Characterization of the Astrophysical Neutrino Flux at the IceCube Neutrino Observatory

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for the IceCube Collaboration

ICECUBE

TAUP 2015

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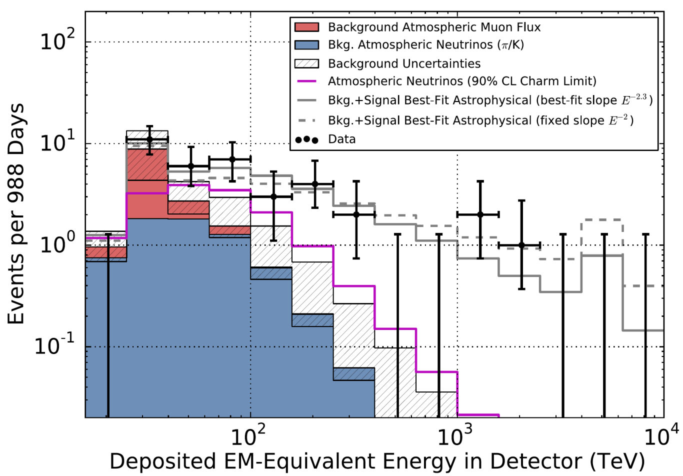
September 10, 2015

HELMHOLTZ ASSOCIATION

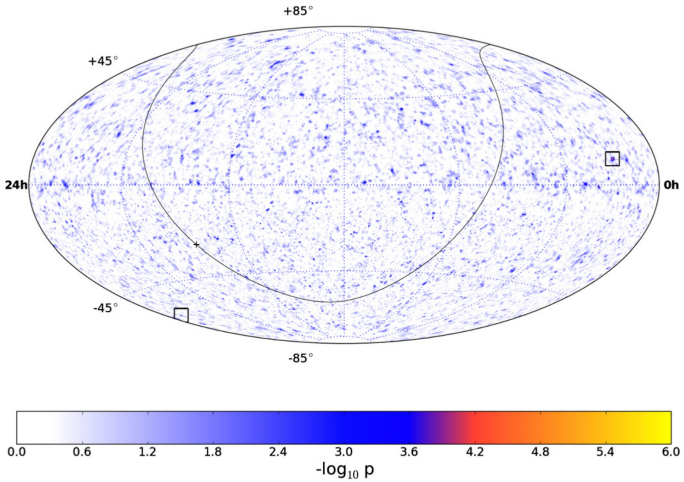
DESY

Cosmic Neutrinos at IceCube

- **Cosmic neutrino flux discovered!**



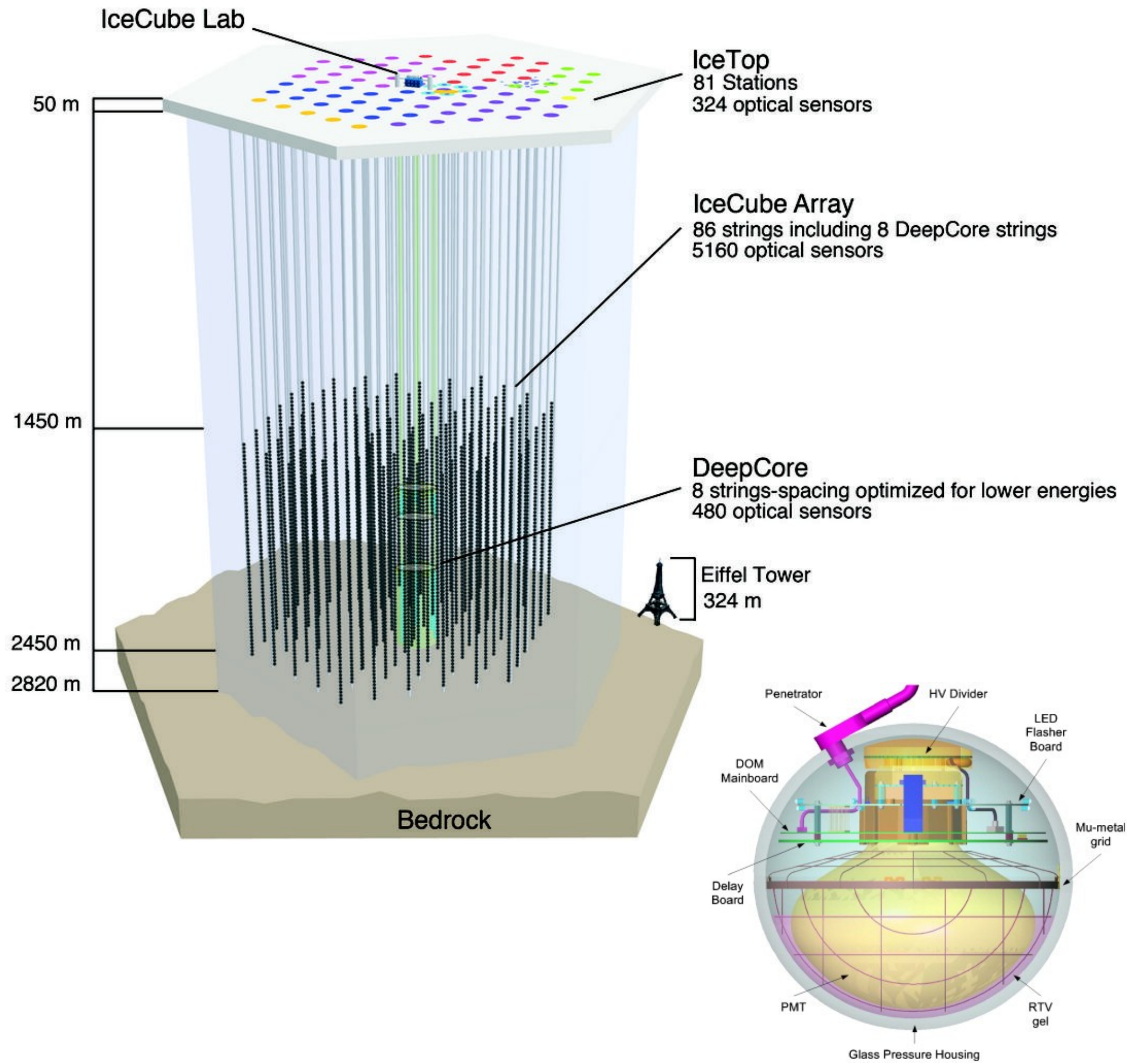
- **Sources still unknown**



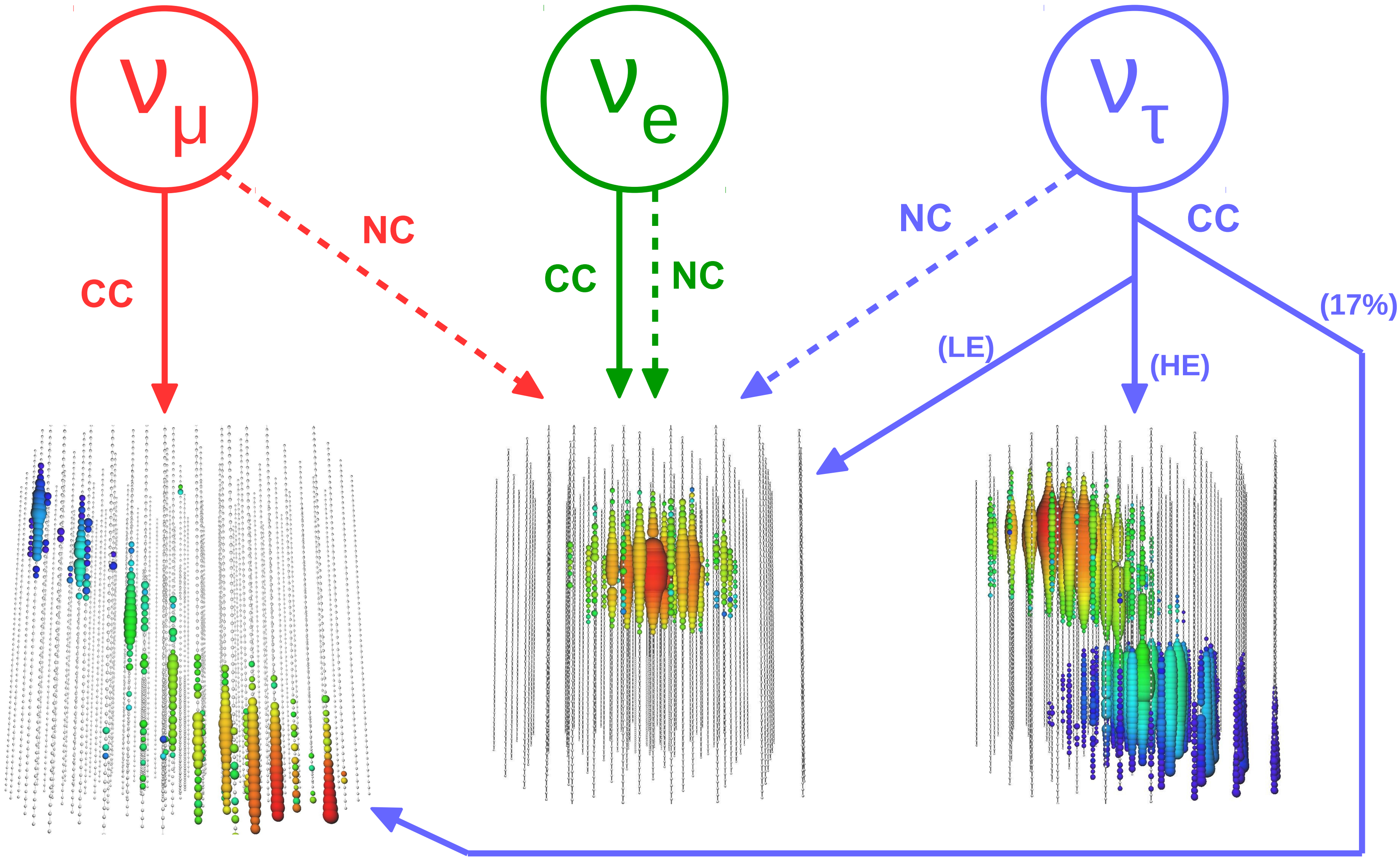
- **Need precise measurement of**
  - **Energy spectrum**
  - **Flavor composition** $(\nu_e : \nu_\mu : \nu_\tau)$
  - $\rightarrow$ **conclusions on sources possible**

The IceCube Detector

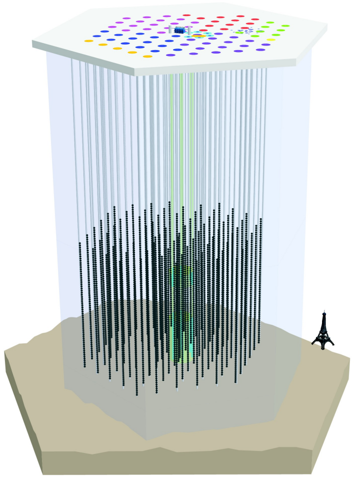
- **1 km^3** of South Pole ice instrumented with **5160 PMTs**
- Detect neutrino interactions via **Cherenkov radiation** of secondary particles
- Full detector with **86 strings** completed in **2010**
- Data already taken with **partial configurations** since **2005**



Neutrino Signatures in IceCube



Atmospheric Backgrounds



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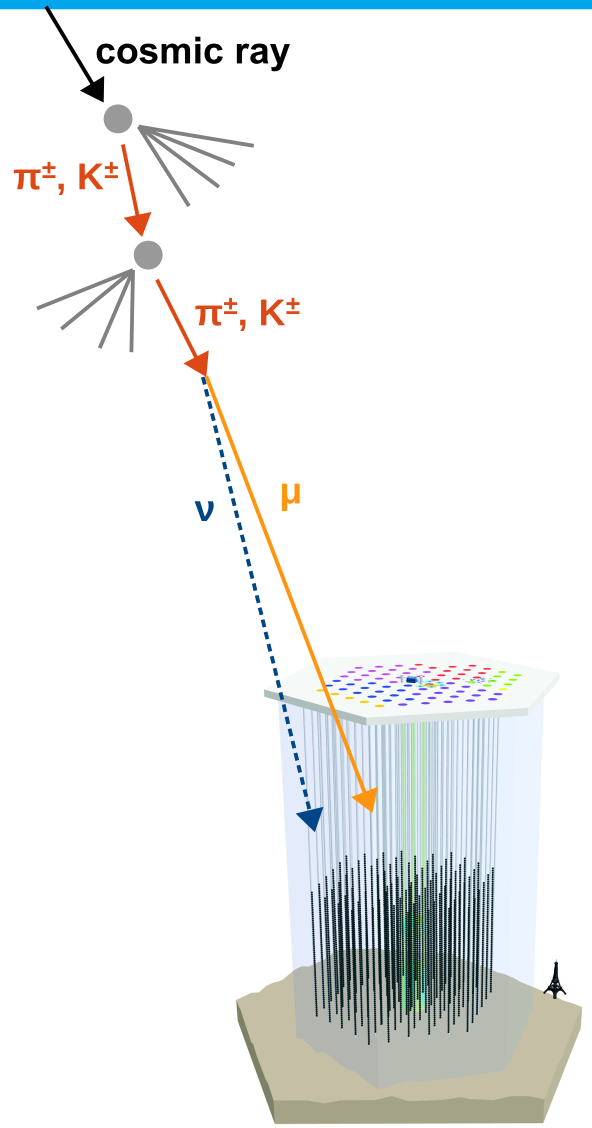
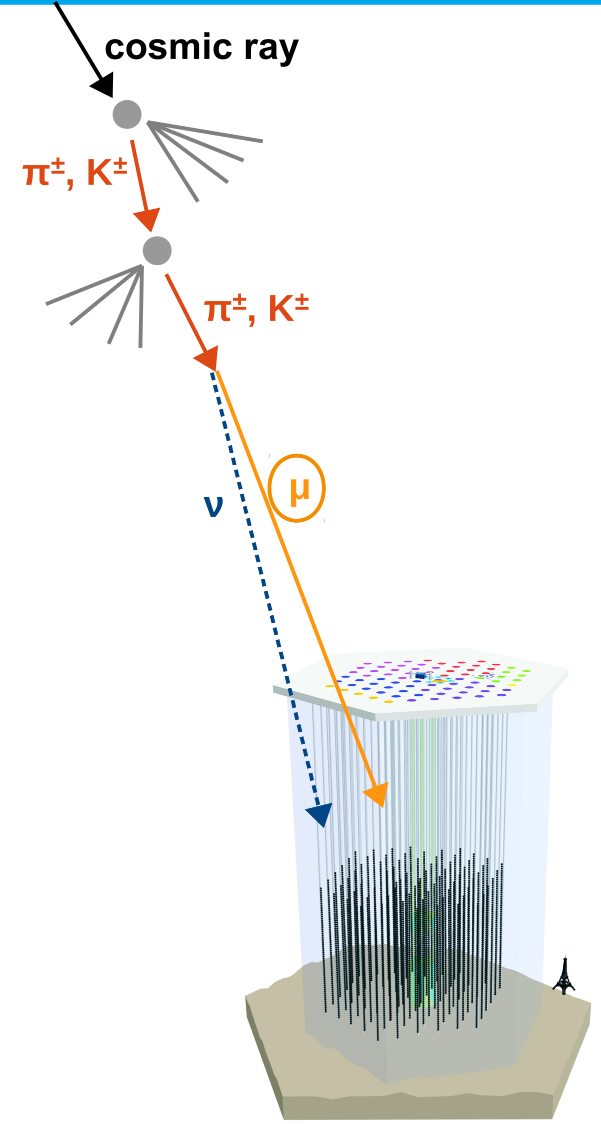
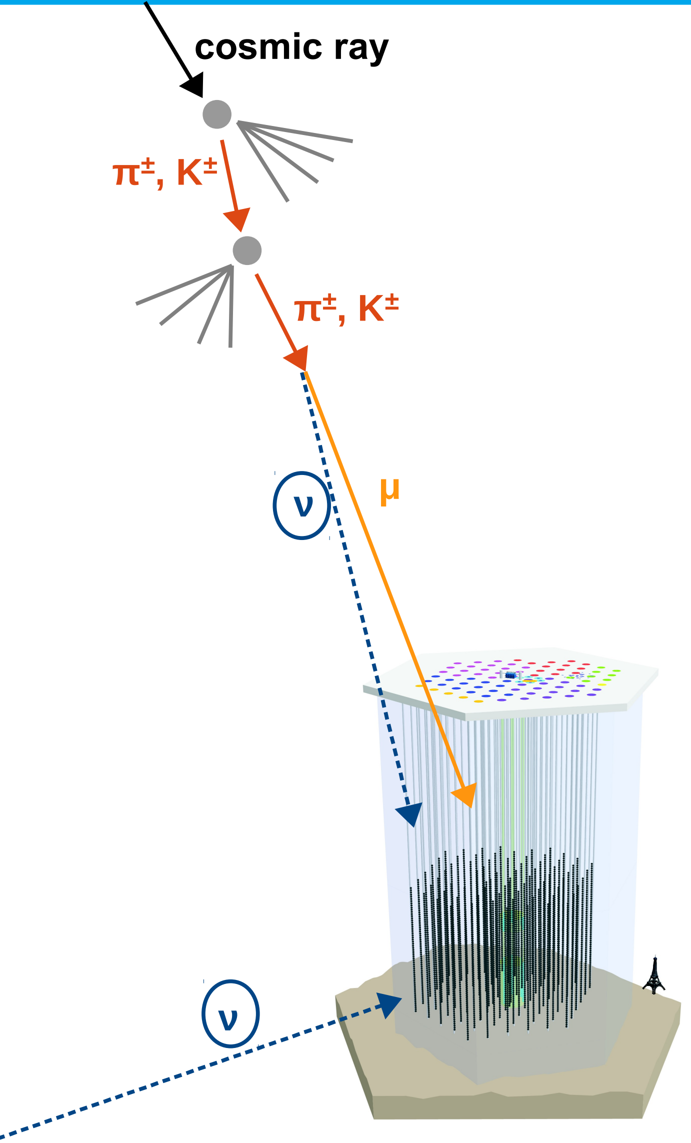


Atmospheric Backgrounds



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

Atmospheric Backgrounds



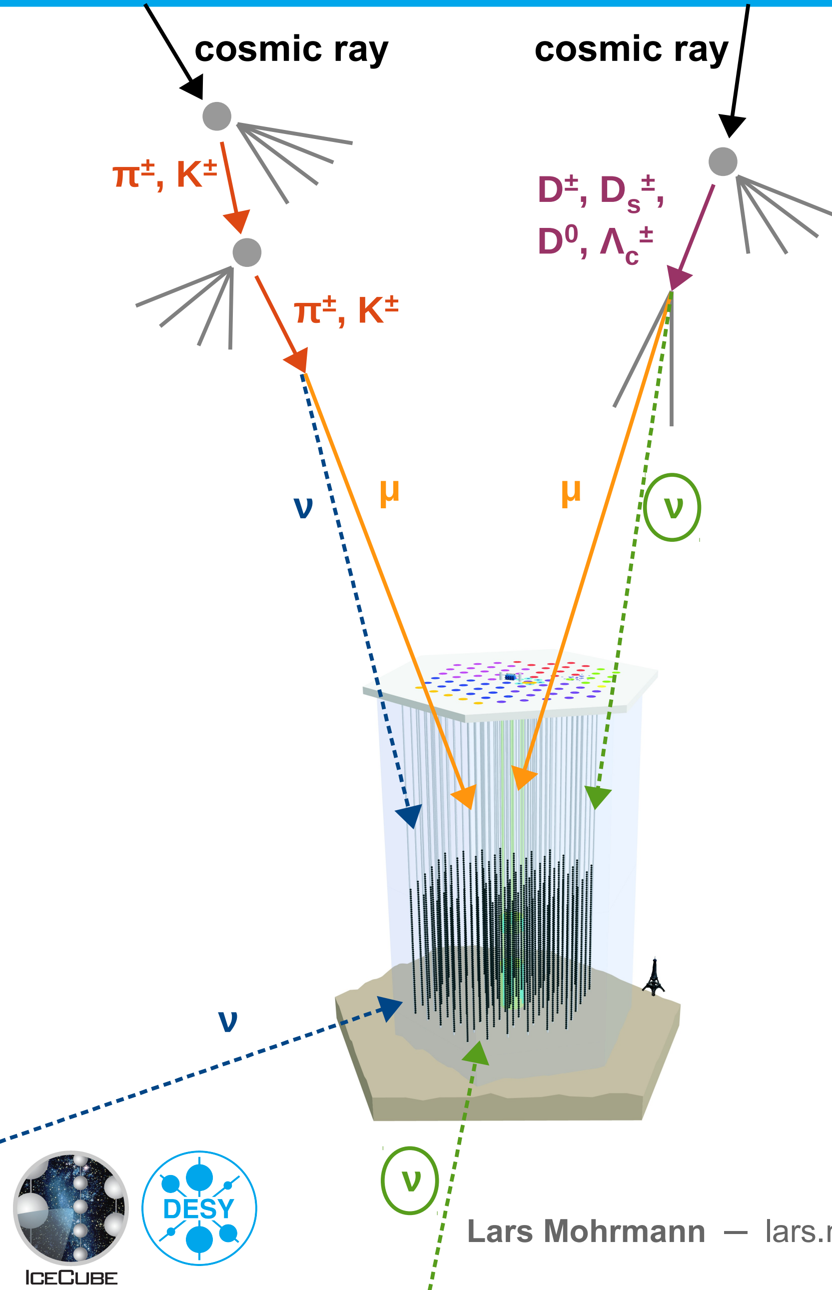
Atmospheric muons

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

"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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- Detection rate: ~ 250 million / day
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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

> "Prompt" atmospheric neutrinos

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

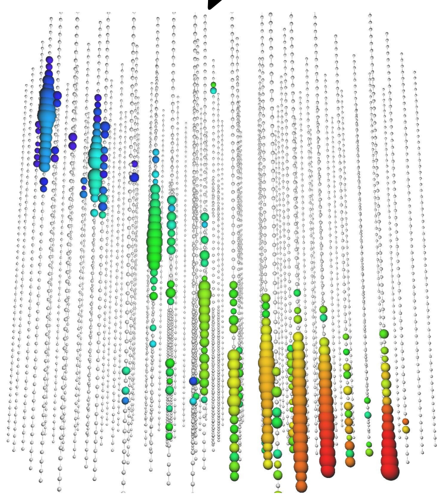
Searching for Cosmic Neutrinos with IceCube

Search for upgoing / horizontal tracks

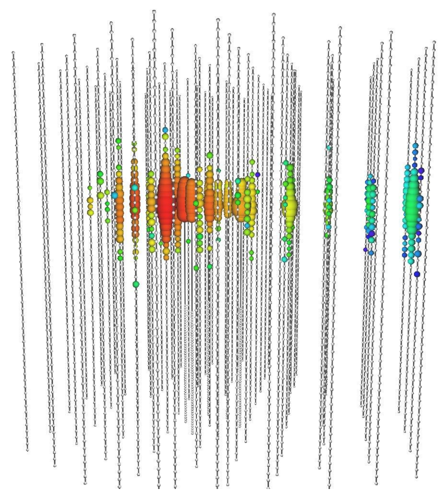
- **Effective area:** $\gg$ detector
- **Muon background:** negligible
- **Channel:** charged-current ν_μ
- **Sky coverage:** northern sky

Search for starting events

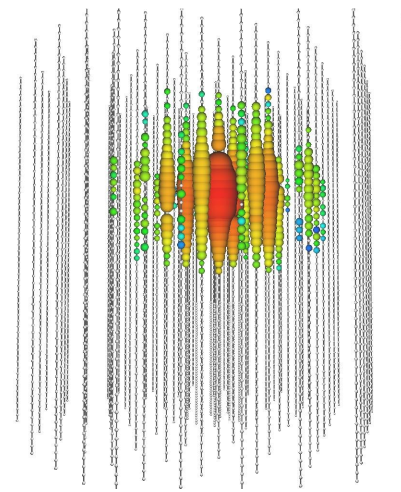
- **Effective area:** $\lesssim$ detector
- **Muon background:** yes
- **Channel:** all
- **Sky coverage:** full



“throughgoing track”



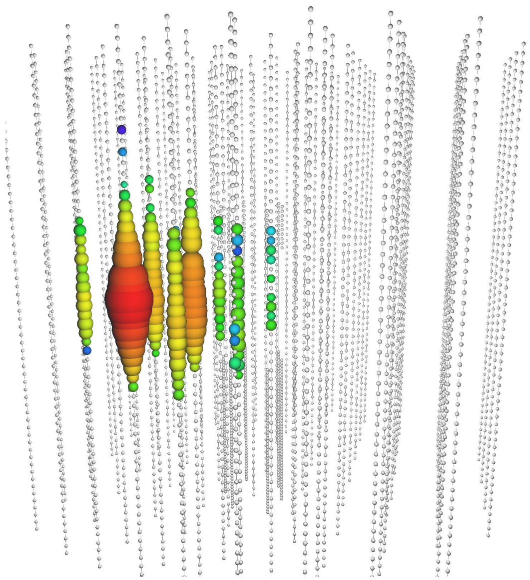
“starting track”



“contained shower”

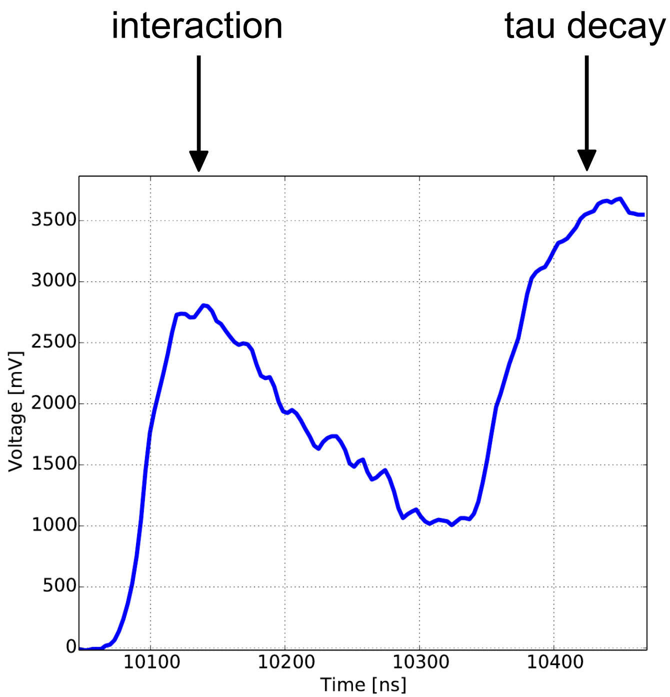
Searching for Cosmic Neutrinos with IceCube

> **Search for partially contained showers**
- **New!**
- Enlarge effective area at high energies



"partially contained shower"

> **Search for double pulse events**
- **New!**
- Identify tau neutrinos



"double pulse"

Combined Analysis

- Combine results from **8 different searches**

ID	Signatures	Observables	Period
T1	throughgoing tracks	energy, zenith	2009–2010
T2	throughgoing tracks	energy, zenith	2010–2012
S1	cont. showers	energy	2008–2009
S2	cont. showers	energy	2009–2010
H1*	cont. showers, starting tracks	energy, zenith	2010–2014
H2	cont. showers, starting tracks	energy, zenith, signature	2010–2012
DP*	double pulse waveform	signature	2011–2014
PS*	part. cont. showers	energy	2010–2012

- Determine **energy spectrum** and **flavor composition** in a **joint fit**
- **Full details** can be found in:
  M. G. Aartsen et al. (IceCube Collaboration), “A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube”, ApJ **809** (2015), 98
  arXiv:1507.03991

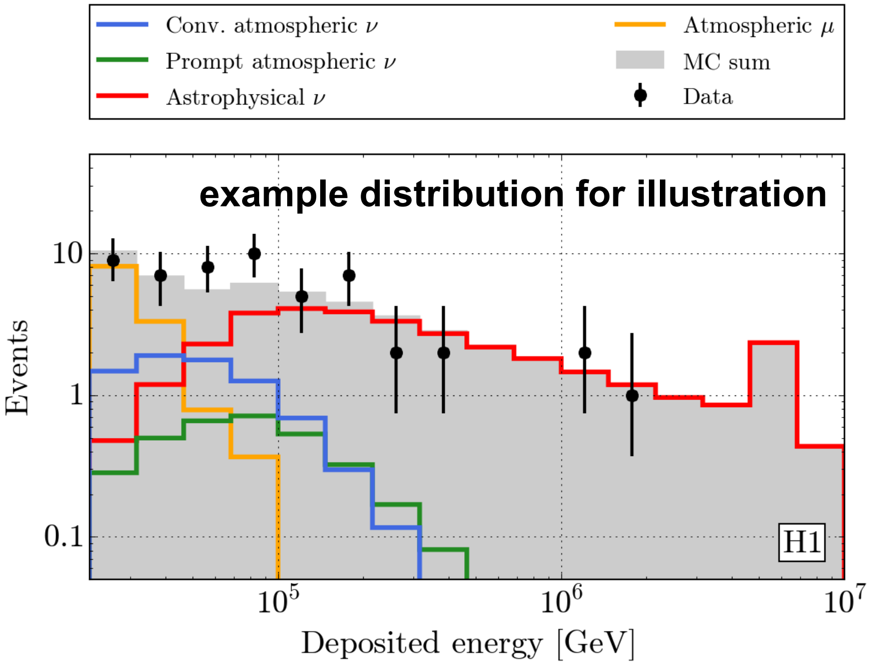
Analysis Method

> "Forward-folding" likelihood fit

- Fold models for background and signal fluxes with detector response
  → templates in observable space
- Compare templates with experimental data
- Vary model parameters until best agreement is reached
- Systematic uncertainties incorporated as nuisance parameters

> Models

- **Atmospheric muons**
  CORSIKA simulation
- **Conventional atmospheric neutrinos**
  HKKMS (Honda et al. 2007)
- **Prompt atmospheric neutrinos**
  ERS (Enberg et al. 2008)
- **Astrophysical neutrinos**
  ???



Signal Hypotheses

Energy spectrum

- **Benchmark model:** Fermi acceleration at shock fronts
  $\rightarrow \quad \Phi_\nu \propto E^{-2}$
- Actual spectrum depends on source class
- **Hypothesis A:** $\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$
- **Hypothesis B:** $\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times \exp(-E/E_{\mathrm{cut}})$

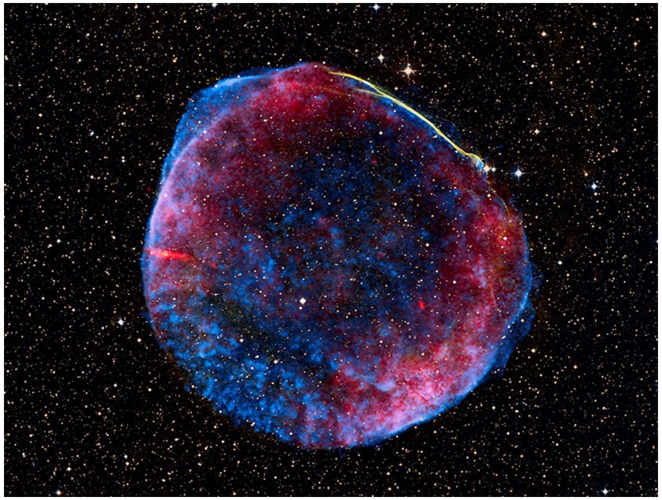


Image credit: NASA, ESA, and Zolt Levay (STScI)

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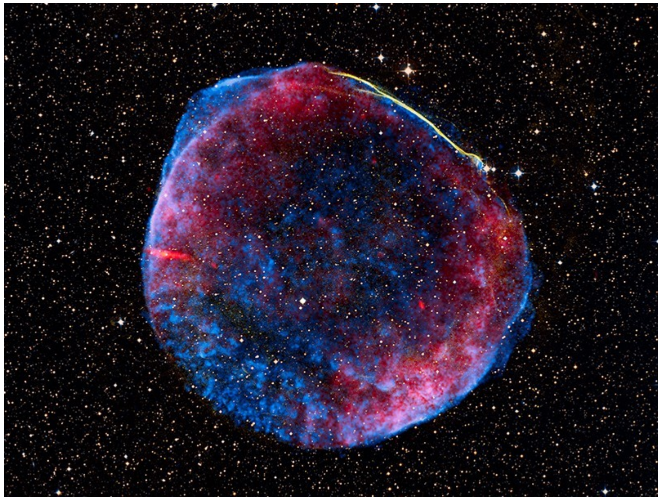


Image credit: NASA, ESA, and Zolt Levay (STScl)

Flavor composition

- **Pion-decay:** $\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$
- **Muon-damped:** $\nu_e : \nu_\mu : \nu_\tau = 0:1:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 0.22:0.39:0.39$
- **Neutron-decay:** $\nu_e : \nu_\mu : \nu_\tau = 1:0:0 \longrightarrow \nu_e : \nu_\mu : \nu_\tau \sim 0.56:0.22:0.22$
- **Fit:** allow any composition

Results – Energy Spectrum

- **Assume isotropic flux and** $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

Results – Energy Spectrum

- **Assume isotropic flux and** $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

- **Best fit hypothesis A:**
  - $\Phi_\nu = \left(7.0^{+1.0}_{-1.0}\right) \times 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.49\pm0.08}$ (all-flavor!)
  - E^{-2} excluded at $4.6\,\sigma$

Results – Energy Spectrum

- Assume isotropic flux and $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

- Best fit hypothesis A:

  all-flavor!

  - $$\Phi_\nu = \left(7.0^{+1.0}_{-1.0}\right) \times 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.49\pm0.08}$$
  - E^{-2} excluded at $4.6\,\sigma$

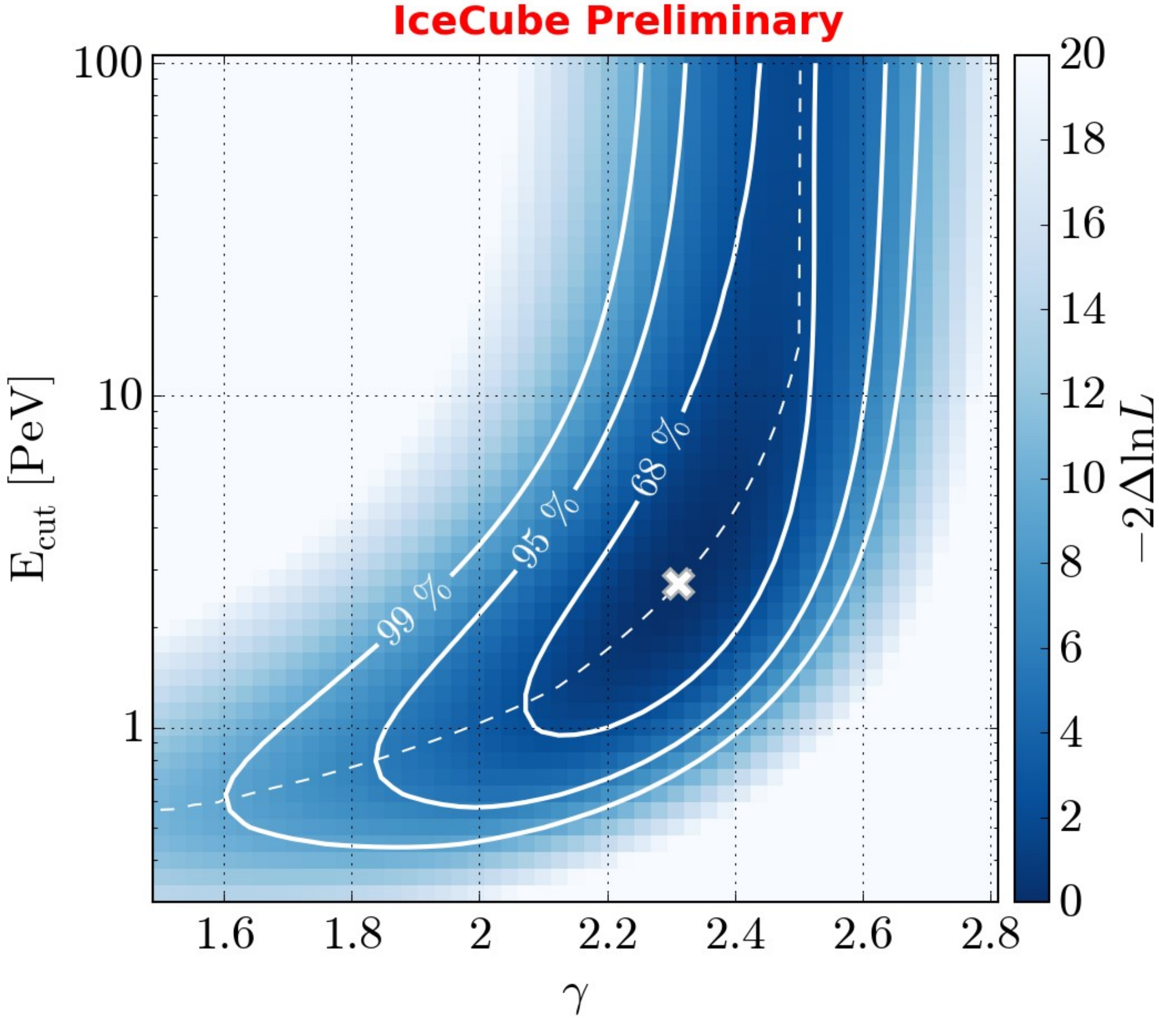
- Best fit hypothesis B:

  all-flavor!

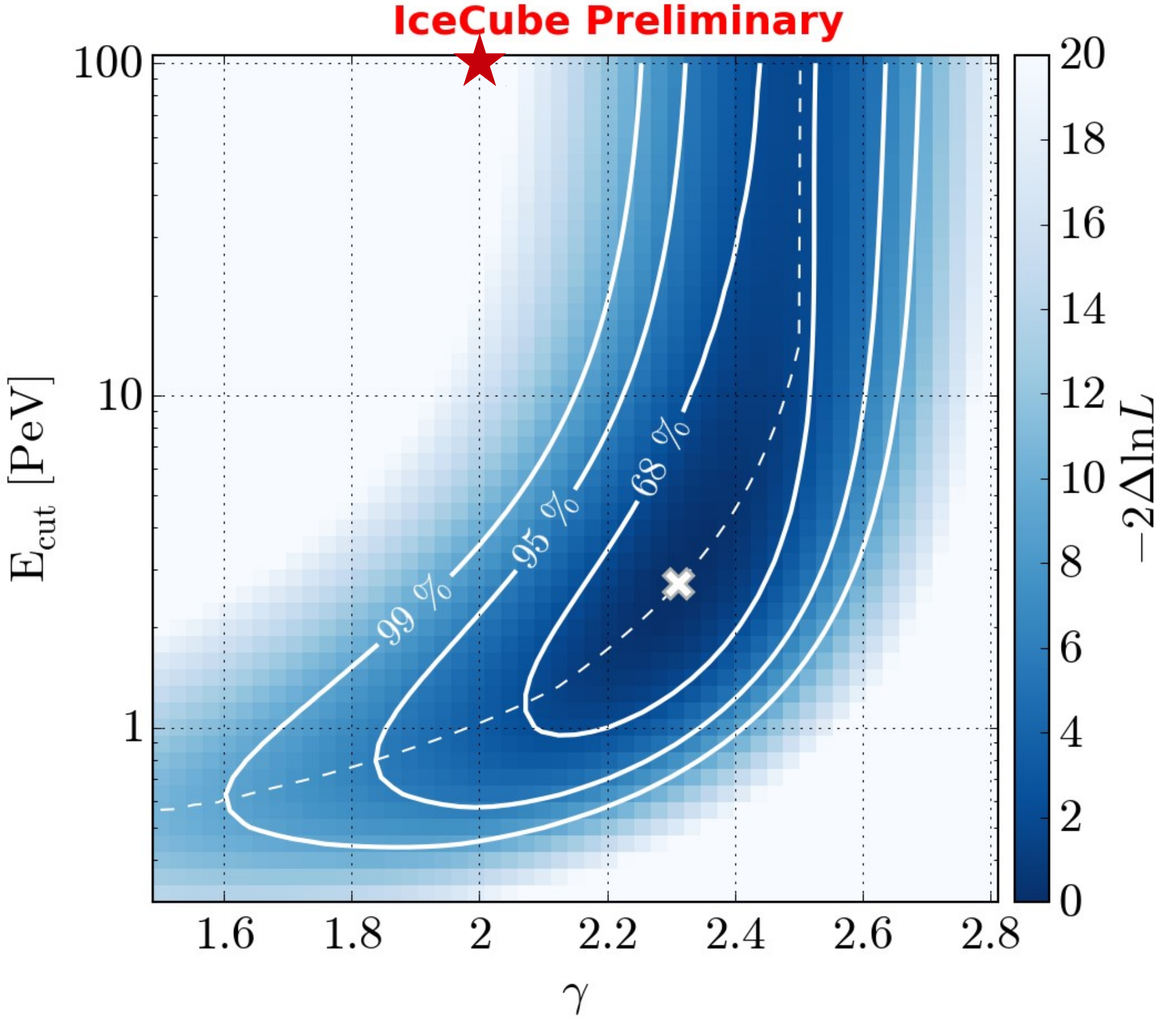
  - $$\Phi_\nu = \left(8.0^{+1.3}_{-1.2}\right) \times 10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.31\pm0.15} \times \exp\left(-E/\left(2.7^{+7.7}_{-1.4}\right)\,\mathrm{PeV}\right).$$
  - preferred over hypothesis A by $1.2\,\sigma$

- Both models describe the data well

- Profile likelihood scan



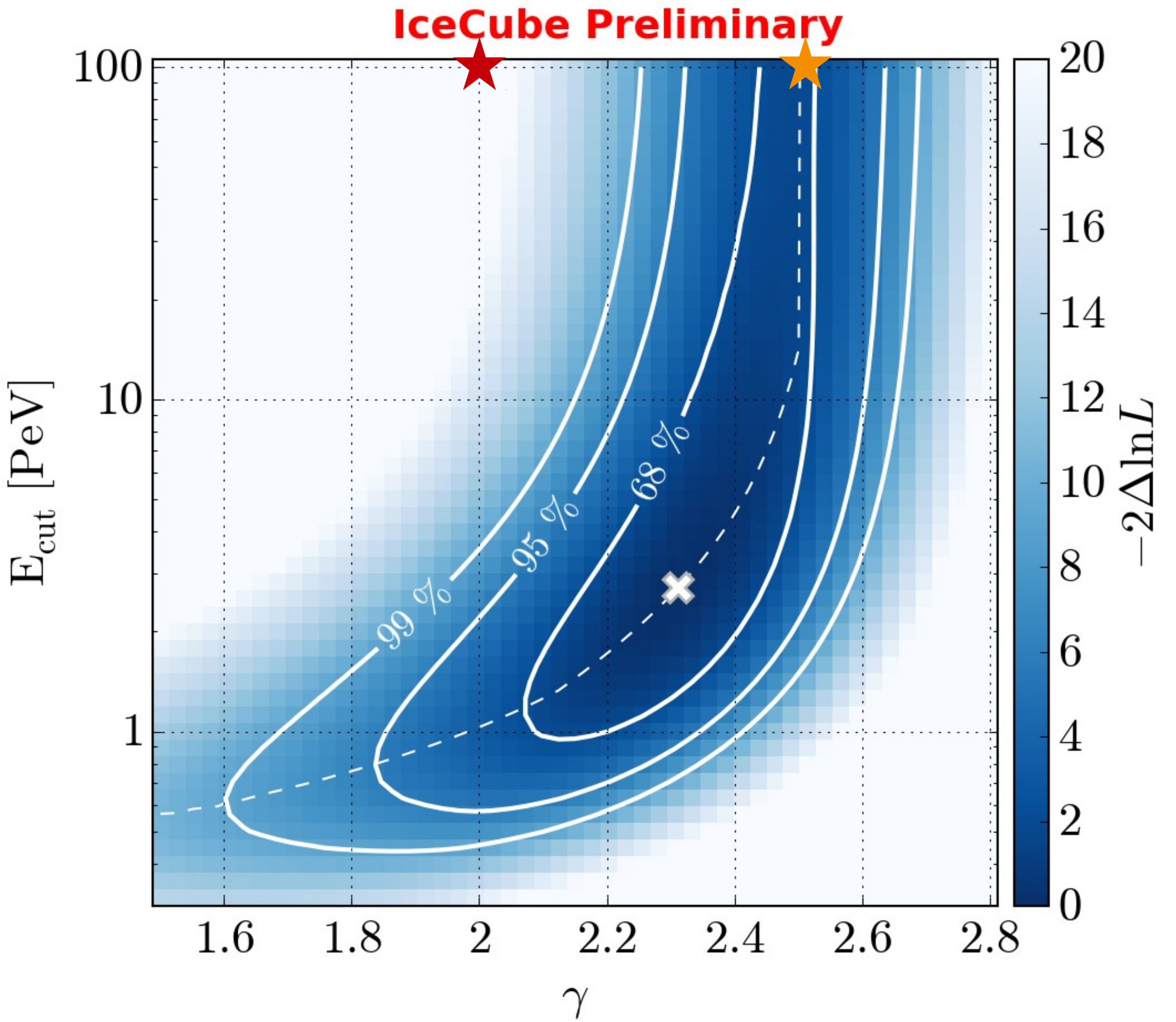
- **Profile likelihood scan**
  - E^{-2}, no cut-off



Results – Energy Spectrum

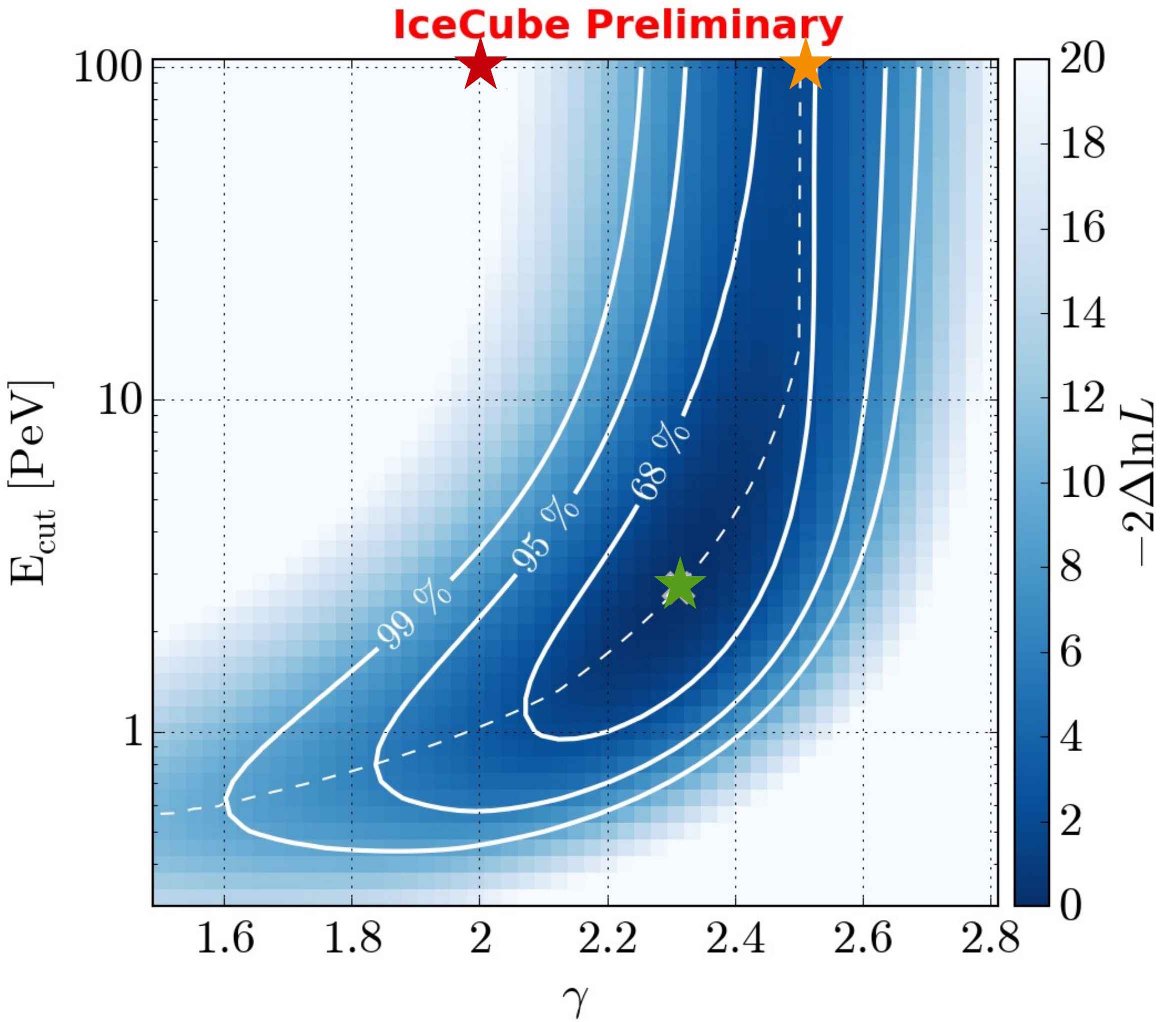
- **Profile likelihood scan**
  - E^{-2}, **no cut-off**

    $\Updownarrow$ $4.6\,\sigma$
  - $E^{-2.49}$, **no cut-off**



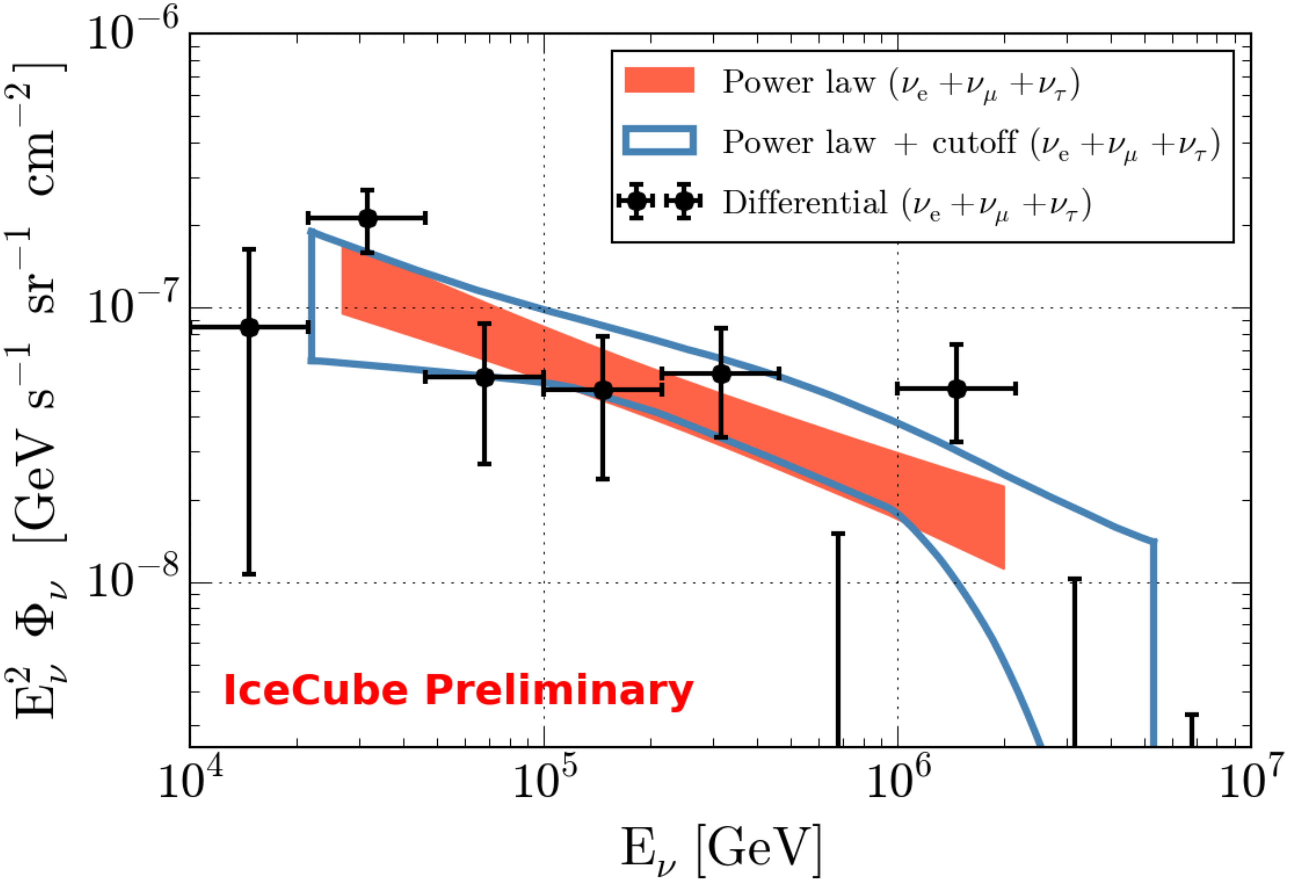
Results – Energy Spectrum

- **Profile likelihood scan**
  - E^{-2}, **no cut-off**
  - $\Updownarrow$ $4.6\,\sigma$
  - $E^{-2.49}$ **, no cut-off**
  - $\Updownarrow$ $1.2\,\sigma$
  - $E^{-2.31}$ **, cut-off at** $2.7\,\mathrm{PeV}$

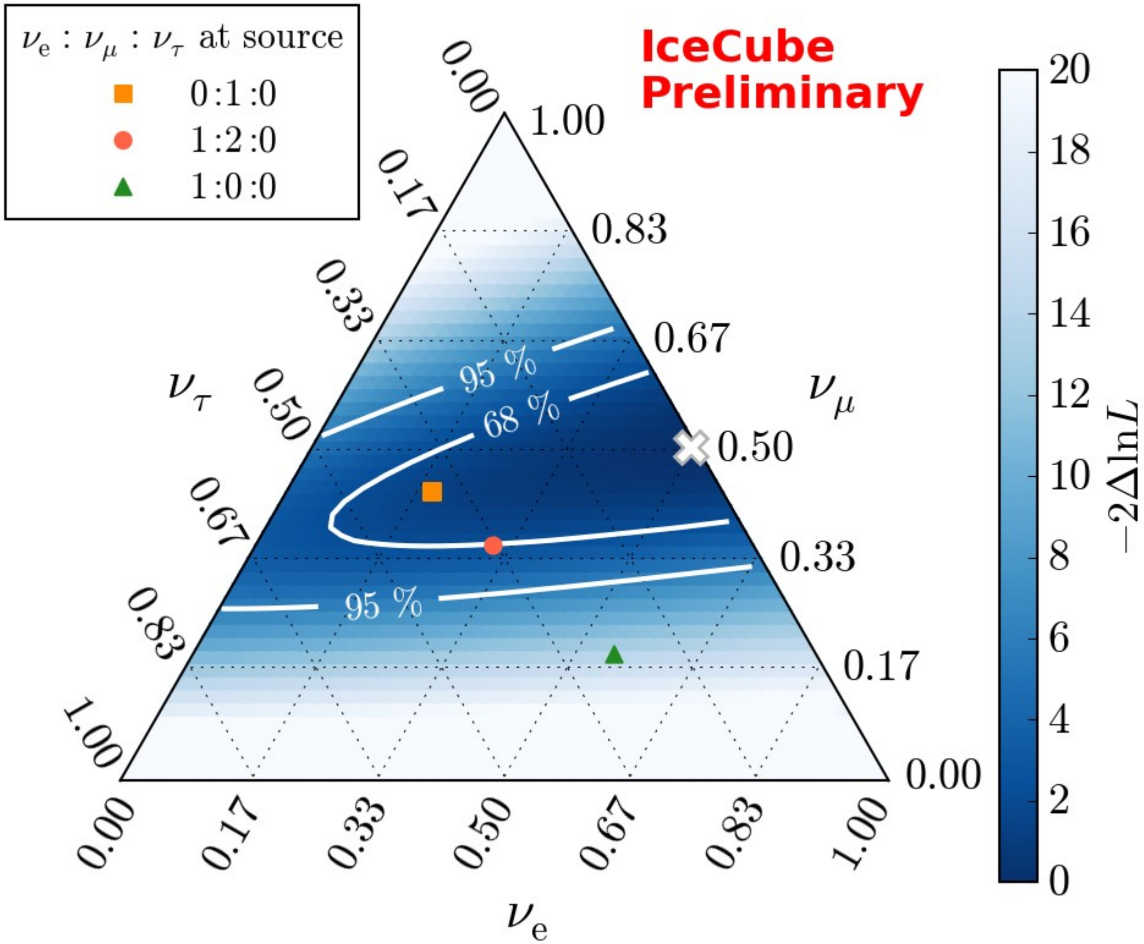


Results – Energy Spectrum

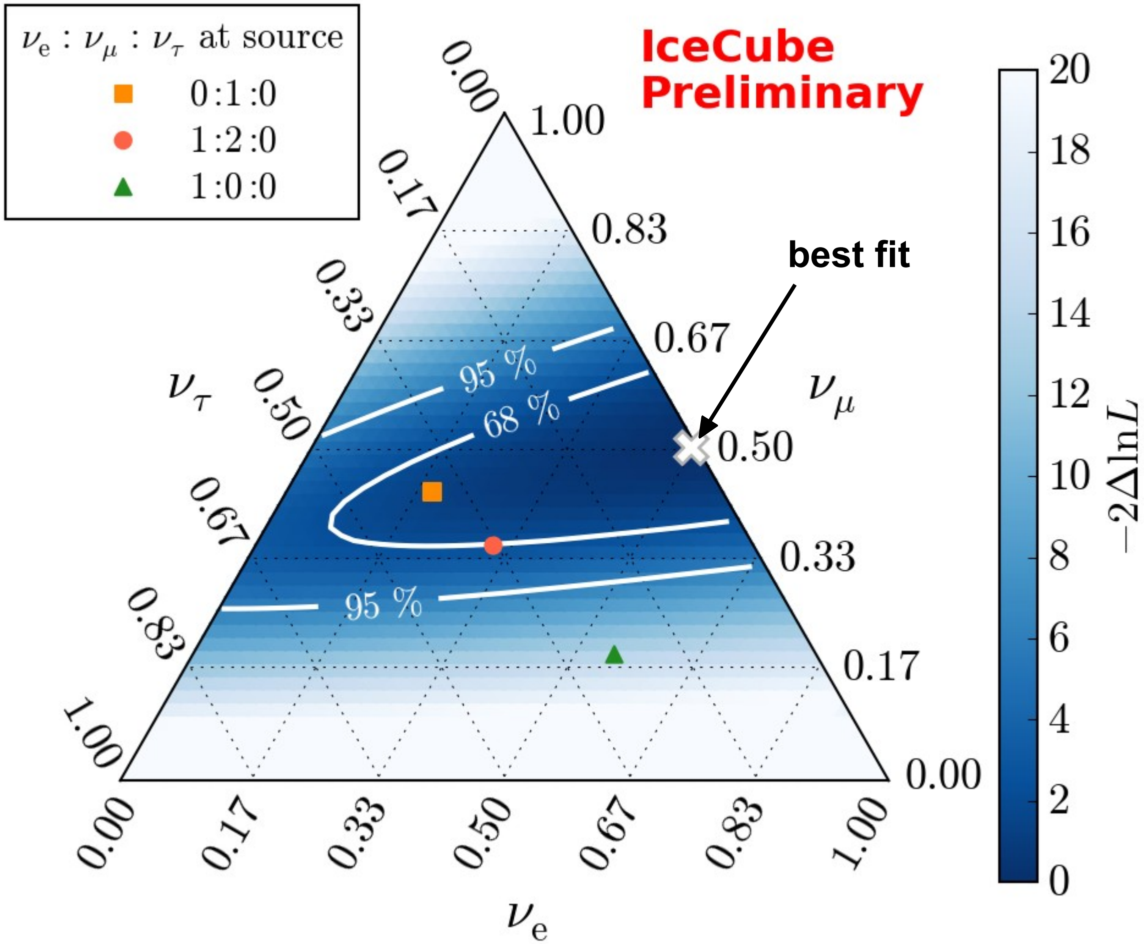
- All-flavor neutrino energy spectrum

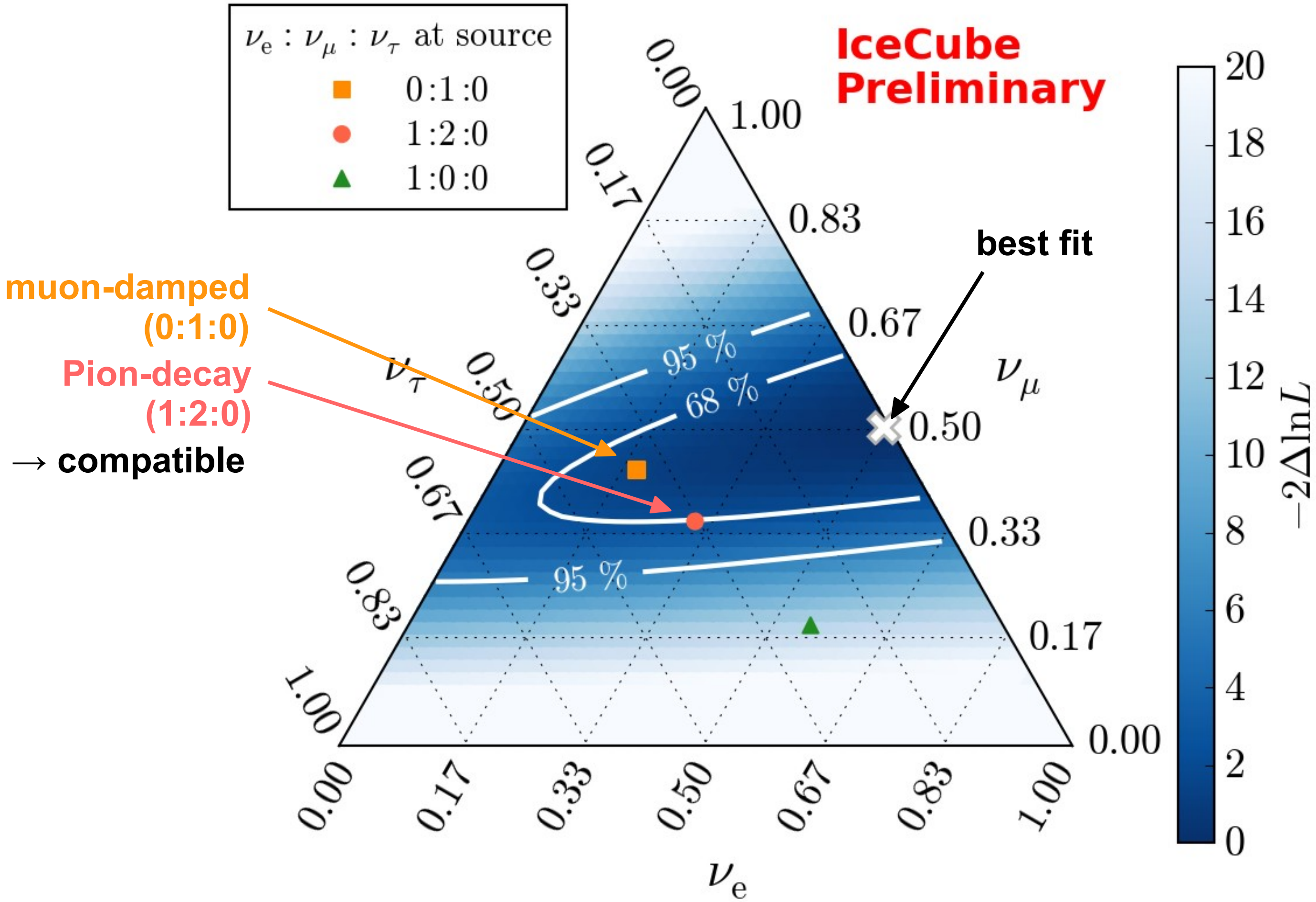


Results – Flavor Composition



Results – Flavor Composition





$\nu_e : \nu_\mu : \nu_\tau$ at source
0:1:0
1:2:0
1:0:0
IceCube Preliminary
best fit
muon-damped (0:1:0)
Pion-decay (1:2:0)
→ compatible
95 %
68 %
95 %
ν_τ
ν_μ
ν_e
0.00
0.17
0.33
0.50
0.67
0.83
1.00
$-2\Delta \ln L$
0
2
4
6
8
10
12
14
16
18
20

Results – Flavor Composition

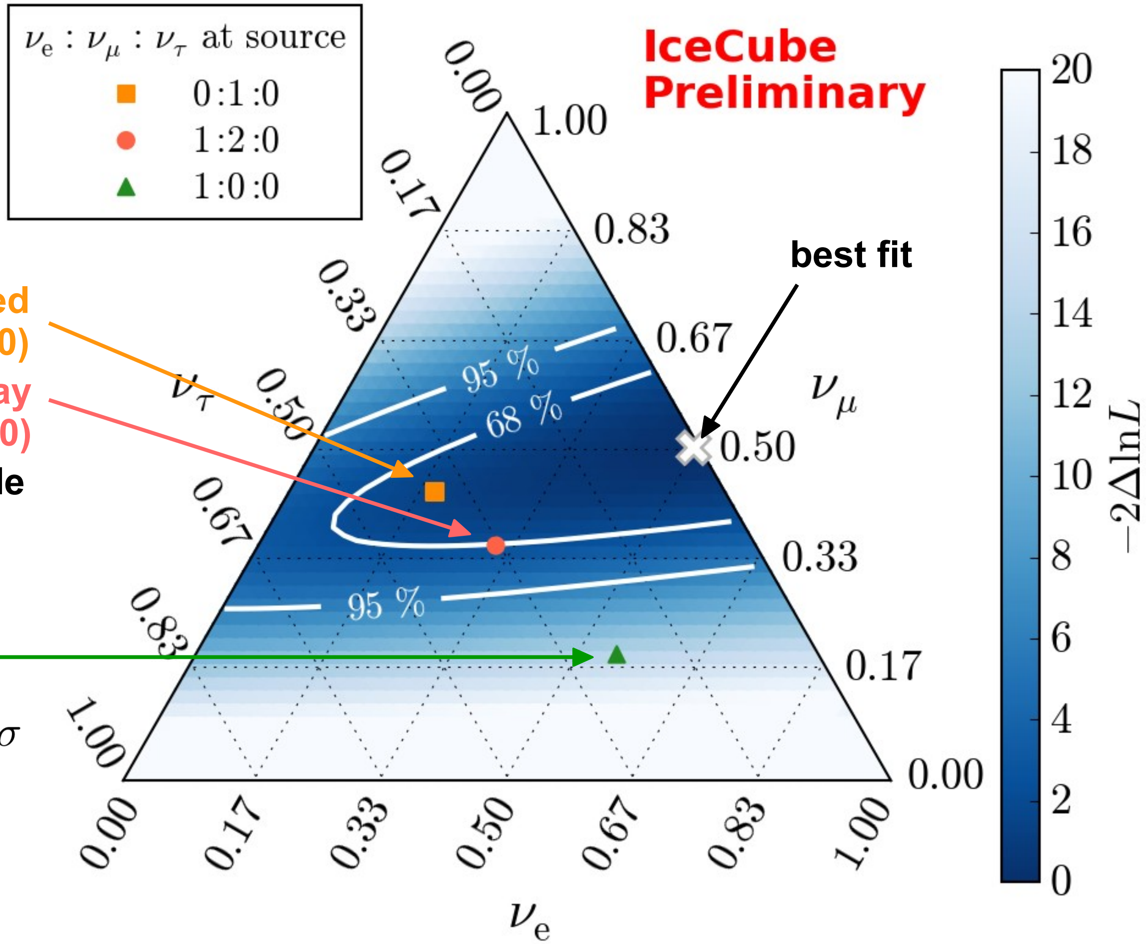
muon-damped (0:1:0)

Pion-decay (1:2:0)

→ **compatible**

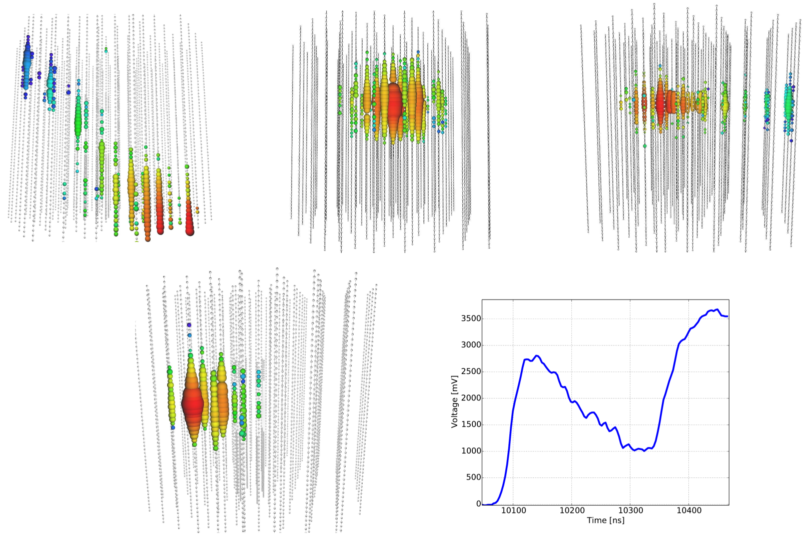
Neutron-decay (1:0:0)

→ **excluded at** $3.7\,\sigma$



Projection of Sensitivities

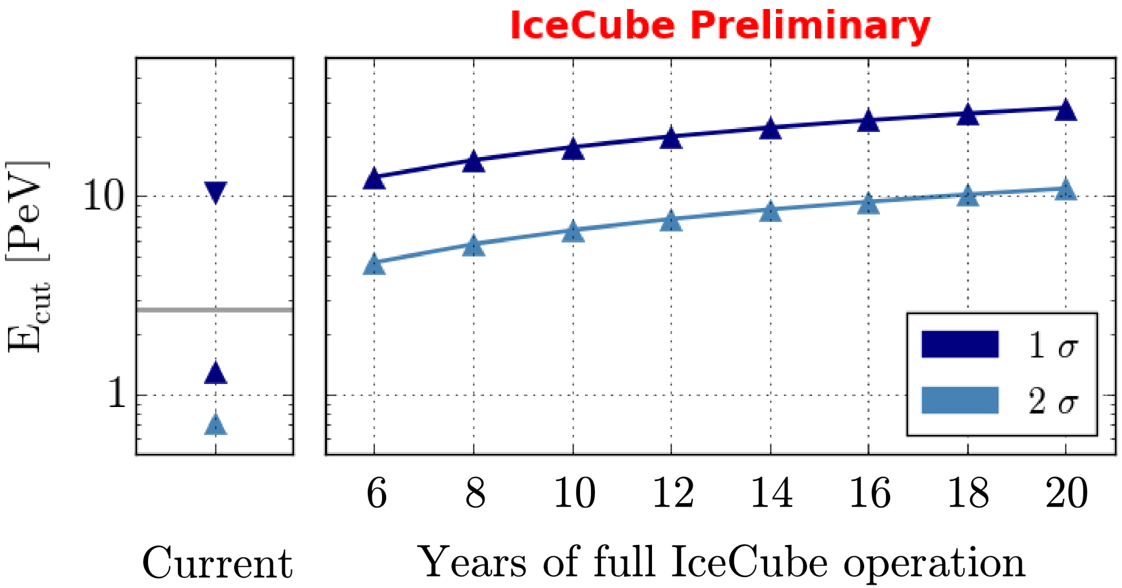
- **Use most recent event samples**
  - **T2** → throughgoing tracks
  - **H2** → contained showers + starting tracks
  - **PS** → partially contained showers
  - **DP** → double pulse waveform events



- **Scale simulation data** to mimic the collection of **additional data**
  - Use current best-fit fluxes as input

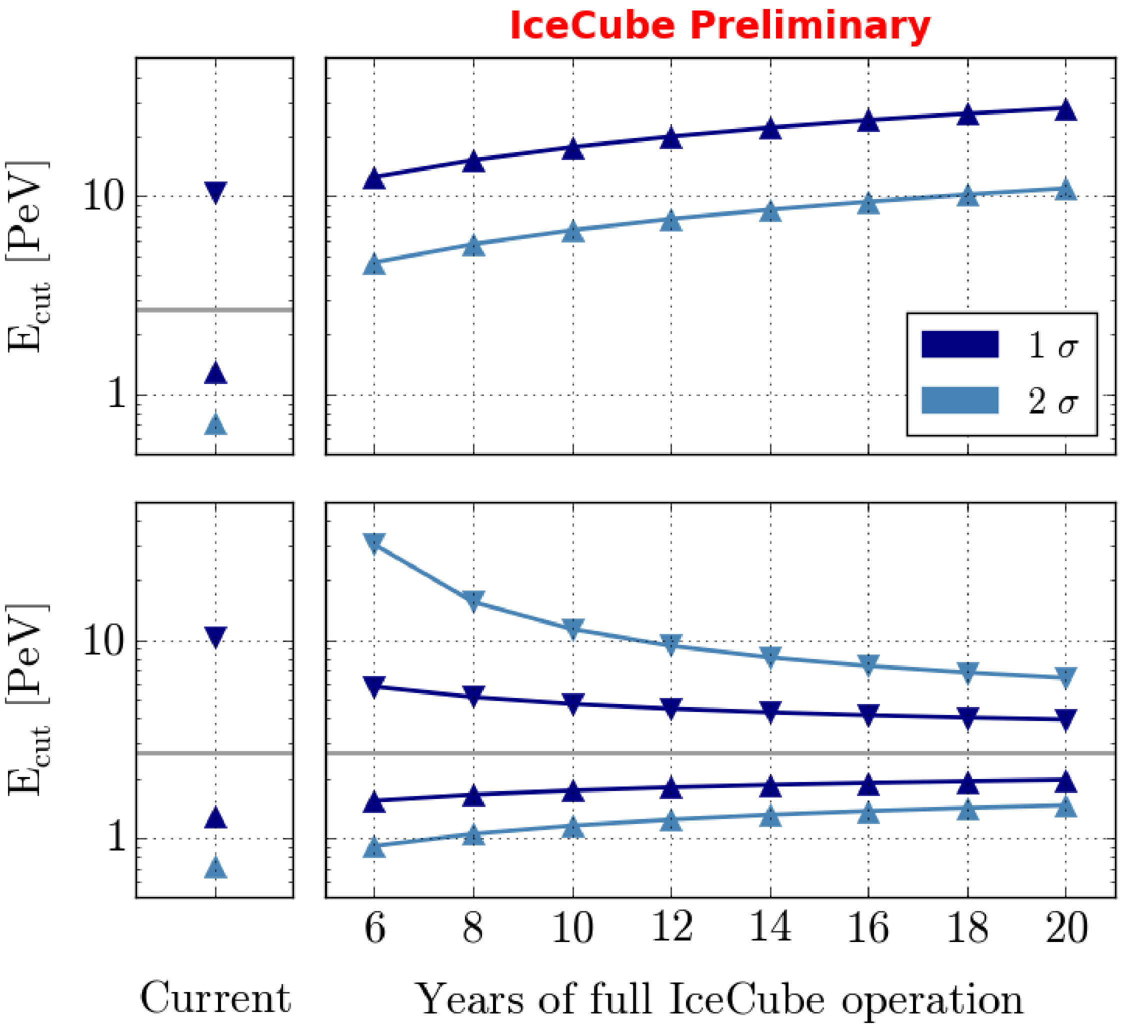
- Perform analysis with the **“Asimov data set”** (Cowan et al. 2011)
  - One “representative” data set (based on input flux)
  - → obtain **median sensitivity**

Sensitivity – Energy Spectrum



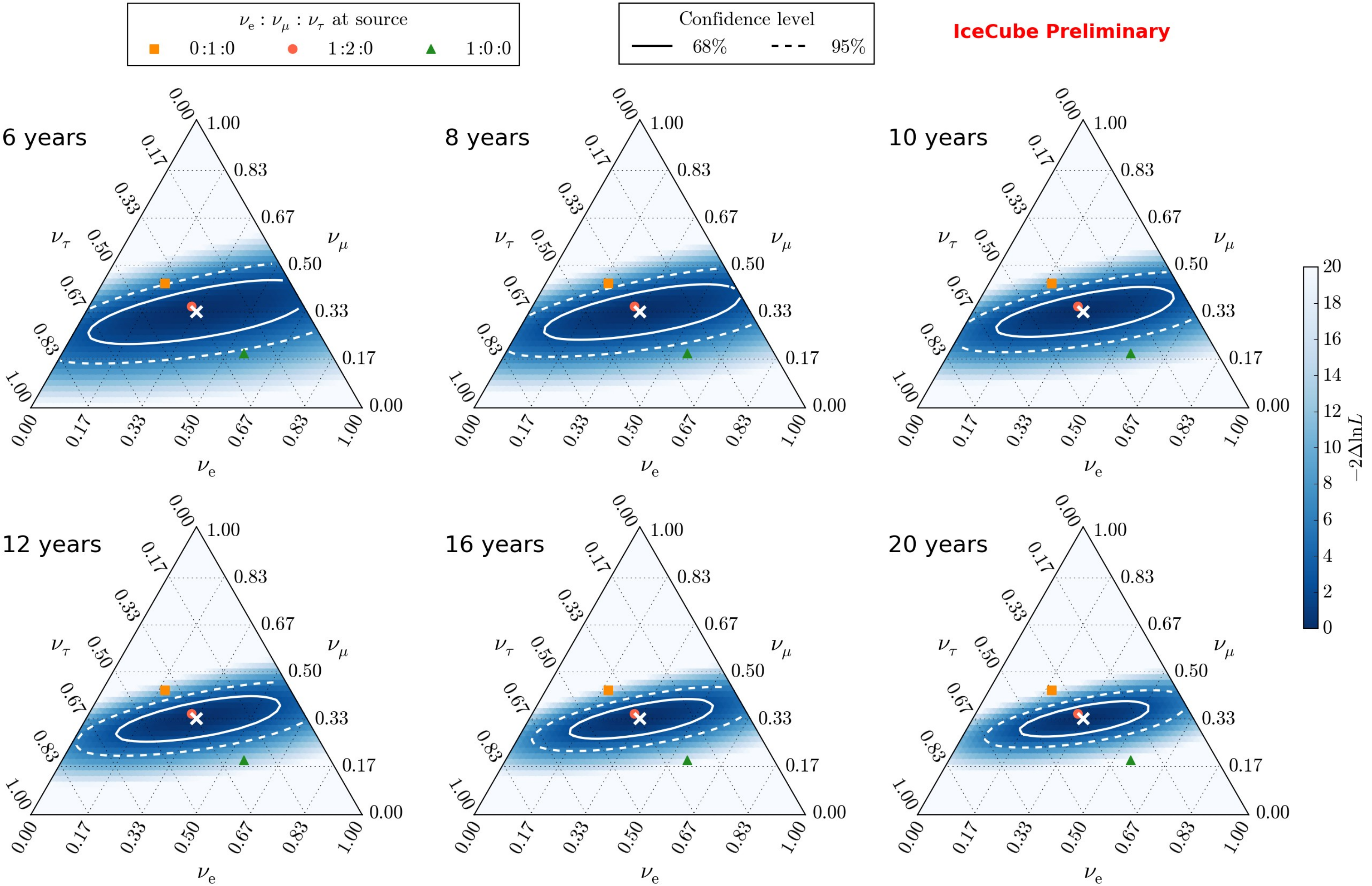
- **Hypothesis A true**
  - $E^{-2.49}$, **no cut-off**
  - $\rightarrow E_{\mathrm{cut}} > 7.7\,\mathrm{PeV}$ $(2\,\sigma$ C.L.) **for 10 years of data**

Sensitivity – Energy Spectrum



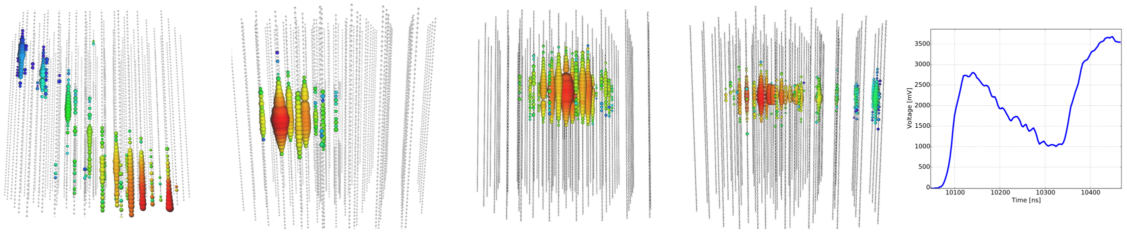
- **Hypothesis A true**
  - $E^{-2.49}$, **no cut-off**
  - $\rightarrow E_{\mathrm{cut}} > 7.7\,\mathrm{PeV}$ $(2\,\sigma$ C.L.) **for 10 years of data**
- **Hypothesis B true**
  - $E^{-2.31}$, **cut-off at** $2.7\,\mathrm{PeV}$
  - $\rightarrow$ **presence of cut-off can be established at** $3\,\sigma$ **with 10 years of data**

Sensitivity – Flavor Composition

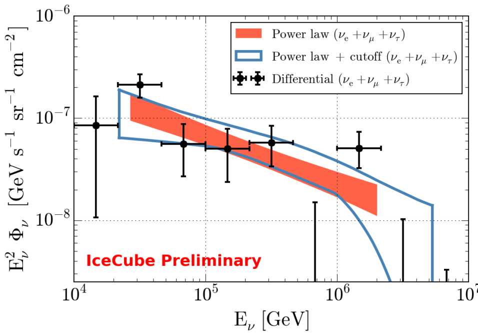


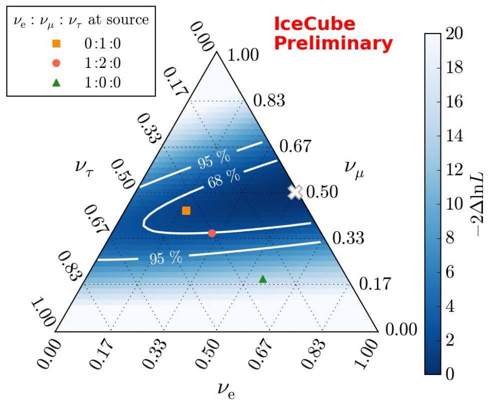
Summary

- **Combined analysis of cosmic neutrino flux**
  - Take into account all signatures
  - Sensitive from ~10 TeV – multi-PeV

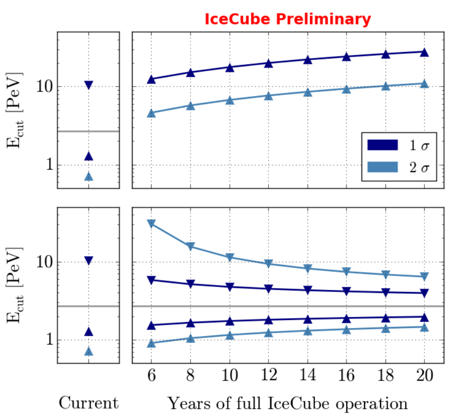


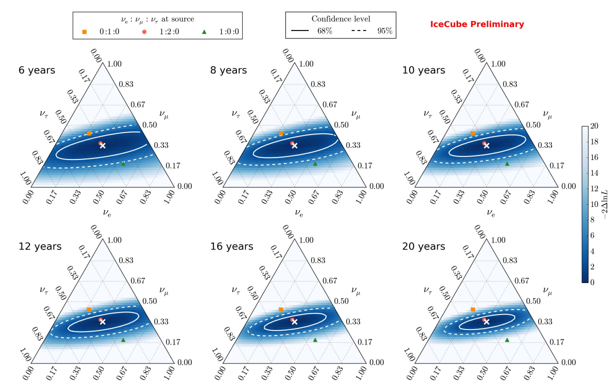
- **Most precise characterization of the flux obtained so far**
  - Energy spectrum
  - Flavor composition





- **Projection of sensitivities**

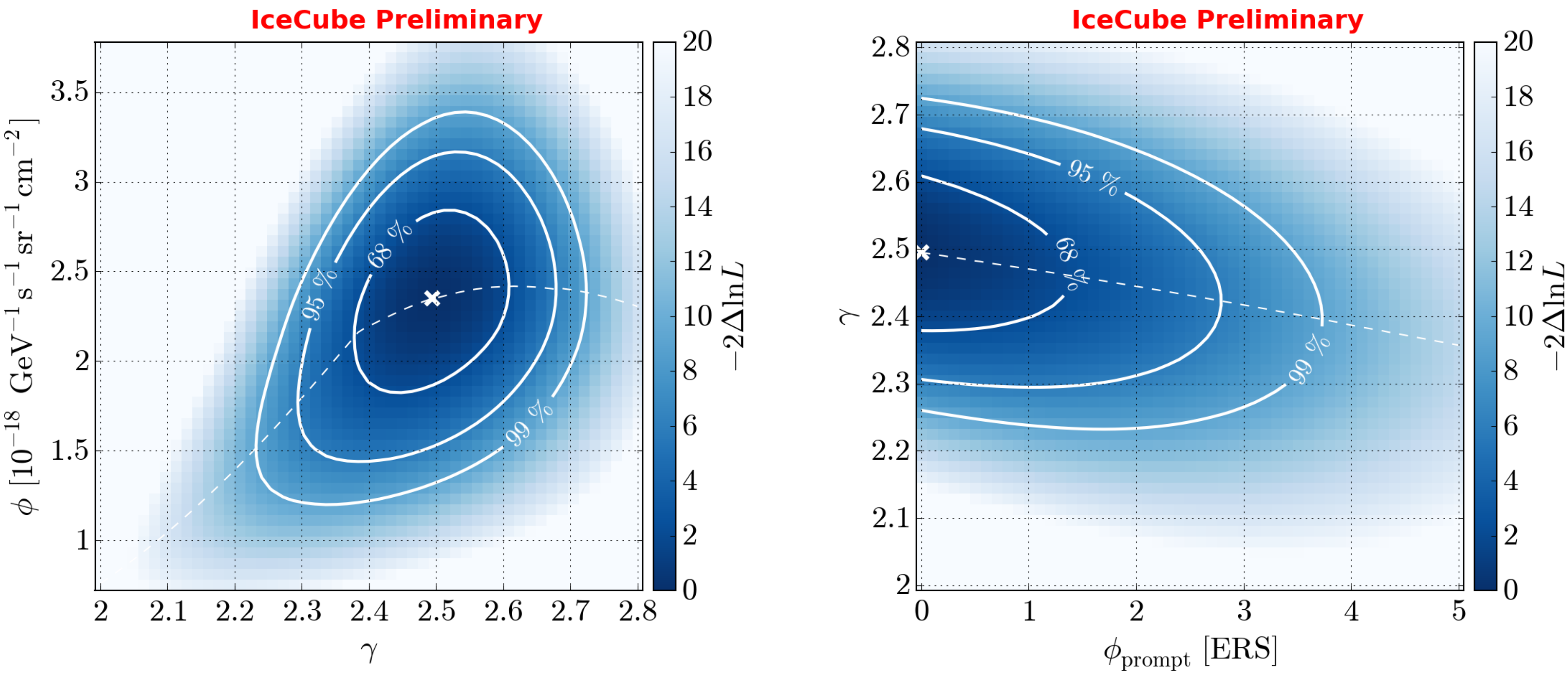




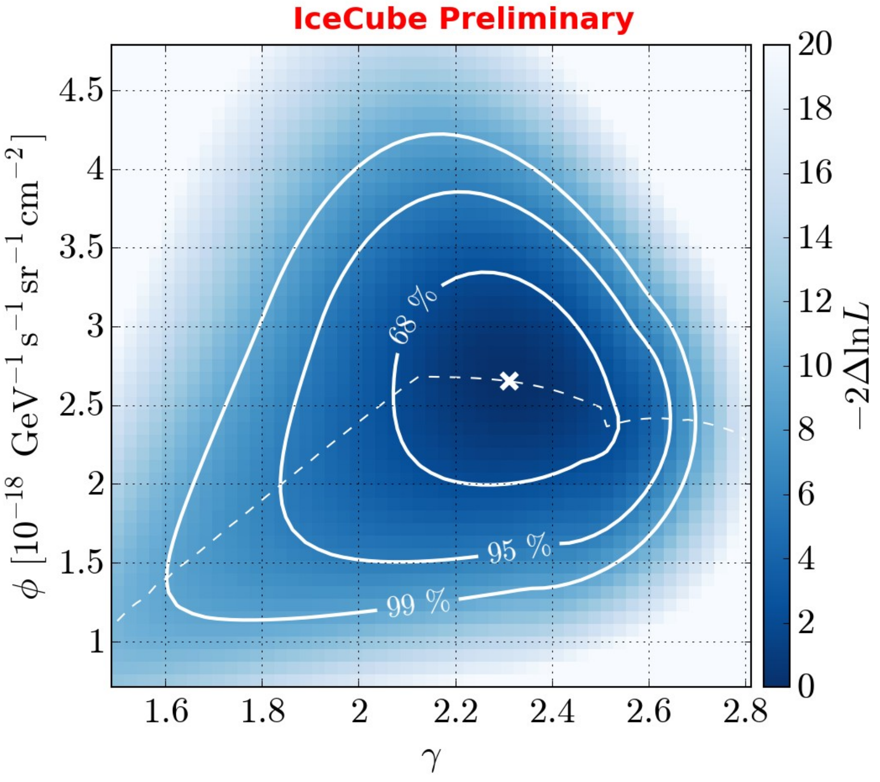
Backup

Results – Energy Spectrum

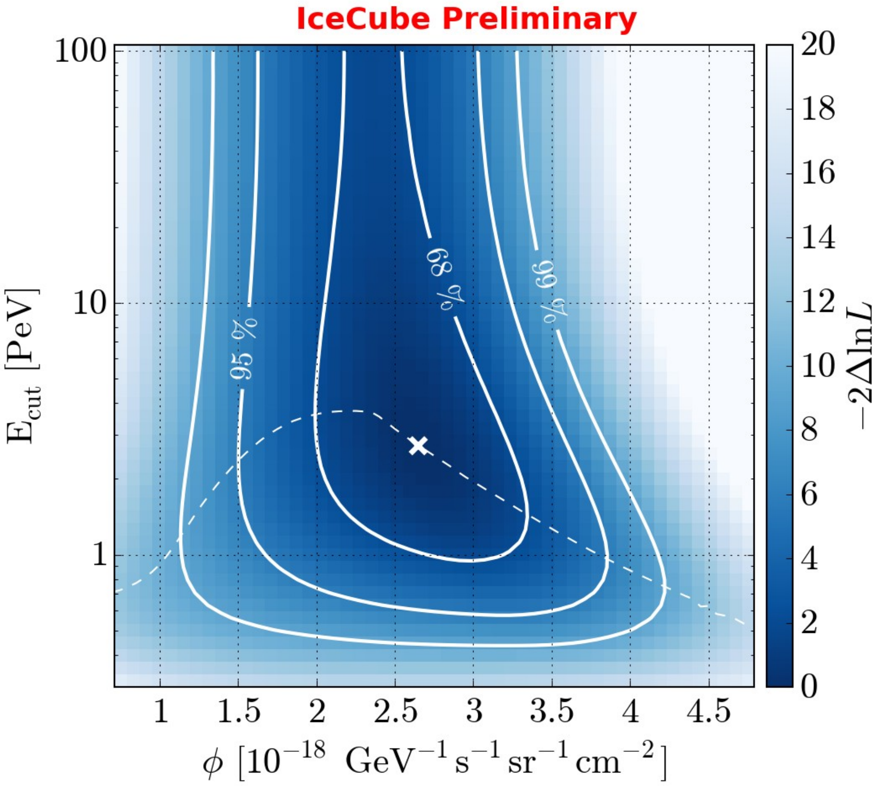
Hyp. 1



Hyp. 2



IceCube Preliminary
ϕ [10^{-18} GeV^{-1}s^{-1}sr^{-1}cm^{-2}]
γ
68 %
95 %
99 %
$-2\Delta\ln L$



IceCube Preliminary
E_{cut} [PeV]
ϕ [10^{-18} GeV^{-1}s^{-1}sr^{-1}cm^{-2}]
68 %
95 %
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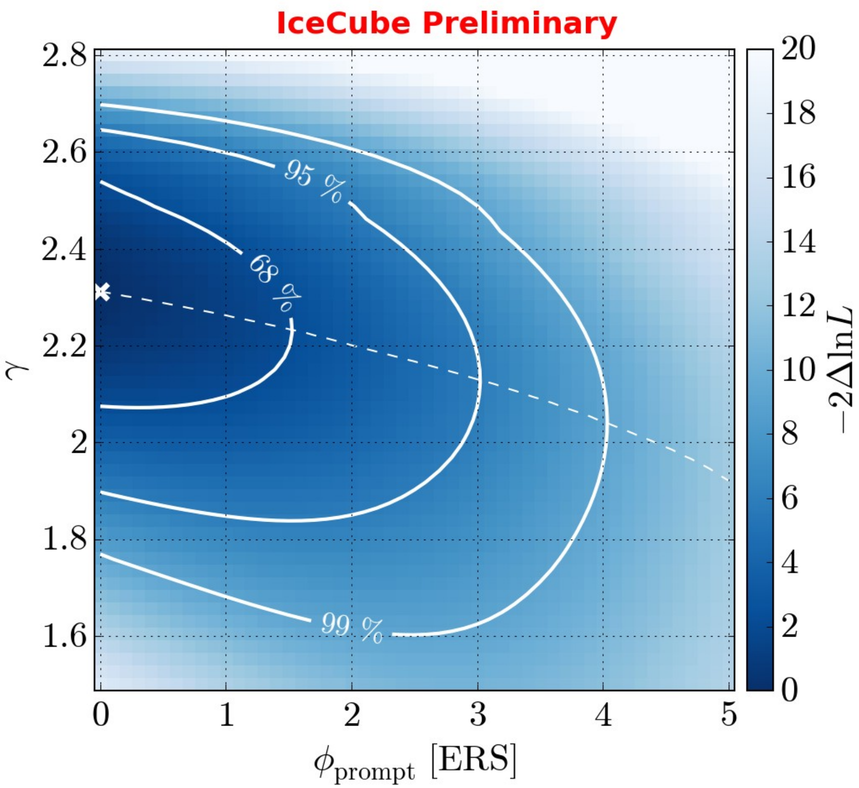
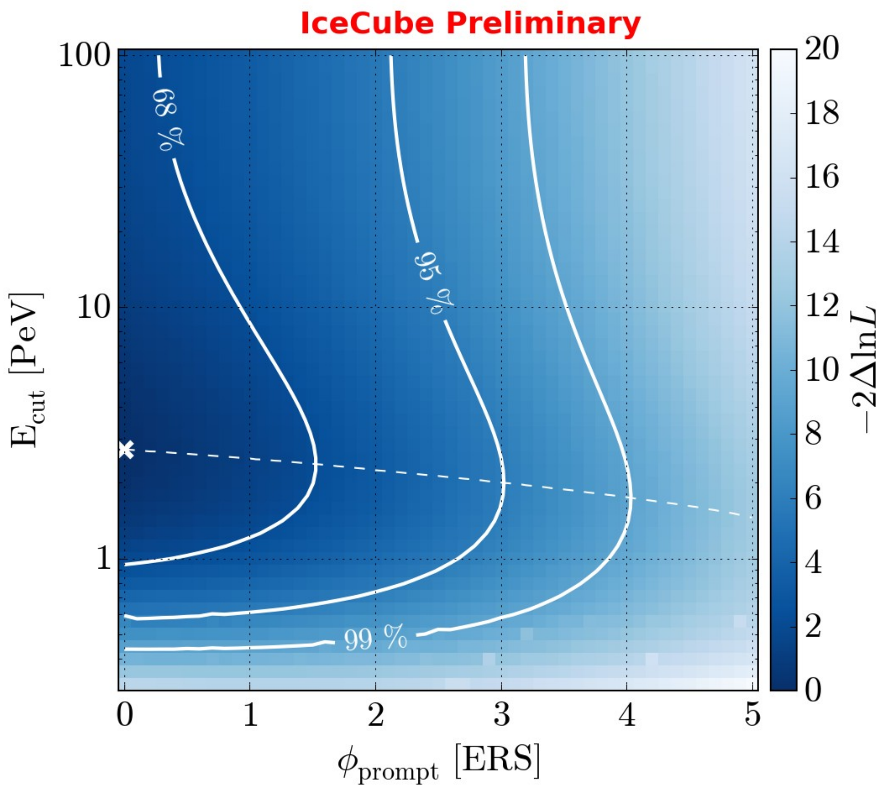
$-2\Delta\ln L$

Hyp. 2


IceCube Preliminary
2.8
2.6
2.4
2.2
2
1.8
1.6
γ
95 %
68 %
99 %
0
1
2
3
4
5
ϕ_{prompt} [ERS]
20
18
16
14
12
10
8
6
4
2
0
$-2\Delta\ln L$


IceCube Preliminary
100
10
1
E_{cut} [PeV]
68 %
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0
1
2
3
4
5
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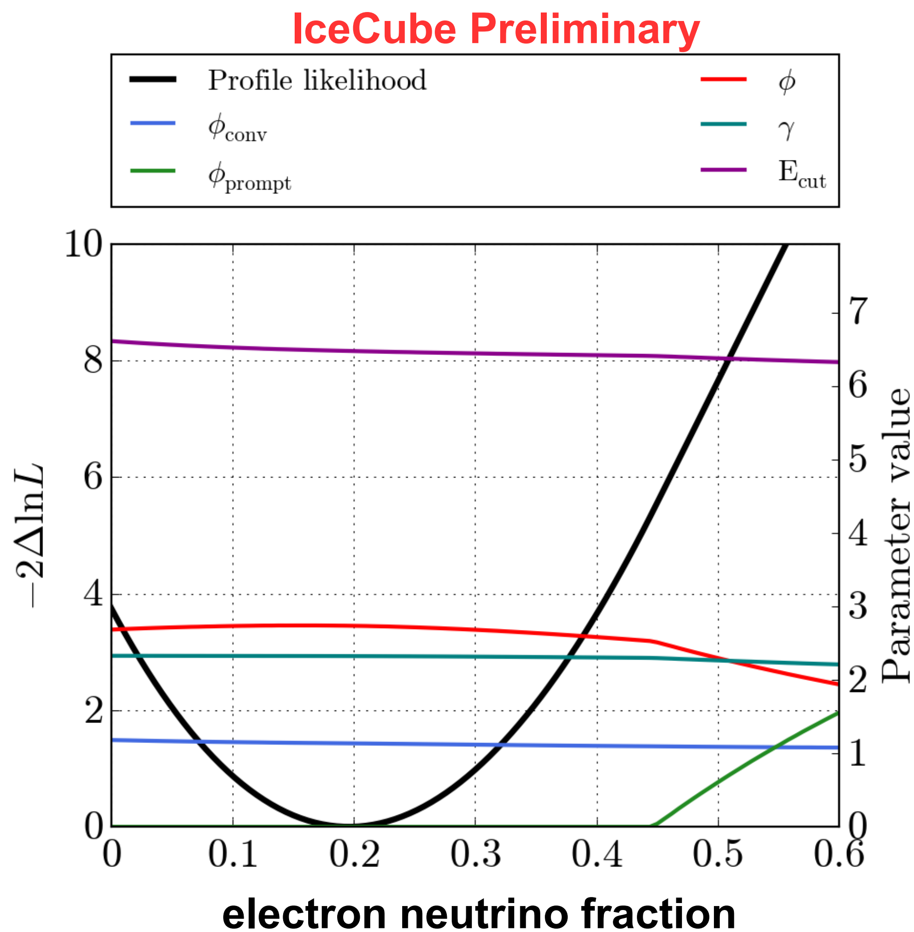
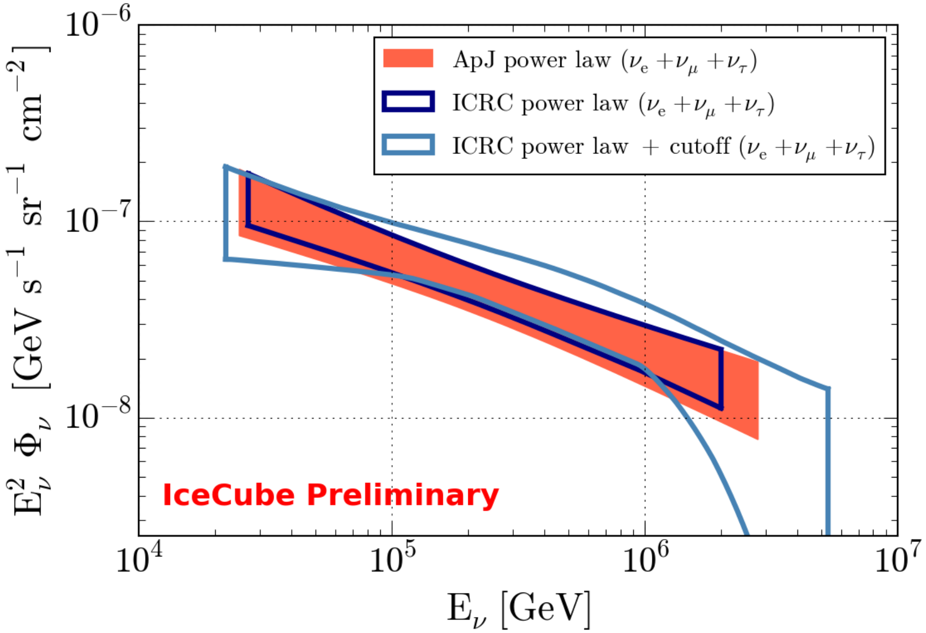
20
18
16
14
12
10
8
6
4
2
0
$-2\Delta\ln L$

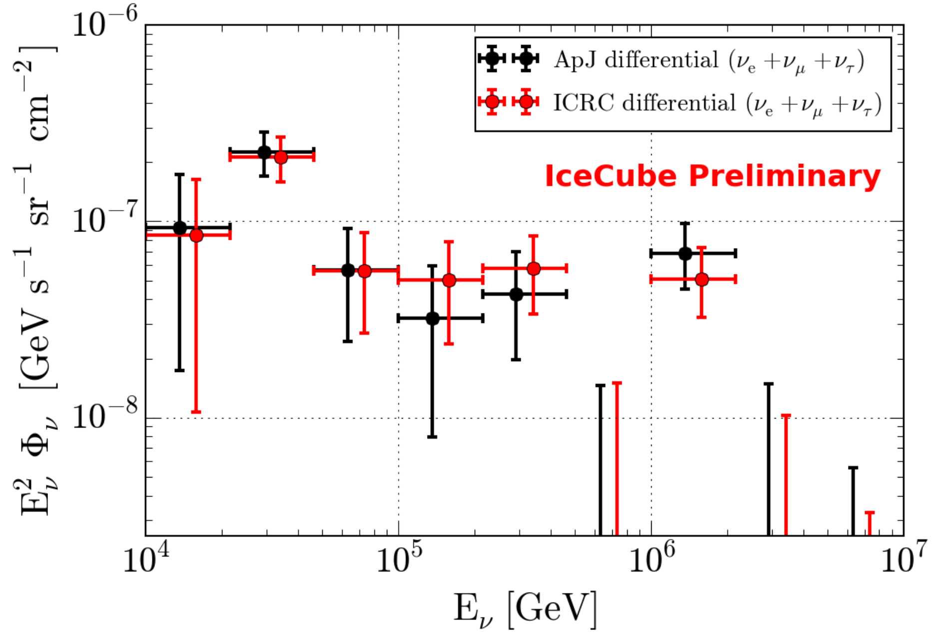
Results – Flavor Composition

- Force $\phi_\mu = \phi_\tau$
- Tribimaximal mixing approximation
- Best-fit electron neutrino fraction: $(20 \pm 11)\%$



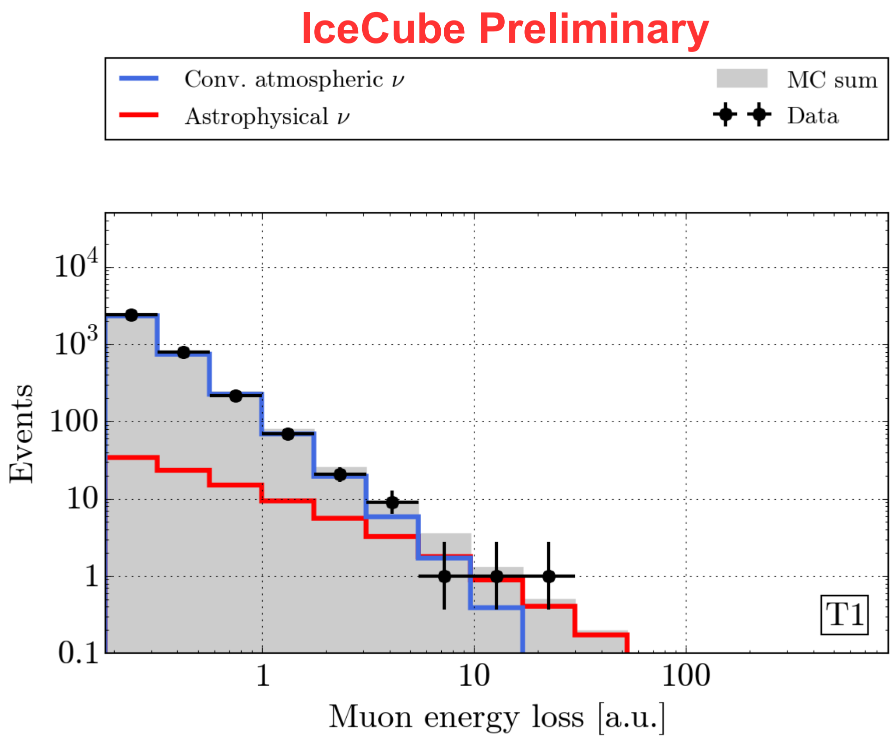
Energy Spectrum – Comparison With ApJ Results

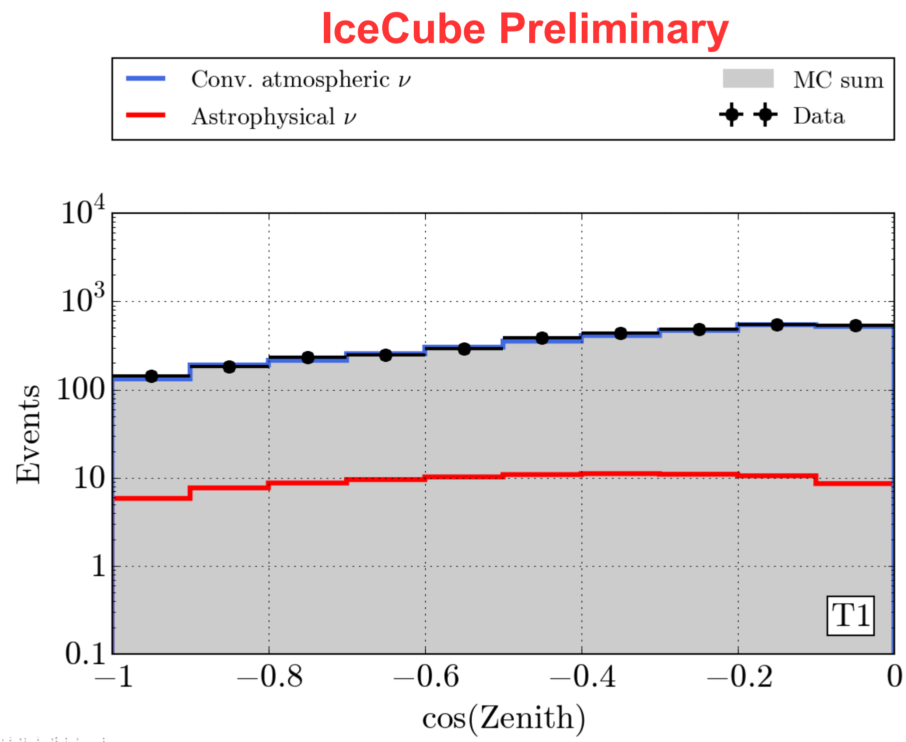


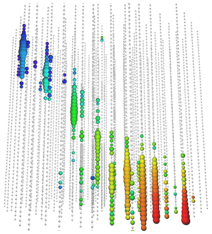


Event Sample T1

Hyp. 2

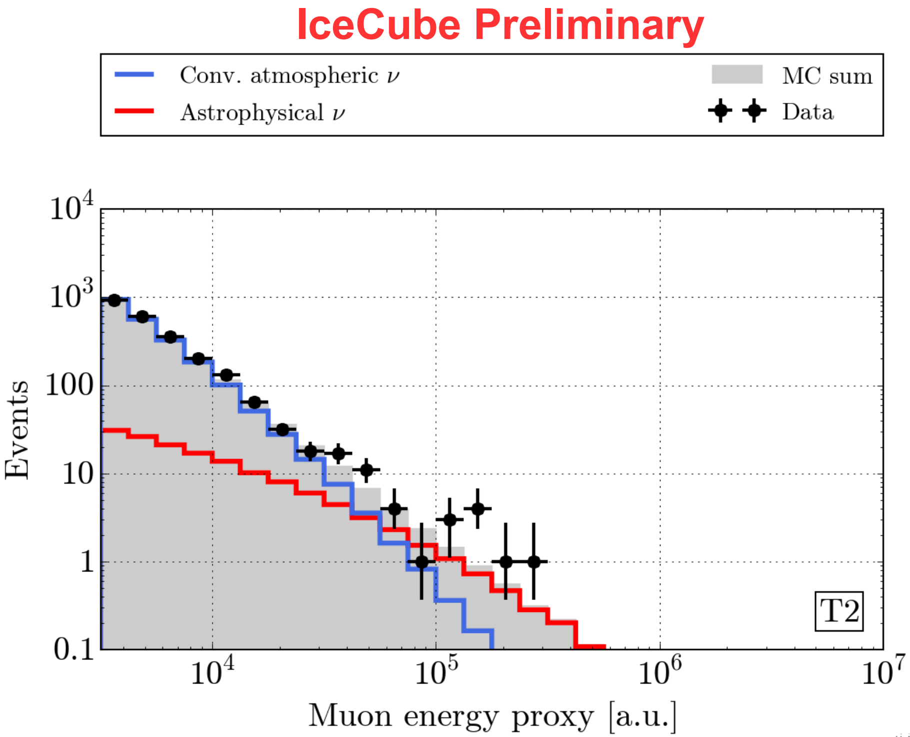


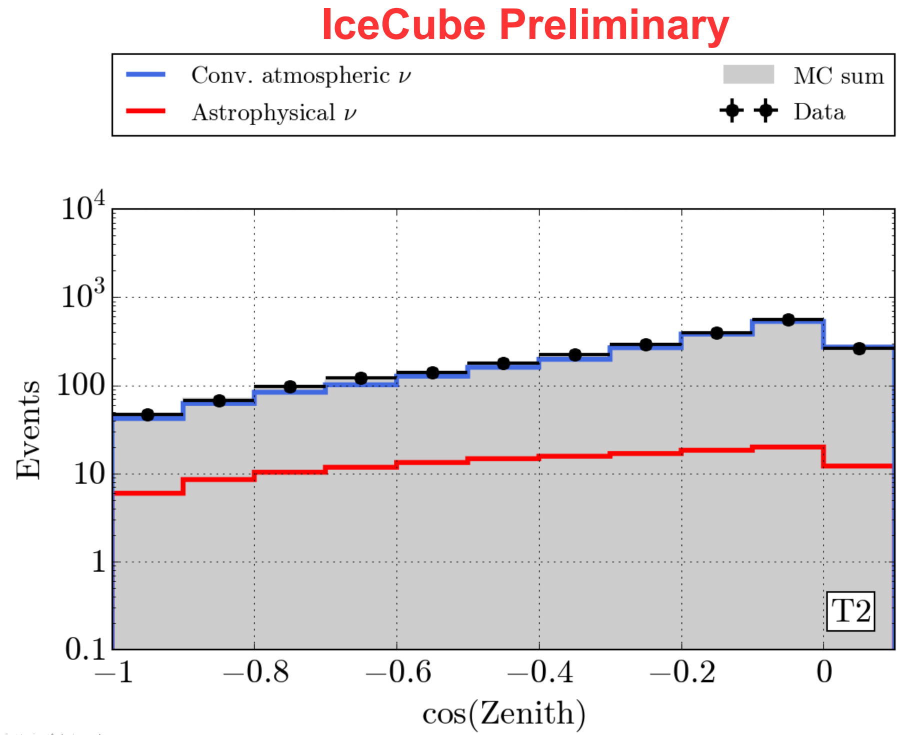


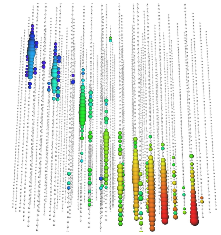


Event Sample T2

Hyp. 2



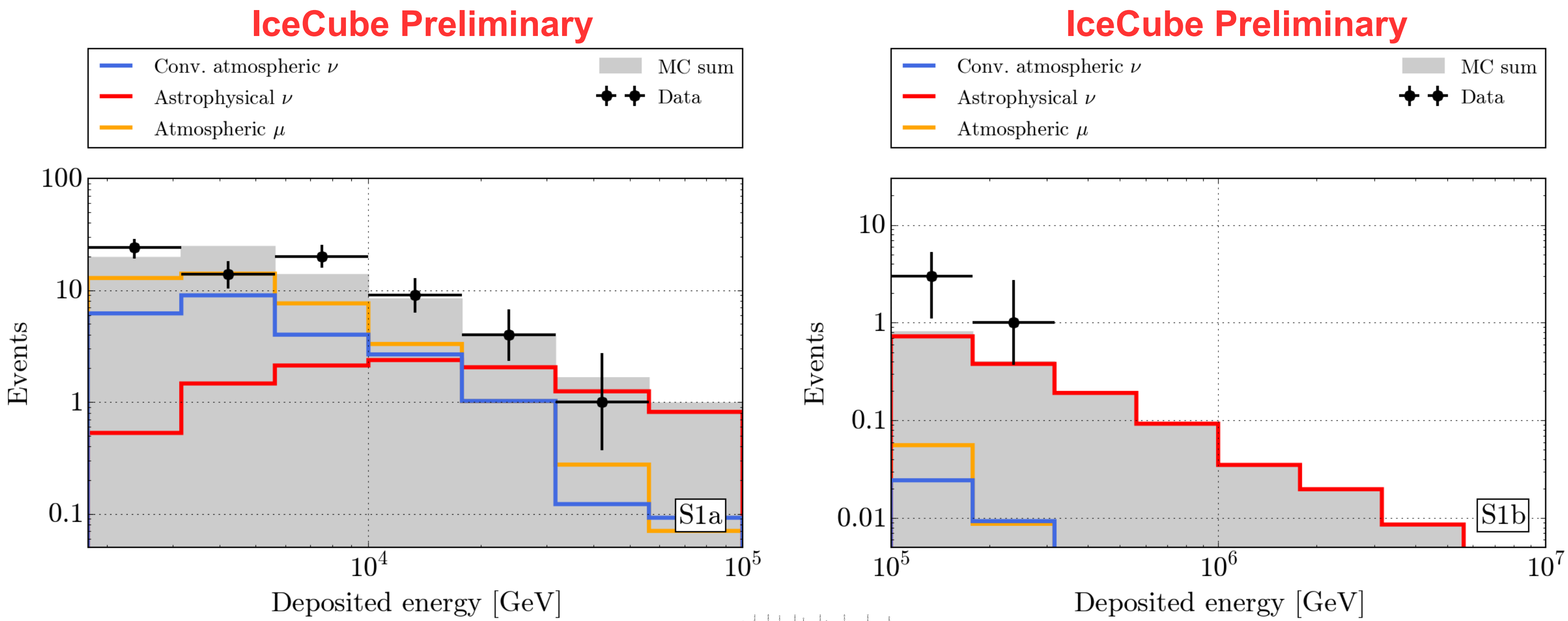


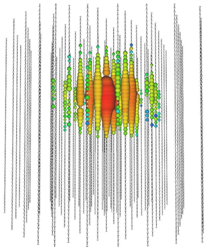


Lars Mohrmann — lars.mohrmann@desy.de — September 10, 2015

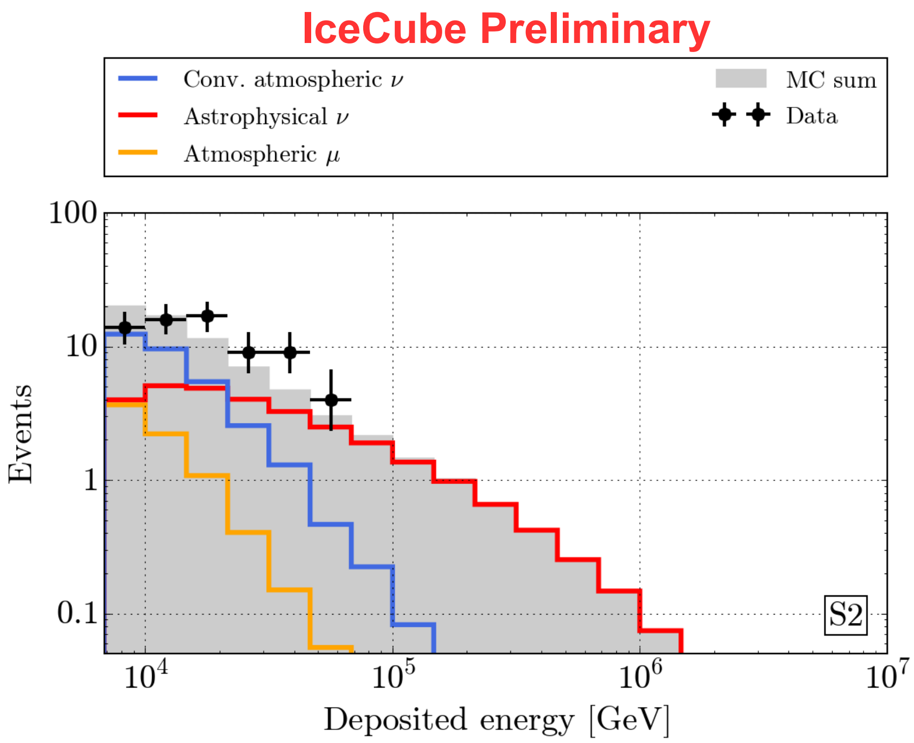
Event Sample S1

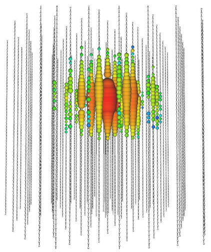
Hyp. 2





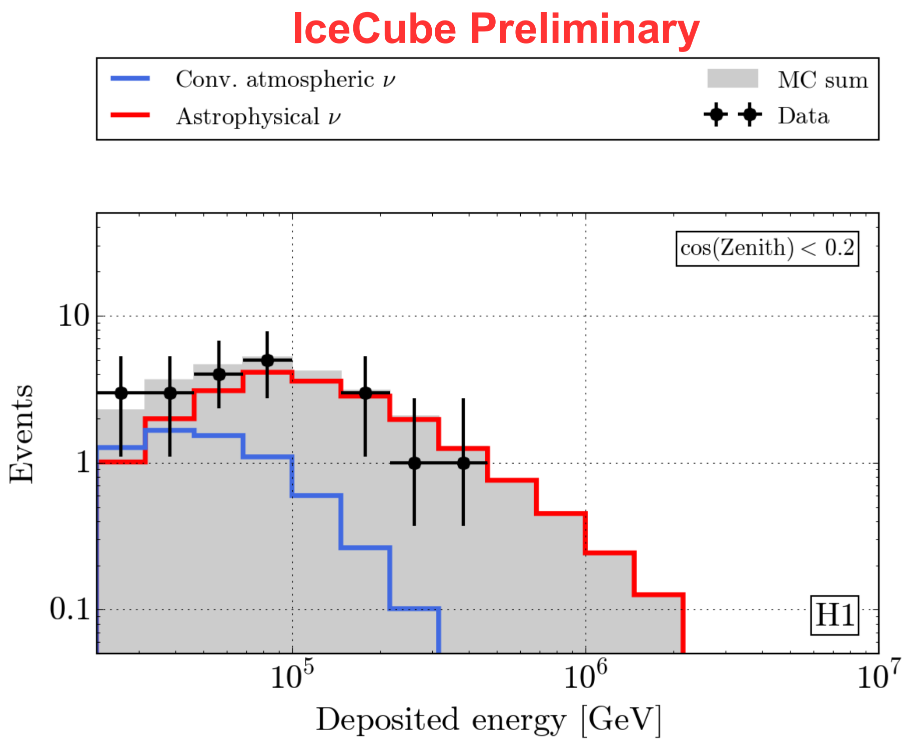
Hyp. 2

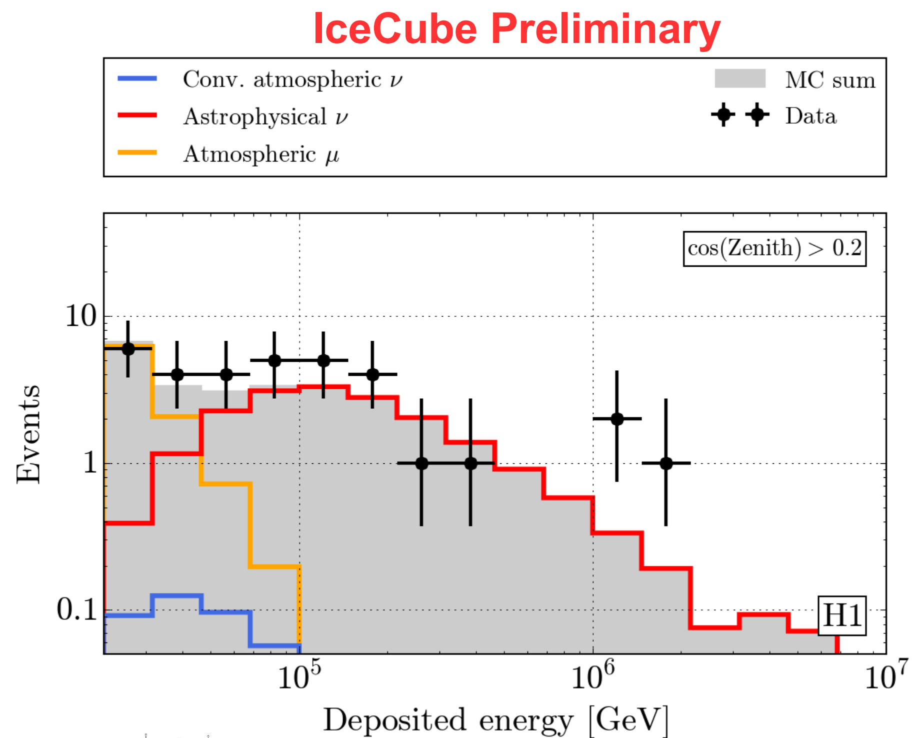

IceCube Preliminary
Conv. atmospheric ν
Astrophysical ν
Atmospheric μ
MC sum
Data
100
10
1
0.1
Events
10^4
10^5
10^6
10^7
Deposited energy [GeV]
S2

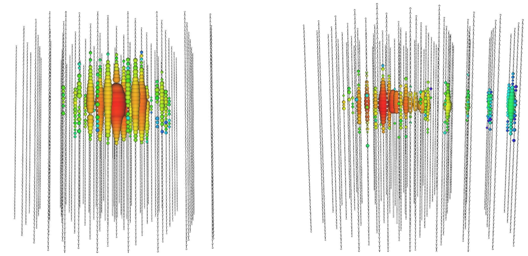


Event Sample H1

Hyp. 2

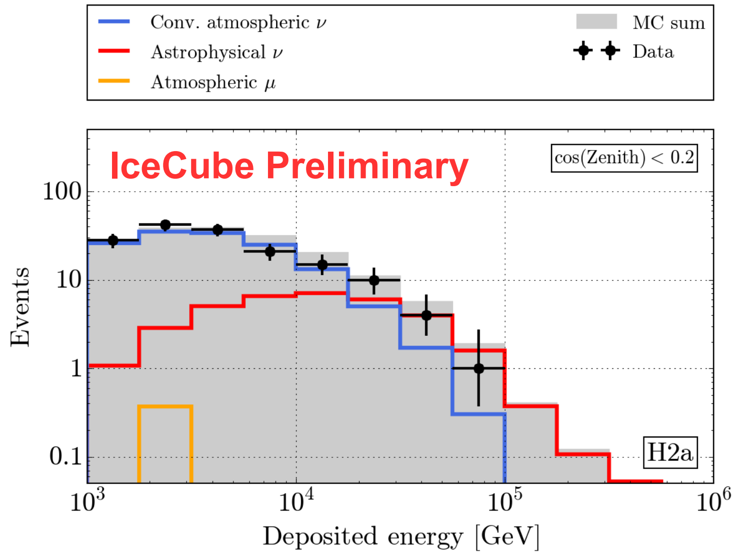


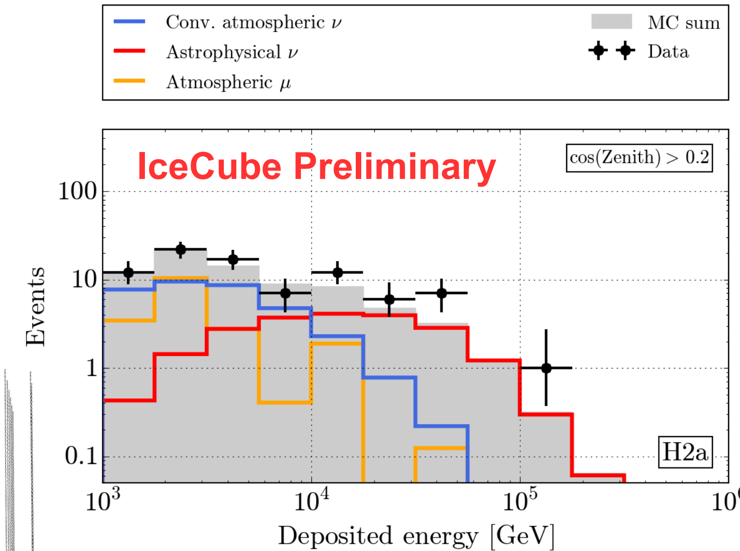


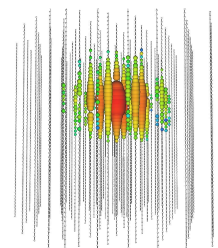


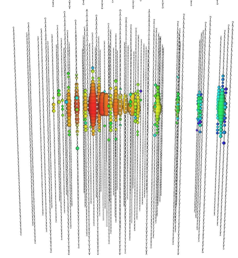
Event Sample H2

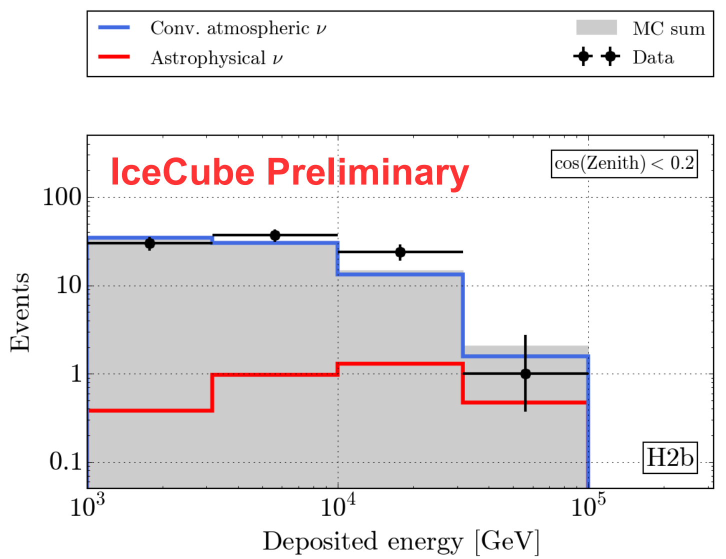
Hyp. 2

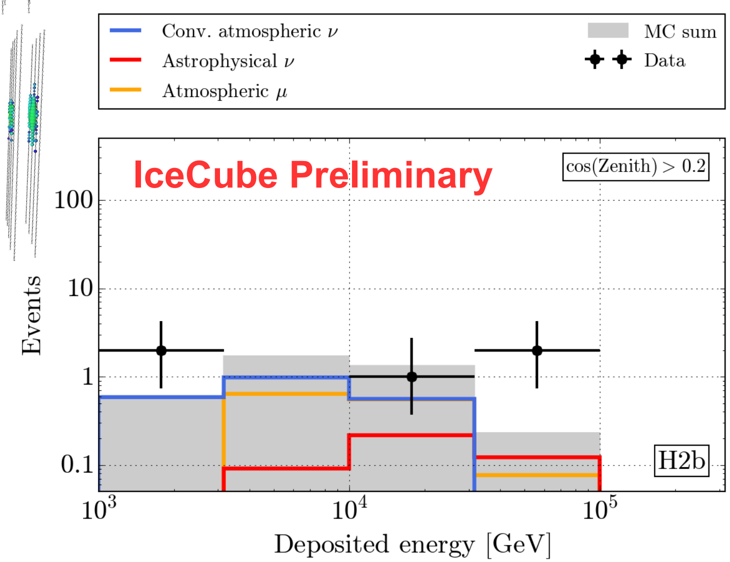






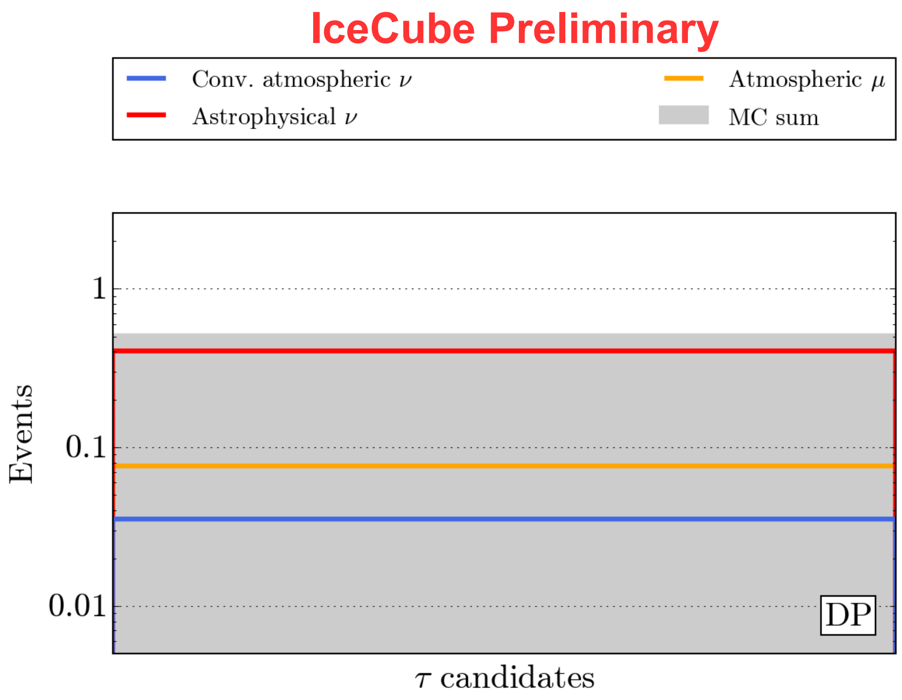


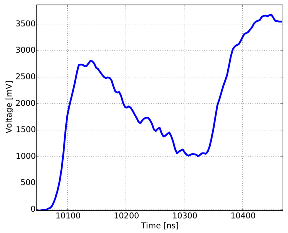




Event Sample DP

Hyp. 2





Event Sample PS

Hyp. 2