Using neutrino telescopes to learn about particle physics and astrophysics

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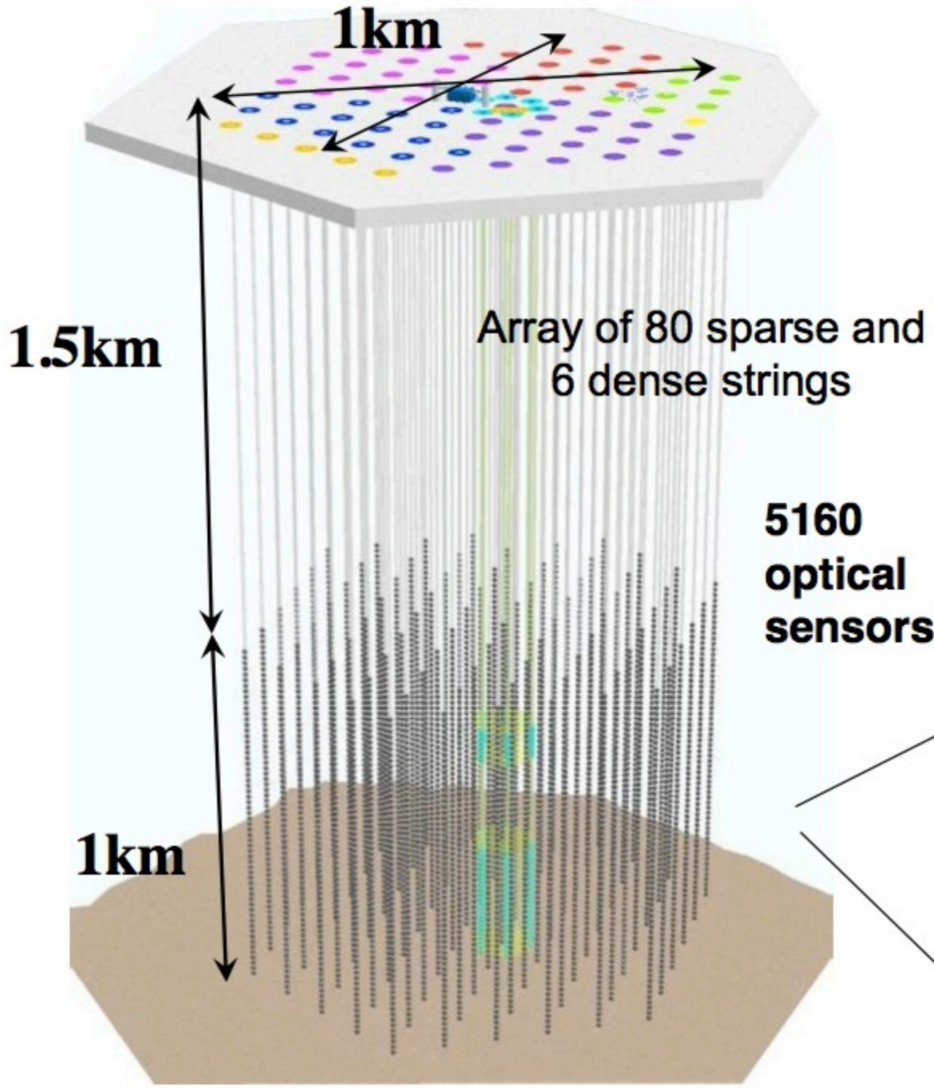
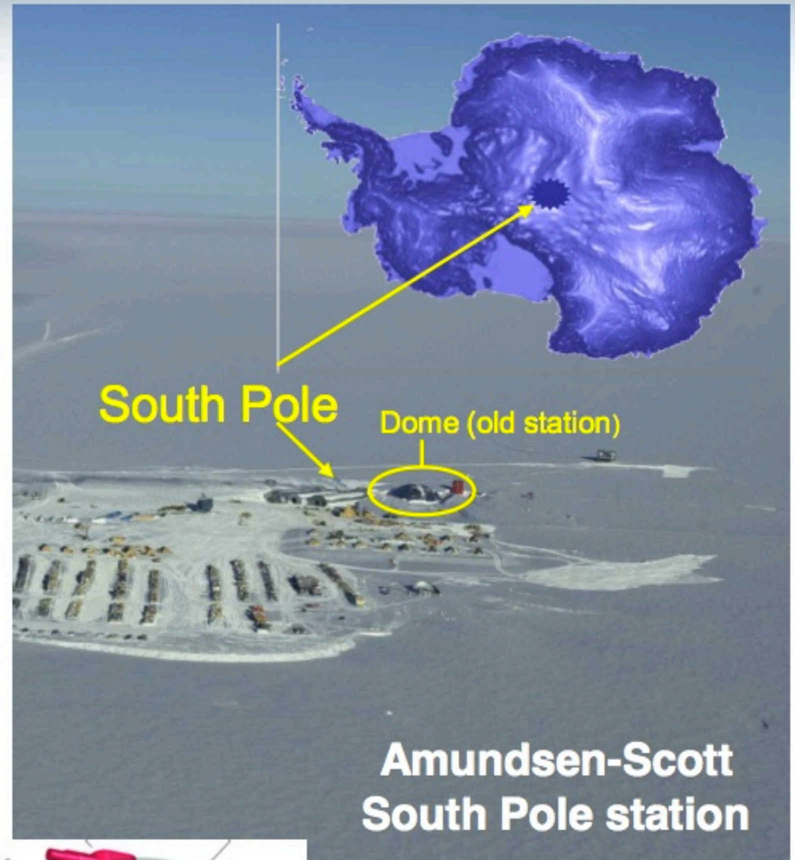
Experiments

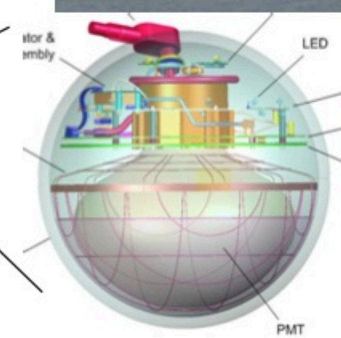
- IceCube/DeepCore: Cherenkov light in ice (South Pole)
- Antares: Cherenkov light in water (Mediteraneen)
- Pierre Auger: air showers (Argentina)
- radio Cherenkov: higher energy
- …

Real data!

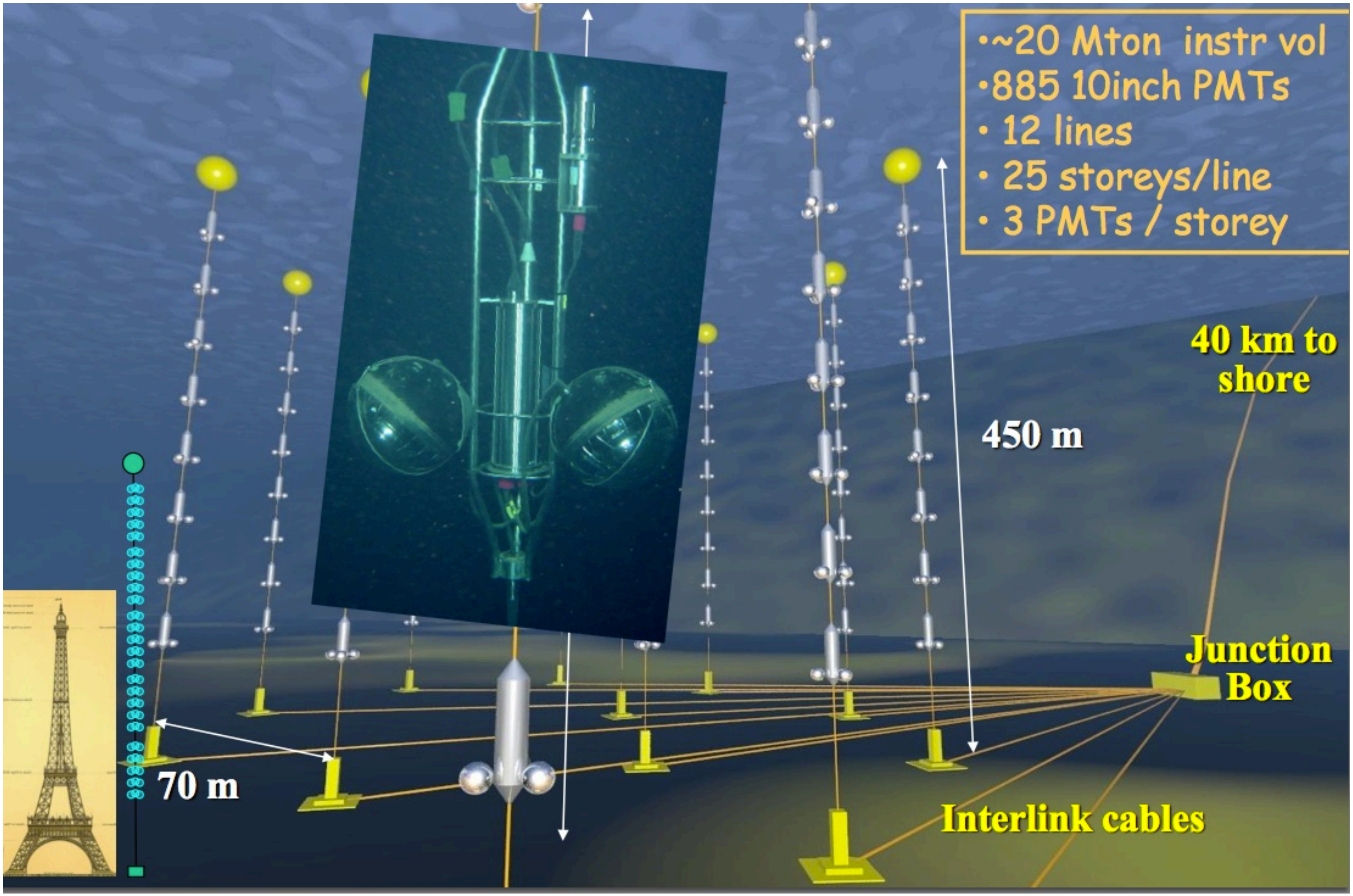
The IceCube Detector





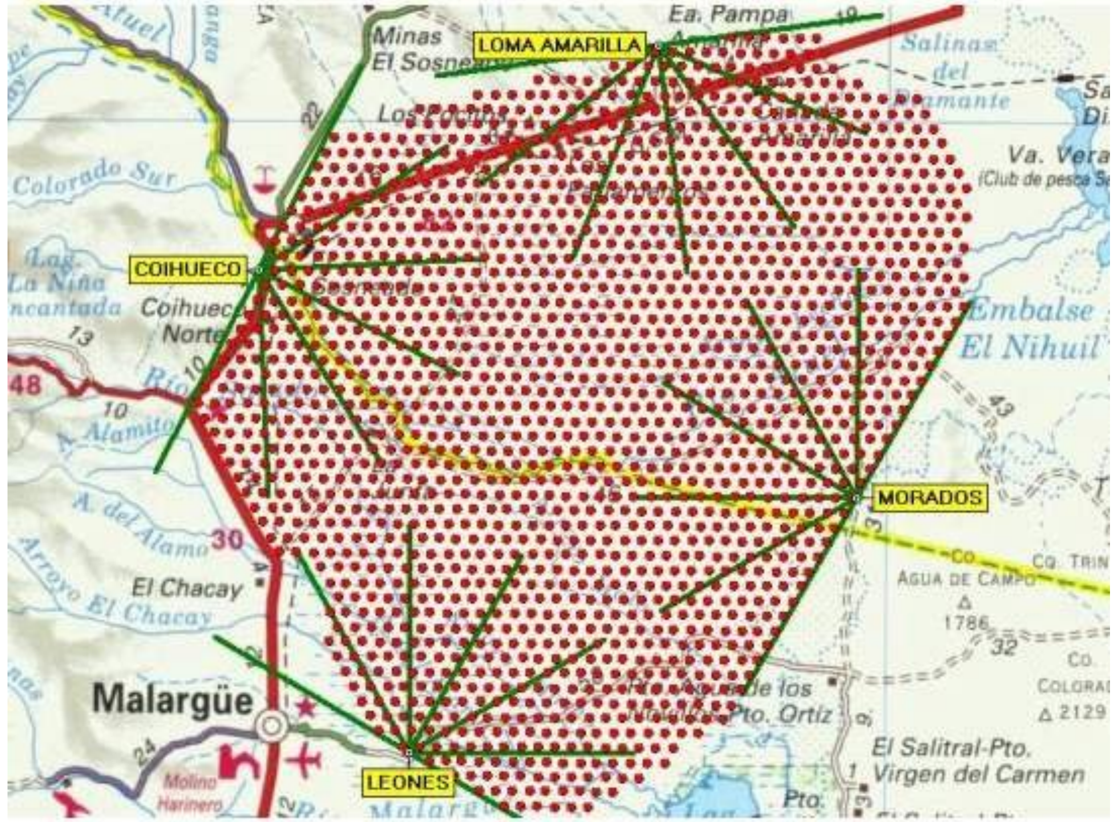


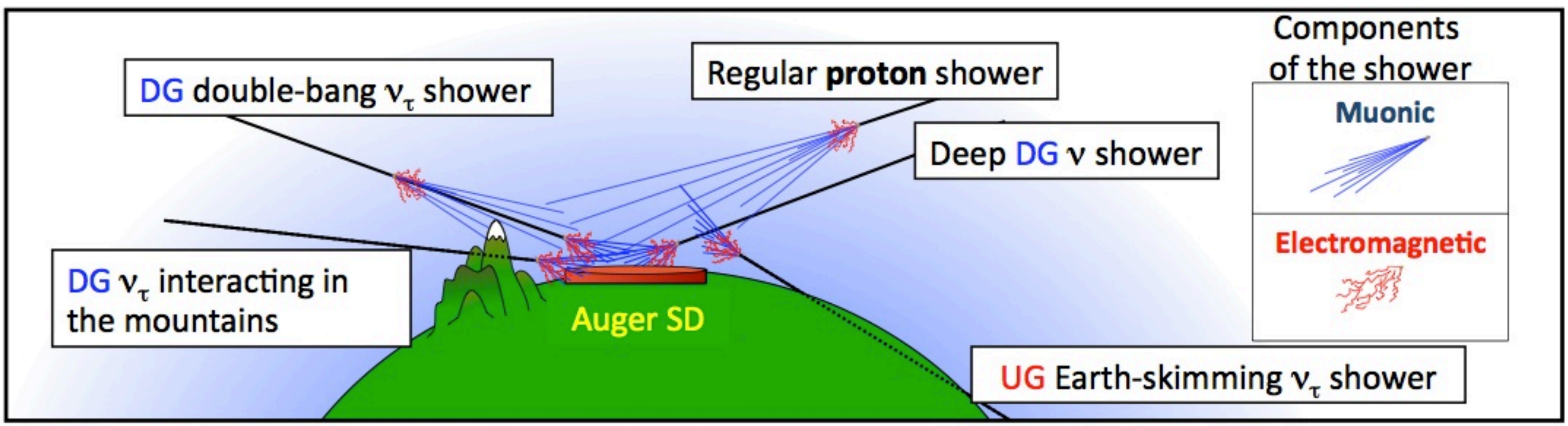
ANTARES


•~20 Mton instr vol
•885 10inch PMTs
• 12 lines
• 25 storeys/line
• 3 PMTs / storey
40 km to shore
450 m
Junction Box
70 m
Interlink cables

Pierre Auger Observatory

- cosmic ray detector
- some sensitivity to high energy neutrinos

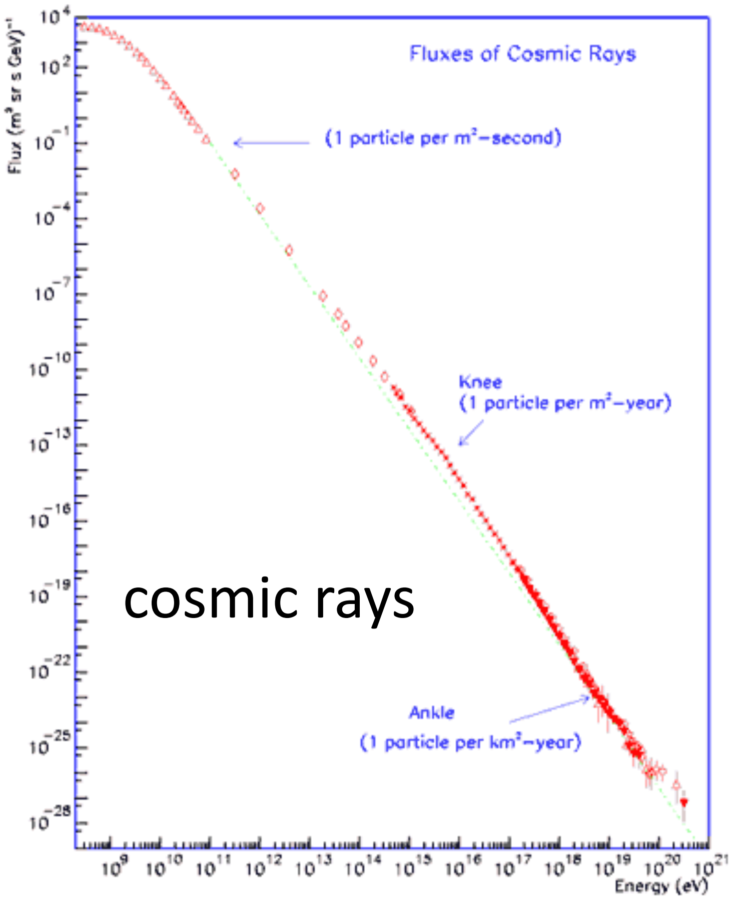


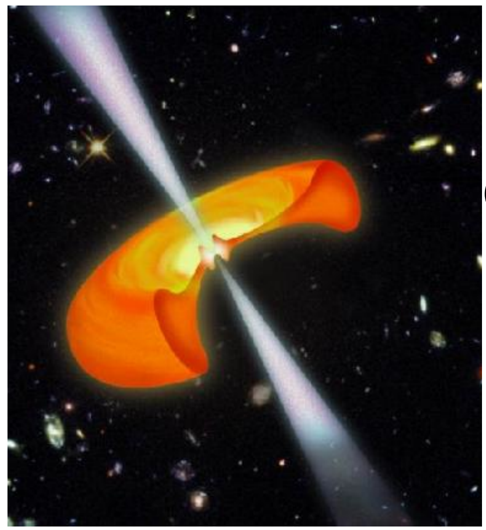


Sources

- some "guaranteed" high energy neutrinos:

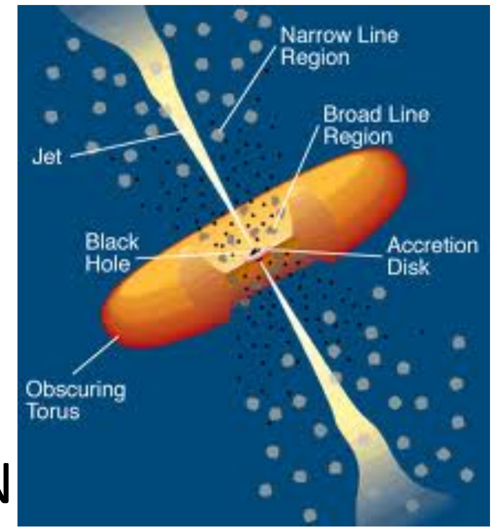
$$p + \ldots \rightarrow \ldots \rightarrow \pi \rightarrow \mu + \nu_\mu$$
$$\downarrow$$
$$e + \nu_e + \nu_\mu$$



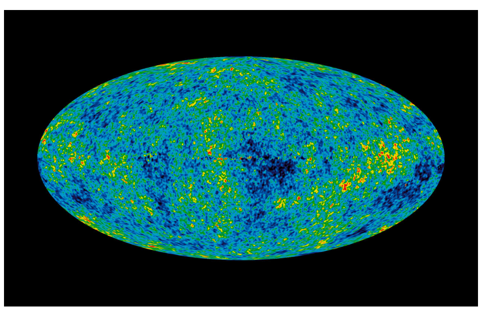


GRB

AGN



CMB



Maybe:

- dark matter annihilation
- topological defects
- cosmic strings
- …

Exactly how many?

Where?

What energies?

Lessons for particle astrophysics

weak interactions

- access to dense, violent environment
- test mechanism powering astrophysical sources
- cosmic ray acceleration processes
- cosmic ray propagation and intergalactic backgrounds
- …

Lessons for particle physics

high energies, beyond those accessible in colliders, etc.
weak interactions

- neutrino interaction cross-sections (in Standard Model!)
- neutrino properties
- new interactions/particles
- dark matter
- …

complementary to photons and charged particles

Sources

- flavor composition

  mostly π decay $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

  not always:

  neutron decay, energy thresholds, energy losses,

  matter effects, magnetic fields

  energy dependent flavor ratios

  depend on neutrino and source properties

Propagation:

- neutrino oscillations over long distances

  πdecay + maximal $\nu_\mu - \nu_\tau$ mixing: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

  different initial state: three flavor mixing important

- non-standard neutrino properties: decay, additional interactions,...
- change flavor composition/energy spectrum

Interactions:

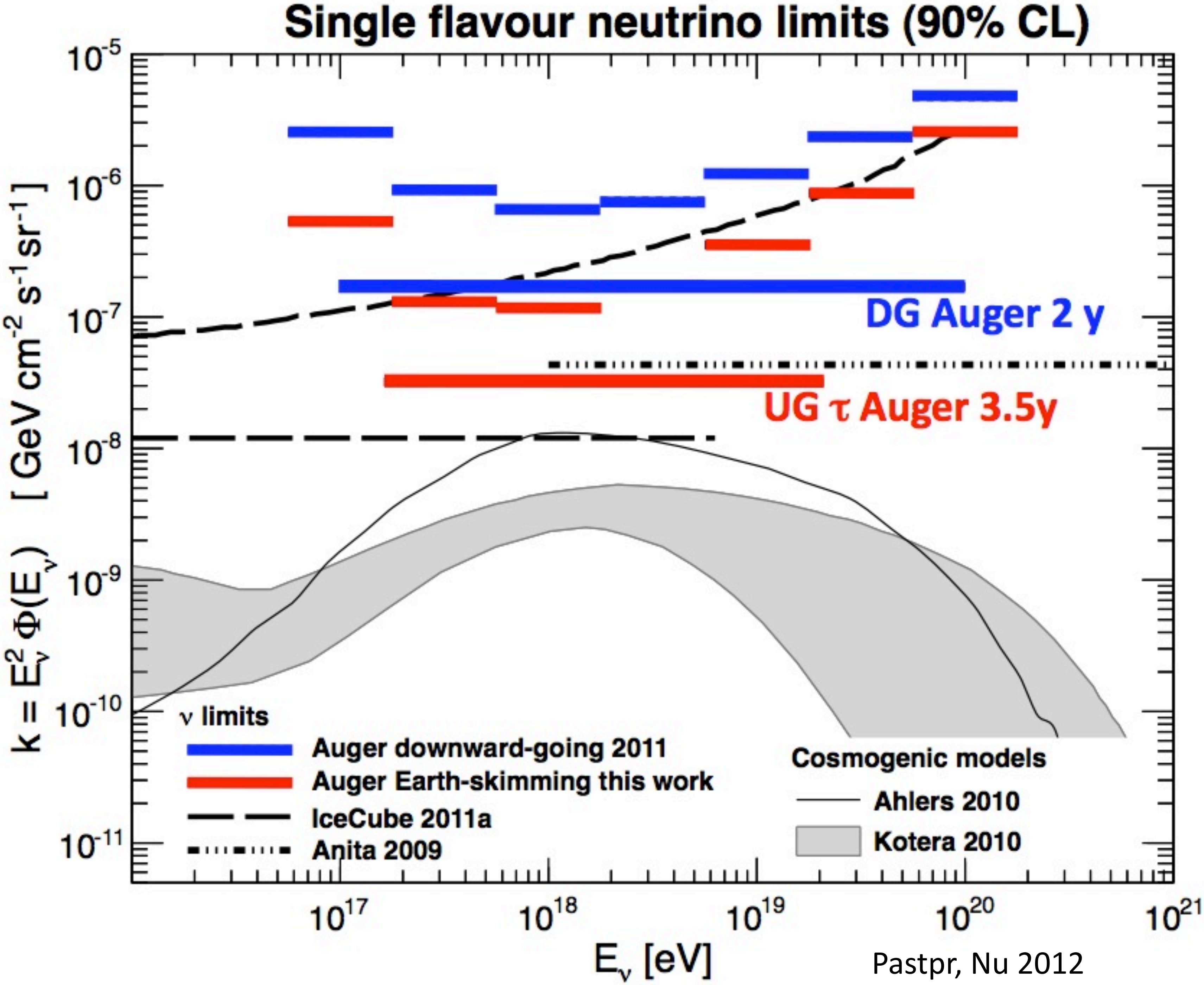
- in SM: cross section extrapolations, energy losses, flavor
- beyond SM: new interactions, LIV, new particles, dark matter, ...

How to do it?

- measure all you can
- take into account everything you know/can think about
- Identify the right observables

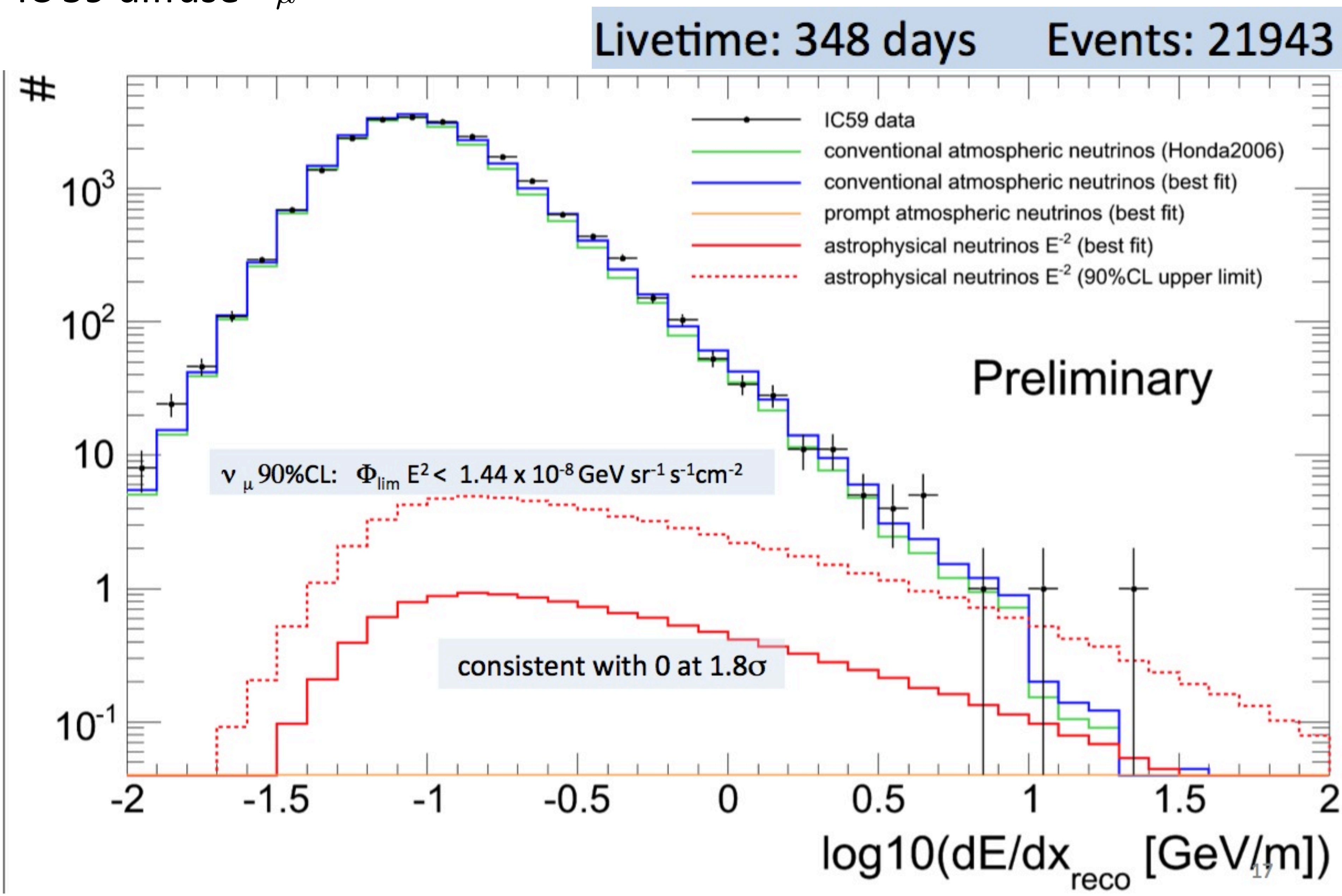
- energy distributions
- angular distributions
- flavor compositions
- better detector techniques
- smart tricks, unique signatures
- very good simulations
- correlations with other observables: photons, protons, etc.

- ➢ can distinguish particle physics from astrophysics effects
- ➢ learn about both



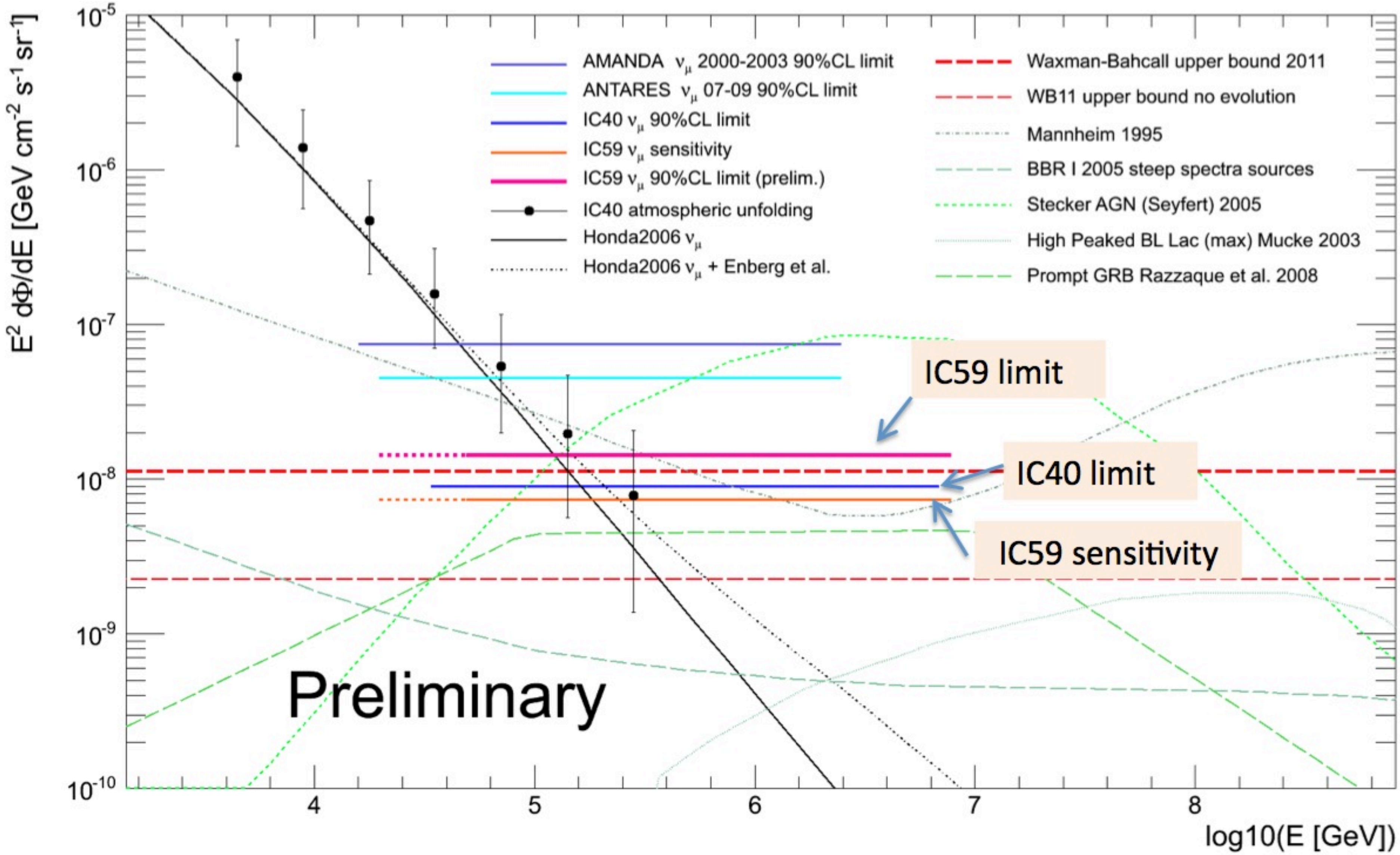
Pastpr, Nu 2012

IC 59 diffuse ν_μ



Sullivan, Nu 2012

ν_μ diffuse limits



Cascades: 14 events; expected bkgd 11.6

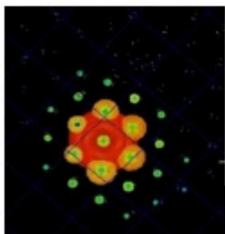
PeV neutrino in Ice Cube ?

highest energies, gamma horizon very limited

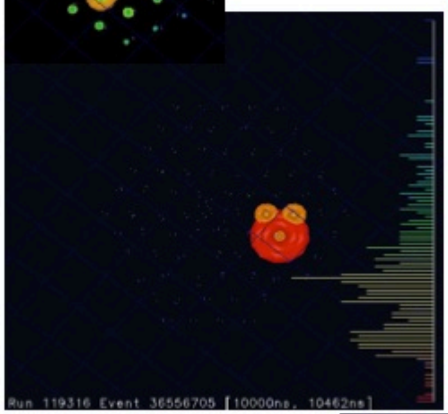
Two events passed the selection criteria

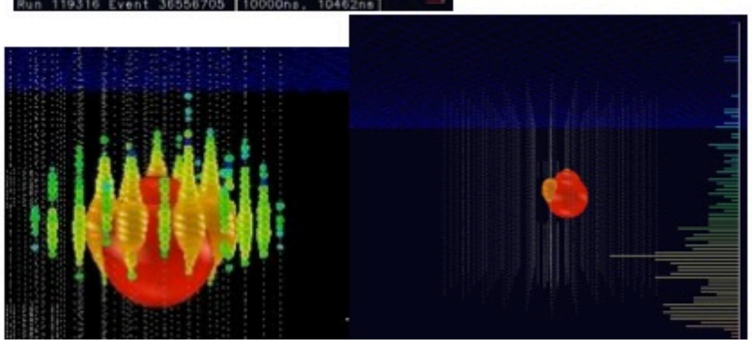
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events

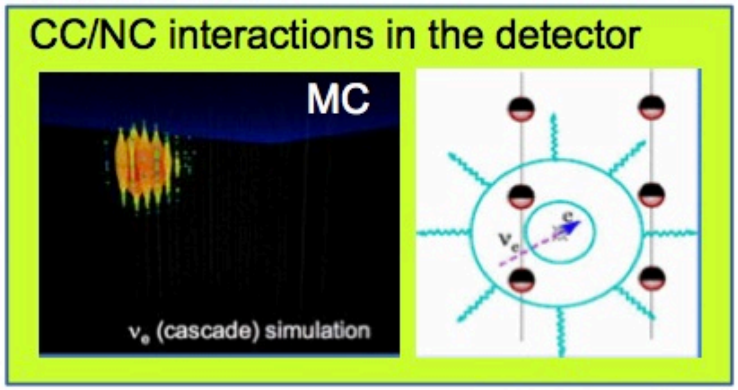
preliminary p-value: 0.0094 (2.36σ)



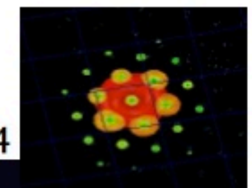
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^4
Number of Optical Sensors 312

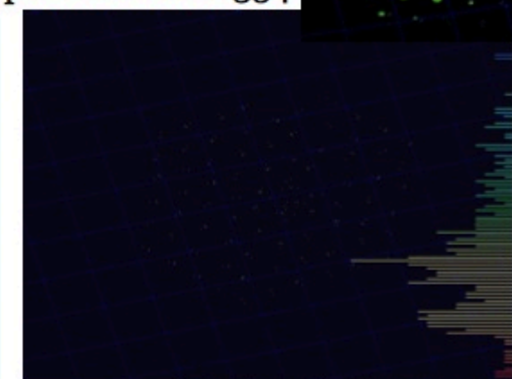


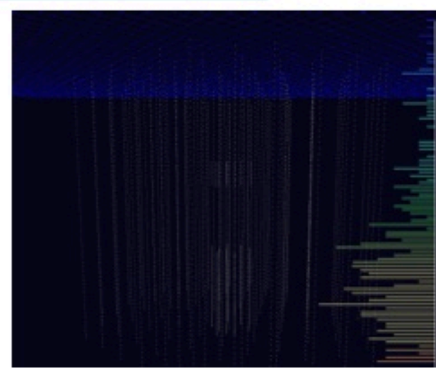


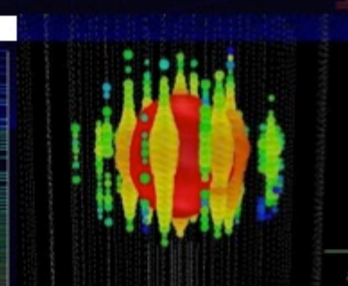


Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^4
Number of Optical Sensors 354



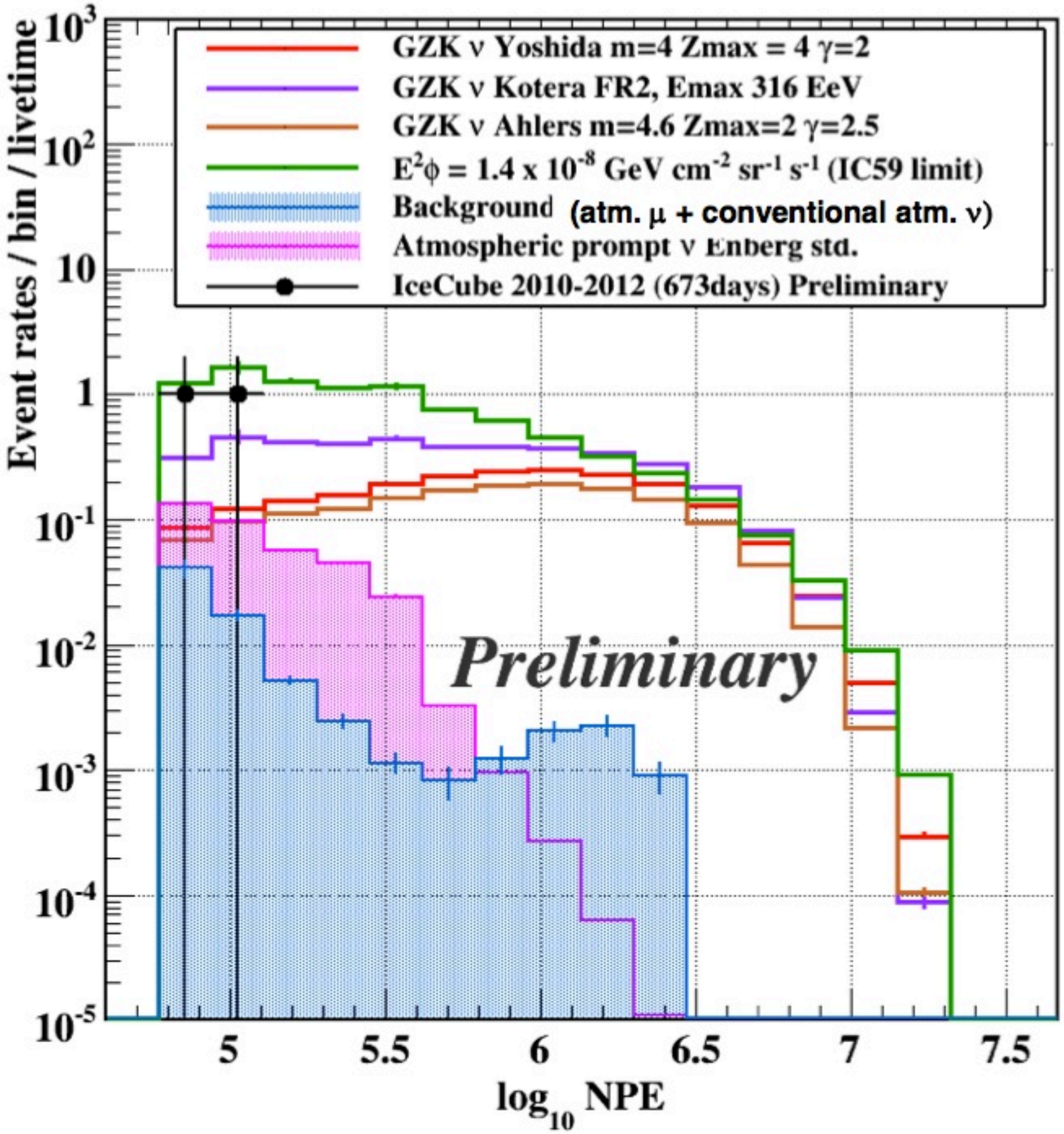






A. Ishihara

Event Brightness (NPE) Distributions 2010-2012



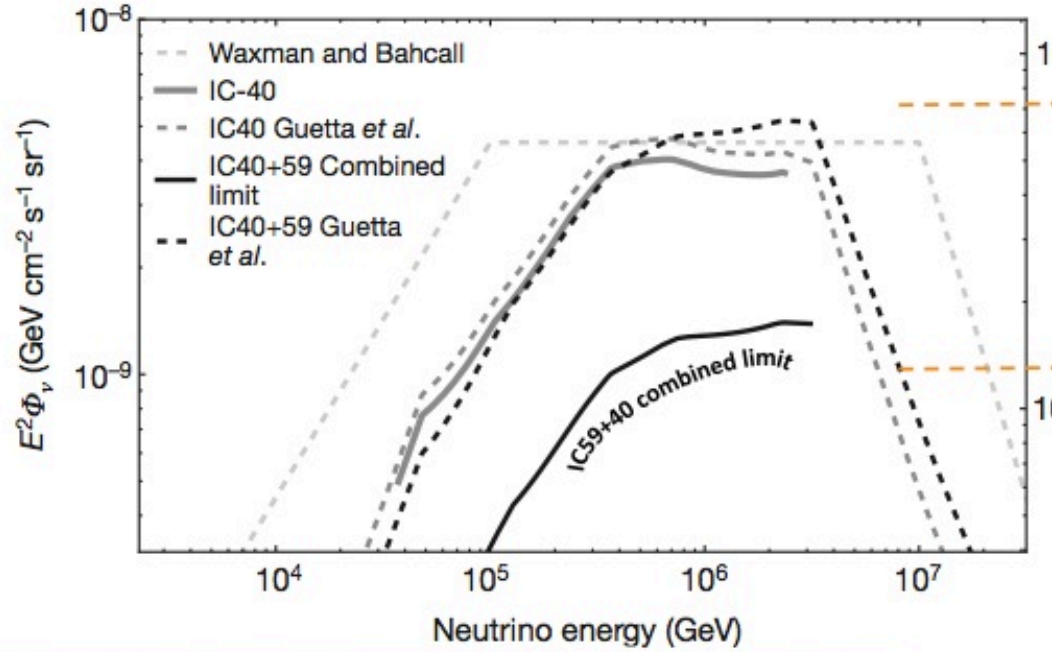
IceCube sensitivity greatly improved

- Observed 2 high NPE events near the NPE threshold
- **No** indication
  - that they are instrumental artifacts
  - that they are cosmic-ray muon induced
- Possibility of the origin includes
  - cosmogenic ν
  - on-site ν production from the cosmic-ray accelerators
  - atmospheric prompt ν
  - atmospheric conventional ν

Ishihara, Nu 2012

IceCube GRB search

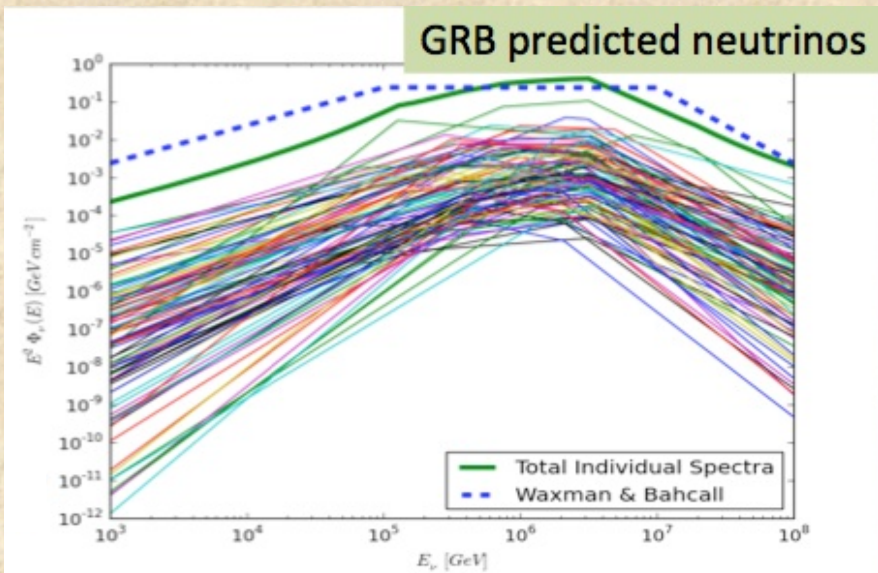
Sullivan, Nu 2012

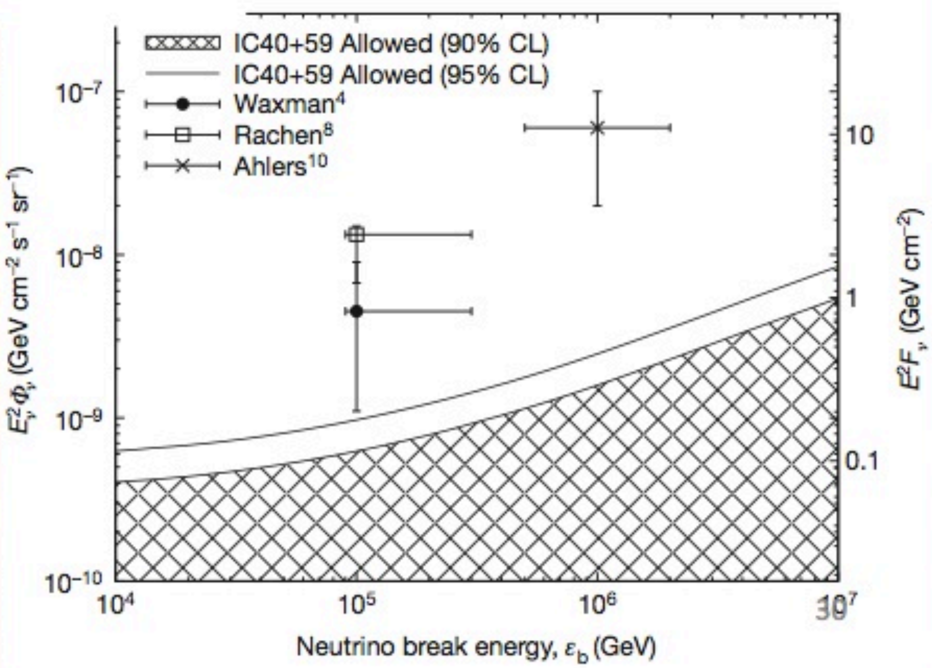


Nature 484, 351 (2012)

90% c.l. = 0.27 model

8.4 events expected
0 events observed



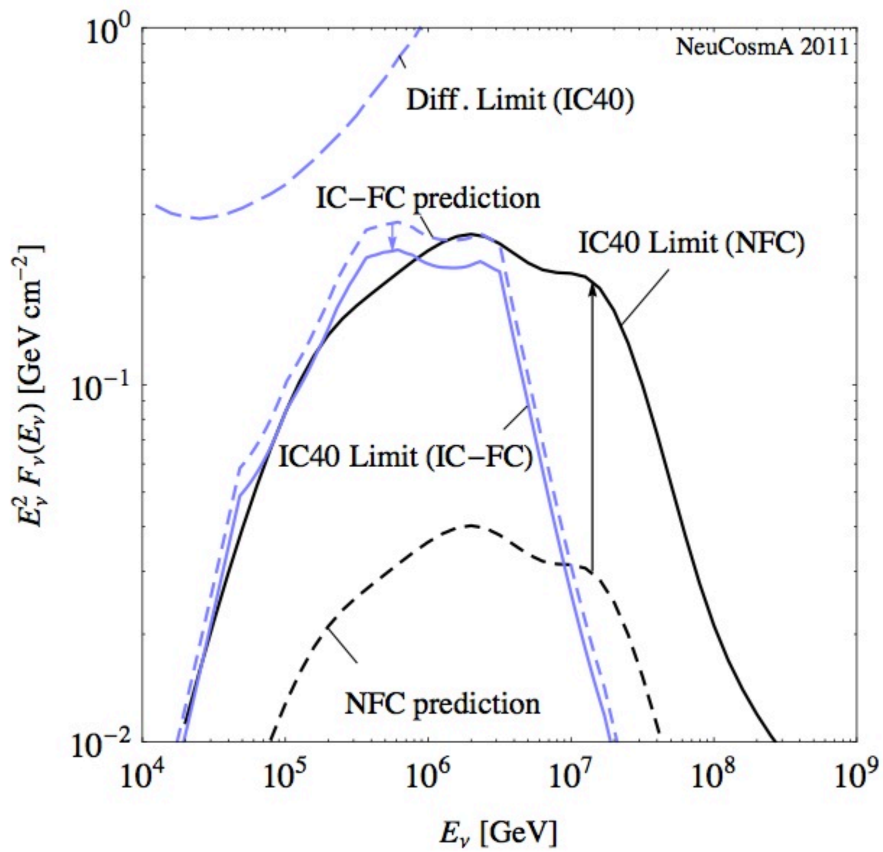


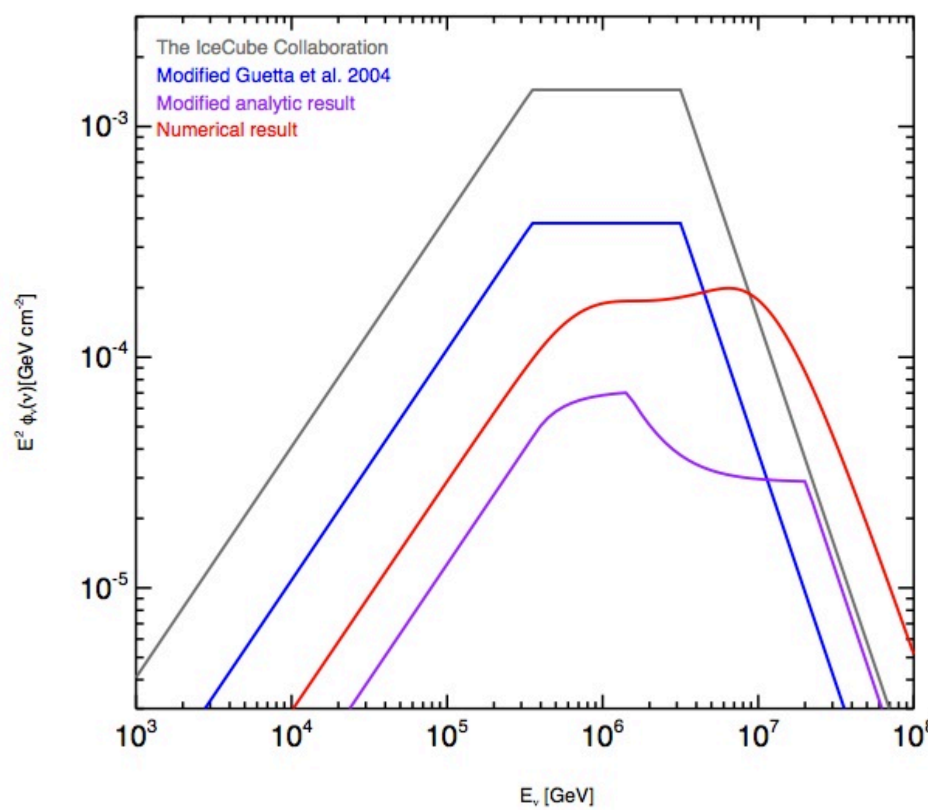
Excluded models?

Hummer, Baerwald, Winter (2012)
He, Liu, Wang, Nagataki, Murase, Dai (2012)

Not yet!

- Detailed analysis
- Energy dependence in spectra -> order of magnitude reduction in nrs





Outlook

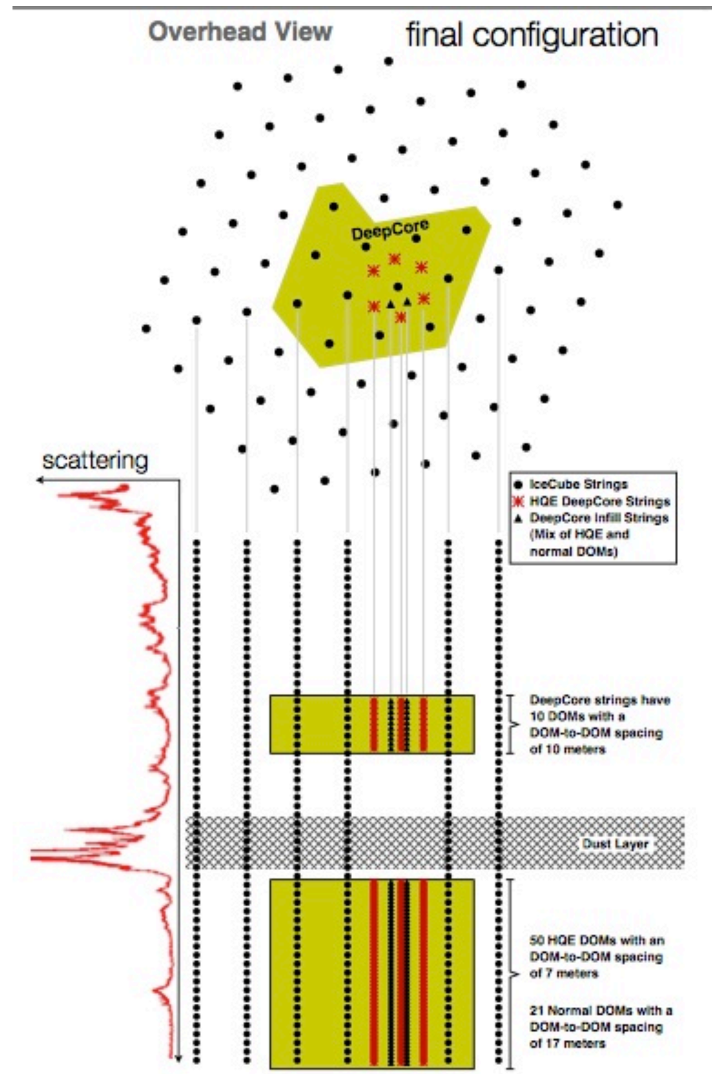
- Neutrino telescopes now real: data!
- Getting better
- Just starting to get interesting
- High energy astrophysical neutrinos
    - smoking gun for hadronic processes
      (few events for point source)
    - need detailed analysis for data interpretation

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

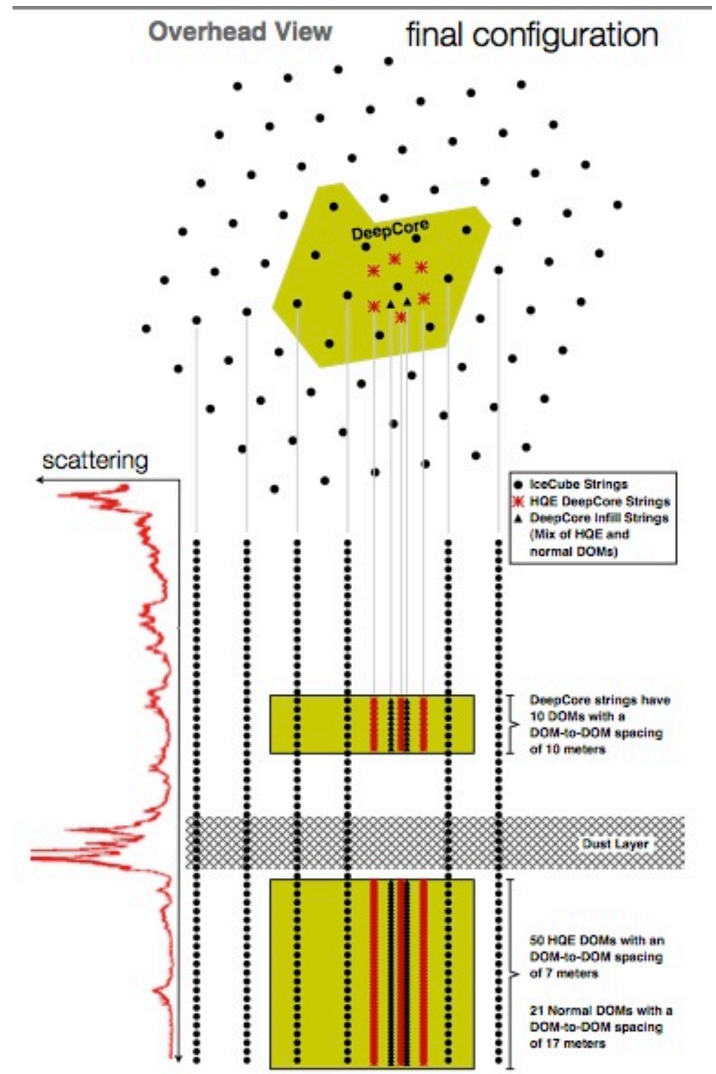
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center

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

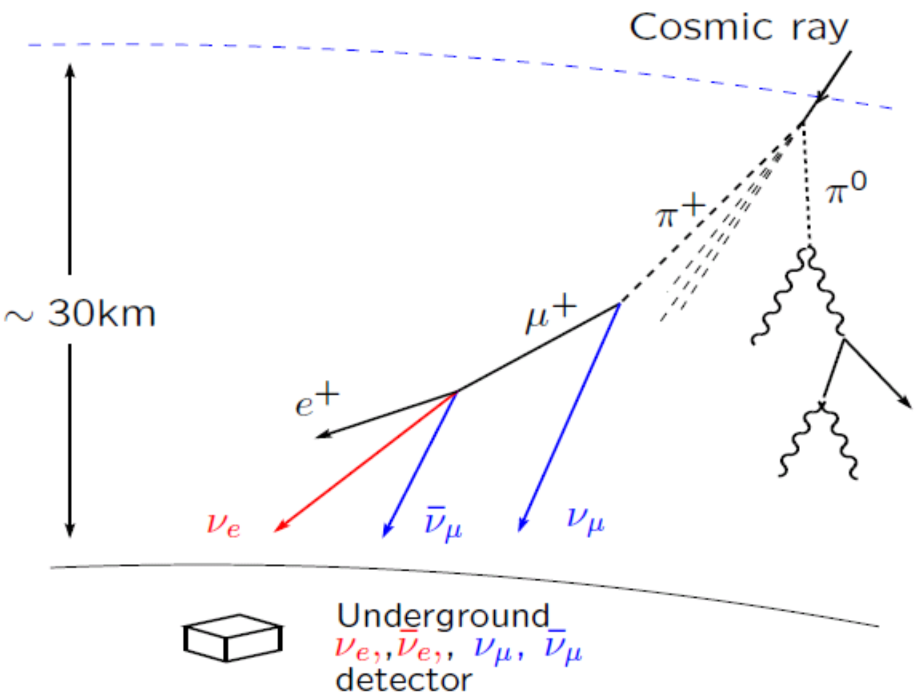


IceCube Deep Core

- 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



Atmospheric neutrinos



Super-Kamiokande

- expect: $\frac{N_{\nu_\mu+\bar{\nu}_\mu}}{N_{\nu_e+\bar{\nu}_e}} \simeq 2$ at low energies

IceCube Deep Core

- $\frac{N_{\nu_\mu+\bar{\nu}_\mu}}{N_{\nu_e+\bar{\nu}_e}} \simeq 10$
- steep energy spectrum ($E_\nu^{-3.7}$)
- ν_e flux not measured at high energies

- Background to many searches
- lots of them
  - > 50,000 events per year!
  - somebody's background is somebody else's signal
- remember:

  solar neutrinos: solar physics, atmospheric neutrinos: proton decay

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

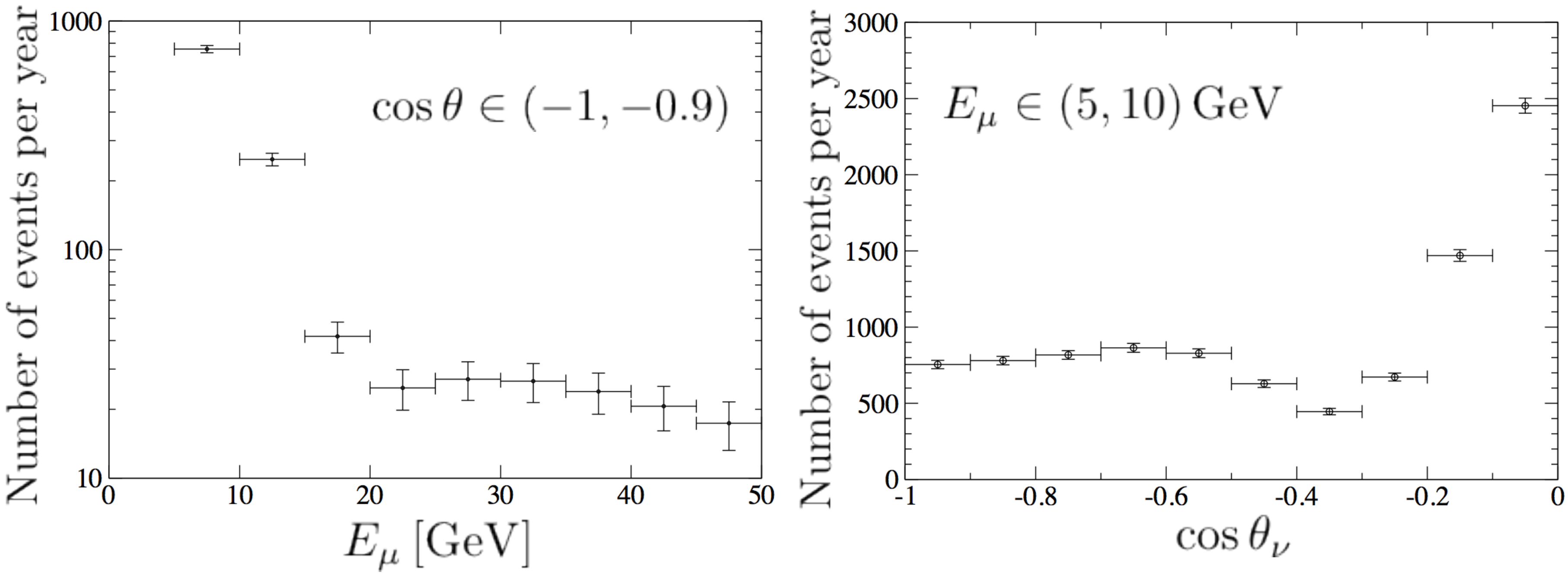
ICDC physical mass: $15 - 20\,\mathrm{Mt}$

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)

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

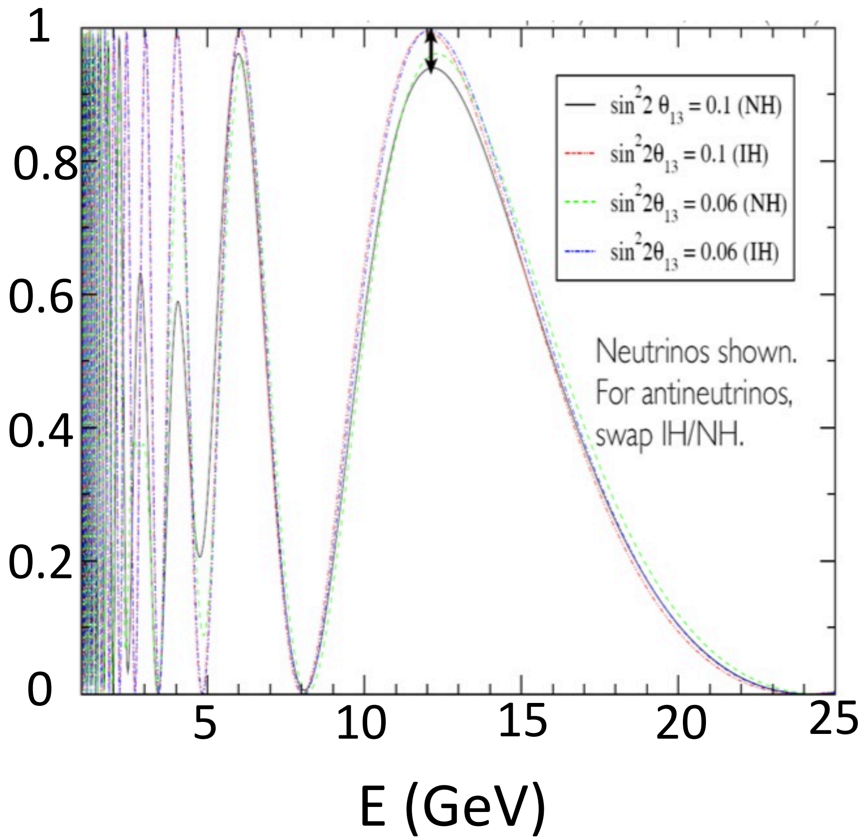
IceCube Deep Core:

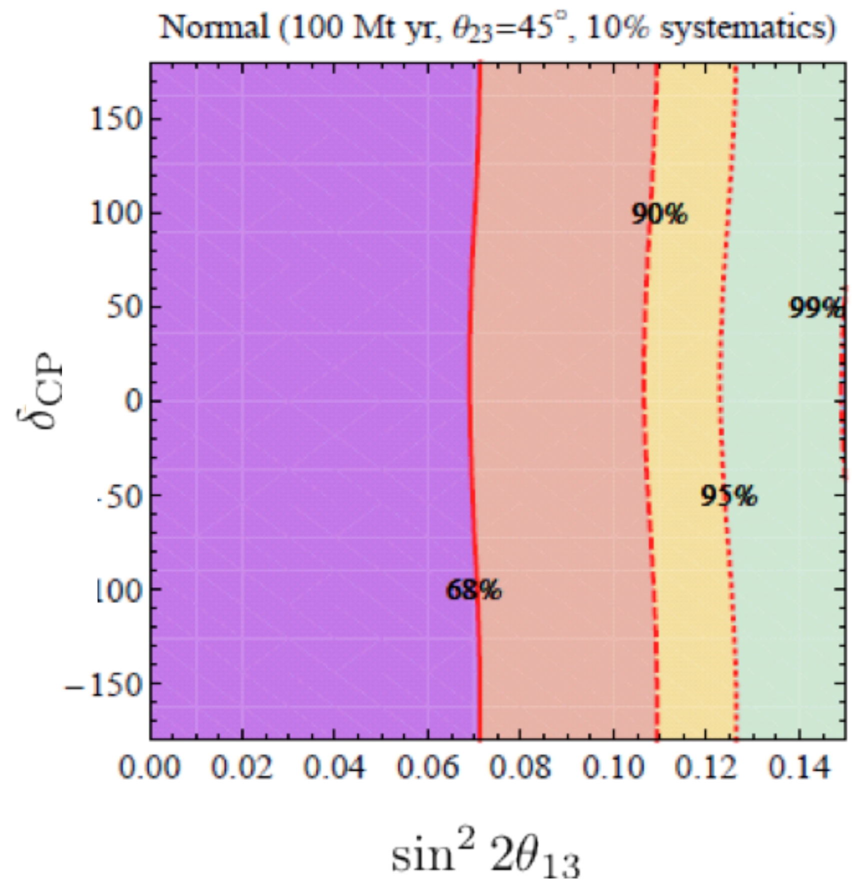
- very large statistics
- contribution from multiple peaks

Normal versus inverted mass hierarchy

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

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





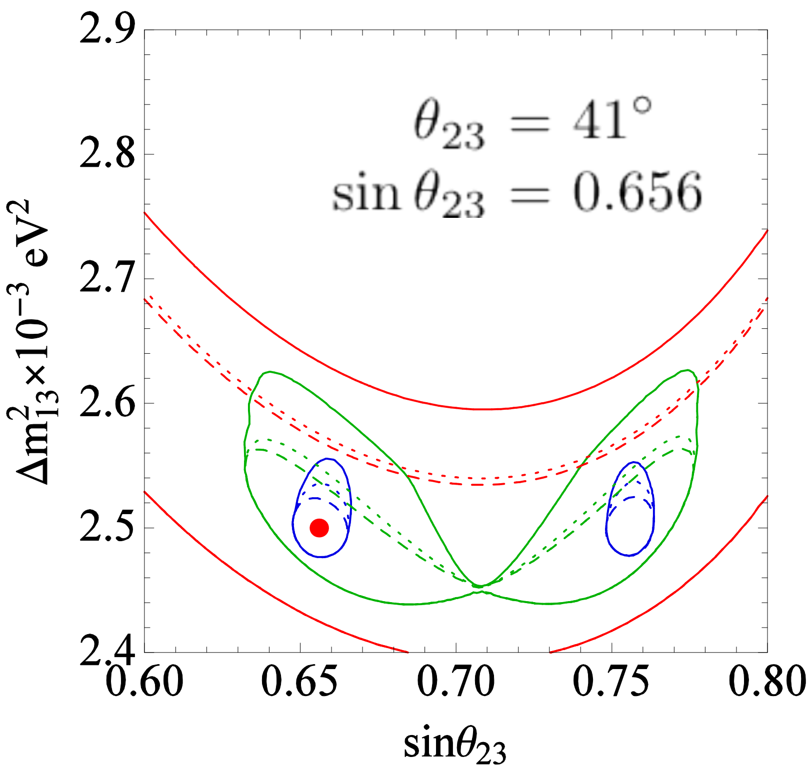
- much better now, with known and large θ_{13}

Presently allowed values:

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

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

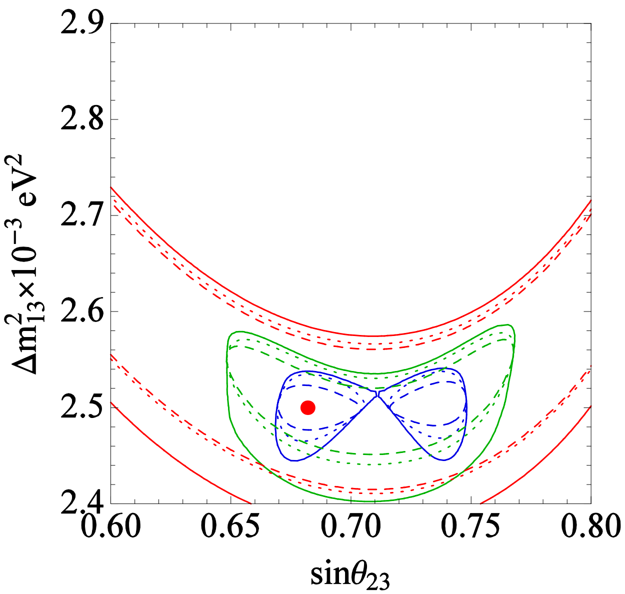
vs

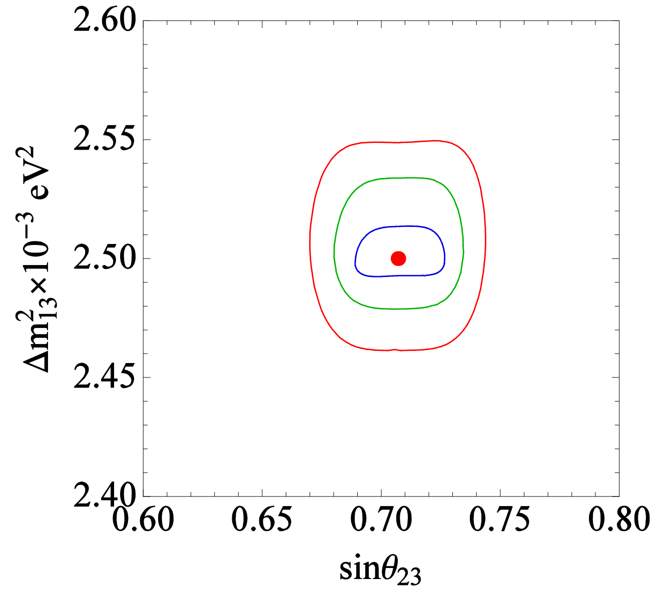
$\theta_{13} = 0.01 \pm 0.02$ ....

vs

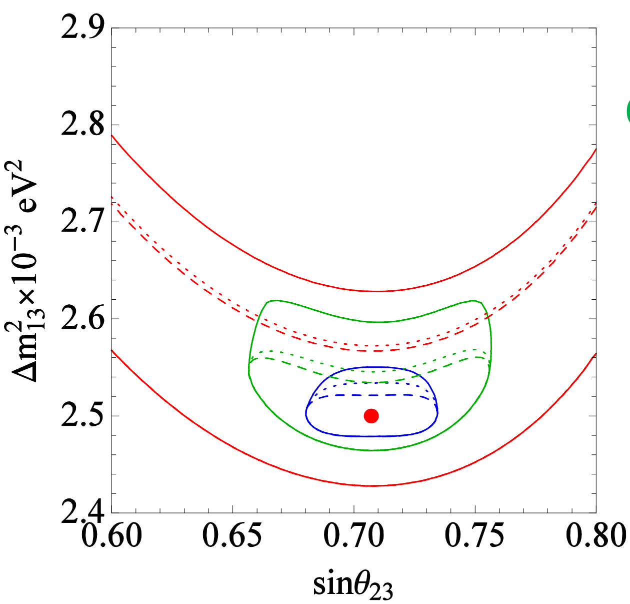
θ_{13} completely free ———————

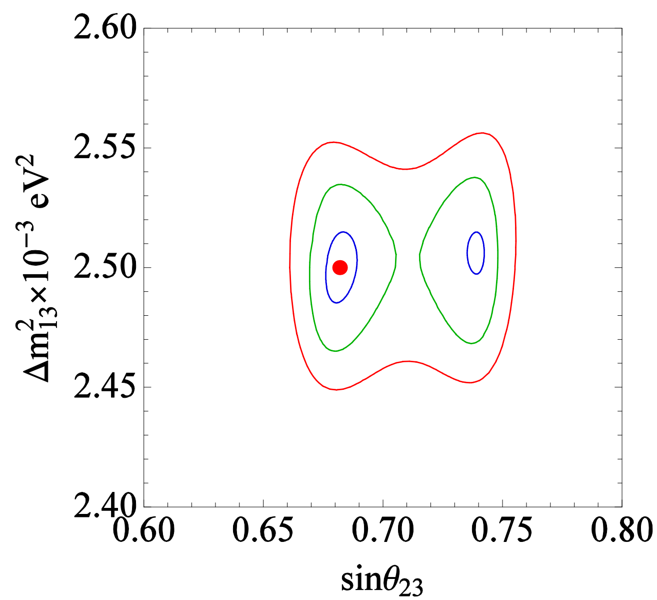
IceCube Deep Core



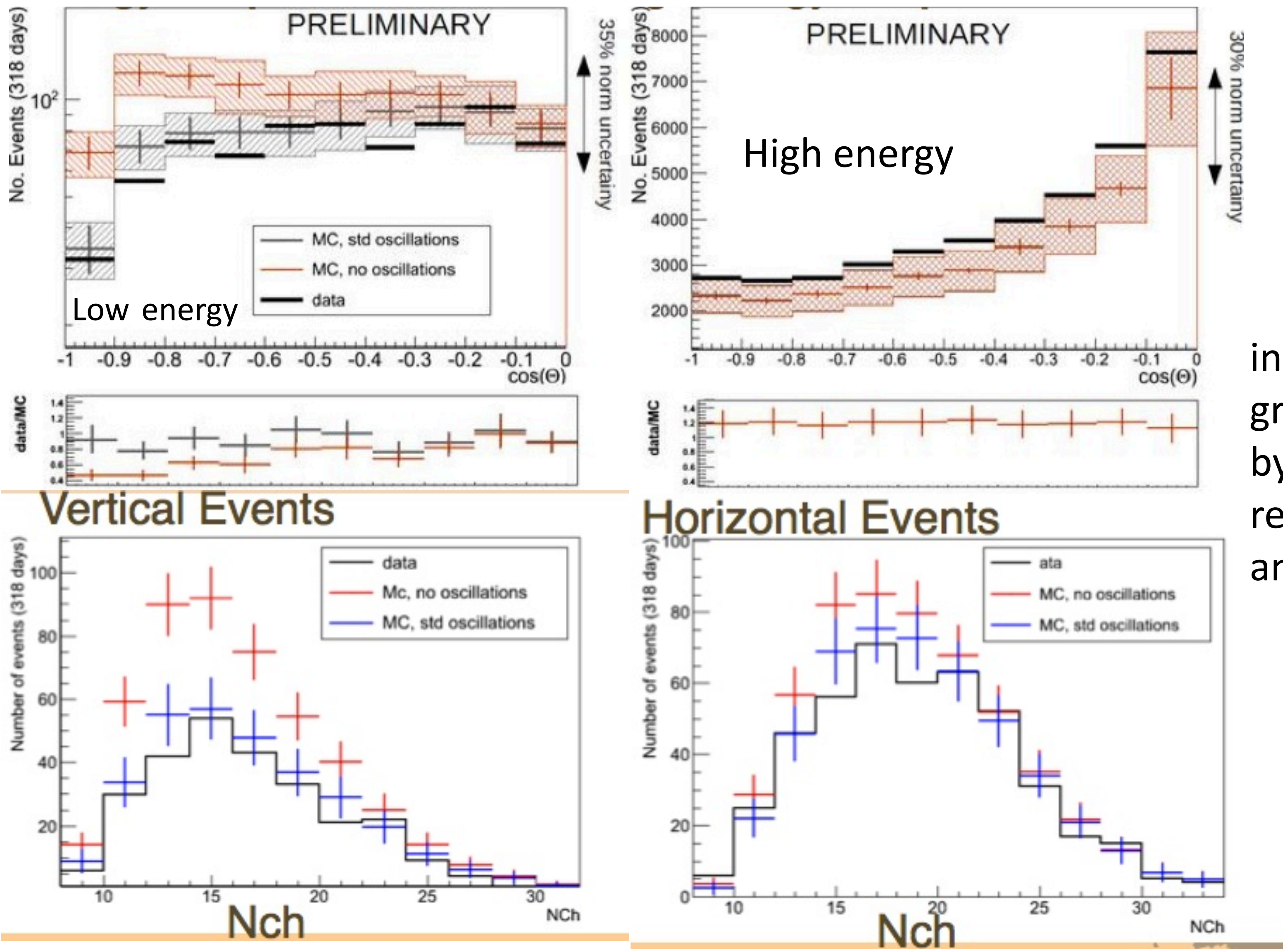


- Expected allowed regions depend on the true values of the parameters and control of systematic uncertainties





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



initial step greatly improved by new/future reconstruction analysis

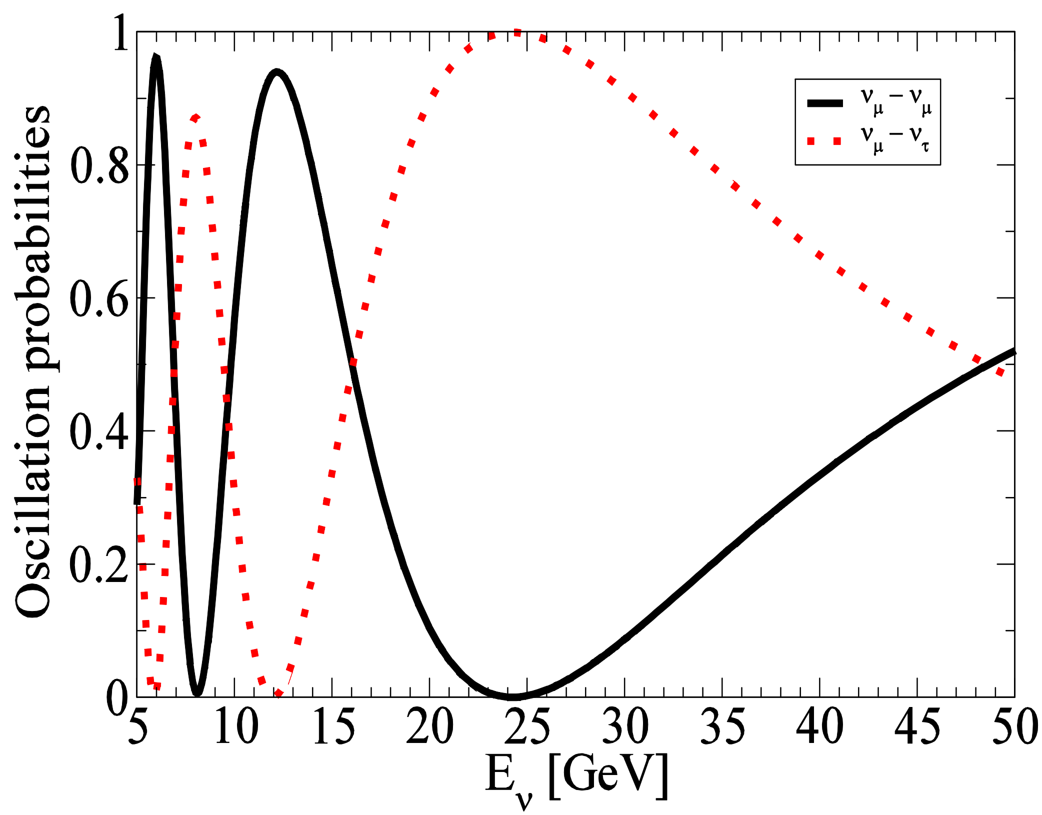
How about cascades?

- ν_e CC interactions: $\nu_e + N \longrightarrow e + X$
- ν NC interactions: $\nu + N \longrightarrow \nu + X$
- τ decay $\tau \longrightarrow e + \bar{\nu}_e + \nu_\tau$ $\tau \longrightarrow \nu_\tau + X$

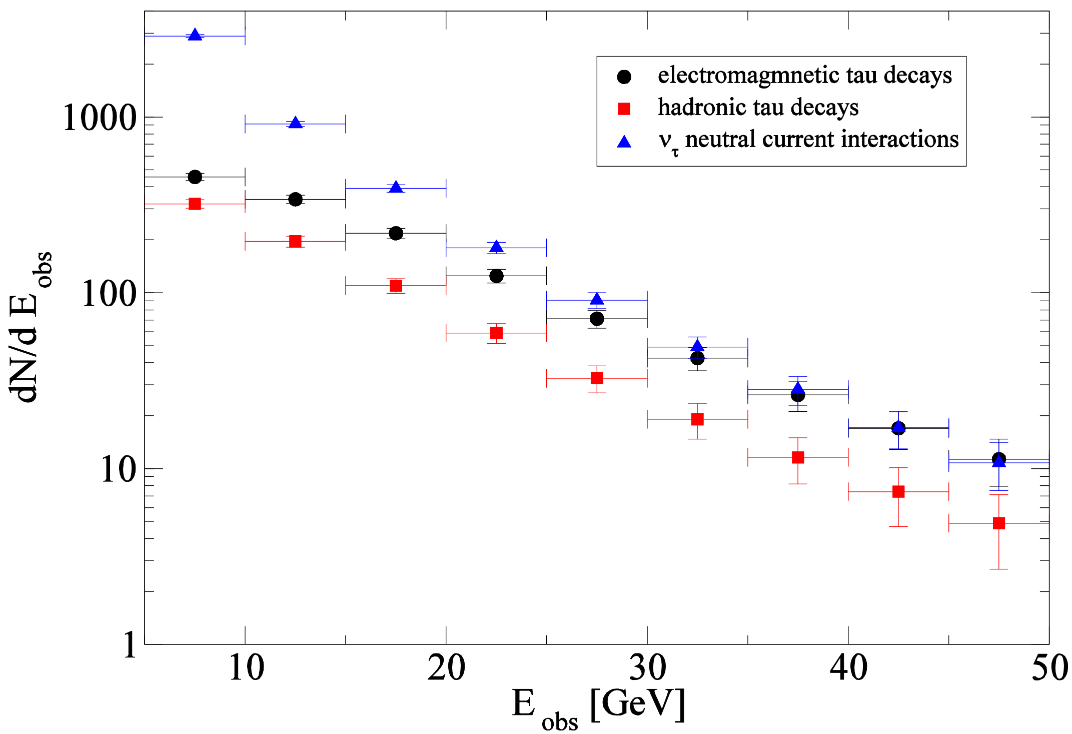
- Looking for ν_τ helped by:

high energy
(tau threshold effects small)
background low: $\Phi_{\nu_\mu} \sim 10\,\Phi_{\nu_e}$
oscillations

Earth diameter



Tau cascade rates



- $\nu_\mu \to \nu_\tau \to \tau \to e$ or hadrons large
- present world sample of ν_τ events:

  5(9) DONUT + (2) (OPERA)

- Super-Kamiokande (after 15 years):

  $180.1 \pm 44.3(stat)^{+17.8}_{-15.2}(sys)$

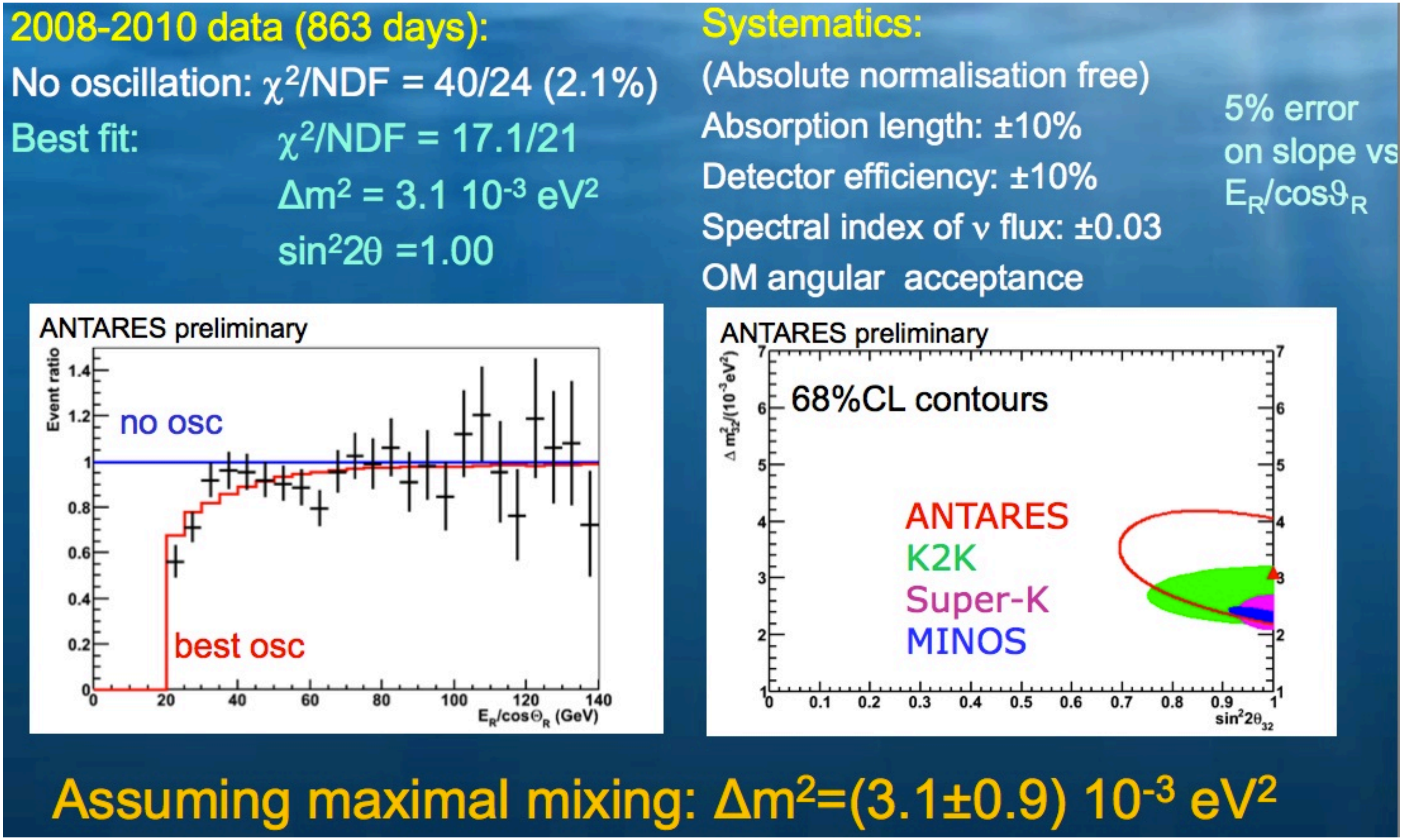
- high statistics ν_τ interactions

- 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 the first small data sample

ANTARES

- Largest neutrino telescope in northern hemisphere
- Sensitivity to galactic sources

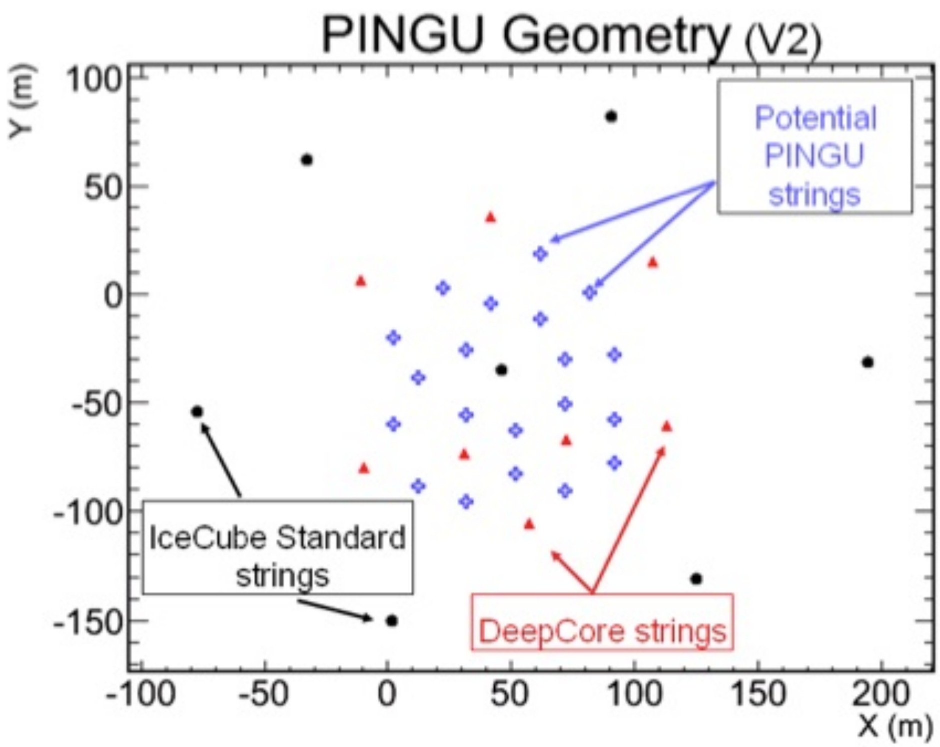


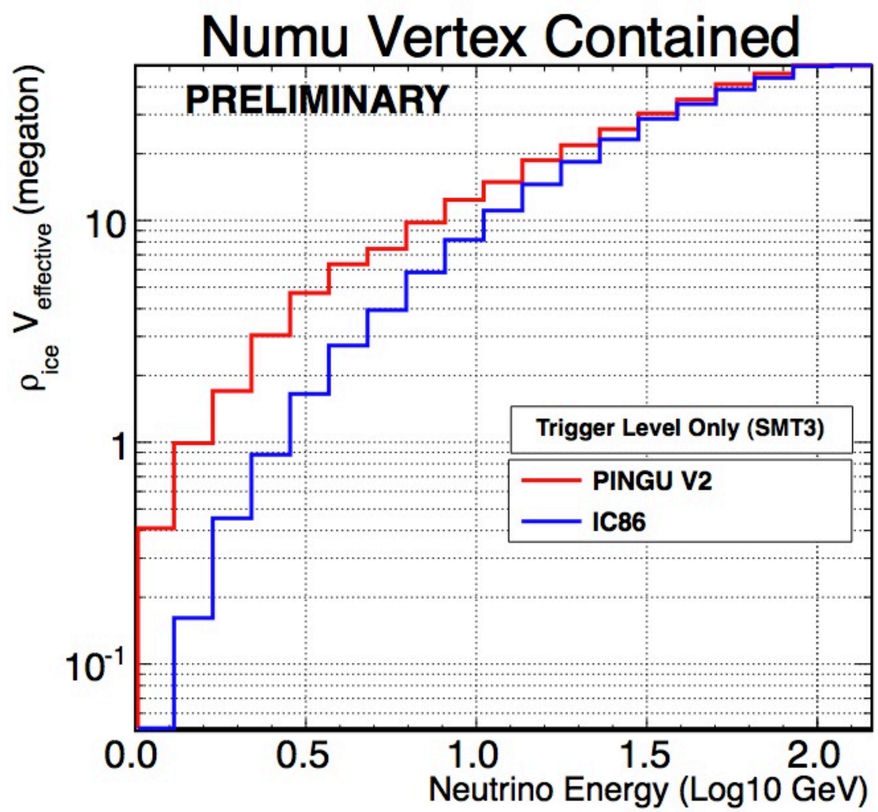
Coyle, Nu 2012

PINGU

- Precision/Phased IceCube Next-Generation Upgrade
- ~ 20 strings, 1000 DOMs
- Inside DeepCore region
- Energy threshold ~ 1GeV

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





Mass Hierarchy in PINGU

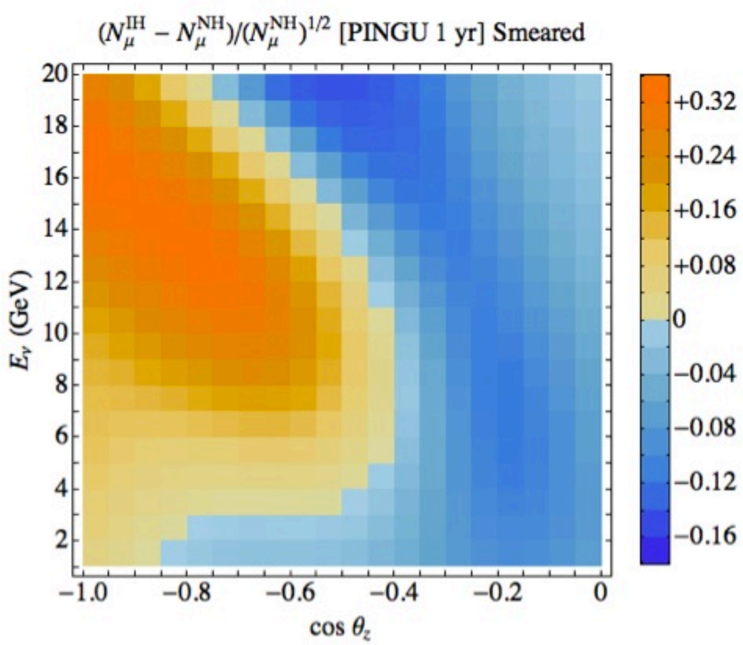
Akhmedov, Razzaque, Smirnov, 2012

$3 - 11\,\sigma$ in 5 years, depending on reconstruction

- systematics $< 10\%$
- very general analysis, no details
- DIS only
- full analysis: likely better outcome!

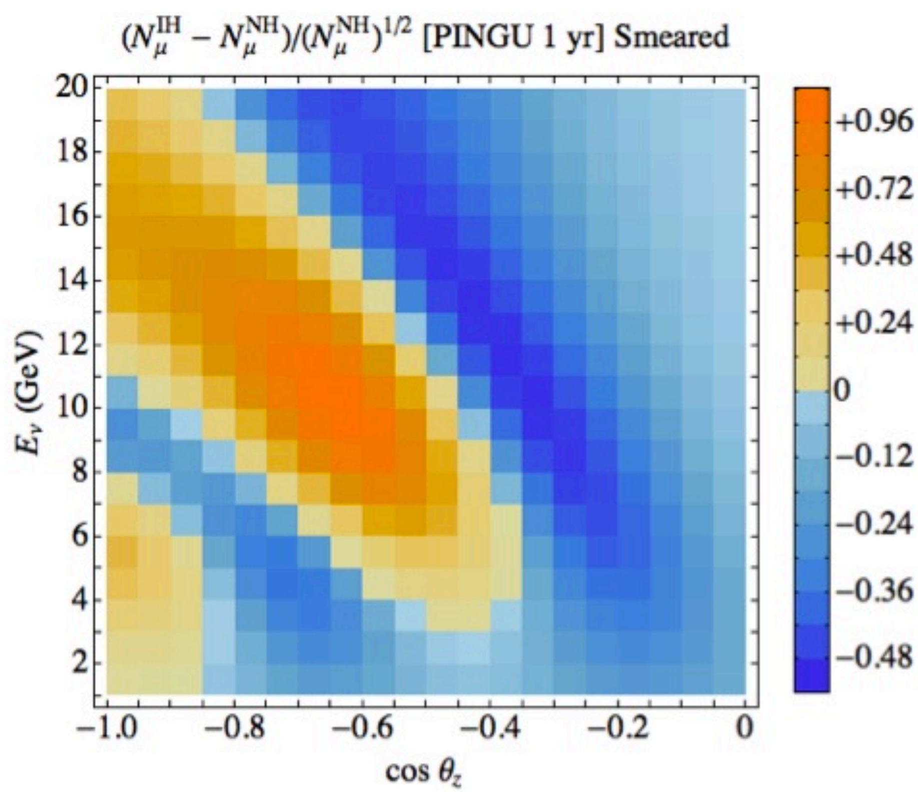
$\sigma_E = 4\,\mathrm{GeV}$

$\sigma_\theta = 22.5^\circ$



$\sigma_E = 2\,\mathrm{GeV}$

$\sigma_\theta = 11.25^\circ$



Outlook

- IceCube Deep Core detector already taking data !
- built to look for galactic sources, dark matter
- someone's background can be someone else's signal
- experiments take a very long time to construct/operate
- atmospheric neutrinos: huge statistics, many energies/distances
- 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!

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