Can neutrino telescopes observe atmospheric charm?

Jakob van Santen

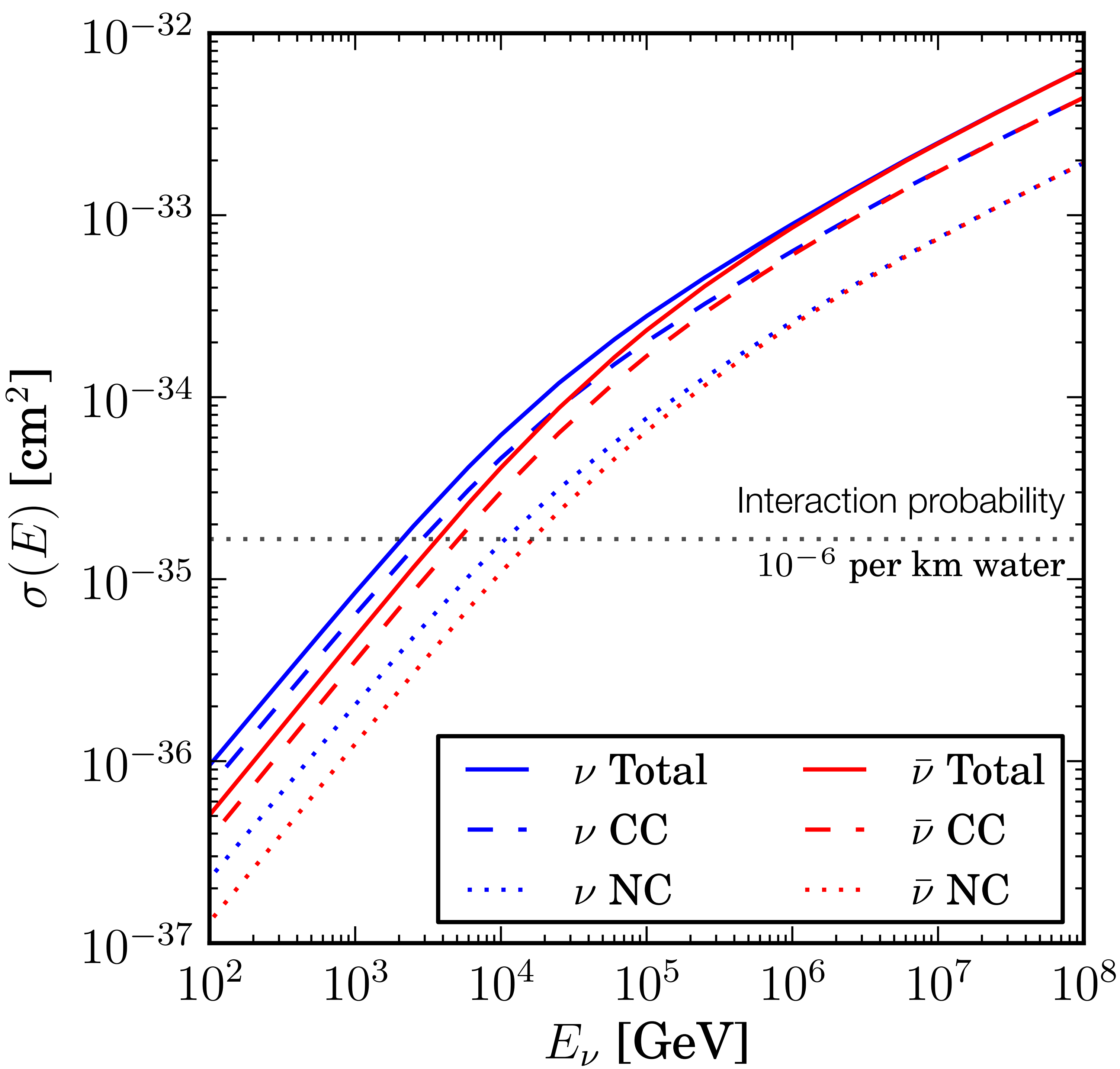
Atmospheric mini-symposium, Zeuthen, 2016-10-19

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

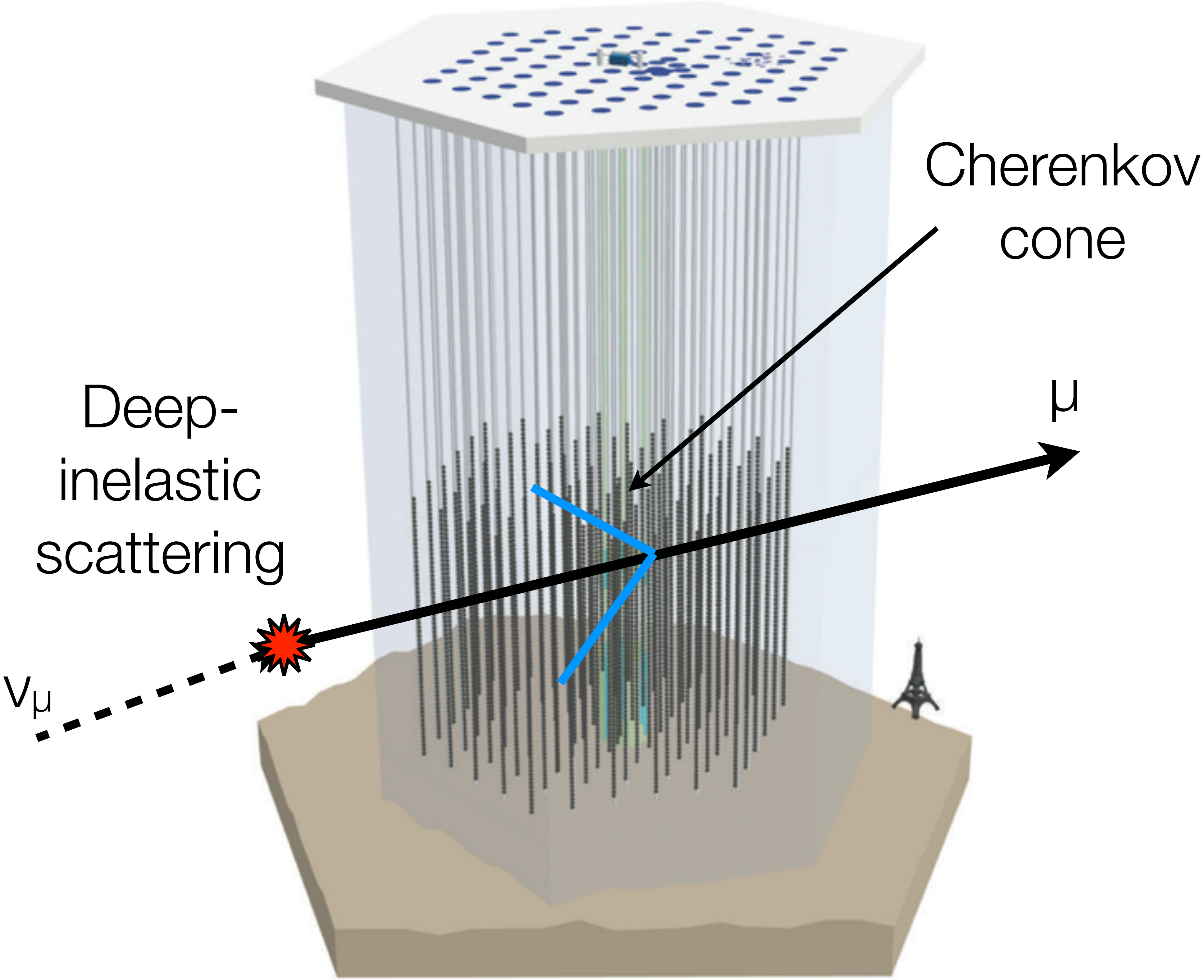
DESY

Detecting TeV neutrinos

- Interaction cross-sections are very small
- Benchmark astrophysical flux: O(10^5) per km^2 per year above 100 TeV
- Need km^3-scale detectors!



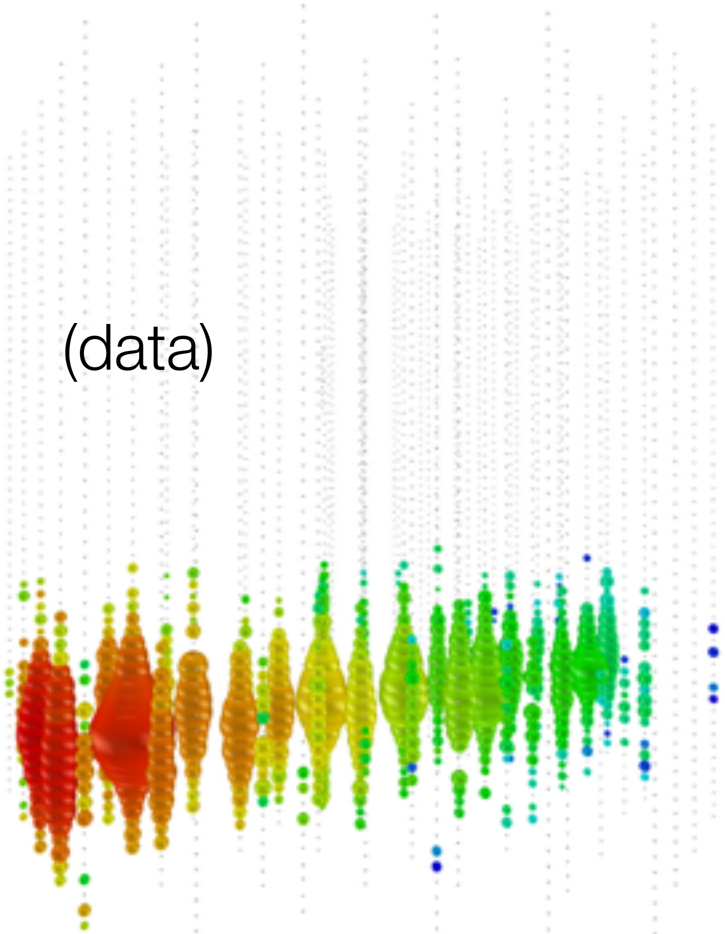
Detecting neutrinos



Neutrino event signatures

Charged-current ν_μ

(data)

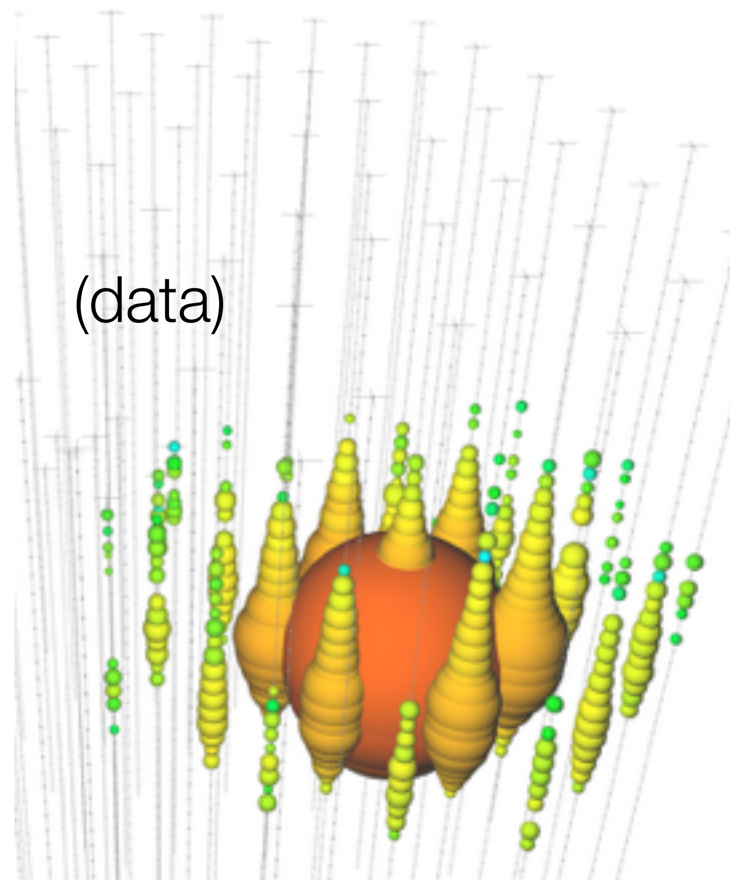


Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

(data)

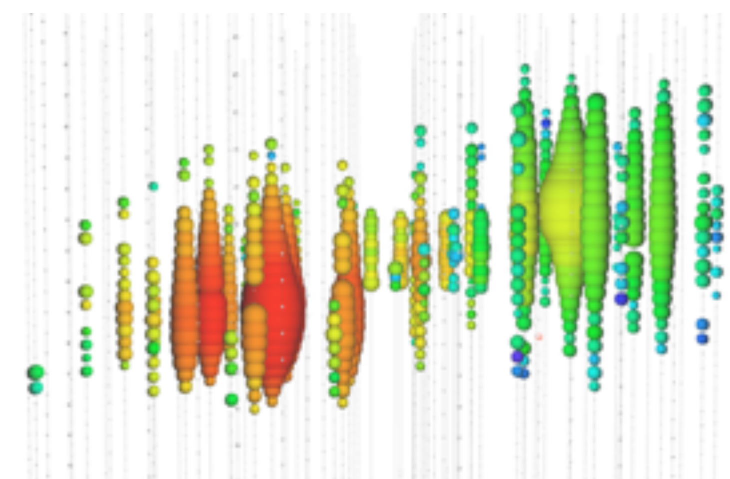


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

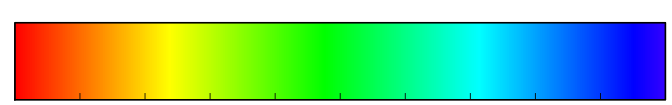
Charged-current ν_τ

(simulation)

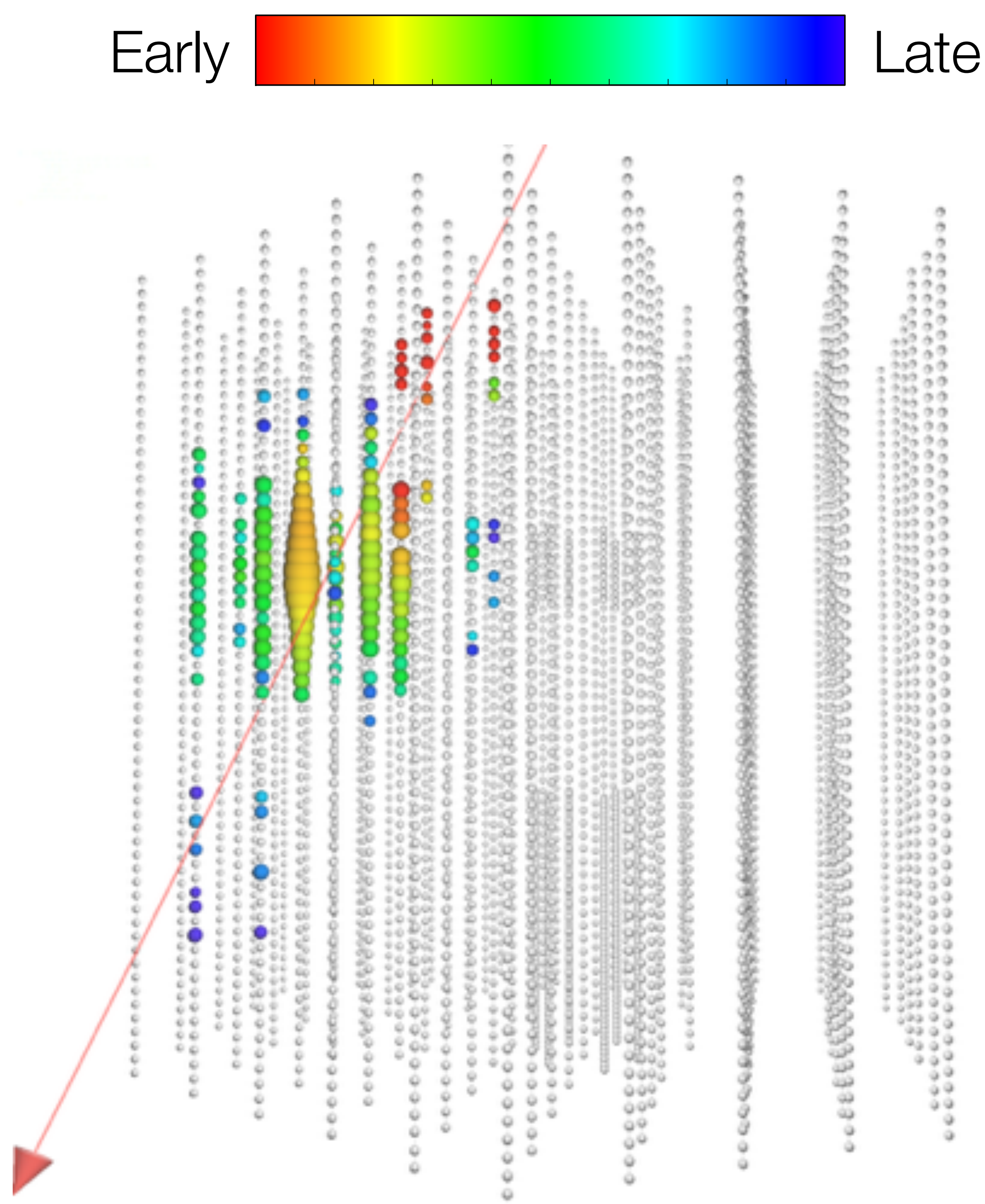


"Double-bang"

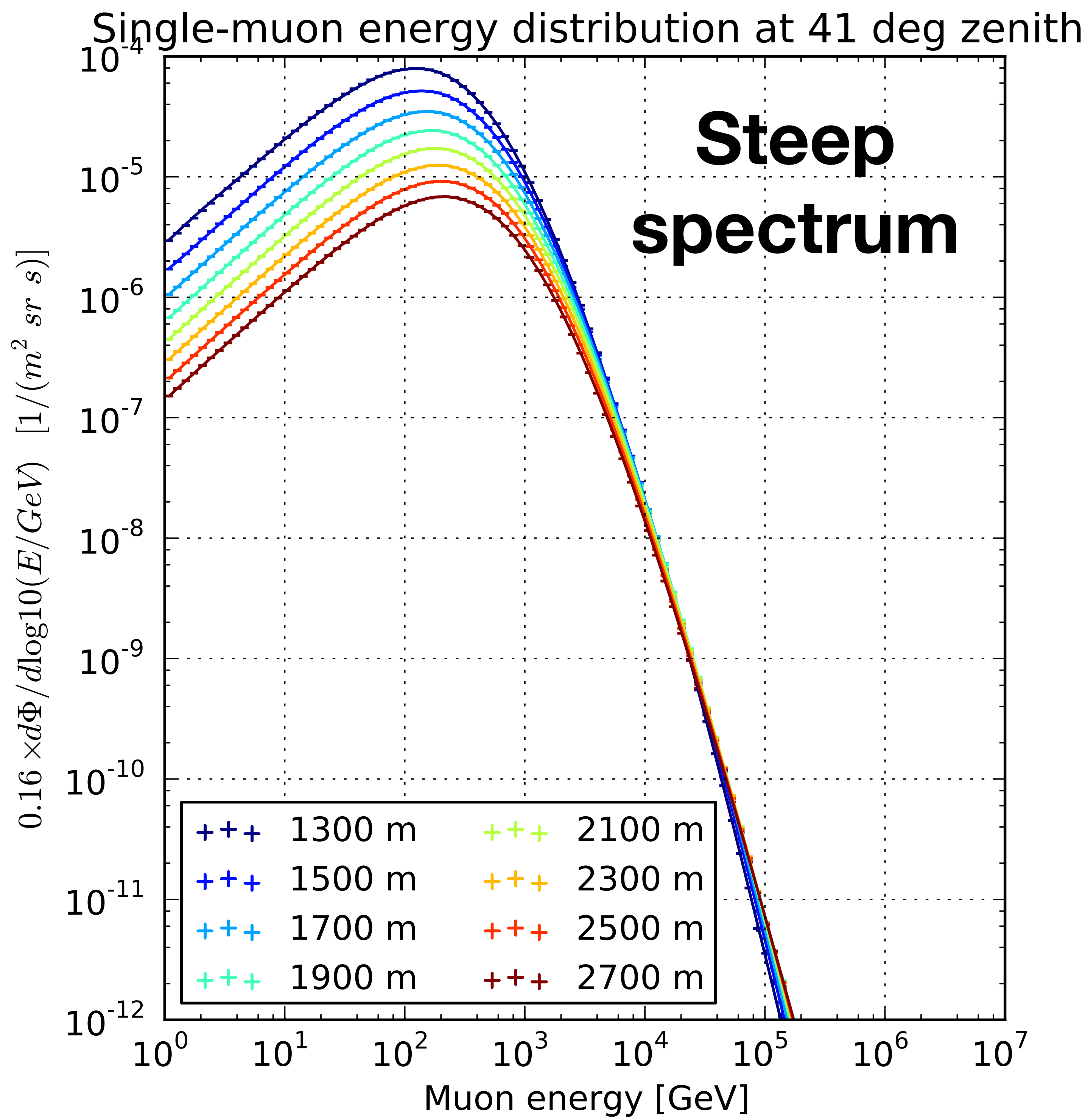
(none observed yet: τ decay length is 50 m/PeV)

Early  Late

Background: penetrating muons

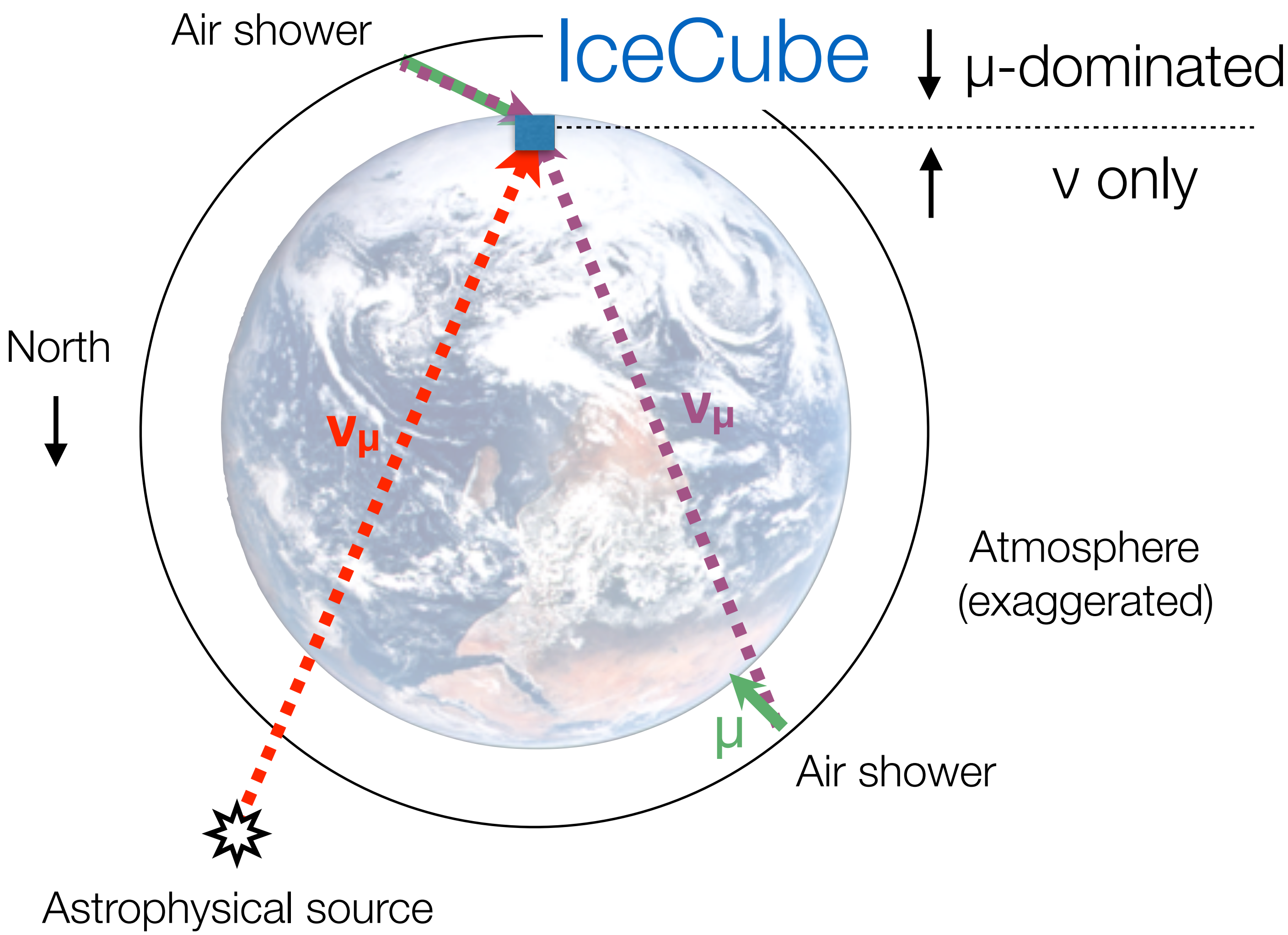


100 TeV single muon



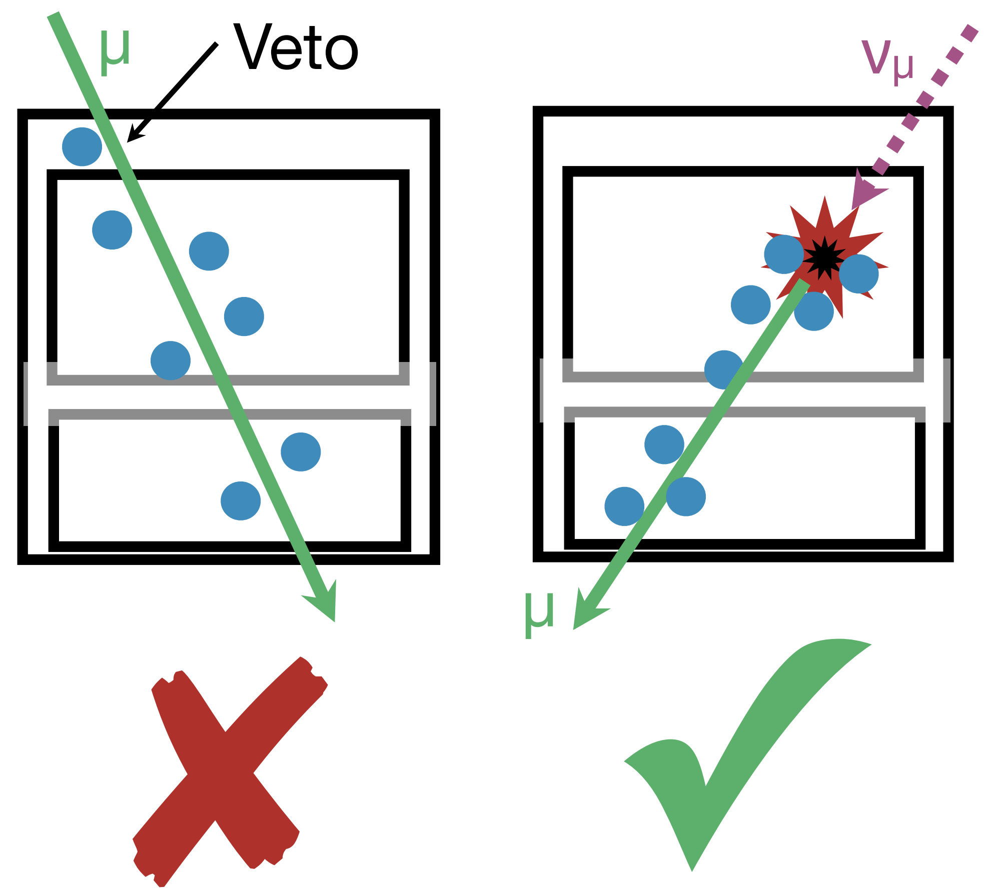
Isolating neutrino events: two strategies

Up-going tracks



- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to ν_μ only
- Sensitive to half the sky

Active veto



- Veto detects penetrating muons
- Effective volume smaller than detector
- Sensitive to all flavors
- Sensitive to the entire sky

Science with IceCube

Low energy neutrinos

- Neutrino oscillations
- Indirect dark matter searches

Penetrating muons

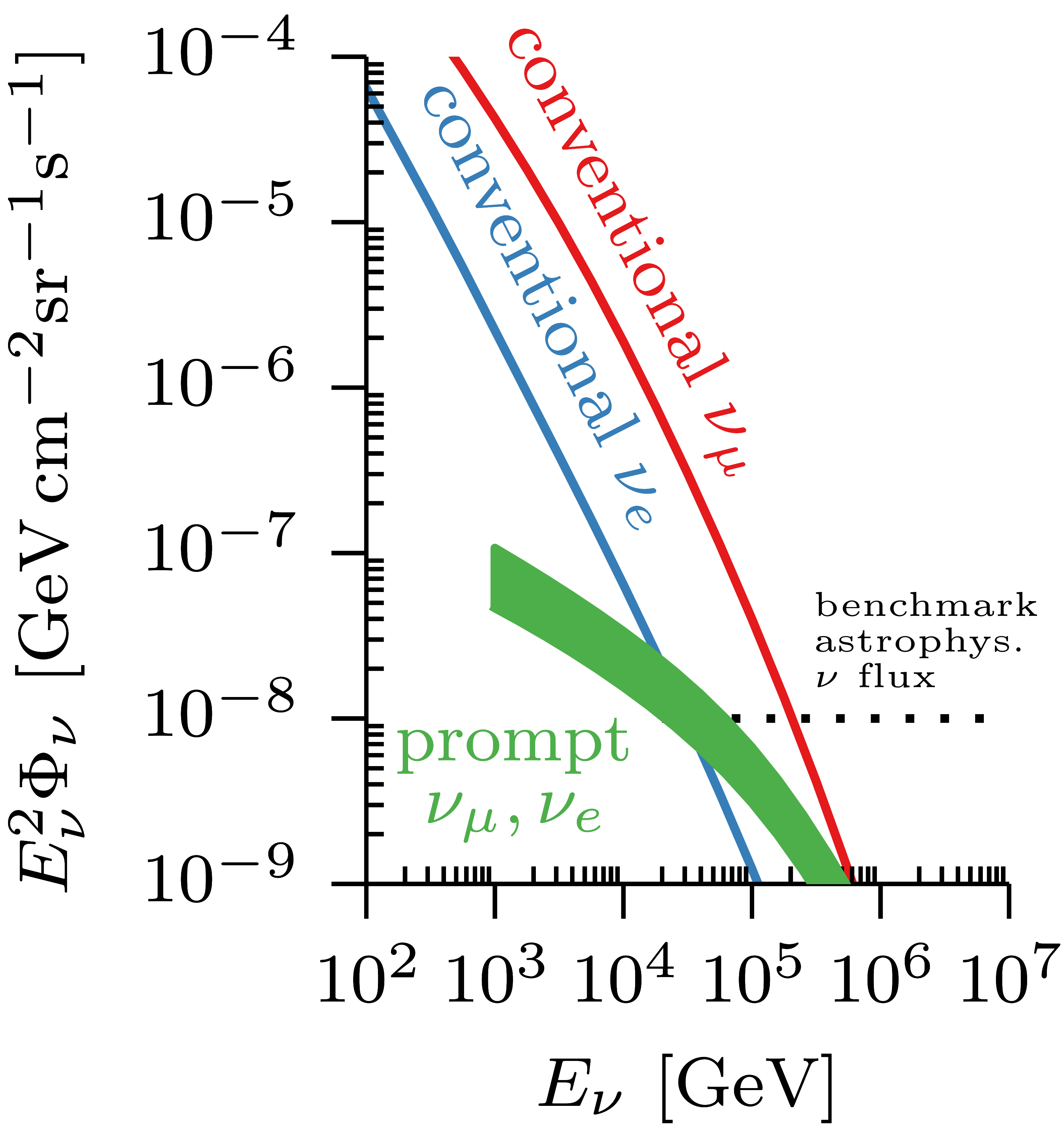
- Cosmic ray composition
- CR anisotropy
- High-energy interaction models

High energy neutrinos

- Clusters of neutrino arrival directions (steady point sources)
- Neutrinos associated with transients (e.g. gamma-ray bursts)
- Diffuse excess over atmospheric neutrino background
- Air shower physics (e.g. charmed-meson production)
- Ultra-high-energy "GZK" neutrinos from proton interactions with the CMB

(and much more…)

Neutrino spectra at Earth



Atmospheric pion/kaon (conventional) component:

- Steeply falling spectrum (1 power steeper than primary cosmic rays)
- Strongly dominated by ν_μ
- Peaked at the horizon

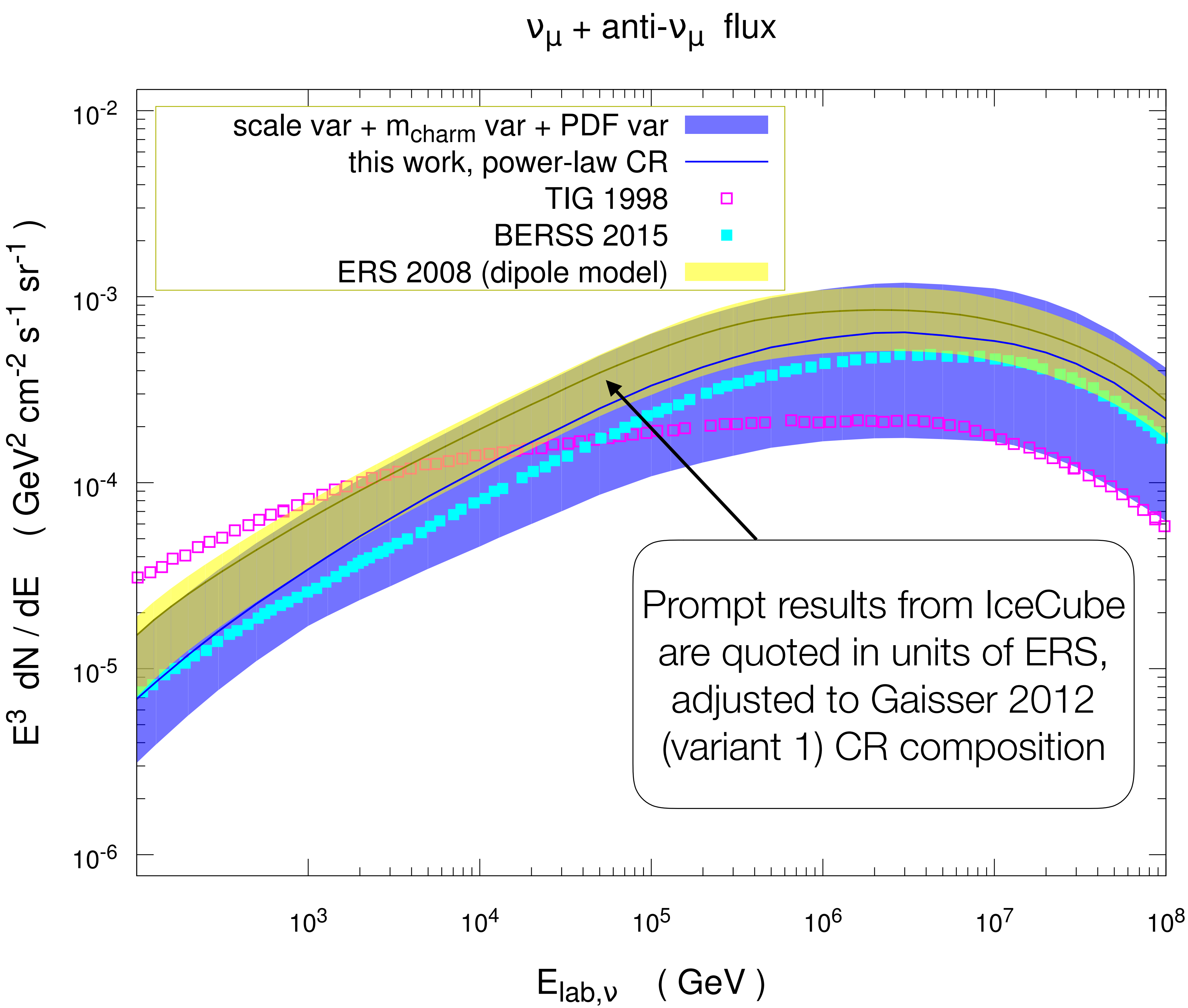
Atmospheric charmed meson (prompt) component:

- Spectrum follows primary cosmic rays
- Equal parts ν_μ and ν_e
- Isotropic
- <u>Not yet conclusively observed</u>

Astrophysical component:

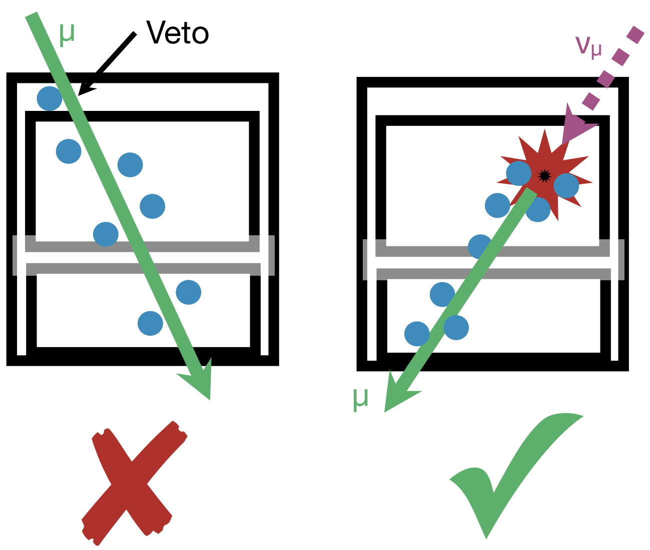
- Spectrum harder than primary cosmic rays
- Equal parts ν_μ , ν_e, ν_τ
- Isotropic?

Aside: flux units



Evidence for high-energy astrophysical neutrinos

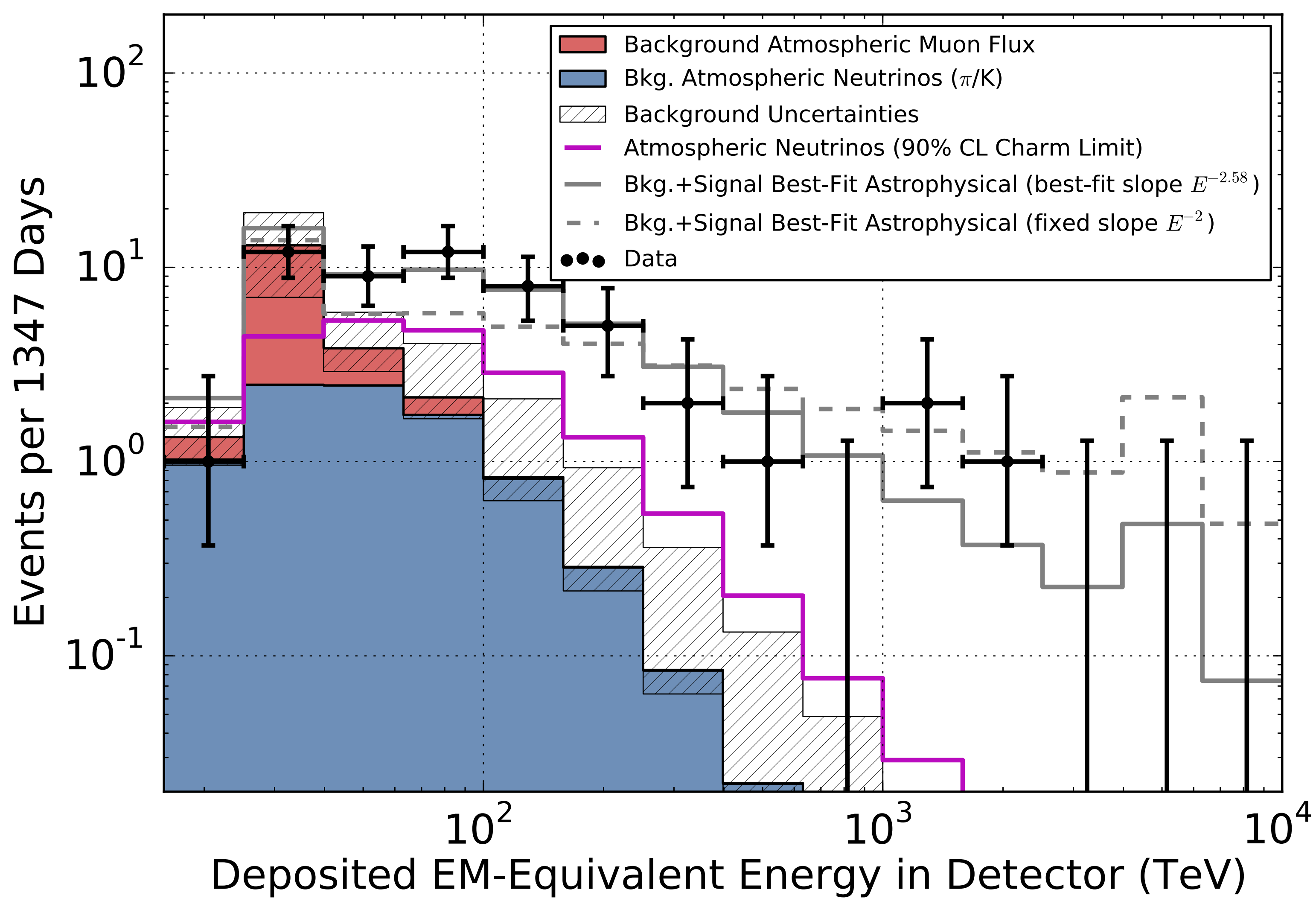
- Selected high-energy starting events in IceCube



- 3 cascades over 1 PeV in 4 years of data

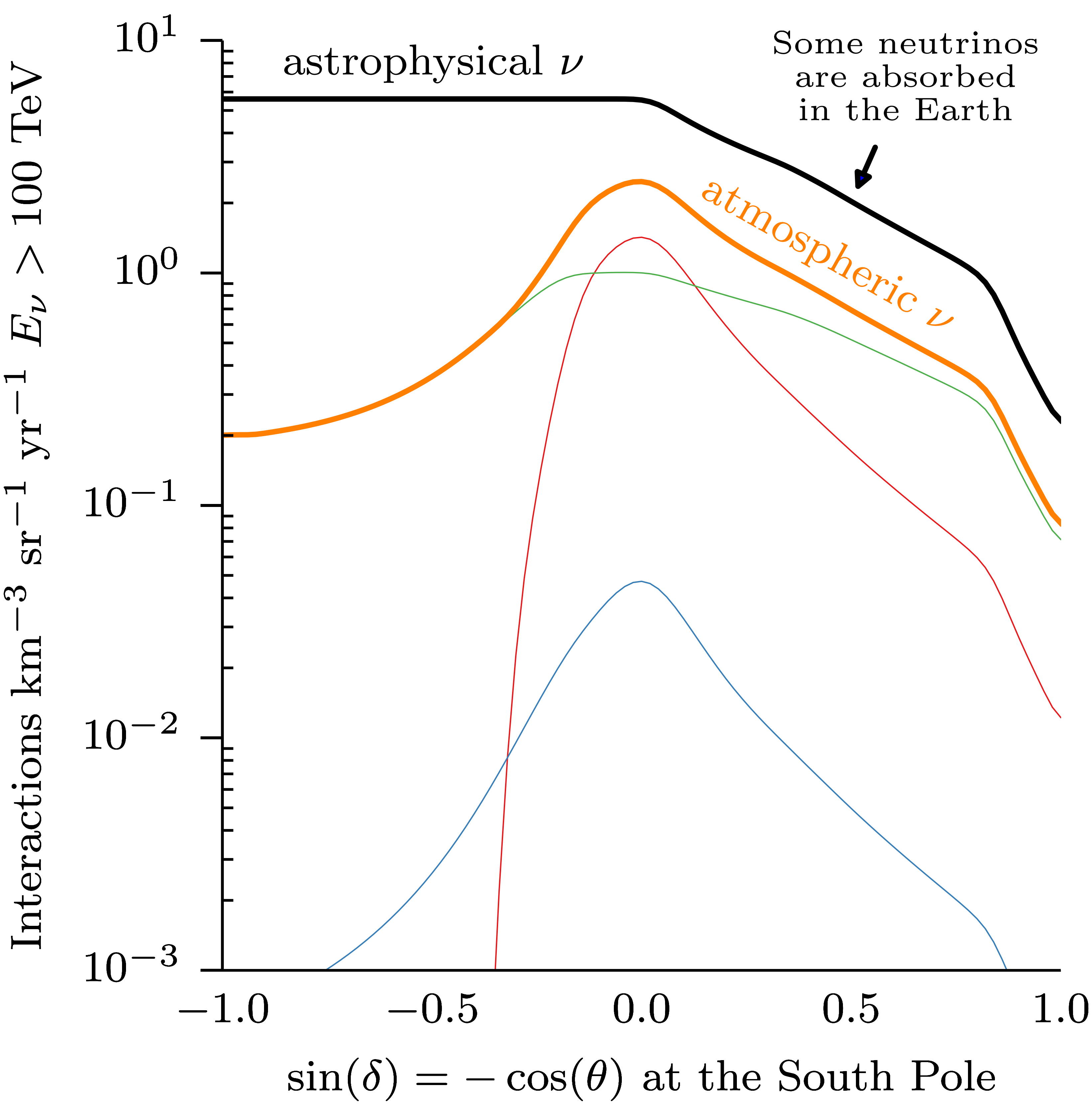
- >5.7 σ evidence for astrophysical neutrinos

Deposited energy



IceCube ICRC 2015 (PoS(ICRC2015)1081)

Atmospheric neutrino self-veto



The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

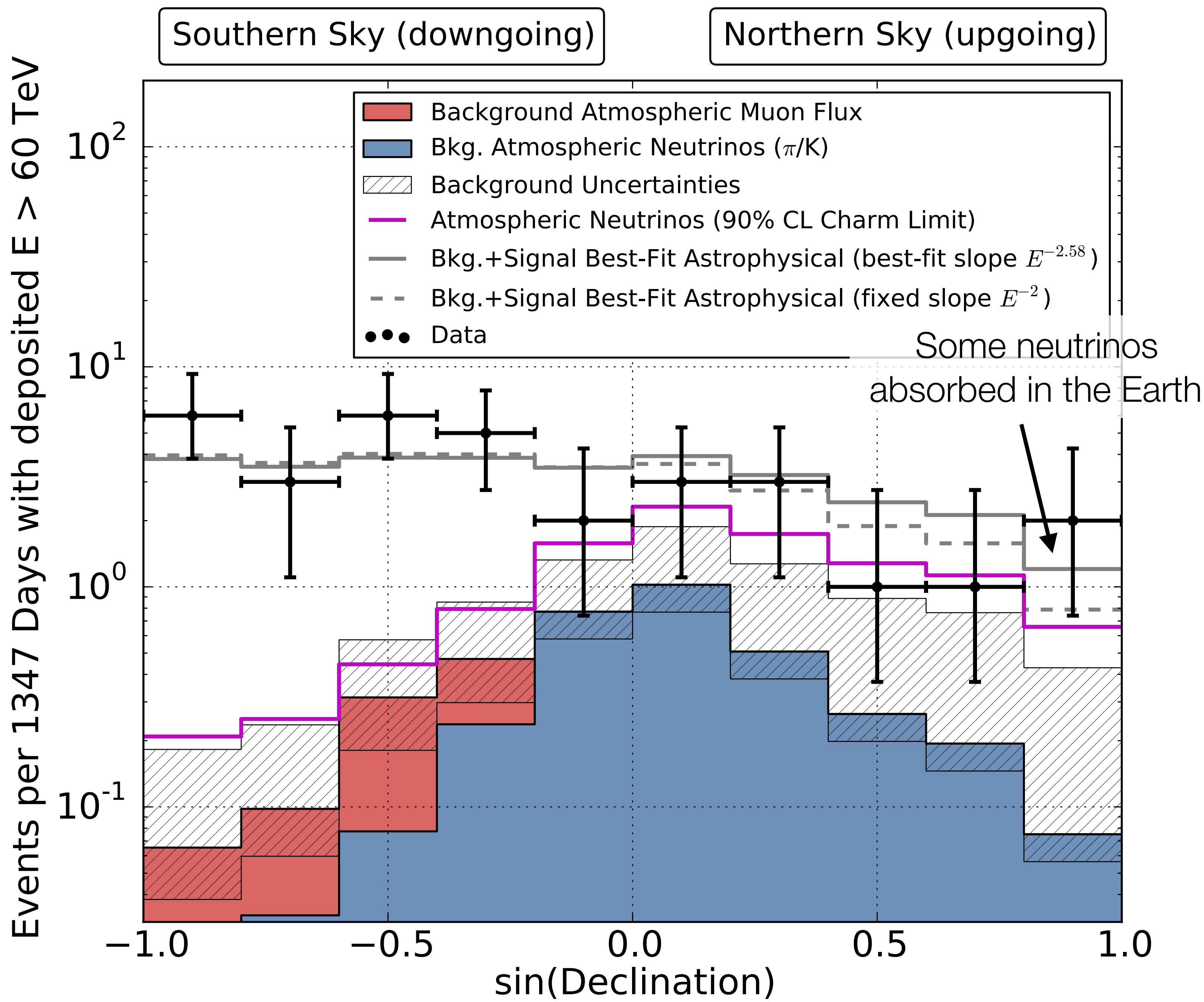
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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

Evidence for high-energy astrophysical neutrinos

- Down-going atmospheric neutrinos are vetoed by accompanying muons, astrophysical neutrinos are not
- Model-independent evidence of astrophysical origin

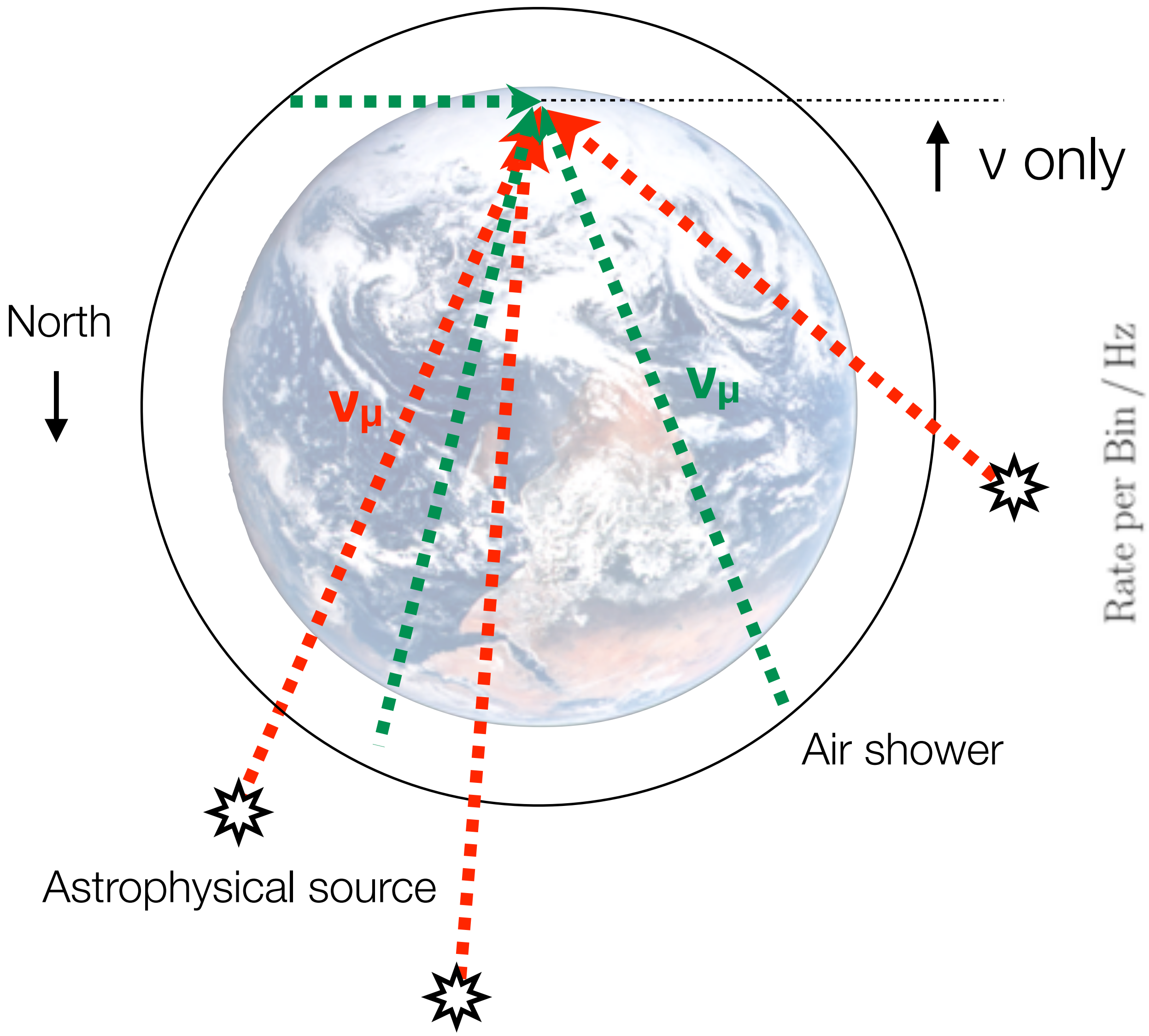
Arrival direction



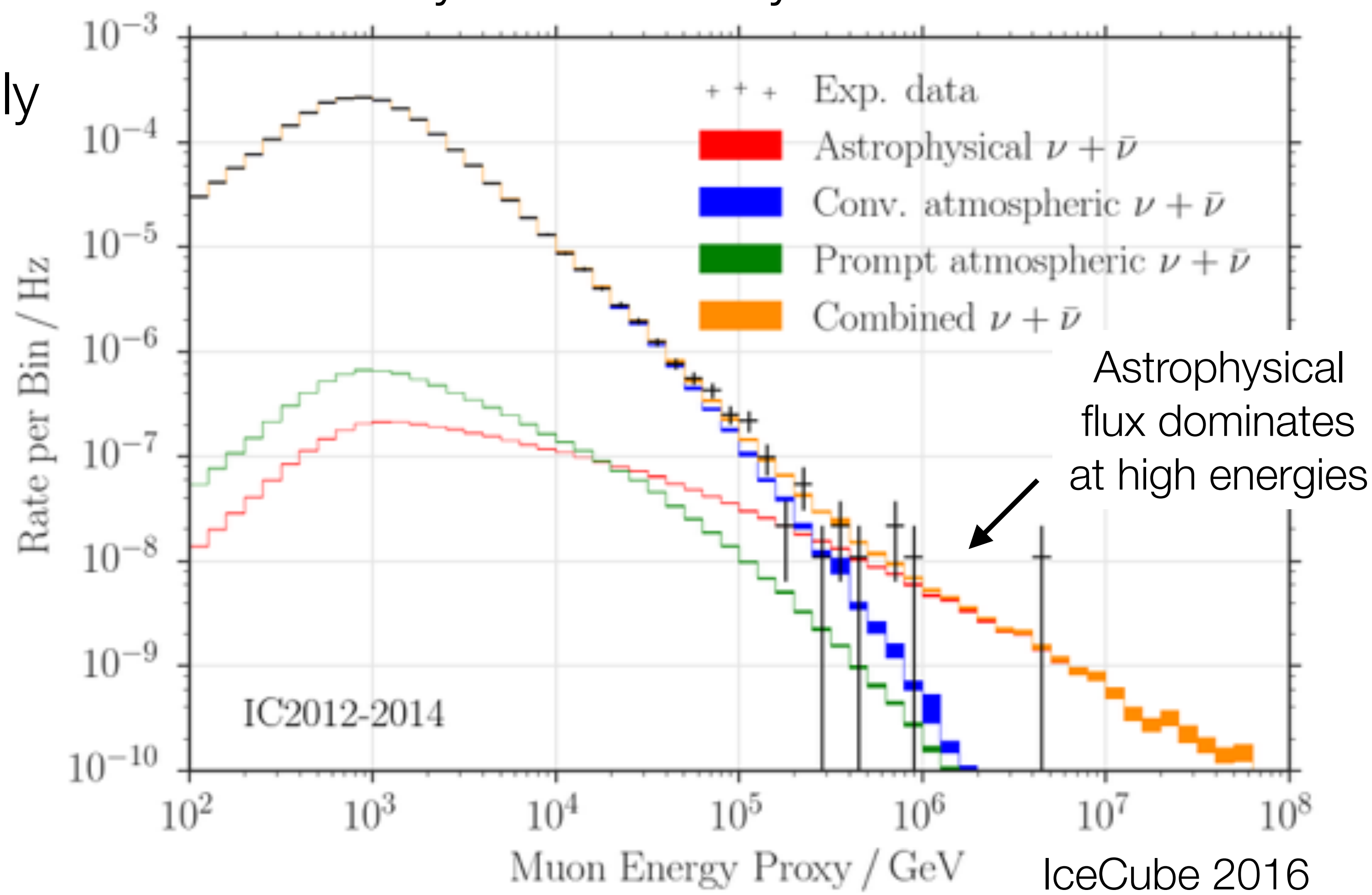
IceCube ICRC 2015 (PoS(ICRC2015)1081)

What about the northern sky and ν_μ?

The high-energy starting event sample is dominated by cascades from the southern sky.



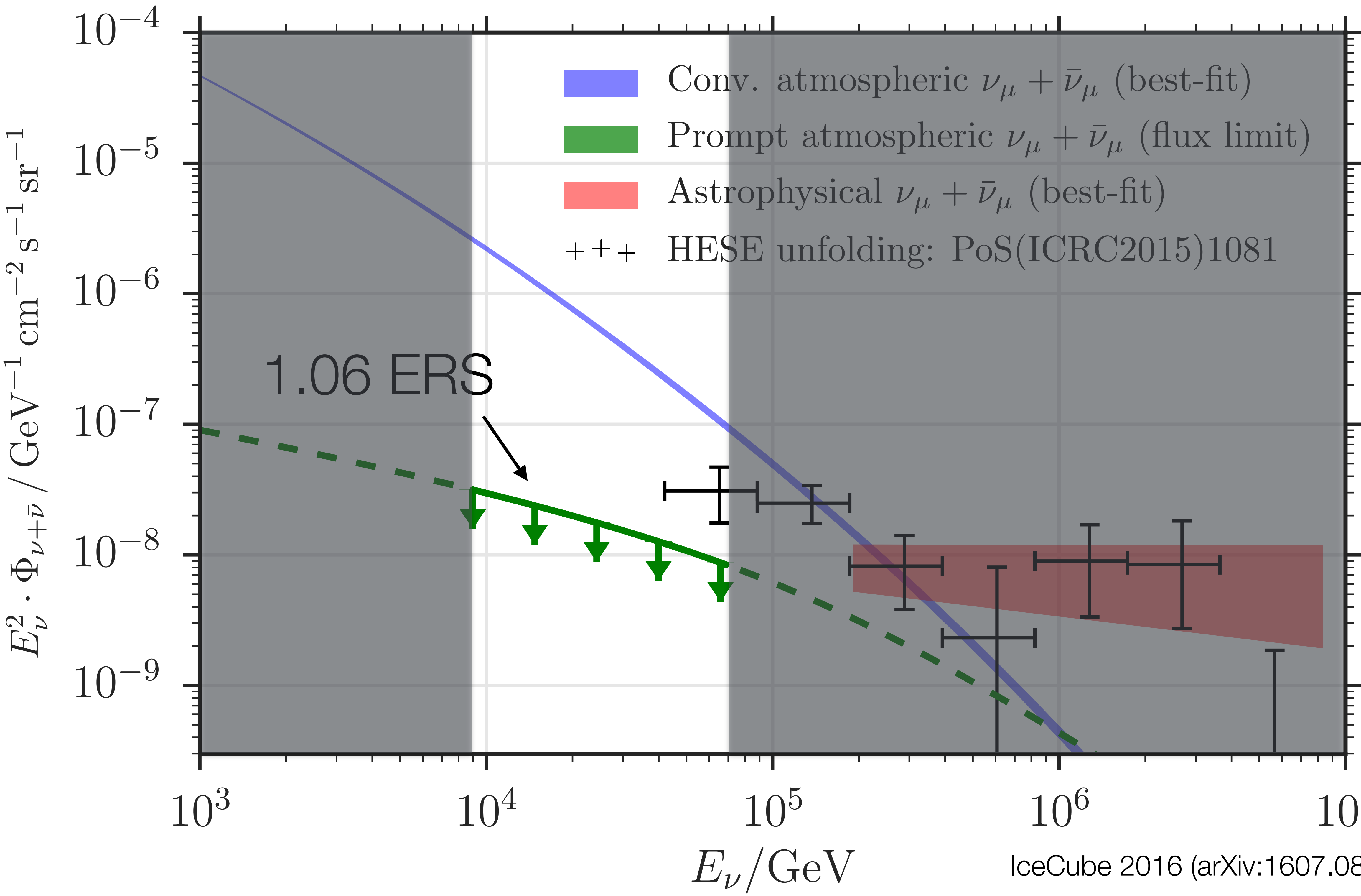
3 years from 6-year dataset



IceCube 2016 (arXiv: 1607.08006)

Excess over atmospheric backgrounds: **5.6 σ**
Prompt atmospheric normalization: **< 1.06 ERS** (90% CL)

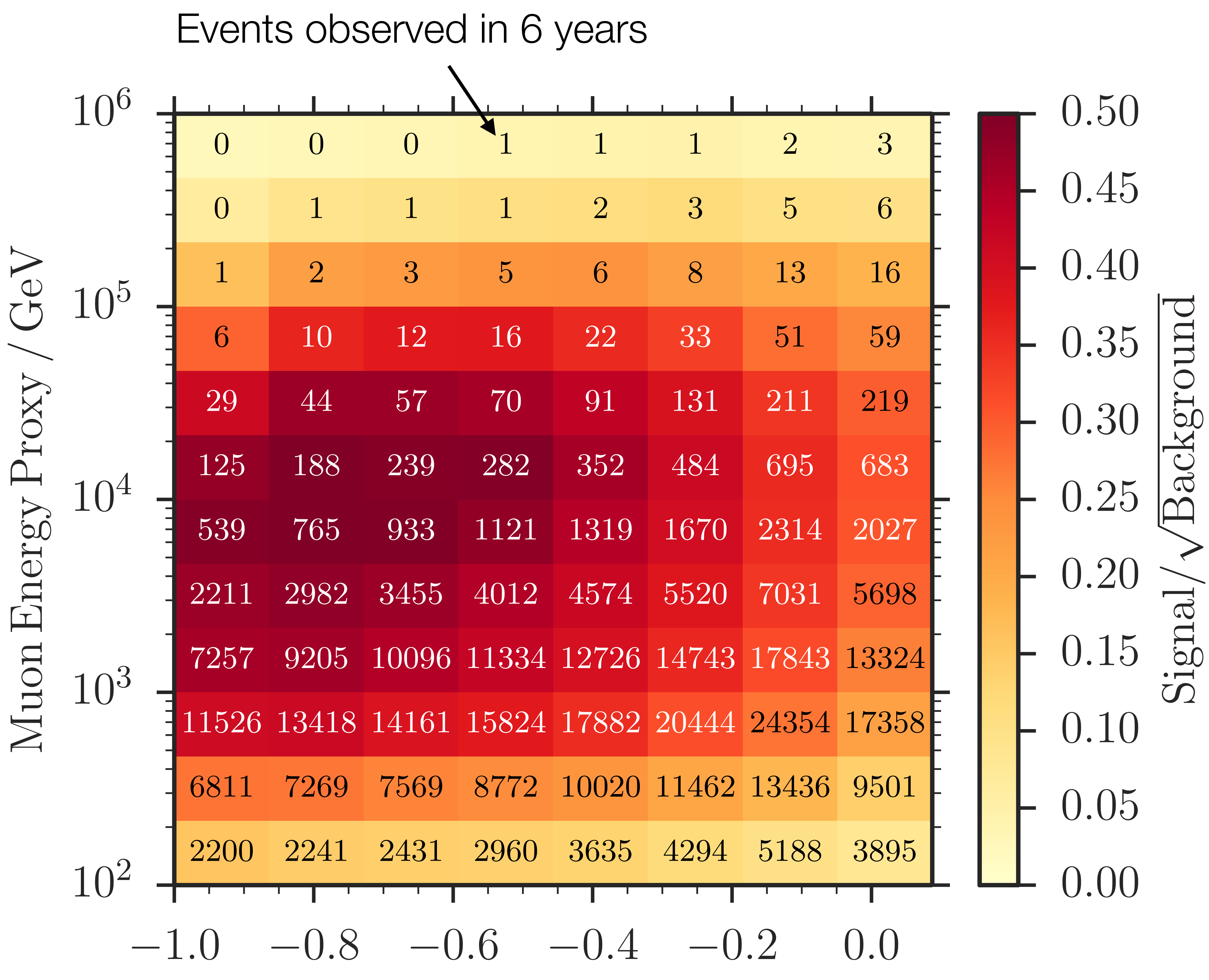
Limit on prompt atmospheric neutrinos



IceCube 2016 (arXiv:1607.08006)

Greyed-out energy region improves prompt limit by less than 10%

Where would prompt neutrinos appear?



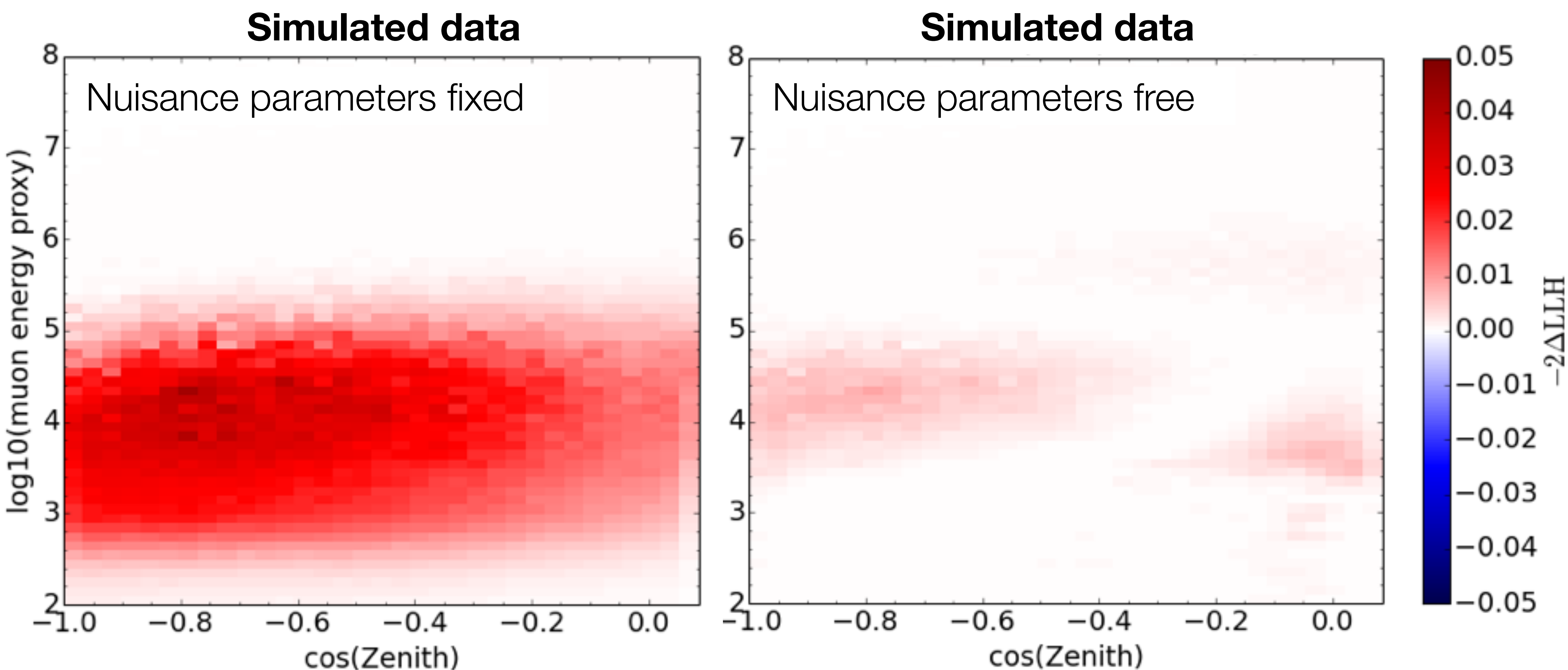
IceCube 2016 (arXiv:1607.08006)

π/K atmospheric + astrophysical (10^{-8} E^{-2})

prompt atmospheric (ERS)

Astrophysical flux **fixed**

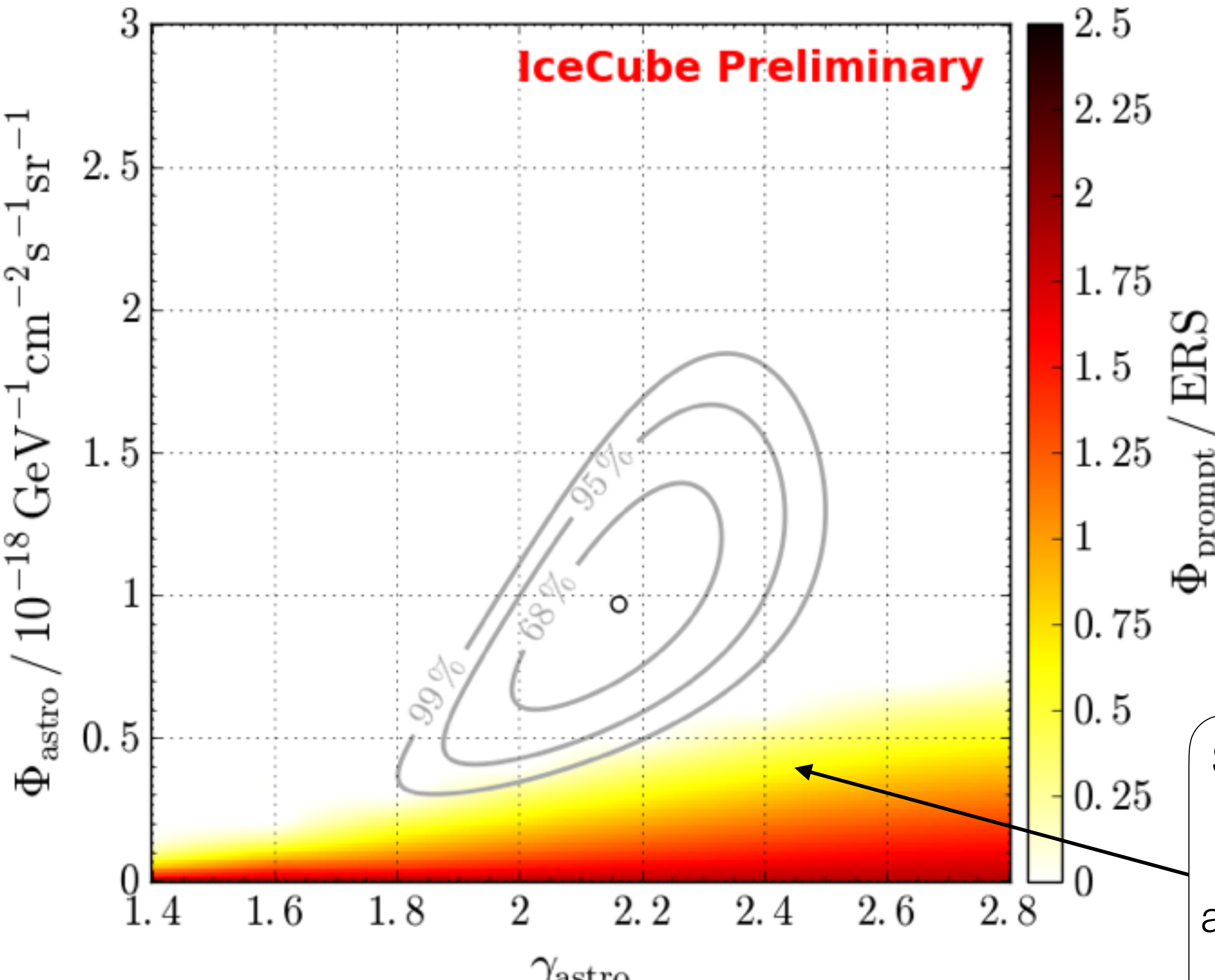
Where would prompt neutrinos appear?



Courtesy S. Schönen

1. Prompt signal washed out by astrophysical background uncertainty
2. No net excess observed in prompt region

Correlation to astrophysical flux parameters



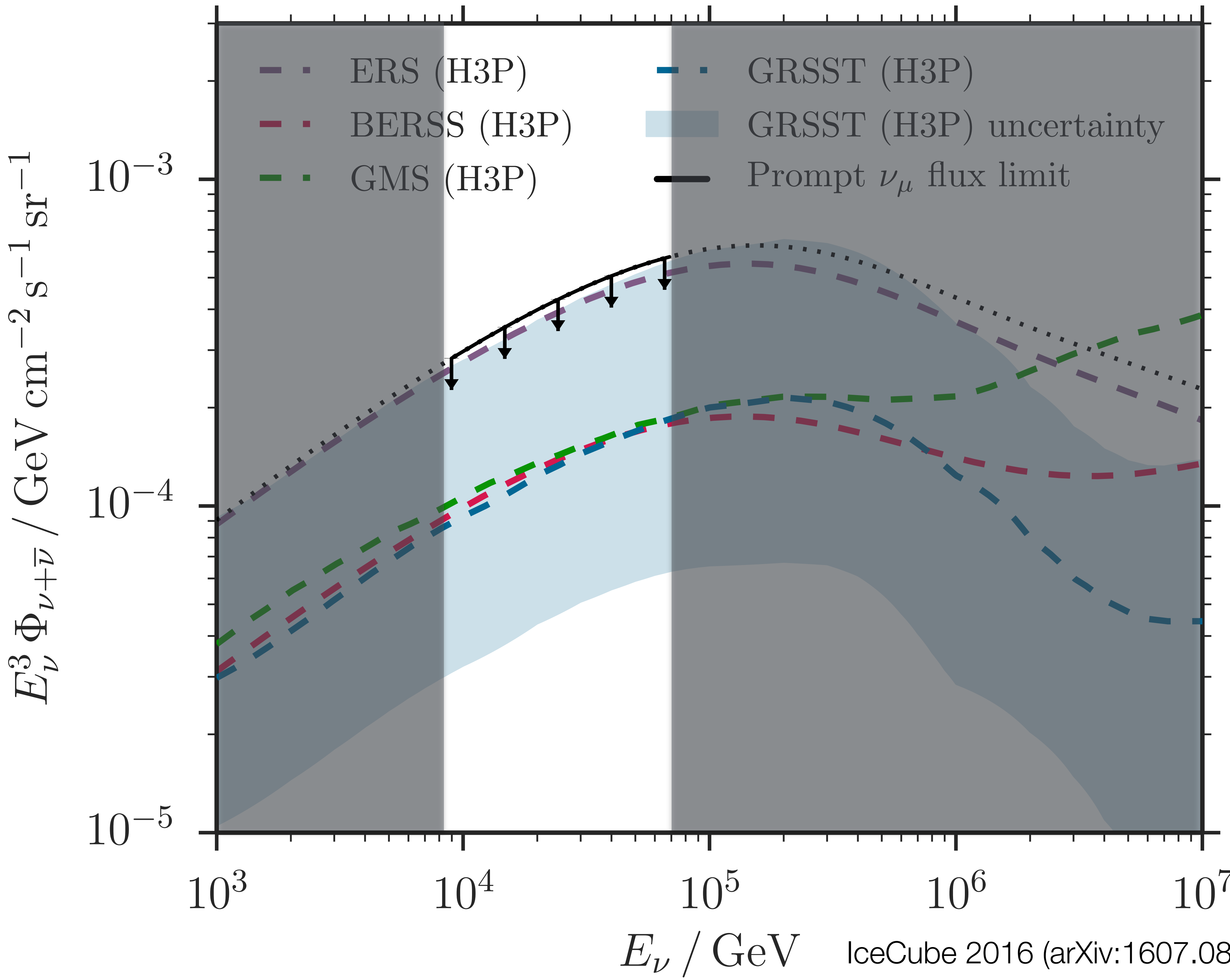
astrophysical neutrino flux

hard **spectral index** soft

Significant prompt component only allowed if astrophysical flux is small and soft (excluded by data)

Shape uncertainty

Spectral shape varies from model to model.



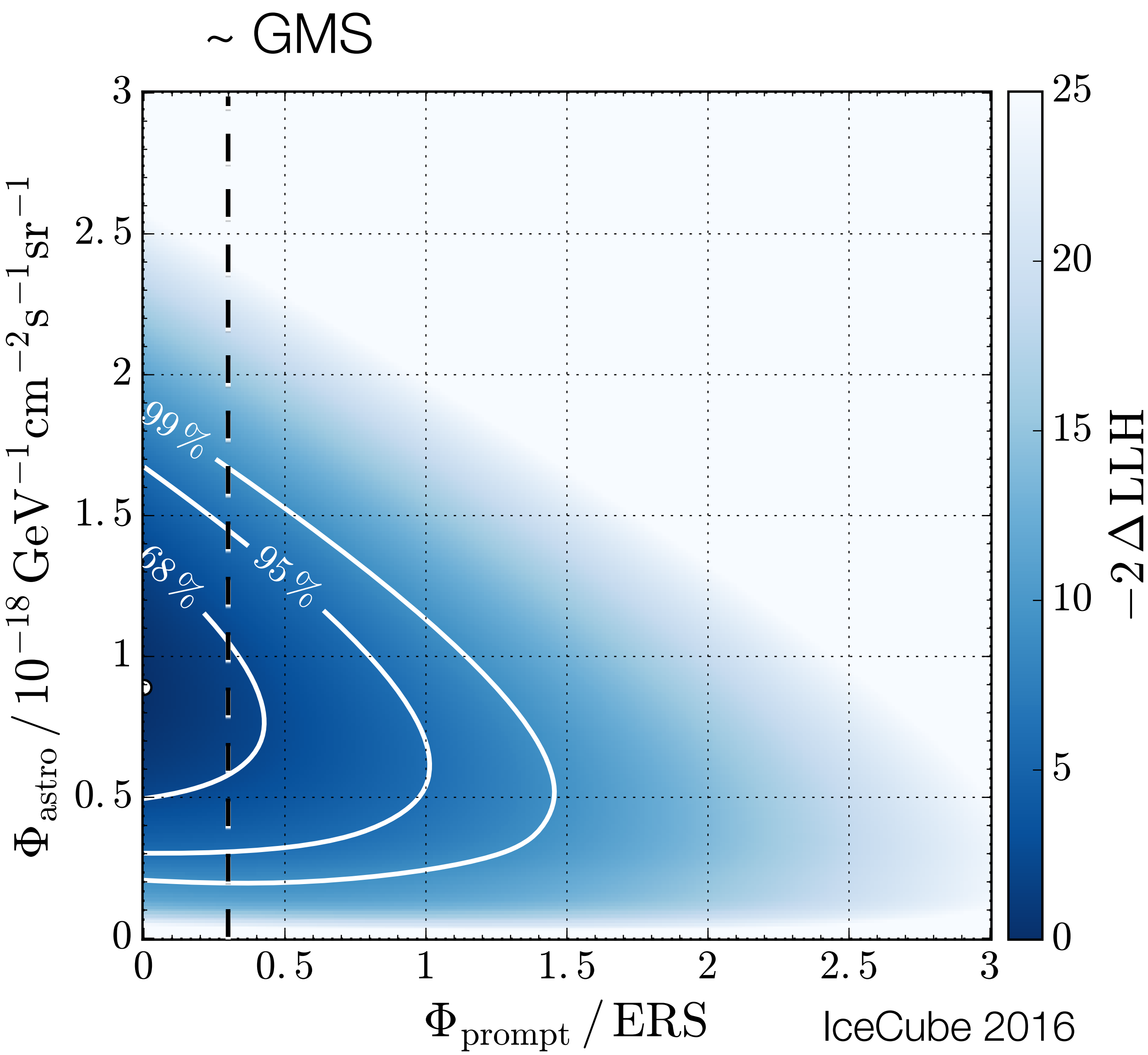
IceCube 2016 (arXiv:1607.08006)

Prompt atmospheric neutrinos only observable up to ~70 TeV (below the knee)

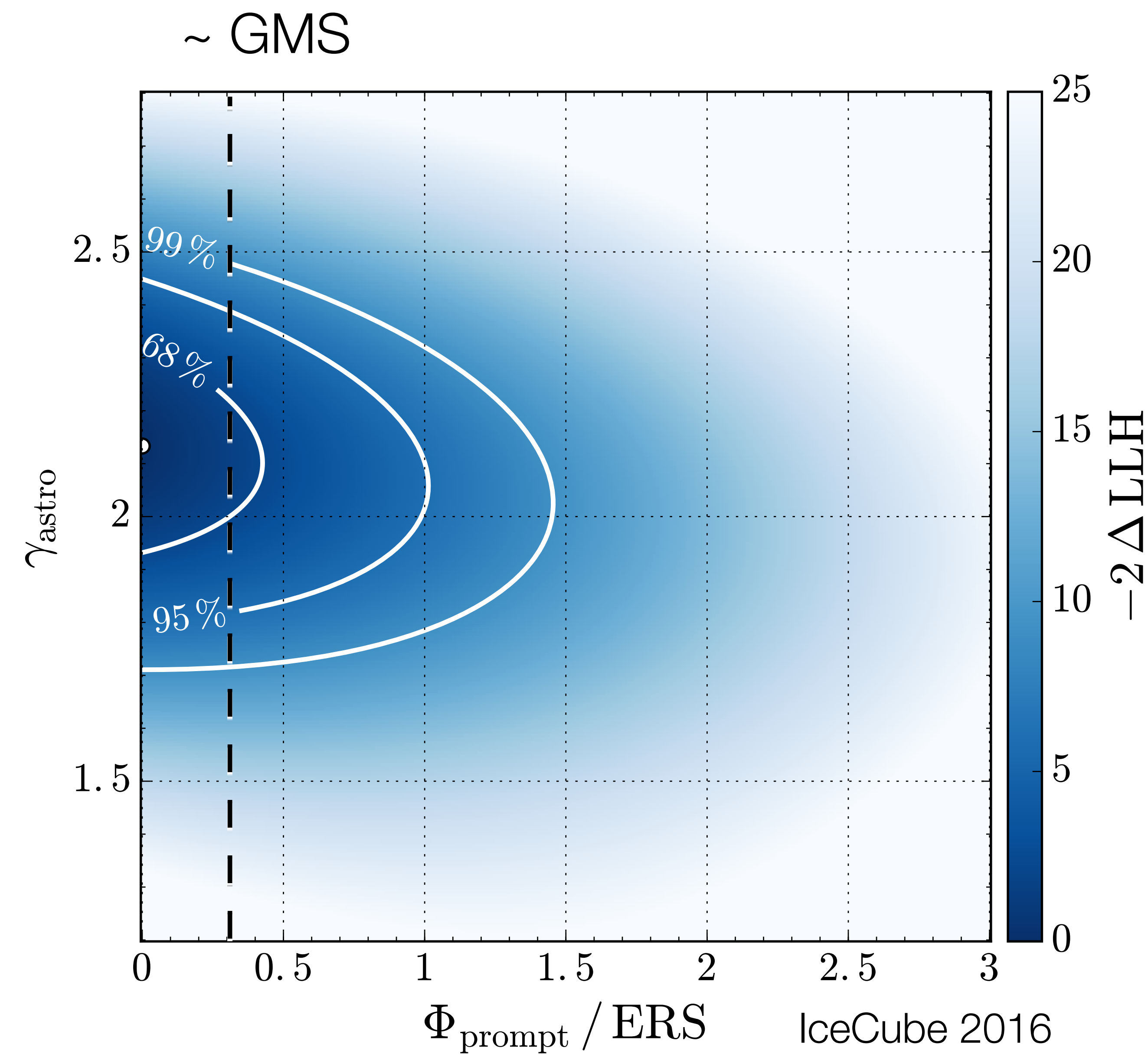
Normalization uncertainty is dominant

Upper limit is a factor 2-3 above modern models

Effect on astrophysical flux measurement



IceCube 2016
(arXiv:1607.08006)

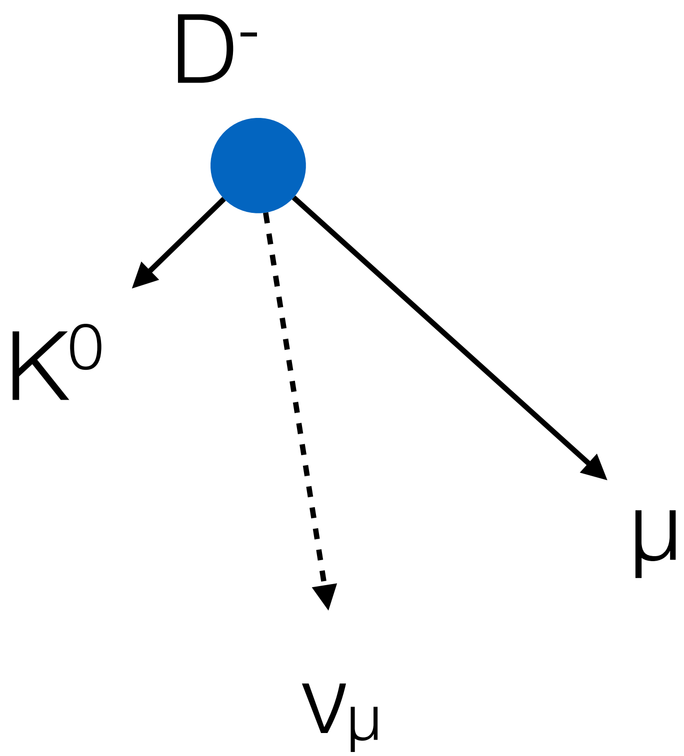


IceCube 2016
(arXiv:1607.08006)

1. Analysis as published leaves prompt component free
2. Fixing prompt normalization to modern calculation shifts astrophysical flux parameters slightly

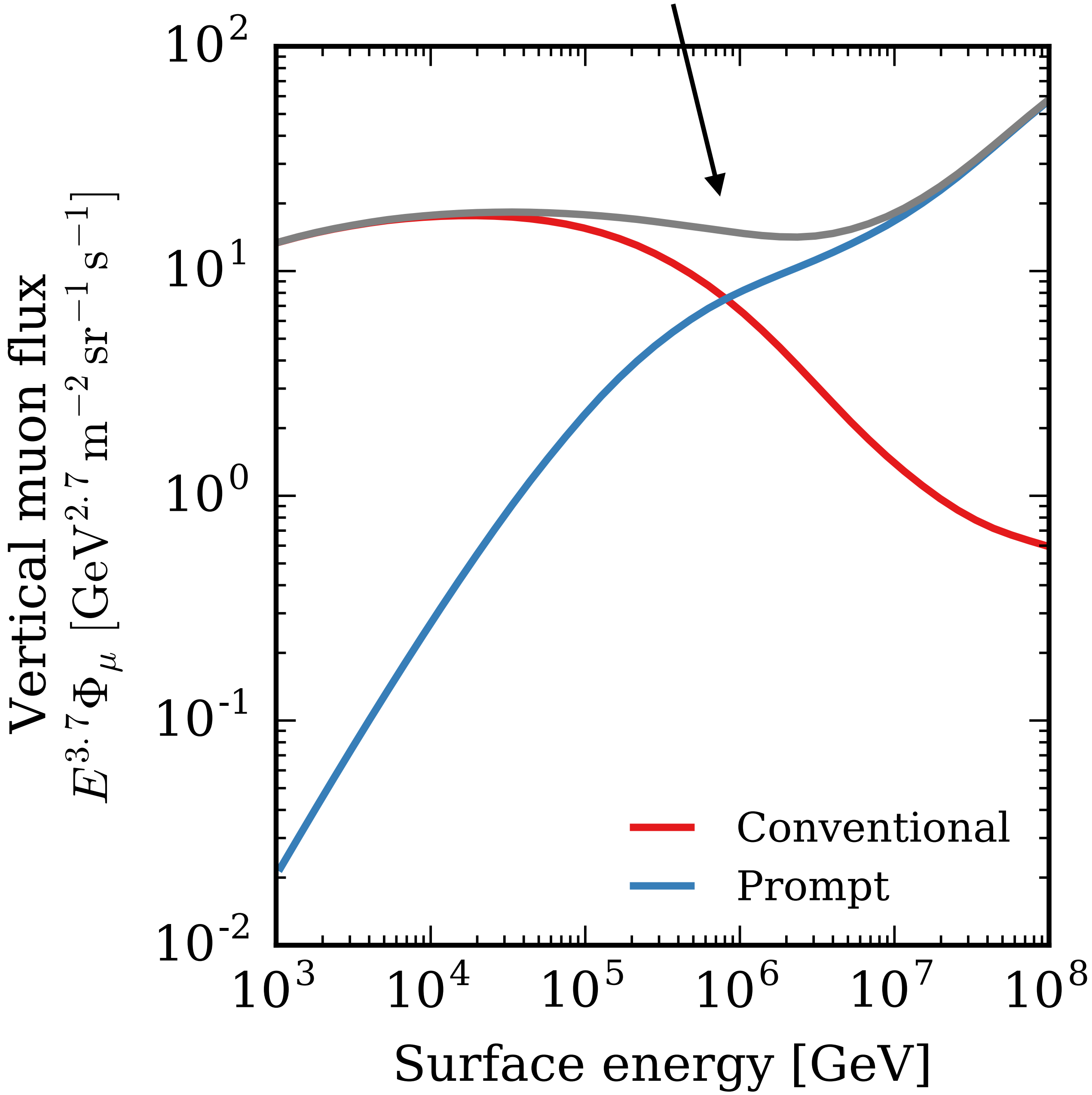
Penetrating muons

Prompt neutrino flux has a muon counterpart



- Much larger event rate
- No astrophysical background

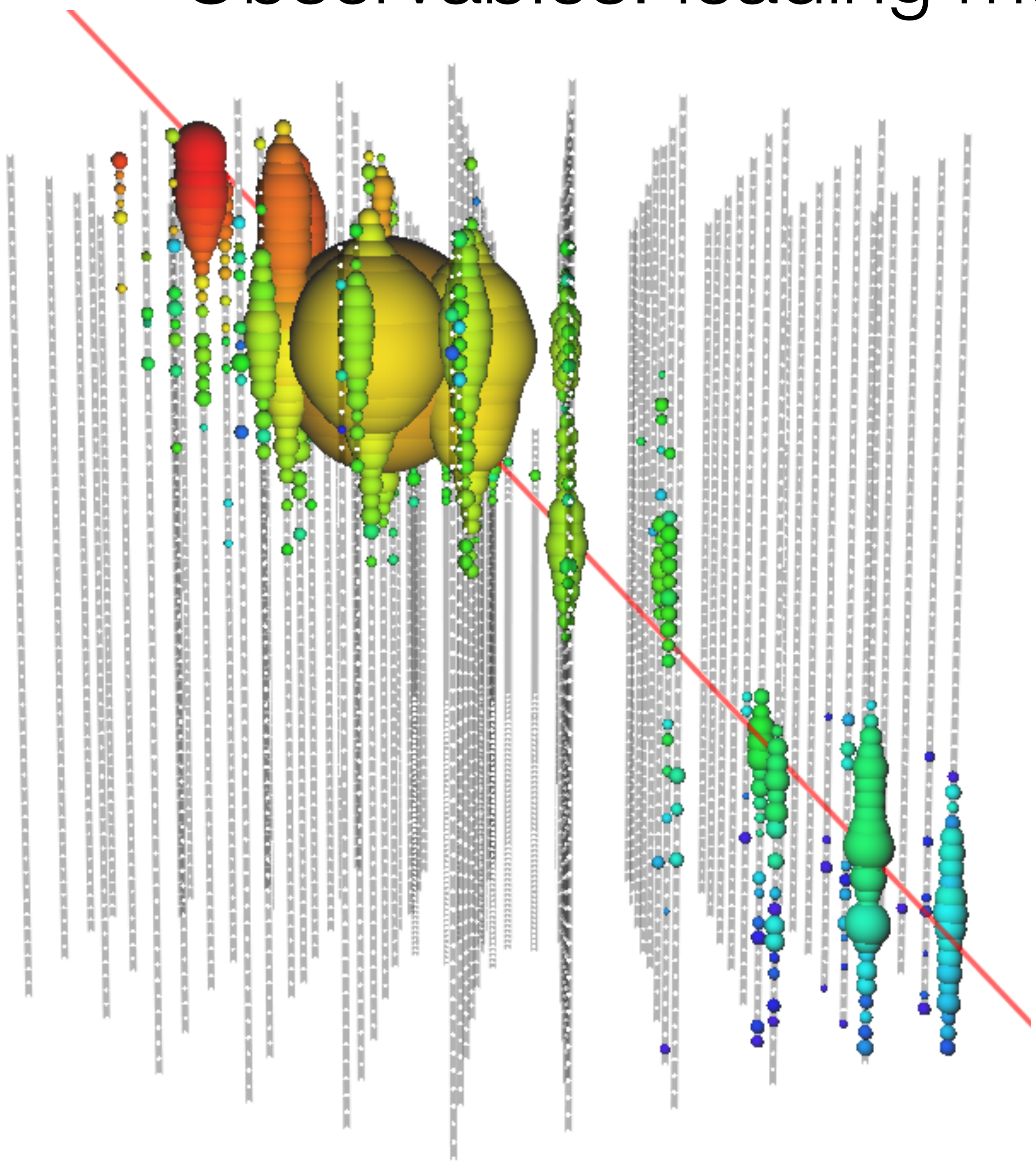
Hardening at ~PeV energies



Vertical muon spectrum (MCEq+SIBYLL 2.3)

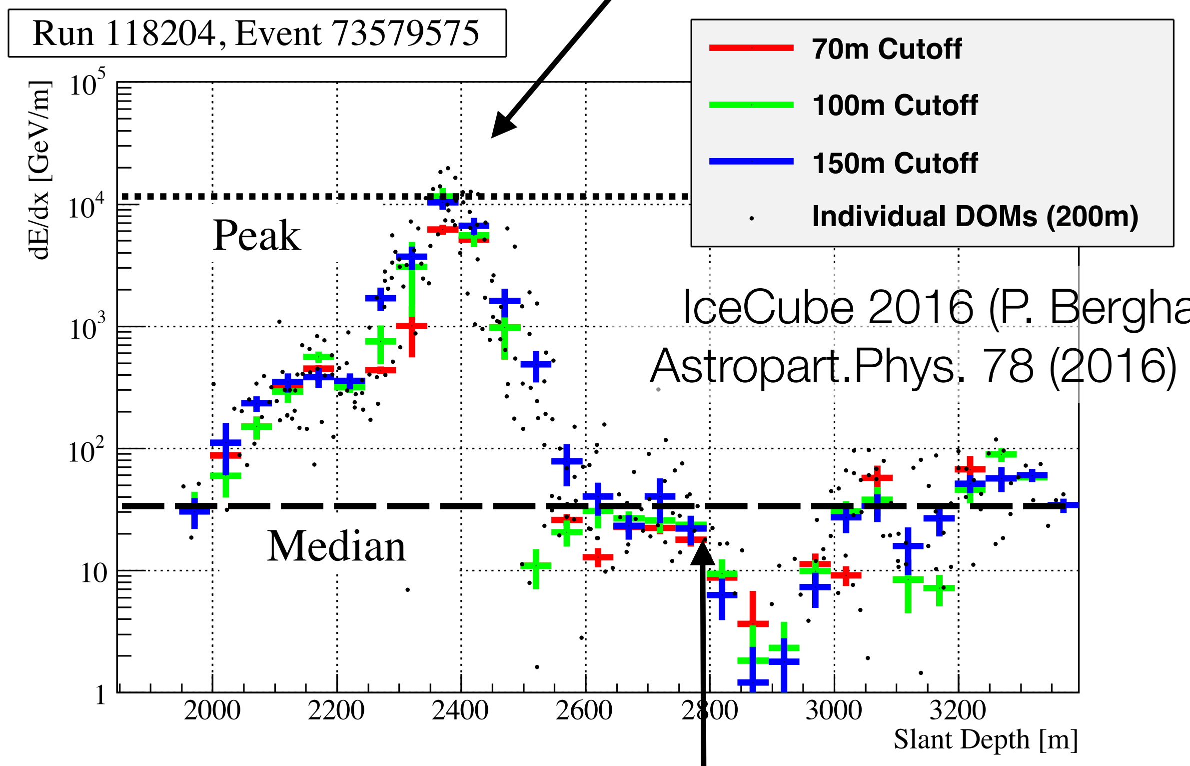
Measuring the muon spectrum

Observables: leading muon energy, zenith angle



~1 PeV muon (surface energy)

Peak energy loss ⇔ leading muon

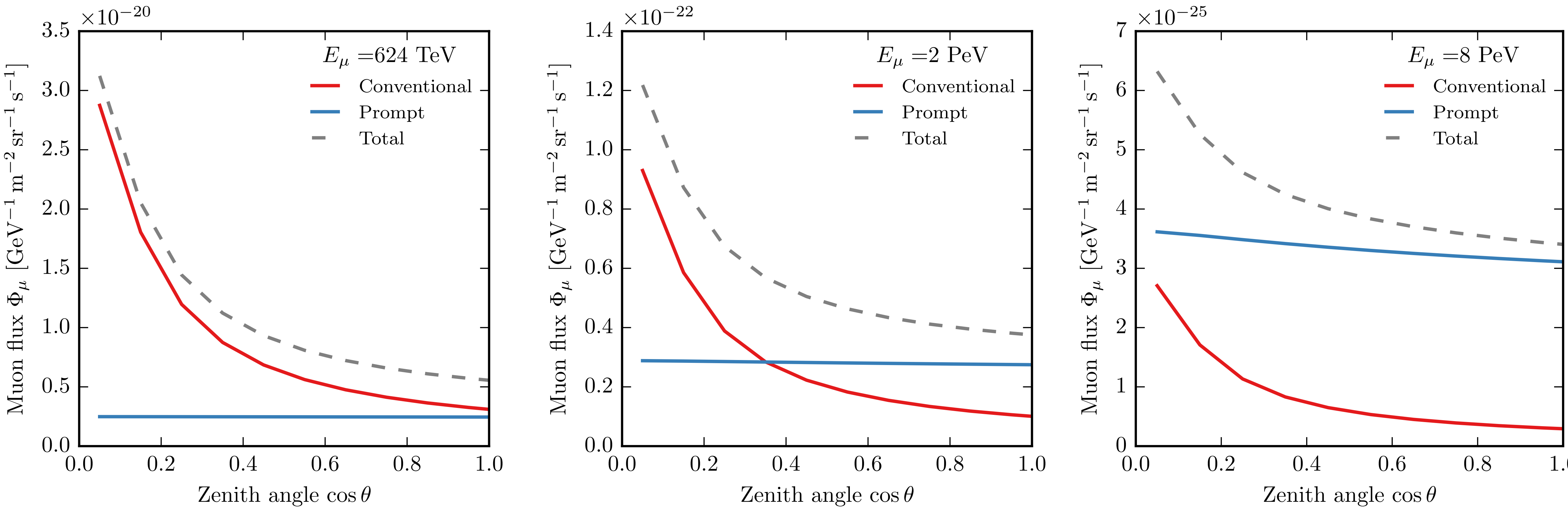


IceCube 2016 (P. Berghaus) Astropart.Phys. 78 (2016) 1-27

Median energy loss ⇔ bundle multiplicity

Energy loss profile

Horizontal/vertical ratio



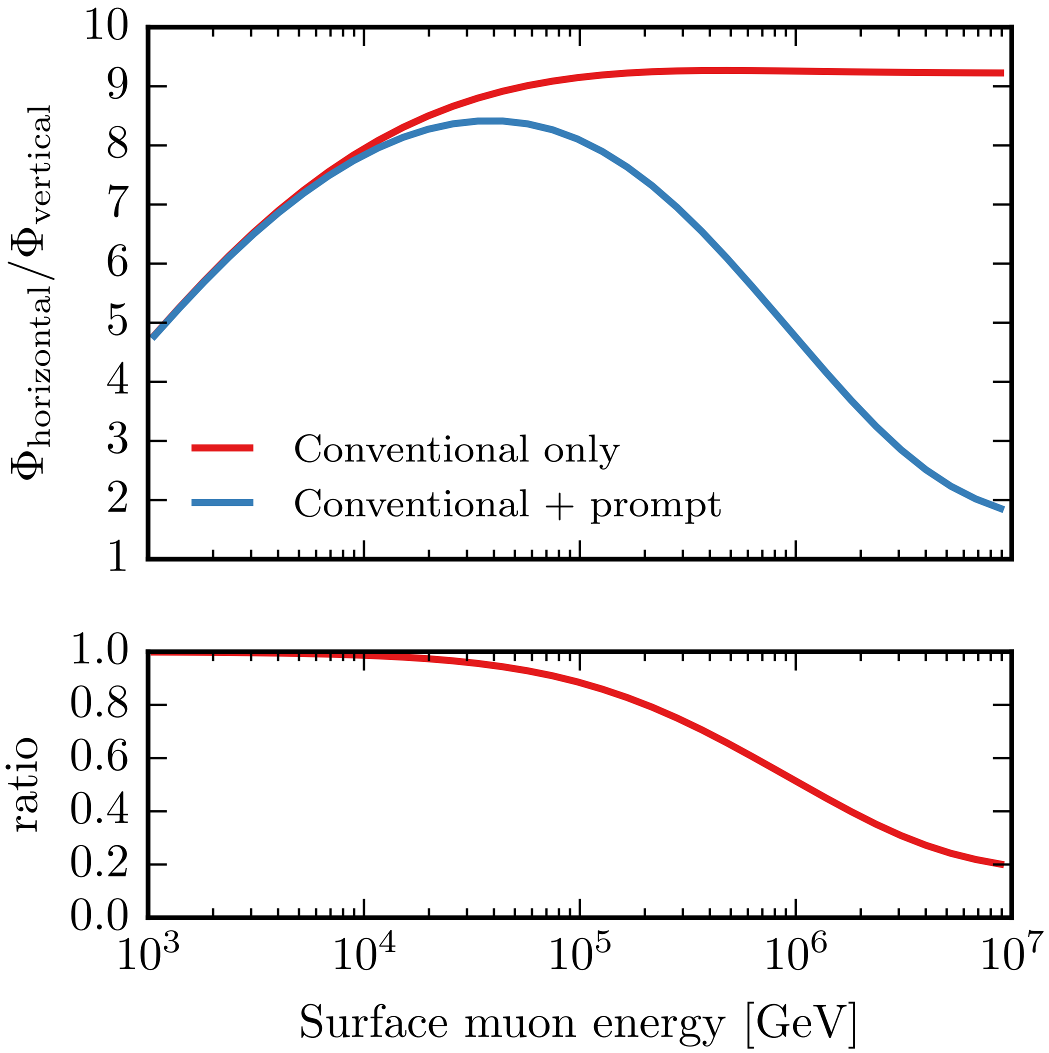
Zenith distribution flattens as prompt component takes over

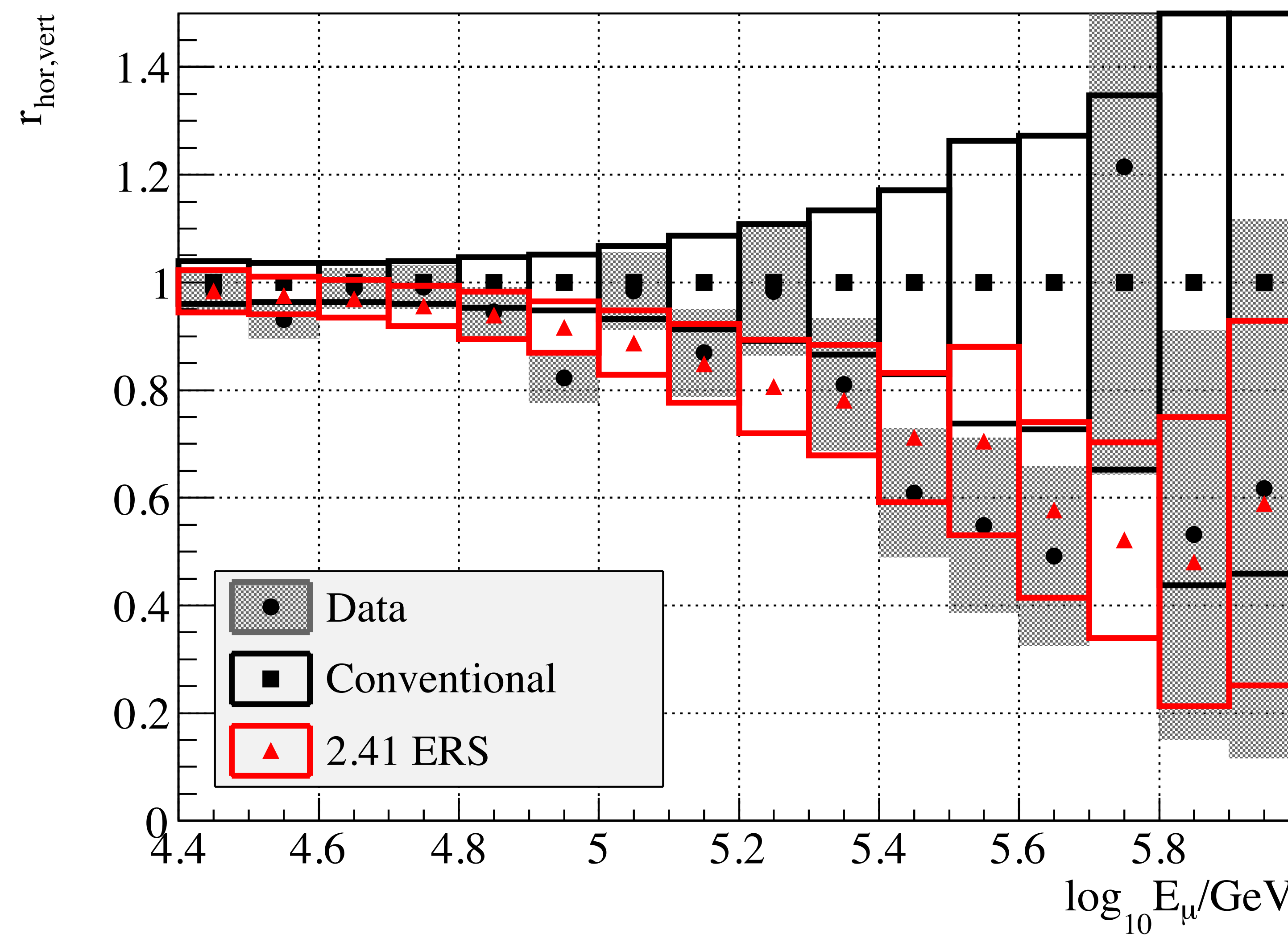
Ratio of horizontal/vertical flux is independent of input cosmic ray flux

Observed ratio

$r_{hor,vert}$: measure of zenith distribution peakedness

1 ⇒ all conventional, < 1 ⇒ prompt component



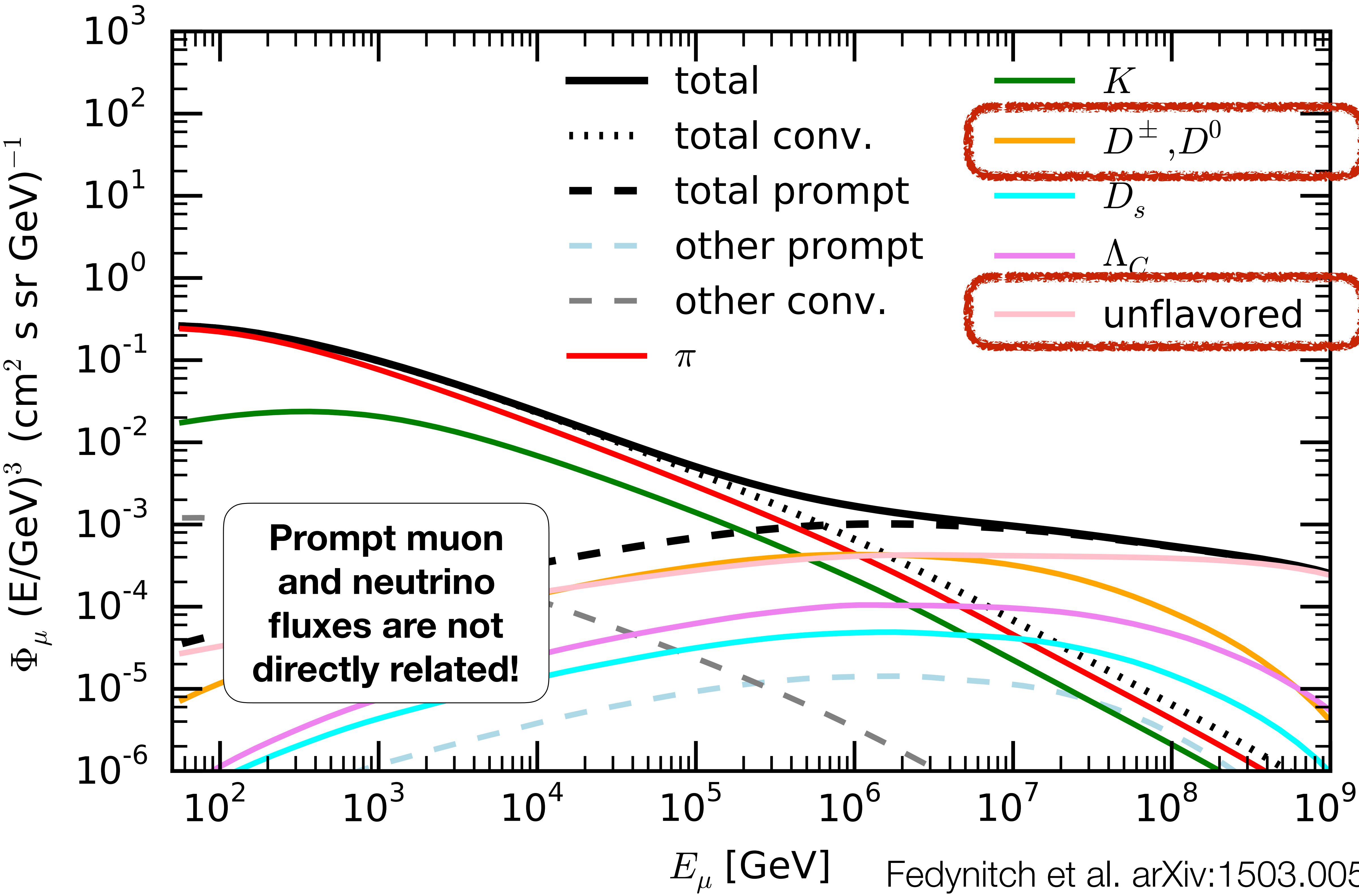


IceCube 2016 (P. Berghaus) Astropart.Phys. 78 (2016) 1-27

Zenith distribution at high energies is flatter than expected for conventional only

Caution: bundle zenith distribution not perfectly understood at low energies

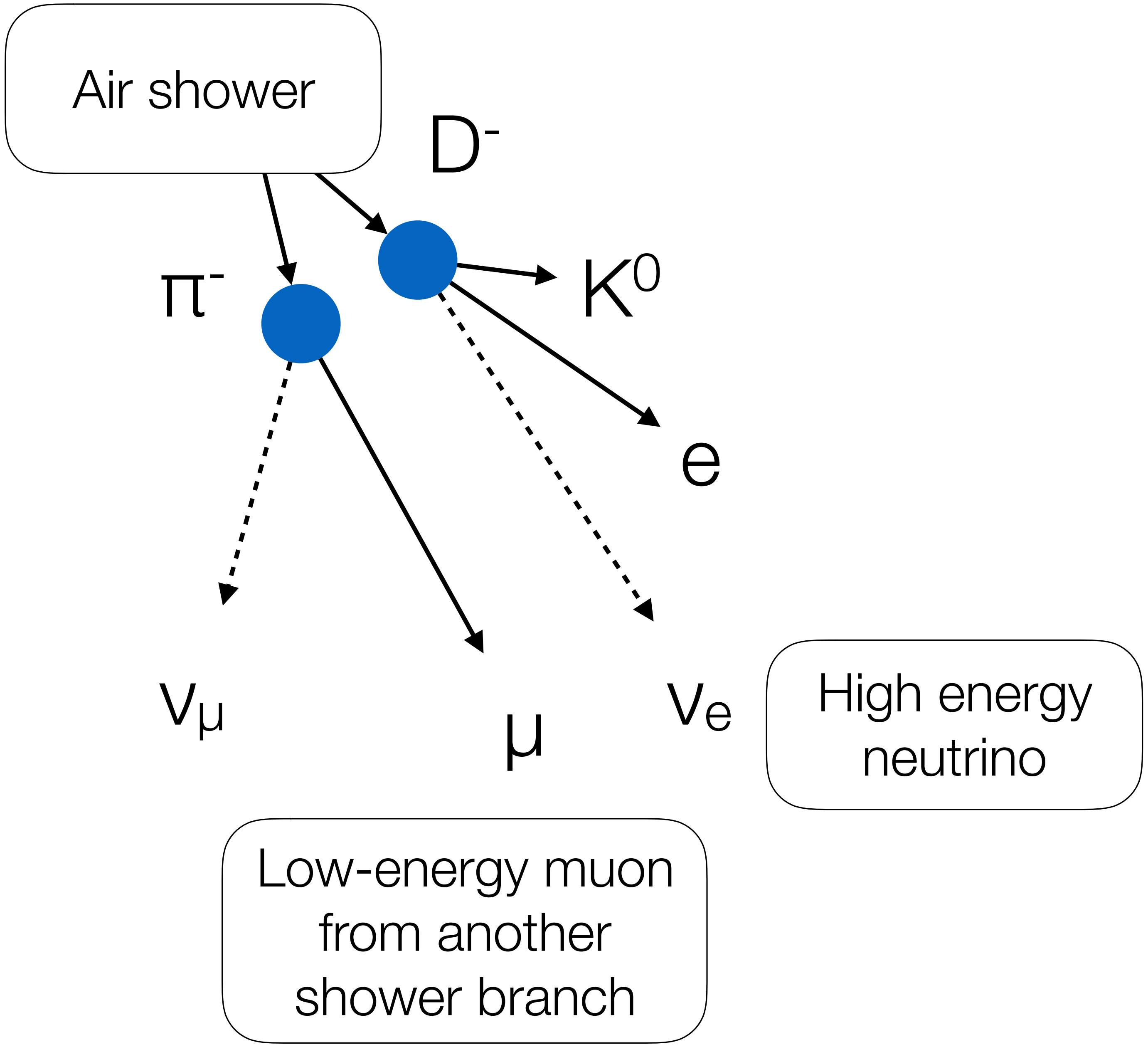
Prompt background from light unflavored mesons

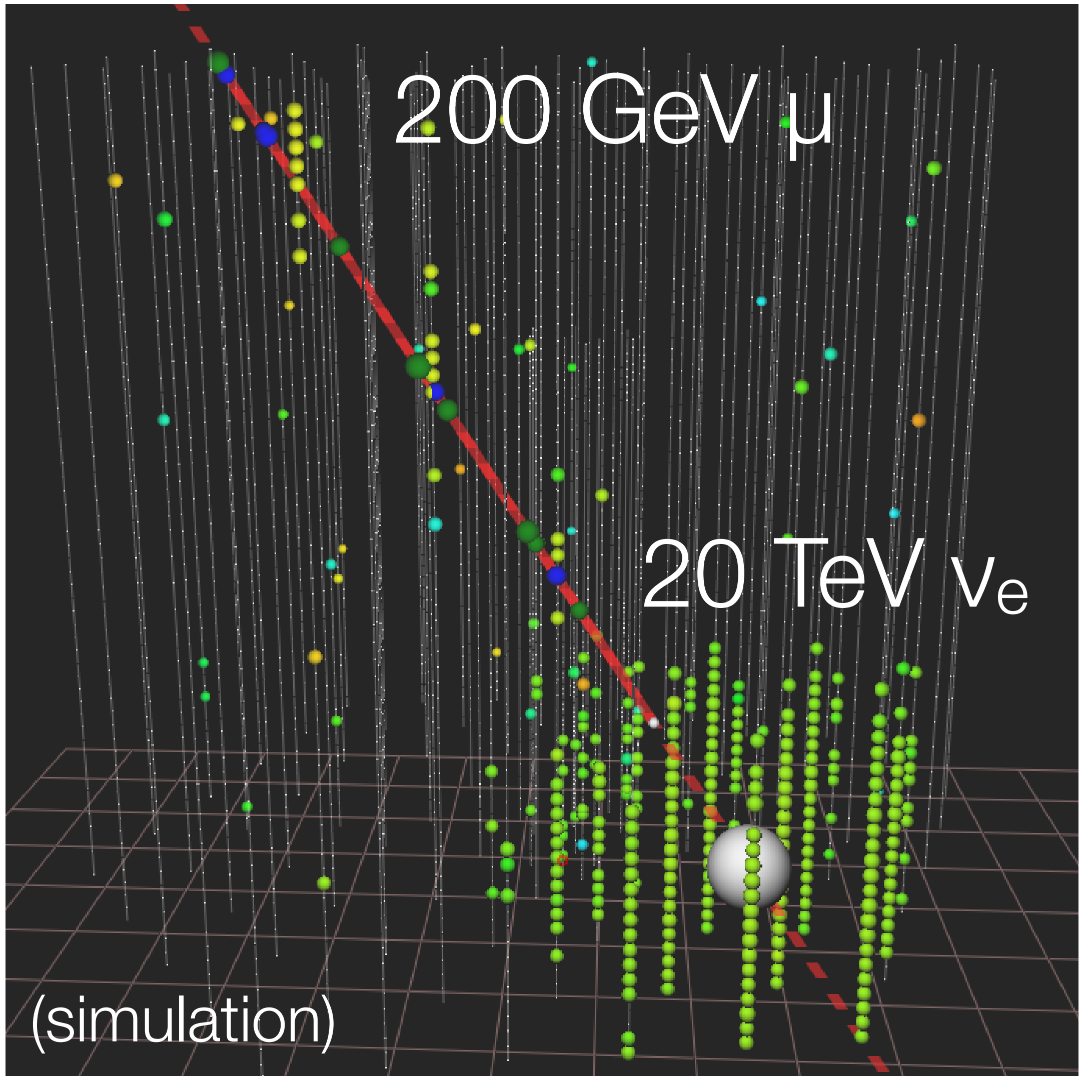


Fedynitch et al. arXiv:1503.00544v2

The future: background-free atmospheric neutrinos

Use accompanying muon to tag neutrino as atmospheric!





L. Wille, K. Jero (UW-Madison)

Neutrinos from charm accompanied by < 1 TeV muon: ~1/year in IceCube (extremely preliminary)

Conclusions

Prompt atmospheric neutrinos are not yet observable
due to uncertainties in the astrophysical background.

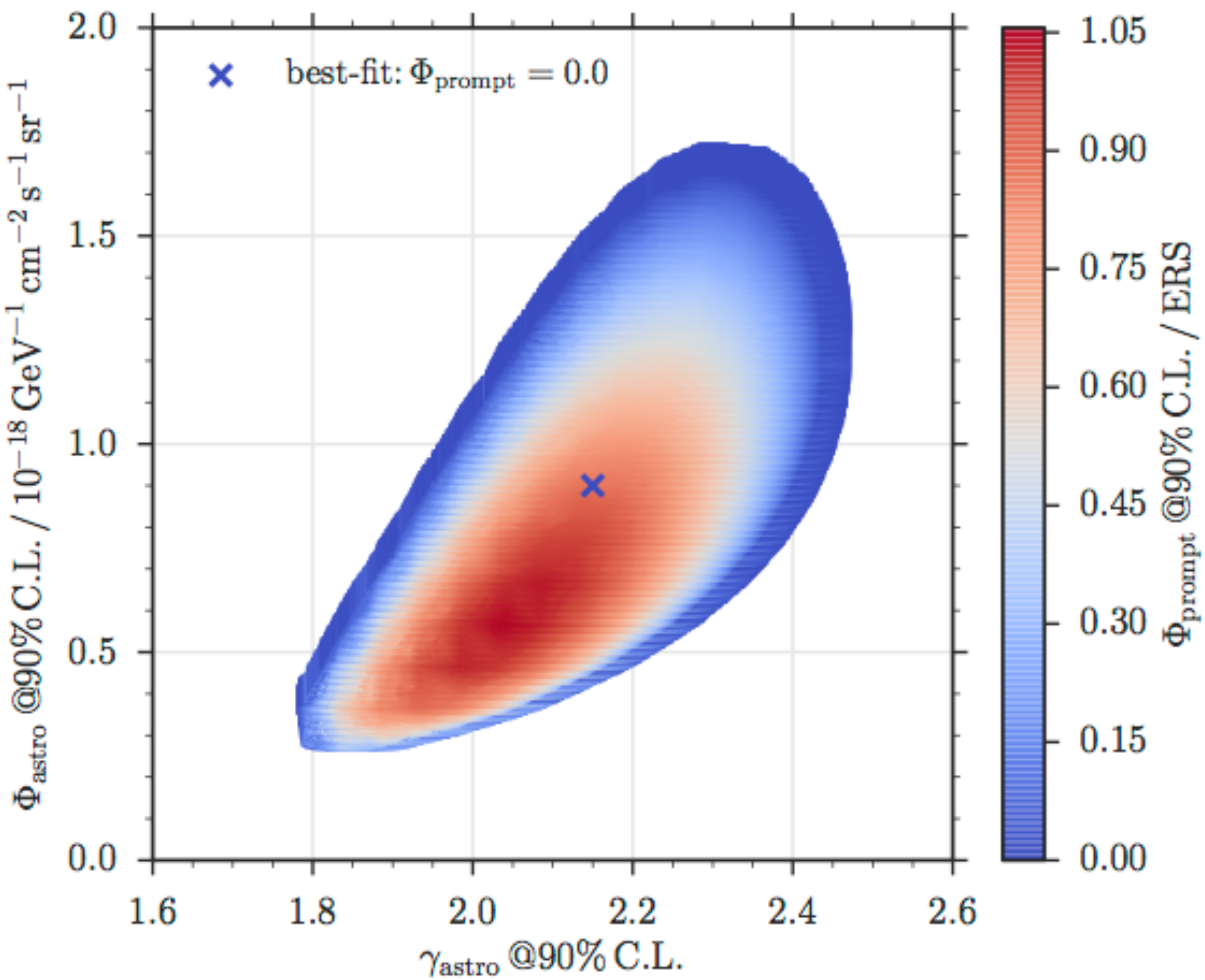
Penetrating muon spectrum appears consistent with a large prompt component,
but suffers from modeling difficulties. Its relationship to the neutrino spectrum remains unclear.

More and different theory inputs are needed.
Constraints can't be applied across detection channels if we ignore correlations between shower components.

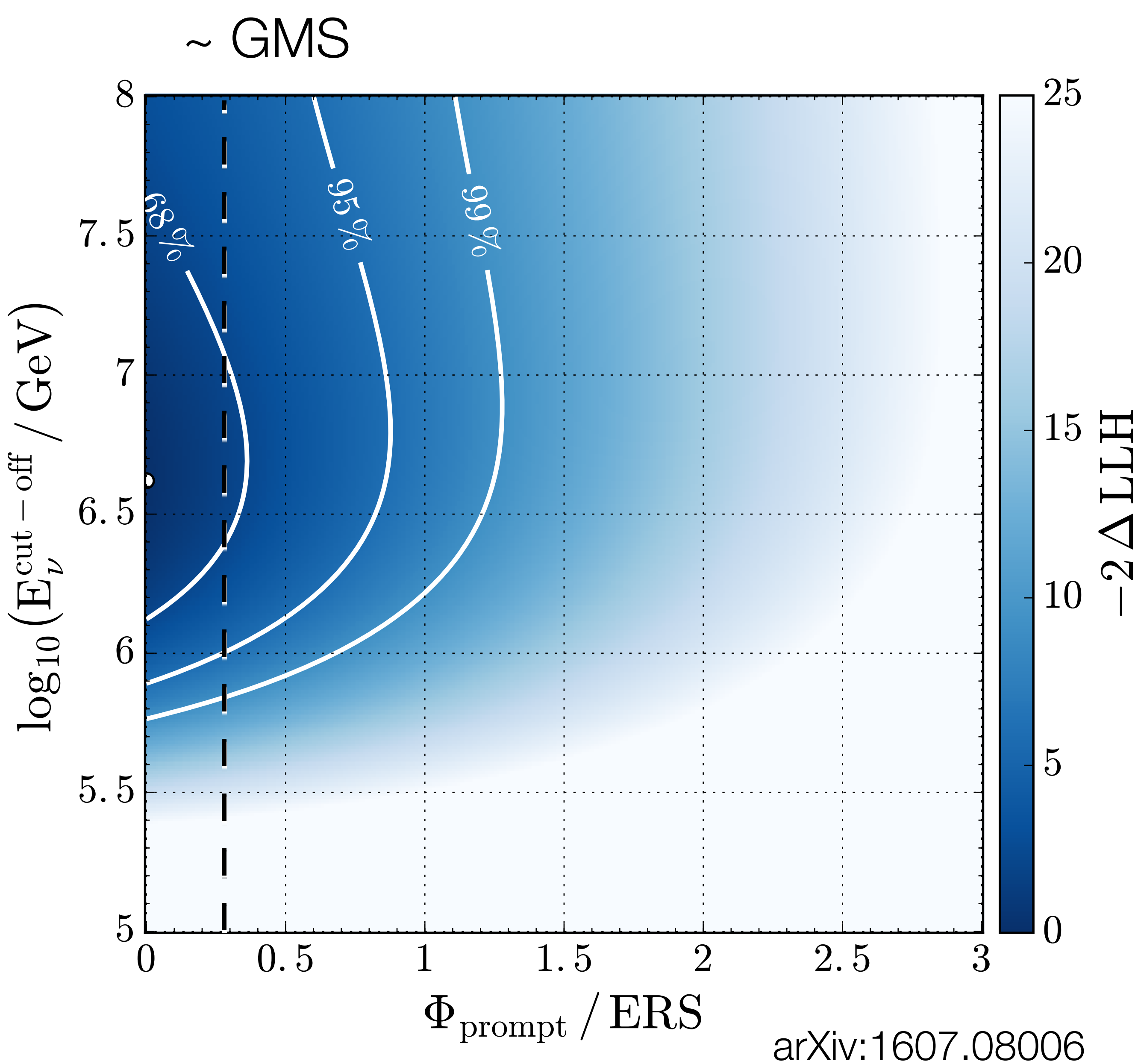
Thank you!

Backup

3D likelihood contour



Effect on cut-off



arXiv:1607.08006

TeV neutrinos from cosmic rays

$$p + \gamma \rightarrow \pi^0 + p$$

(or p)

$$\hookrightarrow \gamma + \gamma + p$$

TeV gamma rays (also from leptonic processes)

$$\rightarrow \pi^+ + n$$

Cosmic rays?

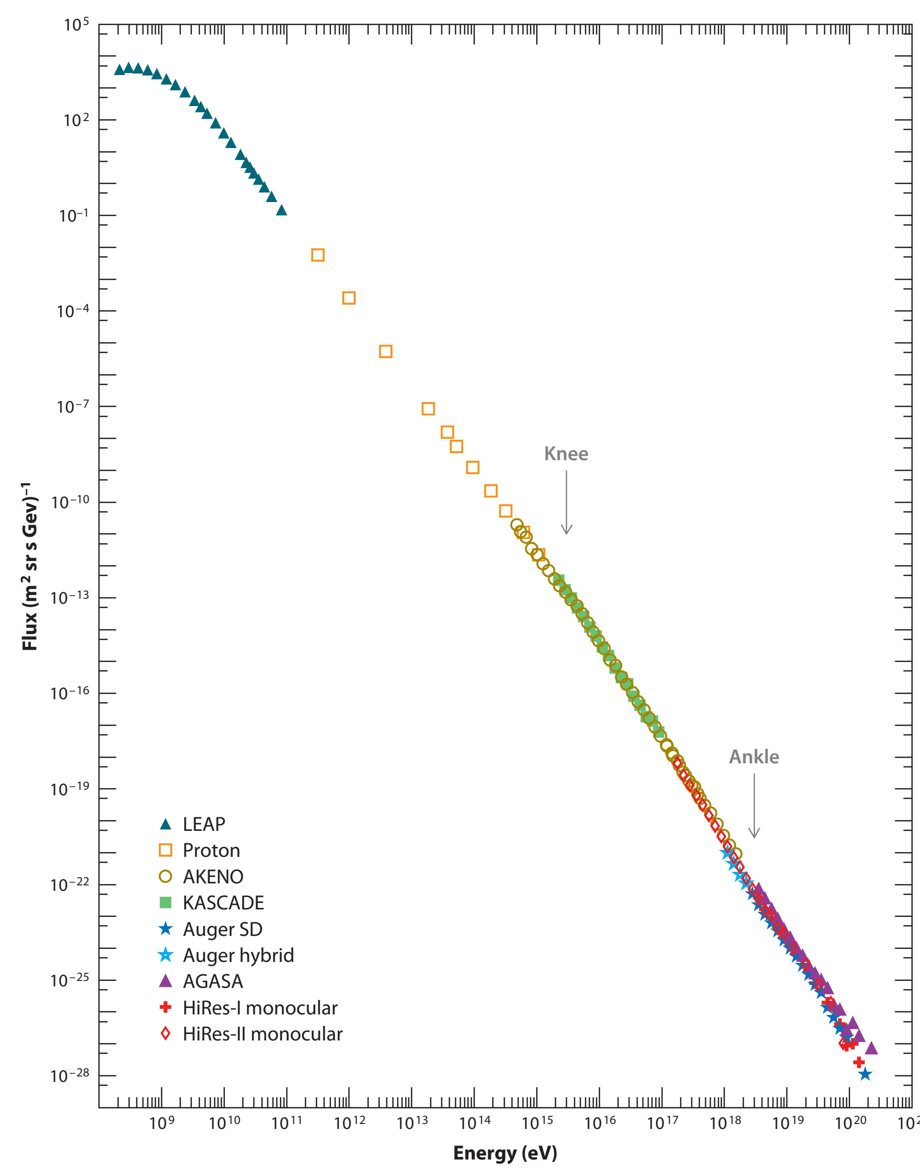
$$\hookrightarrow \mu^+ + \nu_\mu + n$$

$$\hookrightarrow e^+ + \overline{\nu_\mu} + \nu_e + \nu_\mu + n$$

TeV neutrinos

Neutrinos from cosmic ray interactions within

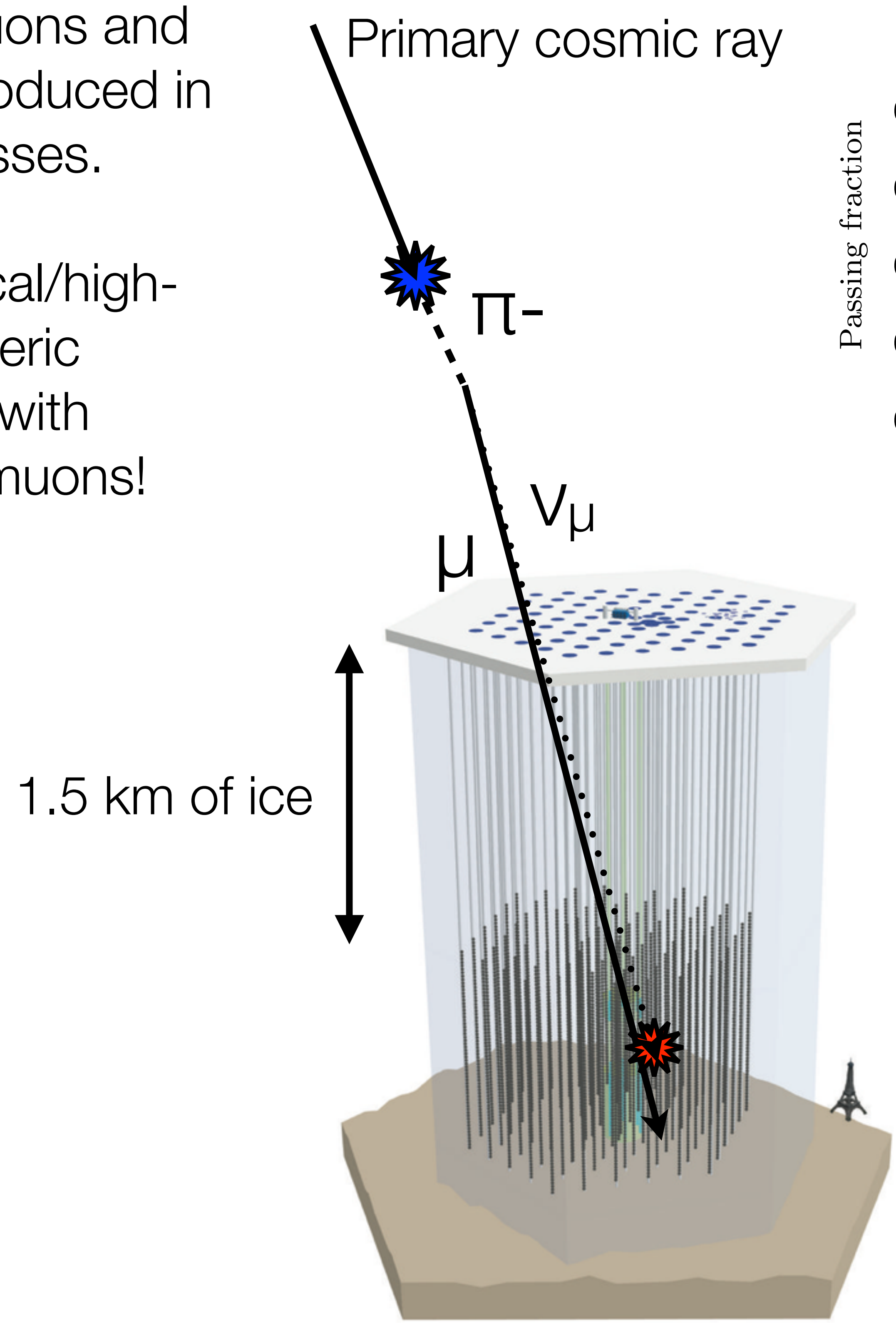
- The atmosphere
- Cosmic Microwave Background
- Gamma-Ray Bursts (acceleration sites)
- Active Galactic Nuclei (acceleration sites)
- ?

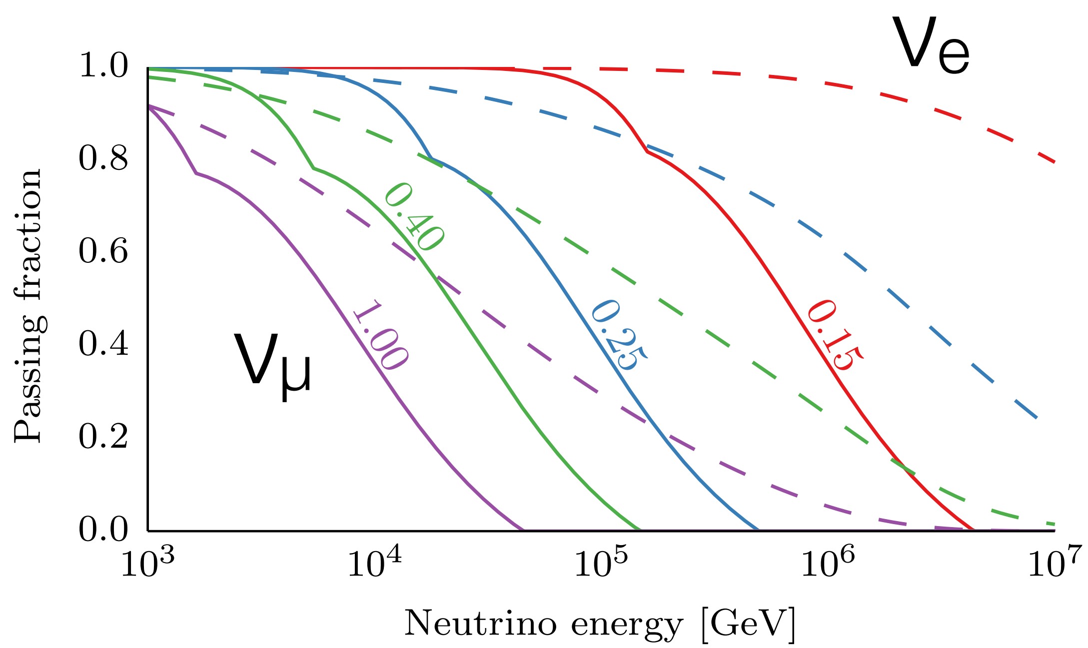


Vetoing down-going atmospheric neutrinos

Atmospheric muons and neutrinos are produced in the same processes.

Sufficiently vertical/high-energy atmospheric neutrinos come with accompanying muons!

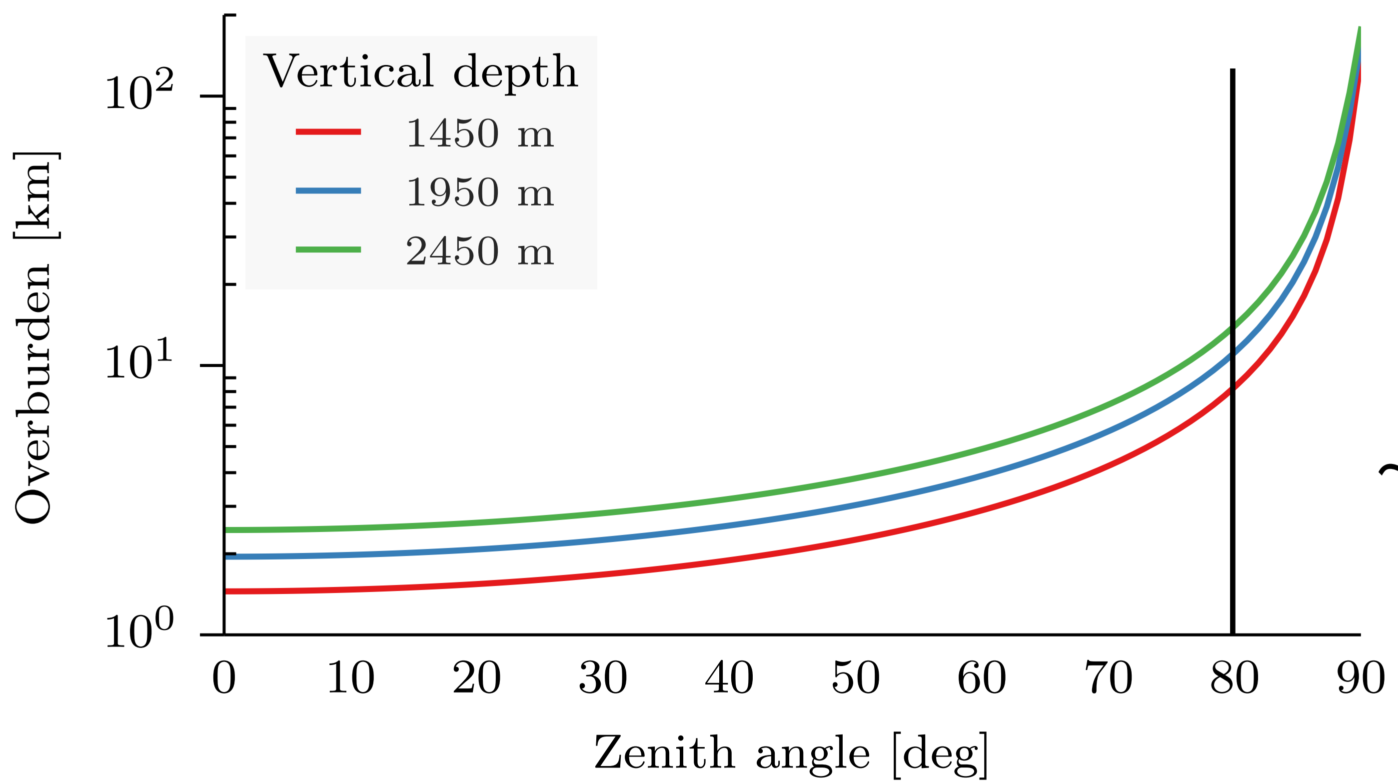




Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009

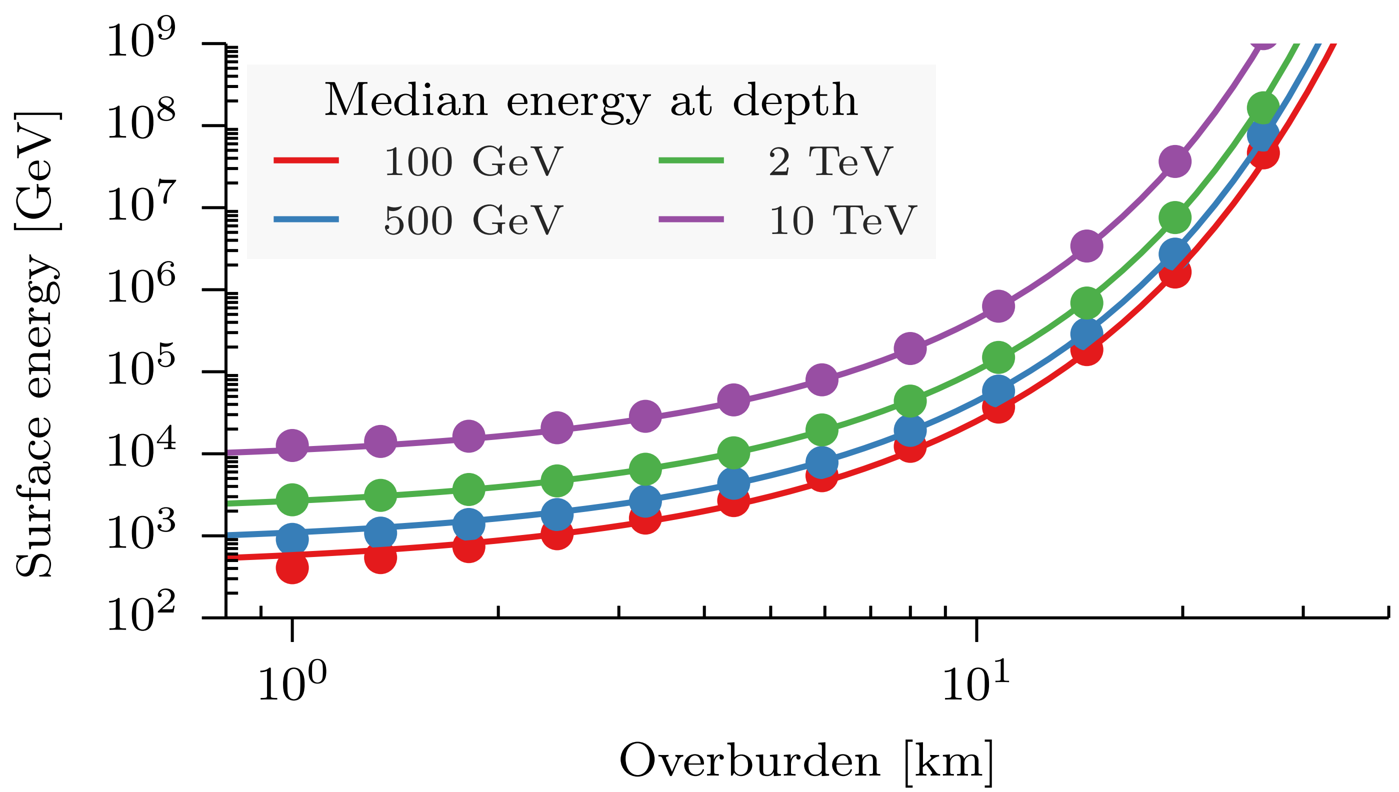
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009

IceCube's overburden



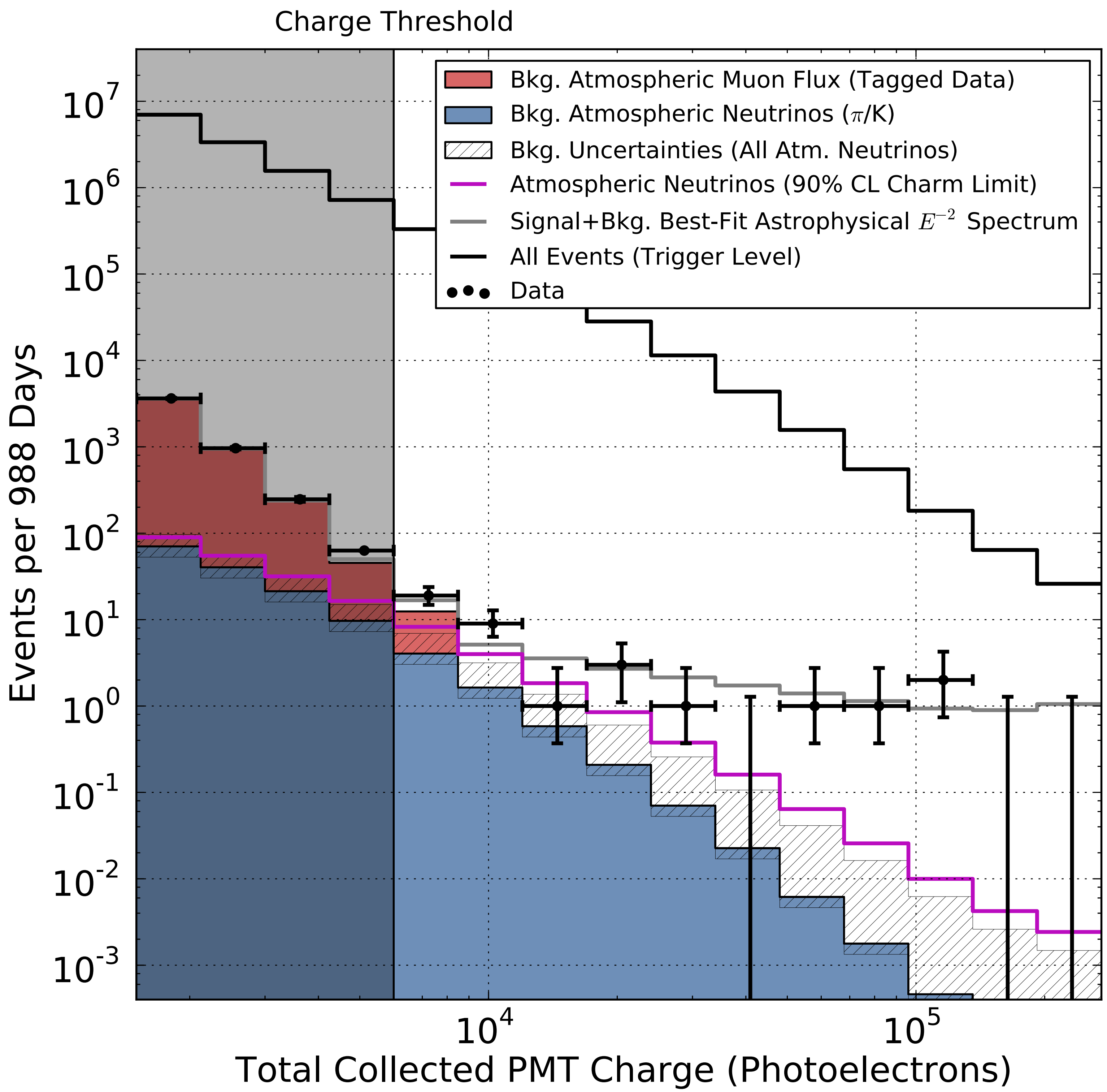
~10 km at 80 degrees

~10 TeV to survive 10 km with 1 TeV



Evidence for high-energy astrophysical neutrinos

- Use outer layer of PMTs as an active veto to select neutrino events
- 36 events with more than 6000 PE (~30 TeV deposited energy) observed in 3 years of data
- 15 events expected from atmospheric backgrounds



arXiv:1405.5303 (accepted for PRL)

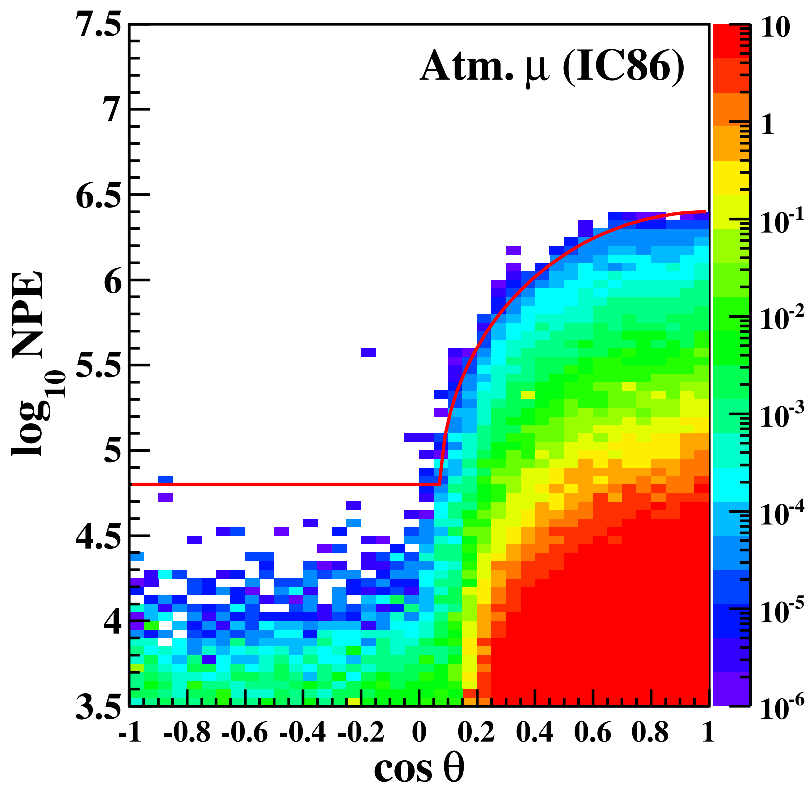
What about extremely high energies?

CR protons > 50 EeV interact with the CMB, producing neutrinos:

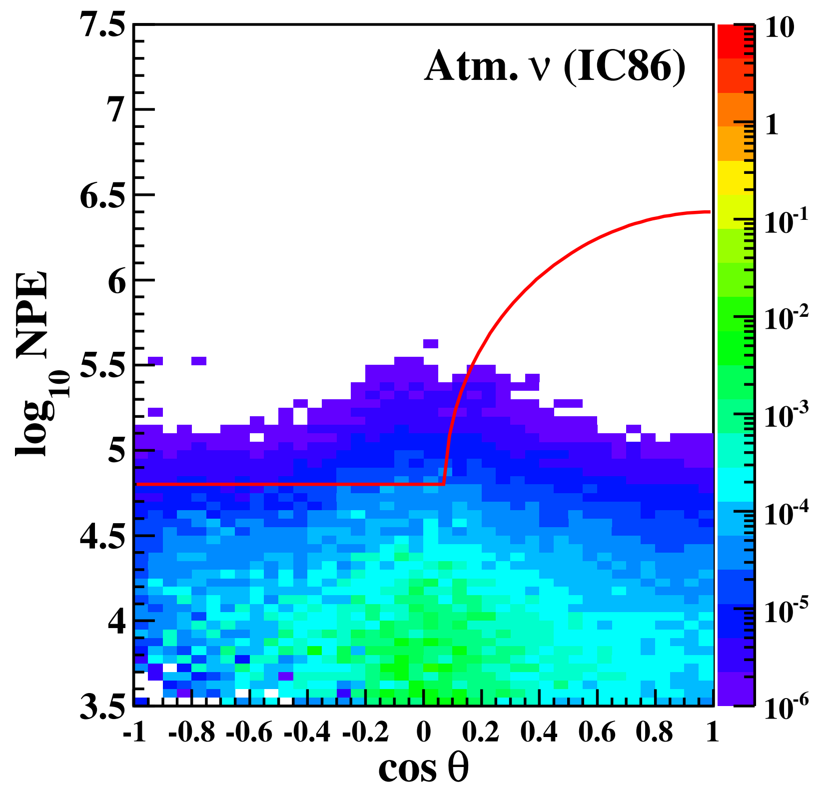
$$p + \gamma_{\text{CMB}} \rightarrow \Delta \rightarrow n + \pi^{+} \rightarrow \nu_{\mu}$$

“GZK” neutrinos would be more energetic than any atmospheric neutrino or muon → simple selection for largest possible acceptance

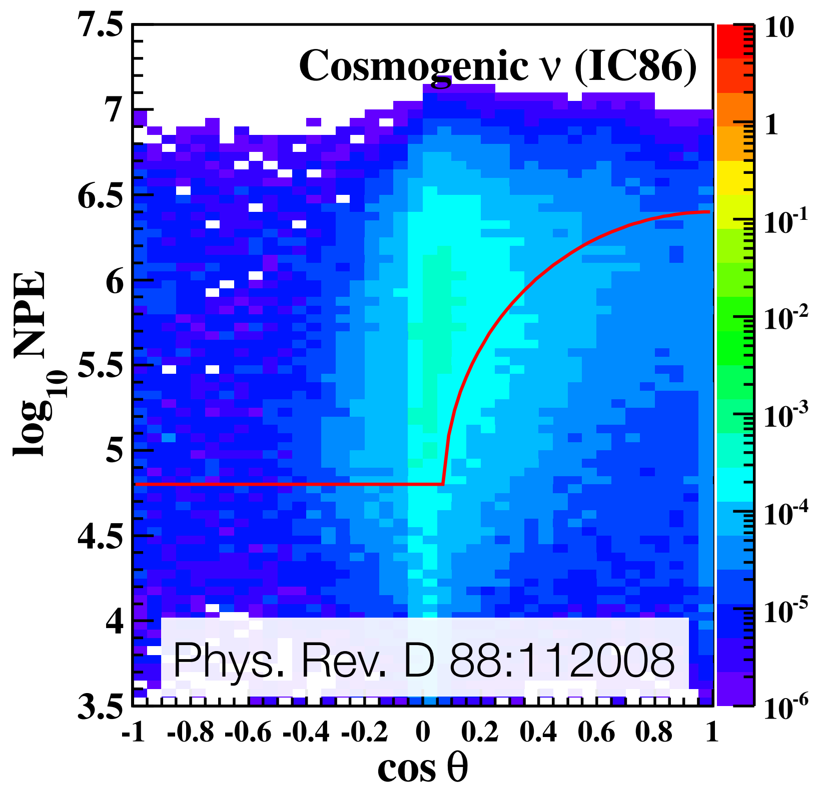
Penetrating muons



Atmospheric neutrinos



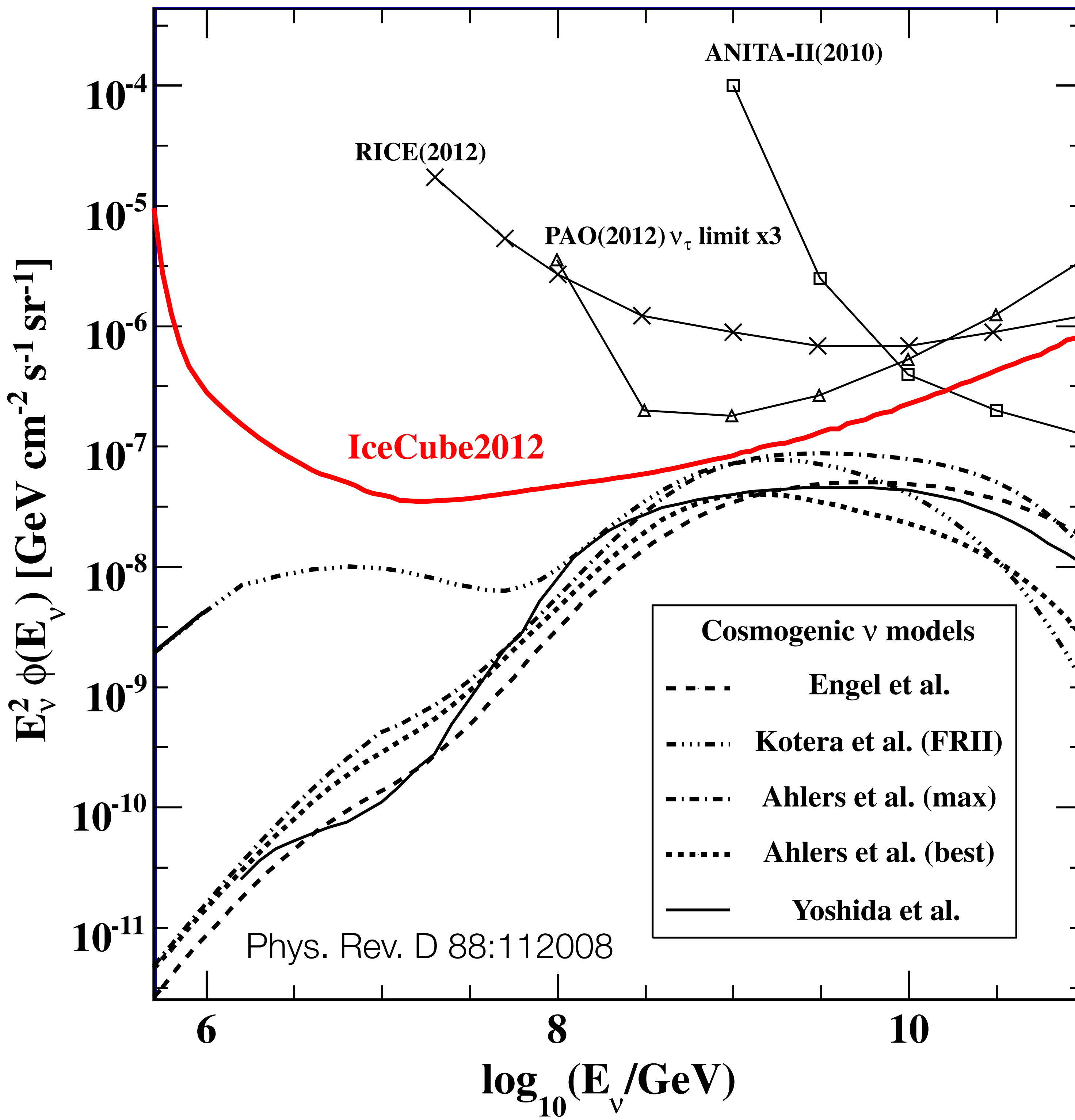
GZK neutrinos



Constraints on GZK neutrino fluxes

- GZK-focused analysis found first 2 > PeV neutrino events near threshold
- Upper limits do not yet exclude current models, but are coming close

90% all-flavor upper limit



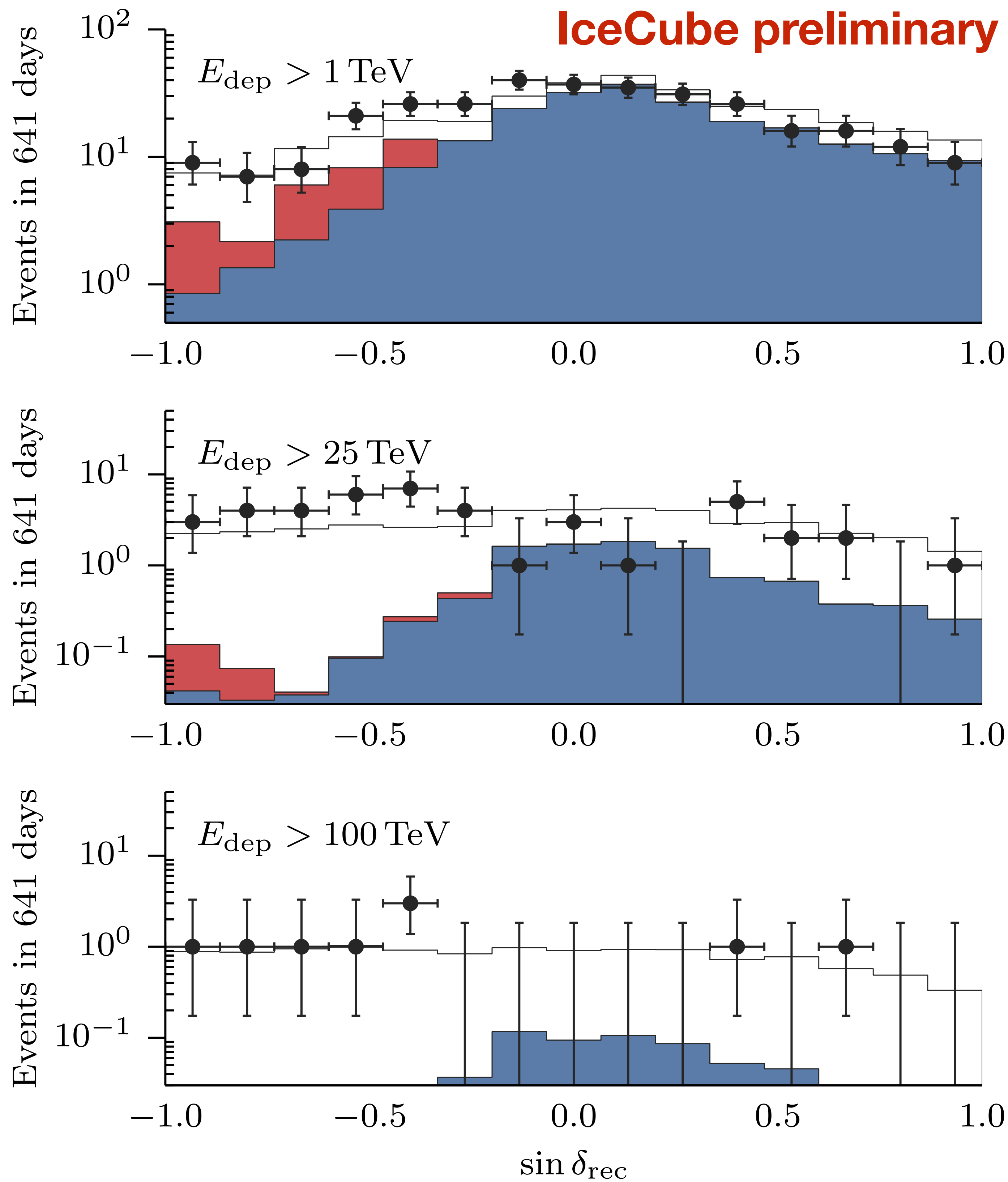
Results: angular distribution

Dominated by conventional atmospheric neutrinos ➞ peaked at the horizon

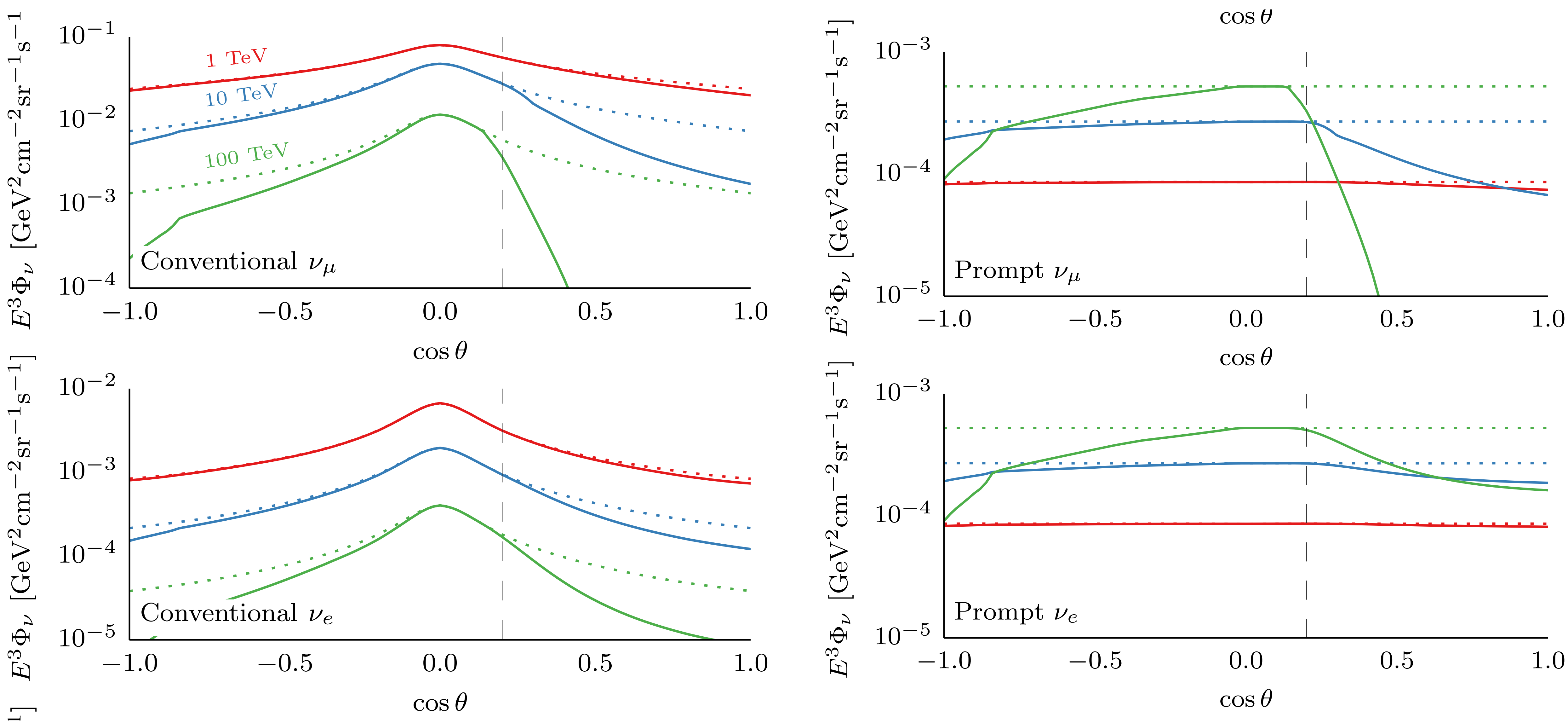
increasing energy threshold

Dominated by astrophysical neutrinos ➞ isotropic (but some up-going neutrinos are absorbed in the Earth)

(IceCube is at the South Pole ➞ $\sin\delta = -\cos\theta$)

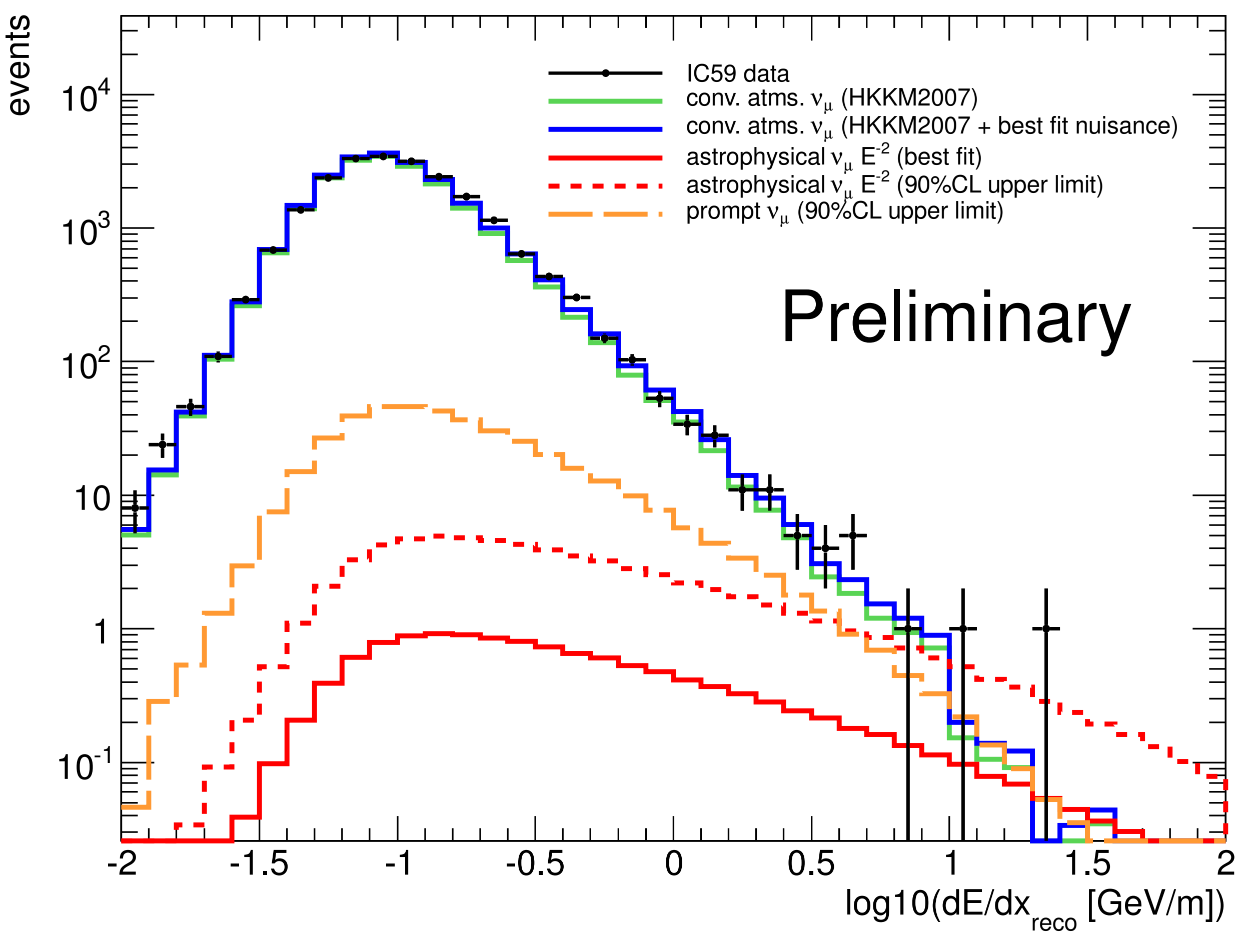


Zenith distributions at IceCube



Early hints of a high-energy excess

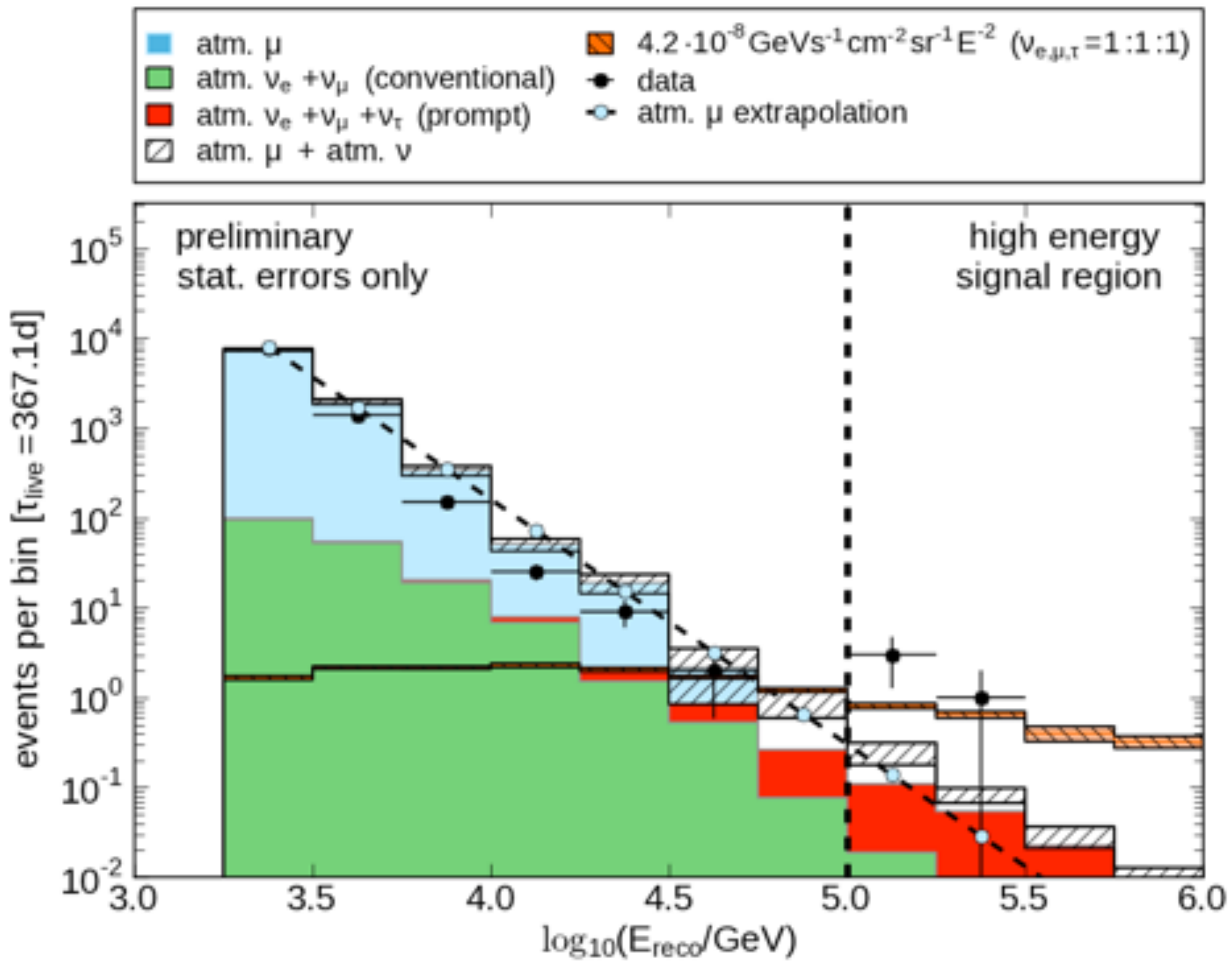
Northern hemisphere ν_μ events in 59-string configuration (2009-2010)



1.8 σ excess over atmospheric expectations

Phys.Rev.D **89** (2014) 062007

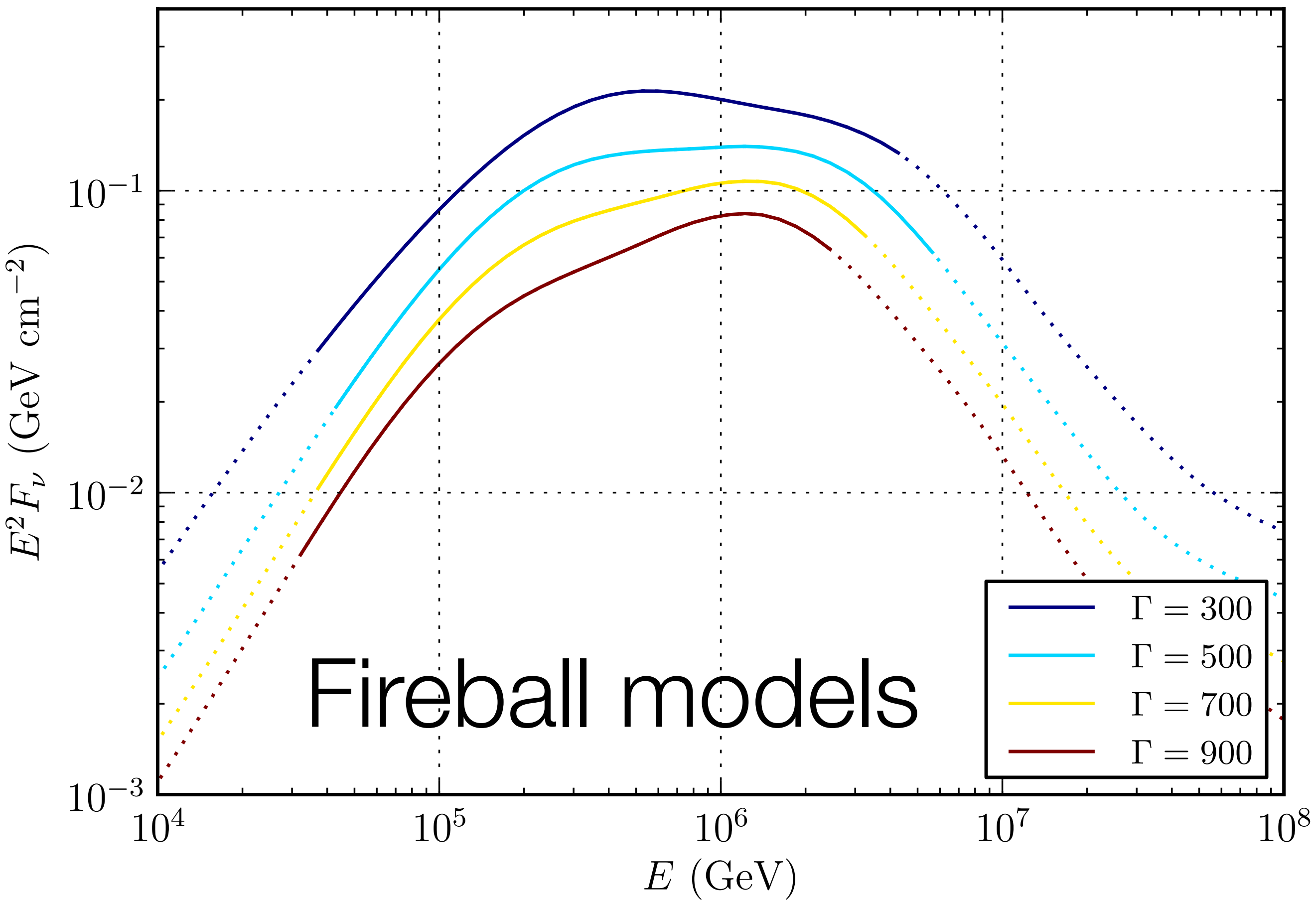
High-energy cascade events in 40-string configuration (2008-2009)

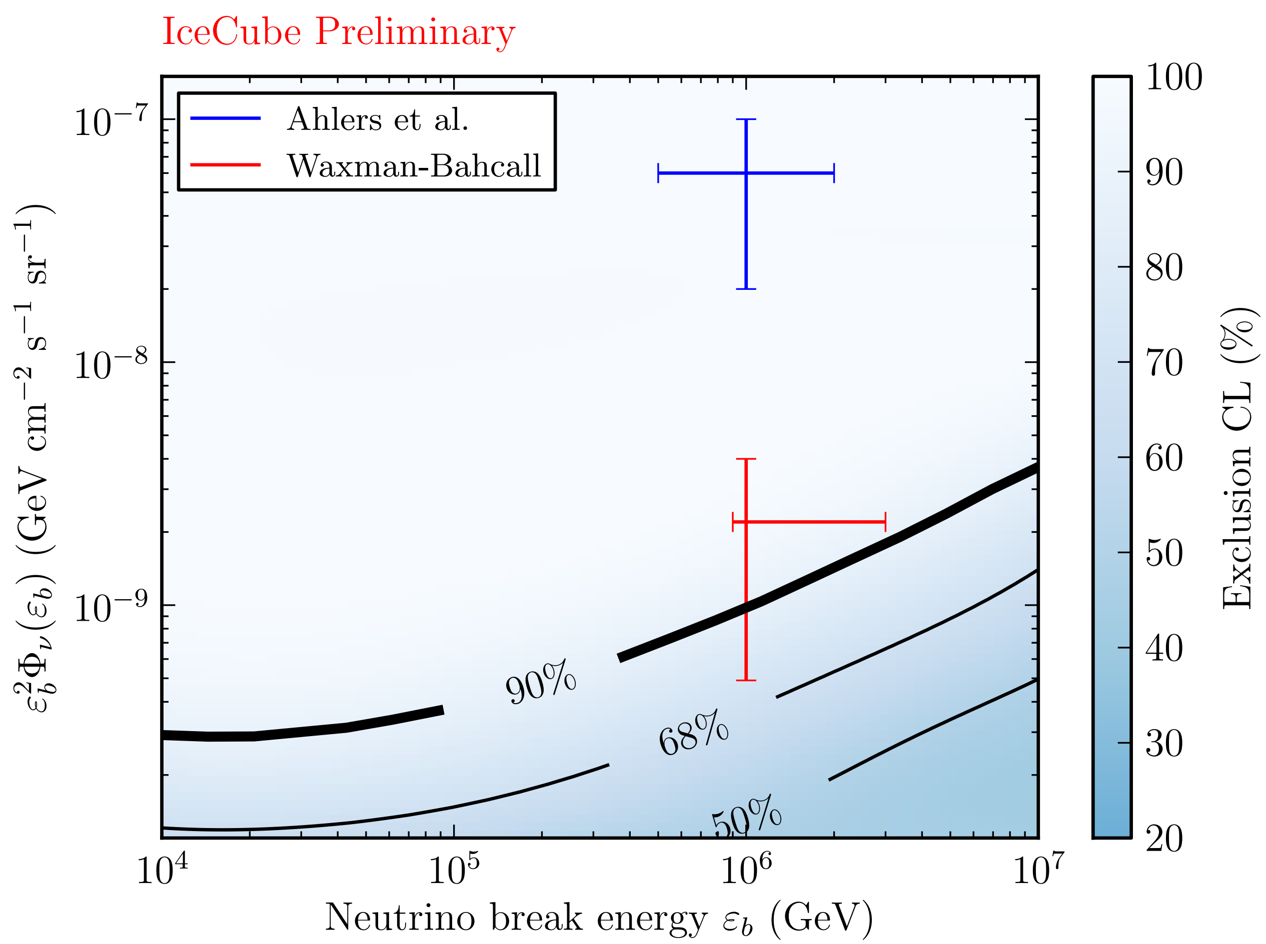


2.4 σ excess over atmospheric expectations

arXiv:1312.0104
(submitted to Phys.Rev.D)

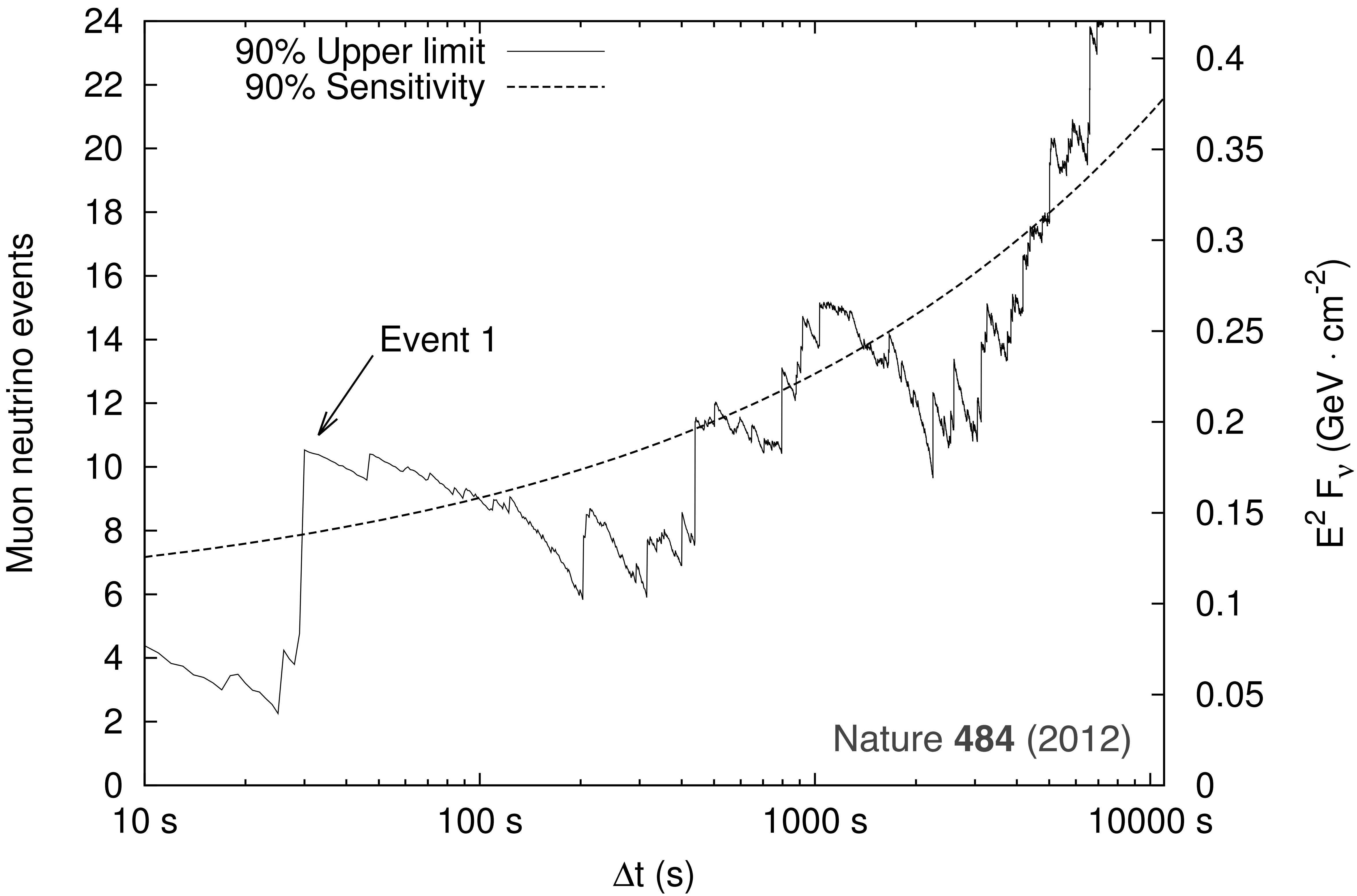
Constraints on neutrinos from GRBs



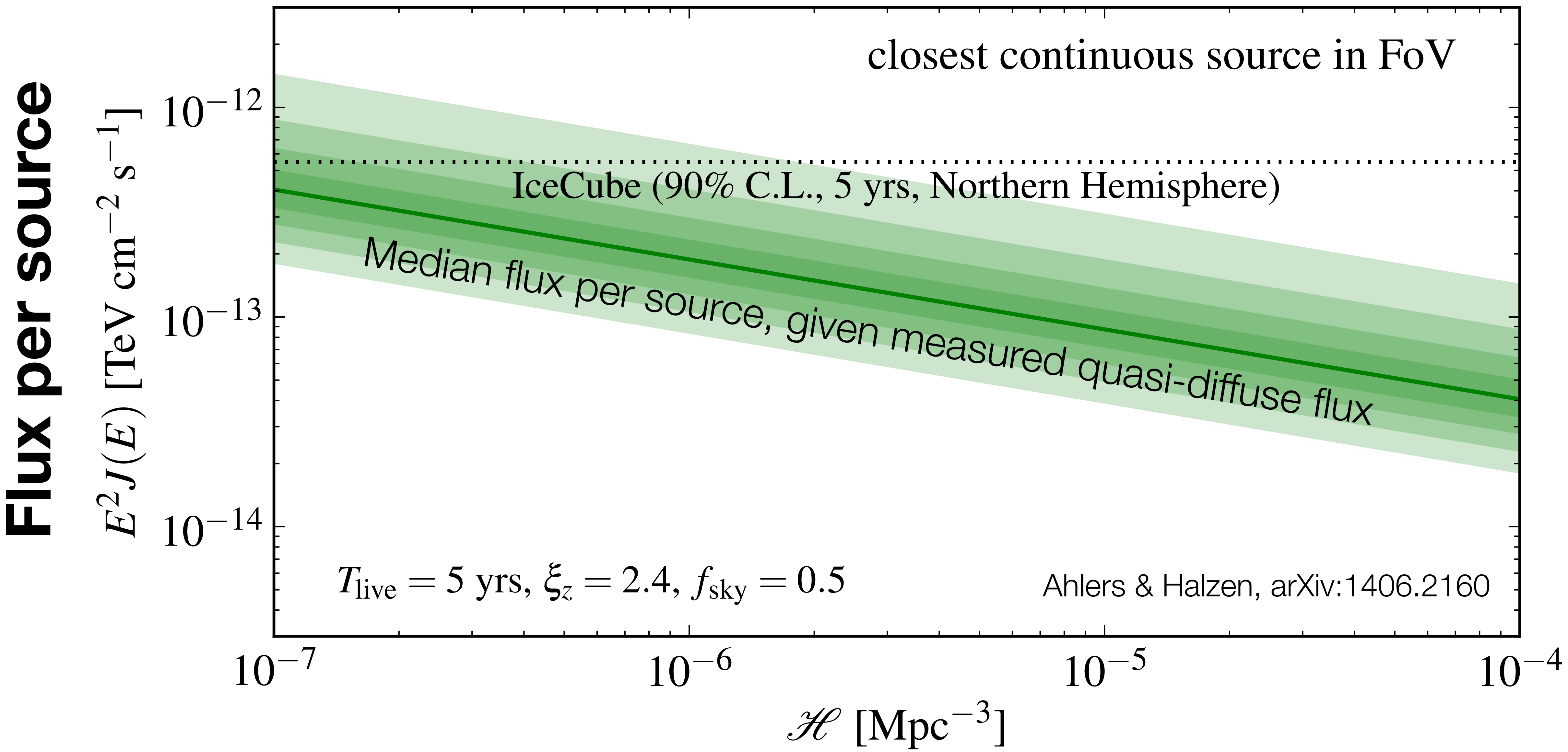


GRB analysis with 4 years of IceCube data (publication in prep)

Model-independent GRB constraints

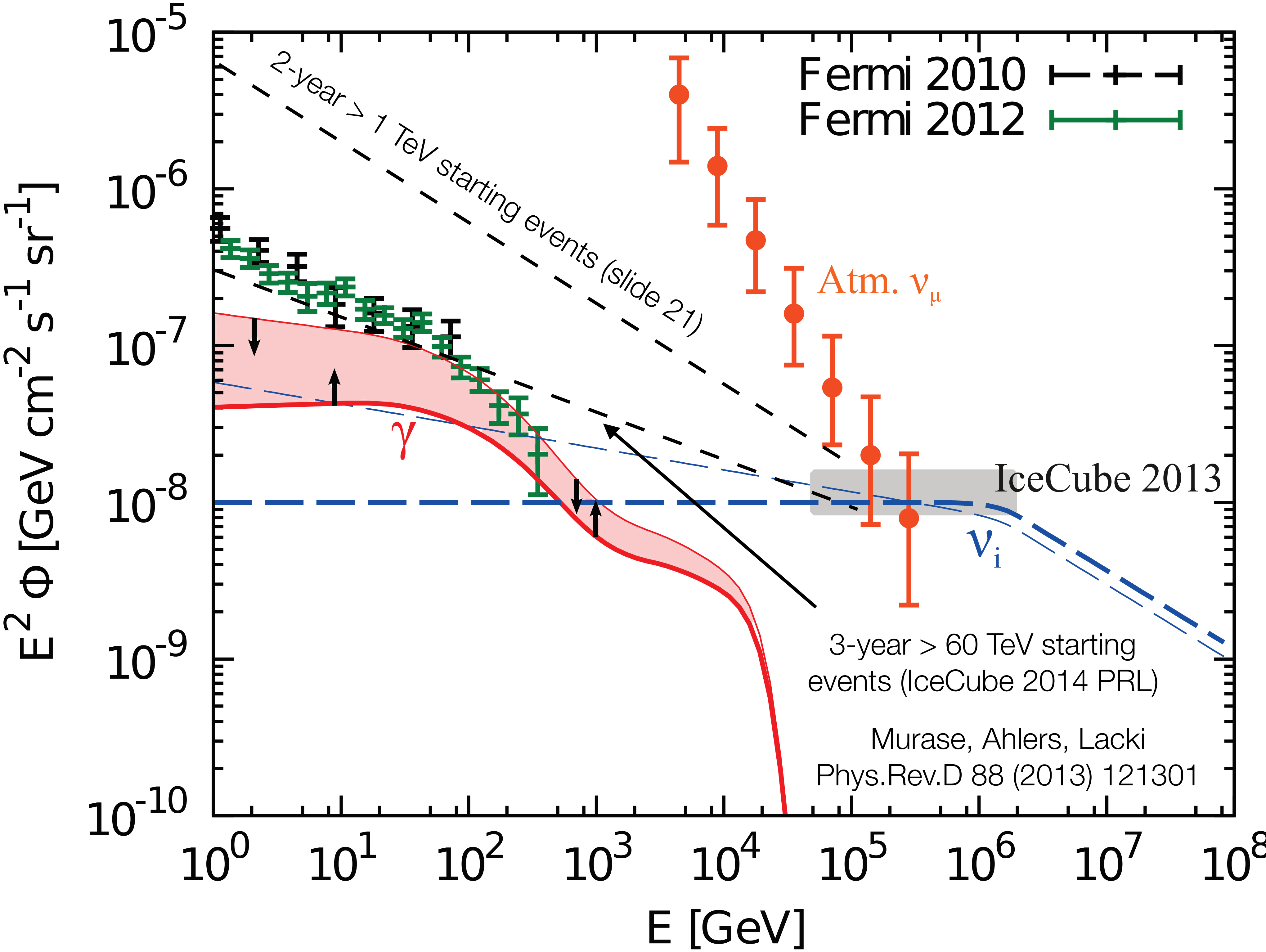


Constraints on fluxes from individual sources



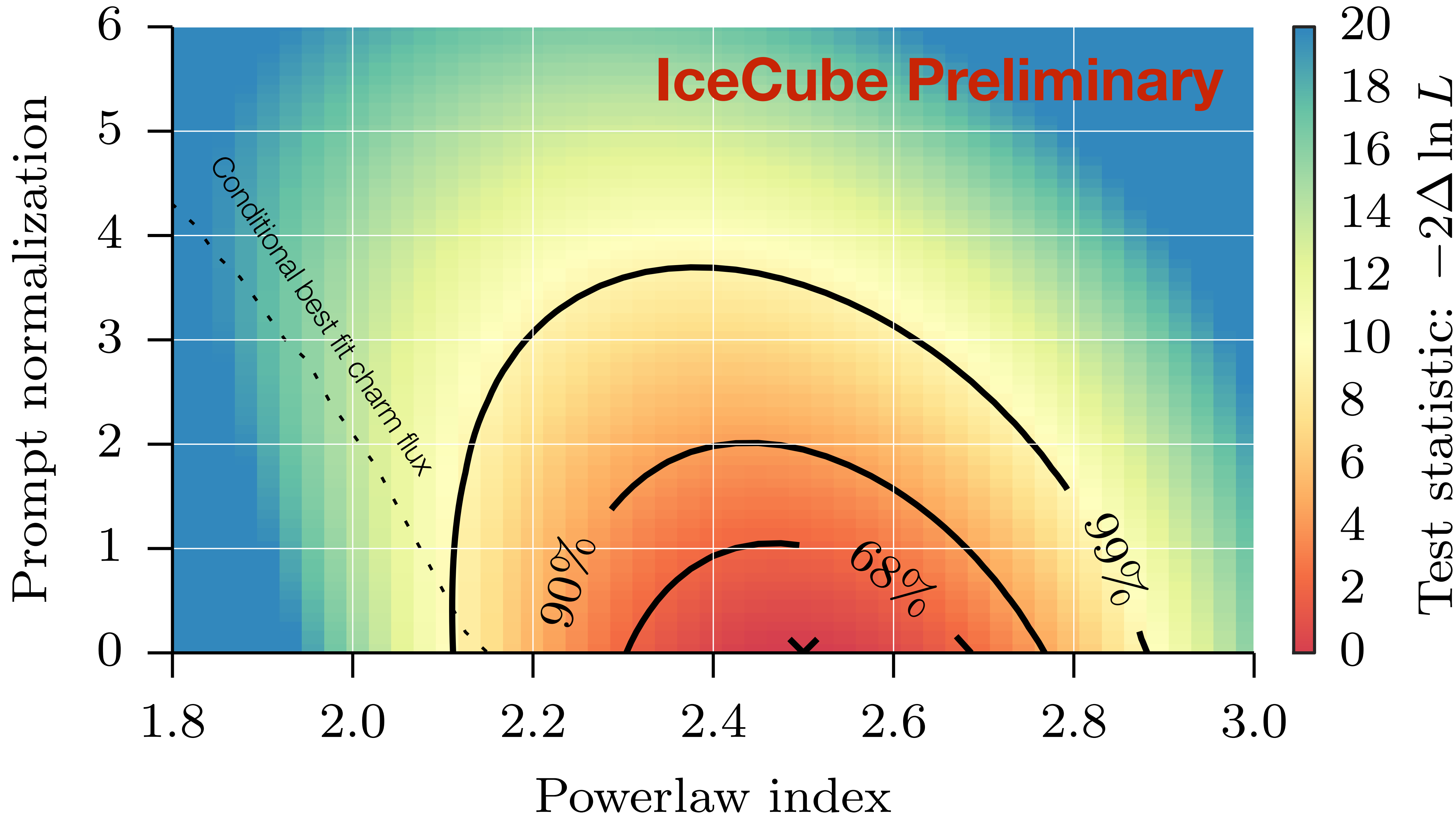
Source density

Relationship to extragalactic diffuse gamma rays

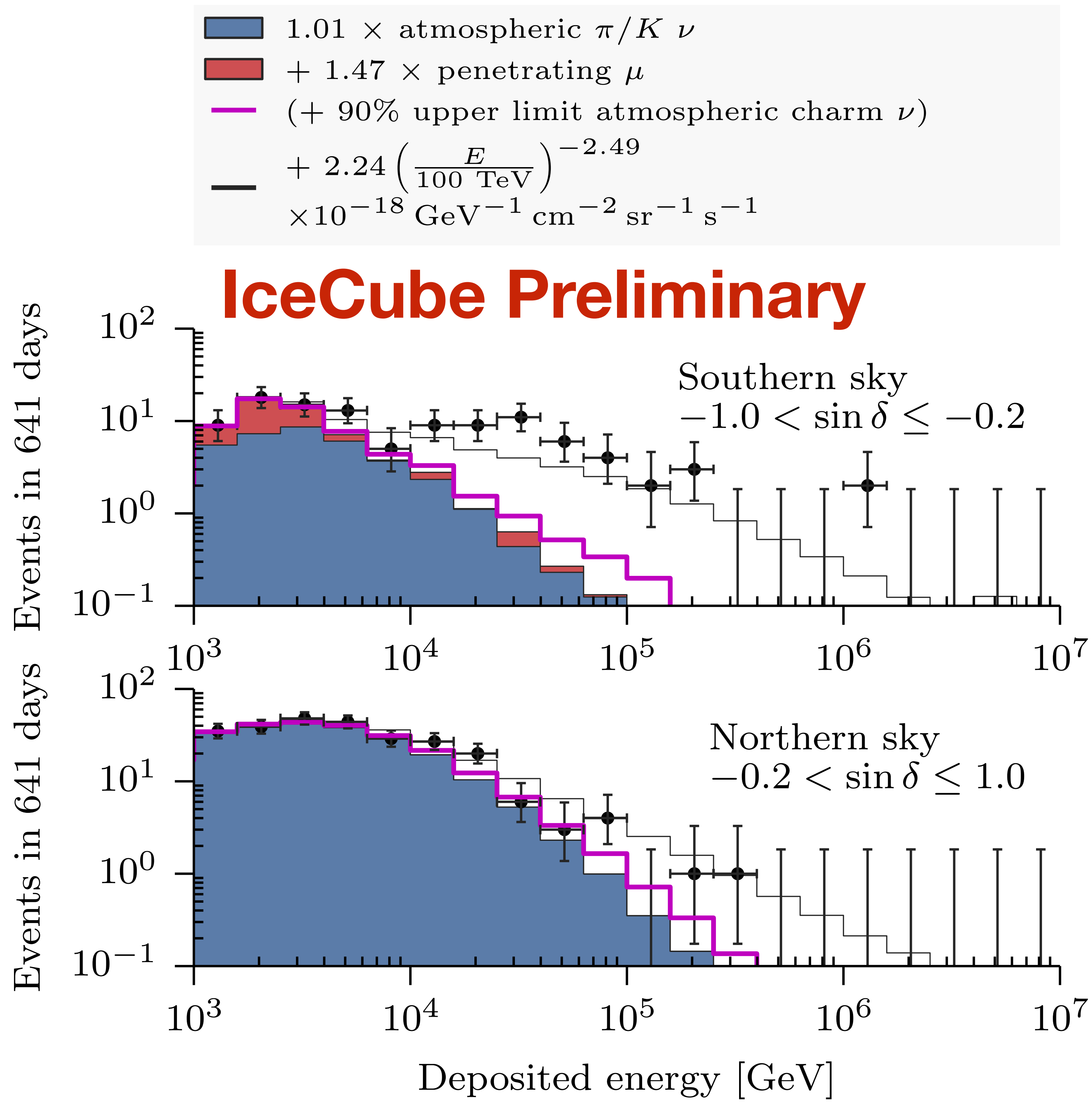


Interpret with care: Fermi data points are extra-galactic only

Correlations with astrophysical index

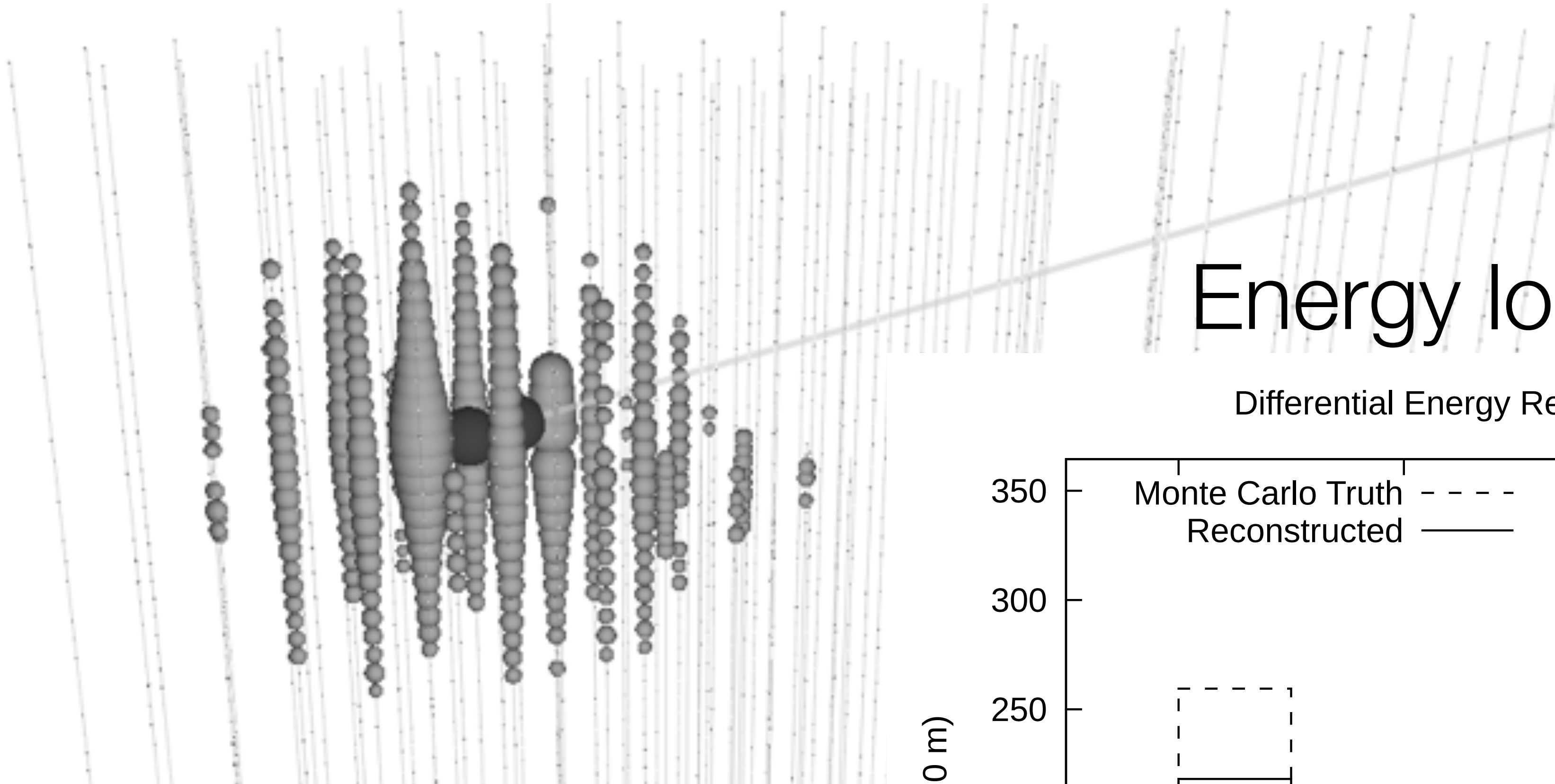


Energy spectrum with charm upper limit

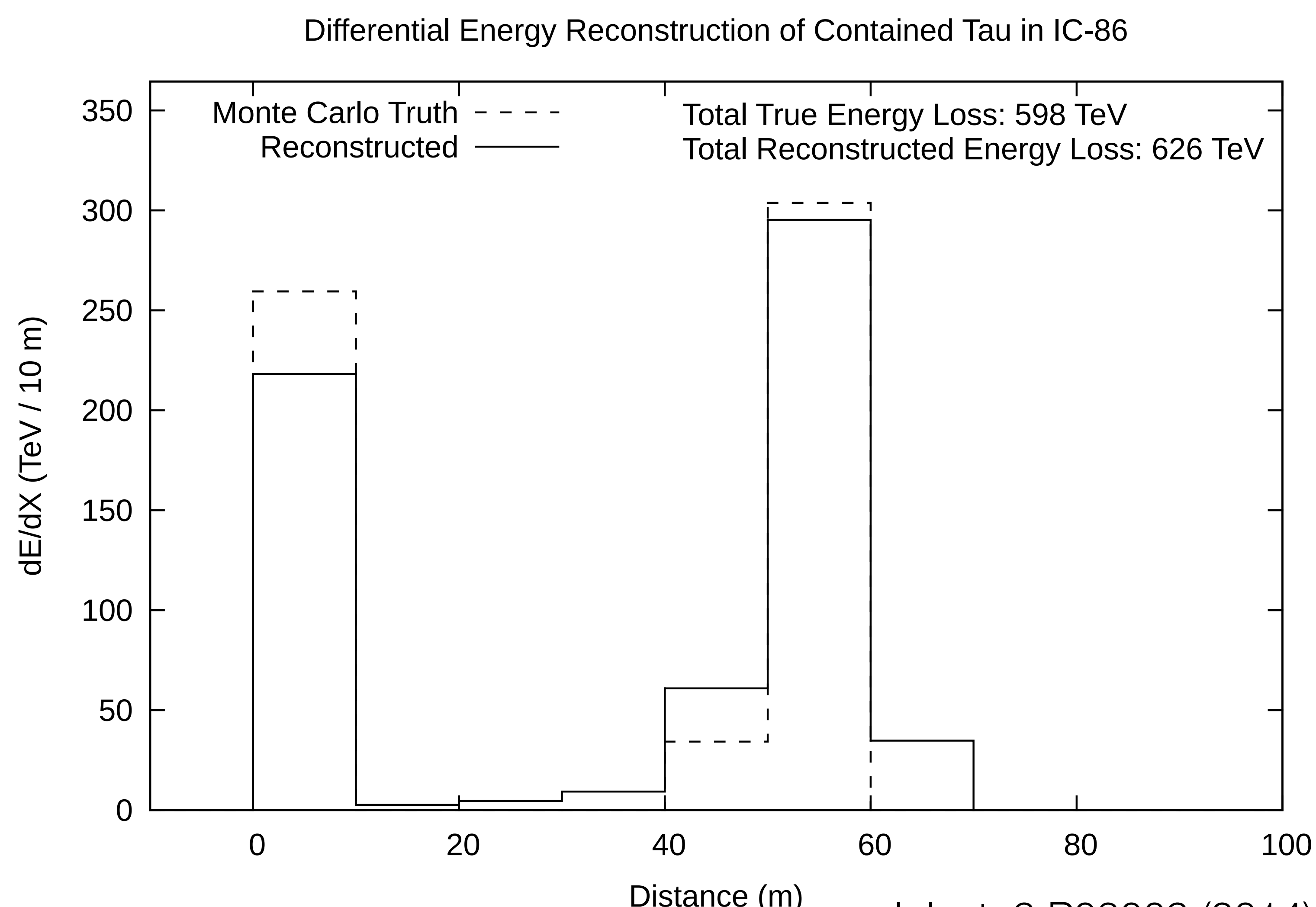


τ double-bang reconstruction

Simulated 1 PeV CC ν_τ interaction: τ decays after 50 m



Energy loss reconstruction

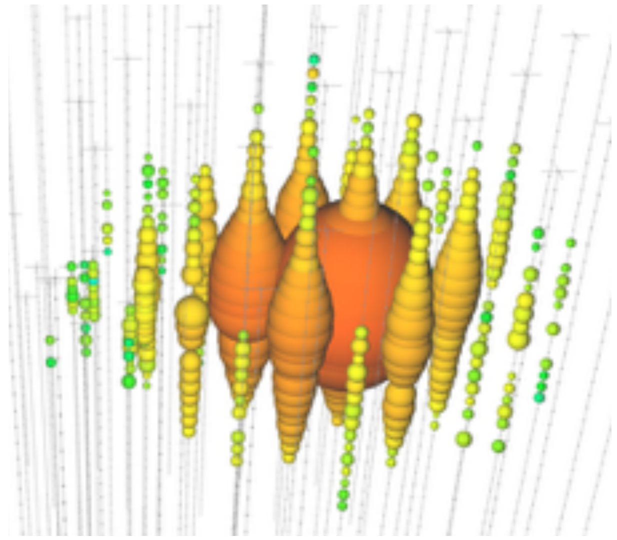


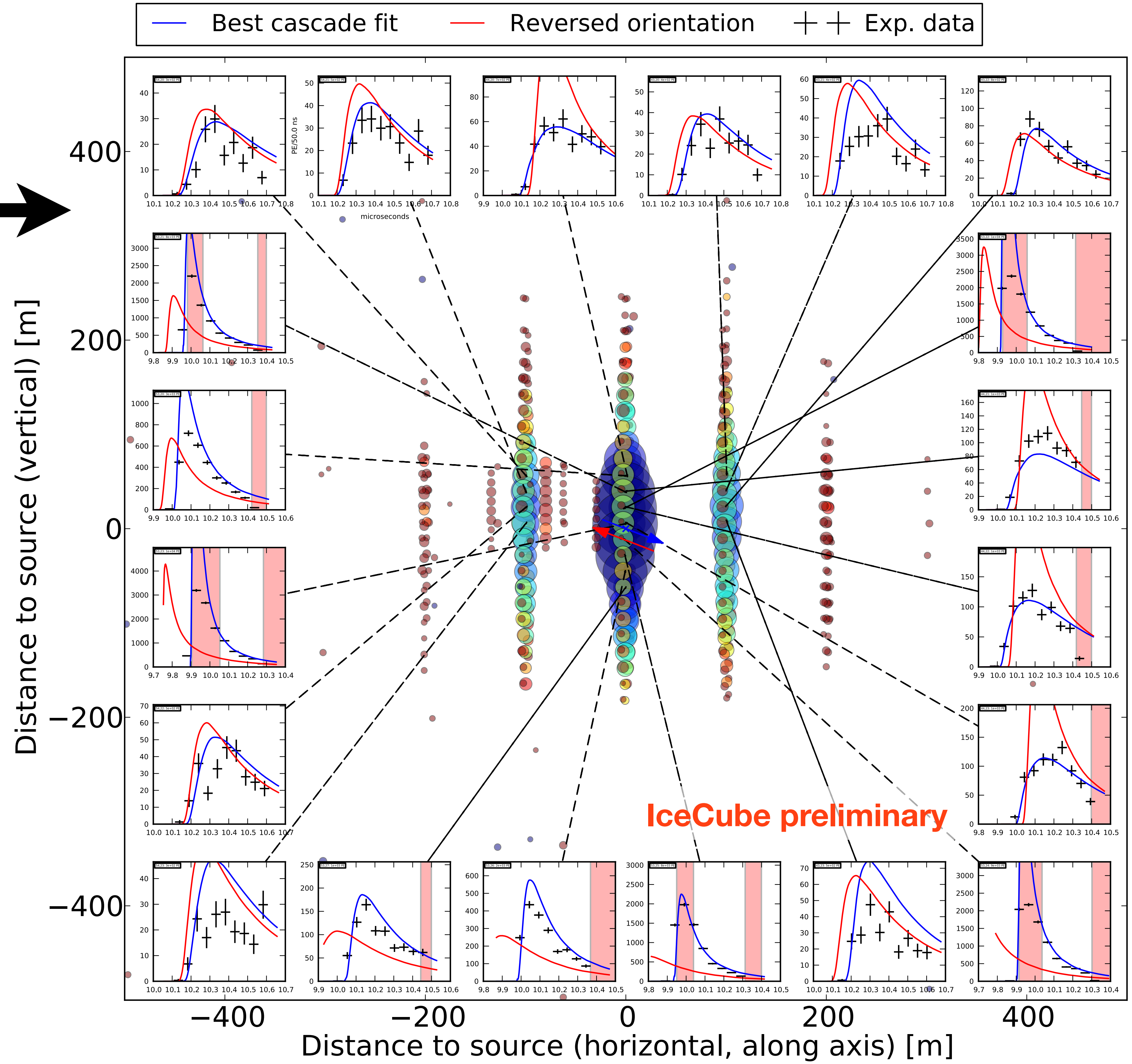
J. Inst. 9:P03009 (2014)

Resolution depends strongly on interaction geometry.

No τ events observed to date.

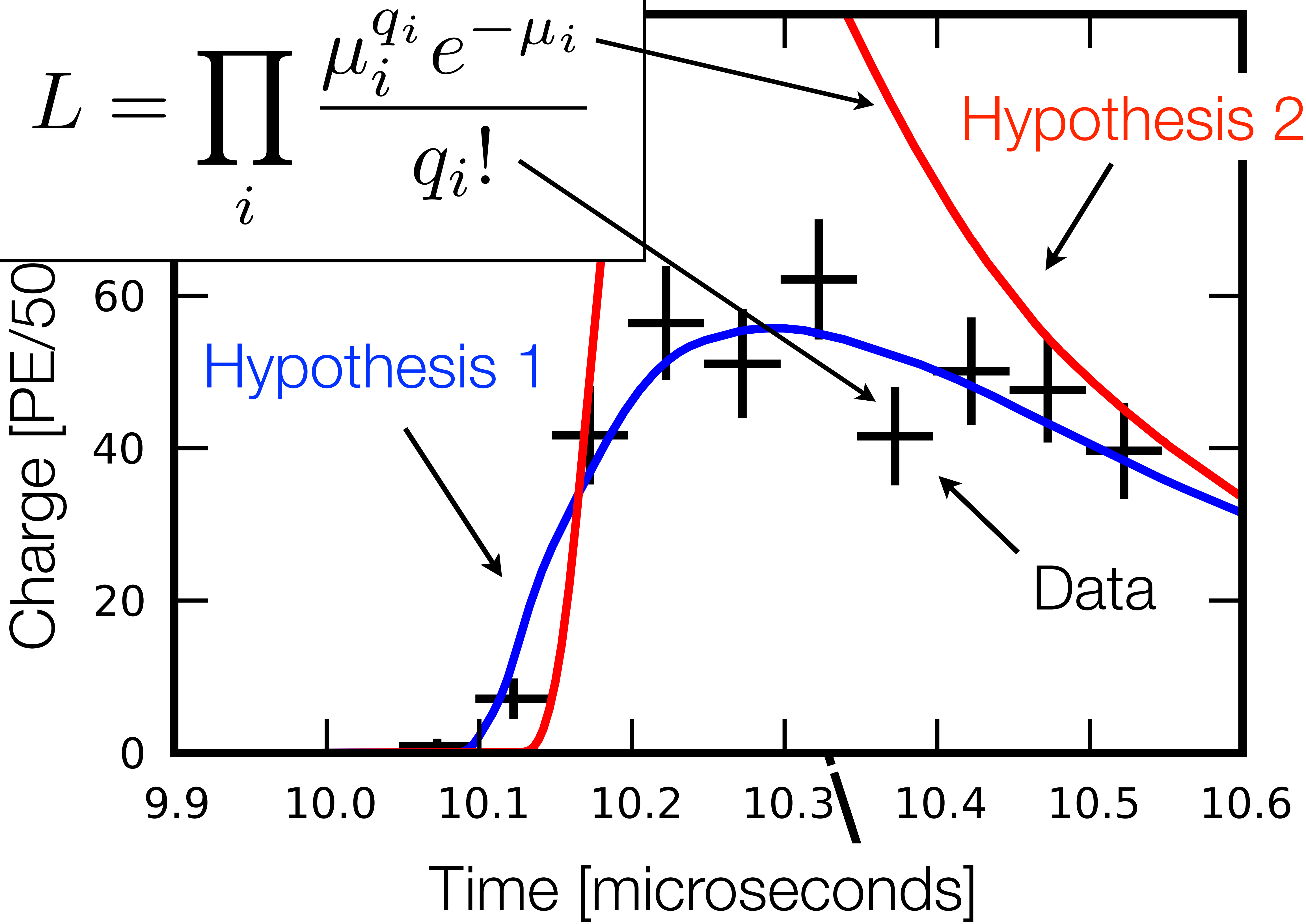
Cascade reconstruction: hypothesis and data



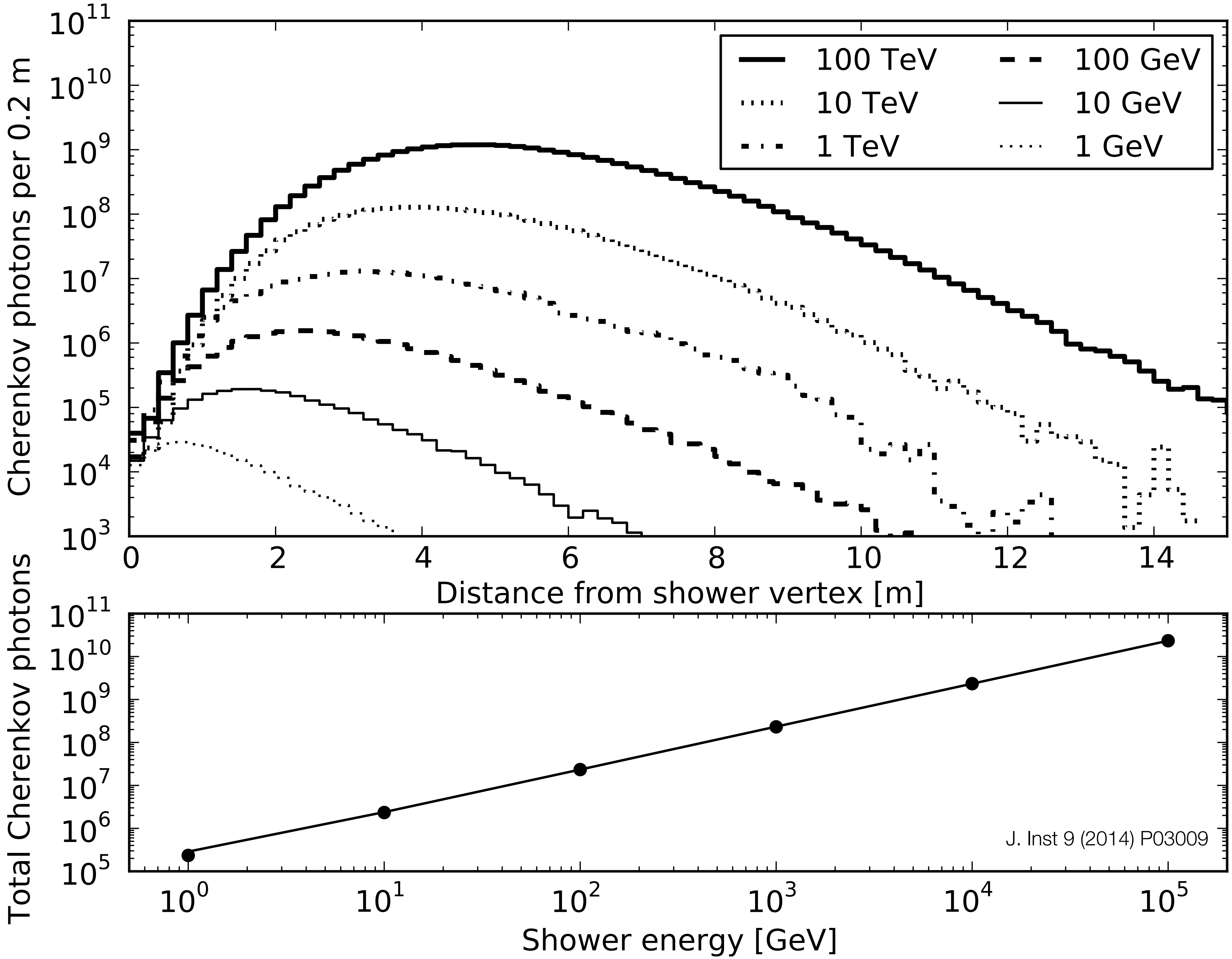


Cascade reconstruction: likelihood fit

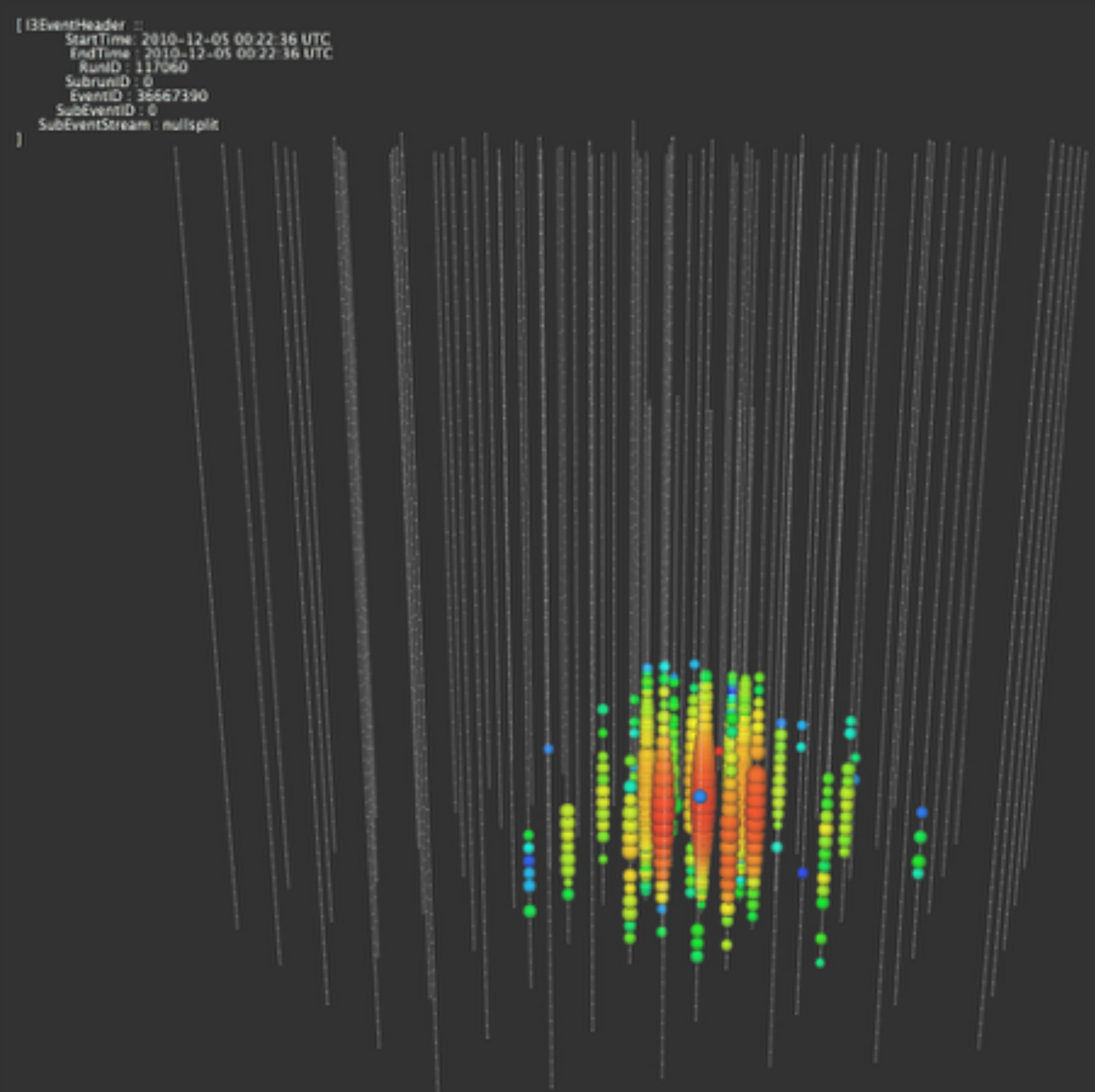
$$L = \prod_i \frac{\mu_i^{q_i} e^{-\mu_i}}{q_i!}$$



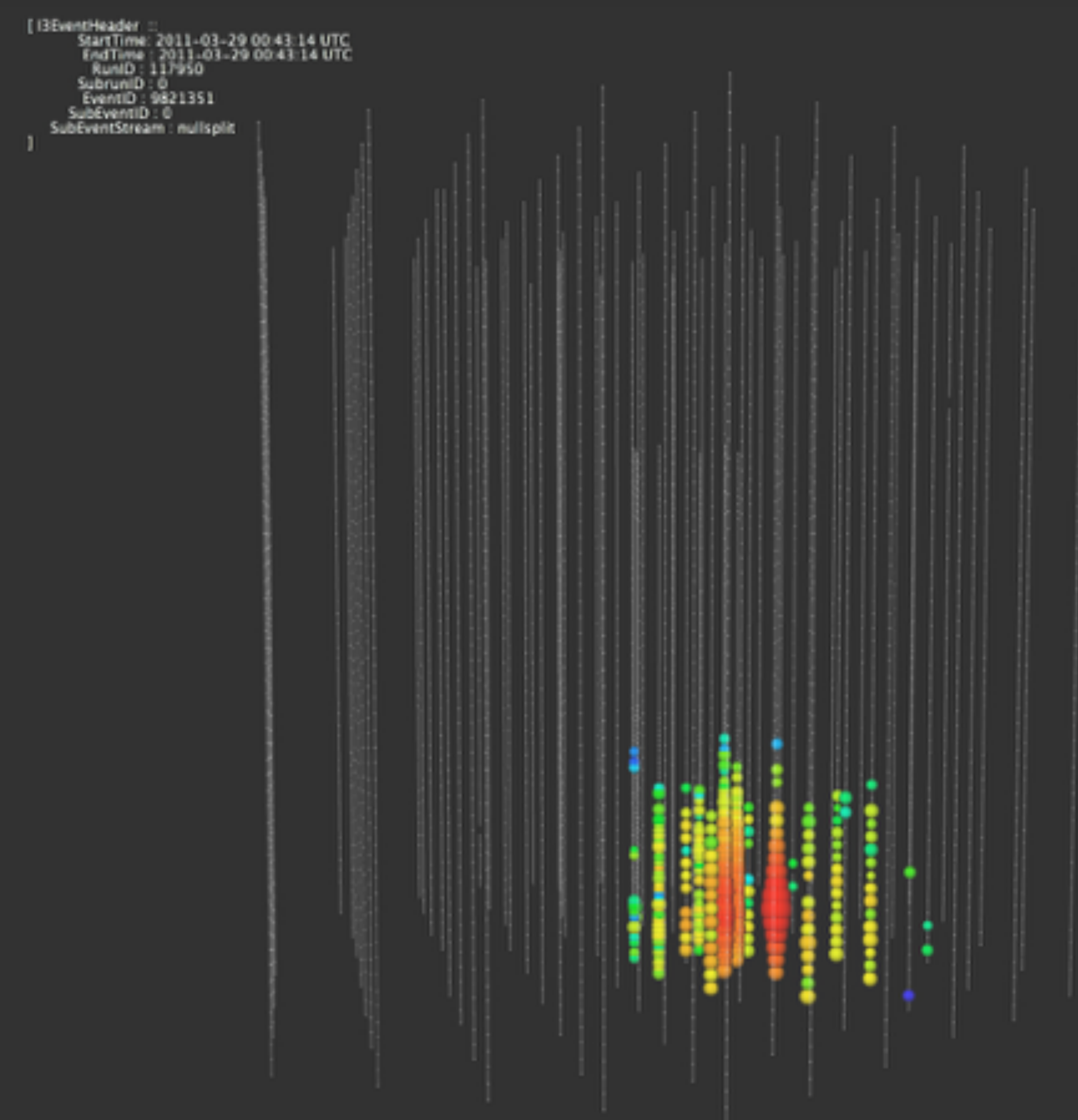
Cascade reconstruction: energy



Cascades

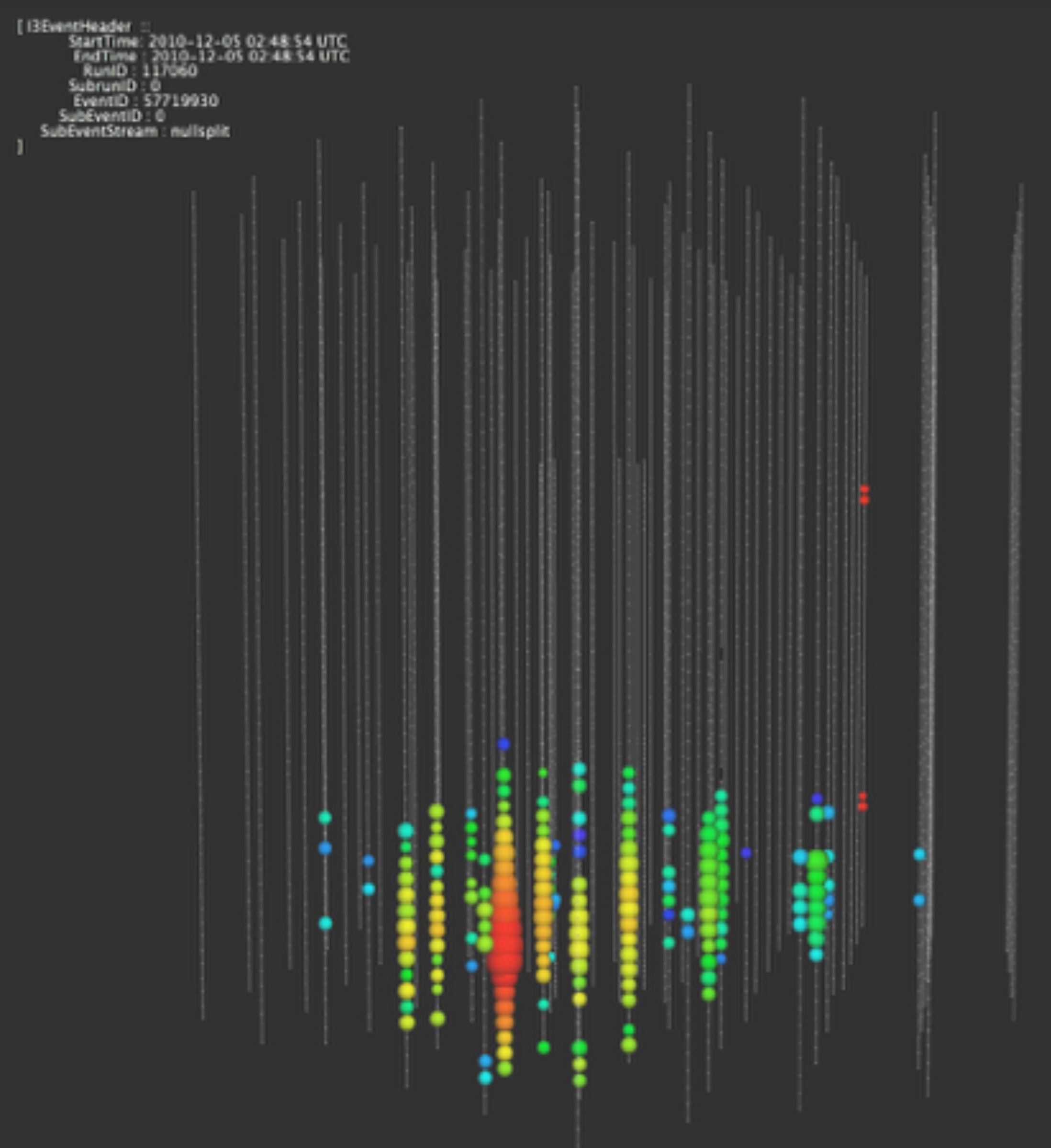


~ 20 TeV deposited

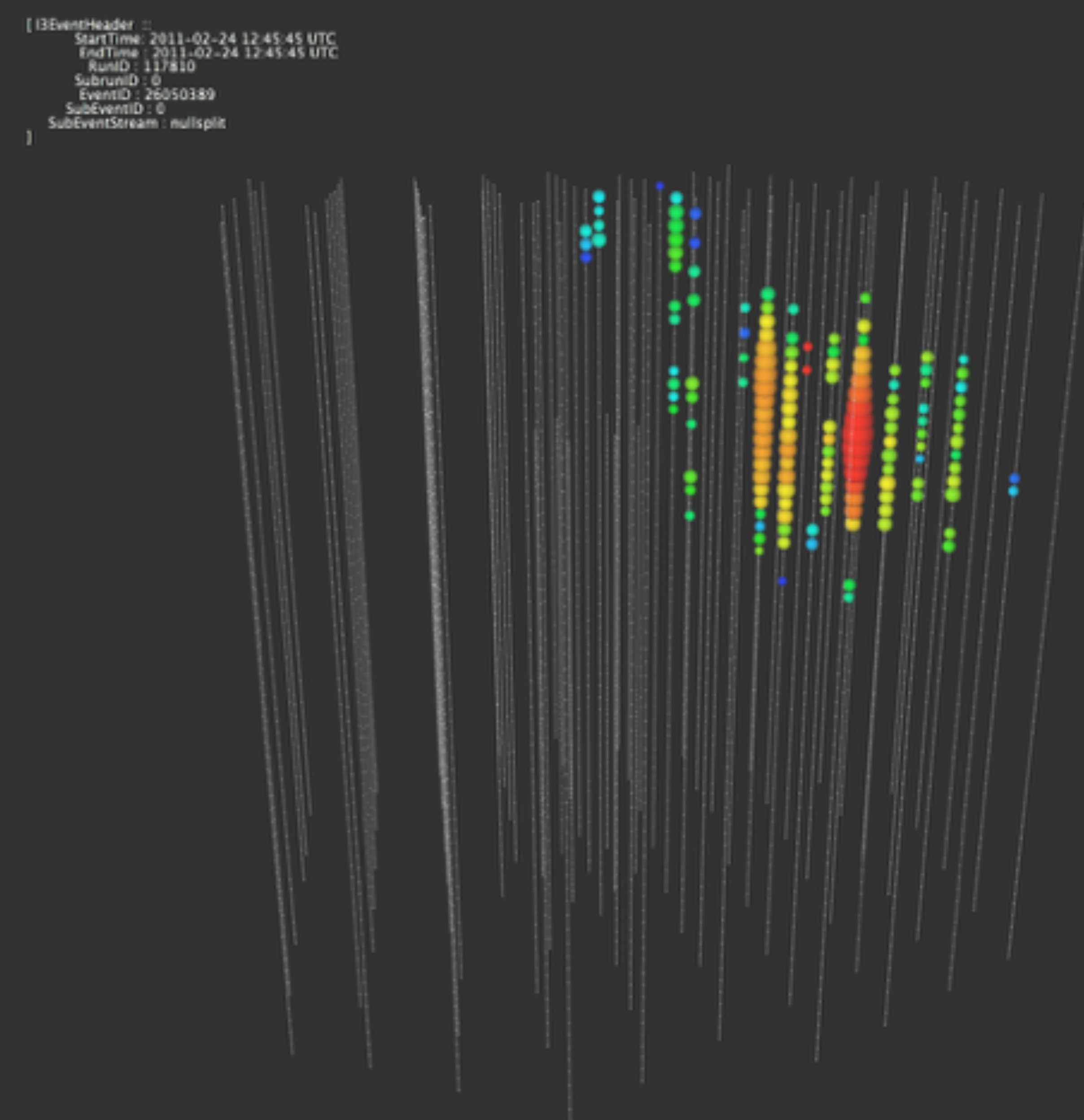


~ 13 TeV deposited

Starting tracks

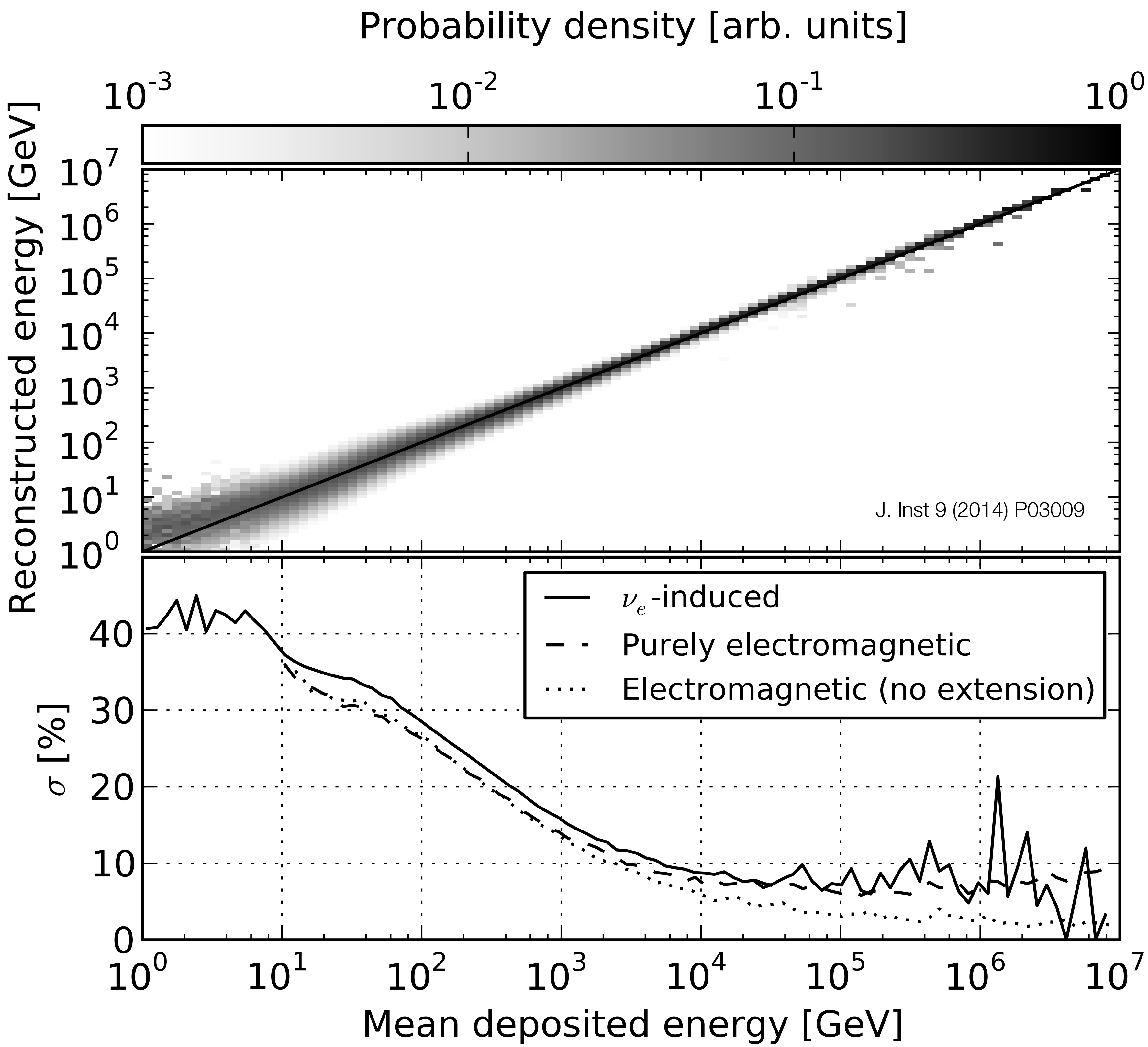


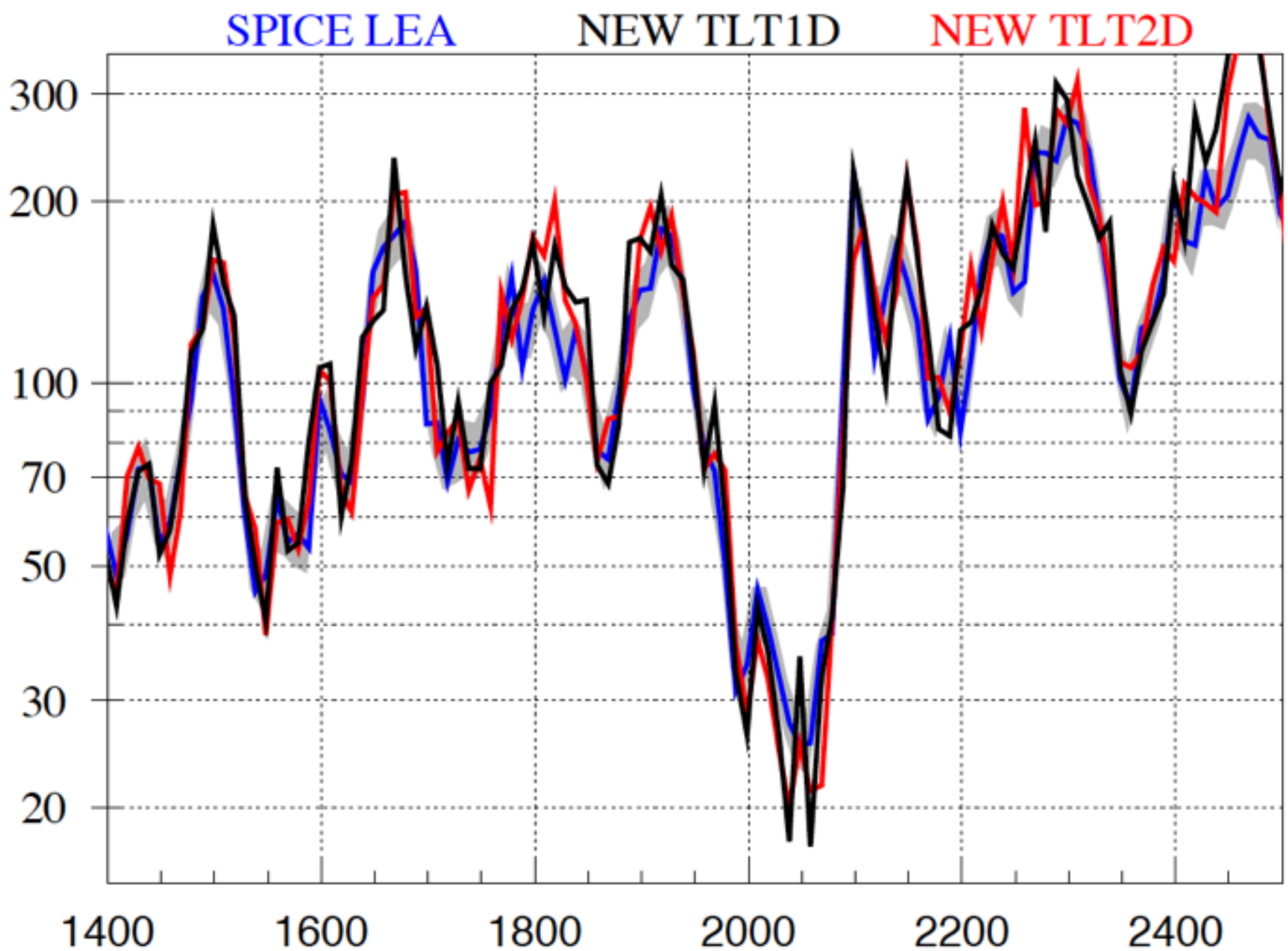
~ 18 TeV deposited



~ 100 TeV deposited

Deposited-energy resolution for showers in IceCube





λ_a(400 nm) [m] vs. depth [m]