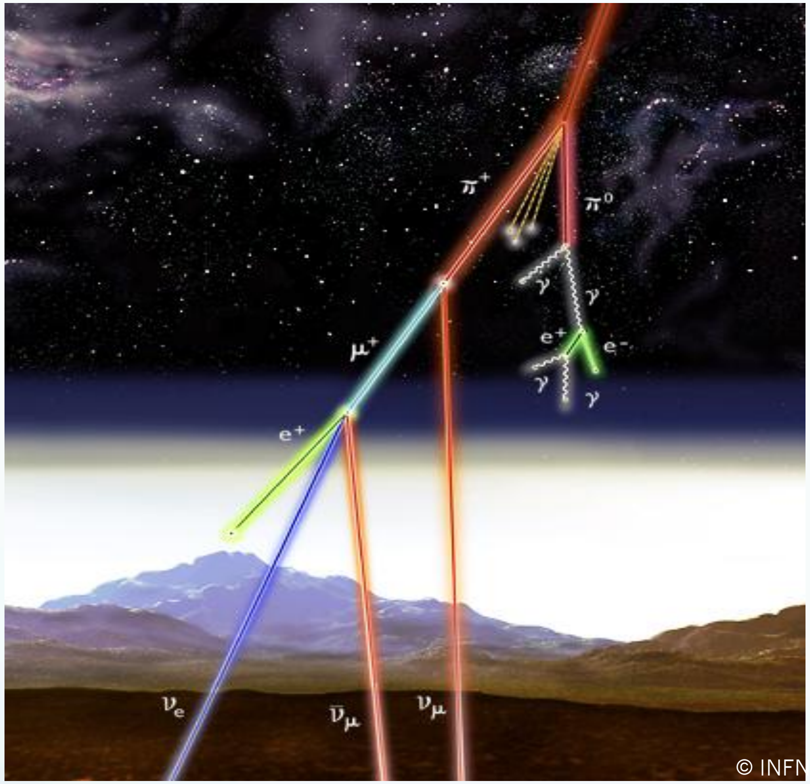
Next-Generation Atmospheric Neutrino Experiments



[Focusing on the Neutrino Mass Hierarchy]

I. Atmospheric Neutrinos

The PMNS Matrix

Matter Effects

Fluxes and Cross Sections

II. Detectors

Water/Ice Cherenkov

Magnetized Trackers

Liquid Argon TPCs

Antoine Kouchner

University Paris 7 Diderot- AstroParticle and Cosmology

(Disclaimer : member of HE neutrino astronomy community)

Credits - Acknowledgements

J. Brunner, A. Cabrera, A. de Gouvea, D. Grant, M. Nakahata, N. Mondal, S. Pascoli, E. Resconi, V. Van Elewyck, C. Walter, R. Wendell…

Oscillations of Massive Neutrinos

- Neutrinos have distinct masses and mix (PMNS)

☞ M.C. Gonzalez-Garcia

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{21} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}e^{i\eta_1} & 0 & 0\\ 0 & e^{i\eta_2} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric **θ_A~45°** | Reactor θ_{13}~9° | Solar $\theta_\odot$~30° | Majorana

↓ CP violating phase δ_{CP}

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

- 3 mixing angles
- 2 mass-squared differences

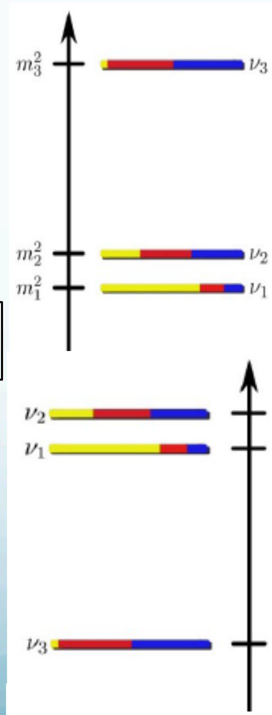
$$m_1^2 < m_2^2$$
$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

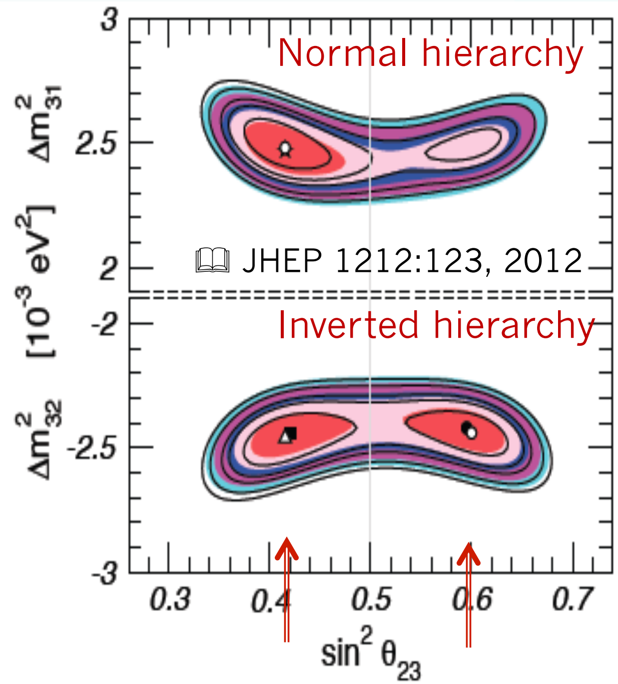
MH

- CP phase

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

☞ G.Fuller





Which octant for θ_{23} ?

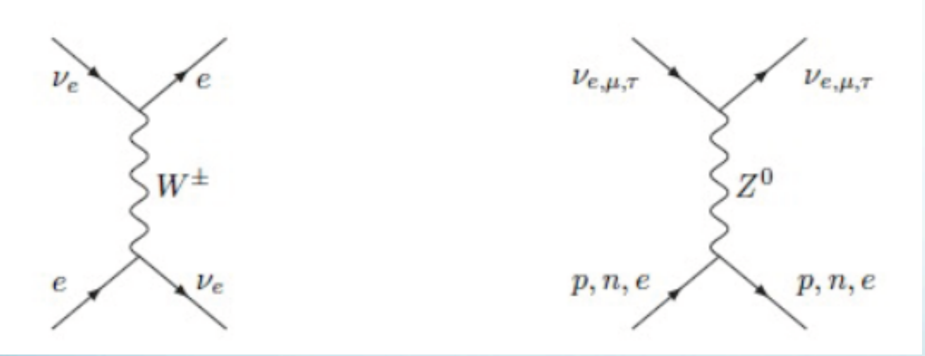
MH with LBL experiments

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

$$P_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}^{\text{eff}}\sin^2\left(\frac{\Delta m^{2\,\text{eff}}_{13} L}{4E}\right) + \text{"subleading"}$$

[Neglecting solar (> a few GeV and >1000's km) and CP violation effects]

- Insensitive to the sign of Δm^2_{13} at leading order.
- Matter effects (MSW) come to the rescue



Through matter, neutrinos interact acquiring an effective mass (forward scattering)
Only electron neutrinos interact through CC with electrons
→ Additional potential A in the Hamiltonian

$$A \equiv \pm\sqrt{2}G_F N_e$$ (−)+ for (anti-)neutrinos

→ Modify the oscillation probability

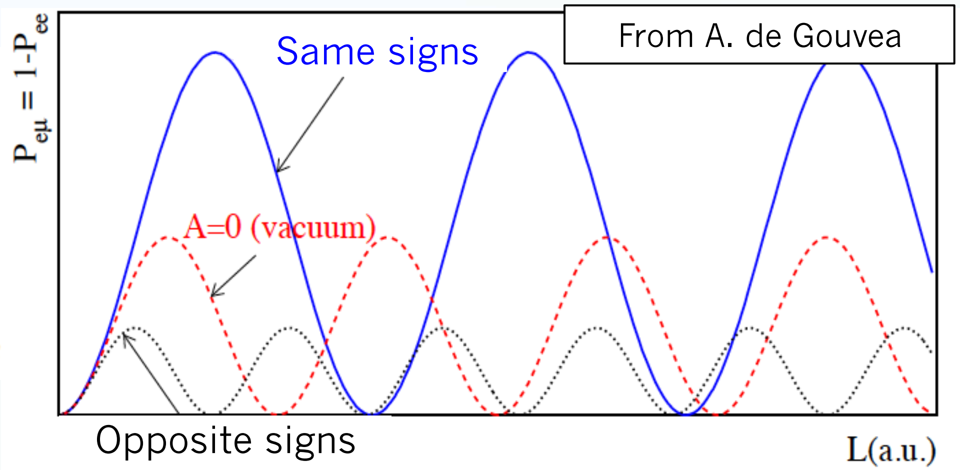
- Earth density variations (e.g. mantle-core) also affect the oscillations (*parametric resonance*)

(Constant Density) Matter Effects

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

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

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

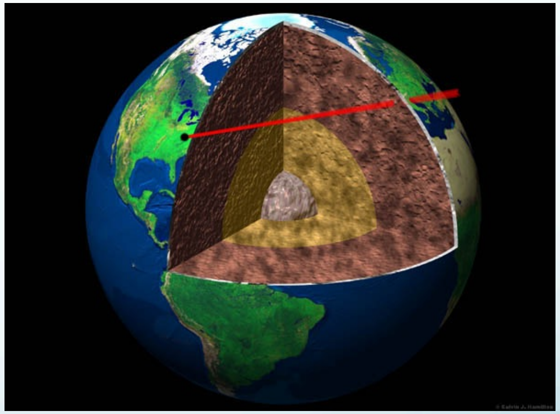


$\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

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

Matter resonance: A ➔ $\Delta_{13}\cos2\theta_{13}$
- Effective mixing maximal
- Effective osc. frequency minimal

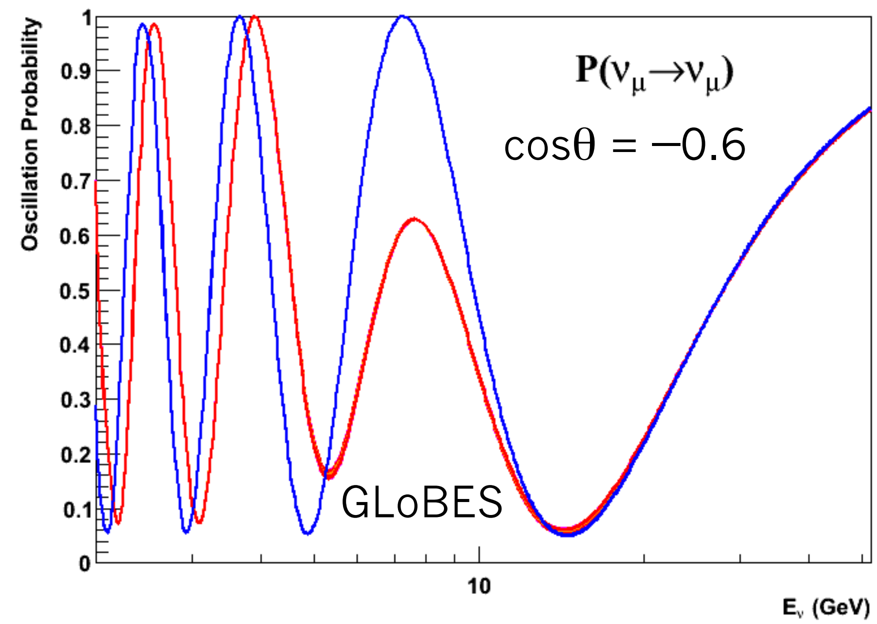
Resonance energy Earth:
- Mantle E_{res} ~ 7 GeV
- Core E_{res} ~ 3 GeV

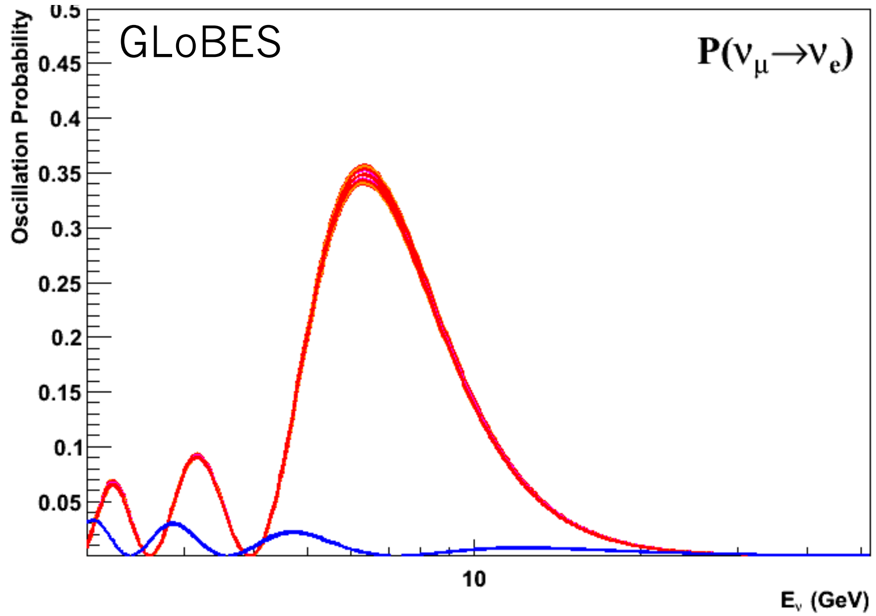


Requirements:
- Δ_{13} ~ A matter potential must be significant but not overwhelming
- L large enough – matter effects are absent near the origin
- Distinction between neutrinos and anti-neutrinos

→ different flux and cross-sections!

Phenomenological Summary



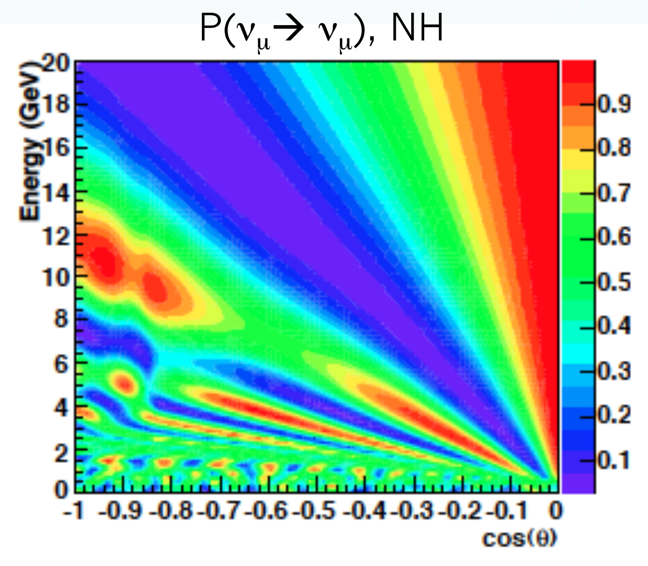


Inverted Hierachy

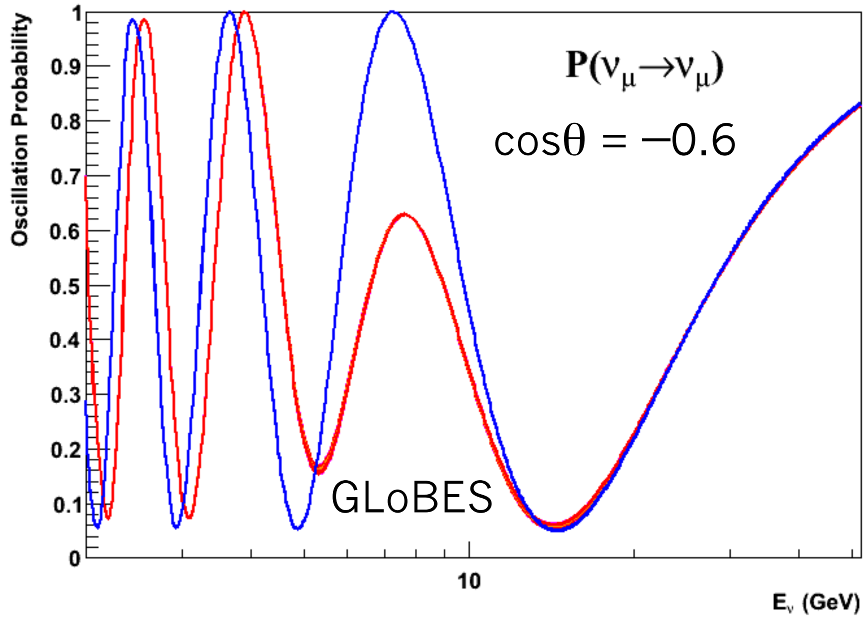
Normal Hierachy

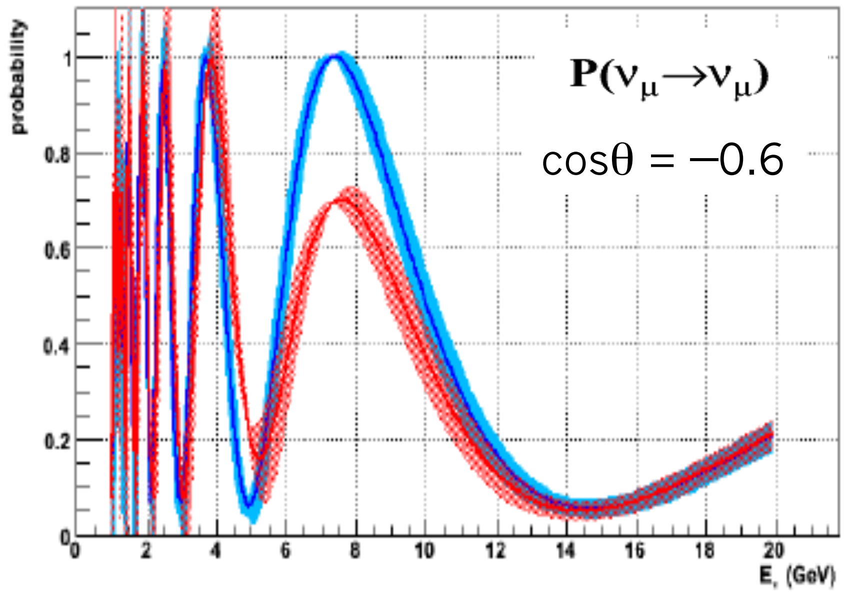
In each case, CP-phase is varied in steps of 30 degrees

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



Phenomenological Summary





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Degeneracies due to parameter uncertainties must be carefully considered!

Fluxes and cross sections

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

A beam for free !

☞ T. Gaisser, Id 51 (09/10/13)

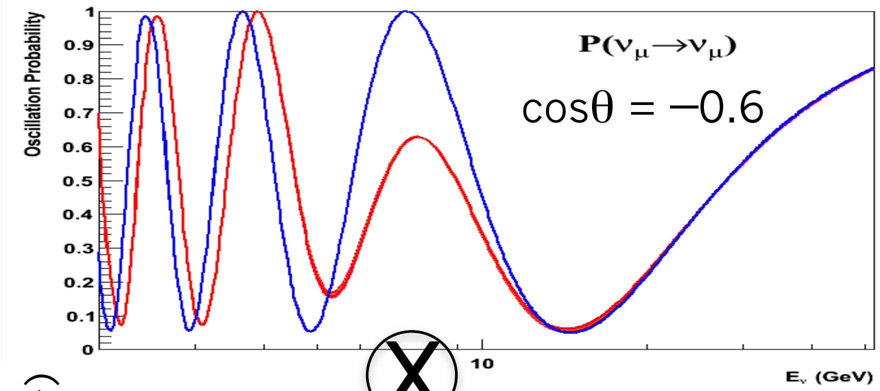
- Produce neutrinos and anti-neutrinos
- Broad energy range: Steeply falling spectrum
  → Requires good energy resolution
- Broad path-length range
  → Requires good direction resolution

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

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

Three main contributions:
Quasi-elastic, Resonant, DIS

→ Use external measurements and regions without oscillations



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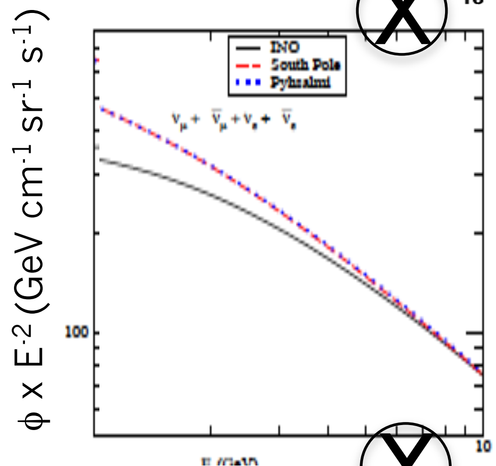

📖 M.S. Athar et al. arXiv:1210.5154

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

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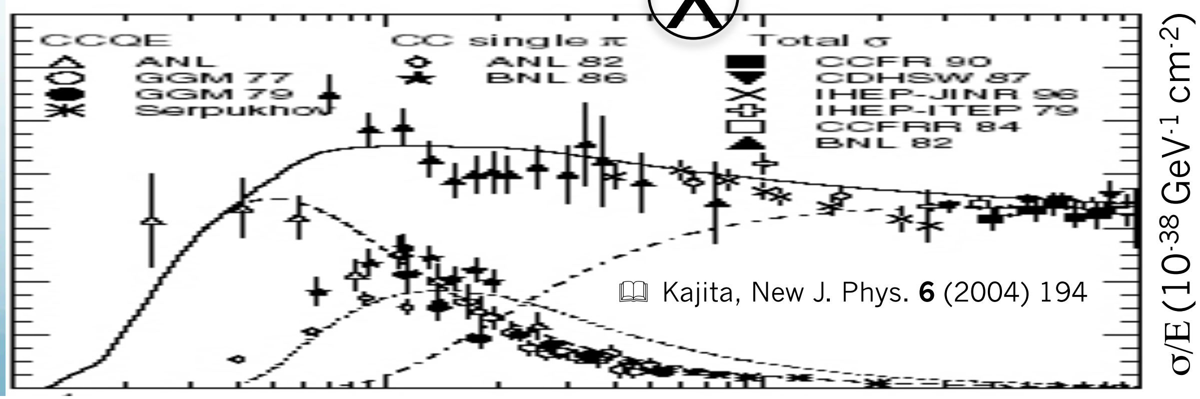
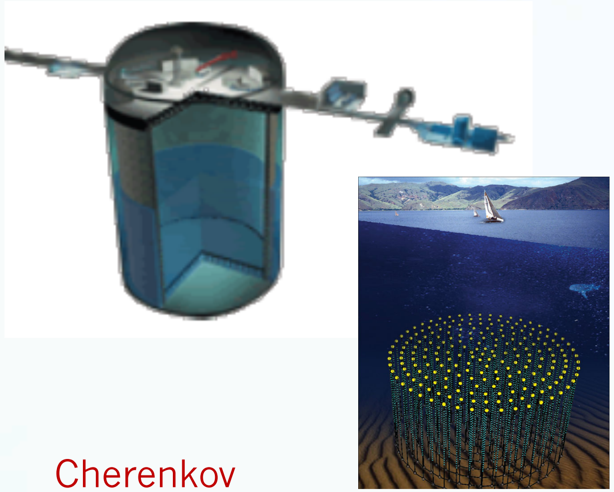
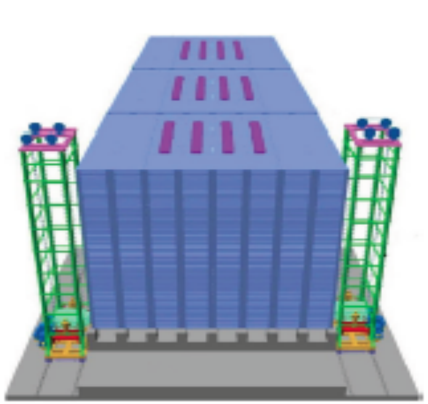
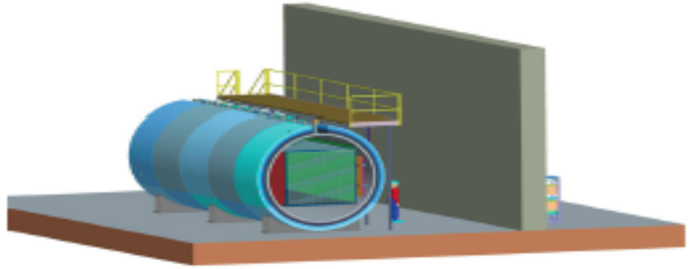


📖 Kajita, New J. Phys. **6** (2004) 194

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

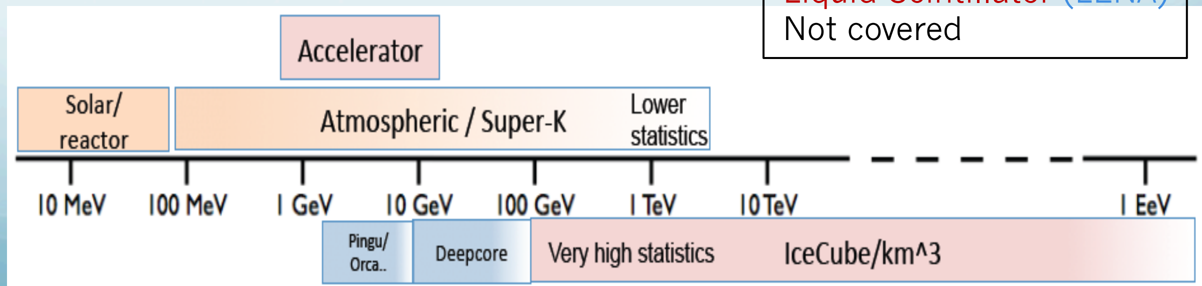
Magnetized Iron Calorimeters
- SOUDAN,MINOS → ICAL, MIND?

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

Liquid Argon
- Icarus → GLACIER

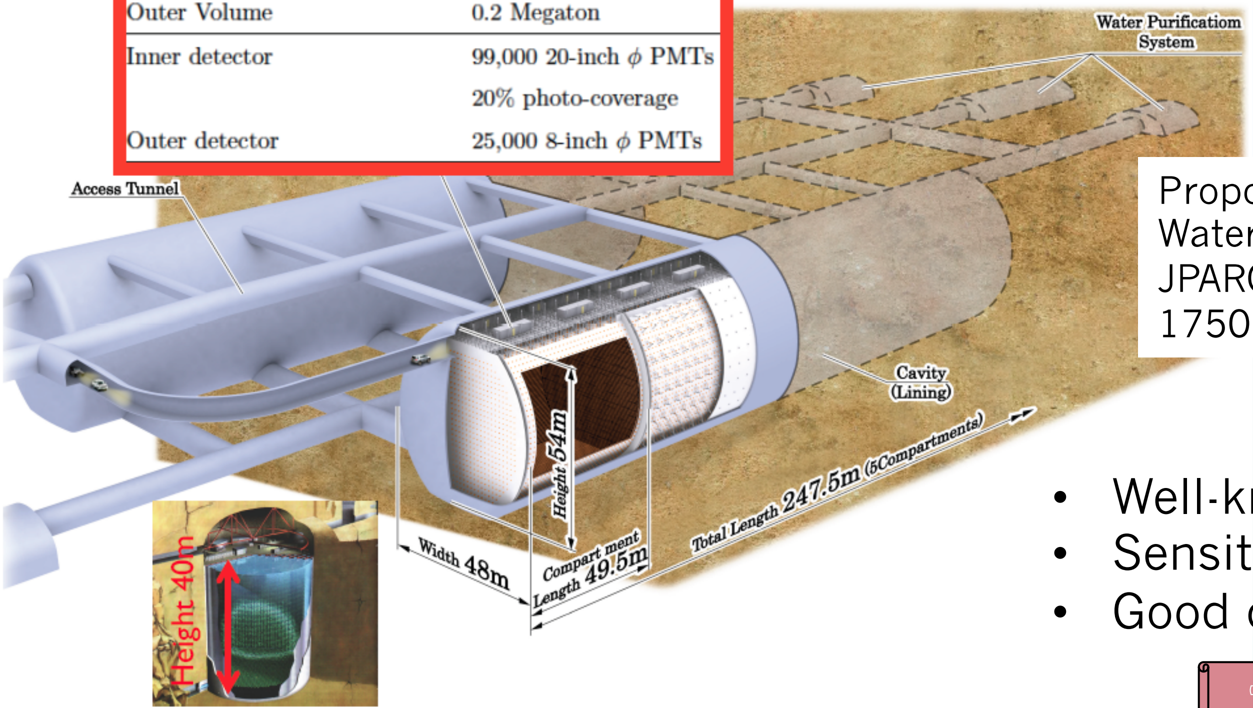
- 20 – 100 kton
- Excellent μ and e tracking
- Hadronic shower
- Low threshold
- Magnetization?

Liquid Scintillator (LENA)
Not covered



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



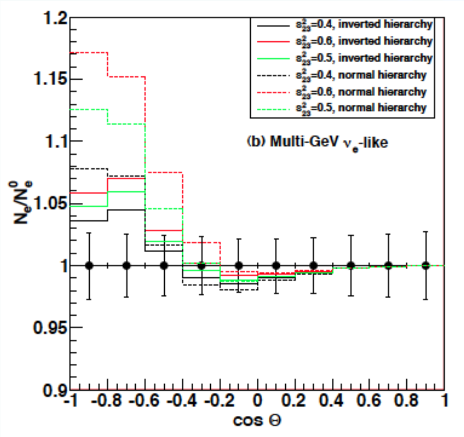
Proposal for ~500 kT multi-purpose Water Cherenkov facility 295 km from JPARC and 8km off from SK.
1750 mwe overburden.

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

☞ K. Okumura, Id 66 (09/12/13)

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

Prospect for the MH (atm)



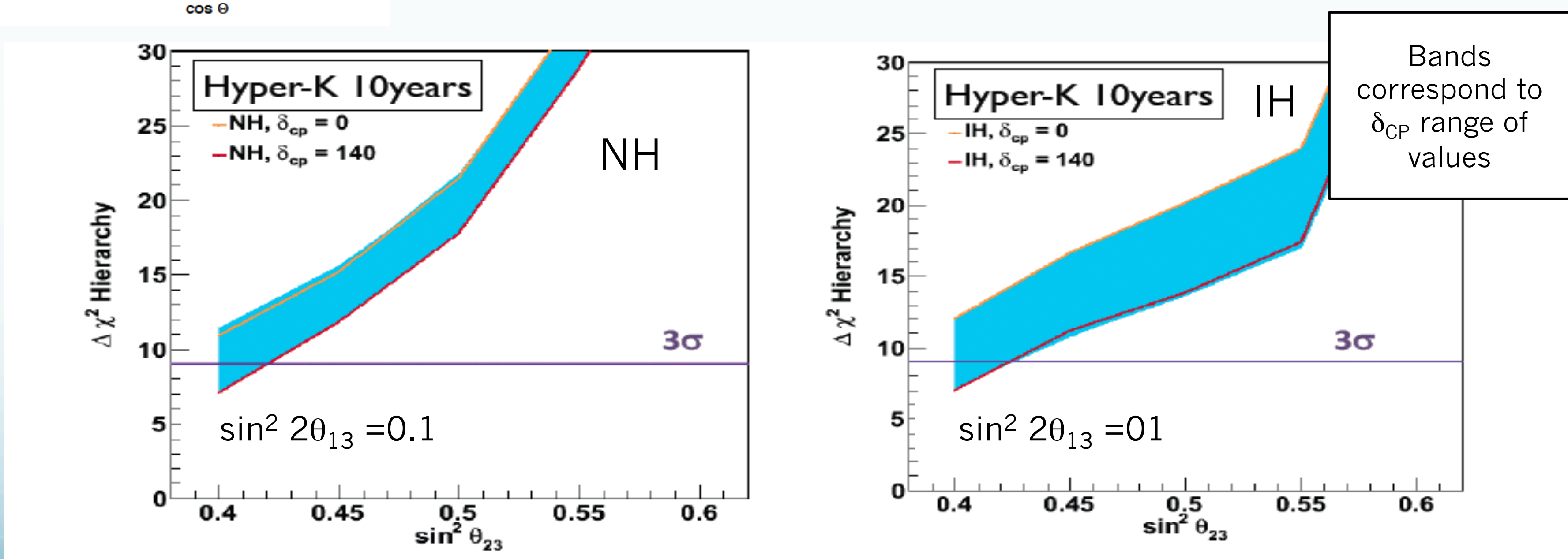
Ratio of oscillated ν_e rate over no oscillation case in sub-GeV and Multi-GeV channels.

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

Statistical separation of ν_e and anti-ν_e.

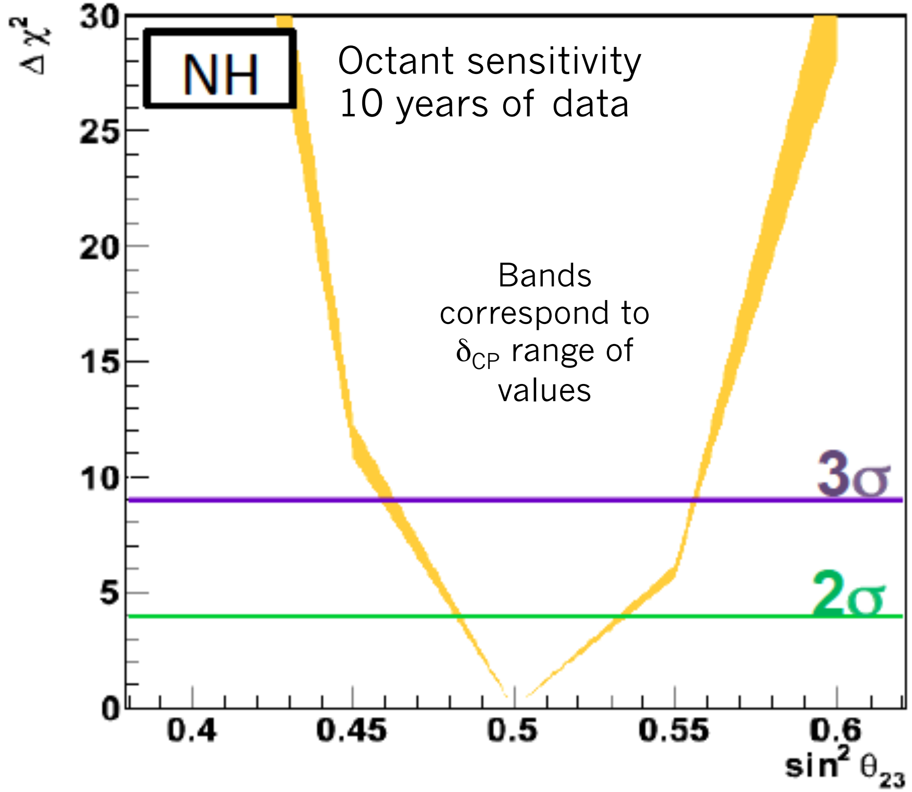
📖 HK letter of Intent, arXiv:1109.3262v1

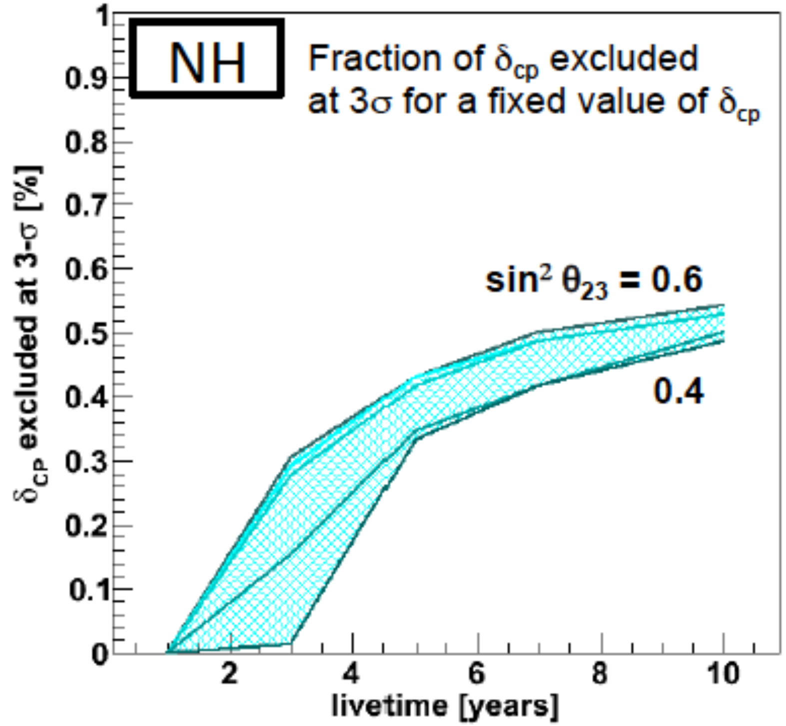
SK Sensitivity (σ)		
$\sin^2\theta_{23}$	now	+10 yrs
0.4	0.70	0.98
0.6	1.50	2.10



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

Prospects for θ_{23} octant and δ_{CP}





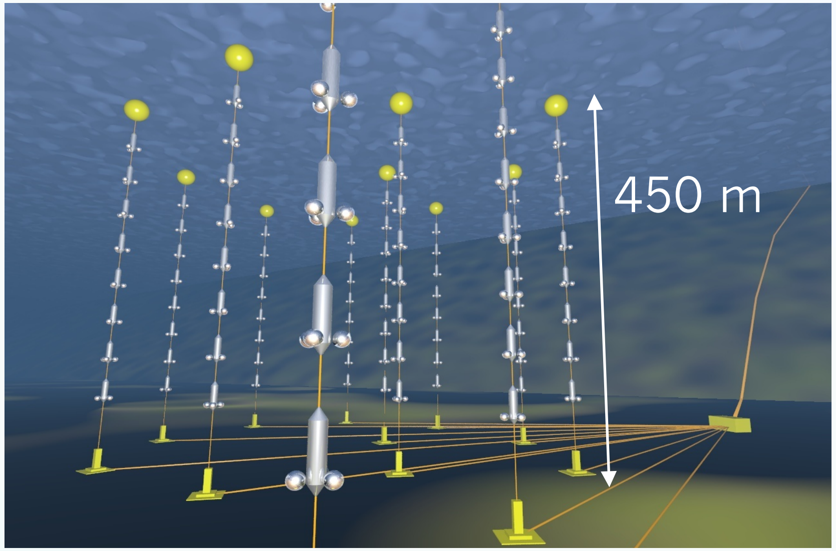
50% δ_{CP} fraction can be excluded at 3 σ after 10 yrs

SK Sensitivity (σ)		
$\sin^2\theta_{23}$	now	+10 yrs
0.4	2.00	2.60
0.6	1.61	2.10

From C. Walter, Neutrino Telescopes 2013

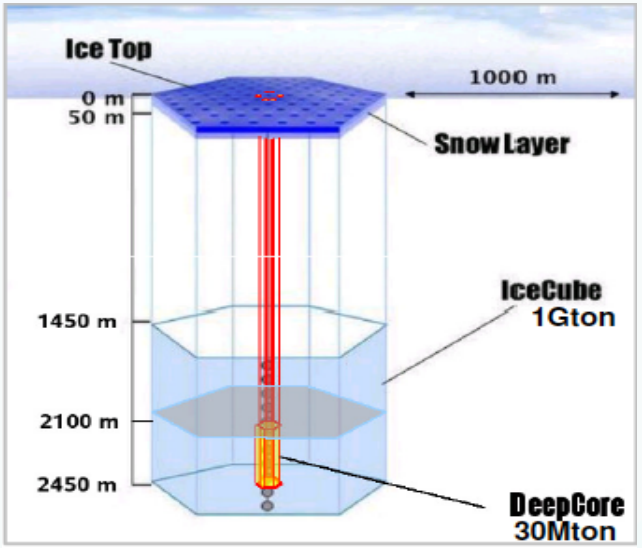
First achievements with Neutrino Telescopes

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)

Single lines ← Larger effect on low energy than higher energy events → DeepCore

Multi lines ← → IceCube

📖 Phys. Lett. B 714 (2012) 22.

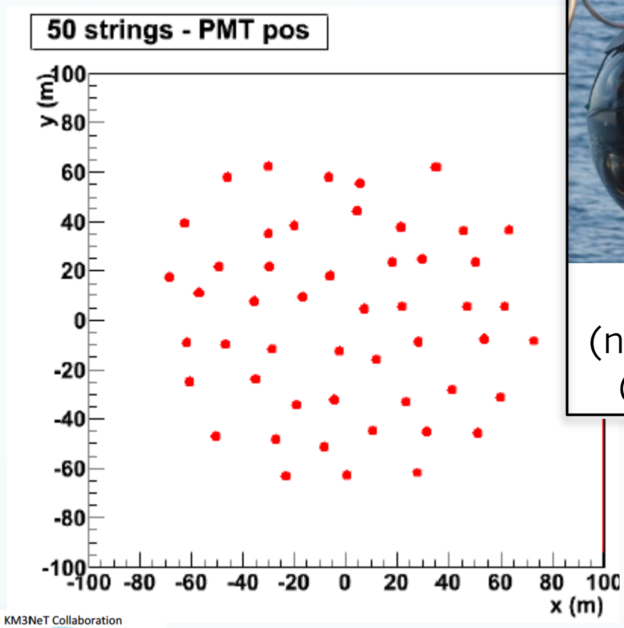
📖 Phys. Rev. Lett. 111, 081801 (2013)

☞ M. Spurio, Id 58 (09/10/13)

☞ S. Euler, Id 217 (09/12/13)

Proposed Low Energy Extensions

ORCA



31 3" PMTs
(now taking data
@ ANTARES)

KM3NeT Collaboration

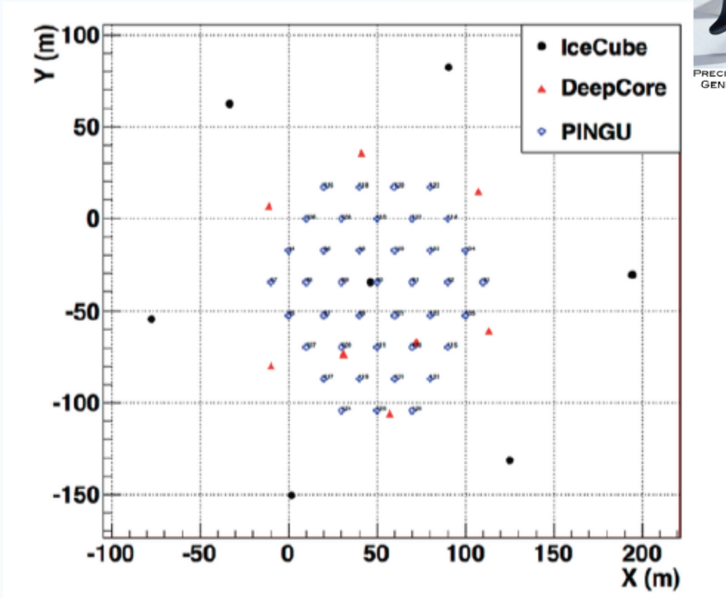
50 lines, 20m spaced,
20 OM/line 6m spaced
Instrumented volume ~2 Mt

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

☞ R. Coniglione, Id 104 (09/12/13)

PINGU

Precision IceCube Next Generation Upgrade



20-40 strings, 26-20m spaced,
60 OM/string 5m spaced
Instrumented volume ~ 6 Mt

Could be deployed 2016-2020 if funded
(8-12 M$ + 1,25M$/string)

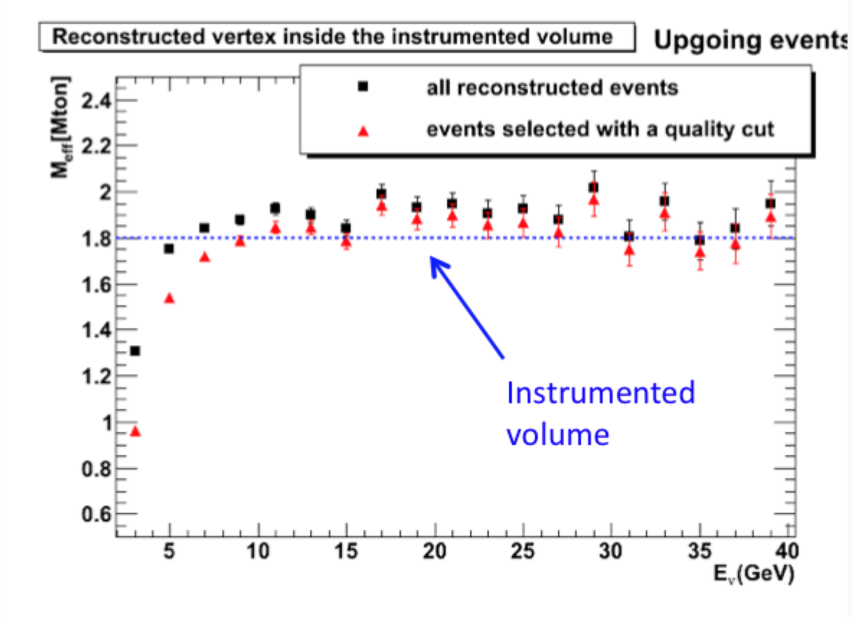
☞ D. Grant, Id 146 (09/11/13)

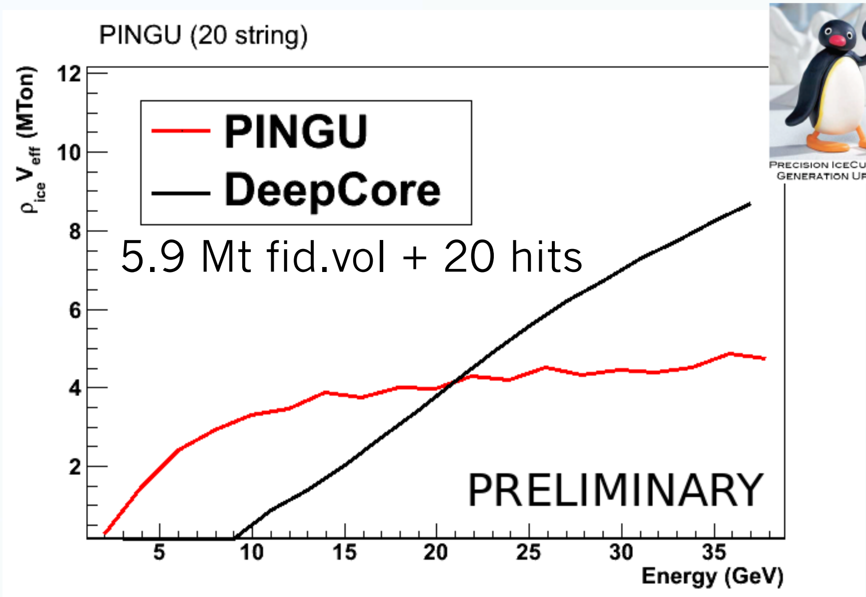
Optimized layouts still under study

📖 P. Koojman et al, ICRC proc 0164

📖 A. Gross et al, ICRC13 proc 0555

Proposed Low Energy Extensions





PRECISION ICECUBE NEXT GENERATION UPGRADE

KM3NeT Collaboration

ORCA

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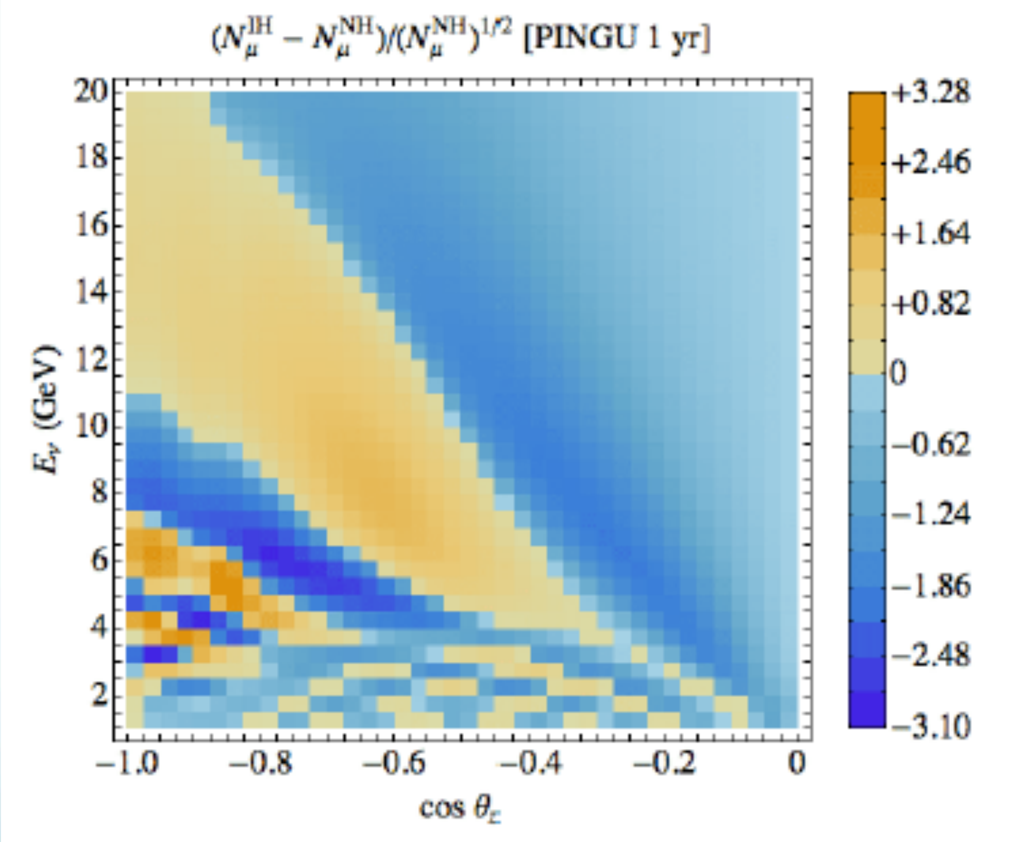
First (optimistic) sensitivities

Akhmedov et al. JHEP 02 (2013) 082



With exceedingly large PINGU effective volume

$$\rho V_{\rm eff}(E_\nu) = 14.6 \times [\log(E_\nu/{\rm GeV})]^{1.8}\ {\rm Mt}$$

$$S^{tot} = \sqrt{\sum_{ij} S_{ij}^2} = \sqrt{\sum_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{\sigma_{ij}^2}}$$

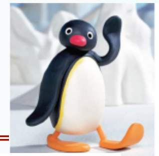
$$\sigma_{ij}^2 = N_{ij}^{NH} + (f N_{ij}^{NH})^2$$

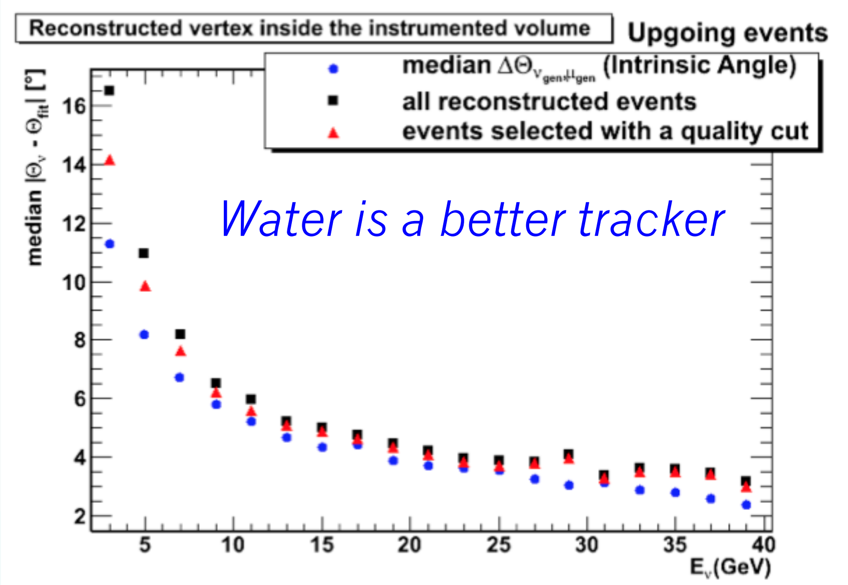
Uncorrelated systematics

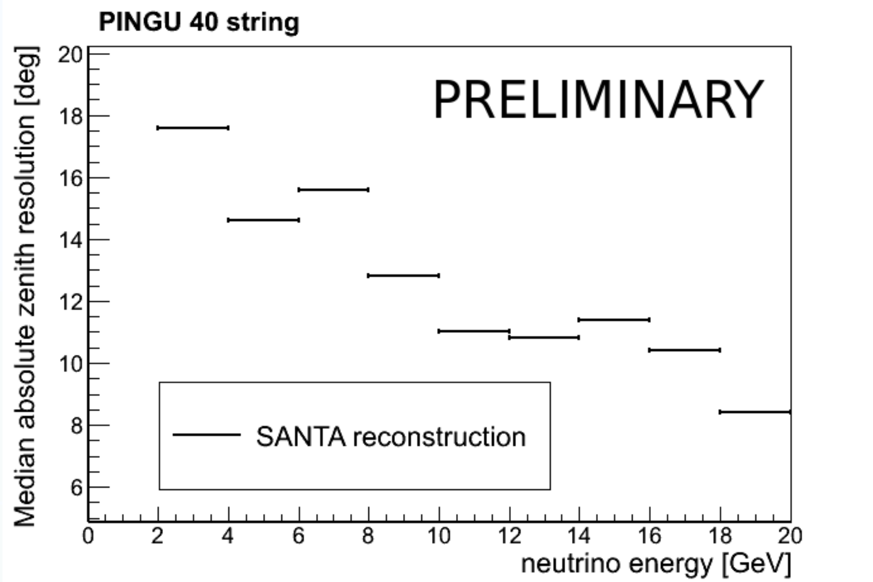
Perfect resolutions		σE=4 GeV, σθ= 22.5°	
S=45.5σ	(f=0%)	S=7.2σ	(f=0%)
S=28.9σ	(f=5%)	S=4.5σ	(f=5%)
S=18.8σ	(f=10%)	S=3.0σ	(f=10%)

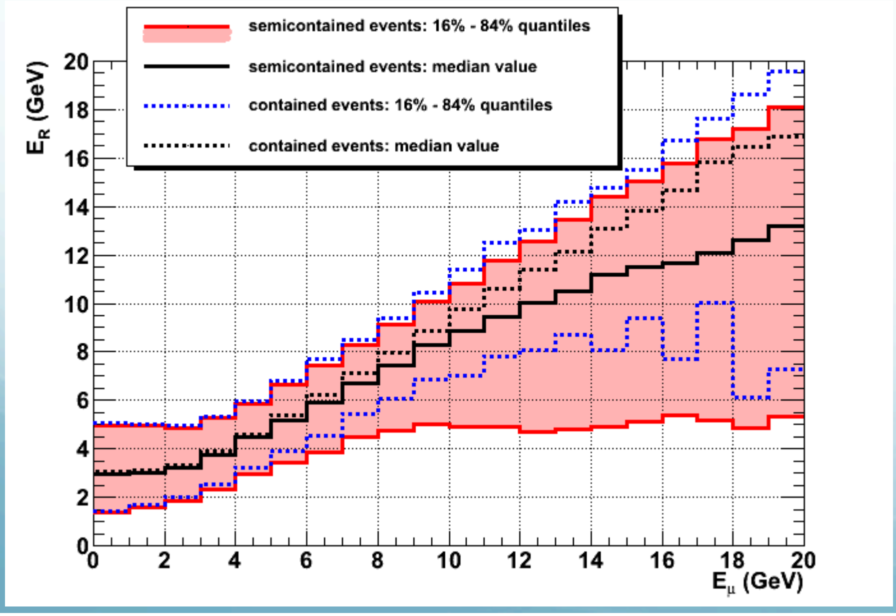
In 5 years

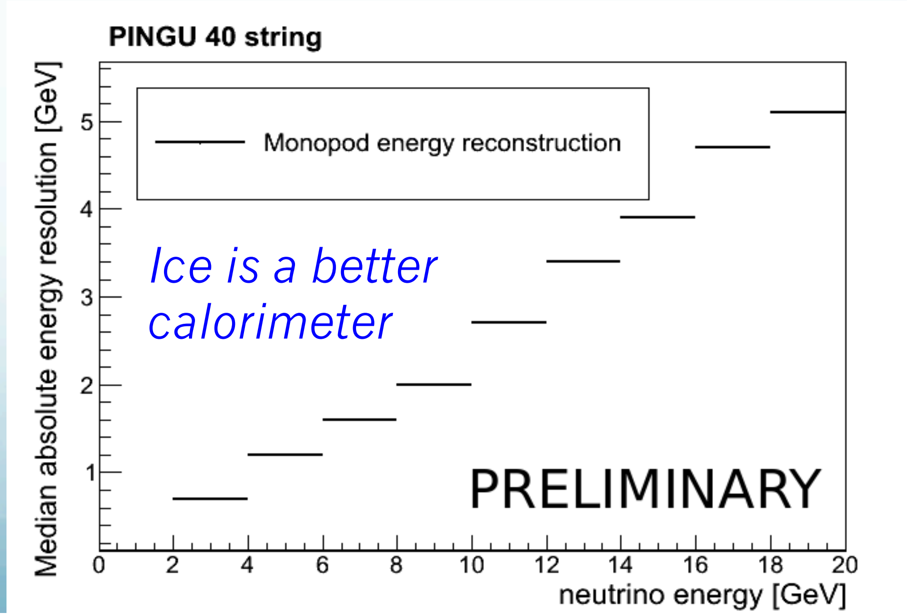
Preliminary performances





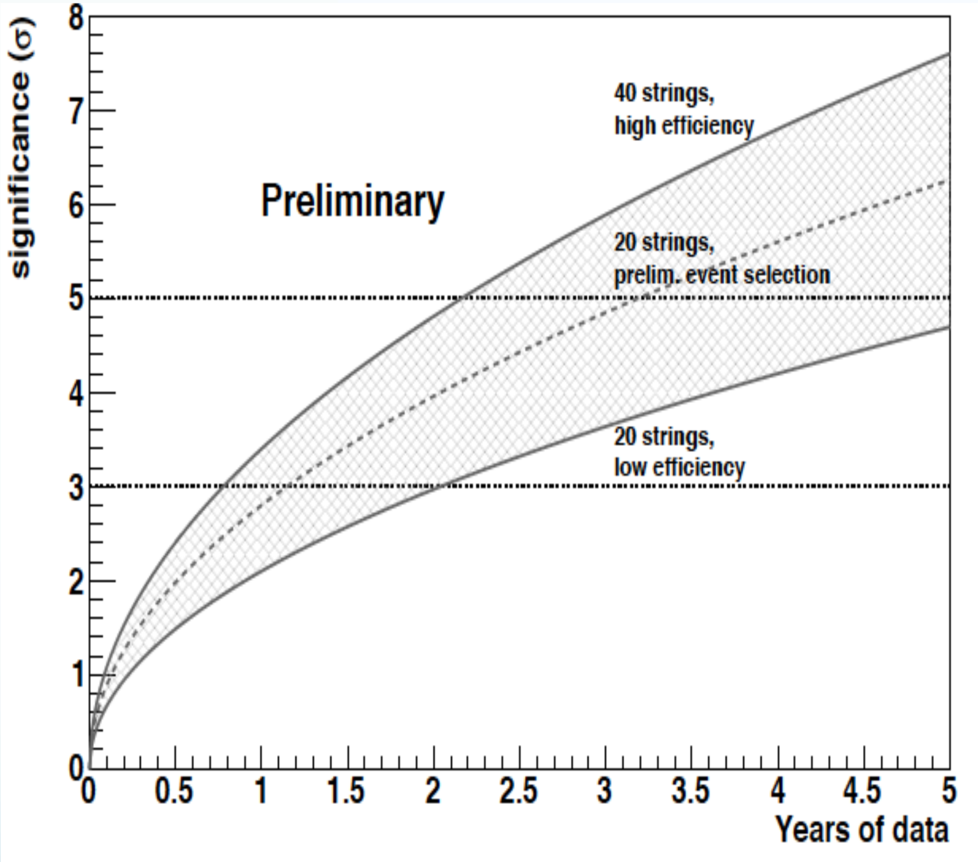






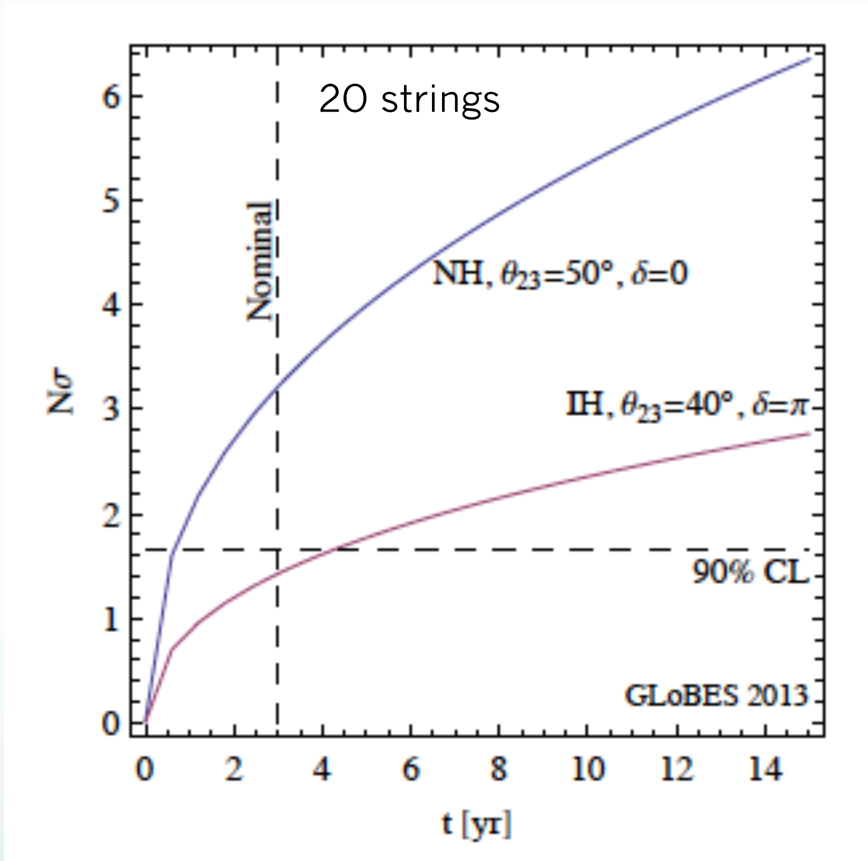
PINGU sensitivities

📖 PINGU collaboration, arXiv:1306.5846



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

📖 W. Winter, arXiv:1305.5539v1



2 extreme cases of true param values.
$\Delta E/E$ = 25% and $\Delta\theta/\theta$= 0.6 $\sqrt{(m_p/E)}$
5% Flavor mis-id
Method : $\Delta\chi^2$
(optimistic 📖 E. Cuifolli et al 1305.5150)

ORCA sensitivity

all results are preliminary

KM3NeT Collaboration

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

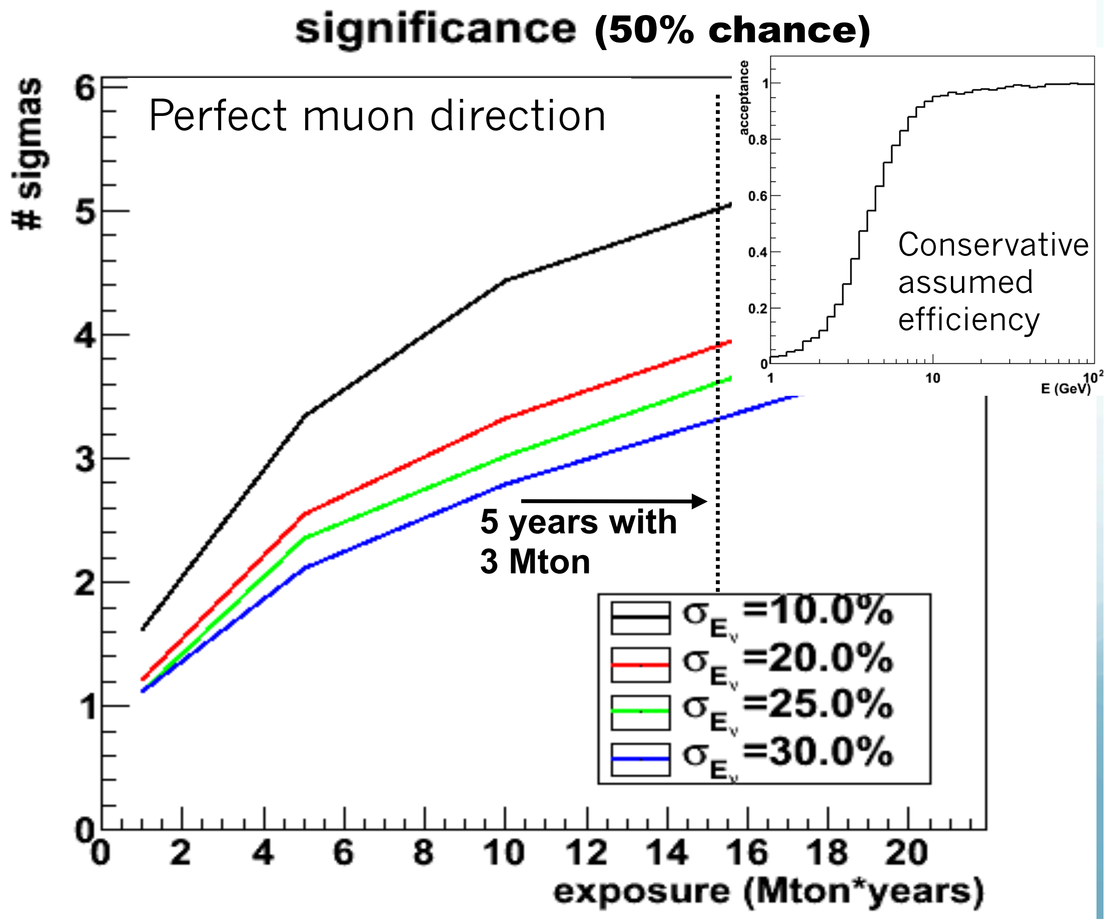
$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\text{H}} =$ 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

PRECISION ICECUBE NEXT GENERATION UPGRADE

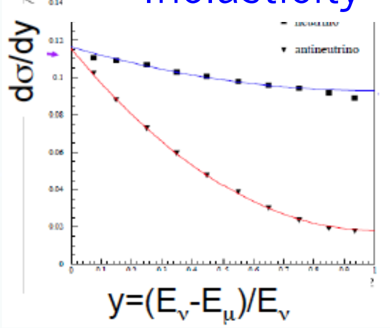
Improvements

✓ Shower reconstruction

Should help to evaluate neutrino energy.
Study of intrinsic energy variations → Current limitation from physics (vertex, prop,...) not detector

✓ 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

Deteriorations

✓ Flavor misidentification

Attempts to study response to ν_e

Development of muon tag to then subtract bkg from ν_x NC, ν_e, ν_τ

✓ Atmospheric muons

Preliminary studies of reconstructed vertex position encouraging → out of instr. volume

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

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

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

δ_{cp} dependence → Small impact varying CP phase

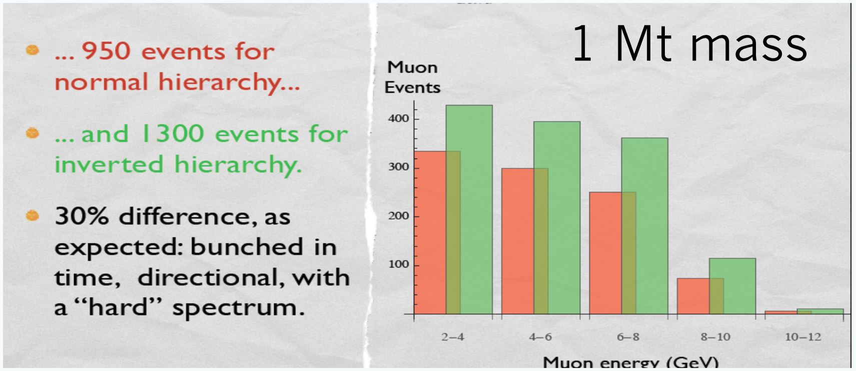
Several other studies point to the same conclusions...

Neutrino beam to PINGU/ORCA?

- 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

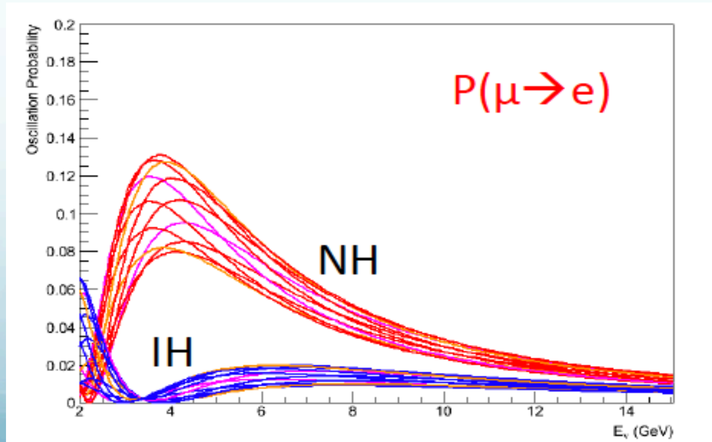
	Fermilab	CERN	J-Parc
South-Pole	11600 km	11800 km	11400 km
Sicily	7800 km	1200 km	9100 km
Baikal Lake	8700 km	6300 km	3300 km



→ 9 σ separation on purely statistical ground in one year

- Electron counting experiment - Protvino-ORCA L=2588 km, beam inclined by 11.7°

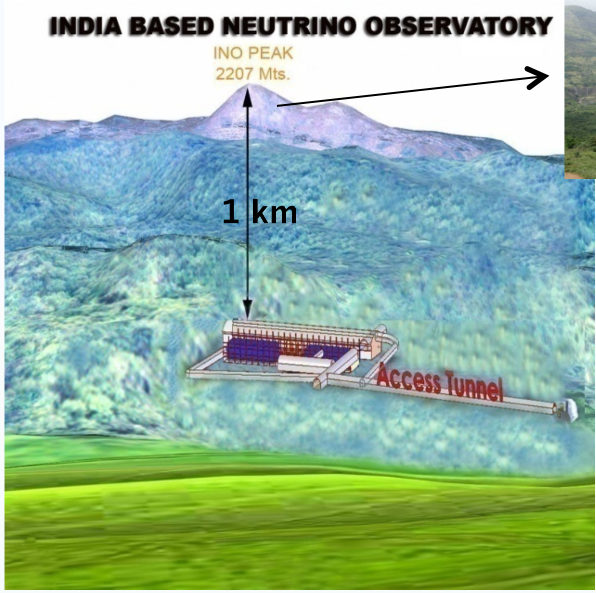
📖 J. Brunner, arXiv:1304.6230

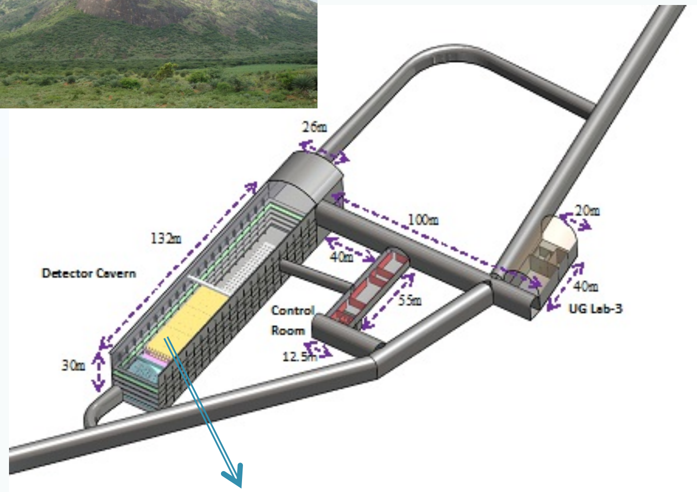


10^{21} pot -- 3 years
7 σ stat. separation
3 σ with 3-4% sys

No need for energy reconstruction

INO: India-based Neutrino Observatory





50 kton ICAL
(room for additional 50kton)

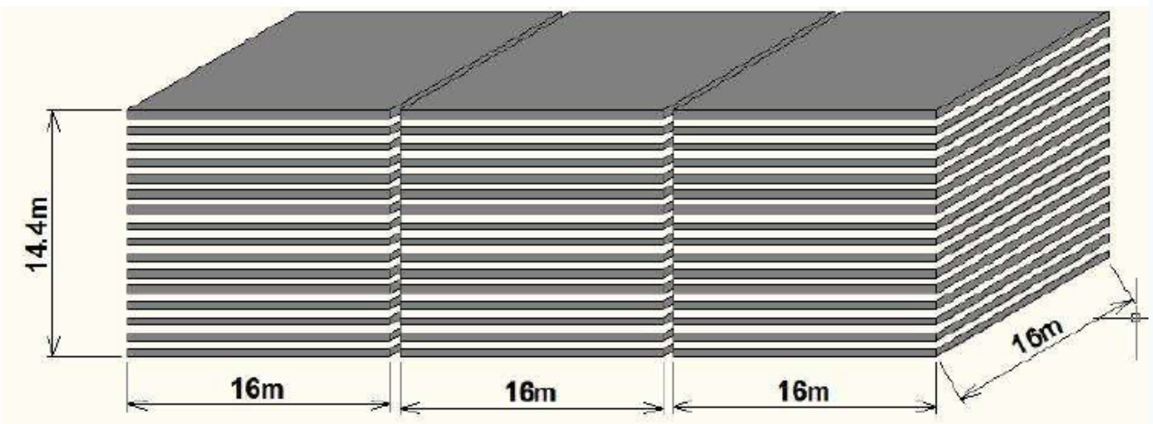
- 115 km west of Madurai (internat. airport)
- Pottipuram Village, Theni District, Tamil Nadu State
- 1.9 km access tunnel
- Indian collab (~20 institutes) + Hawaii Univ (USA)
- Several other experiments when operational ($\beta\beta0\nu$, DM)

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

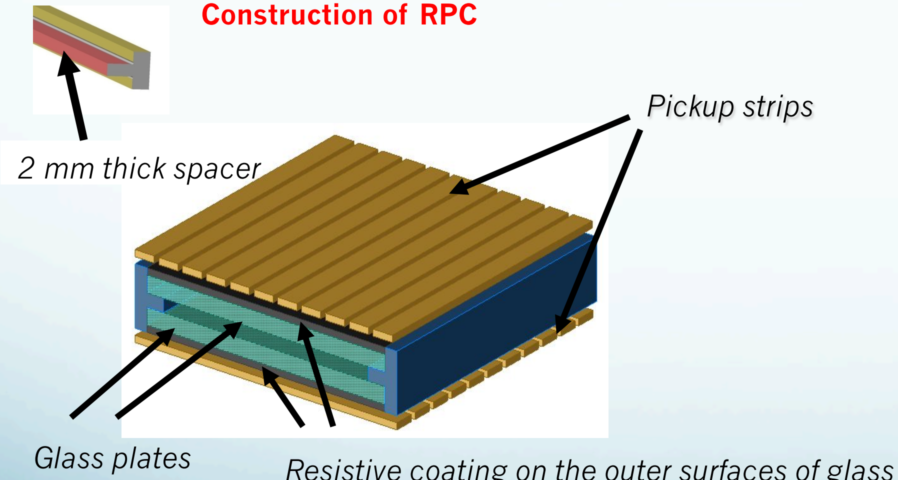
The INO-ICAL detector



- ✓ 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

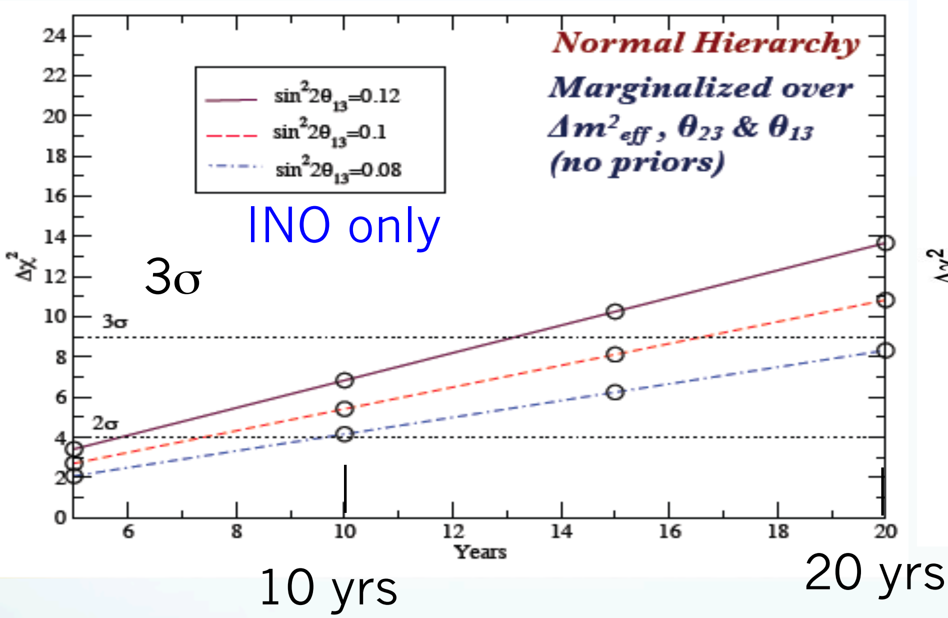
Cosmic –ray tracks are seen…

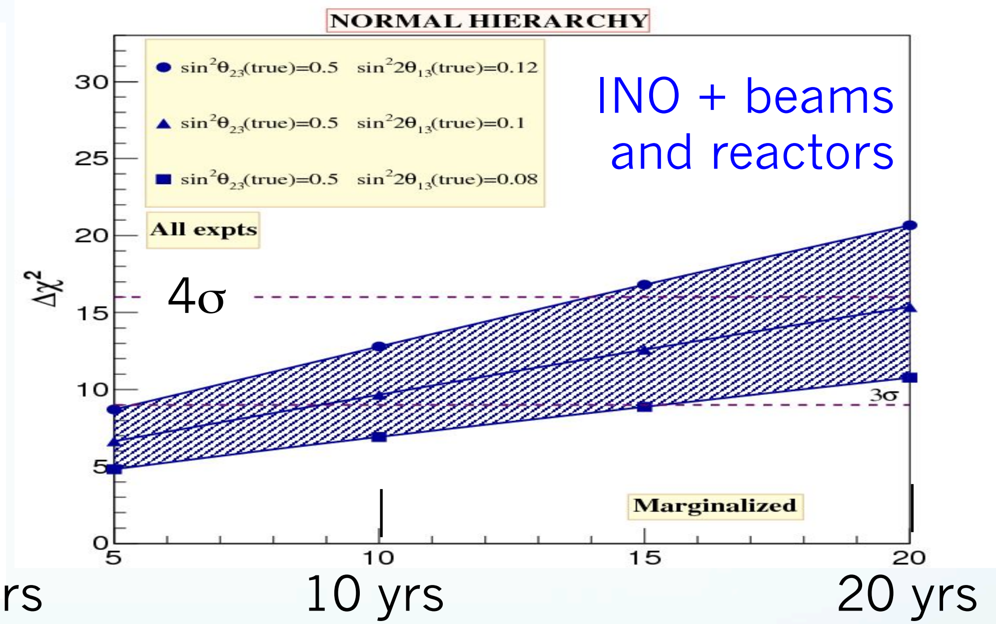
Current Status:

- 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





Further improvements expected by adding hadron events

📖 arXiv:1306.1423v1

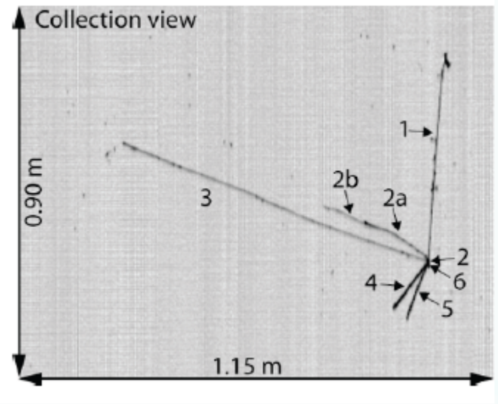
INO + Other experiments

📖 Ghosh, Thakore & Choubey, arXiv:1212.1305

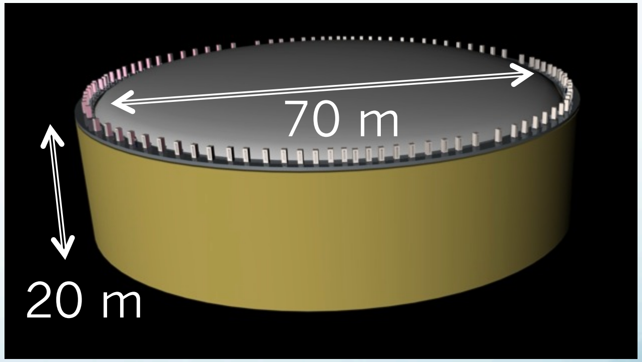
📖 Blennow & Schwetz, JHEP 1208 (2012) 058, Erratum-ibid. 1211 (2012) 098

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
  - Sensitive to muons and electrons
  - Hadronic component can me measured



- Atmospheric neutrino studies
  - Tau neutrino appearance
  - Discrimination between $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ from upward/downward asymmetry

📖 A. Stahl et al, LBNO, SPSC-EOI-007 (2012)

☞ S. Murphy, Id 33 (09/12/13)
☞ M. Buizza Avanzini, Id 43 (09/12/13)

Magnetized LAr-TPC?

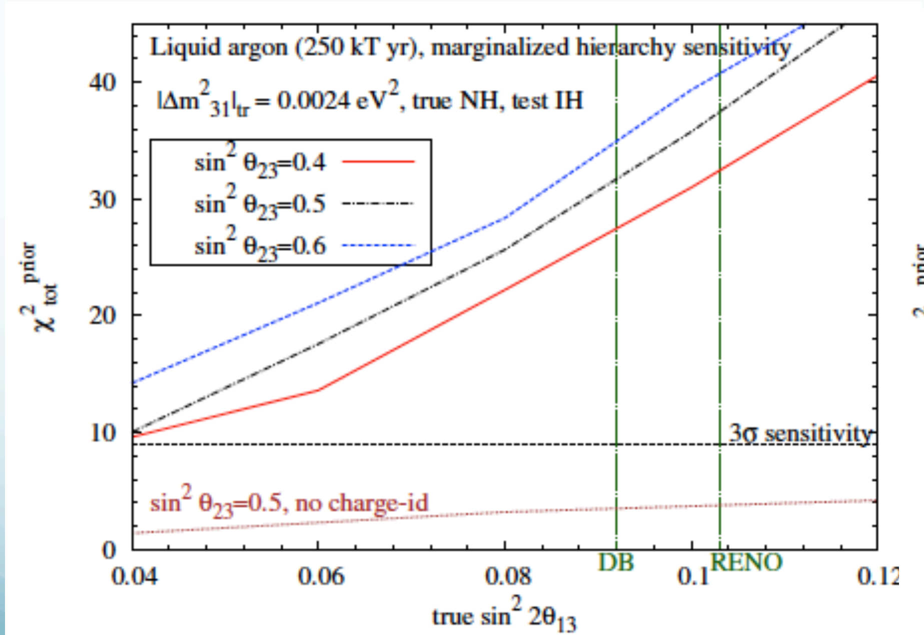
Sensitivity to mass hierarchy require charge identification to compensate low mass
→ Magnetization?

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

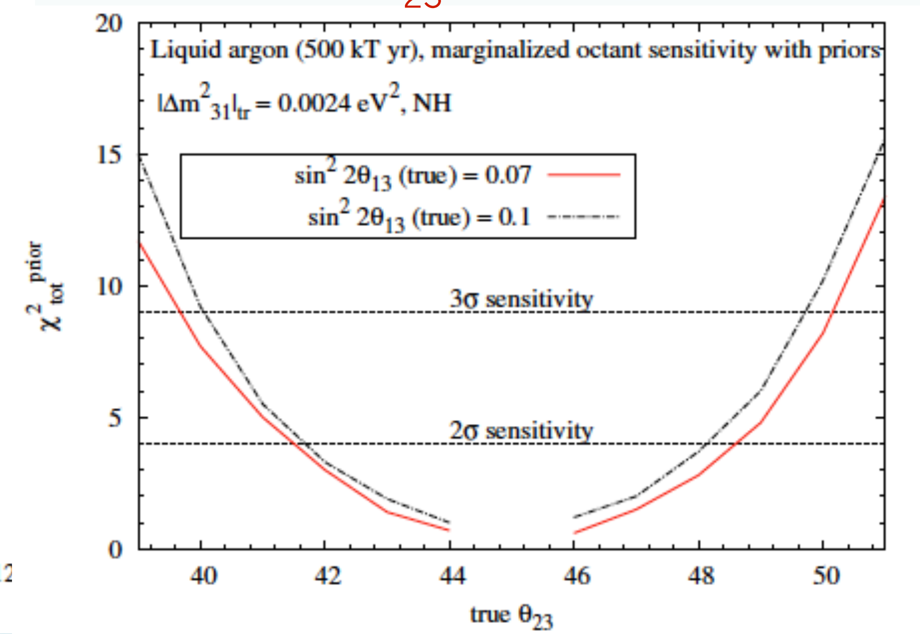
100% CID for muons and 20% for electrons in the energy range 1-5 GeV

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

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

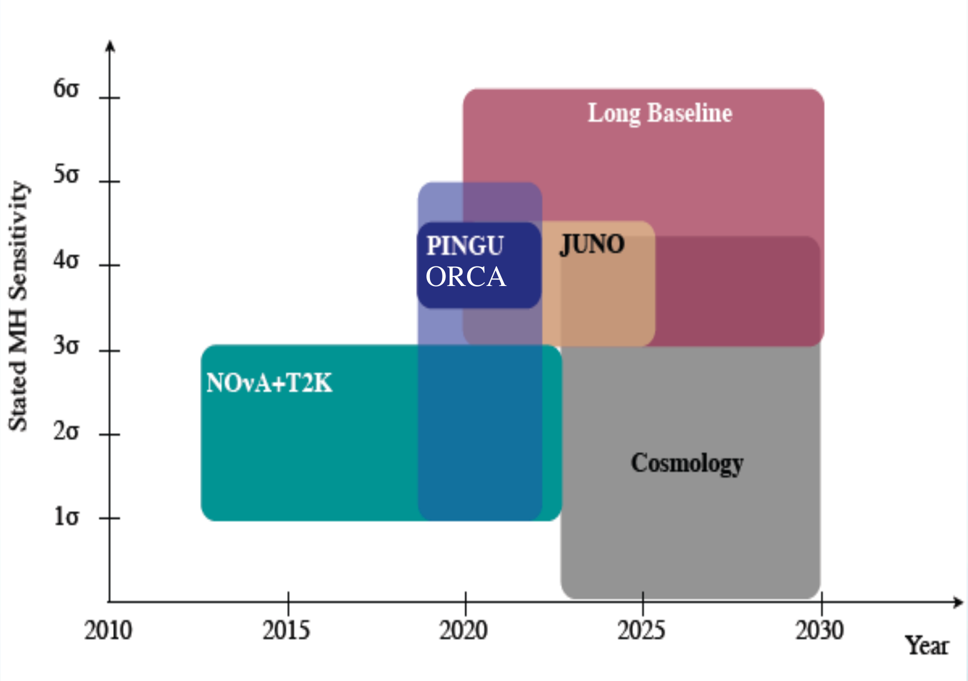
- Atmospheric Neutrinos have still a major role to play for precision measurements and determination of unknown parameters such as the mass hierarchy.

- 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.

- Preliminary ORCA/PINGU sensitivities are quite promising. Collaborative work on-going.



📖 R.N. Cahn et al, arXiv:1307.5487

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