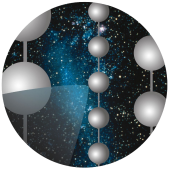


IceCube

RWTH AACHEN UNIVERSITY

Latest results from IceCube on neutrino properties and flux types

Jan Auffenberg

Bundesministerium für Bildung und Forschung

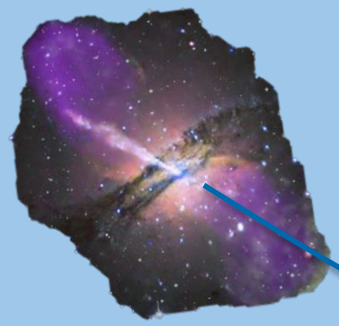
HELMHOLTZ GEMEINSCHAFT
Allianz für Astroteilchenphysik

DFG Deutsche Forschungsgemeinschaft

Content

- Introduction
- Astrophysical Neutrino Flux
- Astrophysical Sources
- Atmospheric Neutrino Flux and Neutrino Oscillation
- Dark Matter WIMPs
- Summary

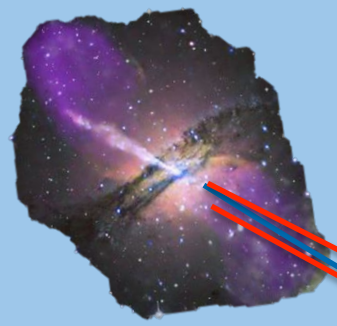
Introduction



Cosmic-Rays: Unknown origin as they get bent in magnetic fields

p, Fe, ?

Introduction

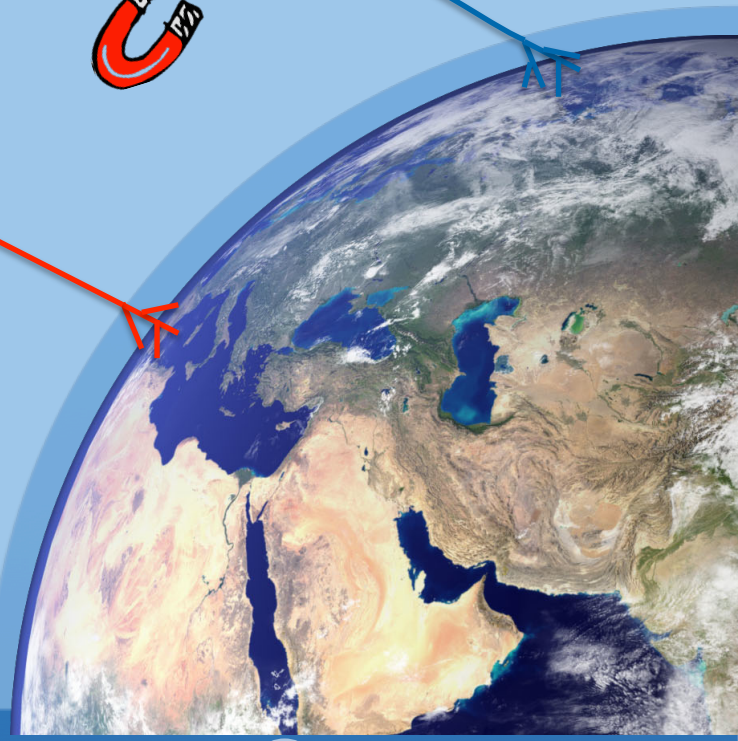


Cosmic-Rays: Unknown origin as they get bent in magnetic fields

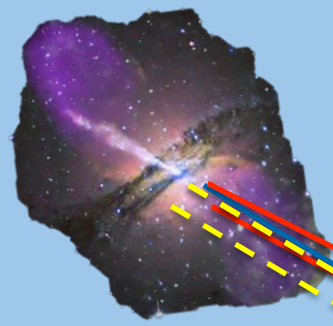
p, Fe, ?

Gamma-ray sources:
- not necessarily hadronic
- gammas potentially get absorbed

ν



Introduction



Cosmic-Rays: Unknown origin as they get bent in magnetic fields

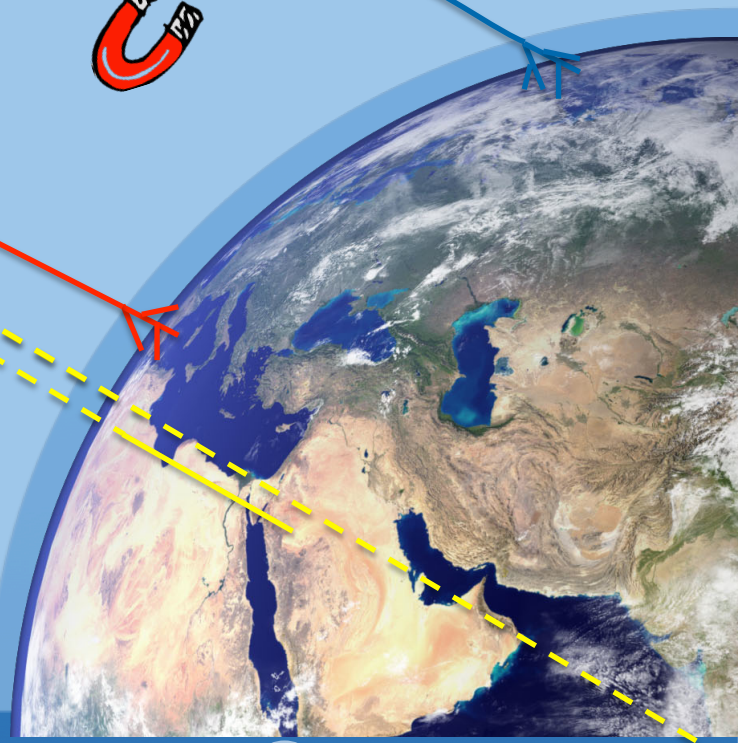
p, Fe, ?

Gamma-ray sources:
- not necessarily hadronic
- gammas potentially get absorbed

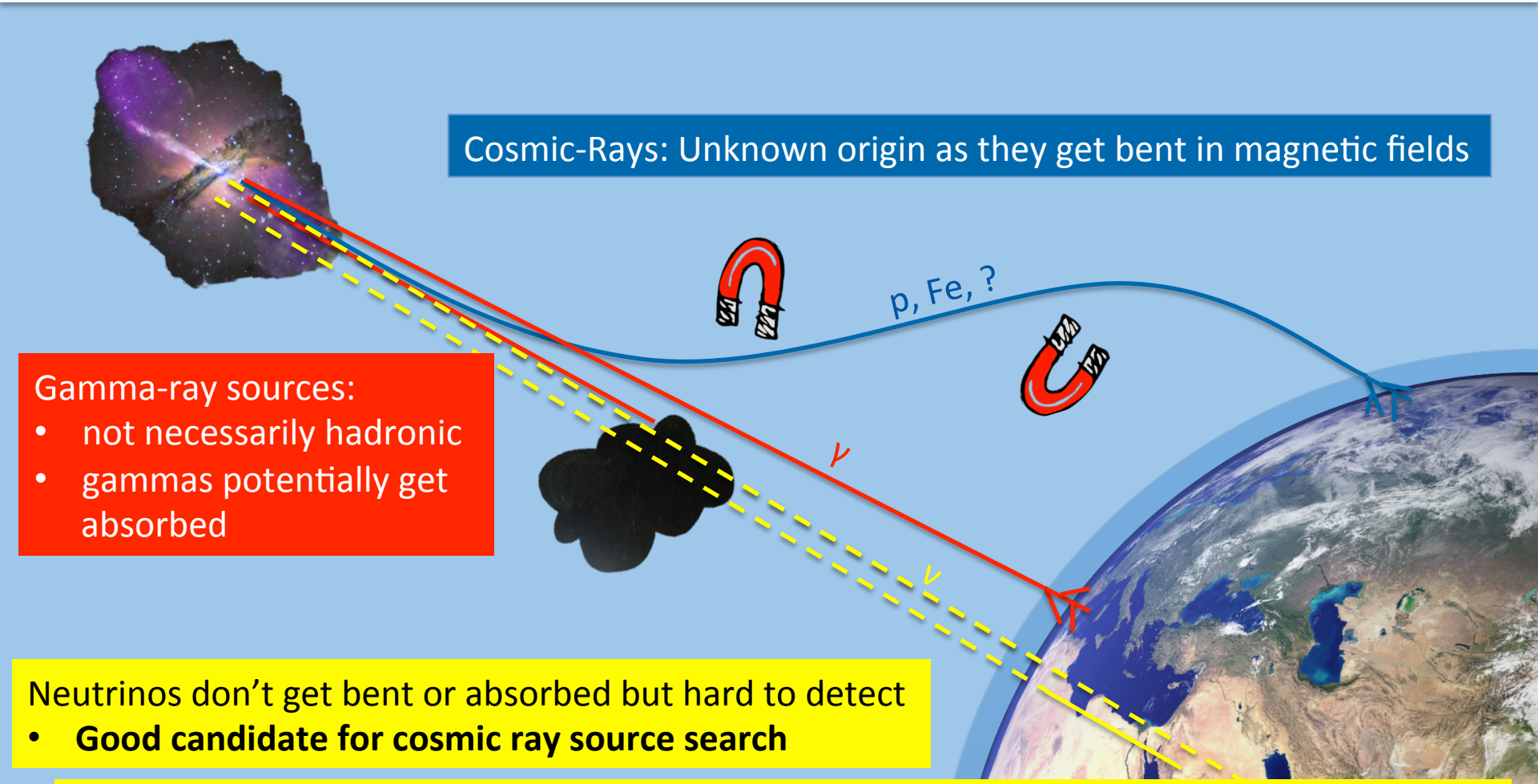
ν

ν

Neutrinos don't get bent or absorbed but hard to detect
- **Good candidate for cosmic ray source search**

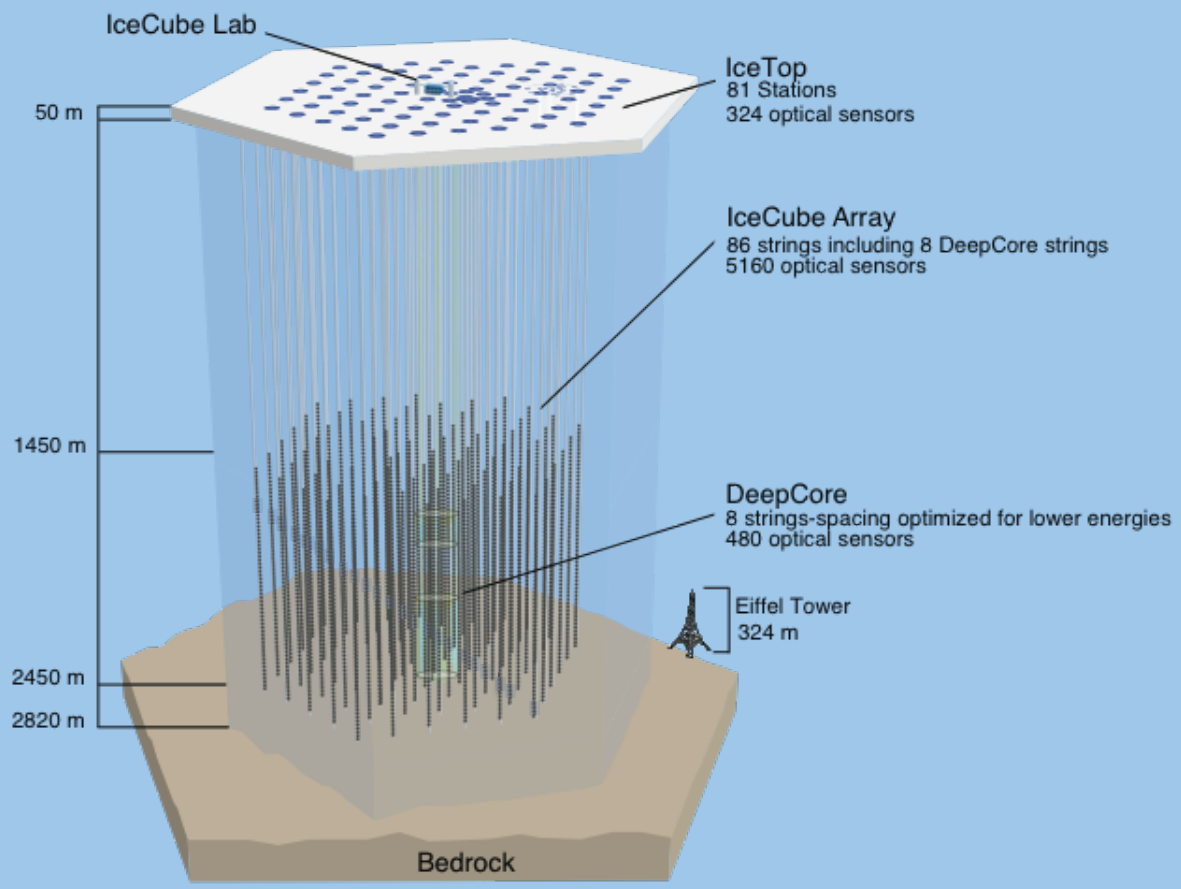


Introduction



Neutrinos point back to their sources !
As an important part of multi-messenger astro-physics

The IceCube neutrino observatory



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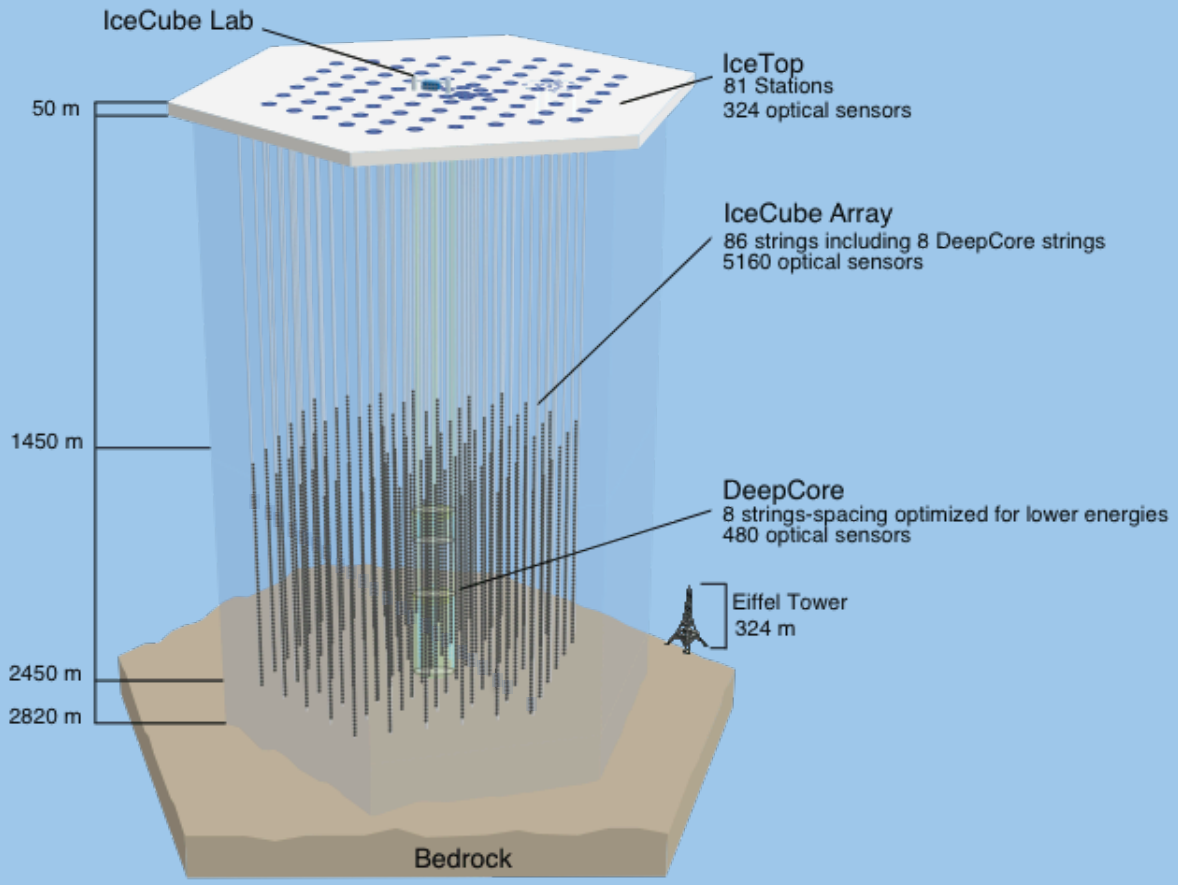

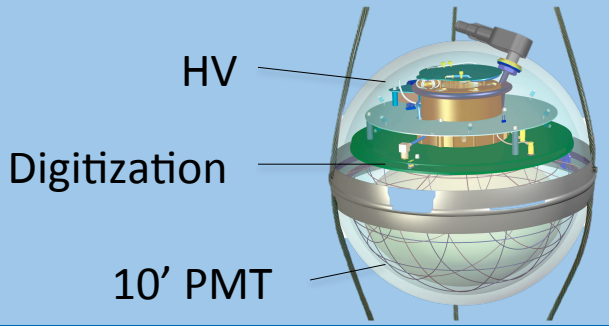

IceCube et al. Nucl. Inst. Meth. A 618 (2010) 139-152

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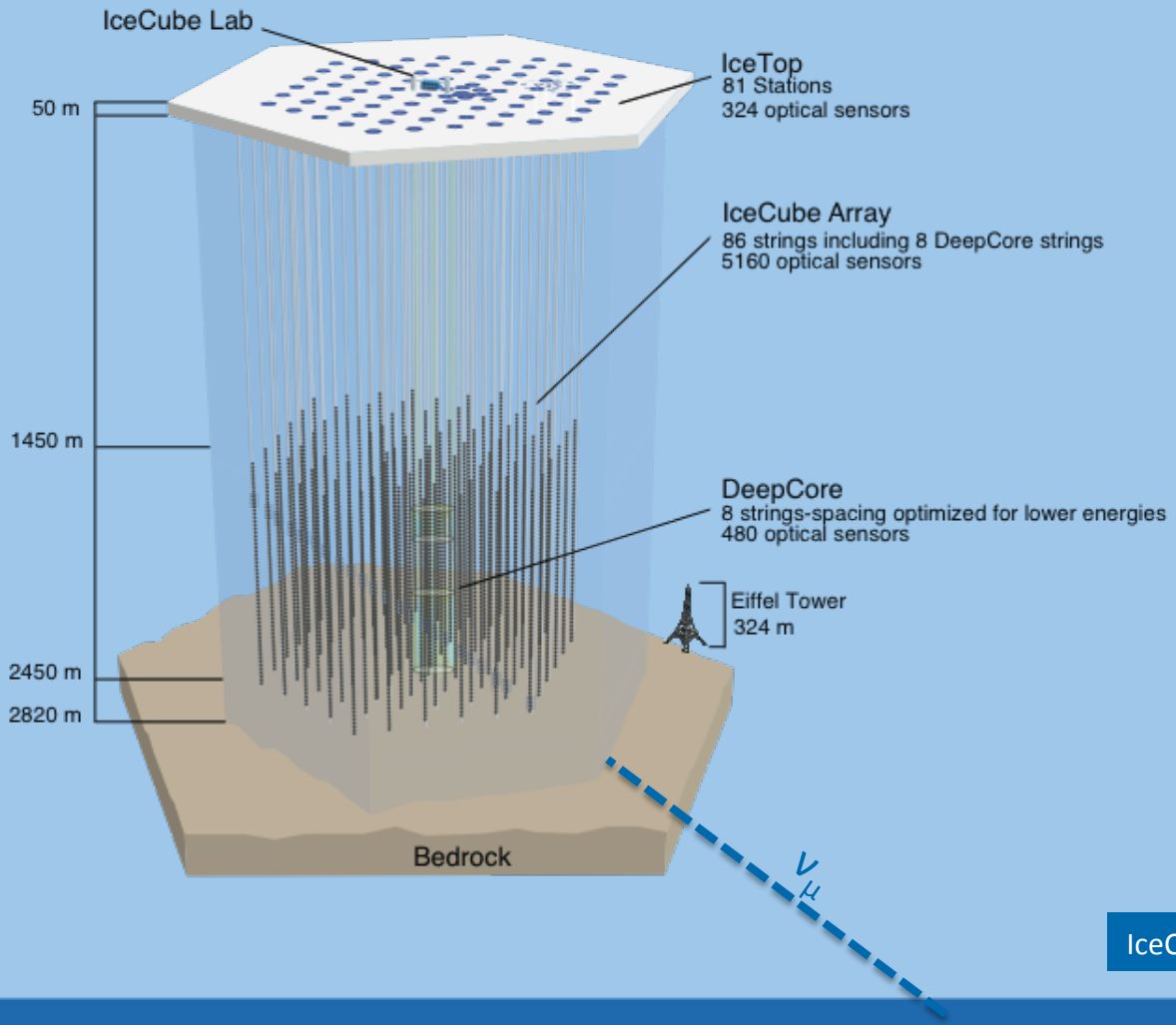

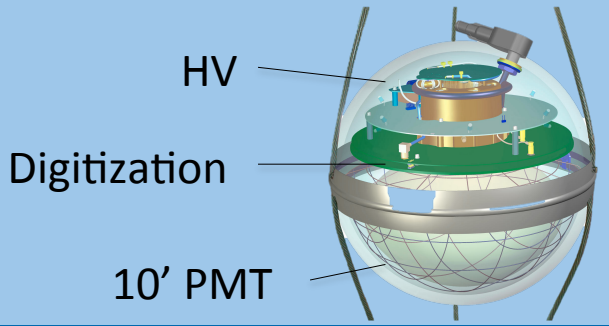

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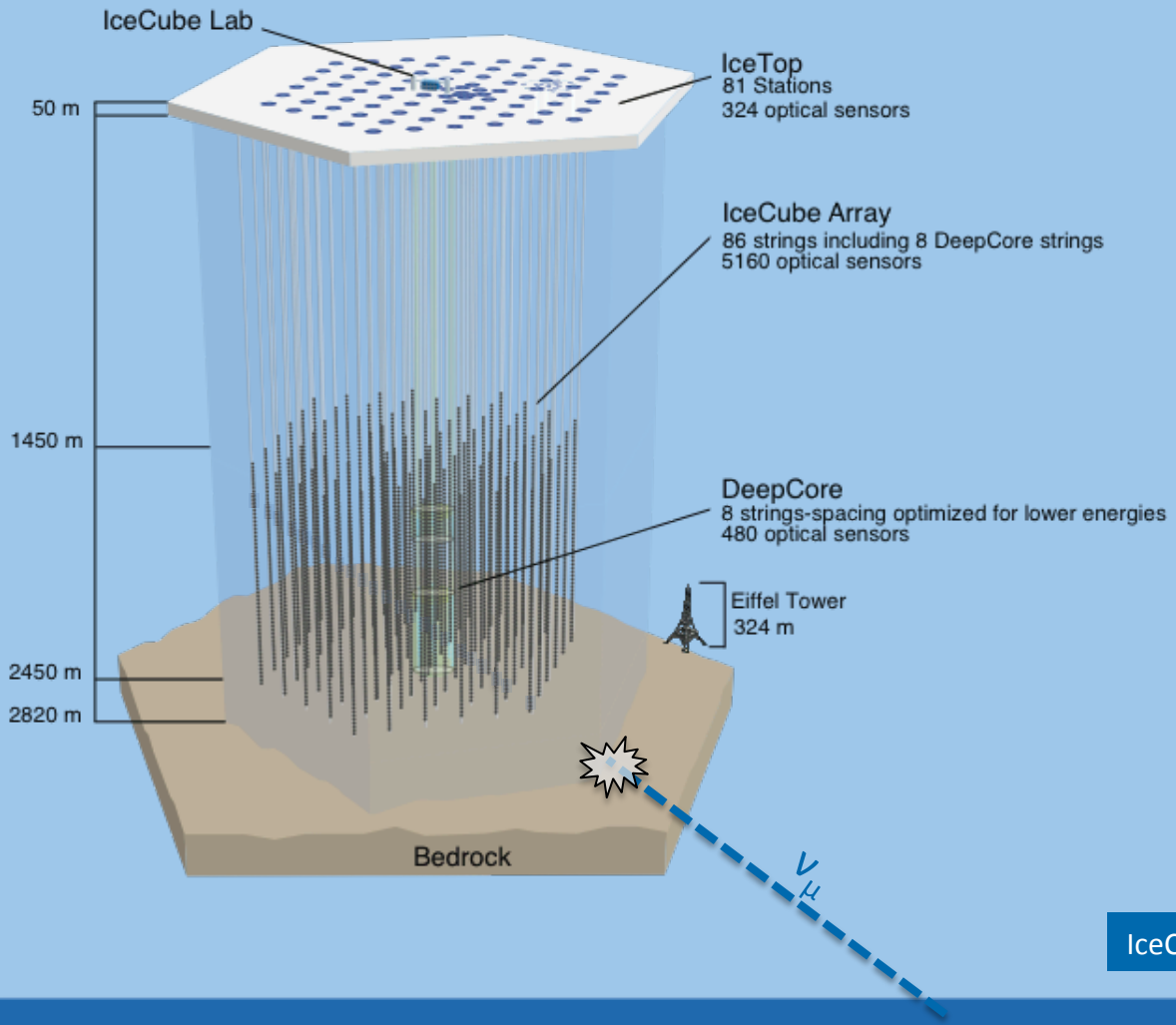

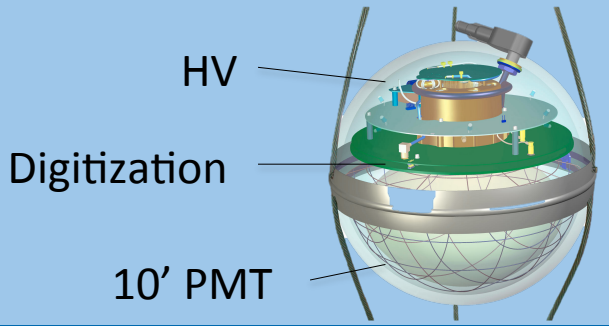

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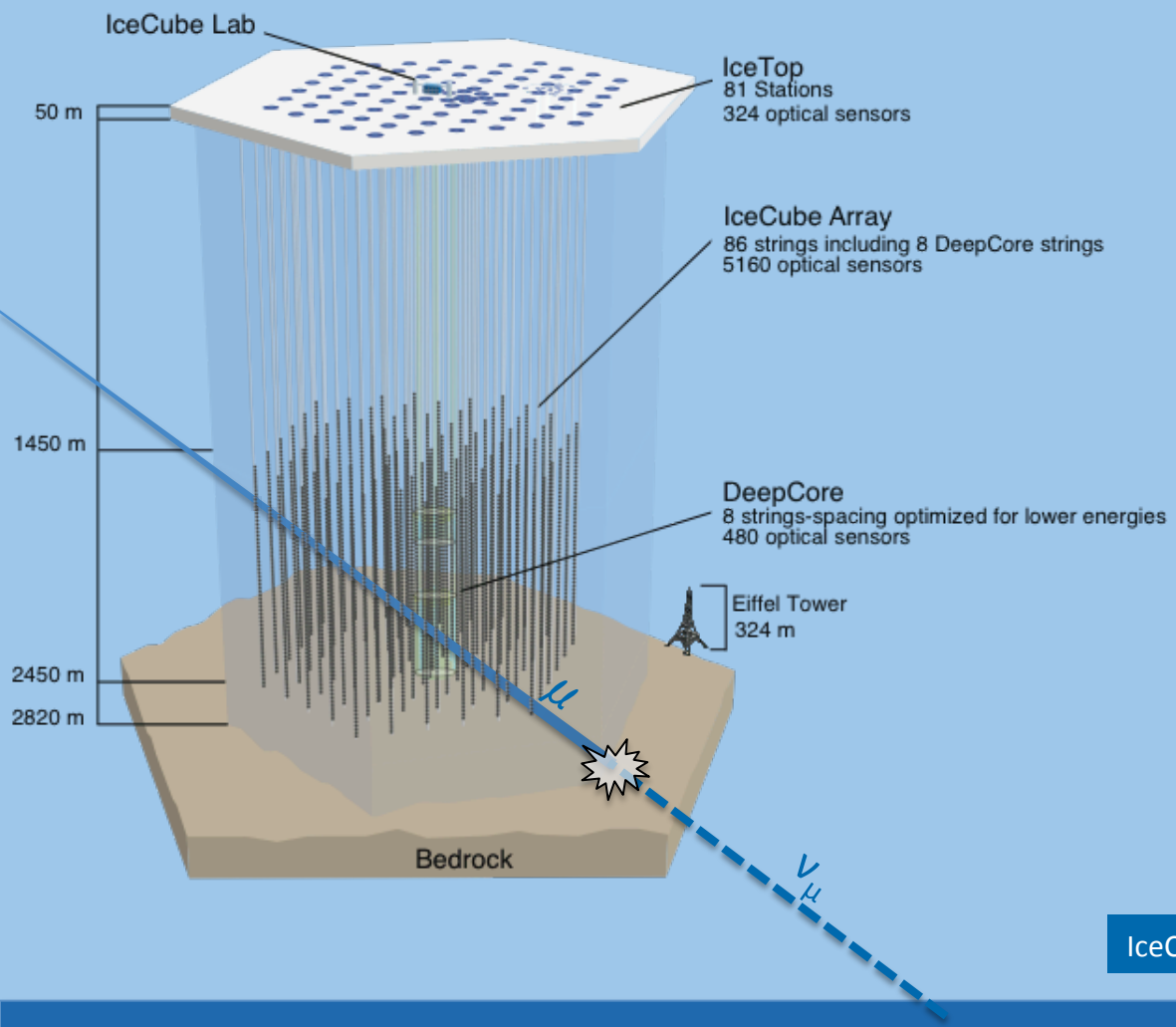

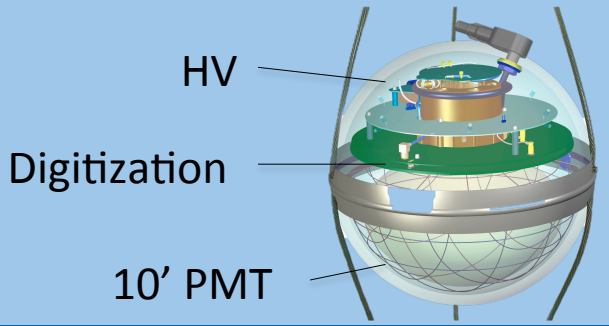

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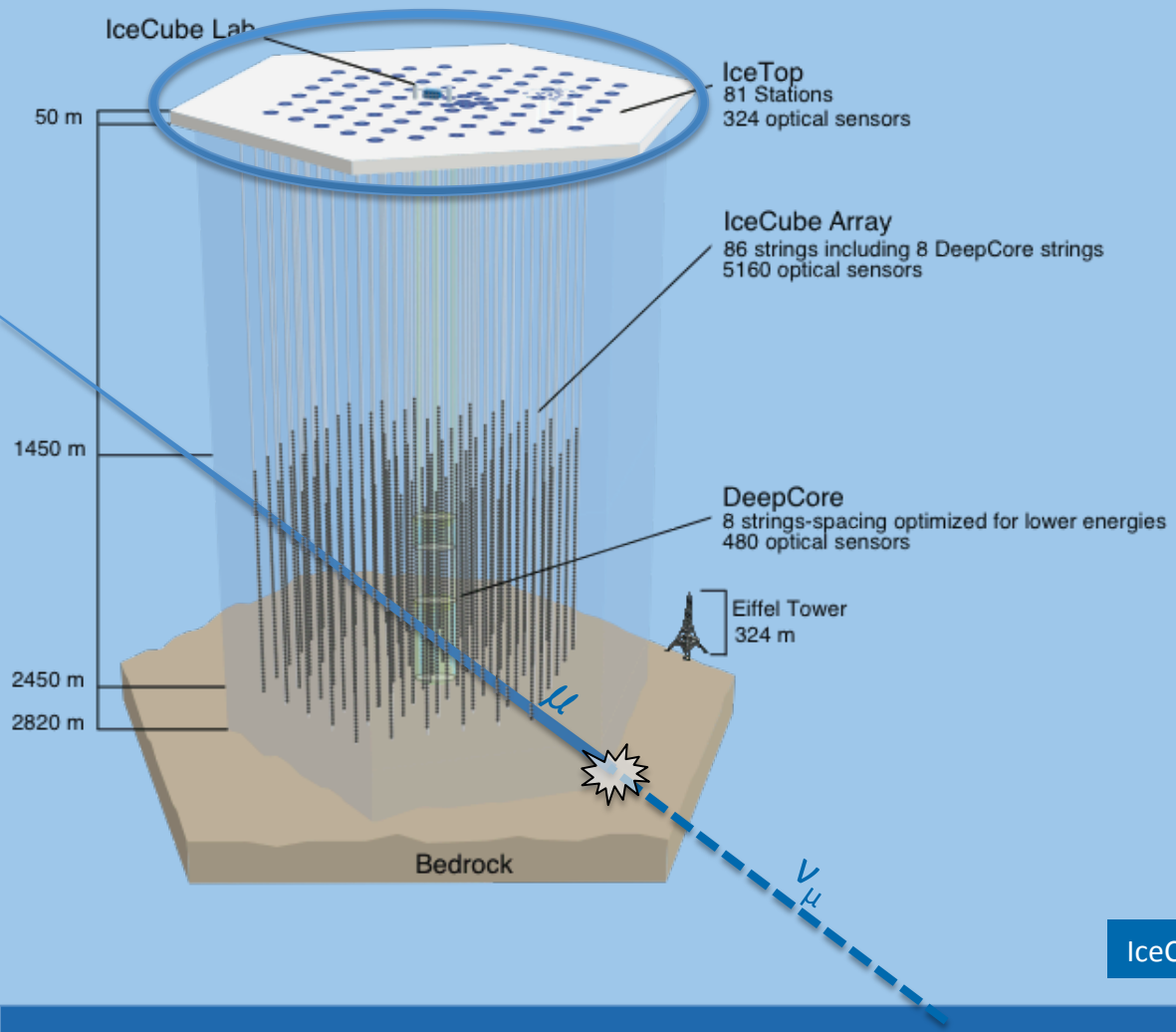

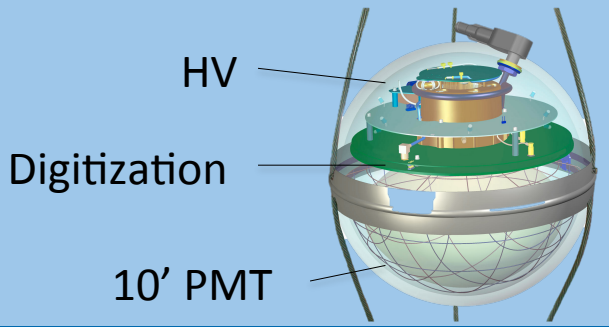

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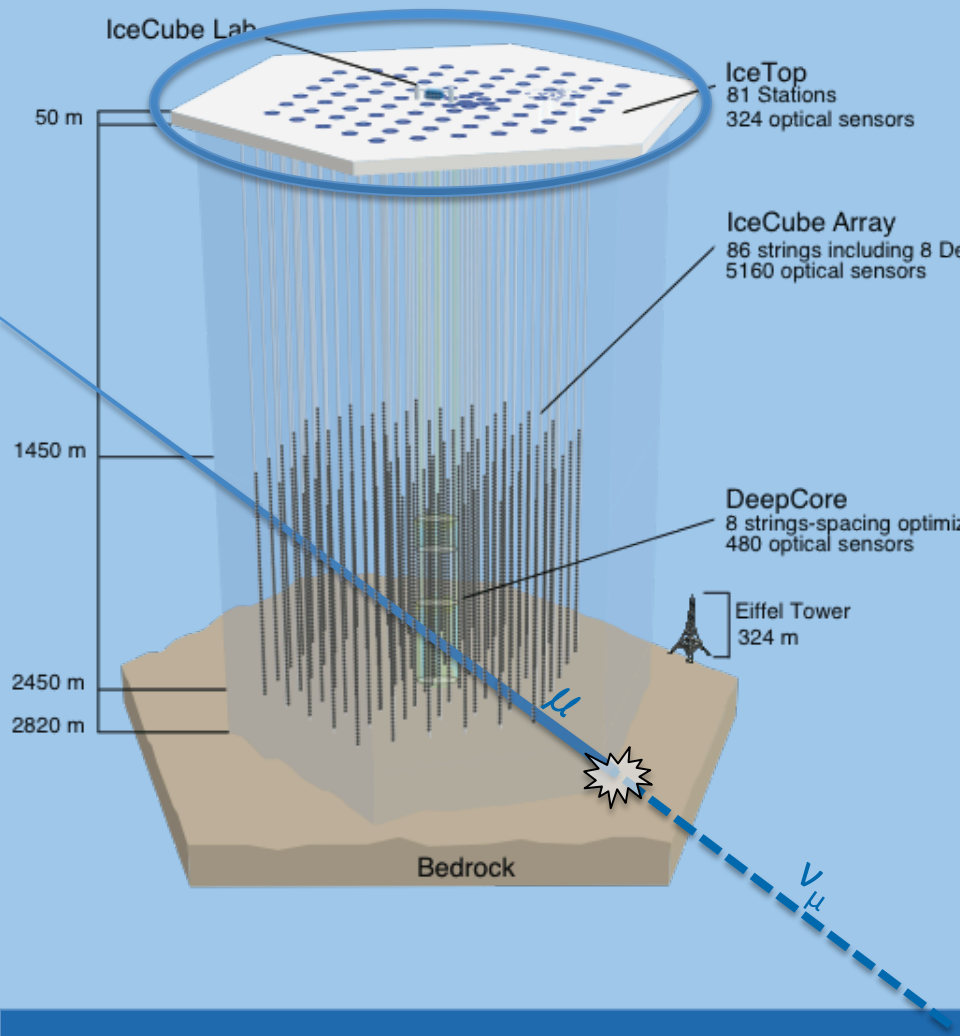

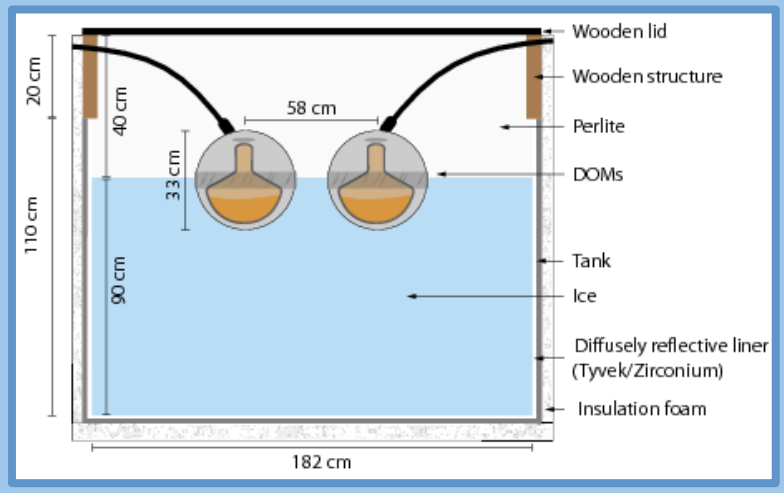

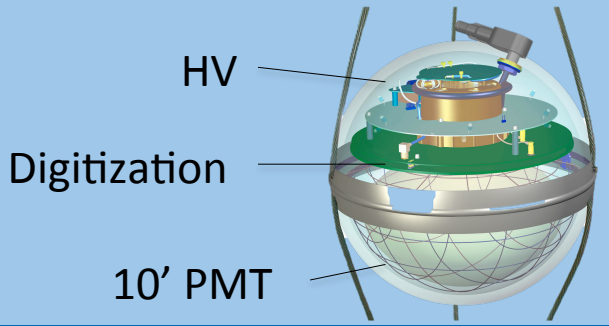

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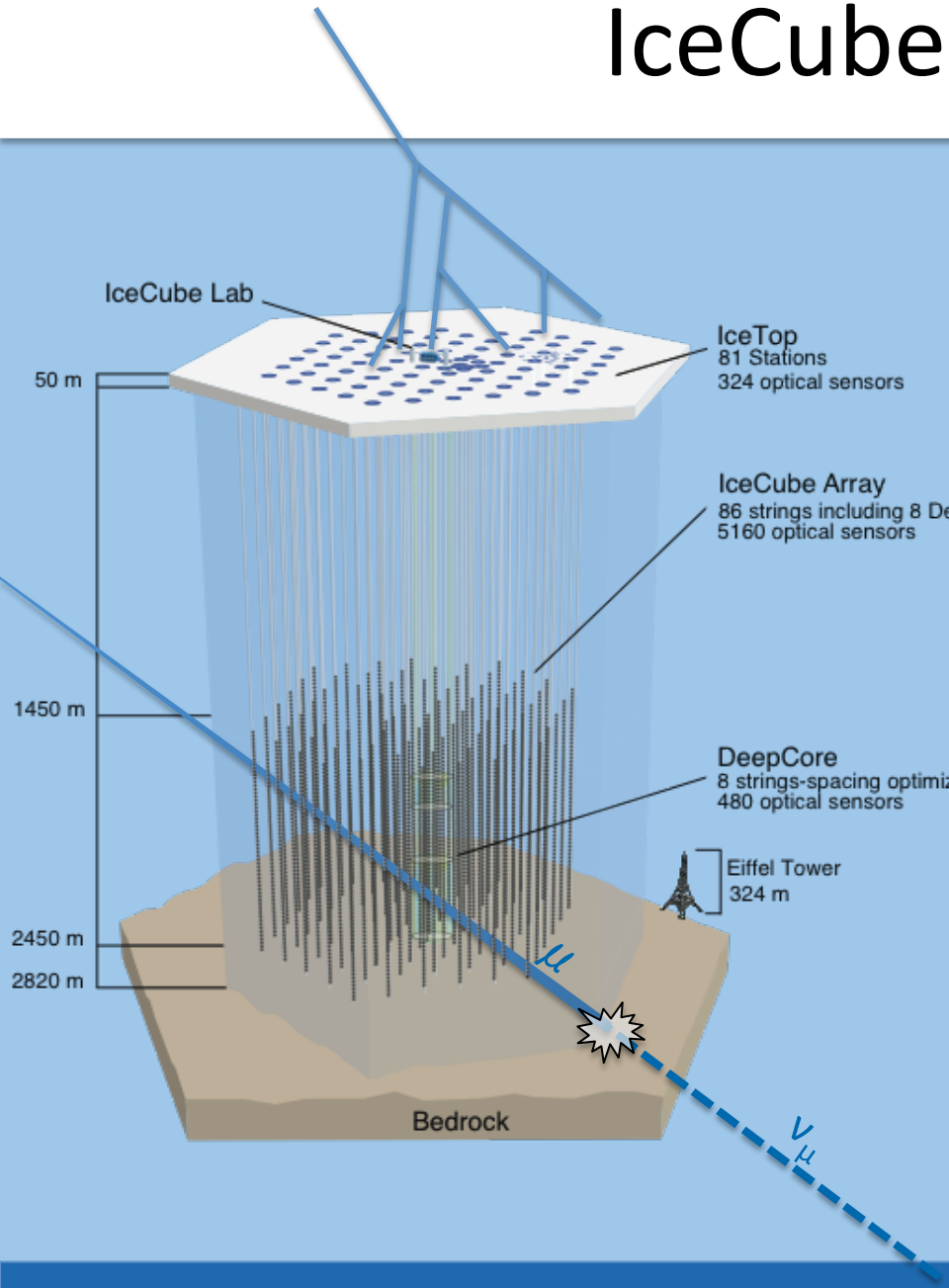
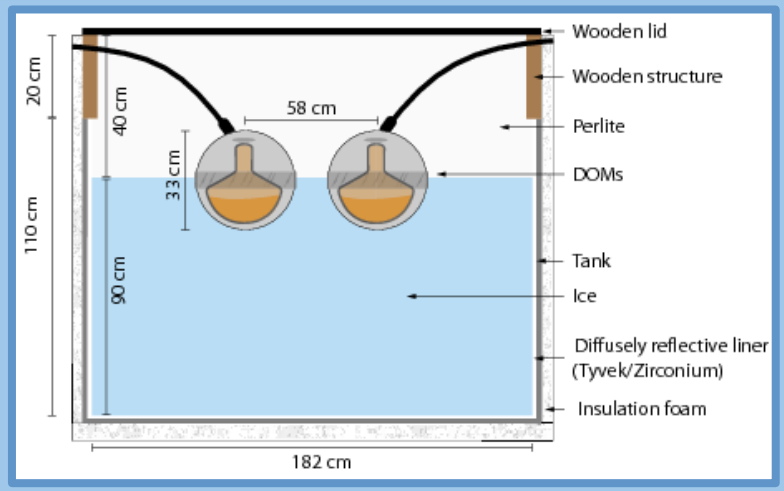
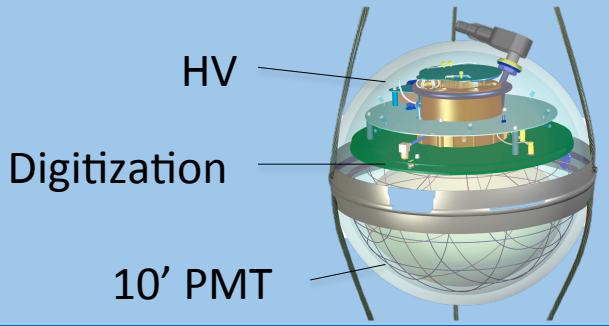
IceCube today







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Neutrino Signatures

Neutrino Signatures

Neutral Current /Electron Neutrino
so called “**shower**”

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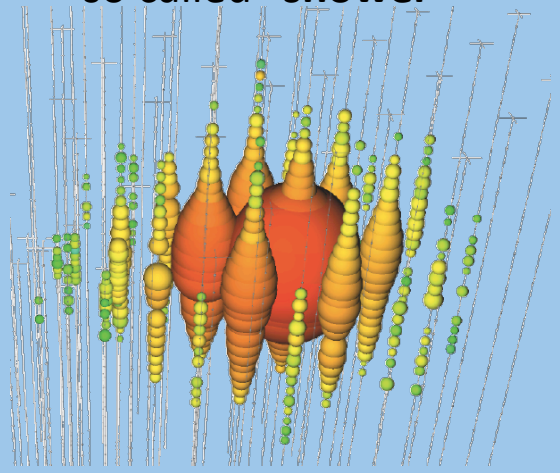

$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

Neutrino Signatures

Neutral Current /Electron Neutrino
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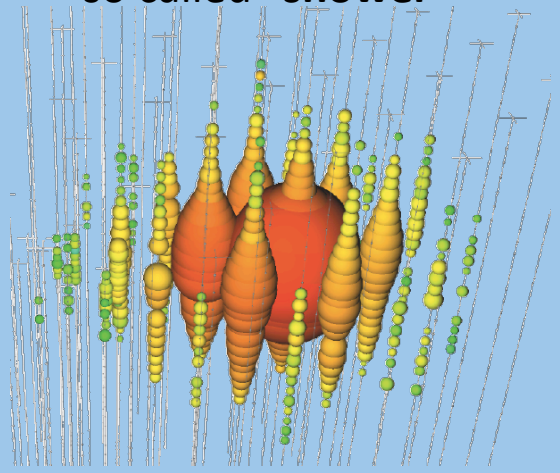

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- Good Energy resolution

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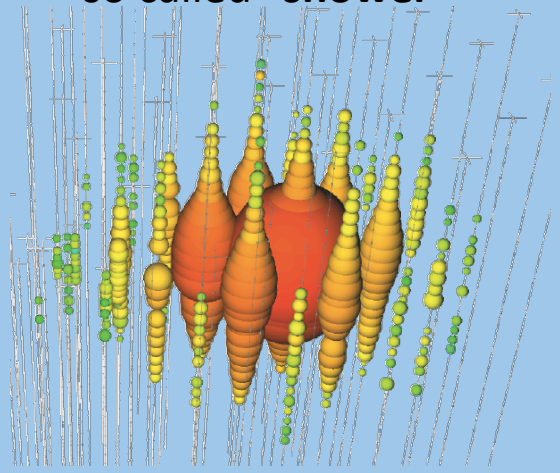

$$\nu_e + N \rightarrow e + X$$

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- Good Energy resolution
- angular resolution around 5°-10°

Neutrino Signatures

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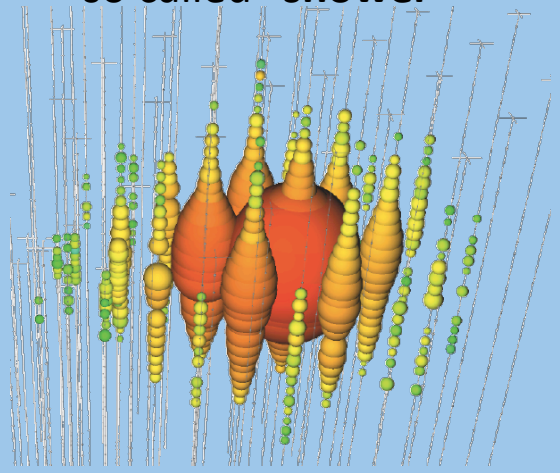

$$\nu_e + N \rightarrow e + X$$

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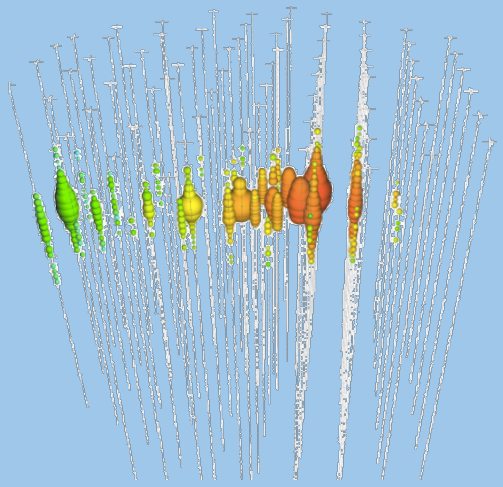
CC Muon Neutrino
so called "**track**"

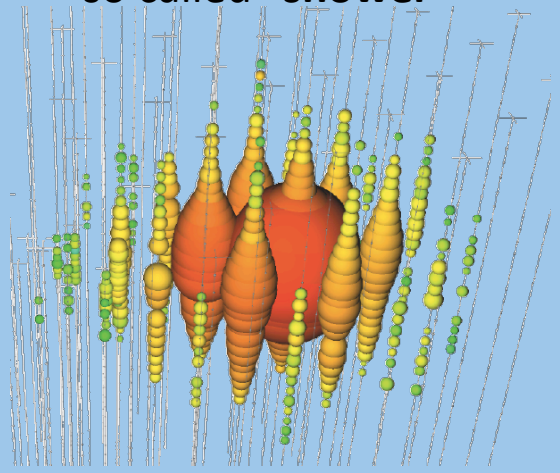


$$\nu_\mu + N \rightarrow \mu + X$$

- Good Energy resolution
- angular resolution around 5°-10°

Neutrino Signatures

Neutral Current /Electron Neutrino
so called "**shower**"



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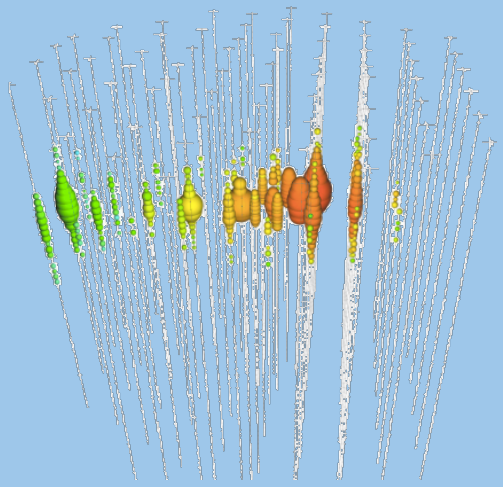

$$\nu_\mu + N \rightarrow \mu + X$$

- Energy resolution limited

Neutrino Signatures

Neutral Current /Electron Neutrino
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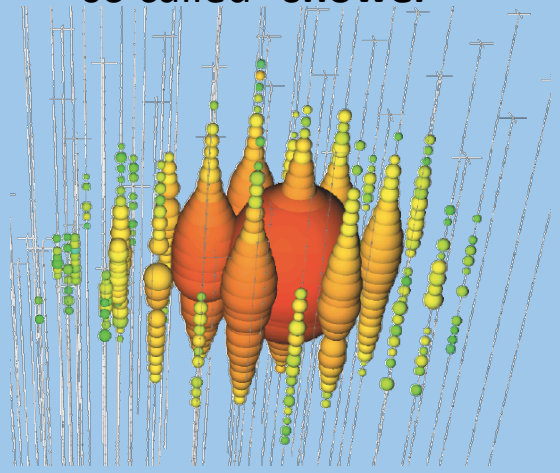

$$\nu_e + N \rightarrow e + X$$

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- Good Energy resolution
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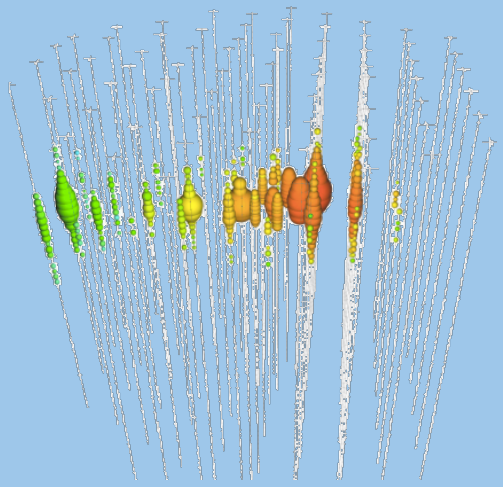
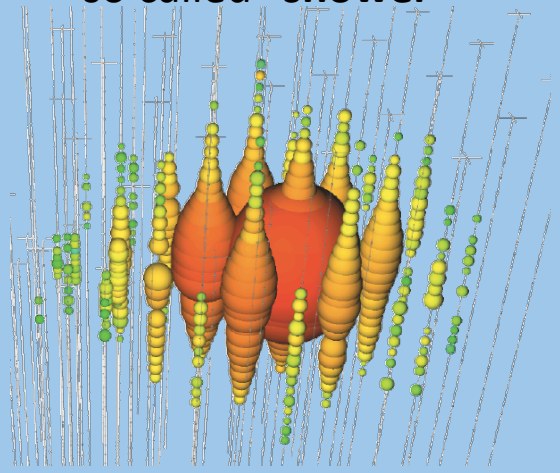


$$\nu_\mu + N \rightarrow \mu + X$$

- Energy resolution limited
- **sub degree pointing**

Neutrino Signatures

Neutral Current /Electron Neutrino
so called "**shower**"

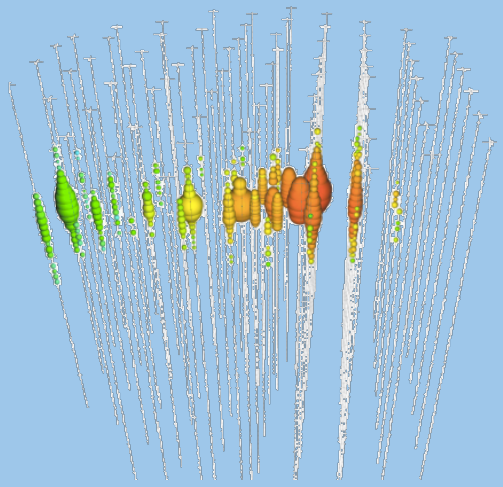


$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

- Good Energy resolution
- angular resolution around 5°-10°

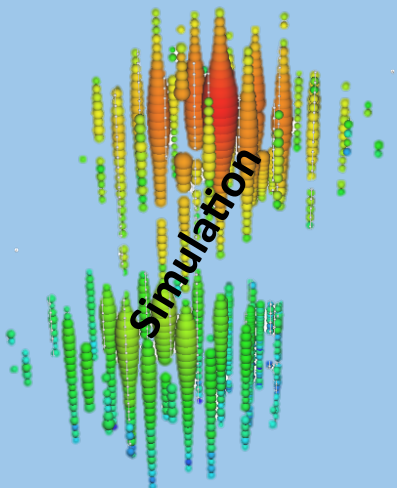
CC Muon Neutrino
so called "**track**"



$$\nu_\mu + N \rightarrow \mu + X$$

- Energy resolution limited
- sub degree pointing

CC Tau Neutrino
so called "**Double Bang**"



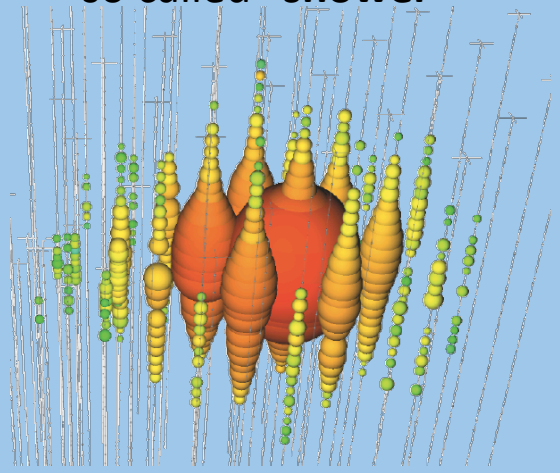
$$\nu_\tau + N \rightarrow \tau + X$$

$$\tau \rightarrow \nu_\tau + X$$

- **Good Energy resolution**
- **Good angular resolution**

Neutrino Signatures

Neutral Current /Electron Neutrino
so called **“shower”**

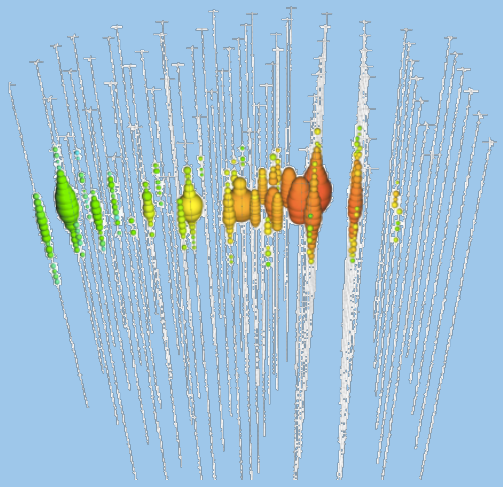


$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

- Good Energy resolution
- angular resolution around 5°-10°

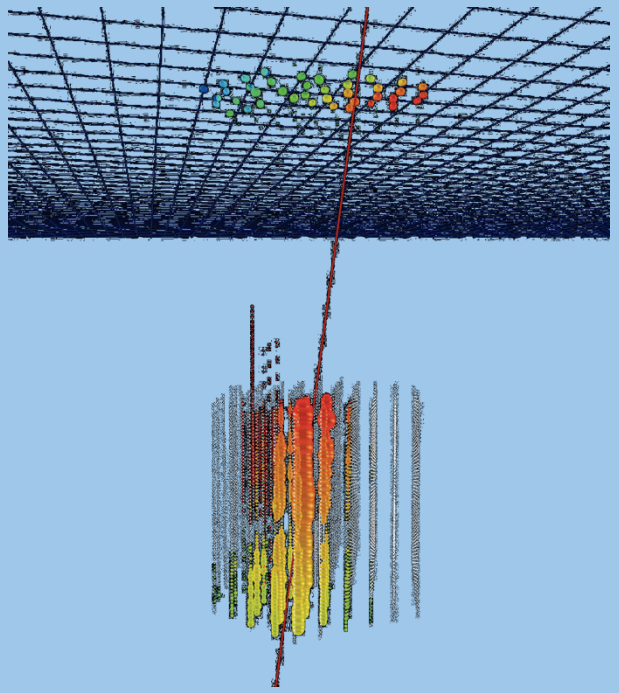
CC Muon Neutrino
so called **“track”**



$$\nu_\mu + N \rightarrow \mu + X$$

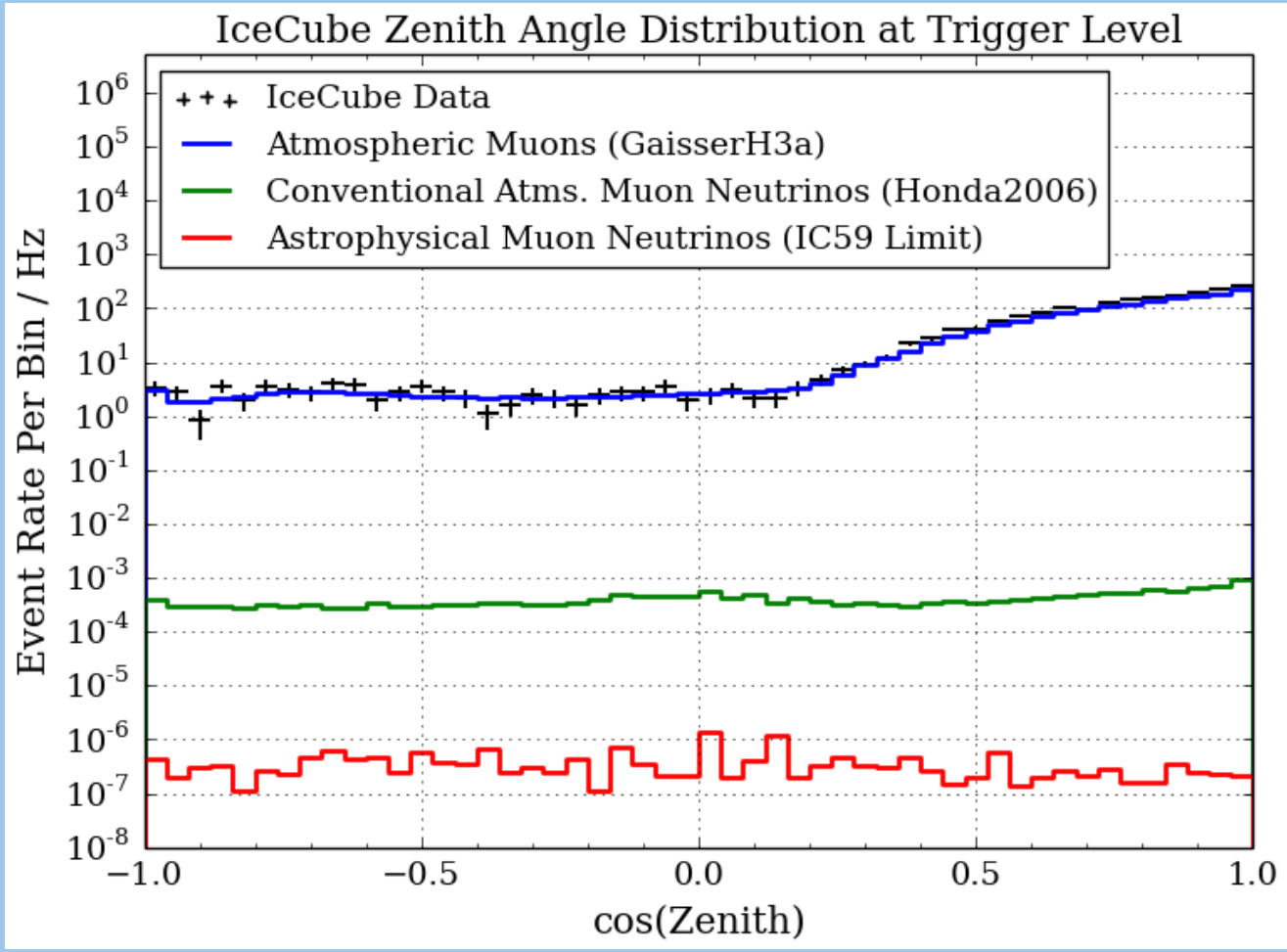
- Energy resolution limited
- sub degree pointing

Cosmic-Ray background



- Energy resolution weak
- Good angular resolution

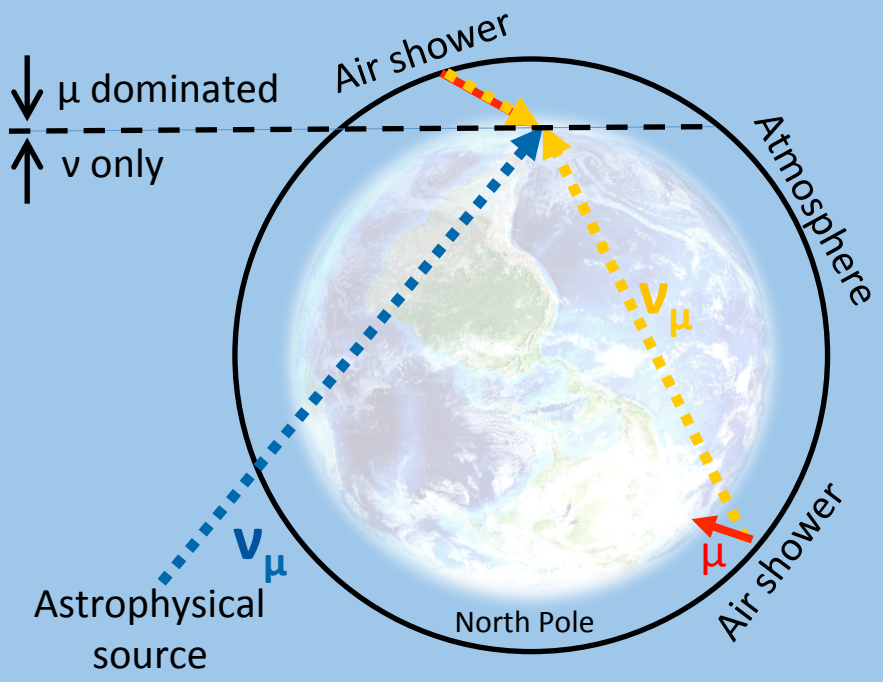
Background for neutrinos



- IceCube triggers at a rate of about 3 kHz
- Dominantly down-going muons produced in cosmic ray air showers

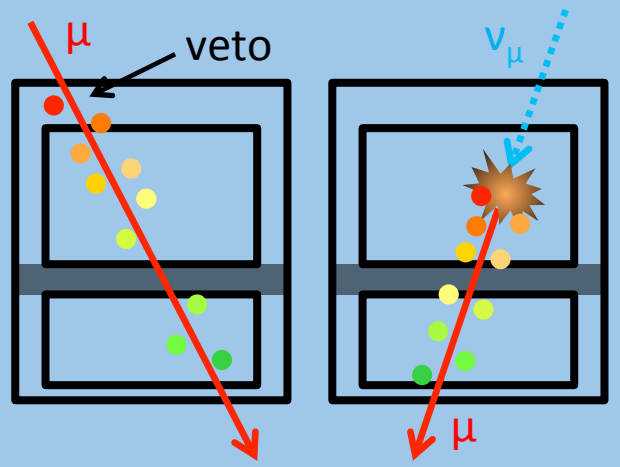
Neutrino selection in IceCube

Up-going tracks



- Selection of events which have passed through Earth
- Effective volume larger than detector
- Sensitive to ν_μ and Northern Hemisphere only

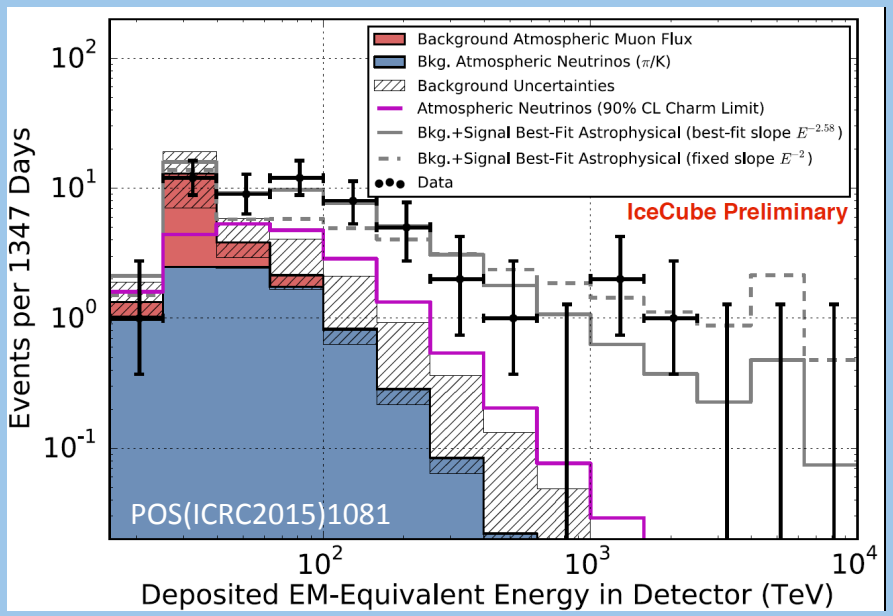
Starting Events

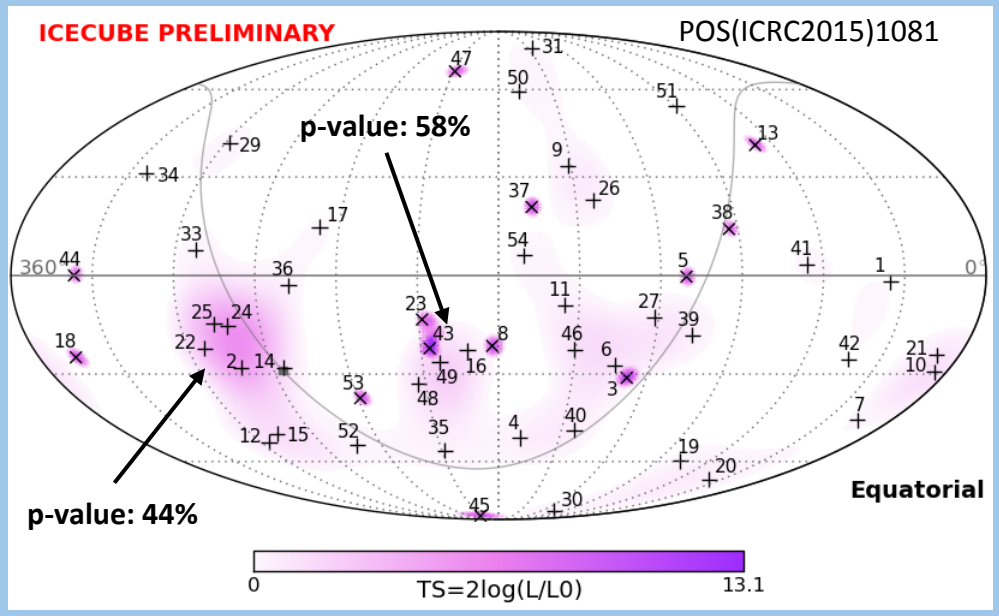


- Selection of events with interaction vertex in detector and no visible entering particles
- Effective volume smaller than detector
- Sensitive to all flavors and full sky

All-Flavor Neutrinos

Starting events using 4 years (all-sky)





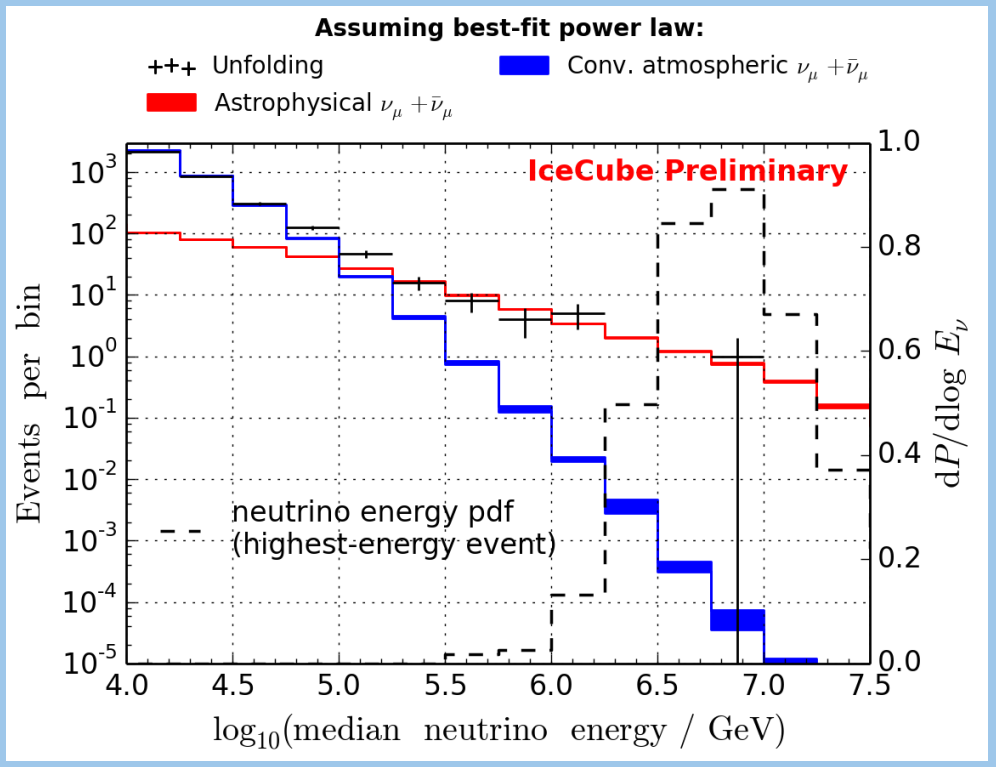
- Analysis of starting events depositing > 60TeV using 4 years of data
- Observation of 53(+1) events up to ~2PeV
- Mostly ν_e charged current and neutral current interactions, mostly sensitive in the southern sky
- Clear excess over background (6.5σ), no clear clustering on the sky
- Near future: real time selection of these starting events (~ hours)

Diffuse Muon Neutrino Search

- Analysis of up-going track events (northern sky) using 6 years of data, ν_μ charged current only, >100 GeV
- Fit with an unbroken power law

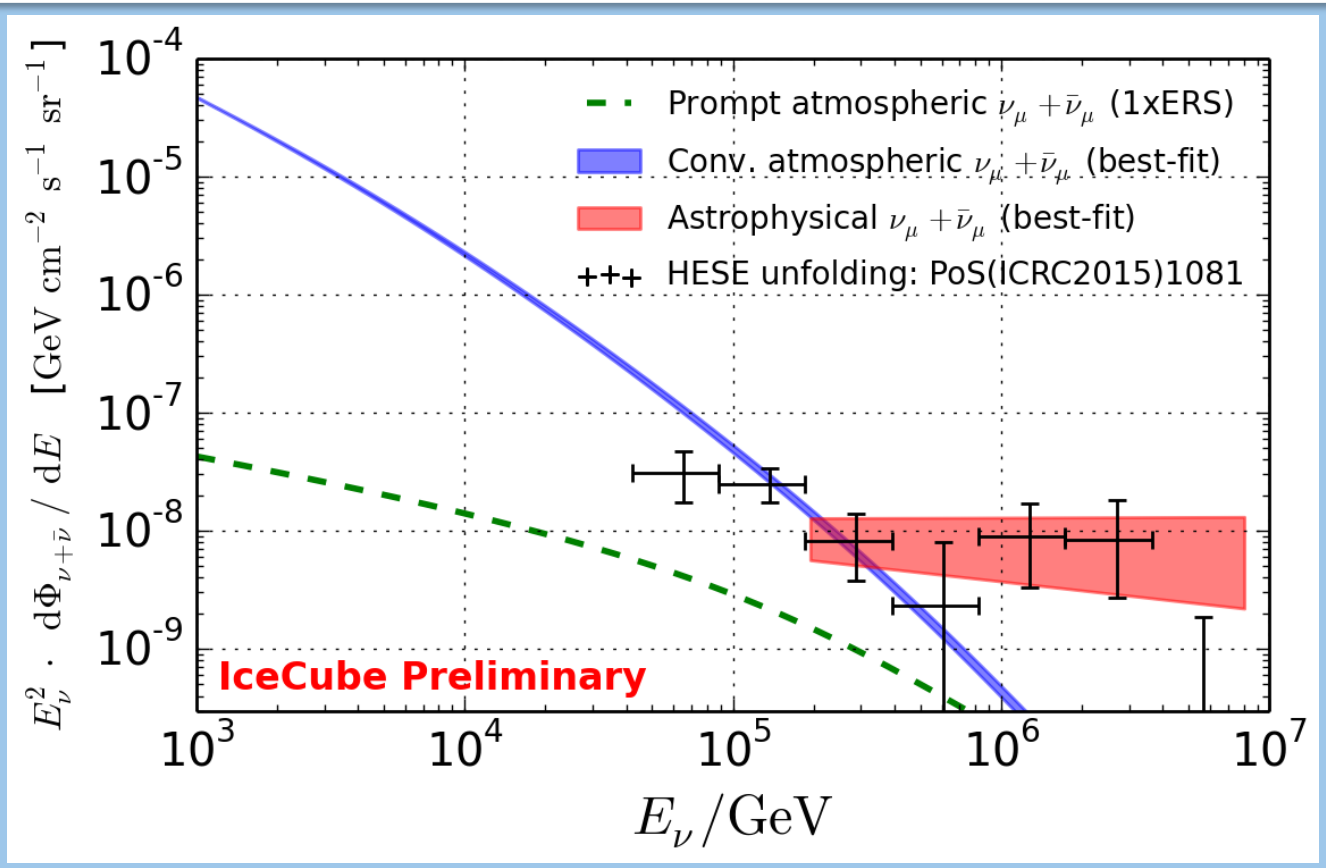
Results:

- Astrophys. norm @100 TeV:
  0.82 +0.3/-0.26 * 10^{-18} GeV cm^{-2} s^{-1} sr^{-1}
- Spectral index:
  γ_{astro} = 2.08 ±0.13
- Energy range:
  220 TeV – 8.3 PeV



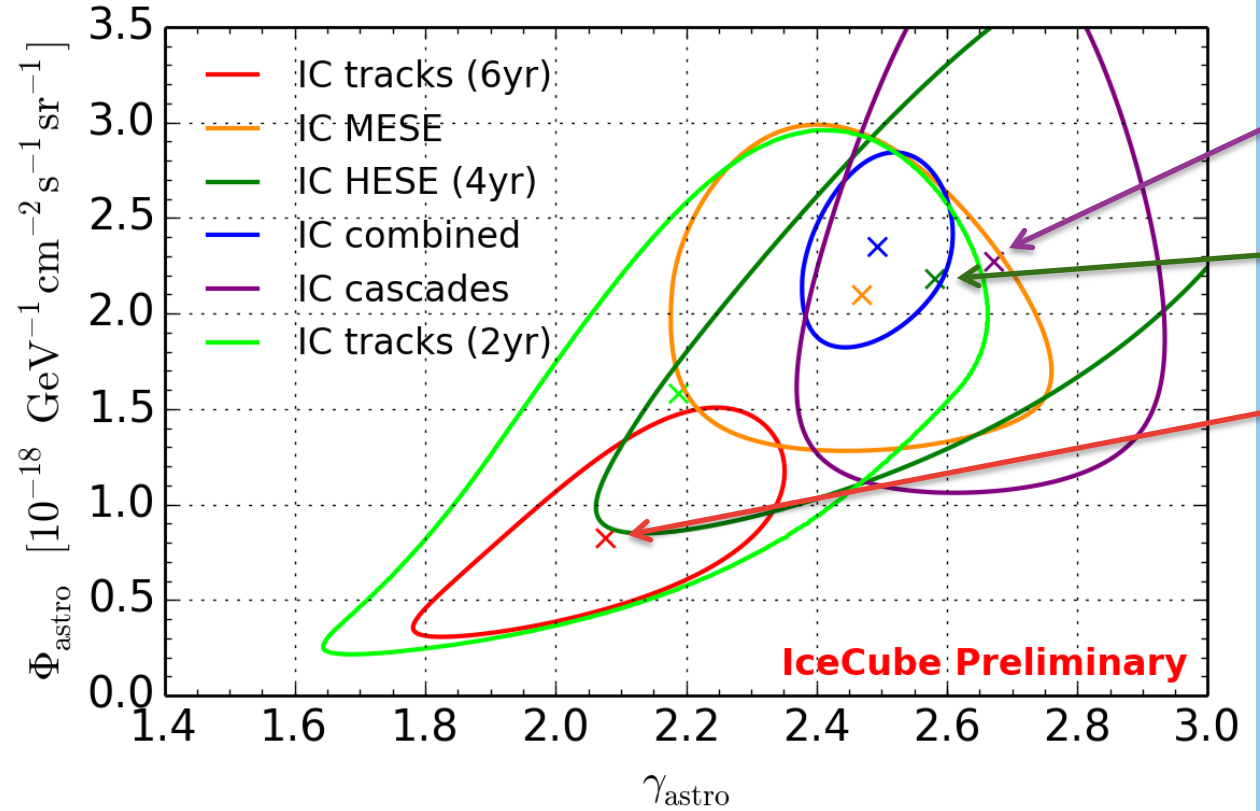
Atmospheric-only hypothesis excluded by 5.9σ

Measured Astrophysical Neutrino Flux



- Best fit astrophysical neutrino flux (unbroken power law) and conventional atmospheric neutrino flux predicted by Honda
- HESE unfolding including 4yr data in black crosses

Summary of diffuse IceCube results



Most sensitive region at about > $5*10^4$ GeV

Most sensitive region at about > 10^5 GeV

Most sensitive region at about > $2*10^5$ GeV

Slight trend:

- With the energy of the sensitive region shifting to higher energies the fitted spectral index increases
- Might be a first hint for features in the astrophysical neutrino flux

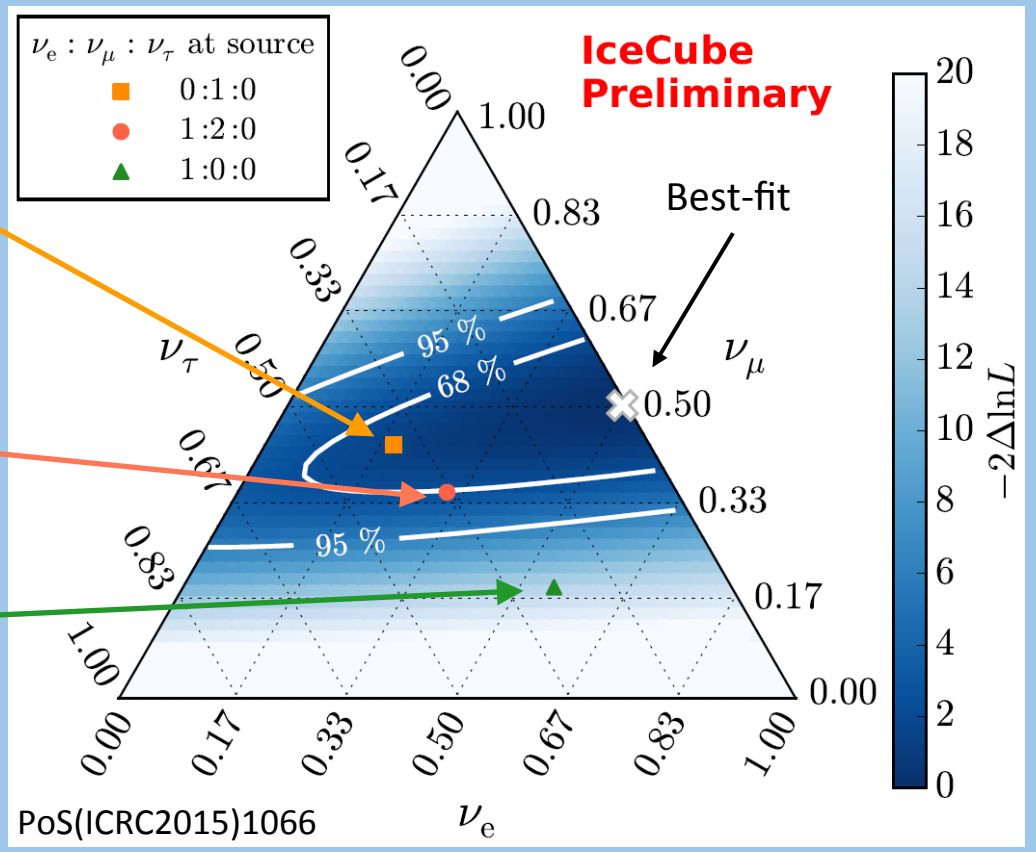
Flavor Composition at Earth

Flavor composition at Earth useful to constrain production mechanism at the source

Muon-damped pion decay: allowed

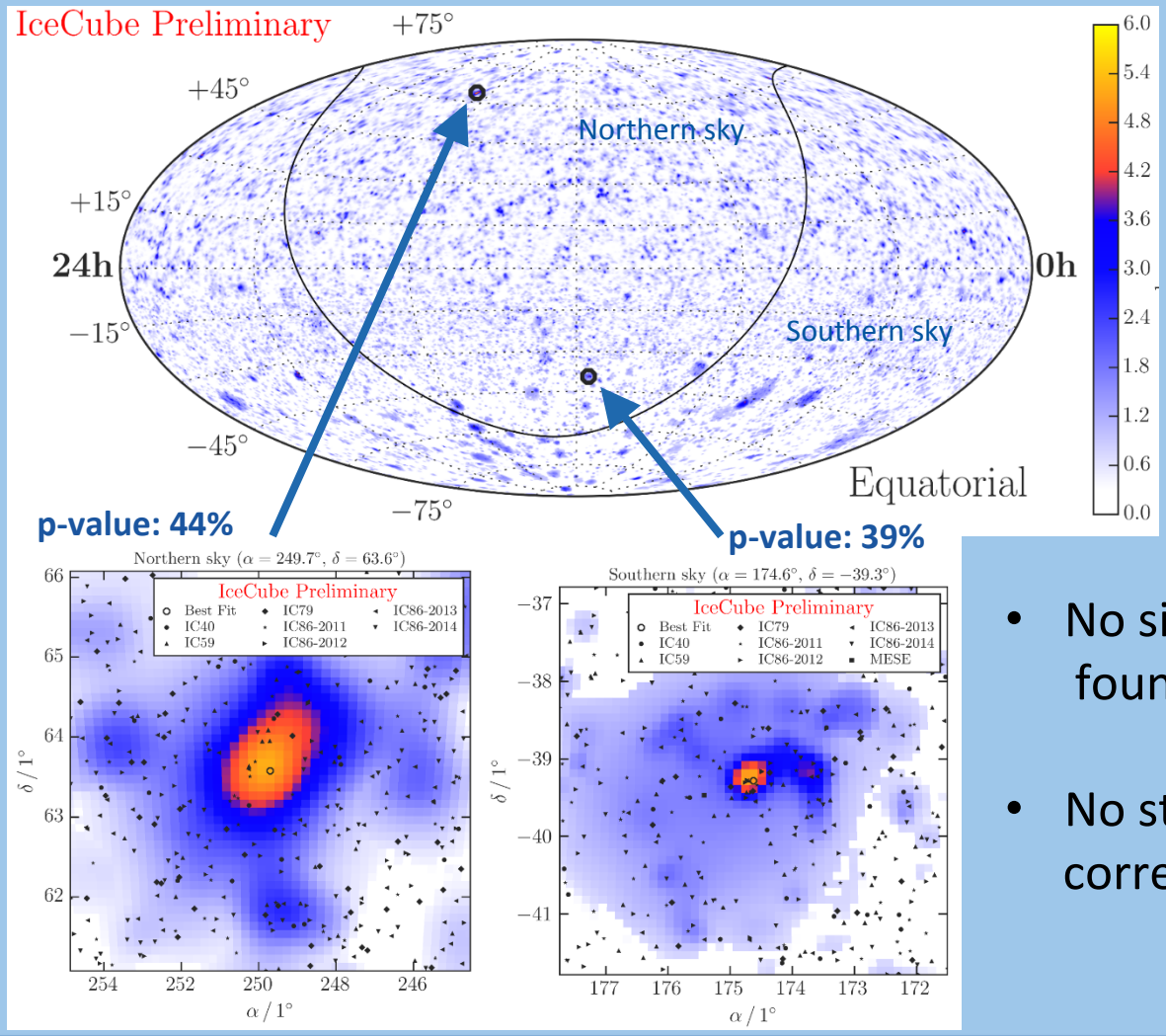
Pion decay: allowed

Neutron decay: rejected at 3.7 σ



- Contribution of ν_τ nearly unconstrained due to low sensitivity of the ν_τ measurements

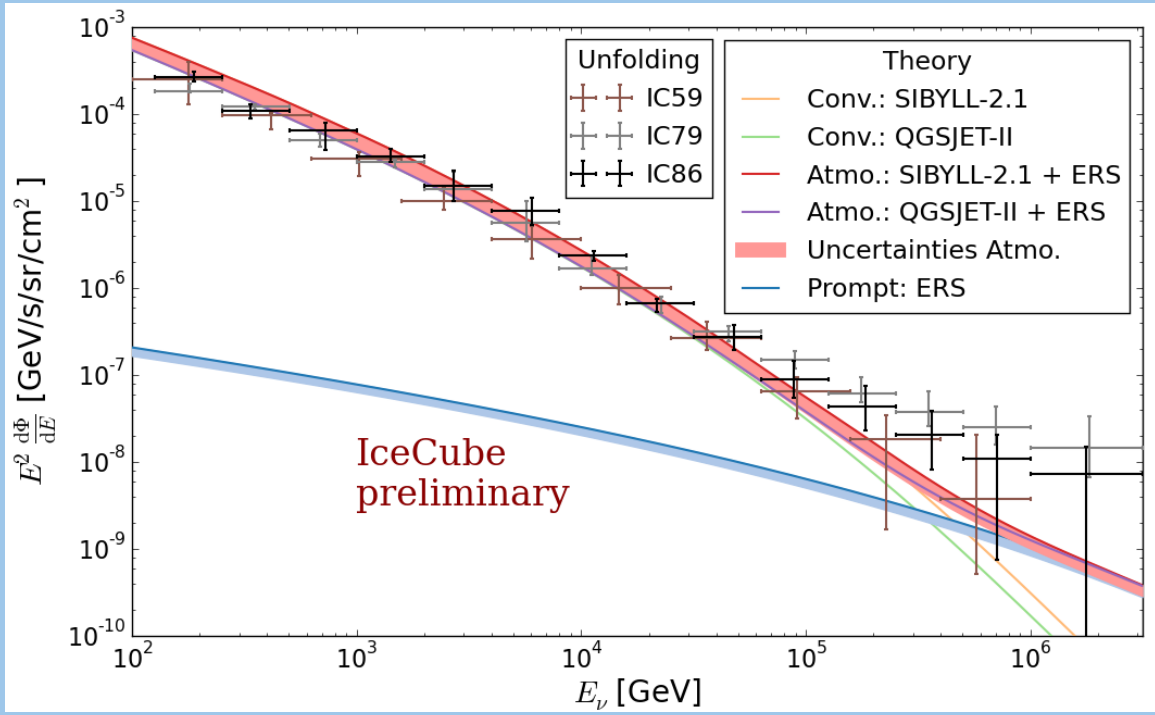
Searches for neutrino sources
Point source search using 7 years



- Analysis of track-like events using 7 years of IceCube data
- Northern sky: only ν_μ
- Southern sky: mostly μ but also ν_μ

- No significant point source found yet
- No strong evidence for correlations with the galactic plane

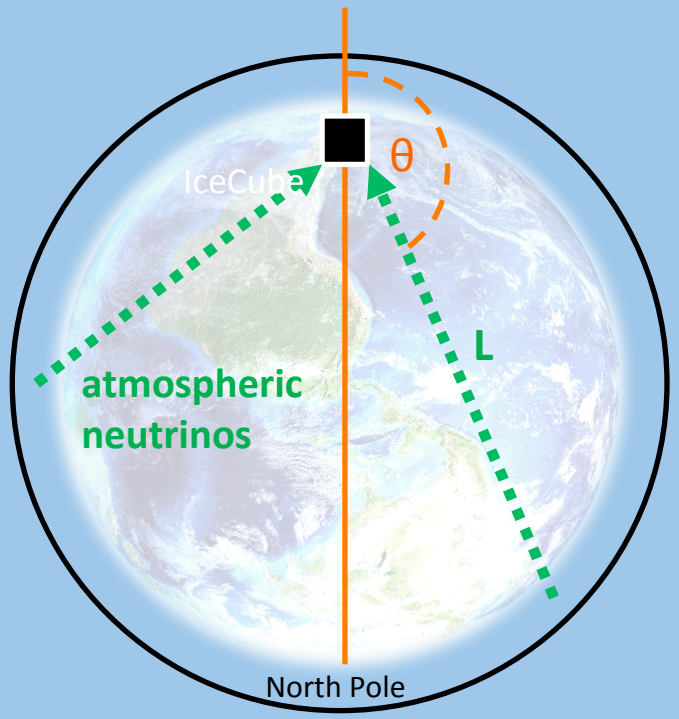
Energy spectrum of atmospheric muon neutrinos

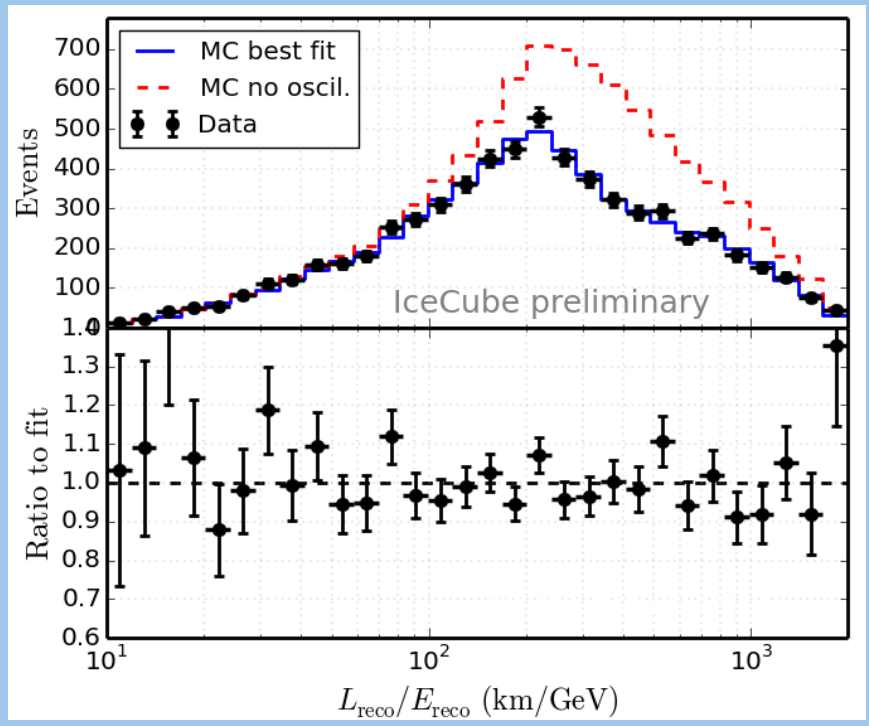


- Unfolding of muon neutrino energy spectrum >100GeV using up-going track events (northern sky) of 3 years of data
- Unfolded spectrum compatible with atmospheric muon neutrino predictions

- The over fluctuation at high energy is consistent with current measurements of the astrophysical muon neutrino flux

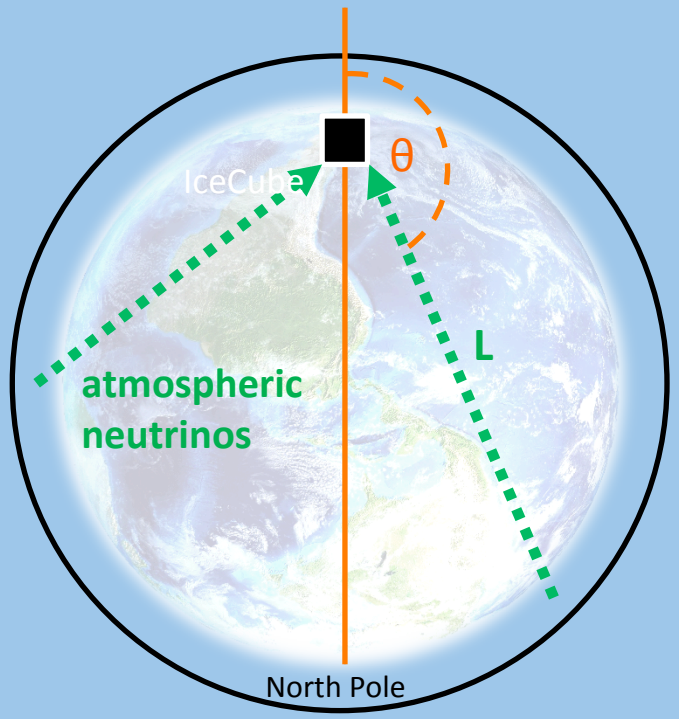
Neutrino Oscillation Measurement using DeepCore

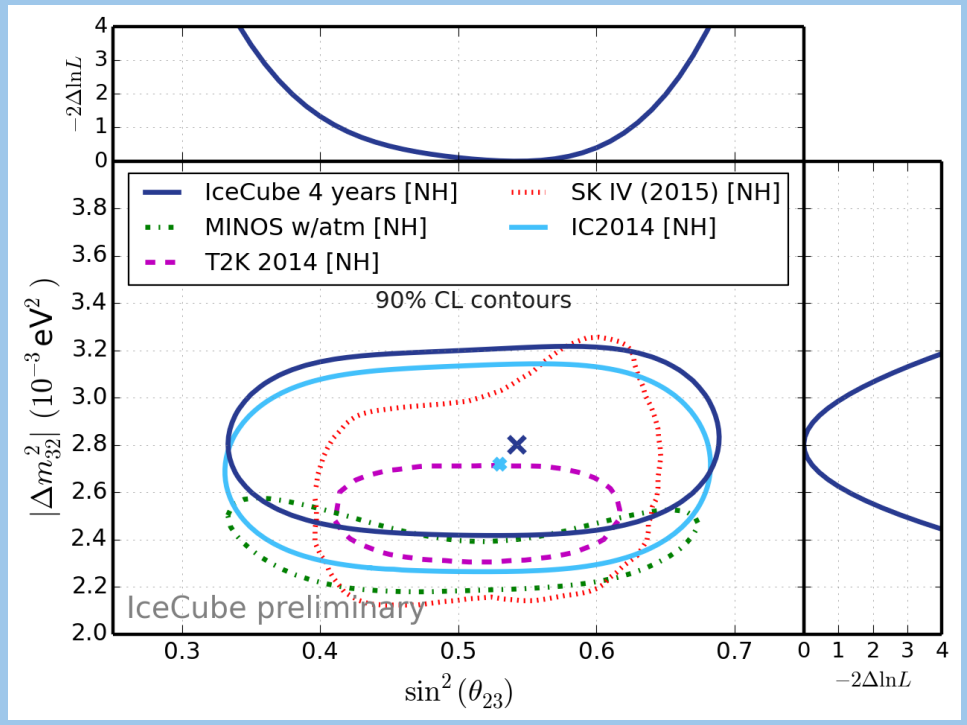




- Disappearance analysis of ~10 GeV-100 GeV atmospheric ν_μ with 4 years of data

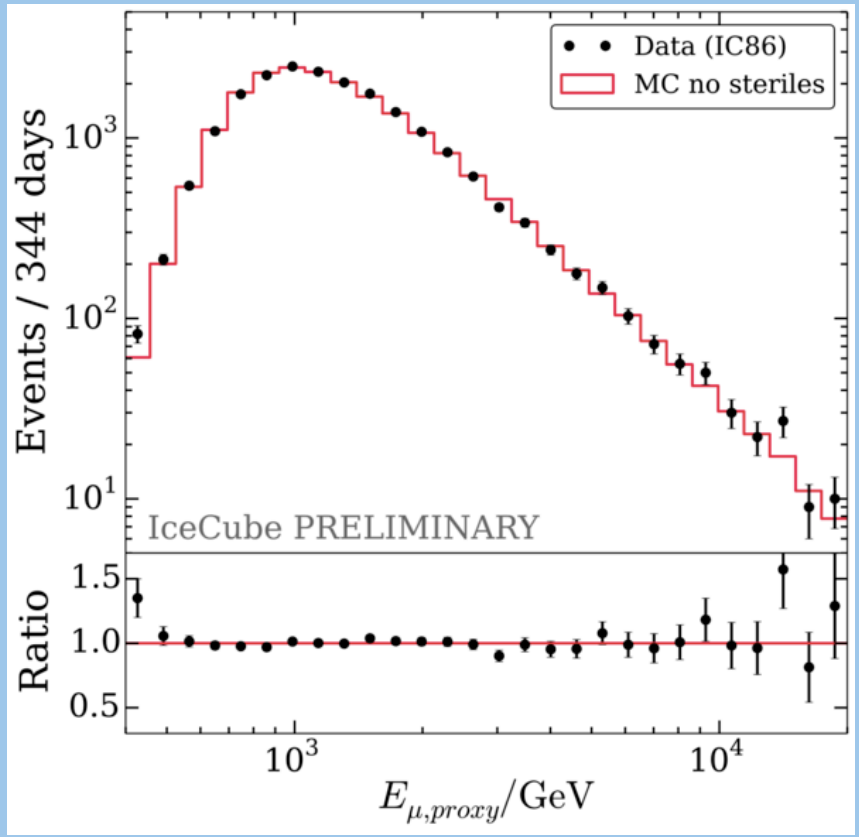
Neutrino Oscillation Measurement using DeepCore

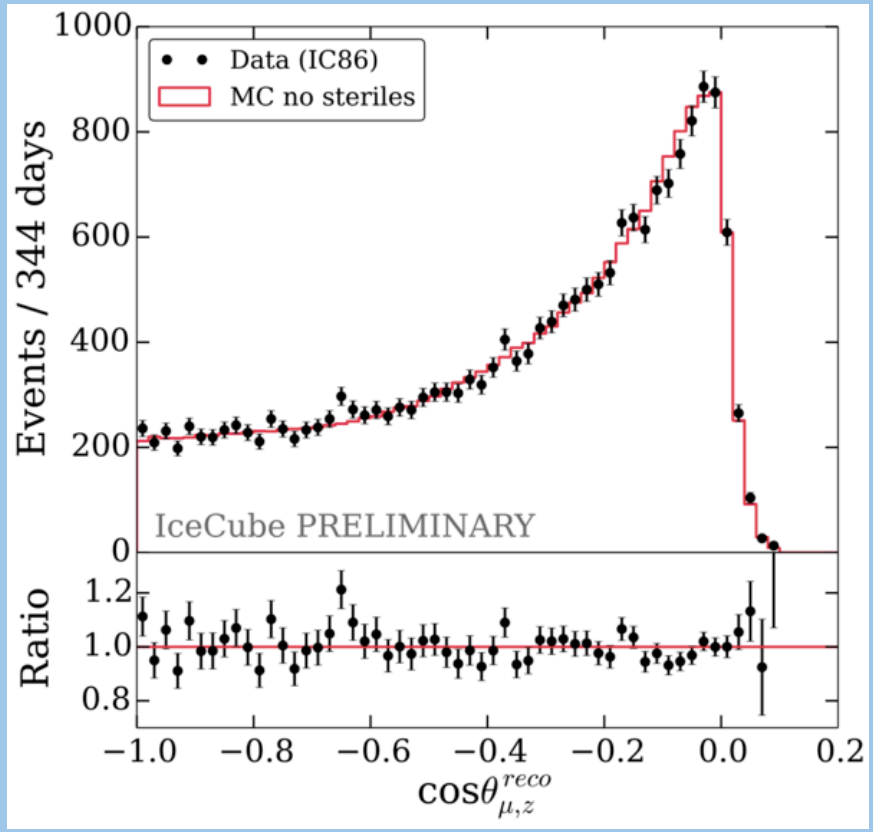




- Neutrino disappearance in the Energy range from about 10 GeV – 100 GeV observed
  Results from normal hierarchy: $\sin^2\theta_{23} = 0.53\ ^{+0.08}_{-0.13}$
  $\Delta m_{23}^2 = 2.8\ ^{+0.20}_{-0.16} \times 10^{-3}\ \mathrm{eV}^2$

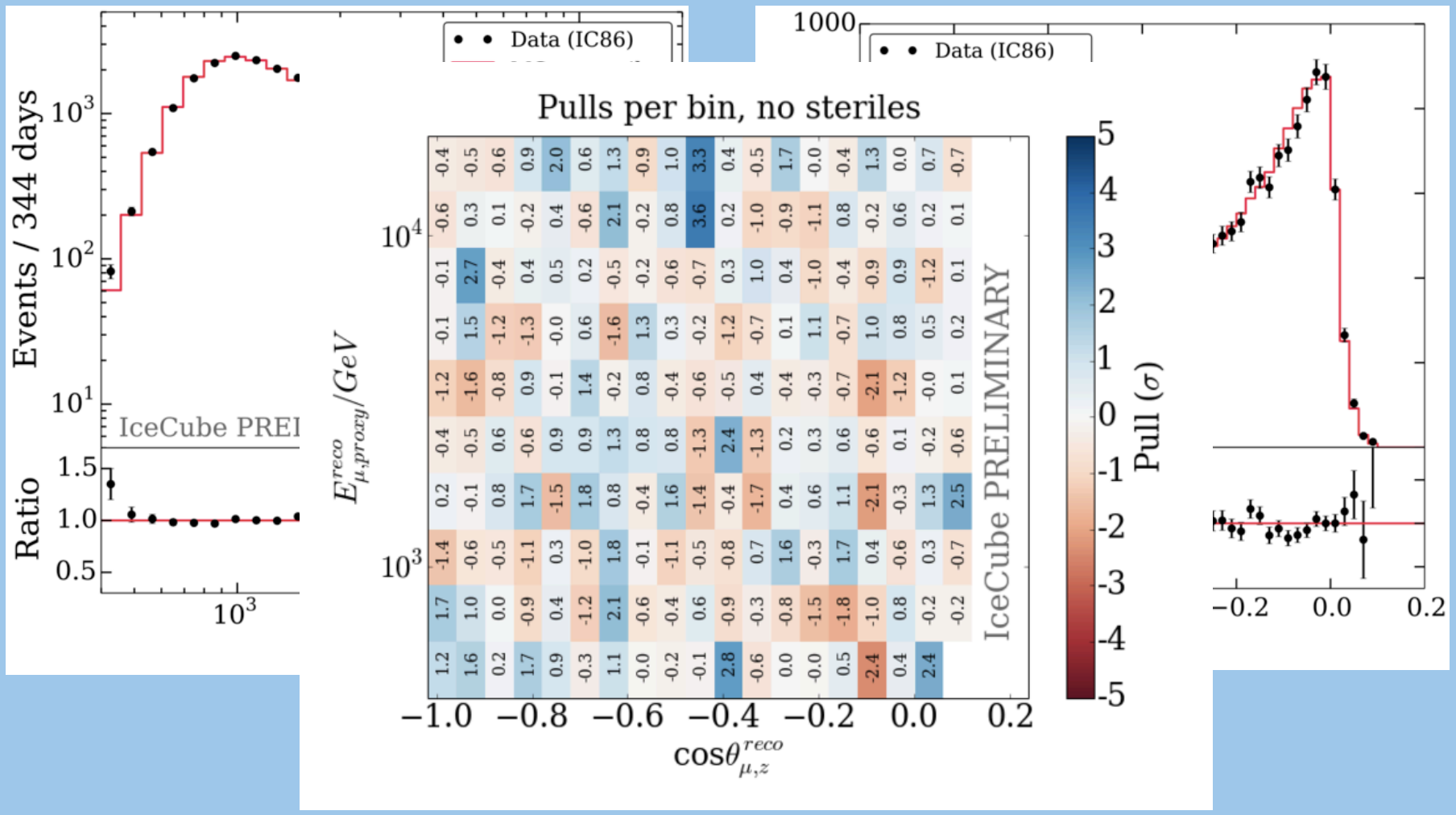
Search for sterile neutrinos





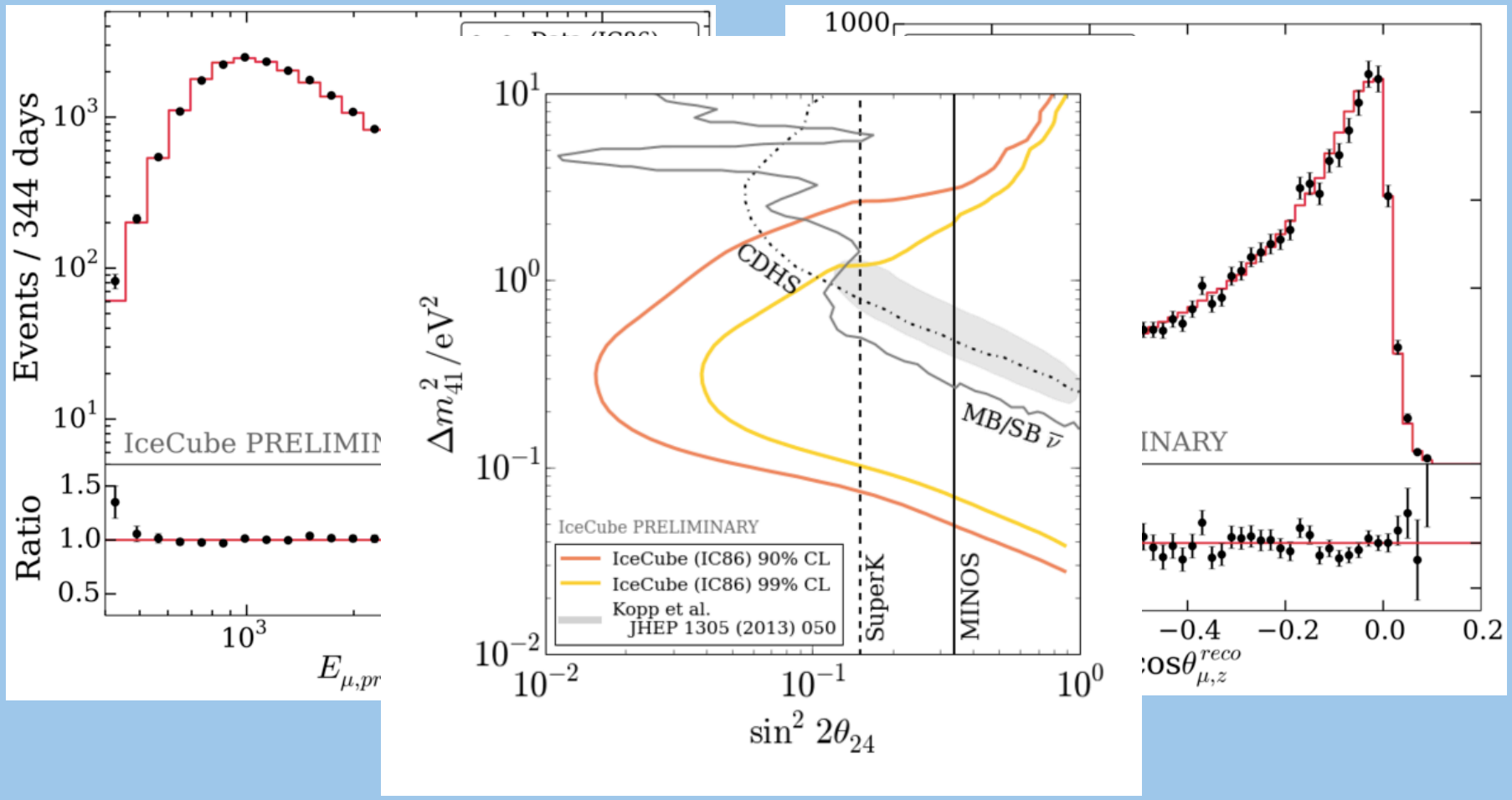
- Disappearance search at higher energy range on top of standard oscillation

Search for sterile neutrinos



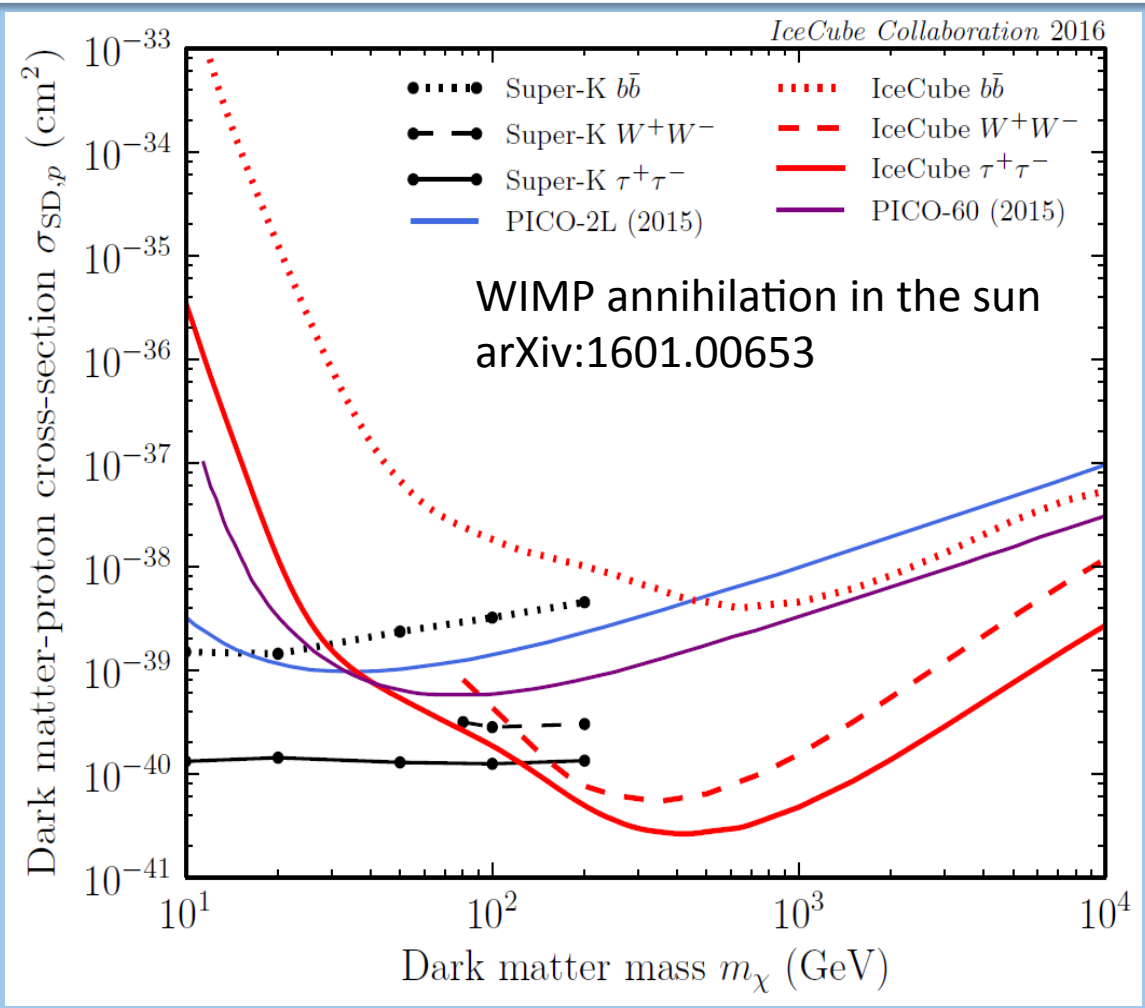
- pulls per bin in the analysis space at the best-fit point. The stat-only p-value is 17%

Search for sterile neutrinos



- No sterile neutrino signature found.
- Another 5 years of data will lead to even stronger results

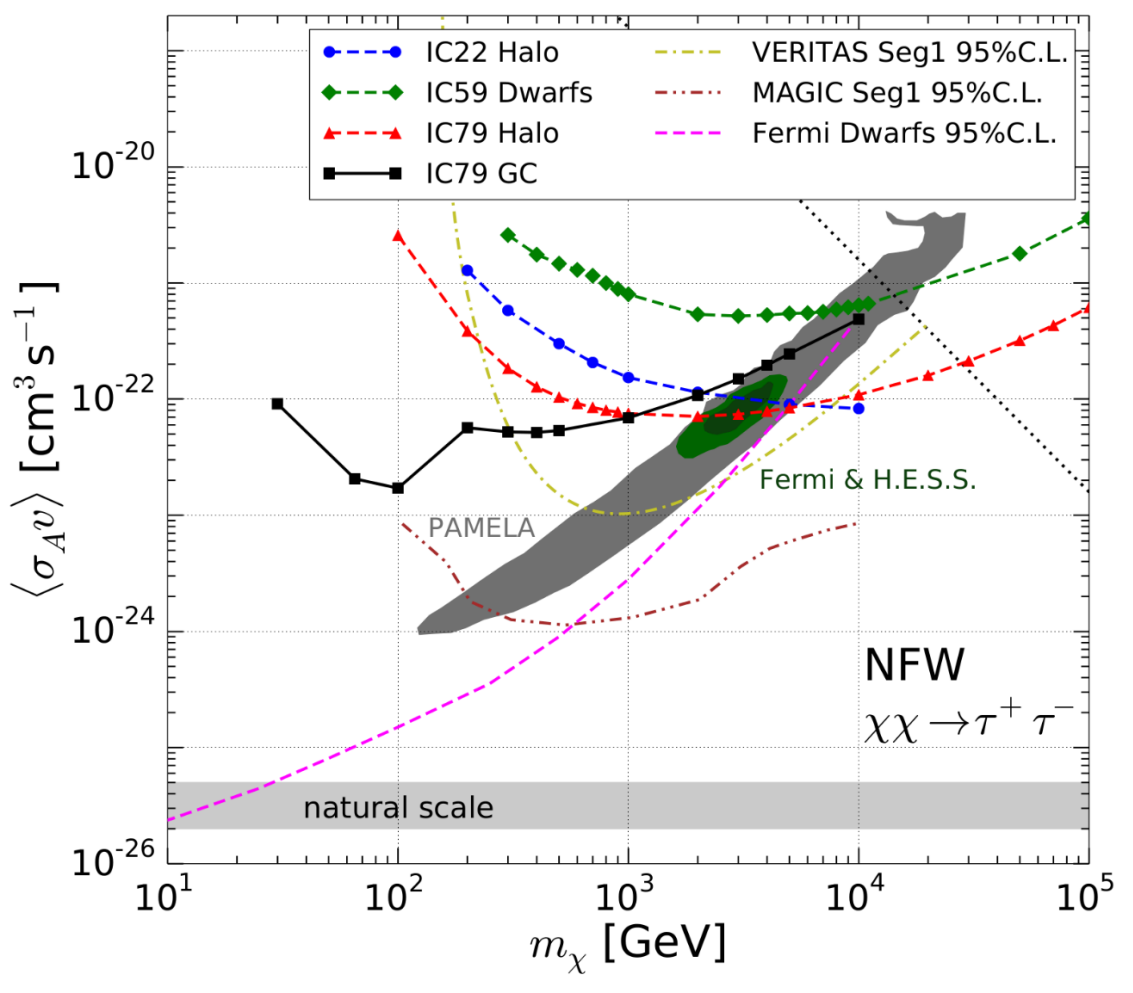
Dark Matter WIMPs



- Analysis of arrival directions of ν_μ to look for correlation with the expected signature of WIMP annihilations in the sun
- Worlds best constraint on spin-dependent cross section above 100 GeV WIMP mass

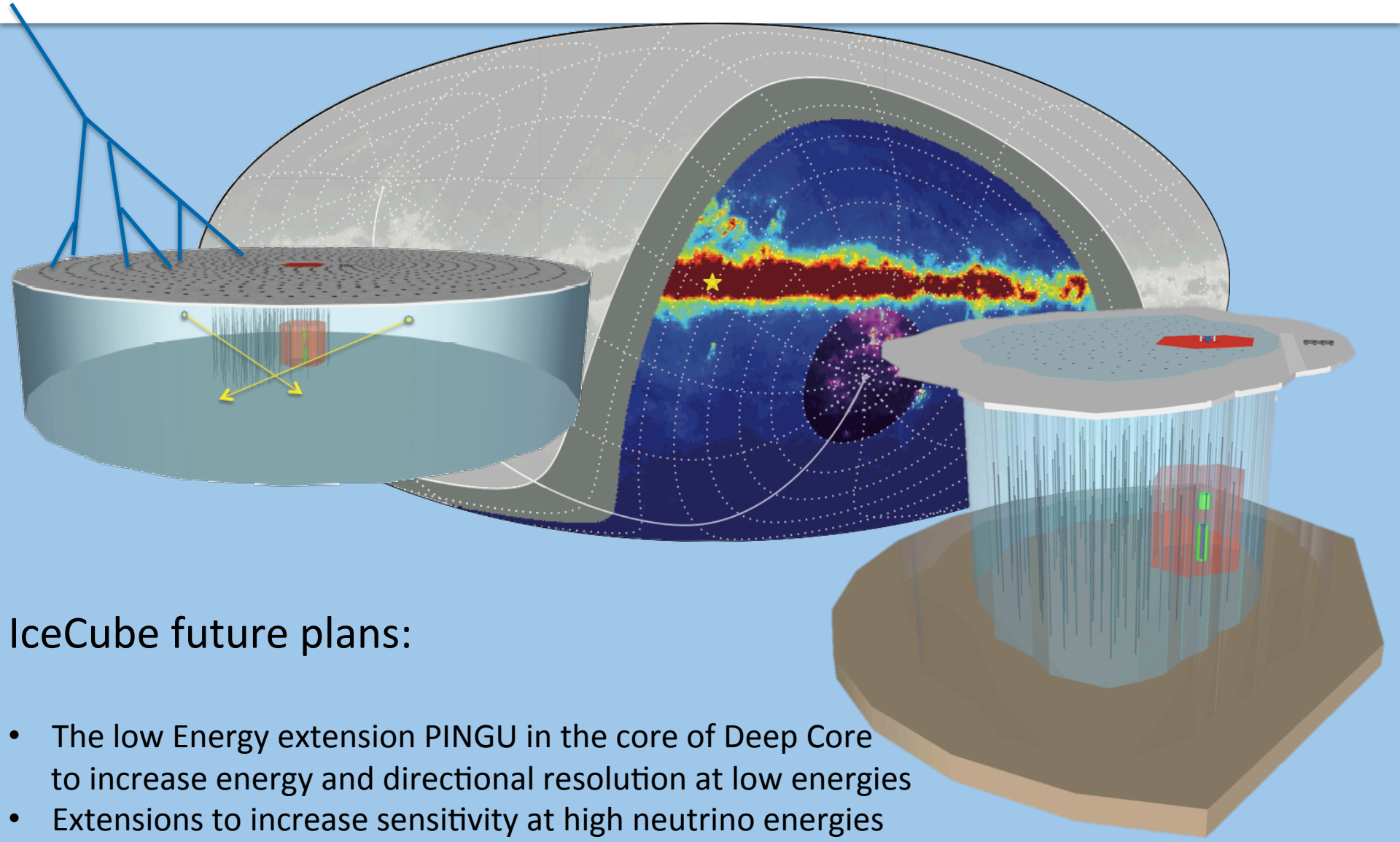
Other neutrinos IceCube my detect from the sun: Solar neutrino flares, **Gwenhaël de Wasseige in the YSF II today evening**

Dark Matter WIMPs



- Analysis of arrival directions of ν_μ to look for correlation with the expected signature of WIMP annihilations in the Galactic halo, Galactic center or Dwarf galaxies
- IceCube is competitive at high WIMP masses

A slide on IceCube extensions



IceCube future plans:

- The low Energy extension PINGU in the core of Deep Core to increase energy and directional resolution at low energies
- Extensions to increase sensitivity at high neutrino energies

Summary

- IceCube observed an astrophysical ν flux with more than 5σ in two different detection channels
- There are hints for features in the astrophysical flux
- Sources of this flux remain unknown
- Observed flavor ratio on Earth constrains neutrino production mechanisms at sources
- IceCube observed neutrino oscillations and produces competitive results
- First sterile neutrino analyses of IceCube sets stringent limits
- IceCube provides complementary constrains for the search of Dark Matter WIMPs

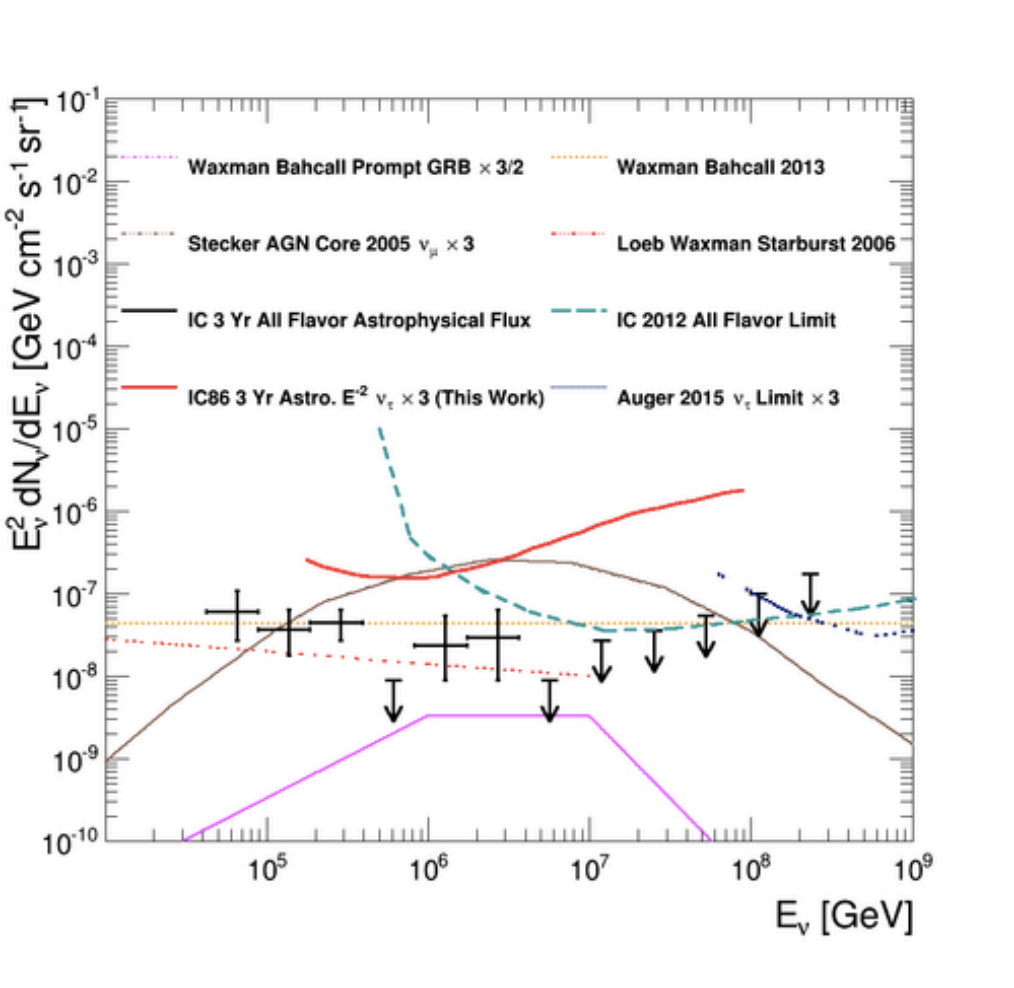
The IceCube Collaboration

Funding Agencies

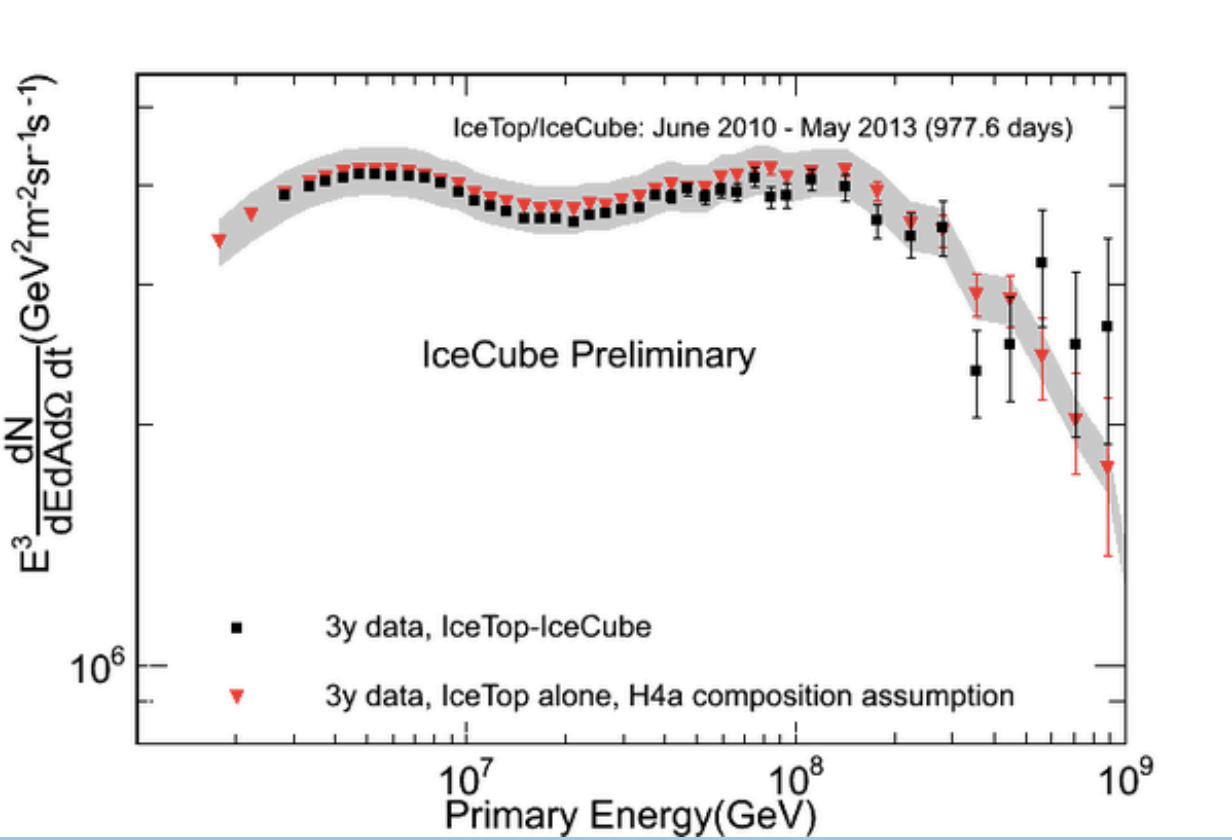
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Thank you for your attention!

Tau search in IceCube

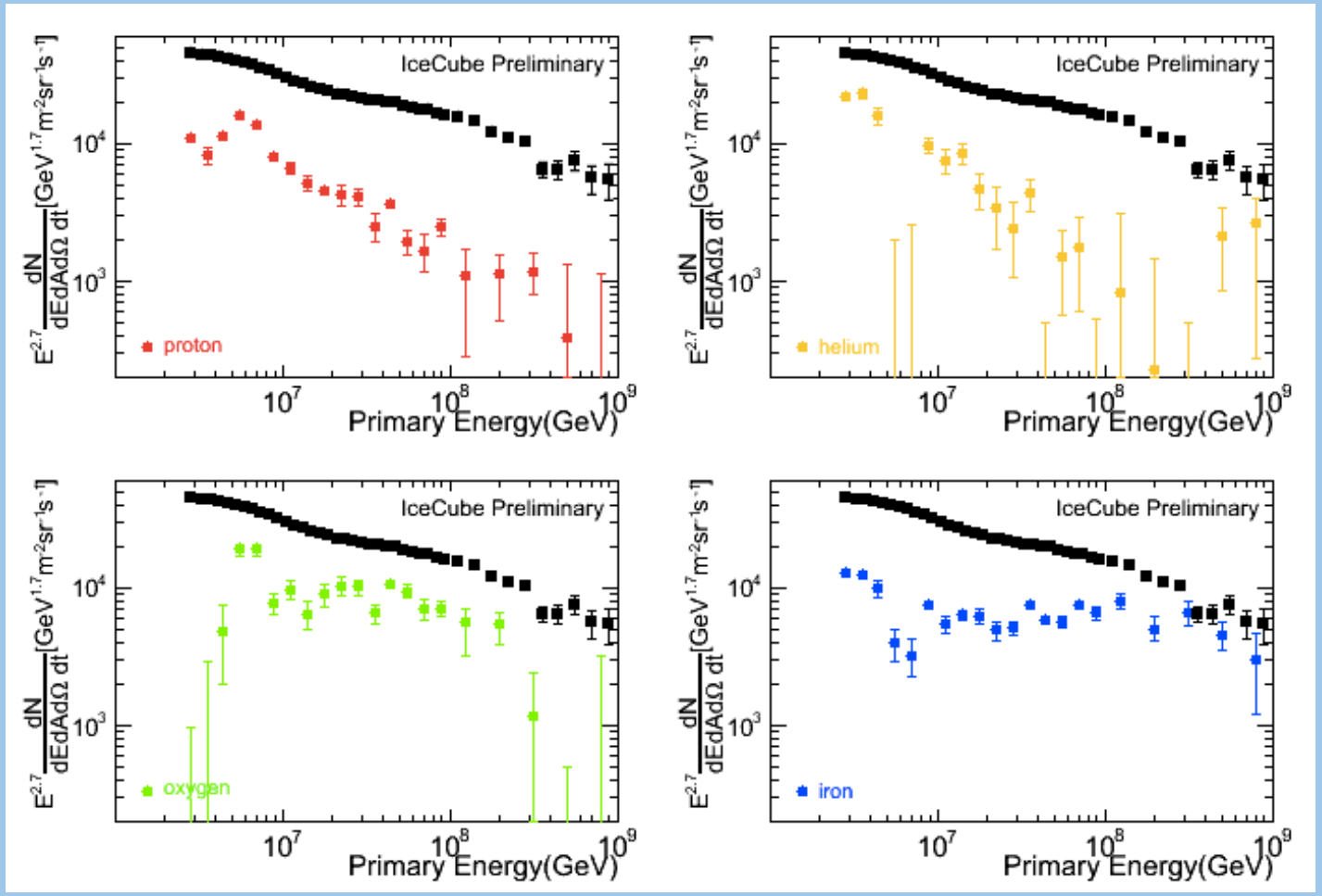


CR Spectrum with IceCube and IceTop



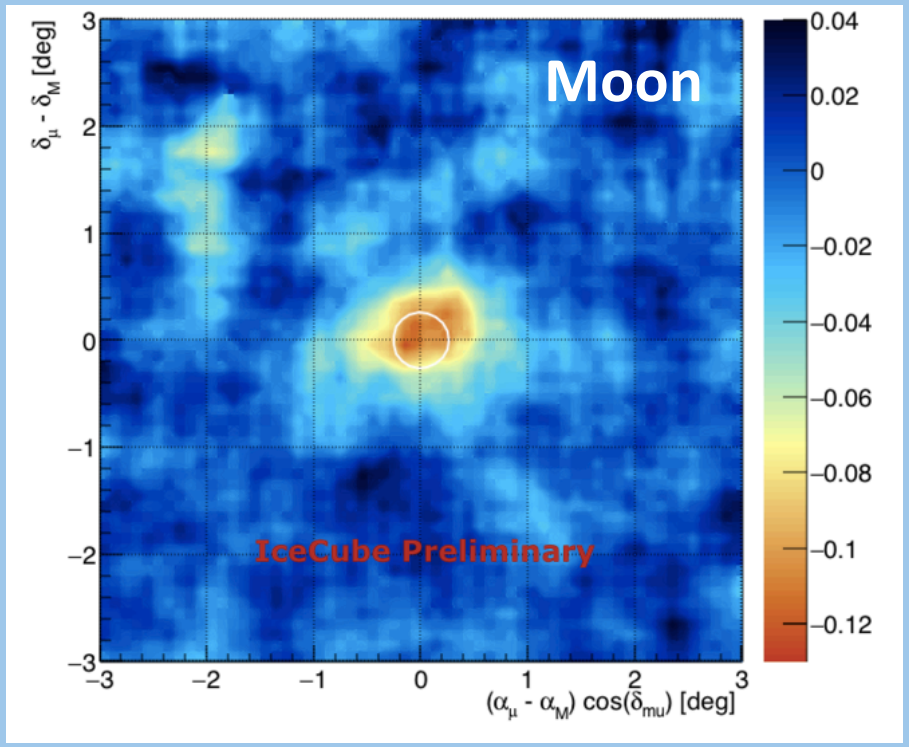
- Cosmic ray spectrum with IceTop and IceCube data show consistent results
- The spectrum shows clear features
- May be a hint for different source classes and/or composition

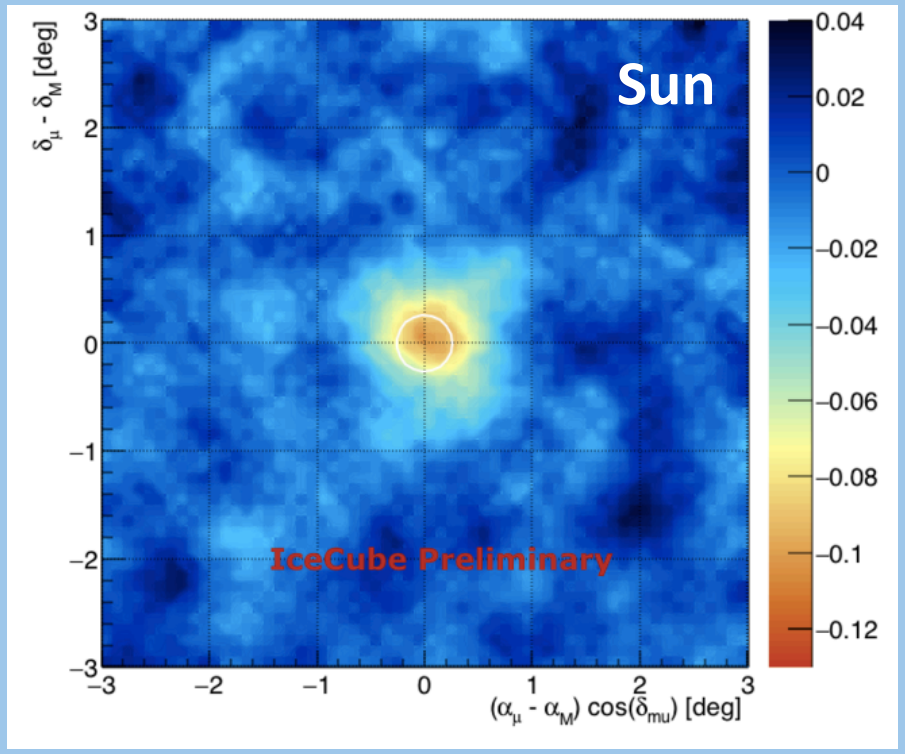
CR Spectrum with IceCube and IceTop



- Evidence for a heavier composition at higher energies

Calibration with Cosmic Rays





- Cosmic ray absorption by the moon and sun
- Width of deficit used to verify the uncertainty on the angular resolution (better than 1°)
- Amplitude of sun shadow is expected to correlate to sun activity