Combined Analysis of the High-Energy Cosmic Neutrino Flux at the IceCube Detector

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for the IceCube Collaboration

IceCube

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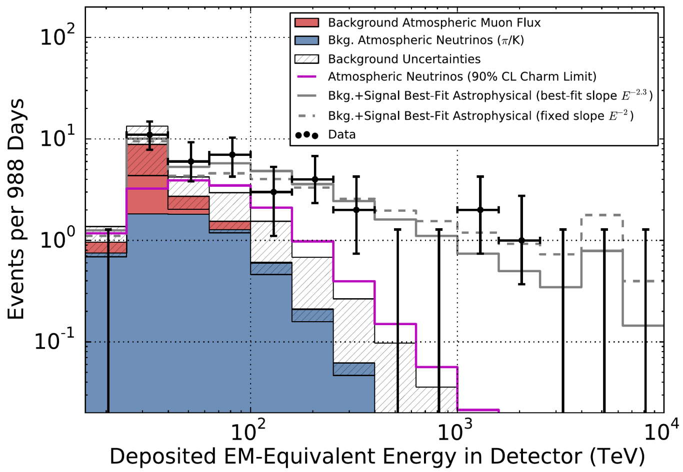
HELMHOLTZ ASSOCIATION

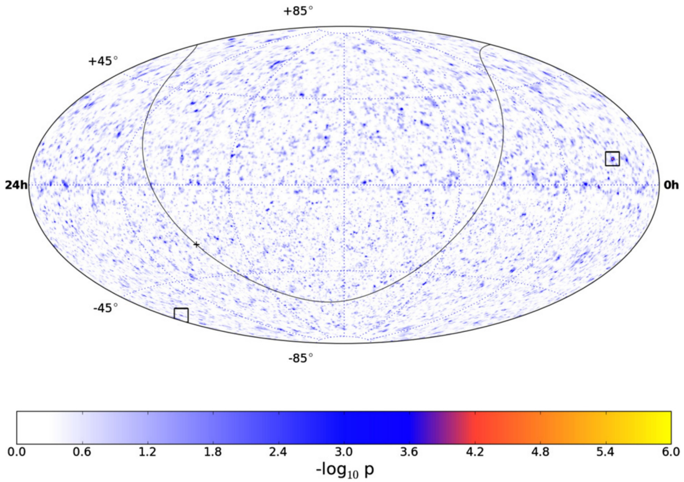
DESY

Cosmic Neutrinos at IceCube

> **Cosmic neutrino flux discovered!**



> **Sources still unknown**



> **Need precise measurement of**

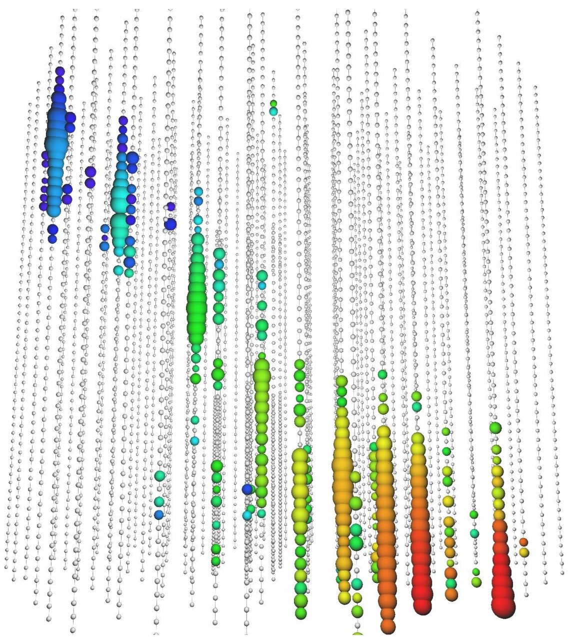
- **Energy spectrum**
- **Flavor composition**

→ **conclusions on sources possible**

Searching for Cosmic Neutrinos with IceCube

Search for upgoing tracks

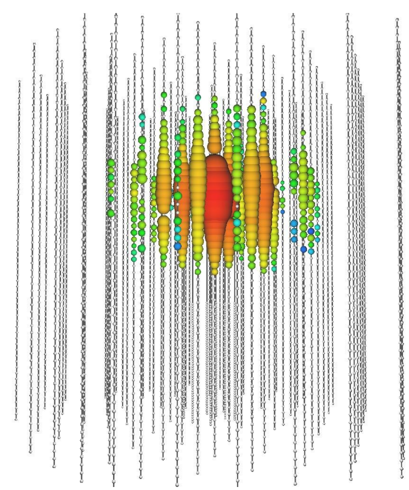
- **Effective area:** $\gg$ detector
- **Muon background:** negligible
- **Channel:** charged-current ν_μ
- **Sky coverage:** northern sky



"throughgoing track"

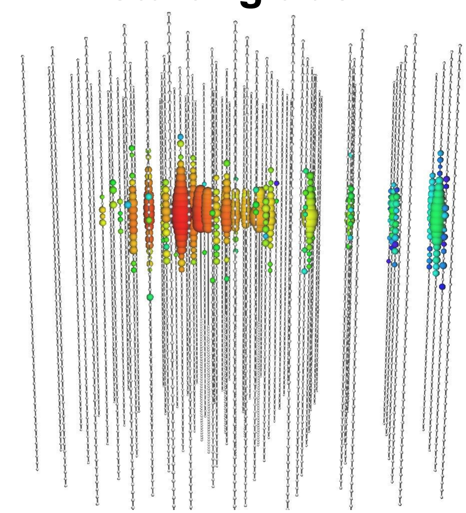
Search for starting events

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



"contained shower"

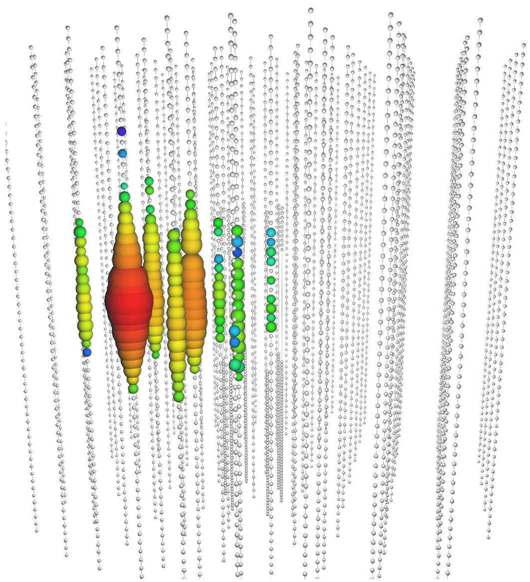
"starting track"



Searching for Cosmic Neutrinos with IceCube

Search for partially contained showers

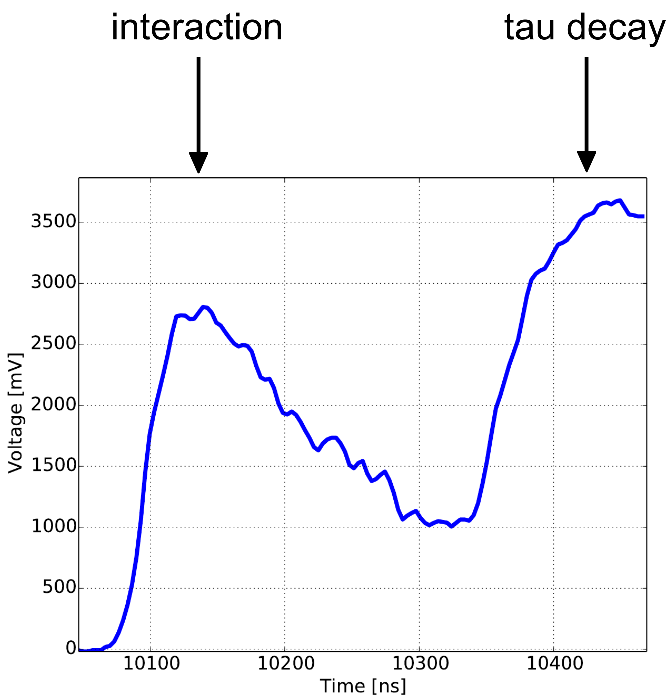
- **New!** → PoS(ICRC2015)1109
- Enlarge effective area at high energies



“partially contained shower”

Search for “double pulse” events

- **New!** → PoS(ICRC2015)1071
- Identify tau neutrinos



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, in press
  arXiv:1507.03991

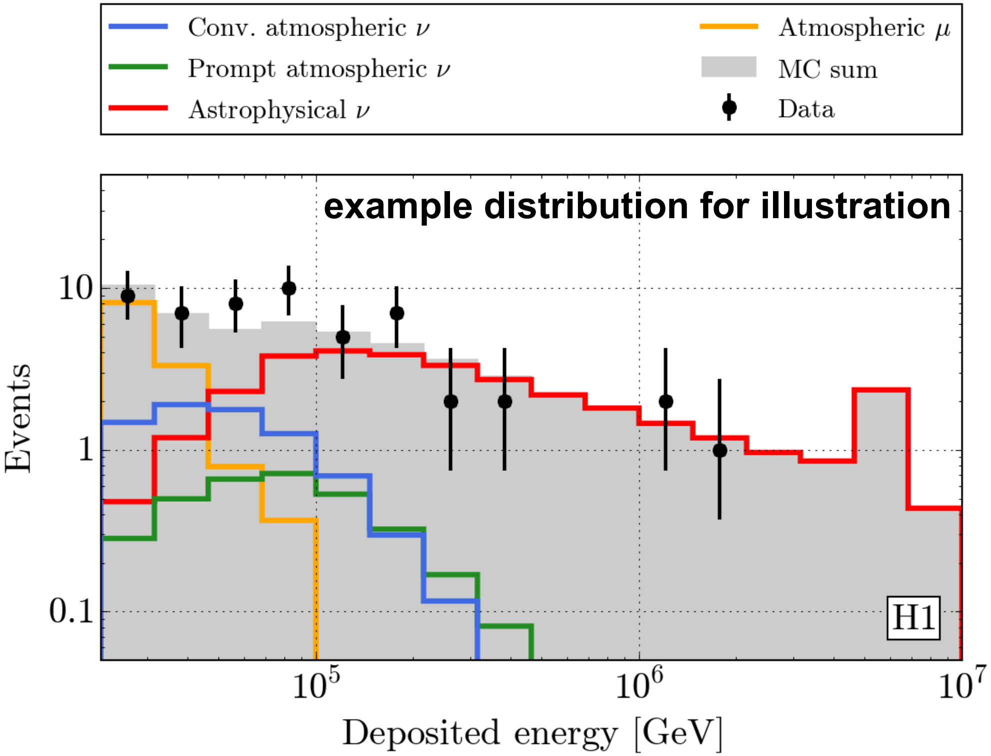
Analysis Method

“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

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:** $\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times \exp(-E/E_{\mathrm{cut}})$

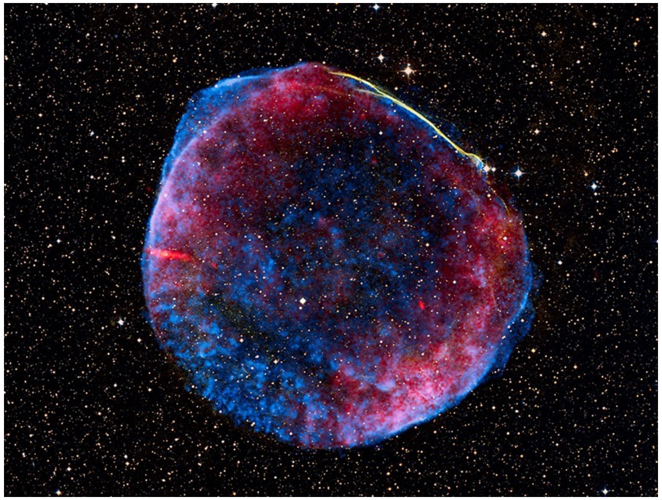


Image credit: NASA, ESA, and Zolt Levay (STScI)

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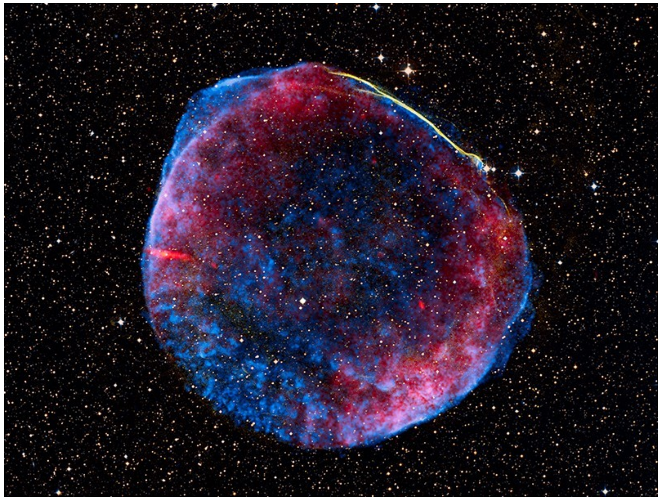

Image credit: NASA, ESA, and Zolt Levay (STScI)

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:**

all-flavor!

  - $\Phi_\nu = \boxed{\left(7.0^{+1.0}_{-1.0}\right) \times 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}} \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{\boxed{-2.49 \pm 0.08}}$
  - E^{-2} excluded at $\boxed{4.6\,\sigma}$

Results – Energy Spectrum

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  - E^{-2} excluded at $\boxed{4.6\,\sigma}$

- **Best fit hypothesis B:**

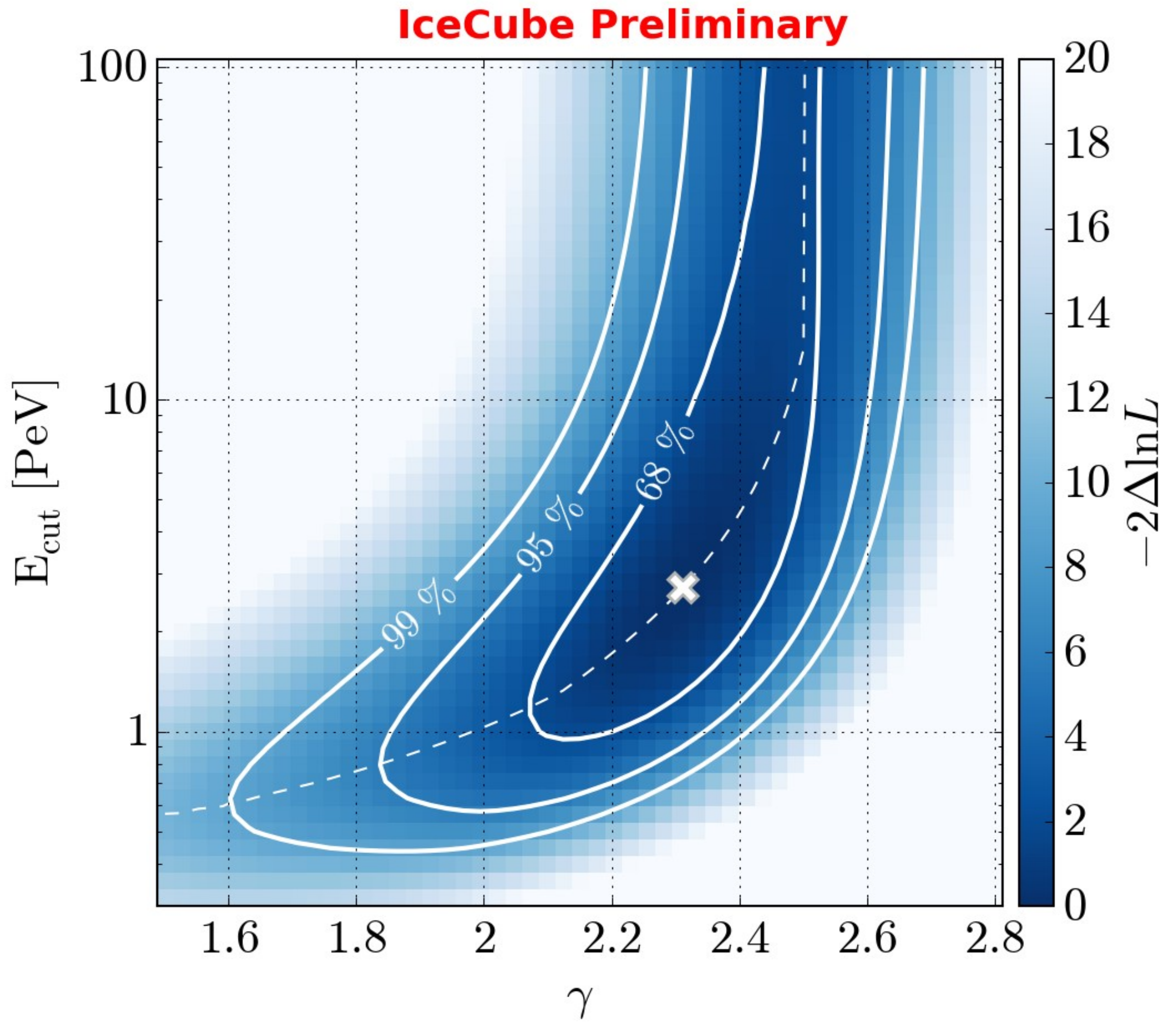
all-flavor!

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

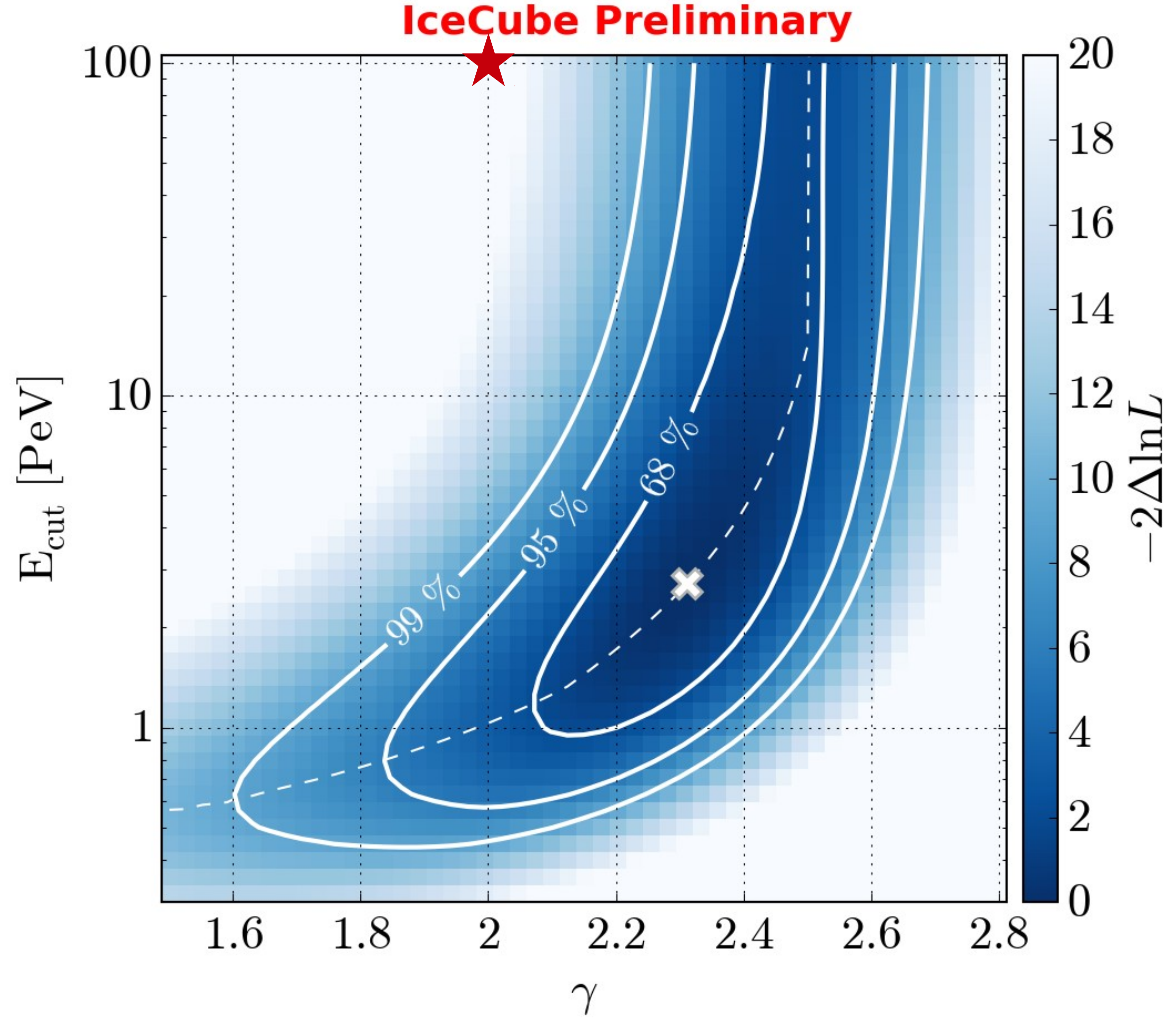
- **Both models describe the data well**

Results – Energy Spectrum

- Profile likelihood scan



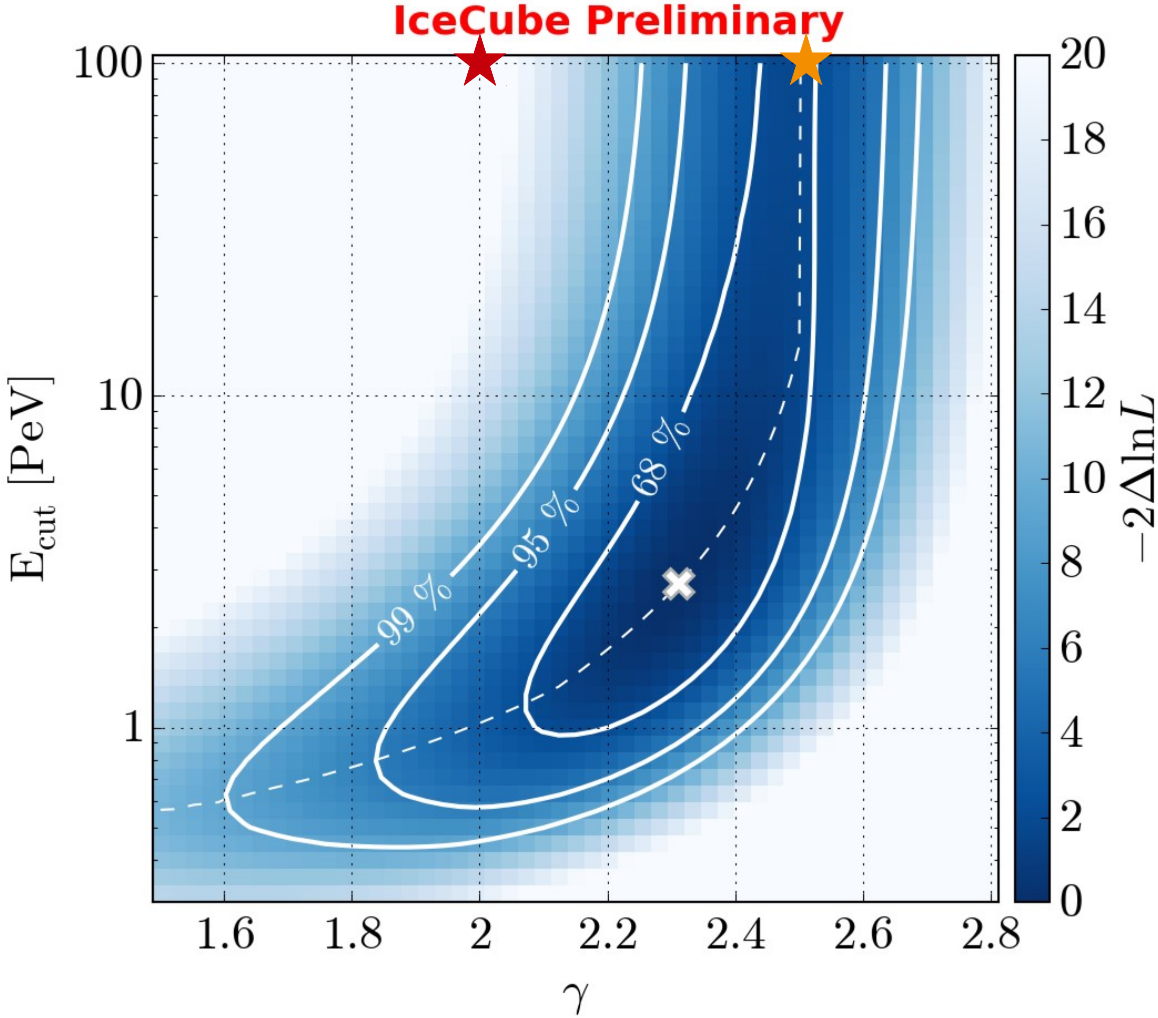
- **Profile likelihood scan**
  - E^{-2}, **no cut-off**



Results – Energy Spectrum

- **Profile likelihood scan**
  - $\boxed{E^{-2}\text{, no cut-off}}$

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

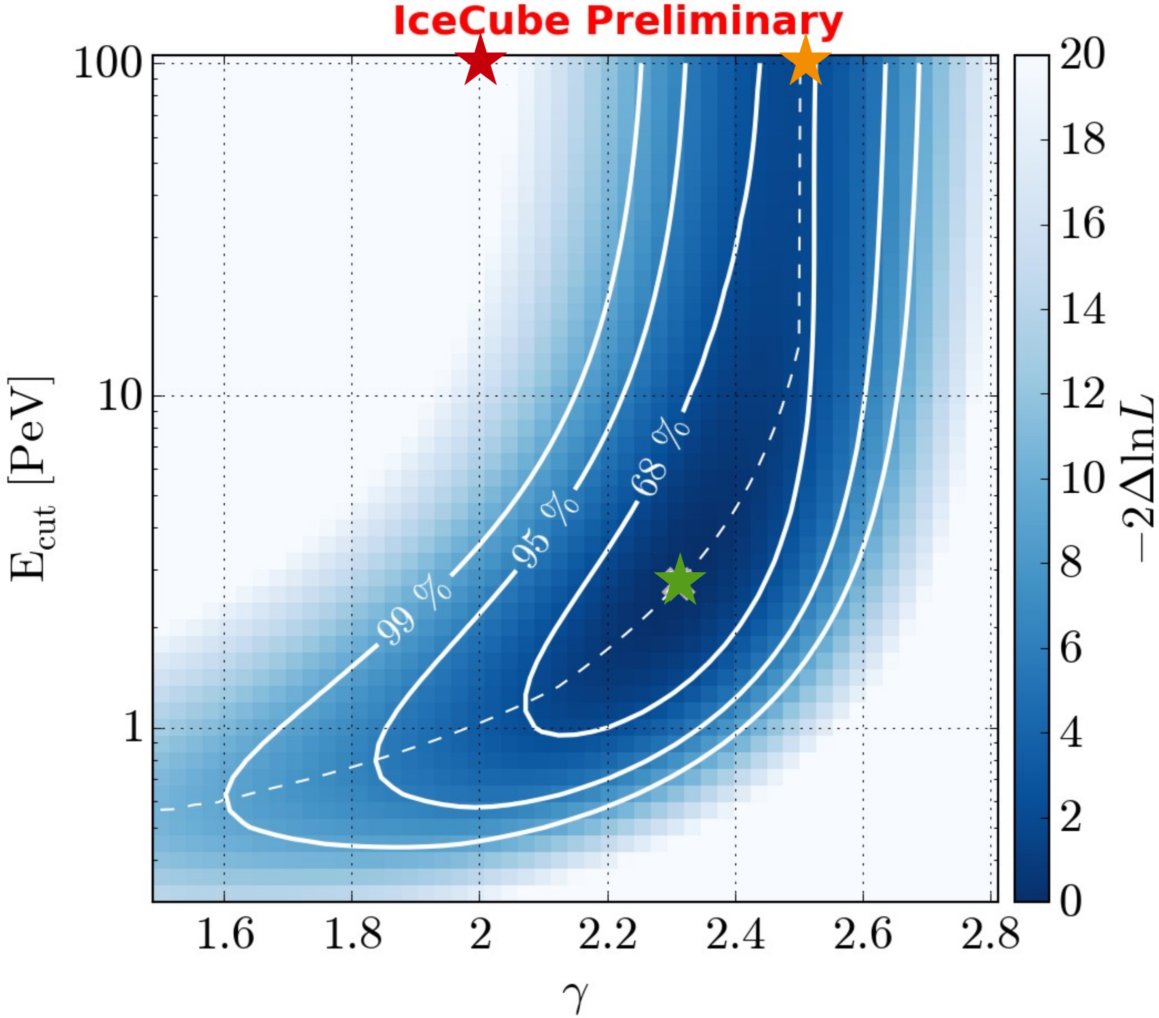


Results – Energy Spectrum

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

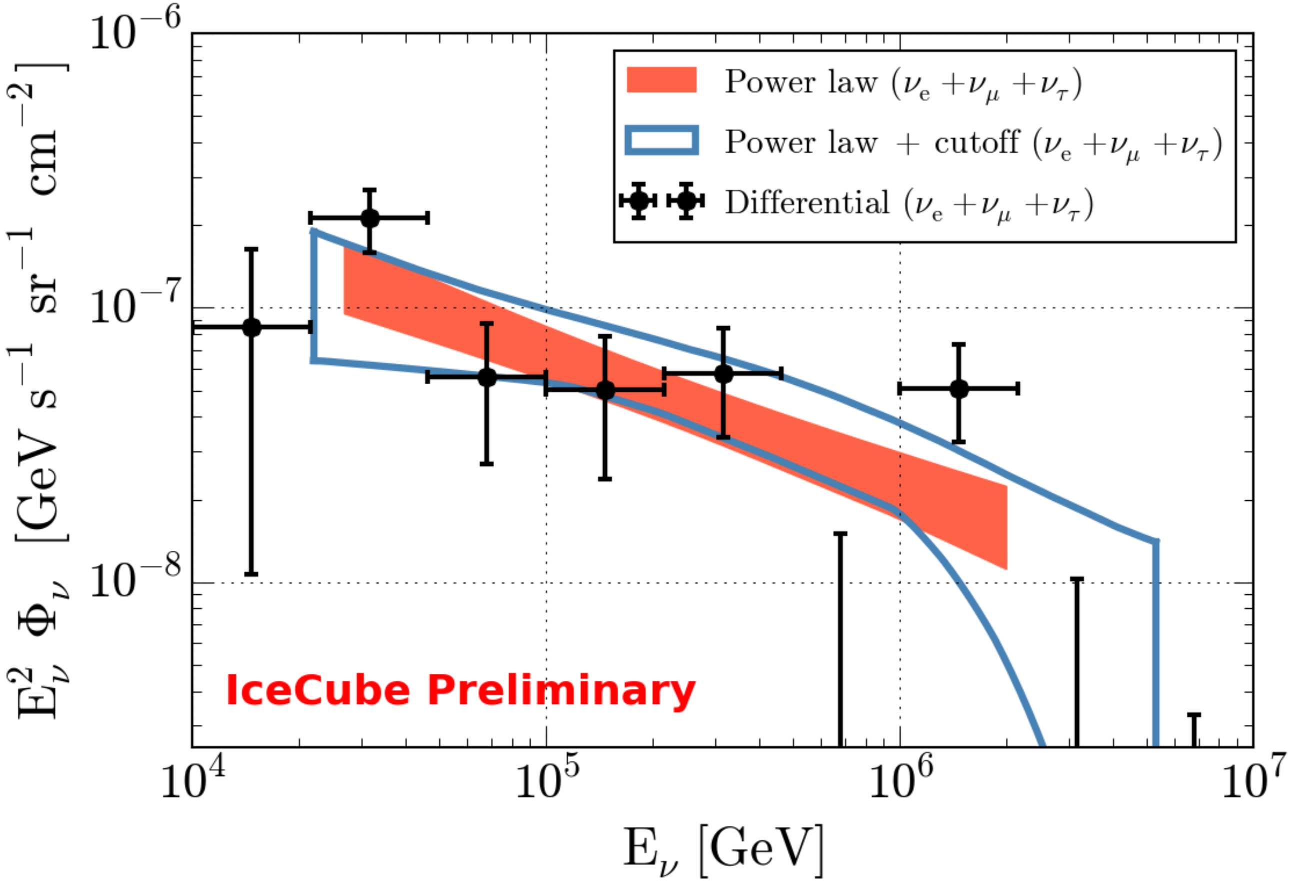
    $\Updownarrow$ $4.6\,\sigma$
  - $E^{-2.49}$ **, no cut-off**

    $\Updownarrow$ $1.2\,\sigma$
  - $E^{-2.31}$ **, cut-off at** $2.7\,\mathrm{PeV}$

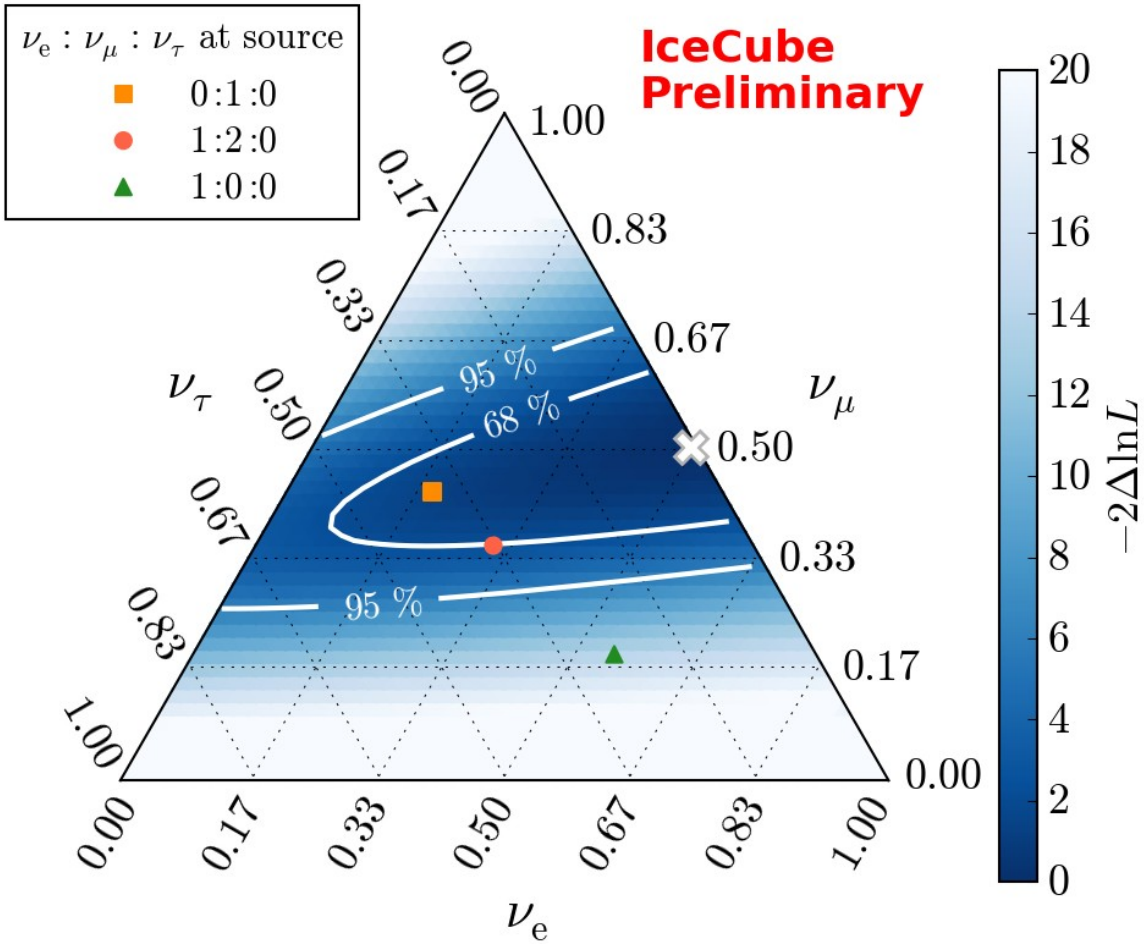


Results – Energy Spectrum

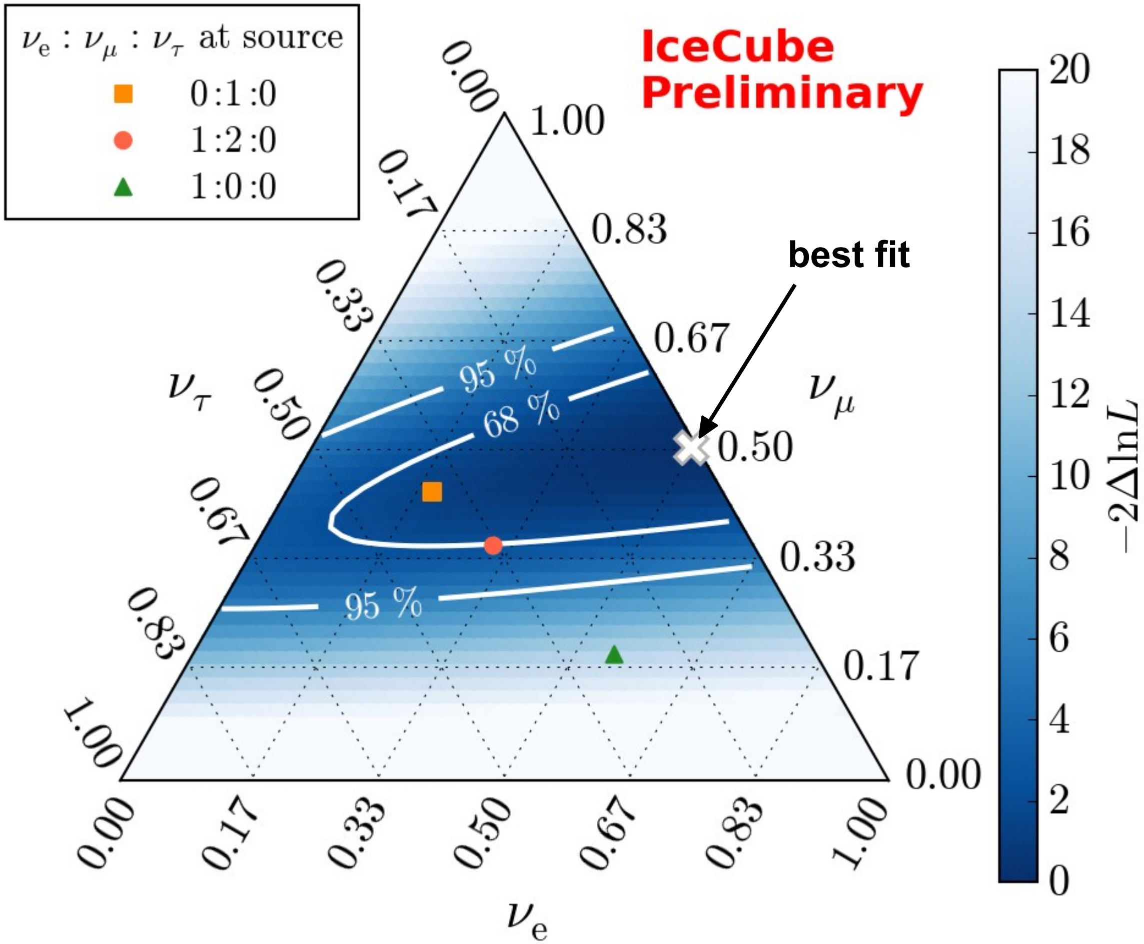
- All-flavor neutrino energy spectrum



Results – Flavor Composition



Results – Flavor Composition

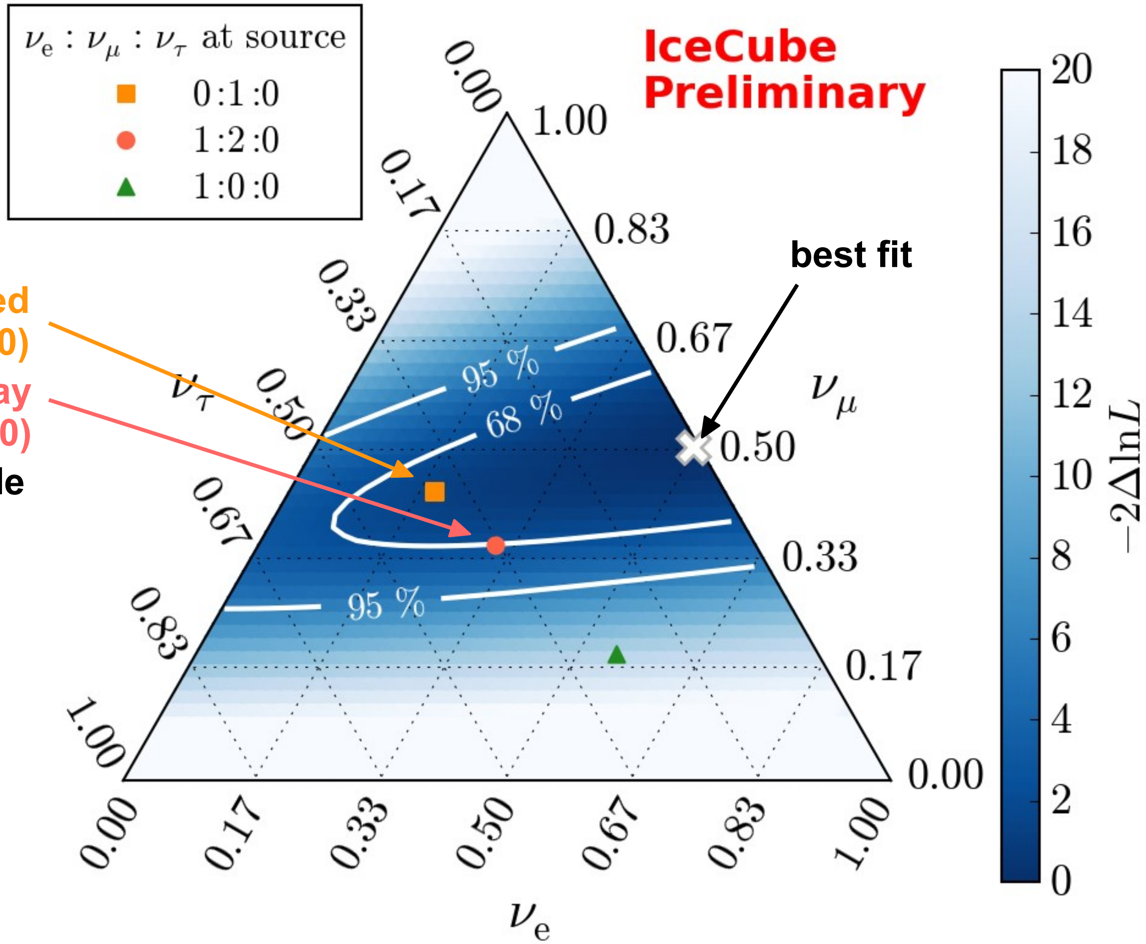


Results – Flavor Composition

muon-damped
(0:1:0)

Pion-decay
(1:2:0)

→ **compatible**



Results – Flavor Composition

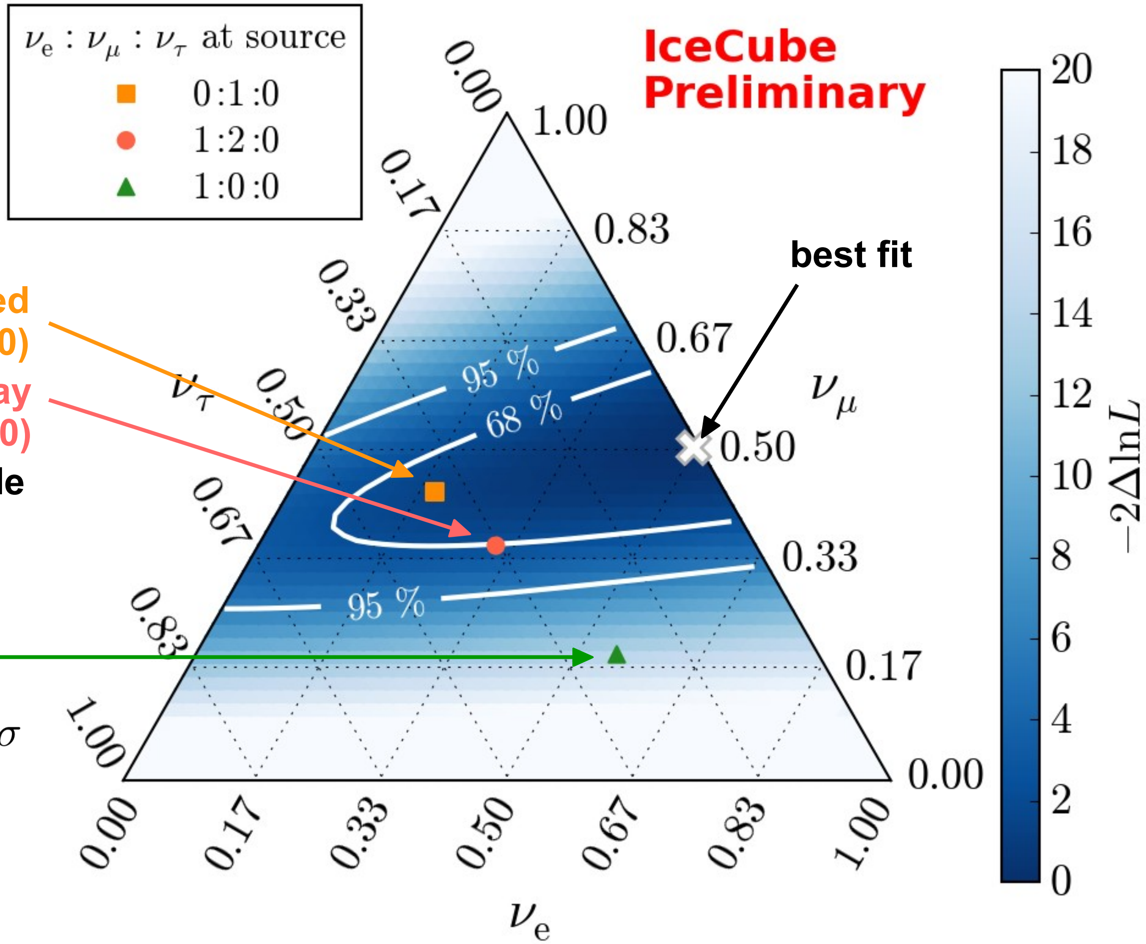
muon-damped
(0:1:0)

Pion-decay
(1:2:0)

→ compatible

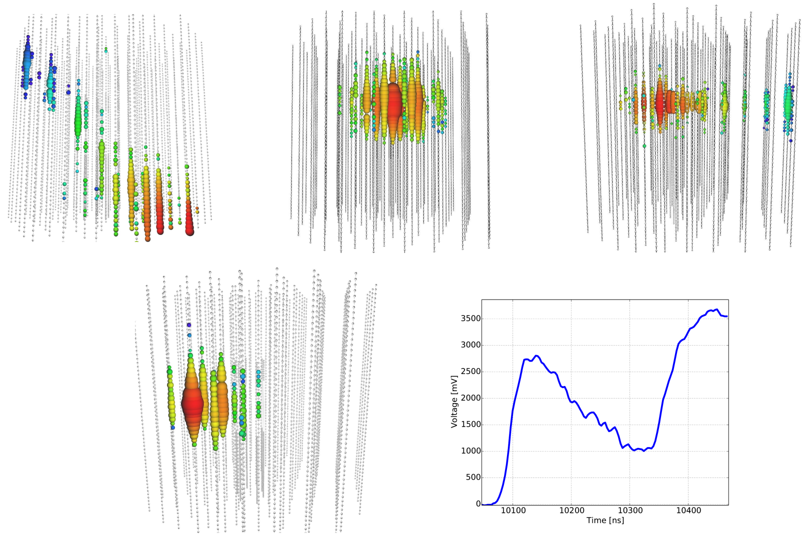
Neutron-decay
(1:0:0)

→ excluded at $3.7\,\sigma$



Projection of Sensitivities

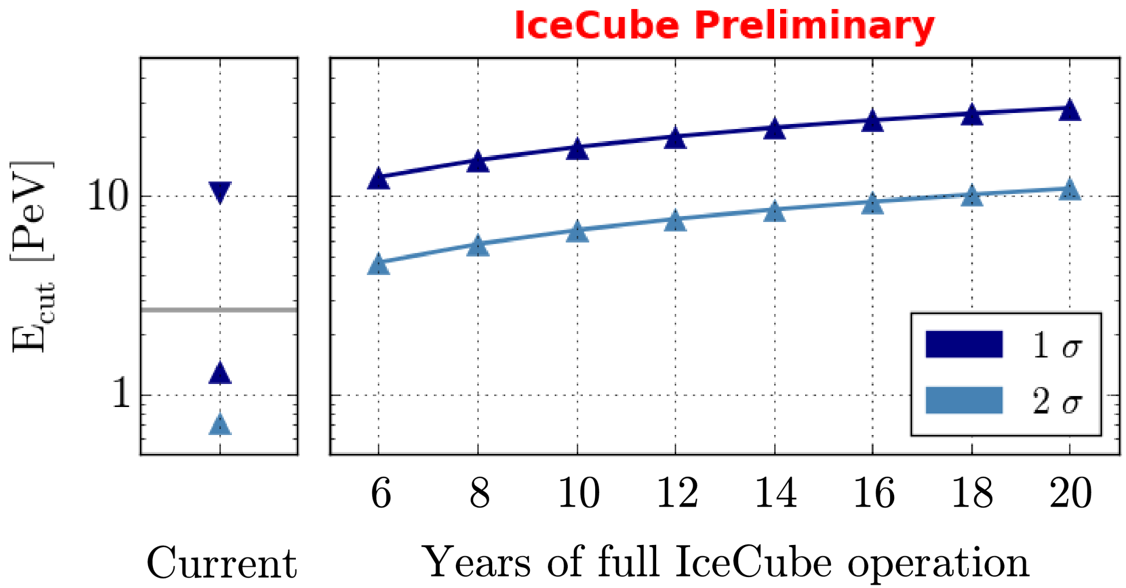
- **Use most recent event samples**
  - **T2** → throughgoing tracks
  - **H2** → contained showers + starting tracks
  - **PS** → partially contained showers
  - **DP** → double pulse waveform events



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

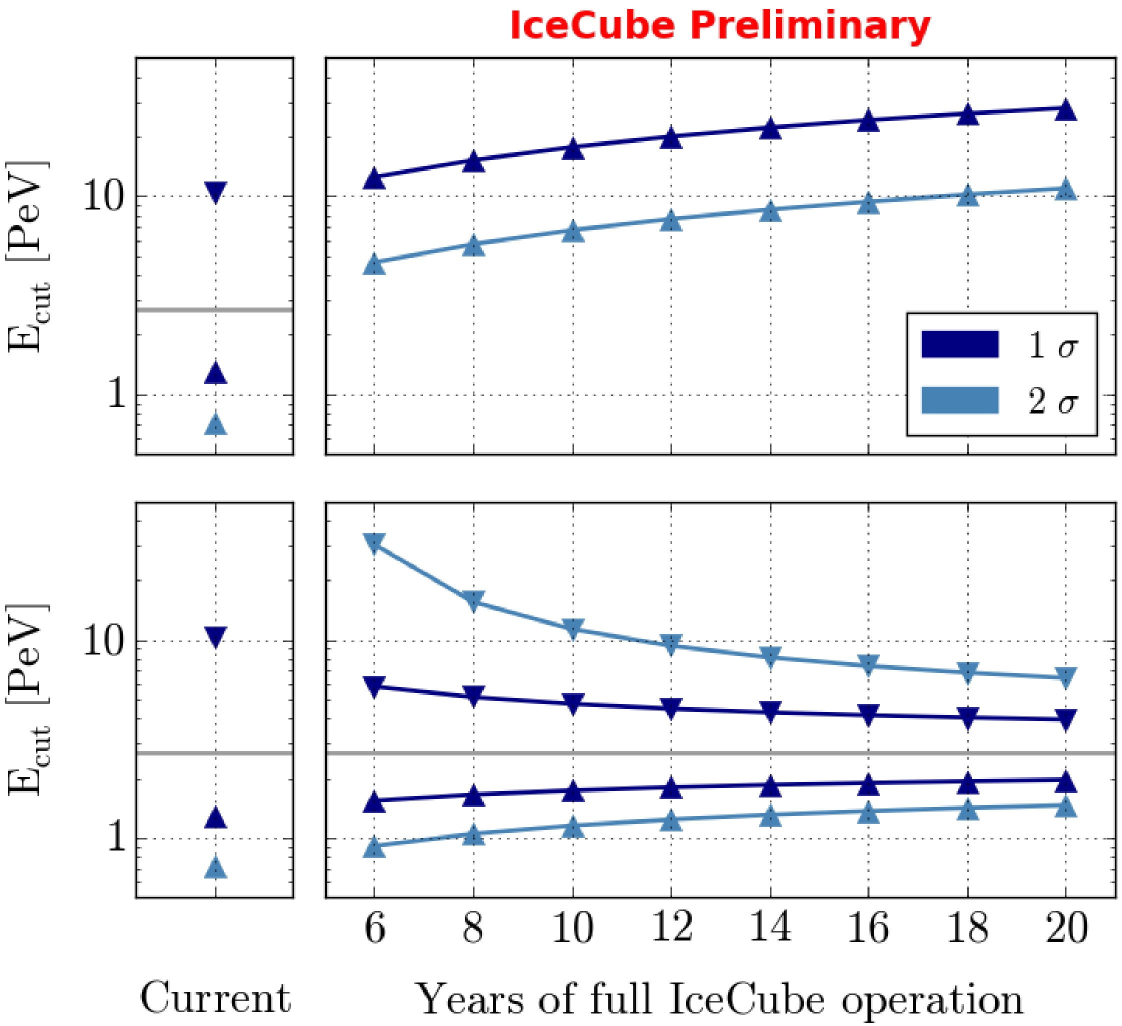
- Perform analysis with the **“Asimov data set”** (Cowan et al. 2011)
  - One “representative” data set (based on input flux)
  - → obtain **median sensitivity**

Sensitivity – Energy Spectrum



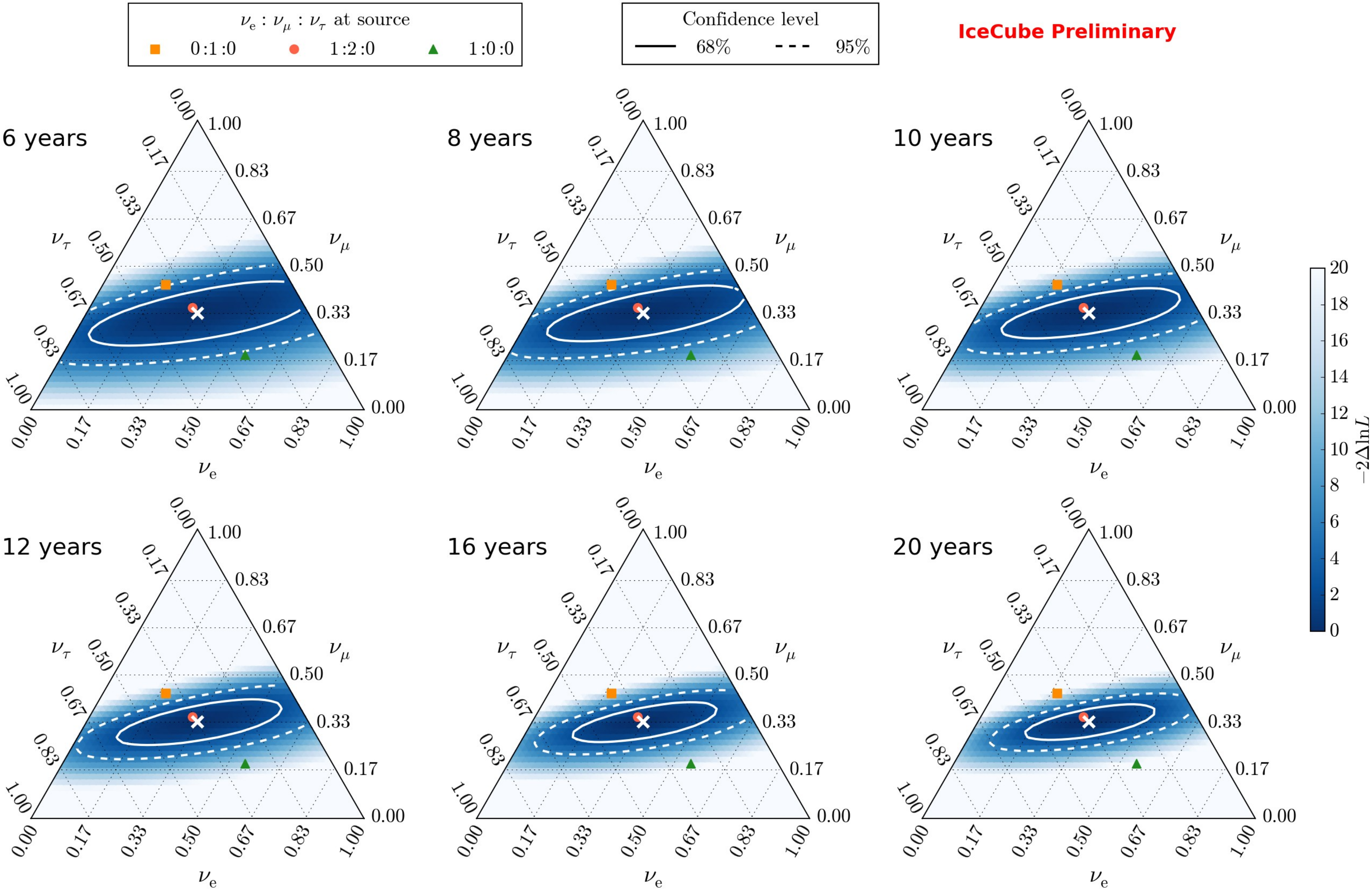
- **Hypothesis A true**
  - $E^{-2.49}$, **no cut-off**
  - $\rightarrow E_{\mathrm{cut}} > 7.7\,\mathrm{PeV}$ $(2\,\sigma$ C.L.$)$ **for 10 years of data**

Sensitivity – Energy Spectrum



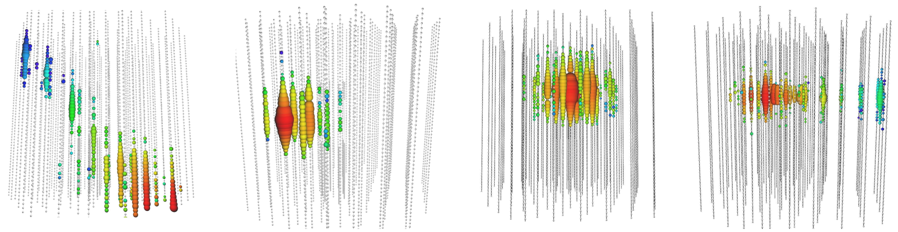
- **Hypothesis A true**
  - $E^{-2.49}$, **no cut-off**
  - $\rightarrow E_{\mathrm{cut}} > 7.7\,\mathrm{PeV}\ (2\,\sigma\ \mathrm{C.L.})$ **for 10 years of data**
- **Hypothesis B true**
  - $E^{-2.31}$, **cut-off at** $2.7\,\mathrm{PeV}$
  - $\rightarrow$ **presence of cut-off can be established at**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

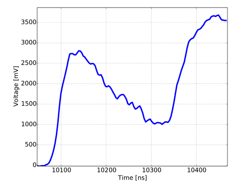
Sensitivity – Flavor Composition



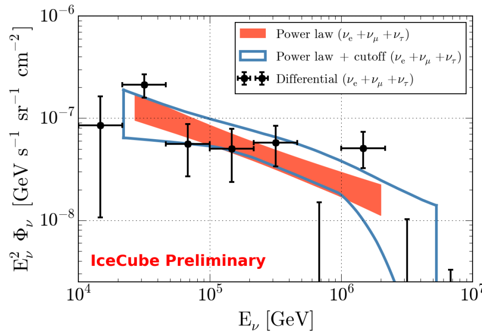
Summary

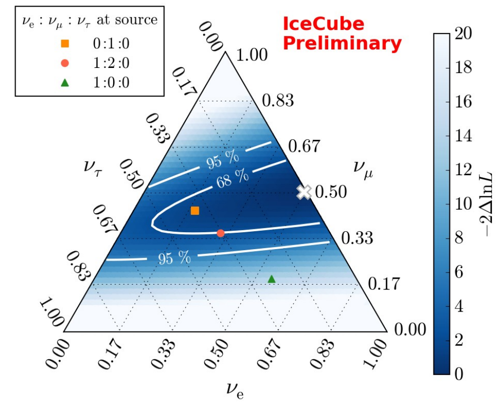
- **Combined analysis of cosmic neutrino flux**
  - Take into account all signatures
  - Sensitive from ~10 TeV – multi-PeV





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





- **Projection of sensitivities**