IceCube and Multimessenger Astronomy

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- other multiwavelength observations
- cosmic neutrinos below 100 TeV?
- the Galaxy

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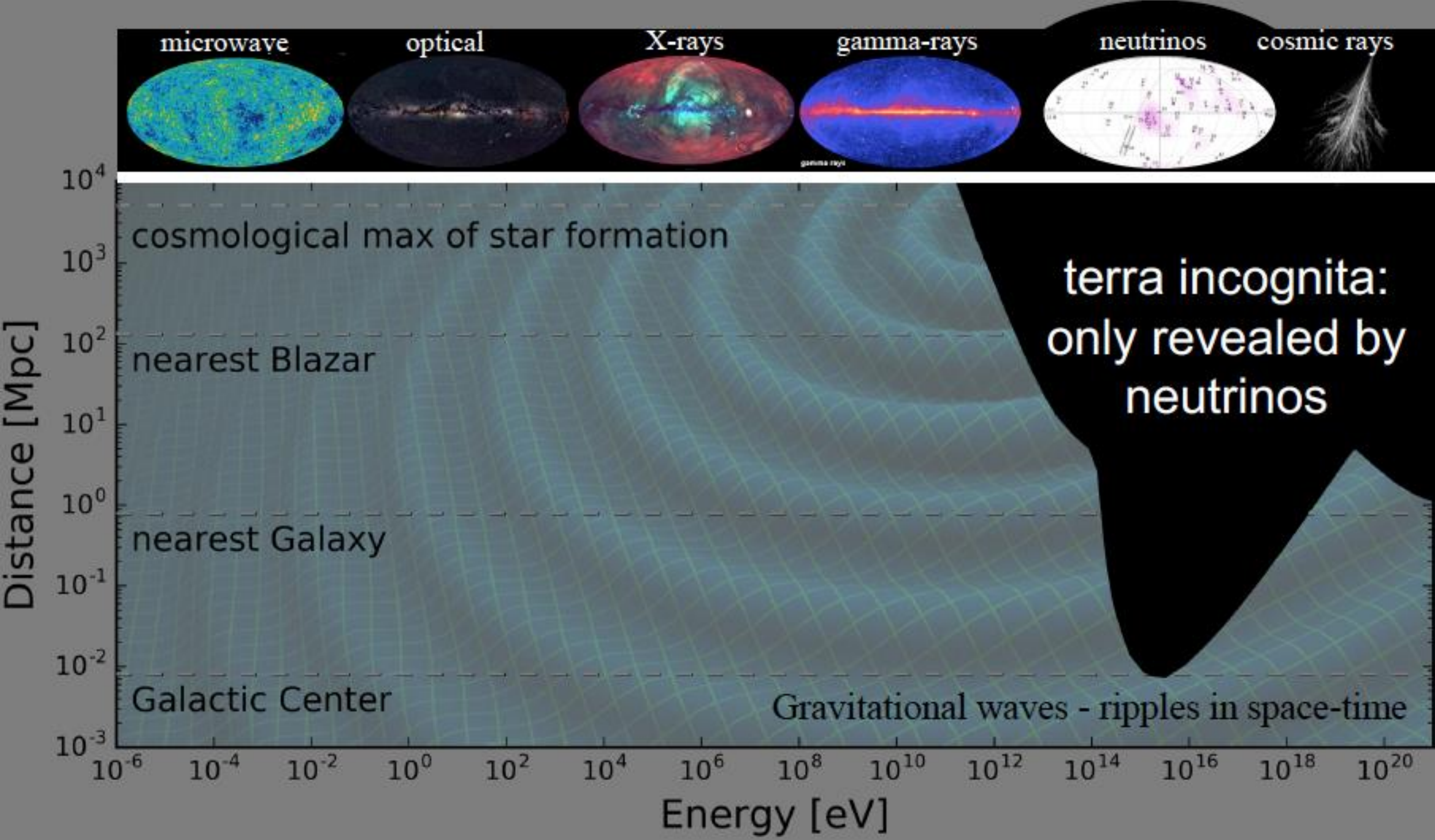
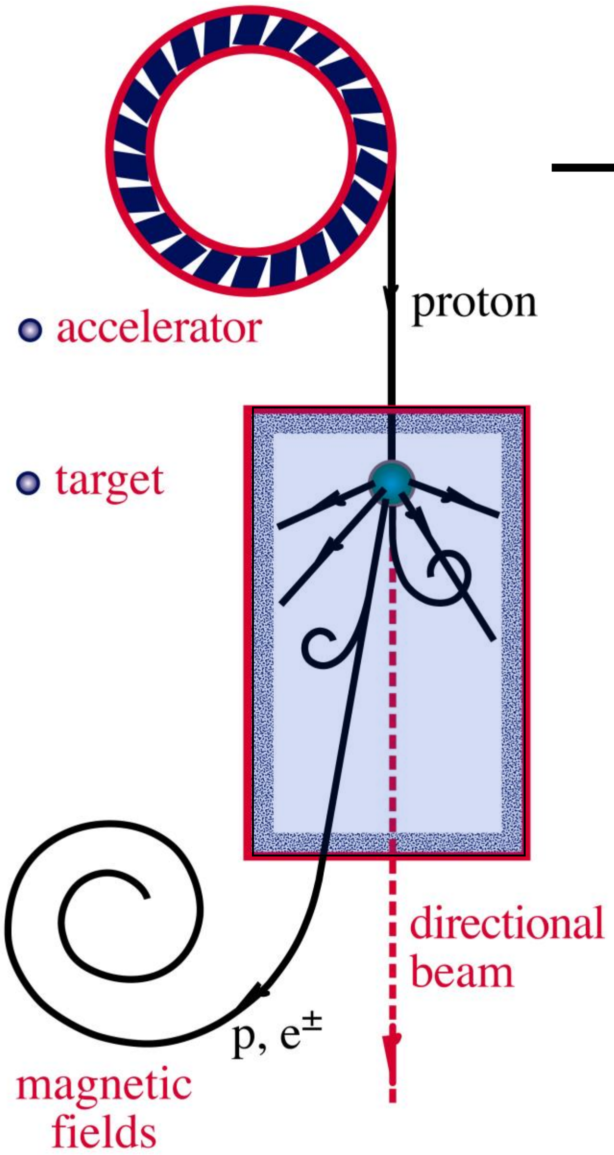


- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

ν and γ 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

neutral pions

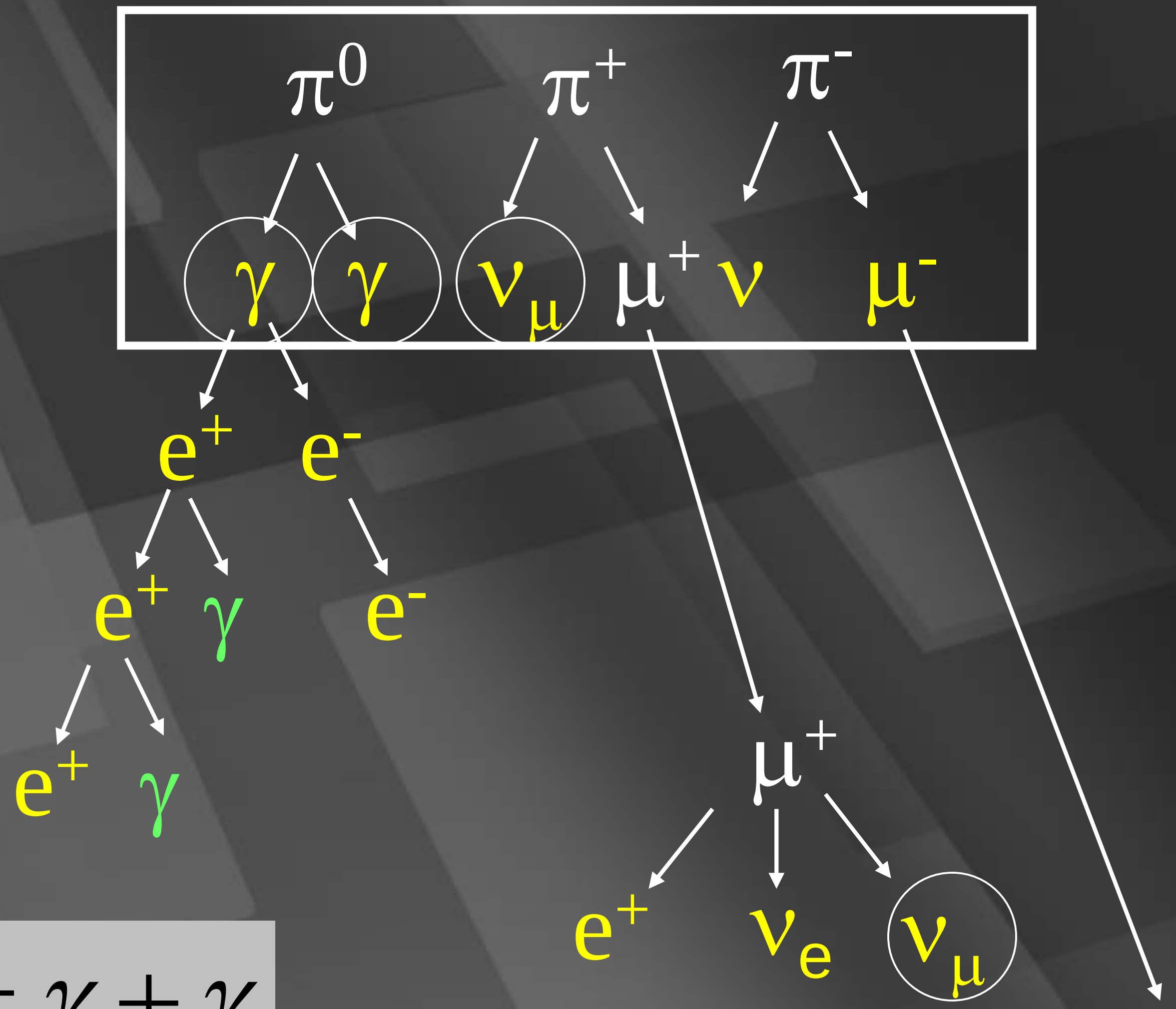
are observed as

gamma rays

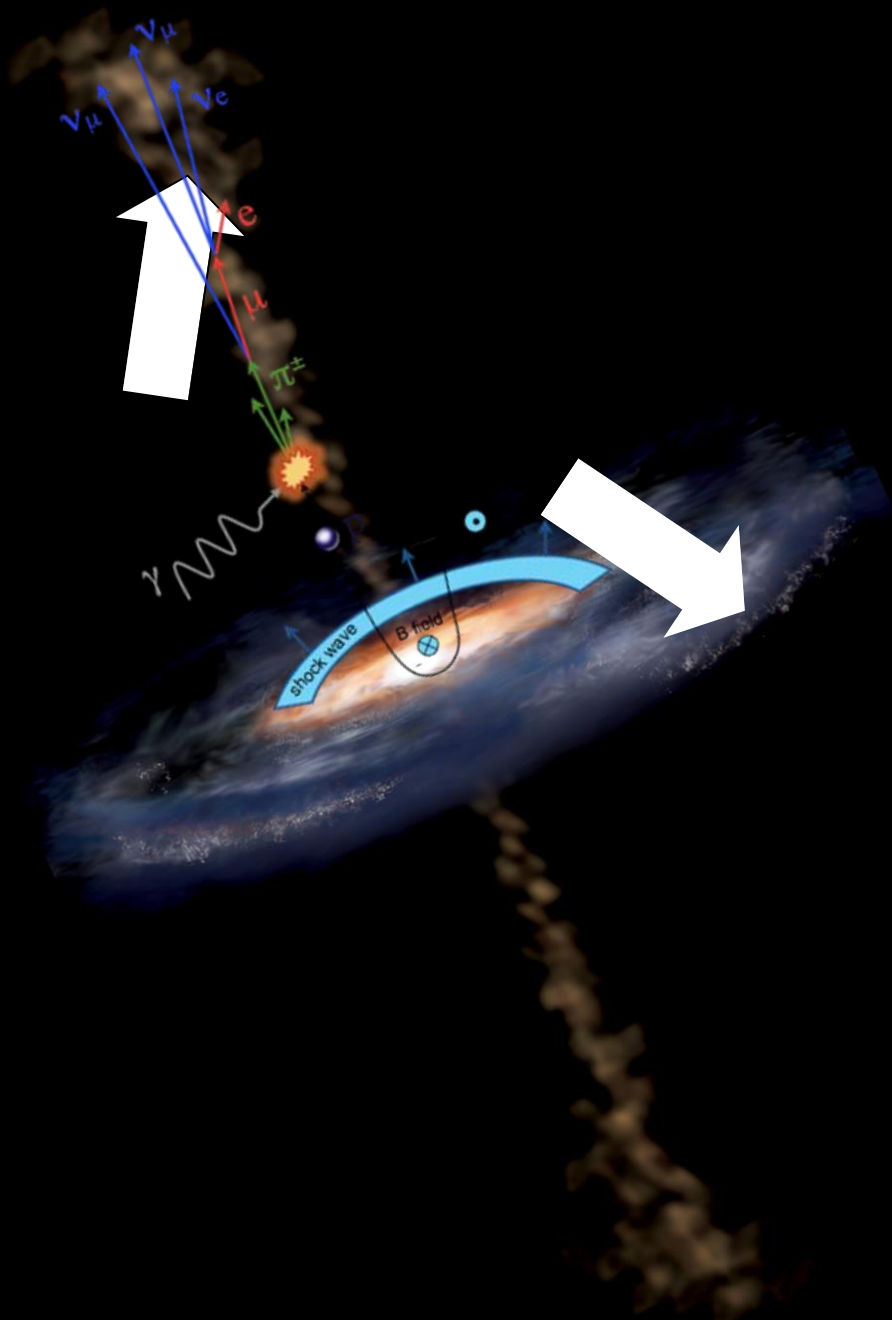
charged pions

are observed as

neutrinos

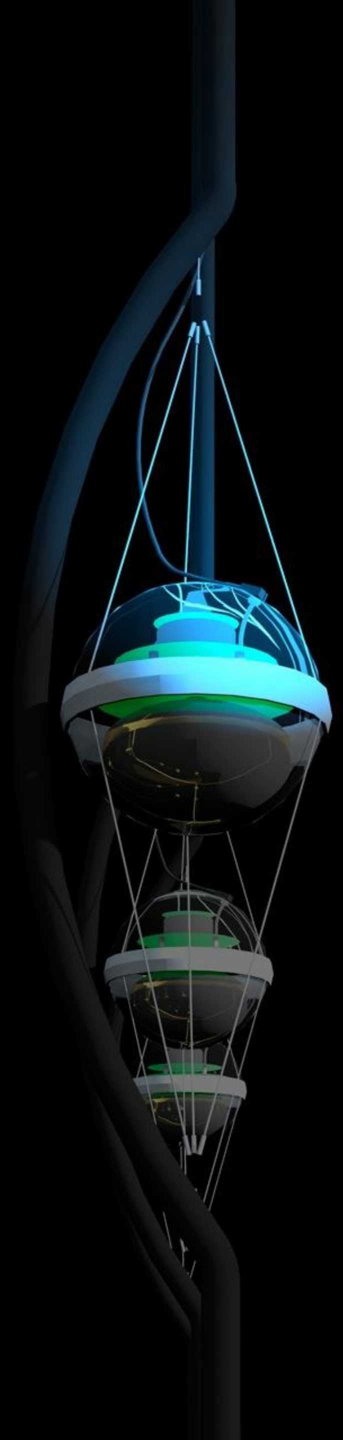


$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$



active galaxy

particle flows near supermassive black hole



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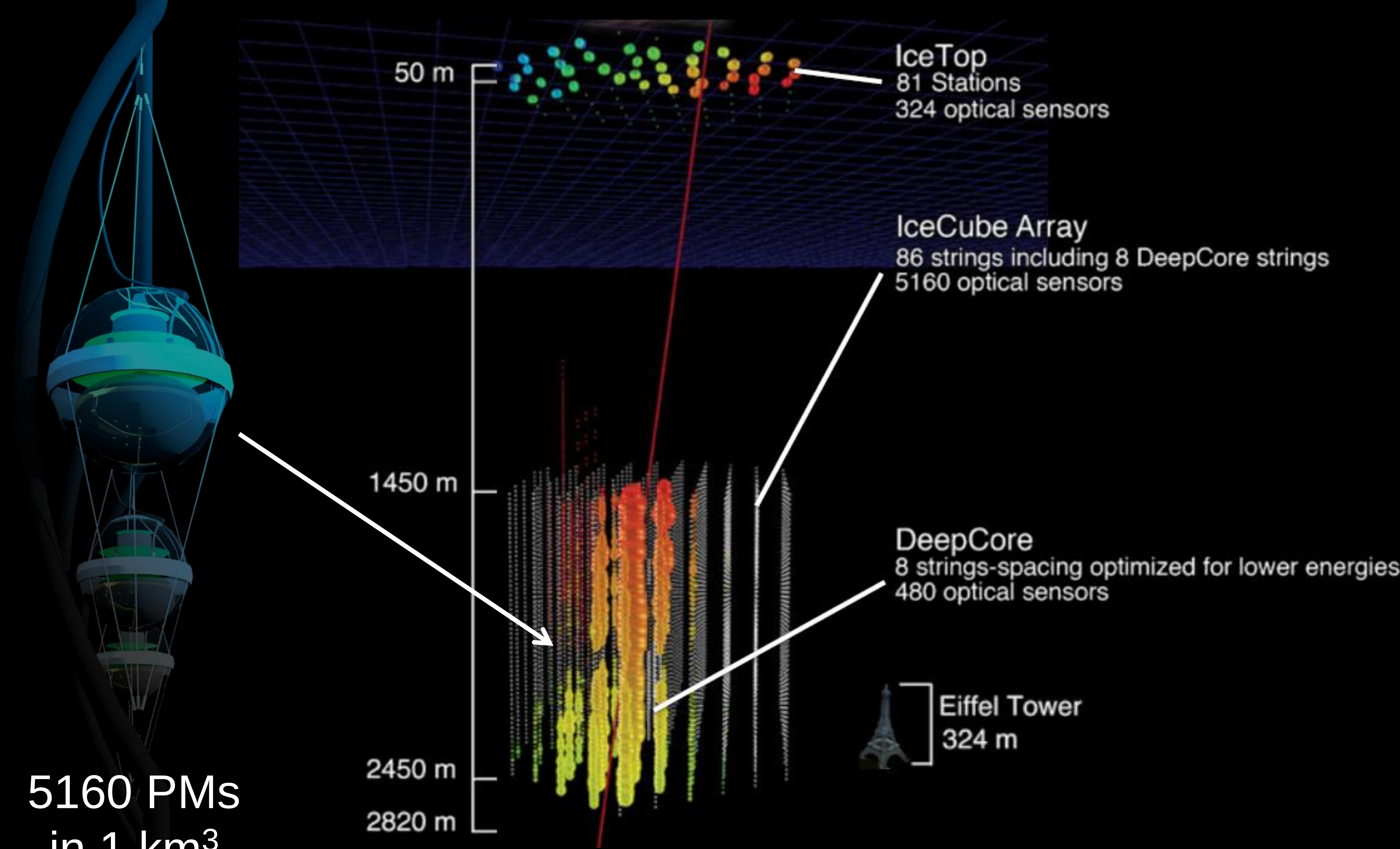
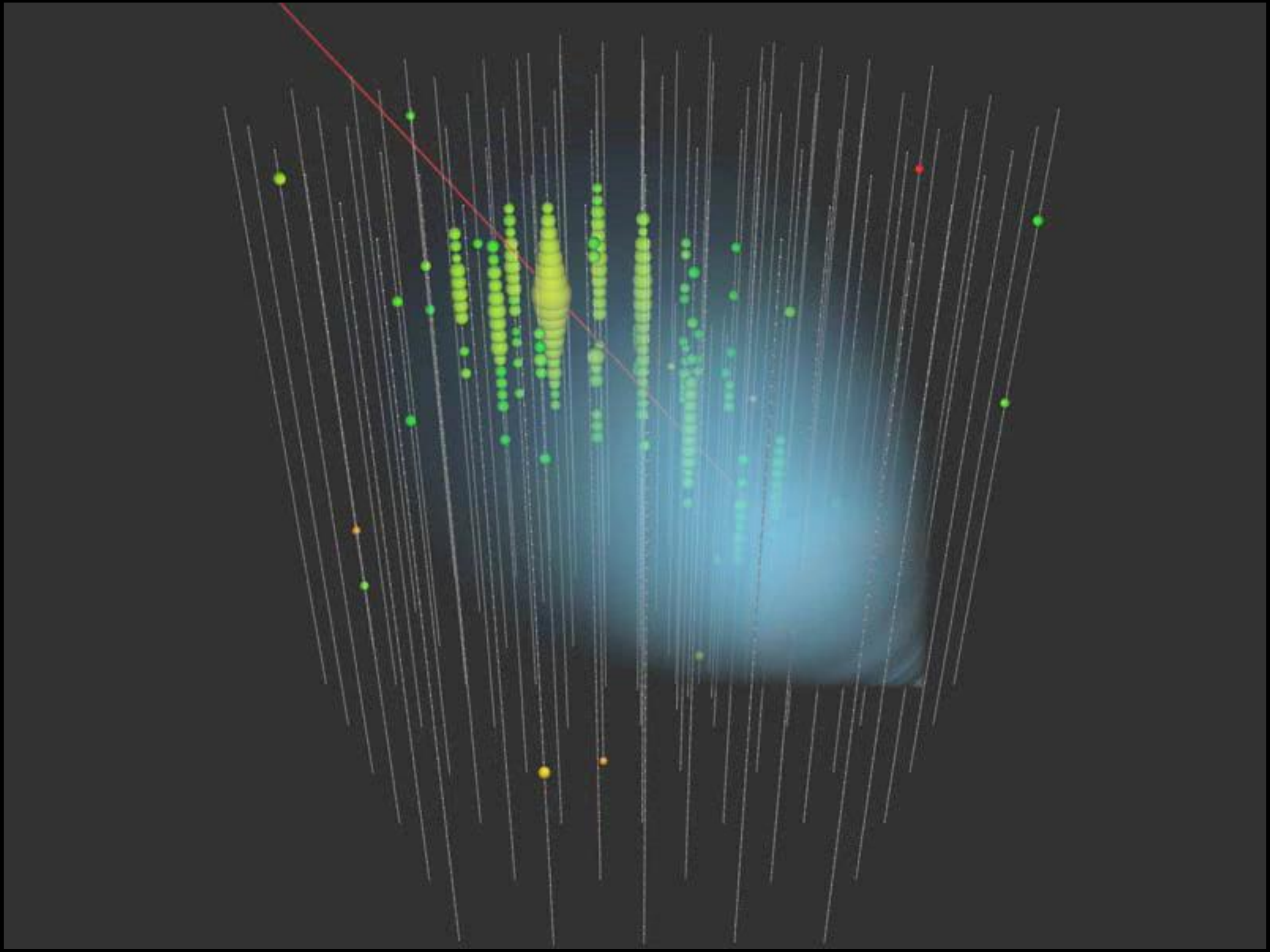
ultra-transparent ice below 1.5 km

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:

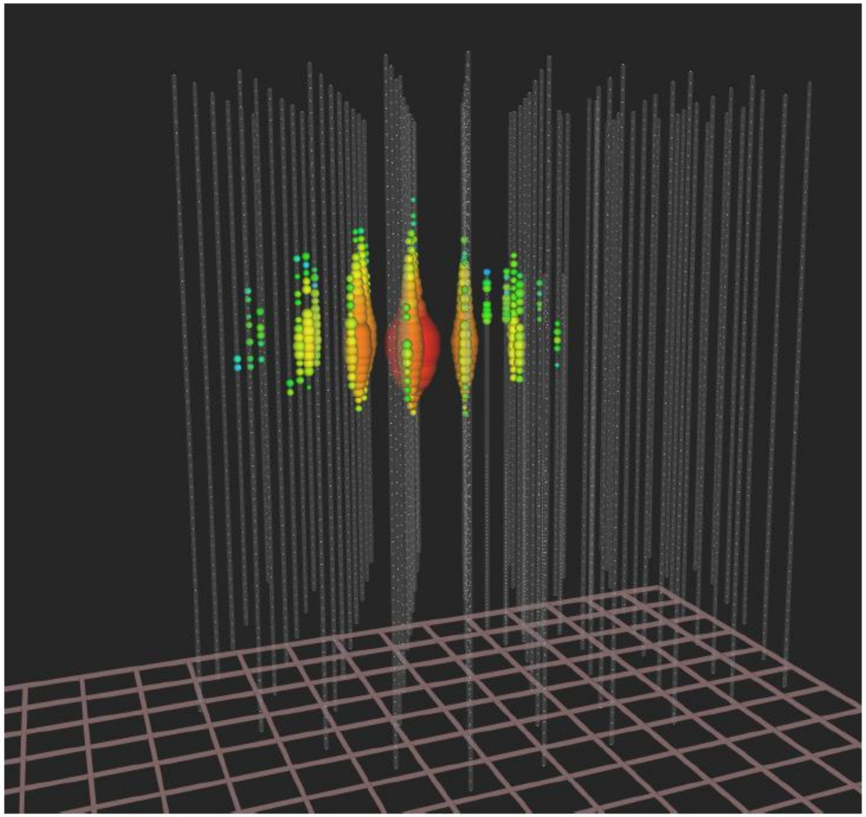
• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	$\sim 10\text{-}10^{2}$

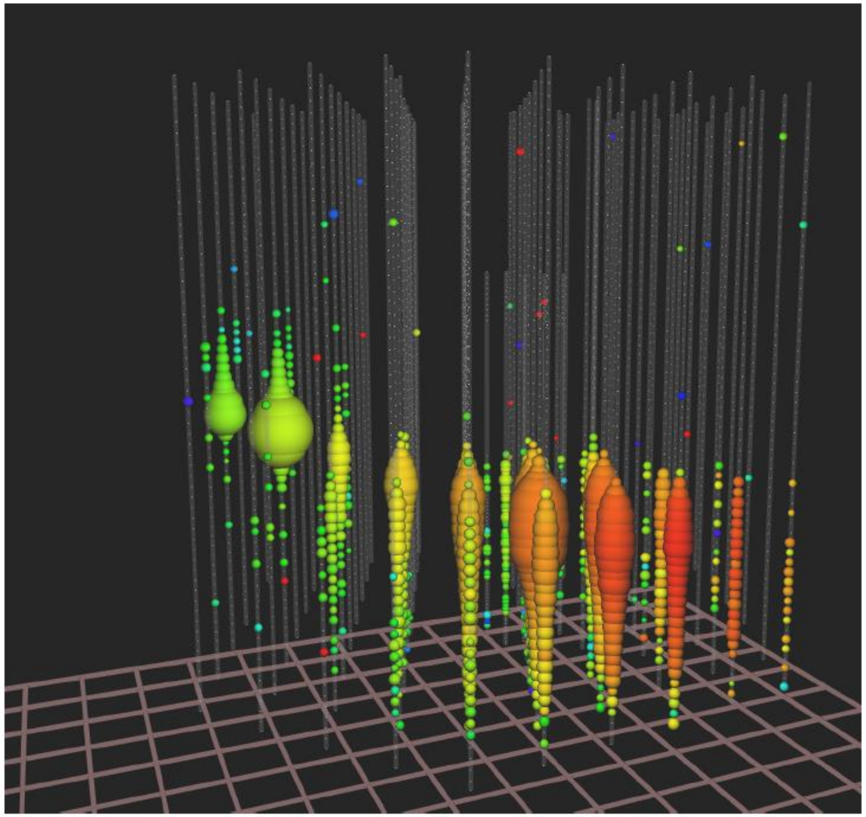
* 3000 per second

** 1 every 6 minutes

isolated neutrinos interacting *inside* the detector (HESE)

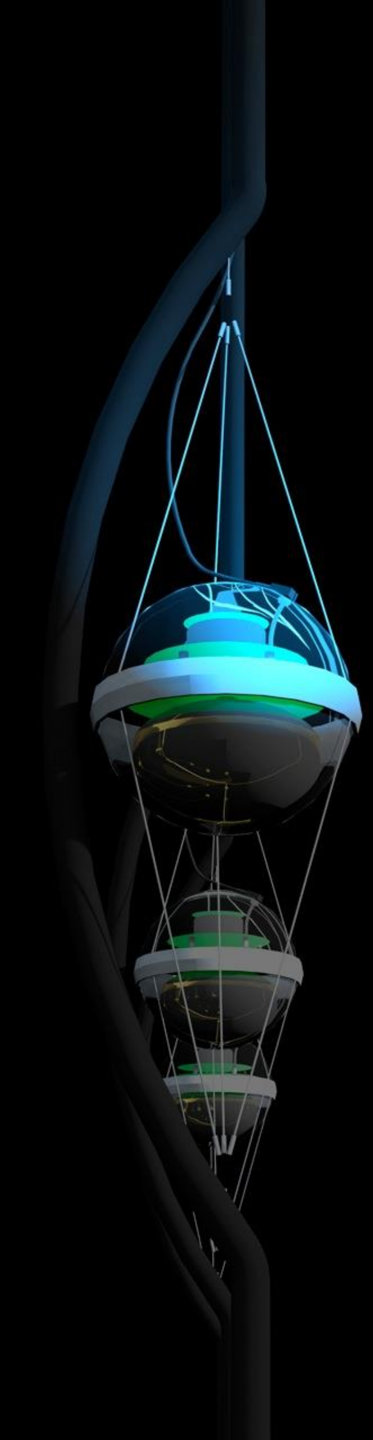
up-going muon tracks (UPMU)





total energy measurement
all flavors, all sky

astronomy: angular resolution superior (<0.5º)



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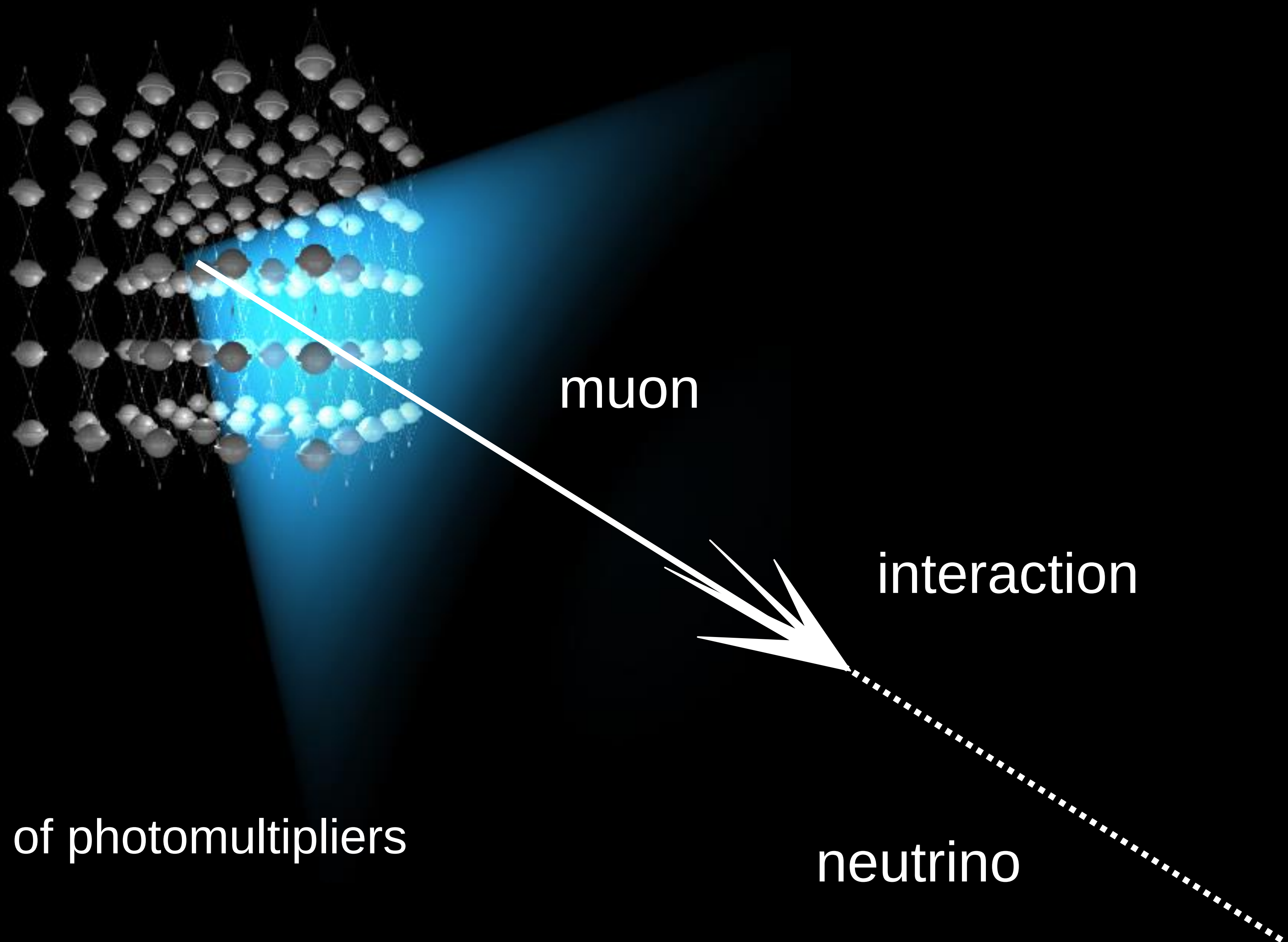
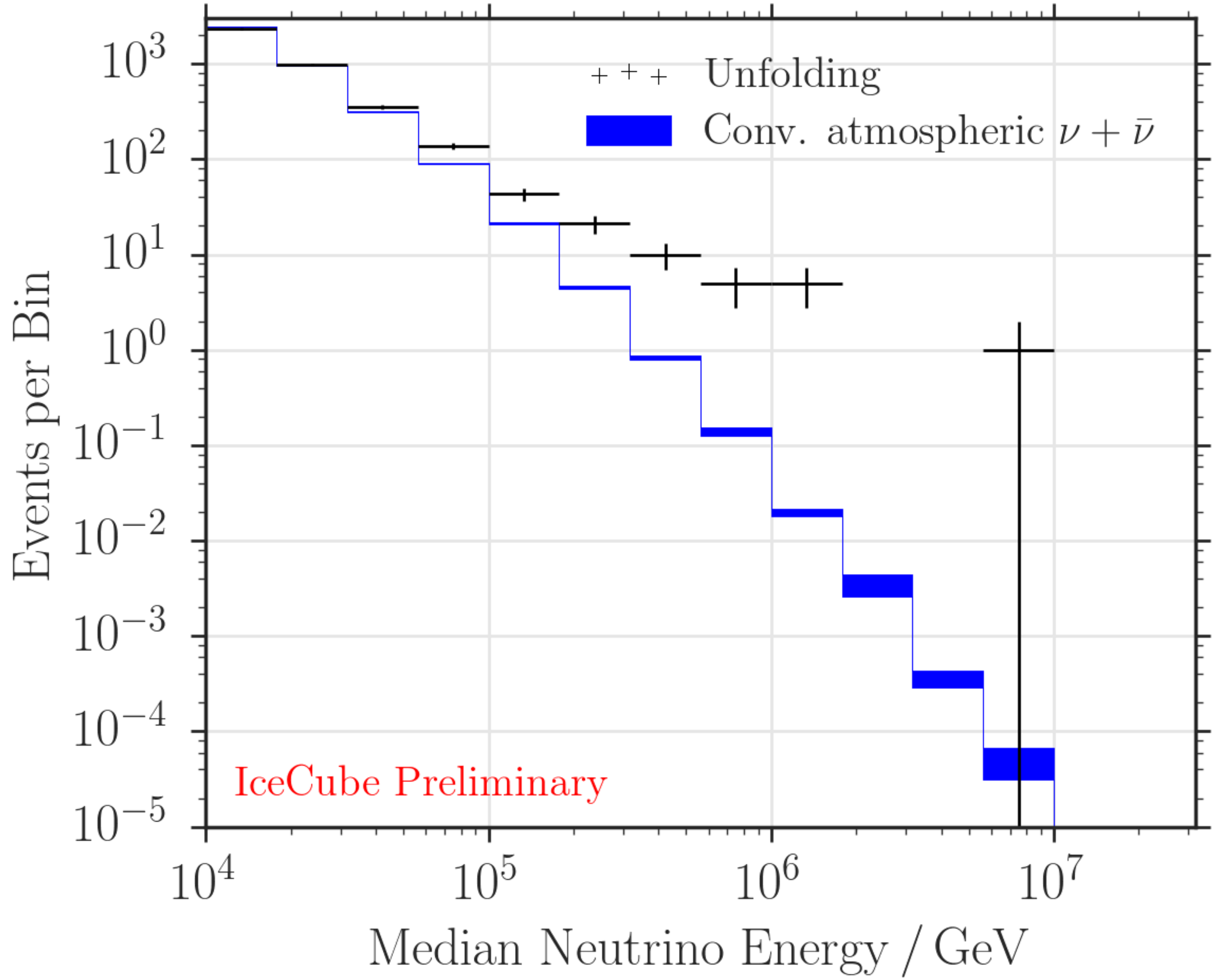


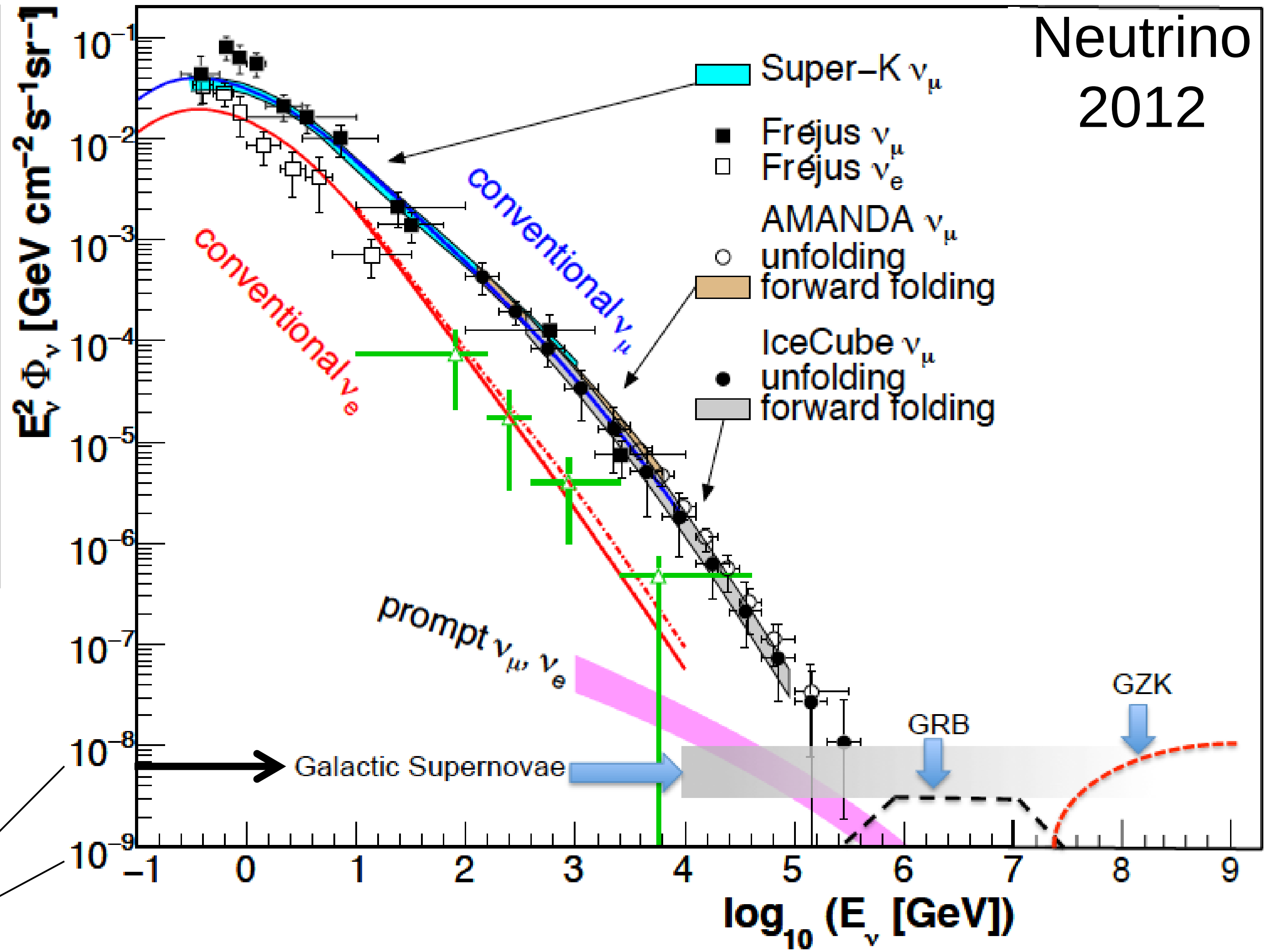
• lattice of photomultipliers

muon neutrinos through the Earth → 6.4 sigma



above 100 TeV

- cosmic neutrinos
- atmospheric background disappears



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

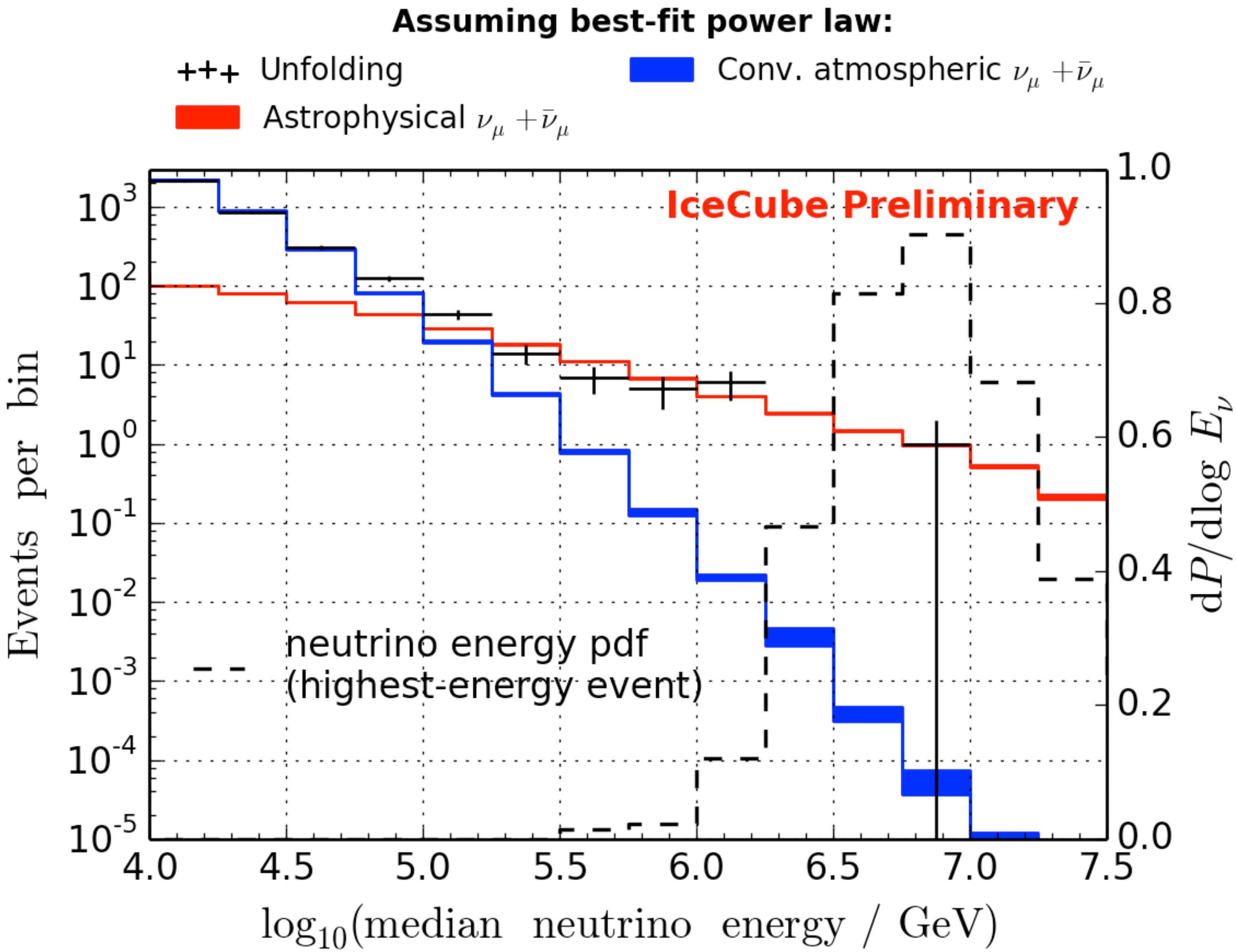
10—100 events per year for fully efficient detector

atmospheric

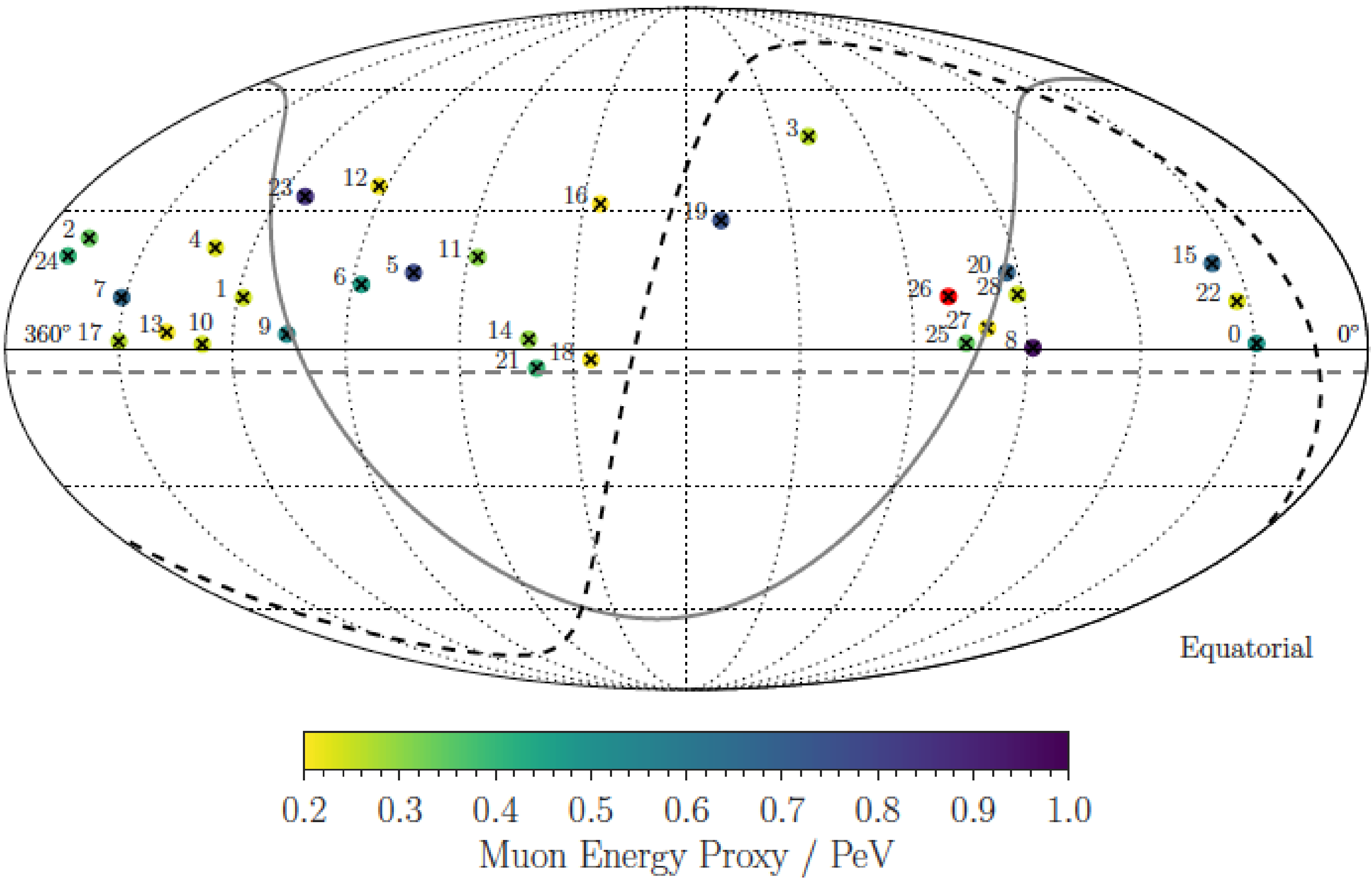
cosmic

100 TeV

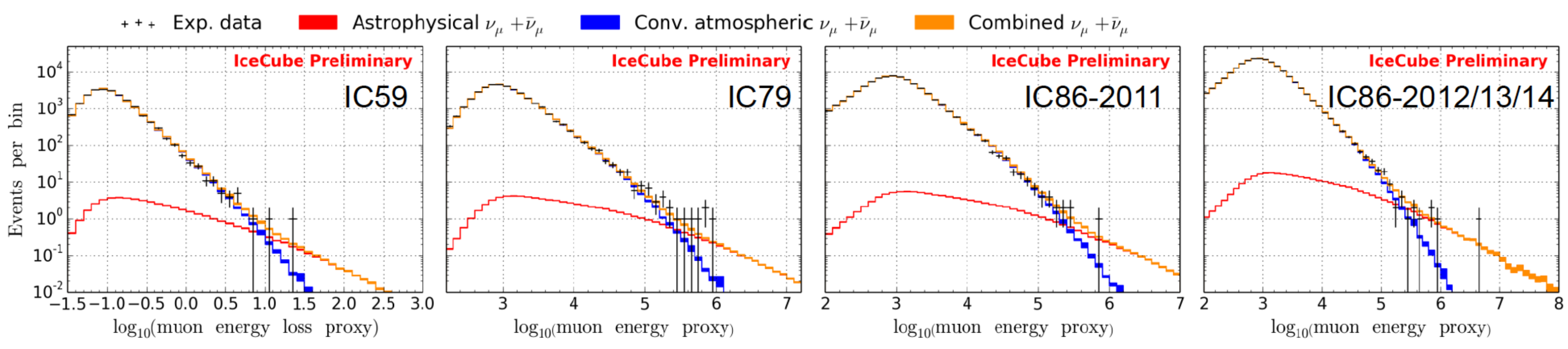
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric
atmospheric background: less than one event/deg^2/year

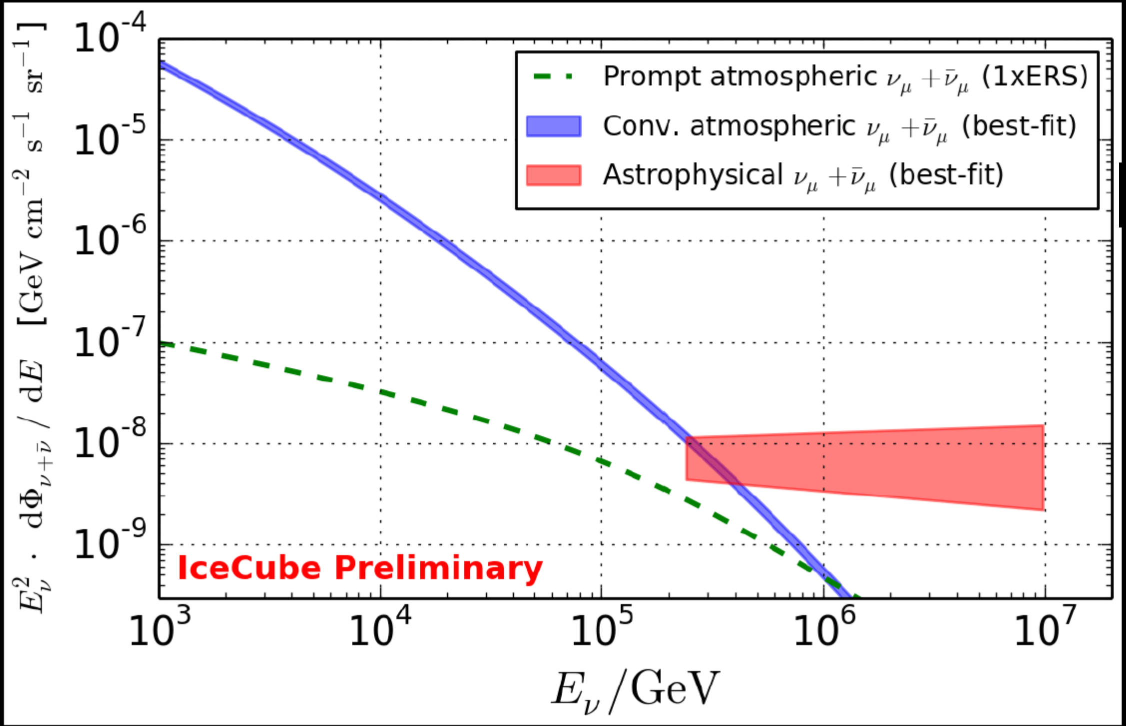


highest energy ν_μ are cosmic:
astronomy with 0.2-0.4 degree resolution !



after 7 years → 6.4 sigma





- Best-fit astrophysical normalization:

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

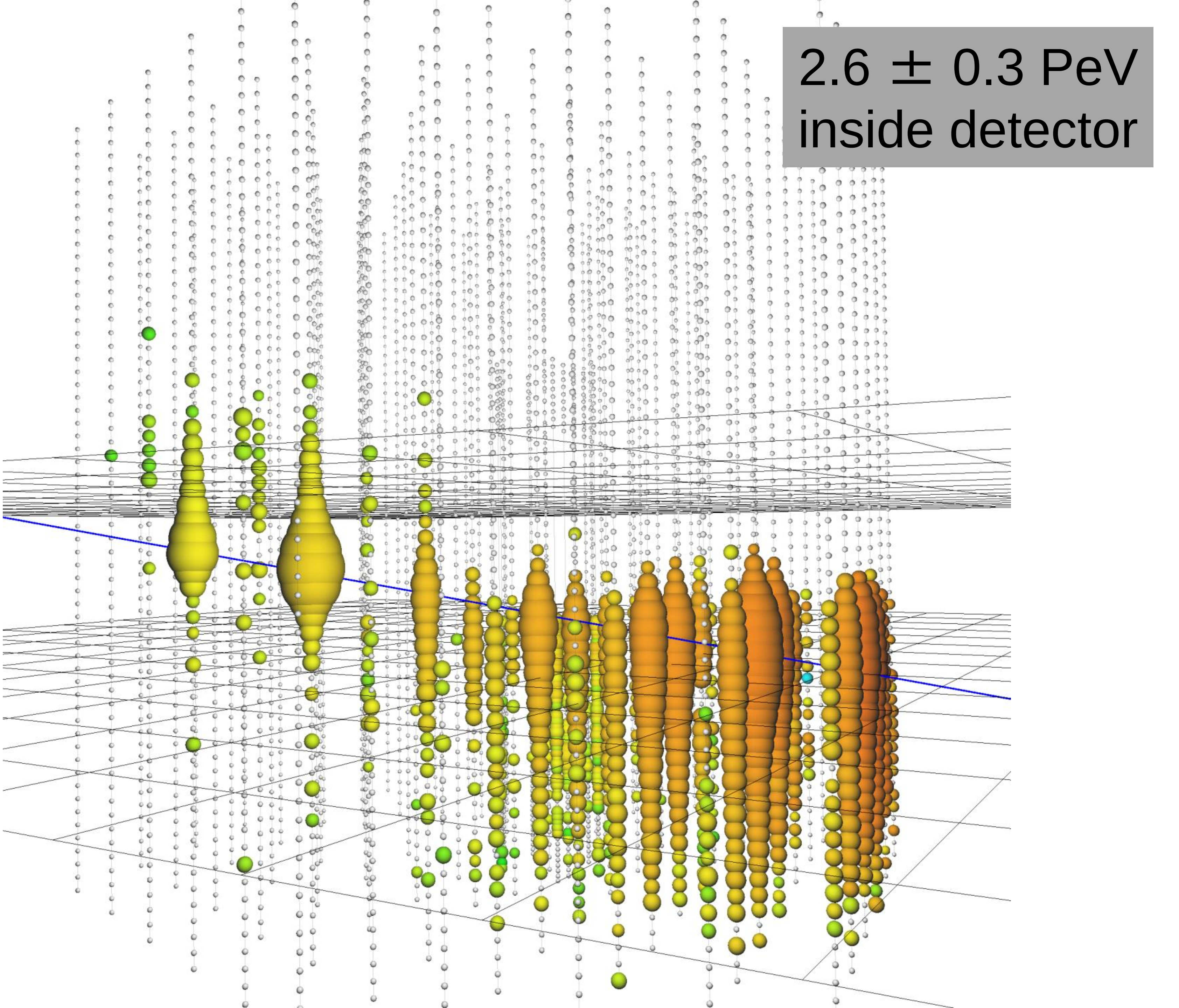
- Best-fit spectral index:

  γ_{astro} = 2.16 ± 0.11

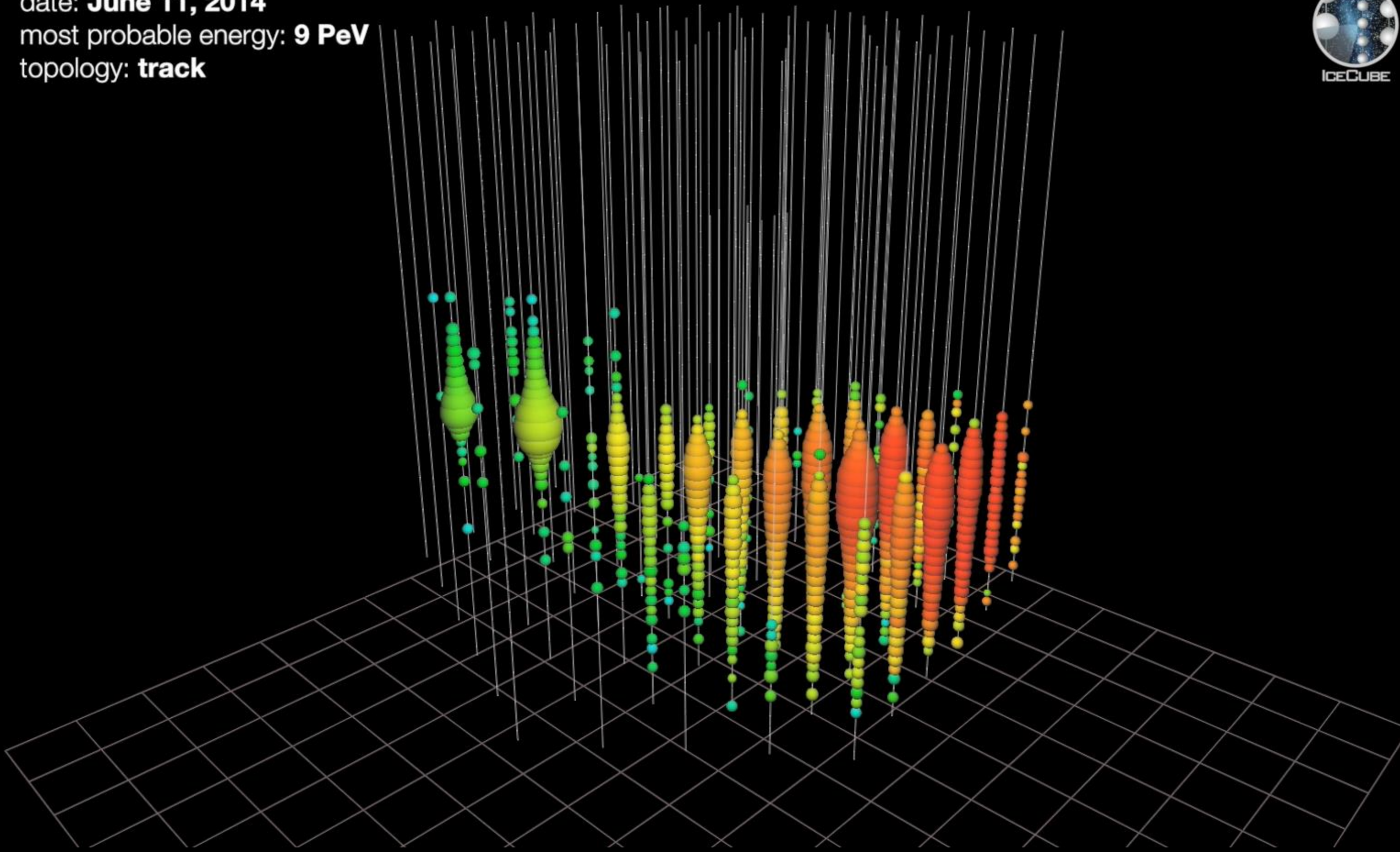
- Energy ranges:

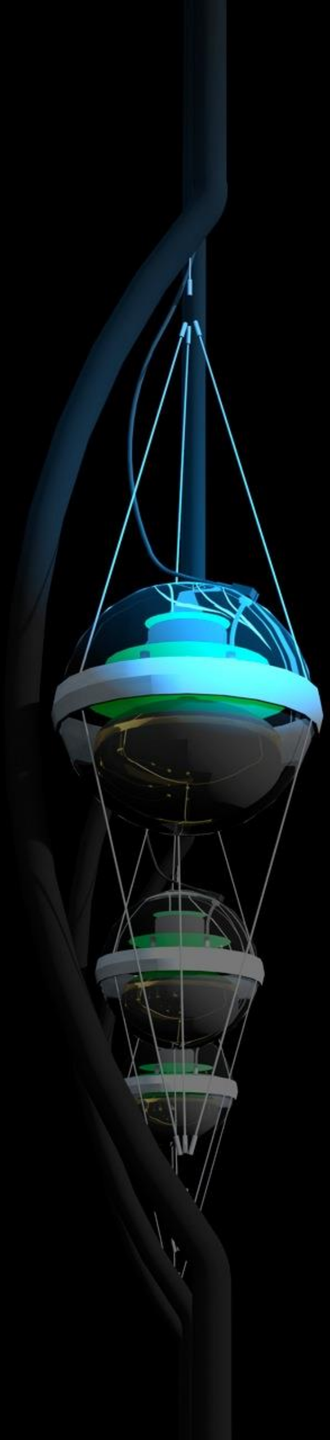
  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ


2.6 ± 0.3 PeV
inside detector

date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**





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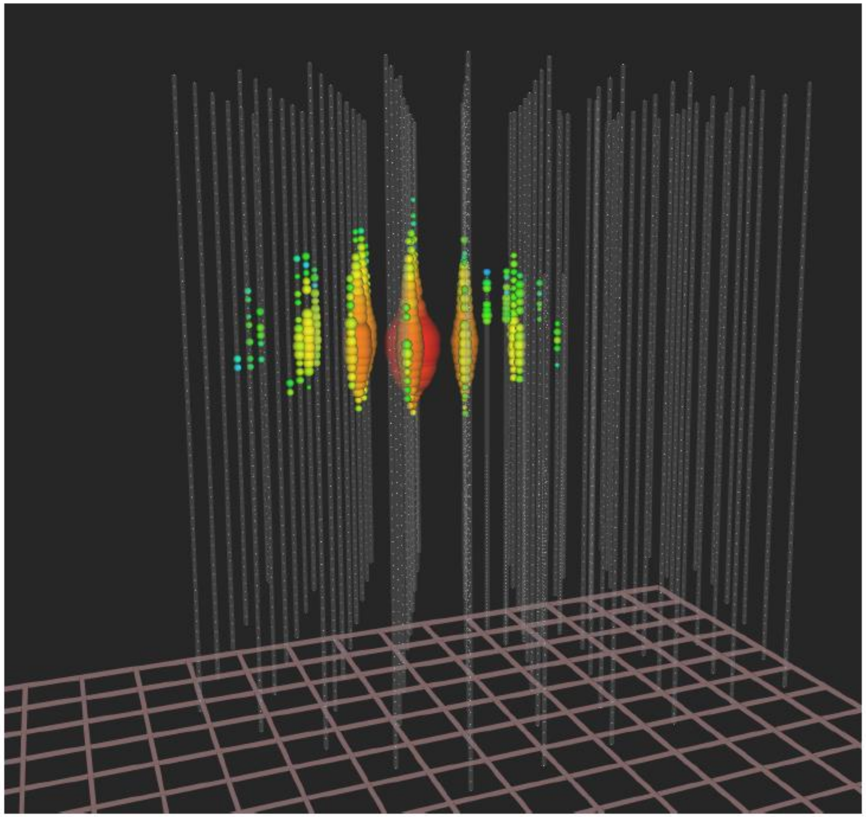
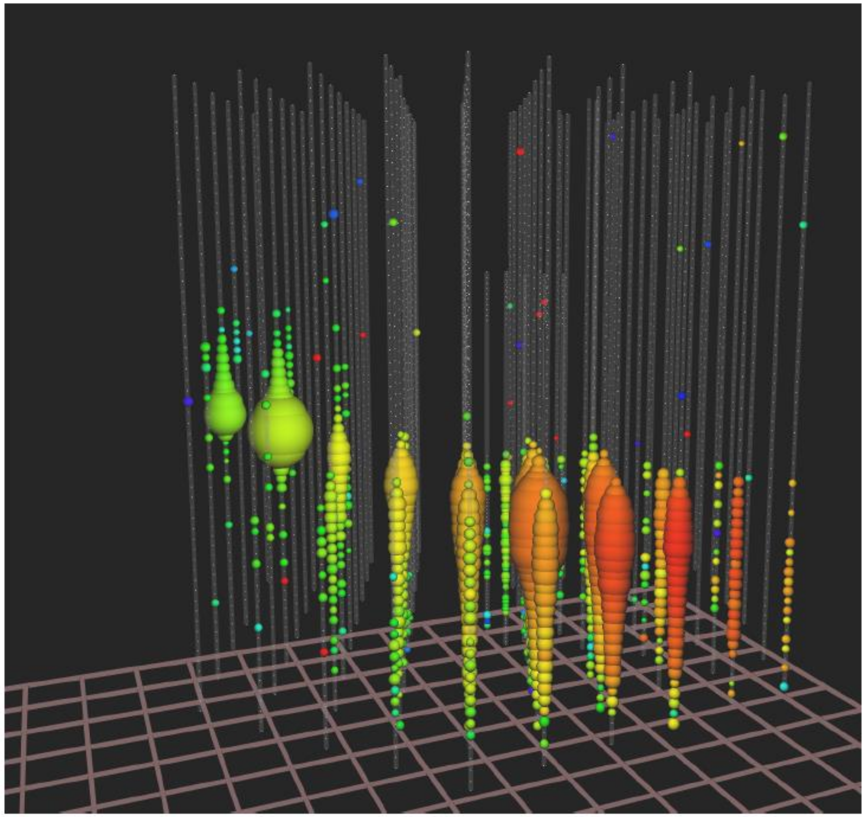
isolated neutrinos interacting inside the detector

up-going muon tracks





calorimetry: direct energy measurement; all flavors

astronomy: angular resolution superior

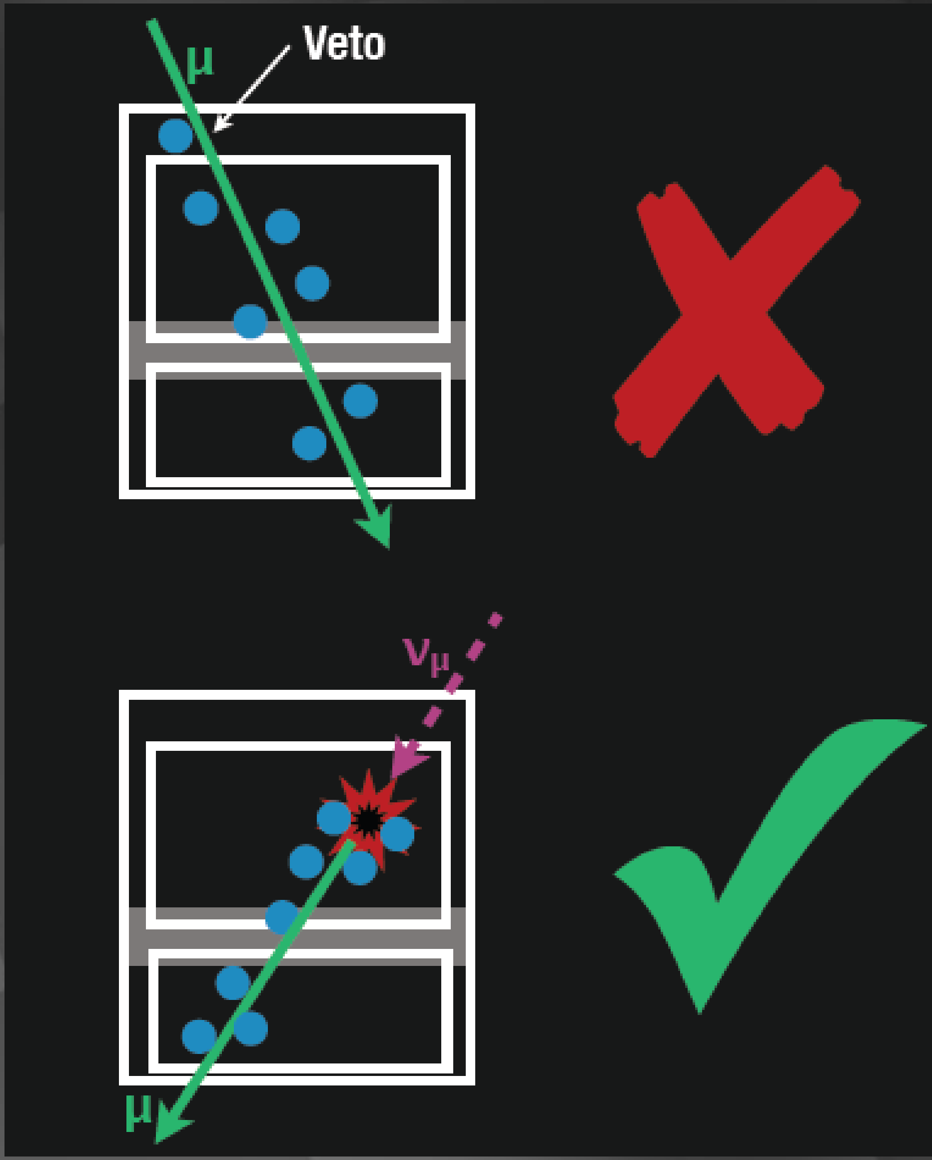
neutrinos starting inside the detector

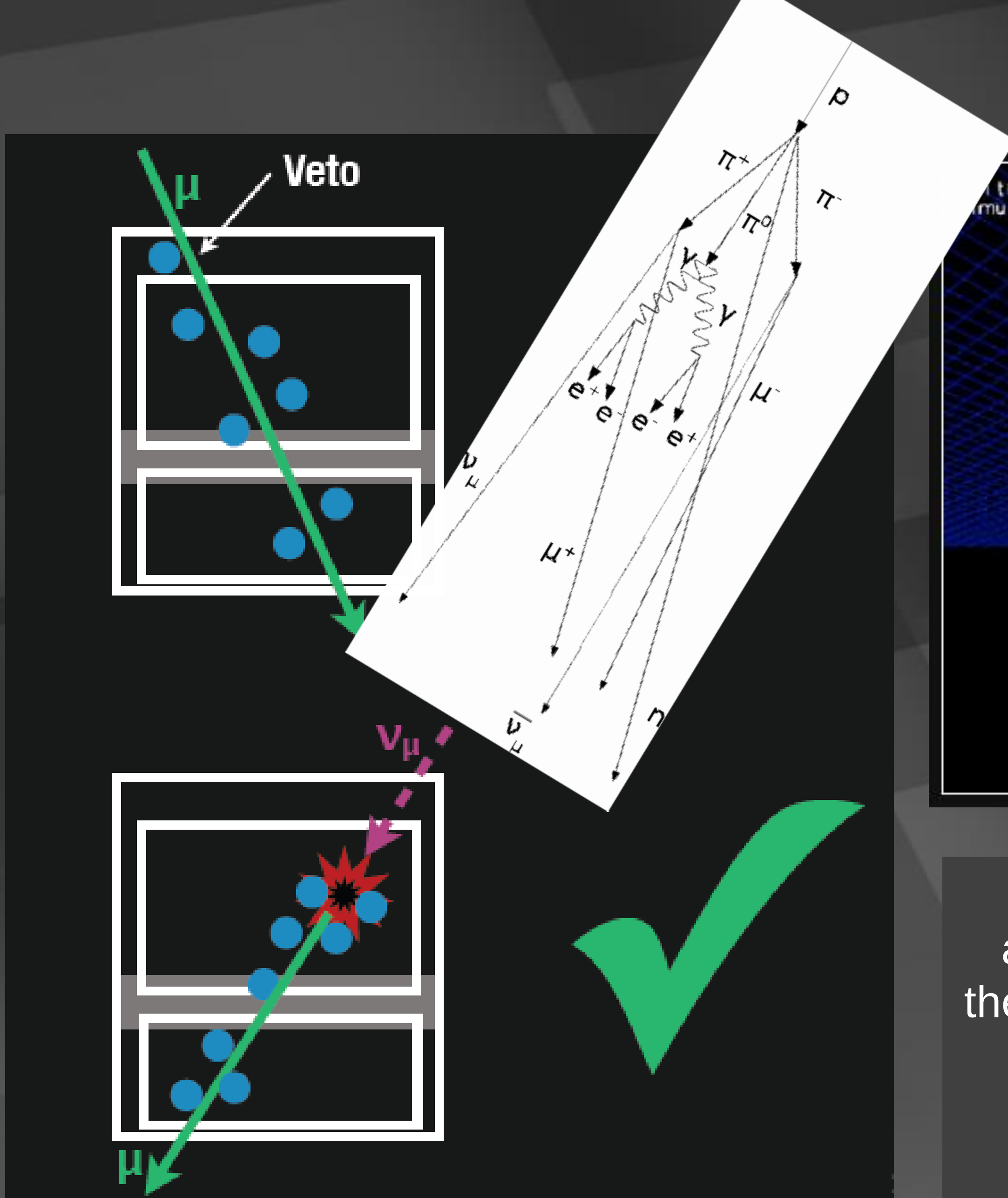
✓ no light in the veto region

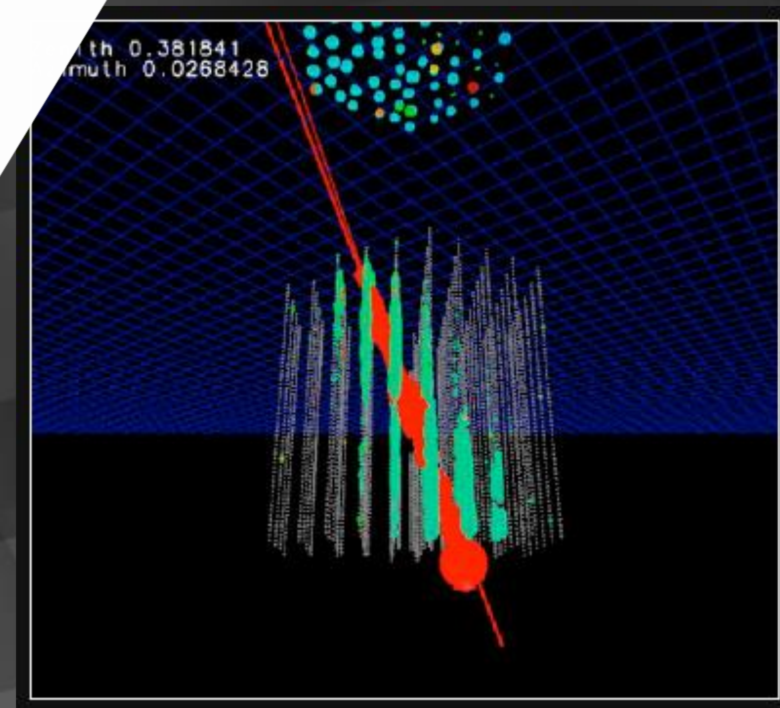
✓ veto for atmospheric neutrinos that are typically accompanied by muons

✓ energy measurement: total absorption calorimetry

✓ all sky, all flavors





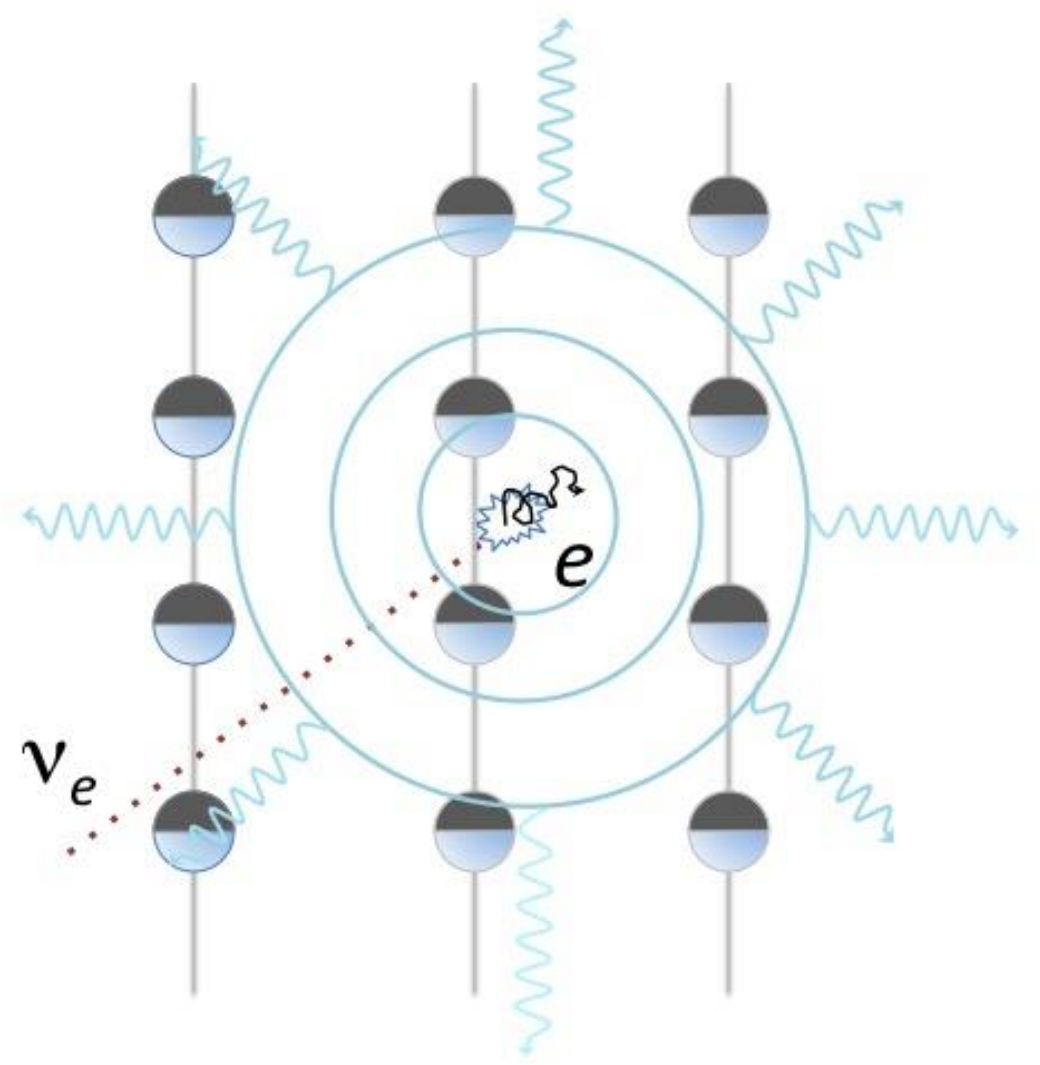


atmospheric neutrinos are accompanied by muons from the decay (and also shower) that produced them → isolated events only (no signals in IceTop)

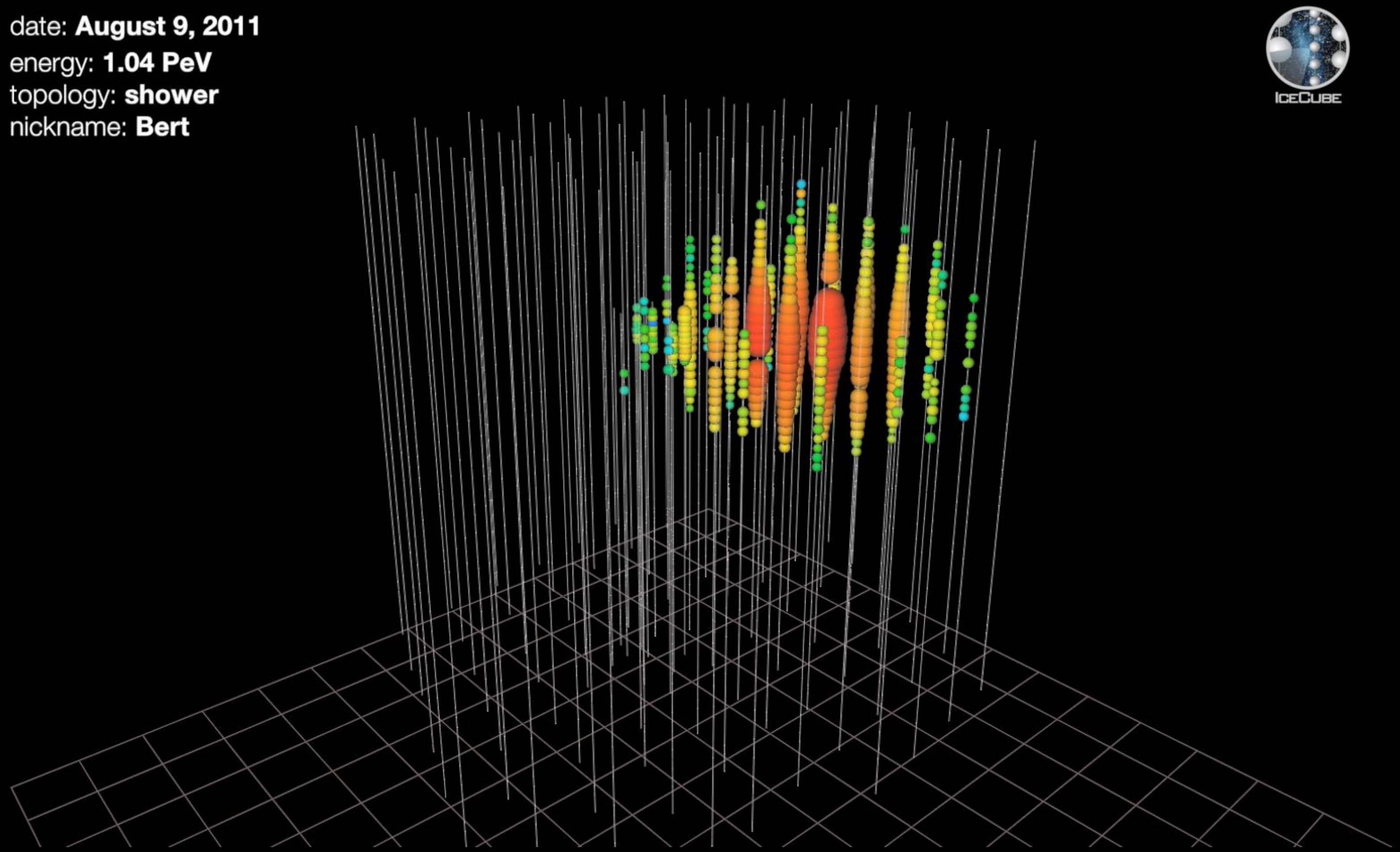
electron showers versus muon tracks

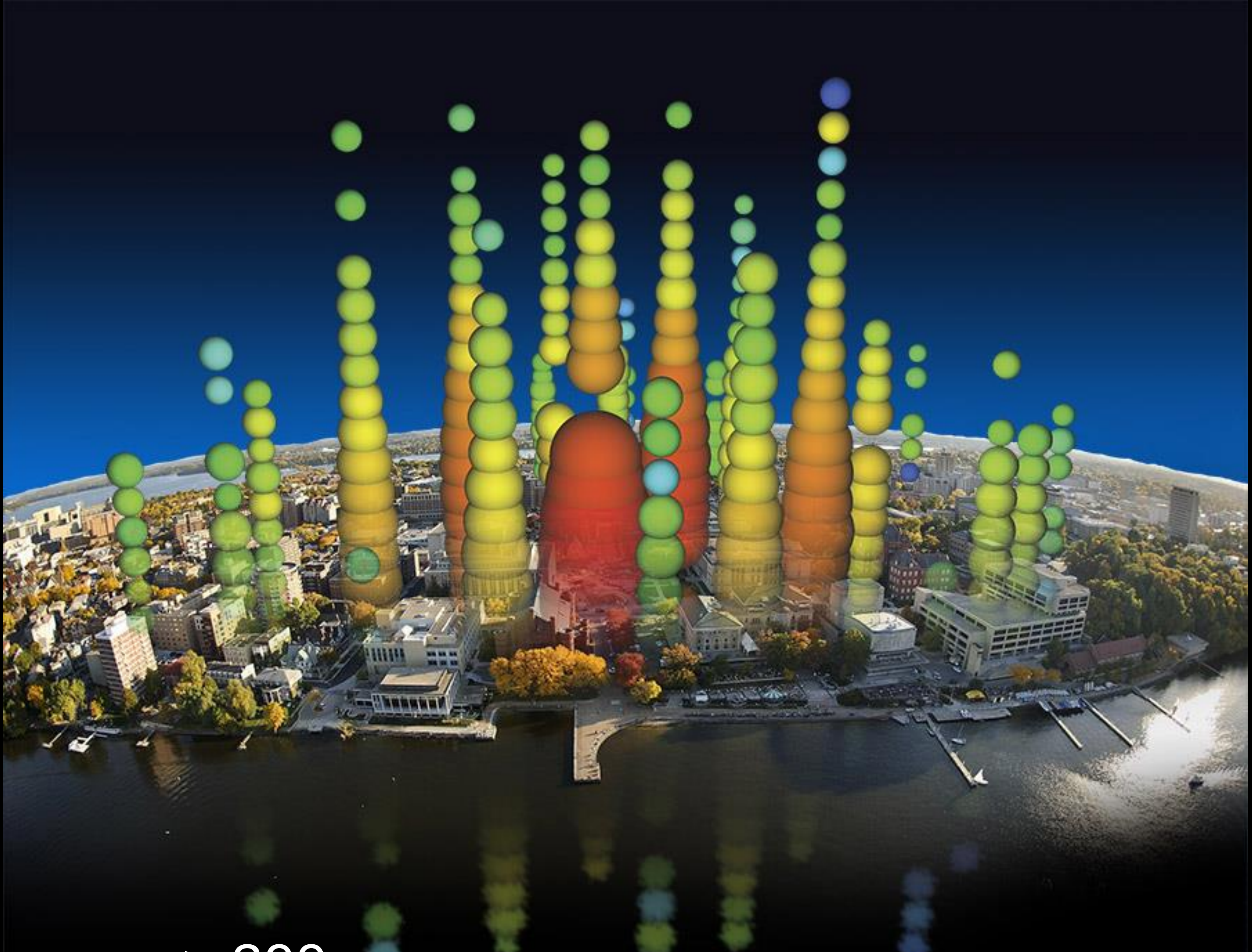
PeV ν_e and ν_τ showers:

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



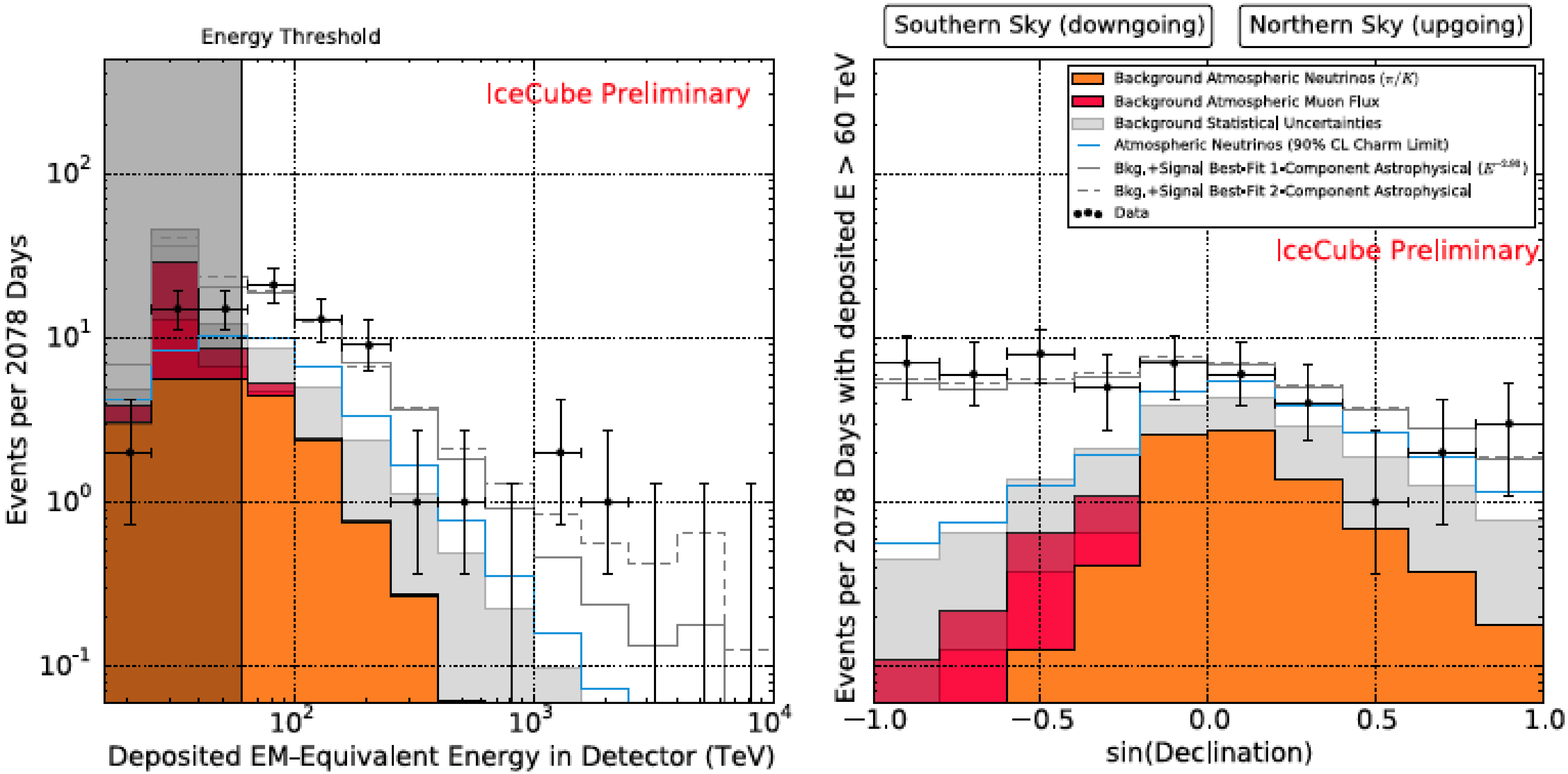
GZK neutrino search: two neutrinos with > 1,000 TeV



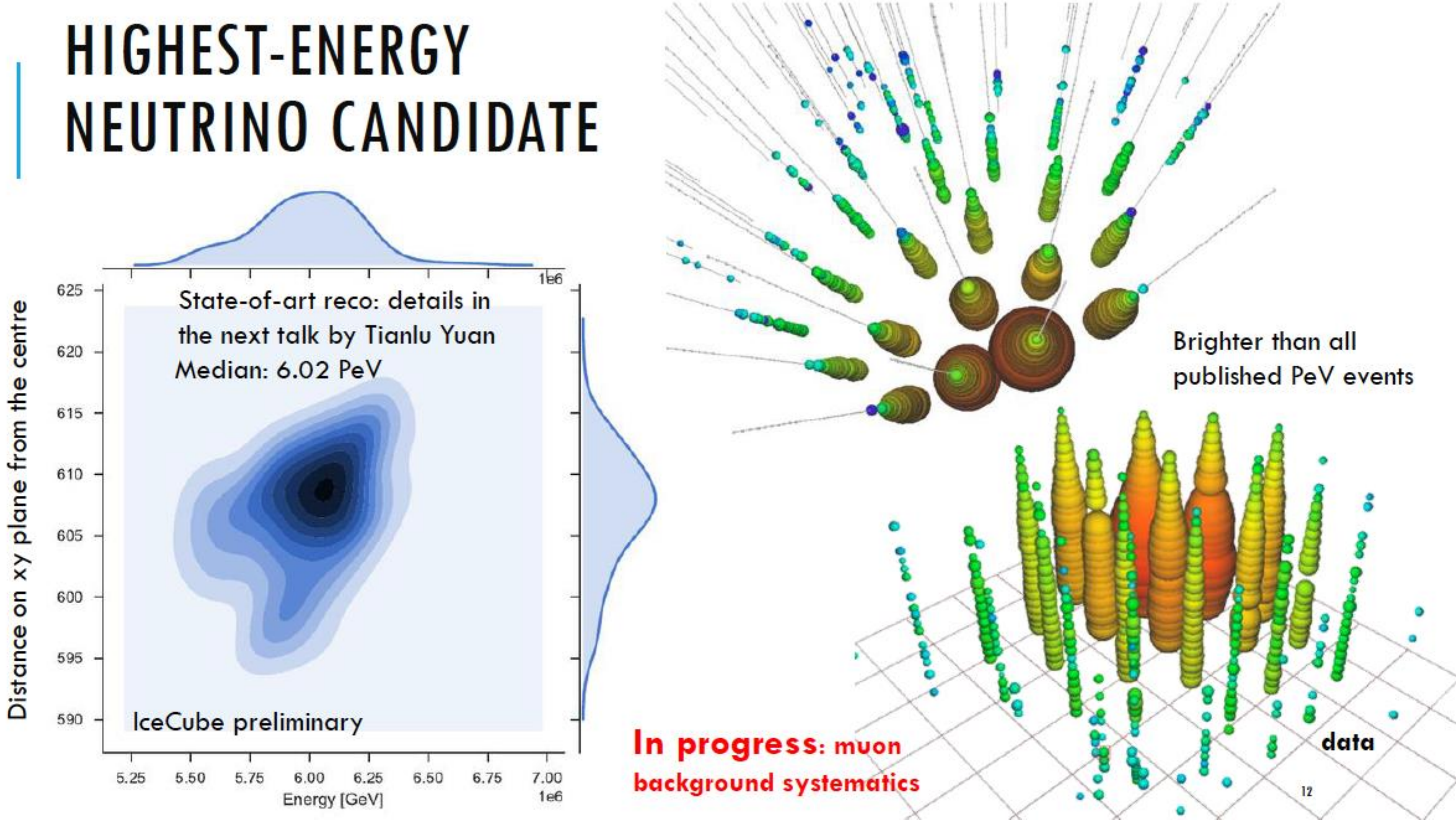


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

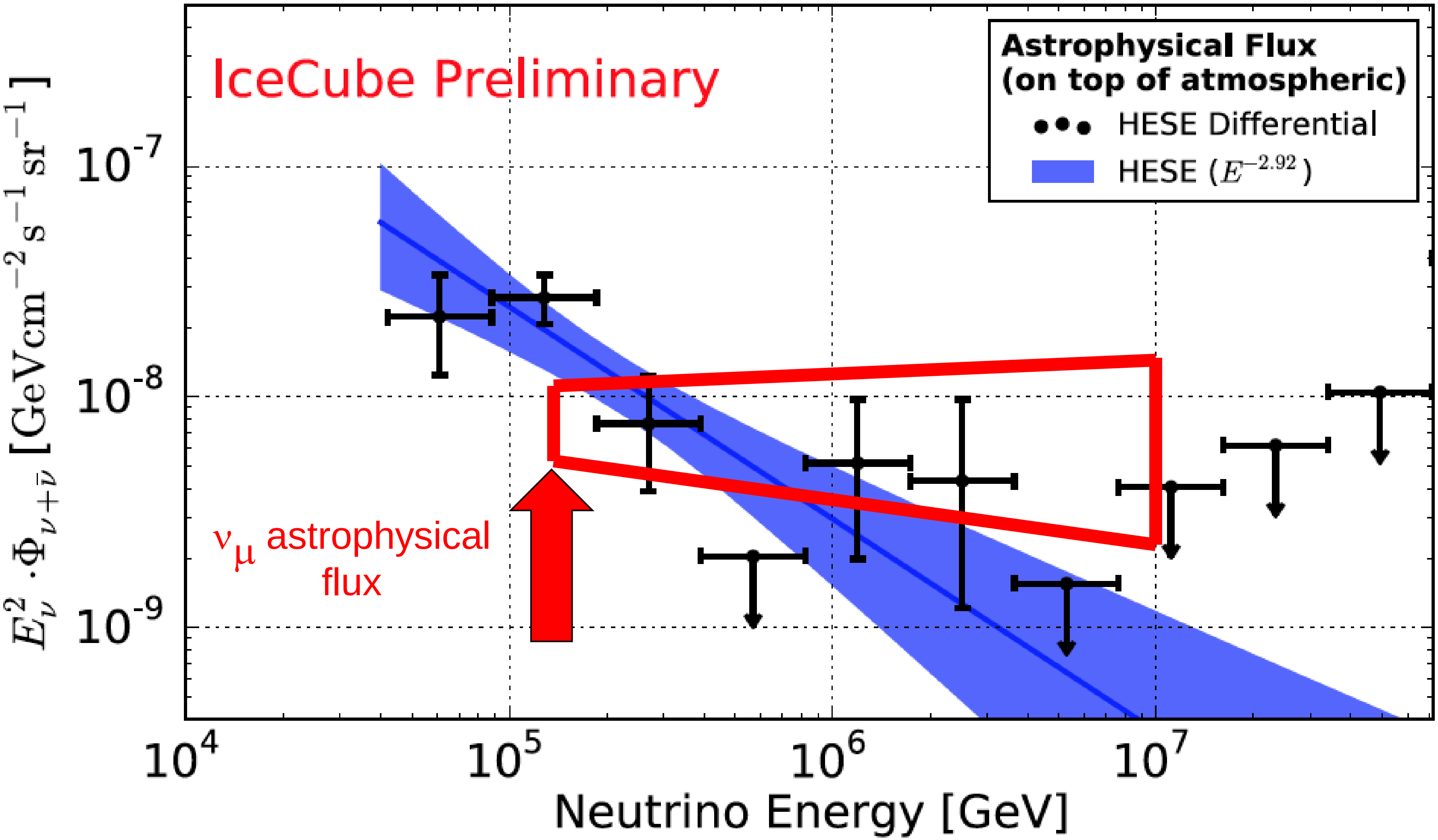
starting events: now 6 years → 8σ



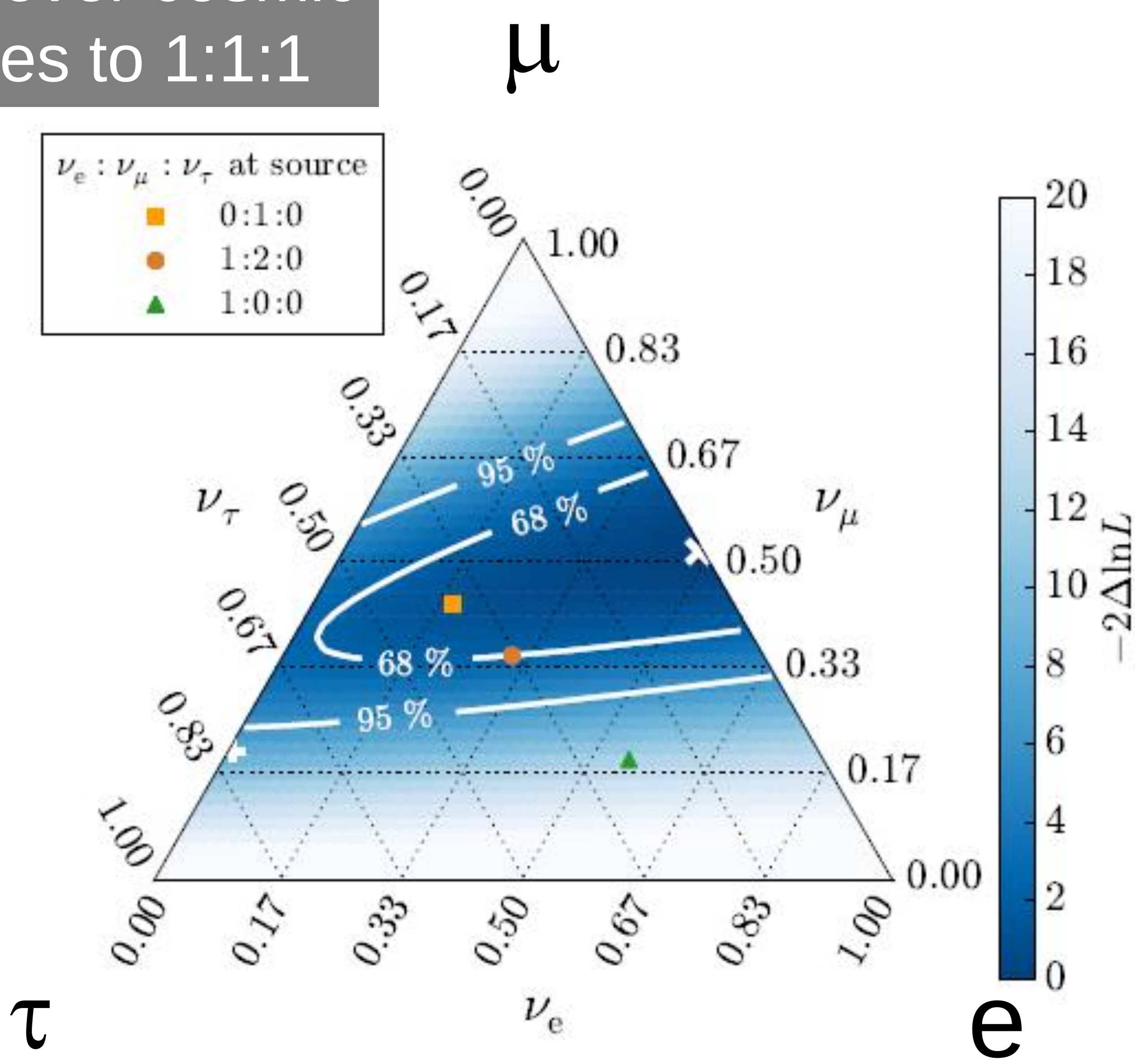
Partially contained event with energy ~ 6 PeV



two methods consistent above 100 TeV



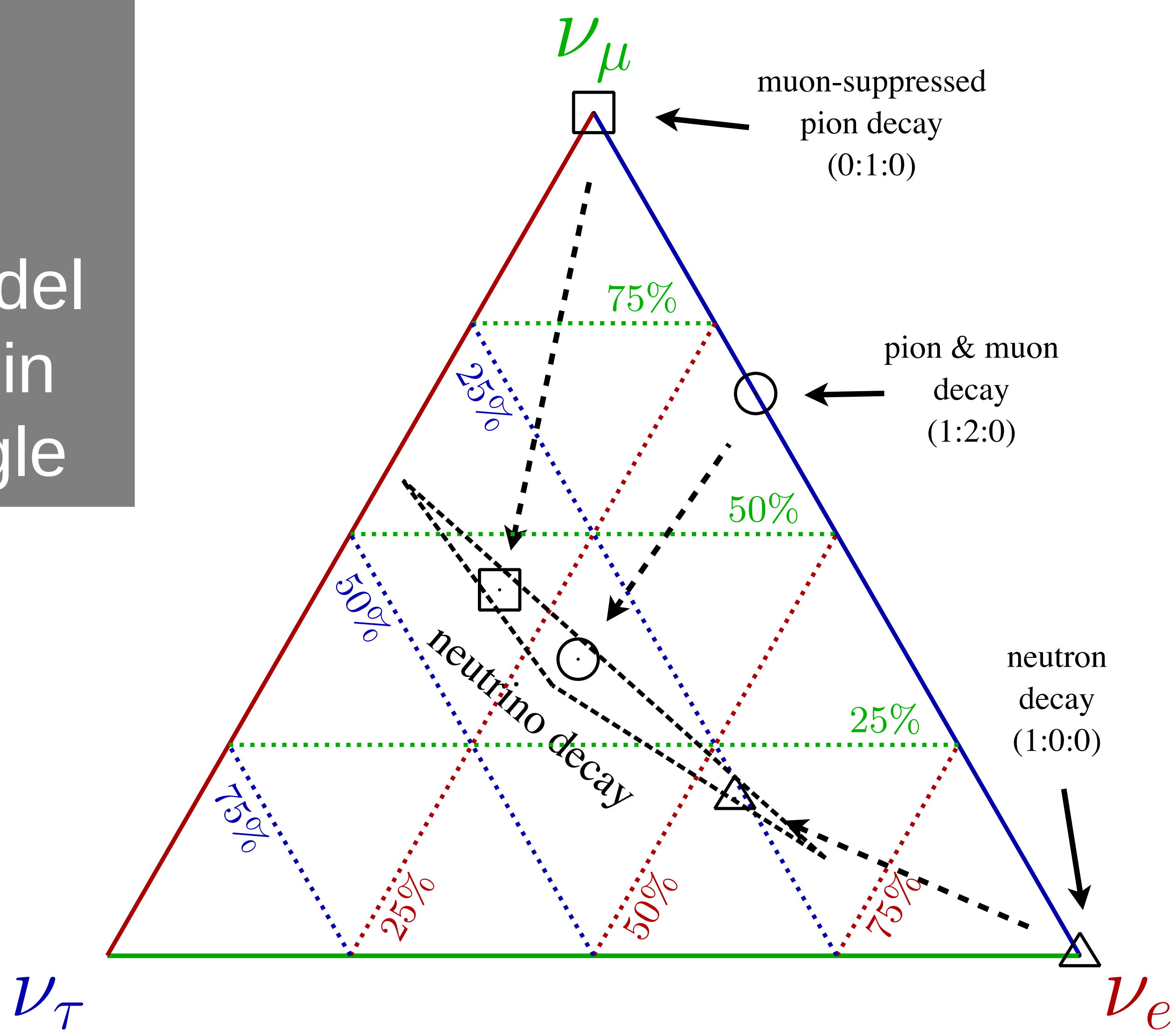
oscillate over cosmic distances to 1:1:1

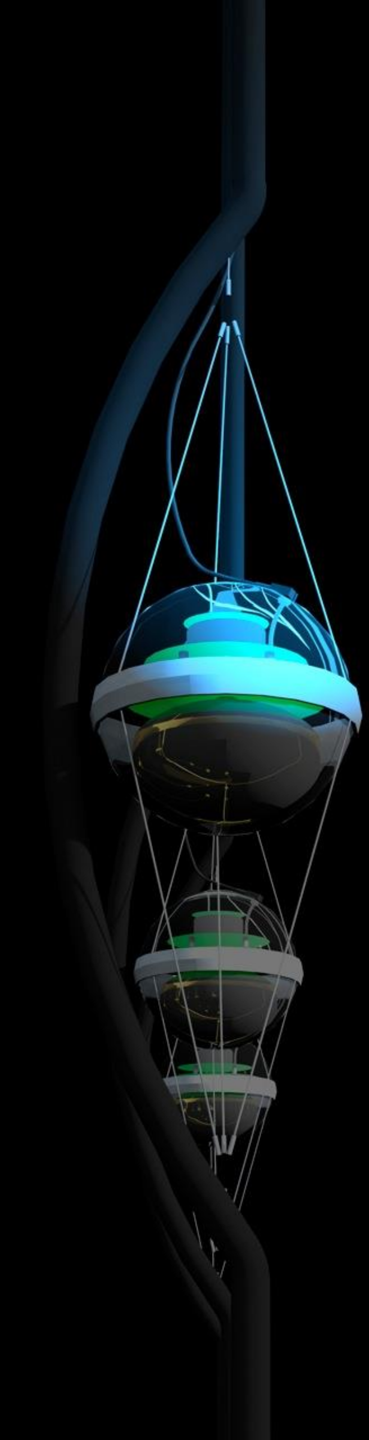


new physics ?

if not…

every model ends up in the triangle





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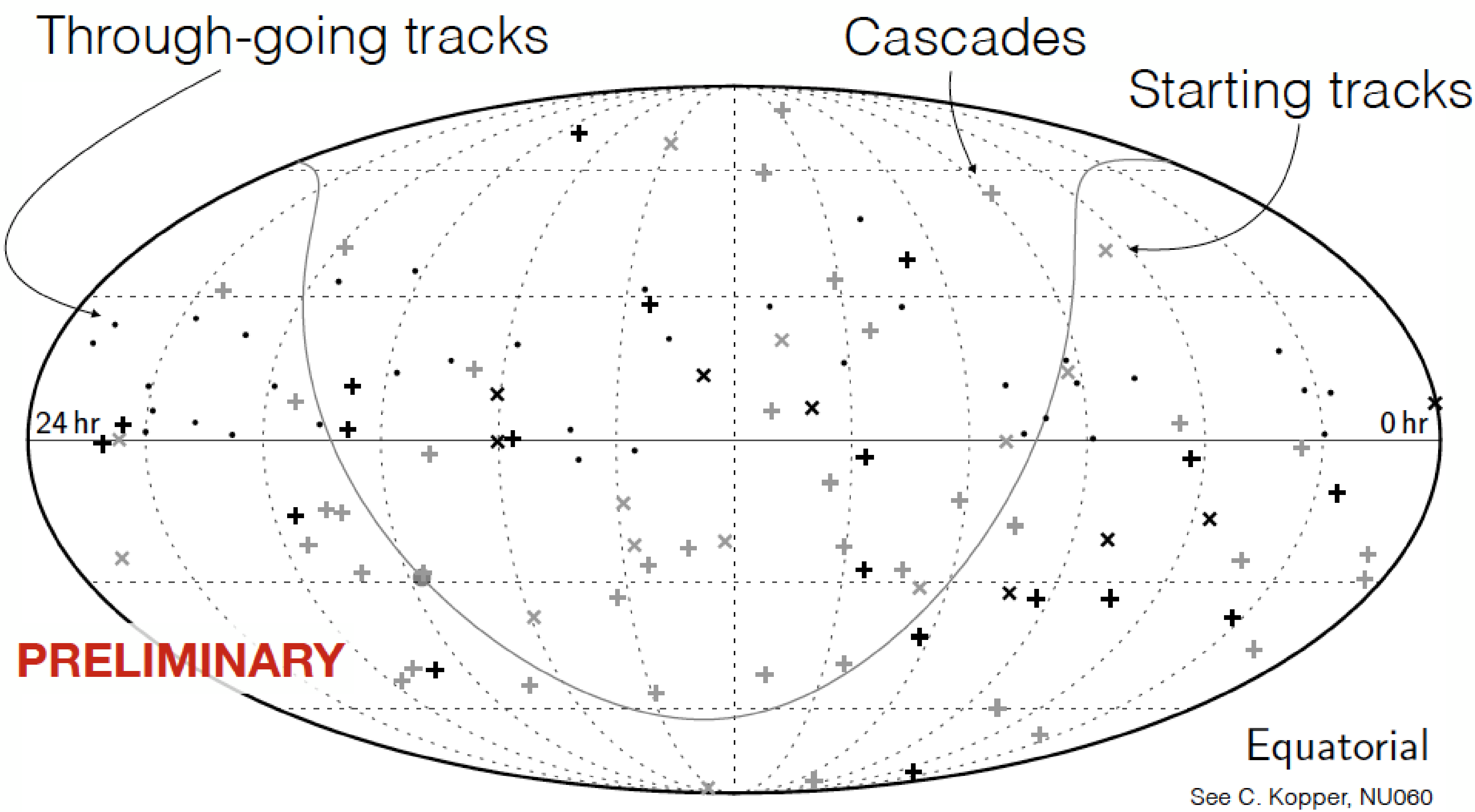
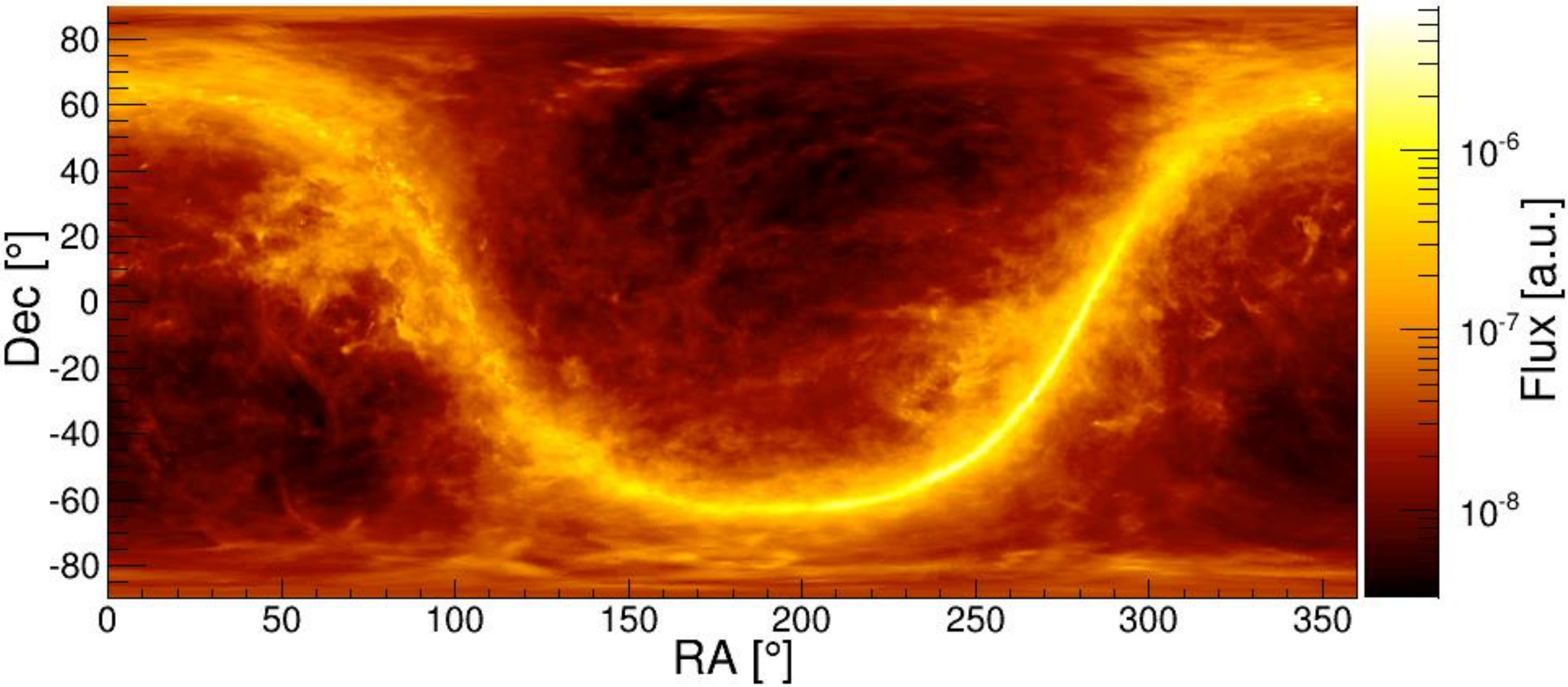
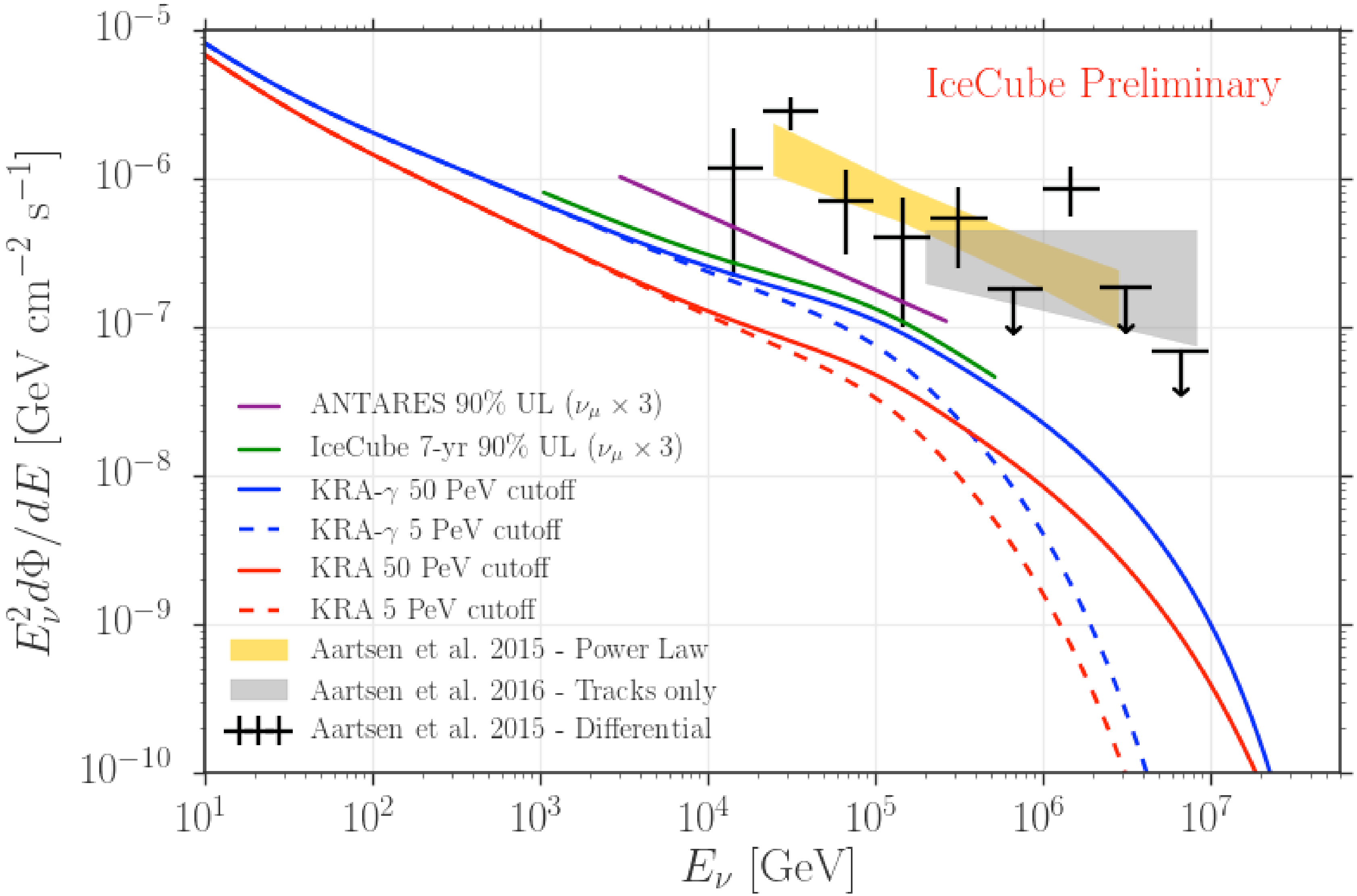


Through-going tracks
Cascades
Starting tracks
24 hr
0 hr
PRELIMINARY
Equatorial
See C. Kopper, NU060

Galactic π^0 gamma rays (Fermi) → charged π → neutrinos

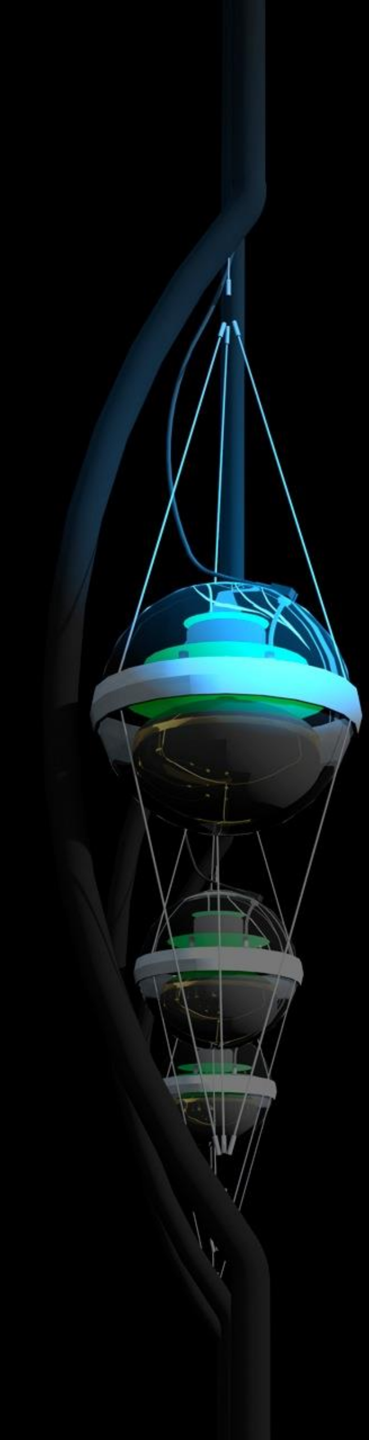


extrapolation GeV → TeV, PeV energy?



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 3σ level)
- where are the PeV gamma rays that accompany PeV neutrinos?



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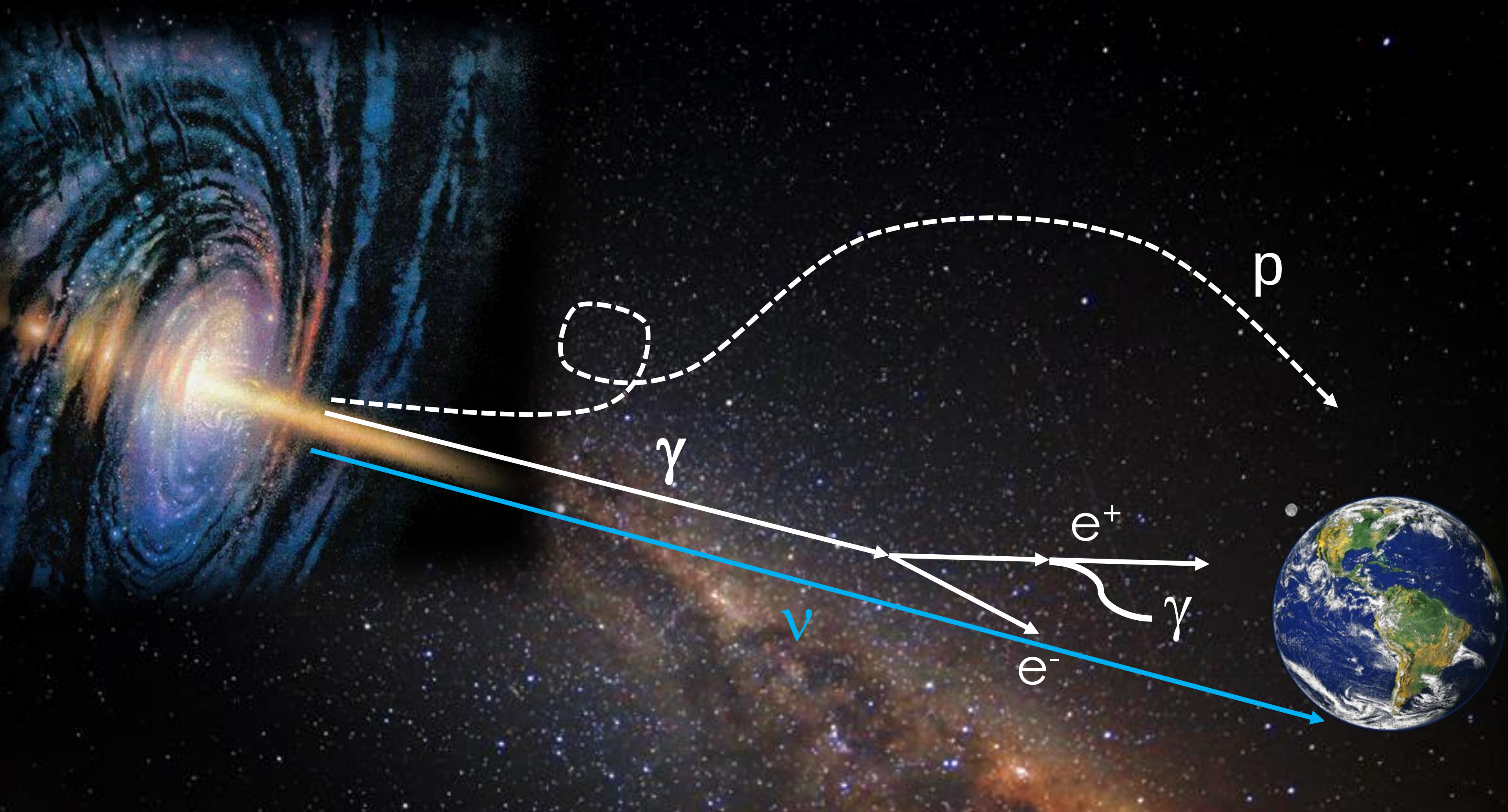
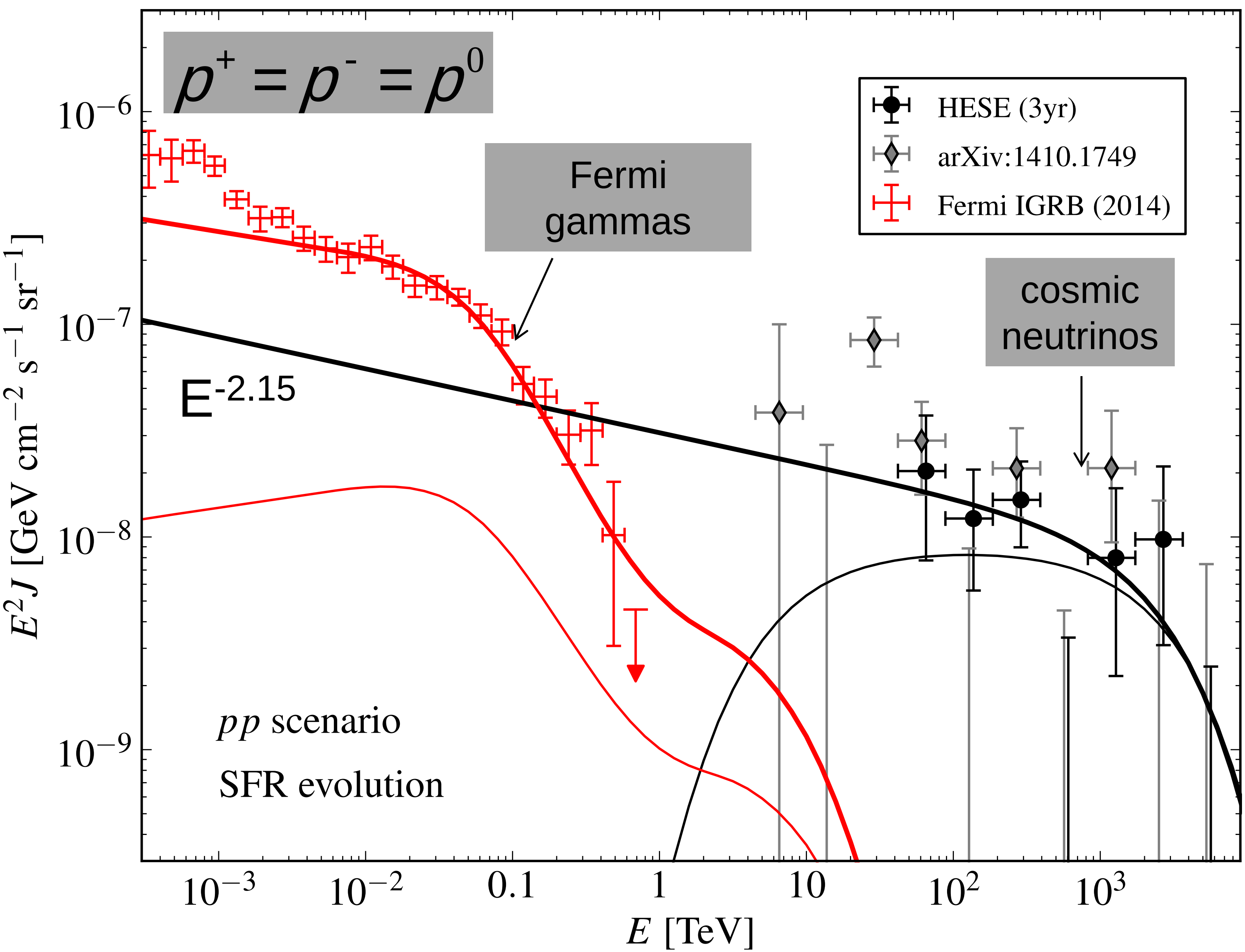


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

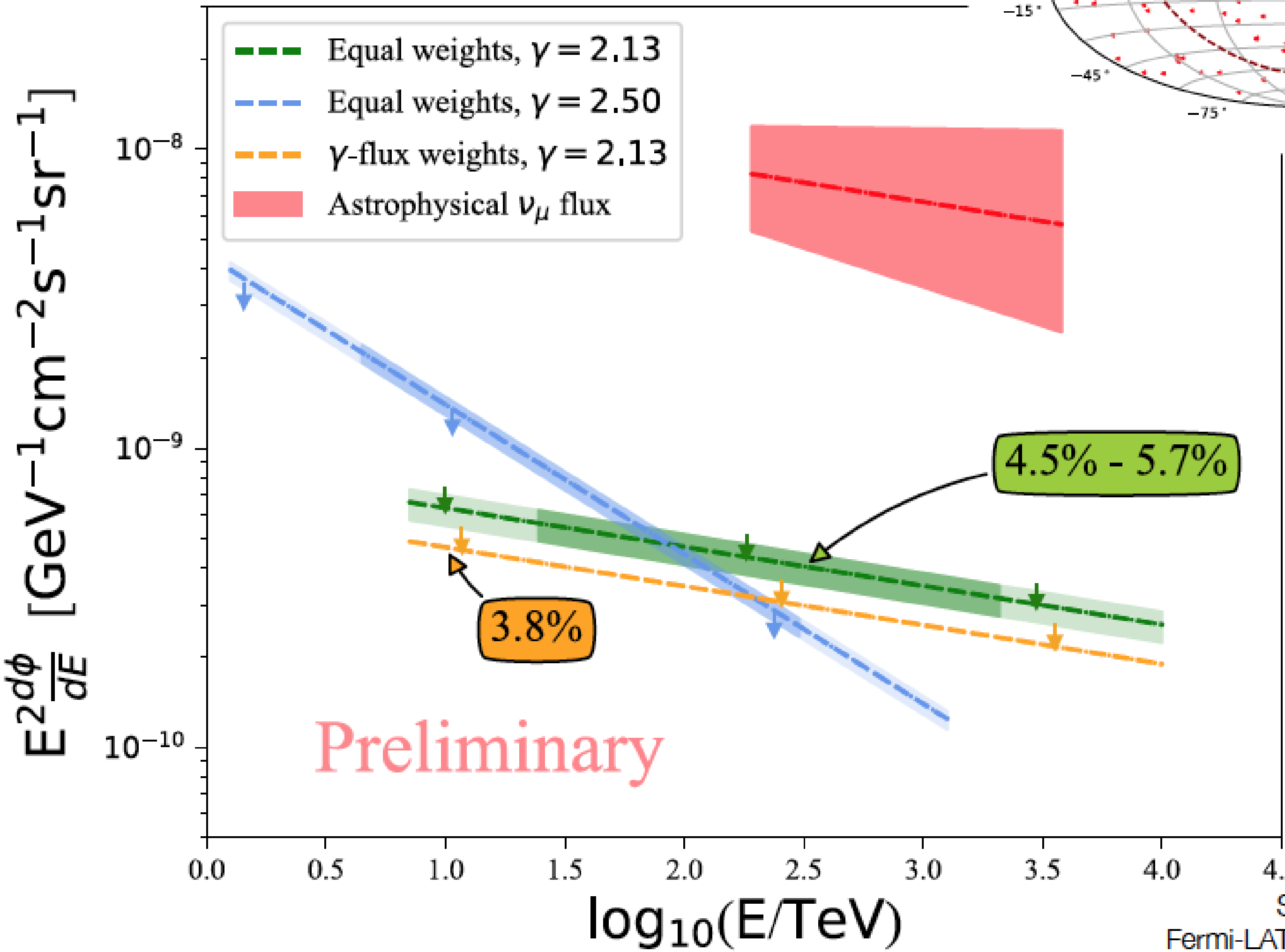


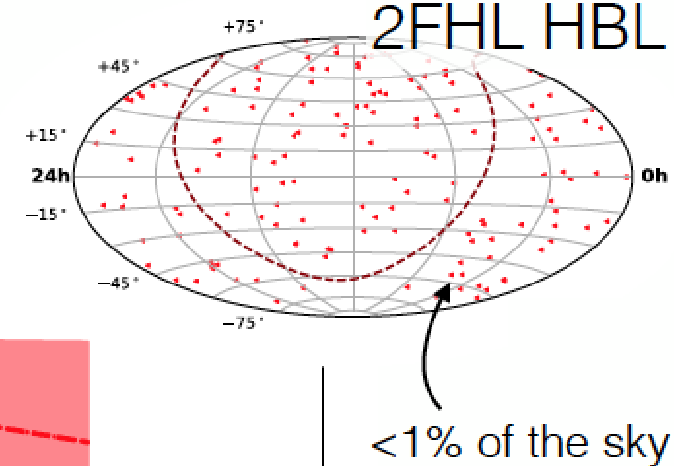
$p^+ = p^- = p^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]

- 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

Population studies: blazar catalog search

Blazars account for:
85% of extragalactic γ background
< 6-27% of the IceCube neutrino flux





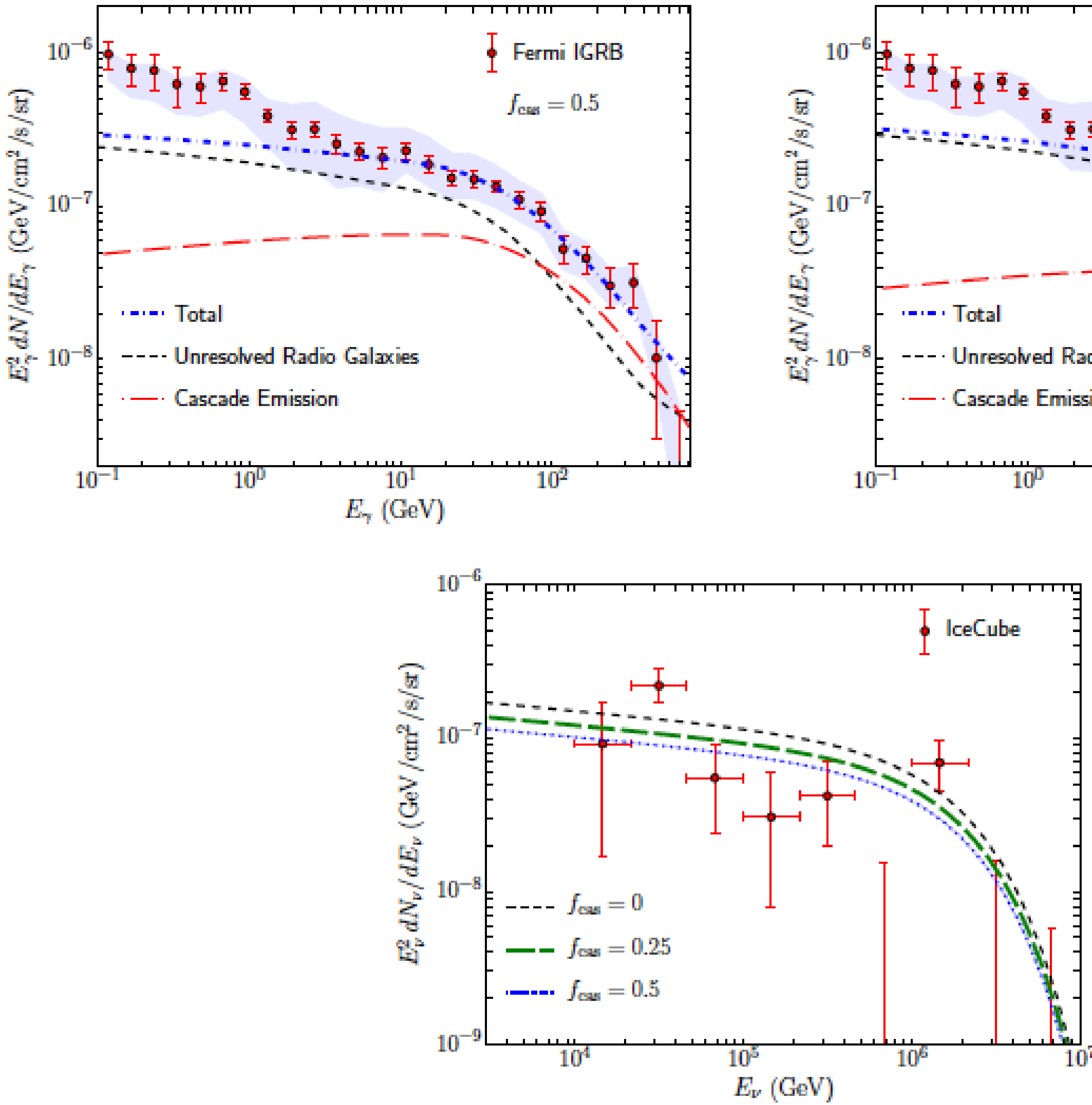
See: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

What are the sources of Fermi's gamma rays?

- 50% identified blazars, non-blazar sources cannot exceed 15%?
- can be accommodated by *starbursts* galaxies that accommodate at most 10% of IceCube (however argument sensitive to spectral index)
- can be accommodated by *radiogalaxies* that accommodate IceCube neutrinos

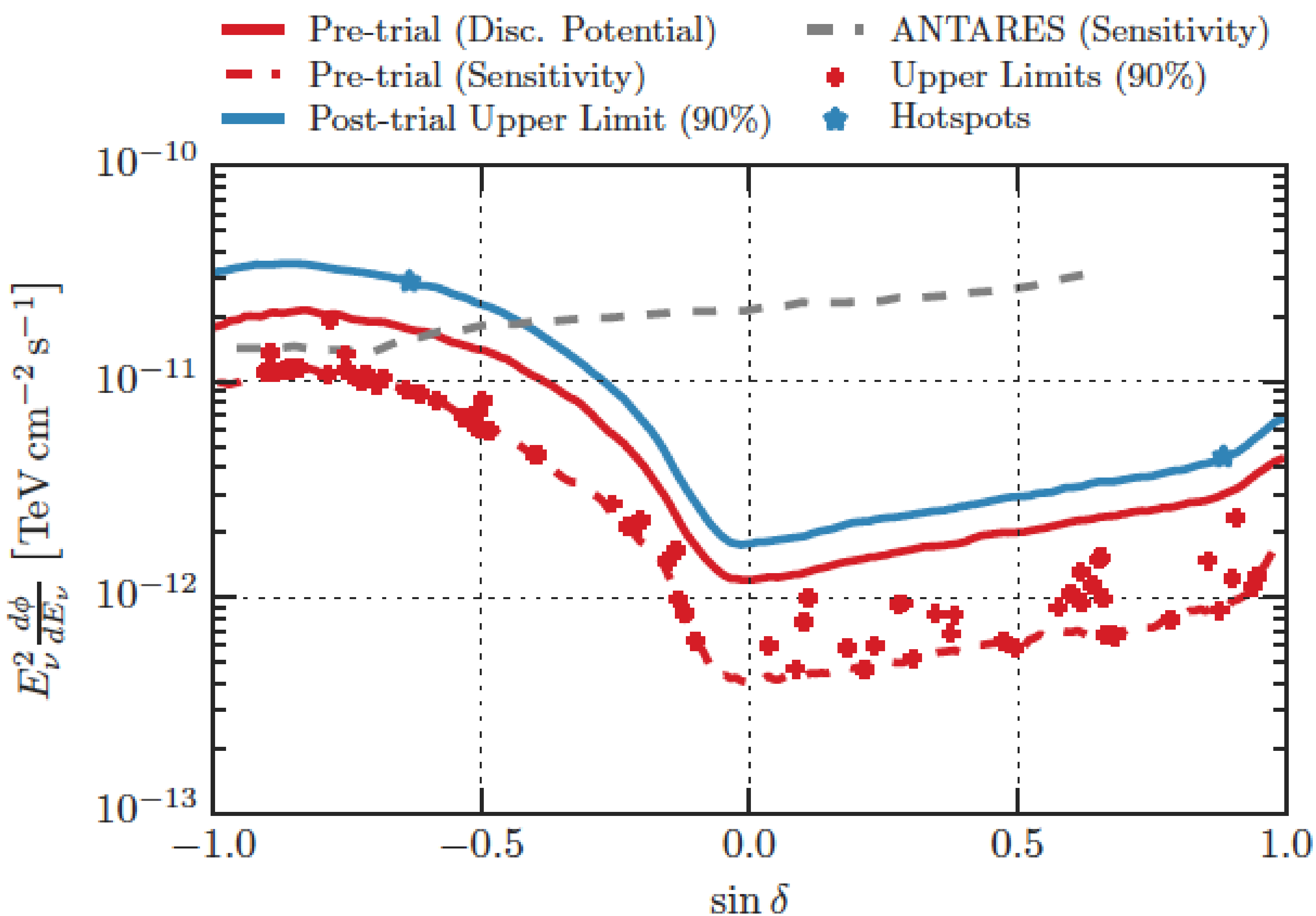
blazars? not the resolved Fermi blazars, but…

- neutrinos originate from a larger volume
- 50% of blazars *not* identified
- sources transparent to high energy gamma rays may not have the target density to produce neutrinos (GRB?)



radiogalaxies

Tjus et al.
Hooper



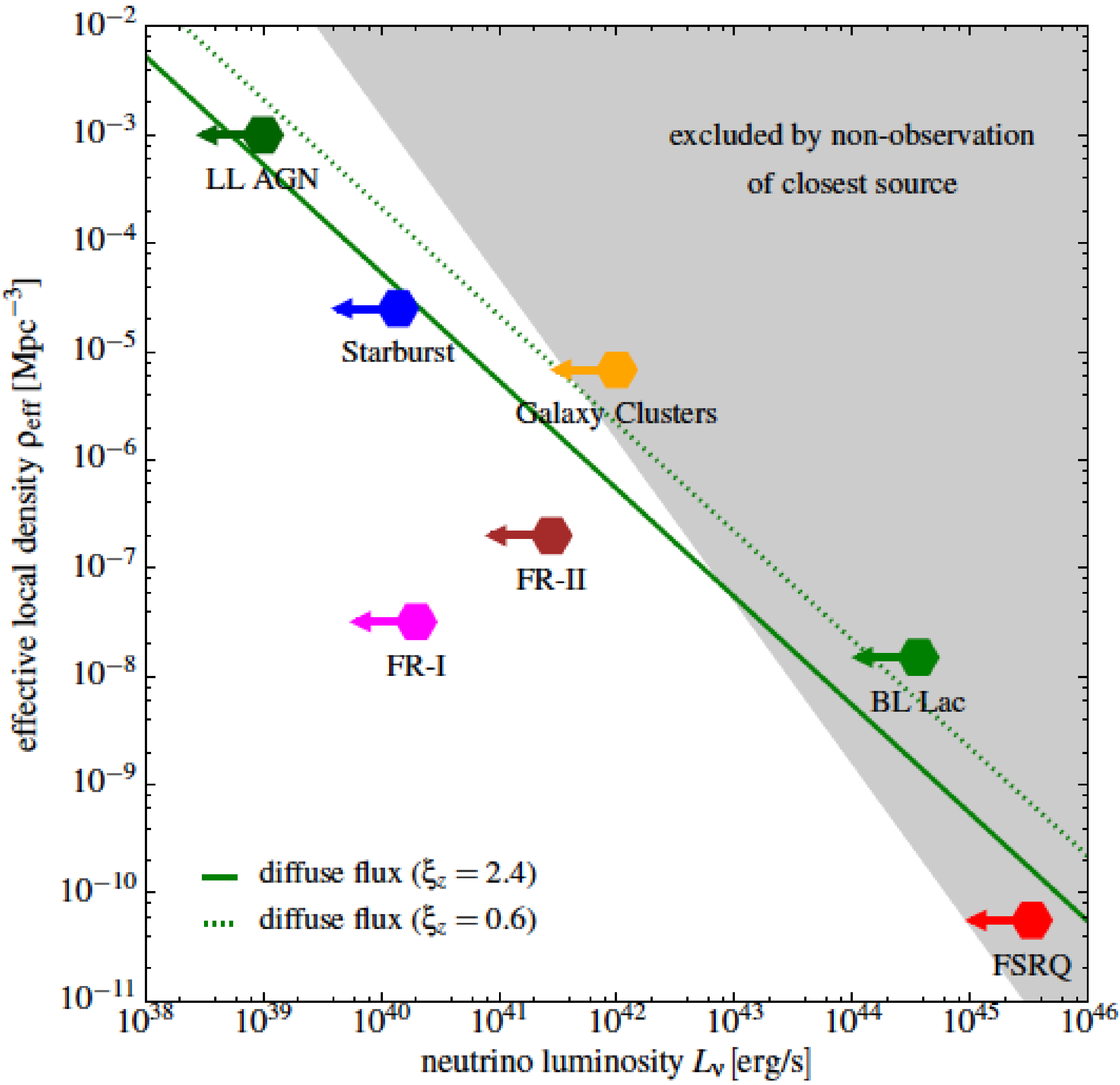
no resolved point sources… yet

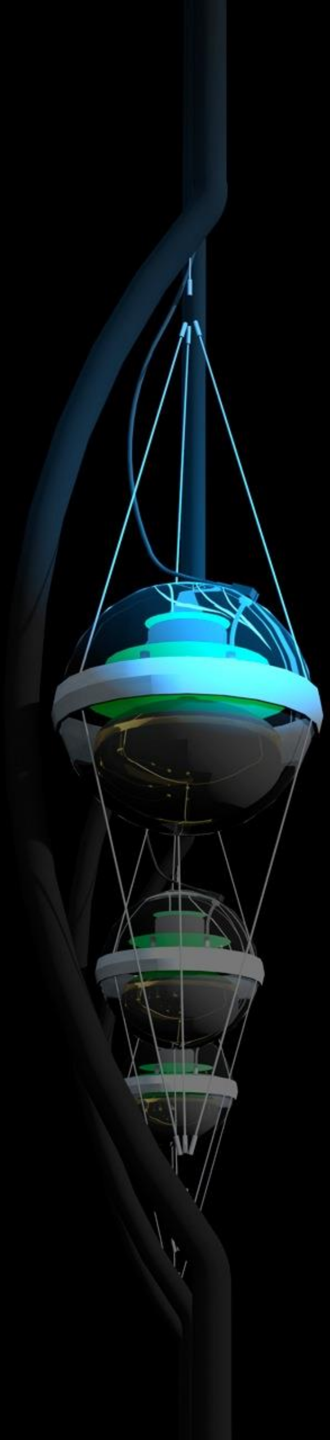
flux nearest source = (diffuse flux observed)(density of sources)$^{1/3}$

Olbers paradox

density 10^{-7} Mpc^{-3} soon !

blazars, FSRQ…





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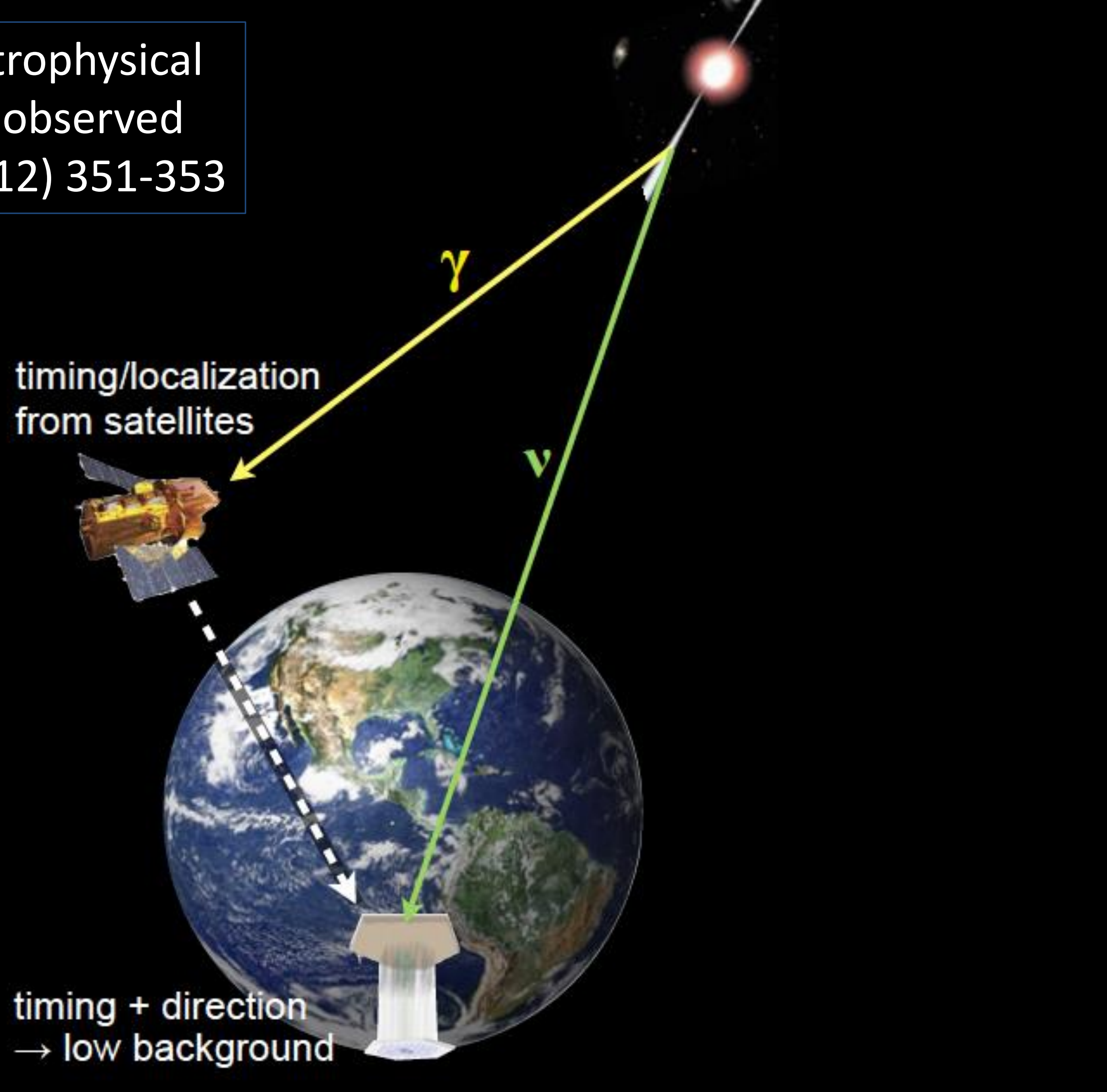
flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353



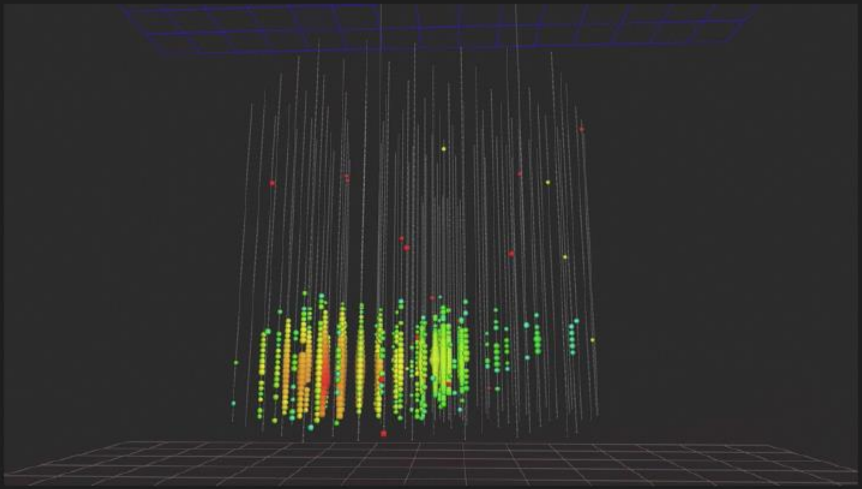
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

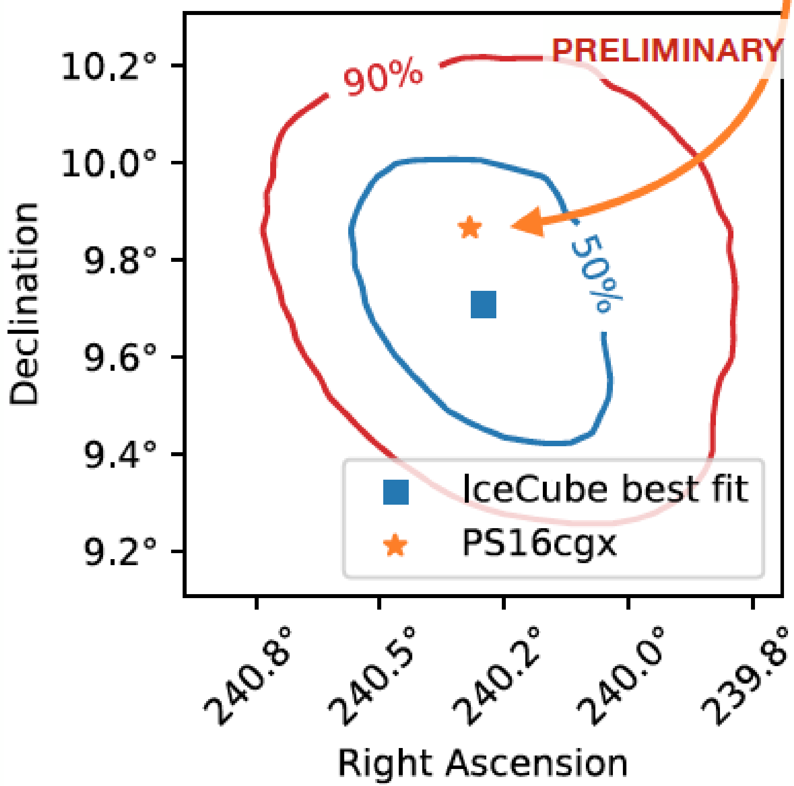
We send **rough reconstructions first** and then **update them.**

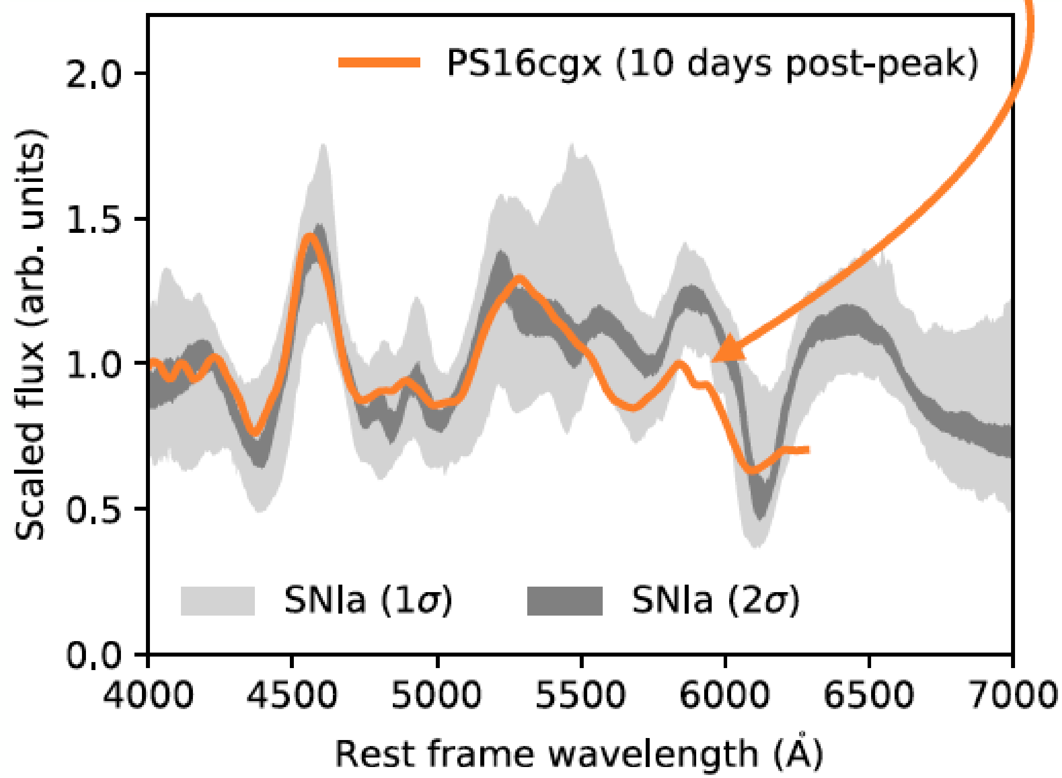


PS16cgx: a young supernova in the field of a HESE neutrino

PAN-Starrs followed up IceCube HESE alert on 2016-04-27 and found a recent supernova at z=0.3:

- Optical spectroscopy 10, 20 days post-peak
- Features atypical for SNIa, but not sufficient to exclude

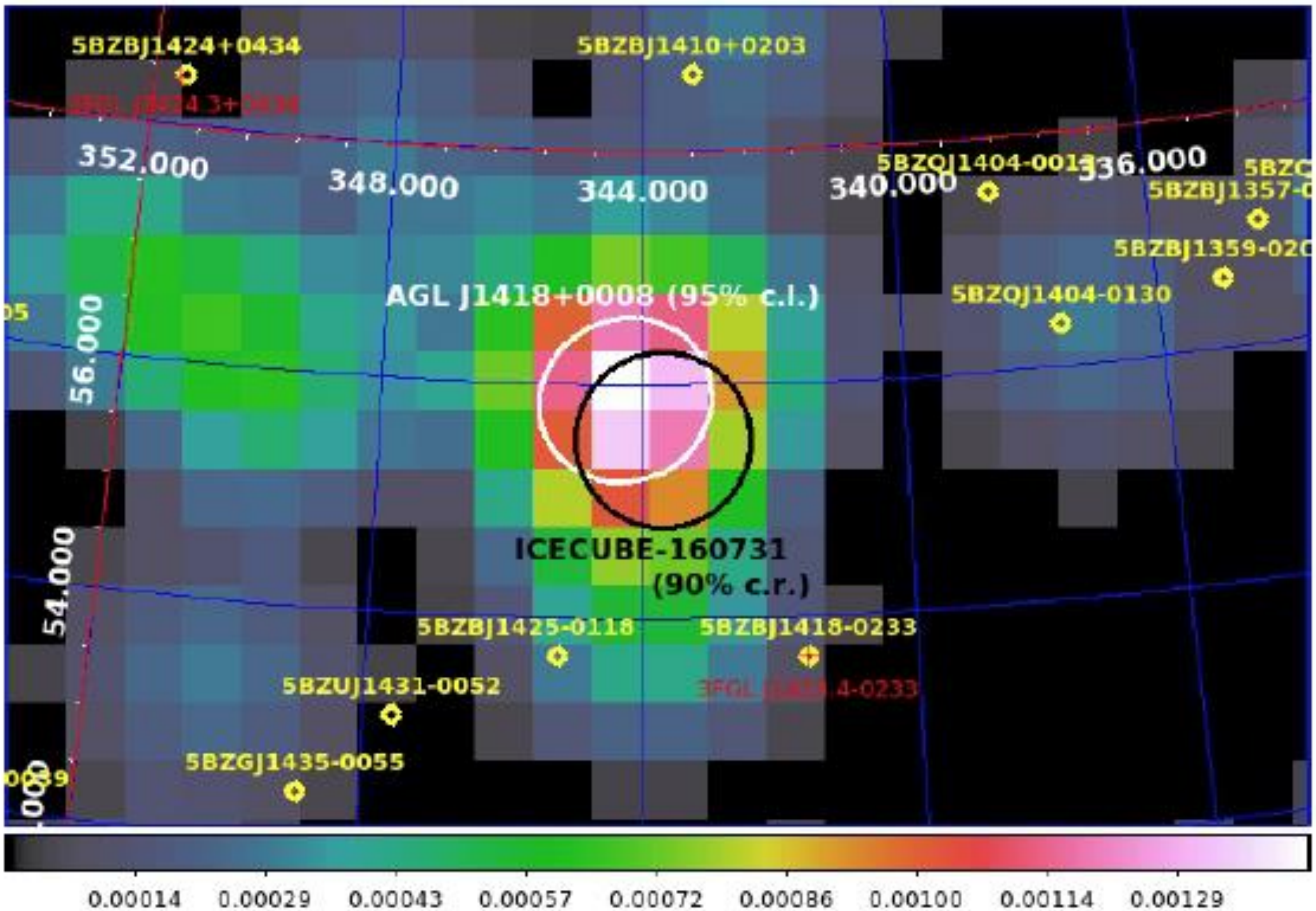




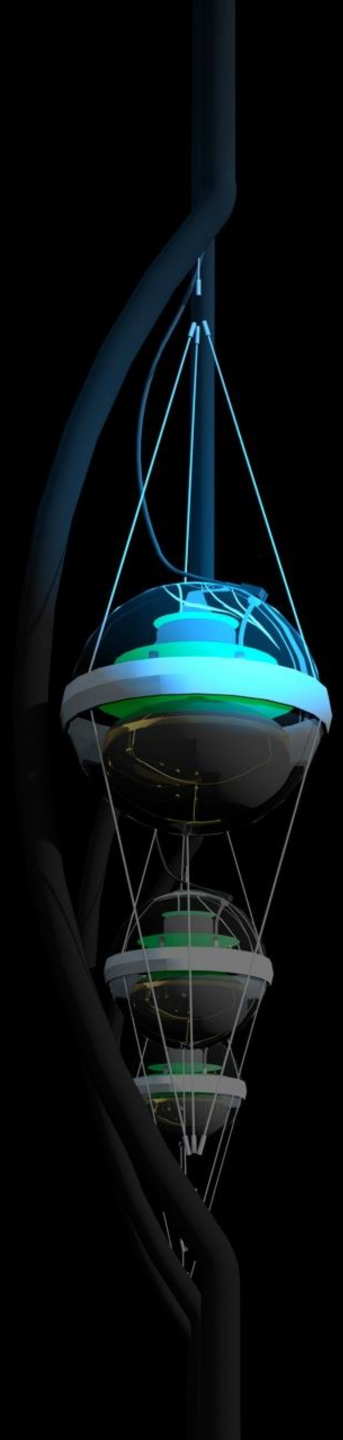
Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

AGILE DETECTION OF A CANDIDATE GAMMA-RAY PRECURSOR TO THE ICECUBE-160731 NEUTRINO EVENT

F. Lucarelli,[1,2] C. Pittori,[1,2] F. Verrecchia,[1,2] I. Donnarumma,[3] M. Tavani,[4,5,6] A. Bulgarelli,[7] A. Giuliani,[8]
L. A. Antonelli,[1,2] P. Caraveo,[8] P. W. Cattaneo,[9] S. Colafrancesco,[10,2] F. Longo,[11] S. Mereghetti,[8]
A. Morselli,[12] L. Pacciani,[4] G. Piano,[4] A. Pellizzoni,[13] M. Pilia,[13] A. Rappoldi,[9] A. Trois,[13] and S. Vercellone[14]



Corresponding author: Fabrizio Lucarelli
fabrizio.lucarelli@asdc.asi.it



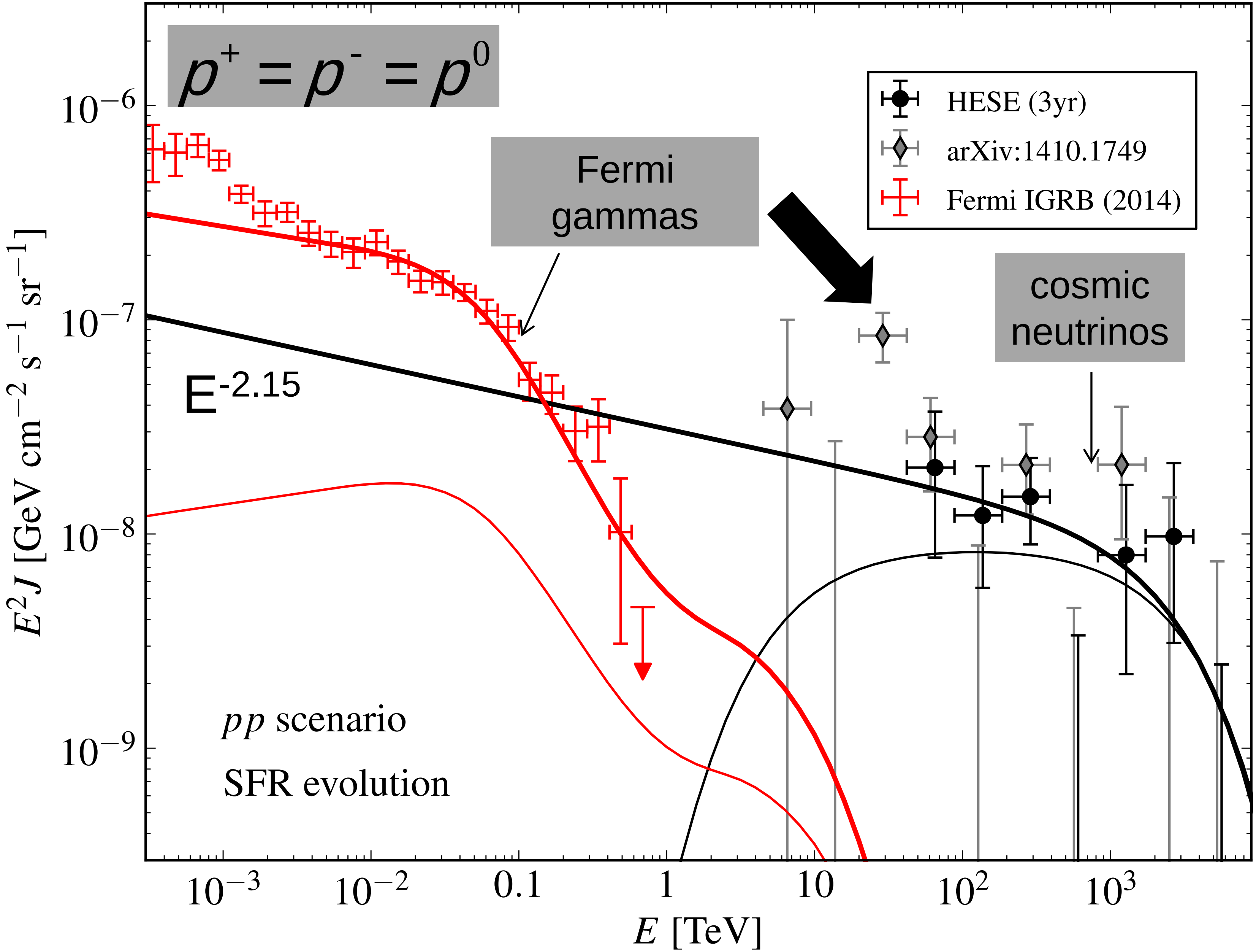
IceCube and Multimessenger Astronomy

francis halzen

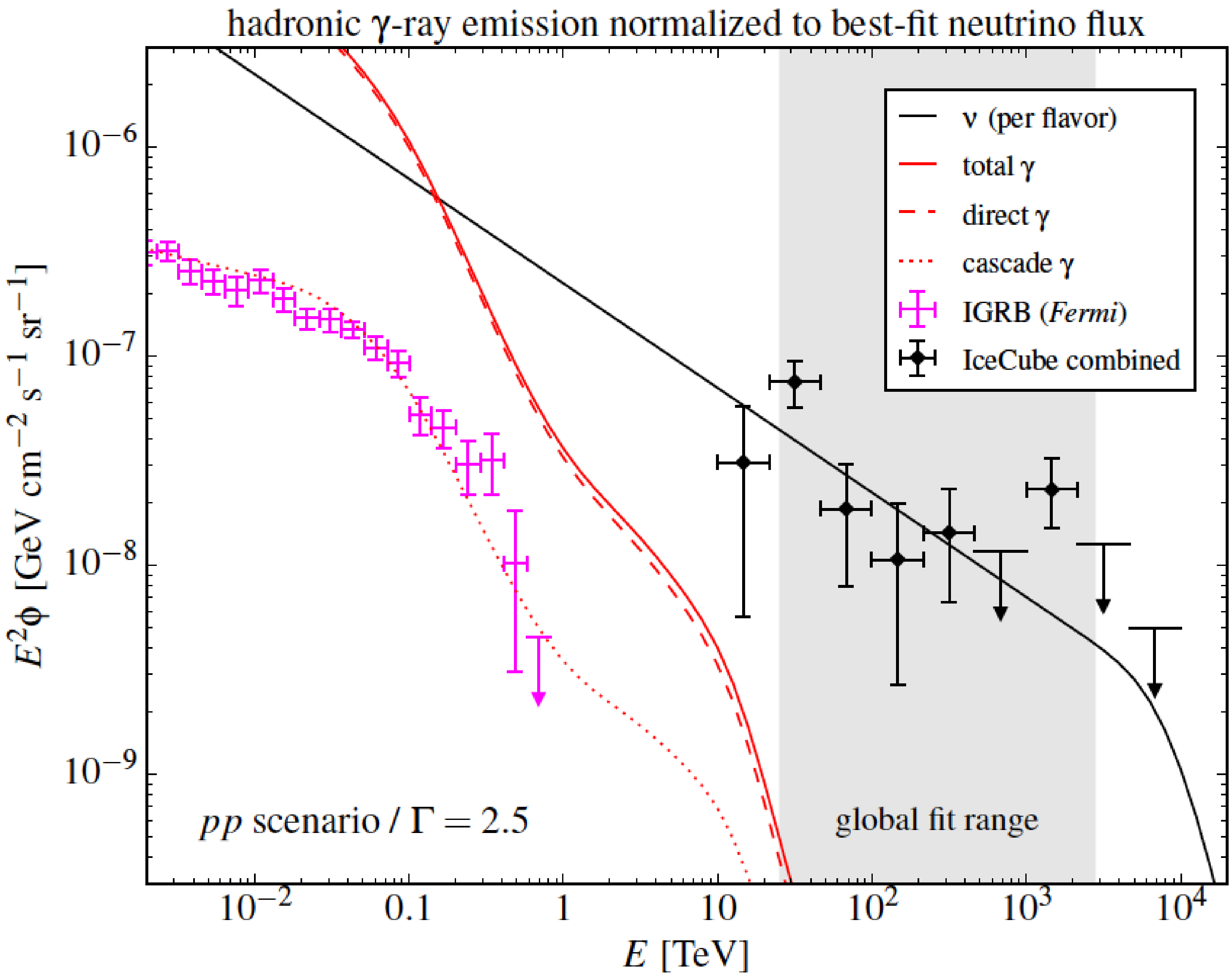
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- other multiwavelength observations
- cosmic neutrinos below 100 TeV?
- the Galaxy

IceCube.wisc.edu

- is there more ?



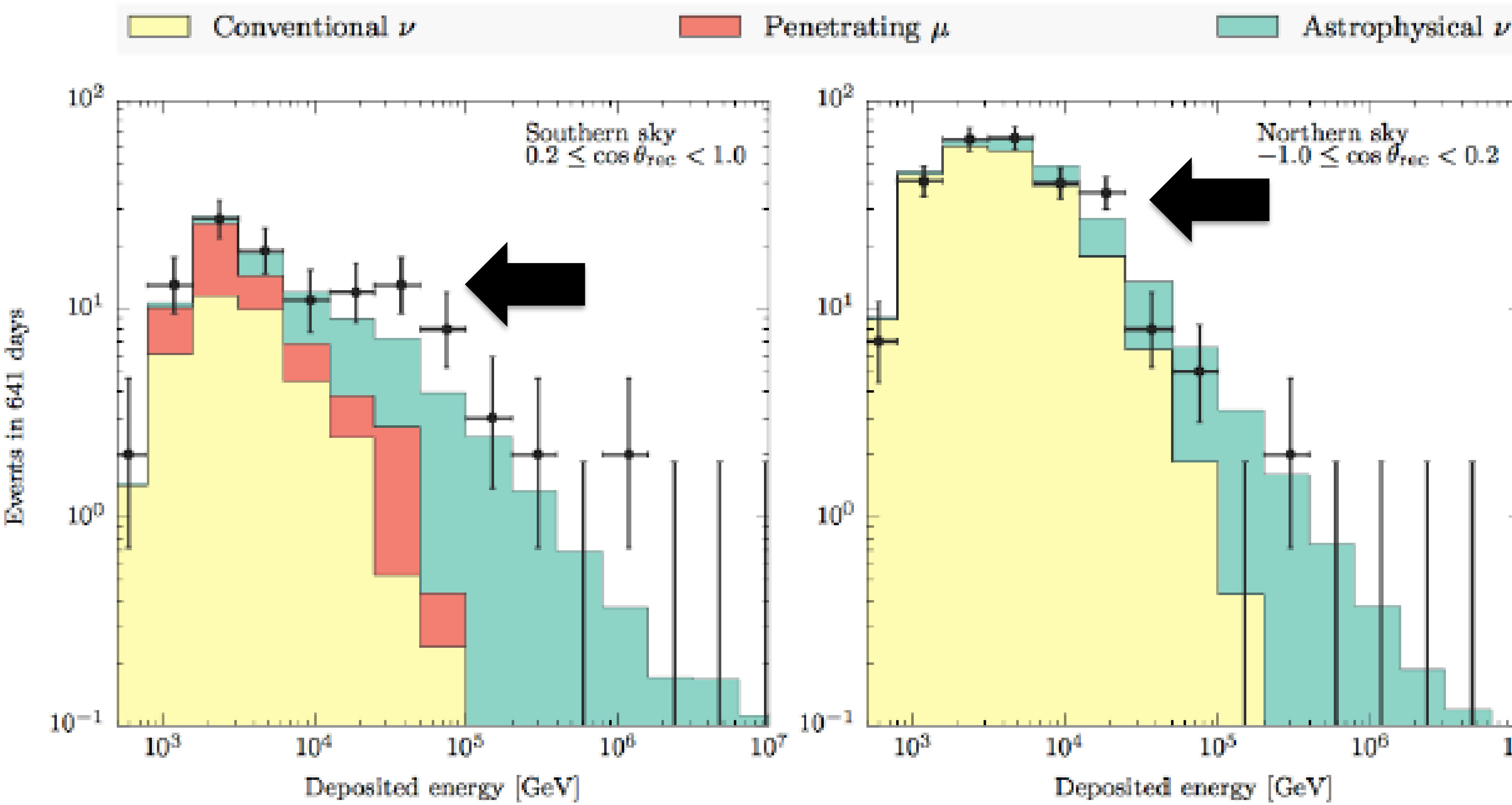
$p^+ = p^- = p^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3



a “problem” ?

gamma rays cascade in the source to < GeV energy

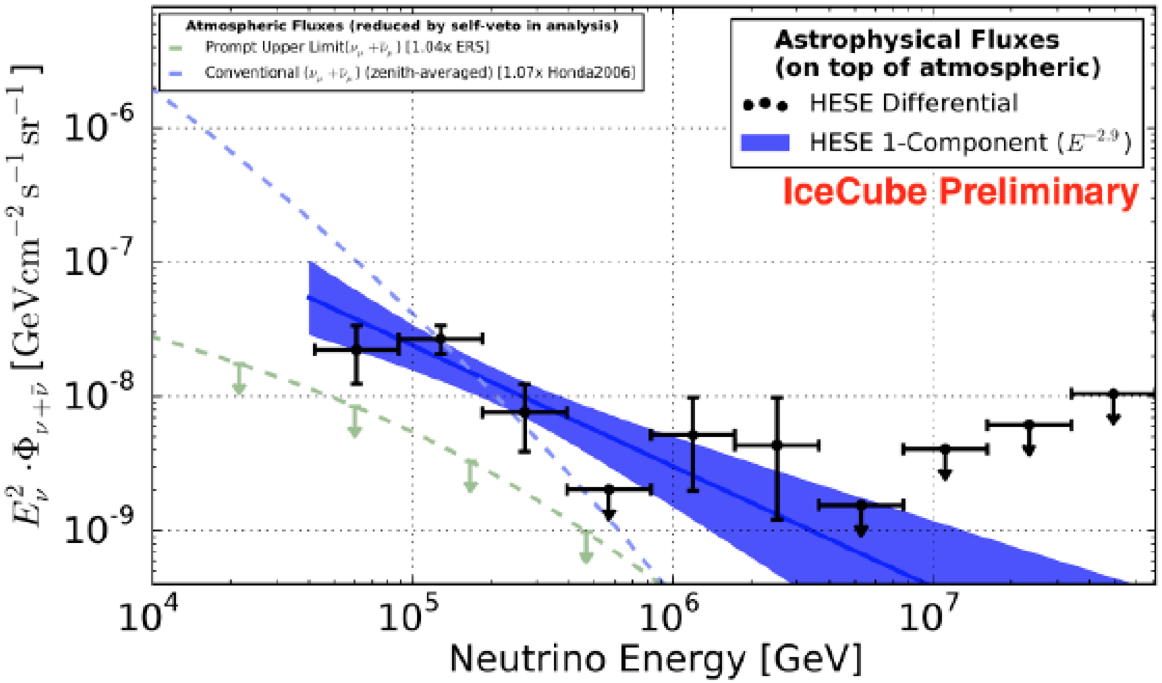
towards lower energies: a second component?



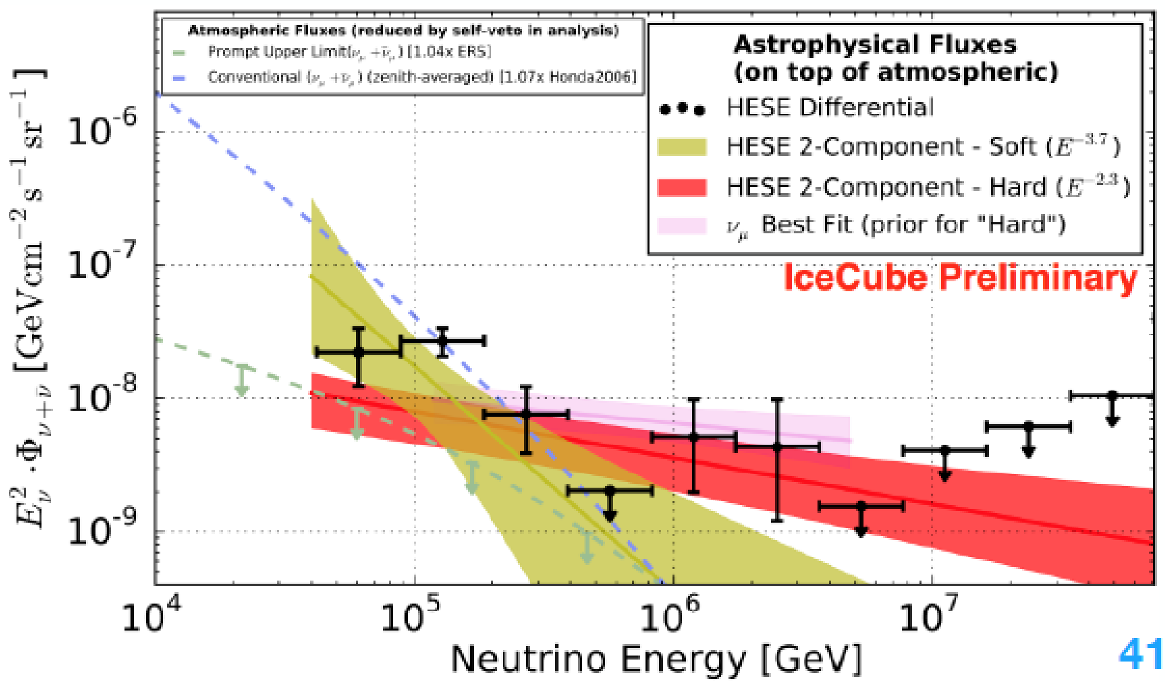
warning:

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

PeV neutrinos absorbed in the Earth

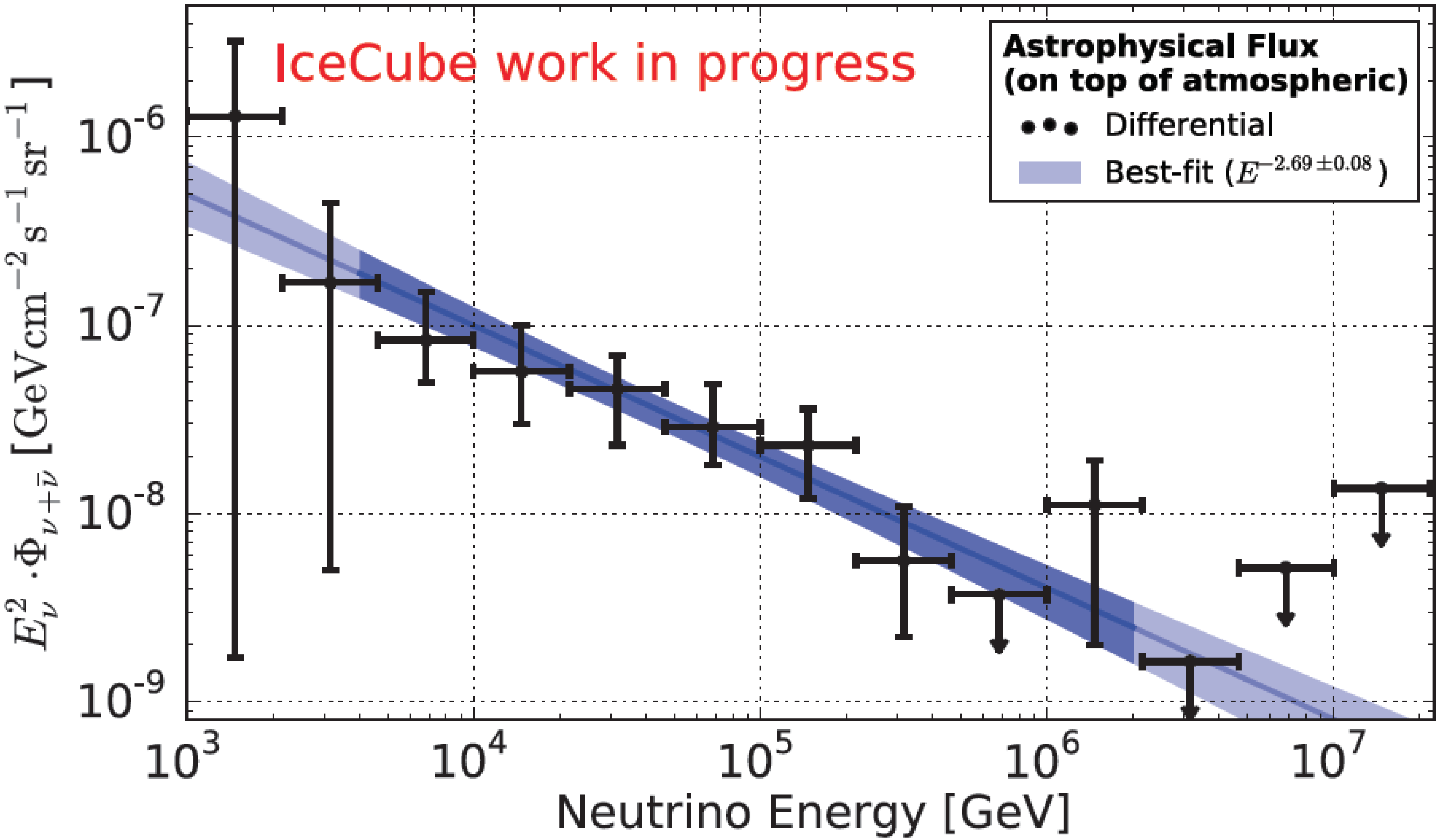


Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes (on top of atmospheric)
HESE Differential
HESE 1-Component ($E^{-2.9}$)
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]

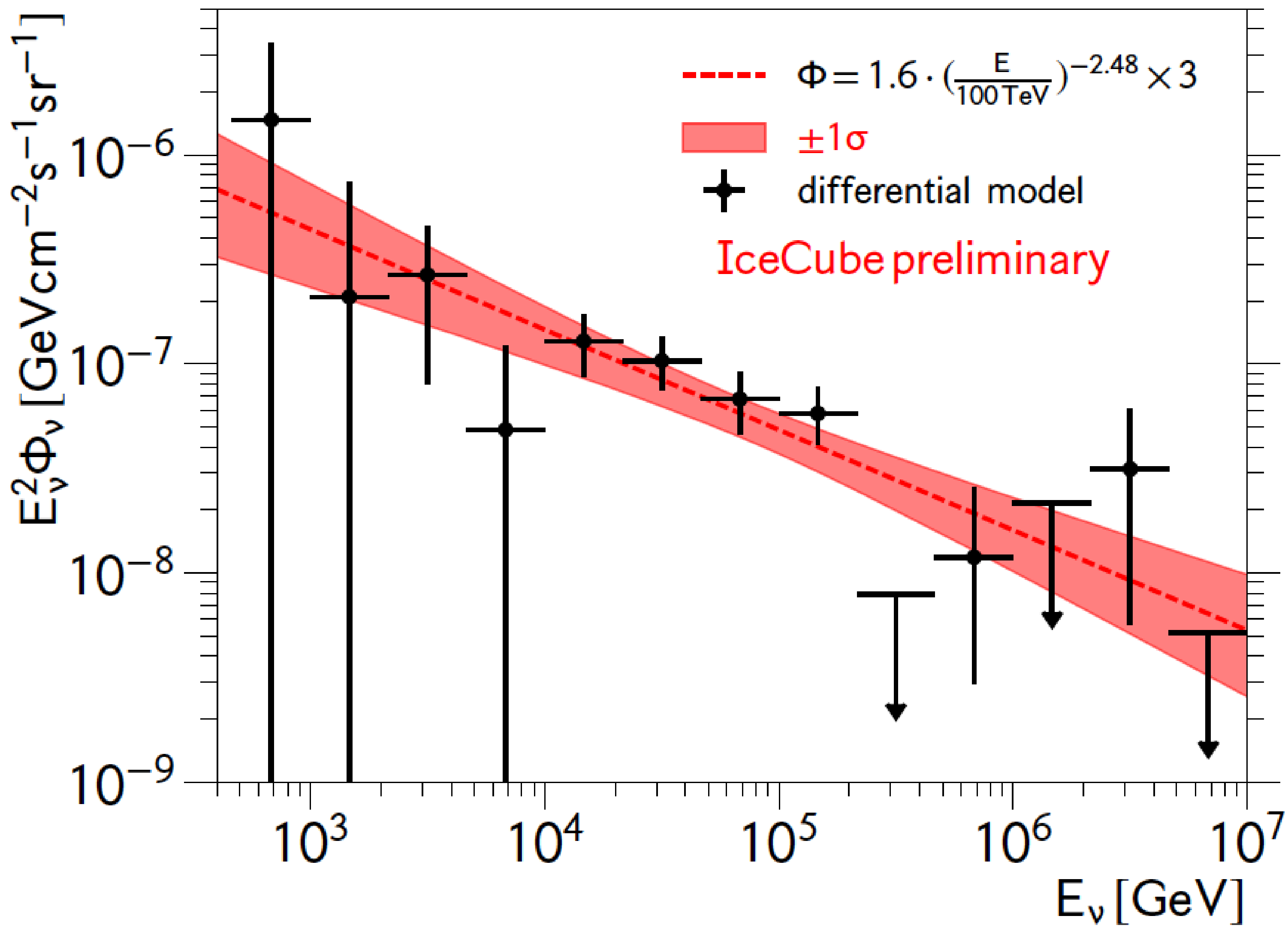


Atmospheric Fluxes (reduced by self-veto in analysis)
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
Astrophysical Fluxes (on top of atmospheric)
HESE Differential
HESE 2-Component - Soft ($E^{-3.7}$)
HESE 2-Component - Hard ($E^{-2.3}$)
ν_μ Best Fit (prior for "Hard")
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]

low threshold starting event analysis; 7 years



shower events only: cosmic flux dominates > 20 TeV

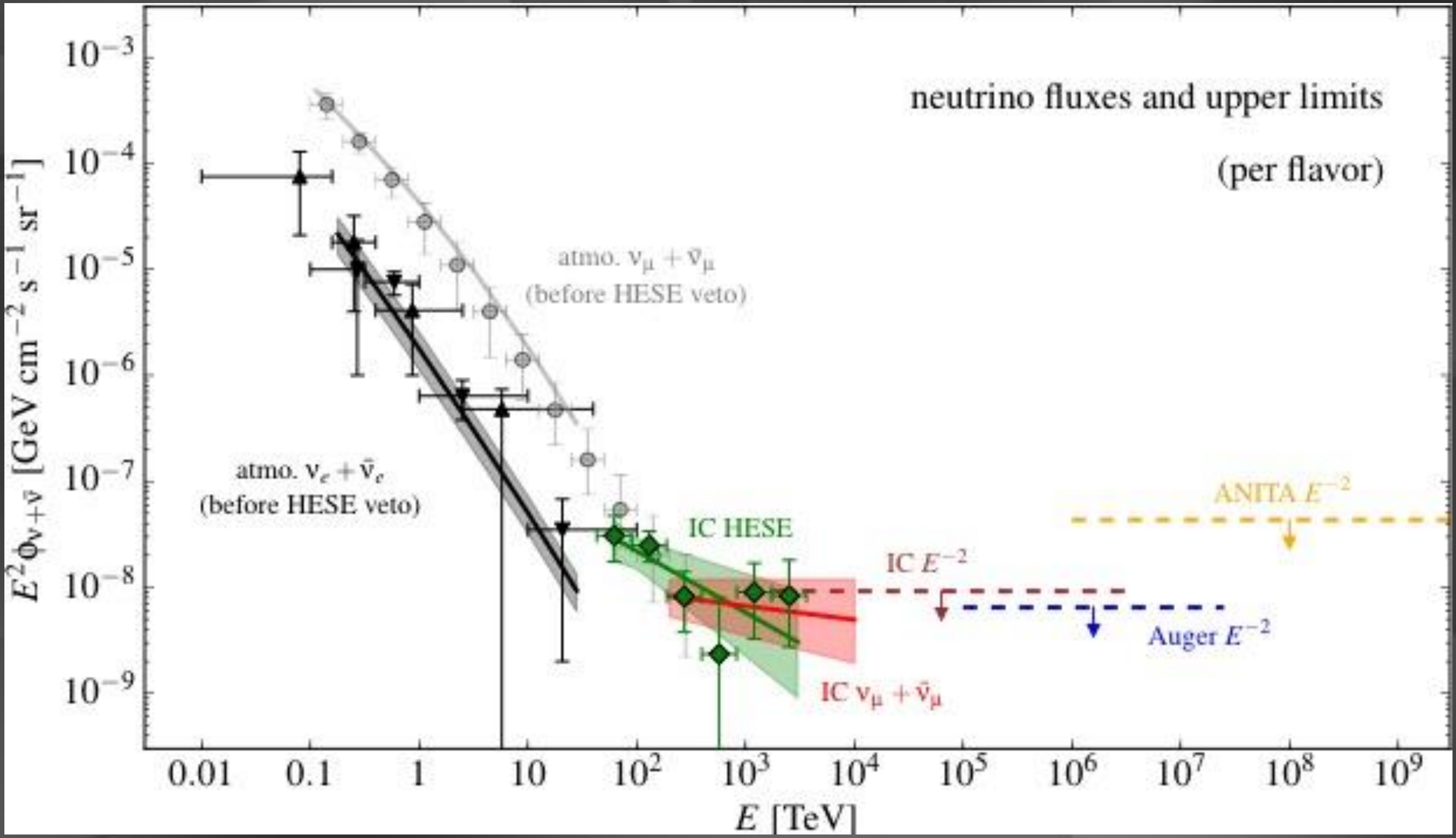


- two component cosmic neutrino flux?
- cosmic accelerators do not follow a power-law spectrum?
- note that the gammas rays accompanying

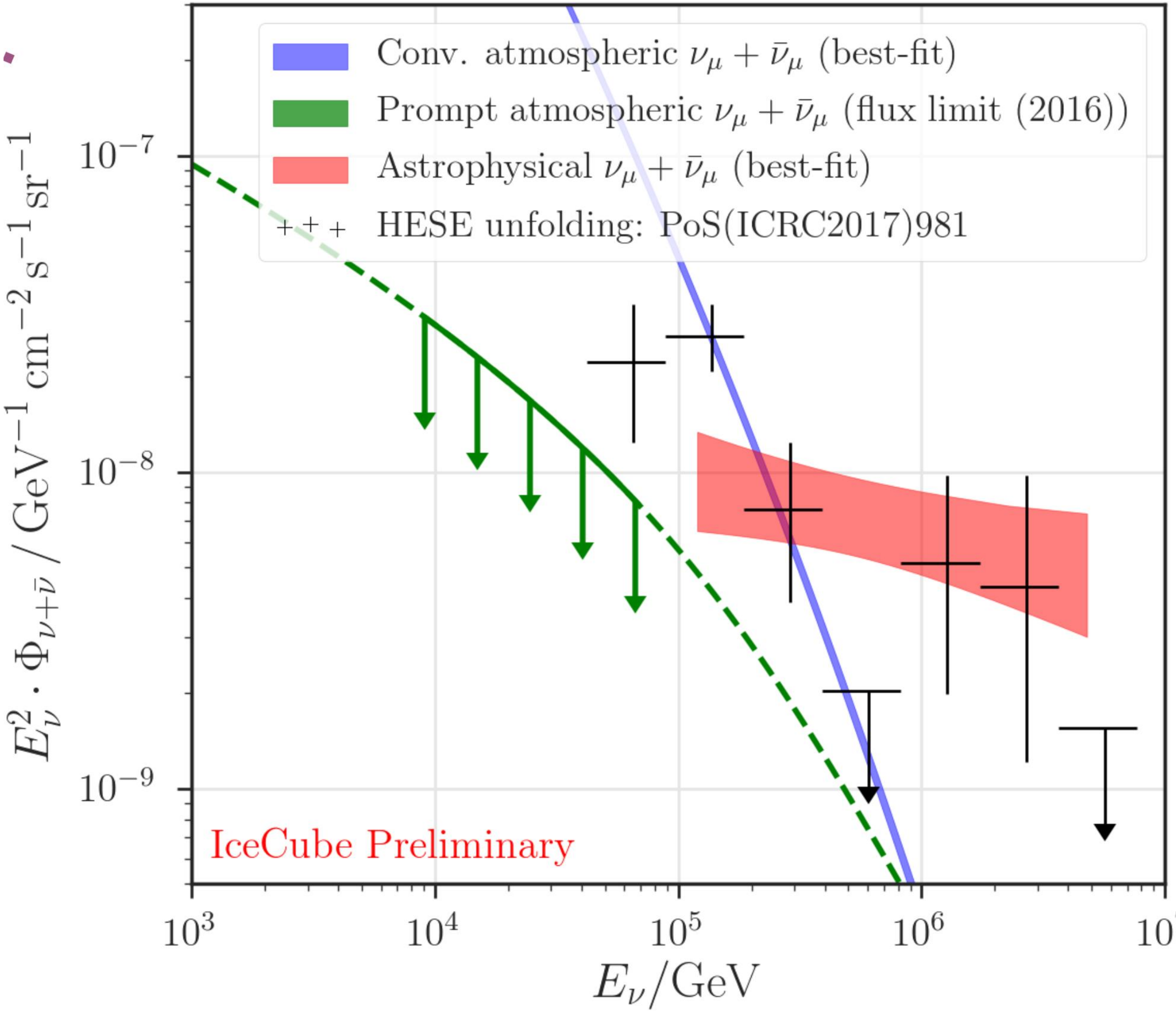
< 100 TeV neutrinos are not seen suggesting a hidden source(s)

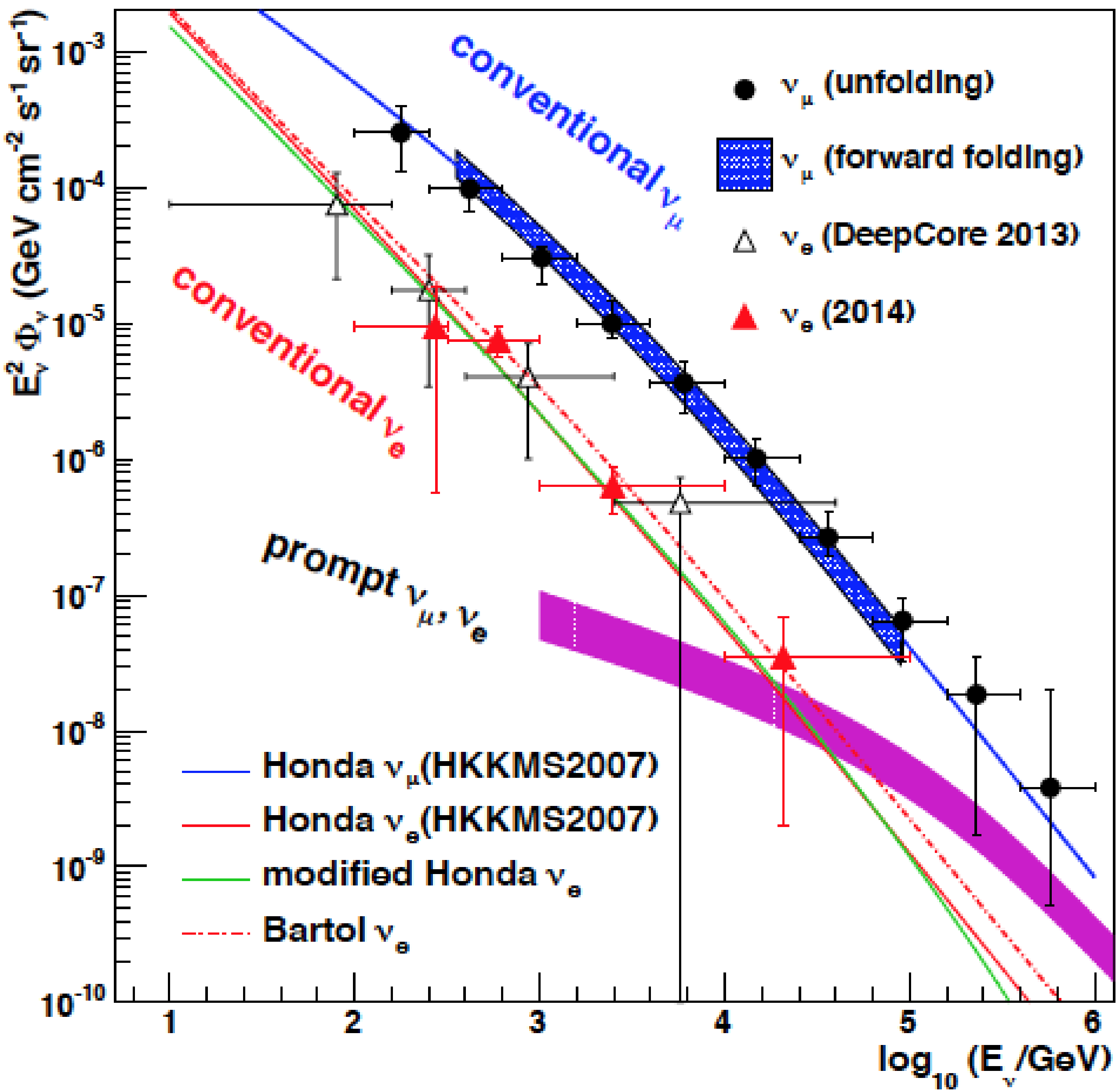
not background: prompt decay of charm particles produced in the atmosphere

- 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



8 years (ICRC 2017)





$E_\nu^2 \Phi_\nu$ (GeV cm^{-2} s^{-1} sr^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1
2
3
4
5
6
$\log_{10}$ (E_ν/GeV)
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
ν_μ (unfolding)
ν_μ (forward folding)
ν_e (DeepCore 2013)
ν_e (2014)
Honda ν_μ(HKKMS2007)
Honda ν_e(HKKMS2007)
modified Honda ν_e
Bartol ν_e

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- cosmic neutrinos below 100 TeV?
- the Galaxy

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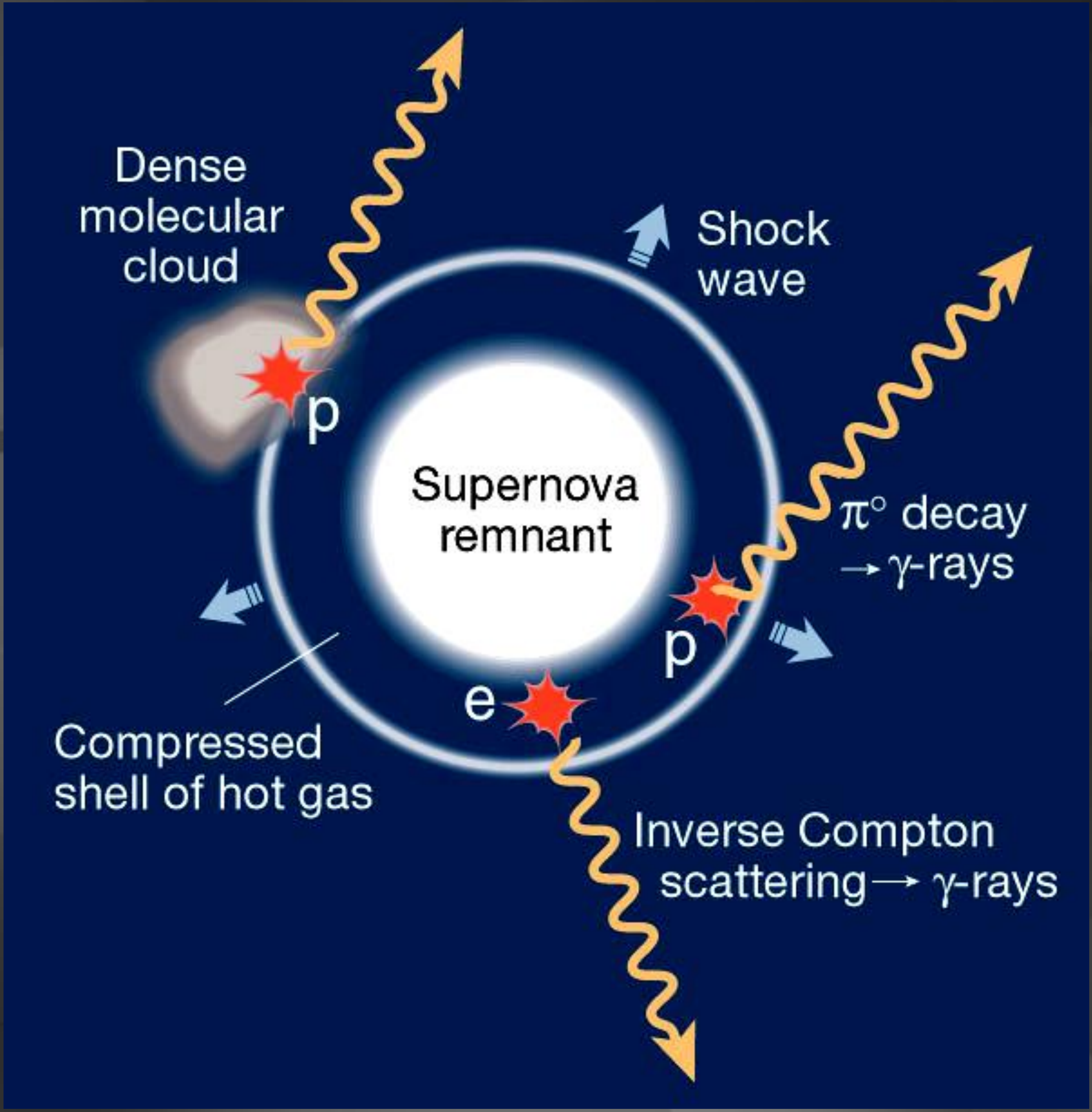
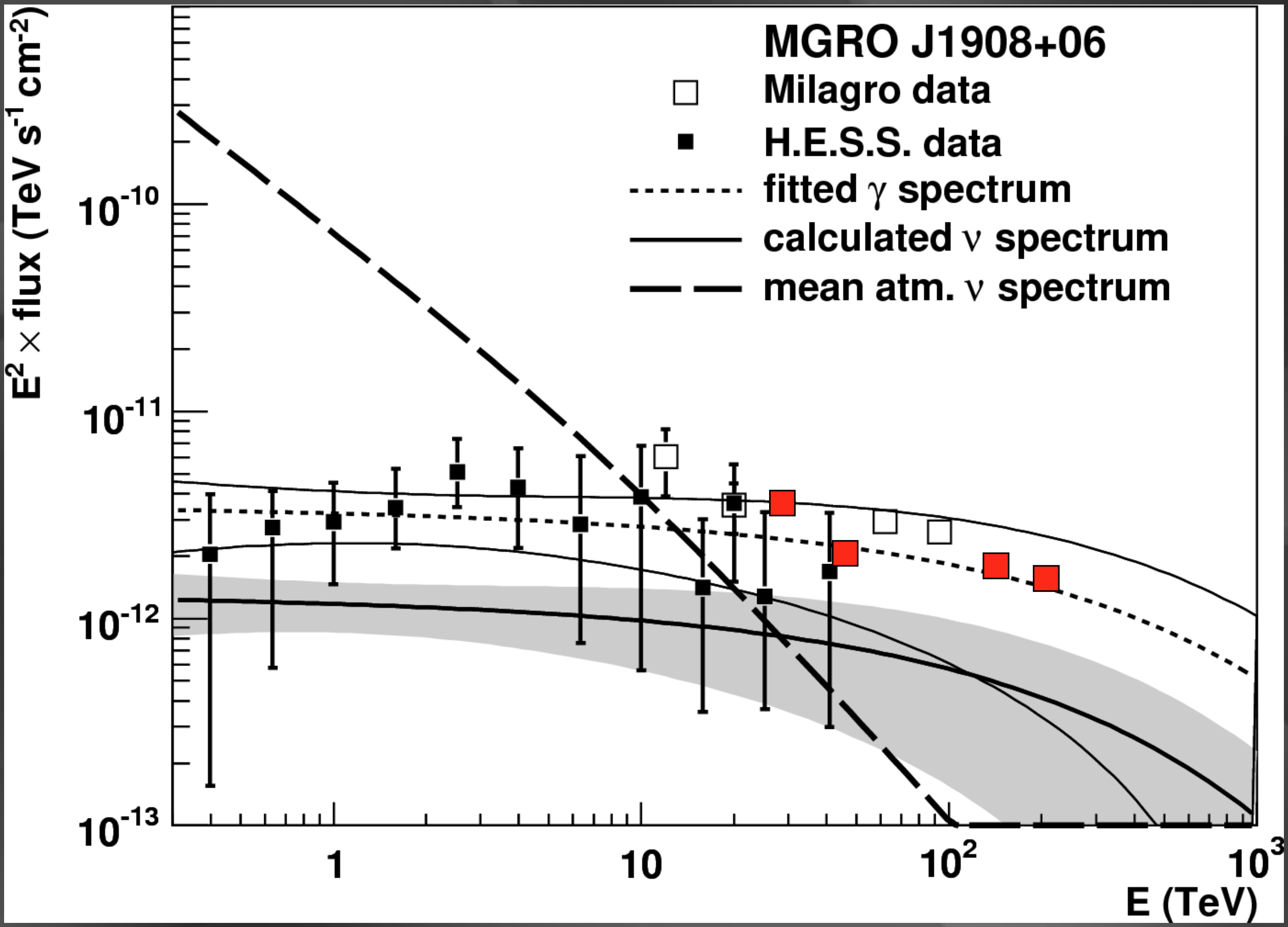
neutrinos from supernova remnants :

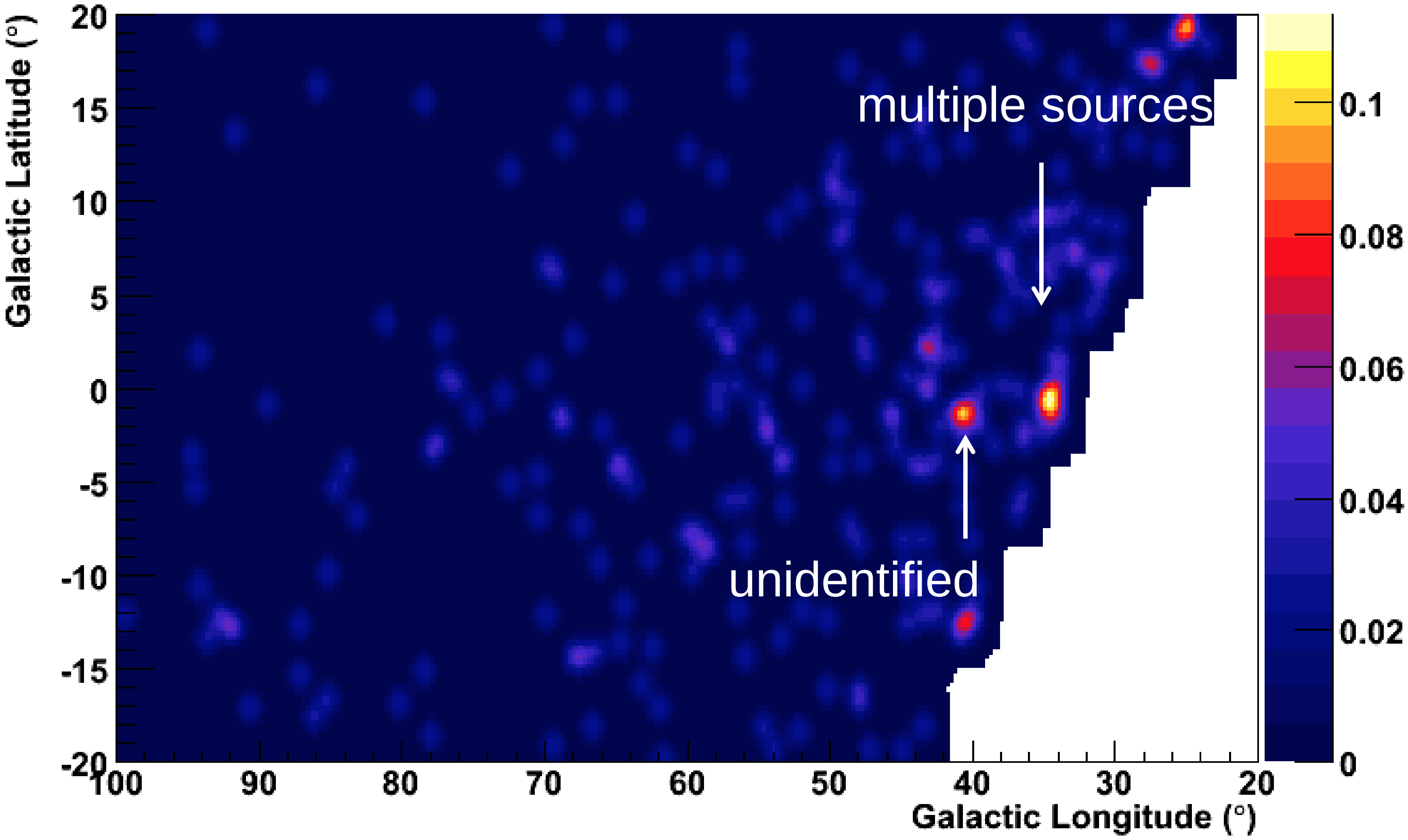
molecular clouds as beam dumps of PeVatrons



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



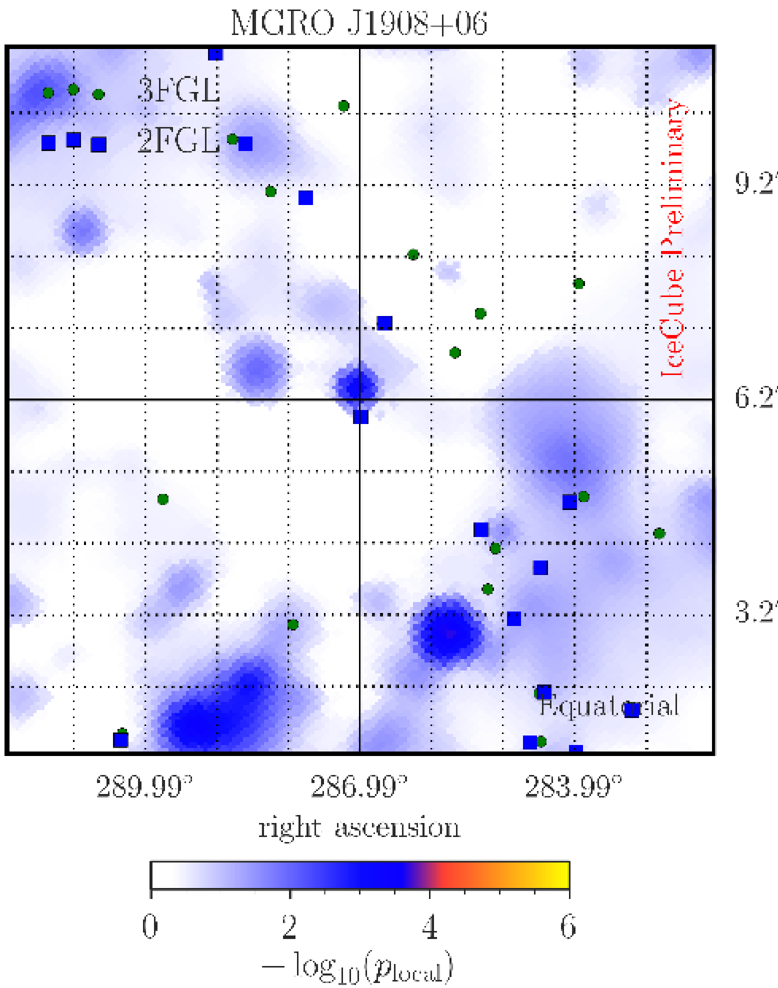
2007 simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.



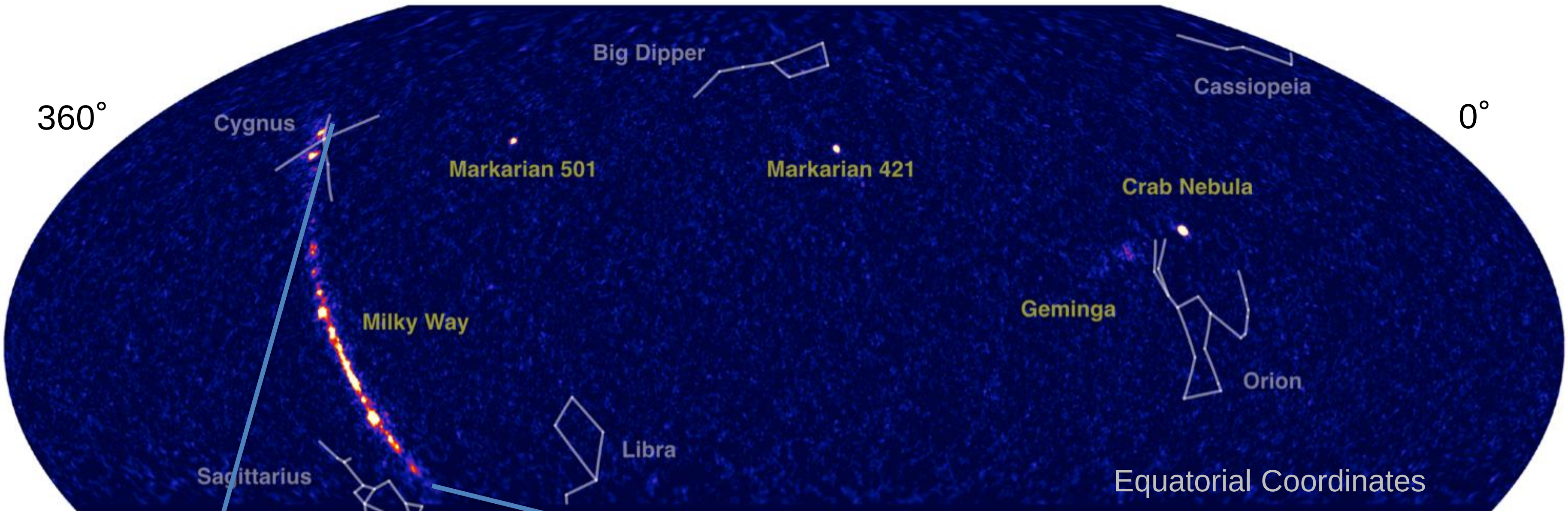
- most significant source in pre-defined list (p-value 0.003 pretrial)
- joined HAWC-IceCube analysis in progress using photon templates

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

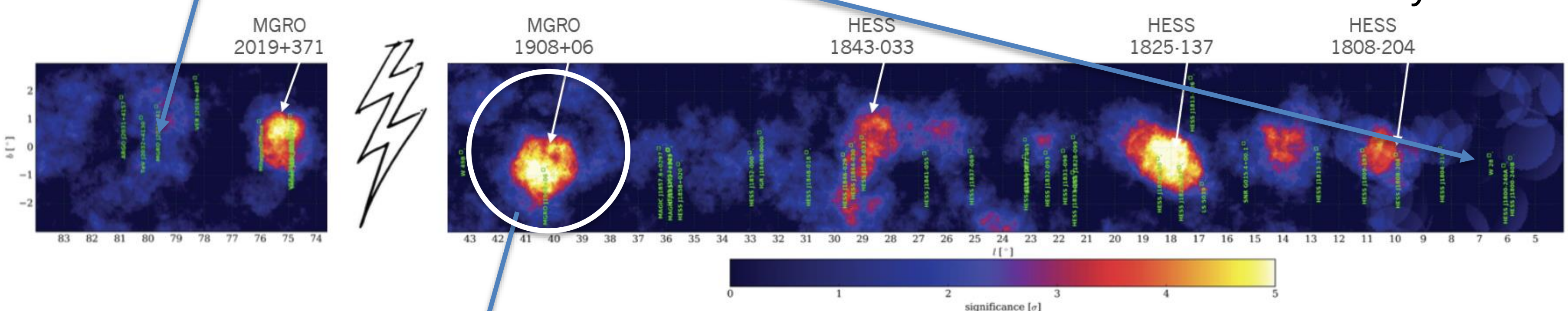
Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [$\mathrm{TeV\,cm^{-2}\,s^{-1}}$]
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04 \cdot 10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.059	0.00	$4.47 \cdot 10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.055	0.00	$5.37 \cdot 10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68 \cdot 10^{-13}$
Mrk 501	BL Lac	253.47	39.76	0.6847	-0.172	0.00	$3.51 \cdot 10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58 \cdot 10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7890	-0.243	0.00	$1.96 \cdot 10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50 \cdot 10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58 \cdot 10^{-13}$
1ES 1959+650	BL Lac	300.00	65.15	0.2003	0.124	1.69	$1.17 \cdot 10^{-12}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84 \cdot 10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42 \cdot 10^{-13}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98 \cdot 10^{-13}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.74 \cdot 10^{-13}$
3C454.3	FSRQ	343.50	16.15	0.0072	5.503	5.98	$1.26 \cdot 10^{-12}$
4C 38.41	FSRQ	248.81	38.13	0.0055	5.686	6.62	$1.72 \cdot 10^{-12}$
MGRO J1908+06	NI	286.99	6.27	0.0032	6.284	3.28	$1.13 \cdot 10^{-12}$
Geminga	PWN	98.48	17.77	0.9754	-2.424	0.00	$1.16 \cdot 10^{-13}$
Crab Nebula	PWN	83.63	22.01	0.1188	0.709	4.32	$8.65 \cdot 10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	0.9884	-3.191	0.00	$1.39 \cdot 10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53 \cdot 10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22 \cdot 10^{-13}$
Cas A	SNR	350.85	58.81	0.2069	0.033	0.88	$1.05 \cdot 10^{-12}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14 \cdot 10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85 \cdot 10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30 \cdot 10^{-13}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78 \cdot 10^{-12}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31 \cdot 10^{-13}$
M82	SRG	148.97	69.68	0.8887	-0.888	0.00	$1.83 \cdot 10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01 \cdot 10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01 \cdot 10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93 \cdot 10^{-13}$
Cyg X-3	XB/mqso	308.11	40.96	0.3230	-0.003	0.00	$7.28 \cdot 10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01 \cdot 10^{-12}$



HAWC View of Gamma Ray Sky



E > 1 TeV 340 days



MGRO J1908+06

HAWC sky above 55 TeV

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

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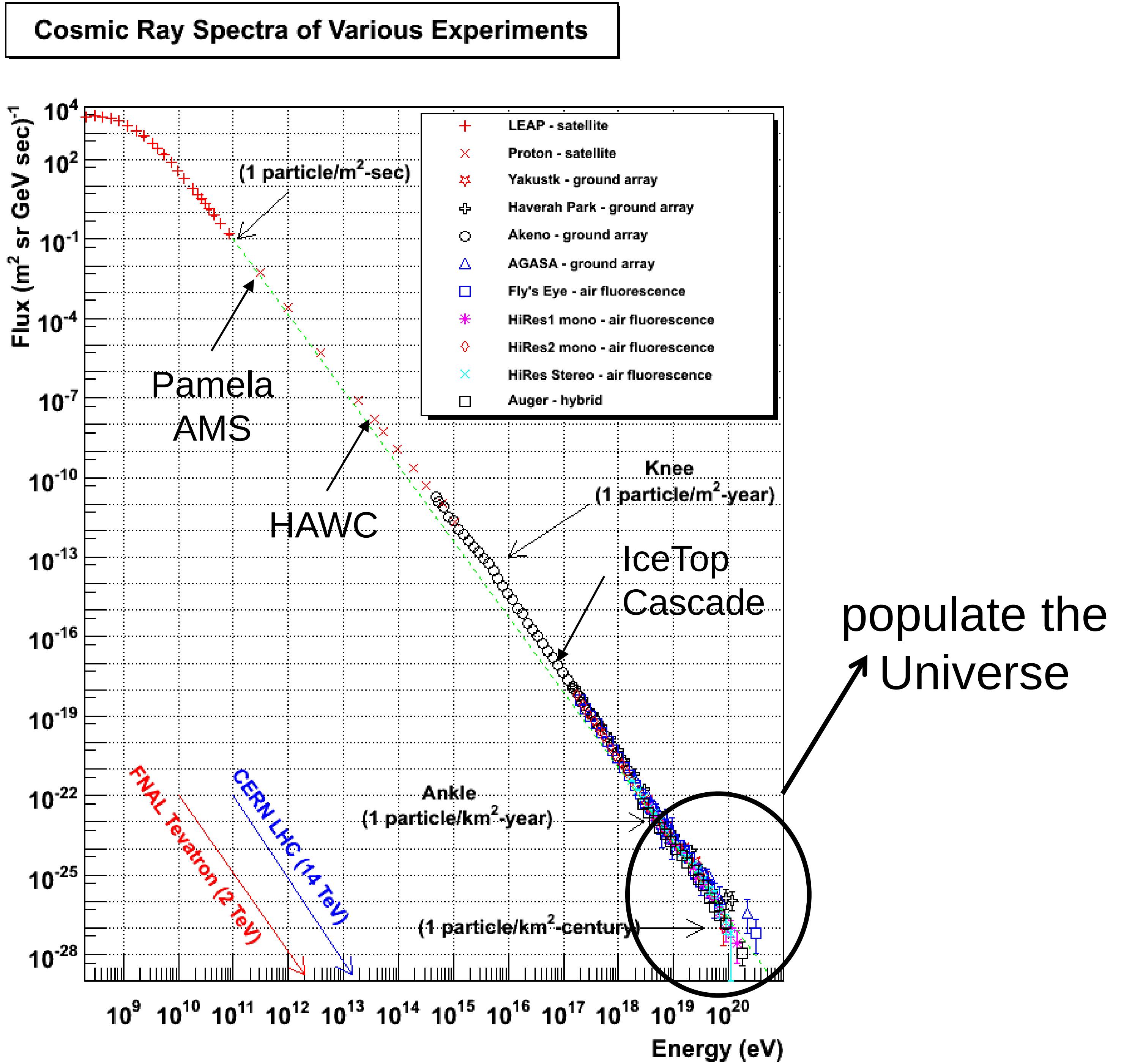
US National Science Foundation (NSF)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

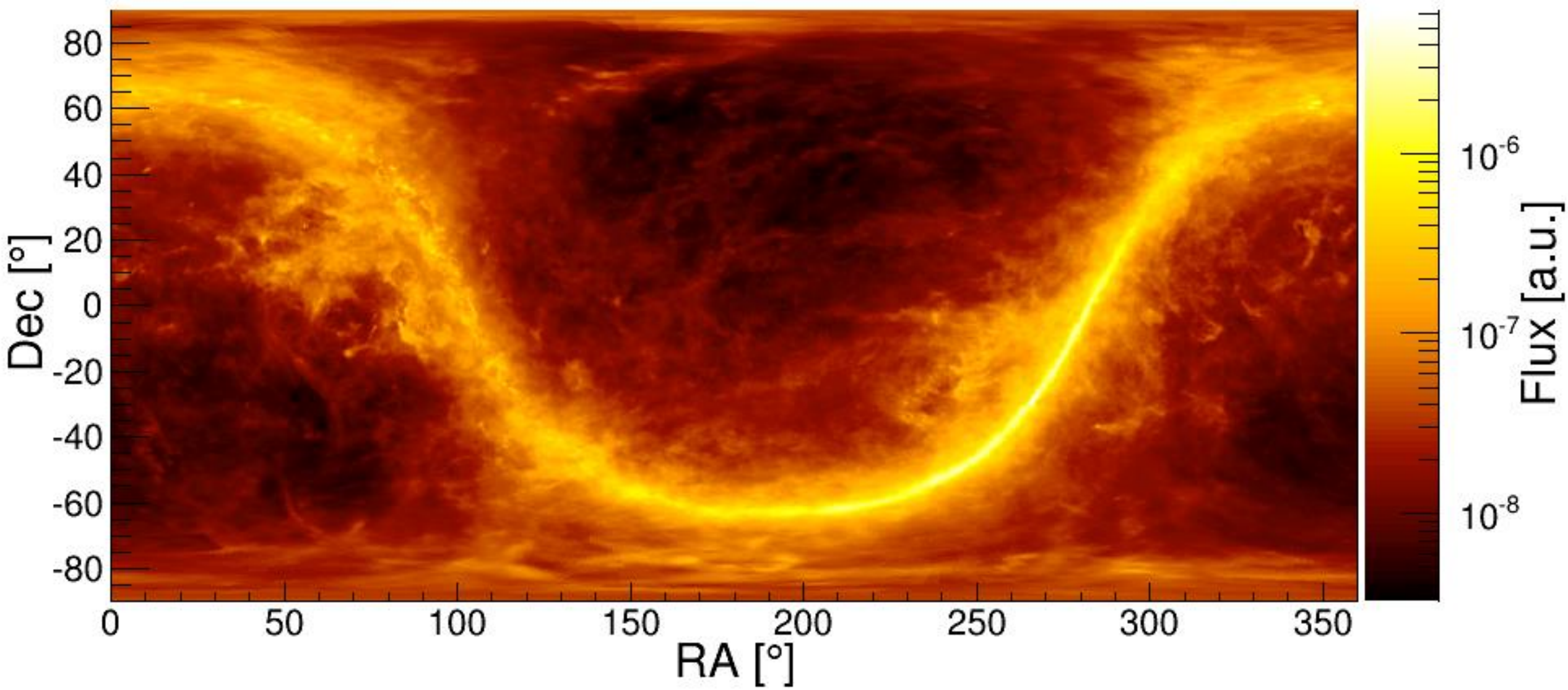
Related talks with more details:

- Nancy Wandkowski– starting events 6 years
- Nancy Wandkowski– low threshold starting events 7 years
- Hans Niederhausen– neutrino induced showers 4 years
- Lu Lu– All flavor very high energy analysis
- Joshua Wood-– joint HAWC-IceCube Galactic analysis
- Sarah Mancina– impoved starting muon neutrino analysis
- Donglian Xu– fast radio burst
- Carsten Rott– neutrinos from the sun
- Mike Richman– point source search 6 years
- Zach Griffith– high energy gamma ray search
- Tianlu Yuan– improved shower reconstruction
- Daan Van Eijk– ANTARES and KM3NeT

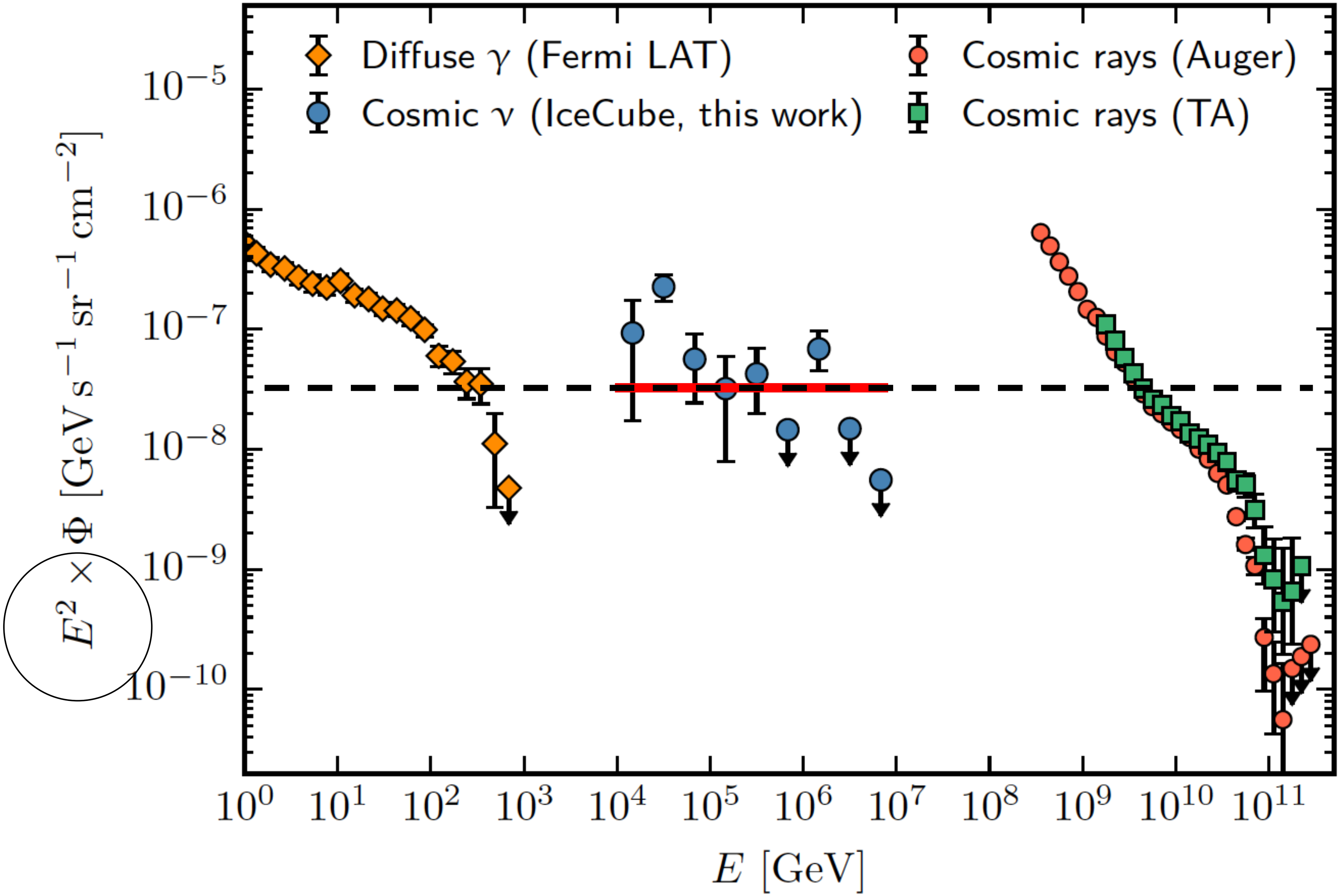
overflow slides



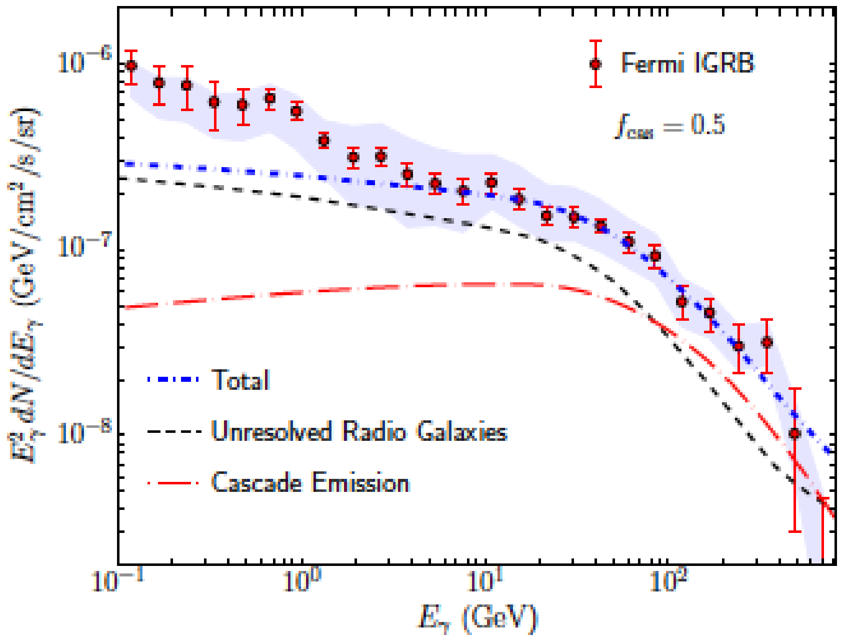
Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes 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

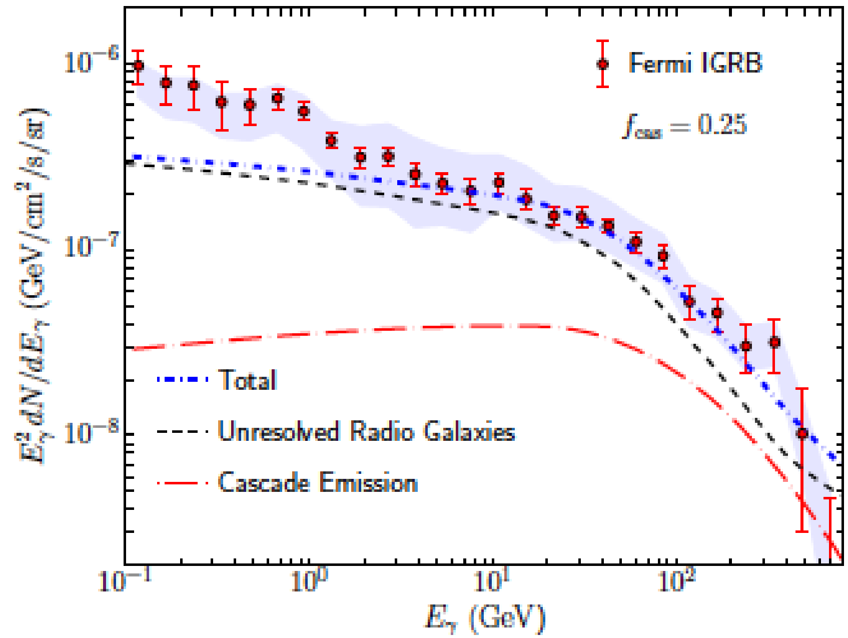


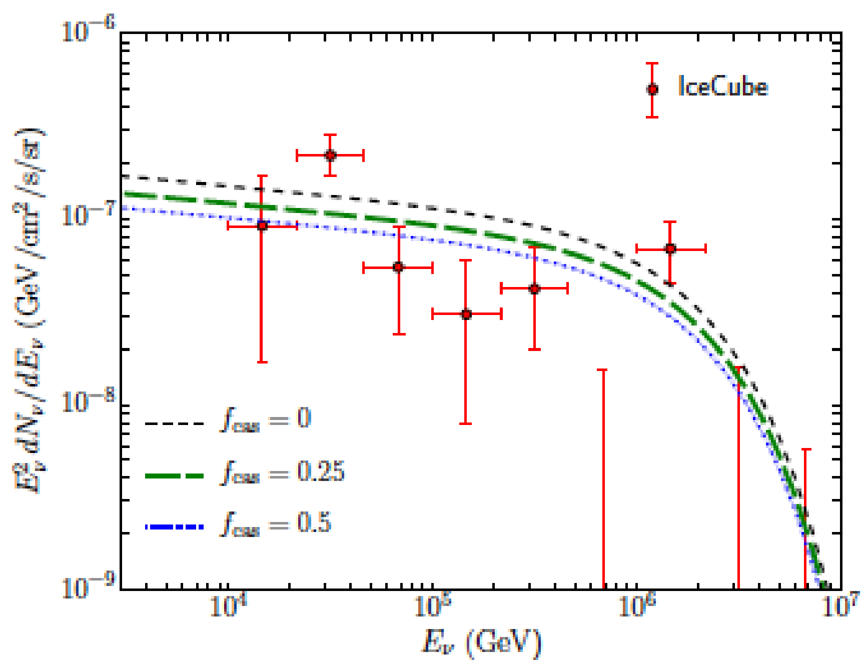
Dec [°]
80
60
40
20
0
-20
-40
-60
-80
0
50
100
150
200
250
300
350
RA [°]
Flux [a.u.]
10^{-6}
10^{-7}
10^{-8}



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



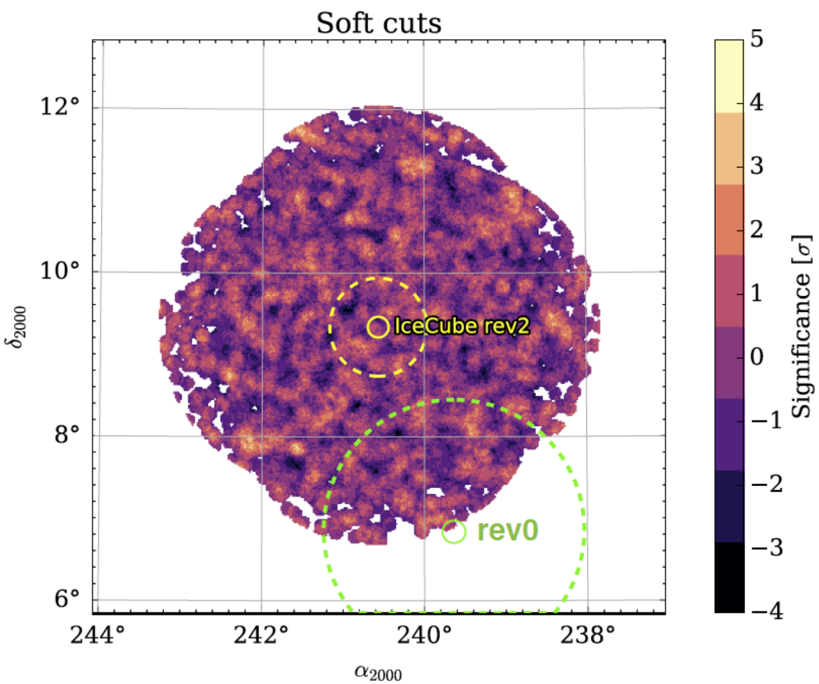




radiogalaxies

Tjus et al.
Hooper

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°

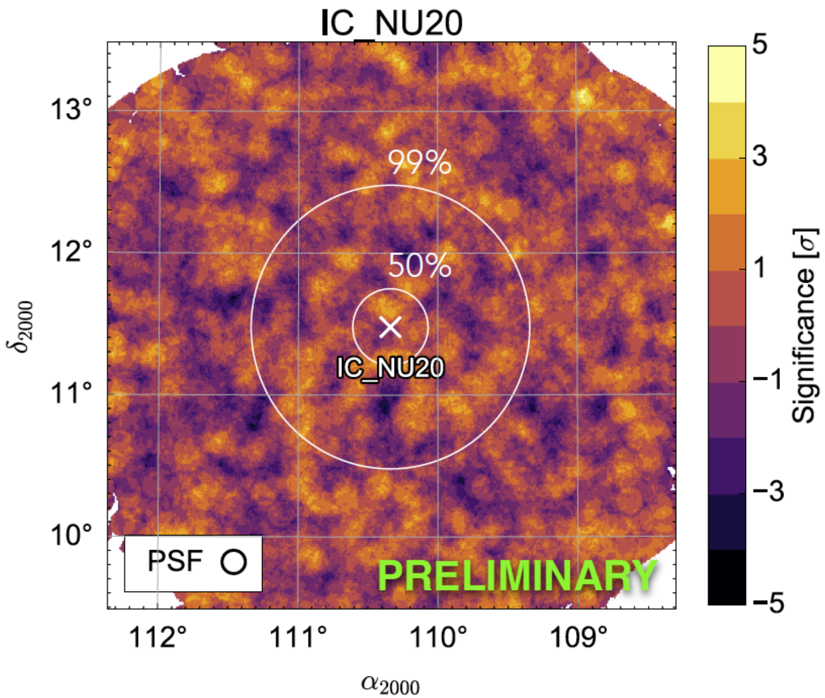
- Rev0: **71 min** live-time (reduced high-voltage)
- Rev2: **118 min** live-time (reduced high-voltage) taken on Apr 28th.
- **No gamma-ray signal in the ROI.**

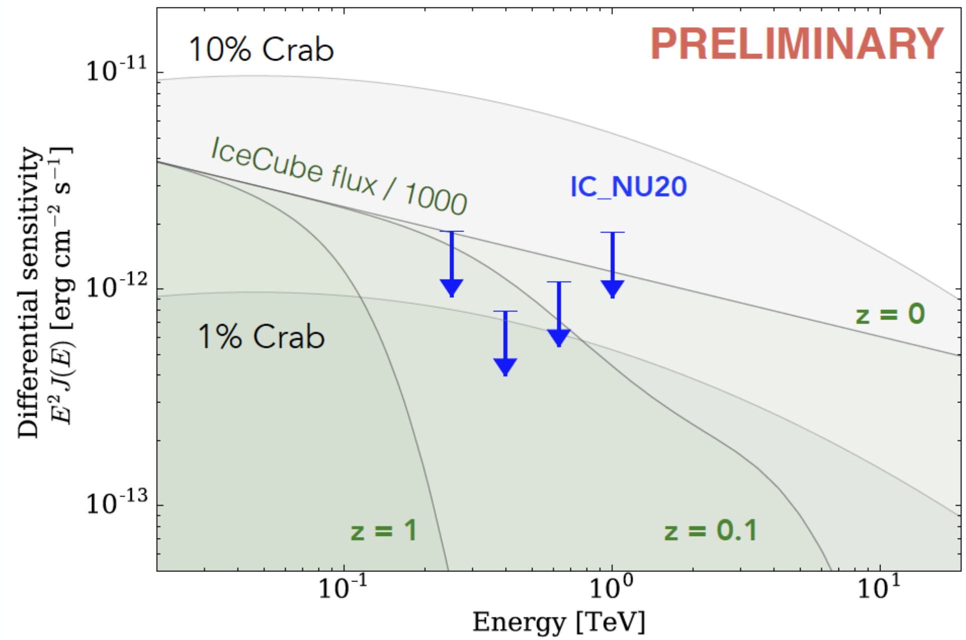
More neutrinos from IceCube!

- 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)

VERITAS observation of the PeV muon location

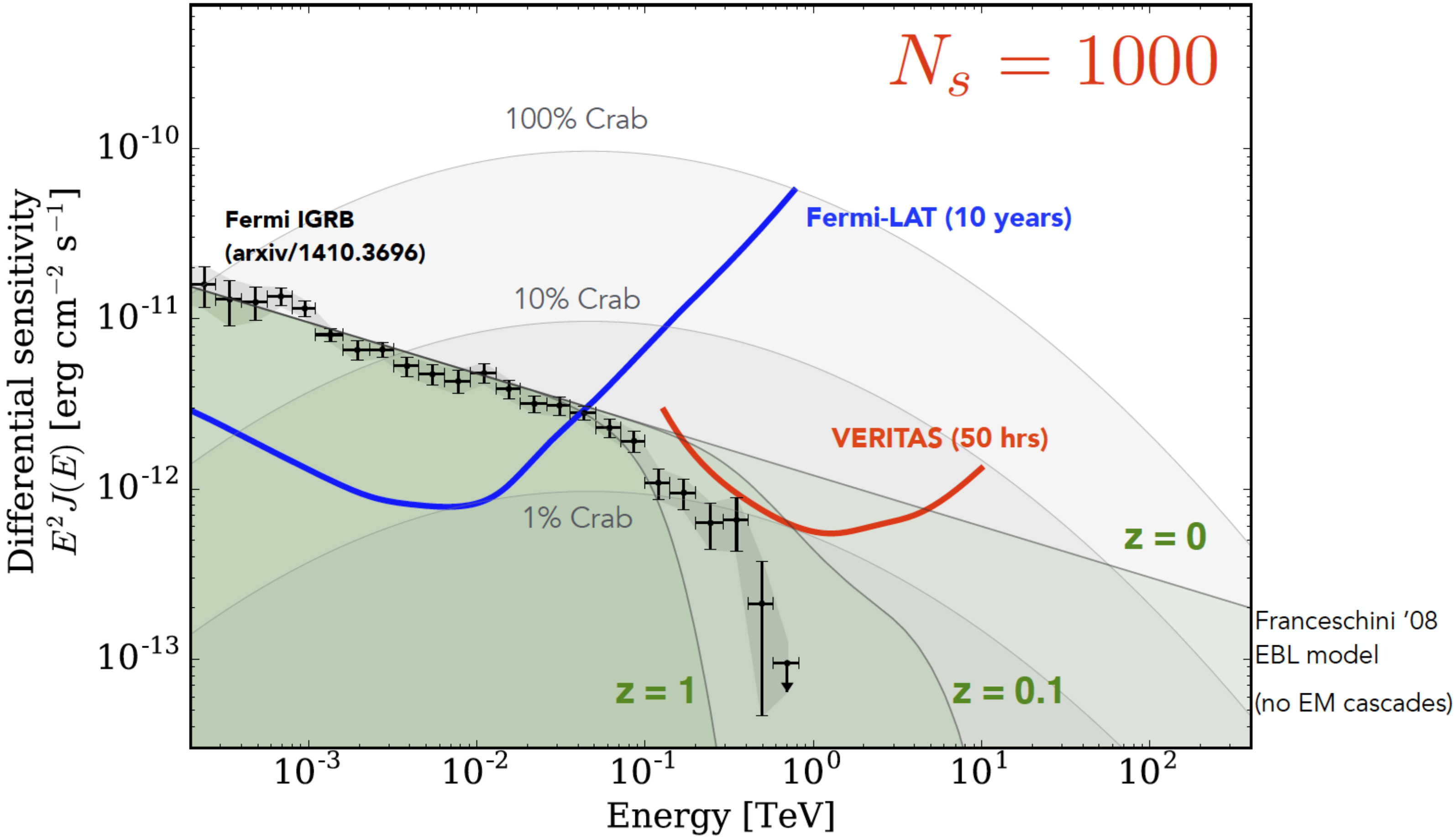




- 4 runs (1.83 hr of live-time) taken on 03/27/2016 under dark conditions. Analysis optimized for soft-spectrum sources.
- **No gamma emission detected** within the neutrino error circle. ULs at the level of a few percent of the Crab.
- **Upper limits at the level of 0.1% of the all-sky astrophysical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

Gamma-ray flux from IceCube sources

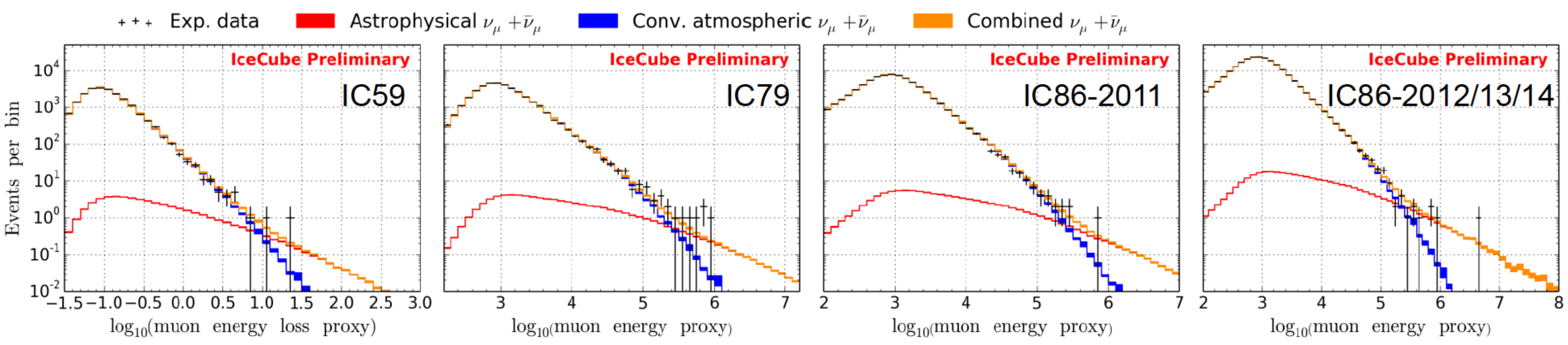
Quasi-isotropic IceCube neutrino flux converted to gamma-ray flux from N_s sources

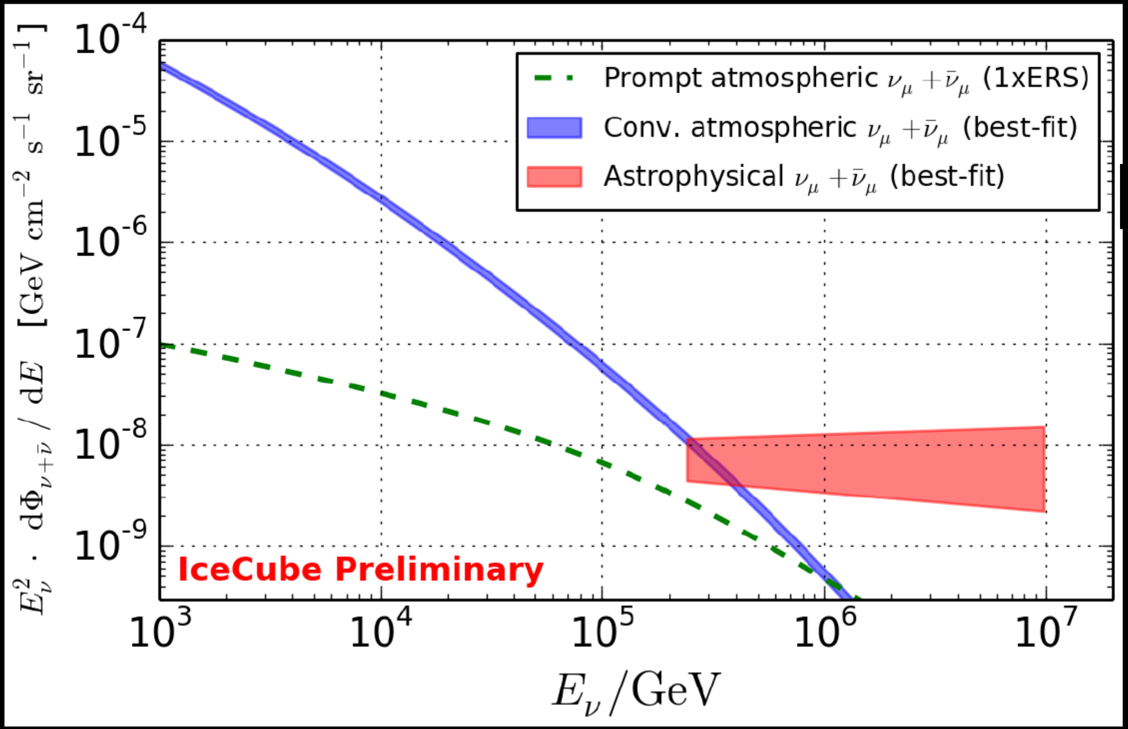


$$E^2 \phi_\gamma^s(E) = \frac{4\pi}{N_s} 1.5 \times 10^{-11} \left(\frac{E}{100\ \mathrm{TeV}} \right)^{-0.3} [\mathrm{TeV\ s^{-1}\ cm^{-2}}]$$

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

after 7 years → 6 sigma





- Best-fit astrophysical normalization:

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

- Best-fit spectral index:

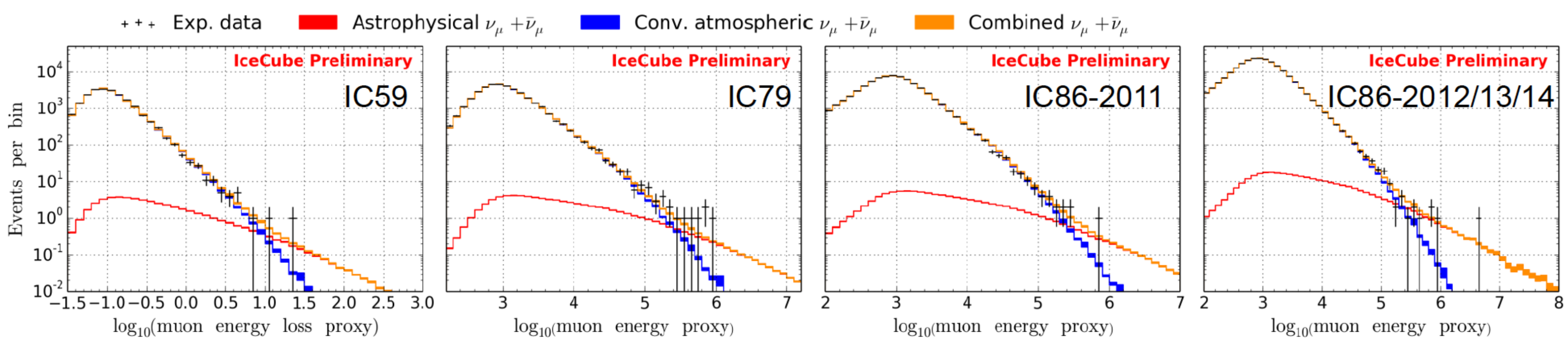
  γ_{astro} = 2.16 ± 0.11

- Energy ranges:

  240 TeV – 10 PeV

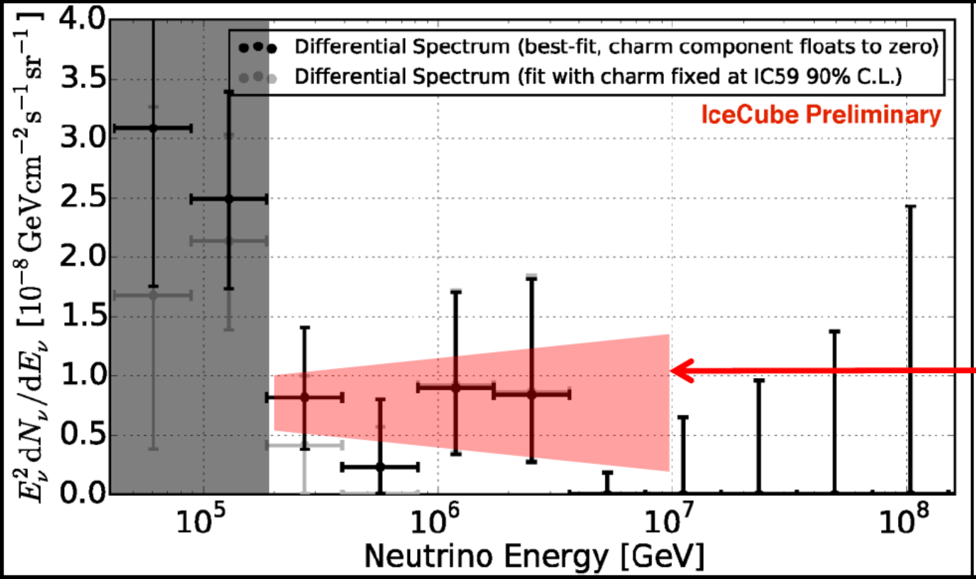
- Atmospheric-only hypothesis excluded by 6.0σ

after 6 years: 3.7→ 6.0 sigma

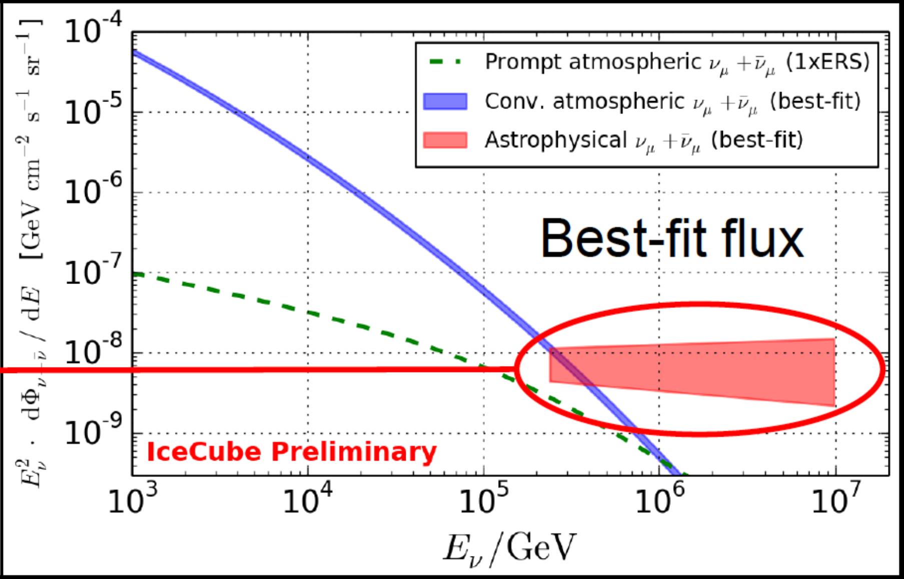


HESE 4 year unfolding

(→ dominated by shower-like events)



6 year up-going numu analysis



- Different event signatures allow flavor separation → primarily μ vs. e, τ

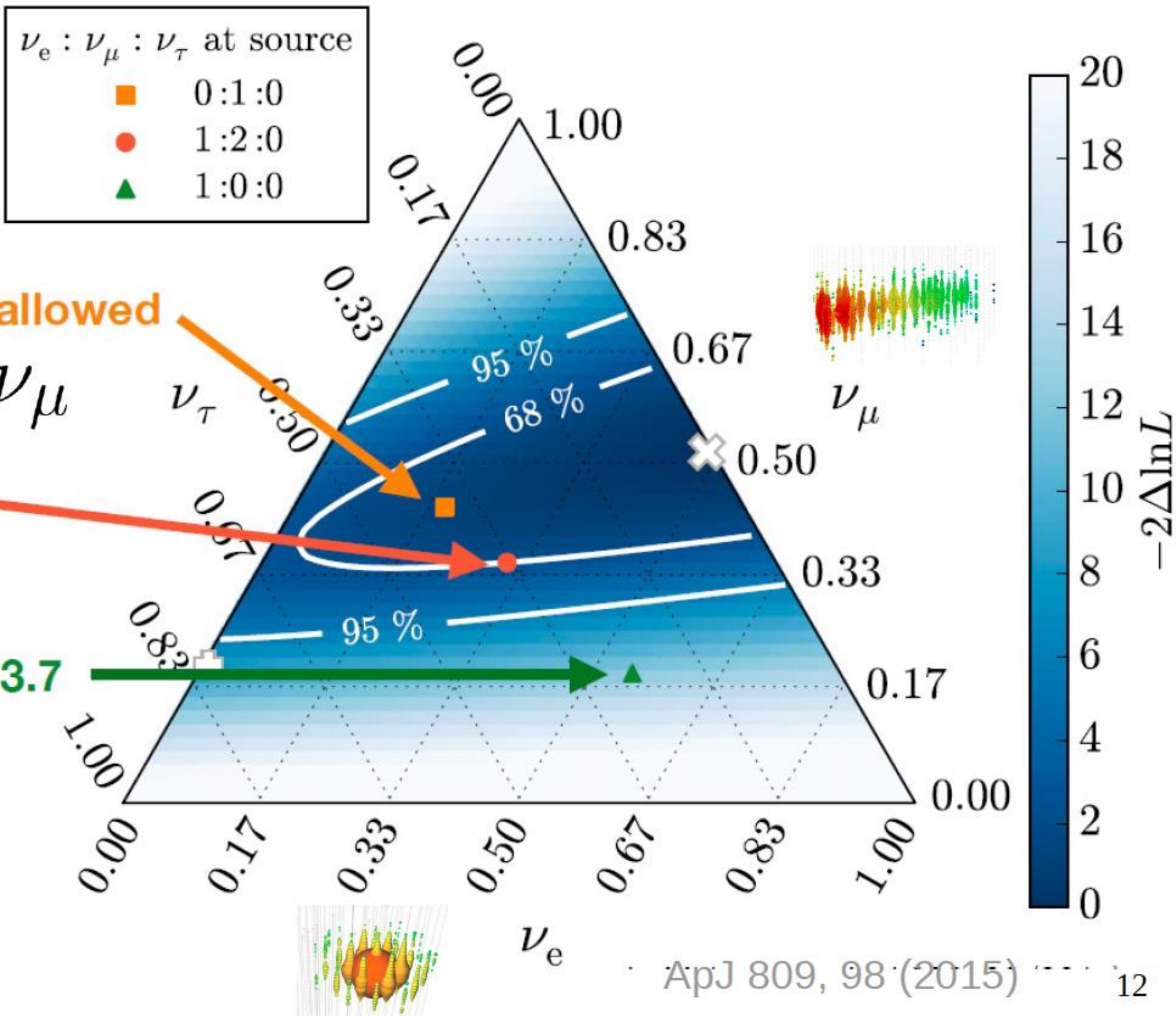
Muon-damped pion decay: allowed

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

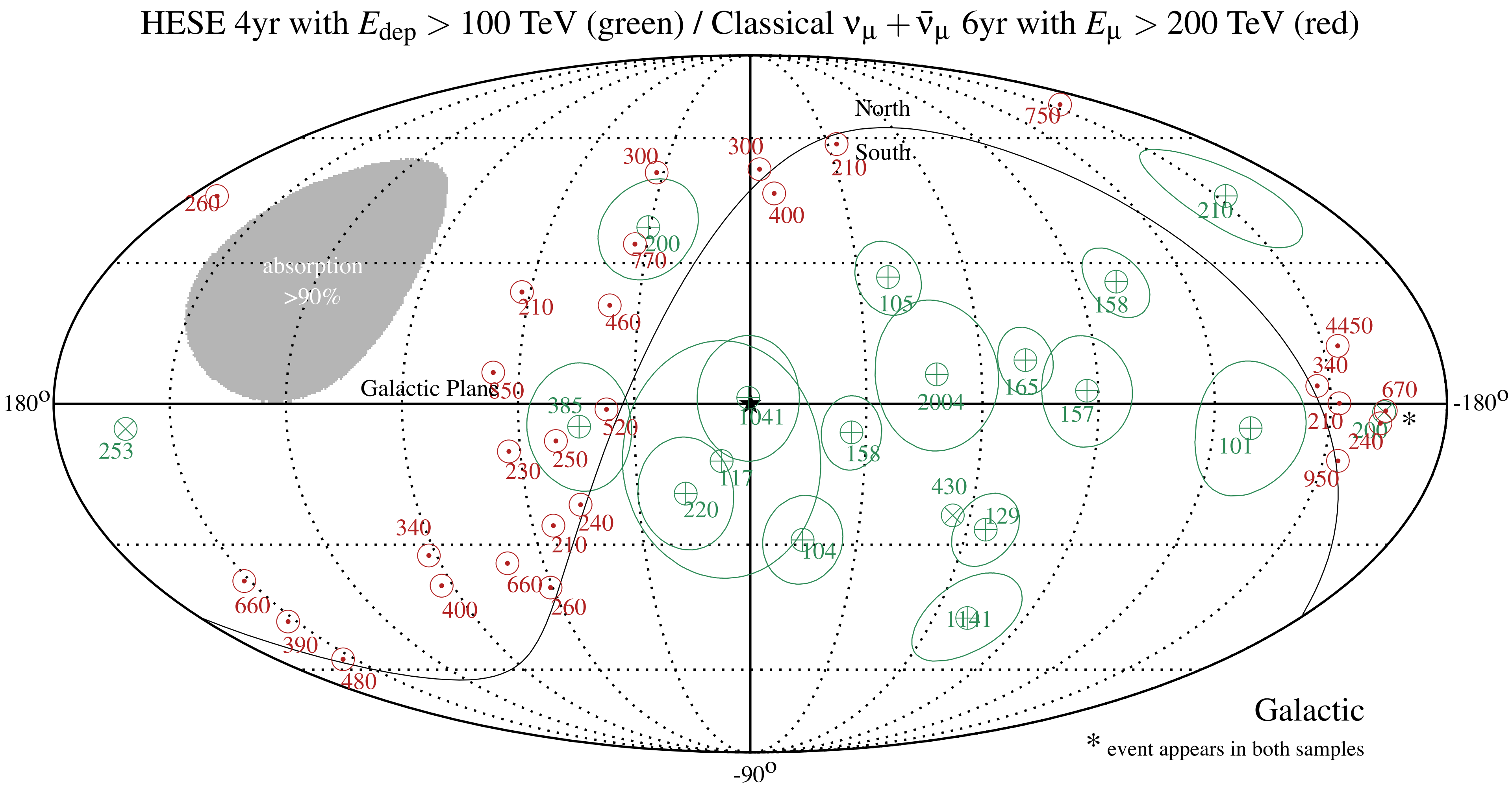
Pion decay: allowed

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

Neutron decay: rejected at 3.7

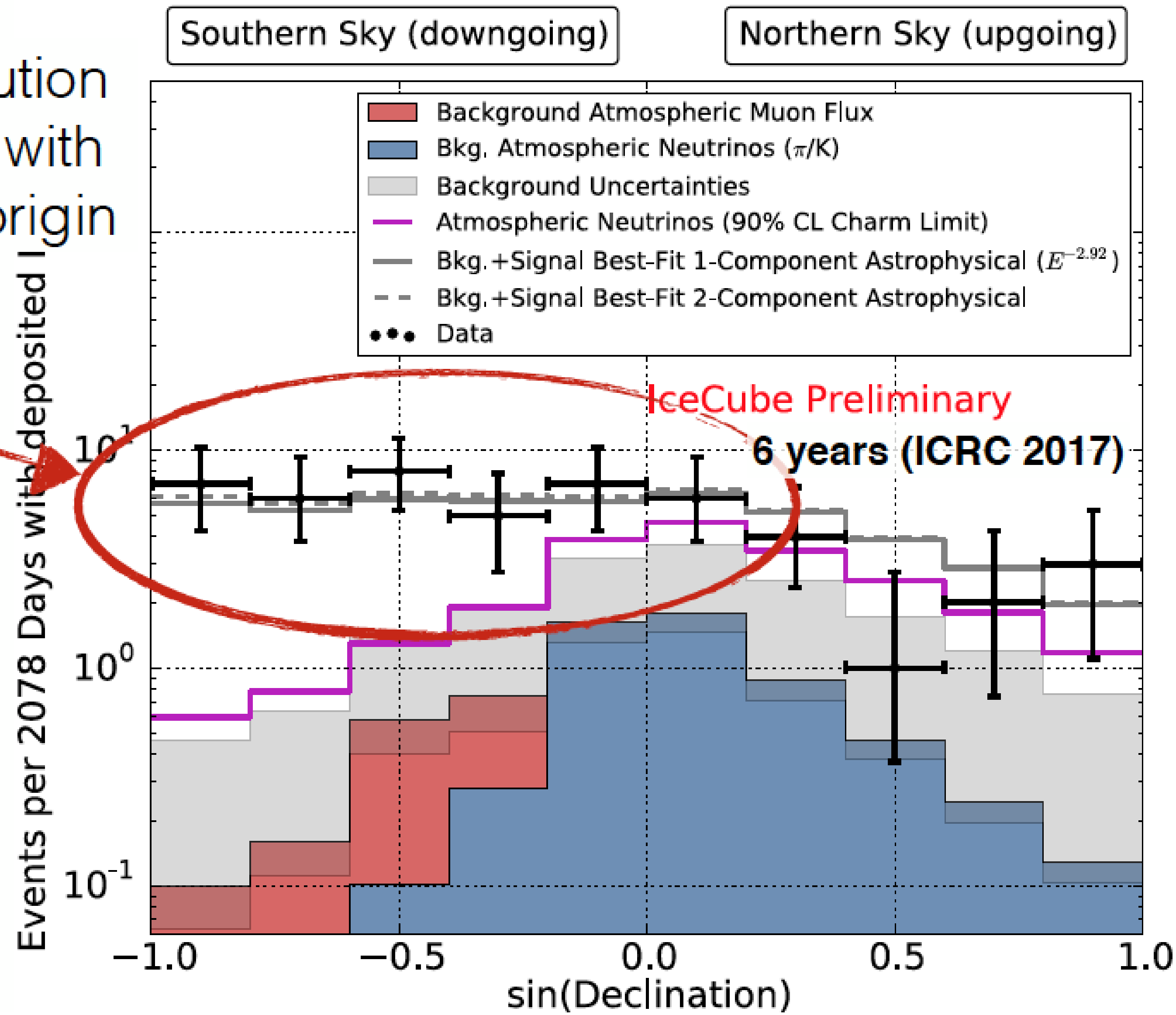


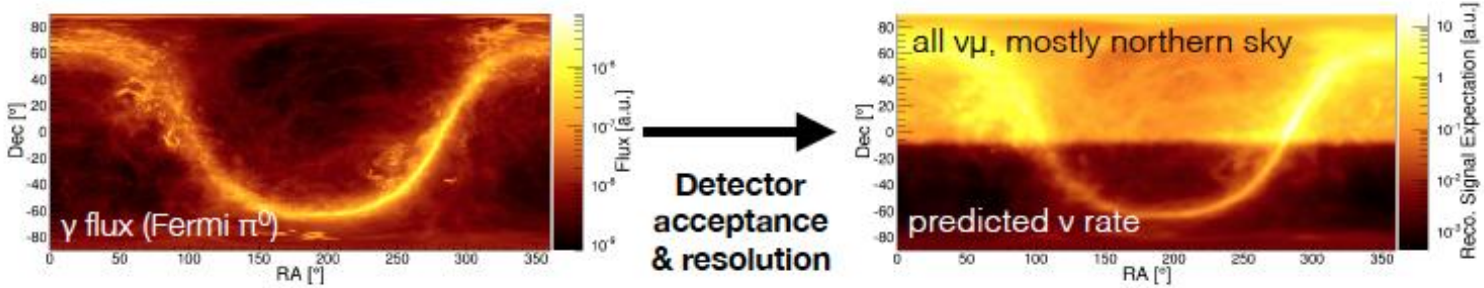
ApJ 809, 98 (2015)

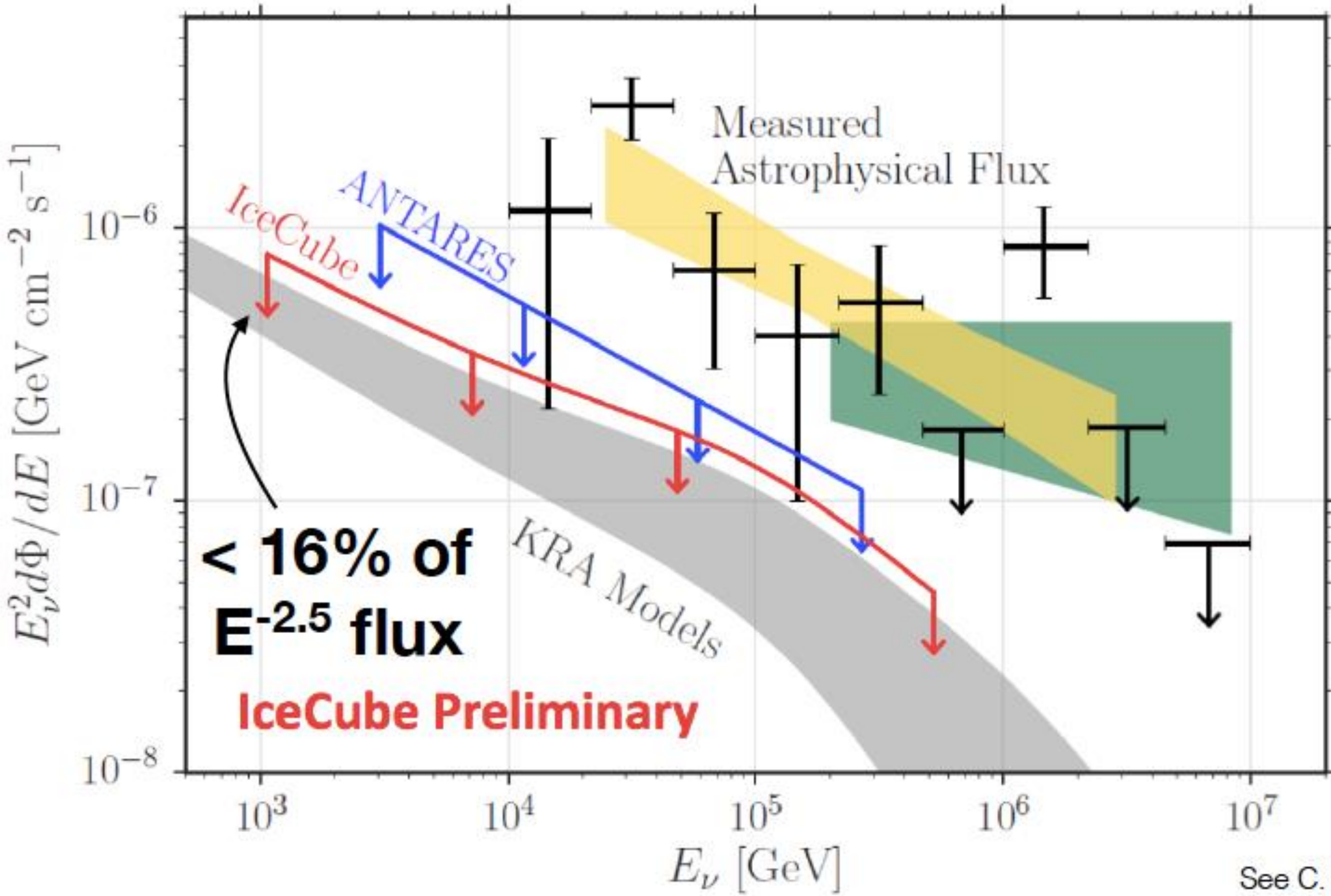


HESE 4yr with E_{dep} > 100 TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with E_μ > 200 TeV (red)
North
South
Galactic Plane
absorption
>90%
180°
-180°
-90°
Galactic
* event appears in both samples
750
300
300
210
400
260
200
770
210
210
460
105
158
4450
340
850
385
520
1041
2004
165
157
670
210
200
240
253
250
230
158
101
950
117
430
240
220
129
340
210
104
660
660
260
400
1141
390
480

Zenith distribution incompatible with atmospheric origin







See C. Haack, NU013
arXiv:1707.03416