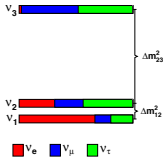
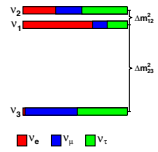




Neutrino Mass Hierarchy with Atmospheric Neutrinos and Neutrino Telescopes: PINGU, ORCA and INO

Snowmass Workshop, SLAC

6-8 March, 2013

Doug Cowen

Penn State

This session:

Mass Hierarchy with Atmospheric Neutrinos and WCDs - Ed Kearns
Mass Hierarchy with Atmospheric Neutrinos and Neutrino Telescopes - Doug Cowen
Mass Hierarchy with Accelerator Neutrino Experiments -
Mass Hierarchy from Man-made Neutrinos (Future Projects) - Xin Qian

Neutrino Mass Hierarchy (NMH)

- The NMH is a fundamental parameter of the neutrino sector: intrinsically interesting
  - Happily, the large θ_{13} gives us the ability to measure NMH via earth matter effects
- For many experiments, the NMH is also degenerate with leptonic CPV
  - CPV is considerably *more* interesting
  - NMH can be viewed as a stepping stone to CPV
    - Important question: If we know the NMH, how do we optimize future experiments to focus purely on CPV?

NMH and Atmospheric Neutrinos

- Few-GeV atm. ν could provide sensitivity to NMH via matter effects
  - Resonant MSW and parametric oscillations for few-GeV earth-crossing neutrinos
  - NMH determines character of oscillations and it is different for ν vs $\overline{\nu}$
    - At these energies, use either
      - magnetic field to distinguish μ^- from μ^+ event-by-event [INO]
      - $\sigma(\nu) \sim 2\sigma(\text{anti-}\nu)$ [PINGU, ORCA]
  - Degeneracy with δ_{CP} is minimal

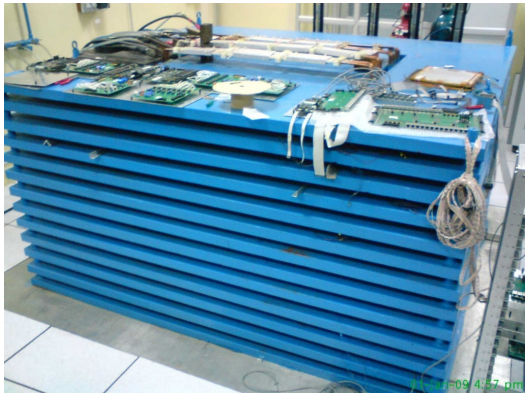
For Each Detector:

- Design concept
- Measurement principles
- Reach, dependencies, complementarities
- Timescale estimate
- Cost estimate

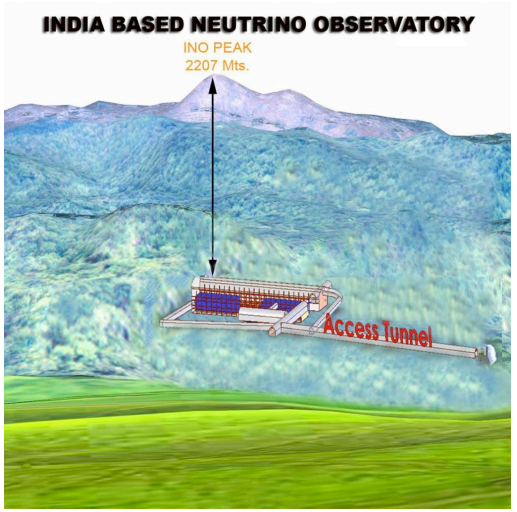
INO (India-based Neutrino Observatory)

- Design concept:
  - 50 kton magnetized iron calorimeter
    - 1.3 T field
    - 48.4m long x 16m wide x 14.4m high
    - 150 layers 5.6cm Fe interleaved with 28,000 2m x 2m glass Resistive Plate Chambers (RPCs)
  - Bury it all under a mountain in Southern India

Cosmic ray test stand

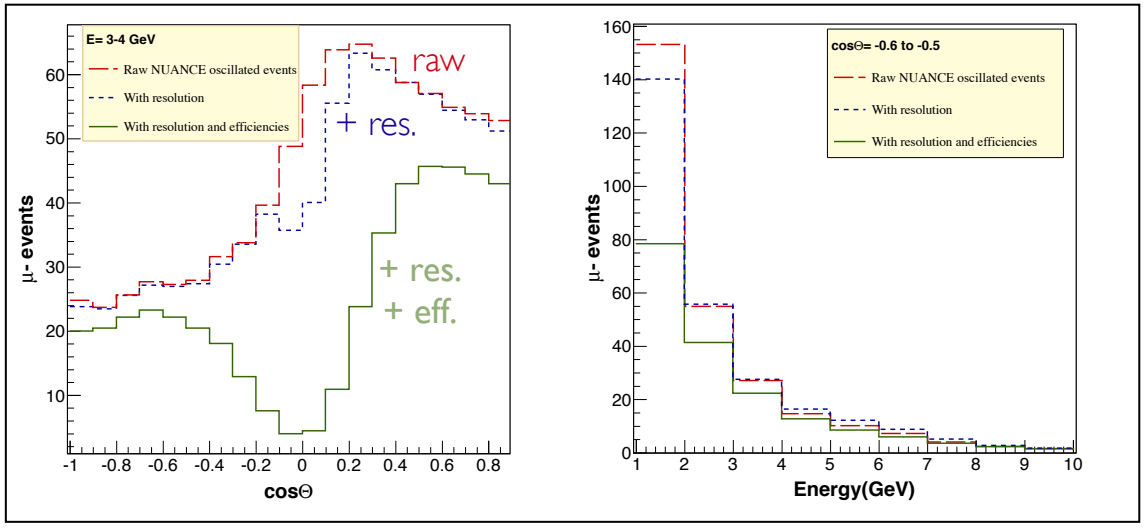


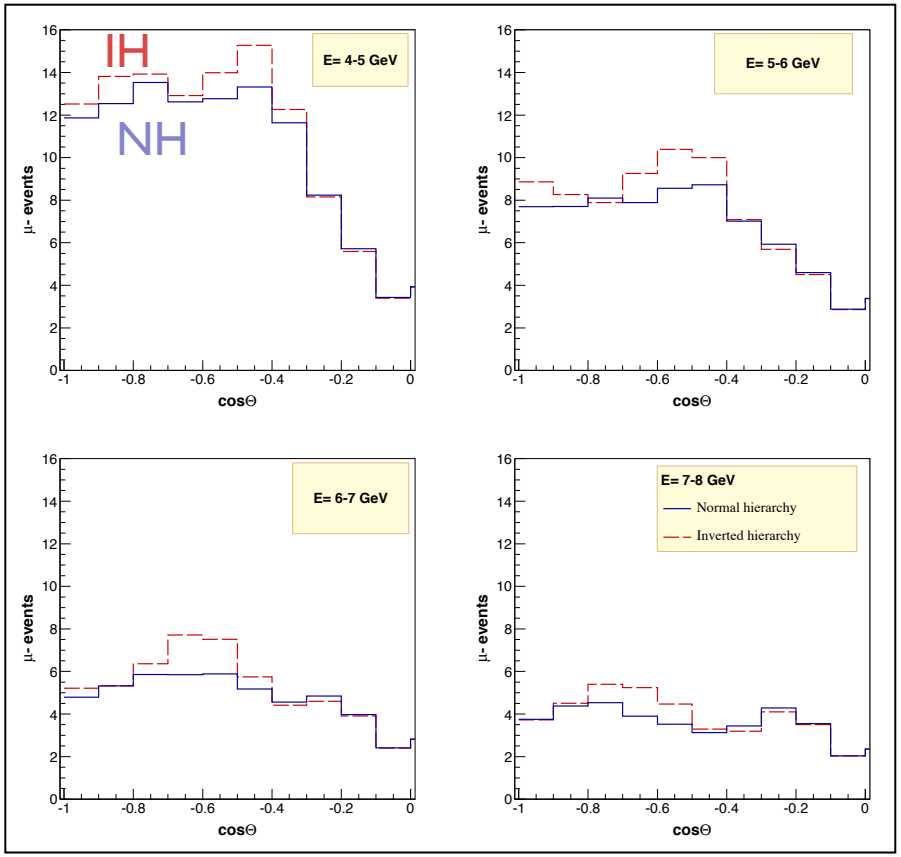
Prototype magnet



INO

- Measure energy and angle of μ^- and μ^+, separately

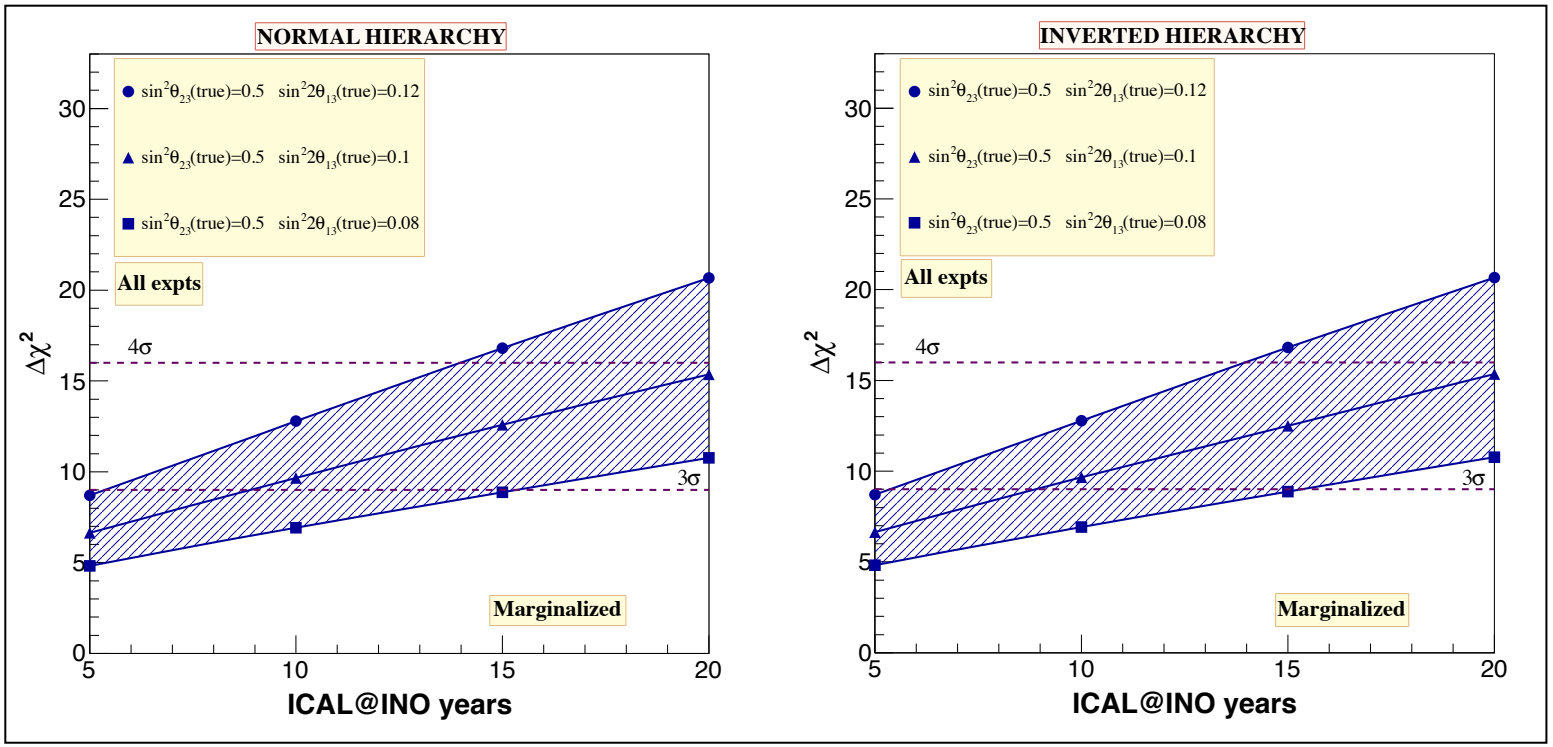




10 years of μ^- data shown

INO

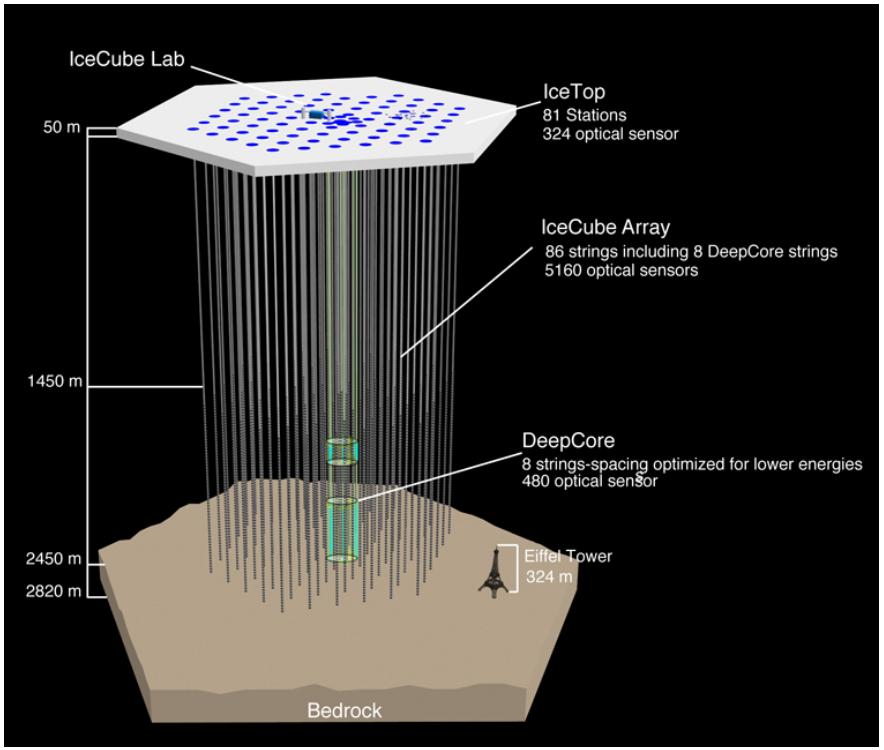
- Sensitivity to NMH



- Start data taking 2017-2018
- 3σ separation in ~10 yrs in combination w/NOvA & T2K
- Cost: $250M

PINGU (Precision IceCube Next Generation Upgrade)

- Design concept:
  - Add in-fill strings to IceCube/DeepCore array
    - further increase module density
      - current detector shown at right...
    - continue to exploit 2km depth and surrounding array as active cosmic ray muon veto
    - optimize and simplify IceCube module design for ~5 GeV E_ν events, reduced cost
    - co-deploy new calibration devices tuned for lower E_ν
    - improve refrozen hole ice clarity
  - Goal: reach few GeV E_ν threshold



The current IceCube/DeepCore detector

PINGU (Precision IceCube Next Generation Upgrade)

- Design concept:
  - Add in-fill strings to IceCube/DeepCore array
    - further increase module density
      - ...sample new geom. shown at right; V ~ few Mt
    - continue to exploit 2km depth and surrounding array as active cosmic ray muon veto
    - optimize and simplify IceCube module design for ~5 GeV E_ν events, reduced cost
    - co-deploy new calibration devices tuned for lower E_ν
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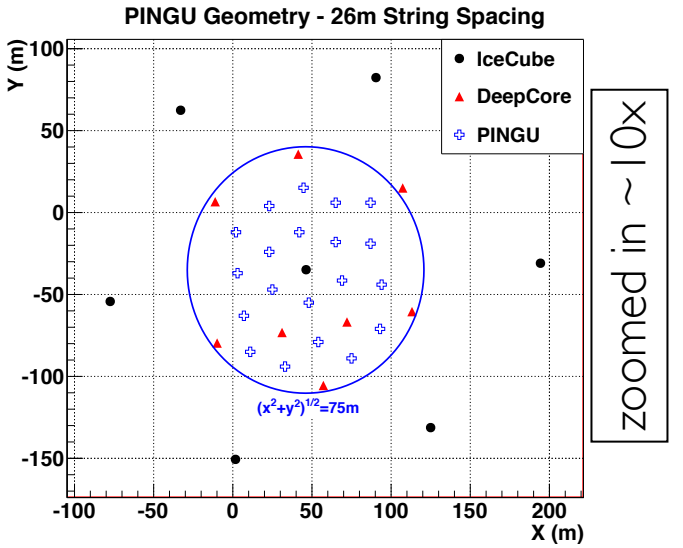
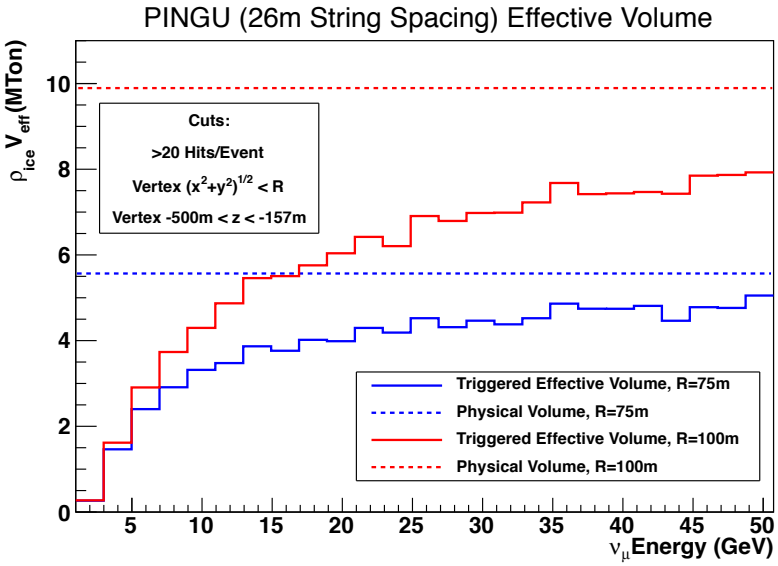
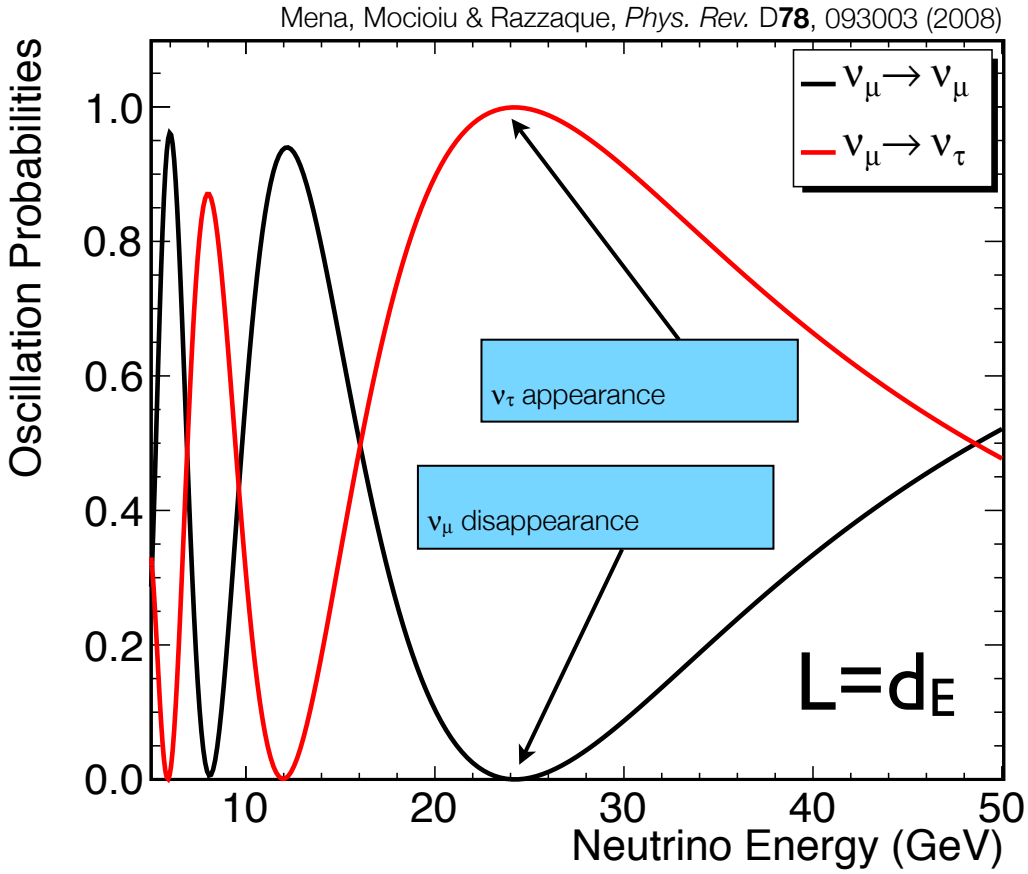




PINGU



- Measurement principle [1,2]
  - Exploit MSW & parametric oscillation effects for high-statistics sample of earth-crossing atmospheric neutrinos
  - Measure $P_{\mu\mu}(E_\nu, \theta)$ for ~5 < E_ν < ~15 GeV
  - Take advantage of

$$\sigma(\nu) \sim 2\sigma(\bar{\nu}) \;\; \& \;\; \phi(\nu) > \phi(\bar{\nu})$$

  - Maybe use inelasticity, too? [3]

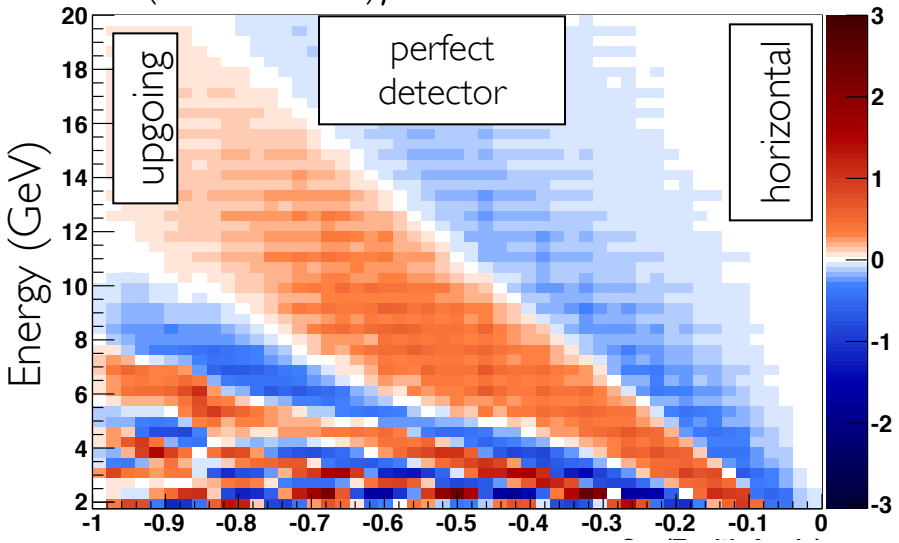
[1] Mena, Mocioiu, and Razzaque 0803.3044
[2] Akhmedov, Razzaque, and Smirnov 1205.7071
[3] Ribordy and Smirnov, 1303.0758

PINGU

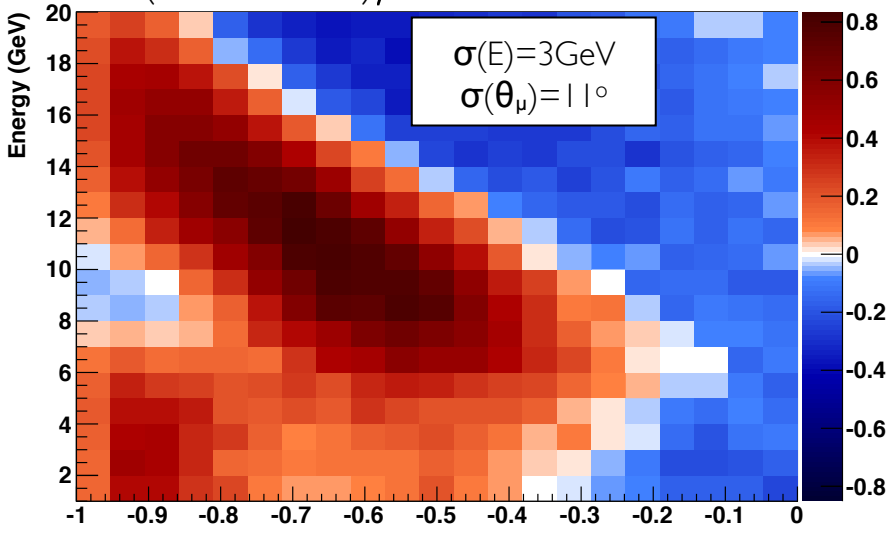
- Following Ref. [2], define "distinguishability" as

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

$\left(N^{IH} - N^{NH}\right)/\sqrt{N^{NH}}$ (PINGU, 1 yr)



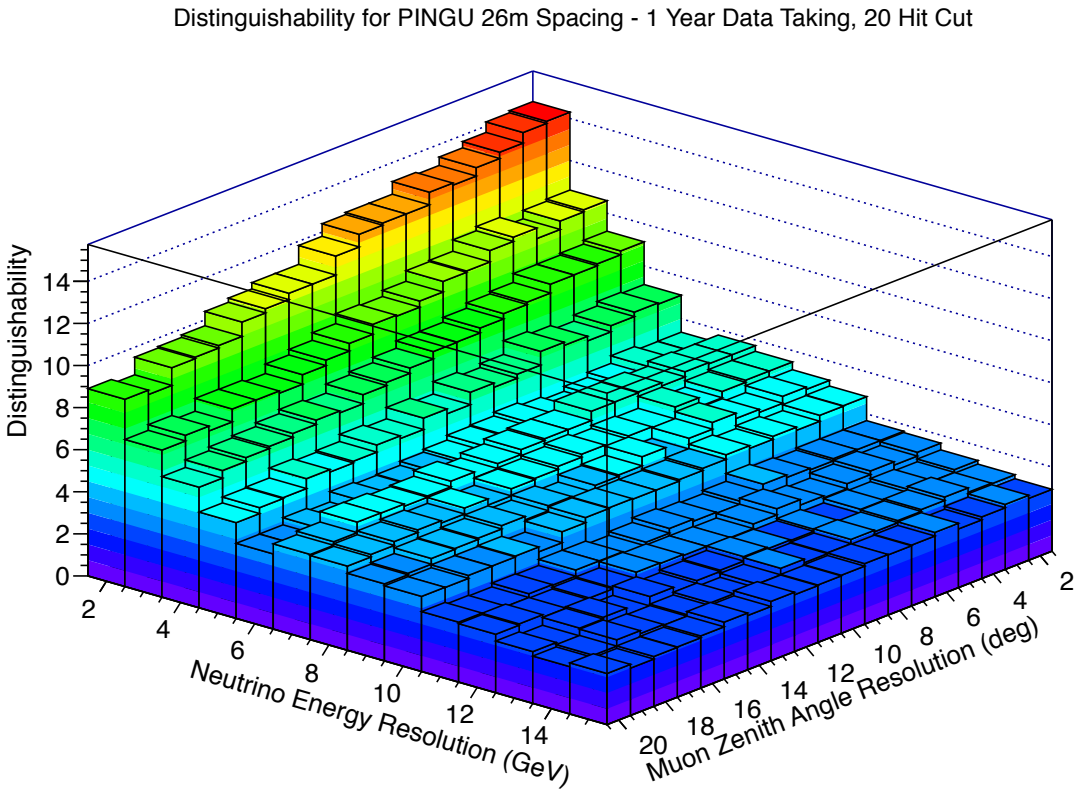
$\left(N^{IH} - N^{NH}\right)/\sqrt{N^{NH}}$ (PINGU, 1 yr)



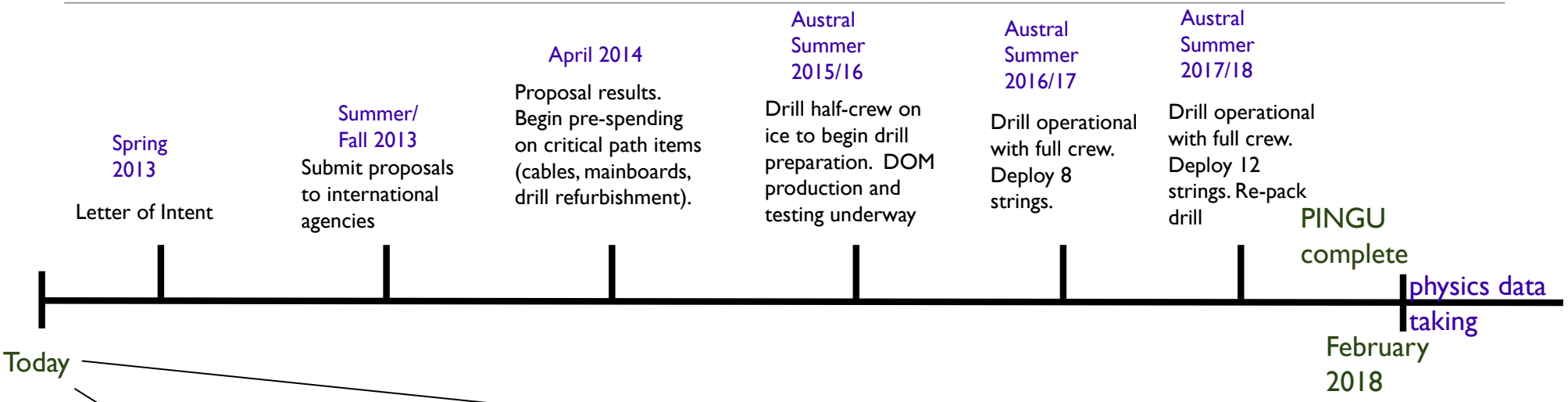
$$N_{i,j}^{NH} = P(\nu_\mu)_{i,j}^{NH} * \Phi(\nu_\mu)_{i,j} * \sigma(\nu_\mu)_j * V_{i,j}^{eff} + P^{NH}(\overline{\nu_\mu})_{ij} * \Phi(\overline{\nu_\mu})_{i,j} * \sigma(\overline{\nu_\mu})_j * V_{i,j}^{eff}$$

PINGU

- Current status
  - Actively working on reco. & geom. optimization to estimate σ's from sim.
    - As a *proxy* for reco. efficiency, require at least 20 detected Cherenkov γs
- Near–future work
  - Evaluate impact or mitigation of anticipated systematics (uncertainties in ice properties, module efficiencies, energy scale, angular reconstruction, cross sections, atm nu fluxes, earth profile, ...)
- Theoretical issues
  - δ_{CP} : small (but with a beam[4], PINGU might *measure* δ_{CP})
  - $\Delta(m_{31})^2$: non-negligible degeneracy with NMH, but manageable



PINGU: Timescale & Cost



Current Status

- Detailed MC simulations nearing completion
- Enhanced low-E reconstruction algorithms from DeepCore being applied to simulated PINGU events
- Estimation of sensitivity to NMH with full reconstruction and estimation of systematics underway
- Letter of Intent in prepration

- Rough cost estimate
  - Drill setup costs: $10M
  - Hardware + deployment cost per string: $1.25M
    - A 20-string in-fill would cost roughly $35M, shared between NSF and European agencies

ORCA (Oscillation Research with Cosmics in the Abyss)

- Design:
  - deploy a dense array of KM3NeT modules ~4km underwater in Mediterranean
    - module prototype exists
    - engineering deployment tests for KM3NeT have been performed
- Measurement principle ~same as PINGU
  - greater depth reduces muon flux relative to PINGU by ~50x, but absence of surrounding array for active muon veto may be challenging
- Timescale and cost
  - In principle have funds already, but they're intended for UHE ν KM3NeT
    - would have to convince agencies to repurpose funds for ORCA
    - cost would be larger than for PINGU but would be partly "amortized" as KM3NeT prototyping
  - Timescale dependent on numerous unknowns regarding module design and detector deployment, but in principle similar to that of PINGU

Conclusions

- Atmospheric neutrino telescopes are the lucky beneficiaries of a known high θ_{13} and a prolific, free neutrino source
- With such generous friends, neutrino telescopes may be able to measure NMH
  - PINGU:
    - gratifyingly short time scale and modest cost
    - construction is straightforward and very low risk
    - now addressing reconstruction and systematics challenges
  - ORCA:
    - somewhat behind PINGU but may already have funding
  - INO:
    - can measure NMH but suffers from low statistics

The End

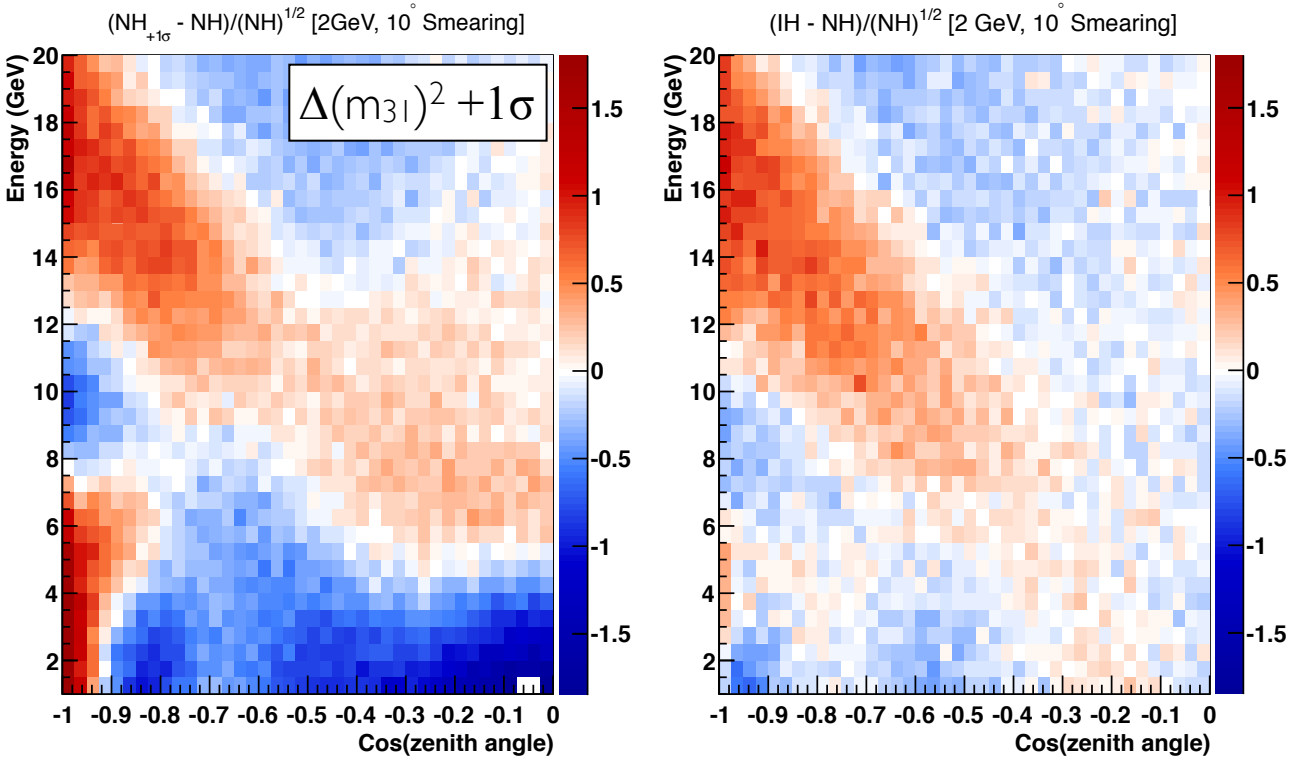
.not.(T2K or NOvA):

Existing & their upgrades
Future atmospheric
Future man-made

Expt. (A-Z)	ν source	Method	Dataset for 3σ:	Earliest Year for 3σ	$-\delta_{CP}$ range (NH)	Cost	Status	Comple-mentarity	Location
CHIPS	NuMI	WCD, ν_e app., 1% $\sin^2 2\theta_{23}$	3+3	~2021	30-120°	$120M	R&D	NOvA, T2K	Minnesota Mine Pits
Daya Bay II	Daya Bay Reactors	$\bar{\nu}_e$ dis.	3	2023	All	?	R&D		China
GLADE	NuMI	LAr (5-10kt)	3+3	NOvA+10	30-140°	$1-200M	R&D	NOvA, T2K	Ash River (NOvA)
Super-K, Hyper-K	Atm.	WCD $\bar{\nu}_e$,ν_e app.	2-10 yrs	~2022	All	$1B	R&D	JPARC	Japan
INO	Atm.	Fe Calorim. ν_μ vs.$\bar{\nu}_\mu$ dis.	~15 yrs	~2030	All	$250M	Under construction	NOvA, T2K, DB, RENO	India
Large WCD	NuMI, Atm.	WCD	~1 yr, > ~6 yrs	?	?, All	$500M	R&D (LBNE)	LBNE LAr TPC	Sanford
LBNE	LBNE beam	LAr	5+5	~2025	-180-36°, 126-180°	$1B	Approved	NOvA, T2K	Sanford
MINOS+	NuMI	MINOS	NOvA	N/A	N/A	?	R&D	NOvA, T2K	Soudan
ORCA (KM3NeT)	Atm.	WCD ν_μ dis. (ocean)	~few yrs?	~2021	All	?	R&D		Mediter-ranean
PINGU (IceCube)	Atm.	WCD ν_μ dis. (ice)	2-3 yrs	2021	All	~$50M	R&D		Antarctica
RENO-50	Yonggwang	$\bar{\nu}_e$ dis.	?	?	All	?	R&D		South Korea

PINGU: $\Delta(m_{31})^2$

- Uncertainty in $\Delta(m_{31})^2$ creates some degeneracy in the distinguishability metric
  - Plots have perfect event ID and 100% selection efficiency, but include energy and angle smearing



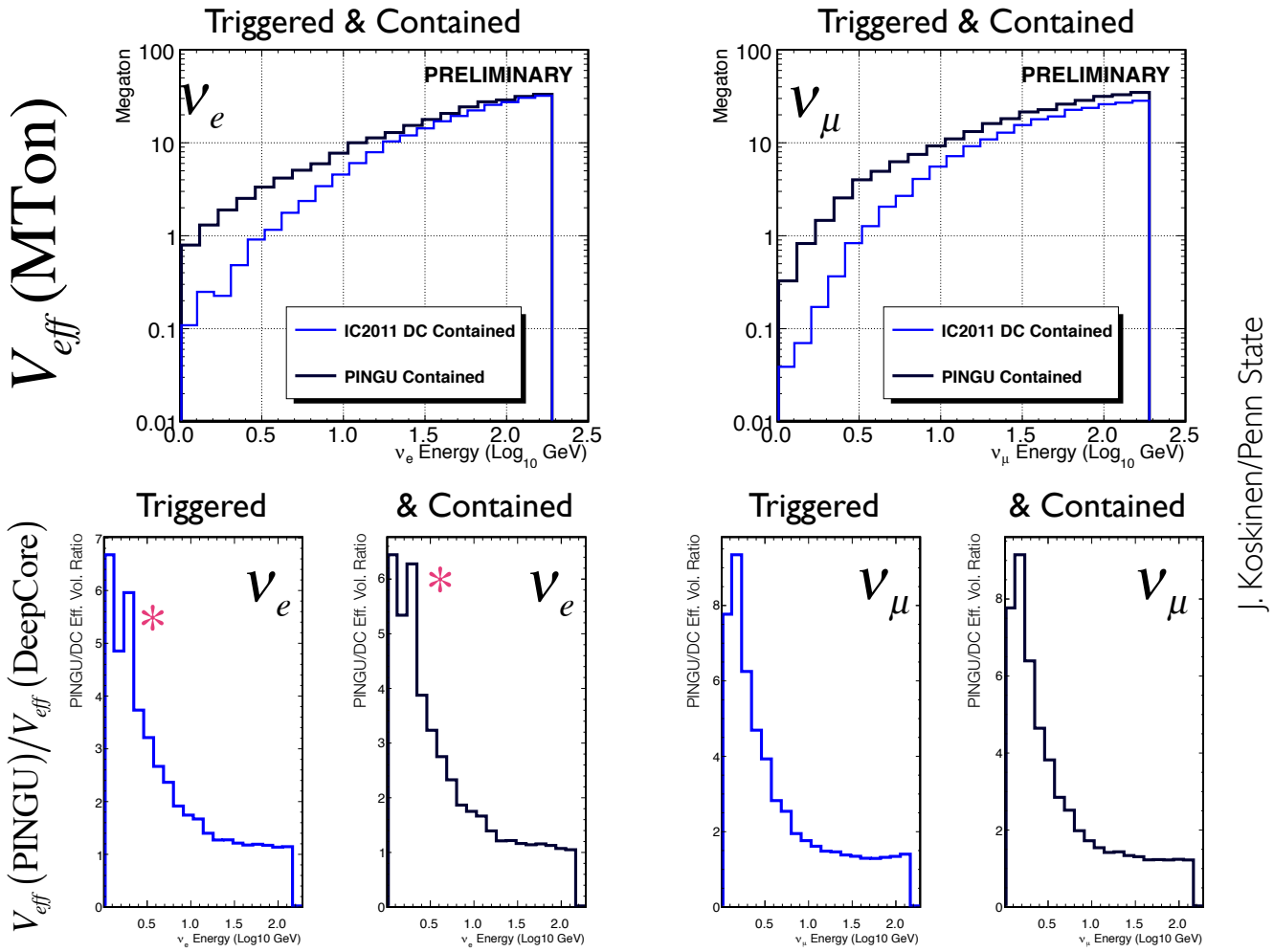
Neutrino Hierarchy and Parametric Resonances

- Parametric resonances can occur as neutrinos cross regions of distinct density
  - Flavor transitions enhanced due to matter-induced modifications in oscillation phase
    - (MSW occurs through modifications in neutrino mixing angle)
  - If travel through periodically varying density, transition probabilities can add up and become large, but generally speaking need lots of periods
- Relevant Exception: For matter densities close to MSW resonance densities, can have parametric enhancement of oscillations with a very small number of periods
  - This is the case for Earth and neutrinos at ~5 GeV(!!) *and*
  - The character of the effect depends strongly on the hierarchy. 

E. Kh. Akhmedov, *Pramana* 54:47-63,2000 or hep-ph/9907435

PINGU Effective Volumes

- V_{eff} increased by ~8x at ~1 GeV relative to DeepCore



J. Koskinen/Penn State

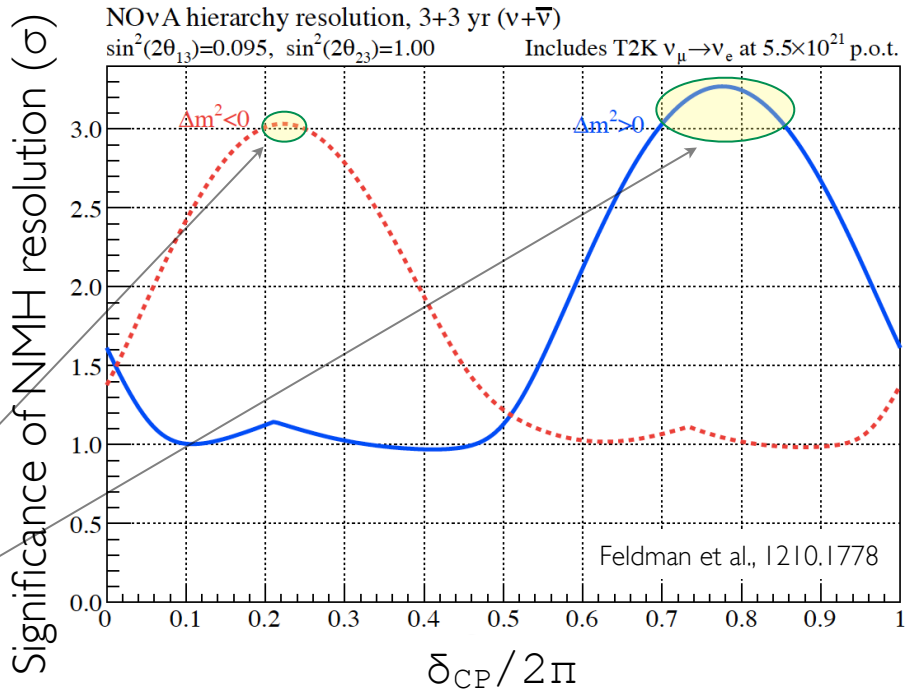
"Triggered": Event satisfies trigger condition of 3 neighboring hits within 1 μs.

"Contained": Event's true vertex is within fiducial volume.

*Wiggles due to low MC statistics

Existing* NMH Experiments

- T2K (running) and NOvA (fully constructed early 2014)
  - search for ν_e appearance over long baselines
    - L_{T2K} = 295km; L_{NOvA} = 810km
    - situated off-axis to get narrow E_ν peak
      - E_{T2K} = ~0.6 GeV; E_{NOvA} = ~2 GeV
- Sensitivity to NMH: Limited
  - Can only determine NMH to 3σ when $\delta_{CP} \sim \pm 90^o$.



*Existing = running or under construction