Atmospheric Neutrino Oscillations with IceCube Deep Core

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Outline

- A bit of history (Learn from the past)
- IceCube Deep Core and atmospheric neutrinos
    - 3 flavors
    - more flavors
    - new physics
- Outlook

History

- First evidence for neutrino oscillations
  - natural sources: atmospheric and solar neutrinos

    (not so surprising: cover large range of L/E, very abundant)
  - detectors were built for different purpose

    (proton decay, solar astrophysics)
- Beams:
  - great control, great precision
  - long time scales

Three-flavor neutrino oscillations

- Three-flavor mixing matrix (in terms of Euler angles)

$$U = R_{23}\, K\, R_{13}\, K^*\, R_{12}$$

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

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

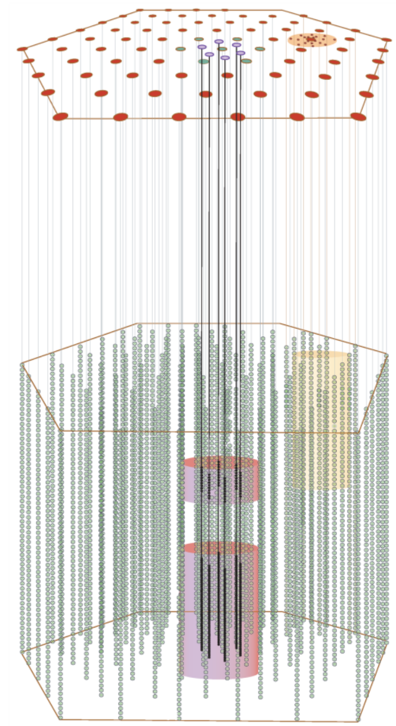
$$\theta_{12} = \theta_{sol} \qquad \theta_{13} = \theta_{reactor} \qquad \theta_{23} = \theta_{atm} \qquad \delta$$

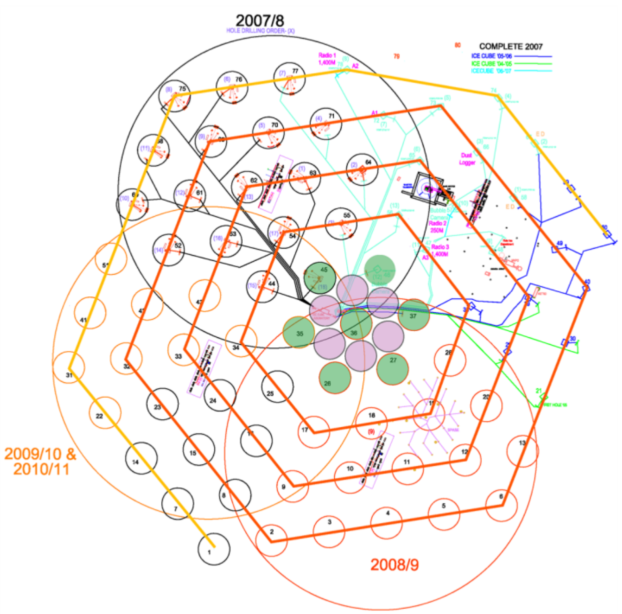
- We want to measure
  - θ_{13}
  - hierarchy (sign of Δm^2_{32})
  - CP violating phase δ

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

IceCube Deep Core

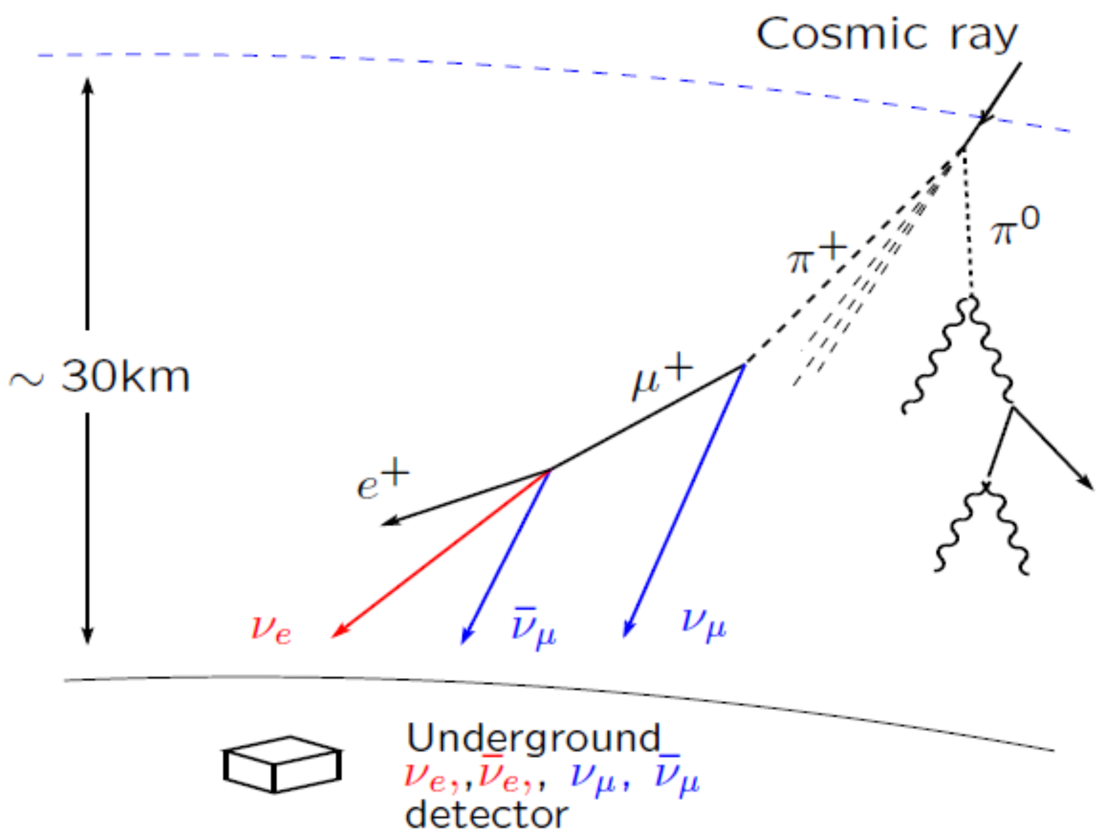
- motivation: look for neutrinos from galactic sources, dark matter annihilation
  - galactic center is above horizon at South Pole
  - need to reduce large cosmic muon background
- 4π coverage
  look at down-going events,
  study galactic sources, galactic center





- 6+2 strings, 7m DOM spacing
- low energy threshold: opens the 10 -- 100 GeV neutrino energy range
- overlap with Super-Kamiokande at low energy and with IceCube at high energies

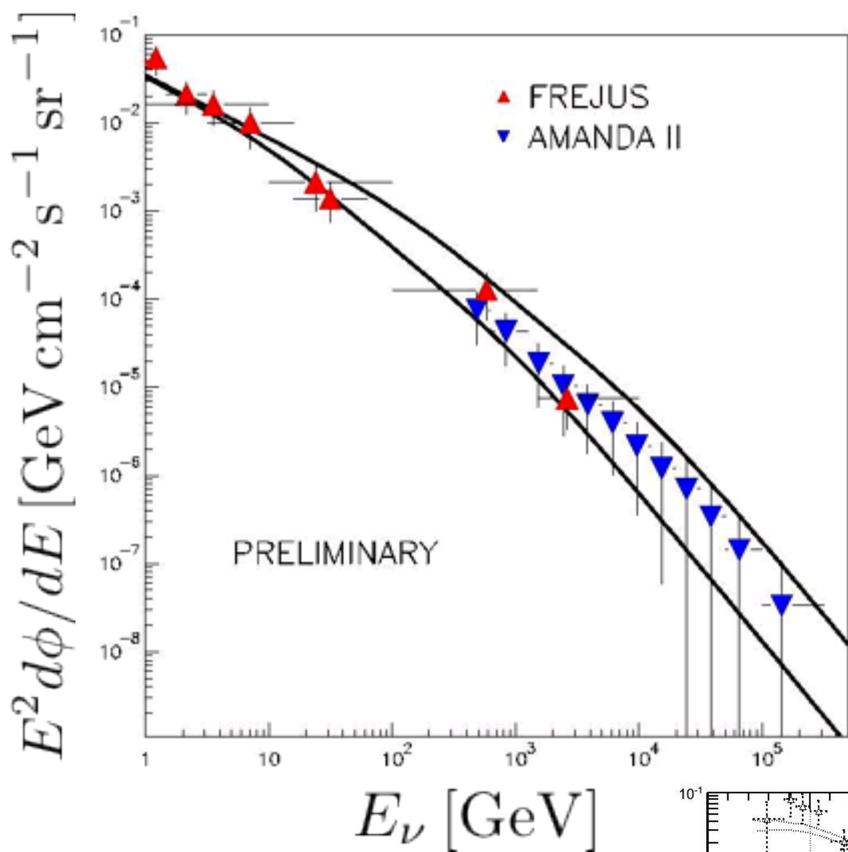
Atmospheric neutrinos

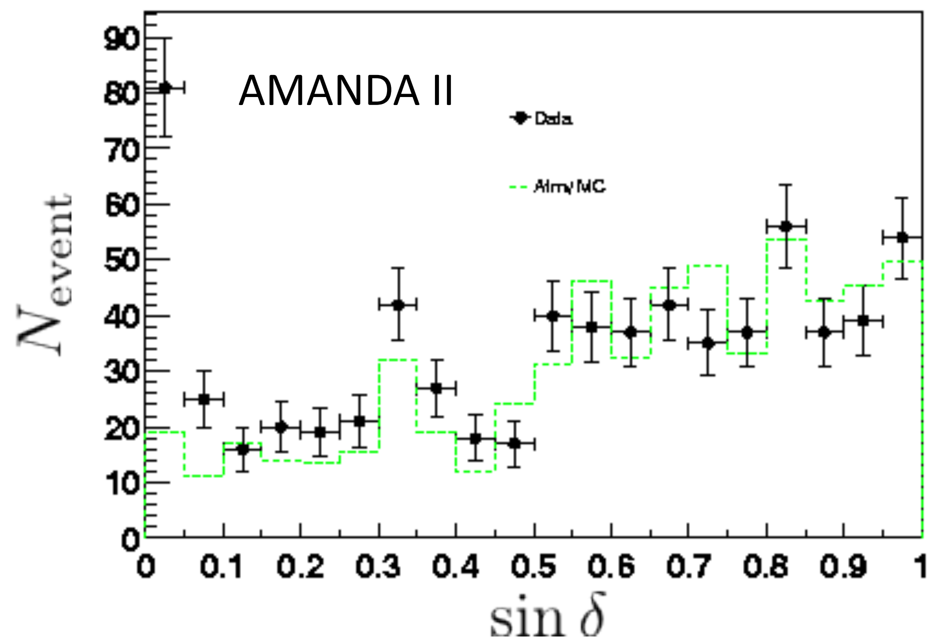


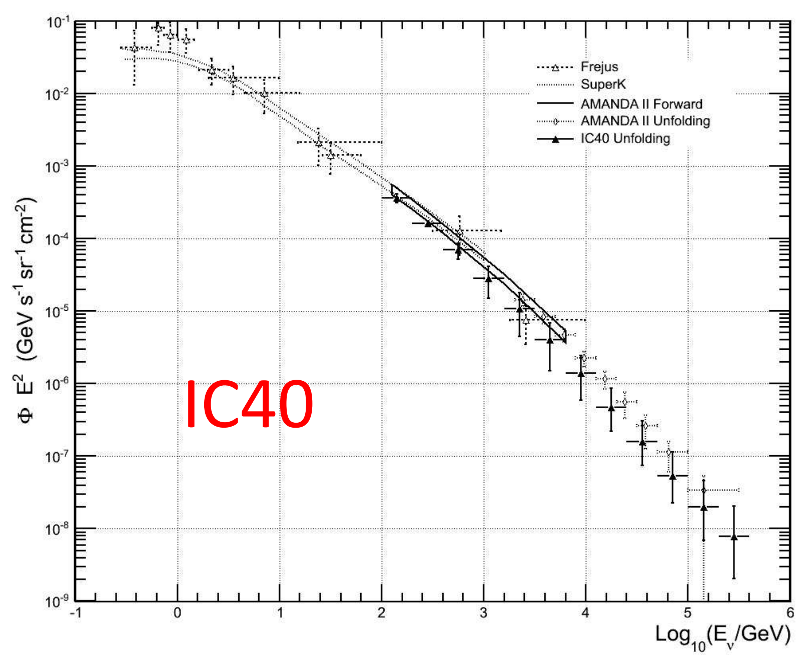
- Background to many searches
- lots of them

50,000 events per year!

Atmospheric neutrinos







Atmospheric neutrinos

Super-Kamiokande

- expect:
  - $\frac{N_{\nu_\mu+\bar{\nu}_\mu}}{N_{\nu_e+\bar{\nu}_e}} \simeq 2$ at low energies
  - approximately isotropic
- use zenith angle distribution to prove neutrino oscillations

IceCube Deep Core

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

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

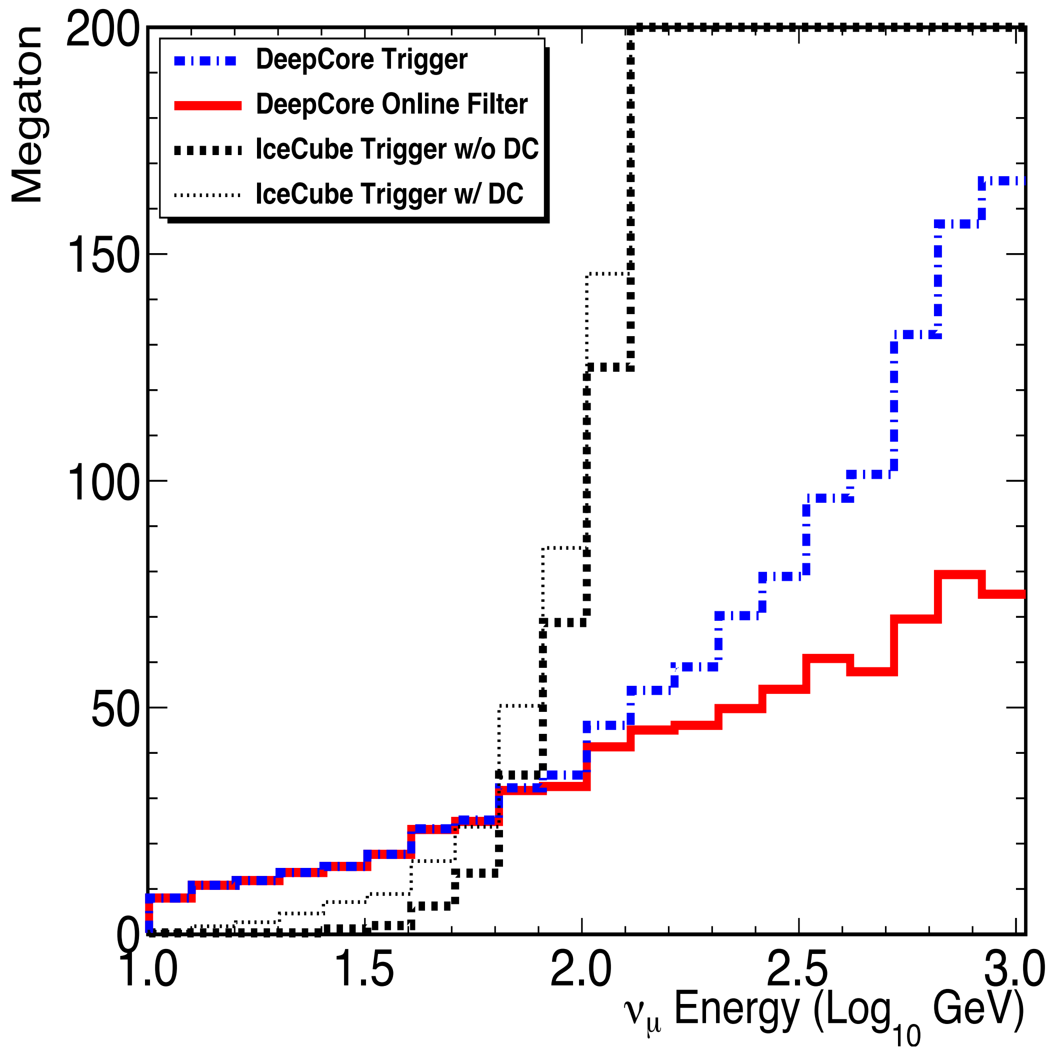
ICDC physical mass: $15\,\mathrm{Mt}$ ($28\mathrm{Mt}$)

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



no fixed energy threshold

can trigger 1 GeV muons

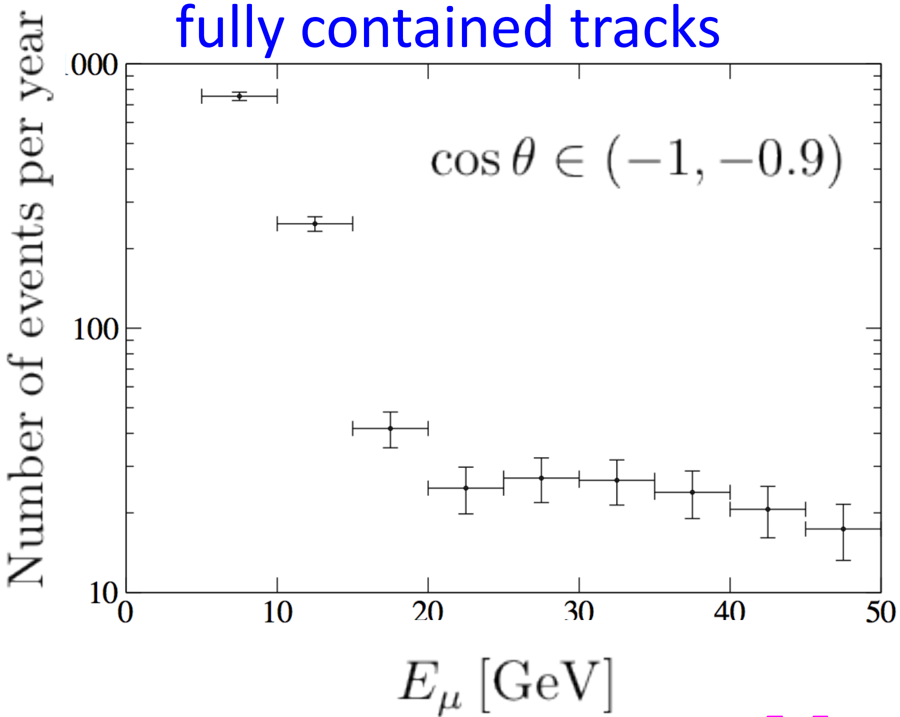
most analysis use 35-50GeV threshold to avoid atmospheric neutrino background

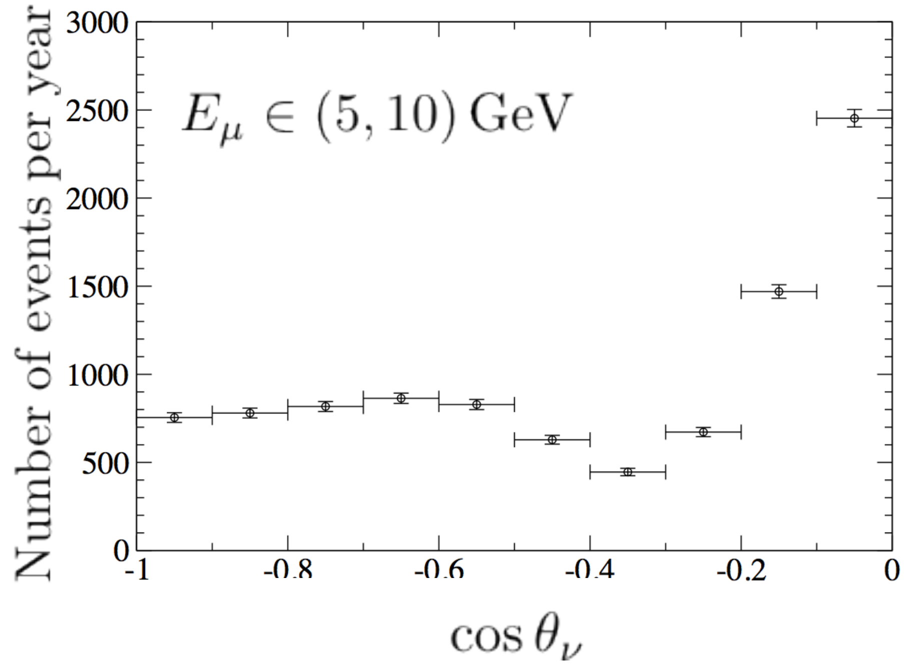
large effective volume above 10 GeV

Jason Koskinen

ICDC atmospheric neutrinos

fully contained tracks





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:

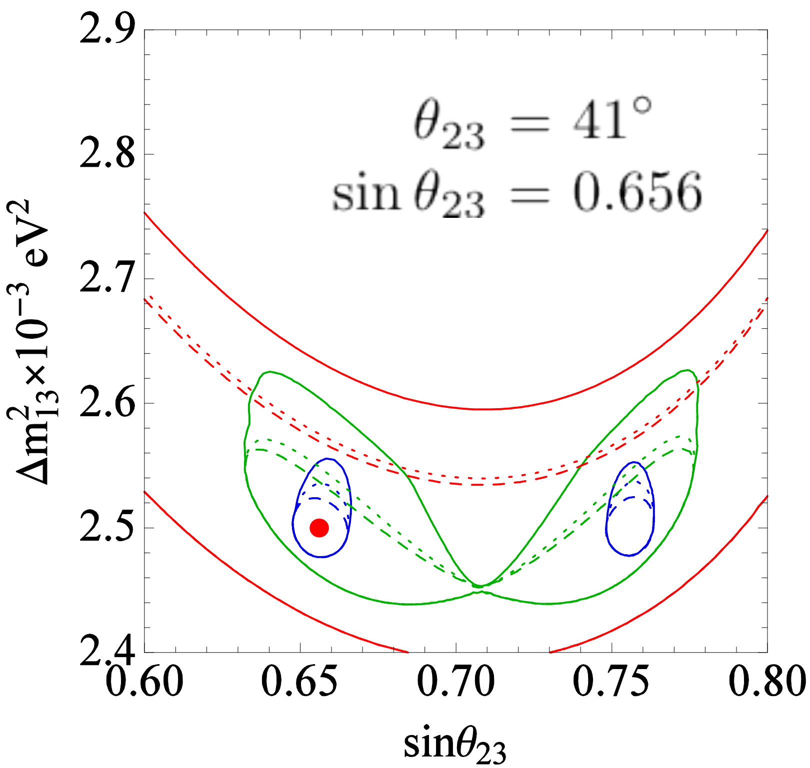
- very large statistics
- contribution from multiple peaks

Presently allowed values:

$$\Delta m^2_{32} \in (2.18 - 2.64)10^{-3}\mathrm{eV}^2(2\sigma)$$ (MINOS)

$$\sin\theta_{23} \in (0.63 - 0.79)(2\sigma)$$ (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

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

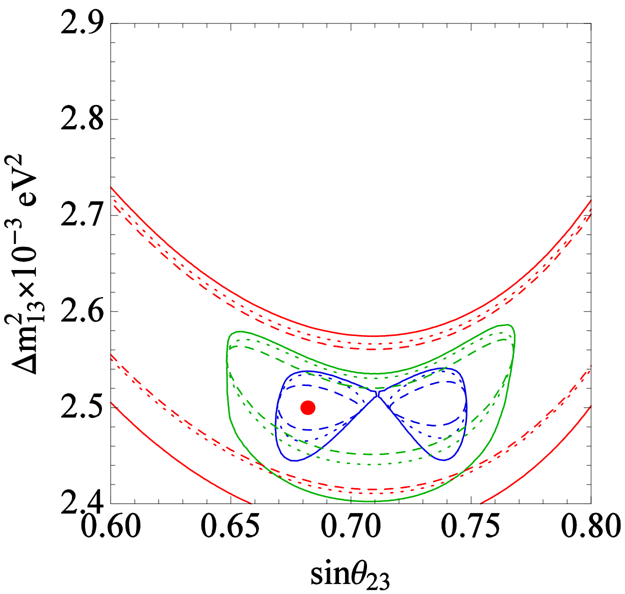
vs

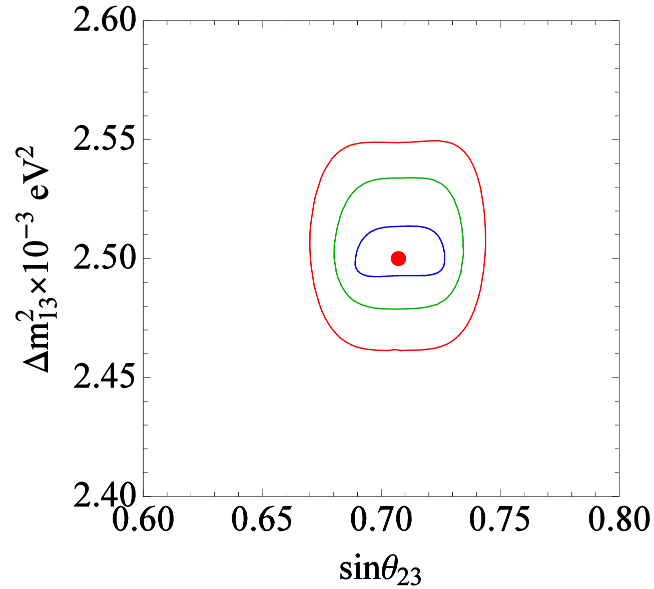
$\theta_{13} = 0.01 \pm 0.02$ ....

vs

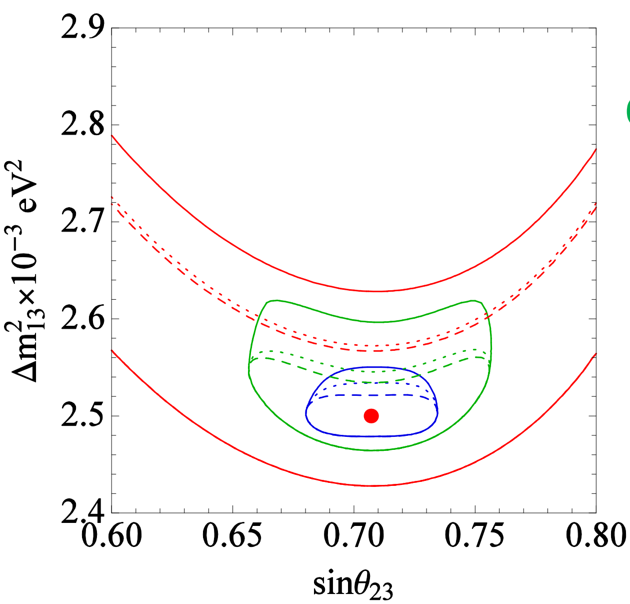
θ_{13} completely free ———

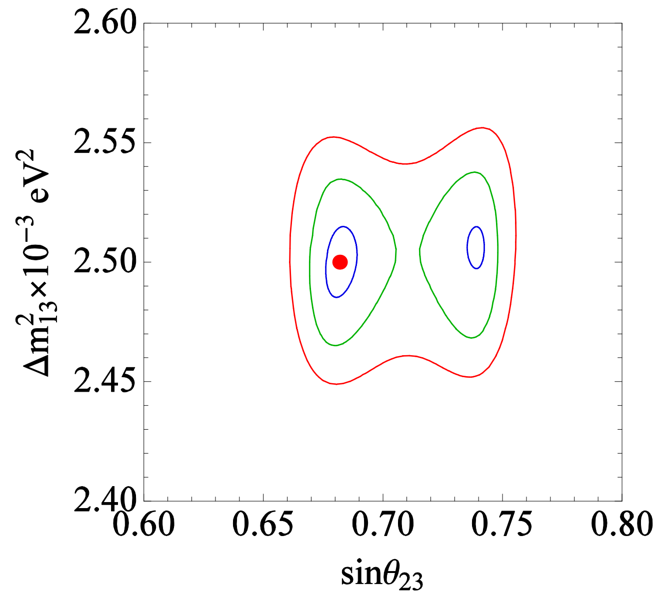
IceCube Deep Core





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





How about cascades?

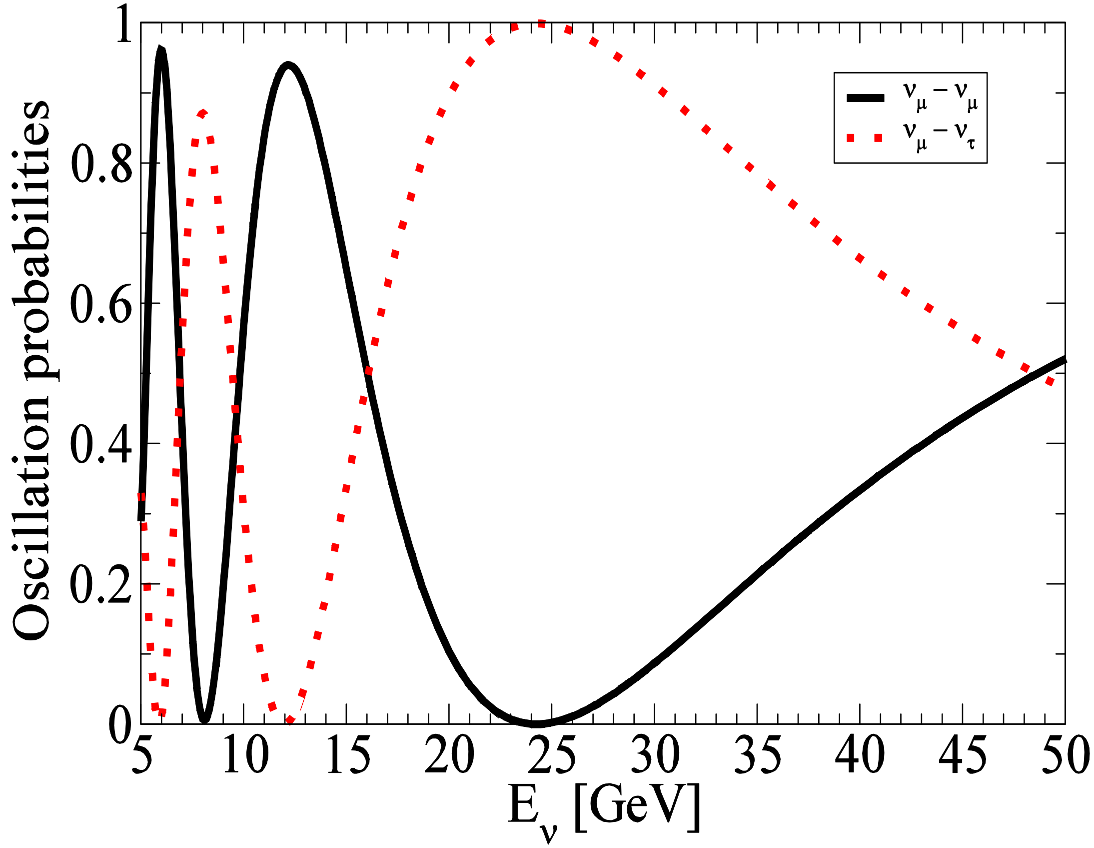
- ν_e CC interactions: $\nu_e + N \rightarrow e + X$
- ν NC interactions $\nu + N \rightarrow \nu + X$
- τ decay

$$\tau \longrightarrow e + \bar{\nu}_e + \nu_\tau$$

$$\tau \longrightarrow \nu_\tau + X$$

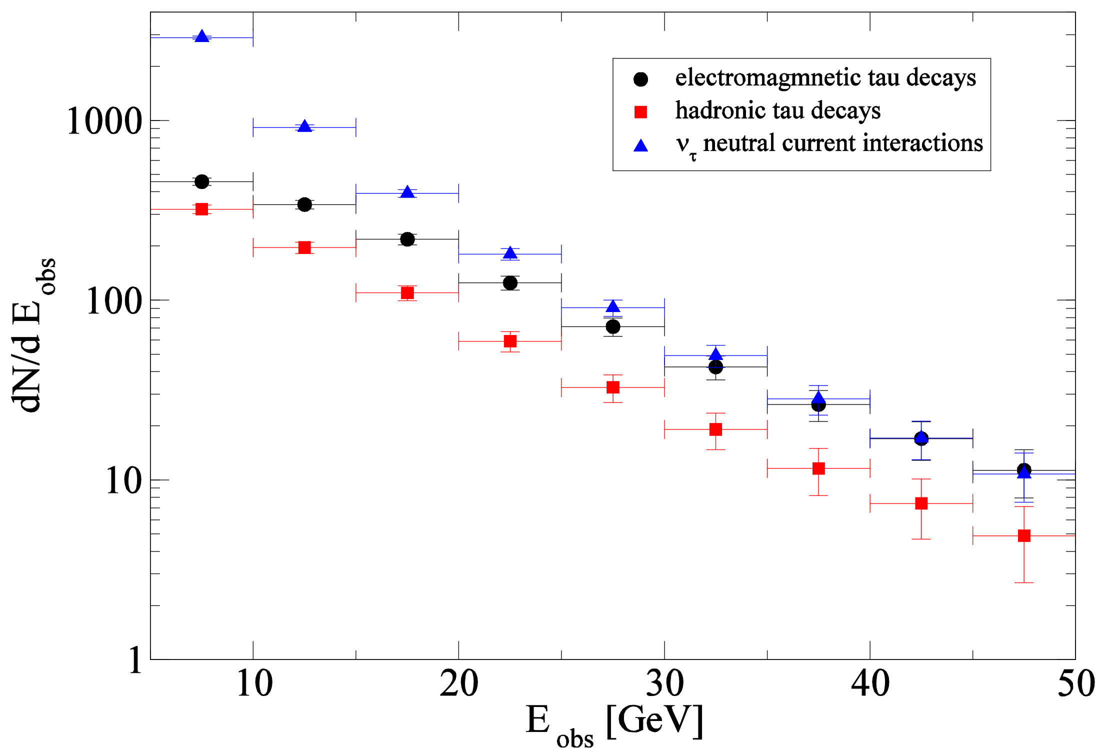
- Looking for ν_τ helped by:
  - high energy (tau threshold effects small)
  - background low : $\Phi_{\nu_\mu} \sim 10\, \Phi_{\nu_e}$
  - oscillations

Oscillation probabilities



Propagation along Earth diameter

Tau cascade rates



ν_τ cascades

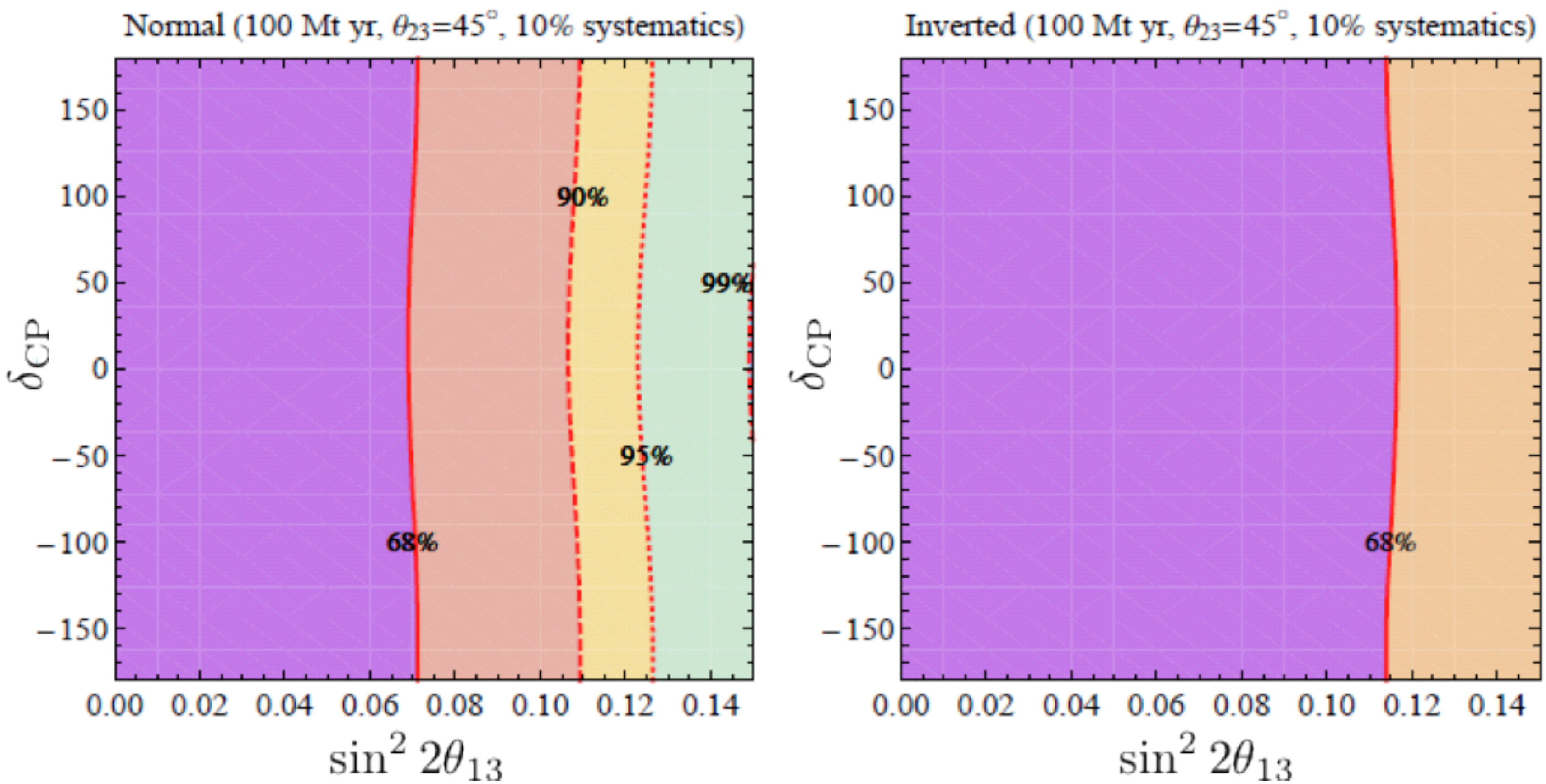
G. Giordano, O. Mena, I. M. (2010)

- $\nu_\mu \to \nu_\tau \to \tau \to e$ or hadrons large
- very few ν_τ detected at present (beams have low energy)
- Super-Kamiokande: consistent with ν_τ appearance
- 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

Normal versus inverted mass hierarchy

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

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



Surprises?

MiniBooNE/LSND

Test sterile neutrino hypothesis?

- Is there ν_μ ($\bar{\nu}_\mu$) disappearance at high Δm^2 ?
- IceCube: high energy: TeV

  for high Δm^2 sensitivity

  matter effects: resonance
- maybe ICDC downgoing: lower E/smaller L
- Energy/angular spectrum: good sensitivity

Sterile Neutrinos

- Model dependence:
  - 3+1 (6 angles), 3+2 (10 angles), 3+2+CP violation
  - angles: sterile mixing with ν_μ , $\nu_\mu - \nu_\tau$, $\nu_\mu - \nu_e$
  - affect ν and $\bar{\nu}$ or only $\bar{\nu}$
- If one present, expect the other
- No one to one correspondence between LSND/ MiniBooNE (mu-e) and IceCube observations (mu-mu,mu-tau)

Sterile Neutrinos

- If signal is mostly in $\bar{\nu}$ sector:
- Limited by high ν versus $\bar{\nu}$ ratio
    - flux: 1.4
    - cross-section: 2
    - oscillations: matter effects help
- Can constrain or discover ν_μ oscillations at high mass scale for angles in the general range probed by MiniBooNE/LSND
- Cannot directly confirm/rule out

  MiniBooNE/LSND sterile nu interpretation

Surprises?

MINOS

- Different effective Δm^2's for ν and $\bar{\nu}$
  - Two oscillation frequencies
- Distortion of energy spectrum
- SuperK has strong constraints based on this analysis
- Some sensitivity
- Limited by
  - high ν versus $\bar{\nu}$ ratio
  - energy resolution?

Non-Standard Interactions (NSI)

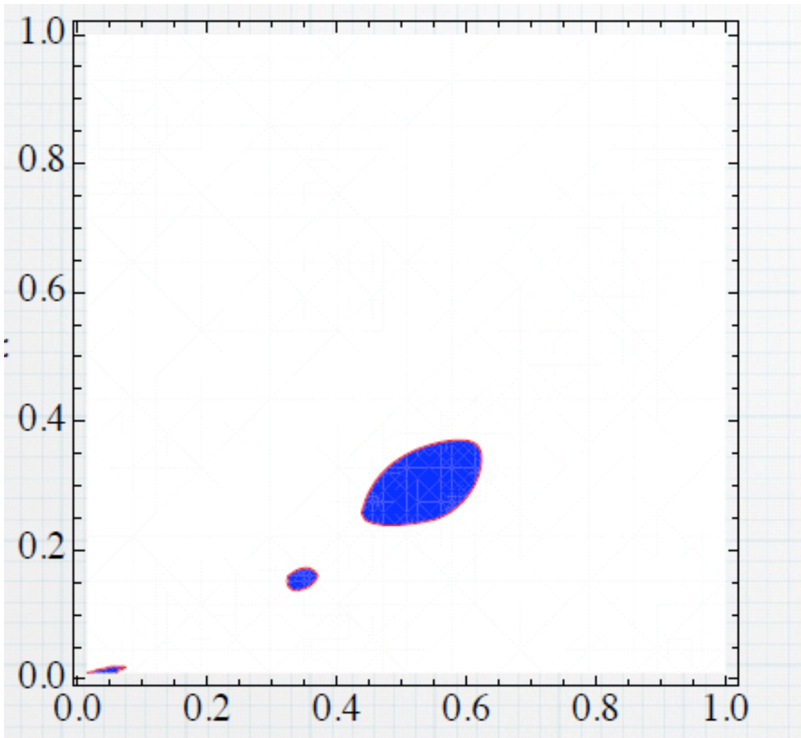
- Expected in connection with mass generation models, sterile neutrinos, etc.
- Parameterize our ignorance by most general form and try to constrain from data

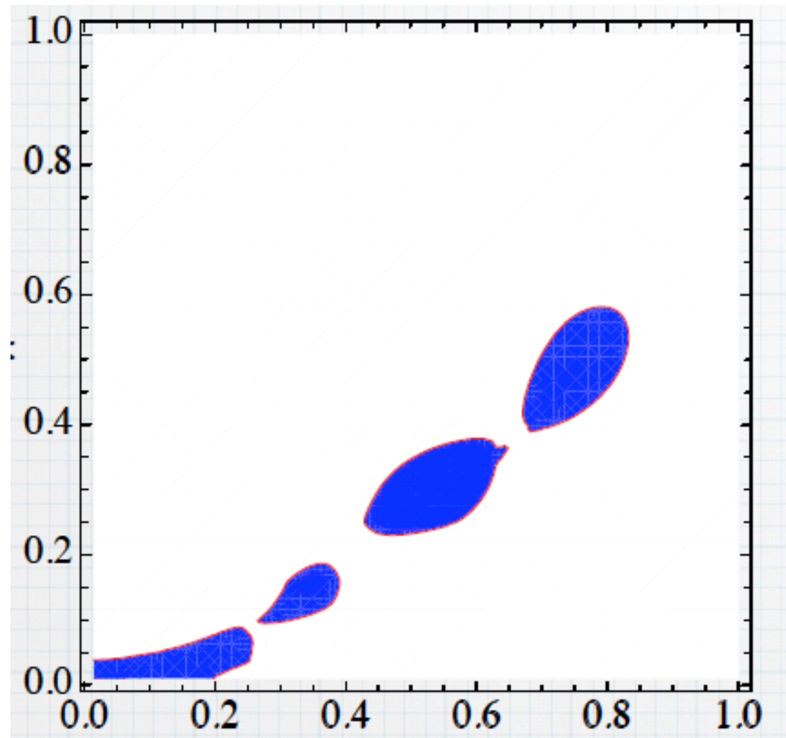
Matter effects in neutrino oscillations

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

Very weak constraints in the τ sector

$\varepsilon_{e\tau}$ - $\varepsilon_{\tau\tau}$





Preliminary

Large correlations/degeneracy between parameters

Outlook

IceCube Deep Core detector already taking data !

- built to look for galactic sources, dark matter annihilation
- atmospheric neutrinos

  high statistics, large energy range, many distances

  50,000 events per year

  better understanding the background for other sources
- neutrino oscillations

  highly significant oscillation signal

  good parameter sensitivity

  ν_τ: oscillations, interactions, cascade detection

  mass hierarchy

  …

Outlook

- IceCube Deep Core detector already taking data !
- someone's background can be someone else's signal
- experiments take a very long time to construct/operate
- use the data we already have and get the most of it!

- long baseline experiments: fixed baseline, limited energy range
- atmospheric neutrinos: many baselines, large energy range
    - ➢ complementary information
- combined data: consistency checks

expect SURPRISES!