Muons and neutrinos in IceCube

(including prompt)

Outline

1. Event types in IceCube
2. Expectations for atmospheric neutrinos
   – Including prompt neutrinos from charm
3. Astrophysical neutrinos in IceCube
4. Upper limits on prompt neutrinos in IceCube
5. Neutrino self-veto
   – Implictaions for angular distributions
6. Muons in IceCube
7. Associated production of charm?

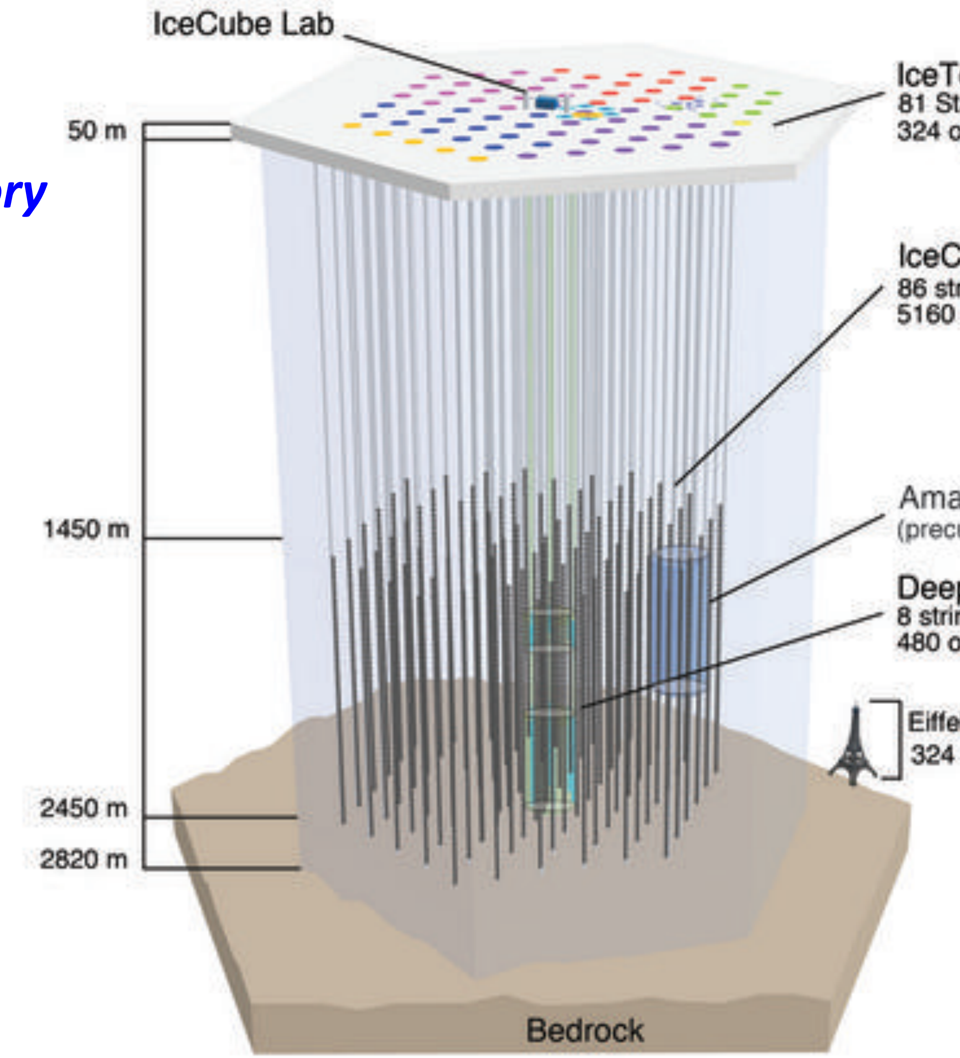
1. IceCube

Deployment history

2002: proposal
2003-04 staging
2004-05 1 4
2005-06 9 16
2006-07 22 26
2007-08 40 40
2008-09 59 59
2009-10 79 73
2010-11 86 81

Deep strings

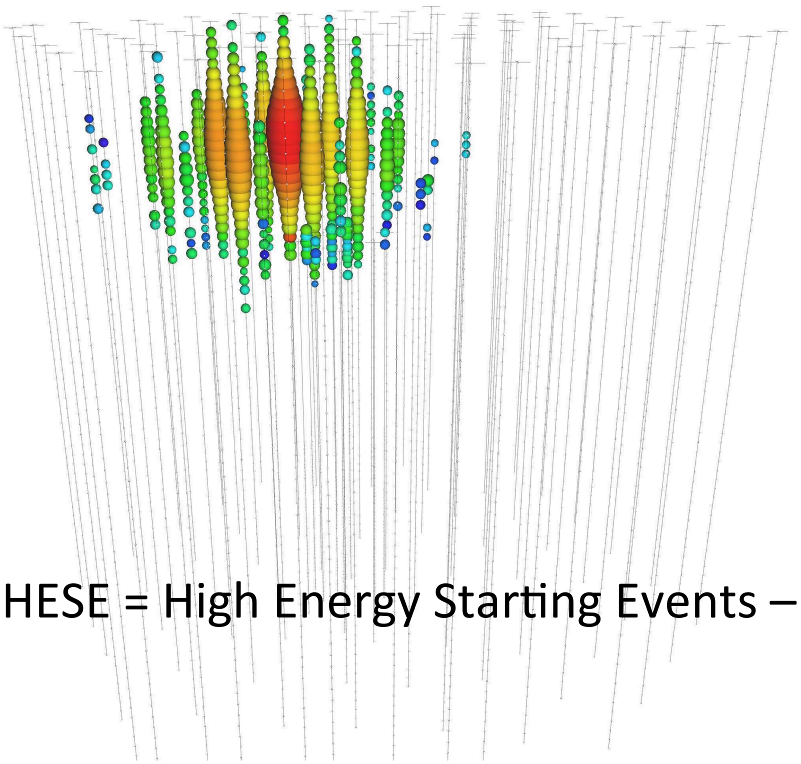
Surface stations

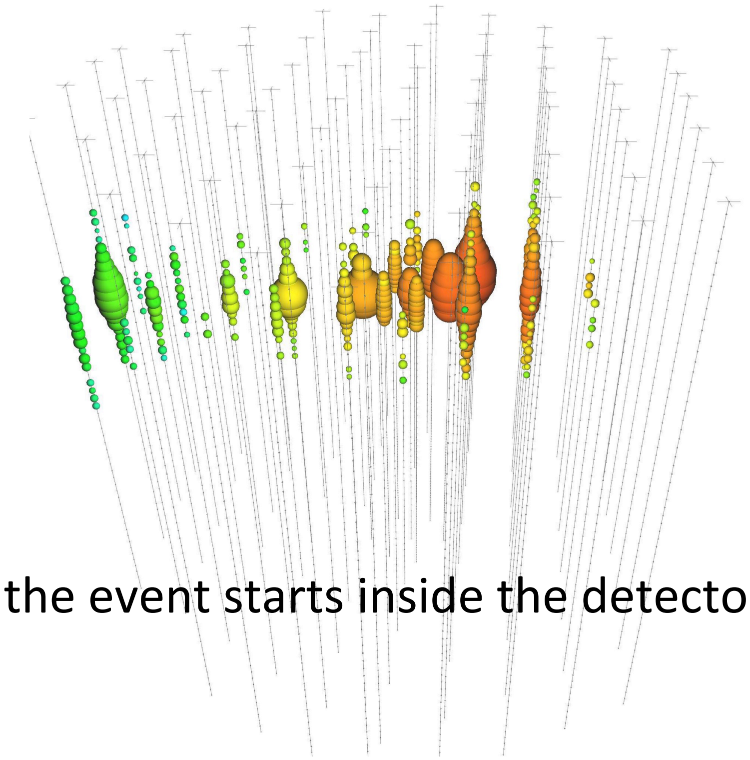


> 5400 Digital Optical Modules

IceCube Construction: 2004-2011

HESE event types in IceCube



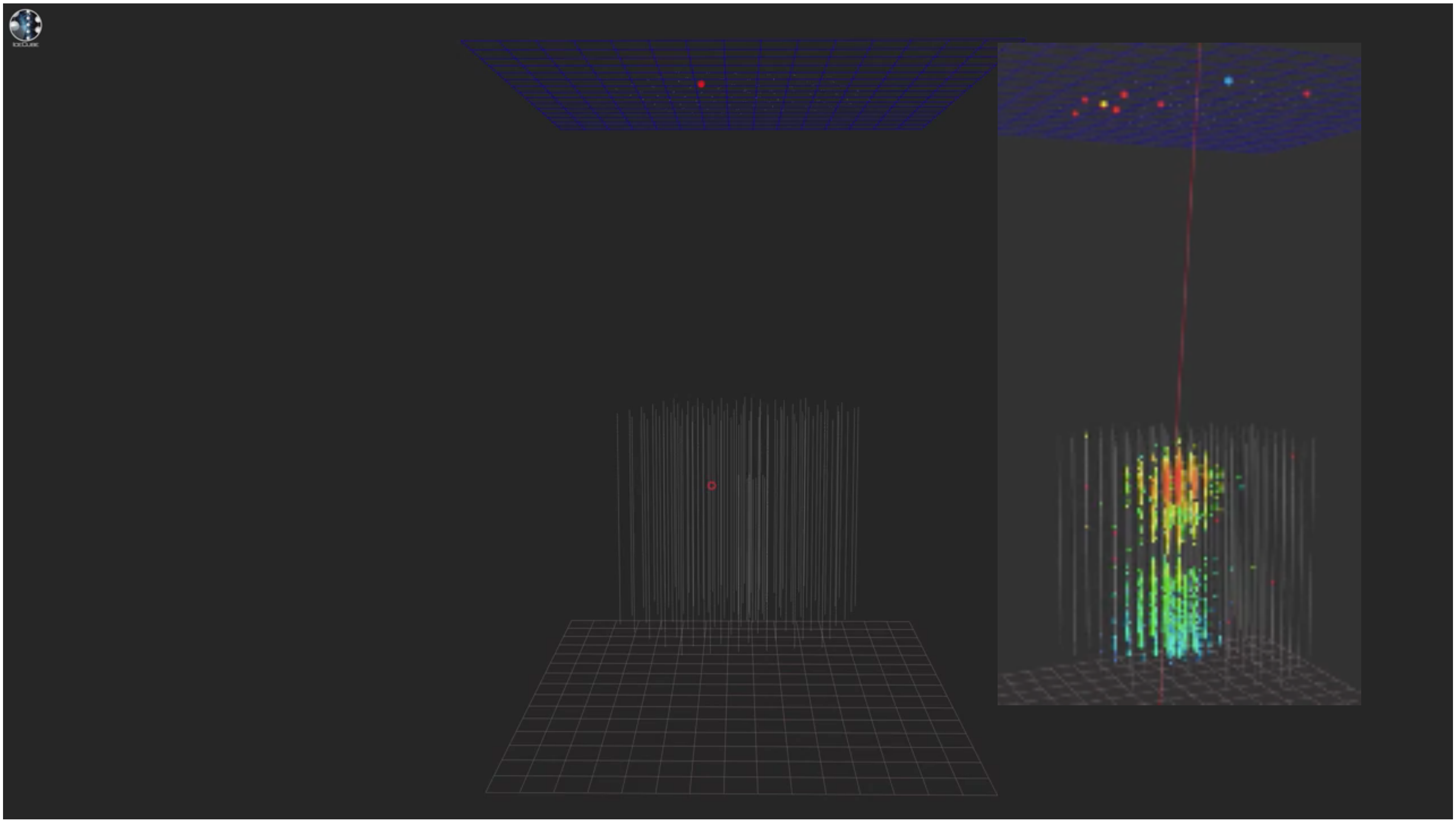


HESE = High Energy Starting Events – the event starts inside the detector

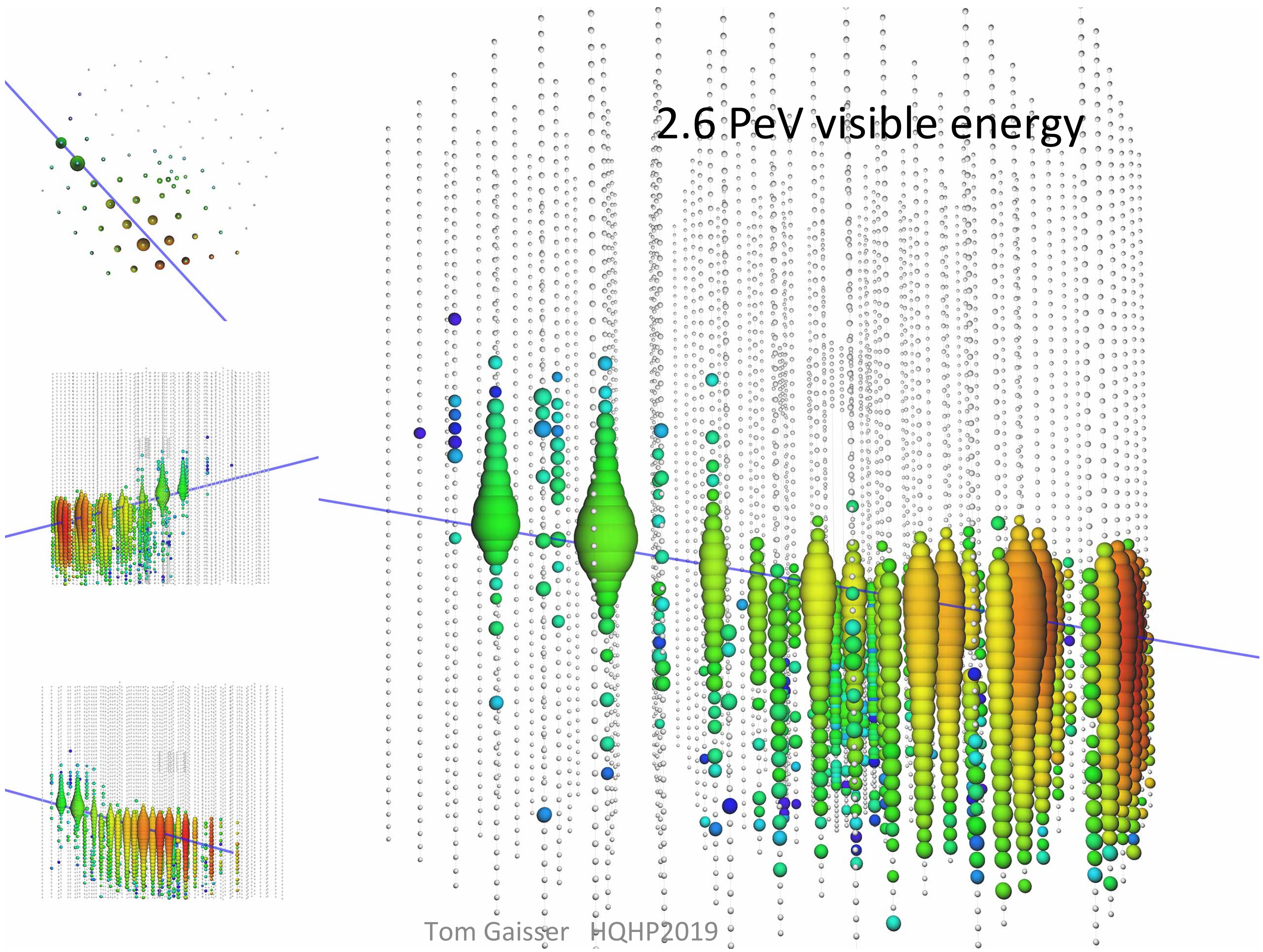
Cascade events:
CC interactions of ν_e and ν_τ
NC interactions of all flavors

Starting track: CC ν_μ
Note initial hadronic cascade

HESE Event #45 (430 TeV)



The largest upward ν_μ induced μ

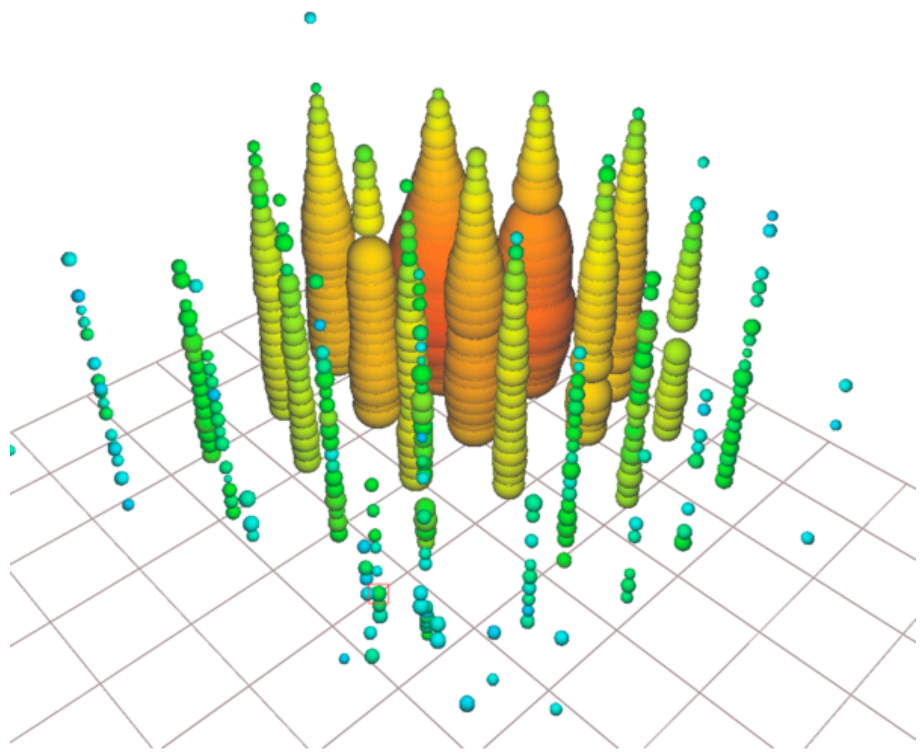


Glashow event candidate in IceCube

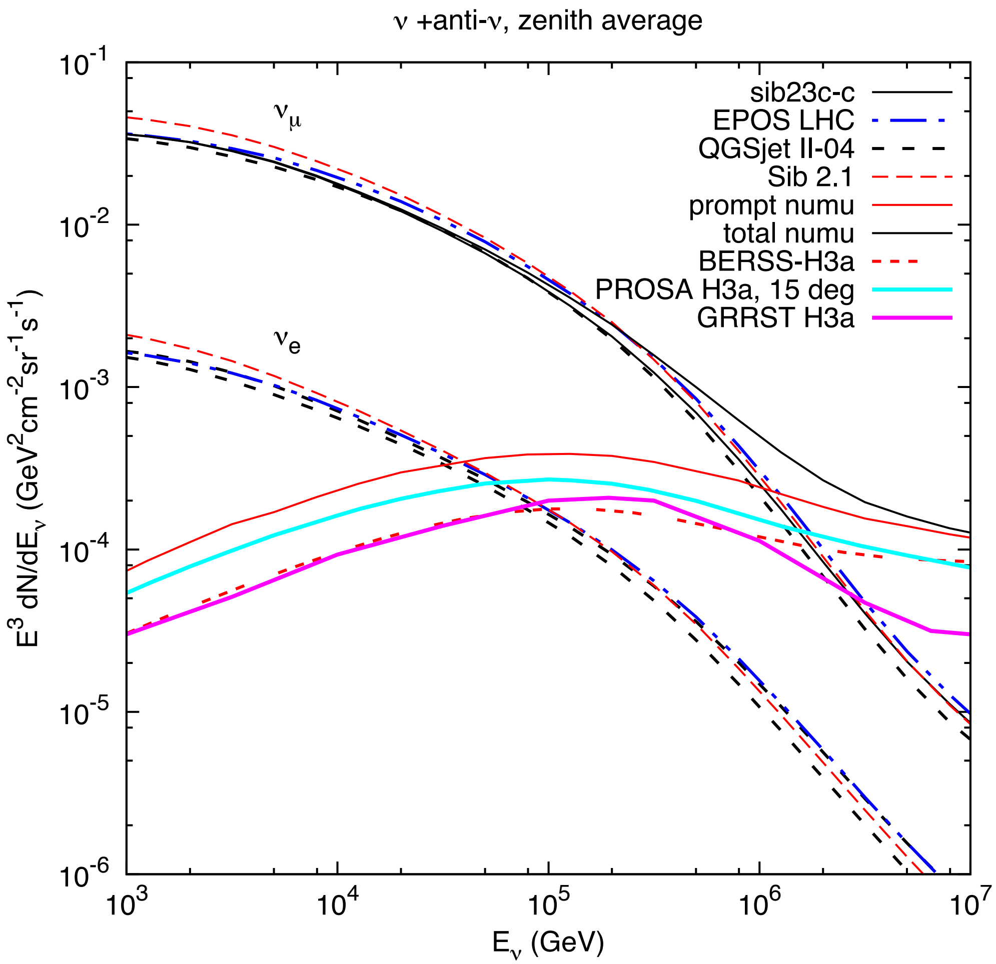
$$\overline{\nu}_e + e^- \rightarrow W^- \rightarrow \text{cascade}$$

- Discovered in a study of partially contained large cascades
- Visible energy consistent with the 6.3 PeV resonance energy
- PoS(ICRC2019)945

  Lu Lu for IceCube



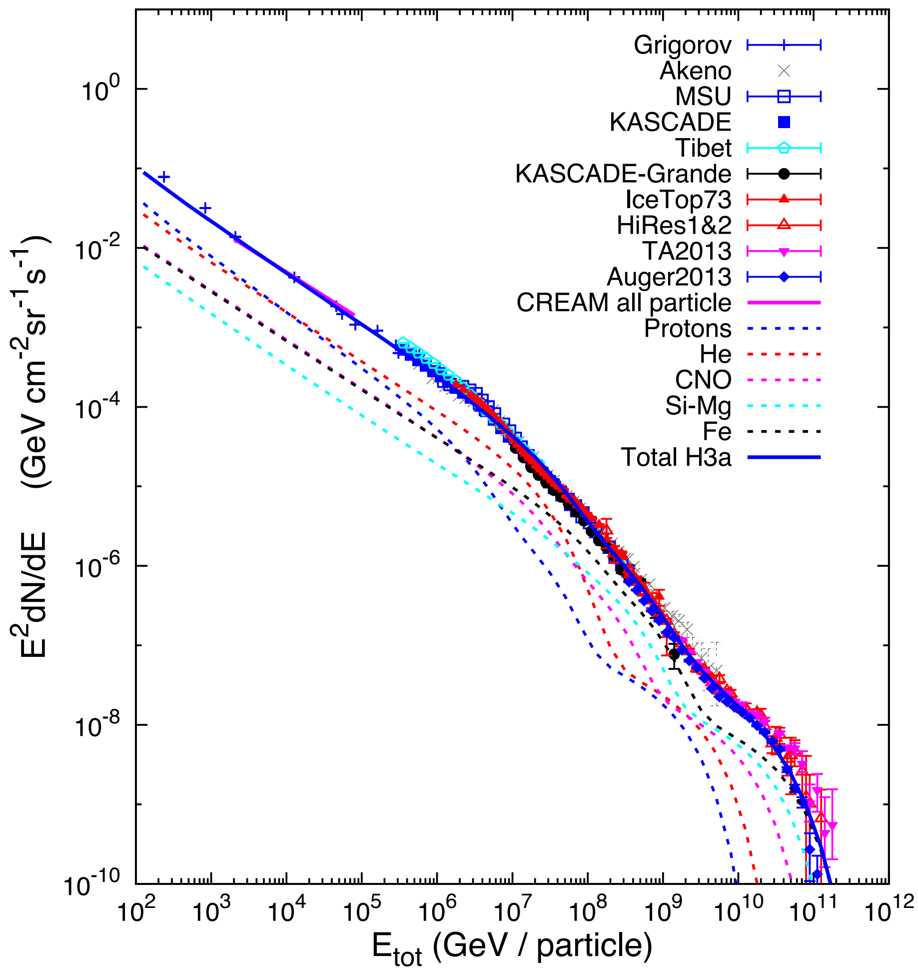
2. Atmospheric neutrinos



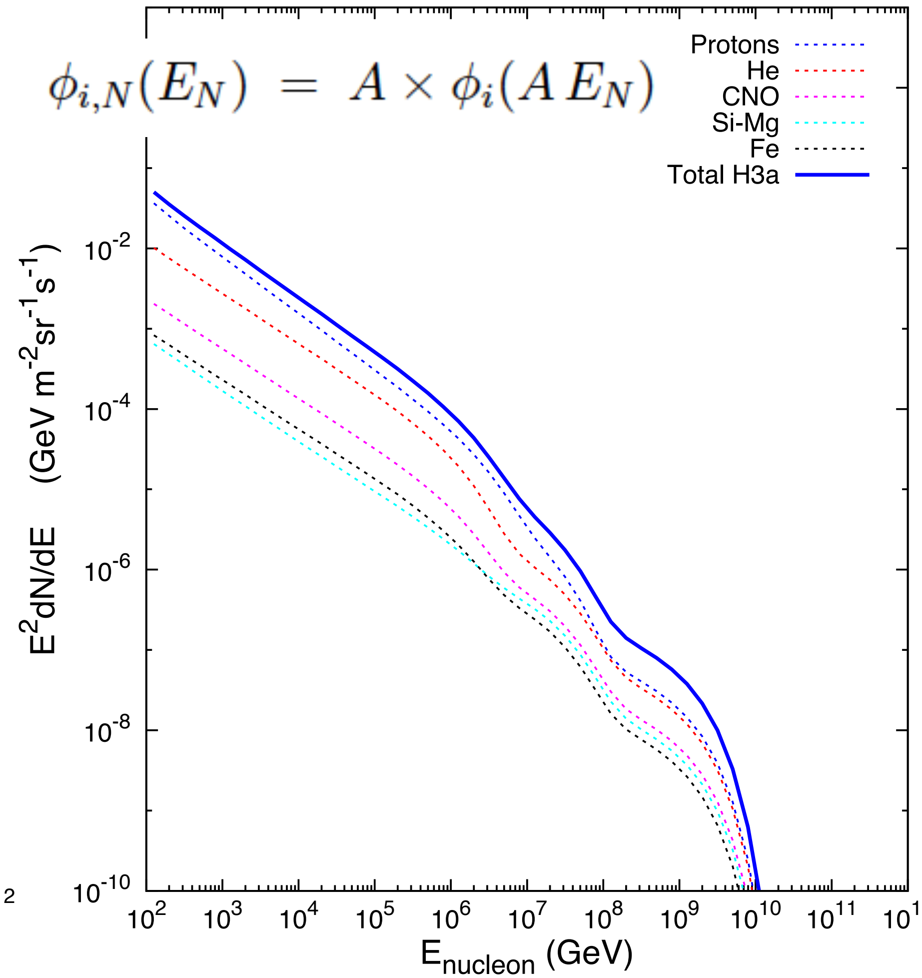
All-particle spectrum to nucleon spectrum

$$\phi_i(E) \equiv E\frac{\mathrm{d}N_i}{\mathrm{d}E} = \Sigma_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

All-particle spectrum



Spectrum of nucleons



Unified approach to calculating $\phi_\nu(E_\nu)$

- Use simple equations $A_{i\nu} = \dfrac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}}$

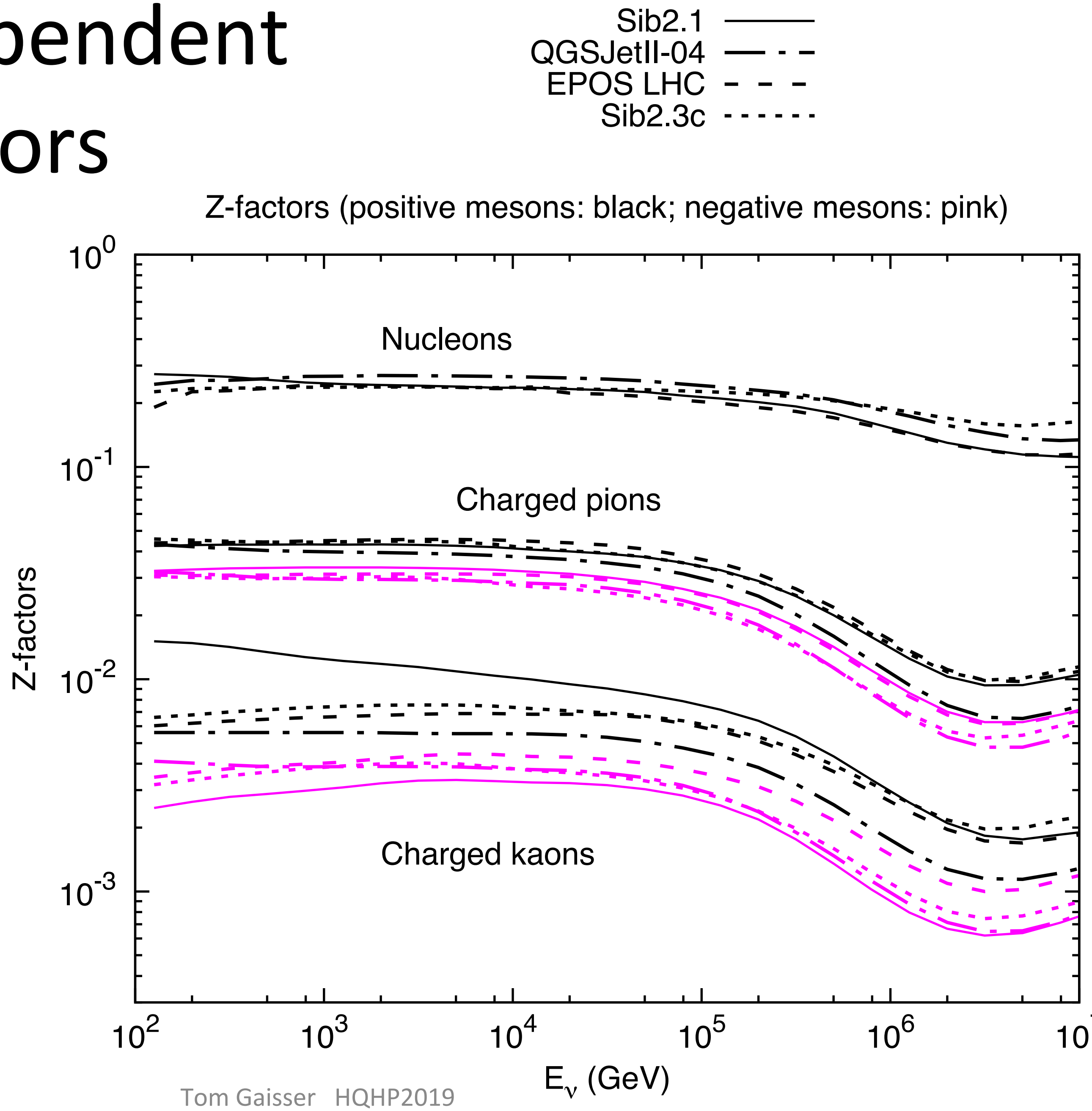
$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \Sigma_{i=1,3}\left(\frac{A_{i\nu}}{1 + B_{i\nu}\cos^*\theta\, E_\nu/\epsilon_i}\right)$$

- With energy-dependent Z-factors

$$Z_{i,j}(E) = \int_E^\infty \mathrm{d}E' \,\frac{\phi_N(E')}{\phi_N(E)}\,\frac{\mathrm{d}n_{i,j}(E', E)}{\mathrm{d}E}$$

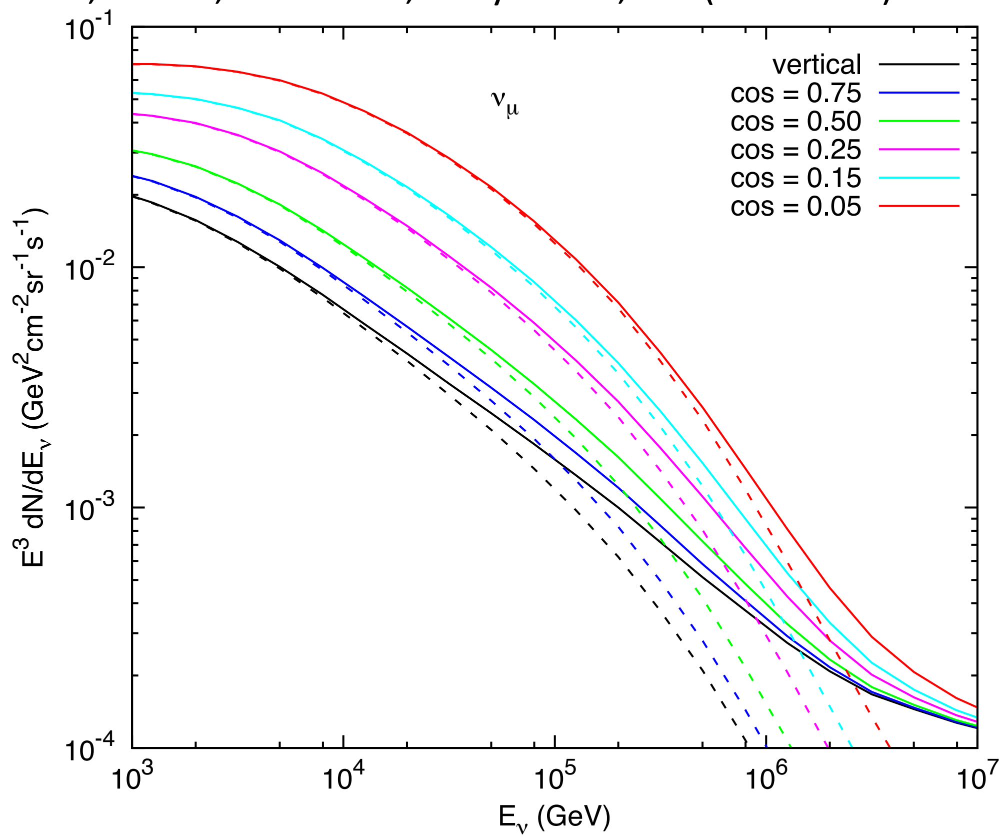
- Allows systematic evaluation of
  - Different primary spectrum/composition models
  - Uncertainties in hadronic interactions

Energy-dependent Z-factors



Atmospheric ν_μ

Fig. : TG, Soldin, Crossman, Fedynnitch, PoS(ICRC2019)893

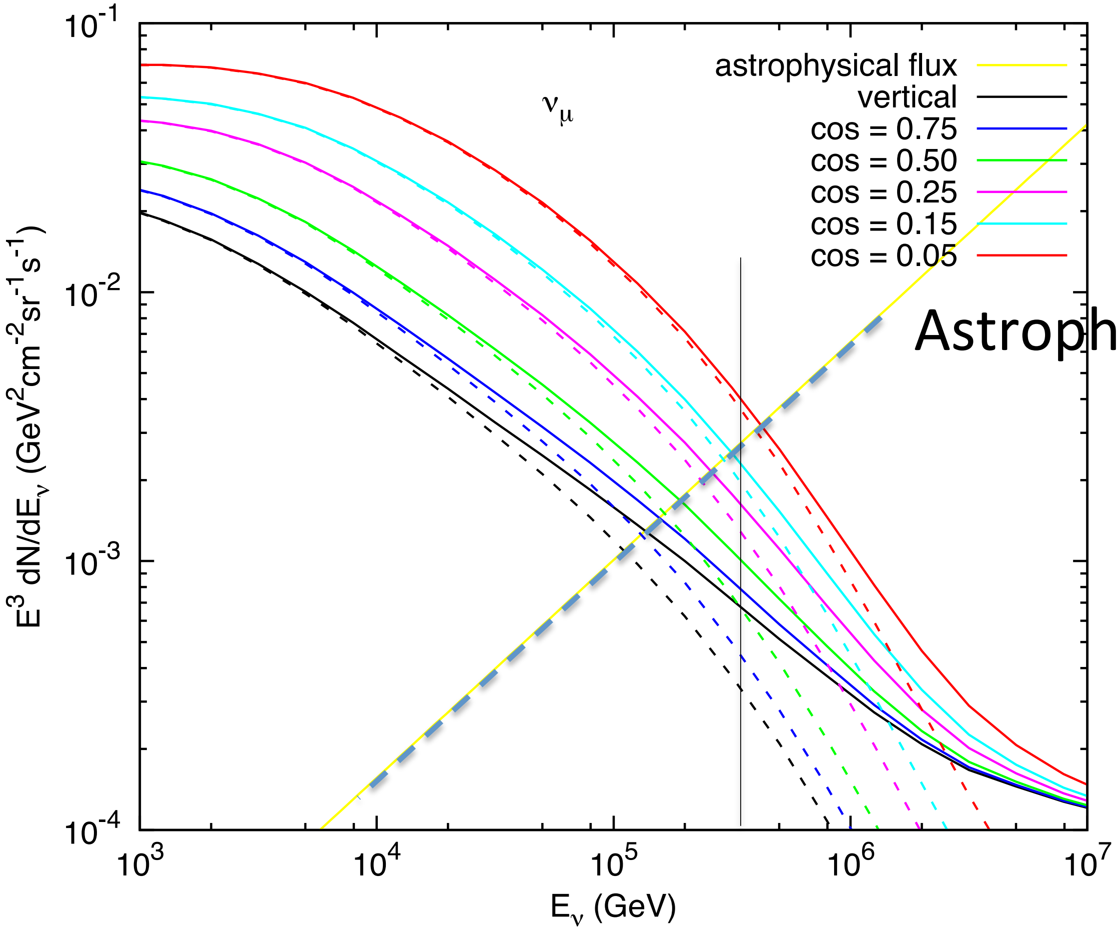


- Flux increases near the horizontal
  - Decay of parent $K^\pm$, $\pi^\pm$ more likely
  - Most ν_μ are from $K^\pm$
- Prompt ν from charm dominate at high E:
  - above 100 TeV for vertical and
  - PeV for horizontal

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \sim \sum_{i=1,3} \frac{\mathcal{A}_{i\nu}}{1+\mathcal{B}_{i\nu}\cos\theta E_\nu/\epsilon_i(T)}$$

$$\epsilon_{\pi^\pm} = 115\,\mathrm{GeV}$$
$$\epsilon_{K^\pm} = 857\,\mathrm{GeV}$$
$$\epsilon_{D^\pm} = 37\,\mathrm{PeV}$$
$$\text{for } T = 220^\circ K$$

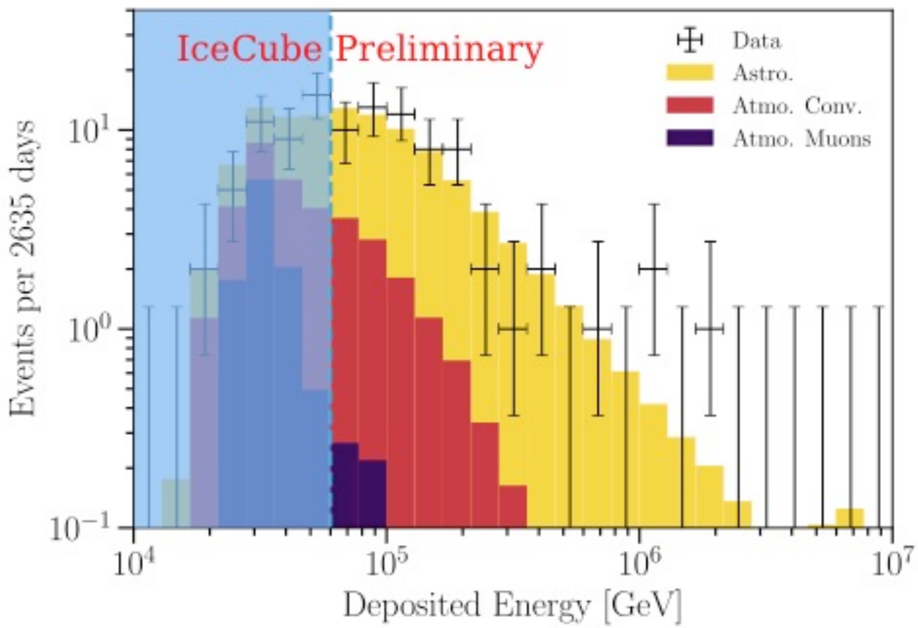
170922A – TXS 0506+056 "signalness"

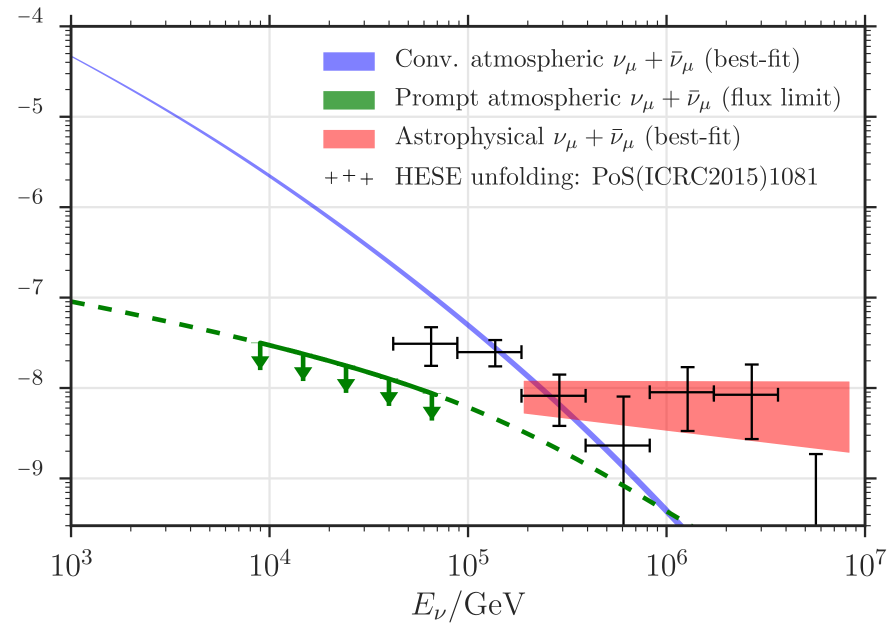


Astrophysical flux ~ $E^{-2.2}$

$E_\nu \approx 300$ TeV, $\cos\theta \approx -0.1$

3. Astrophysical neutrinos





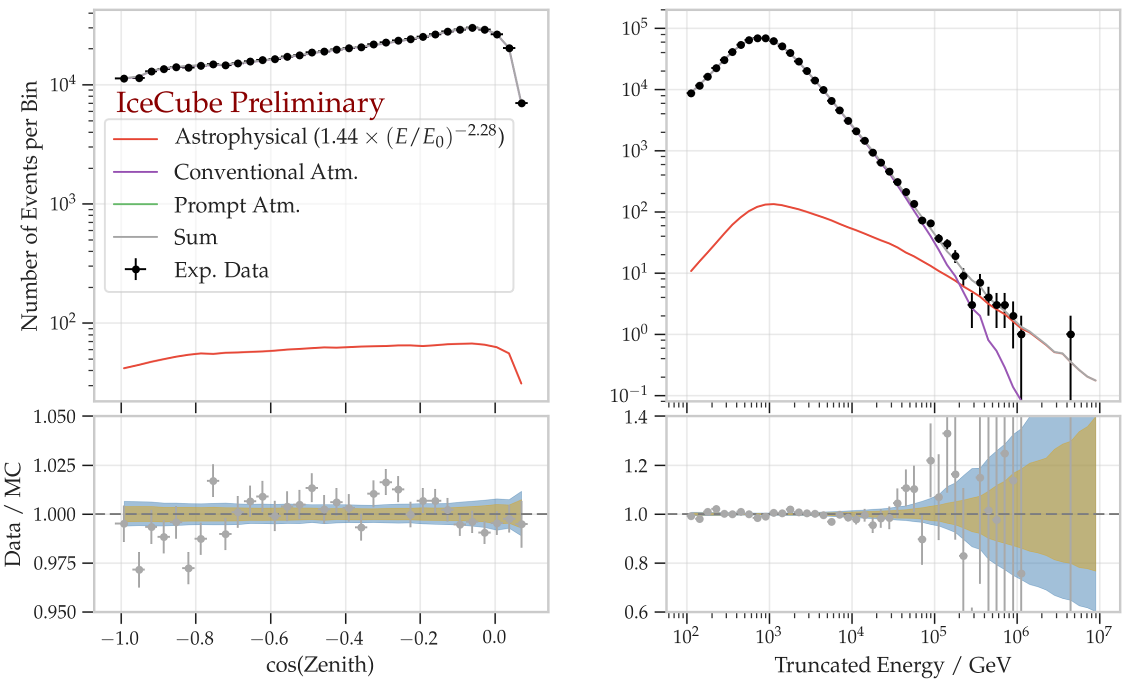
IceCube *7.5 year* HESE analysis
(HESE = High Energy Starting Event)
(all directions) PoS(ICRC2019)1004

IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
(events from below)
arXiv:1607.08006, Ap.J. 833 (2016) 3

The astrophysical signal emerges above a steeply falling background of atmospheric neutrinos

Upward ν_μ-induced muons (10 yrs)

- Red lines show astrophysical component
- Atmospherics dominate the angular distribution
- Signal emerges over background above 100 TeV



(Fig. from PoS(ICRC2019)1017, J. Stettner for the IceCube collaboration.)

4. Upper limit on prompt from upward ν_μ induced muons in IceCube

arXiv:1607.08006, Ap.J. 833 (2016) 3

- Prompt ν are isotropic
- TeV – 100 TeV excess near vertical relative to conventional neutrinos
- Observed angular distribution provides upper limits

Model	Flux limit
ERS (H3p)	1.06
GMS (H3p)	≈ 2.9
BERSS (H3p)	≈ 3.0
GRSST (H3p)	≈ 3.1

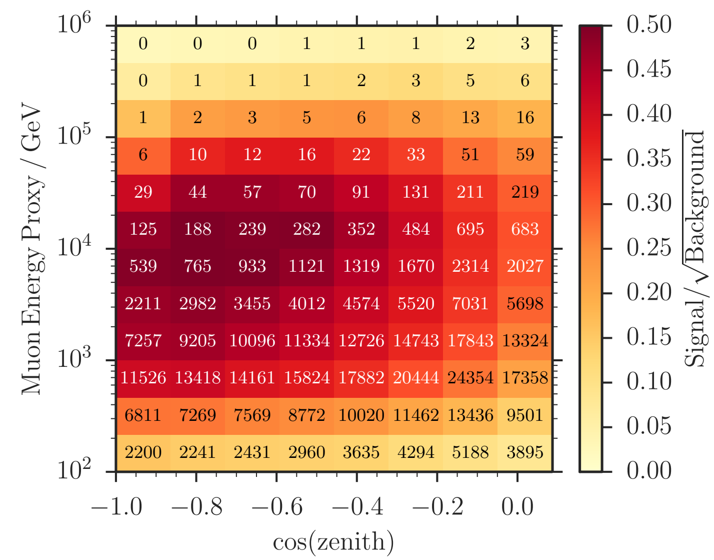
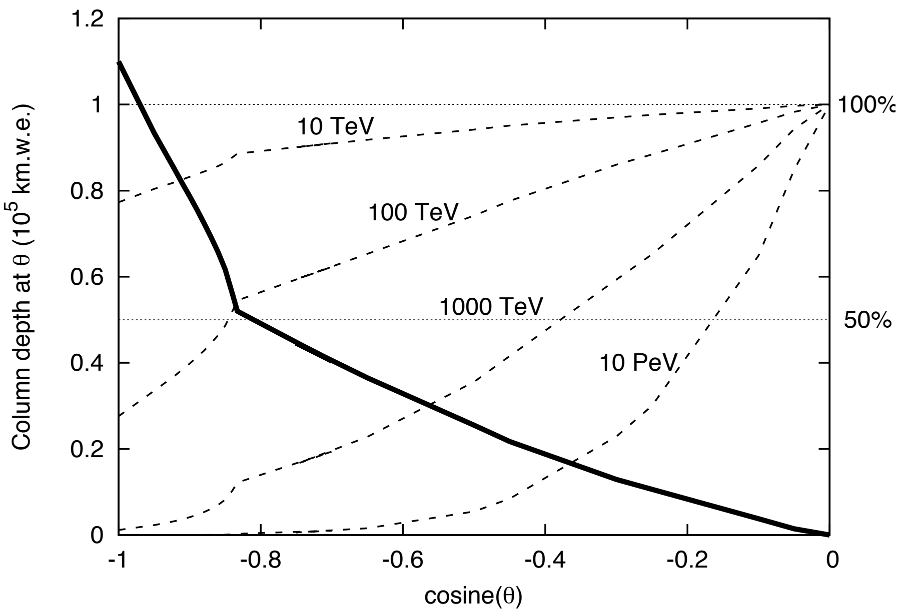


Figure 18. Signal over square root of background for the reconstructed muon energy vs. zenith angle corresponding to 6 years of IceCube data after applying the event selection for the 86-string configuration (IC2012-2014). Here, background is defined as the sum of the conventional atmospheric (Honda et al. 2007) and astrophysical ($10^{-8} \times E^{-2}$) $\nu_\mu + \bar{\nu}_\mu$ flux. The prompt atmospheric (Enberg et al. 2008) $\nu_\mu + \bar{\nu}_\mu$ flux is defined as signal. The numbers in each bin correspond to the expected number of background events in 6 years.

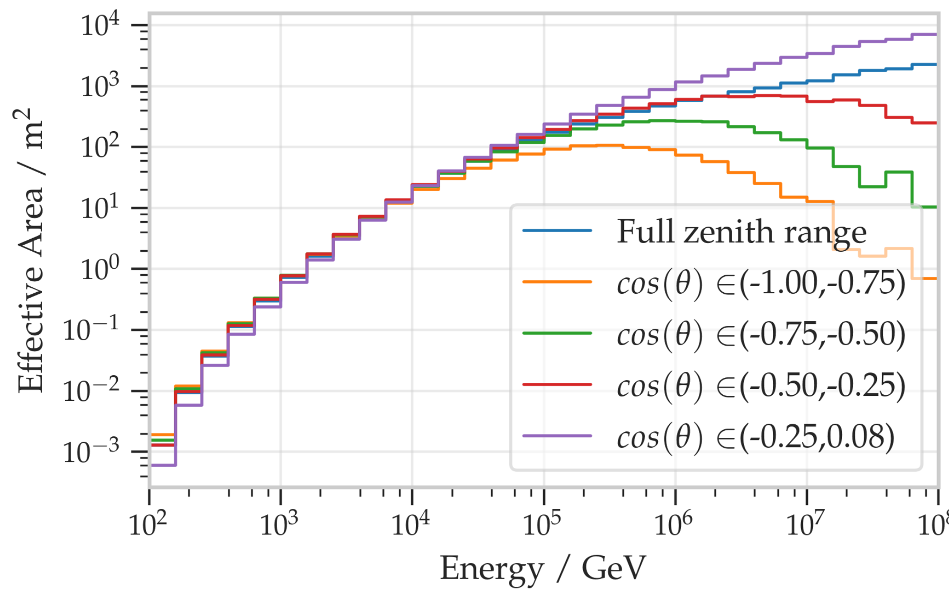
Shadow of the Earth

Affects both atmospheric and astrophysical neutrinos



Transparency of the Earth for neutrinos. Dashed line show passing fractions at four neutrino energies.

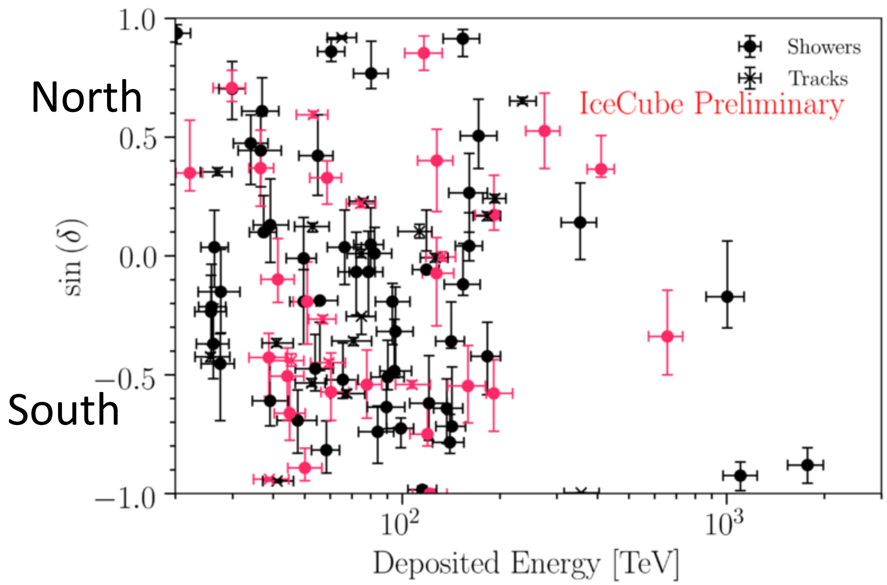
(Figure from *Atmospheric Neutrinos,* TG to appear in "Particle Physics with Neutrino Telescopes", C. Pérez de los Heros, editro, World Scientific.

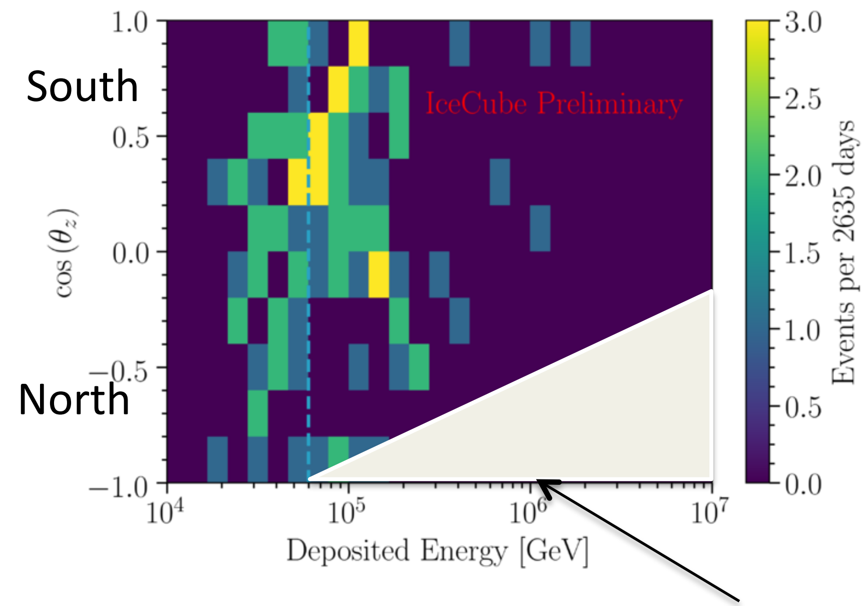


Effective areas for upward ν_μ in IceCube for the Northern hemisphere and for 4 directions below the horizon. Note the absorption of the Earth for high energies from large negative zenith angles.
(Fig. from PoS(ICRC2019)1017, J. Stettner for the IceCube collaboration.)

HESE 7.5 yrs

New reconstructions for all years with IceCube Pass 2





Note change in convention for direction: sin(δ) → cos(θ)

Earth's shadow (>50%)

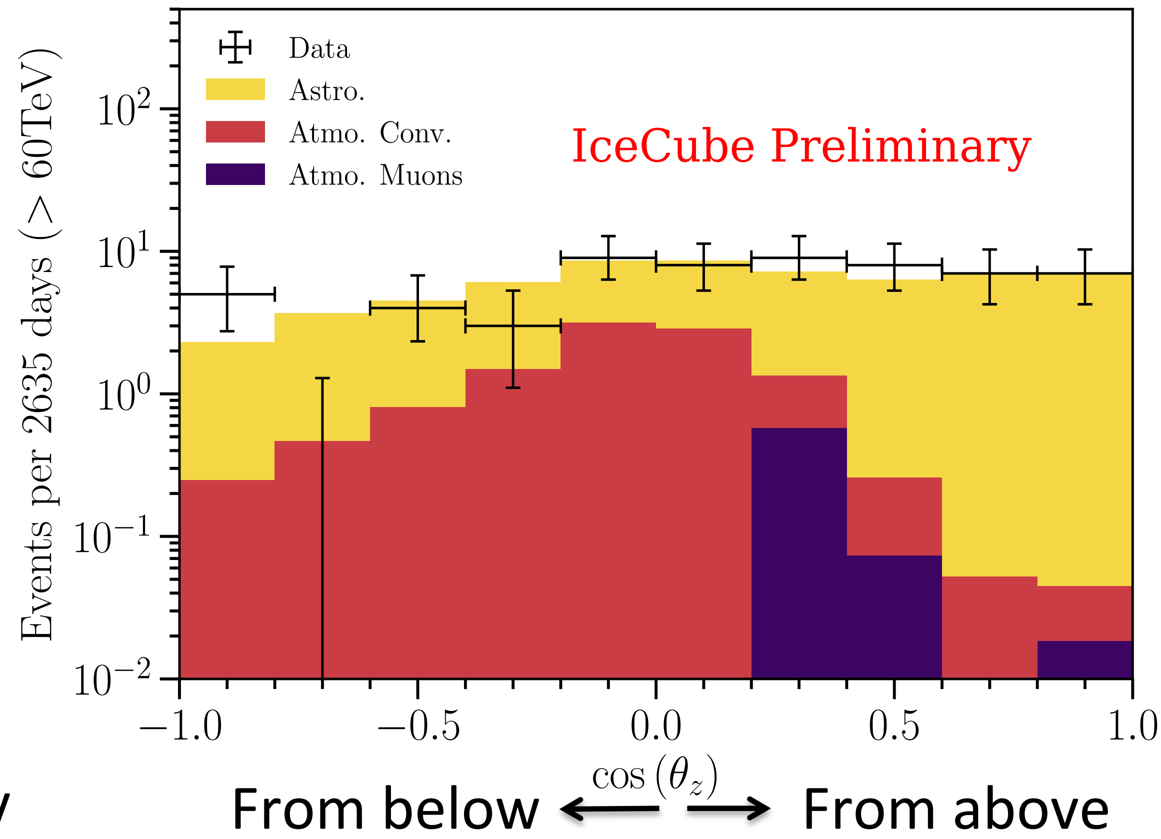
Work in progress reported at TeVPA 2018
(Austin Schneider for IceCube)

HESE Angular distributions $E_{vis} > 60$ TeV

Angular dependence:

- From below:
  - absorption for signal
  - plus intrinsic excess for atmospheric ν near horizon
- From above:
  - self-veto of atmospheric ν by accompanying μ

Fig. from PoS(ICRC2019) 1004, A. Schneider for IceCube

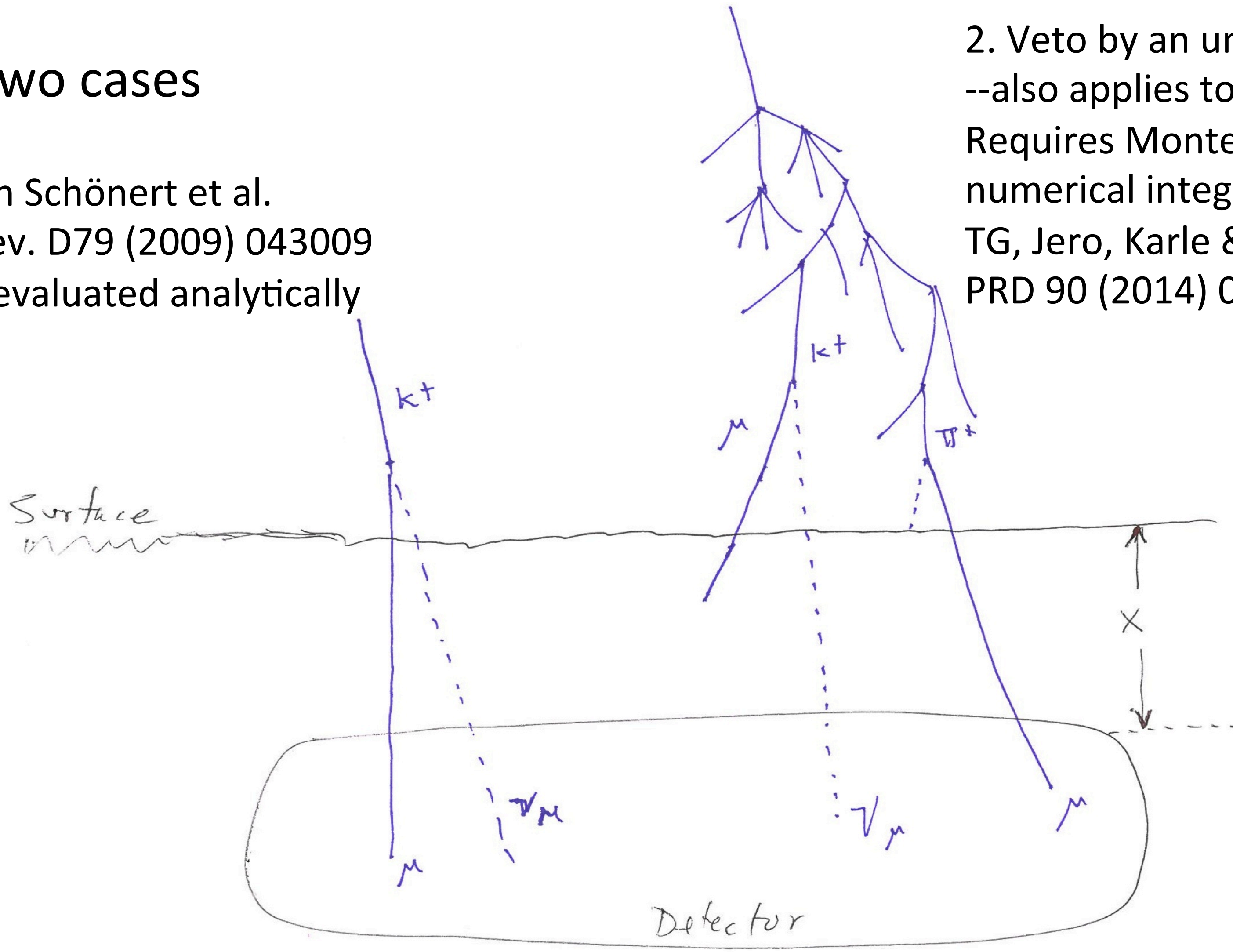


5. Atmospheric neutrino self veto

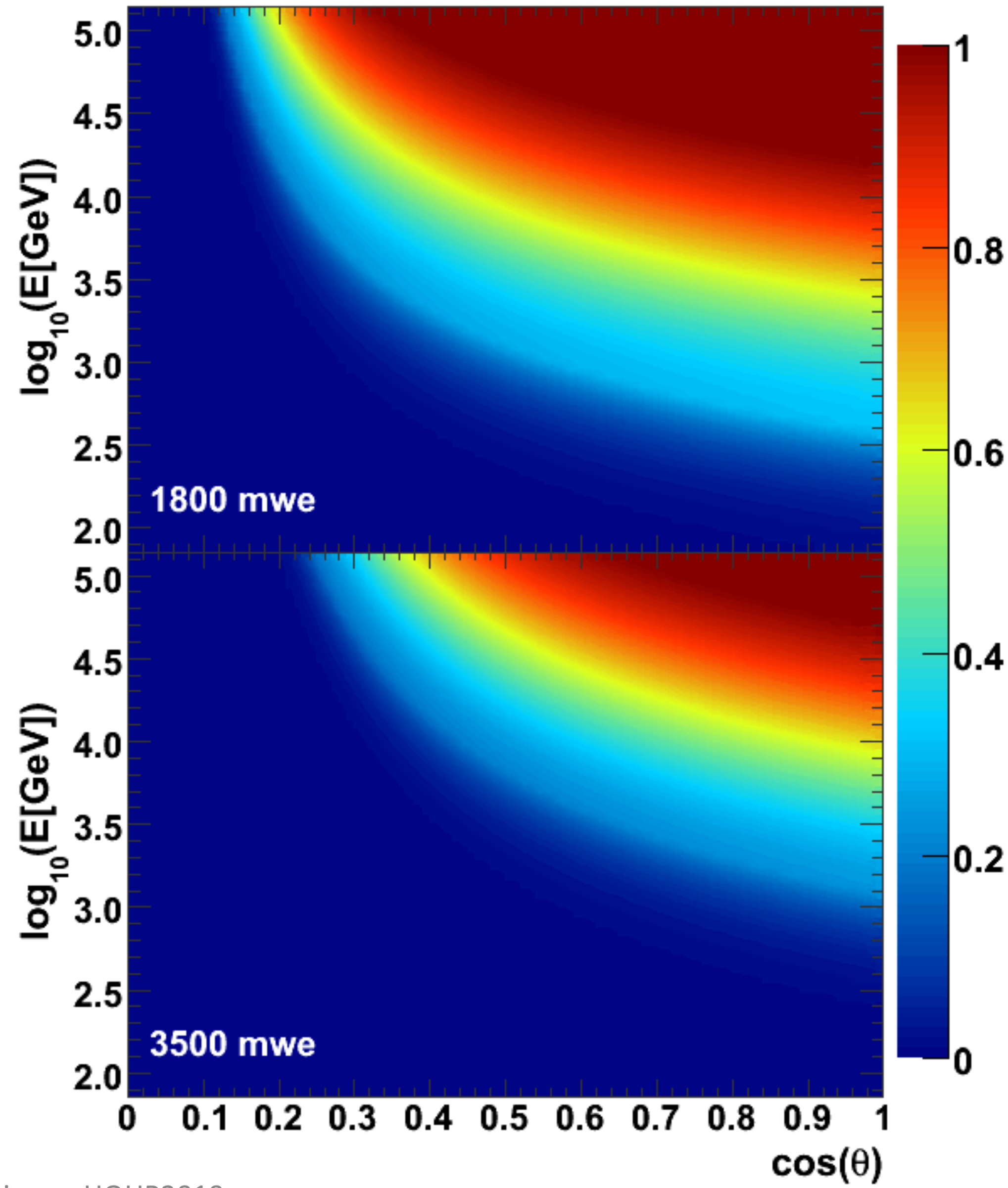
Two cases

1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or numerical integration
TG, Jero, Karle & van Santen, PRD 90 (2014) 023009



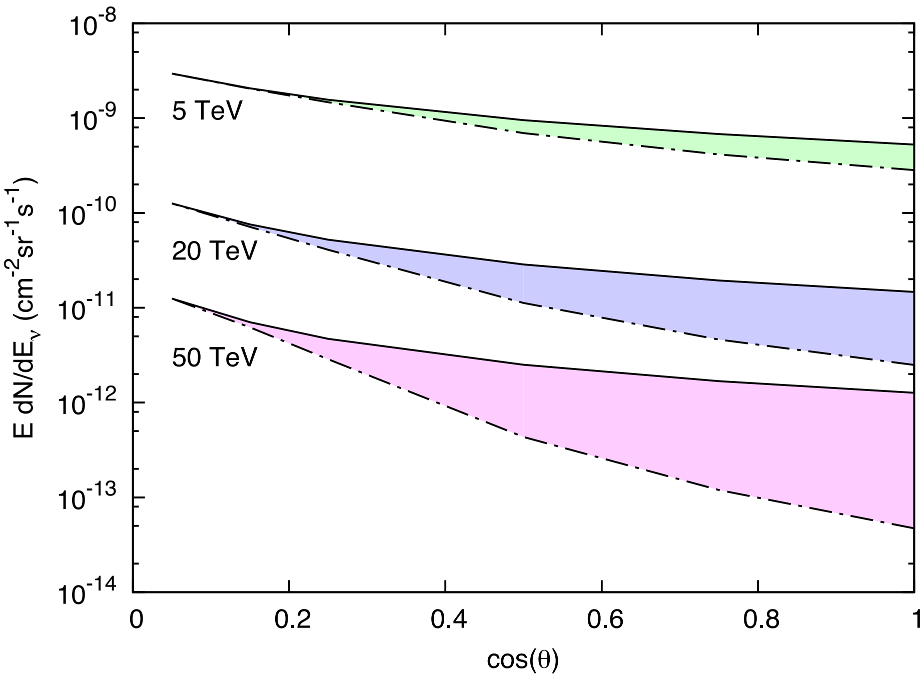
Depth dependence of ν_μ self-veto



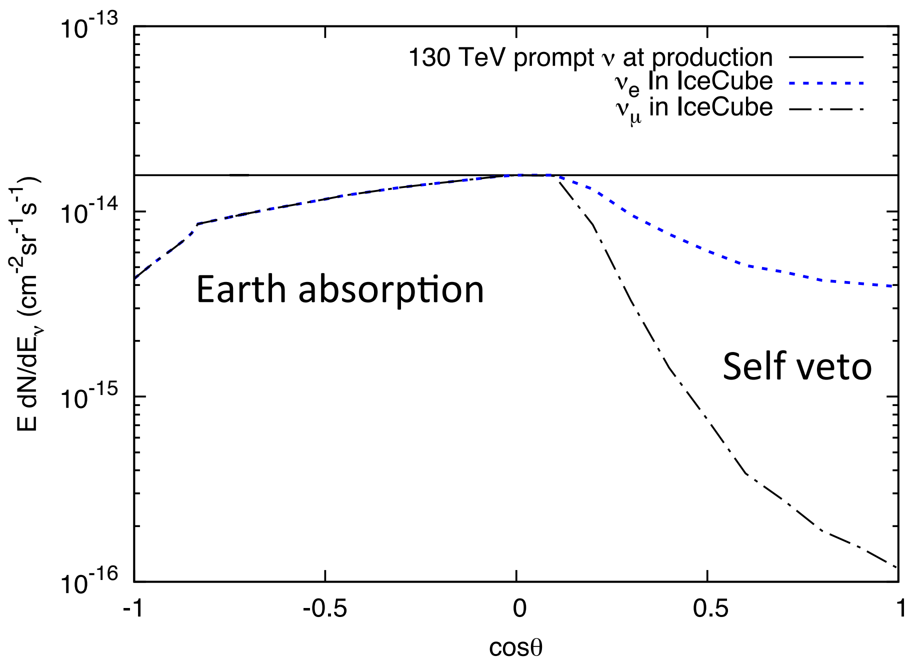
Schönert, TG, Resconi, Schulz,
PRD 79 (2009) 043009

Neutrino self-veto updated*

Conventional ν_μ from above:
Peaked near horizon; veto probability increases with energy, more for vertical



Prompt ν at 130 TeV:
Isotropic at production,
Self veto stronger for ν_μ than for ν_e

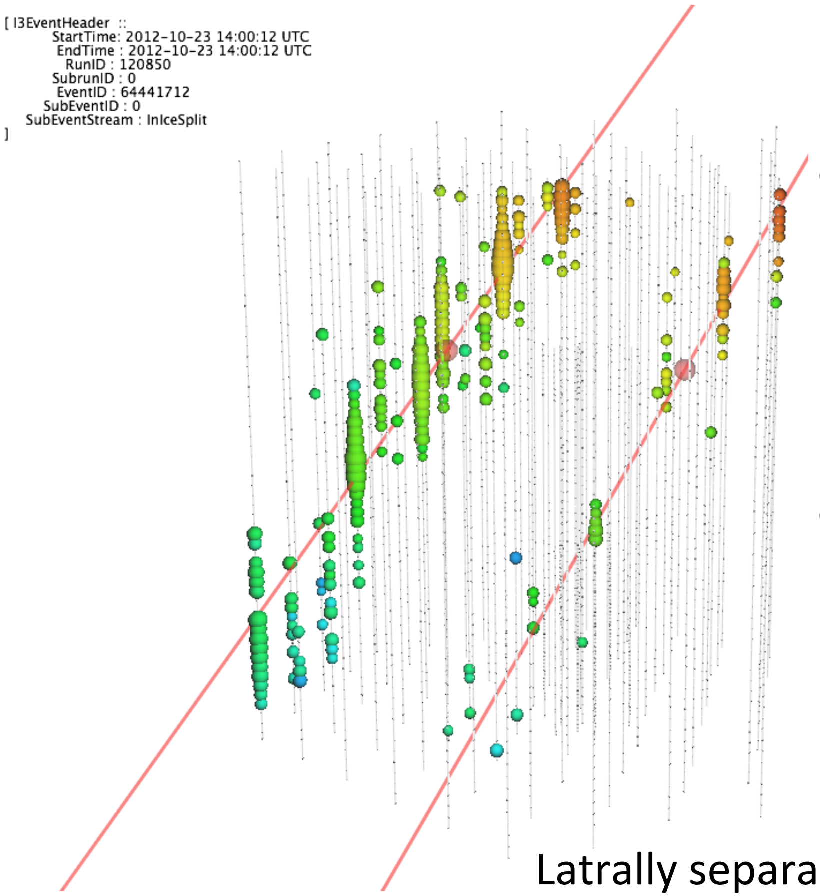


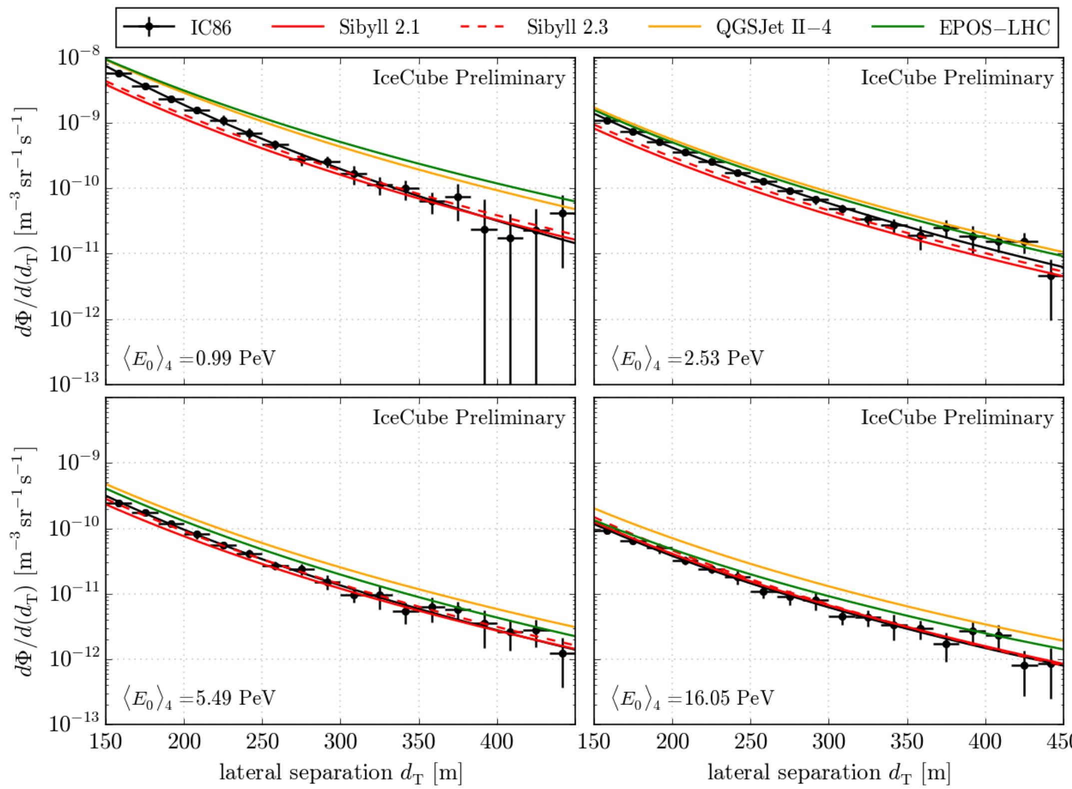
Figures from TG chapter in World Scientific using updated veto*

* Arguelles, Palomares-Ruiz, Schneider, Wille, Yuan JCAP 1807 (2018) no.07, 047

6. Atmospheric muons in IceCube

$$\Delta r \sim \frac{p_T(GeV)}{1\,TeV} \times \frac{15\,\text{km}}{\cos\theta} \sim 30\,m$$ typical size of main muon bundle

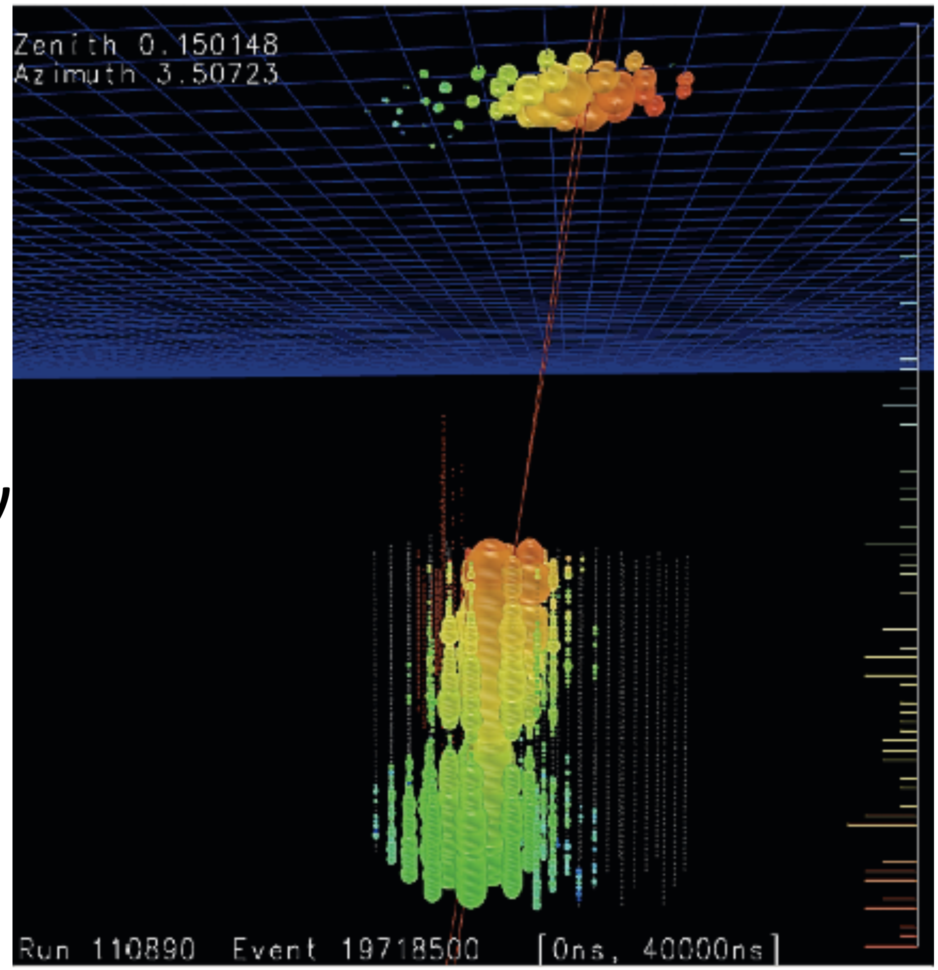




Latrally separated muons in IceCube
D. Soldin for the IceCube Collaboration, arXiv:1811.03651

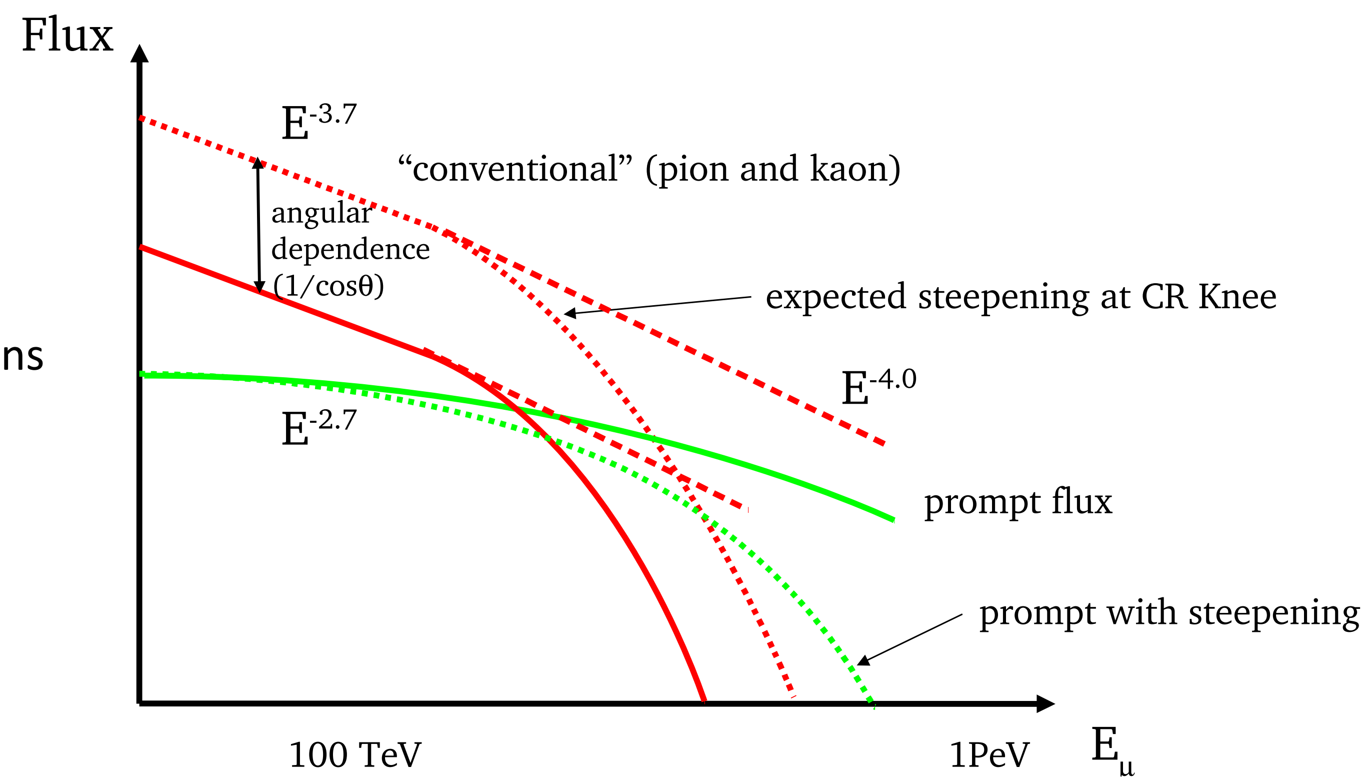
Cosmic-ray physics with IceCube

- Spectrum with IceTop
- Spectrum and composition with coincident events
- Anisotropy
- Seasonal variation μ & ν
- IceTop as a veto
  - To find neutrinos starting in the ice above IceCube
- Muon rates



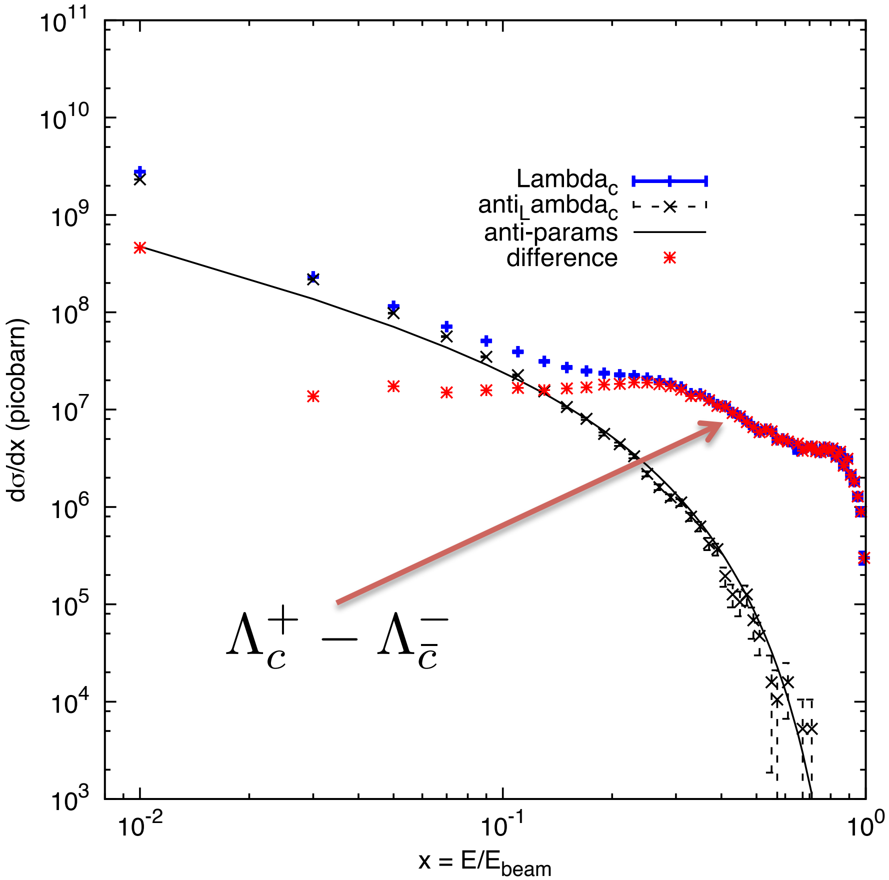
Prompt μ complement prompt ν

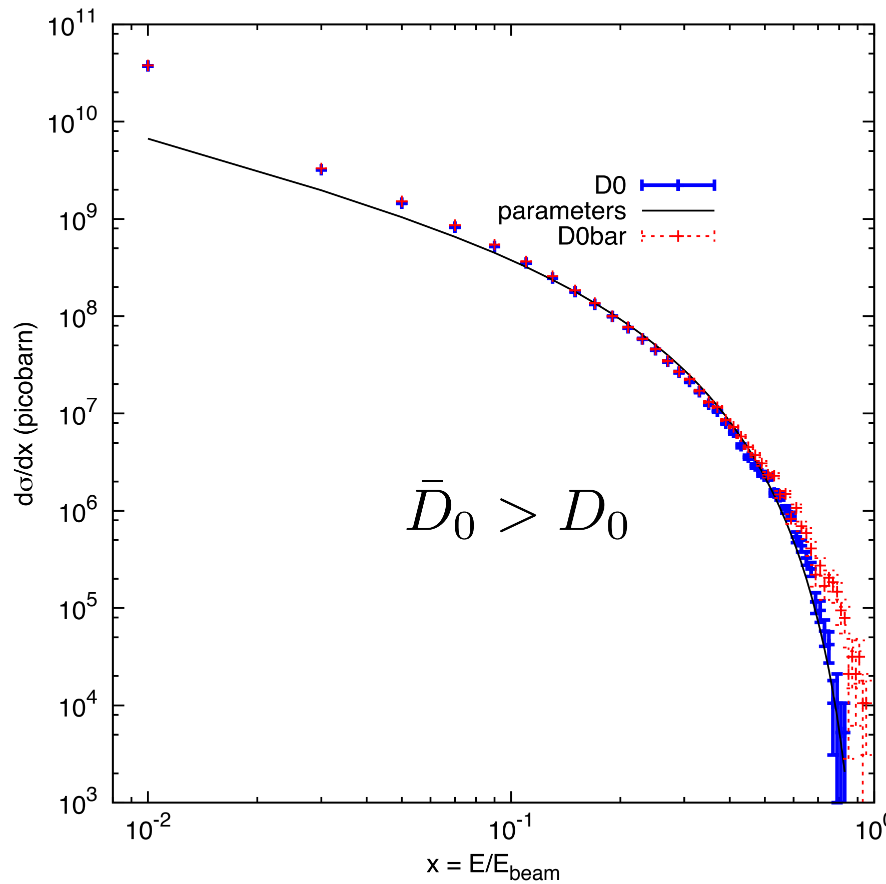
Prompt μ : 2 sources
- Charm decay
- Neutral vector mesons
- Illana, Lipari et al. Astropart. Phys. 34 (2011) 663
- Anatoli's talk today



IceCube, arXif:1506.07981v2 (Astropart. Phys. 78 (2016) 1-27
Results indicate a prompt component

7. Associated production of charm ?

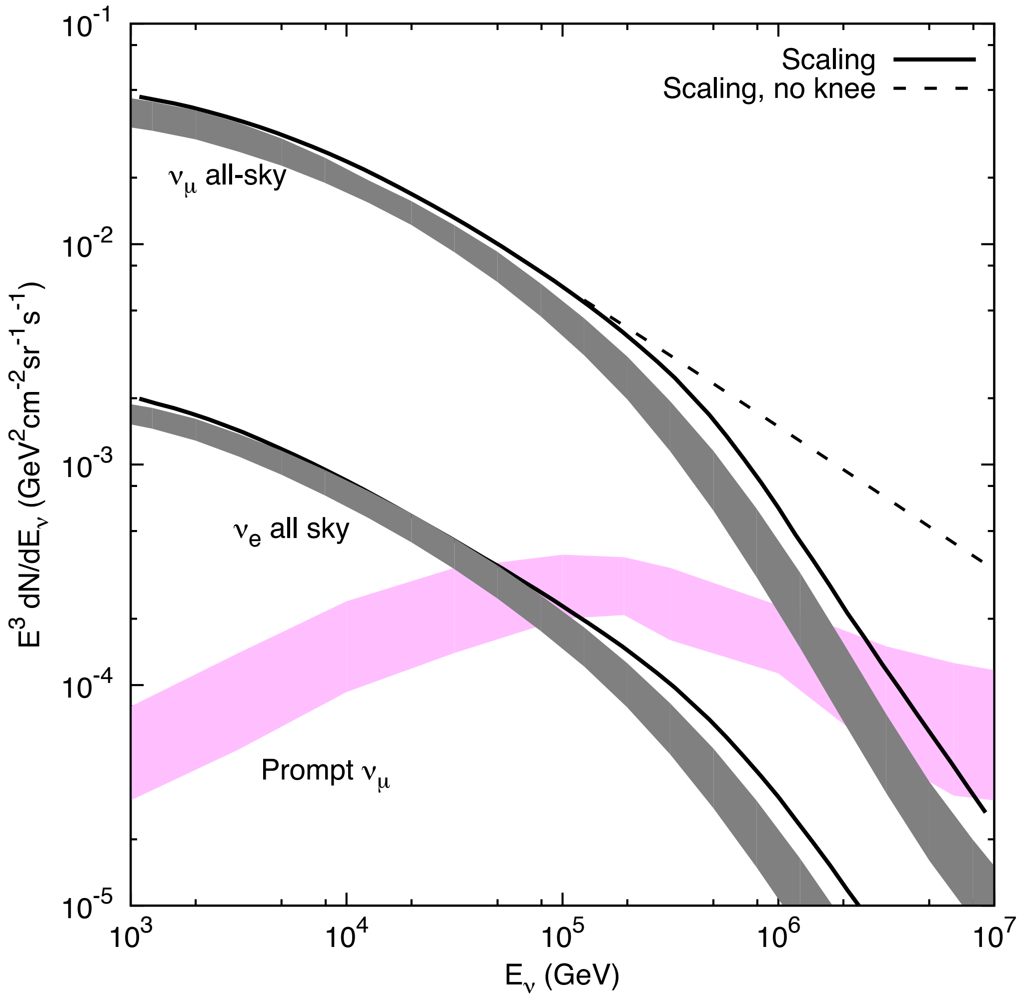




Distributions from M.V.Garzelli et al. suggest a small component

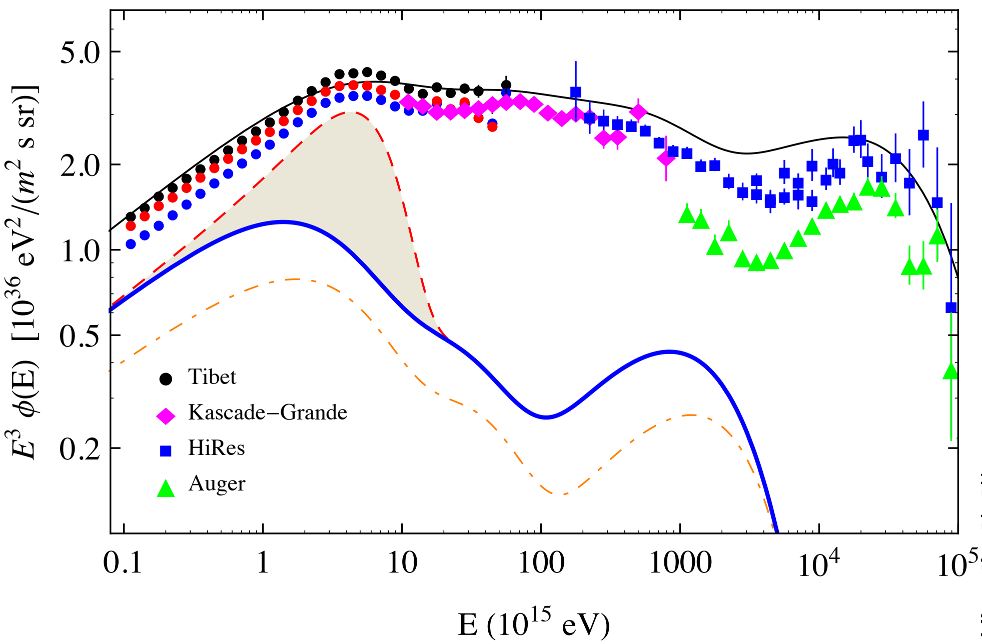
References for prompt neutrinos

- TIG : Thunman, Ingelman, Gondolo, Astropart. Phys. 5 (1996) 309
- ERS : Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005
- BERSS : Bhattacharya, Enberg, Reno, Sarcevic, Stasto, JHEP 06 (2015) 110
- GRRST : Gauld et al., JHEP 02 (2016) 130
- PROSA : M.V. Garzelli et al., JHEP 05 ((2017) 0004
- New alternative to PROSA : Benzke et al., arXiv:1705.10386



Shaded bands for conventional span Sib2.3, Epos LHC, QGSjet II-04, prompt: PROSA, Sib2.3, GRRST, BERSS

Extreme composition model



Paolo Lipari, 1308.2086