Neutrino observations with the IceCube Observatory

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lectures outline

neutrino telescopes & the IceCube Observatory

observing the Universe

neutrino observations

cosmic ray observations

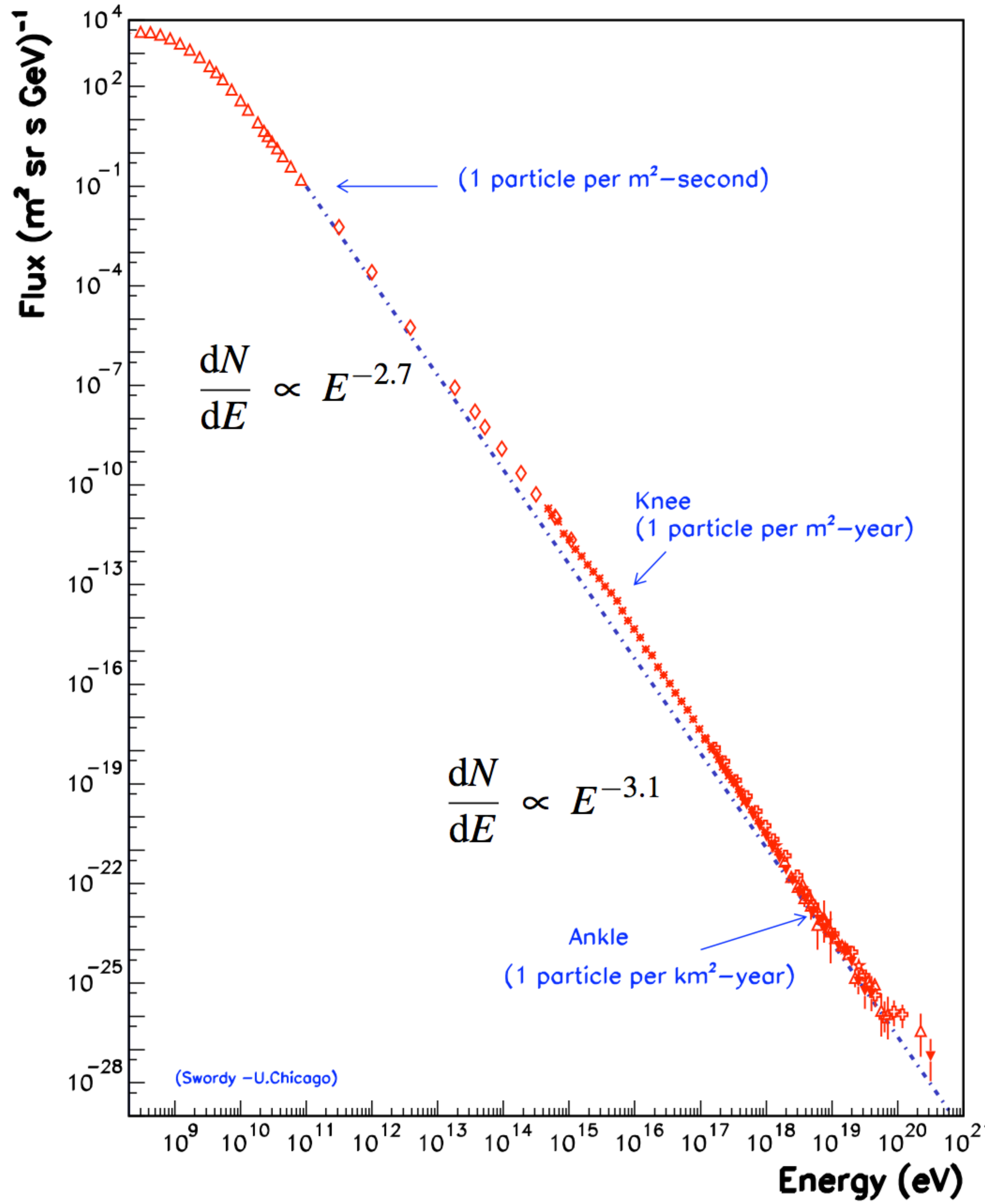
astrophysics & interdisciplinary sciences

outline
neutrino observations with IceCube

- the origin of cosmic rays
- neutrinos as probe into cosmic ray sources
- neutrino identification
- diffuse fluxes of neutrinos
- a window to astrophysical neutrinos

primary cosmic rays
spectrum

- **~E^{-2}** cosmic ray spectrum at the sources
- cosmic ray spectrum at Earth **steeper**
- **knee** traces the end of galactic contribution ?
- **ankle** traces cross-over with extra-galactic contribution ?



primary cosmic rays
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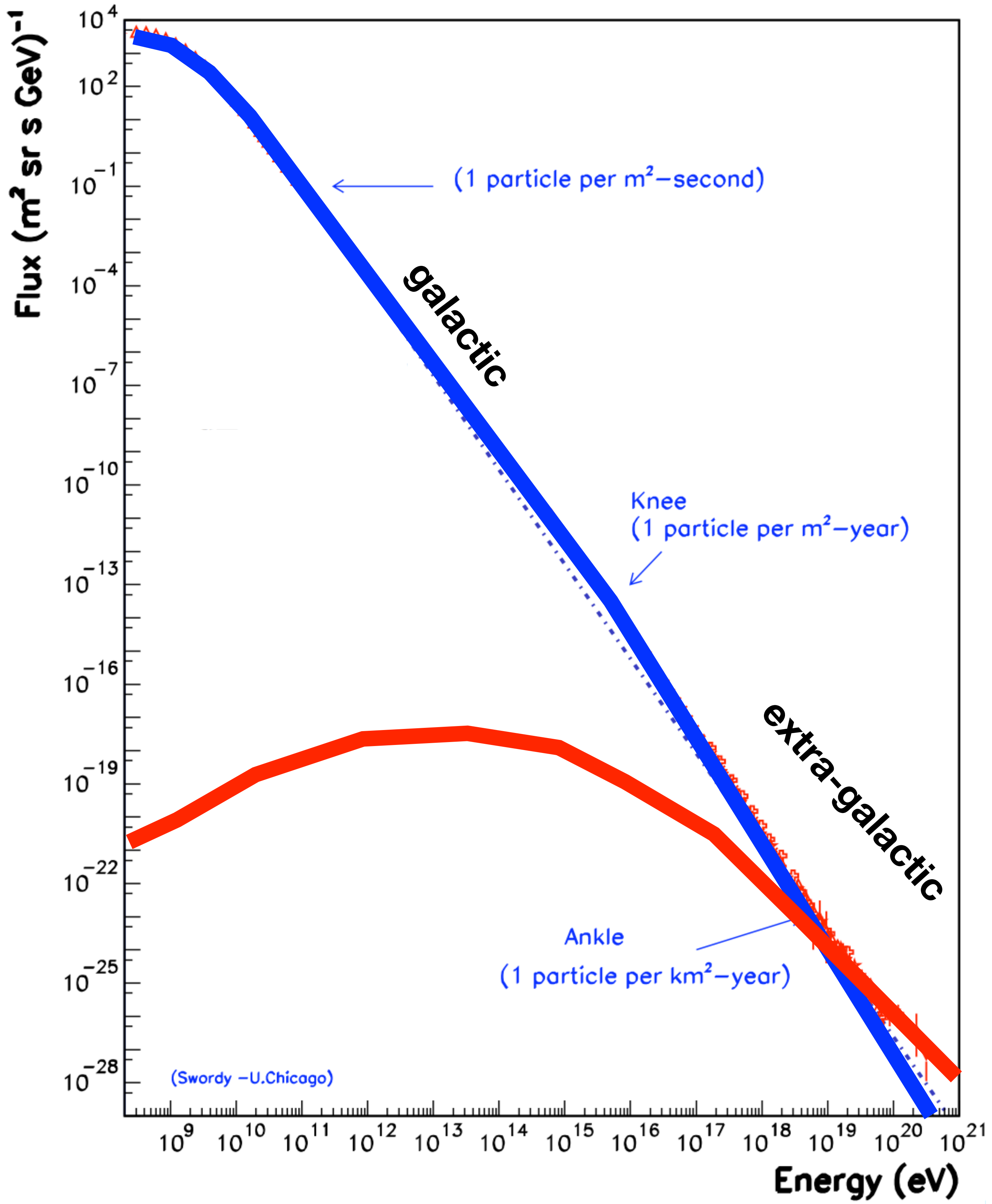


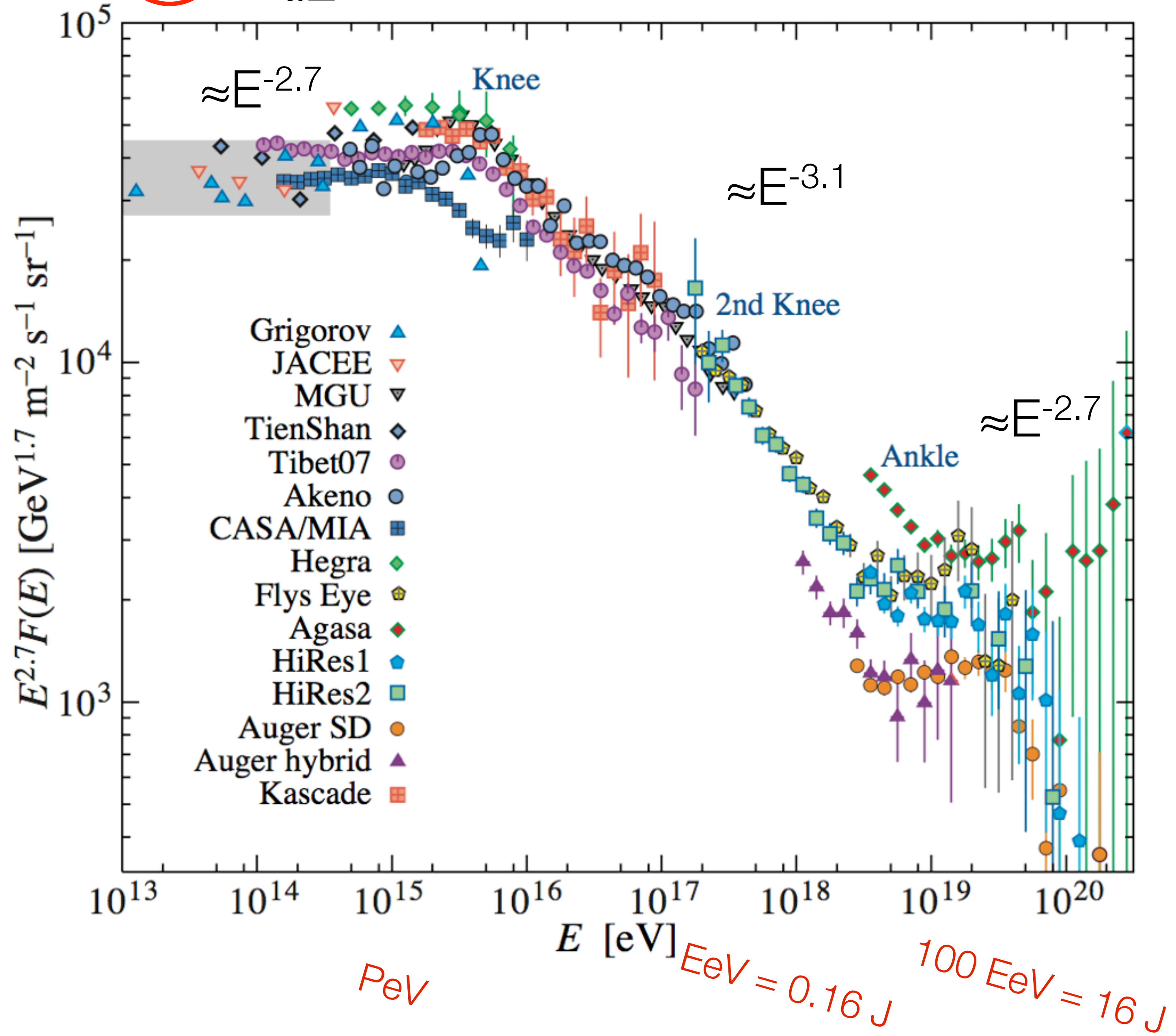
primary cosmic rays

spectrum and composition

what do we learn about their sources ?

$E^{2.7} \cdot \frac{d\Phi_{CR}}{dE}(E)$

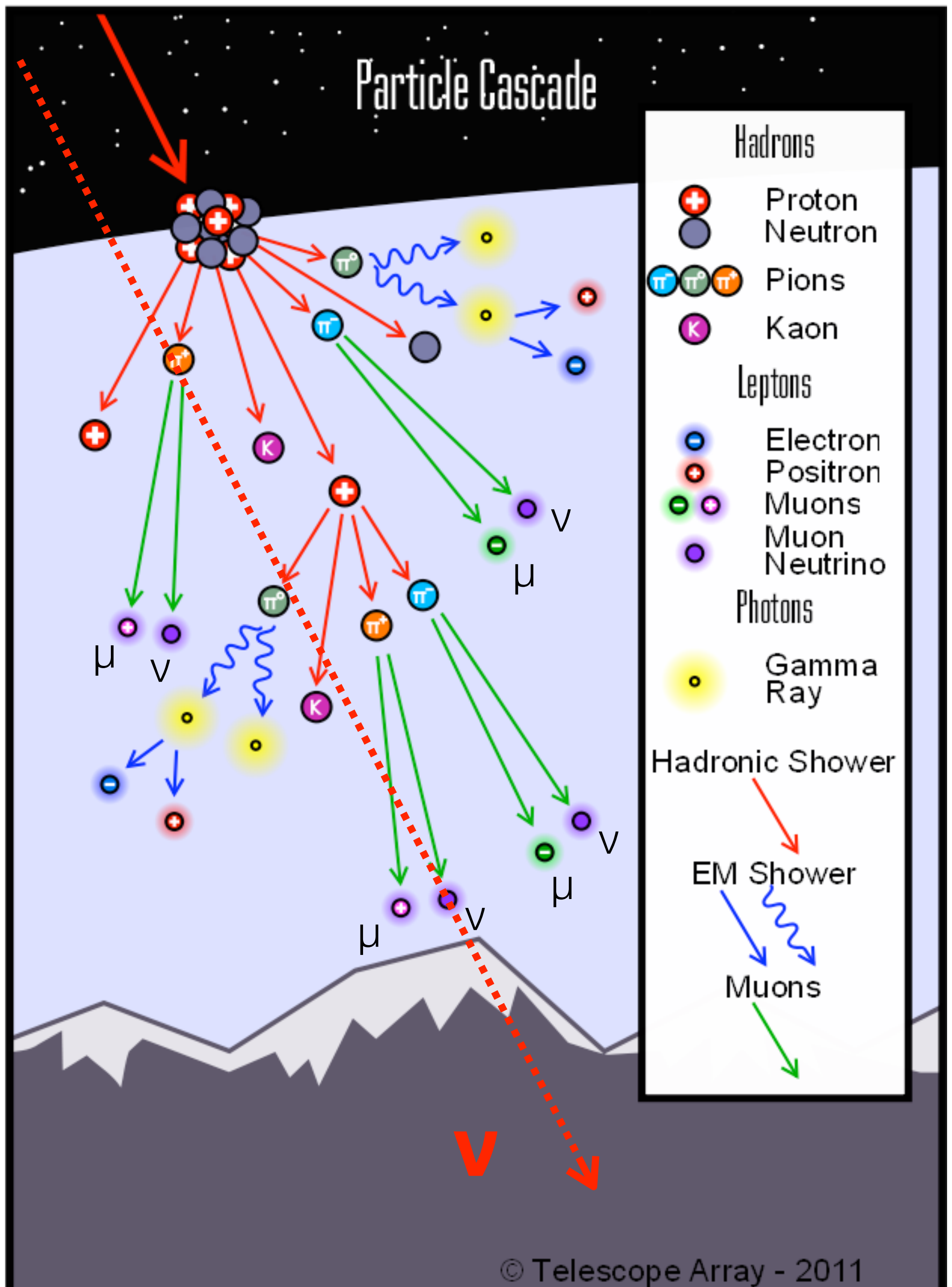
Stanev, Gaisser, PDG

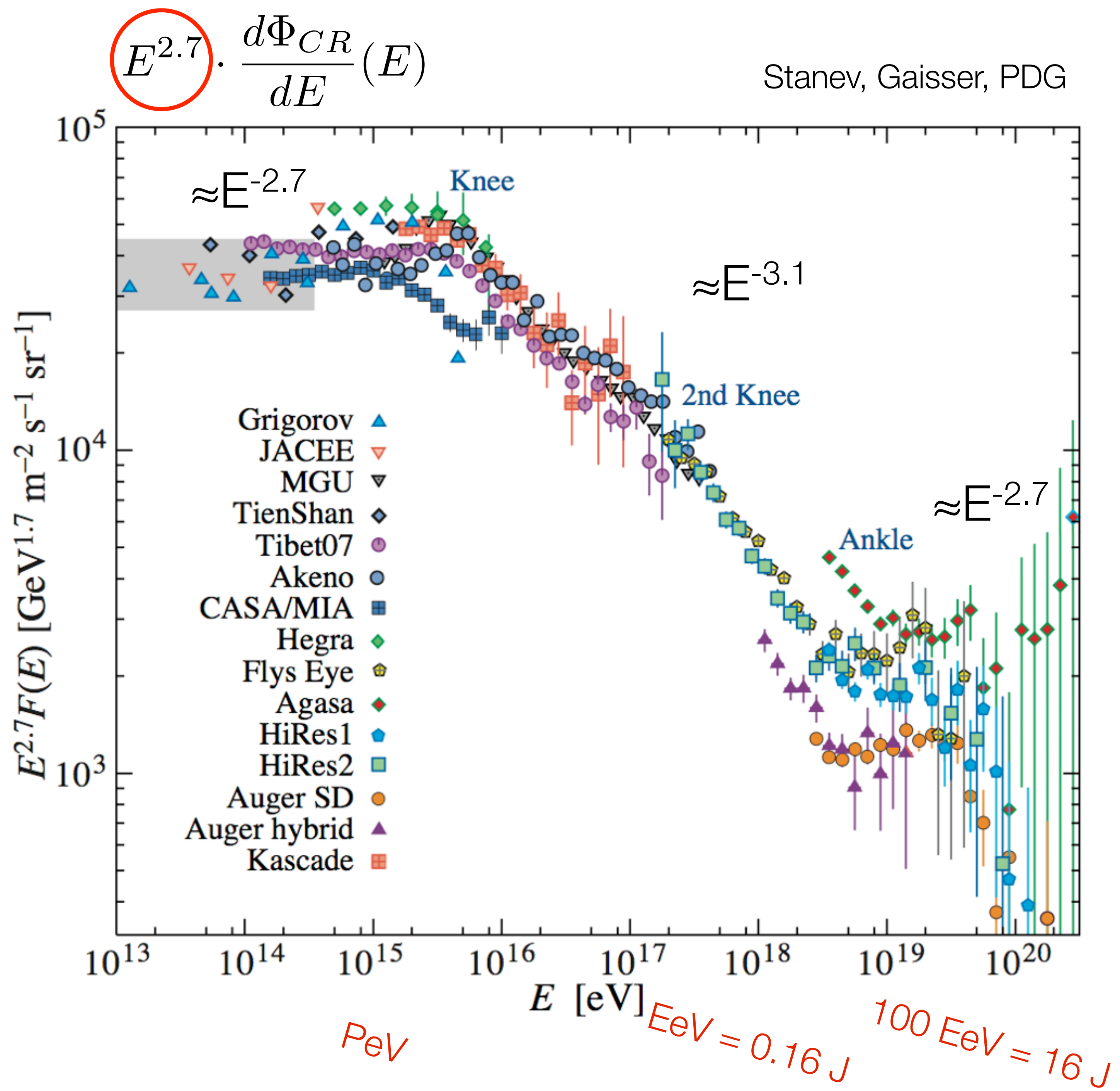


16 J ~ kinetic energy of tennis ball @ 50 mph
~ kinetic energy of baseball @ 25 mph

primary cosmic rays
spectrum and composition

what do we learn about their sources ?





16 J ~ kinetic energy of tennis ball @ 50 mph
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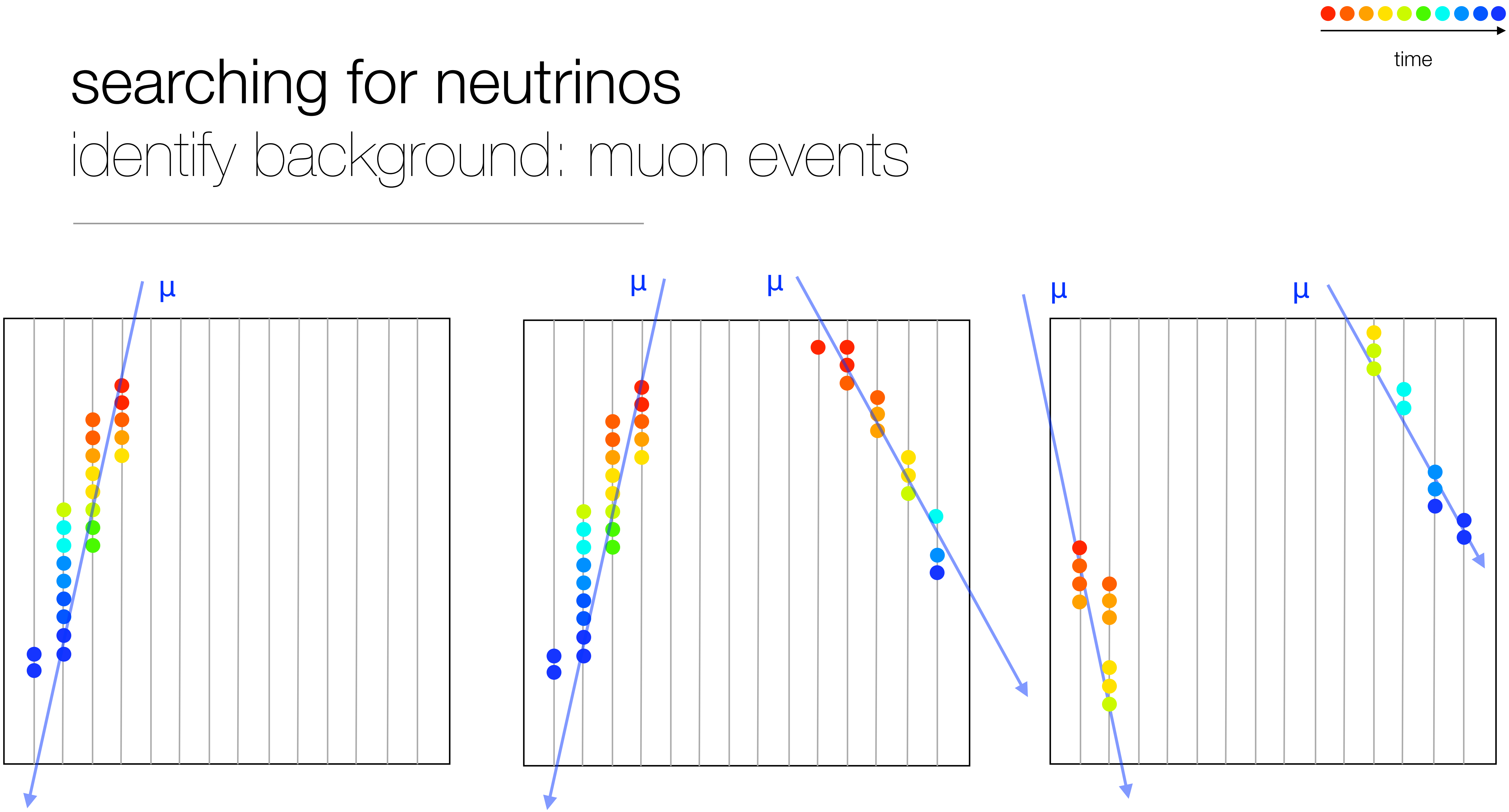
searching for neutrinos

identify background: muon events

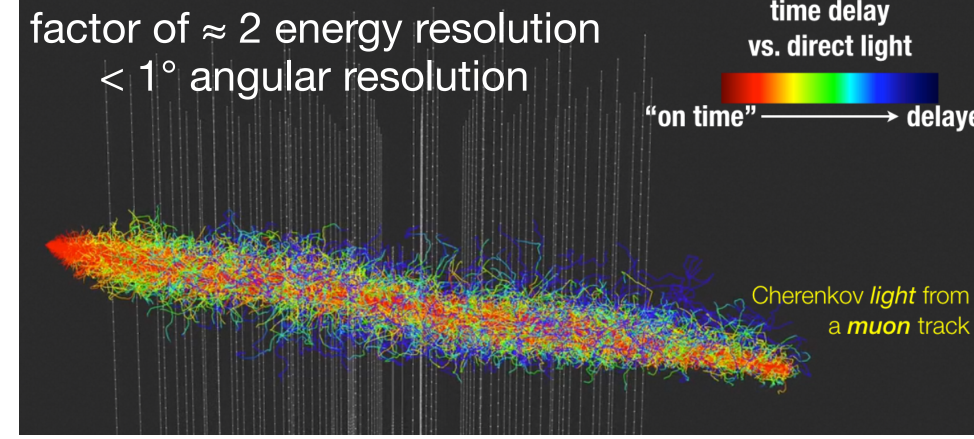


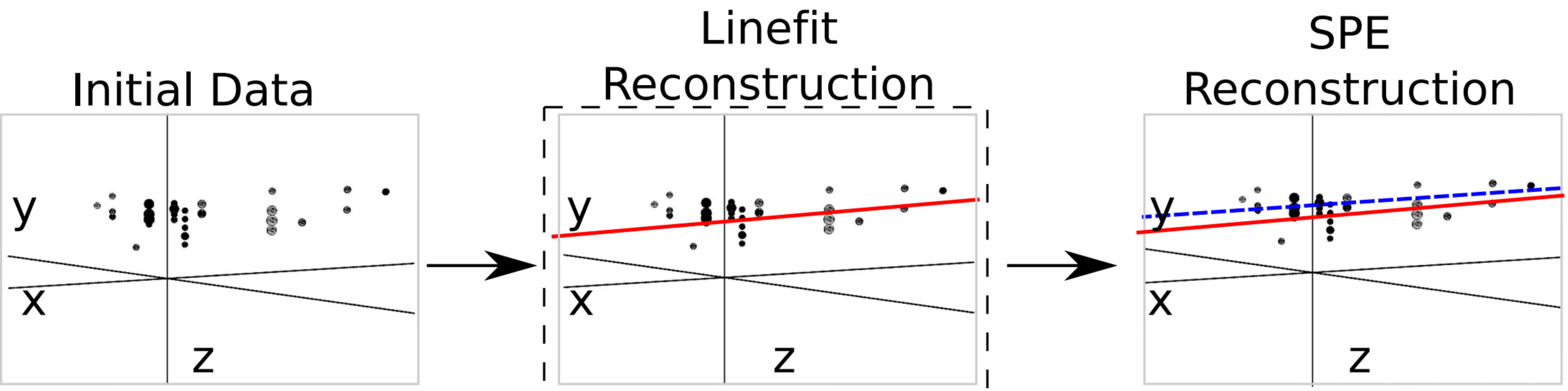
single CR shower event
~2200 Hz

double CR shower event
quasi-synchronous
~40 Hz

double CR shower event
asynchronous
~40 Hz

track-like events
directional reconstruction

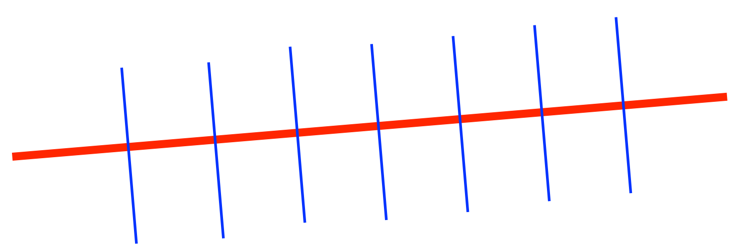




leading edge **pulse time**

pulse charge

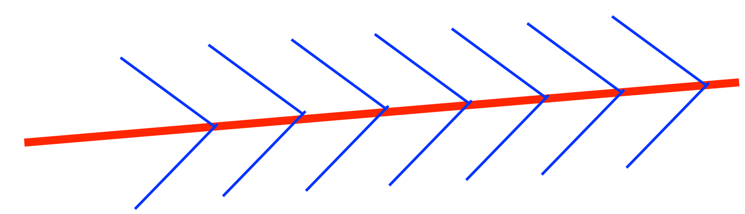
pulse shape (number of photons)



plane wave hypothesis

minimize *line* fit

$$\min_{t_0,\vec{r}_0,\vec{v}} \sum_{i=0}^{N_{hits}} |\vec{v}(t_i - t_0) + \vec{r}_0 - \vec{r}_i|^2$$



account for **Cherenkov cone**

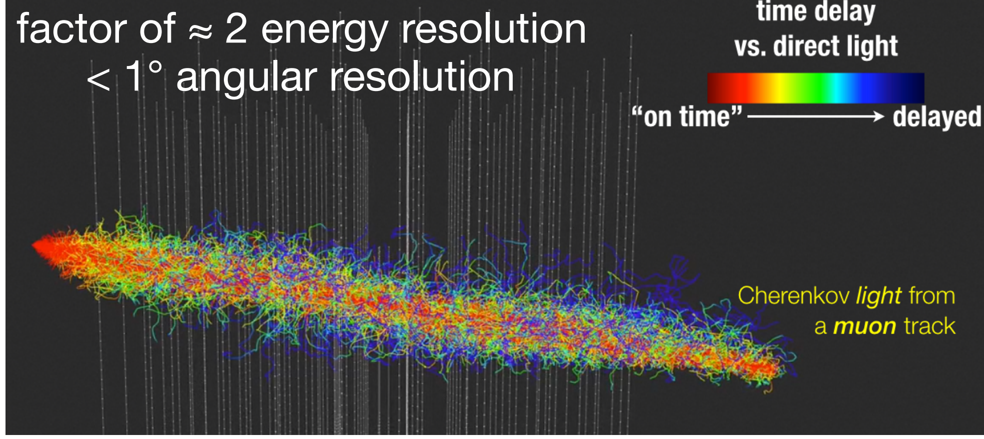
least square methods

likelihood function for SPE, MPE

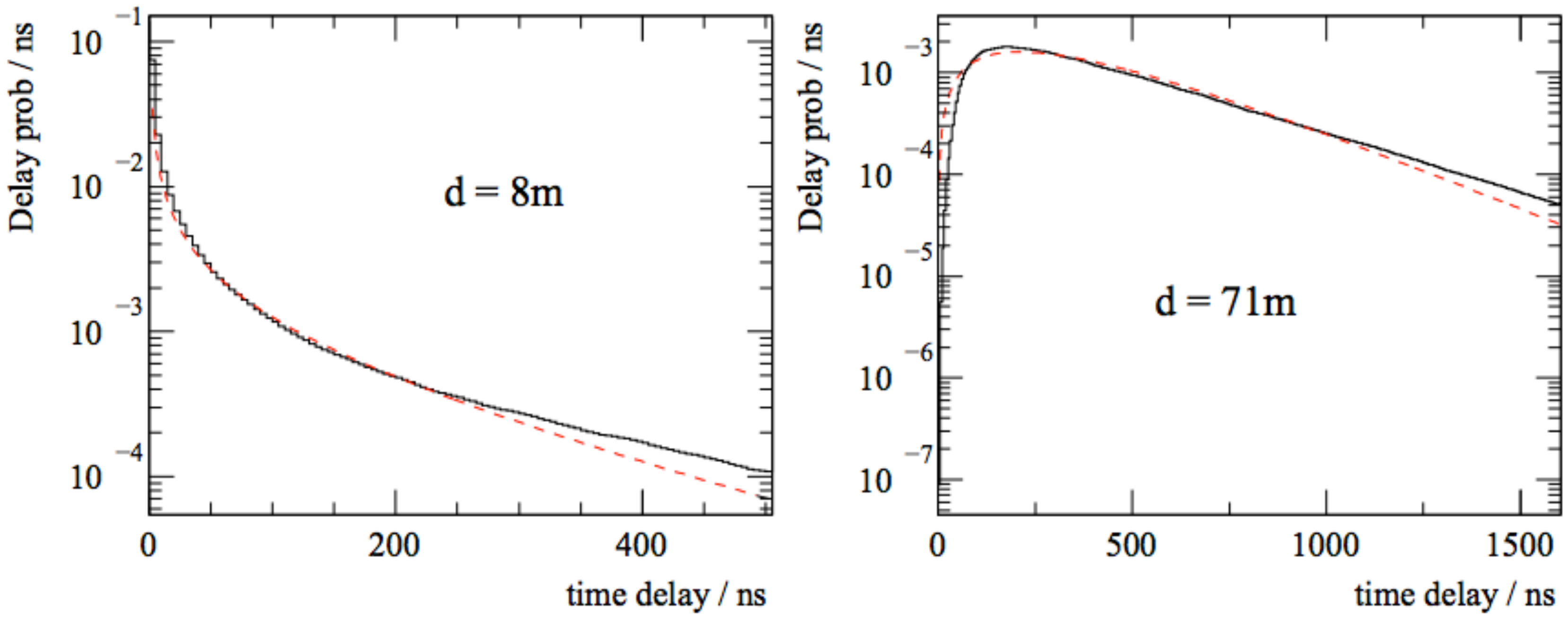
include **actual** ice properties

track-like events

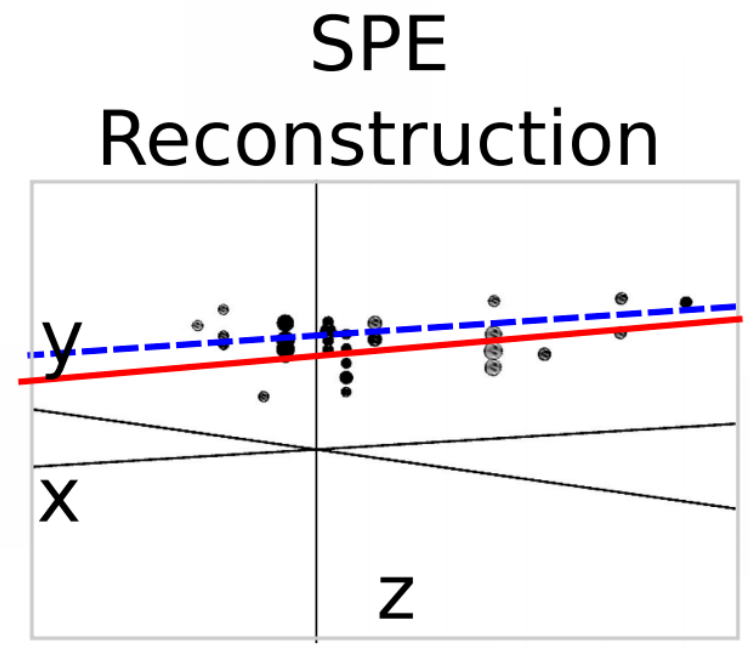
directional reconstruction

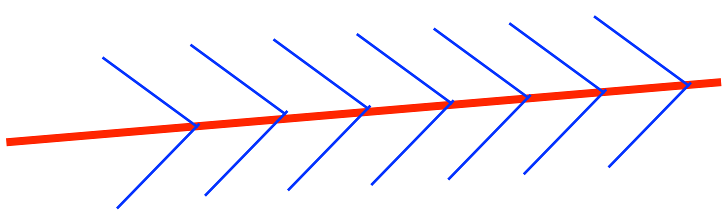


Ahrens et al. NIM A 524 (2004) 169



Aartsen et al. NIM A736 (2014) 143





time residual distributions measured in-situ - account for **absorption** and **scattering**

$$p(t_{\mathrm{res}}) \equiv \frac{1}{N(d)} \frac{\tau^{-(d/\lambda)} \cdot t_{\mathrm{res}}^{(d/\lambda-1)}}{\Gamma(d/\lambda)} \cdot e^{-\left(t_{\mathrm{res}} \cdot \left(\frac{1}{\tau} + \frac{c_{\mathrm{medium}}}{\lambda_a}\right) + \frac{d}{\lambda_a}\right)},$$

$$N(d) = e^{-d/\lambda_a} \cdot \left(1 + \frac{\tau \cdot c_{\mathrm{medium}}}{\lambda_a}\right)^{-d/\lambda},$$

account for **Cherenkov cone**

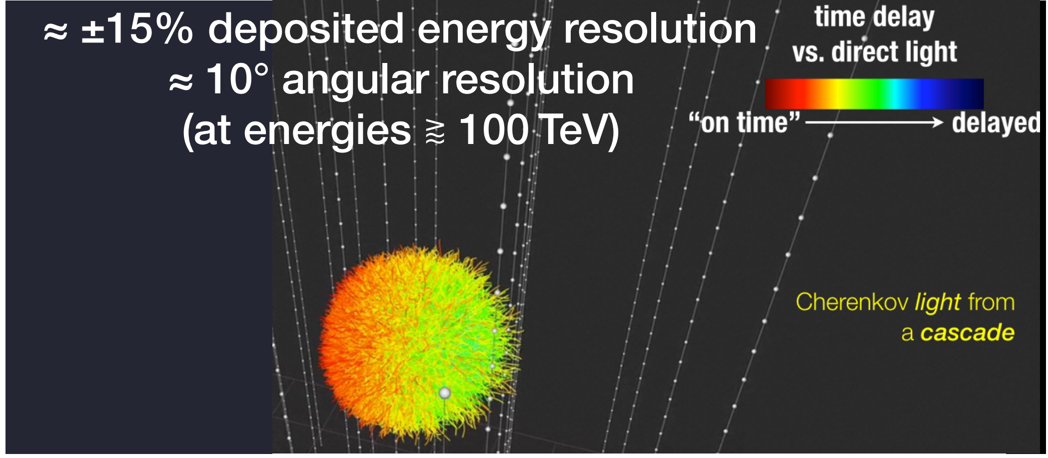
least square methods

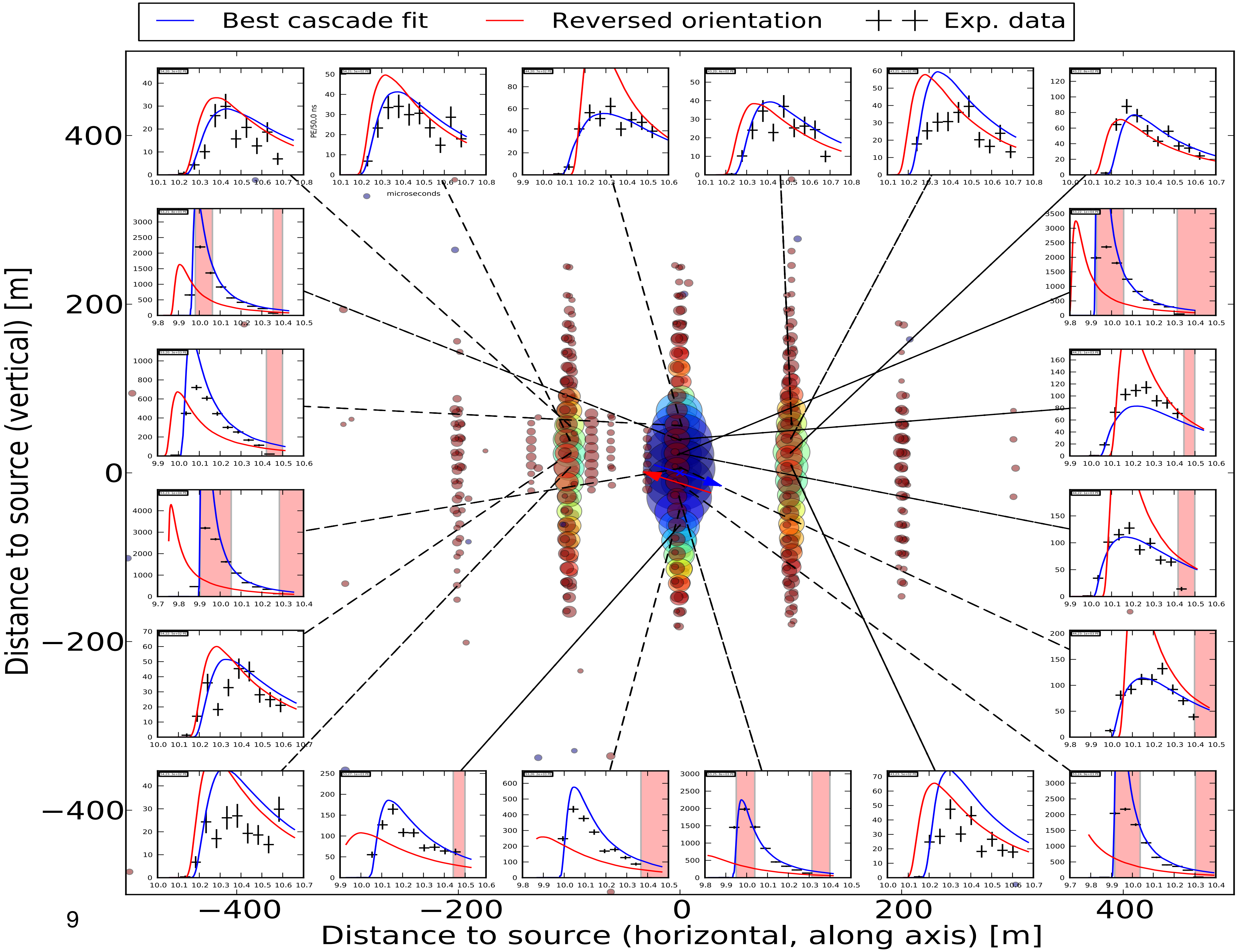
likelihood function for SPE, MPE

include **actual** ice properties

cascade-like events

directional reconstruction





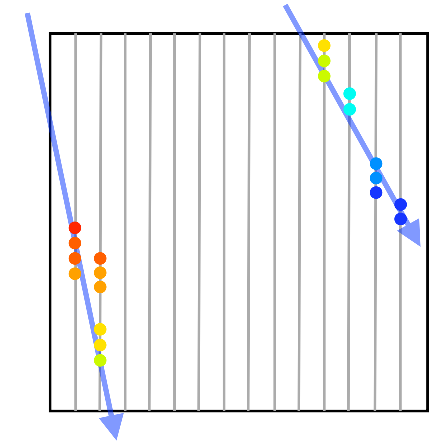
waveform used to reconstruct direction of cascade-like events

accounting for ice optical properties

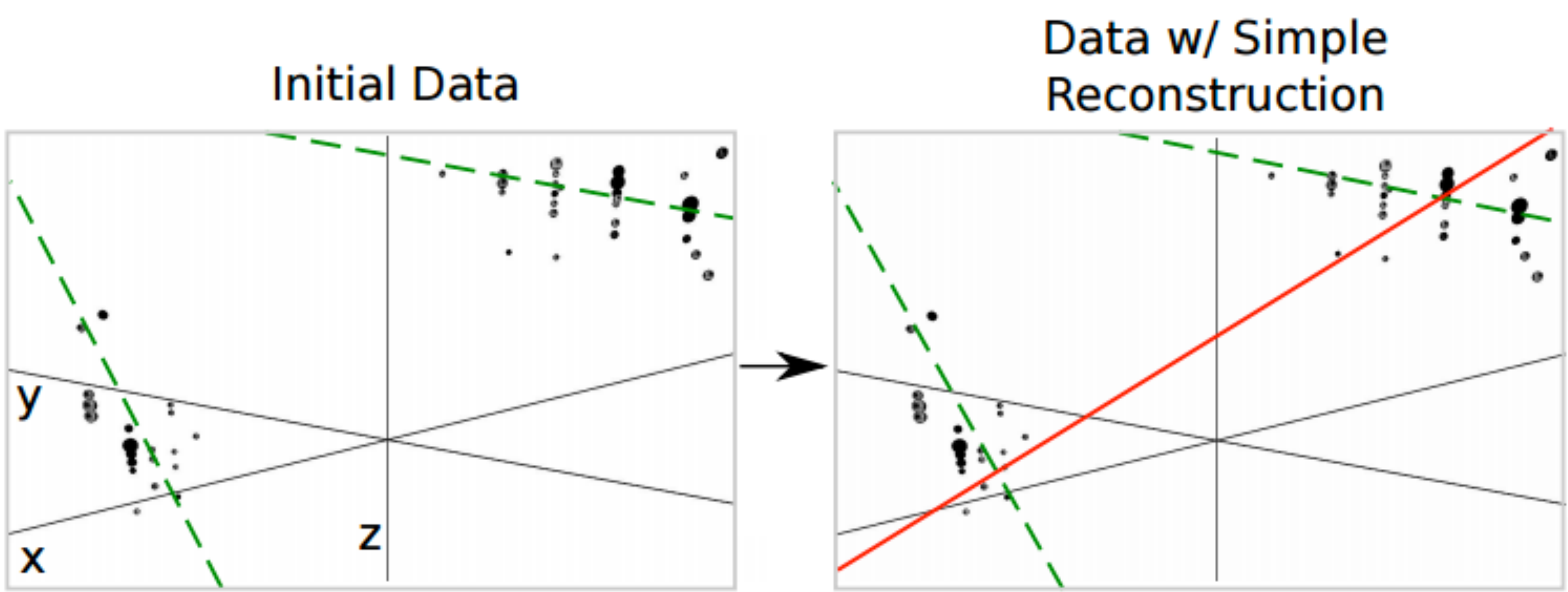
less precise than track-like events

searching for neutrinos

identify background: coincident muon events



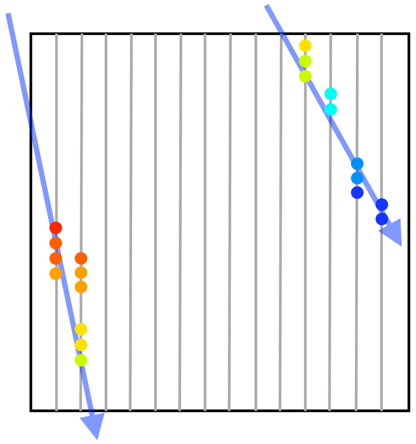
Aartsen et al. NIM A736 (2014) 143



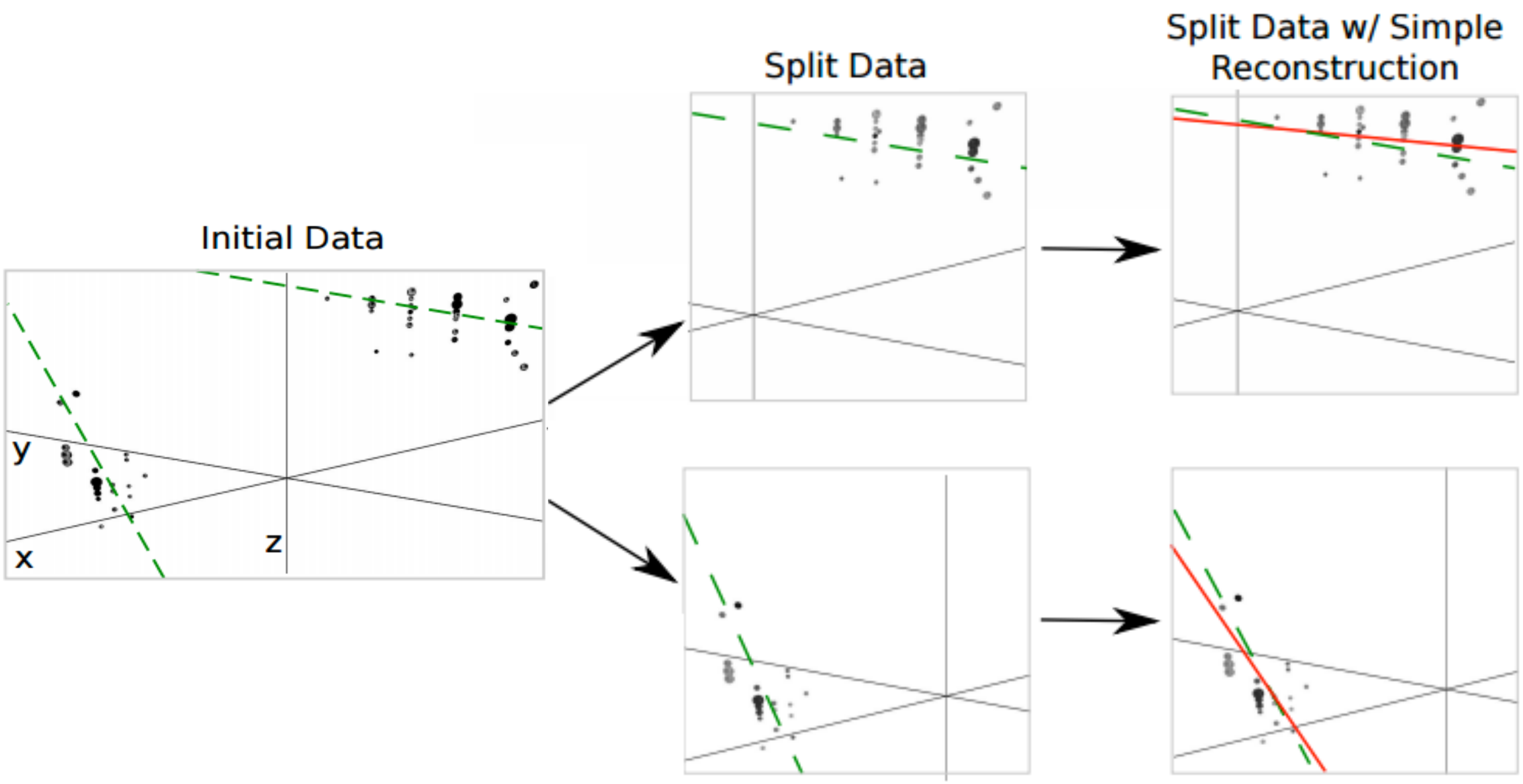
mis-reconstruction of a double coincident muon event as single track event

searching for neutrinos

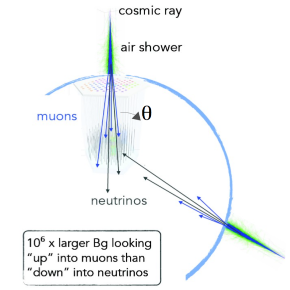
reject background: coincident muon events



Aartsen et al. NIM A736 (2014) 143

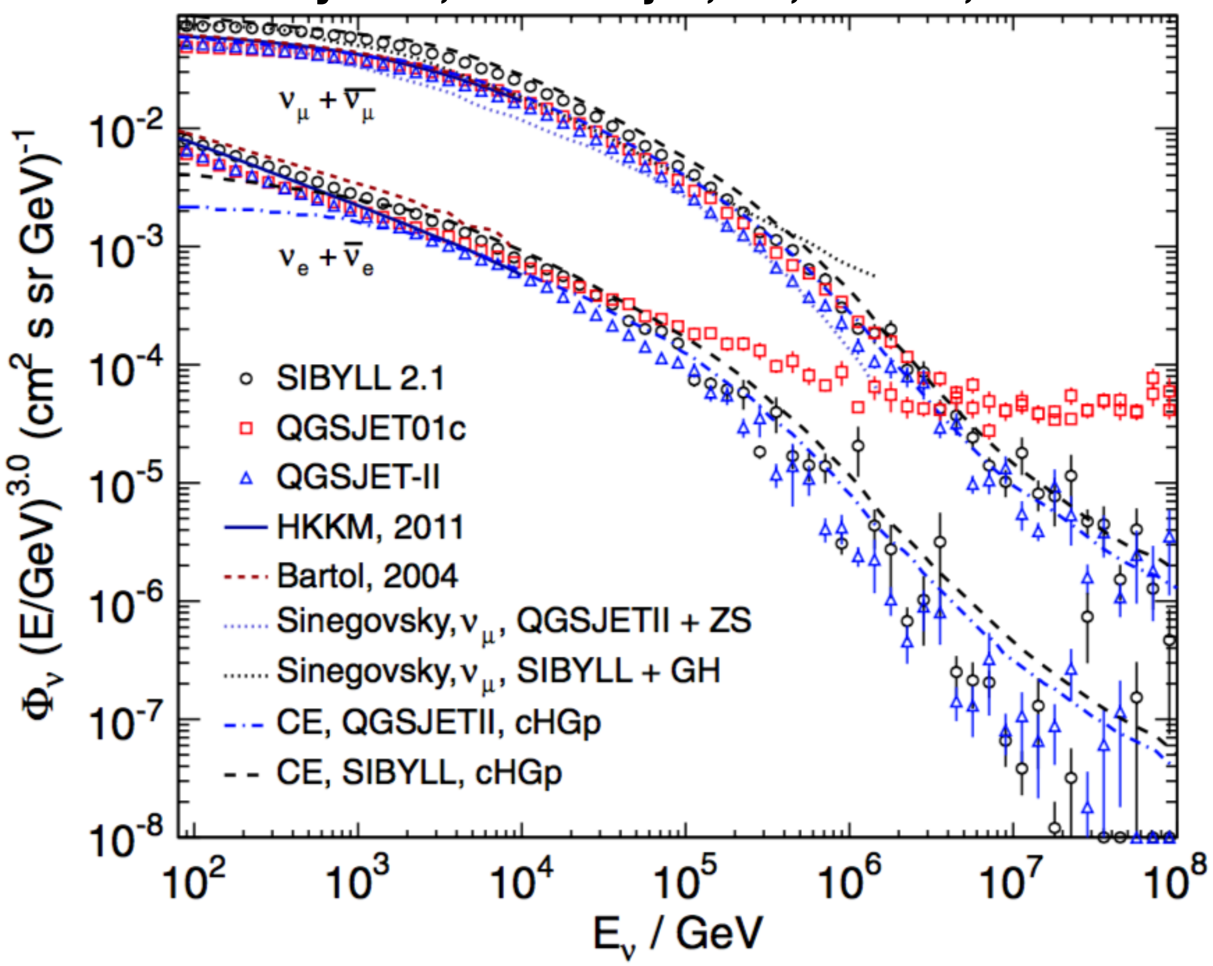


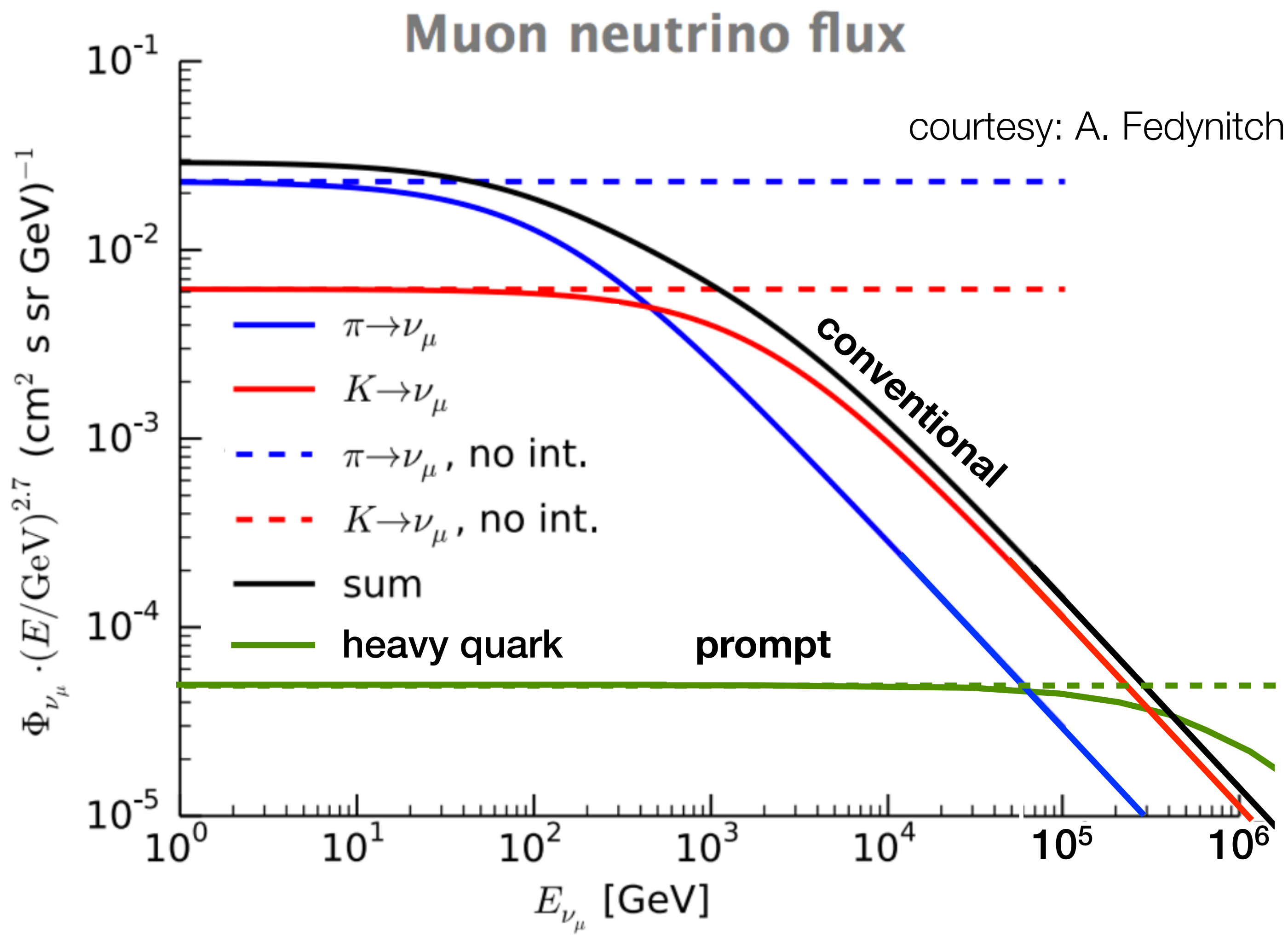
split of a double coincident muon event into **two** single track events



atmospheric neutrinos
energy spectrum

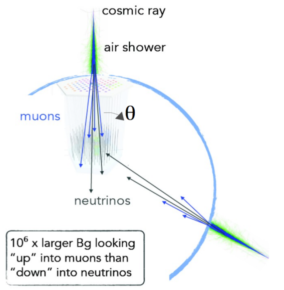
Fedynitch, Becker Tjus, PD, PRD 86, 114024



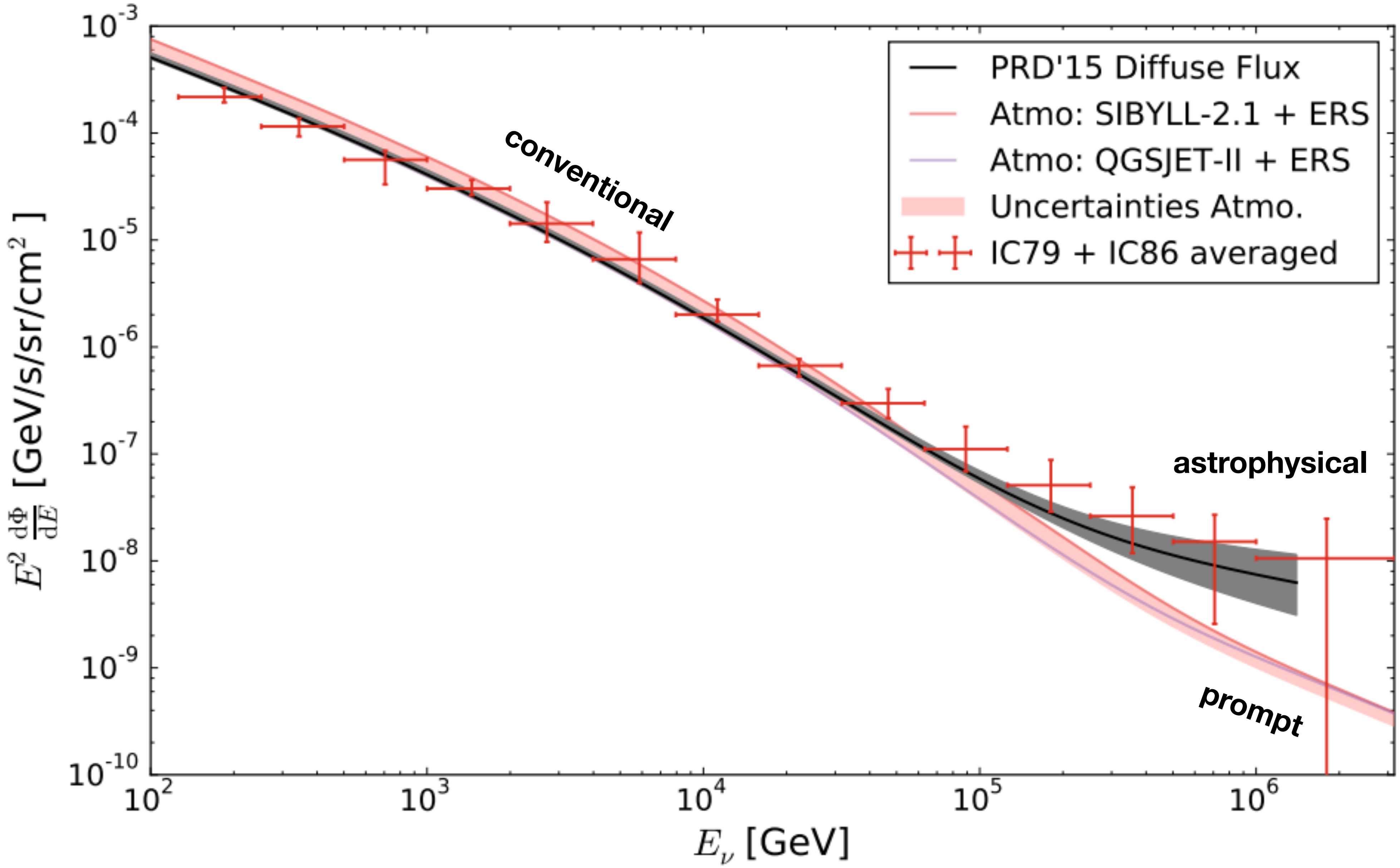


- neutrinos and muons produced by **cosmic rays** in the **atmosphere** from **meson decay**

atmospheric neutrinos
energy window to astrophysical neutrinos



ICRC 2015 - Den Haag, NL



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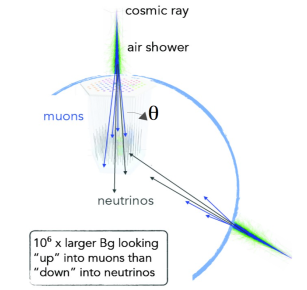
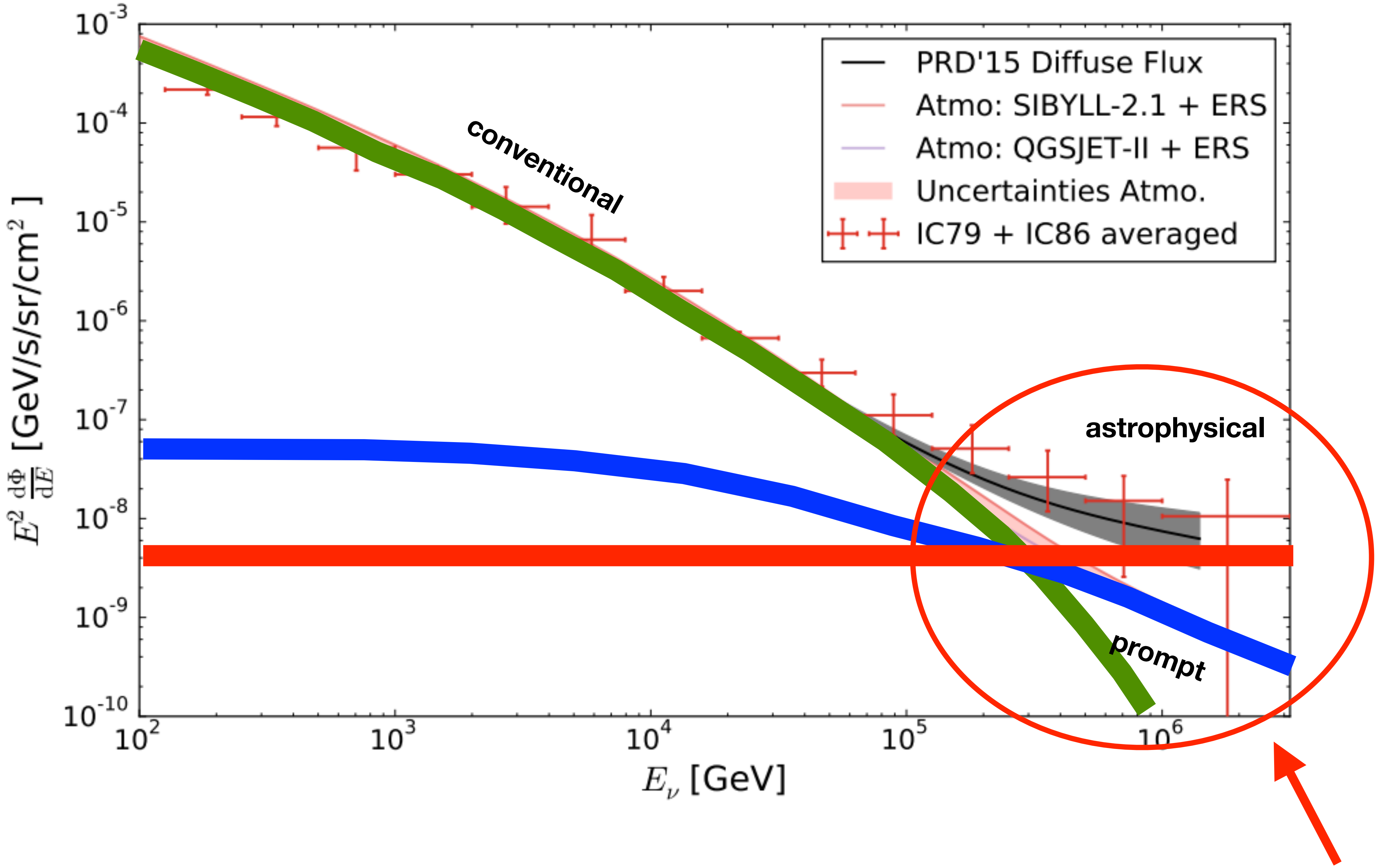


ICRC 2015 - Den Haag, NL

π, K

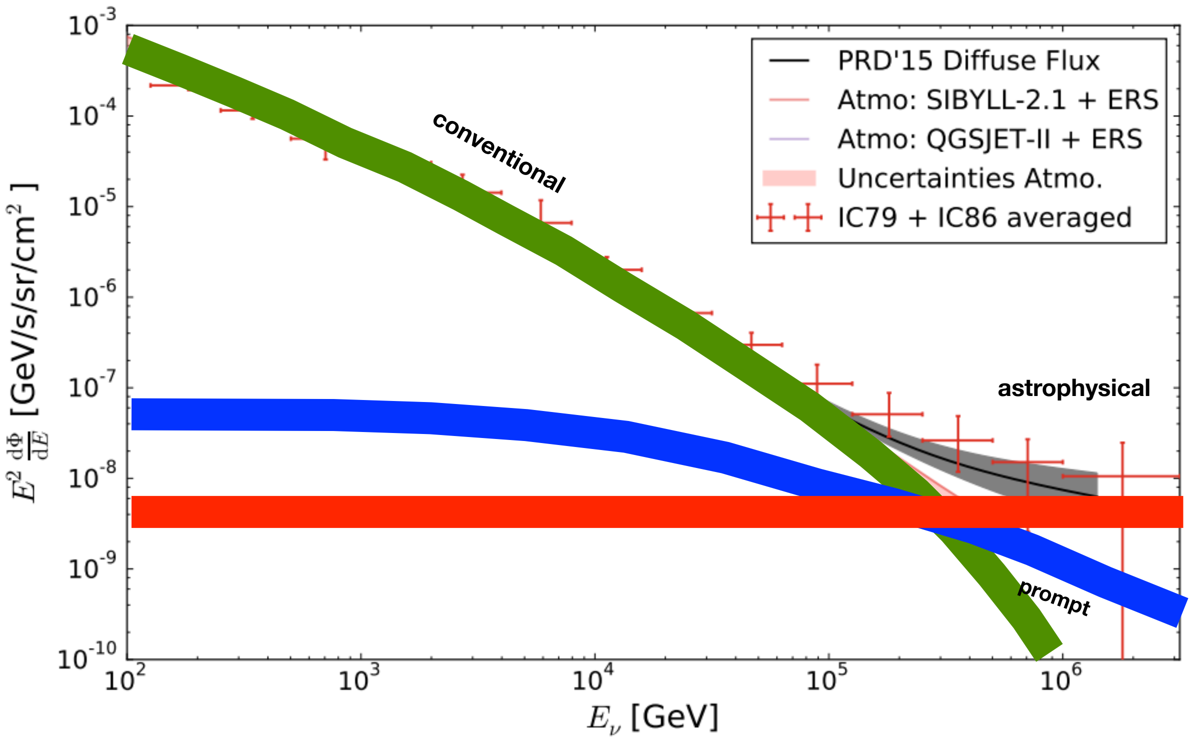
D, Λ
with
charm
quark



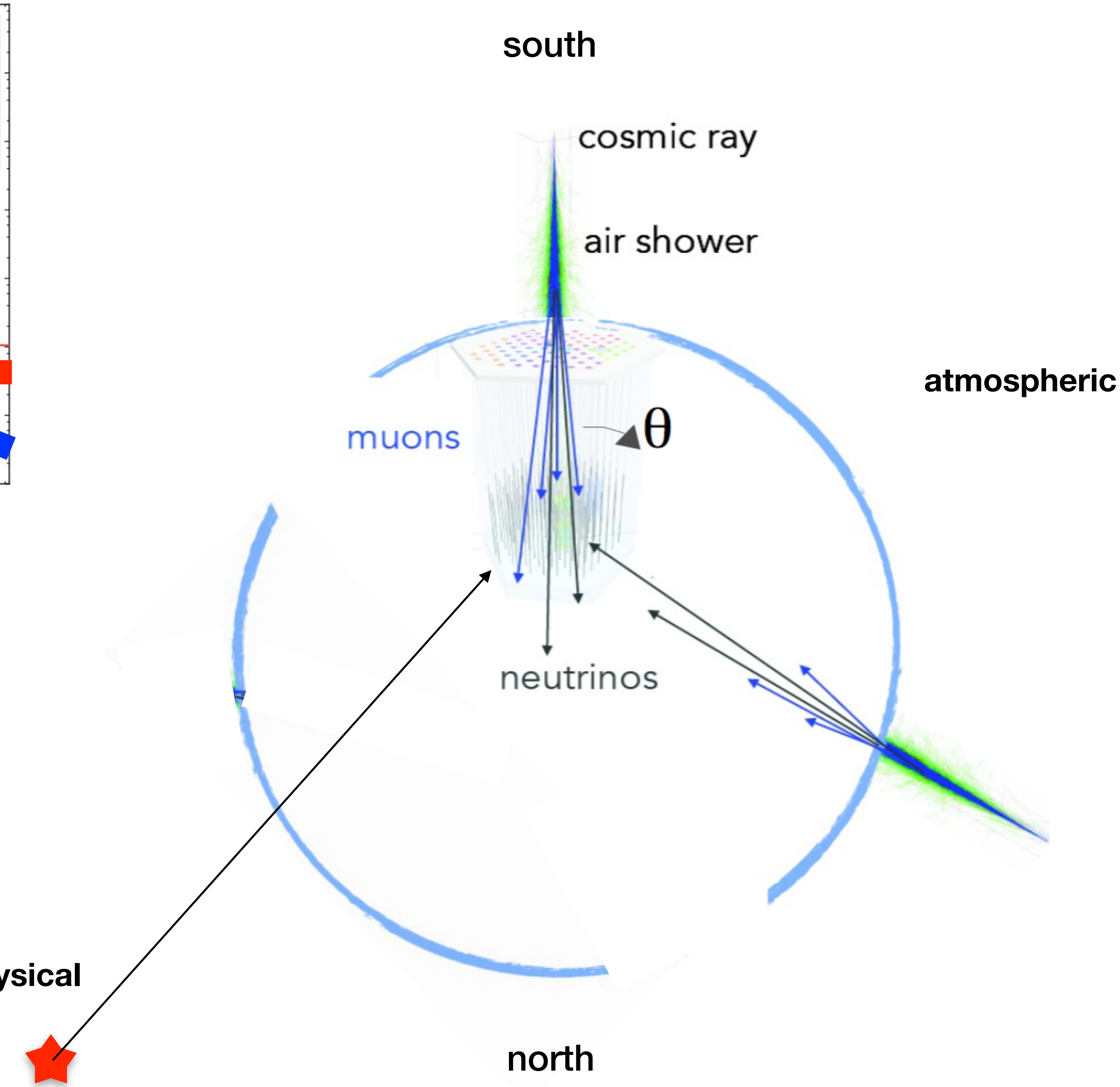
LET'S EXPLORE RIGHT AWAY THE ASTROPHYSICAL SEARCH WINDOW

atmospheric neutrinos

energy window to astrophysical neutrinos

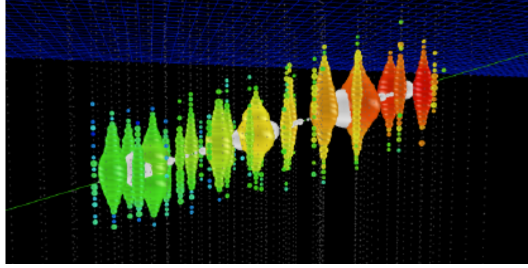


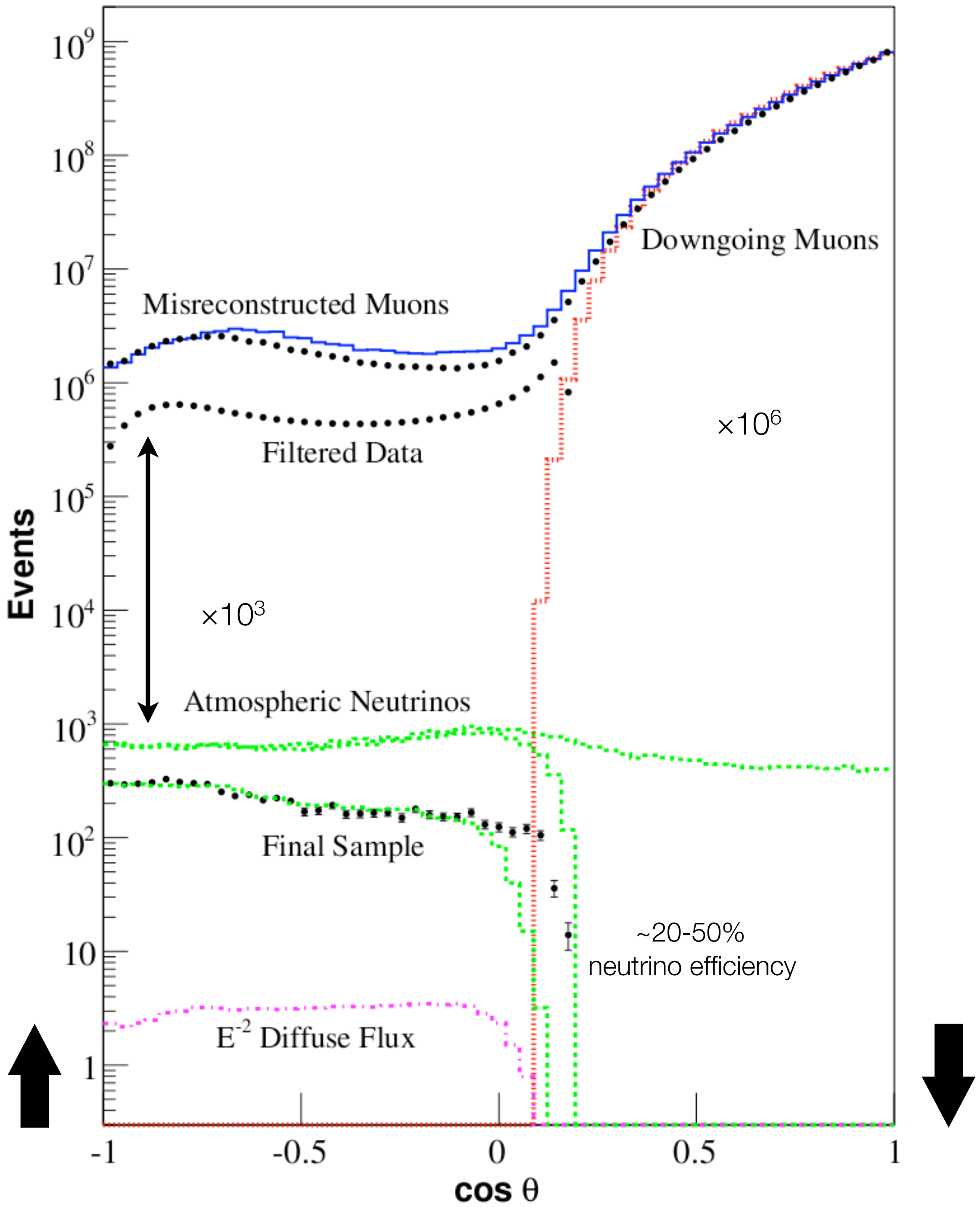
ICRC 2015 - Den Haag, NL

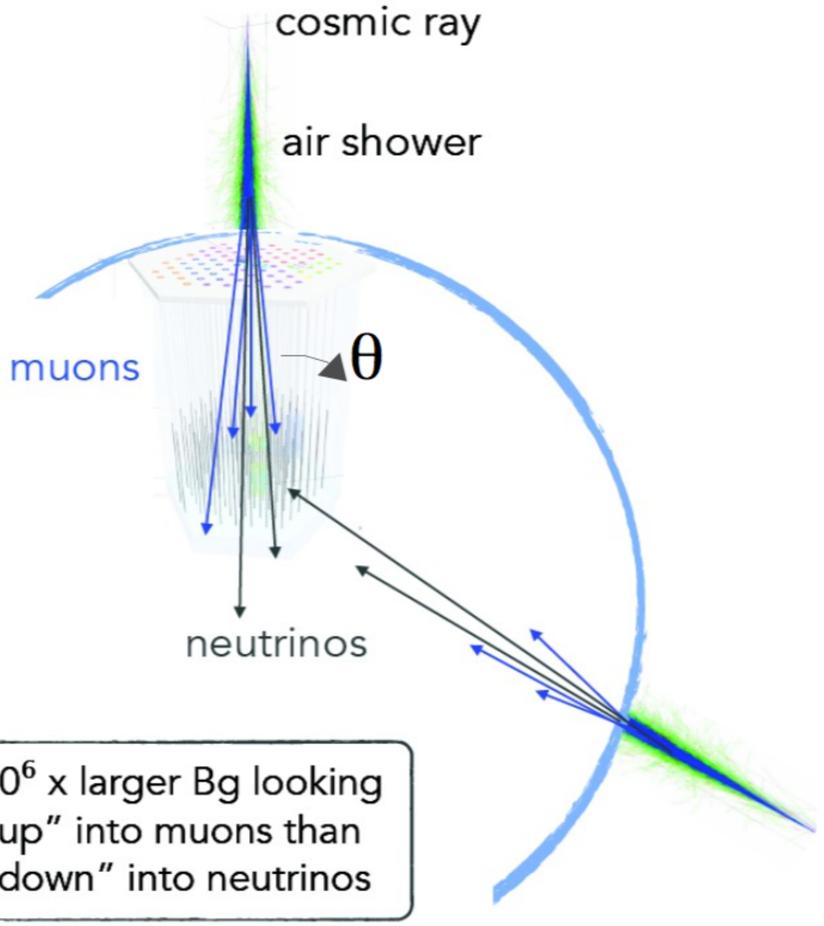


searching for neutrinos

background rejection

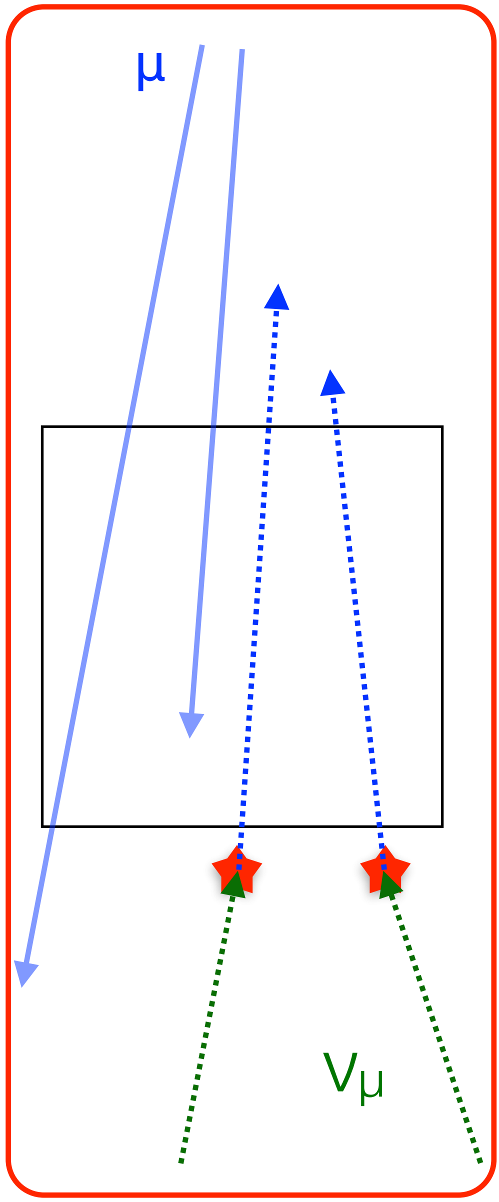






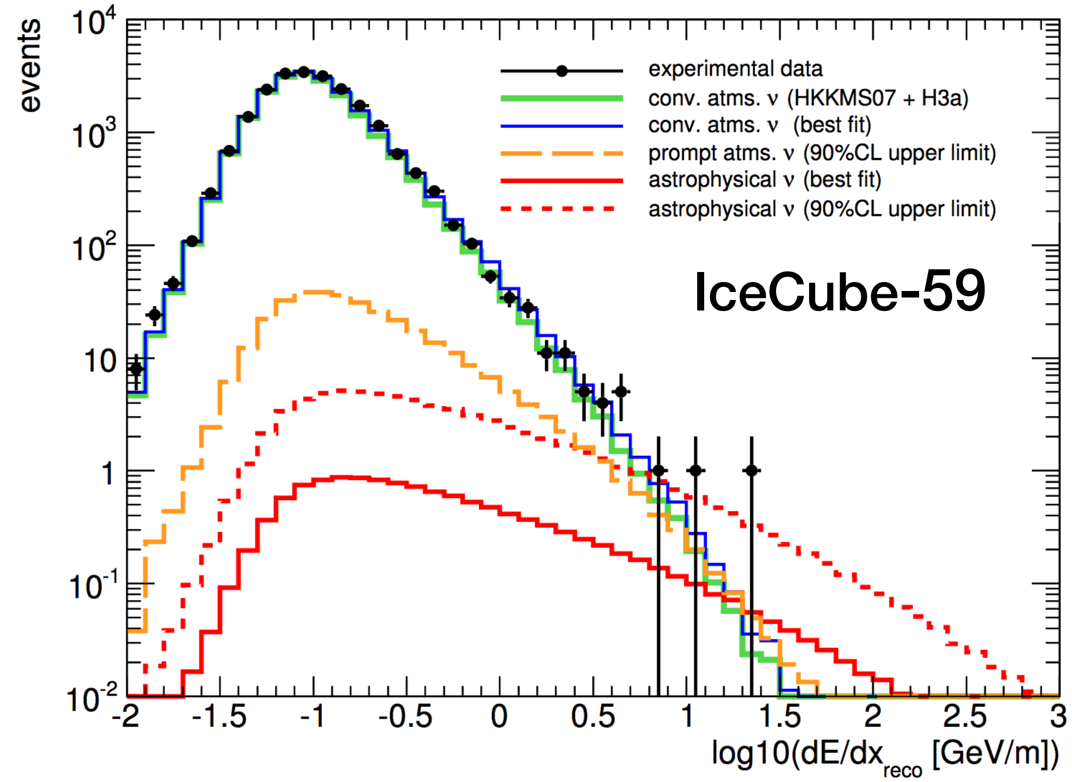
10^6 x larger Bg looking "up" into muons than "down" into neutrinos

up-going through-going (tracks)

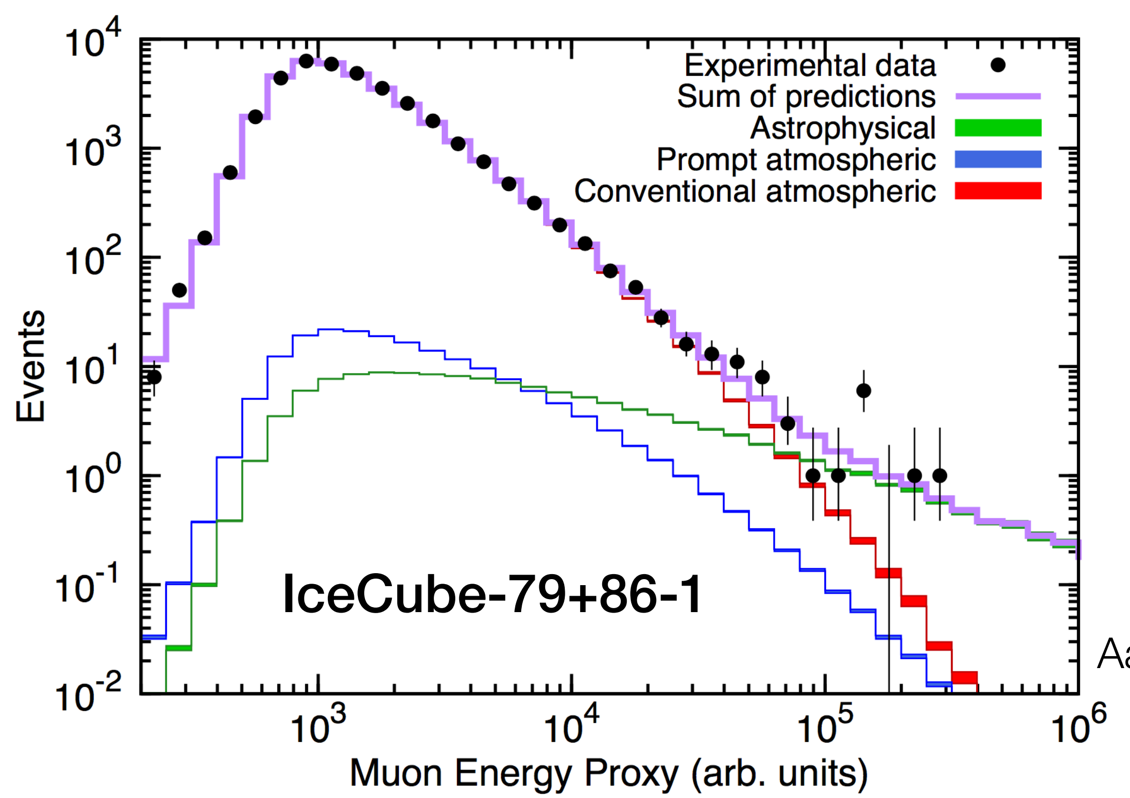


neutrino identification

diffuse flux

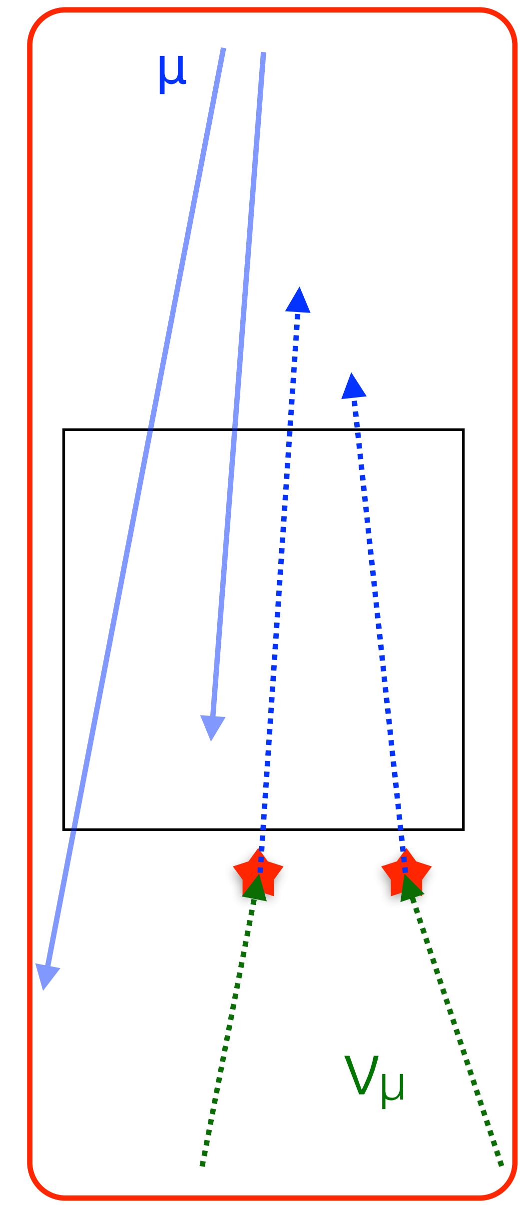


Aartsen et al. Phys. Rev. D 89 (2014), 062007



Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102

up-going through-going (tracks)



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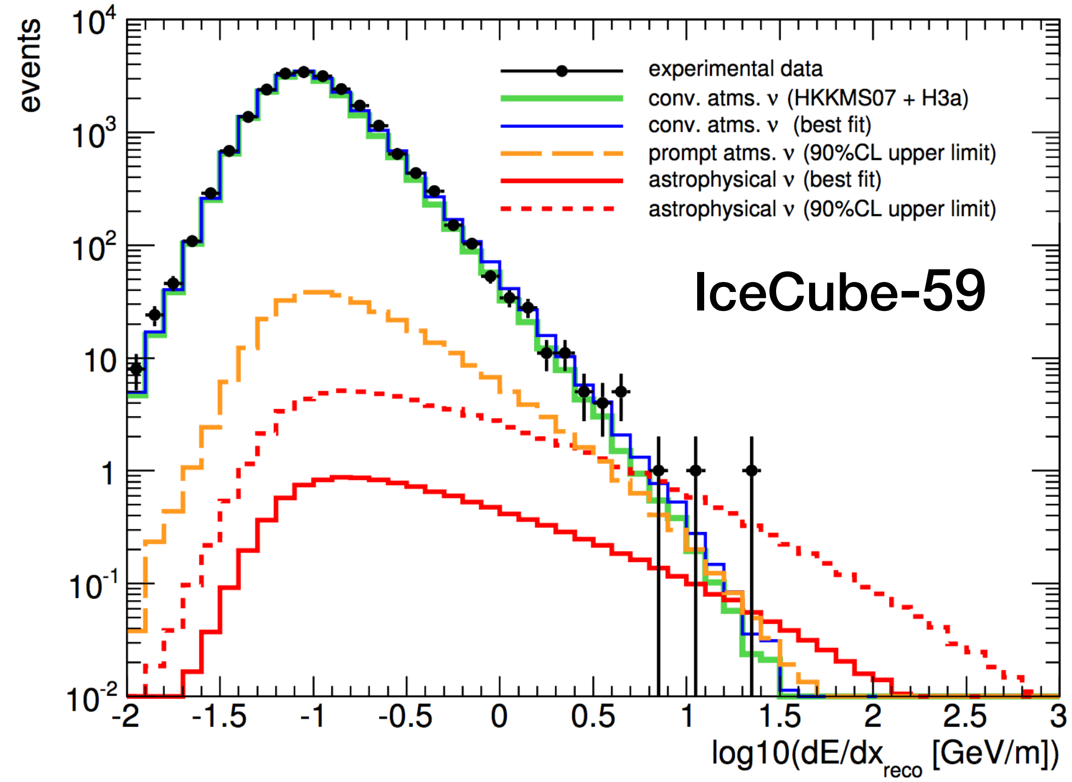

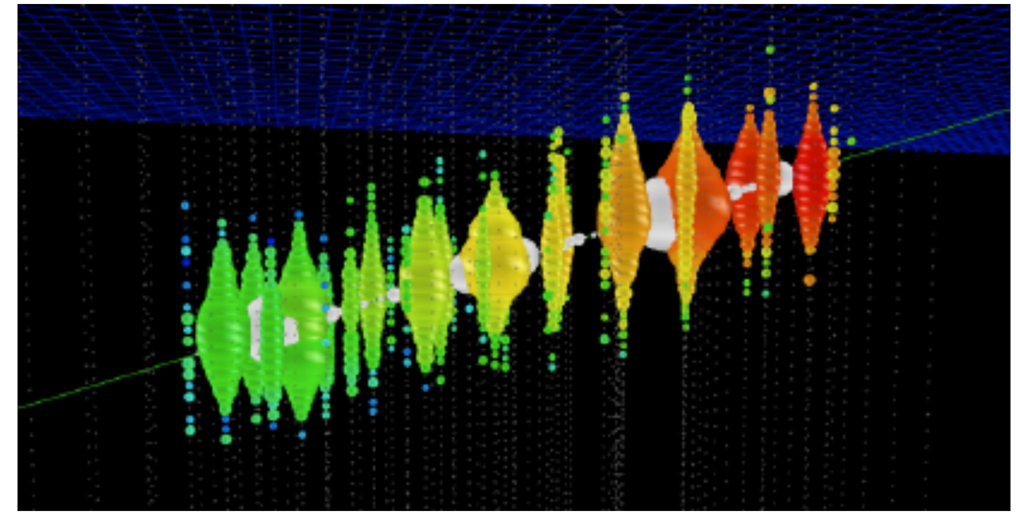

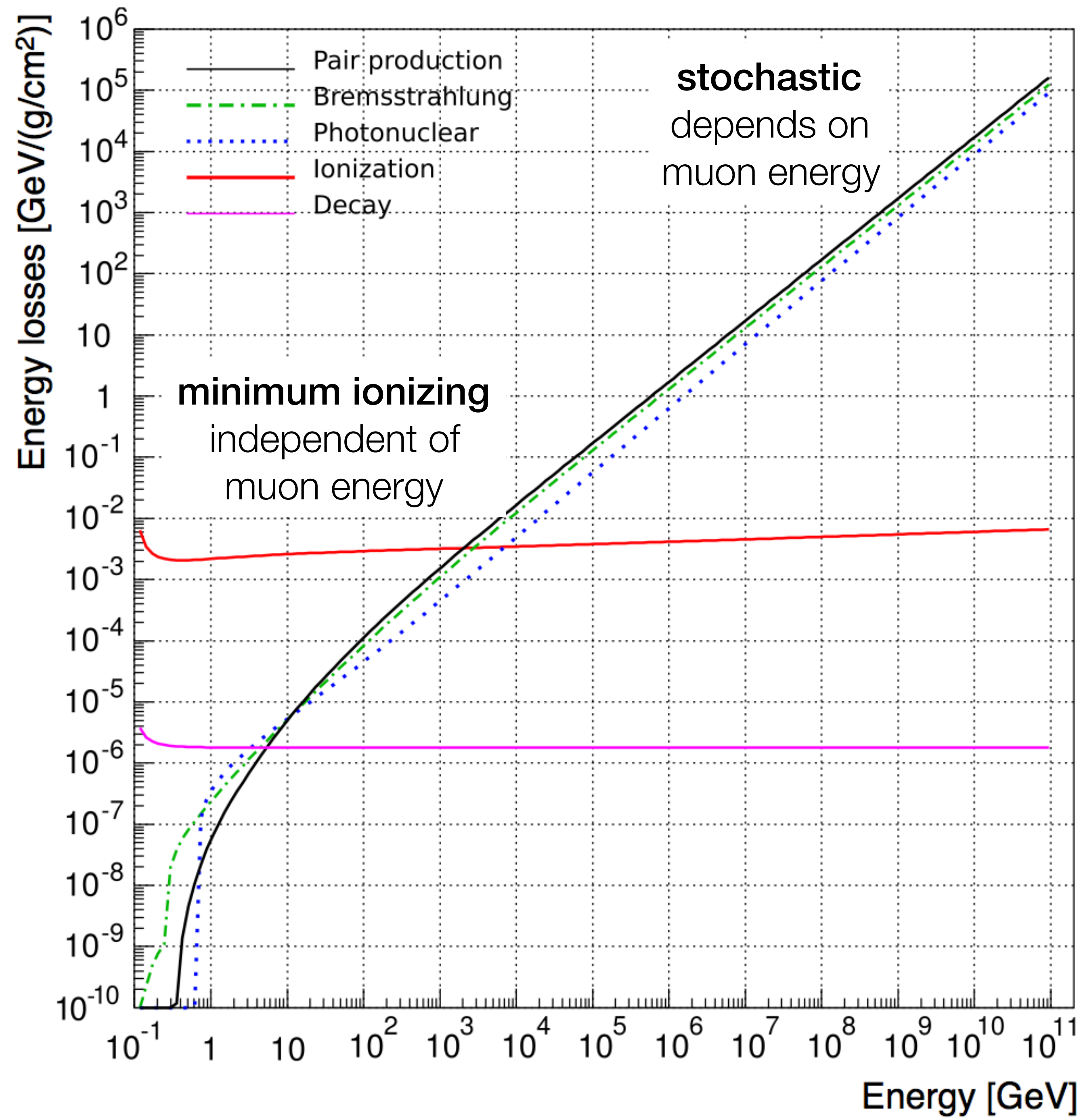

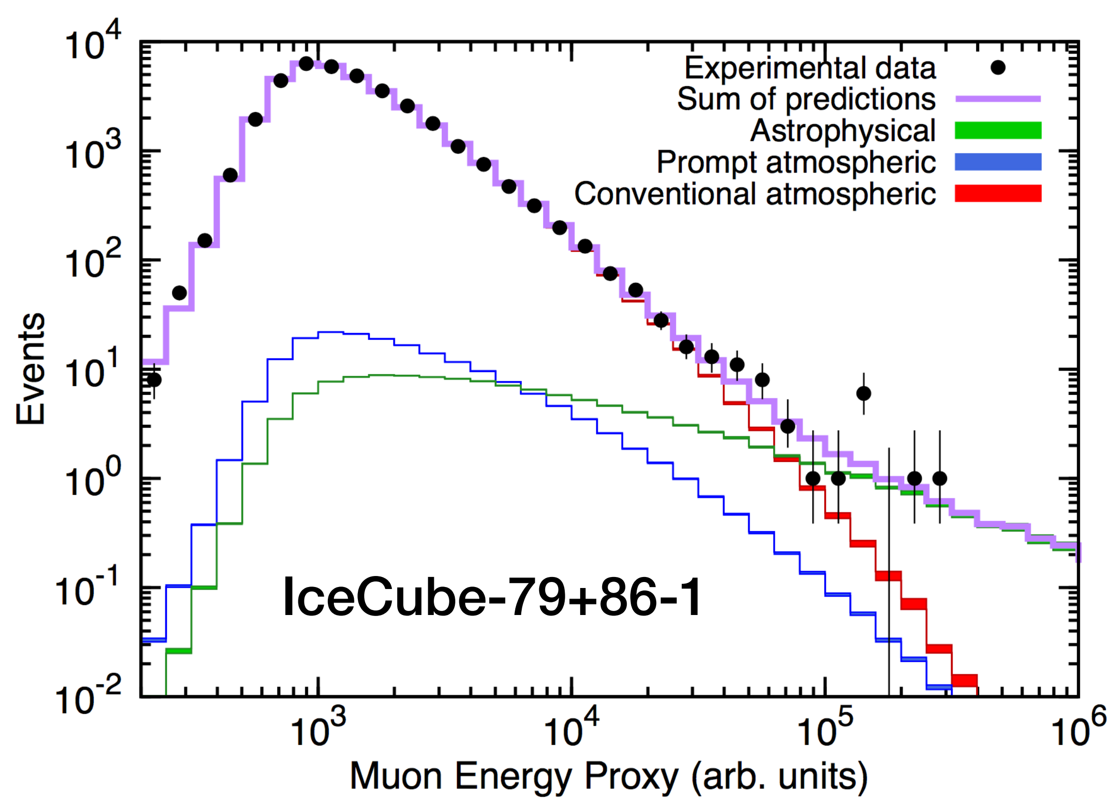

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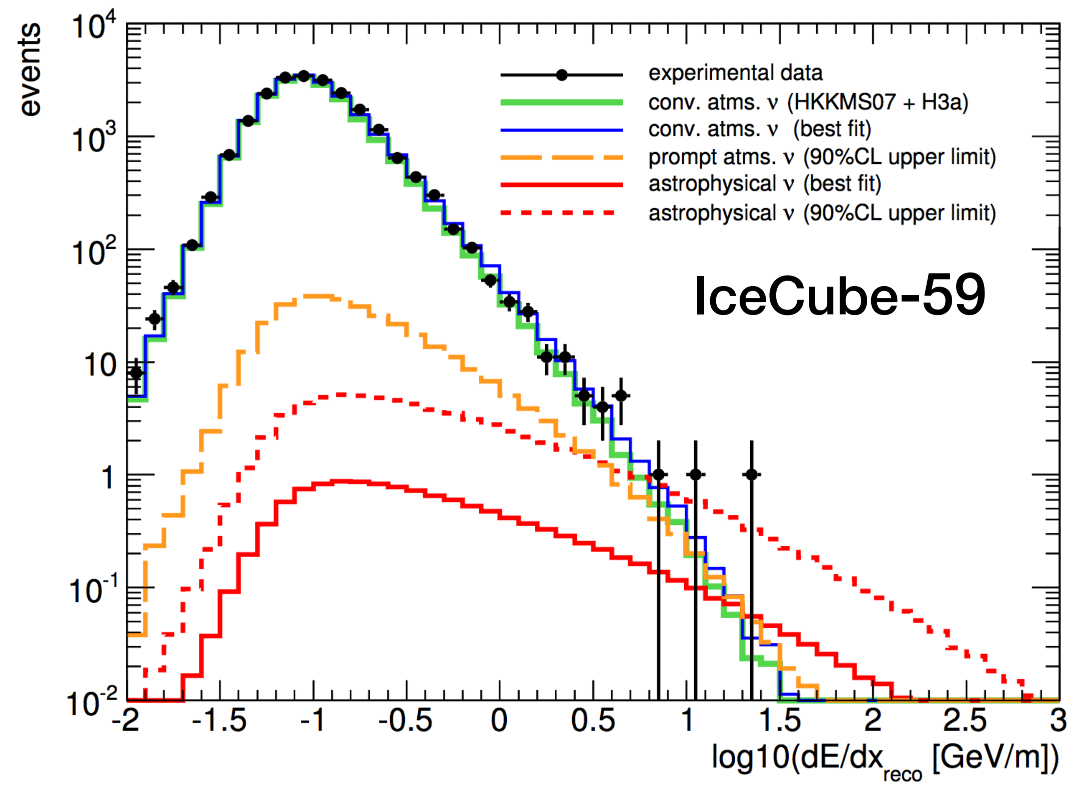
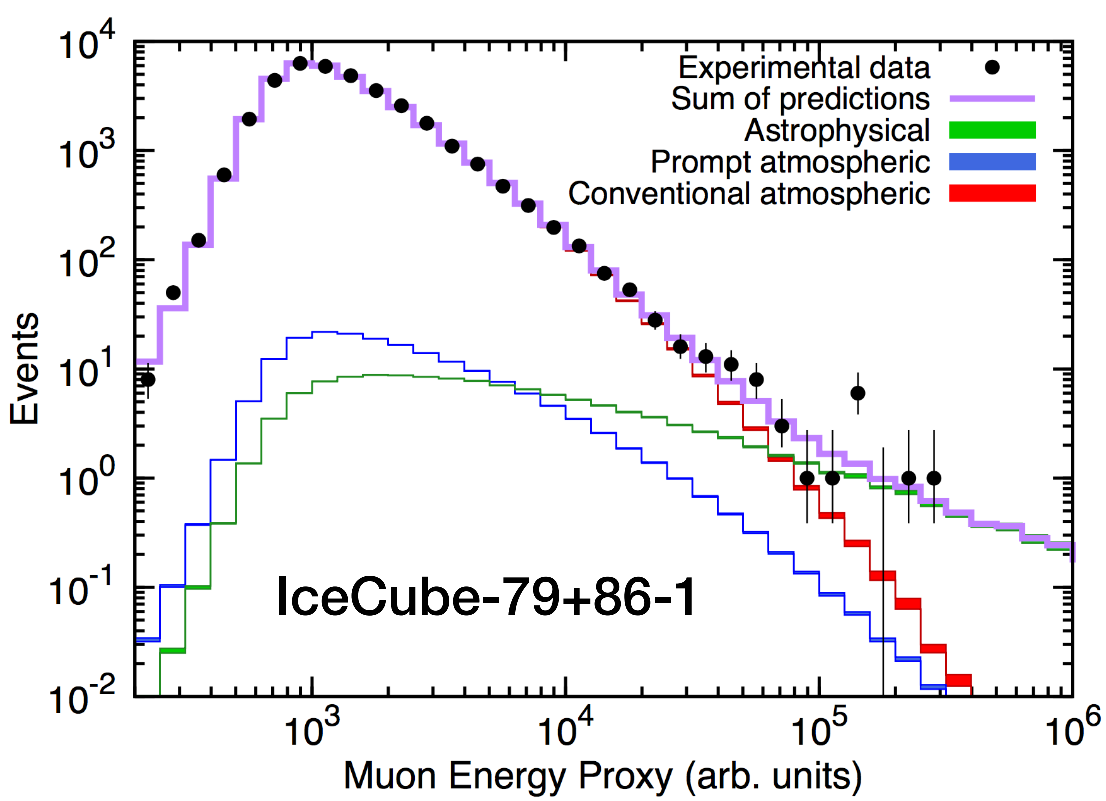
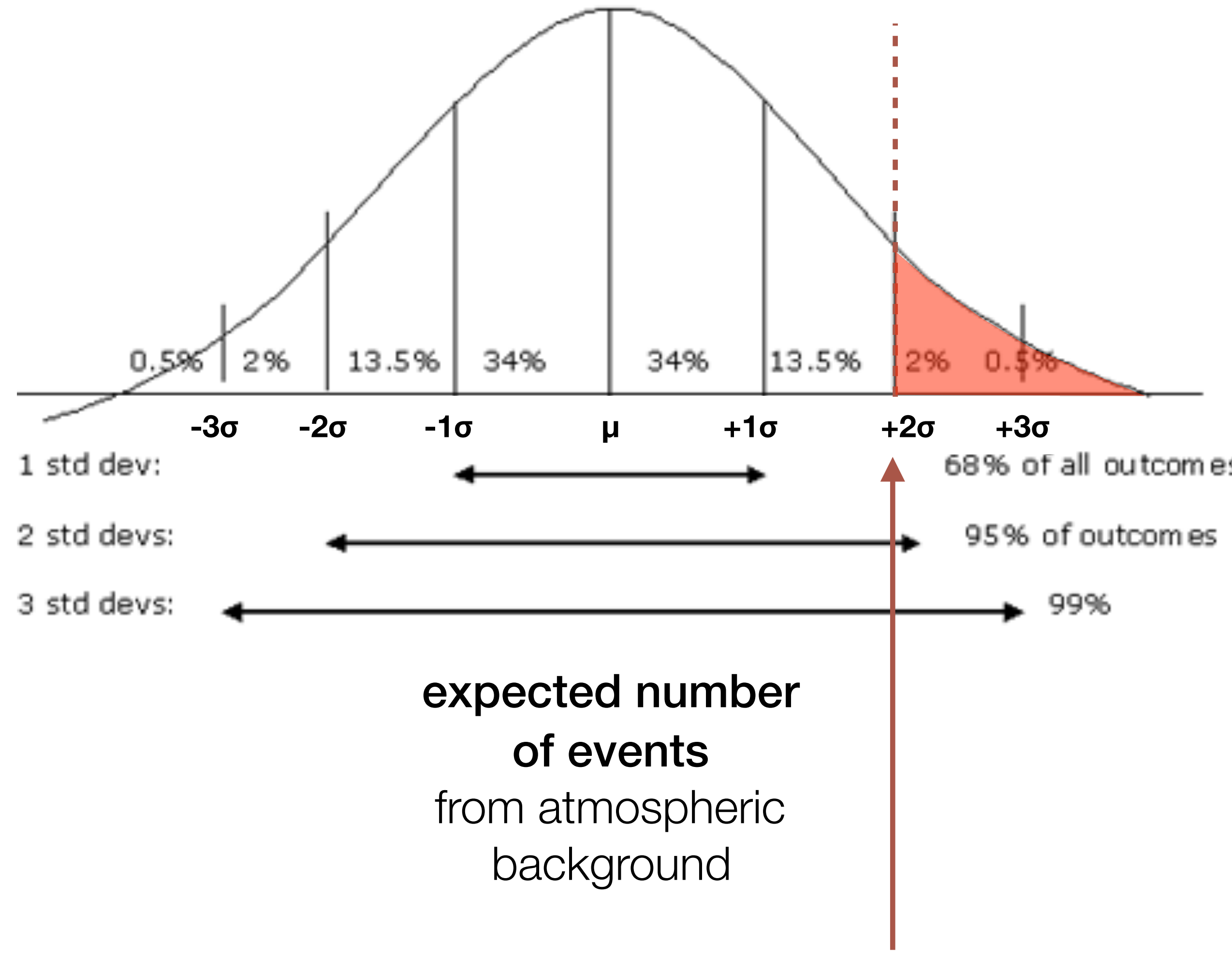






expected number of events
from atmospheric background

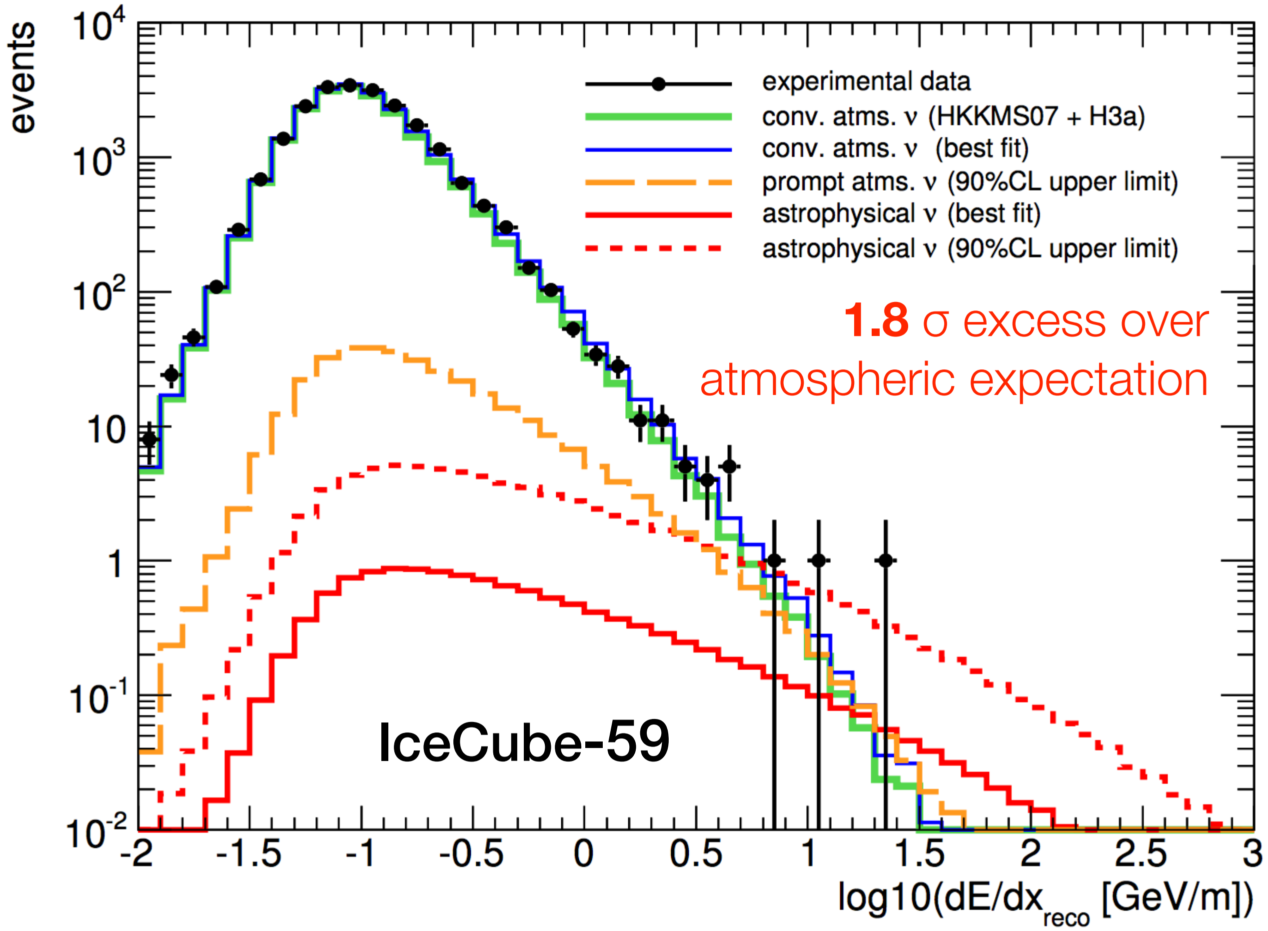
observed number of events
excess from background

Sigma-Level	Confidence Level	Alpha-Level
1	68.3%	0.3174
2	95.45%	0.0455
3	99.73%	0.0027
4	99.9937%	0.0000633
5	99.999943%	0.00000057

ERS: Enberg, Reno, Sarcevic 2008

neutrino identification
diffuse flux

Aartsen et al. Phys. Rev. D 89 (2014), 062007



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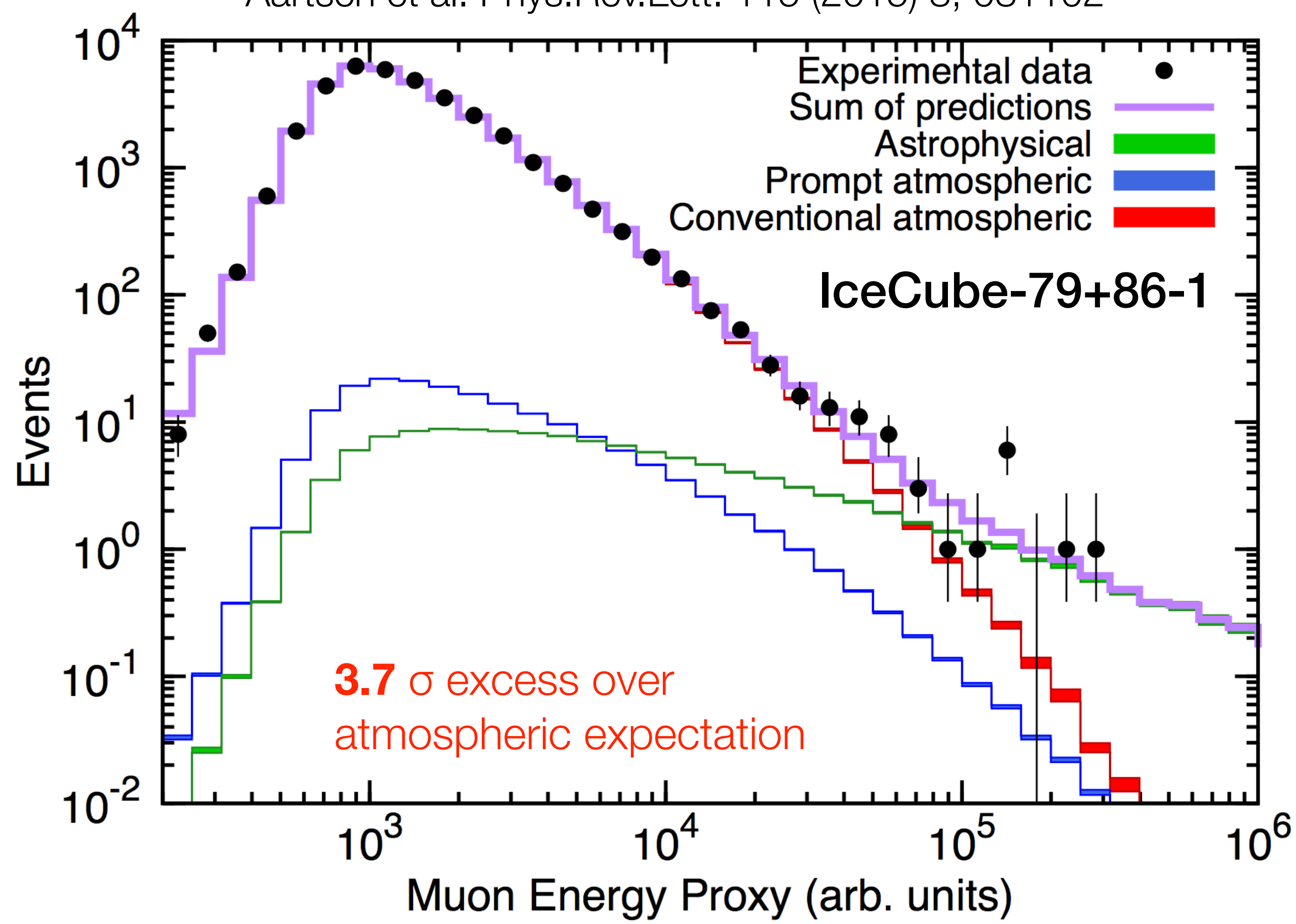


$$\Phi_{fit}^{astro}(E) = 0.25 \times 10^{-8} \times E^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

$$\Phi_{fit}^{prompt}(E) = 0$$

$$\Phi_{90\%CL}^{astro}(E) = 1.44 \times 10^{-8} \times E^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

$$\Phi_{90\%CL}^{prompt}(E) = 3.8 \cdot \Phi_{ERS}(E)$$

$$\Phi_{fit}^{astro}(E) = 9.9 \times 10^{-19} \times \left(\frac{E}{100\,TeV}\right)^{-2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

$$\Phi_{fit}^{prompt}(E) = 0.94 \cdot \Phi_{ERS}(E)$$

$$\Phi_{fit}^{astro}(E) = 1.7 \times 10^{-18} \times \left(\frac{E}{100\,TeV}\right)^{-2.2}\ GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

$$\Phi_{fit}^{prompt}(E) = 0$$

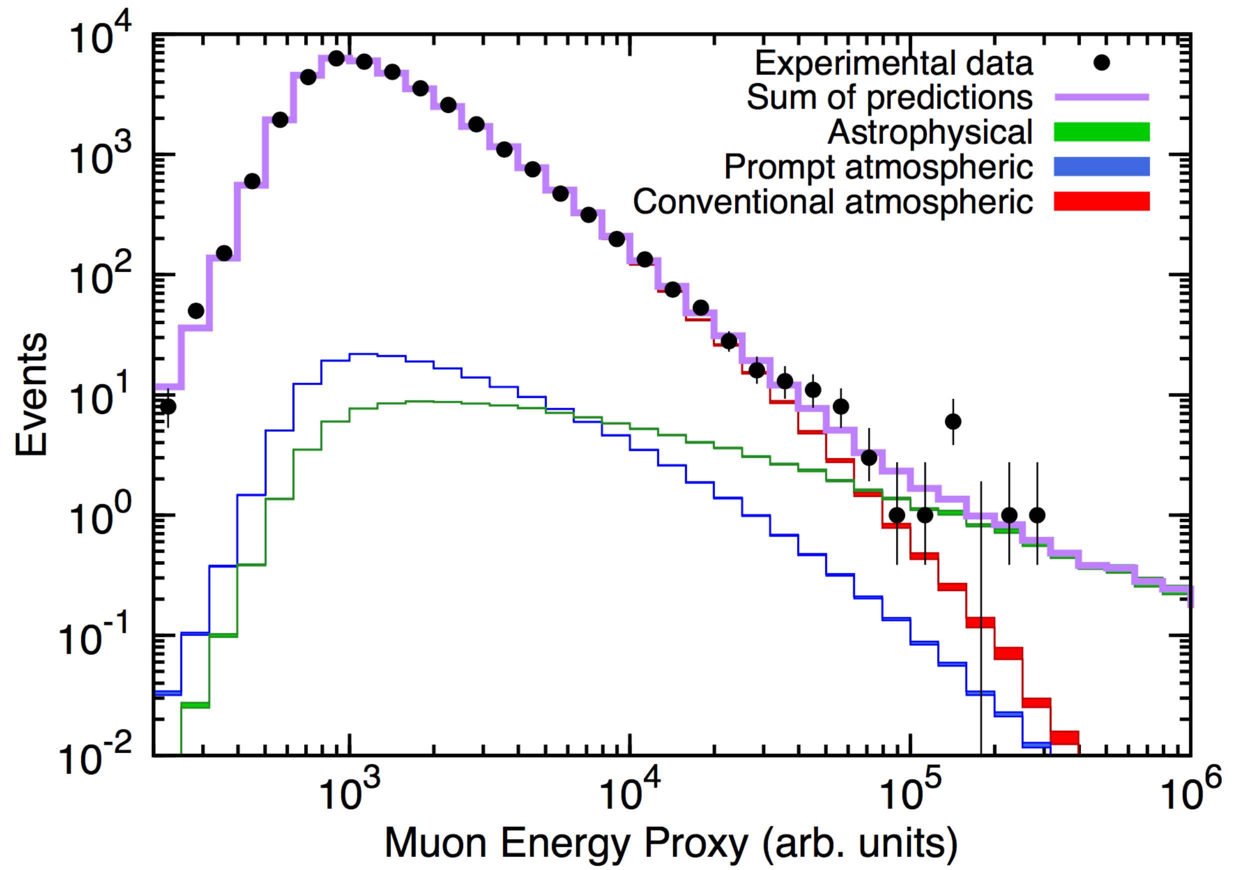
Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102

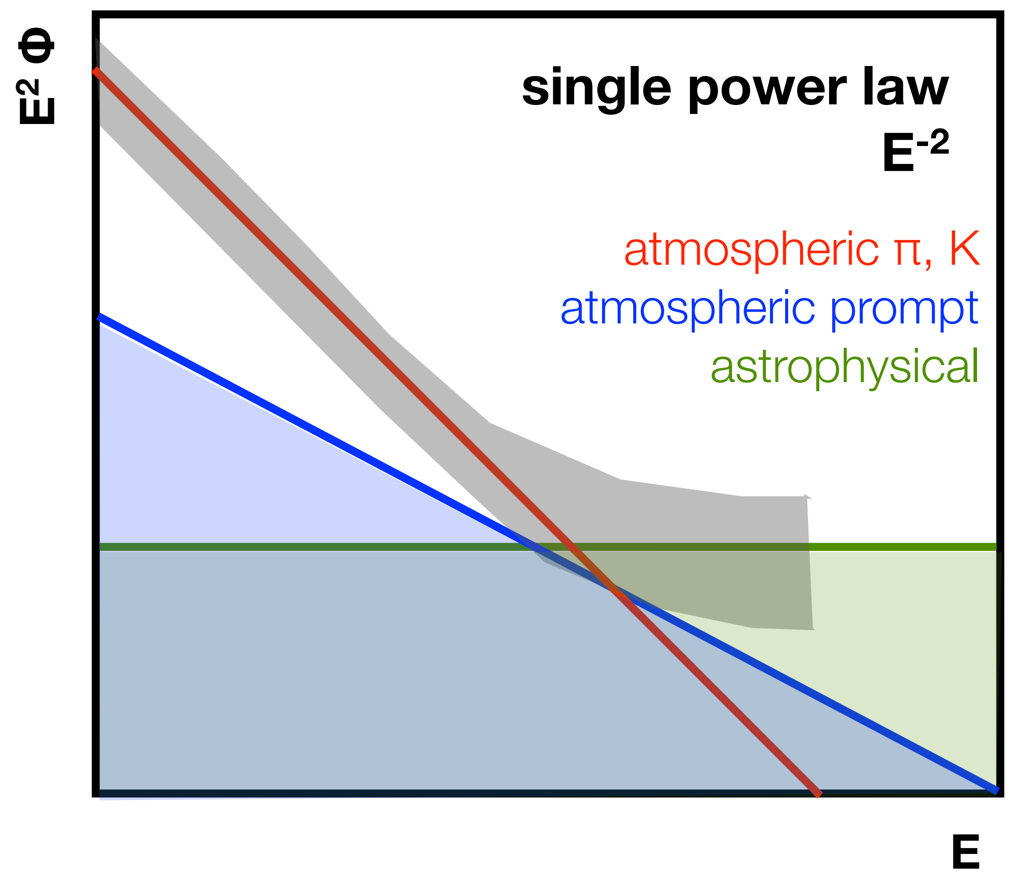
neutrino identification

diffuse flux

- **conventional ν_μ**: Honda et al. 2004 - extended to high energy
- **prompt ν_μ**: Enberg et al. 2008
- **new** calculations available with updated cosmic ray spectrum & composition

- the **harder** astrophysical spectrum the **higher** prompt neutrino needed to fit data
- **low statistics**: results consistent





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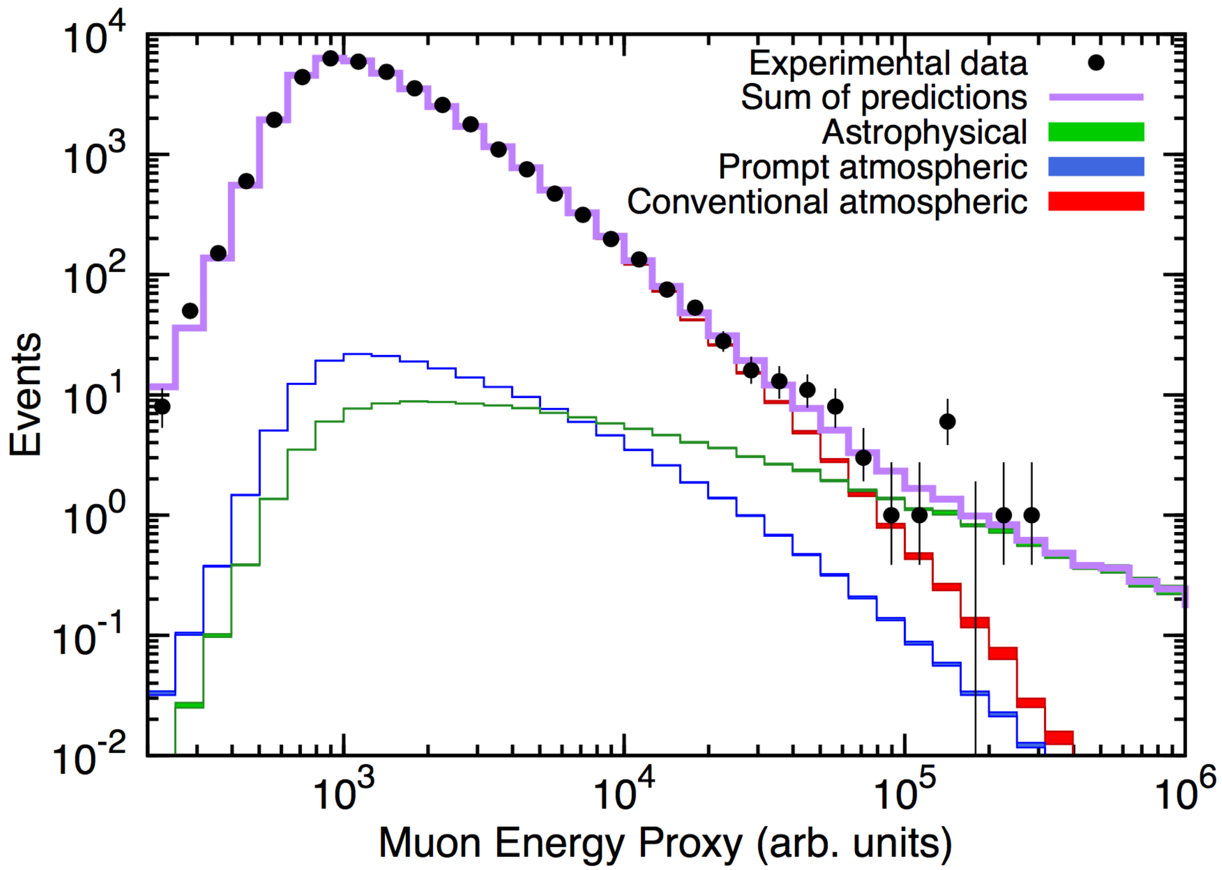

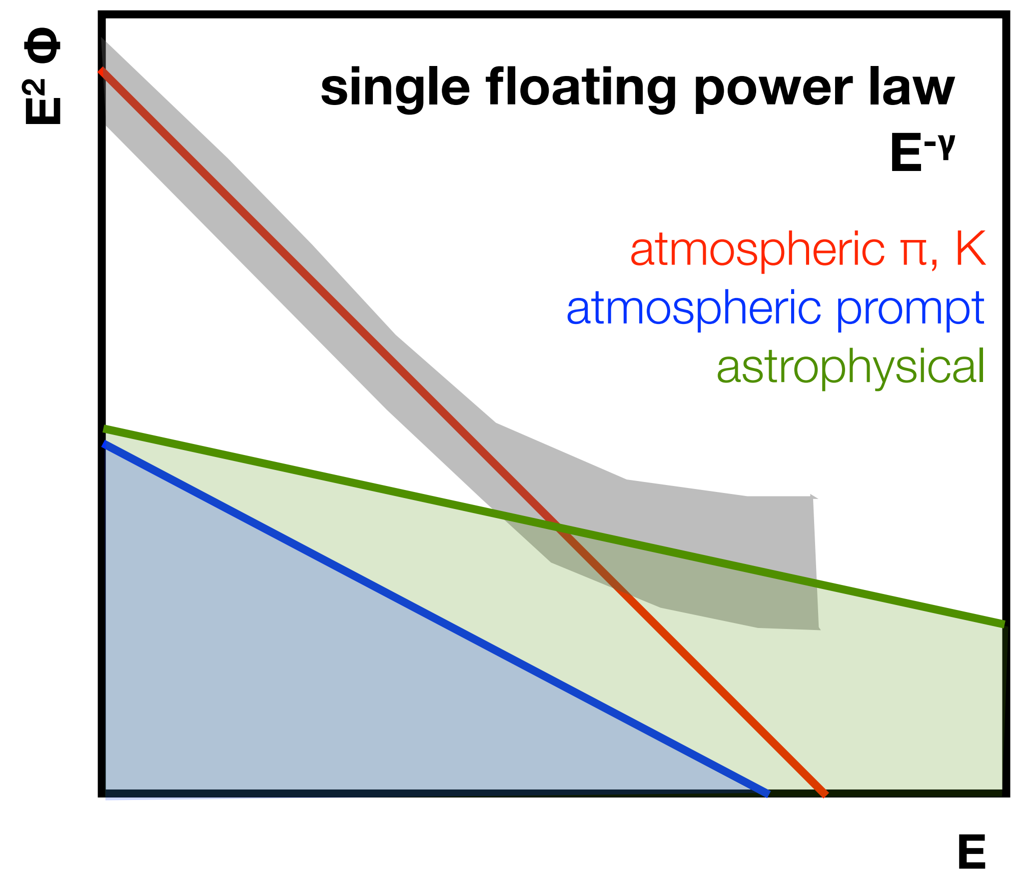

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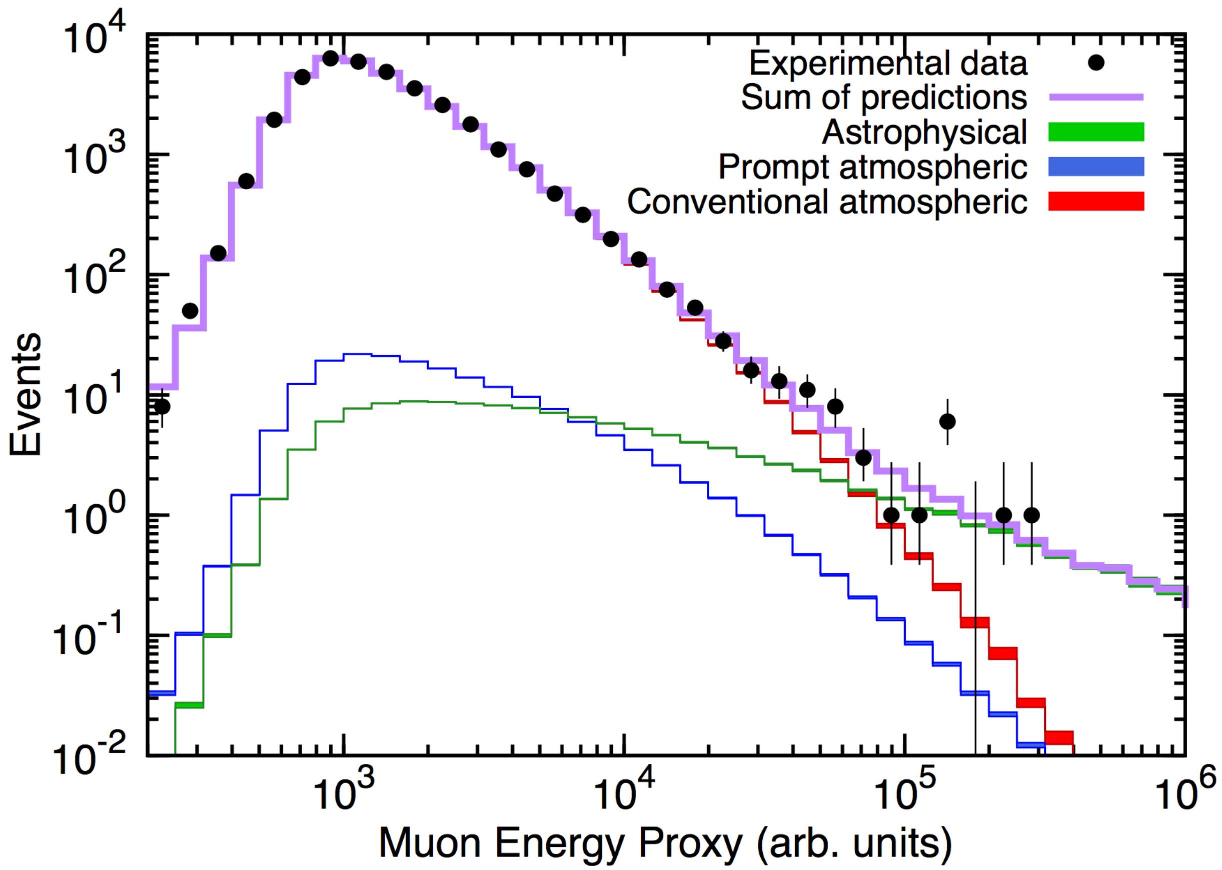

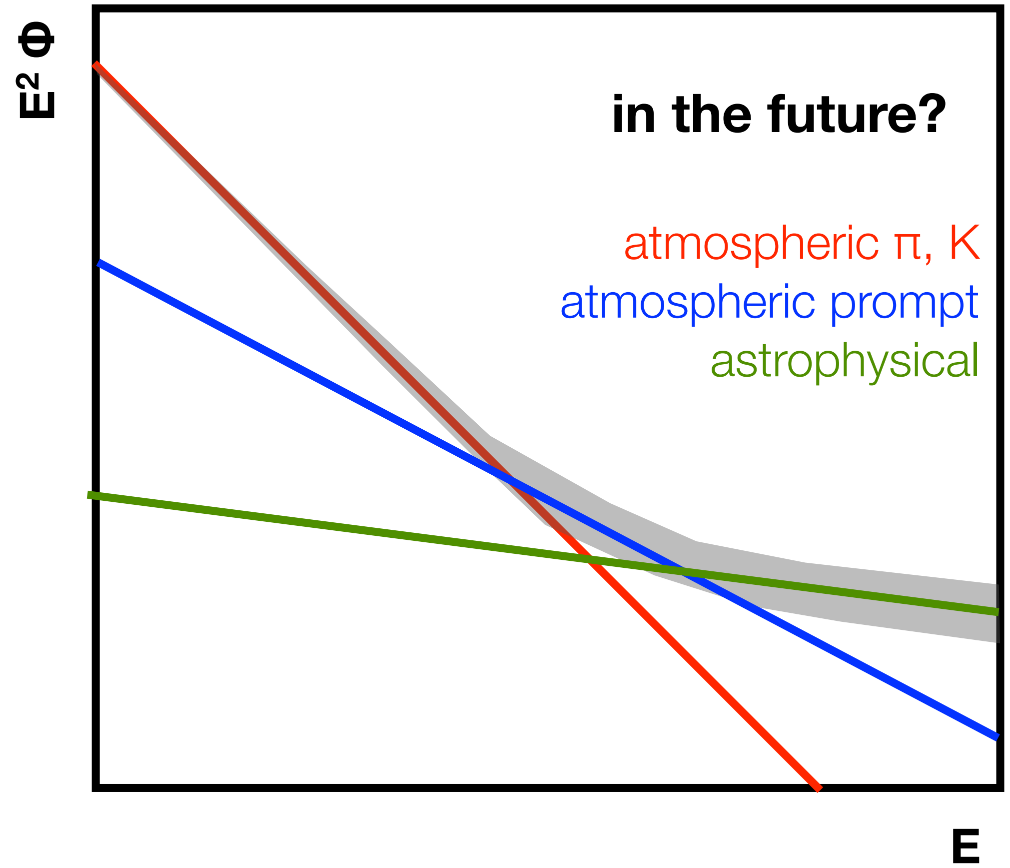

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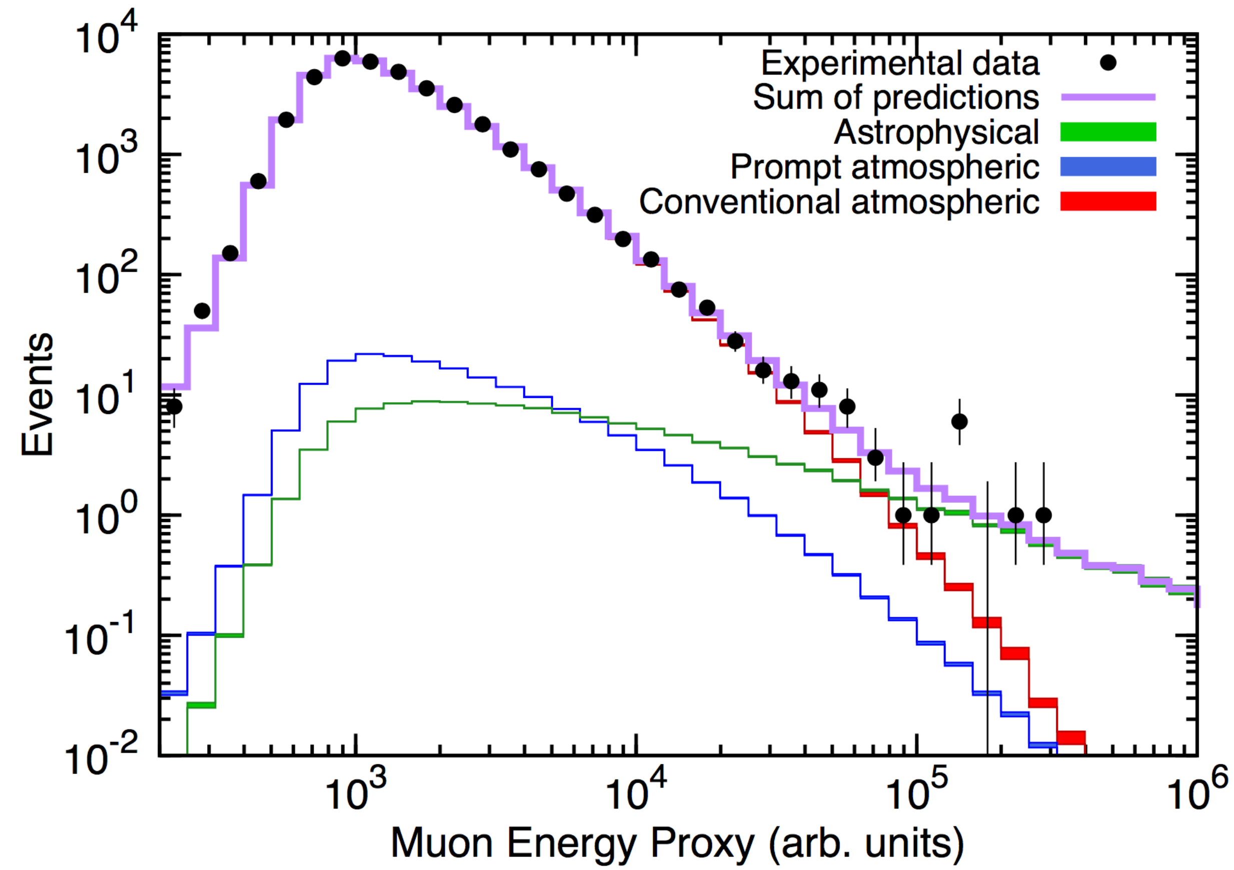

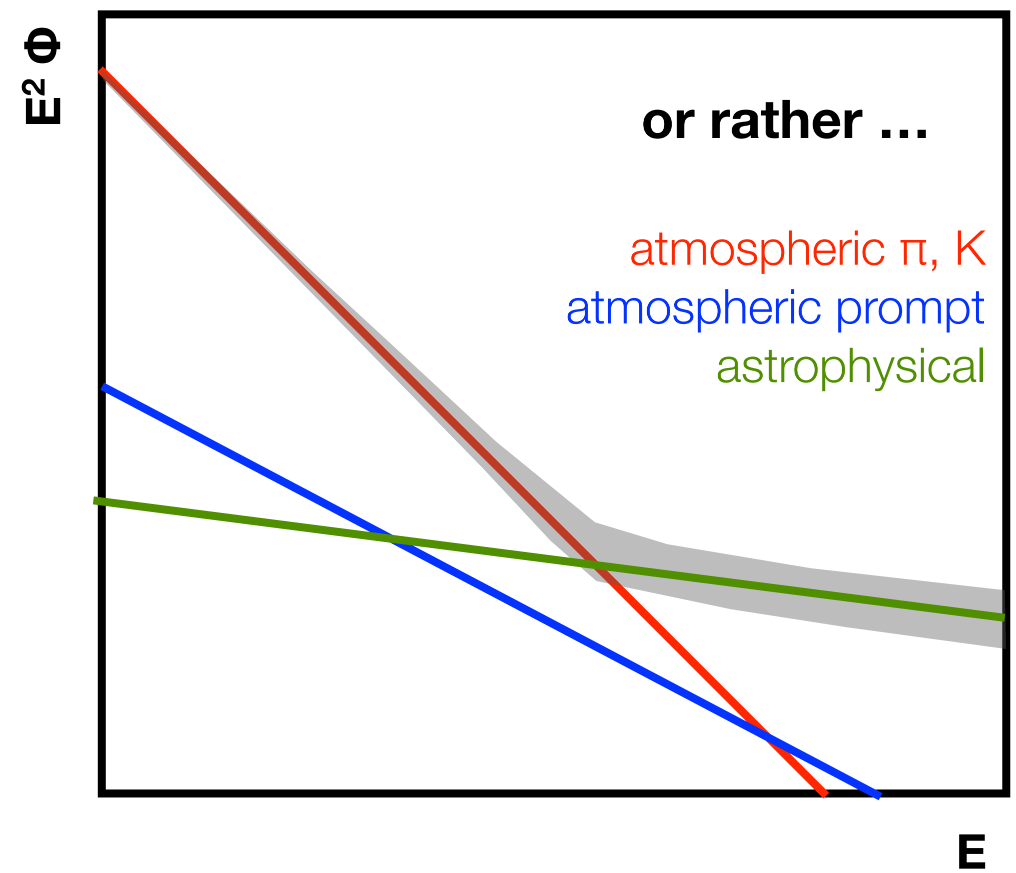

neutrino identification

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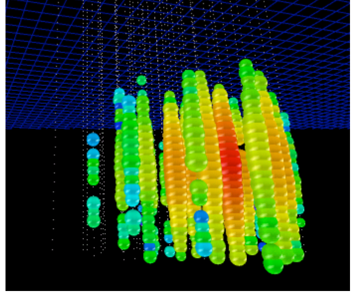
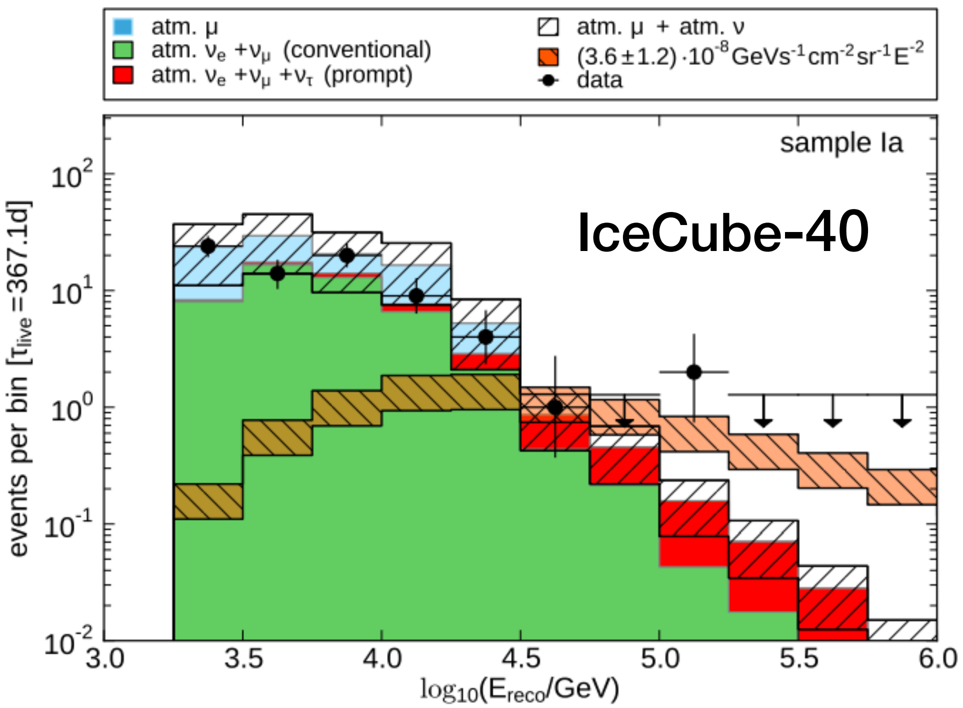
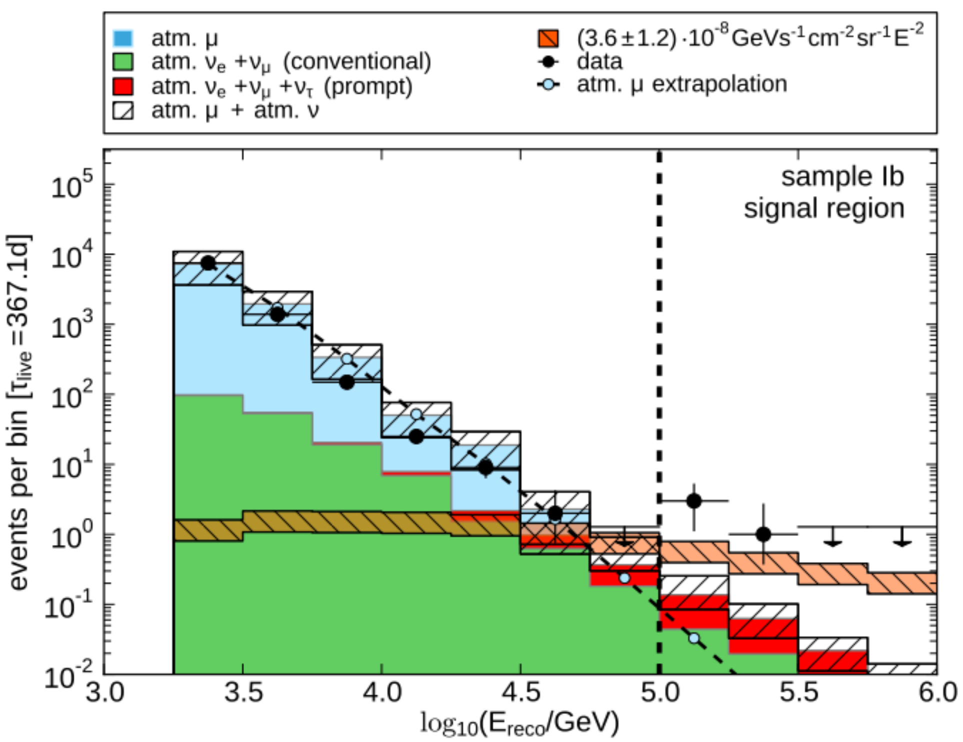
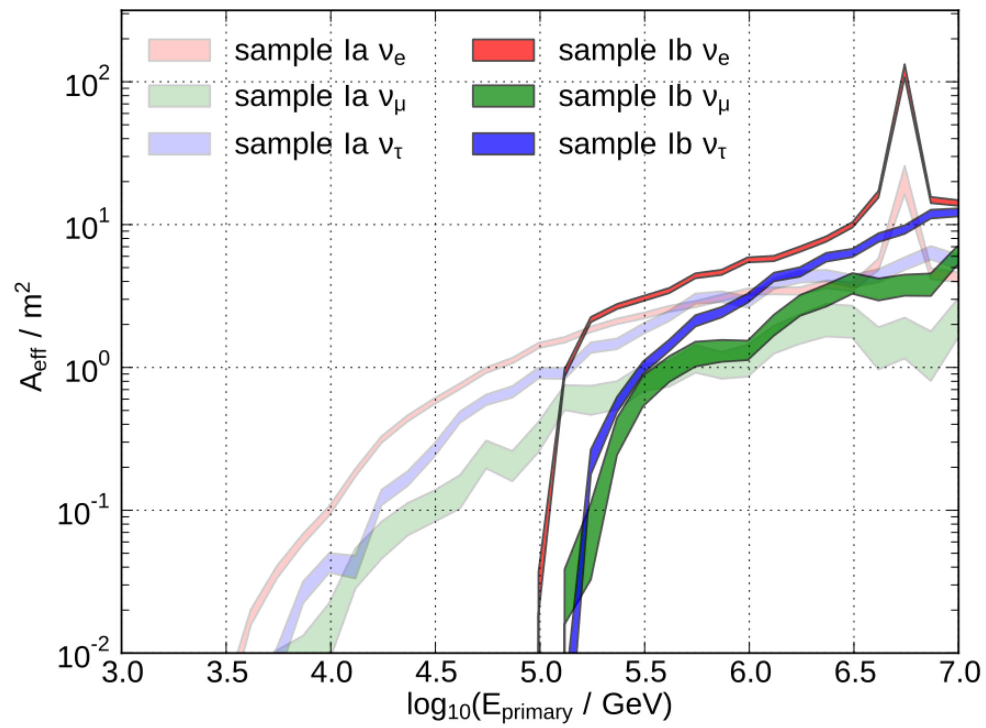




(a) Deposited Energy in sample Ia



Aartsen et al. Phys.Rev. D89 (2014) 10, 102001

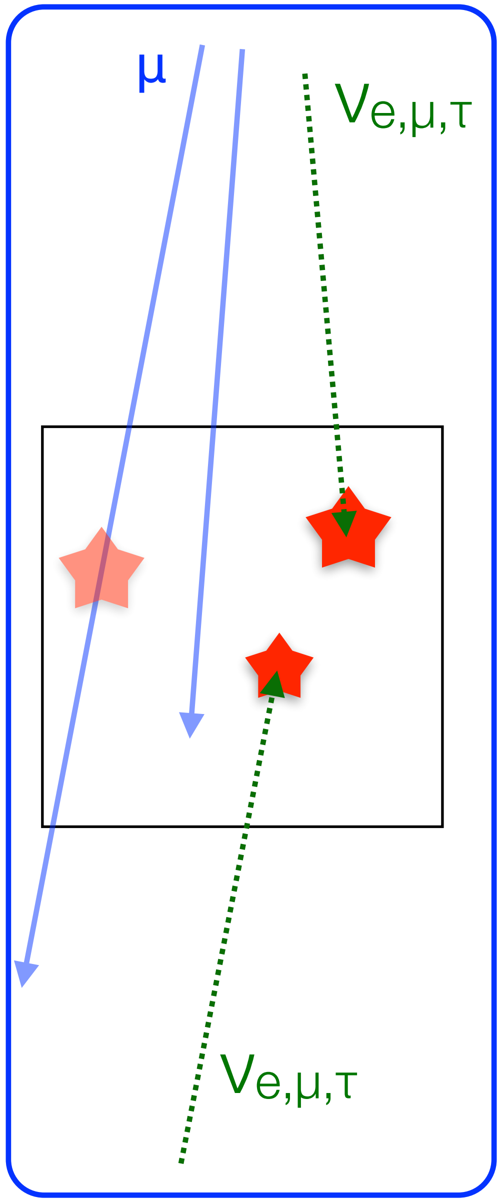


2.4 σ excess over atmospheric expectation

$$\Phi^{astro}_{90\%CL}(E) = 7.46 \times 10^{-8} \times E^{-2}\ GeV^{-1}cm^{-2}s^{-1}sr^{-1}$$

all-flavor

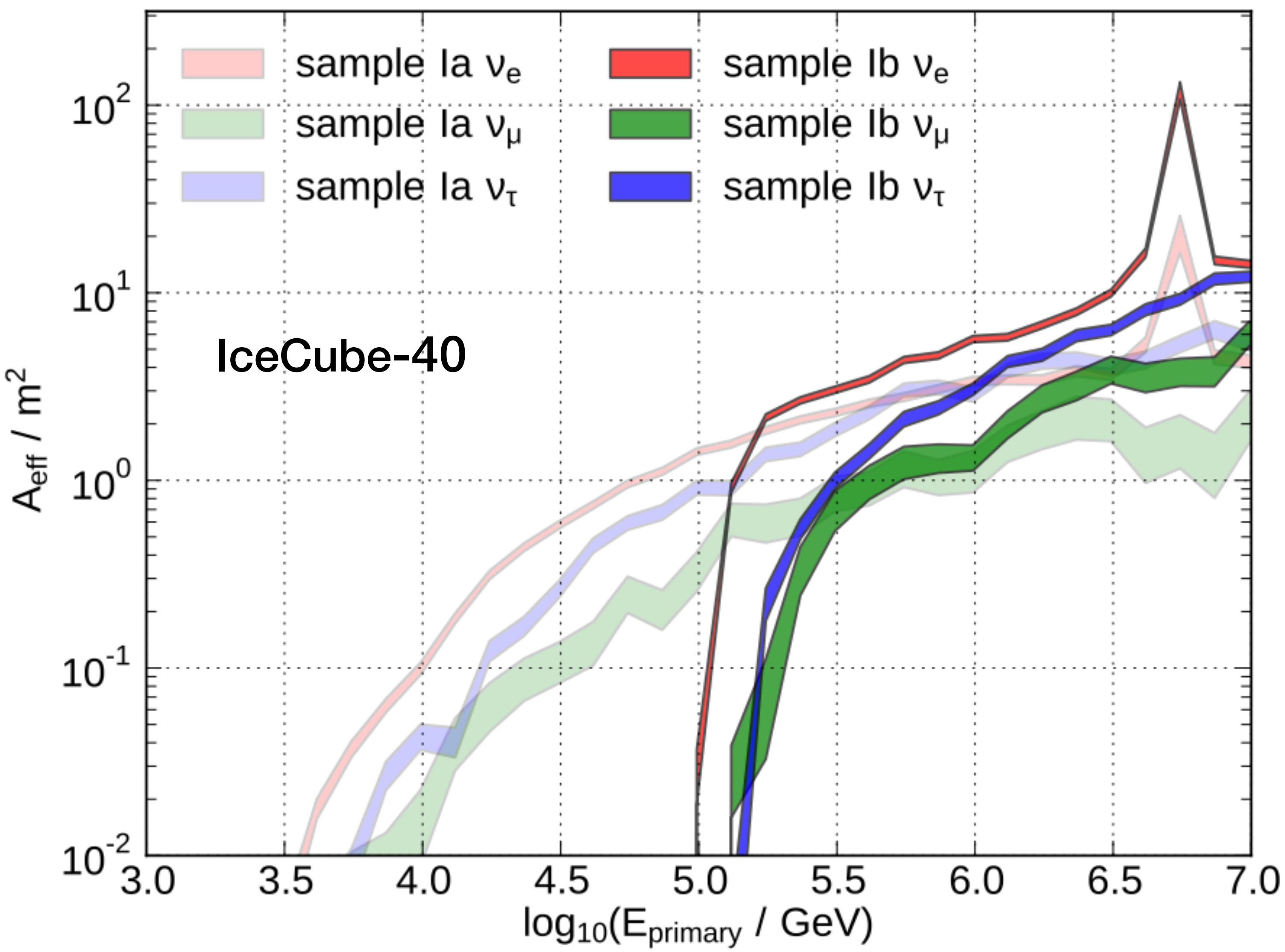
contained (cascades)



neutrino identification
diffuse flux

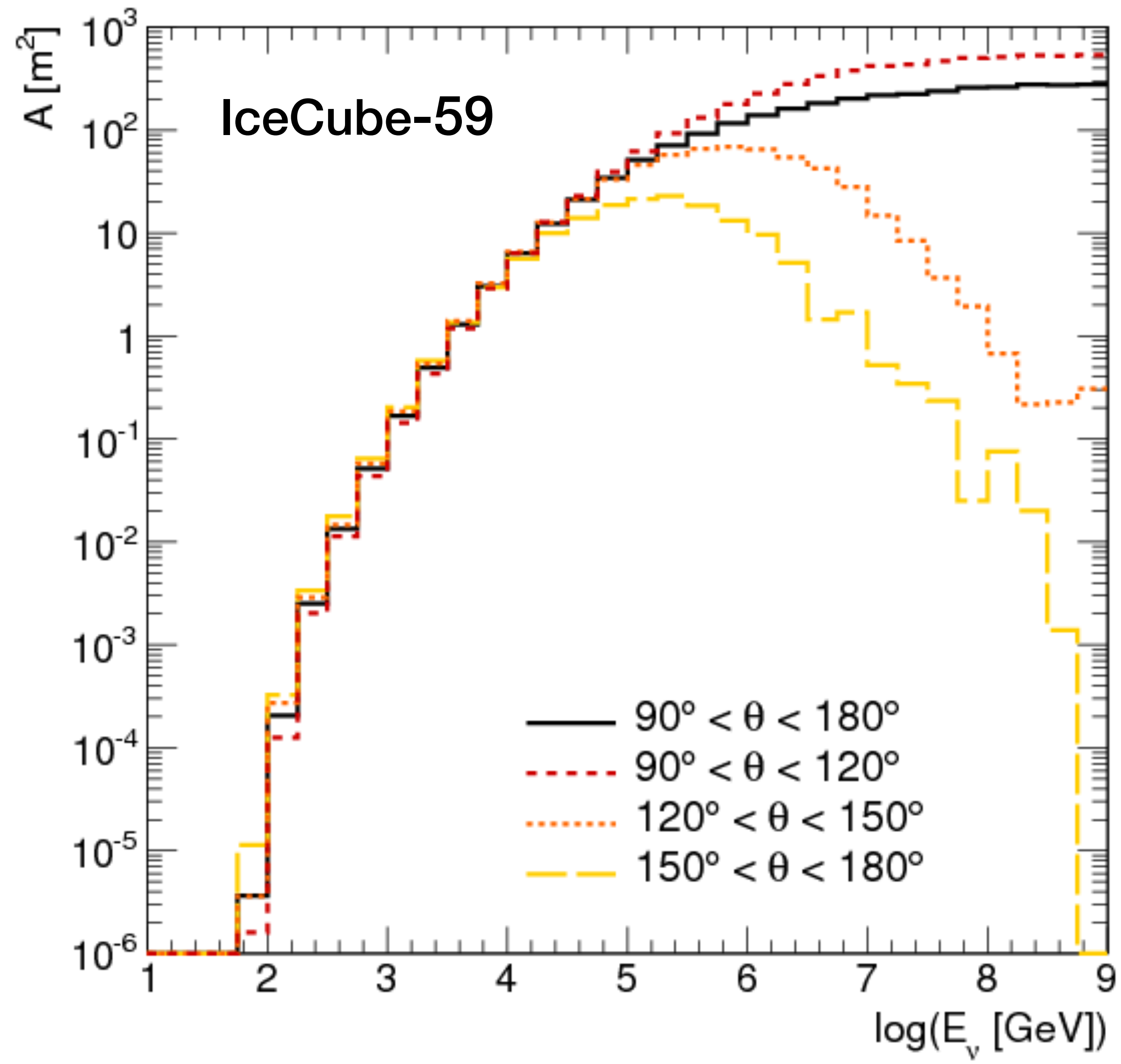
neutrino effective area

Aartsen et al. Phys.Rev. D89 (2014) 10, 102001



cascade-like events
all neutrinos NC interactions &
electron/tau neutrinos CC interactions

Aartsen et al. Phys. Rev. D 89 (2014), 062007



track-like events
muon neutrinos CC interactions

neutrino identification

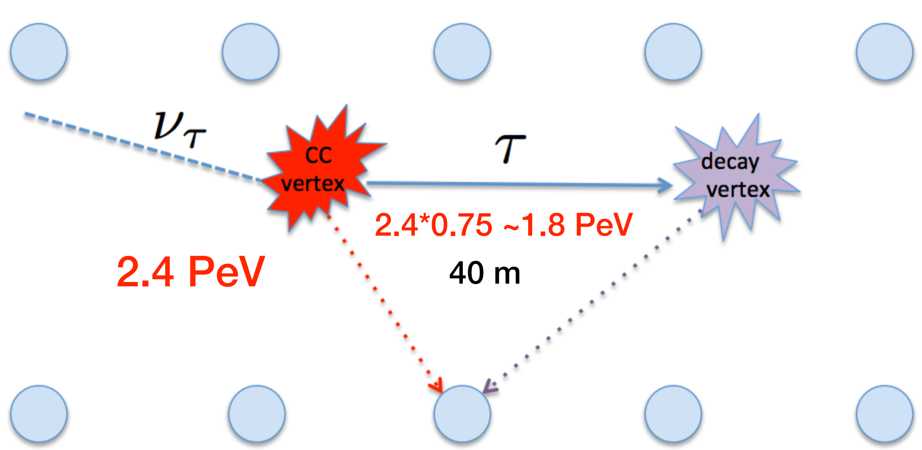
diffuse flux

tau neutrino searches

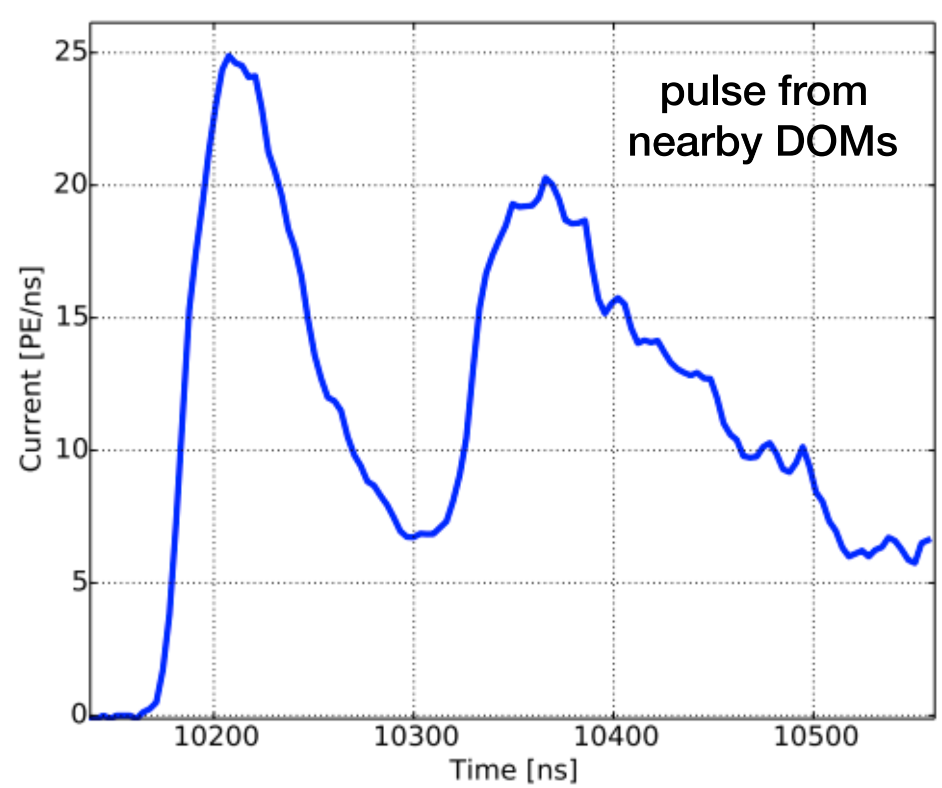
IceCube-86 × 3

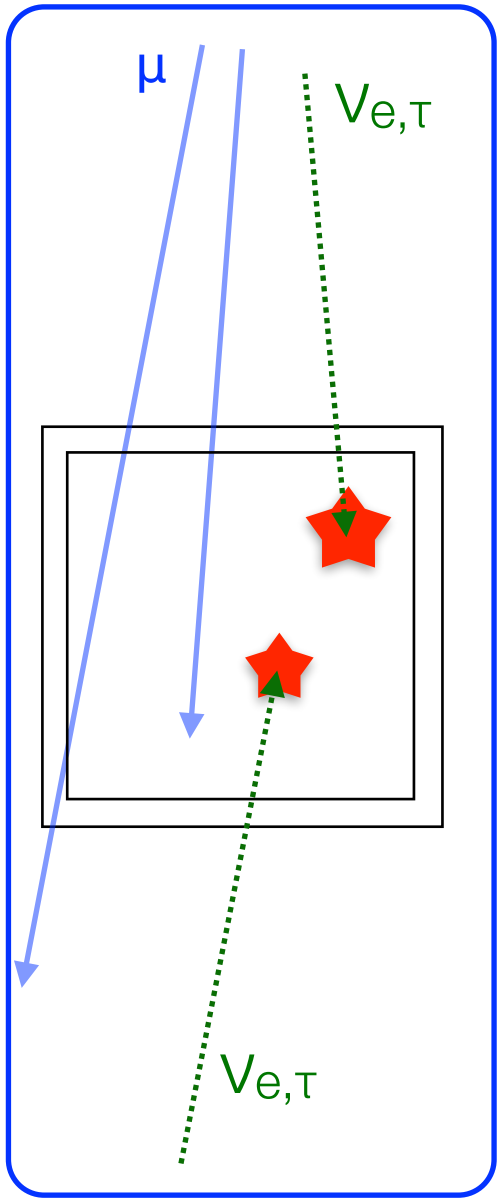
contained (cascades)

Aartsen et al. arXiv:1509.06212



close double bang events



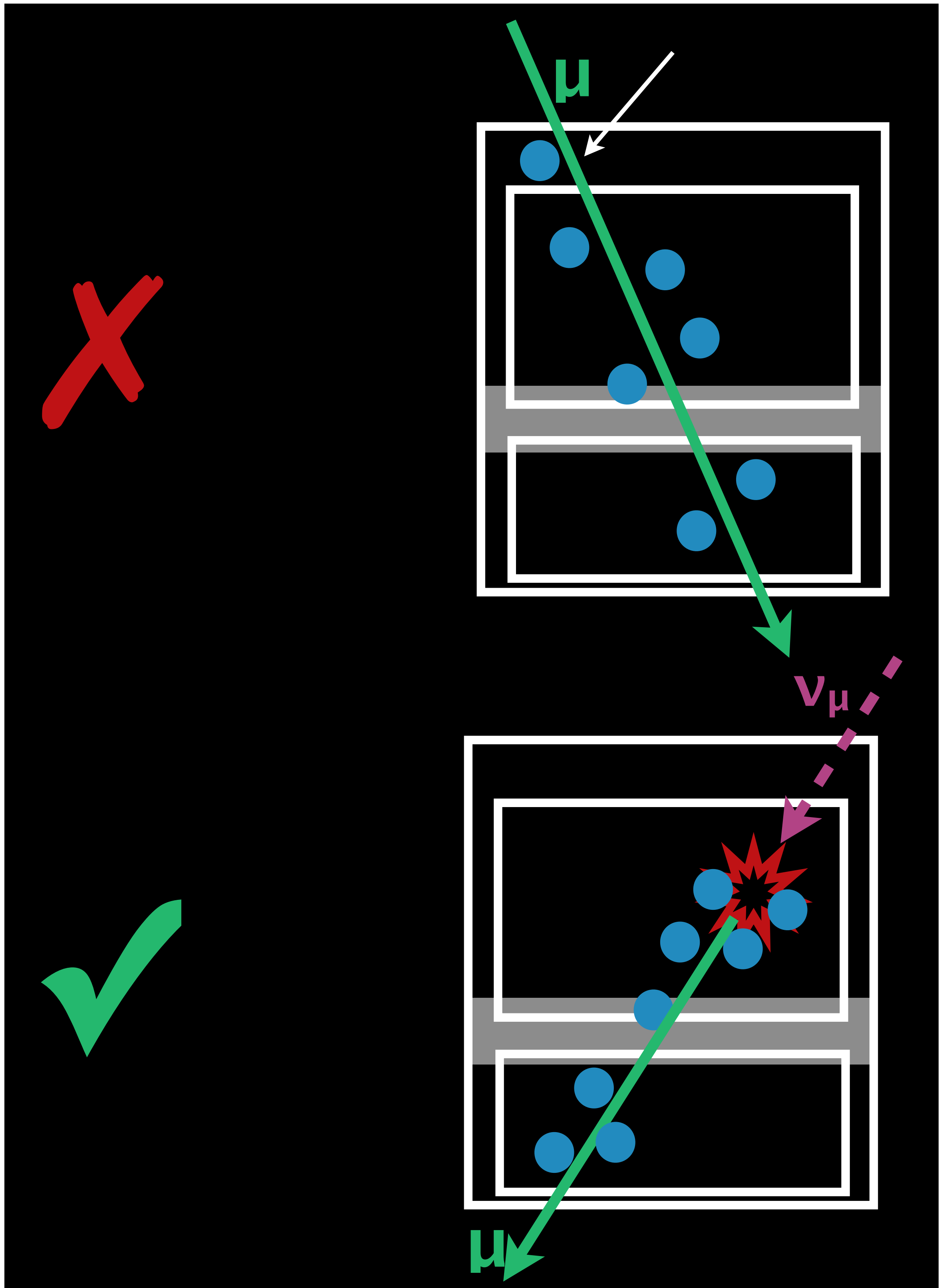


no contained events with double pulses found in 3 years of IceCube-86 data

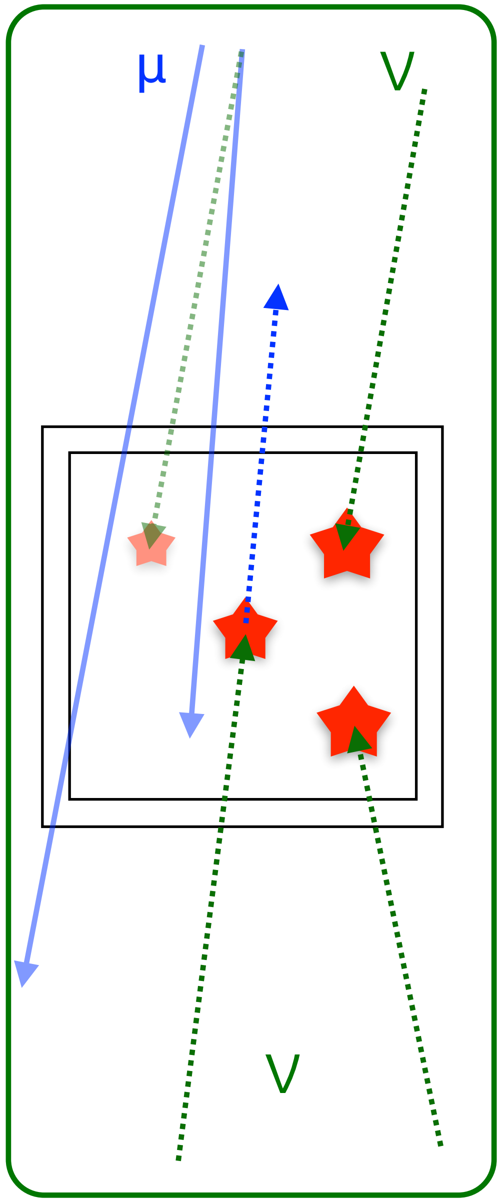
$$\Phi^{\nu_\tau}_{90\%CL}(E) = 5.1 \times 10^{-8} \times E^{-2}\ GeV^{-1}cm^{-2}s^{-1}sr^{-1}$$

214 TeV - 72 PeV

neutrino identification
active veto



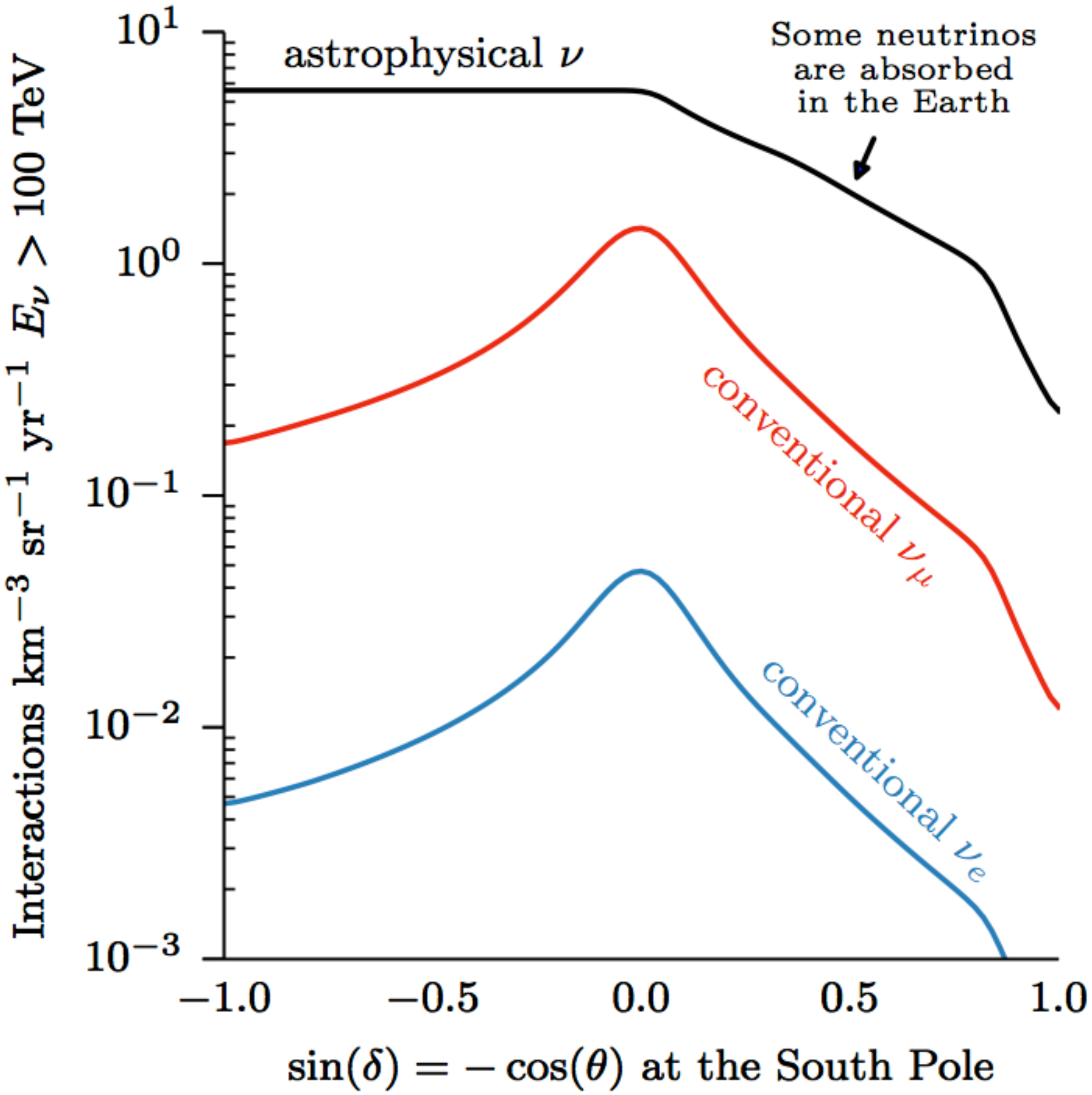
- outer detector veto to **reject muon tracks** passing the experiment boundary
- collect **bright events** with total charge > 6000 p.e.
- identify only events **starting inside** the instrumented volume
- active volume **420 Mton**!
- sensitive to **all flavors**
- sensitive to **whole sky**



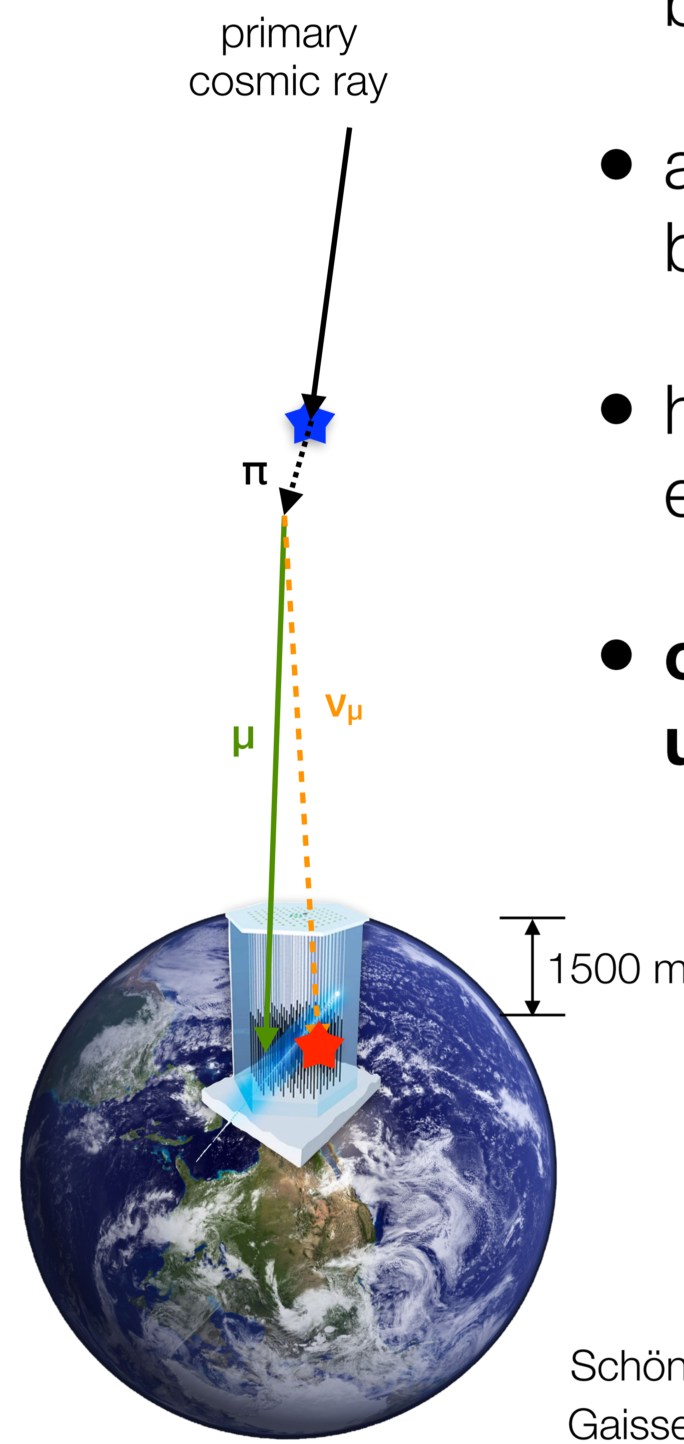
neutrino identification

self veto

>100 TeV energy



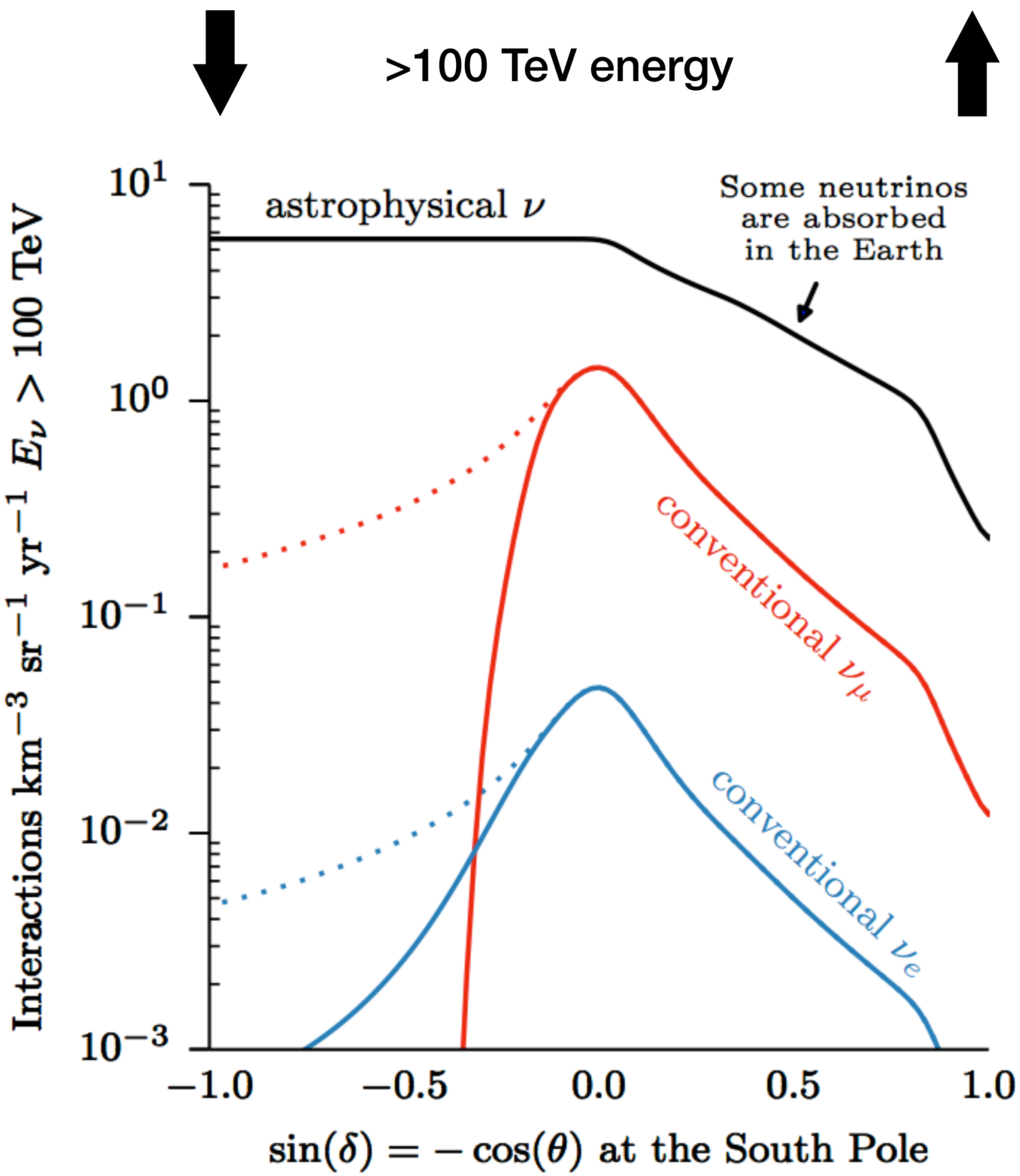
courtesy: J. van Santen

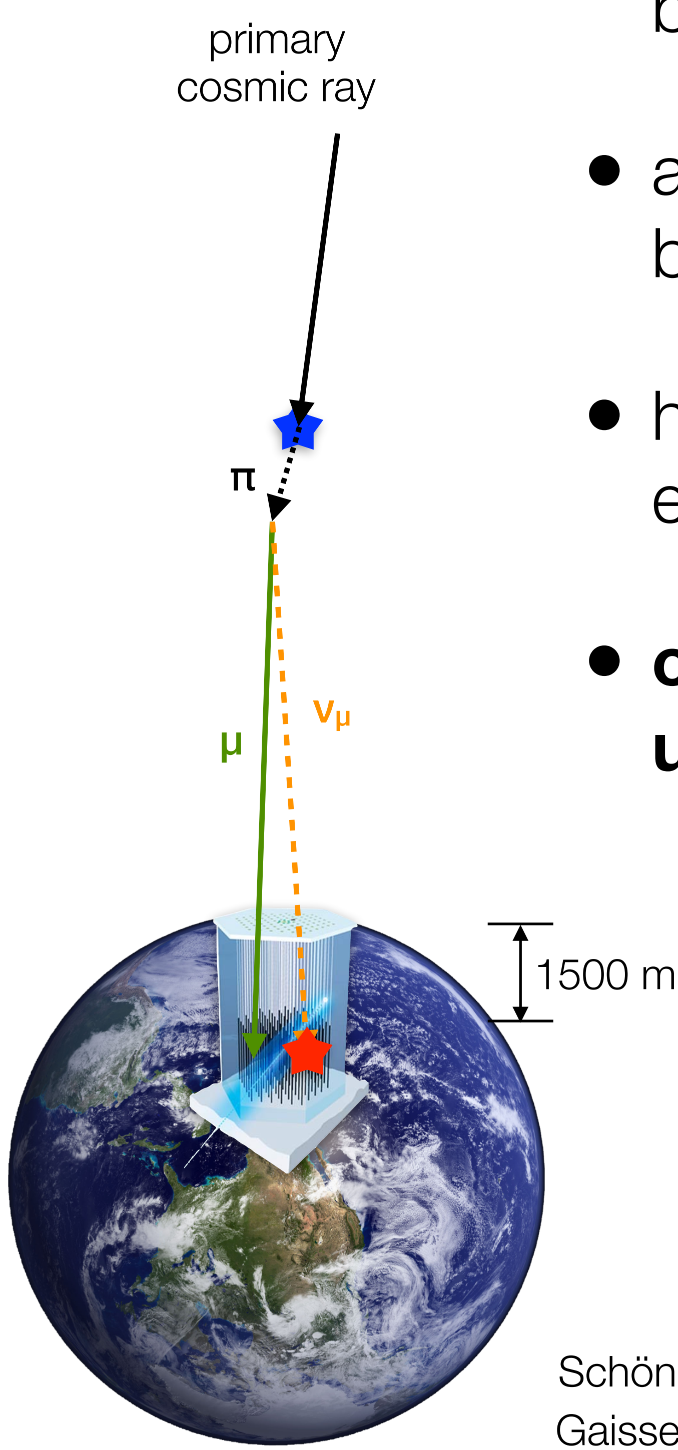


- vetoeing muons reject atmospheric neutrinos
- as long as muons can be detected in IceCube
- and are accompanied by neutrinos
- high energy vertical events best vetoed
- **correlated & uncorrelated** muons

Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

neutrino identification
self veto





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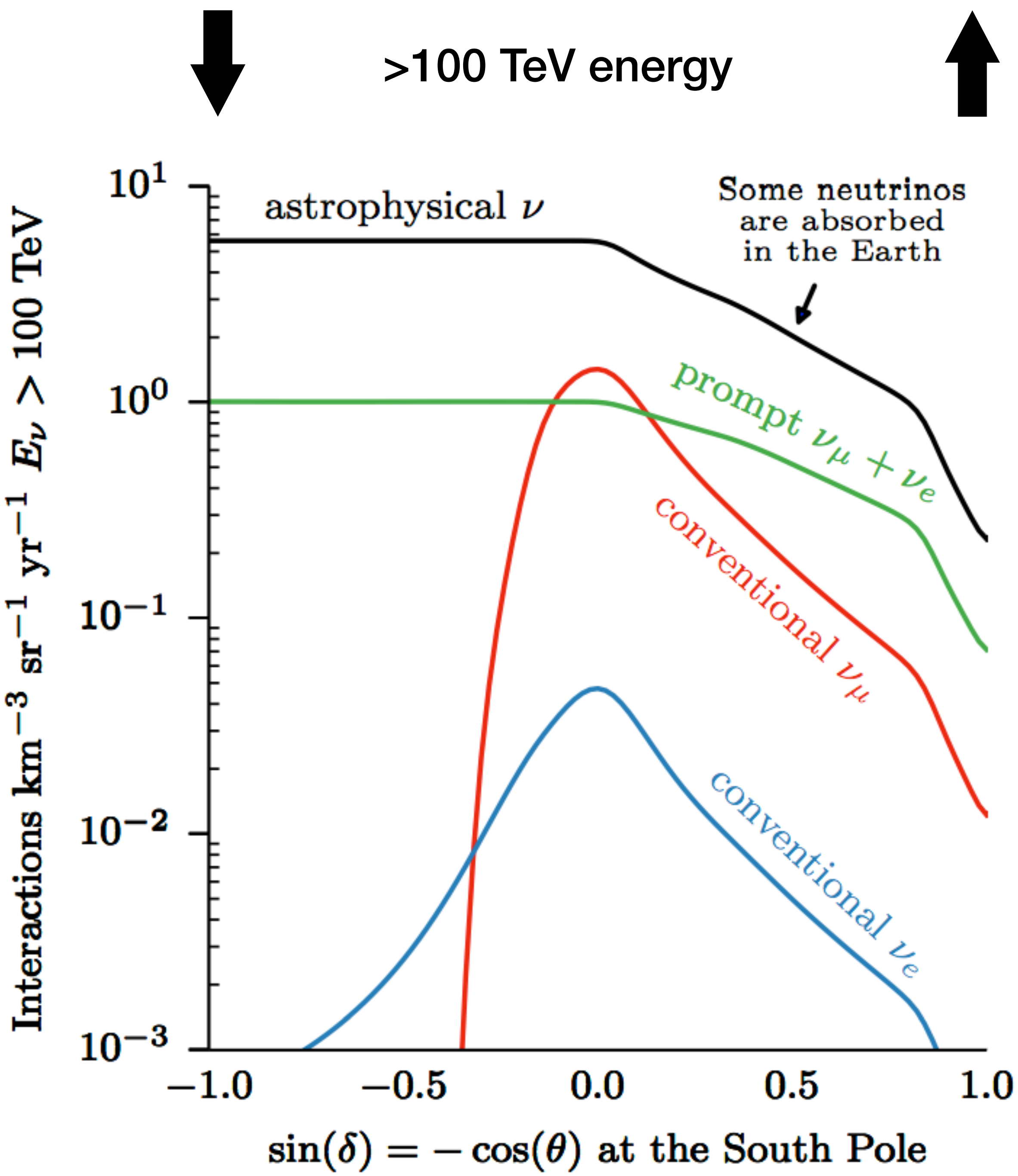
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

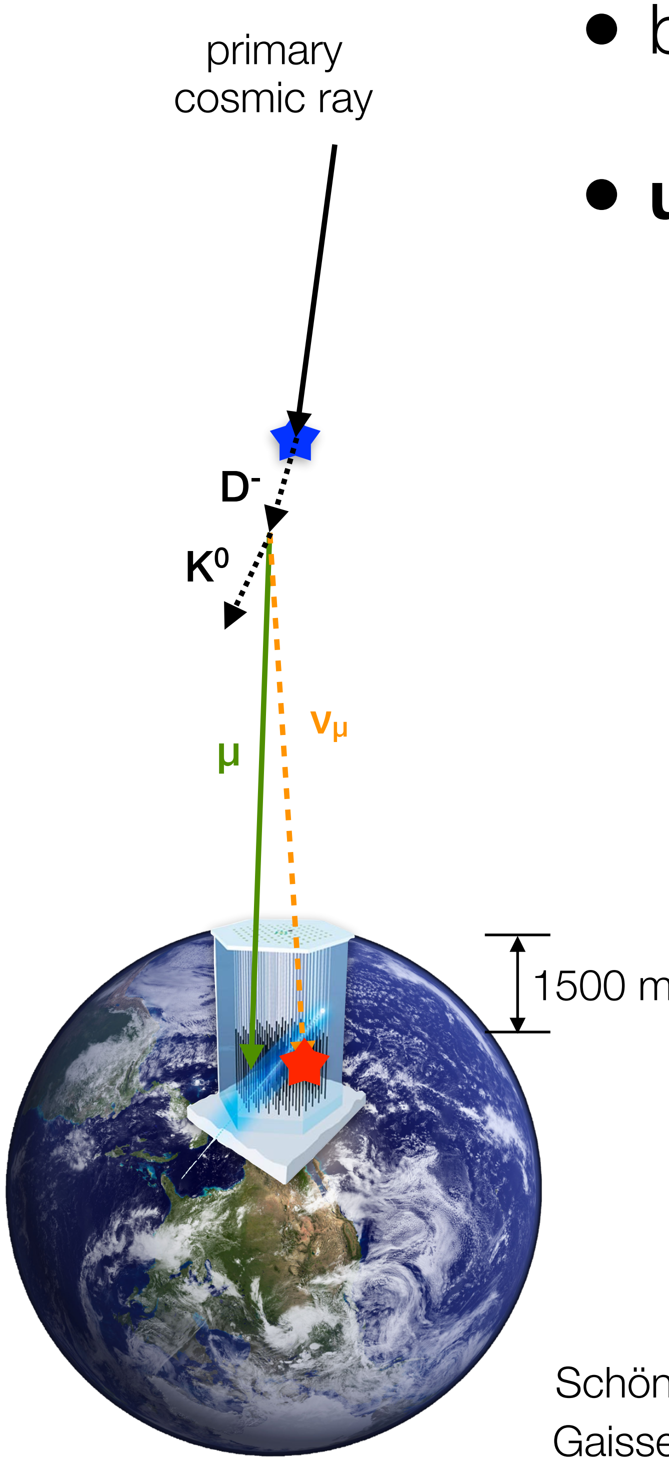
courtesy: J. van Santen

neutrino identification

self veto

- prompt atmospheric neutrinos are rejected too
- but with lower efficiency
- **uncorrelated** muons





Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

courtesy: J. van Santen

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self veto

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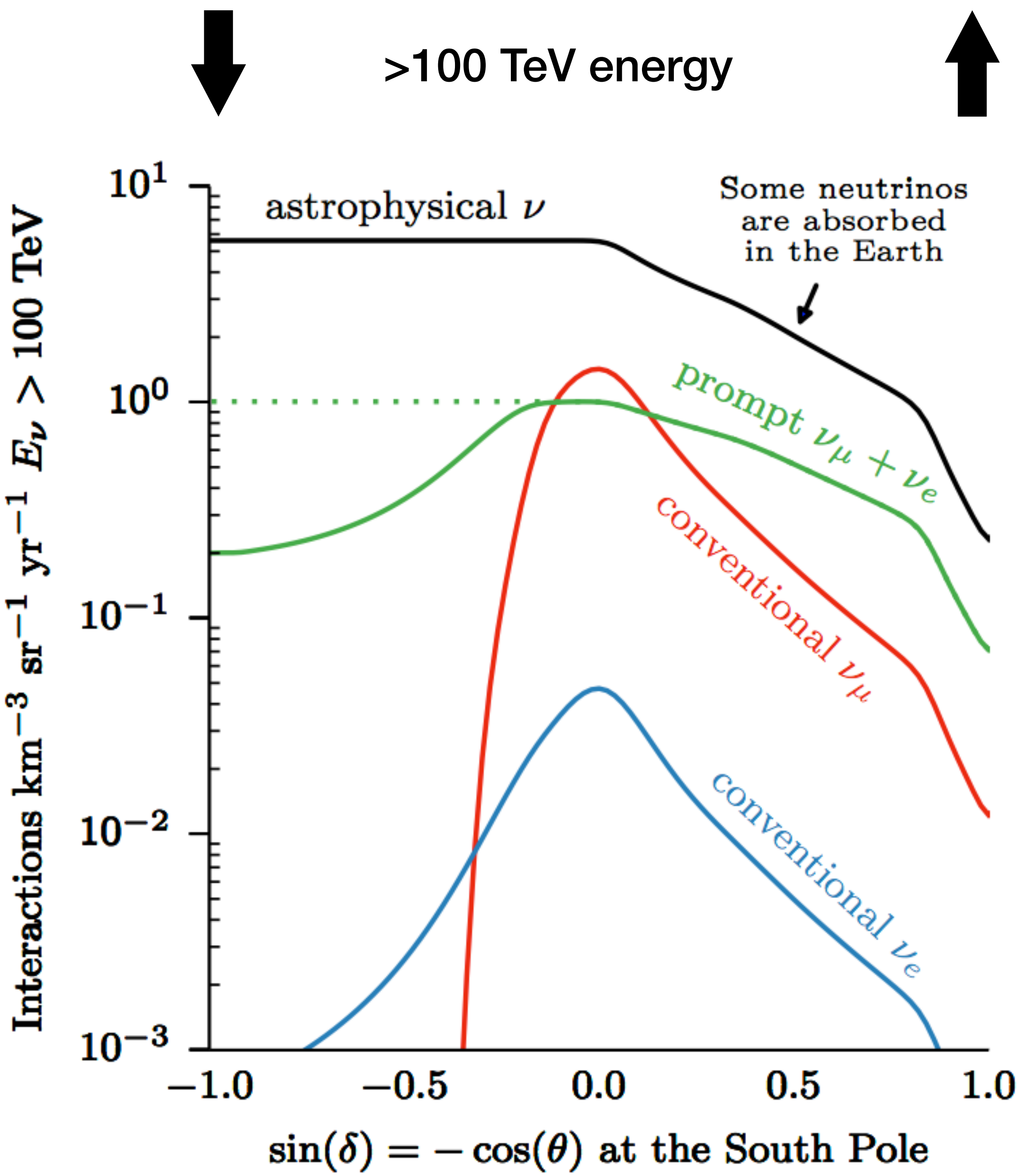
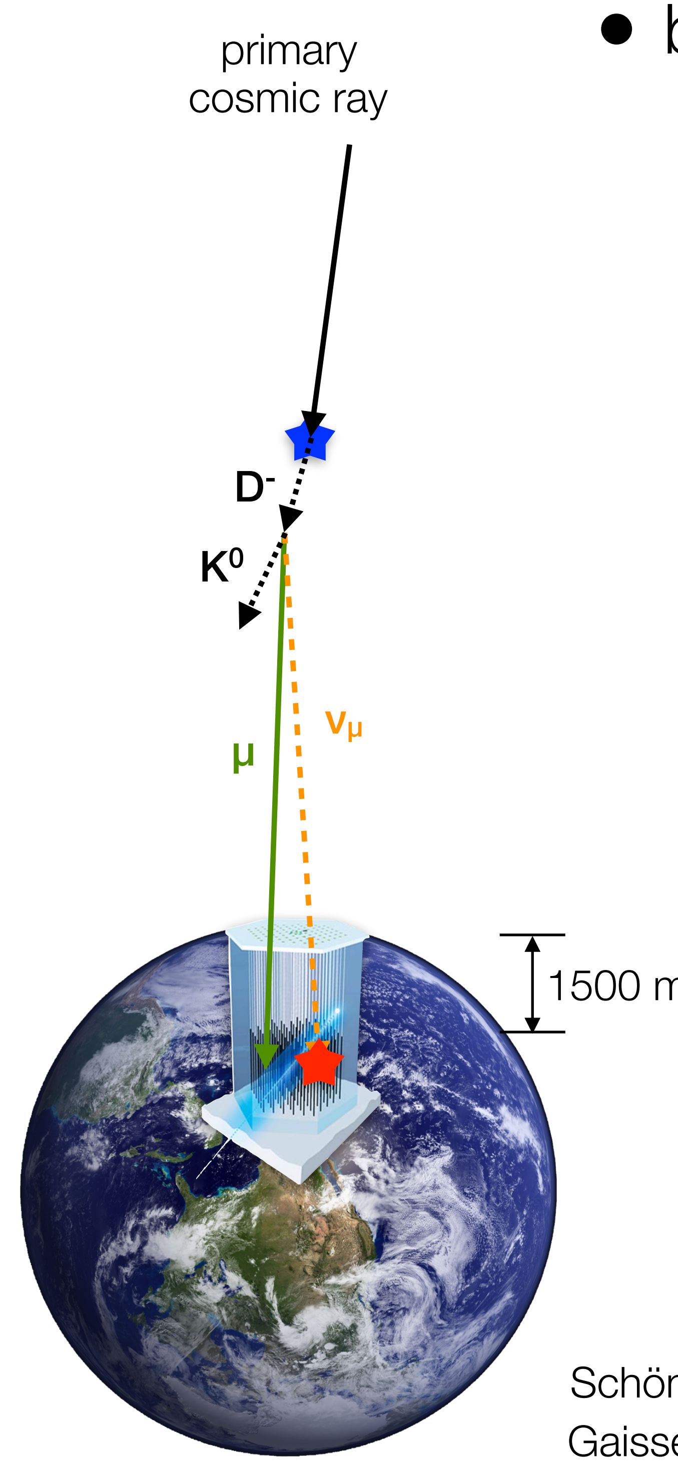
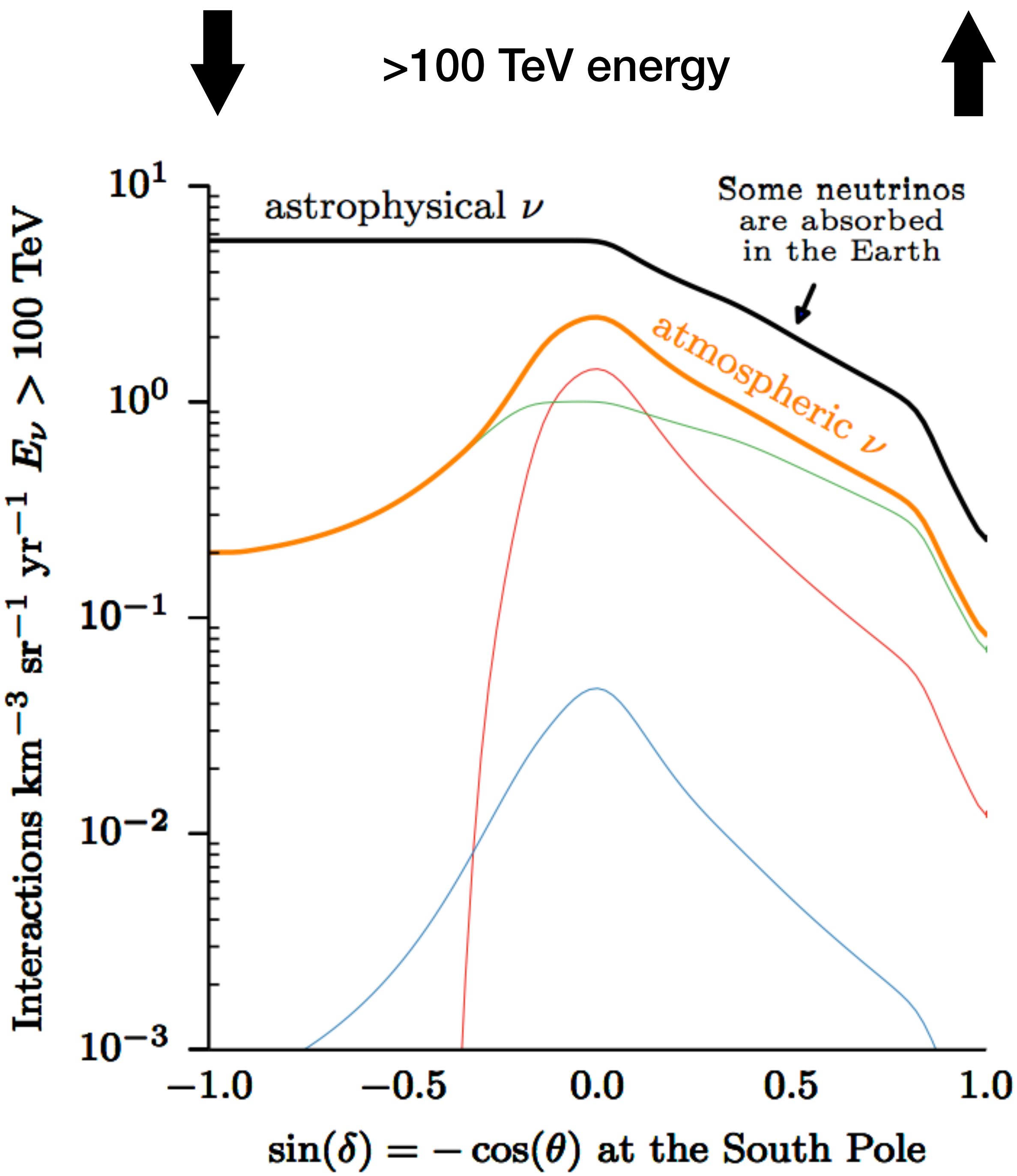


courtesy: J. van Santen



Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

neutrino identification
self veto



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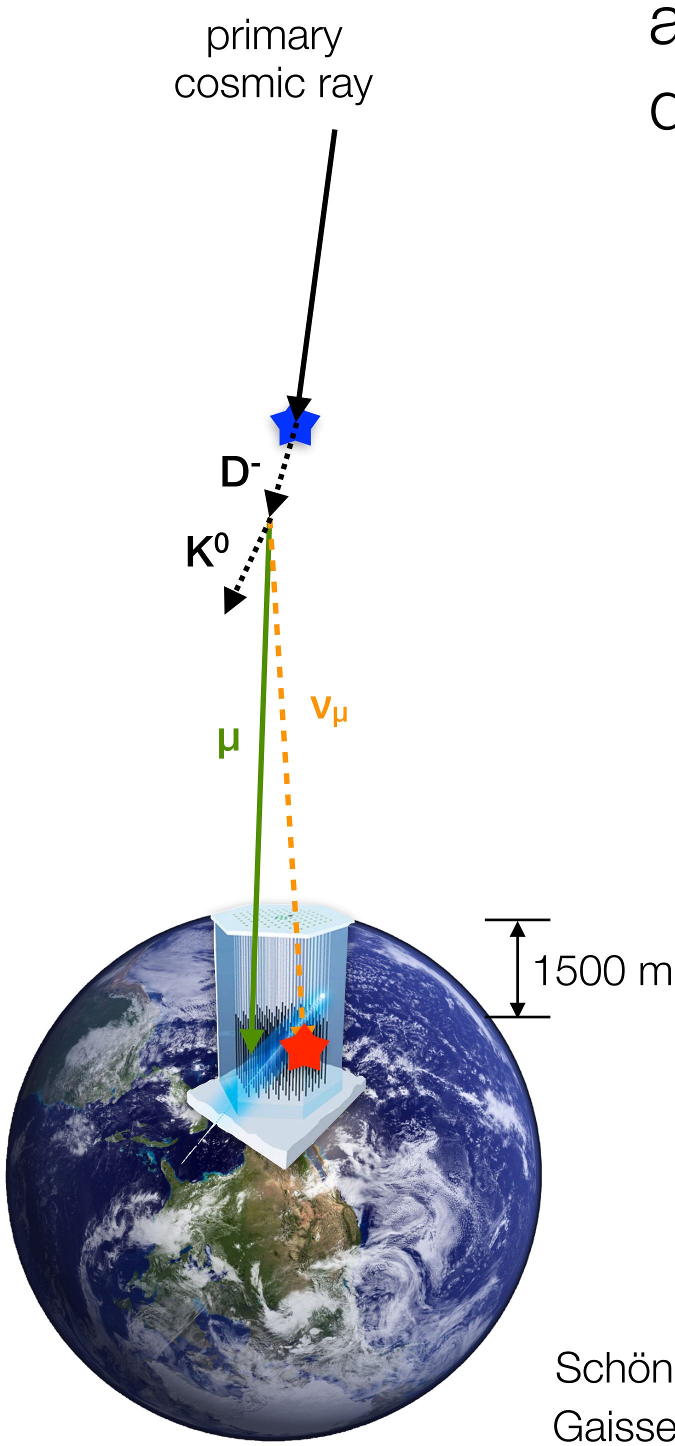


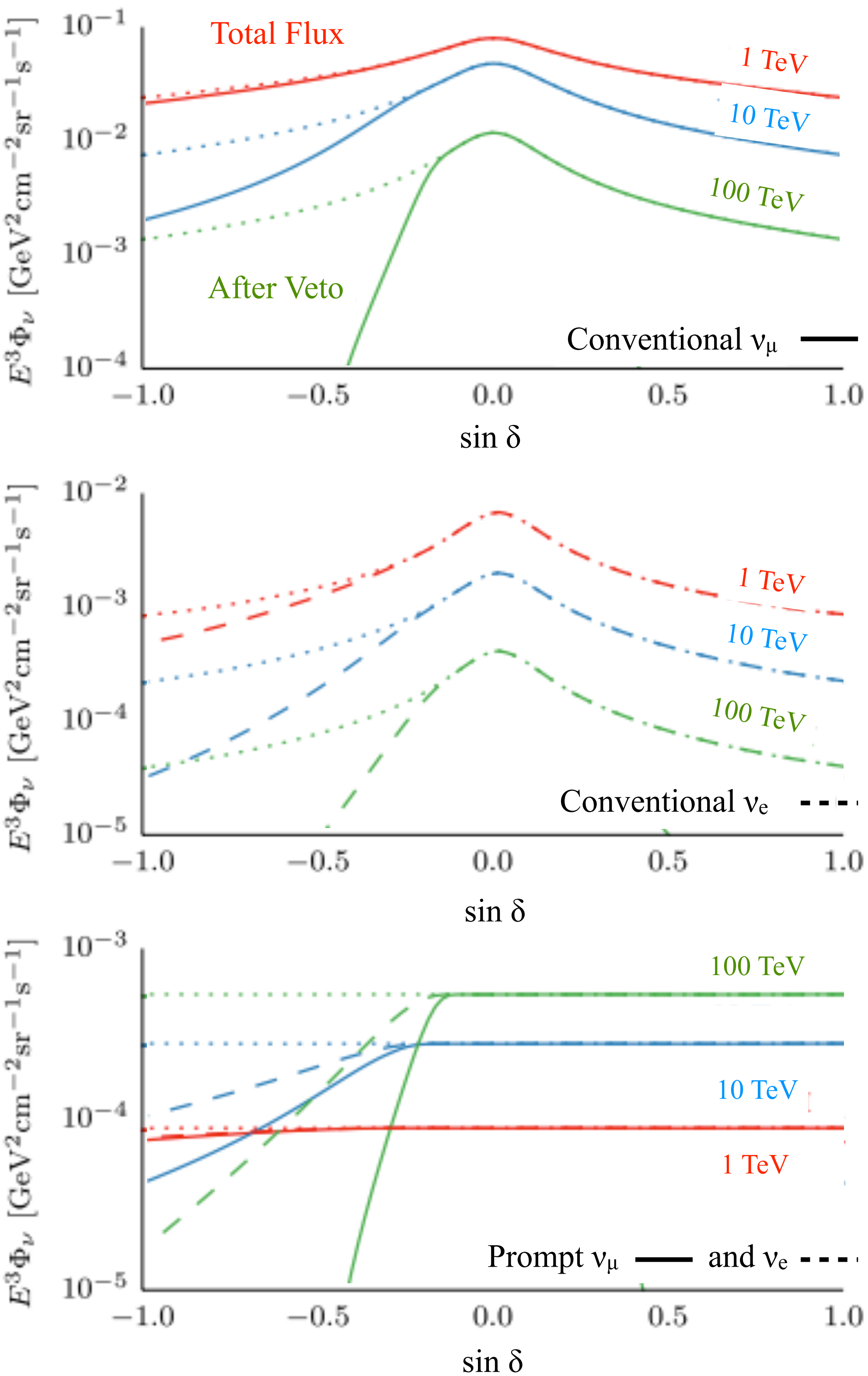
- The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

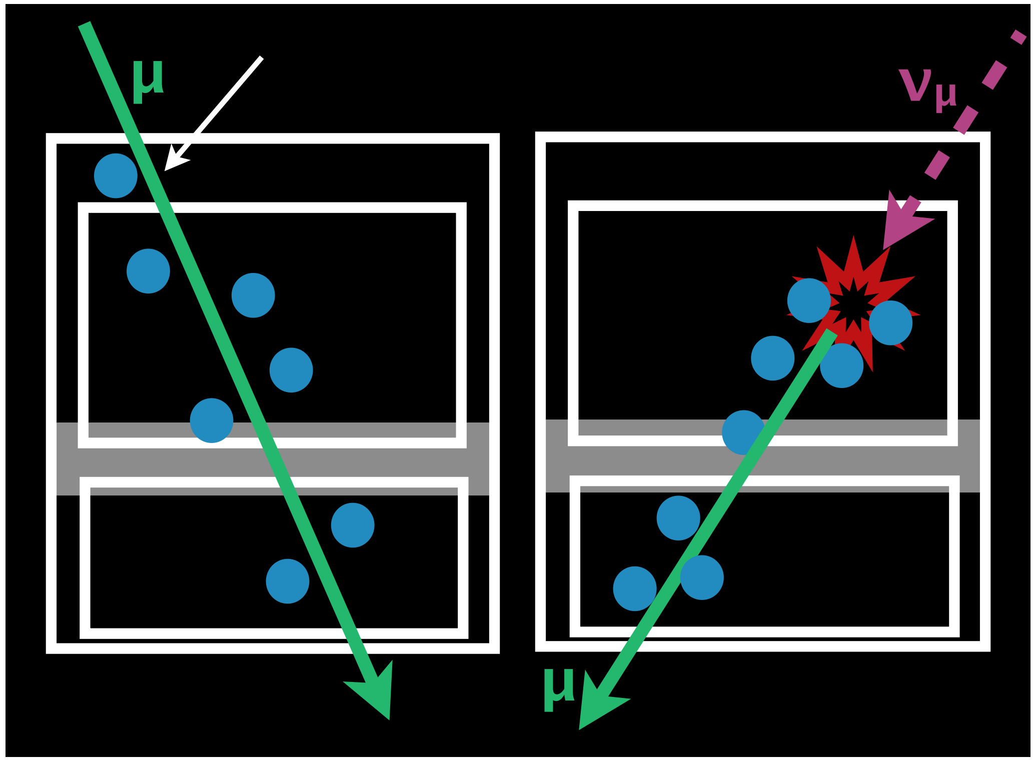
Schönert et al. Phys.Rev.D 79 (2009) 043009
Gaisser et al. Phys.Rev.D 90 (2014) 023009

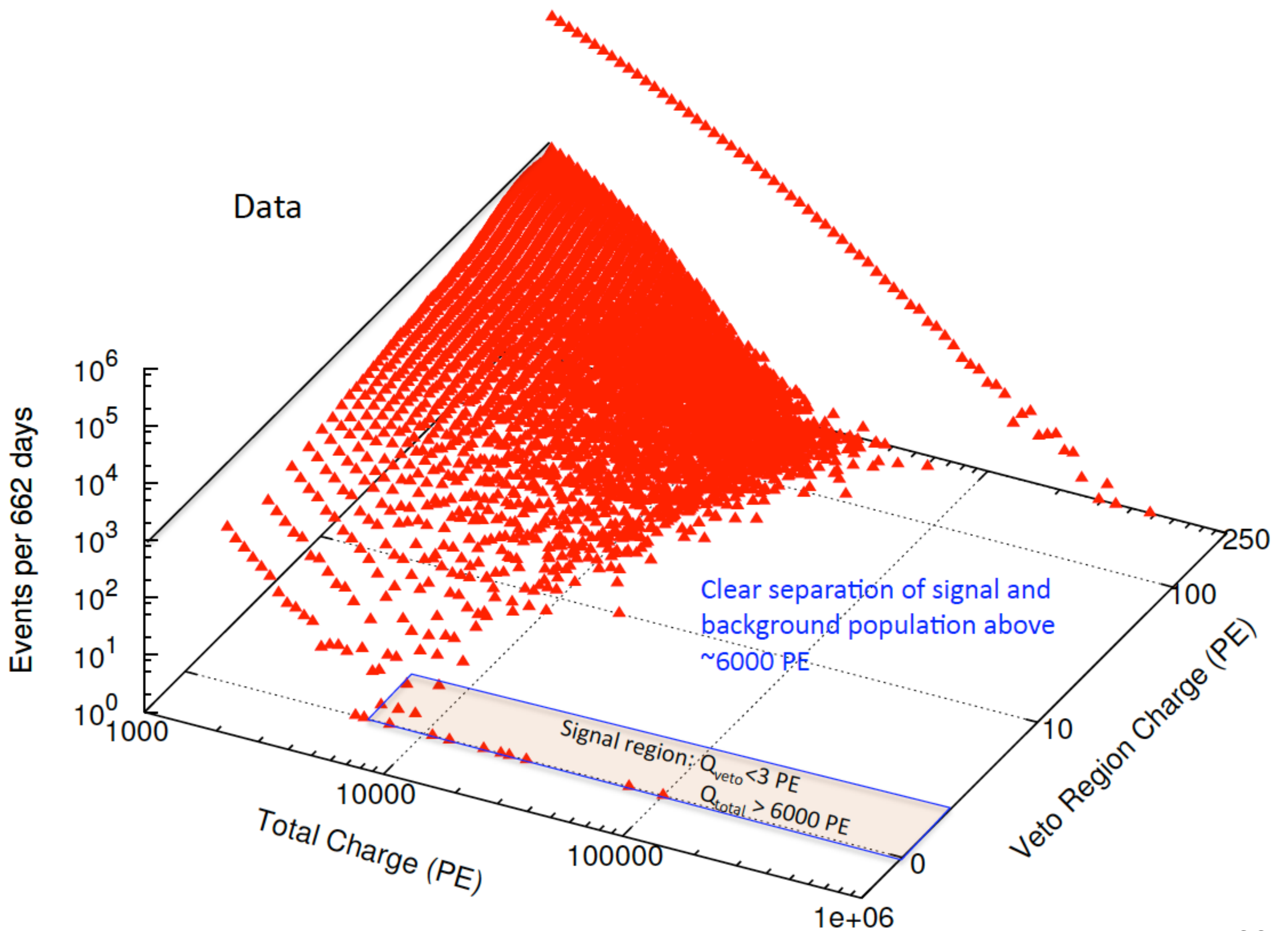
neutrino identification

self veto

Gaisser et al. Phys.Rev.D 90 (2014) 023009



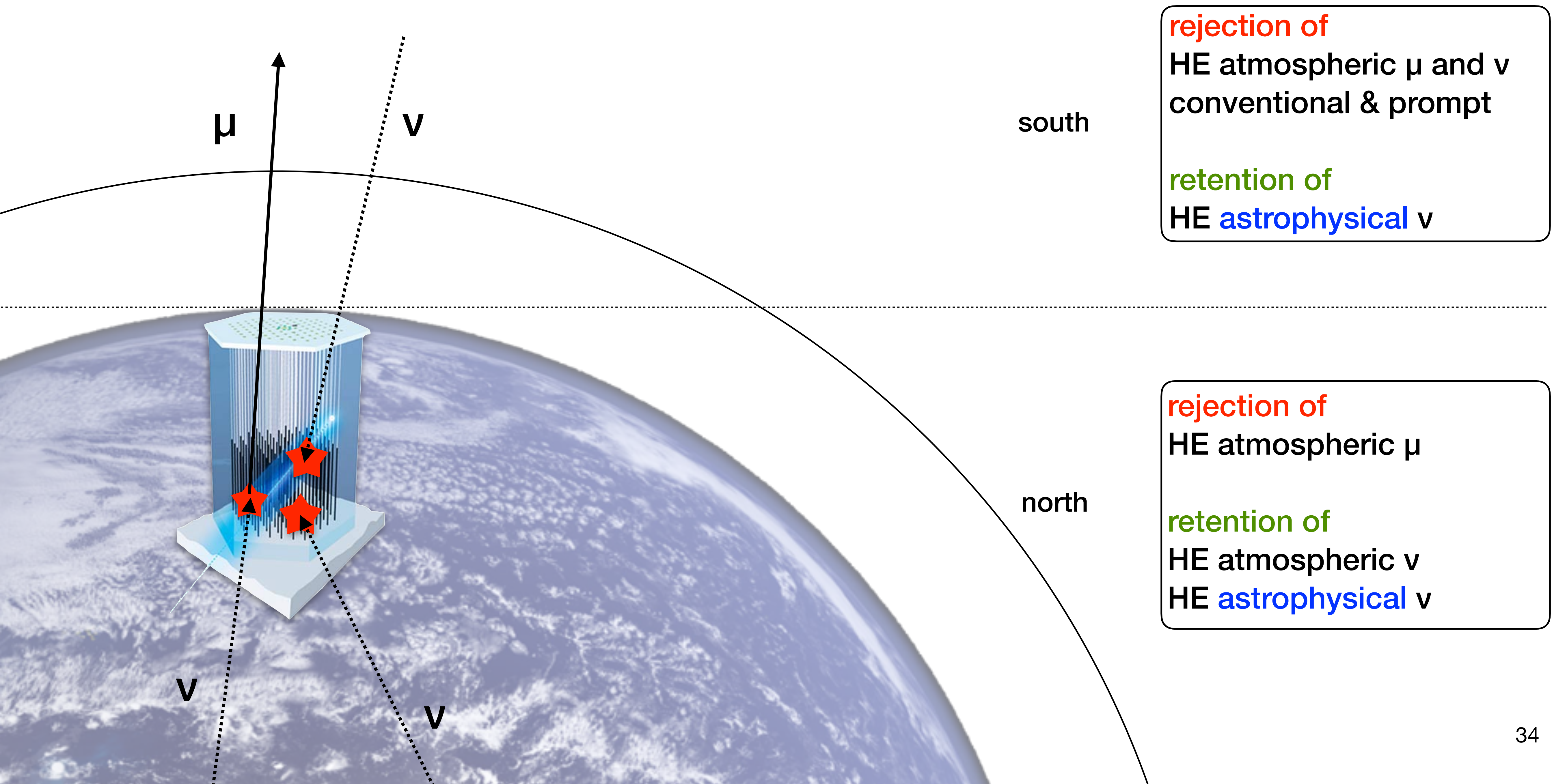




neutrino identification
diffuse flux

veto efficiency increases with energy

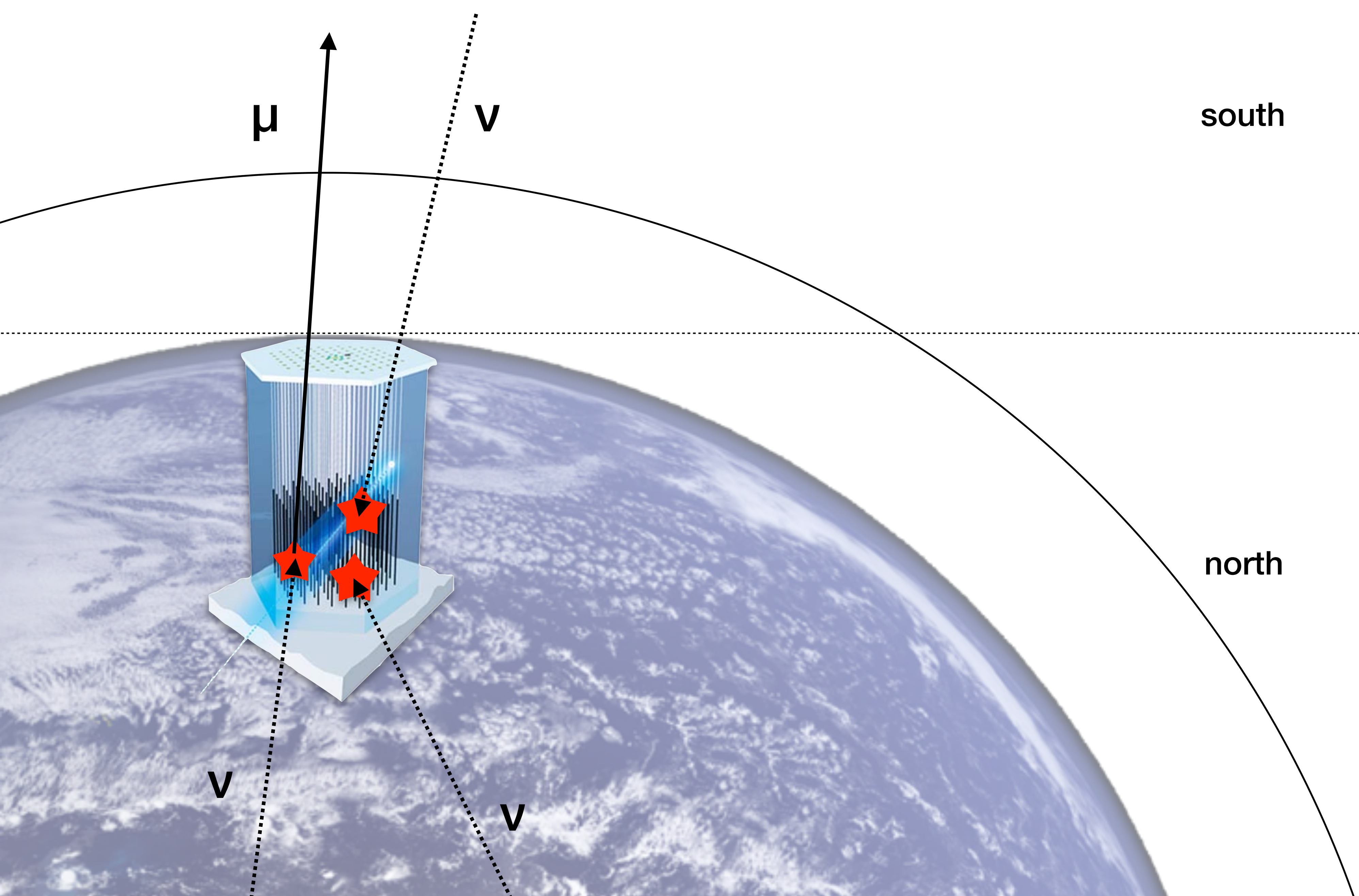
a window to **high energy astrophysical neutrino discovery**



neutrino identification
astrophysical neutrinos

veto efficiency increases with energy

a window to **high energy astrophysical neutrino discovery**



rejection of
HE atmospheric μ and ν
conventional & prompt

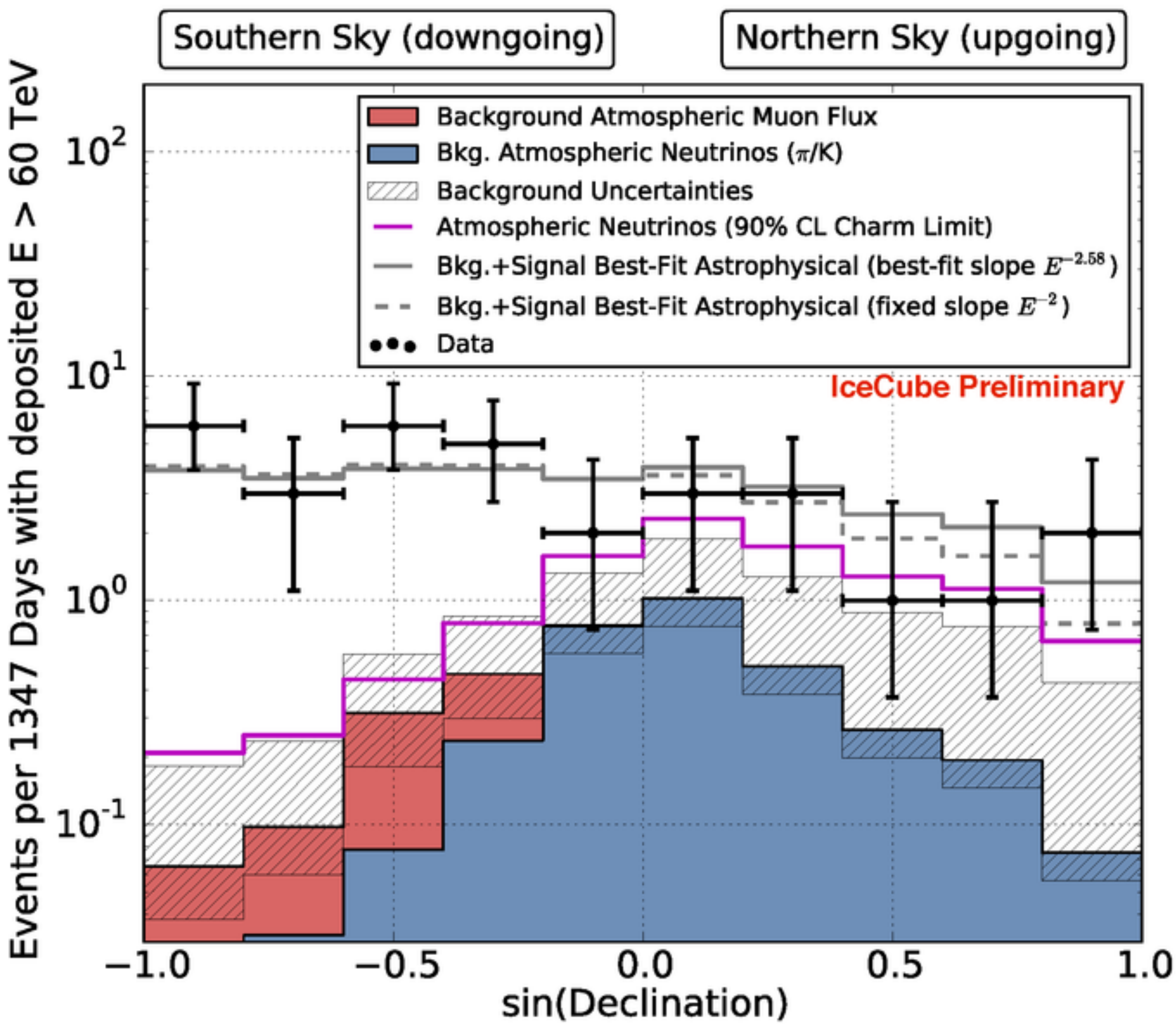
retention of
HE astrophysical ν

rejection of
HE atmospheric μ

retention of
HE atmospheric ν
HE astrophysical ν

neutrino identification
astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV



south

rejection of
HE atmospheric μ and ν
conventional & prompt

retention of
HE astrophysical ν

north

rejection of
HE atmospheric μ

retention of
HE atmospheric ν
HE astrophysical ν

neutrino identification

astrophysical neutrinos

- 53(+1) events found
- estimated background

  $9.0^{+8.0}_{-2.2}$ atm. neutrinos

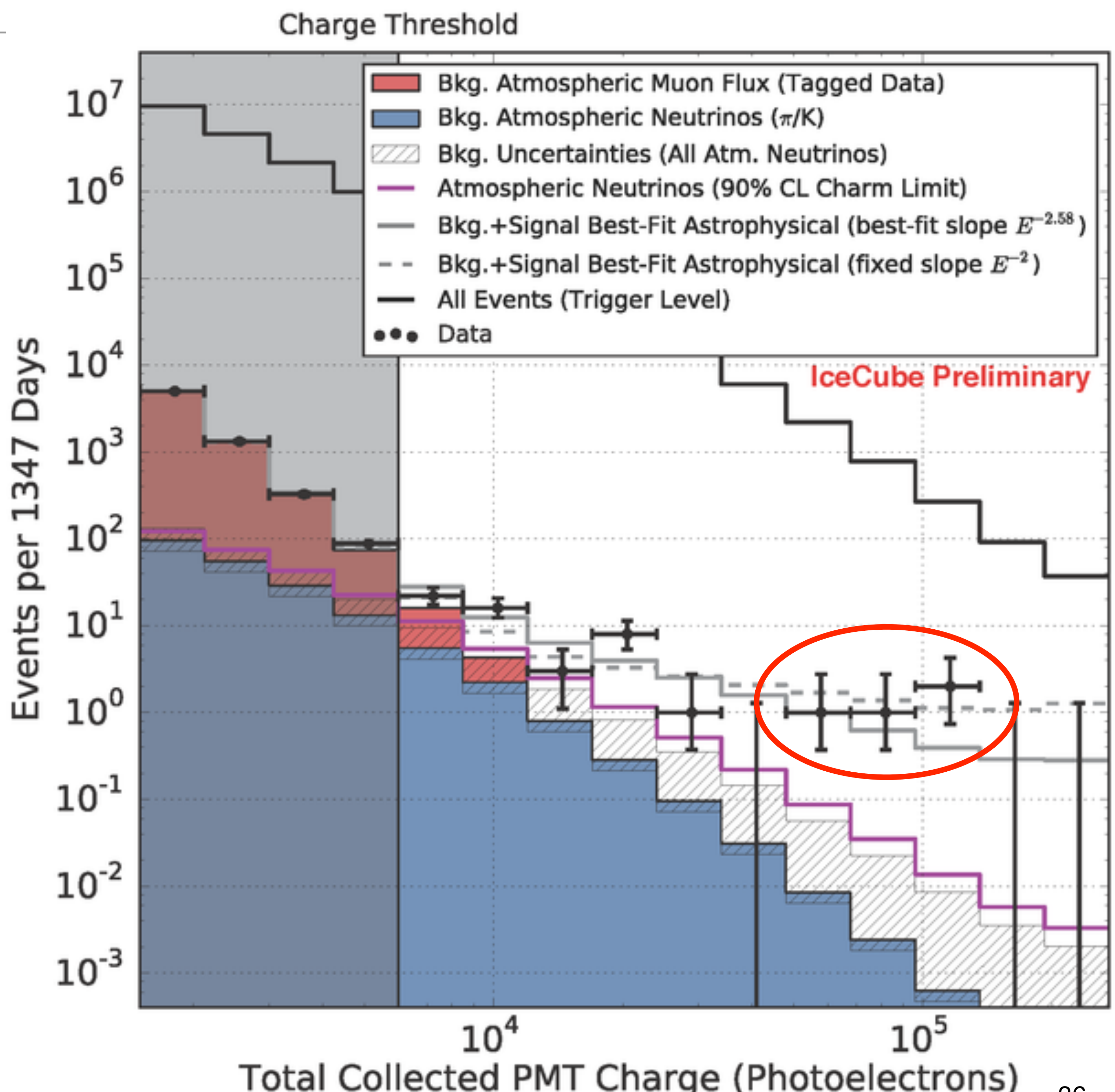
  12.6±5.1 atm. muons

  1 atm. muon passing veto

  coincident CR showers

  6.7 σ significance

4 years of HE starting events
E_ν > 60 TeV



Aartsen et al. PRD 88 (2013) 112008
Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. PRL 113 (2014) 101101

neutrino identification
astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV

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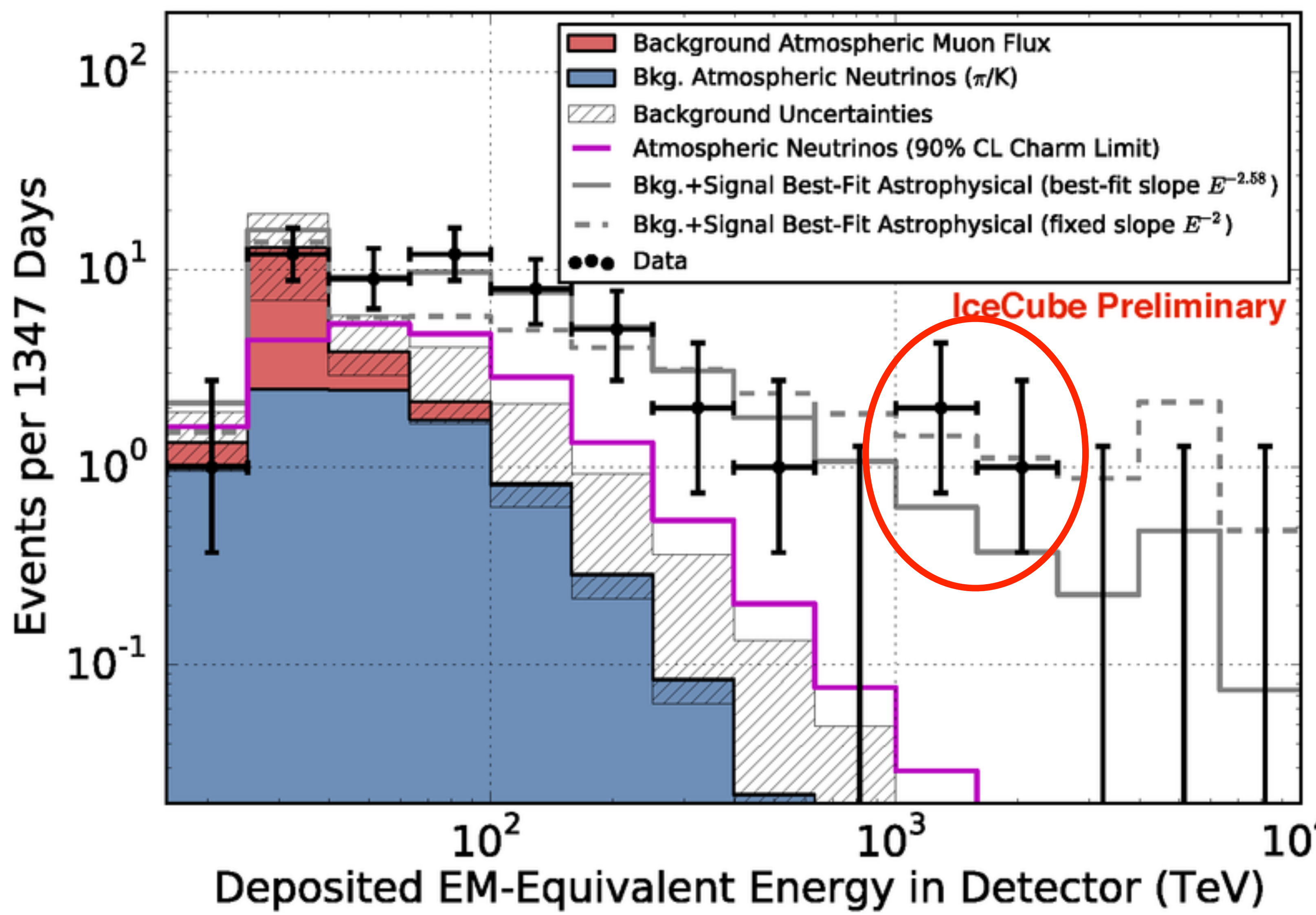

Aartsen et al. PRD 88 (2013) 112008
Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. PRL 113 (2014) 101101

neutrino identification
astrophysical neutrinos

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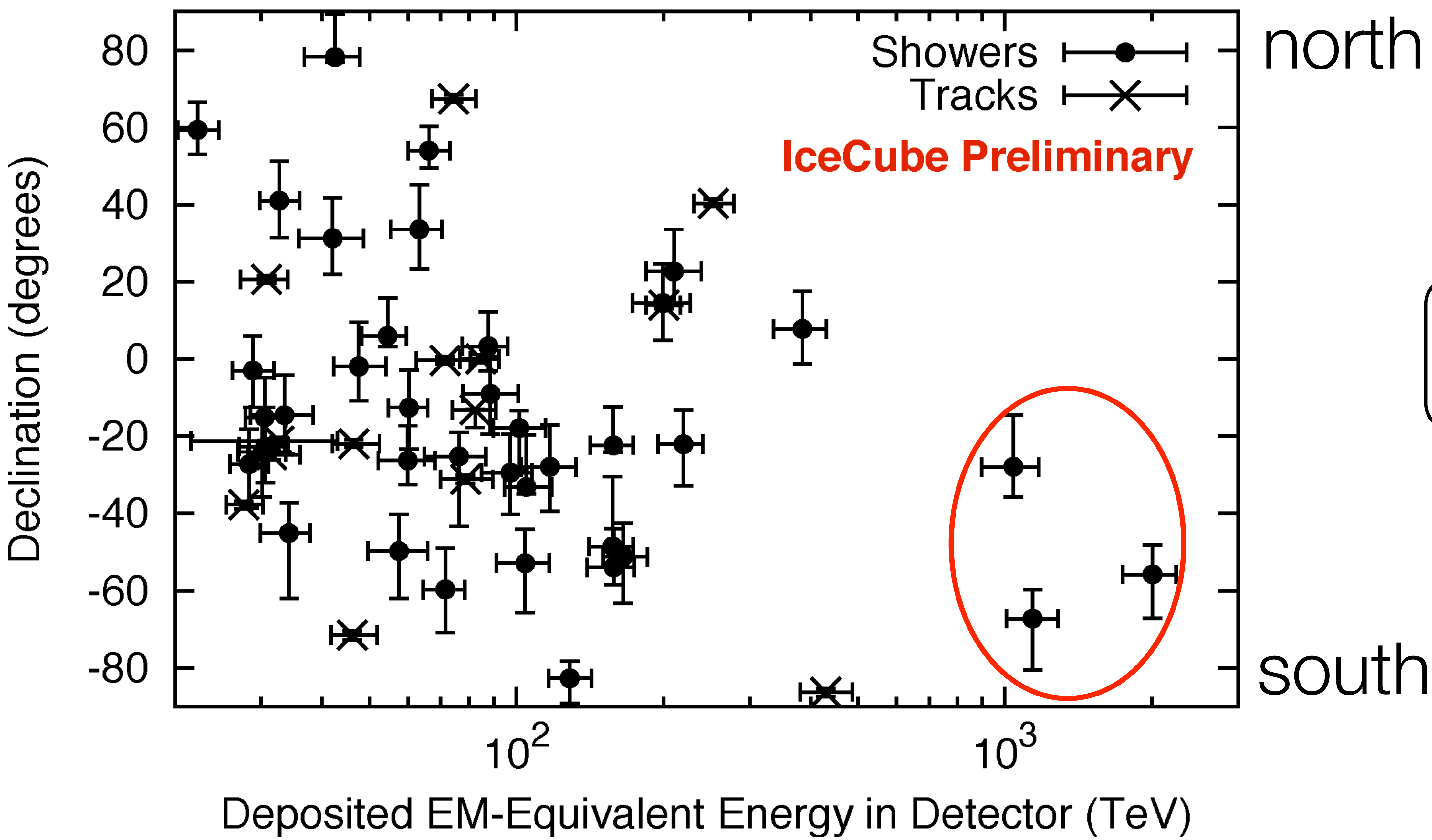
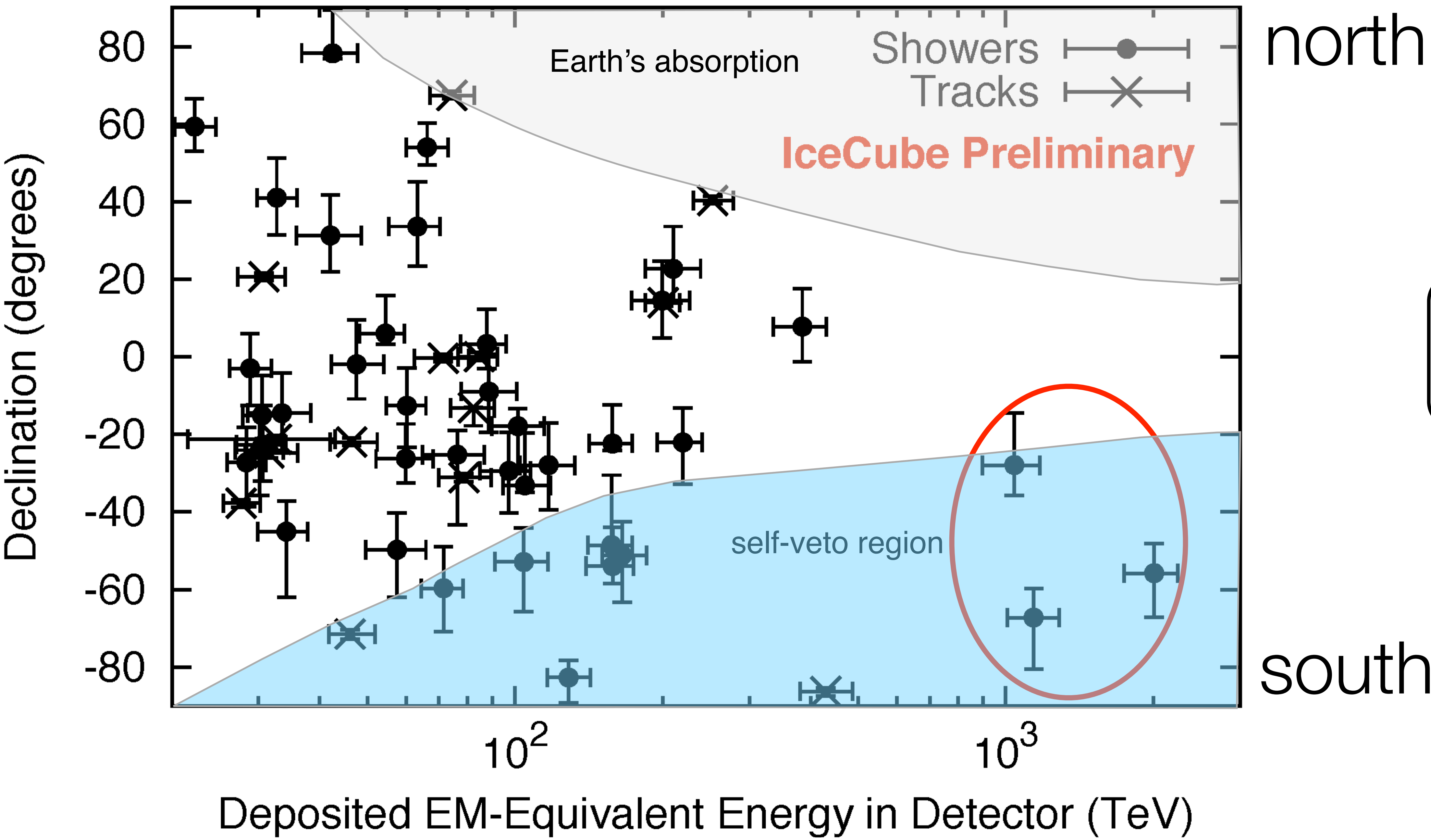


14 tracks
40 cascades

neutrino identification
astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV



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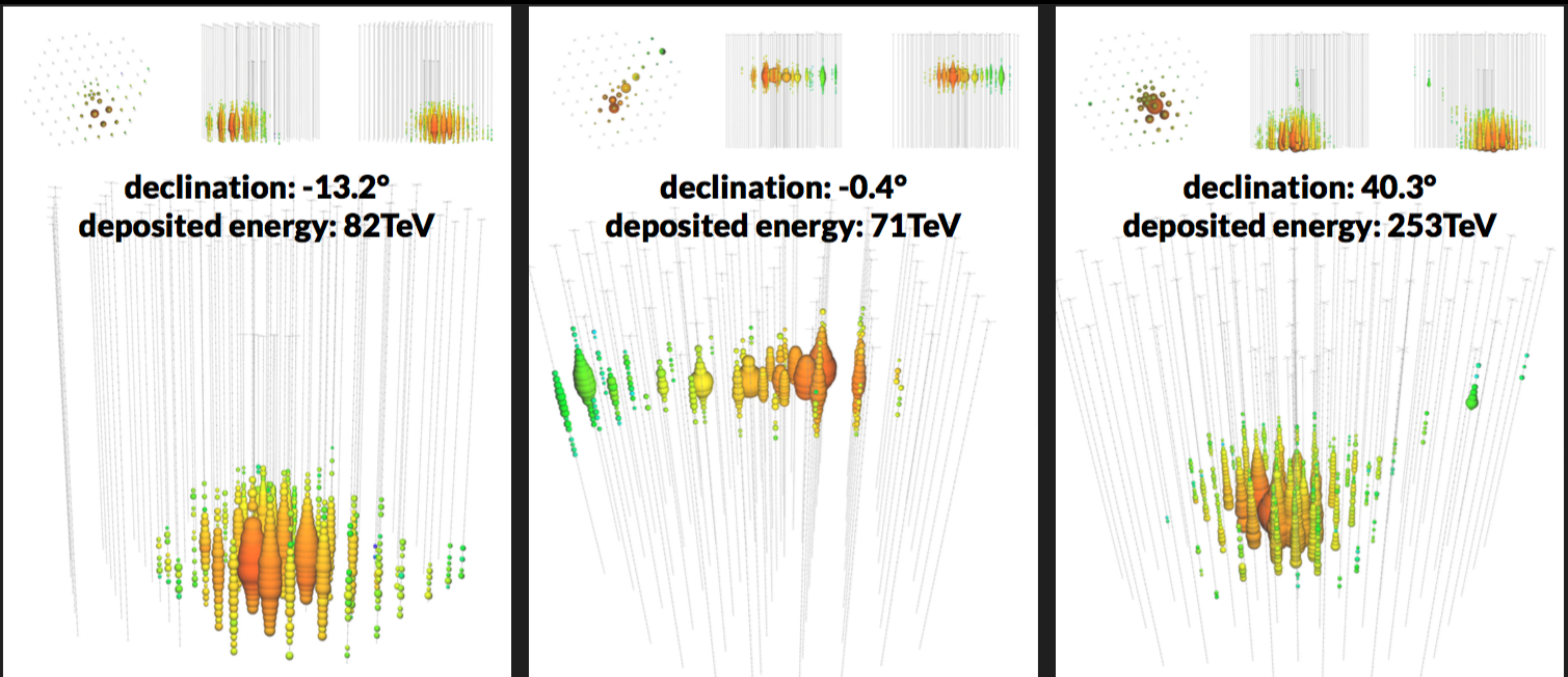


neutrino identification

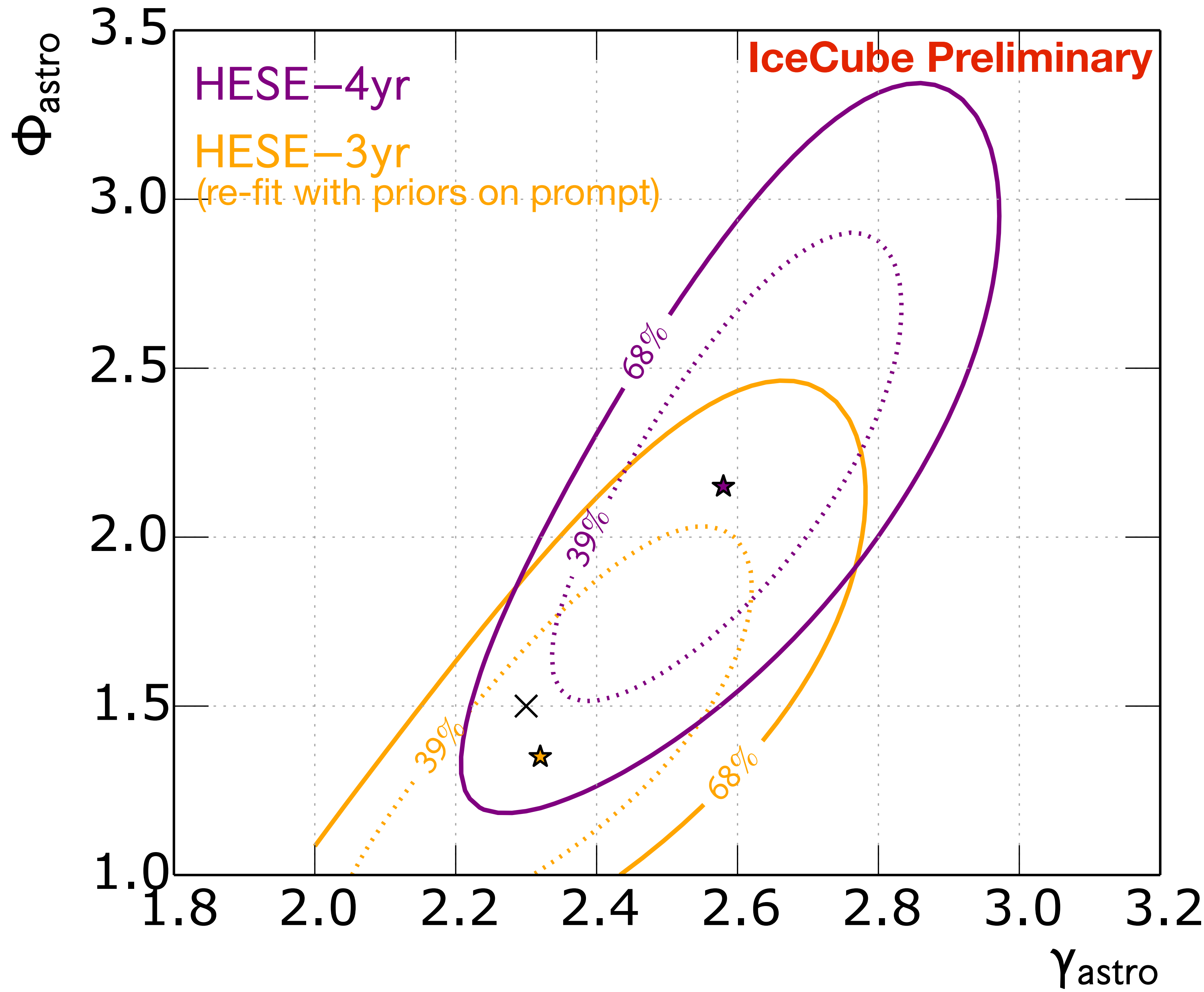
astrophysical neutrinos

4 years of HE starting events
E_ν > 60 TeV

- **likelihood fit** with priors for atmospheric conventional and prompt ν flux
- atmospheric flux assumed to be determined in **shape**
- best fit ***softer*** than $\mathbf{E^{-2}}$

a problem ?

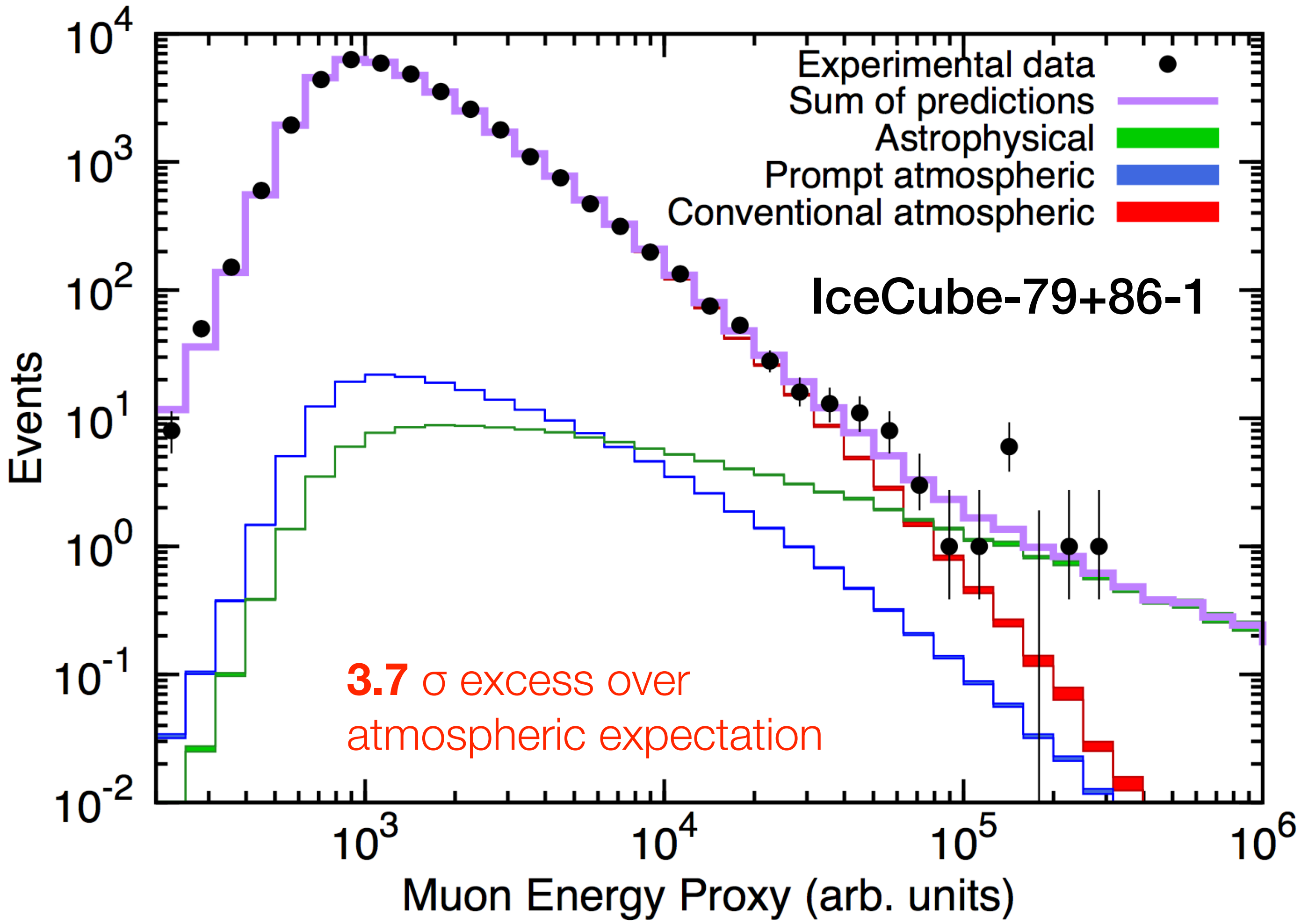
- prompt atmospheric component fit = 0

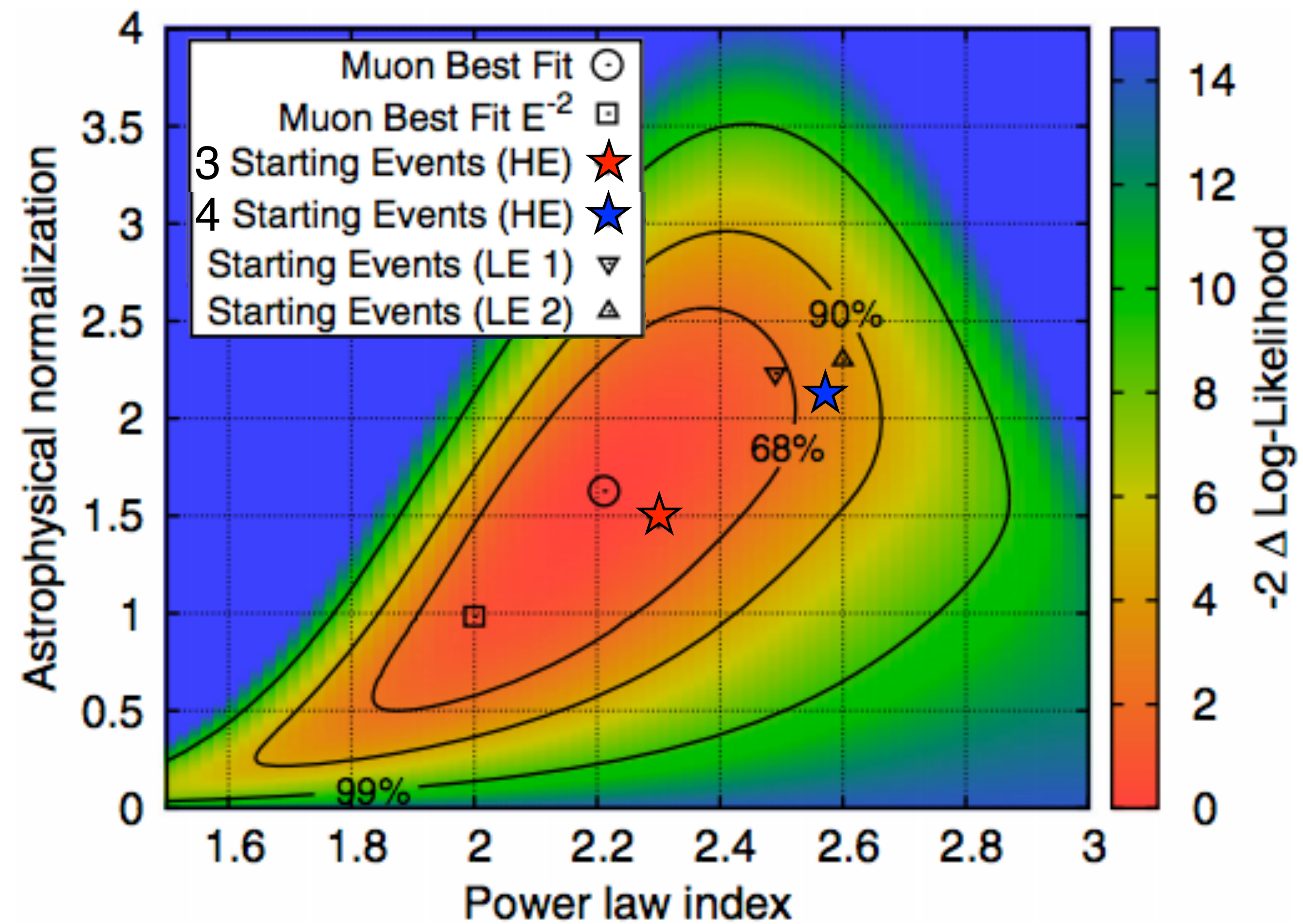


neutrino identification

astrophysical neutrinos

Aartsen et al. Phys.Rev.Lett. 115 (2015) 8, 081102





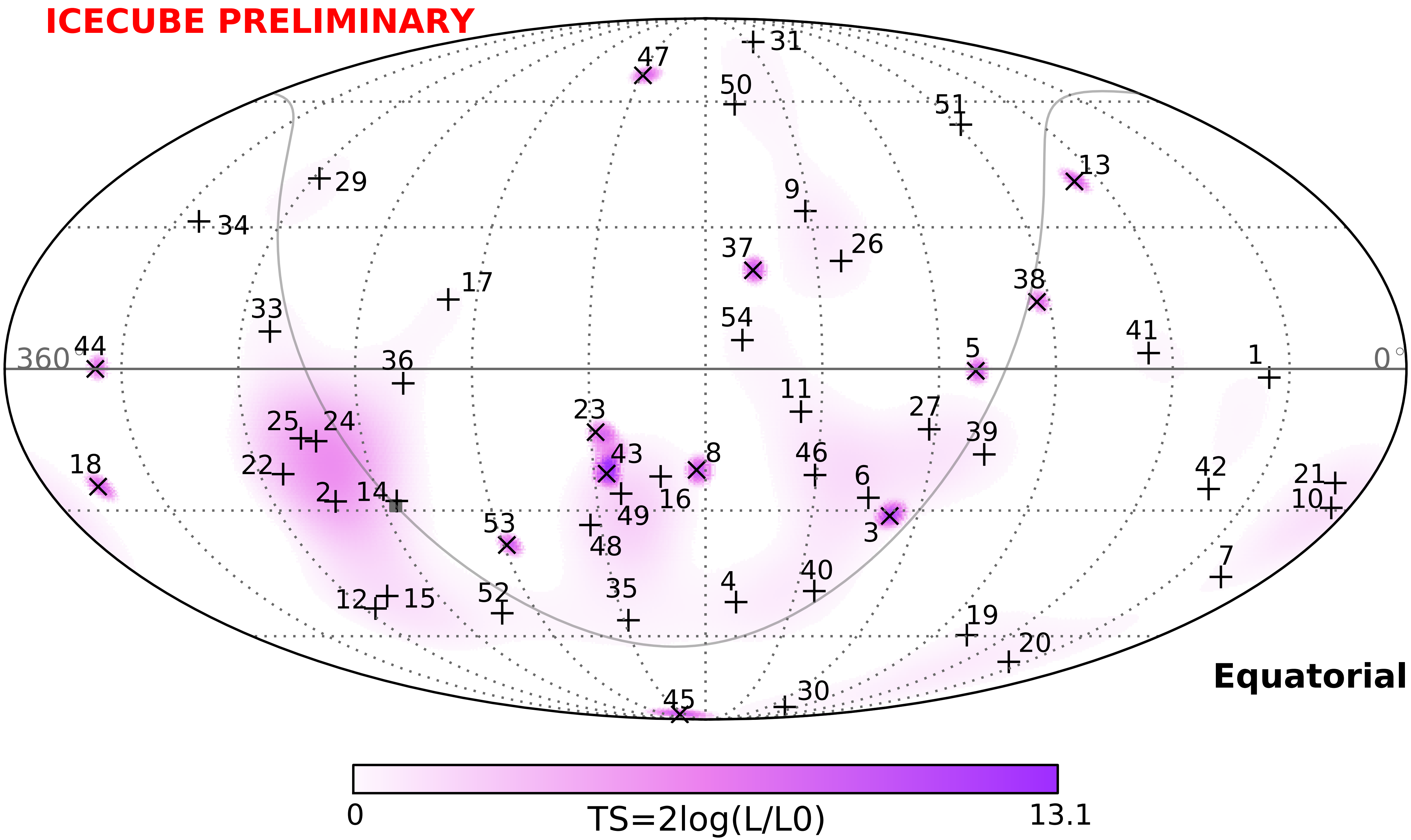
- up-going ν_μ events and HE starting events consistent within uncertainties
- **role of prompt neutrinos ?** Need more events

neutrino identification

point sources ?

4 years of HE starting events
E_ν > 60 TeV

58% (post-trial) for all event clustering
44% (post-trial) for cascade-like event clustering

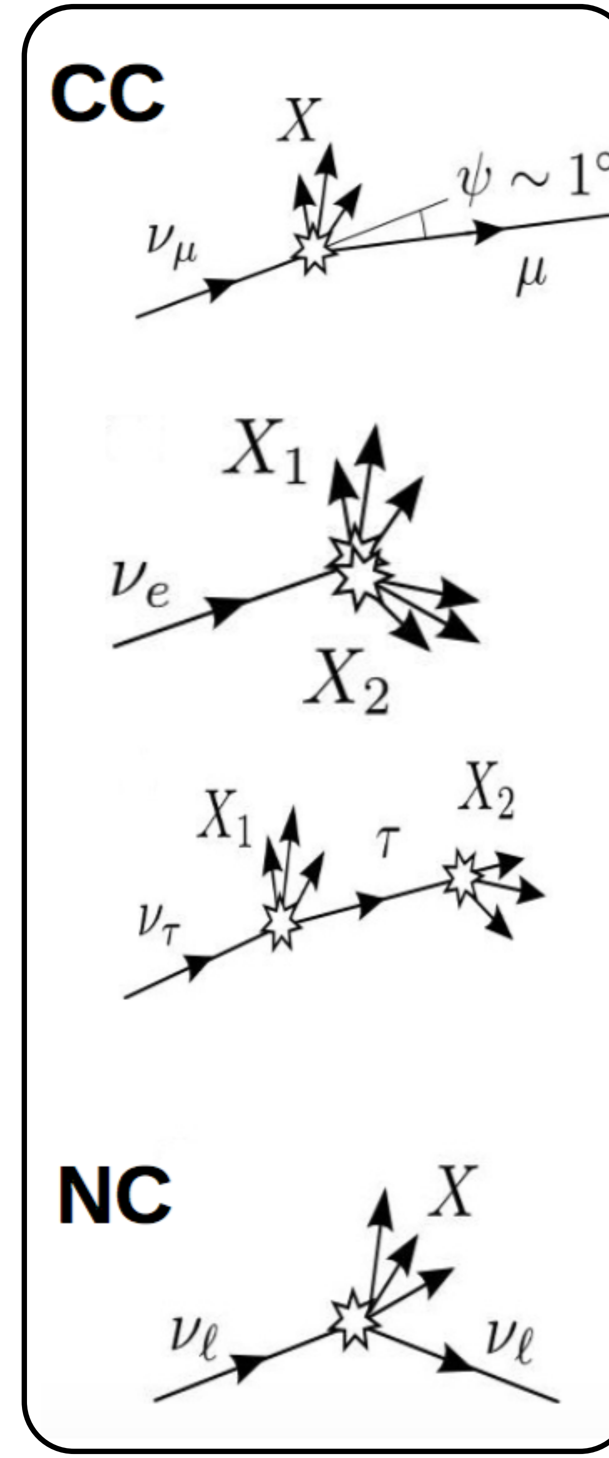


neutrino identification
flavor sensitivity

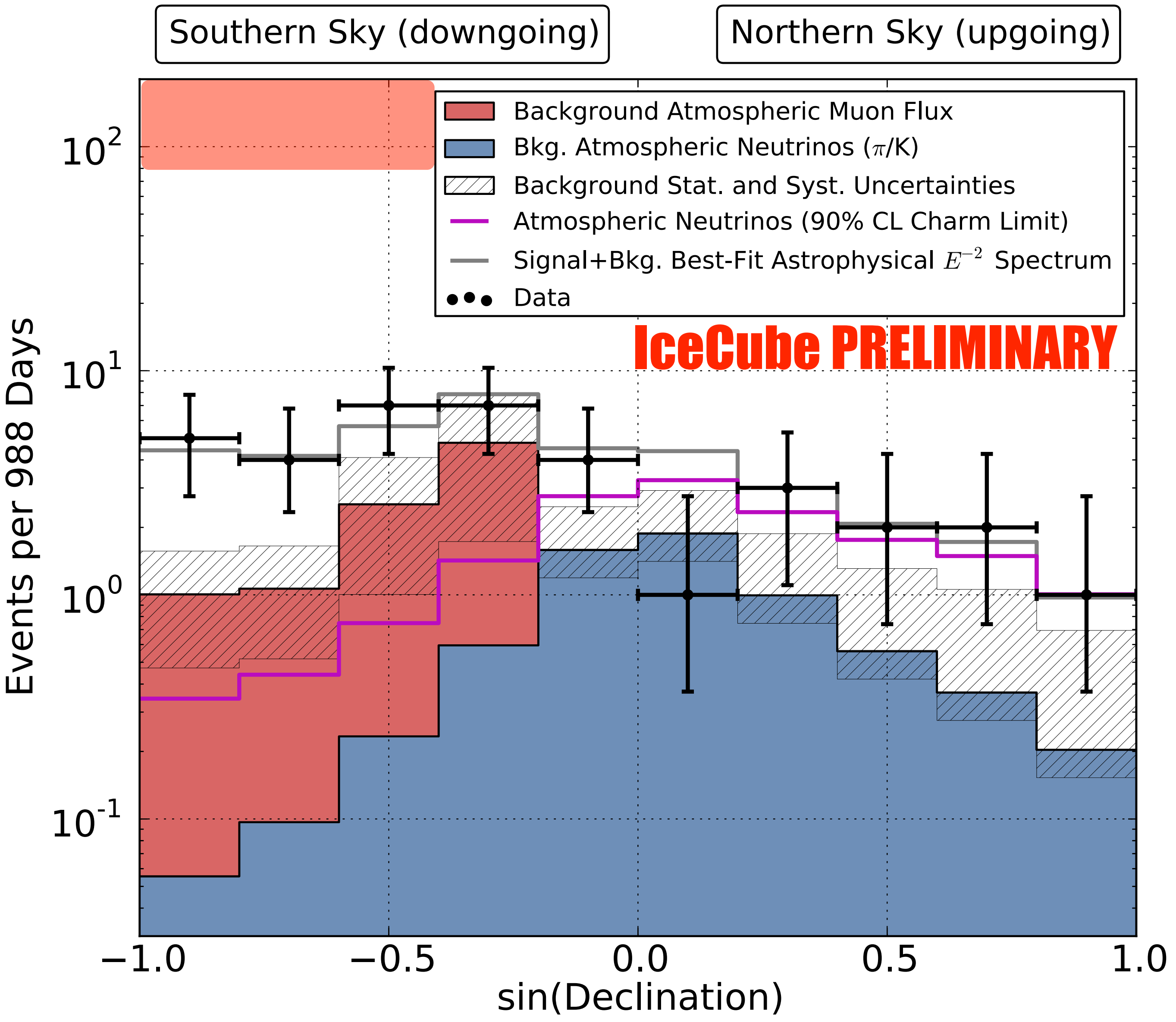
TOO FEW TRACK-LIKE EVENTS ?

- track-like & cascade-like is an **experimental** definition
- in all-flavor searches track-like events are not common
- all flavors look alike in NC interactions
- μ in CC interactions may be concealed in showers
- τ have short tracks except above PeV energies

- flavor identification requires simulation data



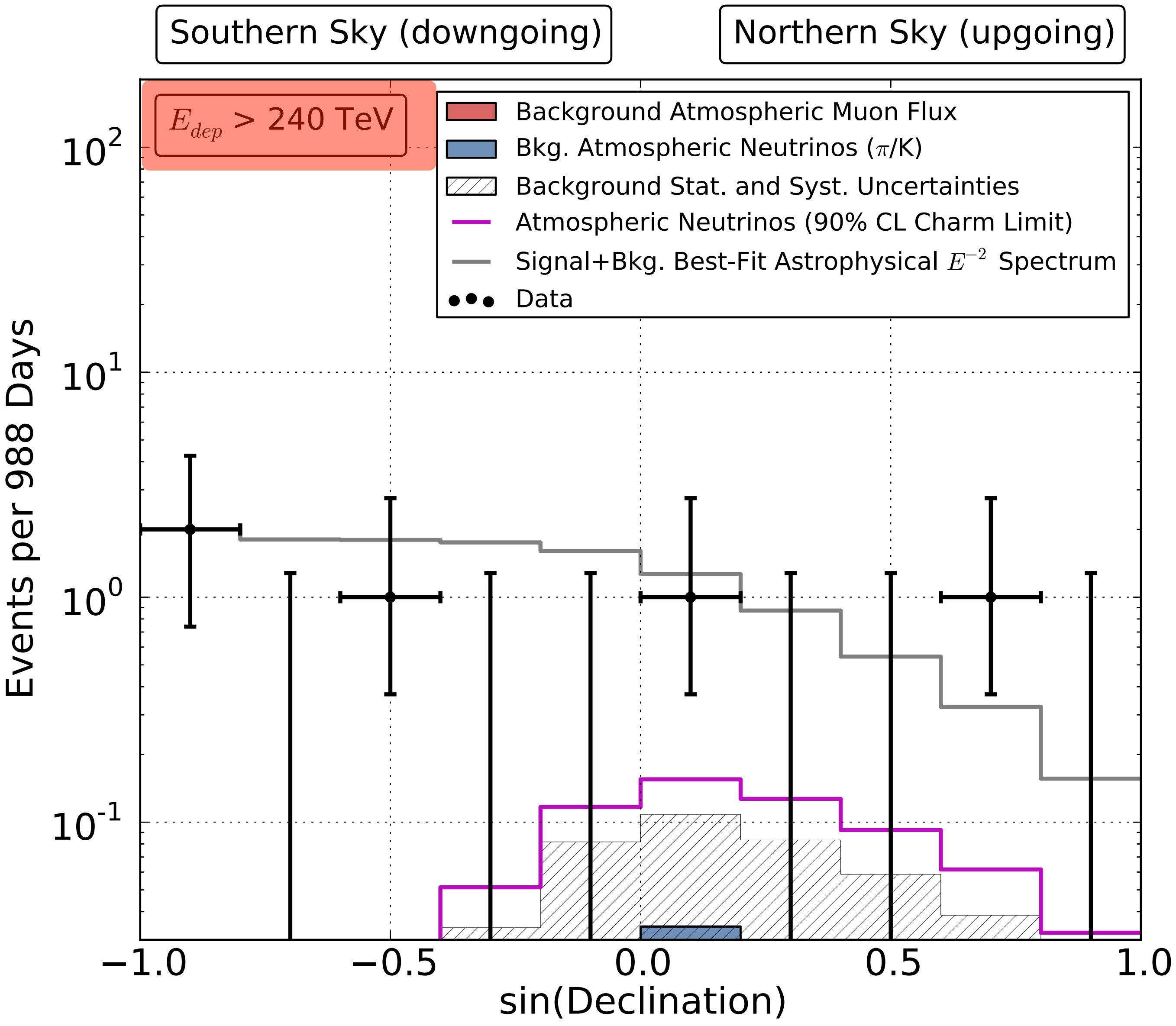
Thank You



Next:

- Cosmic Ray Observations
- Spectrum, Composition & Anisotropy
- Atmospheric Muons

THANK YOU



NEXT:

- COSMIC RAY OBSERVATIONS
- SPECTRUM, COMPOSITION & ANISOTROPY
- ATMOSPHERIC MUONS