

# Neutrino Properties from Large Neutrino Telescopes

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Electroweak Interactions and Unified Theories

## Neutrino Telescopes

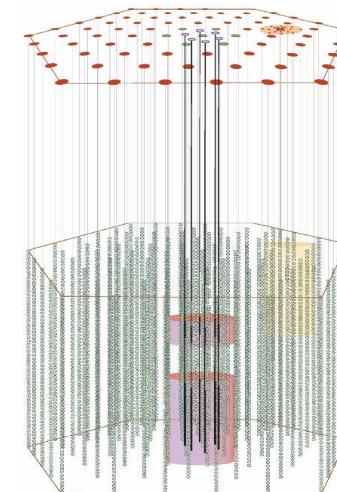
- [AMANDA/ICECUBE](#) : Cerenkov light in ice (South Pole)
- [ANTARES, NEMO, NESTOR, etc.](#) : Cerenkov light in water (Mediterranean)
- [RICE](#): radio Cerenkov in ice (South Pole)
- [ANITA](#): radio Cerenkov from ice (balloon at South Pole)
- [PIERRE AUGER](#): air showers (Argentina,...)
- ...

### What to look for?

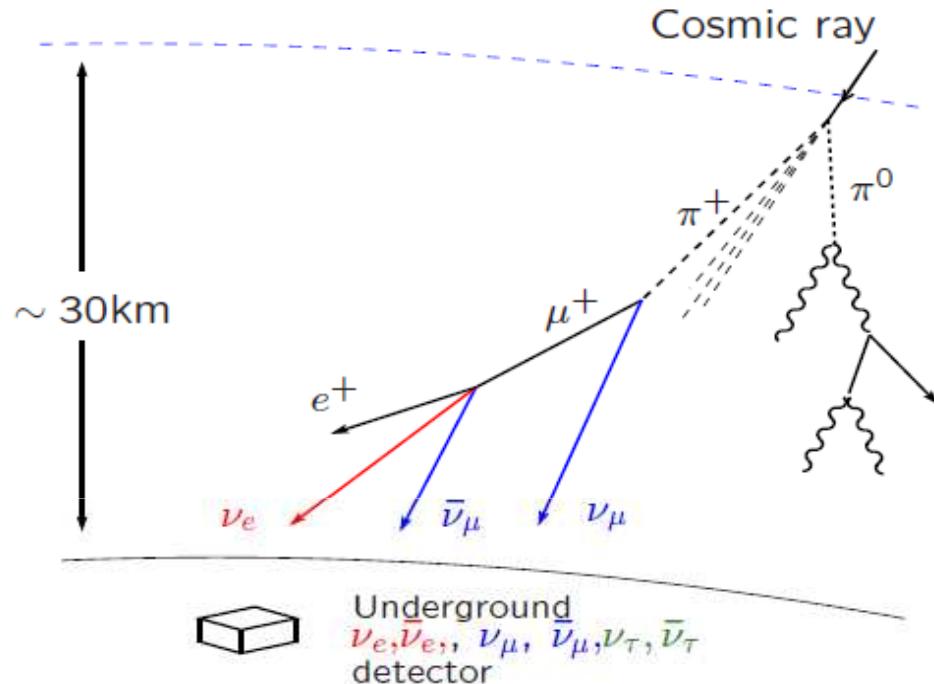
- Point sources
- Diffuse fluxes
  - from astrophysical objects
  - from cosmic ray interactions
  - from dark matter annihilation
  - ...
- Correlations with other observations:  
cosmic rays, gamma rays...

## IceCube Deep Core

- motivation: galactic sources, dark matter annihilation  
galactic center above horizon at South Pole
- reduce large cosmic muon background
- $4\pi$  coverage  
look at downgoing events, galactic sources, galactic center
- low energy threshold  
open up the neutrino energy range from 10 Gev to 100 Gev
- overlap with Super-Kamiokande at low energy and  
IceCube at high energy



## Atmospheric Neutinos



- background to many searches
- Lots of them!

100,000 events per year!

## Atmospheric Neutinos

Super-Kamiokande:

- Expect:  $\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \sim 2$  at low energy  
~isotropic
- used zenith angle distribution to prove neutrino oscillations

IceCube Deep Core

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

## Three flavors neutrino oscillations

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

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

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

We want to measure:

- $\theta_{13}$
- hierarchy (sign of  $\Delta m_{atm}^2$ )
- CP violation ( $\delta$ )

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

## Neutrino Oscillations in the IceCube Deep Core

tracks:  $\mu$  like fully contained events

Angular distribution:

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

Energy distribution:

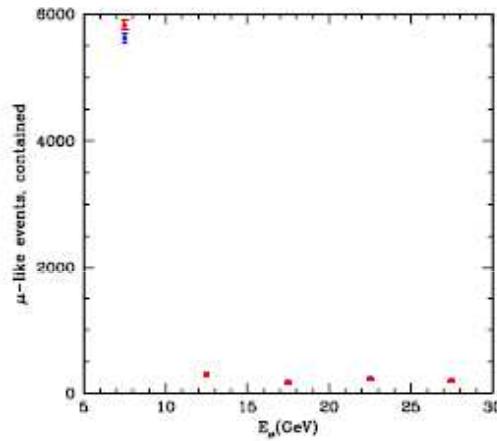
- $E \leq 40\text{GeV}$ : neutrino oscillations
- $50 \text{ GeV} \leq E \leq 5 \text{ TeV}$  atmospheric neutrino flux
- $E \geq 10 \text{ TeV}$ : Earth density profile

ICDC physical mass: 15 Mt

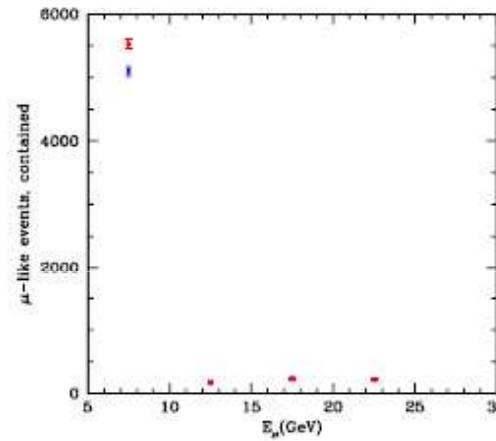
Effective mass in our analysis: 1Mt - 12Mt (energy dependent)

## Normal versus inverted mass hierarchy

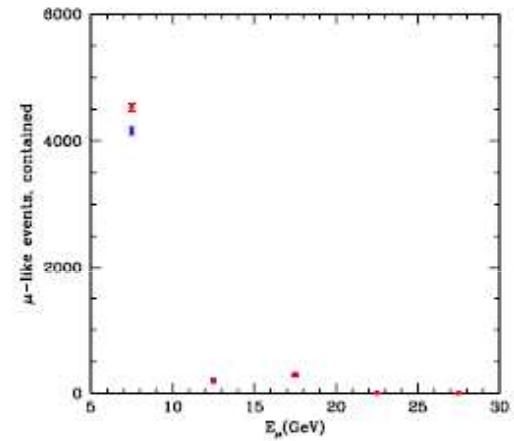
O. Mena, I. M., S. Razzaque, Phys.Rev.D78,093003 (2008)



$$\cos\theta \in (-1, -0.9)$$



$$\cos\theta \in (-0.9, -0.8)$$



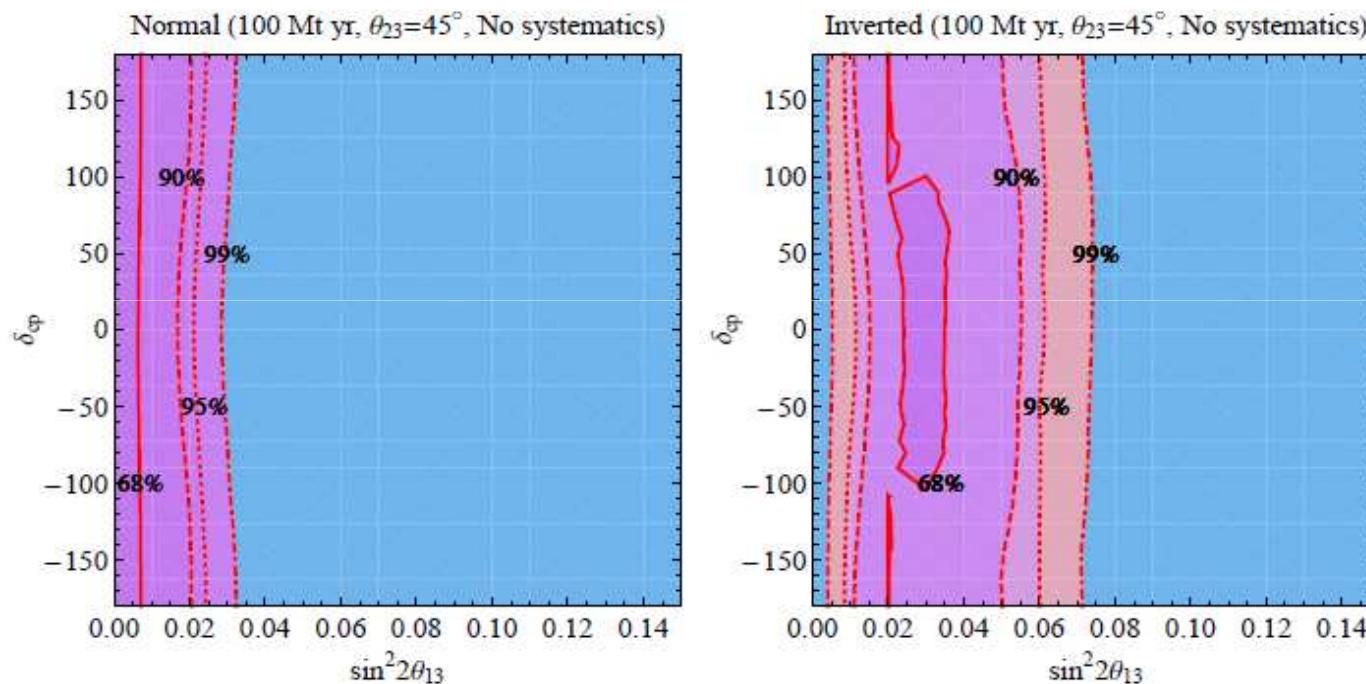
$$\cos\theta \in (-0.8, -0.7)$$

Note  $E_\mu \simeq 0.5E_\nu$

$\sim 50,000$  events per year!

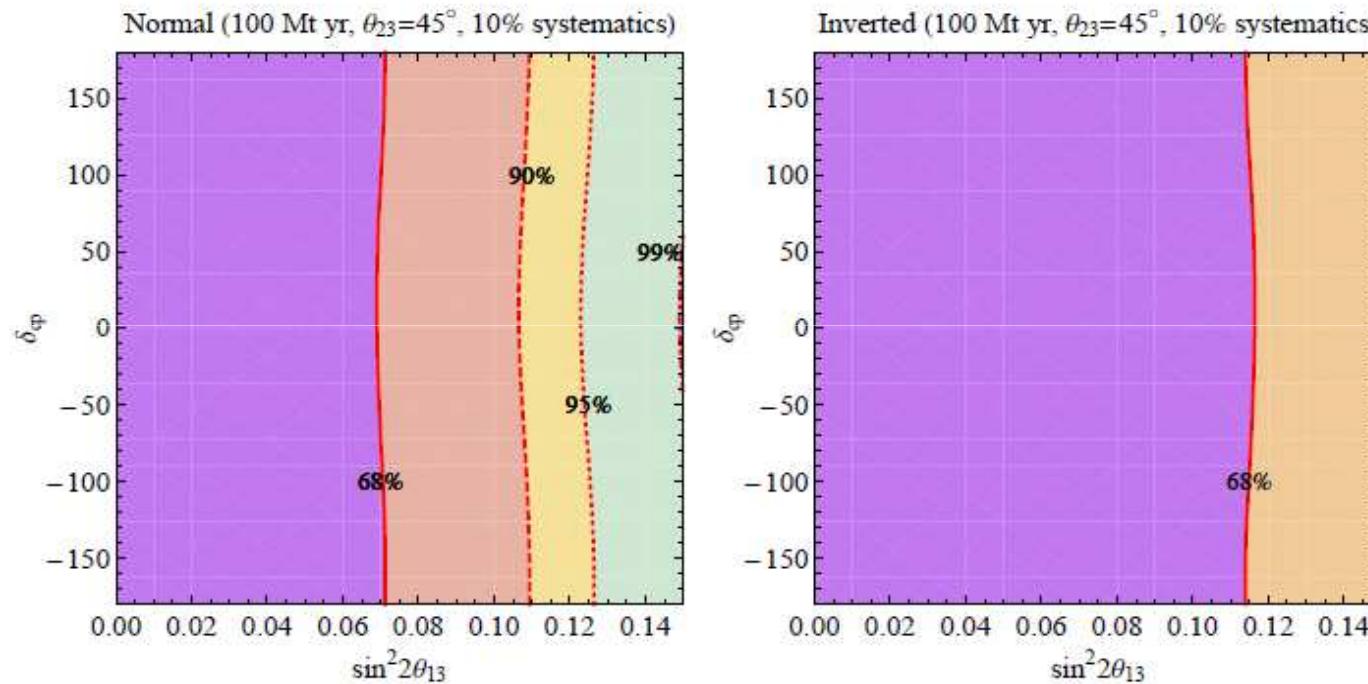
## Normal versus inverted mass hierarchy

- $\chi^2$  fit to discriminate between normal and inverted hierarchy



## Normal versus inverted mass hierarchy

- $\chi^2$  fit to discriminate between normal and inverted hierarchy



## How about cascades?

- Electromagnetic cascades:

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

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

- Hadronic cascades

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

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

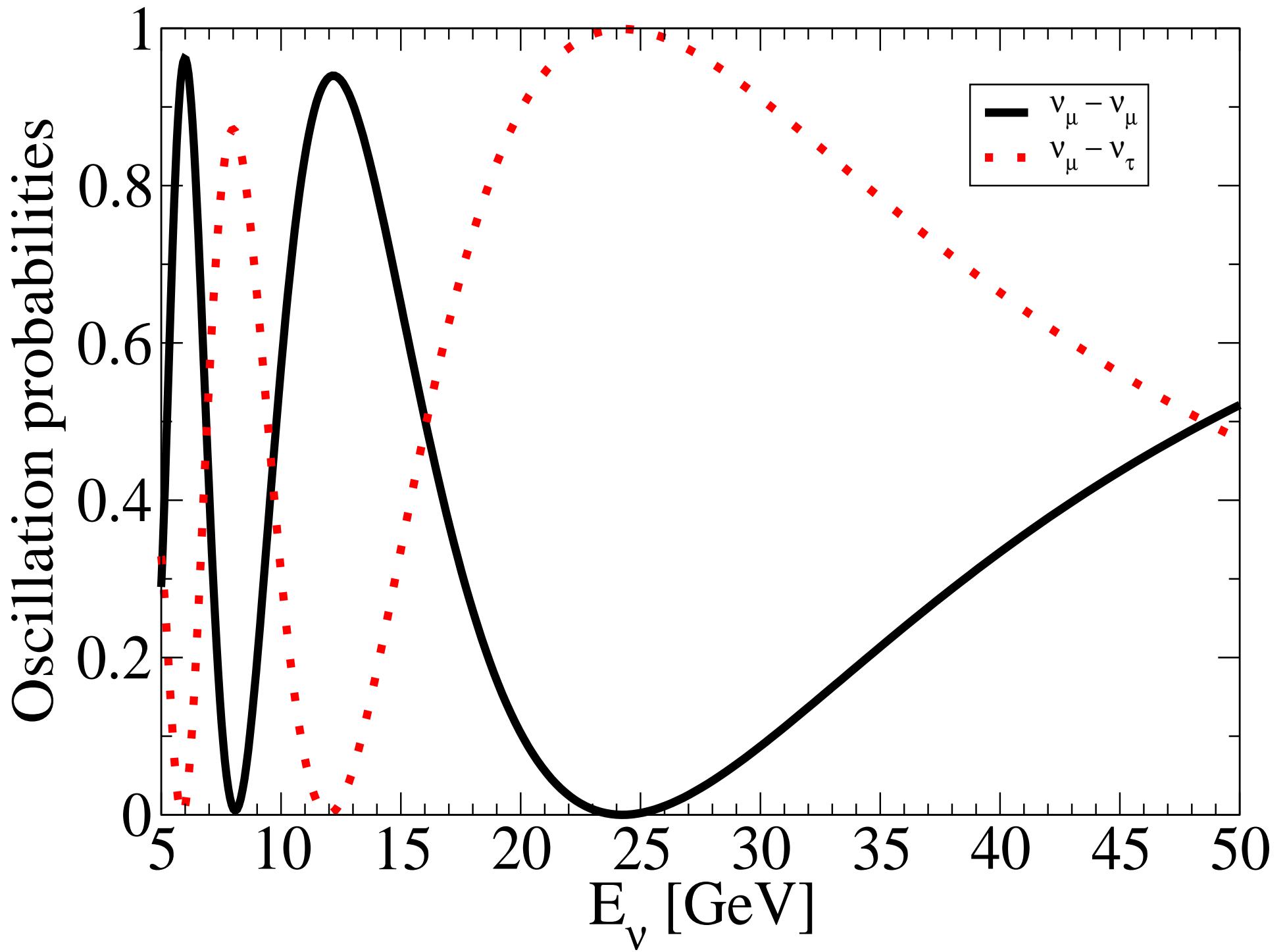
$\nu_\tau$  CC interactions:  $\nu_\tau + N \rightarrow \tau + X$

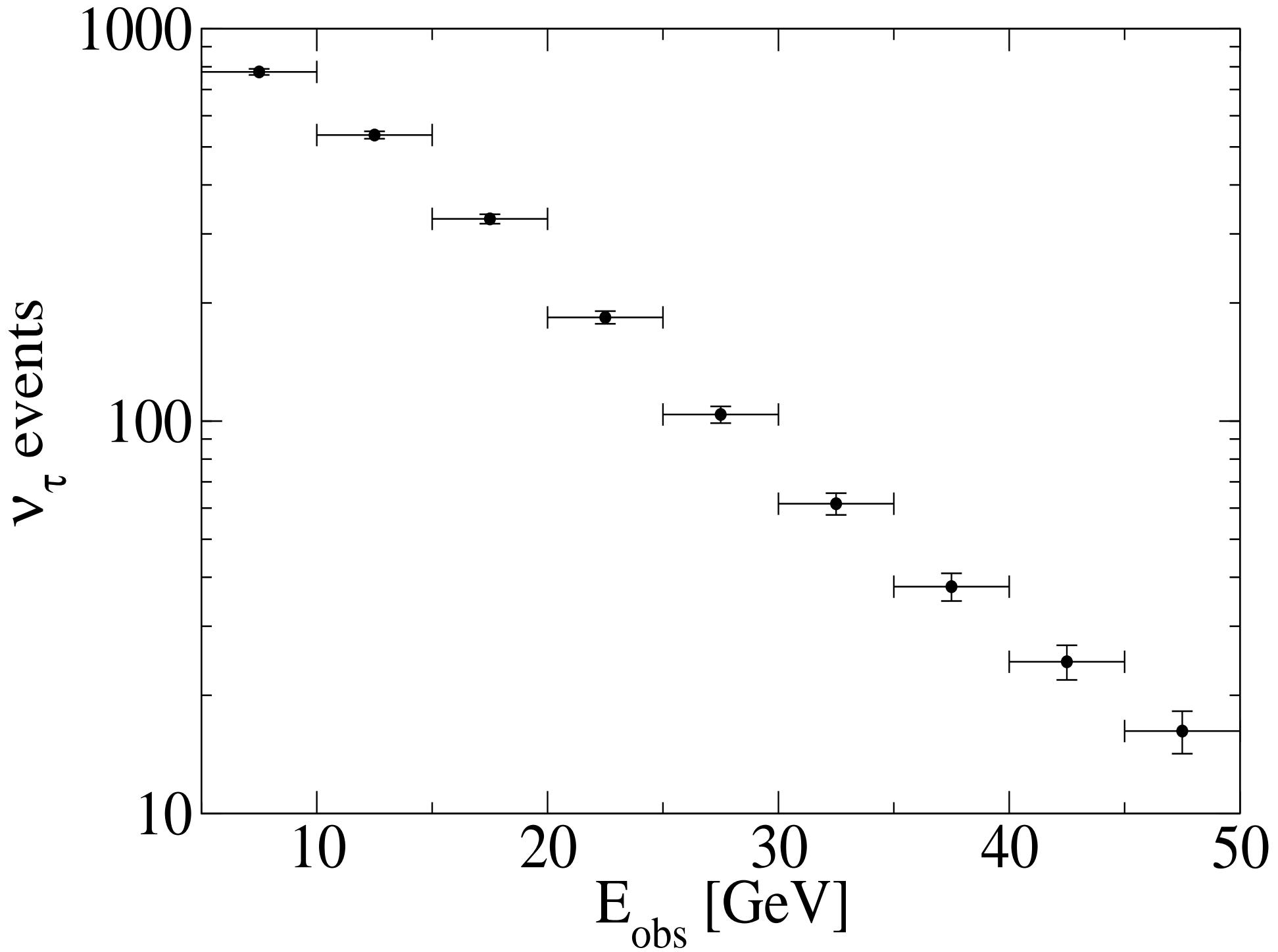
$\nu_{e,\mu}$  NC and CC interactions

Looking for  $\nu_\tau$  helped by:

$$\Phi_{\nu_\mu} \sim 10 \Phi_{\nu_e}$$

oscillations





## $\nu_\tau$ cascades

with G. Giordano and O. Mena

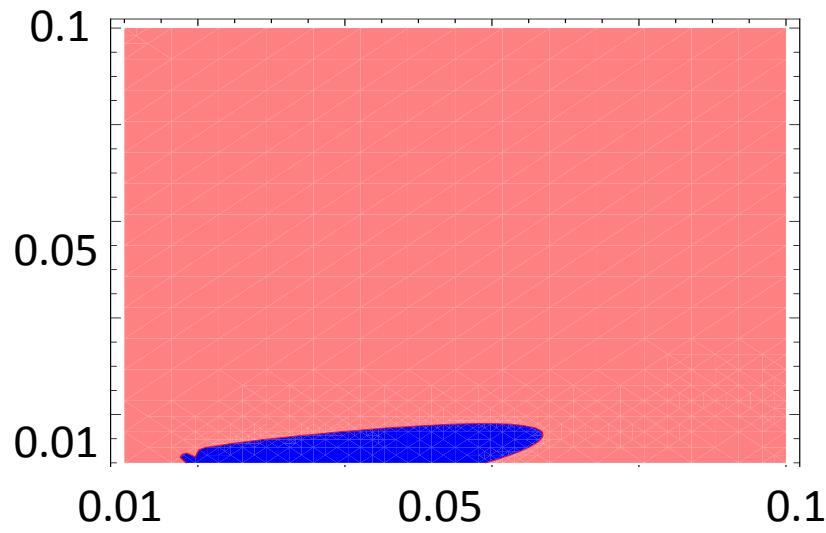
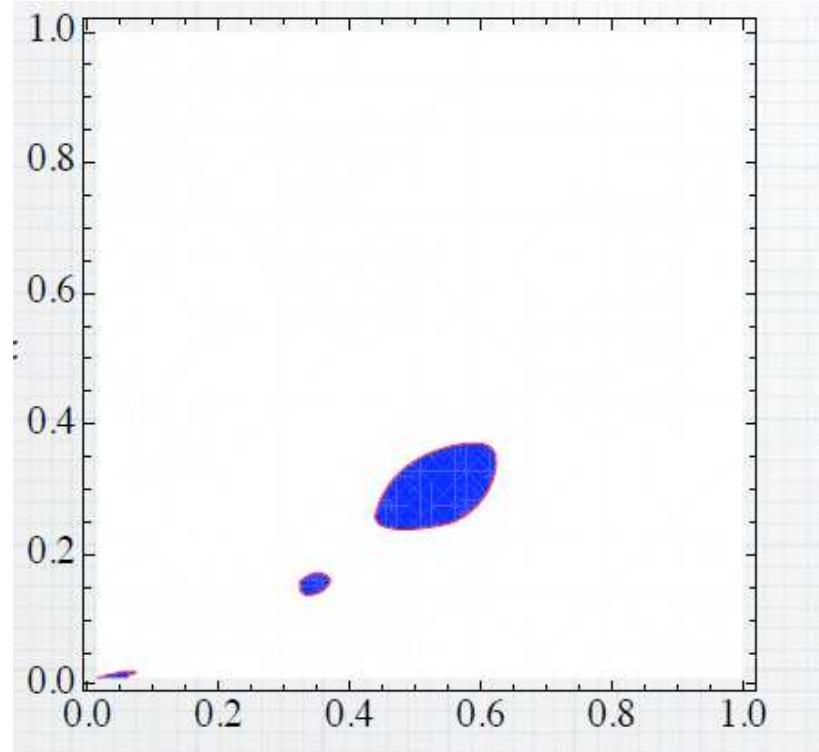
- $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau \rightarrow e$  or hadrons large
- present world sample of  $\nu_\tau$  events: 5(9) (DONUT)
- Super-Kamiokande: *consistent* with  $\nu_\tau$  appearance
- high statistics  $\nu_\tau$  interactions
- direct evidence for  $\nu_\mu \rightarrow \nu_\tau$  appearance
- $\nu_\tau$  interaction cross-section
- non-standard interactions of  $\nu_\tau$
- experience with cascade detection

# Non-Standard Interactions (NSI)

Matter effects in neutrino oscillations

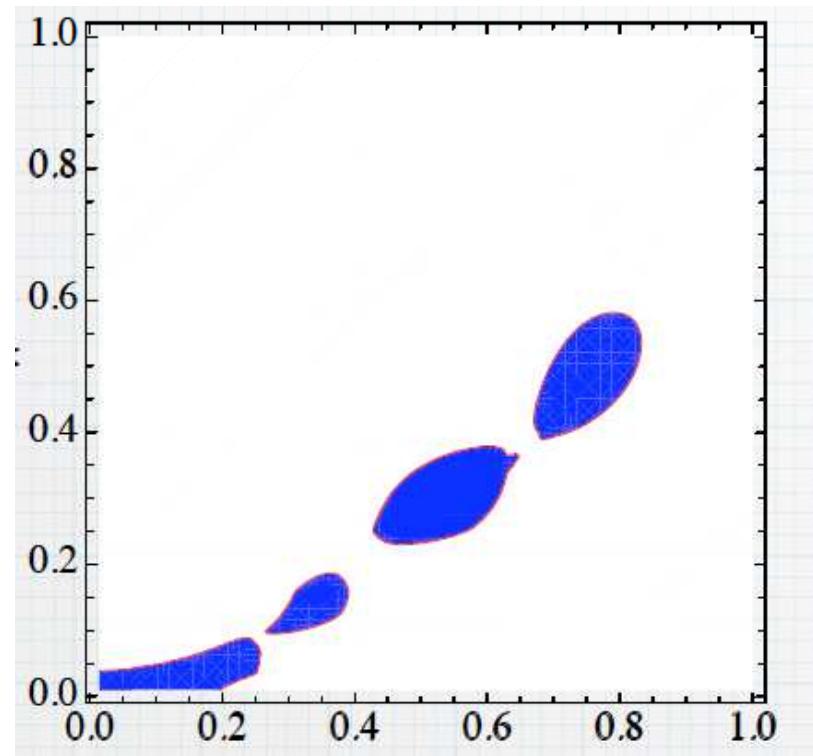
$$H_{\text{mat}} = \sqrt{2}G_F n_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

Very weak constraints in the  $\tau$  sector



$\epsilon_{e\tau} - \epsilon_{\tau\tau}$

Preliminary



## Outlook

### [IceCube Deep Core](#)

detector already **taking data!**

- galactic sources, dark matter annihilation
  - atmospheric neutrinos
    - high statistics, large energy range
    - 100,000 events per year!**
    - better understanding of background for other searches
  - **neutrino oscillations**
    - highly significant oscillation signal
    - good  $\theta_{23}$  sensitivity
    - $\nu_\tau$ : oscillations,  $\nu_\tau$  interactions, cascade detection
    - mass hierarchy
- ...