Neutrino Properties from Neutrino Telescopes

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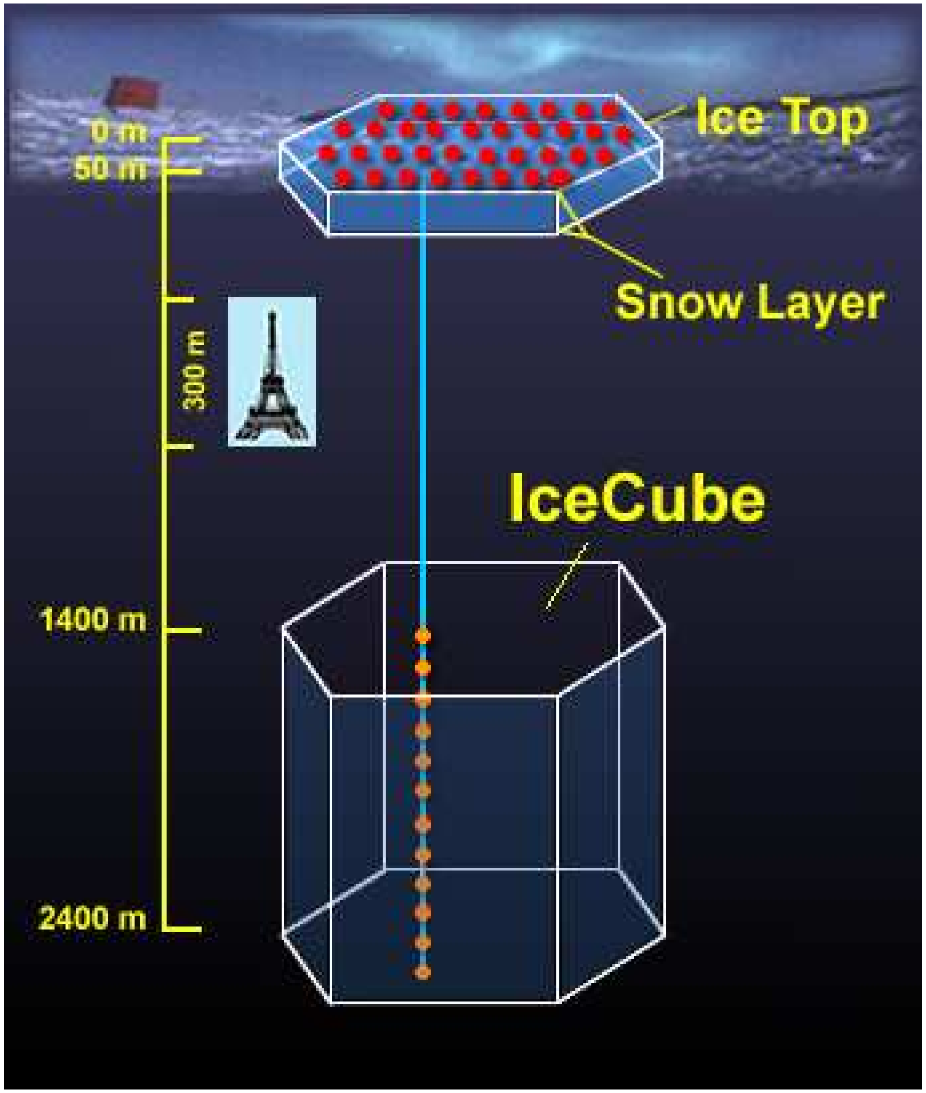
IceCube



What to look for?

- Point sources
- Diffuse fluxes
  - from sources
  - from cosmic ray interactions
  - from dark matter annihilation
  - ...
- Correlations with other observations:
  cosmic rays, gamma rays...

Lessons for Particle Astrophysics

Weak interactions

- access to dense, violent envirenoments
- test mechanism powering astrophysical sources
- cosmic ray acceleration processes
- cosmic ray propagation and intergalactic photon 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
- ...

How to do it?

- energy distributions
- angular distributtions
- flavour composition

Observables

- Muon tracks: ν_μ CC interactions: $\nu_\mu + N \rightarrow \mu + X$
- Electromagnetic showers:

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

ν_e CC interactions: $\nu_e + N \rightarrow e + X$

- Hadronic showers

Tau decay: $\tau \rightarrow \nu_\tau + X$

ν_τ NC interactions: $\nu_\tau + N \rightarrow \nu_\tau + X$

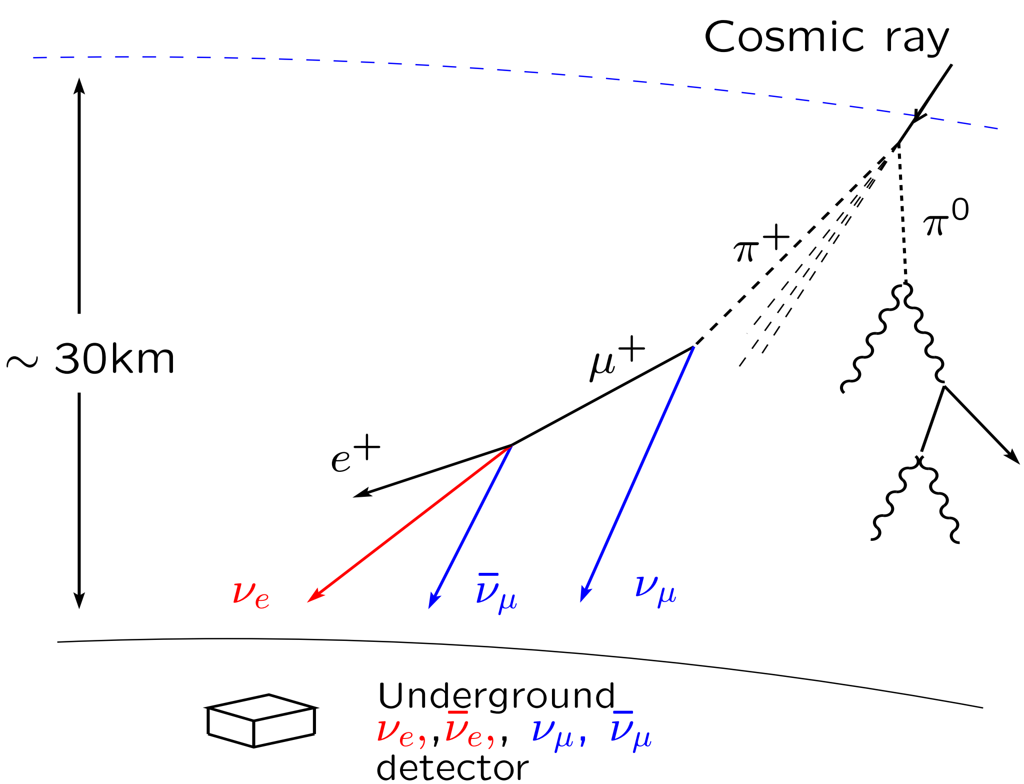
ν_τ CC interactions: $\nu_\tau + N \rightarrow \tau + X$

$\nu_{e,\mu}$ NC and CC interactions

Deep Core Array

- motivation: galactic sources, dark matter annihilation
- need to reduce large cosmic muon background
- dense phototube coverage region
- in the deep ceter region of IceCube
- low energy threshold

Atmospheric Neutinos



- Expect: $\frac{N(\nu_\mu+\bar{\nu}_\mu)}{N(\nu_e+\bar{\nu}_e)} \sim 2$ at low energy

  $\sim$isotropic

- background to many IceCube searches

Summary of Experimental Results

- Solar Neutrinos: $\nu_e \to \nu_x$, $x = \mu, \tau$

+ reactor antineutrinos

$$\begin{aligned} \Delta m^2_{sol} &\simeq 7.6 \times 10^{-5} \mathrm{eV}^2 \\ \tan^2\theta_{sol} &\simeq 0.45 \end{aligned}$$

- Atmospheric Neutrinos: $\nu_\mu \to \nu_x$, $x = \tau$

+ accelerator neutrinos

$$\begin{aligned} \Delta m^2_{atm} &\simeq 2.5 \times 10^{-3} \mathrm{eV}^2 \\ \sin^2 2\theta_{atm} &\simeq 1 \end{aligned}$$

- Reactor antineutrinos: $\bar{\nu}_e \not\to \bar{\nu}_e$

$$\sin^2 2\theta_{reactor} \lesssim 0.1 \text{ for } \Delta m^2 \sim 10^{-3} eV^2$$

Three flavors

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\Delta m^2_{21} = \Delta m^2_{sol}, \quad \Delta m^2_{32} = \Delta m^2_{atm}$$

$$\theta_{12} = \theta_{sol}, \theta_{13} = \theta_{reactor}, \theta_{23} = \theta_{atm}, \delta$$

We want to measure:

- θ_{13}
- hierarchy (sign of Δm^2_{atm})
- CP violation (δ)

large effort to build new accelerator experiments for this purpose
use matter effetcs

Neutrino Oscillations in IceCube

μ like fully contained events

Angular distribution:

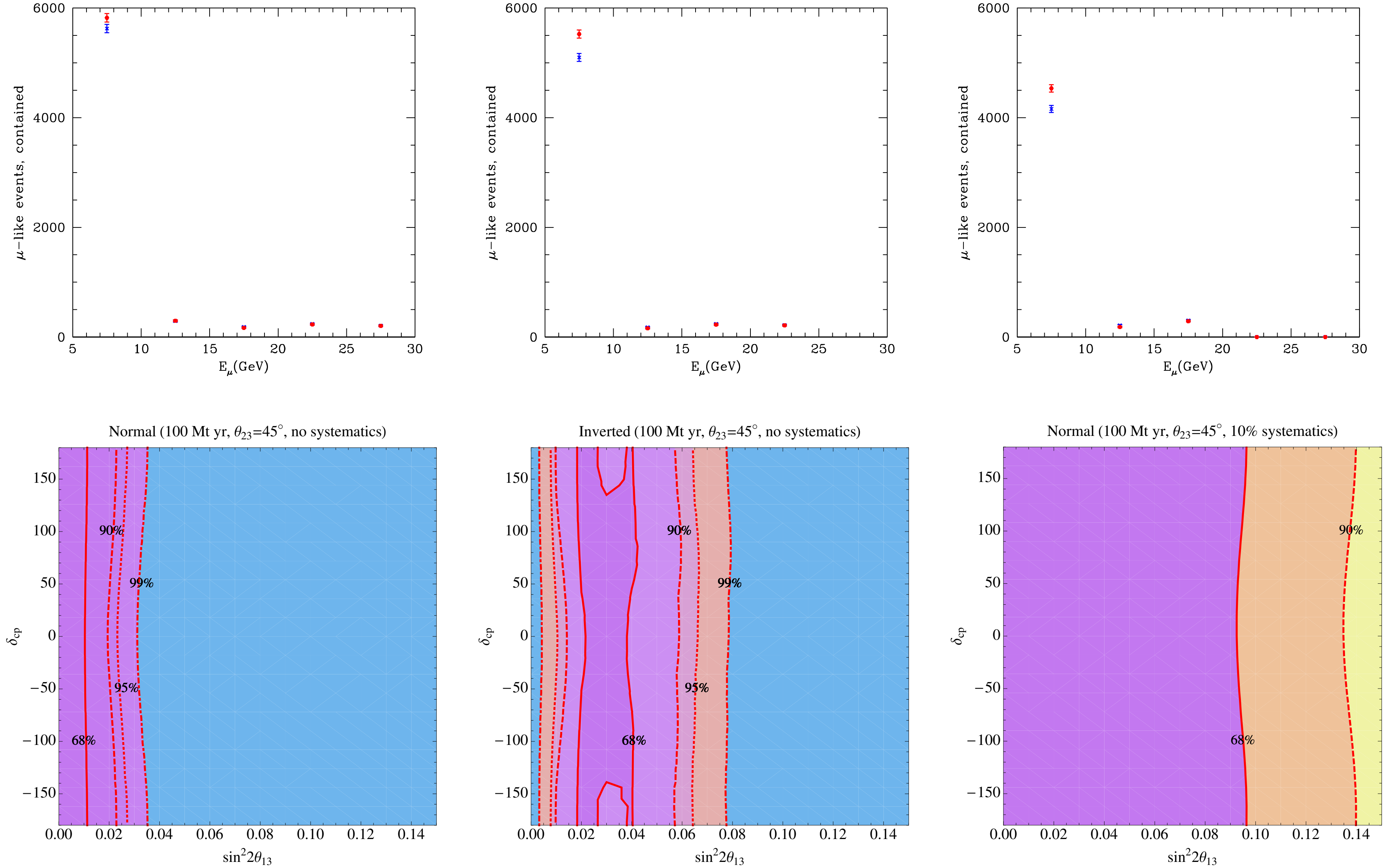
- $\cos\theta \in (0, 1)$ atmosperic flux normalization
- $\cos\theta \in (-0.9, 0)$ + main oscillation signal (Δm^2_{32}, θ_{23})
- $\cos\theta \in (-1, -0.9)$ + matter effects (θ_{13}, hierarchy, CP)

Energy distribution:

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

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

Normal versus inverted hierarchy: O. Mena, I. M., S. Razzaque



Lots to learn from:

- astrophysical neutrinos

- long baseline experiments

In the meantime:

use atmospheric neutrinos in IceCube to determine

neutrino oscillation parameters!