Neutrino Properties and Neutrino Telescopes

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Neutrino Telescopes

- AMANDA/ICECUBE : Cerenkov light in ice (South Pole)
- ANTARES, NEMO, NESTOR, etc. : 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,...)
- ...

What to look for?

- Point sources
- Diffuse fluxes
  - from astrophysical objects
  - 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?

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

- energy distributions
- angular distributttions
- flavour composition

Remember the Sun:

- John Bahcall, Ray Davis: Phys. Rev. Lett. 12, 300 (1964), Phys. Rev. Lett. 12, 303 (1964): solar neutrino experiment: "... to see in the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars"

- 1970 Solar neutrino problem

- solar model versus neutrino properties

- after 2001 SNO CC/NC, Kamland reactor: neutrino oscillations + back to the Sun!

Sources

- flavor composition

  - e.g. mostly π decays

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \bar{\nu}_\mu + \nu_e$$
$$\Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

- energy distribution

- normalization

- correlations with photons, protons, etc.

- Source distribution: point back to source - neutrino astronomy

Sources

Not always $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

- neutron decay, etc. (e.g. GZK neutrinos)
- energy dependent flavour ratios

- energy thresholds

- energy losses

- matter effects (O. Mena, I. M., S. Razzaque)

Most sources: density too low, not enough column density

$\rightarrow$ matter effects negligible

Some sources: can reach resonance $\Rightarrow$ significant matter effects

e.g: neutrinos produced in jets of supernovae

S. Razzaque, P. Meszaros, E. Waxman

$\diamond$ π decay $1 : 2 : 0$ modified by 20% effects at the source

$+$ long distance vacuum oscillations $+$ Earth matter effects

$\rightarrow$ non-standard energy dependent flavour compositions

depends on neutrino parameters and density profile of source

Propagation Through Space

Neutrino Oscillations over long distances

- ν_μ and ν_τ maximally mixed:

$$F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} = 1:2:0 \Rightarrow \nu_e : \nu_\mu : \nu_\tau = 1:1:1$$

- sometimes $F^0_{\nu_e} : F^0_{\nu_\mu} : F^0_{\nu_\tau} \neq 1:2:0$ $\Rightarrow$Three flavour mixing relevant

$$\begin{aligned} F_{\nu_e} &= F^0_{\nu_e} - \frac{1}{4}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \\ F_{\nu_\mu} &= F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \end{aligned}$$

J. Jones, I.M, M. H. Reno, I. Sarcevic

- much smaller effects from deviation from maximal atmospheric mixing, θ_{13}, CP violation

Propagation Through Matter

- interaction cross-sections
  - in the Standard Model

    Parton Distribution Functions extrapolations at high energies
  - beyond the Standard Model
- energy losses
- flavour composition
- other new physics

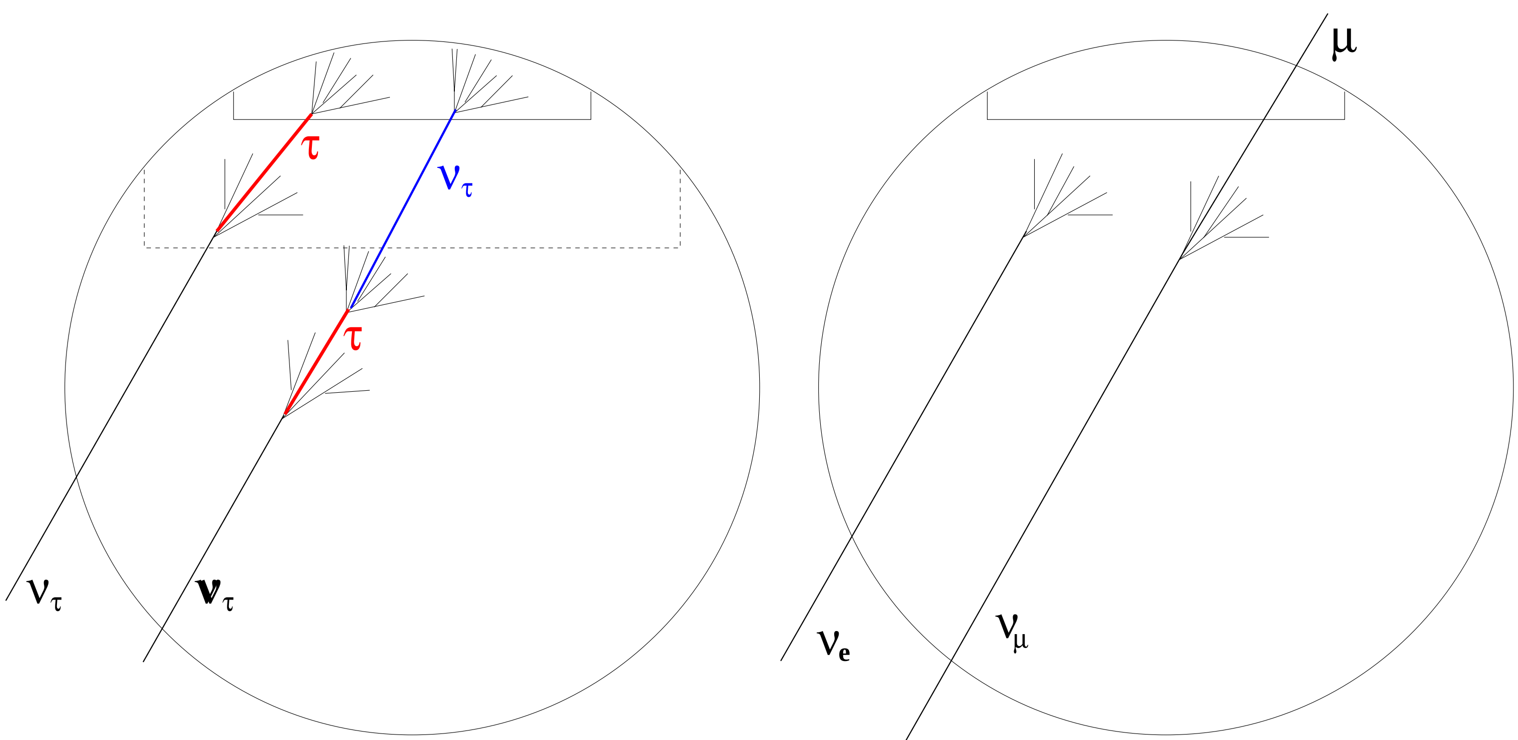
Propagation Through Matter

Above ~ 40 TeV Earth opaque to neutrinos

High rate in detector: large interaction rate $\longrightarrow$ high absorption

- Downward/horizontal
- Use ν_τ:
  - gain volume
  - lose energy

Flavour composition important



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!

Deep Core Array

- motivation: galactic sources, dark matter annihilation

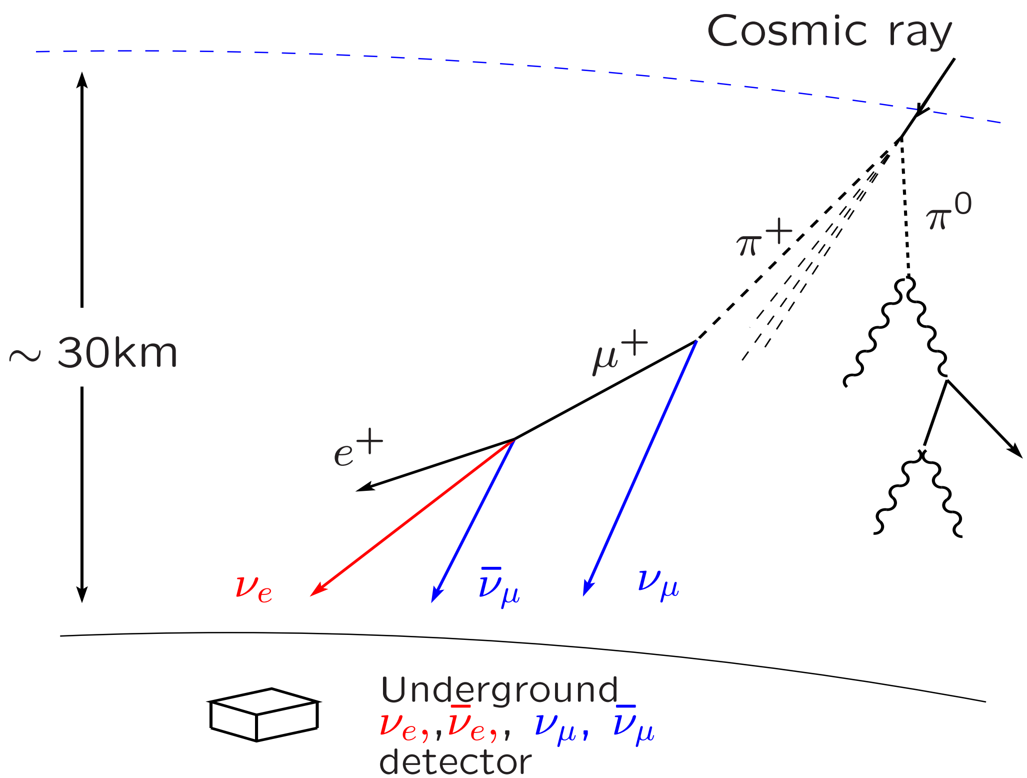
- need to reduce large cosmic muon background

- 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
- Lots of them!

Three flavors neutrino oscillations

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

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

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

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:

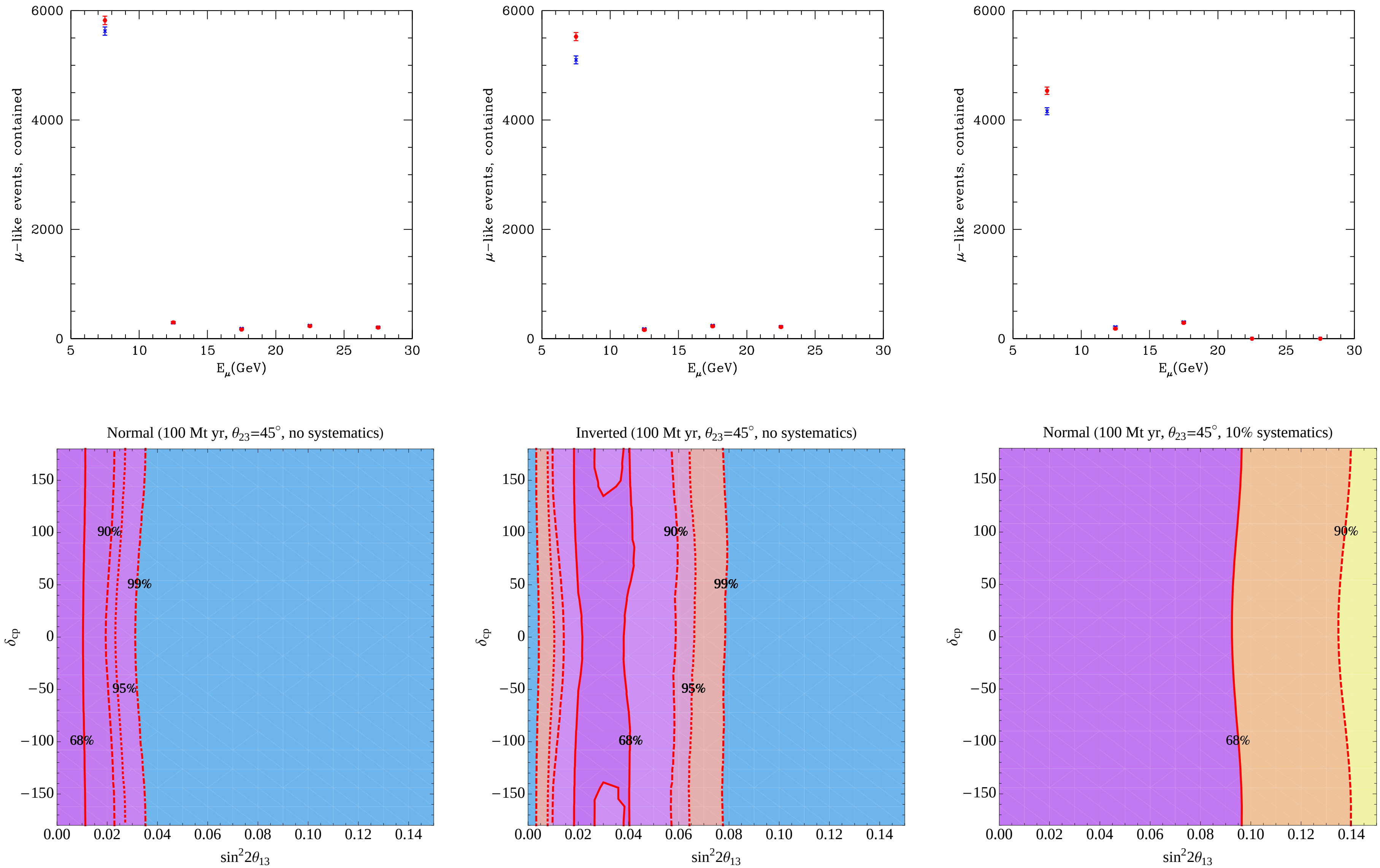
- $\cos\theta \in (0, 1)$ atmosperic flux normalization
- $\cos\theta \in (-0.9, 0)$ + main oscillation signal (Δm^2_{32}, θ_{23})
- $\cos\theta \in (-1, -0.9)$ + matter effects (θ_{13}, hierarchy, CP)

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!