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Fundamental Neutrino Physics with IceCube and PINGU

Doug Cowen
University of Manchester and Penn State

ICECUBE

ICECUBE GEN 2 PINGU

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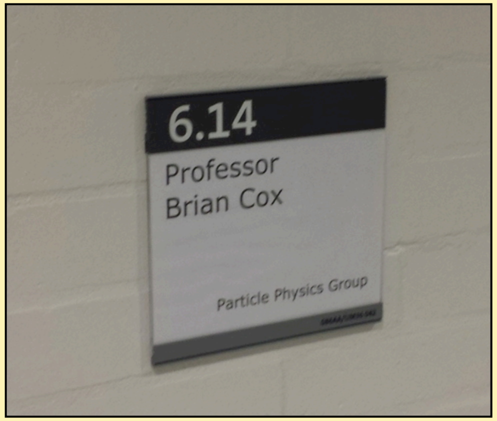
Preliminary

Introduction

- Neutrino Oscillations
- The Detectors:
  - IceCube & DeepCore (taking data)
  - PINGU (proposed as part of IceCube Gen2)
- The Source:
  - Atmospheric neutrinos
- The Signature:
  - Interactions in ice
  - Oscillations

Reasons to Care About Neutrinos



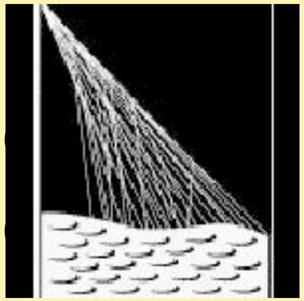
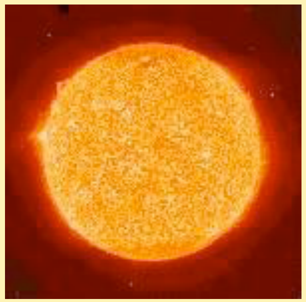
- "Brian Cox" reasons:
  - Ubiquity:
    - 10^{11} ν/s/cm^2 & ~300 in every cm^3 of space
  - Critical for life
    - Fusion in stars requires emission of ν's
  - "Tiniest" or most "anti-social" of all fundamental particle(s)
    - Solar neutrinos can pass unscathed through light-year-long column of lead
    - ~10^{24} neutrinos will pass through your body in your lifetime; only ~1 will deign to touch you
- Other good reasons:
  - Least understood fundamental particles in the Standard Model
  - Studying neutrino properties could yield hints for new physics
  - Their detection poses an irresistible experimental challenge

Neutrino Oscillations

- General 3-flavor mixing described by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
  - analogous to CKM matrix for quarks, but with larger off-diagonal elements
- Different L/E regimes require different sources and detectors

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{bmatrix} s_{ij} \equiv \sin\theta_{ij} \\ c_{ij} \equiv \cos\theta_{ij} \end{bmatrix}$$

= () () ()

atmospheric, beam — reactor, beam — solar

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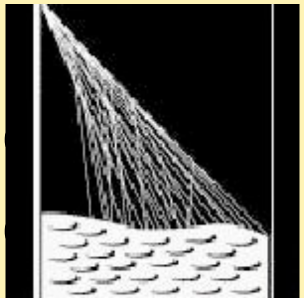
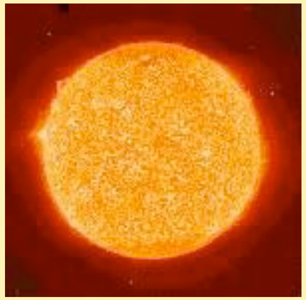


atmospheric, beam

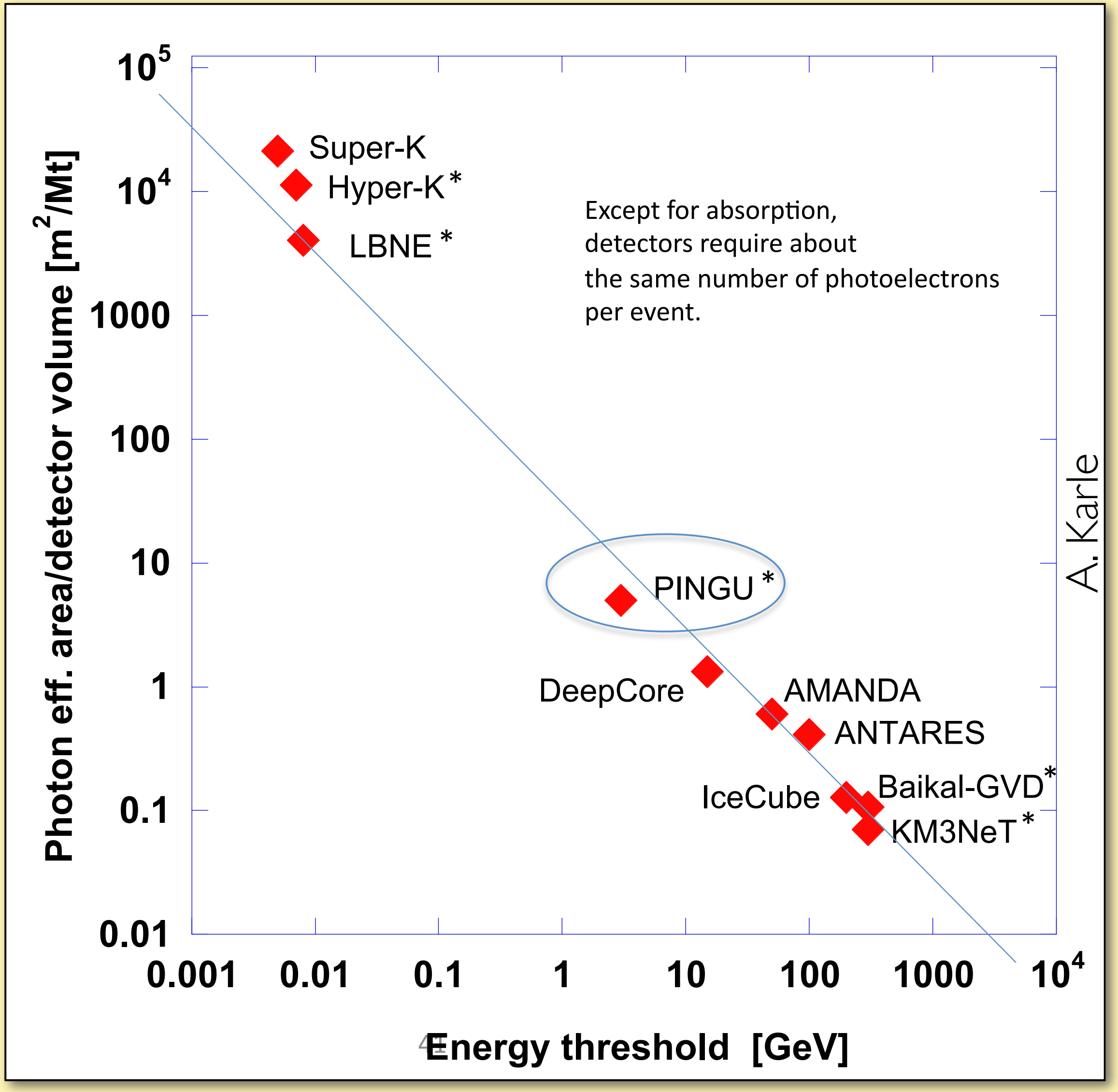
reactor, beam



solar

The Detectors The Source The Signature

- Detectors have a wide range of sizes
  - For higher E(ν), events are rarer but brighter
    - Leads to construction of bigger but more sparsely instrumented detectors



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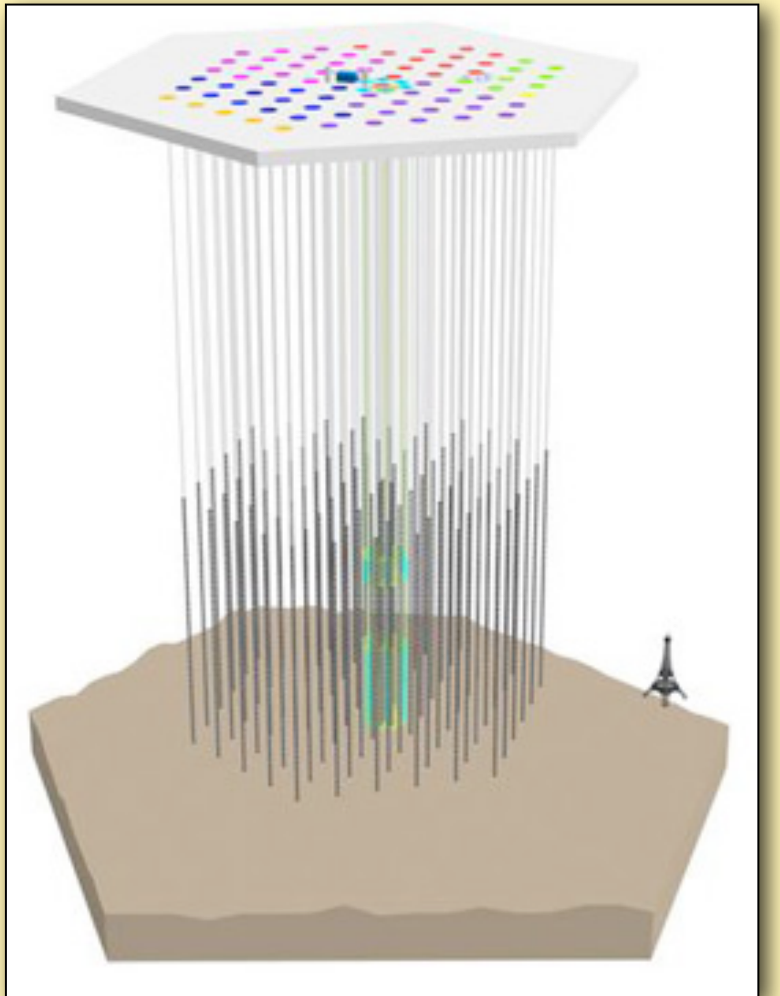
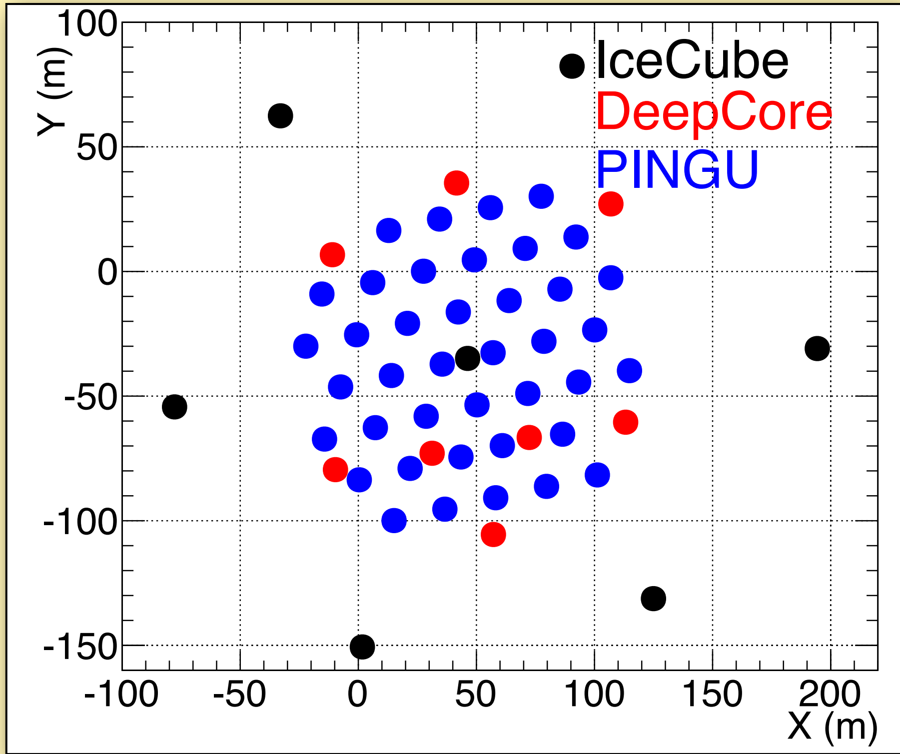
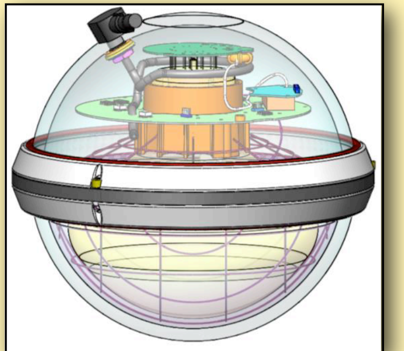


IceCube & DeepCore

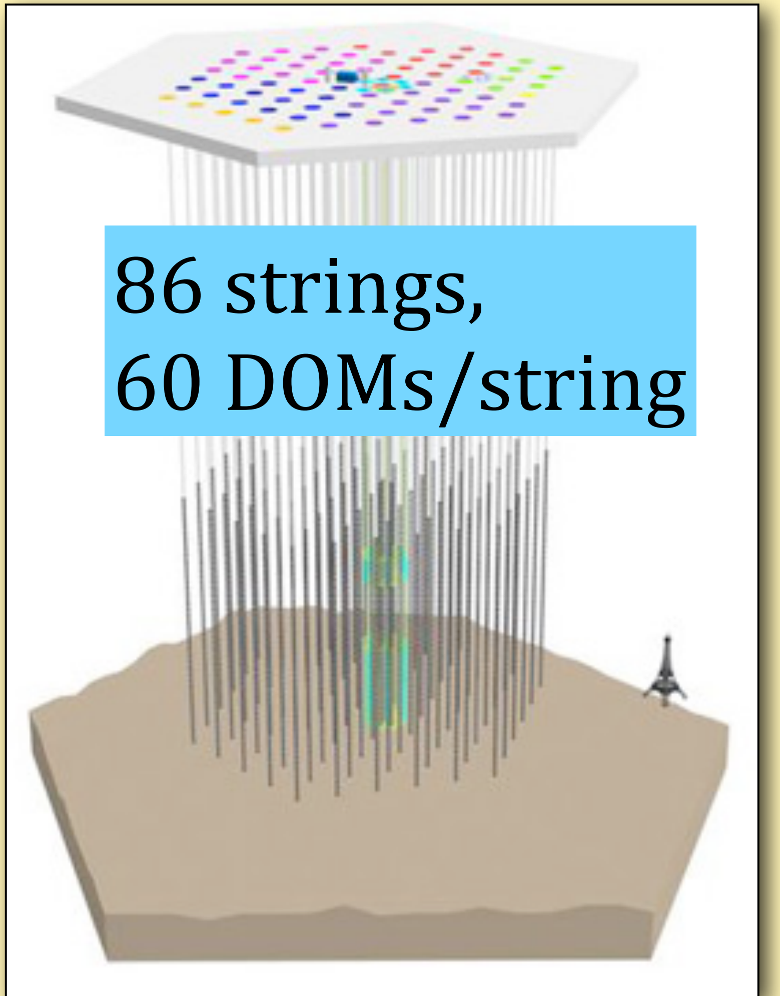


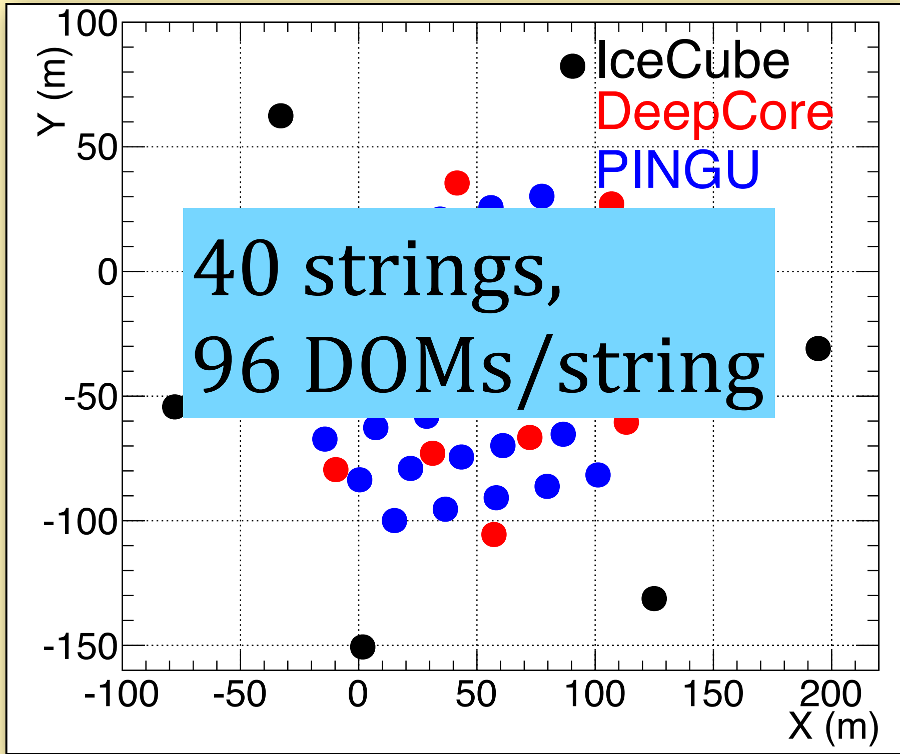
PINGU (Top View)



Digital Optical
Module (DOM)

The Detectors The Source The Signature





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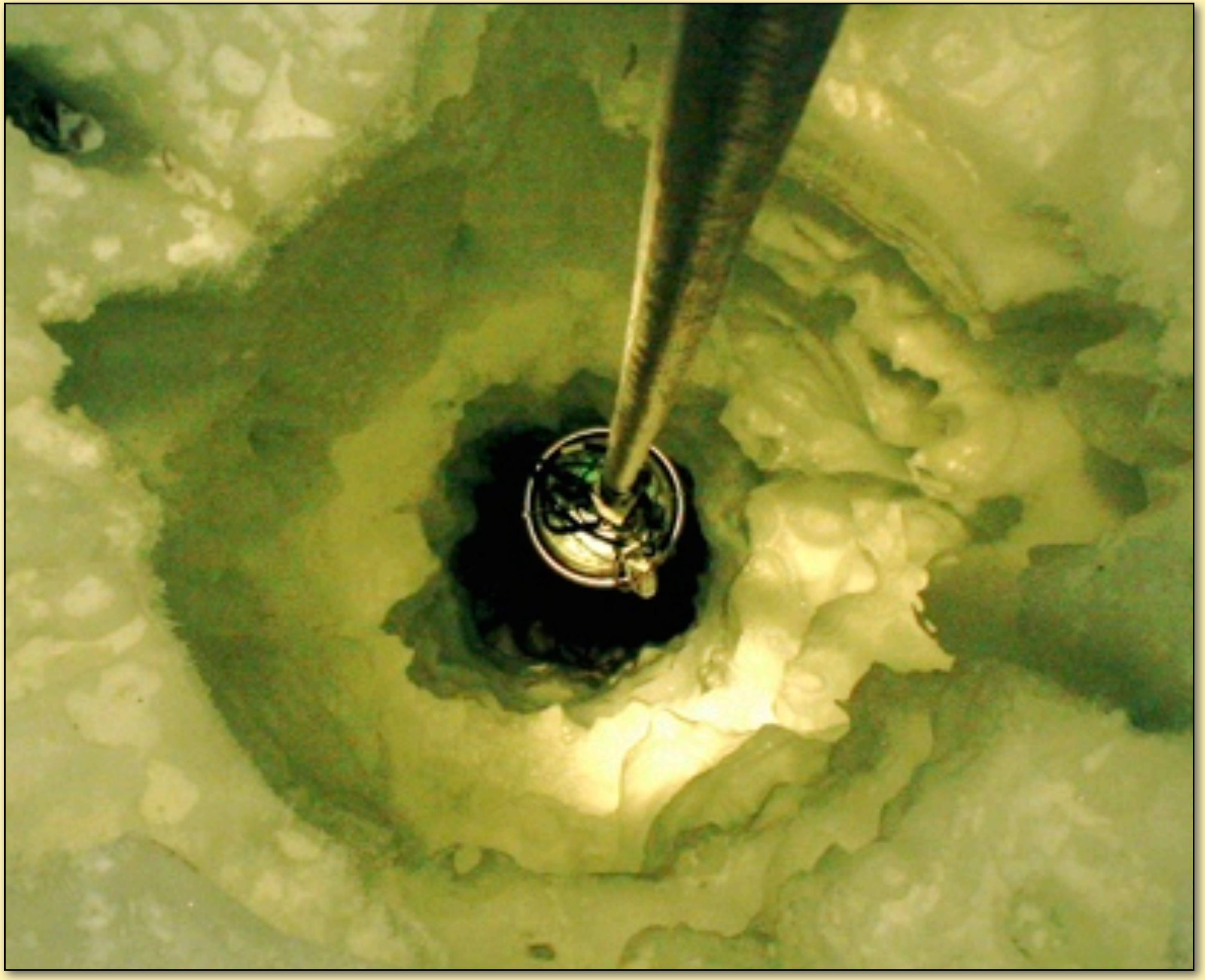
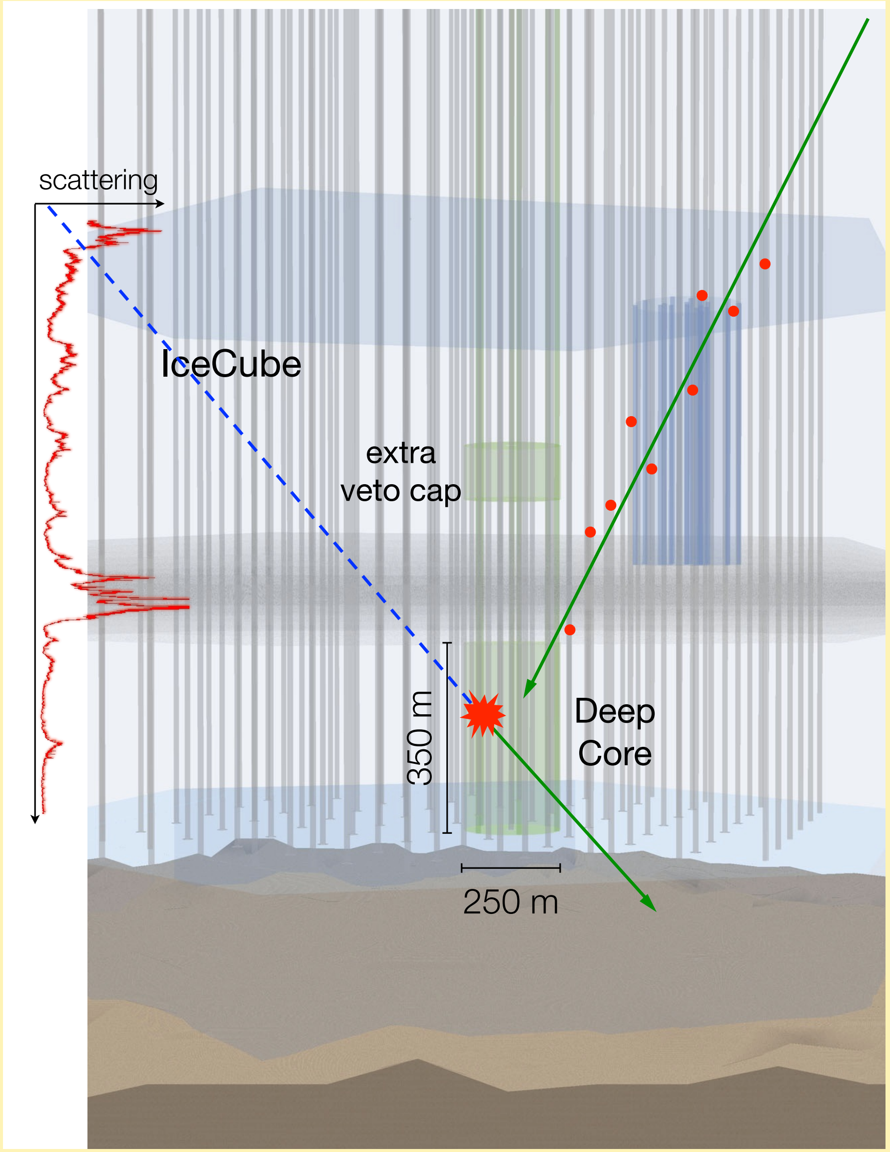


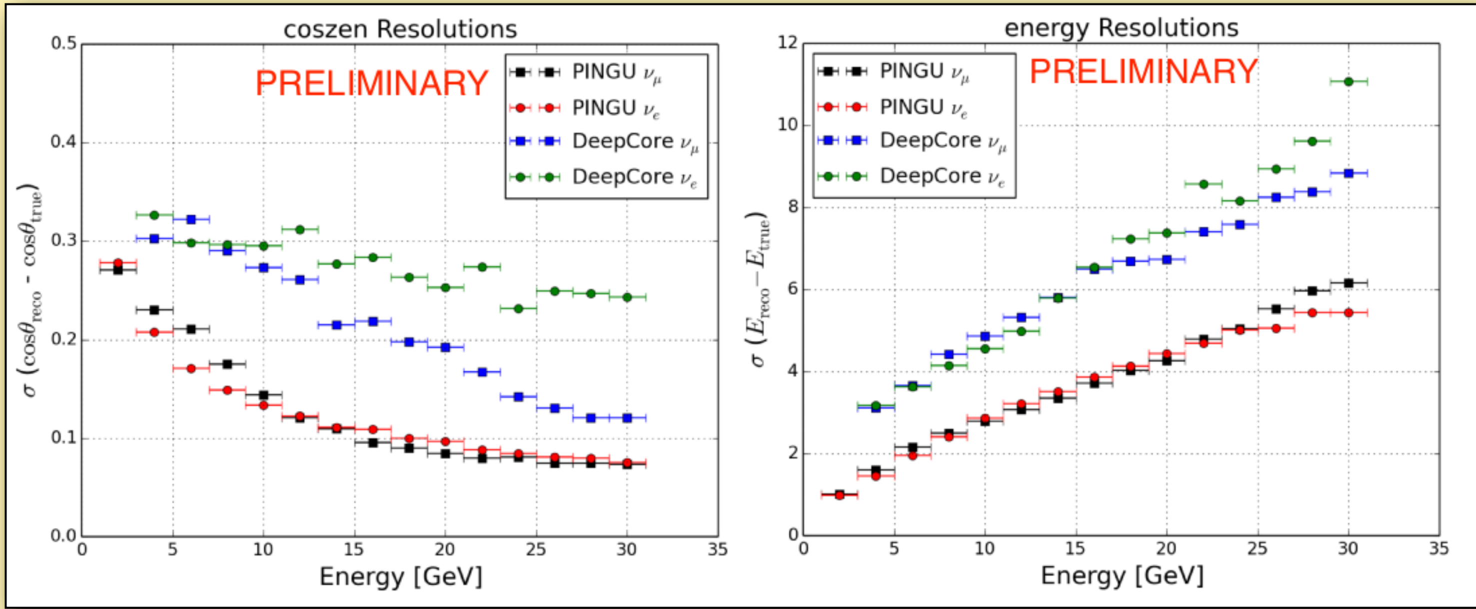
The Detectors The Source The Signature

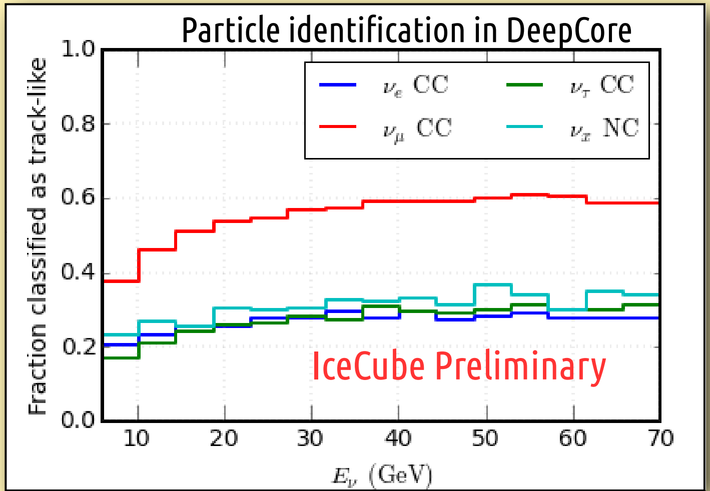
- IceCube DeepCore
  - More densely instrumented region at bottom centre of IceCube
  - Below 2100m, clearest ice
    - $\lambda_{att} \sim 50$m
    - radiopure
  - IceCube provides active downward-going muon veto

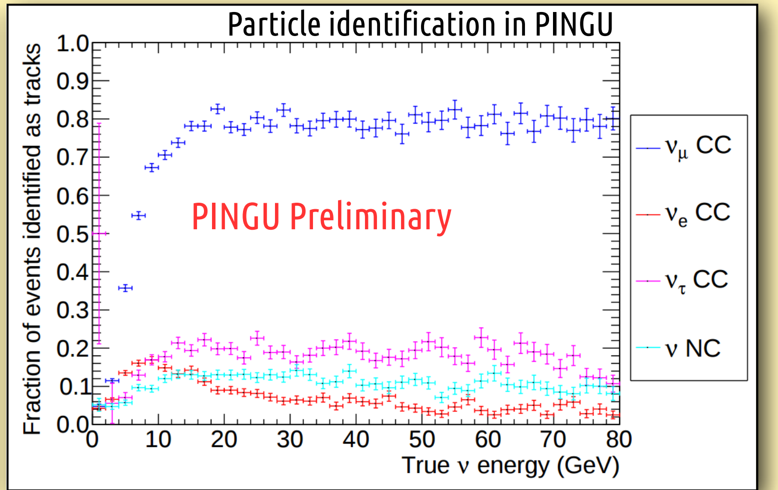


Reconstructions & Resolutions

- From the Cherenkov light pattern we can reconstruct each event's
  - direction,
  - energy, and
  - ~flavor



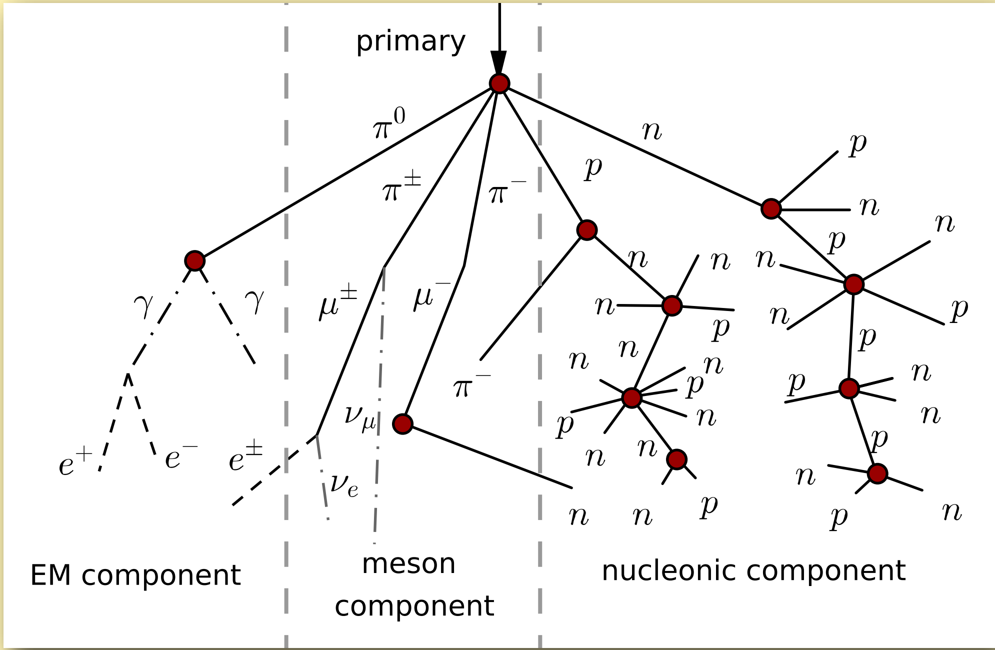




The Detectors The Source The Signature

Atmospheric Neutrinos

- Production mechanism
- Wide variety of energies and baselines
- Lots of possible oscillation signatures



J.P. Yanez, Thesis (DESY/Zeuthen)

$$p + N \rightarrow X + \pi^{\pm},\ K^{\pm}$$
$$\hookrightarrow\ \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\hookrightarrow\ e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}\,.$$

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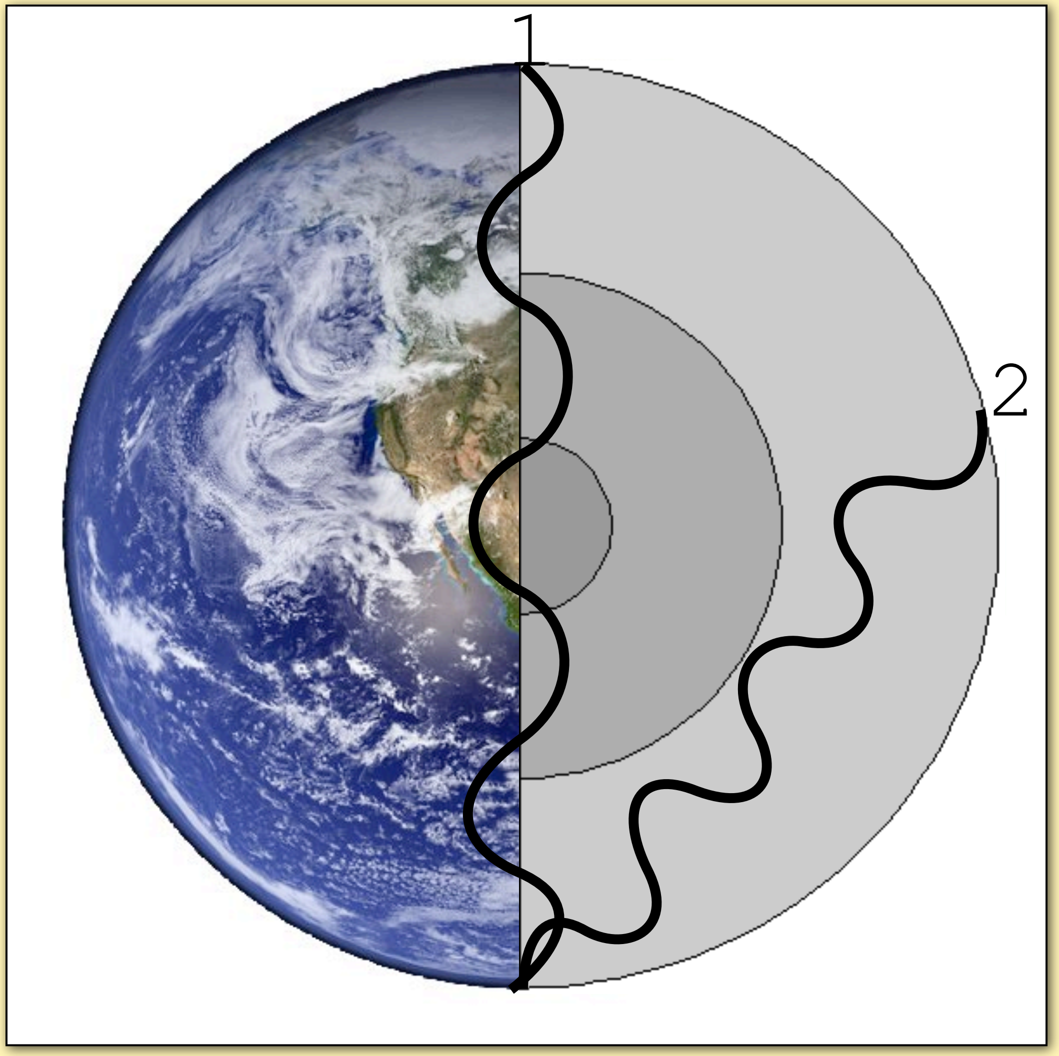
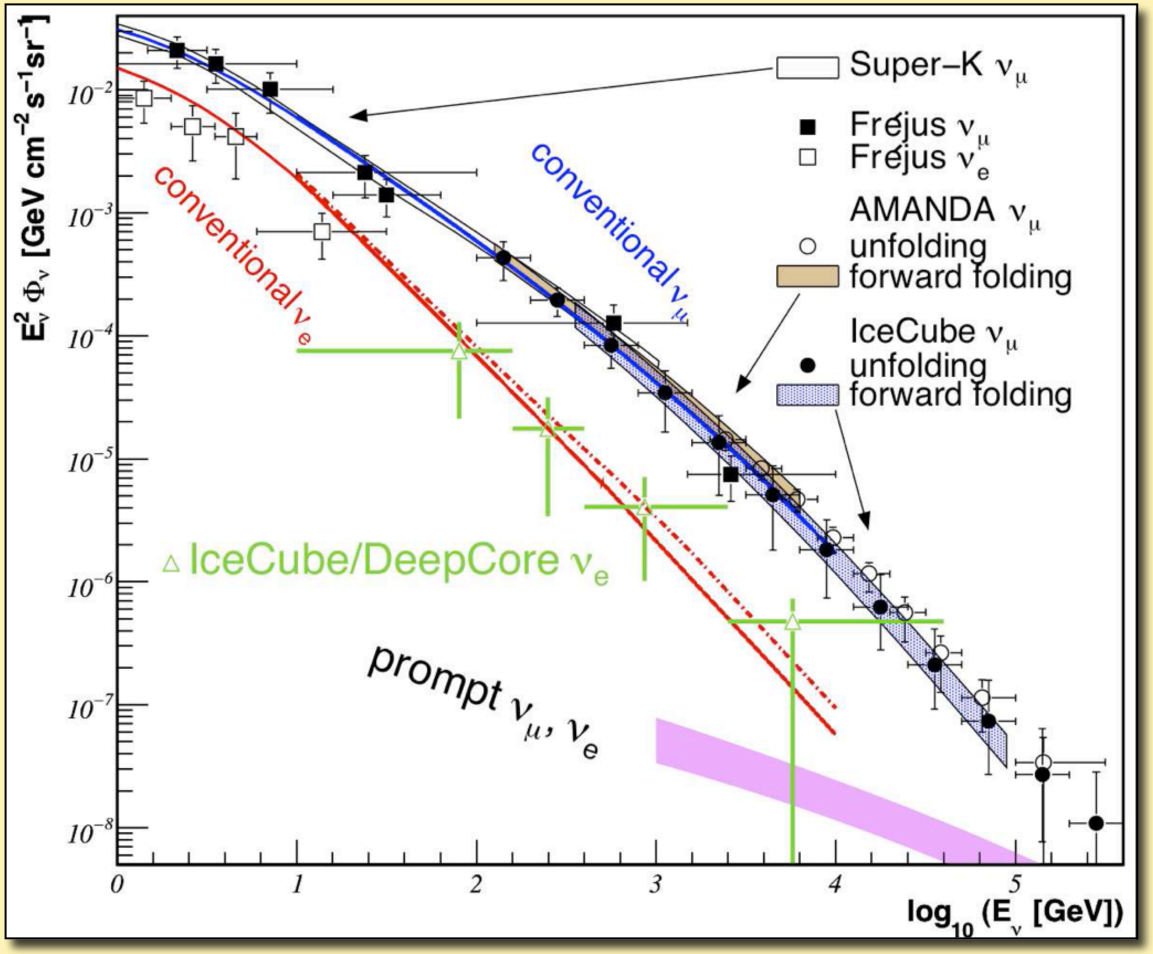


Atmospheric Neutrino Flux

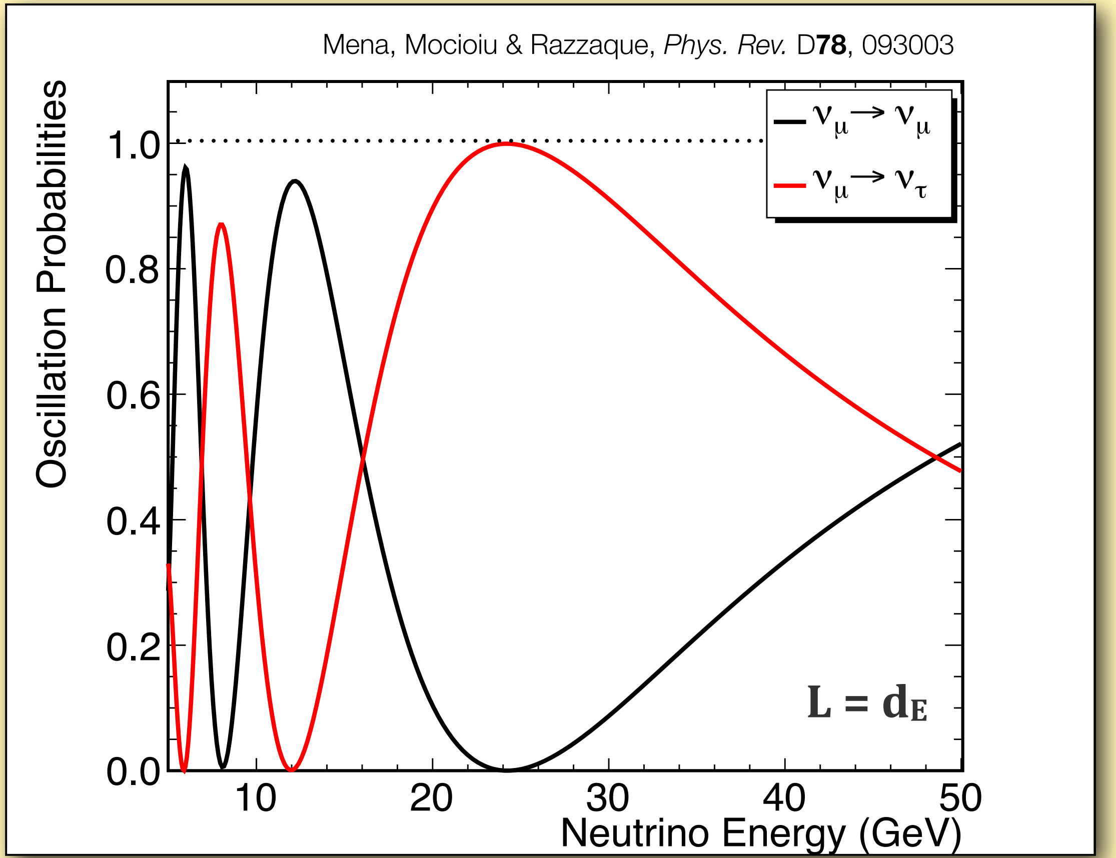
Atmospheric ν Energy Spectrum



IceCube and PINGU will each see tens of thousands of ν/yr

Atmospheric Neutrinos

- Production mechanism
- Wide variety of energies and baselines
- Lots of possible oscillation signatures



The Detectors The Source **The Signature**

- Simulated ν_μ CC event, E_ν = 9.3 GeV
  - 4.4 GeV initial cascade, 4.9 GeV muon
- Physics hits only (no noise)

DeepCore Only

The Detectors The Source The Signature

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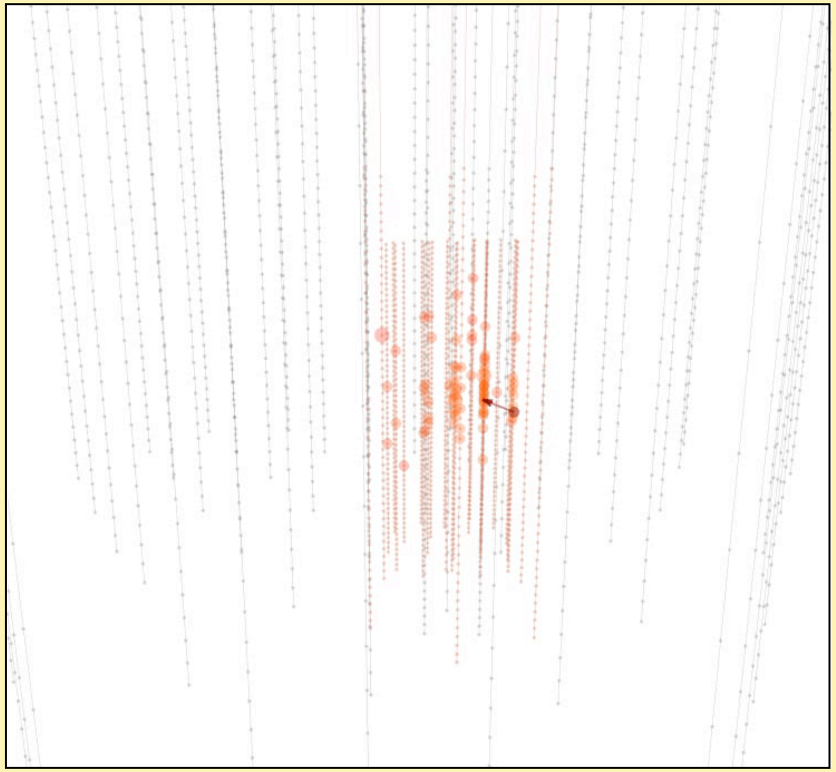
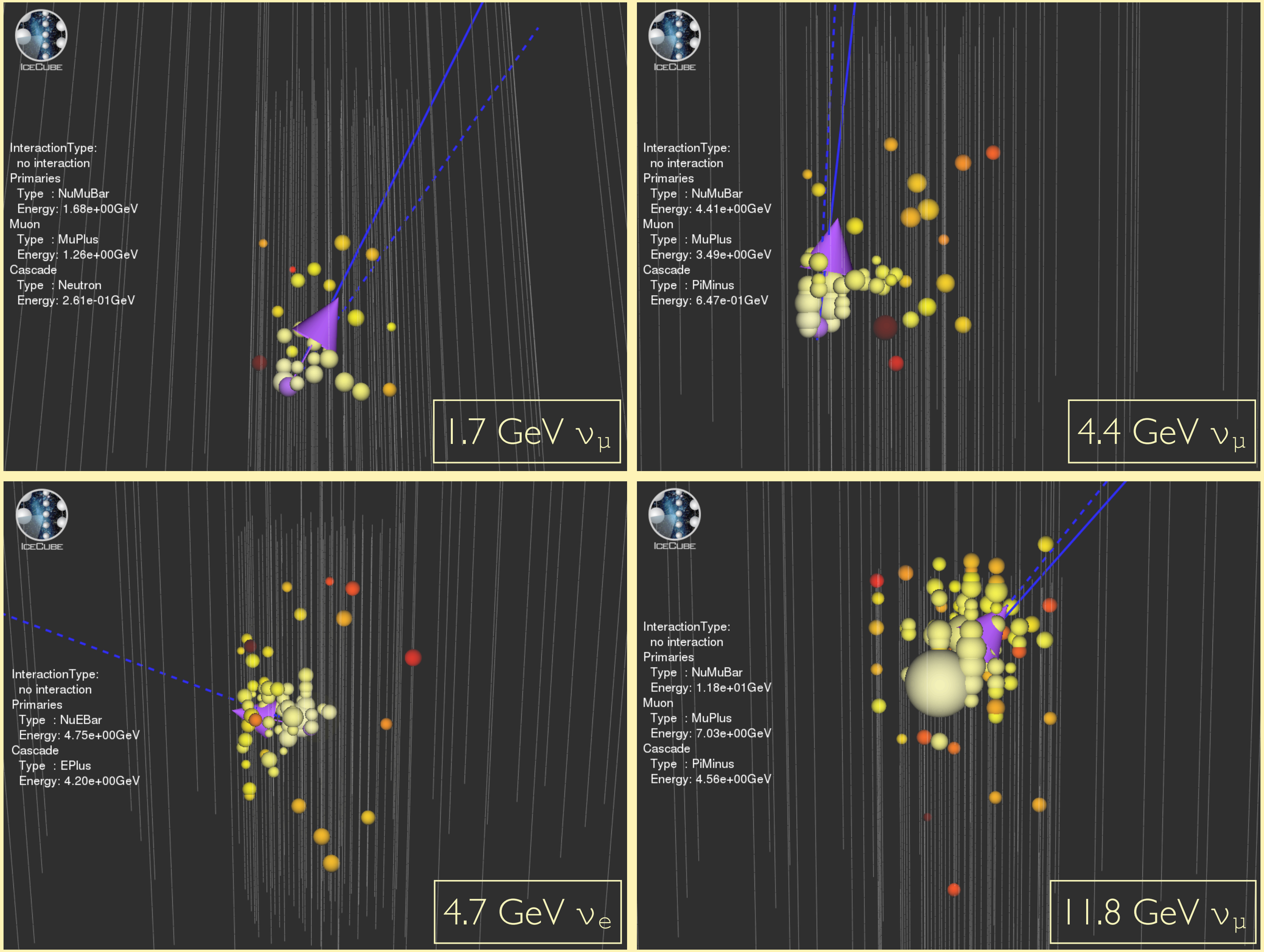
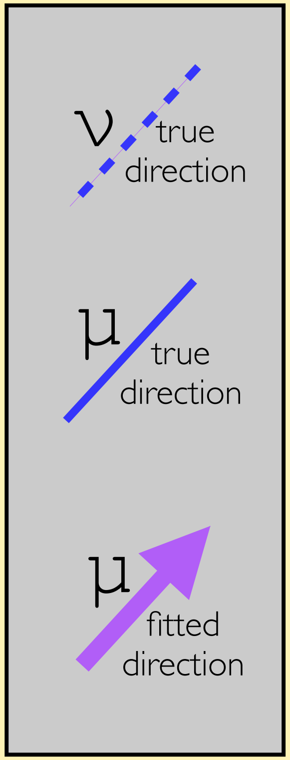
DeepCore Only



DeepCore + PINGU

The Detectors The Source The Signature

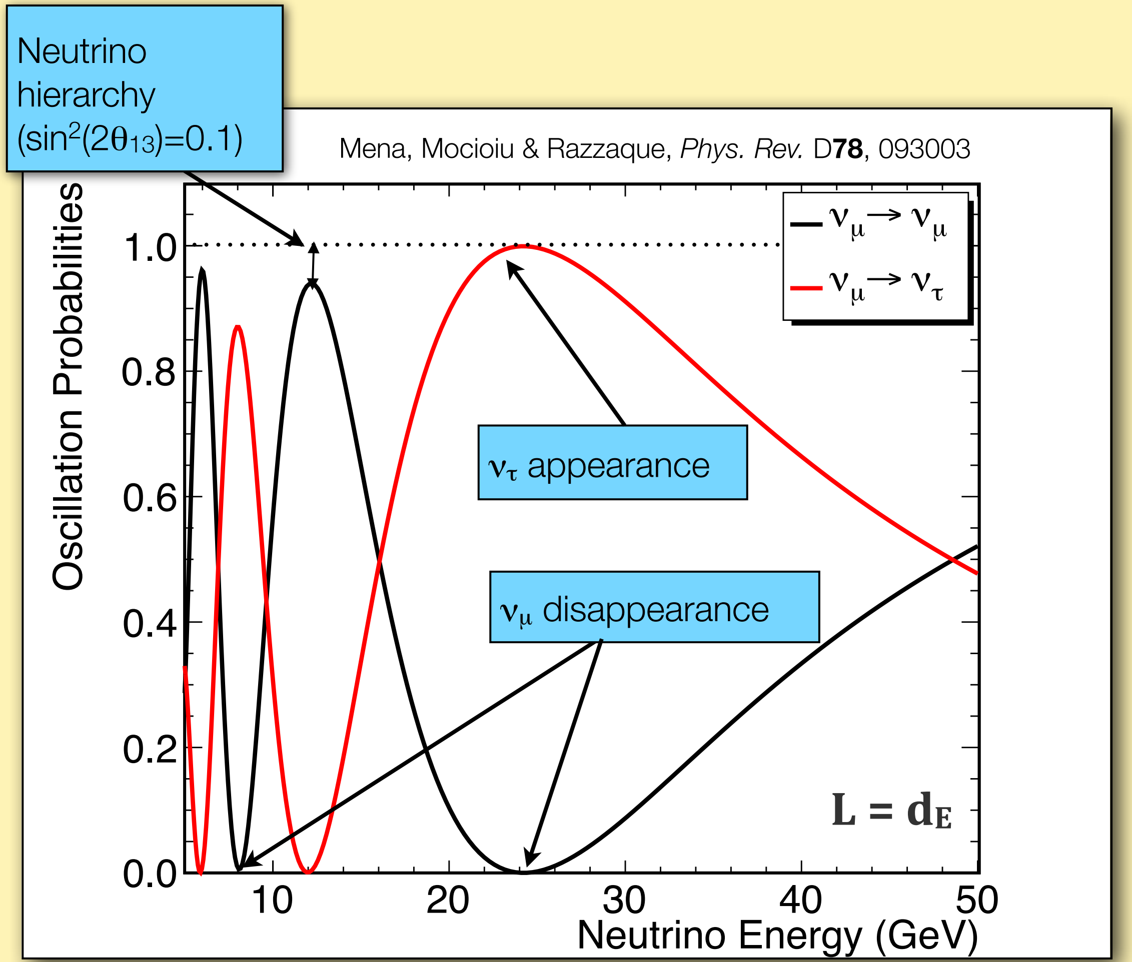




Size of circles: N_γ.
Color: t_γ.

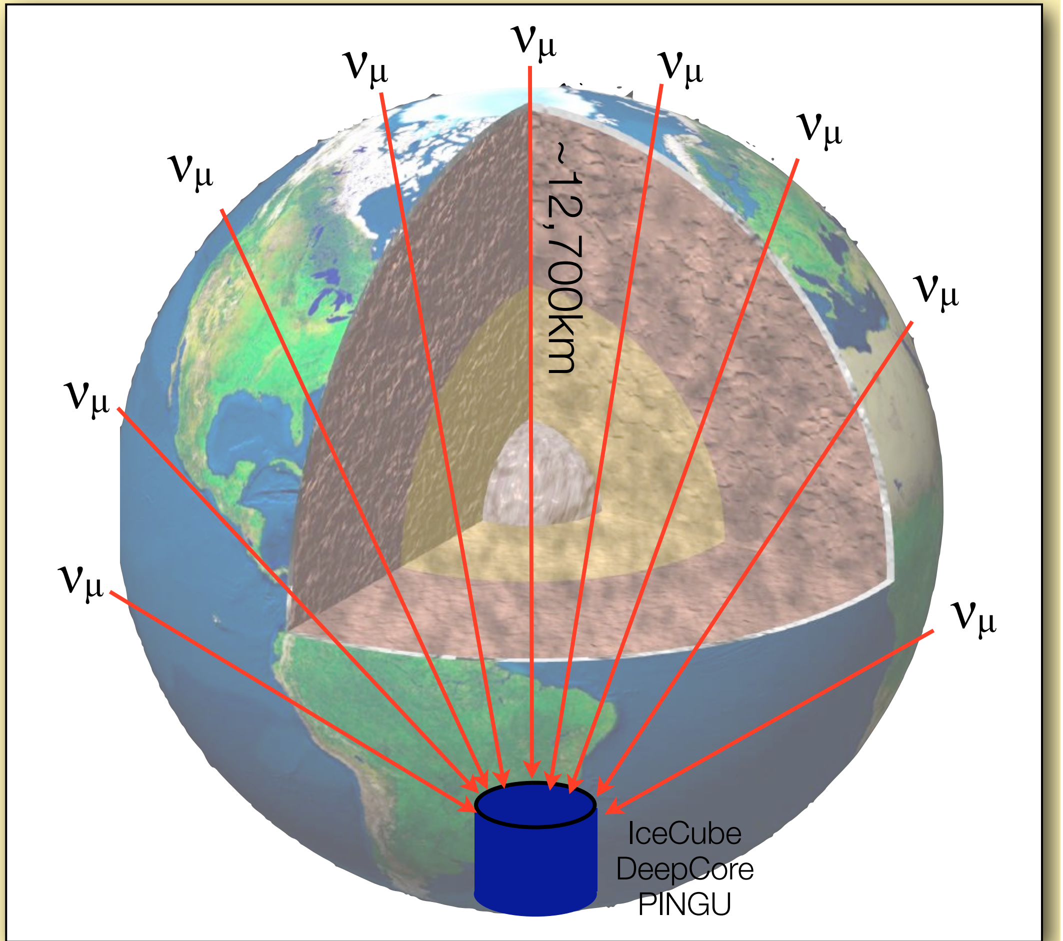
The Detectors The Source The Signature

- Using just ν–induced Cherenkov light, IceCube and PINGU can separate tracks from showers
  - tracks: ν_μ CC interactions with sufficiently energetic muon
  - showers: all other ν interactions
- Provides sensitivity to
  - ν_μ disappearance
  - ν_τ appearance
  - the neutrino mass hierarchy



Atmospheric Neutrino Oscillations

- Atmospheric neutrinos are observed over wide range of energies & pathlengths
  - oscillations produce distinctive pattern in (E_ν,cosθ) space
  - can combat systematics using events in “side band” regions where oscillations do not occur
- For reference:
  - at $L = d_E$, $P(\nu_\mu \to \nu_\mu) = 0$ at $E_\nu \sim 25$ GeV
  - see MSW and parametric oscillations below $E_\nu \sim 20$ GeV



IceCube/DeepCore ν_μ Disappearance

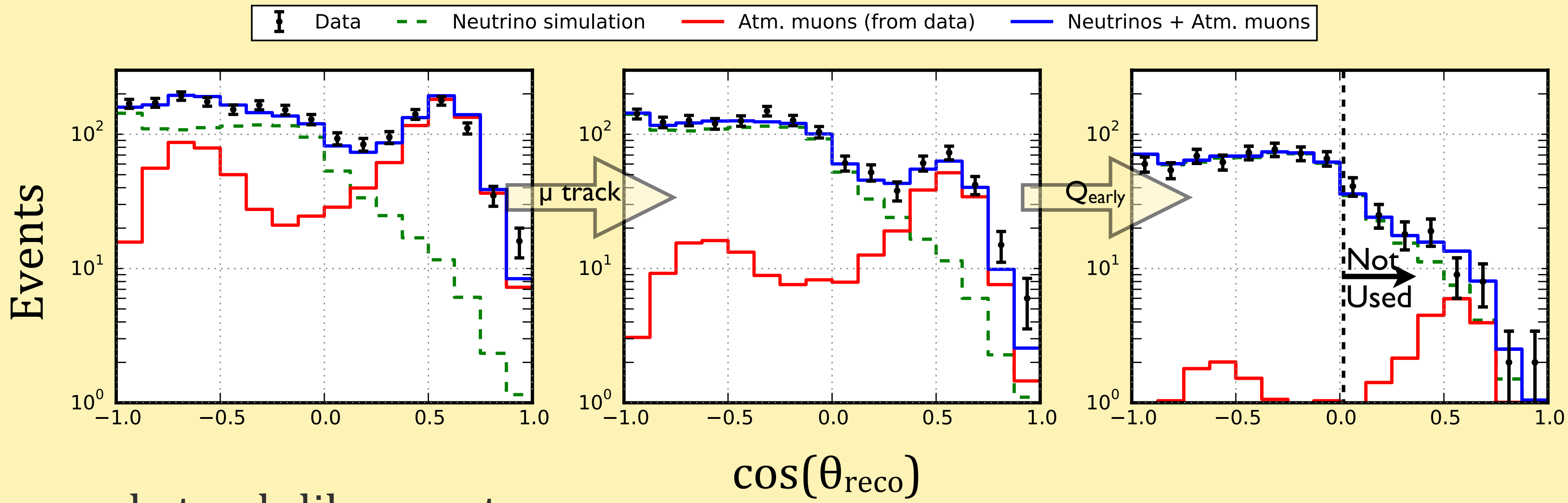
- IceCube has done three analyses so far (two published, third on the way)
  - PRL 111, 081801 (2013)
  - PRD 91, 072004 (2015)
- Differences mainly in sophistication of event reconstruction
- Focus here on the second published analysis and the third analysis in progress

IceCube/DeepCore ν_μ Disappearance

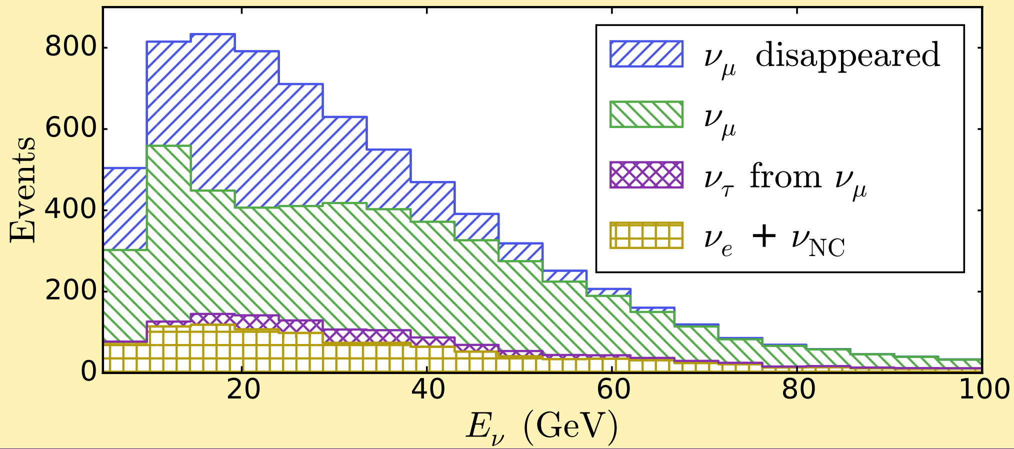
- Analysis steps
  - Reject downward going cosmic ray muon background
    - initially, ↓μ outnumber ν_μ(CC) by 10^5:1
    - use IceCube and outer layers of DeepCore to veto ↓μ
      - Achieve 1:1 with 40% signal retention
  - Require minimum number of "direct" (~unscattered) photons in each event to ensure good reconstruction

IceCube/DeepCore ν_μ Disappearance

- Analysis steps (continued)
  - Fit each event assuming a point-like or track-like hypothesis



  - Keep only track-like events
    - selection criteria keep only those ν_μ CC events with $L_\mu > \sim 20$m
  - Estimate event energy from shower at vertex and L_μ
    - Energy of remaining neutrinos from simulation:

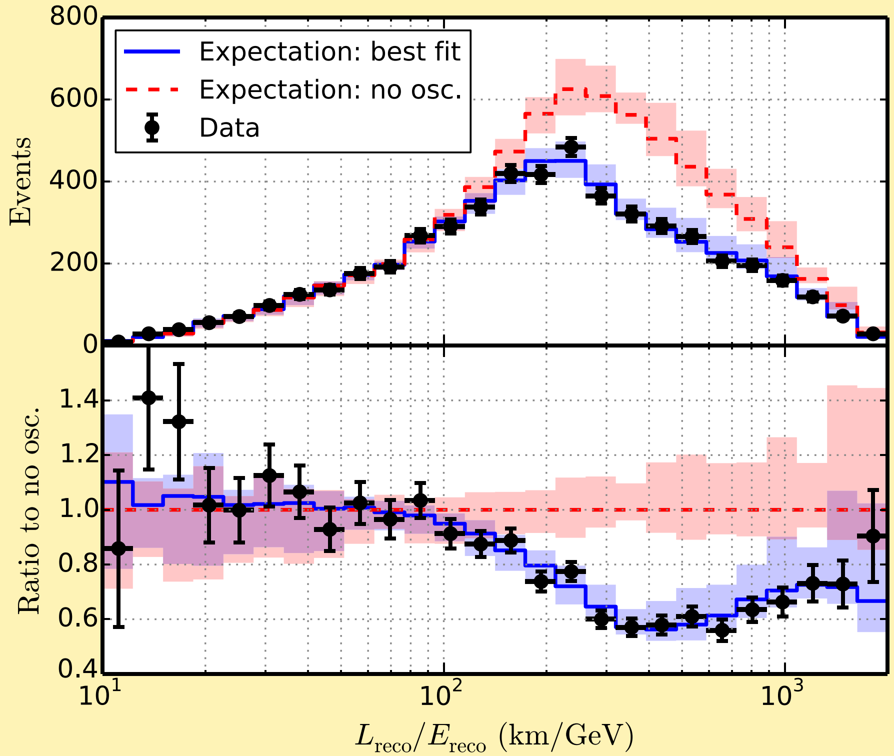


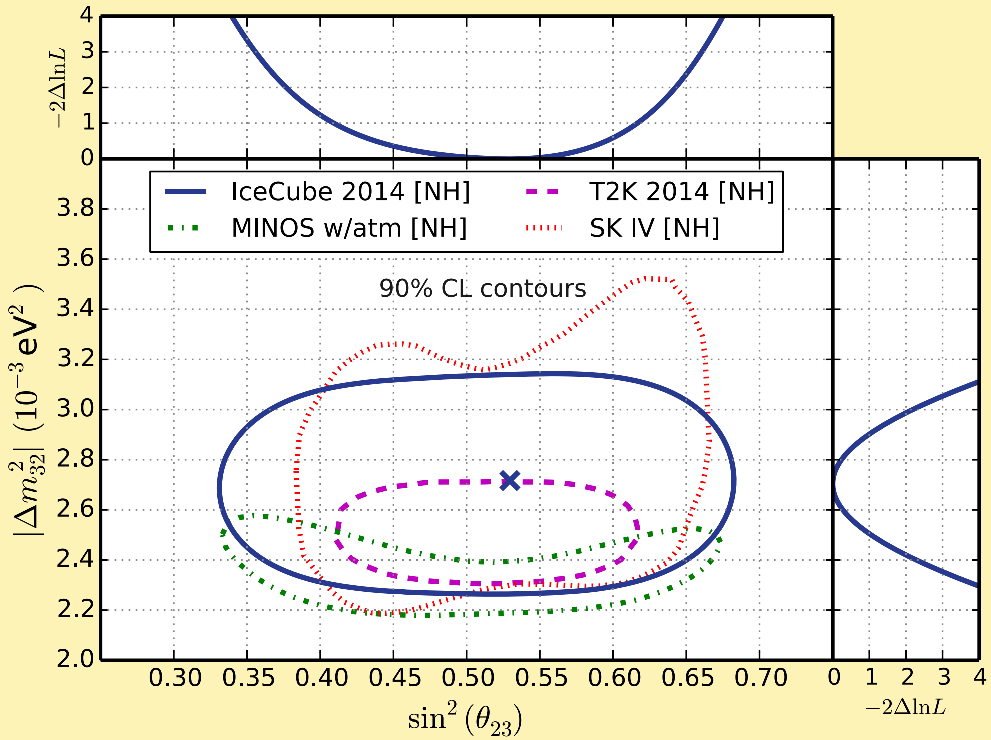
IceCube/DeepCore ν_μ Disappearance

- Fit for θ_{23} and $\Delta(m_{32})^2$ parameters
- Systematics
  - Φ_{atm} normalization, spectral index, ν_e/ν_μ ratio
  - cross section uncertainties (very modest effect)
  - detector uncertainties: DOM efficiency (impacts mass splitting) and ice properties (impact mixing angle)
    - These are the biggest systematic uncertainties
  - θ_{13} treated as nuisance parameter, other oscillation parameters fixed to world averages
- Results
  - Using 953 days of detector livetime, observed 5174 events
    - no oscillation expectation: 6830
    - overall signal efficiency, relative to initial sample of contained events, is ~3%
  - σ_{stat}, σ_{syst} comparable in magnitude; ~80% DIS; ~5% ↓μ;

IceCube/DeepCore ν_μ Disappearance

Final Result

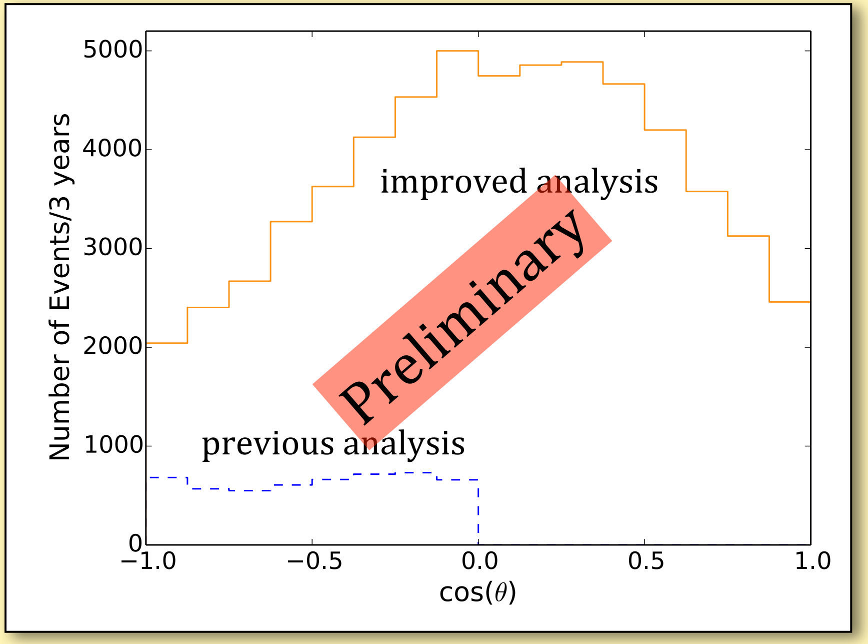


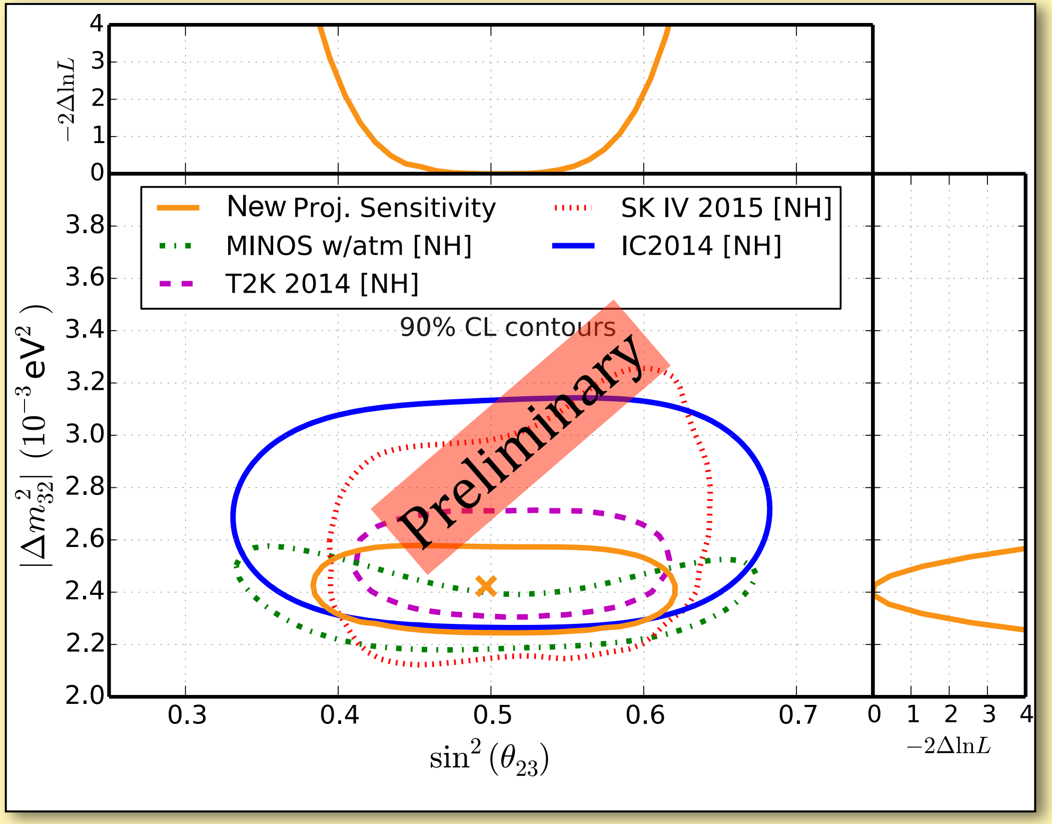


Precision comparable to world's best measurements!
Uses highest energy ν_{atm} sample ever.

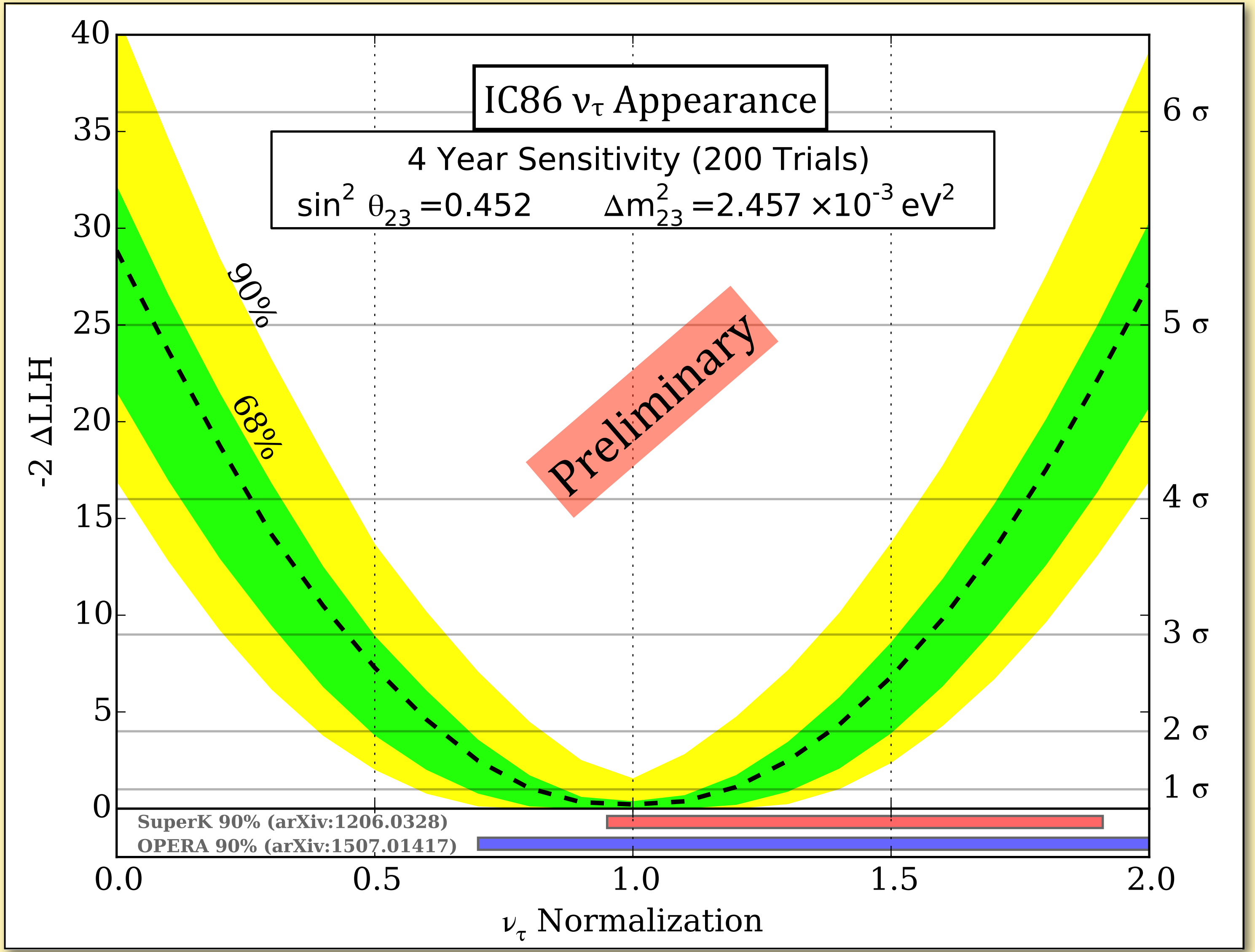
Underway: Third ν_μ Disappearance Analysis

- Employs improved reconstruction
  - better resolutions on angle, energy
  - ~7x better signal efficiency (~20%)





Near Future: ν_τ Appearance



Example: for a ν_τ flux that is 1.0x that which is expected from standard oscillations, DeepCore can exclude the no-ν_τ hypothesis (norm = 0.0) at the level of 4-6.5σ in 90% of the cases.

In the standard oscillation scenario, ν_τ norm = 1

PINGU

The Precision IceCube Next Generation Upgrade can do everything DeepCore can do, only better.

And it can do things IceCube/DeepCore cannot.

Terminology: PINGU is part of IceCube-Gen2, a proposed IceCube upgrade including an enlarged high energy in-ice array and more expansive surface veto, and possibly a radio array.

PINGU Physics Goals

- Neutrino oscillations
  - Neutrino mass hierarchy
  - Muon neutrino disappearance
  - Tau neutrino appearance
- WIMP dark matter
- Earth tomography
- Supernovae
- Low E_ν point sources,...

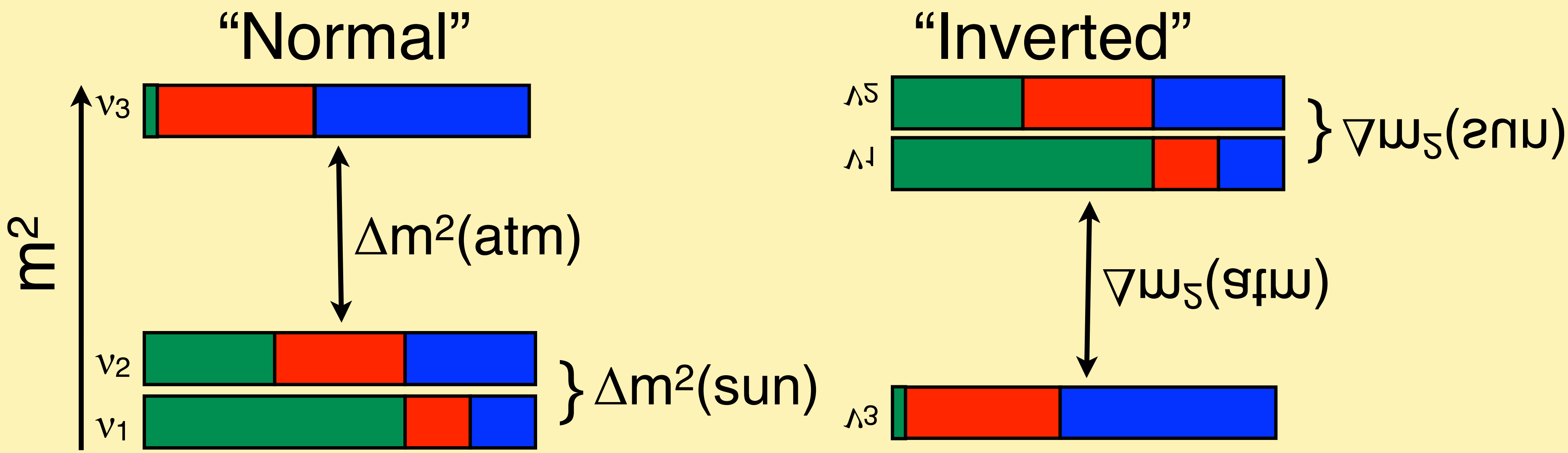
PINGU Physics Goals

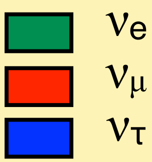
- Neutrino oscillations
  - Neutrino mass hierarchy
  - Muon neutrino disappearance
  - Tau neutrino appearance

  Highly competitive with accelerator & reactor experiments.
- WIMP dark matter — Reaches very low m(χ).
- Earth tomography — Unique measurement.
- Supernovae — New sensitivity to E(ν).
- Low E_ν point sources,...

The Neutrino Mass Hierarchy

One of the few remaining unmeasured fundamental parameters in particle physics





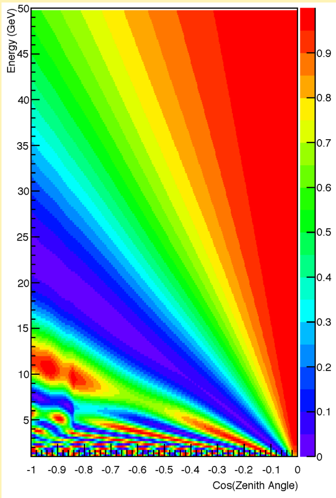
...PINGU can exploit matter effects at E_ν ~ 5-15 GeV to distinguish

Semi-Useful Factoid: The total mass in neutrinos in the universe differs in these two cases by about the mass of our galaxy: $M_{\nu,tot}(IH) - M_{\nu,tot}(NH) \sim M(MilkyWay)$

The NMH Signature in PINGU

ν_μ anti-ν_μ

Normal Hierarchy



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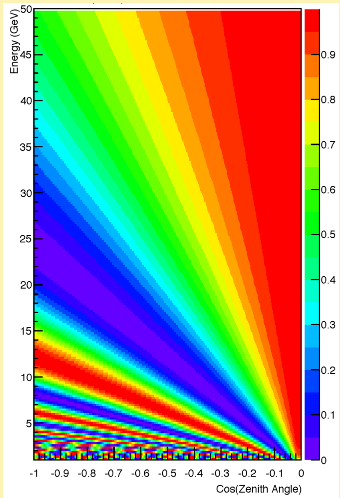
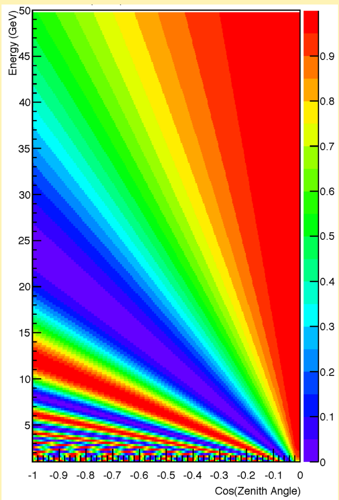


= [pattern A]

Energy

Measurement looks for difference between patterns A & B

Inverted Hierarchy



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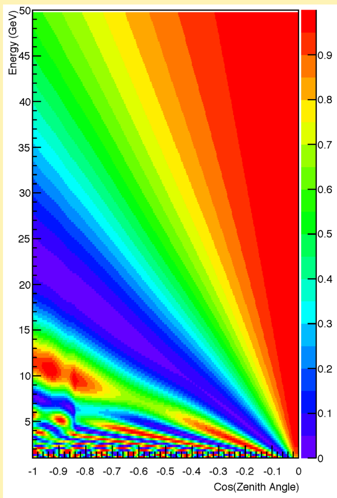


= [pattern B]

A. Gross

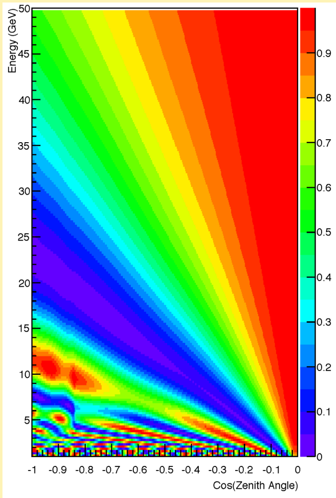
cos(θ)

Without ability to distinguish ν_μ from anti-ν_μ, A = B.

The NMH Signature in PINGU

ν_μ | anti-ν_μ

Normal Hierarchy



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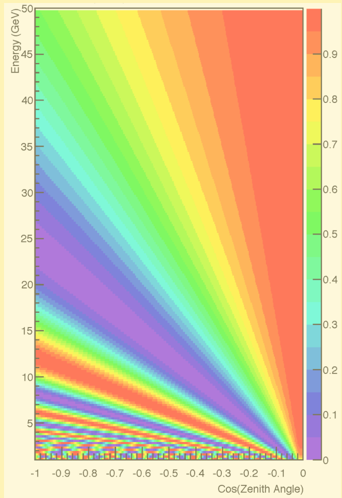
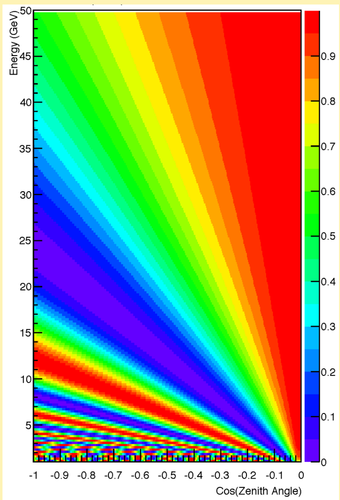


= [pattern A]

Energy

Inverted Hierarchy



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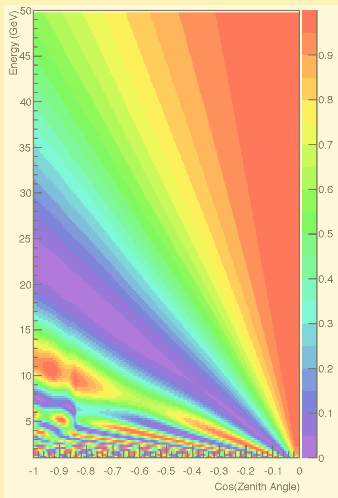


A. Gross

= [pattern B]

cos(θ)

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

Now A≠B!

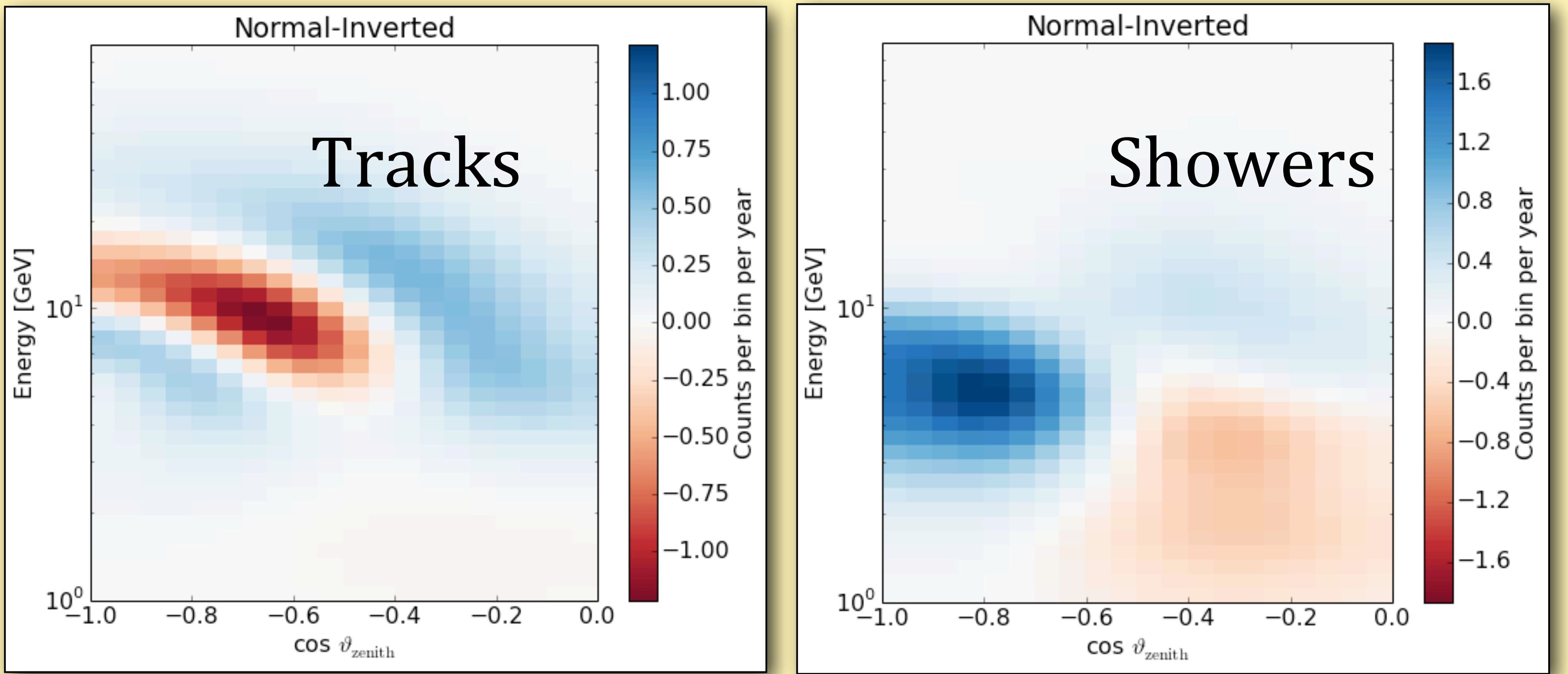
The NMH Signature in PINGU

- Our MC-based analysis is mature. Many challenges have been overcome:
  - Fully simulated event selection & reconstruction
    - Reconstruction required new IceCube approach for contained events
    - Reconstruction also required new optimizer and lots of CPU
  - Particle ID (PID)
    - Required new IceCube approach for low E_ν events
  - Long list of systematic errors (more details later)
    - Required new interfaces with code e.g. GENIE, exhaustive exploration of flux and cross section parameters, non-trivial adaptation of systematics space optimizer, large simulated datasets,...
  - Multiple statistical approaches in good agreement
    - Development of several new IceCube techniques and codes, adaptation of external (SK) code to run on GPUs,...

Visualizing the NMH Signature

- Expect ~50k $\nu_\mu+\nu_\mu$, ~40k $\nu_e+\nu_e$/yr: *Largest ever sample in this E range*
- ~25% energy resolution, ~15^o directional resolution
- PID with 90% purity for tracks above ~10GeV
- Plots of (NH–IH) show distinctive patterns in (E, cosθ) space:

E (GeV)



$\cos(\theta_{zen})$

Predicted NMH Sensitivity

- Results from log-likelihood ratio (LLR) and faster χ^2–pull approaches agree well
- Large list of systematics incorporated from
  - Oscillation parameter uncertainties
  - Flux and interaction uncertainties
  - Detector uncertainties

PINGU Systematic Errors

Systematic Parameters

- Oscillation parameters (from nu-fit.org [1]):
  - **Δm^2_{31}** (NH/IH) = 0.00246 / -0.00237 eV [2] (no prior)
  - **θ_{23}** (NH/IH) = 42.3° / 49.5° (no prior)
  - **θ_{13}** = 8.5° ± 0.2°
- Detector/flux/cross sections:
  - **event rate** (effective area, flux normalization) = nominal (no prior)
  - **energy scale** = nominal ± 0.10 (from current calibration data)
  - **ν_e/ν_μ ratio** = nominal ± 0.03 (ref [2])
  - **ν/anti-ν ratio** = nominal ± 0.10 (ref [2] and [3])
  - **atmospheric spectral index**: nominal ± 0.05 (ref [2])
  - Also studied separately:
    - detailed cross section systematics based on GENIE [3] parameters
    - detailed atmospheric flux uncertainties from [2]

[1] M.C. Gonzalez-Garcia, et al. *JHEP* **11** 052, 2014
[2] G.D. Barr, T.K. Gaisser, et. al. *Phys. Rev. D* **74** 094009, (2006)
[3] C.Andreopoulos et al., *Nucl.Instrum.Meth. A* **614**:87-104 (2010)

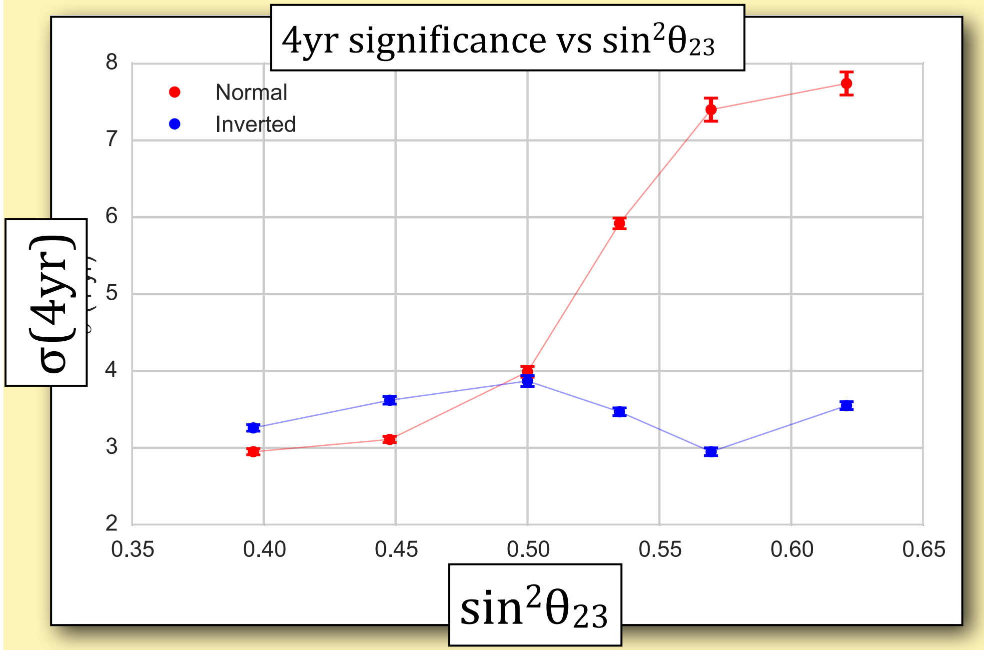
Systematics Impacts (4yr significances)

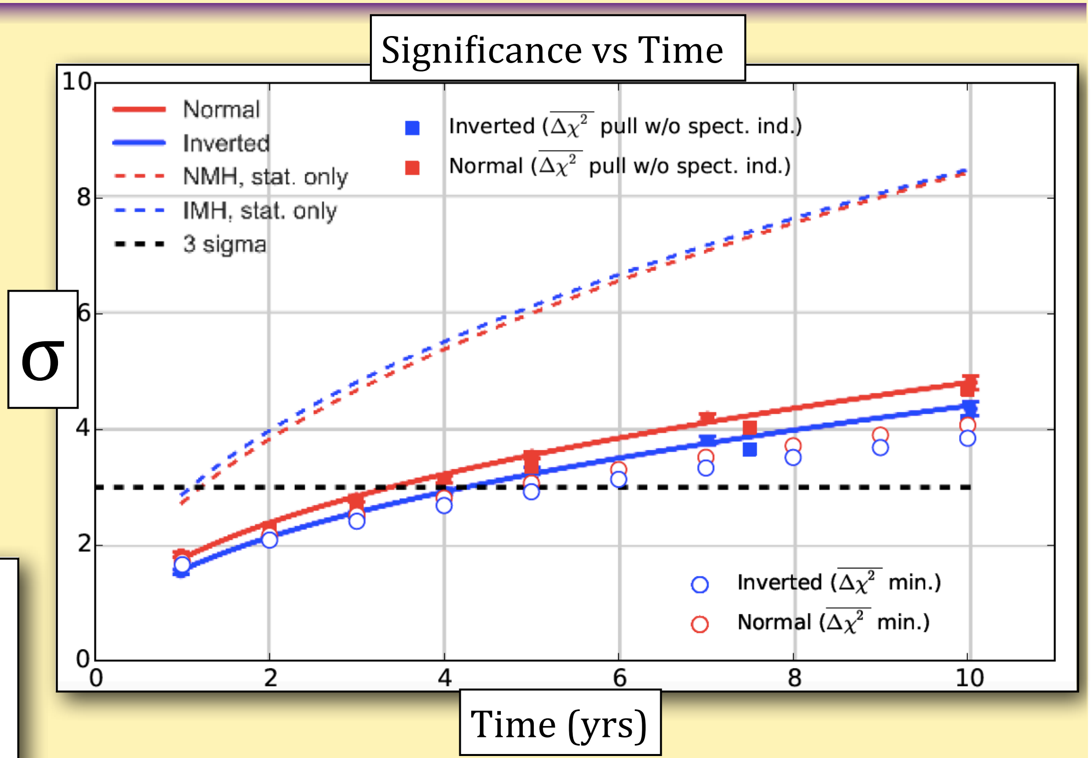
Syst.	NH	IH
None	5.4σ	5.5σ
Osc. only	3.4σ	2.9σ
Flux only	4.3σ	4.6σ
Det. only	4.4σ	4.6σ
All	**3.1σ**	**2.9σ**

Predicted NMH Sensitivity

Predict 3σ significance in 3.5-4yrs of live time (@NuFit 2014 values).

(Shorter if include data from ~10 yrs DeepCore + partially deployed PINGU.)





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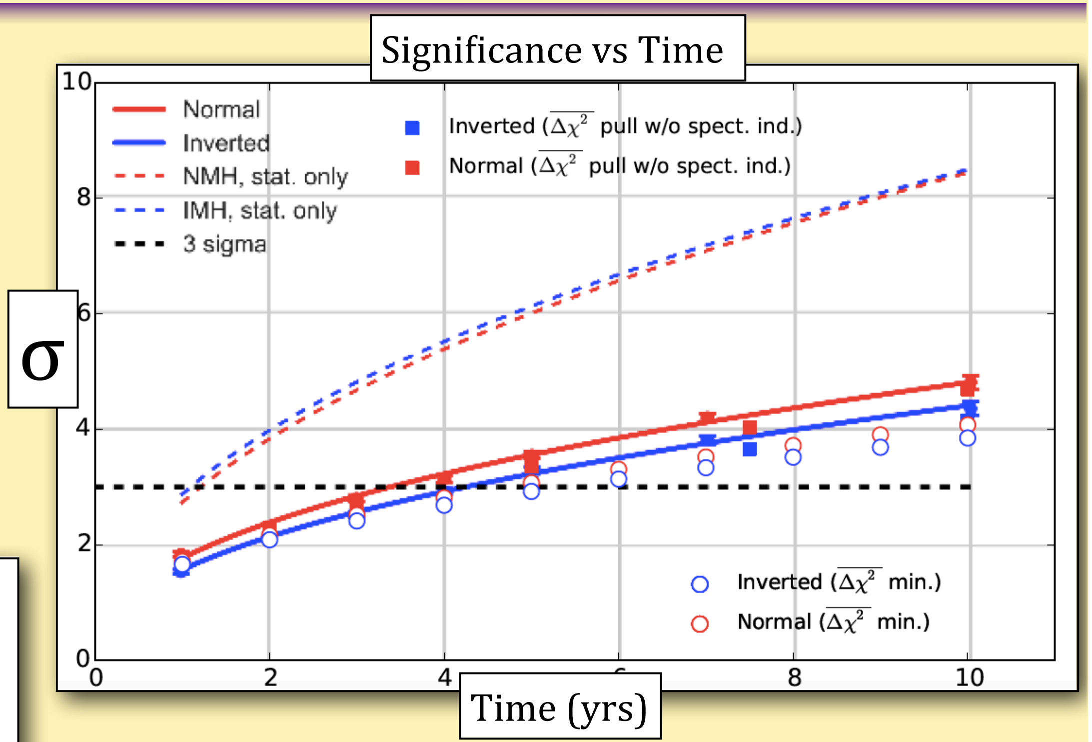
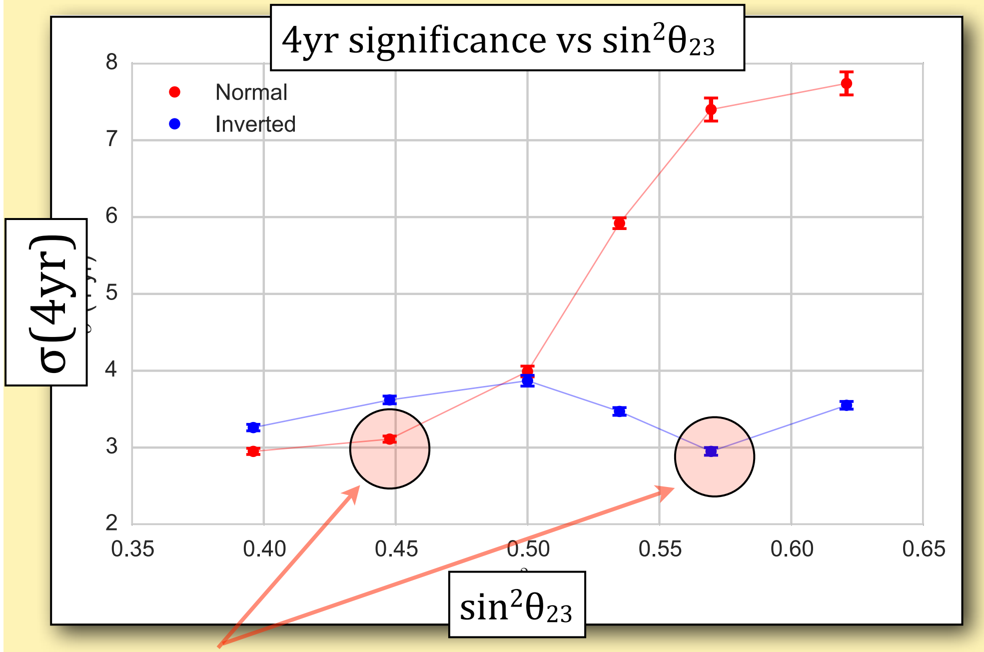
(Shorter if include data from ~10 yrs DeepCore + partially deployed PINGU.)





NuFit 2014 values: ~most conservative!

Predicted NMH Sensitivity

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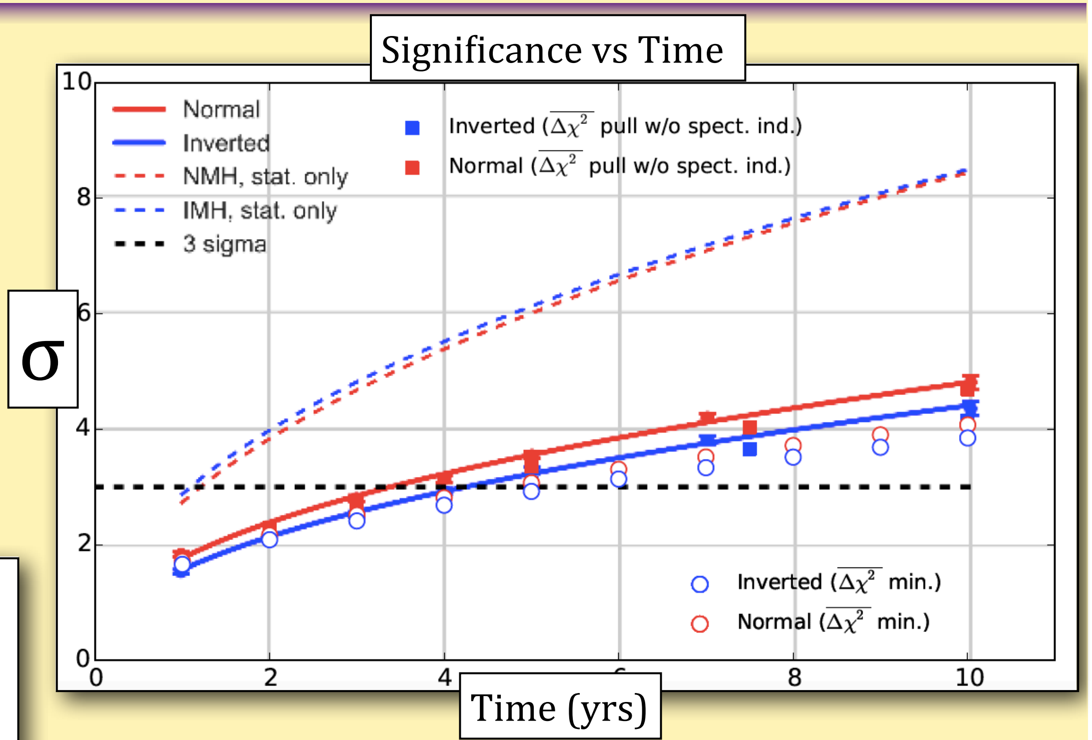
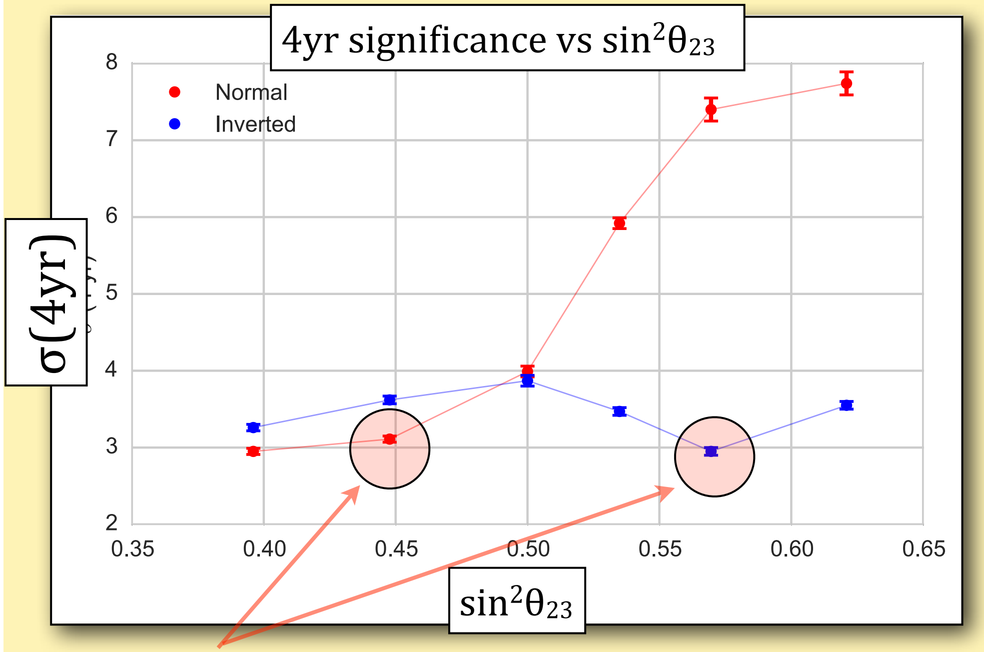
(Shorter if include data from ~10 yrs DeepCore + partially deployed PINGU.)

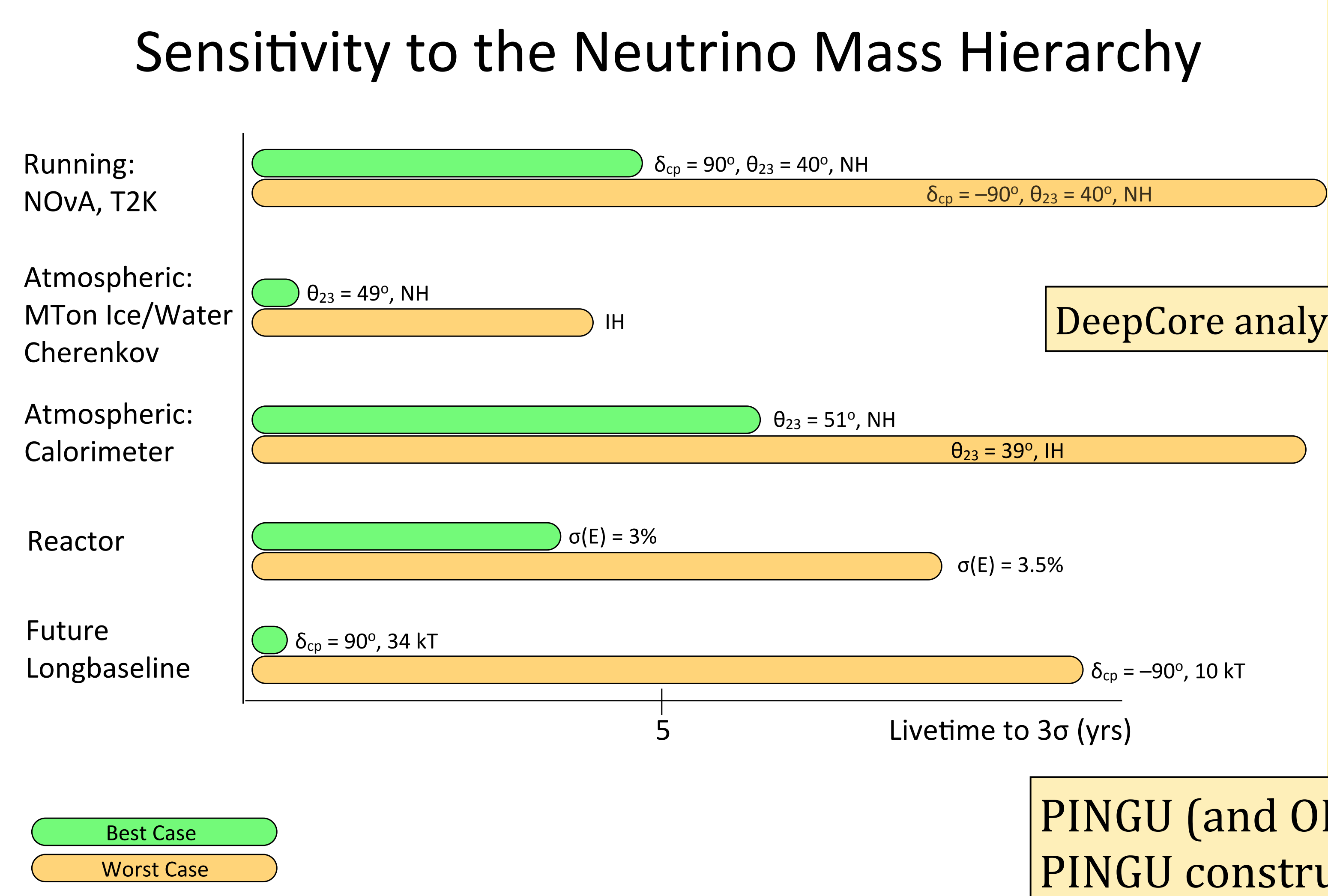




We are currently doing a "dry run" NMH analysis with DeepCore. Expect ~1σ significance.

NuFit 2014 values: ~most conservative!

Global Context



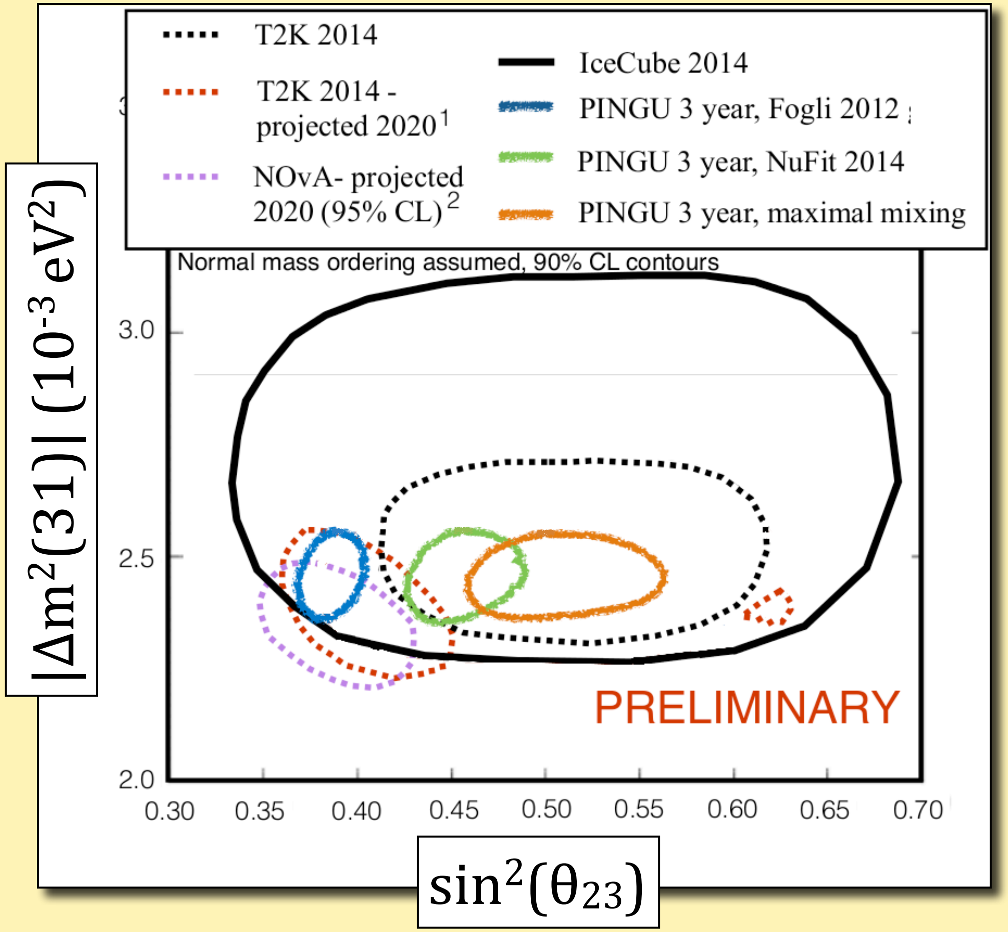
Sources: arXiv:1311.1822, arXiv:1401.2046v1, arXiv:1406.3689v1, Neutrino 2014, LBNE-doc-8087-v10

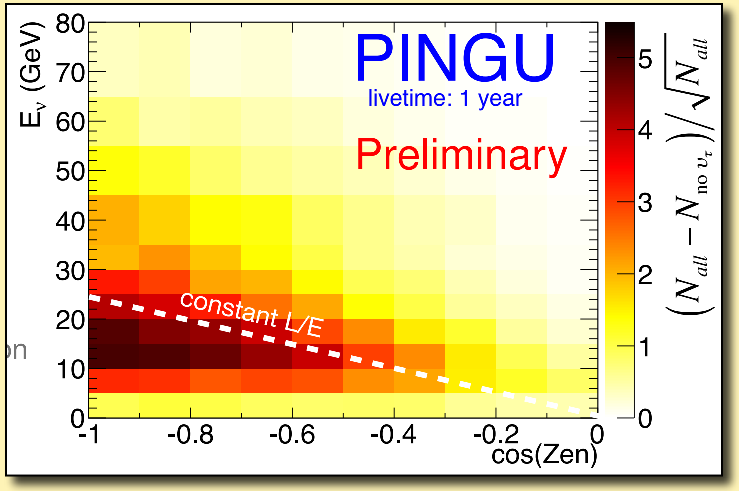
DeepCore analyses: underway

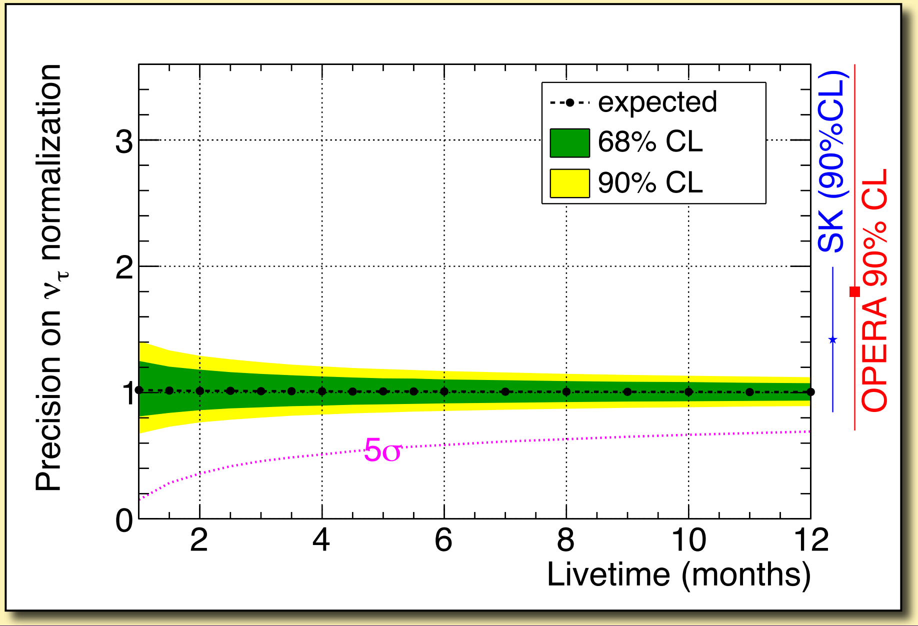
PINGU (and ORCA) are low cost. PINGU construction is low risk and fast. NMH measurement very competitive.

PINGU ν_{atm} Oscillation Physics

World-class measurements of atmospheric ν mixing parameters via ν_μ disappearance and ν_τ appearance

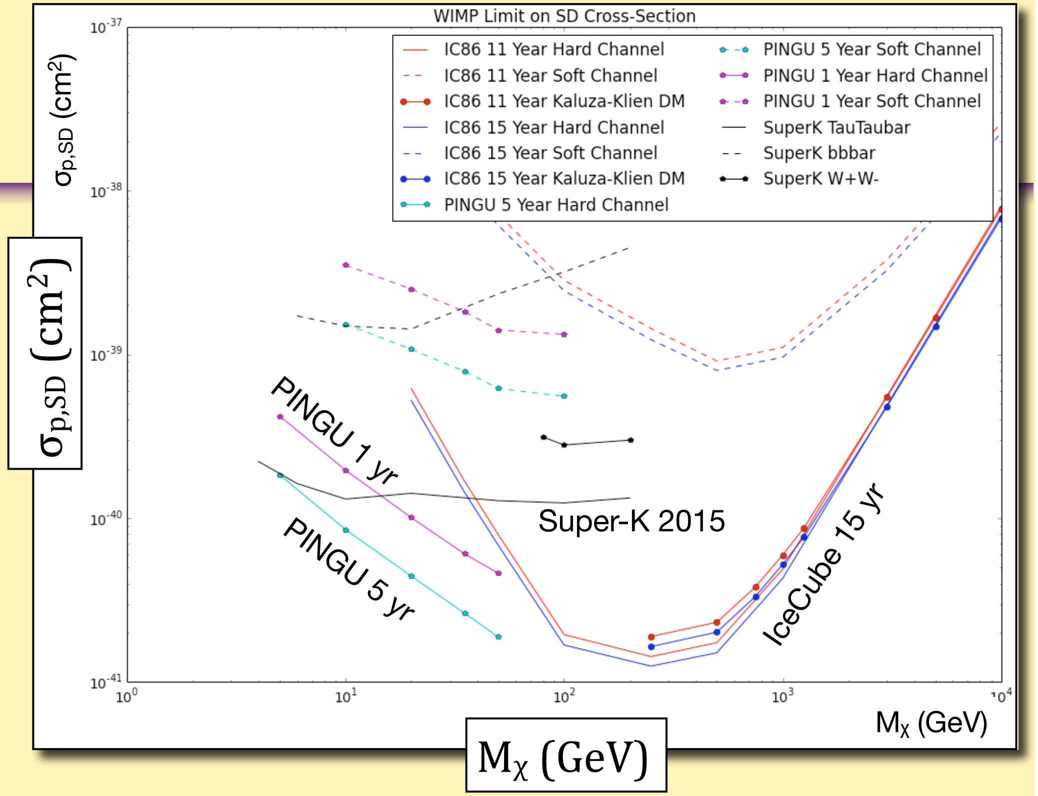


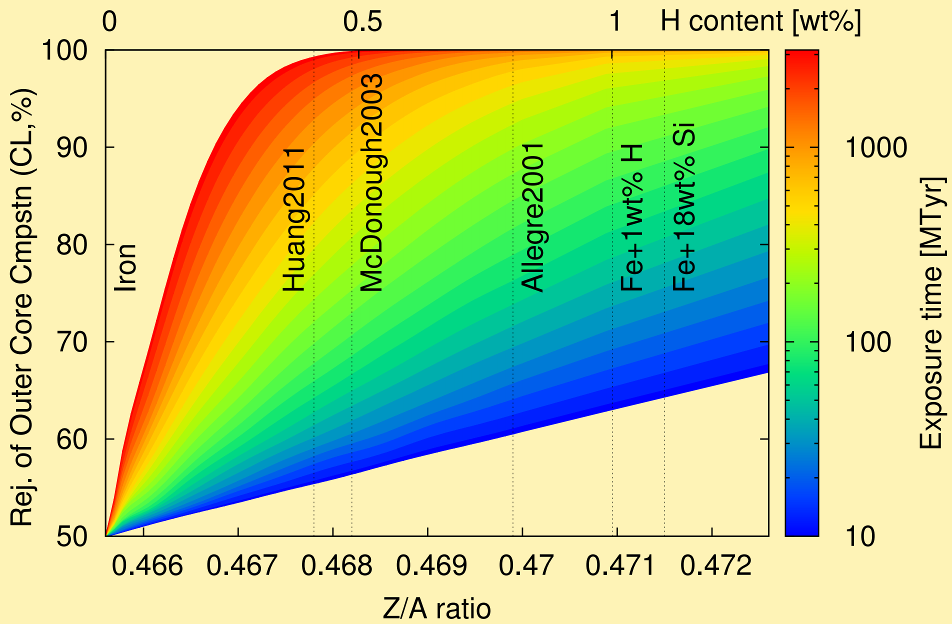




DM, Tomo., SNe

- Solar WIMP dark matter searches would be competitive with Super-K down to 5GeV
- Earth tomography
  - Requires many MT·yrs of data, but unique capability
- Supernova detection would benefit from closer DOM spacing
  - gain measurement of energy spectrum





UK Involvement in Gen2

- Oxford University
  - Subir Sarkar
  - Full membership
    - Theoretical aspects of high energy neutrino interactions
- University of Manchester
  - Justin Evans, Stefan Soldner-Rembold, Steven Wren (grad. student)
  - Associate membership
    - Analyze DeepCore data for NMH
    - Contribute to aspects of Gen2 DAQ firmware development
    - Co-chair PINGU analysis working group
- Queen Mary University London
  - Teppei Katori, Shivesh Mandalia (grad. student)
  - Associate membership
    - Differential cross section analysis
    - PINGU software, Gen2 PMT and DOM noise studies and modeling


The IceCube–PINGU Collaboration
University of Alberta–Edmonton (Canada)
University of Toronto (Canada)
Clark Atlanta University (USA)
Drexel University (USA)
Georgia Institute of Technology (USA)
Lawrence Berkeley National Laboratory (USA)
Massachusetts Institute of Technology (USA)
Michigan State University (USA)
Ohio State University (USA)
Pennsylvania State University (USA)
South Dakota School of Mines & Technology (USA)
Southern University and A&M College (USA)
Stony Brook University (USA)
University of Alabama (USA)
University of Alaska Anchorage (USA)
University of California, Berkeley (USA)
University of California, Irvine (USA)
University of Delaware (USA)
University of Kansas (USA)
University of Maryland (USA)
University of Wisconsin–Madison (USA)
University of Wisconsin–River Falls (USA)
Yale University (USA)
Stockholms universitet (Sweden)
Uppsala universitet (Sweden)
Niels Bohr Institutet (Denmark)
Queen Mary University of London (UK)
University of Oxford (UK)
University of Manchester (UK)
Université de Genève (Switzerland)
Université libre de Bruxelles (Belgium)
Université de Mons (Belgium)
Universiteit Gent (Belgium)
Vrije Universiteit Brussel (Belgium)
Deutsches Elektronen–Synchrotron (Germany)
Friedrich–Alexander–Universität Erlangen–Nürnberg (Germany)
Humboldt–Universität zu Berlin (Germany)
Max–Planck–Institut für Physik (Germany)
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RWTH Aachen (Germany)
Technische Universität München (Germany)
Technische Universität Dortmund (Germany)
Universität Mainz (Germany)
Universität Wuppertal (Germany)
Sungkyunkwan University (South Korea)
Chiba University (Japan)
University of Tokyo (Japan)
University of Adelaide (Australia)
University of Canterbury (New Zealand)
12 Countries
45 Institutions
260 Scientists
International Funding Agencies
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Conclusions

- DeepCore has produced neutrino oscillation results that are highly competitive on the world stage
  - Even better results are in the pipeline
- The PINGU physics case is compelling
  - The neutrino mass hierarchy is a fundamental parameter
    - The PINGU NMH significance has been very robust
  - Capable of numerous other high-profile, very competitive measurements
- Community interest in PINGU is strong and growing
  - Endorsed by high-profile "P5" panel in the US
  - PINGU LoI(v1) has 65 total citations (19 in refereed journals)
    - LoI(v2) in the works
  - So far this year there have been PINGU talks at ~10 conferences
- If you're interested in joining Gen2, let me know!

Backup

DeepCore ν_μ Disappearance Systematics

Reduction in uncertainty with parameter fixed:

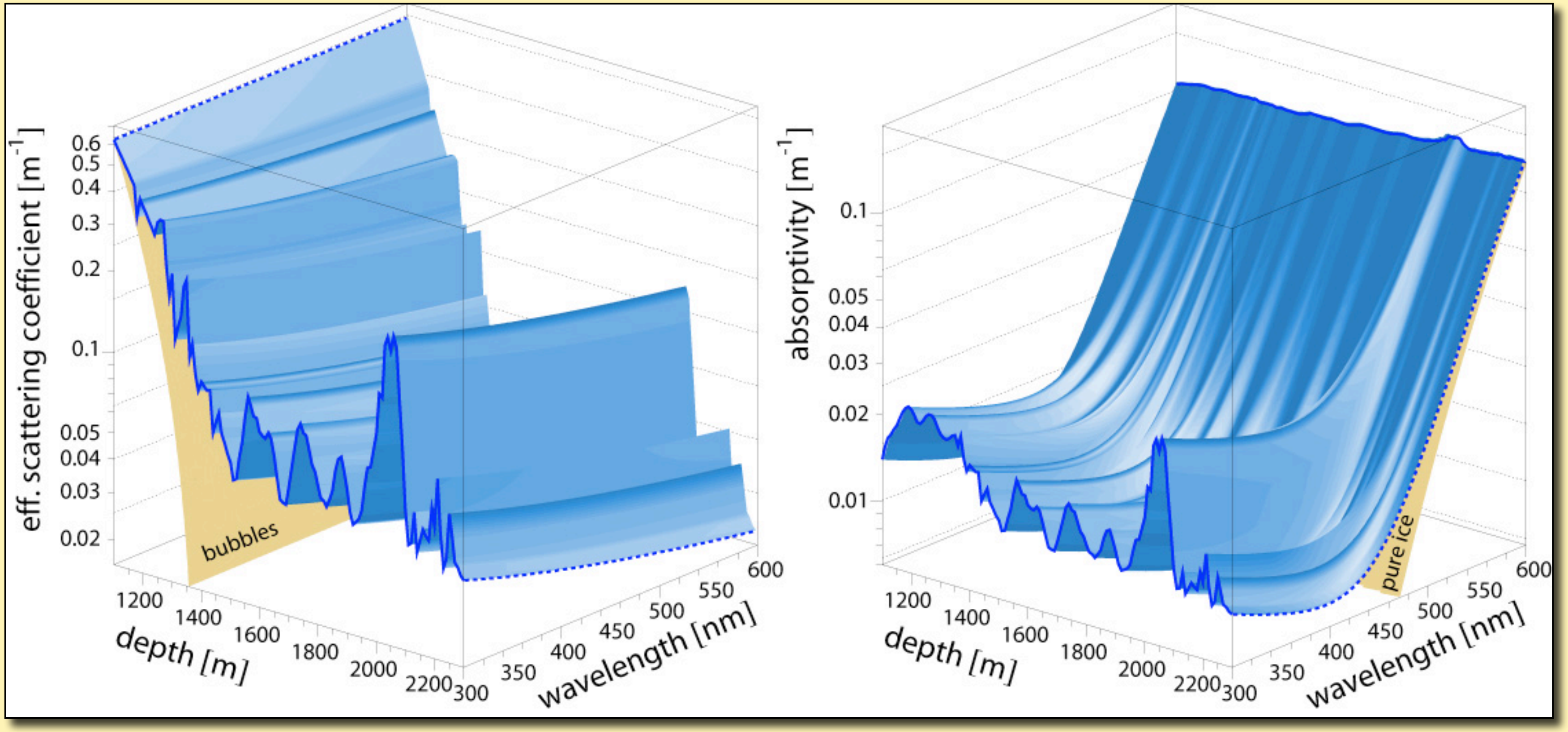
	$\sin^2(\theta_{23})$	$(\Delta m_{31})(10^3\ eV^2)$
PRD Errors	0.10	0.20
Hole Ice	29.9%	2.3%
DOM Efficiency	0.73%	19.1%
Spectral index γ	0.13%	8.7%
$[\Phi(\nu_e)/\Phi(\nu_\mu)]_{atm}$	0.05%	0.94%
Atm. μ bkgd.	0.00%	0.72%

Calibration of DeepCore

- Ice properties are calibrated with a variety of light sources
  - "dust logger" run down through select holes
  - *in situ* LED light sources on each DOM
    - 12 independent LEDs (6 horizontal, 6 at 45^o)
  - *in situ* lasers
- Downward-going muons calibrate directionality and DOM efficiency
- Moon shadow calibrates directionality

Calibration: Ice Properties

- Depth dependence of λ_{eff} and λ_{abs} from in situ LEDs
- Ice below ~2100 m in DeepCore and PINGU fiducial regions is very clear (λ_{eff} ~ 50 m and λ_{abs} ~ 150 m)
- Constant temperature ~ 30C



PINGU Calibration

Numerous devices under study:

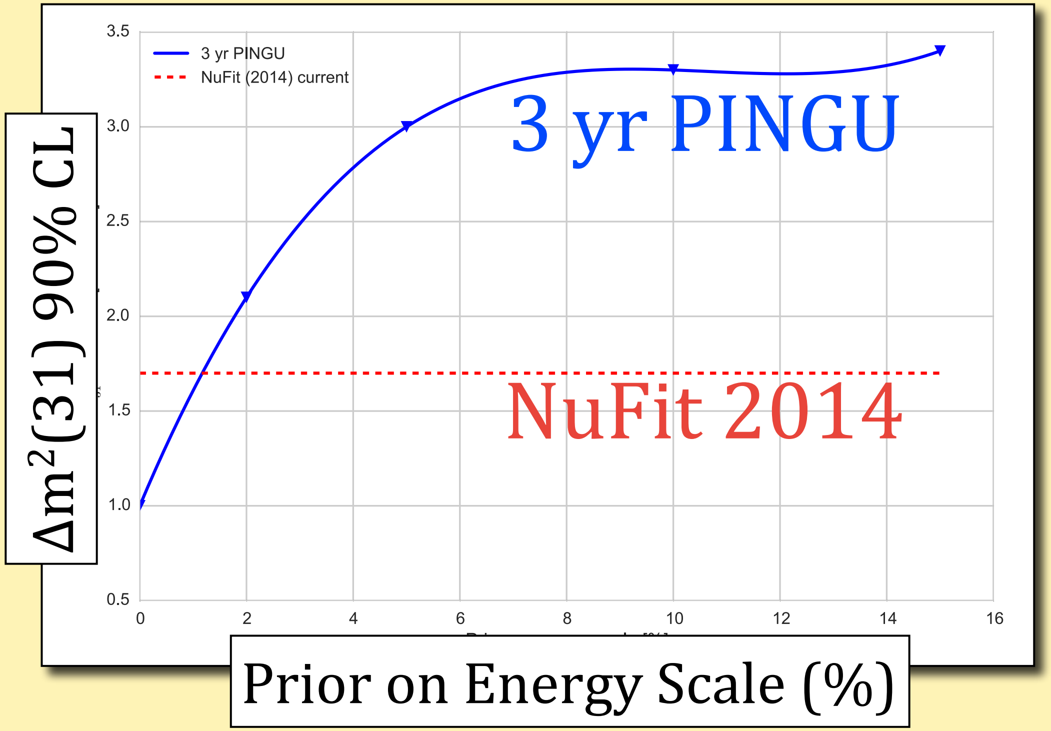
Table 14: Summary of proposed PINGU calibration devices and their purposes.

	LED flashers	POCAM	Cameras	MTOMs	Compass	Inclinometer
Energy scale	✓	✓				
Bulk ice	✓	✓				
Hole ice	✓	✓	✓			
DOM sensitivity	✓	✓		✓		
Geometry	✓		✓		✓	✓
Timing	✓					
Direction	✓		✓		✓	✓
Ice motion	✓					✓
Cable shadow			✓			

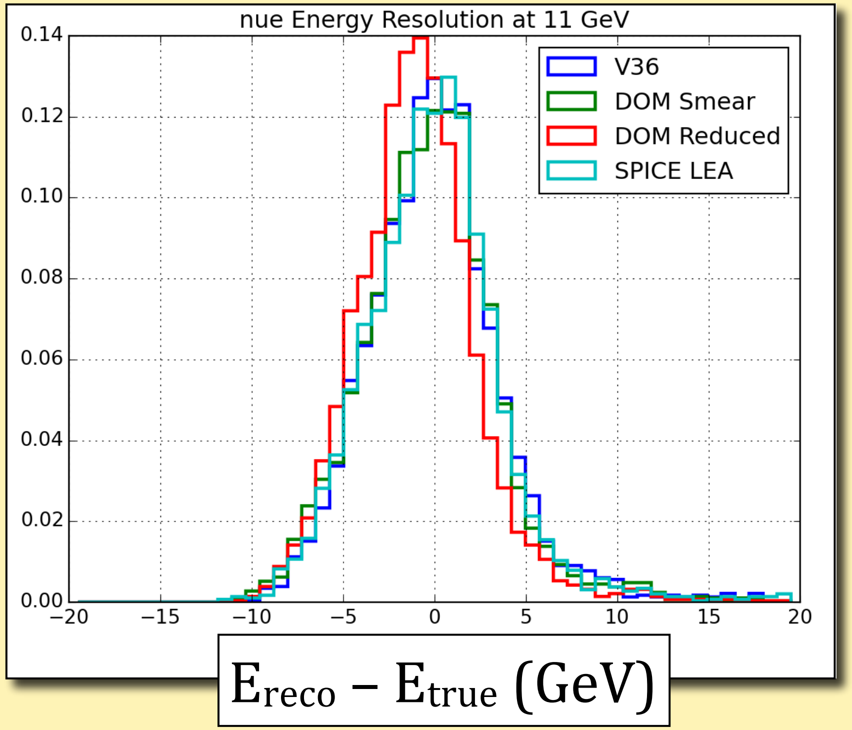
PINGU's close module spacing will enable us to better constrain ice properties, benefiting ν event reconstruction at all energies.

Calibration

Making connections to physics measurements:



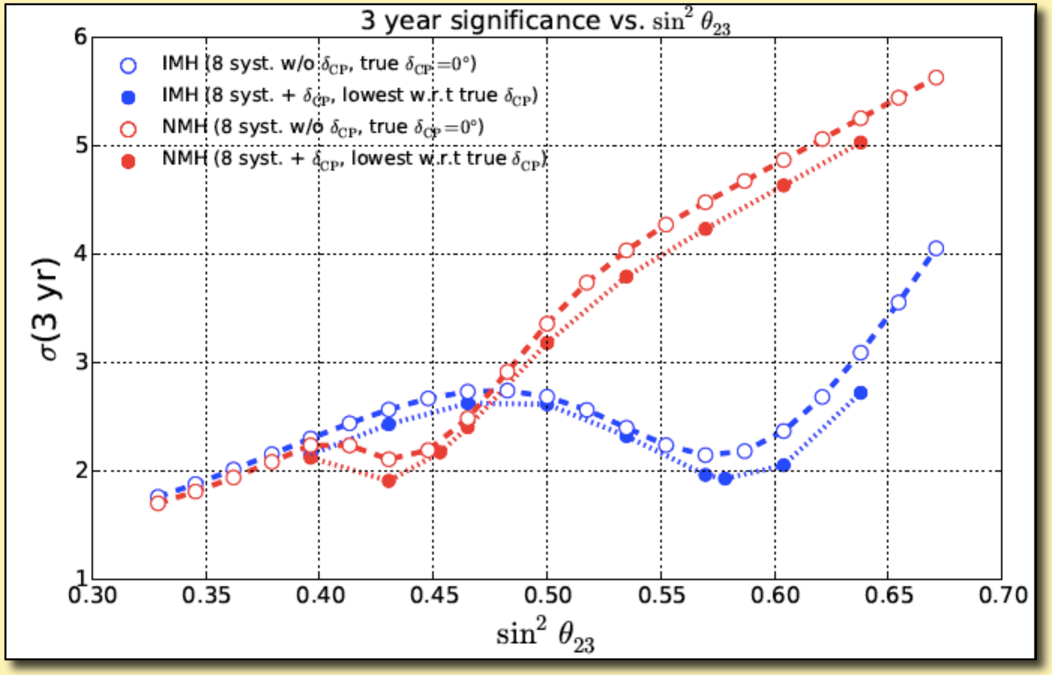
N.B.: Blue line is just spline fit, has no physical significance.



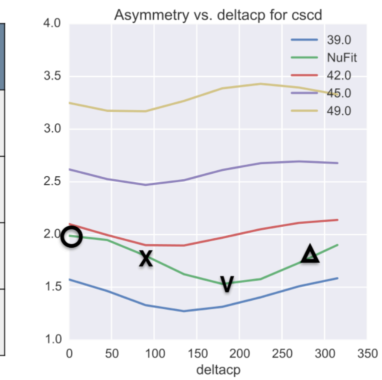
Evaluating detector systematics: With DOM efficiency uncertainty conservatively set to IceCube value (10%), shift in its mean value has biggest impact on PINGU energy scale

Most Recently Studied Systematic: δ_{CP}

- δ_{CP} included as a nuisance parameter
  - via χ^2–Pull
  - Initial LLR study used 4 fixed values; in agreement
- Not yet included in final significance plots

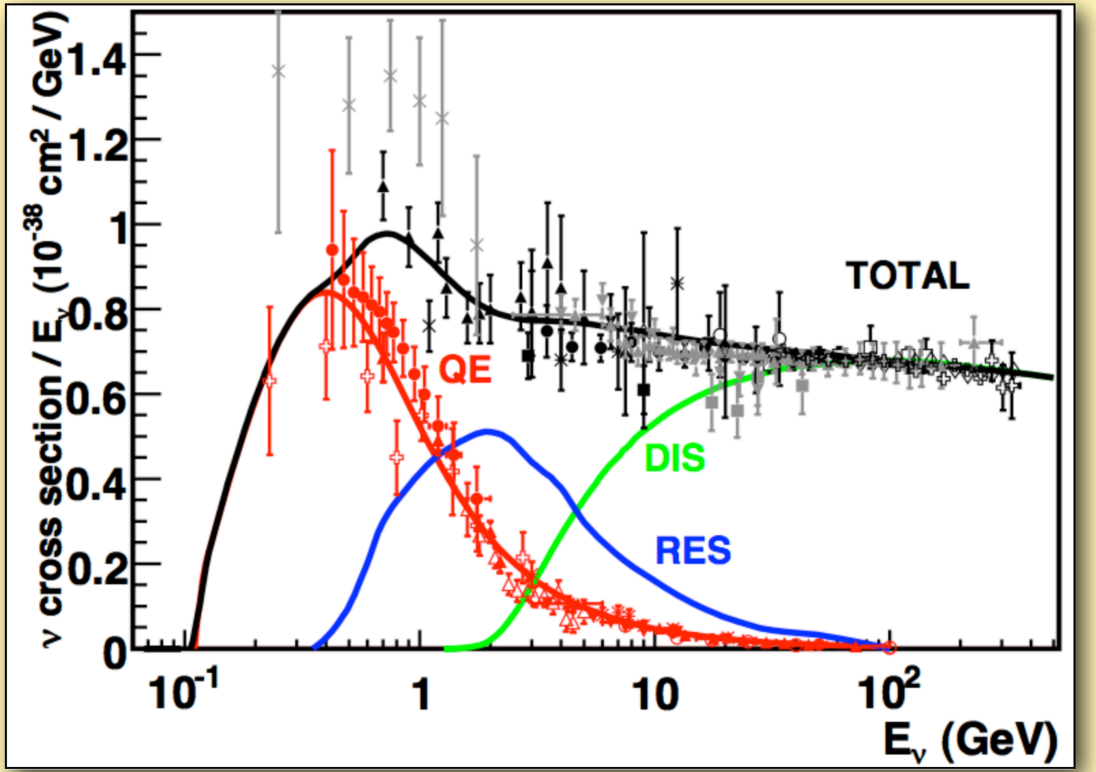


	δ_{cp}(deg)	σ_{NH}	σ_{IH}
○	0	2.80	2.53
X	90	2.49	2.32
V	180	2.32	2.01
△	270	2.40	2.21



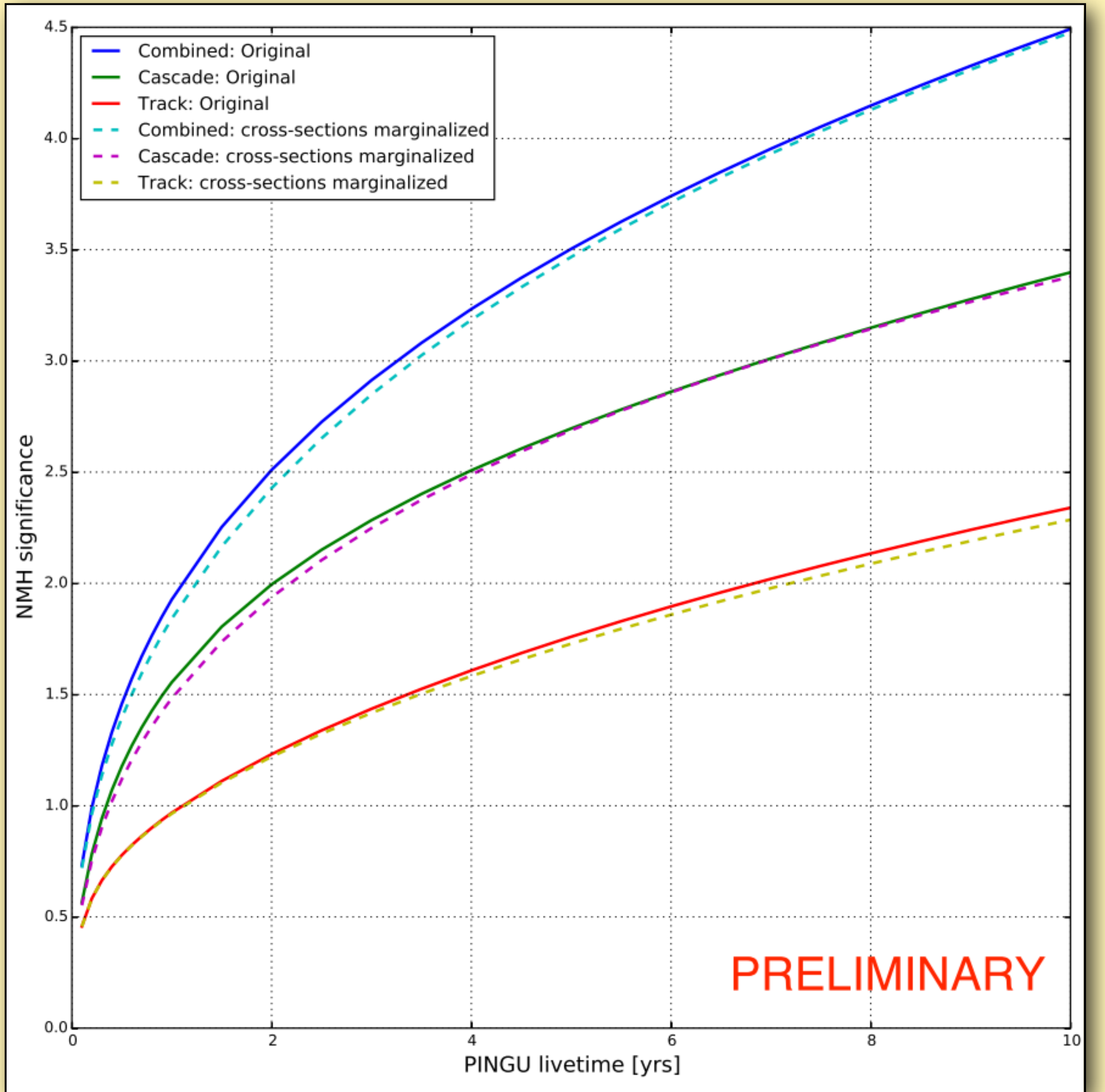
Neutrino Cross Sections

- At the E_ν relevant for DeepCore and PINGU, cross section dominated by DIS
- Would still be useful to measure $\sigma(\nu\text{–}H_2O)$ in the 5–15 GeV energy range
  - Minerva has a water target and can be used for this purpose

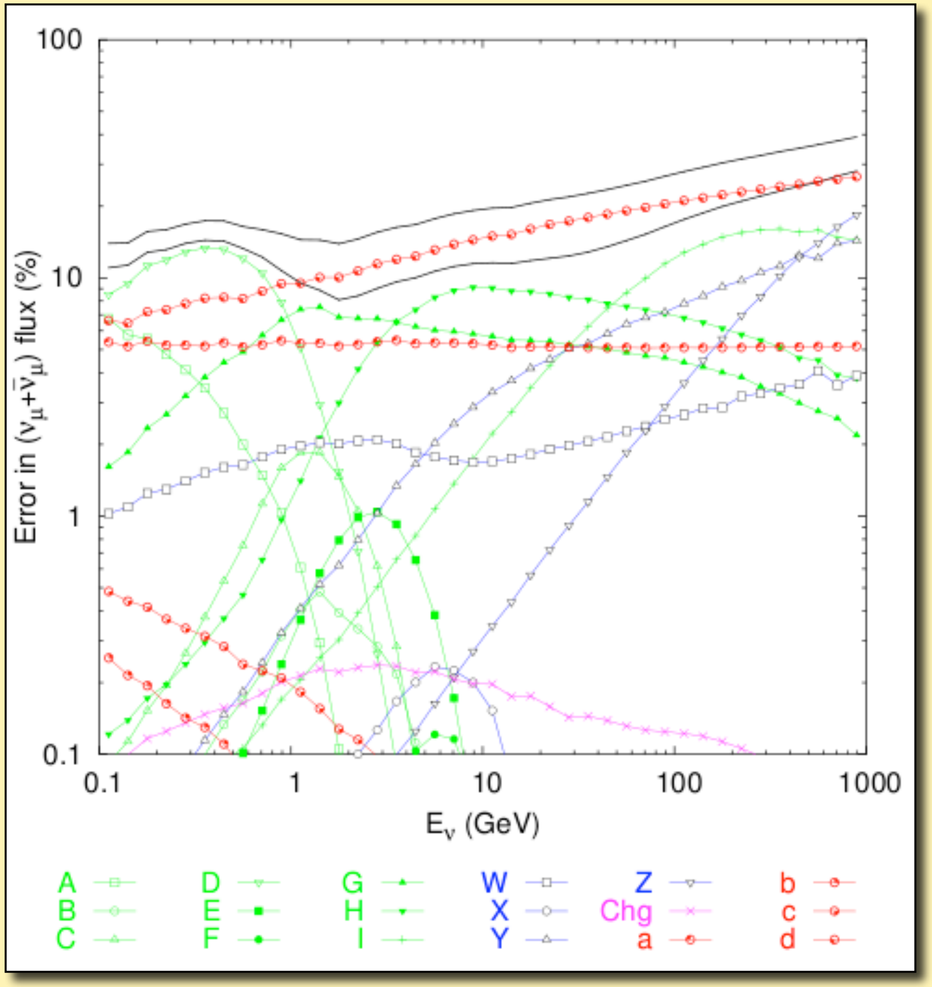


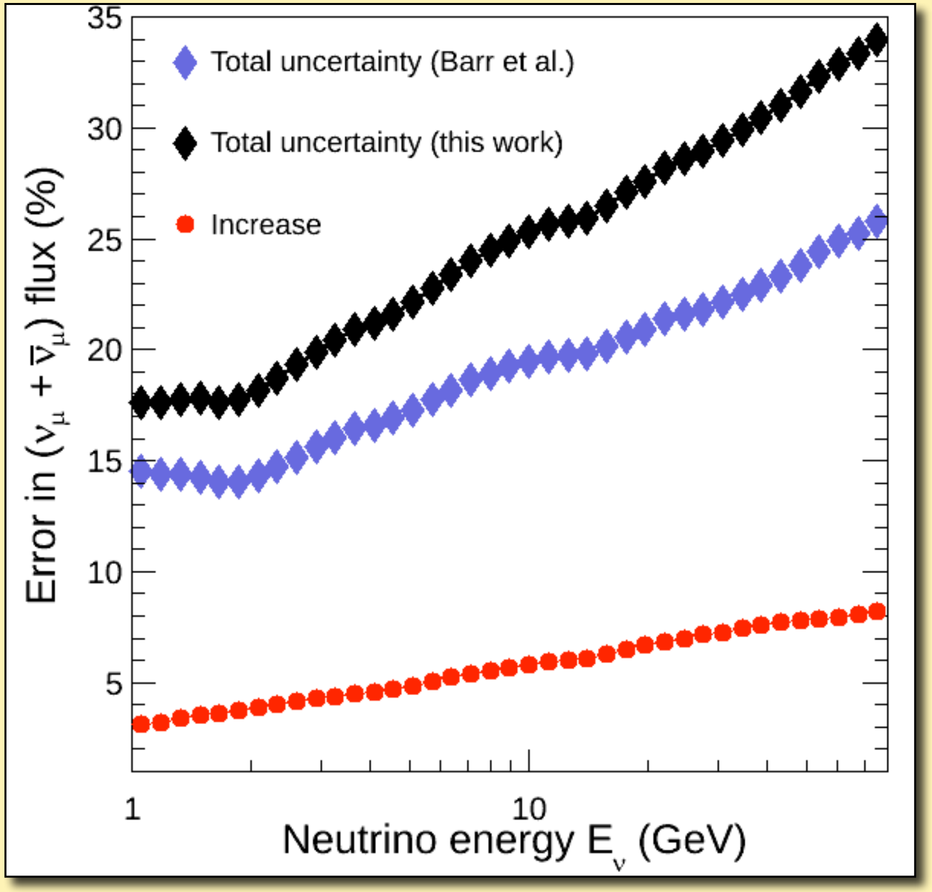
Neutrino Cross Section Systematics

- Performed full treatment of systematics through GENIE, varying over 10 separate parameters
  - Impact on final significance much smaller than that of oscillation parameter uncertainties
  - Largest impacts seen from m_A in CCQE and resonance interactions, and higher twist parameters in Bodek-Yang DIS model

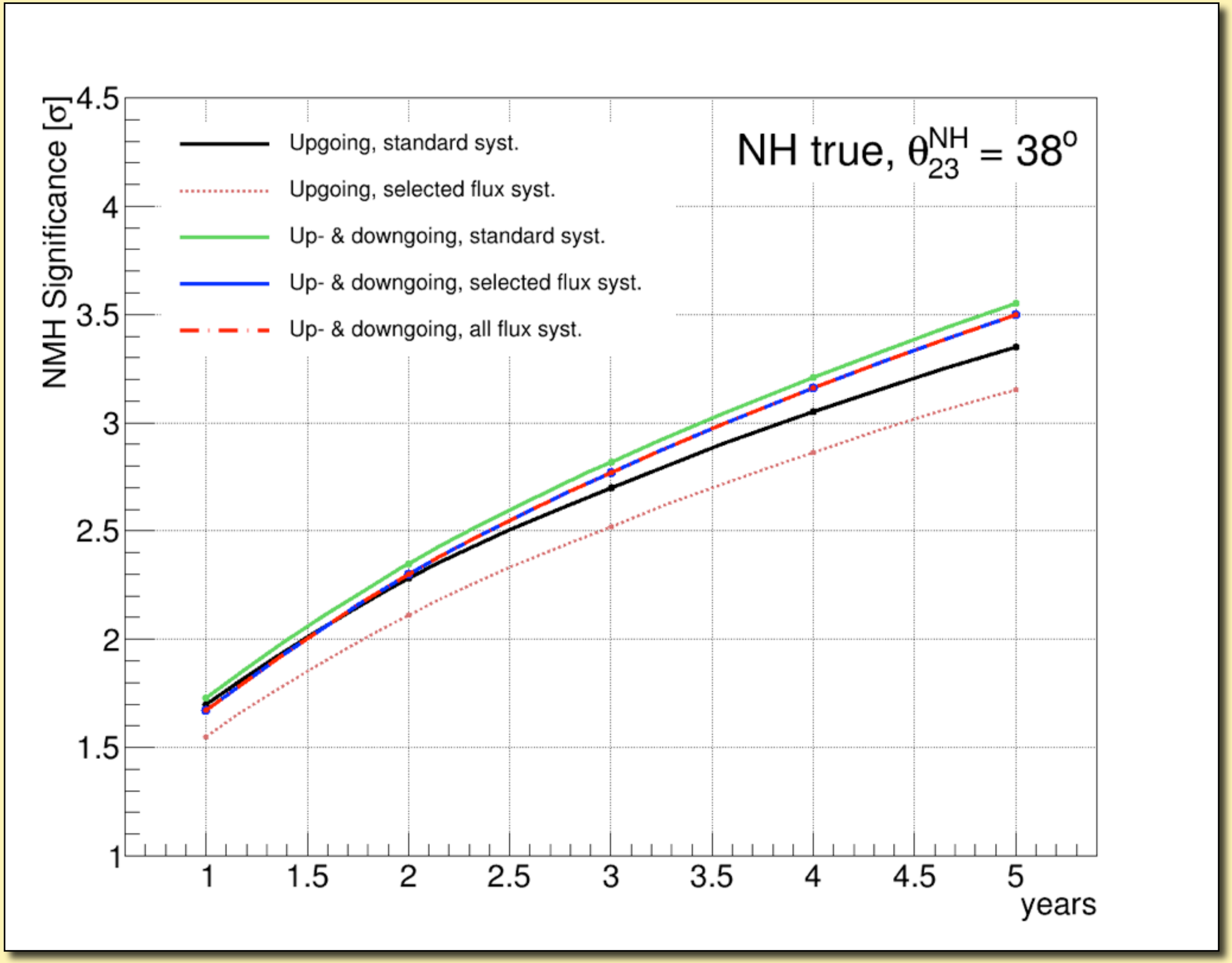


Atmospheric Flux Systematics



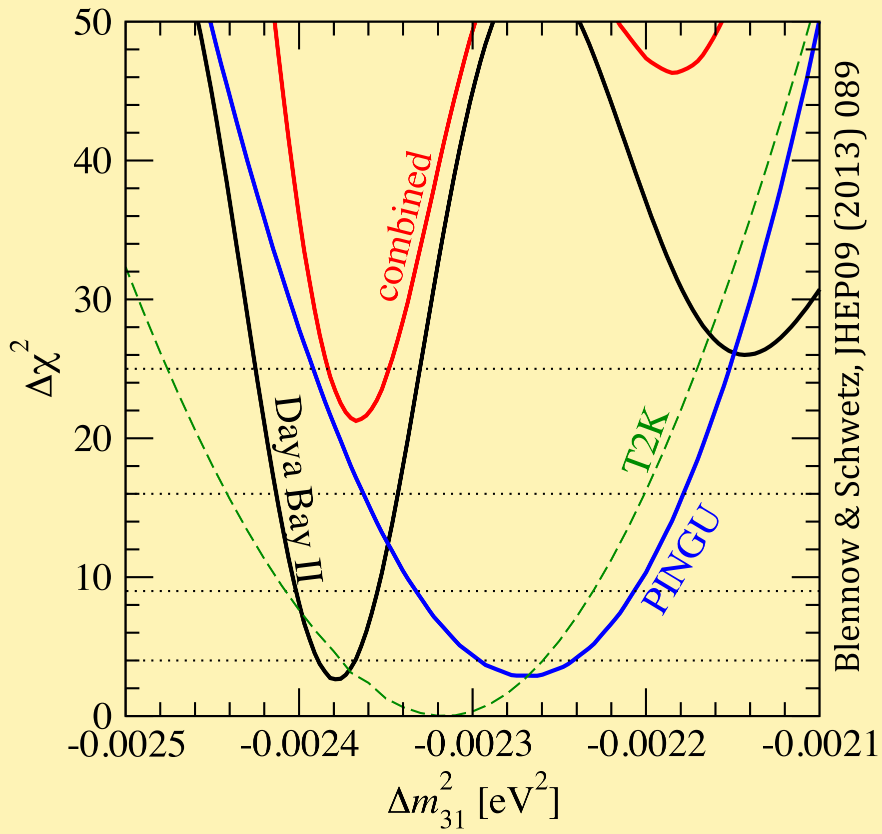


Using Downgoing ν



NMH Synergy: ν_{atm} and $\nu_{reactor}$

- Assume we have two experiments, one using atmospheric ν and the other reactor ν, each have sensitivity to the NMH.
  - PINGU or ORCA, and JUNO or RENO-50
- When data are analyzed under the wrong hierarchy hypothesis, the best fit occurs at different values of $|\Delta m^2(31)|$
  - Reason: ν_e and ν_μ disappearance experiments measure different Δm^2's
    - depends on $(m_3)^2$ and the *flavor-averaged* mass squared of states m_1 and m_2 (see eqns.)
  - Implication: Global significance for rejecting the wrong hierarchy can improve faster than a simple quadratic sum

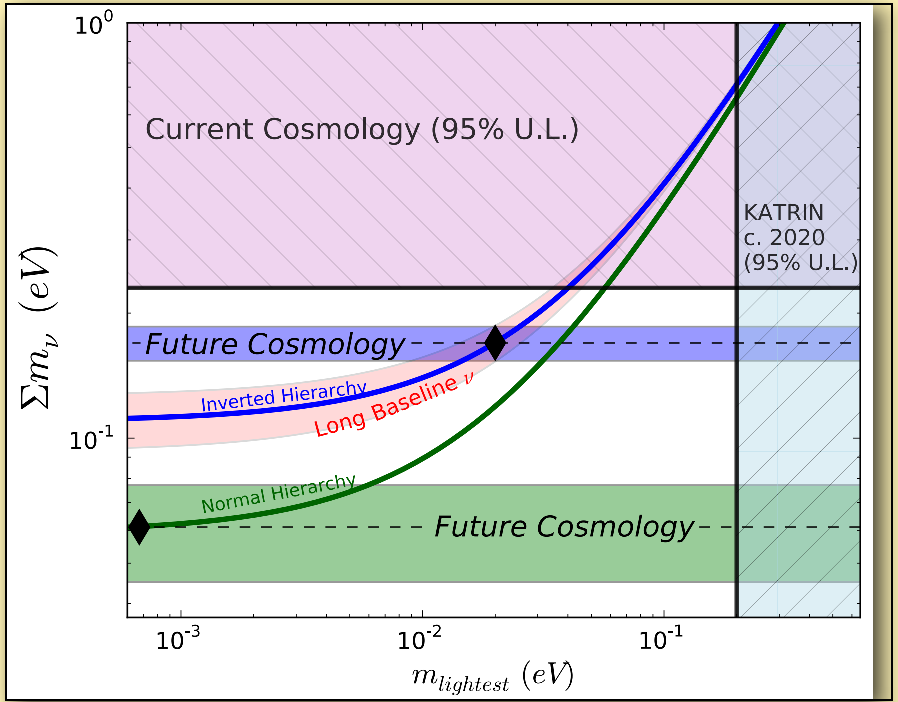


$$\delta m^2_{eff}\Big|_\alpha = m_3^2 - \left\langle m_\alpha^2 \right\rangle_{12}$$

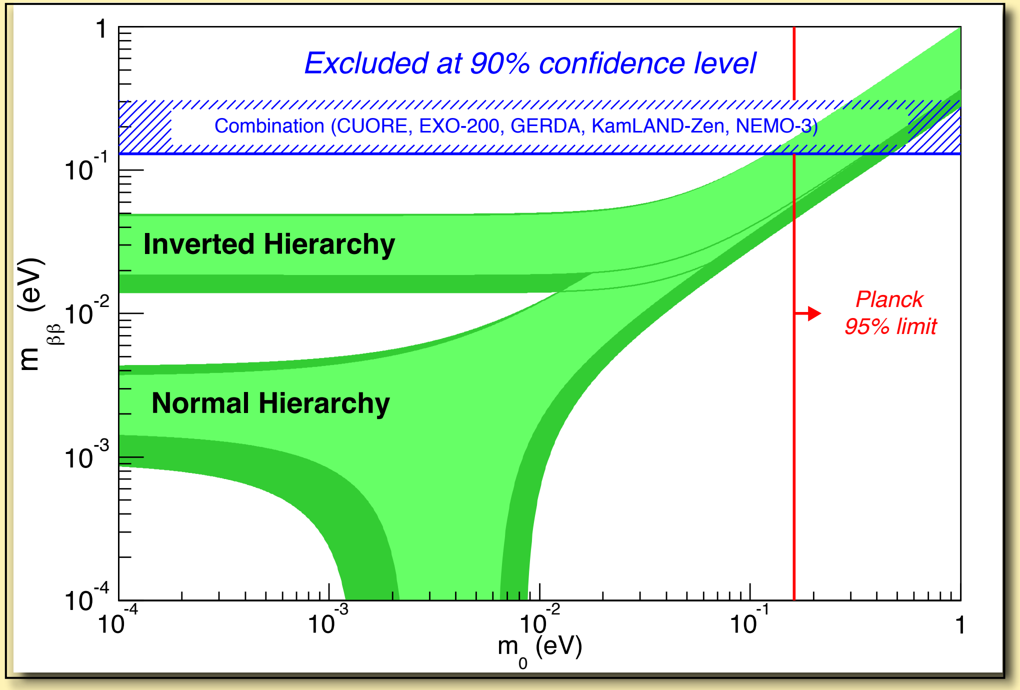
$$\left\langle m_\alpha^2 \right\rangle_{12} = \frac{|U_{\alpha 2}|^2 m_2^2 + |U_{\alpha 1}|^2 m_1^2}{|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2}$$

Nunokawa et al., PRD 72, 013009 (2005)

NMH, CMB, and 0νββ



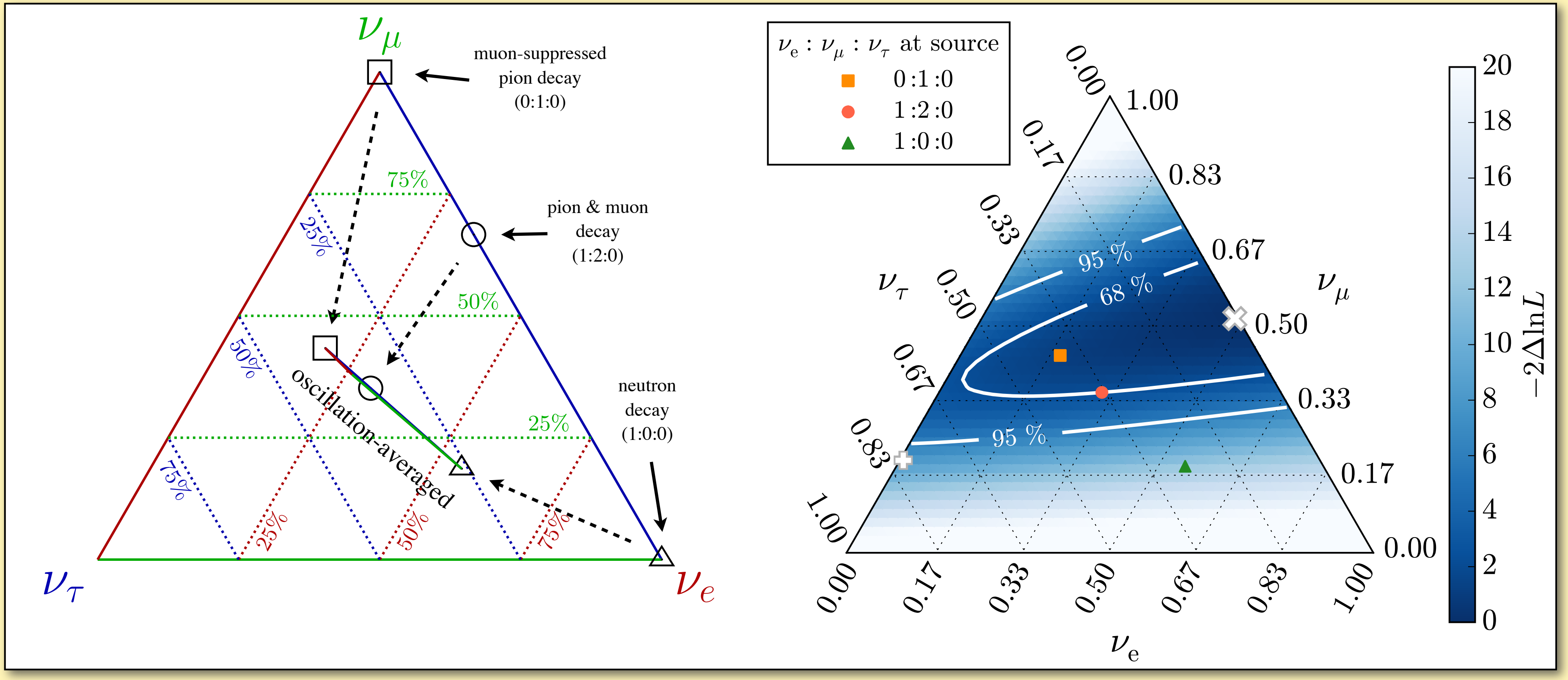
arXiv:1309.5383v3



Guzowski et al., http://arxiv.org/abs/1504.03600

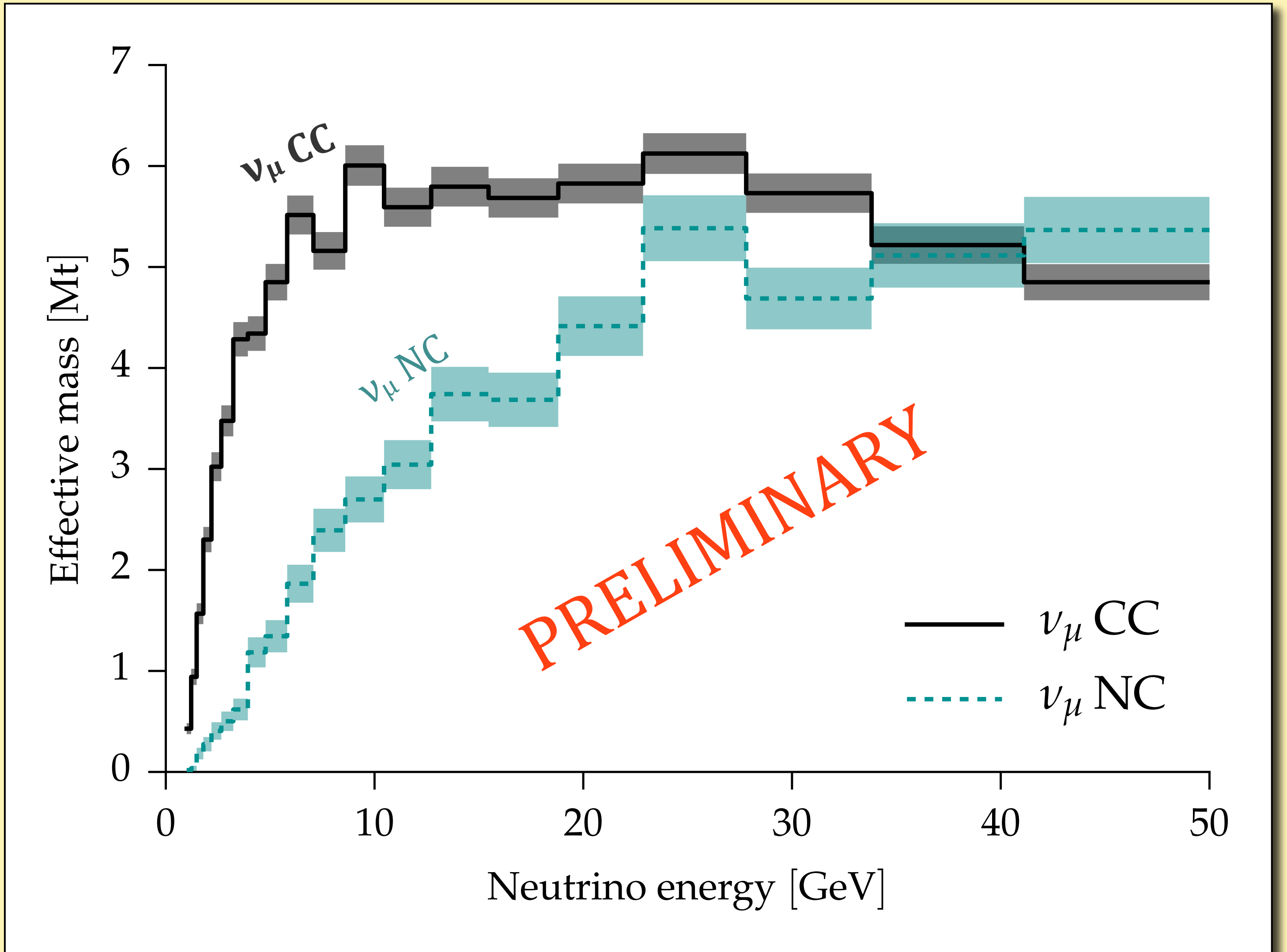
Neutrino Oscillations at the TeV-PeV Scale

- After (standard) oscillations, all sources should end up in the triangle
  - pure neutron-escape scenario is disfavored



Astrophys. J. 809, 98 (2015)

PINGU Meff



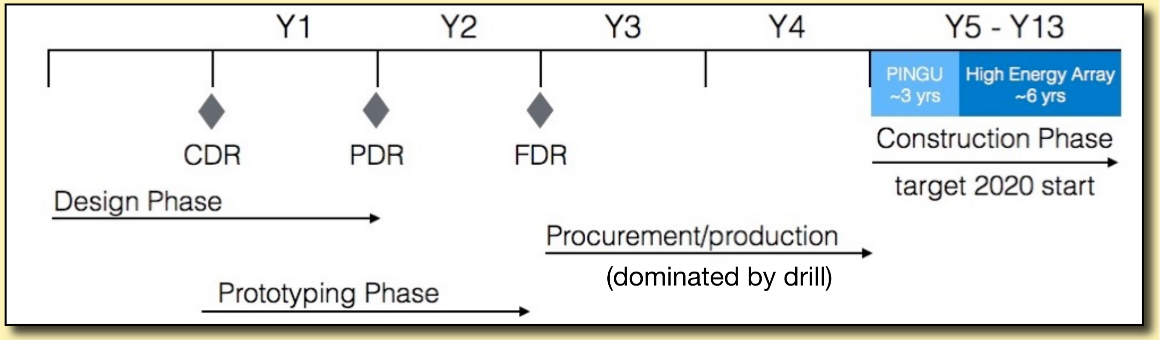
ν_μ CC
ν_μ NC
PRELIMINARY
ν_μ CC
ν_μ NC
Effective mass [Mt]
Neutrino energy [GeV]
0
1
2
3
4
5
6
7
0
10
20
30
40
50

Estimated Cost & Timeline

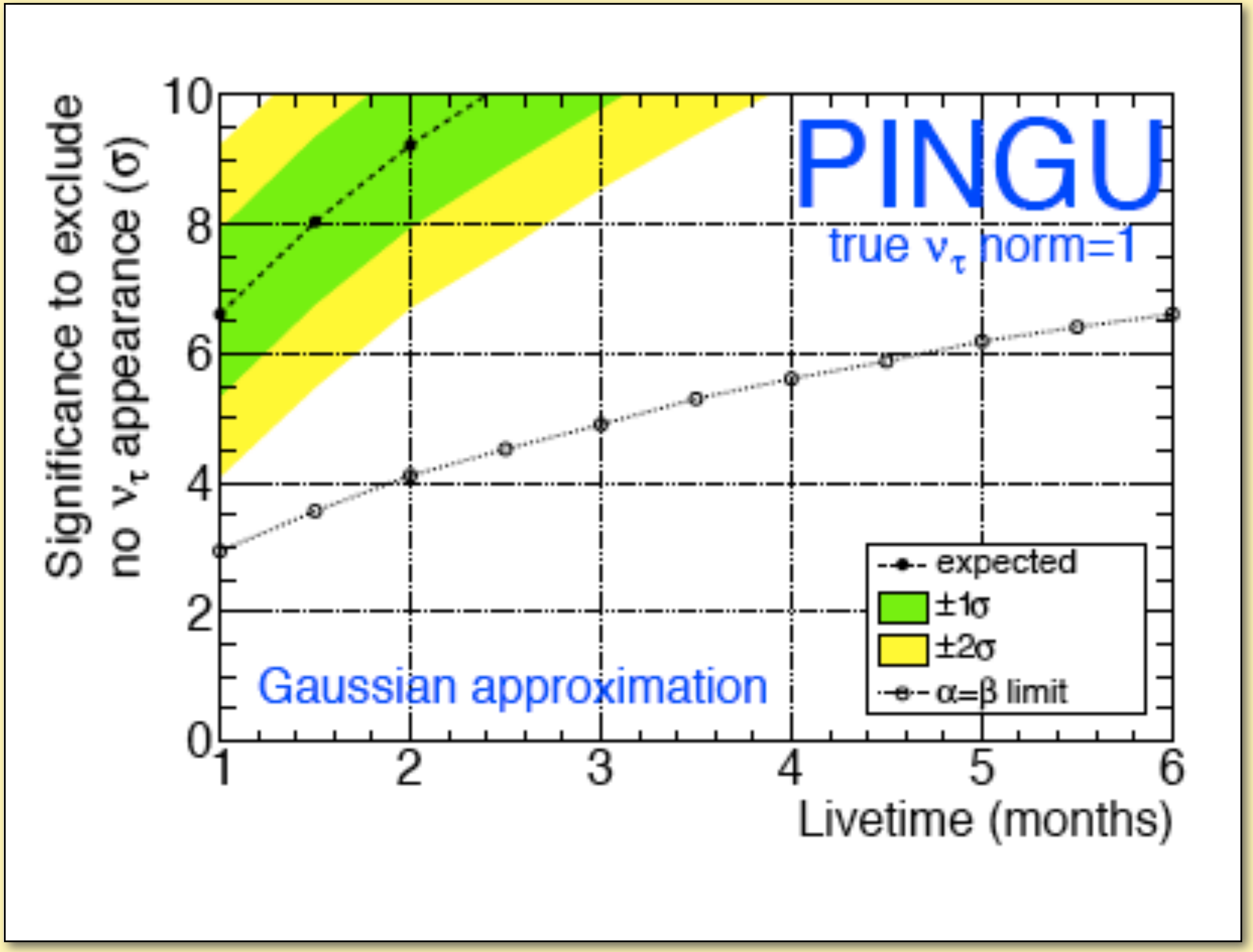
- Cost: Many items are common between various Gen2 subdetectors
  - Drill, module and cable engineering, calibration
  - devices, software, project management,...
  - Anticipate significant contributions for hardware from partner countries

Cost for PINGU Component	
Hardware	$48M
Logistics	$23M
Contingency	$16M
Total	$88M
Partner Contributions	–$25M
Total US Cost	$63M

- Timeline: short, but start time is not yet known.

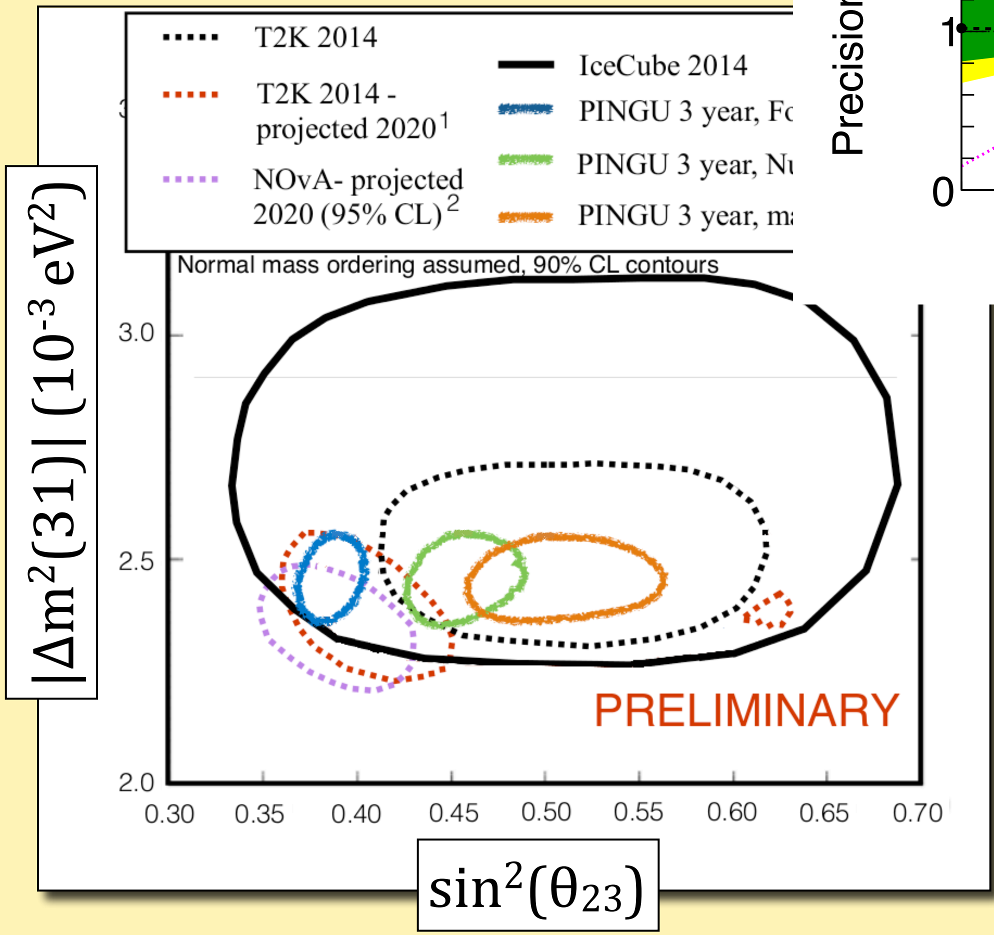


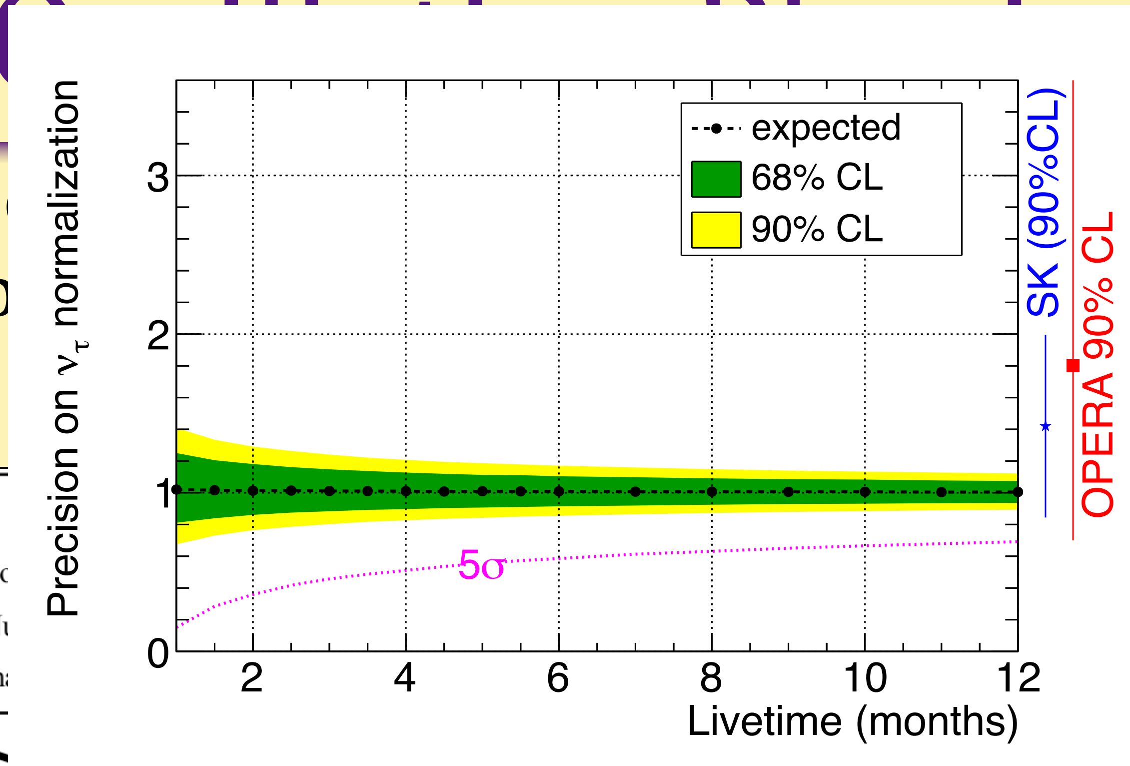
Tau Neutrino Appearance: PINGU

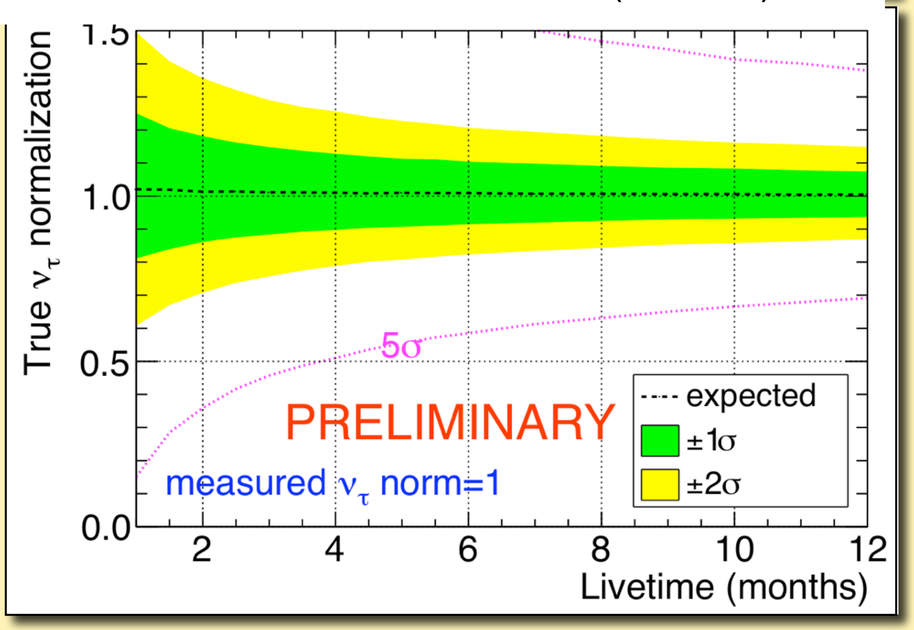


PINGU ν_{atm}

World-class measurem
parameters via ν_{μ} disap
and ν_{τ} appearance

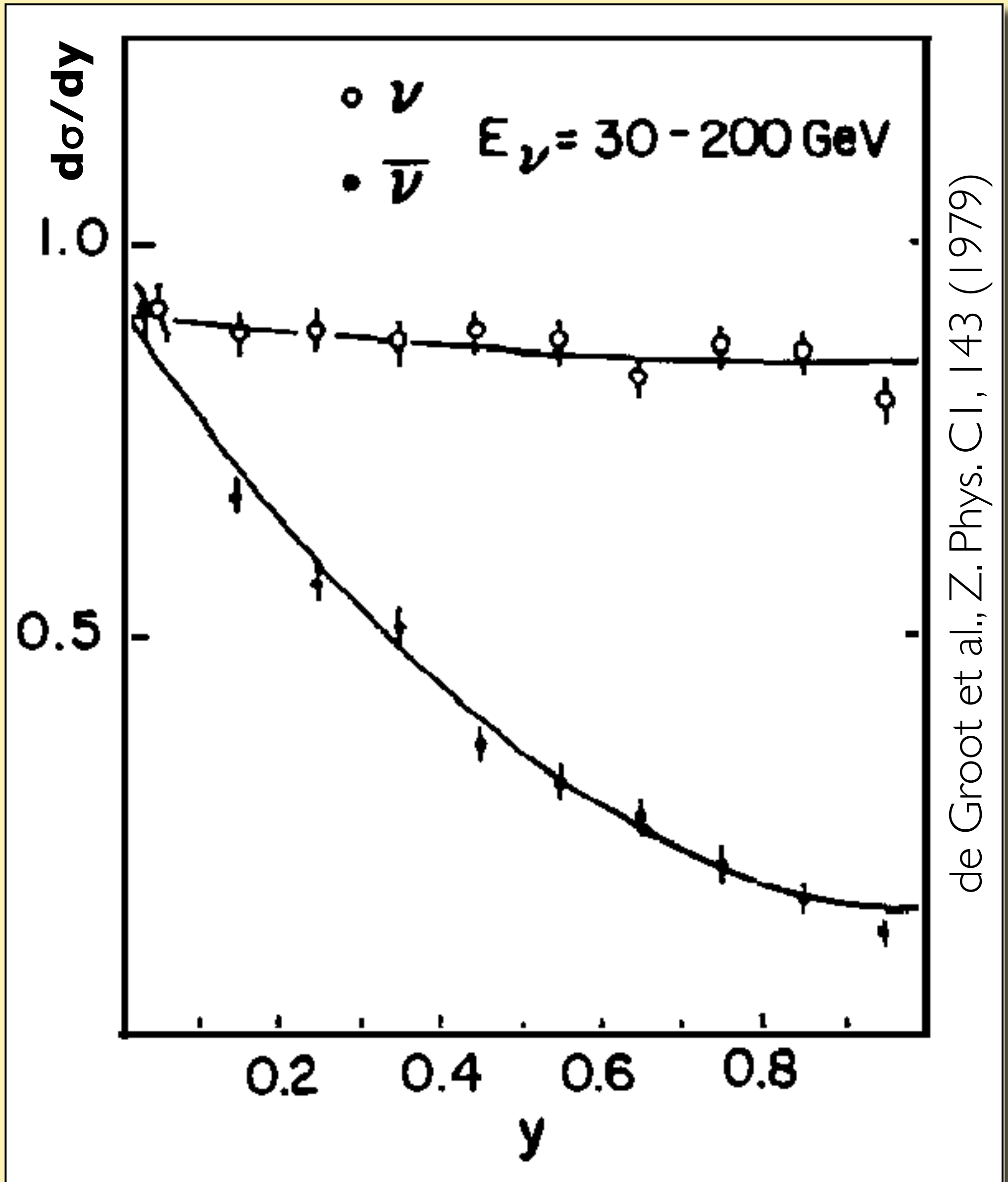






Inelasticity

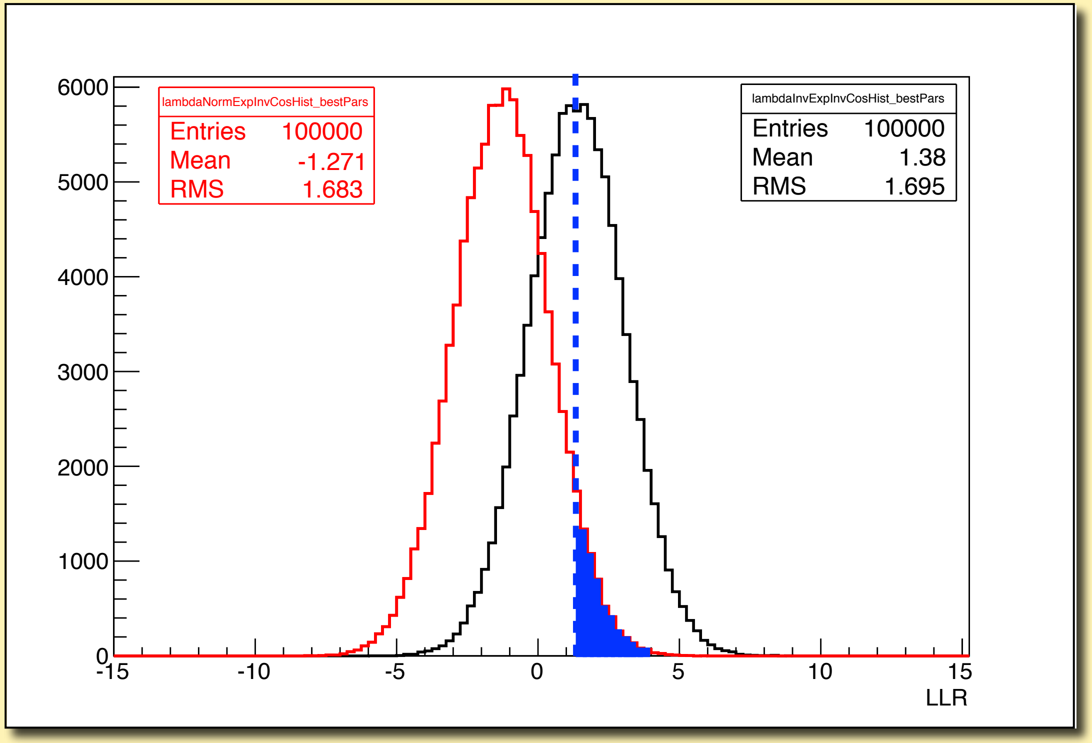
- Inelasticity distribution is different for neutrinos and anti-neutrinos
- Inclusion of inelasticity in the NMH analysis could improve significance by 20-50% (Ribordy and Smirnov, 1303.0758)



de Groot et al., Z. Phys. C1, 143 (1979)

Log-Likelihood Ratio

- Generate templates for all oscillation/systematic parameters and hierarchies
- Create pseudo-dataset by pulling from the template and adding Poissonian fluctuations
- Calculate the likelihood of the pseudo-dataset using ALL templates
- Use the best likelihood to determine the LLR, and repeat many times
- Determine the proportion of the distribution which lies beyond the median point in the opposite distribution, giving the p-value for this test

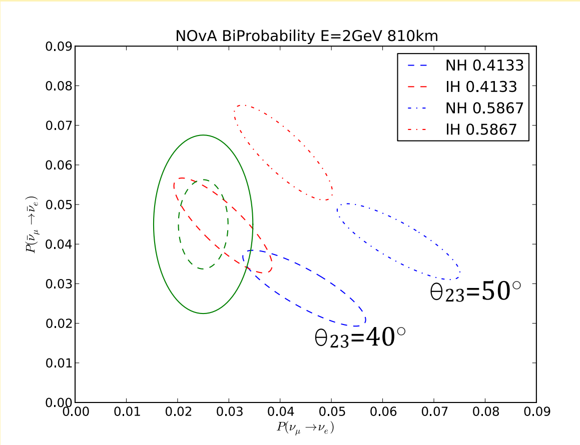


$$LLR = \frac{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{NH}|Template_{IH})}{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{NH}|Template_{NH})}$$

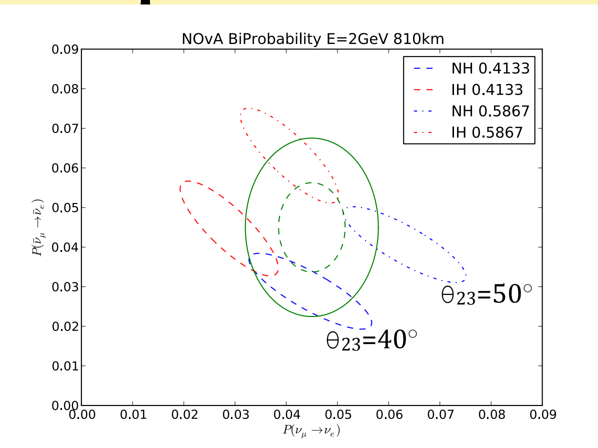
$$LLR = \frac{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{IH}|Template_{IH})}{\sum_{N=0}^{N_{bins}} \mathcal{L}(Data_{IH}|Template_{NH})}$$

NOvA, PINGU and δ_{CP}

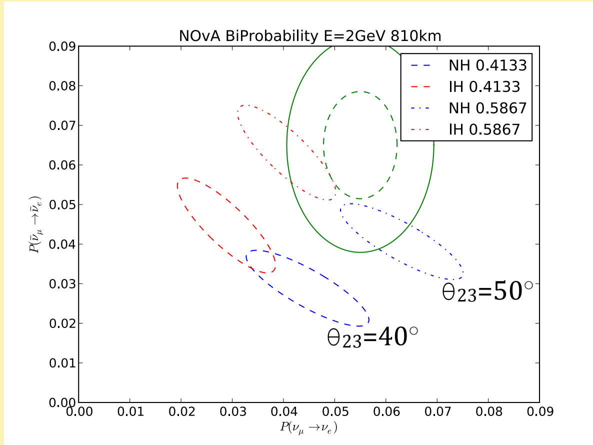
- Explore impact of knowing NMH at several selected points



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



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



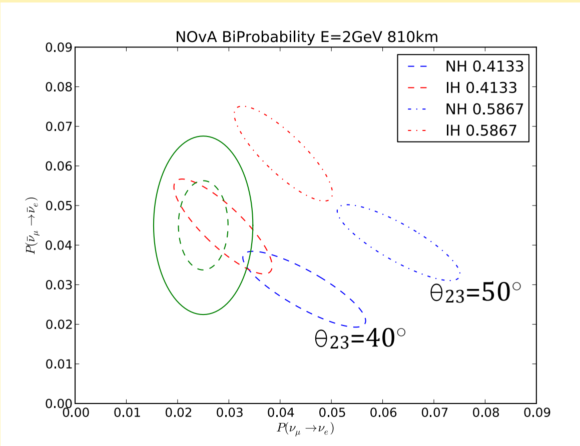
If PINGU says NH, good δ_{CP} and octant resolution for NOvA

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

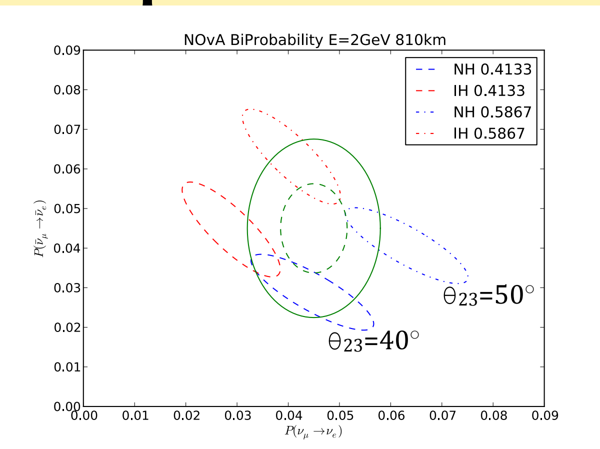
NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554

NOvA, PINGU and θ_{23}

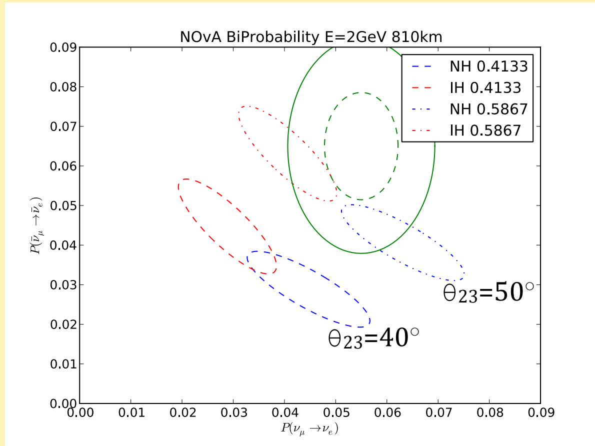
- Explore impact of knowing NMH at several selected points



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



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

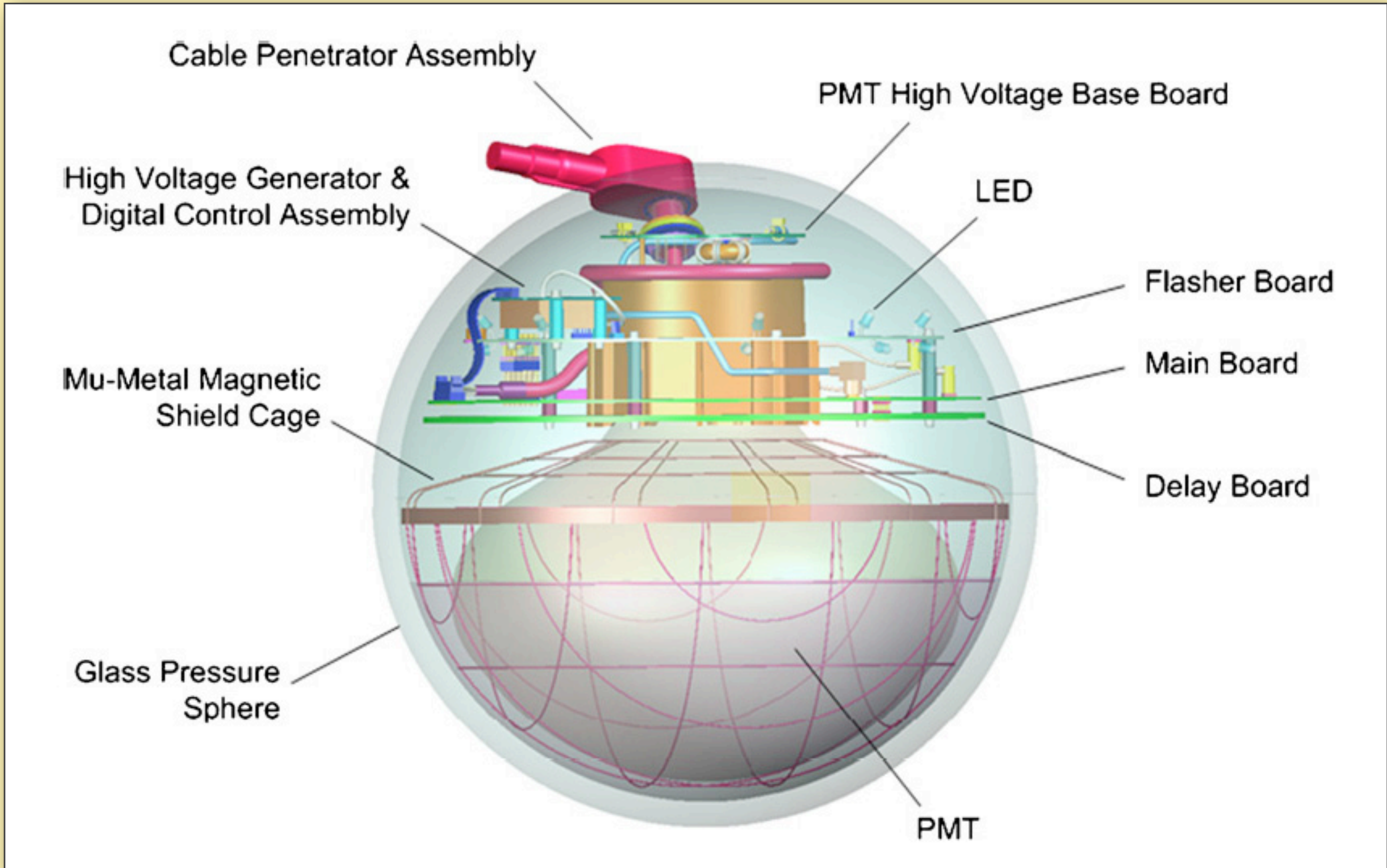


If PINGU says NH, good δ_{CP} and octant resolution for NOvA

		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

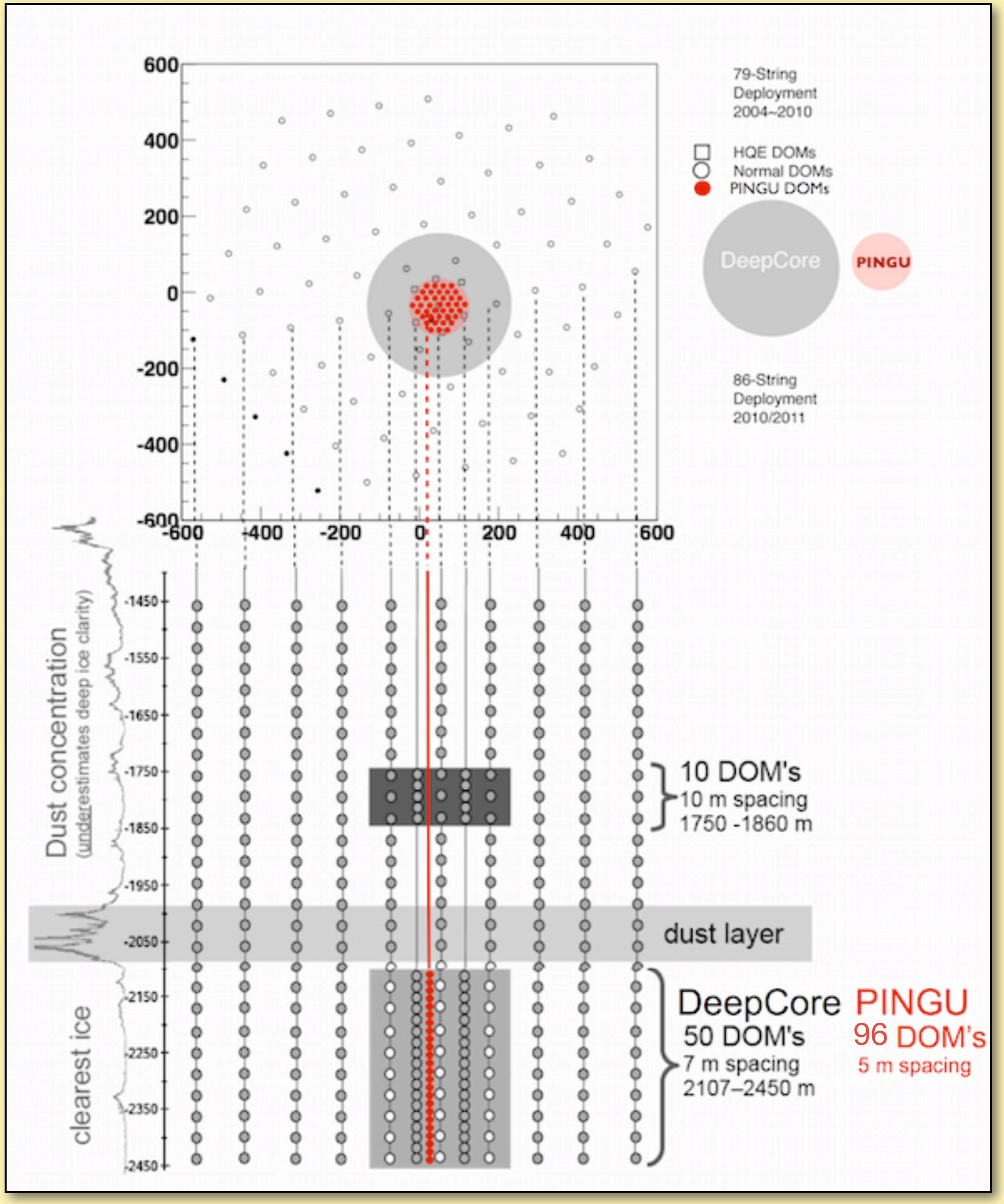
NOvA error ellipses: M. Messier, R. Patterson; theoretical curves based on Nunokawa et al. 0710.0554

The Digital Optical Module

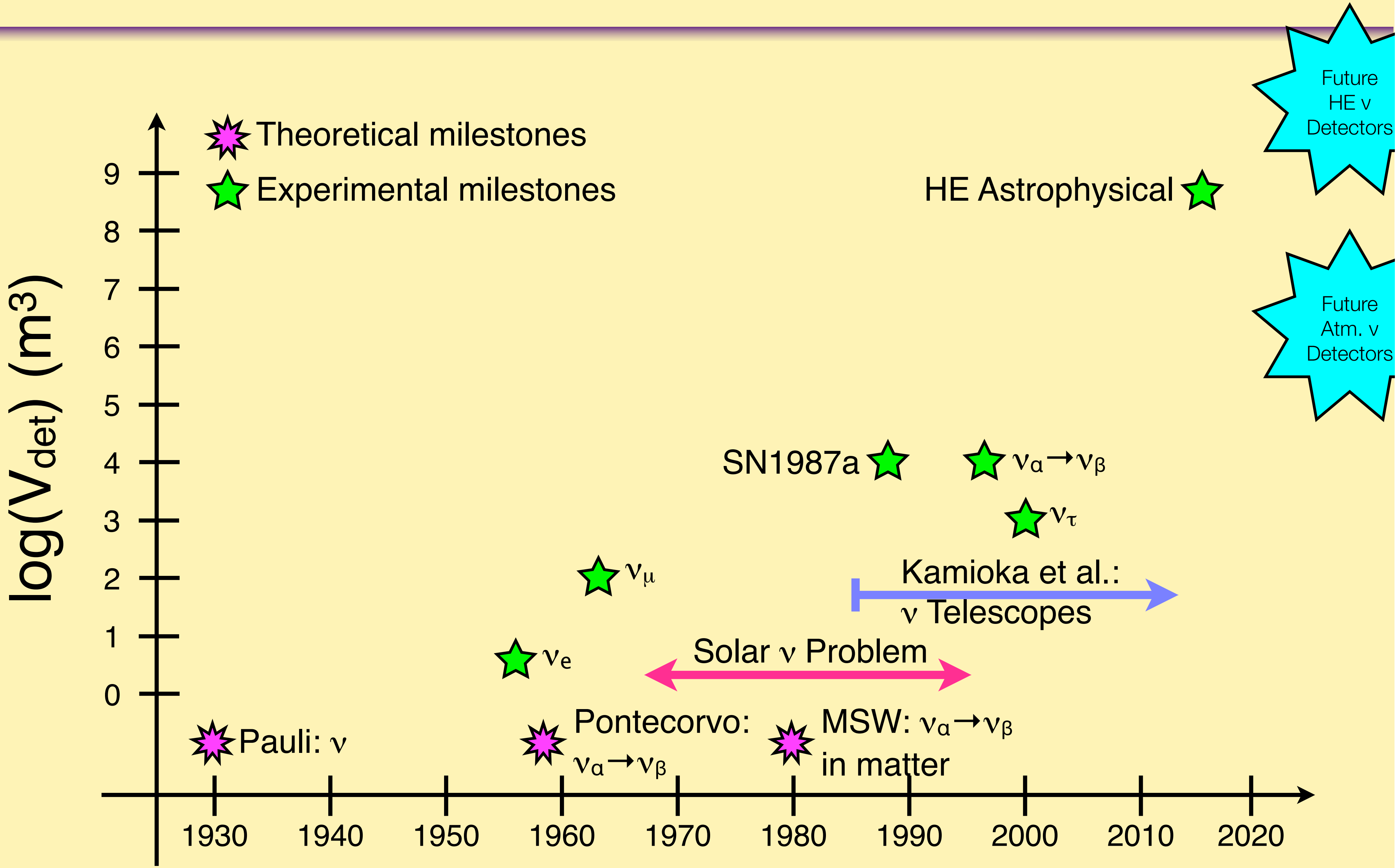


The Detectors The Source The Signature

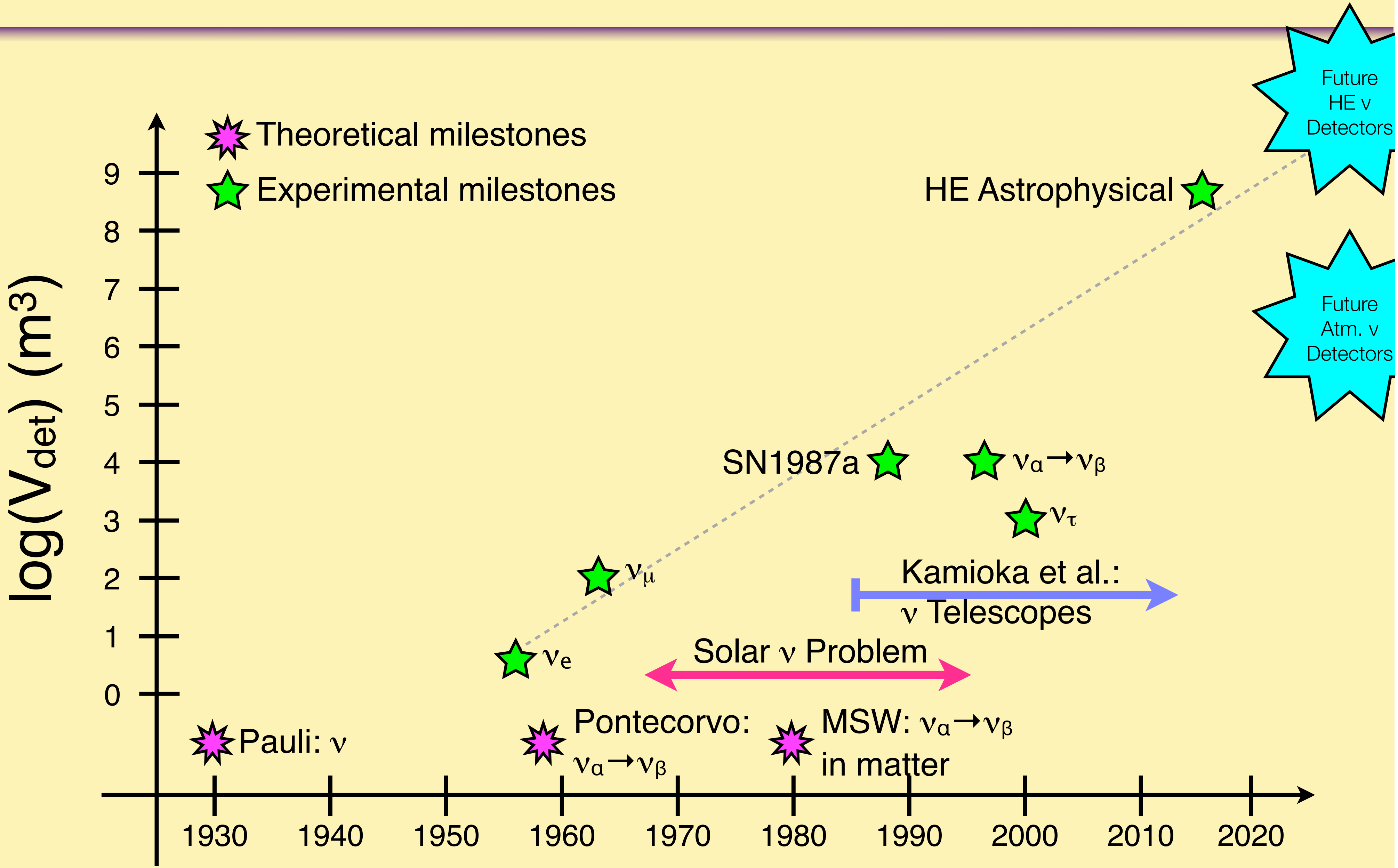
Another view, this time from the side and with PINGU included, too.



Additional Reasons

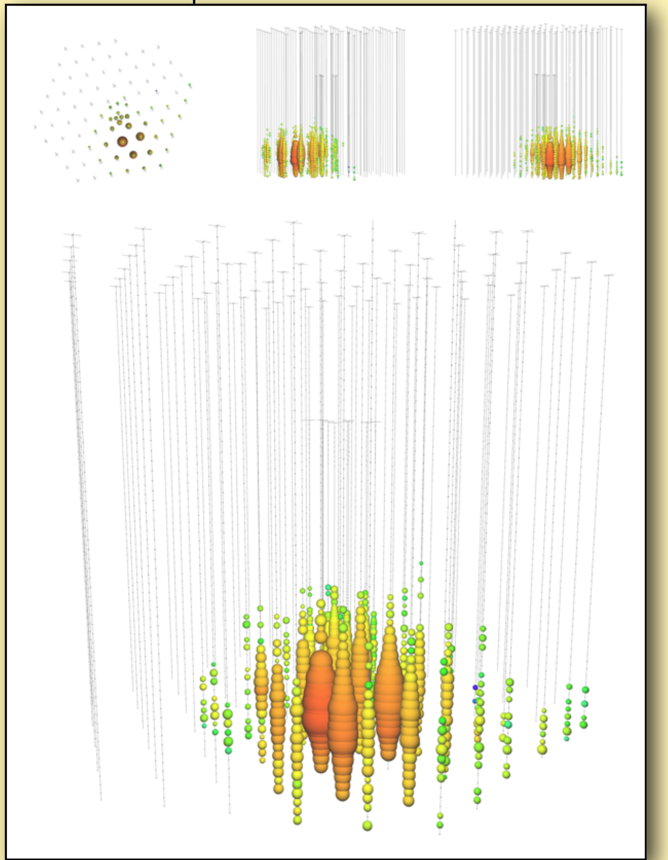


Additional Reasons

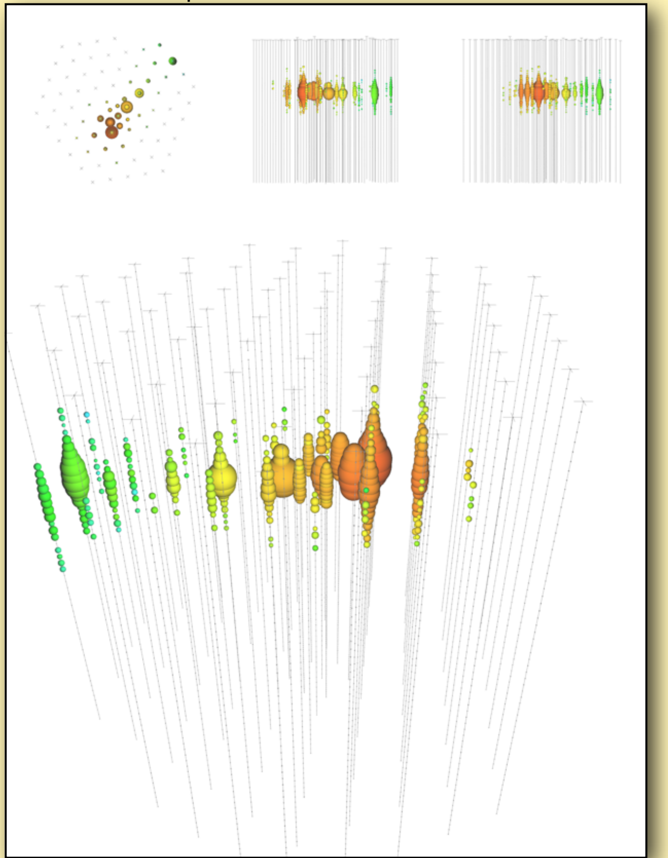


Sample High E_ν Events

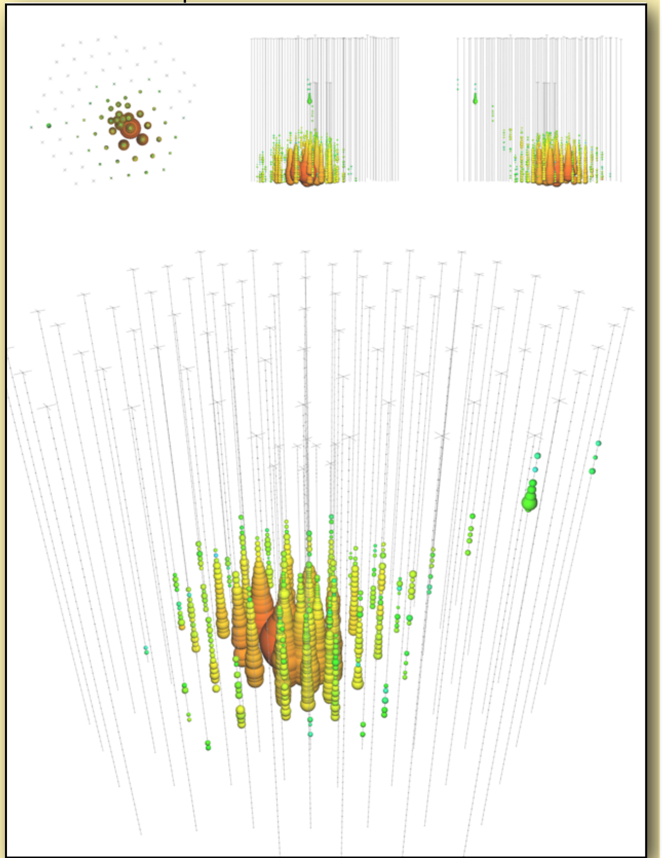
Declination -13.2°
deposited E: 82 TeV



Declination -0.4°
deposited E: 71 TeV

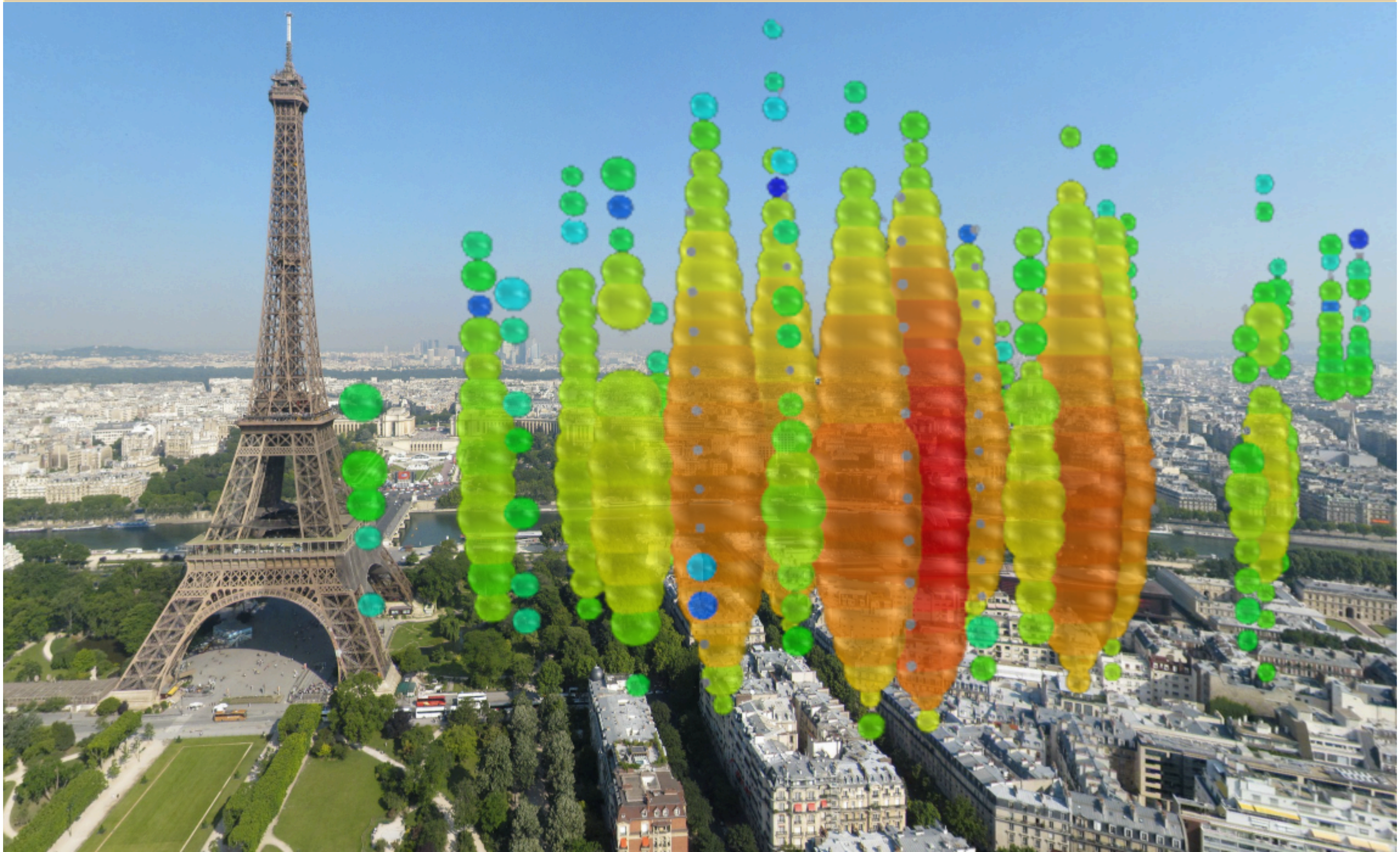


Declination 40.3°
deposited E: 253 TeV



Size Scale

Size Scale



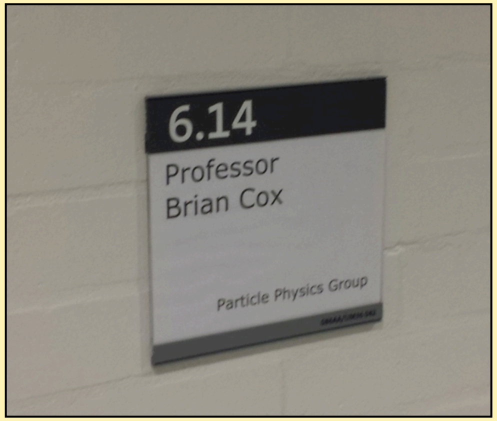
Title and Abstract

High Energy Atmospheric Neutrino Appearance and Disappearance with IceCube

The IceCube neutrino observatory, buried deep in the ice at the South Pole, has detected neutrinos that span over five orders of magnitude in energy. Fulfilling one of its original stated goals of discovering cosmological ultrahigh energy neutrinos, its large instrumented volume also provides us with a surprisingly powerful instrument for studying neutrino oscillations with an unprecedented statistical sample of energetic atmospheric neutrinos.

In this presentation we will describe the IceCube detector and focus on its current and future atmospheric neutrino oscillation measurements with DeepCore, IceCube's low-energy in-fill array. We will also describe a new proposed low-energy extension, the Precision IceCube Next Generation Upgrade (PINGU), highlighting its ability to measure one of the remaining fundamental unknowns in particle physics, the neutrino mass hierarchy.

Reasons to Care About Neutrinos



- "Brian Cox" reasons:
  - Ubiquity:
    - 10^{11} ν/s/cm^2 & ~300 in every cm^3 of space
  - Critical for life
    - Fusion in stars requires emission of ν's
  - "Tiniest" or most "anti-social" of all fundamental particle(s)
    - Solar neutrinos can pass unscathed through light-year-long column of lead
    - ~10^{24} neutrinos will pass through your body in your lifetime; only ~1 will deign to touch you
- Other good reasons:
  - Least understood fundamental particles in the Standard Model
  - Studying neutrino properties could yield hints for new physics
  - Their detection poses an irresistible experimental challenge