Astrophysical neutrinos in IceCube

Jakob van Santen

TeVPA 2015, Kashiwa

What do we know about the cosmic rays?

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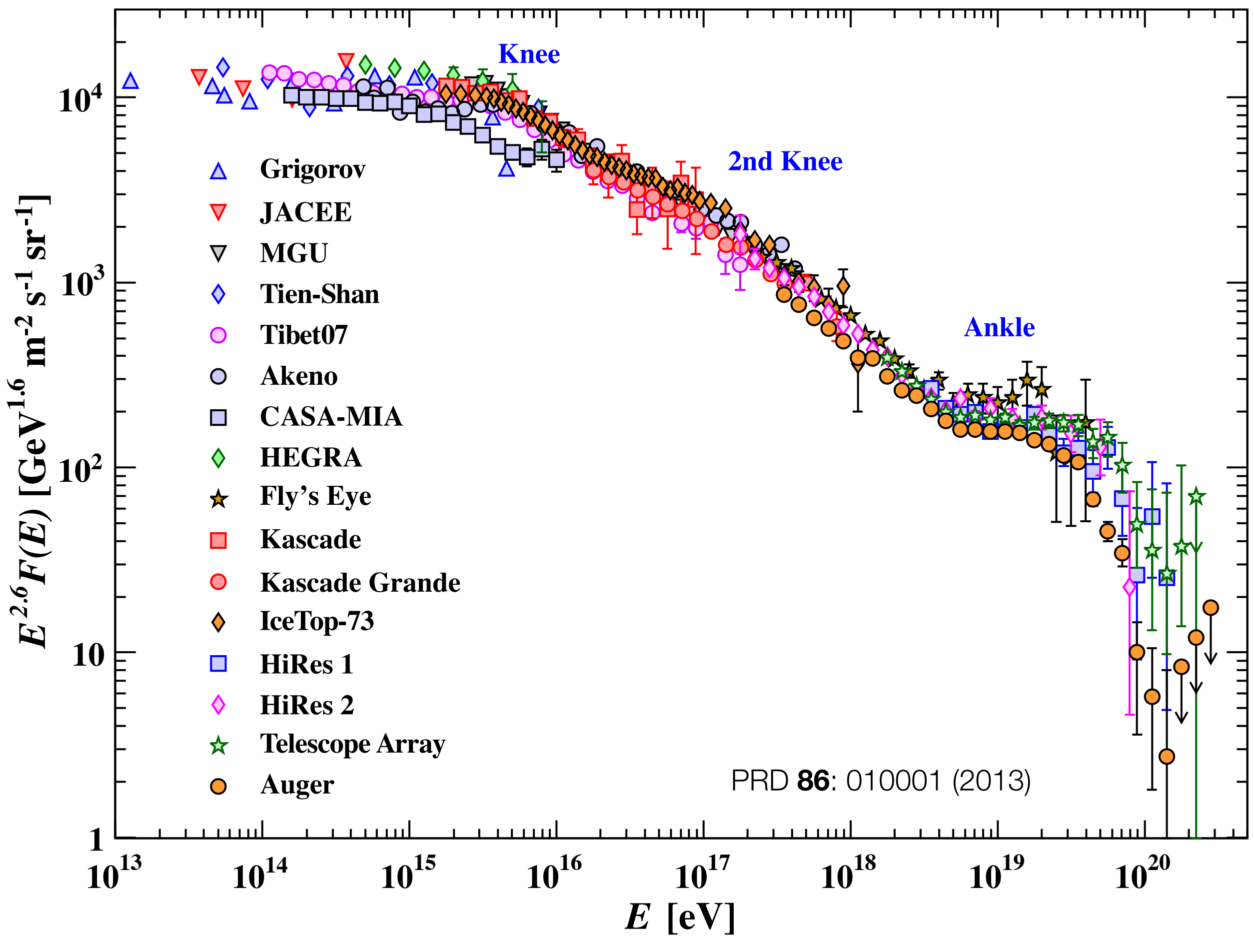
We know their energy spectrum over 11 orders of magnitude (and chemical composition up to 100 TeV)



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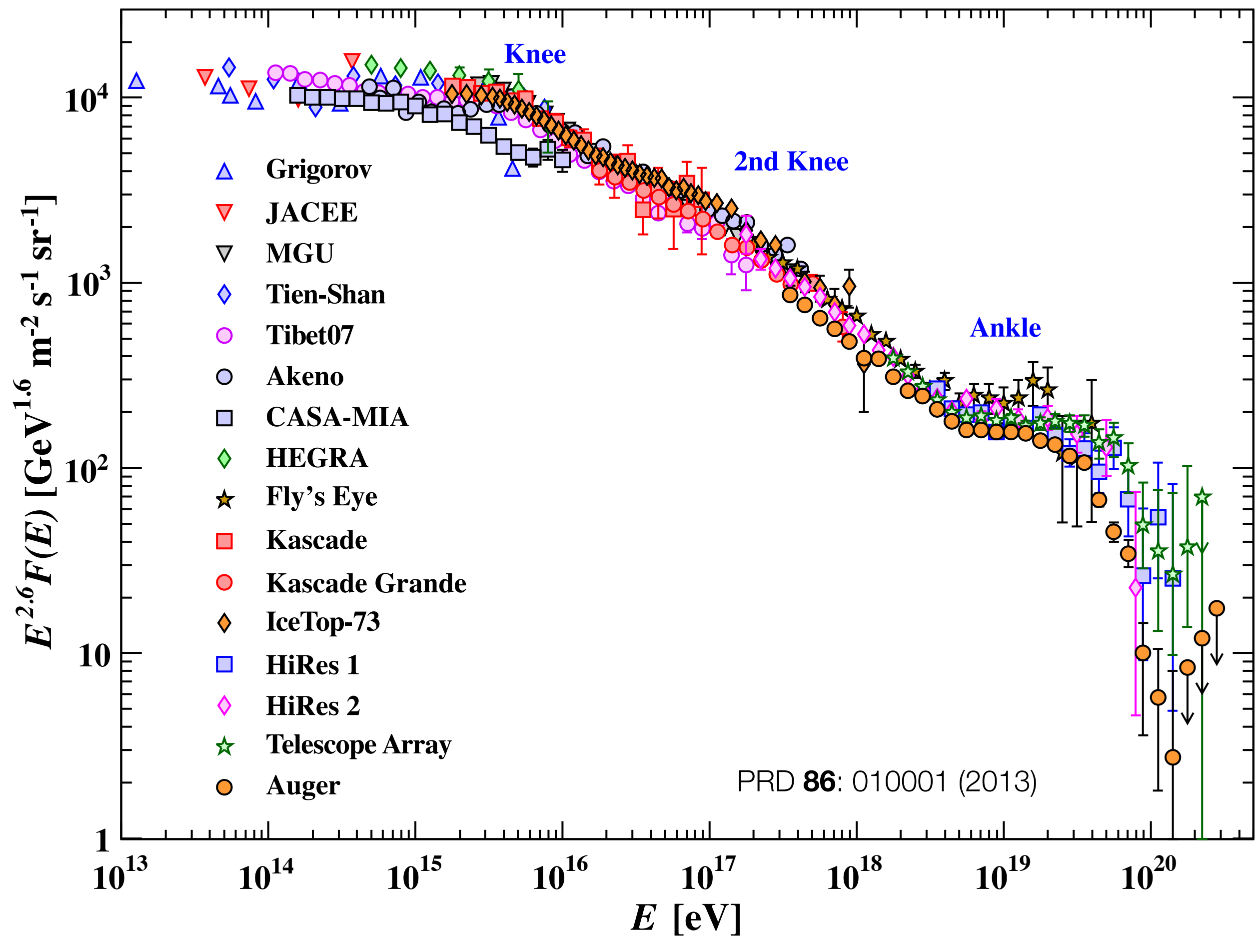
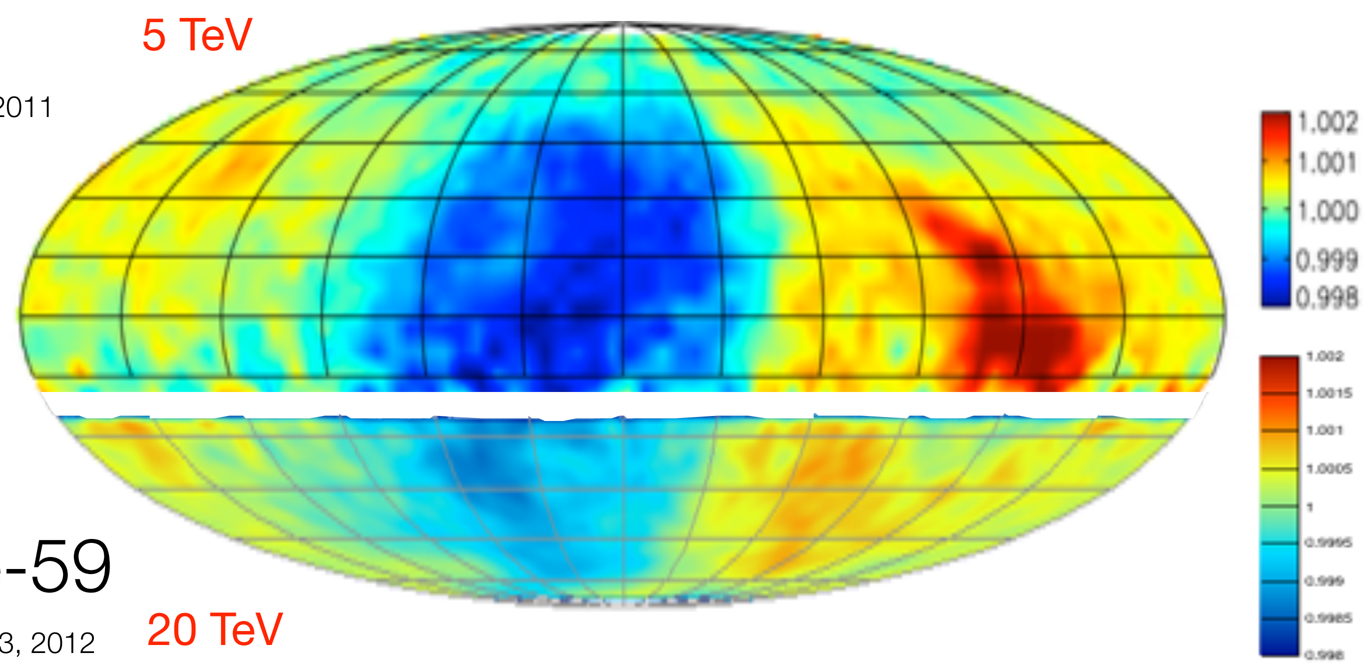


But not where they come from: arrival directions are isotropic to within 1%

Tibet-III

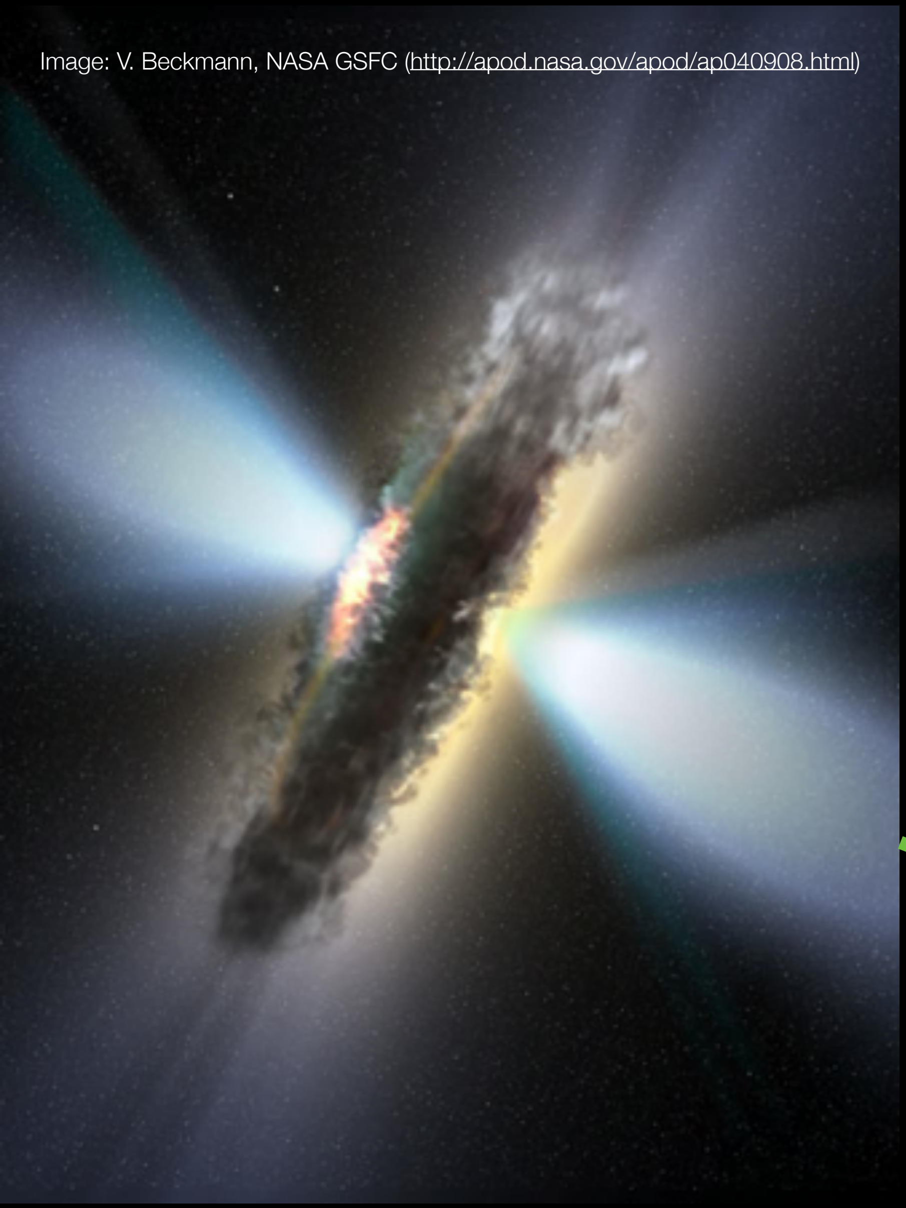
Amenomori et al., ICRC 2011



IceCube-59

Abbasi et al., ApJ, **746**, 33, 2012

Multi-messenger astrophysics with neutrinos



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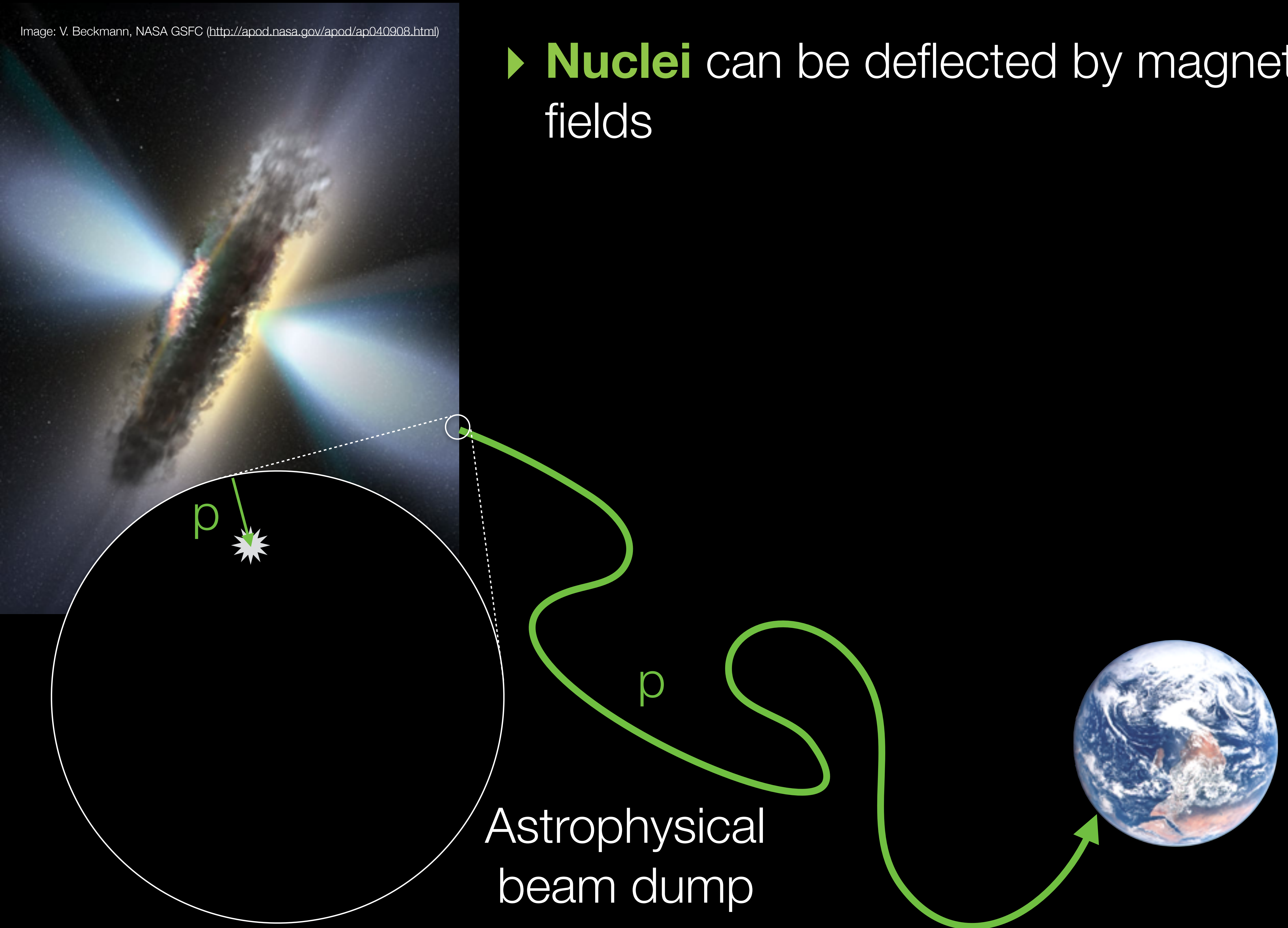

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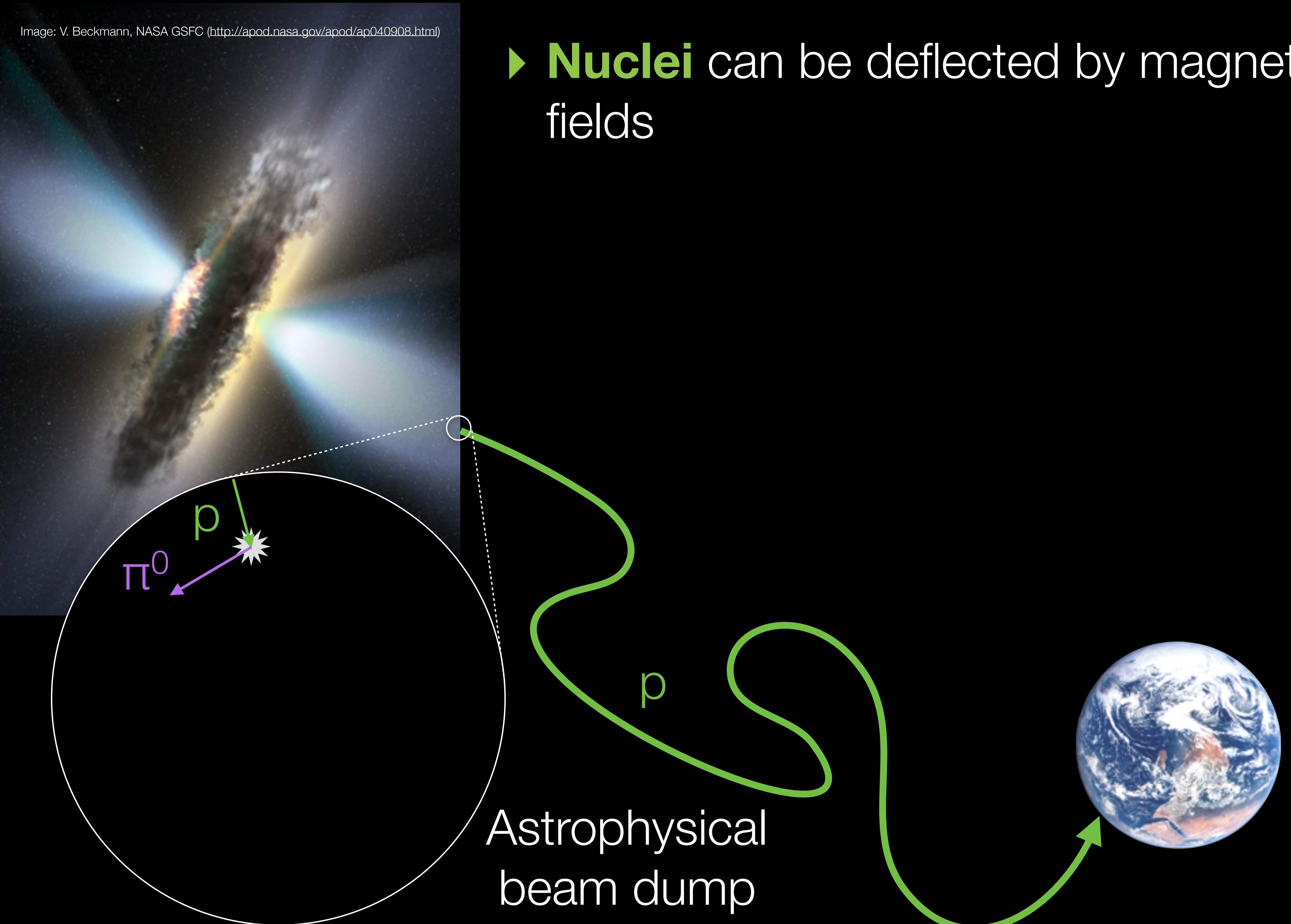

Multi-messenger astrophysics with neutrinos

- **Nuclei** can be deflected by magnetic fields
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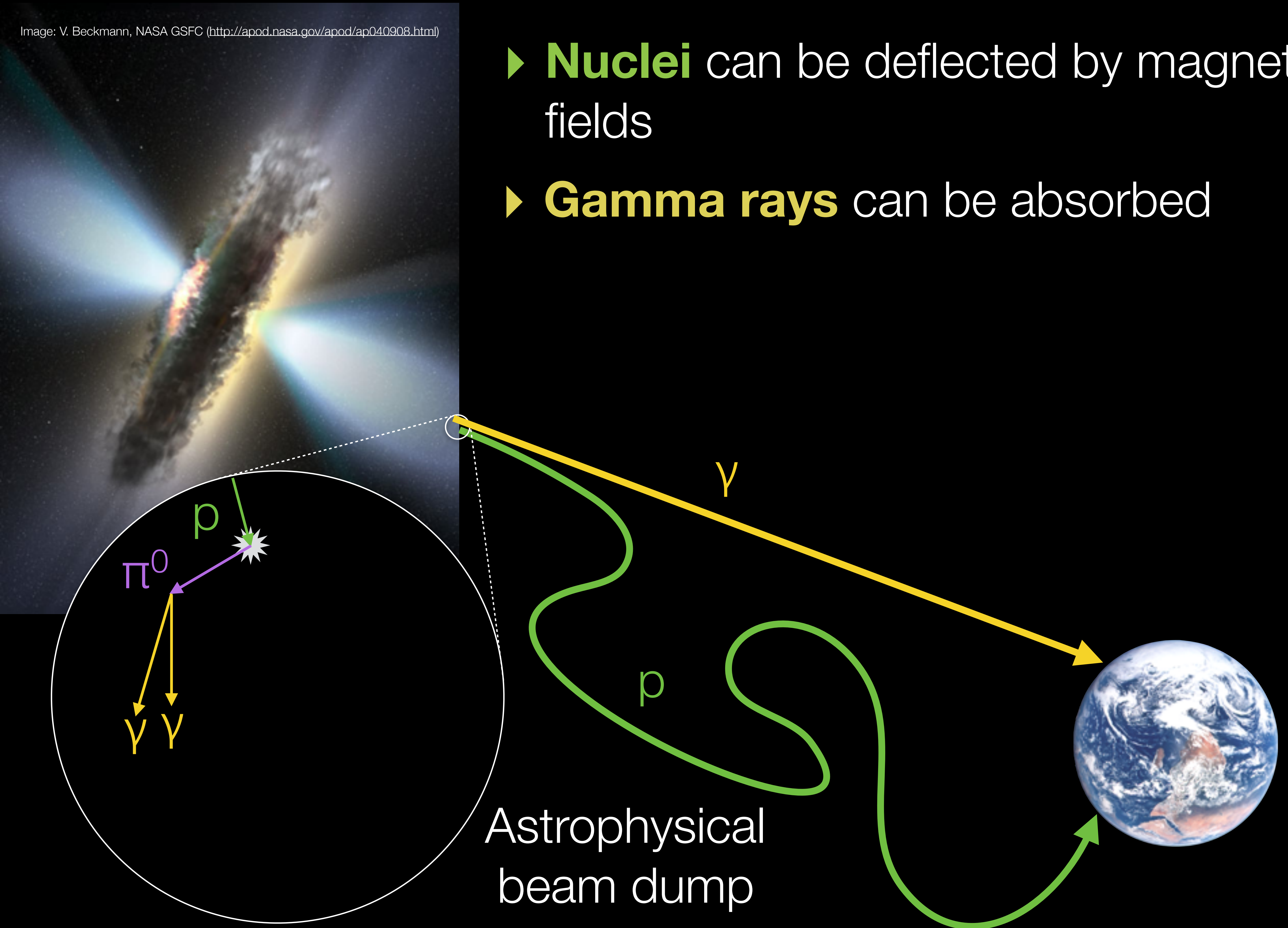

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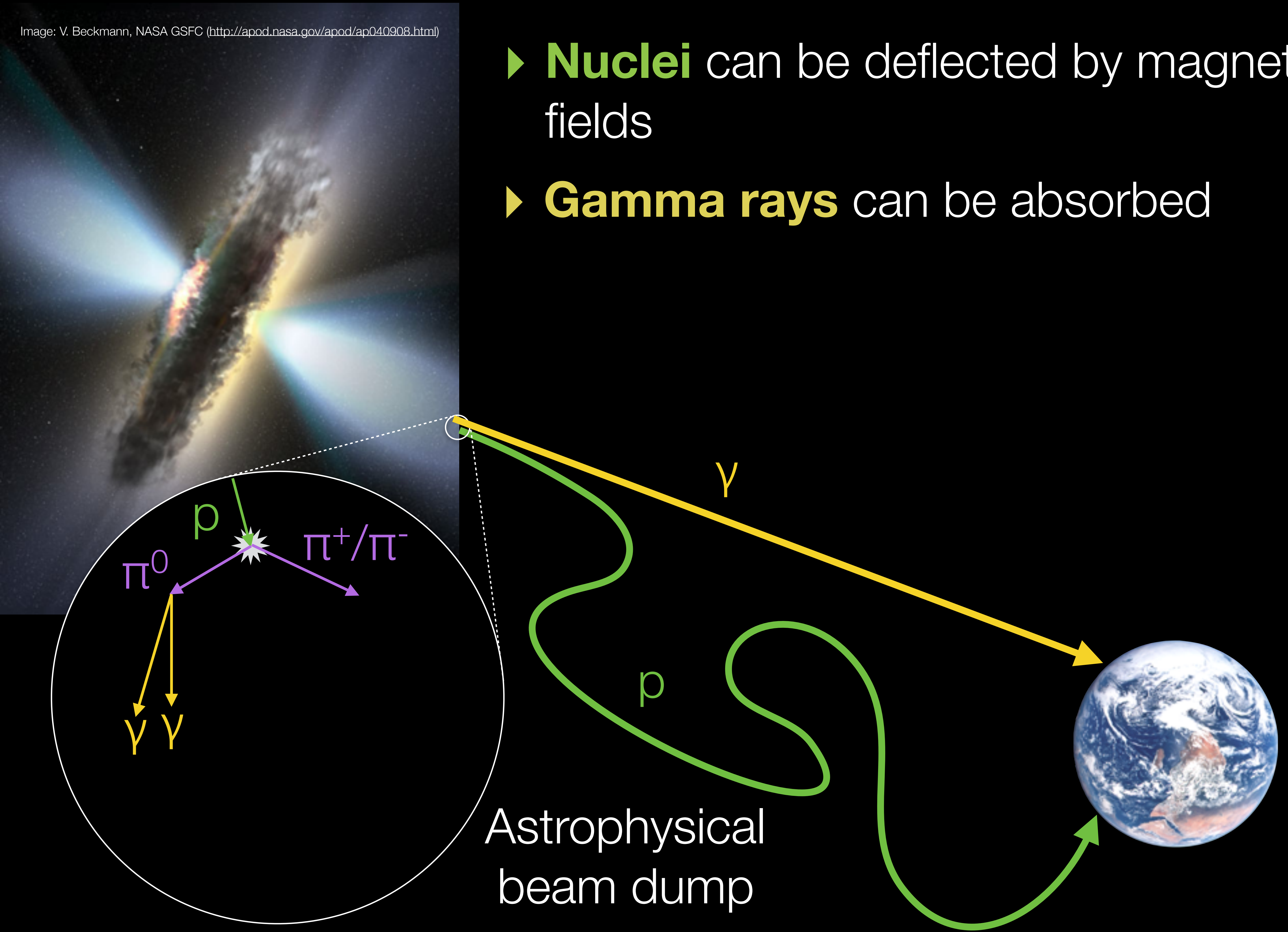

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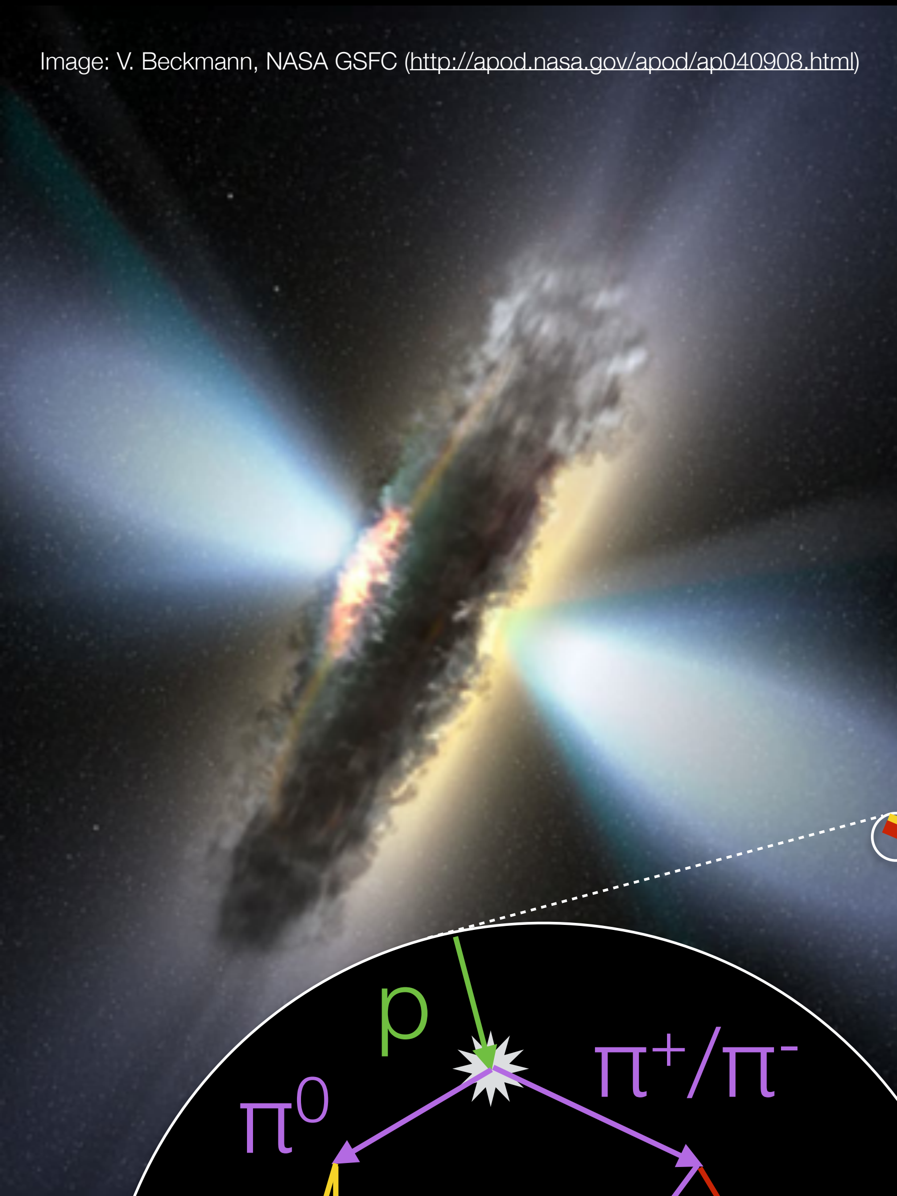
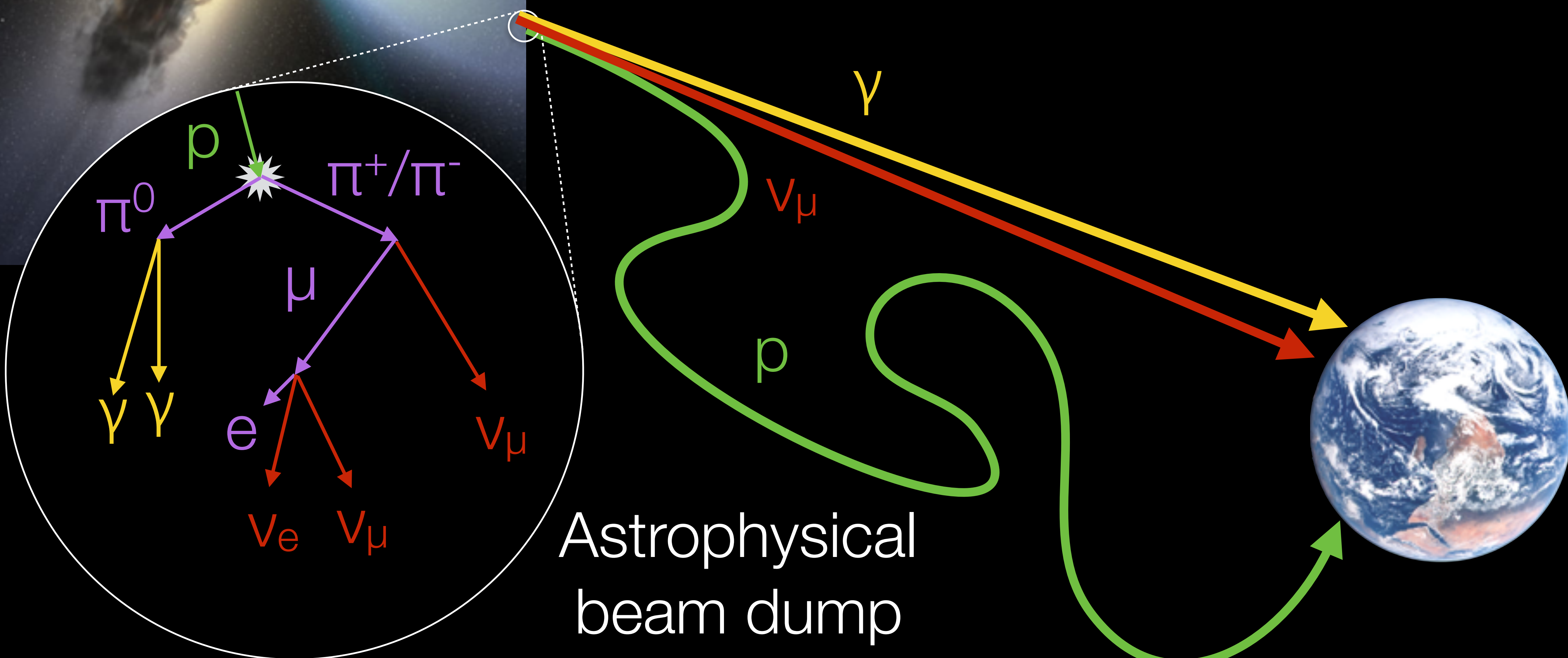
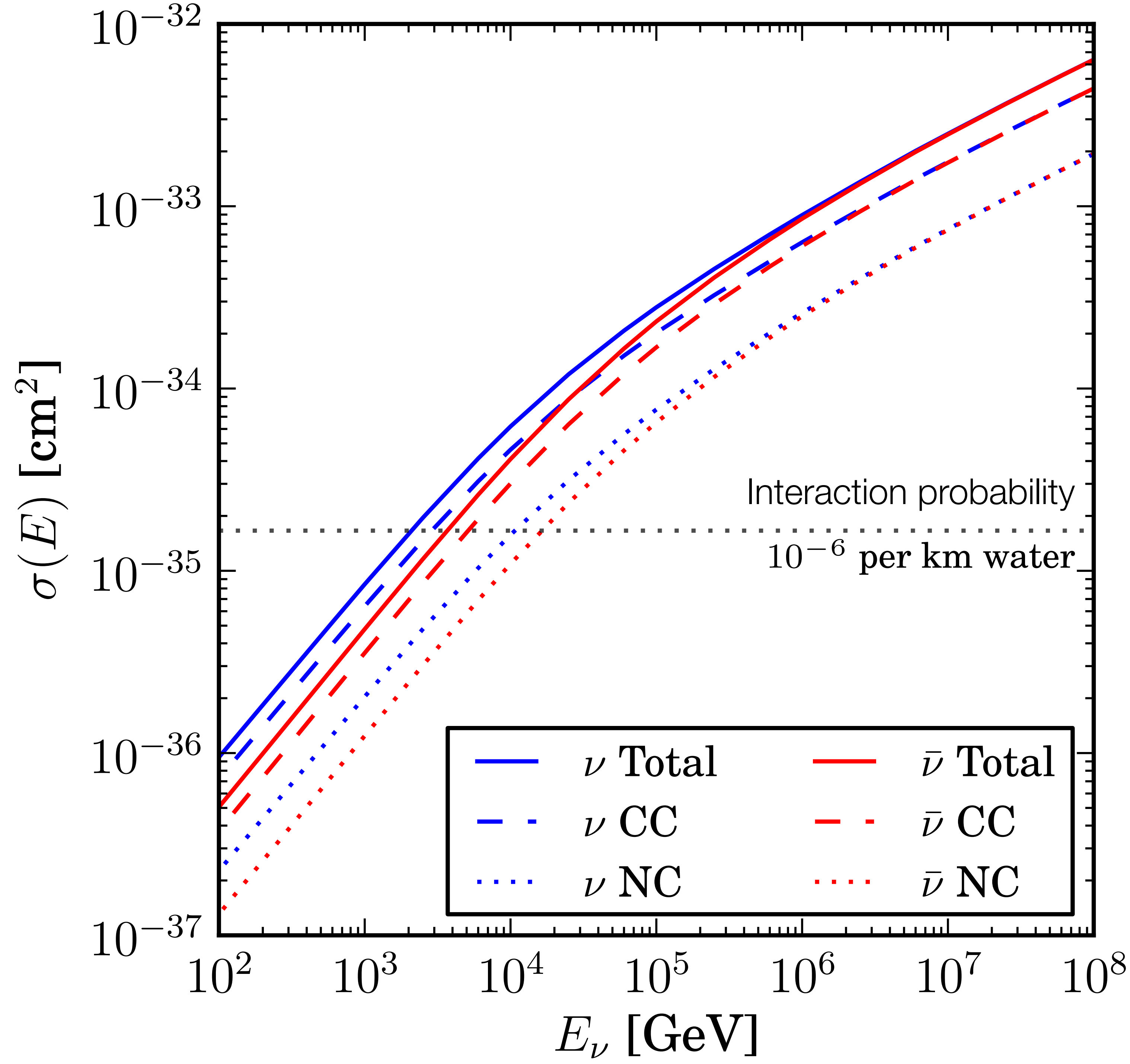


- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines

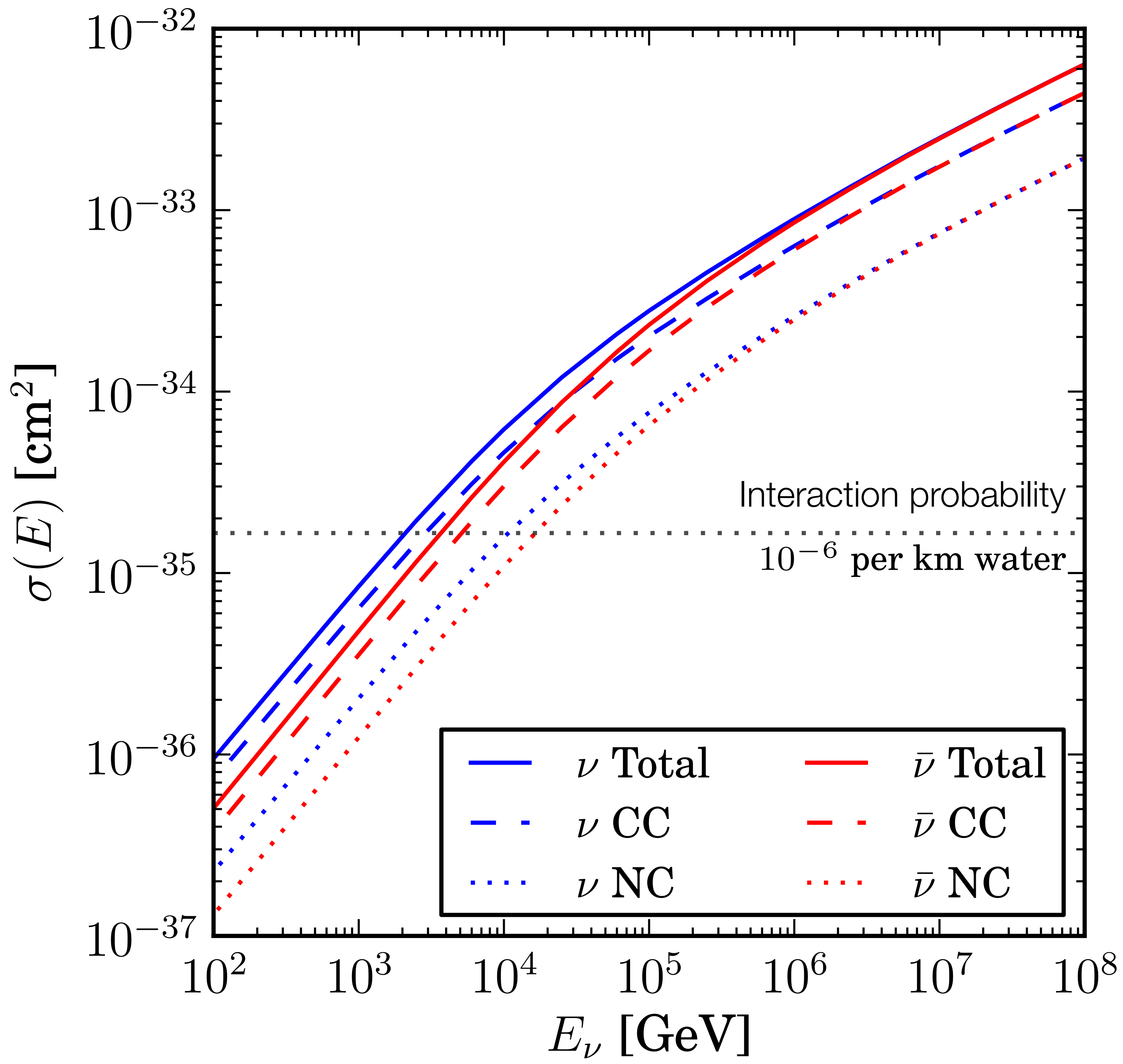


Detecting TeV neutrinos



Detecting TeV neutrinos

- Interaction cross-sections are very small



Detecting TeV neutrinos

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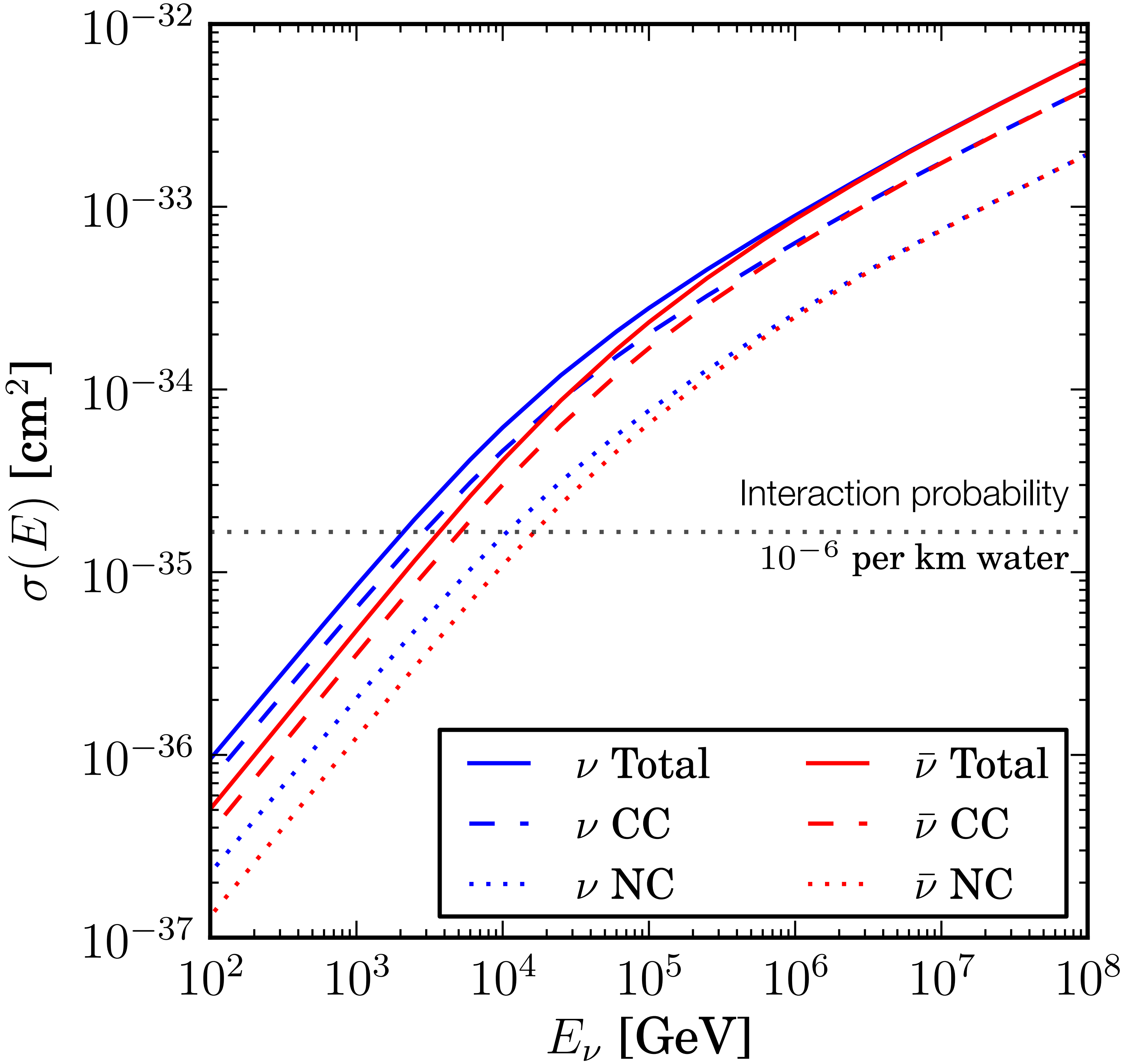
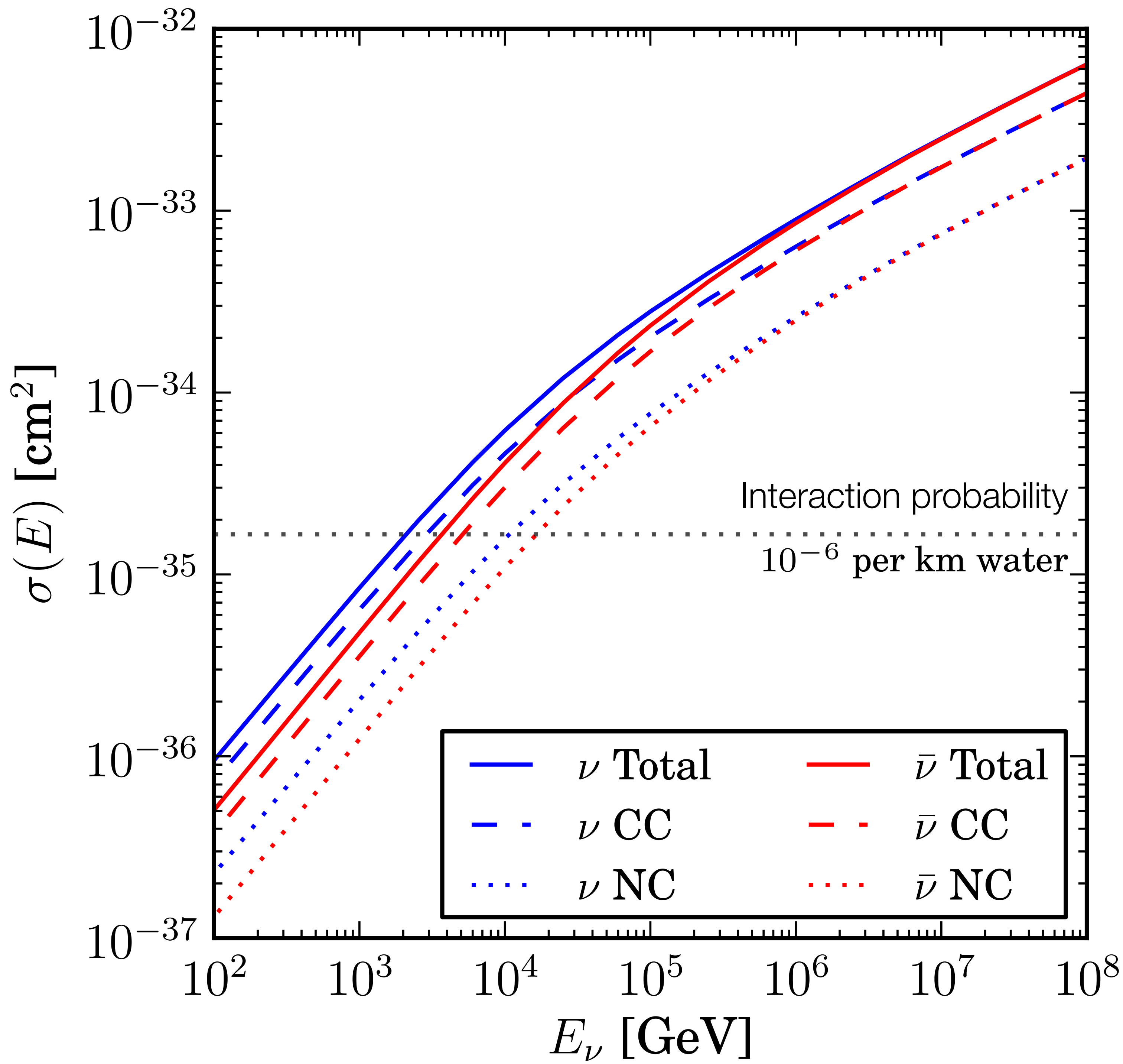
- Benchmark astrophysical flux: O(10^5) per km^2 per year above 100 TeV



Detecting TeV neutrinos

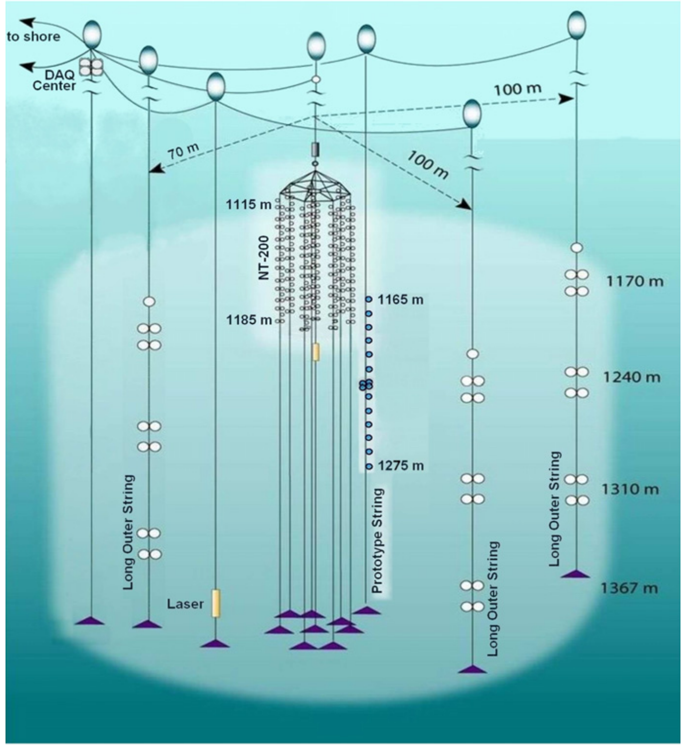
- Interaction cross-sections are very small
- Benchmark astrophysical flux: O(10^5) per km^2 per year above 100 TeV
- Need km^3-scale detectors!



The world's neutrino telescopes

The world's neutrino telescopes

NT-200+



- Lake Baikal
- 1/2000 km^3
- 228 PMTs

The world's neutrino telescopes

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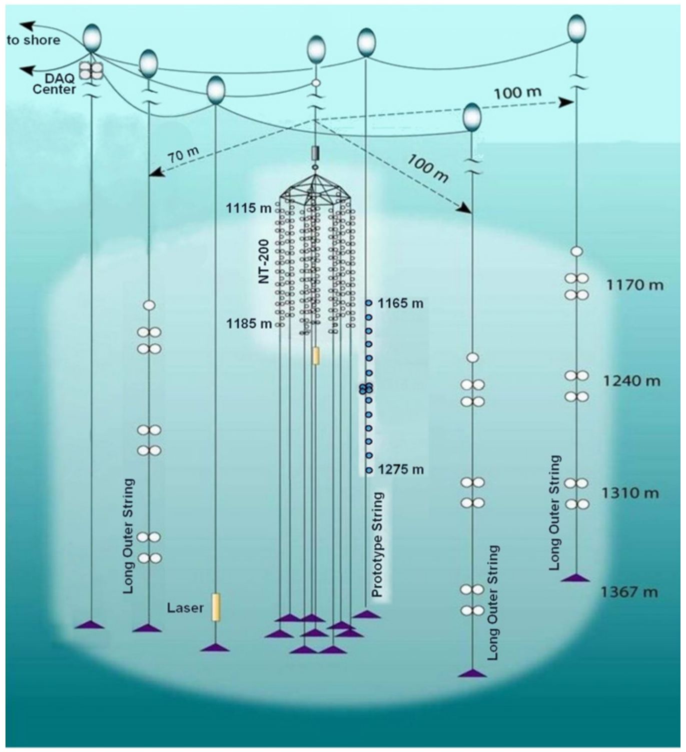
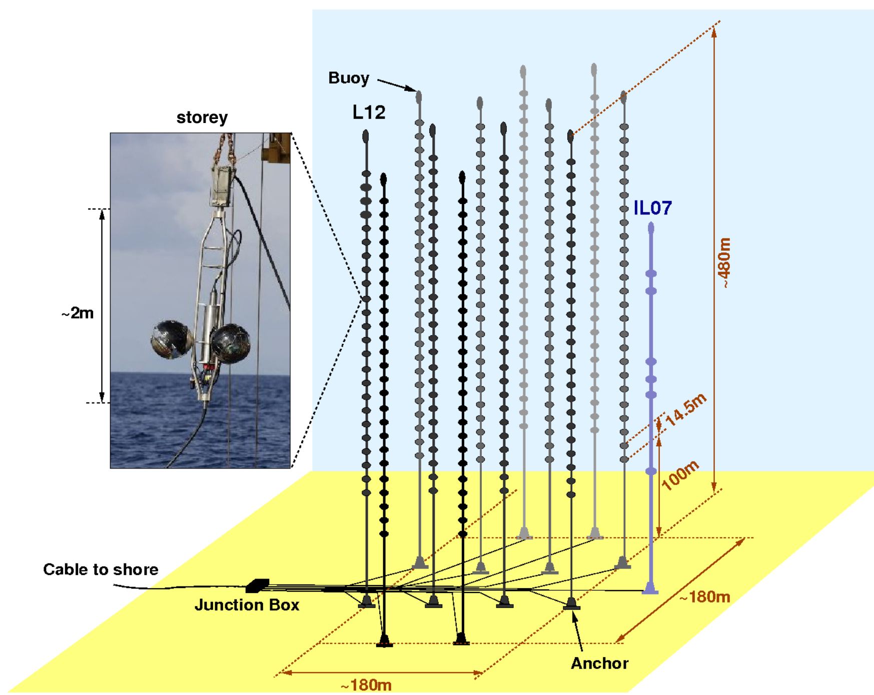


ANTARES



- Lake Baikal
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- 885 PMTs

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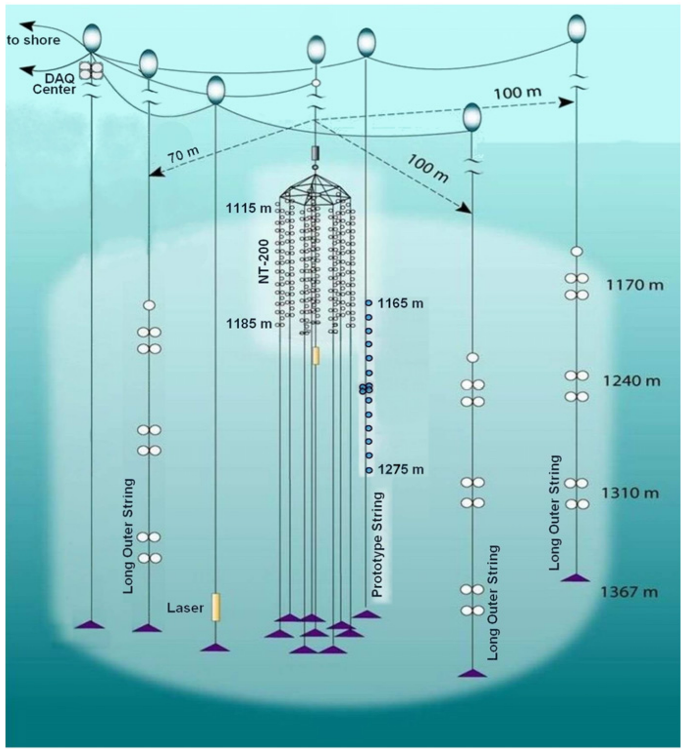
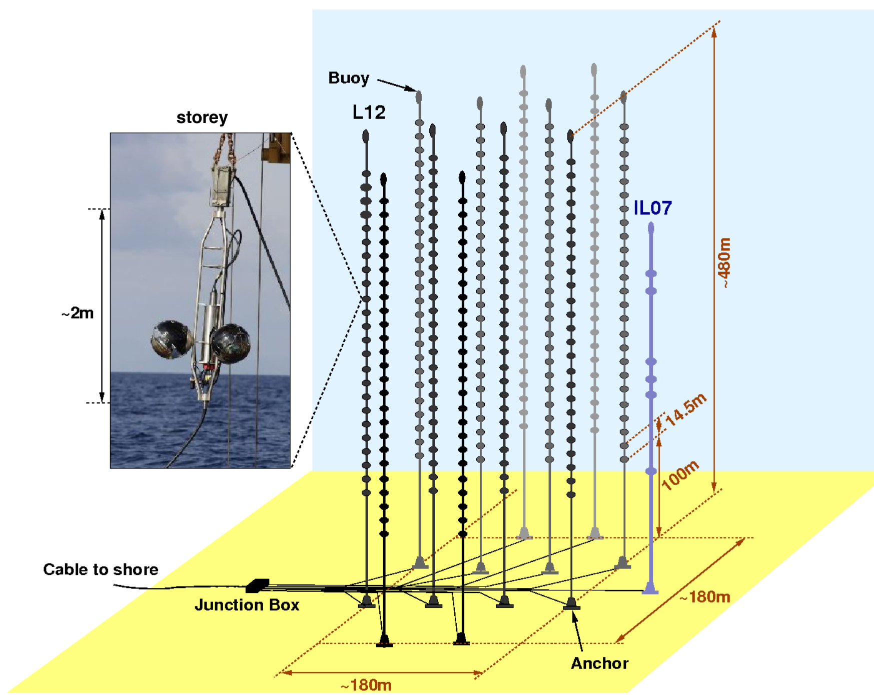
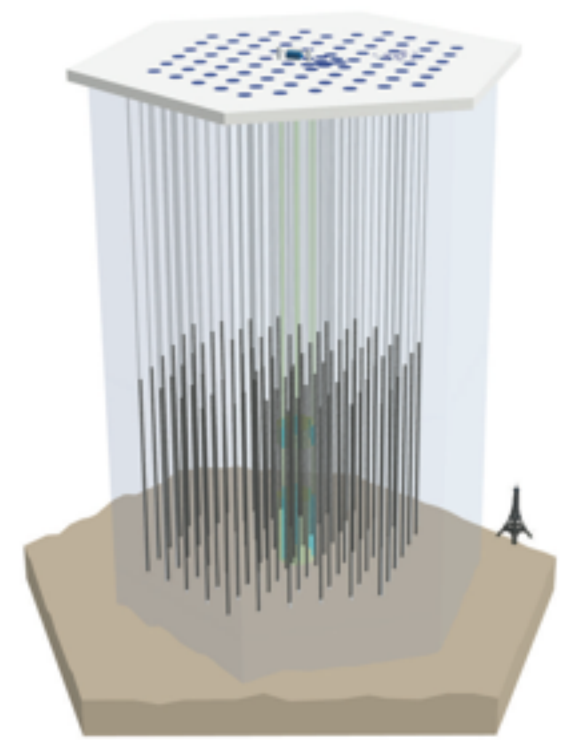
NT-200+	ANTARES	IceCube
		
• Lake Baikal	• Mediterranean Sea	• South Pole glacier
• 1/2000 km^3	• 1/100 km^3	• 1 km^3
• 228 PMTs	• 885 PMTs	• 5160 PMTs

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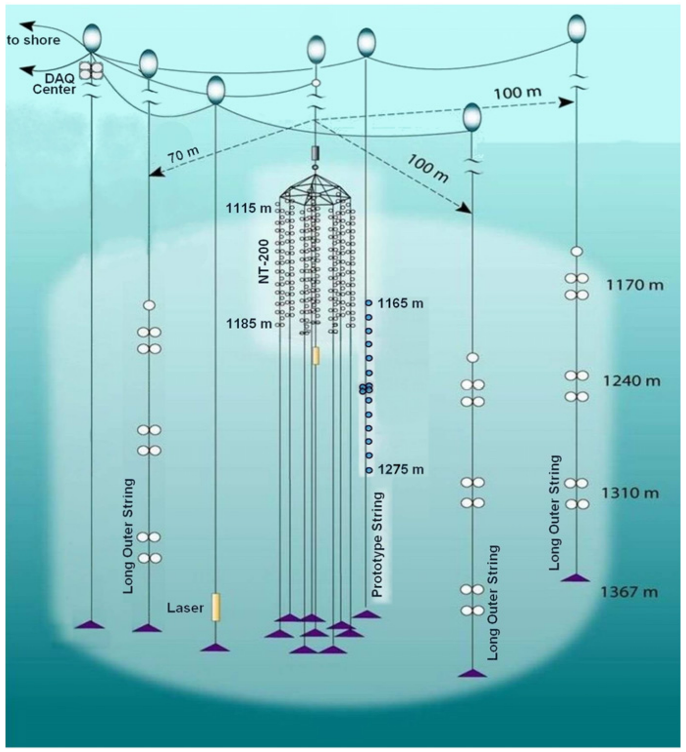	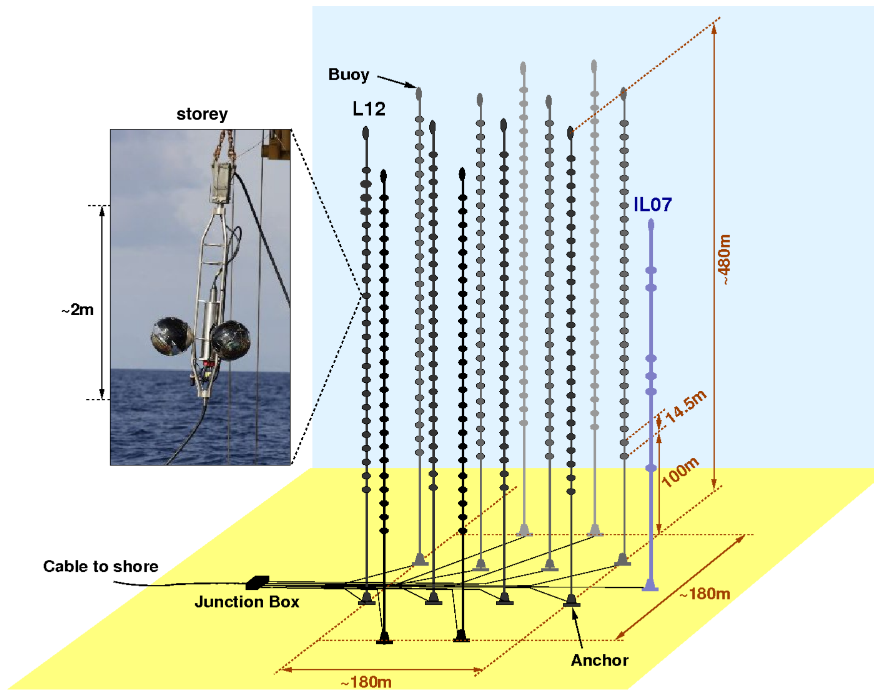	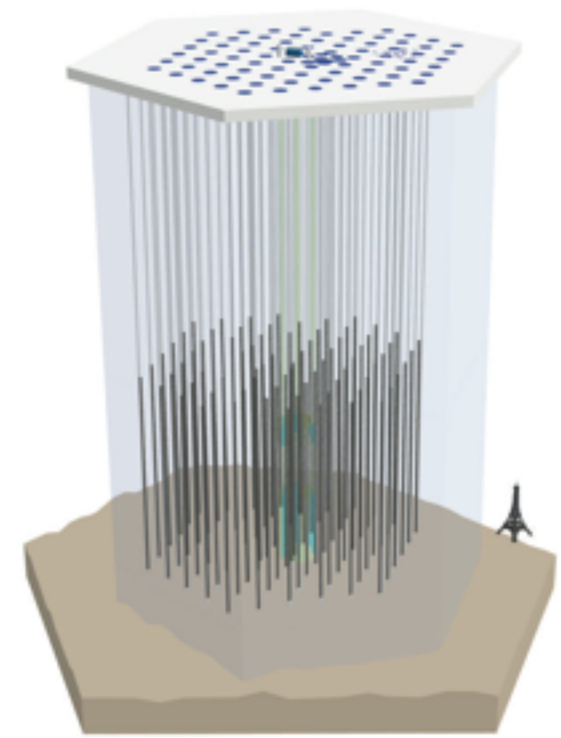
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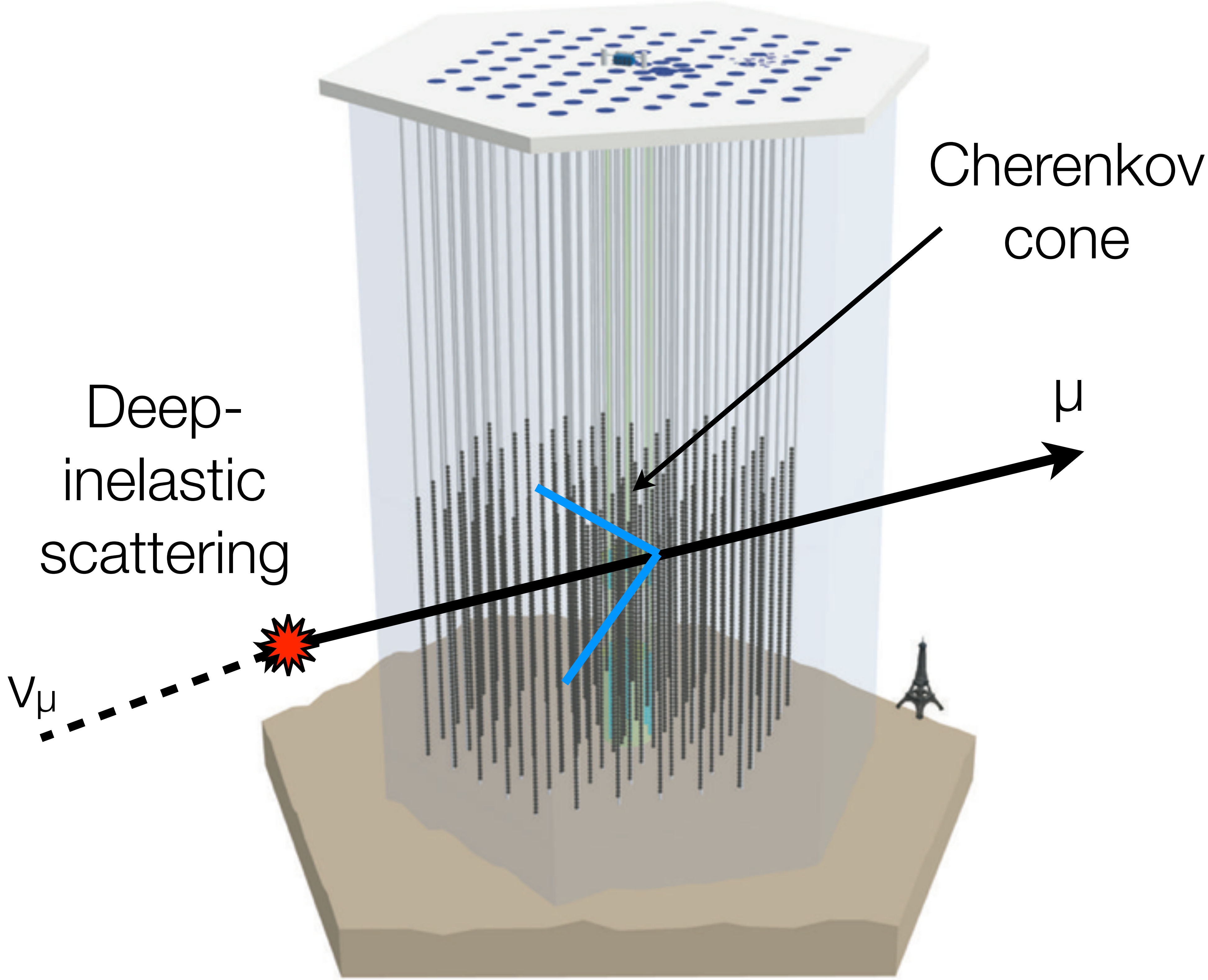
Larger, sparser → higher energies

Detecting neutrinos



Neutrino event signatures

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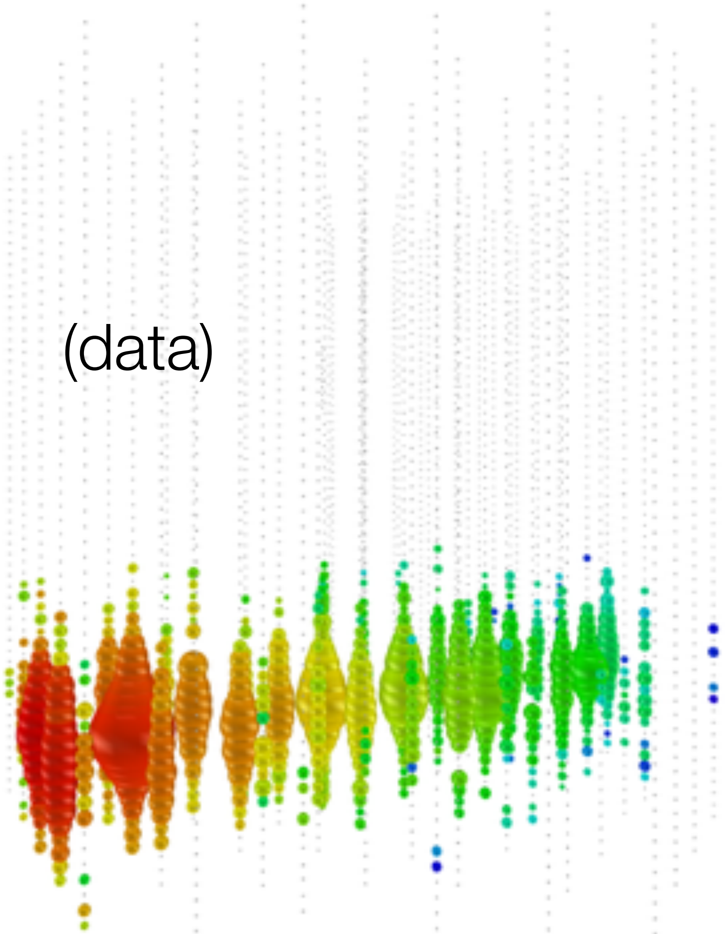
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutrino event signatures

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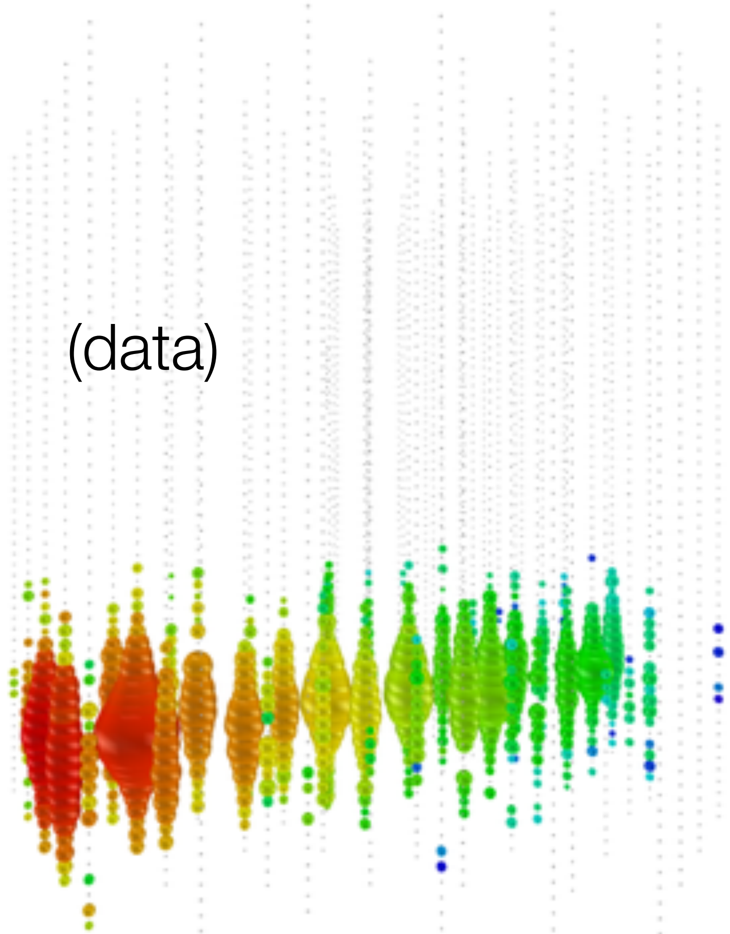

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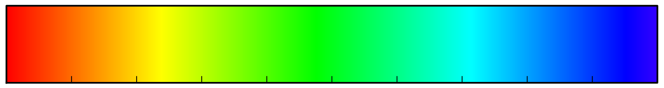
Early  Late

Neutrino event signatures

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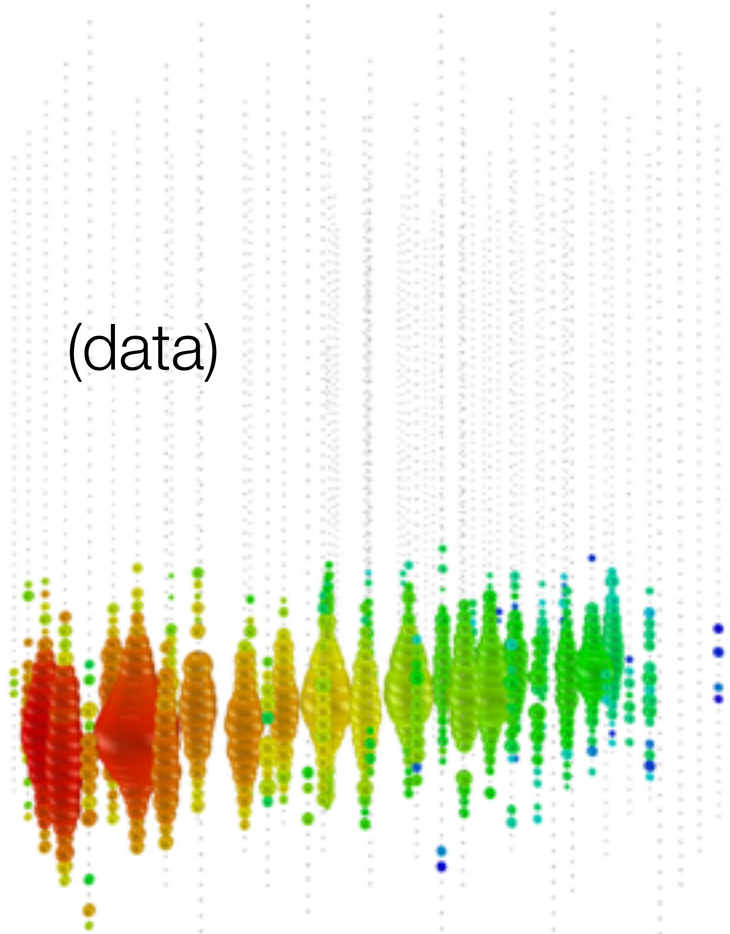

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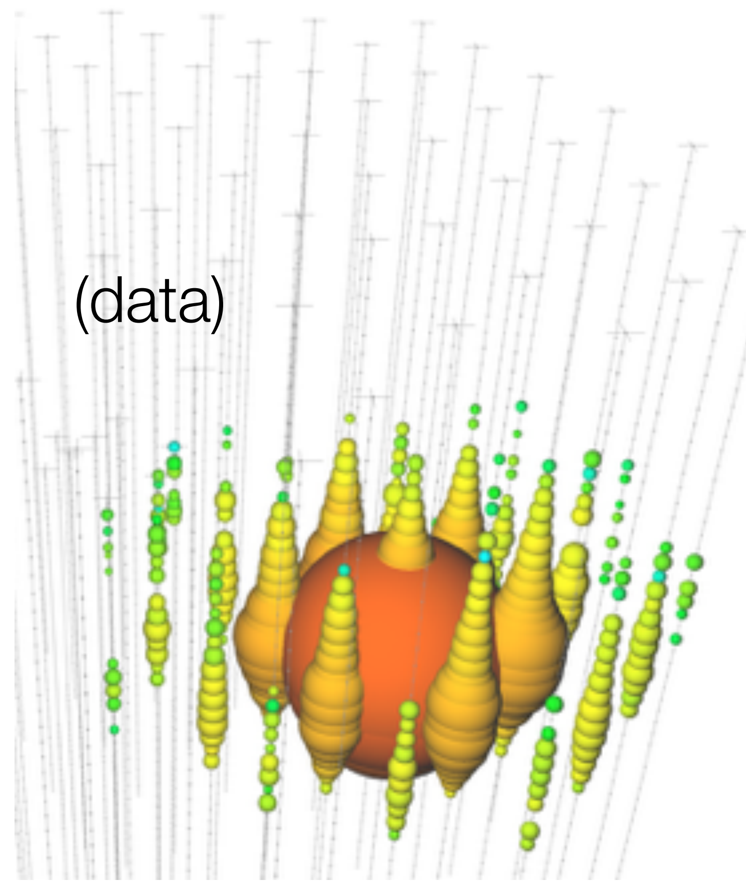
Neutral-current / ν_e



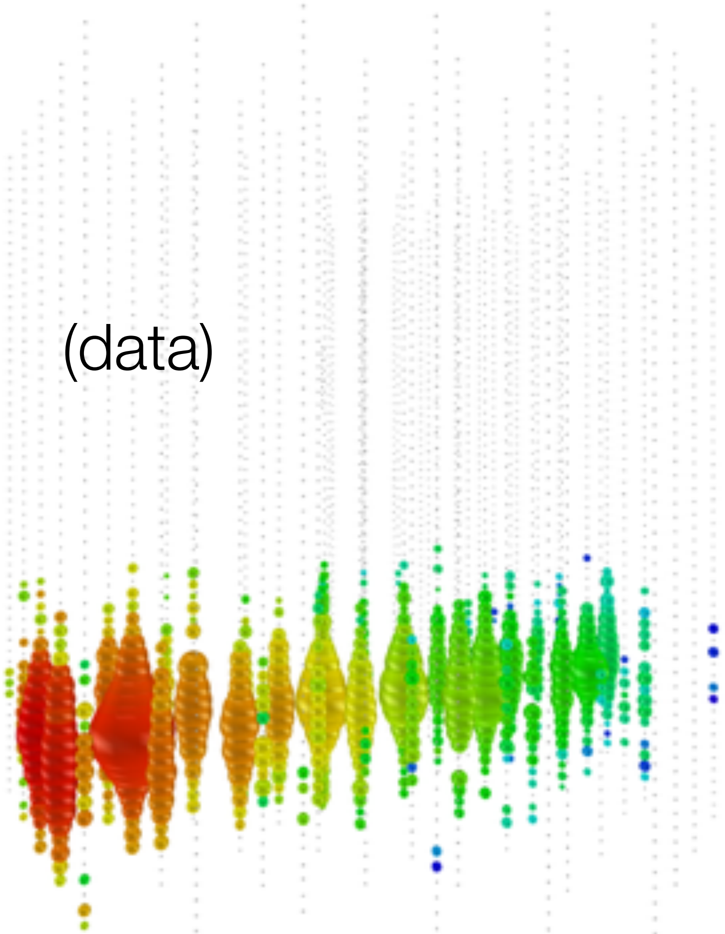
Isolated energy deposition (cascade) with no track

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

Early — Late

Neutrino event signatures

Charged-current ν_μ



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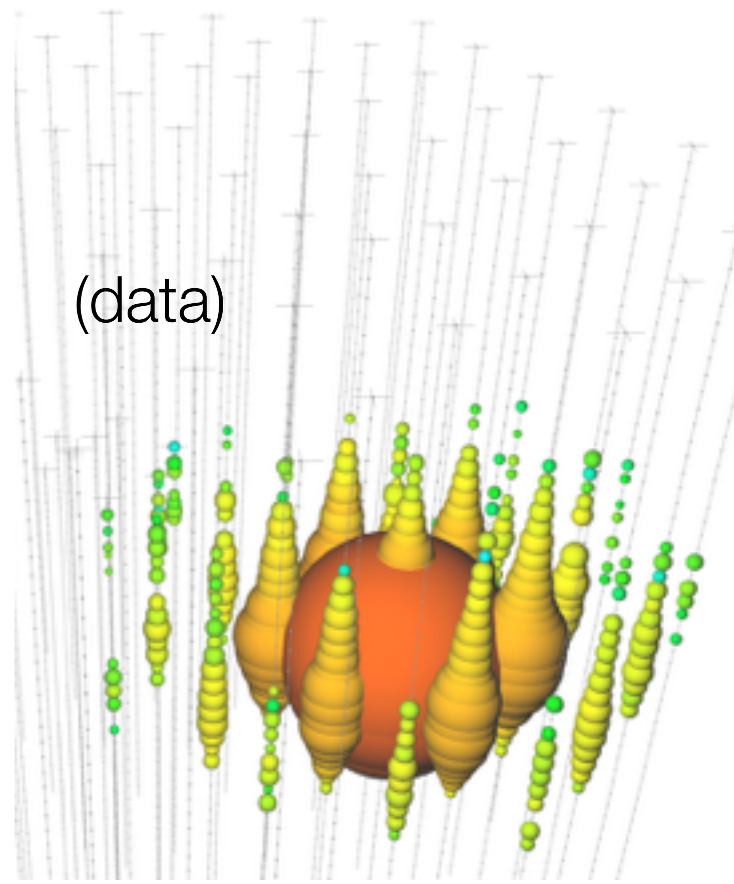

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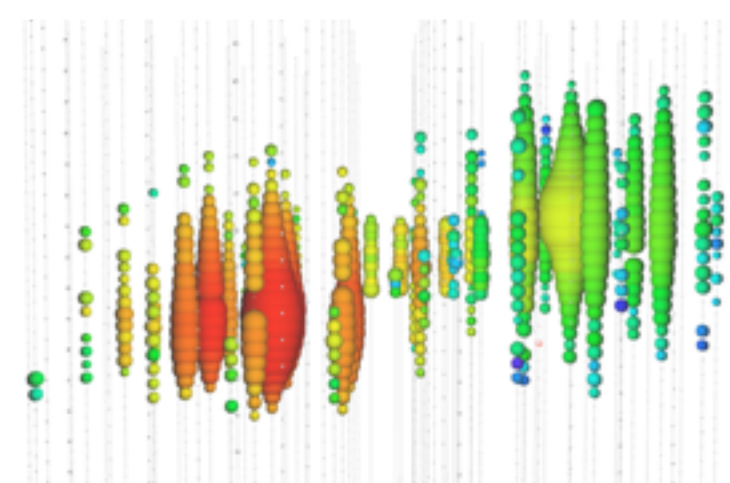
Charged-current ν_τ

(simulation)

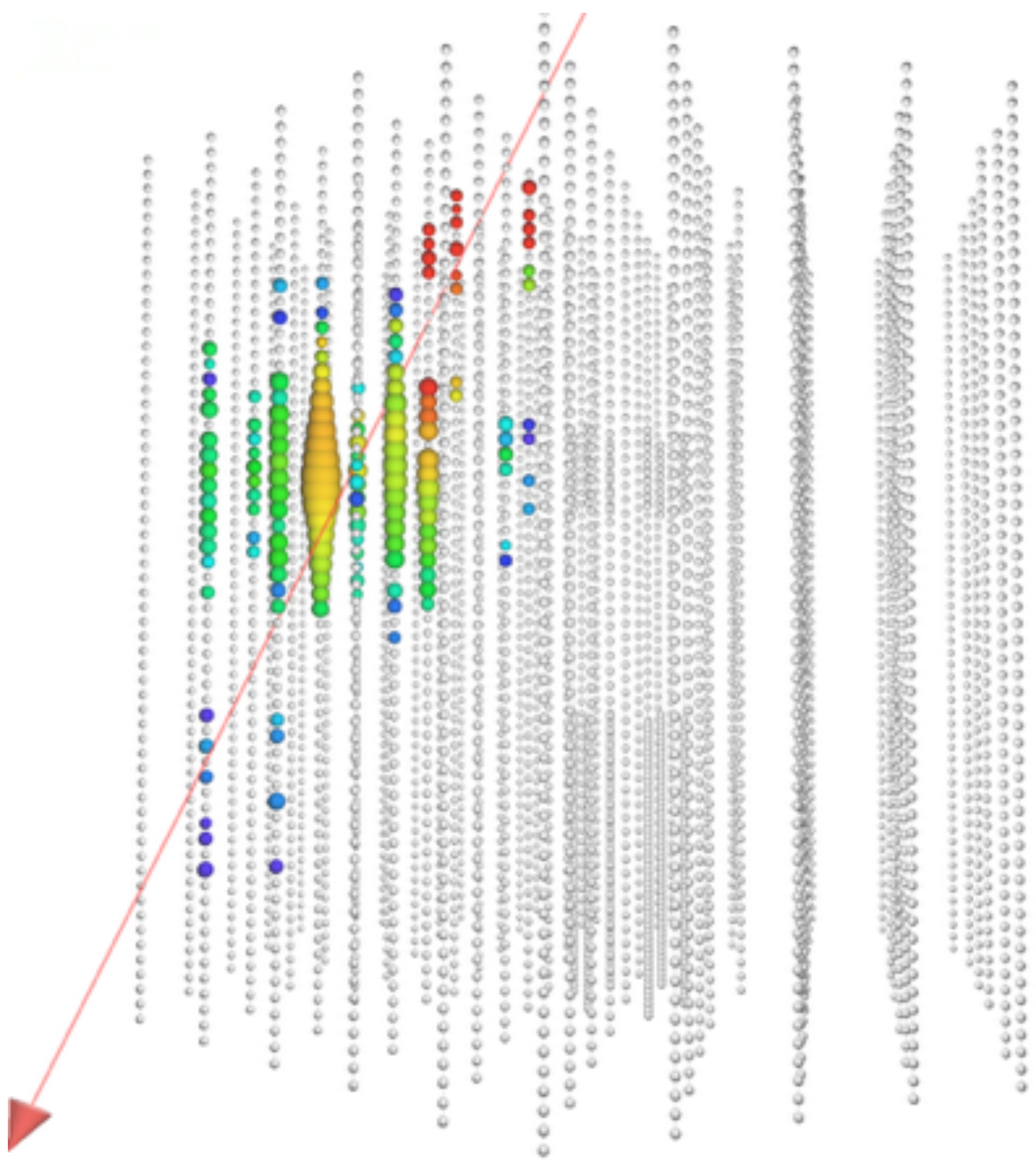


"Double-bang"

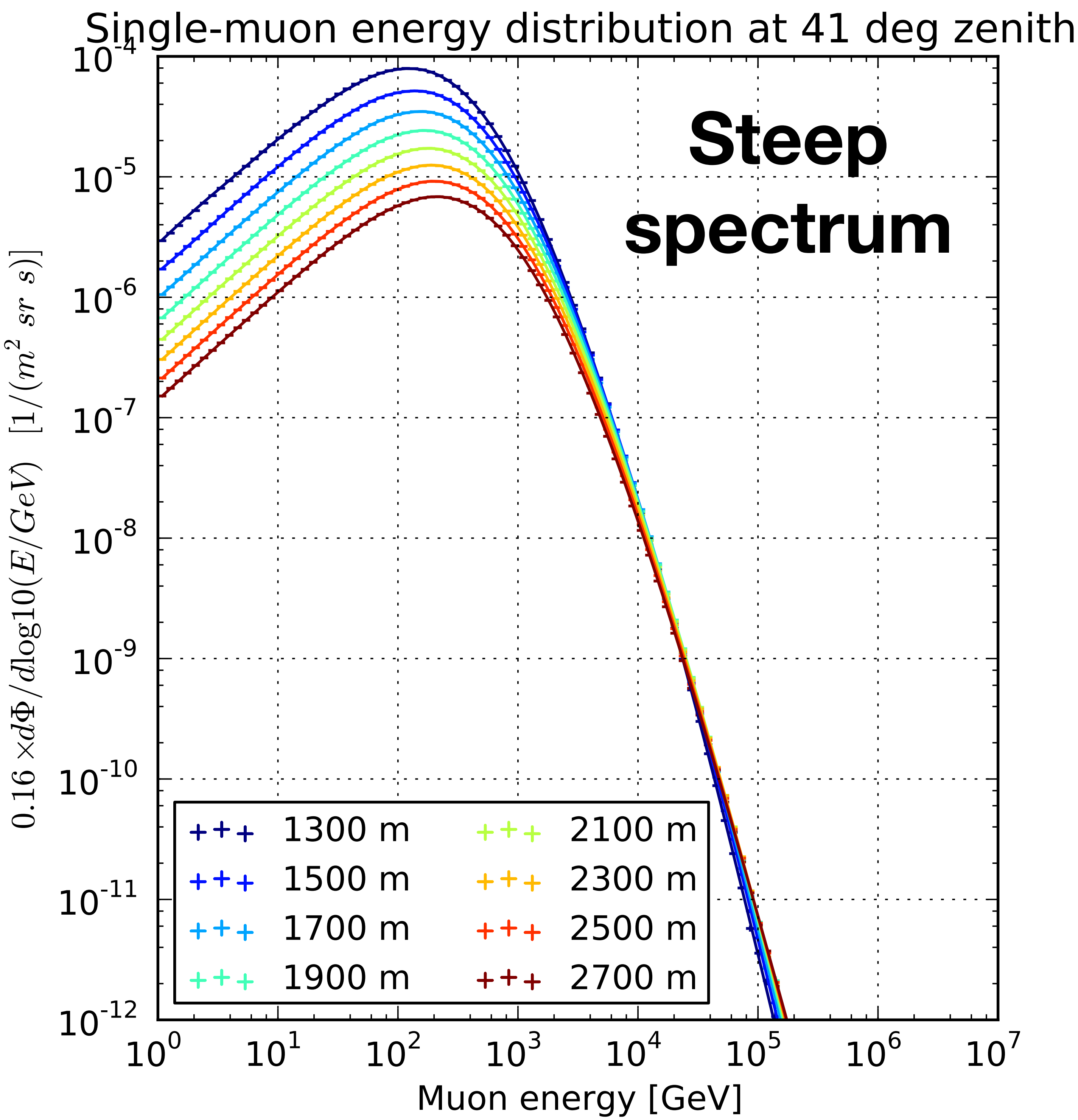
(none observed yet: τ decay length is 50 m/PeV)

Early Late

Background: penetrating muons



100 TeV single muon



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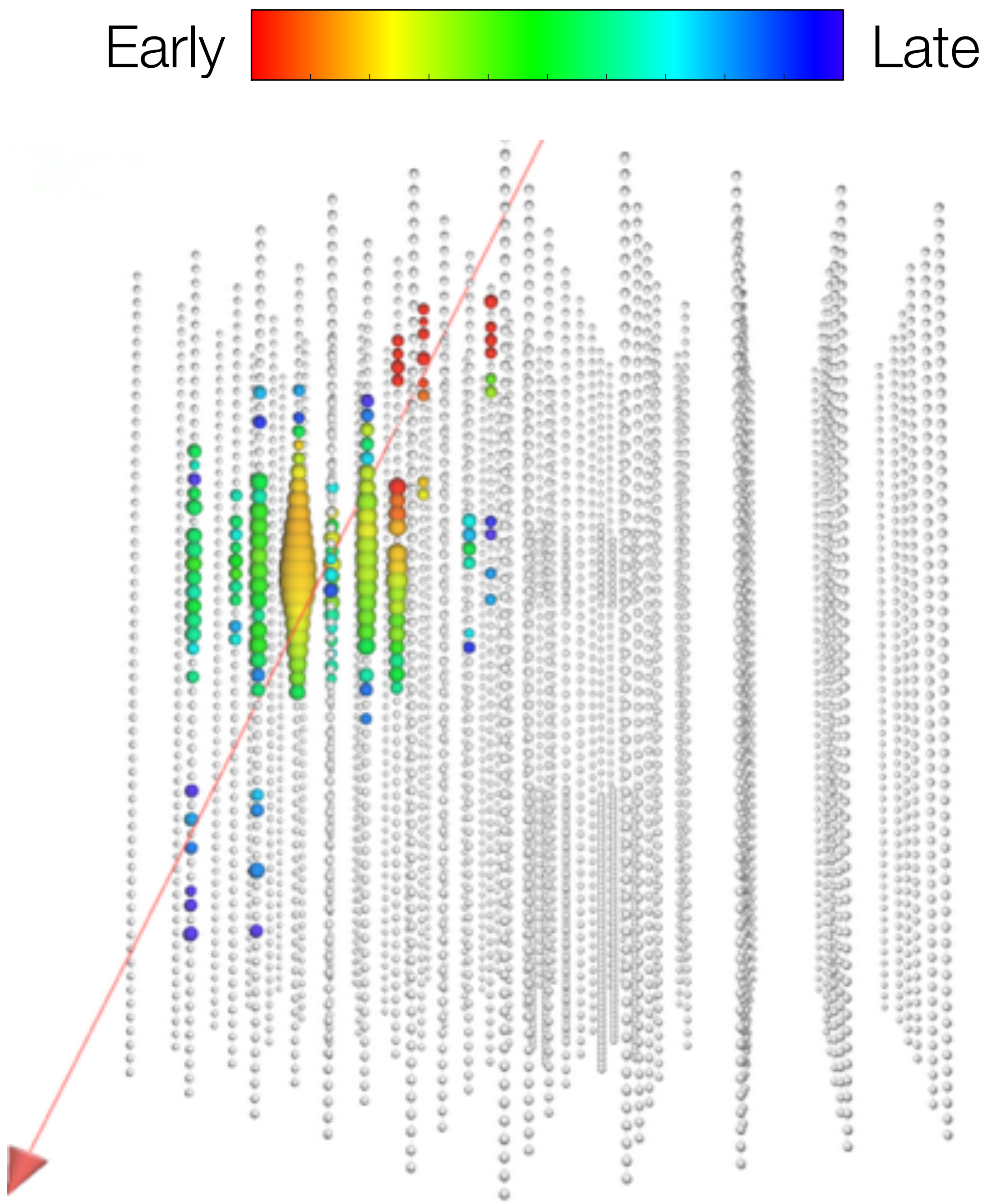

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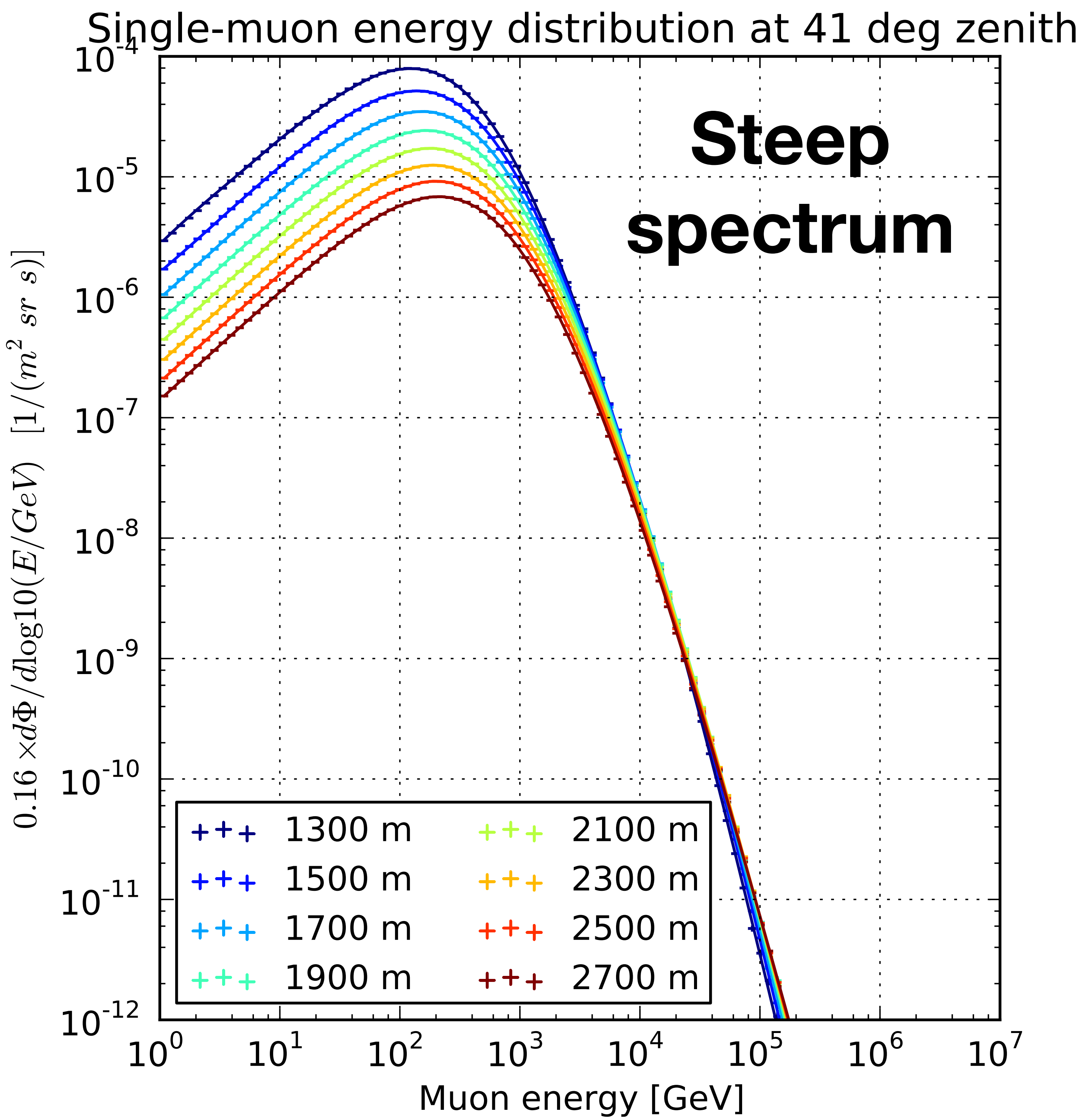

Isolating neutrino events: two strategies

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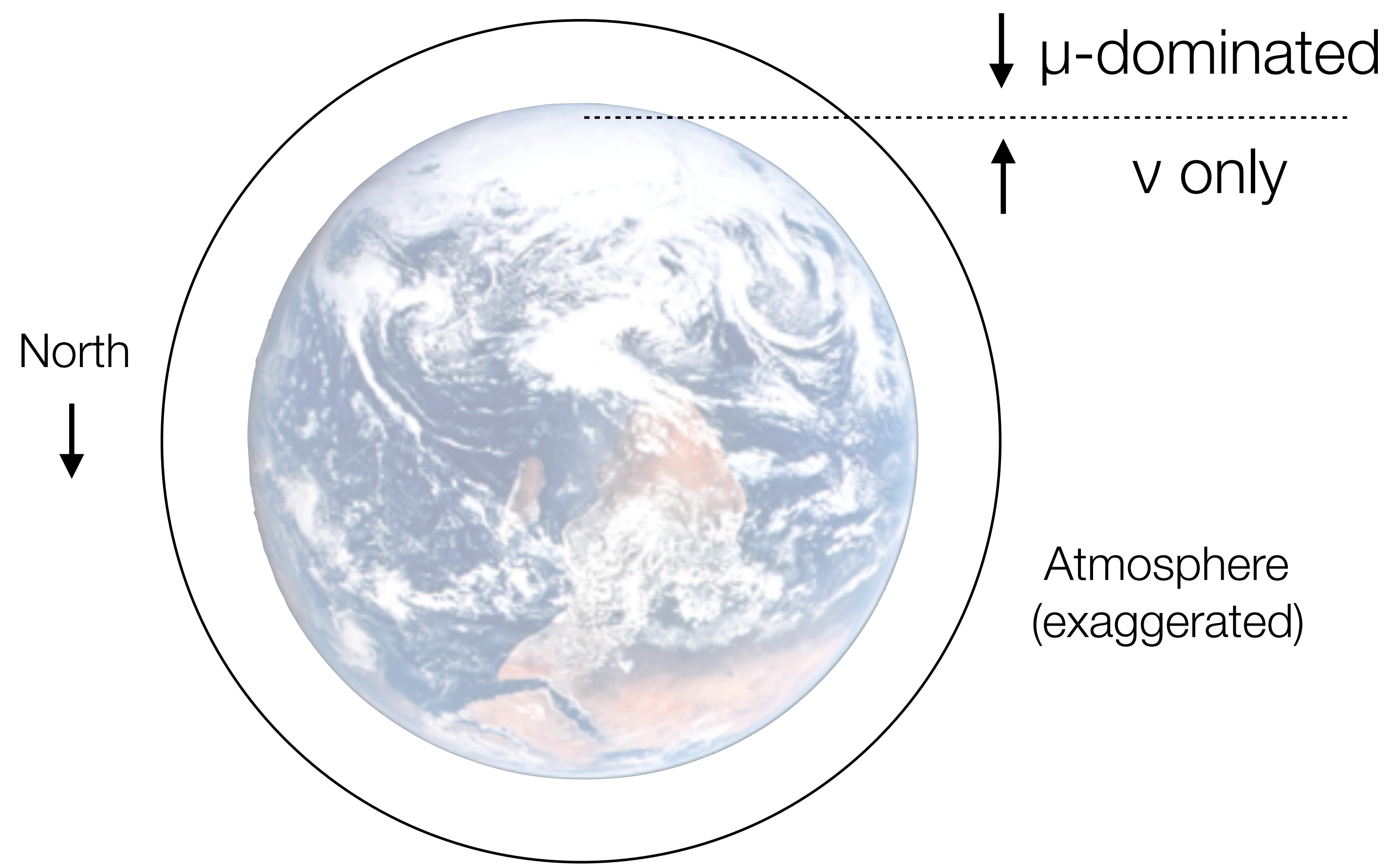

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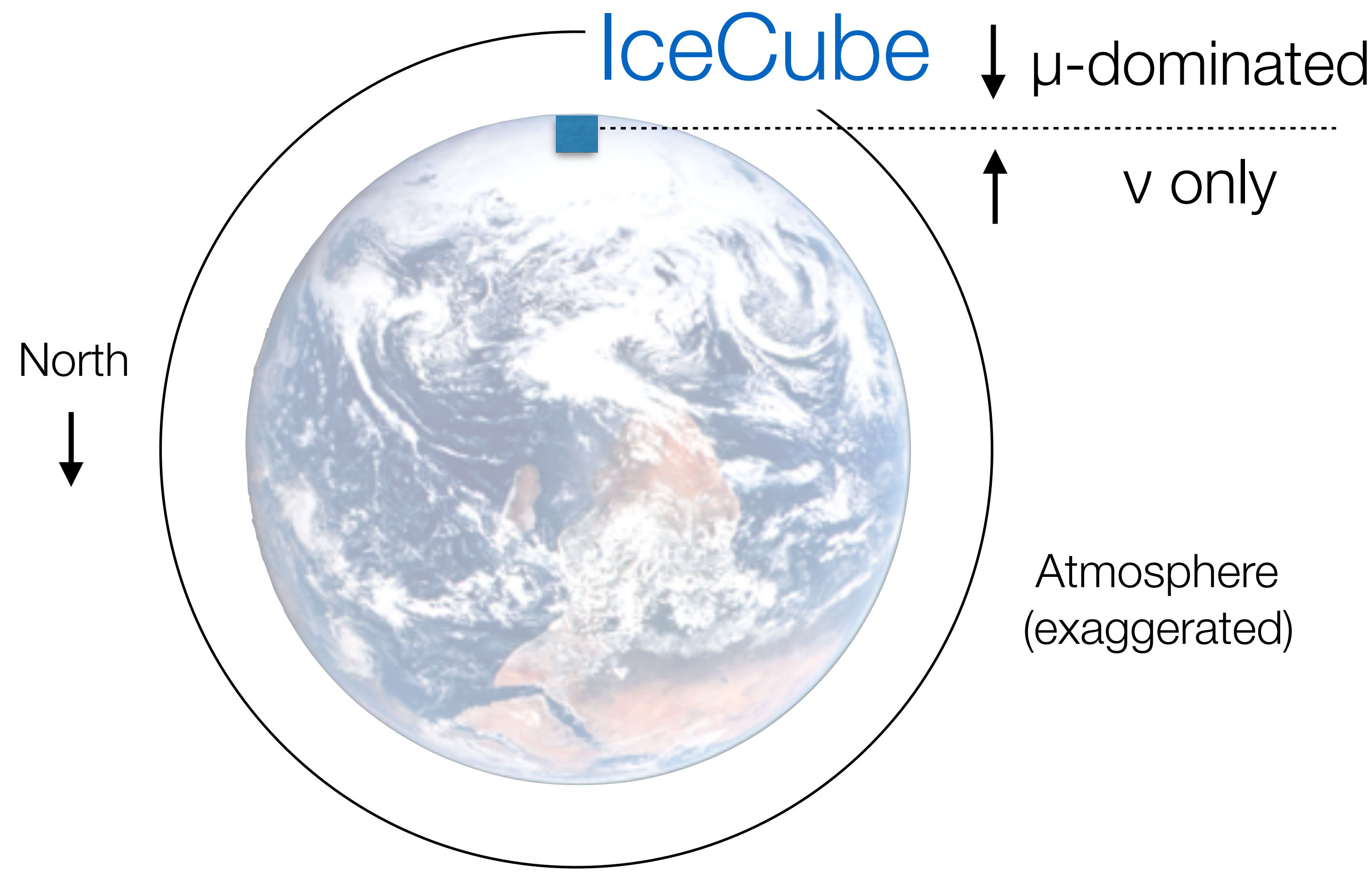

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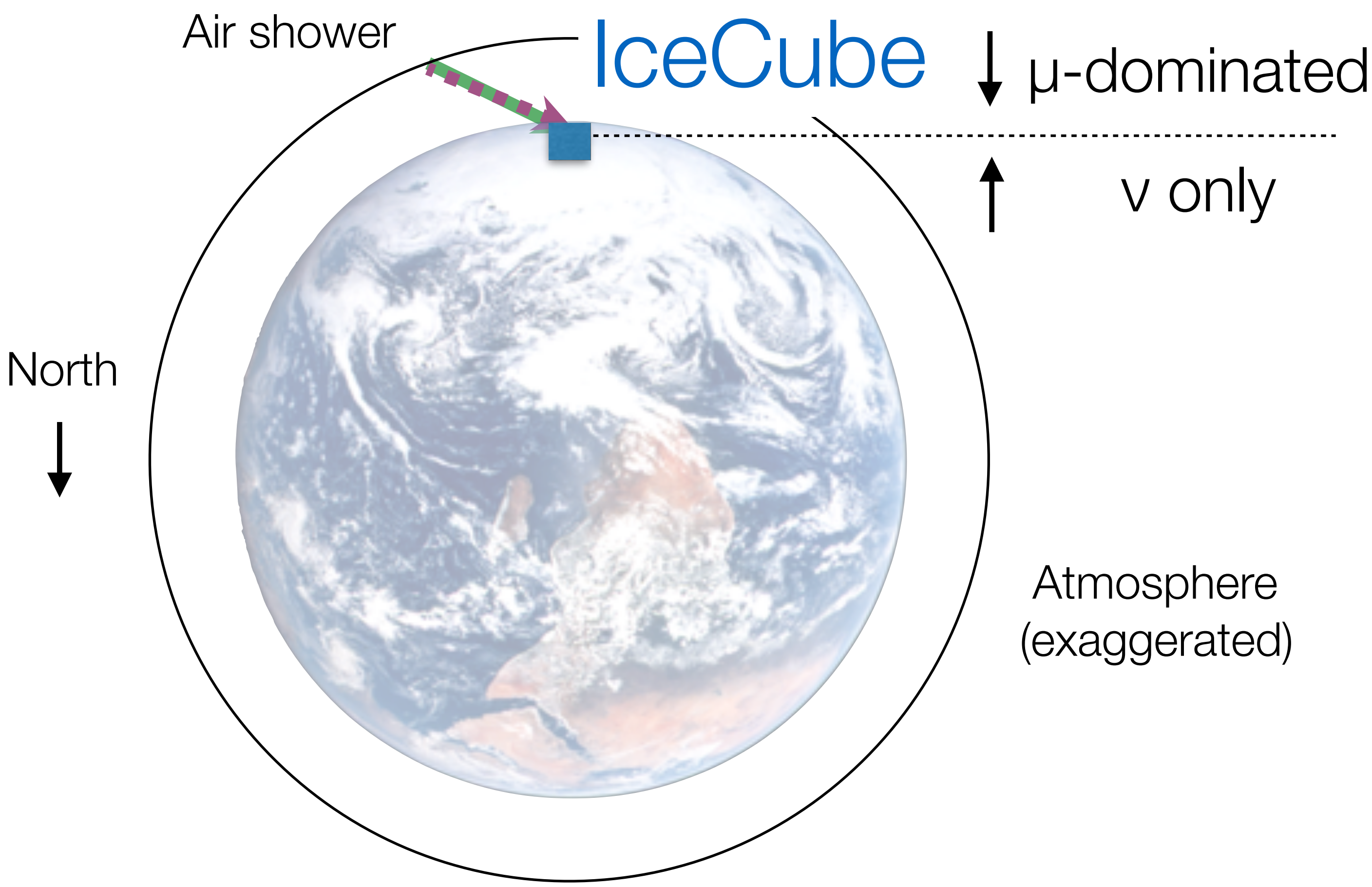

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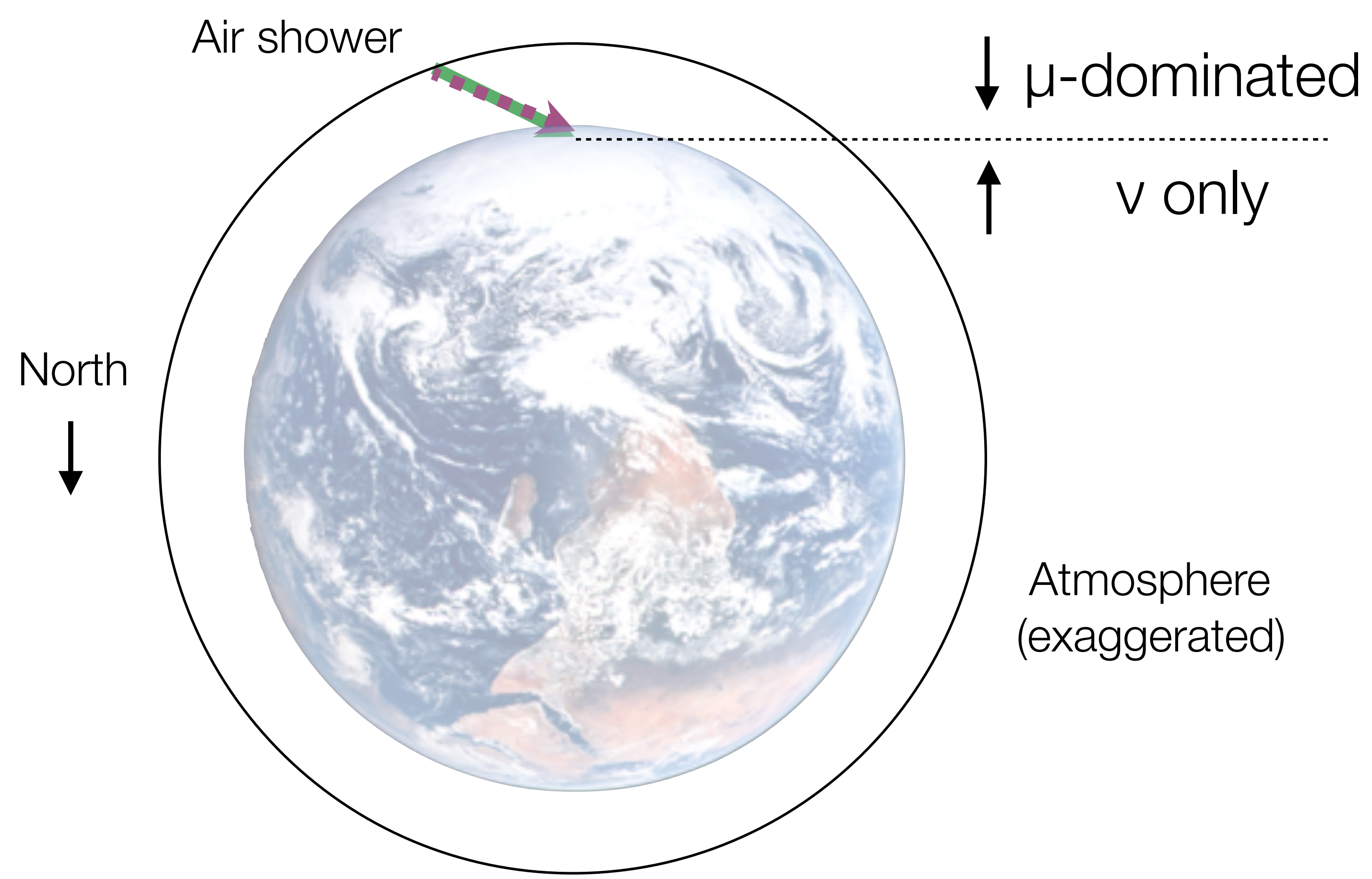

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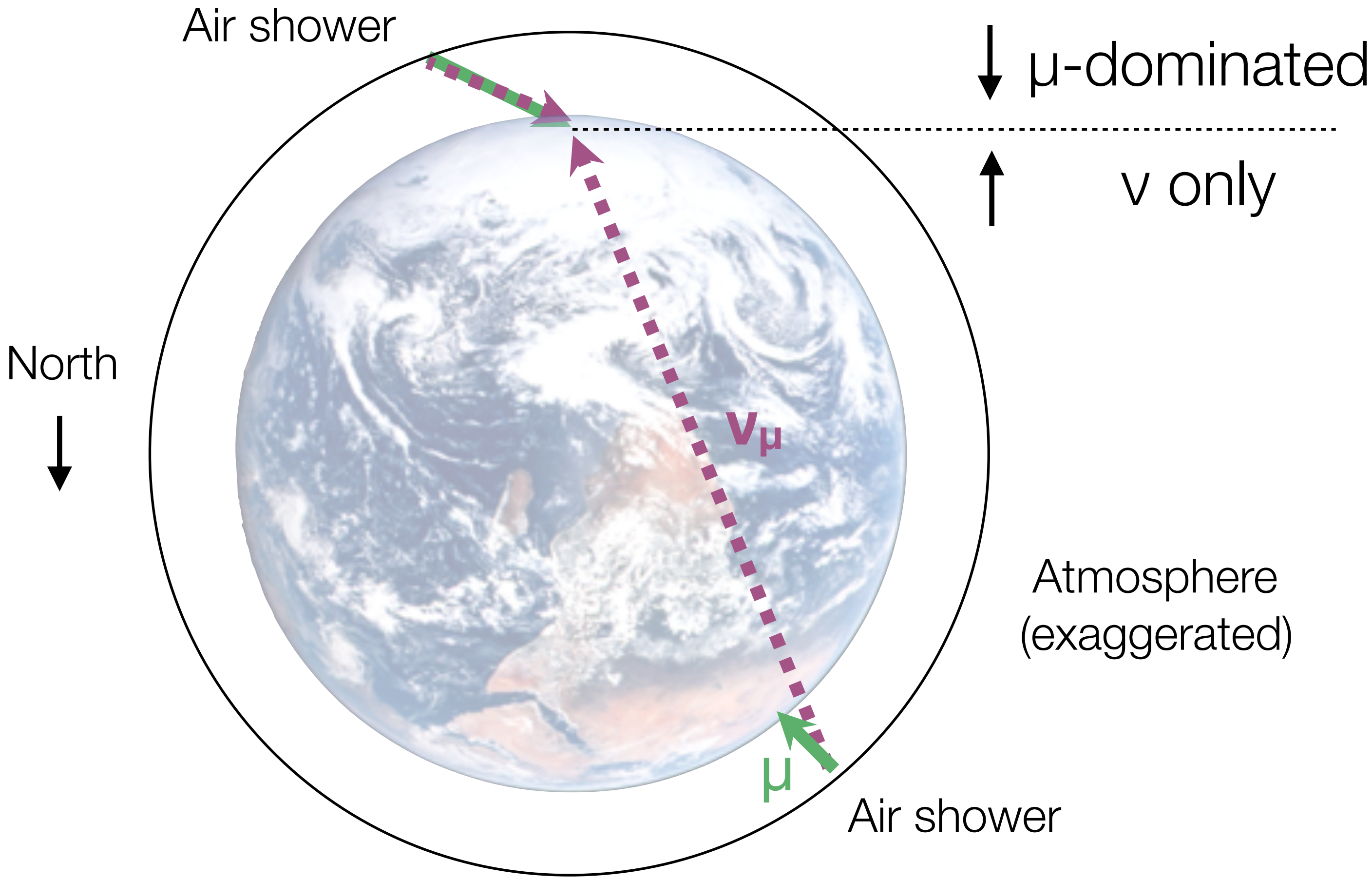

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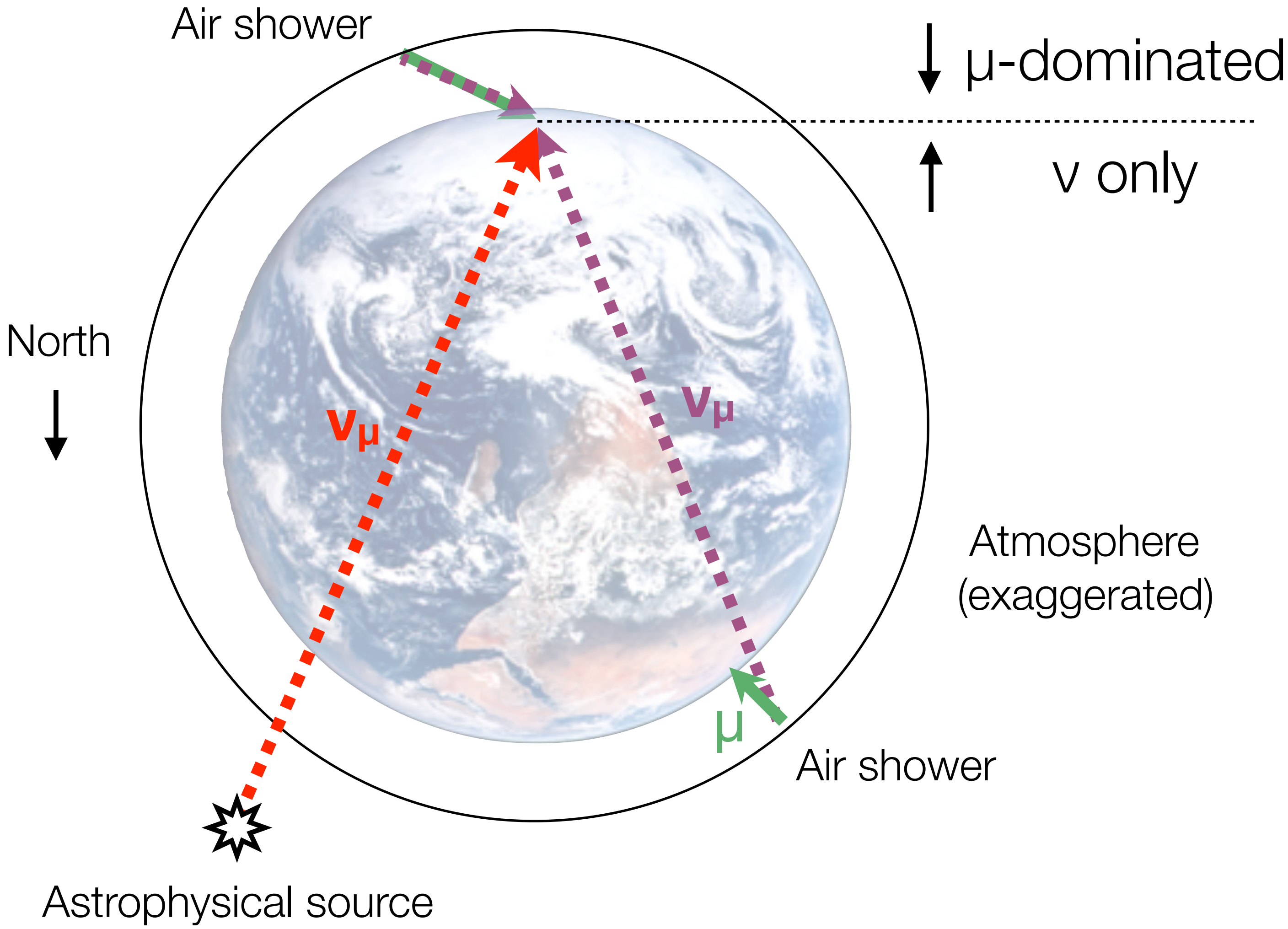

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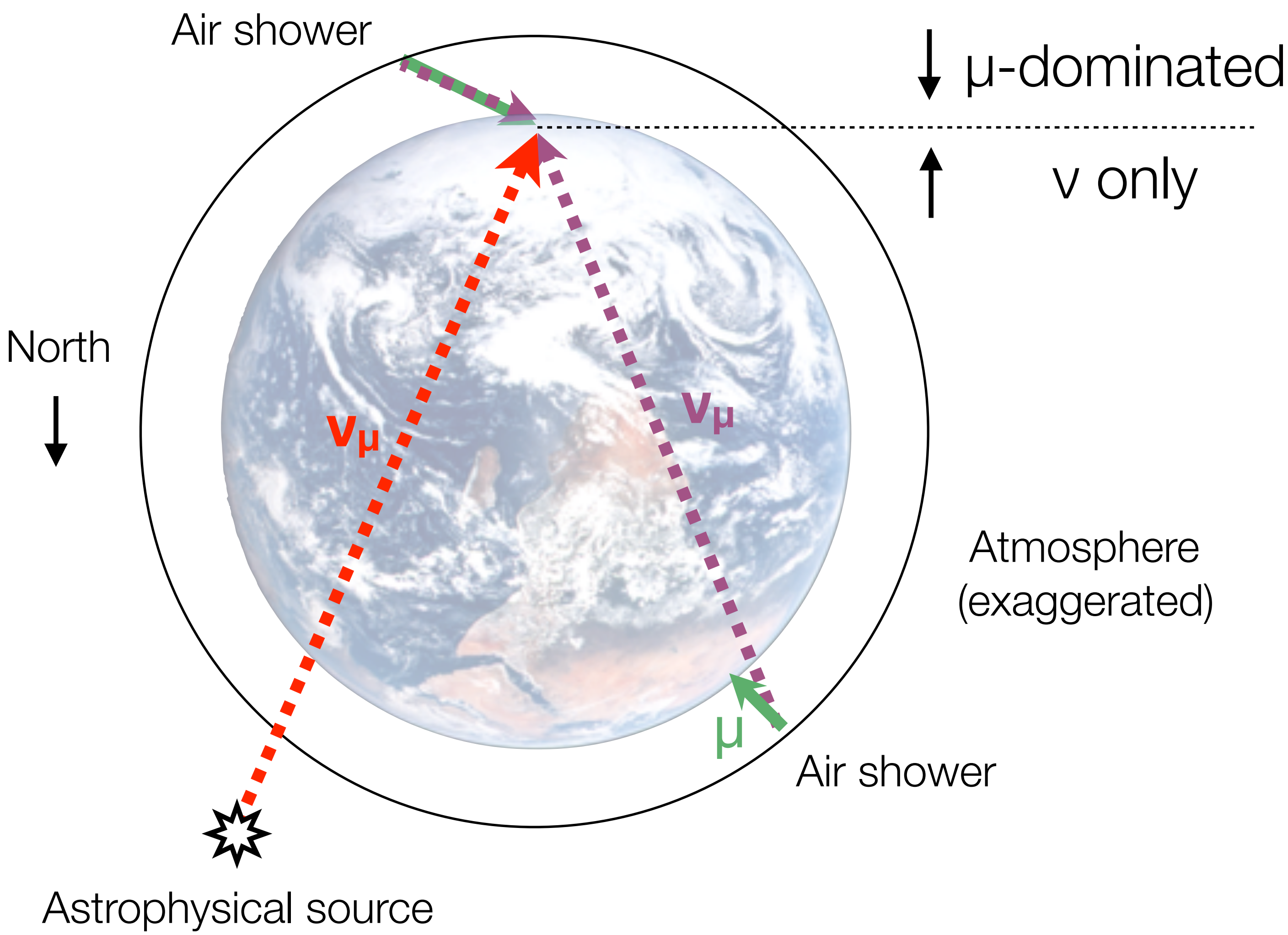

- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to ν_μ only
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- Signal dominated above ~100 TeV

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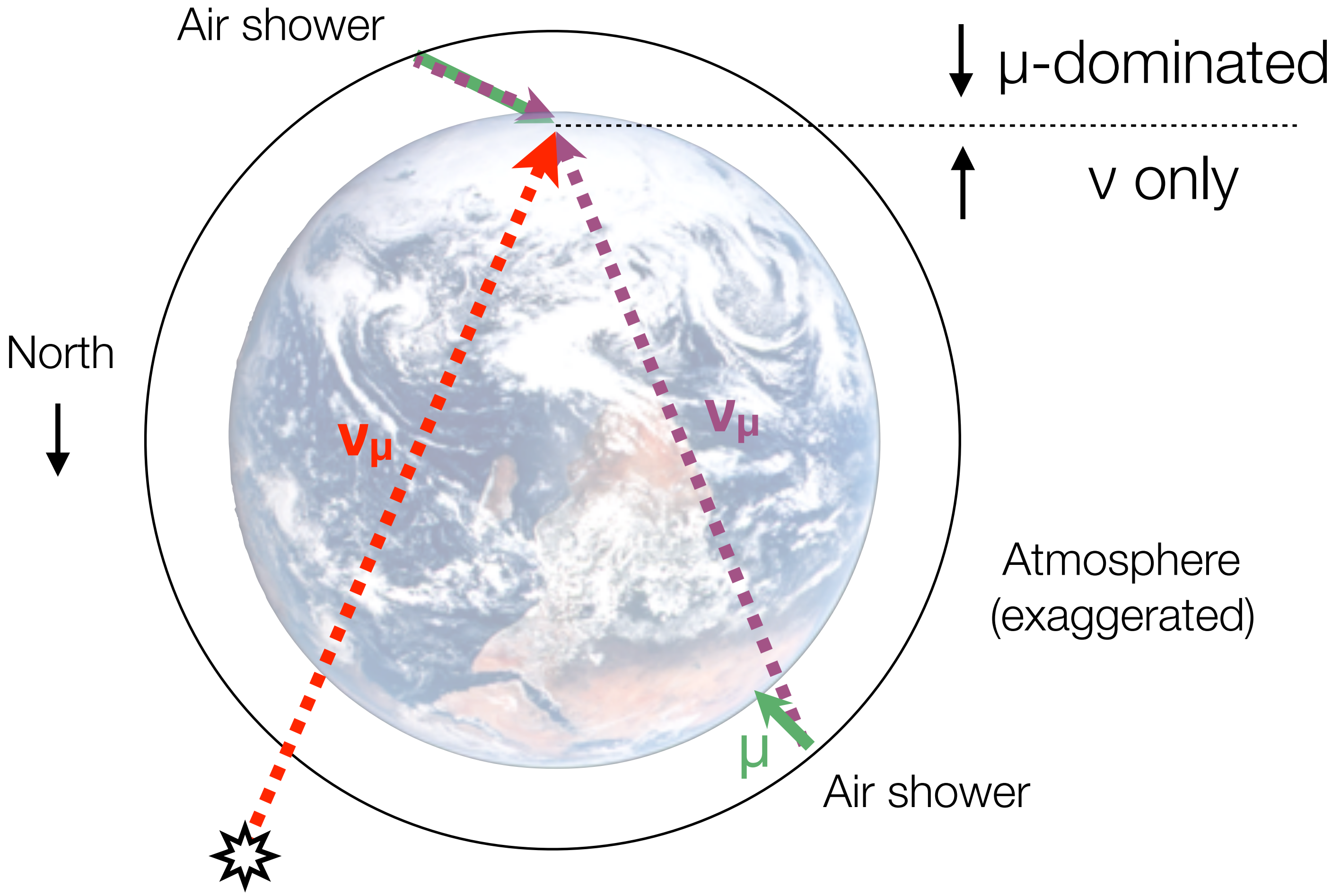

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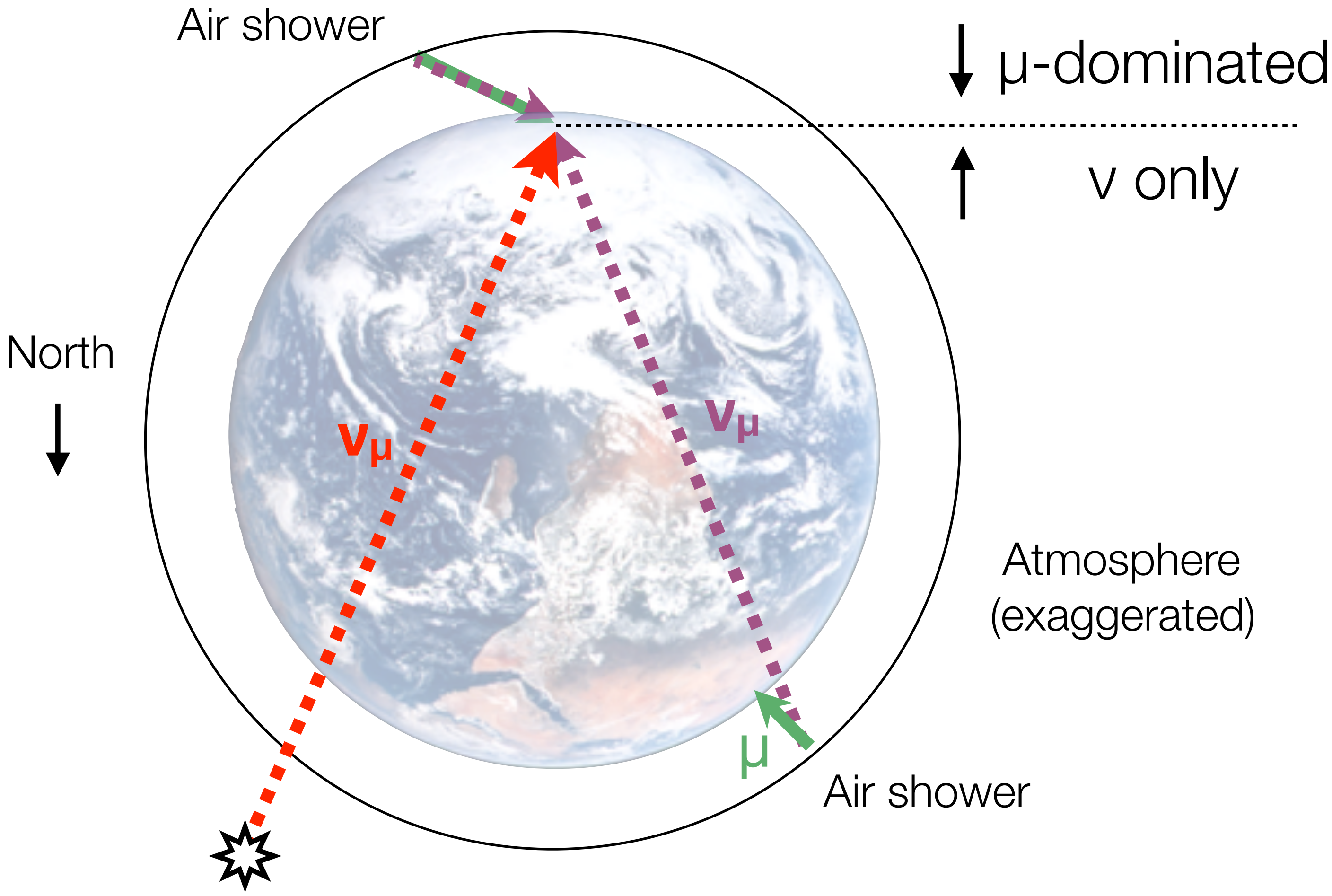

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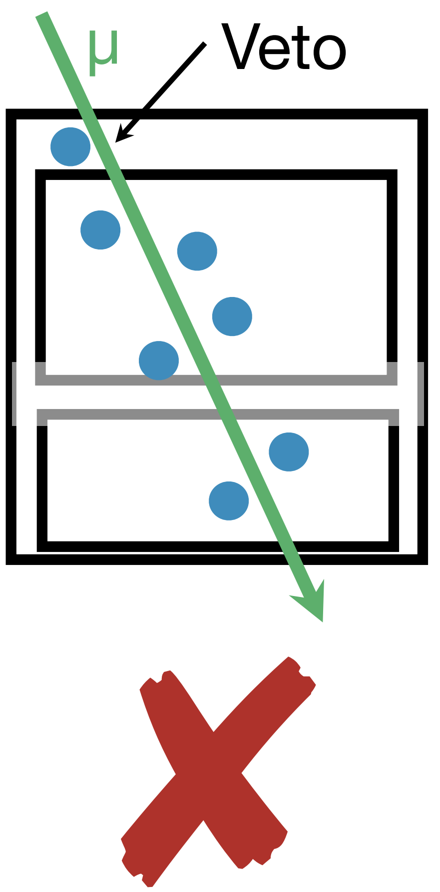

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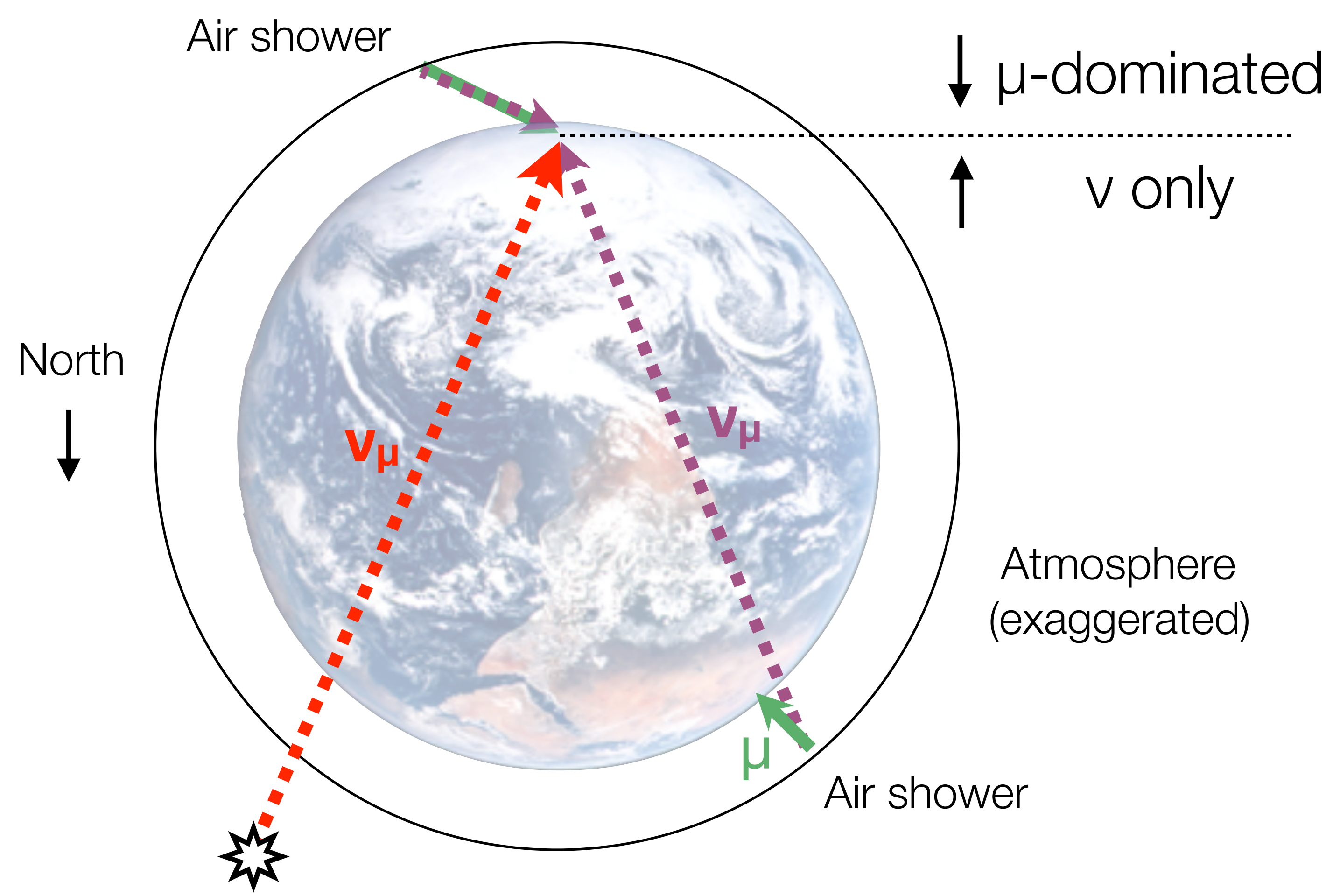

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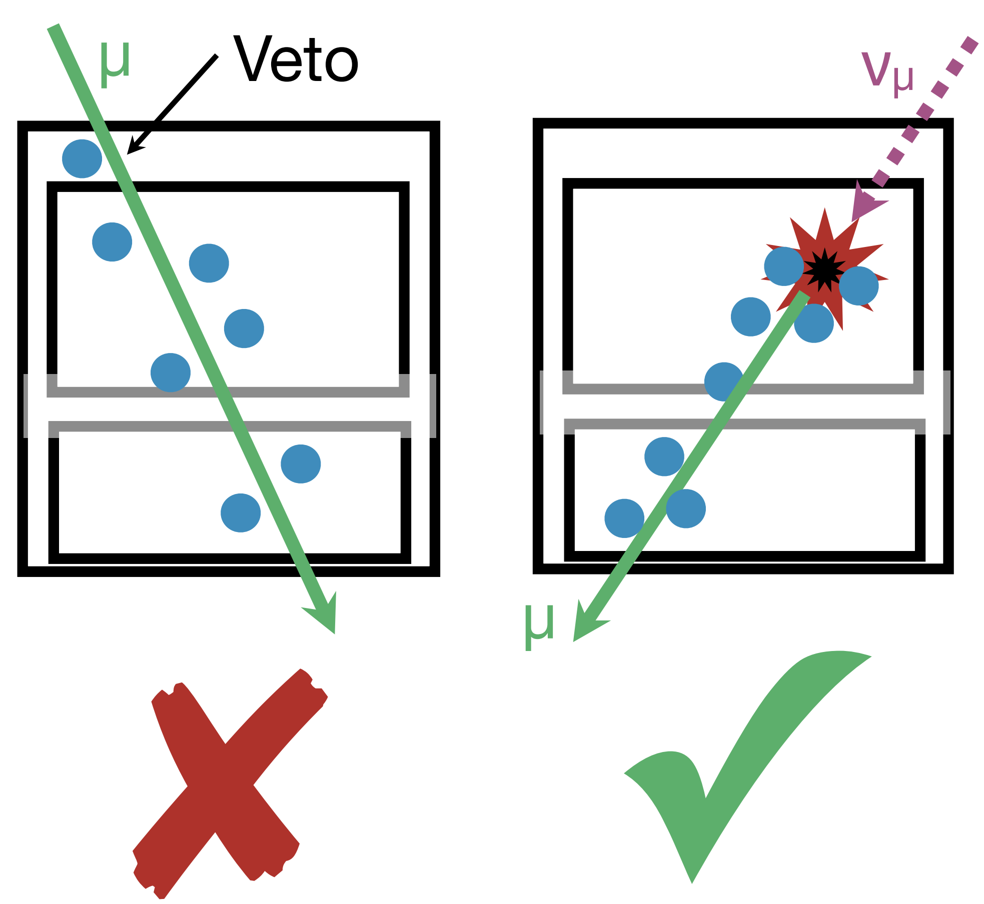

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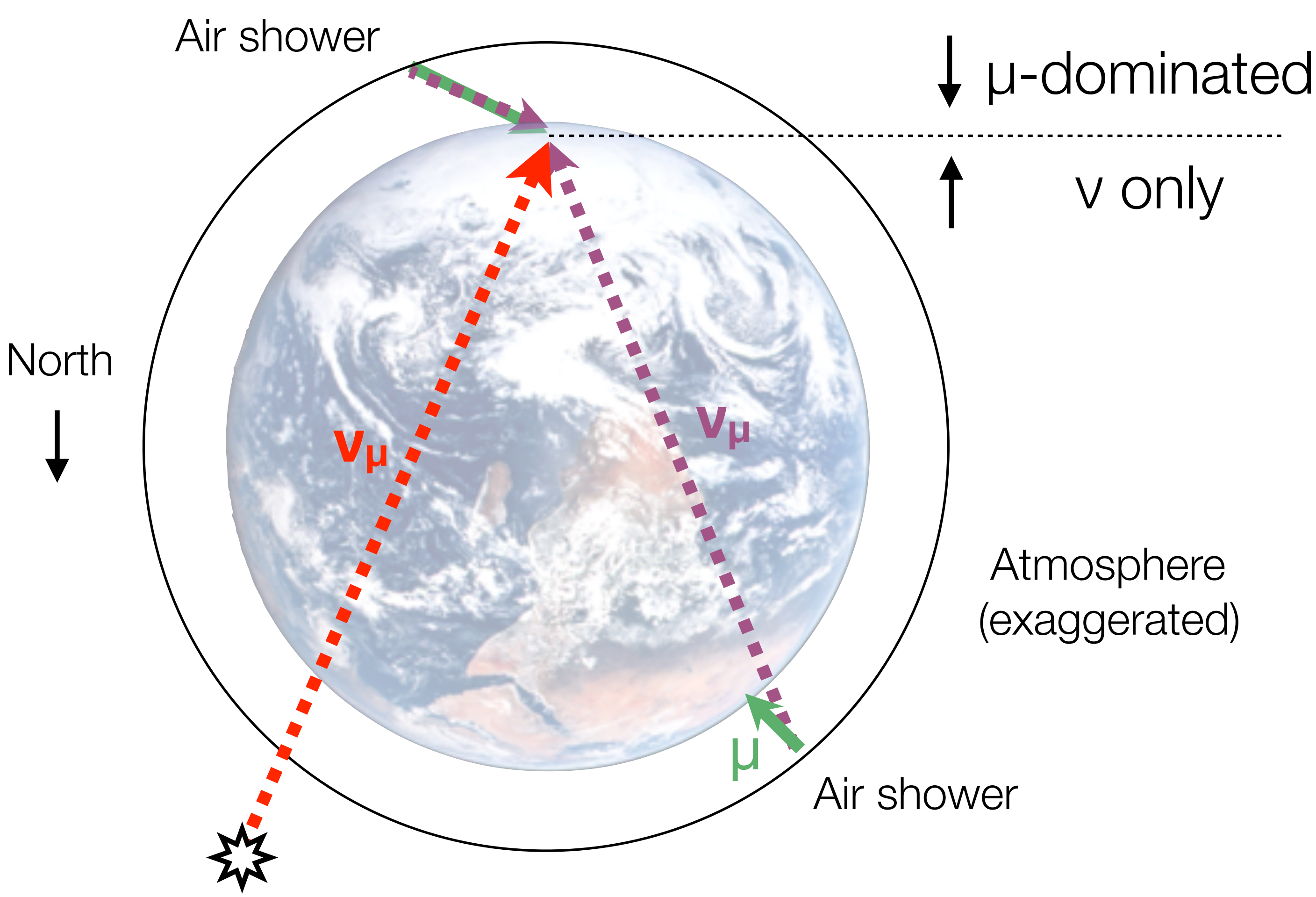

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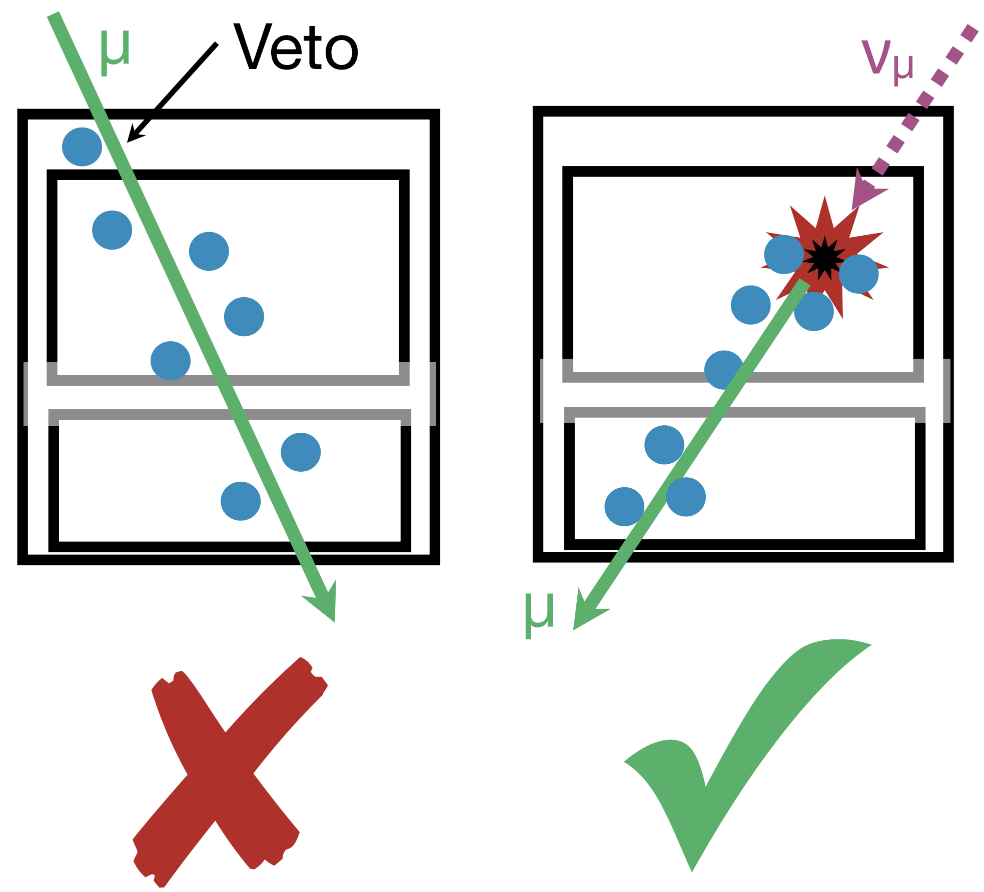

- Veto detects penetrating muons
- Effective volume smaller than detector
- Sensitive to all flavors
- Sensitive to the entire sky
- Signal dominated above ~10-100 TeV

Many different analyses

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Low energy neutrinos

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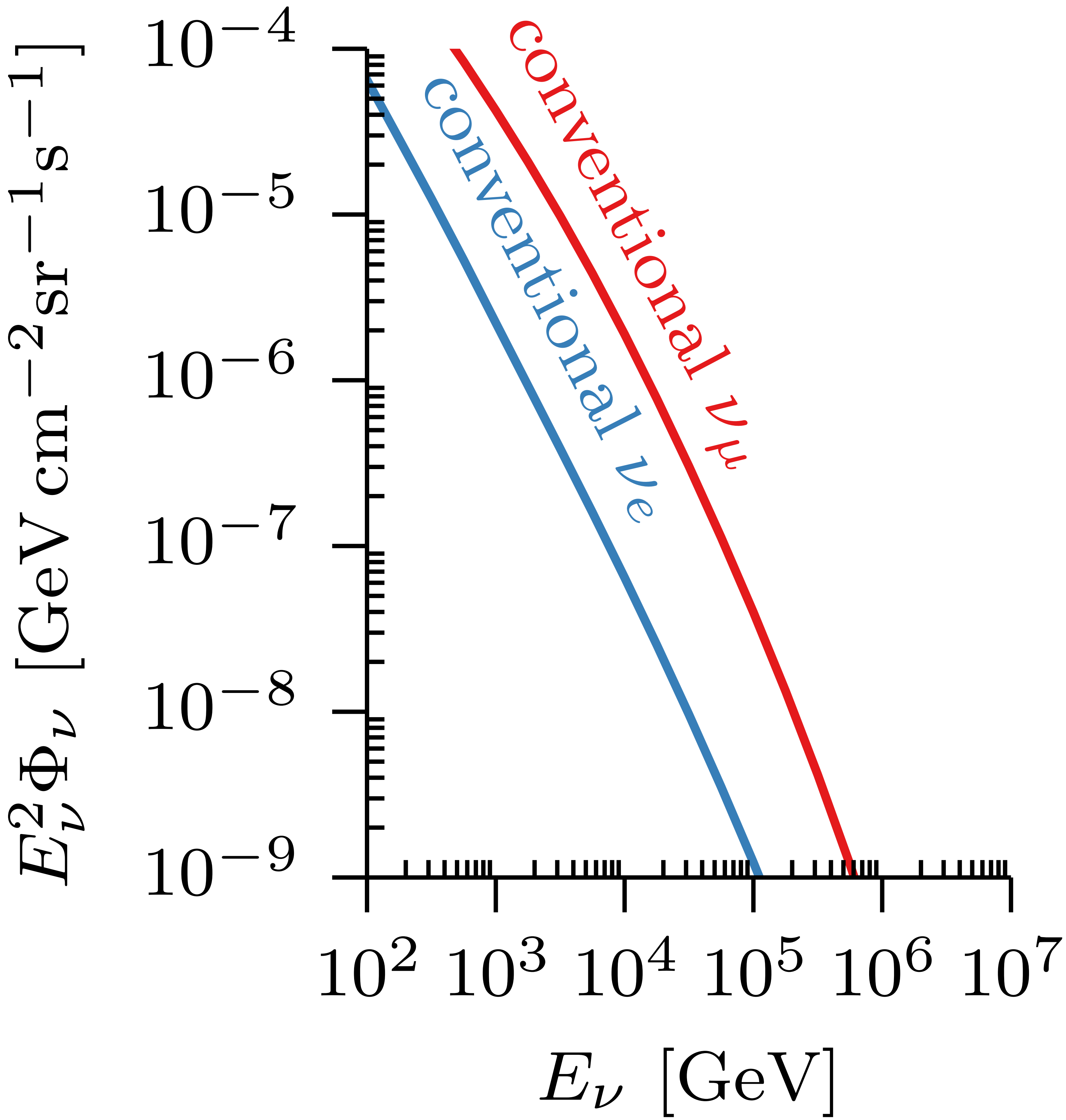
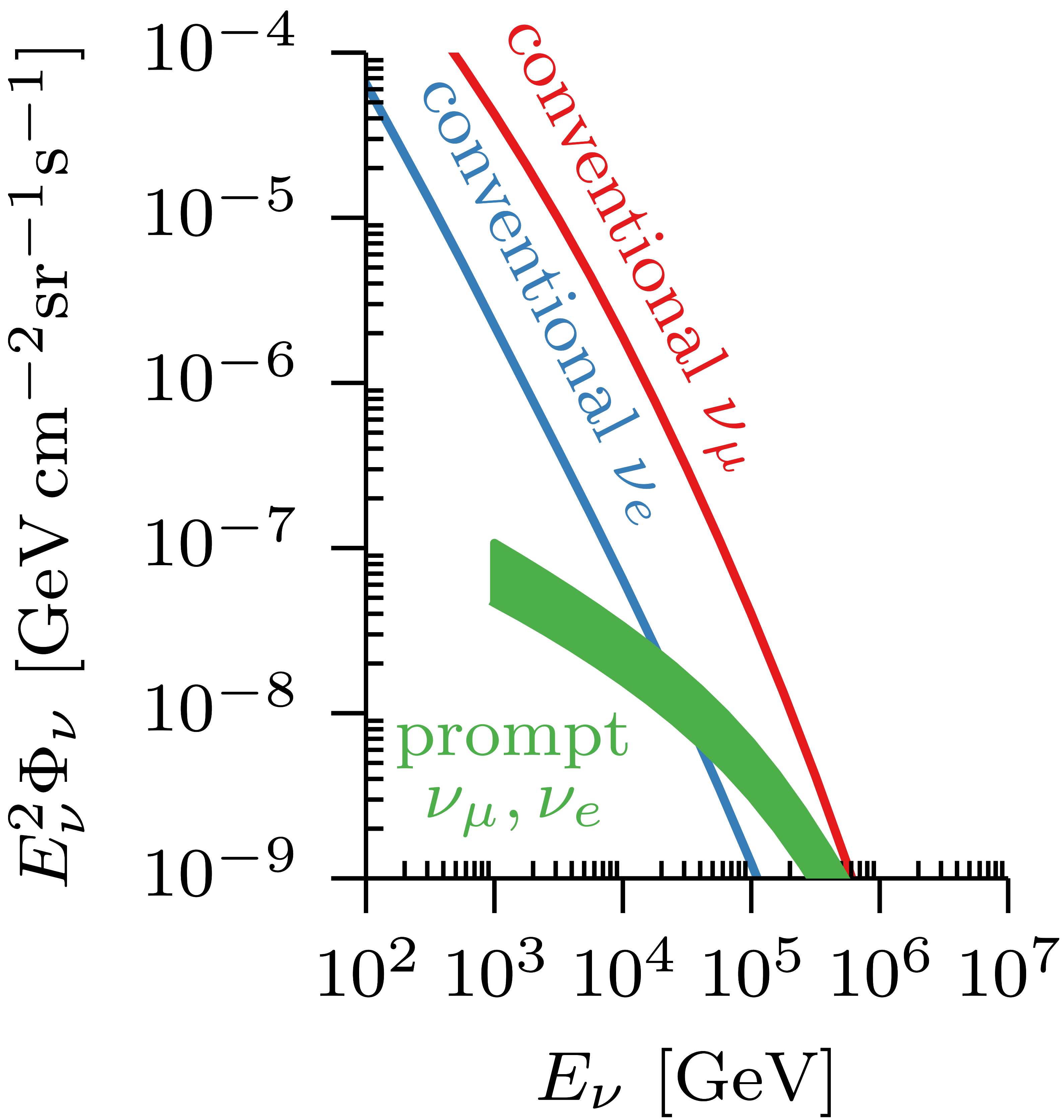
Neutrino spectra at Earth



Atmospheric pion/kaon (conventional) component:

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

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
- Not yet conclusively observed

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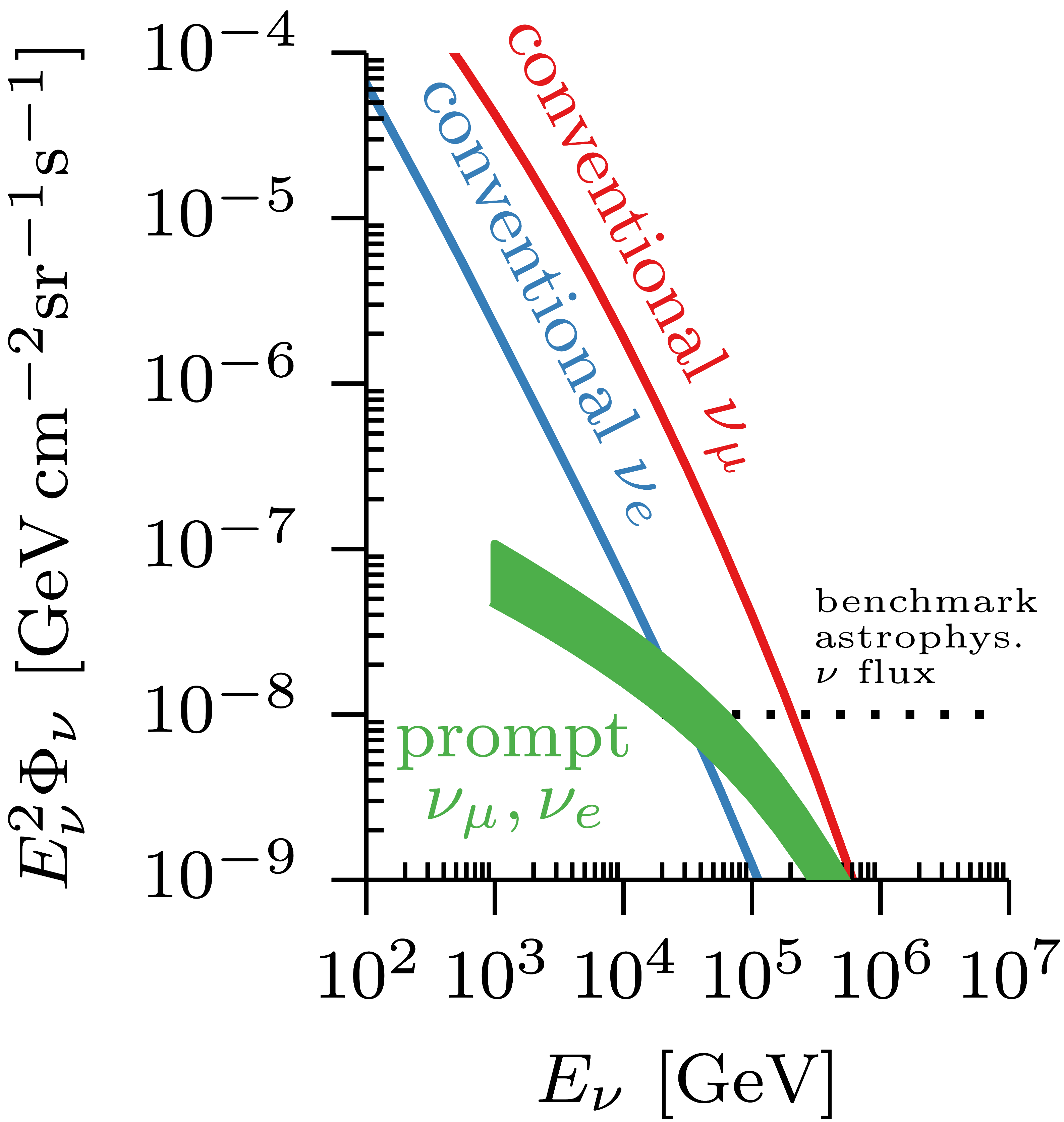

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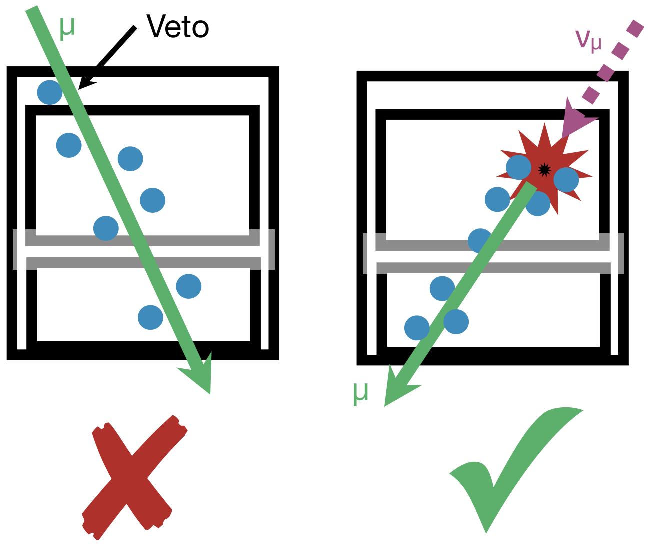
- Equal parts ν_μ and ν_e
- Isotropic
- Not yet conclusively observed

Astrophysical component:

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

Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



C. Kopper et al, PoS(ICRC2015)1081

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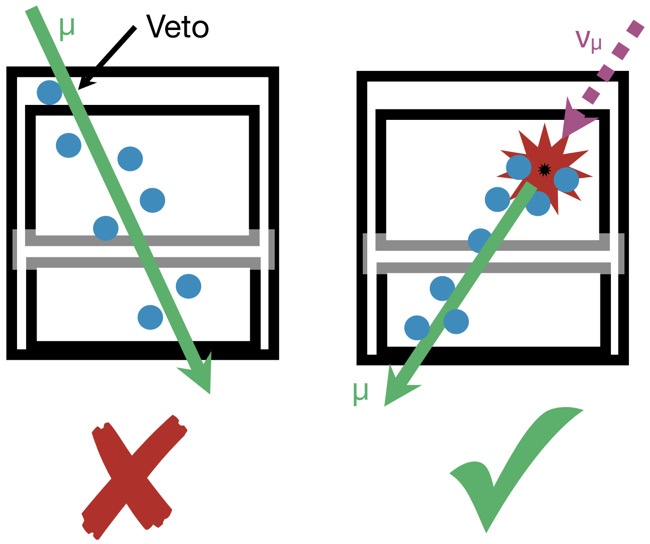
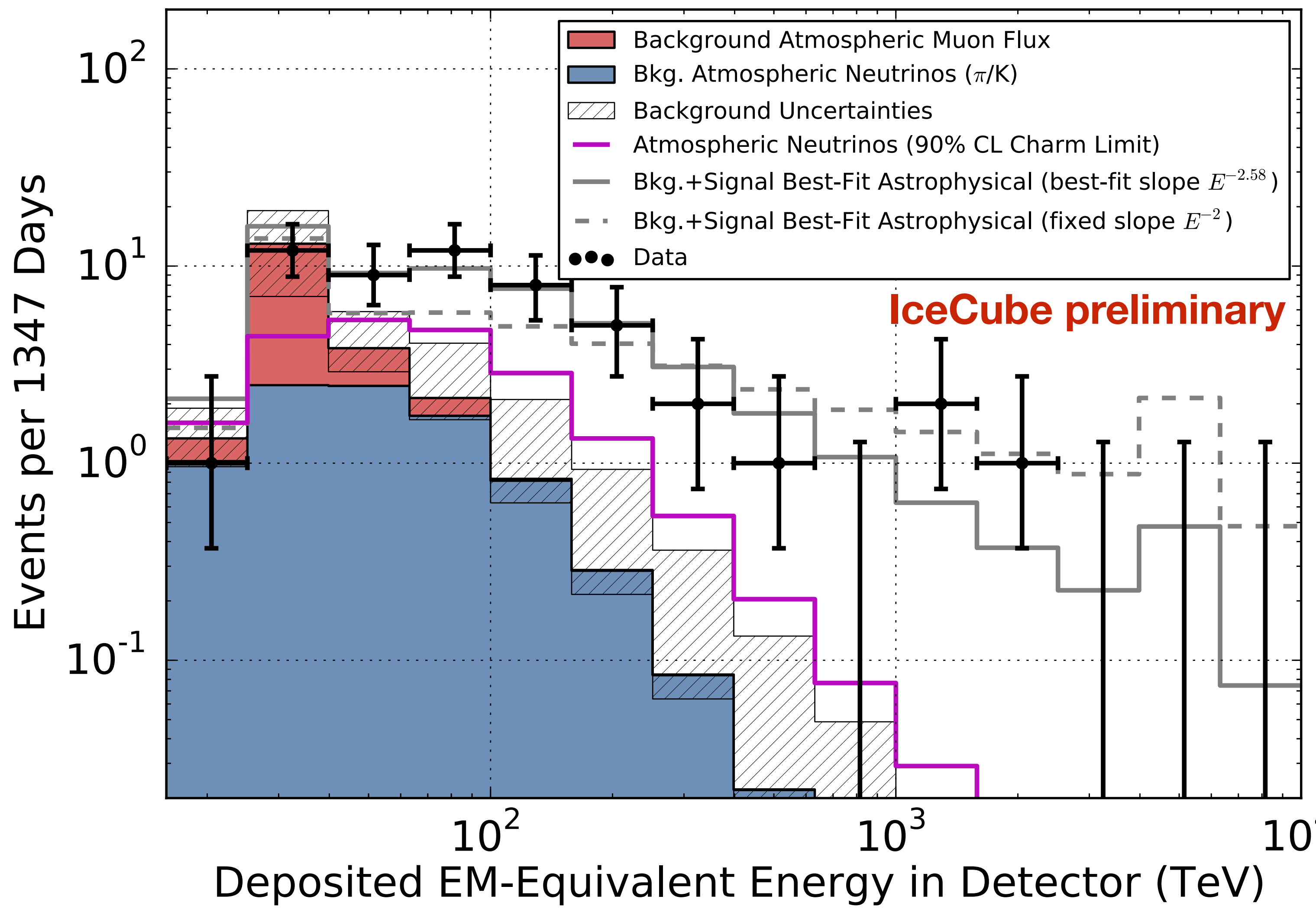


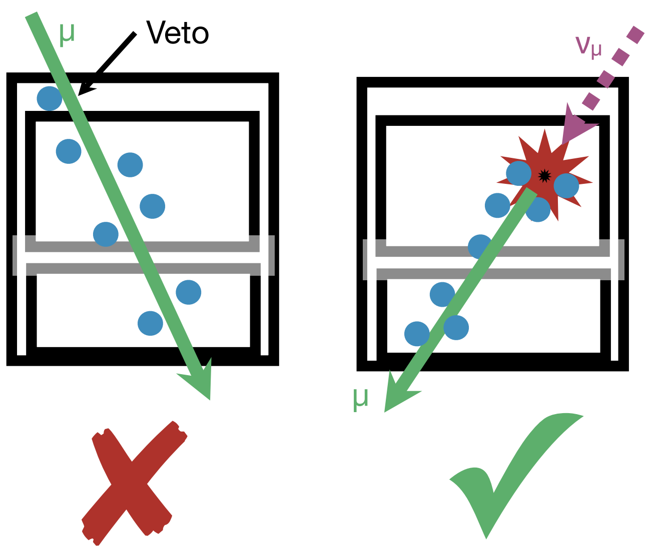
Deposited energy



C. Kopper et al, PoS(ICRC2015)1081

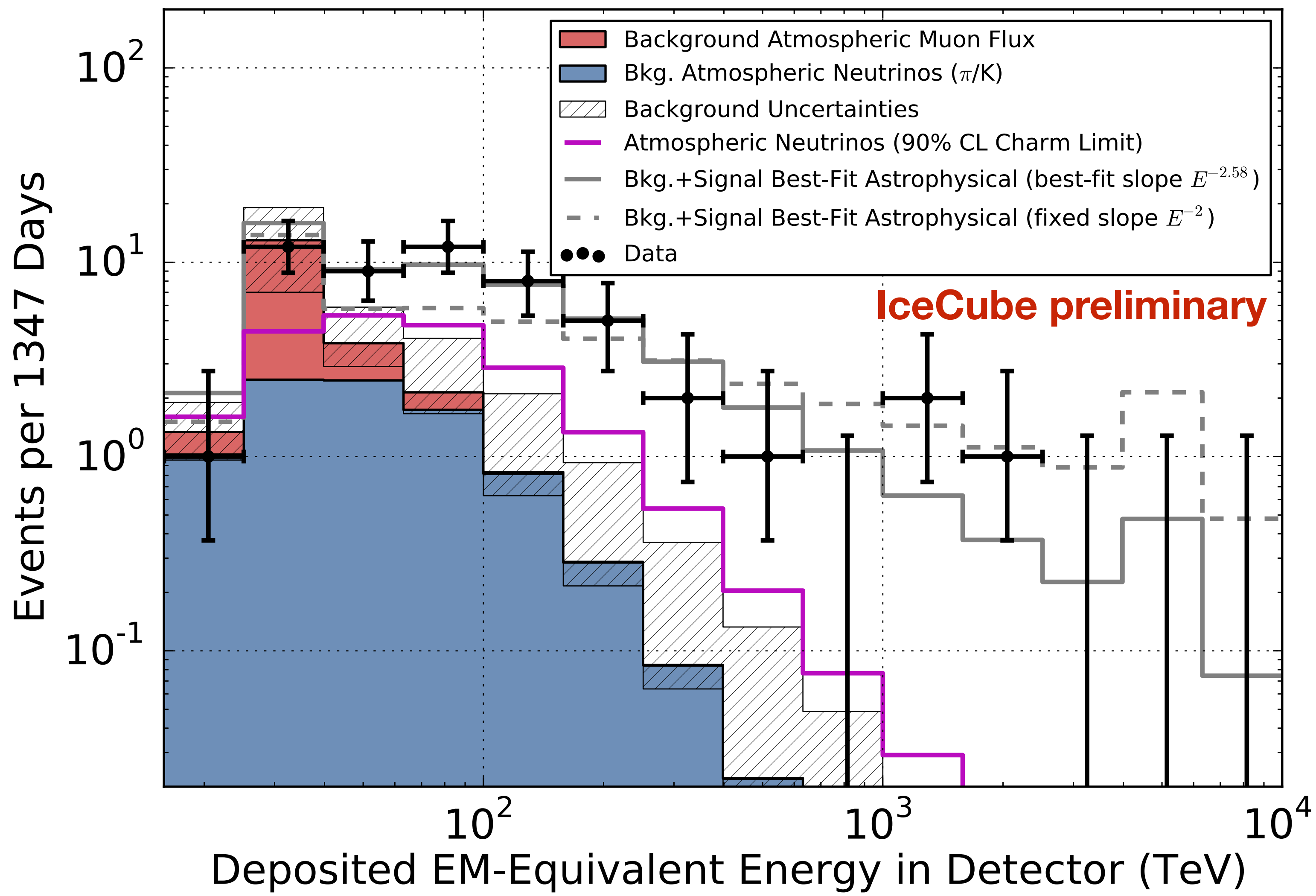
Evidence for high-energy astrophysical neutrinos

- Selected high-energy starting events in IceCube



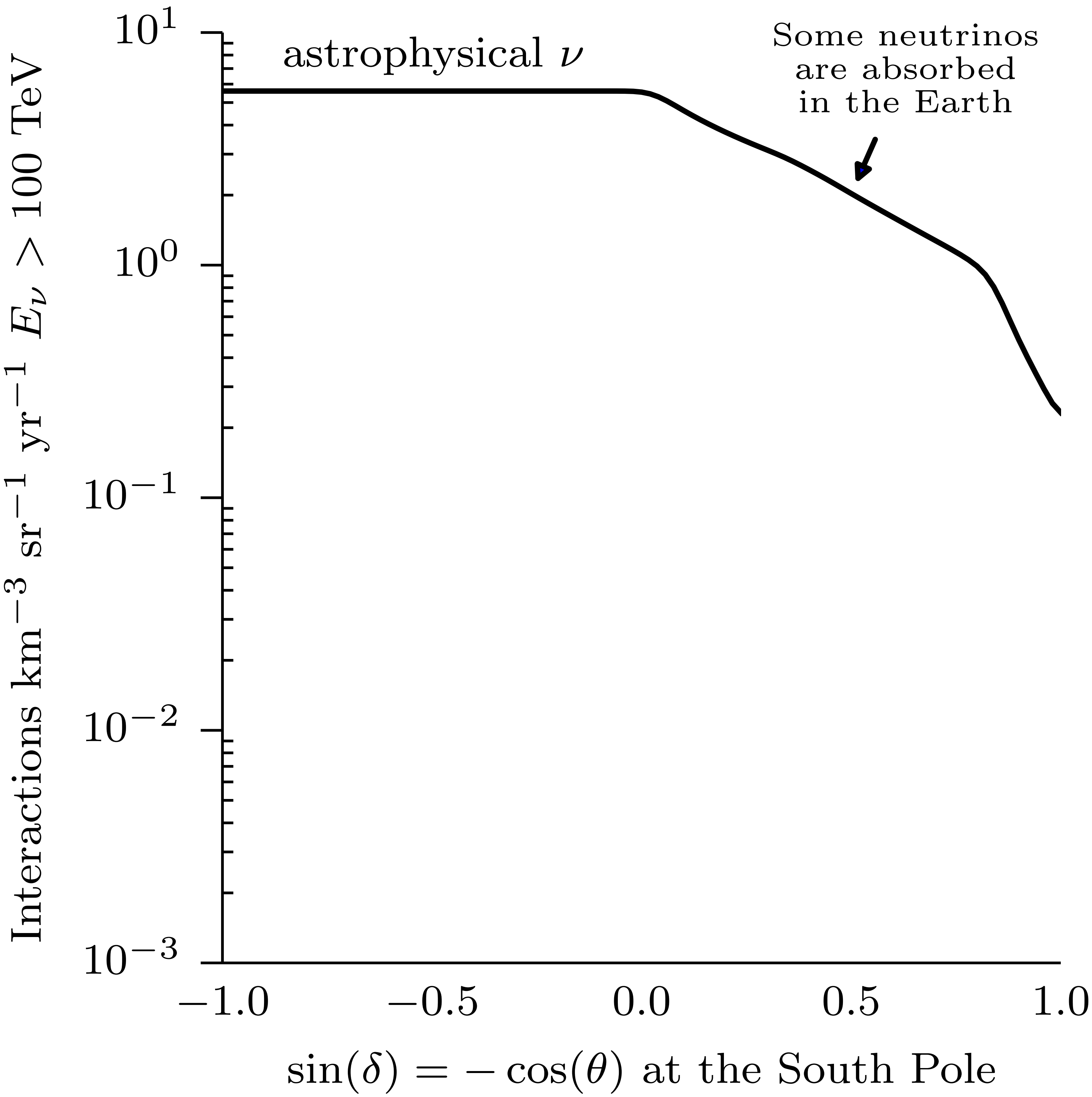
- 3 cascades over 1 PeV in 4 years of data
- > 5.7 σ evidence for astrophysical neutrinos

Deposited energy



C. Kopper et al, PoS(ICRC2015)1081

Atmospheric neutrino self-veto



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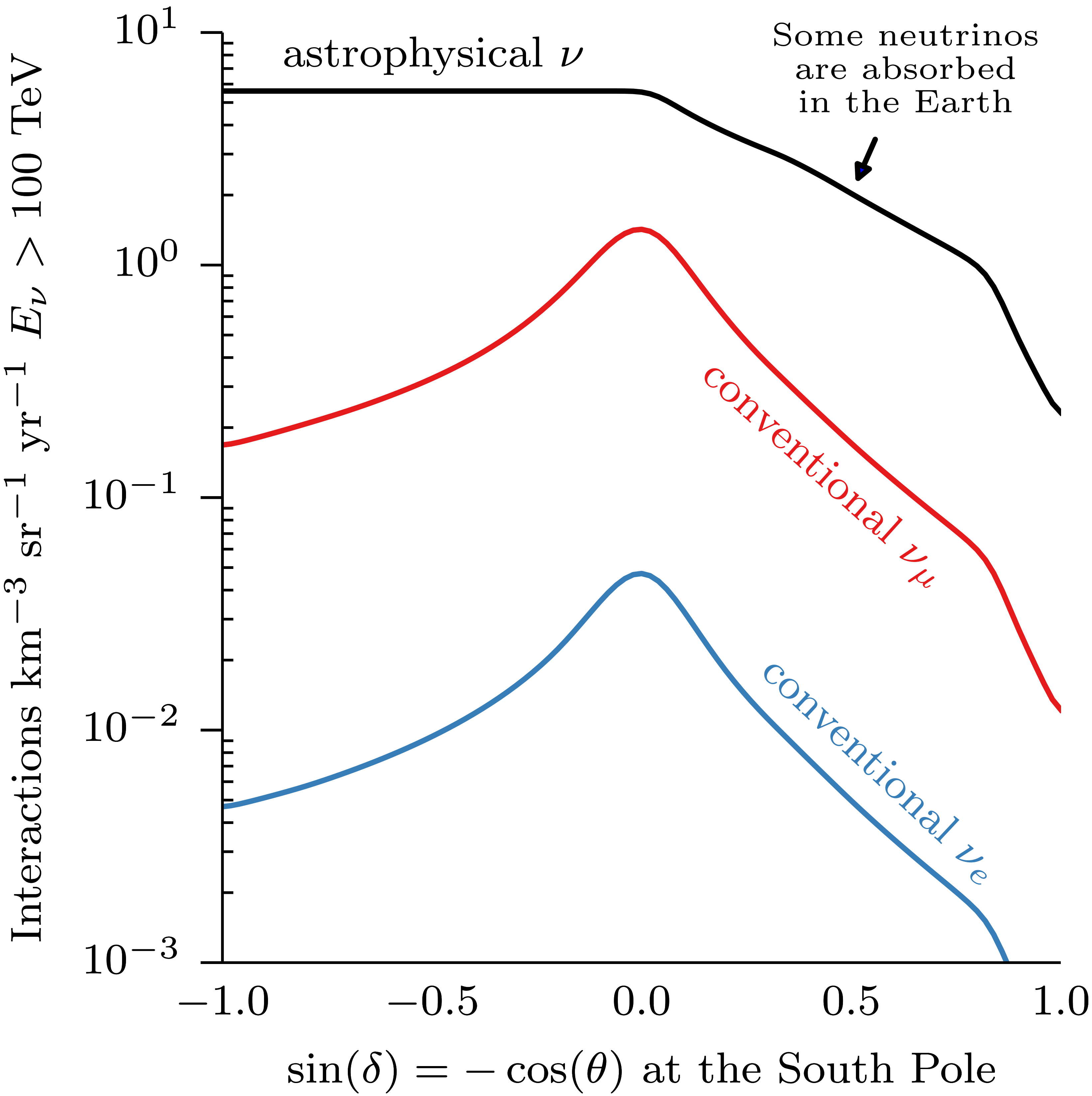

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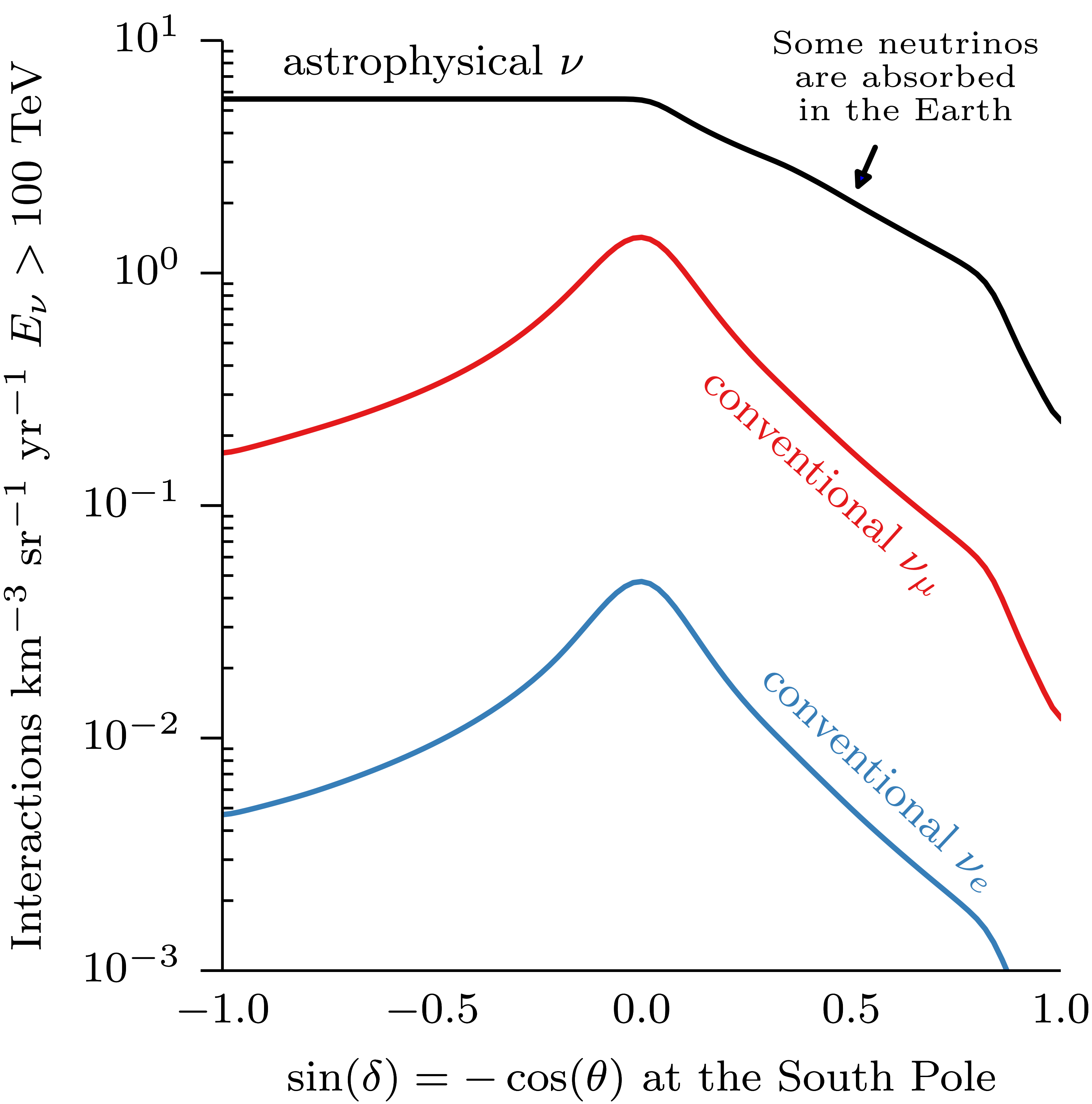
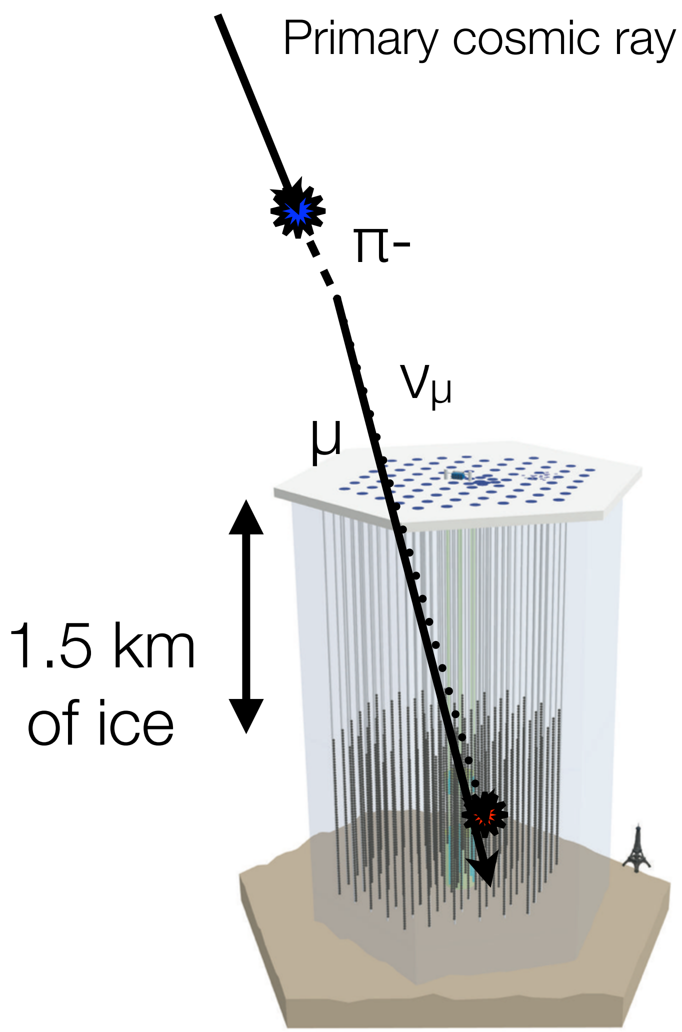


An active muon veto removes down-going atmospheric neutrinos.



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

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

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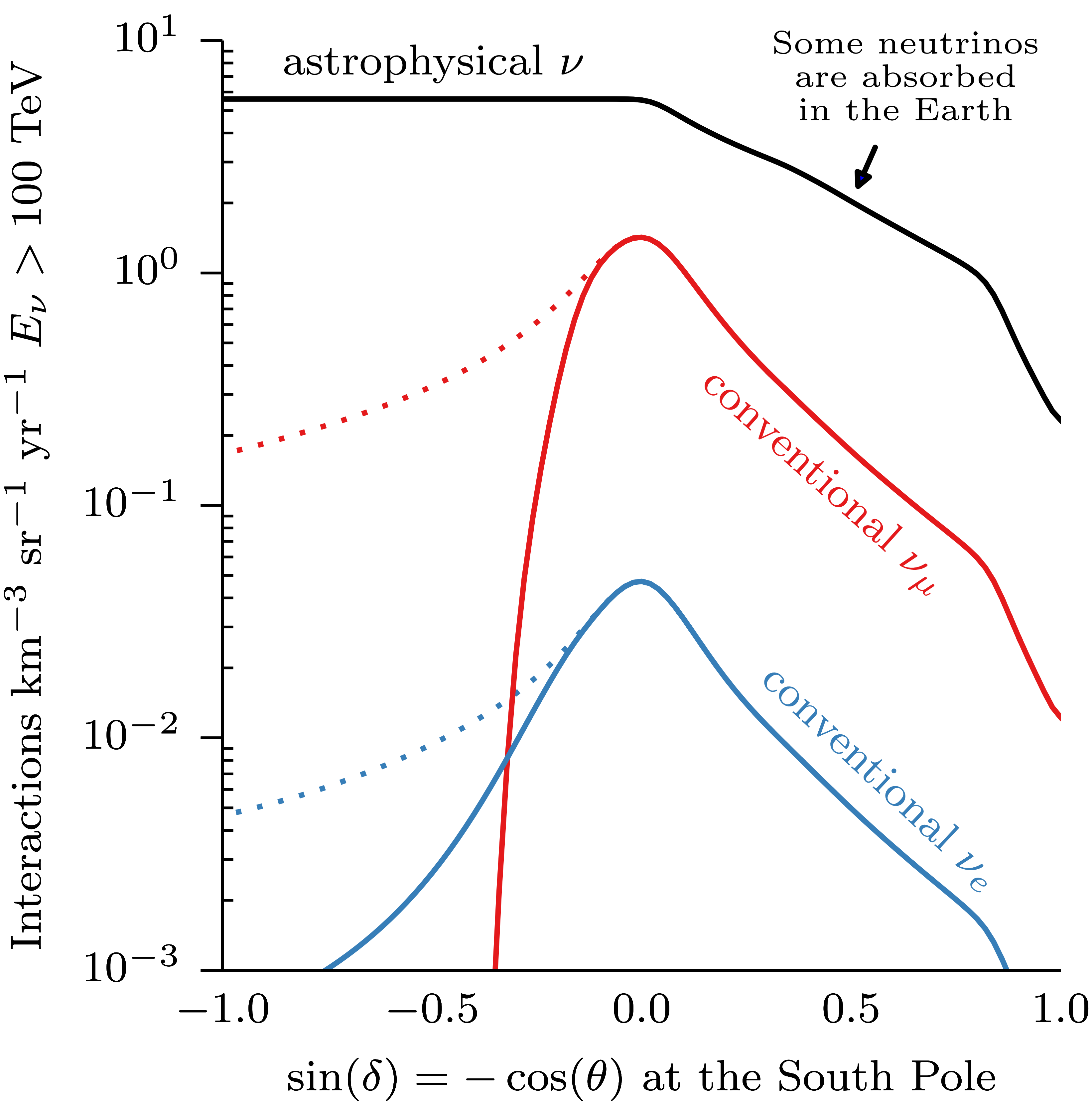

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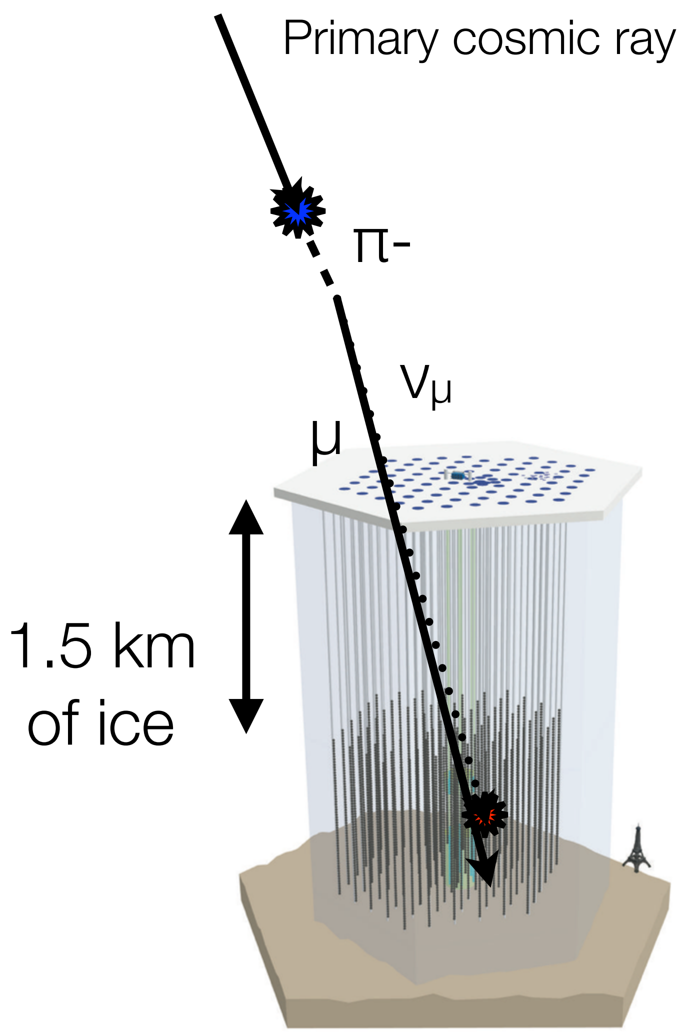

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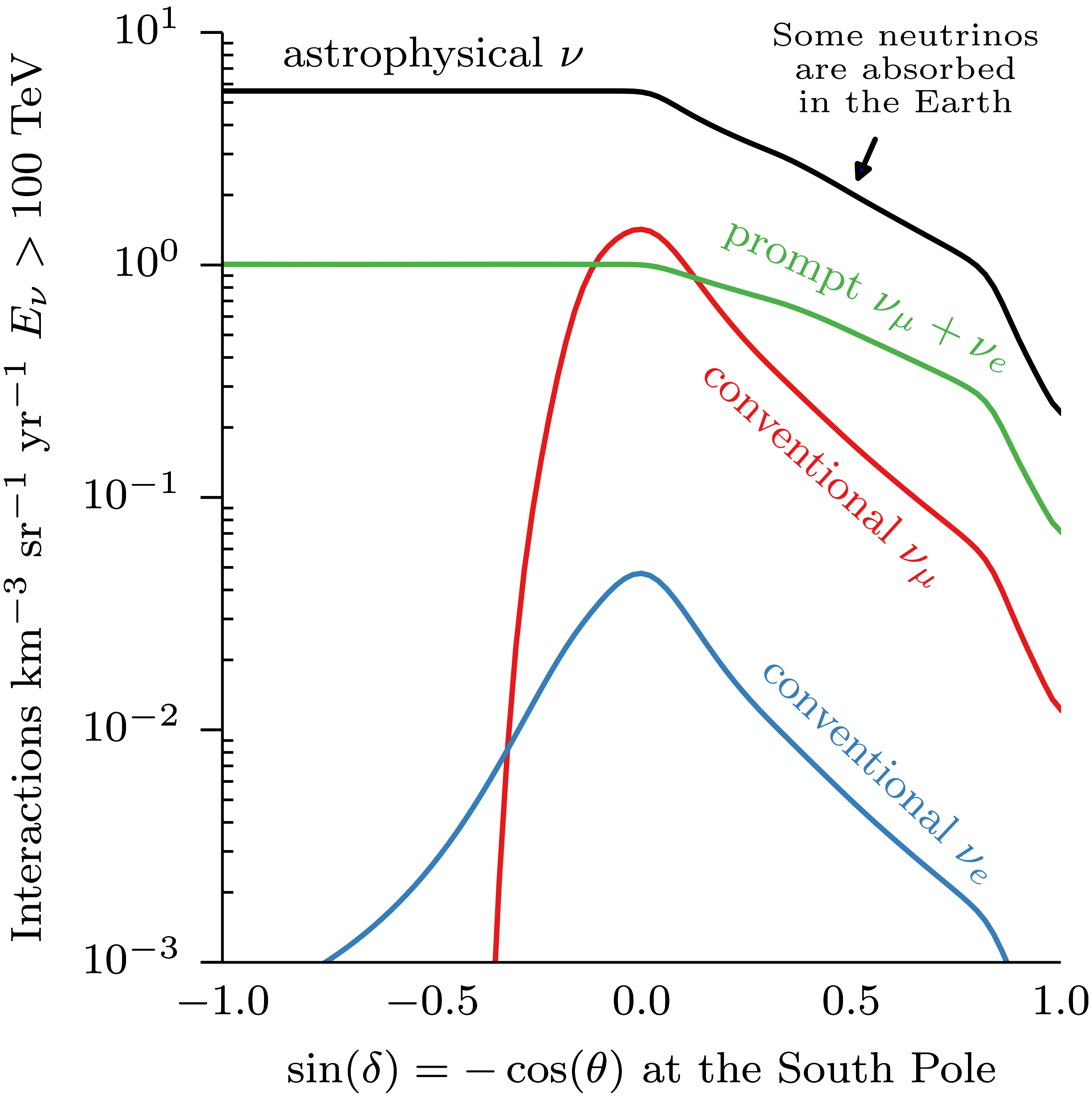

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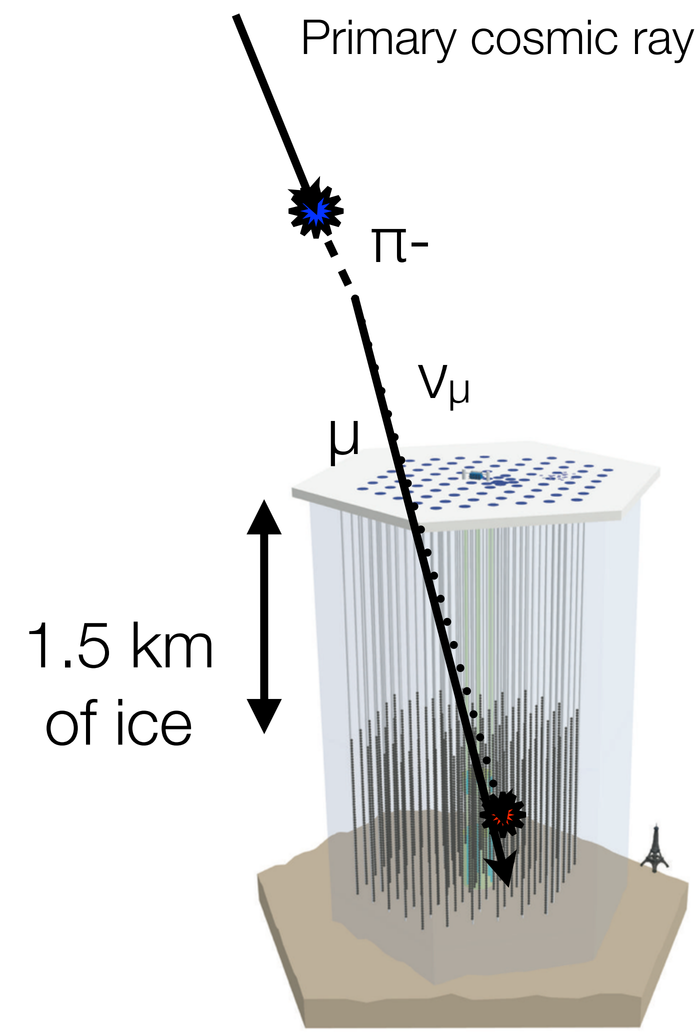

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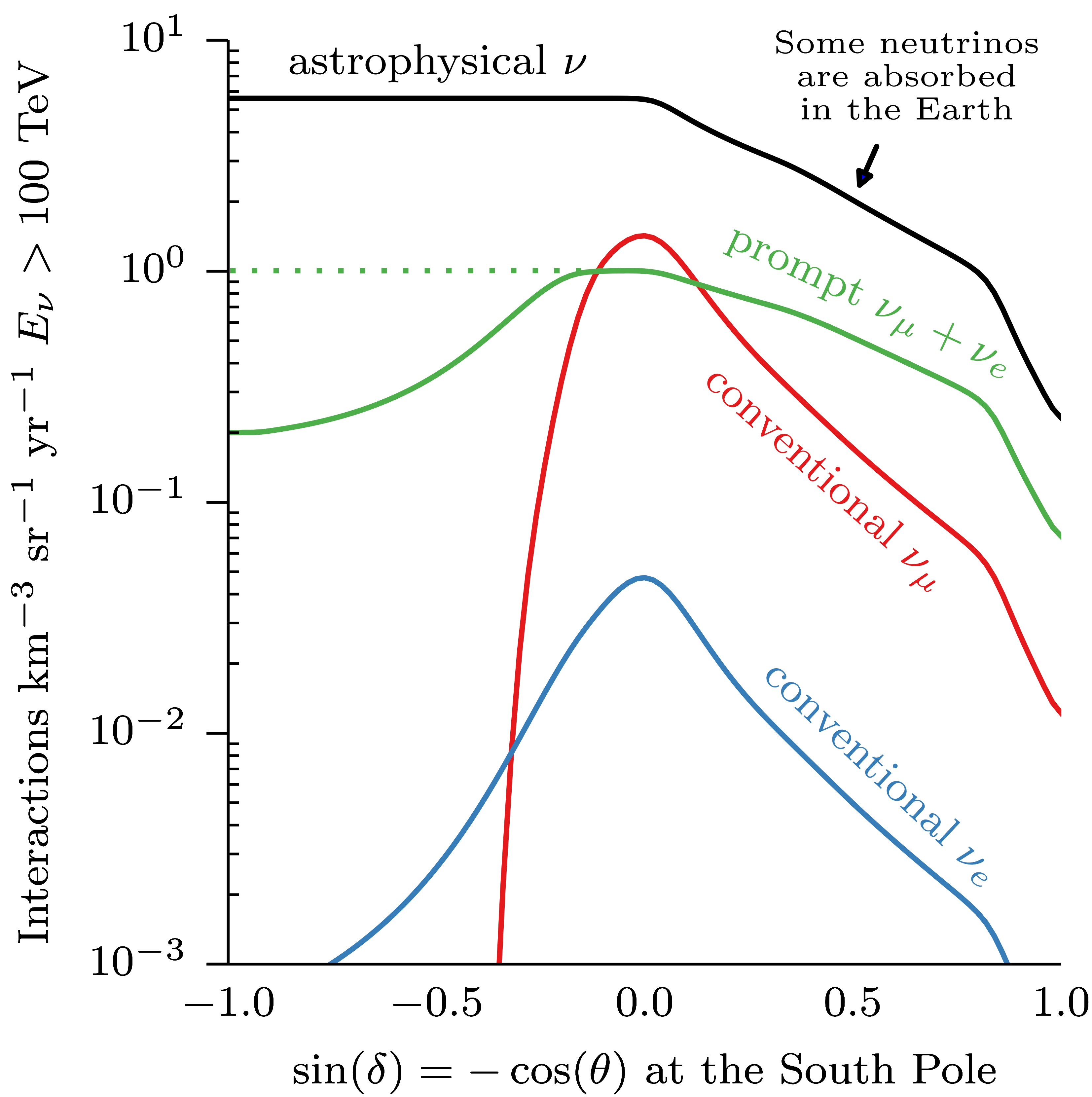
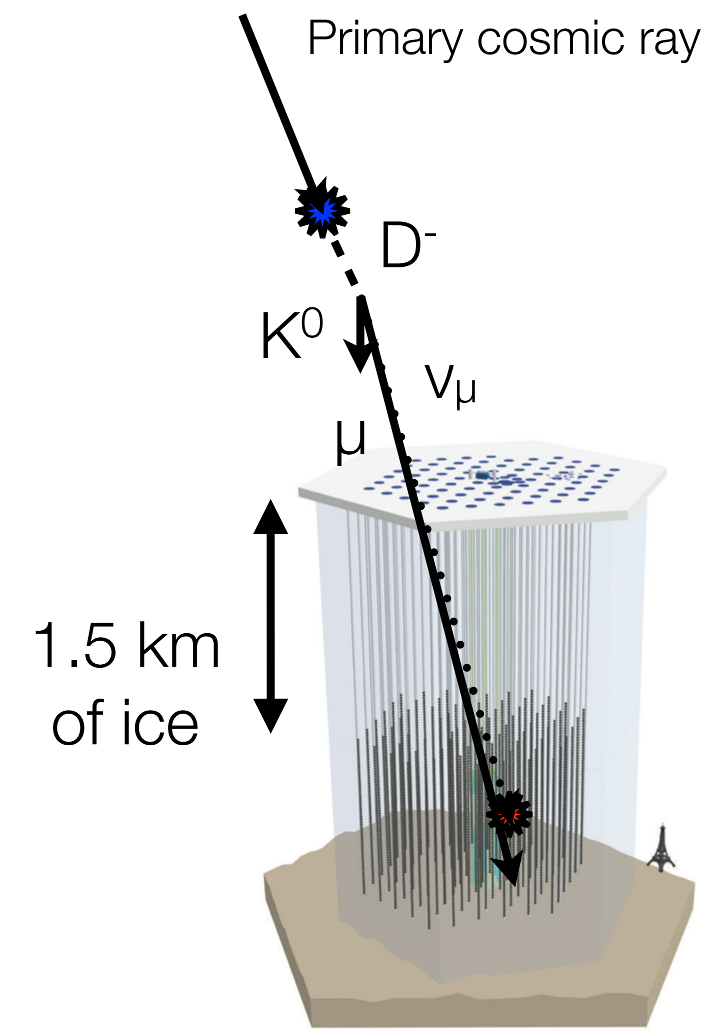


Prompt atmospheric neutrinos are vetoed, too.



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

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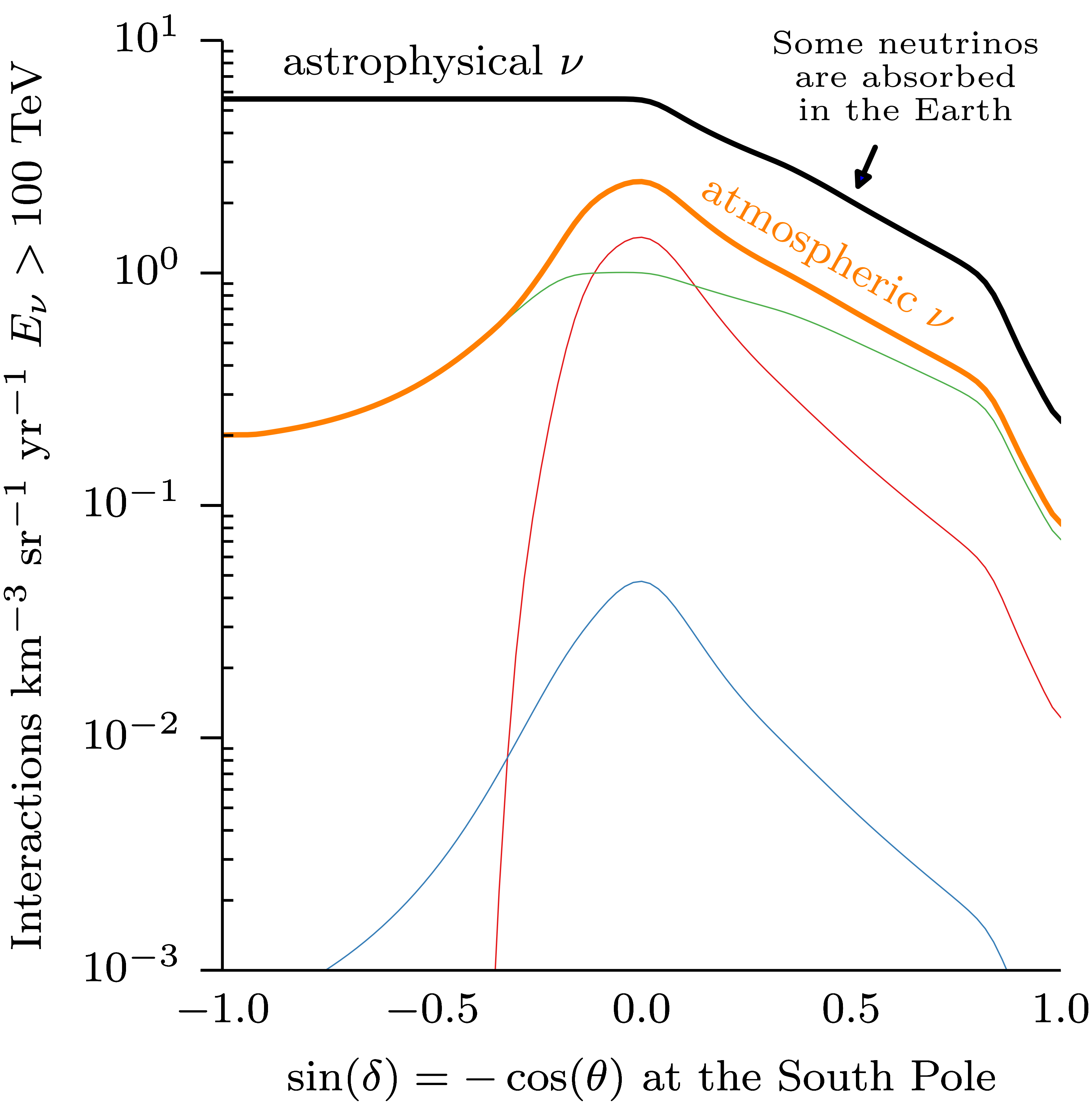


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

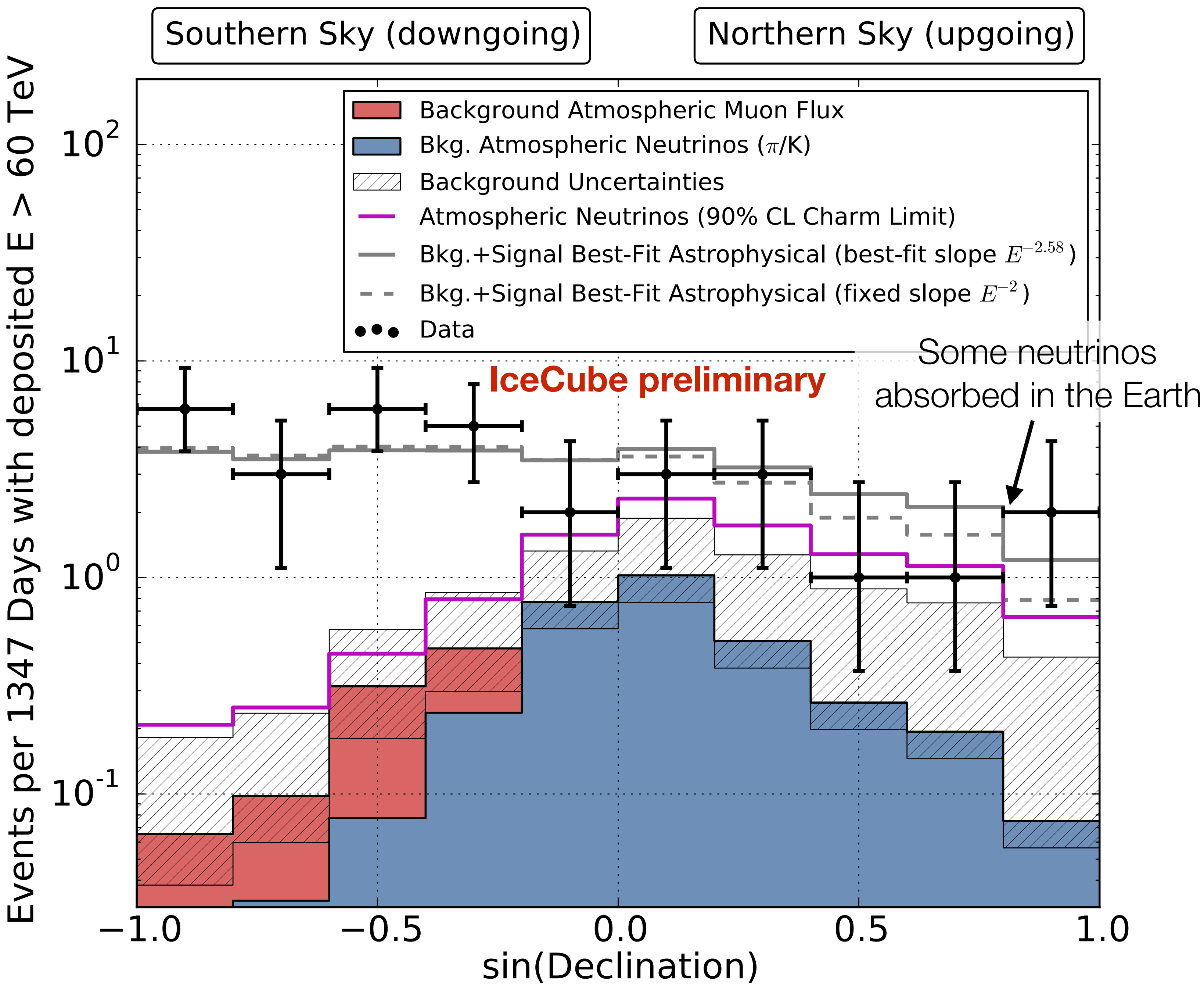
Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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



C. Kopper et al, PoS(ICRC2015)1081

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4-year dataset released 2015-10-21: http://icecube.wisc.edu/science/data/HE-nu-2010-2014

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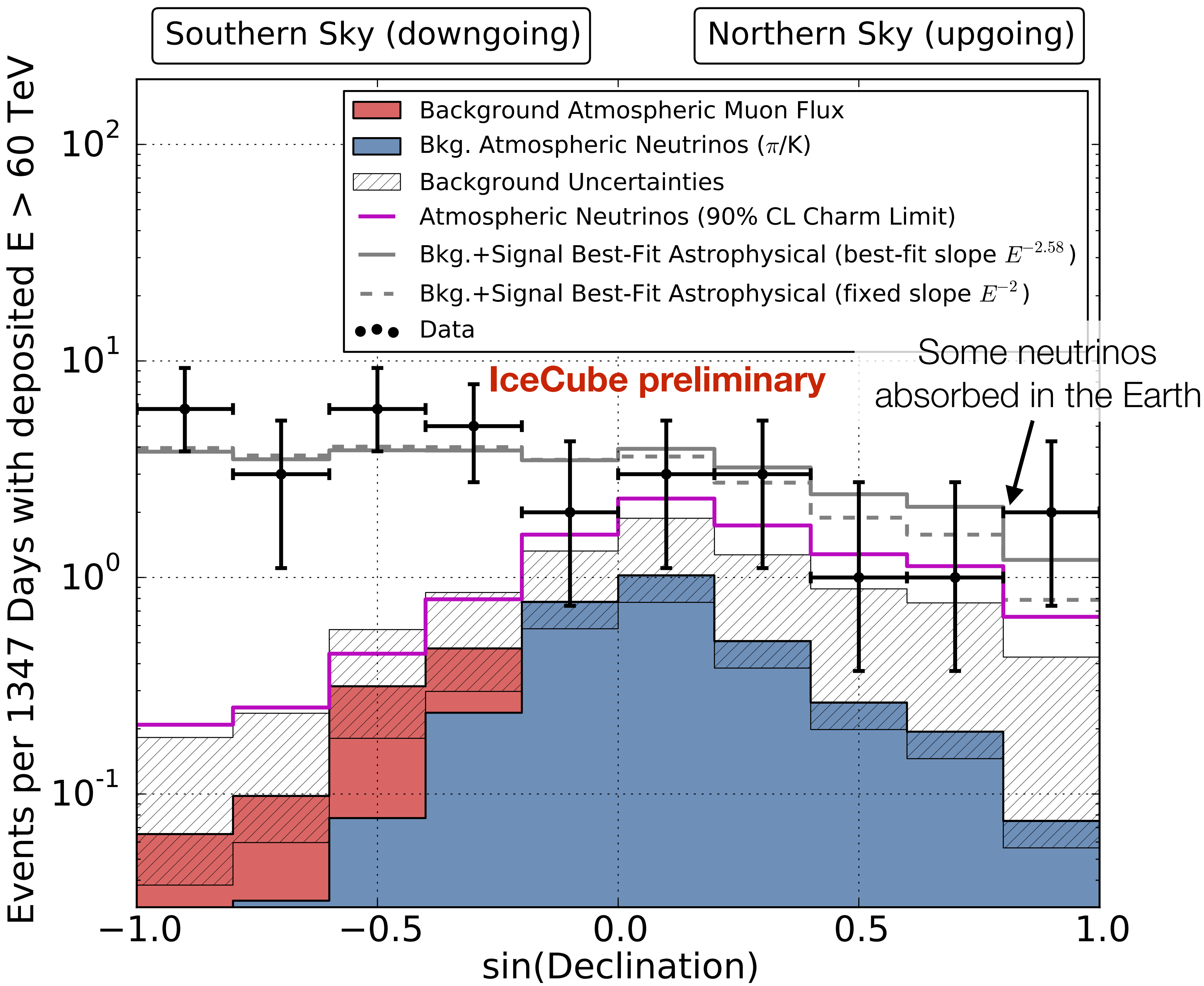
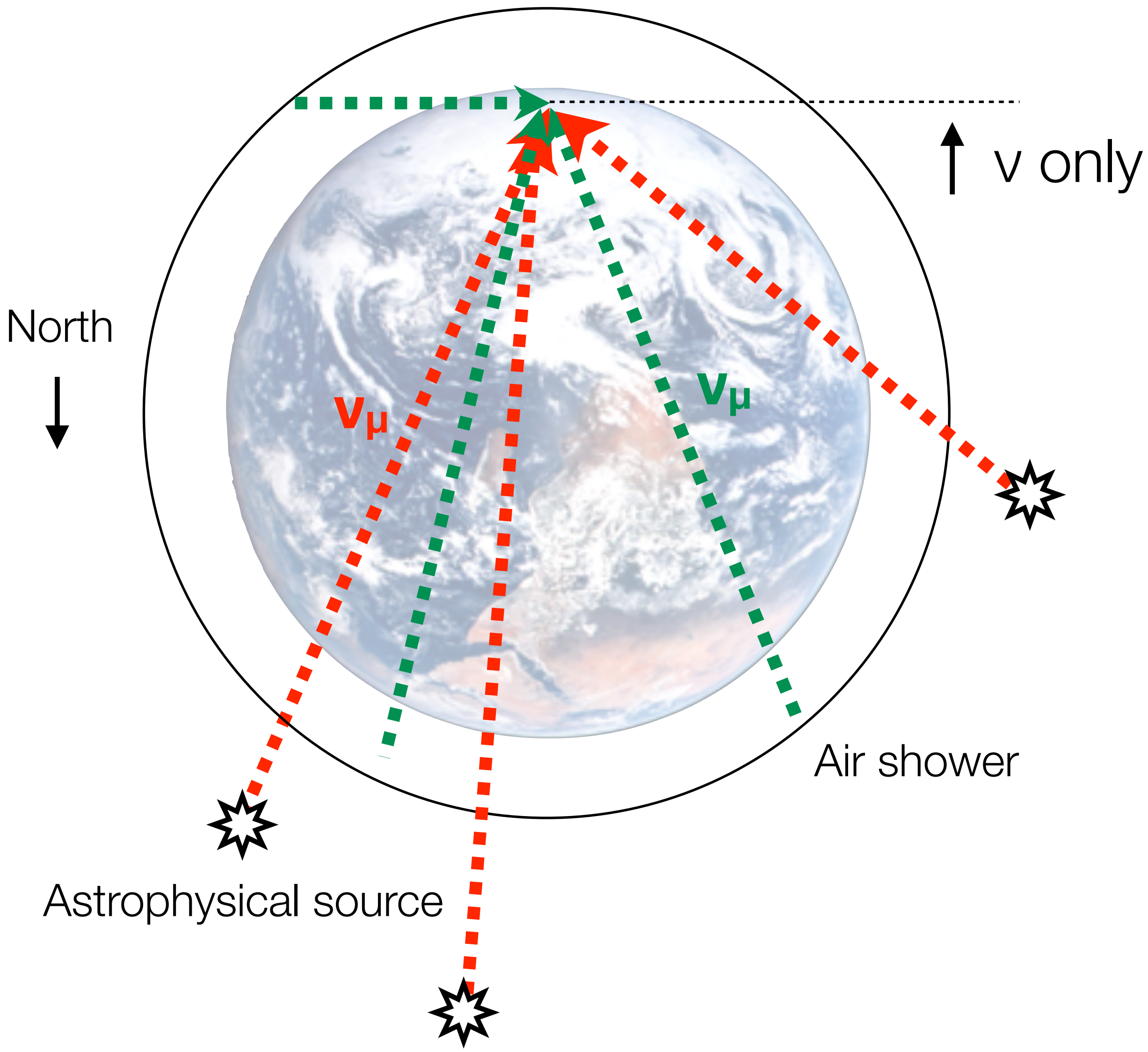
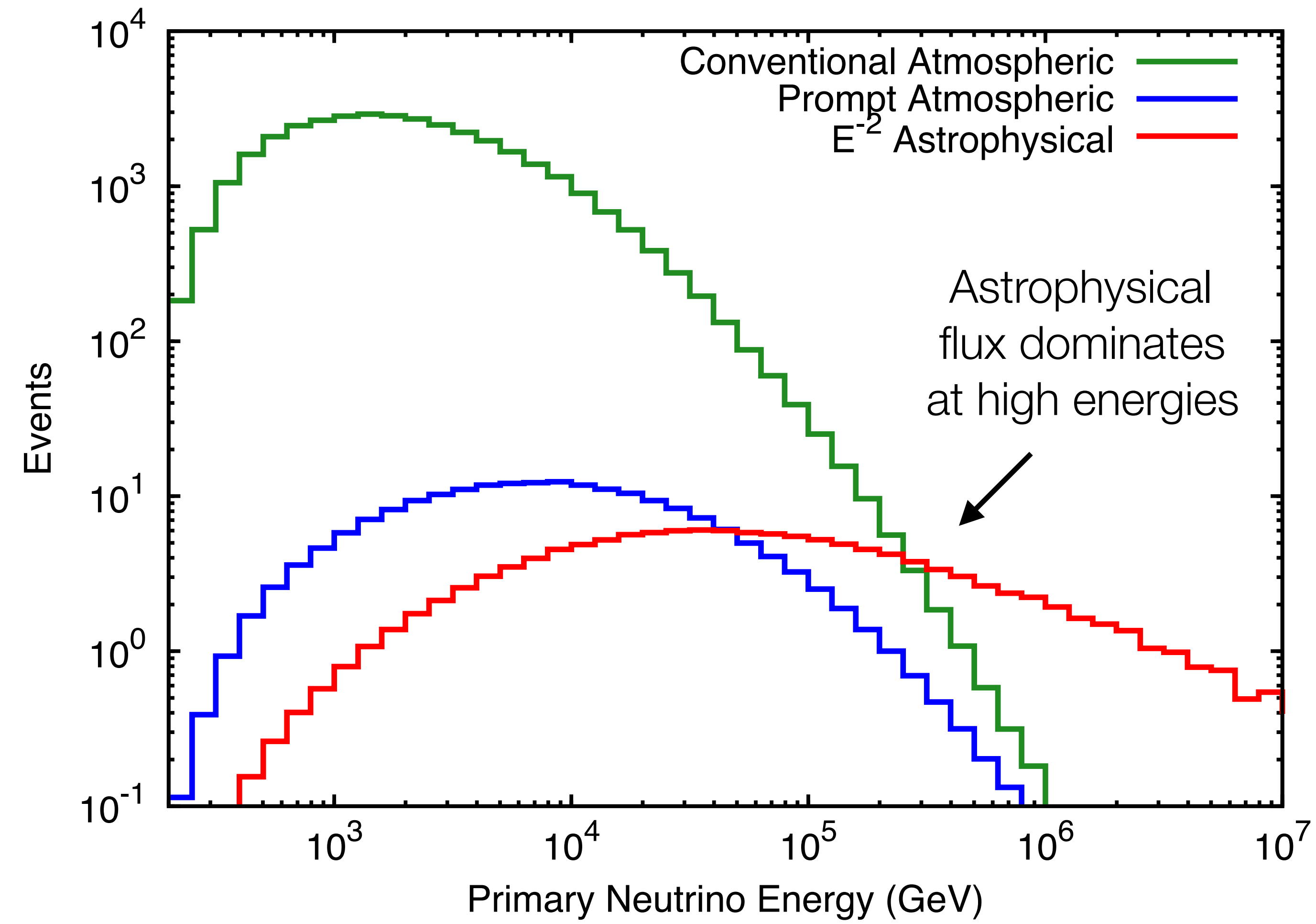


C. Kopper et al, PoS(ICRC2015)1081

What about the northern sky and ν_μ?

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





C. Weaver, PRL 115 (2015) 081102

We look for the same excess in incoming muons from the northern sky
High-energy muons reach the detector from km away → large effective volume
Only sensitive to CC ν_μ → explicit handle on ν_μ flux

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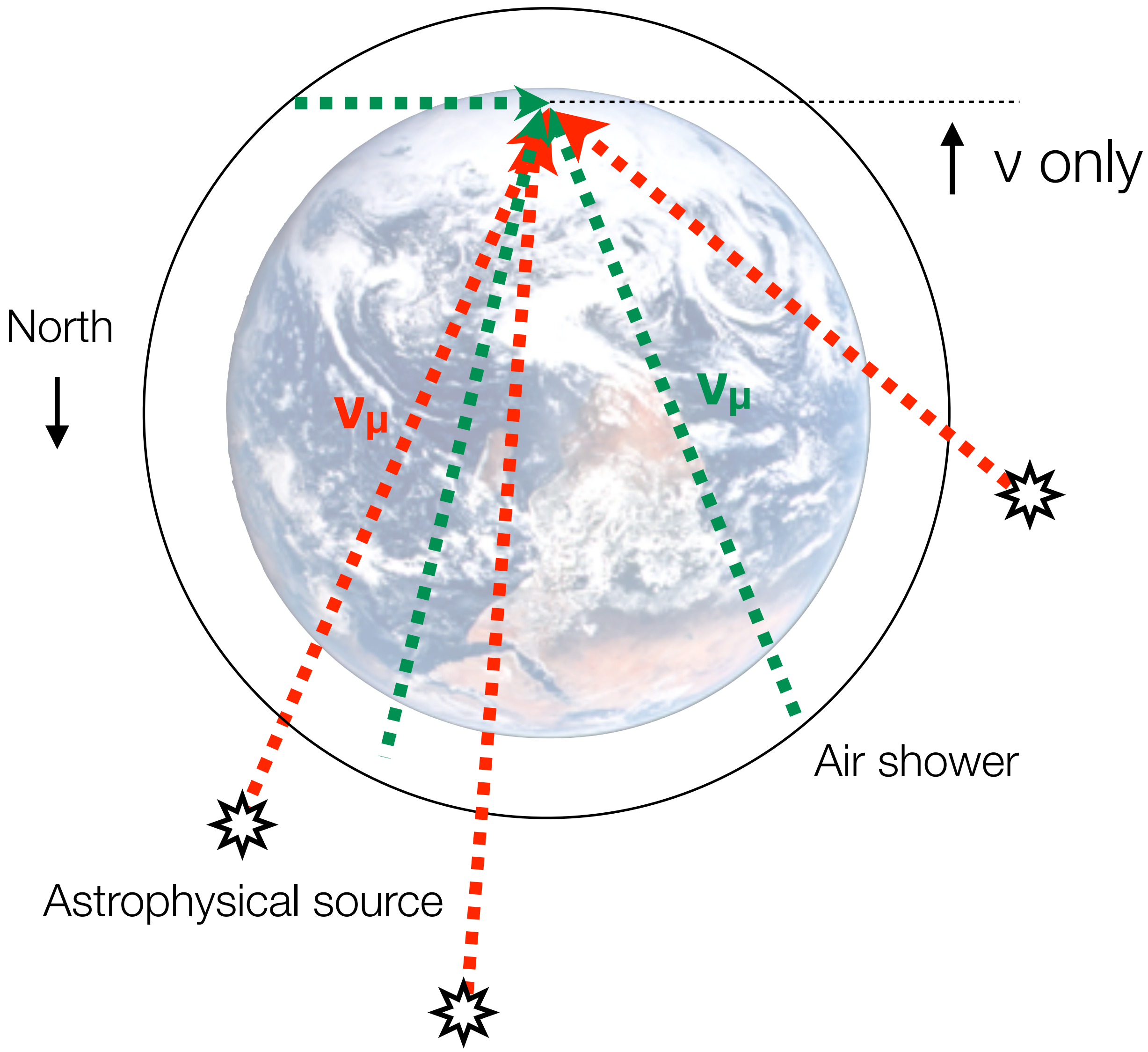

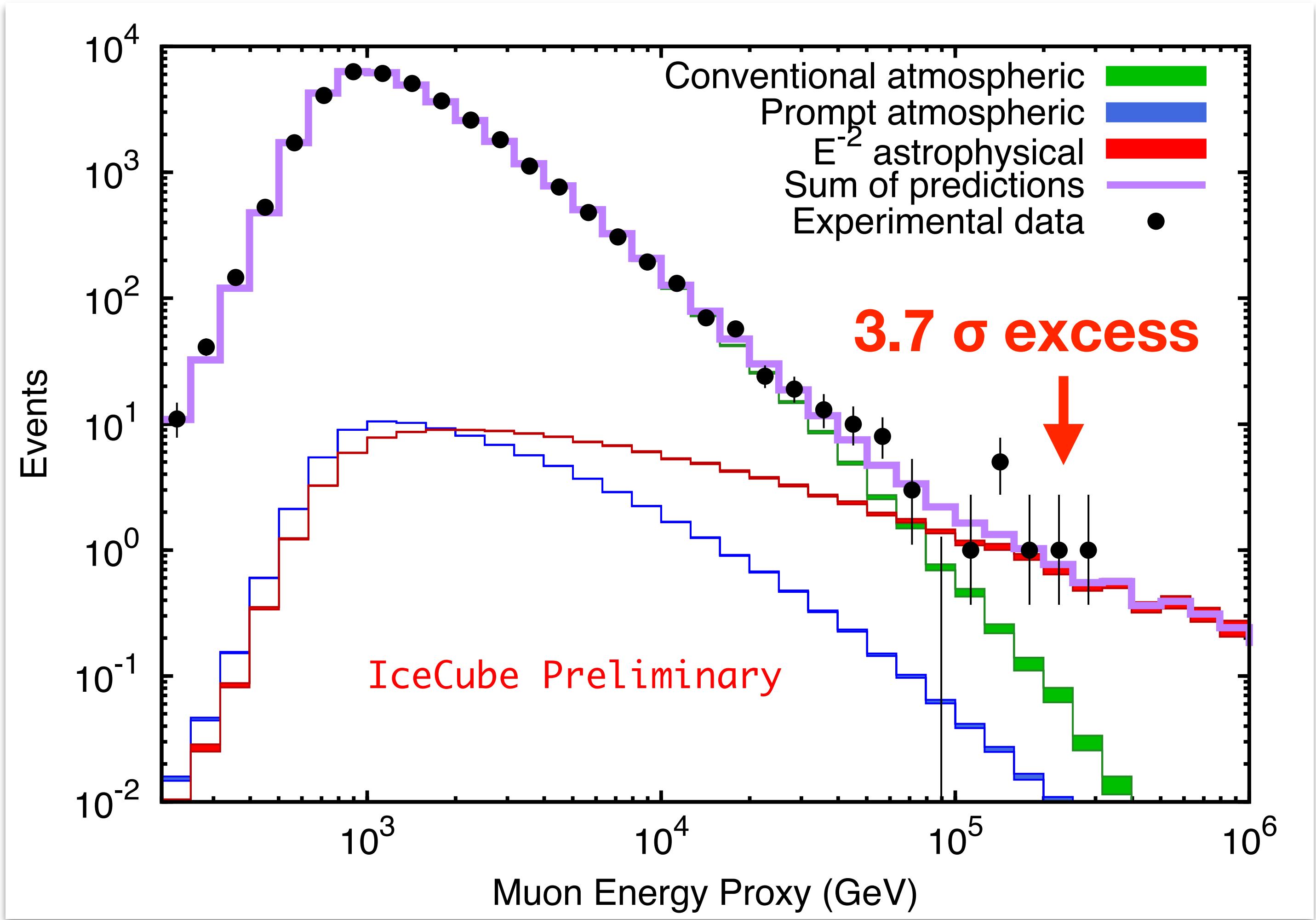

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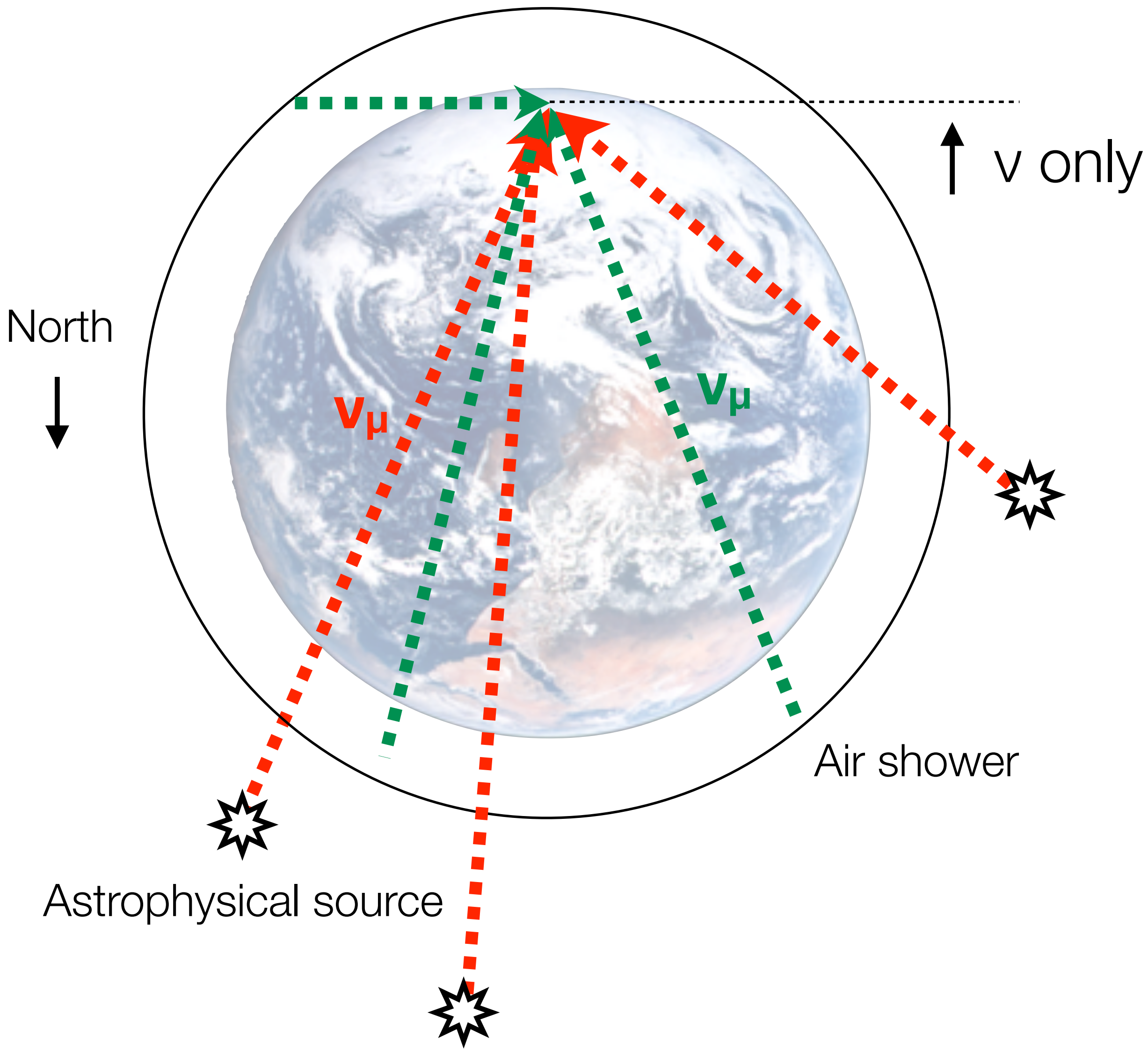

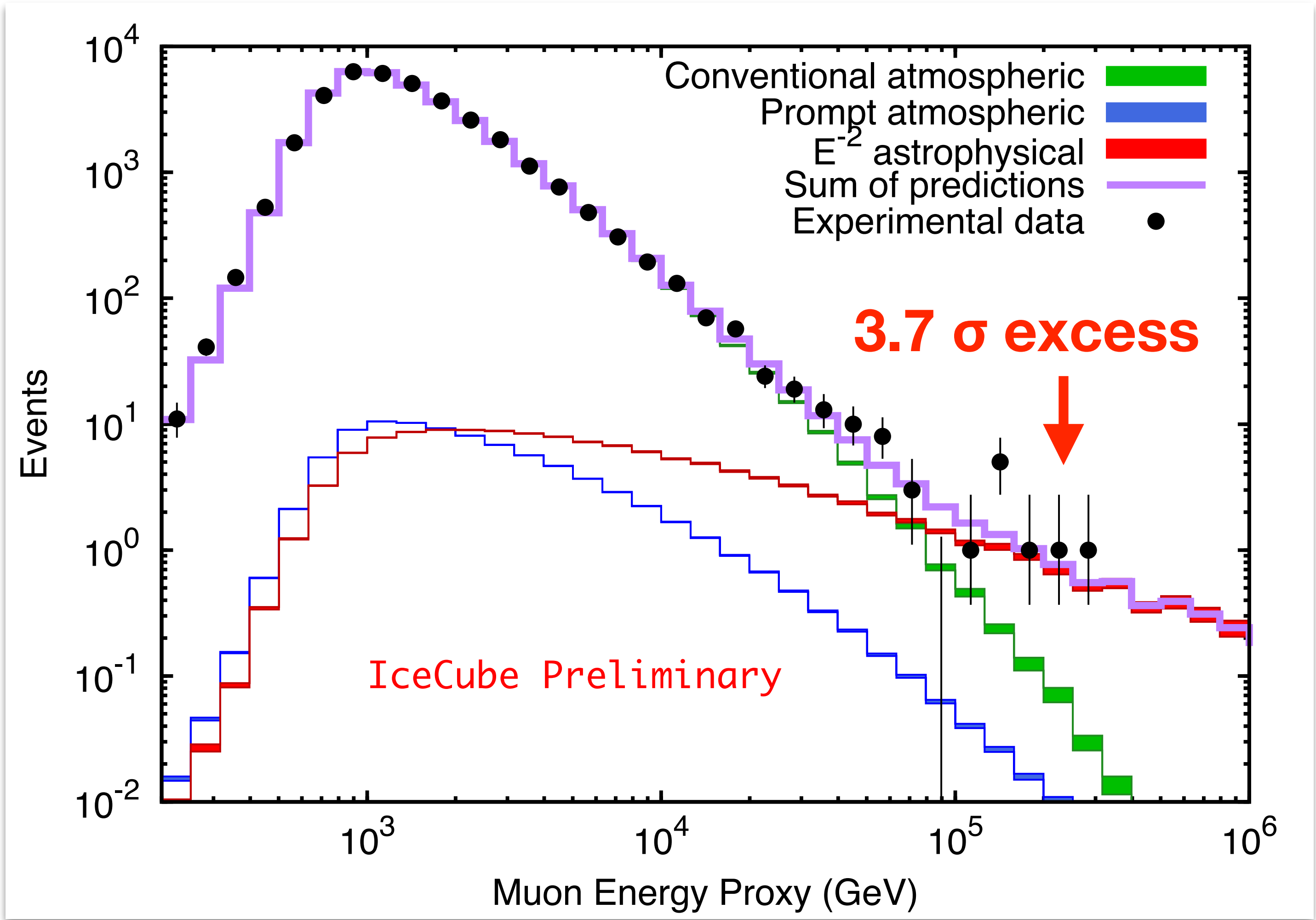

C. Weaver, PRL 115 (2015) 081102

$$E^2\Phi_{\nu+\bar{\nu}} = \begin{cases} 0.85 \pm 0.3 \text{ GeV cm}^{-2}\text{ sr}^{-1}\text{ s}^{-1} & \text{High-energy starting events} \\ 0.99 \pm 0.4 \text{ GeV cm}^{-2}\text{ sr}^{-1}\text{ s}^{-1} & \text{Upgoing } \nu_\mu \end{cases}$$

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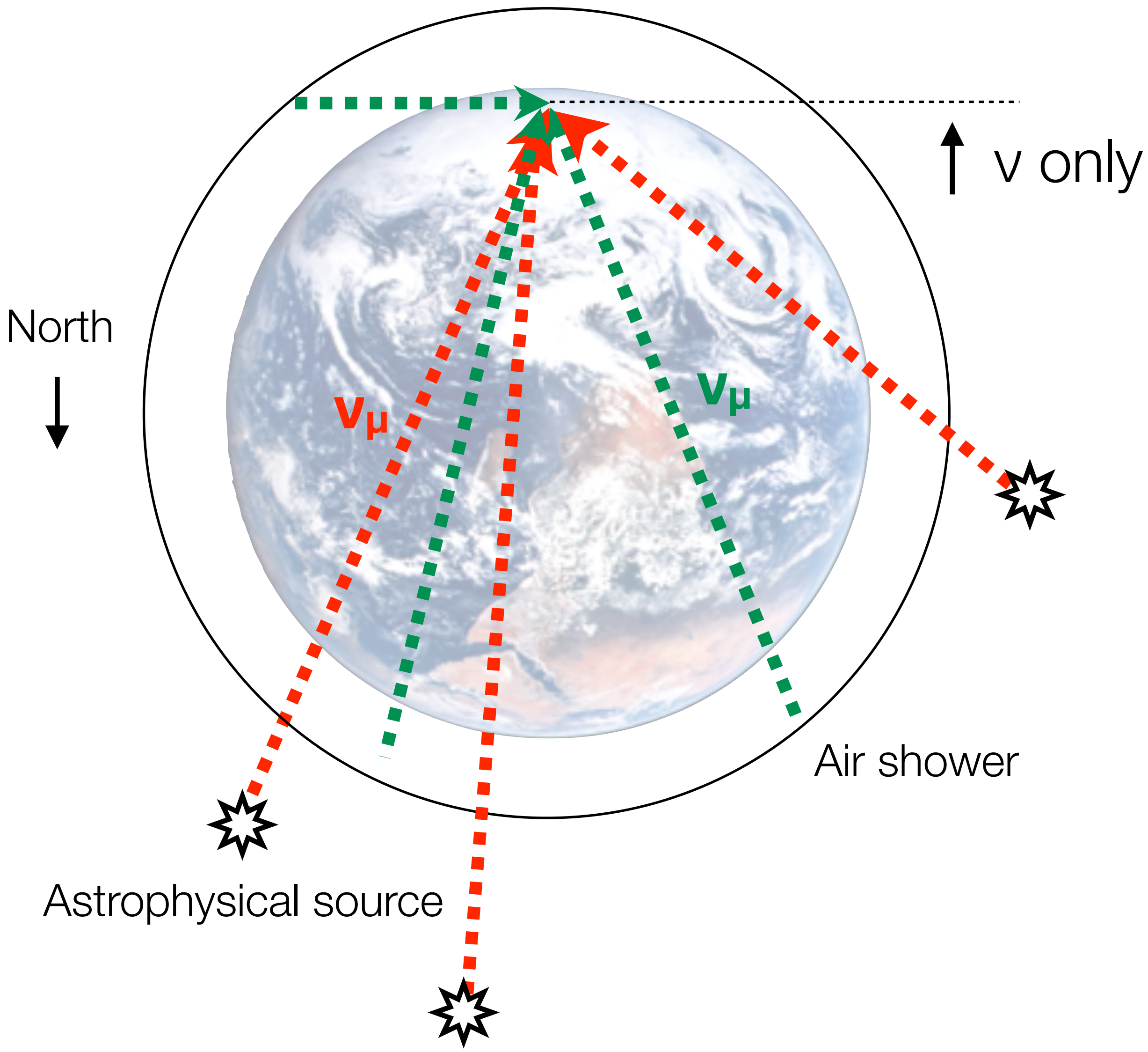
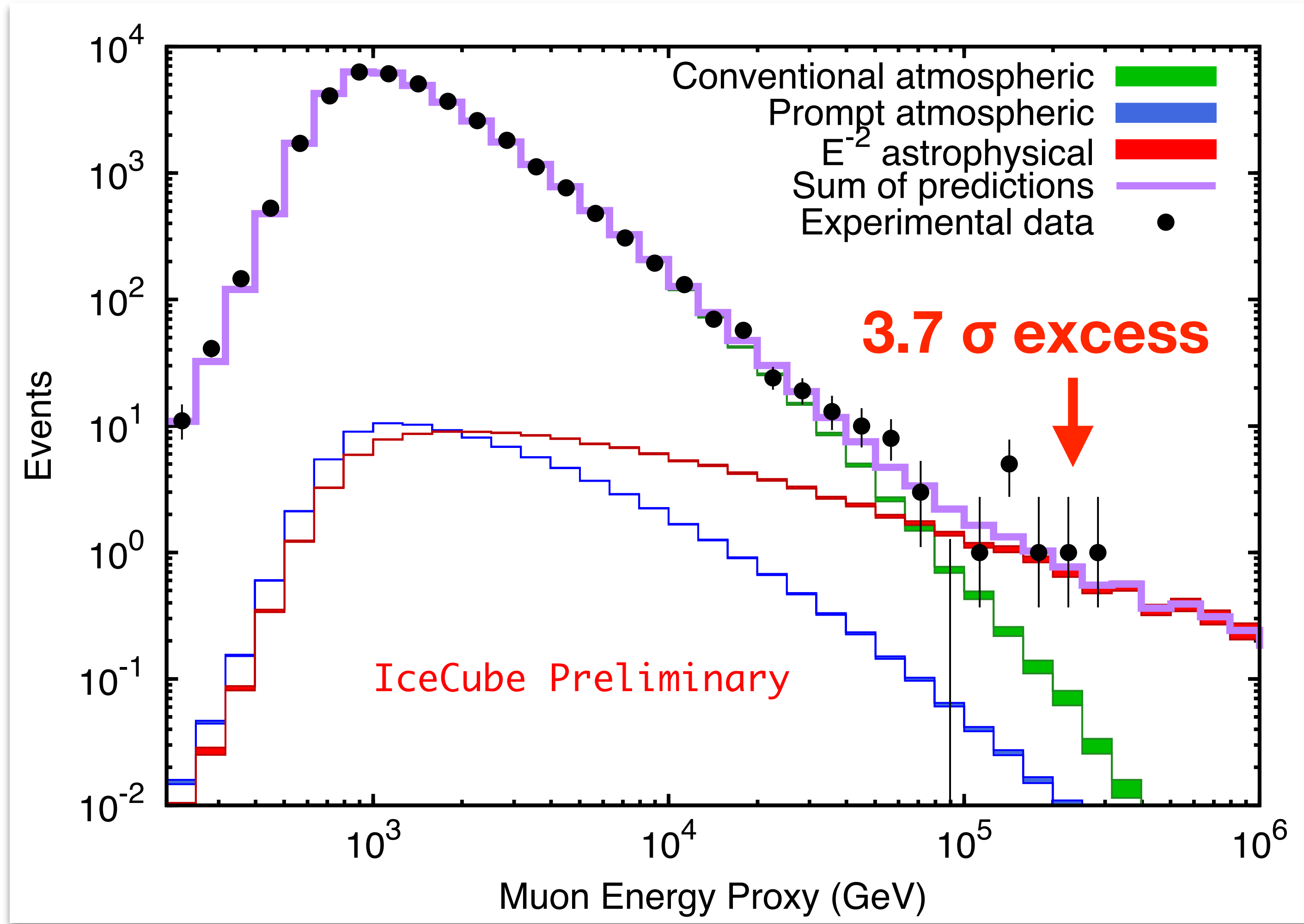
Data release: https://icecube.wisc.edu/science/data/HE_NuMu_diffuse





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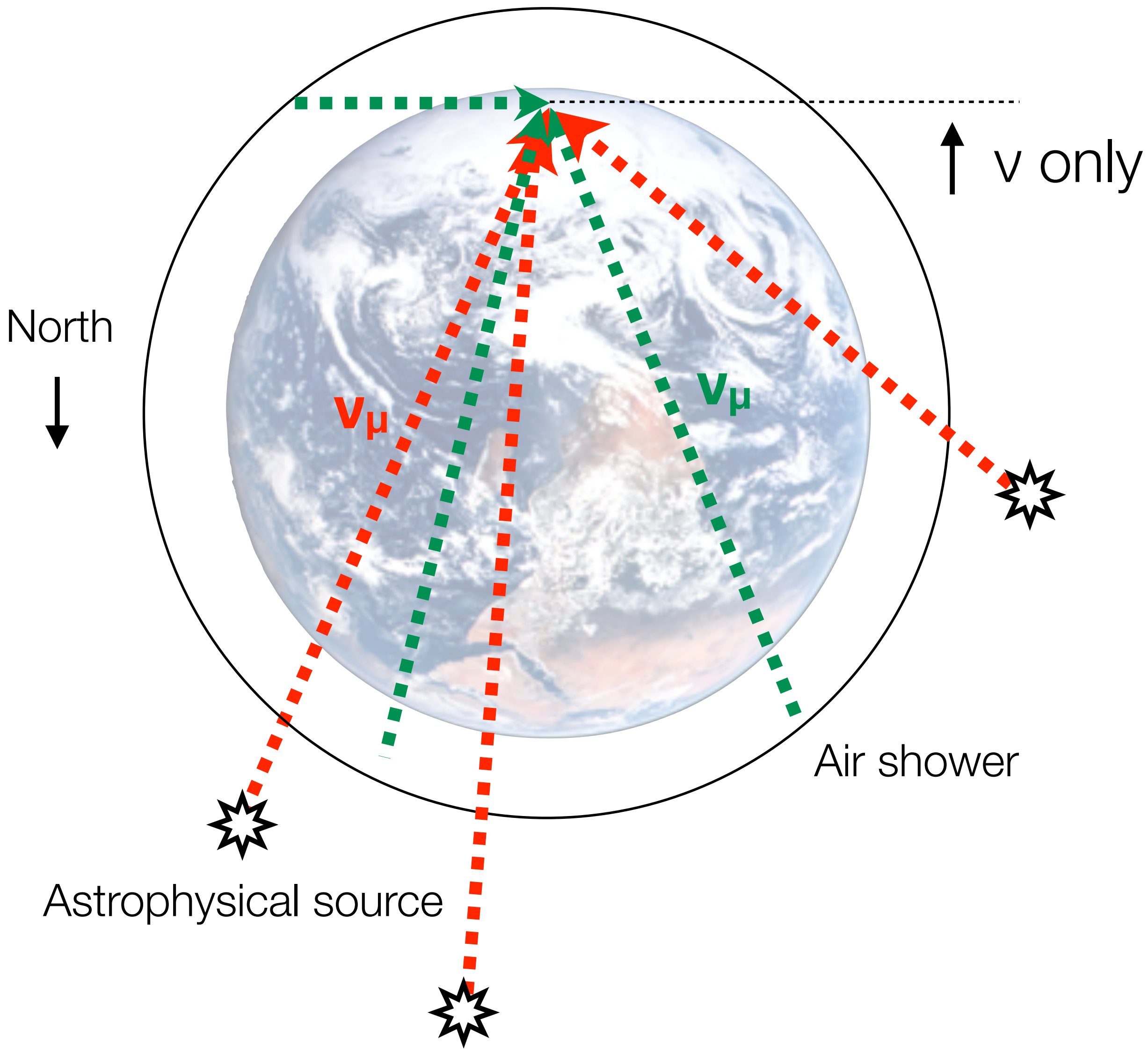

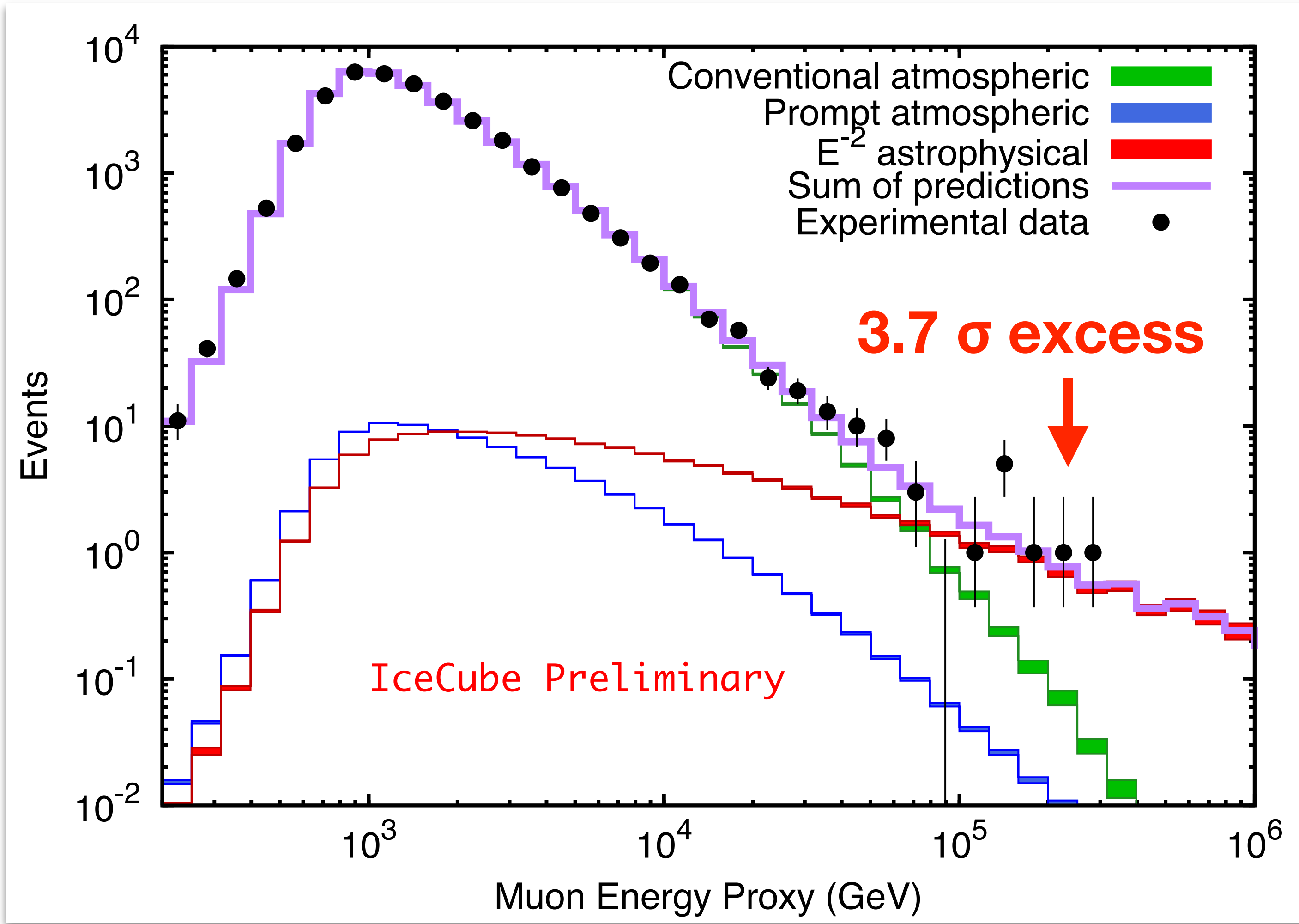

C. Weaver, PRL 115 (2015) 081102

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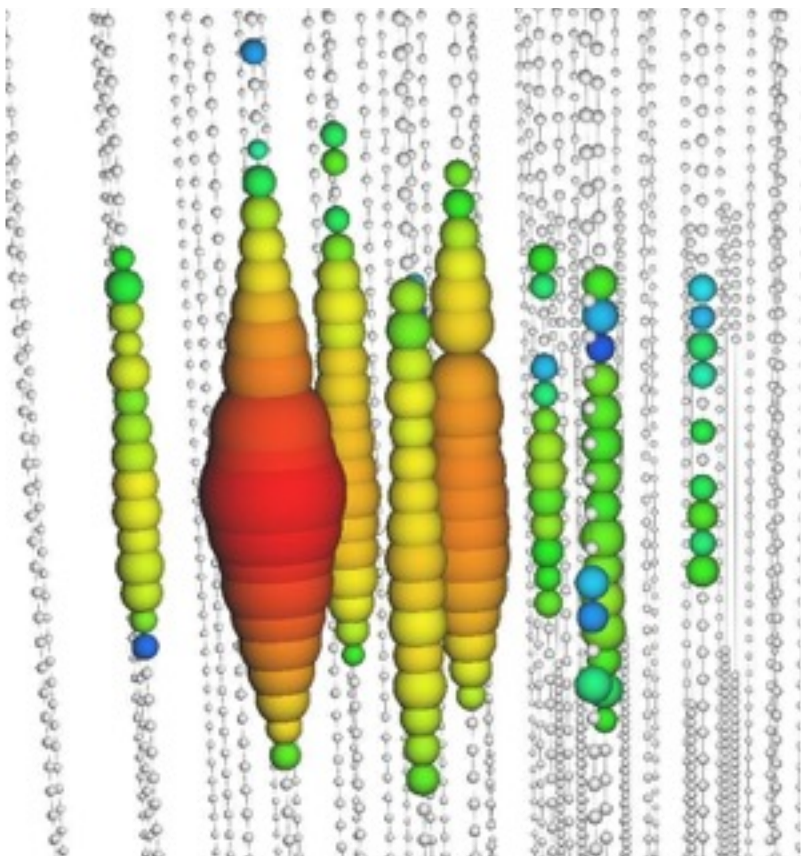
See S. Schönen's talk on 6-year northern hemisphere muon analysis

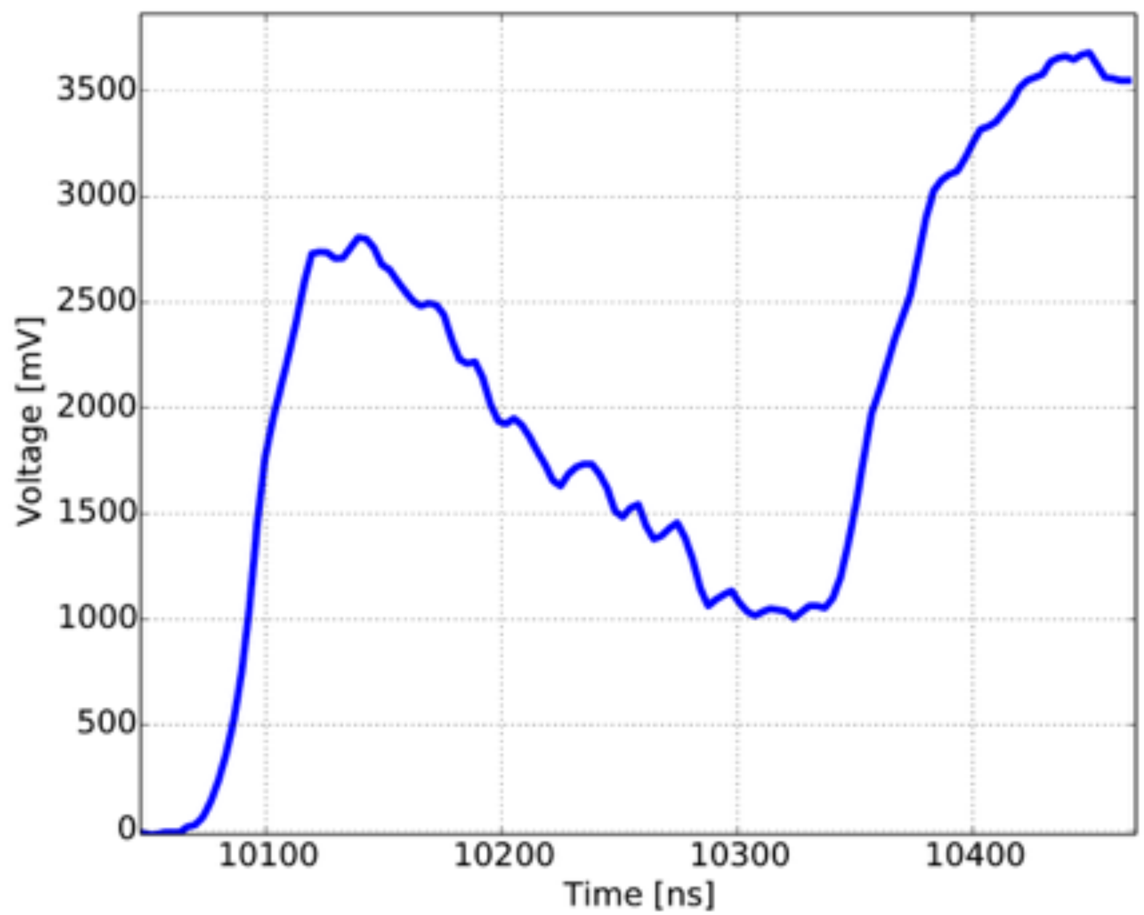
What about ν_τ?

Dedicated search for characteristic τ decay signature



ν_τ interaction, hadronic decay (simulated)

D. Xu, arXiv:1509.06212 (submitted to PRD)



Double-peaked PMT signal (simulated)

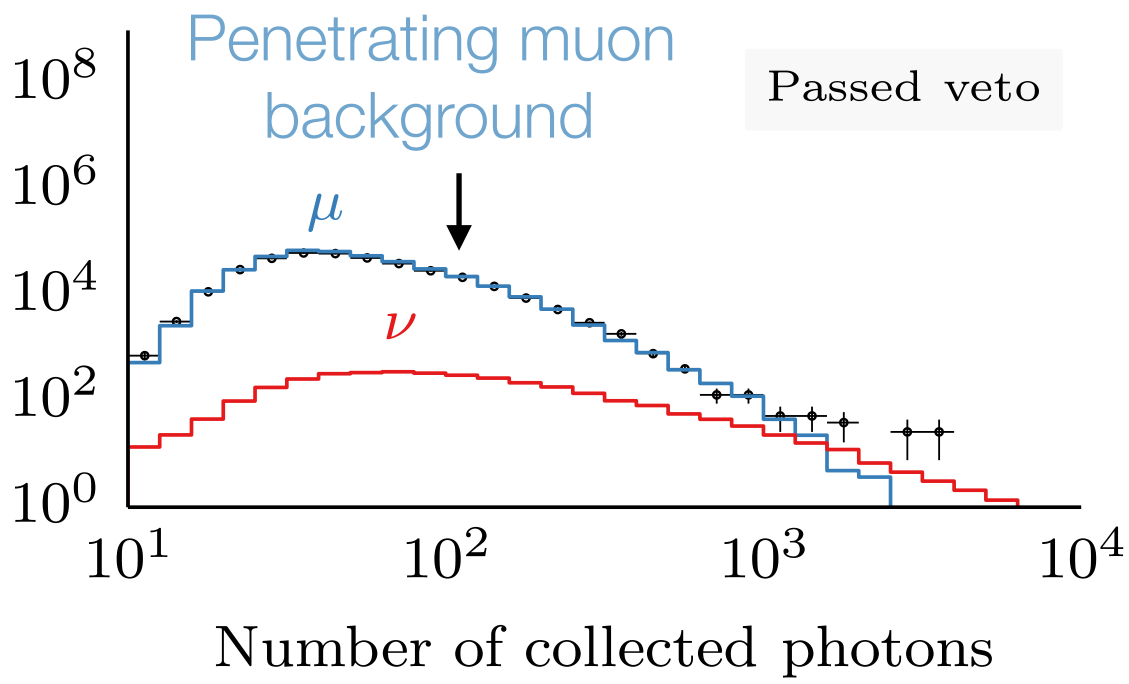
0.5 events expected in 3 years, 0 observed:

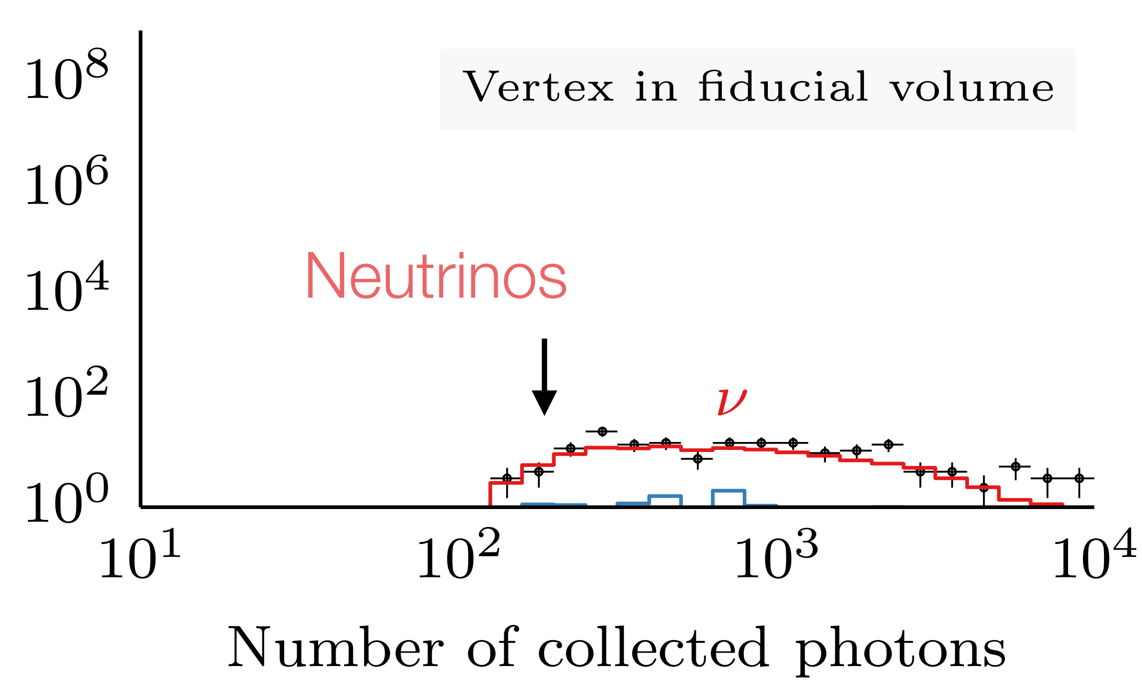
$$E^2\Phi_{\nu_\tau+\overline{\nu}_\tau} < 5.1 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,sr^{-1}\,s^{-1}}$$

What happens below 100 TeV?

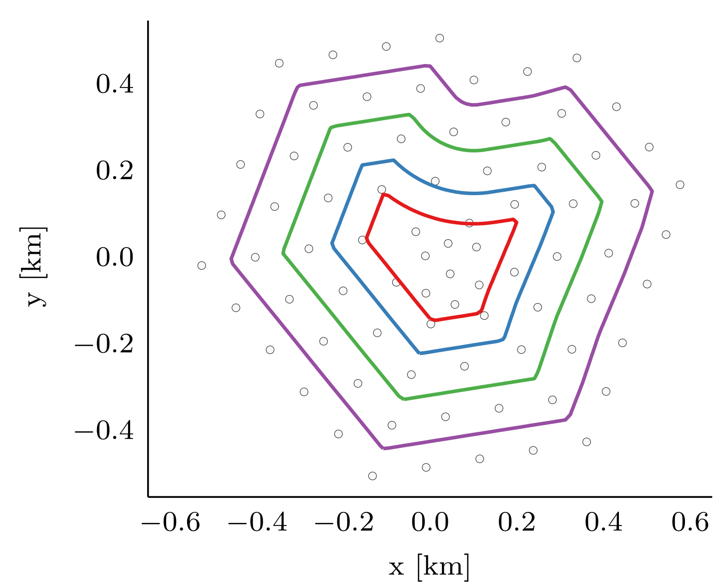
Outer-layer veto → Energy-dependent veto

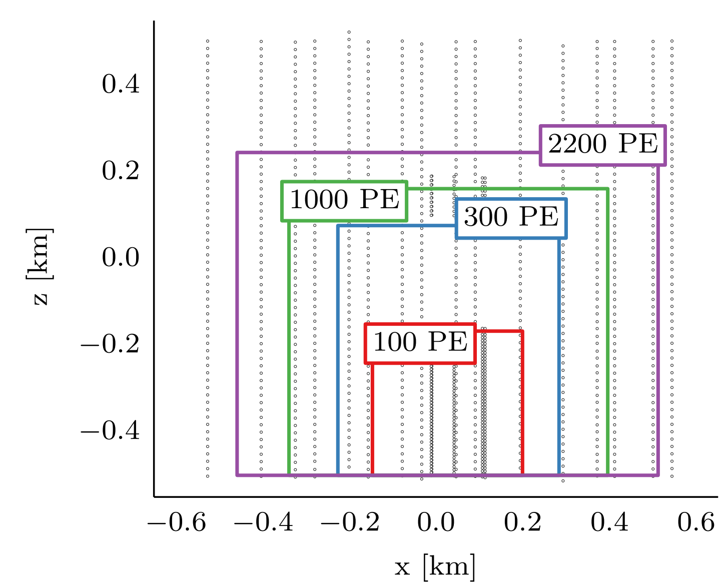
Neutrino-dominated for E_{dep} > 60 TeV **Neutrino-dominated for E_{dep} > 1 TeV**





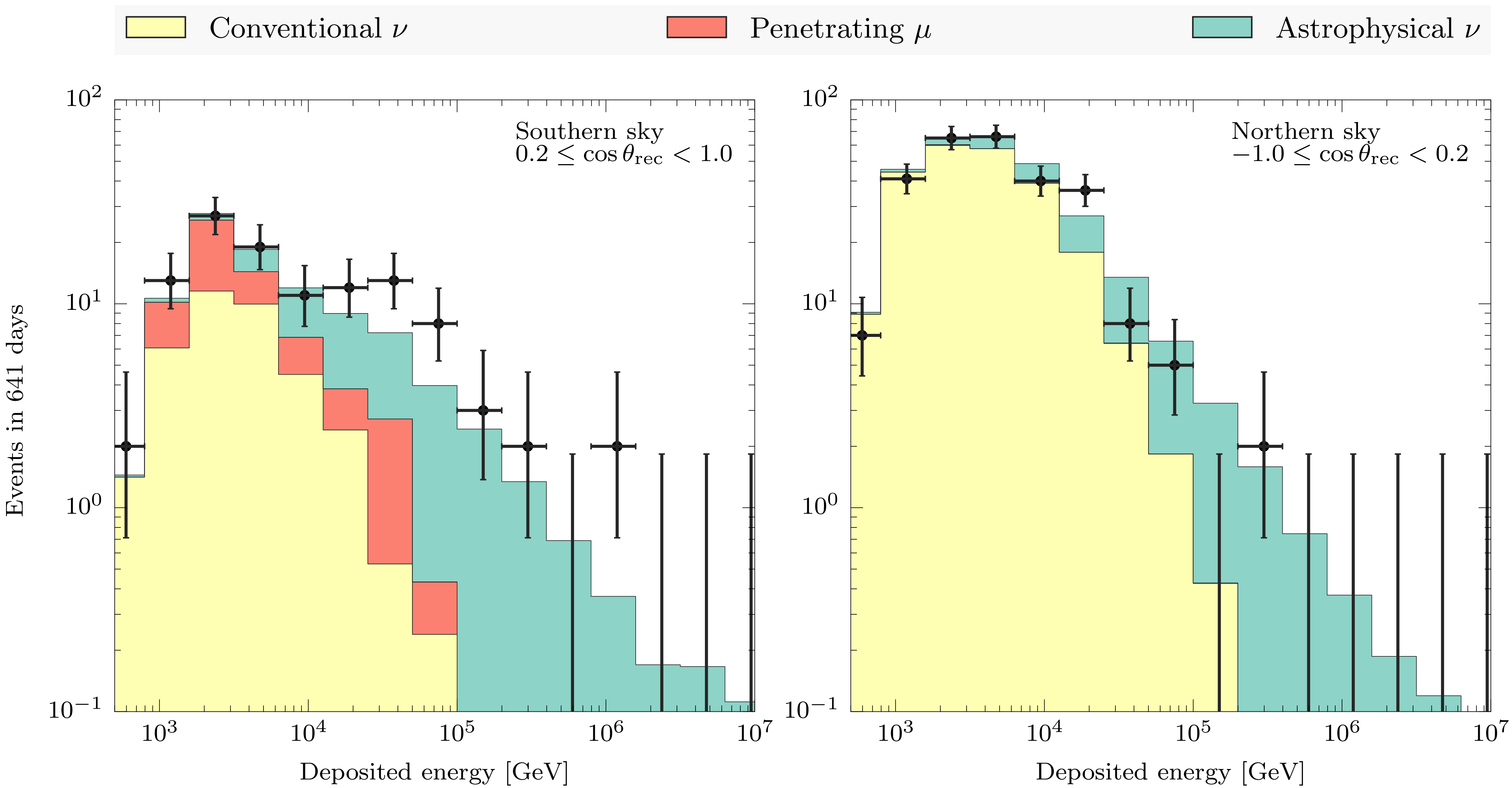
Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance





PRD 91 (2015) 022001

Starting event search above 1 TeV

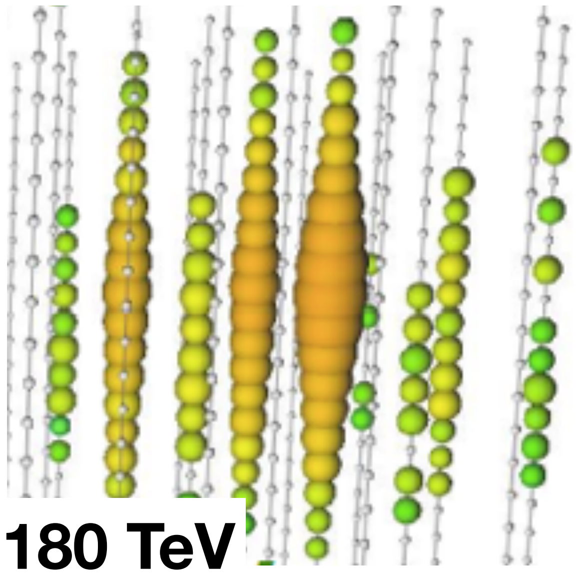


Data release: https://icecube.wisc.edu/science/data/HEnu_above1tev PRD 91 (2015) 022001

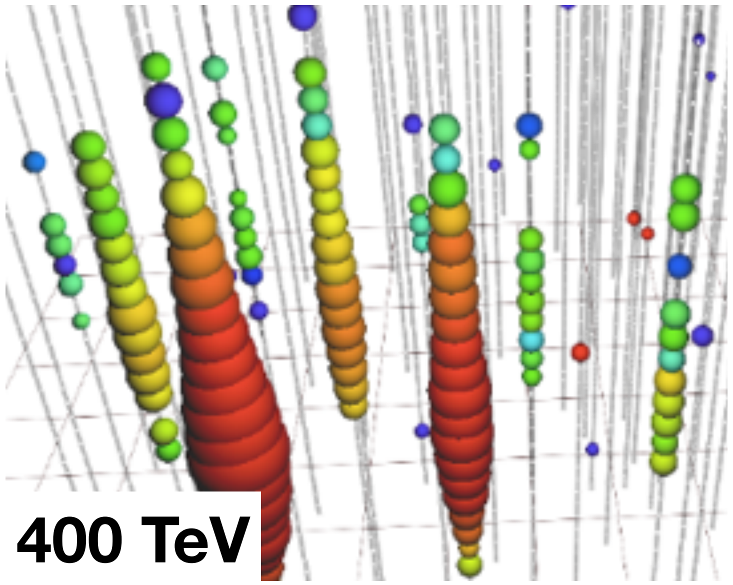
Adding statistics

Select cascade events near the edge and outside of the instrumented volume

Fully contained



Partially contained



Adding statistics

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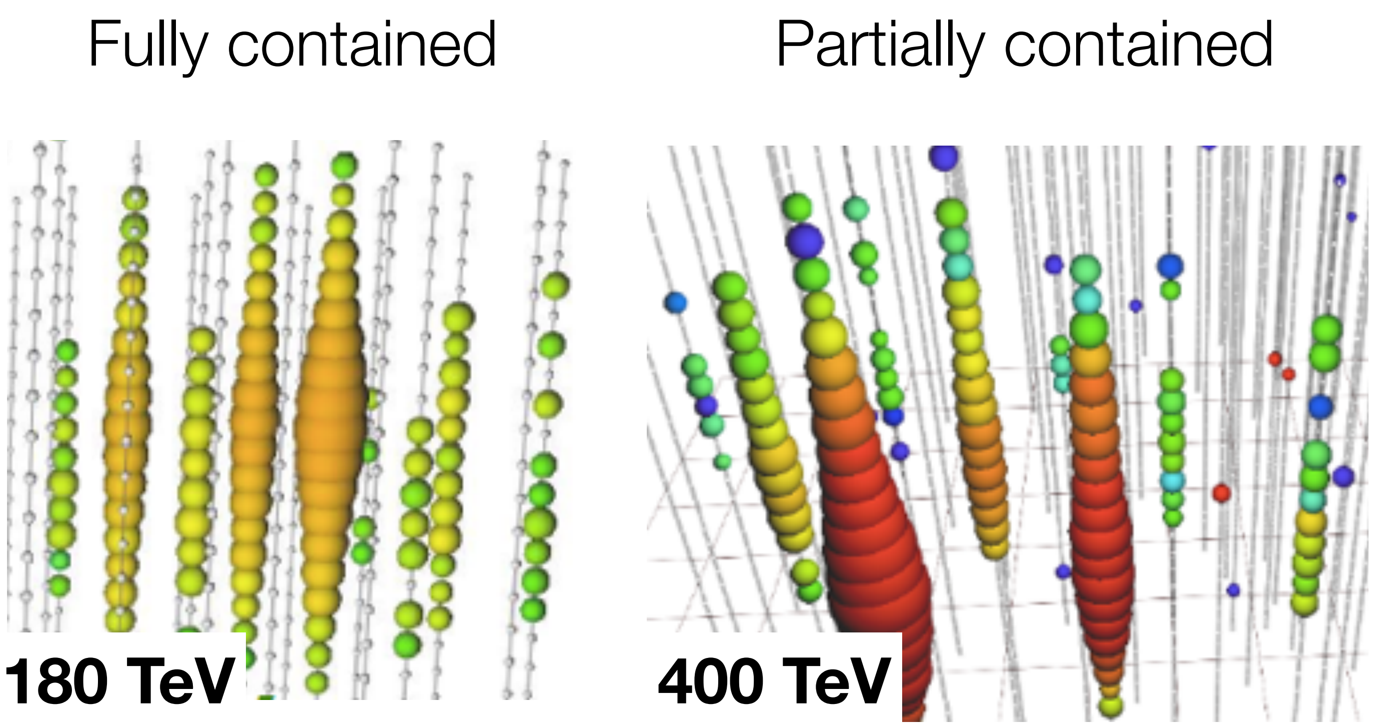
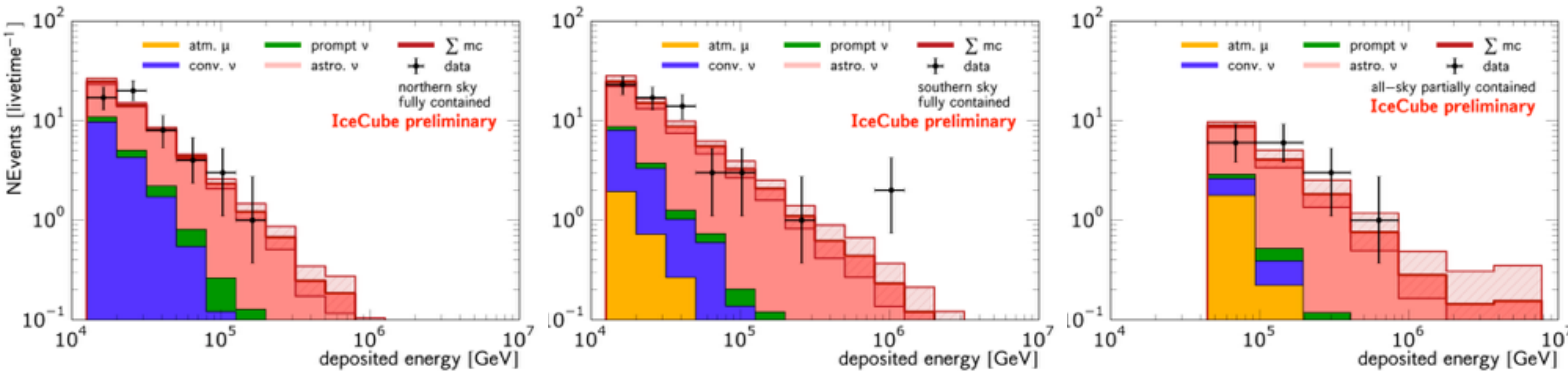


- Observed 172 events above 10 TeV
- < 10% penetrating atmospheric muons
- Only 40% overlap with starting-event samples



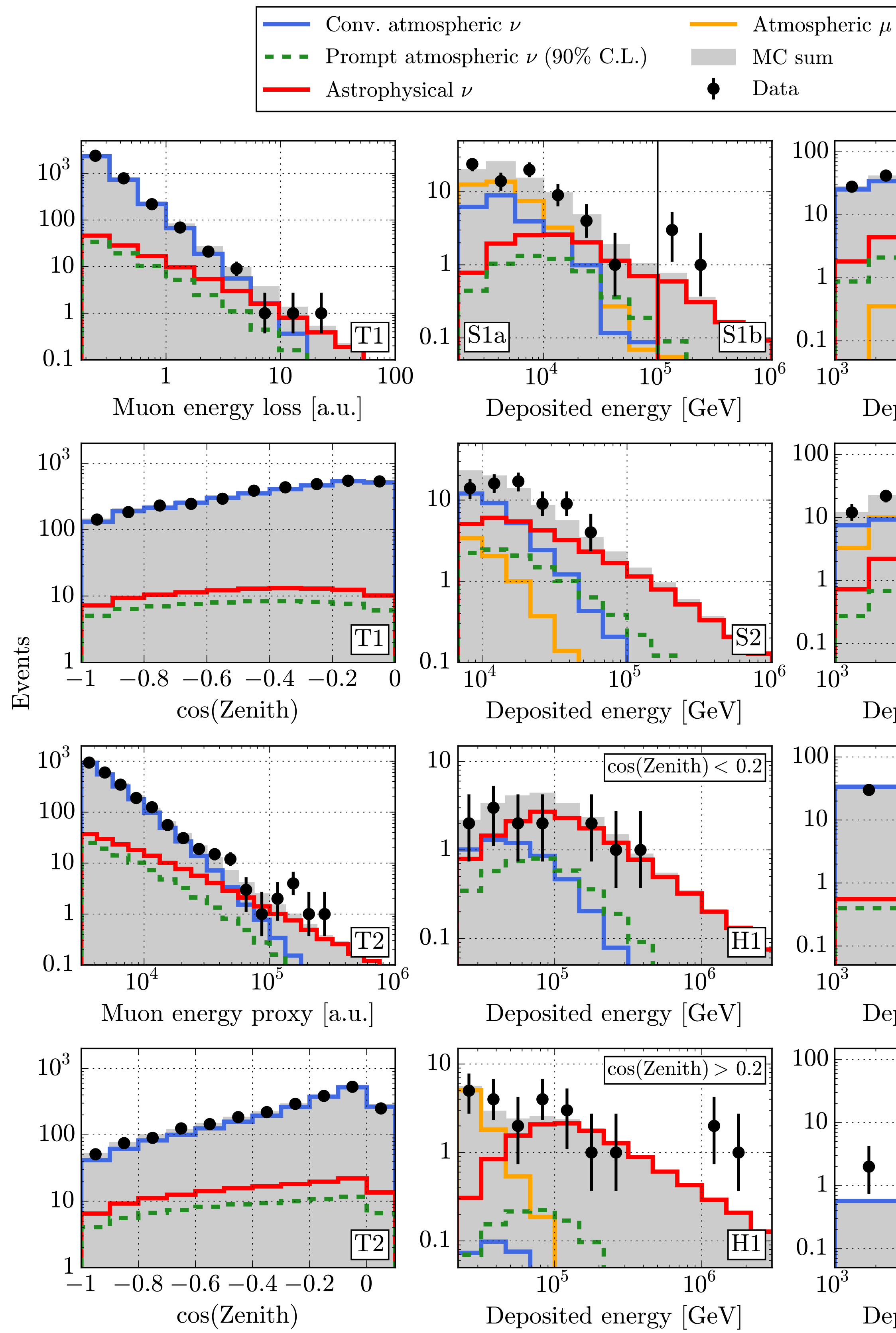
H. Niederhausen, PoS(ICRC2015)1109

Combined analysis

Combine dedicated track, cascade, and starting event samples into a single analysis

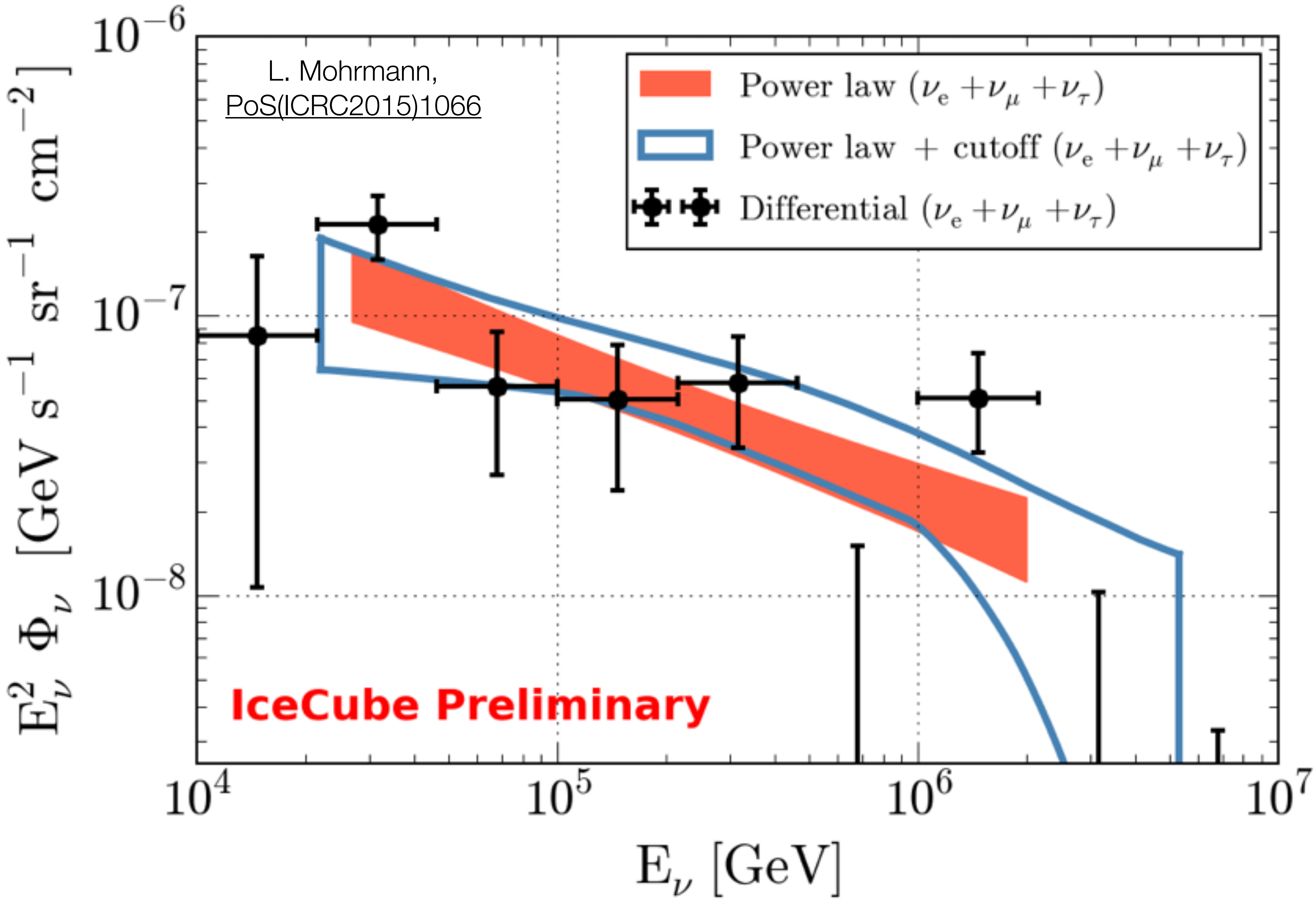
Increased sensitivity to:

- Energy spectrum
- Flavor composition



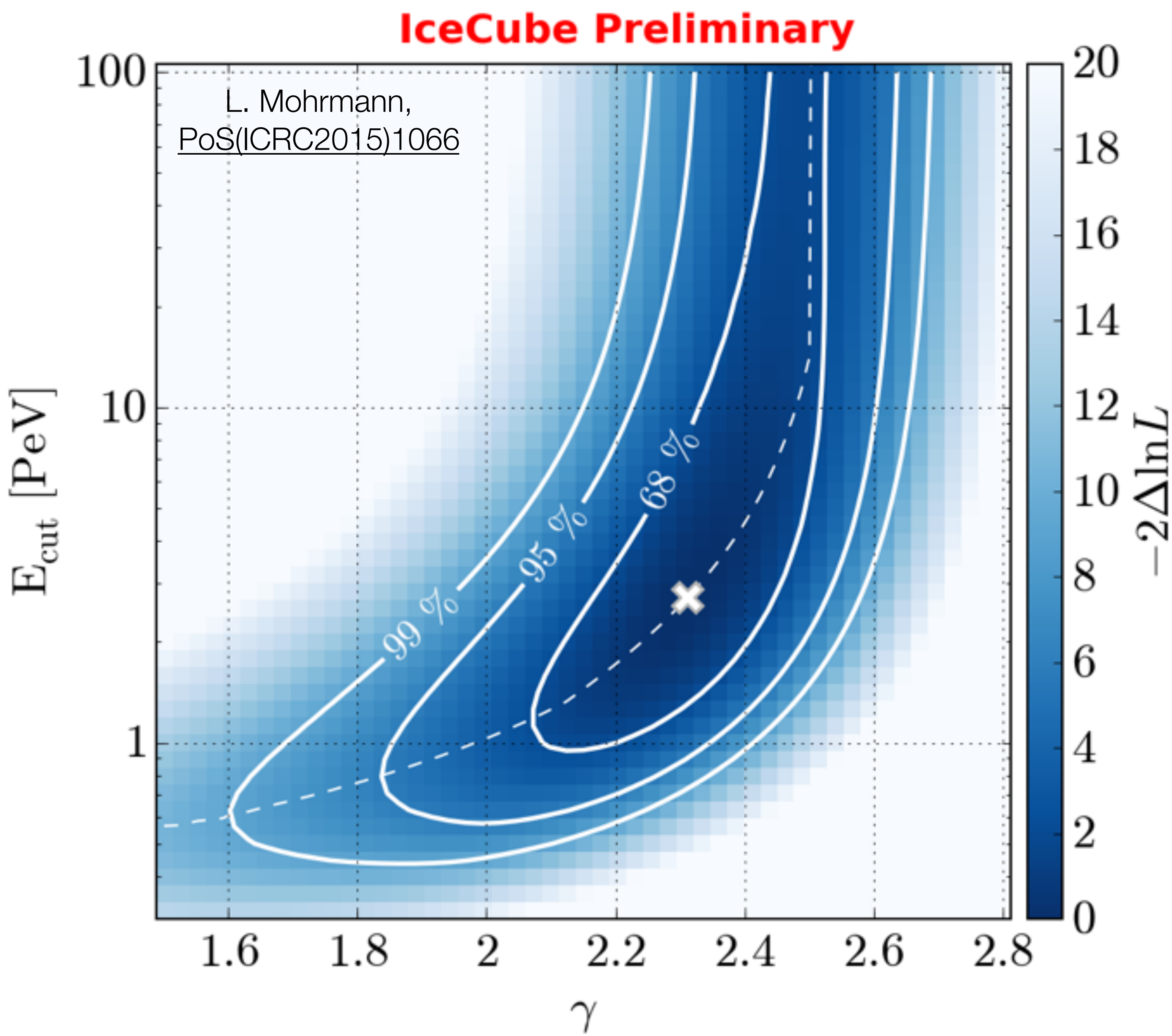
L. Mohrmann, ApJ 809, 98 (2015)

Combined analysis: energy spectrum

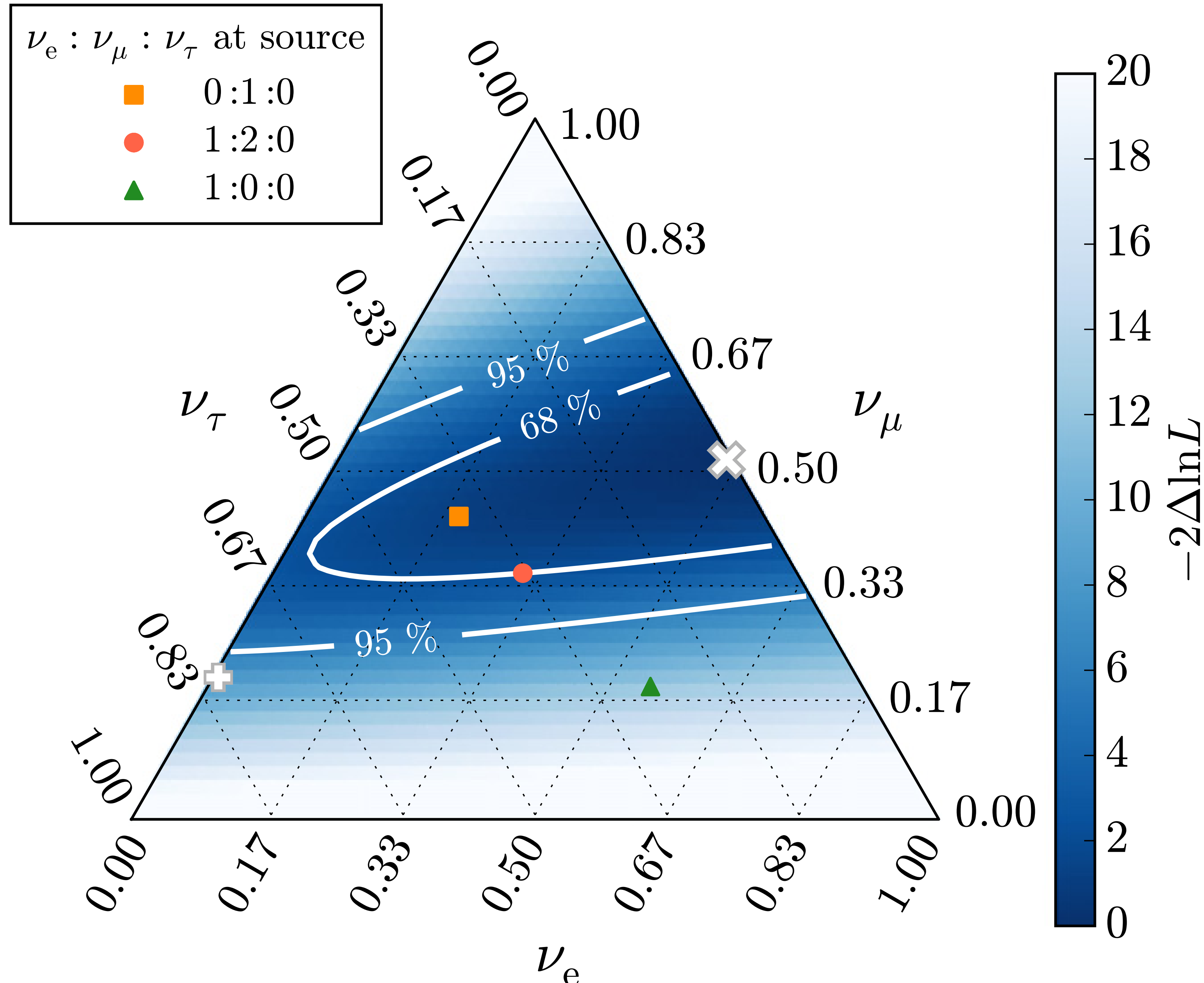


Combined analysis: energy spectrum

Harder spectrum with exponential cutoff mildly preferred to single power law (1.6σ)



Combined analysis: flavor composition



cf. Bustamente et al. PRL 115, 161302 (2015)

L. Mohrmann, ApJ 809, 98 (2015)

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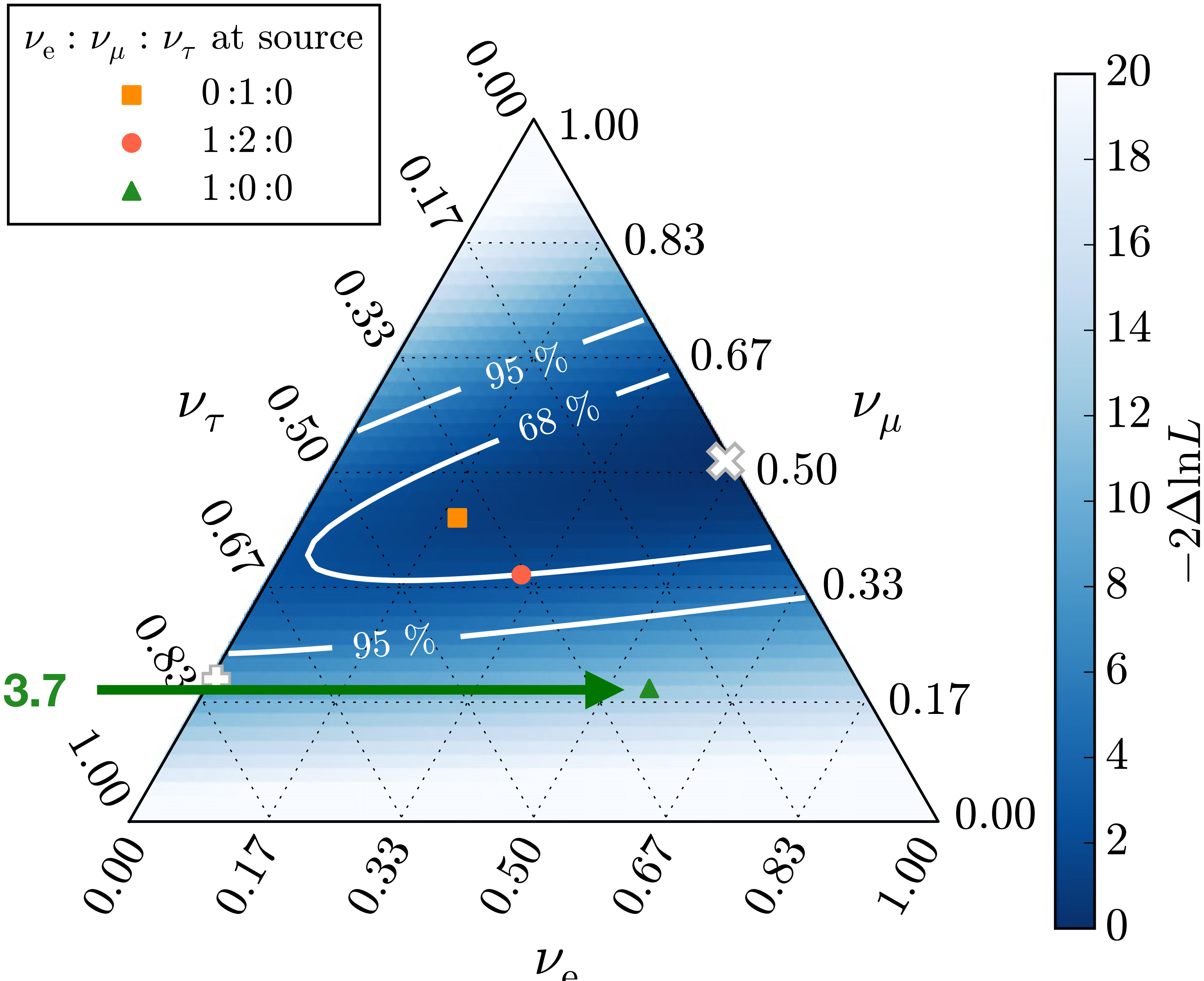

Neutron decay: rejected at 3.7

cf. Bustamente et al. PRL 115, 161302 (2015)

L. Mohrmann, ApJ 809, 98 (2015)

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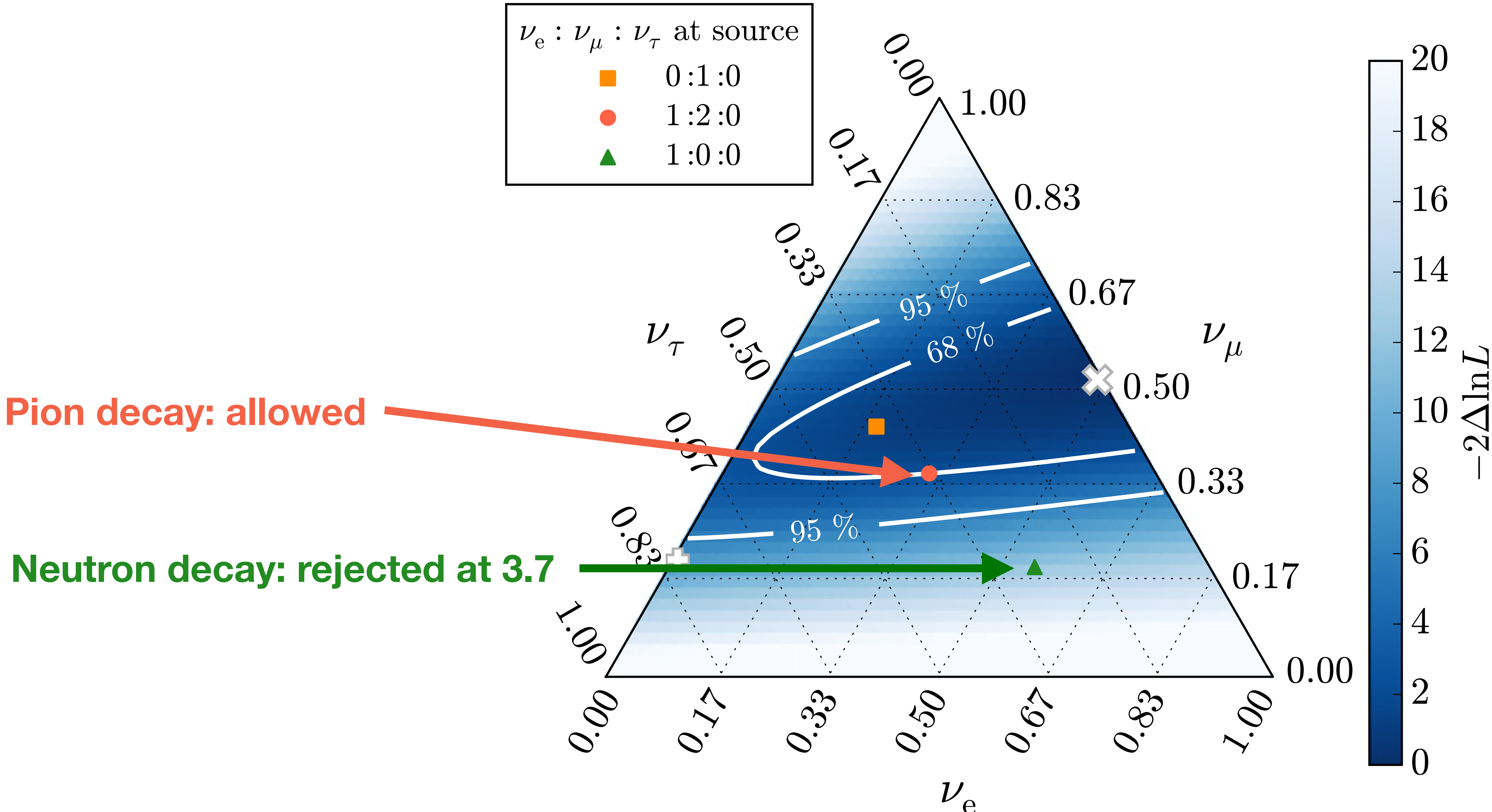


cf. Bustamente et al. PRL 115, 161302 (2015)

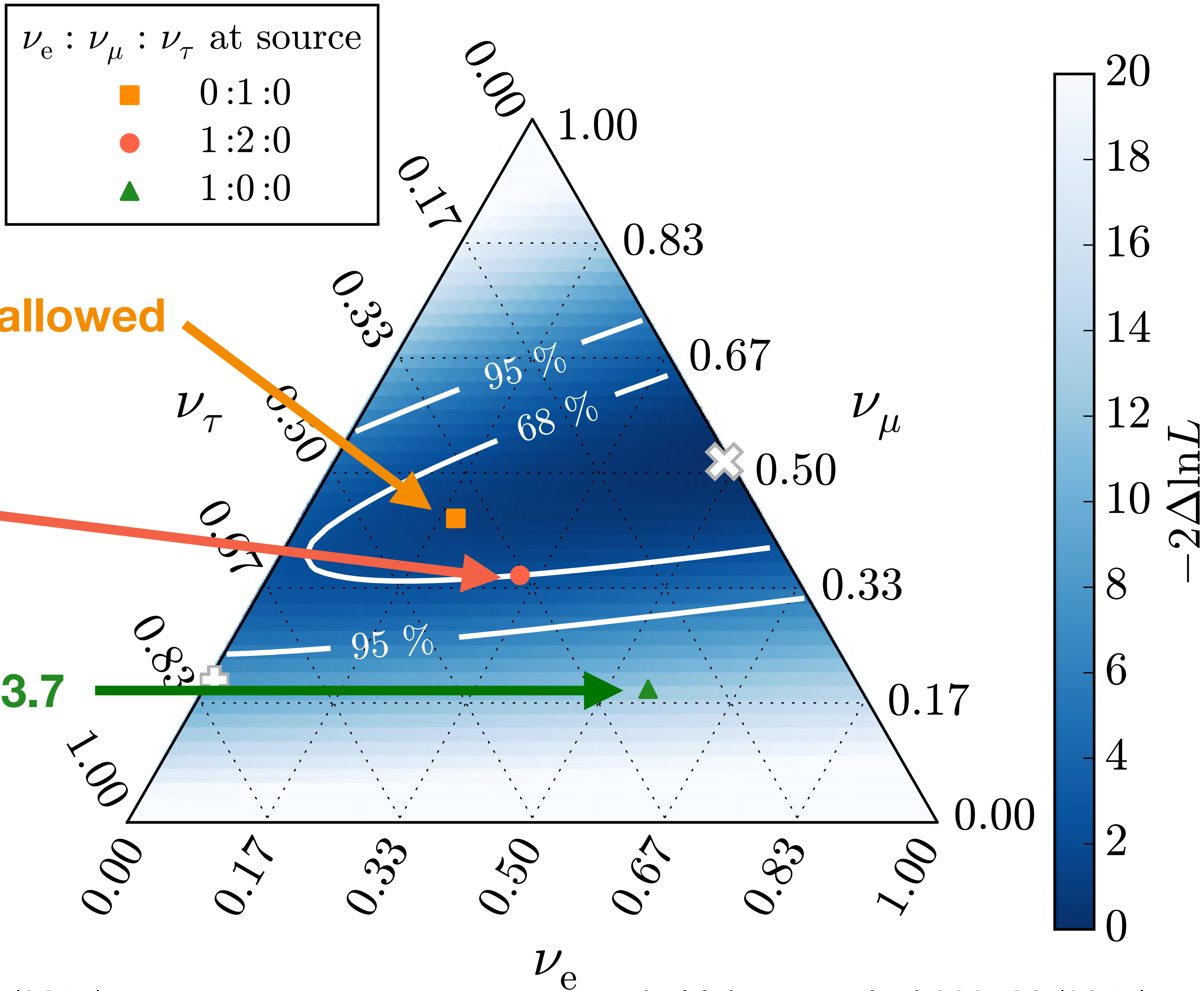
L. Mohrmann, ApJ 809, 98 (2015)

Combined analysis: flavor composition

Muon-damped pion decay: allowed

Pion decay: allowed

Neutron decay: rejected at 3.7



cf. Bustamente et al. PRL 115, 161302 (2015)

L. Mohrmann, ApJ 809, 98 (2015)

Conclusions

IceCube observes an astrophysical neutrino flux

in multiple channels, but its sources are still unknown.

The neutrino flavor ratio is consistent with 1:1:1

Pure neutron decay is excluded, but other scenarios are still allowed.

Astrophysical excess observable down to 10 TeV in the southern sky.

An active muon veto removes atmospheric neutrinos when the overburden is small enough.

This is an exciting time for neutrino telescopes. Stay tuned for more data!

Thank you!


The IceCube Collaboration
Canada
University of Alberta–Edmonton
University of Toronto
USA
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University
Niels Bohr Institutet, Denmark
Chiba University, Japan
Sungkyunkwan University, Korea
University of Oxford, UK
Belgium
Université Libre de Bruxelles
Université de Mons
Universiteit Gent
Vrije Universiteit Brussel
Sweden
Stockholms universitet
Uppsala universitet
Germany
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität München
Universität Bonn
Technische Universität Dortmund
Universität Mainz
Universität Wuppertal
Université de Genève, Switzerland
University of Adelaide, Australia
University of Canterbury, New Zealand
Funding Agencies
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Backup

TeV neutrinos from cosmic rays

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

(or p)

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

TeV gamma rays (also from leptonic processes)

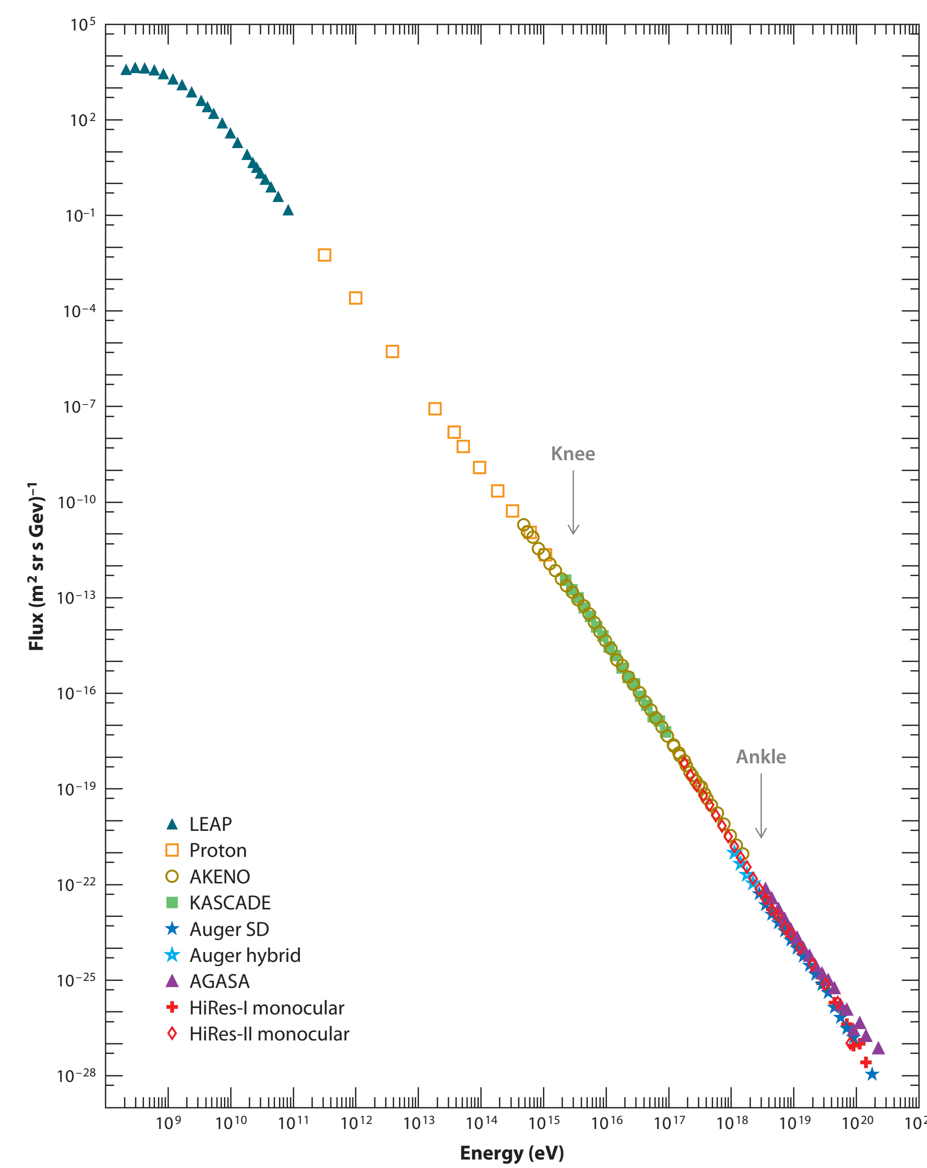
$$\rightarrow \pi^+ + n$$

Cosmic rays?

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

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

TeV neutrinos



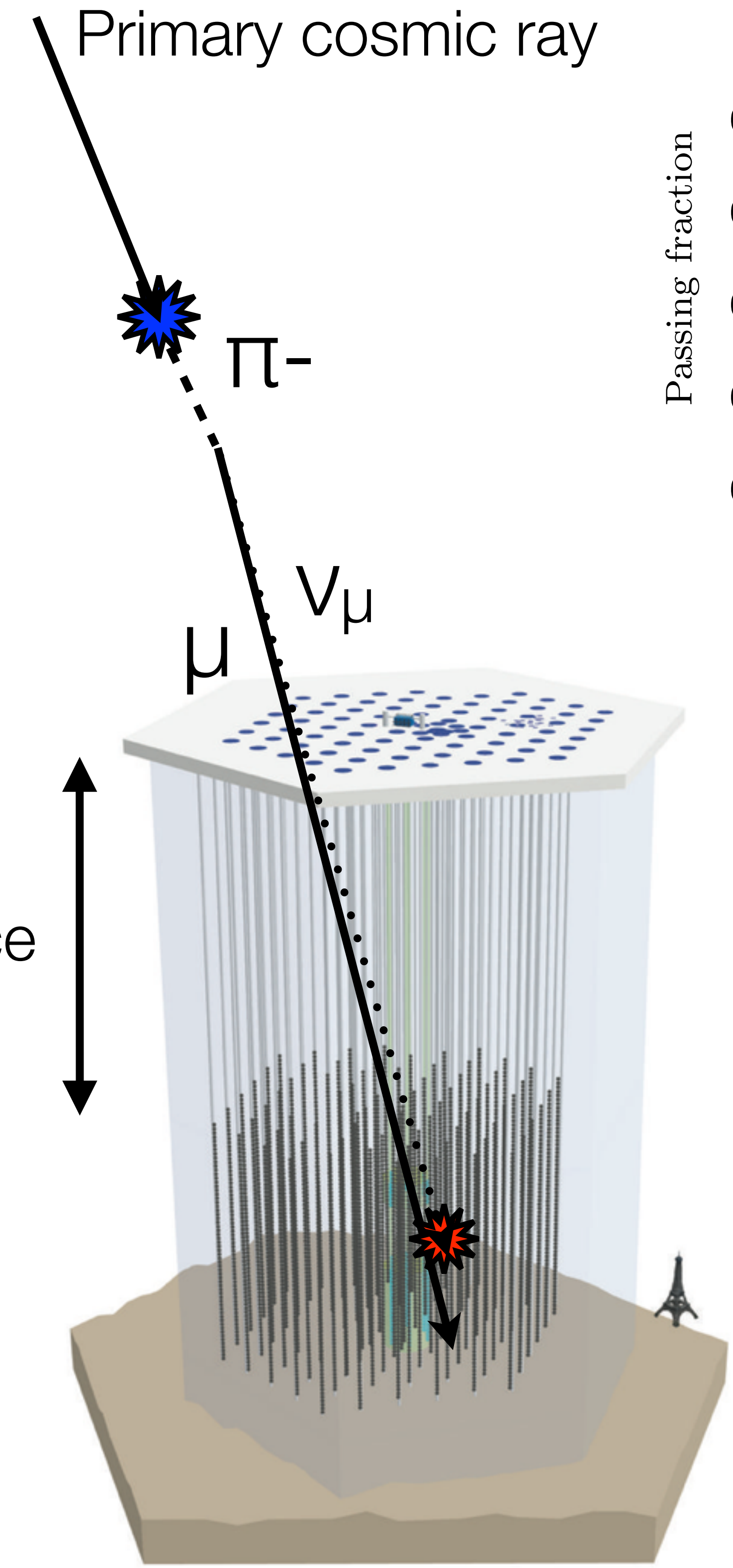
Neutrinos from cosmic ray interactions within

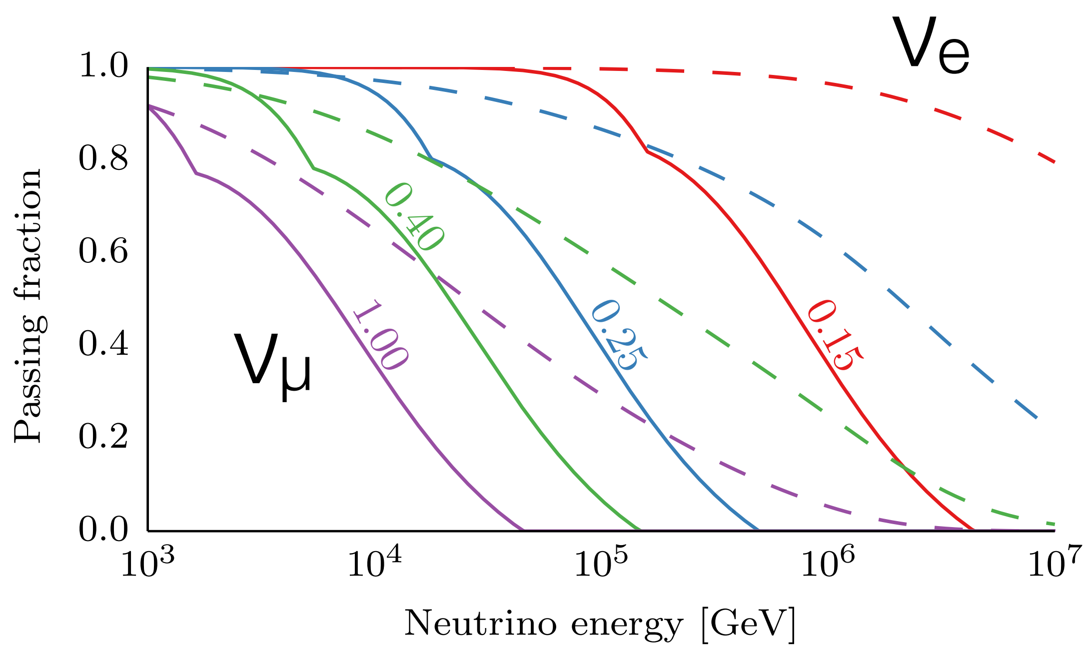
- The atmosphere
- Cosmic Microwave Background
- Gamma-Ray Bursts (acceleration sites)
- Active Galactic Nuclei (acceleration sites)
- ?

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!

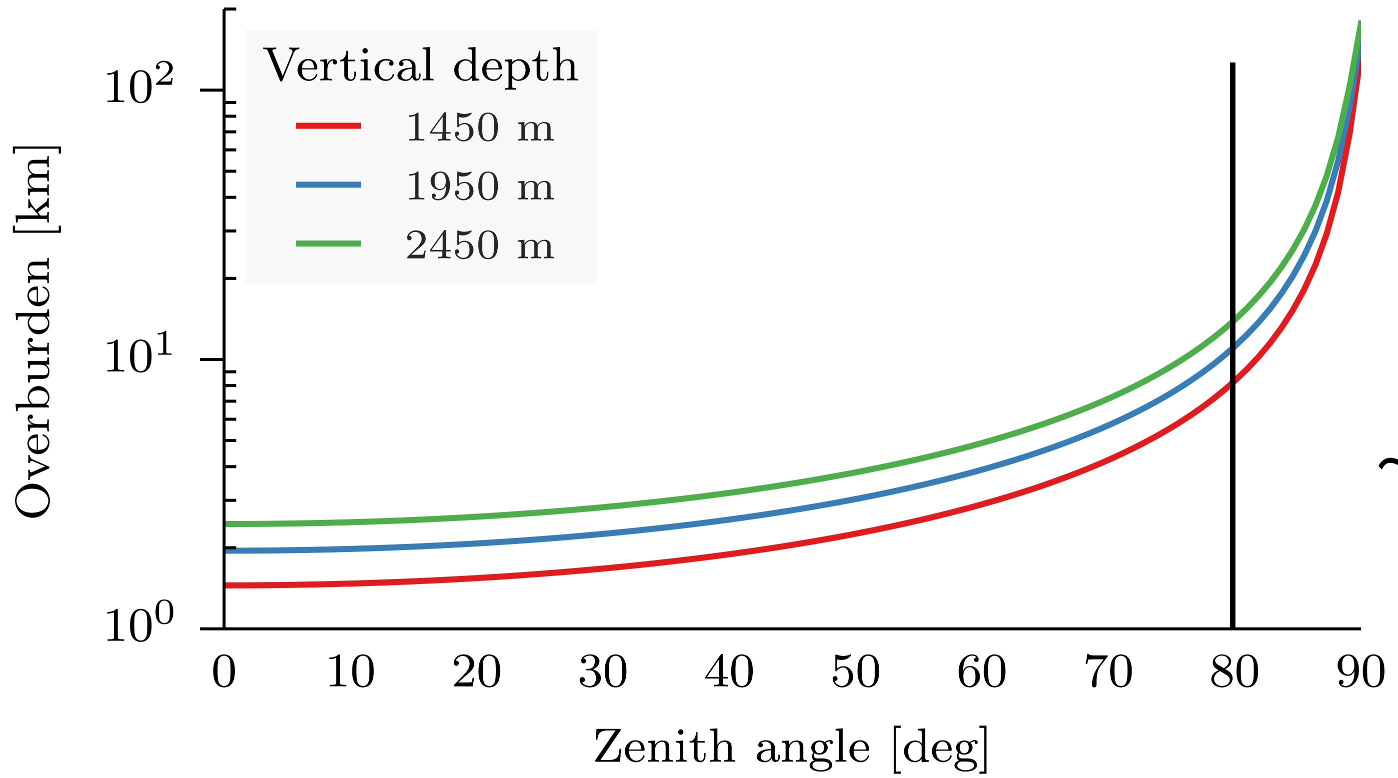




Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009

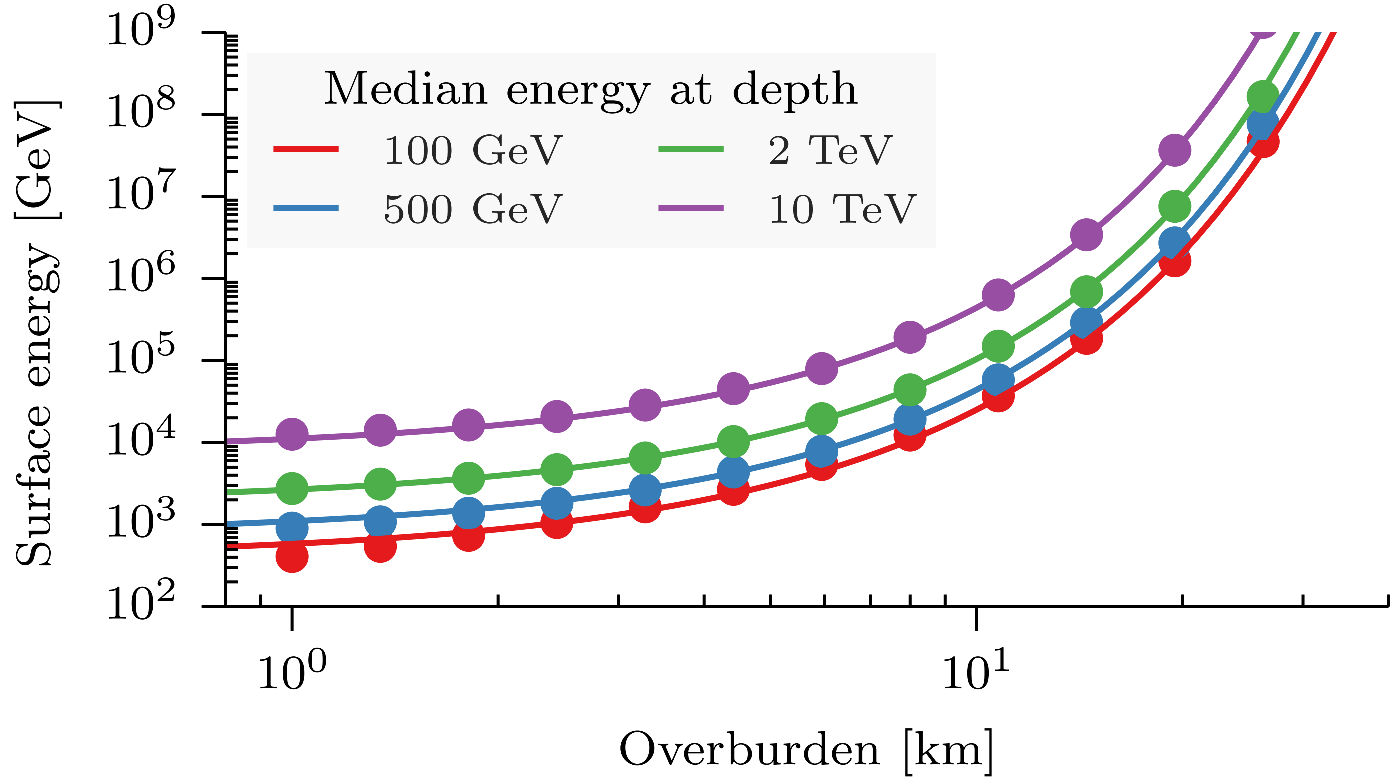
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009

IceCube's overburden



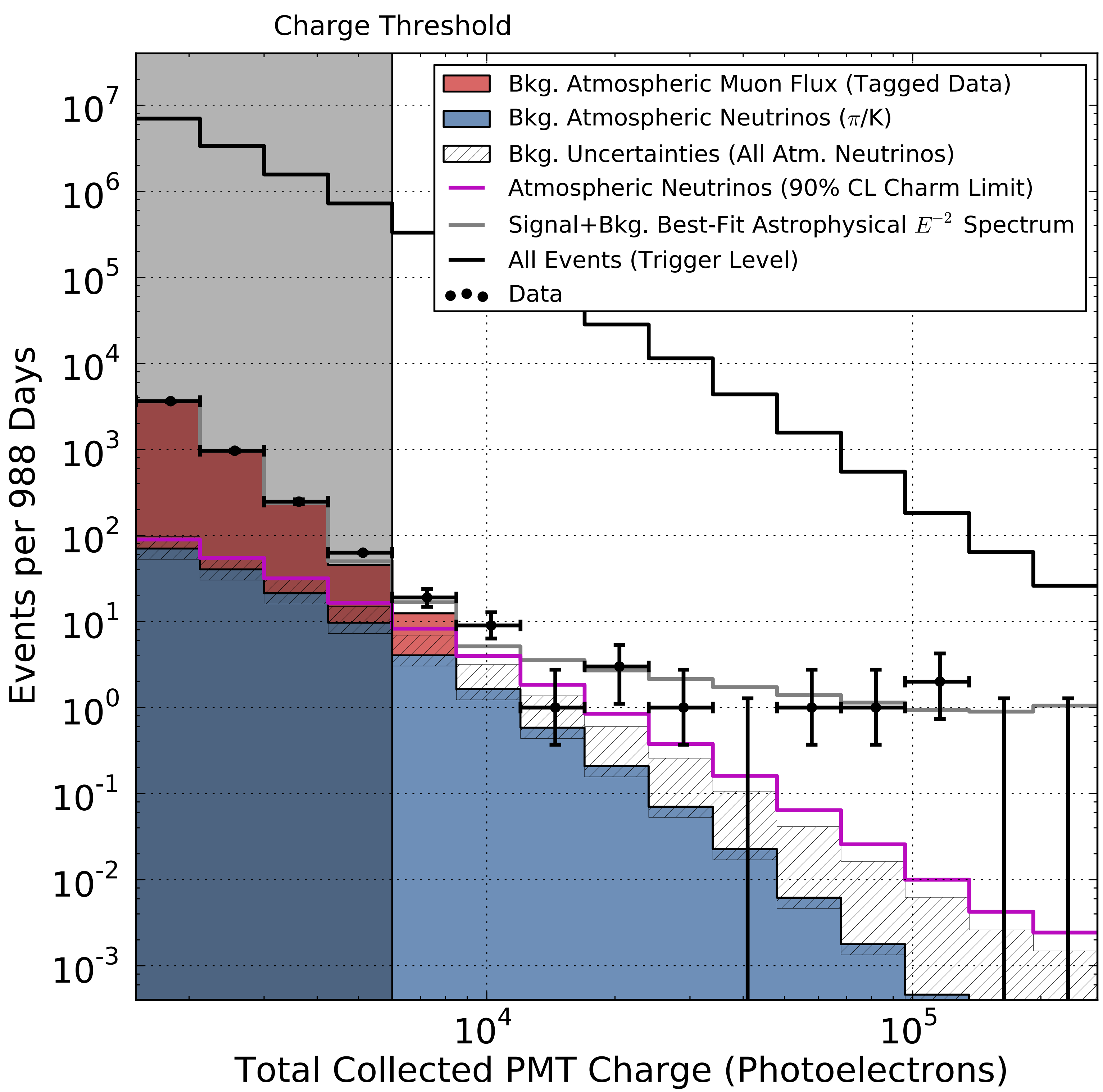
~10 km at 80 degrees

~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)

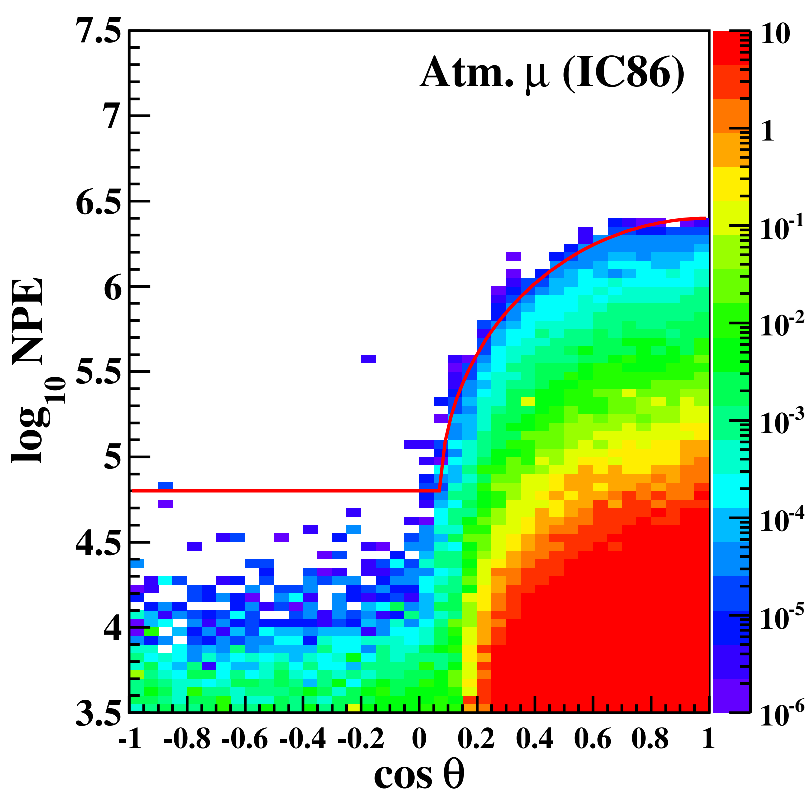
What about extremely high energies?

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

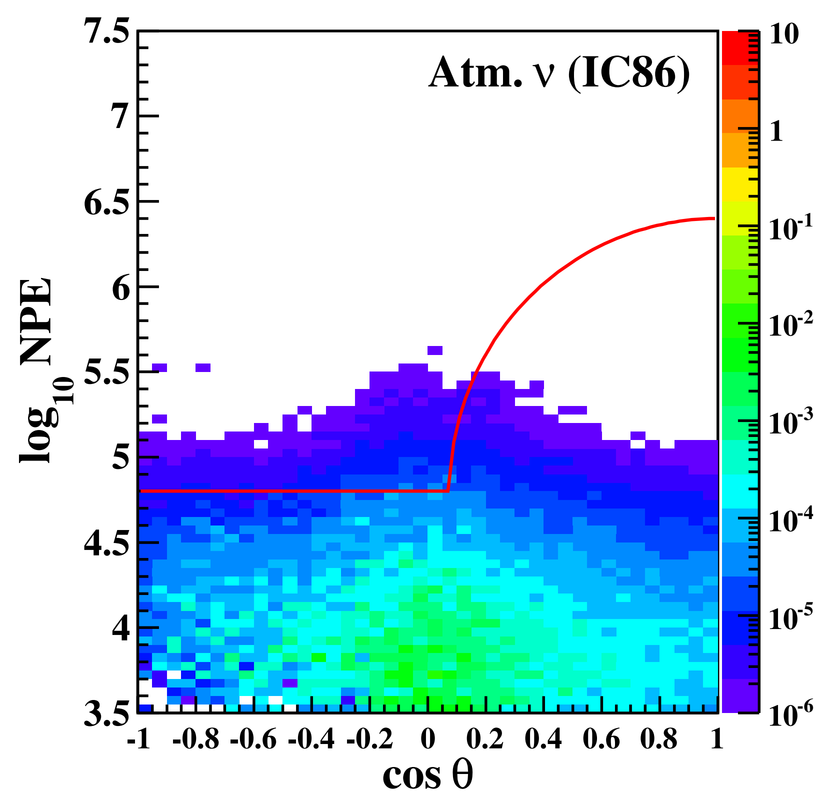
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow n + \pi^{+} \rightarrow \nu_{\mu}$$

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

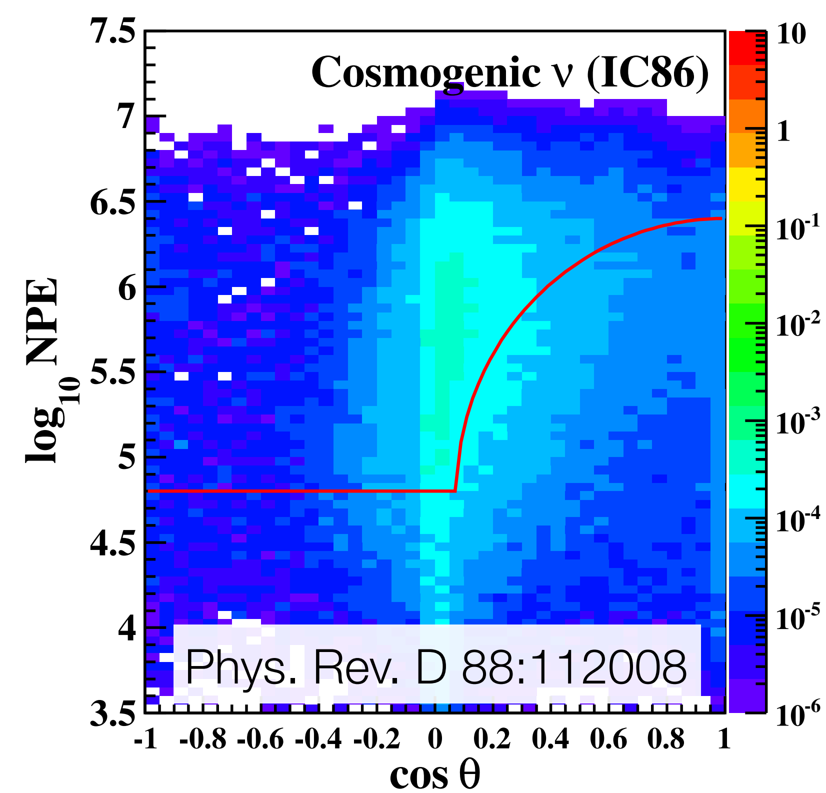
Penetrating muons



Atmospheric neutrinos



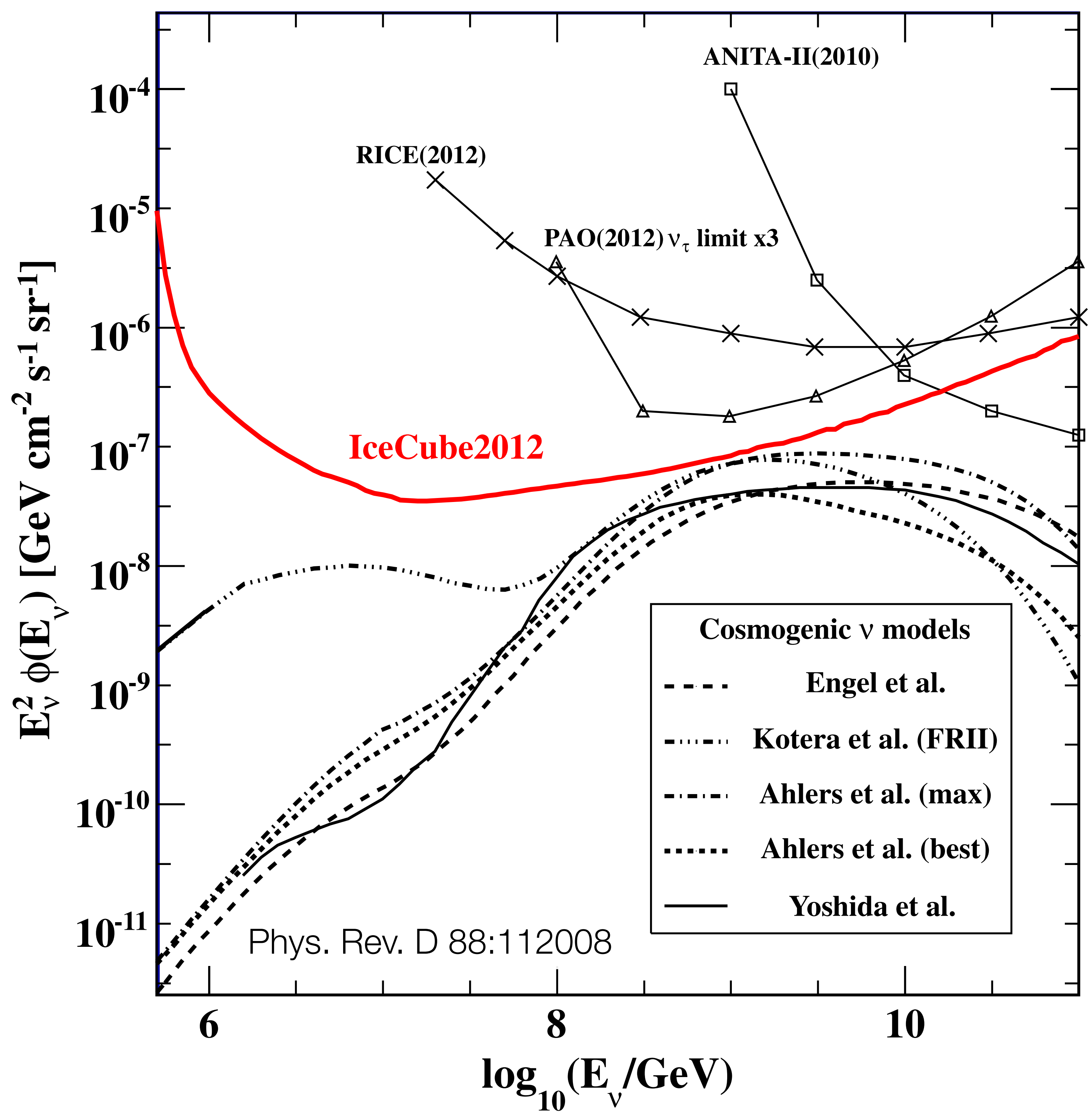
GZK neutrinos



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



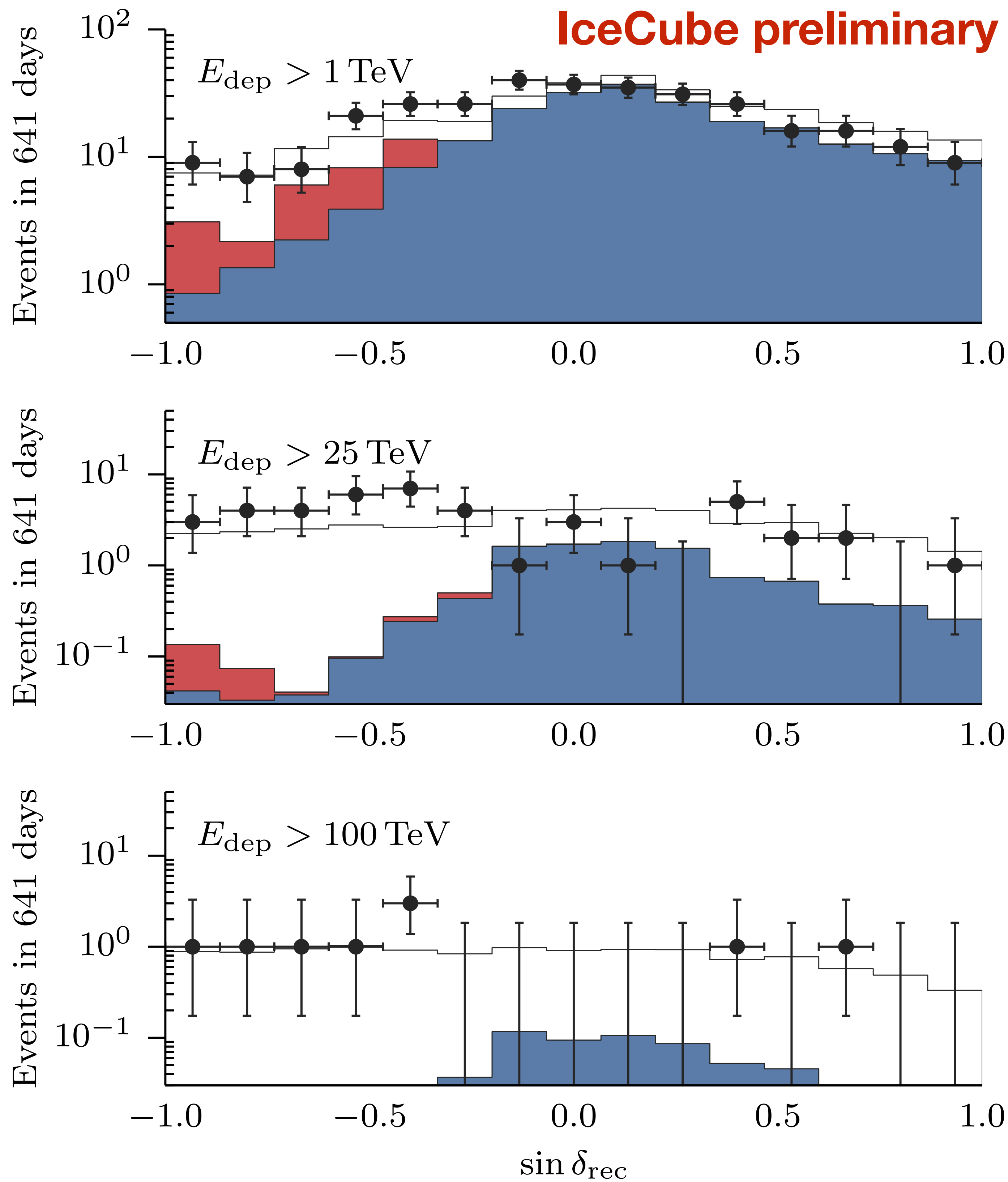
Results: angular distribution

Dominated by conventional atmospheric neutrinos → peaked at the horizon

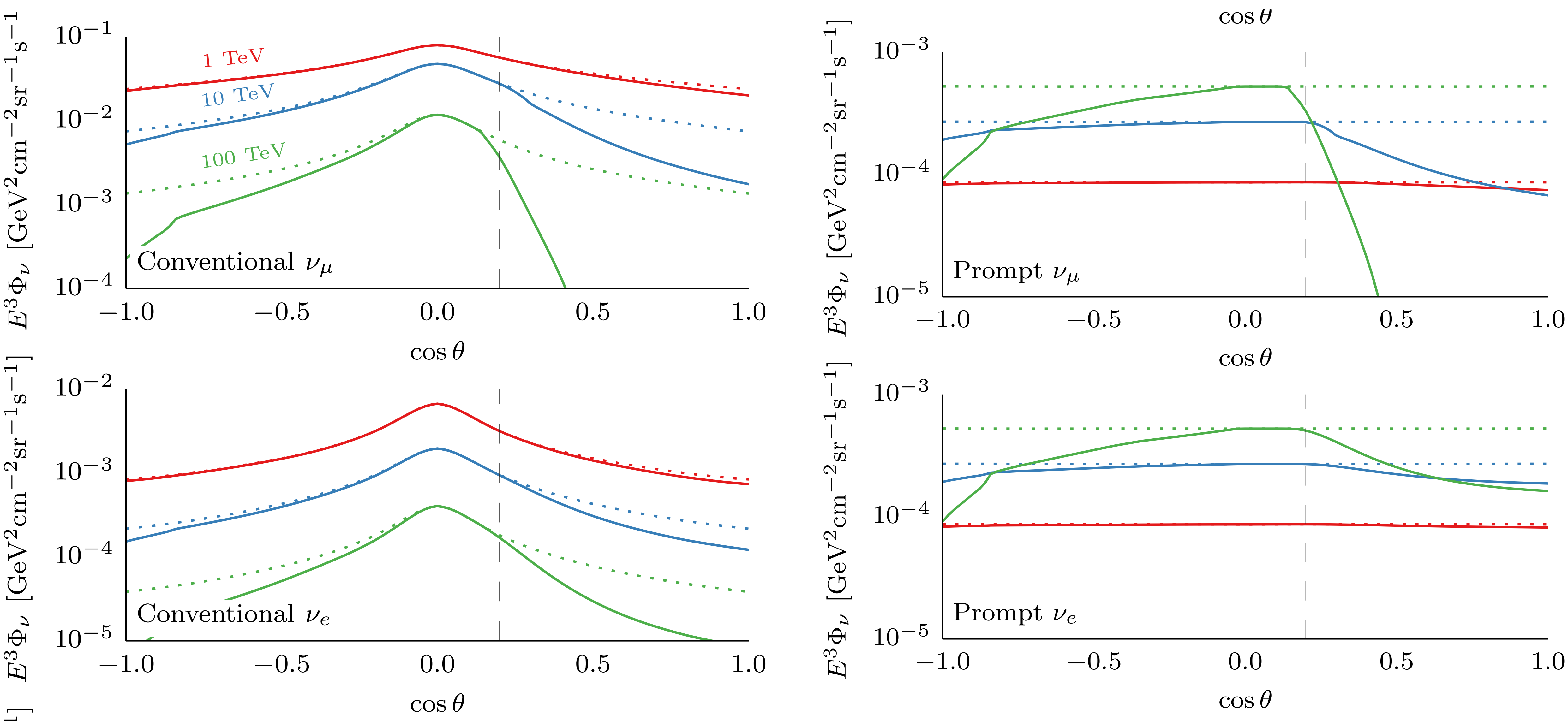
increasing energy threshold

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

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

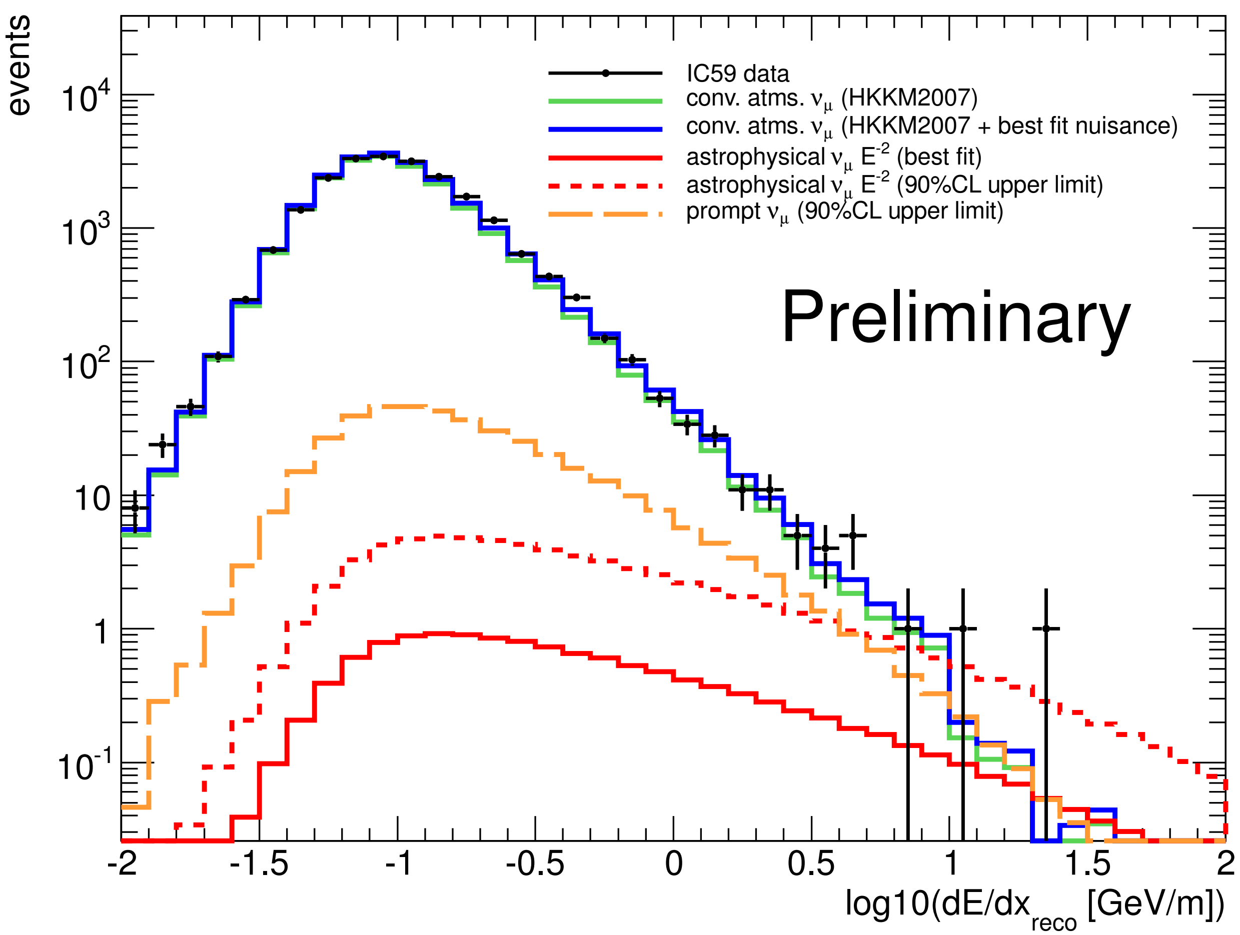


Zenith distributions at IceCube



Early hints of a high-energy excess

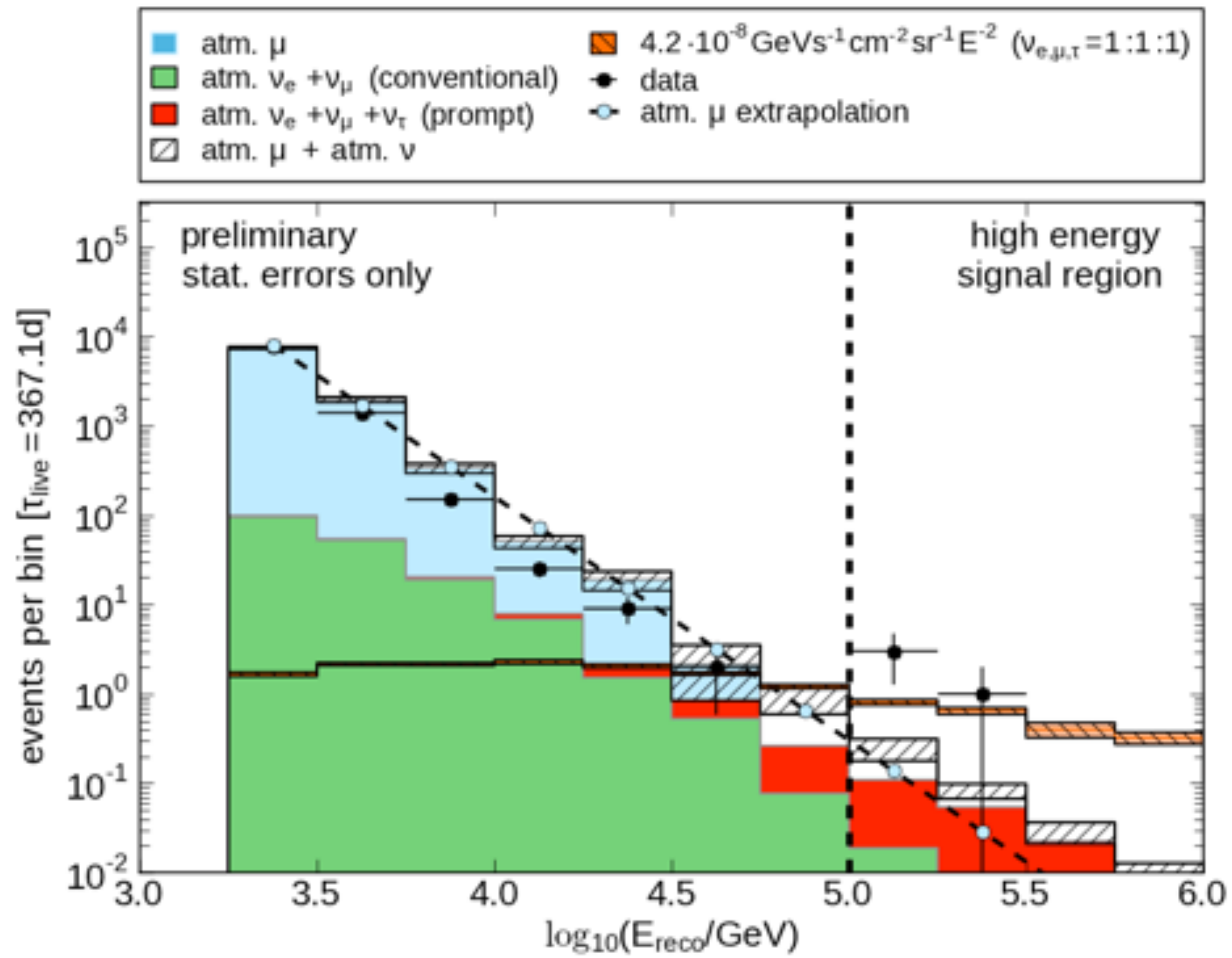
Northern hemisphere ν_μ events in 59-string configuration (2009-2010)



1.8 σ excess over atmospheric expectations

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

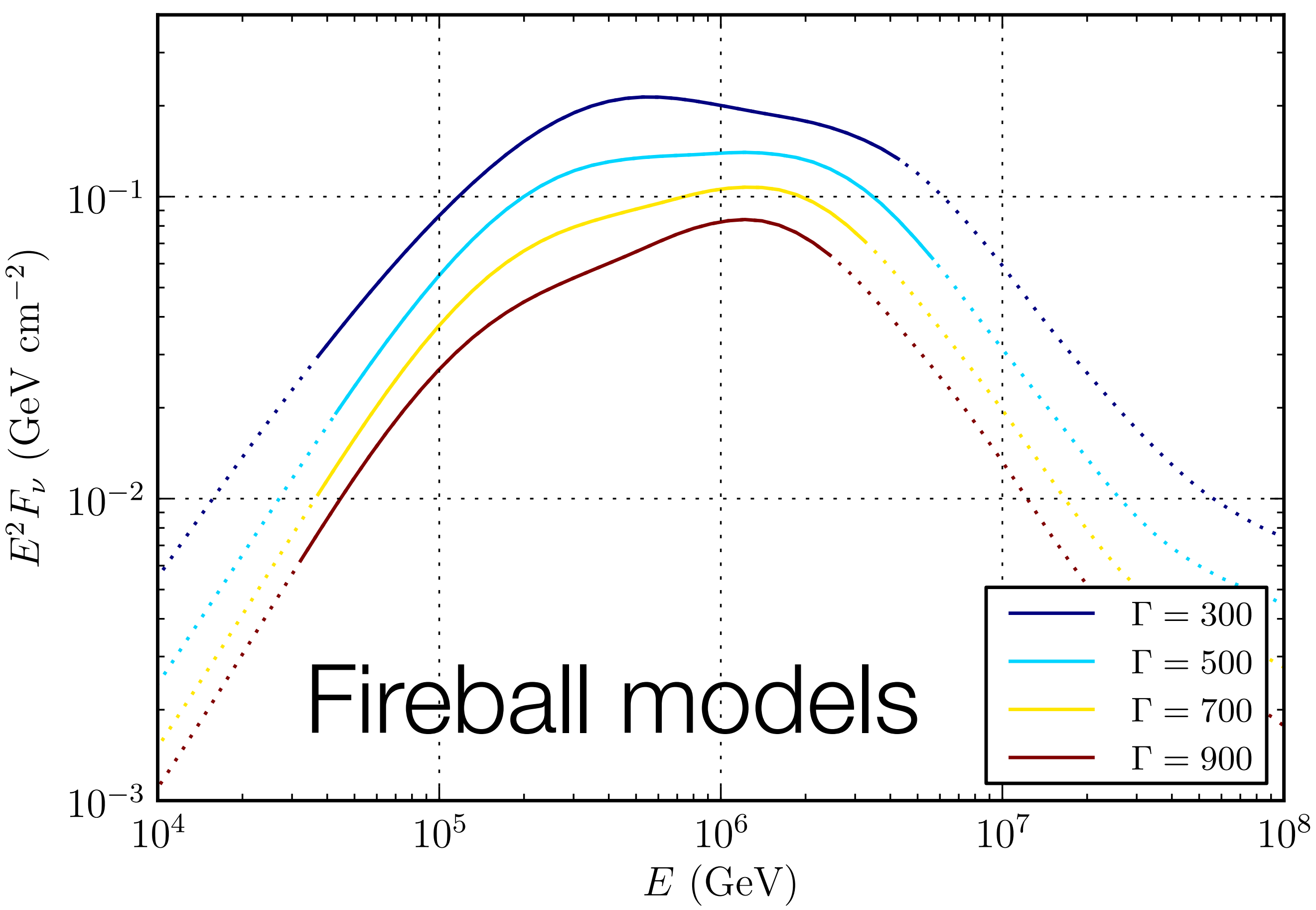
High-energy cascade events in 40-string configuration (2008-2009)

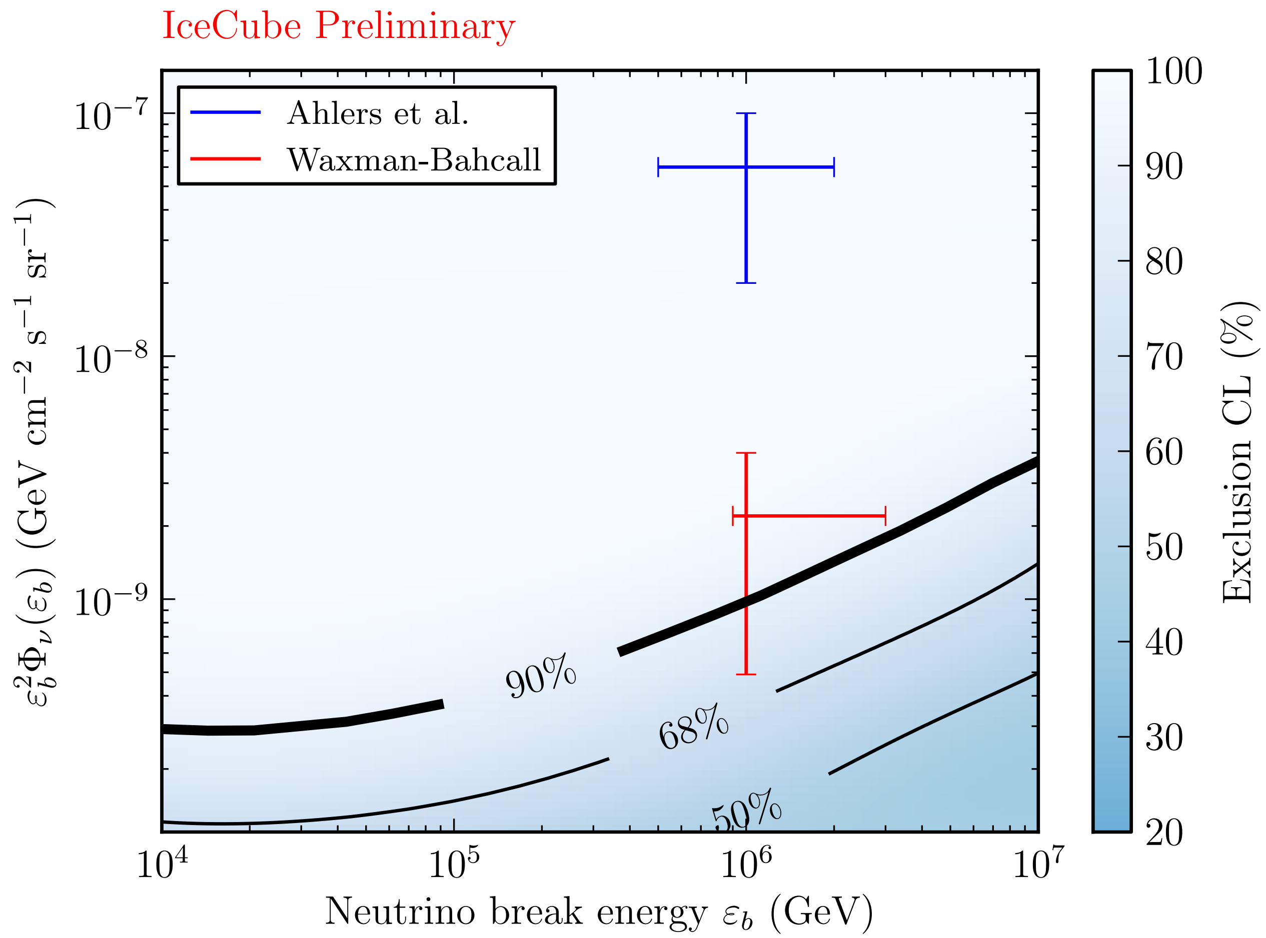


2.4 σ excess over atmospheric expectations

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

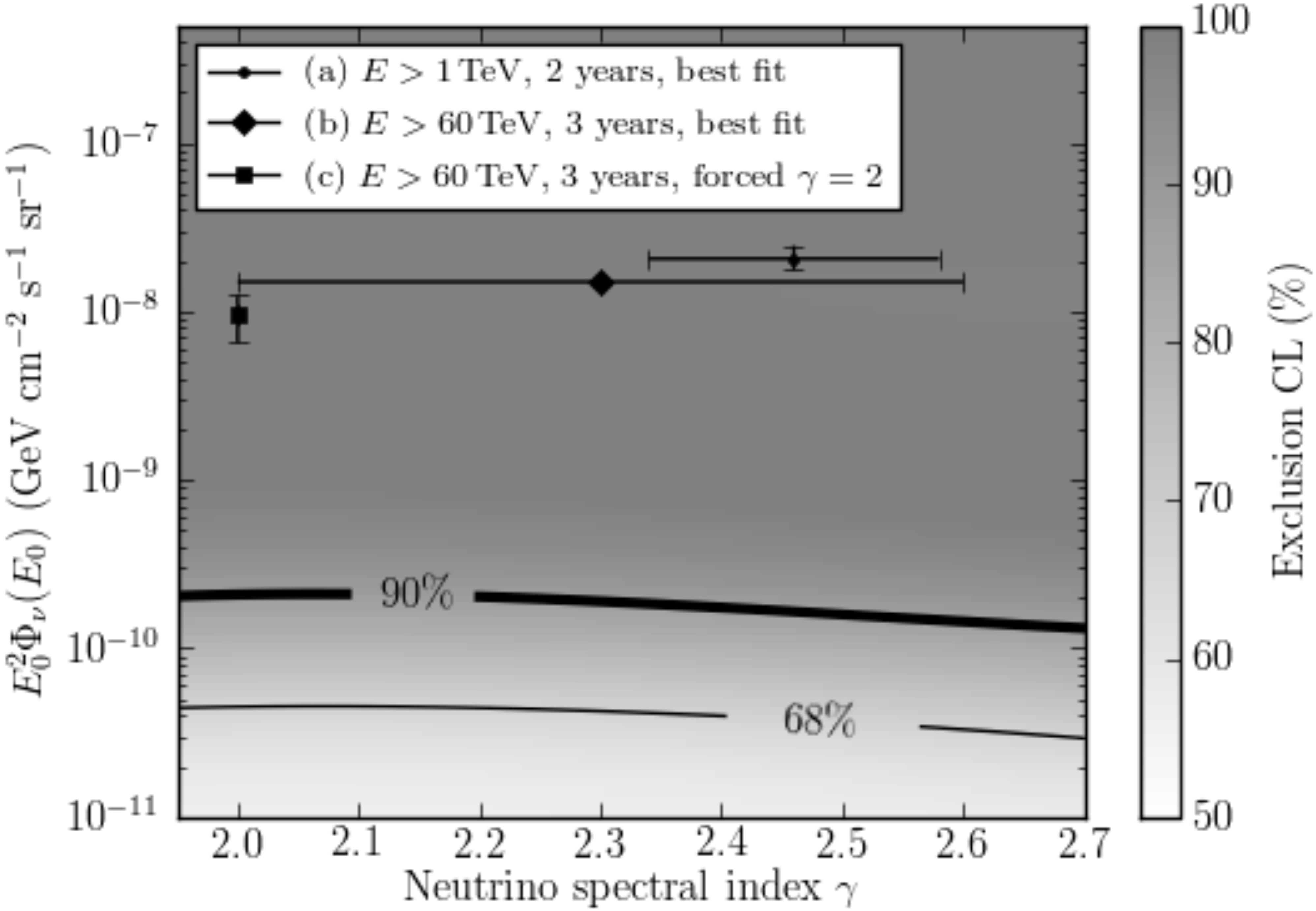
Constraints on neutrinos from GRBs



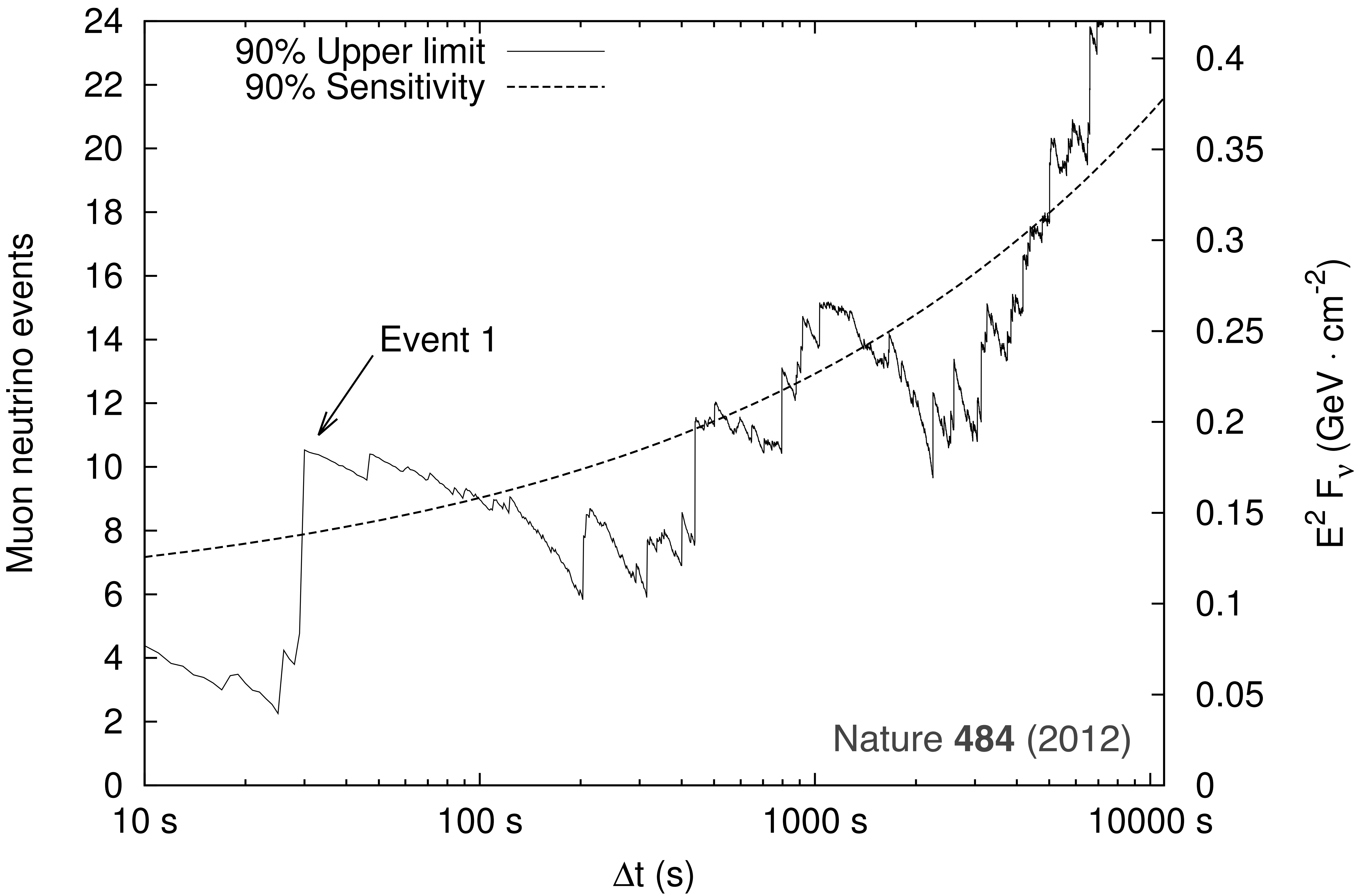


GRB analysis with 4 years of IceCube data (publication in prep)

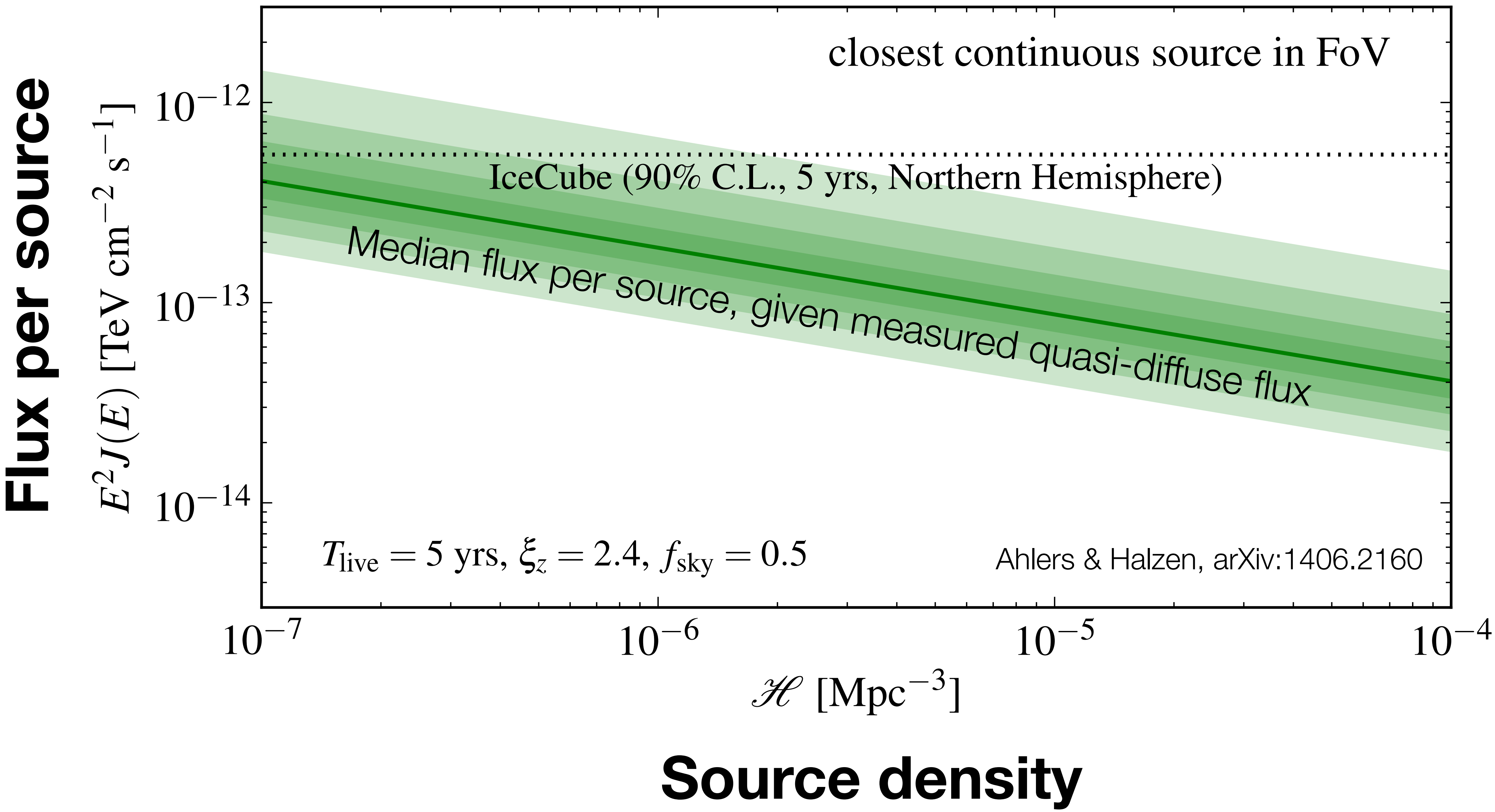
Sub-threshold GRBs can't explain the diffuse flux



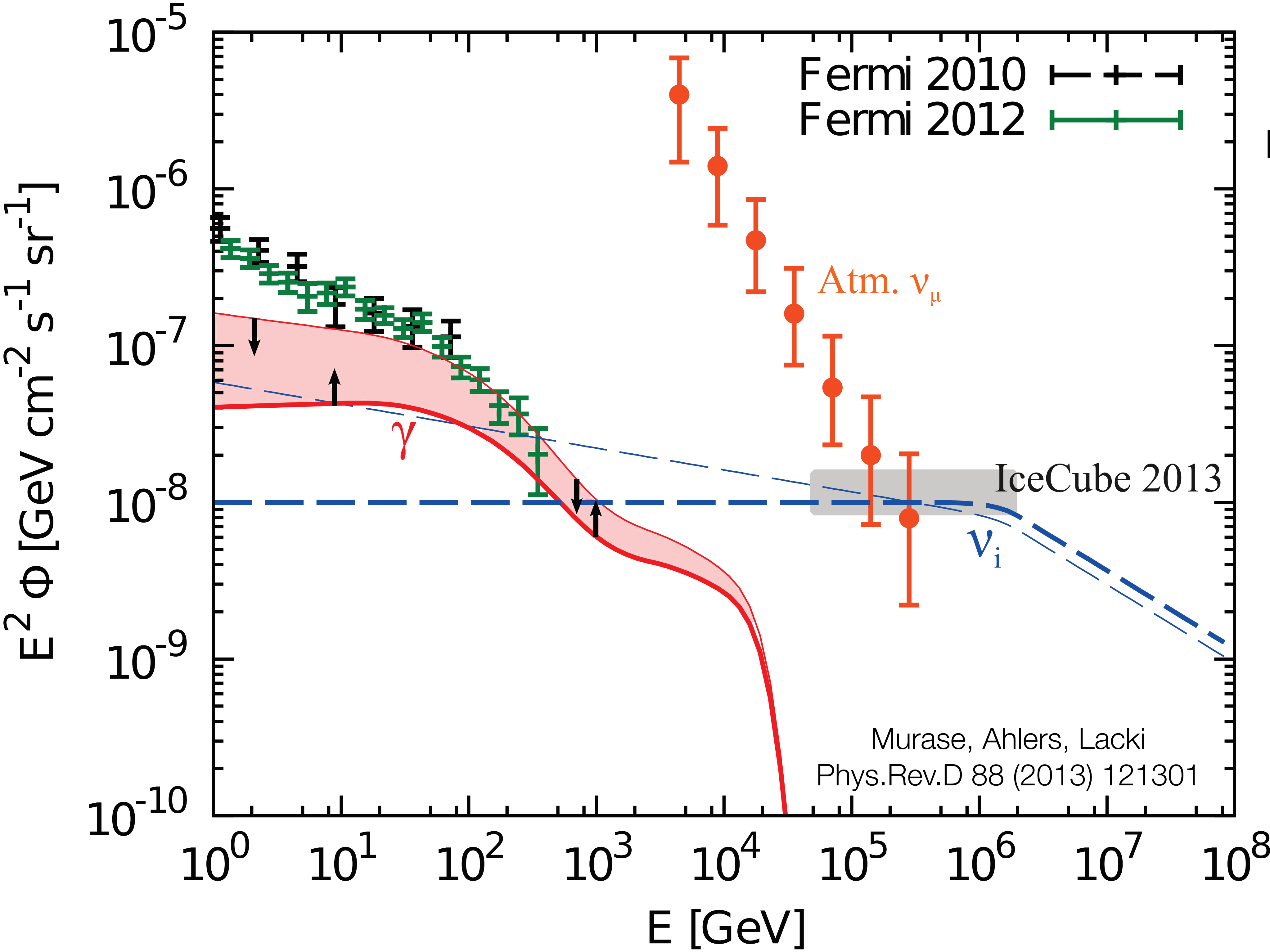
Model-independent GRB constraints



Constraints on fluxes from individual sources

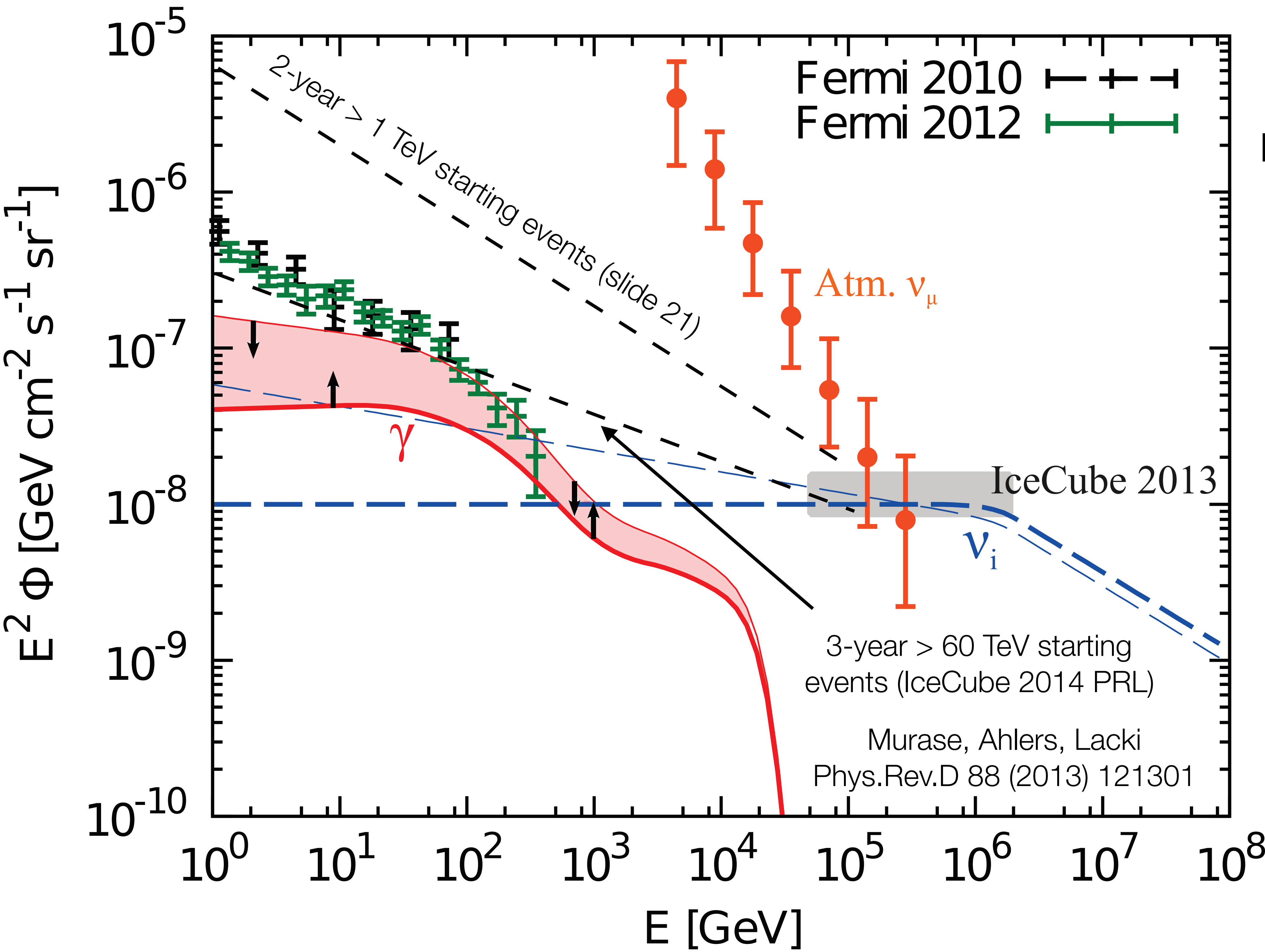


Relationship to extragalactic diffuse gamma rays



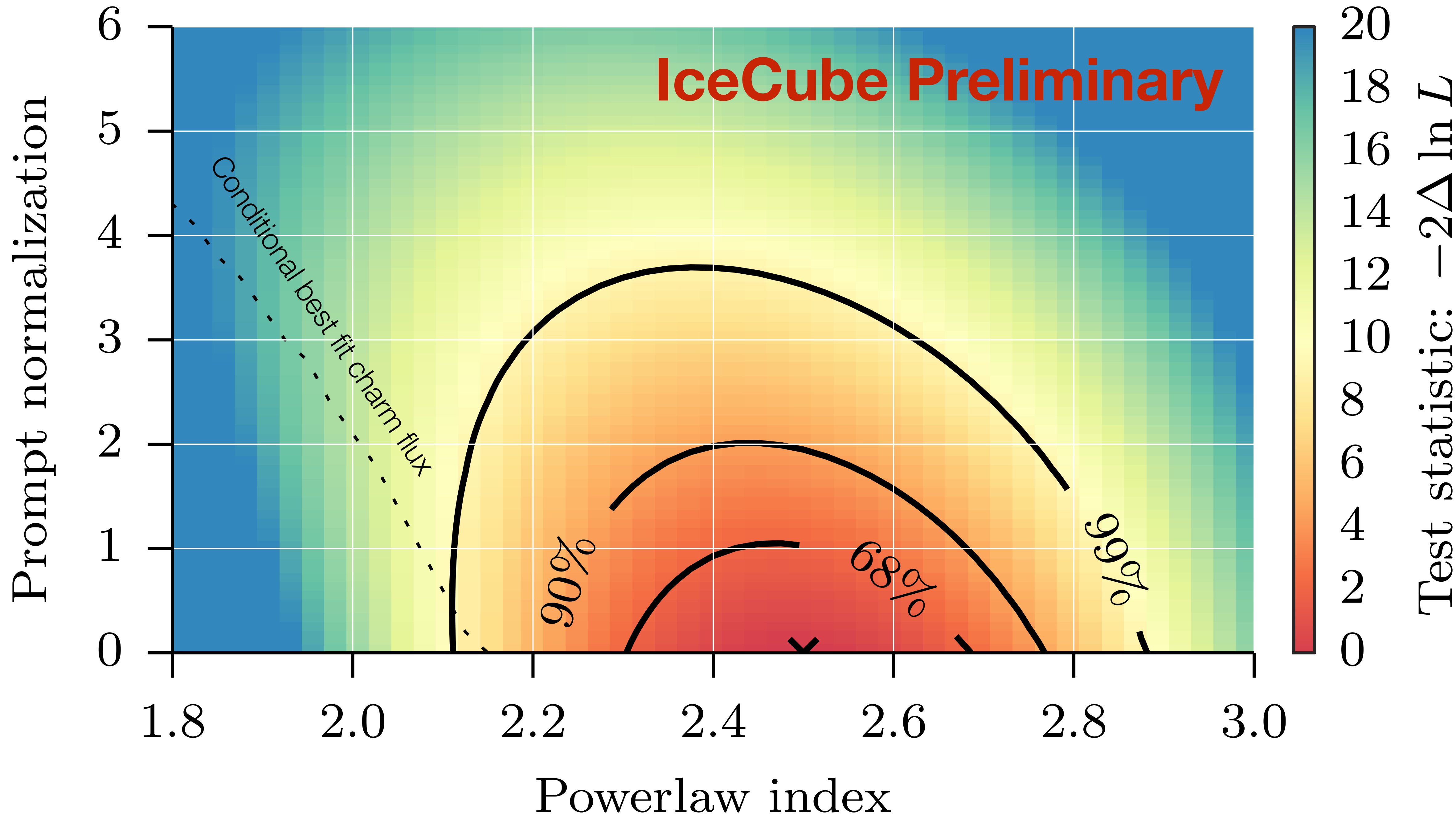
Interpret with care:
Fermi data points are
extra-galactic only

Relationship to extragalactic diffuse gamma rays

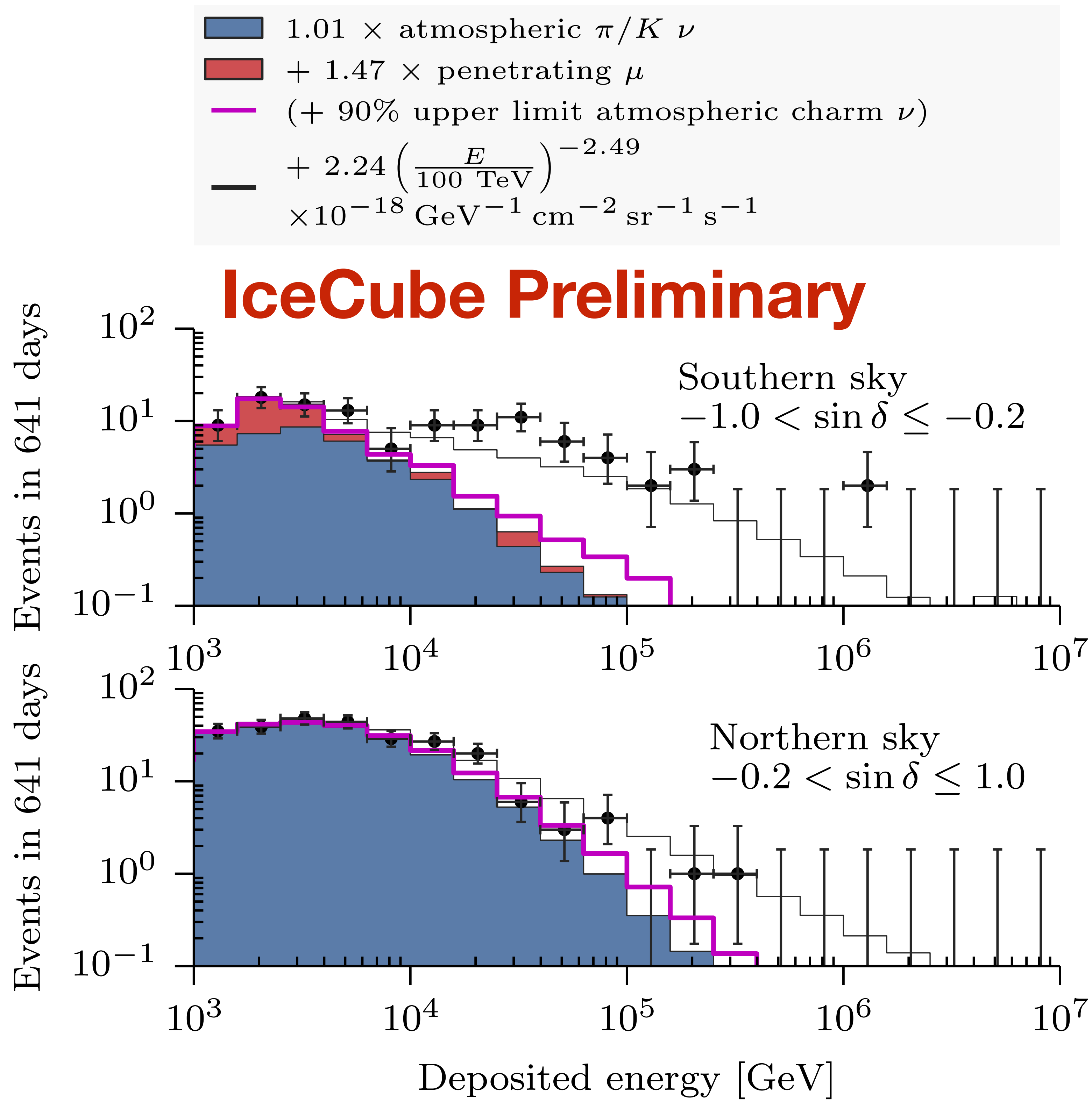


Interpret with care: Fermi data points are extra-galactic only

Correlations with astrophysical index

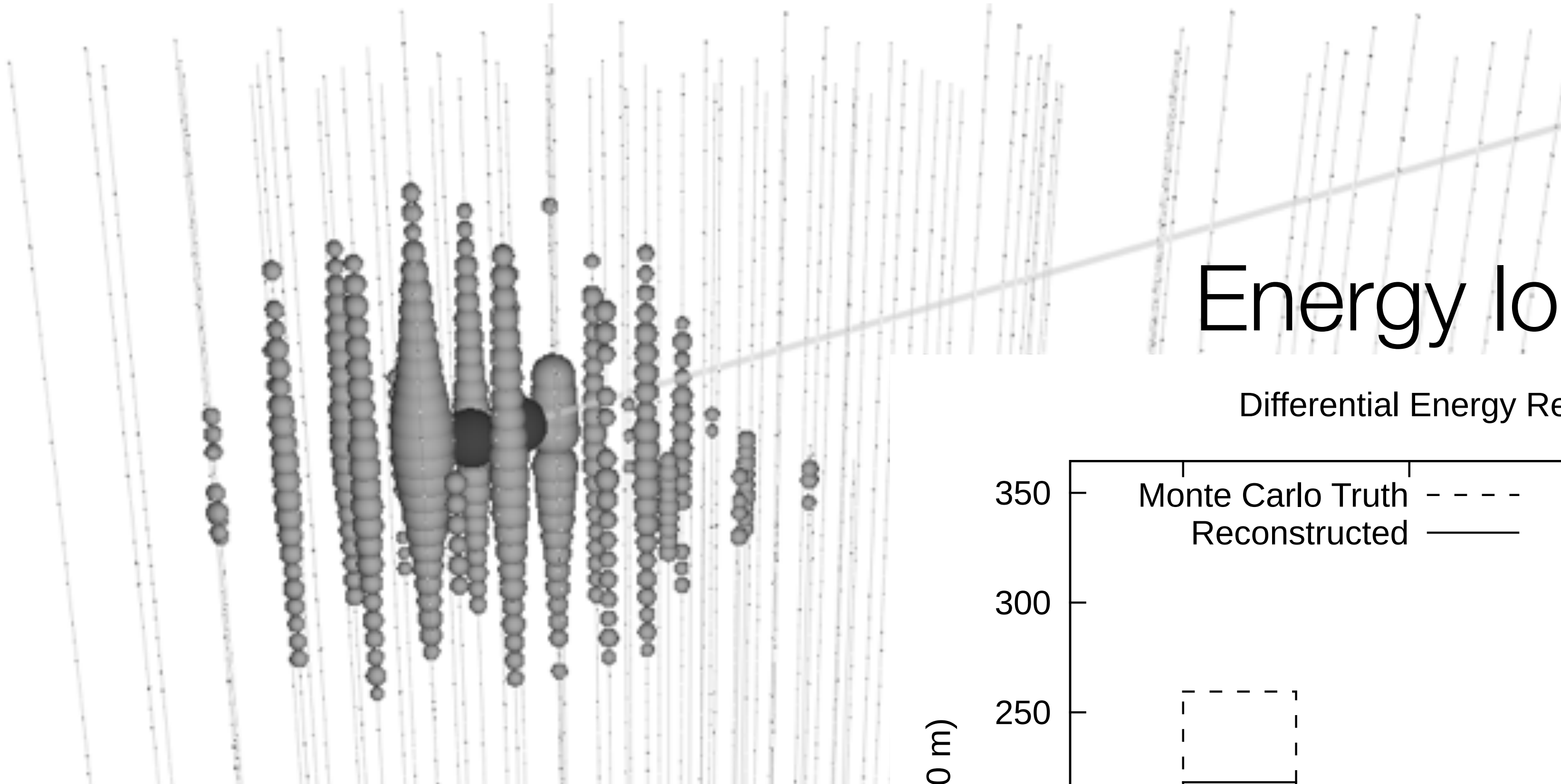


Energy spectrum with charm upper limit

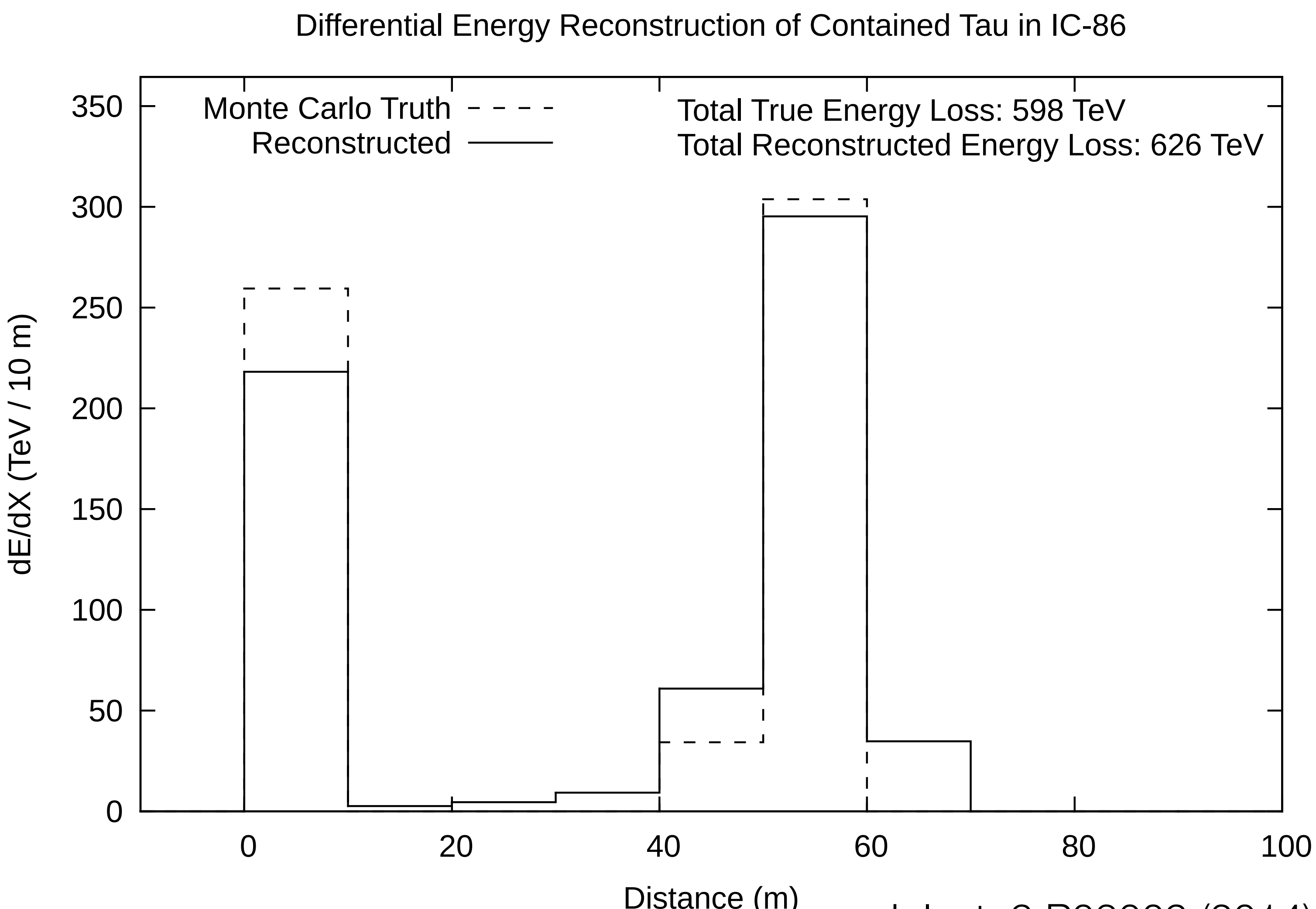


τ double-bang reconstruction

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



Energy loss reconstruction

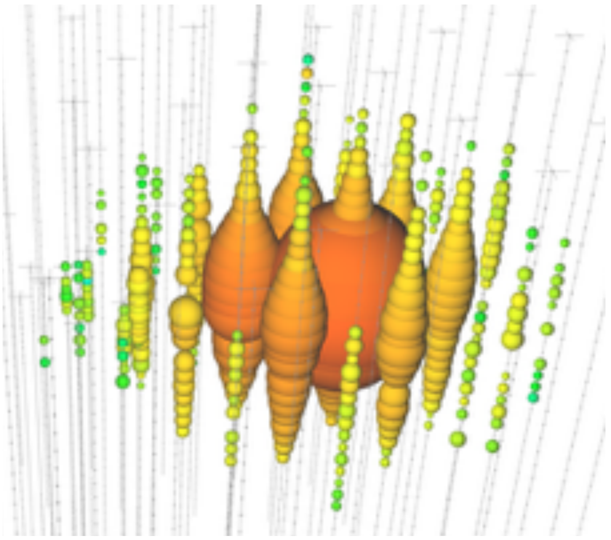


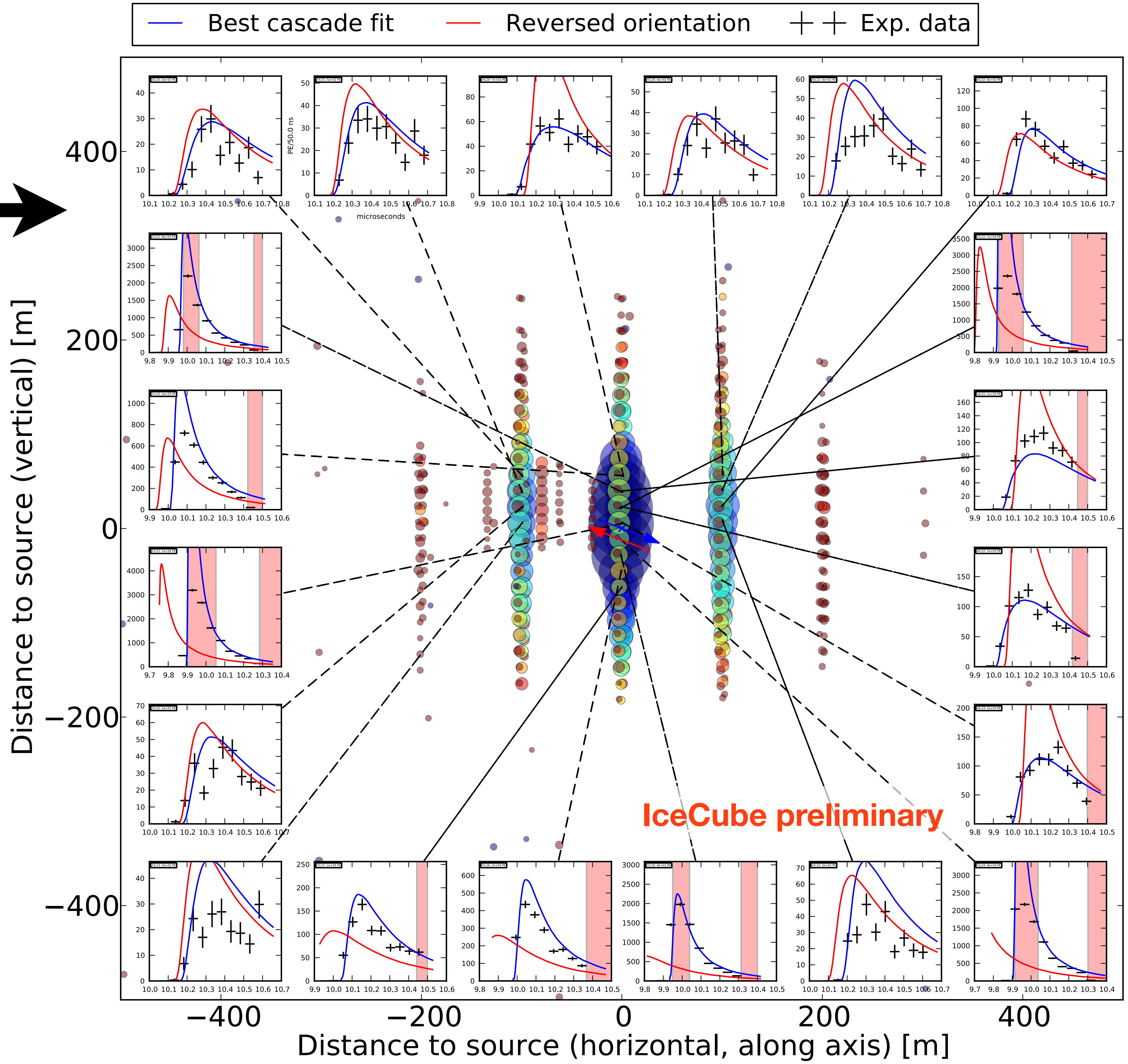
J. Inst. 9:P03009 (2014)

Resolution depends strongly on interaction geometry.

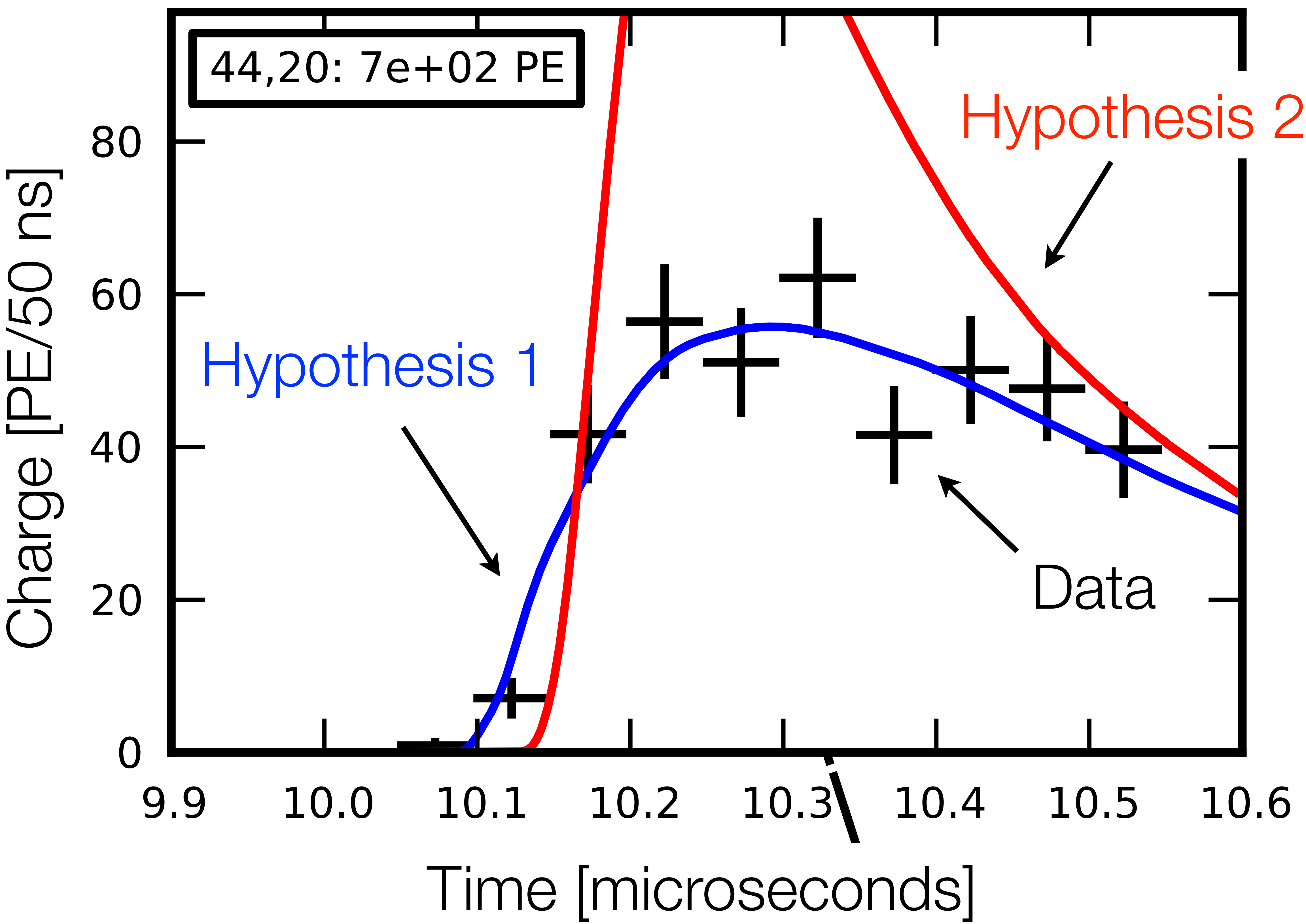
No τ events observed to date.

Cascade reconstruction: hypothesis and data



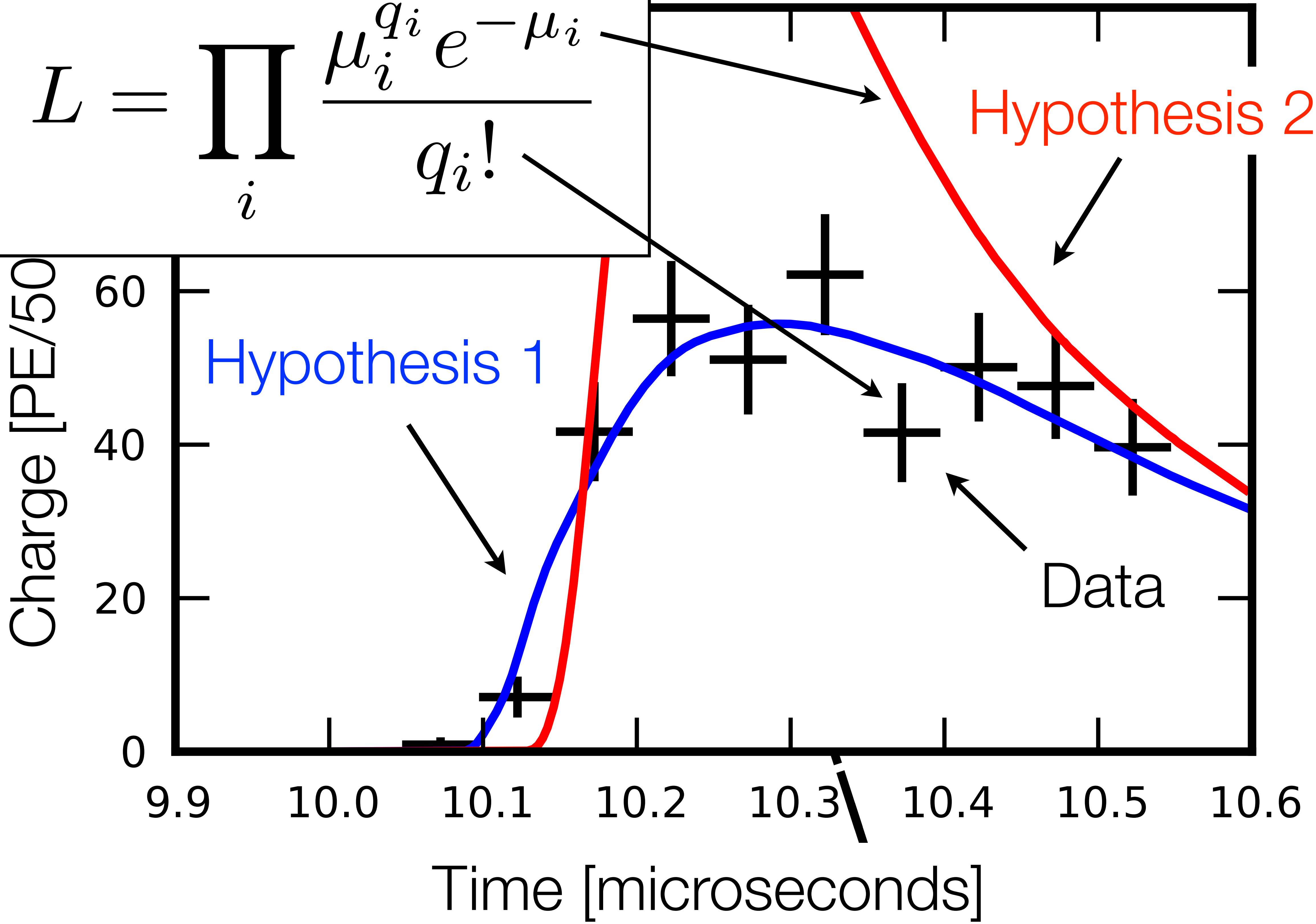


Cascade reconstruction: likelihood fit

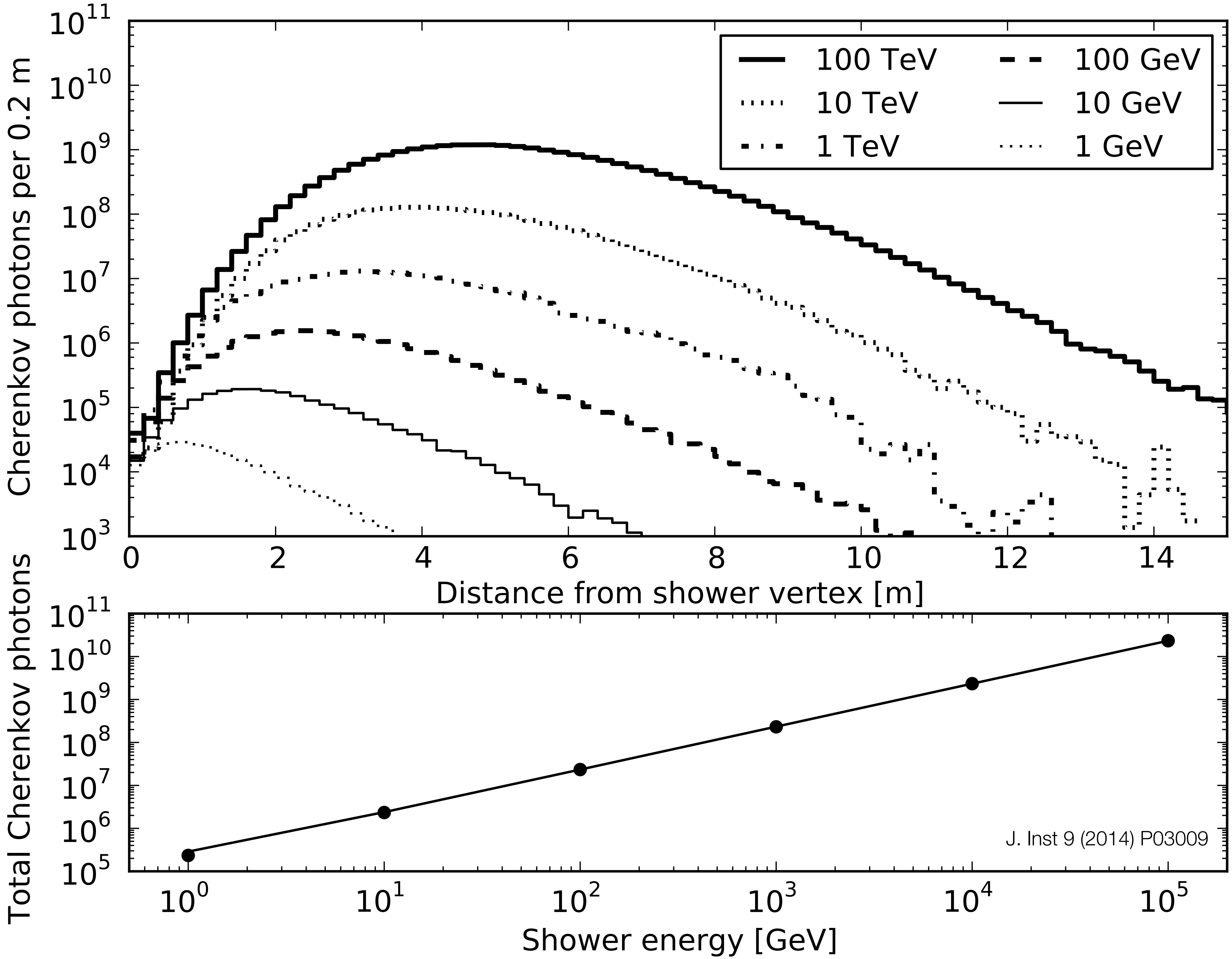


Cascade reconstruction: likelihood fit

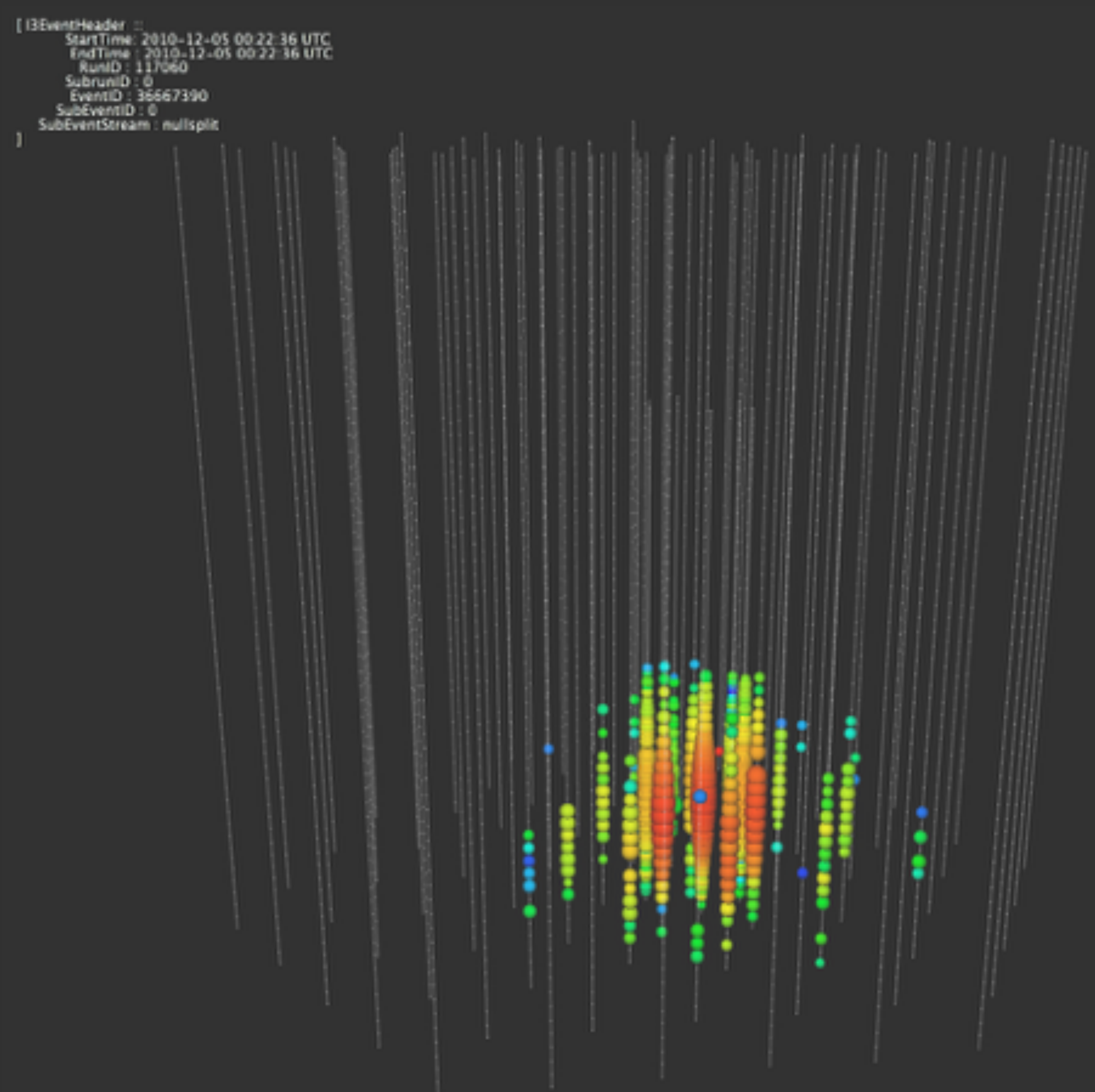
$$L = \prod_i \frac{\mu_i^{q_i} e^{-\mu_i}}{q_i!}$$



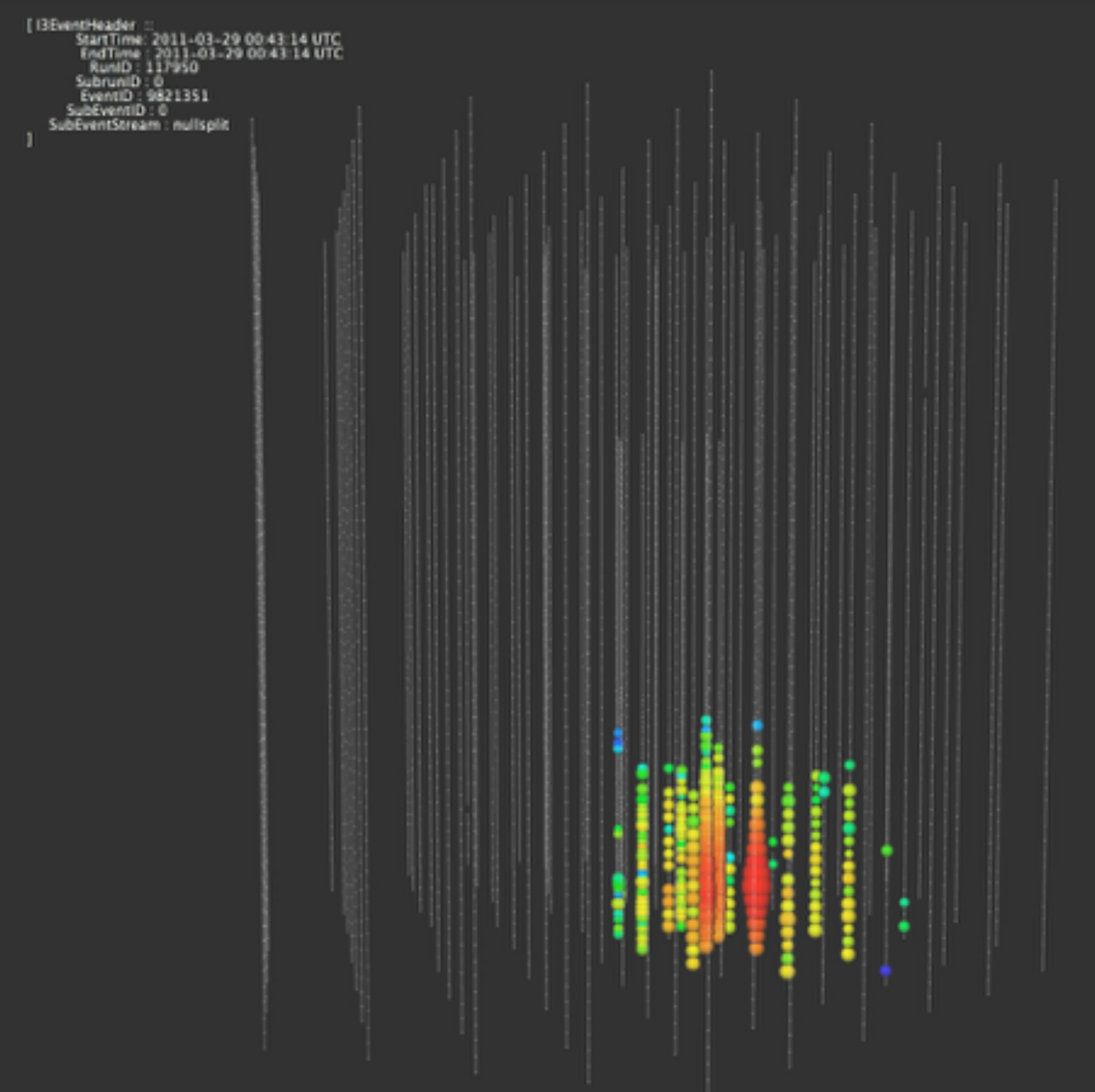
Cascade reconstruction: energy



Cascades

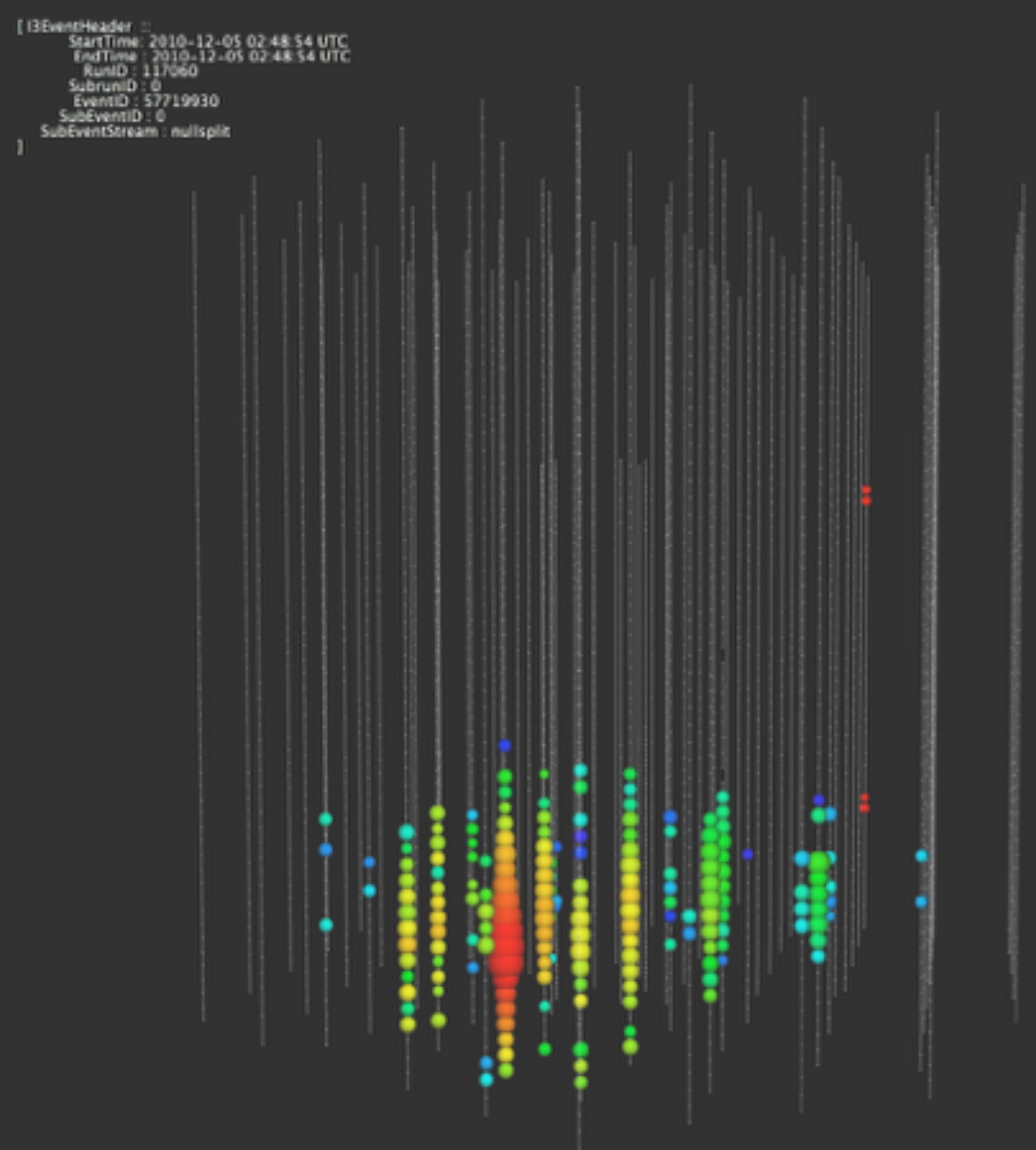


~ 20 TeV deposited

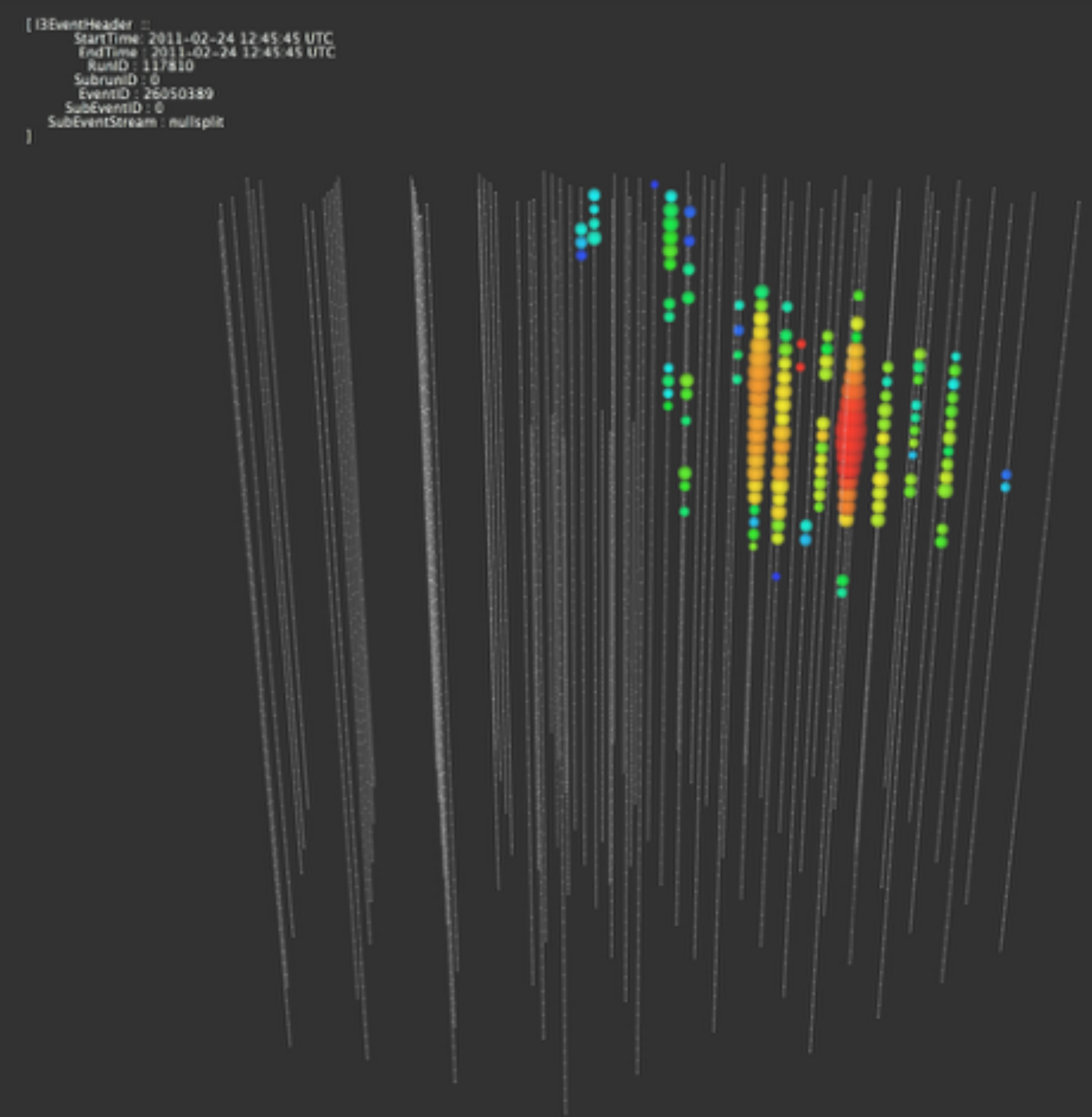


~ 13 TeV deposited

Starting tracks

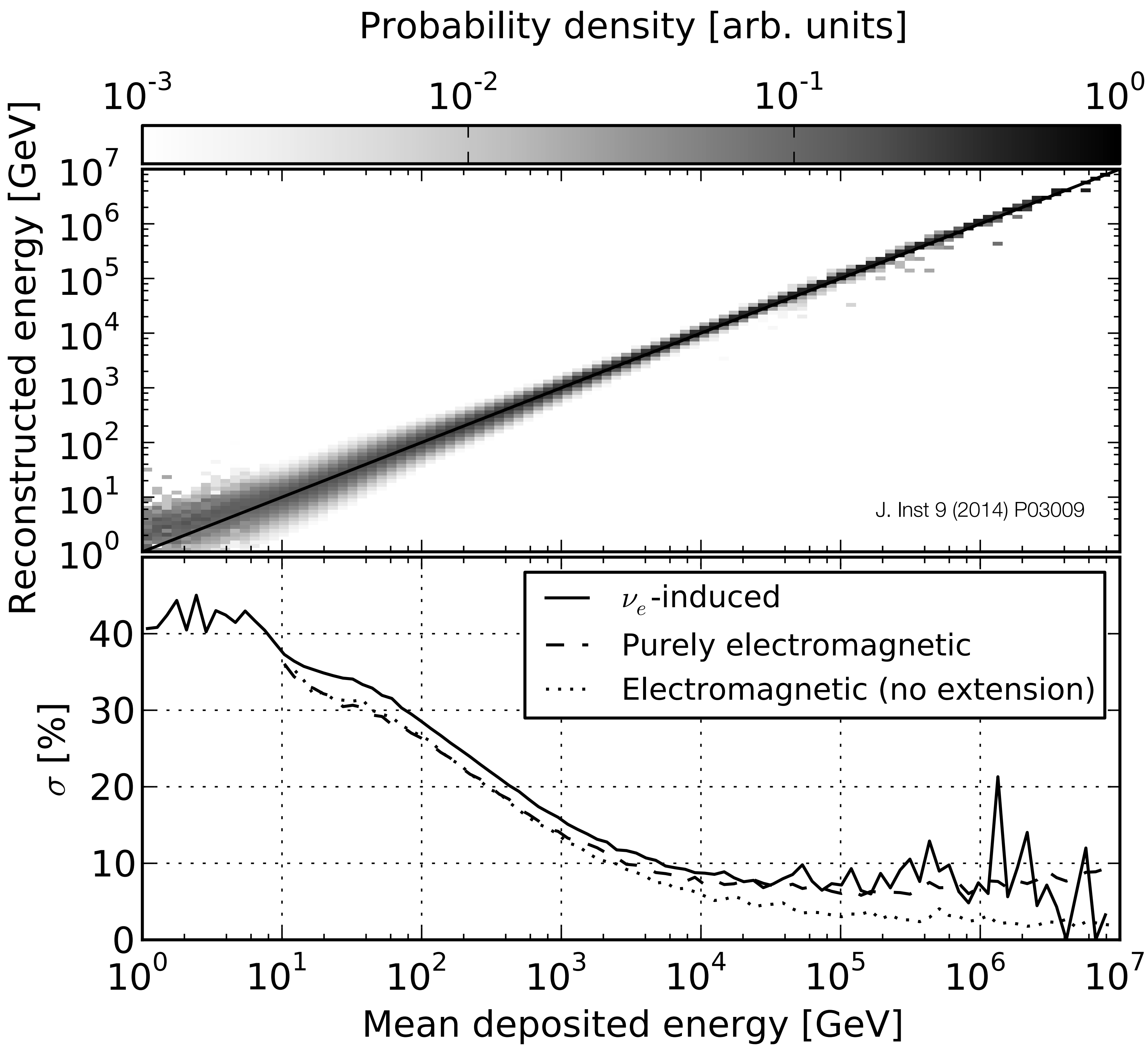


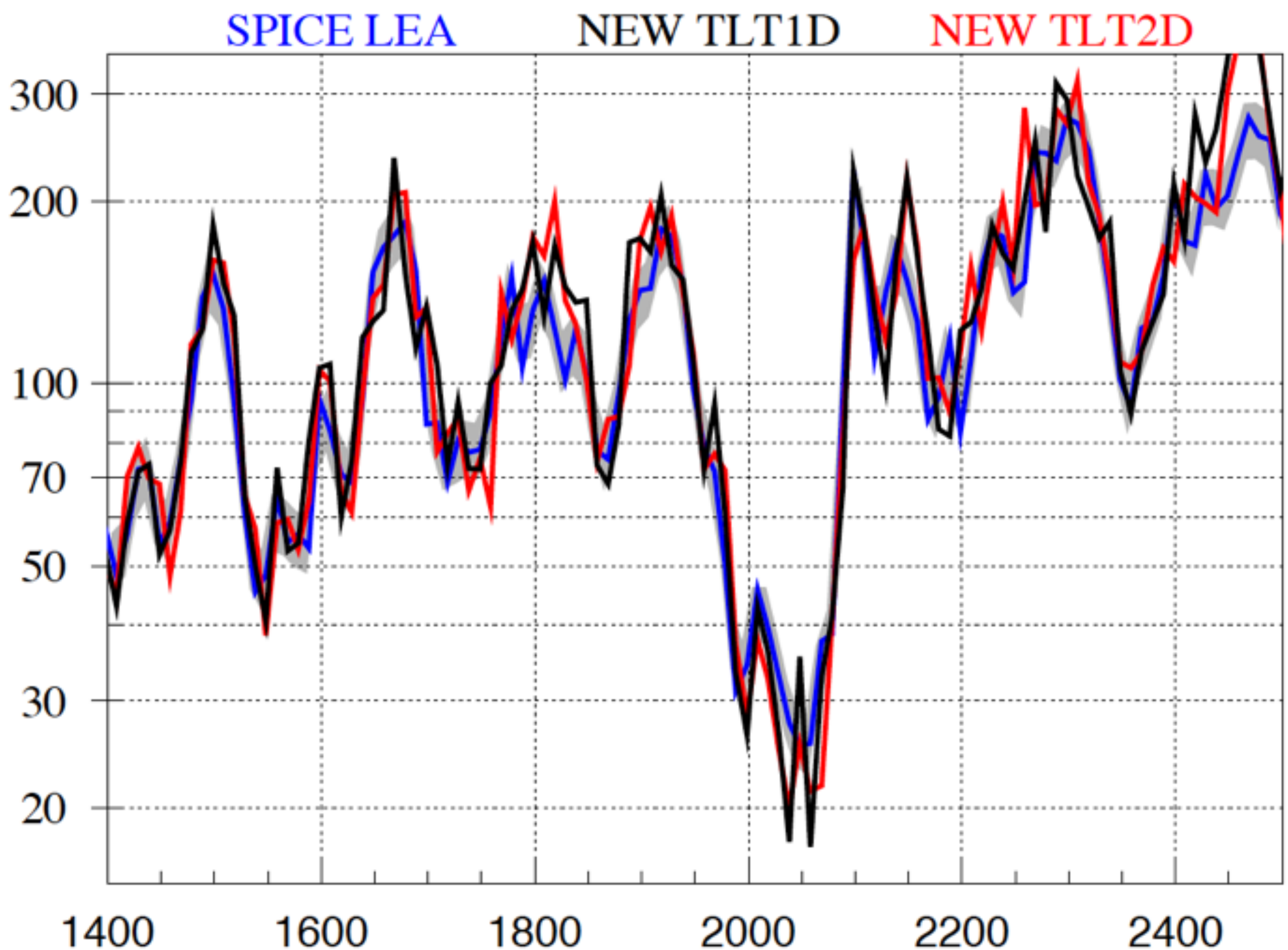
~ 18 TeV deposited



~ 100 TeV deposited

Deposited-energy resolution for showers in IceCube





λ_a(400 nm) [m] vs. depth [m]