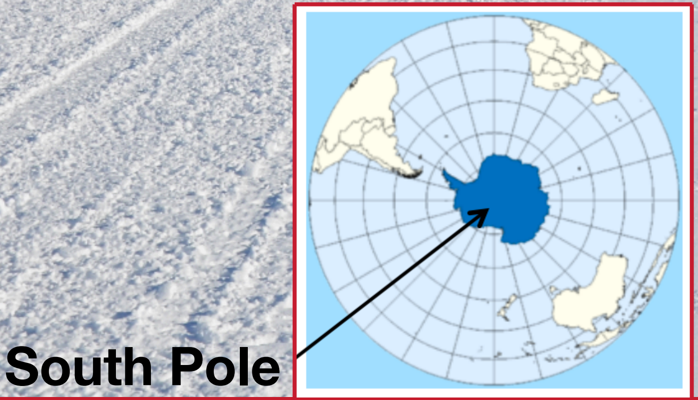
High Energy Astrophysical Neutrino Flux Measurement

Using Neutrino-induced Cascades
Observed in 4 Years of IceCube Data



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Stony Brook University

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Stony Brook University

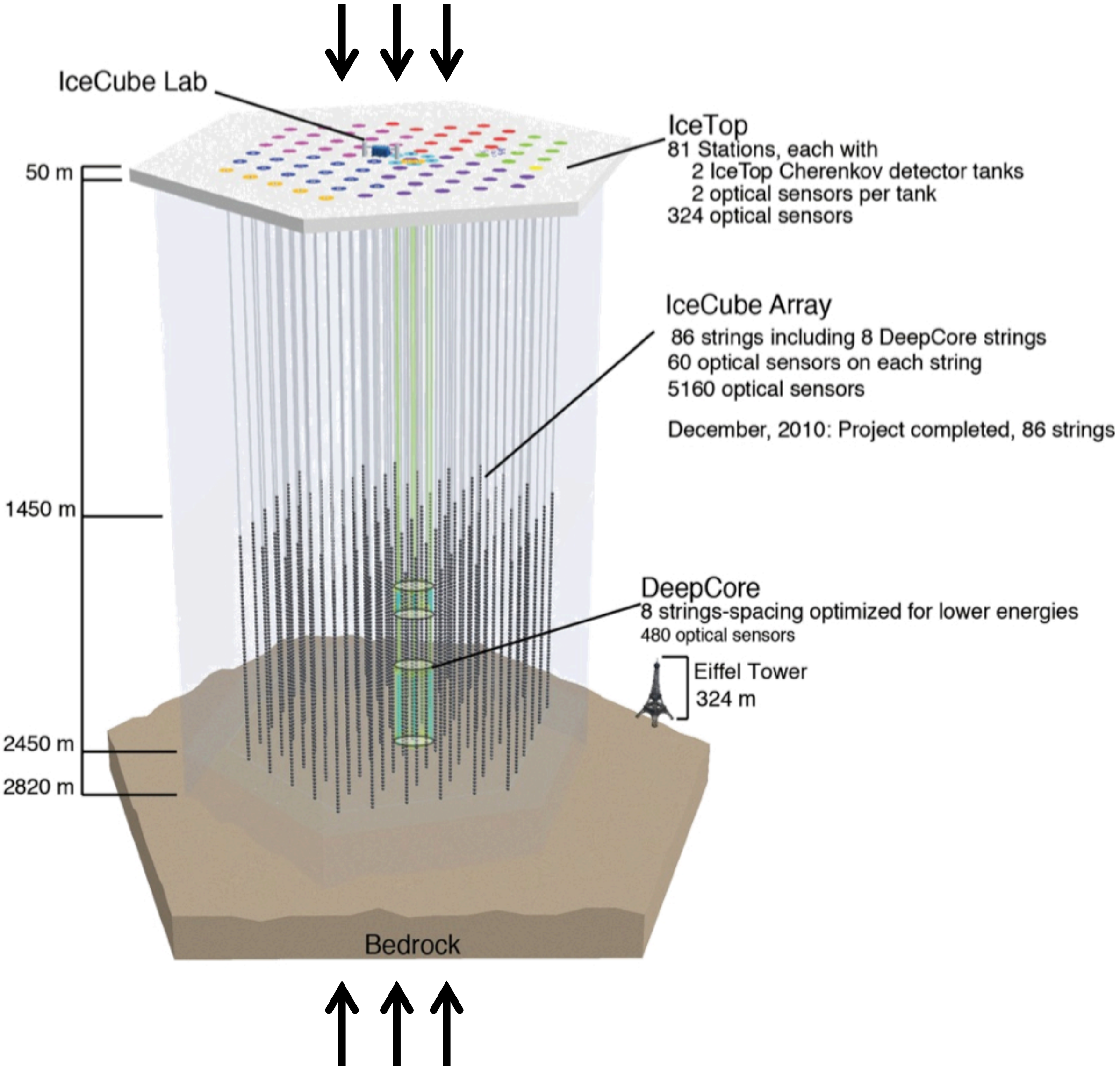
for the IceCube Collaboration

Outline

- Introduction
- Event Selection
- Analysis Method
- Cascade Results
- Summary

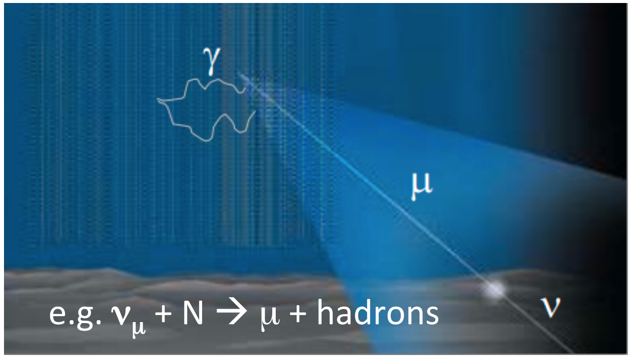
Introduction

from Southern Sky



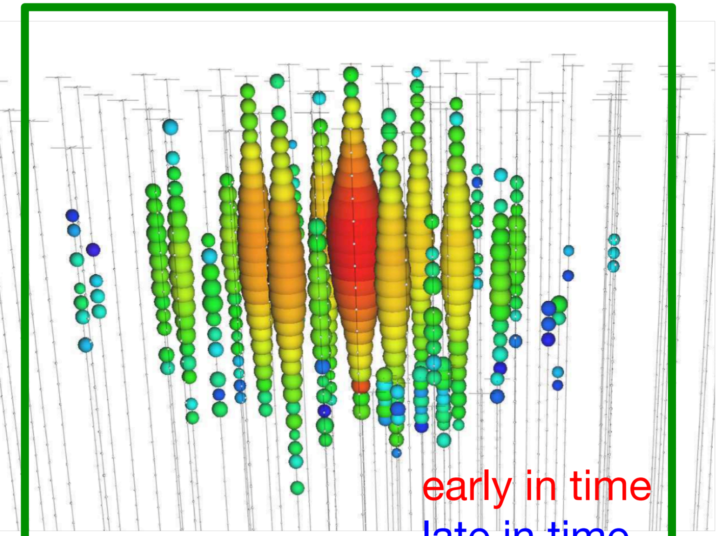
from Northern Sky

Designed to detect
Cherenkov Light (e, μ, τ)



Infer neutrino properties from **total number of photons** and their **arrival times** and in each optical module (DOM)

Introduction



Cascades

CC: $\nu_e(\nu_\tau)$ + N
→ $e(\tau)$ + hadrons

NC: $\nu_e(\nu_\mu, \nu_\tau)$ + N
→ $\nu_e(\nu_\mu, \nu_\tau)$ + hadrons

point-like light emission

angular resolution >10°

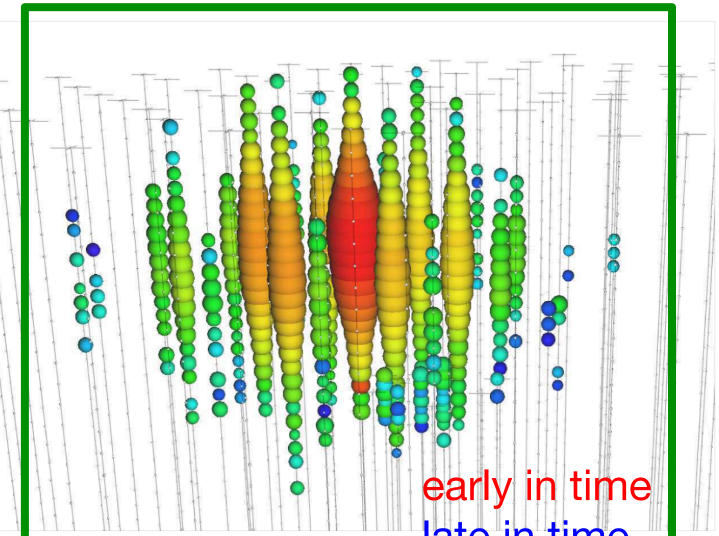
good energy resolution

~15% if contained

(E>100TeV)

Introduction

ICECUBE



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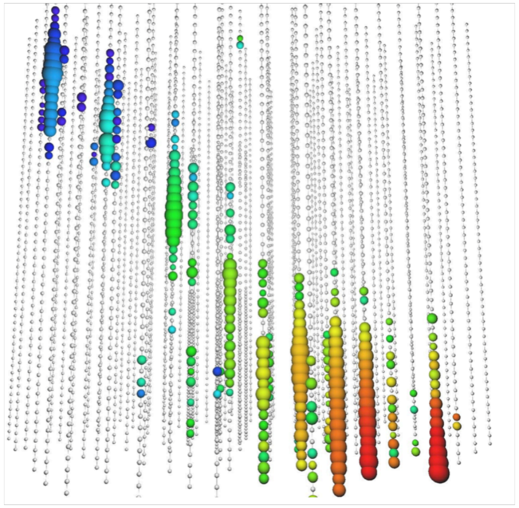


(through-going) Tracks

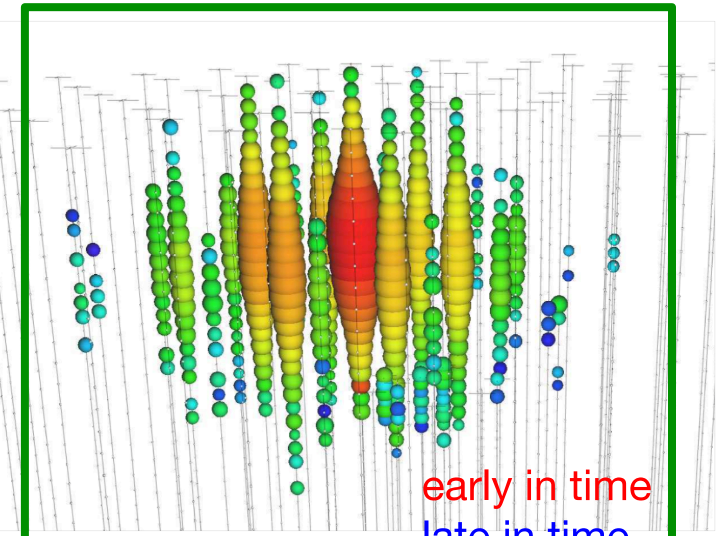
CC: ν_μ + N
→ μ + hadrons

pointing resolution <1°

μ energy resolution
~ factor of 2

limited to Northern Sky

Introduction



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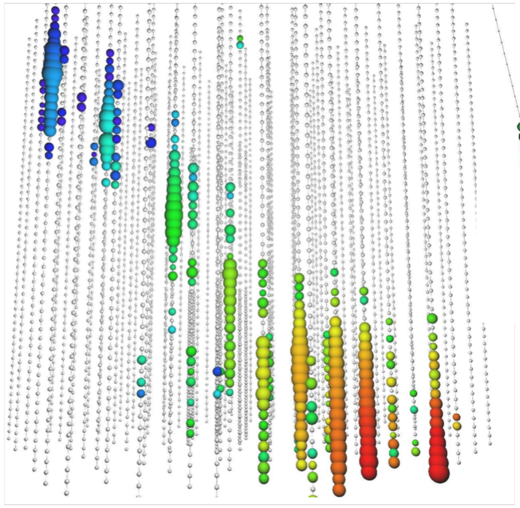

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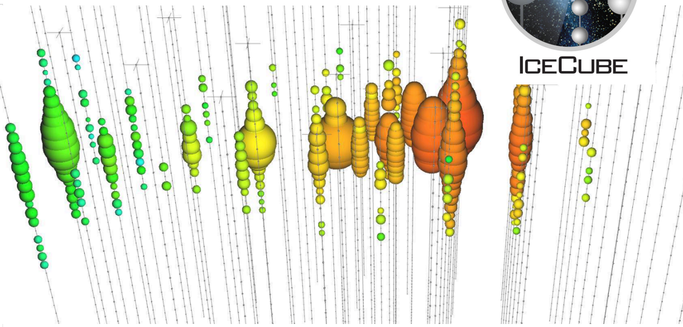

Hybrid Events

ν_τ double bang
(and other signatures)
not yet observed/identified

CC: ν_τ + N
$\rightarrow$ τ + hadrons
$\rightarrow$ hadrons

starting tracks (cascade + track)

CC: ν_μ + N
$\rightarrow$ μ + hadrons

Introduction

this work: require cascade event topology

mostly sensitive to $\nu_e + \nu_\tau$

less background than (starting) track channel!

background stems from atmosphere only!

muons: produced in cosmic ray air showers

neutrinos: produced in the same showers

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similar studies of astro ν using cascades

IceCube IC22 PRD84 072001 (2011)
IceCube IC40 PRD89 102001 (2014)
IceCube IC59 Proc. of 33rd ICRC, arXiv:1309.7003 (2013)
IceCube IC79+IC86-11 PoS(ICRC2015)1109 (2015)

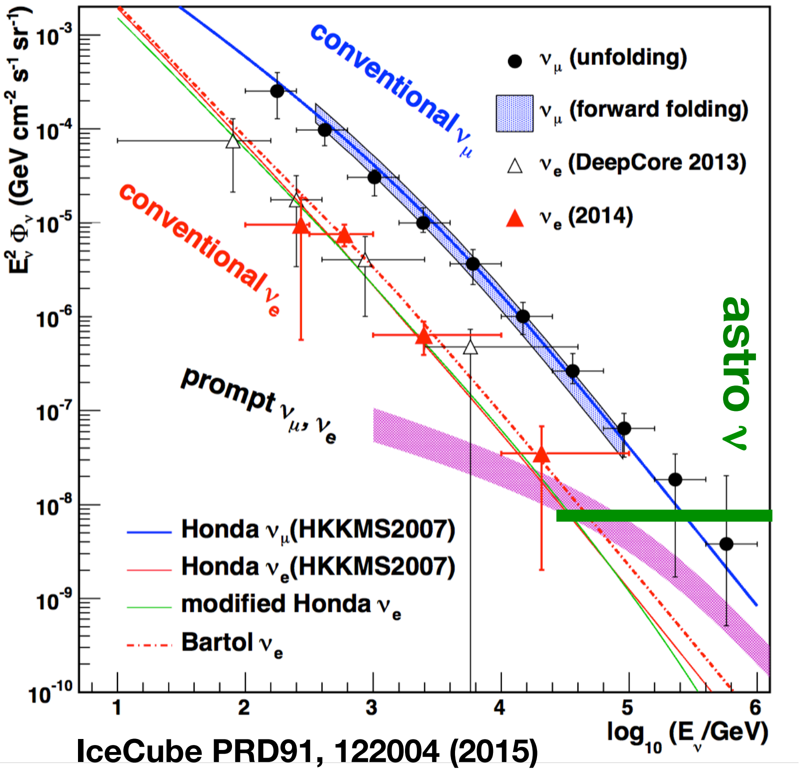
background stems from atmosphere only!

muons: produced in cosmic ray air showers

neutrinos: produced in the same showers

conventional ν: decay of kaons, pions
ν_μ dominated (at relevant energies)
[M. Honda et al., PRD75, 043006, 2007]

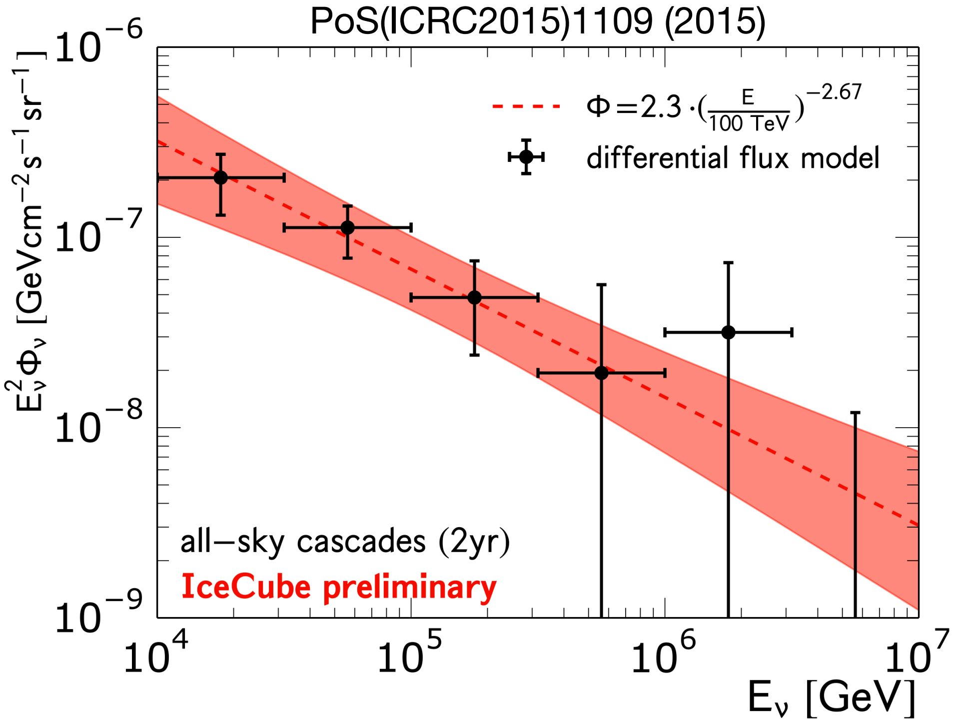
prompt ν: decay of heavier mesons
(charm), produces all flavors equally
[A. Bhattacharya et al., JHEP06, 110, 2015]

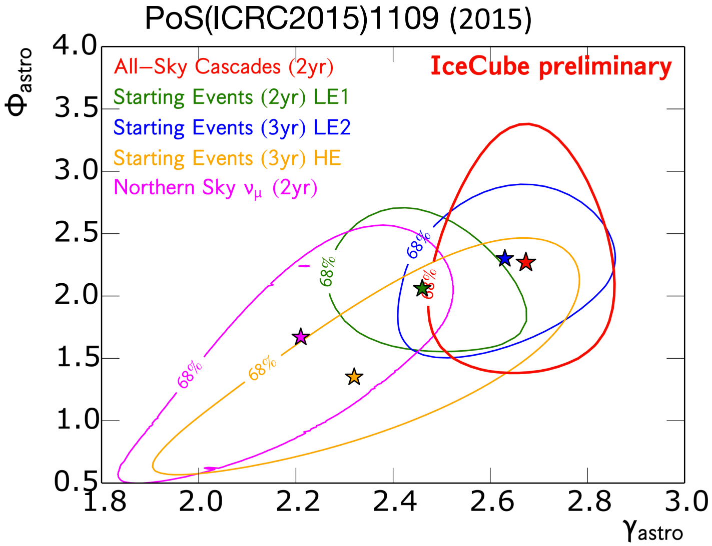


IceCube PRD91, 122004 (2015)

most recent cascade results
“2-yr cascades”

IceCube IC79+IC86 (2010/11)
presented at ICRC 2015 in The Hague





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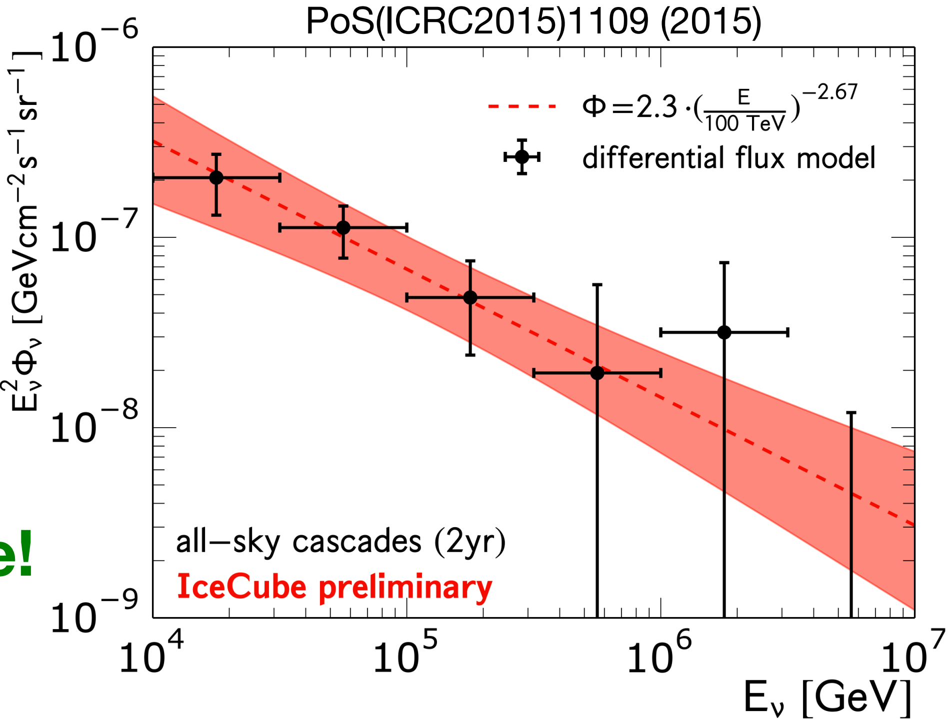
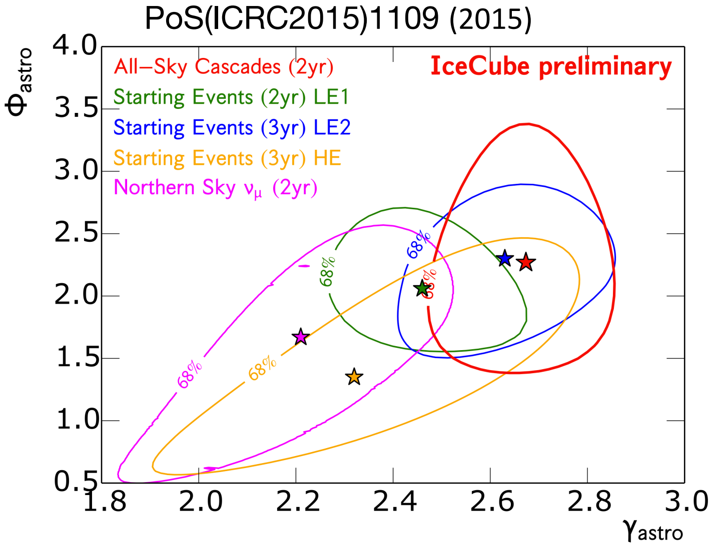
goal of this analysis: improve!

- ✓ **increase statistics (2-yr → 4-yr)**
- ✓ **increase signal efficiency at all energies**
- ✓ **lower energy threshold 10TeV → O(1TeV)**
- ✓ **reduce systematic uncertainties**





Event Selection

analyzed 4 additional years of IceCube data

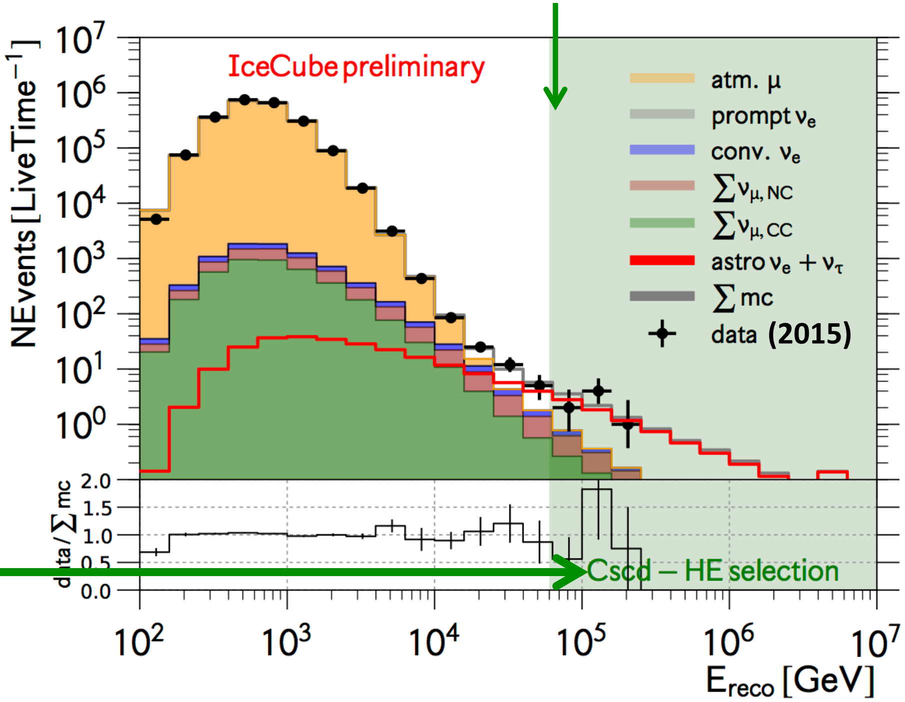
cascades in 2012-2015

<u>combined two cascade event selections</u>

contained high energy cascades (>60 TeV)

- uses straight cuts
- variables inspired by 2-yr cascades [1]
- **<u>free of atm. muon background</u>**

E=60 TeV



✓ **excellent data/mc agreement**

[1] Pos(ICRC2015)1109

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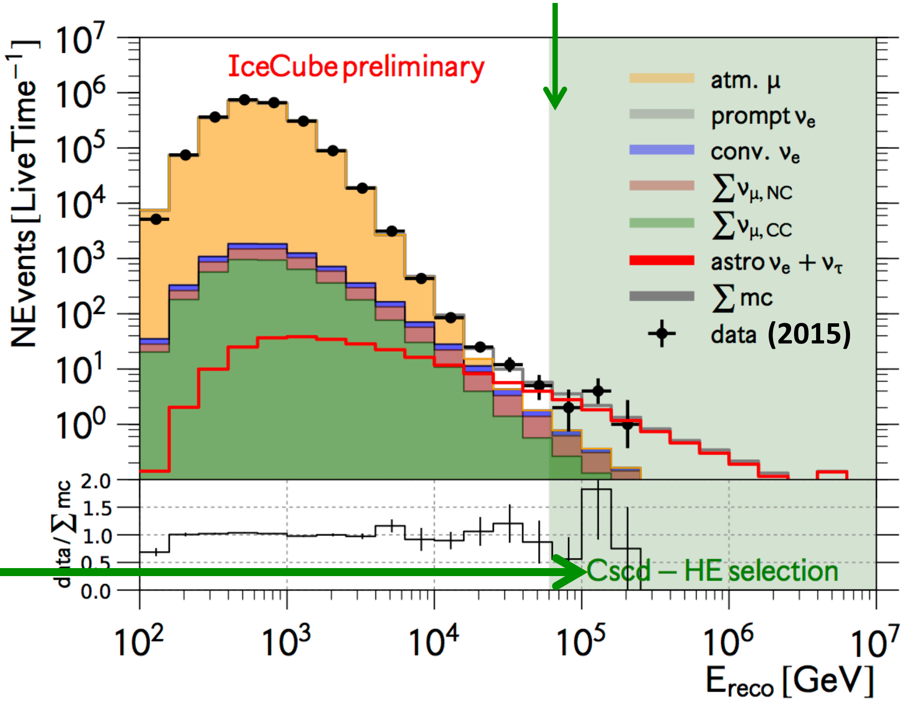


✓ **excellent data/mc agreement**

contained low energy cascades (<60 TeV)

- uses machine learning

  gradient boosted multi-class decision trees [2]

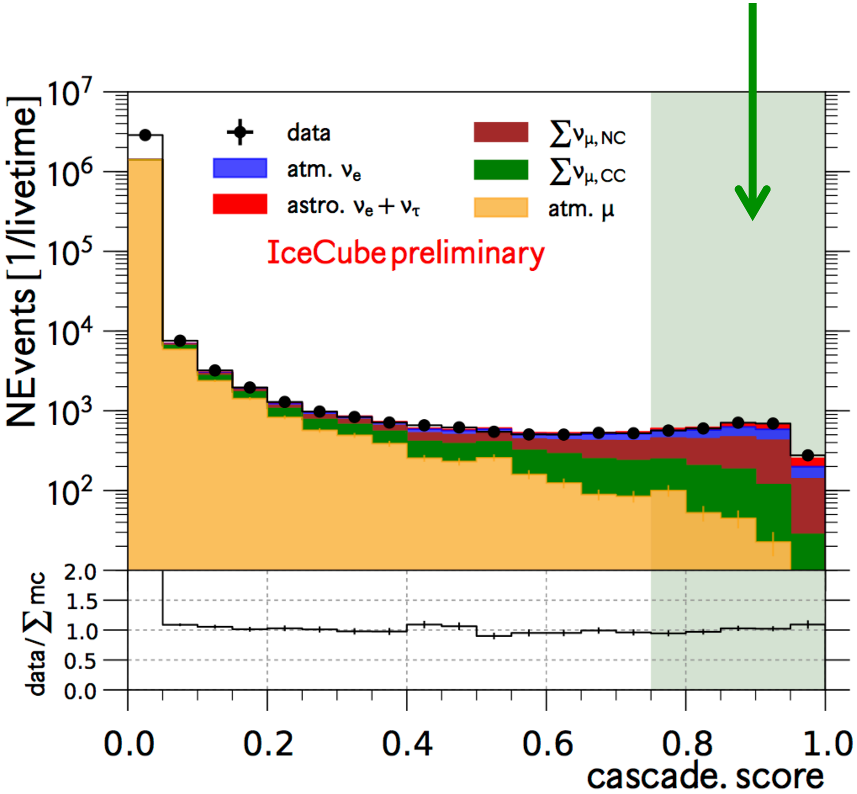
[1] Pos(ICRC2015)1109
[2] arXiv:1603.02754

Event Selection

contained low energy cascades (<60 TeV)

- calculate **three scores for every single event** (sum scores = 1)
- quantifies **compatibility** of event **with** IceCube's **main signatures**
- 13 variables (event topology, location, direction, brightness, reco-quality etc.)

cascade.score → **defines cascade signal sample** (merge with >60 TeV cascades)



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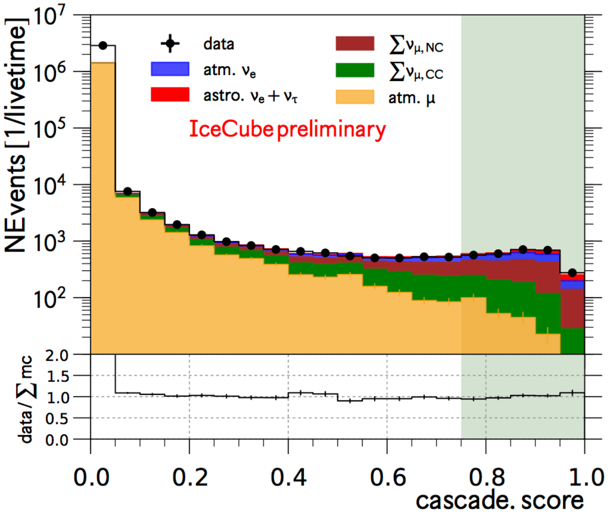
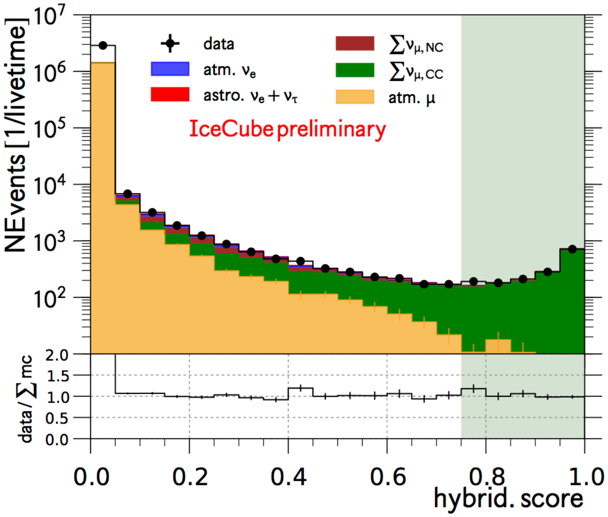
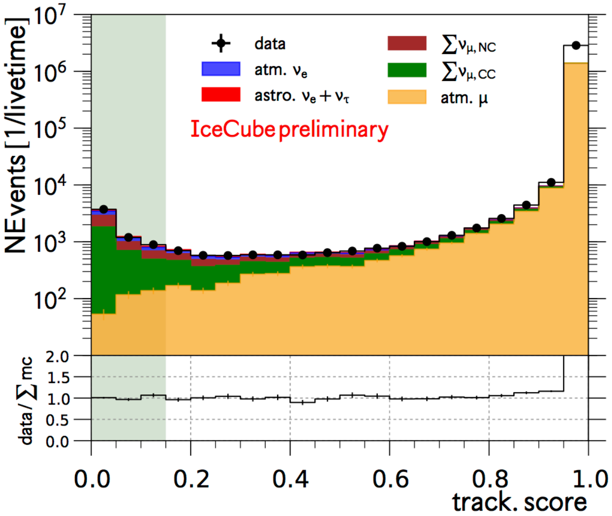
hybrid.score → **ν_μ-CC control sample** (starting tracks, atm. ν background)

track.score → **reject atmospheric μ** (through-going tracks from Southern Sky)







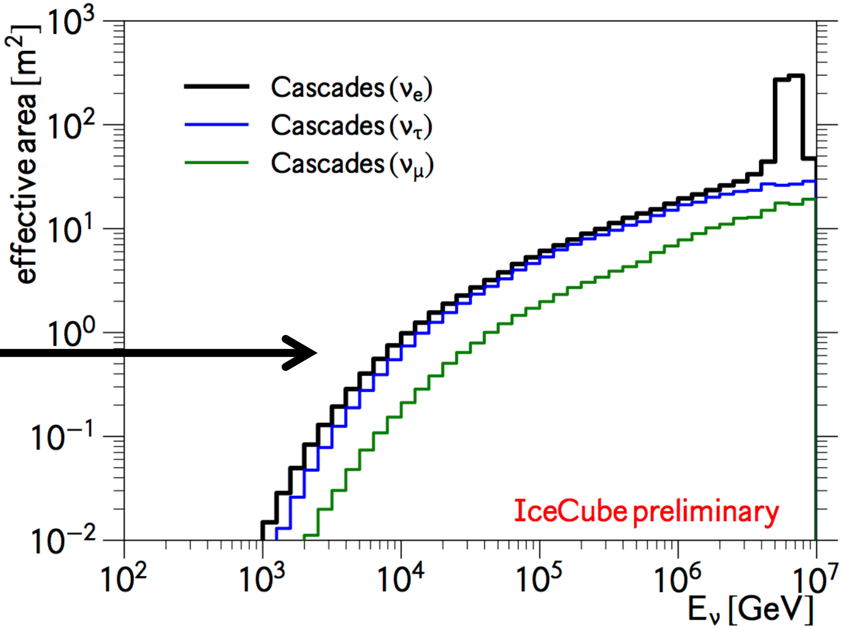
Event Selection

obtained IceCube's largest electron neutrino effective area! (contained vertices)

(>20% enhancement over previous analysis, E > 60 TeV)

> 90% neutrino purity

analysis mostly sensitive to astro. $\nu_e + \nu_\tau$



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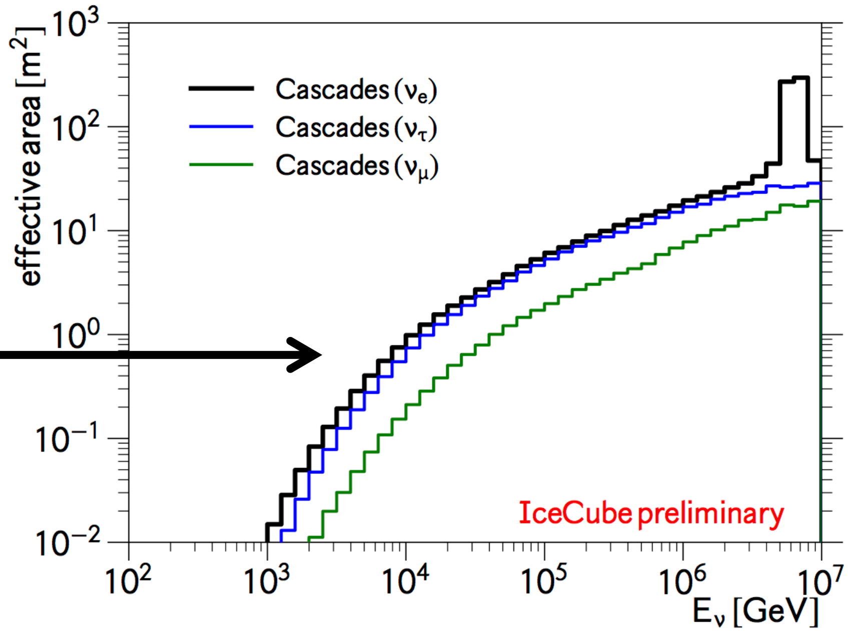
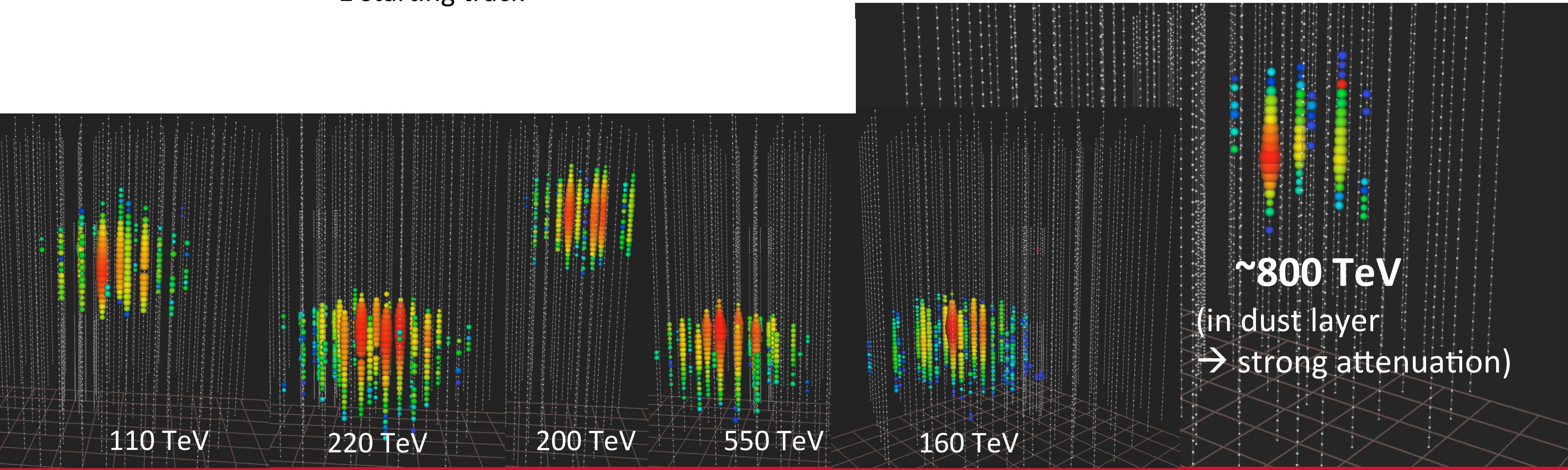


6320 events retained

4740 events in cascade sample

19 events (18 cascades) w. E>100 TeV

+1 starting track

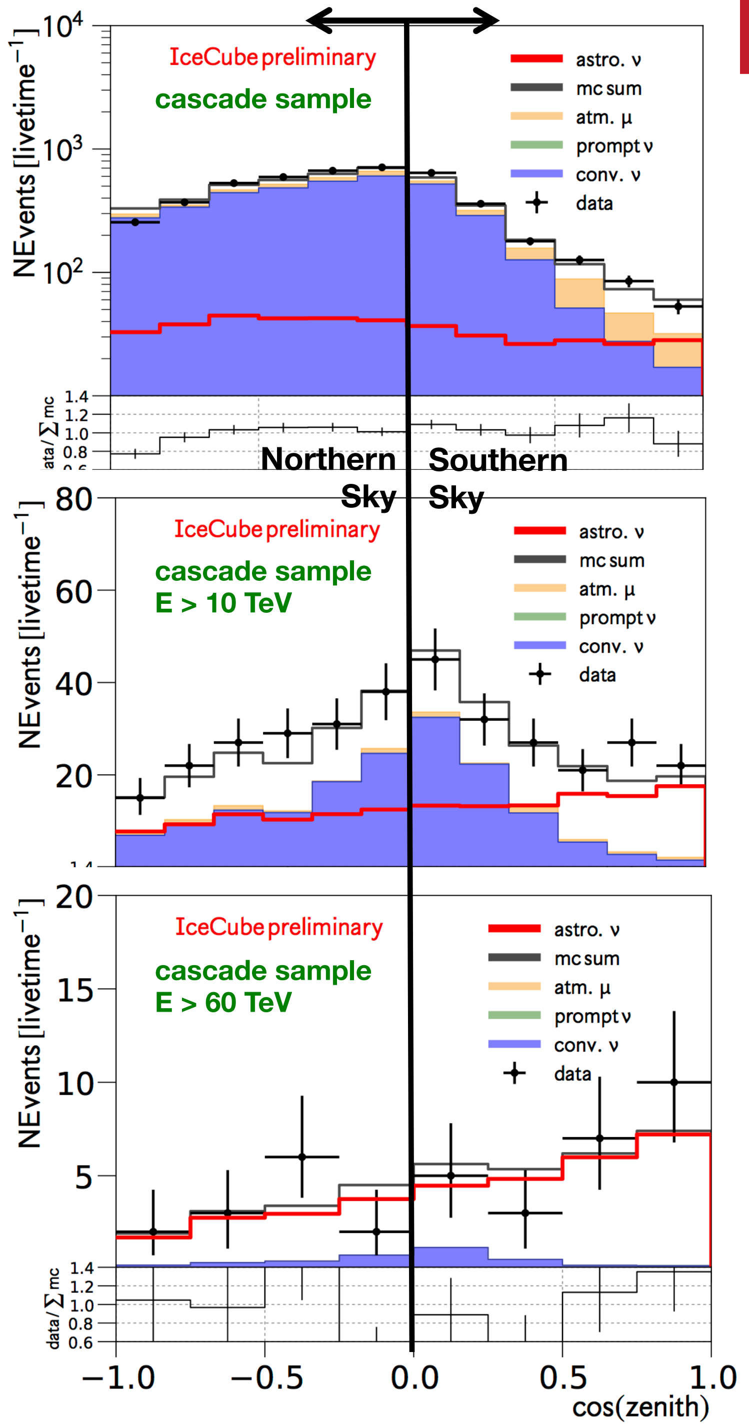


~800 TeV

(in dust layer → strong attenuation)

perform joint fit to three samples
range: 400 GeV to 10 PeV

1) **contained cascades** from **Northern Sky**
2) **contained cascades** from **Southern Sky**



perform joint fit to three samples

range: 400 GeV to 10 PeV

1) **contained cascades** from **Northern Sky**
2) **contained cascades** from **Southern Sky**

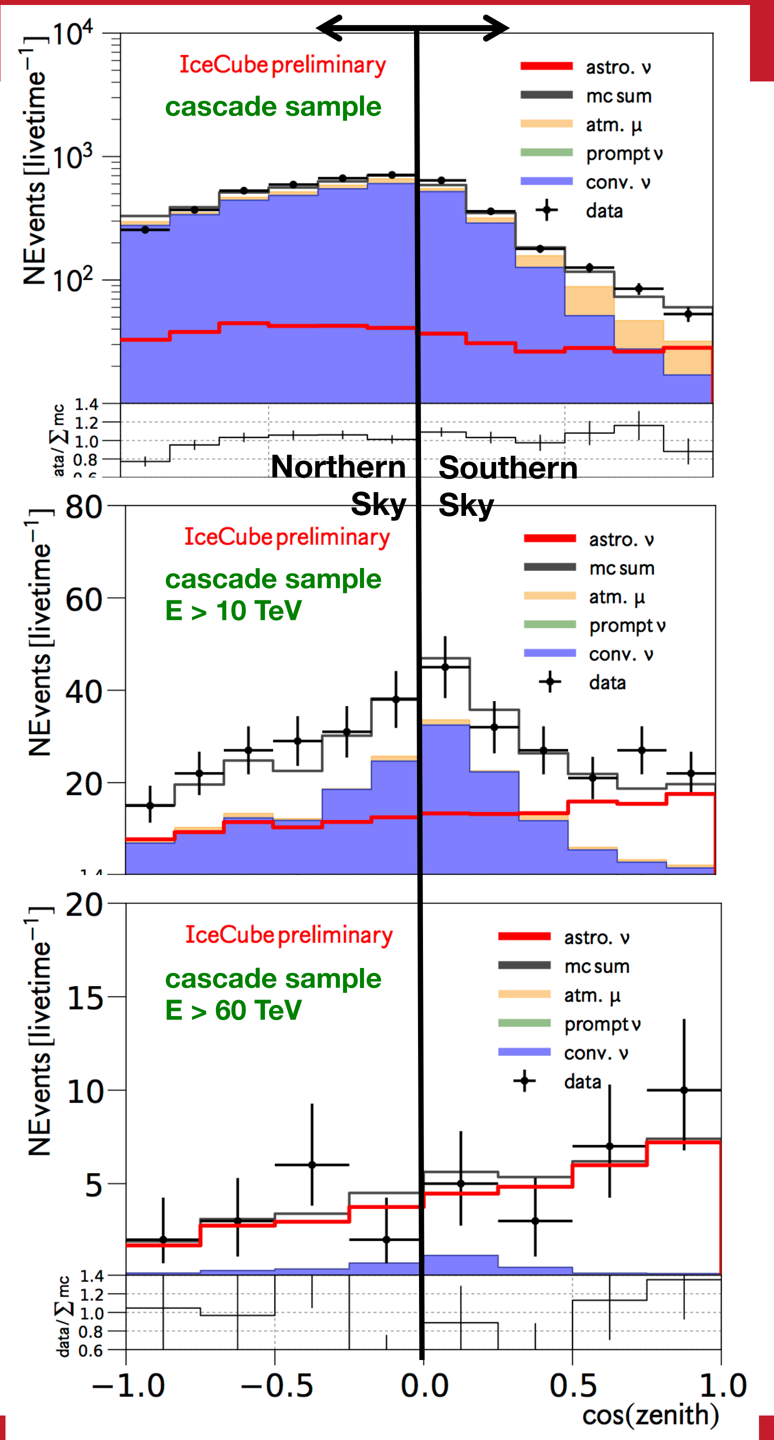
3) **starting tracks (control sample)**
   E<60 TeV, from **entire sky**
   constrains conventional background

Analysis Method

maximum likelihood based **template fit**
(“standard” in IceCube)

match observed deposited energy distribution (data) to prediction (simulation)

parameter constraints from profile-likelihood
(highest posterior density if prior information available)



Analysis Method

model assumptions

astrophysical neutrinos (with $\nu_e : \nu_\mu : \nu_\tau$ = 1:1:1 and $\nu : \bar{\nu}$ = 1:1 at earth)

- **single power-law**

$$\boxed{\Phi_\nu = \boxed{\phi} \times (E_\nu/100\,\mathrm{TeV})^{\boxed{-\gamma}}}$$

spectral index

per-flavor normalization
(at 100 TeV)

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- 2-component power-law

spectral index (soft)

spectral hardening

$$\Phi(E_\nu) = \boxed{\Phi_0} \times 10^{-18} \left\{ (1 - \boxed{\alpha}) \left[\frac{E_\nu}{10^5\, GeV} \right]^{\boxed{-\gamma_{\mathrm{soft}}}} + \alpha \left[\frac{E_\nu}{10^5\, GeV} \right]^{-\gamma_{\mathrm{soft}} \boxed{+\Delta\gamma}} \right\}$$

$$0 < \alpha < 1,\ \Delta\gamma \geq 0$$

$$\phi_{\mathrm{soft}} = (1 - \alpha)\phi$$

$$\gamma_{\mathrm{hard}} = \gamma_{\mathrm{soft}} - \Delta\gamma,\ \phi_{\mathrm{hard}} = \alpha \cdot \phi$$

total per-flavor normalization (at 100 TeV)

mixing fraction

Total Flux = soft component + hard component

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background fluxes

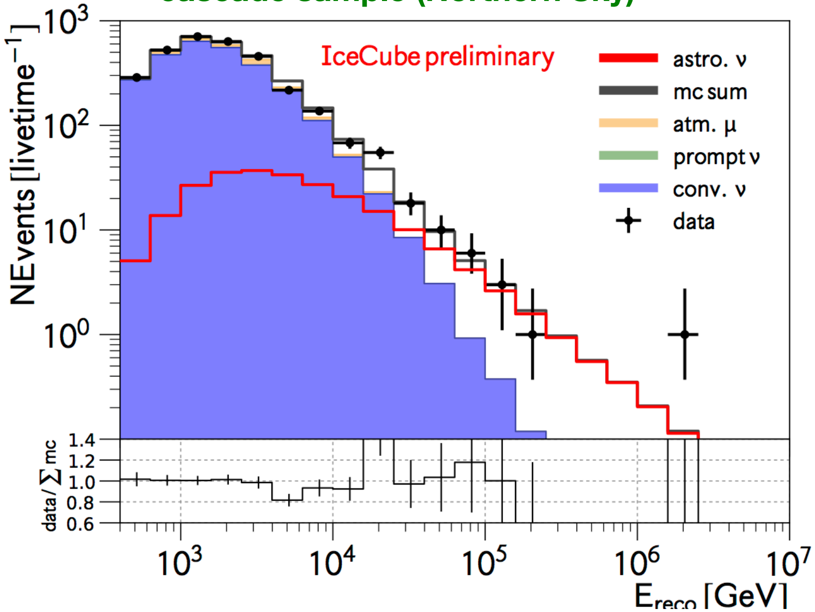
conventional ν:	**HKKMS06**	30% uncertainty conventional ν [A. Fedynitch et al., PRD86 114024, 2012]
prompt ν:	**BERSS15**	uncertainty prompt ν from IceCube upper-limit [IceCube, ApJ 833, No 1, 2016]
atm. μ:	**Gaisser12**	

Stony Brook University

Results

The Single Power-Law

cascade sample (Northern Sky)



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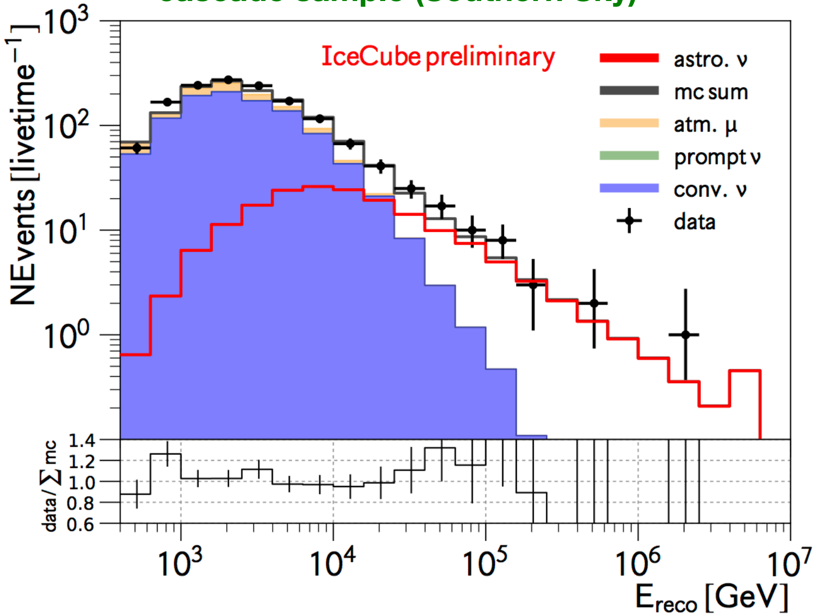
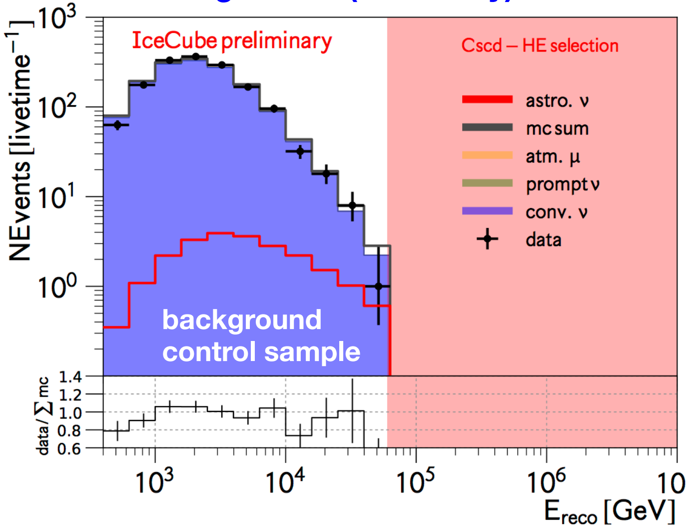


Parameter		Prior	Result
spectral index	γ	-	$\mathbf{2.48 \pm 0.08}$
norm astro	ϕ	-	$(\mathbf{1.57^{+0.23}_{-0.22}})$ c.u.
norm conv	ϕ_{conv}	1.00 ± 0.30	$(1.12 \pm 0.10) \cdot \Phi_{HKKMS06}$
norm prompt	ϕ_{prompt}	$0.0^{+1.8}_{-0.0} \cdot \Phi_{BERSS}$	$< X \cdot \Phi_{BERSS}$(**)
norm muon	ϕ_{muon}	-	1.40 ± 0.04
scattering scale	ε_{scat}	1.00 ± 0.10	1.07 ± 0.02
absorption scale	ε_{abs}	1.00 ± 0.10	0.99 ± 0.03
dom efficiency	ε_{eff}	0.99 ± 0.10	1.00 ± 0.06

$(1\,\text{c.u.} \equiv 10^{-18}\,\text{GeV}^{-1}\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2})$

(**) still being studied

starting tracks (entire sky)



significant energy range: 12 TeV – 2.1 PeV

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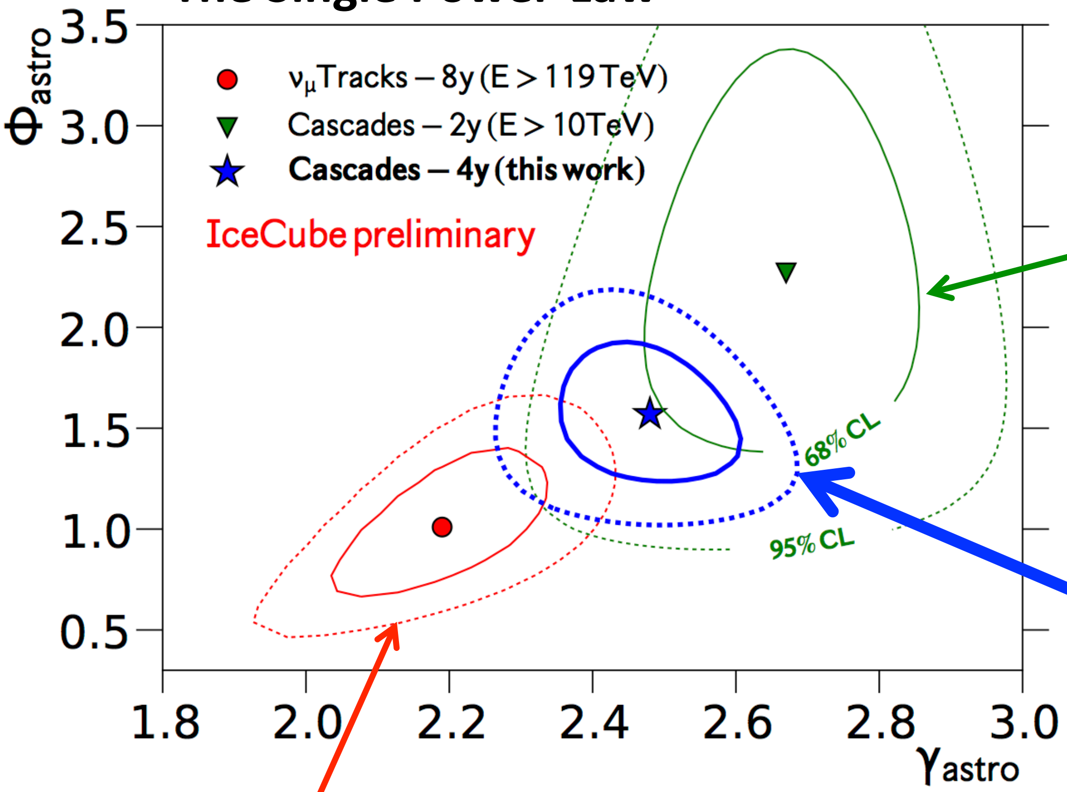


PoS(ICRC2015)1109

$\nu_e + \nu_\tau$

E_{rec} > 10 TeV

this work

PoS(ICRC2017)968

$\nu_e + \nu_\tau$

significant energy range
12 TeV – 2.1 PeV

PoS(ICRC2017)1005

ν_μ Northern Sky

significant energy range
119 TeV – 4.8 PeV

poster NU022

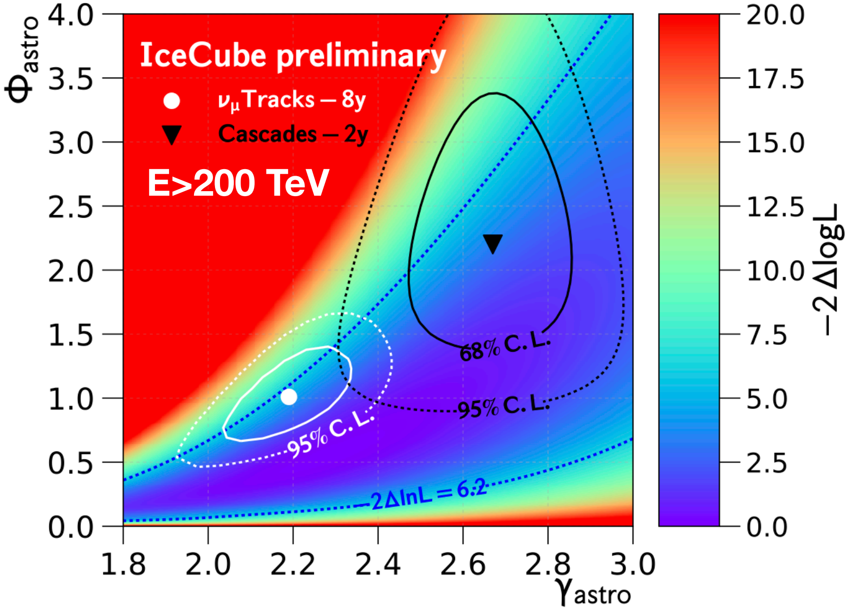
✓ **consistent with previous cascade analysis**

✓ also still consistent with diffuse ν_μ (p=0.04)

Results

The “High Energy E>200 TeV” Tail

- (essentially) no atm. background expected
- only 6 cascades satisfy E_{rec} > 200 TeV
- LLH space of restricted fit does not meaningfully constrain spectral shape!
- **slight preference for lower normalization** than previous results
  P(N <= 6 | x) = 0.14 (0.05) for x = 2-yr cascades (8-yr tracks)



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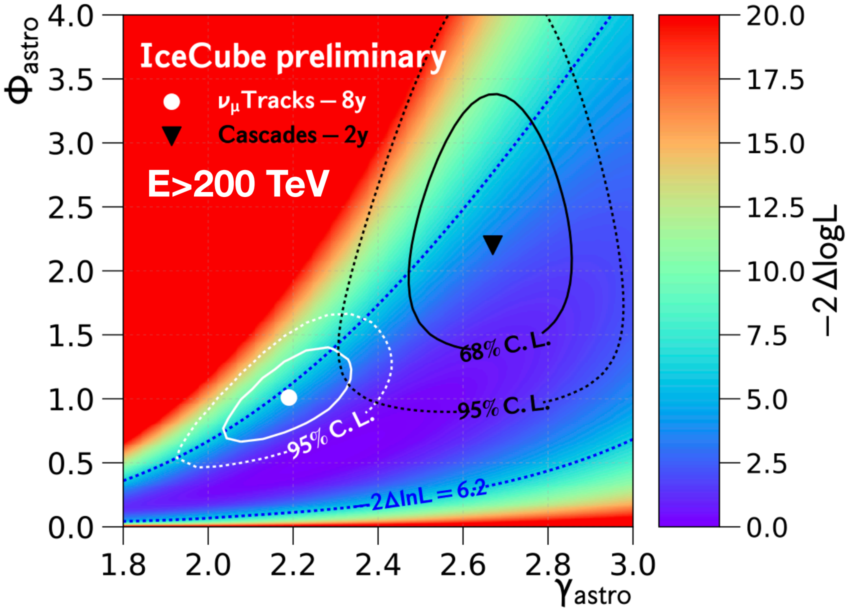
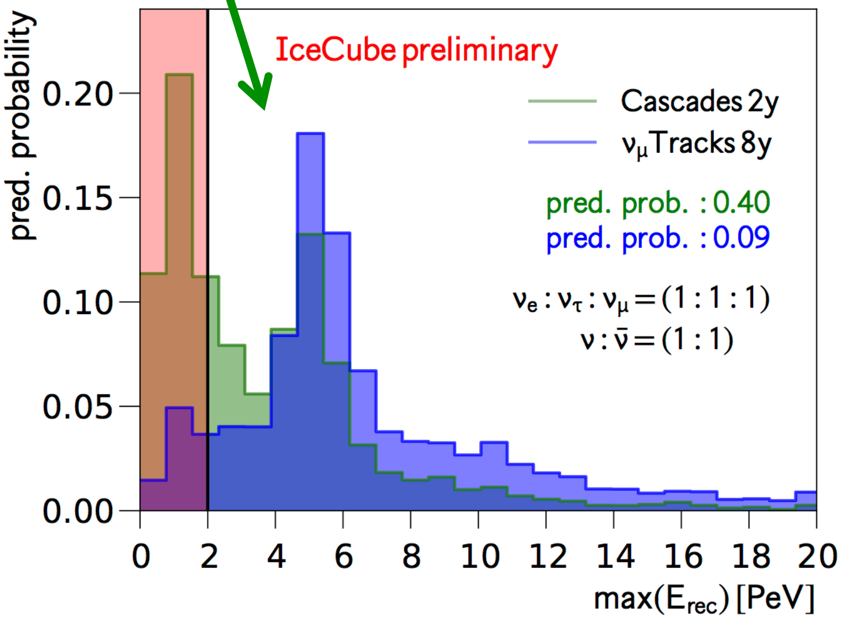
- **highest energy cascade at 2 PeV: plausible for both previous results**





Results

ICECUBE

The 2-Component Power-Law

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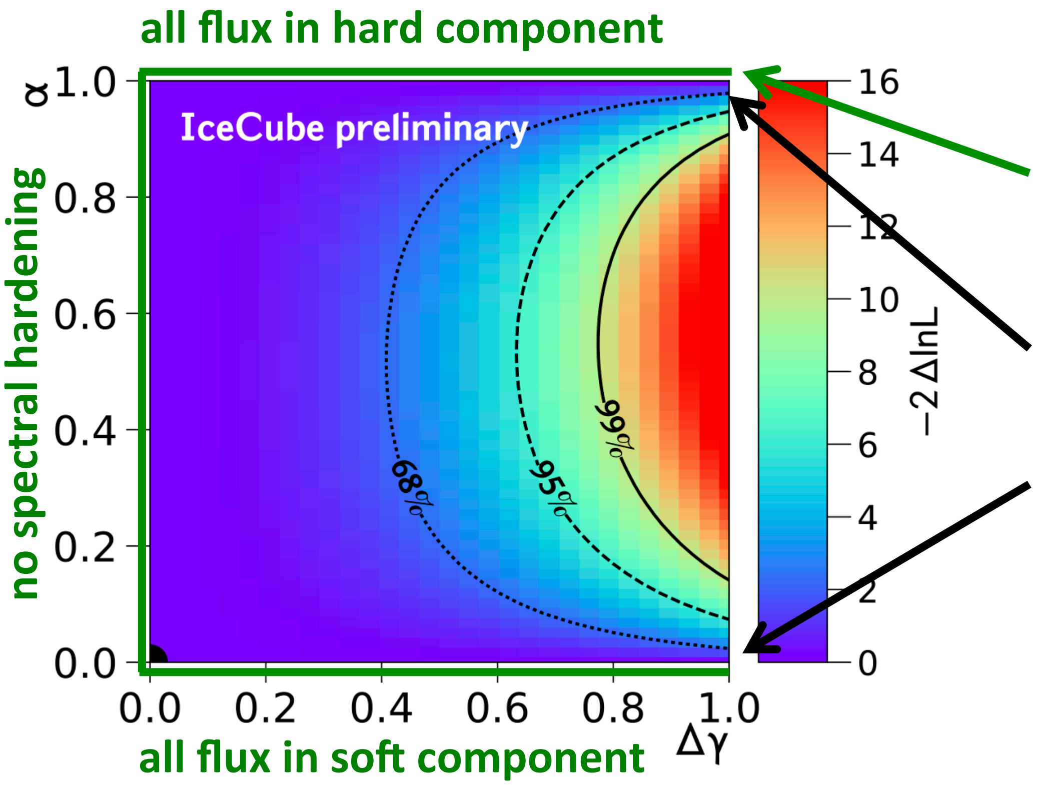

model reduces to single power-law at boundary of parameter space

not sensitive if one component is strongly subdominant

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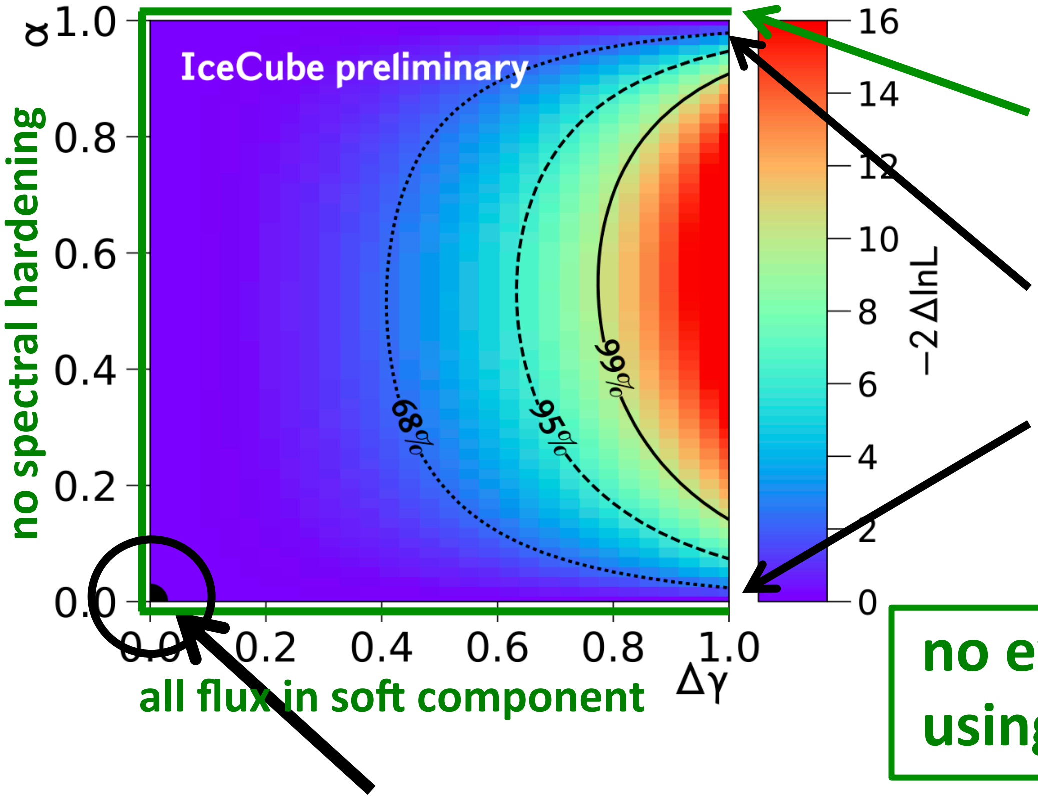


all flux in hard component

no spectral hardening

all flux in soft component

model reduces to single power-law at boundary of parameter space

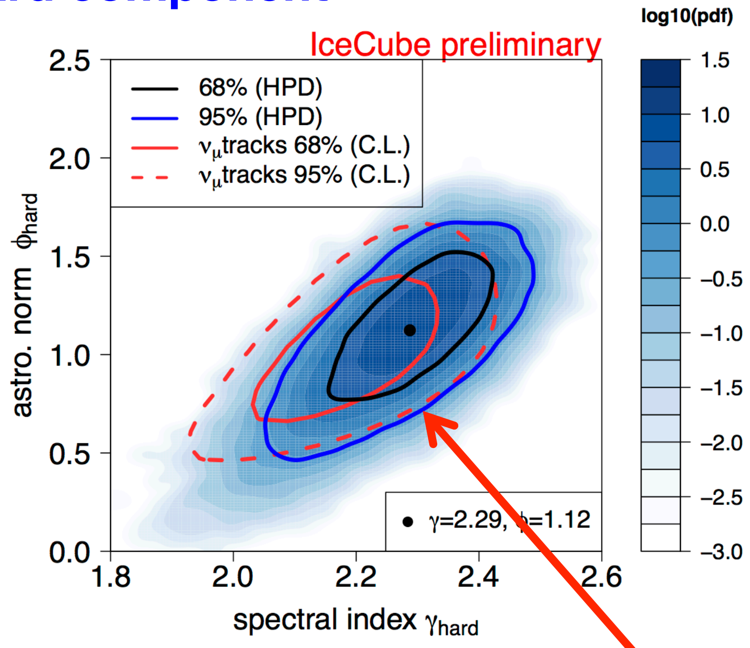
not sensitive if one component is strongly subdominant

no evidence for a 2nd component using cascade events

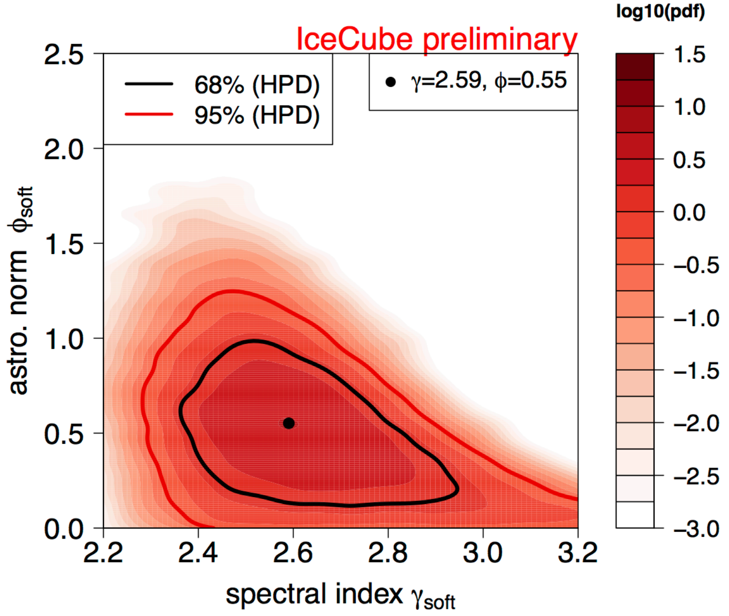
best fit: no spectral hardening, no 2nd component
(identical to single-powerlaw)

Results

hard component



soft component



ICECUBE

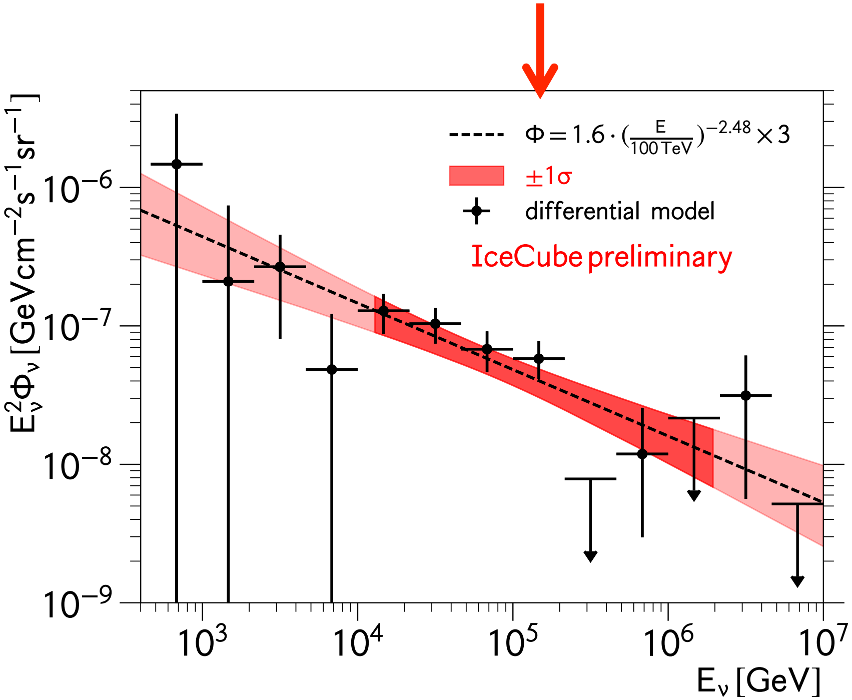
- can include **prior information**: 8yr-tracks result constrains **hard component**
- **posterior distribution**: **soft component** sub-dominant (in this scenario)
- no tension between prior and posterior distributions for **hard component**

Reminder: **no evidence** for this model in this analysis (c.f. previous slide)!

Results

Differential Flux Measurement

- **relax power-law assumption**
  by fitting separate flux normalizations in bins of E_ν (E^{-2} distribution within each bin)
- large uncertainties at low (<10 TeV) and high (>200 TeV) energies
  (→ dominated by conventional background) (→ only 6 events)
- **consistent with single power-law**



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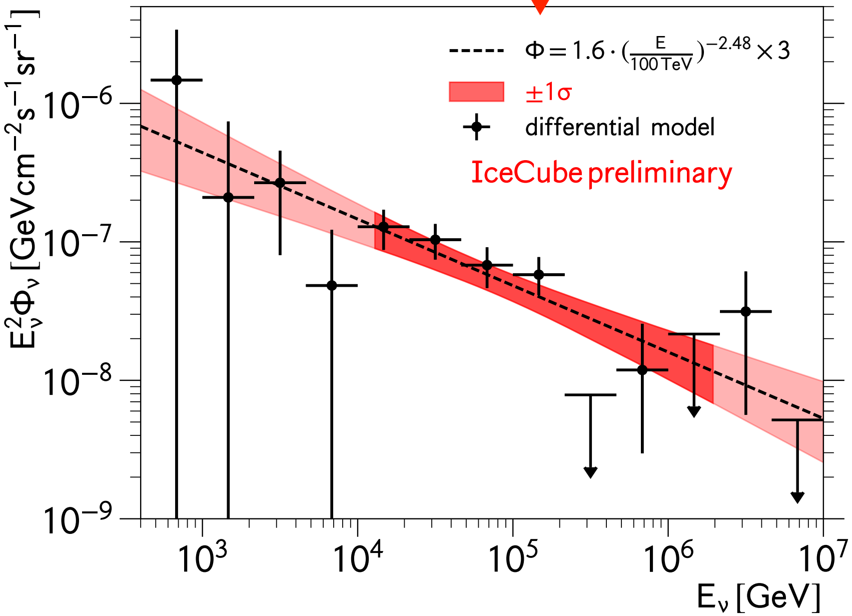
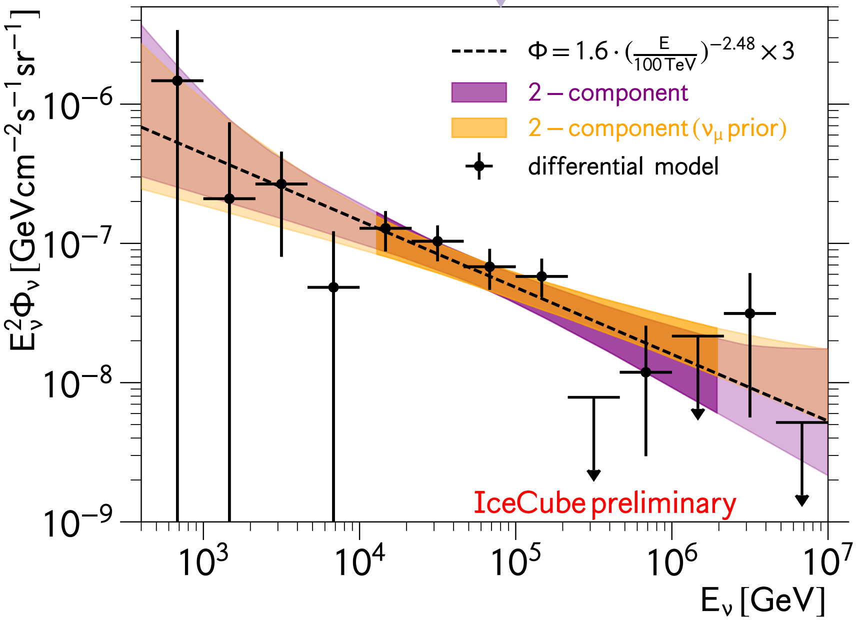
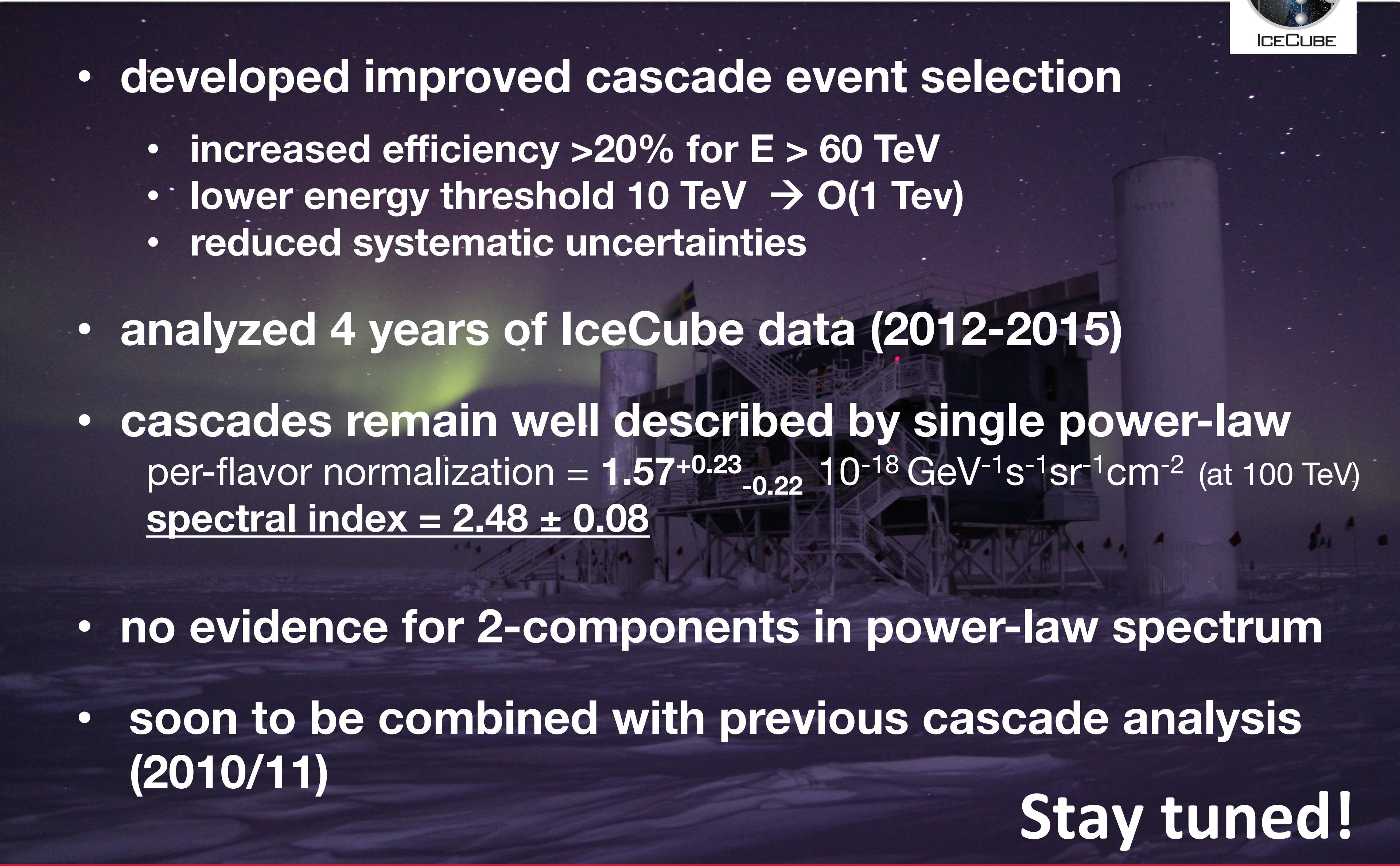
  (→ dominated by conventional background) (→ only 6 events)
- **consistent with single power-law** (and hypothetical 2-component) **scenario**





Summary



- **developed improved cascade event selection**
  - **increased efficiency >20% for E > 60 TeV**
  - **lower energy threshold 10 TeV → O(1 Tev)**
  - **reduced systematic uncertainties**

- **analyzed 4 years of IceCube data (2012-2015)**

- **cascades remain well described by single power-law**

  per-flavor normalization = $\mathbf{1.57^{+0.23}_{-0.22}}$ $10^{-18}\,\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{cm}^{-2}$ (at 100 TeV)

  spectral index = 2.48 ± 0.08

- **no evidence for 2-components in power-law spectrum**

- **soon to be combined with previous cascade analysis (2010/11)**

Stay tuned!

BACKUP

Analysis Method

maximum likelihood based **template method** (“standard” in IceCube)

match observed deposited energy distribution (data) to prediction (simulation)

$$L(\boldsymbol{\theta}_r|\underline{n}) = \underset{\boldsymbol{\theta}_s}{\operatorname{argmax}} L(\overset{\text{astrophysics}}{\boxed{\boldsymbol{\theta}_r}}|\underset{\text{nuisance}}{\boxed{\boldsymbol{\theta}_s}}|\overset{\text{data}}{\boxed{\underline{n}}}) = \underset{\boldsymbol{\theta}_s}{\operatorname{argmax}} \prod_{i=1}^{3}\prod_{j=1}^{N} \frac{\mu_{ij}(\boldsymbol{\theta}_r,\boldsymbol{\theta}_s)^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}(\boldsymbol{\theta}_r,\boldsymbol{\theta}_s)}$$

$$\mu_{ij}(\boldsymbol{\theta}_r,\boldsymbol{\theta}_s) = \mu_{ij}^{atm.\mu} + \boxed{\mu_{ij}^{atm.\nu}} + \boxed{\mu_{ij}^{astro.\nu}}$$

+ quadratic penalty terms for nuisance parameters:

nuisance parameters (in this work):

atm. ν flux normalizations
detector energy scale ε

Analysis Method

100(1-α)% highest posterior density (HPD) region

$$C = \{\theta \in \Theta : \pi(\theta|x) \geq k(\alpha)\} \tag{1}$$

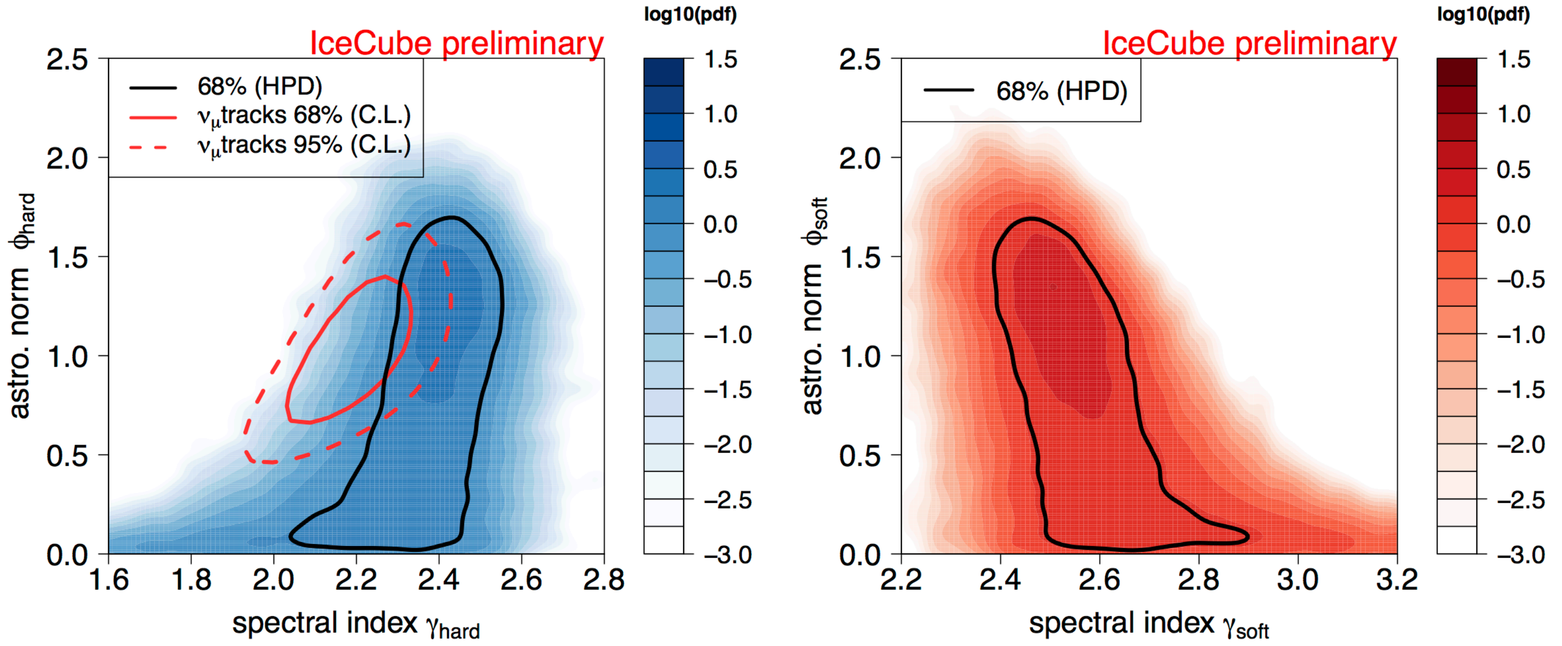
$$1 - \alpha \leq P(C|x) = \int_C \pi(\theta|x)\,\mathrm{d}\theta = \int_C f(x|\theta) \cdot \pi(\theta)\,\mathrm{d}\theta \tag{2}$$

where $k(\alpha)$ is the largest constant satisfying Eq. (2). $\pi(\theta)$, $\pi(\theta|x)$ and $f(x|\theta) \propto L(\theta|x)$ are prior distribution, posterior distribution and likelihood function respectively.

Results

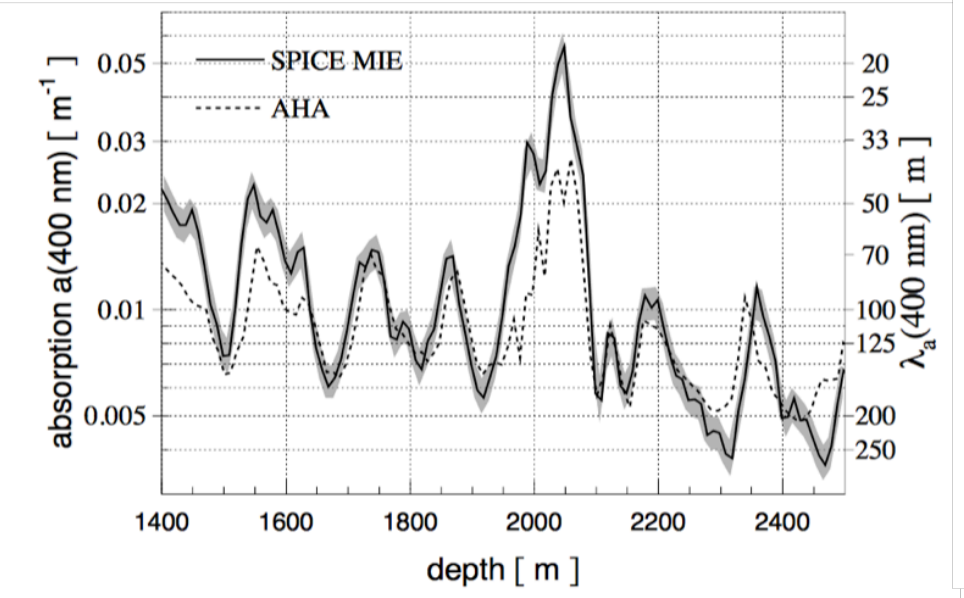
2-Component Powerlaw

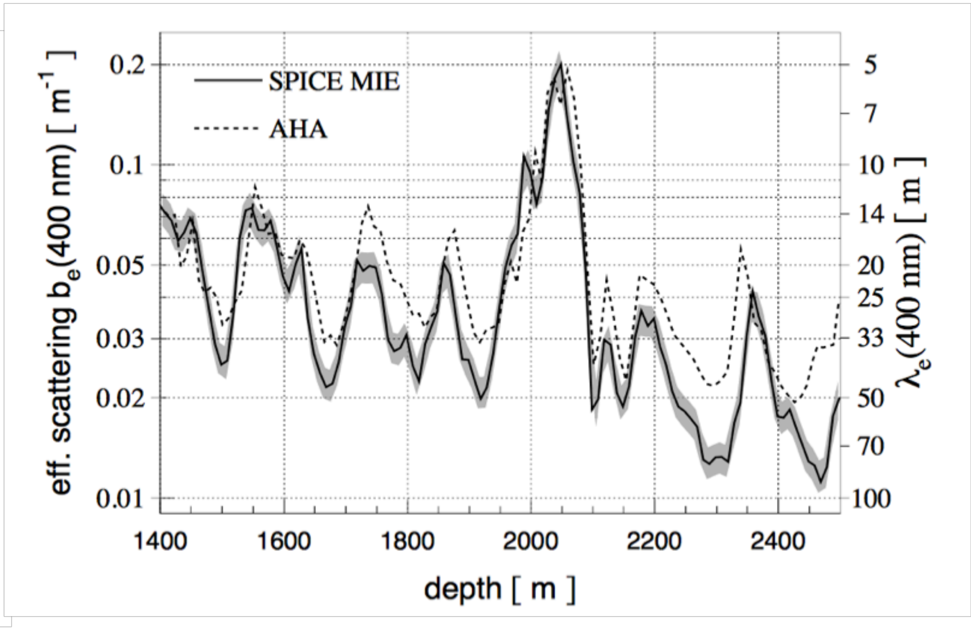
uniform prior on spectral hardening $\Delta\gamma$ and mixture fraction α



South Pole Ice: Optical Properties

IceCube Collaboration, NIM A711 73 (2013)



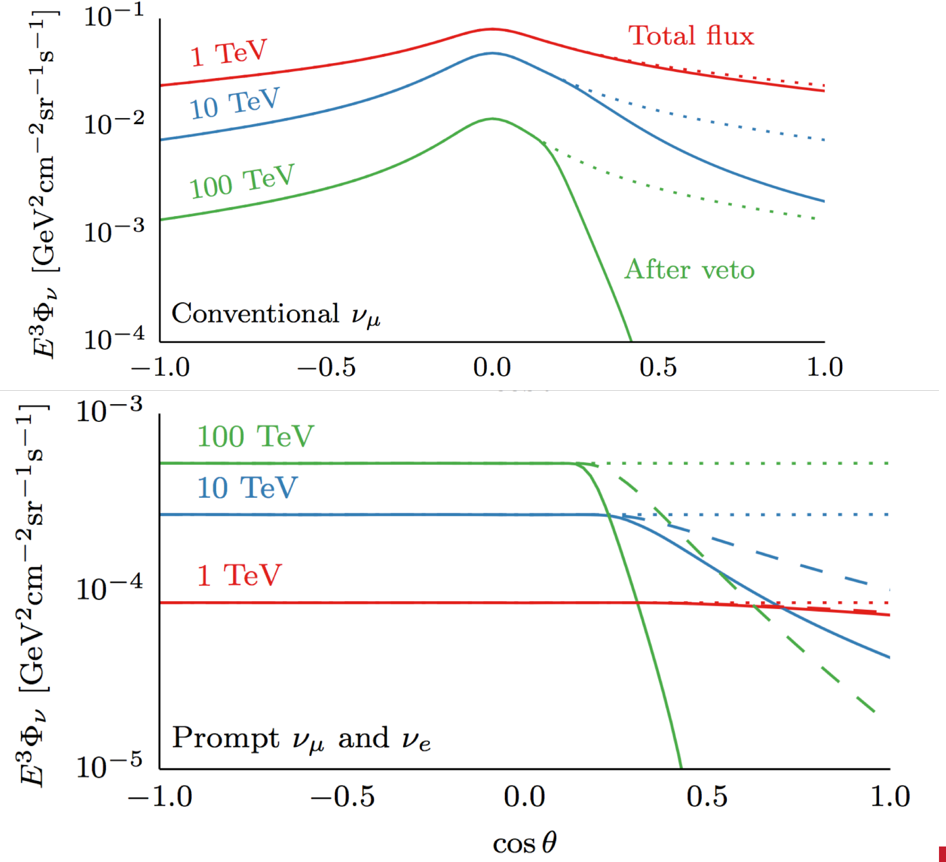


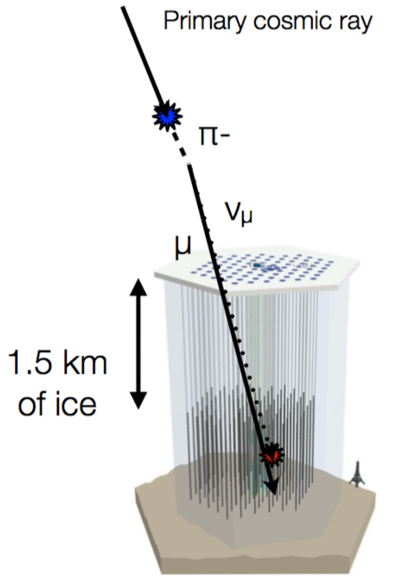
Atm. Self Veto Effect

- atmospheric ν are produced together with atmospheric μ (same cosmic ray induced air showers)
- **southern sky**: atmospheric ν are likely to be accompanied by atmospheric μ

→ atmospheric μ rejection also suppresses atmospheric ν events

Gaisser et al., PRD90, 023009 (2014)





Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)