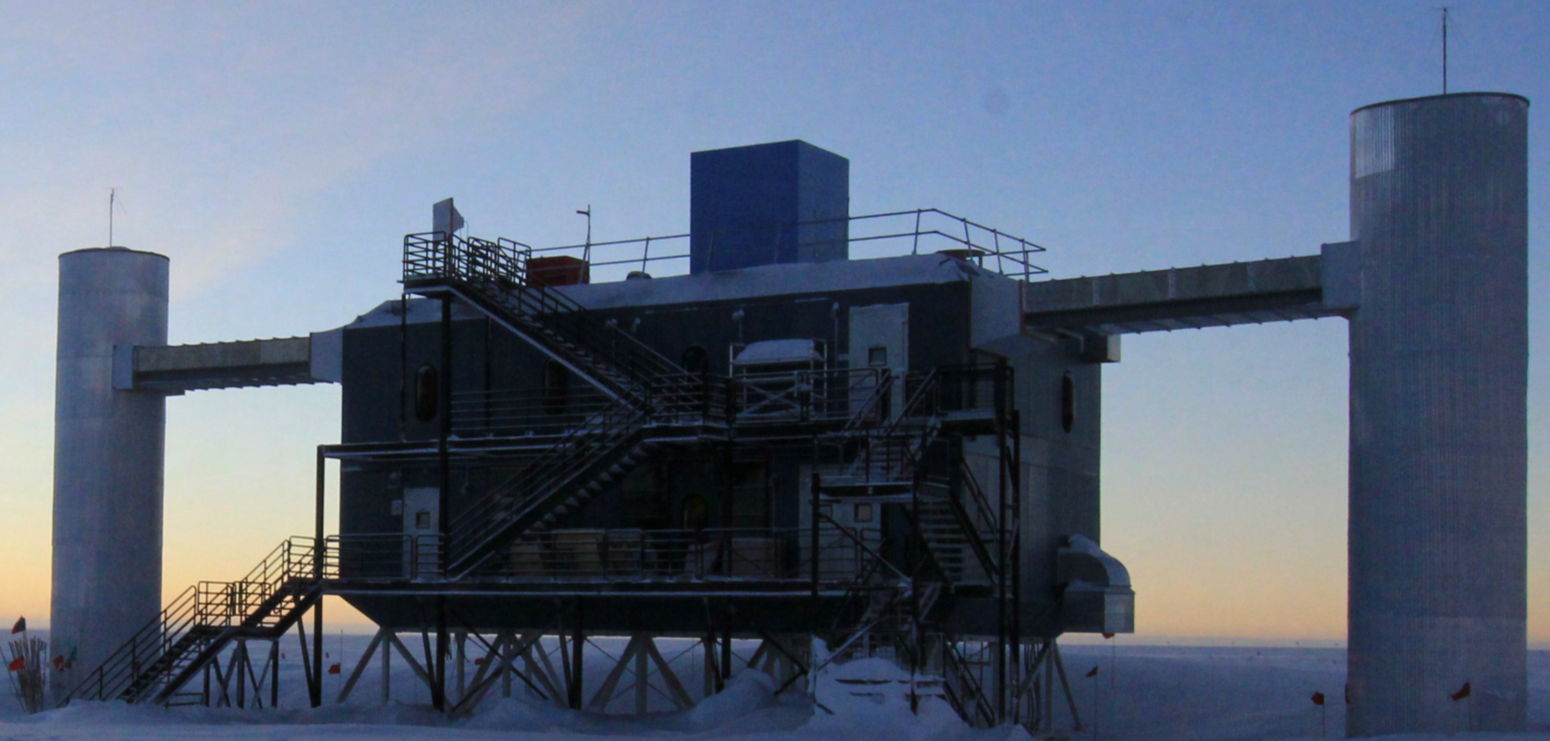
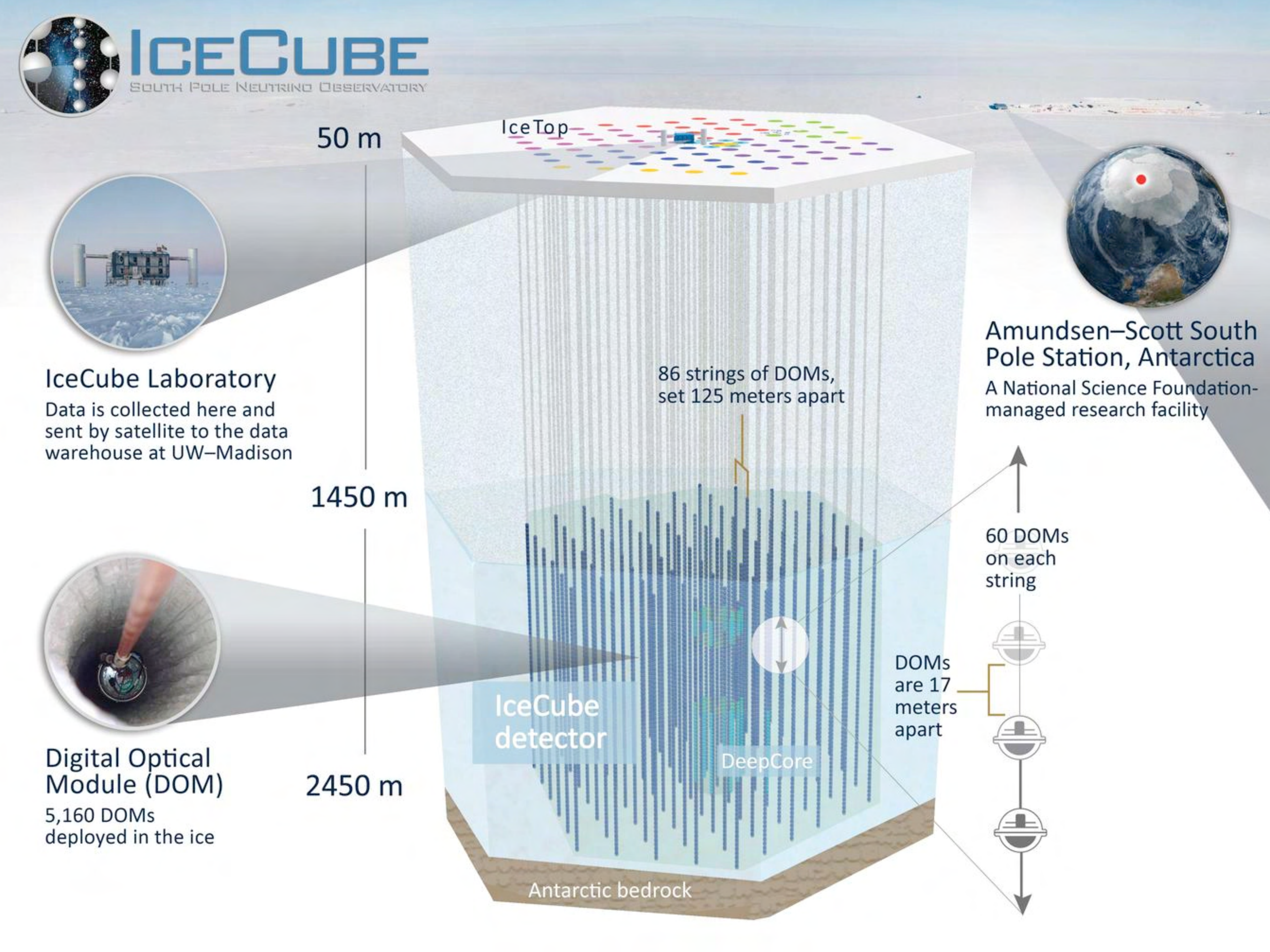
Photo credit: James Casey, IceCube/NSF

IceCube Observations of ~~Astrophysical~~ High Energy Neutrinos

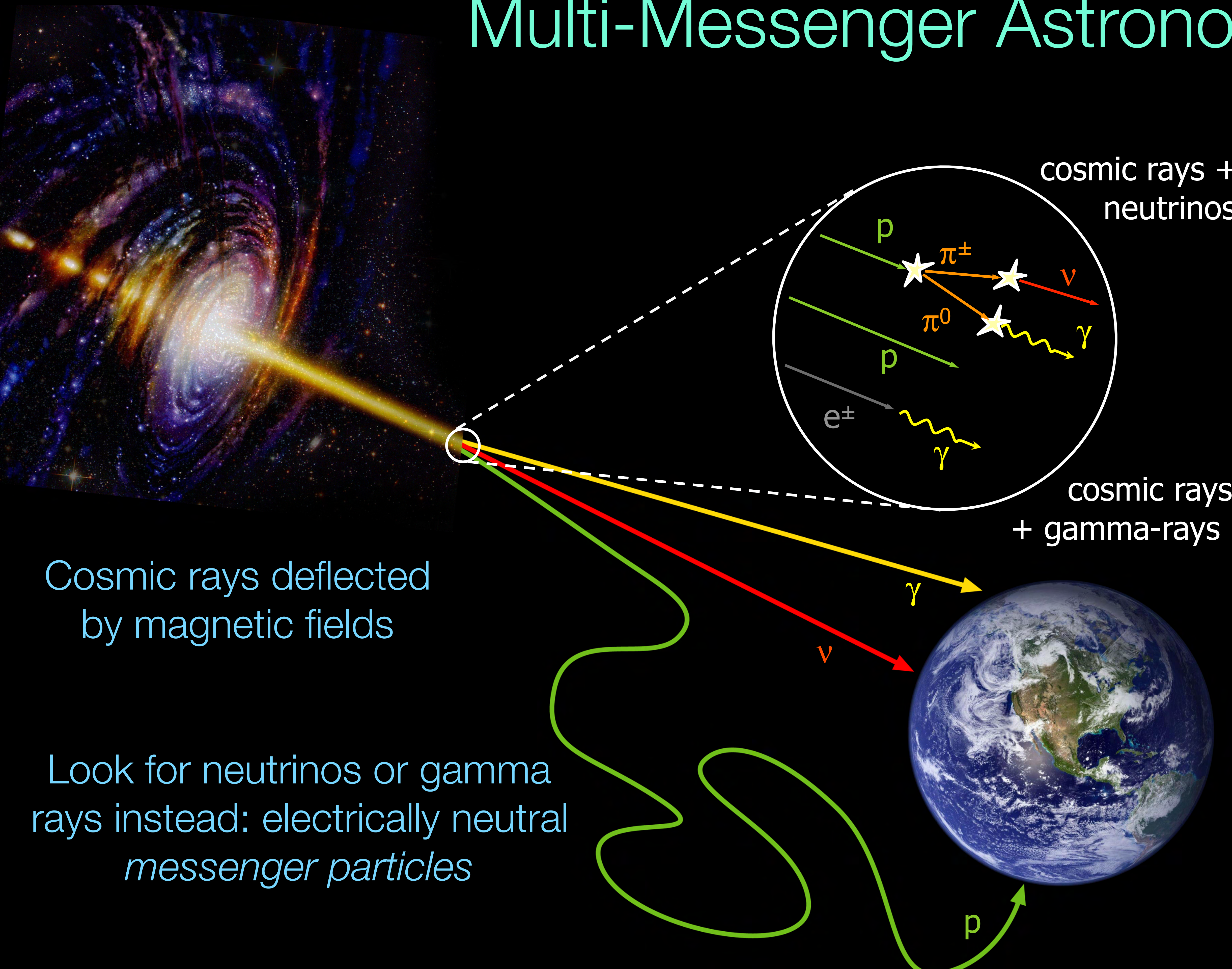


Tyce DeYoung
Department of Physics and Astronomy
Michigan State University

15th Workshop on Non-Perturbative QCD
L'Institut d'Astrophysique de Paris
June 14, 2018

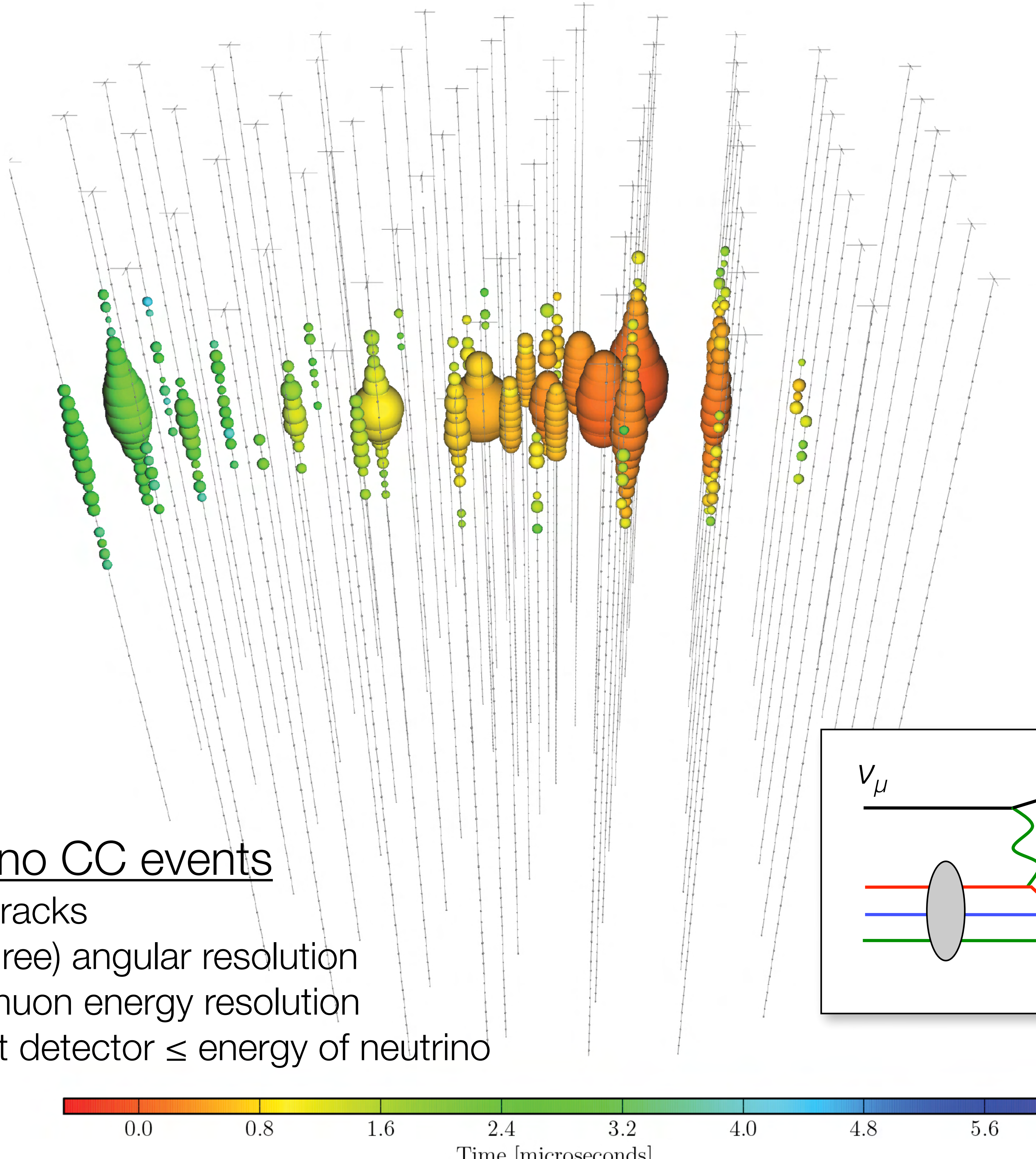

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

Multi-Messenger Astronomy



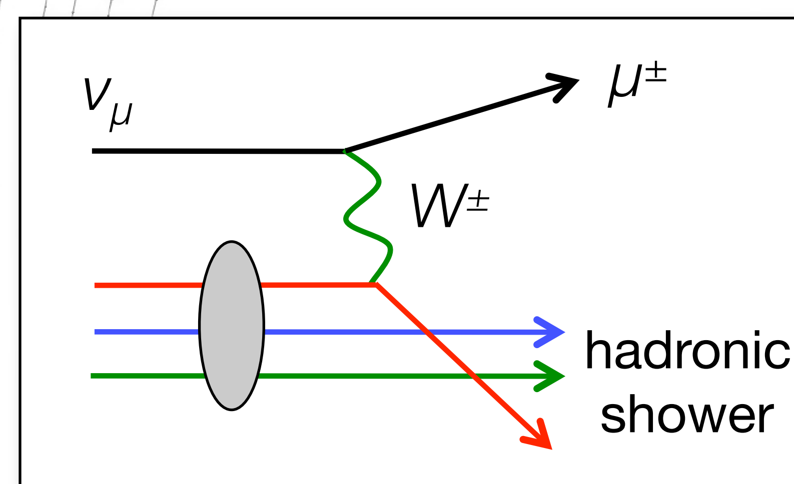
Cosmic rays deflected by magnetic fields

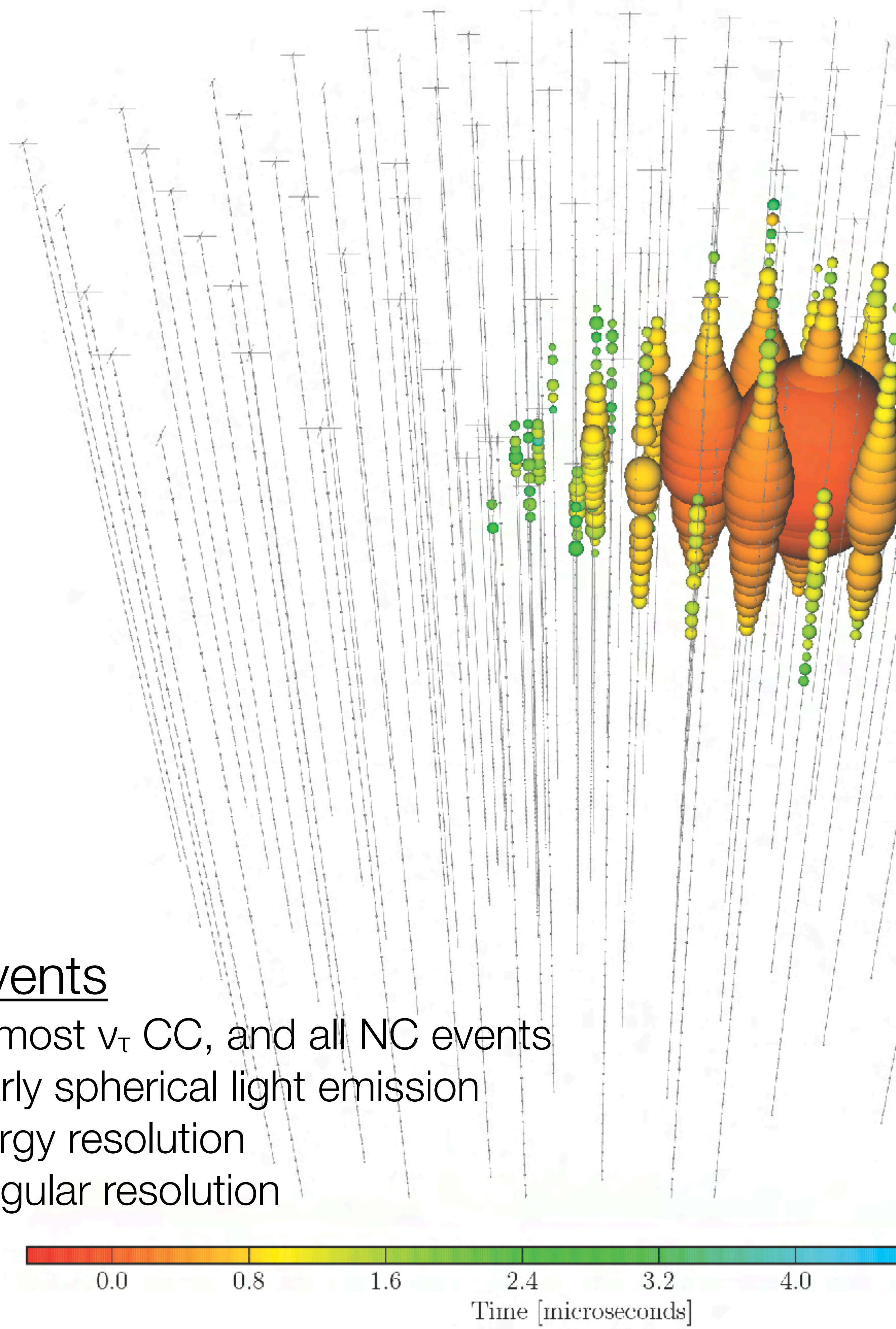
Look for neutrinos or gamma rays instead: electrically neutral *messenger particles*



Muon neutrino CC events

Long, straight tracks
Good (sub-degree) angular resolution
Factor of two muon energy resolution
Muon energy at detector ≤ energy of neutrino





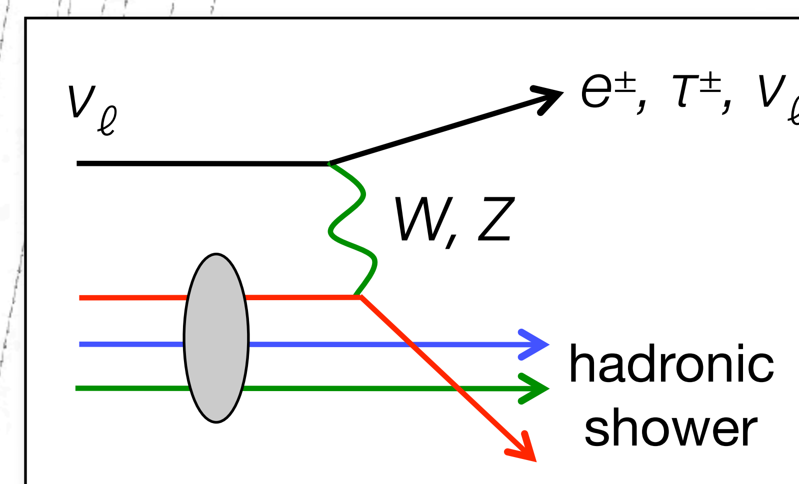
“Cascade” events

Includes ν_e CC, most ν_τ CC, and all NC events

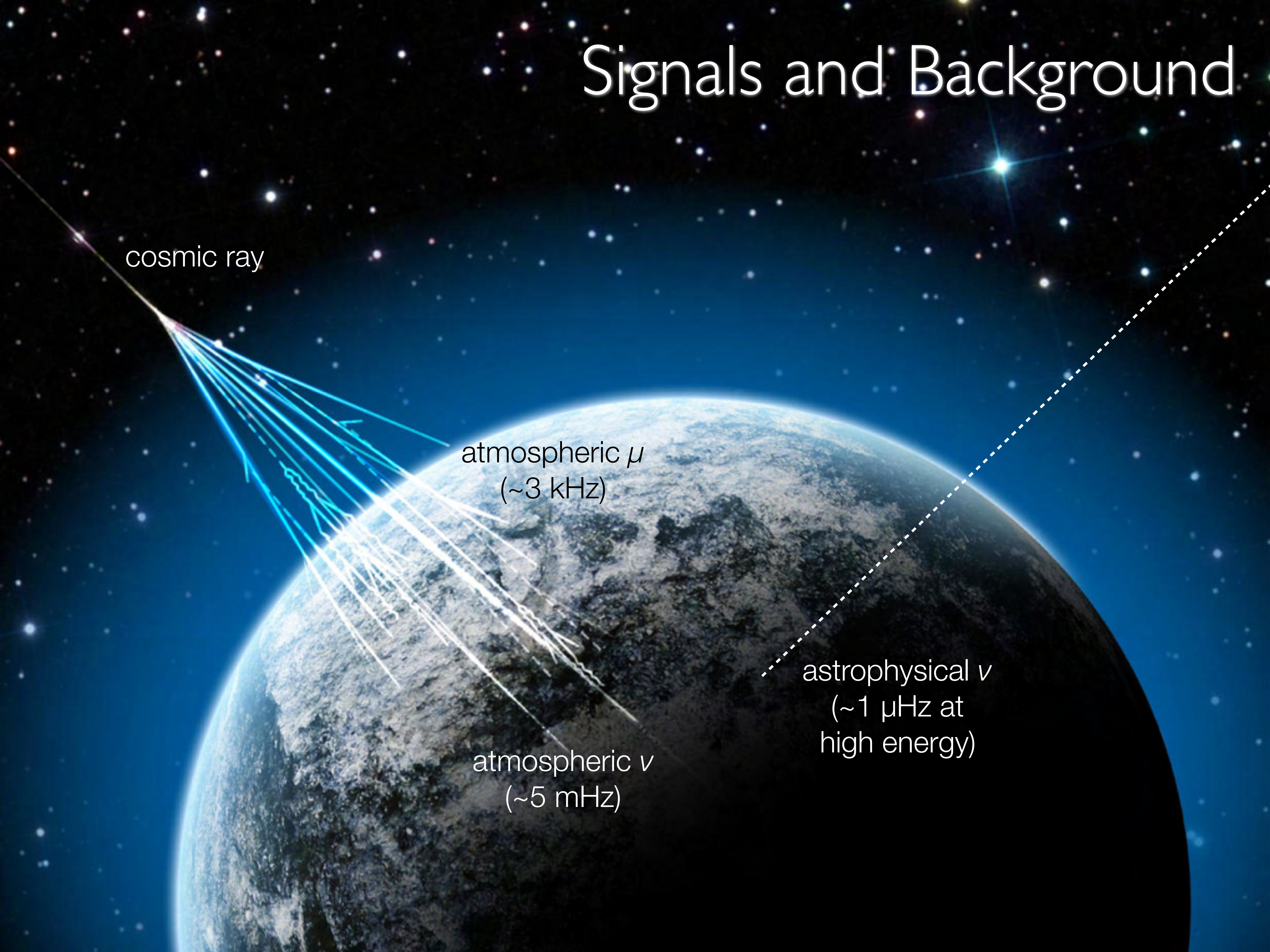
Small event, nearly spherical light emission

Good (15%) energy resolution

Poor (10-15º) angular resolution



Signals and Background



Neutrino Identification – Two Strategies

upgoing tracks

using Earth as filter

- Use the Earth to filter out everything else
  - Primarily ν_μ from the northern sky

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- Look for events starting inside detector
  - Use outer layers of detector to veto muons – neutrinos pass through invisibly
  - Equally sensitive to all flavors, good sensitivity to full sky

"starting" events

using edge to VETO

Neutrino Identification – Two Strategies

upgoing tracks

using Earth as filter

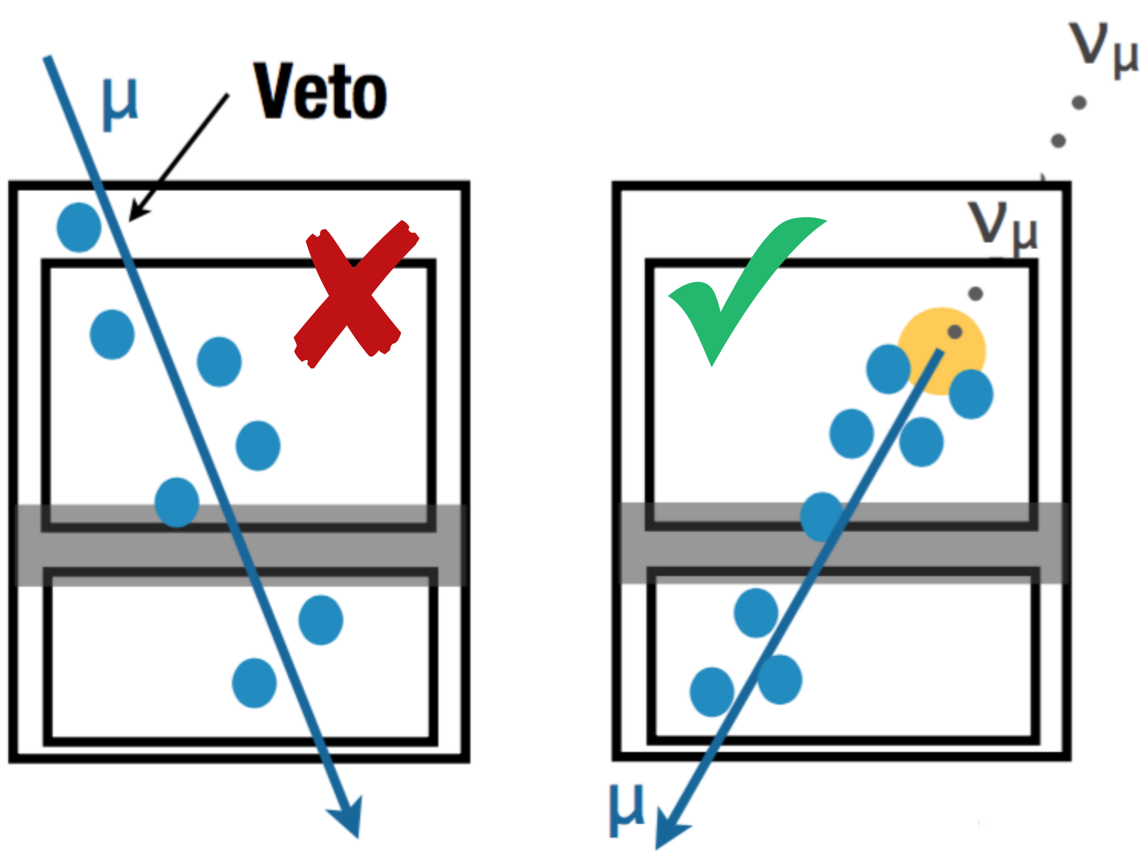
- Use the Earth to filter out everything else
  - Primarily ν_μ from the northern sky
- Look for events starting inside detector
  - Use outer layers of detector to veto muons – neutrinos pass through invisibly
  - Equally sensitive to all flavors, good sensitivity to full sky

"starting" events

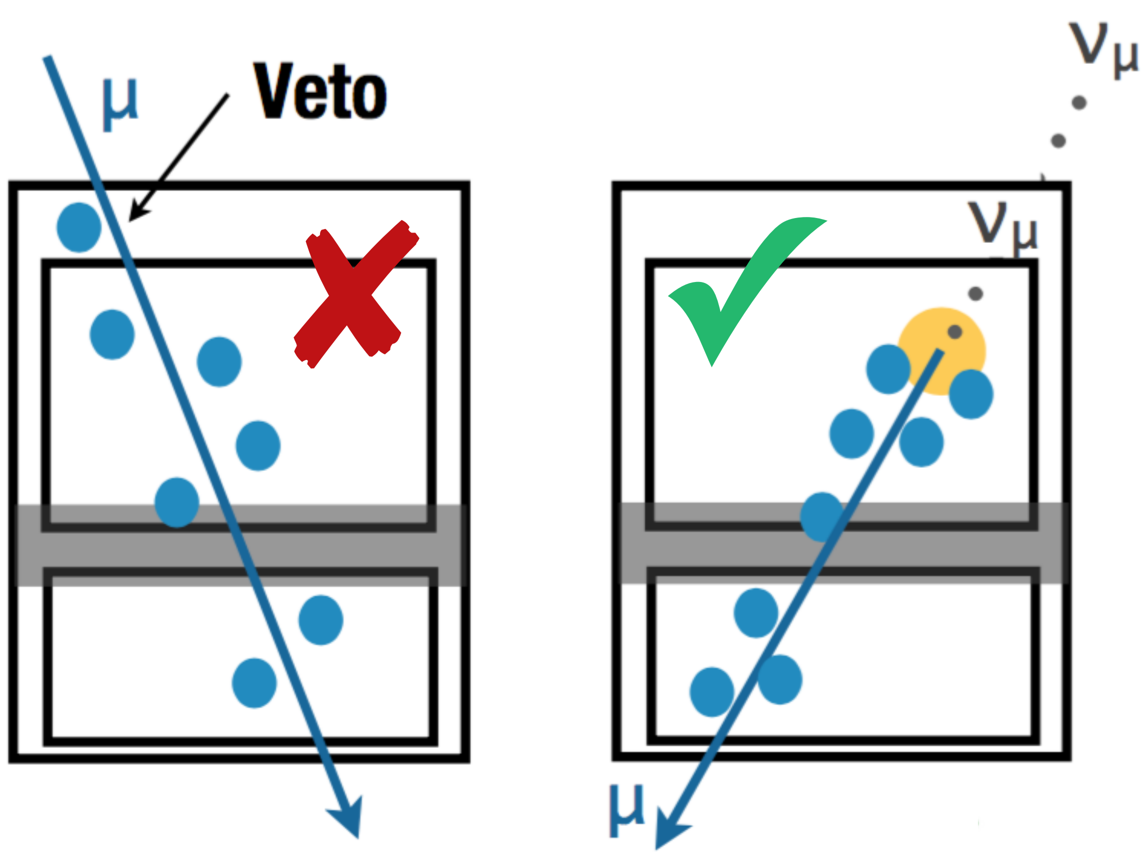
using edge to VETO

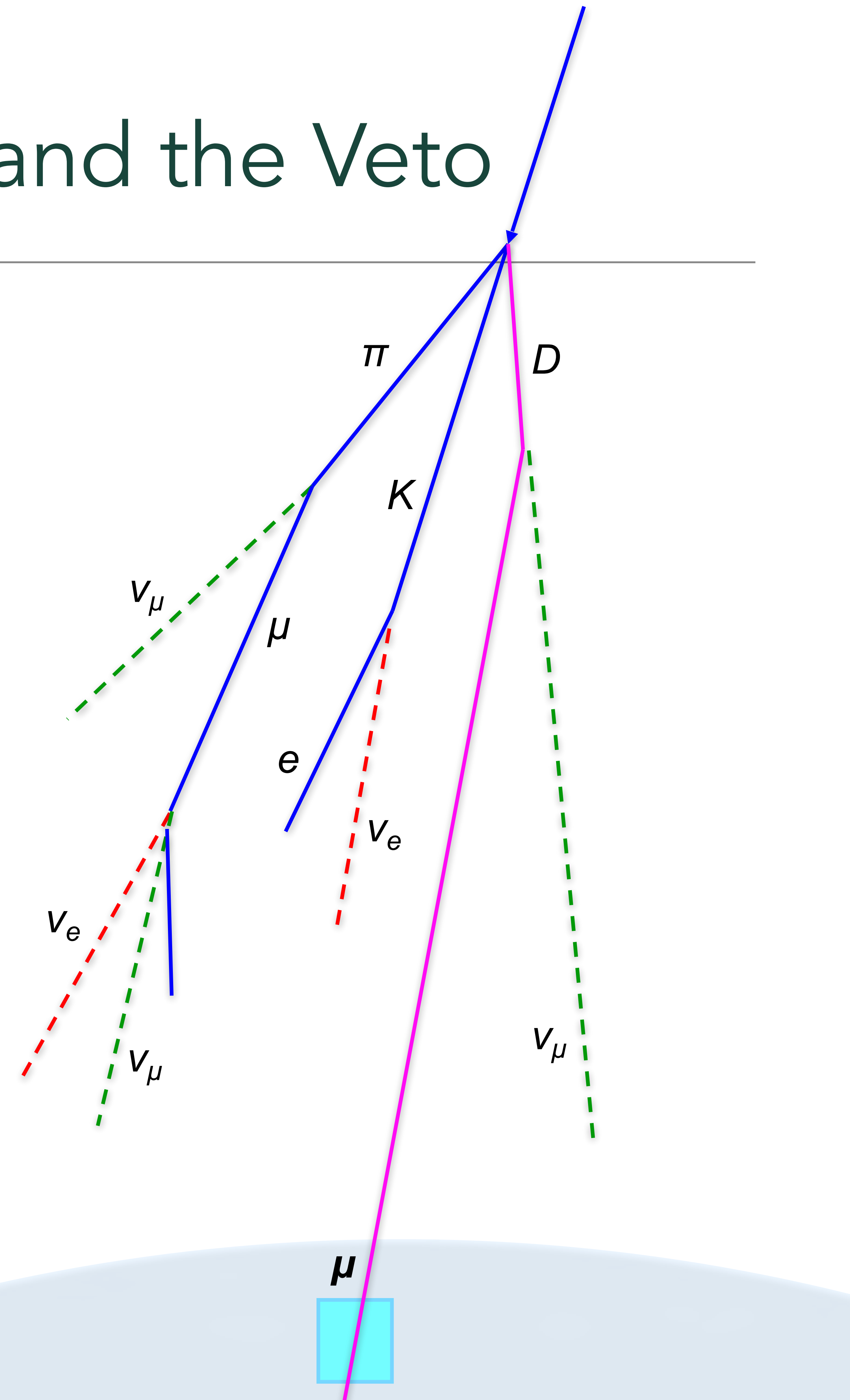
- Atmospheric neutrinos dominate at low energies, astrophysical neutrinos generally have a harder spectrum

Atmospheric Neutrinos and the Veto

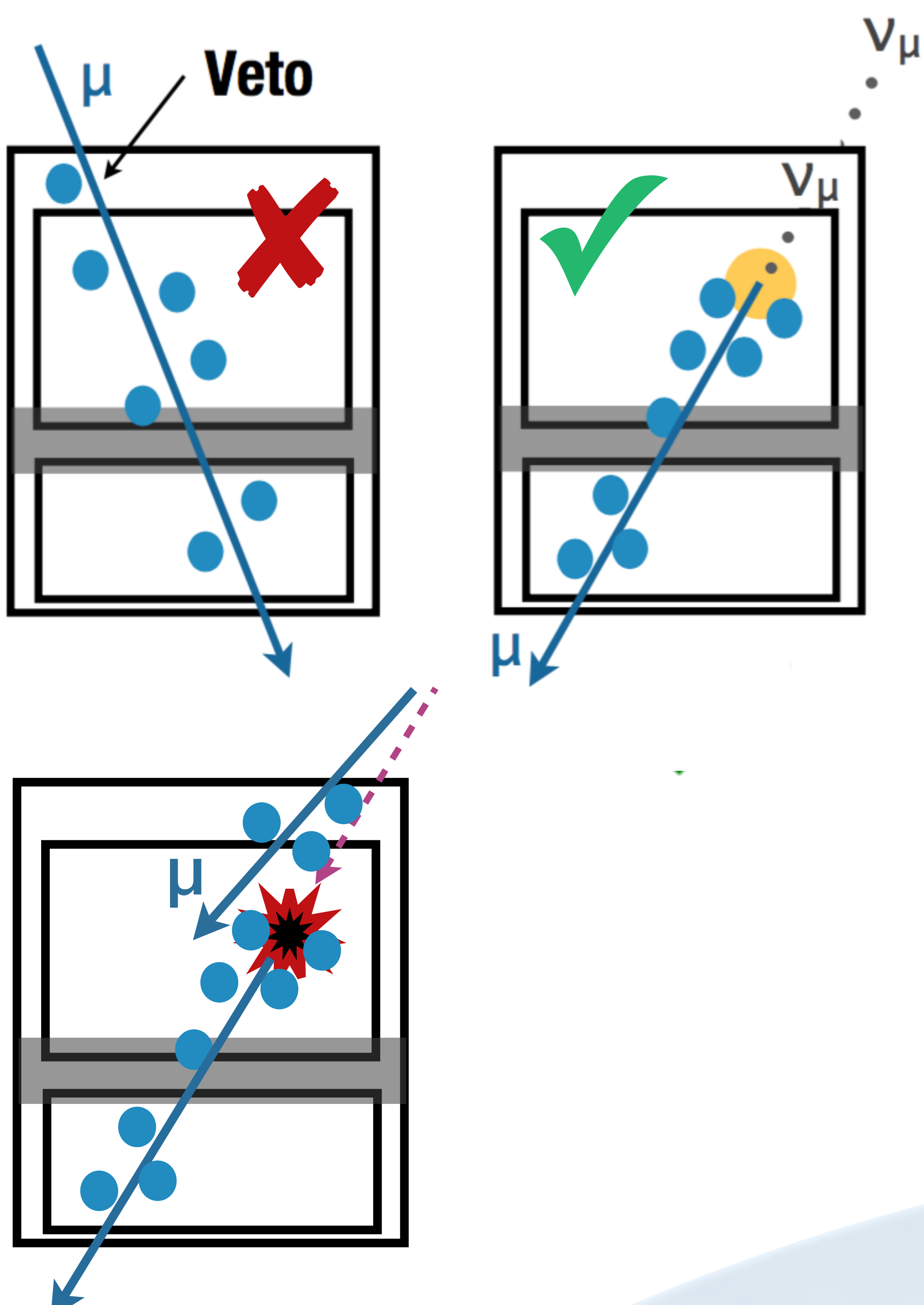


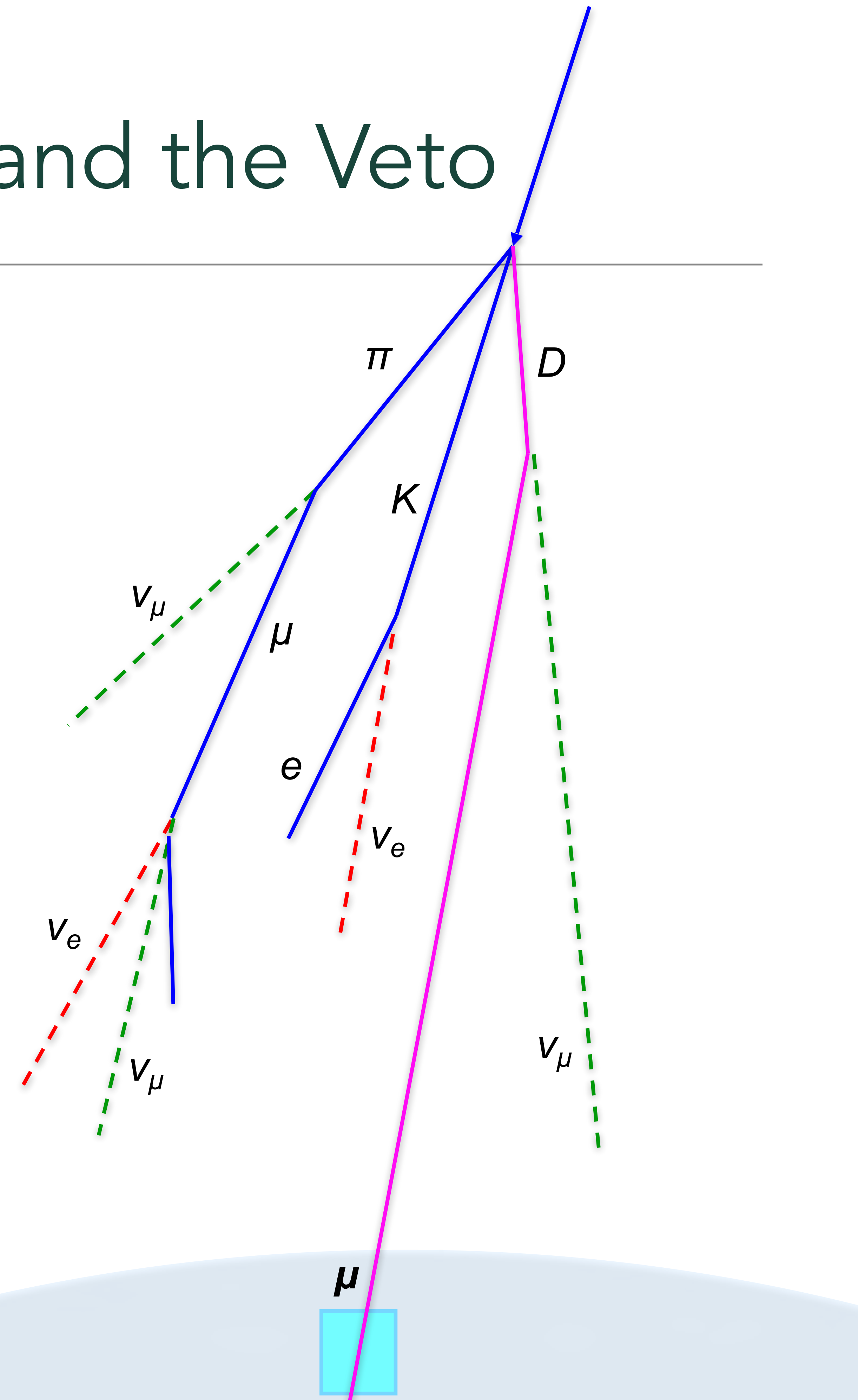
Atmospheric Neutrinos and the Veto



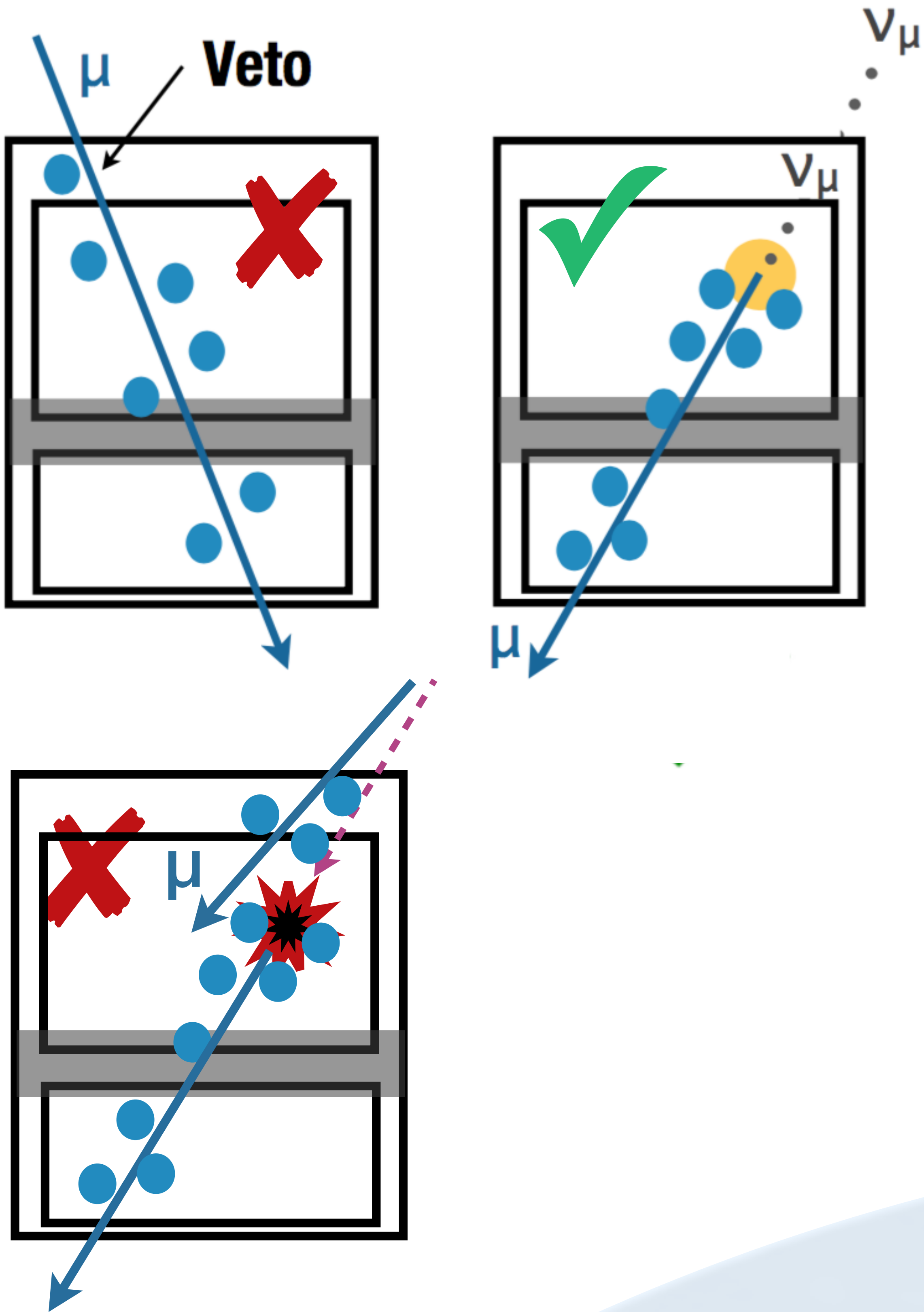


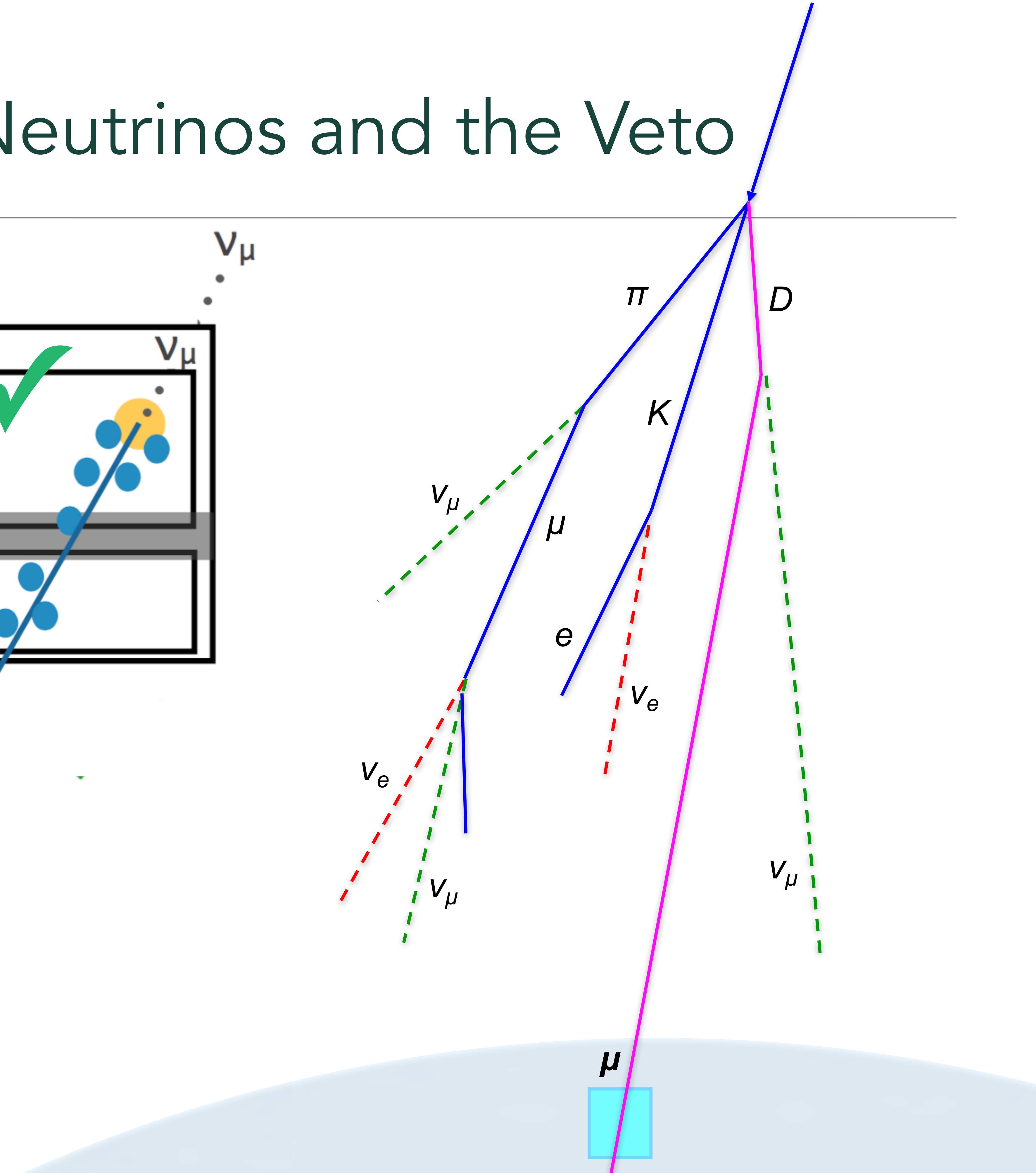
Atmospheric Neutrinos and the Veto





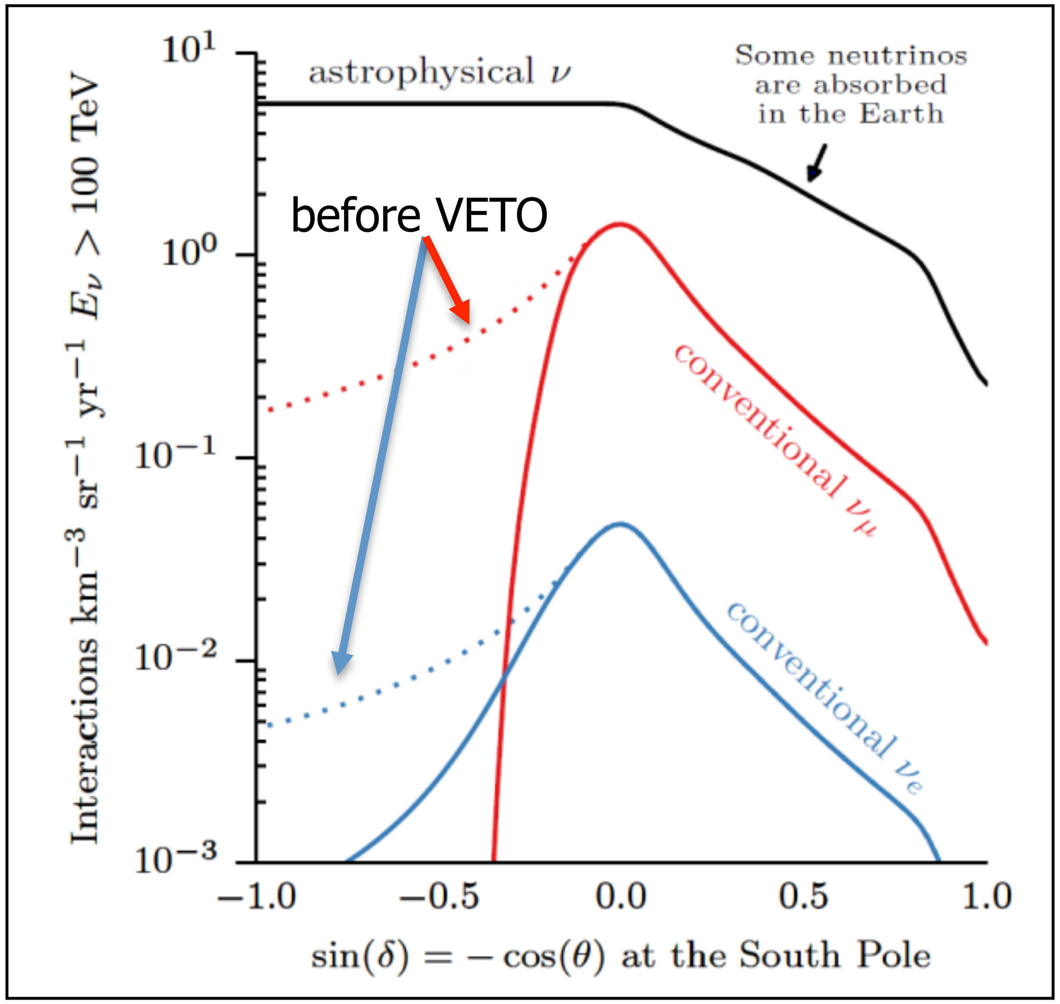
Atmospheric Neutrinos and the Veto





Atmospheric Neutrino Veto

Schönert, Gaisser, Resconi and Schulz, *Phys. Rev*. D79, 043009 (2009),
Gaisser, Jero, Karle and van Santen, *Phys. Rev*. D90, 023009 (2014)



- Up-down asymmetry due to veto is an important observable

Atmospheric Neutrino Veto

Schönert, Gaisser, Resconi and Schulz, *Phys. Rev*. D79, 043009 (2009),
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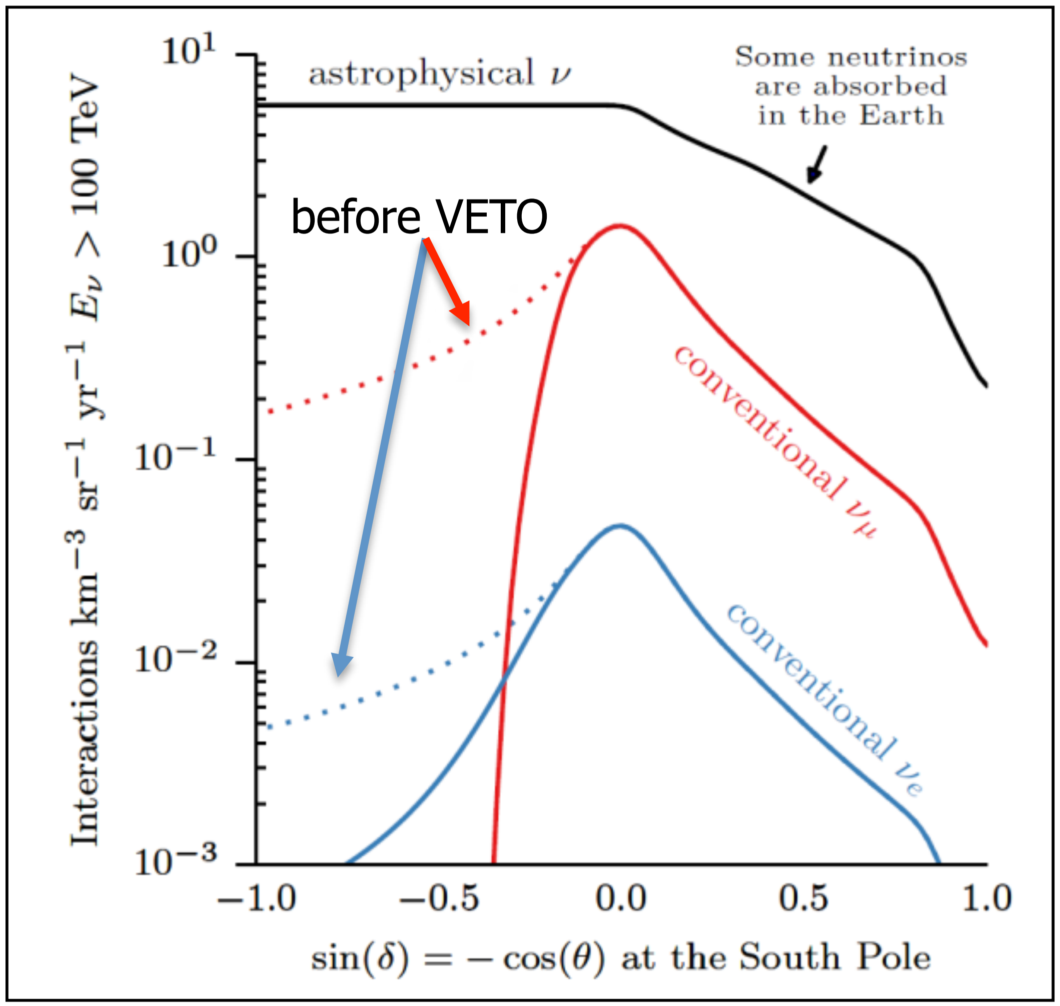
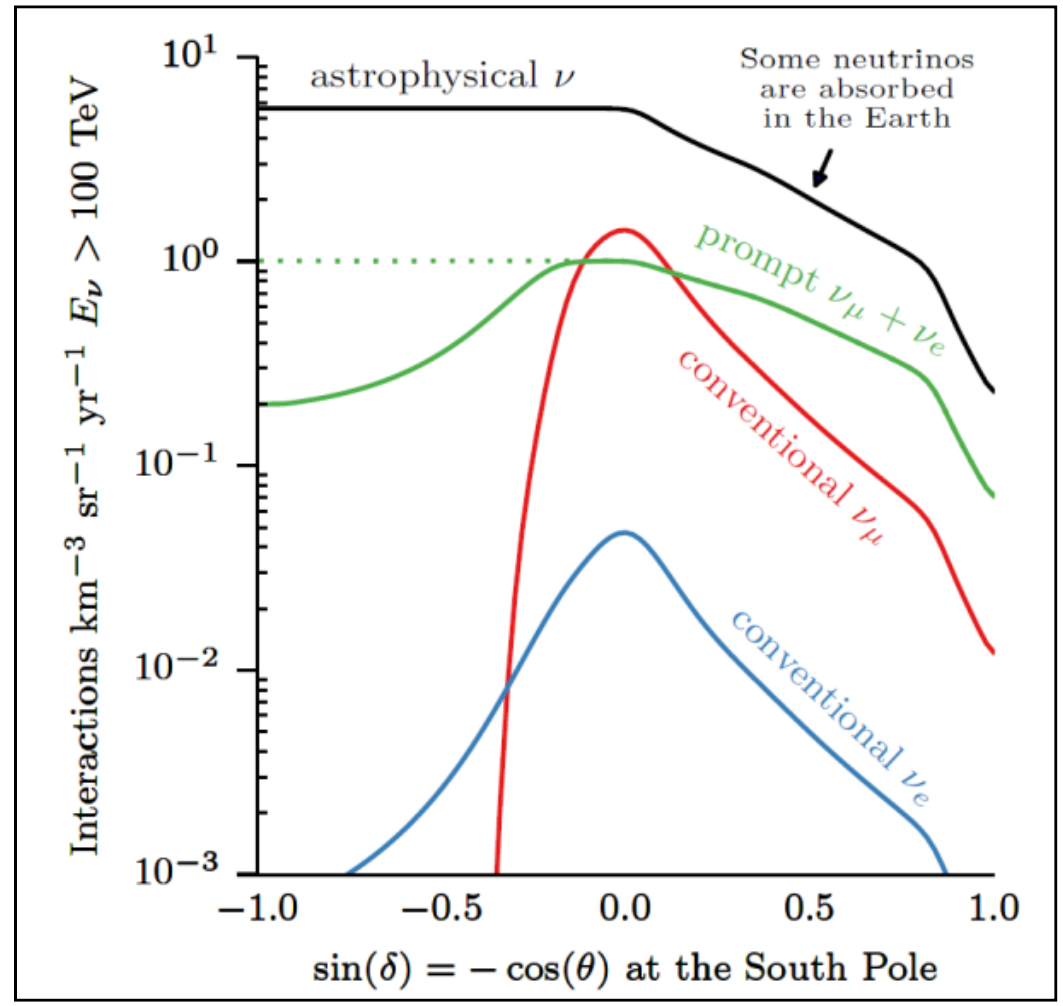
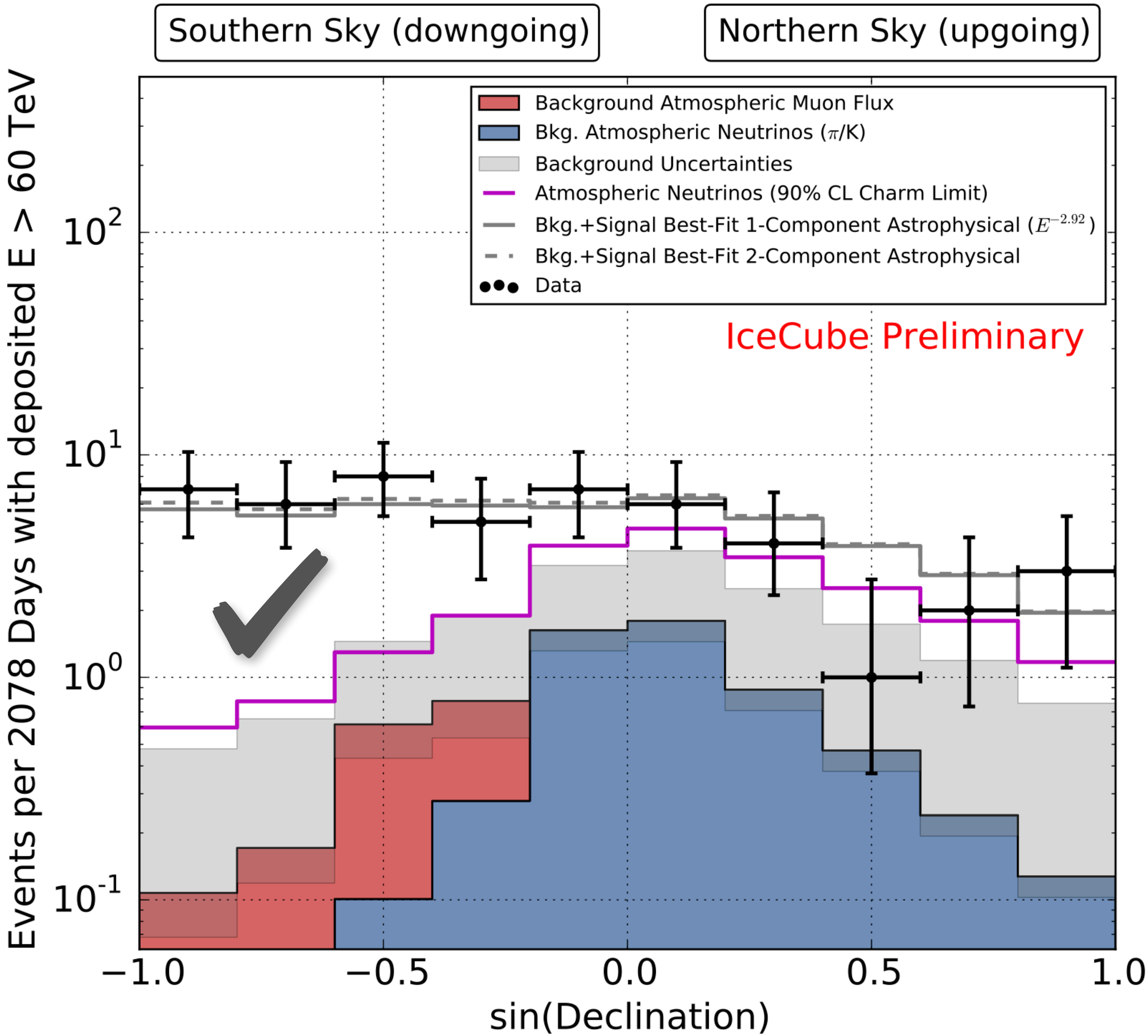




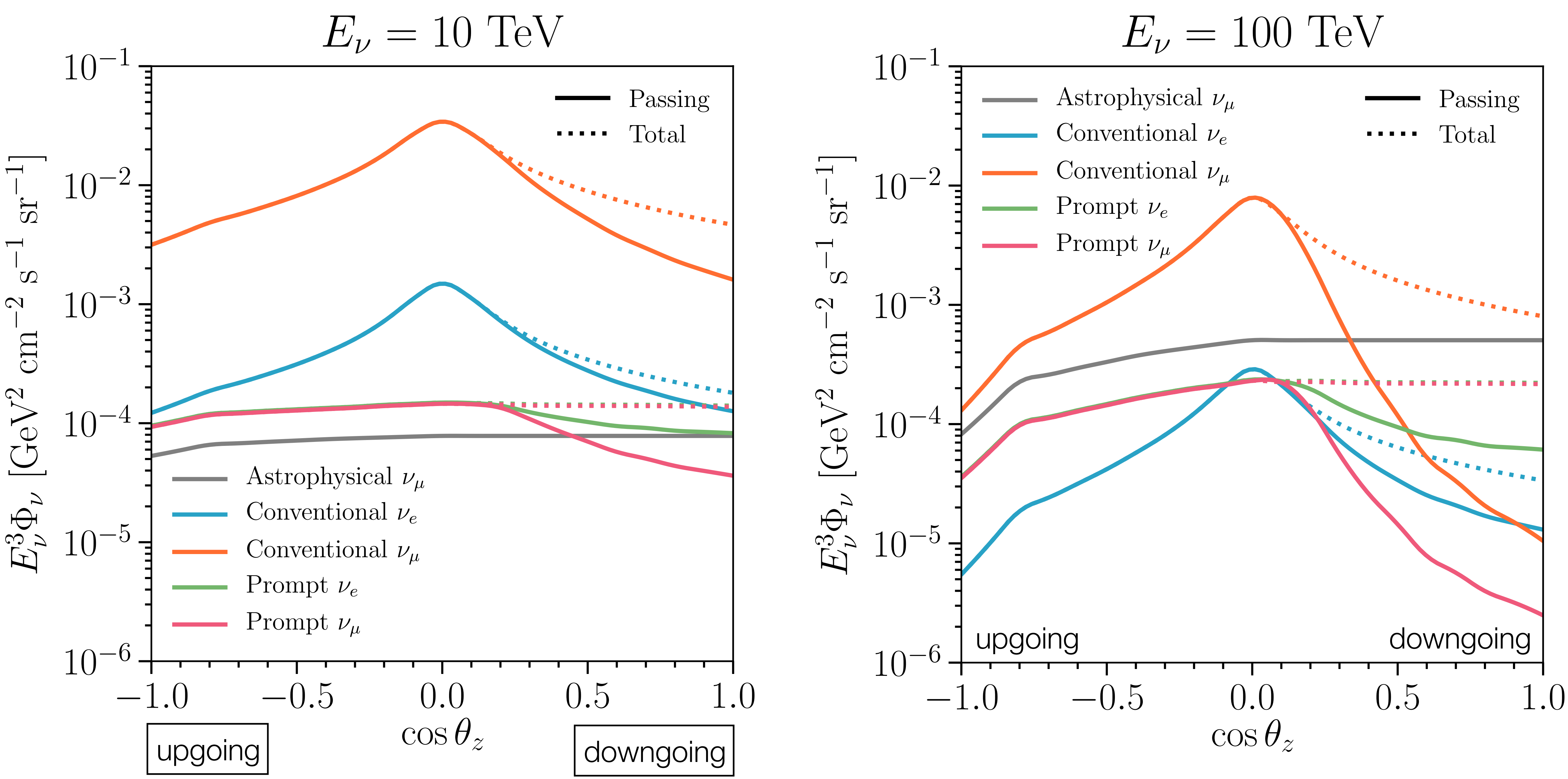
- Up-down asymmetry due to veto is an important observable
  - Prompt contributions from charm uncertain – angular distributions critical



Southern Sky (downgoing)
Northern Sky (upgoing)
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit 1-Component Astrophysical ($E^{-2.92}$)
Bkg.+Signal Best-Fit 2-Component Astrophysical
Data
IceCube Preliminary
Events per 2078 Days with deposited E > 60 TeV
10^{2}
10^{1}
10^{0}
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

New Veto Calculations

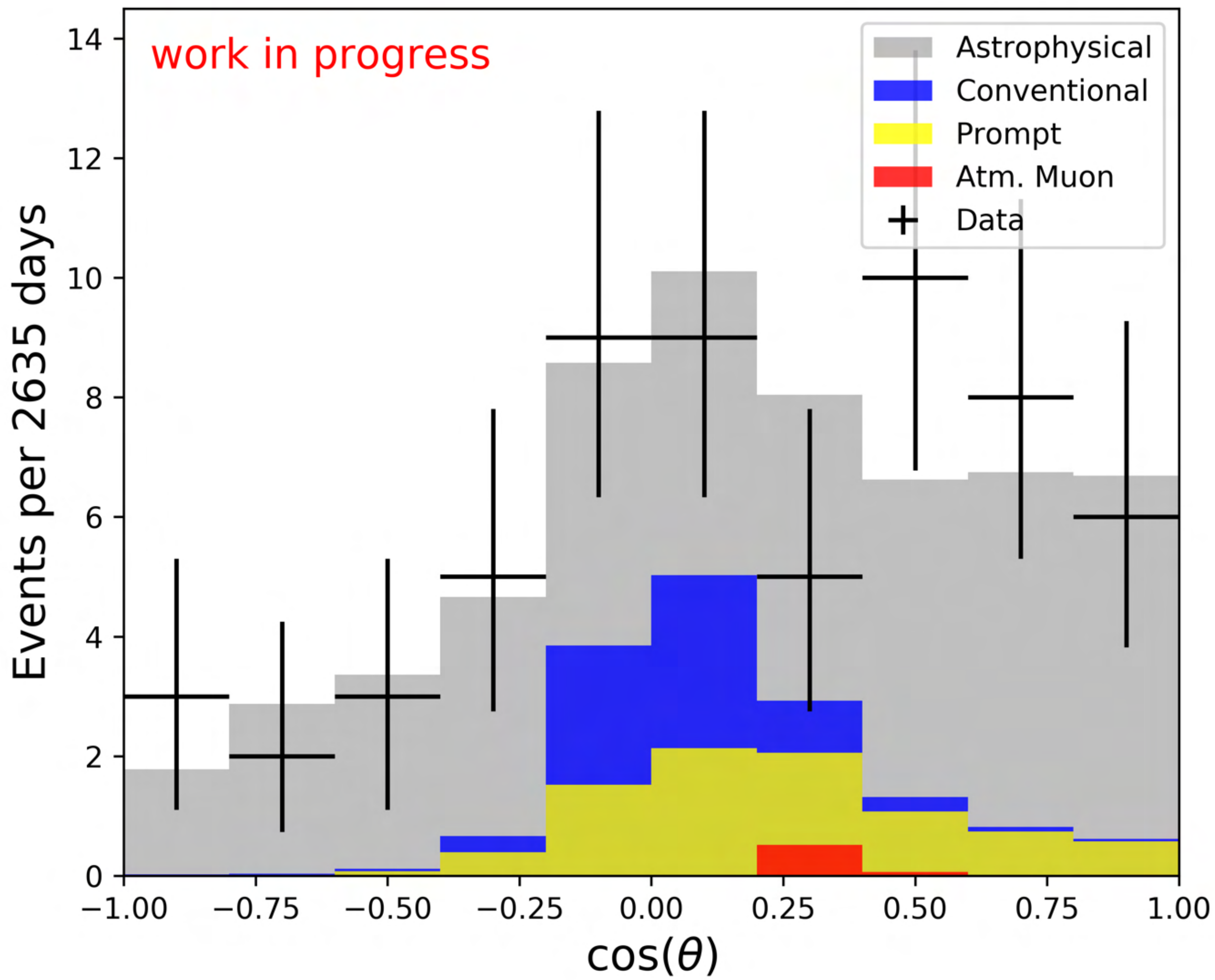
Argüelles, Palomares-Ruiz, Schneider, Wille, and Yuan, arXiv:1805.1103

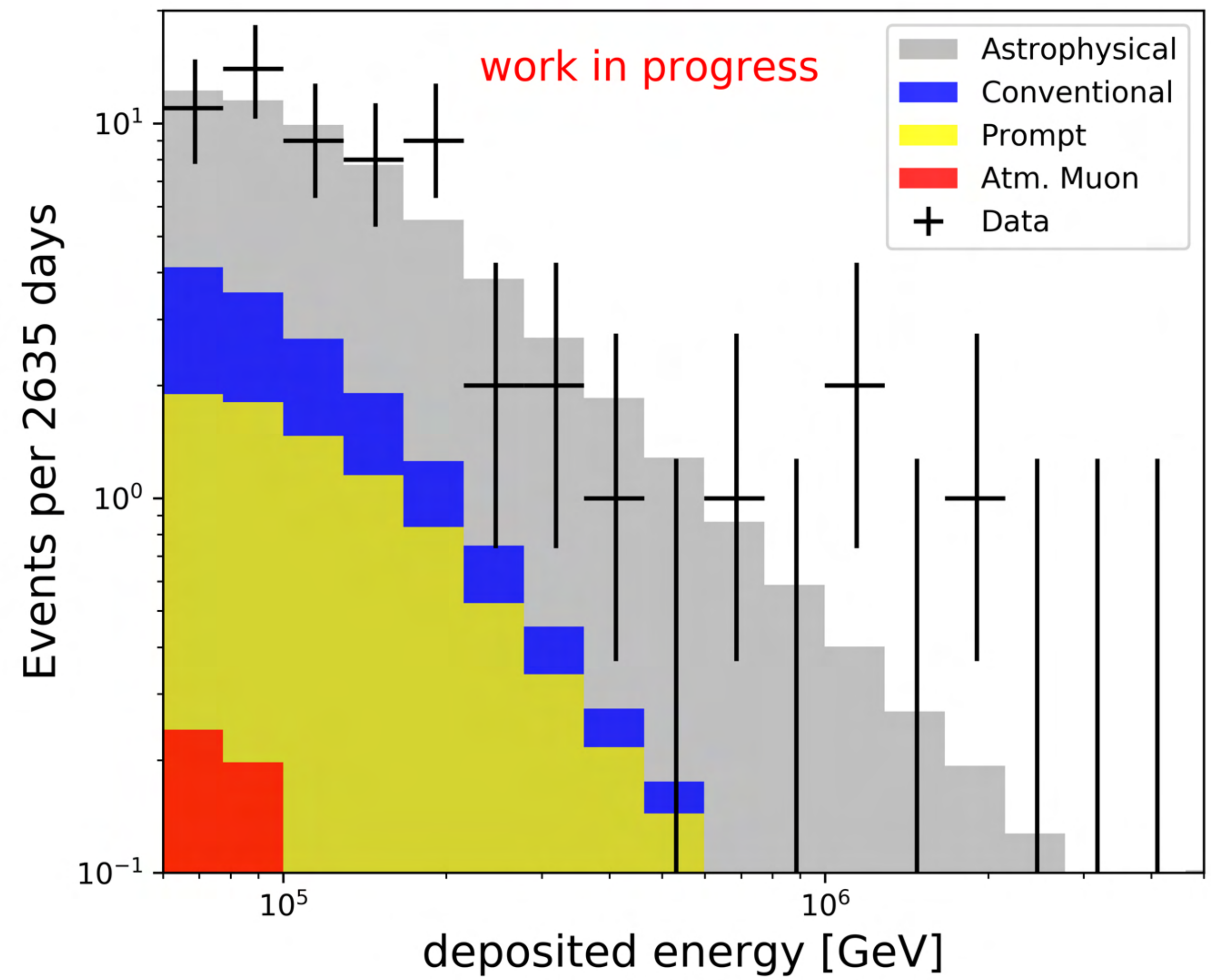


NB: axis reversed!

High Energy Starting Events: 7.5 Years

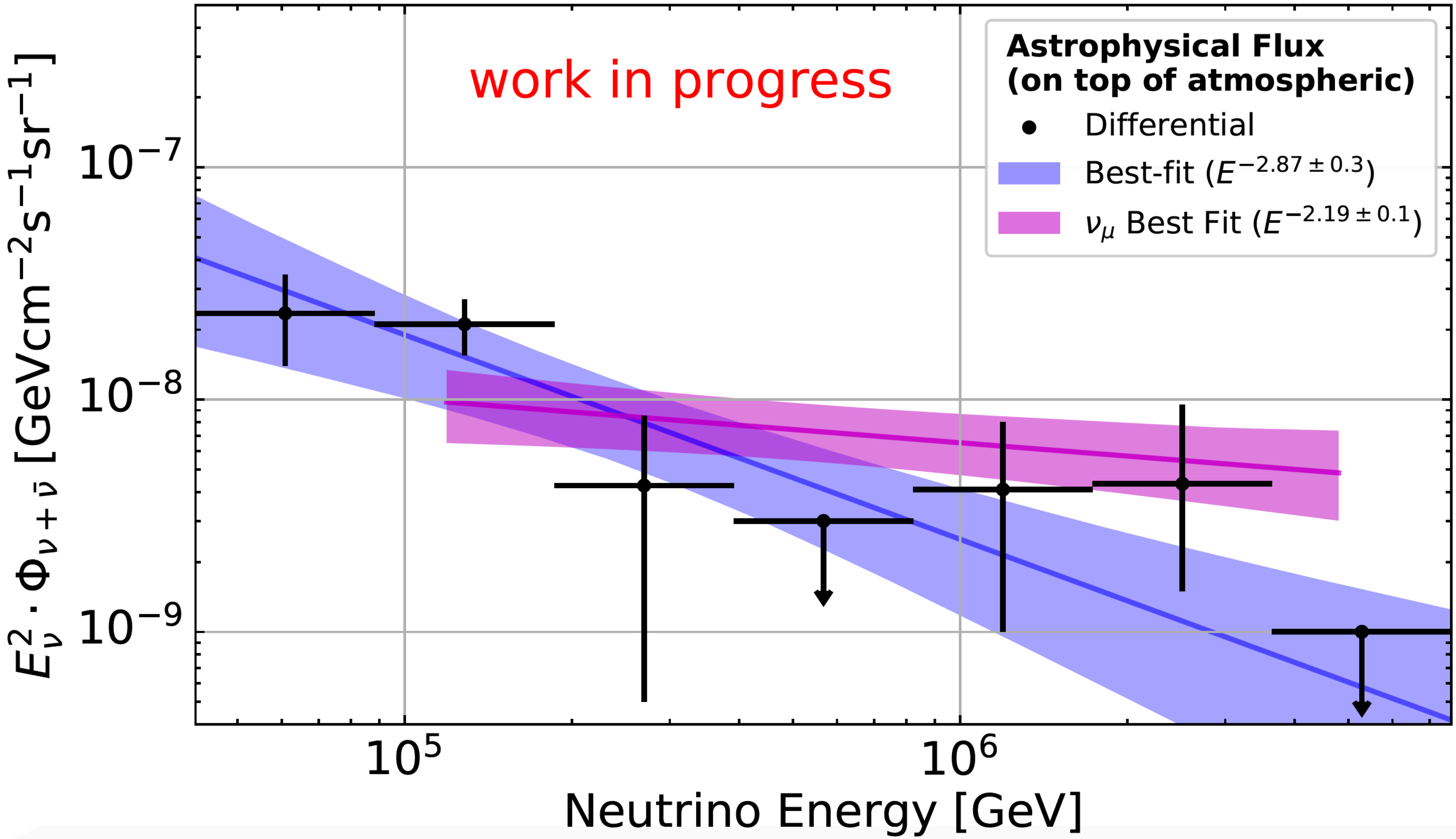
Bhattacharya, Enberg, Reno, Sarcevic, and Stasto, *JHEP* 1506, 110 (2015)



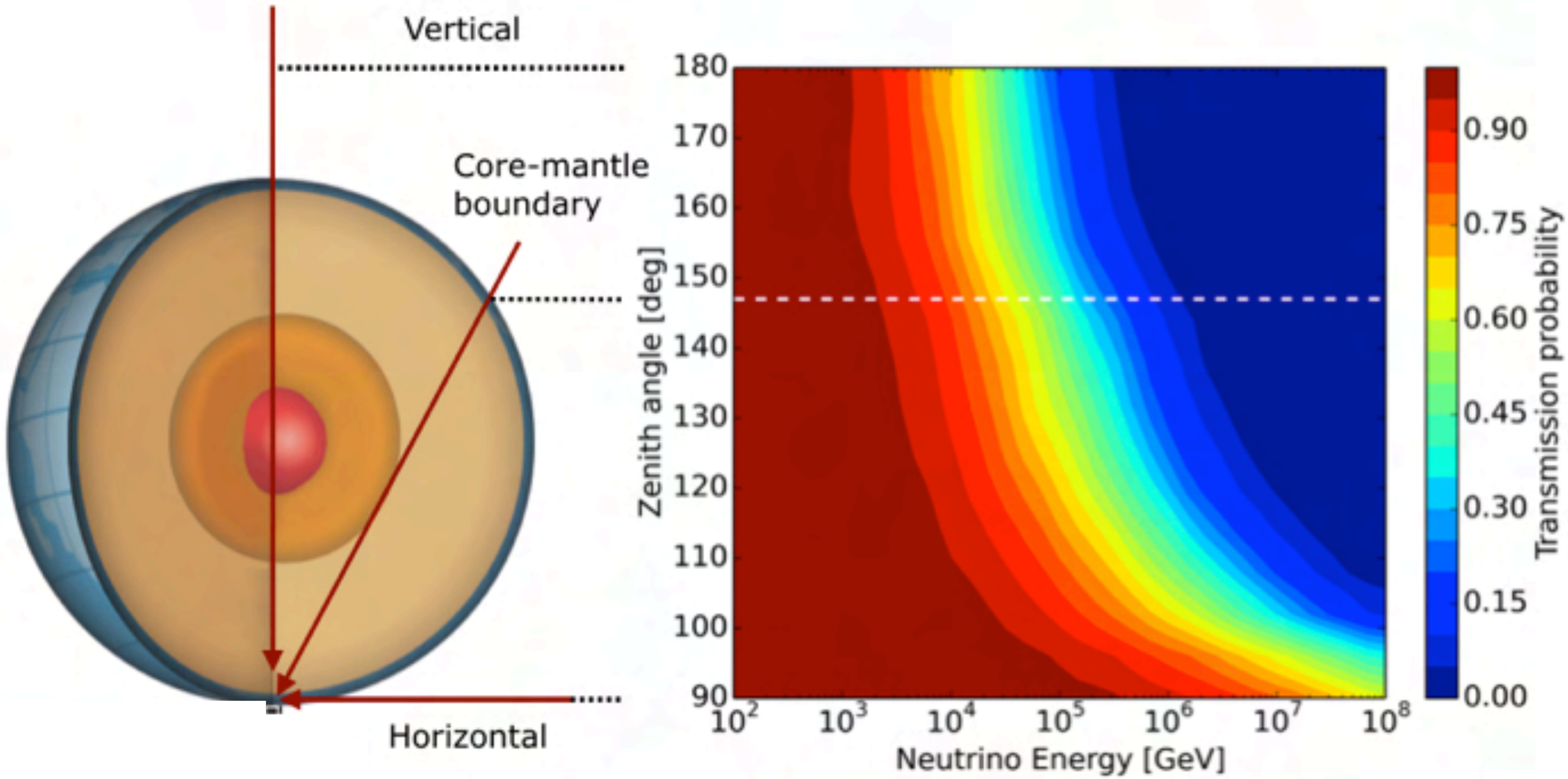


- Best fit now finds small but non-zero prompt contribution (with very low significance: 8^{+10}_{-8} events)
    - Corresponds to 8x modern prompt flux calculations (with huge uncertainty)

Independent Channel: Upward-going Tracks



VHE Neutrino-Nucleon Cross Section

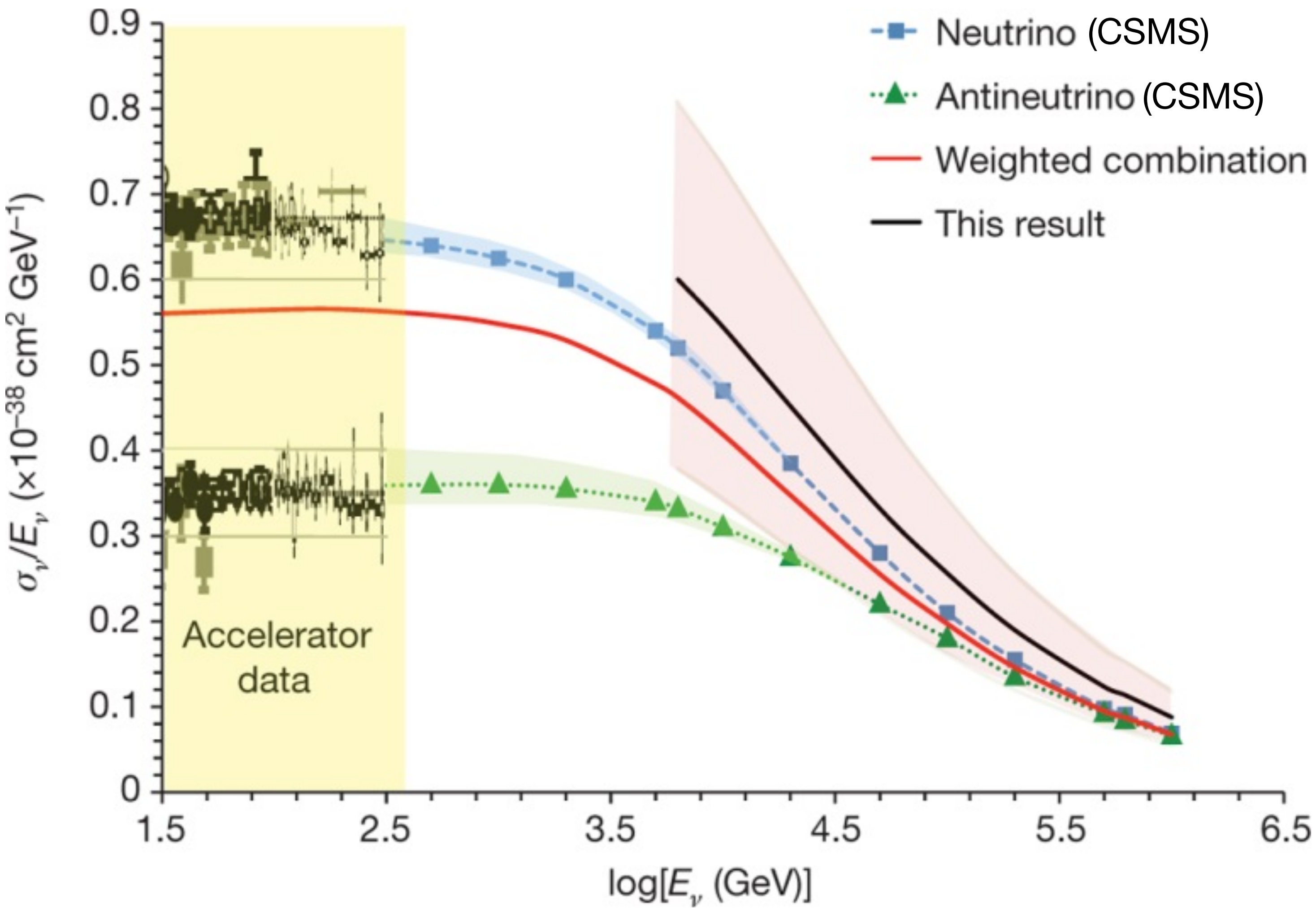


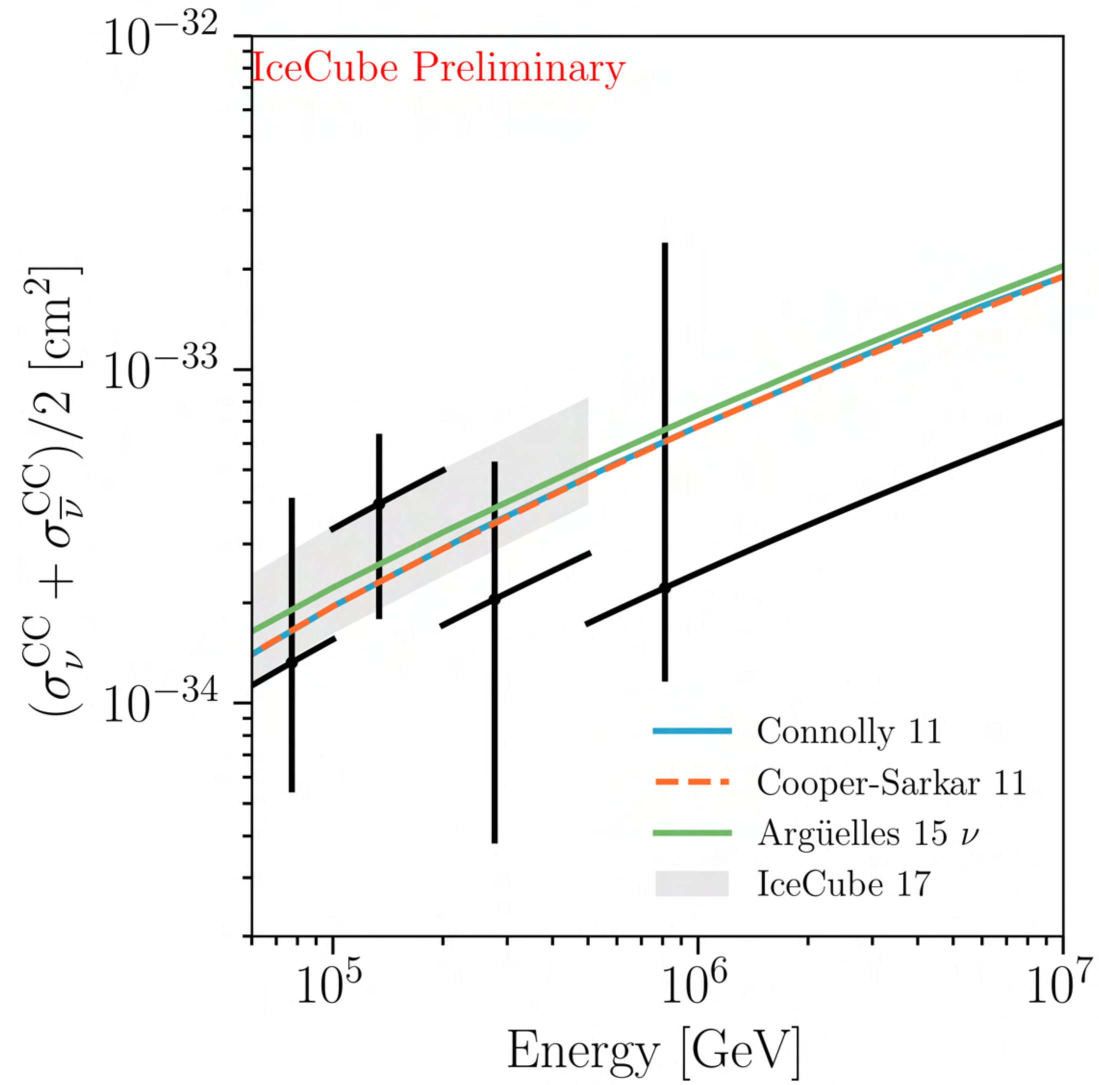
- Cross-section measurable by observing attenuation of the high energy neutrino flux (assumed isotropic) as a function of angle

High Energy Neutrino Interactions

Cooper-Sarkar *et al.*, *JHEP* 08, 042 (2011)
Connolly *et al*. *Phys. Rev*. D83, 113009 (2011)
Argüelles *et al*. *Phys. Rev*. D92, 074040 (2015)

M. Aartsen et al. (IceCube), *Nature* 551, 596 (2017)



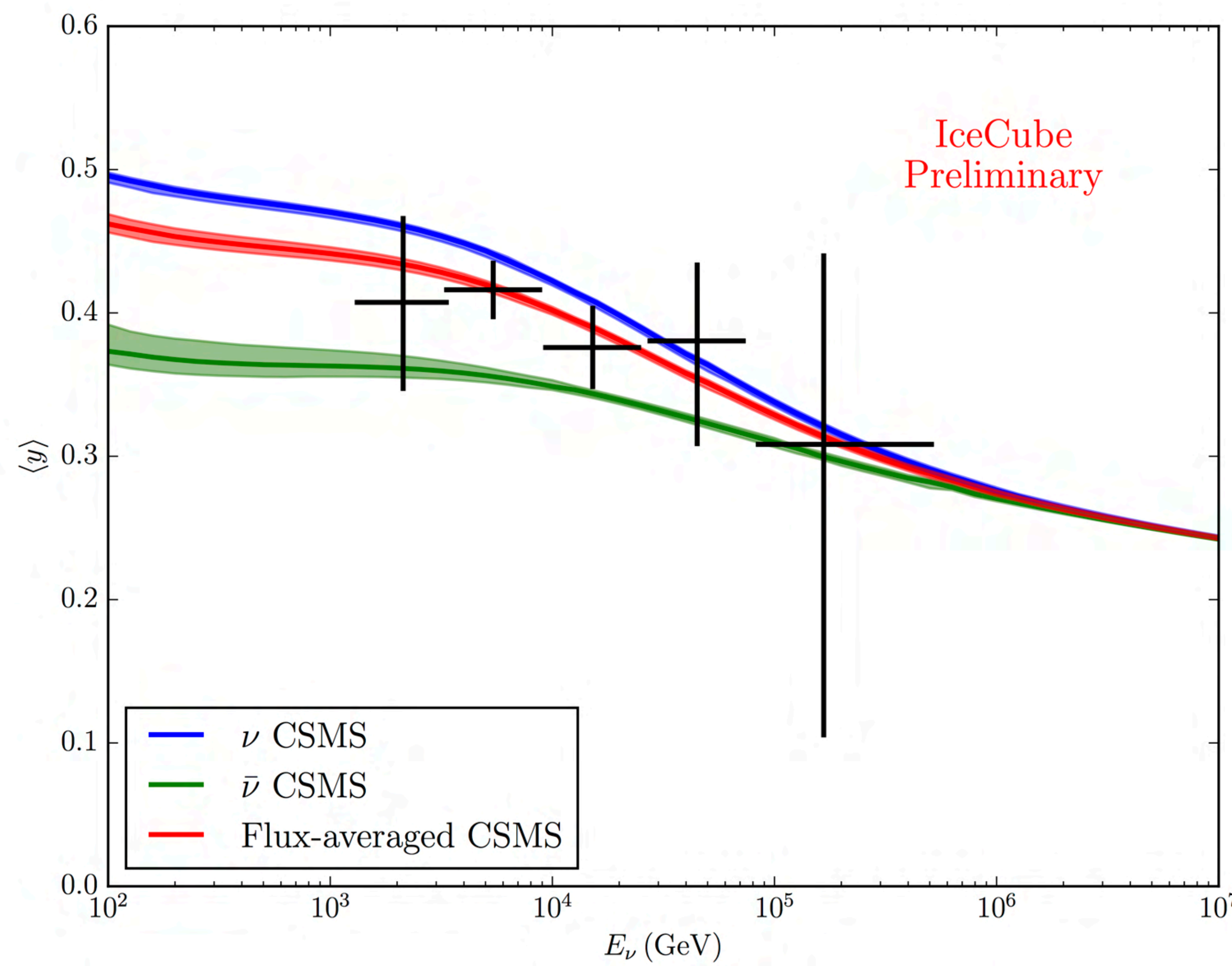


- Atmospheric flux provides neutrino data set extending to ~1 PeV
  - First (integrated) measurement in 2017, new quasi-differential measurement

Inelasticity in VHE Neutrino Interactions

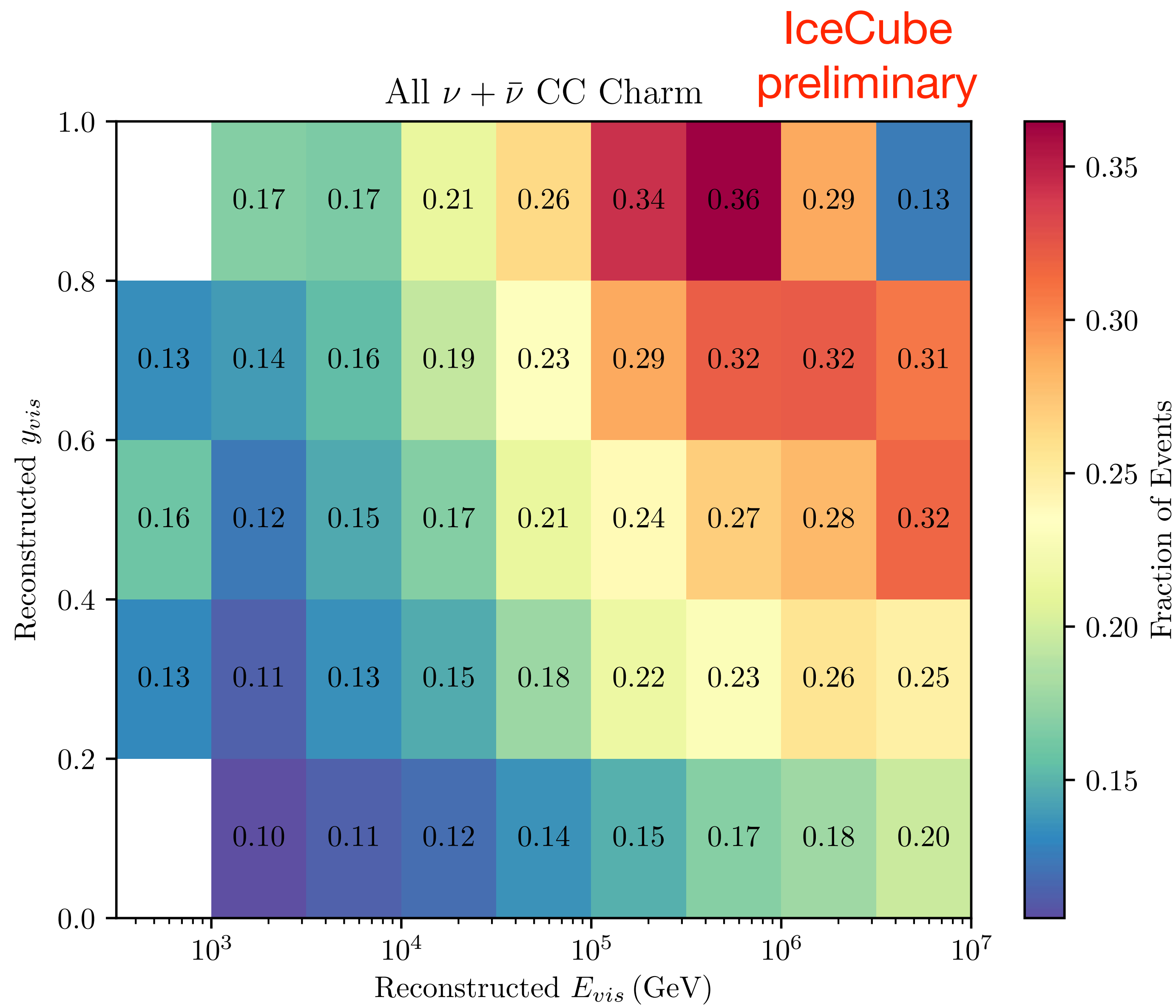
Cooper-Sarkar *et al.*, *JHEP* 08, 042 (2011)

- Measure $(\nu_\mu + \bar{\nu}_\mu)$ inelasticity
  $y = E_c / E_\nu = E_c / (E_c + E_\mu)$
  by reconstructing energies of cascade at νN vertex and of outgoing μ track
  - Consistent with expectations for falling $\langle y \rangle$ from 1-100 TeV
- Also sensitive to $\nu/\bar{\nu}$ ratio of (flux)·(cross-section) below ~10 TeV
  - Observe $R_{\nu/\bar{\nu}} = 0.77^{+0.44}_{-0.12}$ of expected $\nu/\bar{\nu}$ ratio



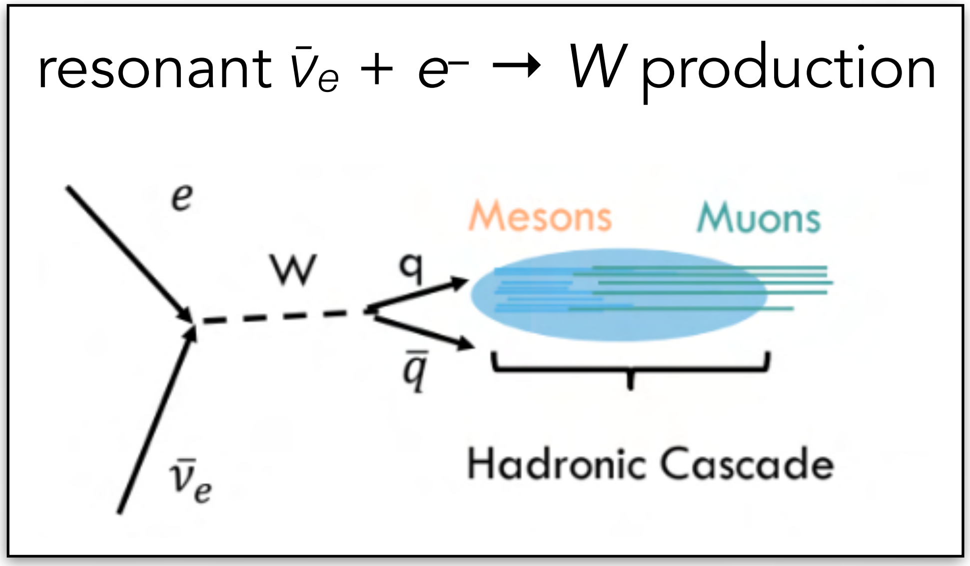
Charm Production in VHE Neutrino Interactions

- Charm production in *νN* vertex cascade measurable through characteristic dependence on y_{vis} vs. E_{vis}
  - Low-energy muons from decay of charmed mesons emerge from *νN* cascade
- Charm production measured at $R_{CC,charm} = 0.93^{+0.73}_{-0.59}$ of the expected level
  - Zero charm excluded at 91% CL

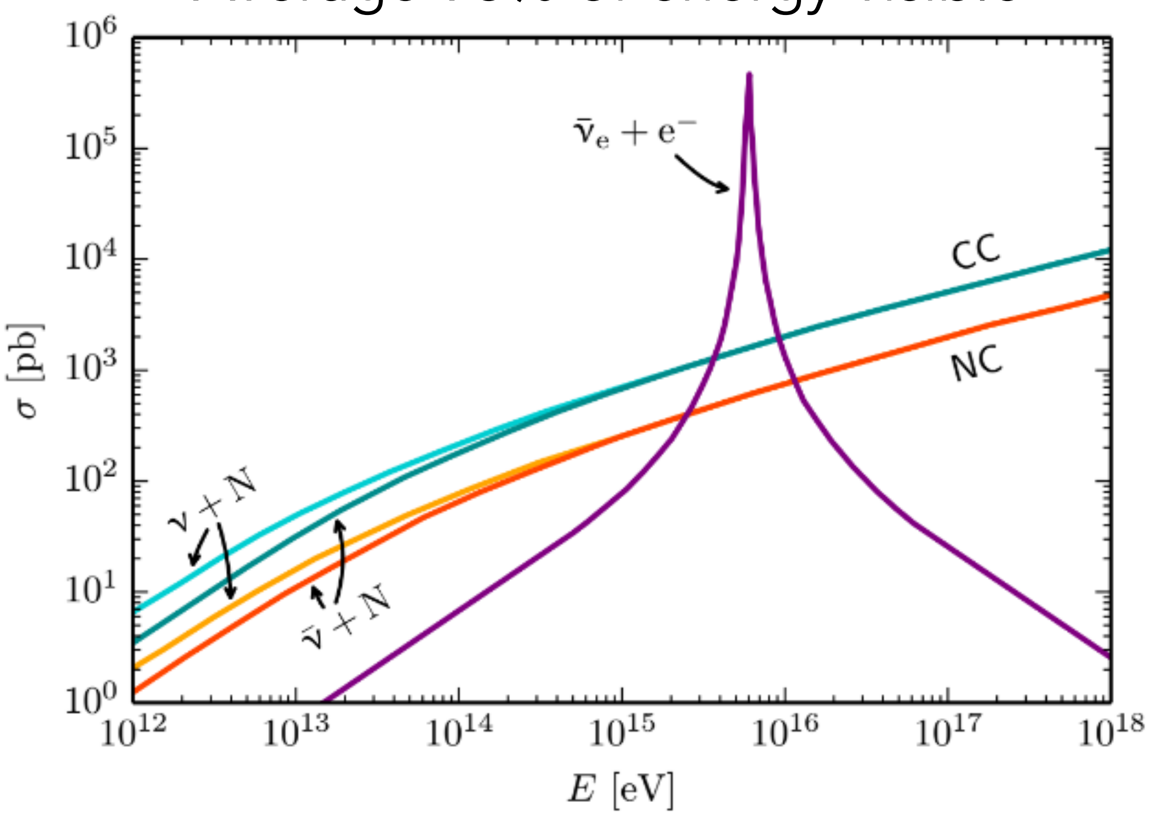


A Glashow Resonance Candidate?

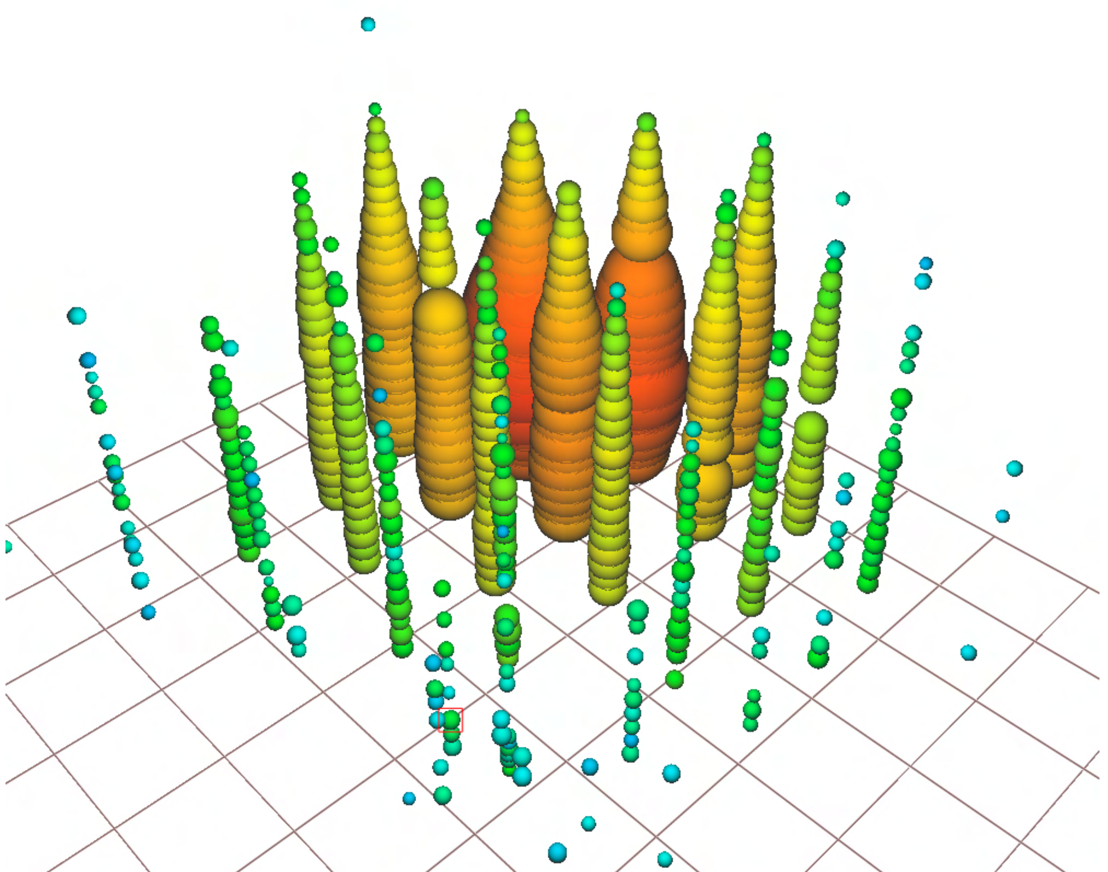
arXiv:1710.01191 (ICRC 2017)



Resonance at $E\nu$ = 6.3 PeV
Average 93% of energy visible



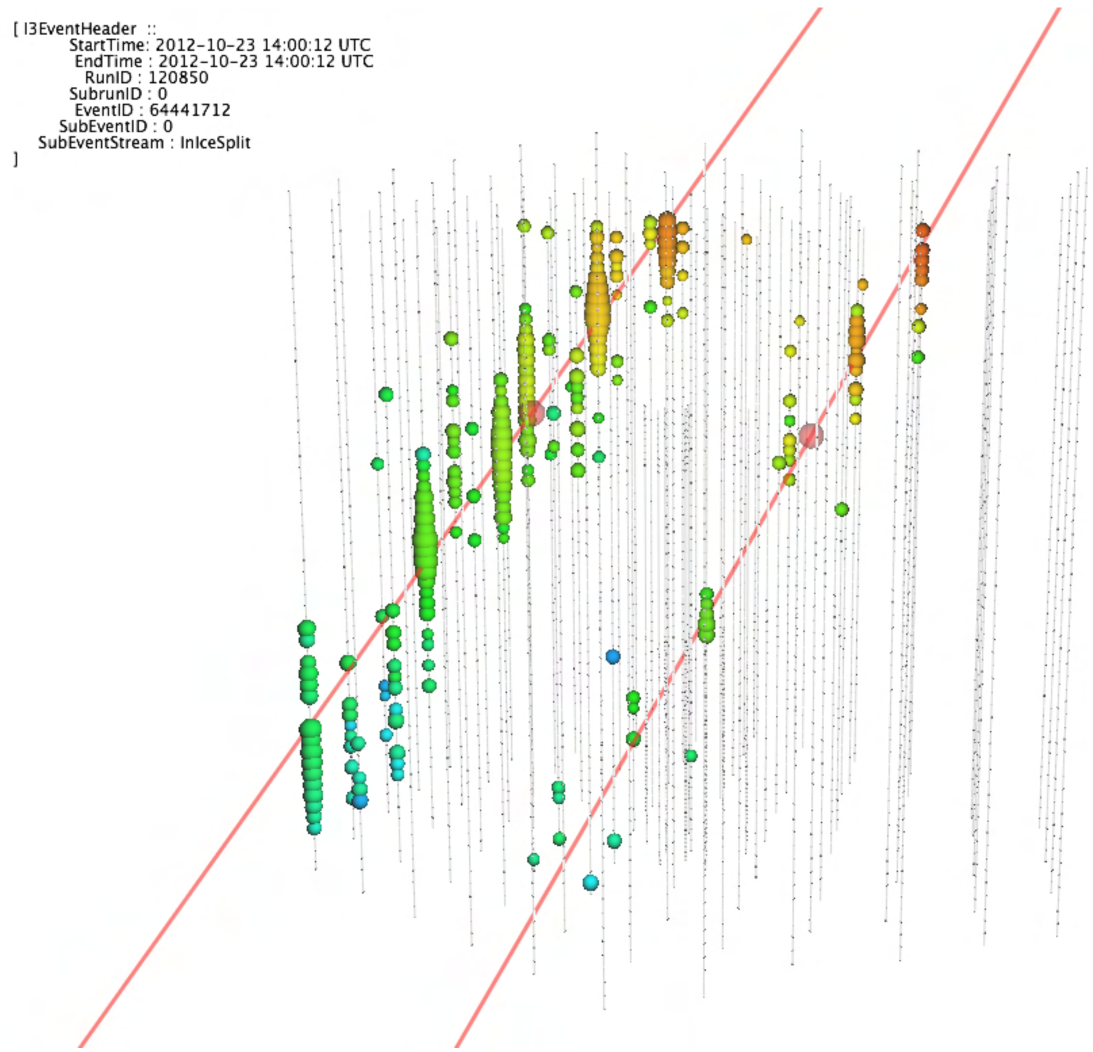
Work in progress

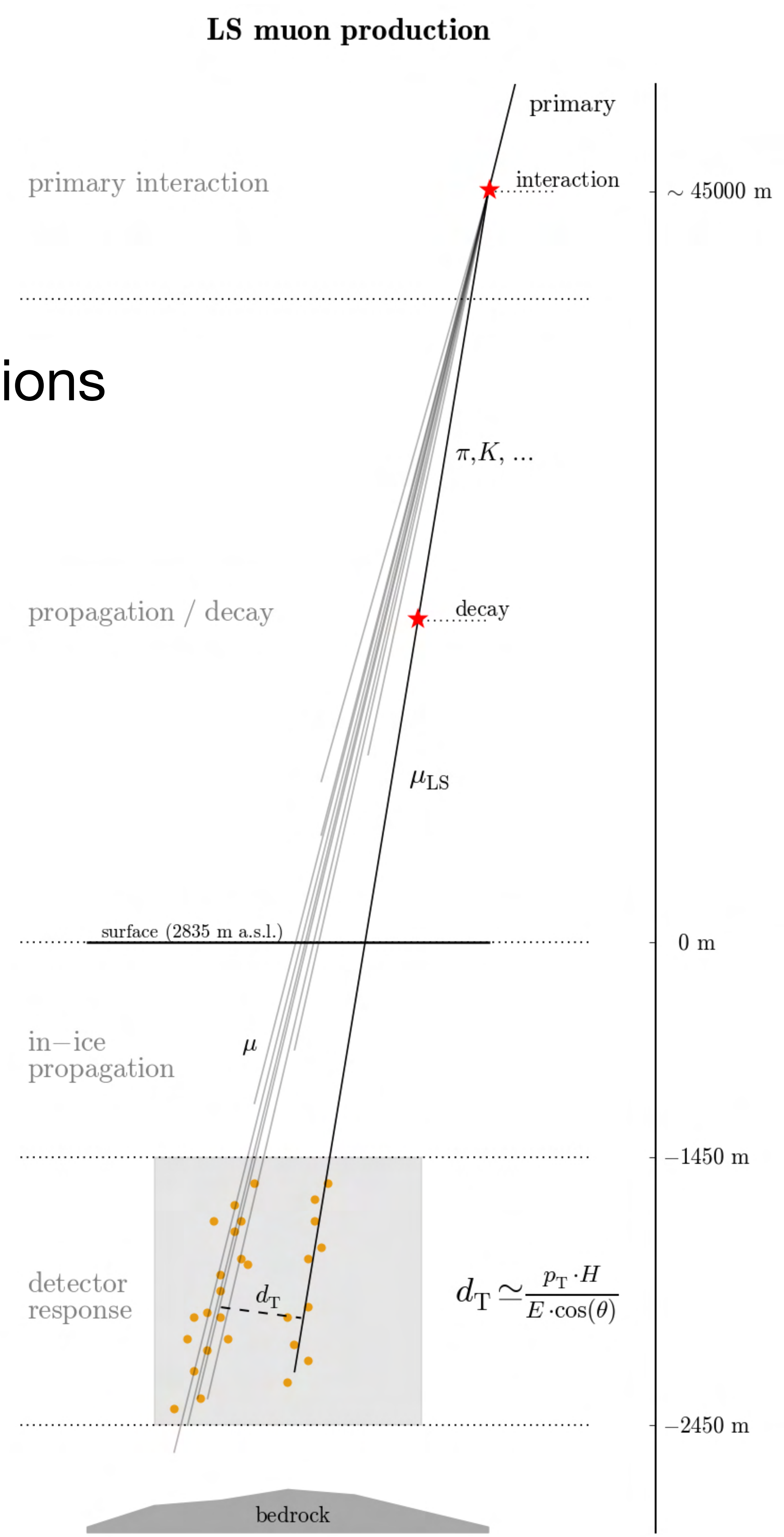


Partially-contained event (reco challenging)
Background levels under investigation
Deposited EM-equivalent energy of
5.9±0.18 PeV (stat. only)

Laterally Separated Muons

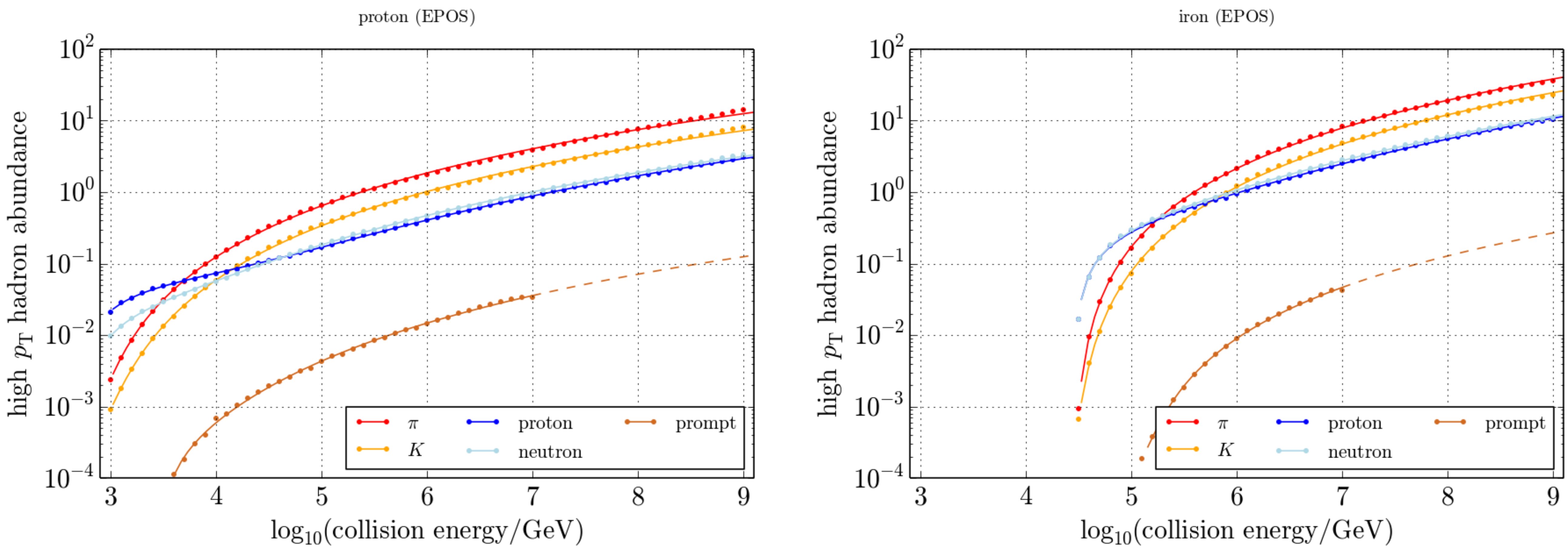
Reflect p_T distribution in cosmic ray-air interactions





Laterally Separated Muons

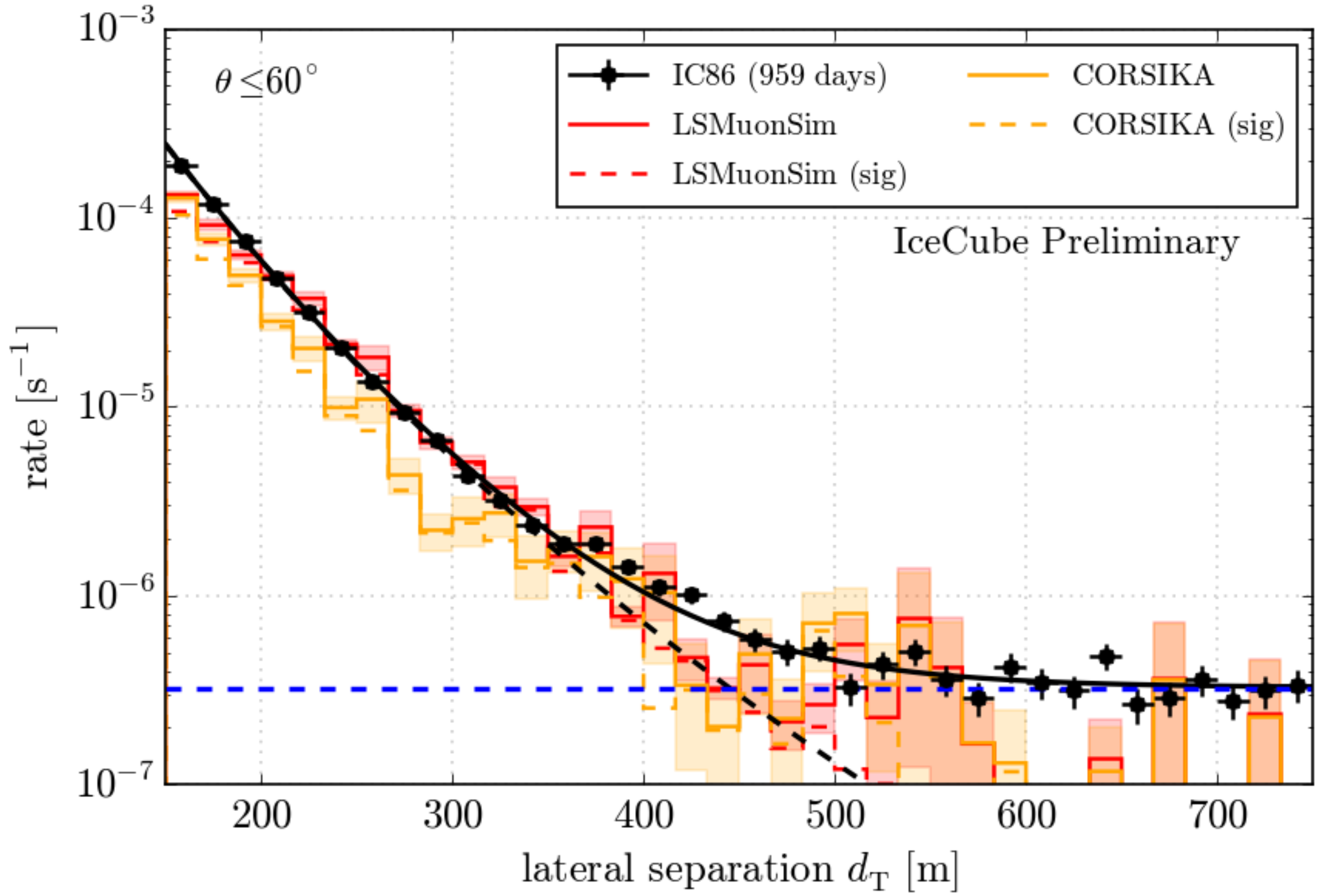
Total shower energy observed depends on E_{CR},
p_T distribution depends on E_{CR}/A



Laterally separated muons provide constraint on cosmic ray composition – or probe hadronic interactions if composition known

Laterally Separated Muons

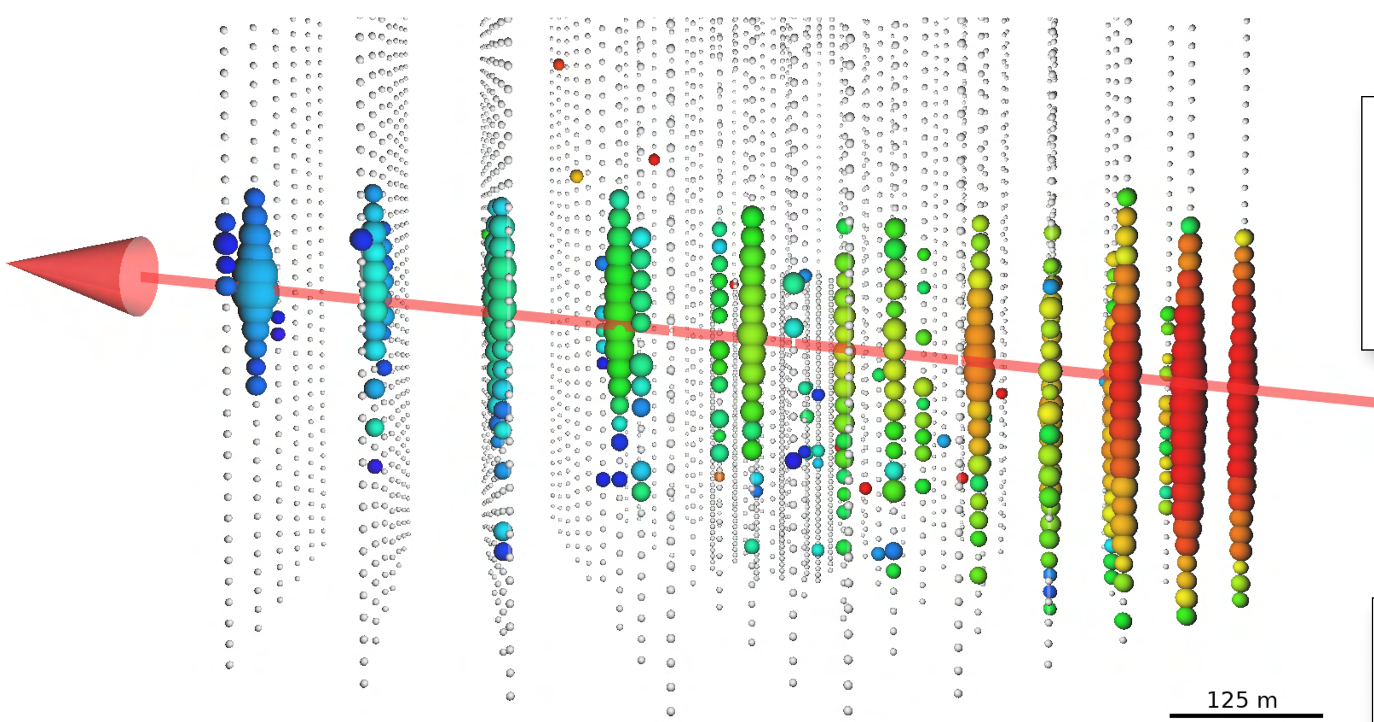
Fit to Hagedorn function of the form $\frac{dN}{d(d_\mathrm{T})} = \alpha \cdot \left(1 + \frac{d_\mathrm{T}}{d_0}\right)^{\beta}$



Transition from exponential to power-law behavior observed – work in progress

Multi-Messenger Observations

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy
neutrino candidate event
[…]
On 22 Sep, 2017 IceCube detected a track-like, very-high-energy
event with a high probability of being of astrophysical origin. The
event was identified by the Extremely High Energy (EHE) track event
selection. The IceCube detector was in a normal operating state.[…]
```



Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.*

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

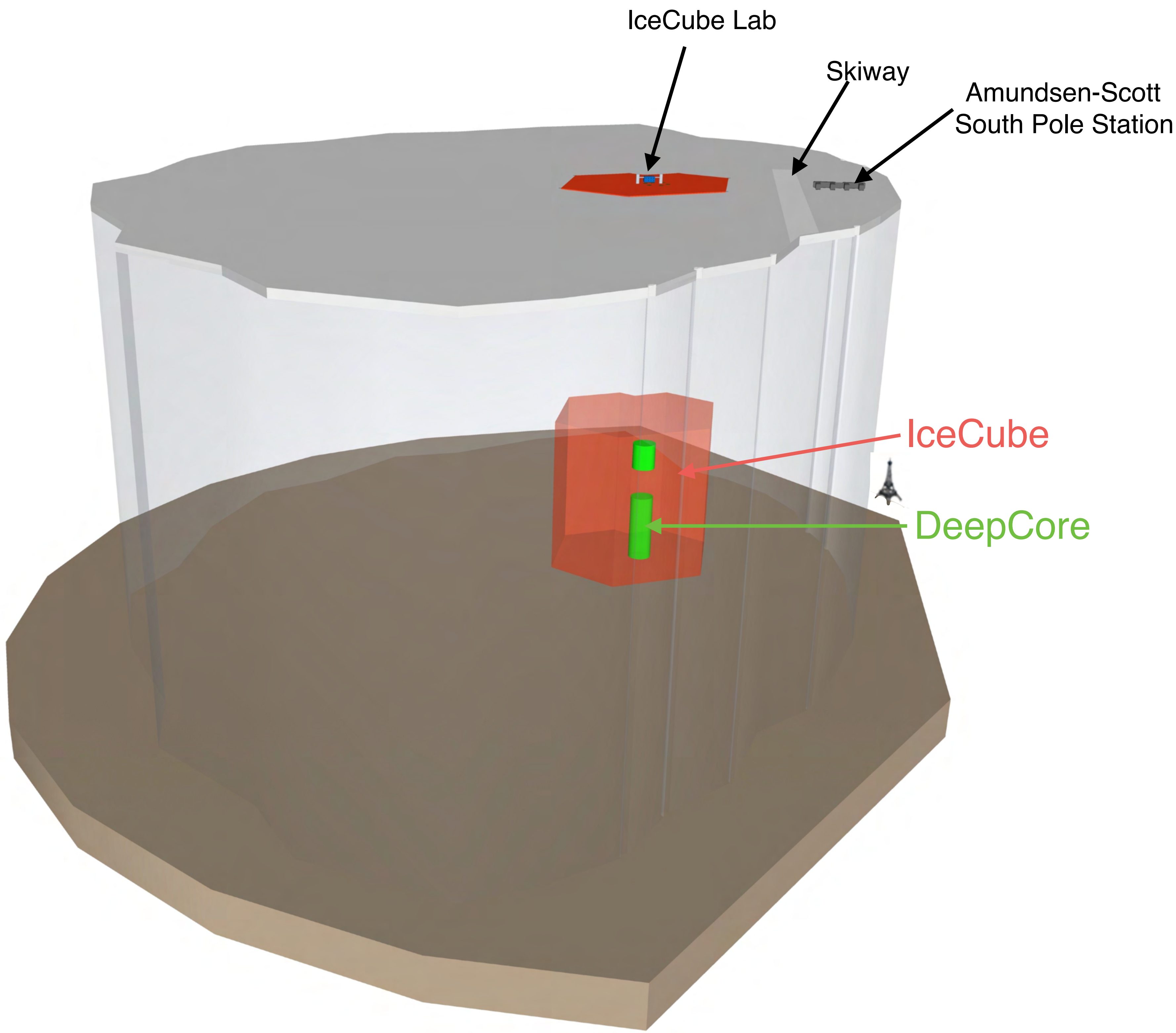
ATel #10845; *D. B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans (U. Leicester), C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)*
on 12 Oct 2017; 16:54 UT

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

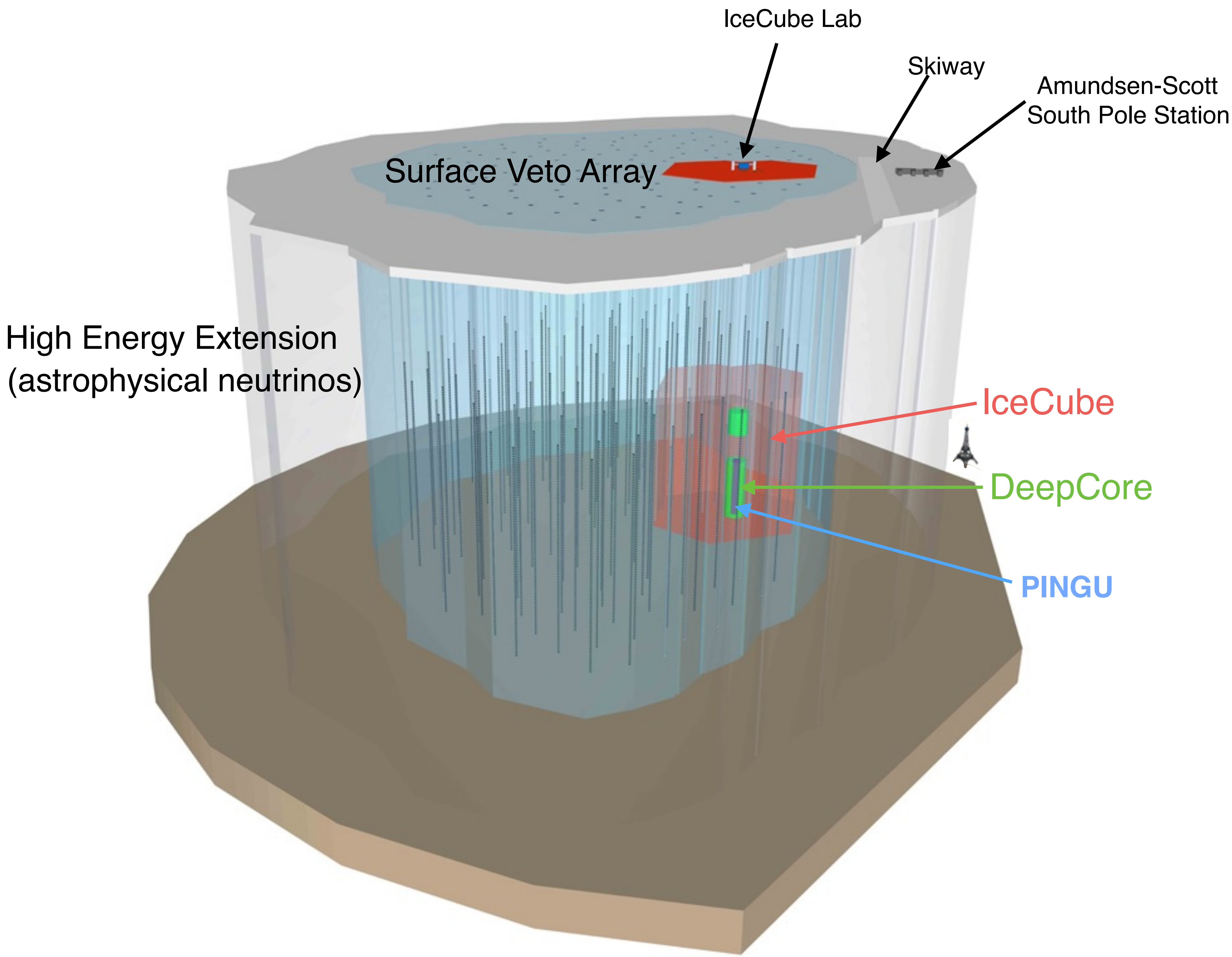
ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT

…stay tuned!

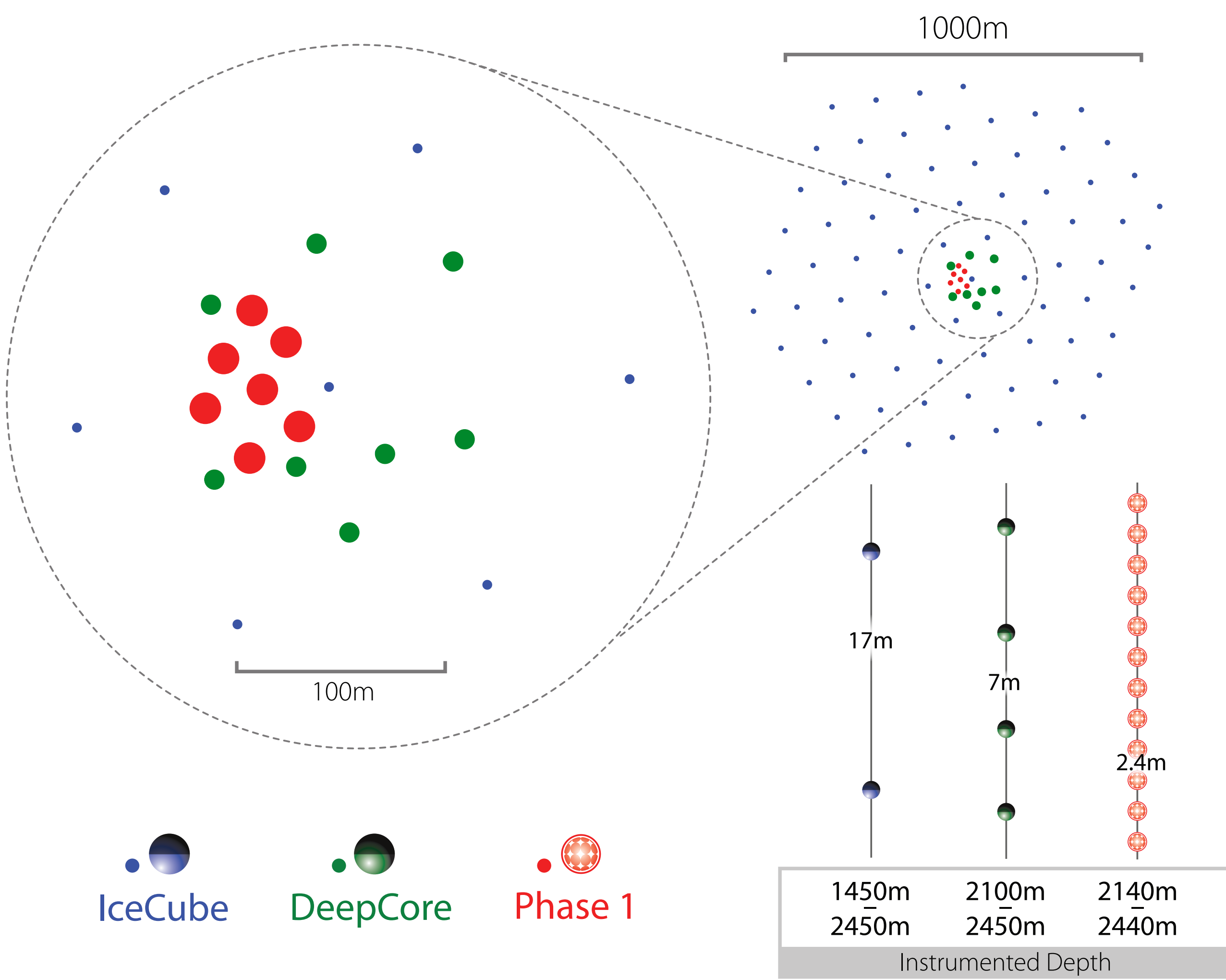
The Future: IceCube-Gen2

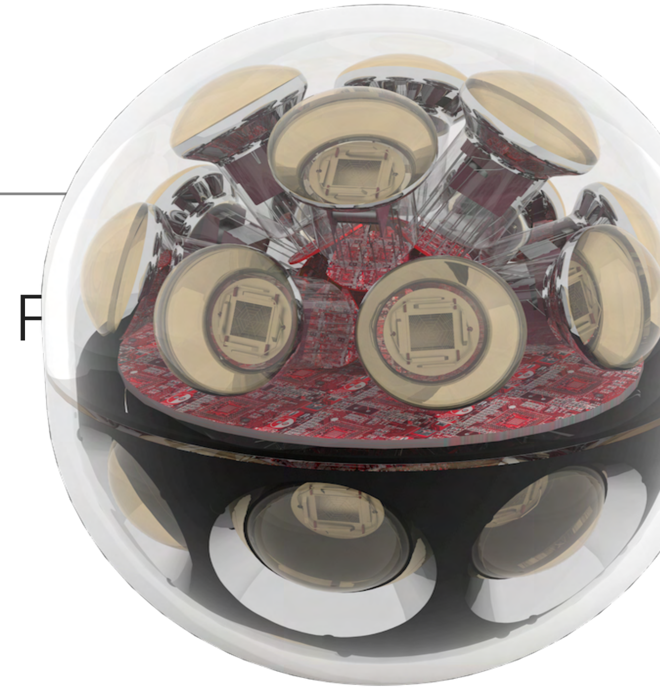


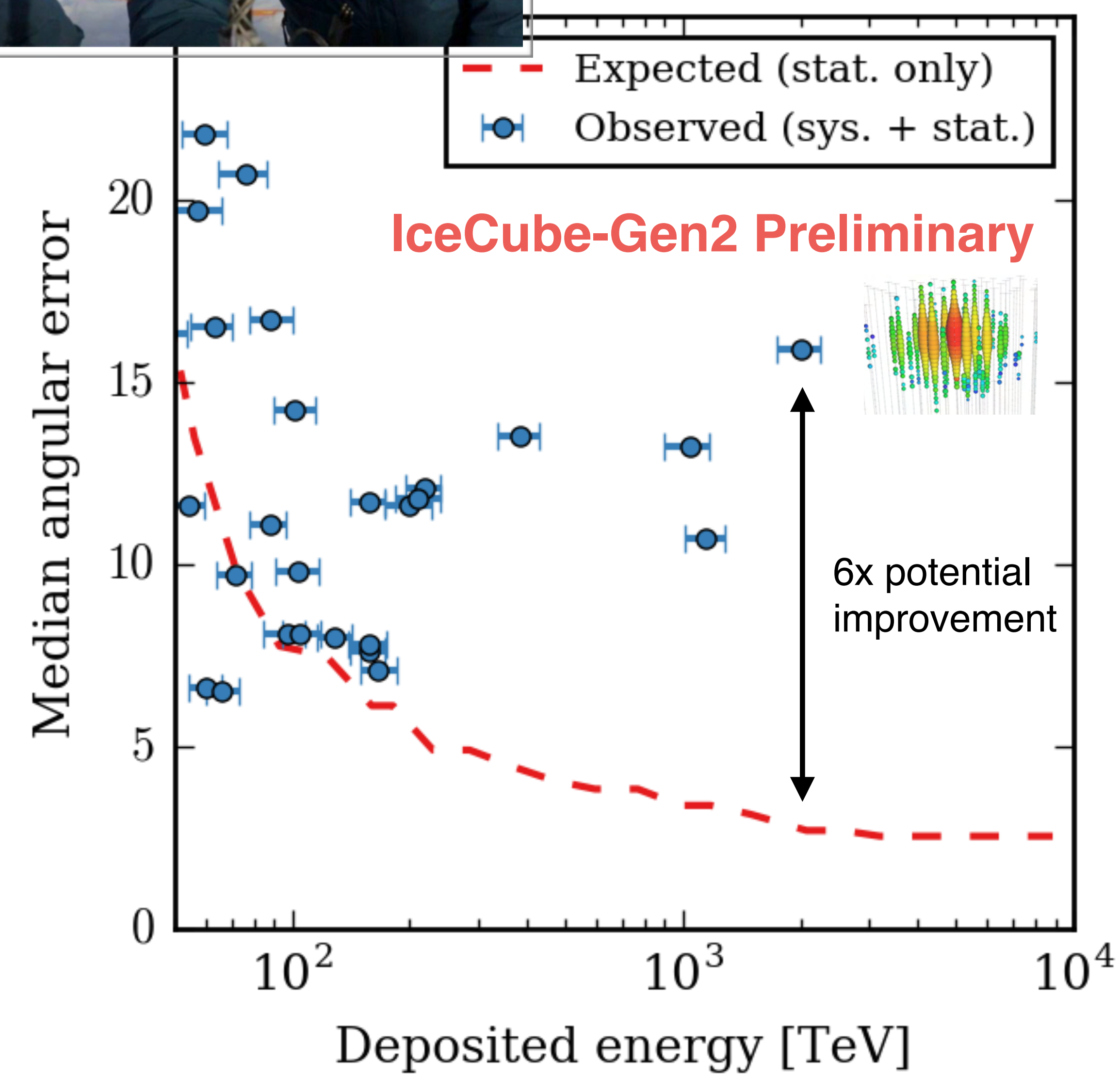
The Future: IceCube-Gen2



First Step: The IceCube Upgrade







- Seven strings of advanced instrumentation, plus an extensive calibration suite
  - Significantly enhance the science program at both high and low energy
  - Under review – news expected very soon

Conclusions and Outlook

- Neutrino astronomy is opening a new window on the high energy universe
- In addition, IceCube data provides a unique probe of neutrino physics from the GeV to the PeV scale and beyond
- Developments now underway for the next generation detector array
  - Potential for substantial improvements in the near term with the IceCube Upgrade

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

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NEW ZEALAND
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Sungkyunkwan University

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Stony Brook University
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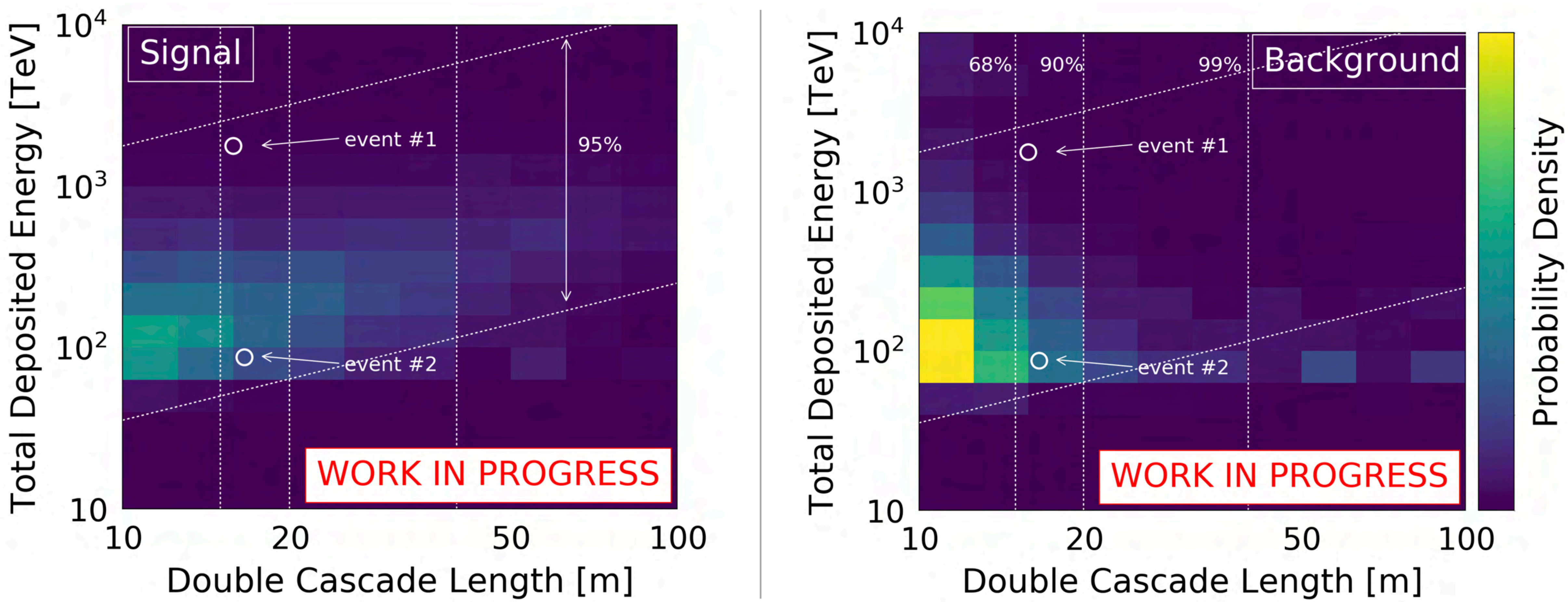
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and 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)

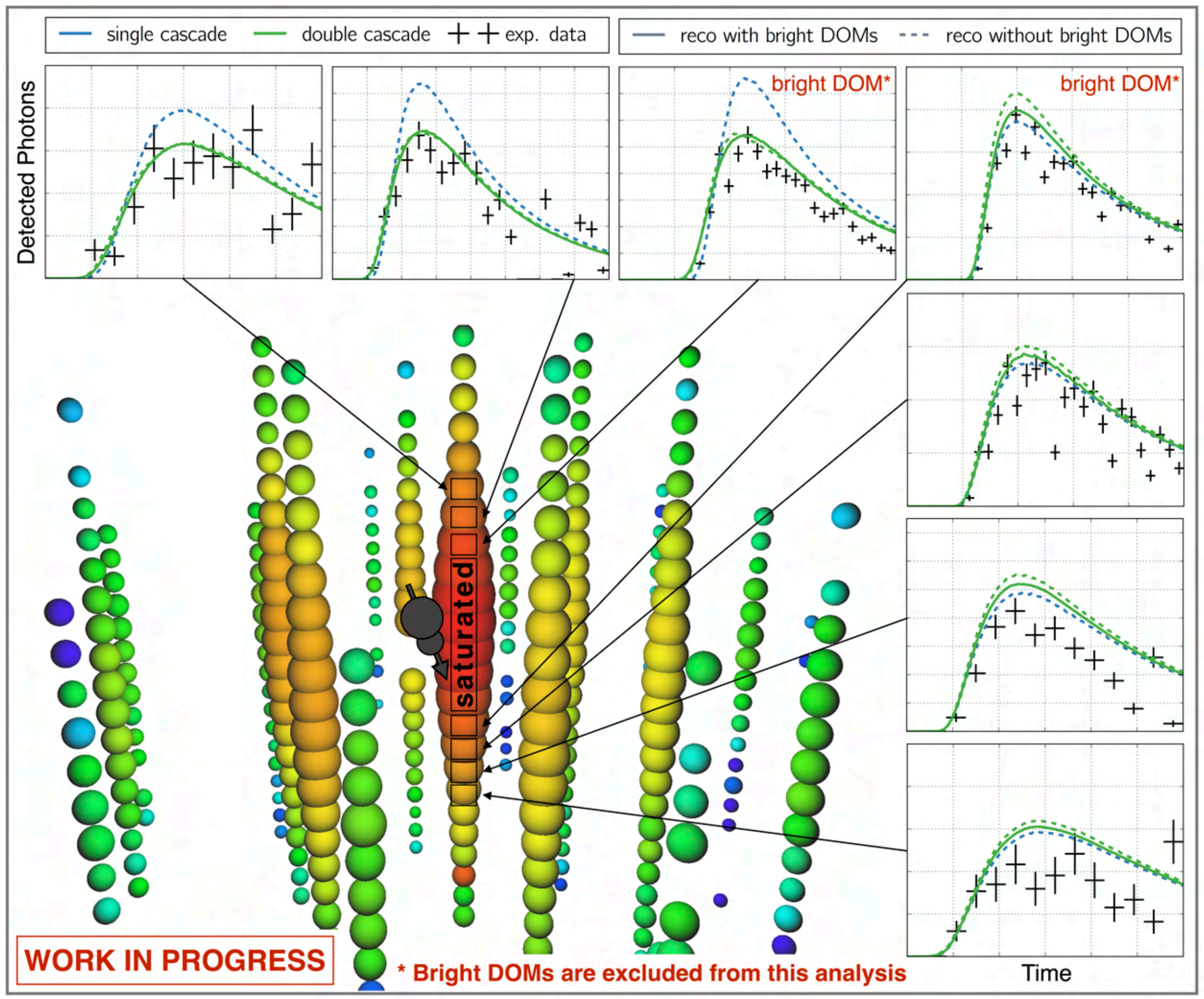
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

Searches for Tau Neutrinos

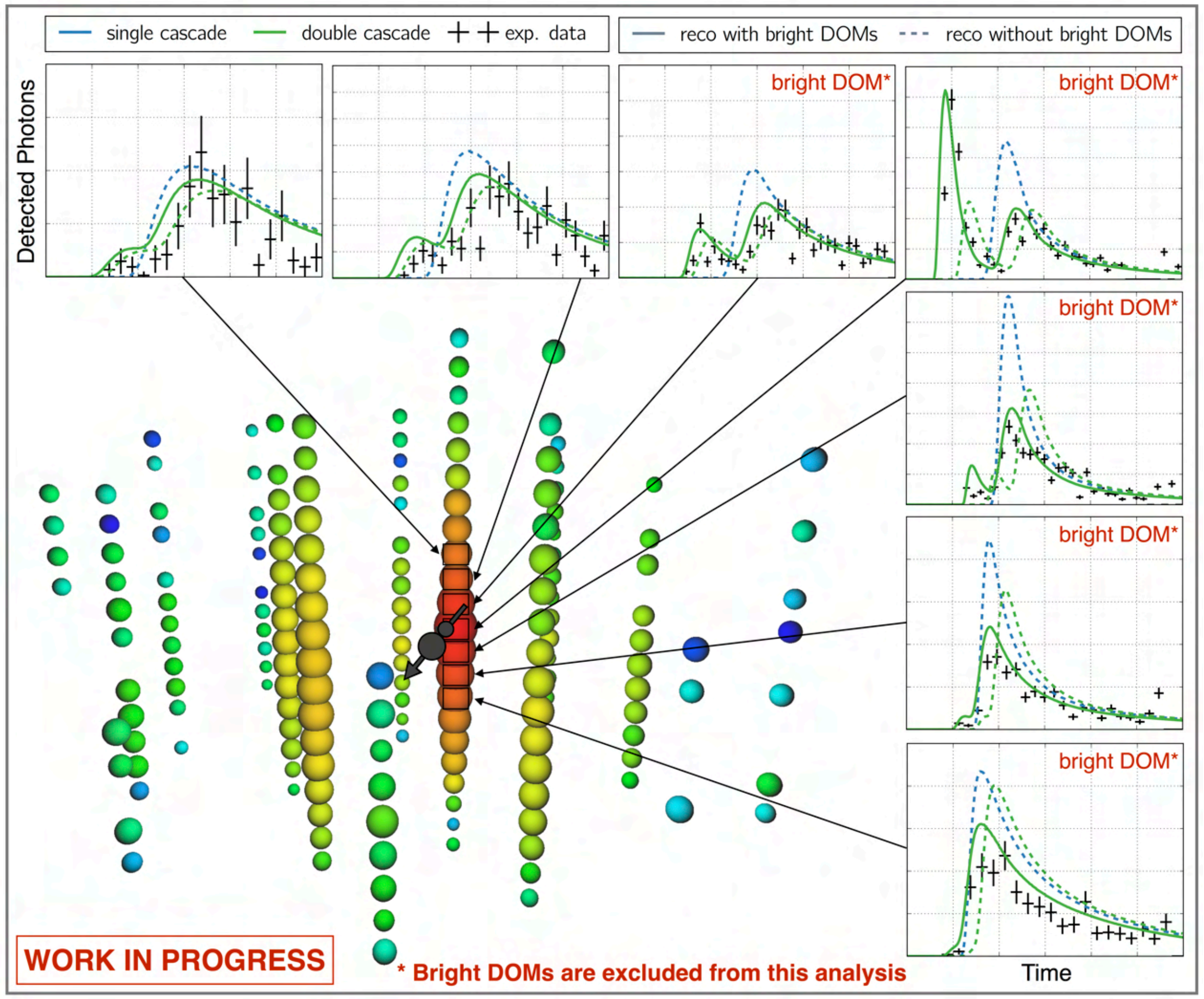


- Extremely low atmospheric ν_τ production – oscillations lead to ~1/3 ν_τ in astro. flux
- Classic ν_τ “double bang” signature: ν_τ interaction followed by τ lepton decay
  - τ lepton decay length $c\tau_\tau \approx 50$ m/PeV: only visible at very high energy
- Two double cascade candidates identified
  - Backgrounds from mis-reco cascades, μ bremsstrahlung, etc. now under evaluation

Double Cascade Candidate Events



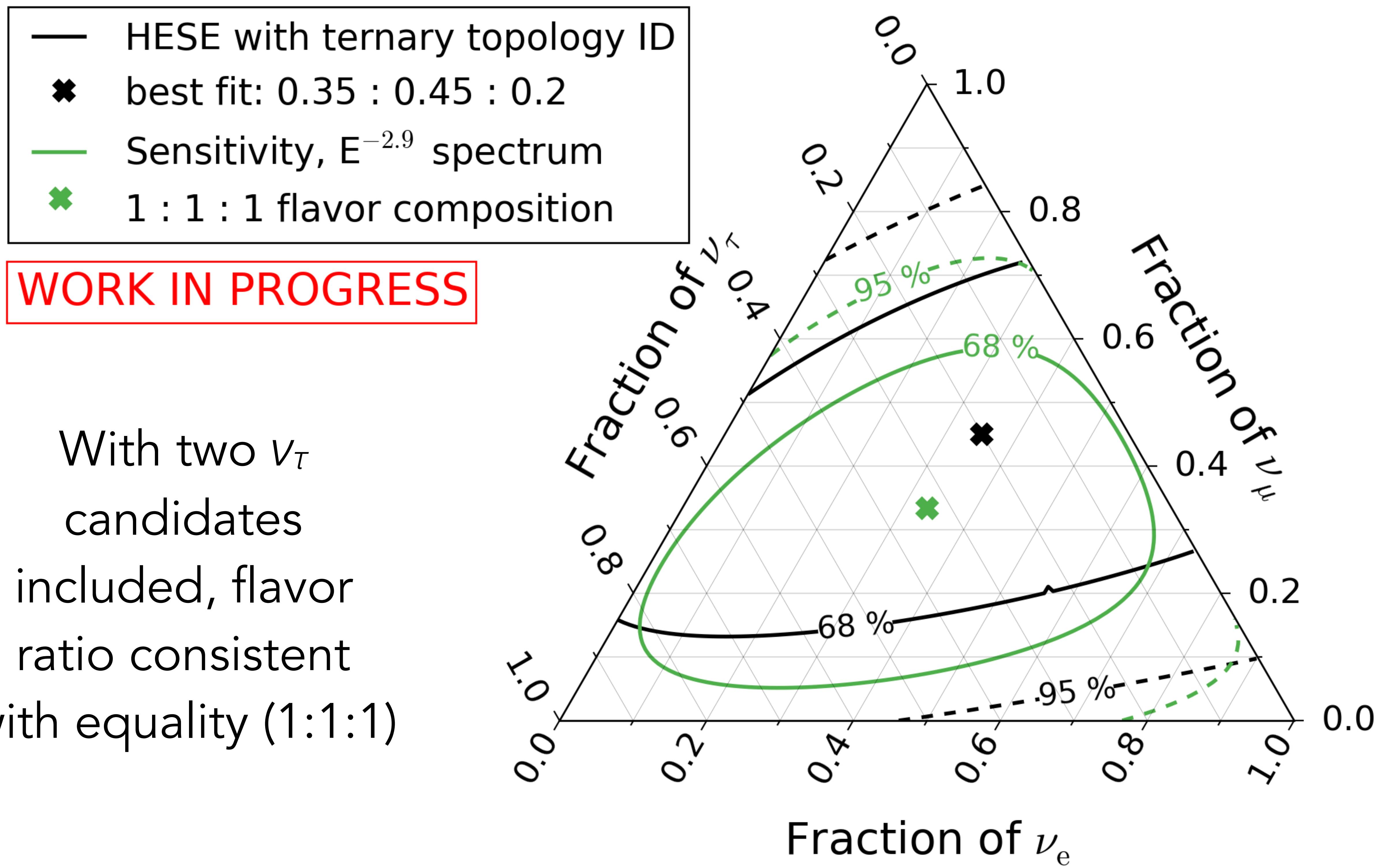
Double cascade candidate #1



Double cascade candidate #2

- Waveforms show evidence of separated cascades in event #2
  - Event #1 passes due to ΔL in double-cascade fit, single cascade fit equally good
  - Parallel analysis focused on waveform shape is in progress

Flavor Triangle



WORK IN PROGRESS

With two ν_τ candidates included, flavor ratio consistent with equality (1:1:1)

Required Source Power

calculation following T. Gaisser

- Whatever the sources are, the total flux emitted must provide the flux detected by IceCube
  - Assume all sources are extragalactic: $F_\nu = \int \rho \frac{L_\nu}{4\pi r^2} d^3r = \frac{1}{4\pi} \int \rho L_\nu \, d\Omega \, dr$

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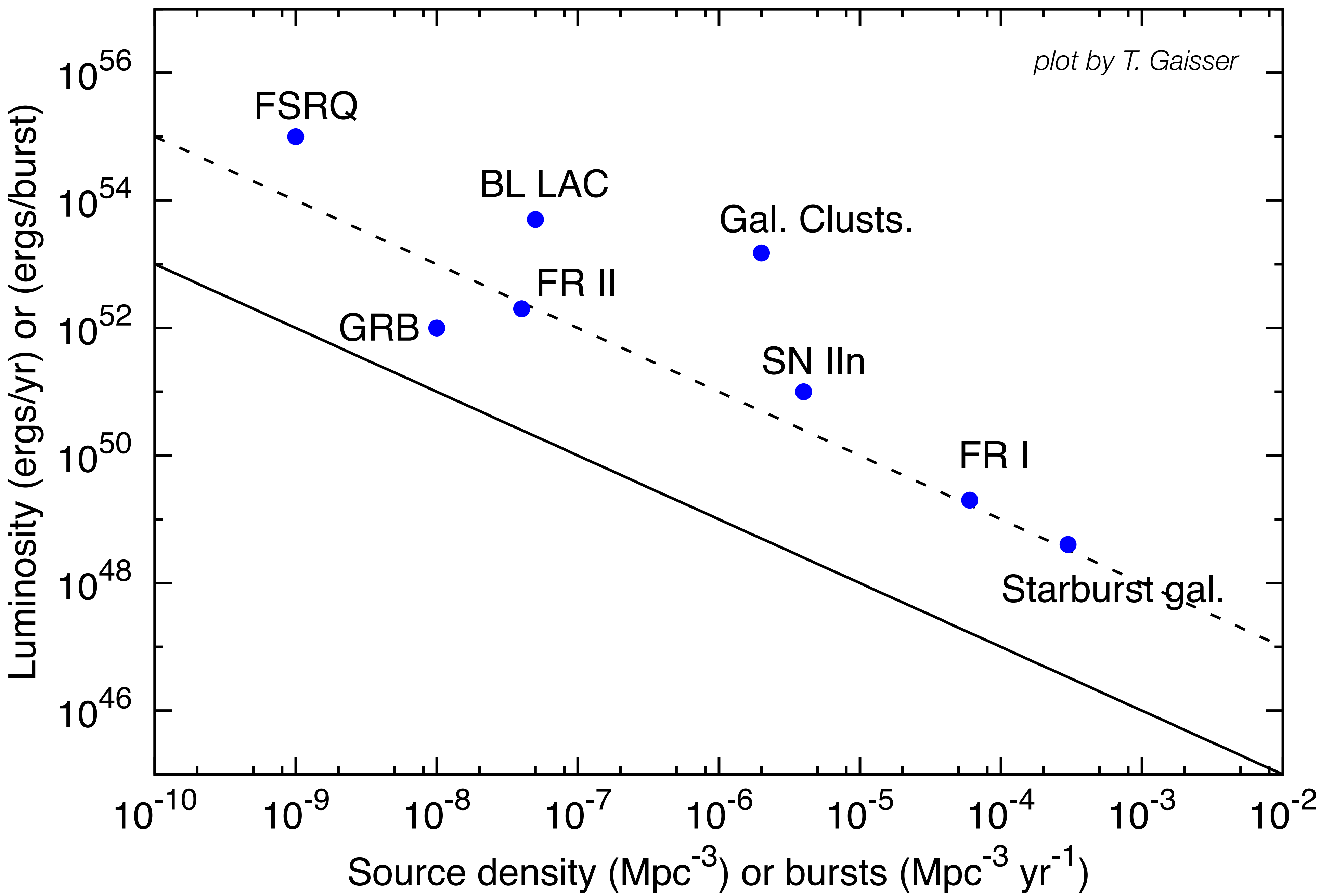
providing the constraint that for ξ around 2-3,

$$\rho L_\nu \sim 10^{43} \frac{\text{erg}}{\text{Mpc}^3 \text{ yr}}$$

Source Population Constraints (Kowalski Plot)



Dashed line assumes 1% efficiency for production of neutrinos

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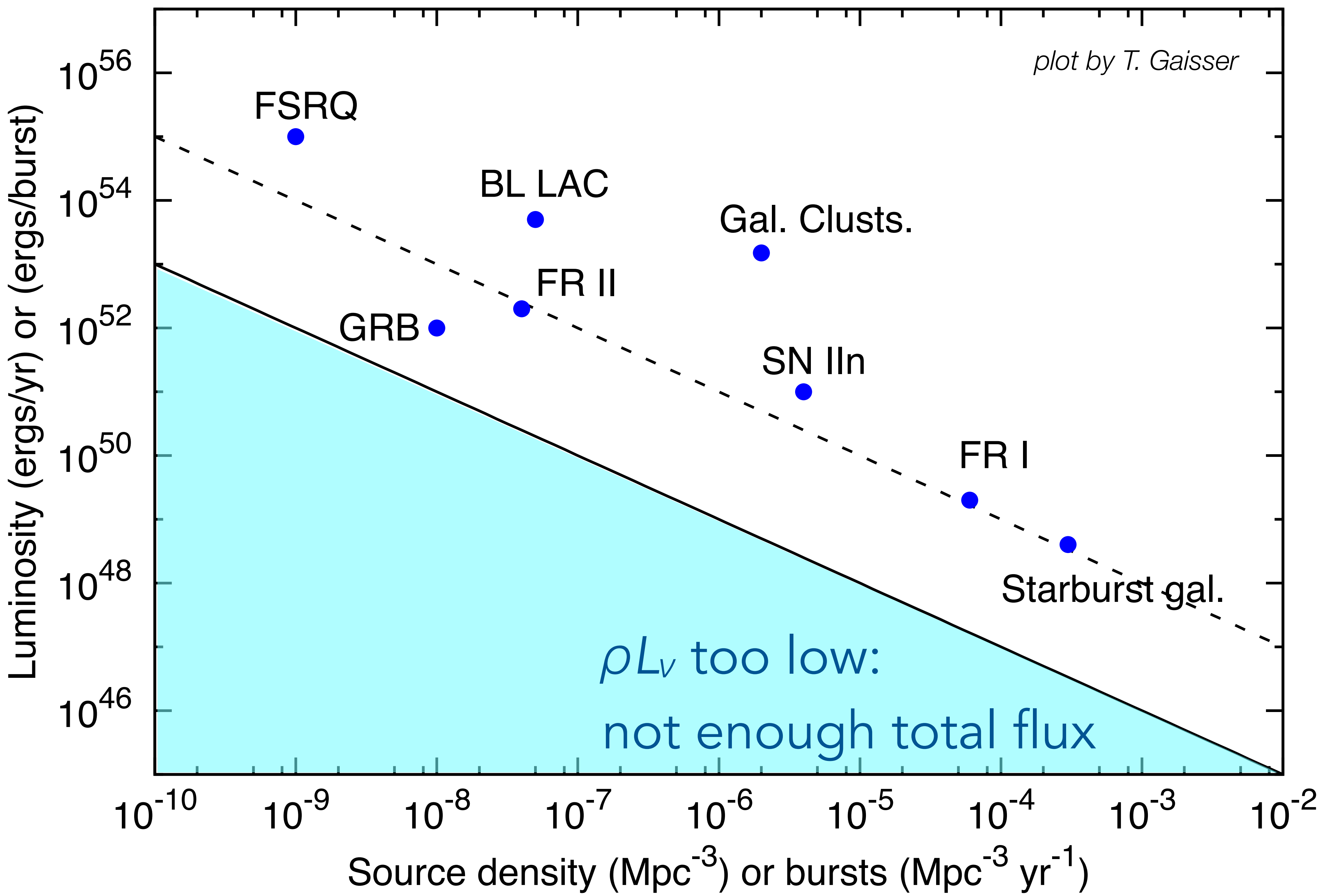

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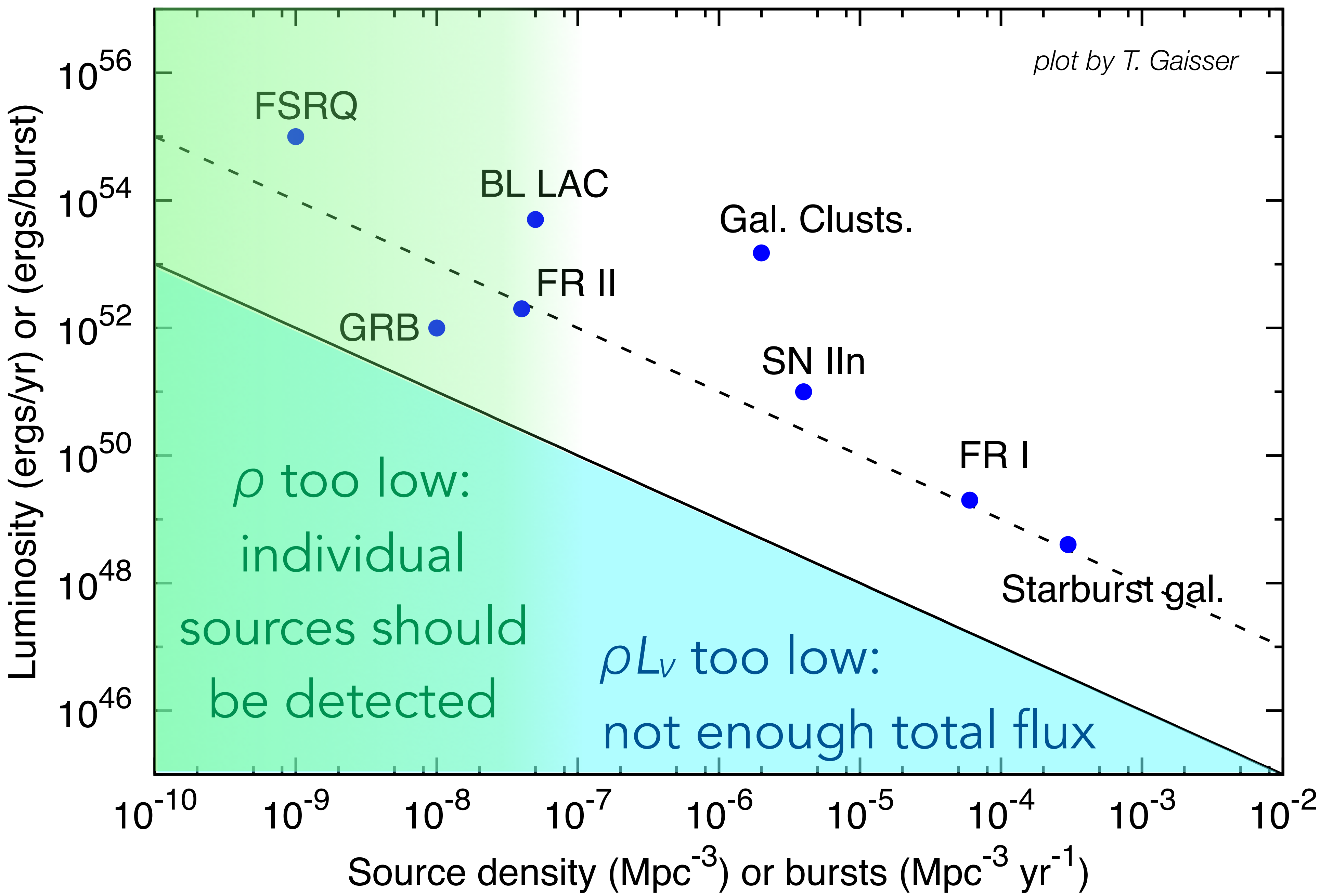

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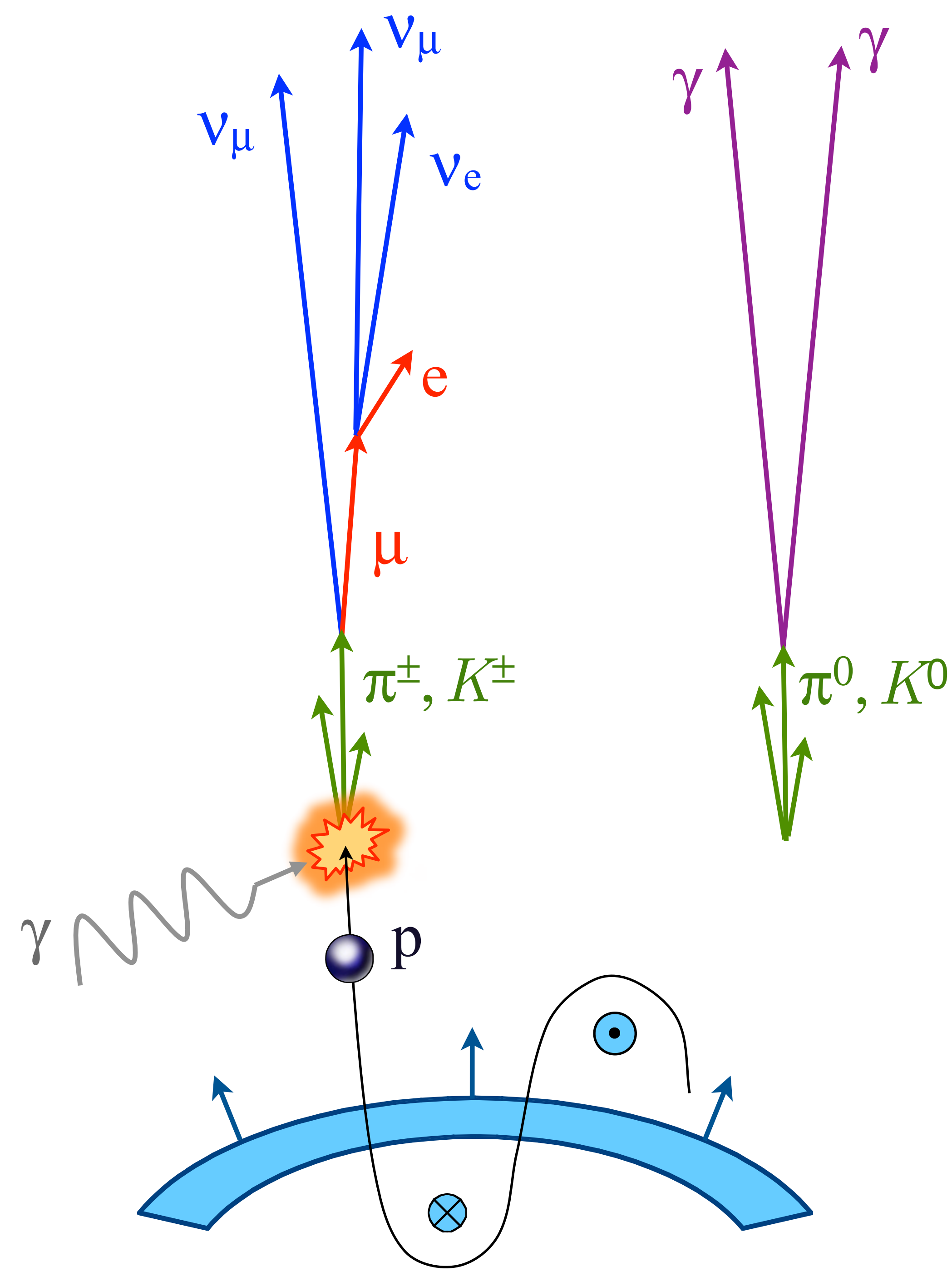
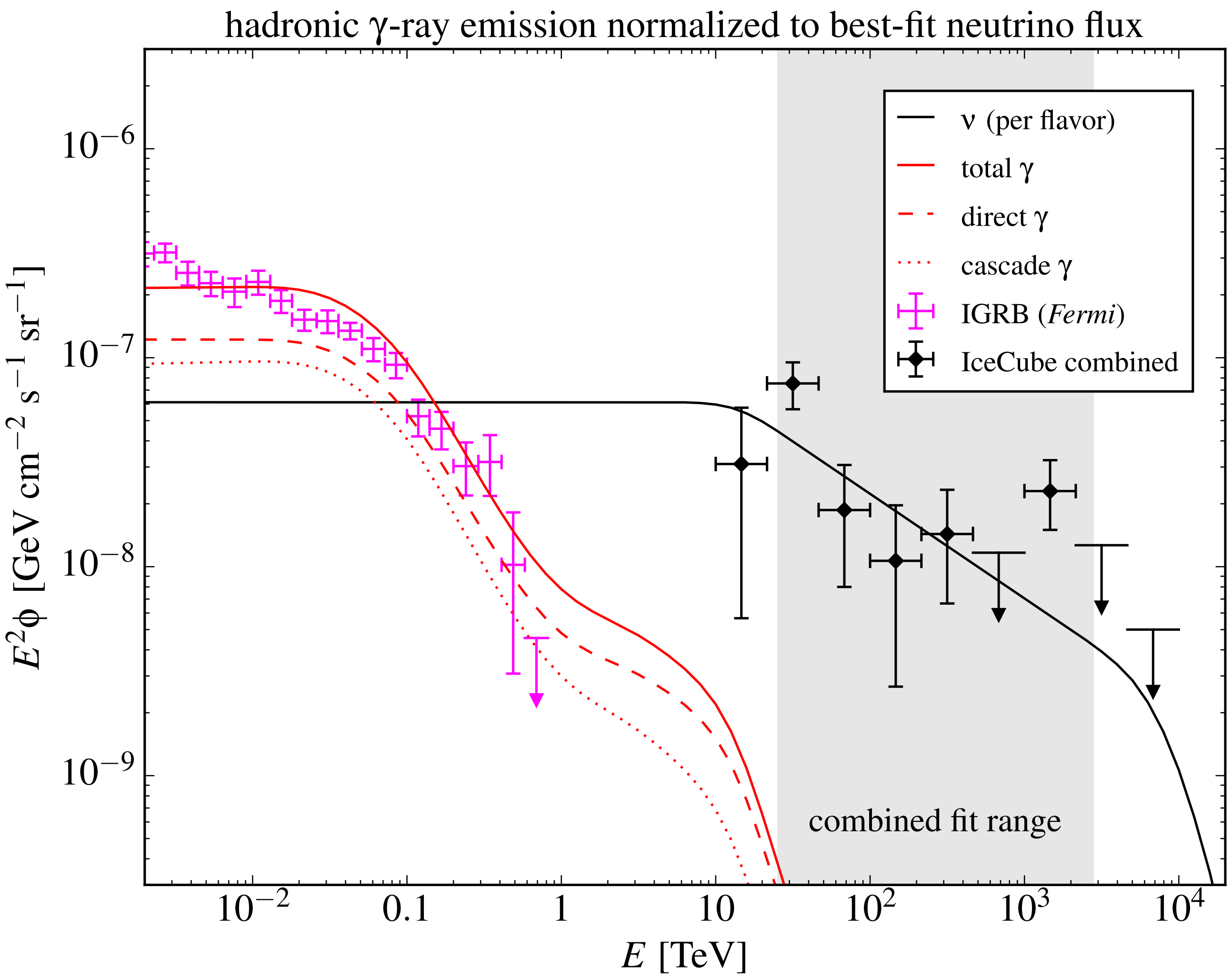
Cosmic Rays, Gamma Rays, and Neutrinos

- Accelerated particles likely to interact with matter or radiation fields in their sources
  - Produce secondary mesons with $\mathcal{O}(10\%)$ of the cosmic ray's energy
  - Details depend on target (p, γ)
- Gamma rays from neutral π, K – but can be absorbed, and may be due to leptonic acceleration instead
- Neutrinos via decay of $\pi^{\pm}$, $K^{\pm}$ – but more difficult to detect



If neutrino sources produce gamma rays, most of the Fermi isotropic gamma ray background comes from these sources…



K. Bechtol *et al.*, *Astrophys. J.* 836, 47 (2017)

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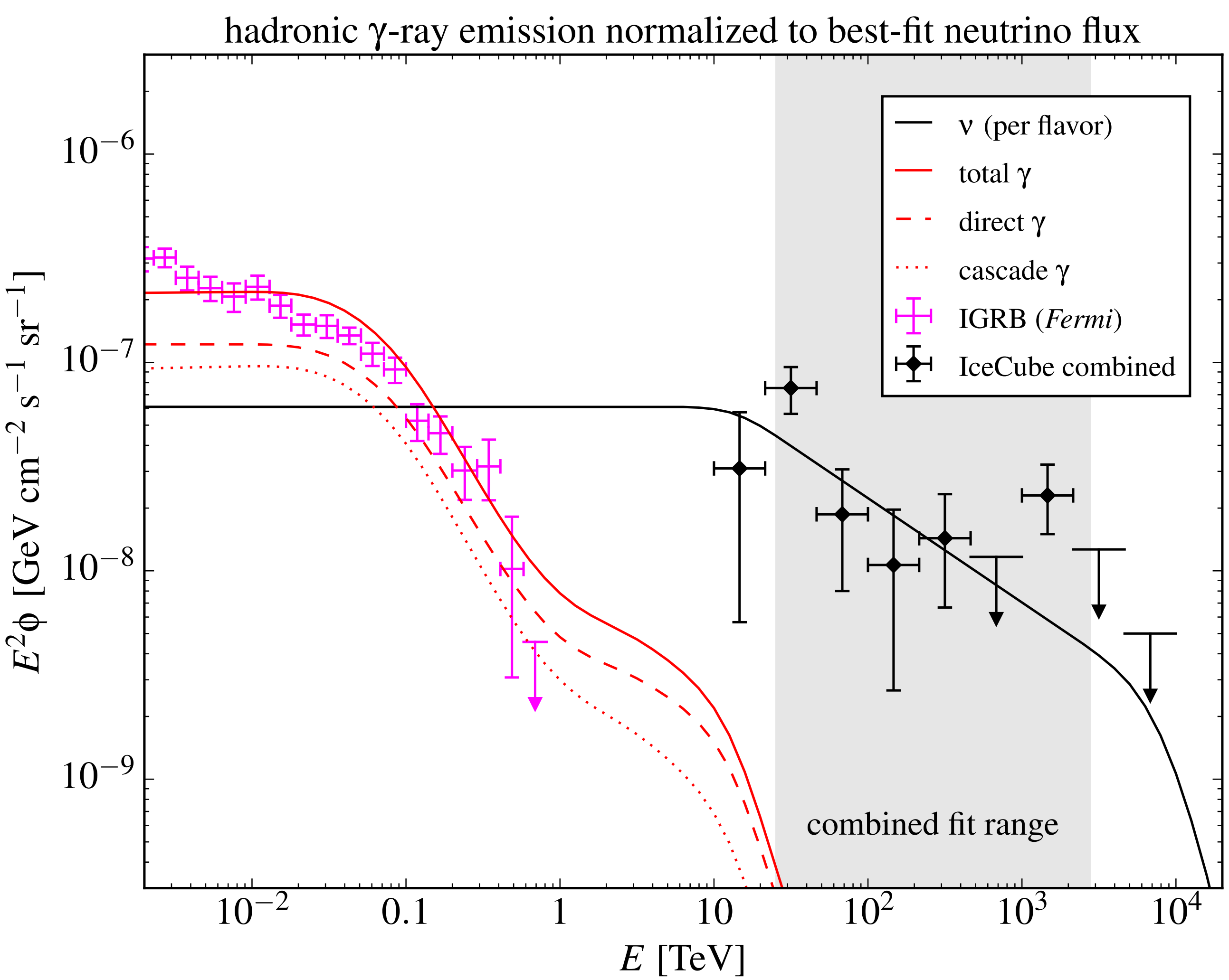
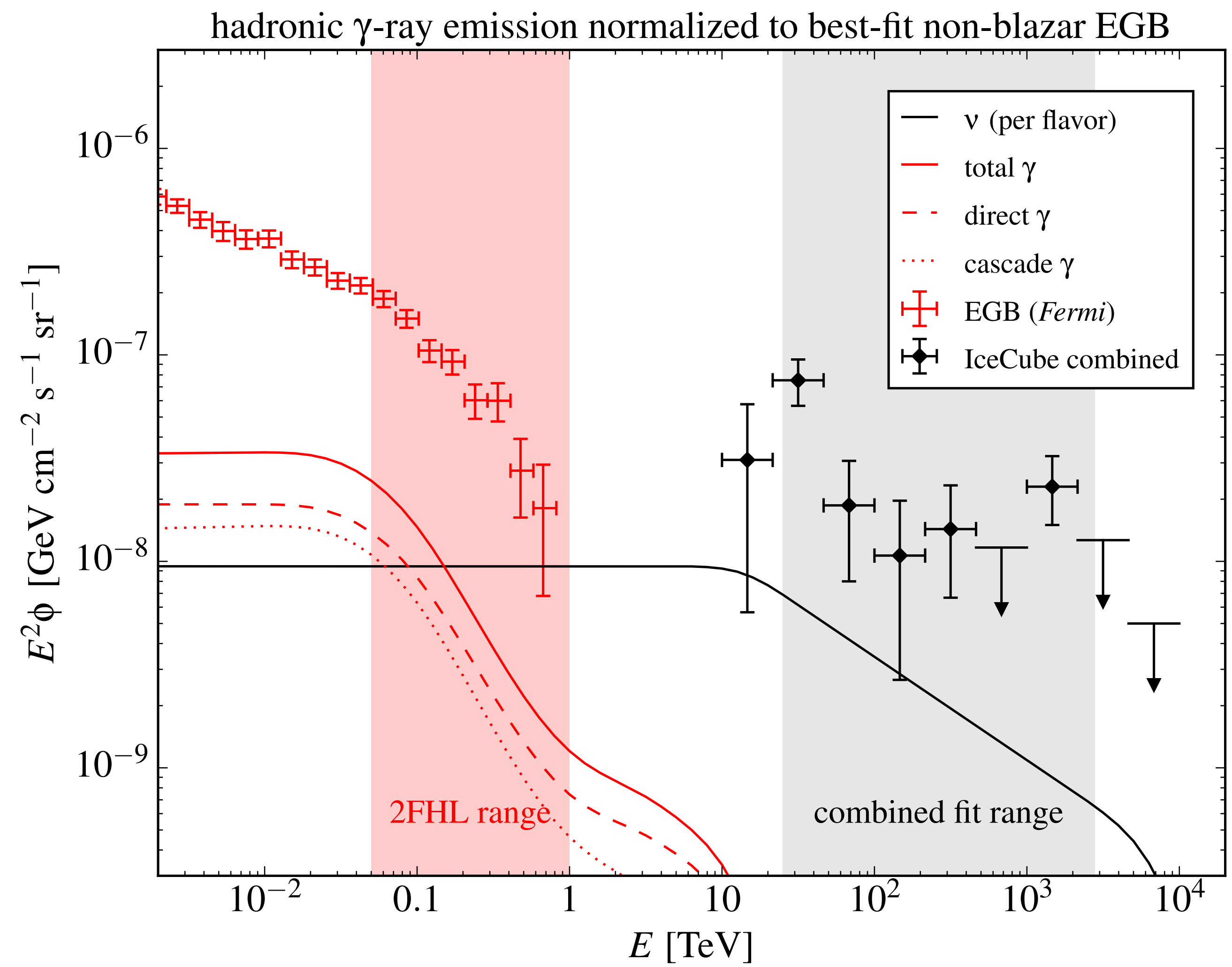


…but if blazars don't produce neutrinos, the remaining gamma ray background is too low for the observed neutrino flux



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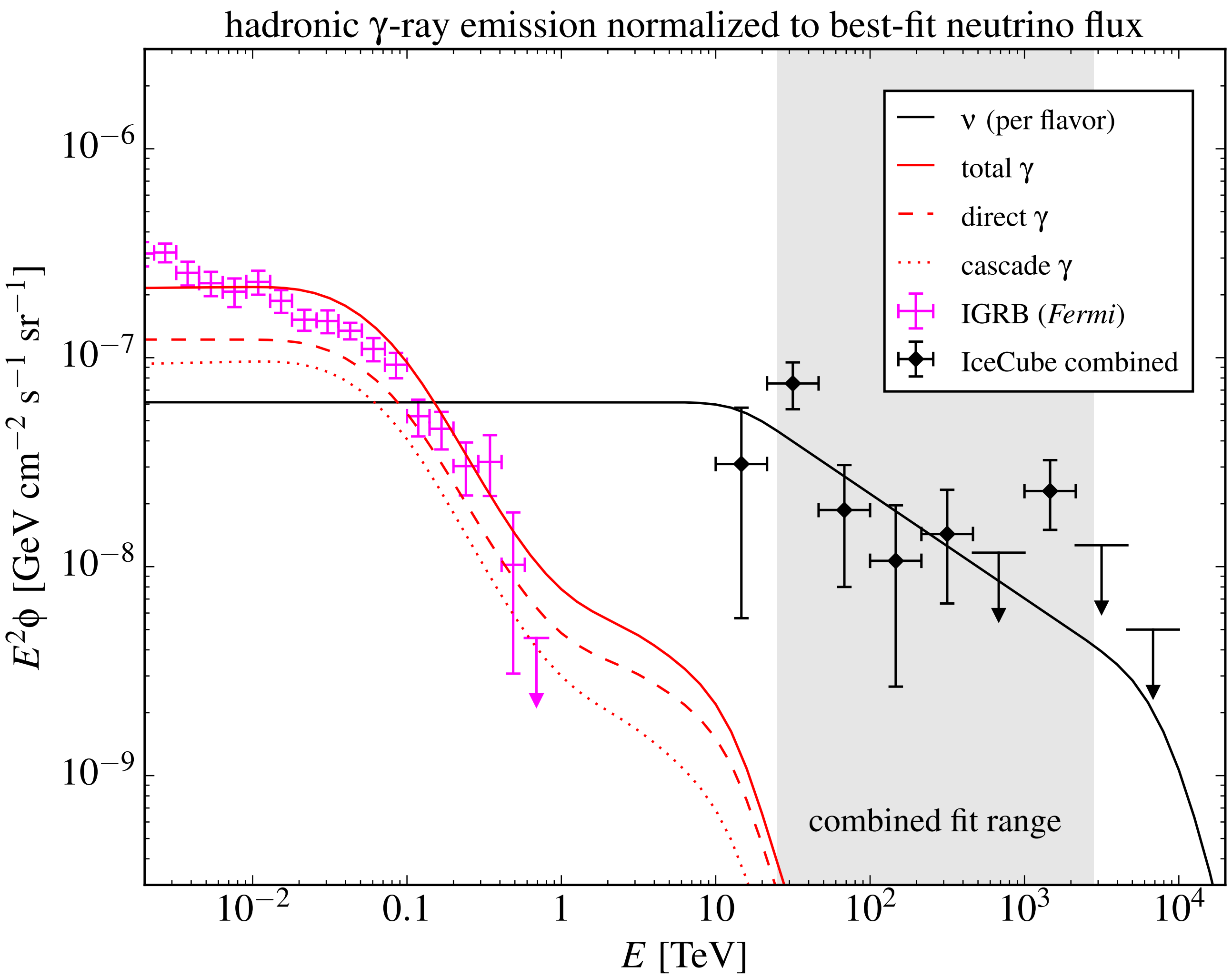
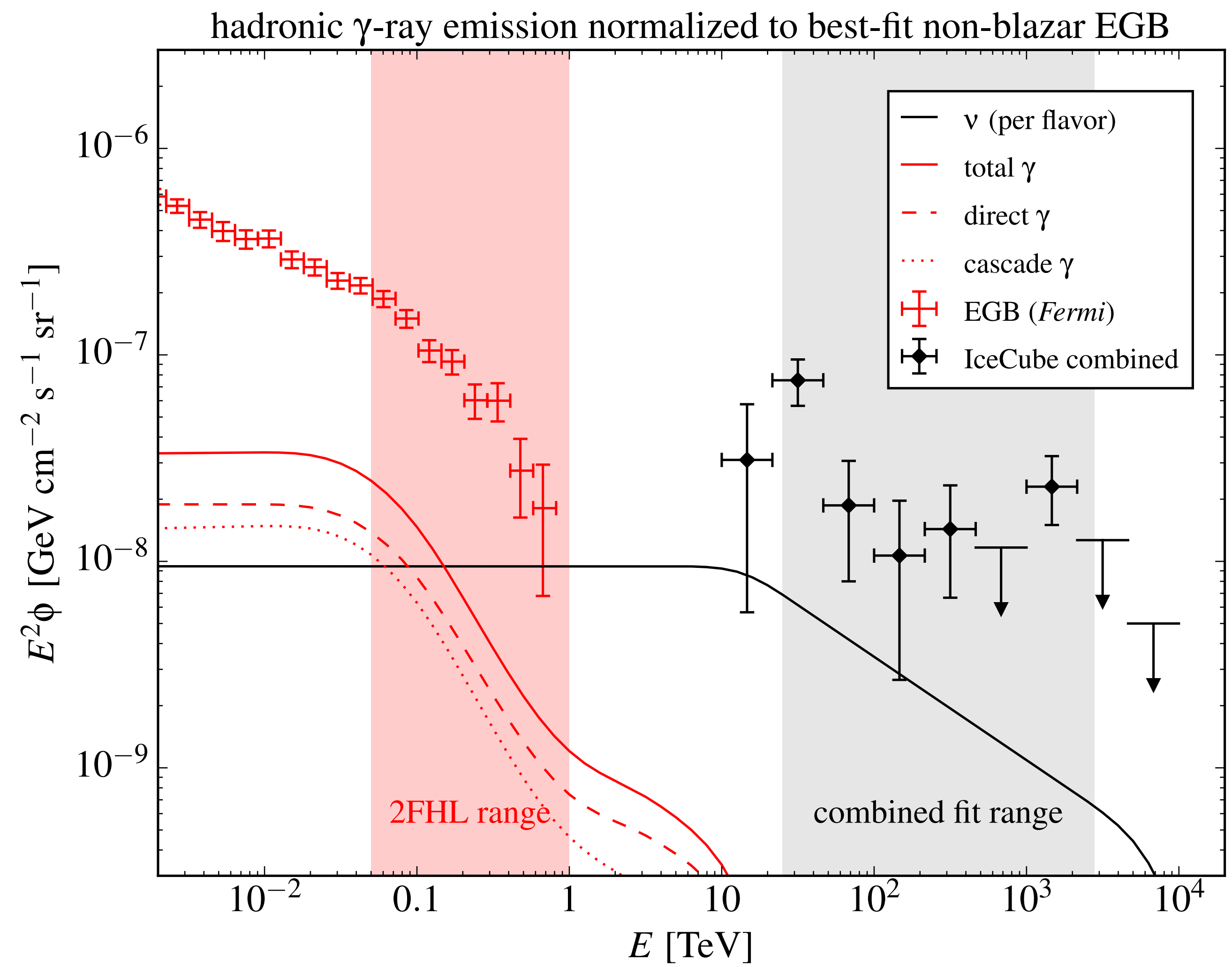




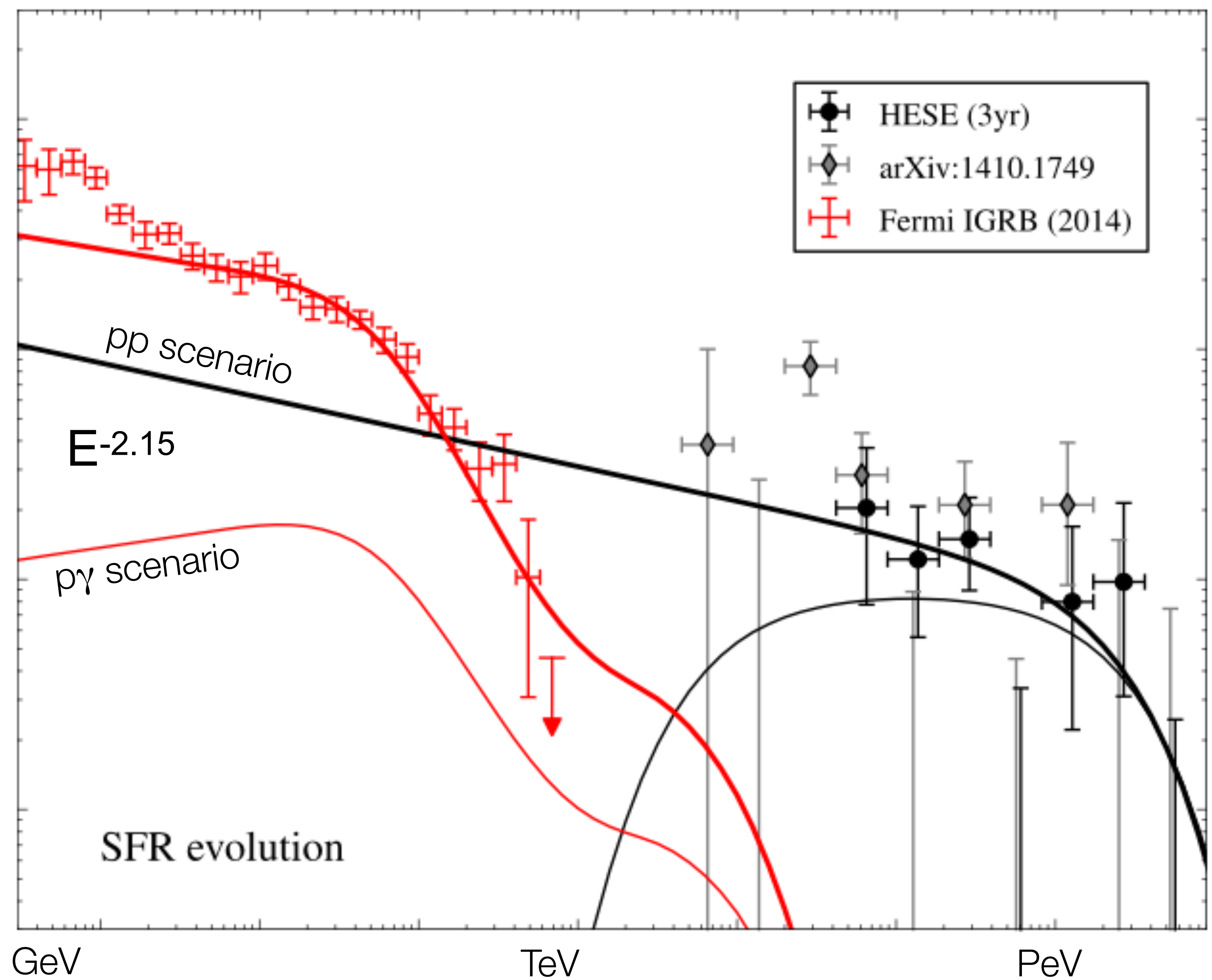
- Neutrinos claim a significant fraction of the non-thermal energy in the Universe
- Are blazars the sources, despite the lack of a clear correlation with Fermi?
- Or are the neutrino sources something new – and opaque to gamma rays?
  - May disfavor popular candidates, such as starburst galaxies or galaxy clusters

K. Bechtol *et al.*, *Astrophys. J.* 836, 47 (2017)

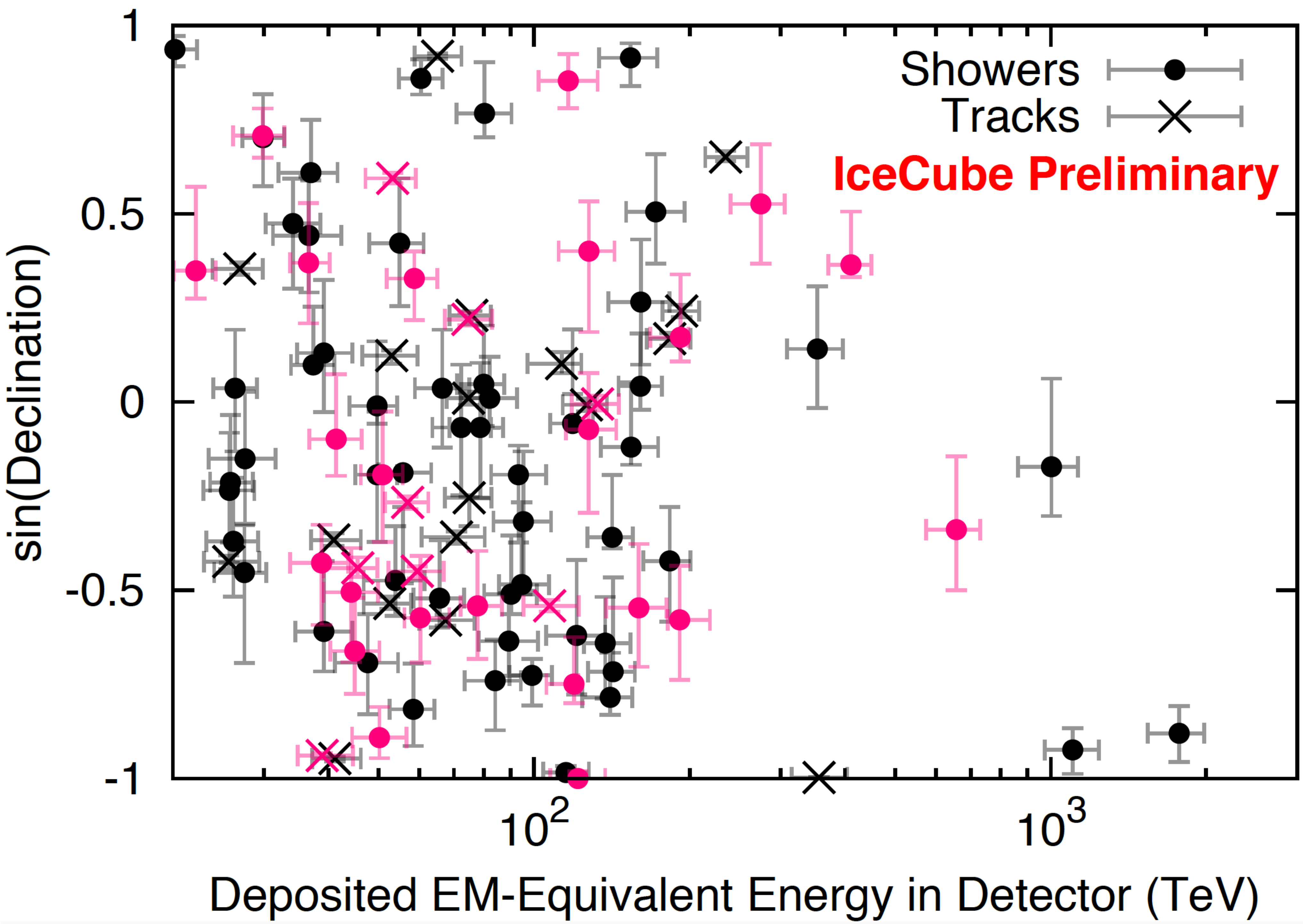
Connections to Gamma Rays

- EHE gamma rays should be co-produced with neutrinos ($\pi^- = \pi^+ = \pi^0$)
    - γ's cascade to lower energies due to interactions with extragalactic background
- Could produce much of the Fermi HE background light
    - Depends on assumed source spectrum, cosmic evolution and production mechanism
- A significant fraction of the non-thermal energy in the Universe may be due to these hadronic accelerators

Ahlers and Halzen 2014

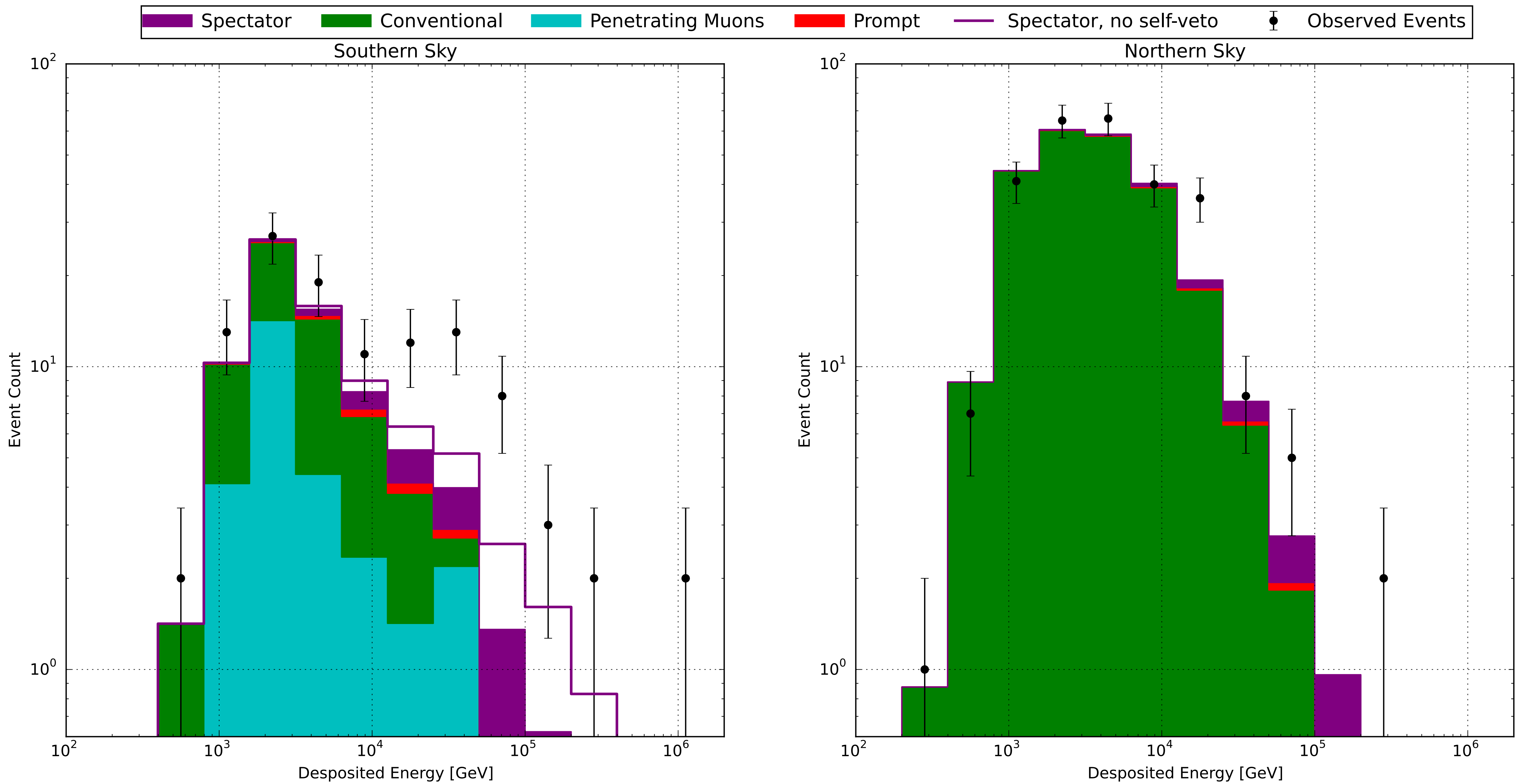


7.5 Year High Energy Starting Events



Intrinsic Charm

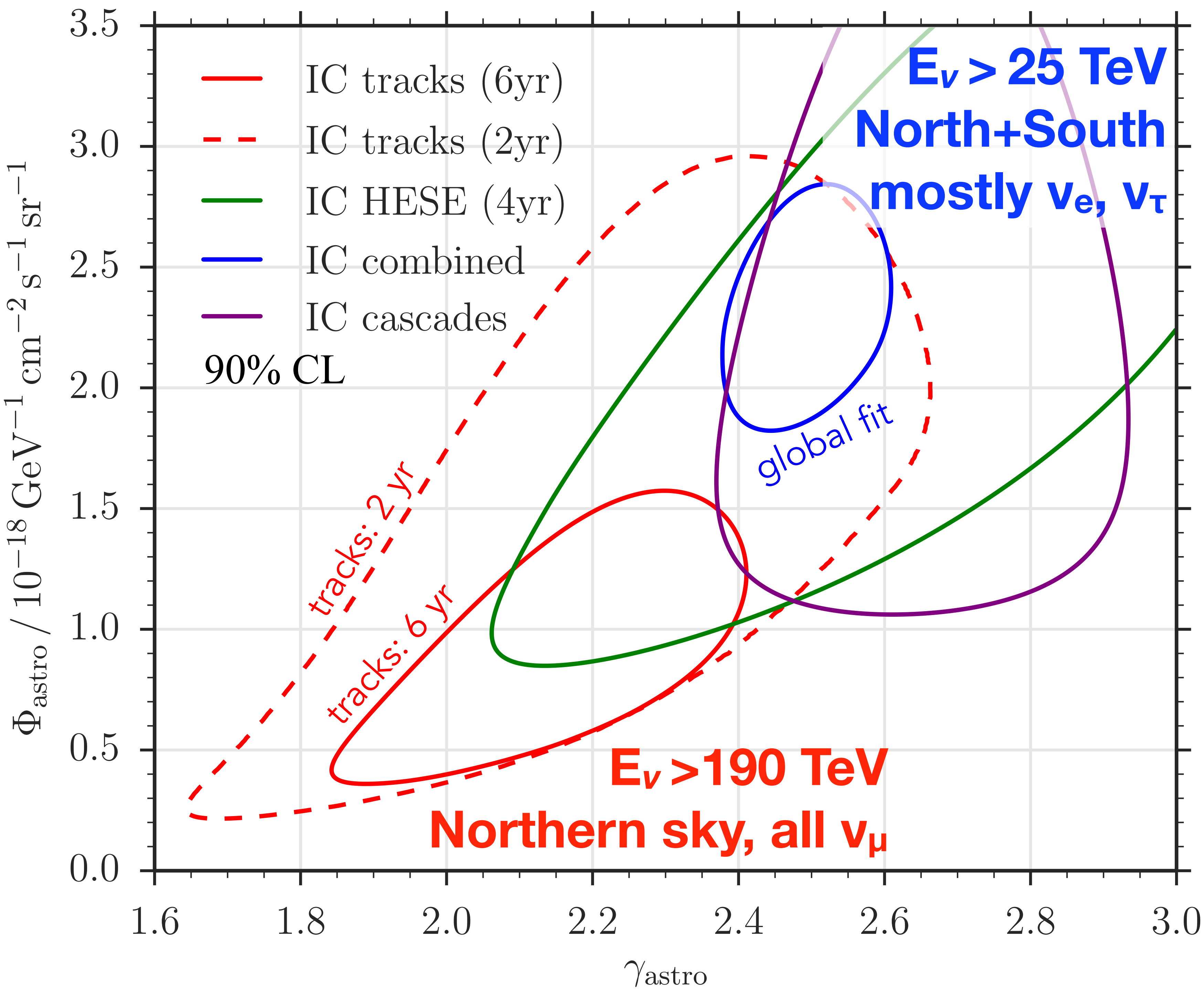
Halzen and Wille, arXiv:1601.03044

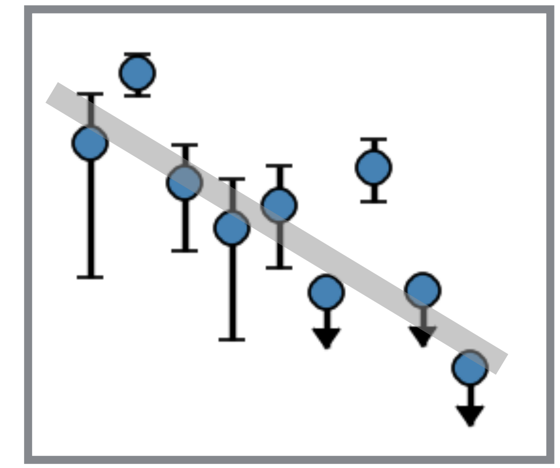


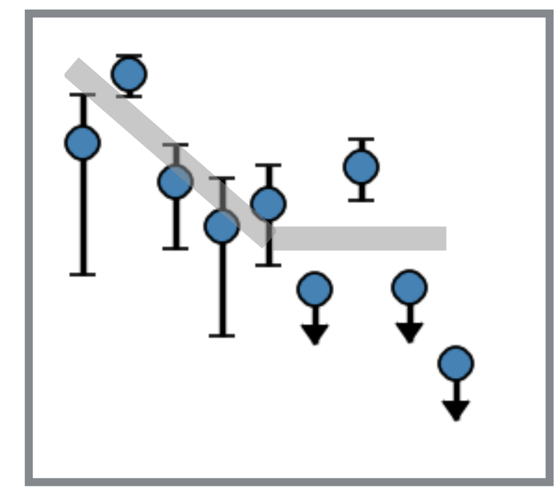
- Normalization chosen to saturate IceCube low-energy observations

A Consistent Picture?

Astrophys. J. 833, 3 (2016)

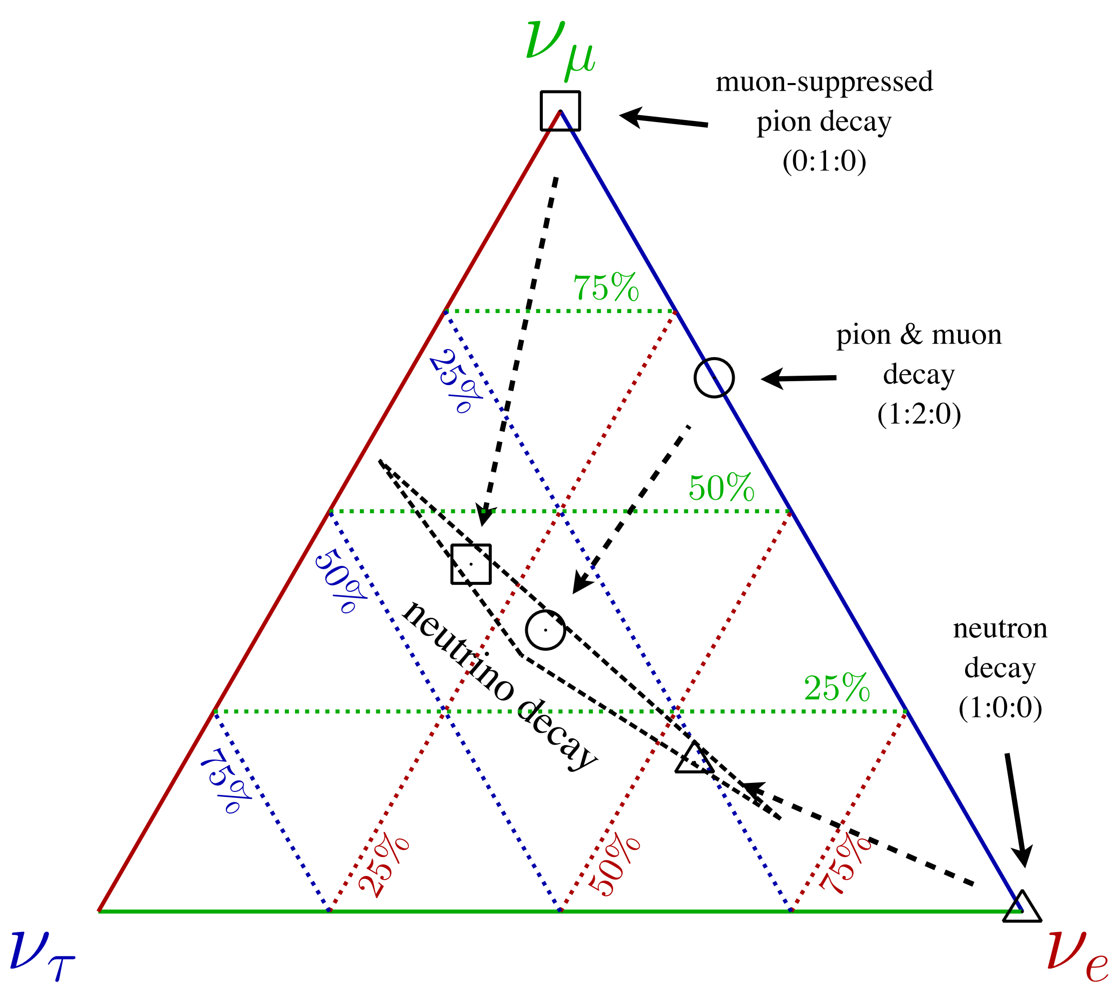


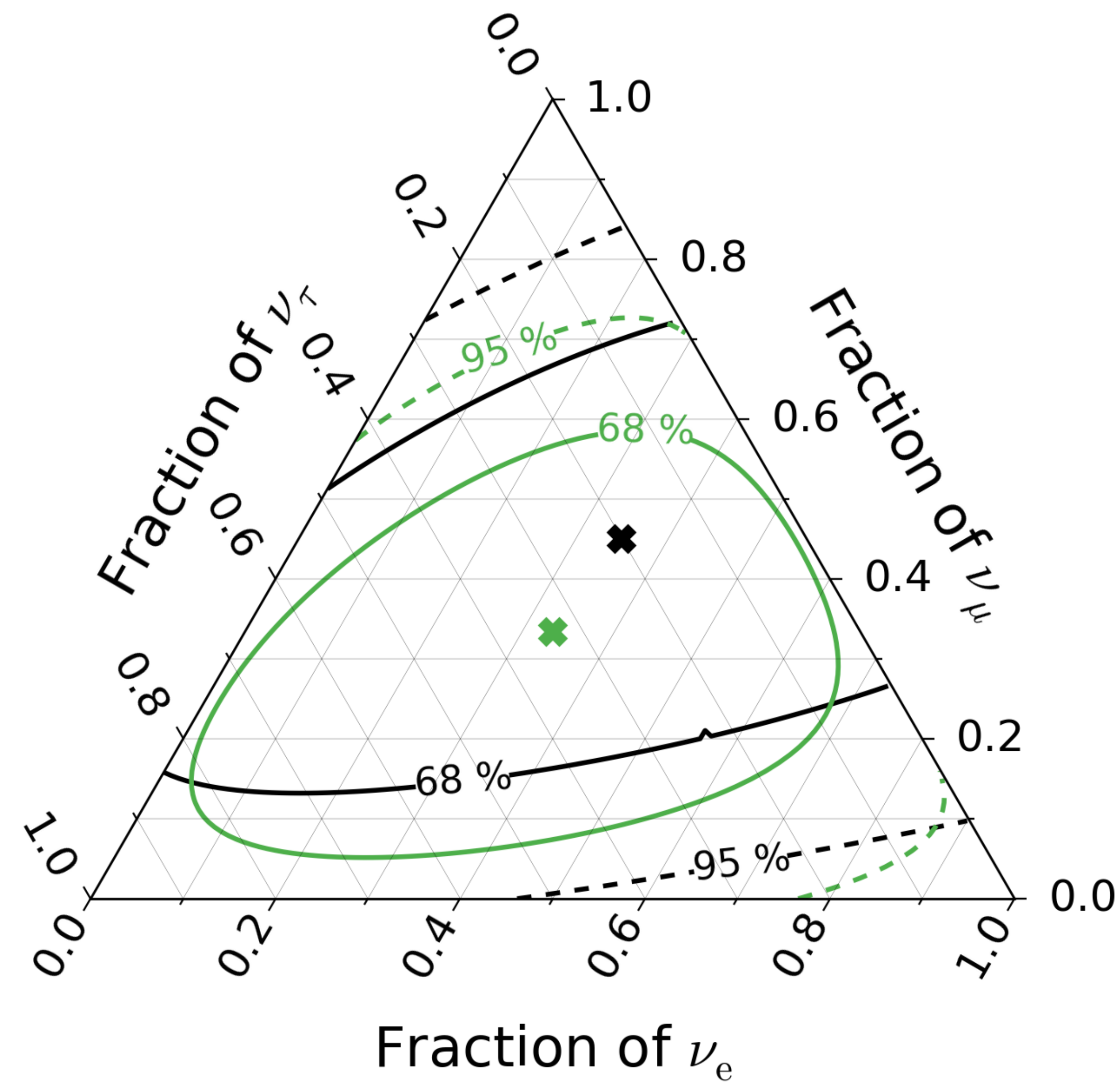




3.4σ tension: are we seeing a spectral break, anisotropy, multiple components,...?

Physics in Flavor Ratios

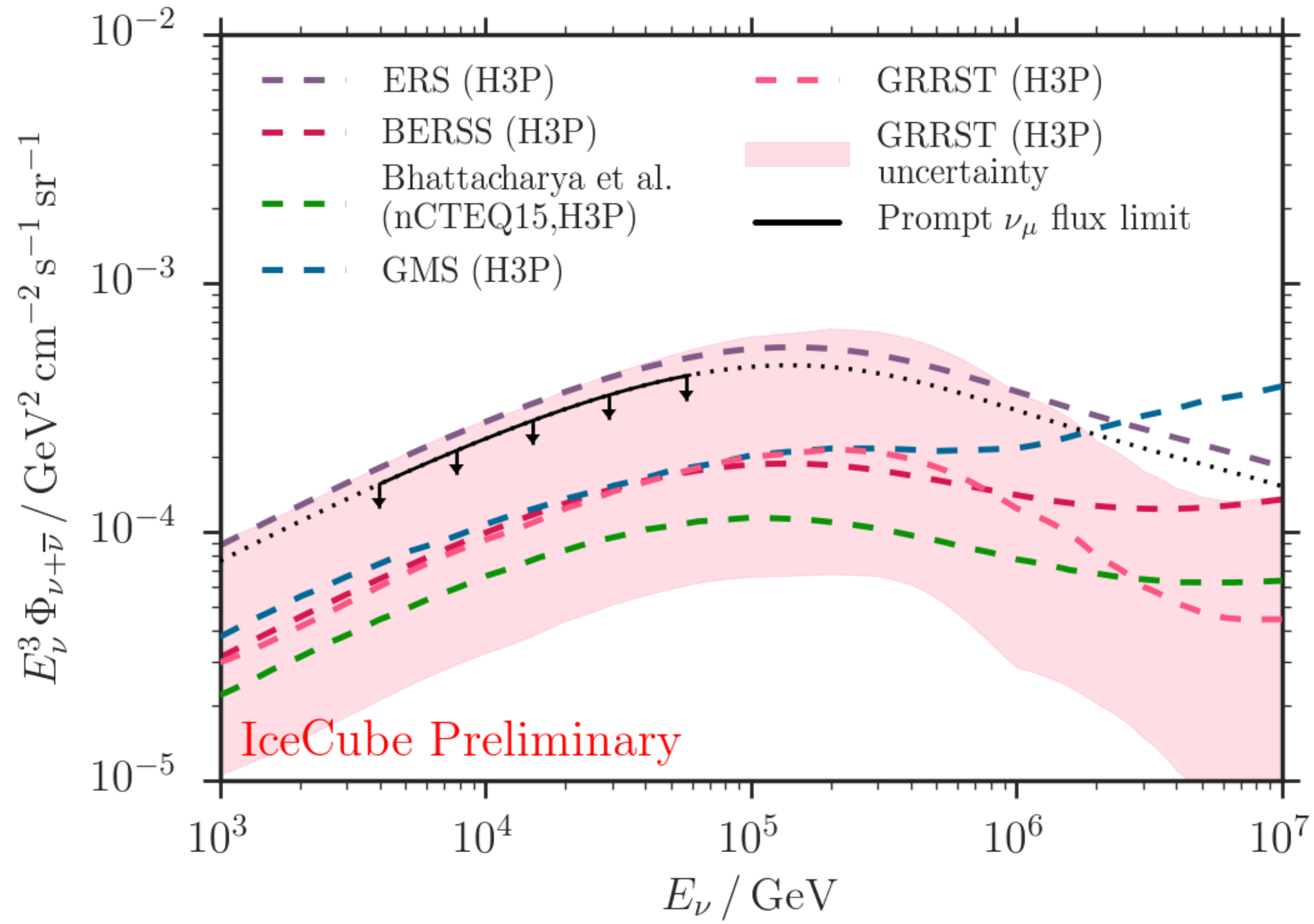




- Flavor ratio can probe astrophysics of sources (or new physics)
  - E.g., strong magnetic fields cool muons before decay, 1:2:0 → 0:1:0

Prompt Neutrinos

- Produced by decays of short-lived charmed mesons ($D^{\pm}$, D^0, D_s, Λ_C,…)
  - Distinguished from "conventional" π/K neutrinos through energy spectrum and angular distribution



- Current limits from high energy muon analysis starting to constrain model space