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IceCube

High Energy Astrophysical Neutrino Flux Characteristics for Neutrino-induced Cascades

(using IC79 and IC86-String IceCube configurations)

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for the IceCube Collaboration

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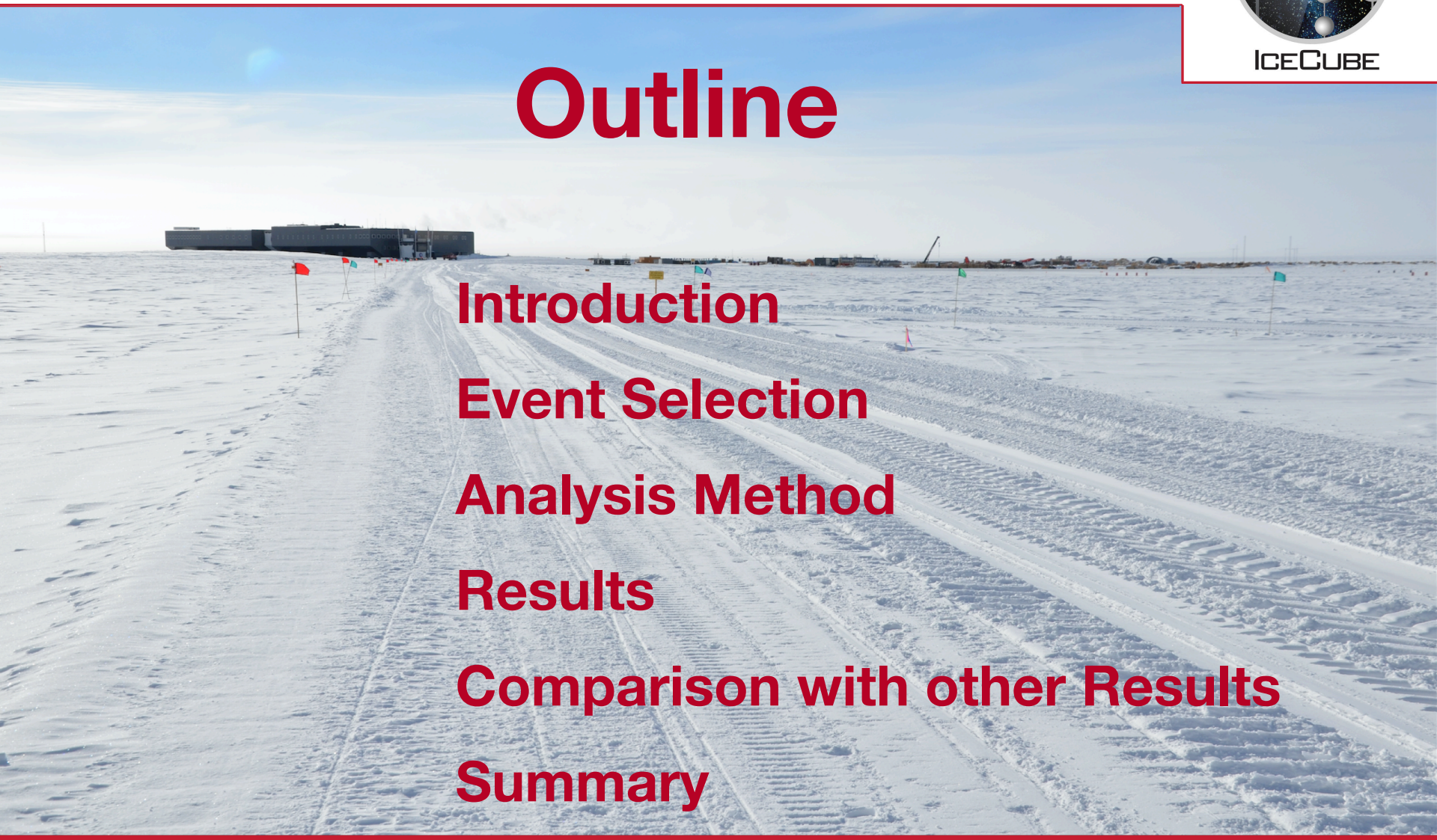
Outline



- Introduction
- Event Selection
- Analysis Method
- Results
- Comparison with other Results
- Summary

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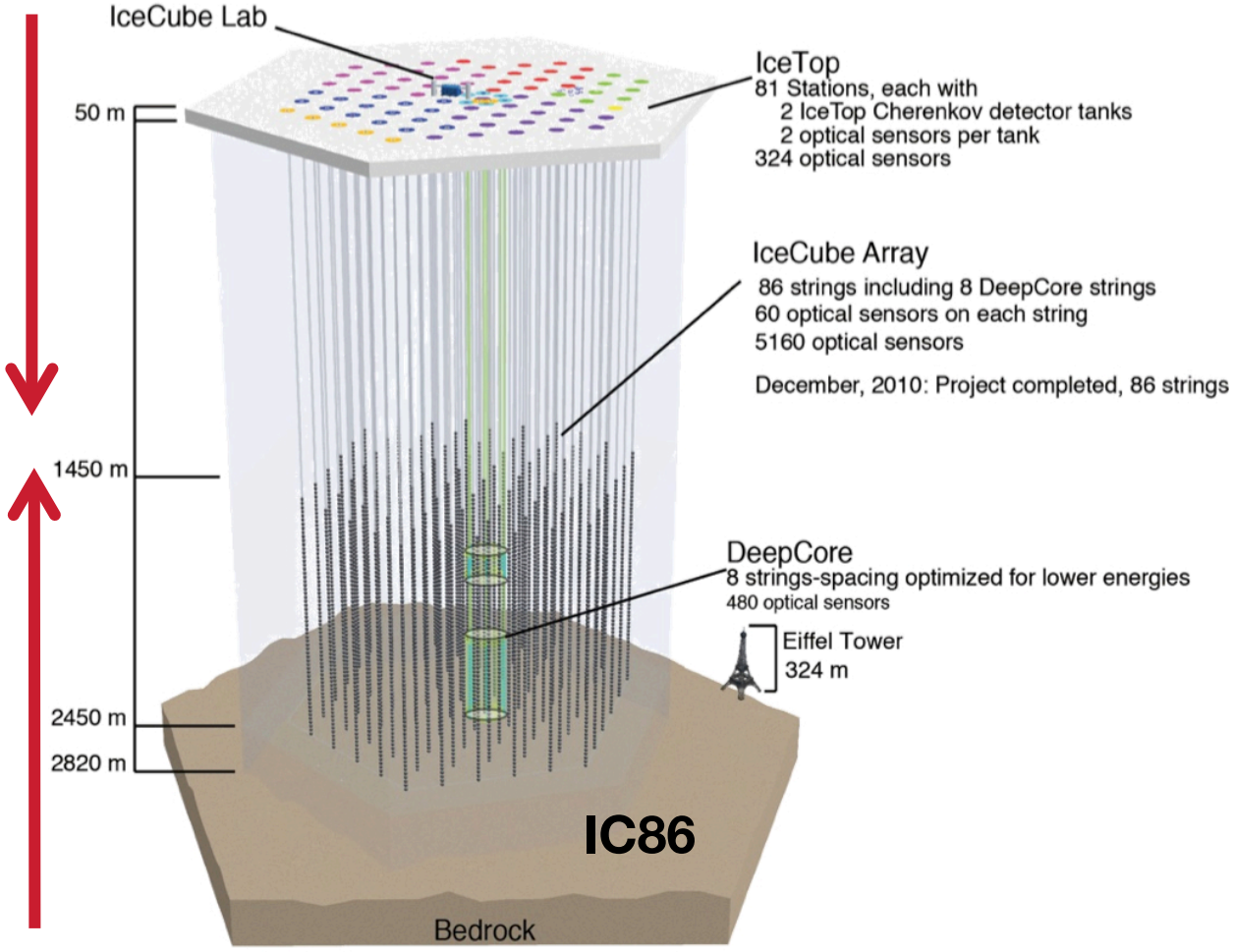
Introduction

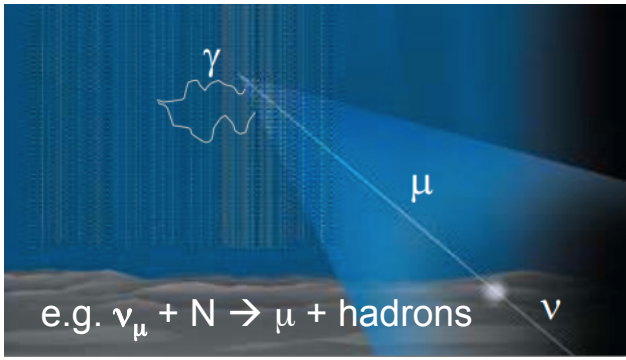
IceCube

from Southern Sky



from Northern Sky

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

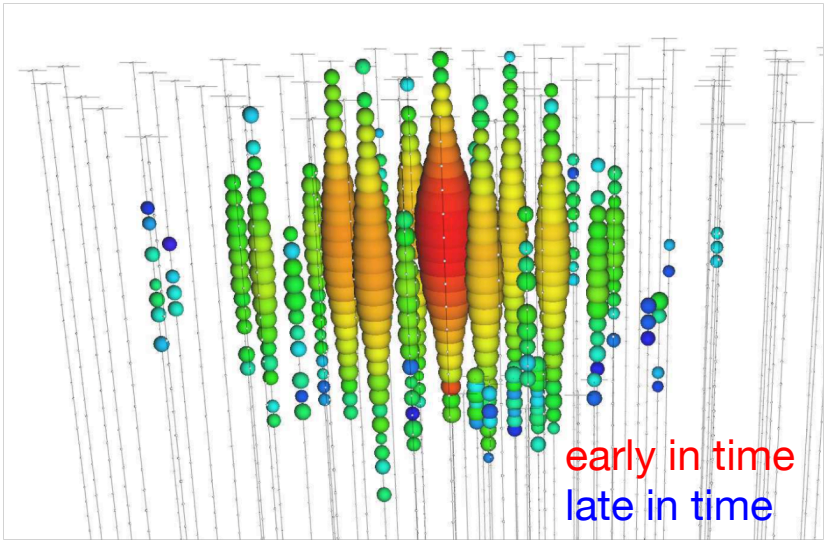


Infer neutrino properties from **photon arrival time distributions** in each optical module (DOM)

ICn := IceCube configuration with n strings

Introduction

Event Signatures in IceCube



Cascades

electromagnetic and hadronic particle showers from:

CC: $\nu_e(\nu_\tau) + N \rightarrow e(\tau) + \text{hadrons}$

NC: $\nu_e(\nu_\mu, \nu_\tau) + N \rightarrow \nu_e(\nu_\mu, \nu_\tau) + \text{hadrons}$

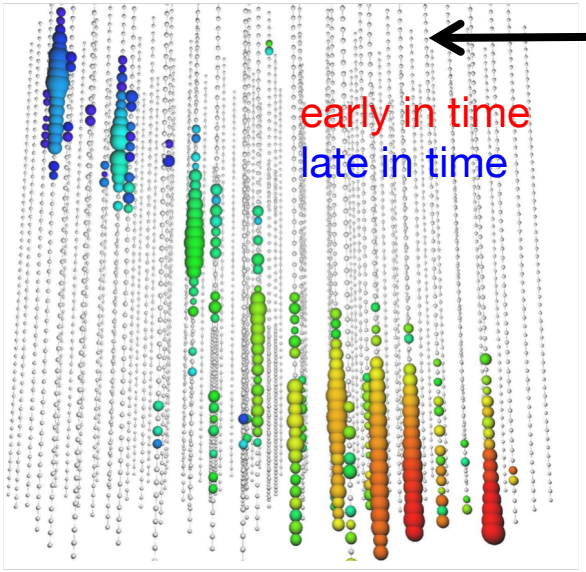
- point-like light emission
- all-sky sensitivity
- angular resolution ~15°
- **very good energy resolution**

  ~15% contained cascades
  ~30% partially contained cascades

→ ideal for spectral characterization of astrophysical ν-flux ($\nu_e + \nu_\tau$)

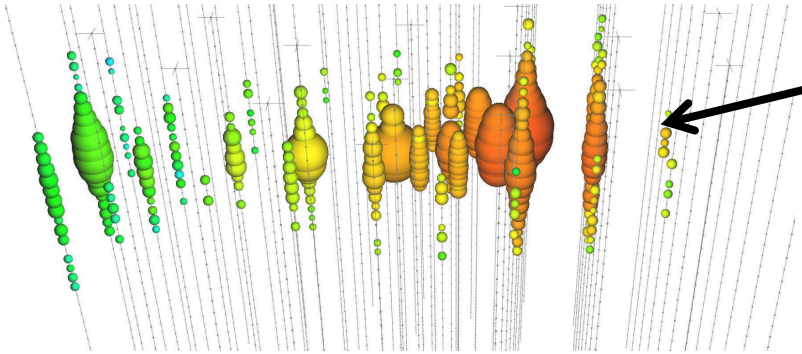
Introduction

Event Signatures in IceCube



through-going tracks

- from through-going muons
- e.g. from ν_μ CC interactions
- angular resolution < 1°
- energy resolution of 0.3 in $\log_{10}E_\mu$
- restricted to northern sky



hybrid events

ν_τ double bang (* not yet observed)

starting tracks (cascade + track)

- requires outer-layer veto technique
- from ν_μ CC interactions

"starting events" := starting tracks + contained cascades

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Introduction

IceCube

✓ **this work IC79+IC86-2011: require cascade event topology**

✓ **sensitive to** $\nu_e + \nu_\tau$

similar searches for extraterrestrial cascades:
IceCube IC22 PRD84 072001 (2011)
IceCube IC40 PRD89 102001 (2014)
IceCube IC59 Proc. of 33rd ICRC, arXiv:1309.7003 (2013)

background stems from atmosphere only!

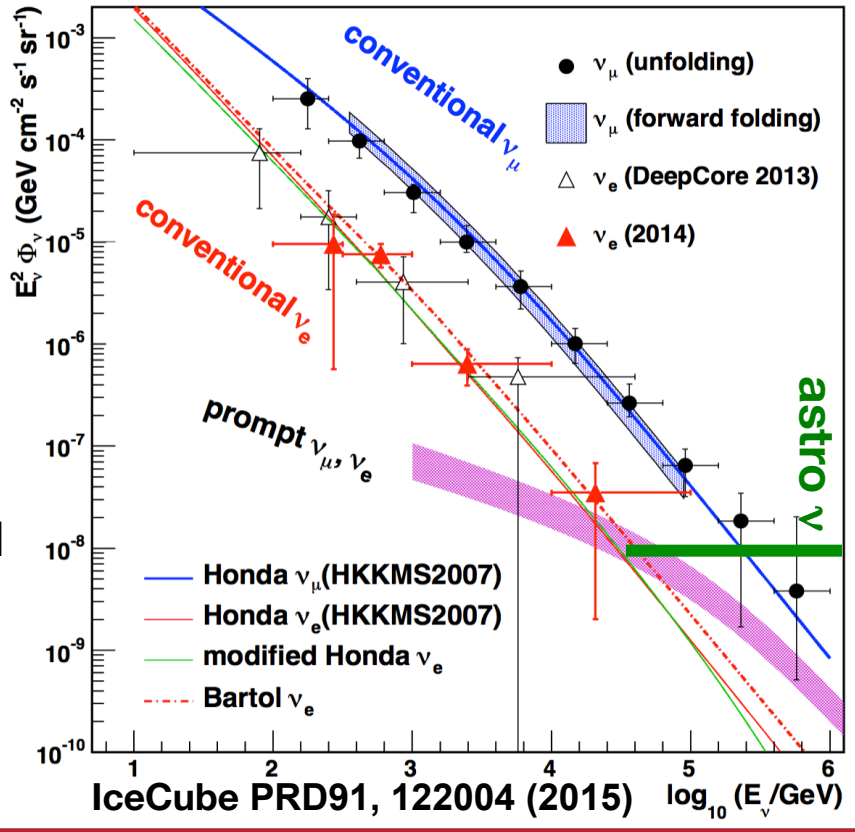
muons: produced in cosmic ray air showers

neutrinos: produced in the same showers

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

prompt ν: decay of heavier mesons (charm), produces all flavors equally
[R. Enberg et al., PRD78,043005,2008 + JHEP06,110,2015]

+ corrections for CR knee and atmospheric neutrino self-veto effects



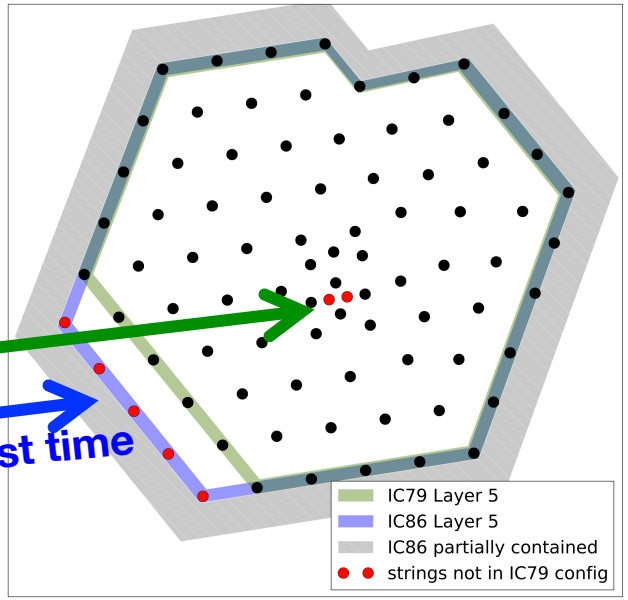
[IceCube IC59, PRD89, 062007, 2014]
[T. Gaisser et. al., PRD90, 023009, 2014]

Event Selection

use 2 years of data (May 2010 – May 2012)

exploit two cascade categories
(defined by vertex position w.r.t instrumented volume)

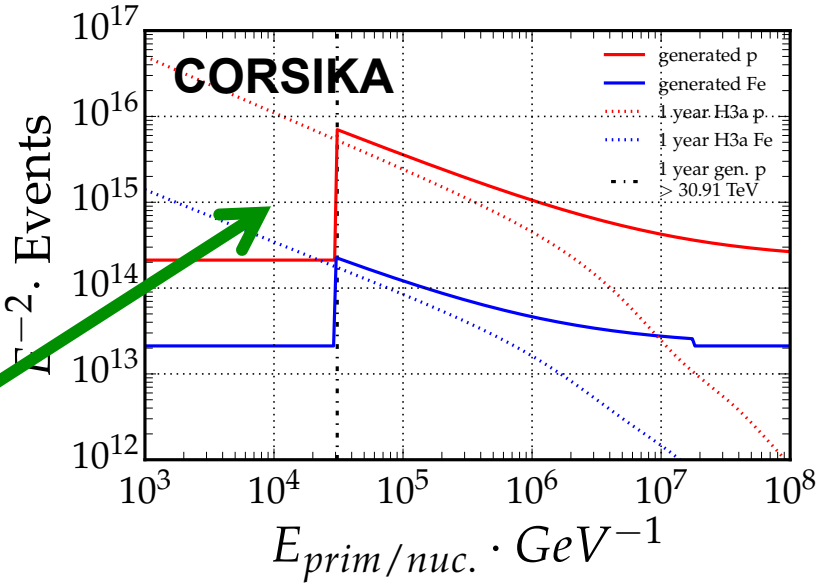
- **fully contained cascades**
- **partially contained cascades**



developed **independent event selection**
(no outer-layer veto used)
cuts on **cascade topology variables**

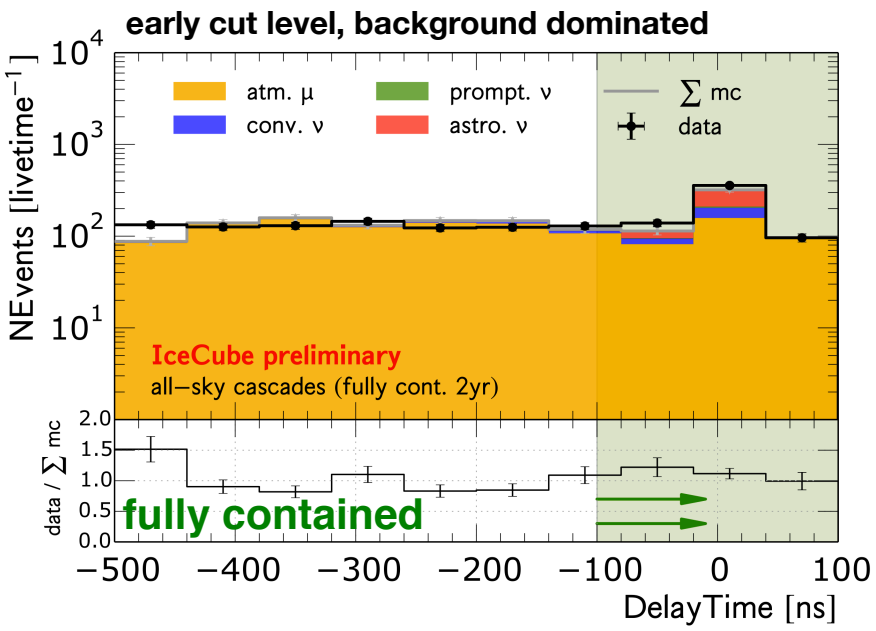
background rejection **using full MC**
extensive air shower simulation
→ computationally extensive

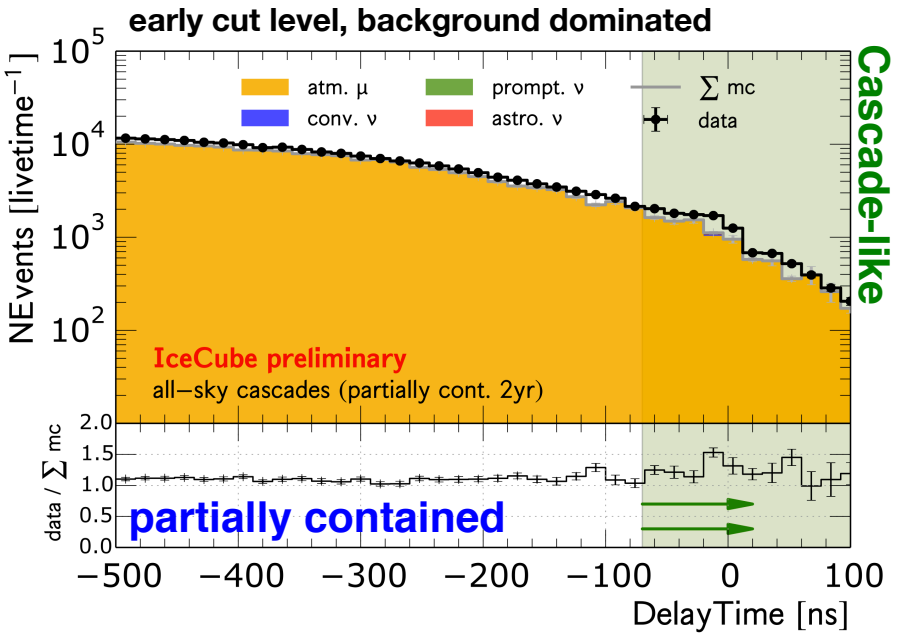
✓ **obtained sufficient background simulation at relevant energies**



Event Selection

optimization performed for **fully contained cascades** and **partially contained cascades** separately

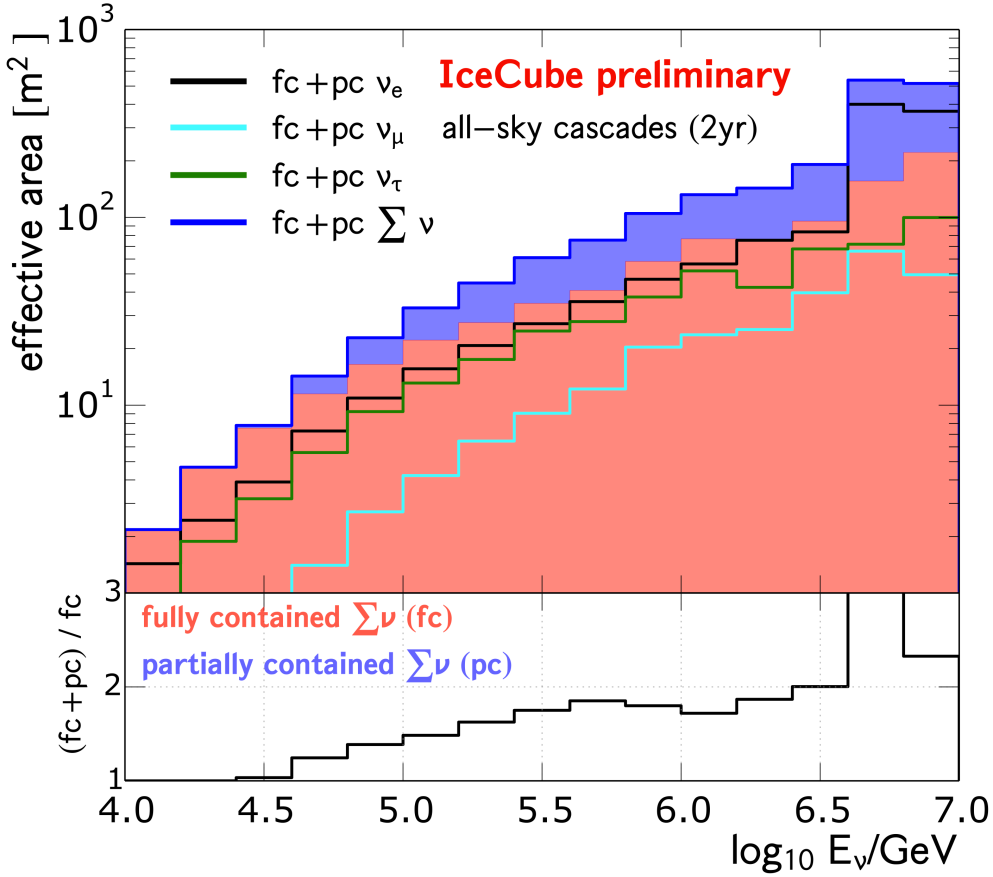




For example **"DelayTime":** delay of first observed photon with respect to expected time of arrival assuming direct propagation from reconstructed cascade vertex (causality!)

✓ **MC describes data well** (early cut level, background dominated)

Event Selection



after all cuts:

partially contained cascades increase A_{eff} by up to x2 (E>100 TeV)

ν_e and ν_τ effective areas similar

but ν_μ effective area small

$A\nu_\mu : (A\nu_e + A\nu_\tau) \sim 1 : 6$

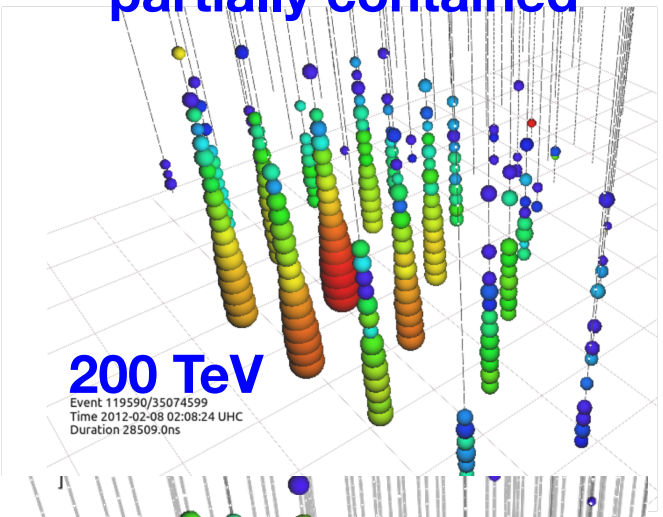
→ **suppressed contribution from atm. ν_μ background**

Event Selection

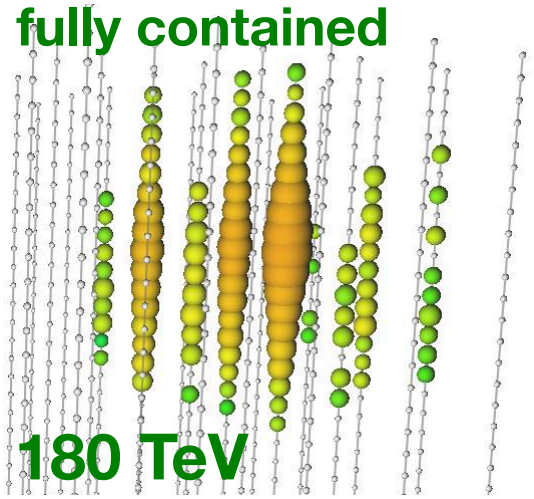
after all cuts

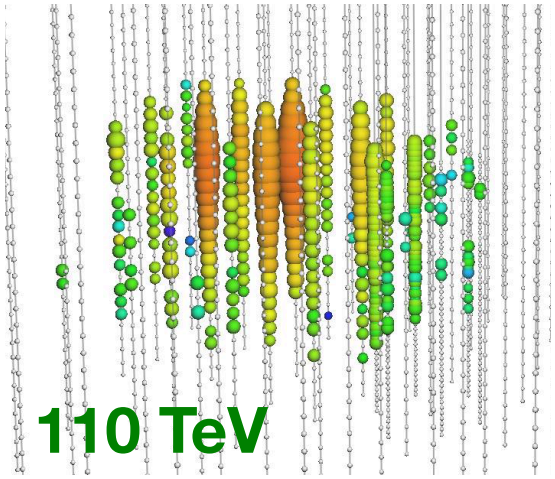
- ✓ **172 Cascades found (E >10 TeV)**
  (including 20 partially contained E > 35 TeV)
- ✓ **60%** (75% above 100 TeV) **are NEW**
  (i.e not found in other IceCube searches)
- ✓ **efficient atm. muon rejection**
  (expect <10% atm. μ to remain after at low E)

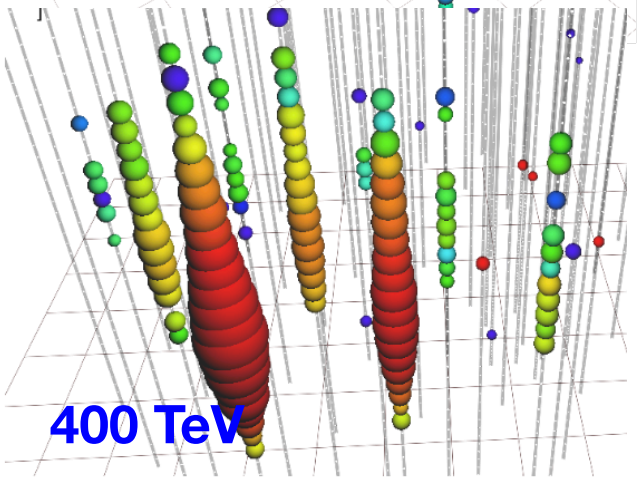
partially contained



fully contained







Analysis Method

maximum likelihood based **template method** ("standard" in IceCube)

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

astrophysics data

$$L(\boldsymbol{\theta_r}|\underline{n}) = \underset{\boldsymbol{\theta_s}}{\operatorname{argmax}}\, L(\boldsymbol{\theta_r}, \boldsymbol{\theta_s}, \underline{n}) = \underset{\boldsymbol{\theta_s}}{\operatorname{argmax}} \prod_{i=1}^{3} \prod_{j=1}^{N} \frac{\mu_{ij}(\boldsymbol{\theta_r}, \boldsymbol{\theta_s})^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}(\boldsymbol{\theta_r}, \boldsymbol{\theta_s})}$$

nuisance

$$\mu_{ij}(\boldsymbol{\theta_r}, \boldsymbol{\theta_s}) = \mu_{ij}^{atm.\mu} + \mu_{ij}^{atm.\nu} + \mu_{ij}^{astro.\nu}$$

+ quadratic penalty terms for nuisance parameters:

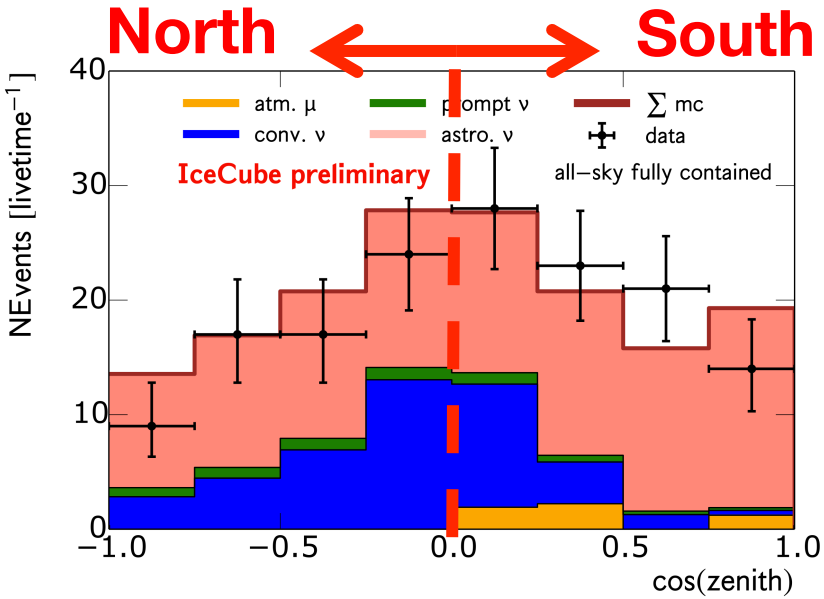
nuisance parameters (in this work): atm. ν flux normalizations
detector energy scale ε

Analysis Method

perform joint fit to three classes

range: $4.1 < \log_{10} E/\mathrm{GeV} < 6/9$

1) **contained** cascades from **Northern Sky**
2) **contained** cascades from **Southern Sky**
3) **partially contained** cascades **(All-Sky)**



model assumptions

astro ν: unbroken powerlaw

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

with $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

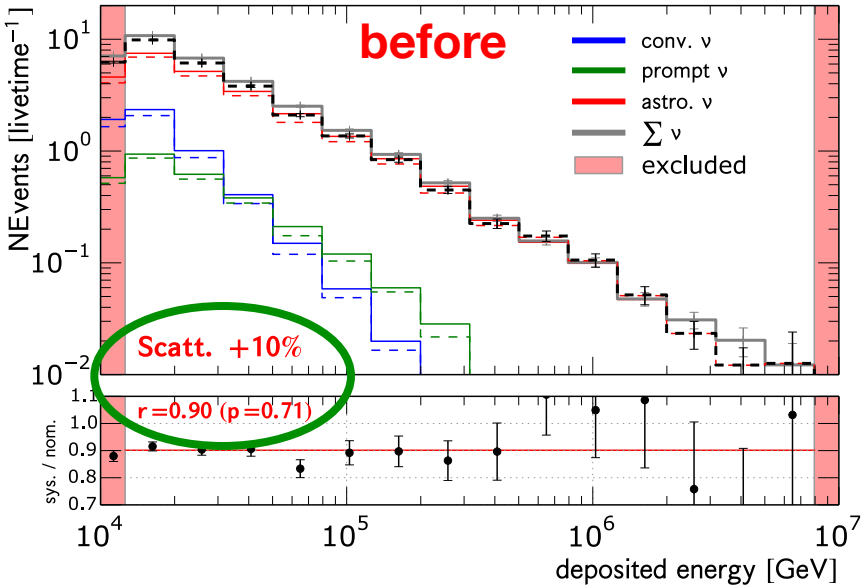
conventional ν: HKKMS06
prompt ν: ERS08

parameter	sys. uncertainty
γ	-
ϕ	-
ϕ_{conv}	1.0 ± 0.3
ϕ_{prompt}	1^{+3}_{-1}
ε	1.00 ± 0.15

uncertainty conventional ν from [A. Fedynitch et al., PRD86 114024, 2012]
uncertainty prompt ν from upper-limit [IceCube, RRD89 062007, 2014]

uncertainty for ε from MC study (see next slide)

Detector Systematics



- **systematics related to energy scale dominant:** E' ~ ε * E (shifting templates)
- **DOM:** efficiency to photons
- **Ice properties**: scattering + absorption
- evaluated using dedicated MC with varying DOM Eff, Ice properties

→ **absorbed by adding ε parameter to fit**

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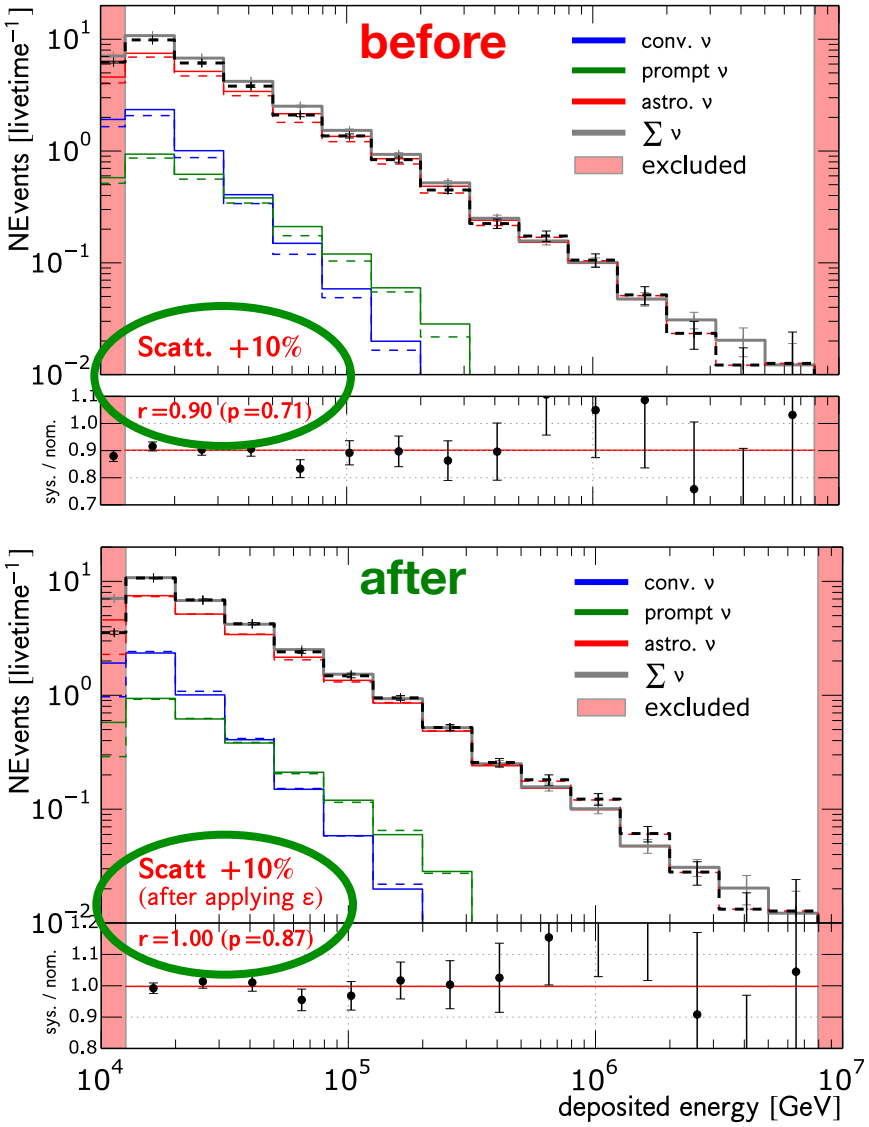
Detector Systematics



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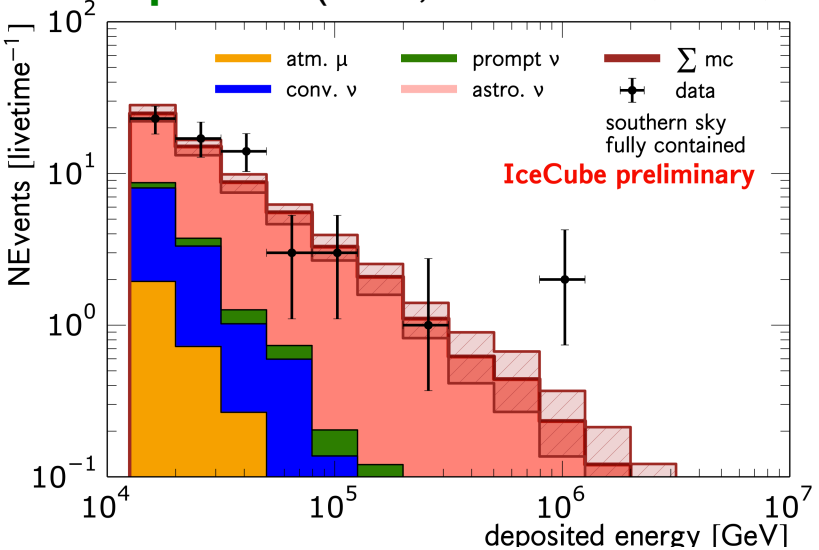
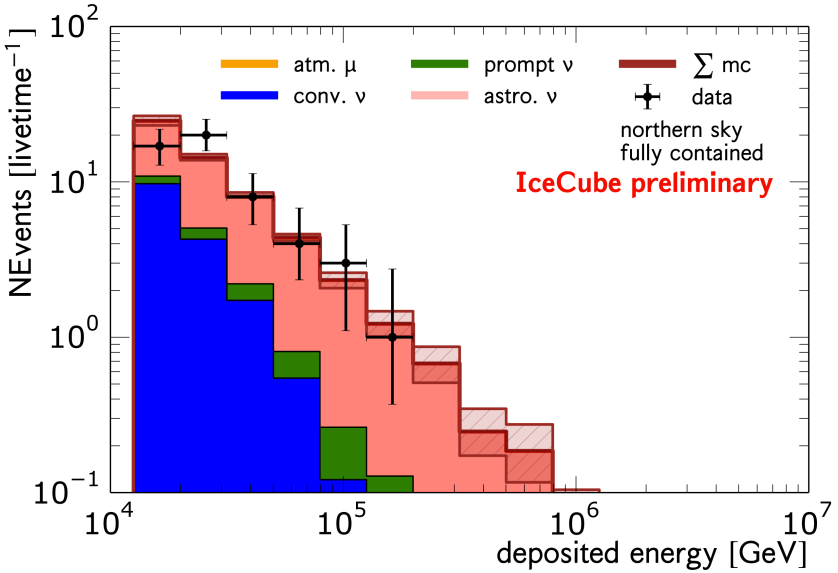
→ **absorbed by adding ε parameter to fit**

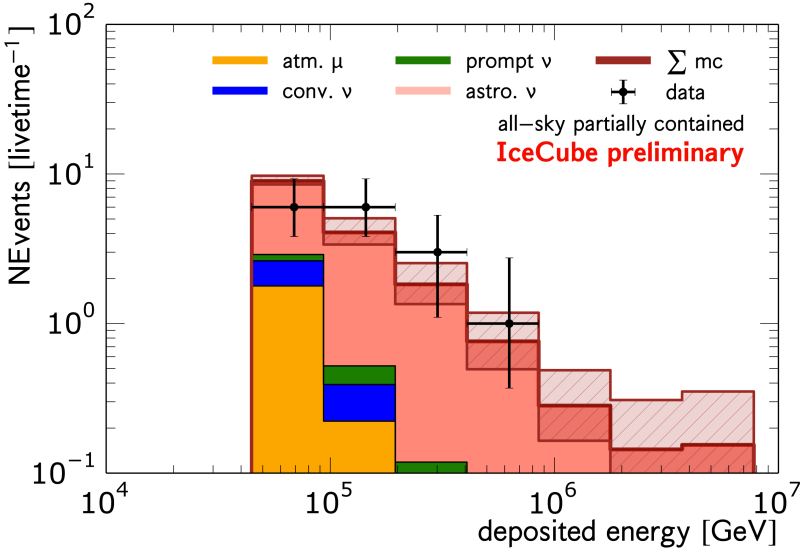
Detector Syst.	Value	$\hat{\varepsilon}$
DOM	−10%	1.11
DOM	−5%	1.06
DOM	+5%	0.94
DOM	+10%	0.91
Scatt.	+10%	1.11
Abs.	+10%	1.11
Scatt./Abs.	−7%	0.96
Combined ε_{tot}	1.00 ± 0.15	

Results

✓ **p=0.32** (GoF, NIMPR Vol. 221, Issue 2, 1984)





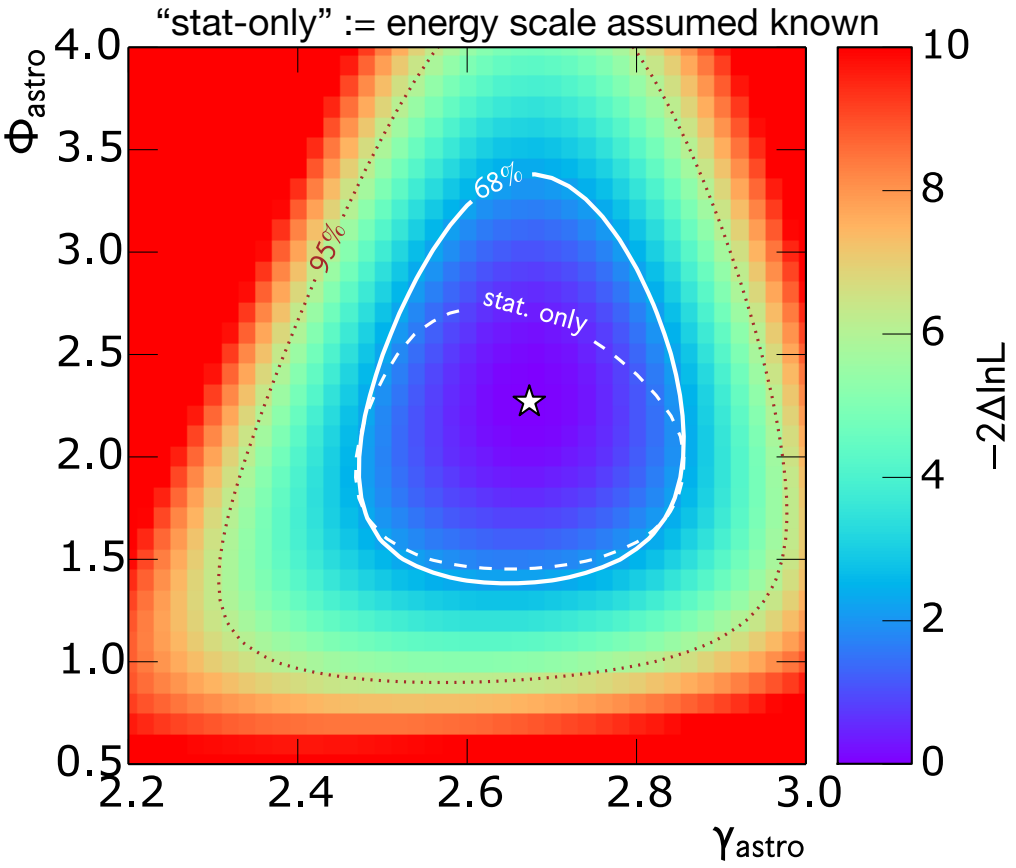


ϕ (per flavor) $[10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}]$	$2.3^{+0.7}_{-0.6}$
γ	$2.67^{+0.12}_{-0.13}$
ϕ_{conv} $[\phi_{HKKMS06}]$	$0.85^{+0.28}_{-0.29}$
ϕ_{prompt} $[\phi_{ERS06}]$	< 2.2 $(0.5^{+2.2}_{-0.5})$
ε	$0.96^{+0.14}_{-0.15}$

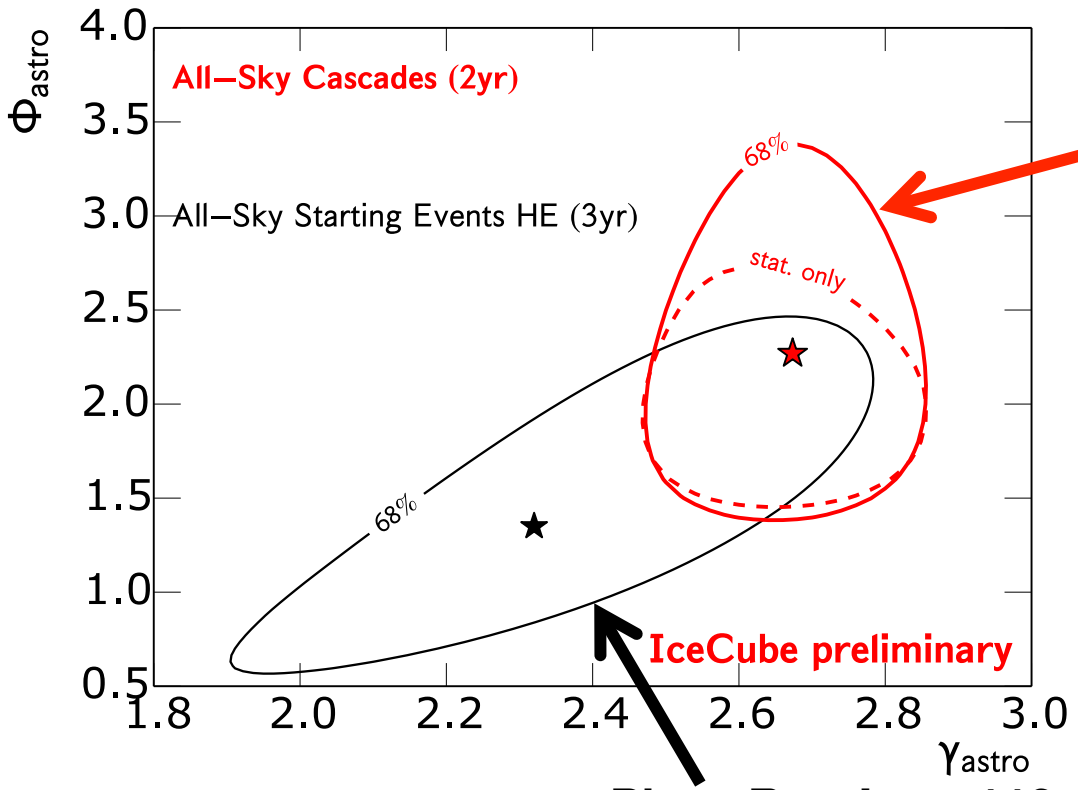
Results

astrophysical cascades above 10 TeV:

- **soft spectral index ($\gamma = 2.67^{+0.12}_{-0.13}$)**
- **reject atmospheric-only origin at 4.7σ** [7 * ERS]
- **~65% of these cascades are extra-terrestrial**
  (according to best-fit)
- **disfavored γ = 2.0 at 3.5σ**
  (" E^{-2} without cutoff ")



Comparison with other Results

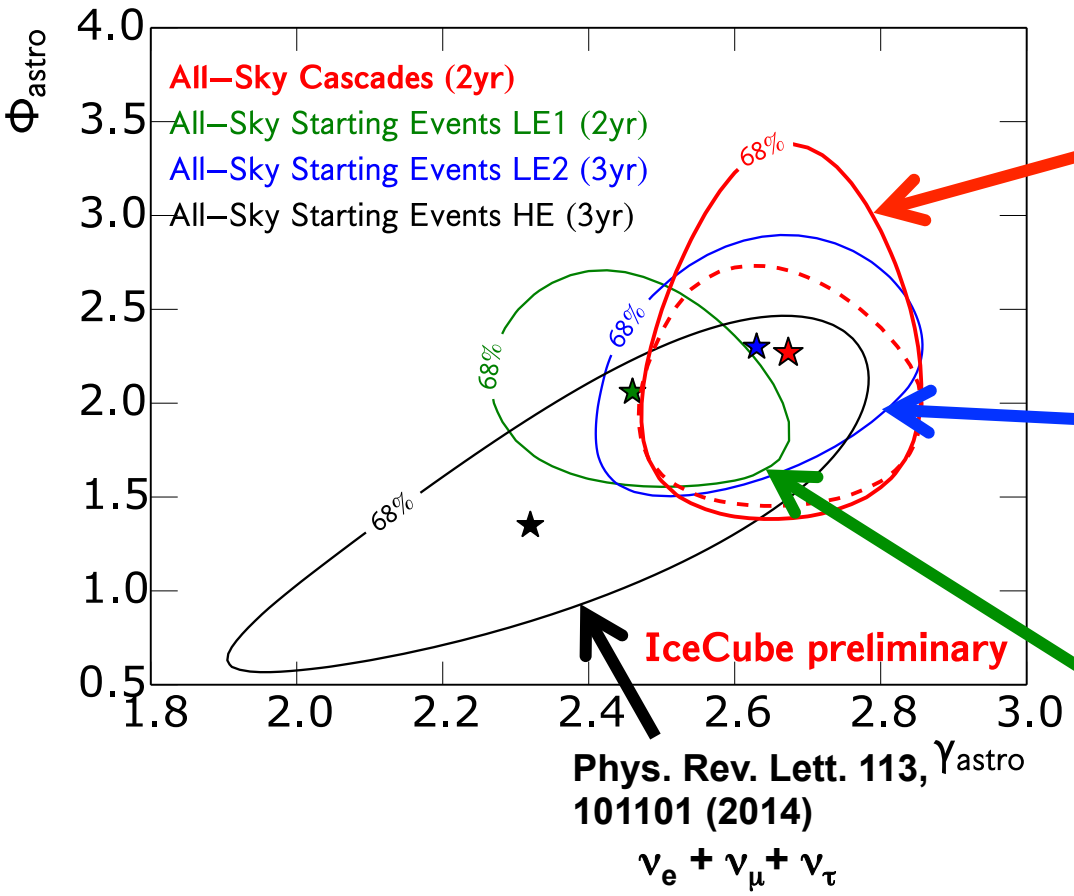


this analysis
$\nu_e + \nu_\tau$

Phys. Rev. Lett. 113, 101101 (2014)
$\nu_e + \nu_\mu + \nu_\tau$

(energy scale systematics not included in the analysis, since dominated by stat. uncertainties)

Comparison with other Results



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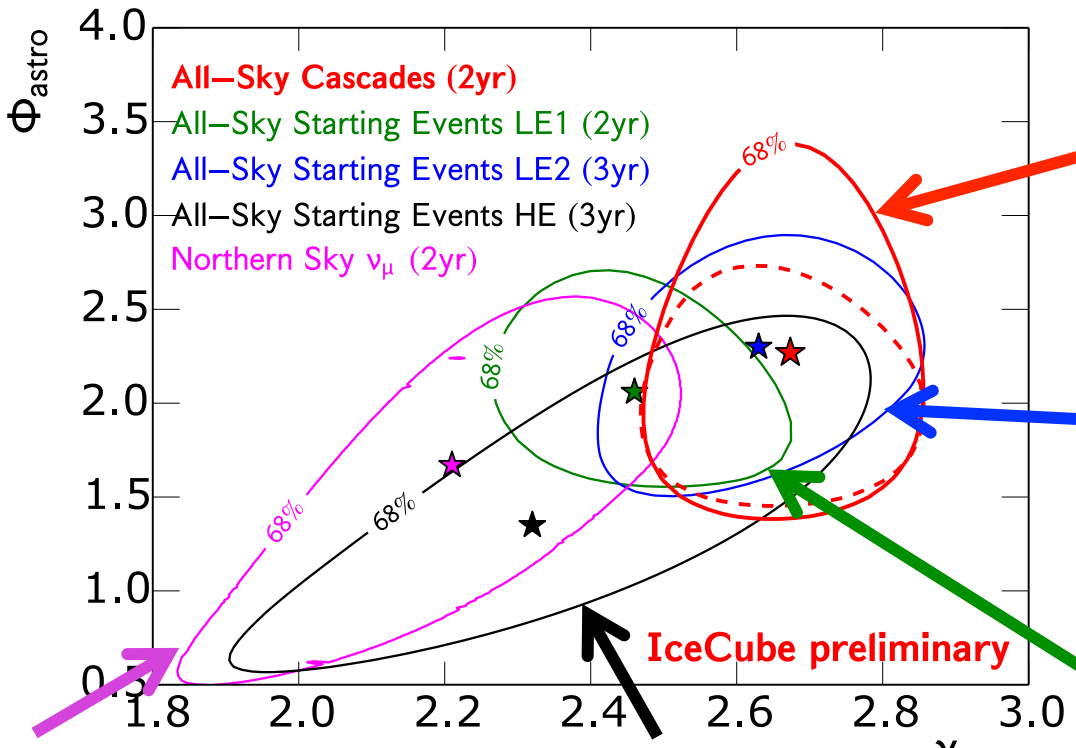
Phys. Rev. Lett. 114, 171102 (2015)
$\nu_e + \nu_\mu + \nu_\tau$

Phys. Rev. D 91, 022001 (2015)
$\nu_e + \nu_\mu + \nu_\tau$

Phys. Rev. Lett. 113, 101101 (2014)
$\nu_e + \nu_\mu + \nu_\tau$

✓ **Cascade result consistent (<1σ) with starting event analyses!**

Comparison with other Results



this analysis
$\nu_e + \nu_\tau$

Phys. Rev. Lett. 114, 171102 (2015)
$\nu_e + \nu_\mu + \nu_\tau$

arXiv:1507.04005
ν_μ (Northern Sky only)

Phys. Rev. Lett. 113, 101101 (2014)
$\nu_e + \nu_\mu + \nu_\tau$

Phys. Rev. D 91, 022001 (2015)
$\nu_e + \nu_\mu + \nu_\tau$

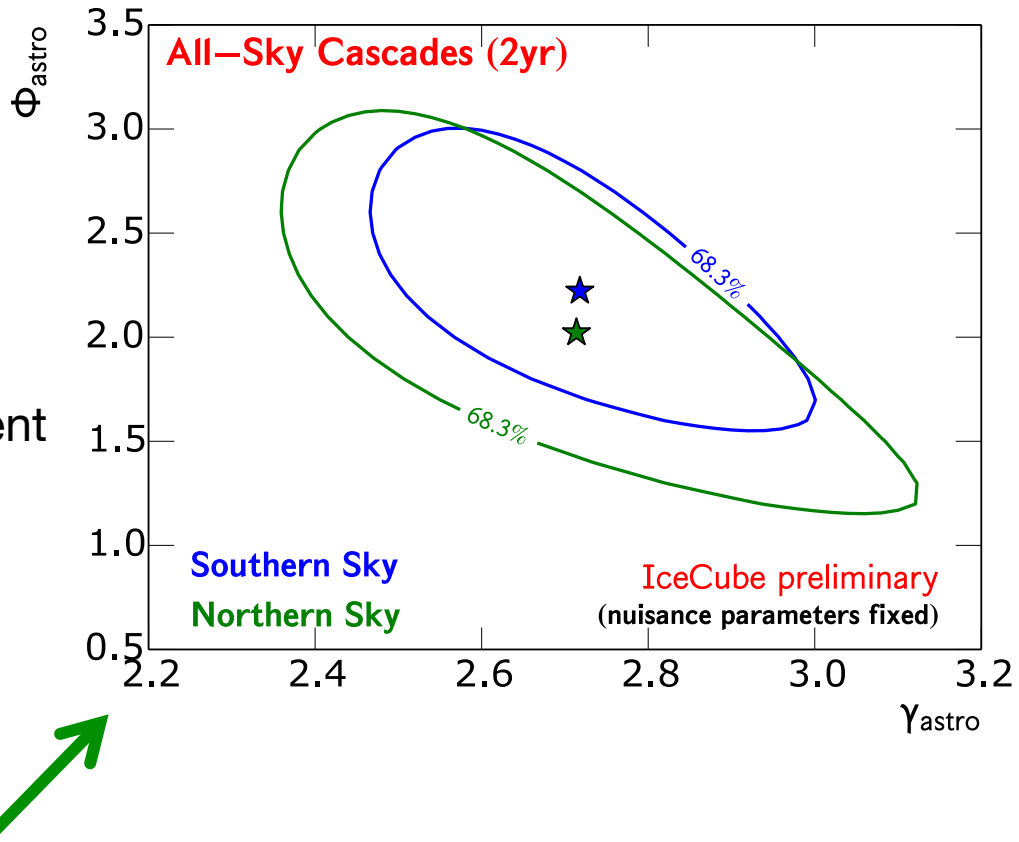
✓ **Cascade result <u>consistent</u> (<1σ) with starting event analyses!**
(insignificant < 2σ tension with northern sky ν_μ)

Results

Challenging Isotropy? No!

- measure Northern and Southern Sky separately
- use contained cascades only
- large uncertainties due to spectral degeneracy with prompt component

→ kept nuisance parameters fixed at all-sky best-fit value



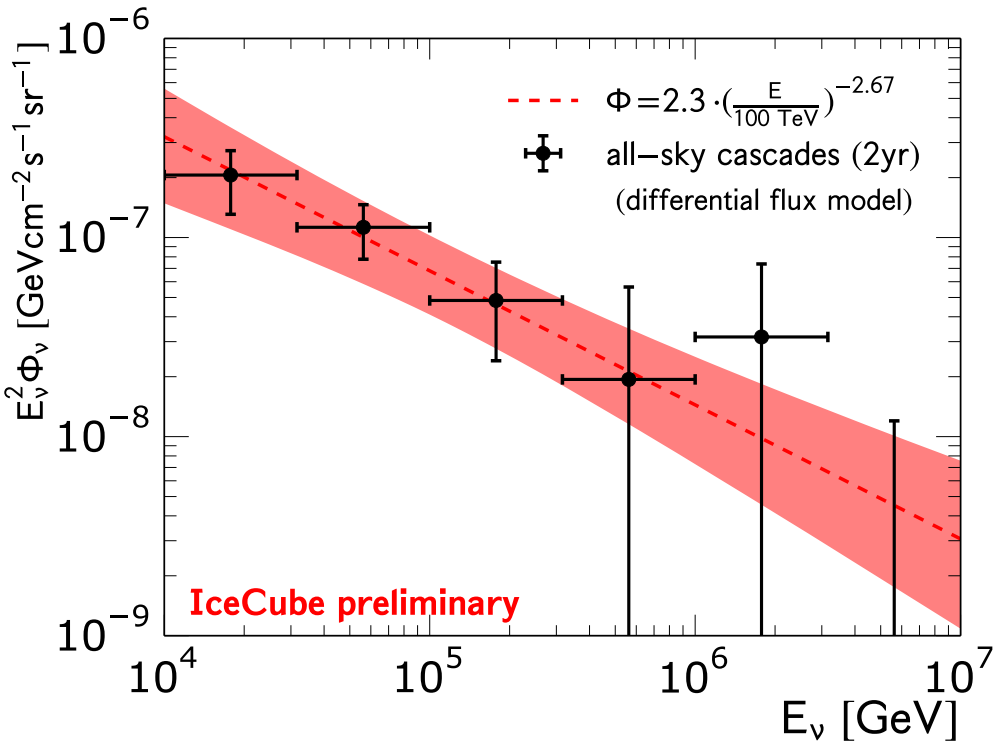
✓ **separate North/South Fits consistent** within the (large) uncertainties

… as expected from an isotropic extragalactic neutrino flux

Results

Differential Flux Measurement

- **relax power-law assumption** using separate flux normalizations in bins of E_ν (E^{-2} distribution within each bin)
- uncertainties via profile likelihood
- **consistent with best fit power-law**



✓ **no evidence for deviation from single, unbroken power-law in the cascade channel** (sensitive to $\nu_e + \nu_\tau$)

Summary

- **new MC based cascade event selection** for IC79+IC86 2011
  using **cascade topology variables** → sensitive to $\nu_e + \nu_\tau$
- included **partially contained cascades**
  → significantly enlarges sample for E_ν>100 TeV
- **majority (~60%) of events new** (not observed in previous IceCube searches!)
- sample is **well described by single, unbroken powerlaw** with
  per-flavor normalization = $2.3^{+0.7}_{-0.6}$ 10^{-18} GeV^{-1}s^{-1}sr^{-1}cm^{-2} (at 100 TeV)
  spectral index = $2.67^{+0.12}_{-0.13}$
- reject purely atmospheric origin **at 4.7σ**
- flux from **northern and southern sky consistent** (within current precision)
- **good agreement** with previous IceCube measurements

more data being analyzed - stay tuned!

BACKUP

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comparing multi-variate results in normal approximation

$$\Delta\boldsymbol{\theta} = \hat{\boldsymbol{\theta}}_1 - \hat{\boldsymbol{\theta}}_2 \sim \mathrm{n}\left(\mathbf{0}, \boldsymbol{\Sigma}_{\theta_1} + \boldsymbol{\Sigma}_{\theta_2}\right)$$

(requires independency)

result 1 result 2

H0: assume consistency

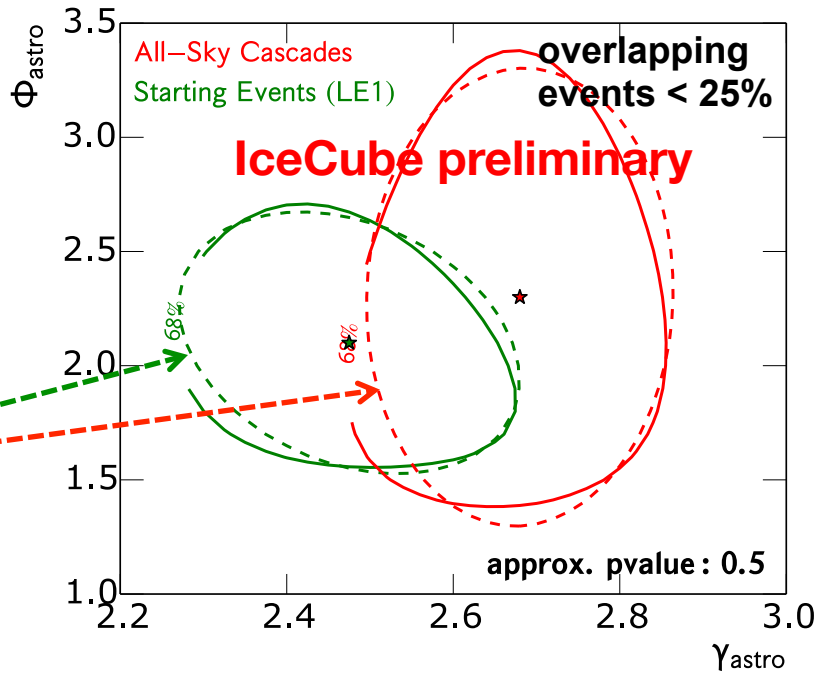
for known covariance matrices:

$$d^2 = \Delta\boldsymbol{\theta}^T \left(\boldsymbol{\Sigma}_{\theta_1} + \boldsymbol{\Sigma}_{\theta_2}\right)^{-1} \Delta\boldsymbol{\theta}$$

$$d^2 \sim \chi^2_k, \text{ where } k := \dim\boldsymbol{\theta} \quad \textbf{(*)}$$

(*) remains true asymptotically (large N)
if covariance matrices are estimated from data

→ use observed information matrix
(hessian of -2 ln L) as estimator



related references

A. Wald, Trans. Amer. Math. Soc. 54 (1943)

T. W. F. Stroud, Ann. Math. Stat., Vol. 42, No. 4 (1971)

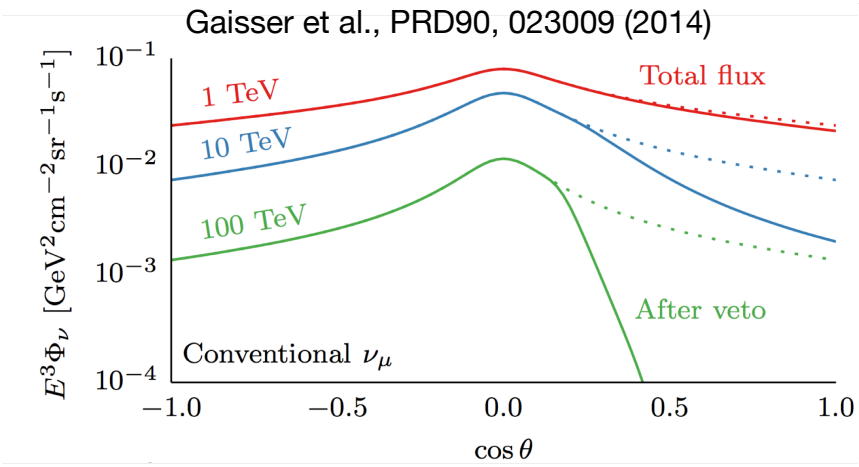
W. M. Patefield, Sankhya Ser. B, Vol. 39, No. 1 (1977)

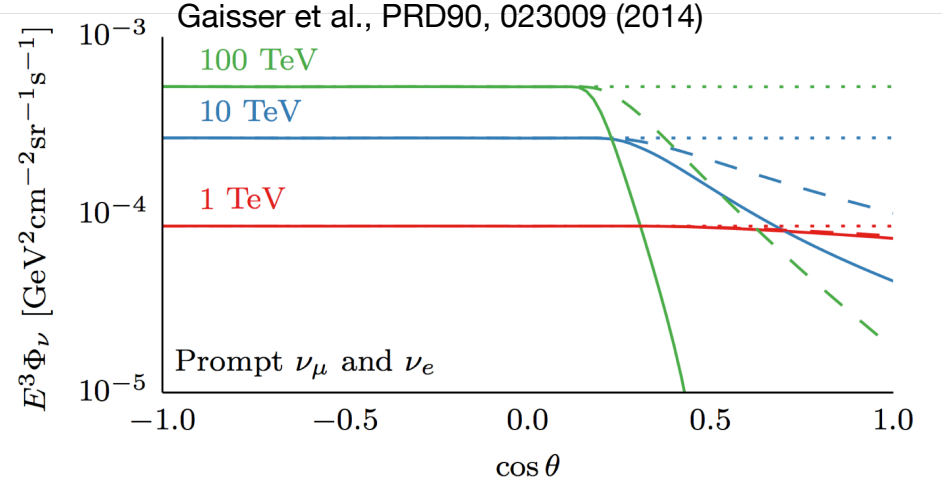
note that uni-variate comparisons of multi-variate measurements may lead to erroneous inference about consistency, as no statement about the other parameters is made (e.g. “looking at index only”)

atmospheric neutrino self-veto effect

- atmospheric 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

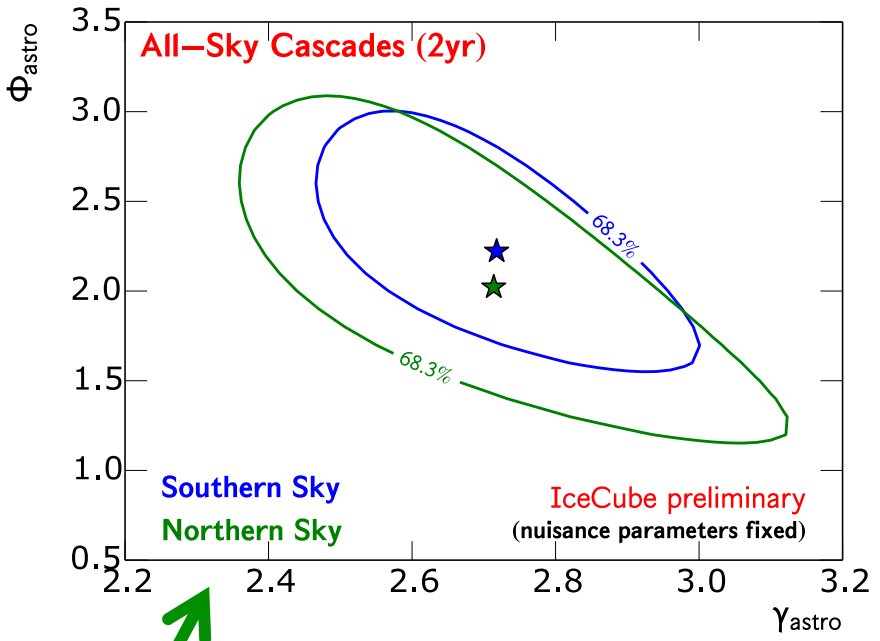




Challenging Isotropy? No! [more details]

→ Measure Northern and Southern Sky separately
→ use contained cascades only

Parameter	Best Fit (South)	Best Fit (North)
ϕ $[10^{-18}\,\mathrm{GeV^{-1}s^{-1}sr^{-1}cm^{-2}}]$	$1.9^{+0.8}_{-0.6}$	$1.7^{+1.3}_{-1.2}$
γ	$2.68^{+0.20}_{-0.22}$	$2.69^{+0.34}_{-0.34}$
ϕ $[\phi_{HKKMS06}]$	$0.97^{+0.30}_{-0.30}$	$0.91^{+0.29}_{-0.29}$
ϕ $[\phi_{ERS06}]$	< 3.0 $(1.1^{+3.0}_{-1.1})$	< 3.0 $(1.5^{+3.0}_{-1.5})$
ε	$1.04^{+0.15}_{-0.17}$	$0.97^{+0.15}_{-0.14}$



- Large uncertainties due to spectral degeneracy
- with prompt component

- **separate North/South Fits consistent**

✓ **North/South consistency remains when nuisance parameters fixed**

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electron neutrino effective area comparison