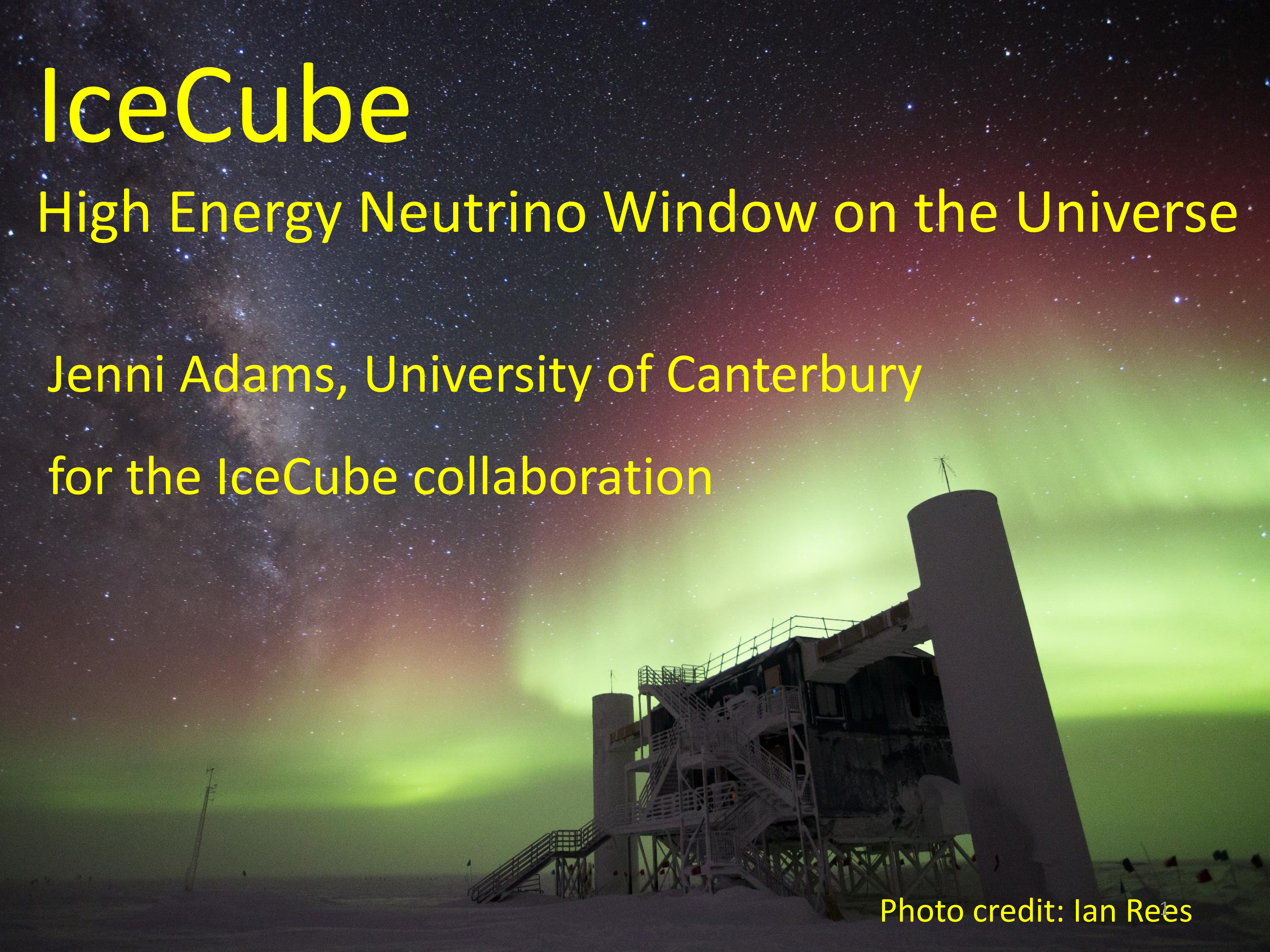


IceCube

High Energy Neutrino Window on the Universe

Jenni Adams, University of Canterbury

for the IceCube collaboration

Photo credit: Ian Rees

IceCube has a diverse physics portfolio

Cosmic-ray physics

Dark matter

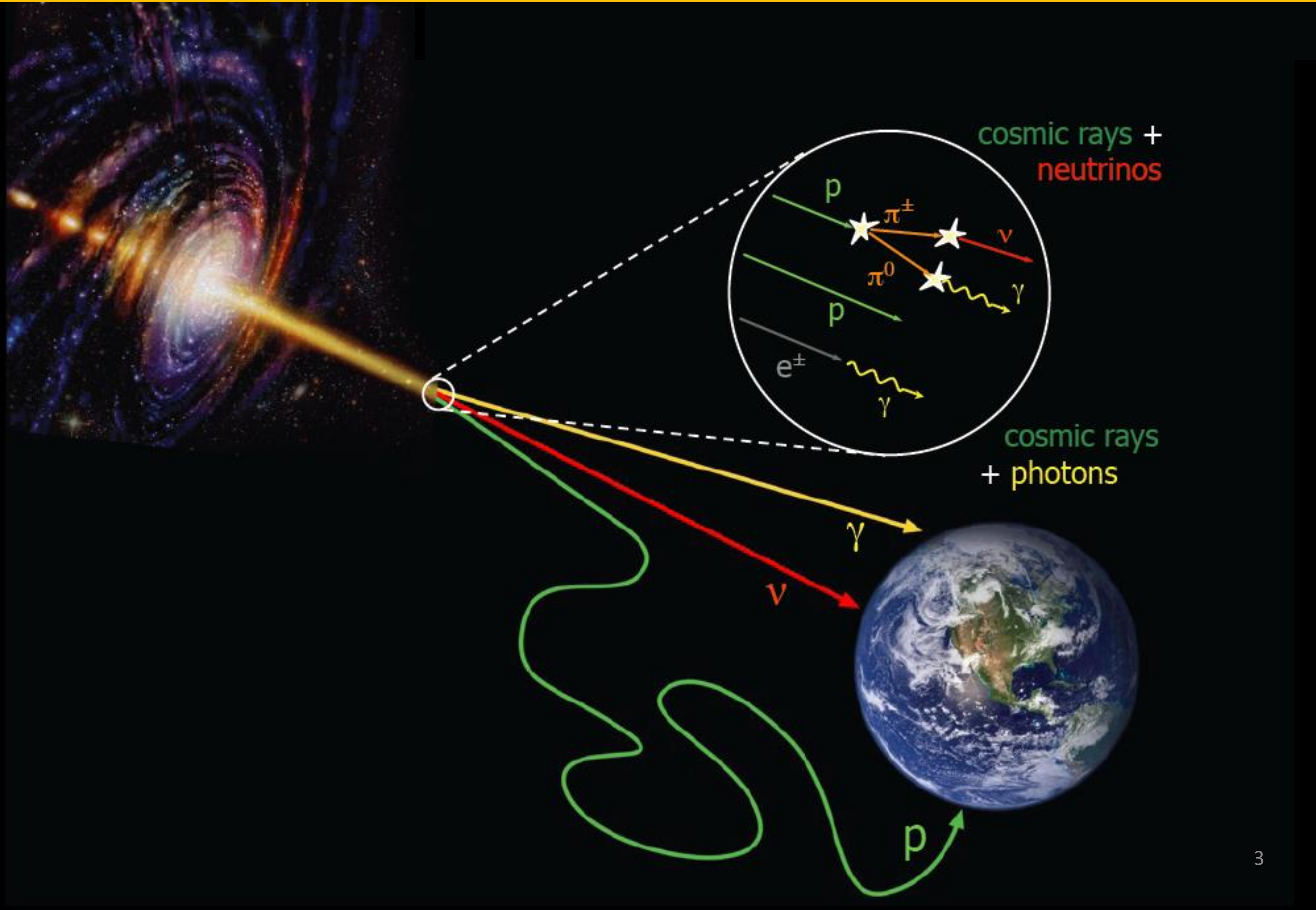
Neutrino oscillation parameters, mass hierarchy, sterile neutrinos

Supernovae

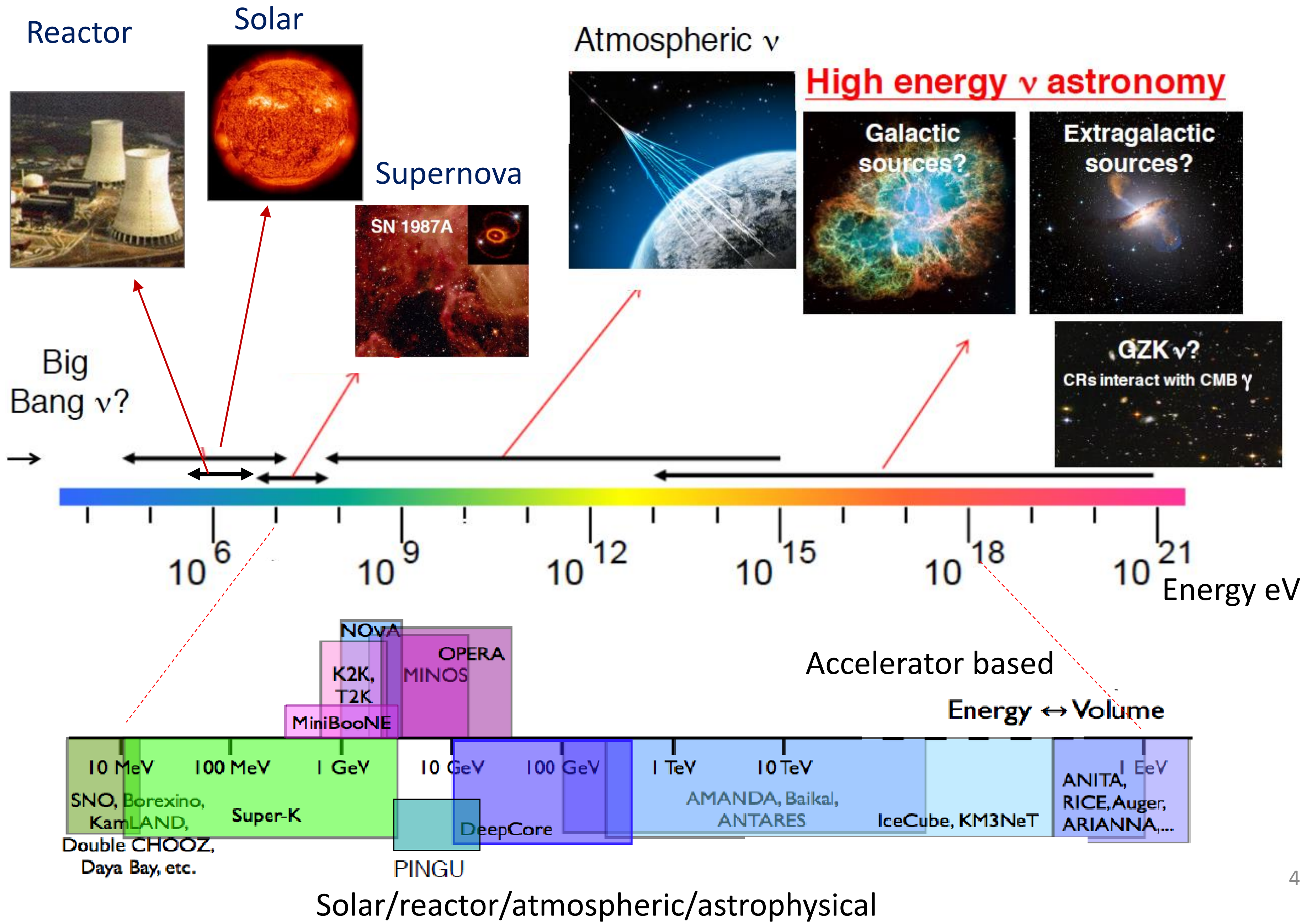
Cosmic ray accelerators and high-energy astrophysics (gamma-ray bursts, active galactic nuclei, gamma-ray sources)

Beyond the standard model physics

Multimessenger astronomy



Neutrino sources and detectors



Neutrino fluxes

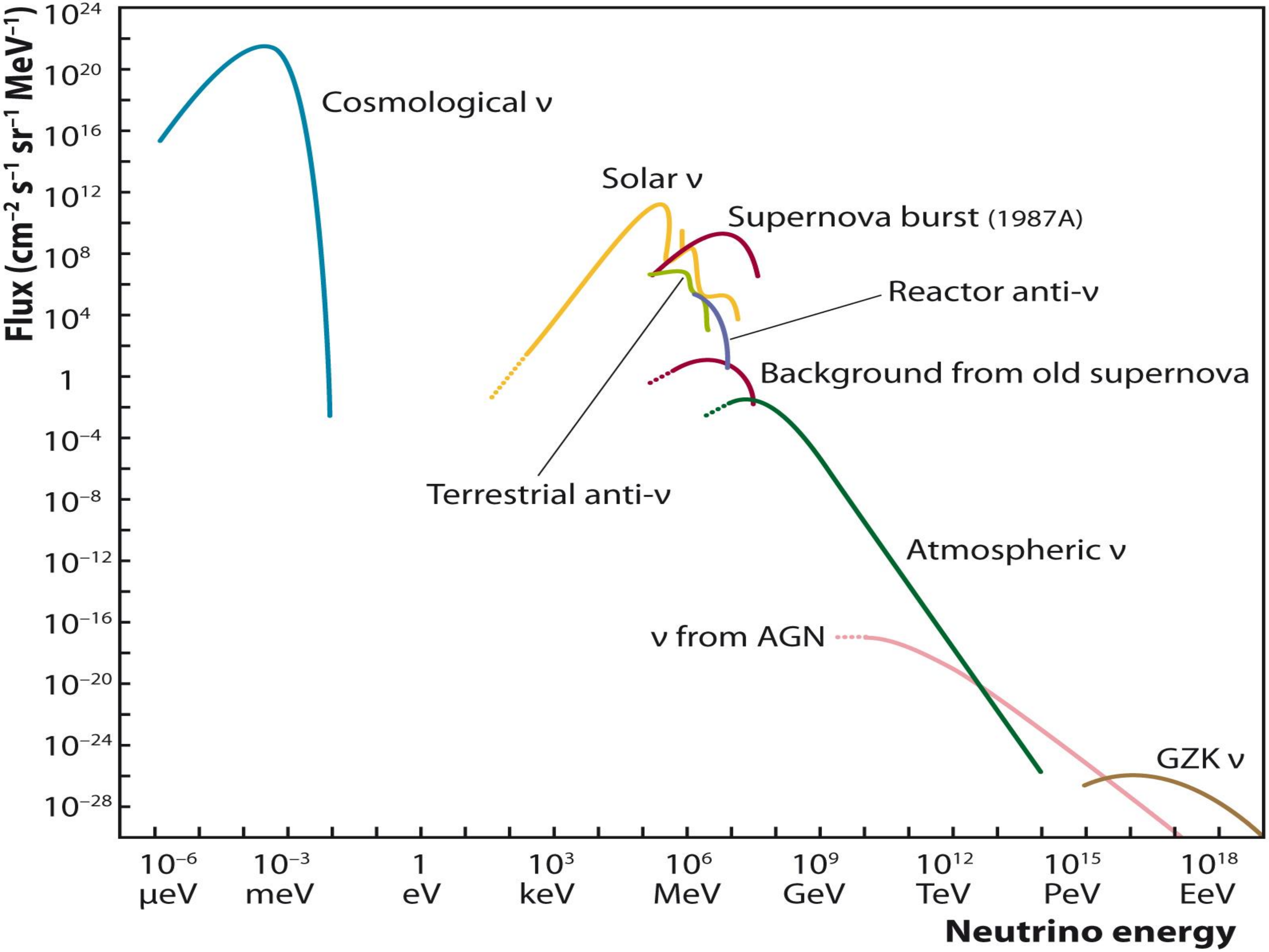
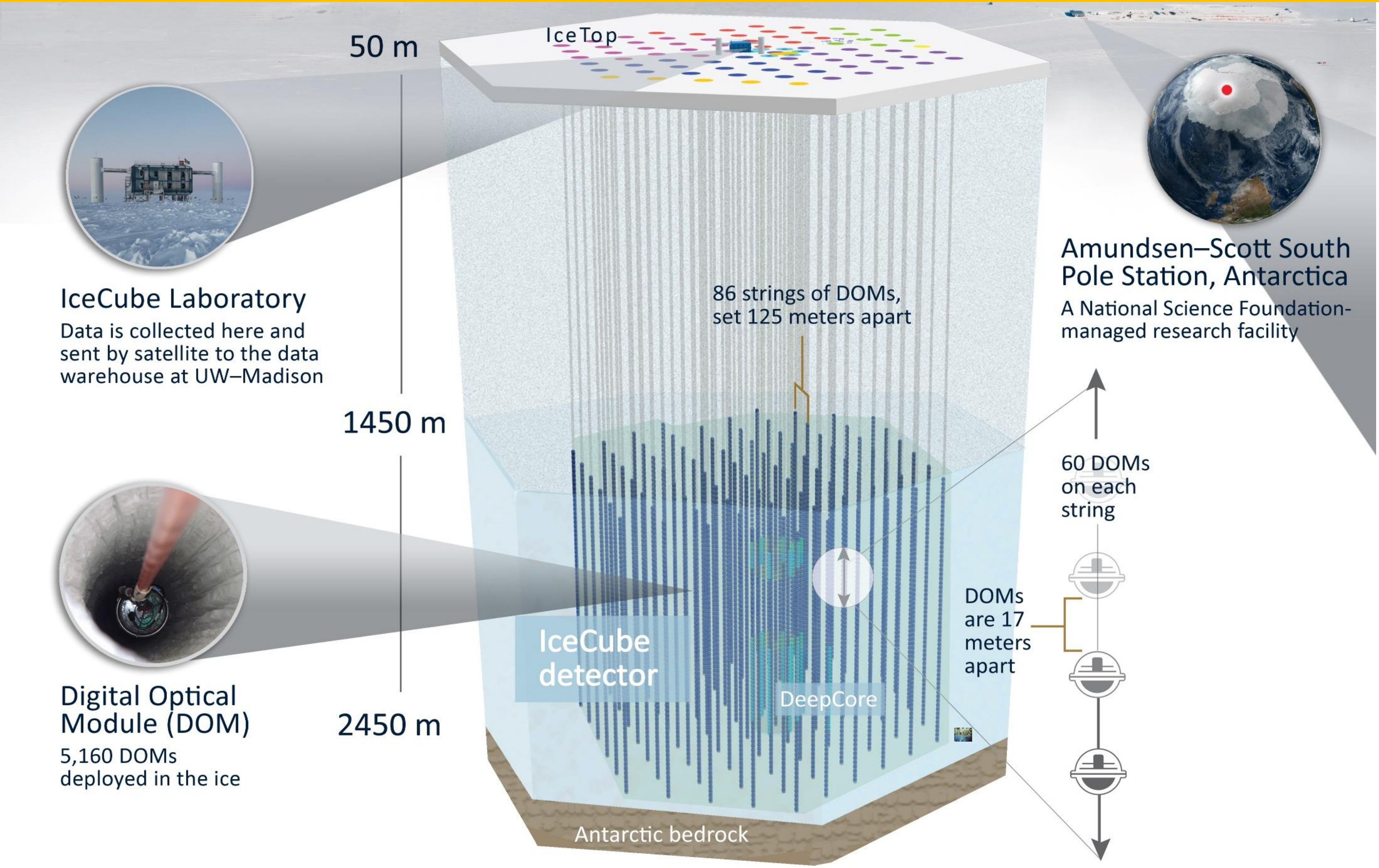
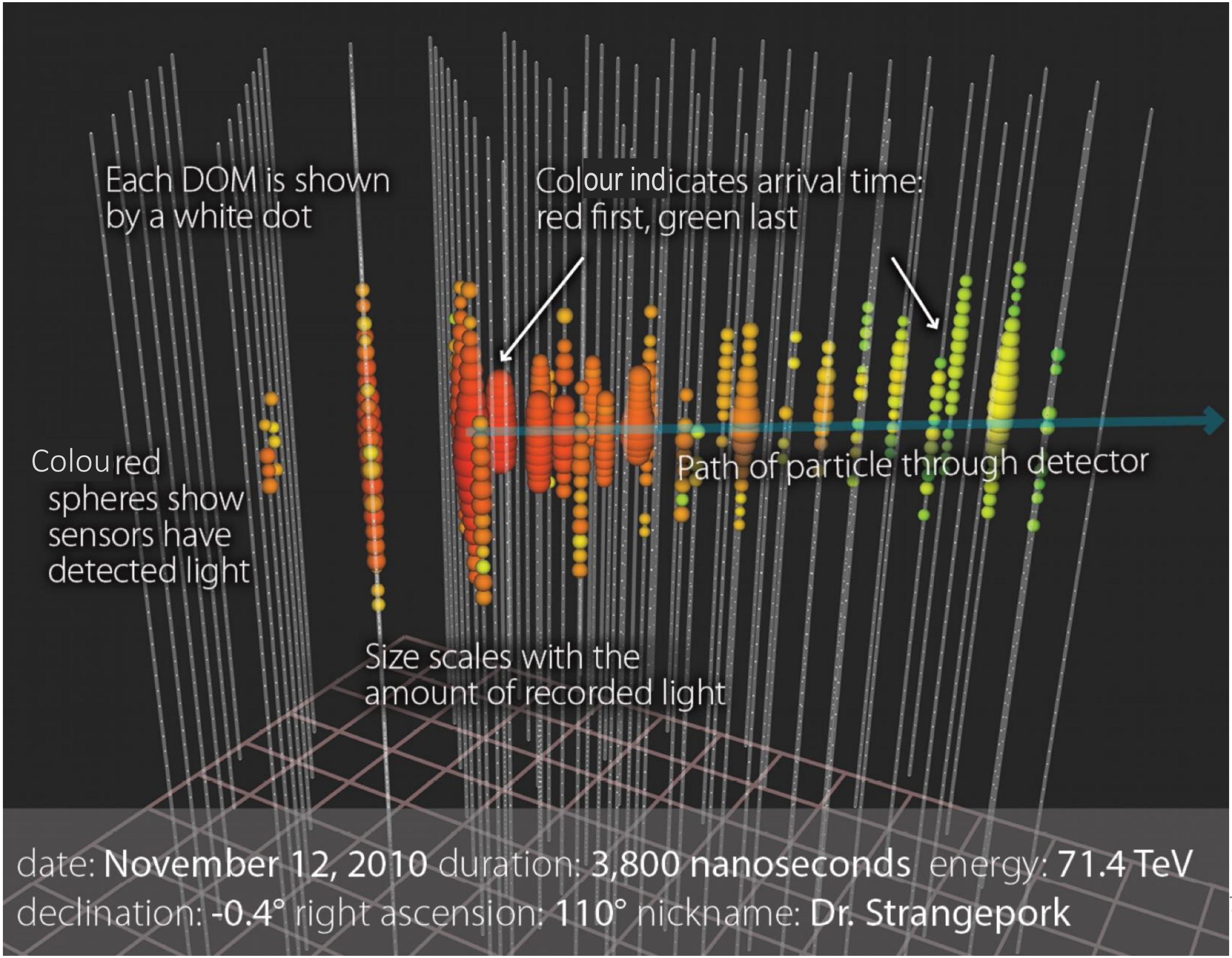


Image: Christian Spiering

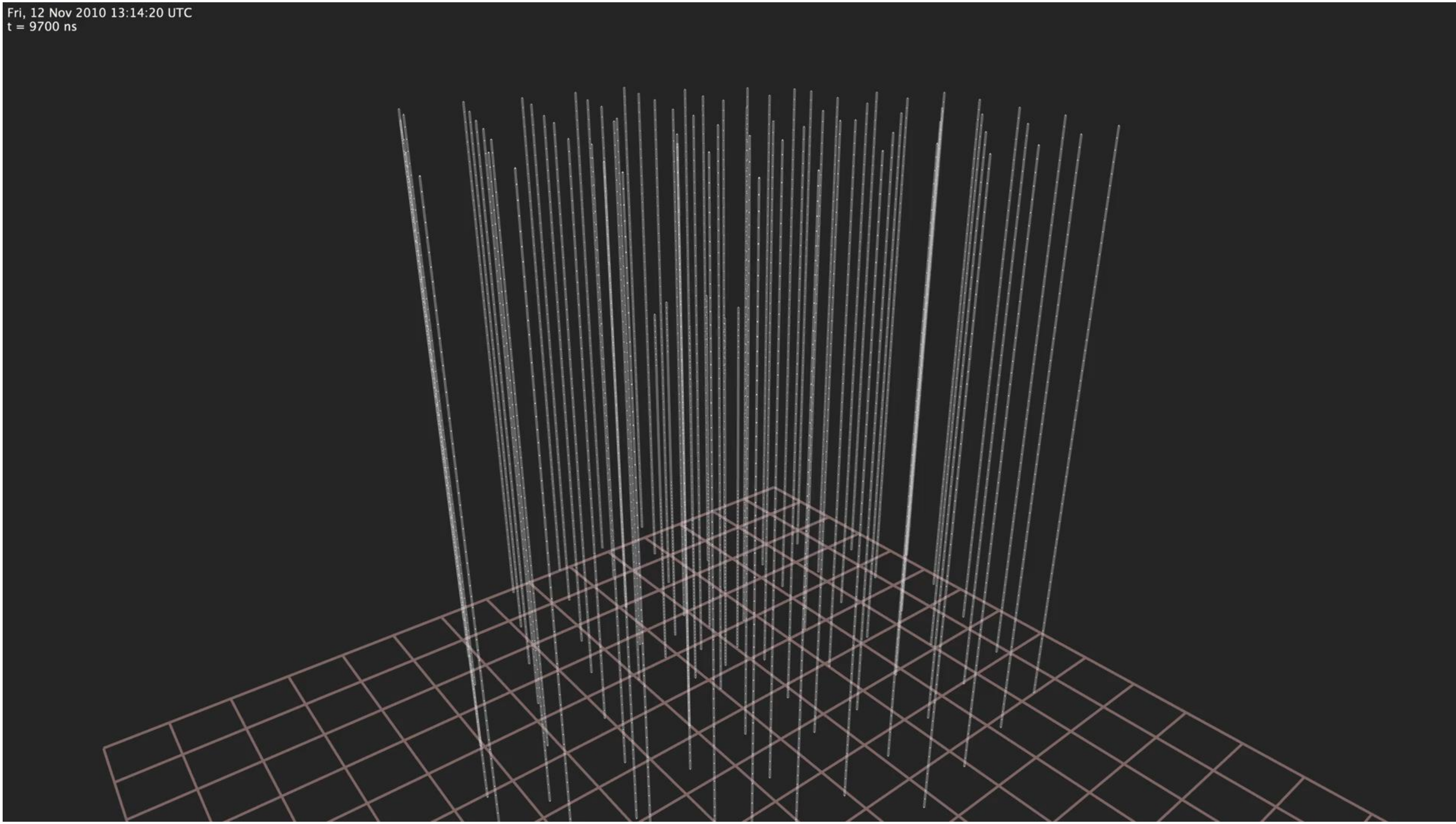
IceCube Neutrino Observatory



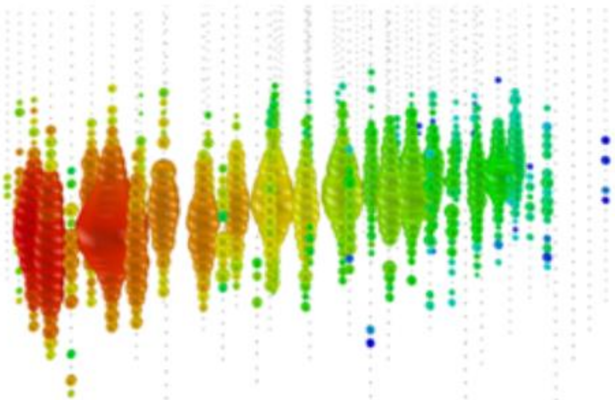
How IceCube detects neutrinos



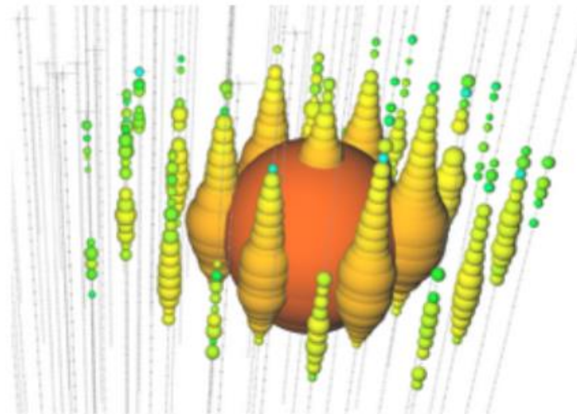
71 TeV neutrino event



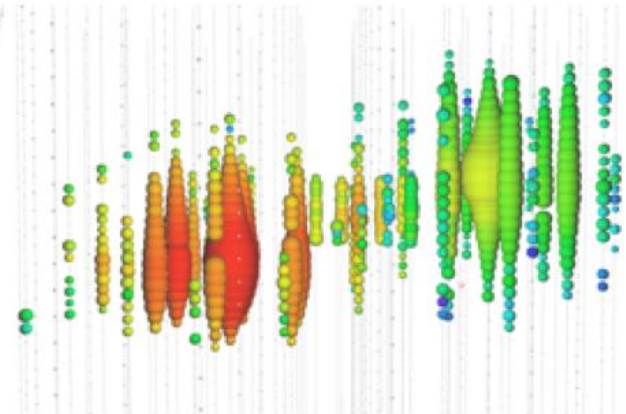
Neutrino signatures



Track
(Data)



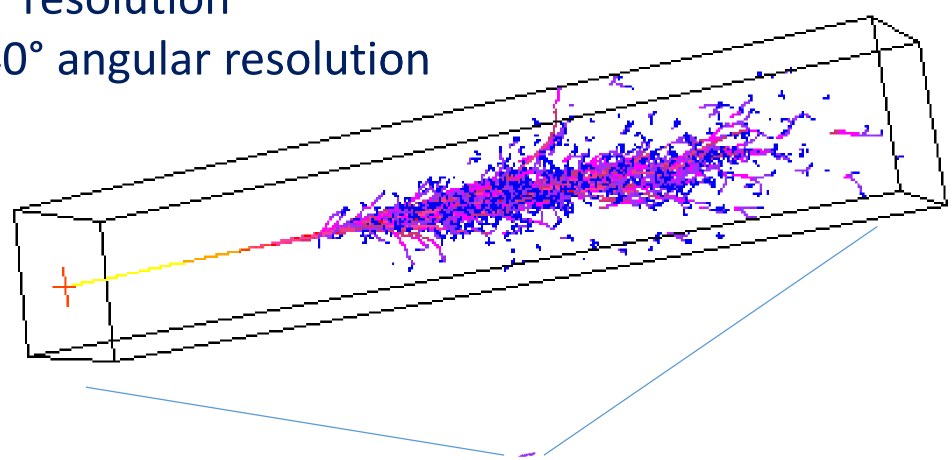
Shower or cascade
(Data)



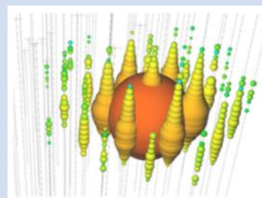
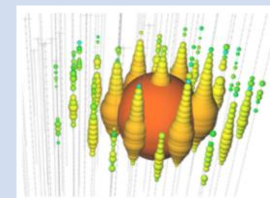
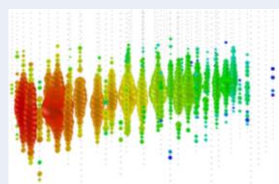
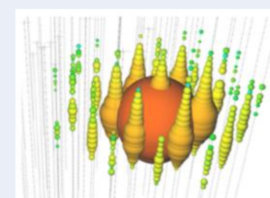
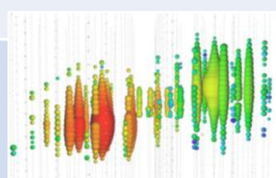
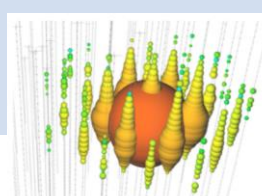
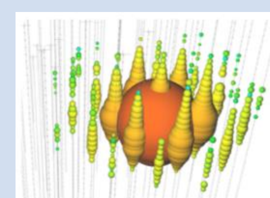
Double Bang
(Simulation)

factor of ≈ 2 energy resolution
(in rather E_μ than E_ν)
< 1° angular resolution

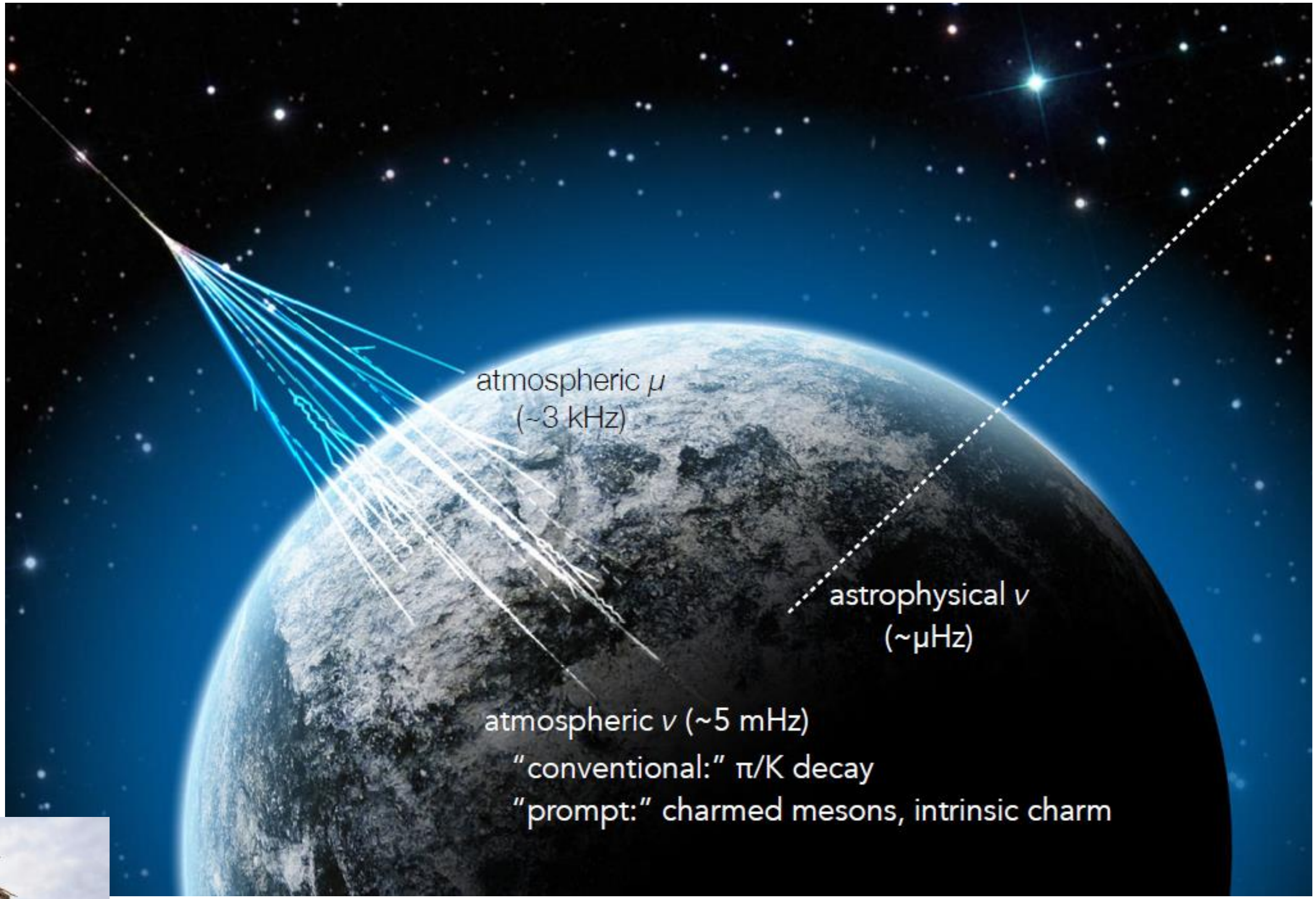
≈ ±15% deposited energy
resolution
≈ 10°- 40° angular resolution



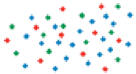
Neutrino signatures

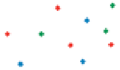
	Charged Current ($W^{+/-}$)	Neutral Current (Z^0)
ν_e	$\nu_e + N \rightarrow e^- + X$ 	$\nu_e + N \rightarrow \nu_e + X$ 
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$ 	$\nu_\mu + N \rightarrow \nu_\mu + X$ 
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$  	$\nu_\tau + N \rightarrow \nu_\tau + X$ 

Backgrounds – the needle in the haystack problem

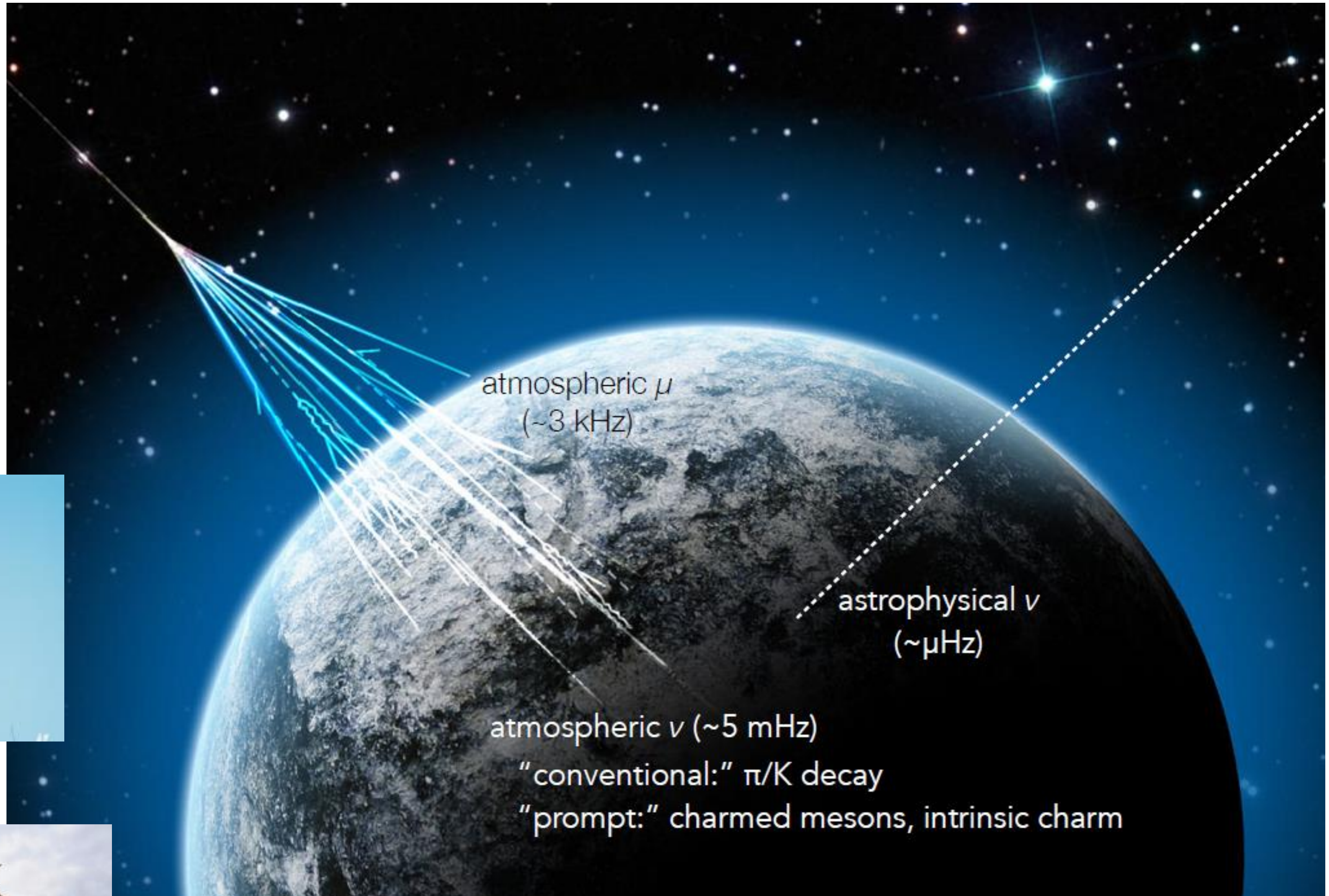


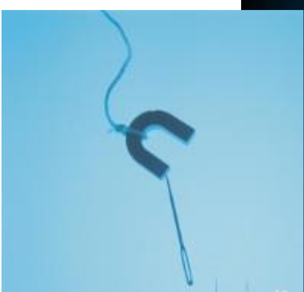
 275 million atmospheric muons are detected daily, created by interactions of cosmic rays with the earth's atmosphere

 8,250 atmospheric neutrinos are detected monthly

 only 10s of cosmic neutrinos are detected per year

Backgrounds – the needle and the haystack problem



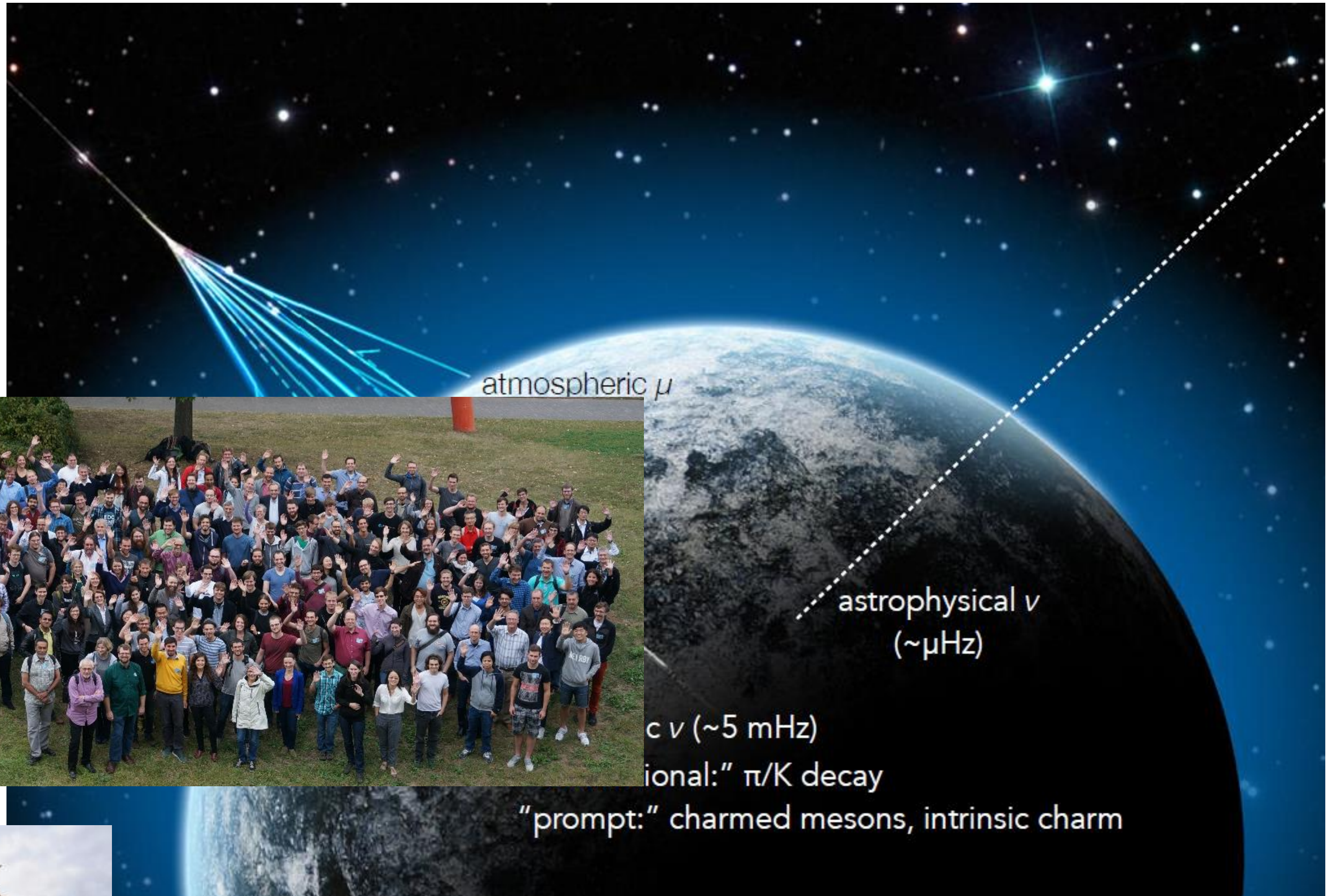


275 million atmospheric muons are detected daily, created by interactions of cosmic rays with the earth's atmosphere

8,250 atmospheric neutrinos are detected monthly

only 10s of cosmic neutrinos are detected per year

Backgrounds – the needle and the haystack problem



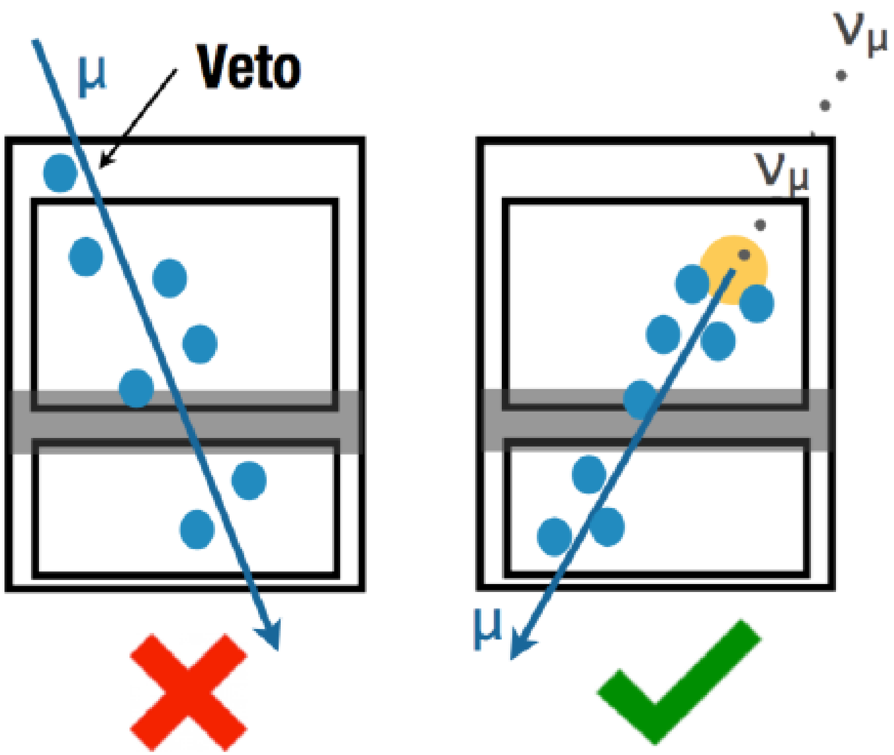
275 million atmospheric muons are detected daily, created by interactions of cosmic rays with the earth's atmosphere

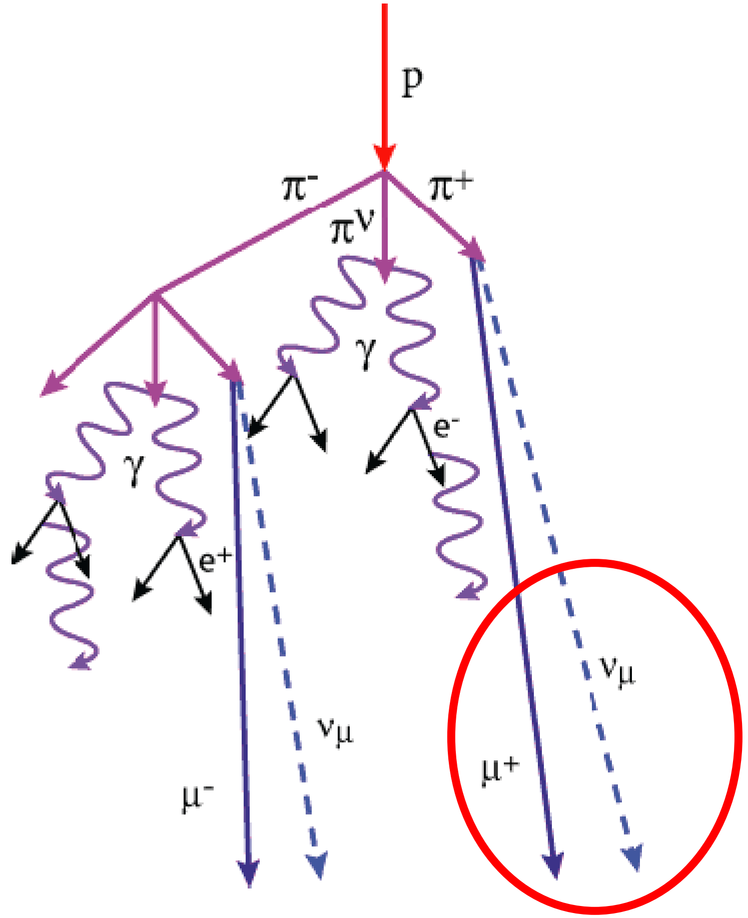
8,250 atmospheric neutrinos are detected monthly

only 10s of cosmic neutrinos are detected per year

Discovery strategy – High Energy Starting Event search

- Use outer parts of the detector as a veto-region
- Reduces both muon and southern hemisphere atmospheric neutrino backgrounds



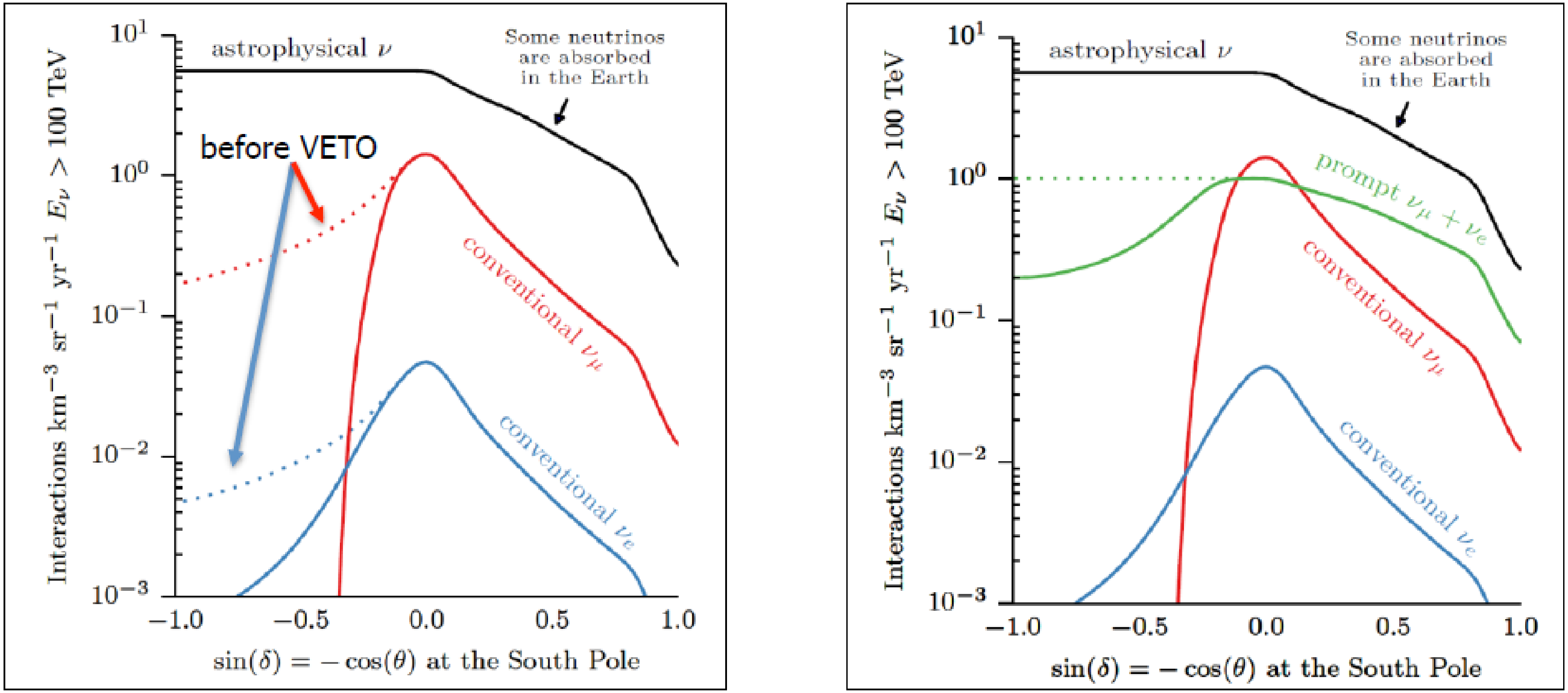


Muon accompanying the neutrino trips the veto

Schönert et al, 2009, Gaisser et al. 2014

Effect of veto on atmospheric backgrounds

- Veto educes **both** muon **and southern hemisphere atmospheric neutrino** backgrounds

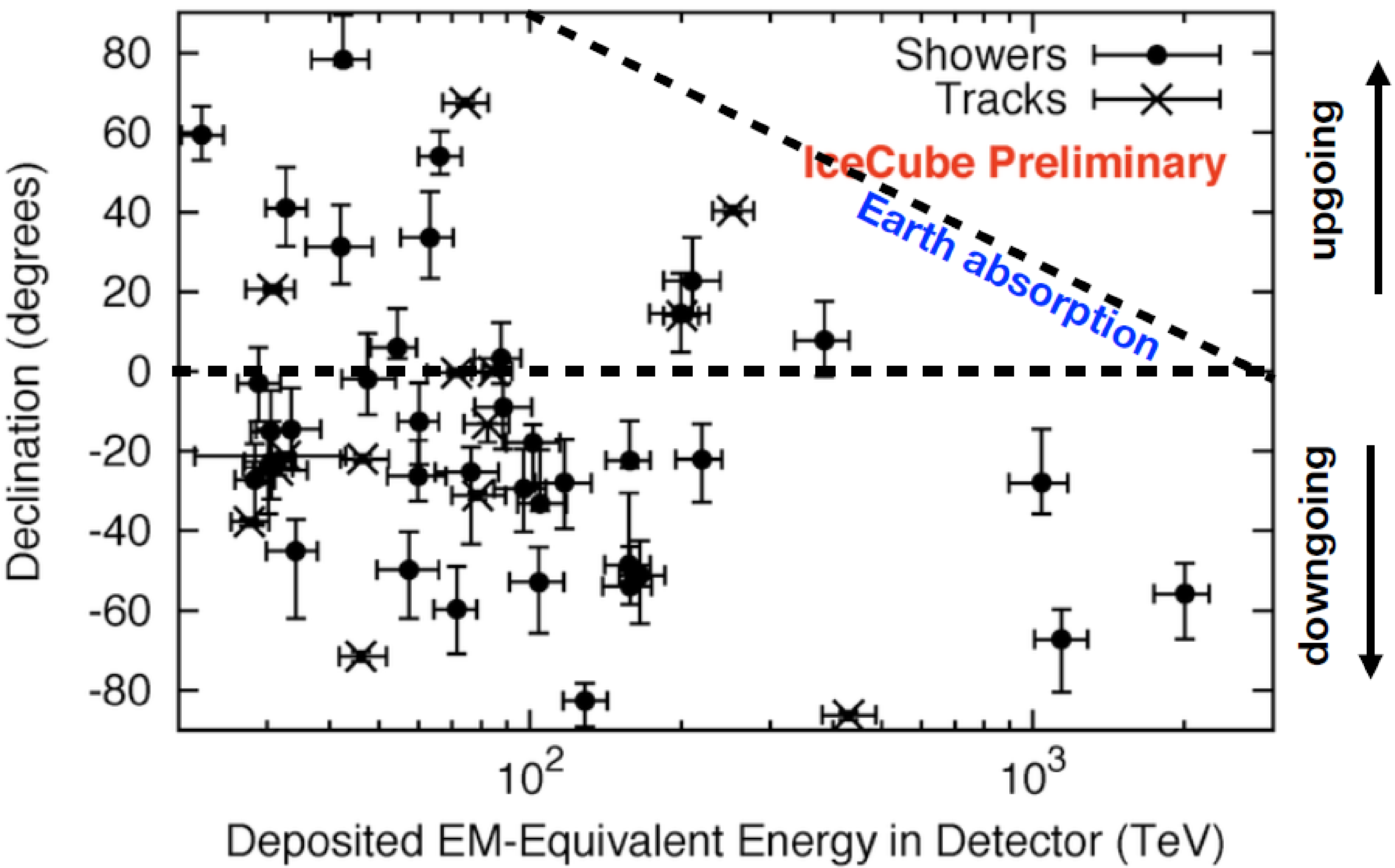


Schönert et al, 2009, Gaisser et al. 2014

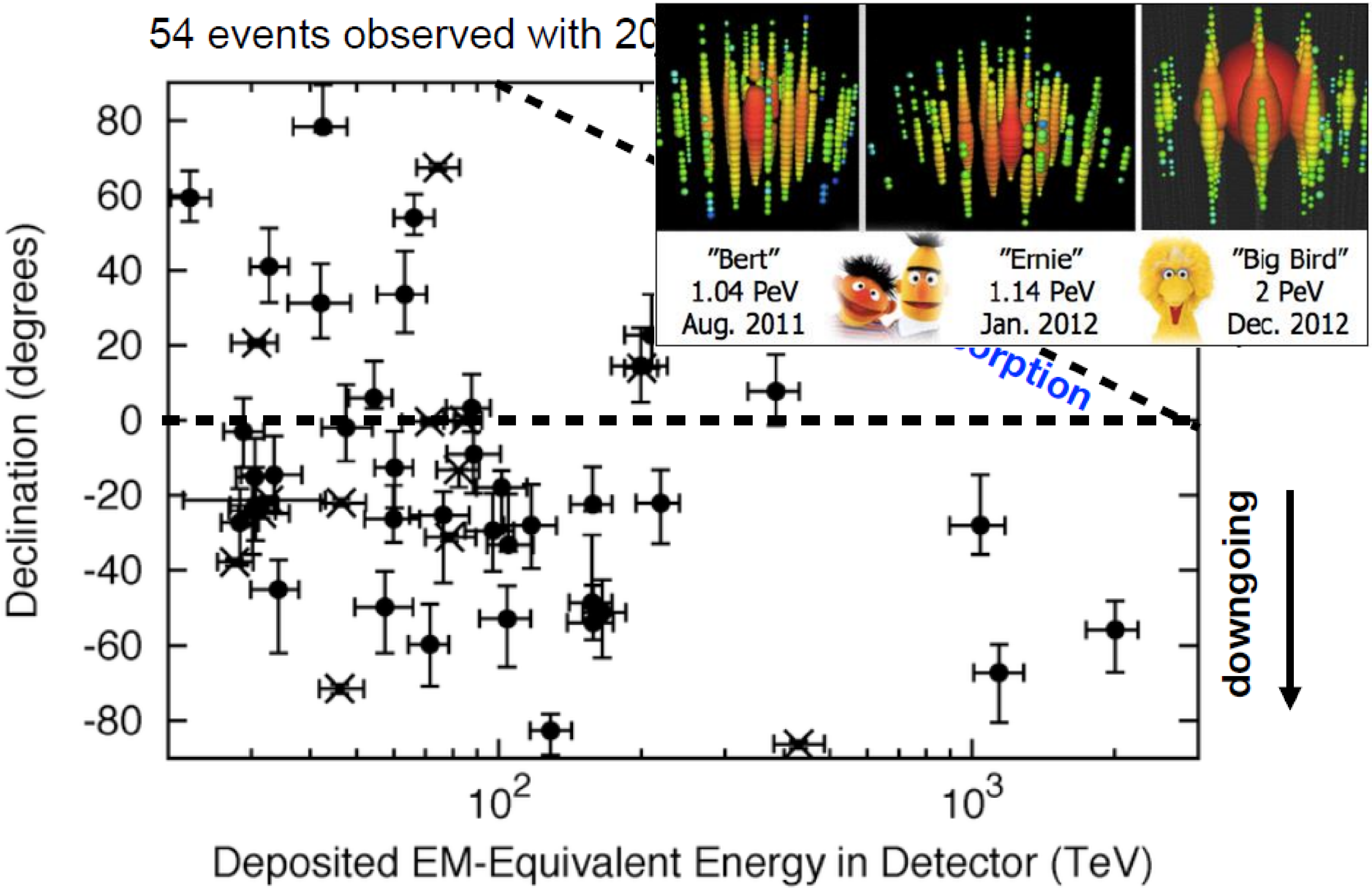
Four Year HESE result

ICRC (2015) arXiv:1510.05223

54 events observed with 20±6 expected from atmosphere



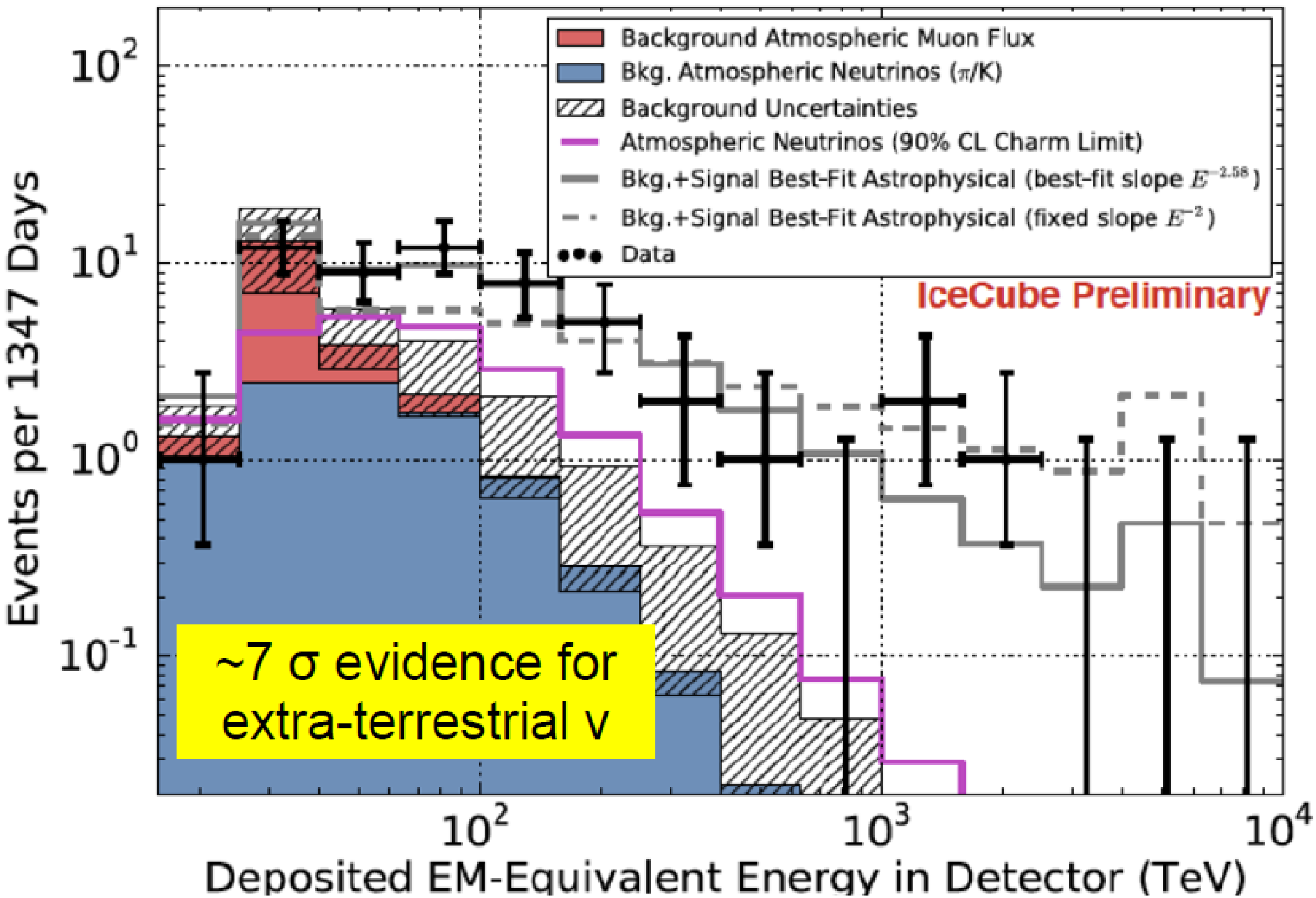
Four Year HESE result



Energy spectrum

ICRC (2015) arXiv:1510.05223

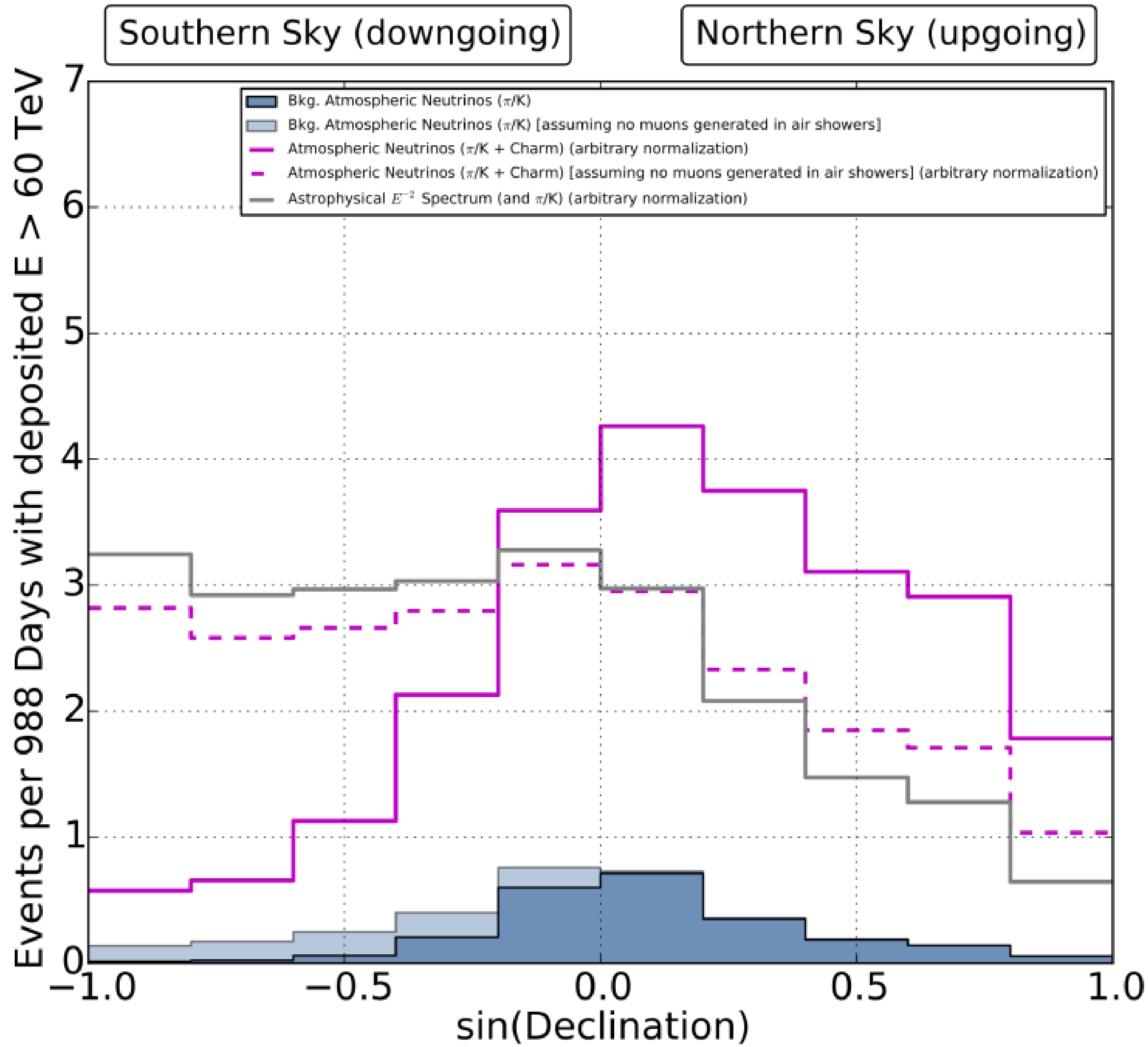
54 events observed with 20±6 expected from atmosphere



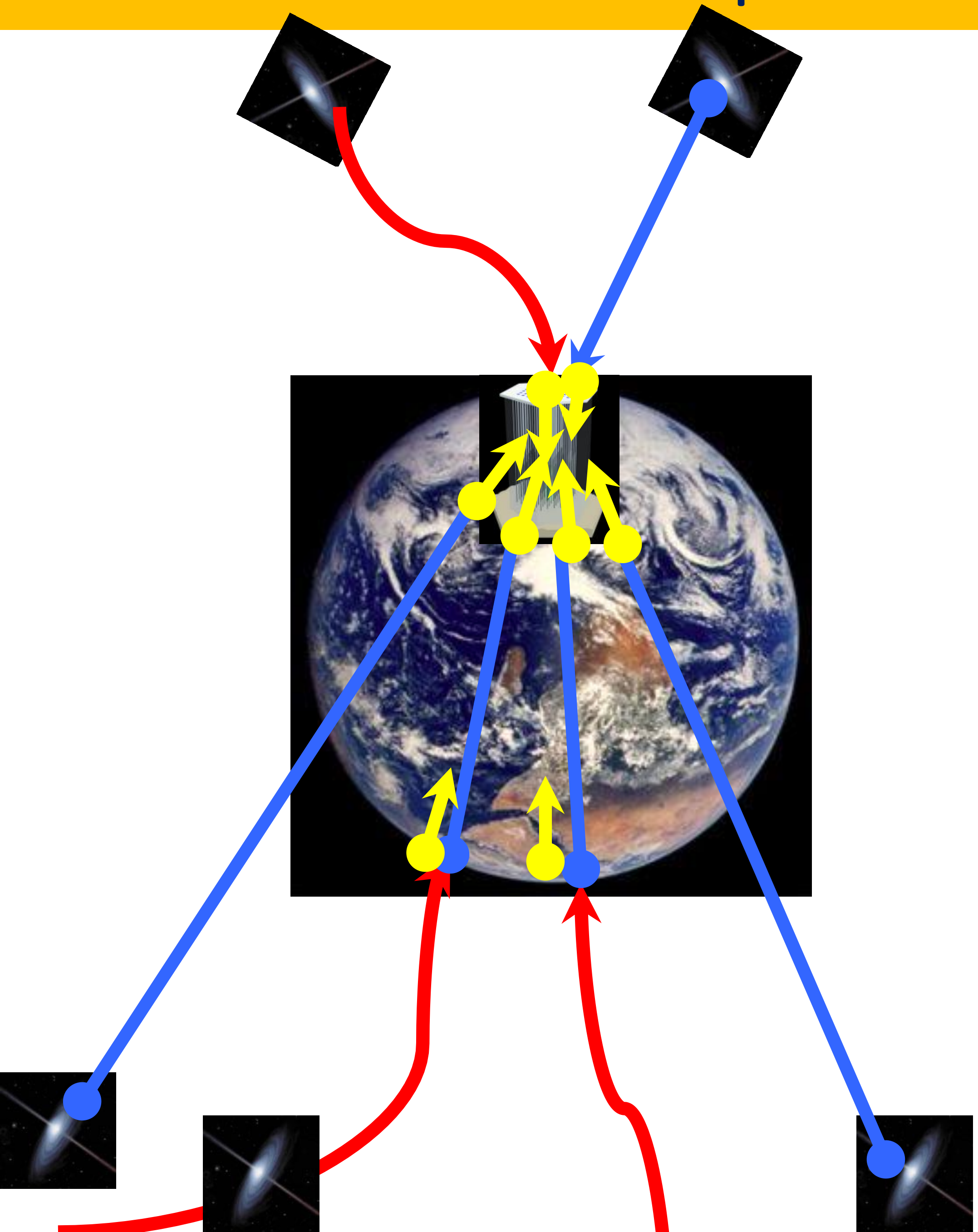
Effect of muon veto on downward going atmospheric ν

Without self-veto astro (grey) and prompt (dash-purple) have same zenith shape

With self-veto prompt (solid-purple) is highly suppressed from above



Classic neutrino telescope strategy



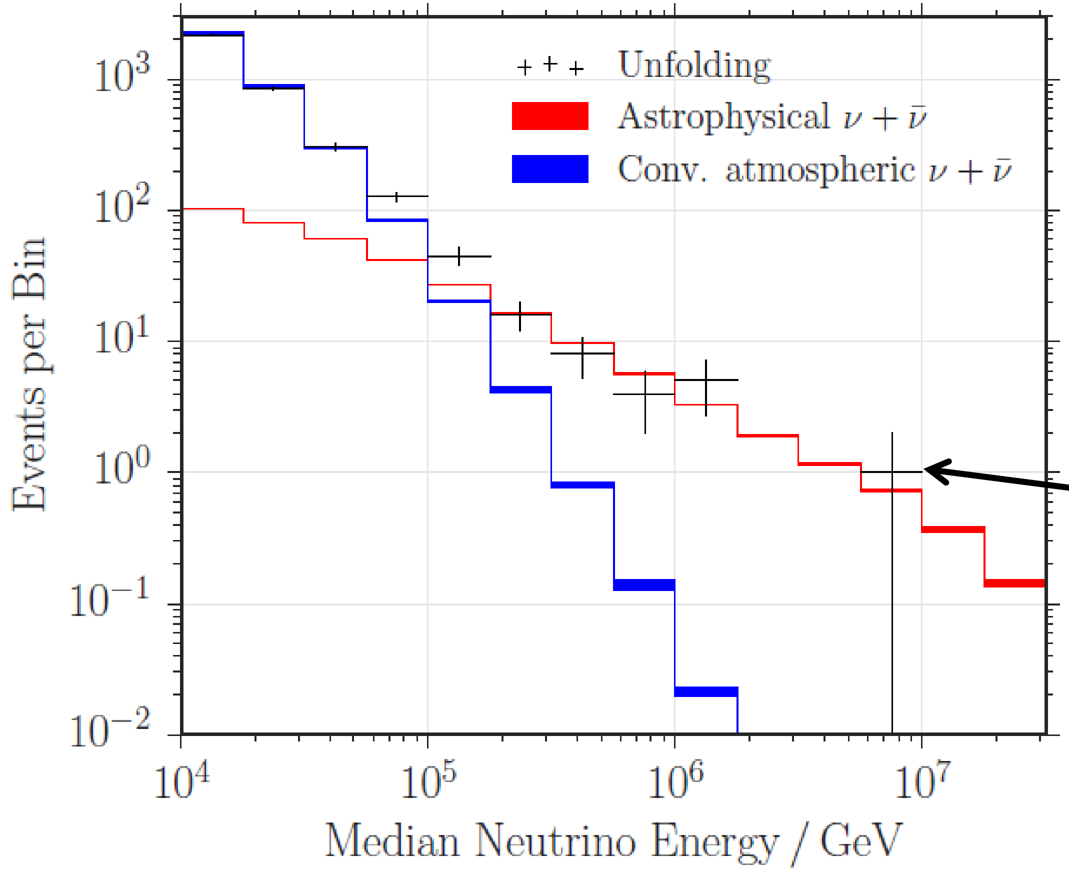
Select upward going muon tracks; these must originate from neutrinos as only neutrinos can traverse the Earth

Upward-going muon search

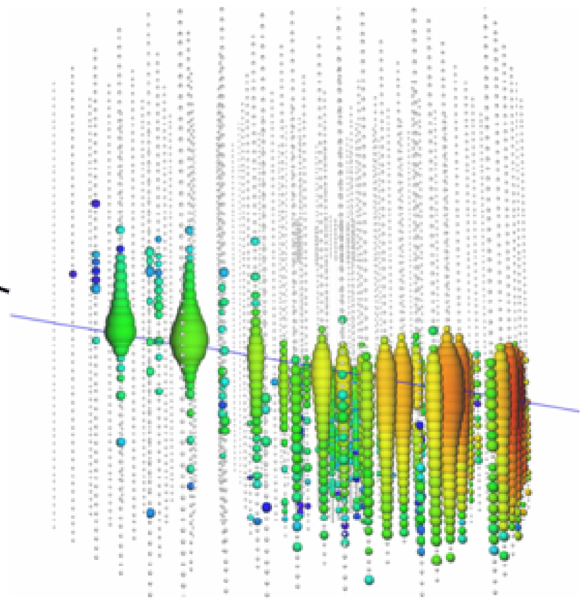
IceCube Preliminary

arXiv:1607.08006

unfolded data assuming unbroken best-fit power law



5.6 sigma detection of astrophysical neutrinos with through-going muons analysis



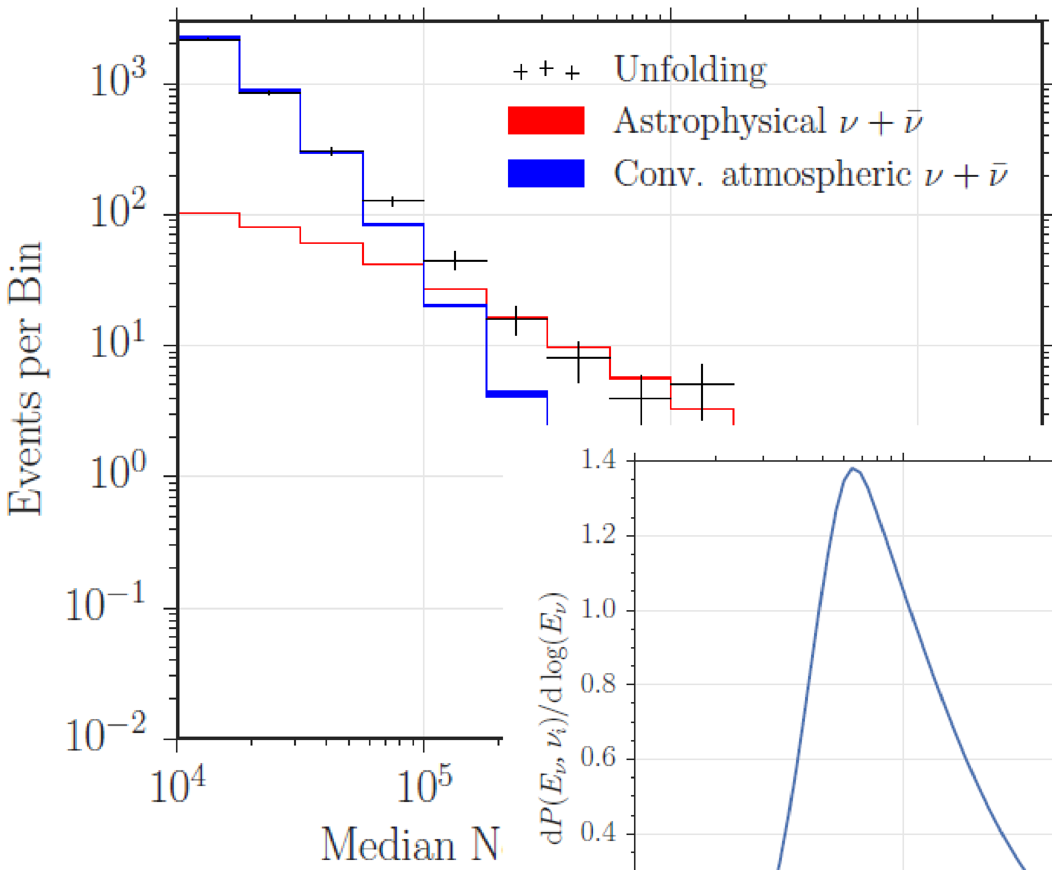
Deposited energy: 2.6±0.3 PeV

Upward-going muon search

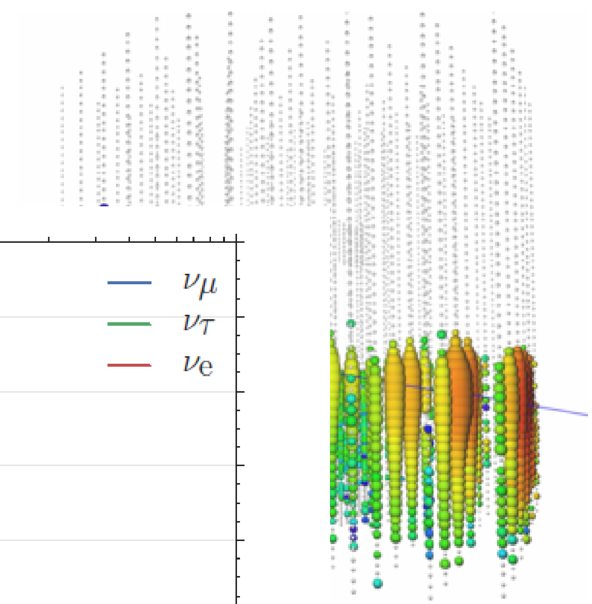
IceCube Preliminary

arXiv:1607.08006

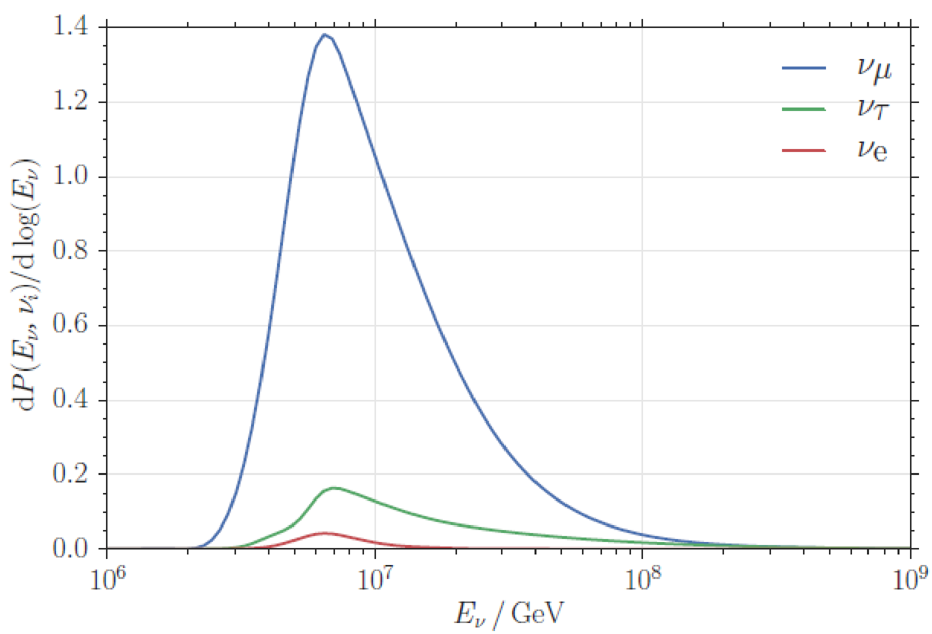
unfolded data assuming unbroken best-fit power law



5.6 sigma detection of astrophysical neutrinos with through-going muons analysis

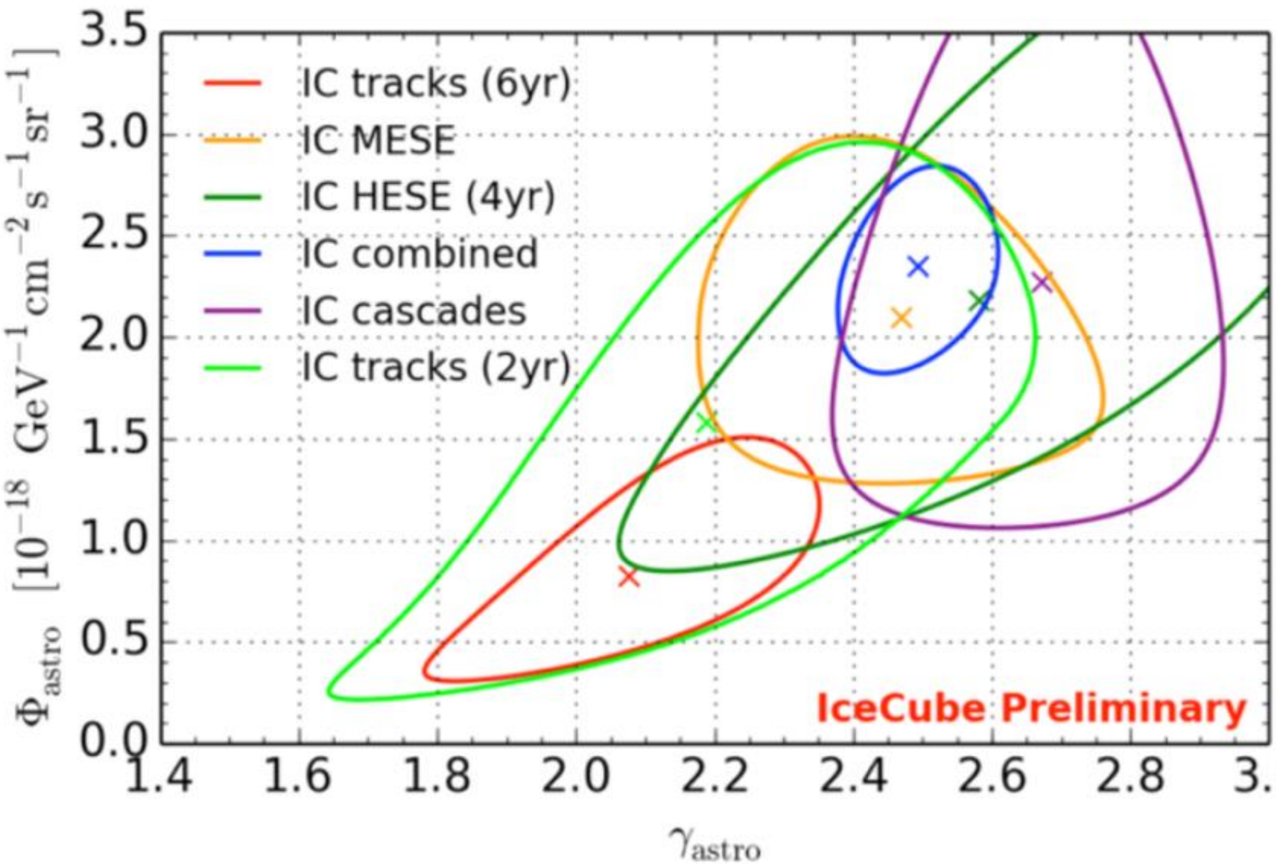


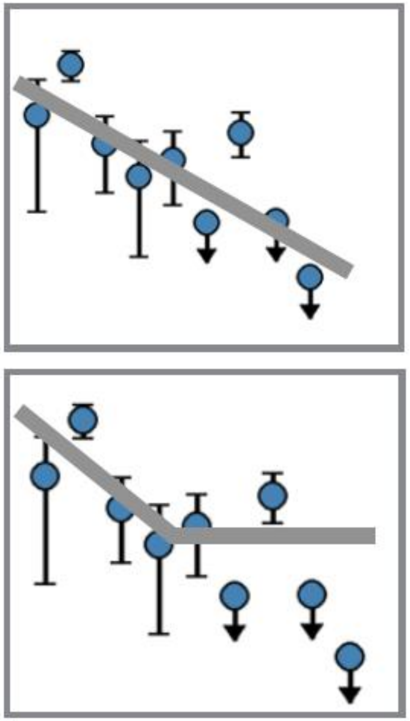
l energy:
eV



Spectral analysis from different channels

ICRC (2015) arXiv:1510.05223



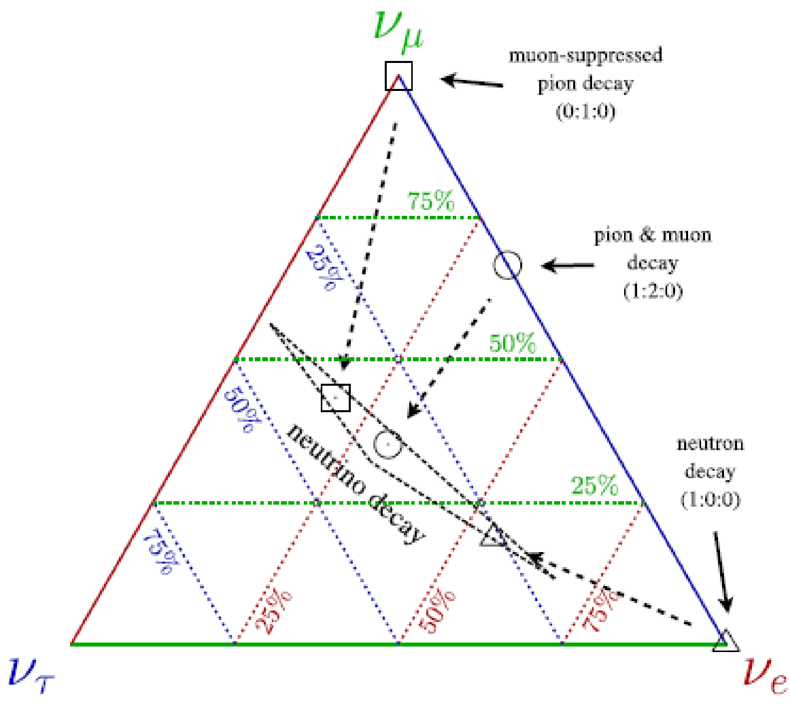


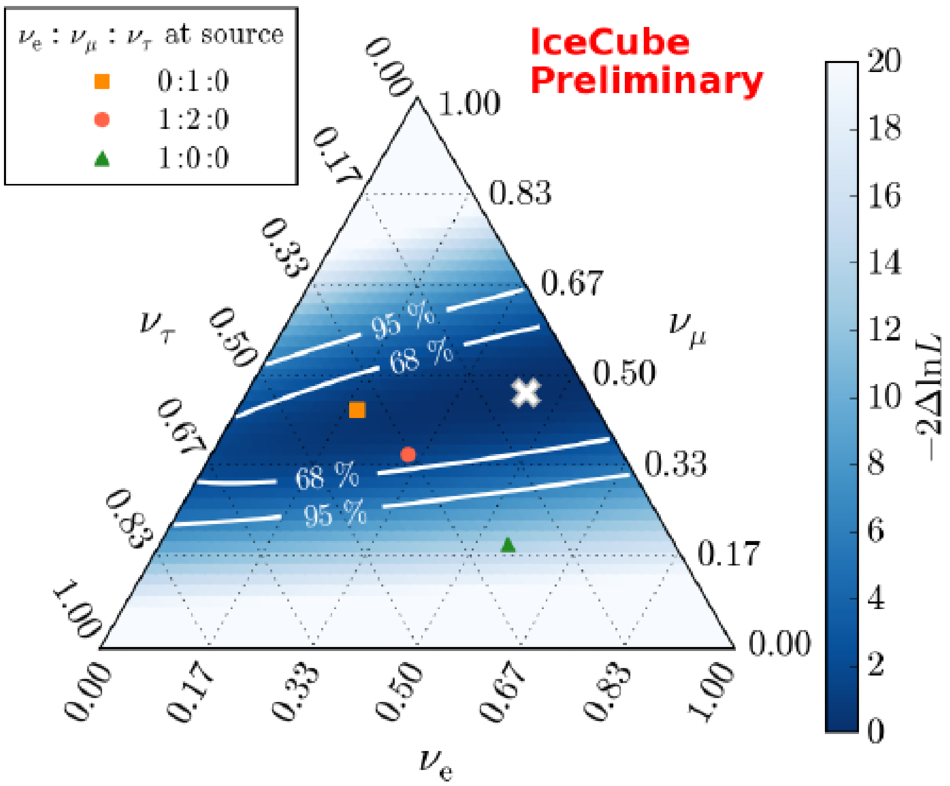
Combined spectral index: γ=2.50±0.09
High-energy tracks: γ=2.13±0.13

Are we seeing a spectral flattening of astrophysical neutrinos?

Astrophysical neutrino flavour ratio

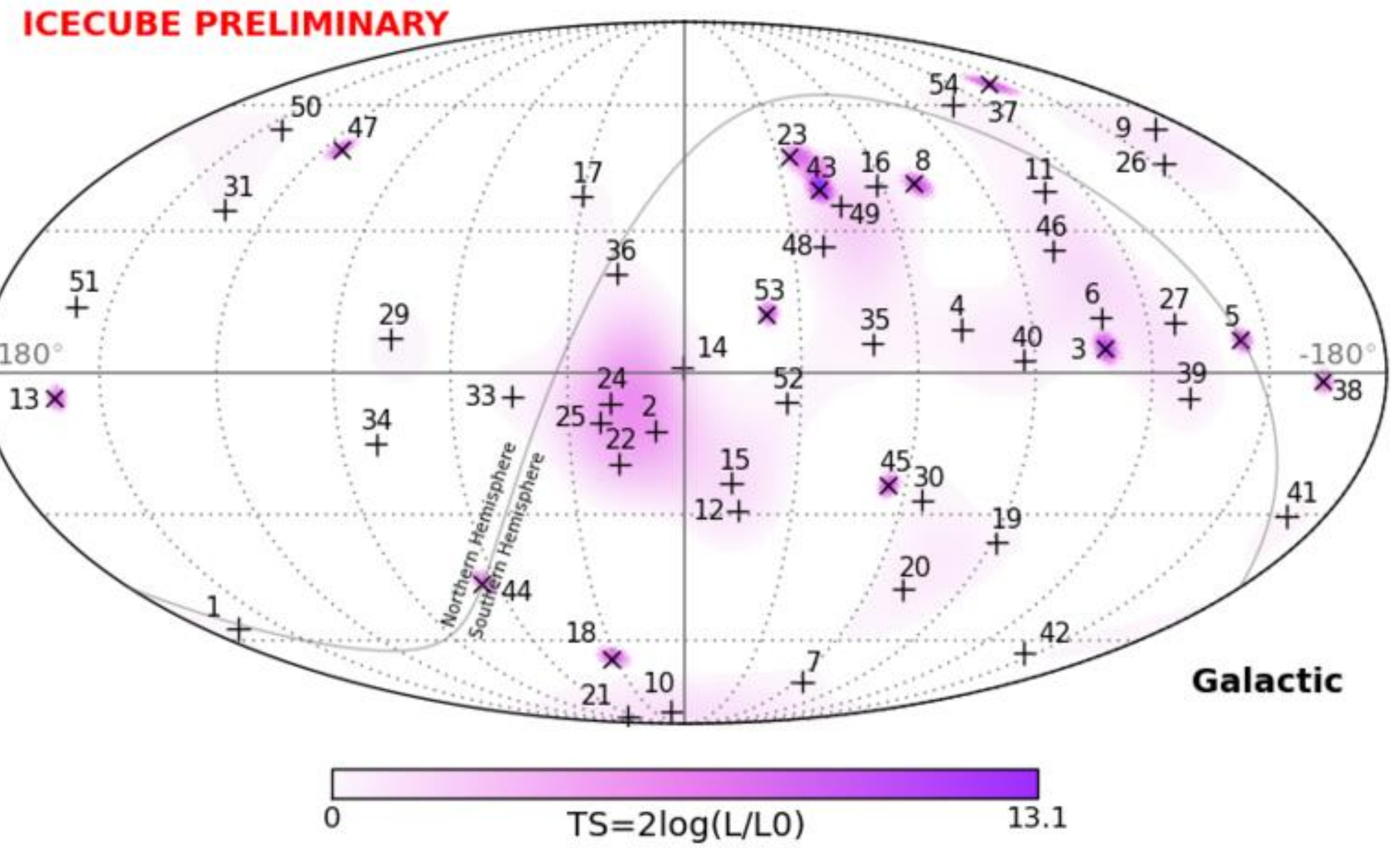
ICRC (2015) arXiv:1510.05223, ApJ 809 (2015) 98





Four Year HESE sky map

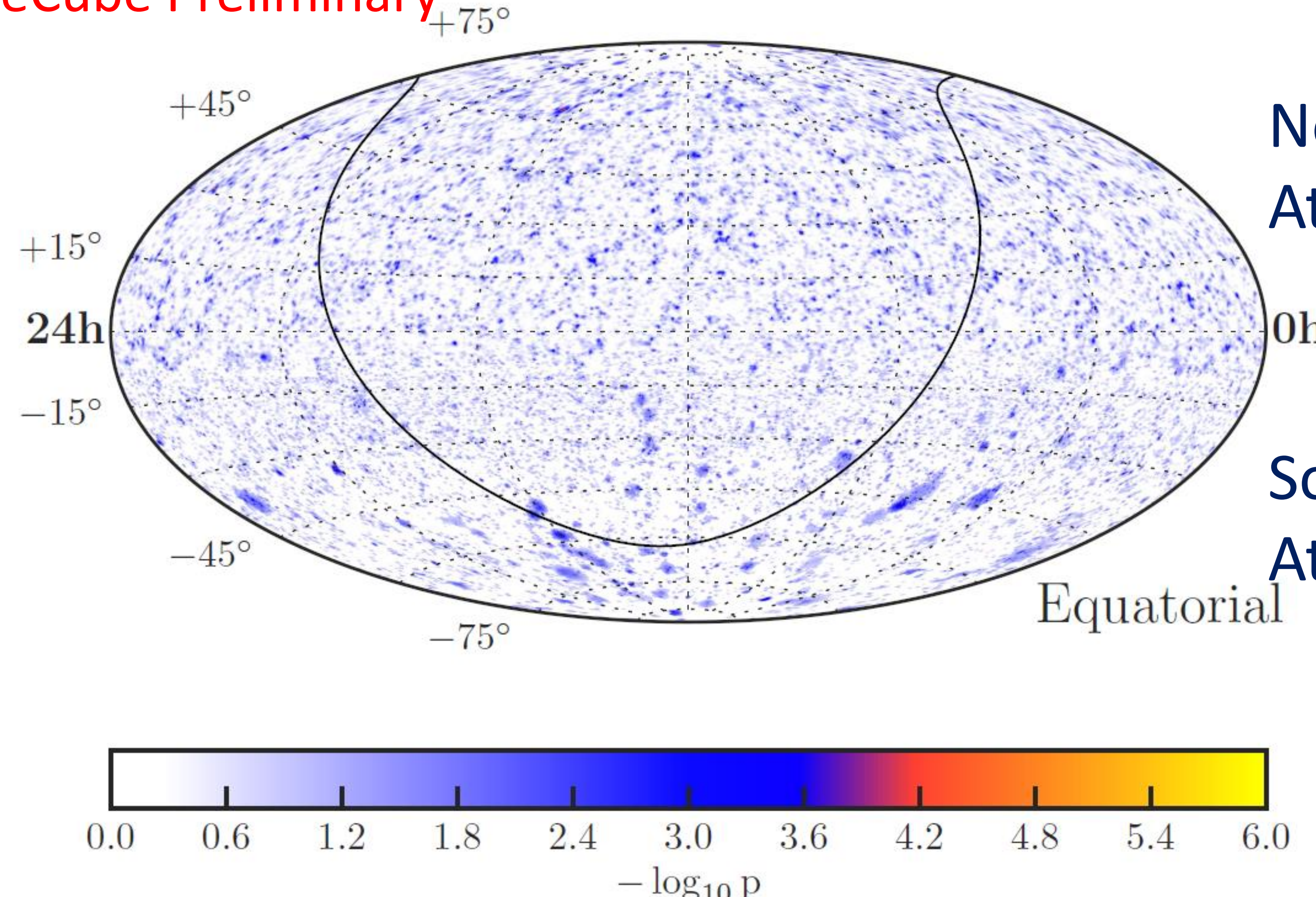
ICRC (2015) arXiv:1510.05223



Search for point sources in 7 years of data

IceCube Preliminary

arXiv:1609.04981



North
Atm. ν

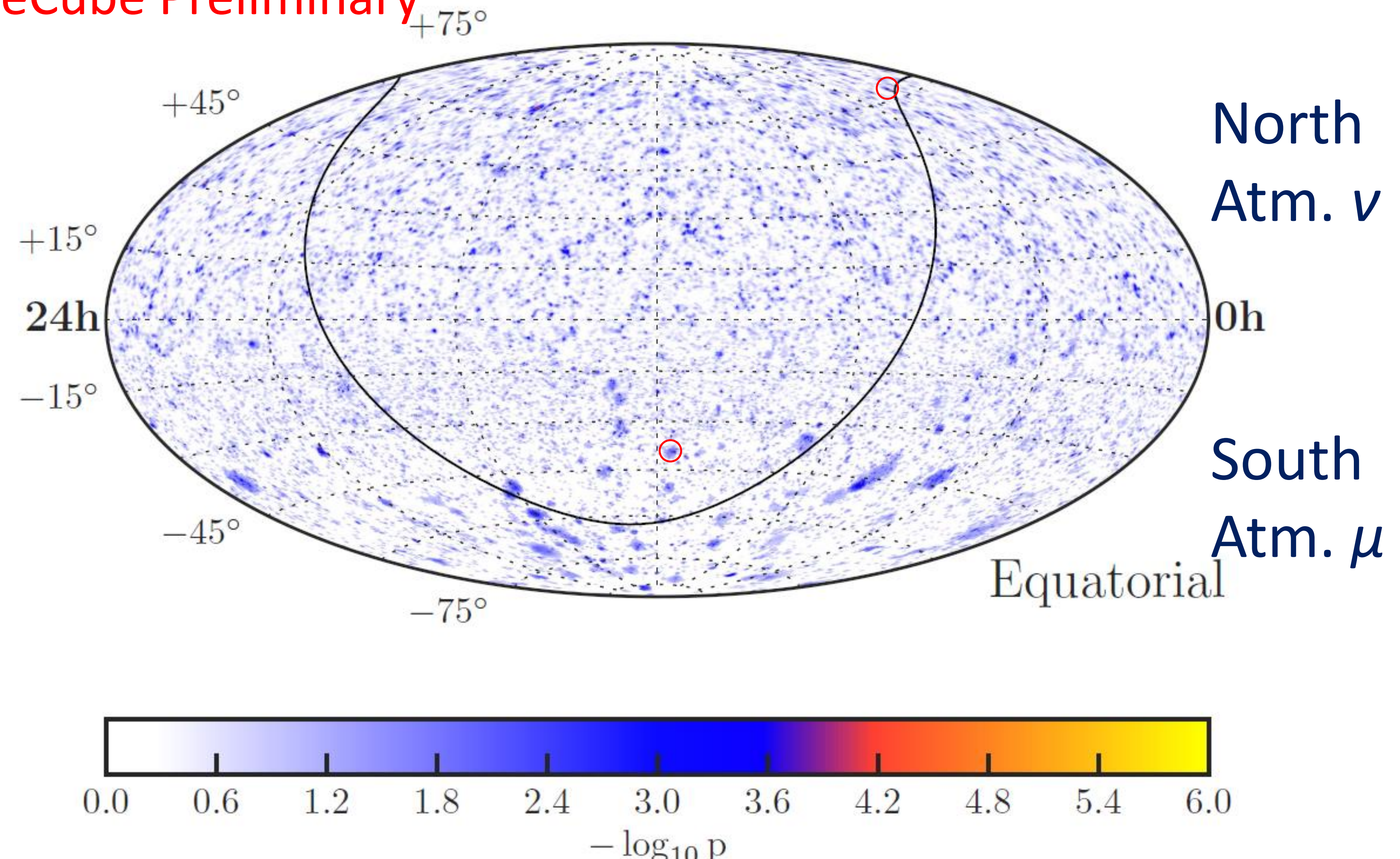
South
Atm. μ

$$\mathcal{L}(n_S, \gamma) = \prod \left(\frac{n_S}{N} \mathcal{S}\left(|\mathbf{x}_S - \mathbf{x}_i|,\, E_i;\, \gamma\right) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}\left(\sin\delta_i,\, E_i\right) \right)$$

Search for point sources in 7 years of data

IceCube Preliminary

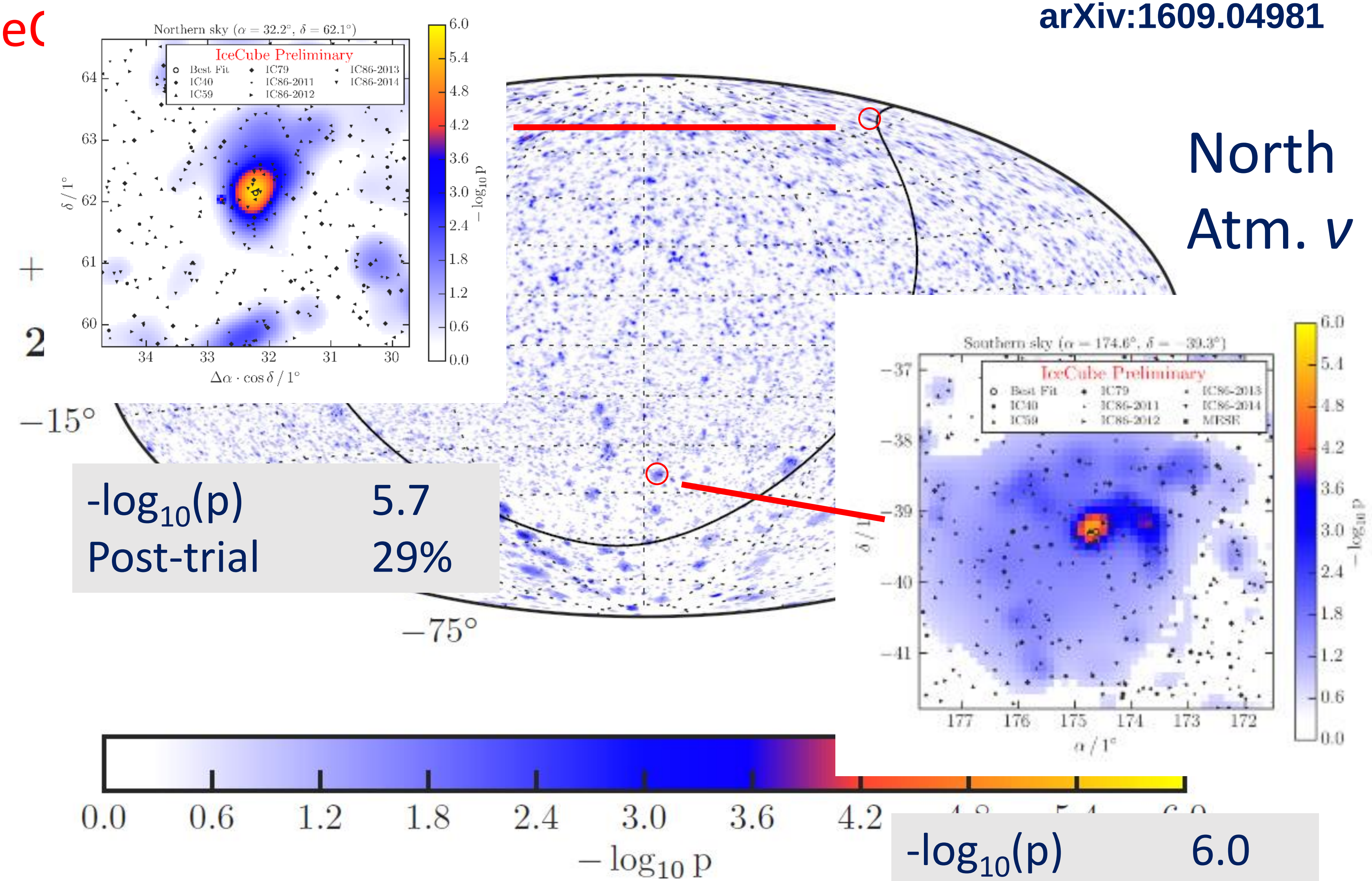
arXiv:1609.04981



$$\mathcal{L}(n_S, \gamma) = \prod \left(\frac{n_S}{N} \mathcal{S}\left(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma \right) + \left(1 - \frac{n_S}{N} \right) \mathcal{B}\left(\sin \delta_i, E_i \right) \right)$$

Search for point sources in 7 years of data

arXiv:1609.04981



North
Atm. ν

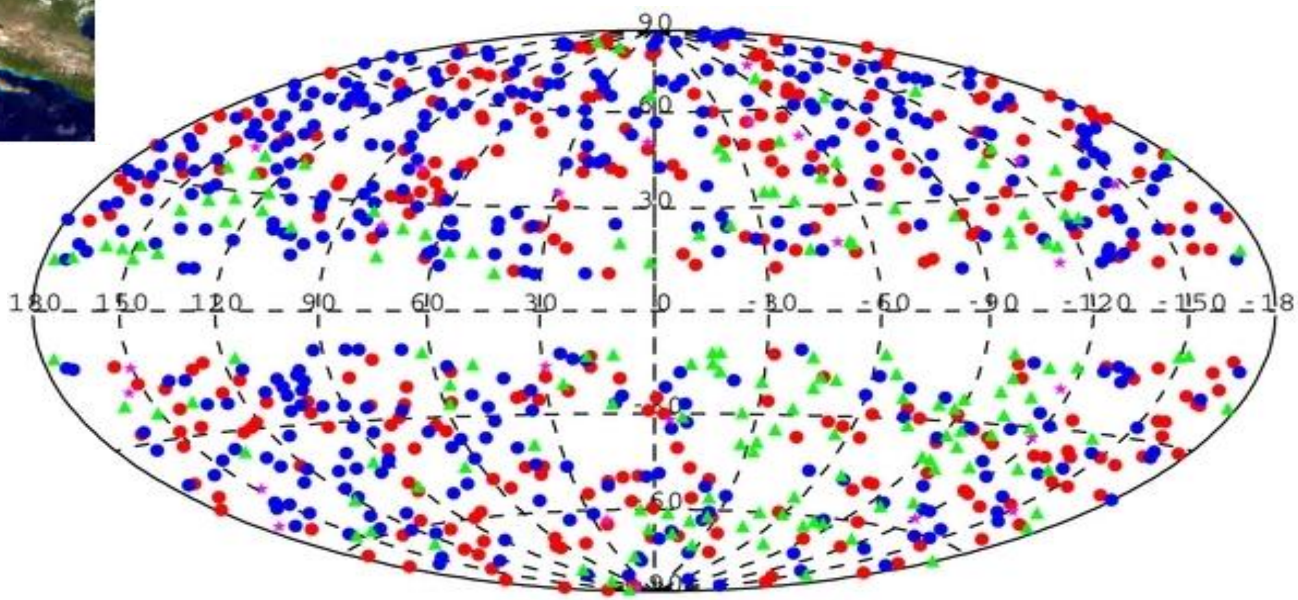
$-\log_{10}(p)$	5.7
Post-trial	29%

$-\log_{10}(p)$	6.0
Post-trial	17%

$$\mathcal{L}(n_S, \gamma) = \prod \left(\frac{n_S}{N} \mathcal{S}\left(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma\right) + \left(\right. \right.$$

Stacked search for neutrinos from Fermi-LAT blazars

Ackermann et al, 2011



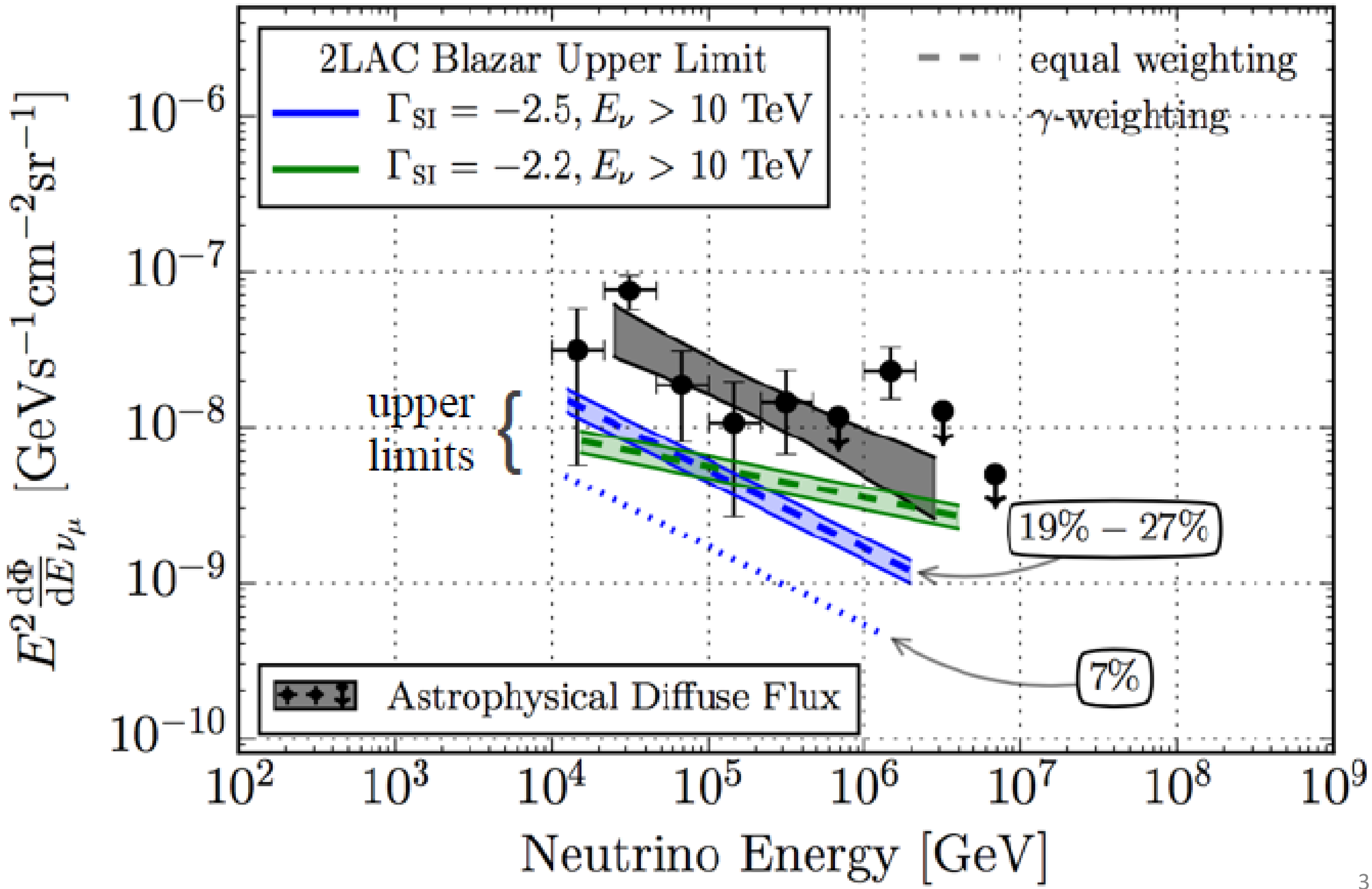
862 sources

FSRQ   BL-LAC   Unknown Blazar

Stacked search for neutrinos from Fermi-LAT blazars

IceCube Preliminary

arXiv:1611.03874



Possible astrophysical sources

✗ Gamma Ray Bursts

- No more than 1% of the observed neutrino flux is associated with GRBs

? Active Galactic Nuclei

- No correlation found < 30% of the astrophysical neutrino flux is correlated with the 2LAC blazars (less if weighted by gamma ray emission)
- Possibly special populations of AGNs

? Starburst Galaxies

Gamma rays should be produced along with neutrinos – would exceed diffuse Fermi-LAT diffuse gamma ray flux not due to blazars (Bechtol et al 2015)

Multi-messenger studies – correlations and alerts

Individual MOU observatories:

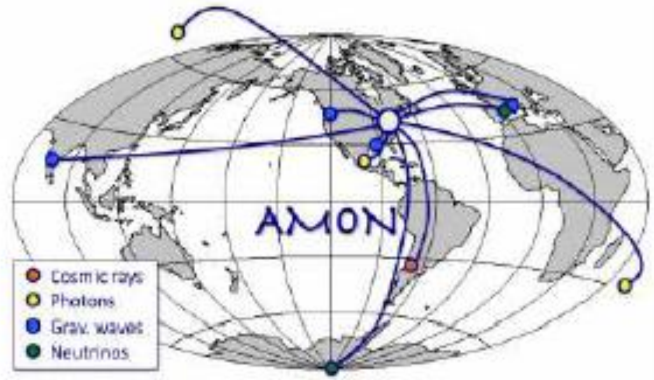
- Swift XRT
- Palomar Transient Factory
- Magic Gamma Ray Telescope
- VERITAS
- HAWC
- HESS
- LIGO/VIRGO
- Murchison Widefield Array

HAWC
High Altitude Water Cherenkov

VERITAS

H.E.S.S.

Networks & public alerts:



The Astrophysical Multimessenger Oberservatory Network:
FACT, VERITAS, MASTER,
LMT, ASAS-SN, LCOGT

„The Astronomer's Telegram"

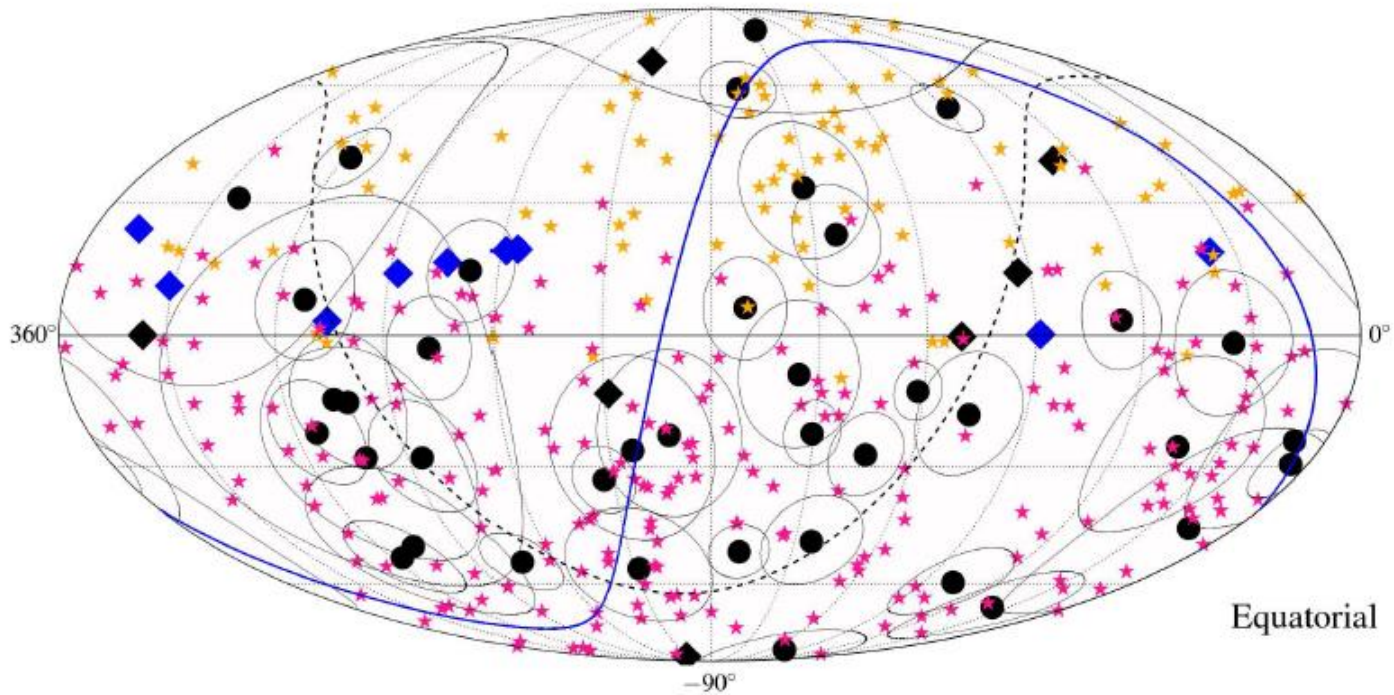
SNEWS

The **G**amma-ray **C**oordinates **N**etwork

Multi-messenger studies – correlations and alerts

JCAP 1601 (2016) 01, 037arXiv:1511.09408

Ultra-high energy cosmic rays



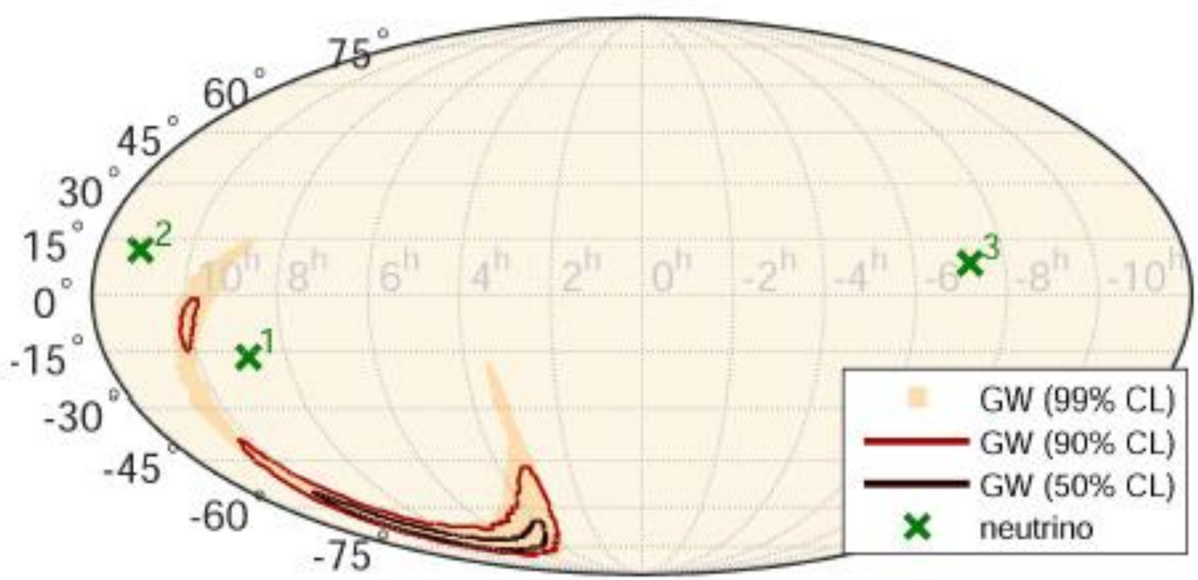
Correlations with UHECRs no correlation beyond 3.3 σ

IceCube cascades (black dots) and tracks (diamonds), UHECRs Pierre Auger Observatory (magenta stars) and Telescope Array (orange stars)

Multi-messenger studies – correlations and alerts

arXiv:1602.05411v3

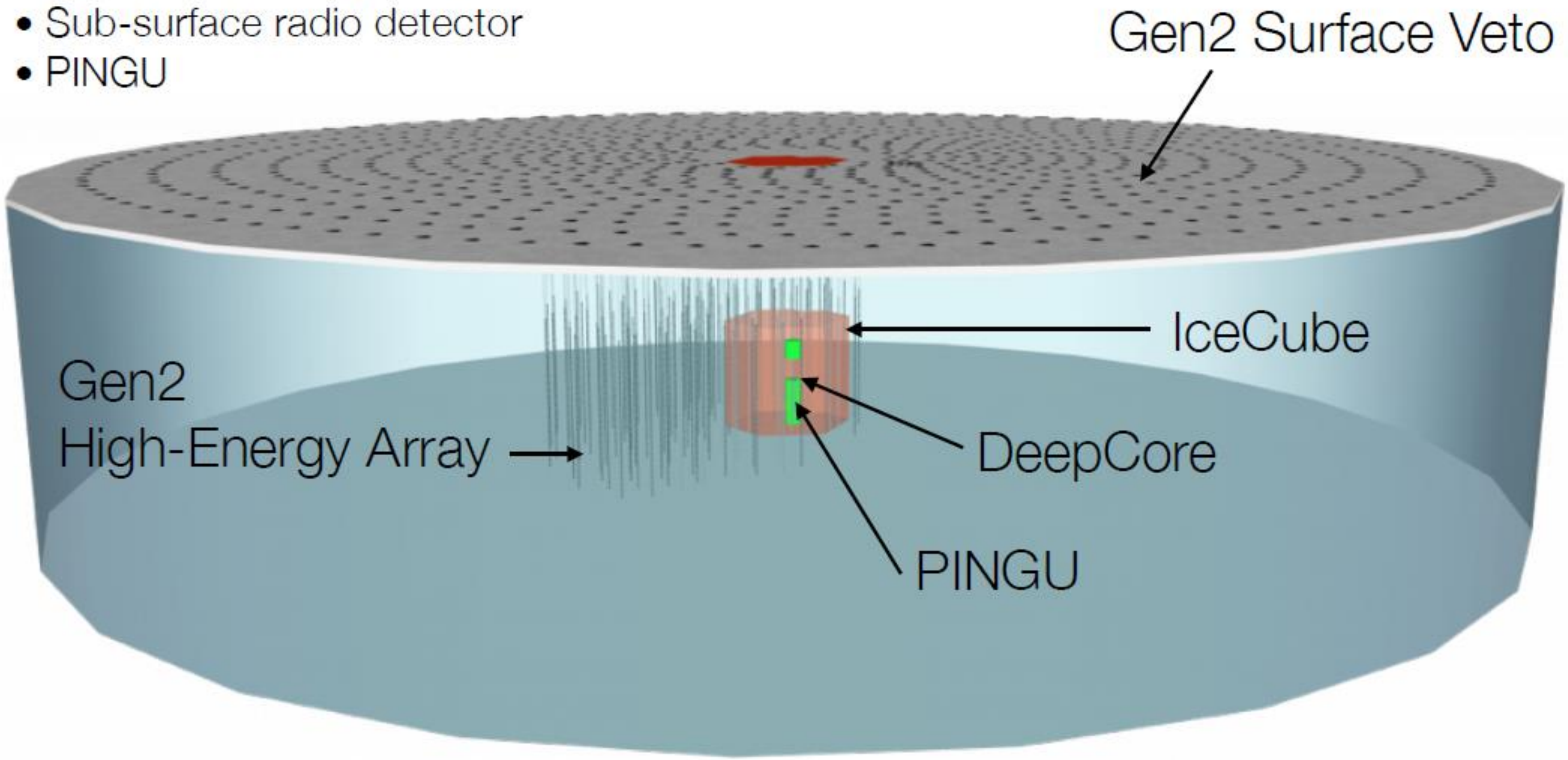
Gravity Waves



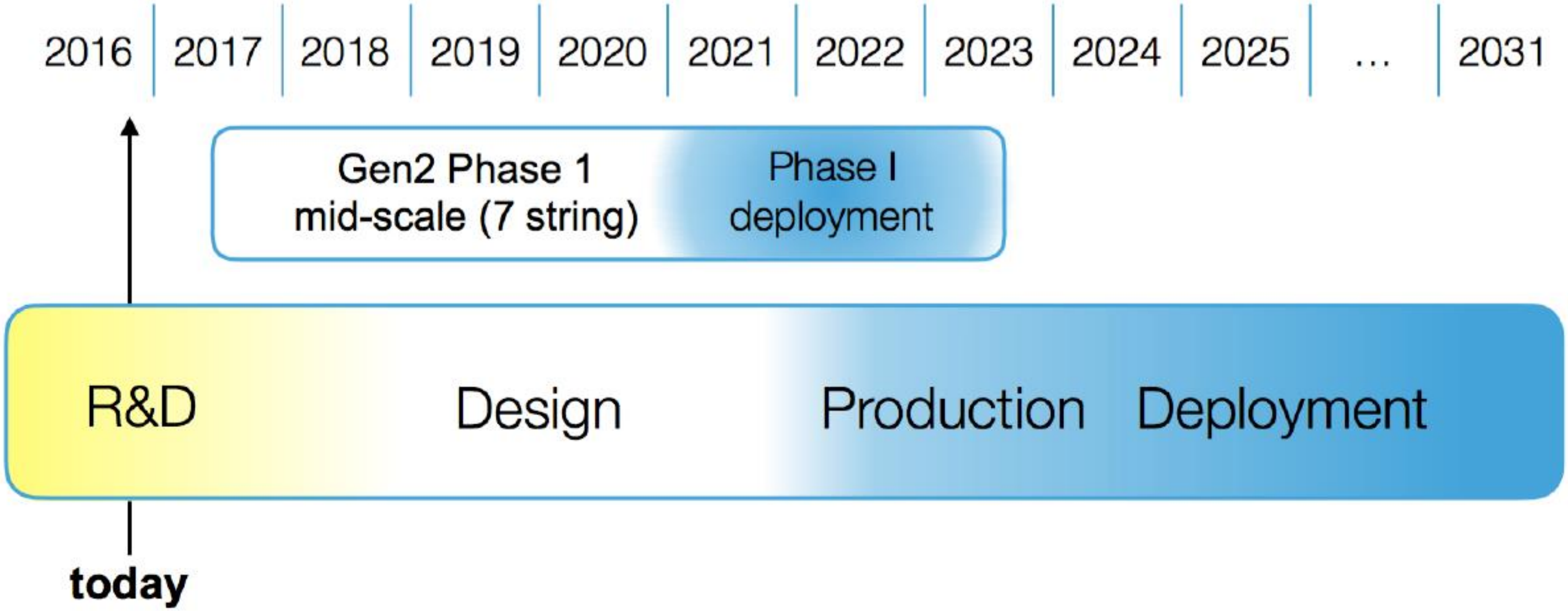
LIGO gravity signal and neutrino events within +/- 500s

IceCube Gen2 Facility

Multi-component observatory:
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



IceCube Gen2 Facility Preliminary Timeline



~250 people in ~40 institutions

The IceCube Collaboration

showing you the high energy neutrino Universe

USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Marquette University
Massachusetts Institute of Technology
Michigan State University
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 Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

Canada
SNOLAB
University of Alberta–Edmonton

University of Copenhagen, Denmark

Chiba University, Japan

Sungkyunkwan University, Korea

University of Oxford, UK

Belgium
Université Libre de Bruxelles
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 Dortmund
Technische Universität München
Universität Mainz
Universität Münster
Universität Wuppertal

Université de Genève, **Switzerland**

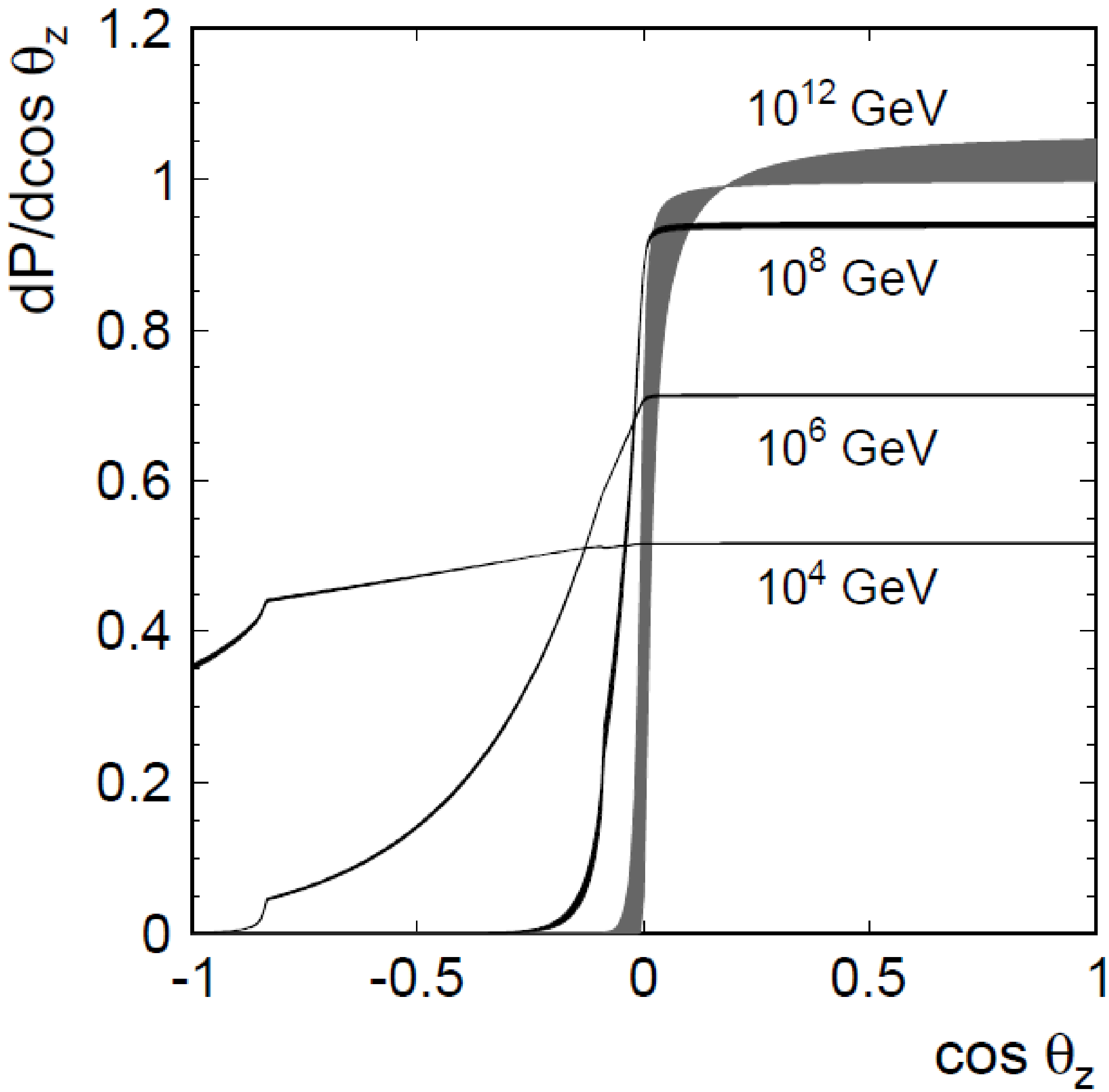
University of Adelaide, **Australia**

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)

Earth absorption



Multi-messenger – comparable energies