Neutrino Lessons for Particle Physics and Astrophysics

Irina Mocioiu

Penn State

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Neutrinos in the Standard Model (10 years ago)

- no electric charge or colour charge
  feel only weak interactions

They are called weak for a reason!

$$\text{For } 100 \text{ GeV neutrinos } \begin{cases} \sigma_{\nu p} \sim 10^{-36} cm^2 \\ \sigma_{pp} \sim 10^{-25} cm^2 \end{cases}$$

- part of left-handed doublet: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$
- three flavours: ν_e, ν_μ, ν_τ
- no ν_R
- massless

Neutrinos Beyond the Standard Model (1998-future)

• **LOTS of DATA** over last 10 years

- massless $\longrightarrow$ massive: **very tiny masses**
- **Oscillations**: the flavors are mixed: **large mixing**
- What does it mean?
  - no ν_R $\longrightarrow$ add ν_R

    Standard Model symmetries alow Majorana mass for ν_R!

    Neutrinos are Majorana fermions

    ν_R at high scale $\longrightarrow$ see-saw$\longrightarrow$ small ν mass
  - no ν_R BUT Neutrinos are Majorana fermions

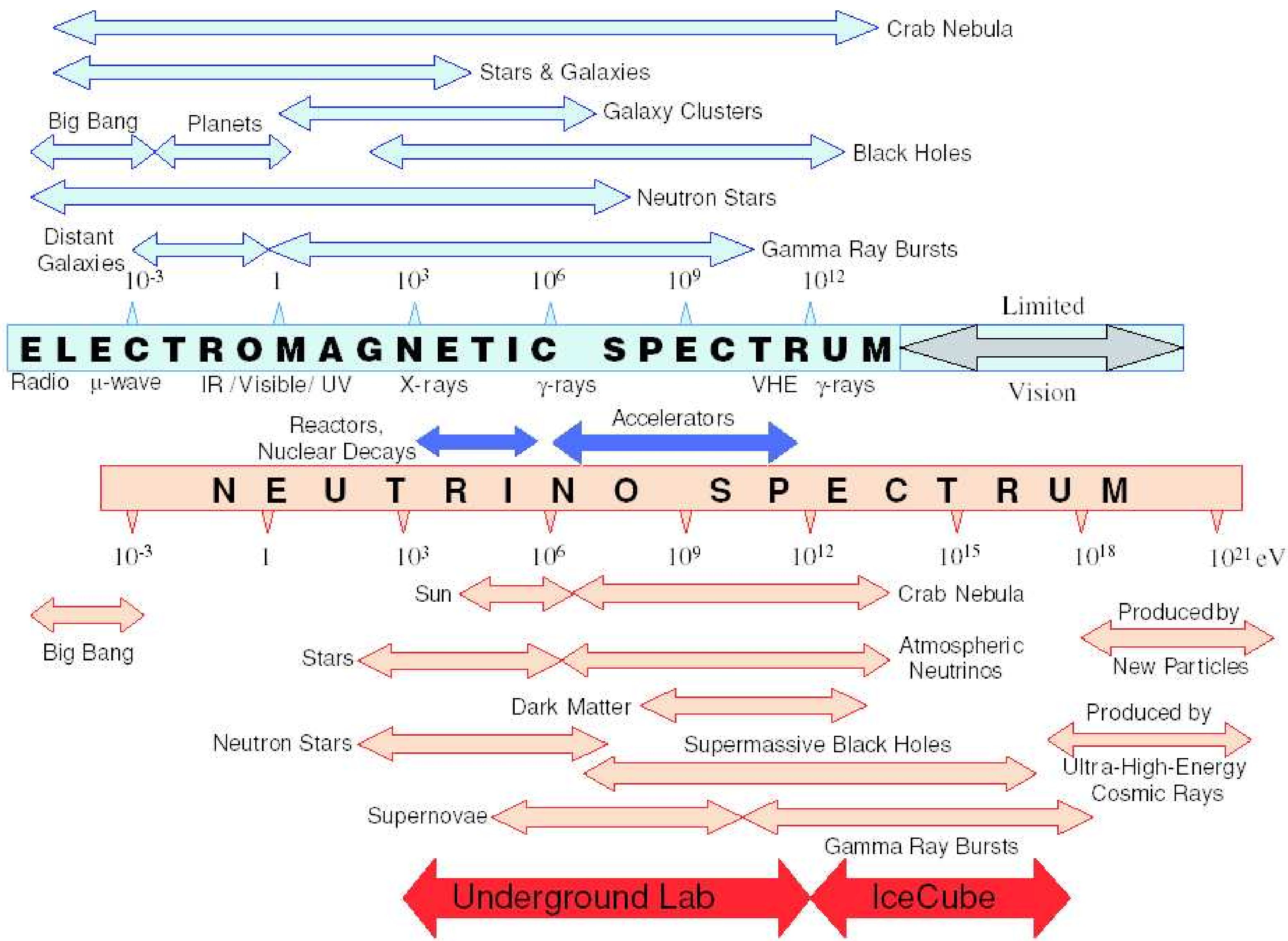
    Majorana mass violates lepton number

    need other Higgs; higher dimension operators

Neutrinos

- Neutrino masses and oscillations
  - confirmed evidence of physics beyond the Standard Model
  - key importance for physics beyond the Standard Model
- Unique probe of extreme environments
- Can probe scales from 10^{-33} to 10^{28} cm
- Play major role in particle physics, astrophysics and cosmology

Neutrino Facilities Assessment Committee, 2002



High Energy Neutrino Sources

Guaranteed

↓

Highly speculative

- "GZK" neutrinos:

$$p + \gamma \rightarrow ... \rightarrow \pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \downarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

- Gamma Ray Bursts

- Active Galactic Nuclei

- Topological Defects

- Decay of Super-Massive Particles

...

-

Experiments

- AMANDA/ICECUBE : Cerenkov light in ice (South Pole)

- ANTARES, NESTOR: Cerenkov light in water (Mediterranean)

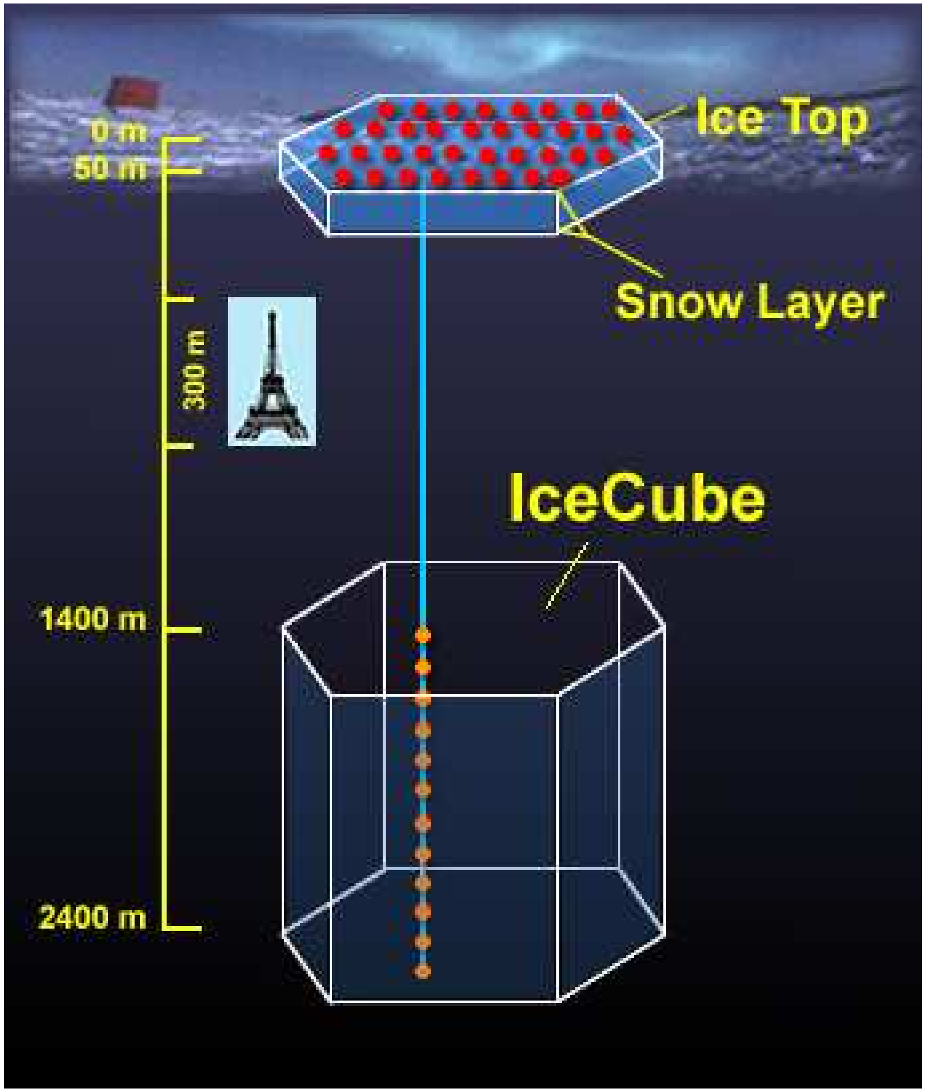
- RICE: radio Cerenkov in ice (South Pole)

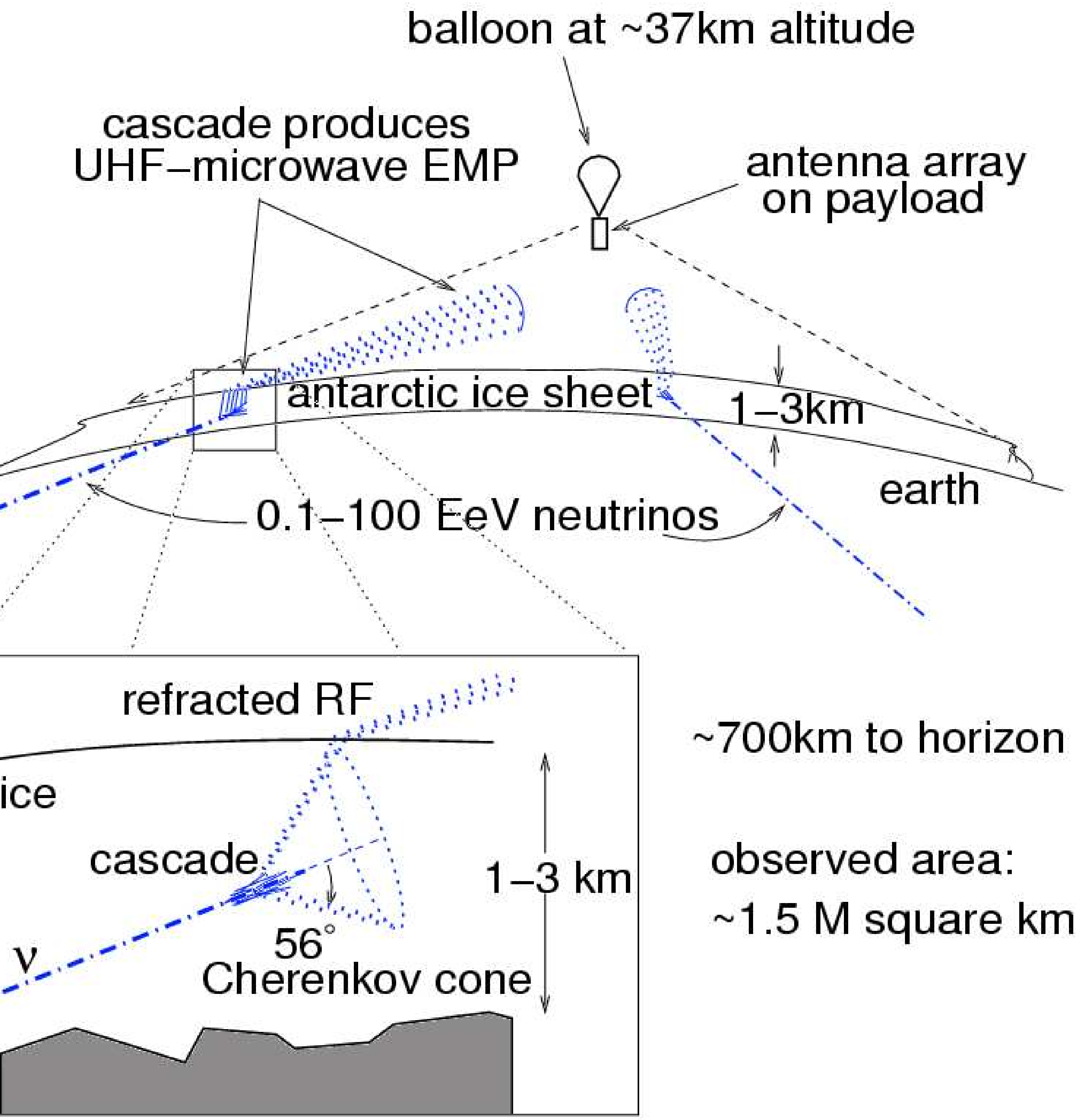
- ANITA: radio Cerenkov from ice (balloon at South Pole)

- PIERRE AUGER: air showers (Argentina,...)

- ...

Detectors





balloon at ~37km altitude
cascade produces
UHF−microwave EMP
antenna array
on payload
antarctic ice sheet
1−3km
earth
0.1−100 EeV neutrinos
refracted RF
ice
cascade
56°
Cherenkov cone
ν
1−3 km
~700km to horizon
observed area:
~1.5 M square km


LIMITE DE L'ATMOSPHÈRE

What to look for?

- Point sources
- Diffuse fluxes
  - from sources
  - from cosmic ray interactions
  - from dark matter annihilation
  - ...
- Correllations 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

- ...

complementary to electromagnetic, cosmic ray data!

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

- ...

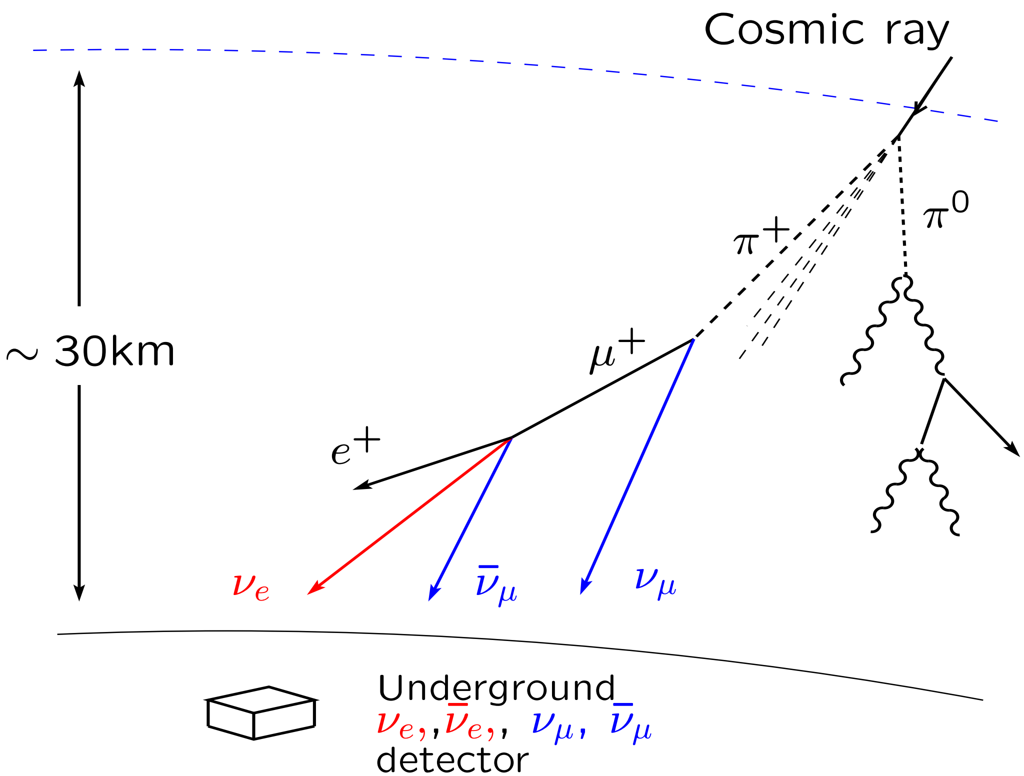
High Energy Neutrinos

- seeing very high energy neutrinos: **ESSENTIAL** $\longrightarrow$ soon!
- counting very high energy neutrinos: first step
- need more! $\longrightarrow$ more work!
  - angular distributions
  - energy distributions
  - flavour composition
  - better detector techniques
  - smart tricks, unique signatures, etc.
  - very good simulations
  - correlations with other observables: photons, protons, etc.
- find right observable and combination of observables
- can distinguish particle physics from astrophysics effects
- learn about both!

Atmospheric Neutinos

- background to many IceCube searches
- Lots of them!
- IceCube Low Energy Core
  - much denser phototube coverage region
  - in the middle deep region of IceCube
  - motivation: galactic sources, dark matter annihilation
- Can all this be put to a good use?

Neutrino Oscillations in IceCube



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

Summary of Oscillation Results

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

+ reactor antineutrinos

$$\begin{aligned} \Delta m^2_{sol} &\simeq 8 \times 10^{-5}\mathrm{eV}^2 \\ \tan^2\theta_{sol} &\simeq 0.45 \end{aligned}$$

- 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)

use matter effetcs

Neutrino Oscillations in IceCube

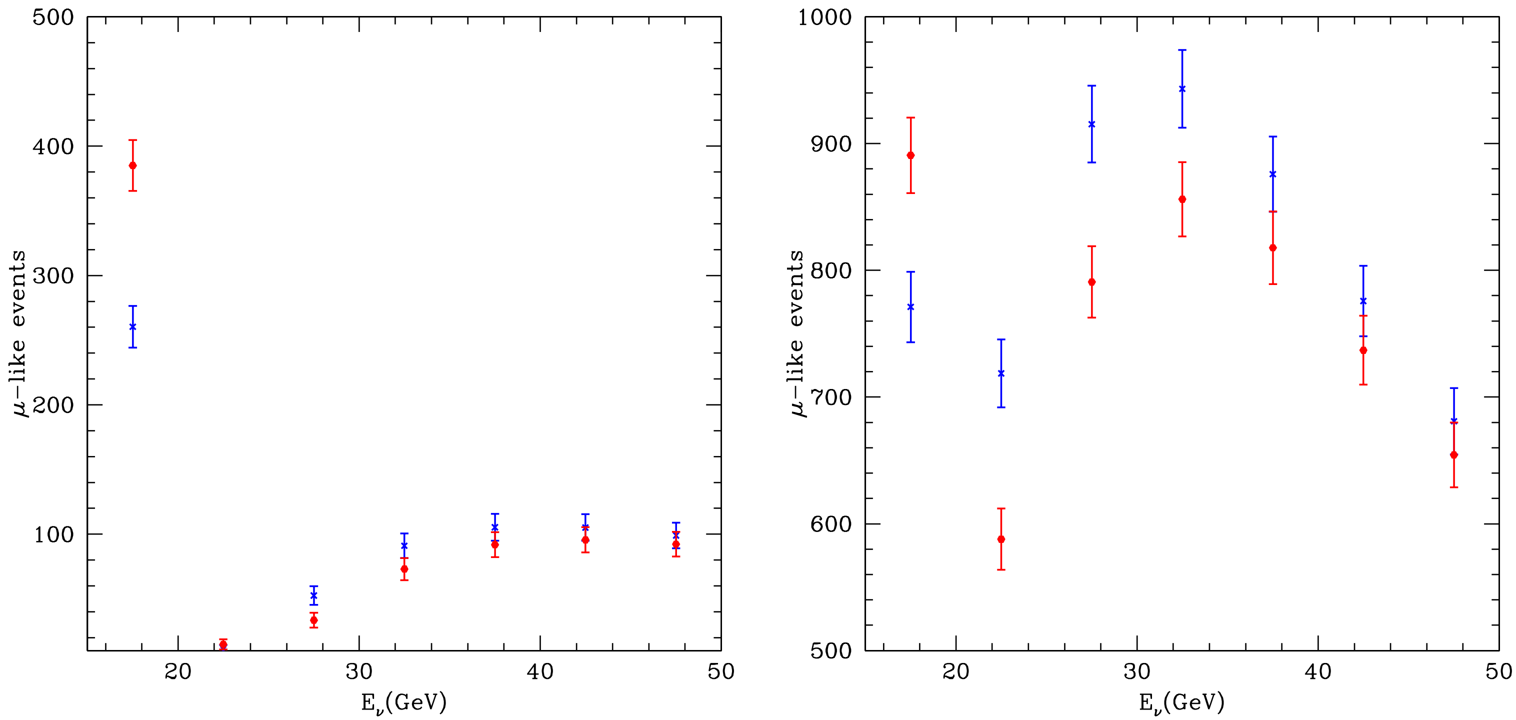
Angular distribution:

- $\cos\theta \in (0, 1)$ 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:

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

Normal versus inverted hierarchy



Olga Mena, I. M., Soeb Razzaque

Hierarchy

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

- μ like fully contained events

- different energy threshold, energy and angular resolution

- different detector configurations

- add cascades

- ...

Possible to distinguish hierarchy for $\sin^2 2\theta_{13} \sim .04$

Lots to learn from:

- astrophysical neutrinos

- long baseline experiments

In the meantime:

use atmospheric neutrinos in IceCube to determine

neutrino oscillation parameters!