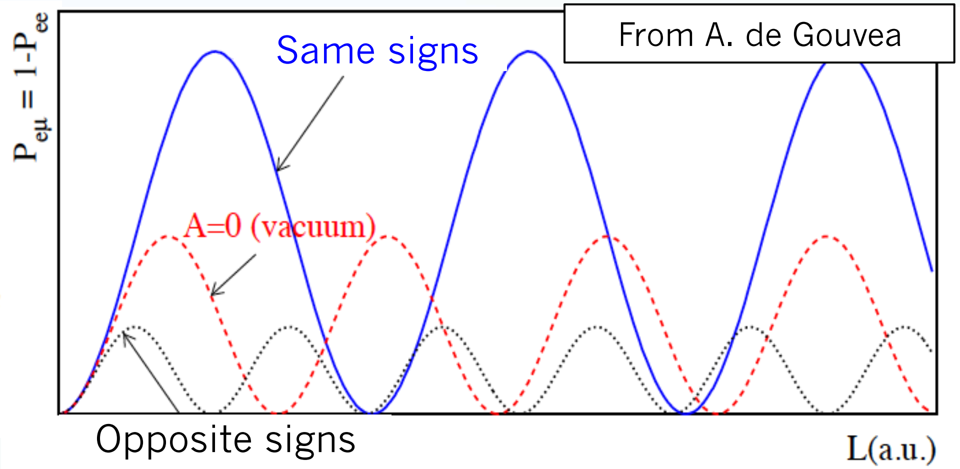
(Constant Density) Matter Effects

$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}^{\rm eff}\sin^2\left(\frac{\Delta_{13}^{\rm eff}L}{2}\right),$$

$$\sin^2 2\theta_{13}^{\rm eff} = \frac{\Delta_{13}^2\sin^2 2\theta_{13}}{(\Delta_{13}^{\rm eff})^2},$$

$$\Delta_{13}^{\rm eff} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta_{13}^2\sin^2 2\theta_{13}}$$

$$\Delta_{13} = \frac{\Delta m_{13}^2}{2E},$$

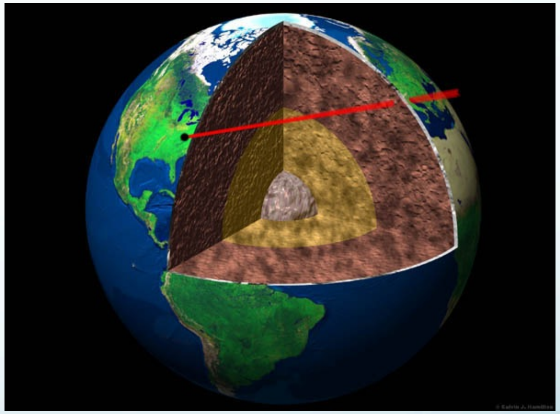


$\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy

Matter resonance: A → $\Delta_{13}\cos 2\theta_{13}$
- Effective mixing maximal
- Effective osc. frequency minimal

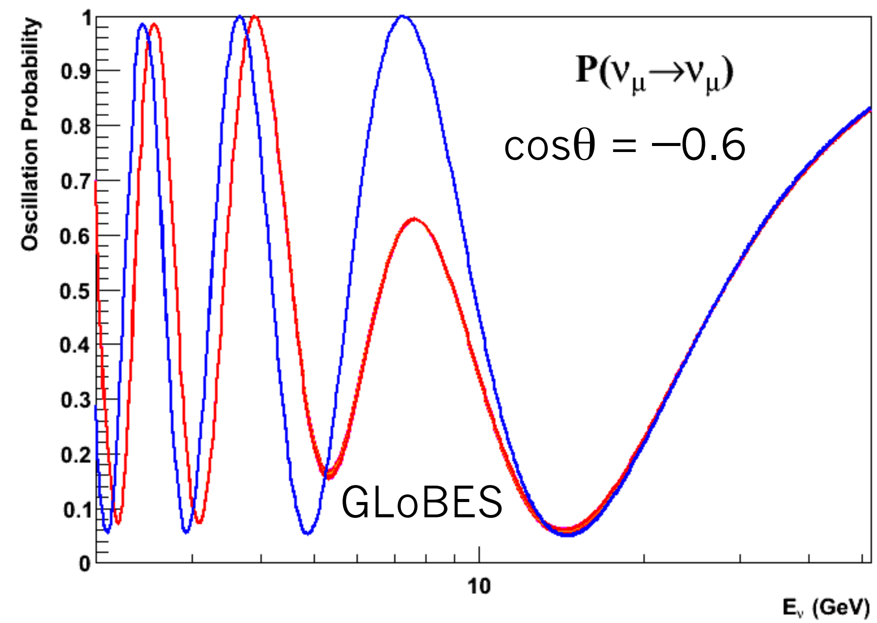
Resonance energy Earth:
- Mantle E_{res} ~ 7 GeV
- Core E_{res} ~ 3 GeV

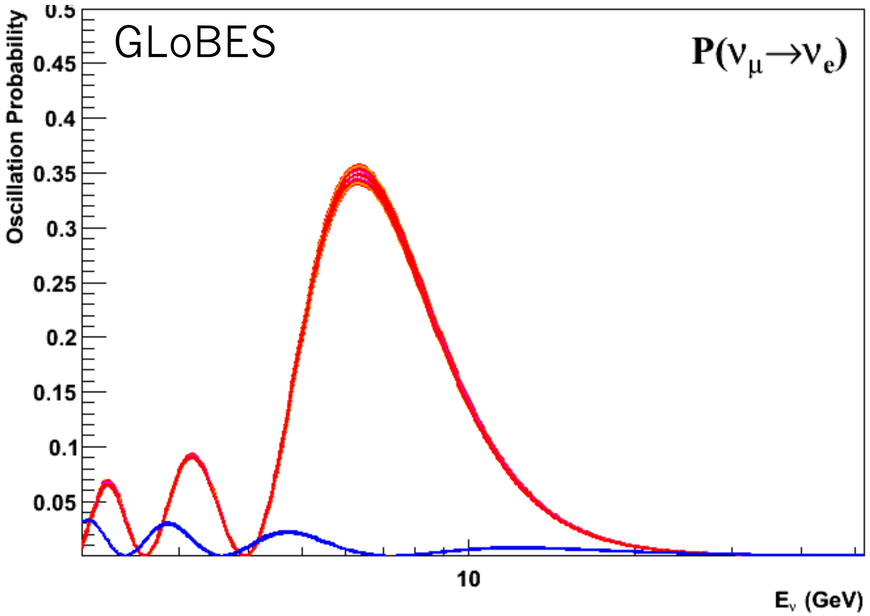


Requirements:
- Δ_{13} ~ A matter potential must be significant but not overwhelming
- L large enough – matter effects are absent near the origin
- Distinction between neutrinos and anti-neutrinos

→ different flux and cross-sections!

Phenomenological Considerations



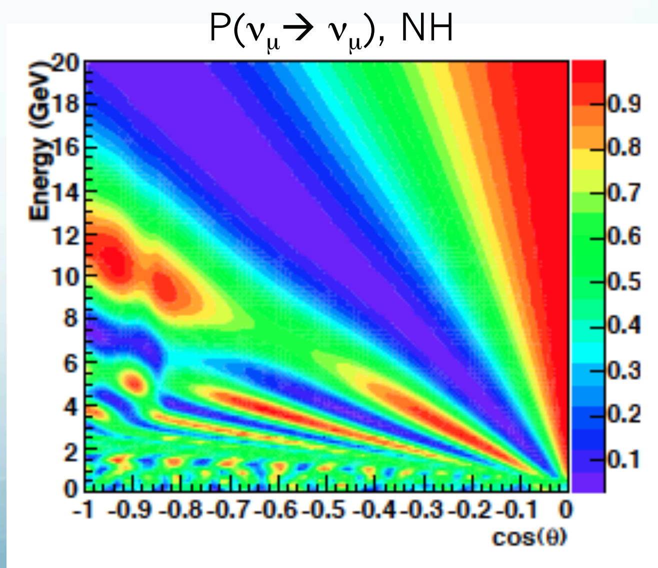


Inverted Hierachy

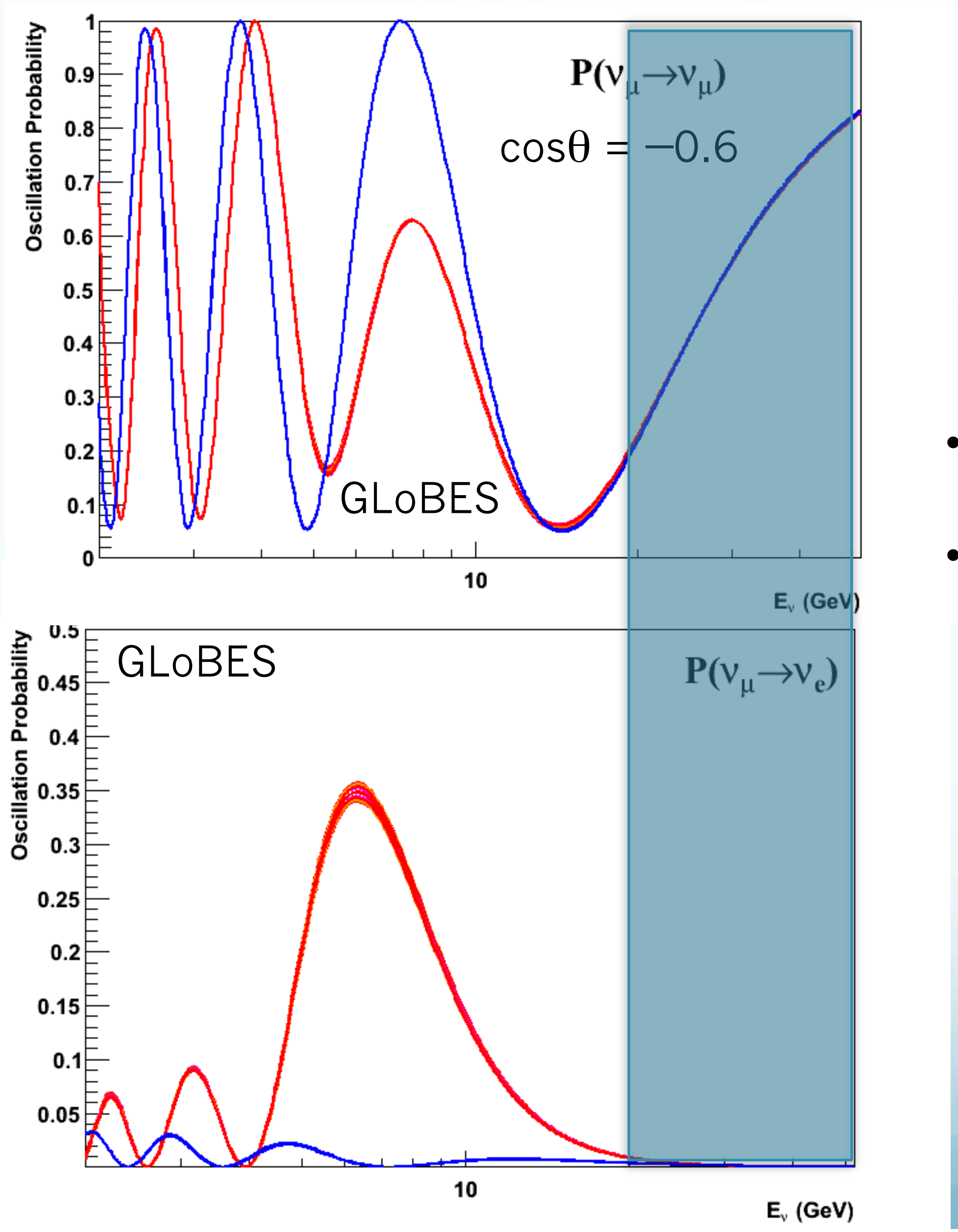
Normal Hierachy

In each case, CP-phase is varied in steps of 30 degrees

- Hierarchy differences disappear at around 15 GeV
- $P(\nu_\mu \rightarrow \nu_e) < 2\%$ at 20 GeV



Phenomenological Considerations



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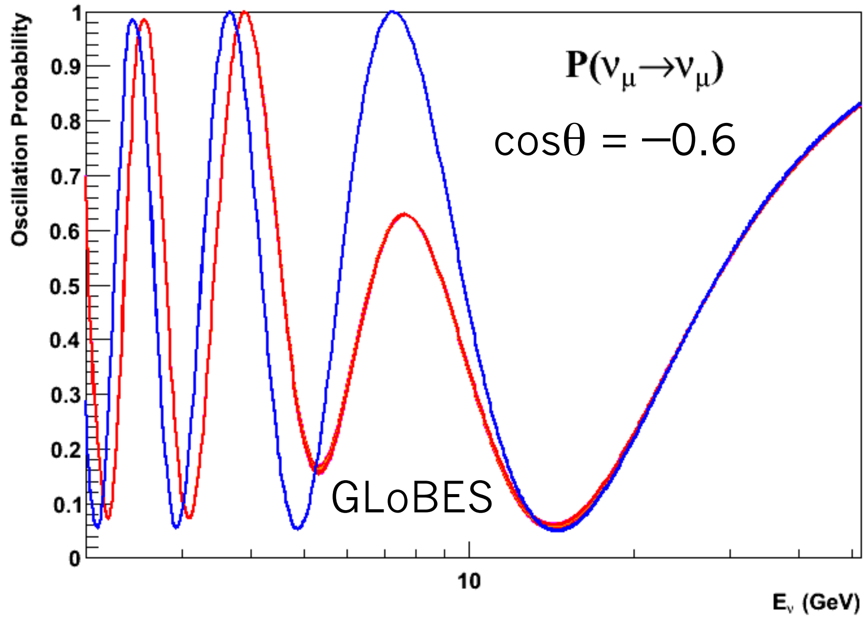
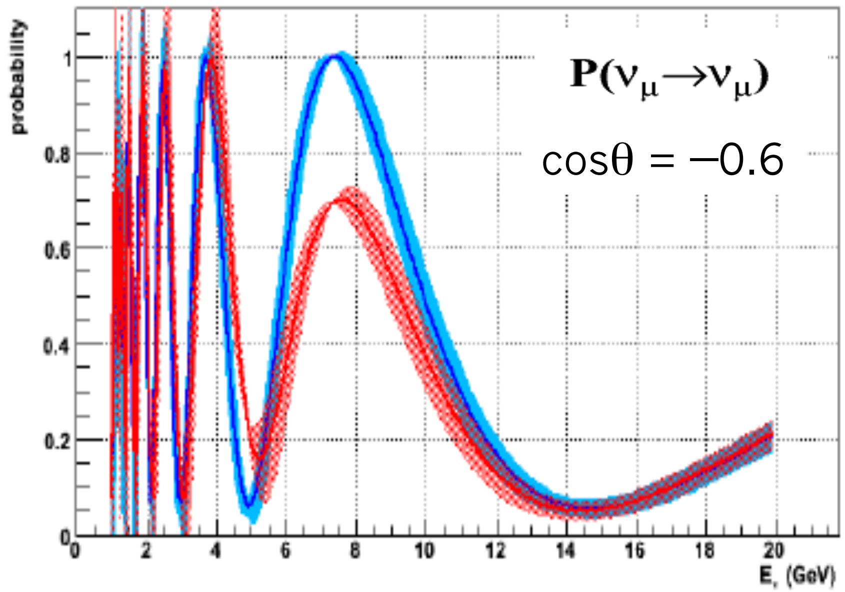
2 flavor $P(\nu_\mu \rightarrow \nu_\tau)$ in vacuum is a valid approximation
Recent results from ANTARES and IceCube

Phenomenological Considerations





Inverted Hierachy

Normal Hierachy

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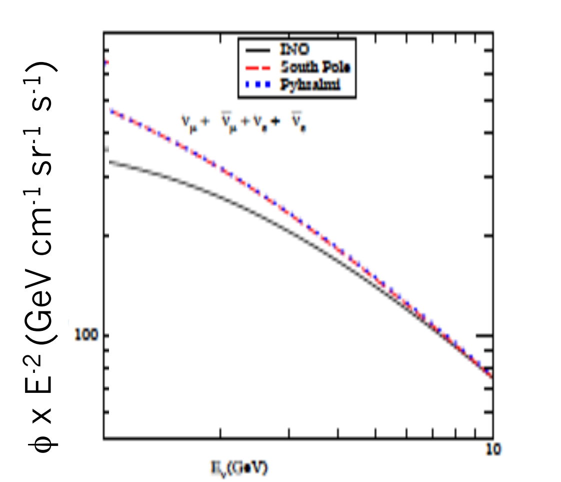
- $P(\nu_\mu \rightarrow \nu_e) < 2\%$ at 20 GeV

Degeneracies due to parameter uncertainties must be carefully considered!

Atmospheric neutrino spectrum

A beam for free!

$$\text{Cosmic Ray} + A_{air} \to \pi^+ + \ldots$$
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

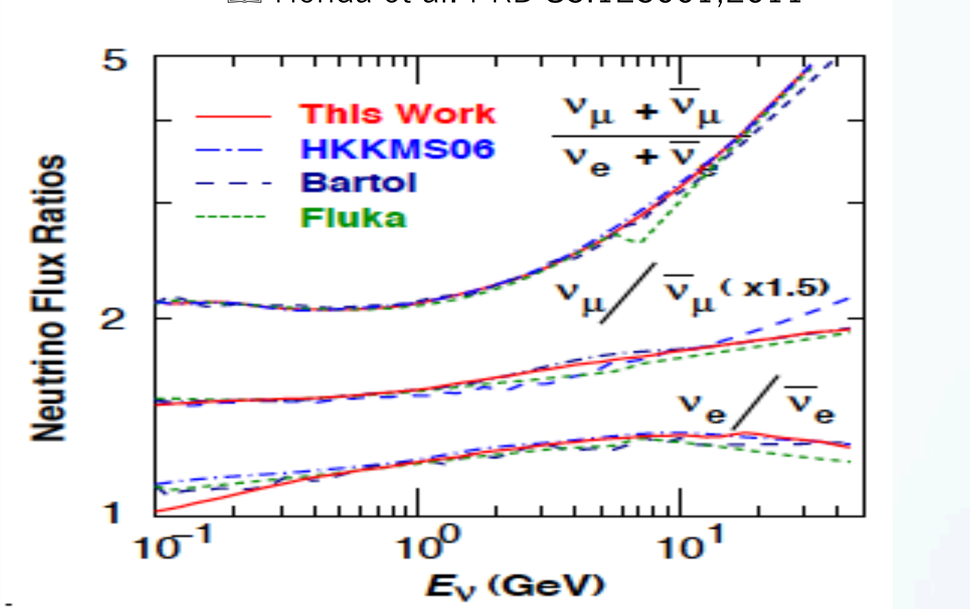


- Produce neutrinos and anti-neutrinos

Calculations now made as a function of the position on Earth and the time in year

- Broad energy range – Steeply falling spectrum
  → Requires good energy resolution
- Broad path-length range
  → Requires good direction resolution

📖 Honda et al. PRD 83:123001,2011



$$\Phi_{\nu_e}(E_\nu,\theta) = \Phi^0_{\nu_e}\, P(\nu_e \to \nu_e) + \Phi^0_{\nu_\mu}\, P(\nu_\mu \to \nu_e)$$
$$\simeq \Phi^0_{\nu_e}\left[1 + (\sin^2\theta_{23}\, r - 1)\, P_{2\nu}\right]$$

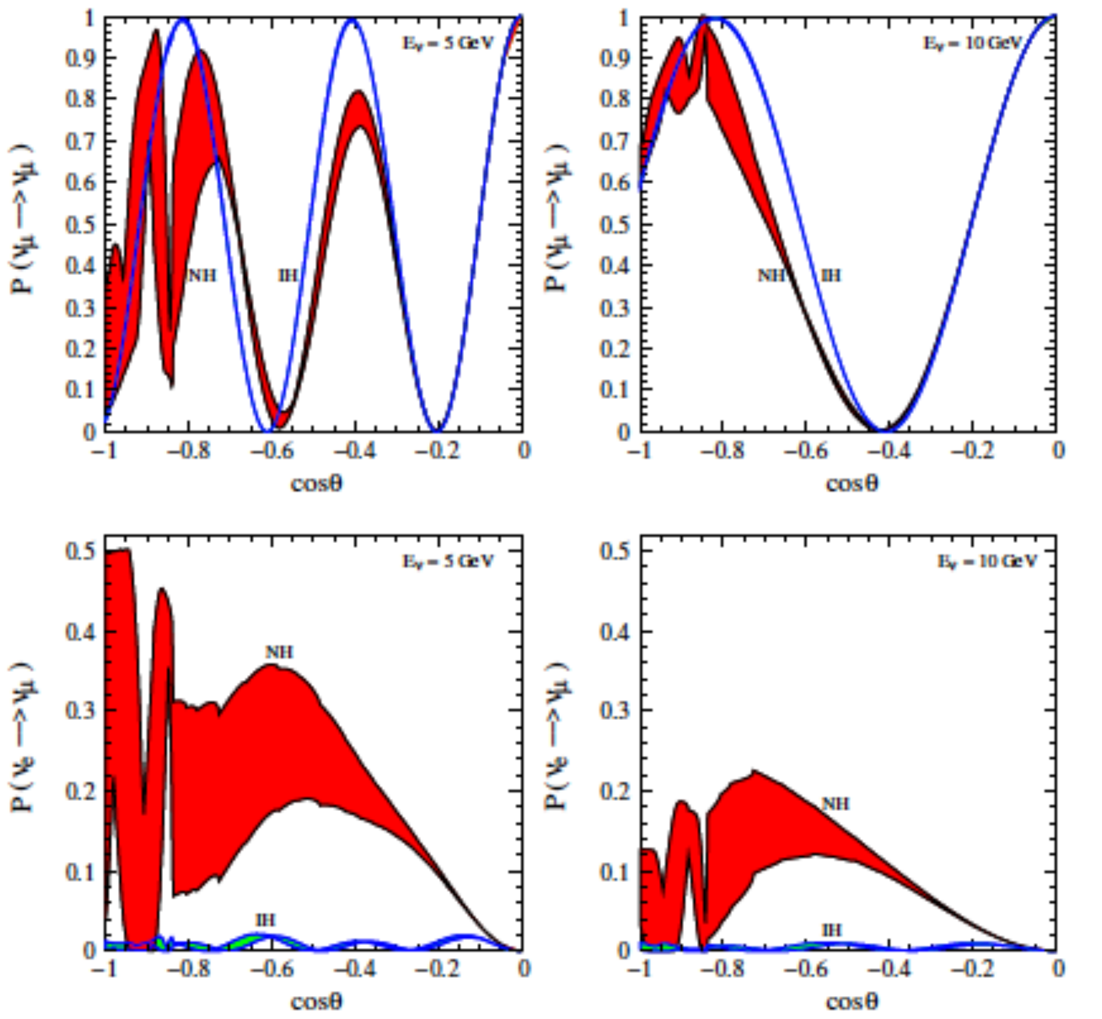
$$r \equiv \frac{\Phi^0_{\nu_\mu}(E_\nu,\theta)}{\Phi^0_{\nu_e}(E_\nu,\theta)}$$

"Screening effect"
$r \sim 2$ & $\sin^2\theta_{23} \sim 0.5$

But enhancement possible:
- r increases with energy
- Larger effect for second octant

Muon versus Electron channels

📖 Agarwalla et al. arXiv:1212.2238



Muons provide more statistics

Electron channel is more robust against detector resolutions…

Brings sensitivity to the Mass hierarchy

Lately considered by PINGU and ORCA while main channel for SK/HK

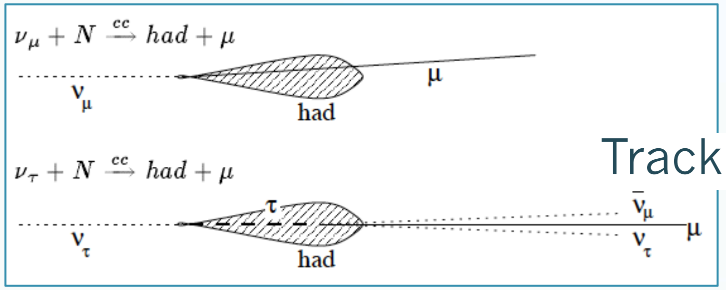
±10% Earth density

Neutrino Interactions

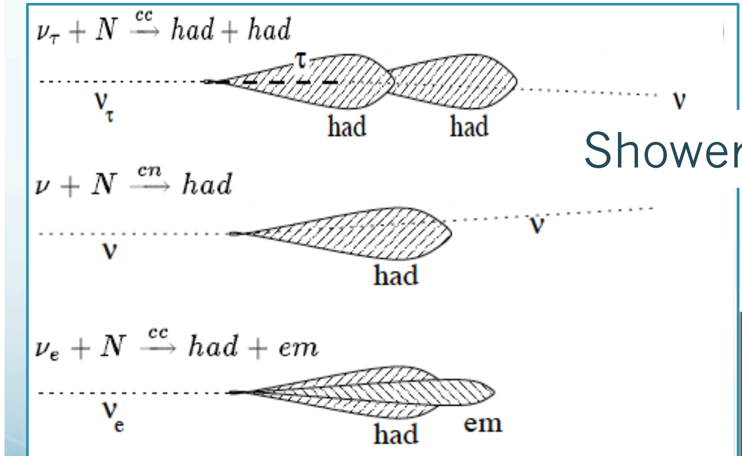
Different cross sections for ν and $\bar{\nu}$!

$$\sigma(\nu) \approx 2\sigma(\bar{\nu})$$

Different topologies:

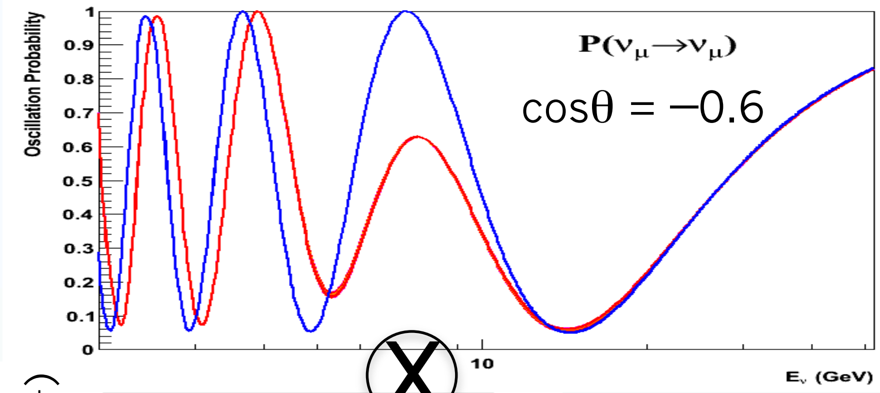


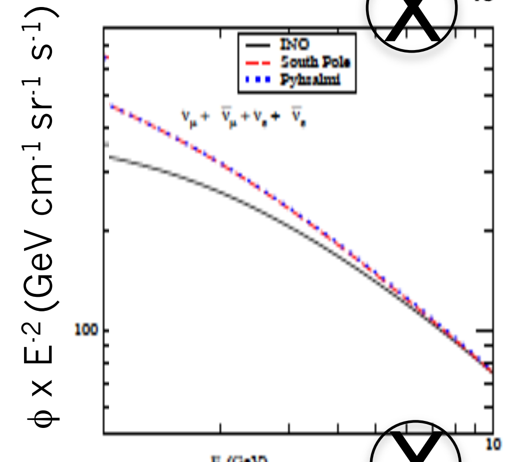
Track-like



Shower-like

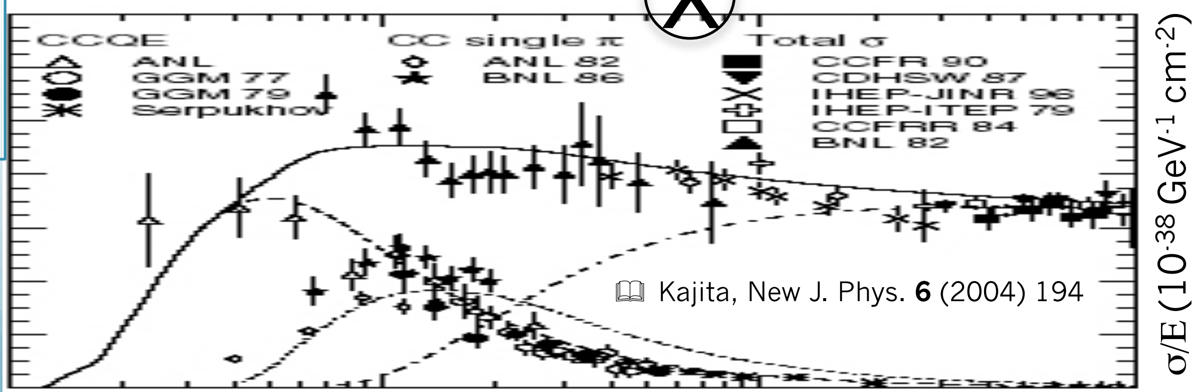
Systematics
→ Use external measurements and regions without oscillations





M.S. Athar et al. arXiv:1210.5154

Calculations now made as a function of the position on Earth and the time in year



Kajita, New J. Phys. **6** (2004) 194

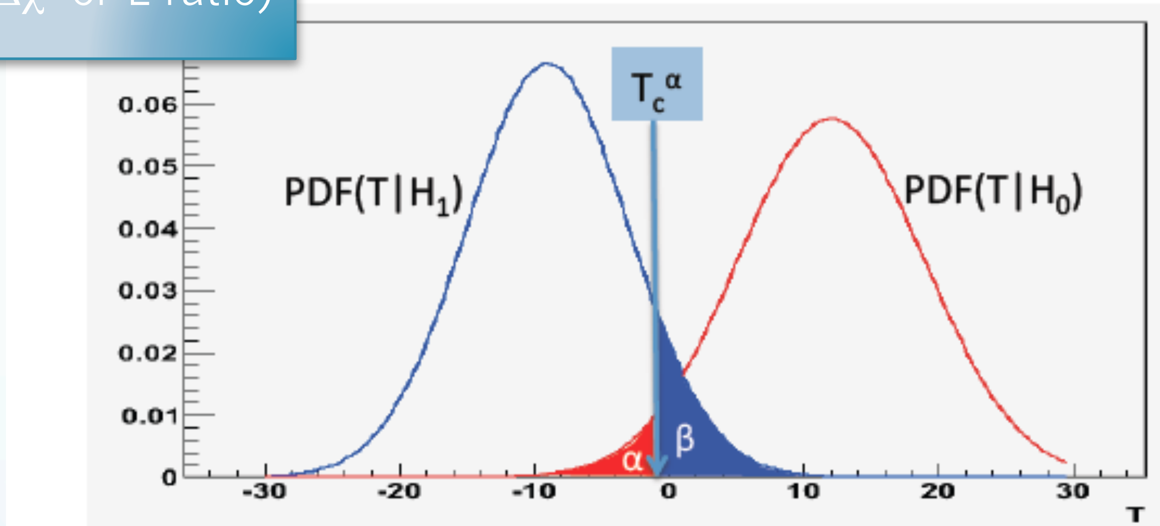
Figure of merit

☞ M. Blennow

For a given test statistic T ($\Delta\chi^2$ or L ratio)

Confidence Level CL = 1-α $= \int_{T_c}^{+\infty} PDF(T|H_0)dT$ → Reject H_0 at $(1-\alpha)$ CL ($T<T_c$)

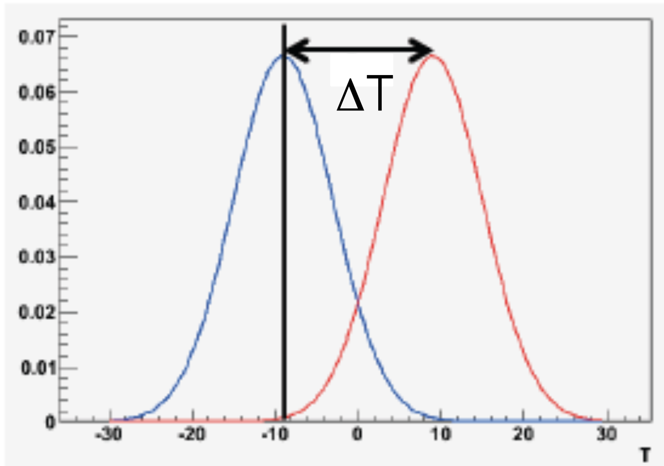
Power p= 1-β $= \int_{-\infty}^{T_c} PDF(T|H_1)dT$ → β probability to give the wrong answer



In the case of 2 Gaussian distributions

$PDF(T|NH)=N(T_0^{NH},2\sqrt{T_0^{NH}})$

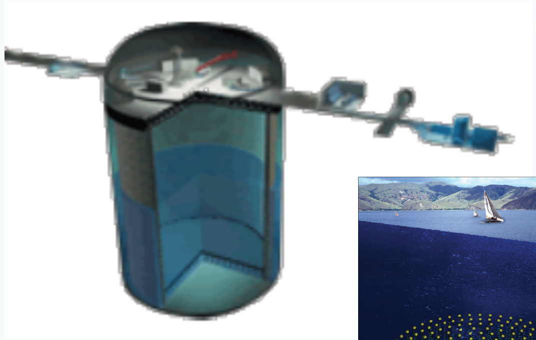
$PDF(T|IH)=N(-T_0^{IH},2\sqrt{T_0^{IH}})$

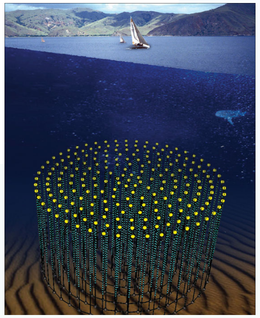


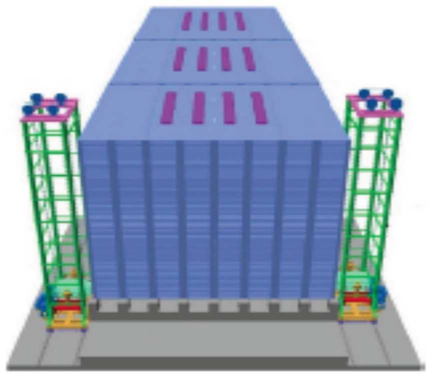
Significance of a "median experiment"
50% power
$\Delta T = 2\ T_0 = \sqrt{T_0}\ \sigma$

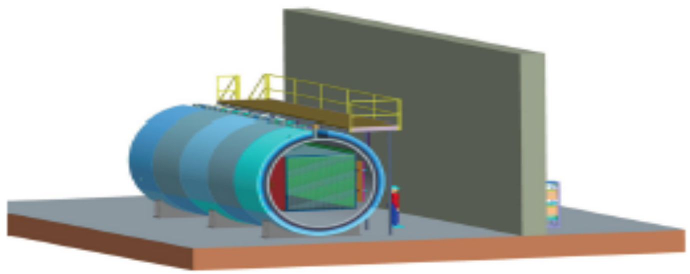
Used for comparisons between experiments

Atmospheric detectors









Cherenkov
- Underground
- SuperK → HyperK, MEMPHYS?

- 500 kton
- Low threshold
- No charge ID

- Deep-sea/ice
- Antares/Icecube →ORCA/PINGU

- Multi-Mton !
- Relatively poor E resolution
- No charge ID
- Relatively high threshold ~ GeV

Magnetized Iron Calorimeters

- SOUDAN,MINOS → ICAL, MIND?

- 50-100 kton
- Charge separation
- Good tracking
- Hadronic shower
- Poor electron sensitivity
- Relatively high threshold ~ GeV

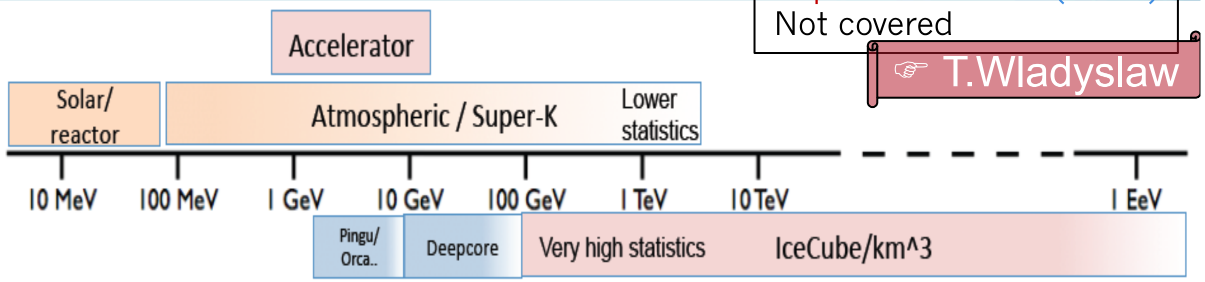
Liquid Argon

- Icarus → LBNO/E

- 20 – 100 kton
- Excellent μ and e tracking
- Hadronic shower
- Low threshold
- Magnetization?

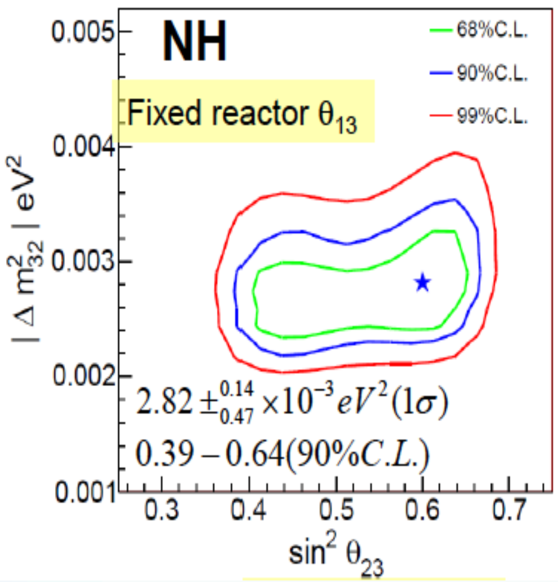
Liquid Scintillator (LENA)
Not covered

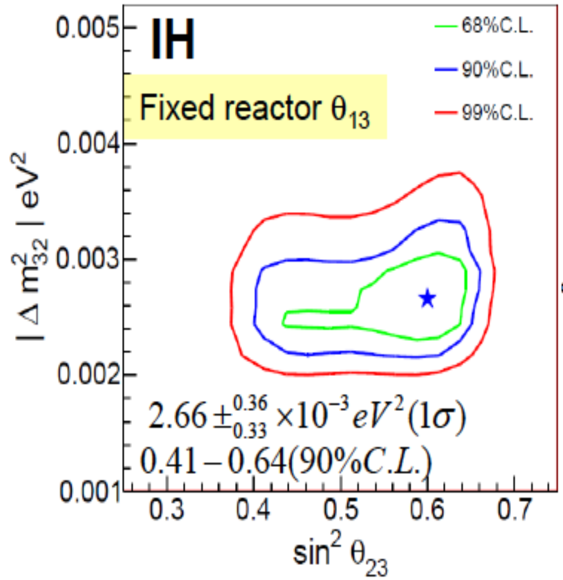
☞ T.Wladyslaw

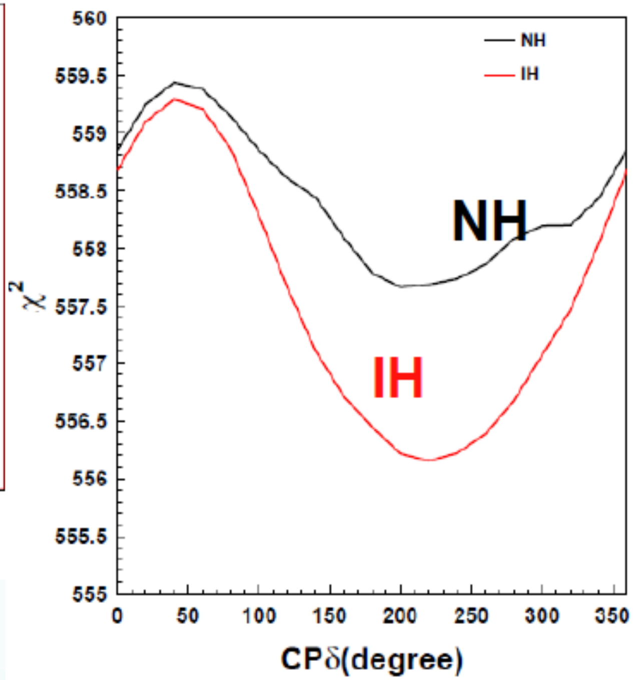


The latest results from SK

📖 Nakahata, ICRC 2013







Sensitivity (σ)		$\sin^2\theta_{23}$	SK Current	SK + 10 years
Hierarchy		0.4	0.70	0.98
		0.6	1.50	2.10
Octant		0.4	2.00	2.60
		0.6	1.61	2.10

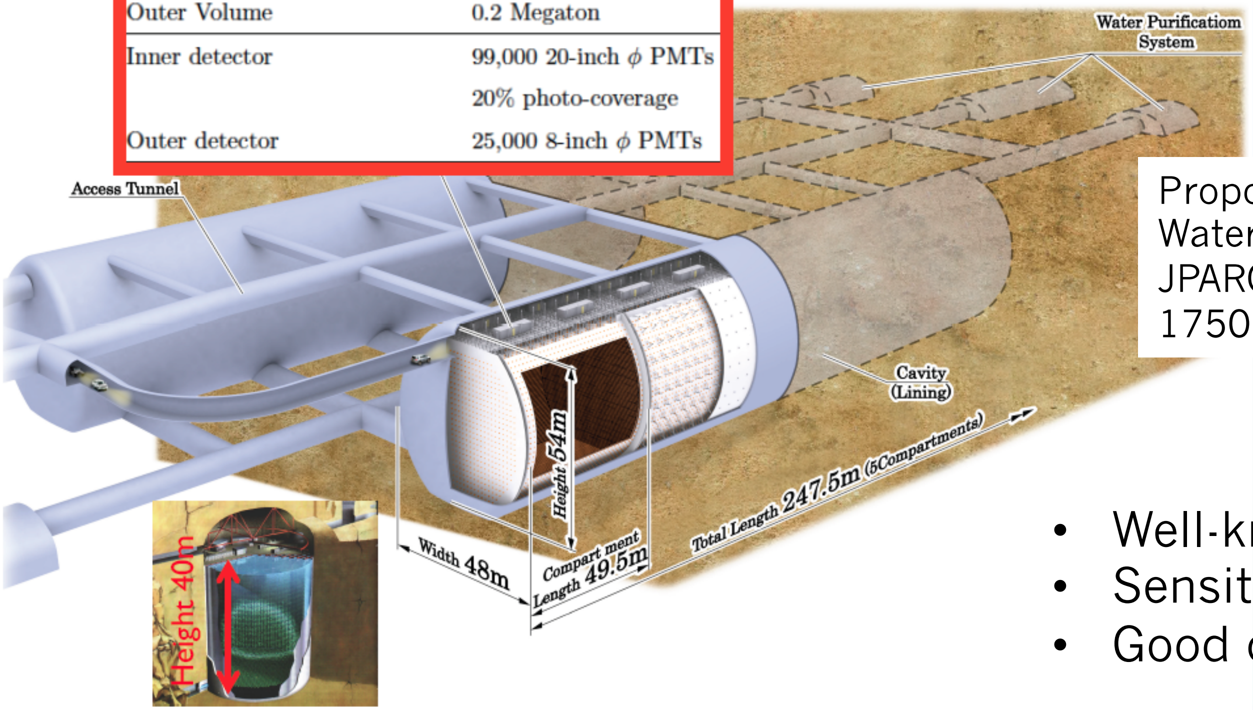
NH χ^2_{min} = 557.7 / 477 dof

IH χ^2_{min} = 556.2 / 477 dof

Preference for
IH
second octant
(not significant though)

Prospects with HyperKamiokande

Total Volume	0.99 Megaton
Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
Outer Volume	0.2 Megaton
Inner detector	99,000 20-inch ϕ PMTs
	20% photo-coverage
Outer detector	25,000 8-inch ϕ PMTs



Proposal for ~500 kT multi-purpose Water Cherenkov facility 295 km from JPARC and 8km off from SK.
1750 mwe overburden.

- Well-known technology
- Sensitive to ν_e and ν_μ (and ν_τ)
- Good control of systematics

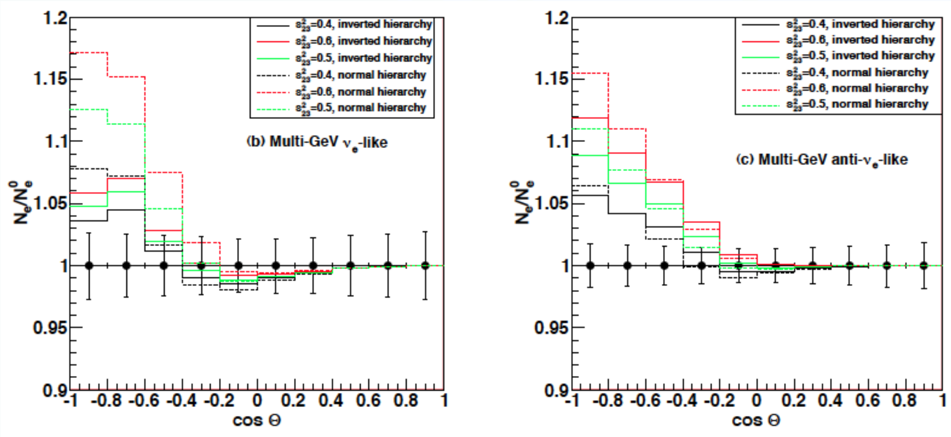
Status:

- Among top priorities in Japan (with ILC) : 800 M$ estimated cost (without beam)
- If funded, access tunnel work should start in 2016
- Excavation works in 2018
- Detector operation in 2023

Similar prospects for MEMPHYS

☞A. Tonazzo

Prospect for the MH (atm)

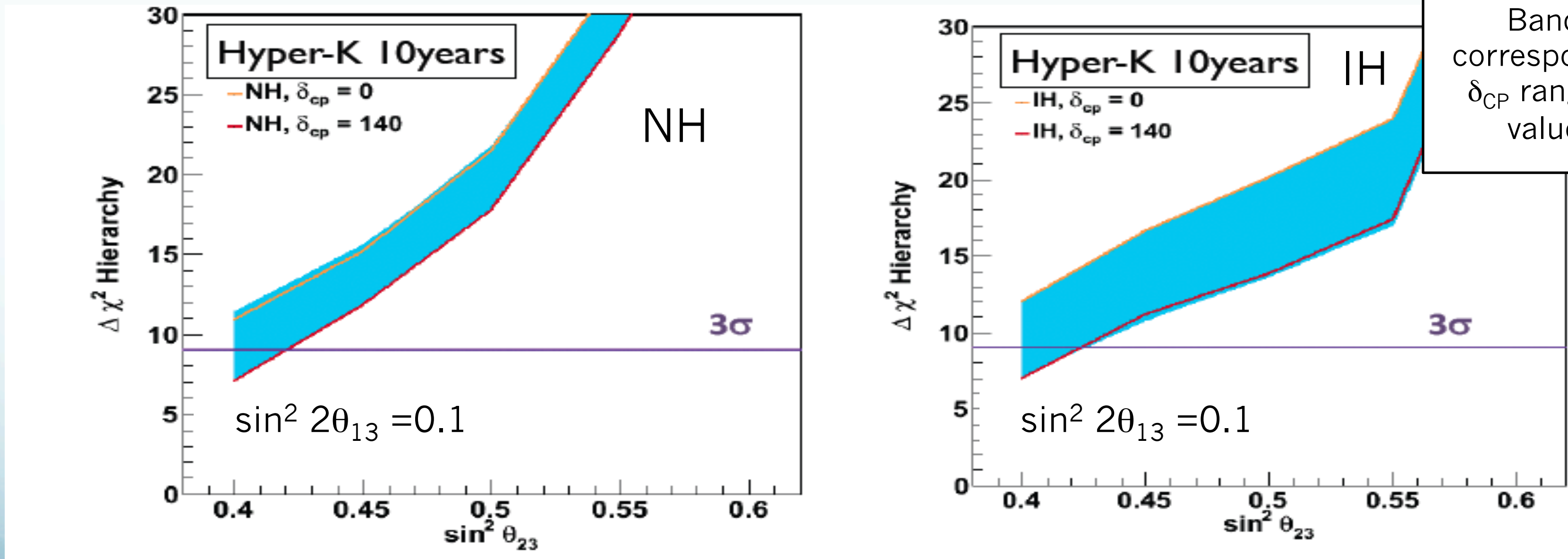


Ratio of oscillated ν_e rate over no oscillation case in sub-GeV and Multi-GeV channels.

$$\frac{N_e}{N_e^0} \cong \Delta_1(\theta_{13}) \Leftarrow \textbf{Matter effect}$$
$$+\Delta_2(\Delta m^2_{12}) \Leftarrow \textbf{Solar term}$$
$$+\Delta_3(\theta_{13}, \Delta m^2_{12}, \delta) \Leftarrow \textbf{Interference}$$

Statistical separation of ν_e and anti-ν_e.

📖 HK letter of Intent, arXiv:1109.3262v1

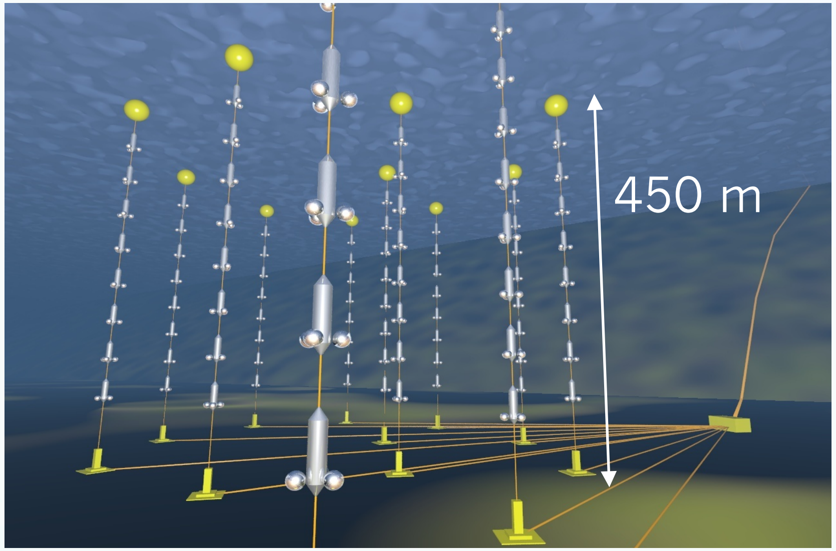


Bands correspond to δ_{CP} range of values

Can determine MH at 3σ or more for values of $\sin^2\theta_{23}$ >0.4 with 10 years of data. Improved sensitivity is expected by adding beam data (>1σ sensitivity alone, depending on δ_{CP}) → >3σ in all cases.

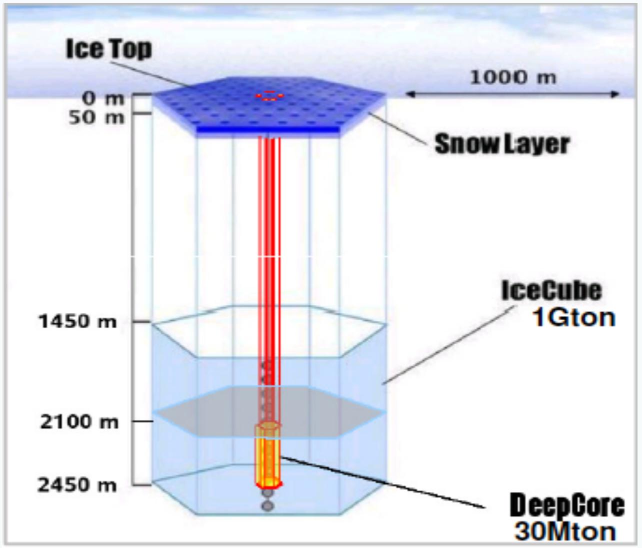
First achievements with Neutrino Telescopes

40 km Off Shore, French Riviera



12 line detector completed 2008

South Pole



IceCube (86 strings)+ DeepCore (8 strings)

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m^2_{32} \cos\Theta}{E_\nu}\right)$$

Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)

Larger effect on

Single lines ⟵ low energy ⟶ DeepCore

than

Multi lines ⟵ higher energy events ⟶ IceCube

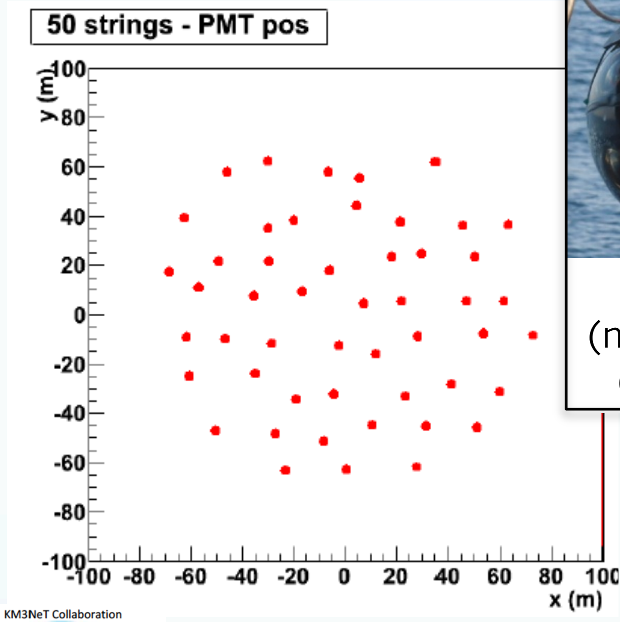
📖 Phys. Lett. B 714 (2012) 22.

📖 Phys. Rev. Lett. 111, 081801 (2013)

Proposed Low Energy Extensions

📖 Akhmedov et al. JHEP 02 (2013) 082

ORCA



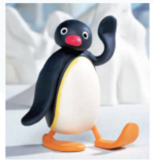
31 3" PMTs
(now taking data
@ ANTARES)

KM3NeT Collaboration

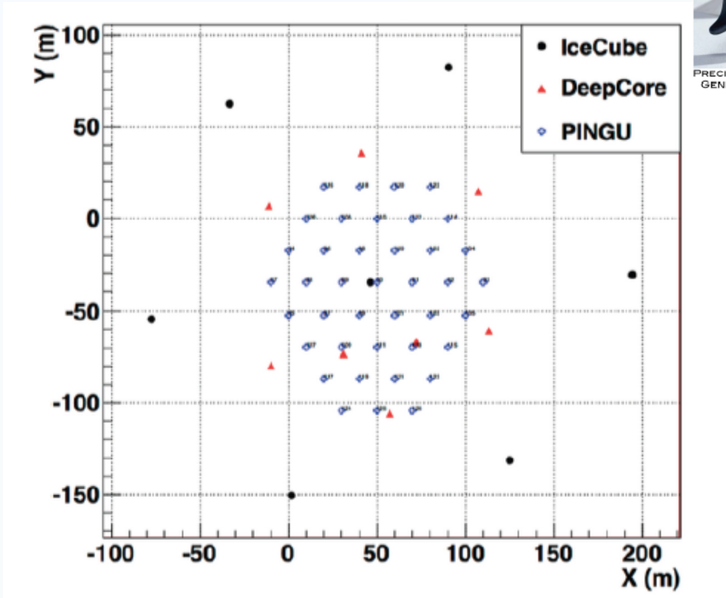
50 lines, 20m spaced,
20 OM/line 6m spaced
Instrumented volume ~2 Mt, 1000 OM

Could be deployed in <5 years
40 M€ available in KM3NeT phase-1

PINGU



Precision IceCube Next Generation Upgrade



40 strings, 20-25m spaced,
60 OM/string 5m spaced
Instrumented volume ~ 6 Mt, 2400 OM

Could be deployed 2016-2020 if funded
(~60-80M$)

Optimized layouts still under study

📖 P. Koojman et al, ICRC proc 0164

📖 A. Gross et al, ICRC13 proc 0555

In situ tests of new Optical Module

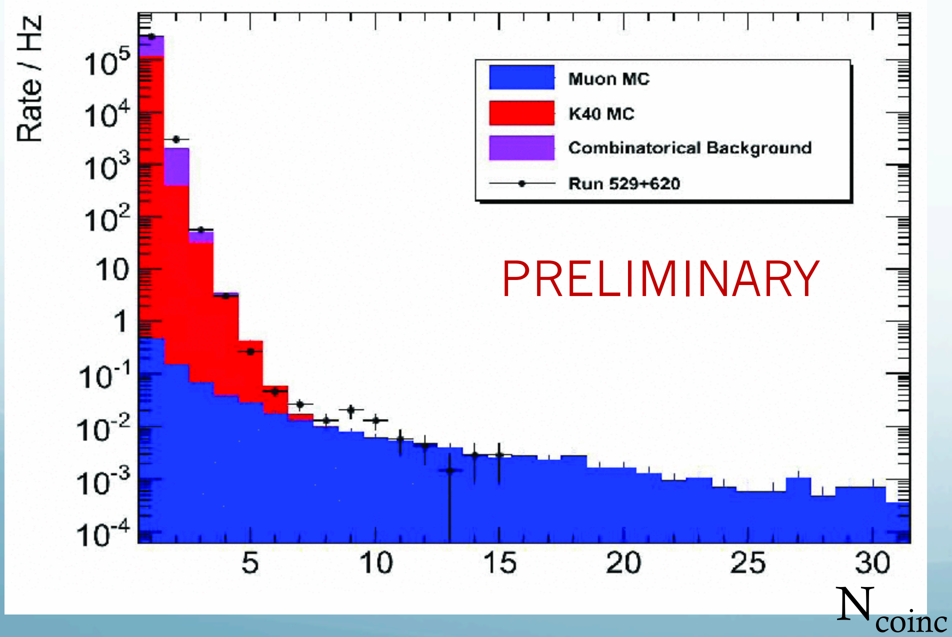
KM3NeT already taking data from an ANTARES line since April 2013

... and sees muons!

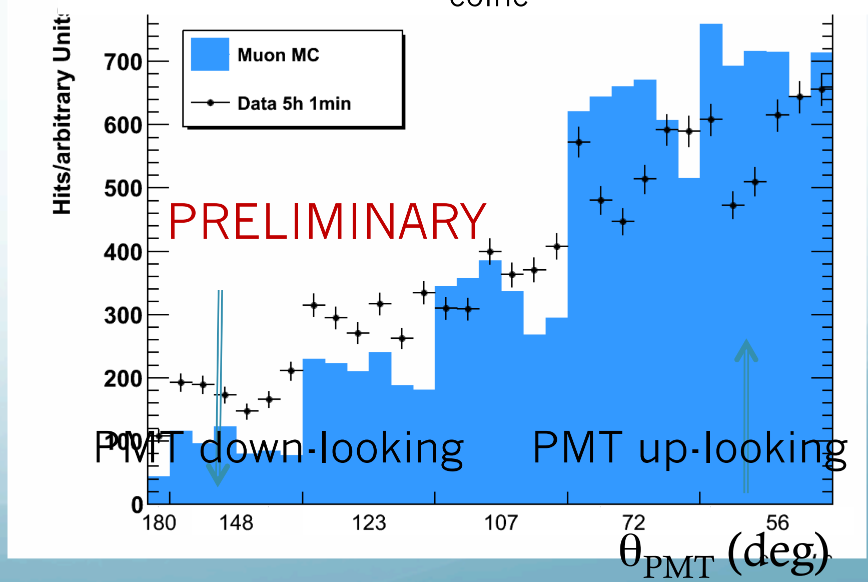
Coincidence in a DOM

↓

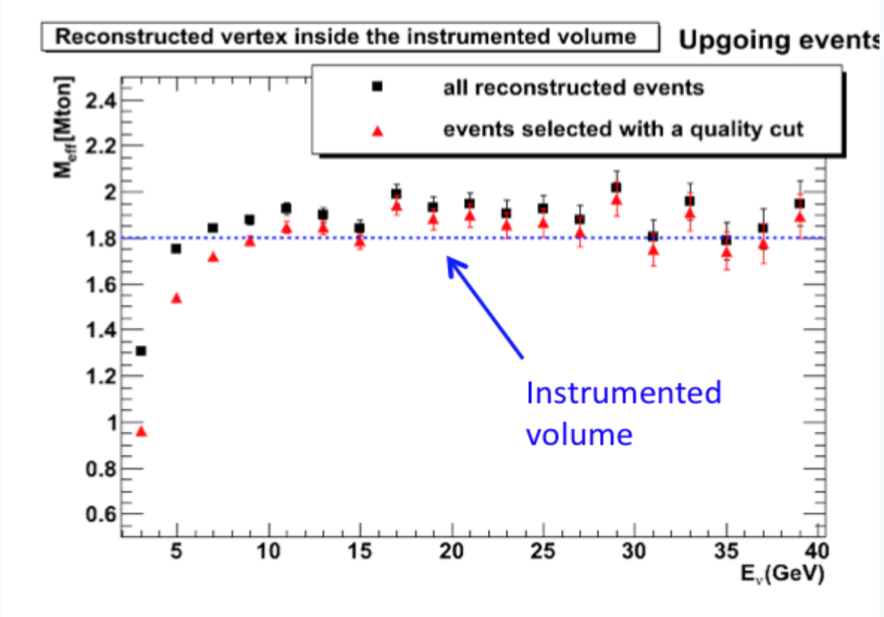
hits in different PMTs in a time window of 20ns

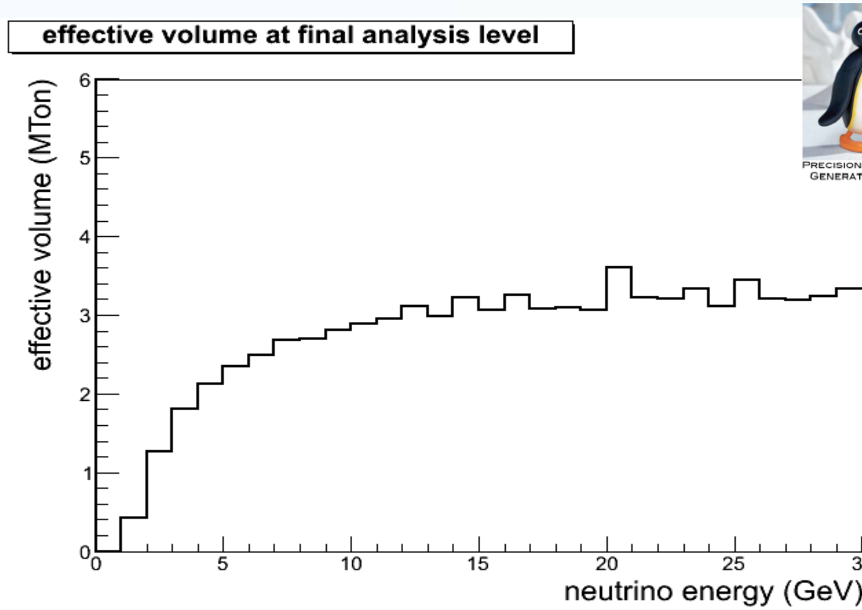


Events with N_{coinc}>6 selected



Proposed Low Energy Extensions





PRECISION ICECUBE NEXT GENERATION UPGRADE

(Muon channel)

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20 OM/line 6m spaced
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Could be deployed in <5 years
40 M€ available in KM3NeT phase-1

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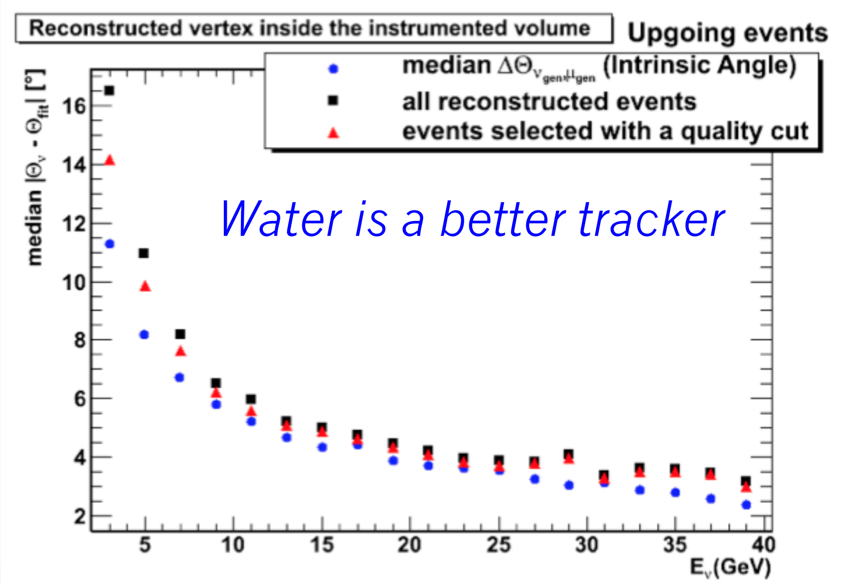
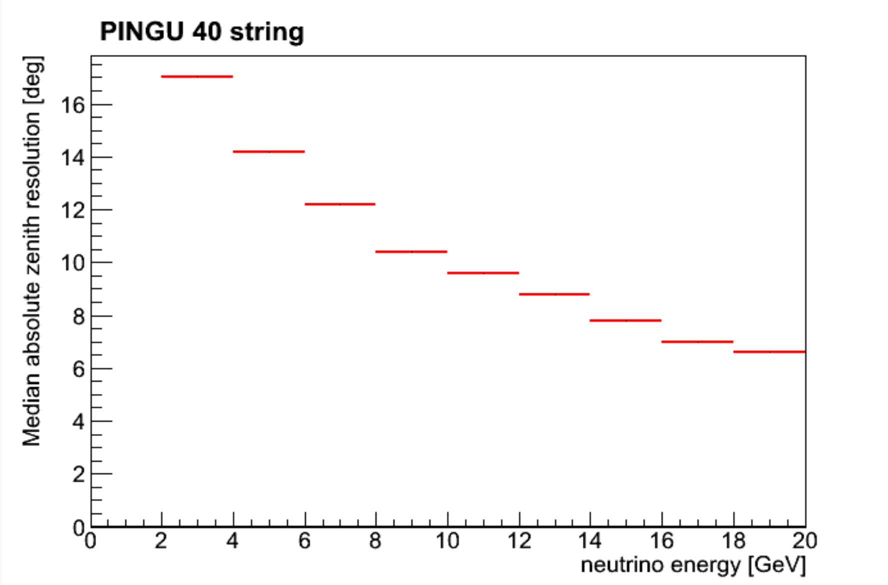
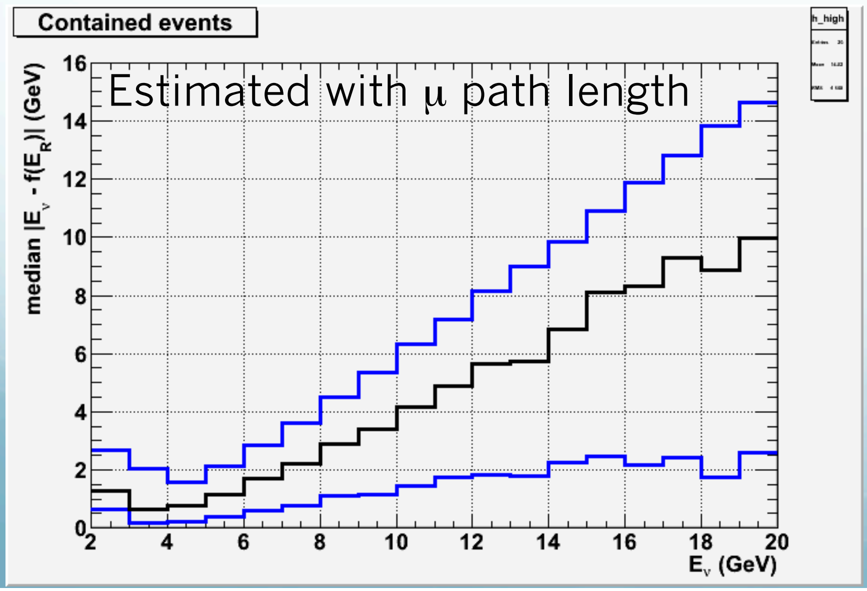
📖 P. Koojman et al, ICRC proc 0164

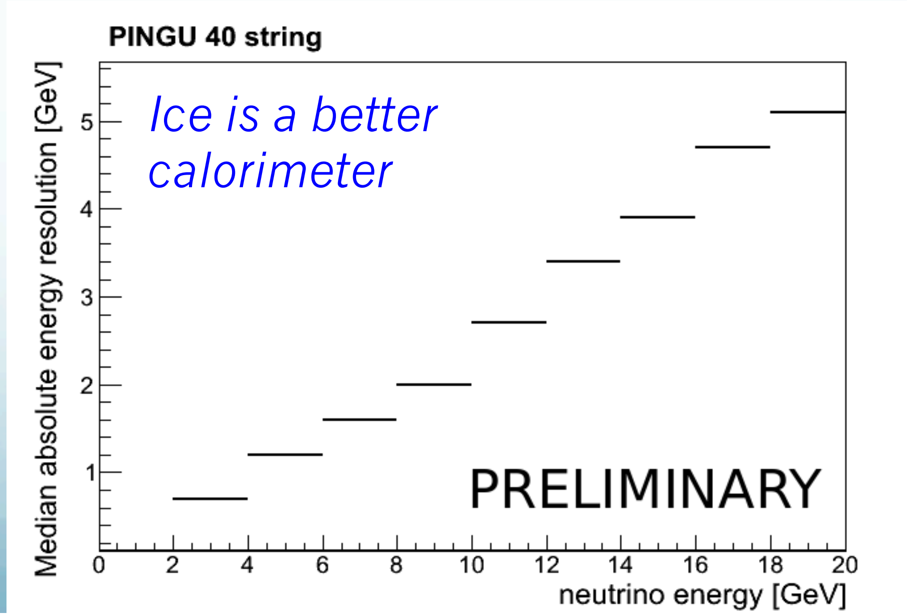
📖 A. Gross et al, NNN13

Preliminary performances







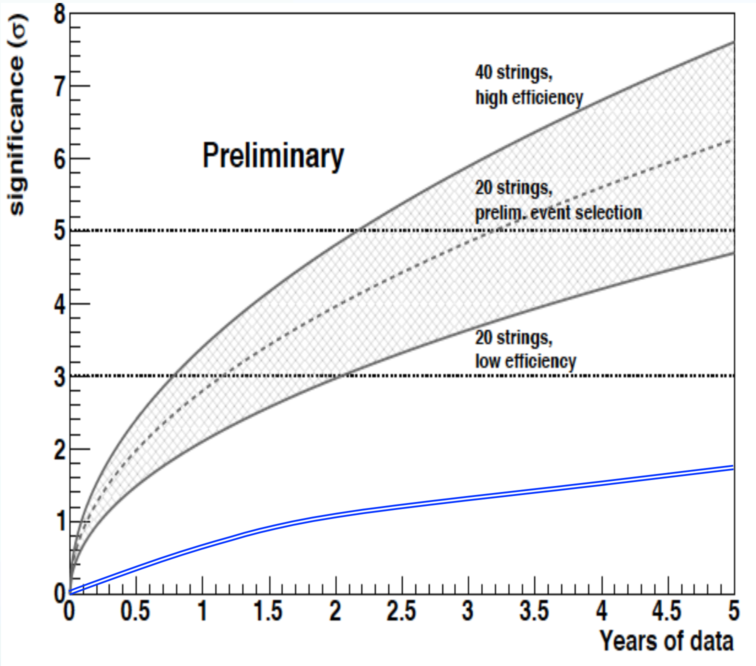


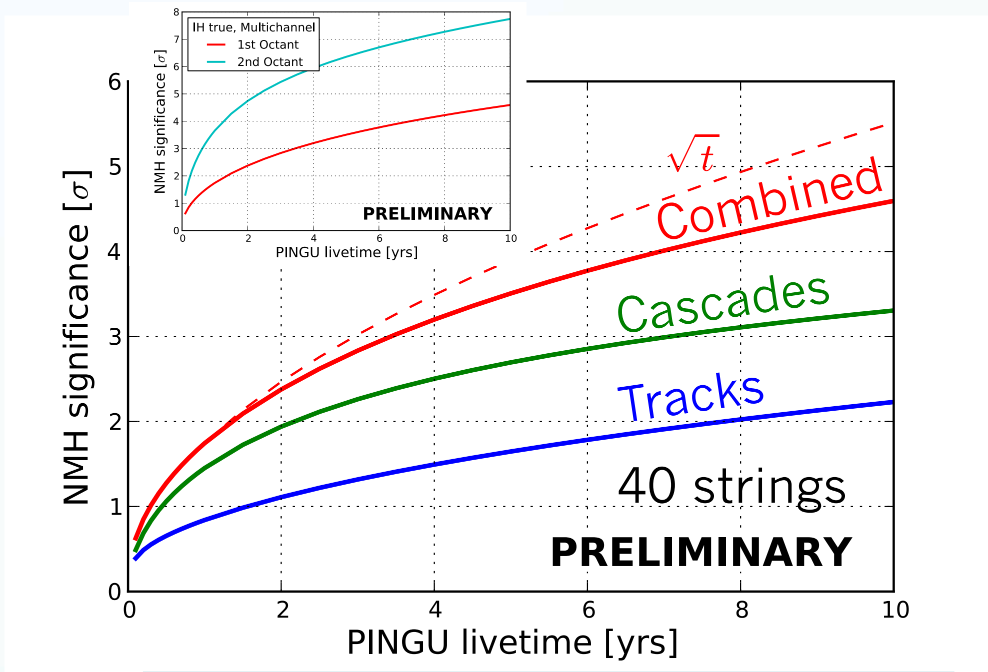
PINGU sensitivities

PRECISION ICECUBE NEXT GENERATION UPGRADE

📖 PINGU collaboration, arXiv:1306.5846

📖 P5 Workshop Future HE Physics, Dec13





Different studies performed.
Sys uncertainties include norm (30%), spectral index (±0.05), energy scale (10%), zenith bias (10%)
Realistic energy and direction resolutions

Some sensitivity recovered with "cascade" events
(same resolutions as tracks)

Now compatible with e.g. W. Winter, PRD 88, 1, 013013

- Analysis fully updated since Snowmass
  - Factors lowering significance:
    - higher MC sampling to eliminate unanticipated systematic bias from fluctuations
    - more accurate resolution parametrizations
    - inclusion of NC events
    - kinematic suppression of ν_τ events
  - Factors raising significance:
    - improved event selection
    - improved event fitting
    - use of cascades, PID

ORCA sensitivity

all results are preliminary

To optimally distinguish between IH and NH: likelihood ratio test with nuisance parameters
→ *deal with degeneracies by fitting!*

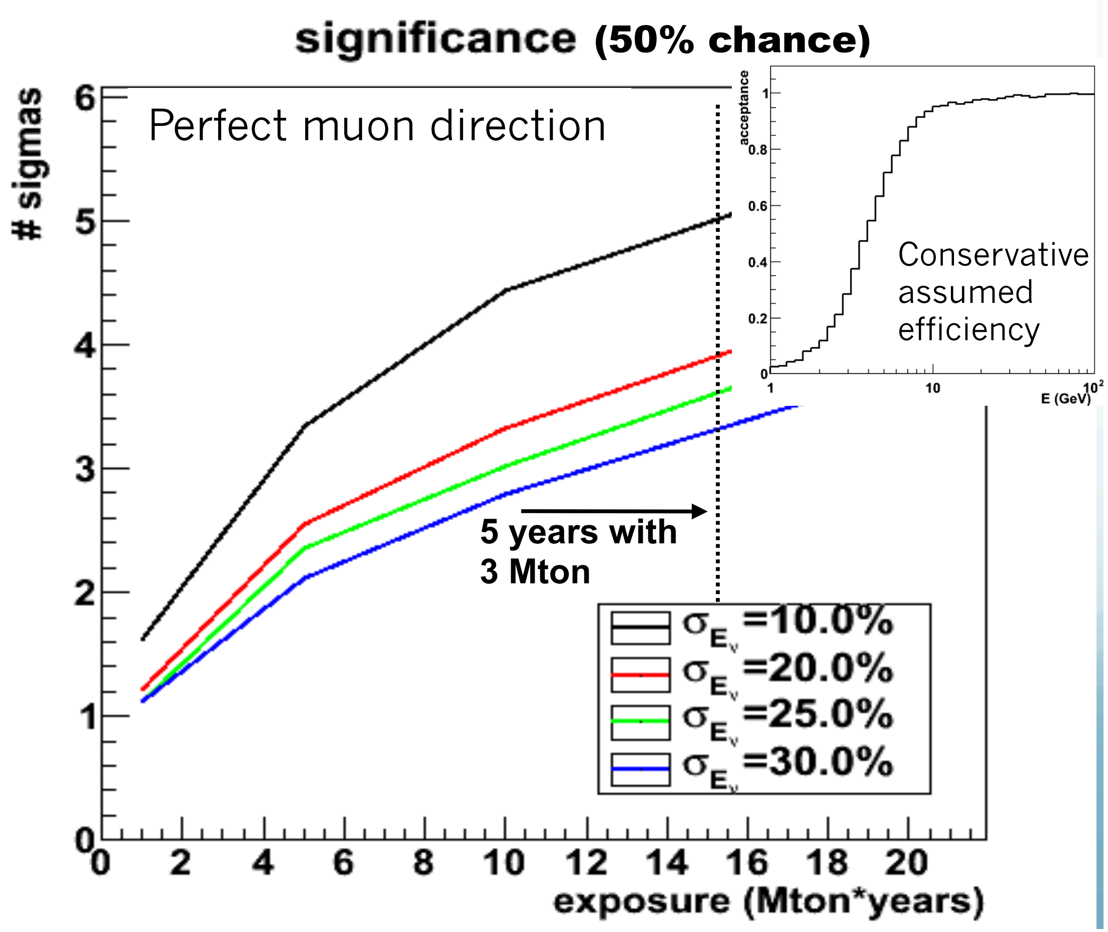
$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\mathrm{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

Uncertainty on the mixing parameters as a function of the exposure

Eres = 25%, 1-100 GeV

Mton x yr	$\sigma(\Delta m^2_{large})$ (eV^2)	$\sigma(\theta_{23})$ (°)	$\sigma(\theta_{13})$ (°)
0(now)	8.0e-5	1.3	0.45
1	4.3e-05	0.61	0.42
5	2.3e-05	0.32	0.44
10	1.8e-05	0.22	0.39
20	1.4e-05	0.16	0.39
30	1.2e-05	0.13	0.37



Further on-going studies

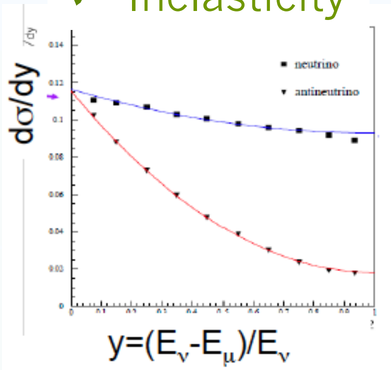
✓ Shower reconstruction

Study of intrinsic energy variations → Current limitation from physics (vertex, prop,...) not detector
Under development.
Expect similar improvement in sensitivity as PINGU

Already included

✓ Inelasticity

Try to separate track-like ($\bar{\nu}$) to shower-like events (ν)



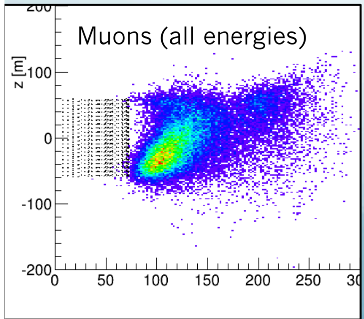
"With the inelasticity, the total significance of establishing mass hierarchy may increase by (20 - 50)%"
📖 Ribordy & Smirnov arXiv:1303.0758v1

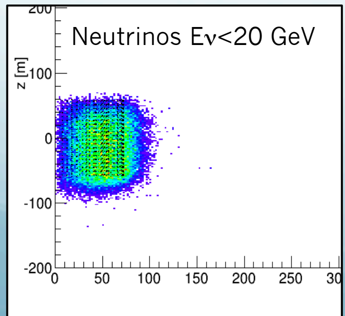
✓ Flavor misidentification

Studying response to ν_e

Preliminary PiD included

✓ Atmospheric muons





Cut on reconstructed vertex

No need for veto

Veto from IceCube/Deepcore

Studies of systematics

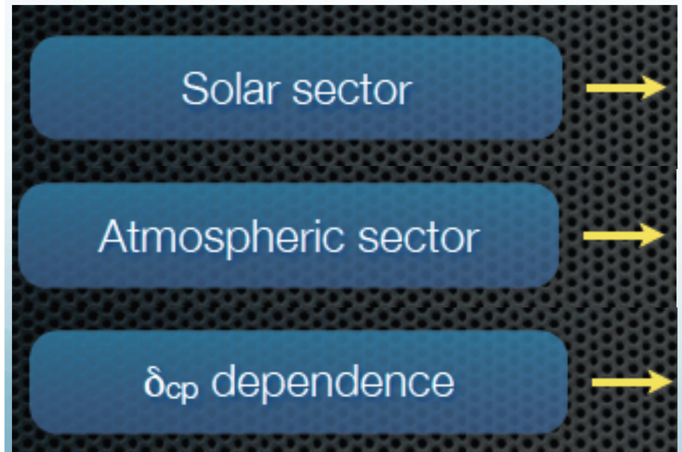
📖 D. Franco et al, JHEP 04 (2013) 008

Method: extended unbinned log-likelihood ratio

Earth Model → Almost negligible impact

Atmospheric neutrinos flux
- Shape → Moderate impact
- Normalization → Large impact but normalization from data

PMNS uncertainties



Negligible impact varying combinations of $\{\theta_{12}, \Delta m^2_{21}\}$ ($\pm 1\sigma$)

Large impact varying combinations of $\{\theta_{13}, \theta_{23}, \Delta m^2_{31}\}$ ($\pm 1\sigma$)

Small impact varying CP phase

Several other studies point to the same conclusions...

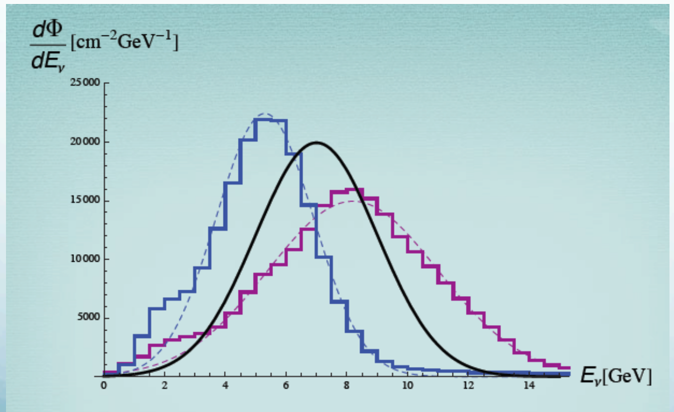
A Neutrino beam to ORCA? I

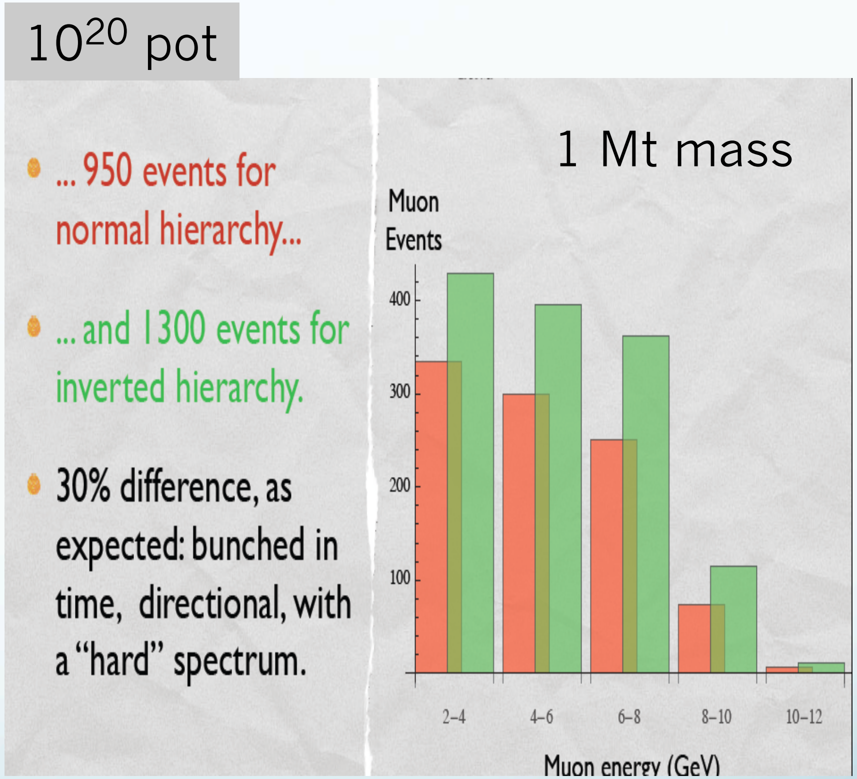
- Muon counting experiment - Optimum 6-8 GeV 6000-8000 km but beam inclination

🕮 Lujan-Peschard et al, Eur. Phys. J. C (2013) 73:2439 ; Tang & Winter, JHEP 1202 (2012) 028

	Fermilab	CERN	J-Parc
South-Pole	11600 km	11800 km	11400 km
Sicily	7800 km	1200 km	9100 km
Baikal Lake	8700 km	6300 km	3300 km

NUMI beam rescaled to 7800 km





→ 9 σ separation on purely statistical ground in one year

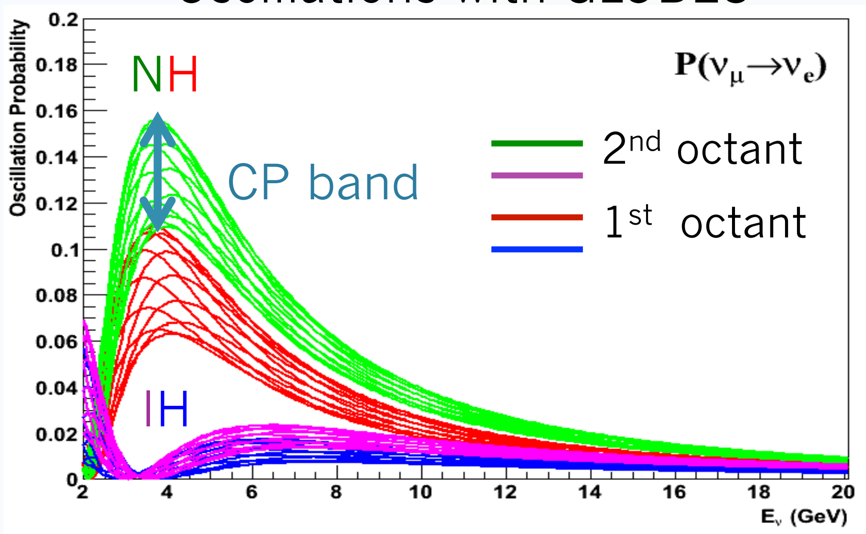
A Neutrino beam to ORCA? II

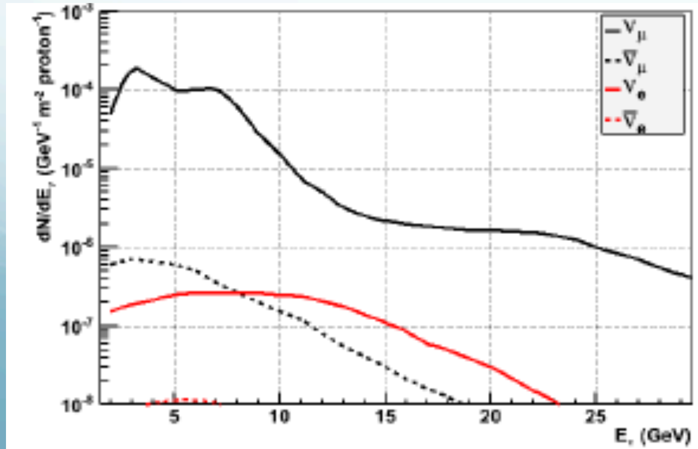
- Electron counting experiment

📖 J. Brunner, arXiv:1304.6230

- Protvino-ORCA L=2588 km, beam inclined by 11.7° (3° off-axis from Fréjus Underground laboratory)

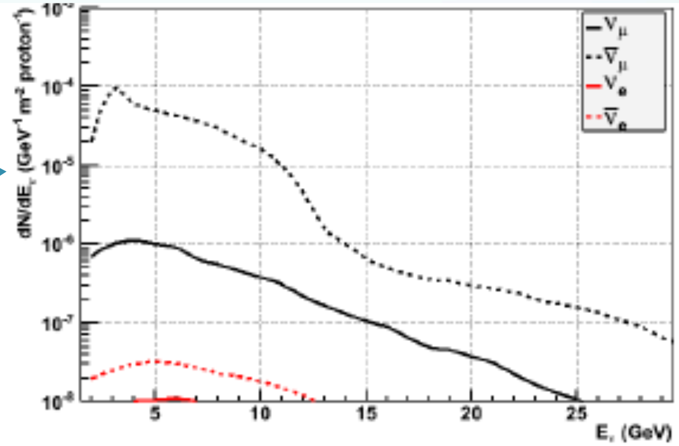
Oscillations with GLOBES





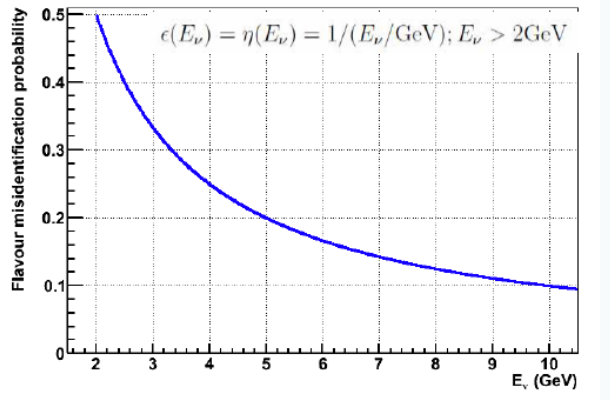
← Neutrino
Anti-neutrino →
Fluxes

(SKAT exp. Needs update)



A Neutrino beam to ORCA? III

- Electron counting experiment - Protvino-ORCA L=2588 km, beam inclined by 11.7°
  - Vertex inside ORCA reference detector
  - Flavor misidentification probability based on C2GT project
  - Event rates for 1.5×10^{21} pot (3 years)



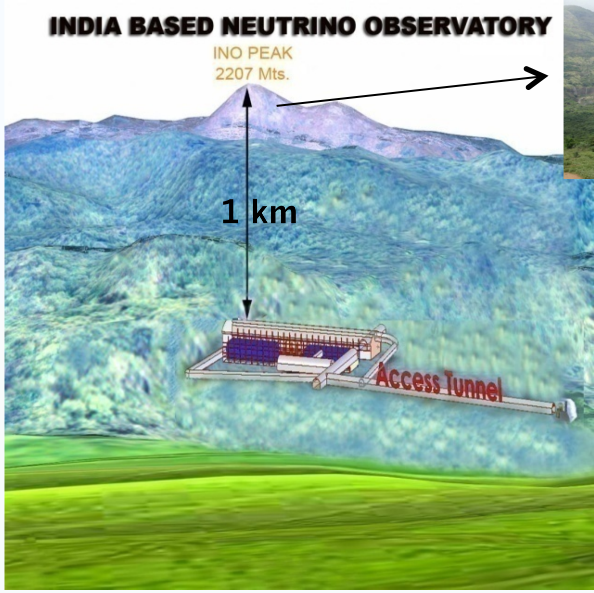
Channel	Tracks NH	Tracks IH	Cascades NH	Cascades IH
No oscil	26315		—	
Signal	8990	8735	1134-1547	350-519
Misreco	232-329	47-79	1326	1280
ν_τ	324-332	351-355	978-998	1057-1068
NC	1092	1092	3640	3640
BG Total	1655-1745	1494-1522	5944-5964	5977-5988
Total	10645-10736	10229-10257	7099-7491	6338-6496

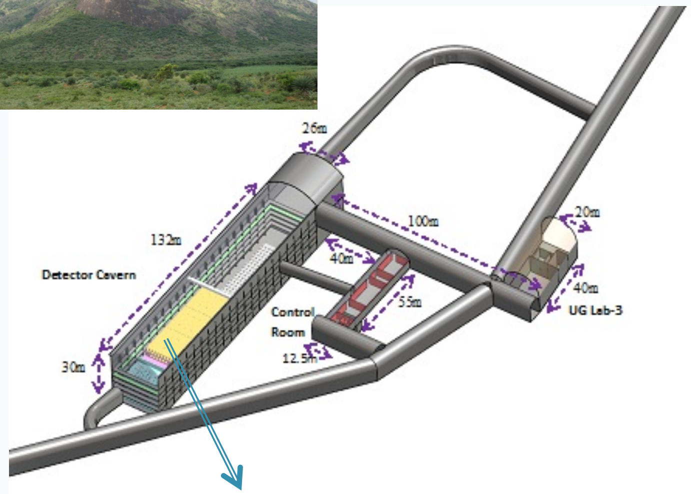
7 σ stat. separation
3 σ with 3-4% sys

No assumption on energy reconstruction

We would be happy to investigate further possible synergies in case of a LAr TPC in the Fréjus underground laboratory, as an indication on the MH may help for the measurement of δ_{CP} by LBNO

INO: India-based Neutrino Observatory





50 kton ICAL
(room for additional 50kton)

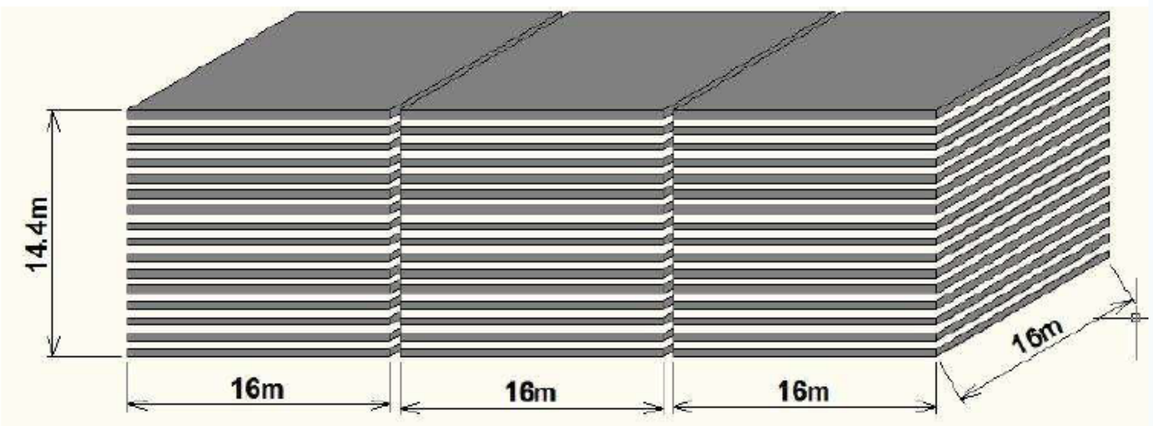
- 115 km west of Madurai (internat. airport)
- Pottipuram Village, Theni District, Tamil Nadu State
- 1.9 km access tunnel
- Indian collab (~20 institutes) + Hawaii Univ (USA)
- Several other experiments when operational ($\beta\beta0\nu$, DM)

CERN-INO: ~7300 km
JPARC-INO: ~6500 km
RAL-INO:~7600
magic baseline ~ 7500 km
FNAL-INO: second magic

Current Status:

- Fencing work started for facilities near portal and Madurai Center for HE Physics
- Waiting for full project approval by Indian Government

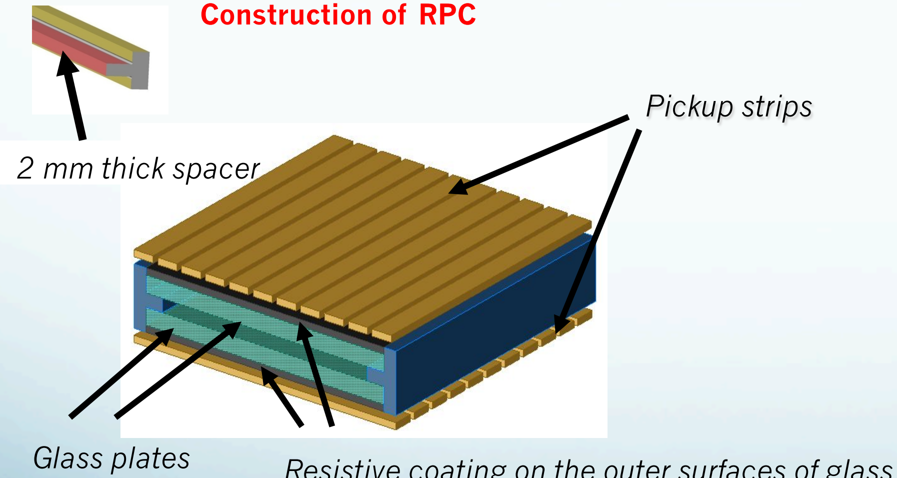
The INO-ICAL detector



- ✓ *50Kton Fe-RPC Detectors*
- ✓ *# of layers = 140*
- ✓ *Fe thickness = 5.6 cm*
- ✓ *Magnetic Field ~ 1.3T*
- ✓ *# of RPCs ~ 27K*
- ✓ *# of channels ~ 3.6M*

[NB: Slightly different numbers exist]

Construction of RPC



2m x 2m glass RPC test stand

Cosmic –ray tracks are seen…

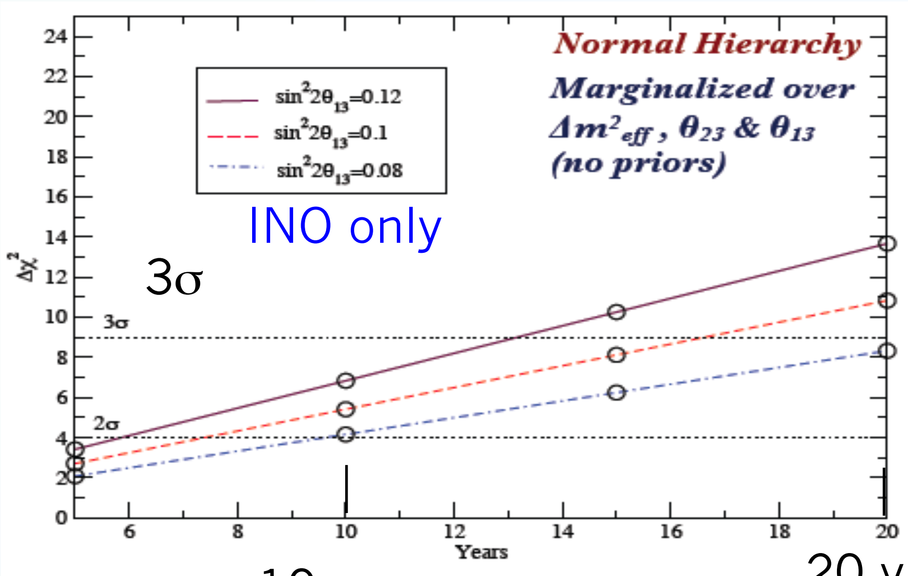
Current Status:

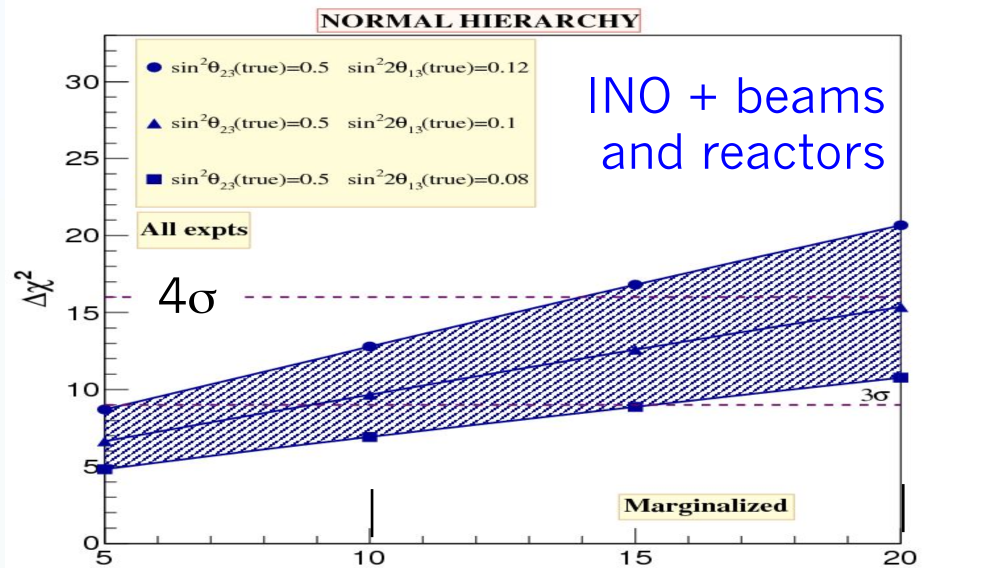
- RPCs: help from Industry expected
- Electronics: ASIC (2nd batch being tested) and DAQ under development

- Magnet: Prototype running at VECC Engineering module (800 ton) will be constructed by 2014.

Mass Hierarchy Discrimination

Expected performances are a bit worse for IH





10 yrs 20 yrs 10 yrs 20 yrs

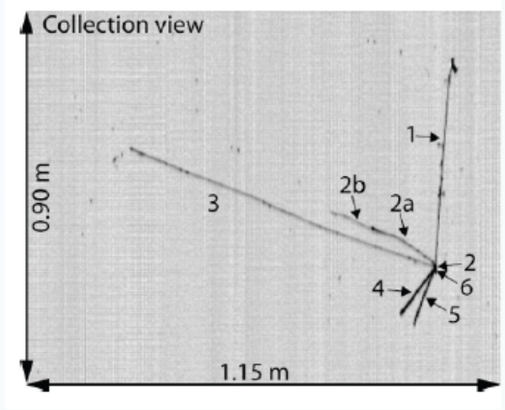
Further improvements expected by adding hadron events
📖 arXiv:1306.1423v1

INO + Other experiments
📖 Ghosh, Thakore & Choubey, arXiv:1212.1305
📖 Blennow & Schwetz, JHEP 1208 (2012) 058, Erratum-ibid. 1211 (2012) 098

The Liquid Ar TPC detectors

- First achievements with ICARUS (760 tons at LNGS)
  → Proof of technology.
- Excellent particle identification with low threshold (MeV)

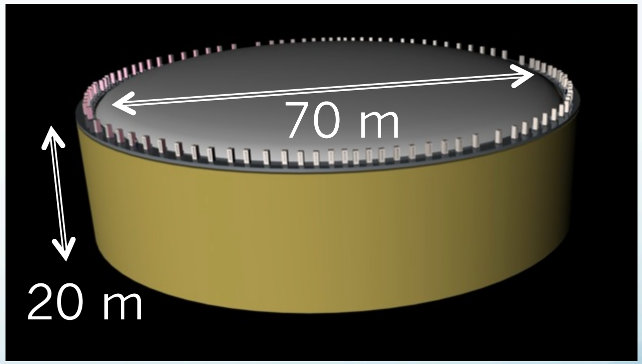
- Proposed detectors (LBNO/E):
  - staged approach up to 100 kton
  - Single (LBNE) double (LBNO) phase
  - Sensitive to muons and electrons
  - Hadronic component can me measured

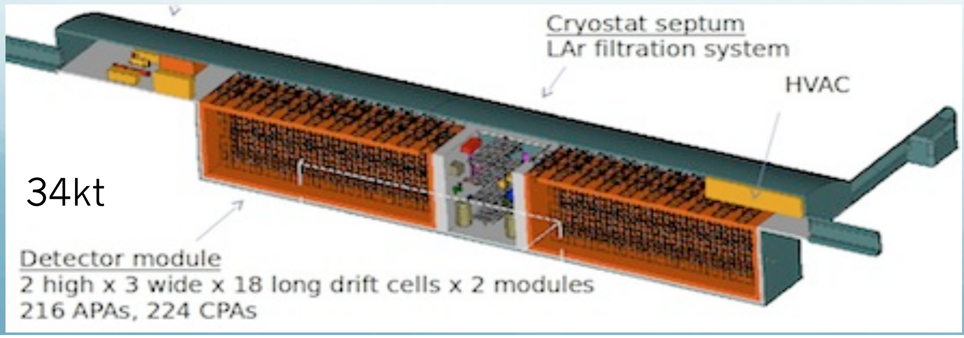


Detectors need to be buried deep underground

- Atmospheric neutrino studies
  - Tau neutrino appearance
  - Discrimination between $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ from upward/downward asymmetry
  - Mass hierachy and octant of $\theta 23$

📖 A. Stahl et al, LBNO, SPSC-EOI-007 (2012)
📖 C. Adams et al, LBNE, arXiv:1307.7335



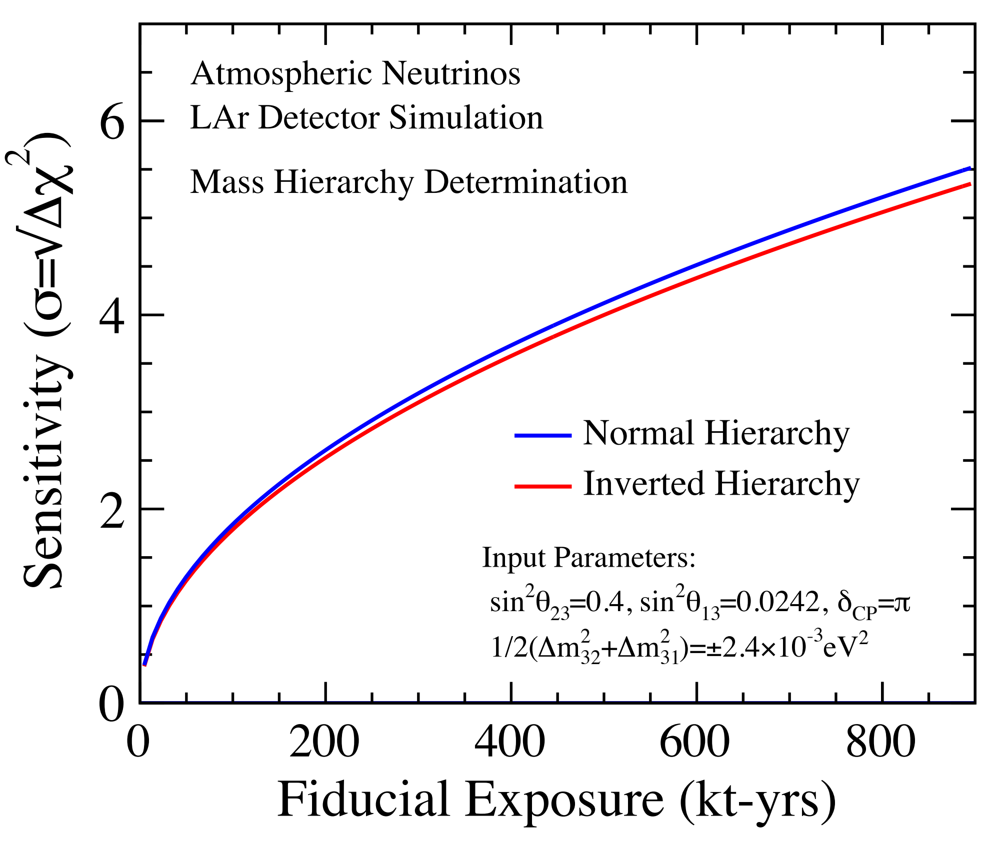


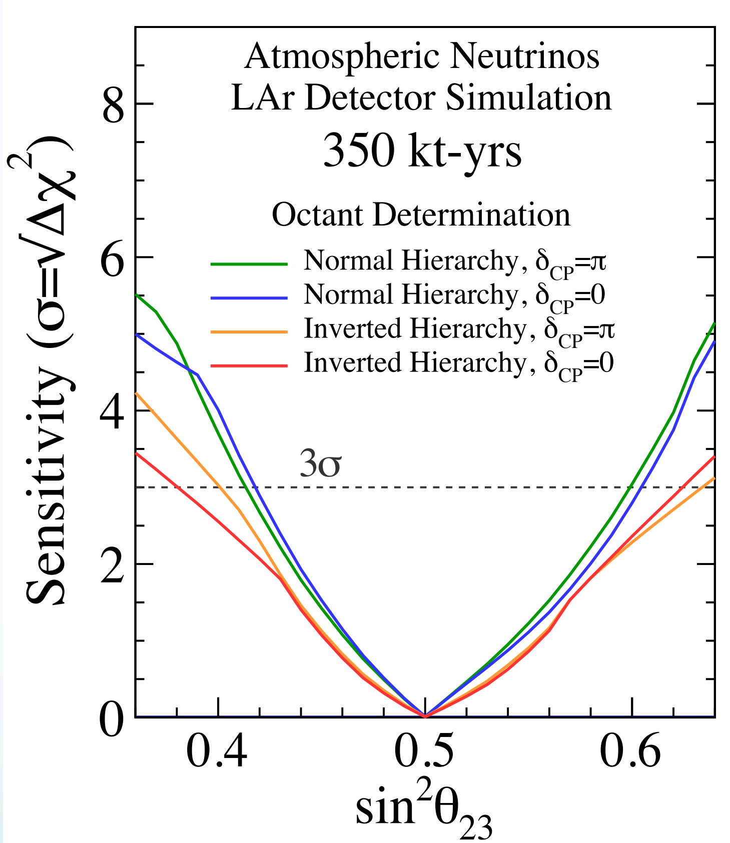
☞ Daniele Gibin
☞ Marco Zito

Mass hierarchy & octant with Lar TPCs

35 kt x 10 yrs = 350 kt-yrs

arXiv:1307.7335





Requires very large detectors

Magnetized LAr-TPC?

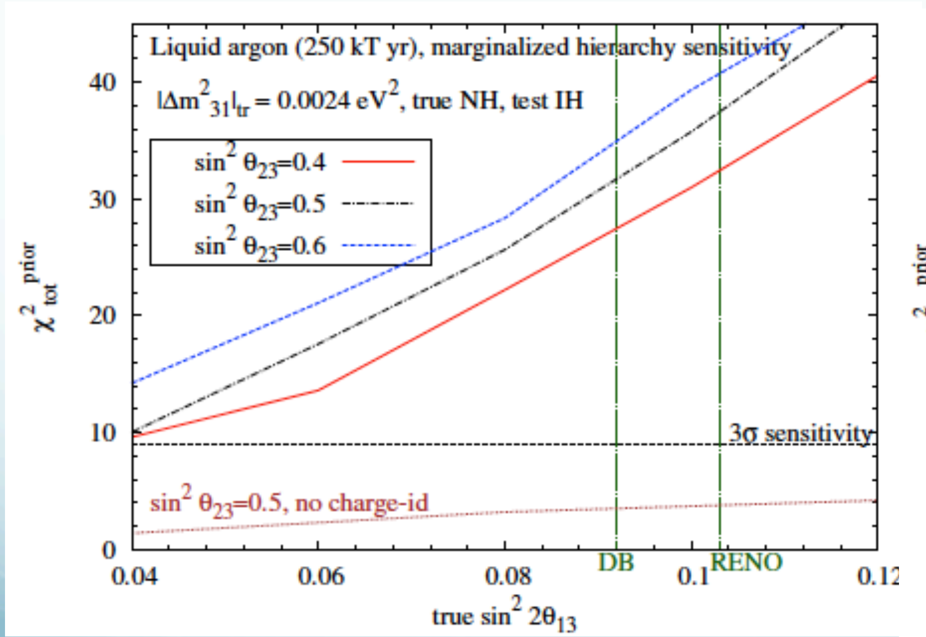
Sensitivity to mass hierarchy require charge identification to compensate low mass
→ Magnetization?

📖 V. Barger et al, Phys.Rev.Lett.109:091801,2012

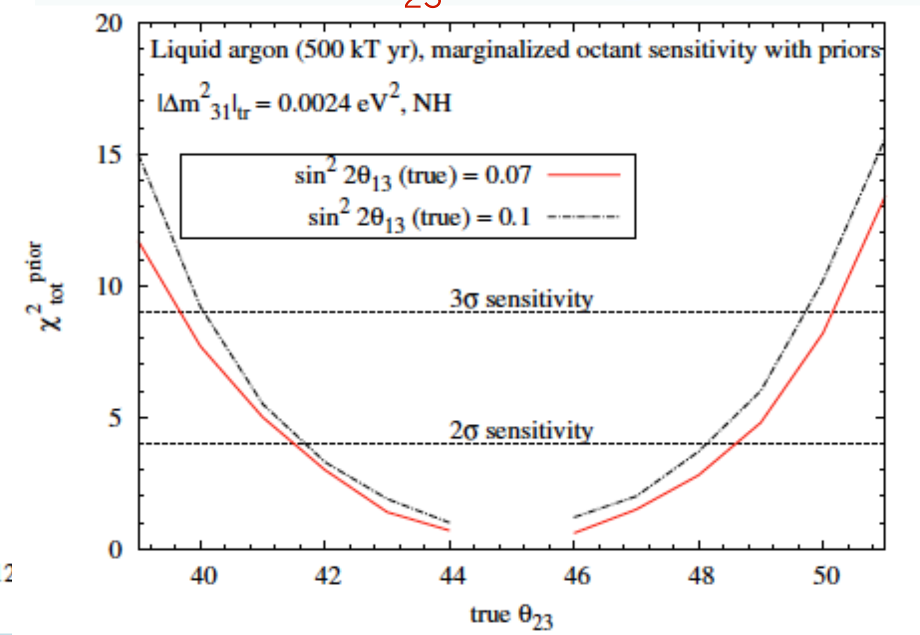
100% CID for muons and 20% for electrons in the energy range 1-5 GeV

$\sigma_{E_e} = \sigma_{E_\mu} = 0.01; \quad \sigma_{E_{had}} = \sqrt{(0.15)^2/E_{had} + (0.03)^2} \qquad \sigma_{\theta_{\nu e}} = 2.8°; \quad \sigma_{\theta_{\nu\mu}} = 3.2°$

MH



θ_{23} octant



~5 σ with 250 kton.year exposure

~3 σ with 250 kton.year exposure with $\sin^2\theta_{23}$ in [0.4; 0.6]

(Results shown for assumed NH)

Summary

- Atmospheric Neutrinos have still a major role to play for precision measurements and determination of unknown parameters such as the mass hierarchy.

- Proposed detectors include Iron Calorimeter, Liquid Argon and Cherenkov detectors. None of these projects being firmly funded.

- Low energy (GeV) extensions of Neutrino Telescopes may be faster and cheaper than other alternatives...

- ...but challenging, as systematics must be carefully controlled. Key parameters are the size of the detector as well as the energy and angle resolutions.

- Synergies/Combination with LBL/ reactor experiments may provide the first high significance MH determination...

R.N. Cahn et al, arXiv:1307.5487

A recent timeline...
... but already outdated...