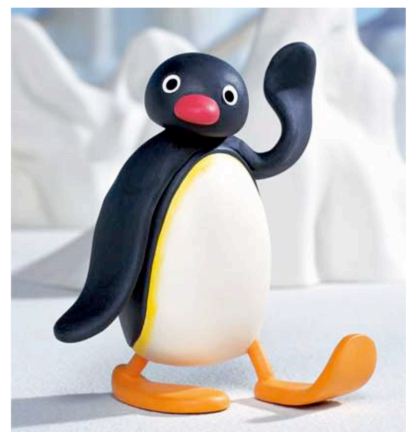
Neutrino Physics with IceCube and PINGU

ICECUBE



PRECISION ICECUBE NEXT GENERATION UPGRADE

PENNSTATE

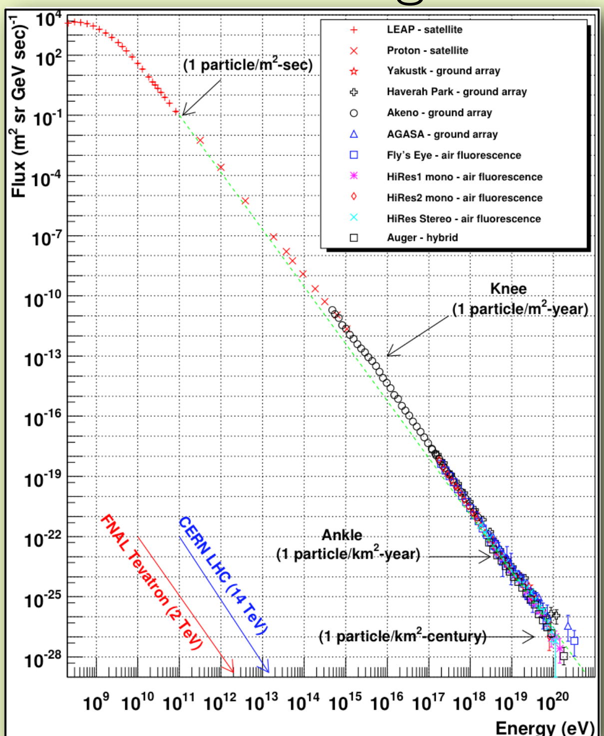
Doug Cowen • Penn State University • IceCube Collaboration

Outline

- The IceCube Neutrino Observatory
  - Physics Motivations
  - Construction and Design
- Fundamental Oscillation Parameters & WIMP Searches
  - ν_μ Disappearance and ν_τ Appearance
  - Solar WIMPs
- Future Extensions of IceCube: "IceCube-Gen2"
  - Low Energies: PINGU
  - High Energies: See talks next session
- Conclusions

IceCube: Physics Motivations

Find the source of ultrahigh energy cosmic rays (up to 10^{20} eV)



SN remnants?
AGN?
GRB?

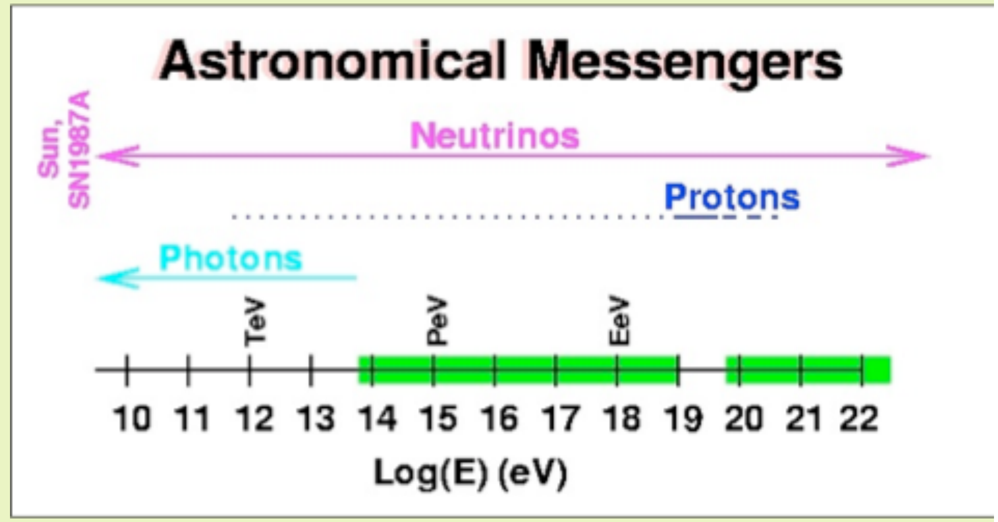
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

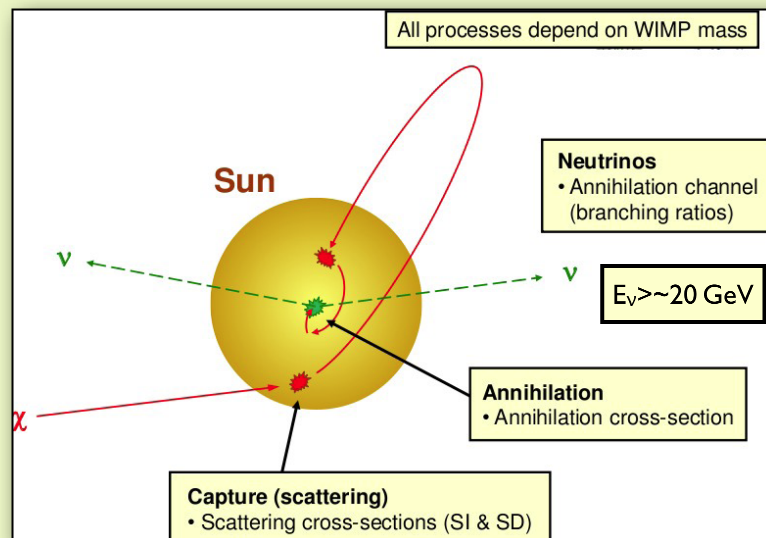
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Open a new astronomical window.



Probe low-mass WIMP dark matter.



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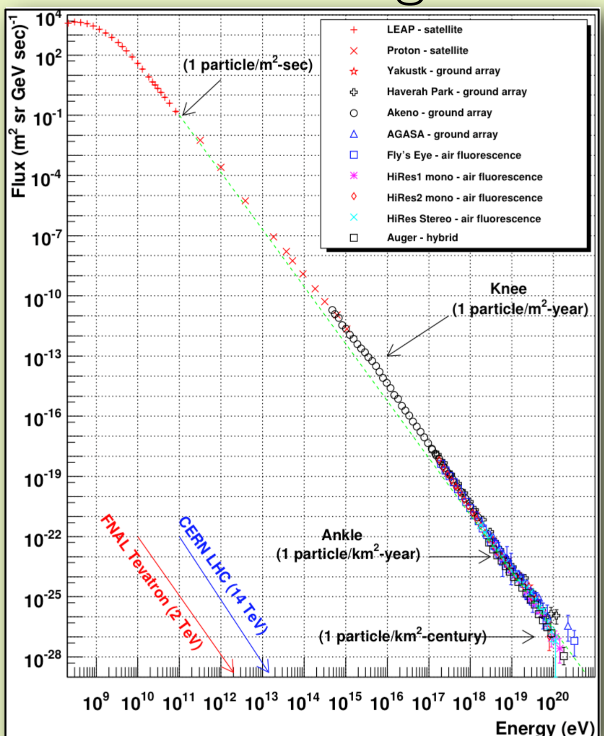

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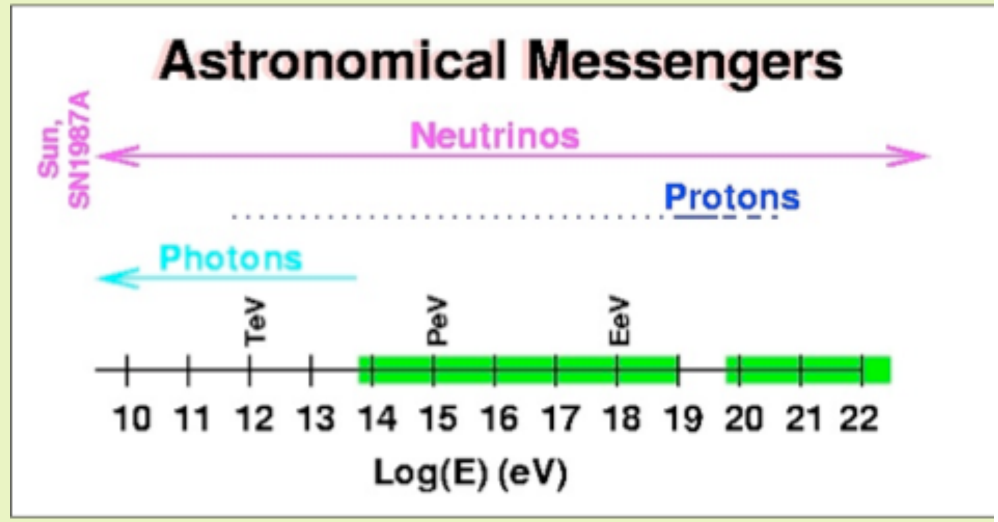
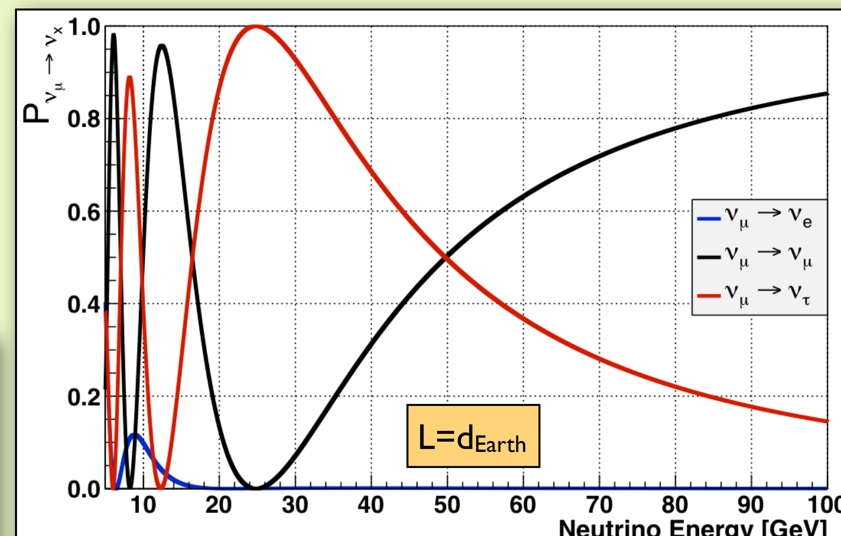


Bonus!: Neutrino oscillations.



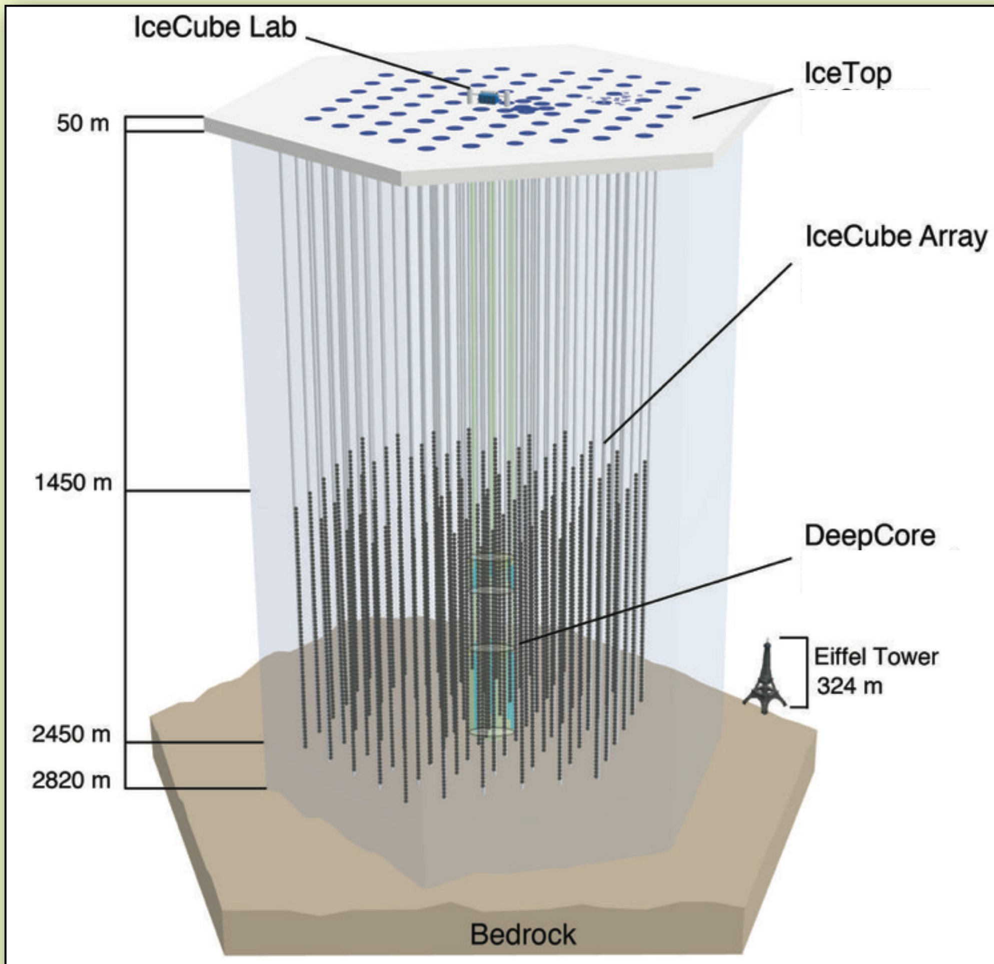
Leptons			
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

IceCube Construction & Design

Huge effort!

43 Institutions,
12 Countries,
~300 Authors

IceCube Construction and Design



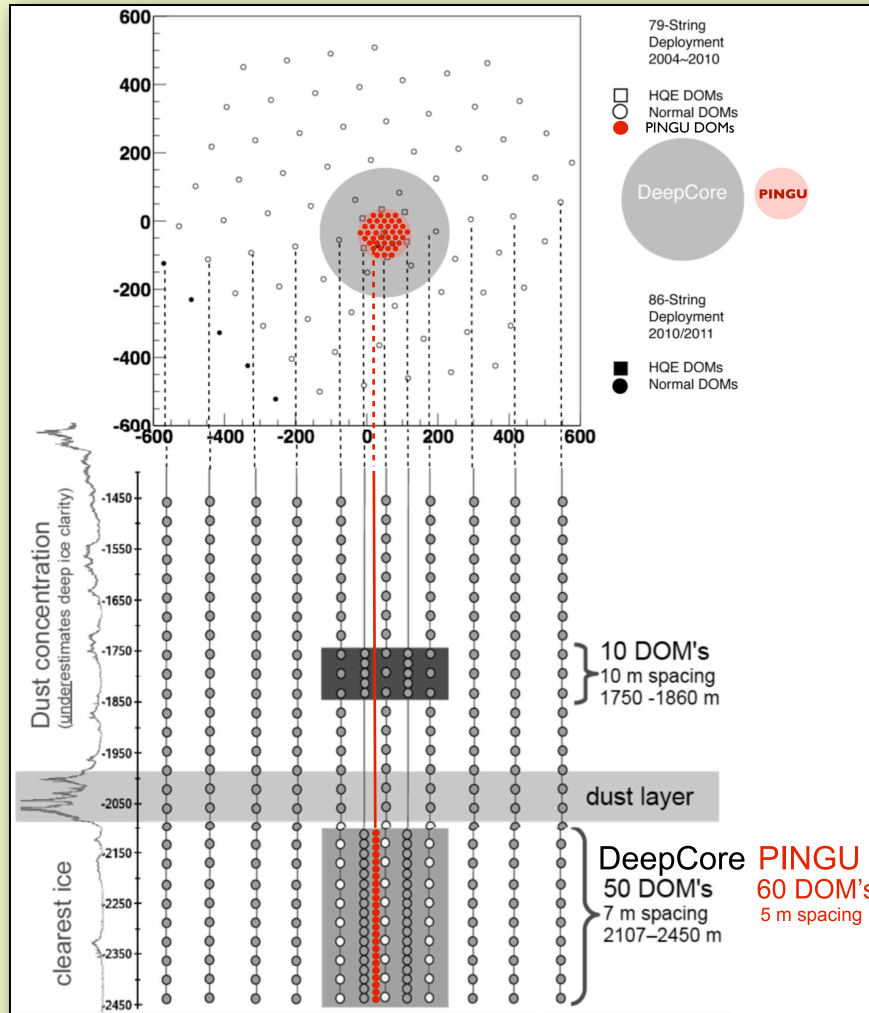
86 strings, 5160 modules, 7 yrs, 1km^3

IceCube (DeepCore):

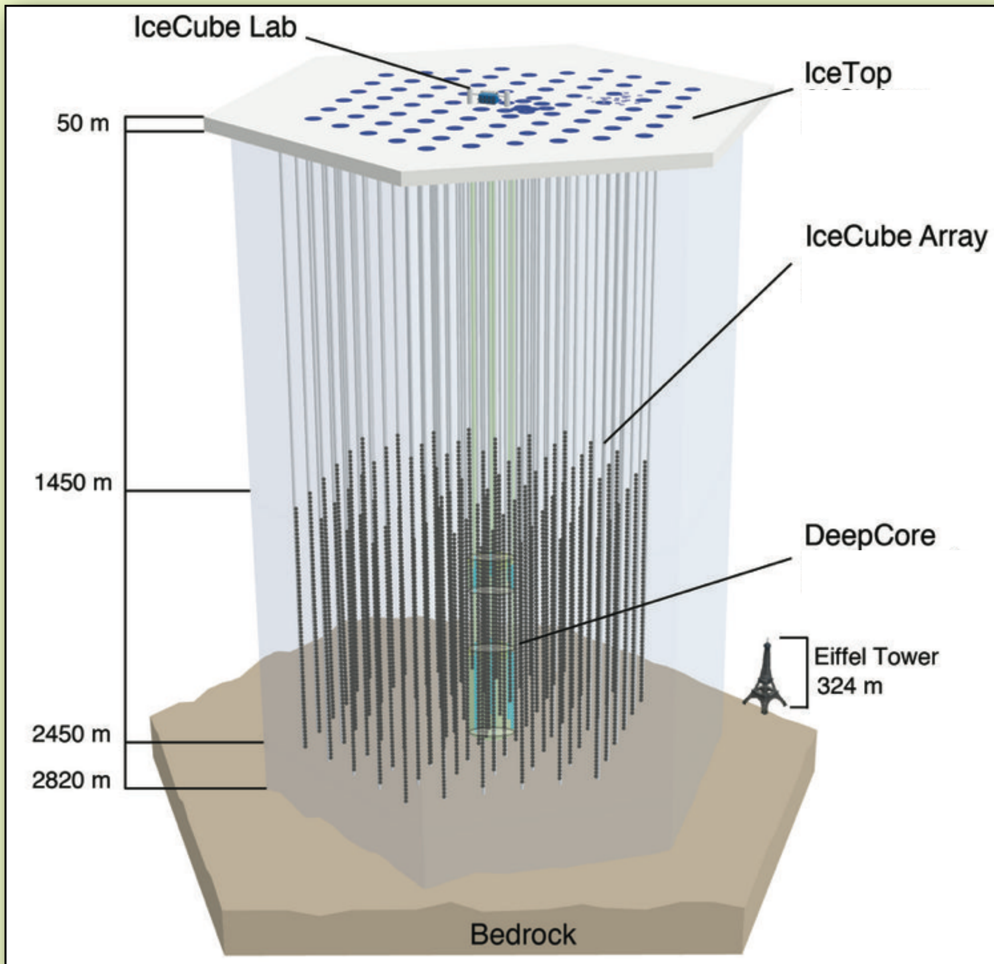
125m (70m) horizontal spacing

17m (7m) vertical spacing

Top & side views (ignore red stuff for now)



IceCube Construction and Design



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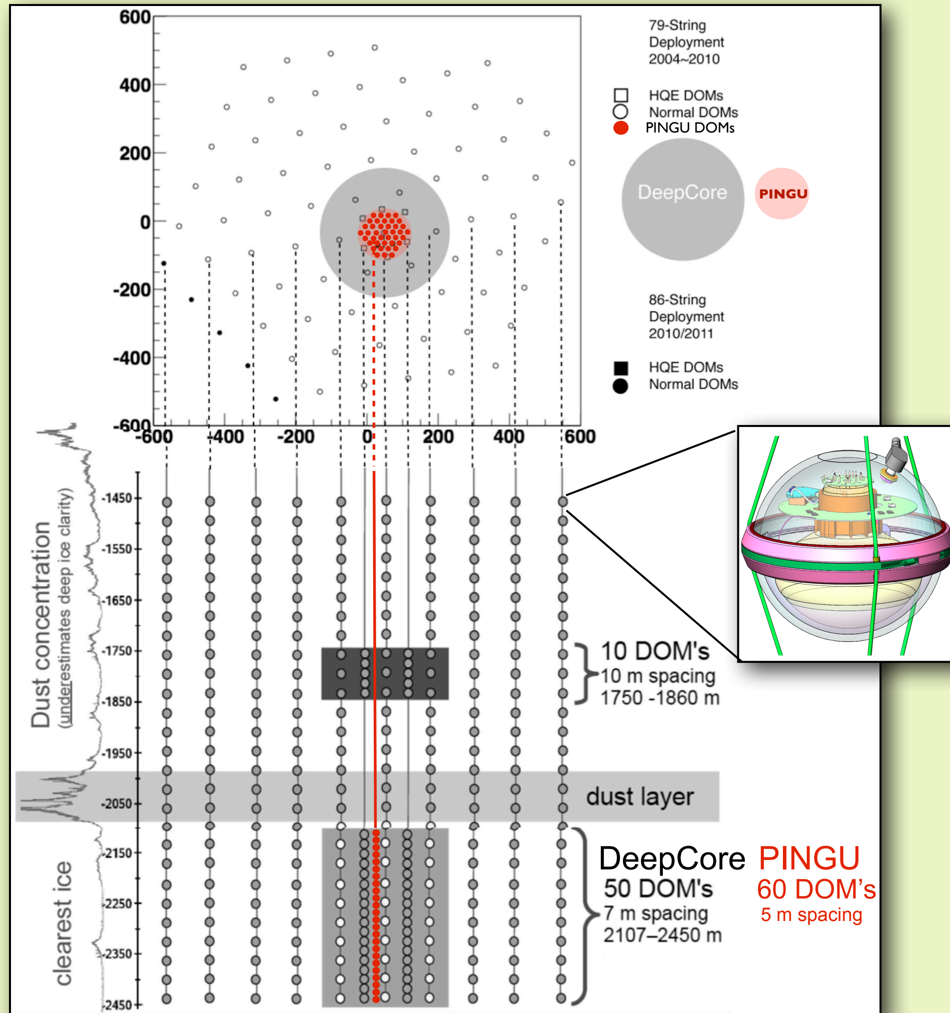

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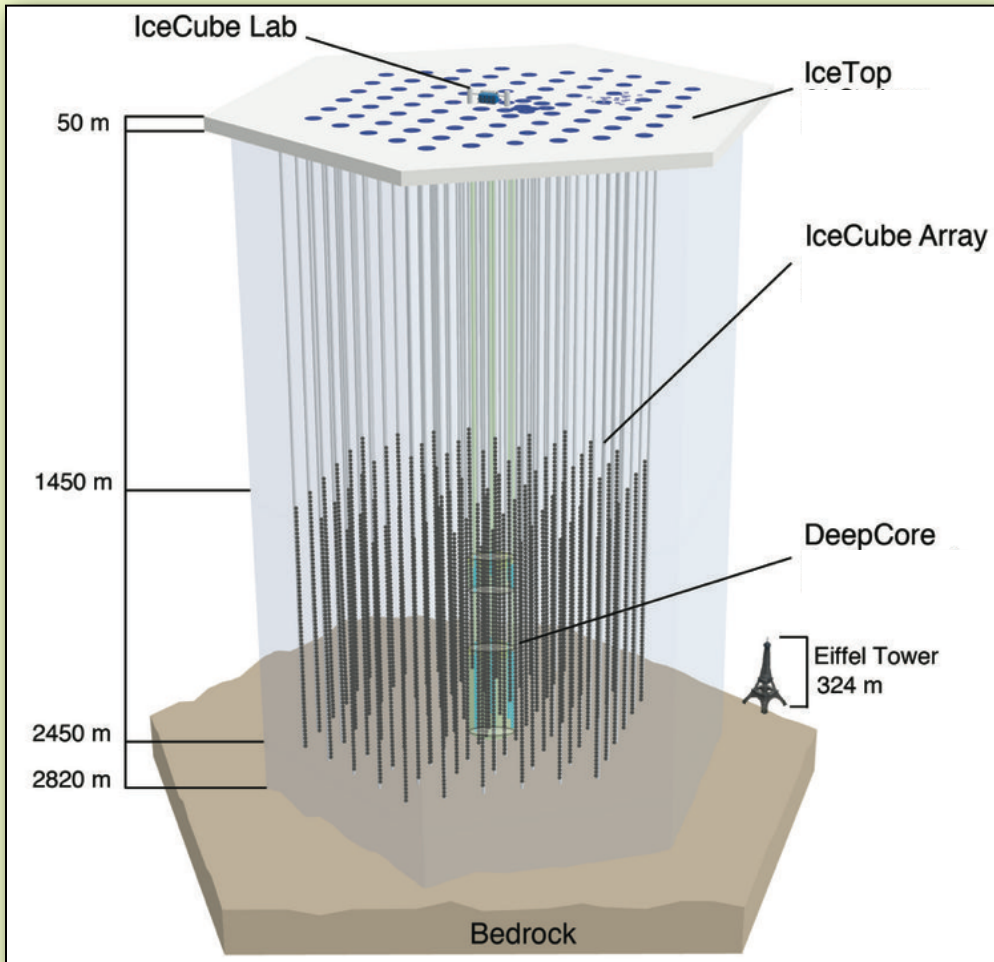
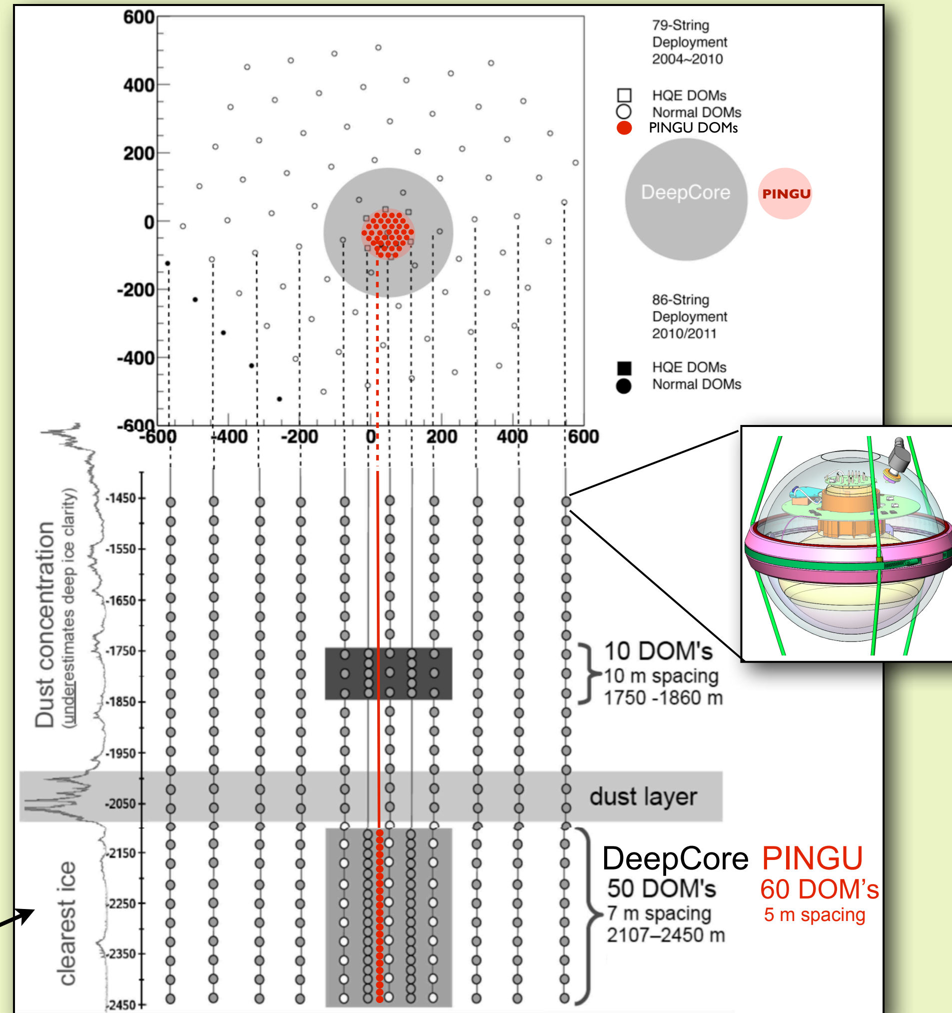


86 strings, 5160 modules, 7 yrs, 1km^3
IceCube (DeepCore):
- 125m (70m) horizontal spacing
- 17m (7m) vertical spacing

Clear ice!

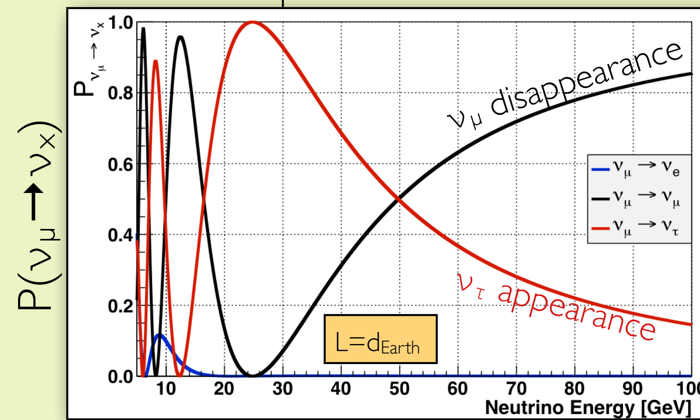
Top & side views (ignore red stuff for now)



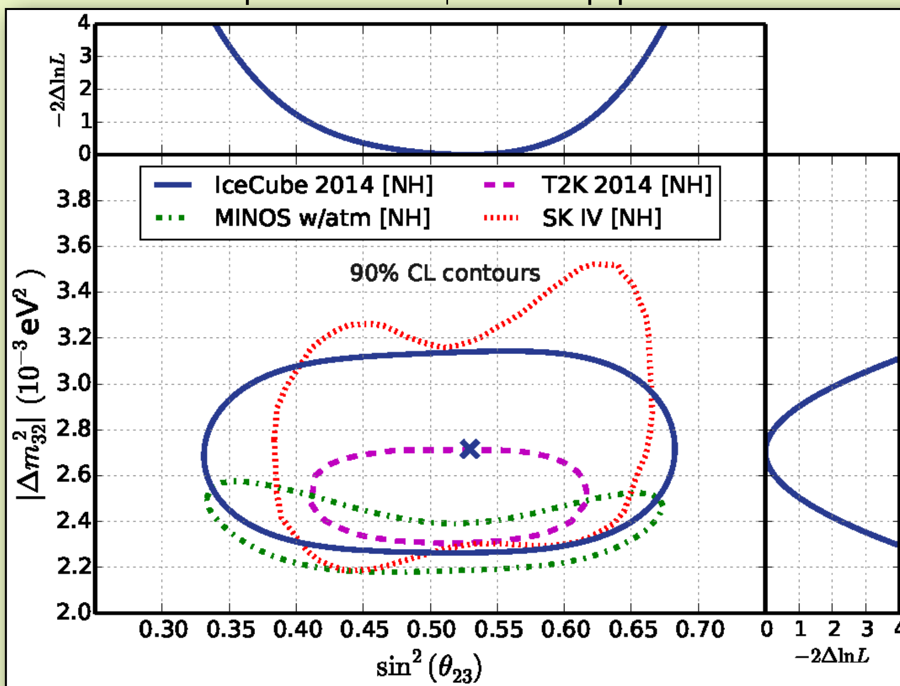
IceCube/DeepCore and ν Oscillations

- DeepCore energy threshold is ~10 GeV
  - Sensitive to highest neutrino energies of any oscillation experiment
  - Can see that big "*first minimum*" of ν_μ disappearance
  - (And, in the near future, the big "*first maximum*" of ν_τ appearance)
- "New player in the game."–Convener, ν2014 International Conference, Oscillation Plenary

Atmospheric ν Oscillations



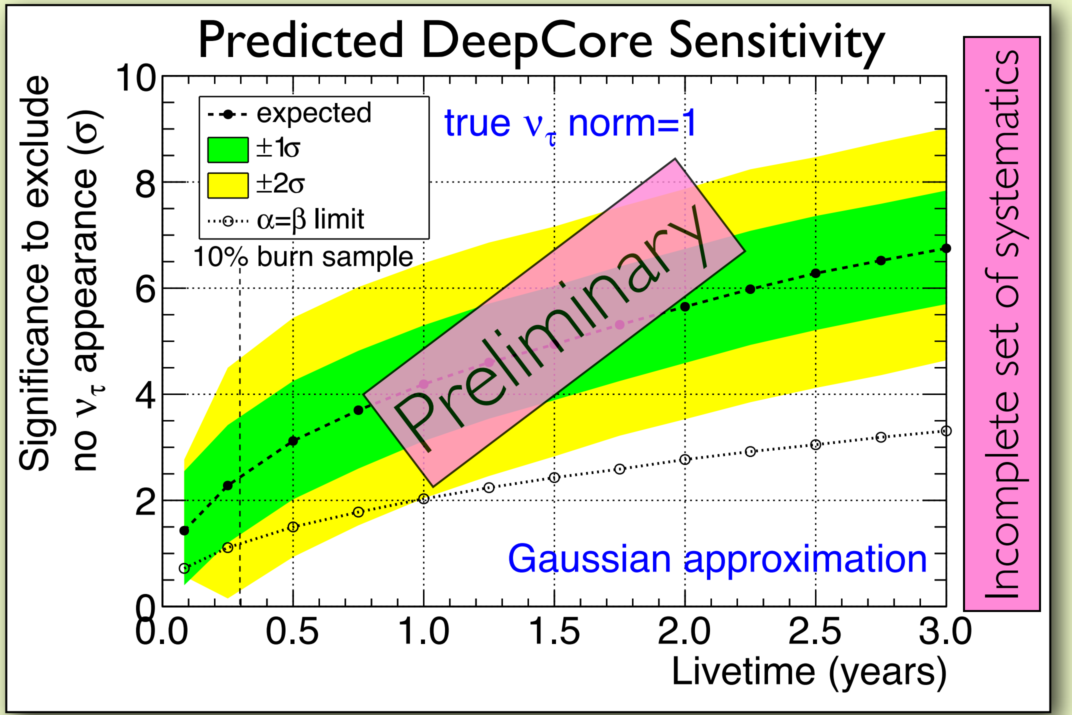
Atmospheric ν_μ Disappearance



arXiv:1410.7227v1

IceCube/DeepCore and ν Oscillations

- Existing ν_τ appearance measurements
  - Super-K excludes the no-ν_τ appearance hypothesis at 3.8σ.
    - Observed about 60 ν_τ events
  - OPERA confirms ν_τ appearance at >4σ
    - Observed 4 ν_τ events

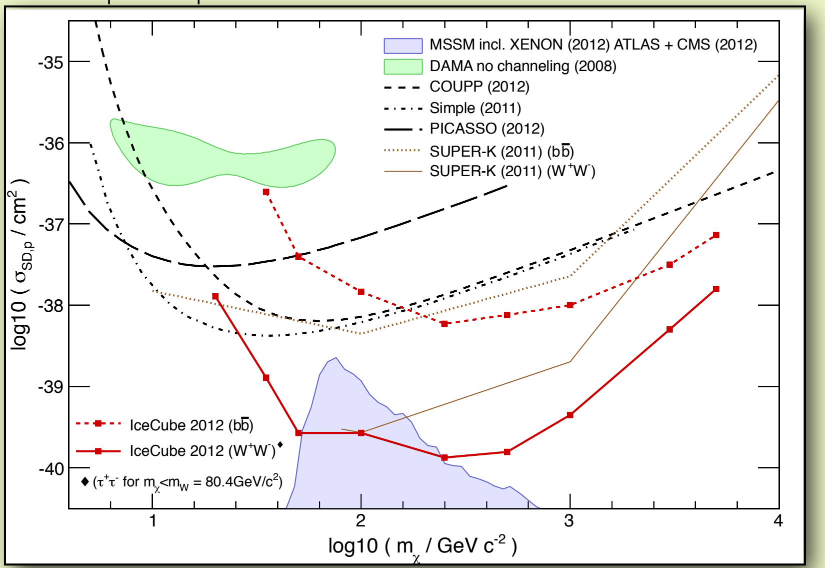


- DeepCore data has thousands of ν_τ events

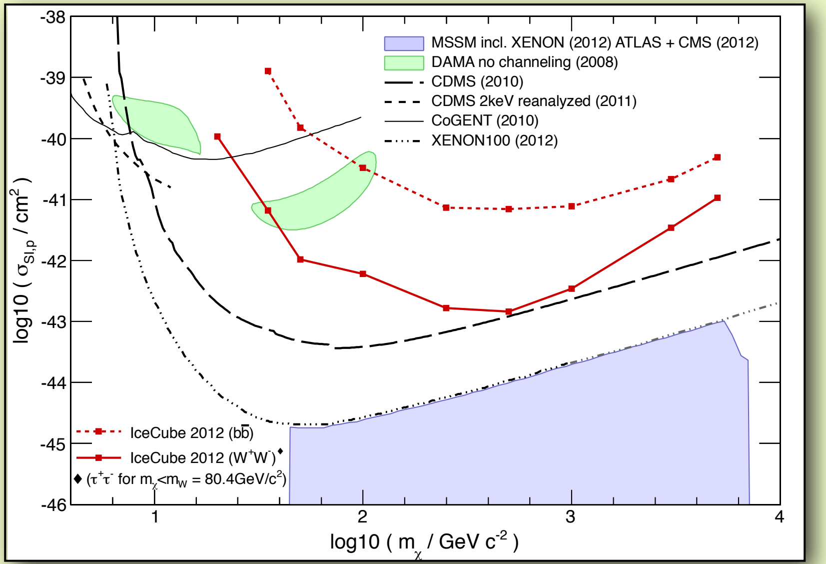
IceCube/DeepCore and WIMPs

- We're looking hard, especially where other (direct detection) experiments claim a signal
- Recent solar WIMP result:

Spin-dependent WIMP-matter interactions



Spin-independent WIMP-matter interactions

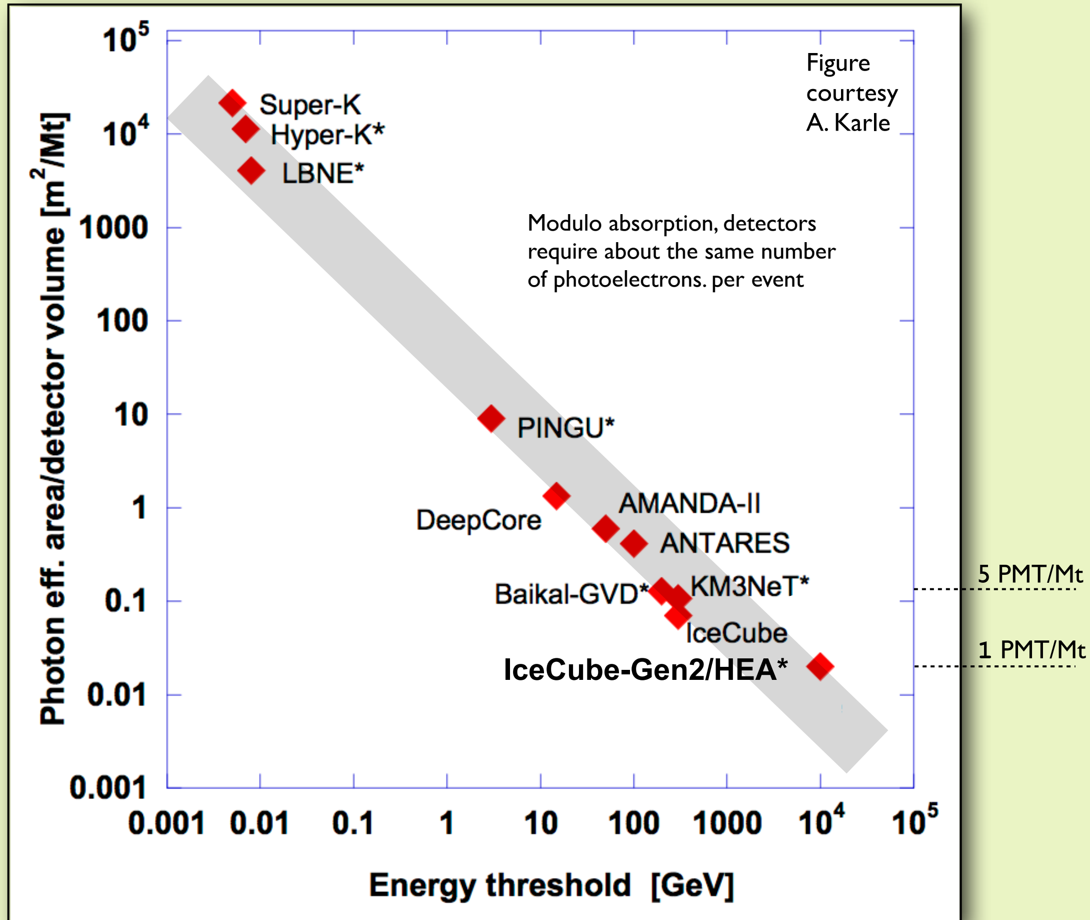


What Next?

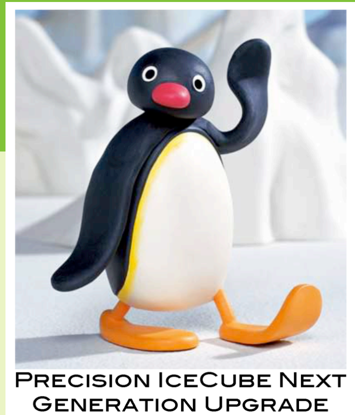
- DeepCore results prove viability of neutrino oscillation measurements in the ice
- IceCube has discovered high energy astrophysical neutrinos
  - See next session
- Future extensions of IceCube/DeepCore: IceCube-Gen2. With more instrumentation we can do MUCH more.
  - Low E(ν): Precision IceCube Next Generation Upgrade (PINGU)
    - ν mass hierarchy, dark matter & other ν oscillation physics
  - High E(ν): see next session

Photocathode Density

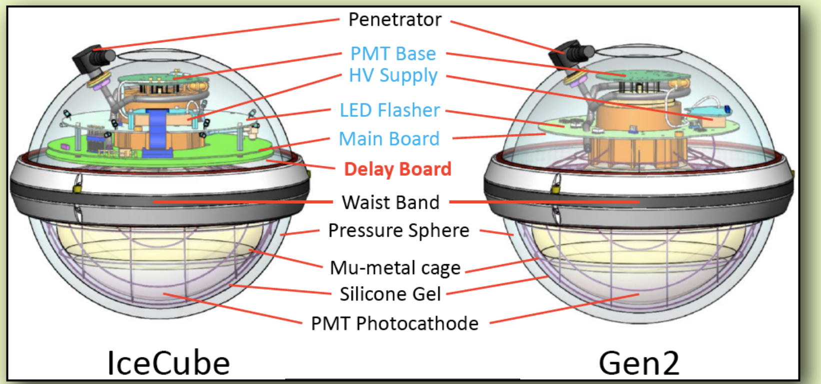
- There is a roughly linear relationship between
  - photocathode density
  - desired threshold E_ν
- Proposed new detectors are consistent with their predecessors



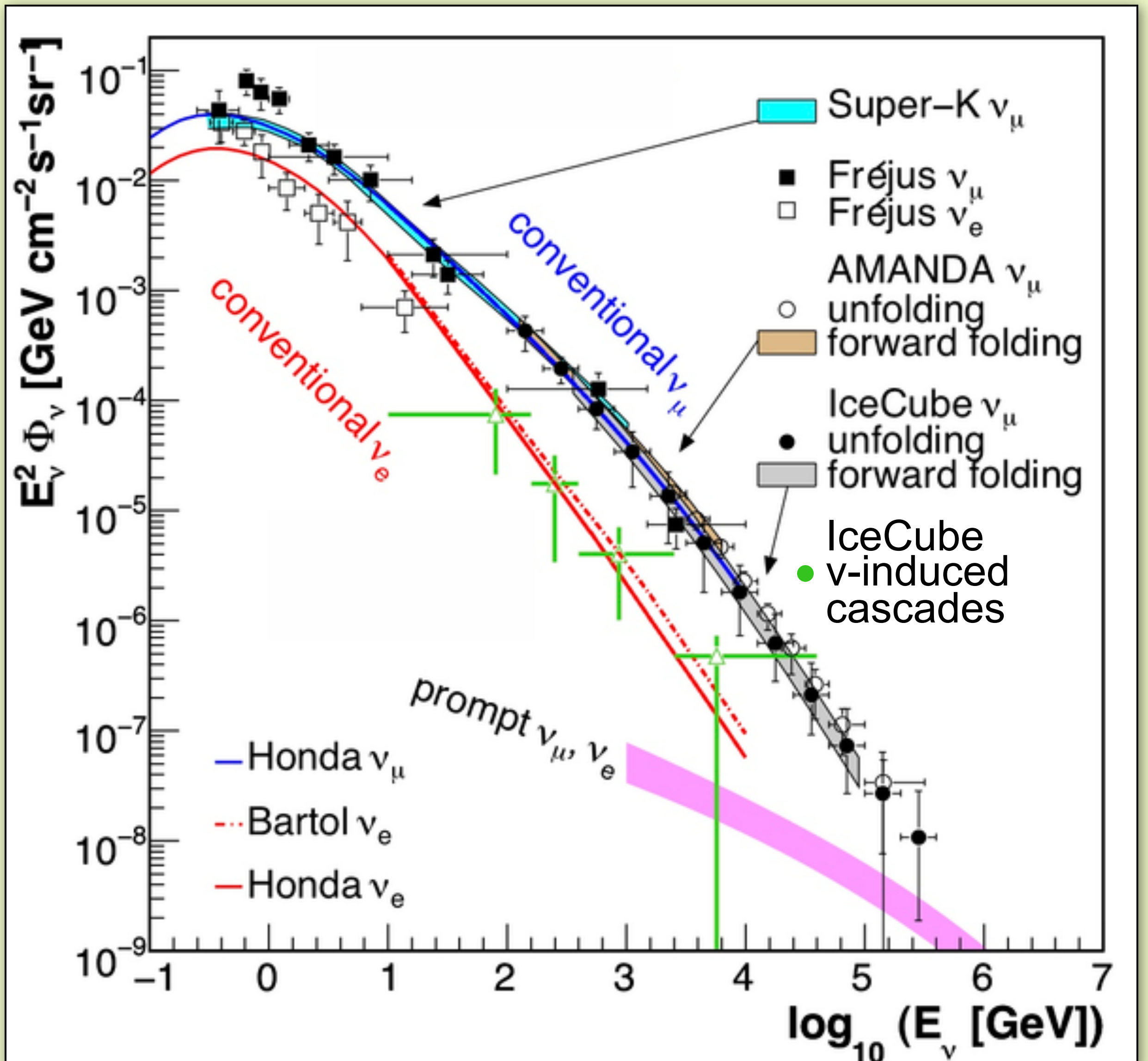
PINGU Low Energy Extension



- PINGU would lower neutrino energy threshold to a few GeV
  - Baseline geometry:
    - Add 40 new strings interleaved with existing DeepCore strings
    - 60 (updated) DOMs on each string
      - Also evaluating impact of more DOMs/string
  - Use technology very similar to that used with IceCube (drill, digital optical module,...)
    - Substantially lowers overall risk
    - You'll hear more about plans for IceCube-Gen2 technology at this workshop
  - Would take 2-3 seasons to deploy
  - Could be taking data as early as 2020



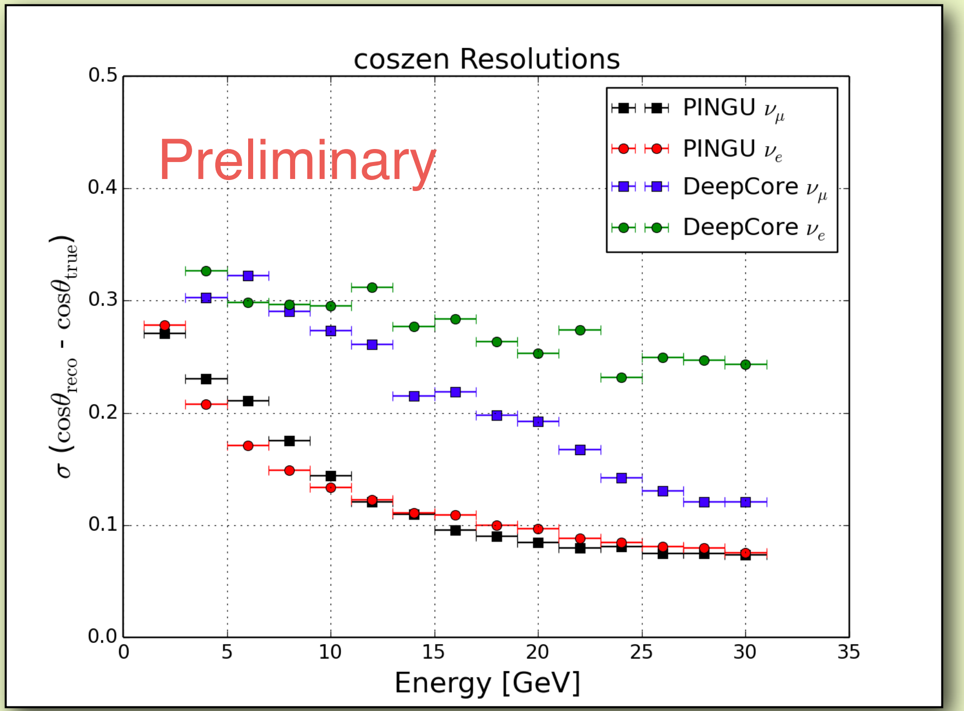
Atmospheric Neutrino Signal

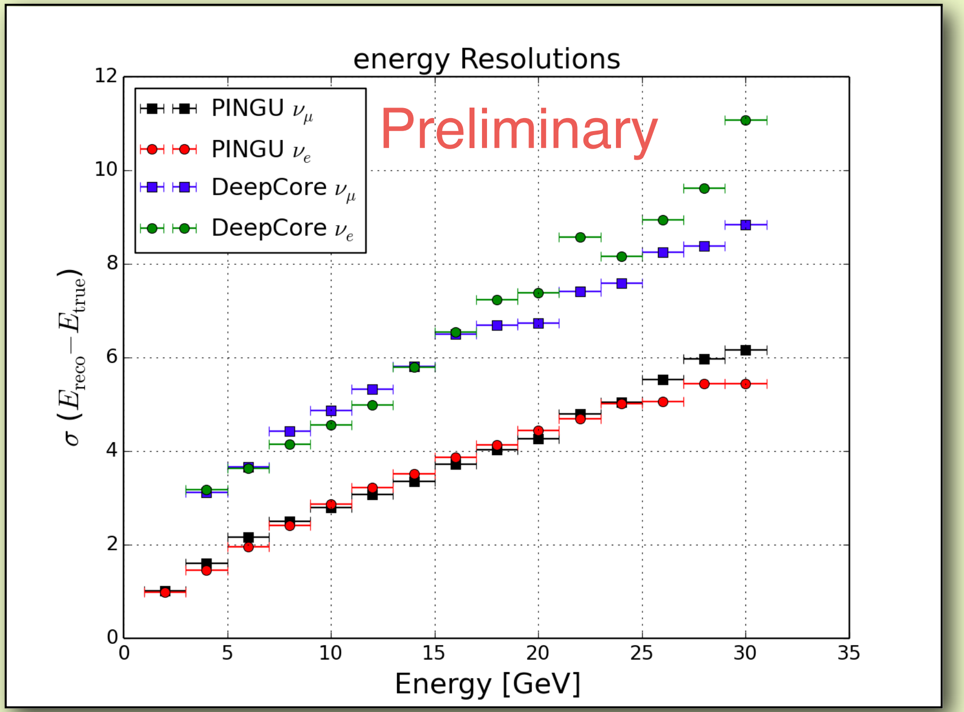


N(Events) Expected in PINGU per Year		
	Trigger Detector	Pass Baseline Analysis
ν_e CC	52k	26k
ν_μ CC	86k	35k
ν_τ CC	6.4k	2.7k
ν_x NC	17k	7.9k

PINGU event reconstruction

Baseline Geometry (40 string, 60 DOMs/string)

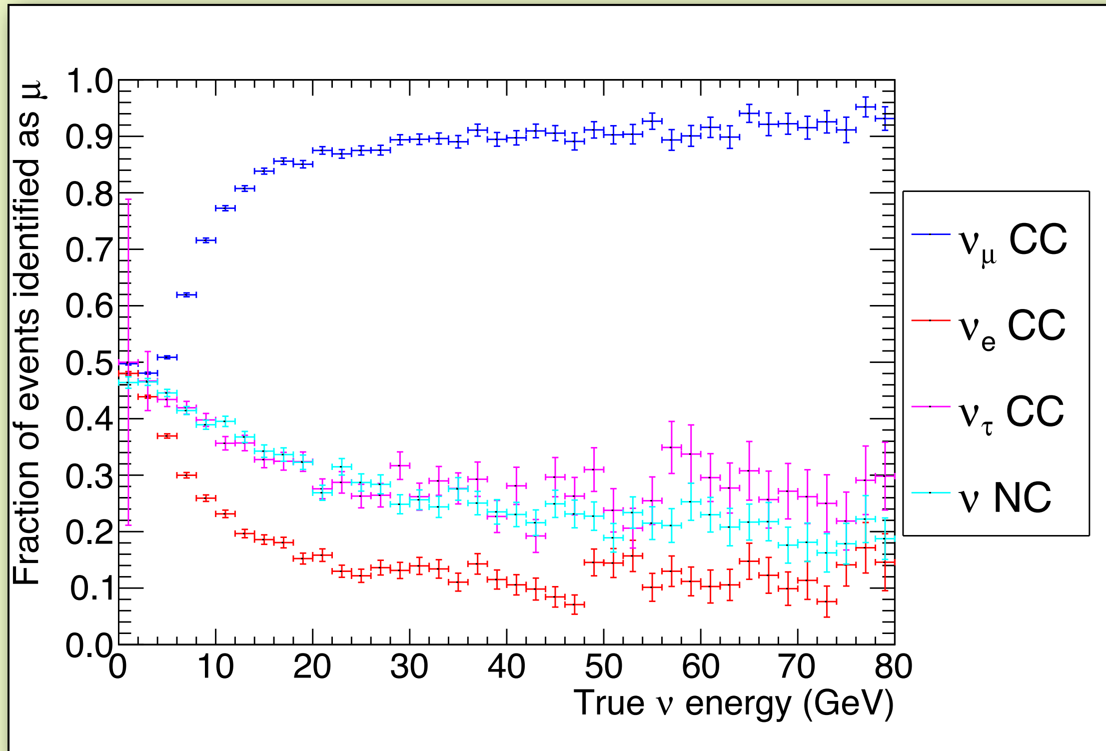




Noise not fully simulated, but noise removal algorithms are very efficient: small impact on the resolutions.

PINGU Particle ID

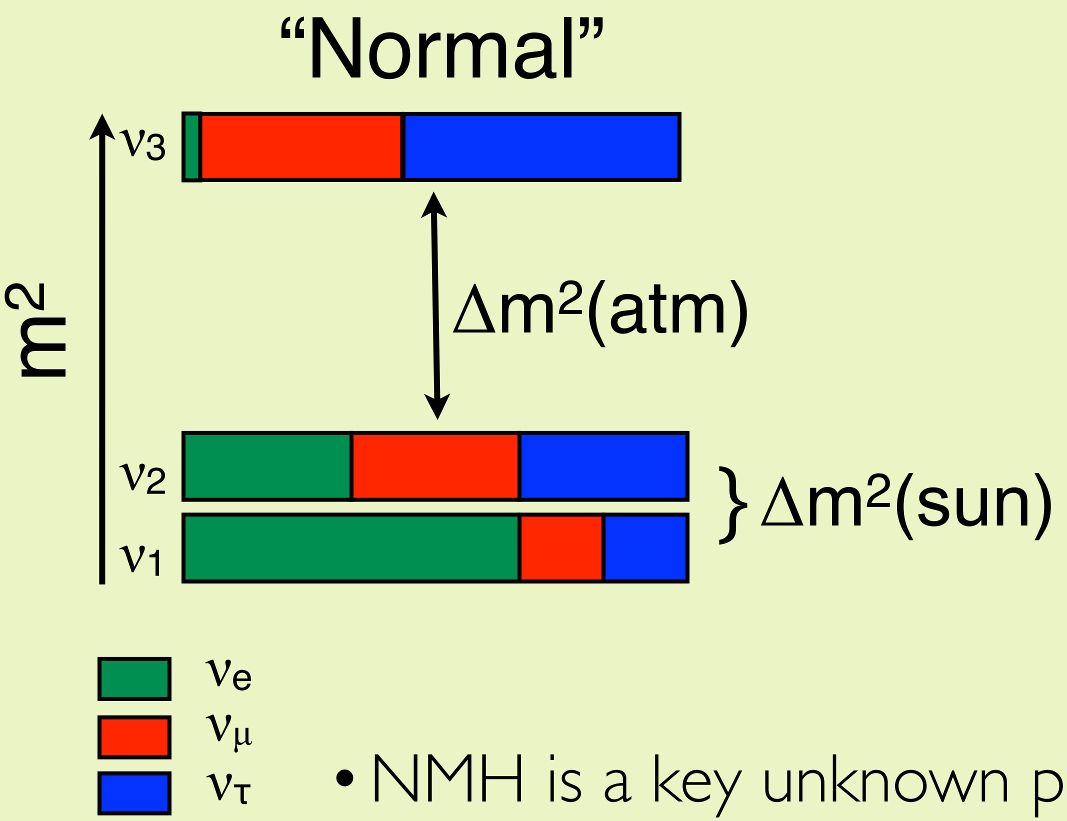
- At higher energies, ν_μ CC events are easily identified by the presence of a long muon track
  - At lower energies, light from the track may be confused with light from the interaction vertex



- First approach:
  Use variables such as event size, reconstructed track length, presence of "early" hits (faster than c/n)

The Neutrino Mass Hierarchy (NMH)

Main goal of PINGU



- NMH is a key unknown parameter in the neutrino sector
- NMH can be determined as neutrinos pass through matter
  - ν oscillation probability is enhanced if hierarchy is normal
  - $\bar{\nu}$ oscillation probability is enhanced if hierarchy is inverted

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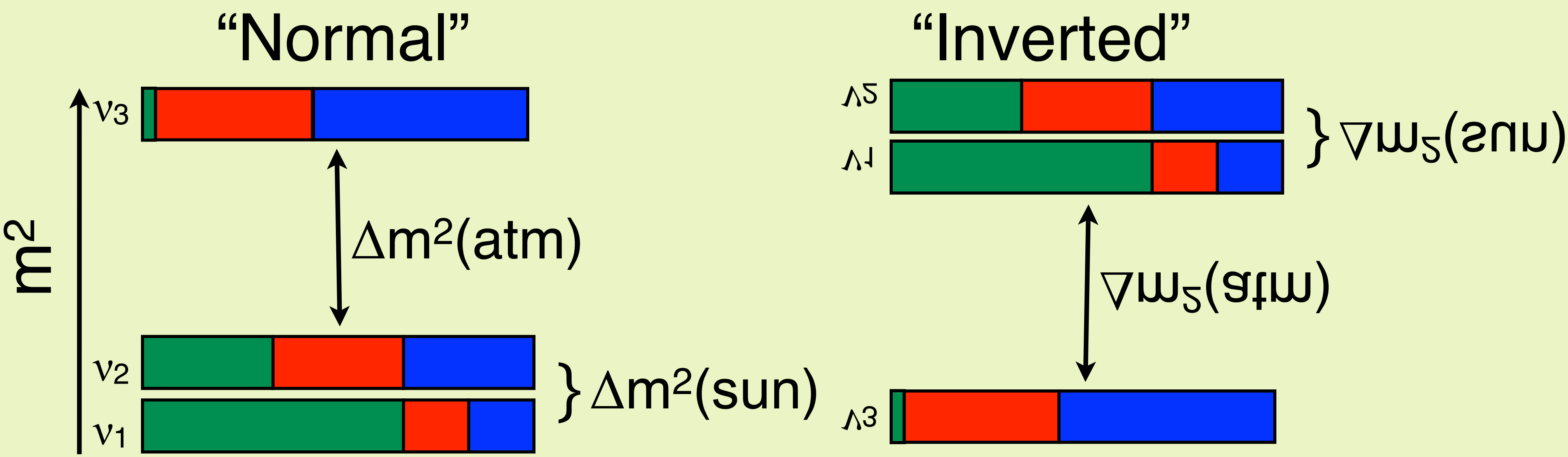

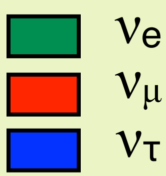

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  - ν oscillation probability is enhanced if hierarchy is <u>normal</u>
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Estimation of NMH Sensitivity

- Three independent analysis techniques
  - "Fisher" approach: detailed detector parametrization, all systematics
    - Quickest evaluation of systematics, new techniques
    - Cross-checked external parametric evaluations of PINGU
    - Verified our implementation of 3-flavor oscillations
  - "Asimov" approach: average data set, full sim., many systematics
    - Relatively fast evaluation using fully simulated data
    - Agrees well with Fisher (within ~5% on final significance)
  - "LLR" approach: log likelihood ratio, full sim., large number of Poisson-fluctuated pseudo datasets
    - Technique with minimal assumptions; slower than Fisher and Asimov
    - With new method with improved speed, have now run w/all key systematics
    - Very good agreement with Fisher and Asimov (within few % on final significance)

Systematics: Incorporated via Fisher

Verified with Asimov and LLR

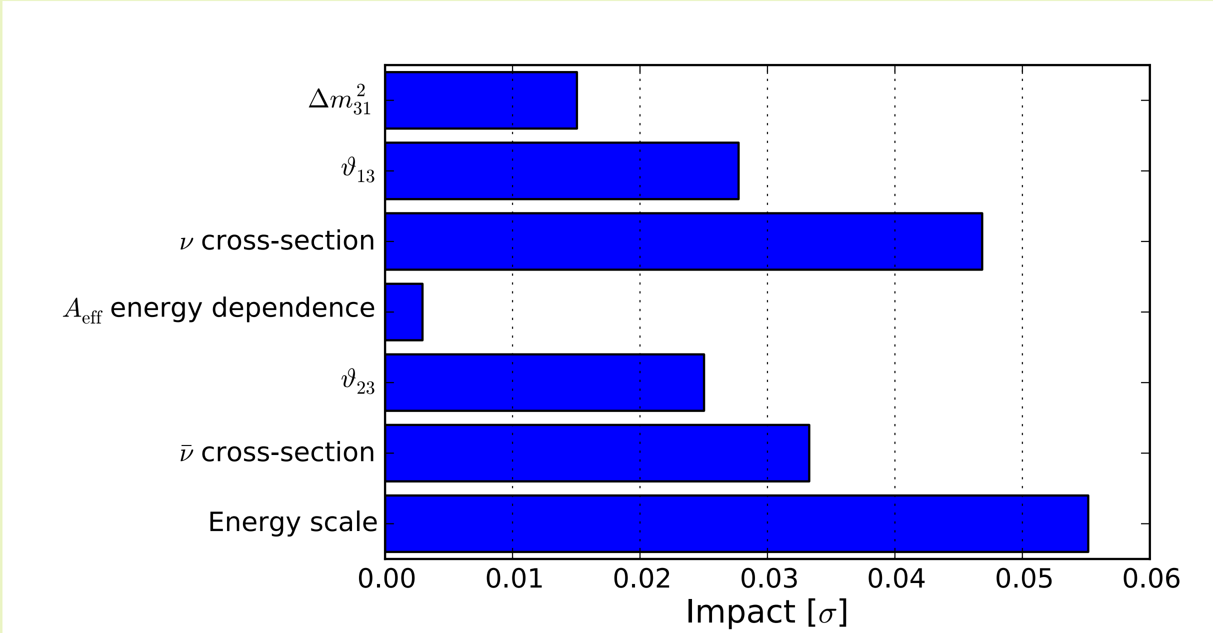
1. Physics-related

- $\Delta(m_{31})^2$ (prior: ±1σ)*
- θ_{13} (±1σ)
- θ_{23} (±1σ)
- cross sections (±15%)
  - ν, anti-ν independently
- interaction vertex uncertainties

2. Detector-related

- A_{eff}(E, σ(ν), σ(anti-ν))
- Energy scale (±5%)
- particle ID uncertainties
- ice properties

- Apply all systematics
- Un-apply one, "impact" is the observed increase in significance

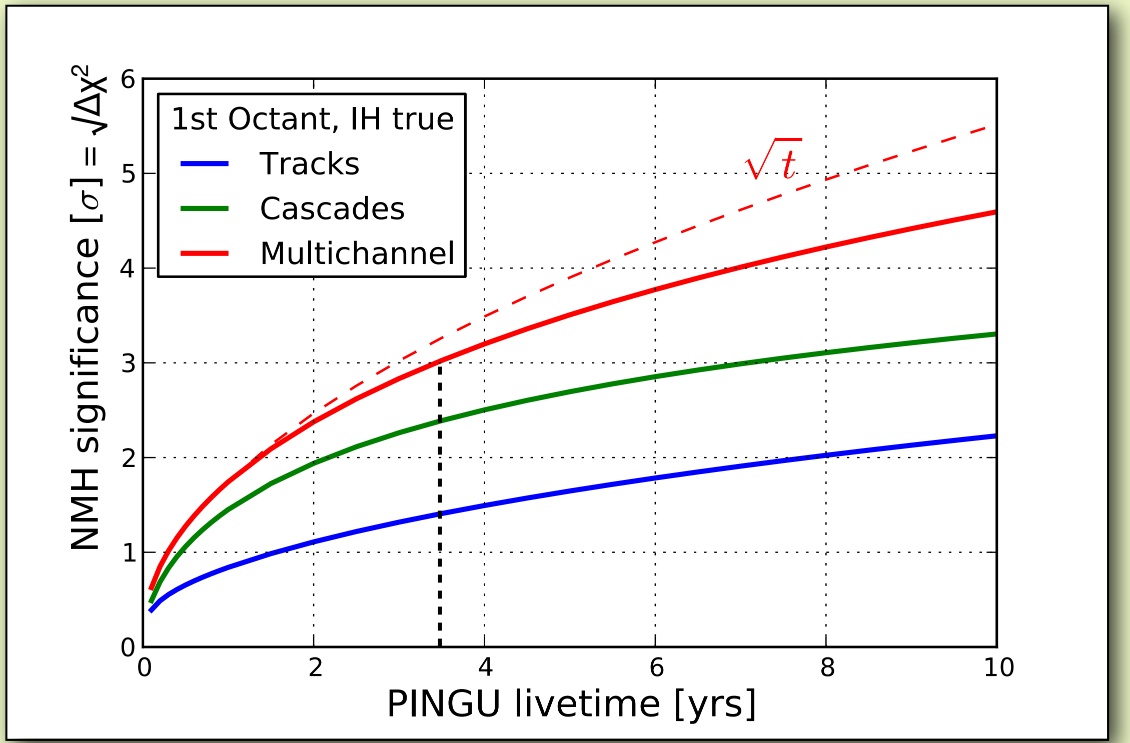


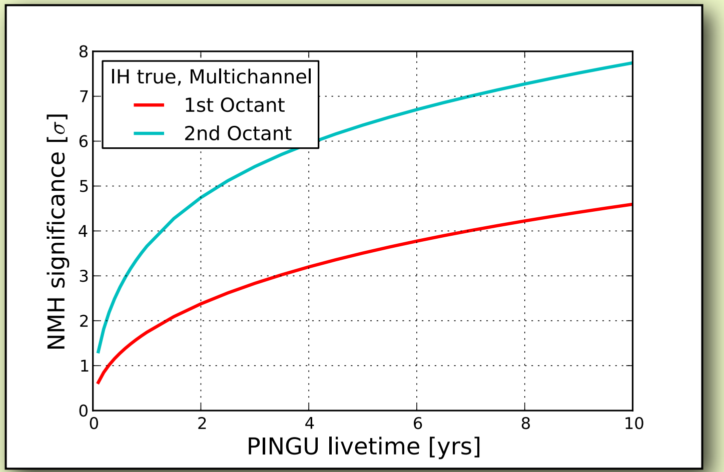
- Other (smaller) errors:
  - $\Delta(m_{21})^2$, θ_{12}, δ_{CP}
  - Scale factors for mis-ID, overall flux normalization

*Prior = ±1σ error of world ave. msmt.

Estimated Sensitivity (Baseline Geom.)

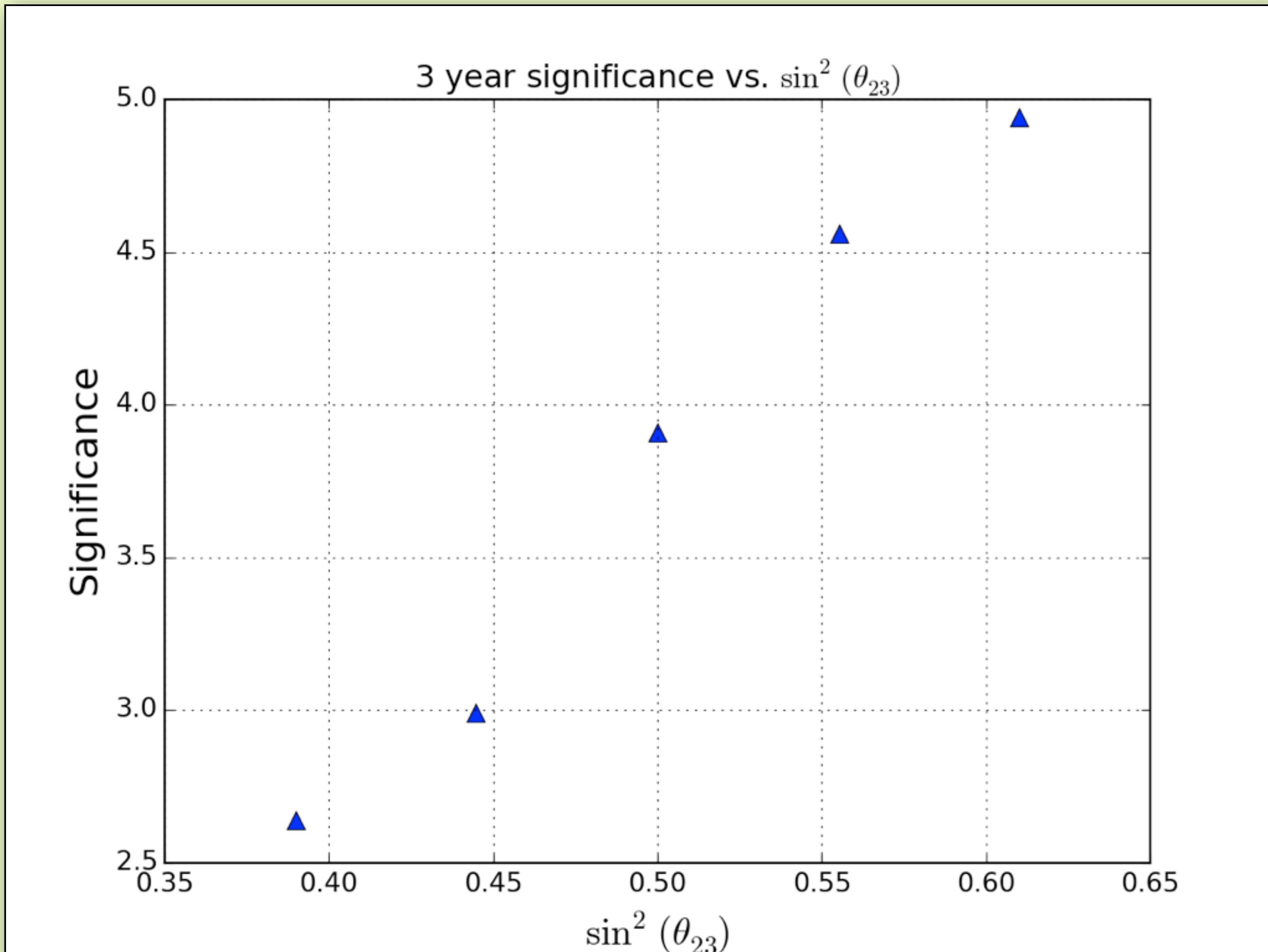
- Significance including all systematics + basic PID
  - Calculated with Fisher approach
- Result:
  - 1.8σ in first year of data (first octant)
- Growth in significance as shown
  - Reach 3σ in roughly 3.5 yrs
    - (N.B.: Livetime from partially built detector not included here)
- Much higher significance in 2nd octant
  - (see also next slide)





NMH Sensitivity vs. θ_{23}

3-yr significance

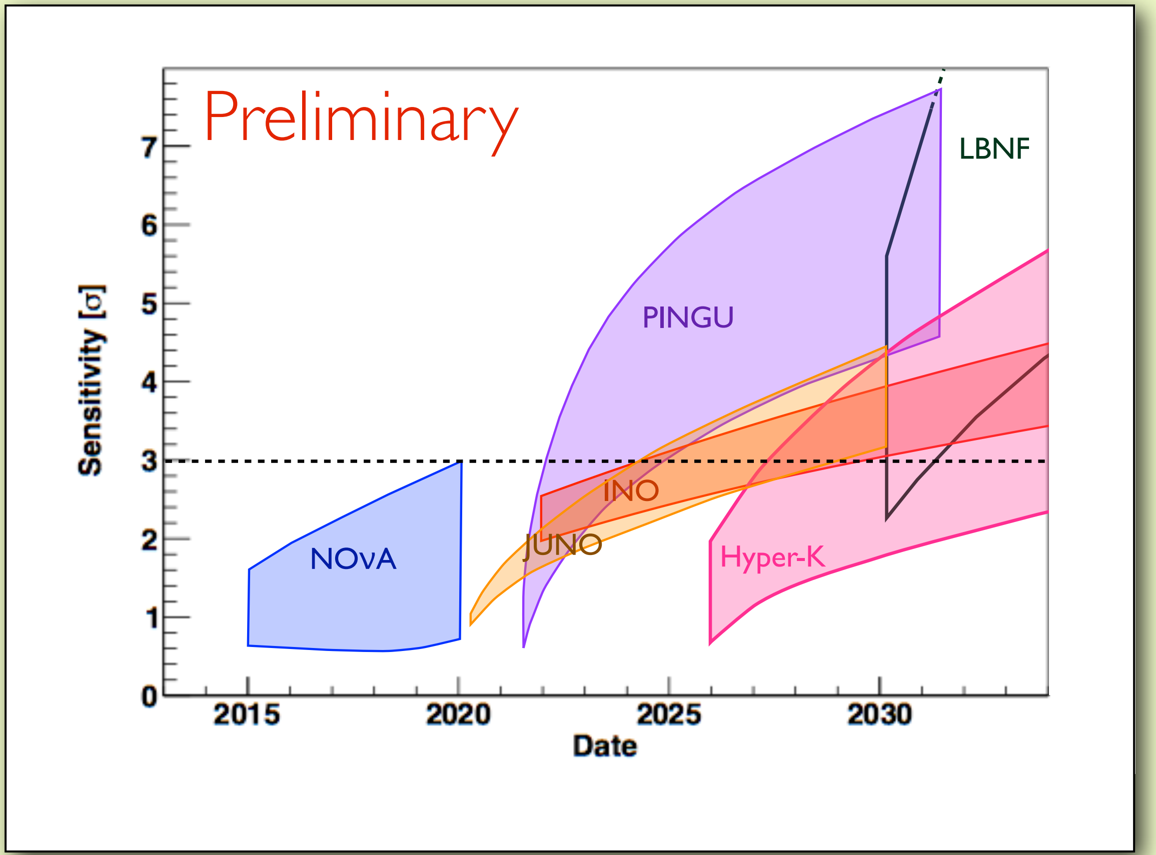


$\sin^2(\theta_{23})$

The Neutrino Mass Hierarchy Landscape

- Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years
  - NB: median outcomes shown – large fluctuations possible
- Widths indicate main uncertainty
  - LBNF/NOvA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°–51.3°, 40°–50°)
  - Other projections presented here assume worst-case parameters (1st octant)
- PINGU timeline based on aggressive but feasible schedule

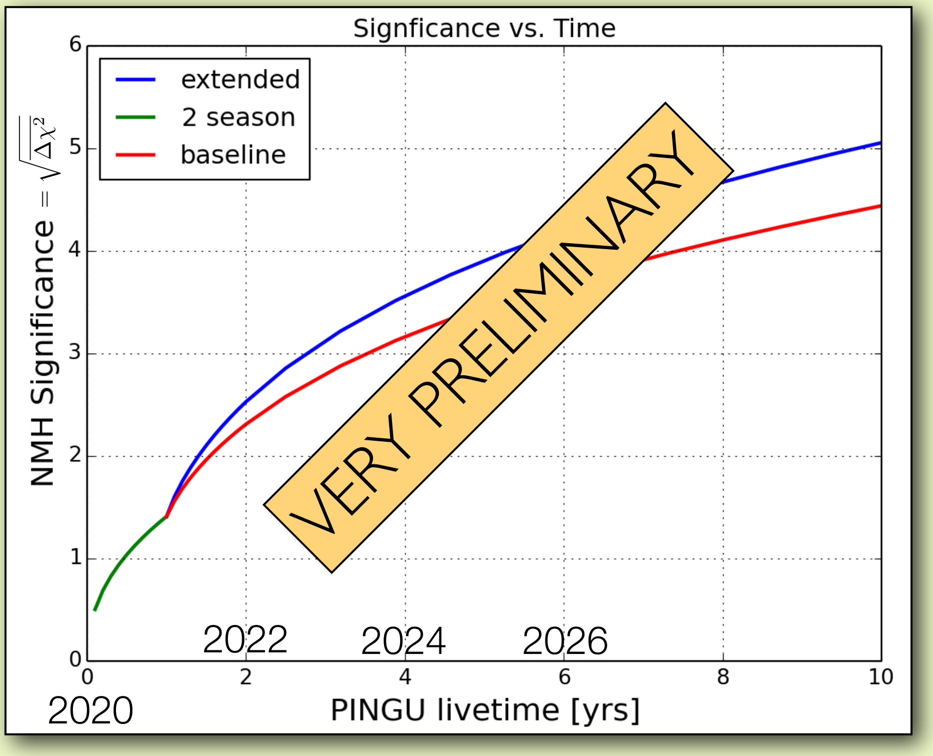
after Blennow et al., arXiv:1311.1822



- LBNE from LBNE-doc-8087-v10, Hyper-K from 1109.3262, INO from 1406.3689, others from Blennow

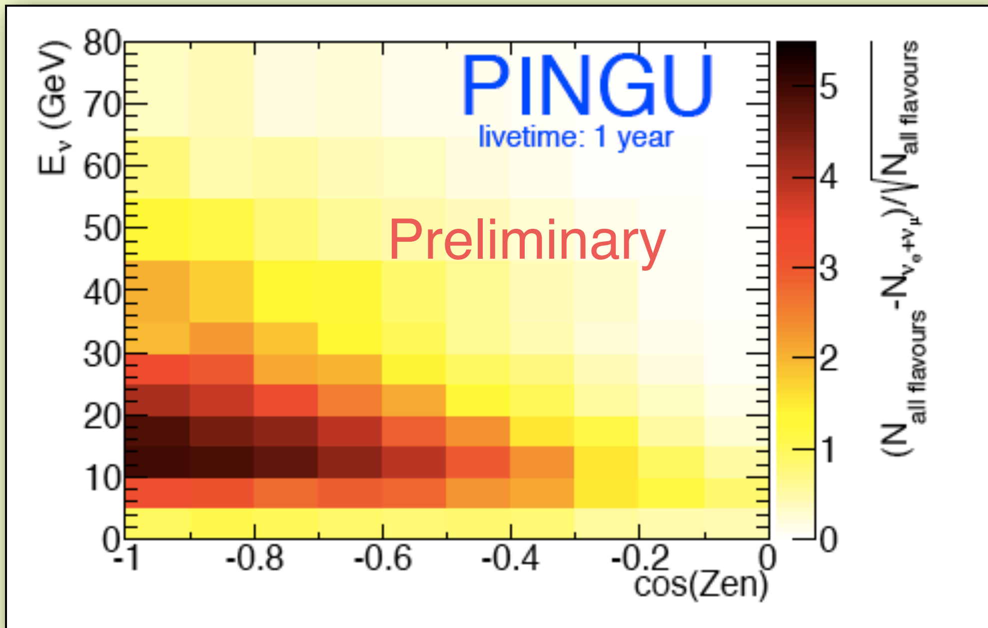
Estimated Sensitivity (Extended Geometry)

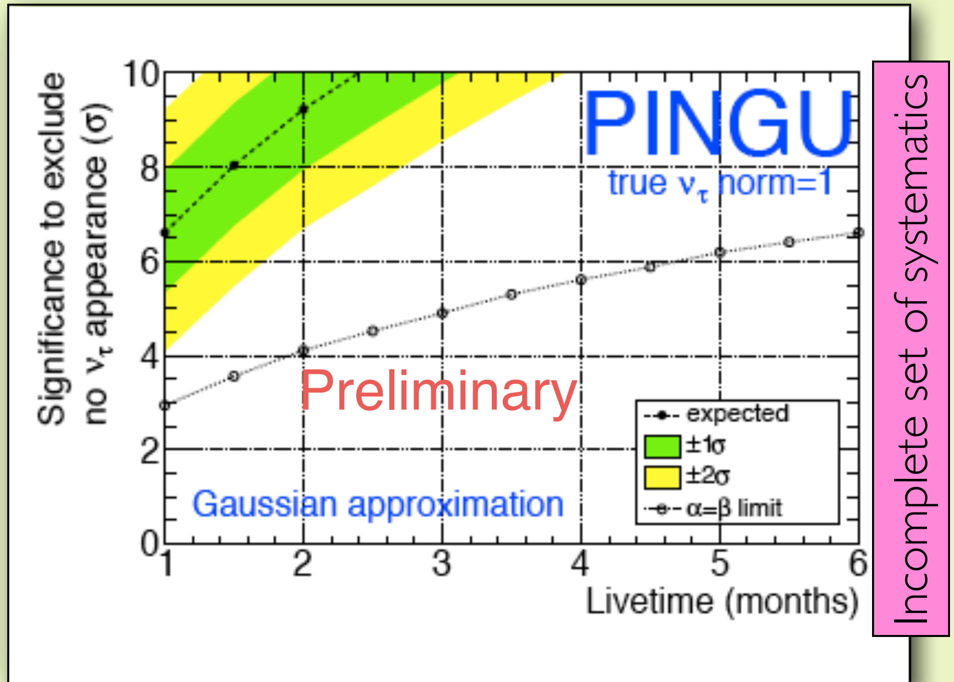
- Exploring the sensitivity improvement with more modules per string
  - Additional strings are stronger cost driver than modules
    - keep $N_{str} = 40$
    - increase modules/string from 60→96
  - Additional ~$150k/string
    - Corresponding to additional $6M total



Example ν Oscillation: ν_τ Appearance

- Provides a test of the unitarity of the mixing matrix
- Selection of events uses same criteria as for the NMH analysis with the goal now to reject atmospheric muons
- Same trained BDT as the NMH analysis for selecting "pure" cascade-like events



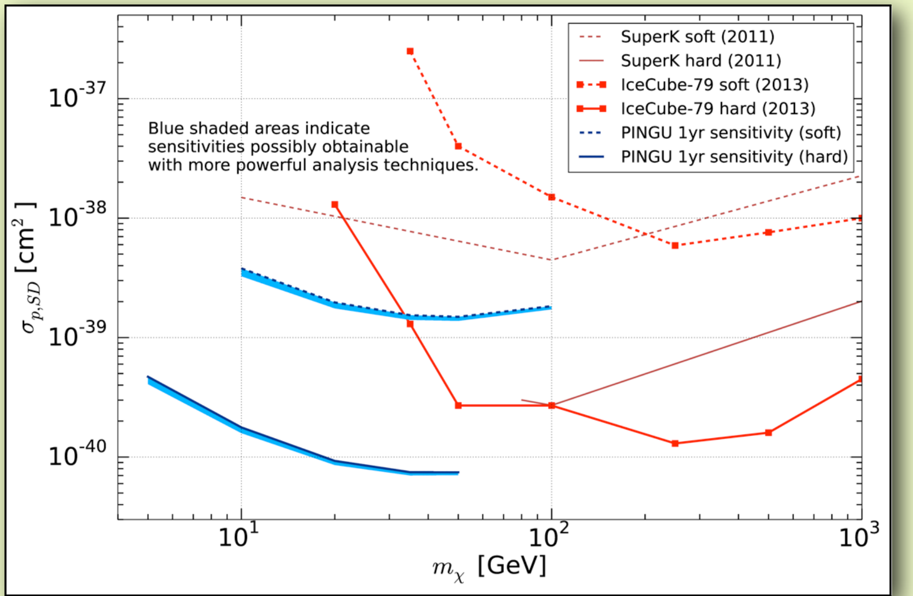


- 5σ exclusion of no ν_τ appearance expected after 1 month of data
- 10% precision in the ν_τ normalization after 6 months.

PINGU and WIMPs

Predicted sensitivity for extended PINGU geometry

Spin-dependent WIMP-matter interactions



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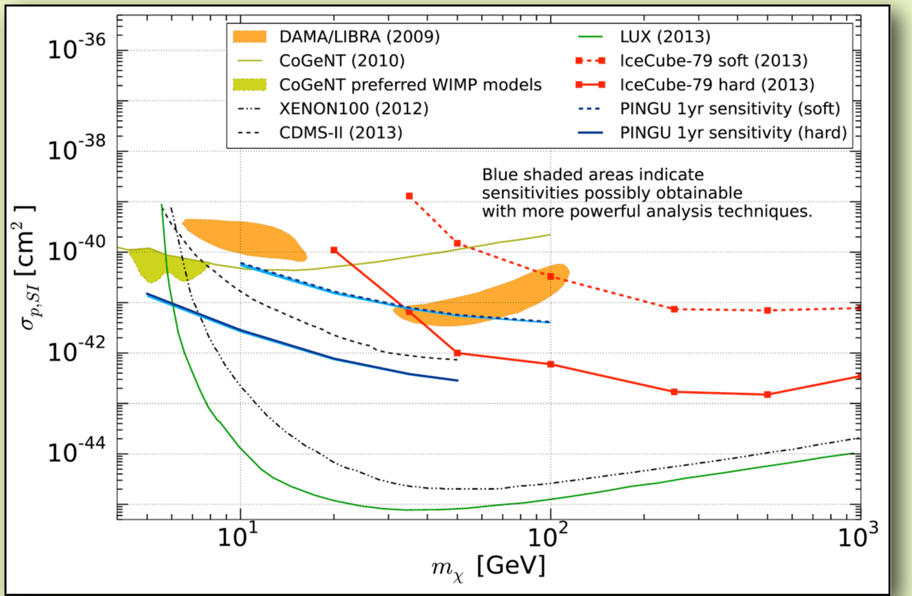
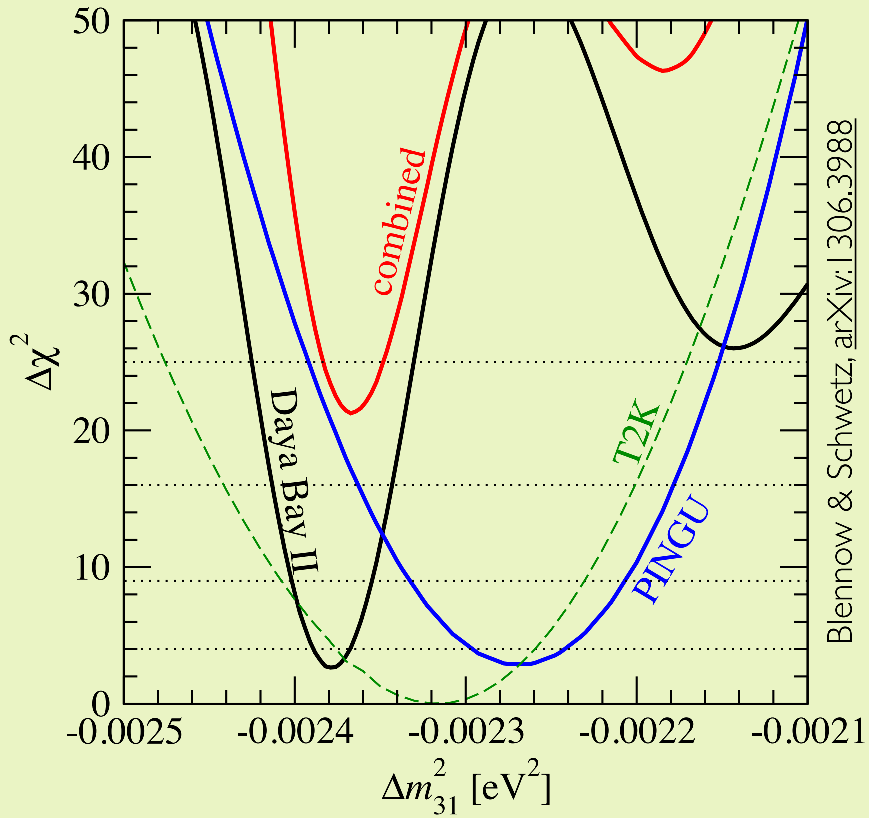


Reach as low as M_χ = 5GeV

PINGU Synergy with Reactor Experiments

- Possible to get reasonable fit to wrong hierarchy by adjusting $\Delta m^2(31)$
  - But: These values of $\Delta m^2(31)$ will be *different* in PINGU vs. JUNO/RENO-50
    - PINGU uses atmospheric neutrinos over wide energy range that experience matter effects
    - JUNO/RENO-50 use reactor neutrinos and look for distortions in energy spectrum without matter effects



- Combination of two low significance measurements can attain high significance!

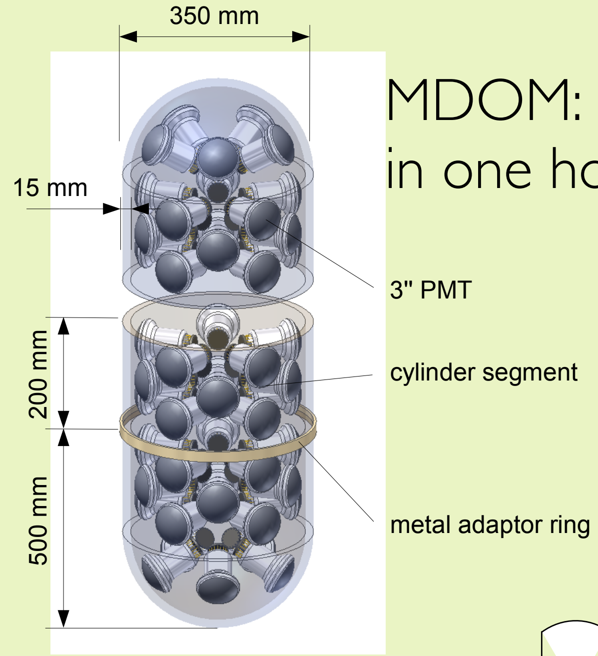
Datasets:
- PINGU: 1 yr
- JUNO: 1000 kt GW yr
- T2K: 5 yrs 0.77MW

Current and Near Future Studies

- Impact of cross section and vertex interaction uncertainties
  - Analysis in progress
- Impact of PID uncertainties
  - Analysis in progress
- Impact of clear hole ice
  - Simulations/Reconstructions underway
- Determine physics-driven requirements for *in-situ* calibration sources
  - See talks at this workshop
- Impact of segmented DOMs (e.g., MDOM)
  - provide some directionality, how much does this improve reconstruction and noise rejection?
  - potentially beneficial at all energy scales (PINGU, HEA, MICA)

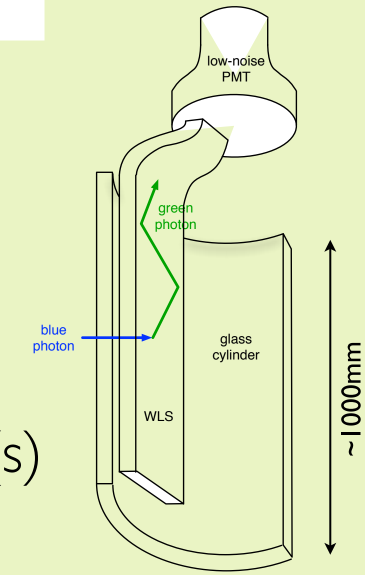
R&D

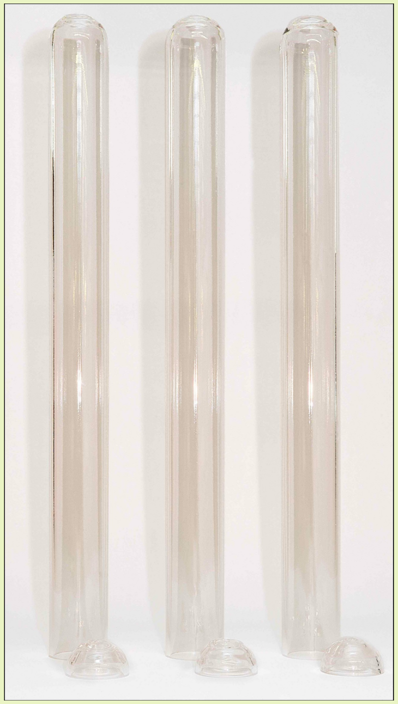
- Plan to deploy several R&D modules with PINGU
  - See presentations, this workshop
- Aim: Test modules for
  - high energy extension
  - MICA (megaton-scale in-ice Cherenkov ring imaging array) with low noise and threshold $E_\nu \sim 1$ GeV



MDOM: Many 3" PMTs in one housing

WOM: Wavelength-shifter tubes, PMT at end(s)





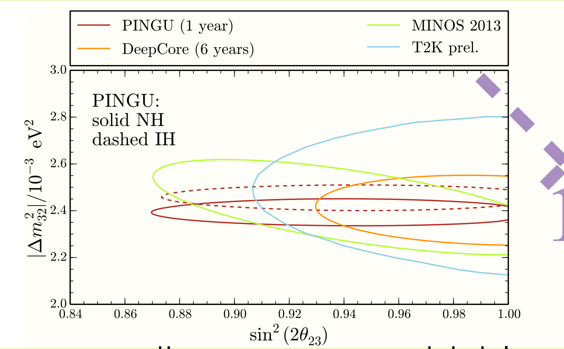
Quartz housings

Conclusions

- PINGU will have very good sensitivity to the neutrino mass hierarchy
  - For marginal extra cost, extended geometry will have even better sensitivity
- PINGU will also
  - push search for WIMPs as low as $M_\chi = 5$GeV
  - produce highly competitive results in ν_μ disappearance and ν_τ appearance
- PINGU is low risk and can be constructed quickly
- Excellent R&D platform for future photon detection module options

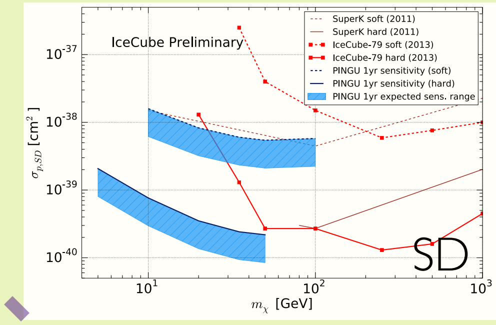
Backup

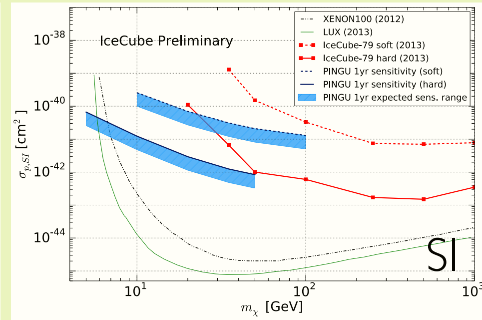
Other Physics Potential of PINGU



ν_μ disappearance: highly competitive after 1 yr

See IceCube result, PRL 111, 081801 (2013)





Indirect WIMP searches: reach M_χ~5 GeV, world-leading limits in SD channel after 1 yr

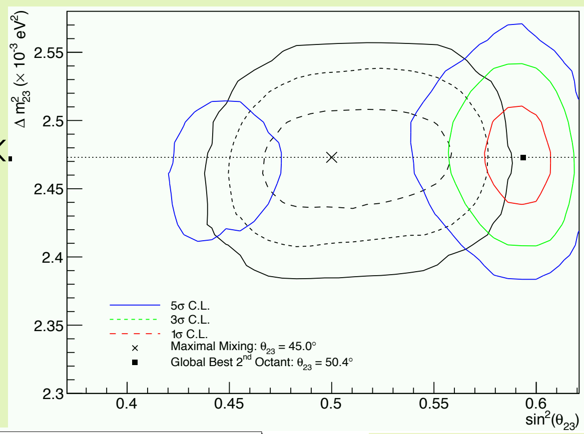
PINGU Livetime (years)

1

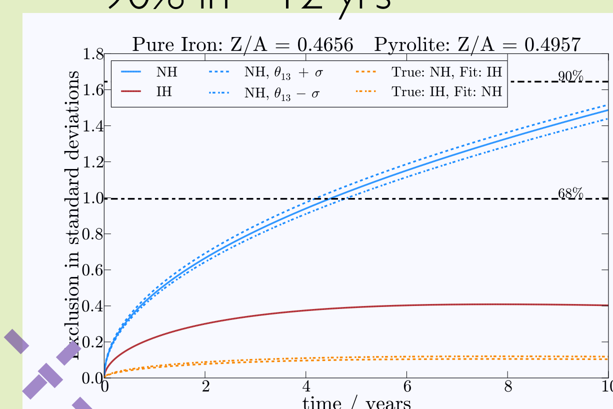
5

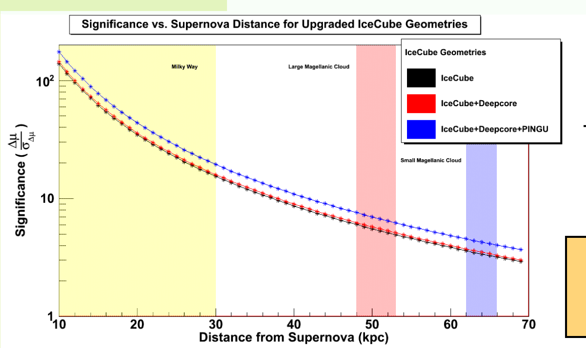
10

Exclude max. mixing @5σ after 5 yrs



Earth tomography: exclude pure Fe core at 90% in ~12 yrs





2x sensitivity to galactic SN (at any time)

Please see PINGU LoI for more details!
http://lanl.arxiv.org/abs/1401.2046

PINGU Schedule and Budget

Performed rough top-down estimate first, scaling from IceCube.

Followed with bottoms-up estimate detailed to L3 in WBS. Budgets provided by PINGU L2 leads, all of whom have IceCube experience.

Two numbers came out nearly the same.

PRELIMINARY	Item	PINGU Alone	PINGU as part of IceCube Facility*
Fixed Costs	PINGU Project	20.6	7.0
Per-String Costs	PINGU Project	46.9/40=1.17	41.3/40=1.03
	Polar Support	17.4/40=0.44	16.45/40=0.41
	Total	1.61	1.44
Non-US Contribution	Total	25	25
Net US Cost	Total w/o Contingency	20.6+(1.61*40)-25= **$59.9M**	7.0+(1.44*40)-25= **$39.7M**
	Total w/Contingency (~23%)	25.5+(1.99*40)-25= **$80.1M**	8.7+(1.77*40)-25= **$54.6M**

*__Facility__: HE Extension, PINGU, surface array (plus ARA? DM-Ice?), all can leverage IceCube presence and experience. Savings accrue from shared resources: drill, cable/PDOM devel., Mgmt., IC Integ., ICL upgrade...

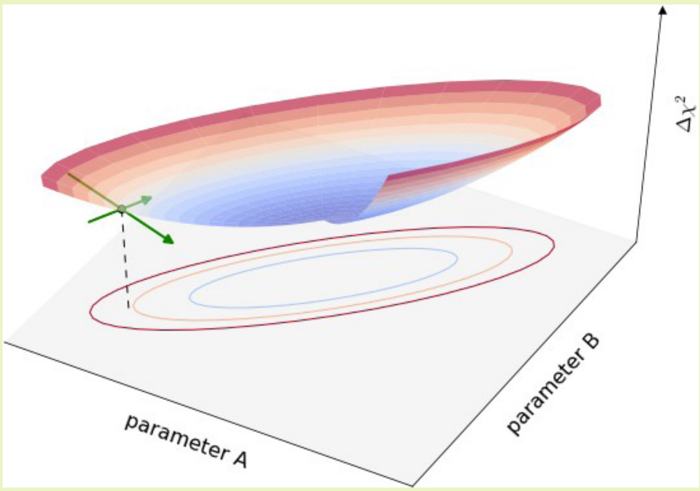
Estimated PINGU Costs (European Accounting)

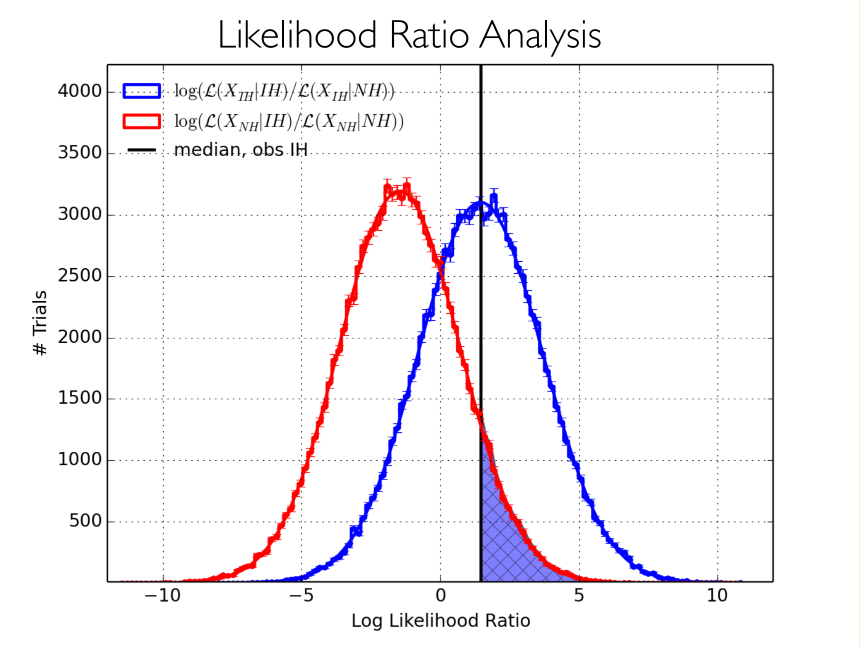
Rough PINGU Marginal Costs:
European Accounting

Item	**Labor**	**Capital Equipment**	*Shared Infrastructure*
Drilling	$3.5M		*L: $3.3M* *CE: $3.7M*
PDOM, Cables, Surface DAQ, Calibration Devices		$23.4M	
Antarctic Support Contractor	$7.6M	~$8M (fuel)	*CE: ~$2M*
Total	$11.1M	$31.4M	*$9M*

PINGU and the NMH - extracting the sensitivity

Fisher Information Matrix





- Estimations from the full simulation operating on event histograms in Energy and cos(zenith)
  - Fast evaluation using the Fisher Information Matrix where the gradates at each point fully describe the parabolic minimum (invert and obtain the full covariance matrix for the experiment
  - Full analysis from pseudo data sets applied as templates; LLR provides degree of agreement between pseudo set and one hierarchy vs. the other.
  - The Likelihood distributions are fit well by Gaussians; the two methods agree

Fisher Information Matrix

- (Fisher) Information matrix = inverse of covariance matrix
  ➔ full information of all errors and correlations
  ➔ easy implementation of (gaussian) priors

- Construction of the Information Matrix

observables

$$\mathcal{F}_{ij} = \sum_n \frac{1}{\sigma_n^2} \frac{\partial f_n}{\partial p_i} \frac{\partial f_n}{\partial p_j} \bigg|_{\text{fid. model}}$$

measurement error

parameters

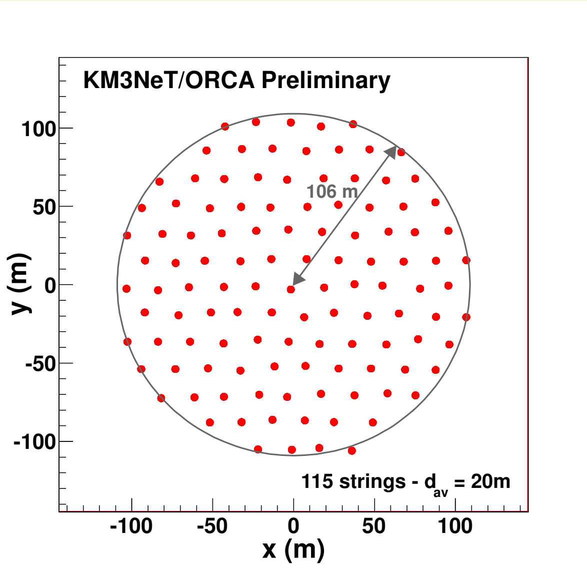
  ➔ valid within gaussian limit of fiducial model

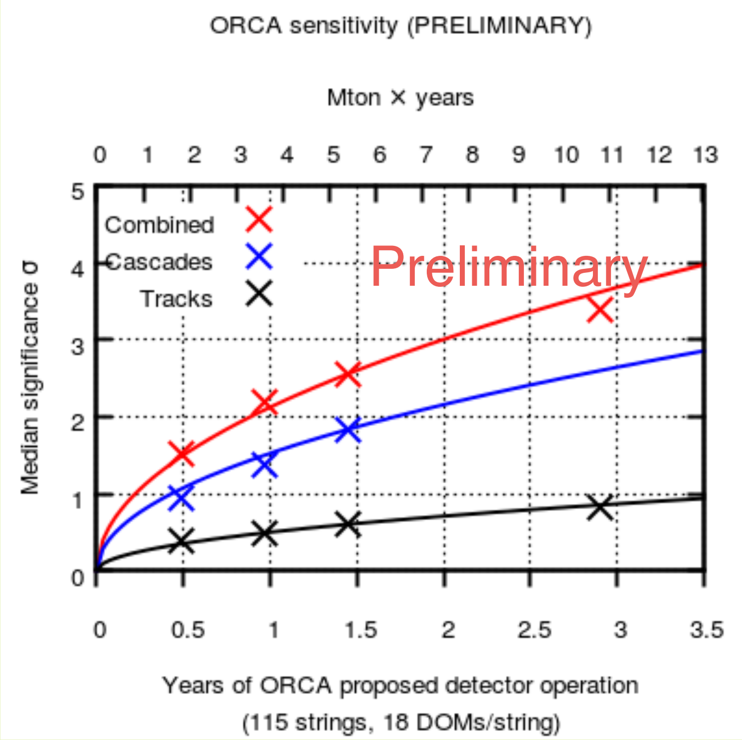
- Implementation for NMH
  ➔ hierarchy parameter: $P(h) = hP_{NH} = (1\text{-}h)P_{IH}$
  ➔ physics (Δm_{31}, θ_{23}, …) and detector parameters (A_{eff}, σ_{reco},…)

- Total error on hierarchy parameter yields significance (marginalized over other parameters it is correlated with)

PINGU and the NMH - comparison to ORCA

- ORCA follows a similar detector design philosophy to PINGU
  - Assumed is the first octant with fits to the oscillation parameters.
  - Included is some misidentification of rate based on MC
  - Not yet included are overall flux uncertainty, NC events, altered resolution for mis-identified events
  - 40 string PINGU and 115 string (18 module/string) ORCA predictions are in reasonably good agreement



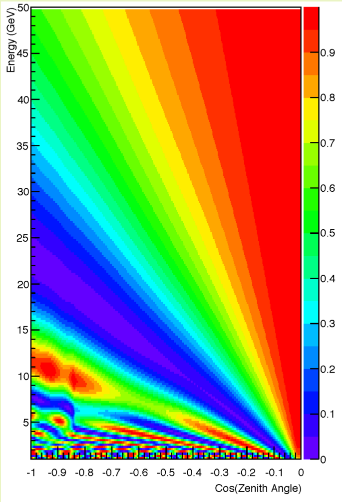


40 M€ investment

The Signature in PINGU

ν_μ anti-ν_μ

Normal Hierarchy



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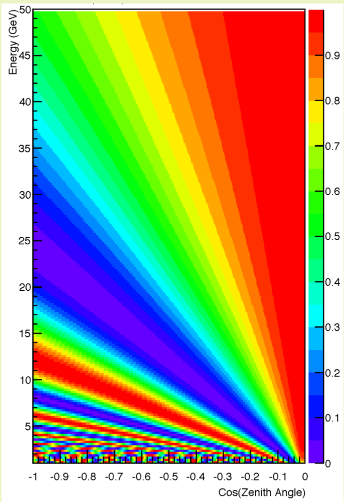
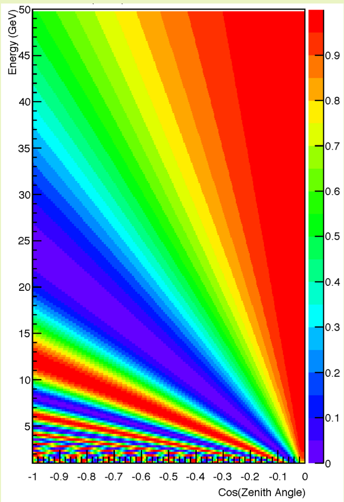


= [pattern A]

Measurement looks for difference between patterns A & B

Inverted Hierarchy



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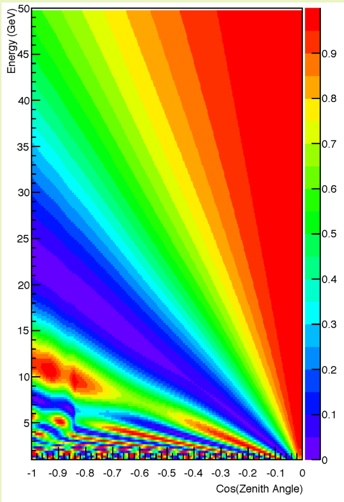


= [pattern B]

Energy

cos(θ)

A. Gross

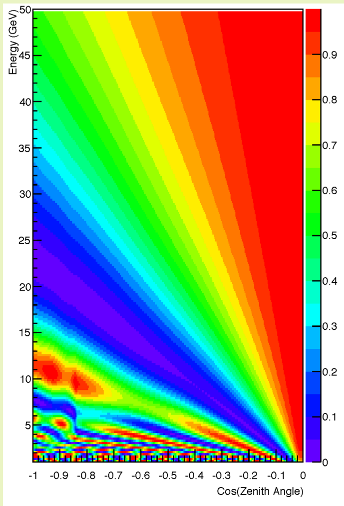
Without ability to distinguish ν_μ from anti-ν_μ, A = B! Impossible measurement?

The Signature in PINGU

ν_μ + anti-ν_μ

But:
$\sigma(\nu) \sim 2\sigma(\text{anti-}\nu)$
$\varphi(\nu_{atm}) > \varphi(\text{anti-}\nu_{atm})$

Normal Hierarchy



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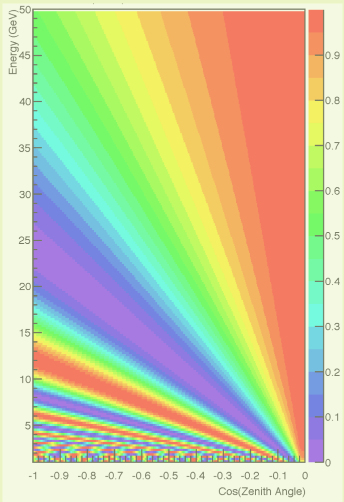

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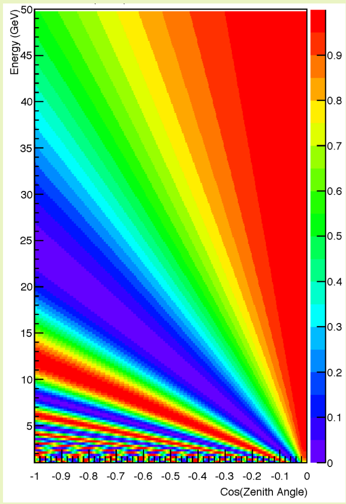

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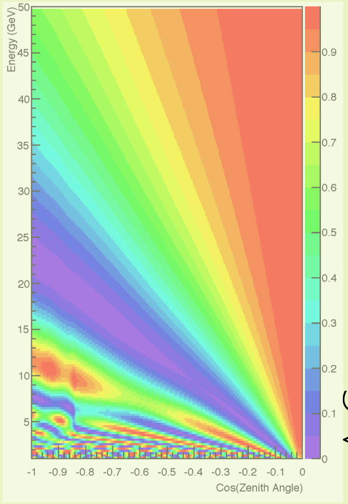


= [pattern B]

Now A≠B!

Energy

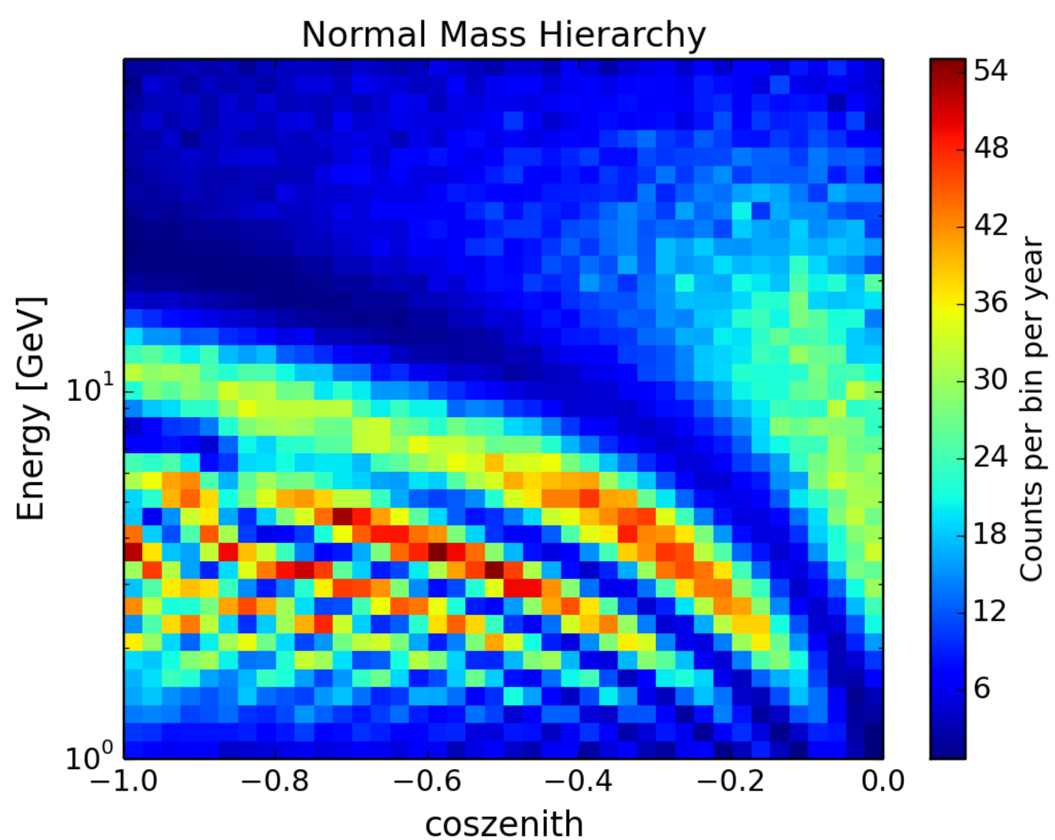
cos(θ)

A. Gross

Similar for ν_e

Signatures of the Neutrino Mass Hierarchy

- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
  - Rates of all flavors are affected
  - Note: effect of detector resolution not shown here
- At higher energies, ν_μ CC events distinguishable by the presence of a muon track
  - Distinct signatures observable in both track (ν_μ CC) and cascade (ν_e and ν_τ CC, ν_x NC) channels



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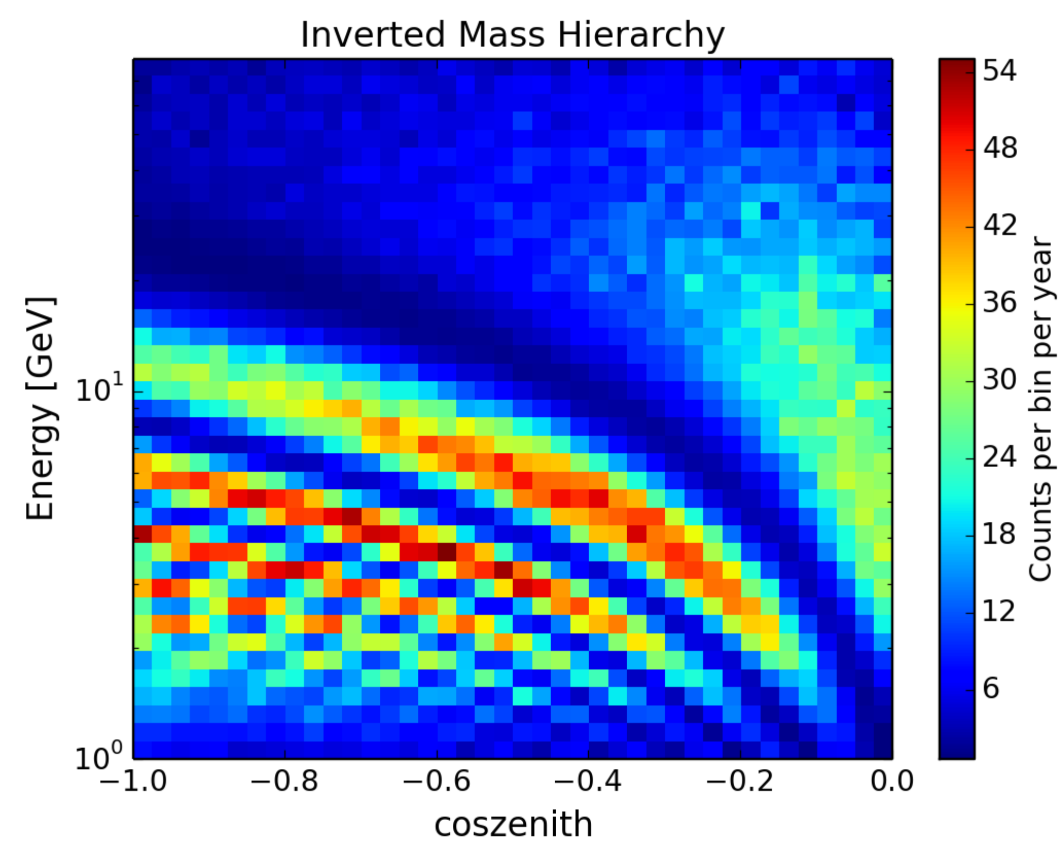
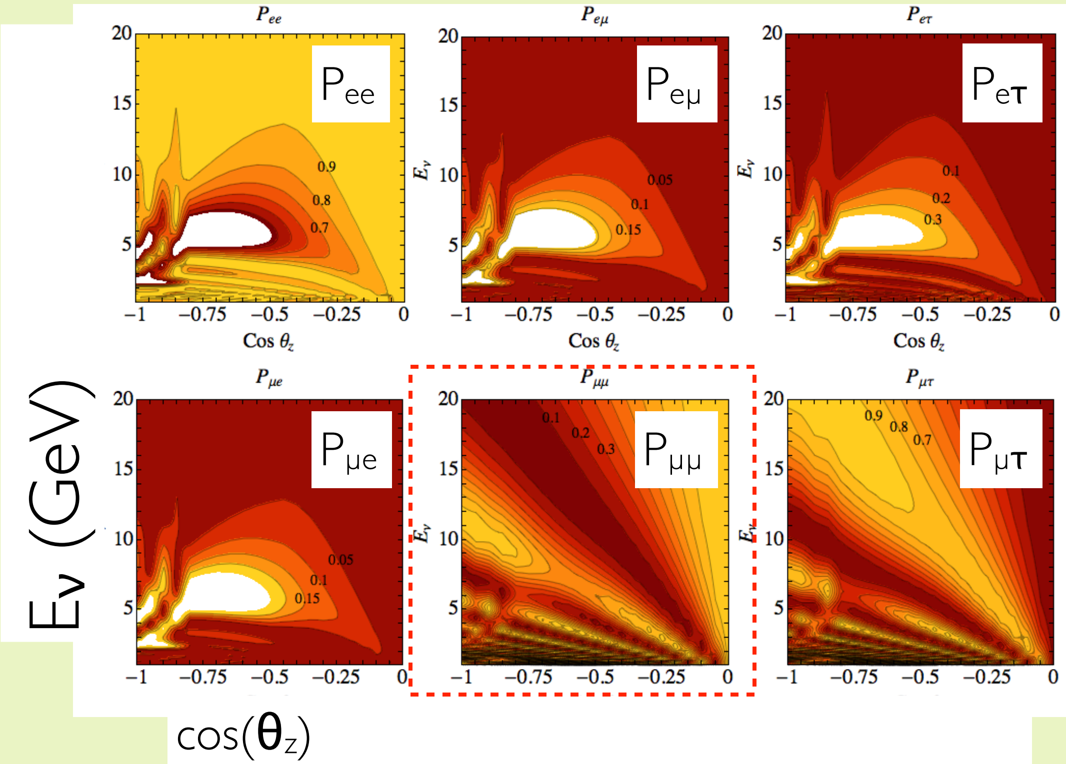


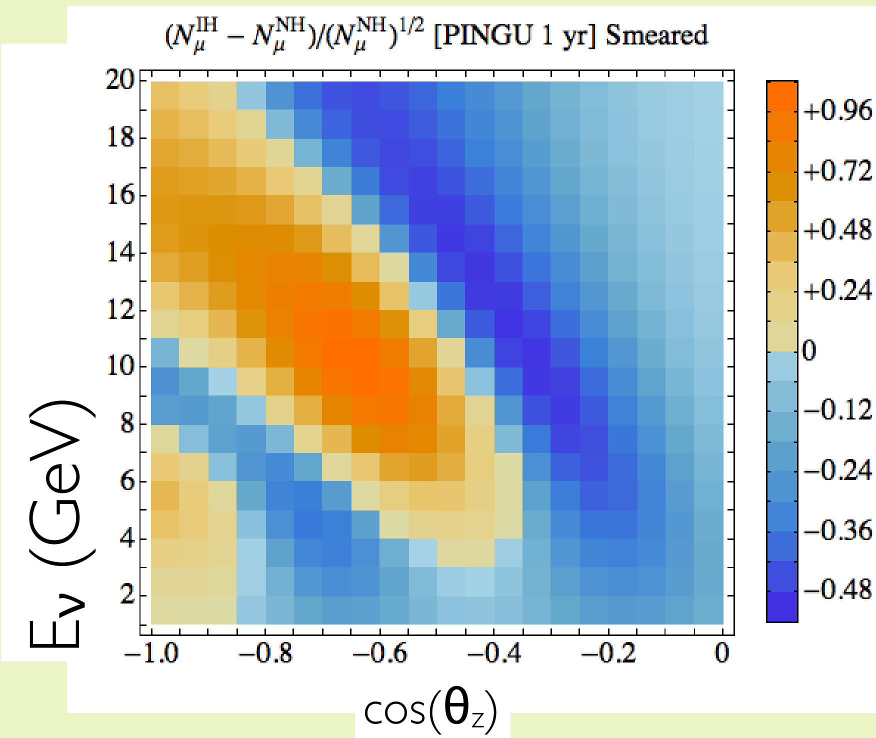
Neutrino Mass Hierarchy

$\Delta m^2_{32} = 2.35\times10^{-3}$
$\Delta m^2_{21} = 7.6\times10^{-5}$
$\sin^2\theta_{23} = 0.42$
$\sin^2\theta_{12} = 0.312$
$\sin^2\theta_{13} = 0.025$

Neutrino Oscillograms (Normal hierarchy)



Hierarchy Asymmetry (σ_E=3GeV σ_φ=15°)



Impact of smearing: summed significance drops to 10σ (no systematics), 7σ (5% uncorr. syst.), 4.5σ (10% uncorr. syst.).

Impact of δ_{CP} negligible.

Study by IceCube collaboration with full detector simulation, more conservative statistical treatment, and reconstructions underway.

Akhmedov, Razzaque, Smirnov. arXiv:1205.7071

Neutrino Hierarchy

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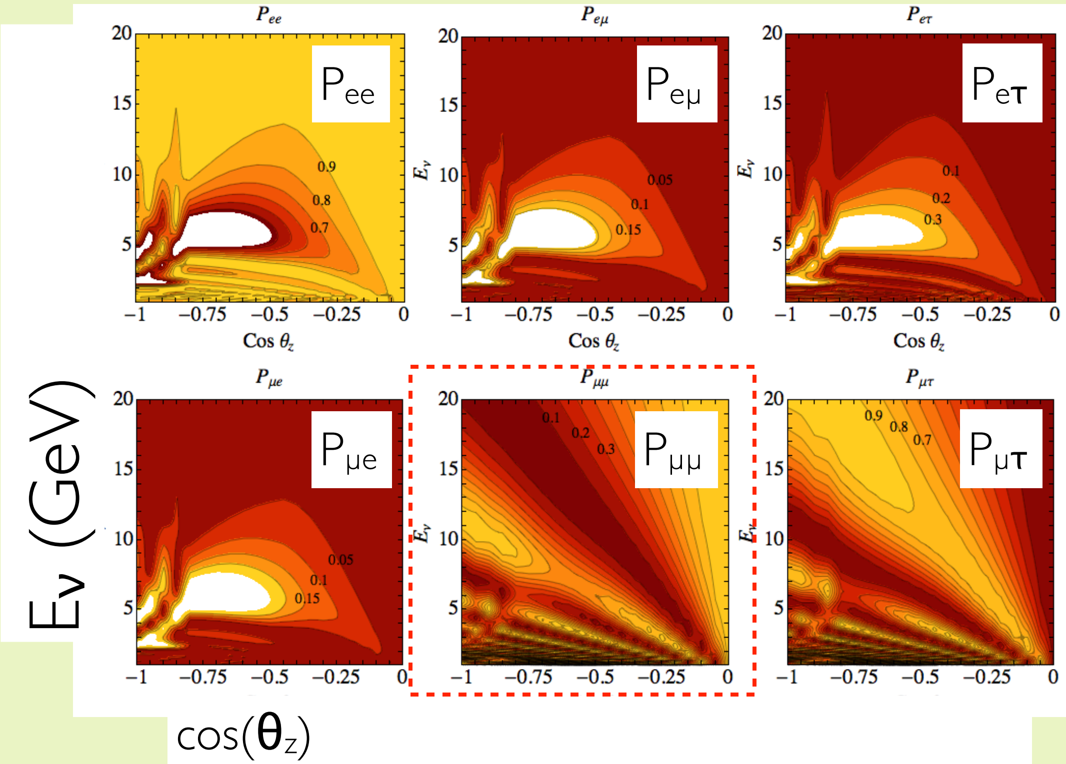
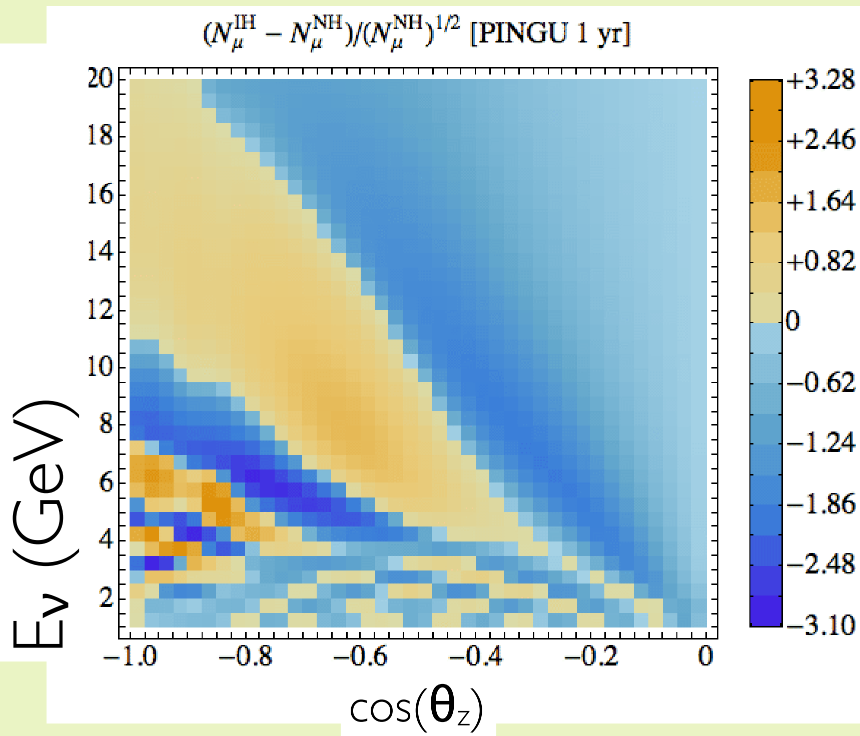


Hierarchy Asymmetry (Perfect detector)



Summed significance: 45σ

Impact of δ_{CP} negligible.

Study by IceCube collaboration with full detector simulation, more conservative statistical treatment, and reconstructions underway.

Akhmedov, Razzaque, Smirnov. arXiv:1205.7071

Estimation of NMH Sensitivity

- Event selection and background rejection requirements:
  - Reconstructed event vertex well-contained
  - Reconstructed event direction upward
- Reconstruction
  - Full likelihood minimization in 8-d parameter space (uses "MultiNest")
    - Interaction vertex (x,y,z,t,E), outgoing muon (θ, φ), track length
  - Resolutions (improve with energy; given here at $E_{\nu,\mathrm{true}} \sim 5$ GeV):
    - $\Delta E/E \sim 0.27$, $\sigma_\theta \sim 13^\circ$ (θ: zenith angle; track & cascade resolutions ~same)
  - Basic track vs. cascade particle ID (improves with energy)
    - 52% of ν_μ (37% of ν_e) (mis-)identified as track-like at ~5 GeV
    - 75% of ν_μ (25% of ν_e) (mis-)identified as track-like at ~10 GeV

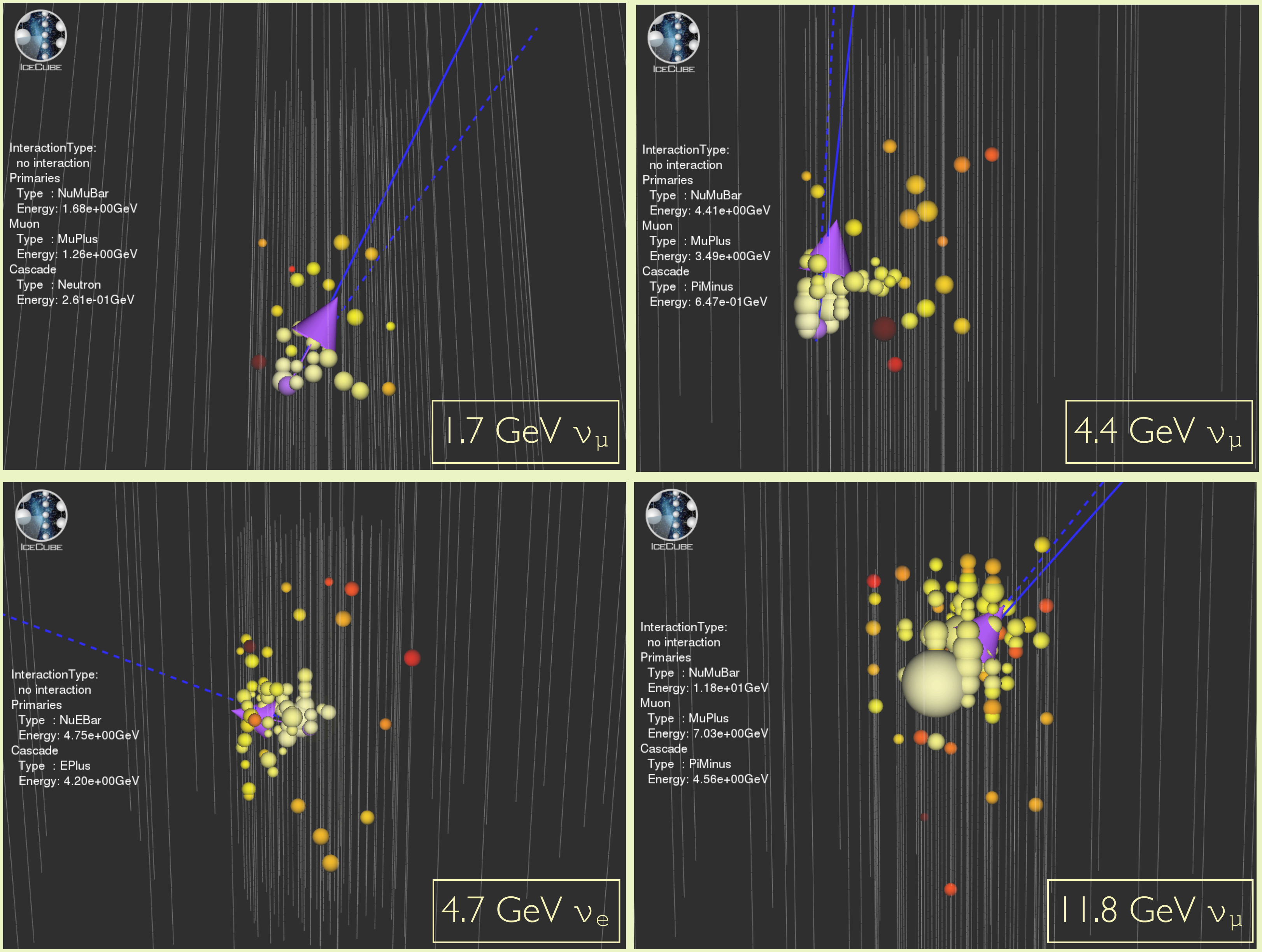
Expected Systematics Mitigation

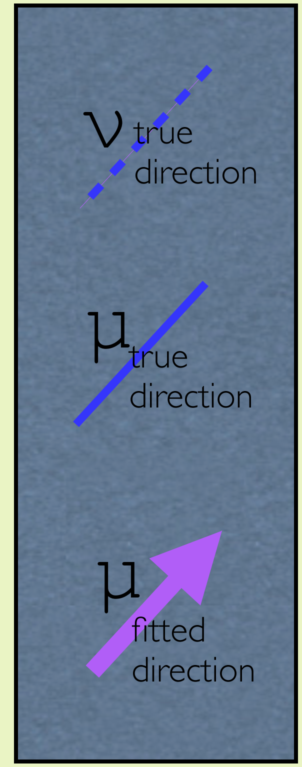
- Energy scale uncertainty
  - Precision *in-situ* calibration light sources
    - Expect better than 3% calibration of light output (E scale systematic was 5%)
- Ice property uncertainties
  - calibration light sources
- Neutrino, anti-neutrino cross section uncertainties
  - future Minerva results
- Other possible systematics
  - Cascade and track energy resolution uncertainties
    - calibration light sources
  - Cascade directional resolution uncertainty
    - muon-tagged cosmic ray air shower neutrinos

Known Future Enhancements

- Geometry optimization (now underway)
  - Initial look at higher density shows promise
  - Studying tradeoff between improved resolution & PID vs. decreased statistics
- Improved particle ID
  - Higher density array does better
- Inelasticity "y"
  - Predict 20-50% significance increase (Ribordy & Smirnov, 1303.0758)
  - Study underway
- Upgrade fitter (now underway)
  - include separate directions of outgoing lepton and initial vertex
- 10%-scale improvements in acceptances

Sample Reconstructed Events





Size of circles: N_γ.
Color: t_γ.

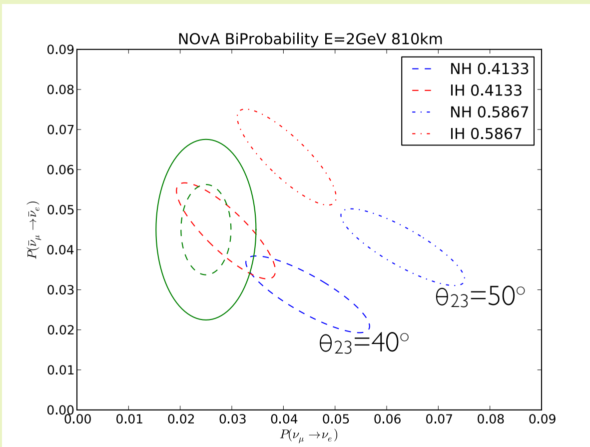
Neutrino Hierarchy and Parametric Resonances

- 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. 

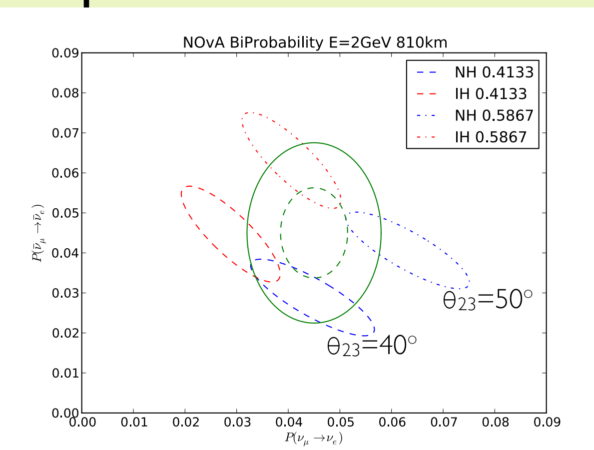
E. Kh. Akhmedov, *Pramana* 54:47-63,2000 or hep-ph/9907435

NOvA, PINGU and δ_{CP}

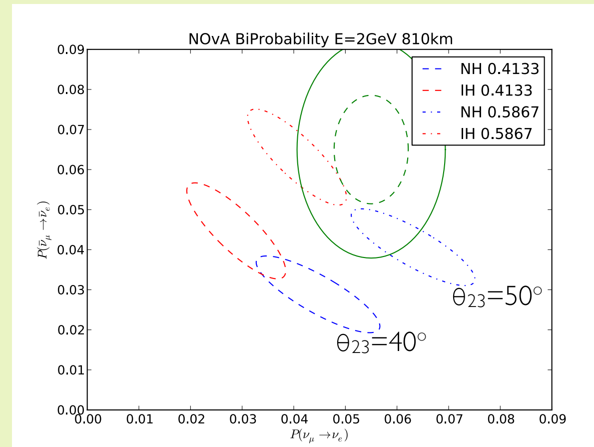
- Explore impact of knowing NMH at several selected points



If PINGU says NH, good δ_{CP} and octant resolution for NOvA



If PINGU says NH, improves NOvA's δ_{CP} measurement



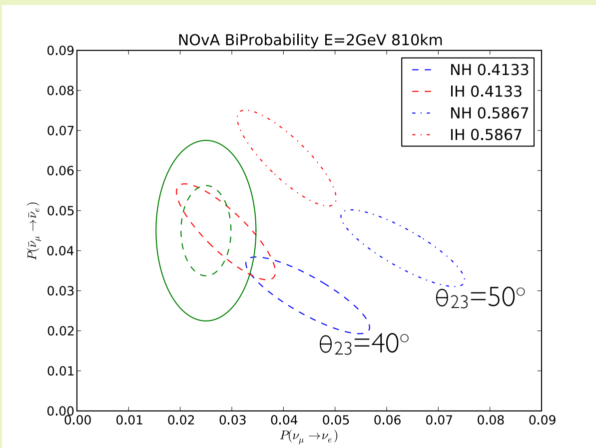
If PINGU says NH, good δ_{CP} and octant resolution for NOvA

		fraction of δ_{CP} within 2σ	fraction of δ_{CP} within 2σ	fraction of δ_{CP} within 2σ
$\theta_{23}=40°$	Unknown NMH	0.68	0.87	0.00
	NH	0.14	0.57	0.00
$\theta_{23}=50°$	Unknown NMH	0.00	0.89	0.90
	NH	0.00	0.36	0.46

NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554

NOvA, PINGU and θ_{23}

- Explore impact of knowing NMH at several selected points



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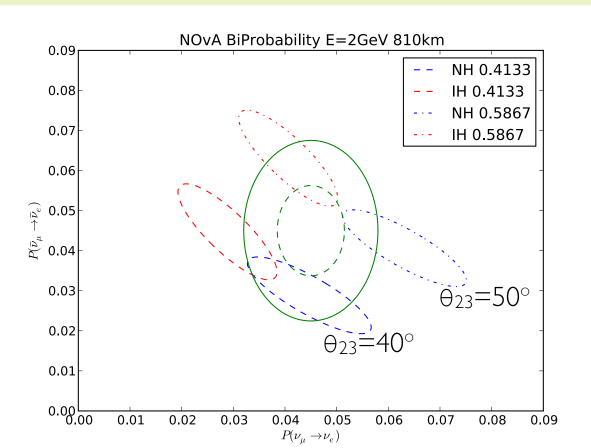

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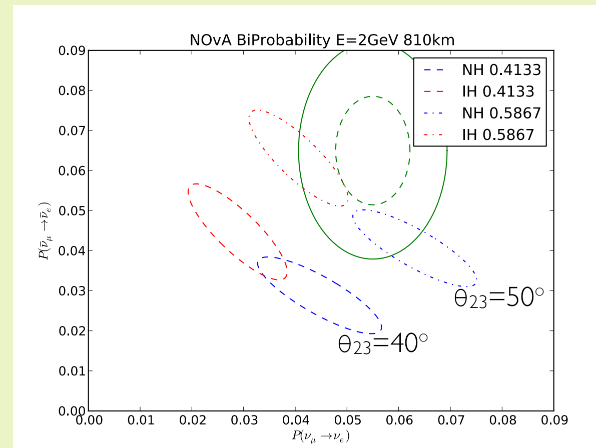


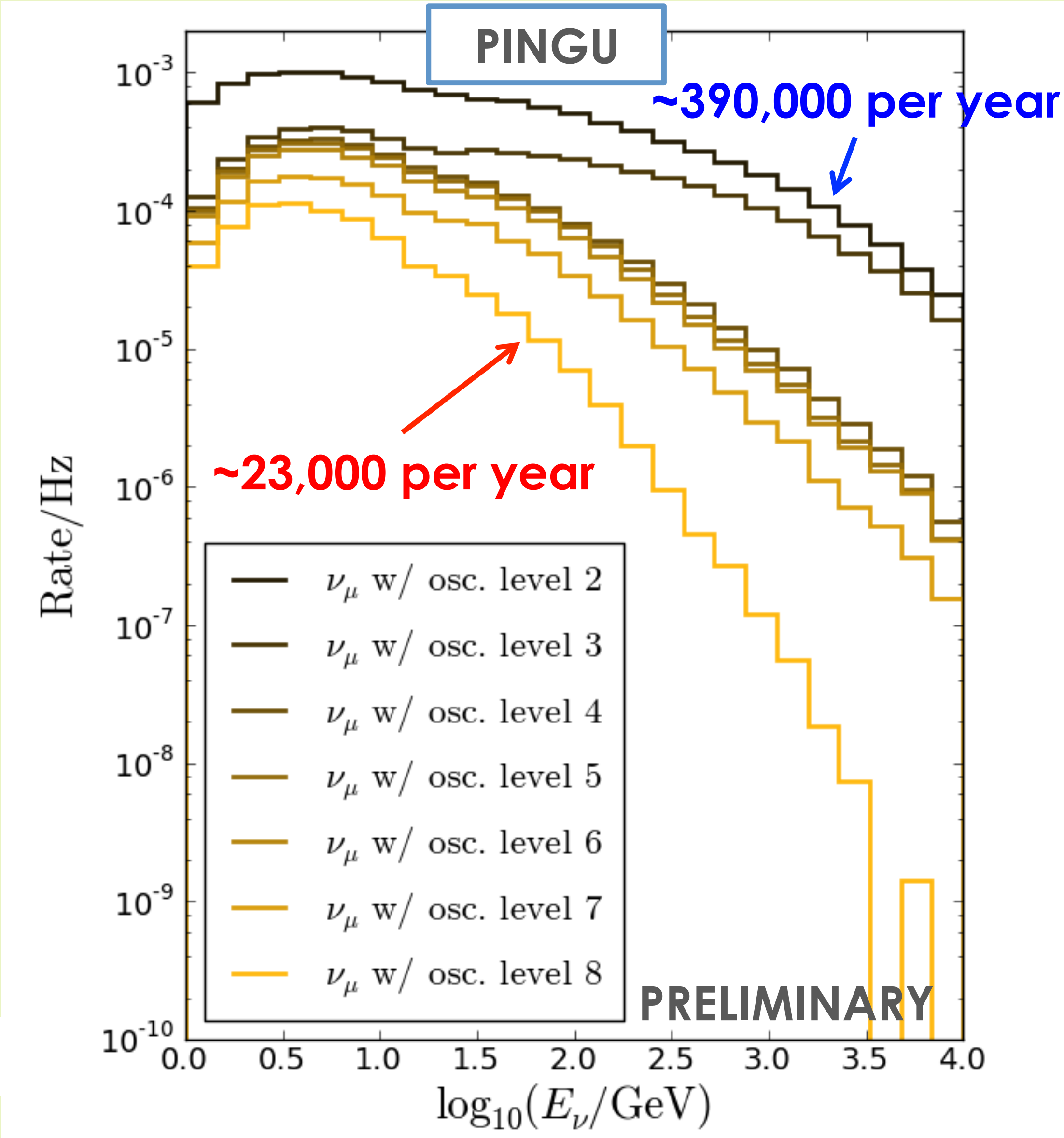
If PINGU says NH, good δ_{CP} and octant resolution for NOvA

		MinDist[(P,Pbar)→(δ_{CP} ellipse)]	MinDist[(P,Pbar)→(δ_{CP} ellipse)]	MinDist[(P,Pbar)→(δ_{CP} ellipse)]
$\theta_{23}=40°$	Unknown NMH	0.2σ	0.9σ	2.6σ
	NH	1.7σ	0.9σ	2.6σ
$\theta_{23}=50°$	Unknown NMH	2.6σ	0.6σ	1.0σ
	NH	5.4σ	1.0σ	1.1σ

NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554

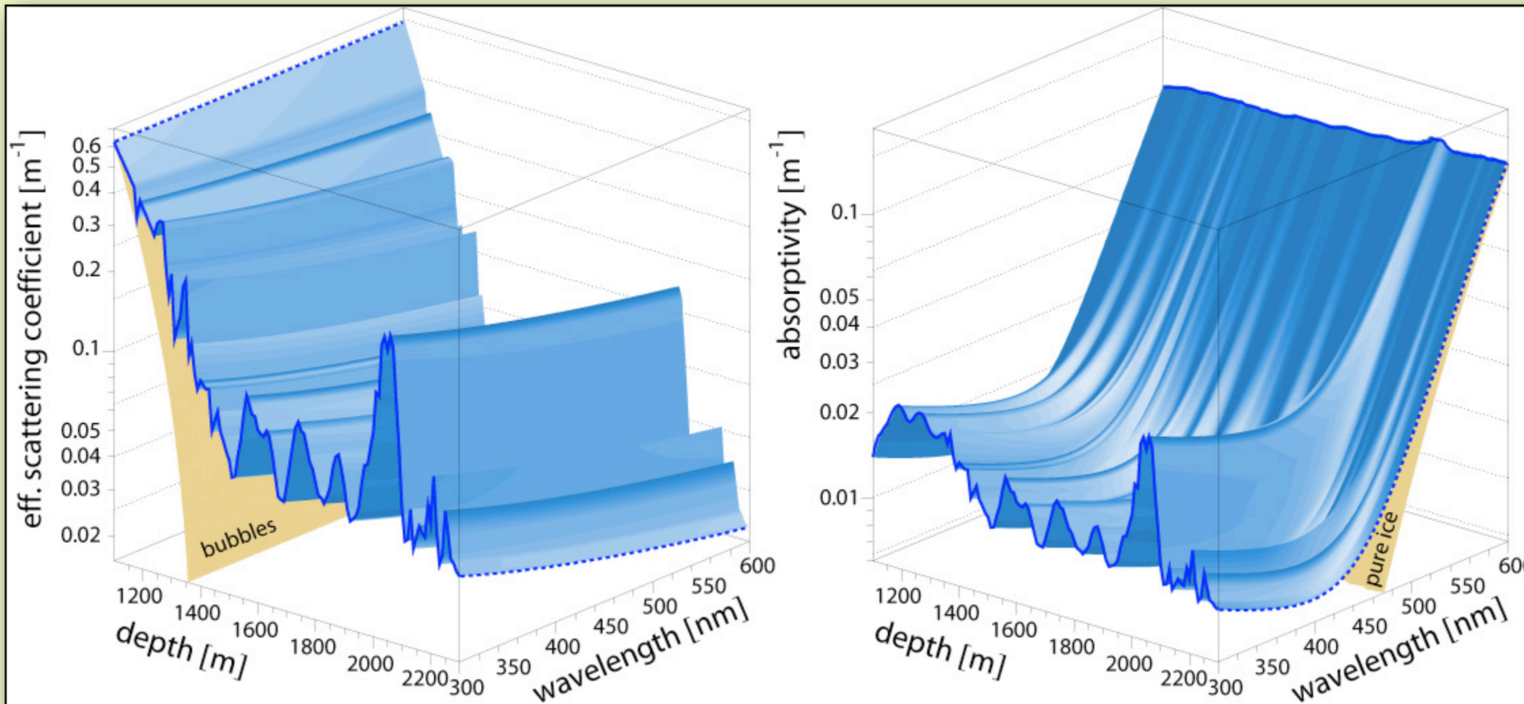
PINGU Energy Range

- A preliminary event selection based on DeepCore analysis
  - 23,000 muon neutrinos per year after oscillations
  - Oscillation signature is the disappearance of 12,000 events per year
- Sufficient to measure neutrino mass hierarchy via matter effects in the 5-20 GeV range without direct $\nu_\mu - \bar{\nu}_\mu$ discrimination
  - Exploit asymmetries in cross sections and kinematics



Ice Properties

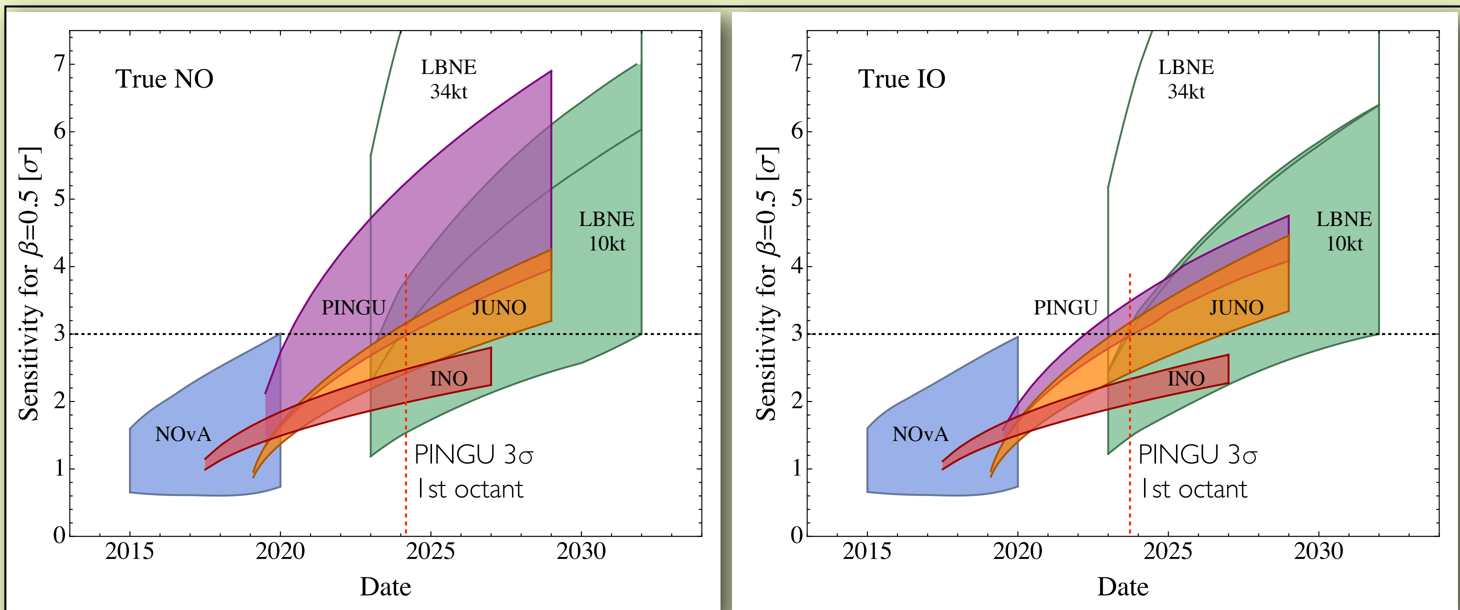
- Depth dependence of λ_{eff} and λ_{abs} from *in situ* LEDs
- Ice below 2100 m in DeepCore fiducial region very clear
  - $<\lambda_{eff}> \sim 47$ m, $<\lambda_{abs}> \sim 155$ m



- Constant temperature ~ -35C

The Neutrino Mass Hierarchy Landscape

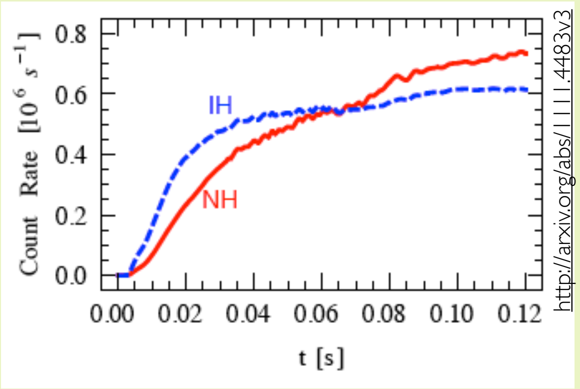
- PINGU, ORCA, HyperK, INO
  - NMH sensitivity for all δ_{CP}
- NOvA, T2K (running)
  - NMH sensitivity for limited δ_{CP} range
- JUNO (funded) and RENO-50 (R&D)
  - NMH sensitivity for all θ_{23}, δ_{CP}
- LBNE (approved)
  - measure both NMH and δ_{CP}
- Indirect methods:
  - Cosmic surveys (optical, CMB), SNe neutrino burst, $0\nu\beta\beta$ decay



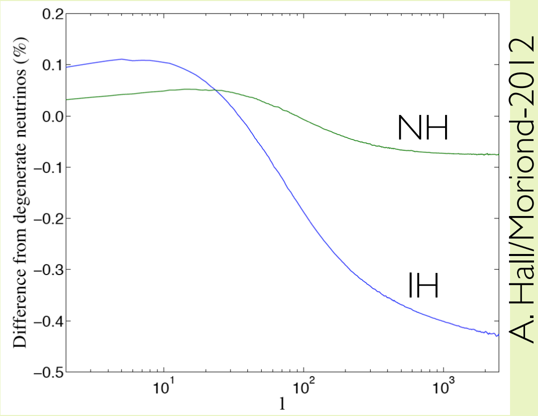
Blennow et al. 1311.1822v1

Width of bands depends on range of parameters (for PINGU: $40<\theta_{23}<50$).
We assume 1st octant (θ_{23}=40), the lower PINGU boundary in both plots.

- Supernovae



- CMB



- $0\nu\beta\beta$