Atmospheric neutrino oscillations in IceCube DeepCore

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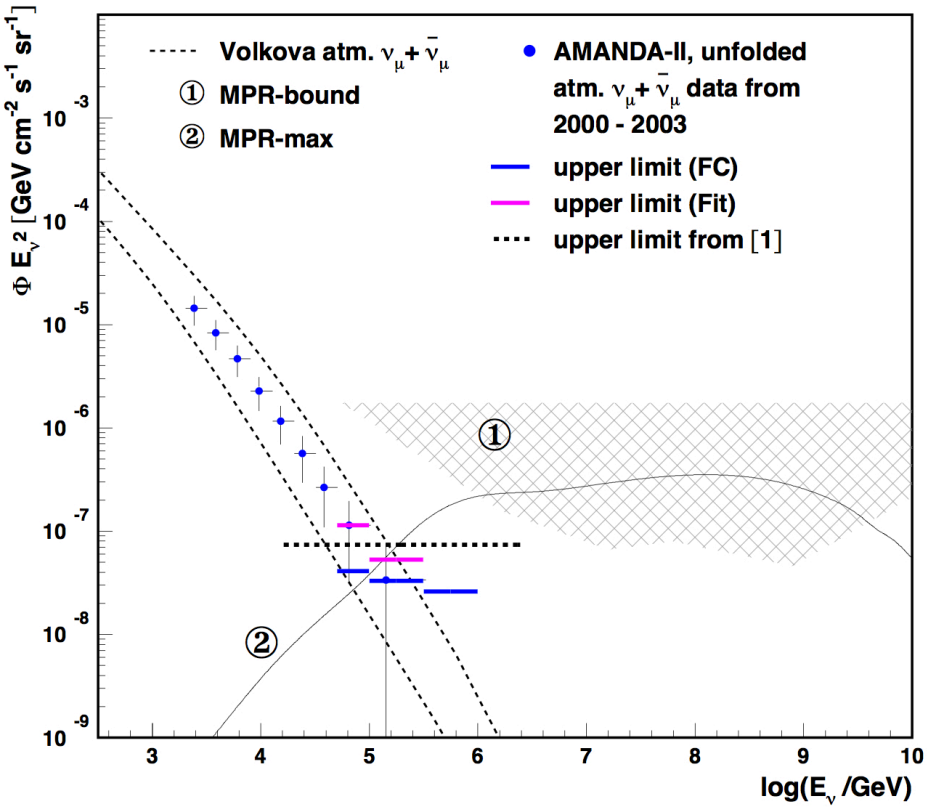
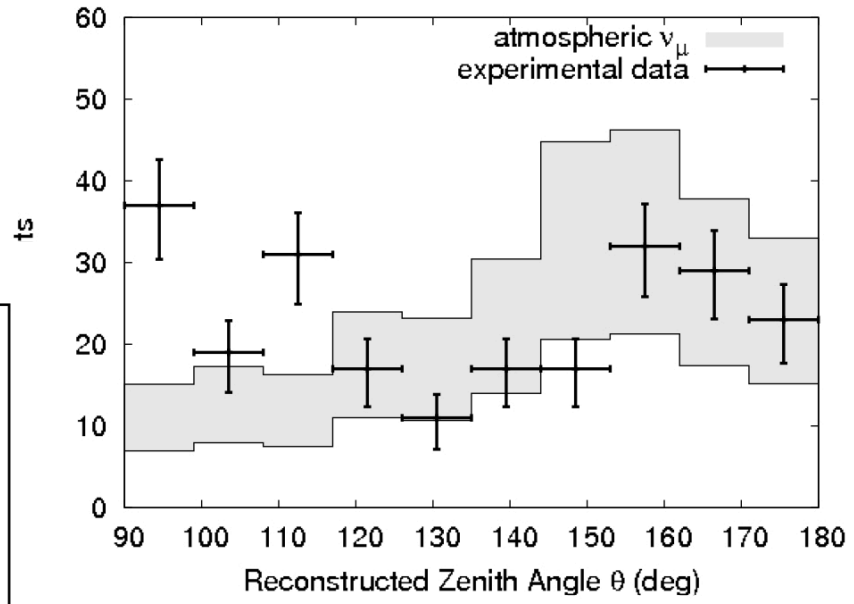
Neutrino Telescopes
IceCube

- 2007
  - AMANDA II + 9 string IceCube
  - atmospheric ν_μ: background





- Searches for diffuse and point astrophysical sources, dark matter
- Focus on up-going ν_μ analysis

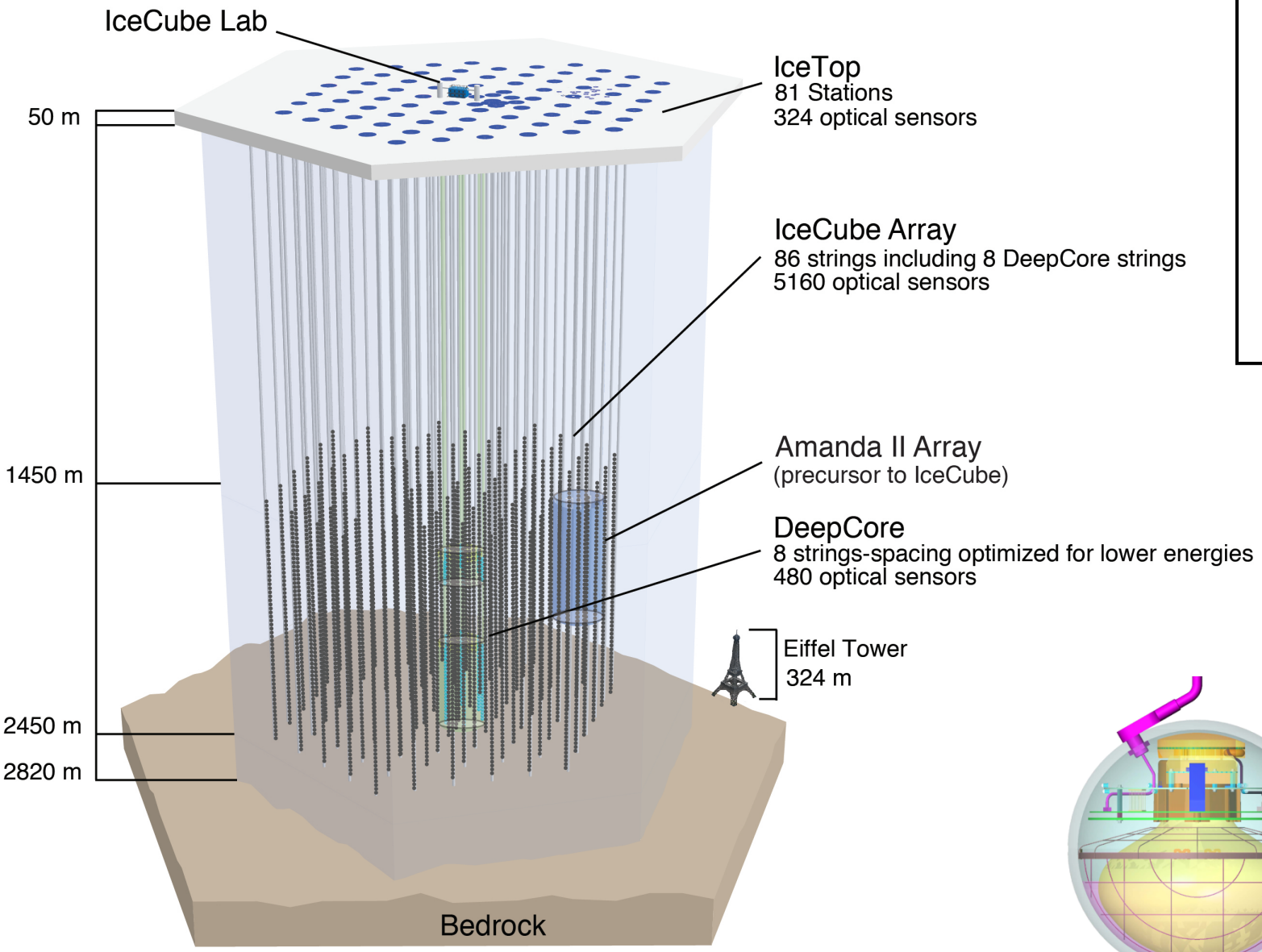
Neutrino Telescopes
IceCube

- Now

  - High energy neutrinos from astrophysical sources detected!
  - High statistics atmospheric neutrinos
  - All flavors

  - Want to understand:
    - astrophysics:
      - origin, source characteristics, relation to cosmic rays, gamma rays, etc.
      - …
    - physics:
      - sensitivity to new interactions, new states
      - tests of fundamental symmetries
      - …

The IceCube Neutrino Observatory



Configuration chronology

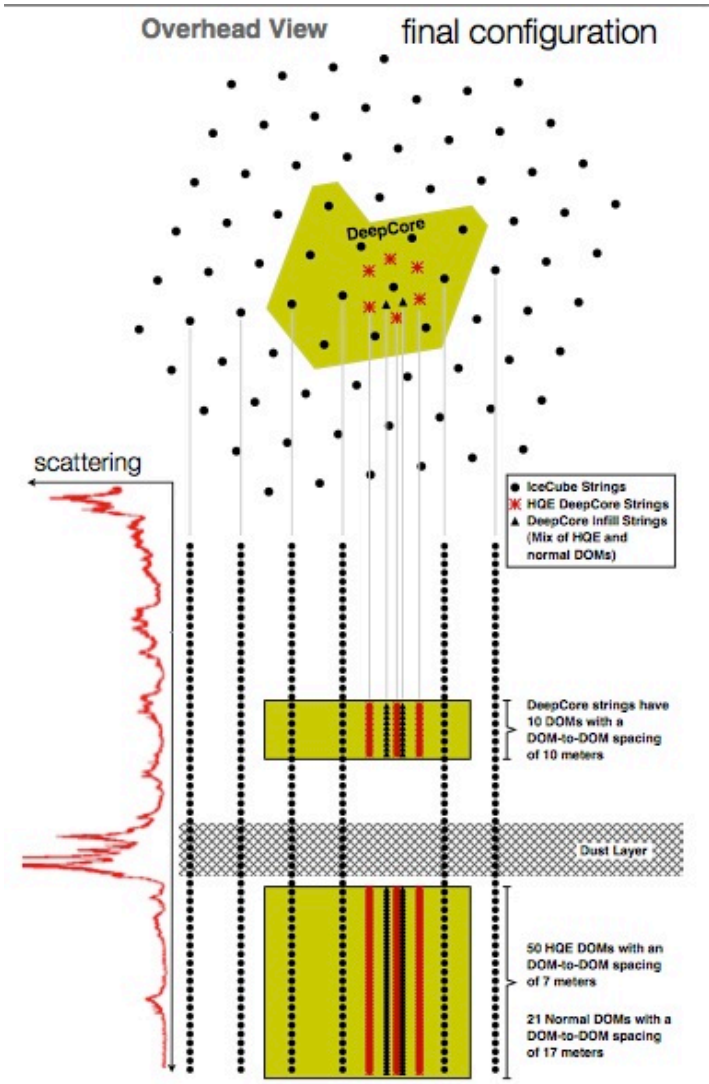
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86

Digital Optical Module (DOM)

IceCube DeepCore

- 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

- 8 special strings, 72m IS, 7m DOM spacing
- ~ 5x higher effective photocathode density
- deep region
- clear ice
- IceCube's top and outer layers: active veto
  ~ 15 Mton



IceCube/Deep Core

- Atmospheric neutrinos
  - Background
  - Lots of them
  - Lots of work to get rid of them

IceCube/DeepCore

- Atmospheric neutrinos
  - Background
  - Lots of them
  - Lots of work to get rid of them
  - Useful!

- Up to 50,000 events/year! Use them!
- Energy range 10-40 GeV great for oscillation physics
- Statistics compensate for systematics for many issues
  - Use energy and angular distributions sensitive to physics
  - Normalizations can be determined from data

PHYSICAL REVIEW D **78,** 093003 (2008)

Neutrino mass hierarchy extraction using atmospheric neutrinos in ice

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(Received 27 March 2008; published 6 November 2008)

We show that the measurements of 10 GeV atmospheric neutrinos by an upcoming array of densely-packed phototubes buried deep inside the IceCube detector at the South Pole can be used to determine the neutrino mass hierarchy for values of $\sin^2 2\theta_{13}$ close to the present bound, if the hierarchy is normal. These results are obtained for an exposure of 100 Mton years and systematic uncertainties up to 10%.

- Data already there: need the right tools to analyze it

IceCube/Deep Core/Upgrade

- Data already there: need the right tools to analyze it
- Part of IceCube but different due to "low" energy
  - > 10 TeV : charged lepton carries ~80% of initial neutrino energy
    strongly peaked distribution ⟶ total cross-section
  - 10 GeV: charged lepton carries 50% of initial neutrino energy on average, with relatively flat distribution ⟶ need full differential cross-section ⟶ can get more information with full kinematics
  - Track/cascade separation
  - Different light propagation and reconstruction
  - energy threshold: more physics vs systematics at low energy

- Atmospheric neutrinos but different flux from Super-Kamiokande due to "high" energy
  - Super-Kamiokande: π+ μ decay ⟶ $\nu_\mu : \nu_e = 2 : 1$
  - ICDC: μ hit ground before decay ⟶ $\nu_\mu : \nu_e \sim 10 : 1$
    spectrum much steeper

IceCube/DeepCore/Upgrade

- Atmospheric neutrinos
  - background
  - lots of them
  - useful!

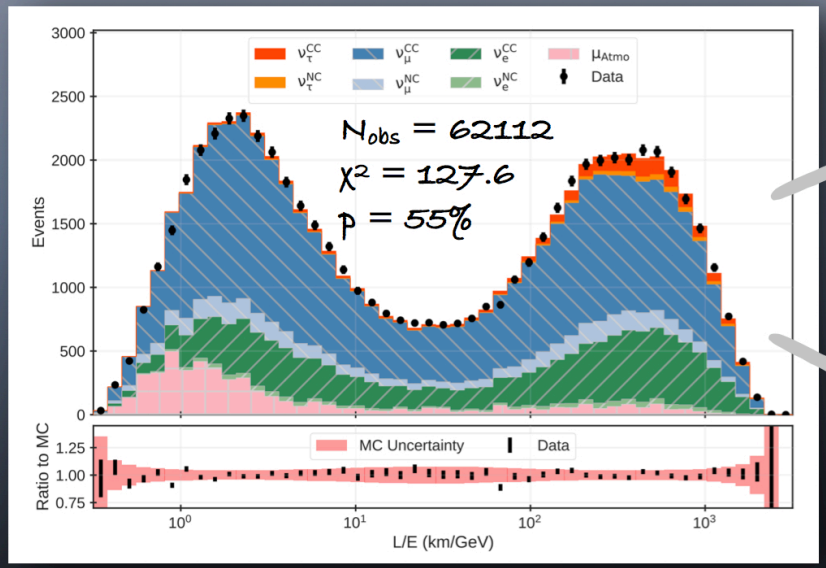
- mass hierarchy (O.Mena, I.Mocioiu, S.Razzaque, Phys. Rev. D78(2008) 093003)
- precision on all parameters
  (G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D82 (2010) 093001)
- tau neutrino appearance
  (G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D81 (2010) 113008)

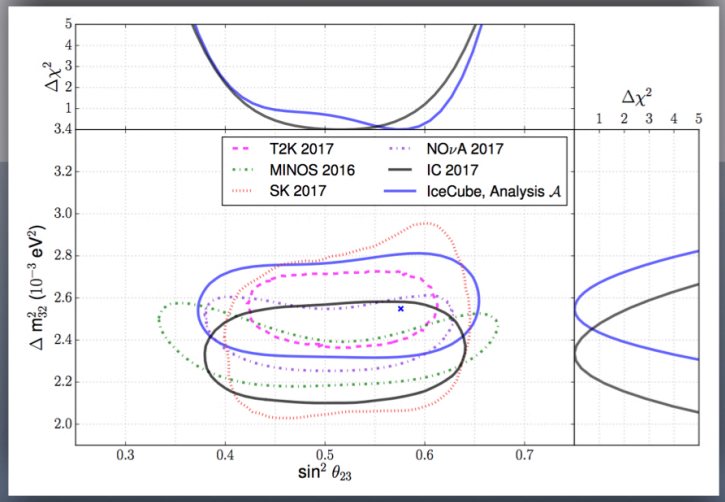
- new physics in neutrino sector
  (NSI+degeneracies I.Mocioiu, W.Wright, *Nucl.Phys.B* 893 (2015) 376)
- astrophysics:
  - atmospheric neutrino production in cosmic ray interaction
  - better understanding of background for astrophysical searches

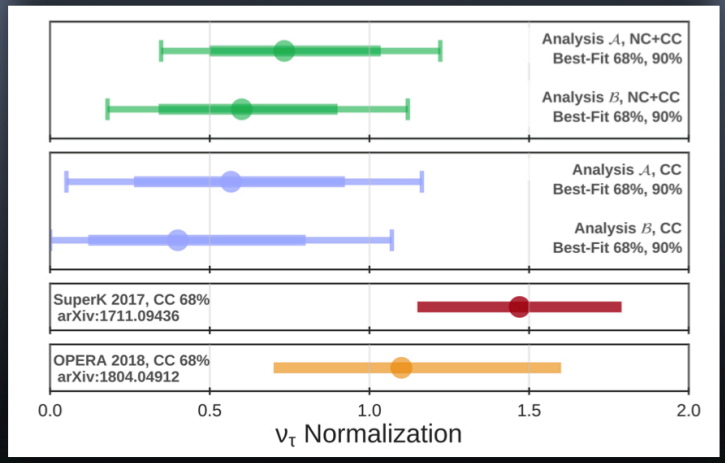
Standard oscillation results

Phys. Rev. D 99, 032007 (2019)

$\Delta m^2_{32} = 2.55\,^{+0.12}_{-0.11} \times 10^{-3}\ eV^2$ $\quad \sin^2\theta_{23} = 0.58\,^{+0.04}_{-0.13}$

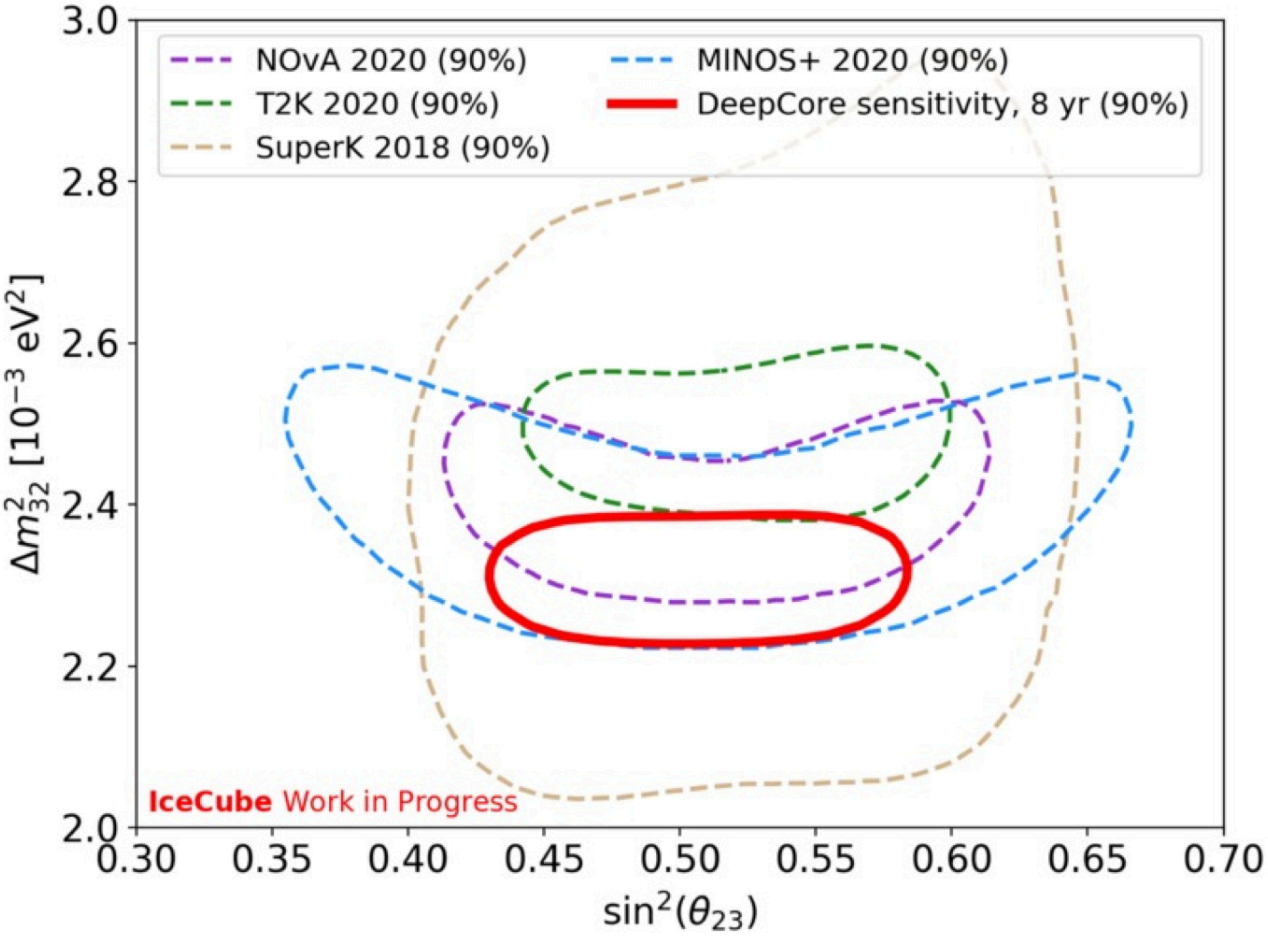


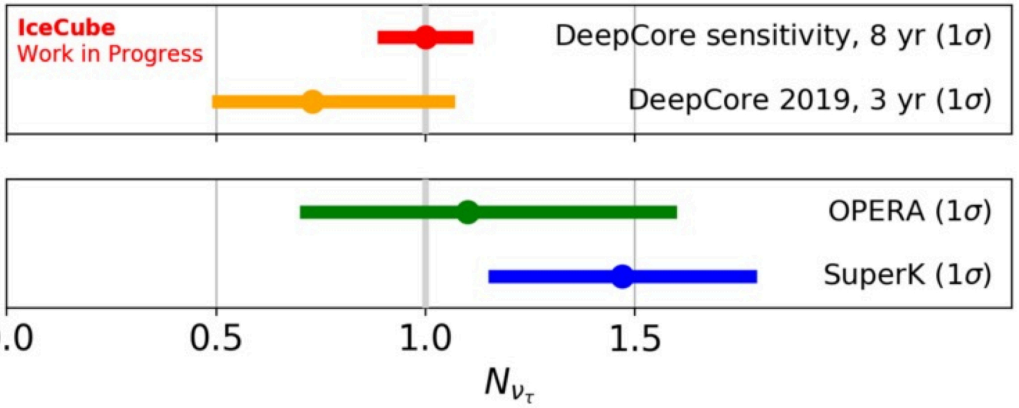




Norm $\nu_\tau^{(CC+NC)} = 0.73\,^{+0.34}_{-0.24}$ $\quad$ Reject no-ν_τ with 3.2σ (CC+NC)

IceCube DeepCore NuFact2021





Tau Neutrino Appearance

Electromagnetic cascades

(G. Giordano, O.Mena, I.Mocioiu, Phys. Rev. D81 (2010) 113008)

- Tau decay: $\tau \rightarrow e + \bar{\nu}_e + \nu_\tau$
- ν_e CC interactions: $\nu_e + N \rightarrow e + X$

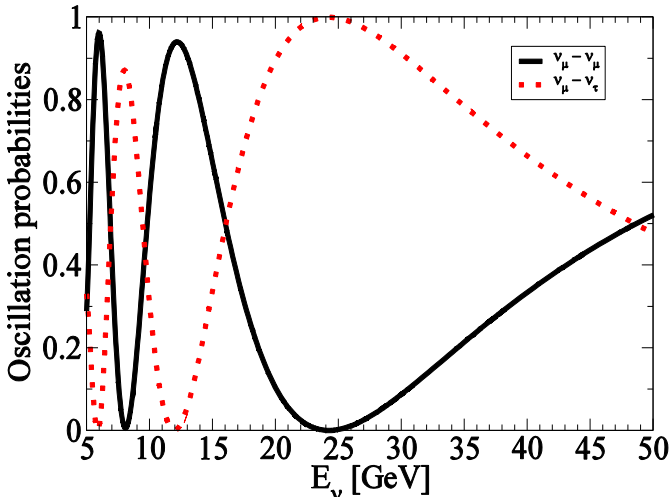
Hadronic cascades

- 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

Looking for ν_τ helped by:

- $\Phi_{\nu_\mu} \sim 10\,\Phi_{\nu_e}$
- oscillations
- high energy: well above threshold

- spectrum important



ν_τ

- high statistics ν_τ interactions
- direct measurement of $\nu_\mu \rightarrow \nu_\tau$ appearance
- ν_τ interaction cross-section
- non-standard interactions of ν_τ
- direct leptonic unitarity test

Precision era

- High precision long baseline beam experiments
- Atmospheric neutrinos
    - crucial consistency check in
        - testing framework
        - search for new physics
    - high statistics
    - large range of energies
    - large range of distances
    - high densities: matter effects
- need complementary observables to break degeneracies

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 (Δm^2_{32}, θ_{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

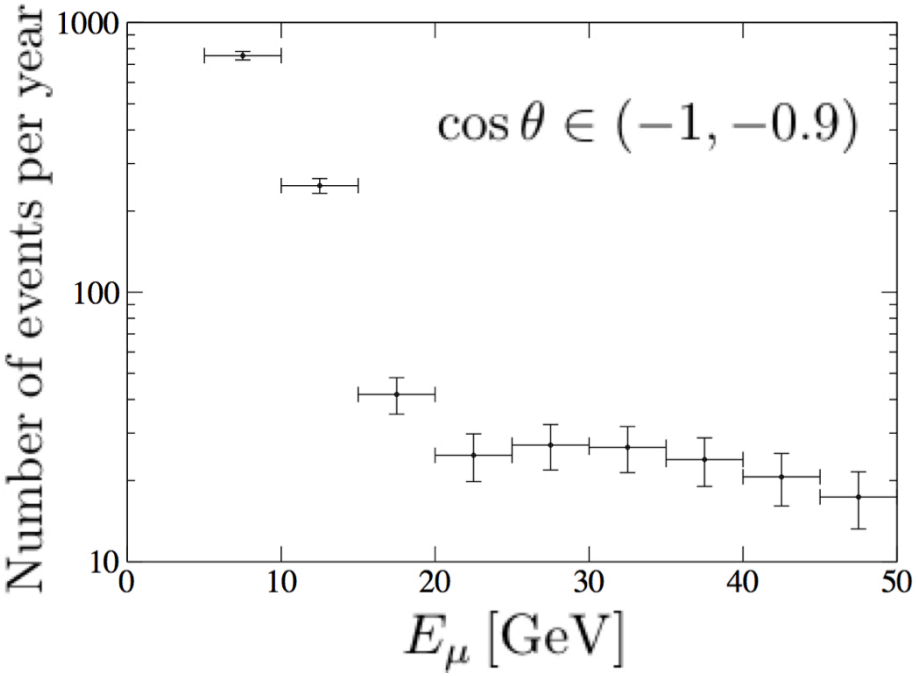
ICDC physical mass: $15\,\mathrm{Mt}$

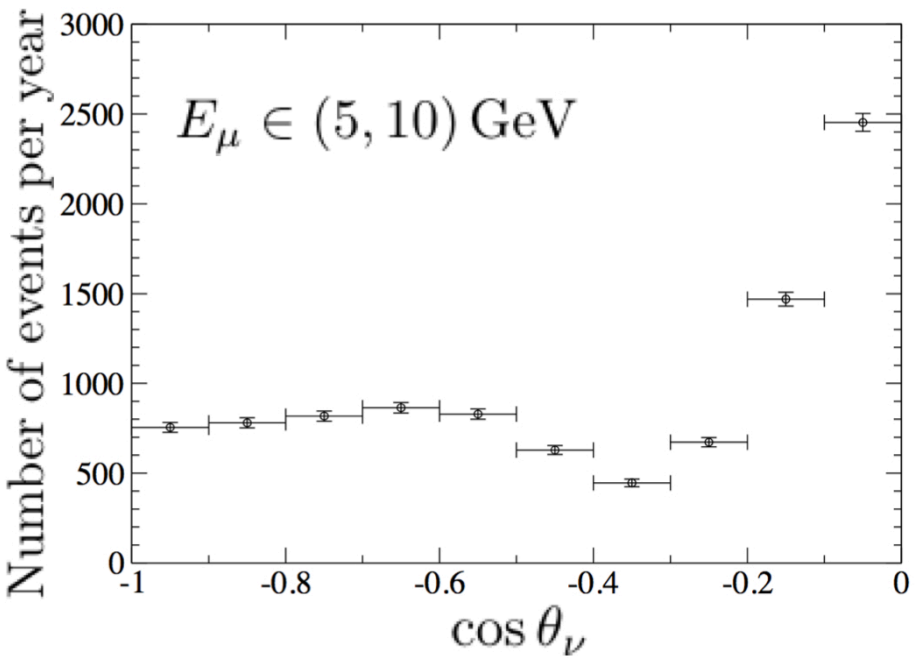
Effective mass in our analysis: $1\,\mathrm{Mt} - 12\,\mathrm{Mt}$ (energy dependent)

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 atmospheric neutrinos





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:

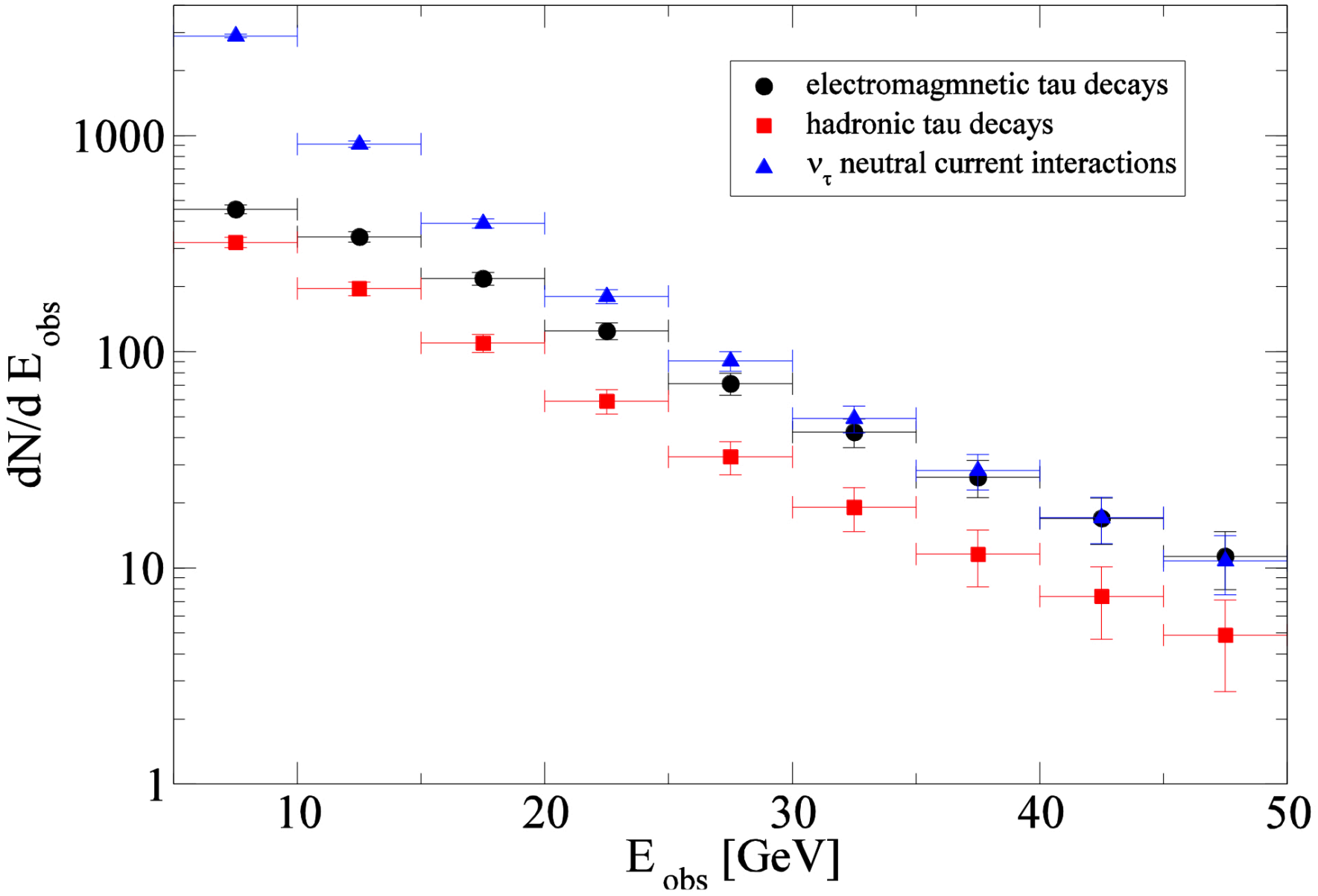
Δm^2: MINOS

θ_{23} : Super-Kamiokande

IceCube Deep Core:

- very large statistics
- contribution from multiple peaks

Tau cascade rates



Normal versus inverted mass hierarchy

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

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