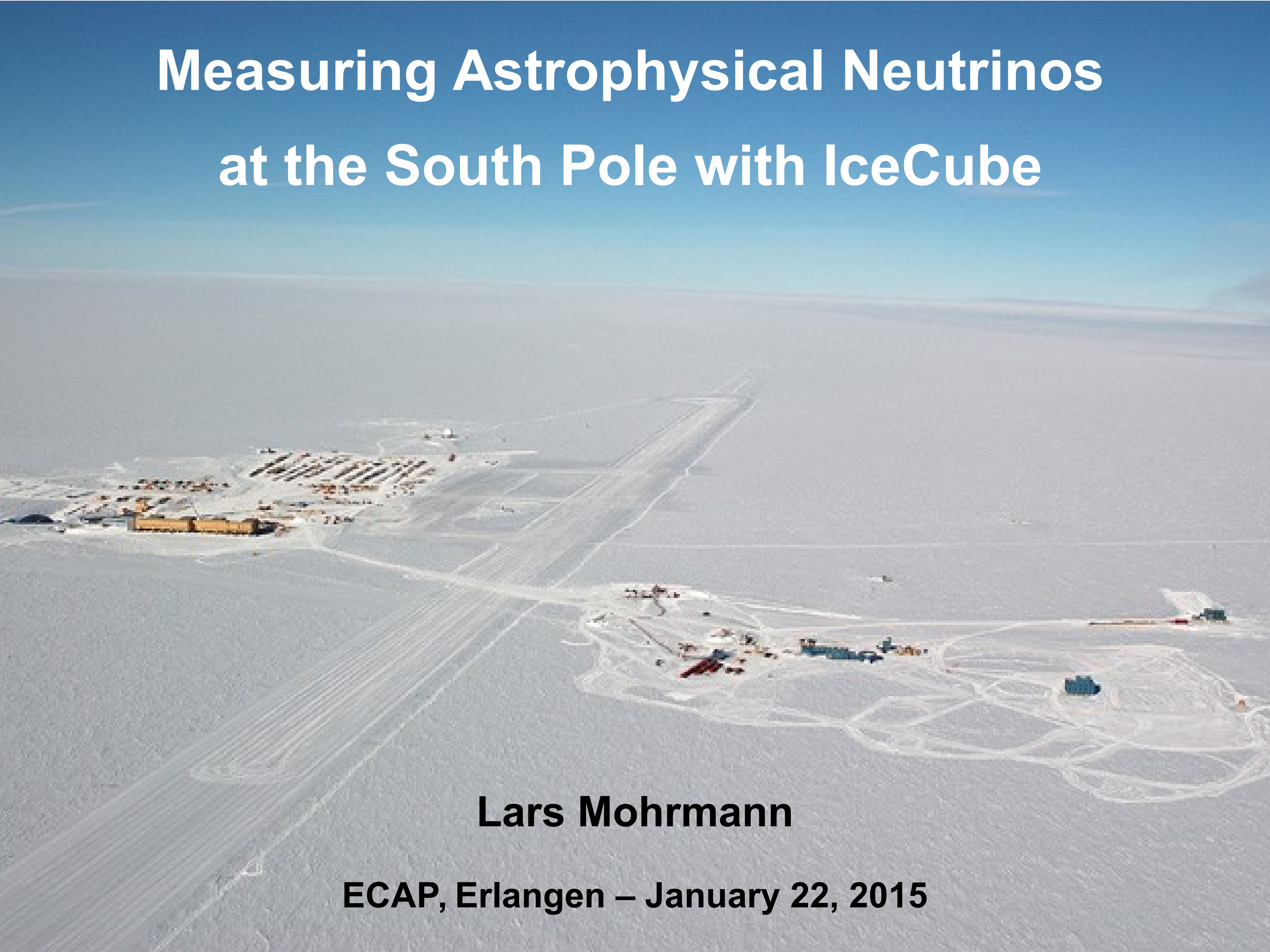
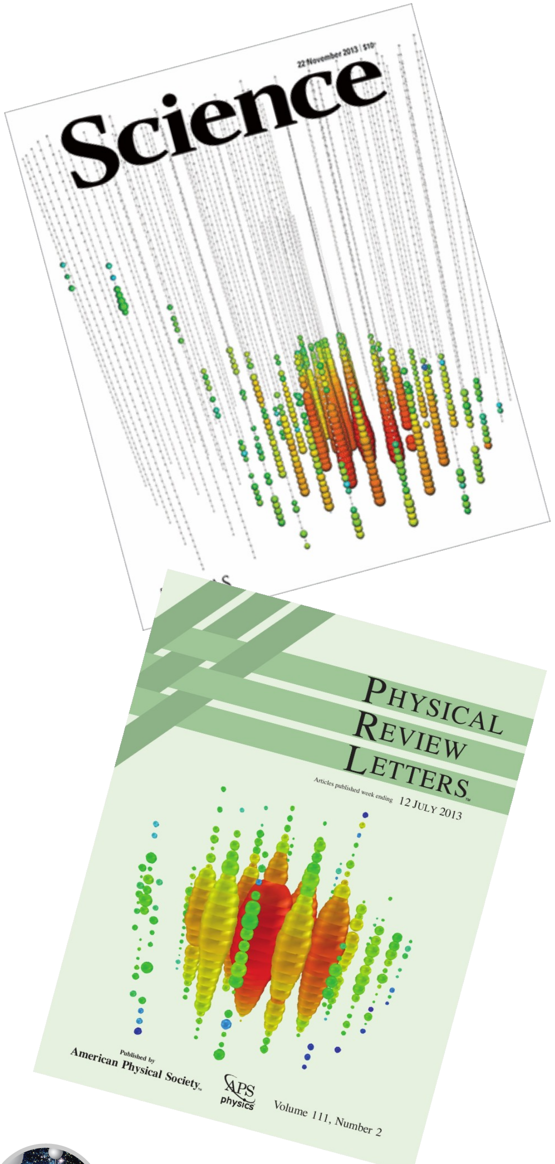
Measuring Astrophysical Neutrinos at the South Pole with IceCube



Lars Mohrmann

ECAP, Erlangen – January 22, 2015

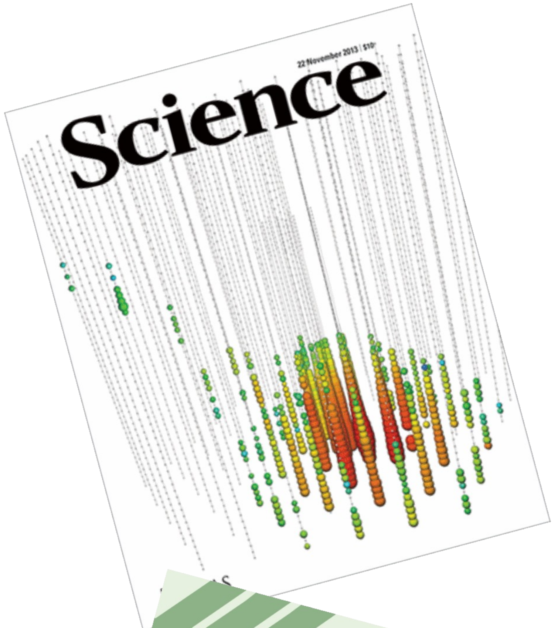
Astrophysical Neutrinos at IceCube

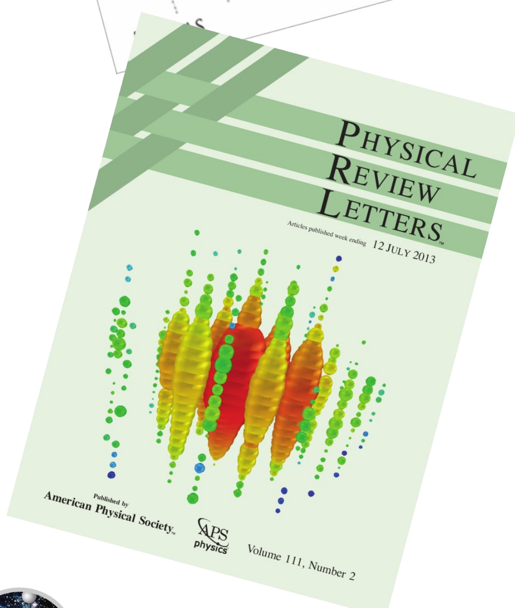


physicsworld
BREAKTHROUGH OF THE YEAR
2013

- **What did we expect to measure?**
- **How do we measure them?**
- **What do we actually measure?**

Astrophysical Neutrinos at IceCube





- ***What did we expect to measure?***
- **How do we measure them?**
- **What do we actually measure?**

The Cosmic Ray Connection

- **Cosmic rays produce neutrinos!**

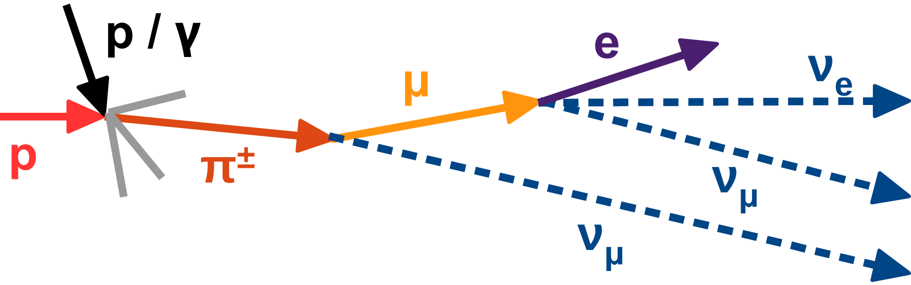
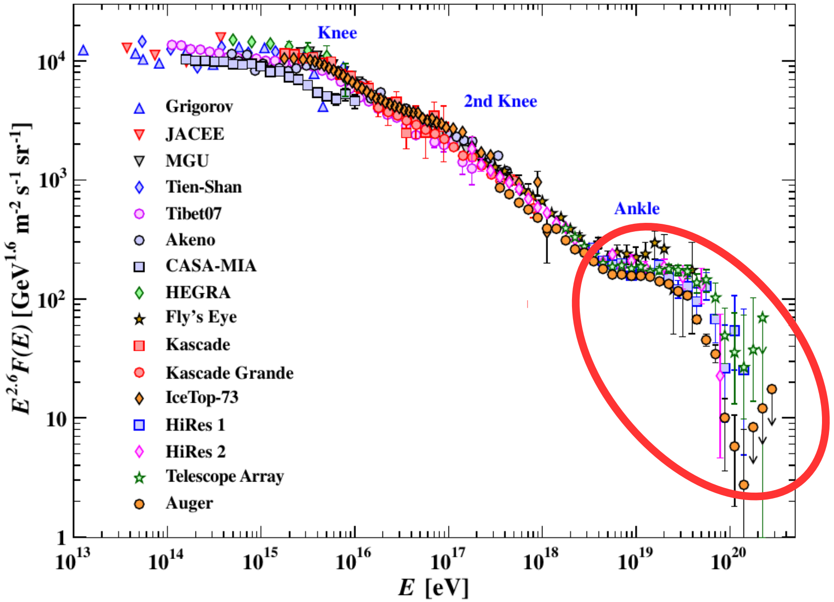


Image credit: NASA/Dana Berry/Skyworks Digital

The Waxman-Bahcall Upper Bound



- **Local (z<1) cosmic ray production rate:**

$$\left(E_{CR}^2 \frac{d\dot{N}_{CR}}{dE_{CR}} \right)_{z=0} = 10^{44} \ \mathrm{erg\,Mpc}^{-3}\,\mathrm{yr}^{-1}$$

- **Assumptions:**
  - Primary proton spectrum ~E^{-2}
  - All protons produce pions
  - Sources are "thin" → protons can escape
  - Evolution → contribution of far-away sources

- $E_\nu^2 \Phi_\nu \lesssim 10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$

Expected Neutrino Energy Spectrum

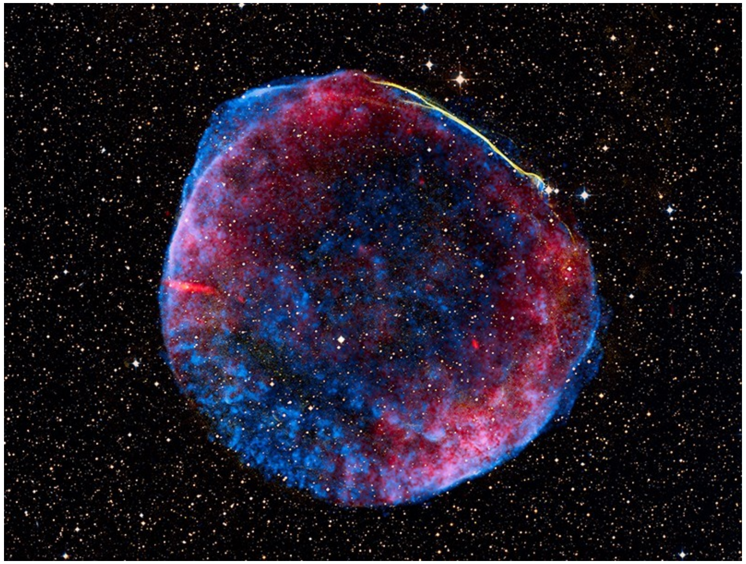
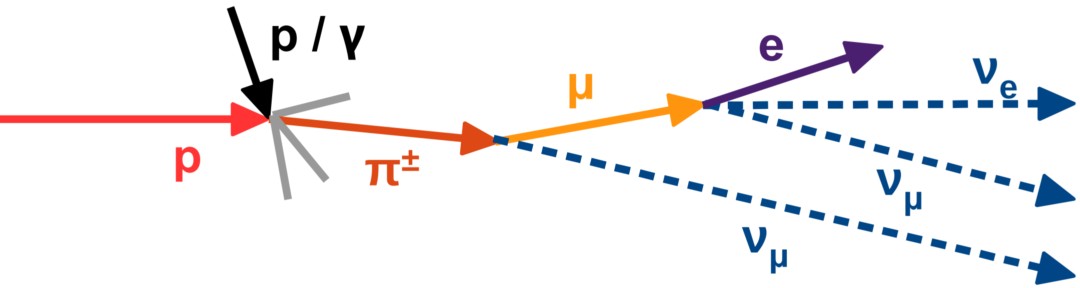


Image credit: NASA, ESA and Zolt Levay (STScI)

- **Fermi shock acceleration**
  - Power law spectrum ~ $E^{-\gamma}$
  - Generic prediction: $\gamma = 2$
  - Value depends on specific source class

Expected Neutrino Flavor Composition

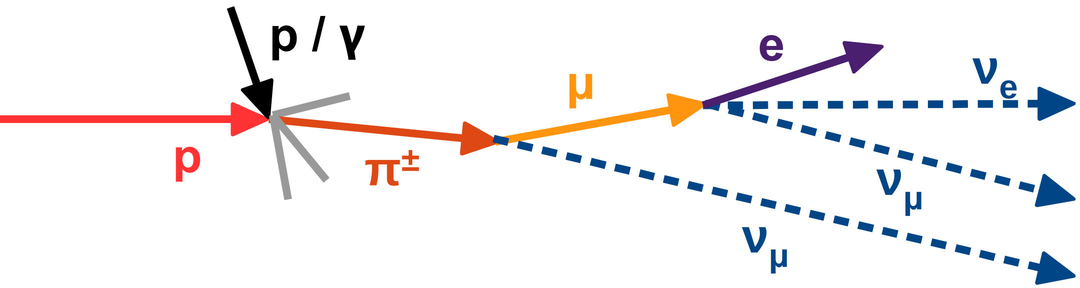
- "Standard" sources



- **At the source**
  - $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$
- **After oscillations**
  - $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$

Expected Neutrino Flavor Composition

- “Standard” sources



- At the source
  - $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$
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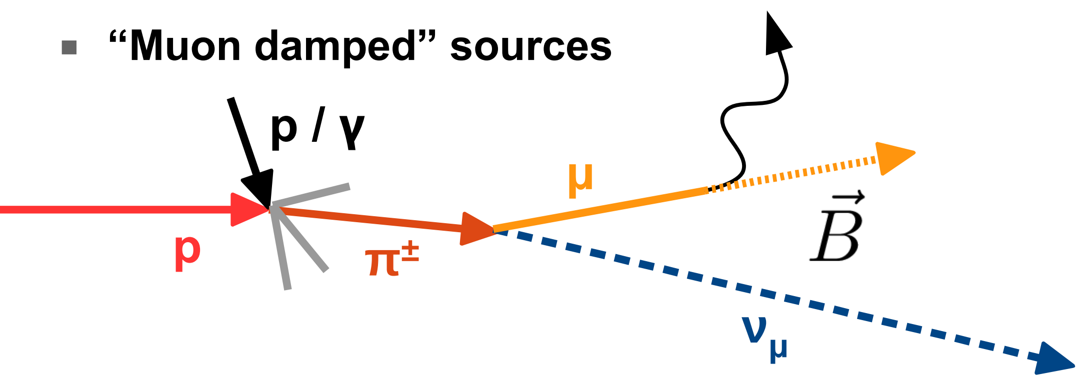
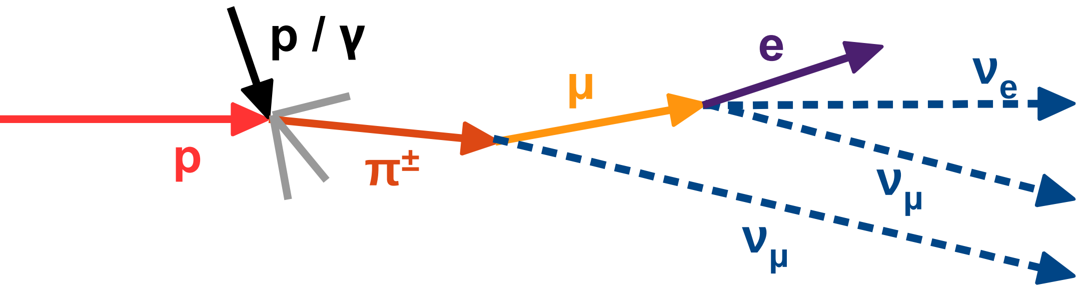
- “Muon damped” sources



- At the source
  - $\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$
- After oscillations
  - $\nu_e : \nu_\mu : \nu_\tau \sim 0.22 : 0.39 : 0.39$

Expected Neutrino Flavor Composition

- “Standard” sources



- At the source
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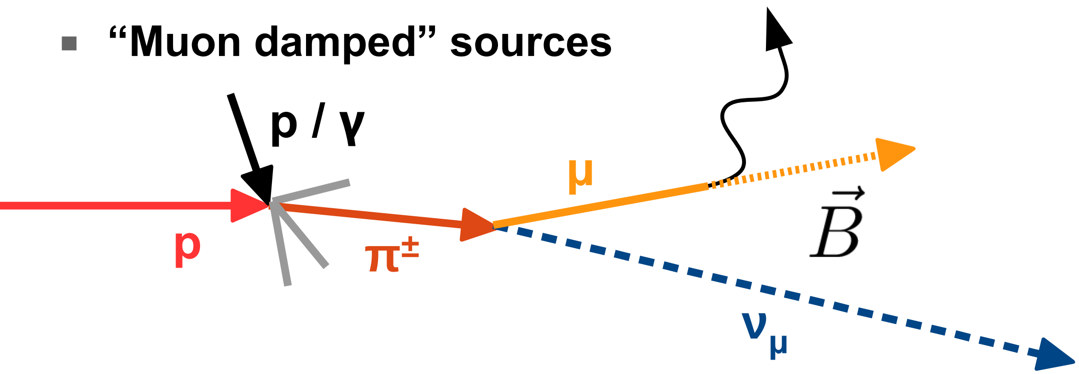
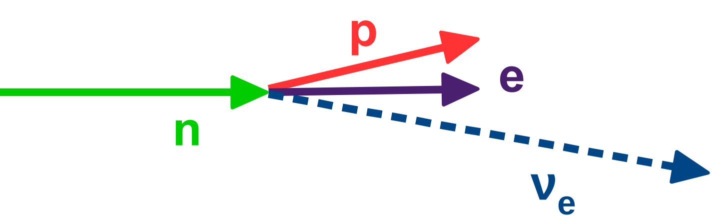


- At the source
  - $\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0$
- After oscillations
  - $\nu_e : \nu_\mu : \nu_\tau \sim 0.22 : 0.39 : 0.39$

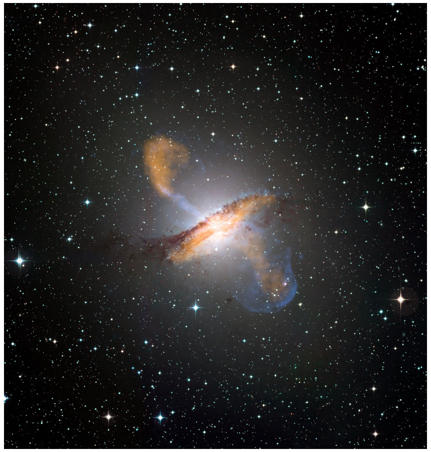
- “Neutron beam” sources



- At the source
  - $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$
- After oscillations
  - $\nu_e : \nu_\mu : \nu_\tau \sim 0.56 : 0.22 : 0.22$

Popular Source Candidates

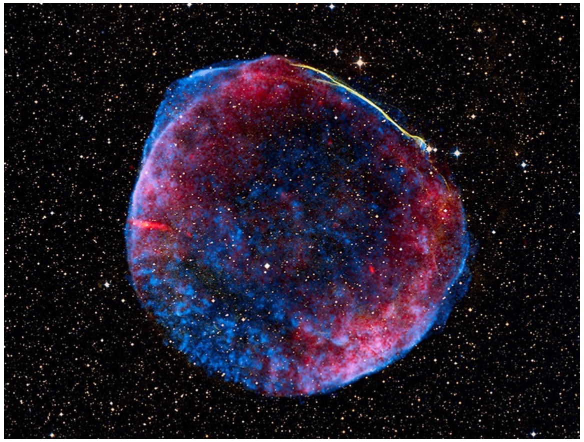
- **Active Galactic Nuclei**



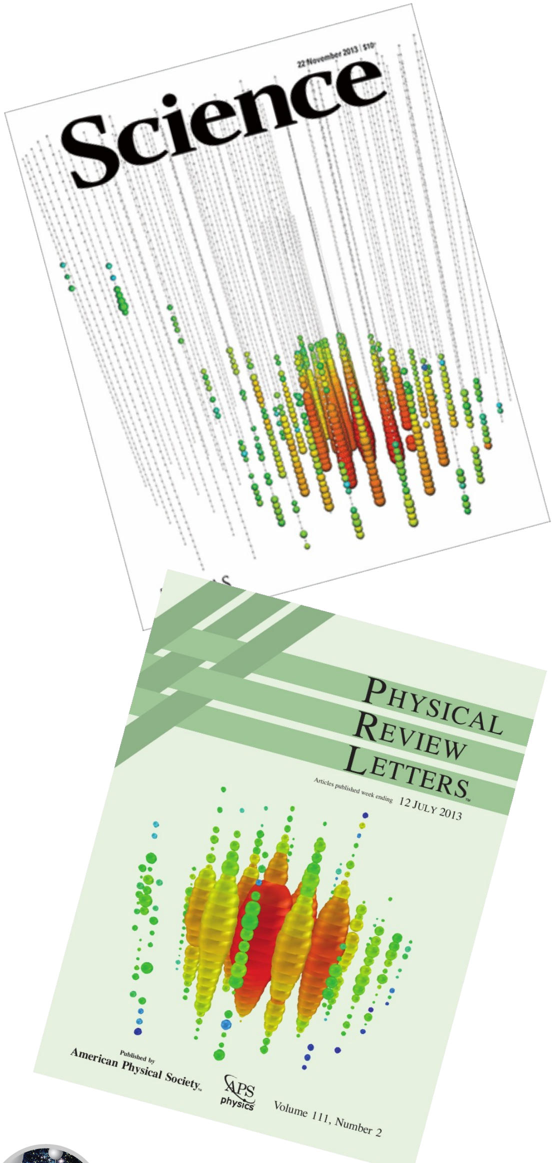
- **Starburst Galaxies**

- **Gamma Ray Bursts**

- **Supernova Remnants**



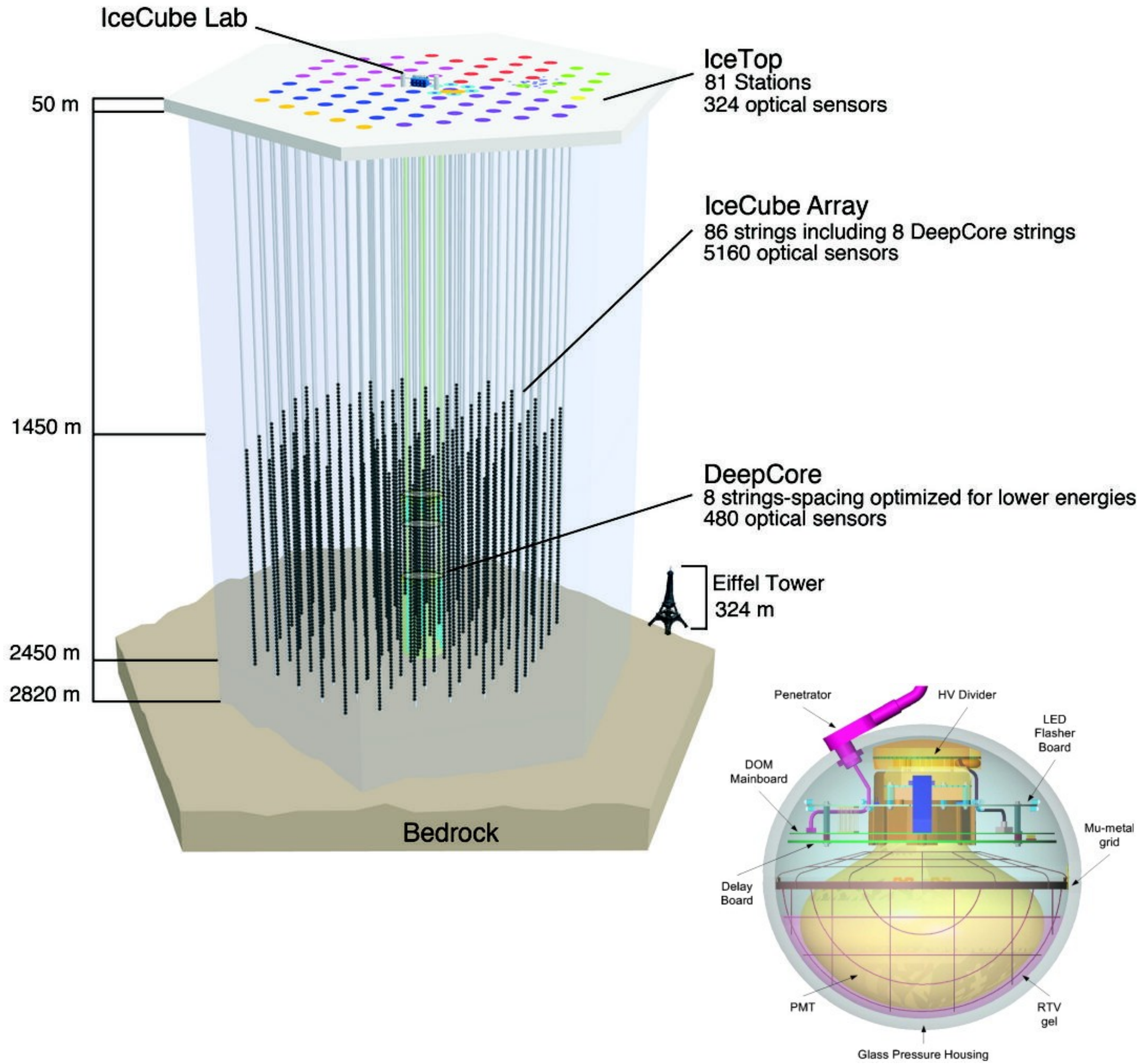
Astrophysical Neutrinos at IceCube



- What did we expect to measure?
- ***<u>How do we measure them?</u>***
- What do we actually measure?

The IceCube Neutrino Observatory

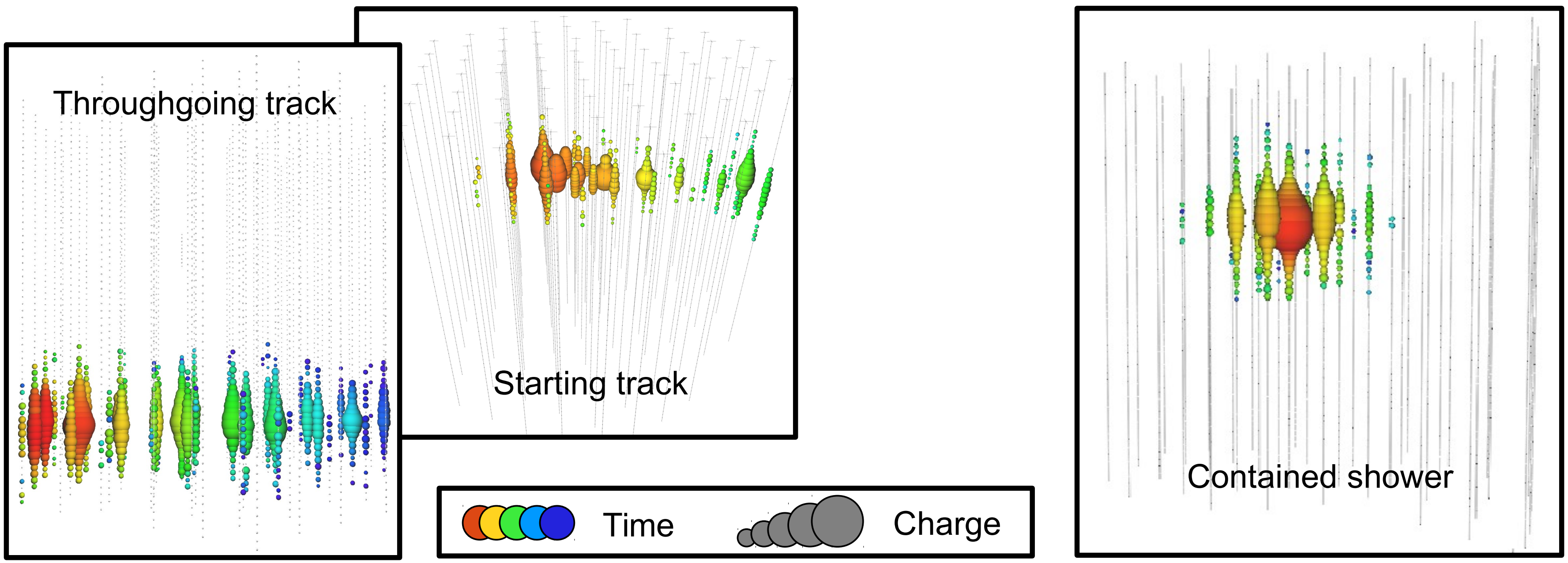
- **1 km^3** of South Pole Ice instrumented with **5160 PMTs**
- Detect neutrino interactions via **Cherenkov radiation** of secondary particles
- Full detector with **86 strings** completed in **2010** → **IC86**
- Previous configurations:
  - **IC79**
  - **IC59**
  - **IC40**



Neutrino Event Signatures in IceCube

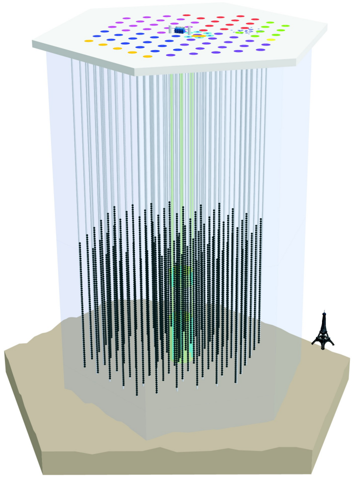
- **Tracks**
  - ν_μ charged-current interaction
  - Throughgoing ↔ starting
  - Angular resolution ~ 1°
  - Can measure muon dE/dx only

- **Showers**
  - $\nu_e + \nu_\tau$ charged-current interaction + $\nu_e + \nu_\mu + \nu_\tau$ neutral-current interaction
  - Angular resolution > 10°
  - Energy resolution ~ 15% (on deposited energy)



Lars Mohrmann – lars.mohrmann@desy.de – January 22, 2015

Atmospheric Backgrounds



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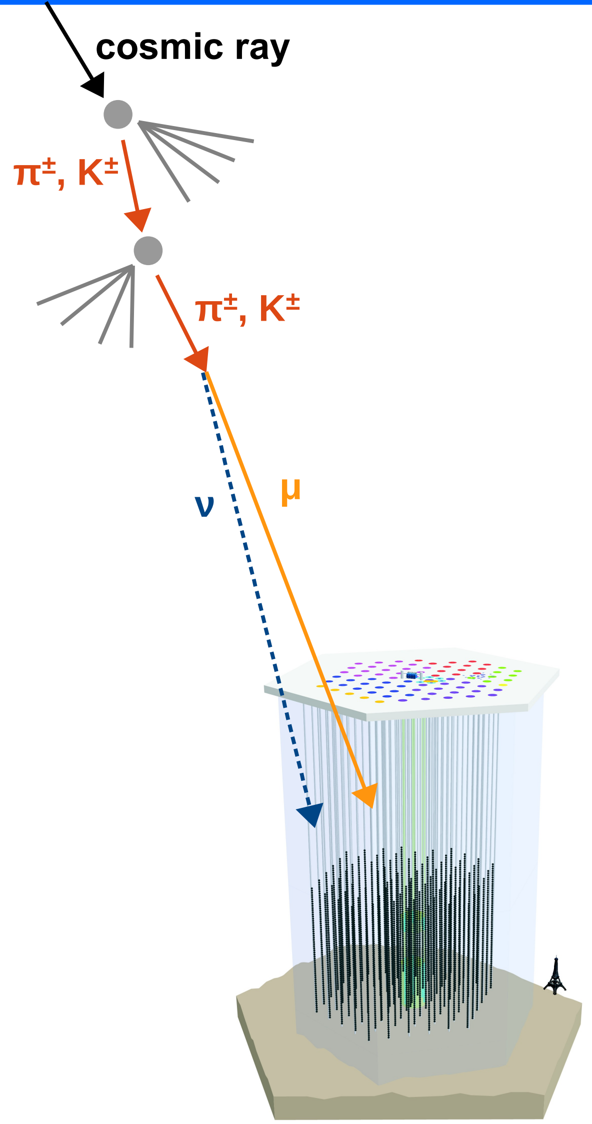

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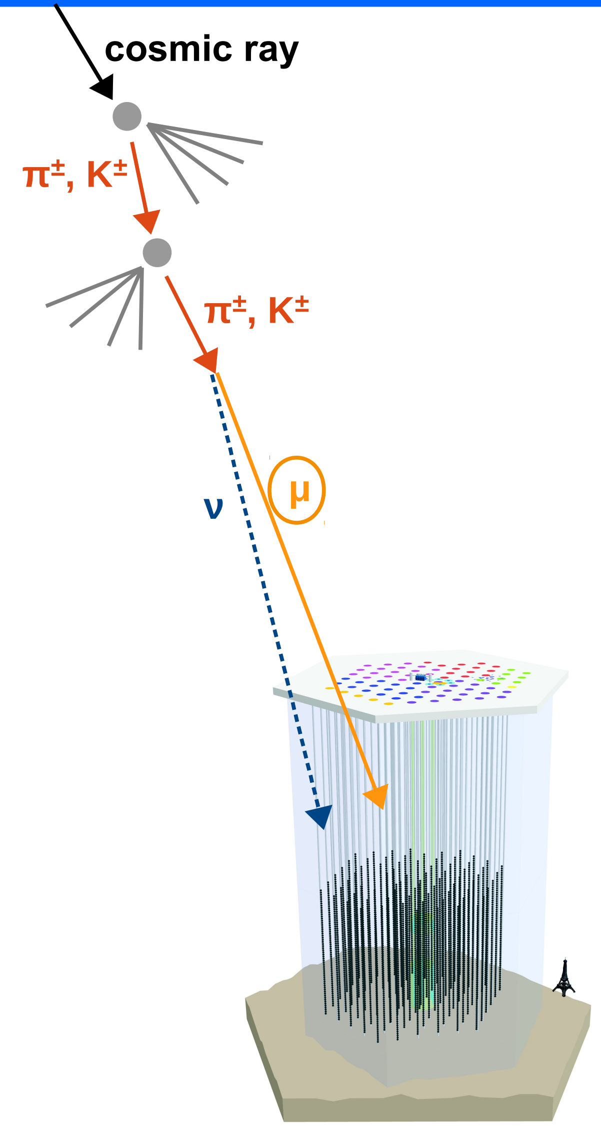
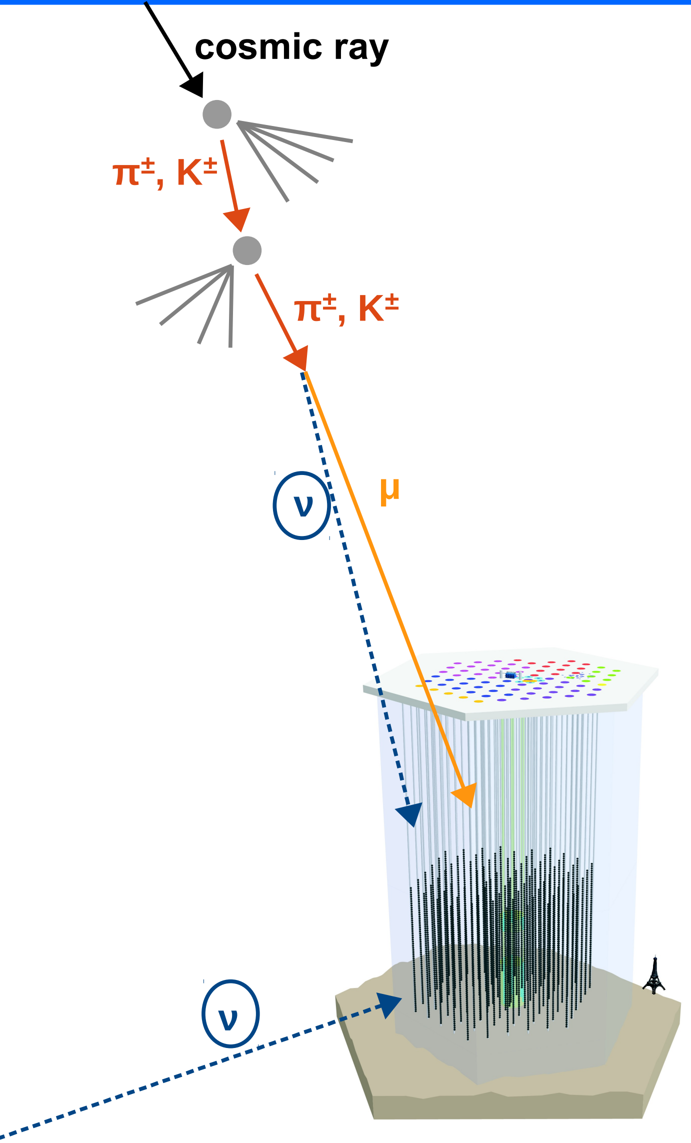


- **Atmospheric muons**
  - Detection rate: ~250 million / day
  - Arrive from above
  - First detected on the detector boundary

Atmospheric Backgrounds



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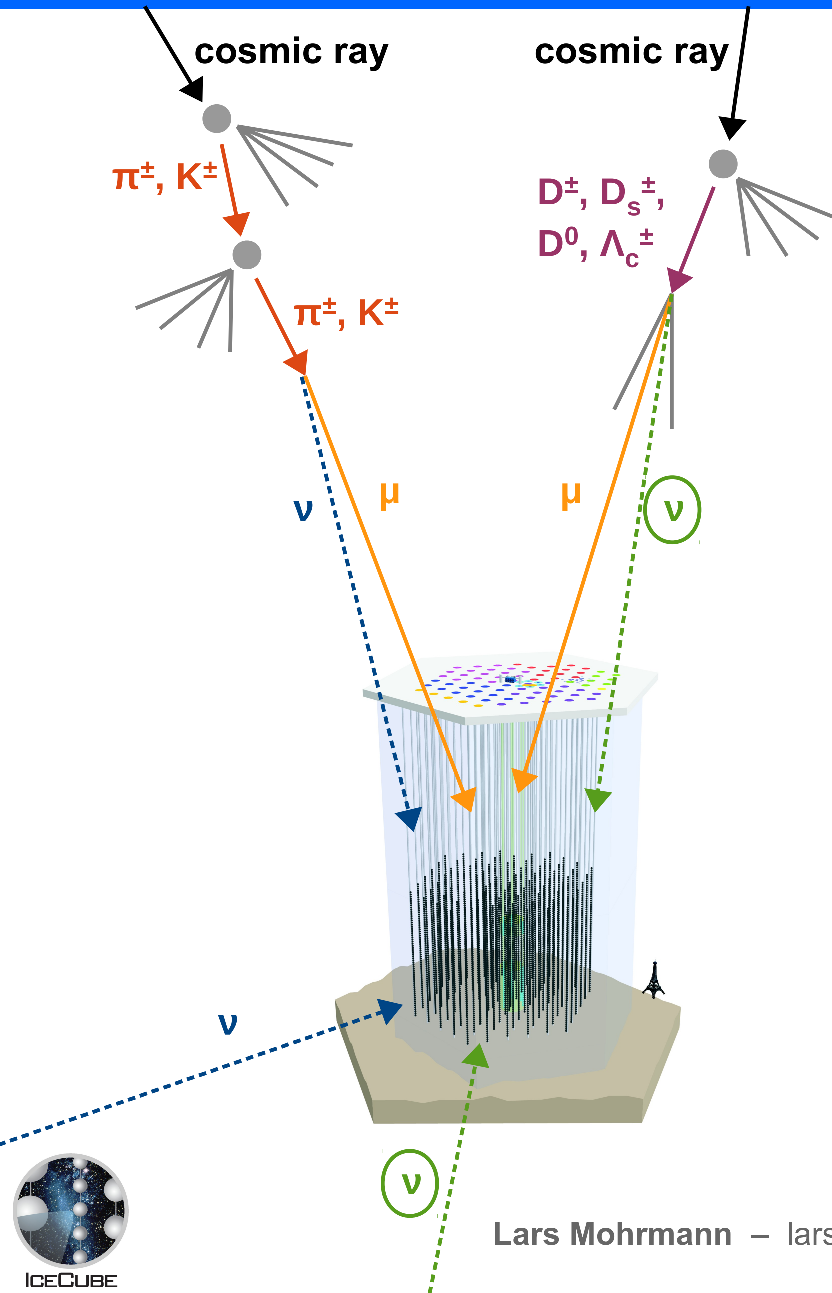
> **"Conventional" atmospheric neutrinos**
  - Detection rate: ~few hundred / day
  - Arrive from all directions (peaked at horizon)
  - Energy spectrum ~$E^{-3.7}$
  - If downgoing → often accompanied by muons

Atmospheric Backgrounds



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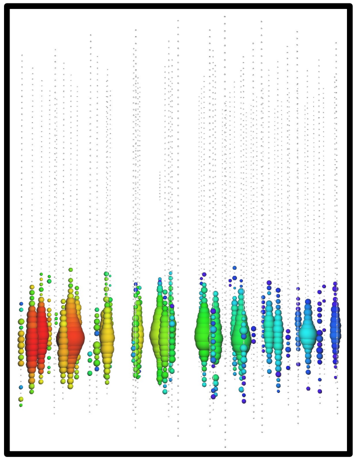
> **"Conventional" atmospheric neutrinos**
  - Detection rate: ~few hundred / day
  - Arrive from all directions (peaked at horizon)
  - Energy spectrum $\sim E^{-3.7}$
  - If downgoing → often accompanied by muons

> **"Prompt" atmospheric neutrinos**
  - Detection rate: ~few / day
  - Arrive from all directions (isotropically)
  - Energy spectrum $\sim E^{-2.7}$
  - If downgoing → often accompanied by muons
  - Not observed yet → rate uncertain

Event Selection Techniques

- **Select upgoing / horizontal track events**
  - High neutrino purity
  - Large effective area
  - Only sensitive to ν_μ CC interactions
  - Only sensitive to the northern sky
  - Cannot distinguish atmospheric / astrophysical neutrinos



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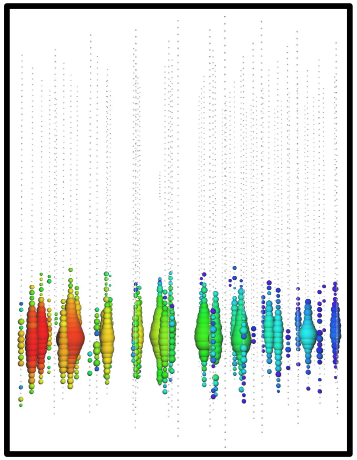
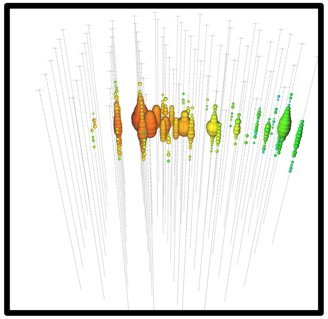
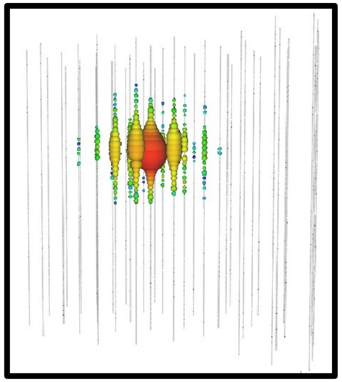
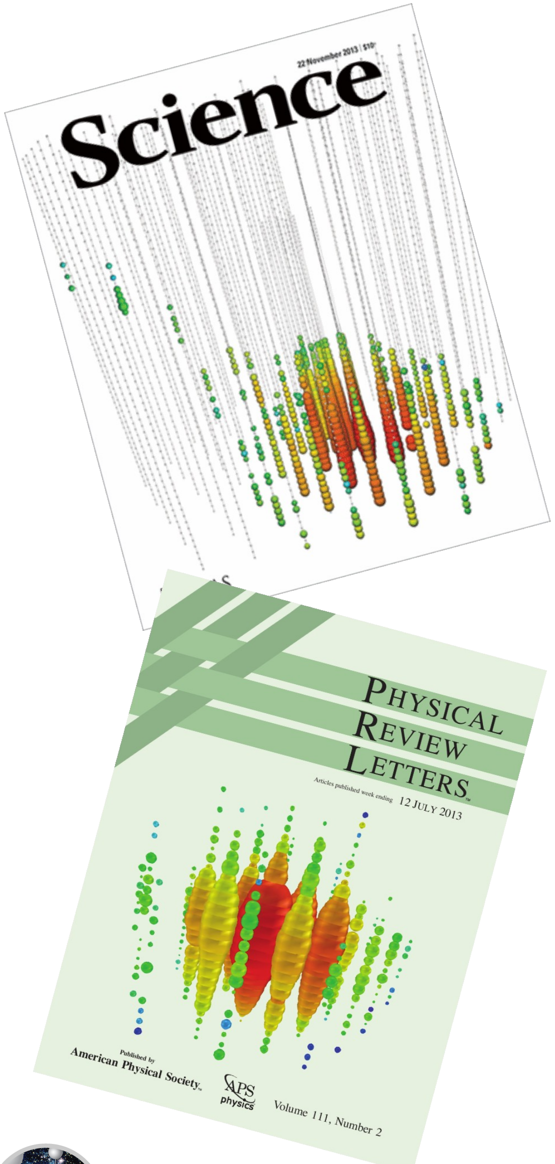


- **Select contained showers / starting tracks**
  - Sensitive to all neutrino flavors
  - Sensitive to the whole sky
  - Can reject downgoing atmospheric neutrinos (“self-veto”)
  - Smaller effective area
  - Needs bright muons to veto on
    → residual muon background at low energies





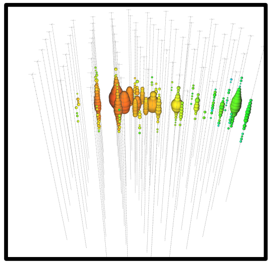
Astrophysical Neutrinos at IceCube

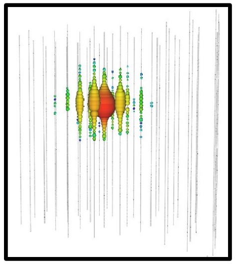


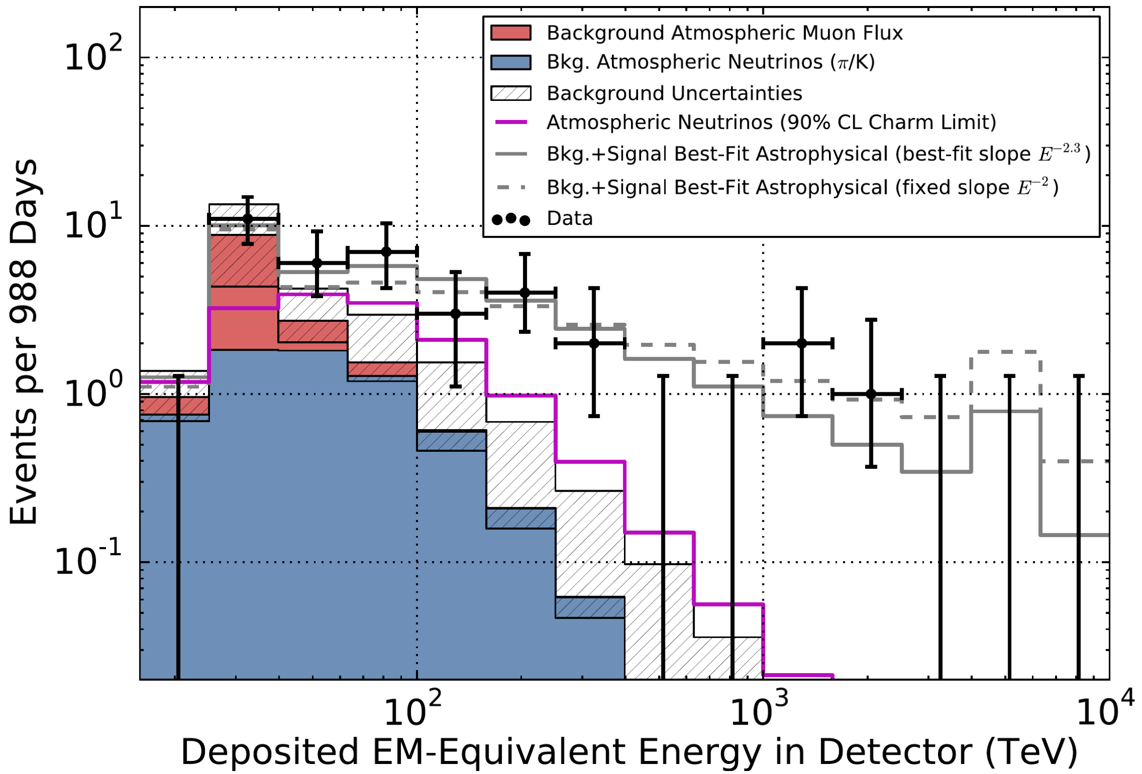
- **What did we expect to measure?**
- **How do we measure them?**
- ***<u>What do we actually measure?</u>***

Evidence for Astrophysical Neutrinos

- **Starting event analysis**
  - Starting tracks + contained showers
  - 37 events in 3 years
  - 5.7 σ excess above background
  - Spectrum consistent with E^{-2}

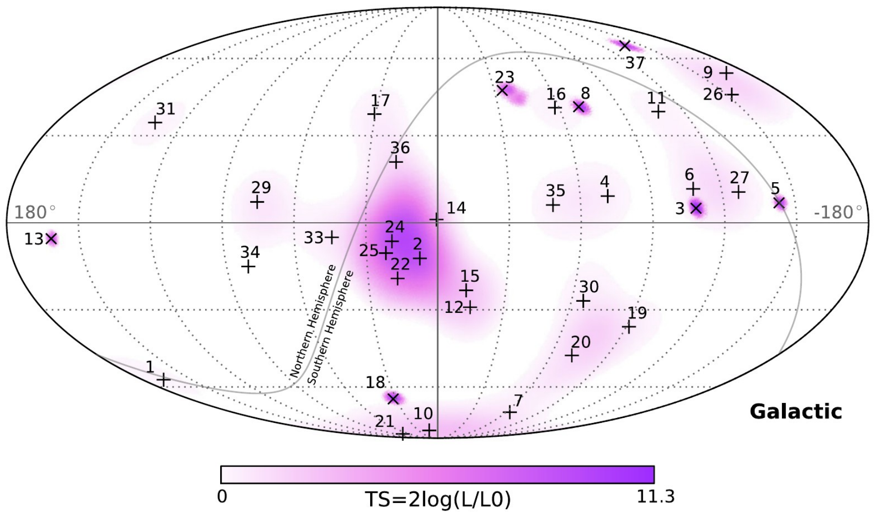




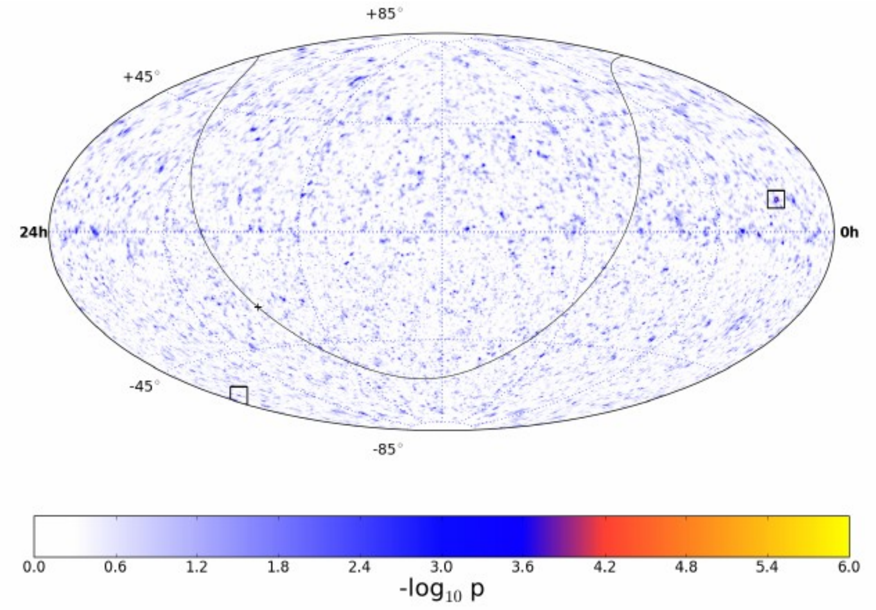


Point Source Searches

- **37 starting events**



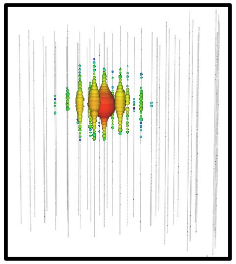
- **~400 000 muon tracks**

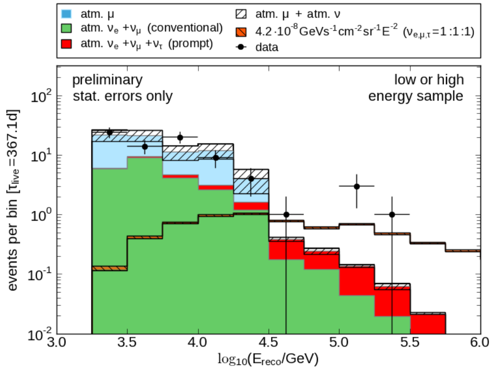


- **No significant excess found**
- **Need a diffuse analysis!**
  → study...
  - energy spectrum
  - zenith angle distribution
  - event signatures (tracks/showers)

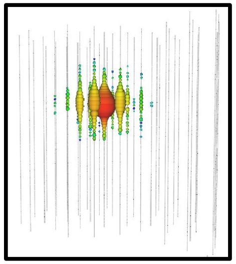
Diffuse Analyses on Construction Phase Data

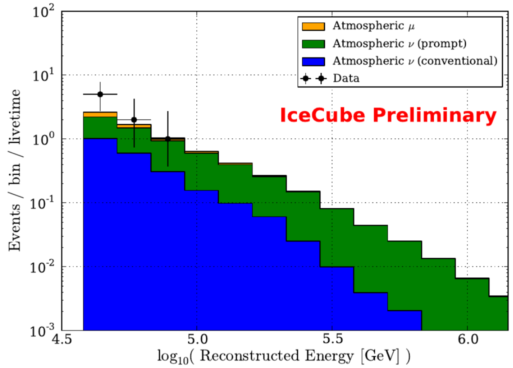
- **"S1"**
  - Contained showers
  - Live time: 1 year (IC40)
  - Sensitive energy range: > 100 TeV
  - Sensitive zenith range: 0° – 180°



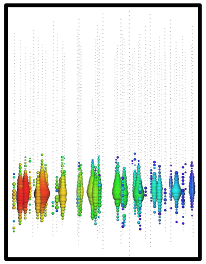


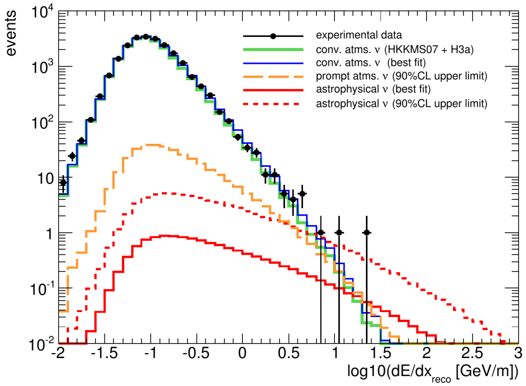
- **"S2"**
  - Contained showers
  - Live time: 1 year (IC59)
  - Sensitive energy range: > 10 TeV
  - Sensitive zenith range: 0° – 180°





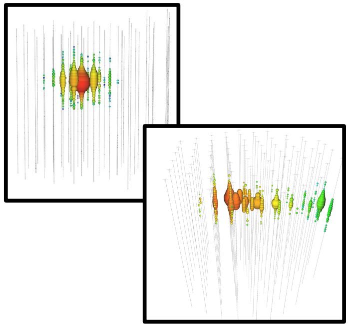
- **"T1"**
  - Throughgoing tracks
  - Live time: 1 year (IC59)
  - Sensitive energy range: > 100 TeV
  - Sensitive zenith range: 90° – 180°

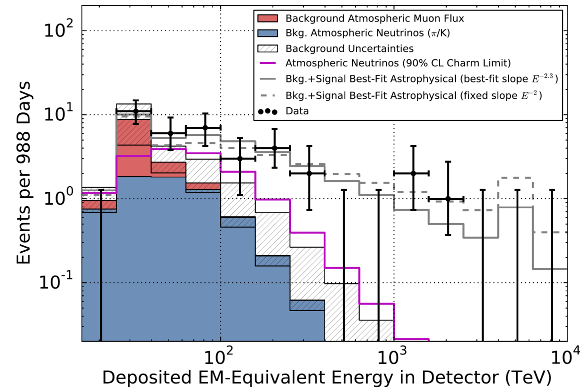




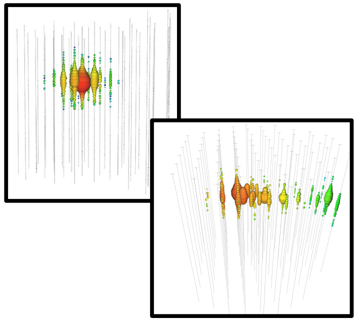
Diffuse Analyses on Full Detector Data

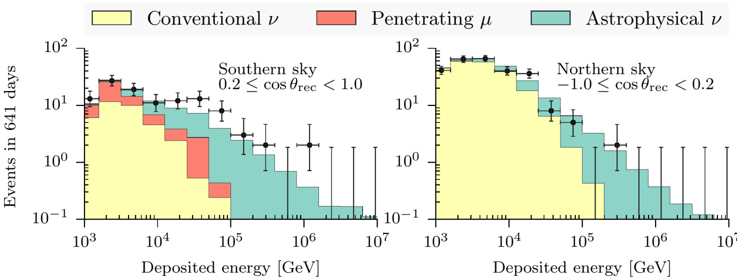
- **"H1"**
  - Starting tracks + contained showers
  - Live time: 3 years (IC79 / IC86 / IC86-2)
  - Sensitive energy range: >30 TeV
  - Sensitive zenith range: 0° – 180°



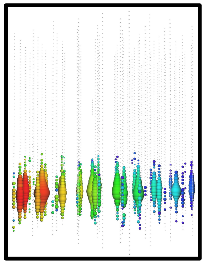


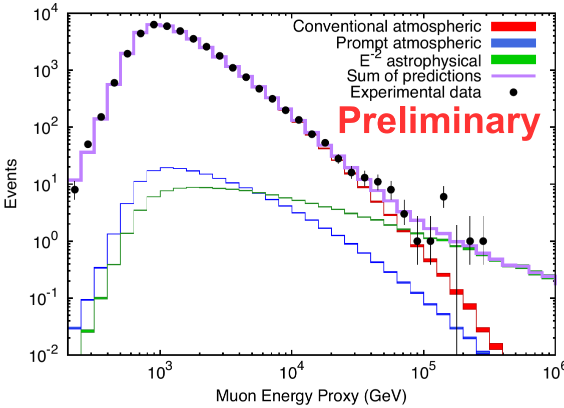
- **"H2"**
  - Starting tracks + contained showers
  - Live time: 2 years (IC79 / IC86)
  - Sensitive energy range: > 5 TeV
  - Sensitive zenith range: 0° – 180°





- **"T2"**
  - Throughgoing tracks
  - Live time: 2 years (IC79 / IC86)
  - Sensitive energy range: >100 TeV
  - Sensitive zenith range: 85° – 180°





Global Likelihood Analysis

- **Questions**
  - Do the individual analyses form a consistent picture?
  - Can we detect spectral features that are different from E^{-2}?
  - Is the flavor composition compatible with the generic 1:1:1 scenario?

- **Global Likelihood Analysis**
  - For different observables (energy, zenith angle, event signature), compare simulation and experimental data
  - Tweak parameters of simulation until best agreement is achieved

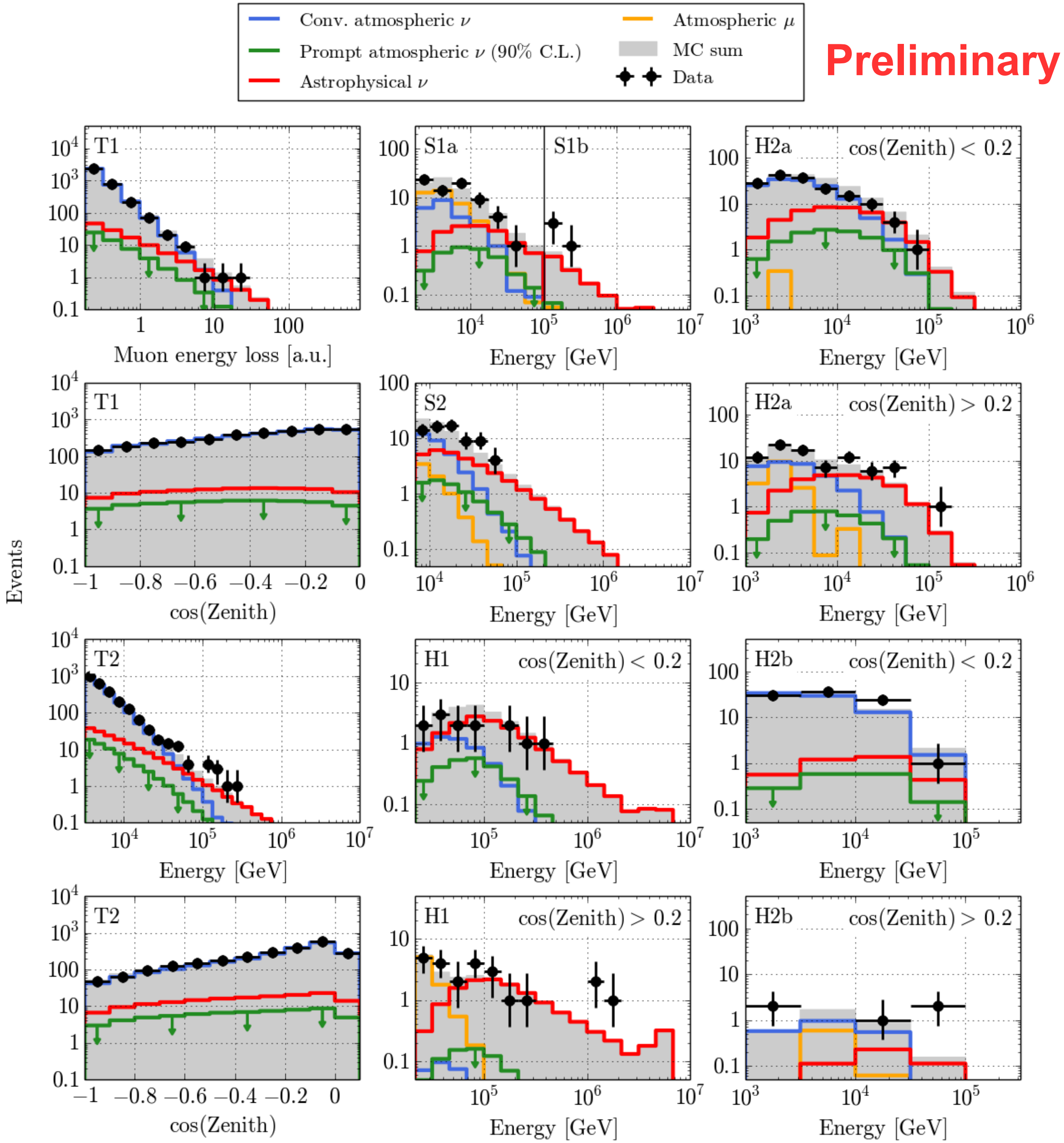
- **Fit total flux as a linear combination of:**
  - **Atmospheric muons**
  - **Conventional atmospheric neutrinos**
  - **Prompt atmospheric neutrinos**
  - **Astrophysical neutrinos**

Models and Parameters

- **Conventional Atmospheric Neutrino Flux**
  - **Model:** HKKMS (Honda et al. 2007)
  - **Free parameter:** Normalization
- **Prompt Atmospheric Neutrino Flux**
  - **Model:** ERS (Enberg et al. 2008)
  - **Free parameter:** Normalization
- **Astrophysical Neutrino Flux**
  - **Model:** E.g. isotropic power law, $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
  - **Free parameters:** Normalization, Spectral index
- **Systematic Uncertainties → Nuisance Parameters**
  - **Cosmic ray spectral index**
    Prior: ± 0.05
  - **Muon background normalization**
    Fitted individually per analysis
    Prior: ± 50%
  - **Energy scale**
    Fitted individually per analysis
    Prior: ± 15%

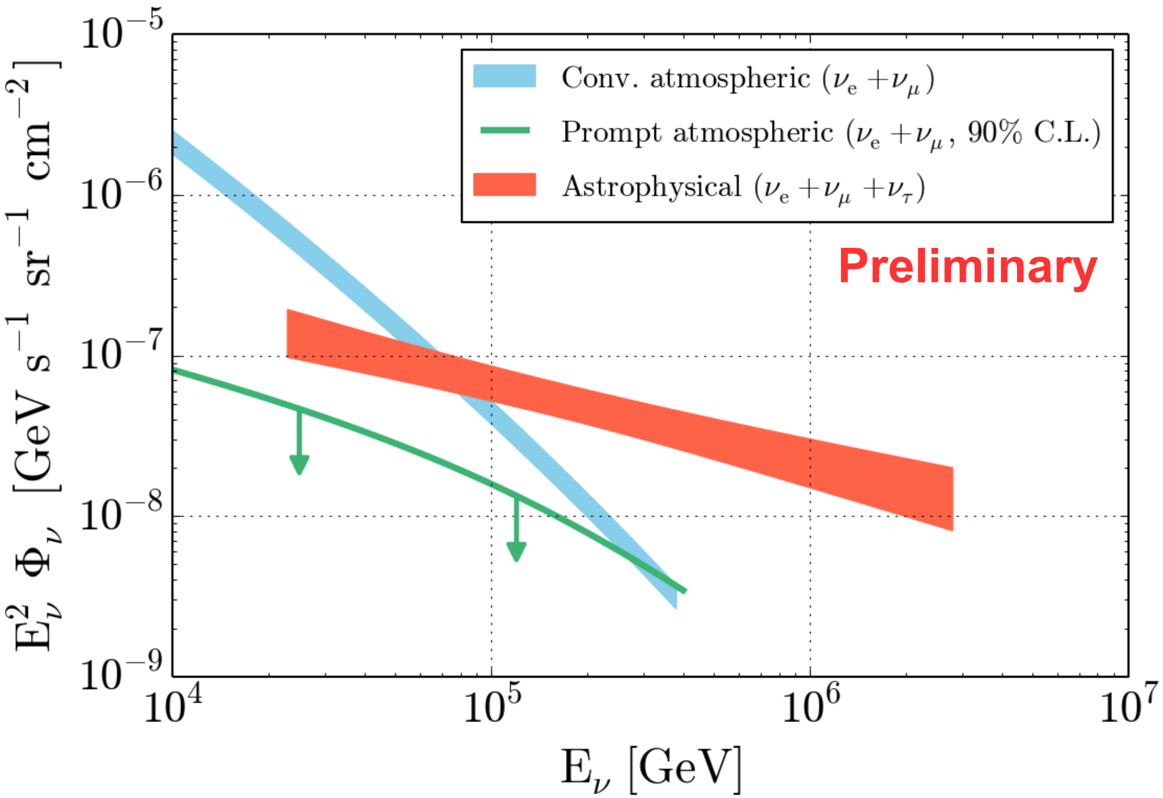
Results

Results – Data and Simulation



Results – Power Law Model

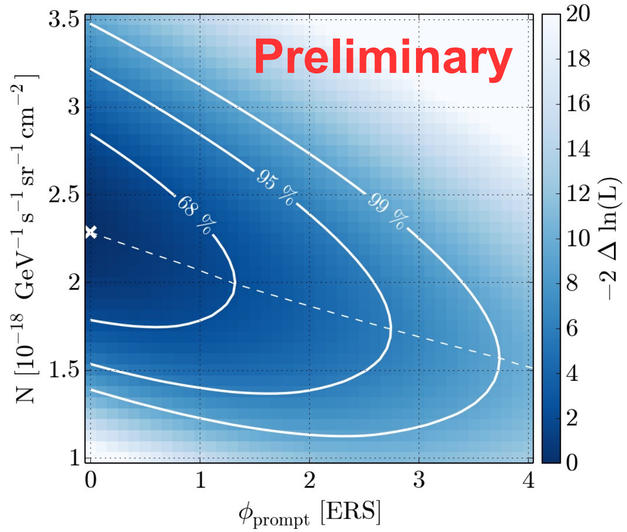
- **Single Power Law Model**
  - $\Phi_\nu = N \cdot \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$
  - Isotropy
  - $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$
- **Best Fit Model Parameters**
  - $N = (6.9 \pm 1.1) \cdot 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{cm}^{-2}$
  - $\gamma = 2.50 \pm 0.08$

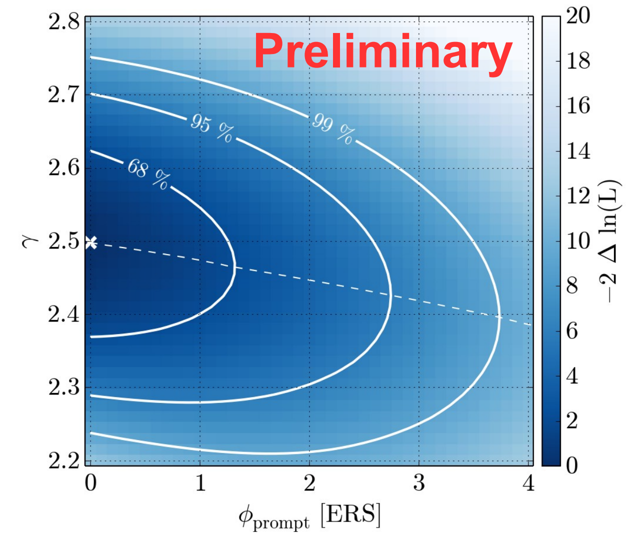


Results – Power Law Model

- **Prompt component fitted to zero**
  - < 1.5 x ERS @ 90% C.L.
- **Background-only rejection**
  - ~ 8 σ
- **E^{-2} rejection**
  - ~ 4.3 σ
- **Also tested**
  - Power law + cut-off
  - Sum of two power laws

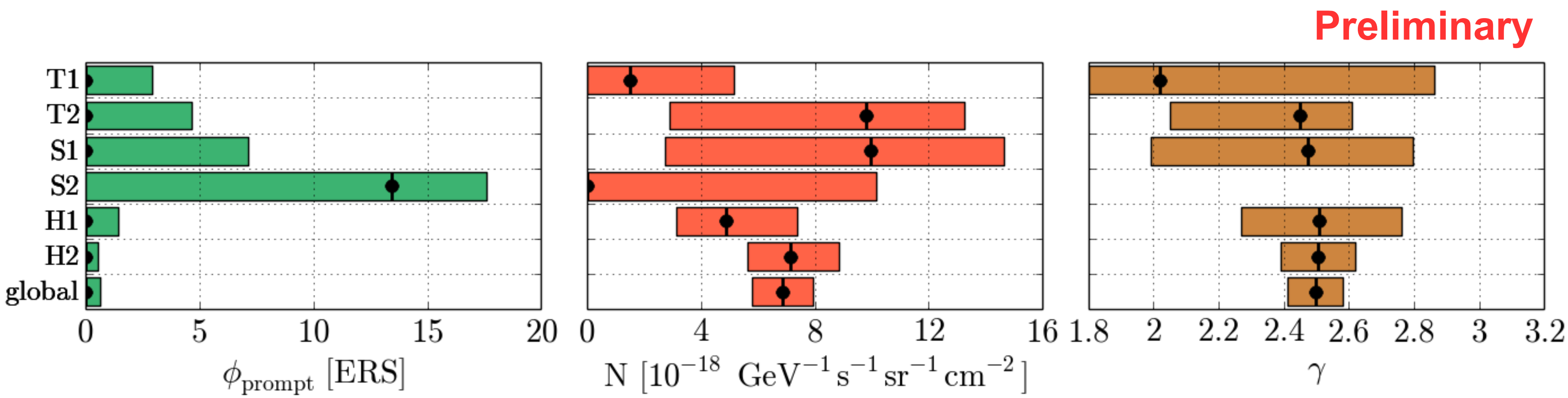
→ no improvement in fit





Consistency Check

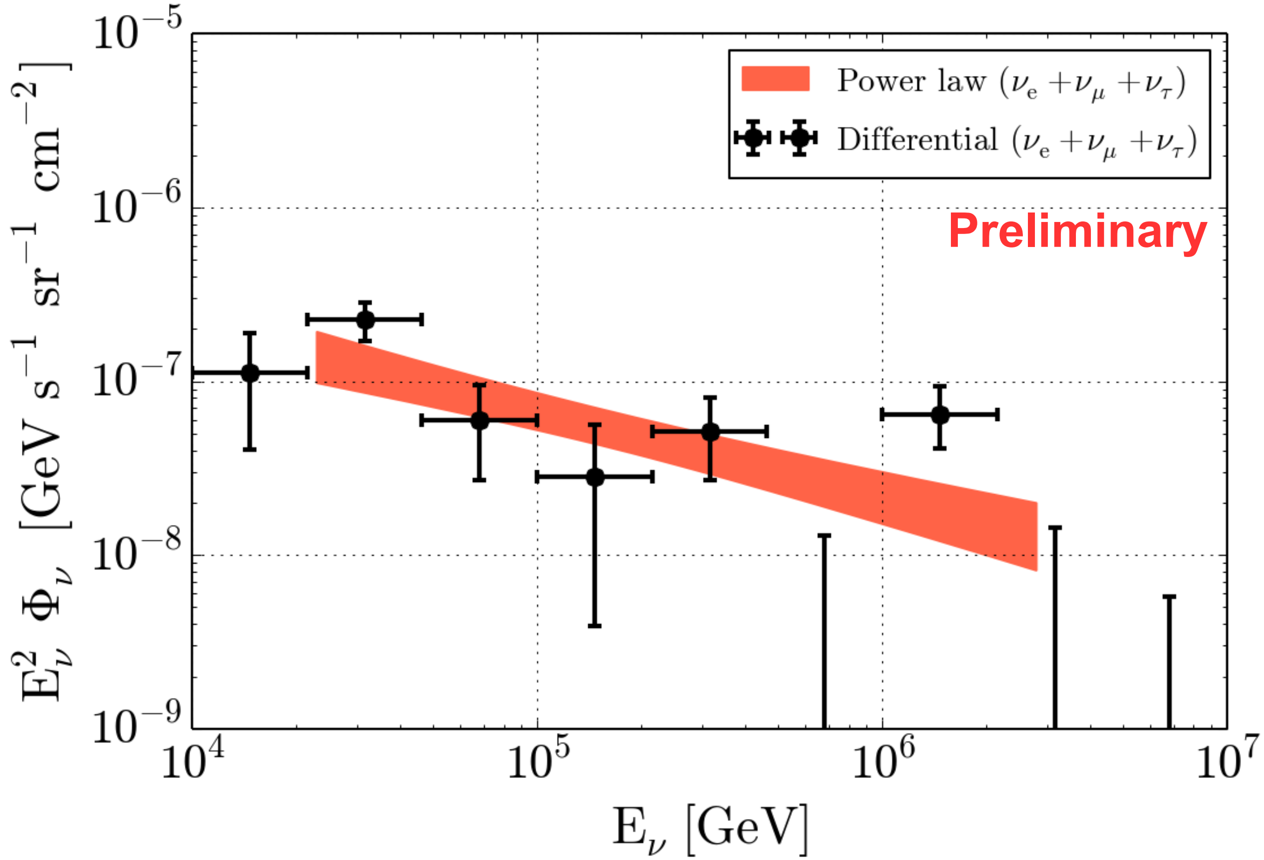
- **Fits on individual samples:**



- **Different samples appear to be consistent**

Results – Differential Spectrum

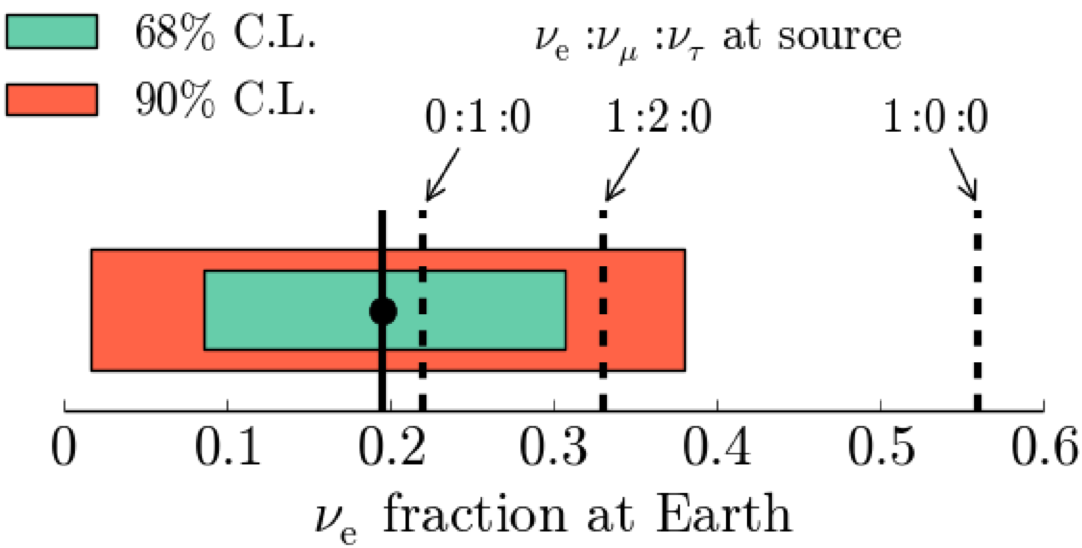
- **Differential Model**
  - Parametrize astrophysical flux with independet basis functions in different energy intervals
  - In each energy bin, assume E^{-2} spectrum



Results – Flavor Composition

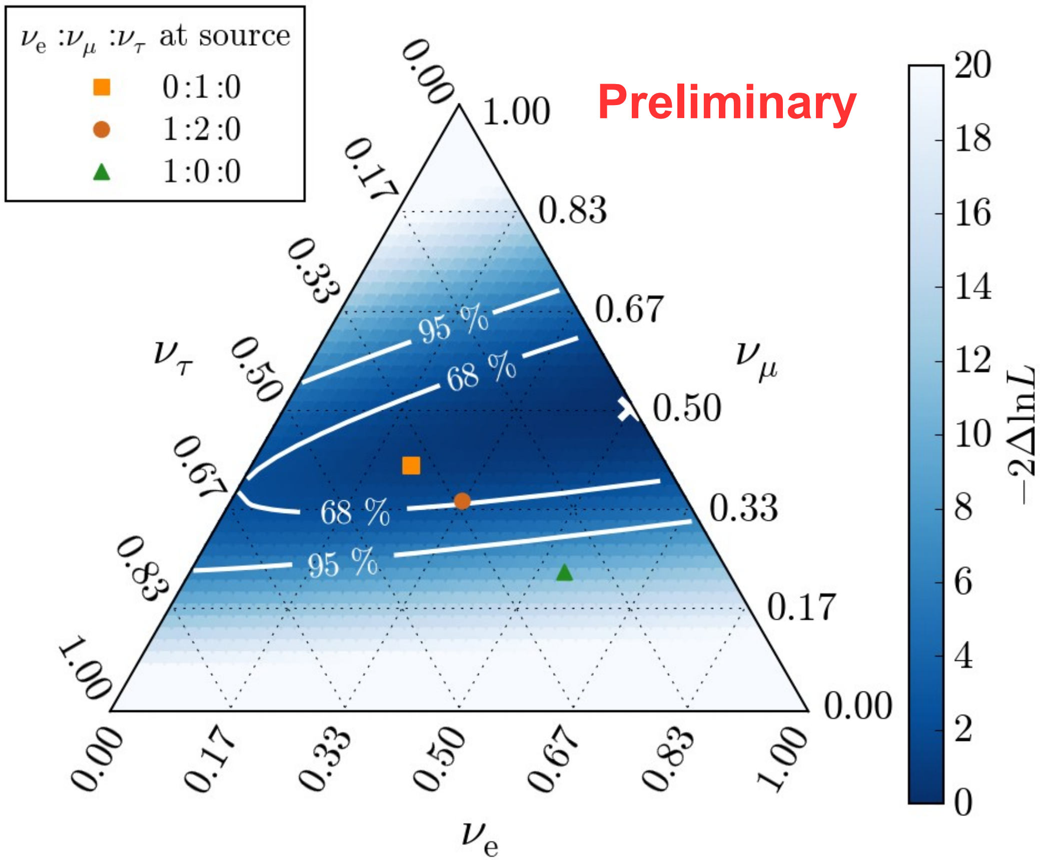
- **2-Flavor model**
  - Fit normalization of ν_e and $(\nu_\mu + \nu_\tau)$ separately
  - → assume standard oscillations
- **Results**
  - ν_e fraction at Earth: 0.19 ± 0.11

Preliminary



Results – Flavor Composition

- **3-Flavor model**
  - Leave all three normalizations (ν_e, ν_μ, ν_τ) free to float
  - → allow for non-standard oscillations
- **Results**
  - Best fit: 50% ν_e, 50% ν_μ
  - Pure electron neutrino composition at the source excluded with 3.2 σ



Conclusion

- **Astrophysical neutrinos detected in various channels / analyses**
  - Global analysis framework → combines the results
  - Different results are consistent with each other

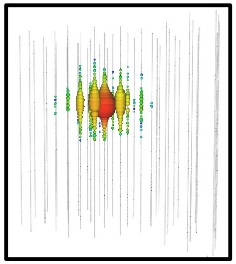
- **If we assume a power law, isotropy and flavor-equality (1:1:1), then**
  - a spectrum ~E^{-2} is disfavored with 4.3 σ
  - the best fit spectral index is 2.50 ± 0.08
  - the prompt component is <1.5 x ERS at 90% C.L.

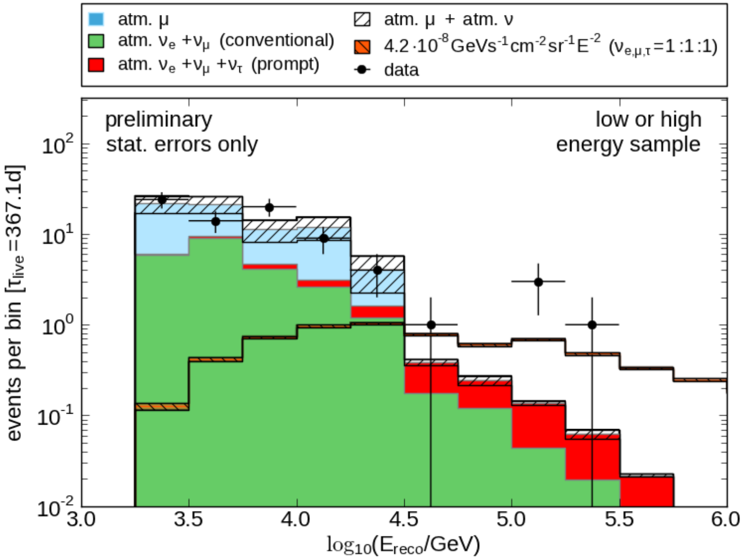
- **If we allow unequal flavor contents (with the same spectral index), then**
  - the best fit electron neutrino fraction is 0.19 ± 0.11
  - a pure electron neutrino composition at the source can be excluded with 3.2 σ

Backup slides

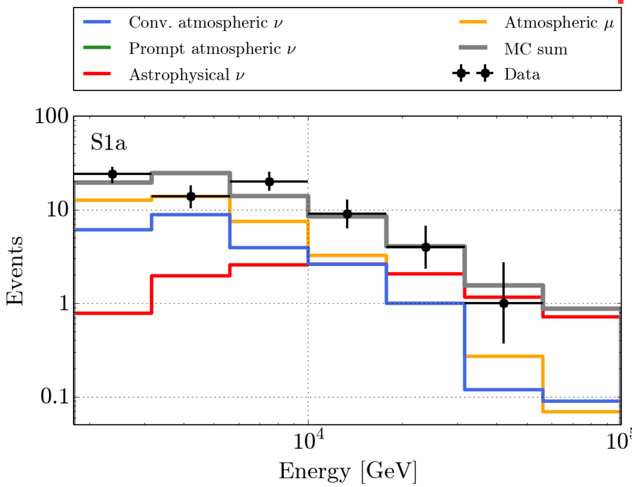
IC40 contained showers

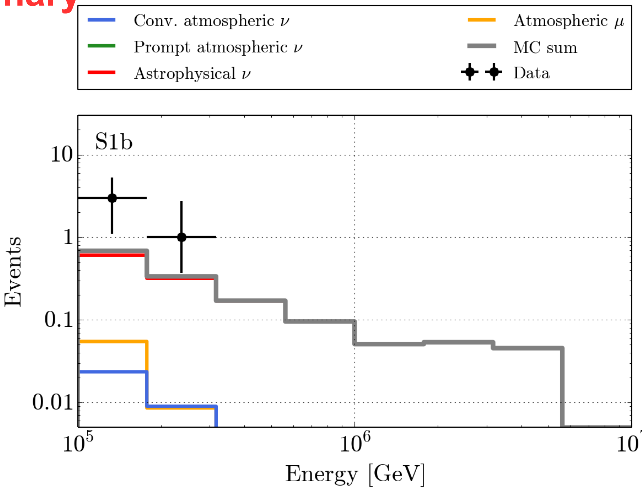
- **"S1"**





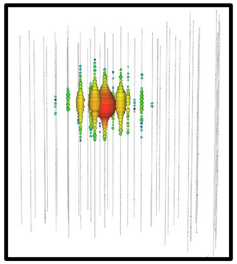
Preliminary

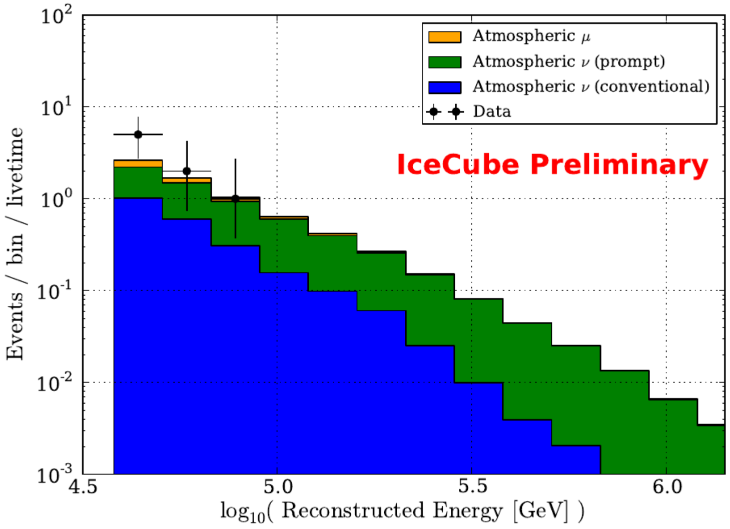


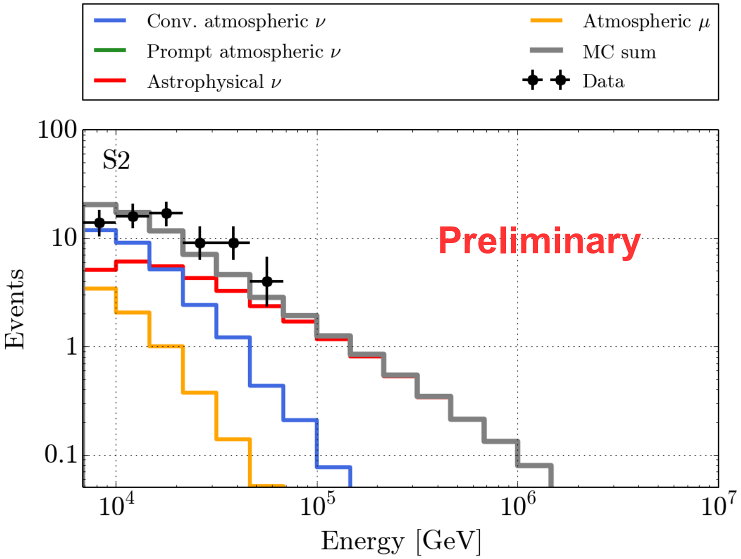


IC59 contained showers

- **"S2"**

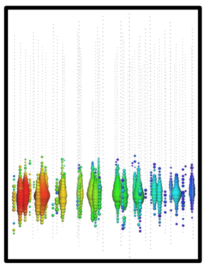


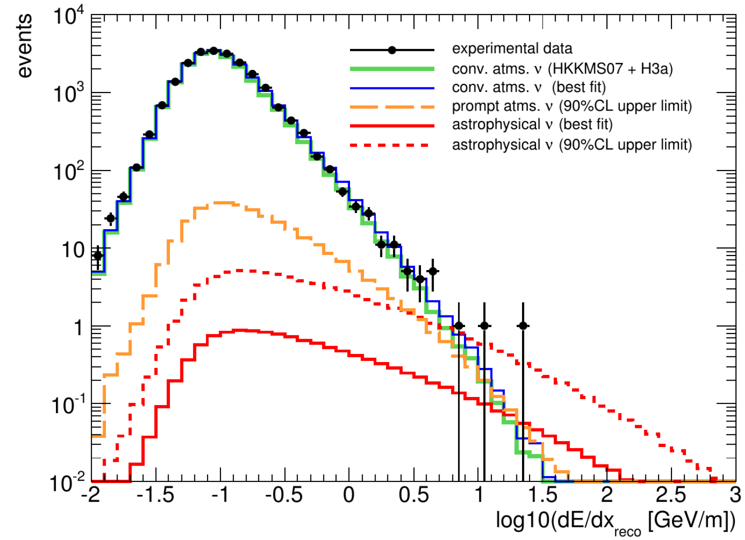




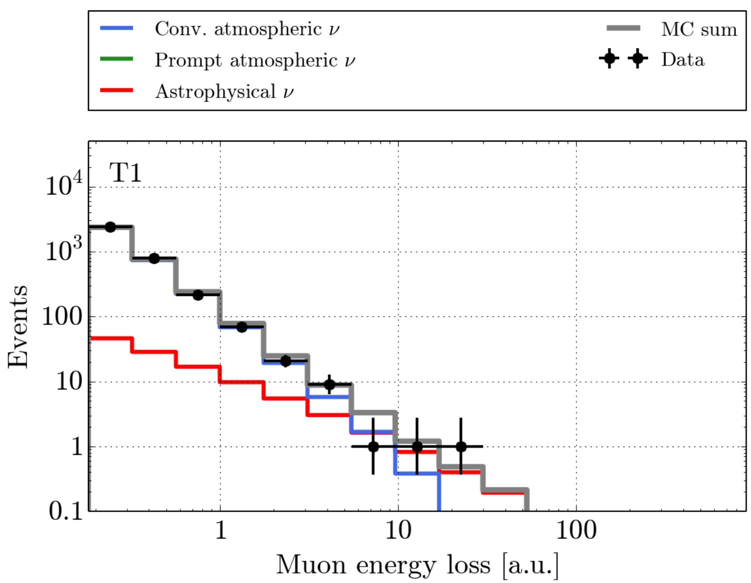
IC59 throughgoing tracks

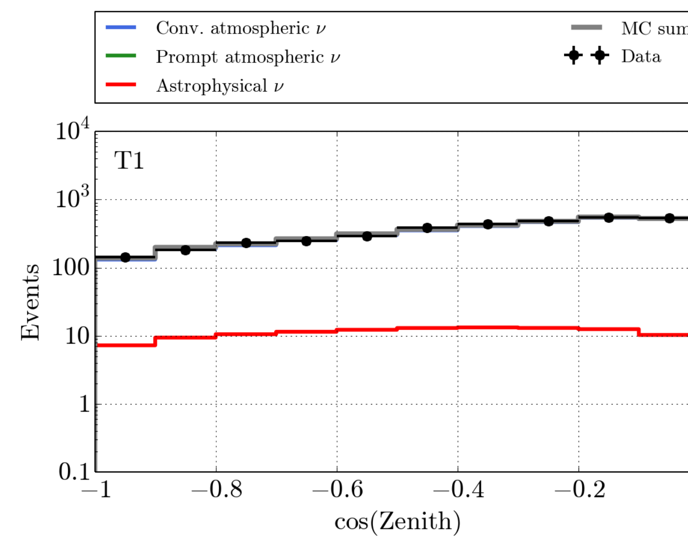
- **“T1”**





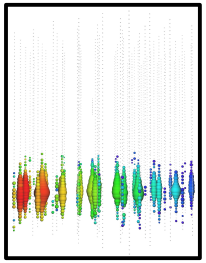
Preliminary

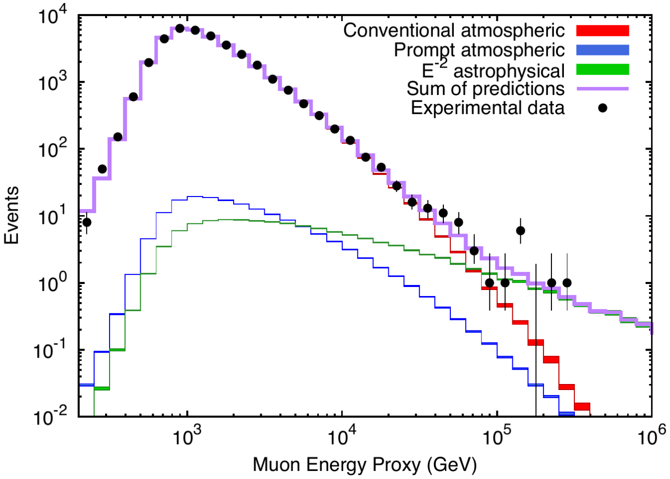




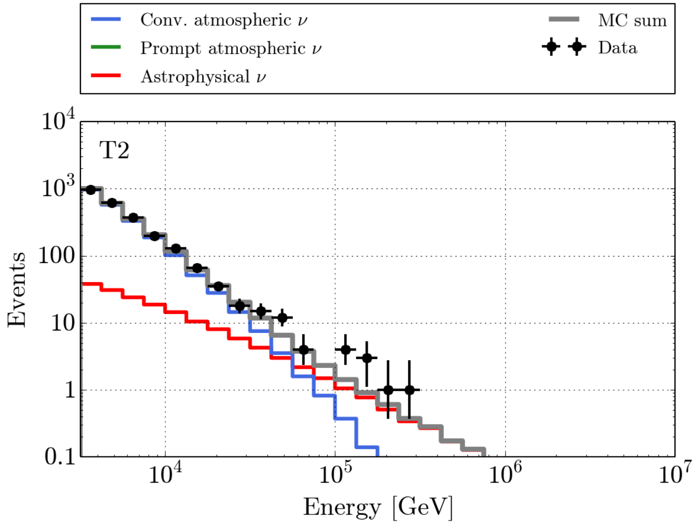
IC79/86 throughgoing tracks

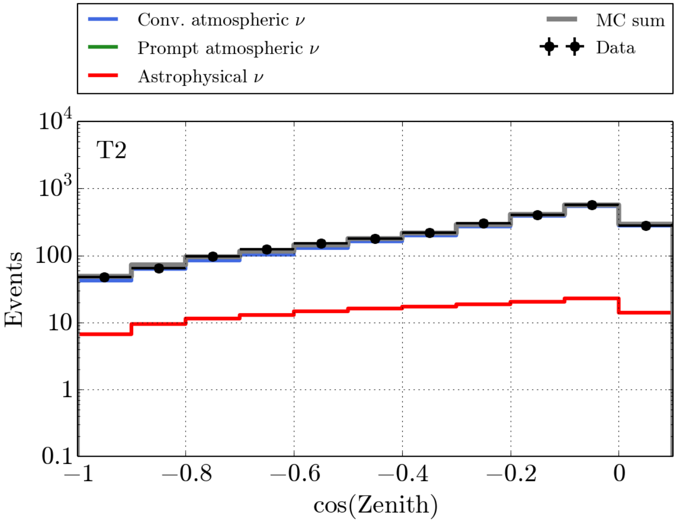
- **"T2"**



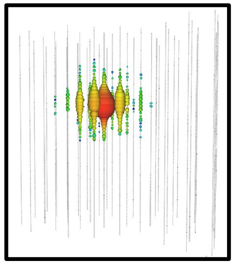


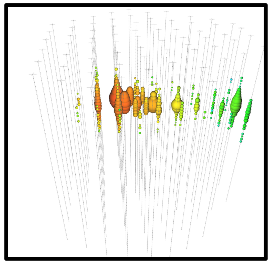
Preliminary

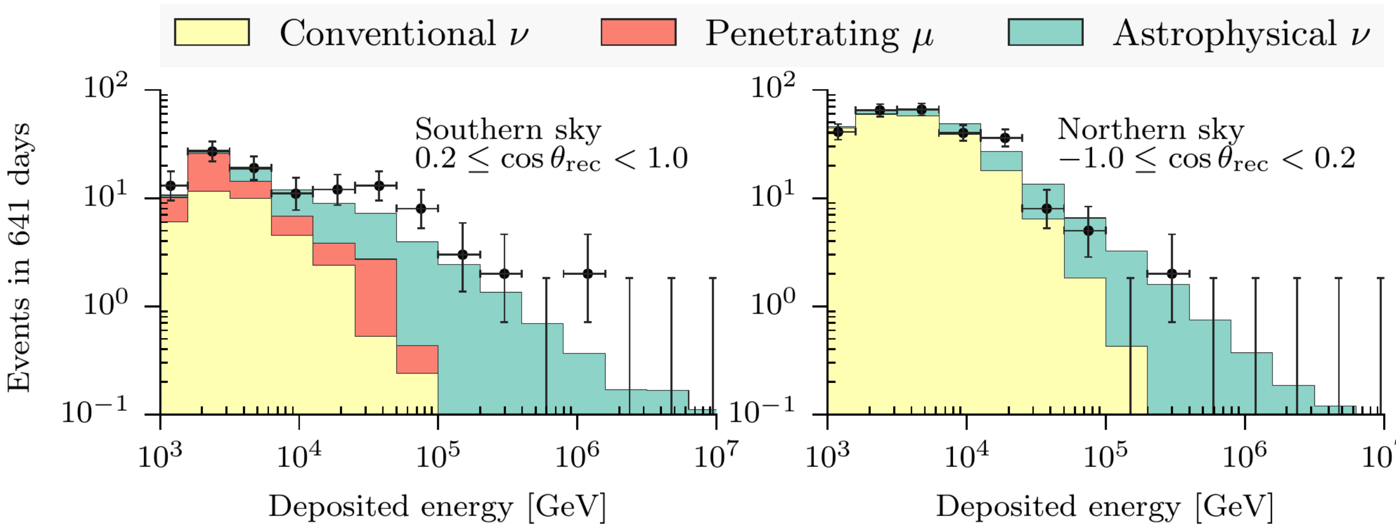




- **“H2”**

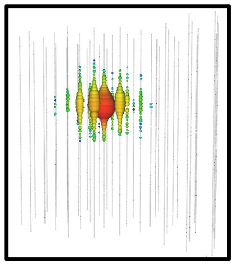


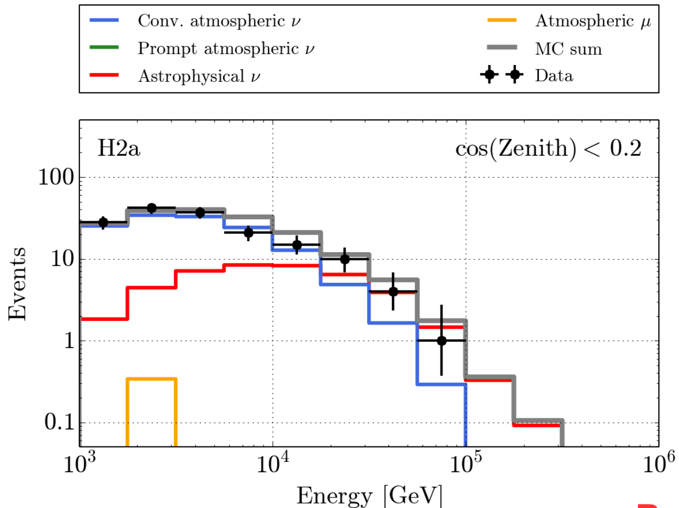


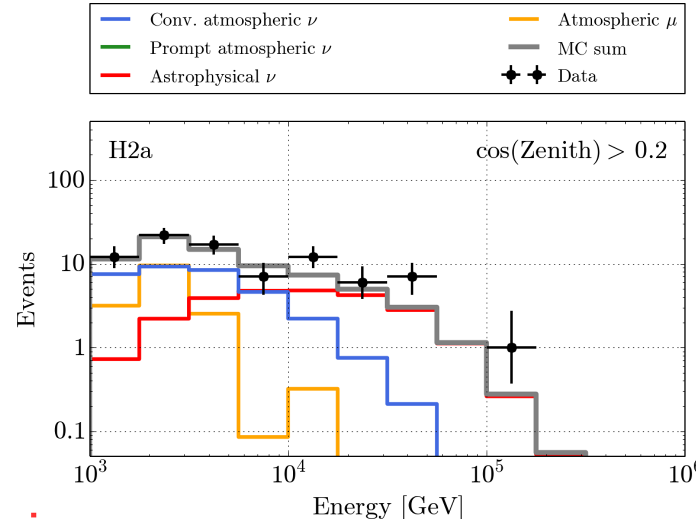

Conventional ν
Penetrating μ
Astrophysical ν
Events in 641 days
Southern sky
$0.2 \leq \cos\theta_{rec} < 1.0$
Northern sky
$-1.0 \leq \cos\theta_{rec} < 0.2$
10^{-1} 10^{0} 10^{1} 10^{2}
10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
Deposited energy [GeV]
Deposited energy [GeV]

IC79/86 starting tracks and showers

- **“H2”**







Preliminary