Neutrino Oscillations with IceCube DeepCore and PINGU

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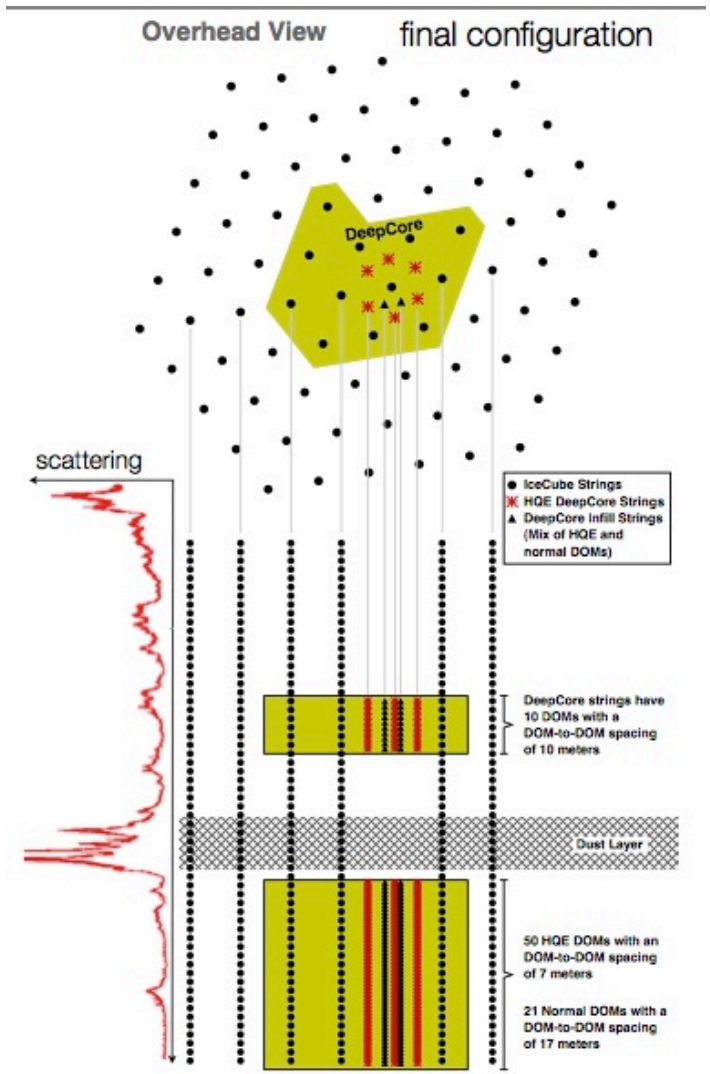
- ICDC/PINGU: before Project X: 3-10 years
- Atmospheric neutrinos: before and with Project X
- ICDC/PINGU with Project X

IceCube Deep Core

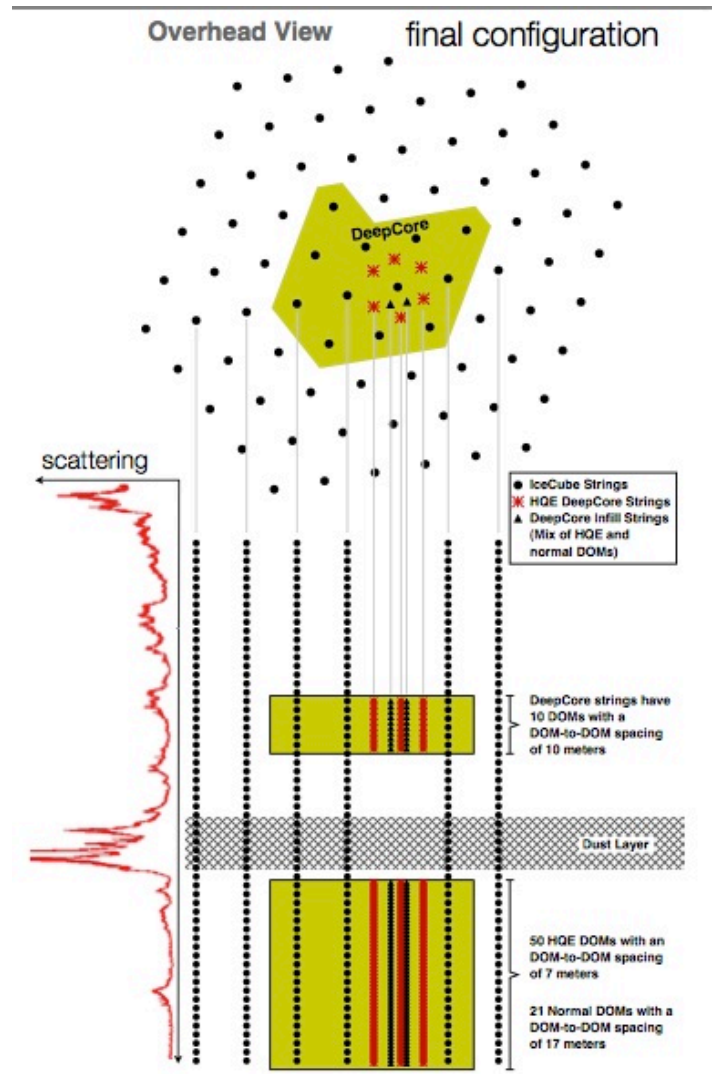
- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center

- 8 special strings, 72m IS, 7m DOM spacing
- ~ 5x higher effective photocathode density
- ~ 20Mton
- IceCube's top and outer layers: active veto

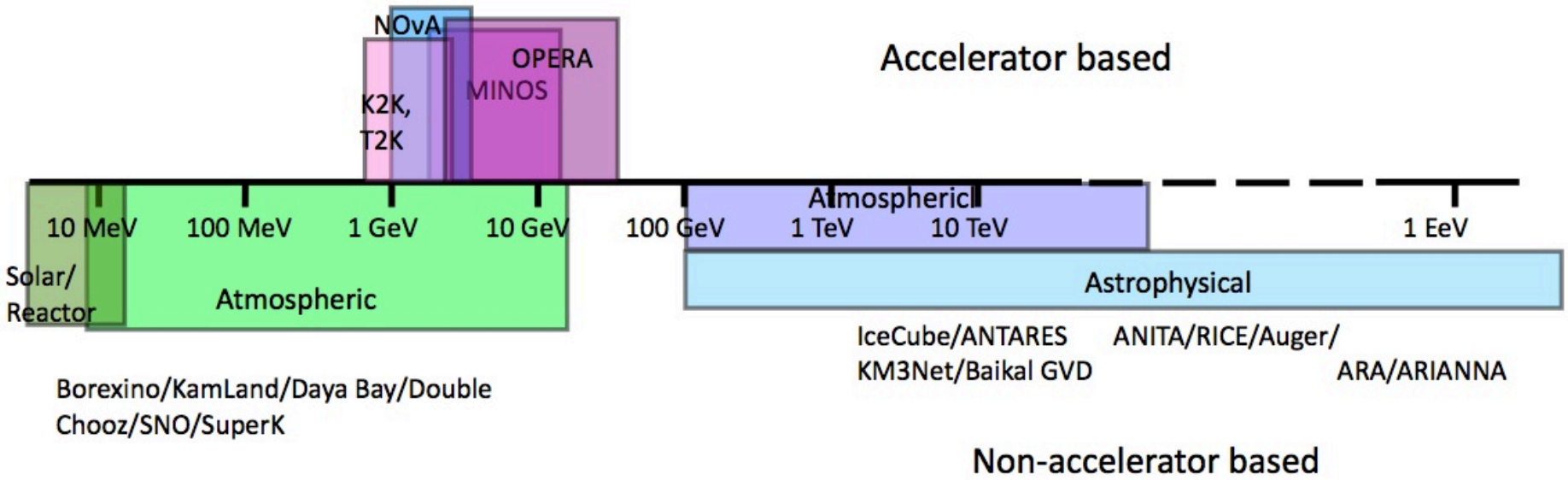


IceCube Deep Core

- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center
- low energy threshold: opens the 10 -- 100 GeV neutrino energy range
- overlap with Super-Kamiokande at low energy and with IceCube at high energies

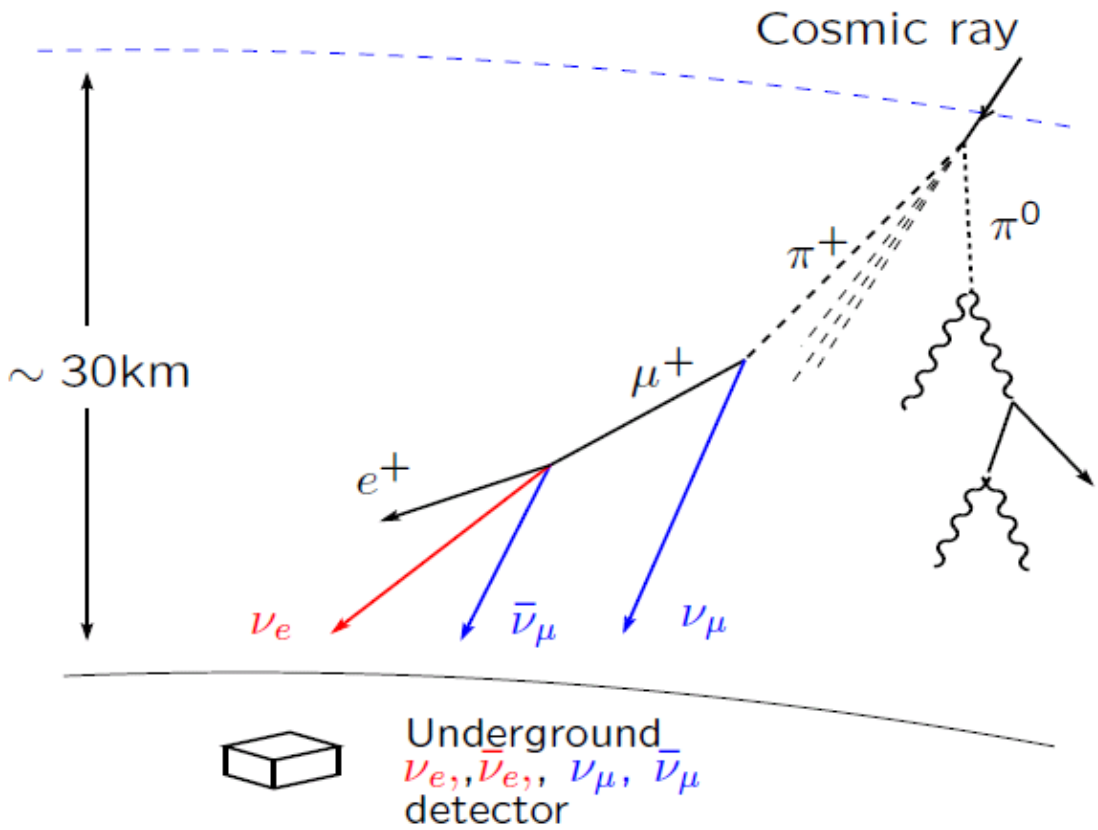


Neutrino Detector Spectrum



Darren Grant

Atmospheric neutrinos



- Background to many searches
- lots of them

> 50,000 events per year!

Neutrino oscillations in the IceCube Deep Core

tracks: μ-like fully contained events

Angular distribution:

- $\cos\theta \in (0,1)$ atmospheric flux normalization
- $\cos\theta \in (-1,0)$ + main oscillation signal ($\Delta m^2_{32},\ \theta_{23}$)
- $\cos\theta \in (-1,-0.7)$ + matter effects (θ_{13}, hierarchy, CP)

Energy distribution:

- $E \leq 40\,\mathrm{GeV}$: neutrino oscillations
- $50\,\mathrm{GeV} \leq E \leq 5\,\mathrm{TeV}$: atmospheric neutrino flux
- $E \geq 10\,\mathrm{TeV}$: Earth density profile

ICDC physical mass: $15\,\mathrm{Mt}$

Effective mass in our analysis: $1\,\mathrm{Mt} - 12\,\mathrm{Mt}$ (energy dependent)

O. Mena, I. M., S. Razzaque (2008); G. Giordano, O. Mena, I. M. (2010)

E. Fernandez-Martinez, G. Giordano, O. Mena, I. M. (2010)

Atmospheric neutrinos

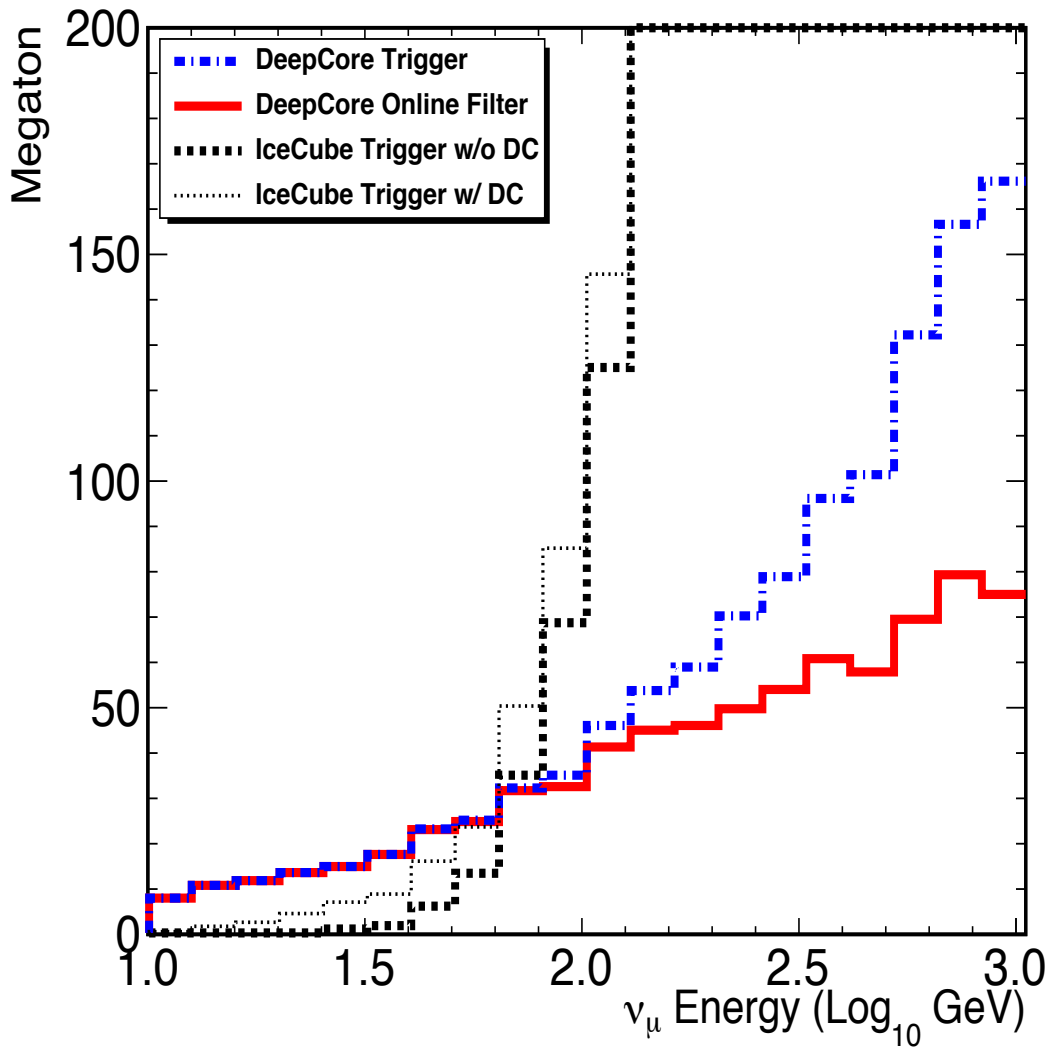
Super-Kamiokande

- expect:
  - $\frac{N_{\nu_\mu+\bar{\nu}_\mu}}{N_{\nu_e+\bar{\nu}_e}} \simeq 2$ at low energies
  - approximately isotropic
- use zenith angle distribution to prove neutrino oscillations

IceCube Deep Core

- $\frac{N_{\nu_\mu+\bar{\nu}_\mu}}{N_{\nu_e+\bar{\nu}_e}} \simeq 10$
- steep energy spectrum (E_ν^{-3})
- ν_e flux not measured at high energies

ICDC



no fixed energy threshold

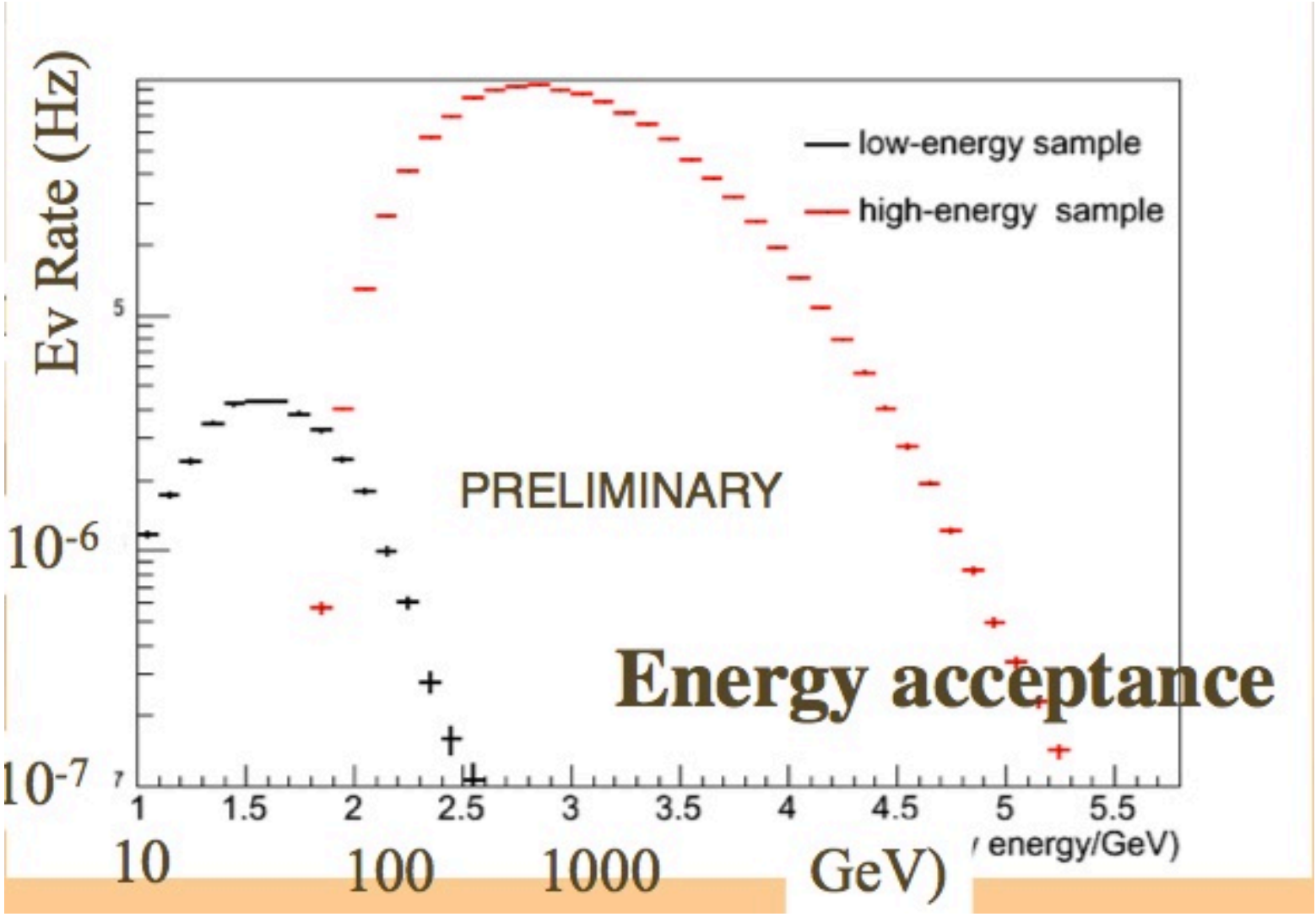
can trigger 1 GeV muons

most analysis use 35-50GeV threshold to avoid atmospheric neutrino background

large effective volume above 10 GeV

Jason Koskinen

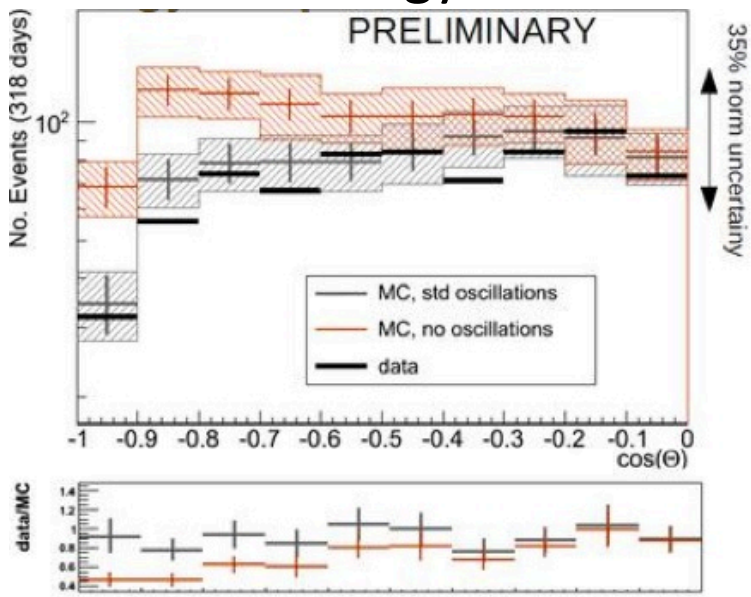
- Neutrino oscillations: now important physics goal of ICDC
- ν 2012: first neutrino oscillations observed in IC79
- IC86 taking data for the last year



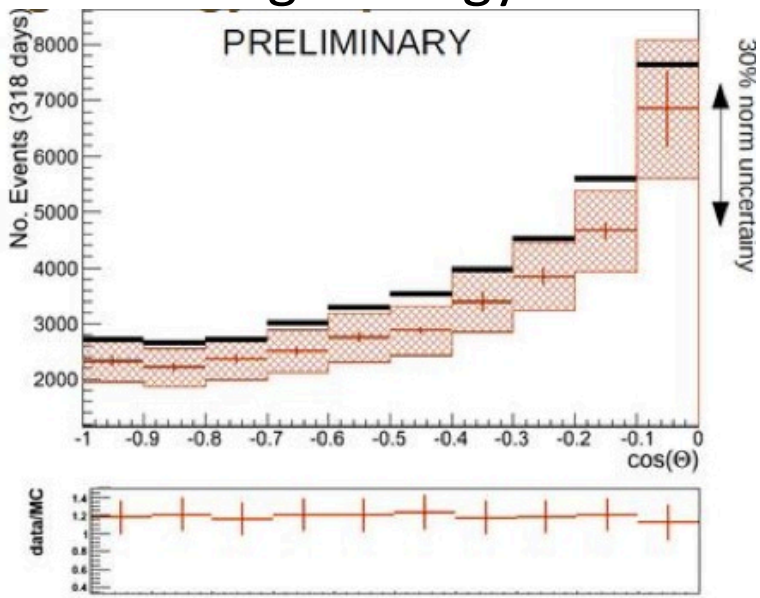
Neutrino oscillations: ν 2012

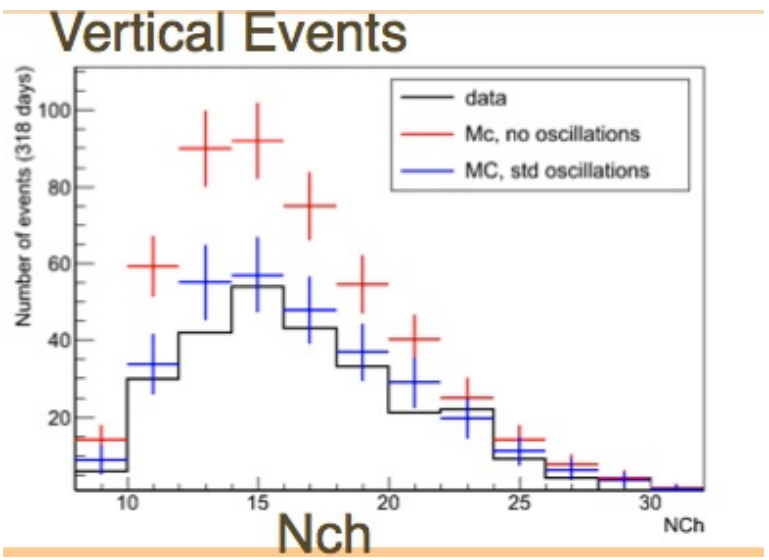
initial step - greatly improved by new/future reconstruction analysis

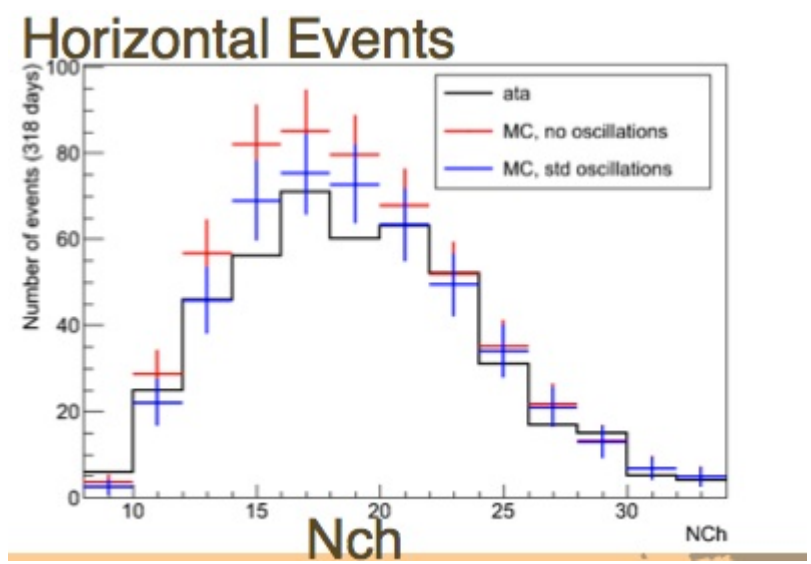
Low energy



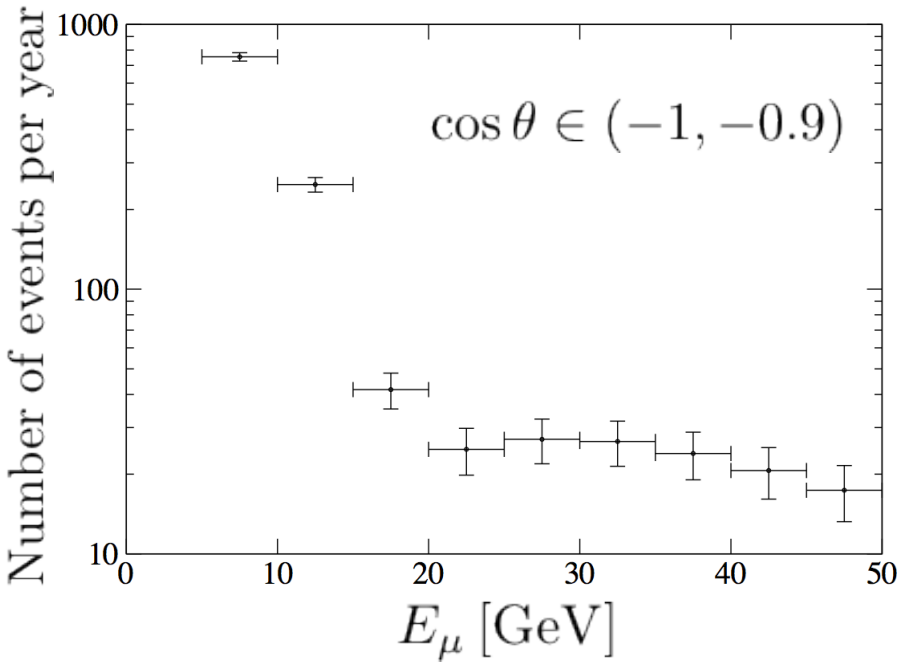
High energy

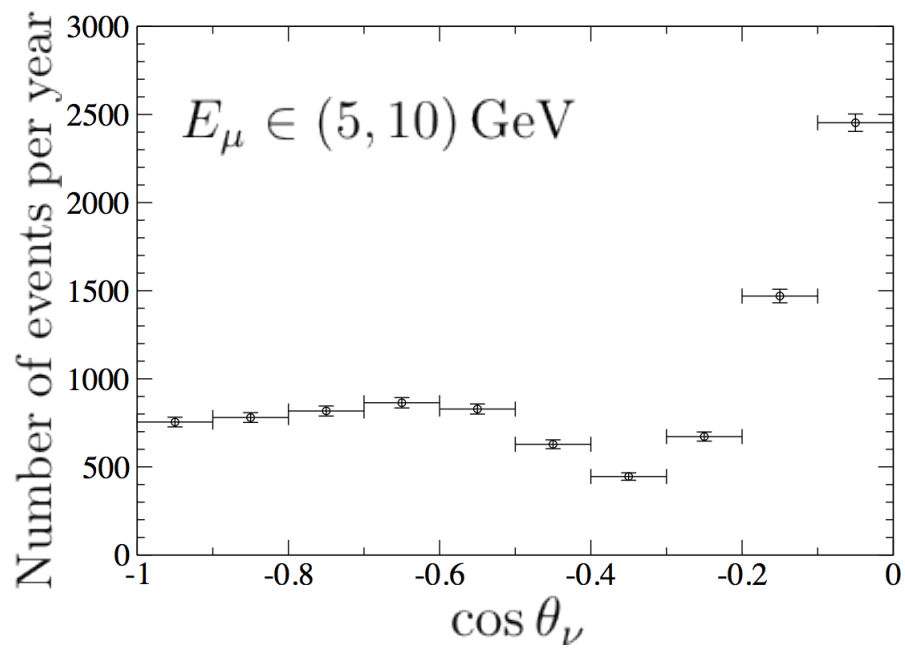






ICDC atmospheric neutrinos





E. Fernandez-Martinez, G. Giordano,O. Mena, I. M.(2010)

- Observable energy: $E_\mu \simeq \frac{1}{2} E_\nu$

Measure main oscillation parameters

Present:

Δm^2: MINOS

θ_{23} : Super-Kamiokande

IceCube Deep Core:

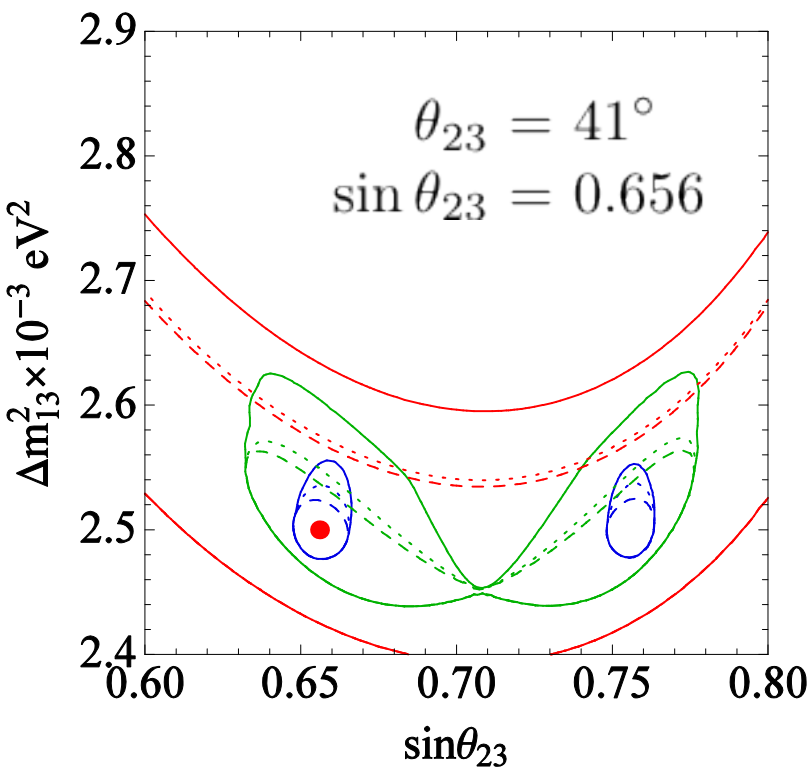
- very large statistics
- contribution from multiple peaks

Presently allowed values:

$$\Delta m^2_{32} \in (2.25 - 2.58)10^{-3}\mathrm{eV}^2(2\sigma)$$ (MINOS)

$$\sin\theta_{23} \in (0.59 - 0.79)(2\sigma)$$ (Super-Kamiokande)

IceCube Deep Core:



Observable energies of 5 to 50 GeV
10 energy bins, 4 angular bins

vs.

1st energy bin, 1 angular bin +
9 energy bins, 4 angular bins

vs.

Exclude first 2 energy bins:
8 energy bins, 4 angular bins

$\theta_{13} = 0.01$ - - - - - - - - - -

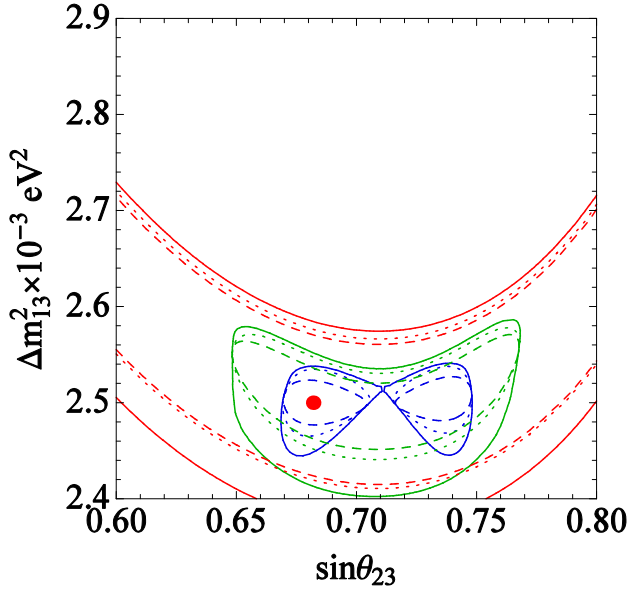
vs

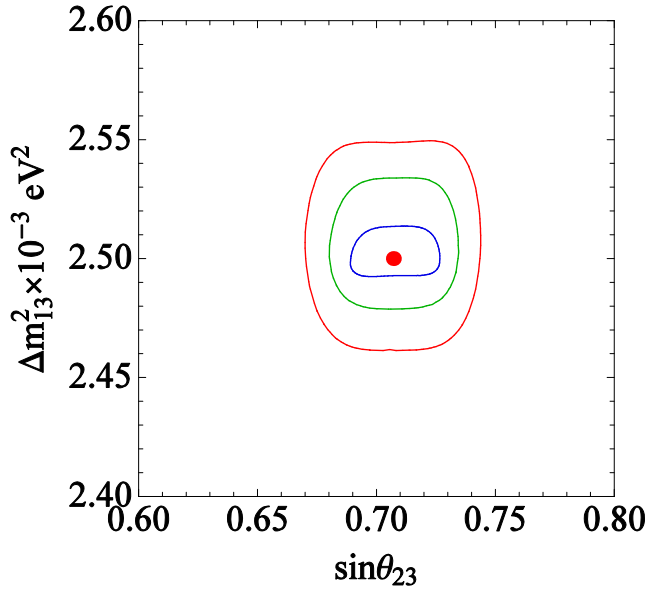
$\theta_{13} = 0.01 \pm 0.02$ .....

vs

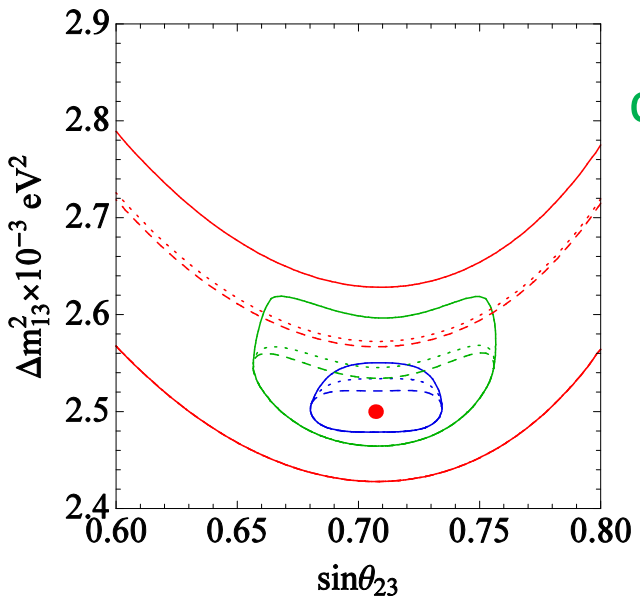
θ_{13} completely free ————————

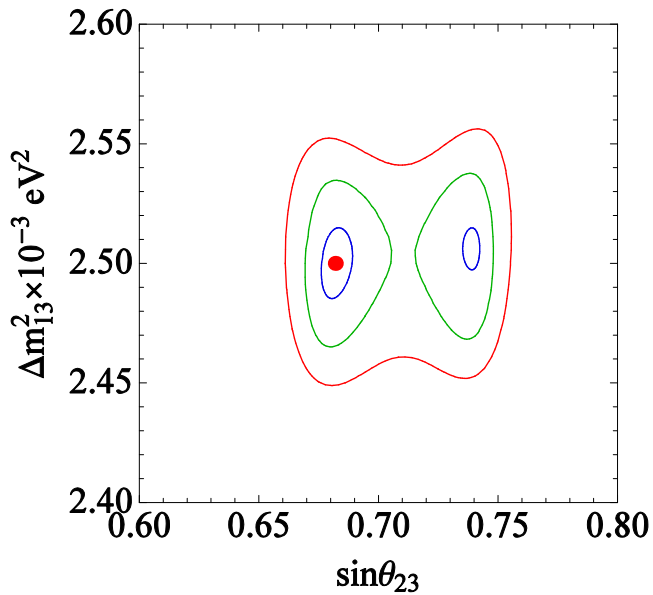
IceCube Deep Core





- Expected allowed regions depend on the true values of the parameters and control of systematic uncertainties





How about cascades?

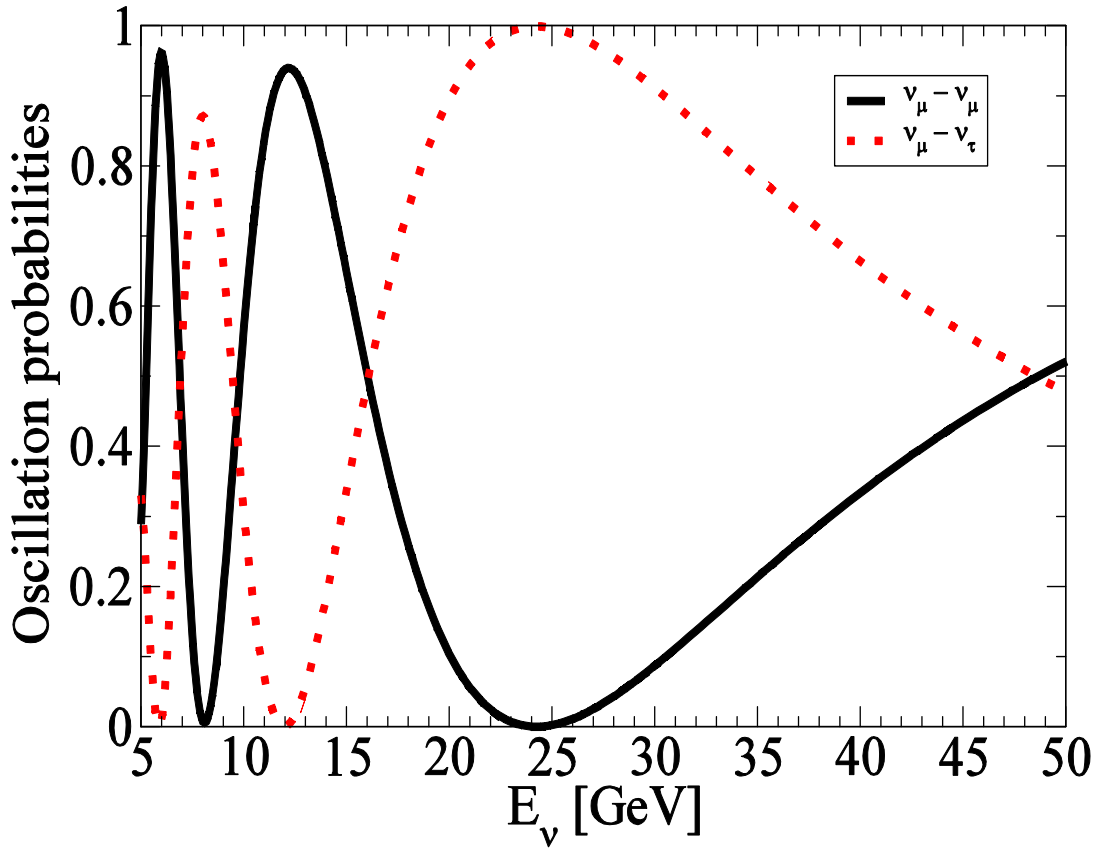
- ν_e CC interactions: $\nu_e + N \rightarrow e + X$
- ν NC interactions $\nu + N \rightarrow \nu + X$
- τ decay

$$\tau \rightarrow e + \bar{\nu}_e + \nu_\tau$$

$$\tau \rightarrow \nu_\tau + X$$

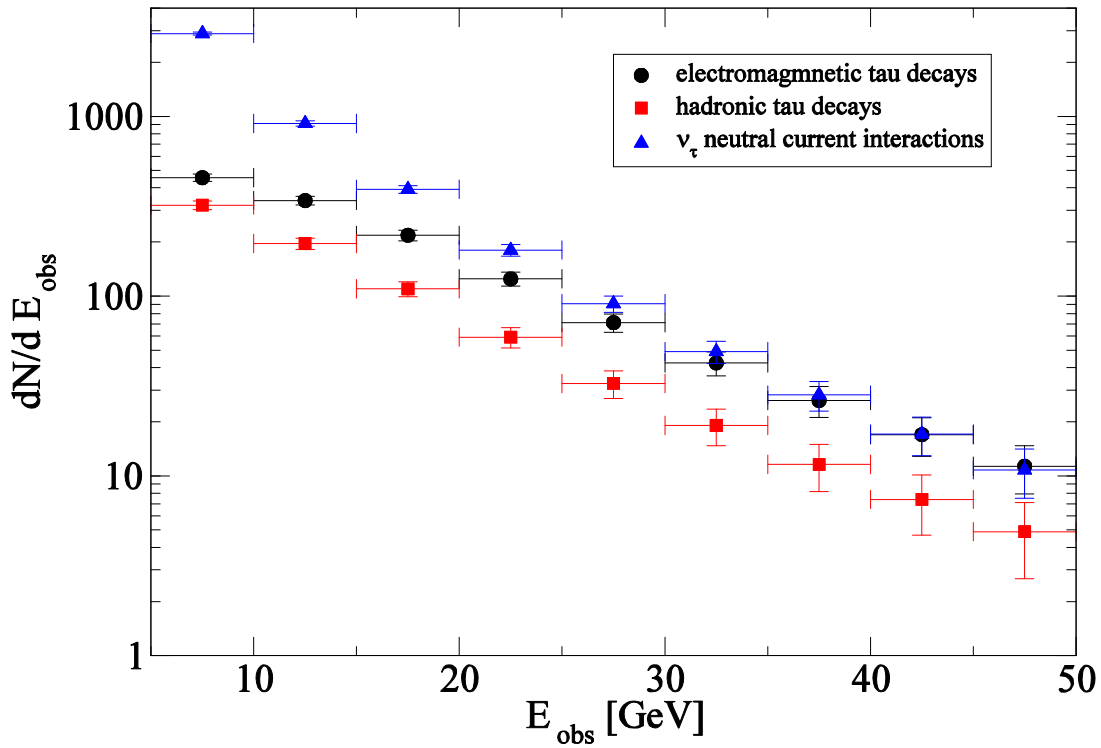
- Looking for ν_τ helped by:
  - high energy (tau threshold effects small)
  - background low : $\Phi_{\nu_\mu} \sim 10\, \Phi_{\nu_e}$
  - oscillations

Oscillation probabilities



Propagation along Earth diameter

Tau cascade rates



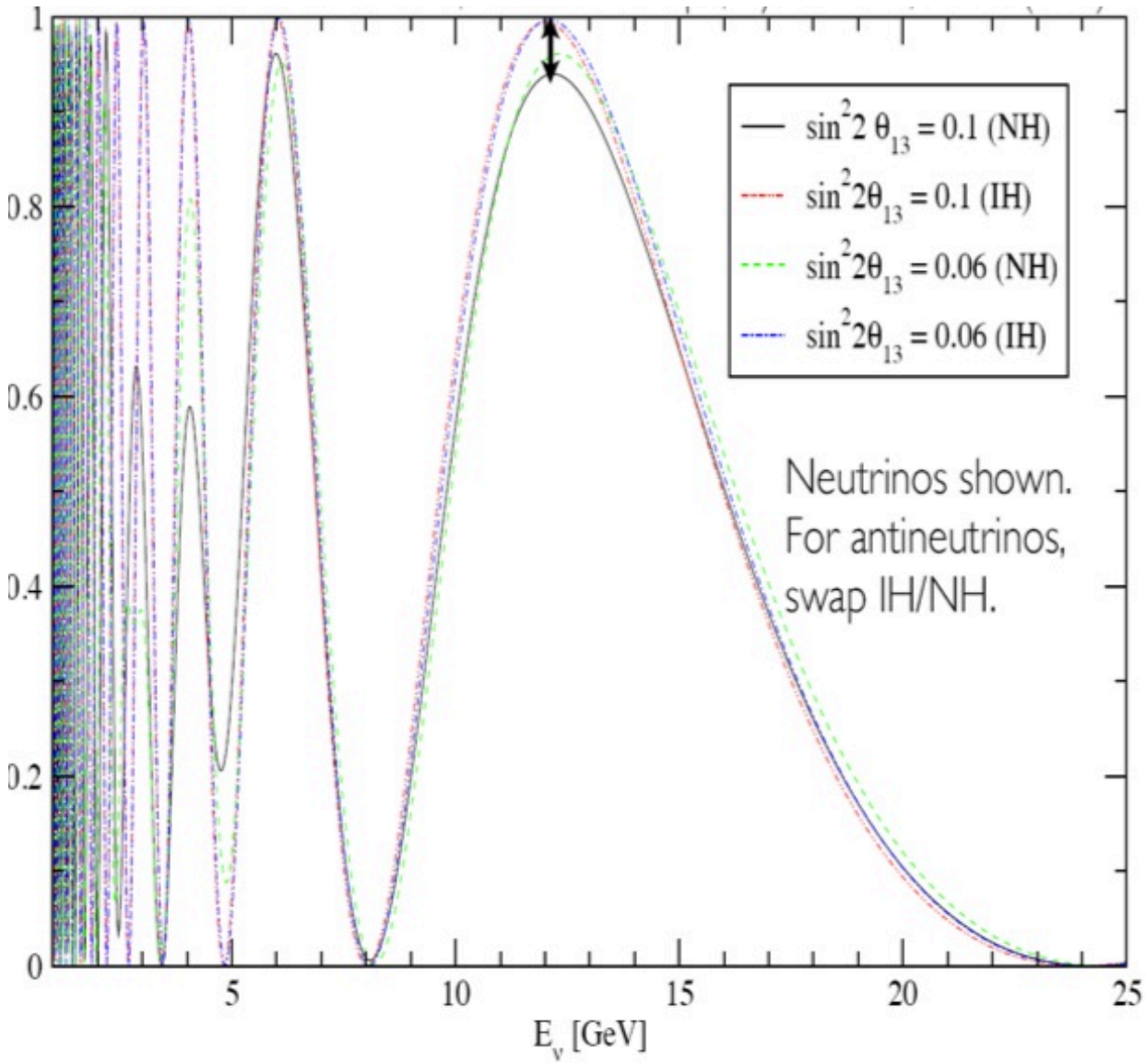
ν_τ cascades

G. Giordano, O. Mena, I. M. (2010)

- $\nu_\mu \to \nu_\tau \to \tau \to e$ or hadrons large
- present world sample of ν_τ events: 5(9) DONUT + (2) (OPERA)
- Super-Kamiokande: $180.1 \pm 44.3(stat)^{+17.8}_{-15.2}(sys)$ (after 15 years)
- high statistics ν_τ interactions
- direct evidence for $\nu_\mu \to \nu_\tau$ appearance
- ν_τ interaction cross-section
- non-standard interactions of ν_τ
- experience with cascade detection
- ICDC has already observed cascade events in their first small open data sample !

Normal versus inverted mass hierarchy

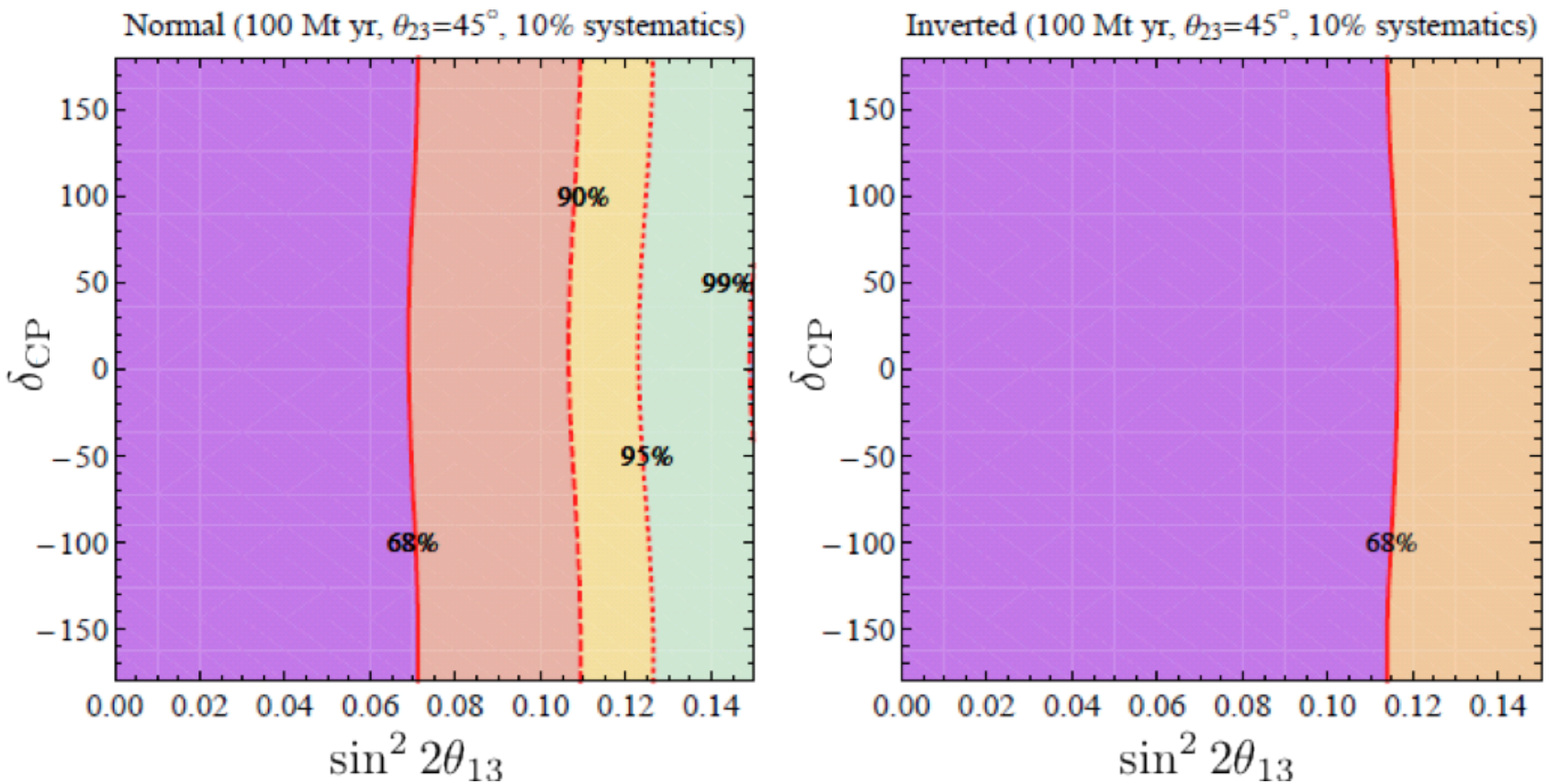
O. Mena, I. M., S. Razzaque (2008)



Normal versus inverted mass hierarchy

- χ^2 fit to discriminate between normal and inverted hierarchy

O. Mena, I. M., S. Razzaque (2008)

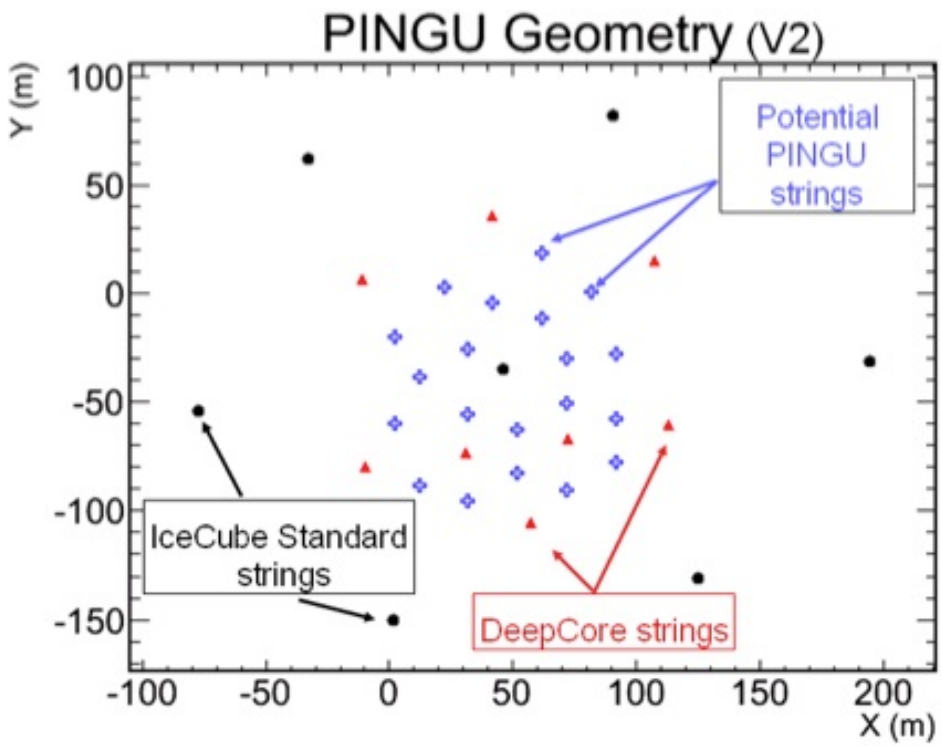


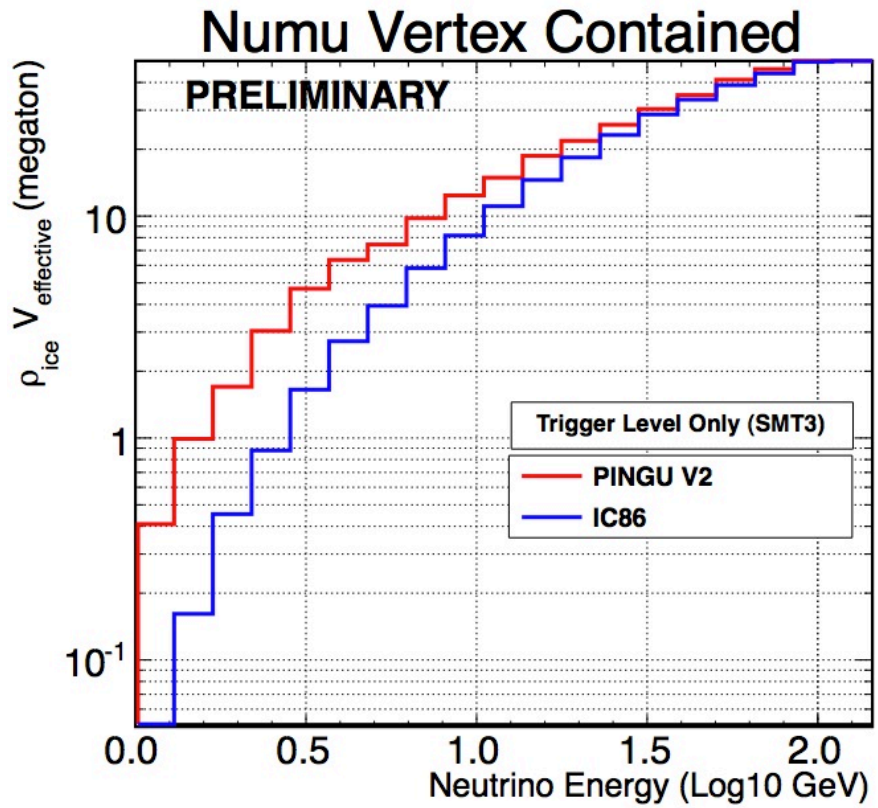
- much better now, with known and large θ_{13}

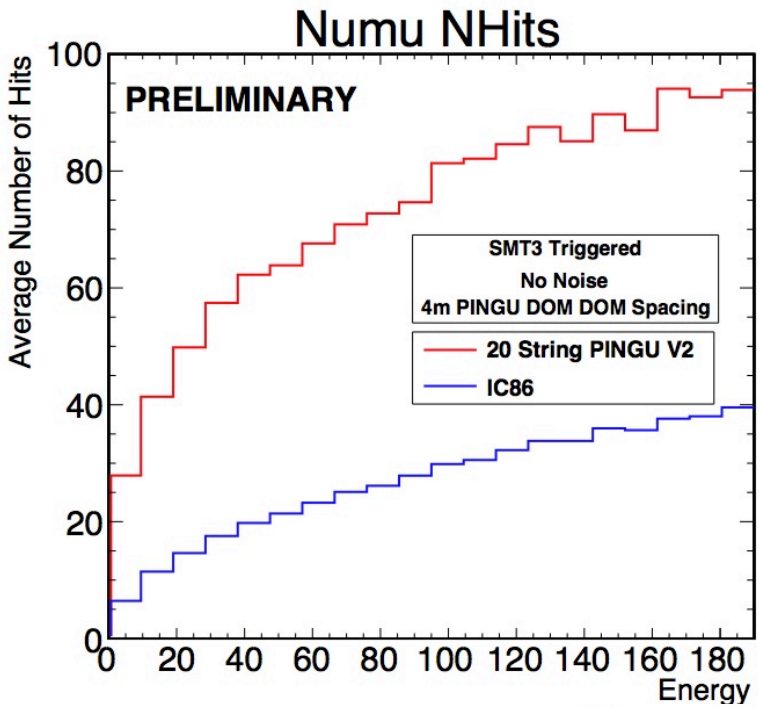
PINGU 

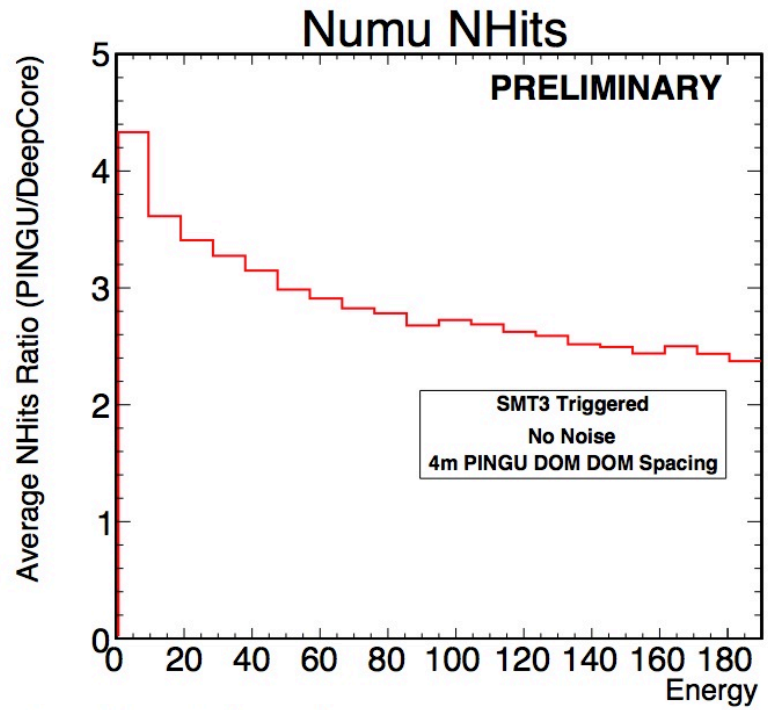
- Phased IceCube Next-Generation Upgrade
- Add 20 strings with ~1000 optical modules inside the Deep Core region (~500PMT)
- Expected energy threshold near 1 GeV

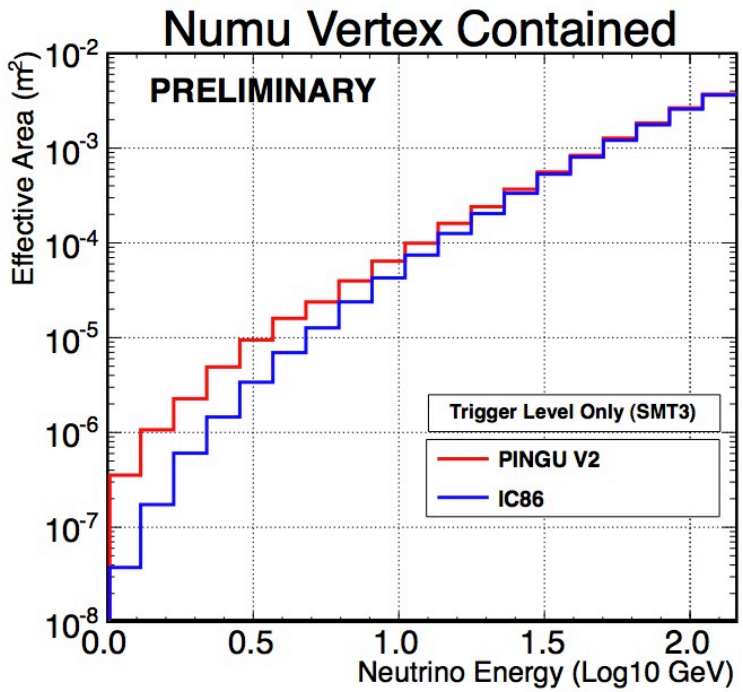
- ~$25-30 million
- 2 years deployment
- White paper Fall 2012
- full proposal 2013
- R&D for further infill to reach below GeV range





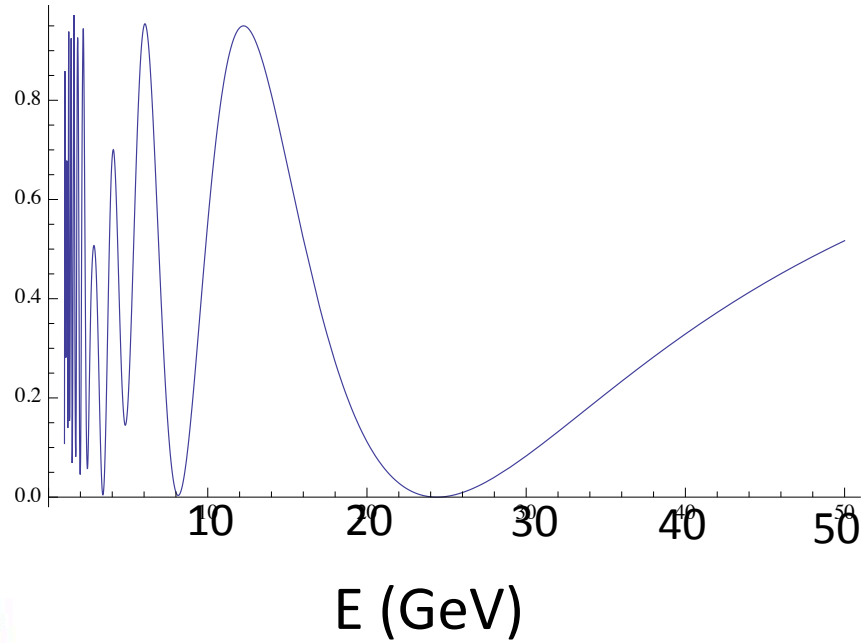

Numu NHits
PRELIMINARY
Average Number of Hits
Energy
SMT3 Triggered
No Noise
4m PINGU DOM DOM Spacing
20 String PINGU V2
IC86

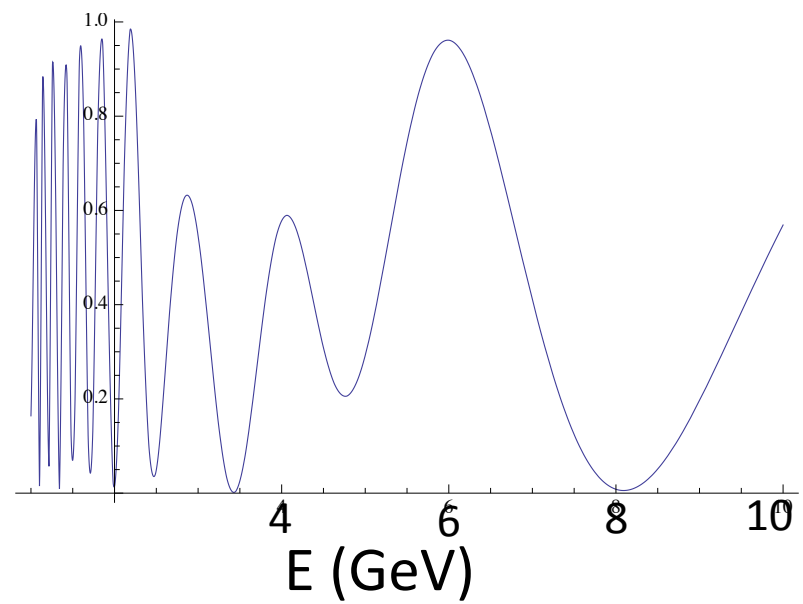

Numu NHits
PRELIMINARY
Average NHits Ratio (PINGU/DeepCore)
Energy
SMT3 Triggered
No Noise
4m PINGU DOM DOM Spacing


Numu Vertex Contained
PRELIMINARY
Effective Area (m²)
Neutrino Energy (Log10 GeV)
Trigger Level Only (SMT3)
PINGU V2
IC86

- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - enhanced sensitivity to neutrino mass hierarchy
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate across entire detector volume
  - Only 2±1 core collapse SN/century in Milky Way
    - need to reach out to our neighboring galaxies
- Gain depends strongly on noise reduction via coincident photon detection (e.g., in neighbor DOMs)

$$P(\nu_\mu \to \nu_\mu)$$



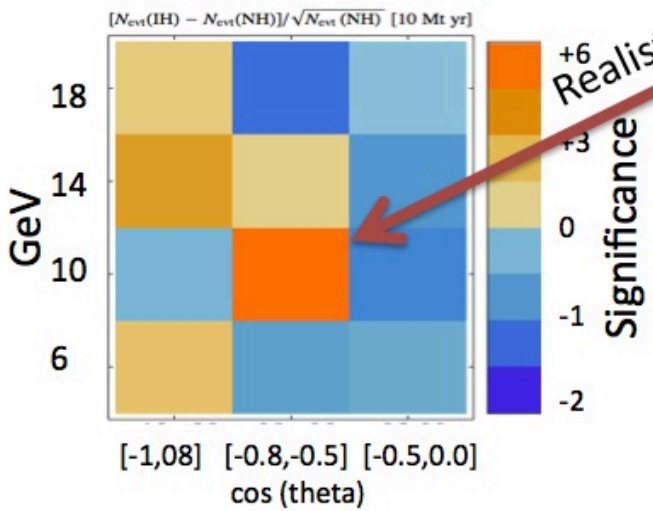


Mass hierarchy

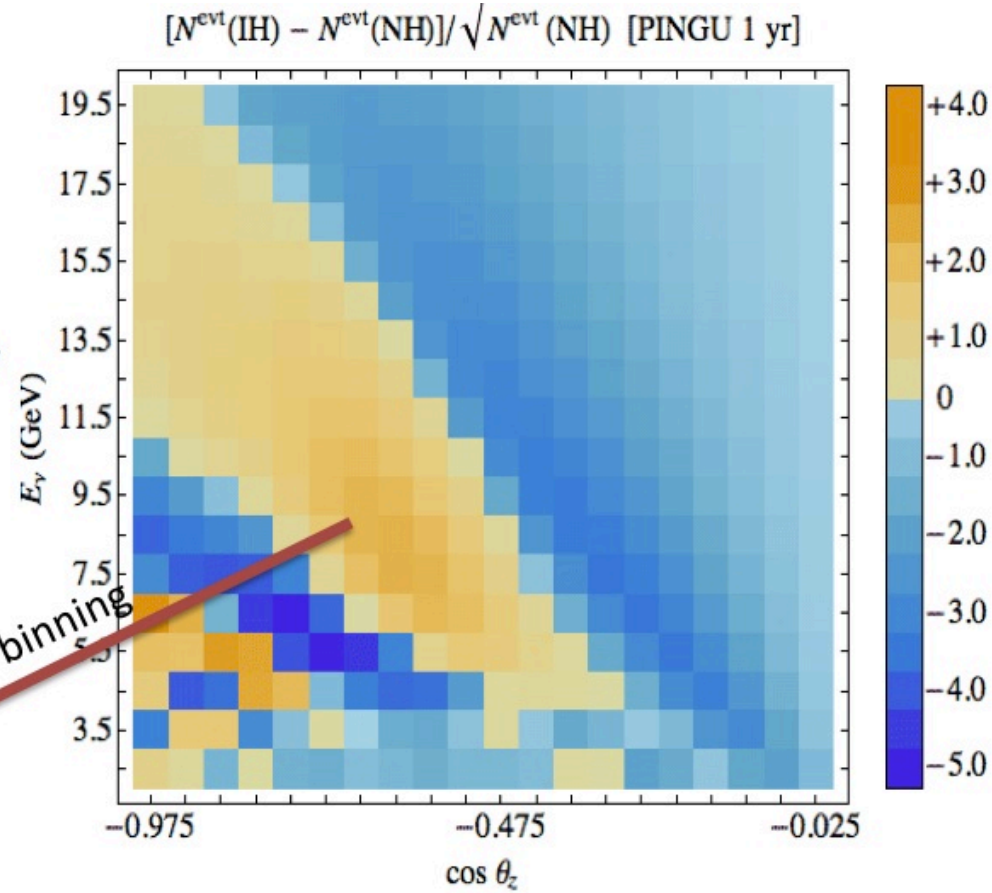
Figure and Analysis from:
Akhmedov, Razzaque, Smirnov, arXiv: 1205.7071

- Expected significance for observed number of events for IH vs NH are shown in energy vs. zenith plot
- If required energy and directional resolution is achievable:

  → high statistical significance



Realistic binning



Conclusion (Akhmedov et al.):
"Our preliminary estimates show that after 5 years of PINGU 20 operation the significance of the determination of the hierarchy can range from 3 to 11 (without taking into account parameter degeneracy), depending on the accuracy of reconstruction of neutrino energy and direction."

Assumed above:

Energy resolution: 4 GeV,

Angular resolution: 0.3 in cos(theta)

Exposure: 10 Mt yr

- very general analysis, many details missing
- DIS only
- full analysis: likely better outcome!

PINGU

- Full PINGU simulations ongoing
- Our analysis ongoing
    - more involved than ICDC
    - atmospheric flux: transition between mu+pi and pi:
        - flavor and energy dependence
    - cross-sections: many contributions

Atmospheric Neutrino Oscillations

- Large energy range: 100 MeV - 100 GeV
- Many baselines: 15 km – 13000 km

cover large parameter space

Long Baseline Neutrino Oscillation Experiments

- Fixed distance
- Good energy measurement
- Well known flux (near detector)

good parameter determination

- Complementary information
- Consistency checks very important

Surprises?

Surprises?

MiniBooNE/LSND

Test sterile neutrino hypothesis?

- Is there ν_μ ($\bar{\nu}_\mu$) disappearance at high Δm^2 ?
- IceCube: high energy: TeV

  for high Δm^2 sensitivity

  matter effects: resonance
- maybe ICDC downgoing: lower E/smaller L
- Small mixing effects in ICDC
- Energy/angular spectrum: good sensitivity

Sterile Neutrinos

- Model dependence:
  - 3+1 (6 angles), 3+2 (10 angles), 3+2+CP violation
  - angles: sterile mixing with ν_μ , $\nu_\mu - \nu_\tau$, $\nu_\mu - \nu_e$
  - possible affect ν and $\bar{\nu}$ differently
- If one present, expect the other
- No one to one correspondence between LSND/ MiniBooNE (mu-e) and IceCube observations

  (mu-mu,mu-tau)
- Can constrain or discover oscillations at high mass scale for angles in the general range probed by MiniBooNE/LSND
- Cannot directly confirm/rule out MiniBooNE/LSND sterile nu interpretation

Non-Standard Interactions (NSI)

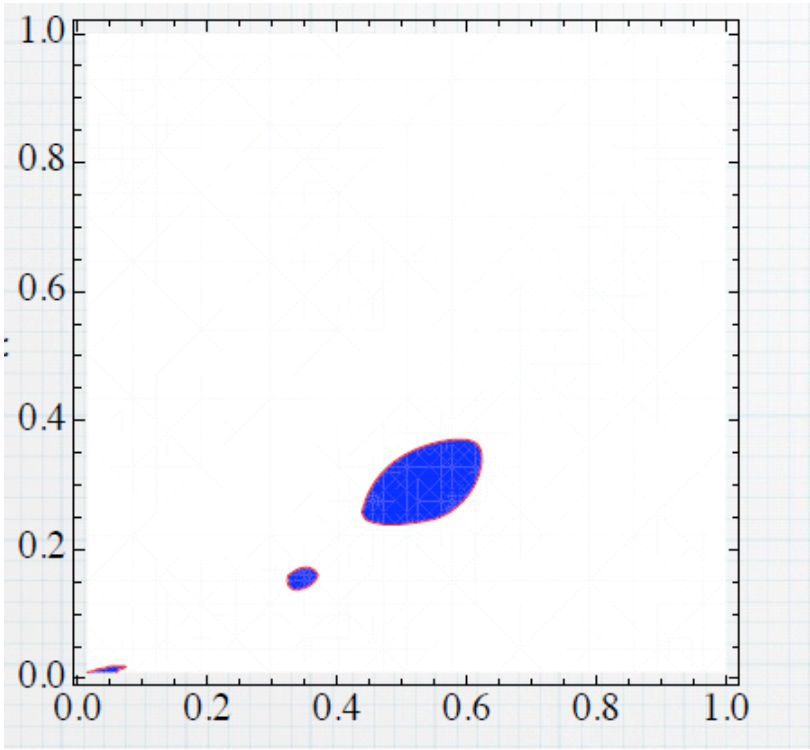
- Expected in connection with mass generation models, sterile neutrinos, etc.
- Parameterize our ignorance by most general form and try to constrain from data

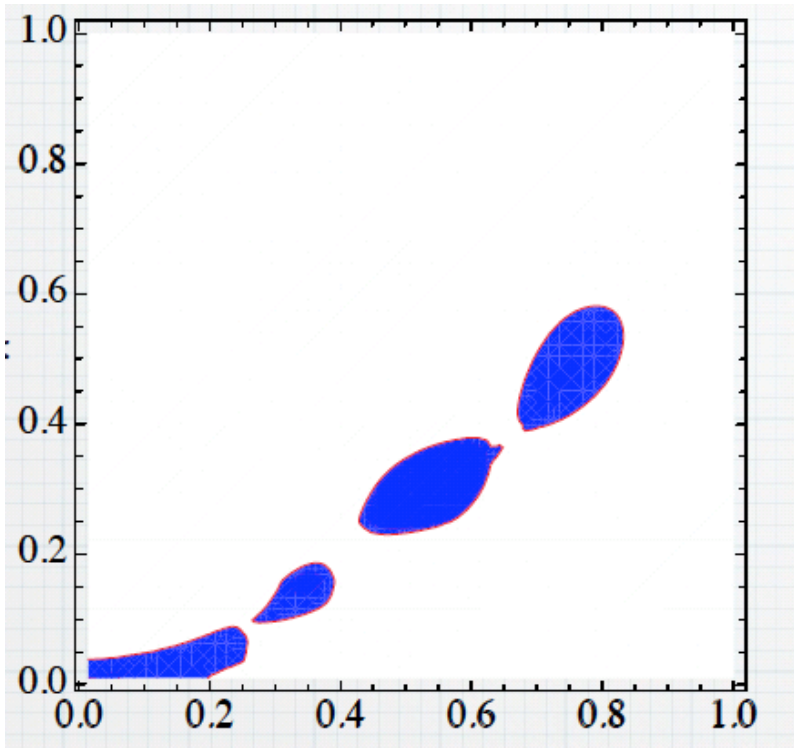
Matter effects in neutrino oscillations

$$H_{\rm mat} = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon^*_{e\mu} & \epsilon^*_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon^*_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

Very weak constraints in the τ sector

$\varepsilon_{e\tau}$ - $\varepsilon_{\tau\tau}$





Preliminary

Large correlations/degeneracy between parameters

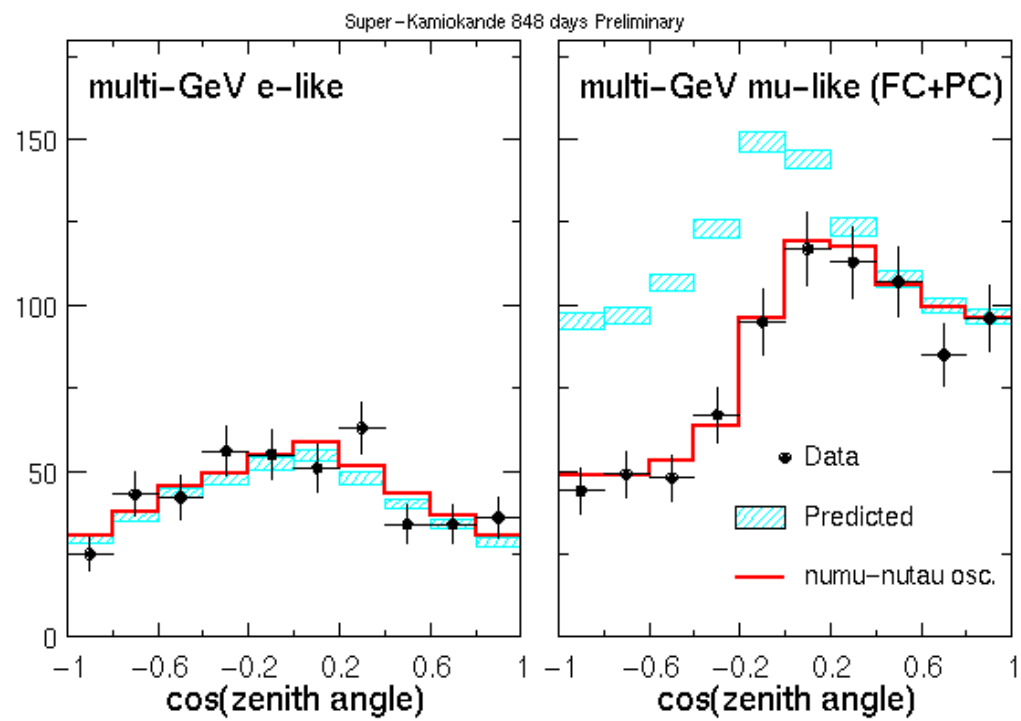
Remember some history

- 1980's: large detectors looking for proton decay, grand unification, etc.; atmospheric neutrinos are background

$$R = \frac{\left(N_{\nu_\mu+\bar{\nu}_\mu}/N_{\nu_e+\bar{\nu}_e}\right)\Big|_{\rm data}}{\left(N_{\nu_\mu+\bar{\nu}_\mu}/N_{\nu_e+\bar{\nu}_e}\right)\Big|_{\rm MC}} \simeq 0.6$$

atmospheric neutrino problem

Super-Kamiokande (1998)



Atmospheric neutrinos:

many uncertainties

Beamline Proposals:

MINOS 1995

OPERA 1998

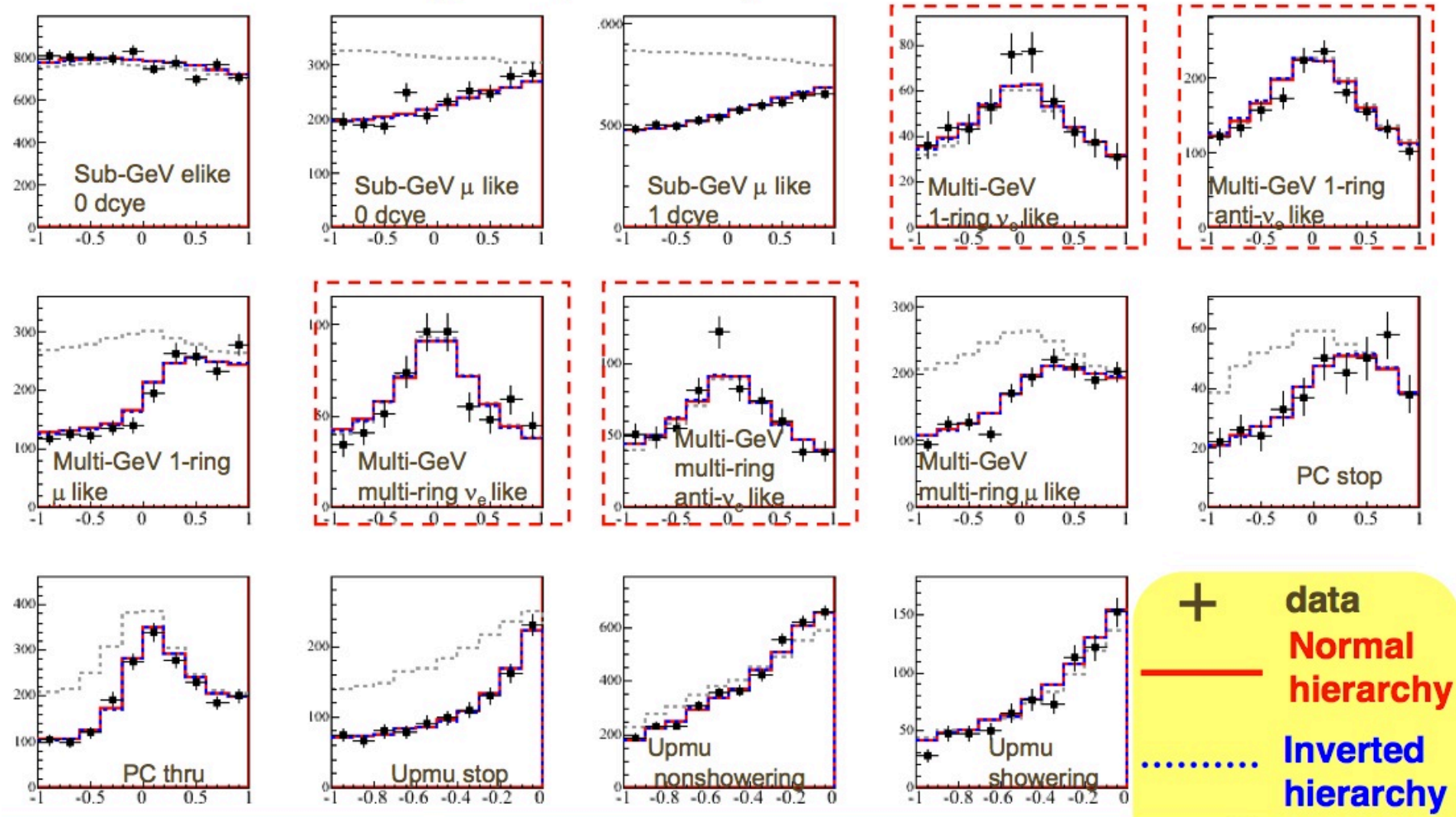
ICARUS 1993 (detector),

1996 (neutrino oscillations)

Long Baseline Neutrino Oscillation Experiments

- K2K (2000): confirmation of neutrino oscillations
- MINOS (2006): energy spectrum, best mass difference measurement
- OPERA: (2010) first tau candidate neutrino detection
- ICARUS: taking data
- T2K: taking data -> precision measurements, sub-dominant effects
- NOVA: under construction

3 flavor analysis (SK1-4) with reactor constraint



- Fixed $\sin^2\theta_{13} = 0.025$

Tang, Winter:

- FNAL-PINGU
  - **Megaton-size ice detector** as upgrade of DeepCore with lower threshold; very cost-efficient compared to liquid argon, water
  - Unique mass hierarchy measurement through **parameteric enhancement**; proton beams from main injector may just have right energy
  - In principle, MH even with counting experiment measurable (compared to MH determination using atmospheric neutrinos)
- Challenges on beam side (questions from PINGU meeting):
  - Tilt of beam line – feasibility, cost?
  - Near detector necessary? Maybe not, if 10% systematics achievable …
  - Beam bunching (to reduce atmospheric backgrounds)?

  NB: **very low exposure required for MH**; shorter decay pipe, one horn only, …?
- Perspectives
  - CP violation challenging (requires energy resolution, flavor identification), but not in principle excluded; **needs further study on detector side**
  - Measurement of Earth's core density, in principle, possible
    (Tang, Winter, JHEP 1202 (2012) 028)
  - Upgrades of PINGU discussed (MICA)
- **Truly unique and spectacular long-baseline experiment with no other alternative proposed doing similar physics!?**
  ⇨ The LBNE alternative if T2HK is going to be funded?

Outlook

IceCube Deep Core detector already taking data !

- built to look for galactic sources, dark matter annihilation
- atmospheric neutrinos

  high statistics, large energy range, many distances

  > 50,000 events per year

  better understanding the background for other sources
- neutrino oscillations

  highly significant oscillation signal

  good parameter sensitivity

  ν_τ: oscillations, interactions, cascade detection

  mass hierarchy

  …

Outlook

- IceCube Deep Core detector already taking data !
- someone's background can be someone else's signal
- experiments take a very long time to construct/operate
- use the data we already have and get the most of it!
- PINGU: huge, cheap, fast
- long baseline experiments: fixed baseline, limited energy range
- atmospheric neutrinos: many baselines, large energy range
  - ➢ complementary information
- combined data: consistency checks

expect SURPRISES!