# From DeepCore to PINGU

## Measuring atmospheric neutrino oscillations at the South Pole

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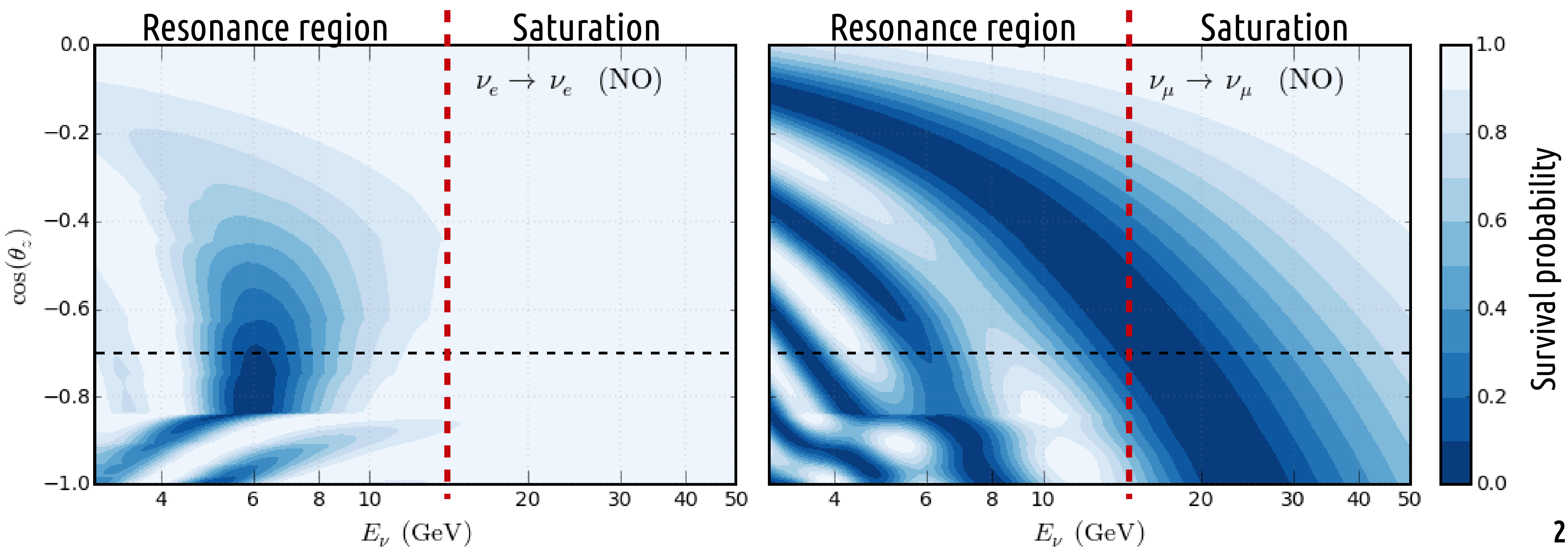
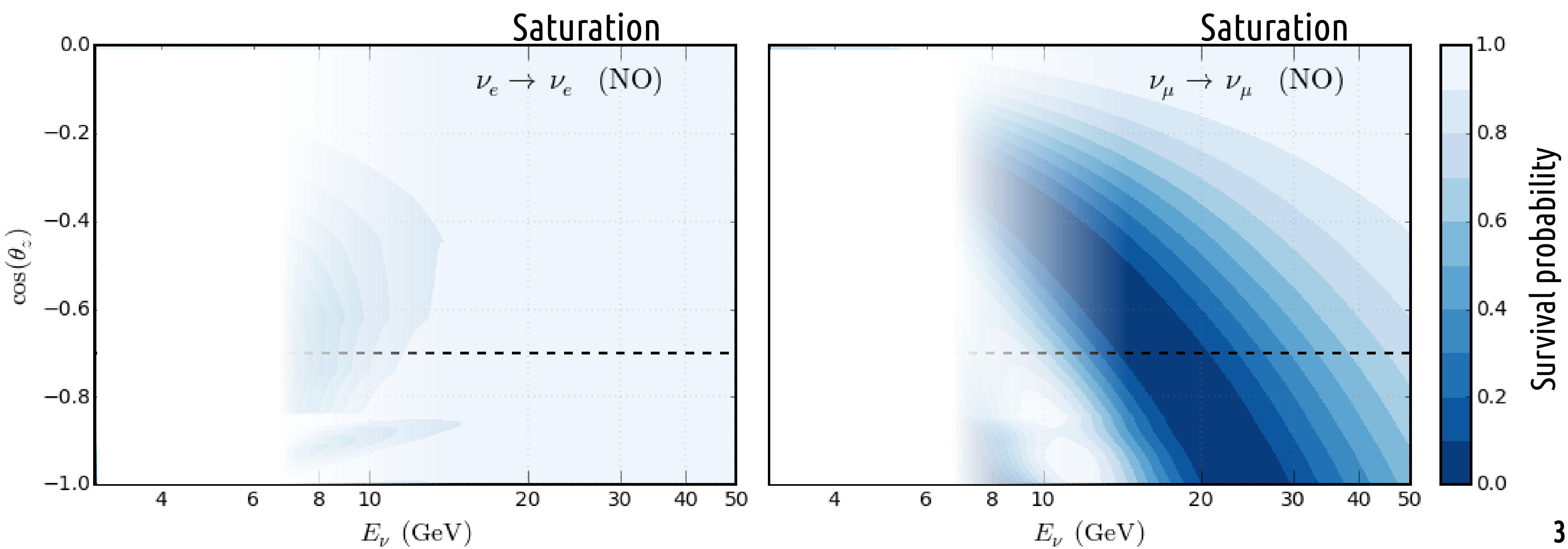
# Atmospheric neutrino oscillations

- Neutrinos change flavor as they travel $P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$
- Earth's matter profile modifies expectation from vacuum oscillations
  - Between $E_\nu$ = 2-15 GeV → resonances, transitions $\nu_e \leftrightarrow \nu_\mu$ take place
  - For $E_\nu$ >15 GeV → saturation ($\theta_{13} \to \pi/2$), dominated by $\nu_\mu \leftrightarrow \nu_\tau$ transitions



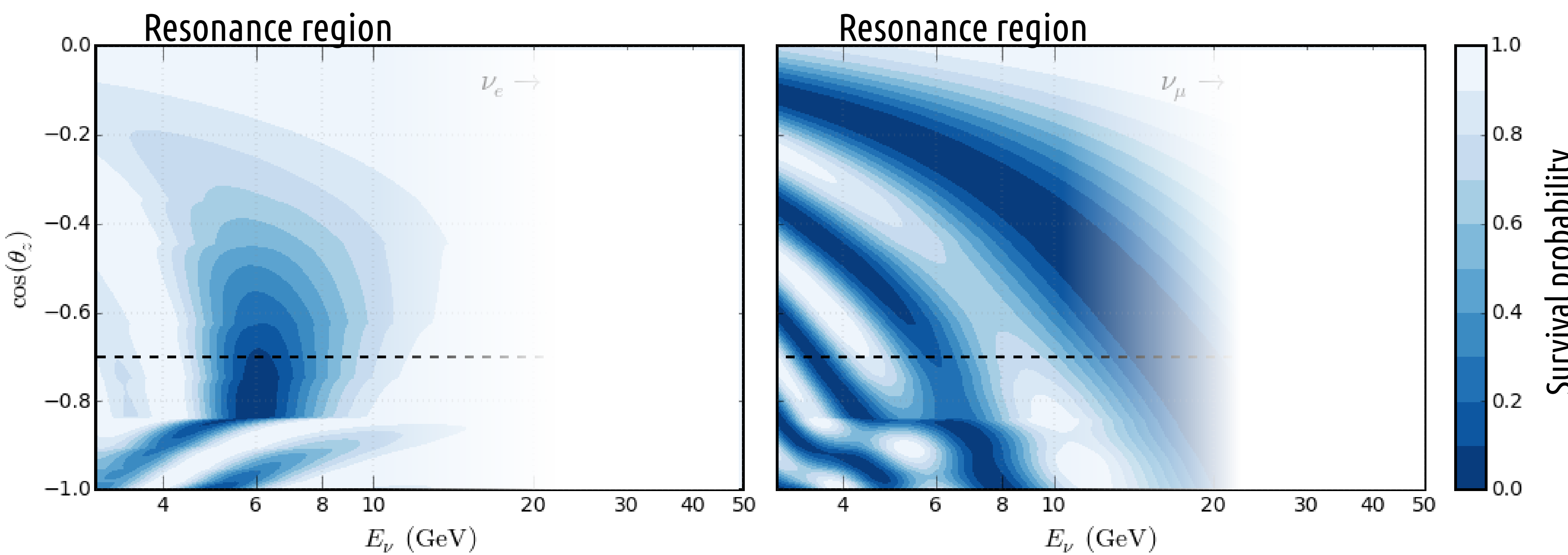
# Atmospheric neutrino oscillations

- Saturation region
  - Simple disappearance depends on $\theta_{23}$ and $|\Delta m^2_{32}| \simeq |\Delta m^2_{31}|$
  - Largely insensitive to $\theta_{13}$
  - Accessible with IceCube DeepCore



# Atmospheric neutrino oscillations

- Resonance region
  - Complicated disappearance pattern, different for neutrinos/antineutrinos
  - Oscillations depend on $\theta_{13}$, $\theta_{23}$ and $\Delta m^2_{32}, \Delta m^2_{31}$ **including their sign**
  - At/Below the threshold of IceCube DeepCore → PINGU



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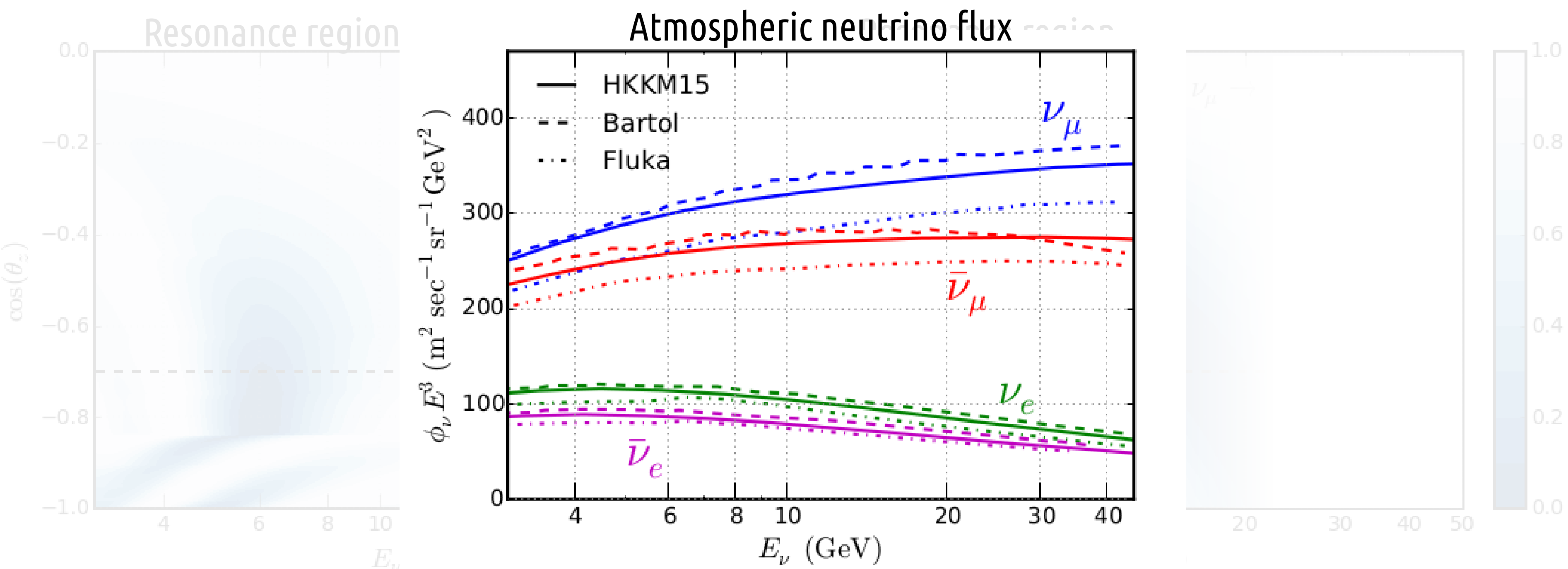
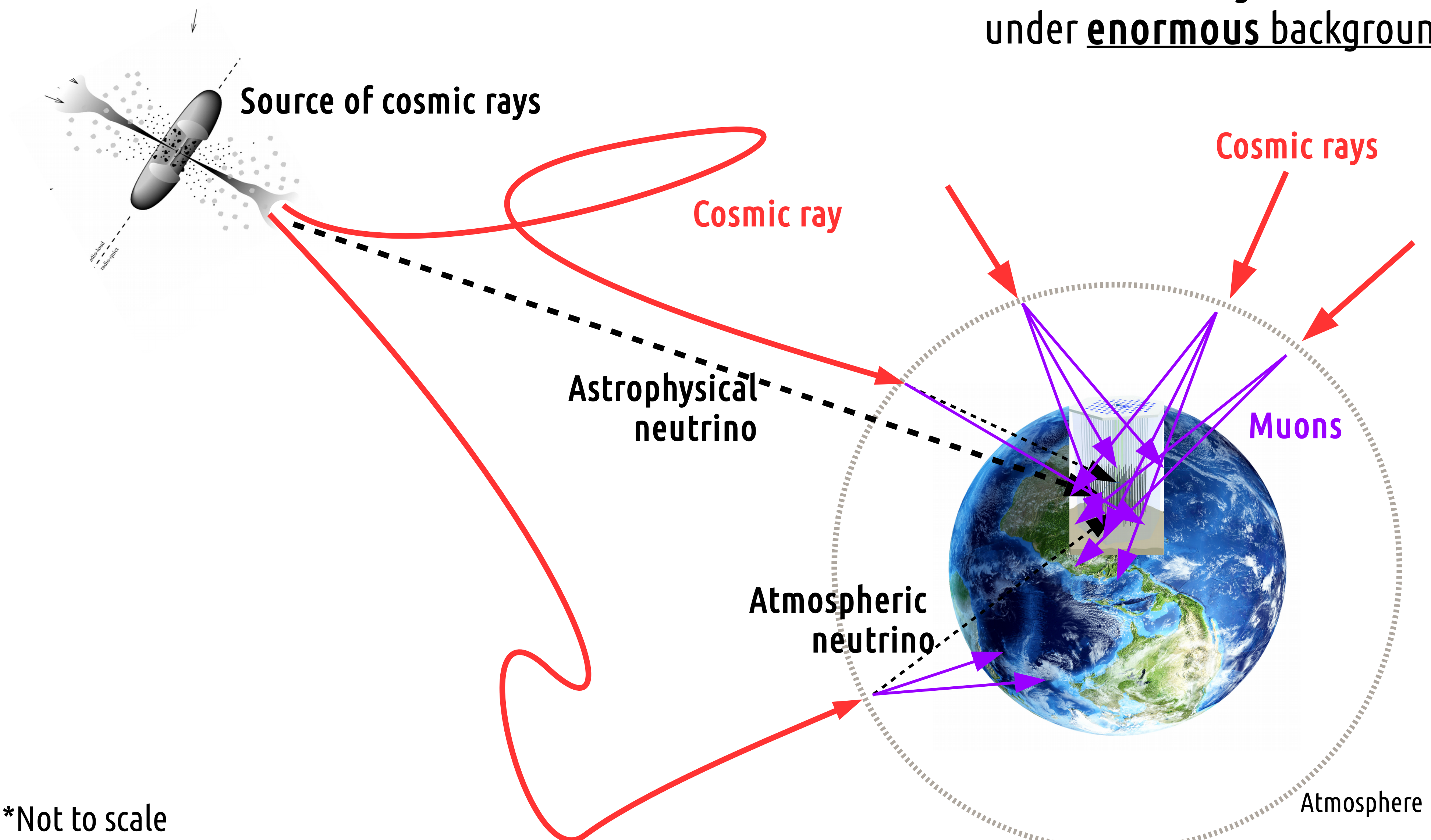


# Measuring atmospheric neutrino oscillations

where the signal is buried
under **enormous** background

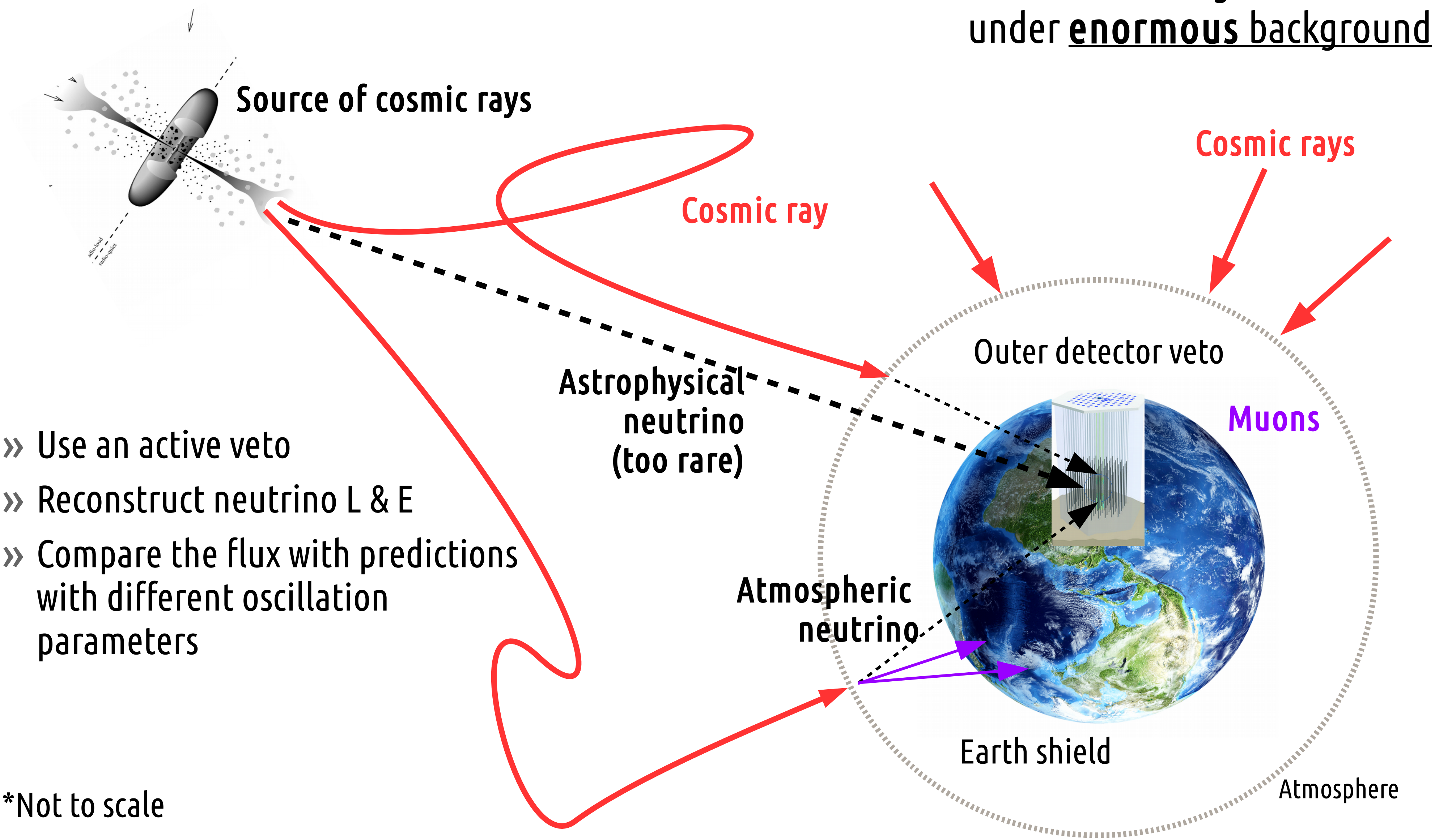



*Not to scale

Image: http://globe-views.com/dreams/earth.html

# Measuring atmospheric neutrino oscillations

where the signal is buried under **enormous** background

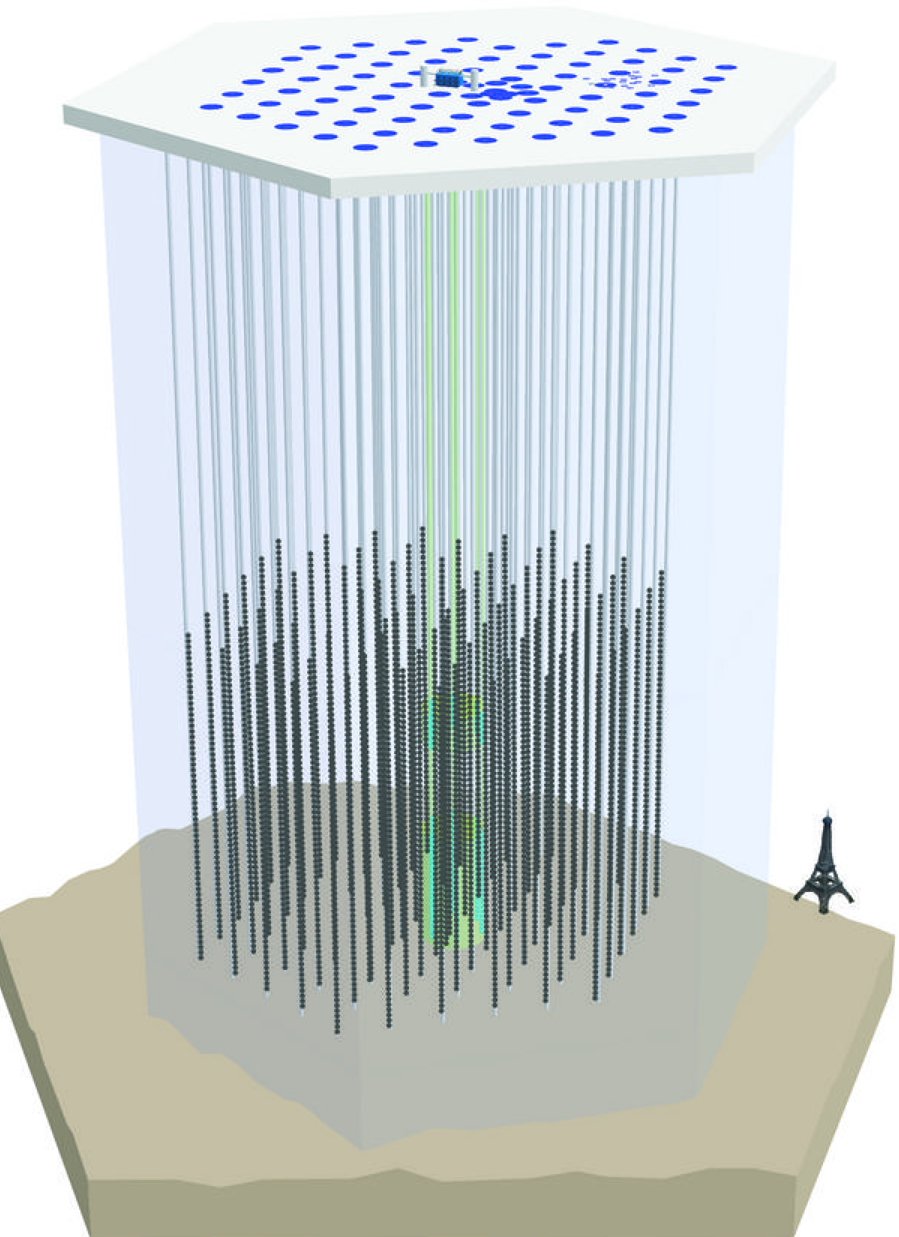



- Use an active veto
- Reconstruct neutrino L & E
- Compare the flux with predictions with different oscillation parameters

*Not to scale

Image: http://globe-views.com/dreams/earth.html

# The detectors in IceCube



- IceCube – $E_\nu$ > 100 GeV
  - 78 strings w/60 DOMs
  - 17m DOM spacing, 125m string spacing
- DeepCore – $E_\nu$ > 10 GeV
  - +8 strings w/60 HQE DOMs
  - 7m DOM spacing, 40-70m string spacing
- PINGU (proposal) – $E_\nu$ > 4 GeV
  - +40 strings w/96 HQE DOMs
  - 3m DOM spacing, 20m string spacing
  - ~20x photocathode density

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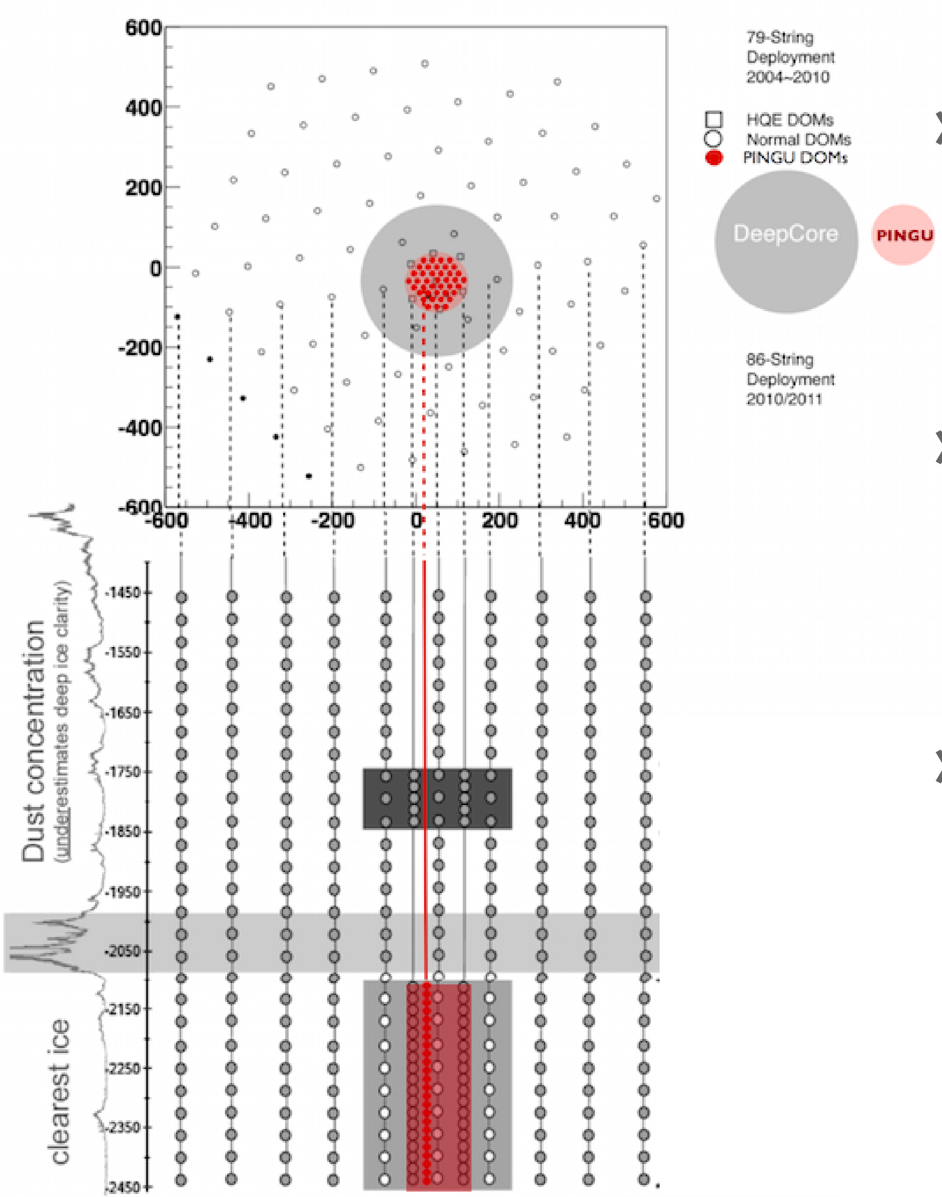


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# Increasing precision

How to move down in energy to make more precise measurements of neutrino oscillations?
- Background
- Reconstruction
- Analysis

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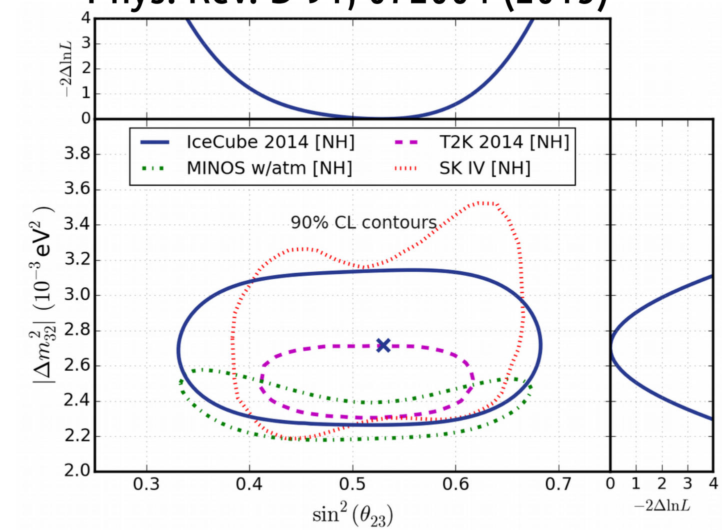
# Increasing precision

Phys. Rev. D 91, 072004 (2015)

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- Analysis

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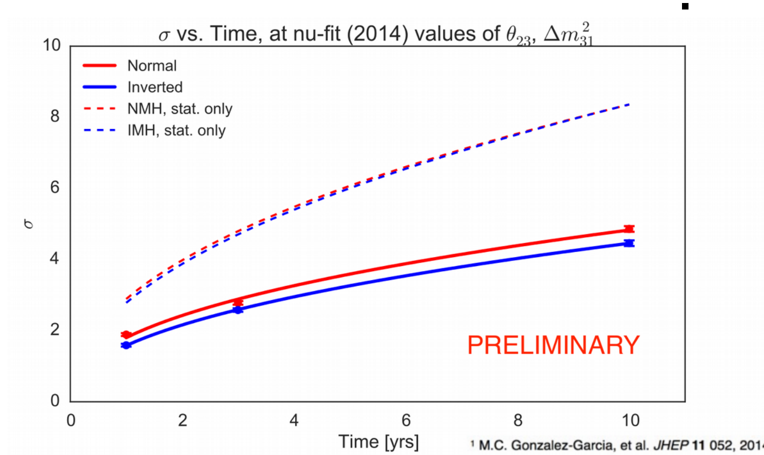
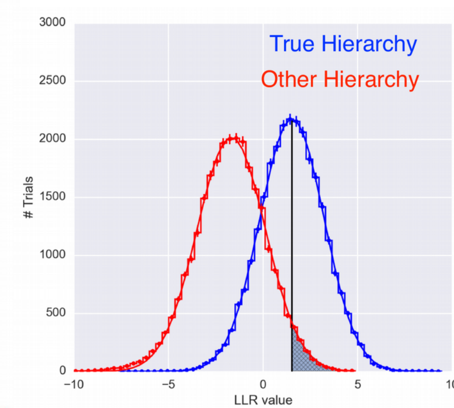


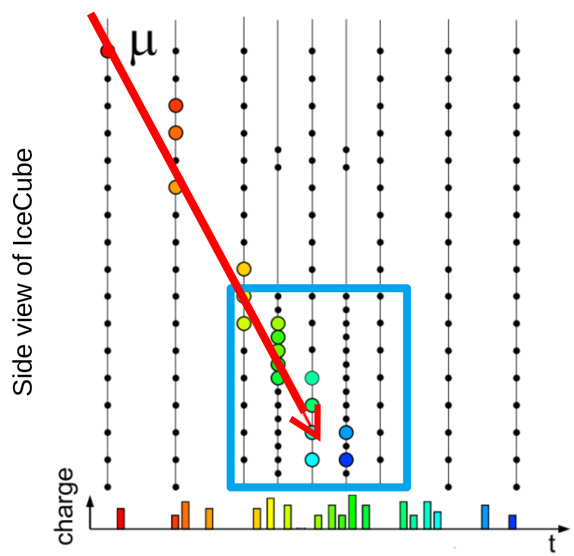
# I. Background

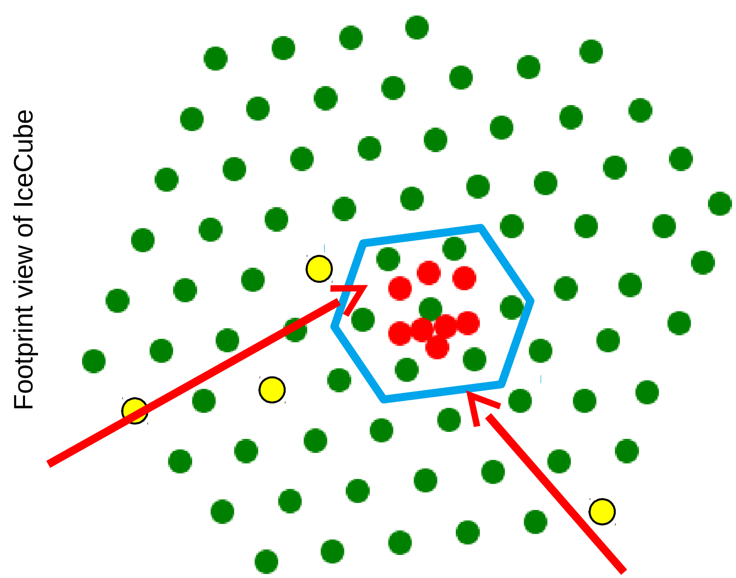
» Muons from air showers

  » Starting events → IceCube as veto for DeepCore & PINGU

  » Tag muons directly from data

  » Use “event quality” to remove misreconstructions



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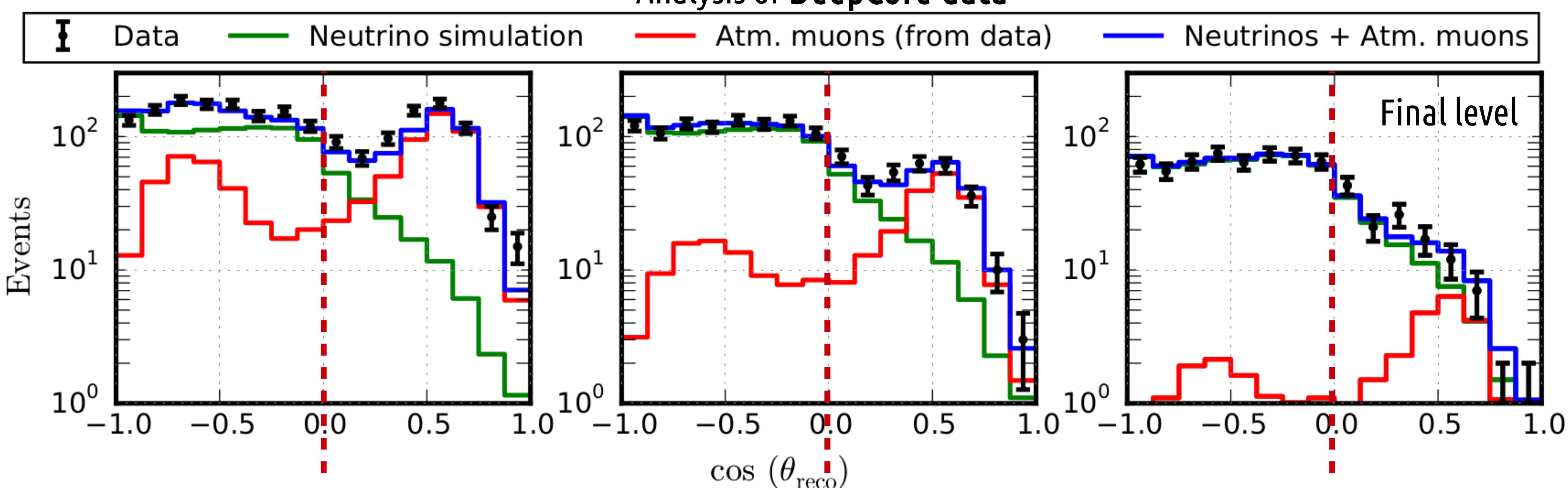
Analysis of **DeepCore data**

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# I. Background

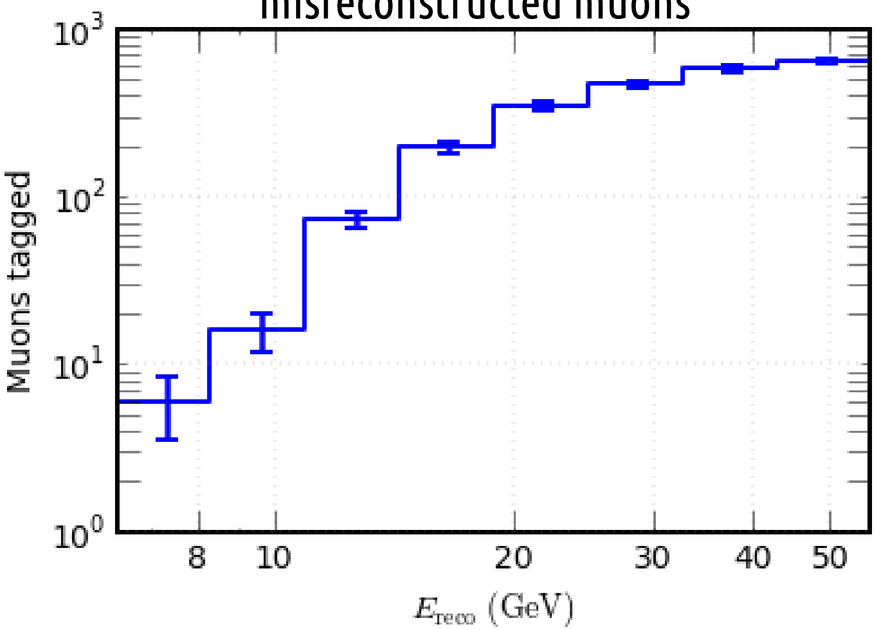
» Muons from air showers

  » Starting events → IceCube as veto for **DeepCore & PINGU**

  » Tag muons directly from data

  » Use "event quality" to remove misreconstructions

Analysis of **DeepCore data** misreconstructed muons




» IceCube veto useful for DC & PINGU

» Background muon rate α Ereco

  » Less relevant for PINGU than DC

» **DC results used only up-going events**

  » Down-going region under study in DC

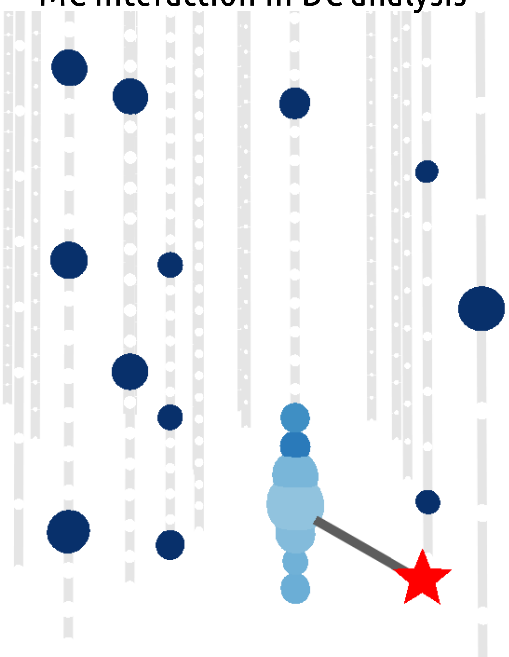
  » PINGU plans to (eventually) use all-sky

# I. Background

- Individual DOM noise rates studied
  - 400-700 Hz individual noise rates
  - Simulation parameters varied
  - Models updated with calibration campaigns
  - **DeepCore**
    - Negligible impact on reconstructed observables and results
  - **PINGU**
    - Negligible impact on reconstructions, small impact on eff. area

# II. Neutrino reconstruction

MC interaction in DC analysis

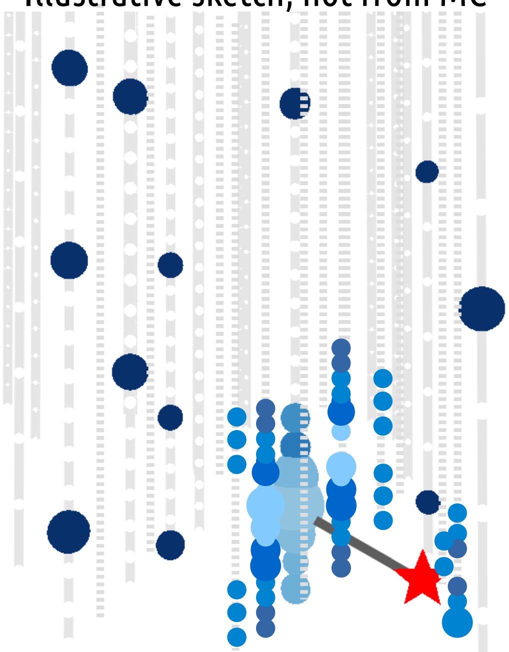


- Typical LE neutrino in **DeepCore**
- 7 DOMs with signal hits
- Enu = 12 GeV
  - 8 GeV muon (42 m)
  - 4 GeV hadronic shower

- Neutrino identification by daughters
  - CC $\nu_\mu$ → Muons (long-range particles, taggable)
  - CC $\nu_\tau$ & $\nu_e$ → Short lived leptons
  - Every interaction → Hadrons
  - Main ID power: muons → muon neutrinos
- Neutrino reconstruction
  - Based on # of photons & arrival times
  - Mostly noise-free signals at DOMs
  - Delayed by scattering, reduced by absorption
  - **DeepCore**: few photons in interesting events

# II. Neutrino reconstruction

*Illustrative sketch, not from MC



- Typical LE neutrino in **PINGU***
- ~70 DOMs with signal hits
- Enu = 12 GeV
  - 8 GeV muon (42 m)
  - 4 GeV hadronic shower

## Neutrino identification by daughters

- CC $\nu_\mu \rightarrow$ Muons (long-range particles, taggable)
- CC $\nu_\tau$ & $\nu_e$ $\rightarrow$ Short lived leptons
- Every interaction → Hadrons
- Main ID power: muons → muon neutrinos

## Neutrino reconstruction

- Based on # of photons & arrival times
- Mostly noise-free signals at DOMs
- Delayed by scattering, reduced by absorption
- **PINGU**: ~10x more photons per event

# II. Neutrino reconstruction

<u>**Latest published DeepCore results**</u>

» Zenith: Require a core of *direct* (unscattered) photons

» **Minimize impact of ice properties**

» 30% efficiency

» **Fit zenith angle with direct photons (assume no scattering)**

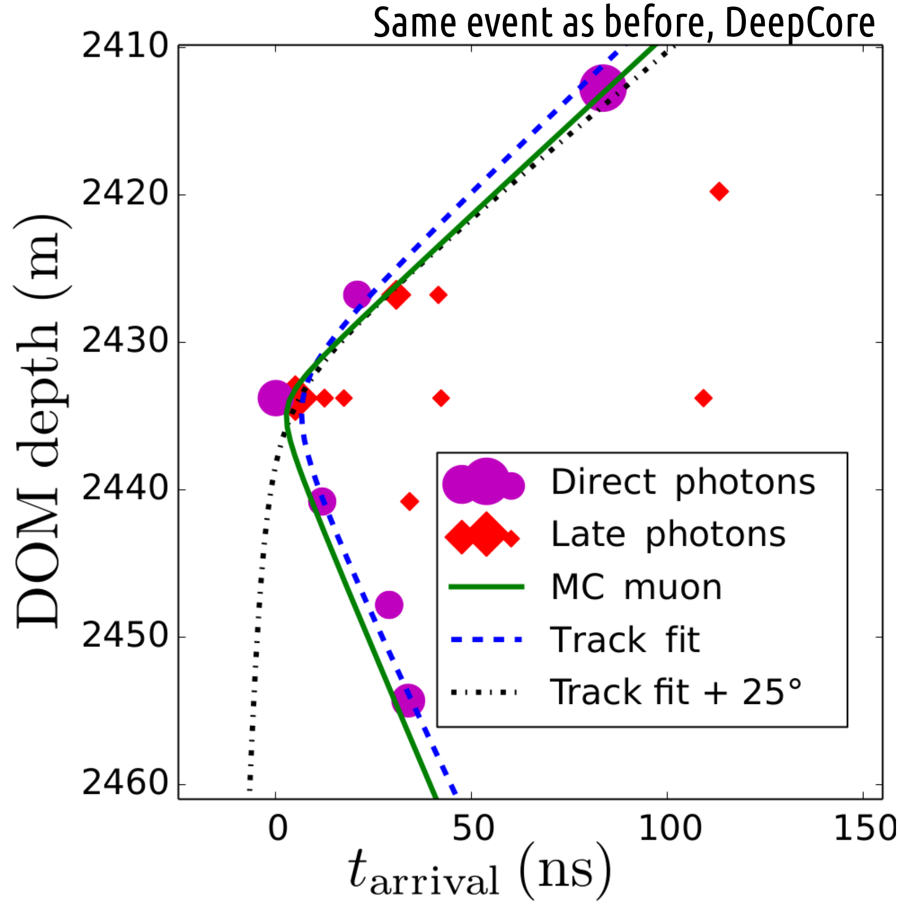
» Energy: track+cascade hypothesis

» Fit track length and vertex position/E

» Keep direction fixed

» Assume track and cascade are collinear

Same event as before, DeepCore



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  - Keep direction fixed
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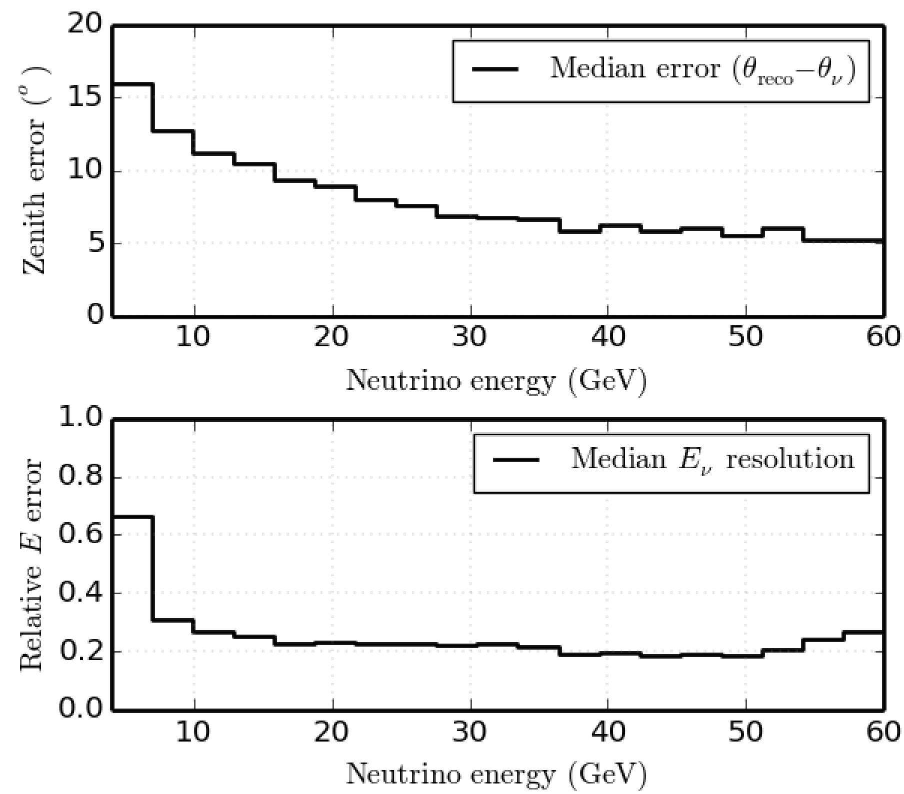
Resolutions for DeepCore (published result)

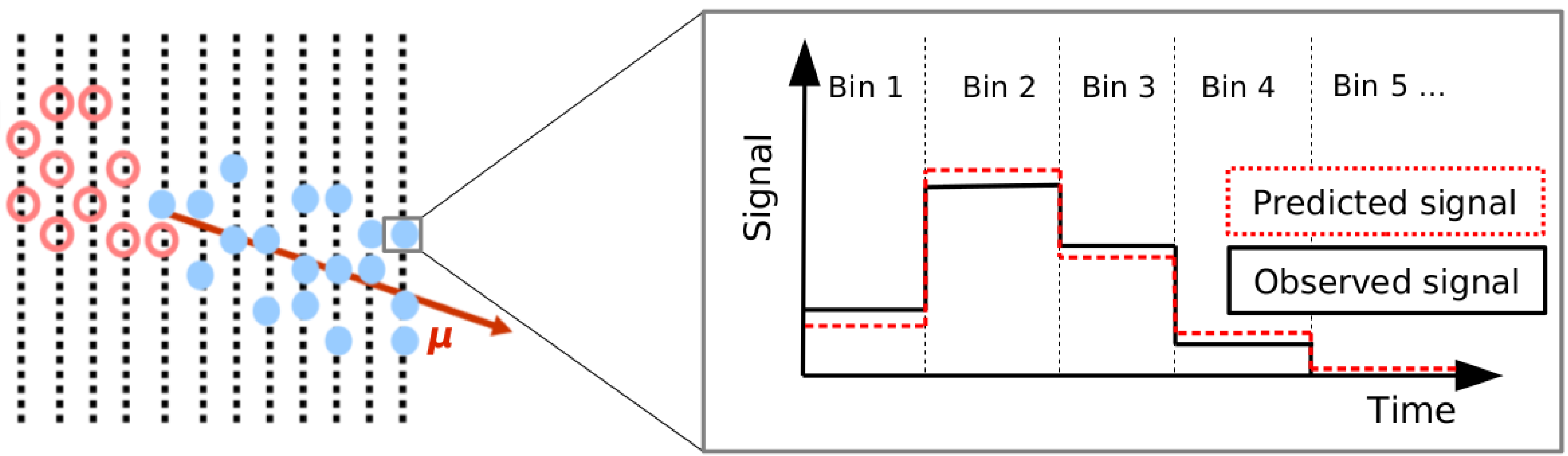


# II. Neutrino reconstruction

<u>More sophisticated reconstruction</u>

- Use arrival time of individual photons
- Fit energy + direction simultaneously
- <u>No need for direct photons, use all events</u>
- Include ice properties (from ice models)
- Assume track and cascade are collinear

- **Similar resolutions in DeepCore**
- **Higher efficiency**
- Working in **DeepCore**, testing vs data
- Used in **PINGU** analyses



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**More sophisticated reconstruction**

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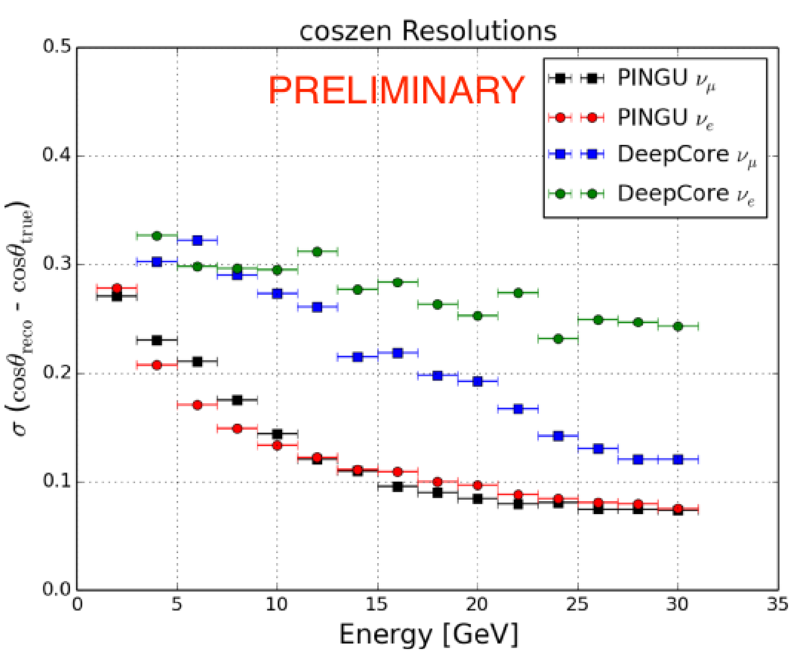
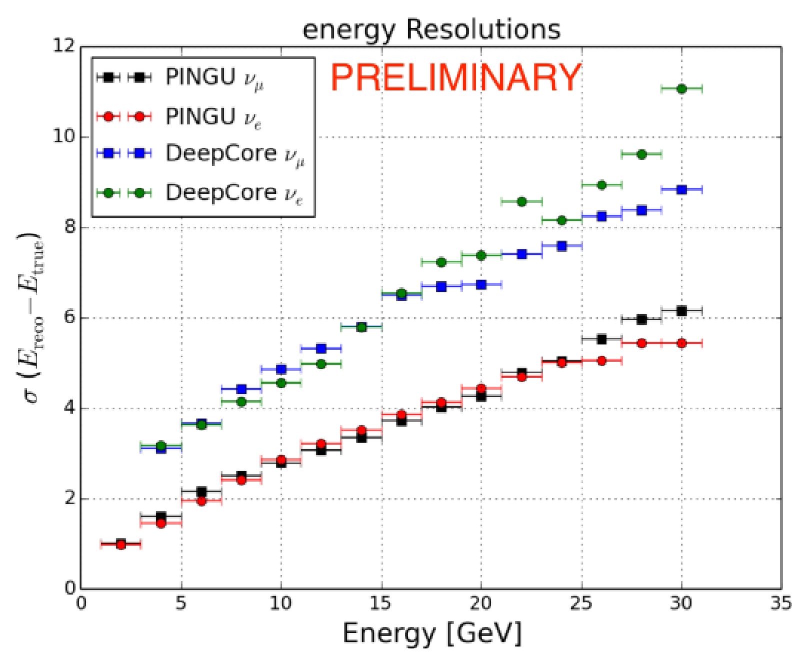


# II. Neutrino identification

- In **DeepCore** → ratio of 2 fits
  - Assume track+cascade vs only cascade
  - Current results: $\chi^2$ ratio in directional fit →
  - Studying ΔLLH in "sophisticated" reco

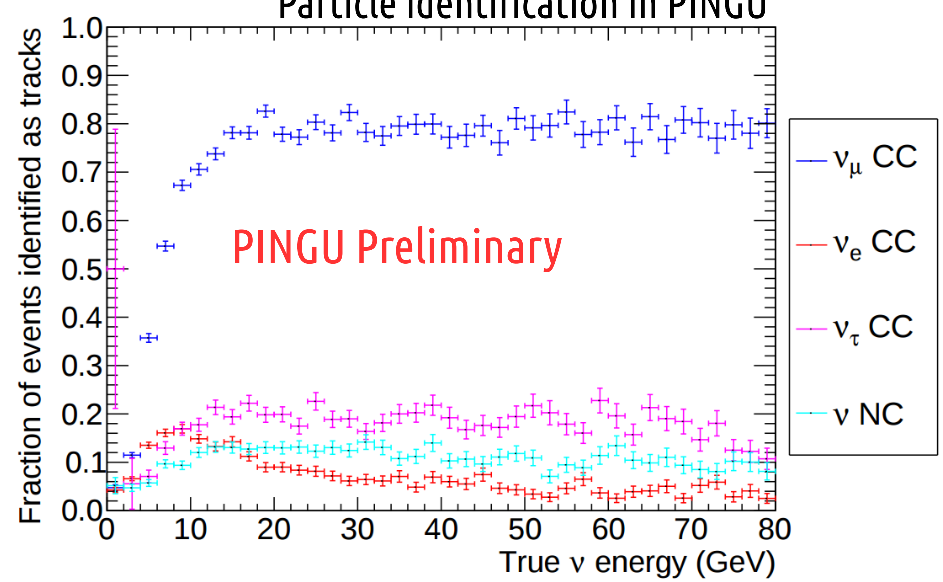
Particle identification in DeepCore

Stabilizes for E > 30 GeV
60% of muon tracks classified correctly
30% of cascades misclassified as tracks

Difference in probabilities of 30%
Reduced to 20% at 10 GeV

- In **PINGU** → multivariate method
  - Exploit topological variables
  - Combine discrimination power
  - Can be optimized for sensitivity
  - Better performance than DeepCore

Particle identification in PINGU



# III. Analysis – syst. uncertainties

## Implemented in **DeepCore** latest result

| Source of error | | Nominal value from | Uncertainty |
|---|---|---|---|
| Neutrino interactions | Total cross-section scaling | GENIE model | Free |
| | Linear energy dependence | | E^(+/-0.03) |
| | Axial mass of non-DIS events | | ~ +/-20%* |
| Atmospheric neutrino flux | Overall normalization | Honda 2015 | Free |
| | Spectral index | | E^(+/-0.04) |
| | NuE relative normalization | | +/- 20% |
| Detection | Hadronic energy scaling | Geant4 (model) | +/- 5% |
| | DOM overall efficiency | Muons, flashers | +/- 10% |
| | DOM angular acceptance (scattering in hole-ice) | Fit to flasher data | As large as 50%‡ |
| | Bulk-ice model | | Two models |

+neutrino oscillation parameters

* Exact value depends on the individual process

‡ Largest deviation for photons perpendicular to PMT direction

# III. Analysis – syst. uncertainties

## Being studied in **DeepCore data analyses**

| Source of error | | Nominal value from | Uncertainty |
|---|---|---|---|
| Neutrino interactions | Total cross-section scaling | GENIE model | Free |
| | Linear energy dependence | | E^(+/-0.03) |
| | DIS cross section | | From models |
| | Axial mass of non-DIS events | | ~ +/-20%* |
| Atmospheric neutrino flux | Overall normalization | Honda 2015 | Free |
| | Spectral index | | E^(+/-0.04) |
| | Neutrino/Antineutrino ratio | | E dependent |
| | NuE relative normalization | | +/- 3% |
| Detection | Hadronic energy scaling | Geant4 (model) | +/- 5% |
| | Hadronization/propagation | | From models |
| | DOM overall efficiency | Muons, flashers | +/- 10% |
| | DOM angular acceptance* (scattering in hole-ice) | Fit to flasher data | As large as 50%‡ |
| | Bulk-ice model | | Two models |

+neutrino oscillation parameters

* Exact value depends on the individual process

‡ Largest deviation for photons perpendicular to PMT direction

# III. Analysis – syst. uncertainties

## Being studied in **PINGU simulation/analyses**

- Uncertainties on oscillation parameters included (atmospheric parameters dominant)
  - Using priors from nu-fit.org on solar parameters and $\theta_{13}$ (delta-cp fixed at 0)
- Detailed studies of **cross sections (6 parameters)** and **flux uncertainties (18 parameters)**
- The most relevant (non-oscillation) uncertainties are listed

| Source of error | | Nominal value | Uncertainty |
|---|---|---|---|
| Neutrino interactions and effective area (7+ parameters) | Total cross-section scaling | GENIE model | Free |
| | DIS cross section (4 parameters) | | From models |
| | Axial mass of non-DIS events (2 parameters) | | ~ +/-20%* |
| Atmospheric neutrino flux (18+ parametes) | Overall normalization (Aeff scaling) | Honda 2015 | Free |
| | Spectral index | | E^(+/-0.05) |
| | π & κ production and decays | | From models |
| | Neutrino/Antineutrino ratio | | 10% |
| | NuE relative normalization | | +/- 3% |
| Detection | Energy scale | Muons, flashers | +/- 10% |

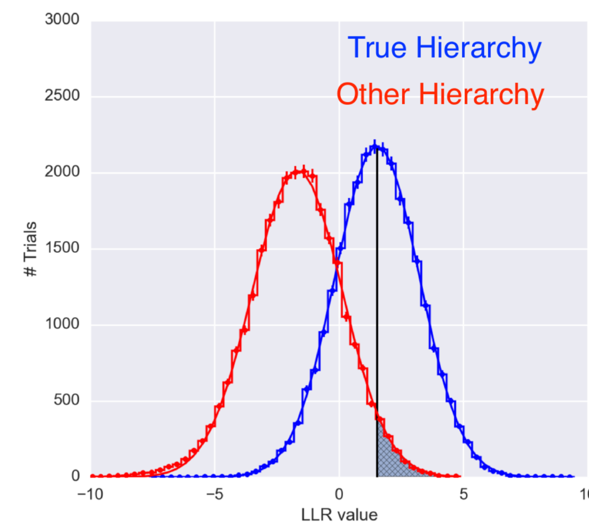
Atmospheric neutrino uncertainties from Phys.Rev.D74:094009,2006

# III. Analysis – methods

» **DeepCore**

Likelihood ratio with high stats. MC

- » Data and full MC sets selected, reconstructed
- » Detector systematics simulated in full → parameterized




» **PINGU**

- » Detector response from MC (created, selected, reconstructed and parameterized)

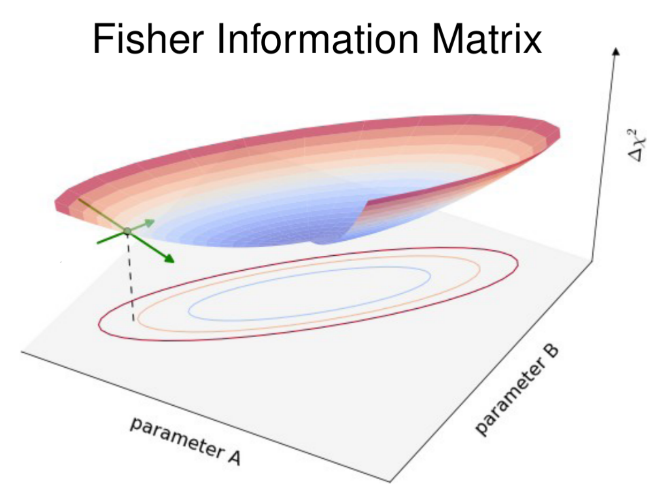
a) Likelihood ratio

- » Draw and fit pseudo-experiments

b) $\Delta\chi^2$ based analysis

- » Gradients in parameter space to get covariance matrix
- » Angle $\theta_{23}$ covariance matrix calculated directly (no gradients)
- » Fast, well suited for optimization

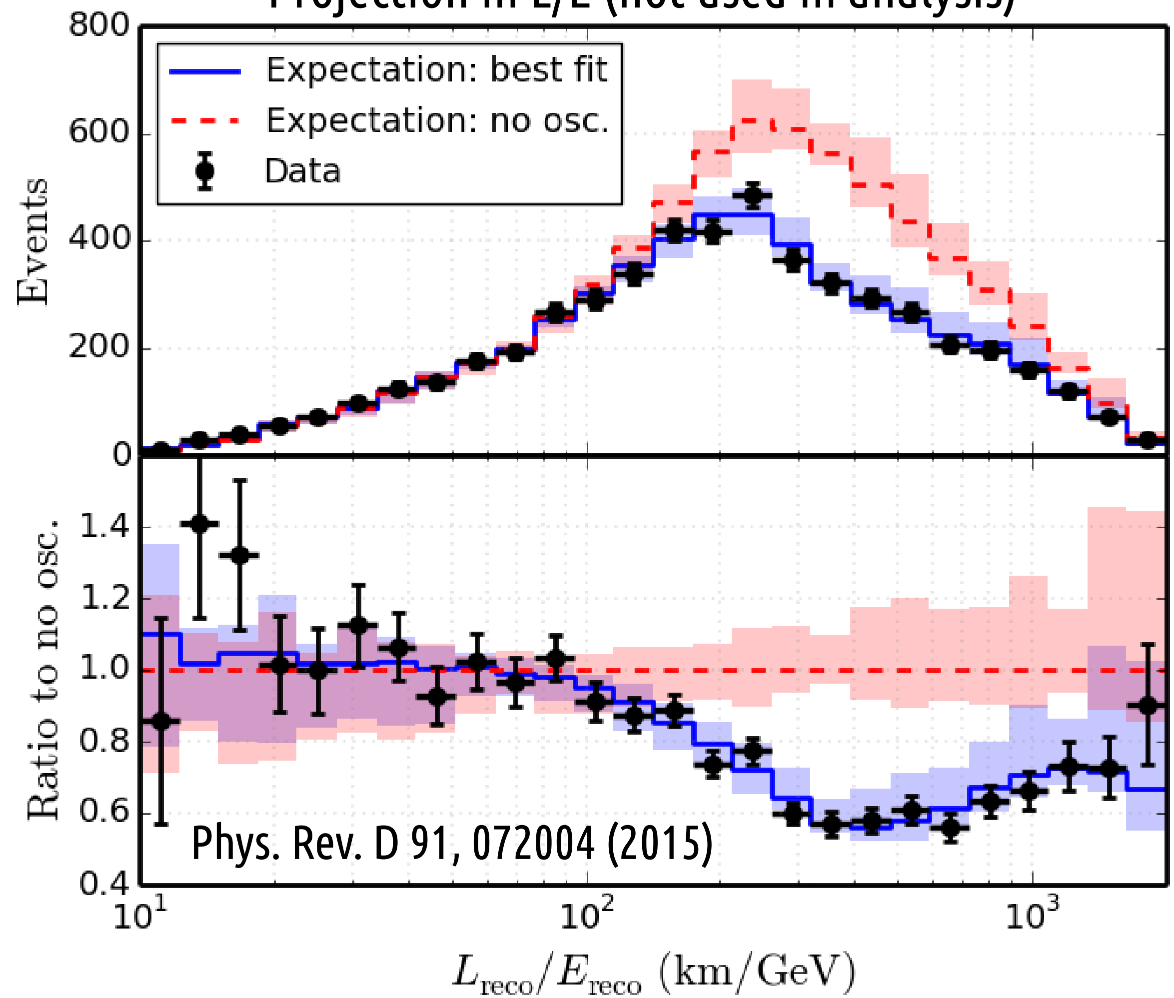
Good agreement between methods



# DeepCore results

- Using **muon tracks only**
- Best fit to the data from a 2D analysis (E, θ)
- Up-going events
- Using E < 56 GeV
- 5174 events in 3 years
- In 2D fit histogram
  - $\chi^2$ = 54.9 / 56 d.o.f.

Projection in L/E (not used in analysis)




Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc

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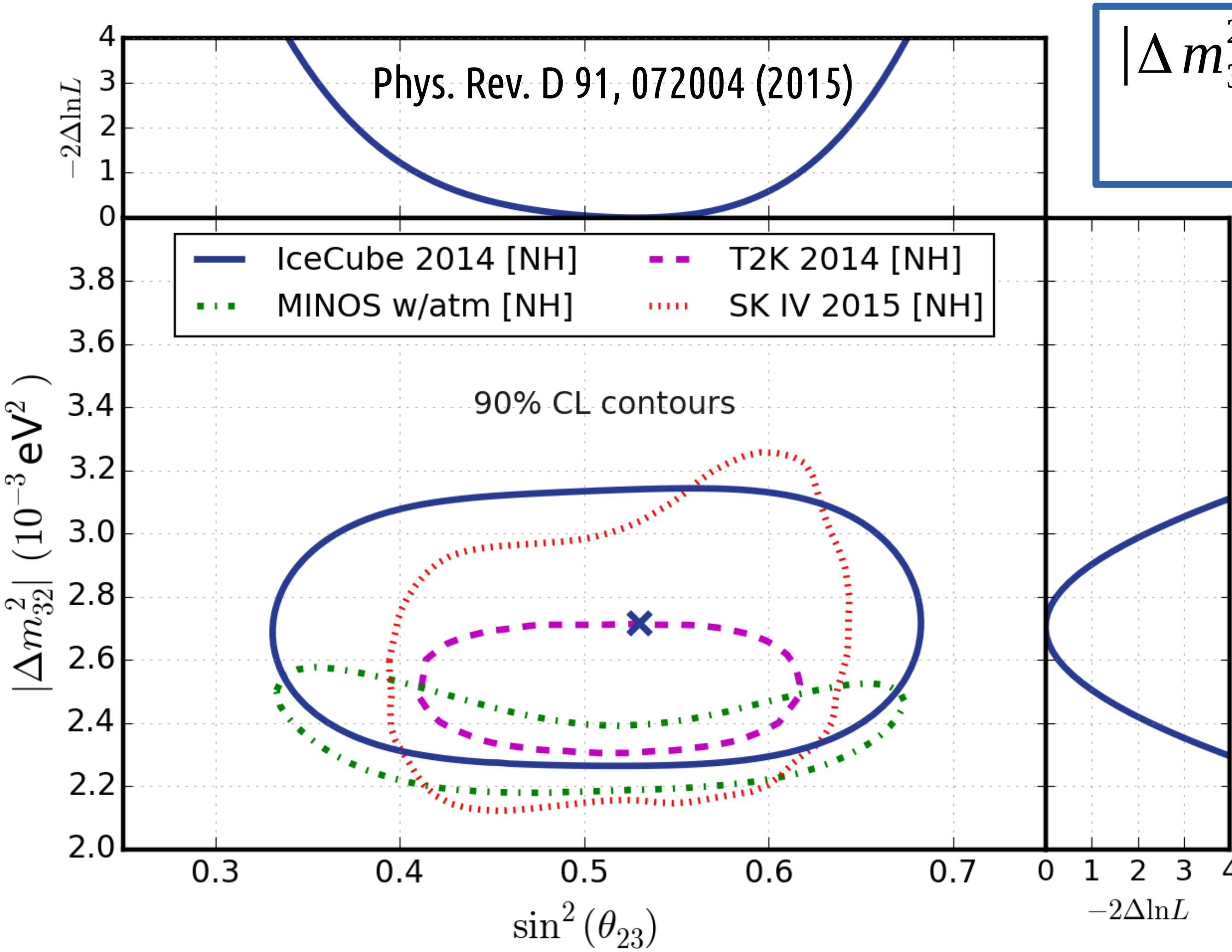



$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

- First time a very large volume neutrino detector fits in this figure
- Measuring large L/E range
- Affected by different syst. than accelerator results
- Stat. only errors

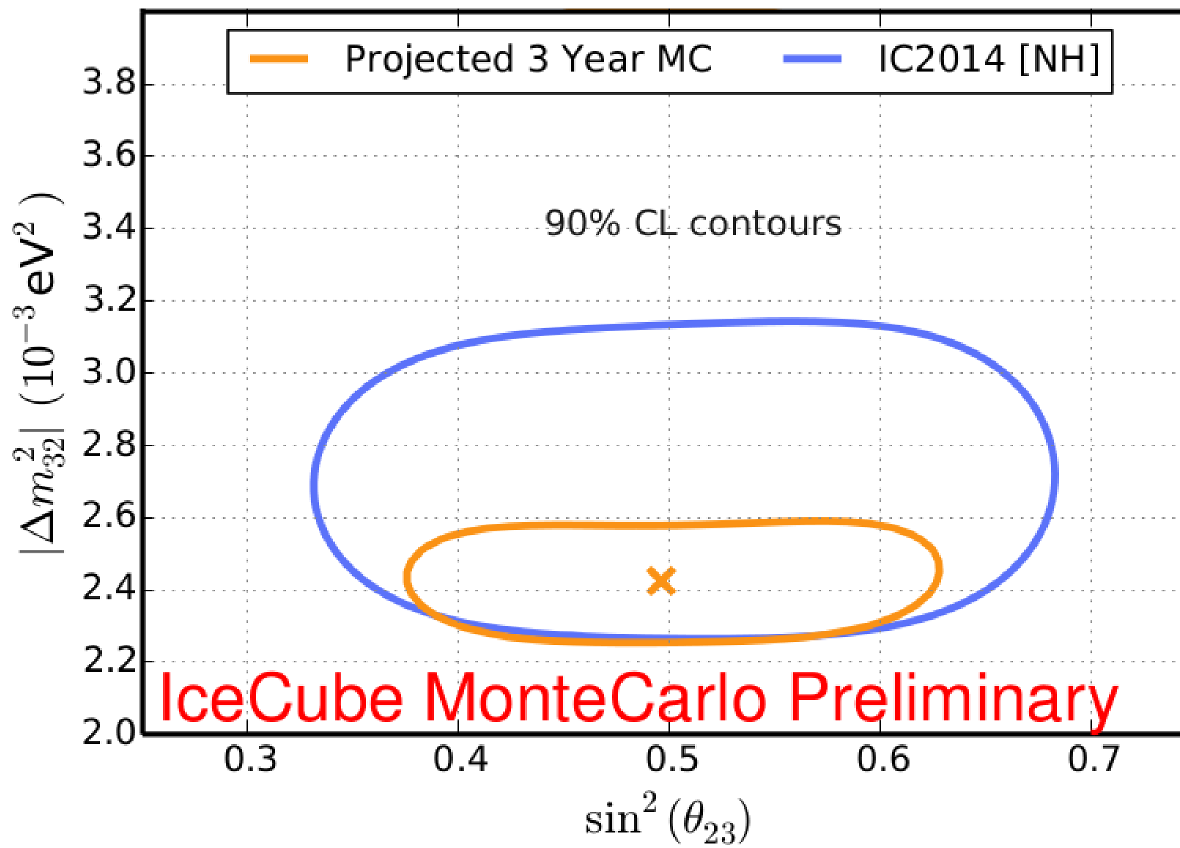
$$\sigma(|\Delta m^2_{32}|) = ^{+0.14}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sigma(\sin^2\theta_{23}) = ^{+0.06}_{-0.08}$$

Data of this analysis available at http://icecube.wisc.edu/science/data/nu_osc

# DeepCore – projected sensitivity

Projected MC sensitivity from re-analysis of 3 years of DeepCore data*

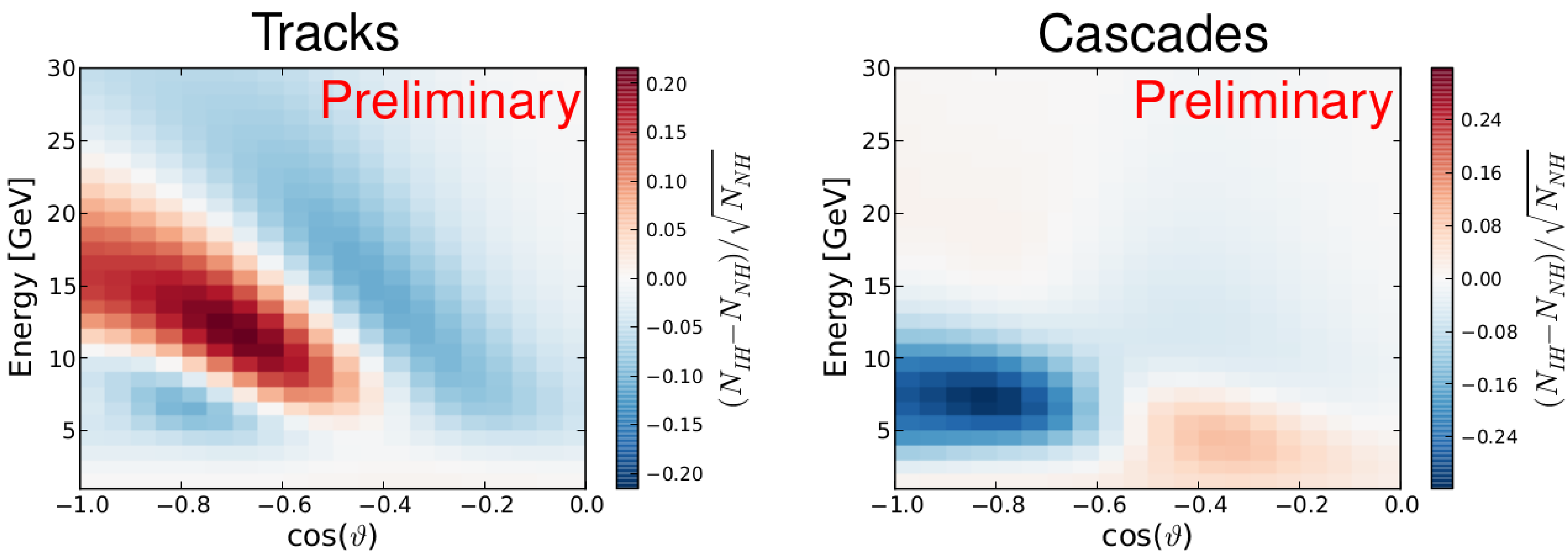
- Classify interactions:
  - Between track- and cascade-like
- Inclusive selection:
  - Direct hits required (5 → 3)
- Sophisticated reconstruction
  - Global fit of all parameters
- Including events from all directions
  - Also down-going (atm. Muons)
- Renewed calibration efforts
  - Noise modeling, angular acceptance, individual DOM behavior




*Projections produced assuming current knowledge. Can change if newer information is available.

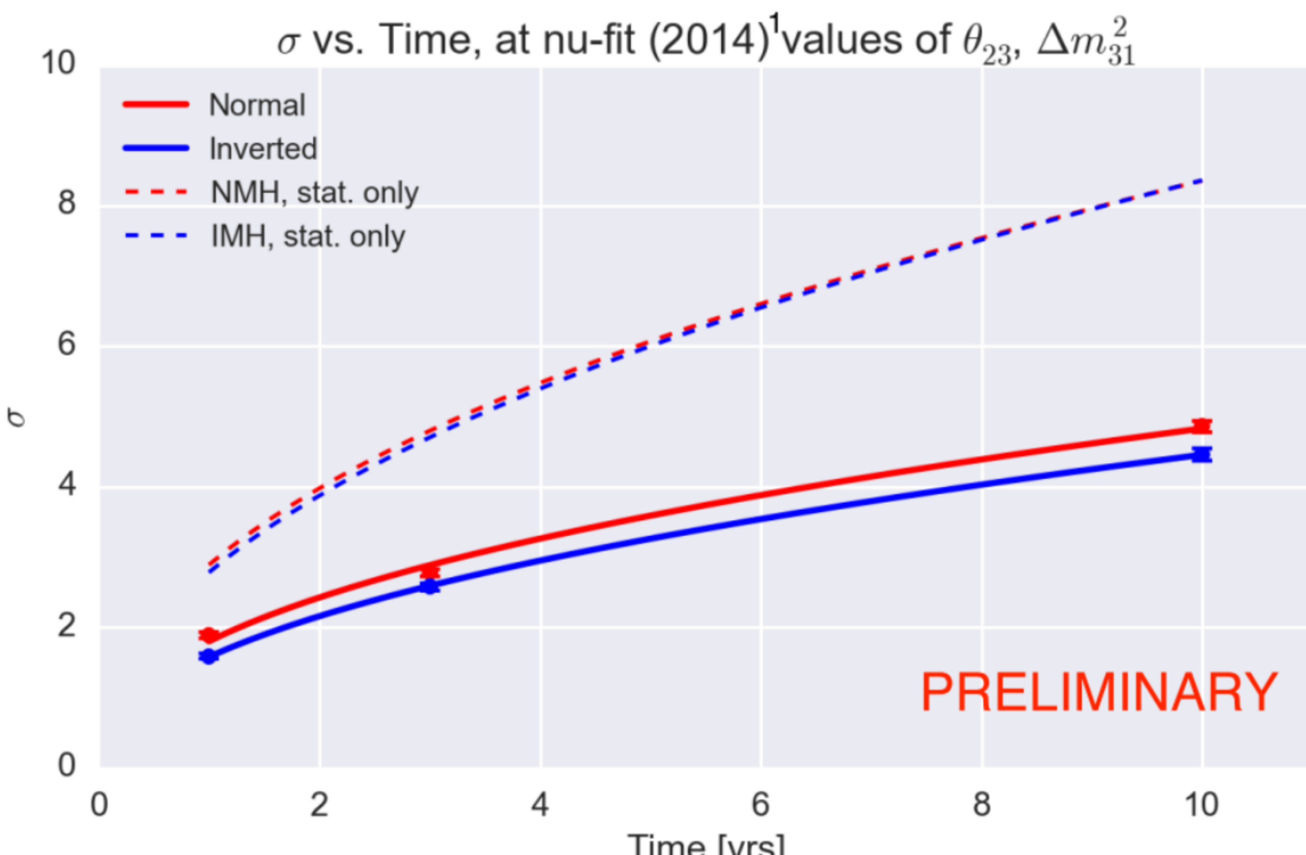
# PINGU – mass ordering signature

- Bin-wise significance for one year of data
- Tracks are mostly muon neutrinos
- Cascades are mostly electron neutrinos



# PINGU – sensitivity vs time

- 3σ identification with 3-4 years of data
  - Oscillation parameters are most important source of error
  - Slightly better sensitivity to normal hierarchy




Significance including only one set of uncertainties

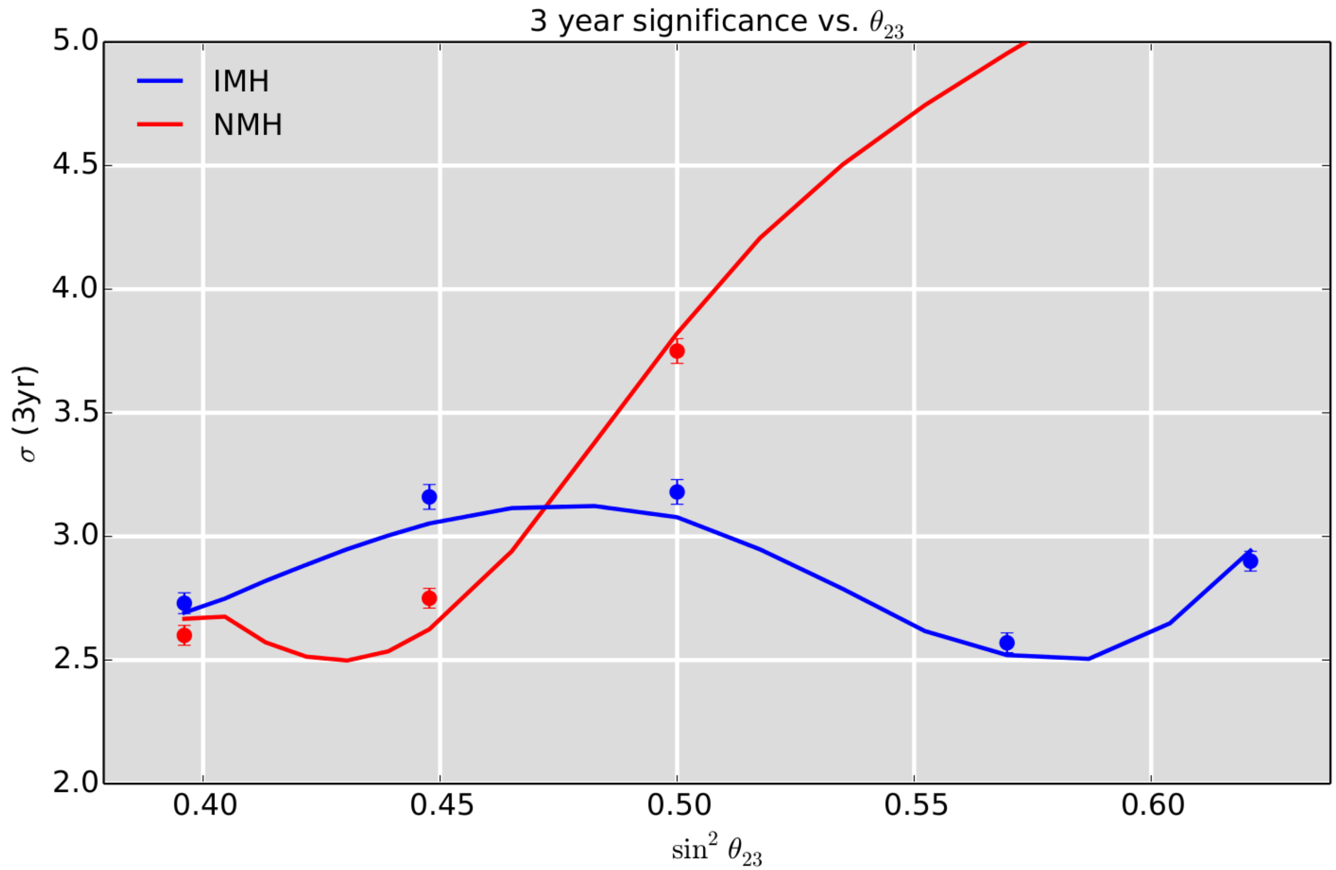
| Type | 3yr σ (NMH) | 3yr σ (IMH) |
|---|---|---|
| stat. only | 4.84 | 4.82 |
| flux only | 4.55 | 4.56 |
| det. only | 4.06 | 3.99 |
| $\theta_{23}$ only | 3.52 | 3.26 |
| osc. only | 2.96 | 2.53 |
| All | 2.90 | 2.51 |

Preliminary

*delta-cp kept fixed at 0 (injected)

# PINGU – sensitivity vs $\theta_{23}$

- Mass ordering sensitivity dependence on $\theta_{23}$
  - Lines from $\Delta\chi^2$ based analysis
  - Points from likelihood ratio studies



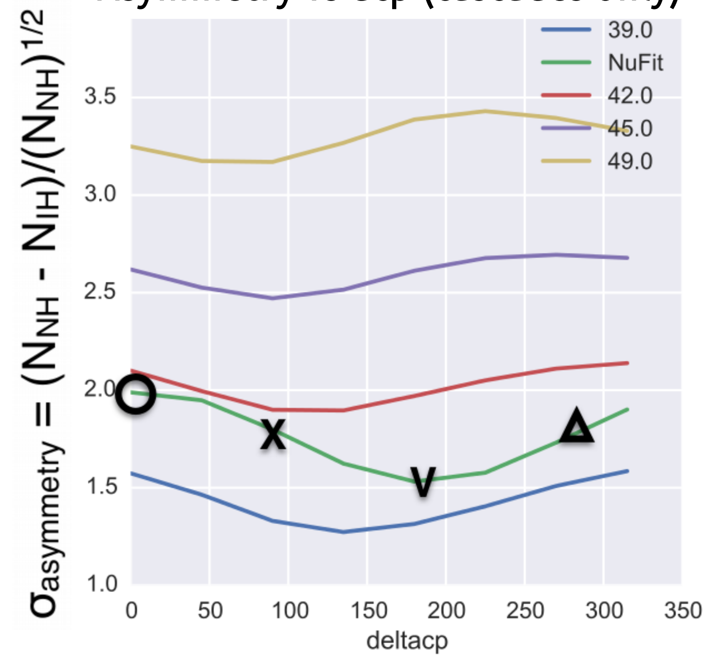
# PINGU – sensitivity vs $\delta_{CP}$

» Impact of the imaginary phase on sensitivity
  - » Projections shown for the 3-year benchmark
  - » Sensitivity changes by ½σ depending on true $\delta_{CP}$ value

Full LLR analysis

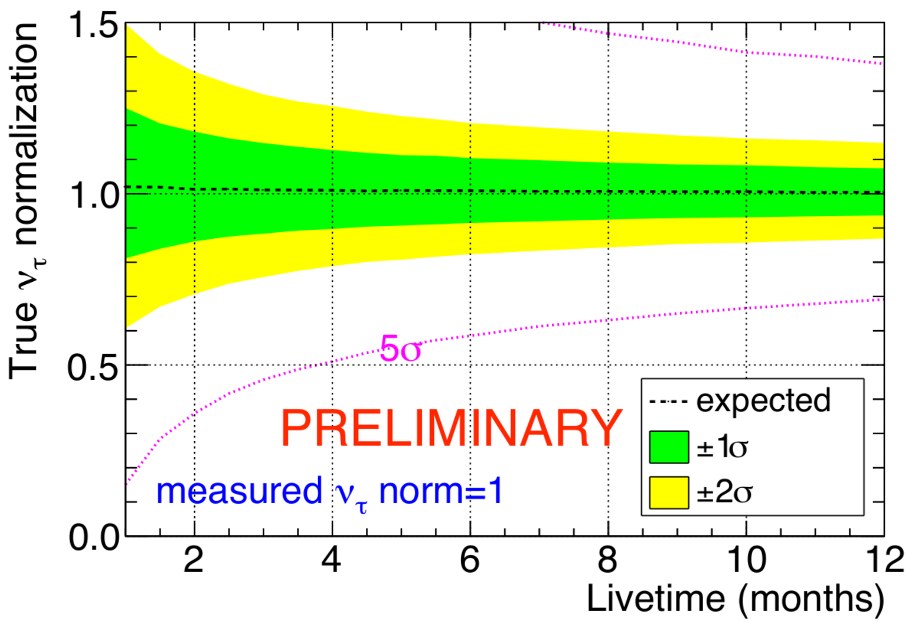
| | $\delta_{cp}$(deg) | $\sigma_{NH}$ | $\sigma_{IH}$ |
|---|---|---|---|
| ○ | 0 | 2.80 | 2.53 |
| X | 90 | 2.49 | 2.32 |
| V | 180 | 2.32 | 2.01 |
| △ | 270 | 2.40 | 2.21 |

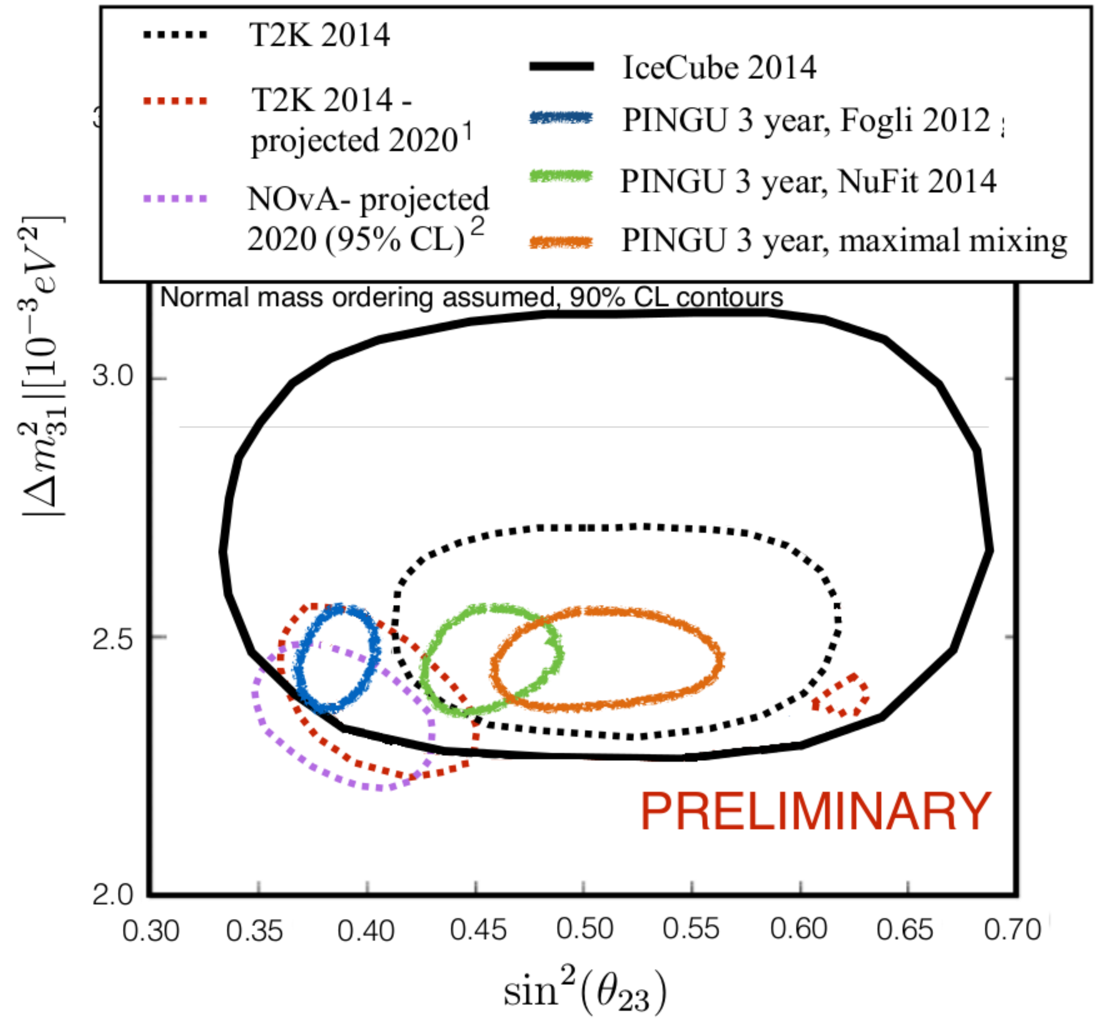
Asymmetry vs dcp (cascades only)



# PINGU – atm. params. sensitivity

- Competitive sensitivity to oscillation parameters expected
- Appearance of tau neutrinos at 5σ within a month of operation



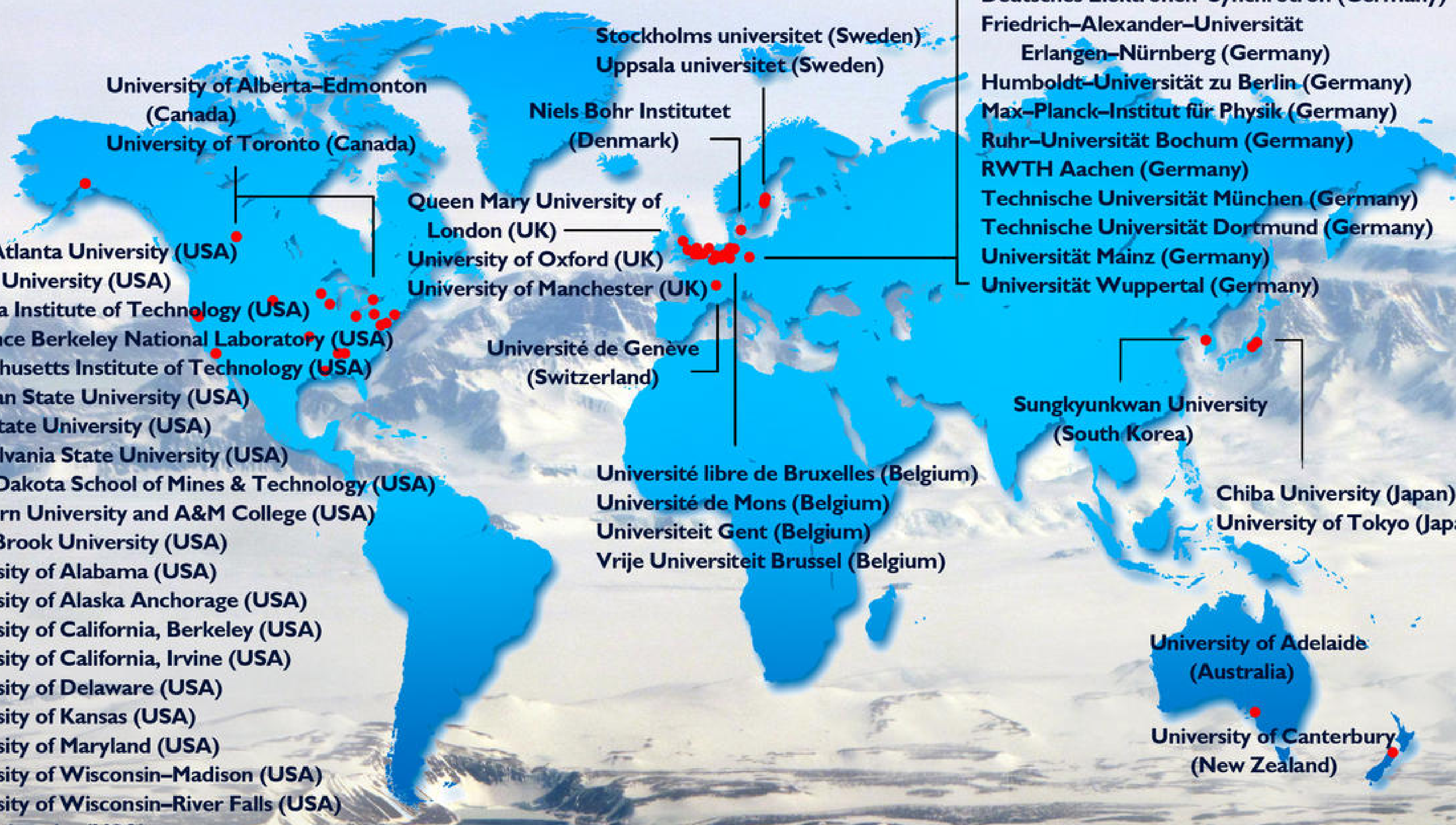



# Summary and outlook

- IceCube DeepCore has demonstrated it can measure atmospheric neutrino oscillations
  - Current results in the same scale as dedicated experiments
  - Still far from its full potential, significant improvement expected

- PINGU can greatly enhance these measurements
  - Large statistics, reconstruction errors halved
  - Capable of identifying the mass ordering with 3σ in 3-4 years
  - Improve precision of oscillation parameters

# The IceCube–PINGU Gen2 Collaboration




## International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
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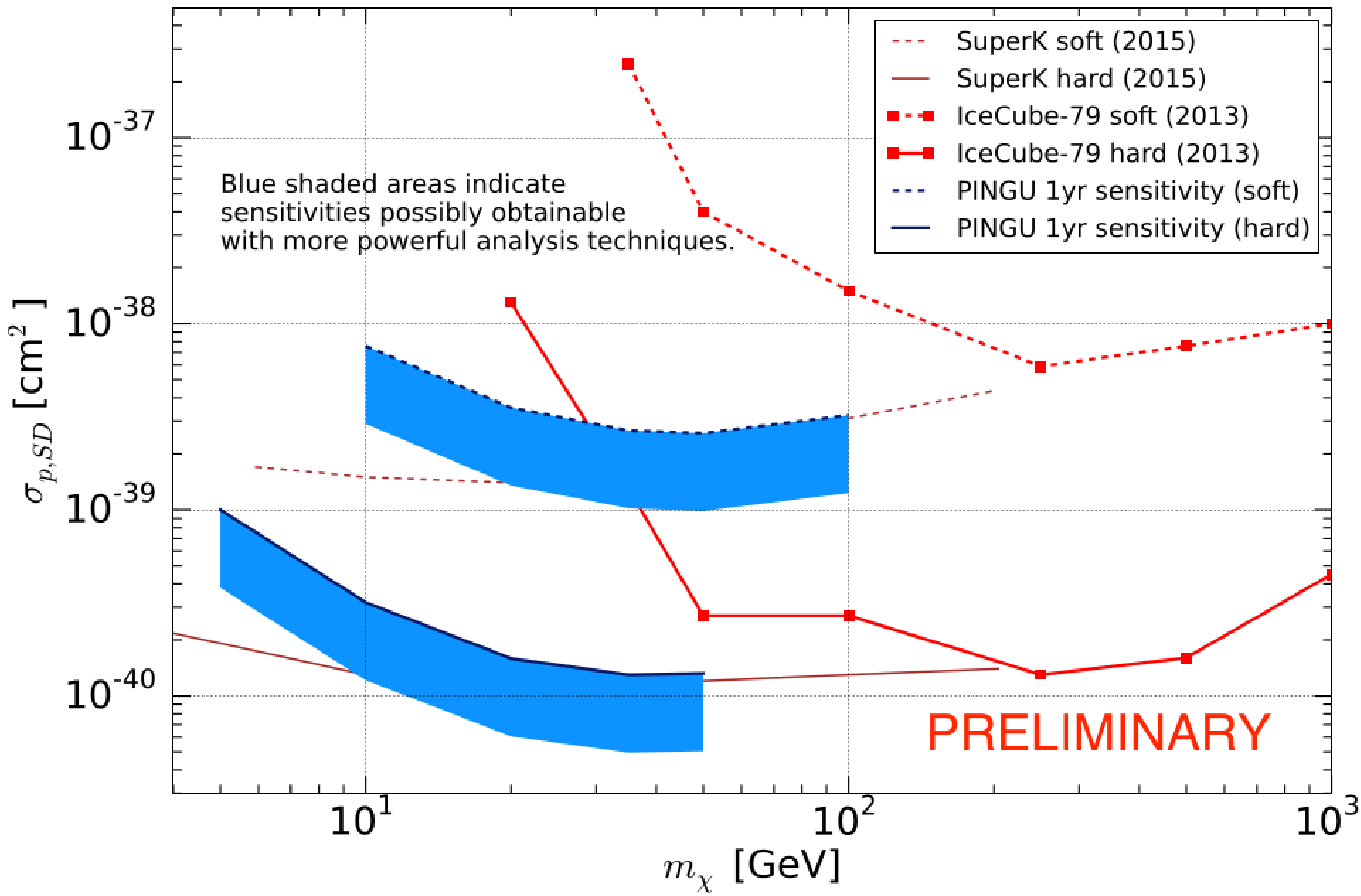
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

# PINGU – Dark matter searches



# PINGU - Atmospheric mixing