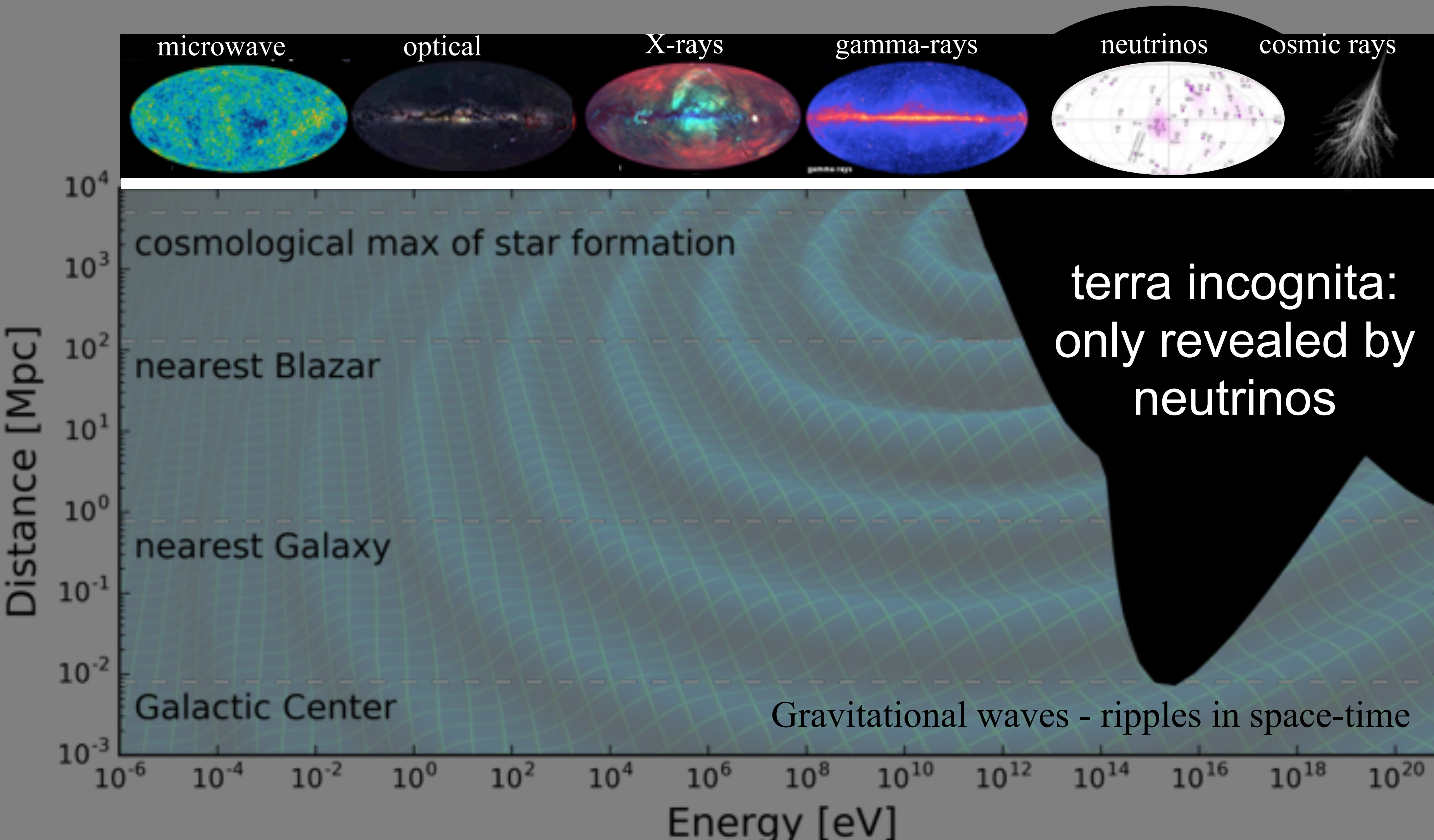
# IceCube: the discovery of cosmic neutrinos

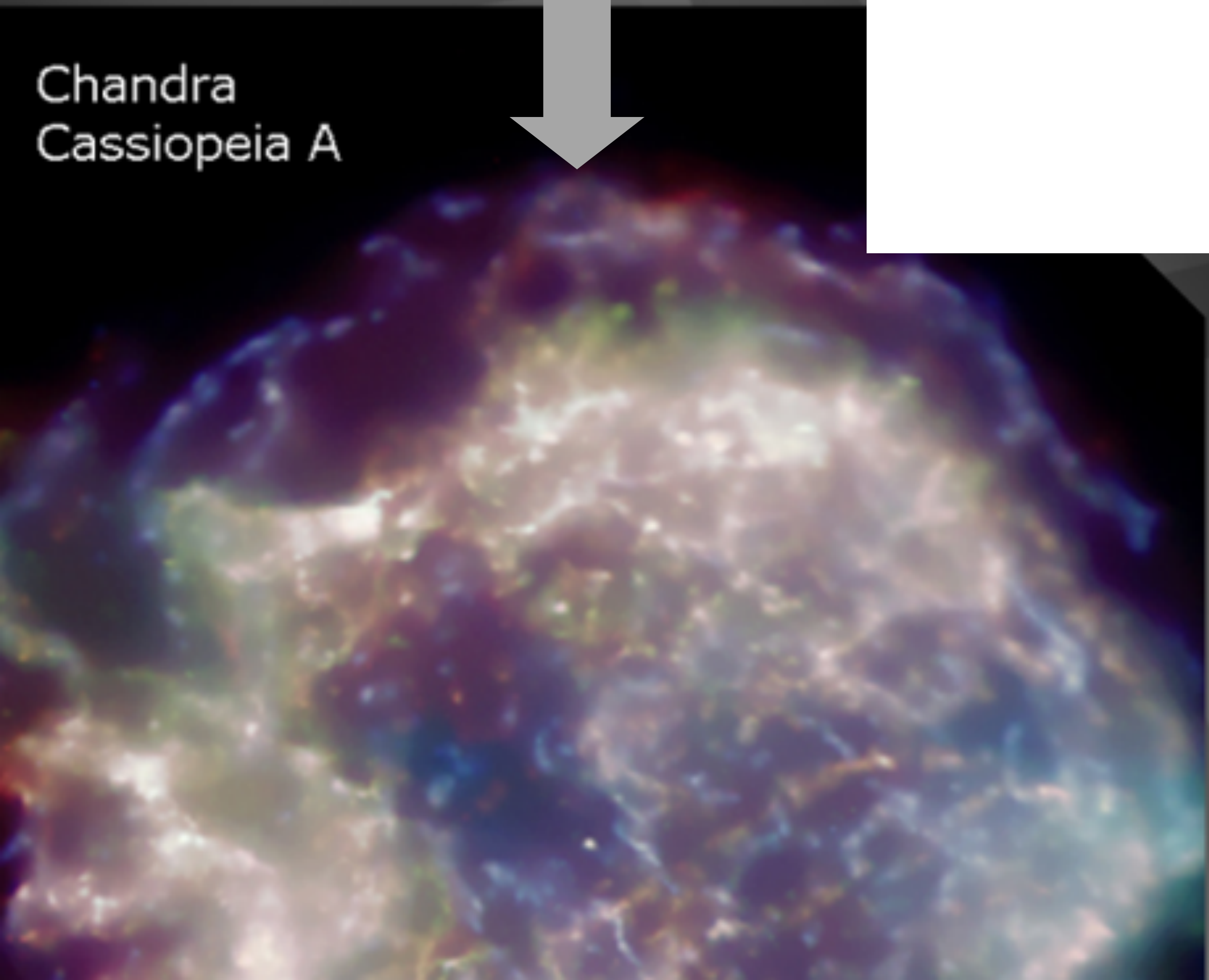
francis halzen

- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

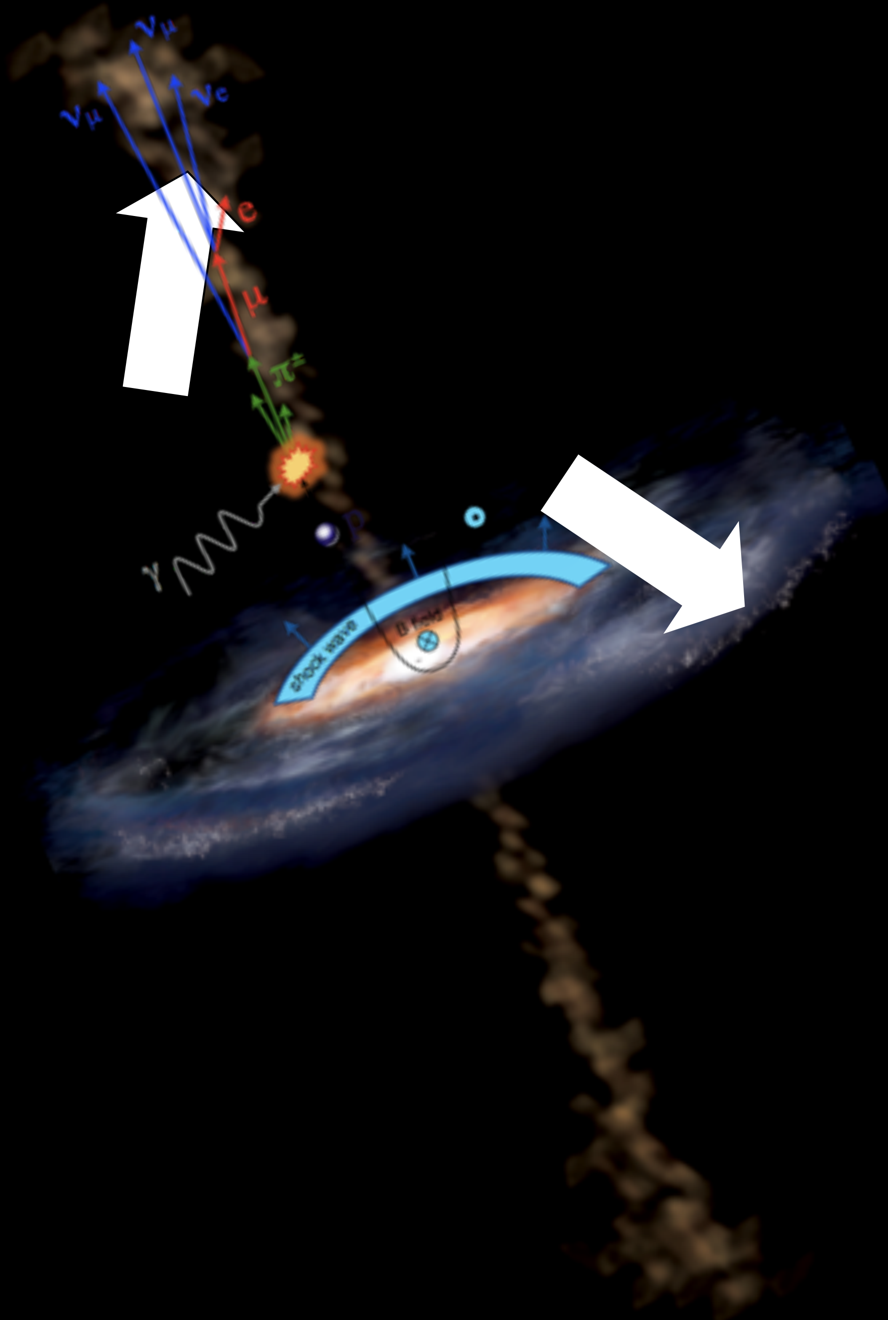
# Multi-Messenger Astronomy




20% of the Universe is opaque to the EM spectrum supernova remnants



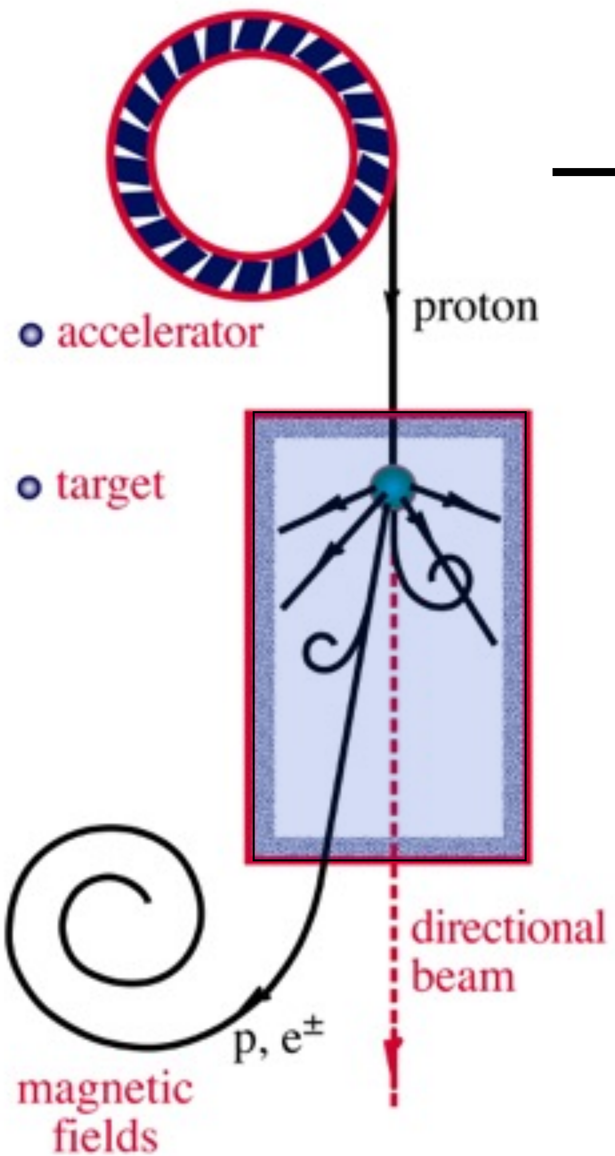

gamma ray bursts




active galaxy

particle flows near
supermassive
black hole

# ν and γ beams : heaven and earth




accelerator is powered by large gravitational energy

**black hole**
**neutron star**

**radiation,**
**dust, molecular clouds...**

$p + \gamma \rightarrow n + \pi^{+}$

~ cosmic ray + neutrino

$\rightarrow p + \pi^{0}$

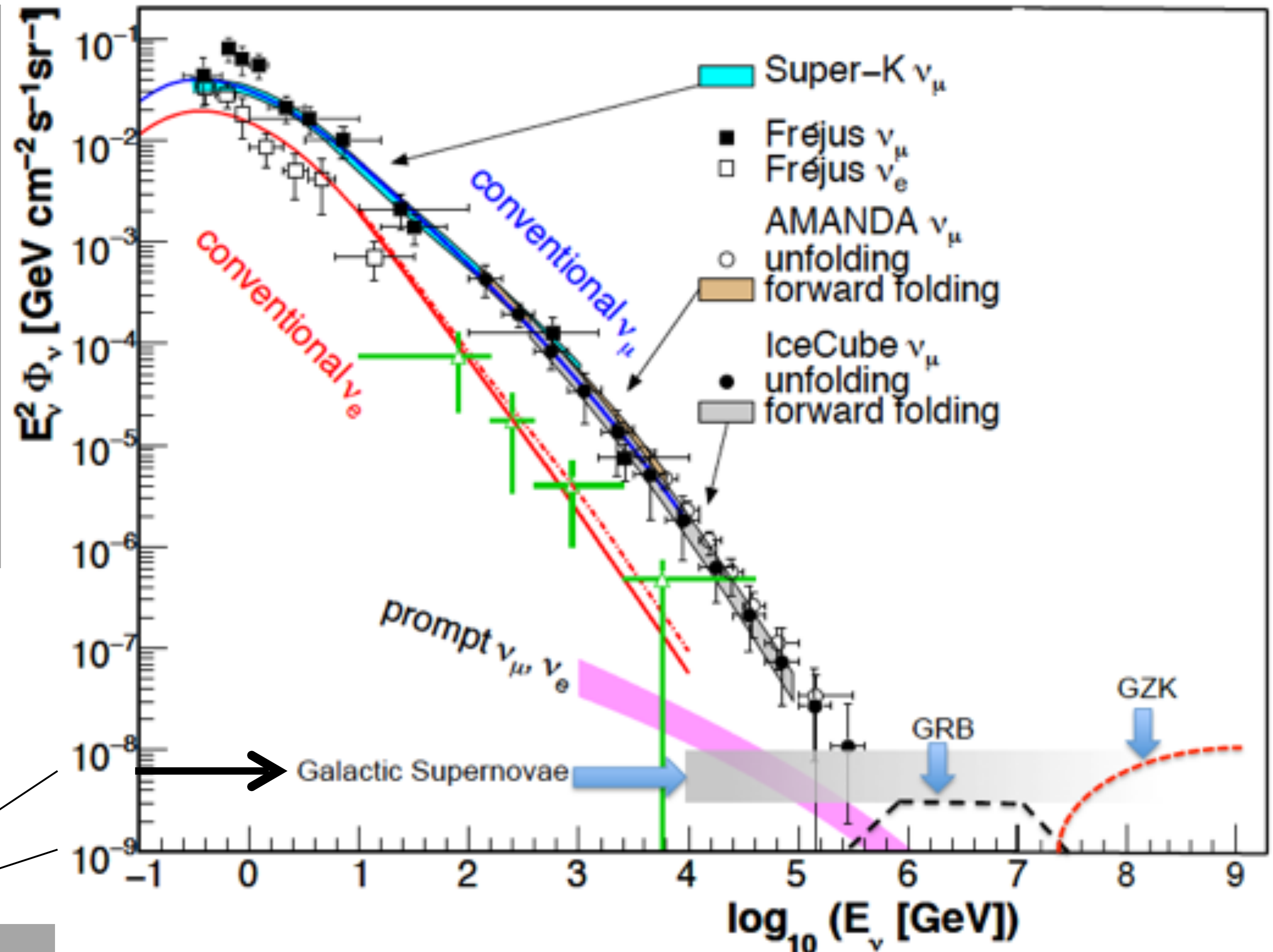
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$dN/dE \sim E^{-2}$

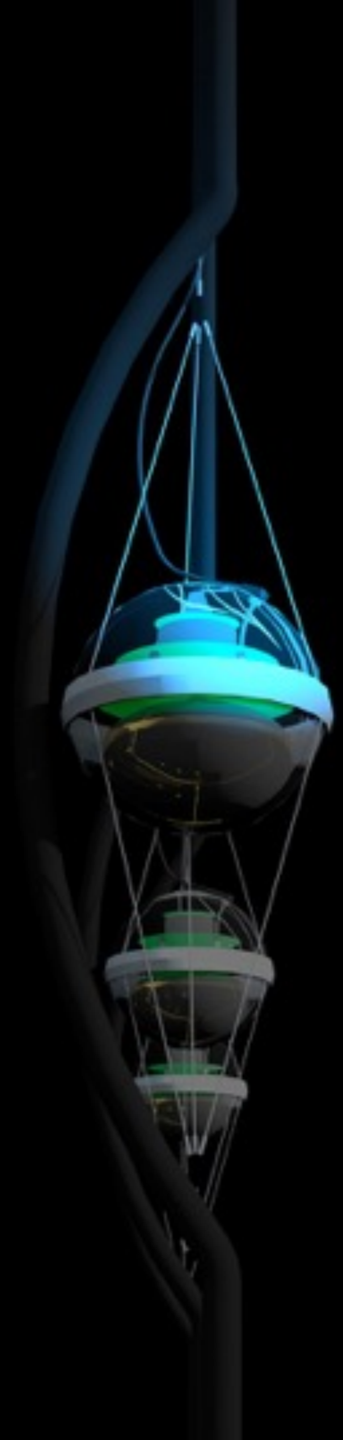
10—100 events per year for fully efficient 1 km$^3$ detector




atmospheric

cosmic

100 TeV



IceCube: the discovery of cosmic neutrinos

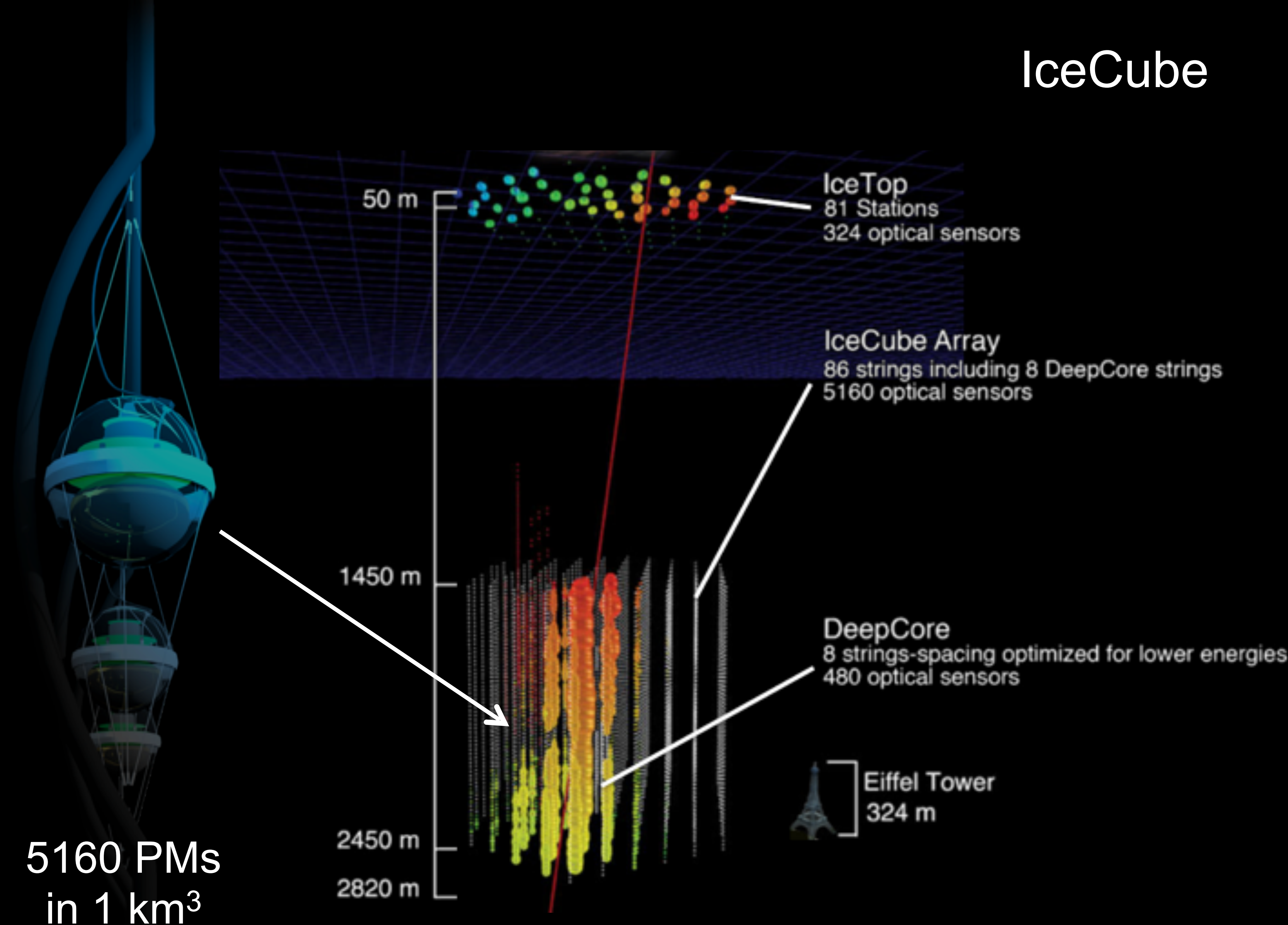
francis halzen

- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

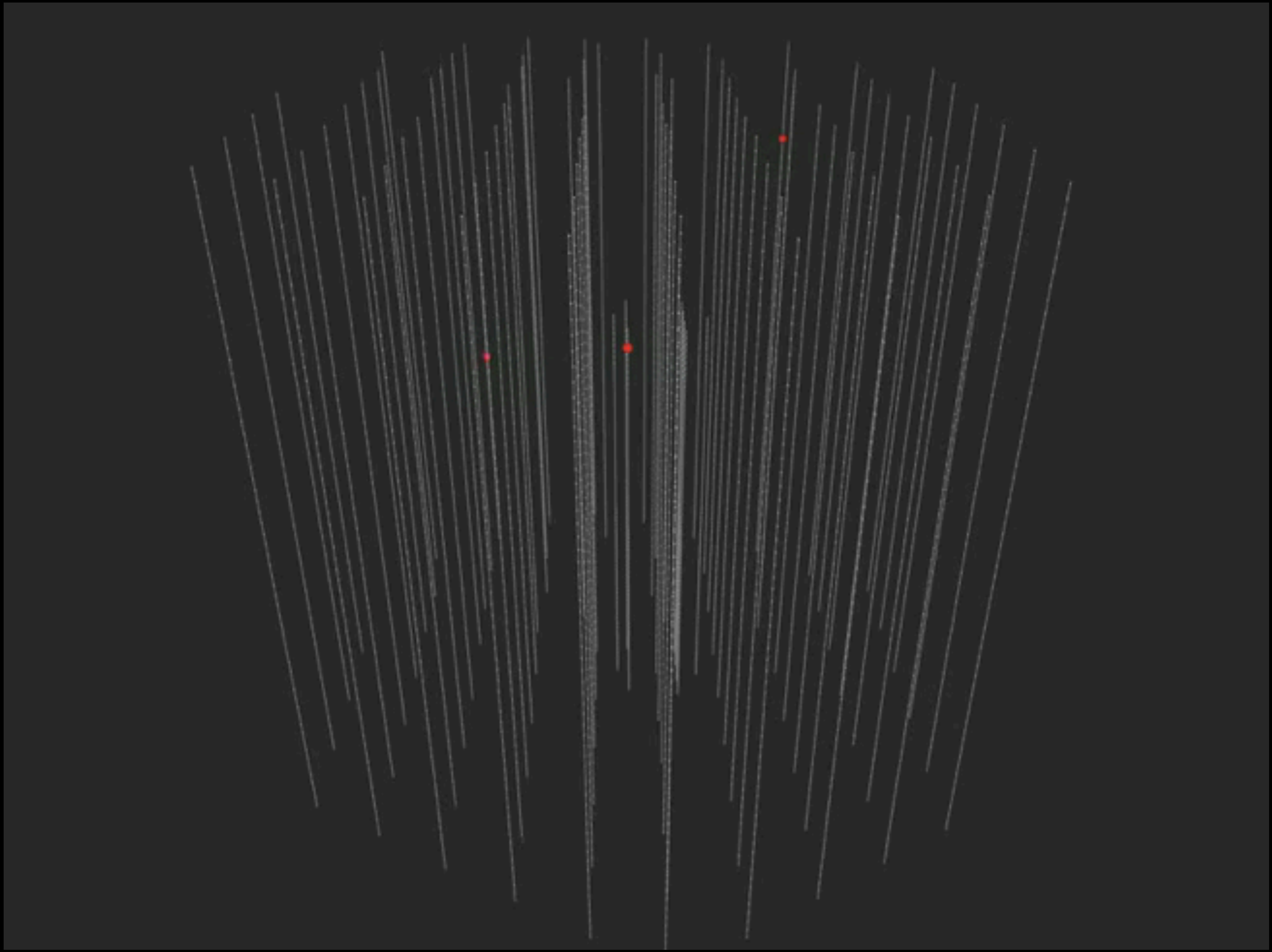
IceCube.wisc.edu

ultra-transparent ice below 1.5 km

# IceCube




5160 PMs in 1 $km^3$



muon track:  color is time; number of photons is energy

# separating signal and "background"

muons detected per year:

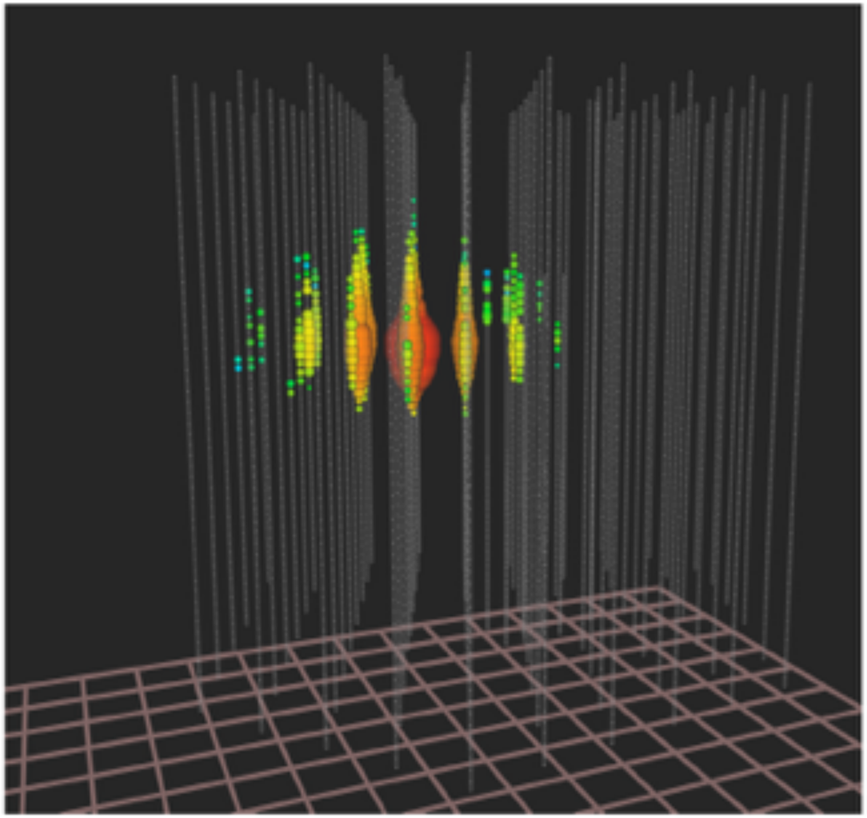
- atmospheric* $\mu$ ~ $10^{11}$
- atmospheric** $\nu \rightarrow \mu$ ~ $10^{5}$
- cosmic $\nu \rightarrow \mu$ ~ $10\text{-}10^{2}$

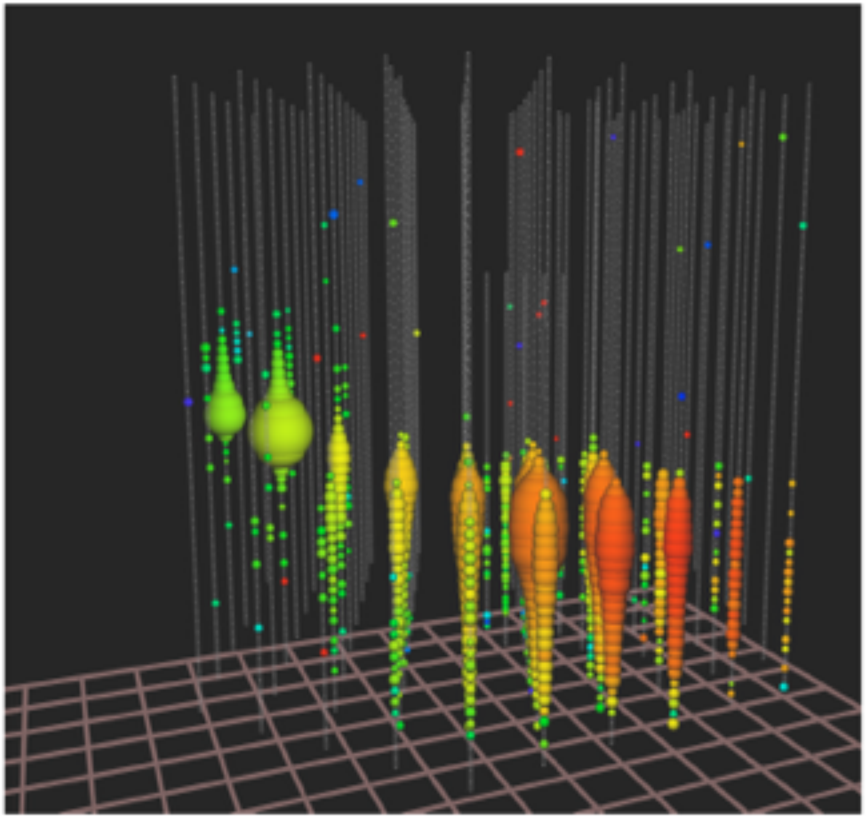
* 3000 per second

** 1 every 6 minutes

*isolated* neutrinos interacting *inside* the detector (HESE)

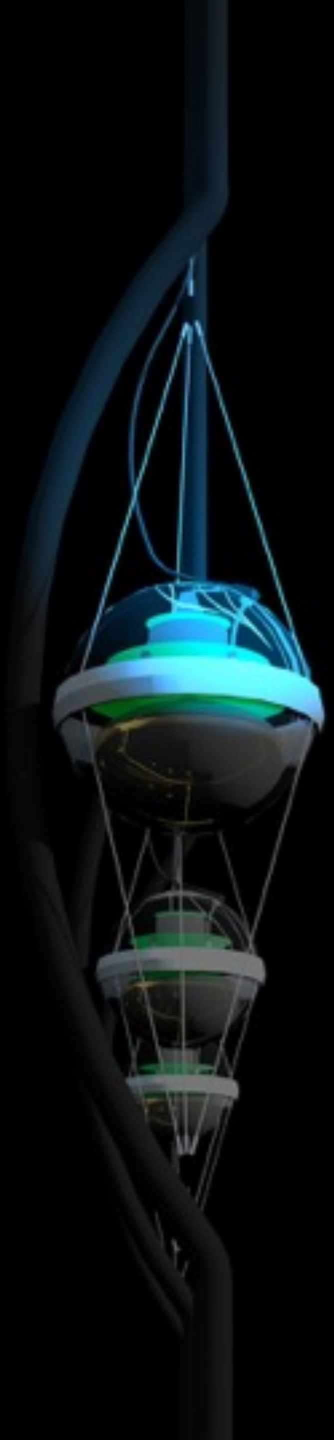
up-going muon tracks (UPMU)





total energy measurement
all flavors, all sky

astronomy: angular resolution superior (<0.5$^{o}$)

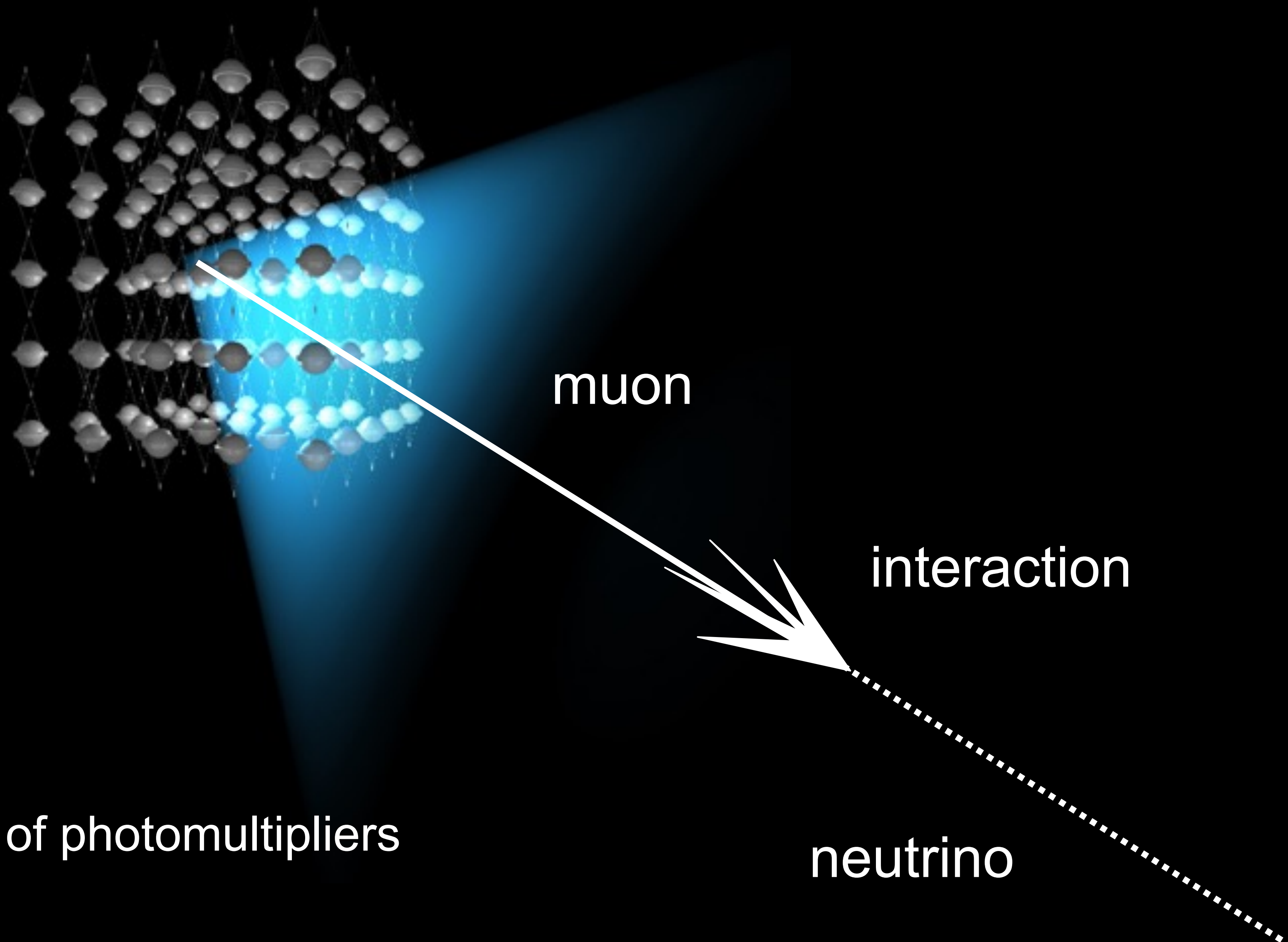


IceCube: the discovery of cosmic neutrinos

francis halzen

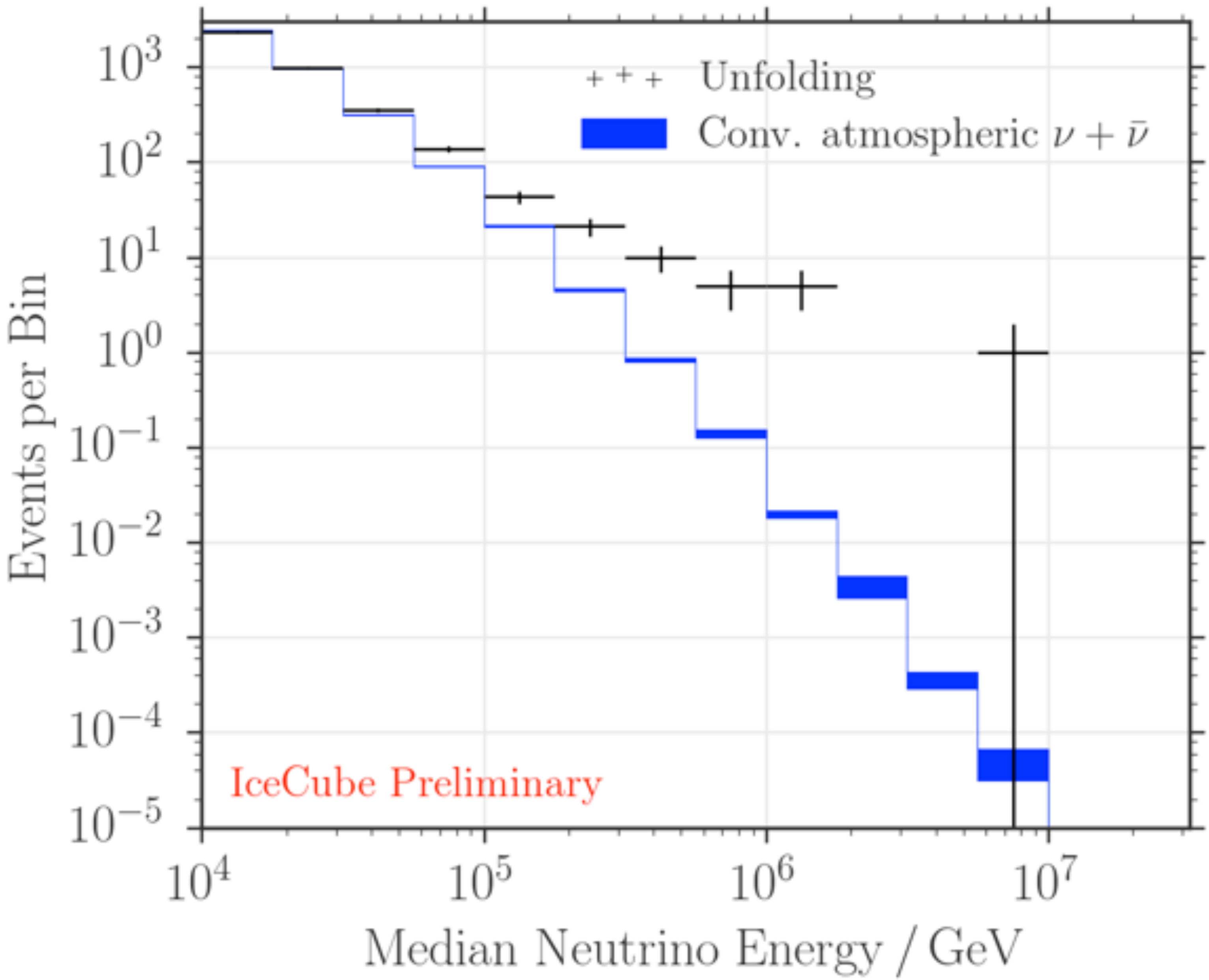
- IceCube
- the discovery of cosmic neutrinos (2)
- where do they come from?
- beyond IceCube

IceCube.wisc.edu



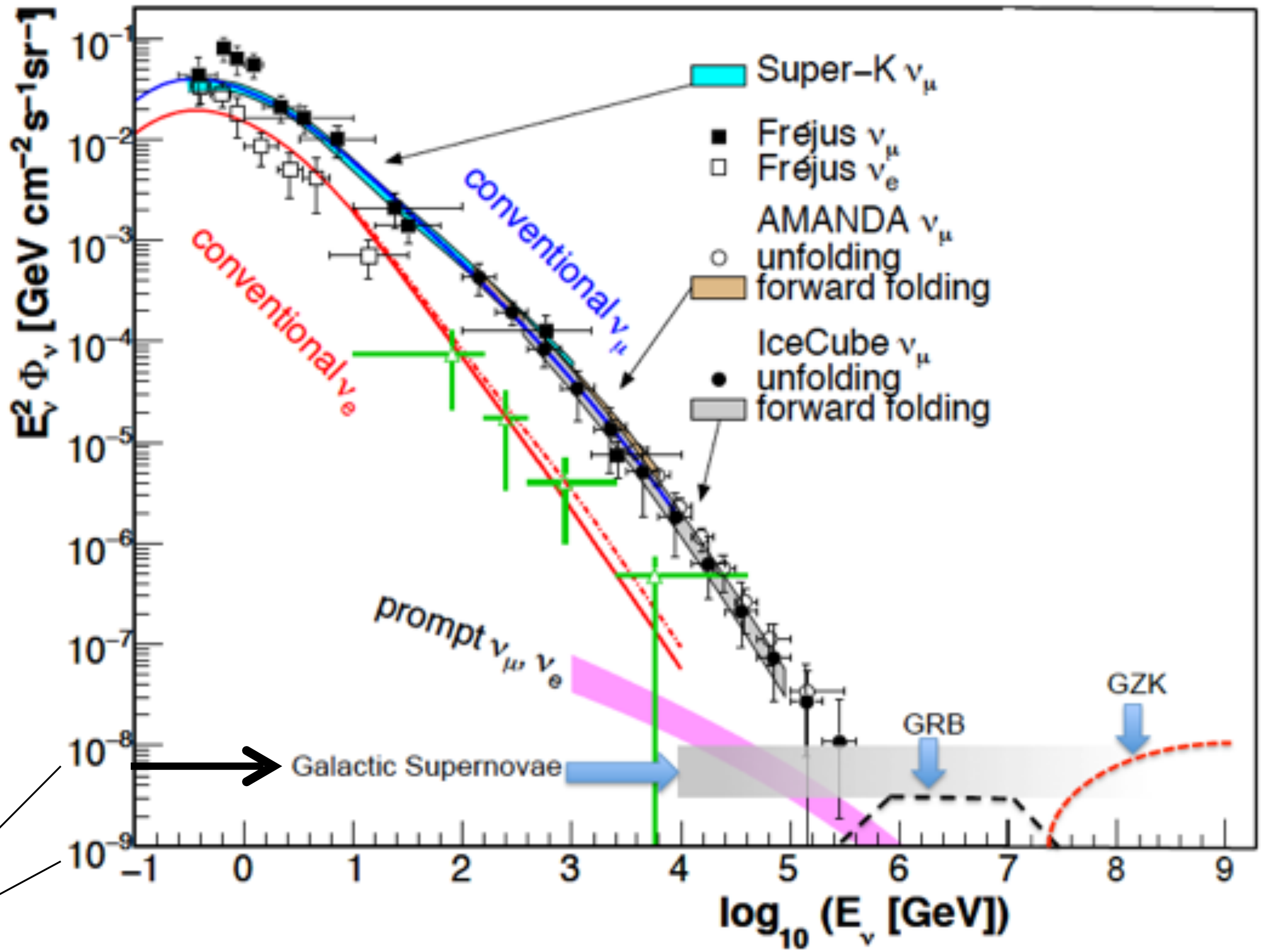

• lattice of photomultipliers

## muon neutrinos through the Earth → 6 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears



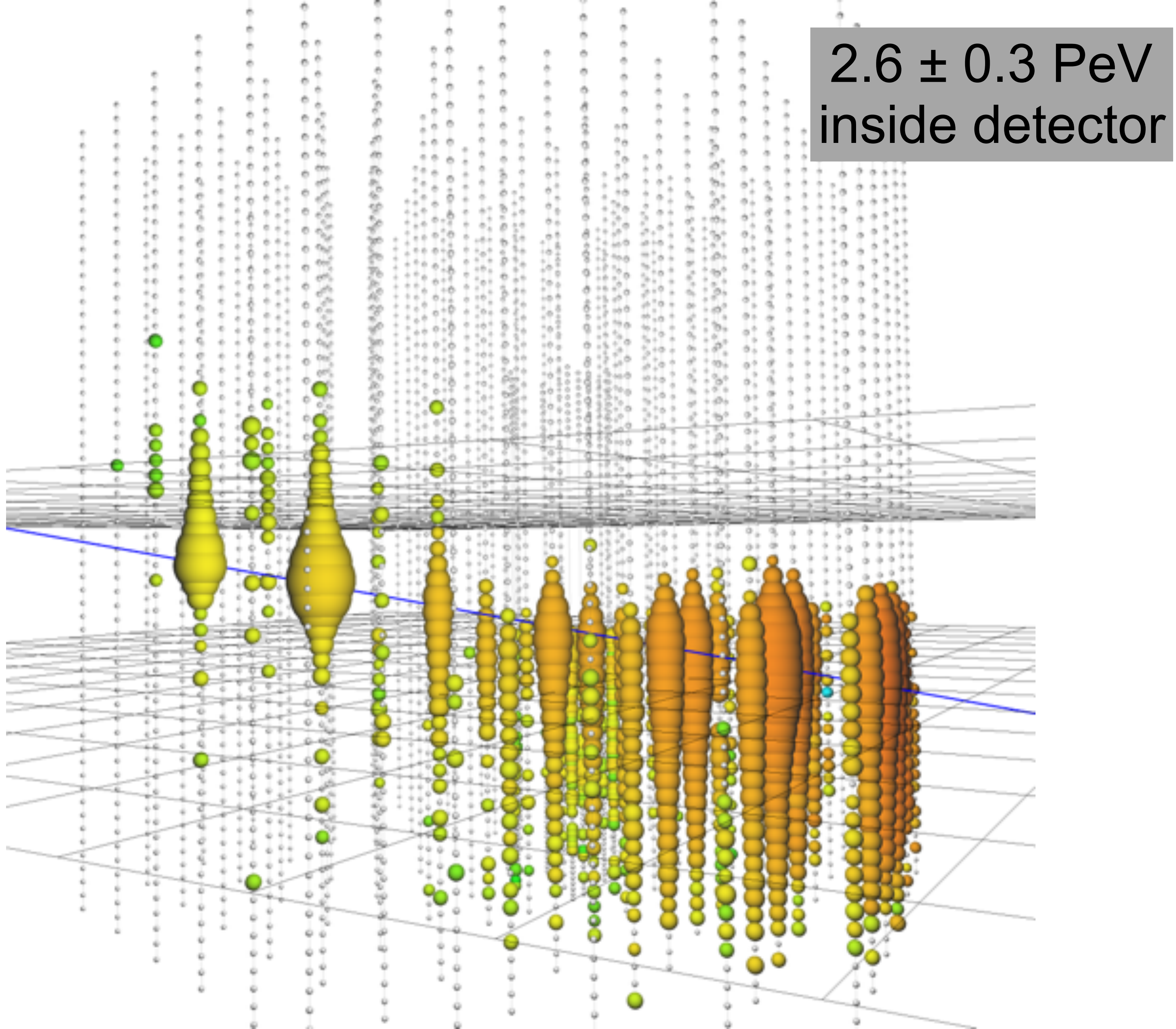

$dN/dE \sim E^{-2}$

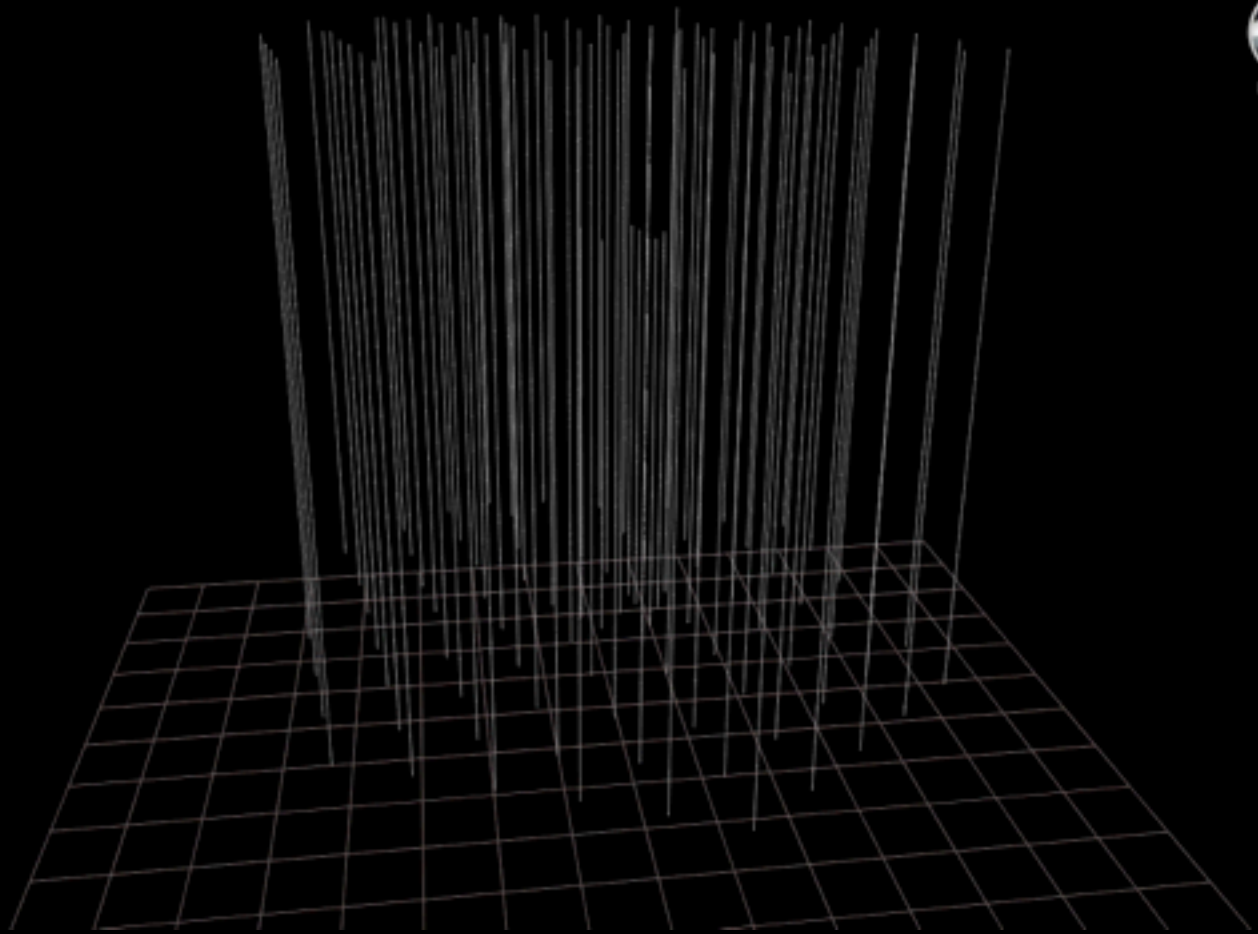
10—100 events per year for fully efficient detector

atmospheric

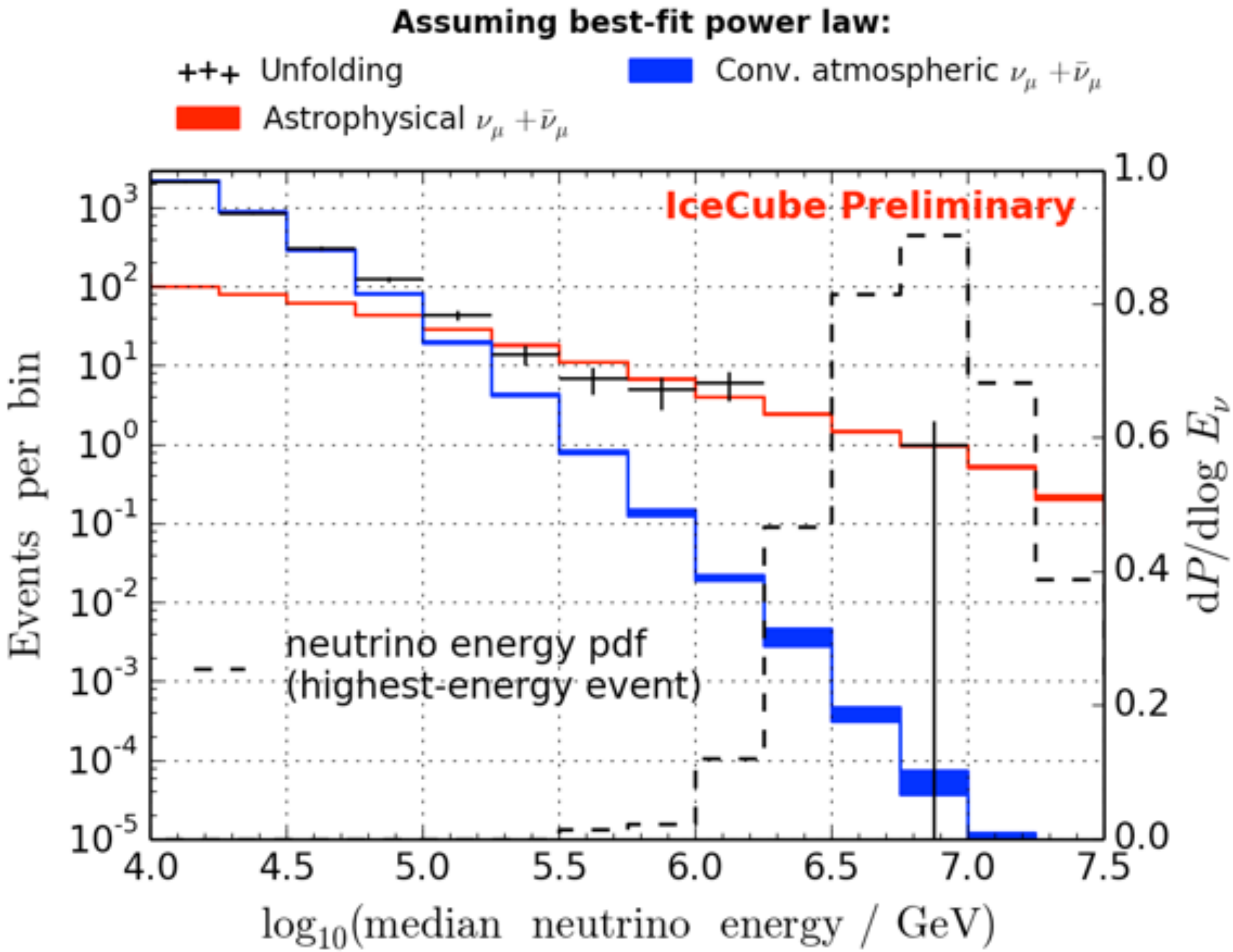
cosmic

100 TeV

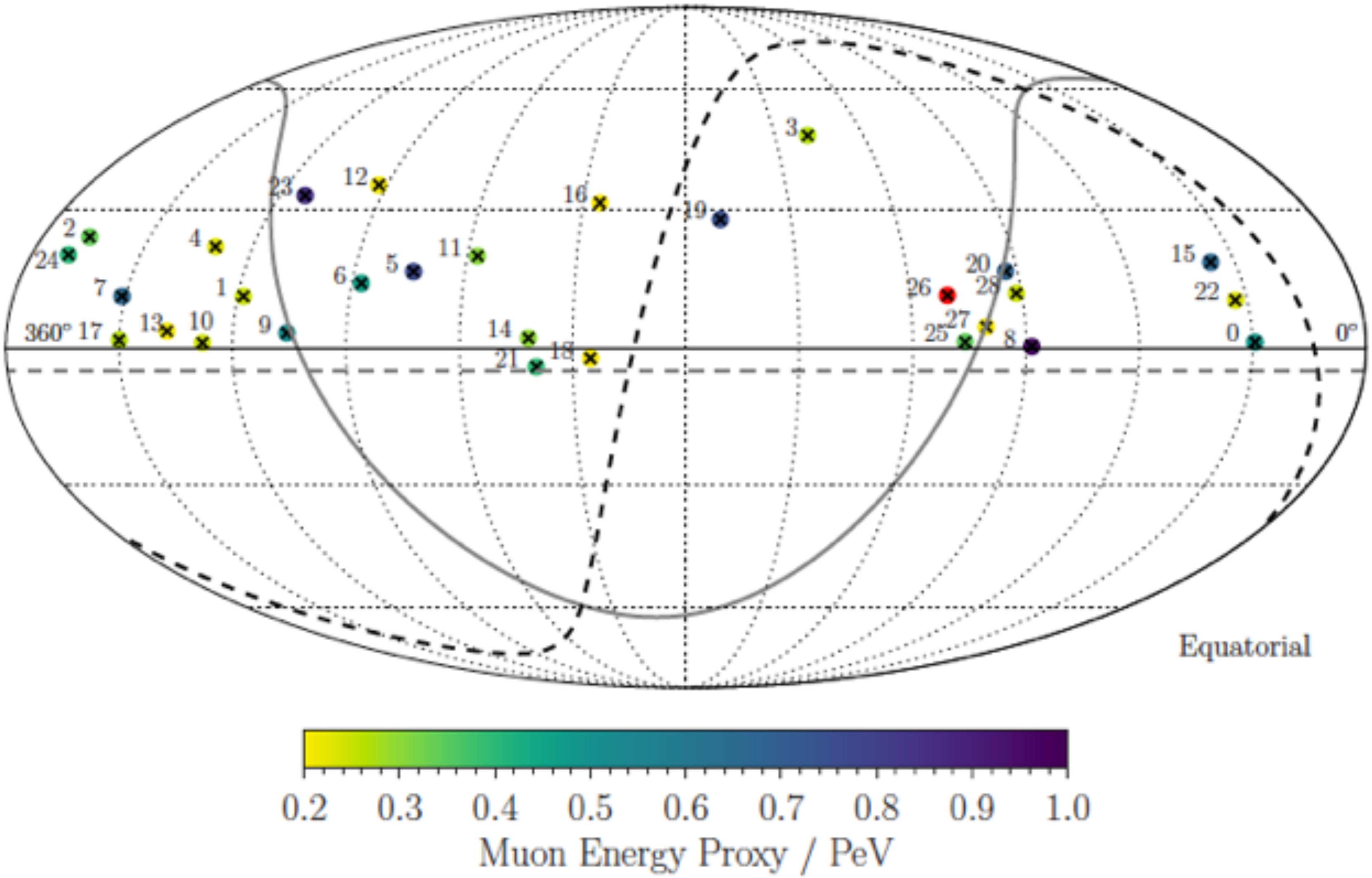

2.6 ± 0.3 PeV
inside detector



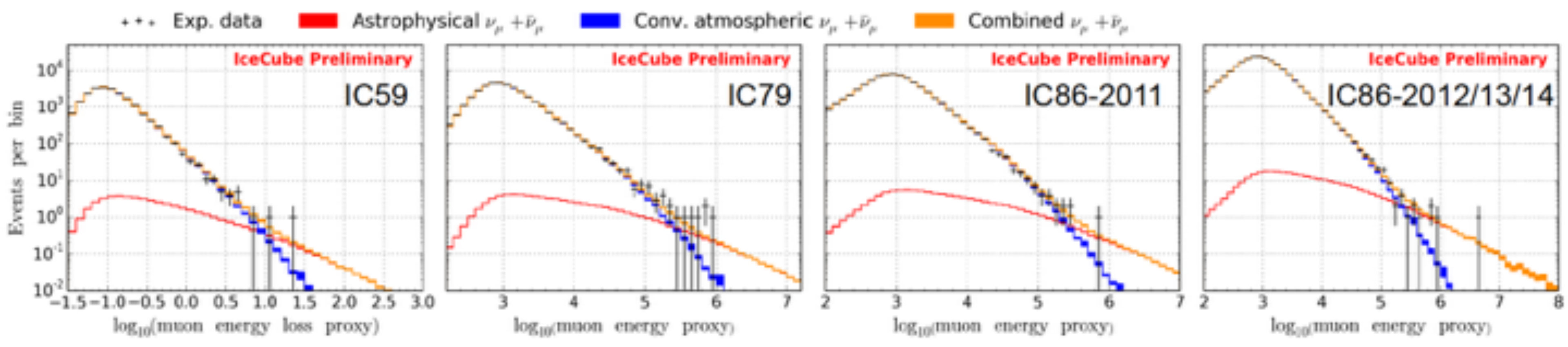
~550 cosmic neutrinos in a background of ~340,000 atmospheric

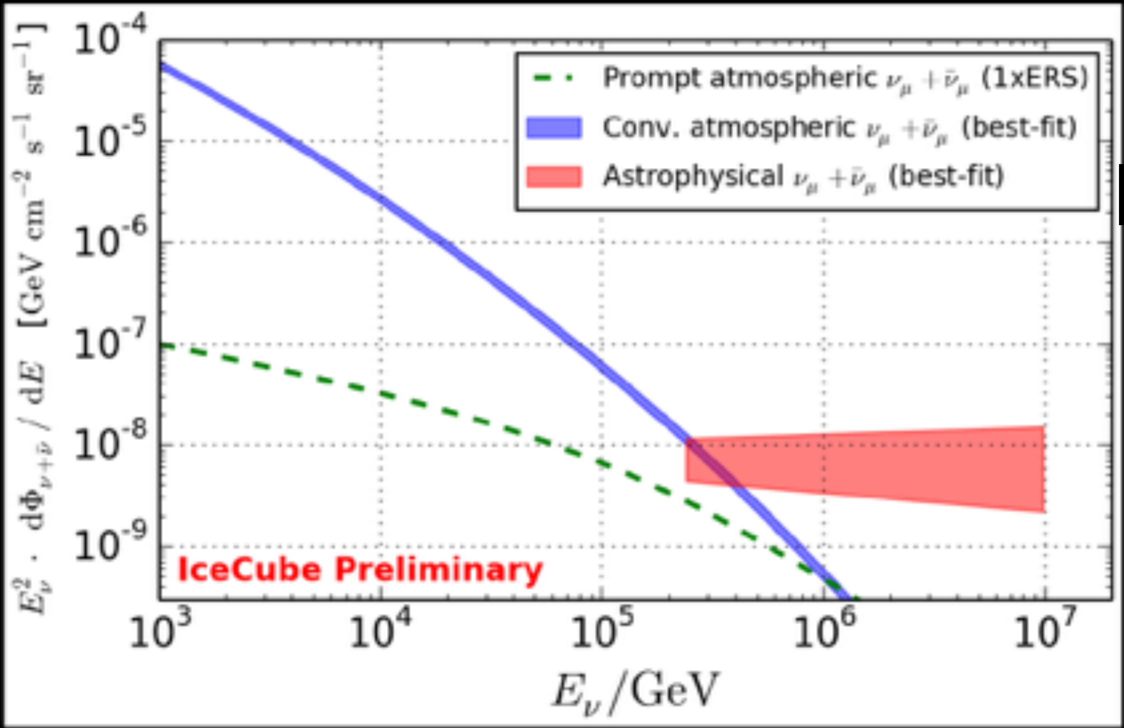


highest energy $\nu_\mu$: astronomy with 0.2-0.4 degree resolution !
events above 200 TeV only



# after 7 years → 6 sigma




- Best-fit astrophysical normalization:

  $0.97^{+.27}_{-.25} \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$

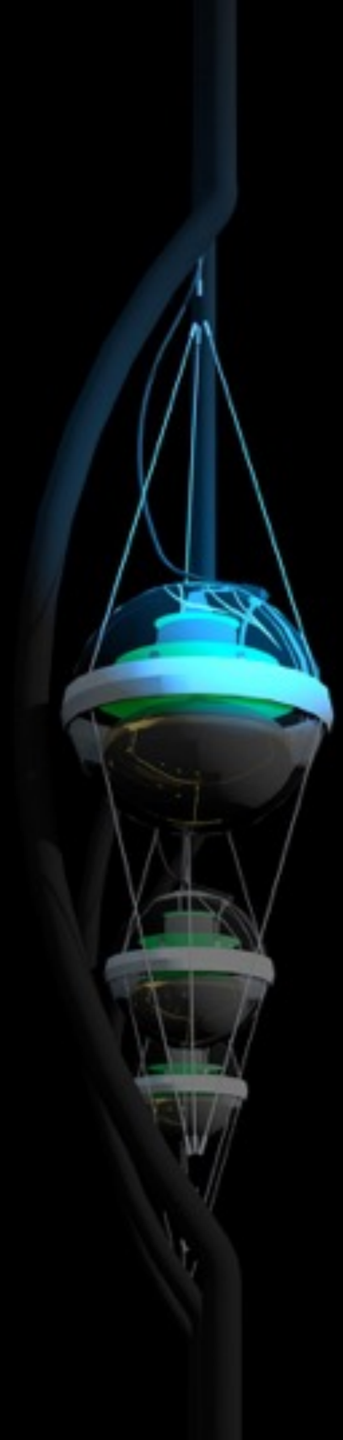
- Best-fit spectral index:

  $\gamma_{astro} = 2.16 \pm 0.11$

- Energy ranges:

  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ



IceCube: the discovery of cosmic neutrinos

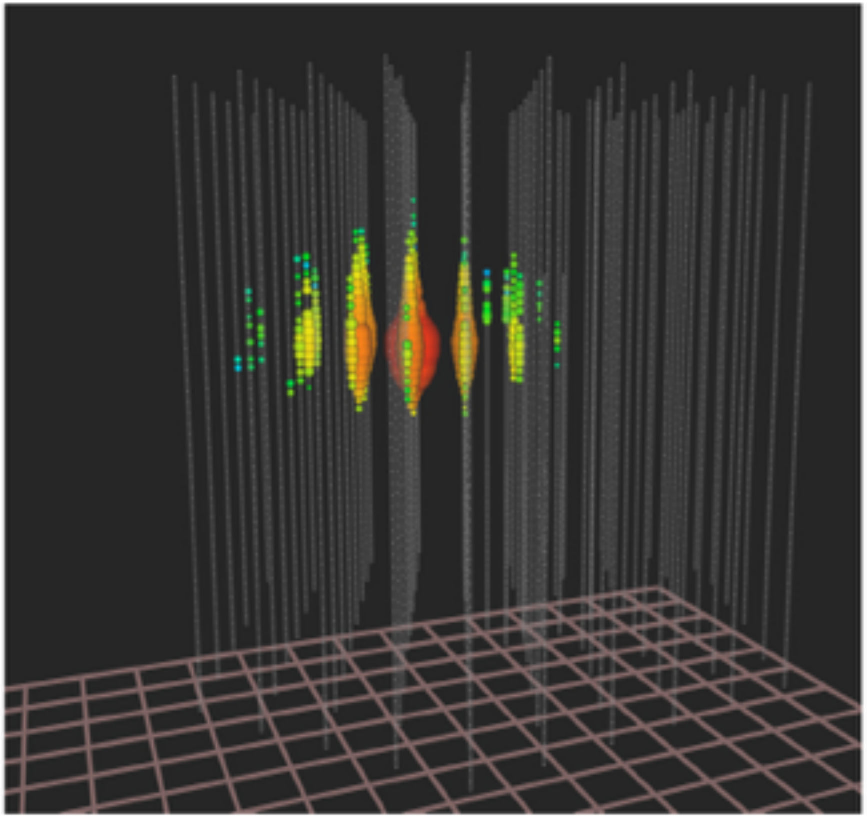
francis halzen

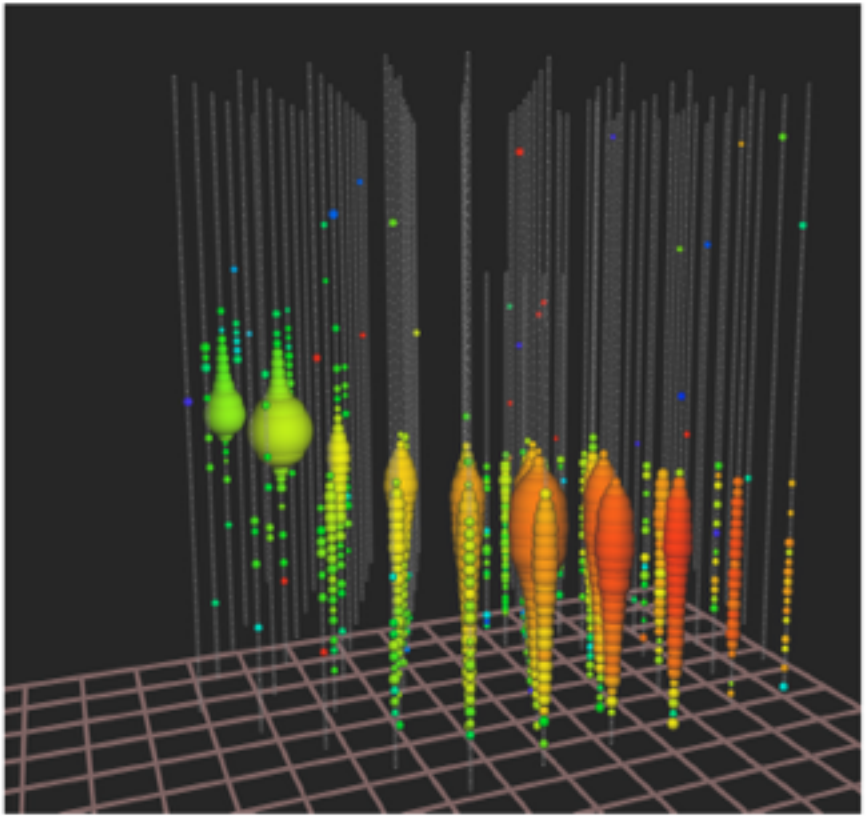
- IceCube
- the discovery of cosmic neutrinos (1)
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

isolated neutrinos interacting inside the detector

up-going muon tracks



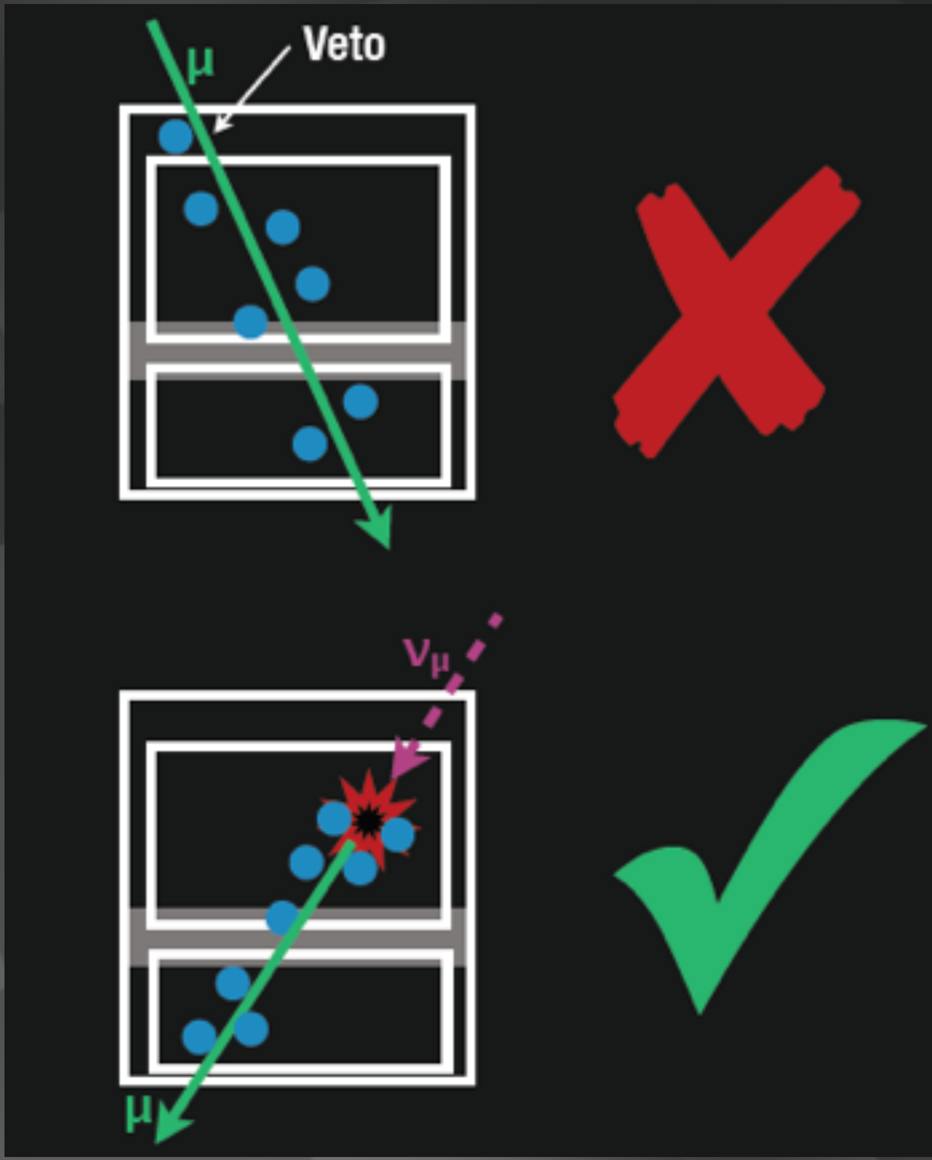


calorimetry: direct energy measurement; all flavors

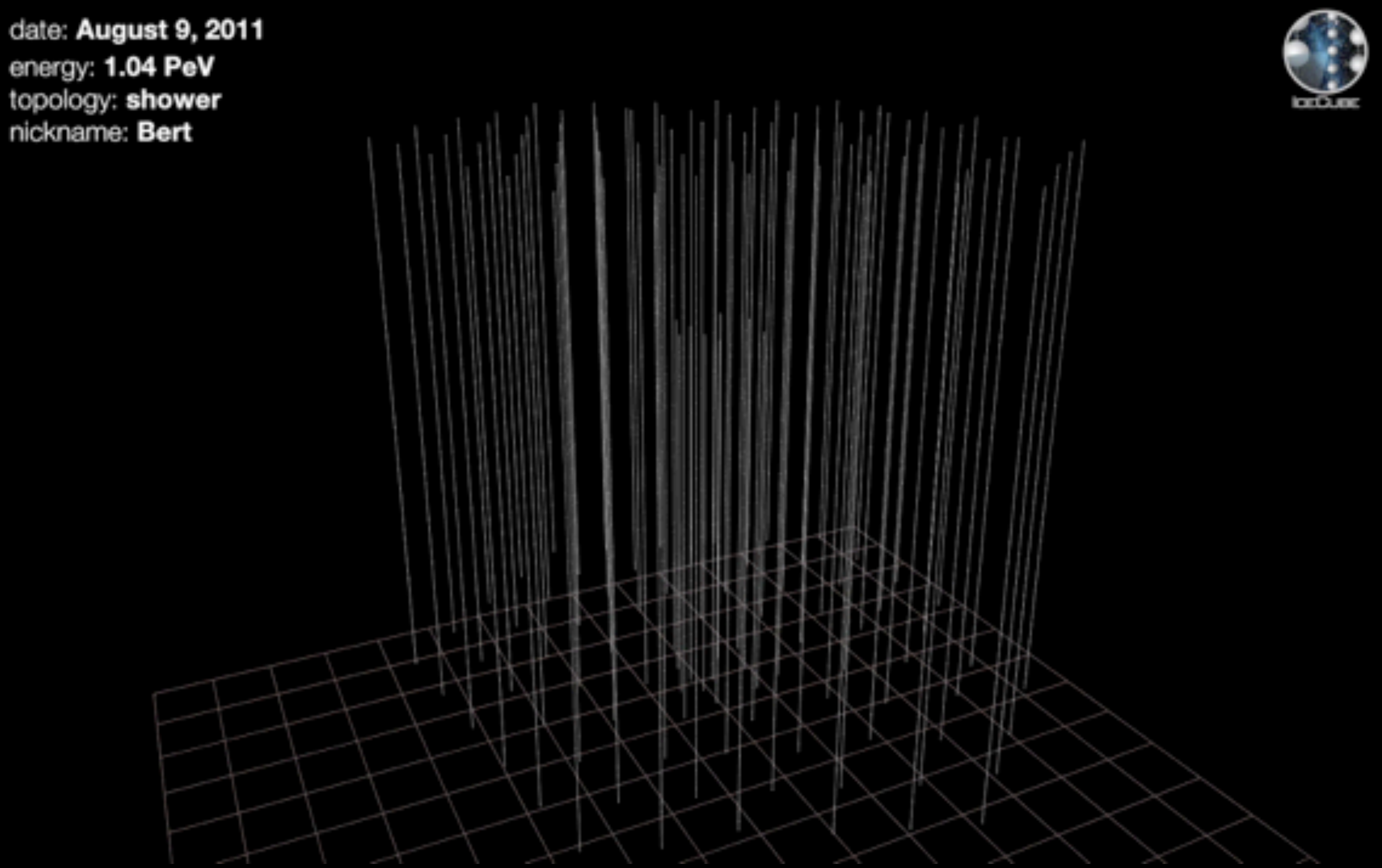
astronomy: angular resolution superior

# neutrinos starting inside the detector

- ✓ no light in the veto region
- ✓ veto for atmospheric neutrinos that are typically accompanied by muons
- ✓ energy measurement: total absorption calorimetry
- ✓ all sky, all flavors



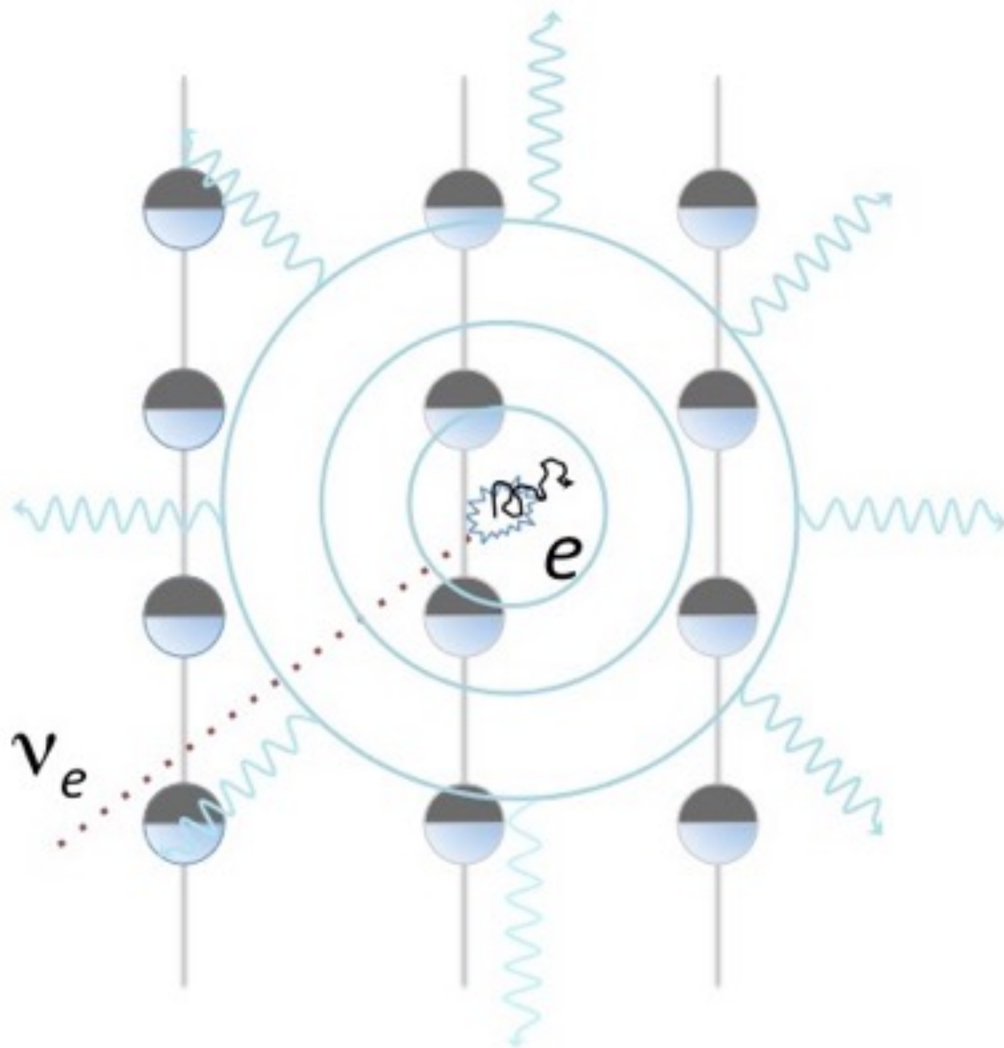
# GZK neutrino search: two neutrinos with > 1,000 TeV

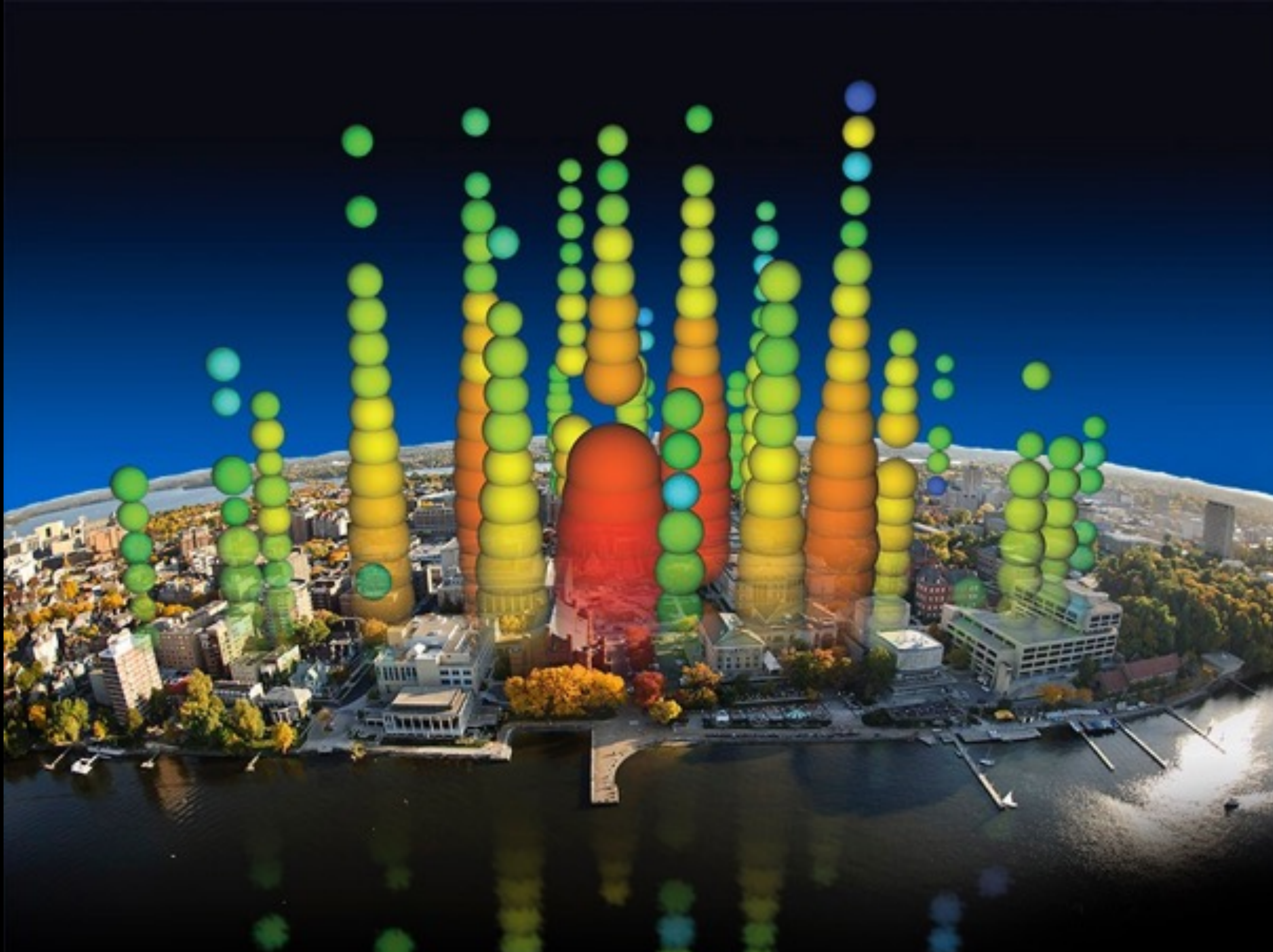


# electron showers versus muon tracks

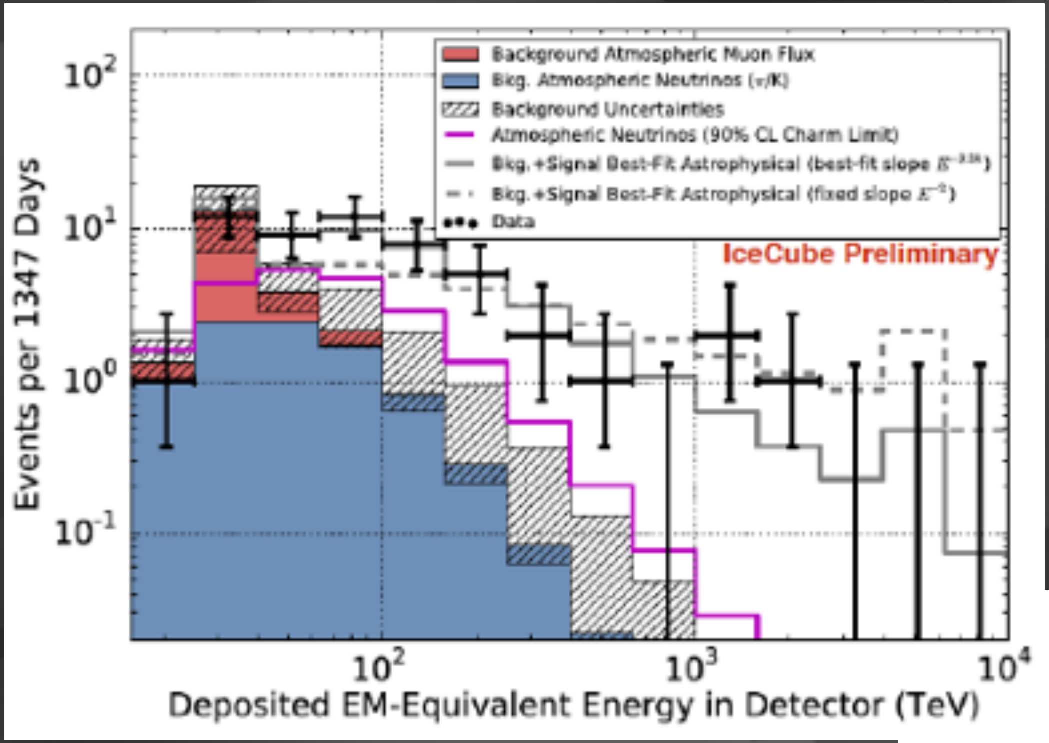
PeV $\nu_e$ and $\nu_\tau$ showers:

- 10 m long
- volume ~ 5 $m^3$
- isotropic after 25~50m

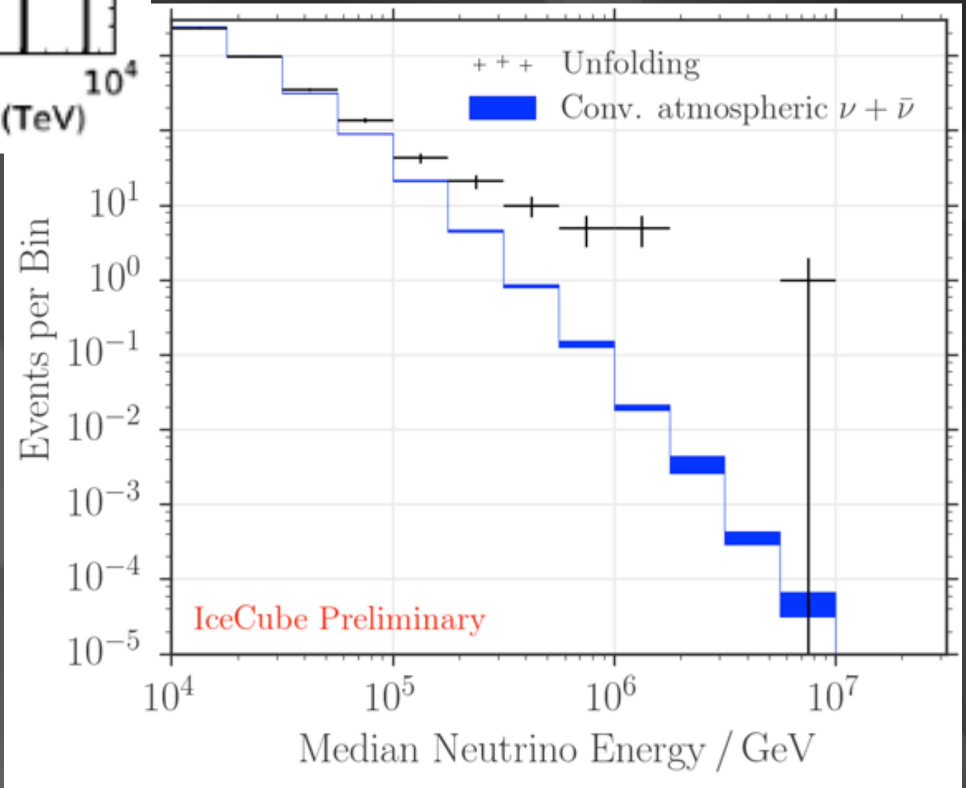




- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

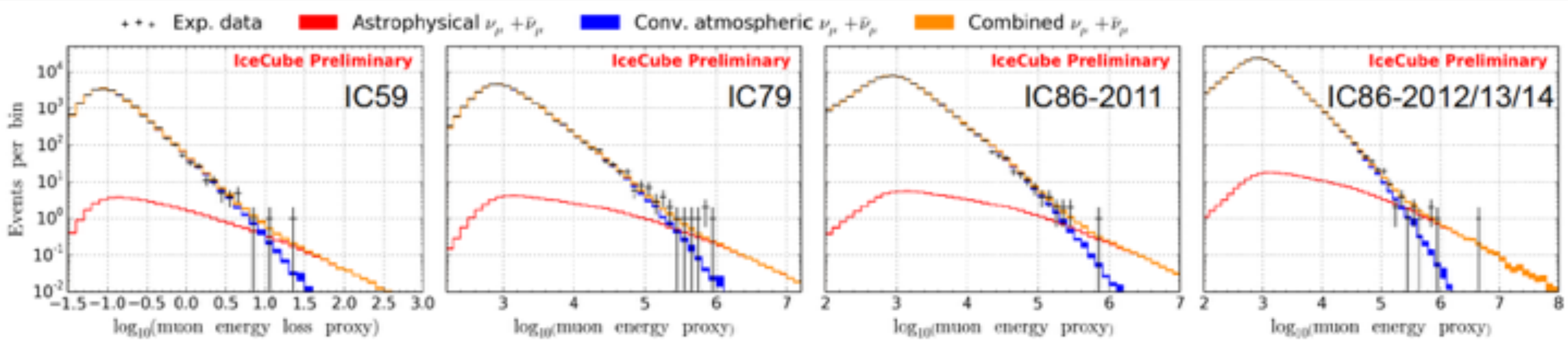



confirmation!
flux of muon neutrinos
through the Earth (6σ)



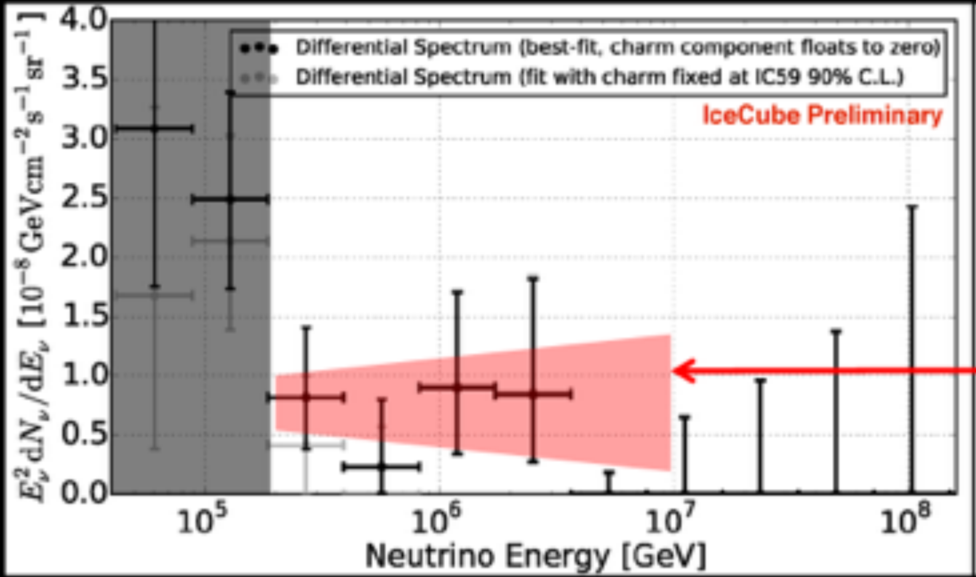

neutrinos of all flavors
interacting inside
IceCube (7σ)

# after 6 years: 3.7→ 6.0 sigma

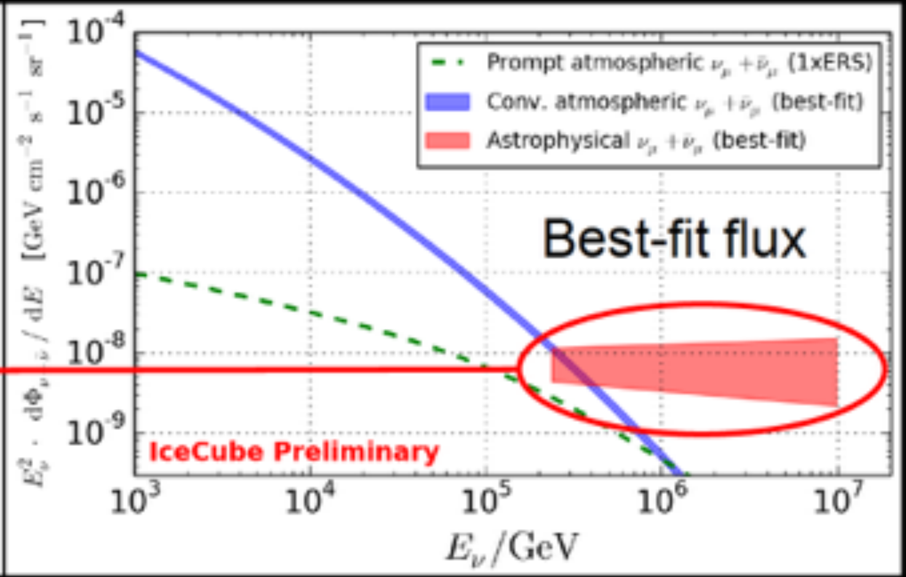


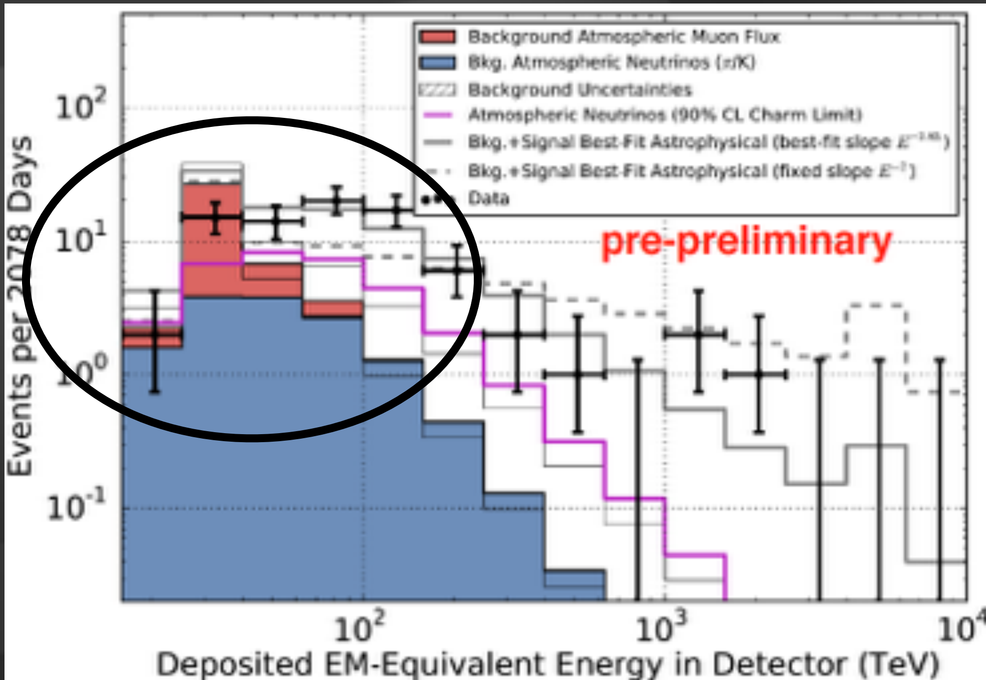

HESE 4 year unfolding

(→ dominated by shower-like events)

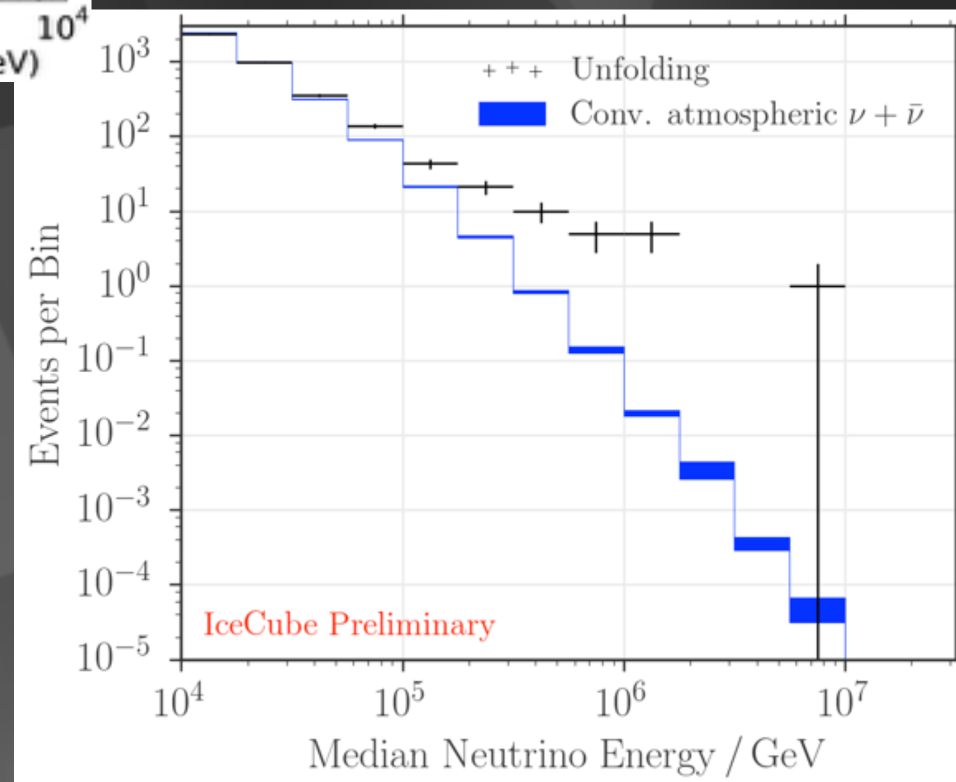



6 year up-going numu analysis



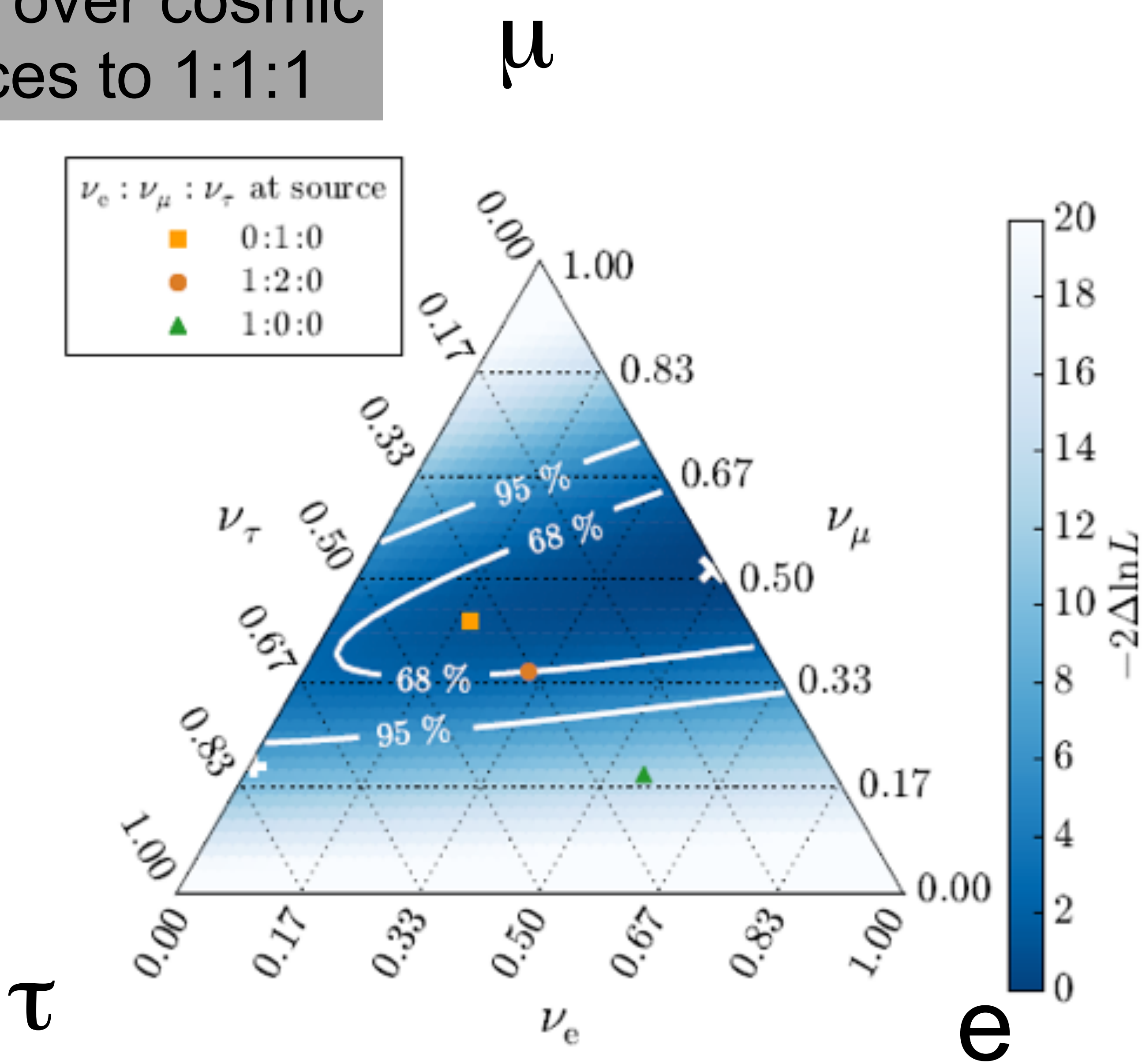


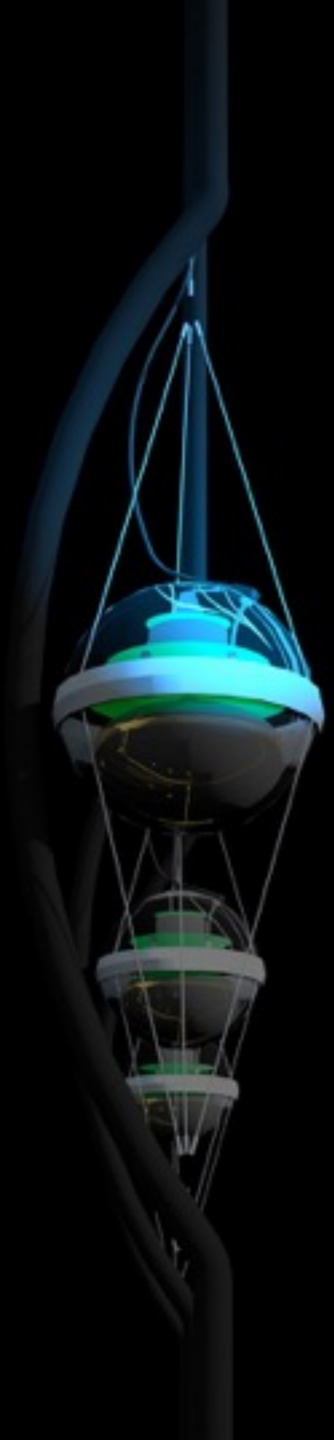

confirmation!
flux of muon neutrinos
through the Earth




neutrinos of all flavors
interacting inside
IceCube

oscillate over cosmic distances to 1:1:1



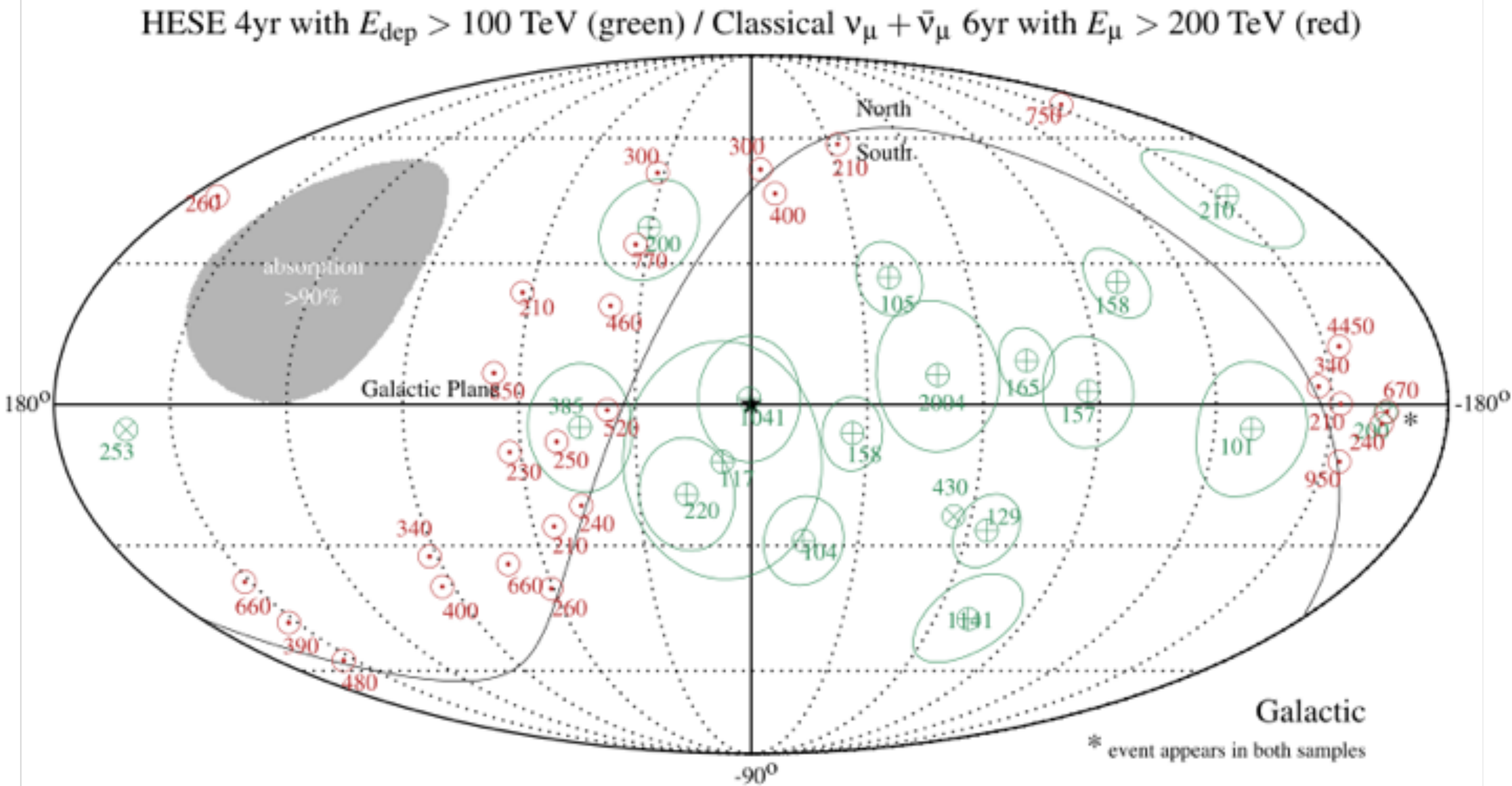


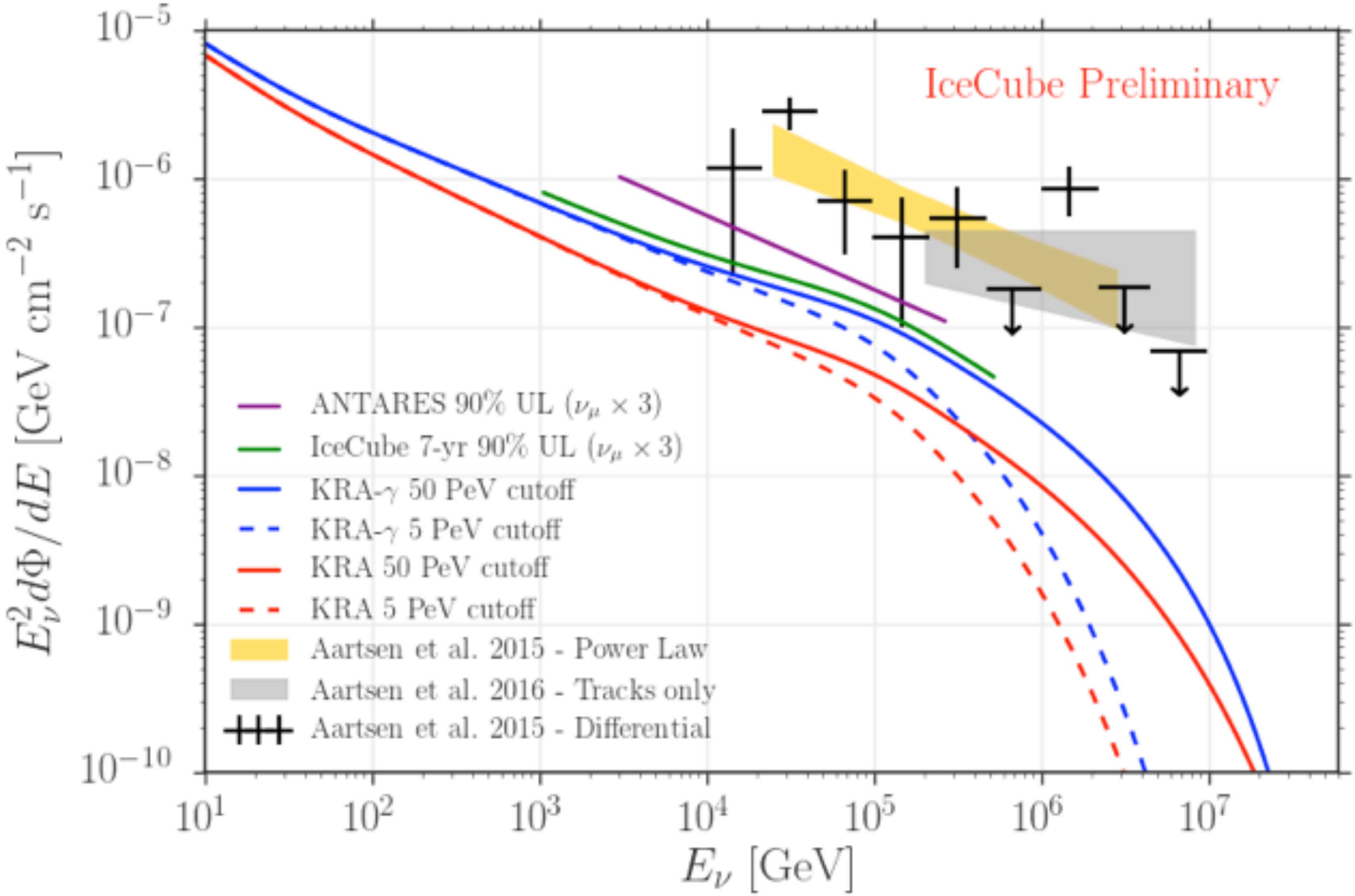
IceCube: the discovery of cosmic neutrinos

francis halzen

- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu


HESE 4yr with $E_{dep}$ > 100 TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with $E_\mu$ > 200 TeV (red)
North
South
absorption
>90%
Galactic Plane
180°
-180°
-90°
Galactic
* event appears in both samples



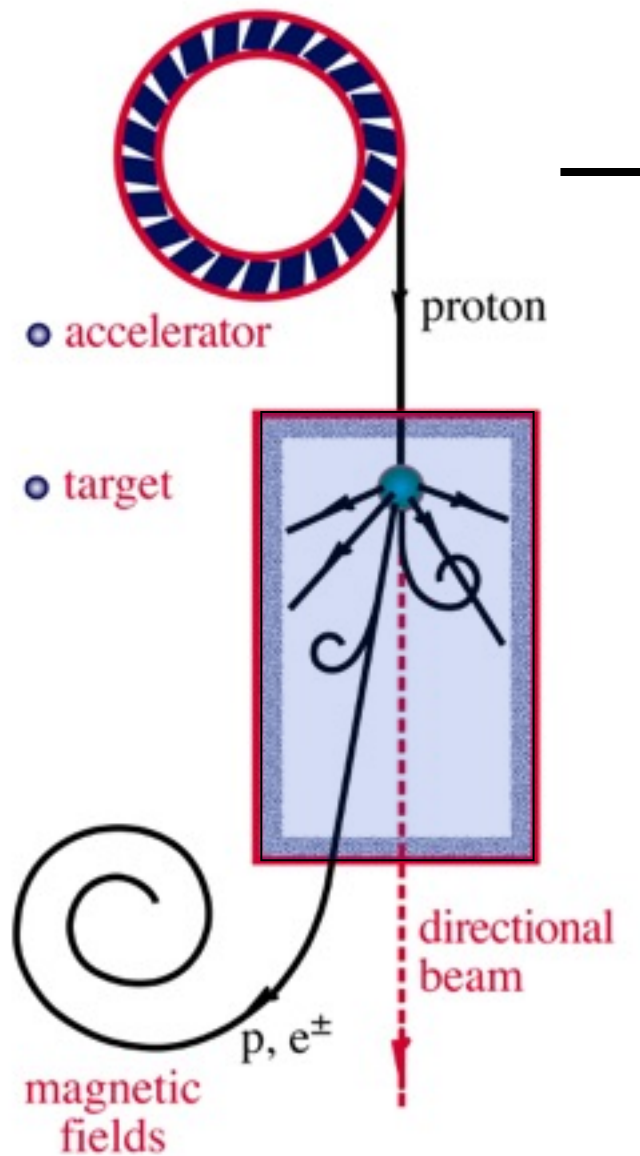

at most ~10% of the events are Galactic in origin

- we observe a diffuse flux of neutrinos from extragalactic sources

- a subdominant Galactic component cannot be excluded (no evidence reaches $3\sigma$ level)

- where are the PeV gamma rays that accompany PeV neutrinos?

# $\nu$ and $\gamma$ beams : heaven and earth




accelerator is powered by large gravitational energy

**black hole**
**neutron star**

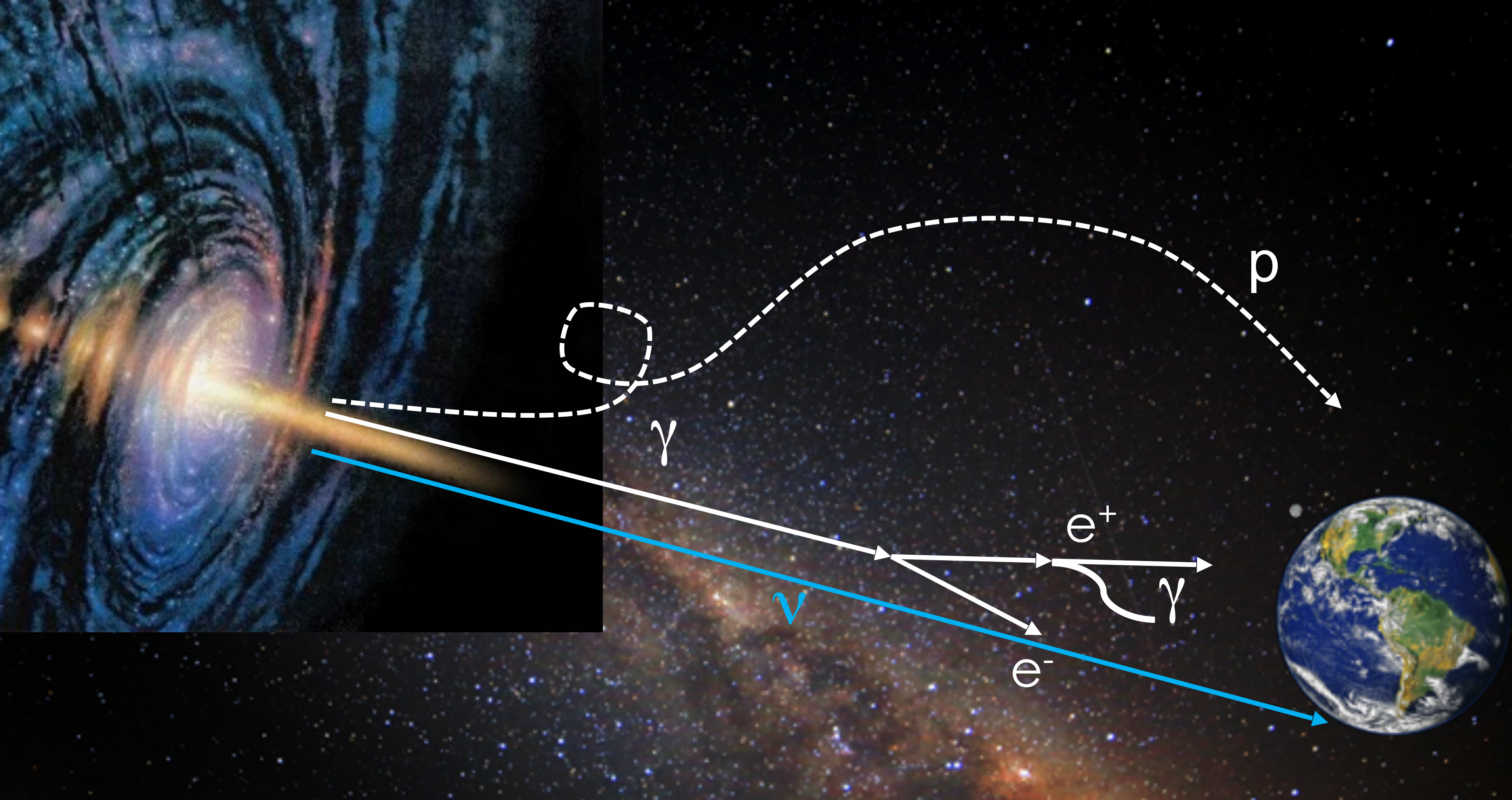
**radiation and dust**

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

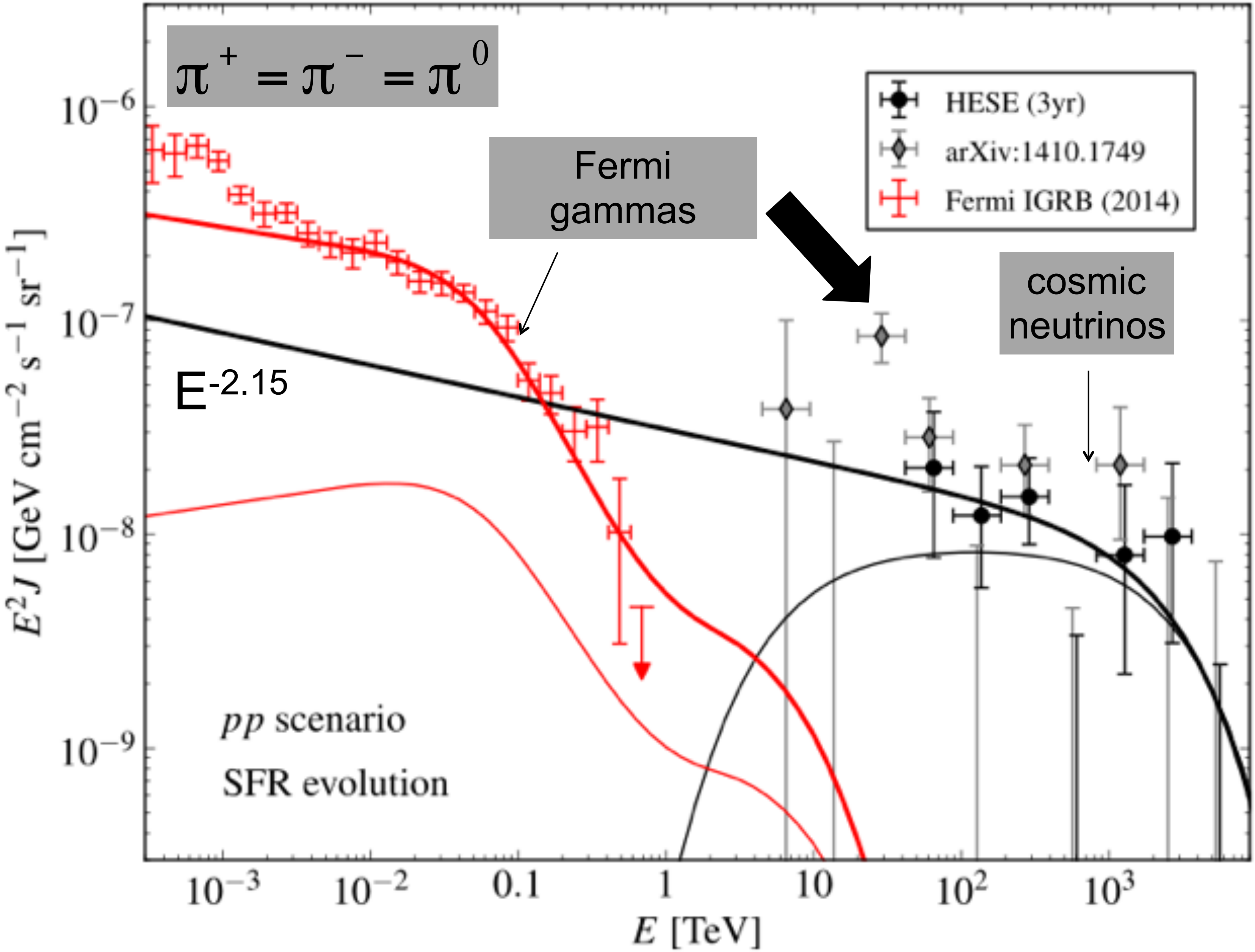
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma




gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

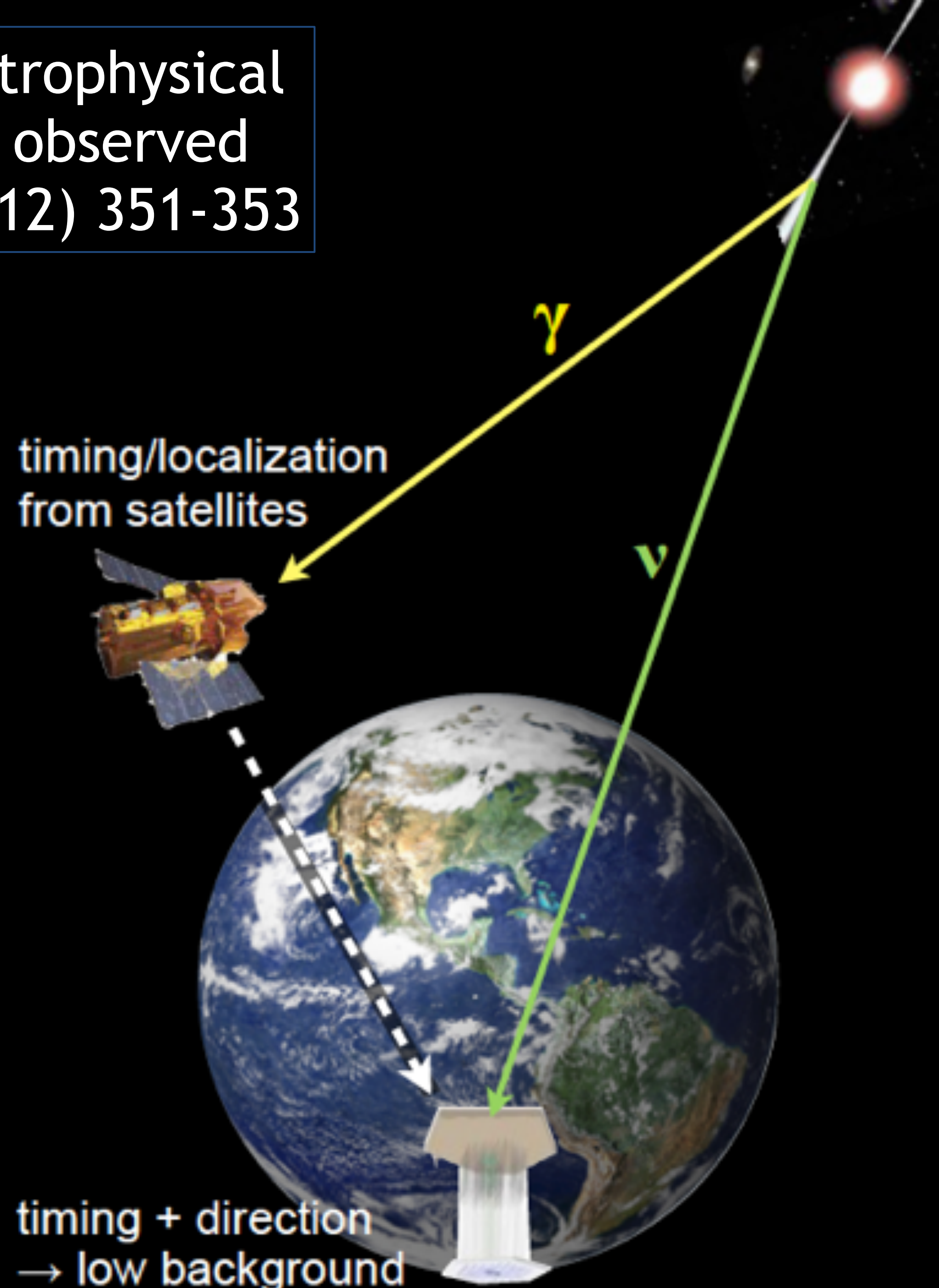


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
pp scenario
SFR evolution
$E^2 J$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
$E$ [TeV]
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-3}$
$10^{-2}$
0.1
1
10
$10^2$
$10^3$

- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays

- at some level common Fermi-IceCube sources?
  → multimessenger campaign of telescope follow-up of IceCube real-time neutrino alerts

flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353



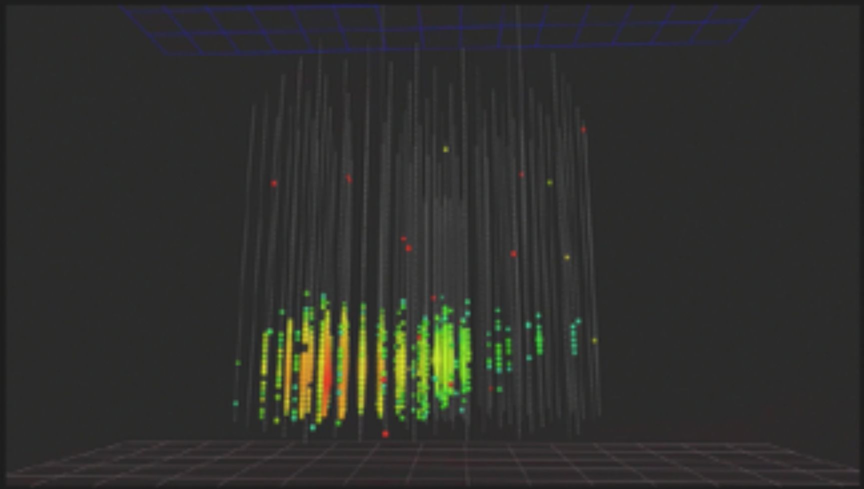
# HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

*We send our high-energy events in real-time as public GCN alerts now!*

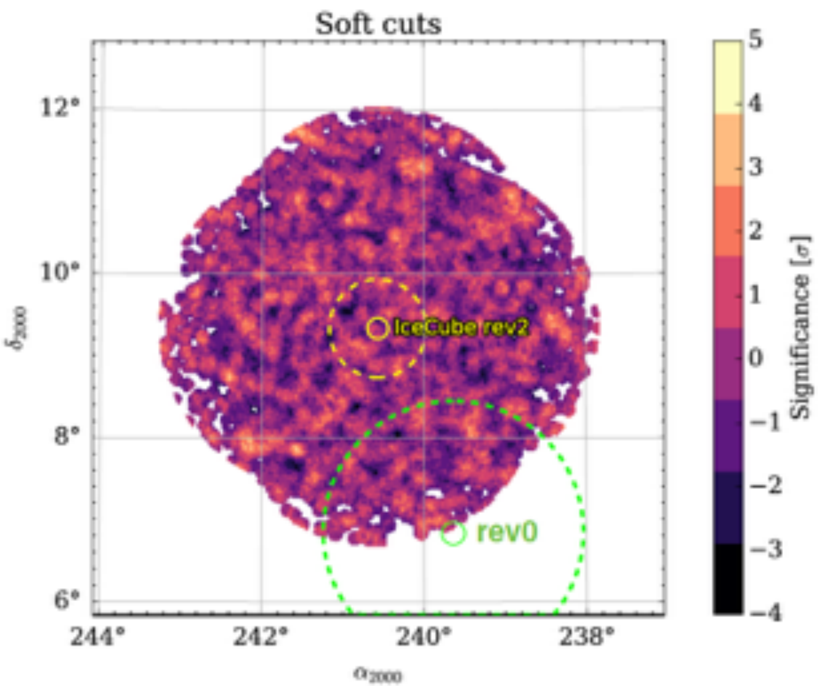
```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;   118 DOY;   16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

## GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them**.



# Rapid neutrino follow-up observations



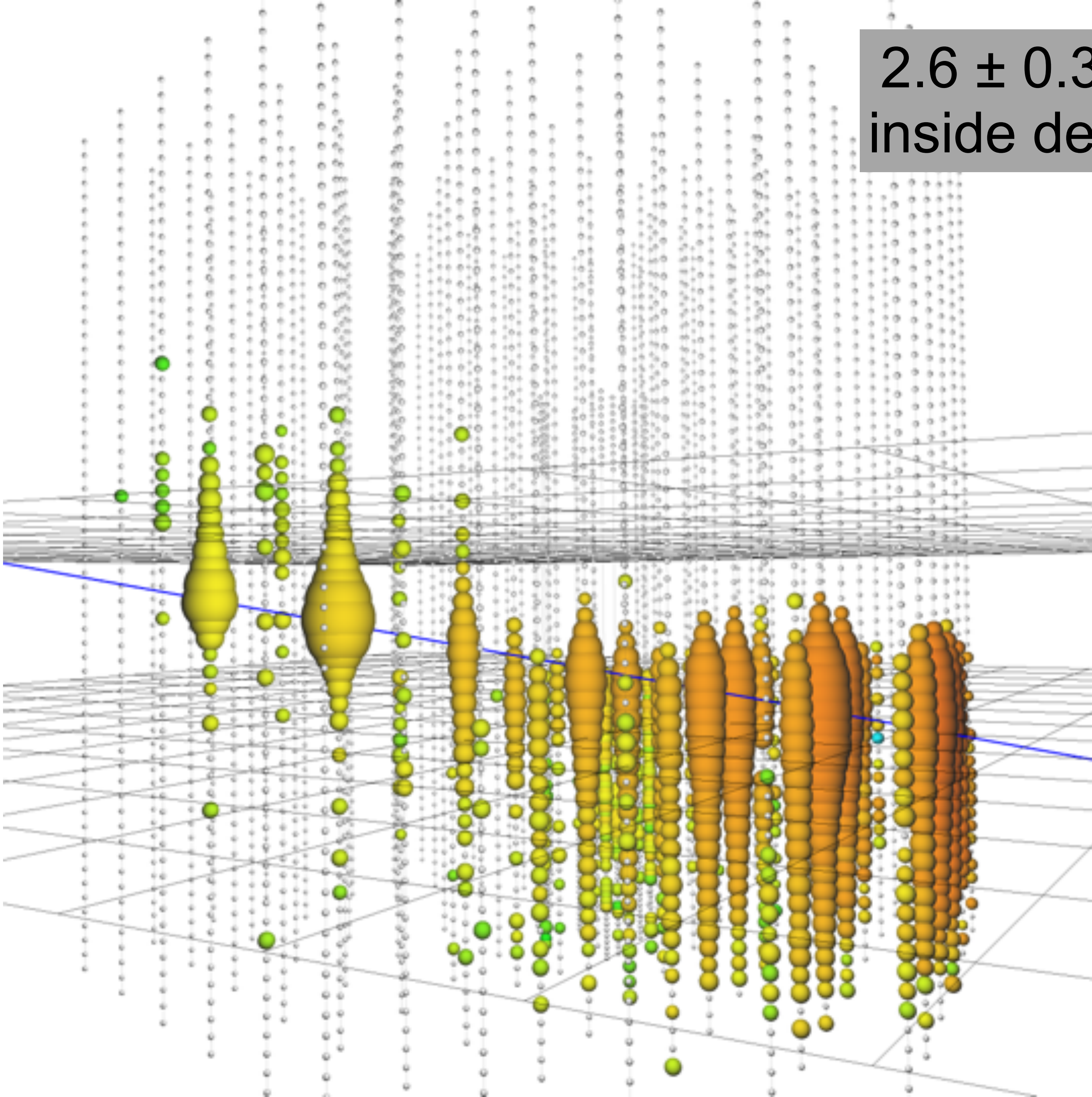

| | Time | RA | Dec | Err (50%) | Err (90%) |
|---|---|---|---|---|---|
| rev0 | Apr 27, 05:54 | 239.66° | 6.85° | 1.6° | 8.9° |
| rev2 | Apr 27, 23:24 | 240.56° | 9.34° | — | 0.6° |

- Rev0: **71 min** live-time (reduced high-voltage)
- Rev2: **118 min** live-time (reduced high-voltage) taken on Apr 28th.
- **No gamma-ray signal in the ROI.**

**More neutrinos from IceCube!**

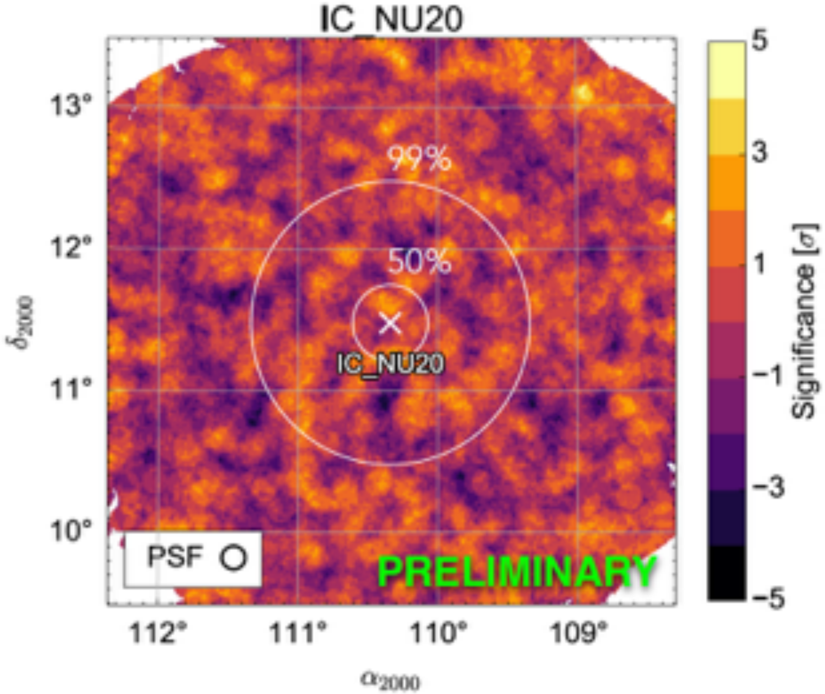
- Selection of IceCube extreme high-energy (EHE) muon neutrinos.
- GCN alerts went public on July 15th.
- First alert on Jul 31st, 2016. VERITAS was not operating.
- Rate ~ 4-6/year (**~2 astro/~4 bkg**). Latency ~ 0.5 - 3 minutes. **0.1°-0.4°** ang. resolution.

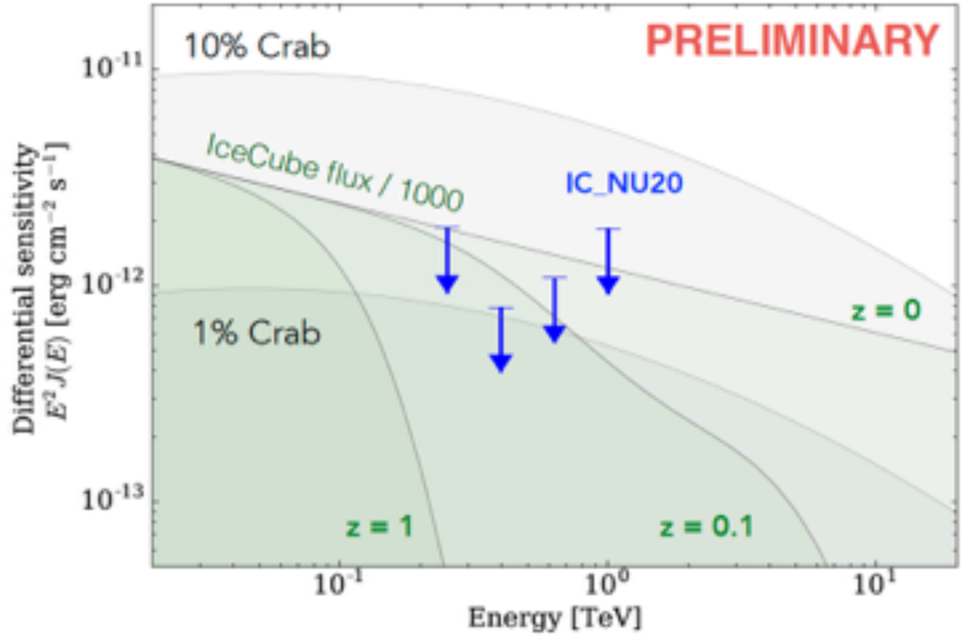
(http://gcn.gsfc.nasa.gov/notices_amon/6888376_128290.amon)



2.6 ± 0.3 PeV
inside detector

# VERITAS observation of the PeV muon location

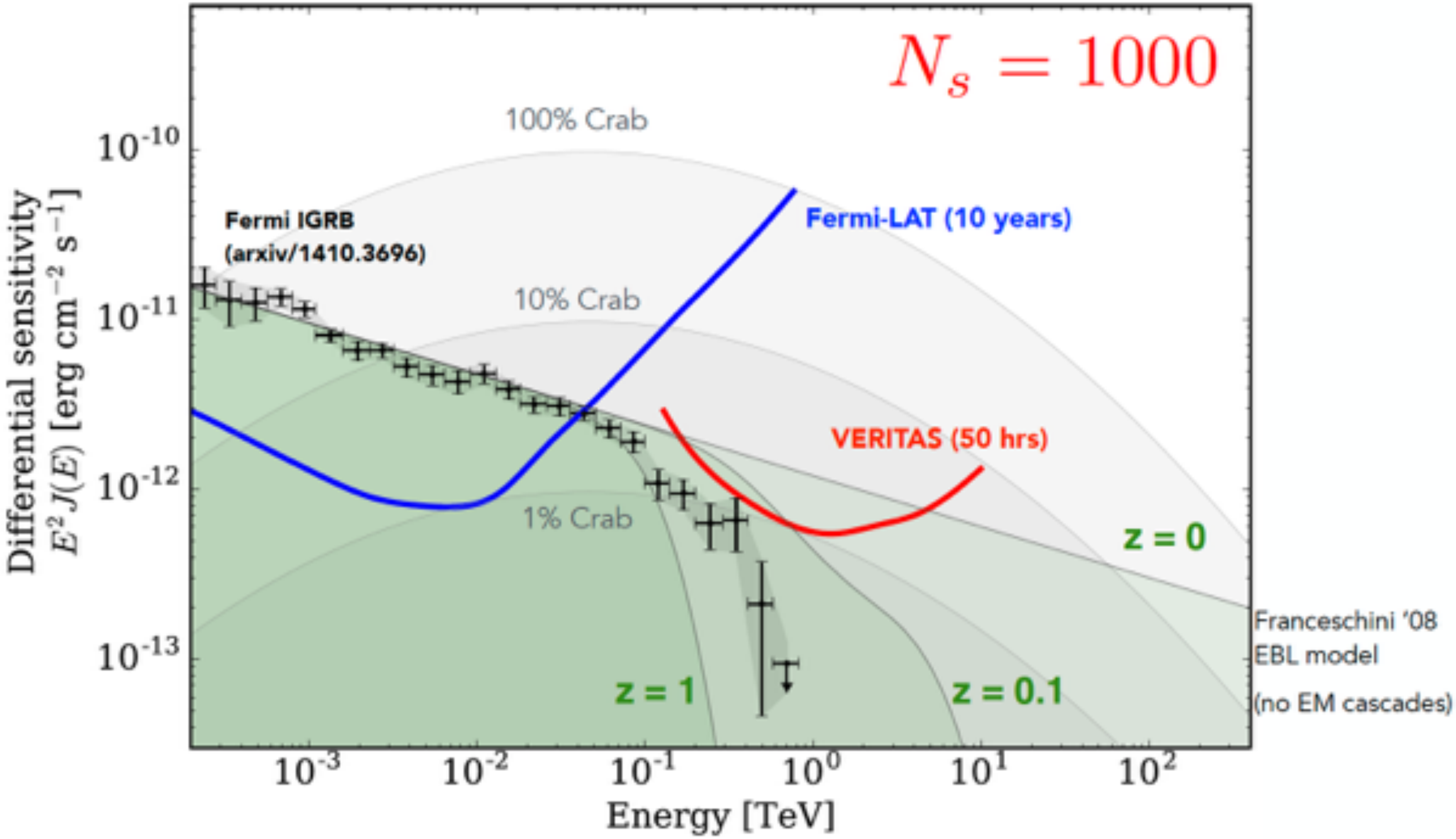



- 4 runs (1.83 hr of live-time) taken on 03/27/2016 under dark conditions. Analysis optimized for soft-spectrum sources.
- No gamma emission detected within the neutrino error circle. ULs at the level of a few percent of the Crab.
- **Upper limits at the level of 0.1% of the all-sky astrophysical neutrino flux** (depends on spectral extrapolation and source redshift).

# Gamma-ray flux from IceCube sources

**Quasi-isotropic IceCube neutrino flux converted to gamma-ray flux from $N_s$ sources**

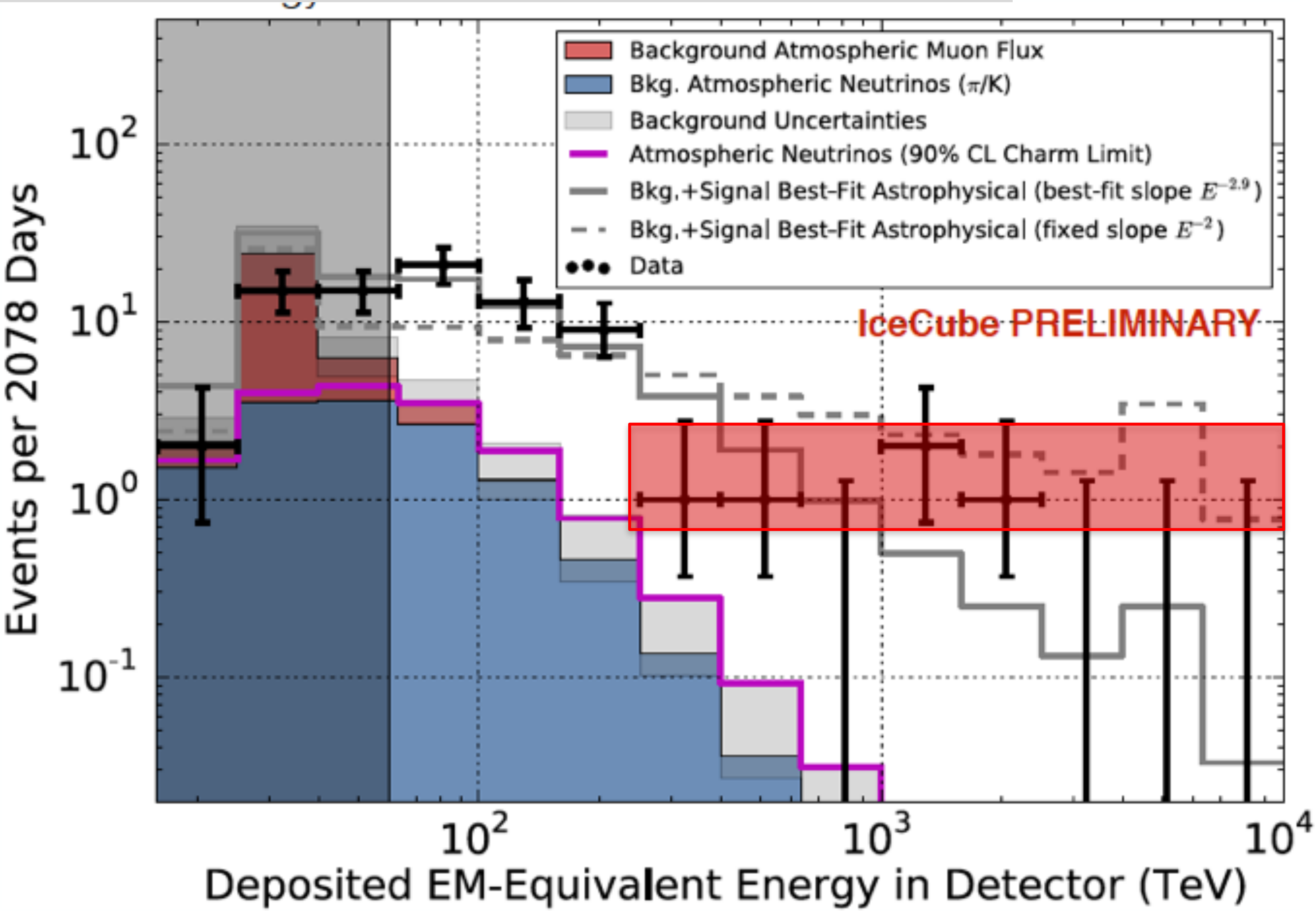



$$E^2\phi_\gamma^s(E) = \frac{4\pi}{N_s} 1.5 \times 10^{-11} \left(\frac{E}{100\ \text{TeV}}\right)^{-0.3} [\text{TeV s}^{-1}\ \text{cm}^{-2}]$$

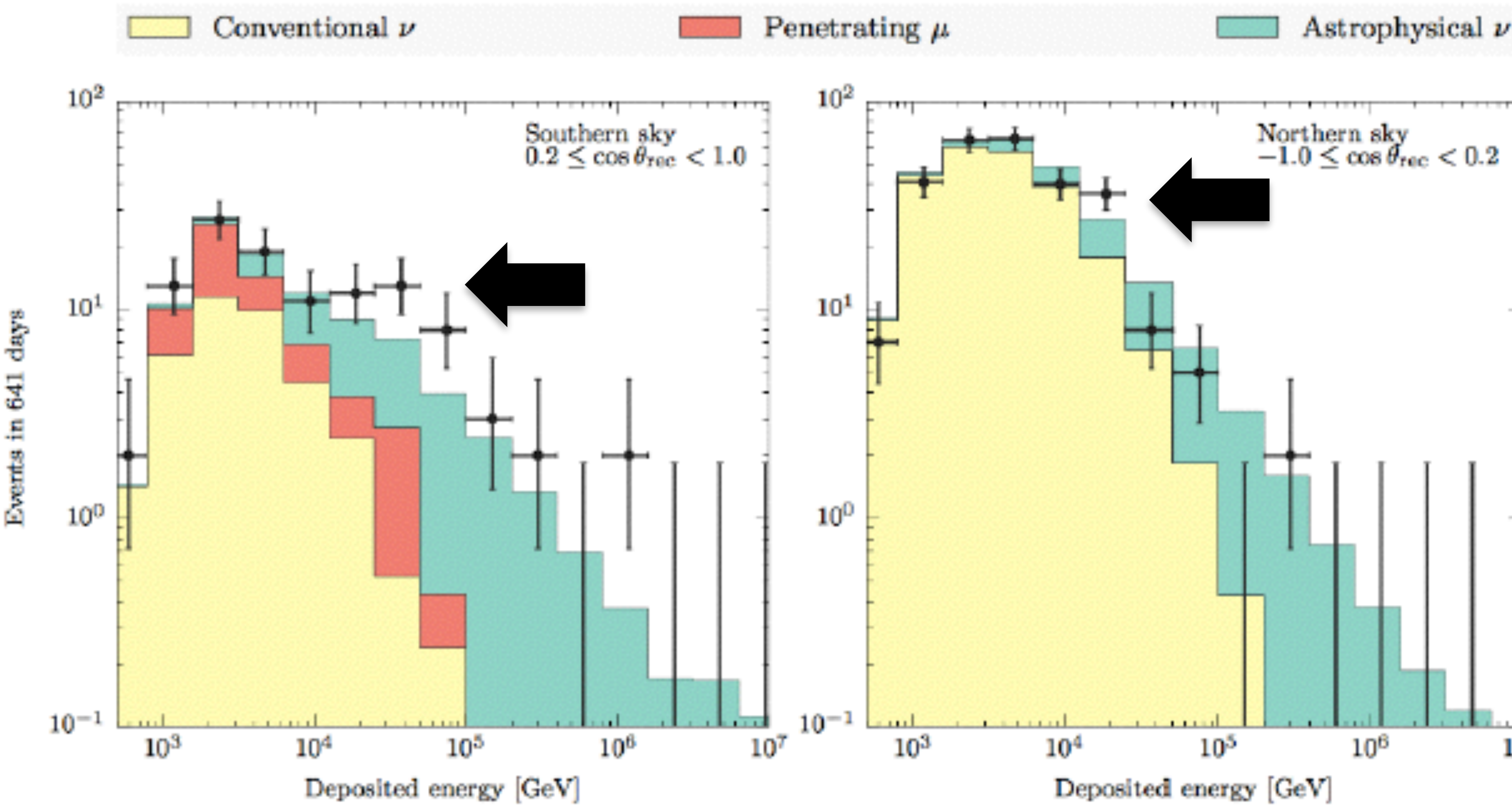
**Gamma-ray flux** **IceCube flux (arxiv/1405.5303)**

- there is more

comparison HESE and muon results (red overlay)



# towards lower energies: a second component?



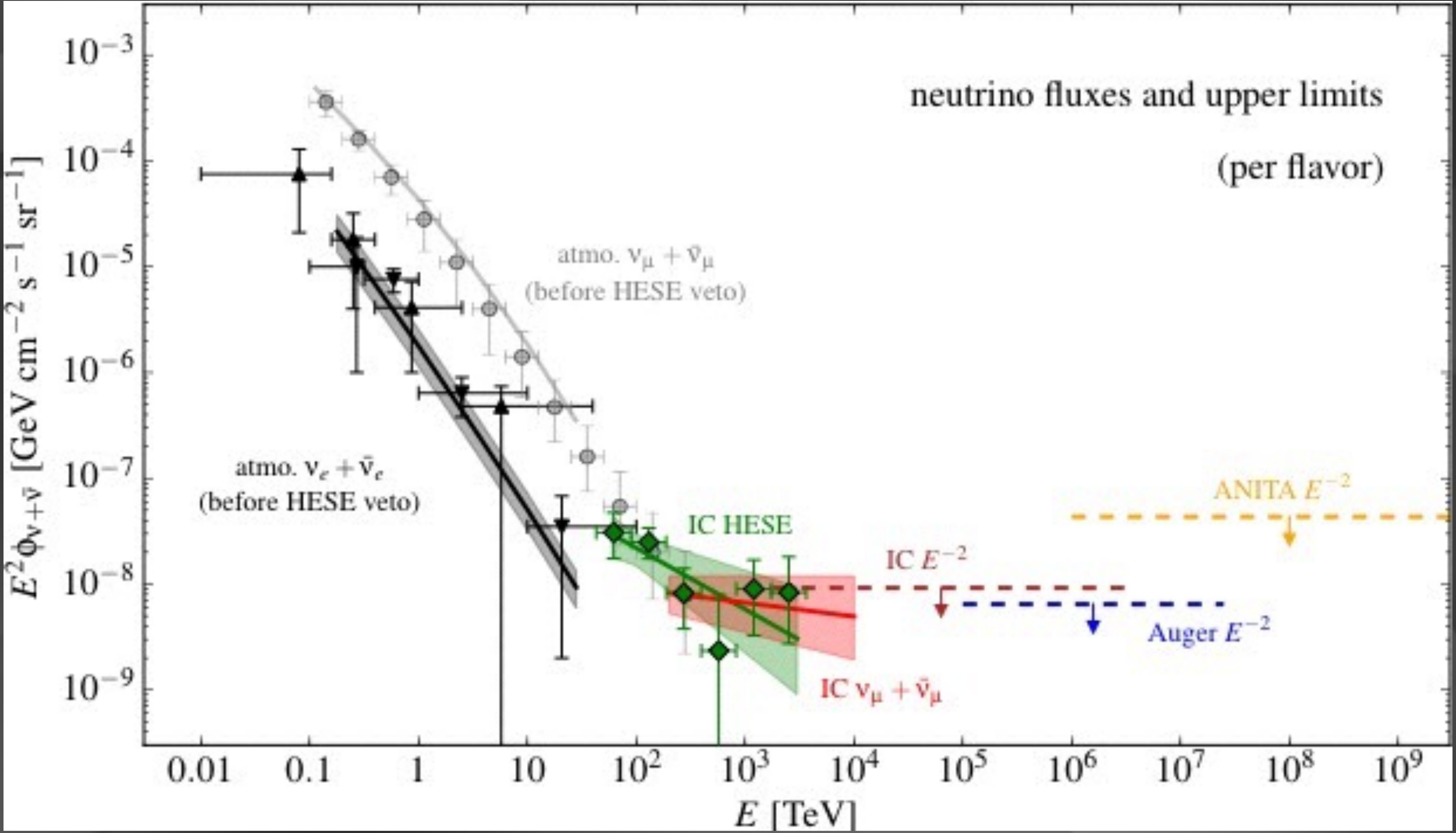

warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

- two component cosmic neutrino flux?
- cosmic accelerators do not follow a power-law spectrum?
- note that the gammas rays accompanying
  < 100 TeV neutrinos are not seen suggesting a
  hidden source(s)

## not background: prompt decay of charm particles produced in the atmosphere

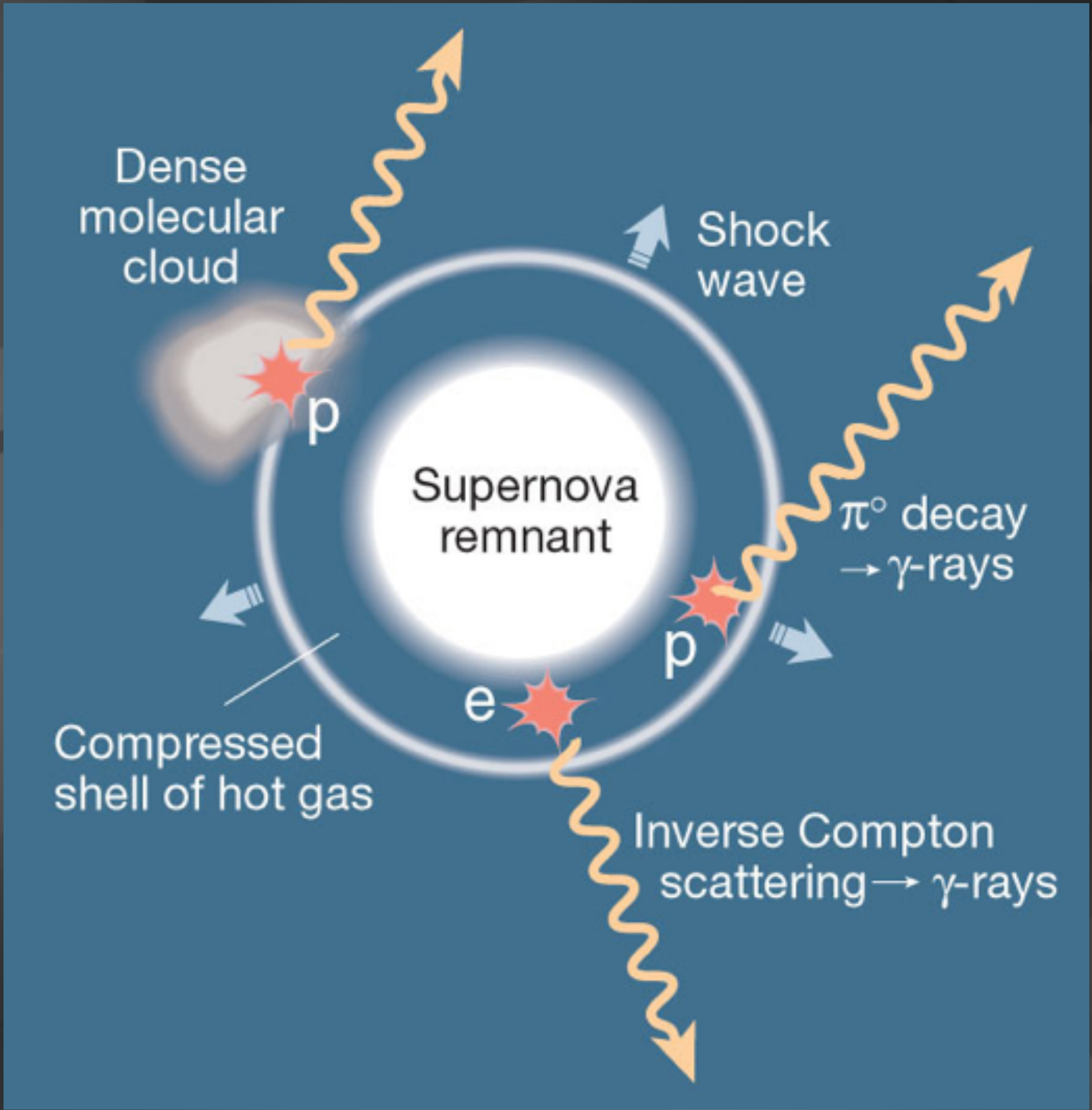
- tracks cosmic ray flux in energy, isotropic in zenith, normalization unknown: does not fit the data
- neutrino events are isolated
- incompatible with observes atmospheric *electron* neutrino spectrum



- Galactic sources?

neutrinos from supernova remnants :

molecular clouds as beam dumps → pion production



# Detector Complementarity

Wide-field / Continuous Operation

VHE Sensitivity

Fermi, AGILE, EGRET

HAWC, ARGO, Milagro

VERITAS, HESS, MAGIC

Space-Based

- All sky coverage
- GeV range (area->flux limited)

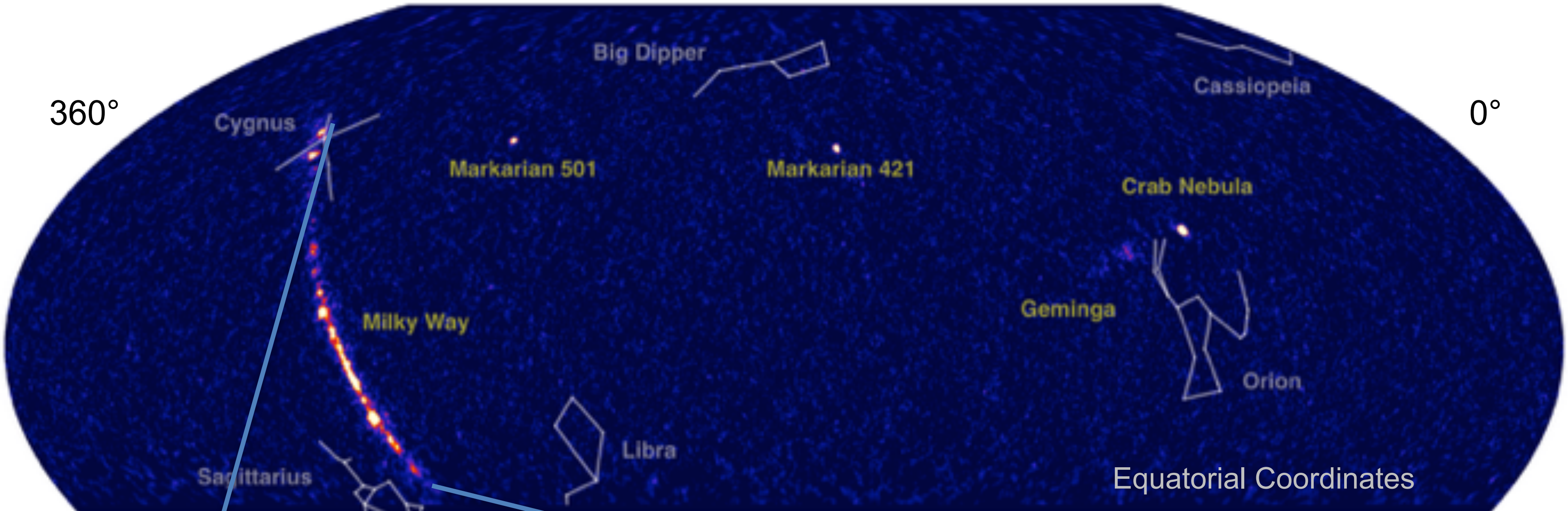
Ground Arrays

- 95% duty cycle, ~2 sr f.o.v.
- Daily coverage of $2/3$ sky
- Unbiased surveys
- Highest energies, E > 100 GeV

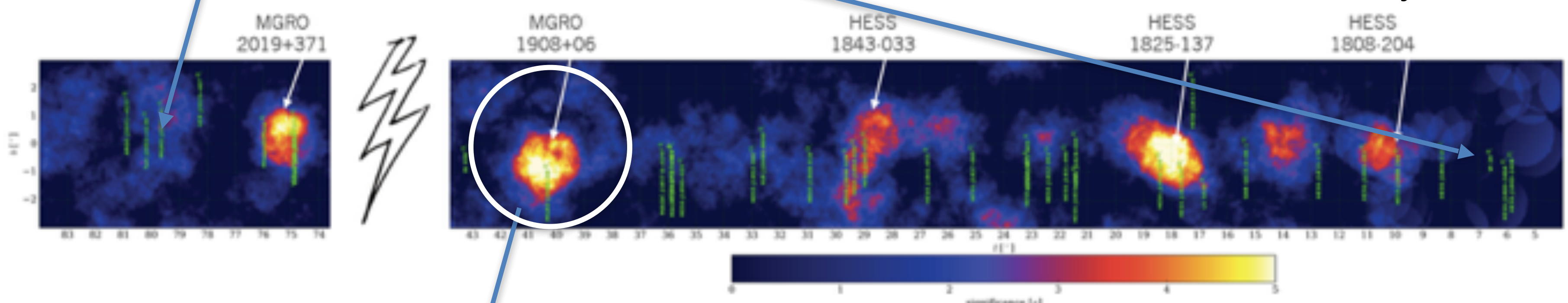
IACTs

- Excellent pointing
- Highest energies
- Surveys limited

# HAWC View of Gamma Ray Sky




E > 1 TeV 340 days




MGRO J1908+06

HAWC sky above 55 TeV

neutral pions

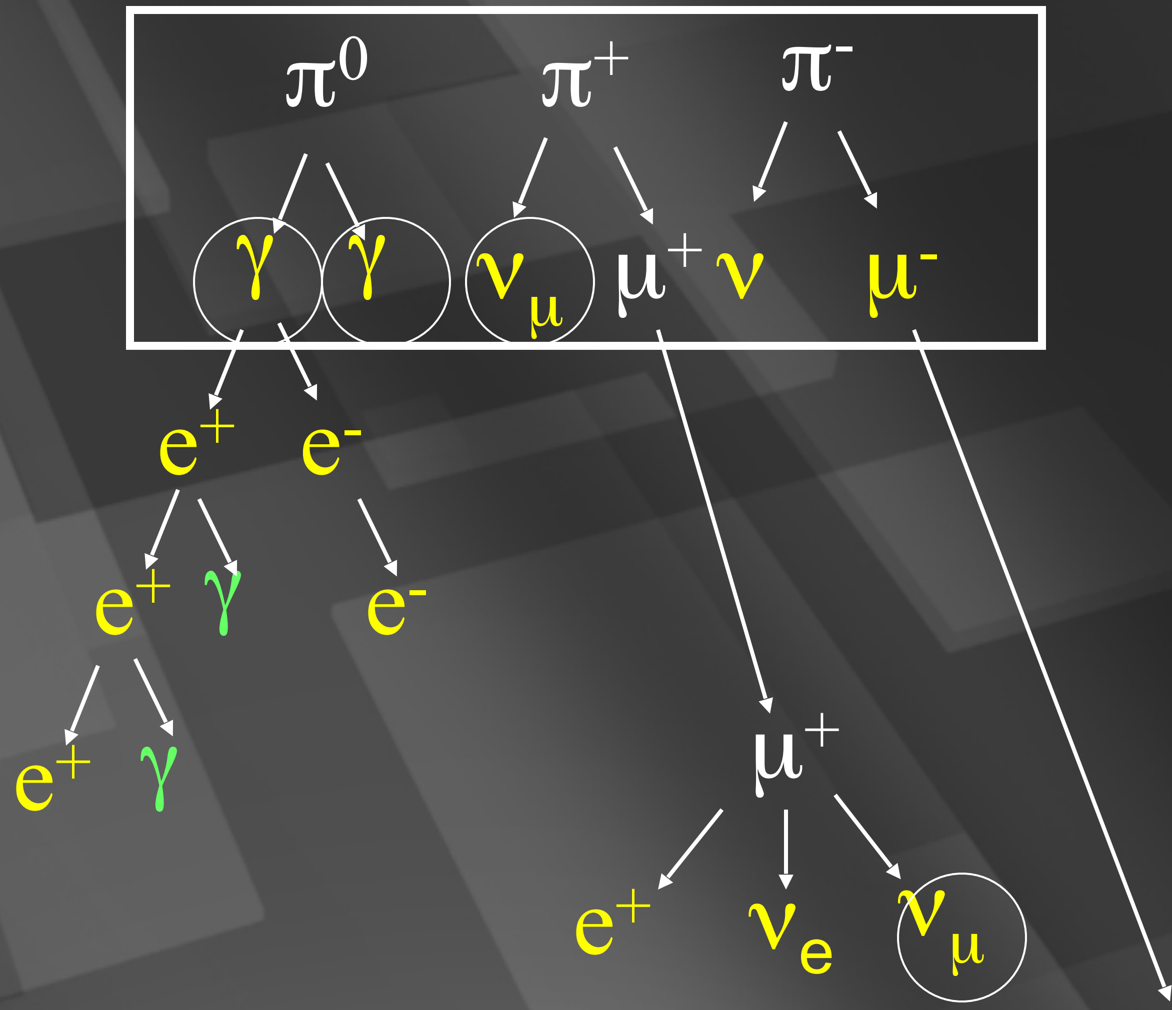
are observed as

gamma rays

charged pions

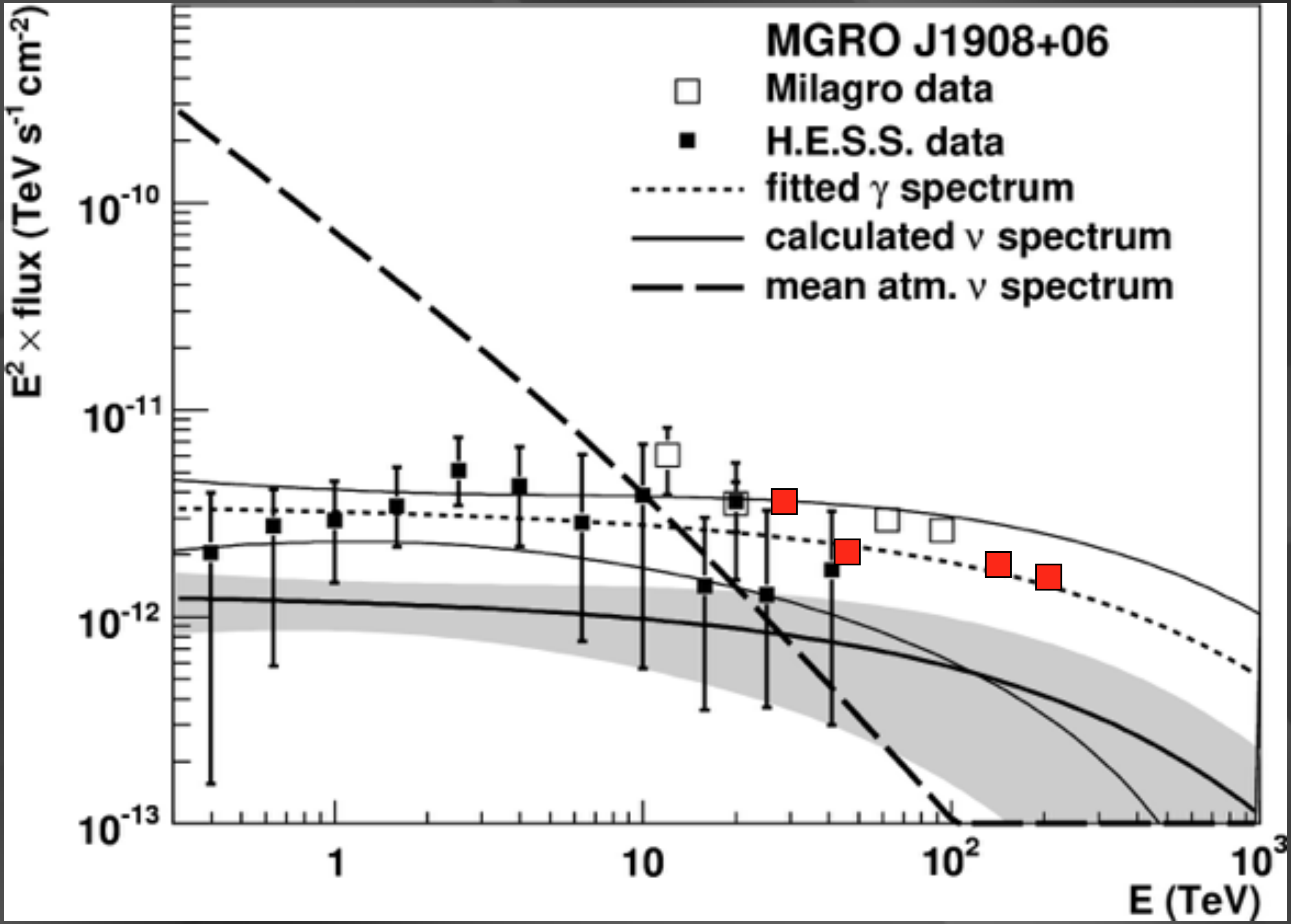
are observed as

neutrinos

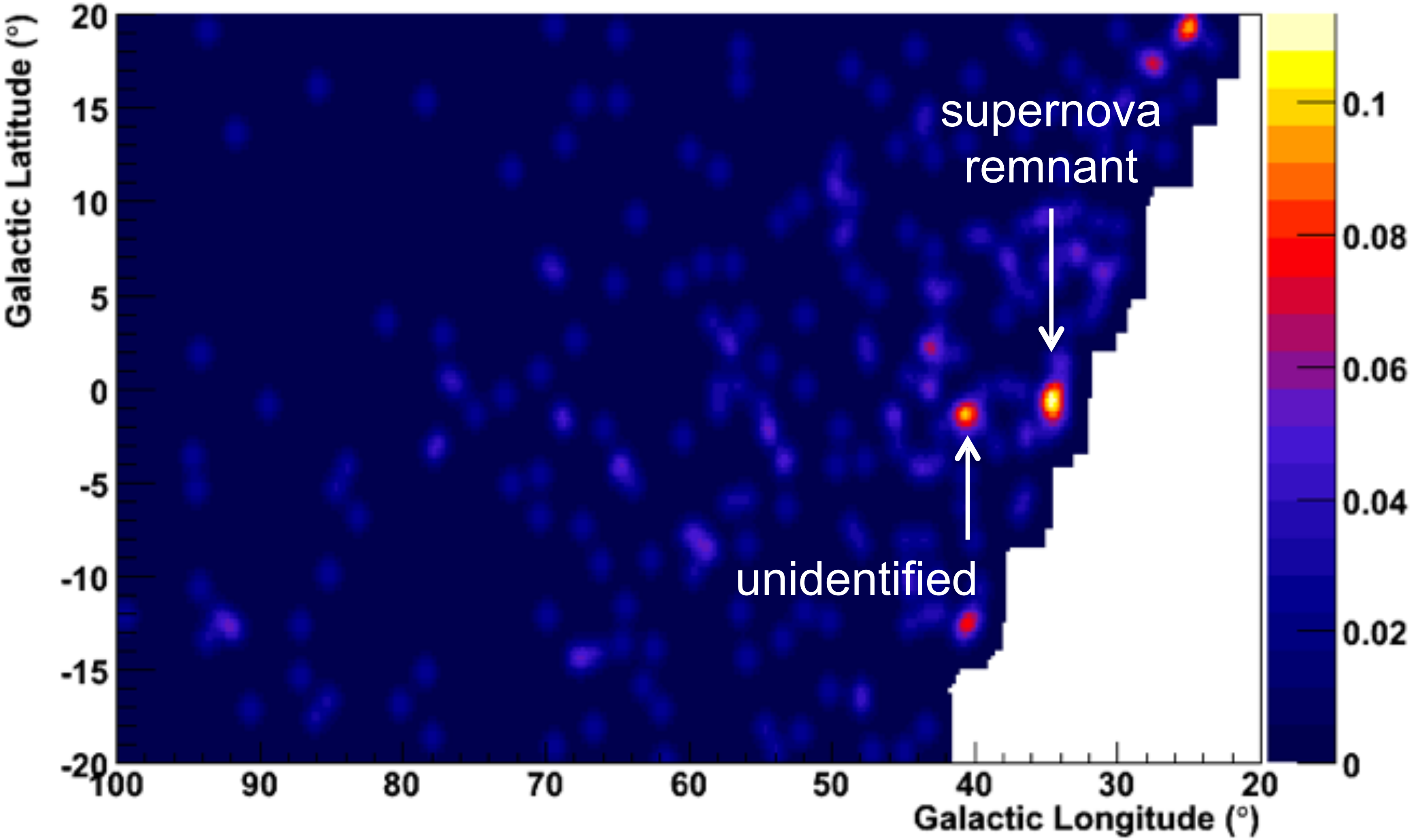



$$\nu_\mu + \nu_\mu = \gamma + \gamma$$

# MGRO J1908+06: the first Pevatron? (2007!)



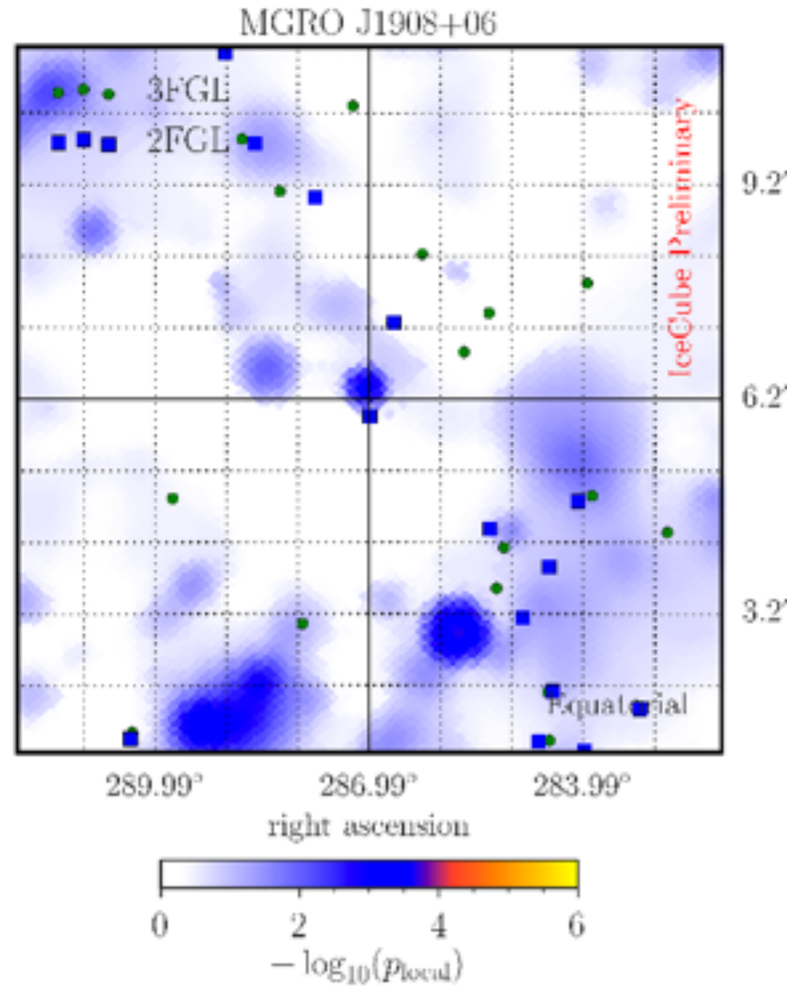
2007 simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.

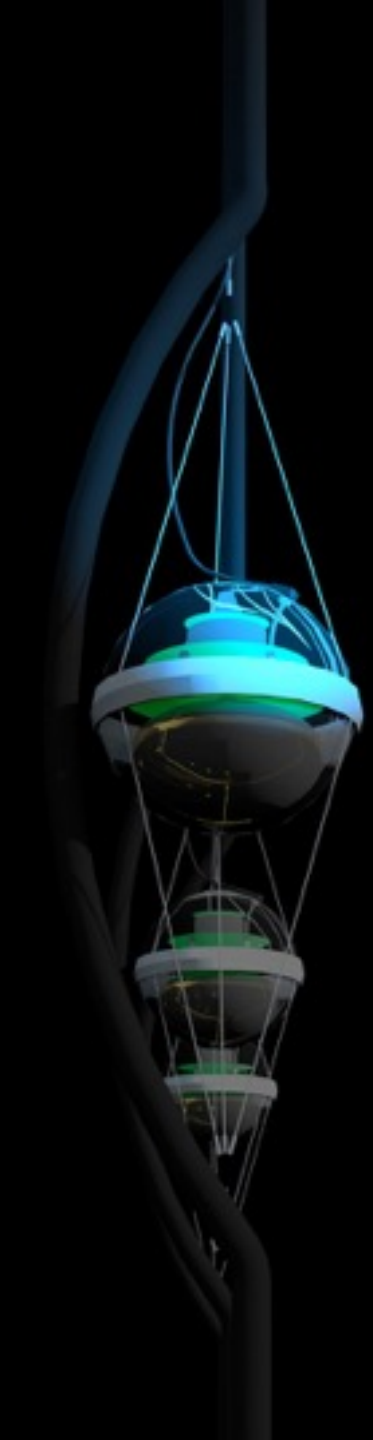


- most significant source in pre-defined list (p-value 0.003 pretrial)
- joined HAWC-IceCube analysis in progress using photon templates

Table 1: Results of the pre-defined source list.

| Source | Type | $\alpha$ [deg] | $\delta$ [deg] | p-Value | $TS$ | $n_s$ | $\Phi_0$ [TeV cm$^{-2}$ s$^{-1}$] |
|---|---|---|---|---|---|---|---|
| PKS 0235+164 | BL Lac | 39.66 | 16.62 | 0.7355 | -0.400 | 0.00 | $2.04\cdot10^{-13}$ |
| 1ES 0229+200 | BL Lac | 38.20 | 20.29 | 0.4762 | -0.059 | 0.00 | $4.47\cdot10^{-13}$ |
| W Comae | BL Lac | 185.38 | 28.23 | 0.4420 | -0.055 | 0.00 | $5.37\cdot10^{-13}$ |
| Mrk 421 | BL Lac | 166.11 | 38.21 | 0.2433 | 0.029 | 0.48 | $8.68\cdot10^{-13}$ |
| Mrk 501 | BL Lac | 253.47 | 39.76 | 0.6847 | -0.172 | 0.00 | $3.51\cdot10^{-13}$ |
| BL Lac | BL Lac | 330.68 | 42.28 | 0.5104 | -0.028 | 0.00 | $5.58\cdot10^{-13}$ |
| H 1426+428 | BL Lac | 217.14 | 42.67 | 0.7890 | -0.243 | 0.00 | $1.96\cdot10^{-13}$ |
| 3C66A | BL Lac | 35.67 | 43.04 | 0.3306 | -0.001 | 0.00 | $7.50\cdot10^{-13}$ |
| 1ES 2344+514 | BL Lac | 356.77 | 51.70 | 0.9264 | -0.808 | 0.00 | $1.58\cdot10^{-13}$ |
| 1ES 1959+650 | BL Lac | 300.00 | 65.15 | [illegible] | 0.124 | 1.69 | $1.17\cdot10^{-12}$ |
| S5 0716+71 | BL Lac | 110.47 | 71.34 | 0.7230 | -0.380 | 0.00 | $3.84\cdot10^{-13}$ |
| 3C 273 | FSRQ | 187.28 | [illegible] | 0.3807 | -0.014 | 0.00 | $4.42\cdot10^{-13}$ |
| PKS 1502+106 | FSRQ | 226.10 | [illegible] | 0.2322 | -0.000 | 0.00 | $5.98\cdot10^{-13}$ |
| PKS 0528+134 | FSRQ | 82.73 | [illegible] | 0.2870 | -0.002 | 0.00 | $5.74\cdot10^{-13}$ |
| 3C454.3 | FSRQ | 343.50 | [illegible] | 0.0072 | [illegible] | 5.98 | $1.26\cdot10^{-12}$ |
| 4C 38.41 | FSRQ | 248.81 | 38.13 | 0.0055 | 5.686 | 6.62 | $1.72\cdot10^{-12}$ |
| MGRO J1908+06 | NI | 286.99 | 6.27 | 0.0032 | 6.284 | 3.28 | $1.13\cdot10^{-12}$ |
| Geminga | PWN | 98.48 | 17.77 | 0.9754 | -2.424 | 0.00 | $1.16\cdot10^{-13}$ |
| Crab Nebula | PWN | 83.63 | 22.01 | 0.1188 | 0.709 | 4.32 | $8.65\cdot10^{-13}$ |
| MGRO J2019+37 | PWN | 305.22 | 36.83 | 0.9884 | -3.191 | 0.00 | $1.39\cdot10^{-13}$ |
| Cyg OB2 | SFR | 308.09 | 41.23 | 0.3174 | -0.002 | 0.00 | $7.53\cdot10^{-13}$ |
| IC443 | SNR | 94.18 | 22.53 | 0.8153 | -0.457 | 0.00 | $1.22\cdot10^{-13}$ |
| Cas A | SNR | 350.85 | 58.81 | 0.2069 | 0.033 | 0.88 | $1.05\cdot10^{-12}$ |
| TYCHO | SNR | 6.36 | 64.18 | 0.4471 | -0.019 | 0.00 | $8.14\cdot10^{-13}$ |
| M87 | SRG | 187.71 | 12.39 | 0.6711 | -0.256 | 0.00 | $2.85\cdot10^{-13}$ |
| 3C 123.0 | SRG | 69.27 | 29.67 | 0.9055 | -0.747 | 0.00 | $1.30\cdot10^{-13}$ |
| Cyg A | SRG | 299.87 | 40.73 | 0.0049 | 6.335 | 4.30 | $1.78\cdot10^{-12}$ |
| NGC 1275 | SRG | 49.95 | 41.51 | 0.2582 | 0.007 | 0.25 | $8.31\cdot10^{-13}$ |
| M82 | SRG | 148.97 | 69.68 | 0.8887 | -0.888 | 0.00 | $1.83\cdot10^{-13}$ |
| SS433 | XB/mqso | 287.96 | 4.98 | 0.8738 | -1.085 | 0.00 | $1.01\cdot10^{-13}$ |
| HESS J0632+057 | XB/mqso | 98.24 | 5.81 | 0.8359 | -0.917 | 0.00 | $1.01\cdot10^{-13}$ |
| Cyg X-1 | XB/mqso | 299.59 | 35.20 | 0.5422 | -0.106 | 0.00 | $4.93\cdot10^{-13}$ |
| Cyg X-3 | XB/mqso | 308.11 | 40.96 | 0.3230 | -0.003 | 0.00 | $7.28\cdot10^{-13}$ |
| LSI 303 | XB/mqso | 40.13 | 61.23 | 0.2843 | 0.001 | 0.17 | $1.01\cdot10^{-12}$ |





IceCube: the discovery of cosmic neutrinos

francis halzen

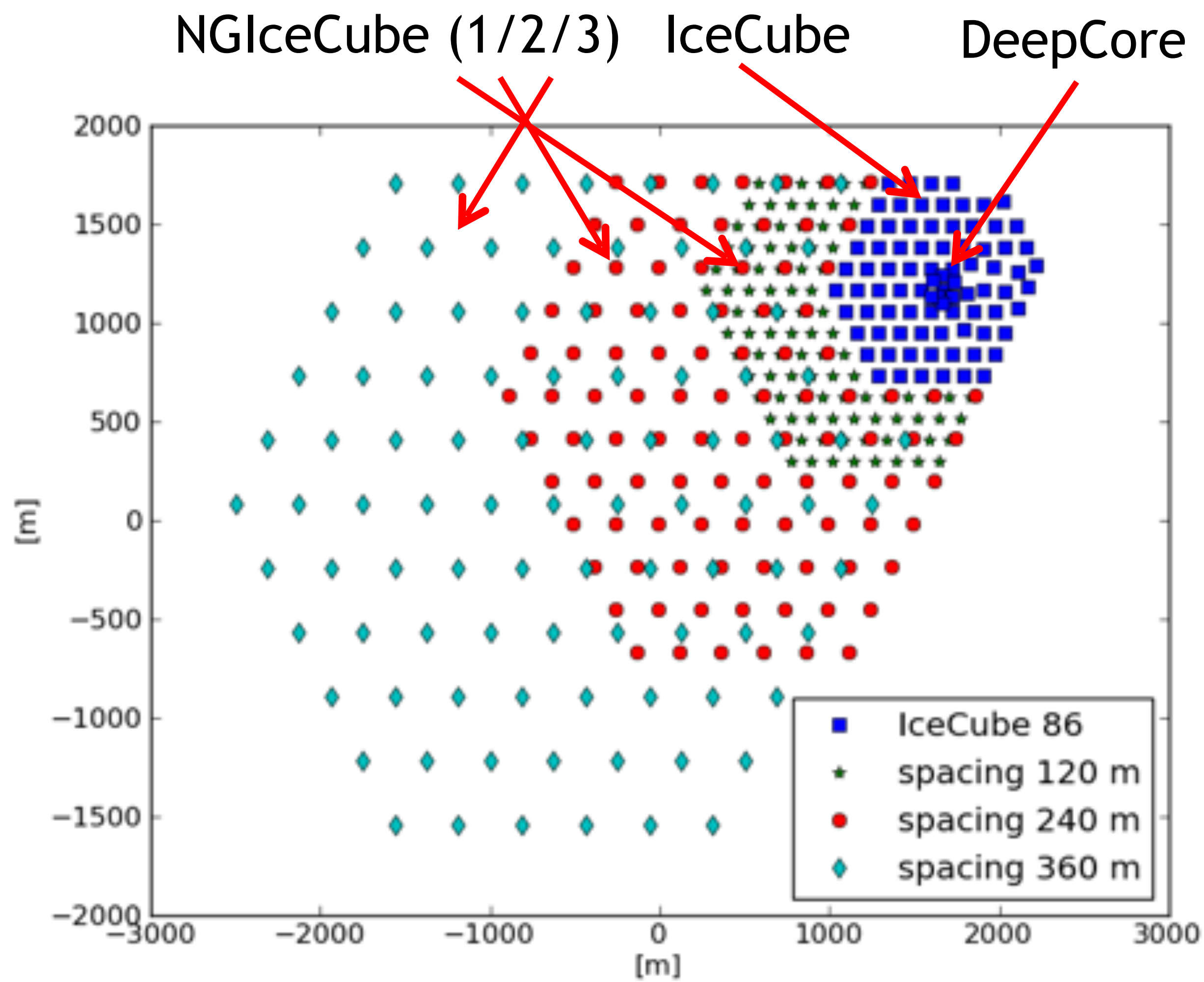
- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

- a next-generation IceCube with a volume of 10 $km^3$ and an angular resolution of ~0.1 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years
- need 1,000 events versus 100 now in a few years
- discovery instrument → astronomical telescope

# measured optical properties → twice the string spacing

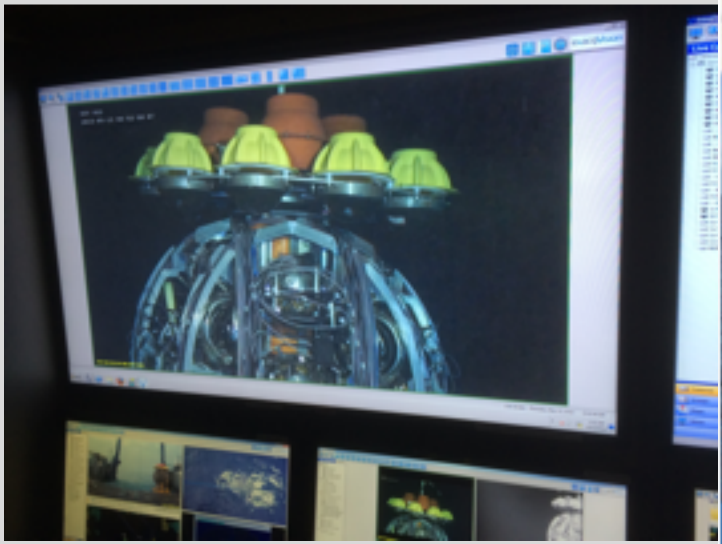
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

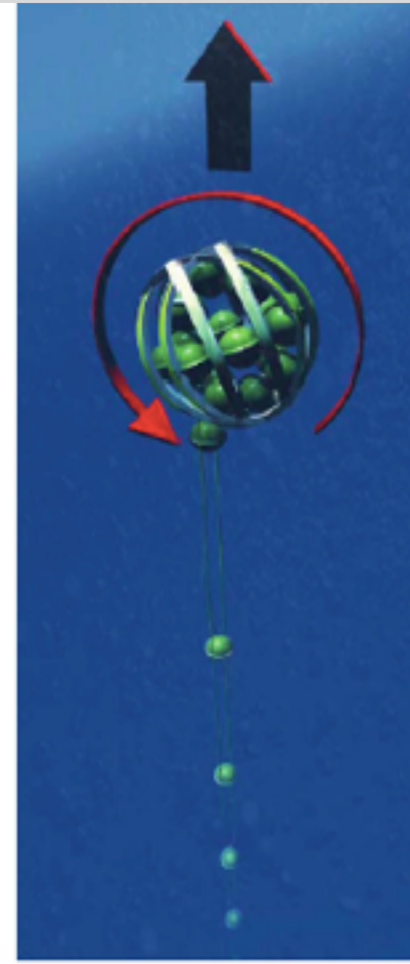



Spacing 1 (120m): IceCube (1 km$^3$)
+ 98 strings (1,3 km$^3$)
= 2,3 km$^3$

Spacing 2 (240m):
IceCube (1 km$^3$)
+ 99 strings (5,3 km$^3$)
= 6,3 km$^3$

Spacing 3 (360m):
IceCube (1 km$^3$)
+ 95 strings (11,6 km$^3$)
= 12,6 km$^3$



also GVD
in lake Baikal

KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf

## Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos (cosmic rays) are essential in understanding the non-thermal universe.
- from discovery to astronomy: more events, more telescopes
- neutrinos are never boring!

# 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
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt-Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
Universität Münster
Universität Mainz
Universität Wuppertal

**JAPAN**
Chiba University

**NEW ZEALAND**
University of Canterbury

**REPUBLIC OF KOREA**
Sungkyunkwan University

**SWEDEN**
Stockholms Universitet
Uppsala Universitet

**SWITZERLAND**
Université de Genève

**UNITED KINGDOM**
University of Oxford

**UNITED STATES**
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and 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

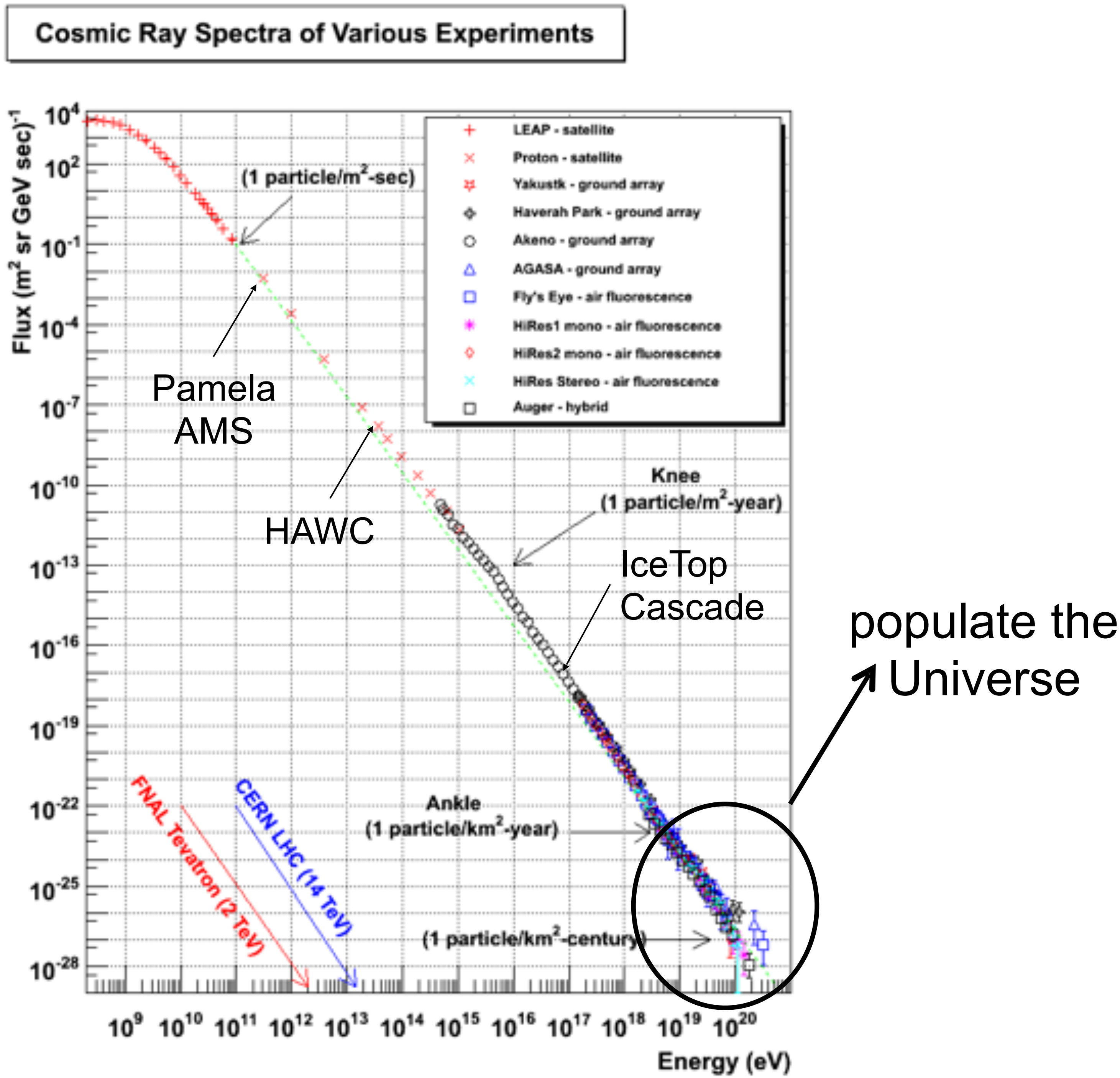
**FUNDING AGENCIES**

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)

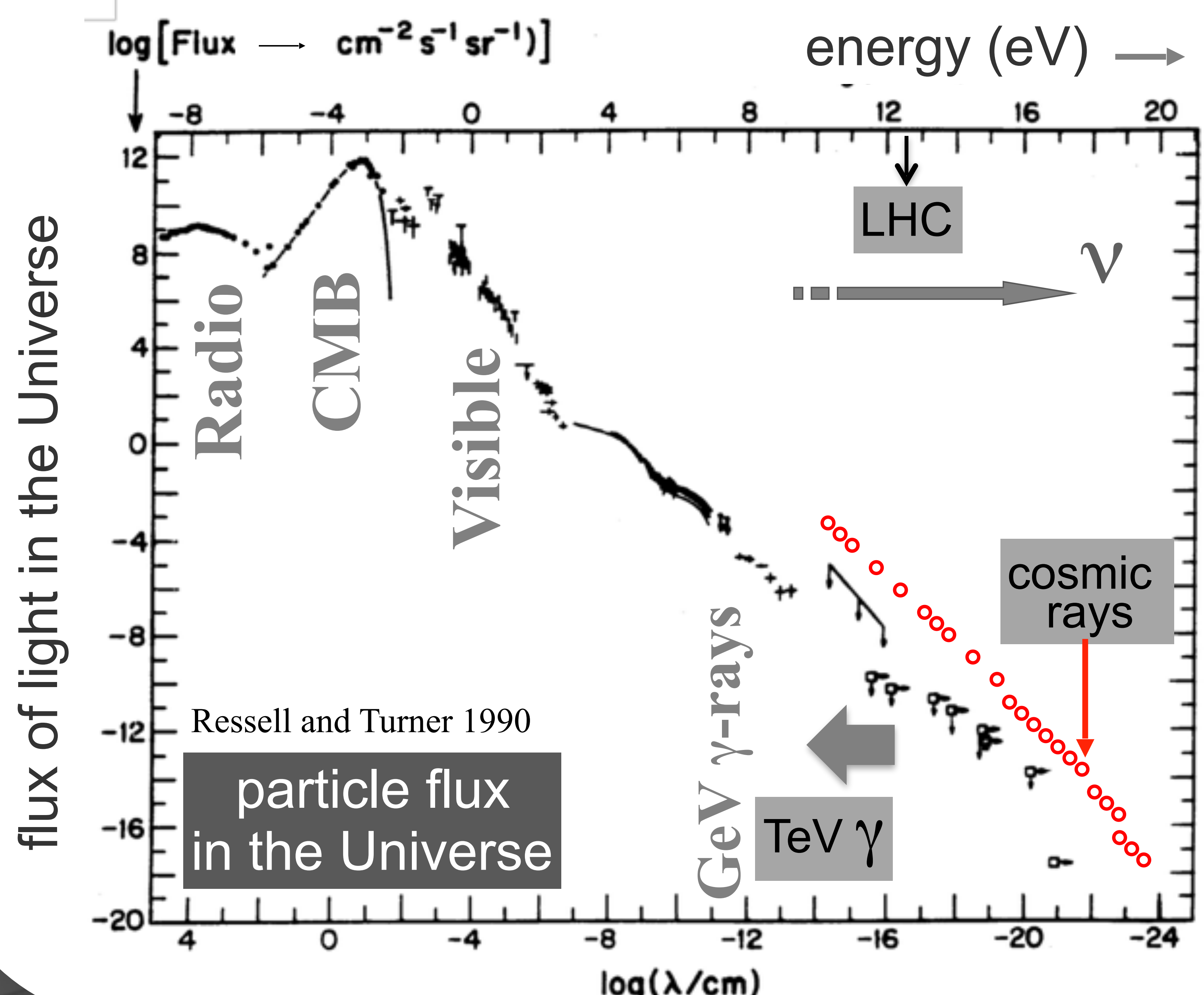
ICECUBE

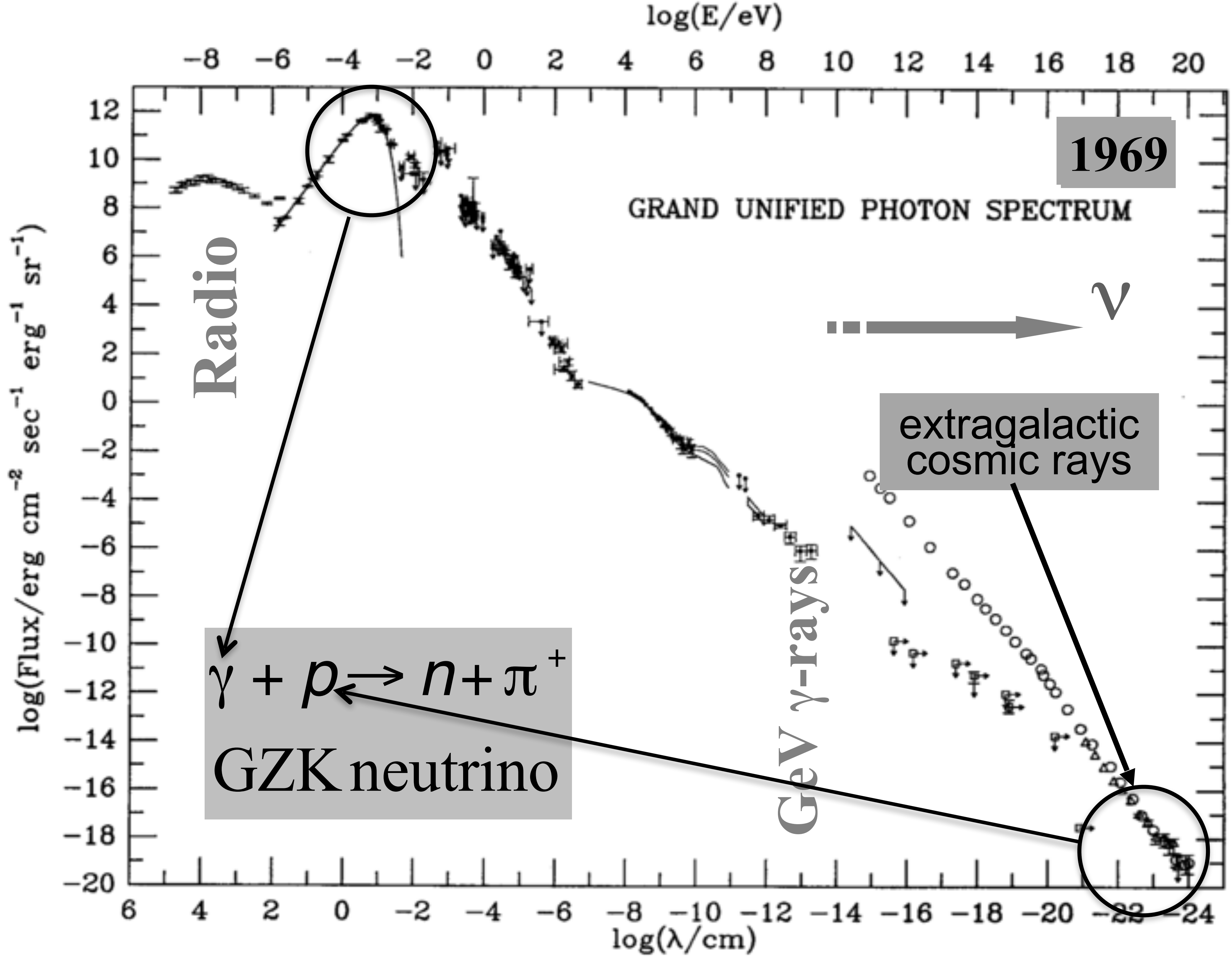
# overflow slides

# photomultiplier tube -10 inch



Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m²-sec)
Pamela
AMS
HAWC
Knee
(1 particle/m²-year)
IceTop
Cascade
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
populate the
Universe


log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV)
-8
-4
0
4
8
12
16
20
LHC
ν
Radio
CMB
Visible
GeV γ-rays
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe
flux of light in the Universe
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)



log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
extragalactic cosmic rays
$\gamma + p \longrightarrow n + \pi^+$
GZK neutrino
GeV γ-rays
log(Flux/erg cm$^{-2}$ sec$^{-1}$ erg$^{-1}$ sr$^{-1}$)
log(λ/cm)

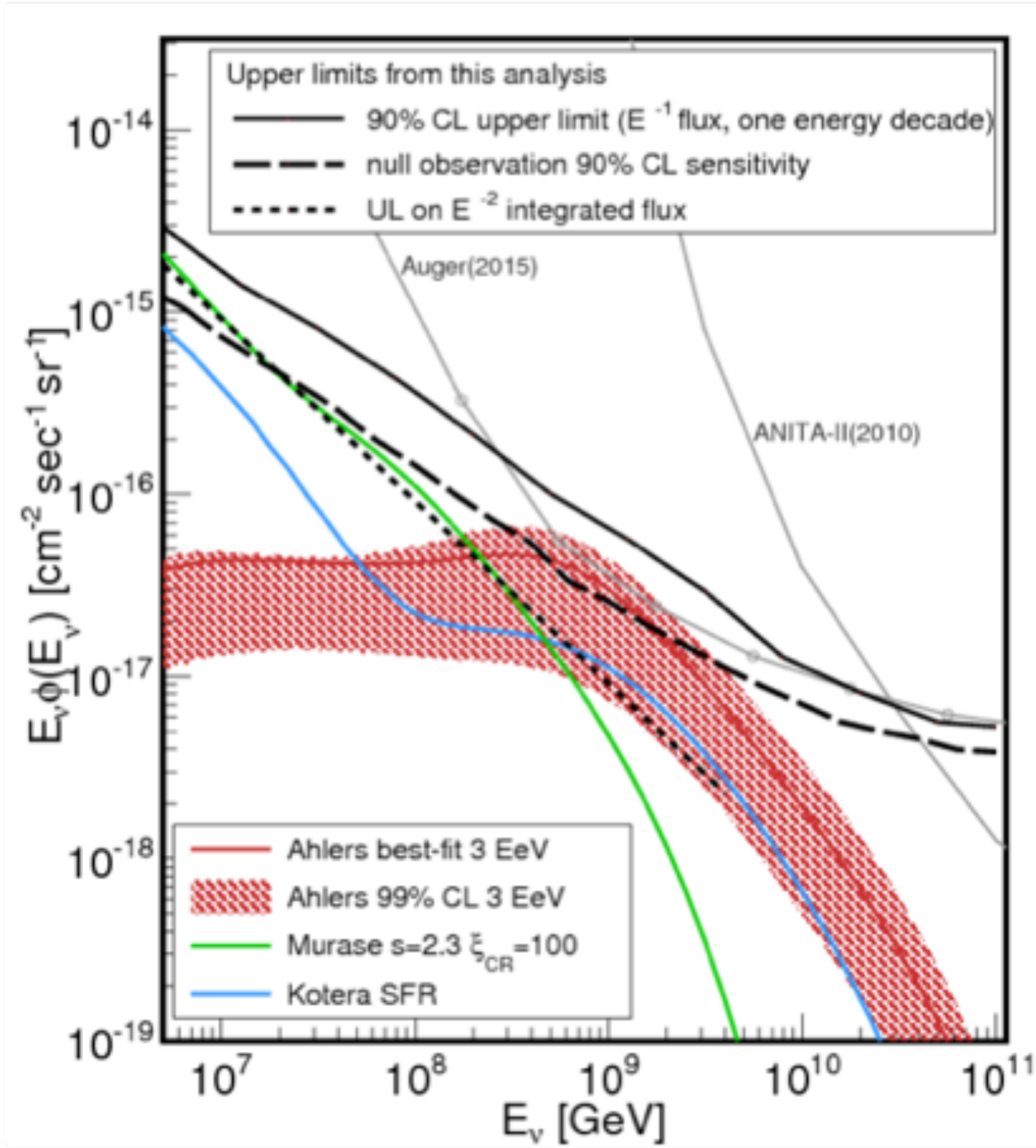
cosmic rays interact with the microwave background

$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV ($10^6$ TeV) energy appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year
...but it points at its source!

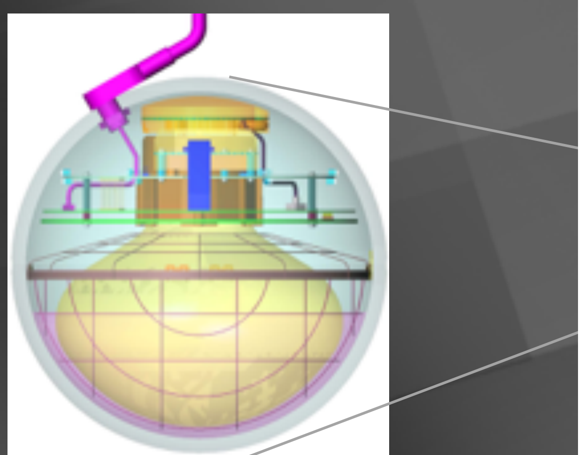


Upper limits from this analysis
90% CL upper limit (E⁻¹ flux, one energy decade)
null observation 90% CL sensitivity
UL on E⁻² integrated flux
Auger(2015)
ANITA-II(2010)
Ahlers best-fit 3 EeV
Ahlers 99% CL 3 EeV
Murase s=2.3 ξ_CR=100
Kotera SFR
$E_\nu \phi(E_\nu)$ [cm⁻² sec⁻¹ sr⁻¹]
$E_\nu$ [GeV]

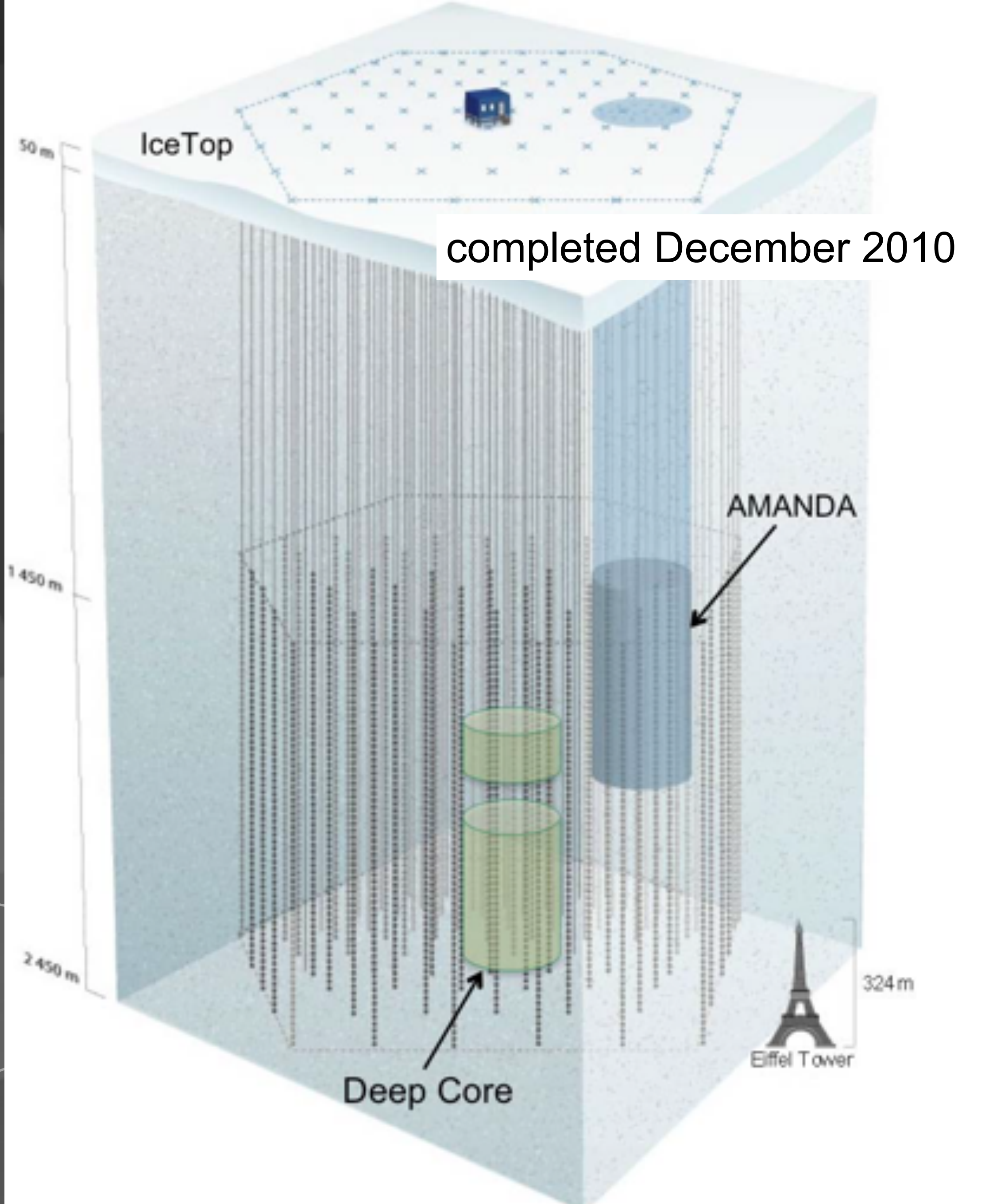

1607.05886

# IceCube / Deep Core

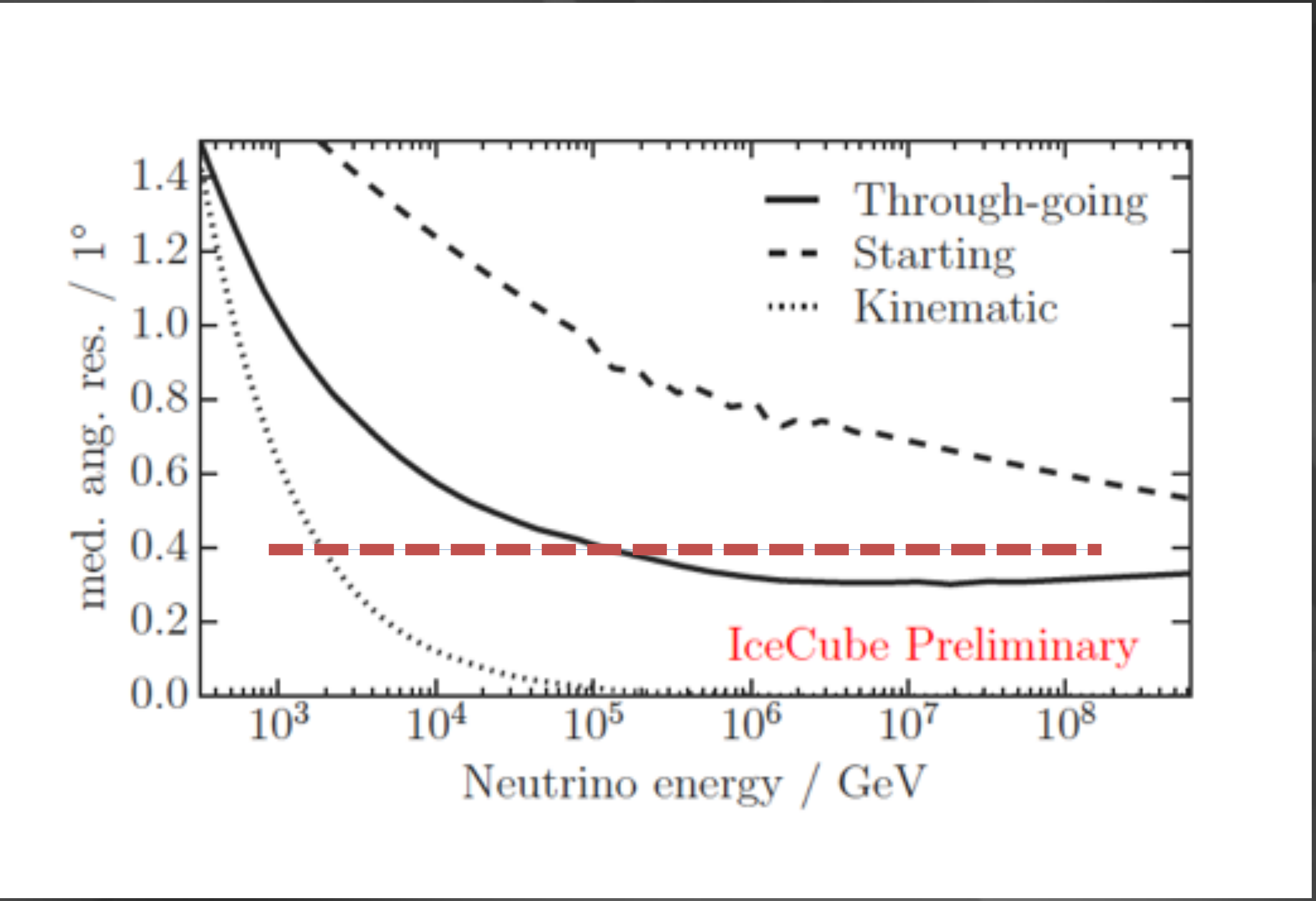
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.4 degree muon track ~ 10 degree shower
- < 15% energy resolution

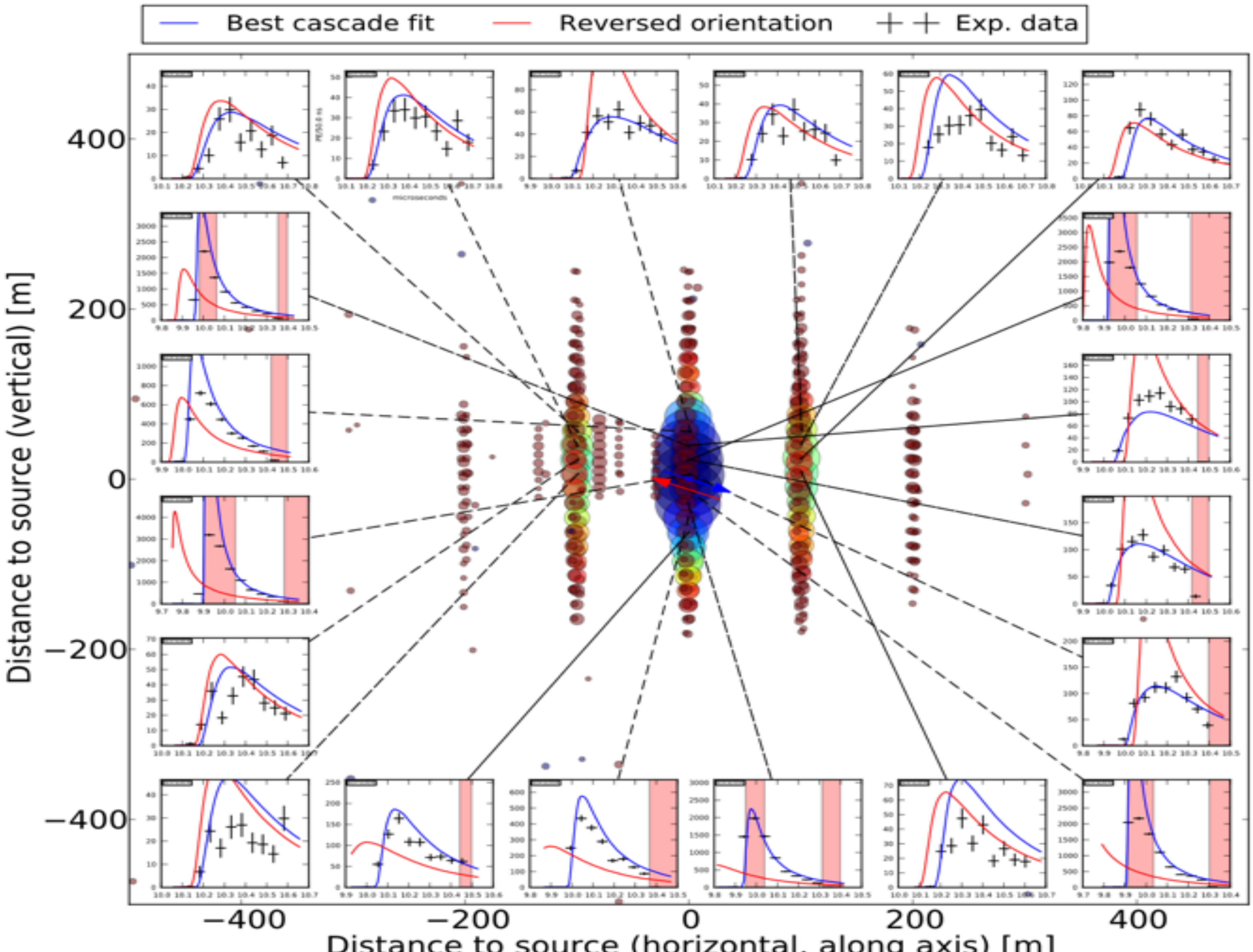


Digital Optical Module (DOM)



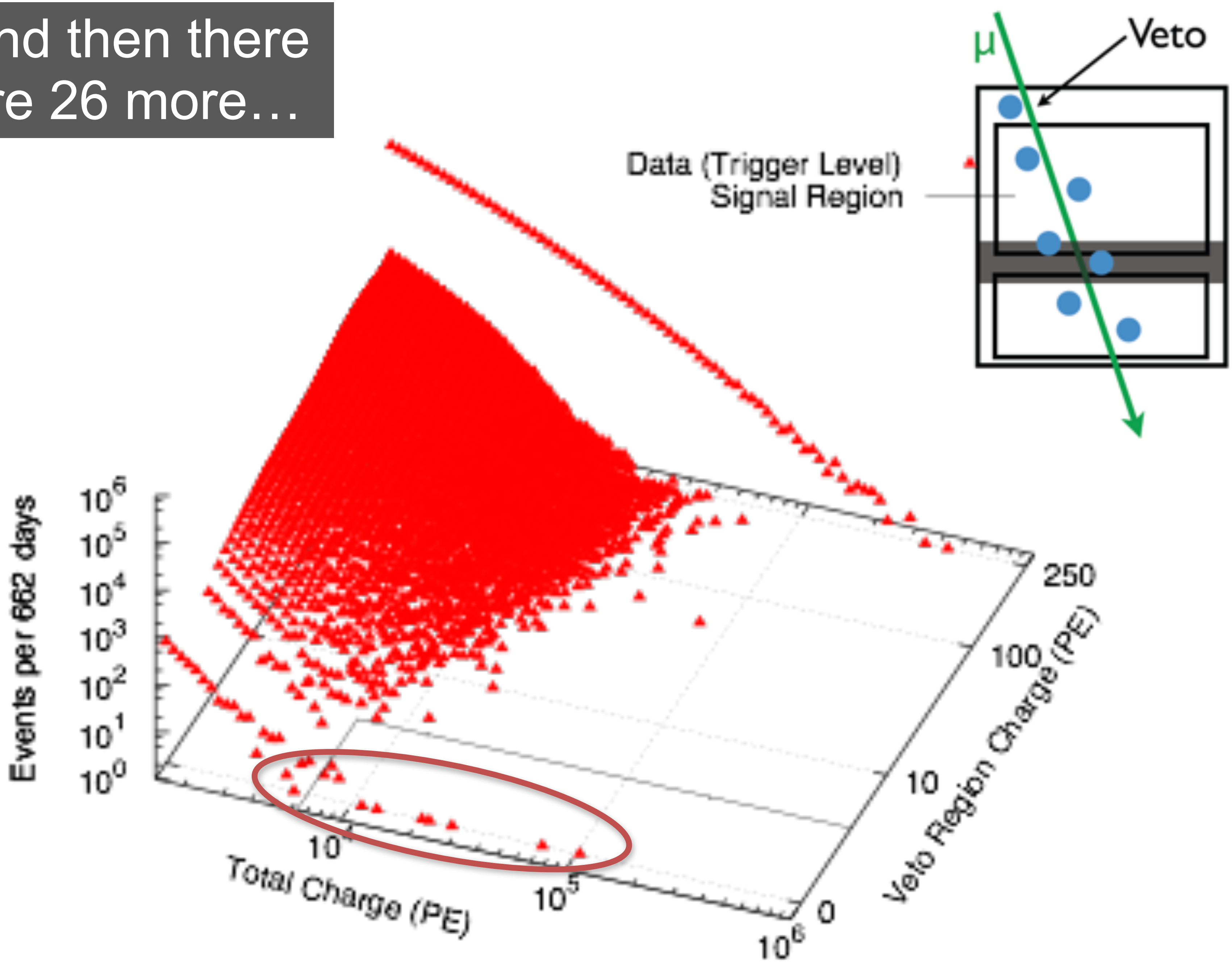
# astronomy here: through-going muons with resolution $0.2 \sim 0.4^0$





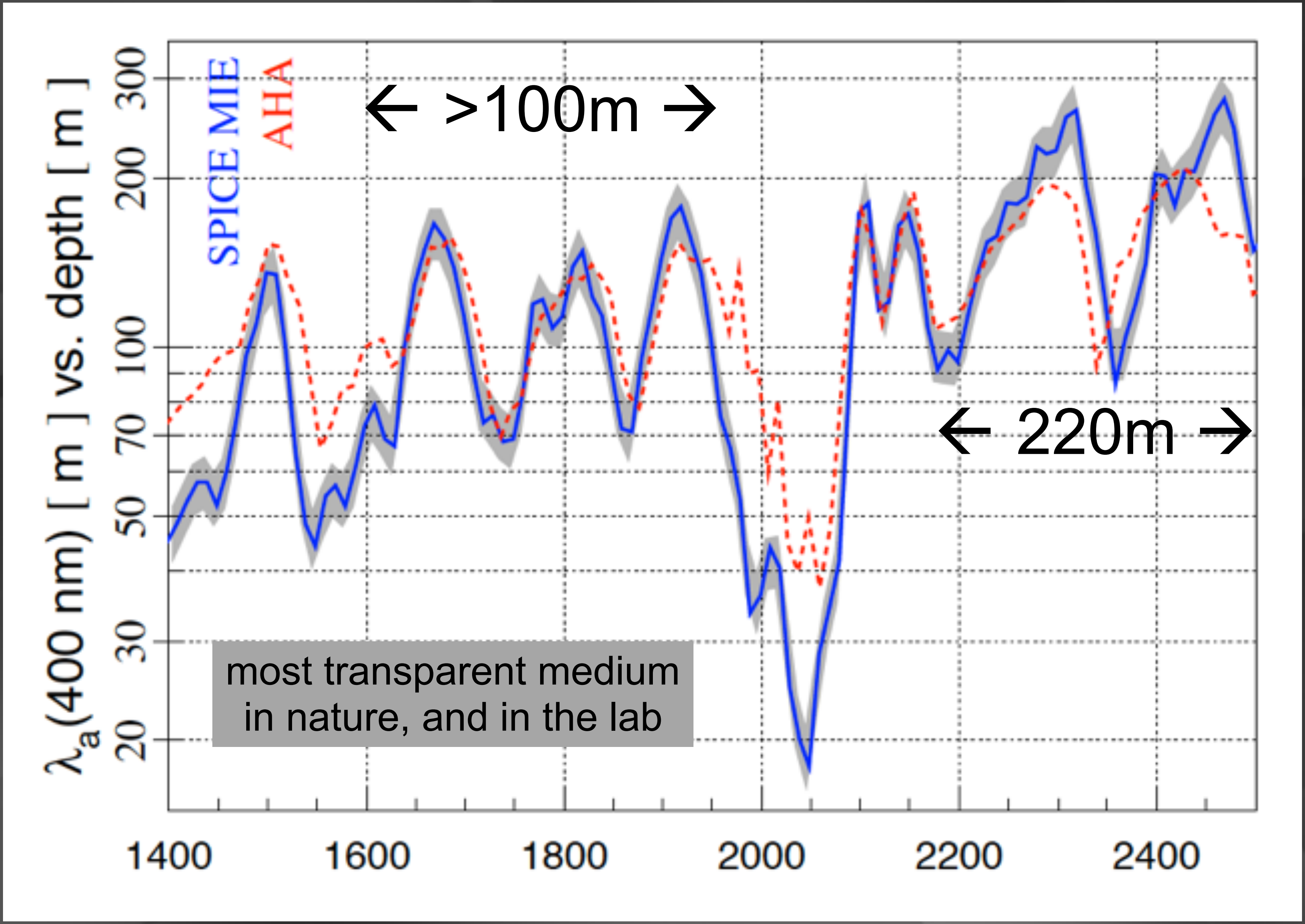
Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
microseconds

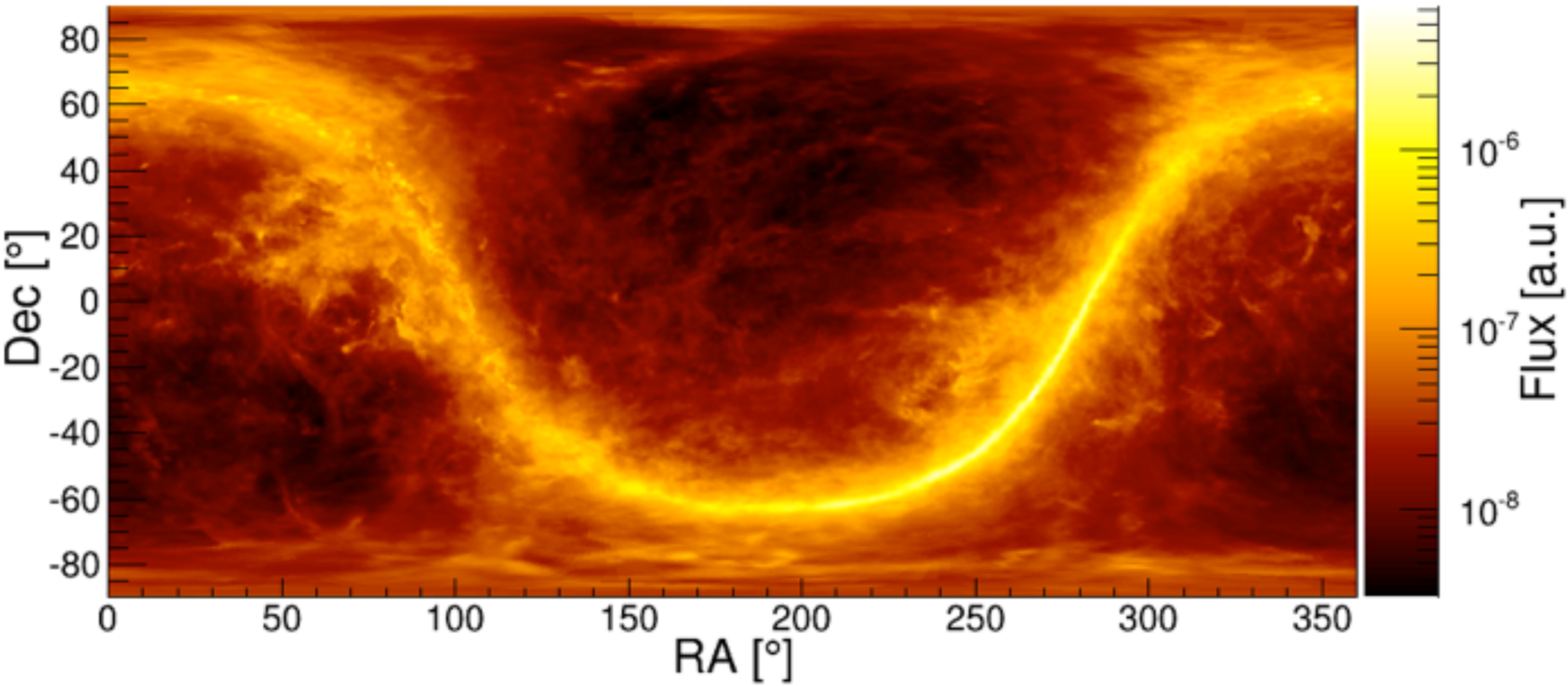
…and then there were 26 more…

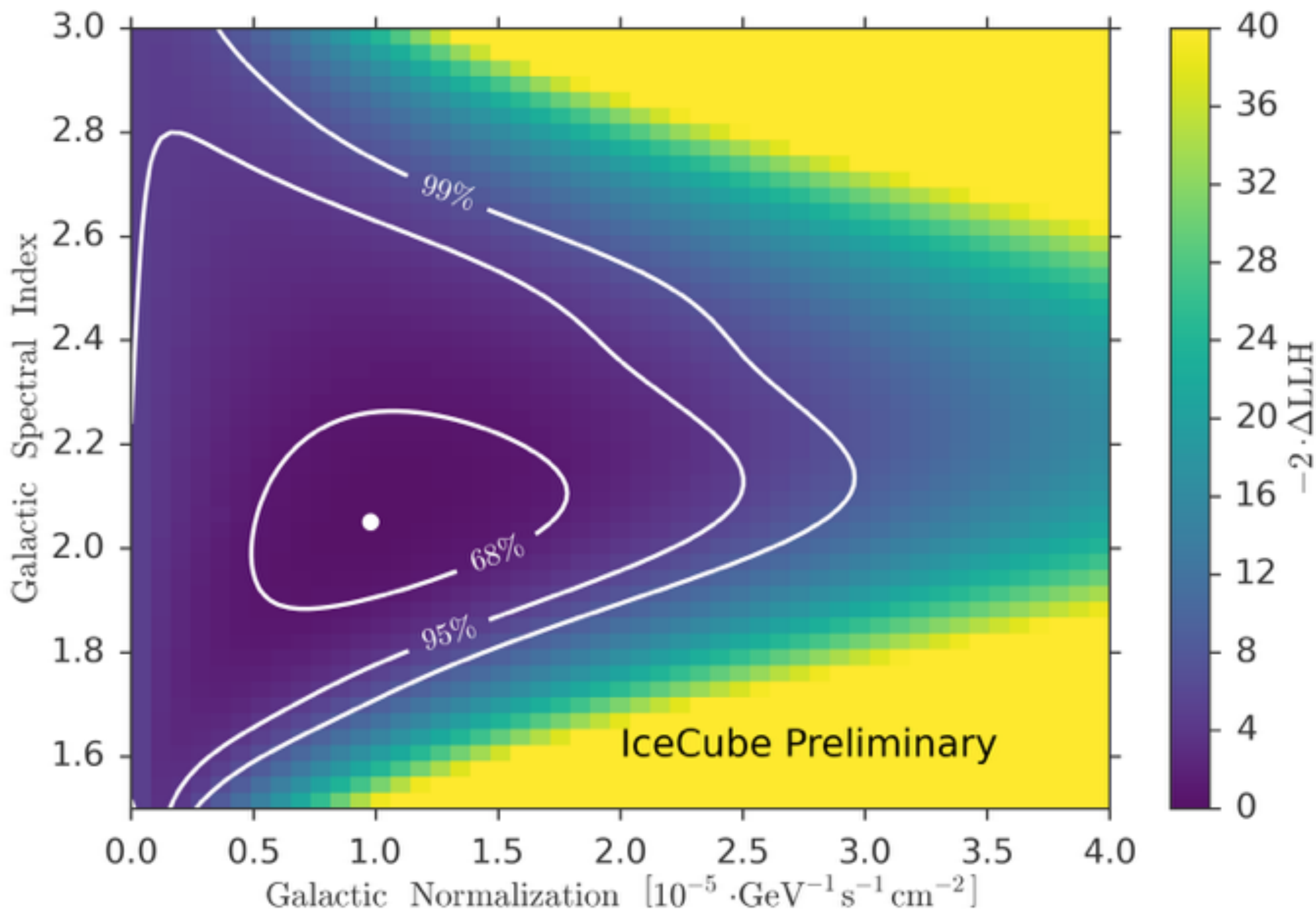



data: 86 strings one year

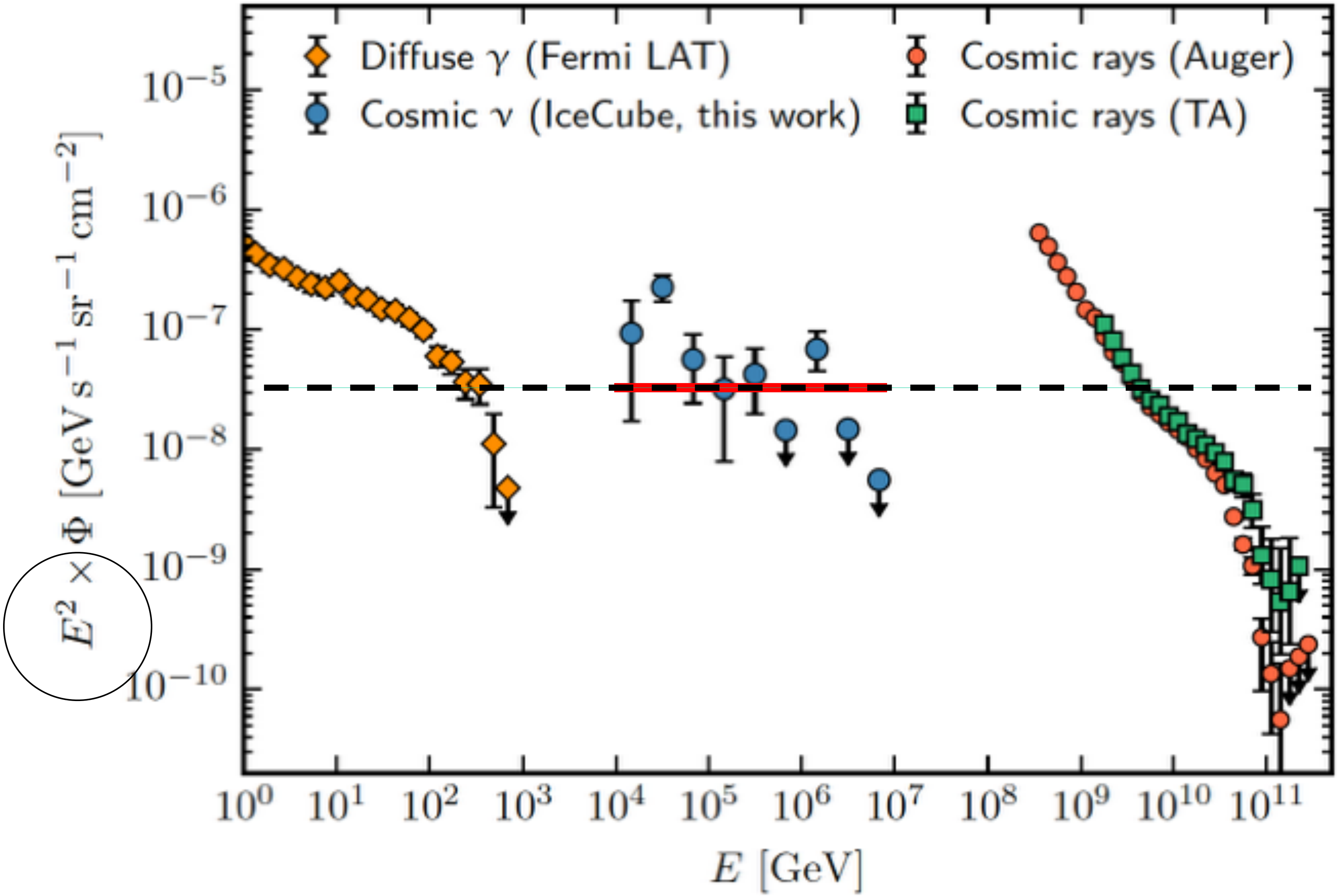
# absorption length of Cherenkov light



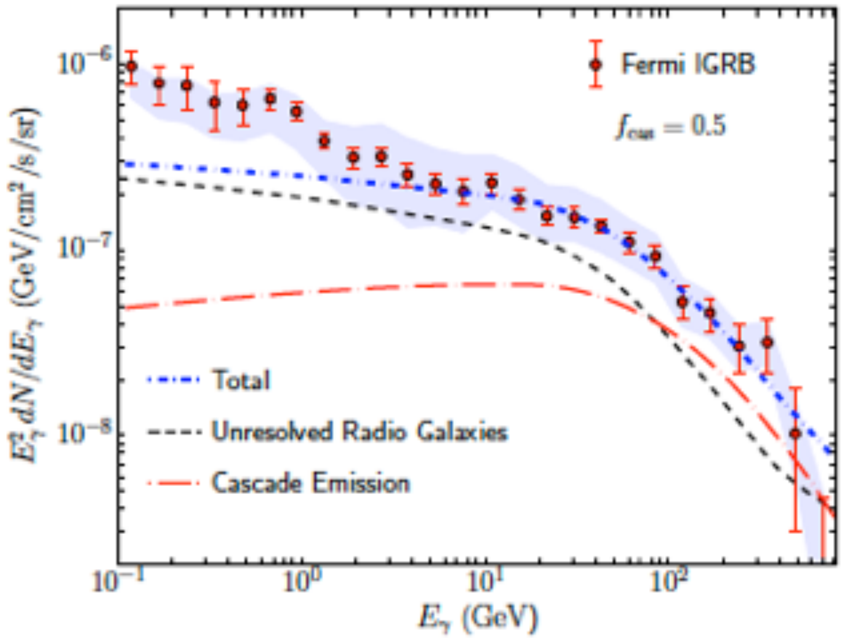

80
60
40
20
0
-20
-40
-60
-80
Dec [°]
0
50
100
150
200
250
300
350
RA [°]
$10^{-6}$
$10^{-7}$
$10^{-8}$
Flux [a.u.]

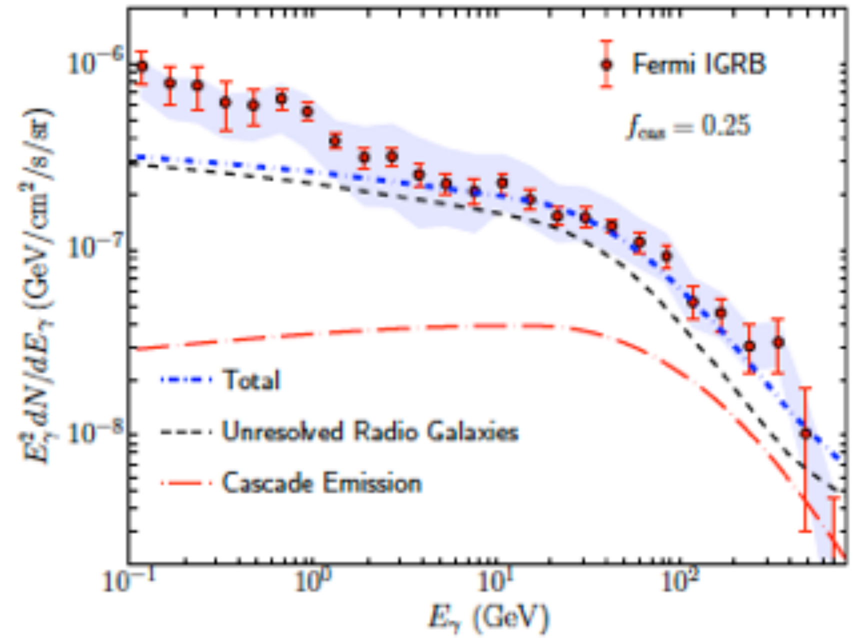


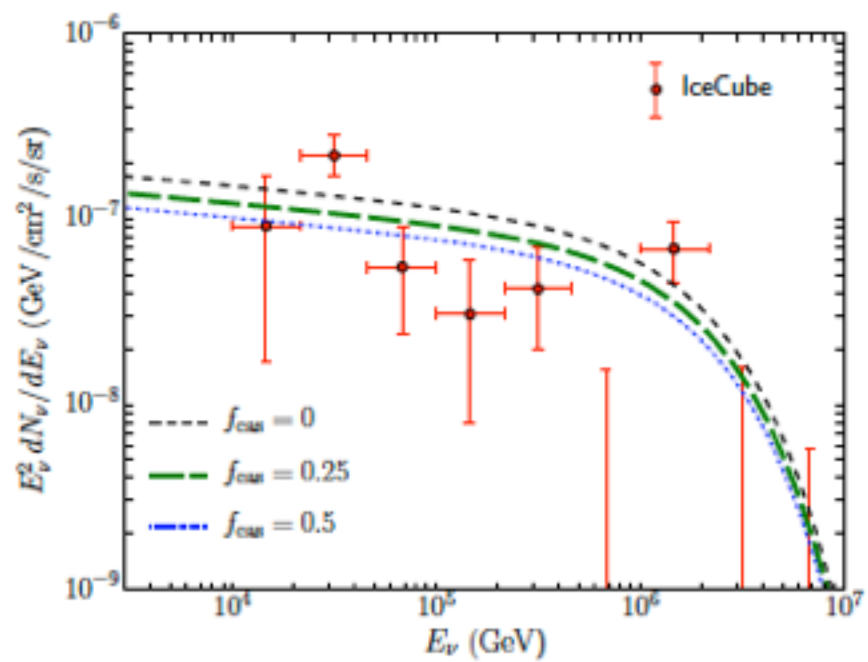
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
Galactic Spectral Index
99%
95%
68%
IceCube Preliminary
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Galactic Normalization [$10^{-5}\cdot\mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}$]
40
36
32
28
24
20
16
12
8
4
0
$-2\cdot\Delta\mathrm{LLH}$




energy in the Universe in gamma rays, neutrinos and cosmic rays



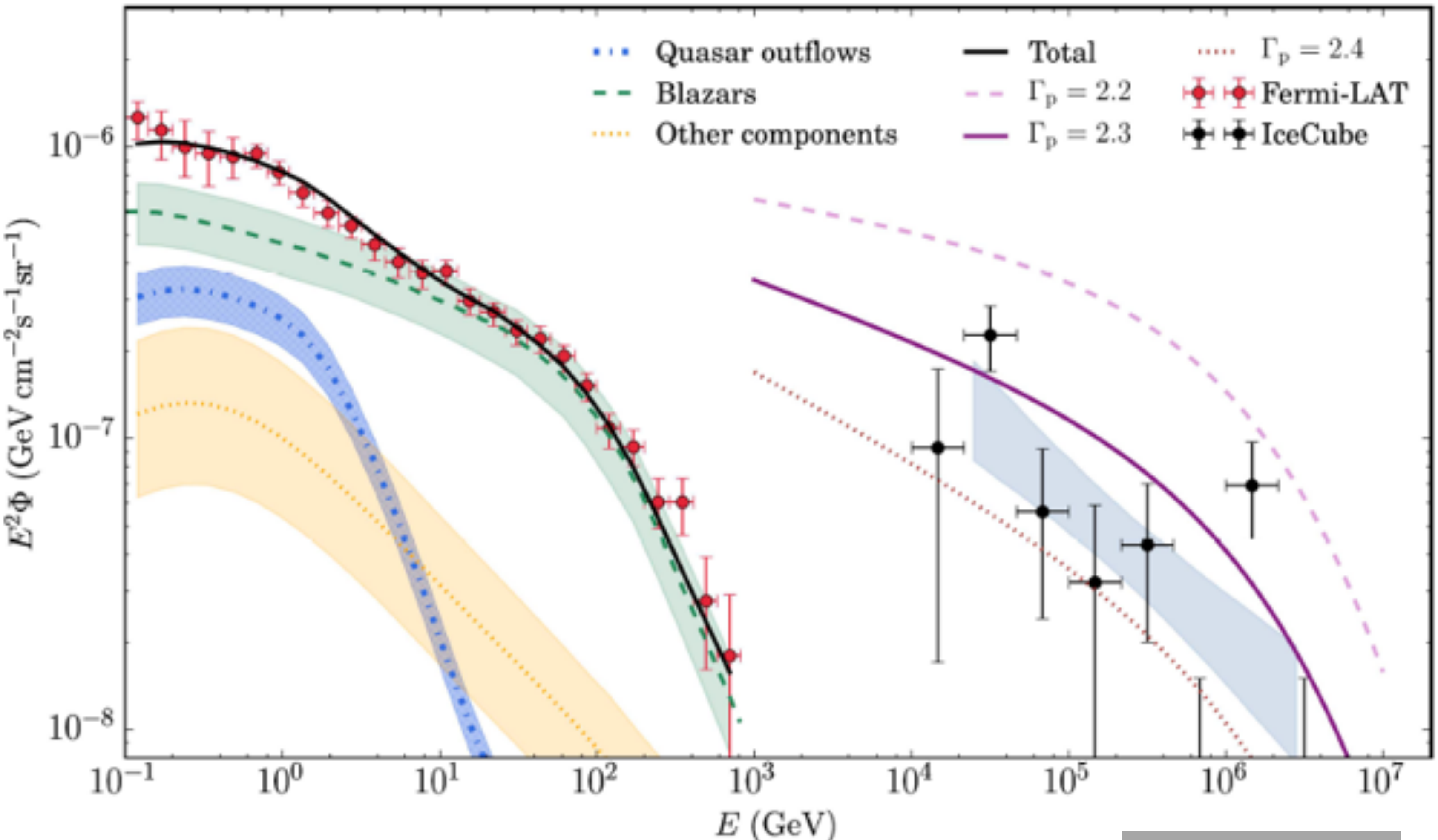




radiogalaxies

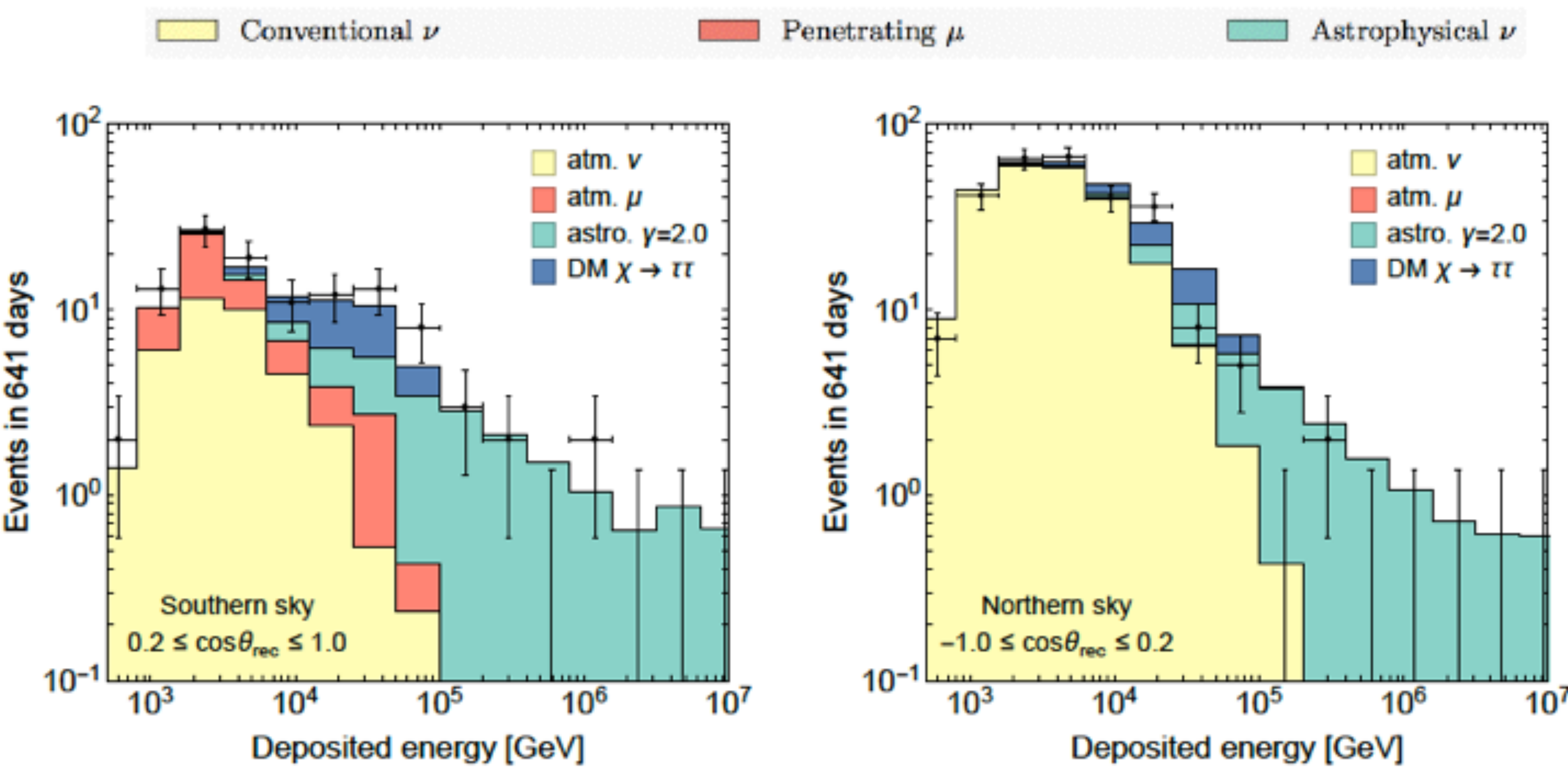
Tjus et al.

Hooper




quasars
Loeb

# towards lower energies: a second component?




warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth