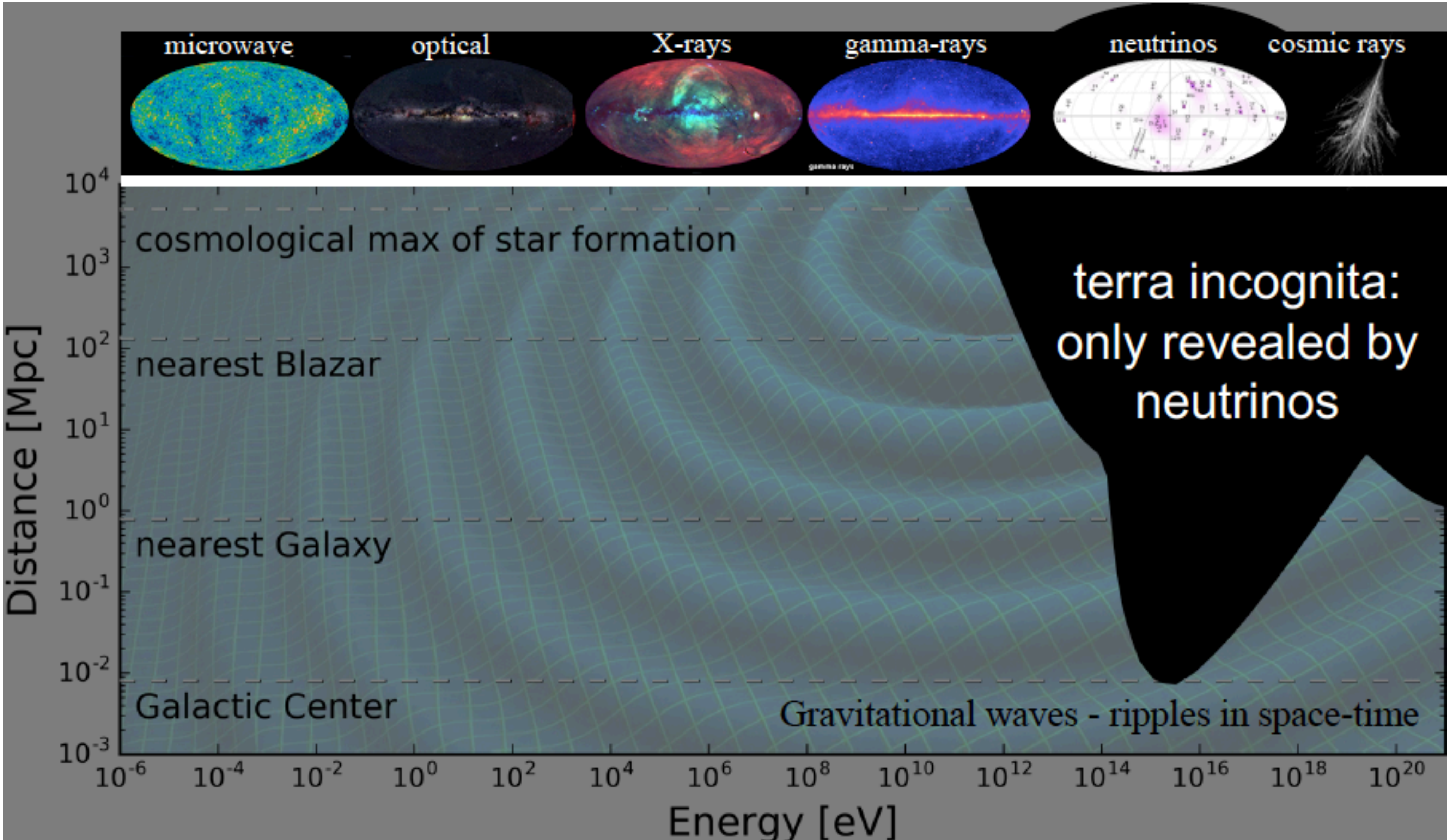
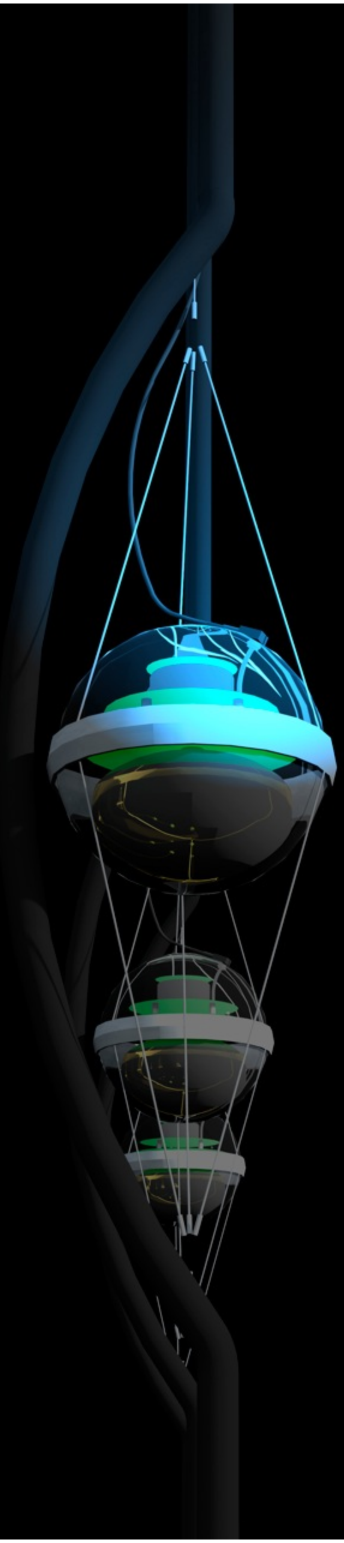
IceCube:
Building a New Window on the Universe

- 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

francis halzen- IceCube.wisc.edu



- 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



IceCube and Multimessenger Astronomy

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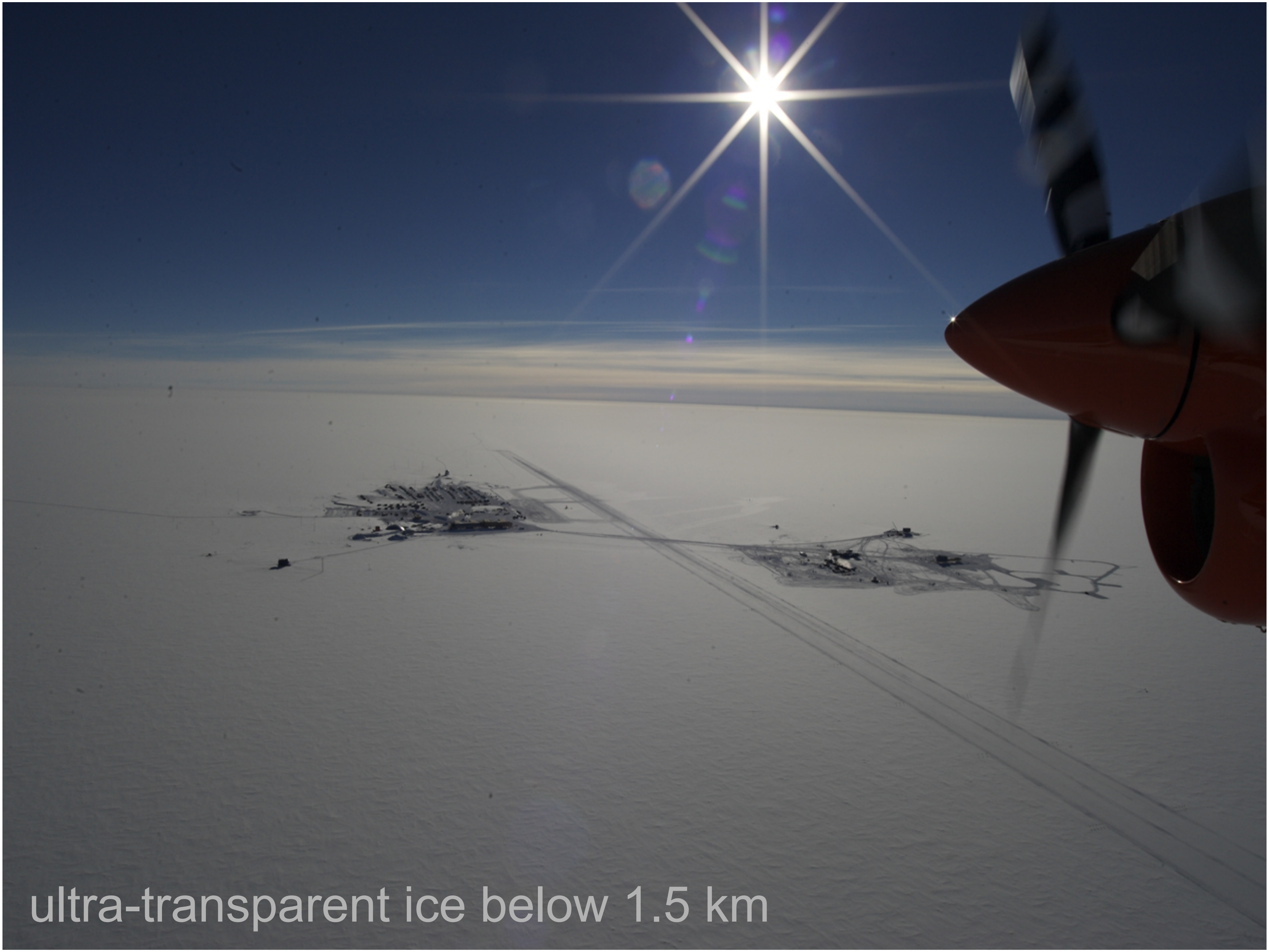
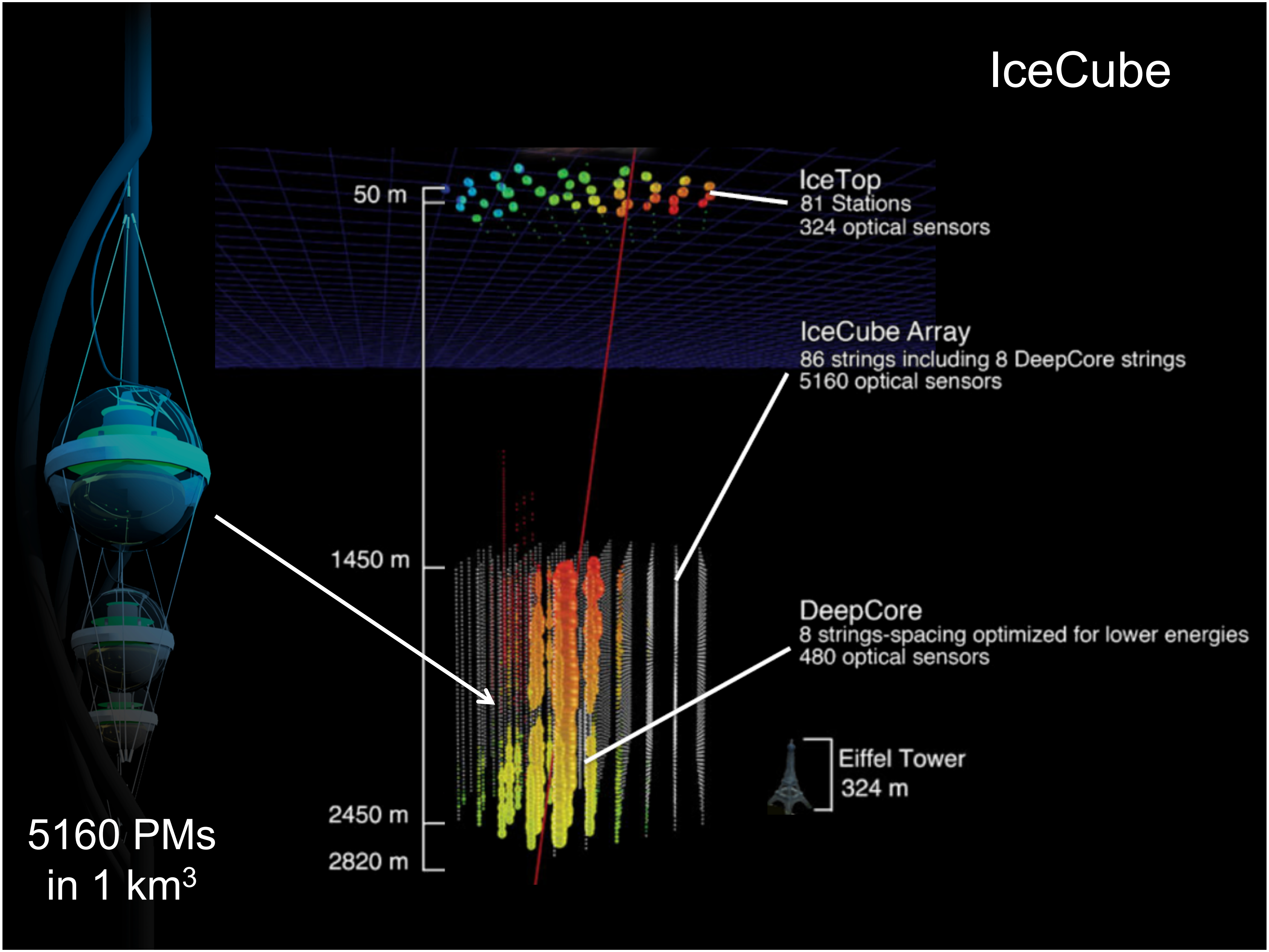
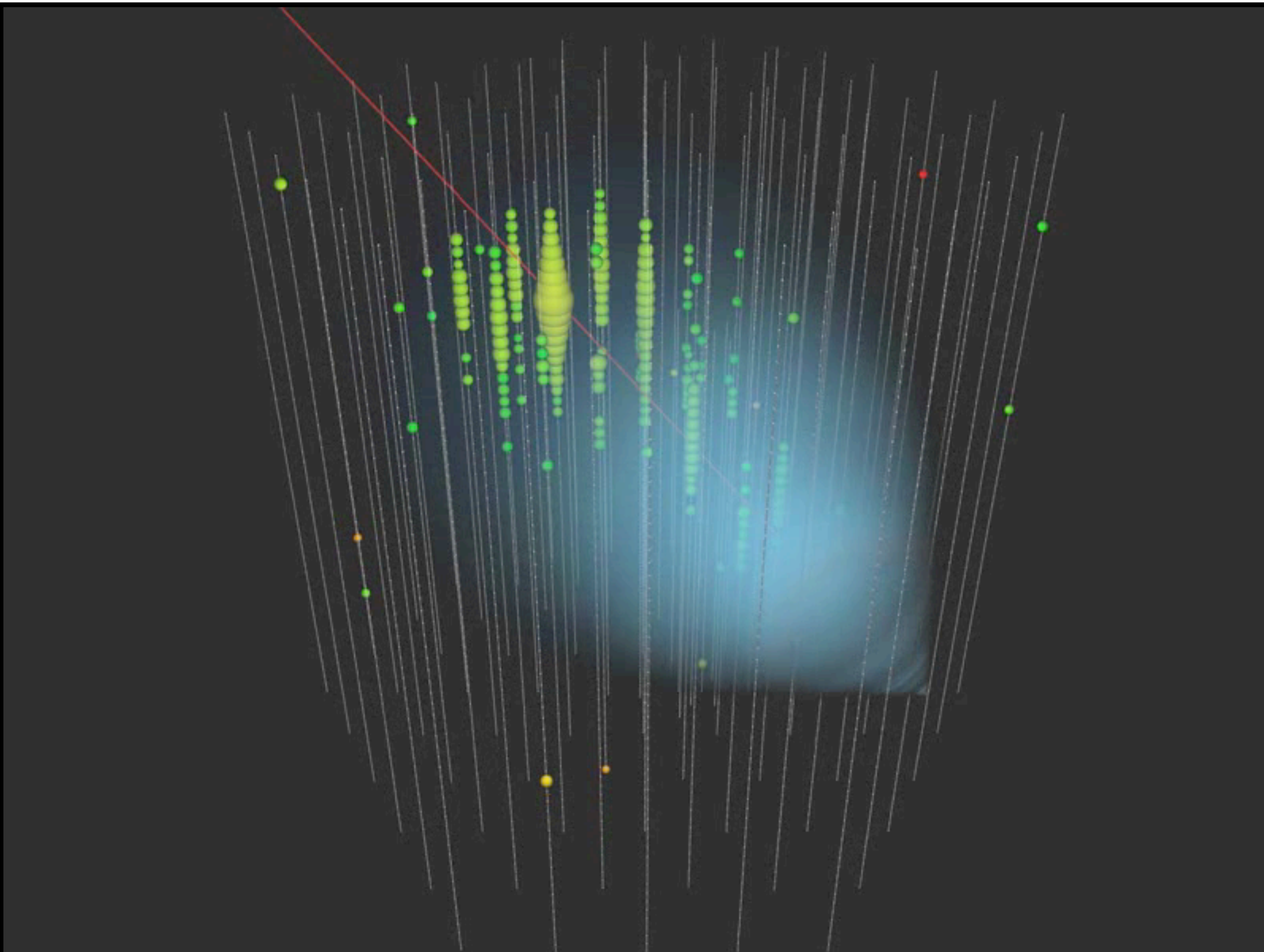

ultra-transparent ice below 1.5 km


IceCube
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km^3



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

separating signal and “background”

muons detected per year:

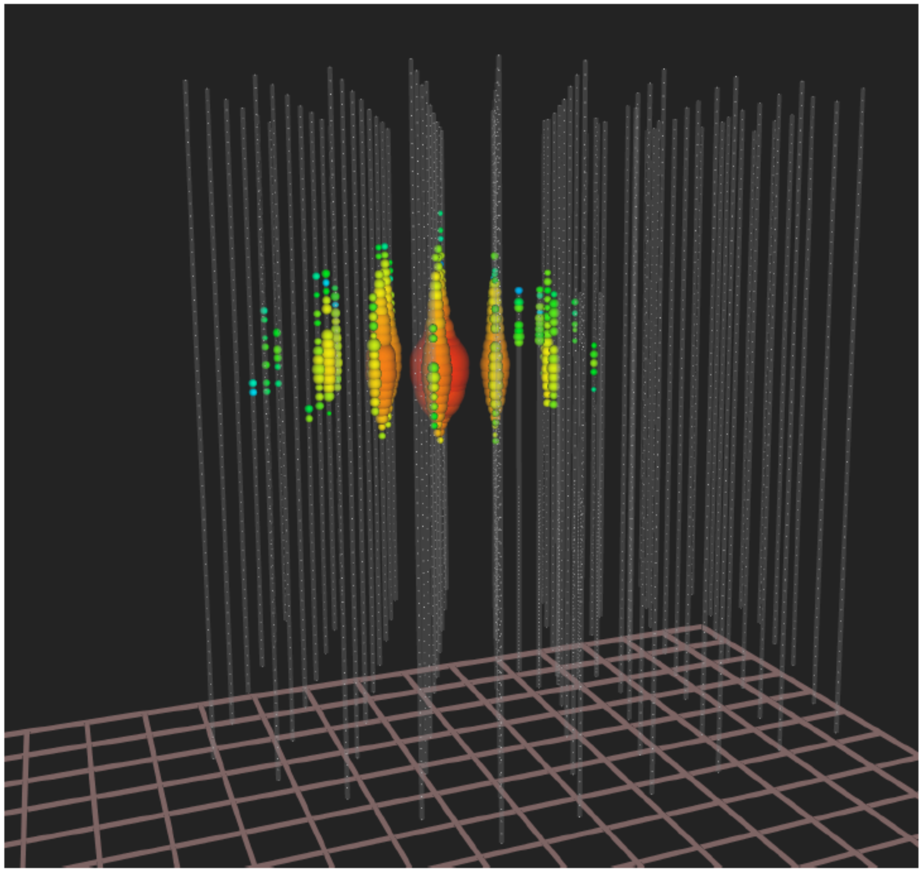
- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ $\sim 10\text{-}10^2$

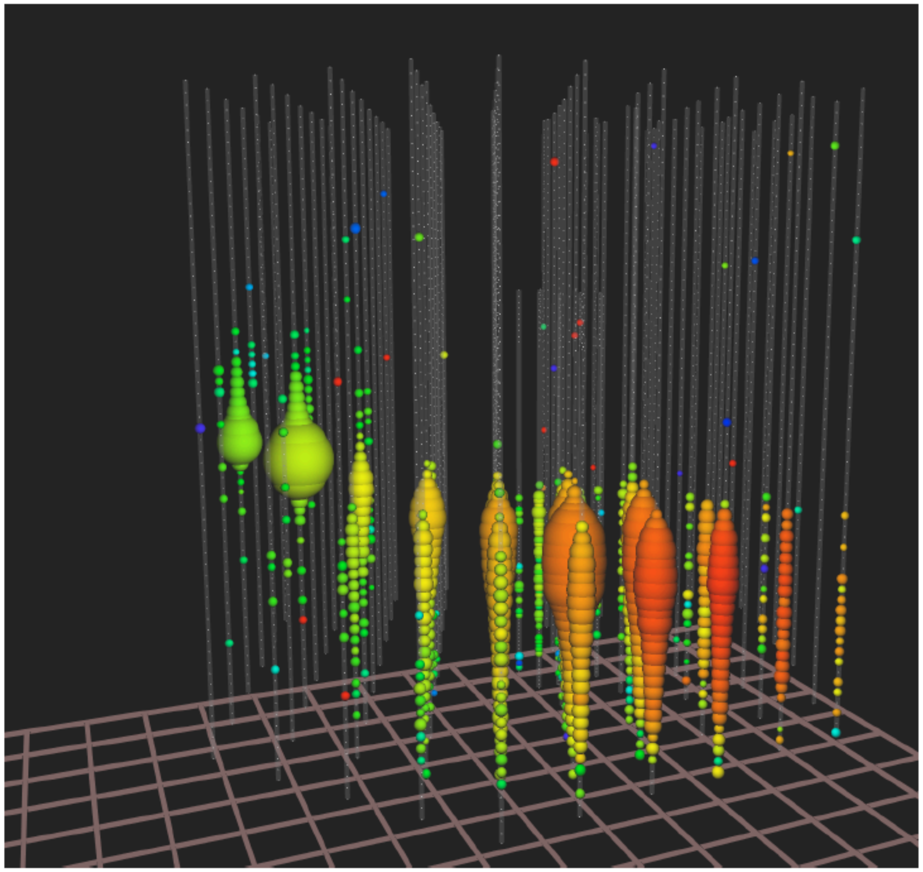
* 3000 per second

** 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 (<0.5°)

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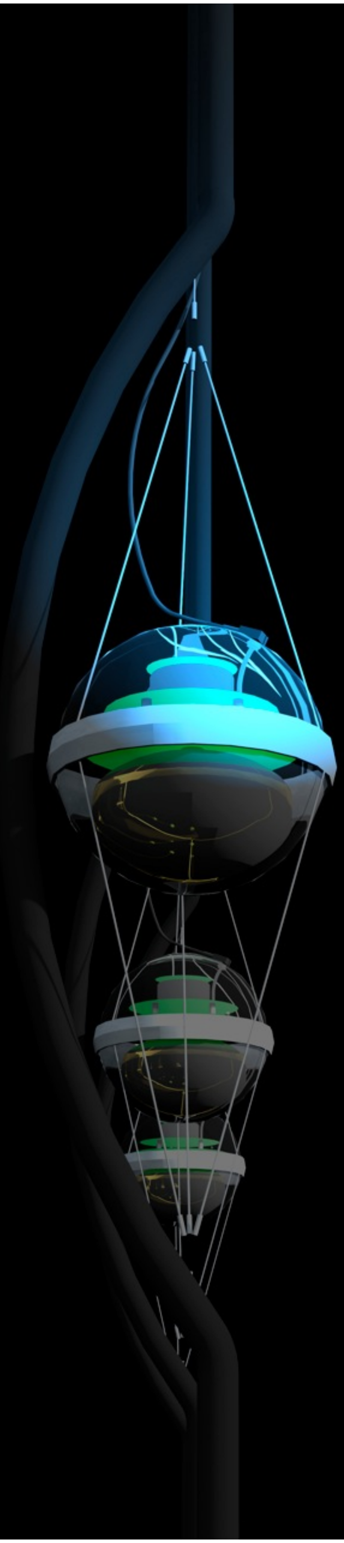

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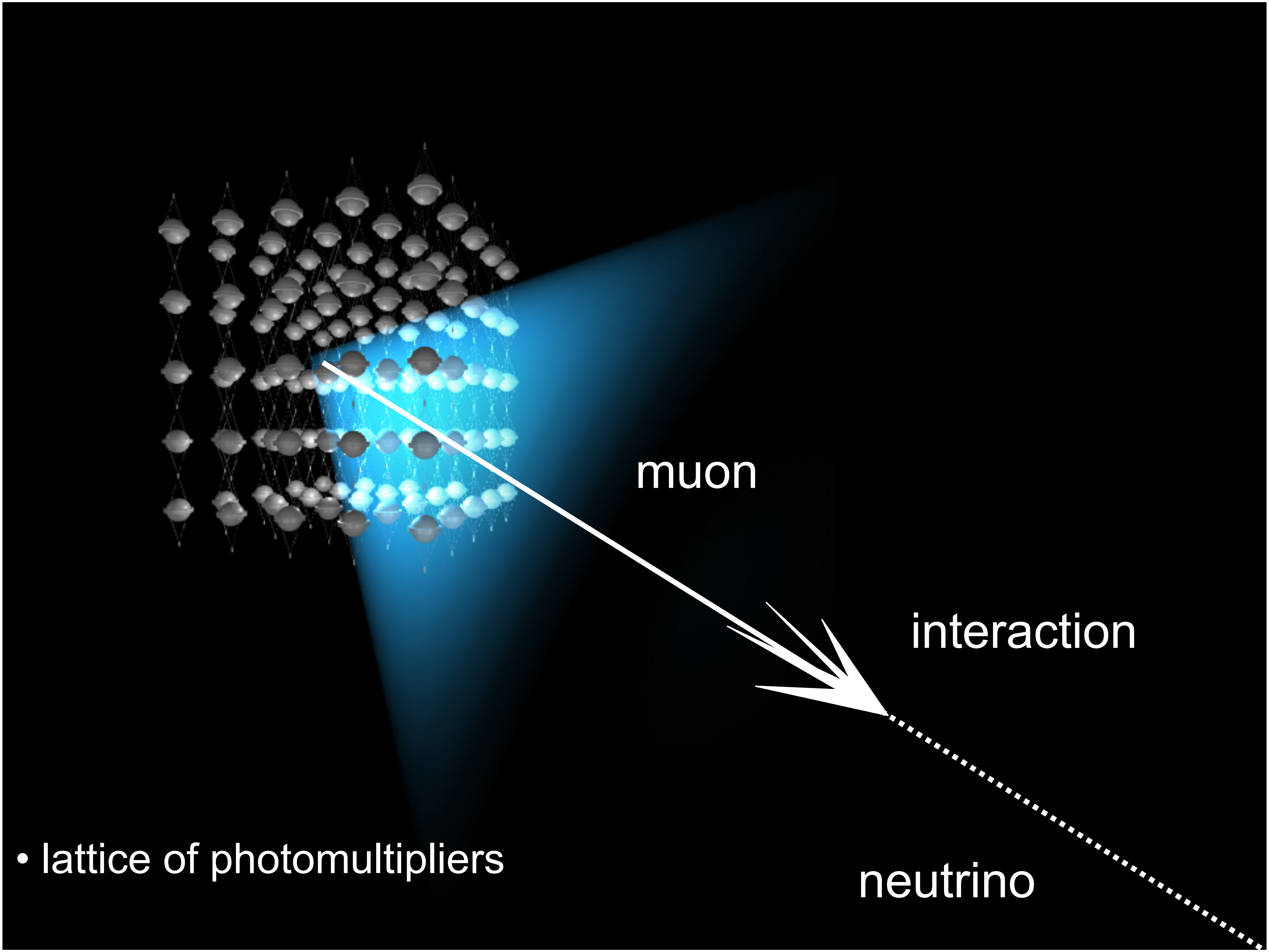
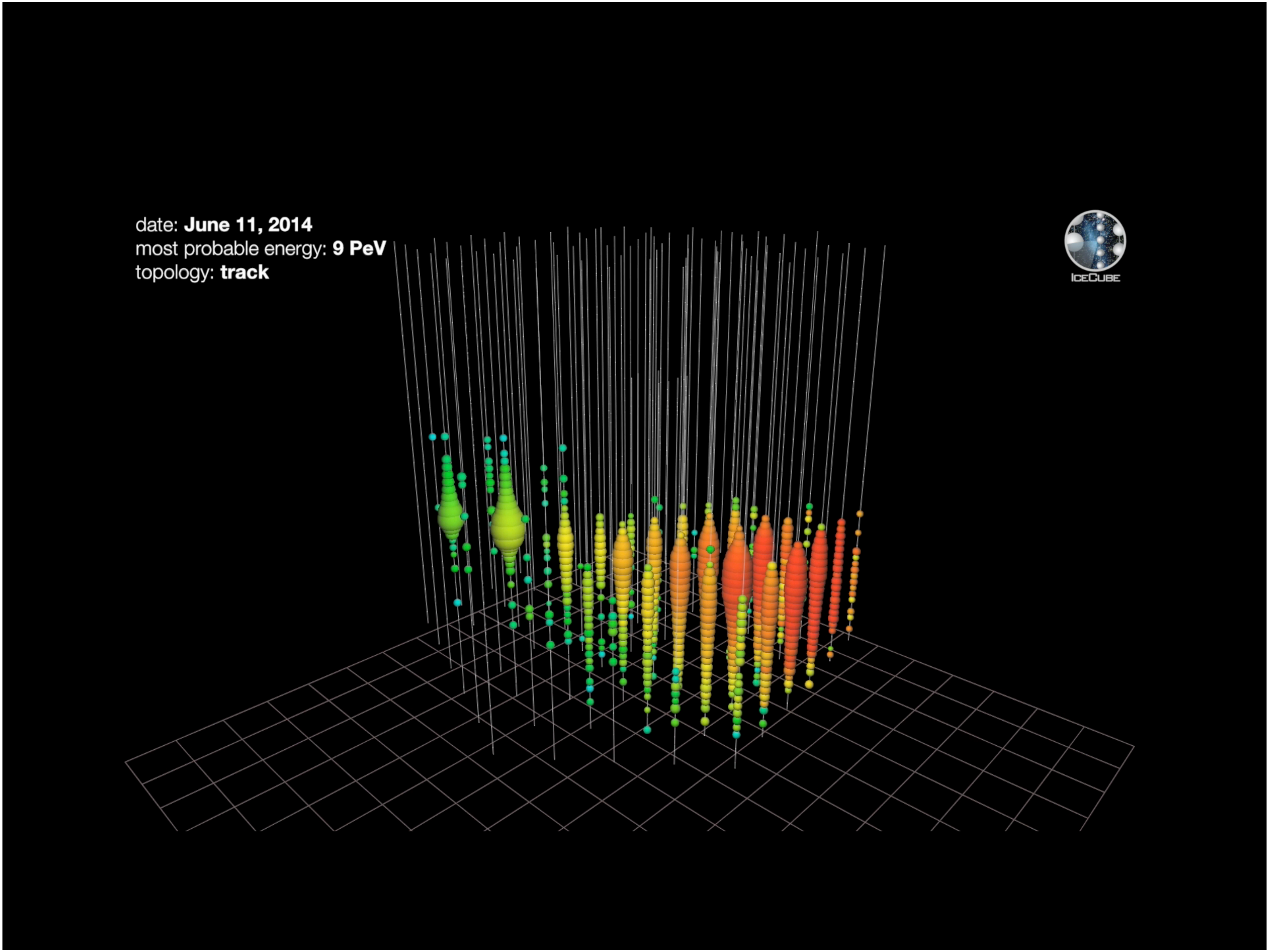
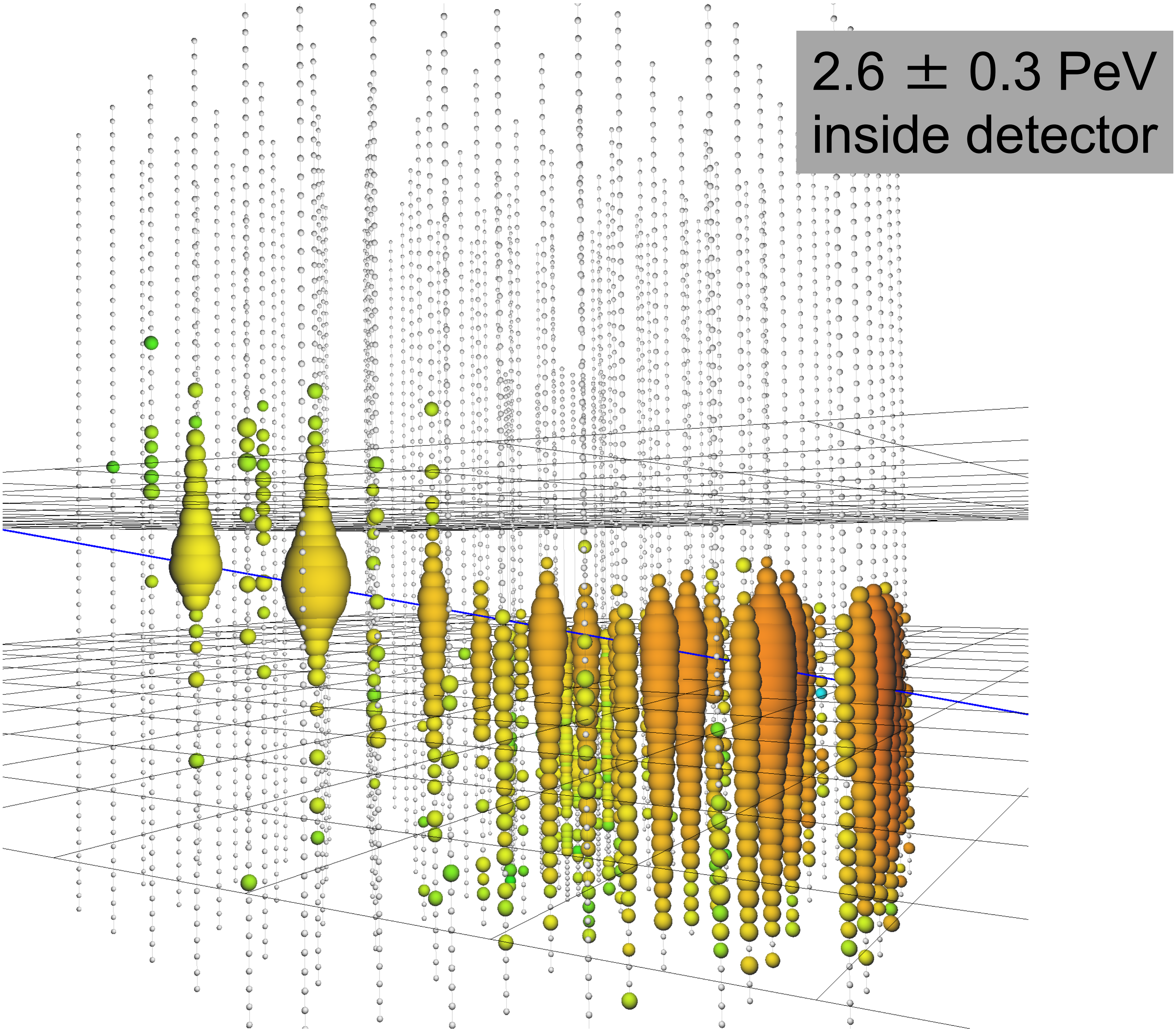
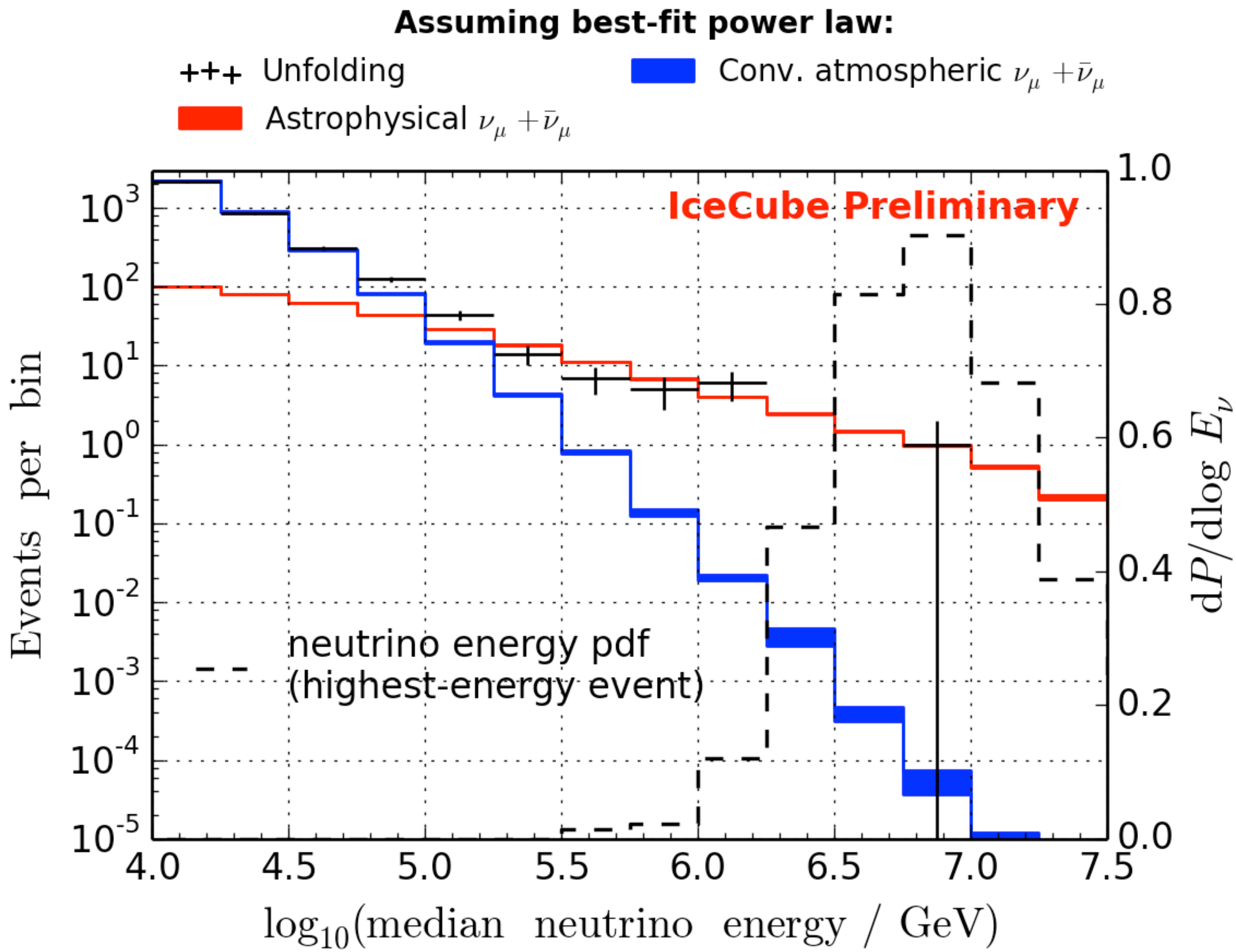

muon
interaction
• lattice of photomultipliers
neutrino


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


2.6 ± 0.3 PeV
inside detector

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

atmospheric background: less than one event/deg^2/year

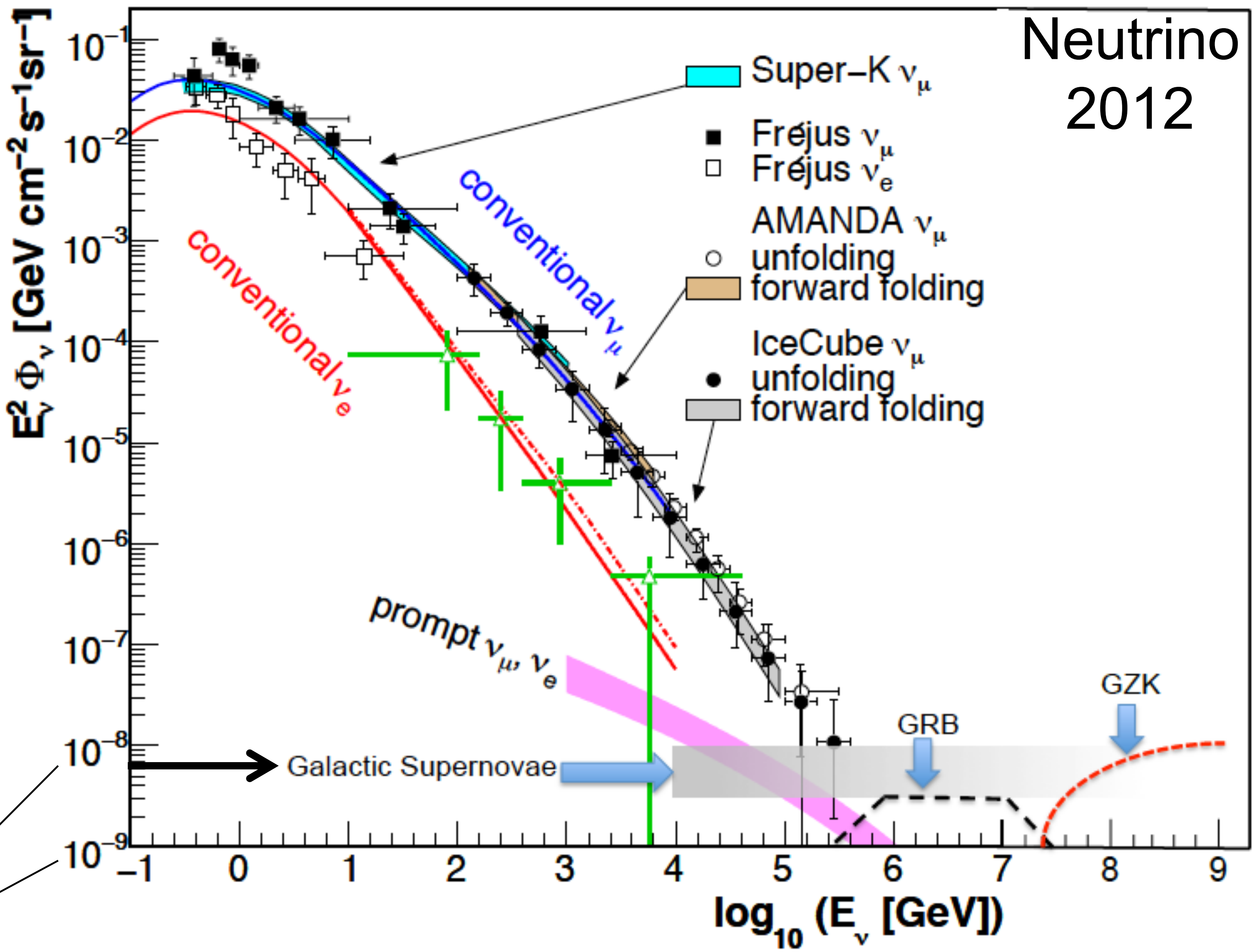


above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

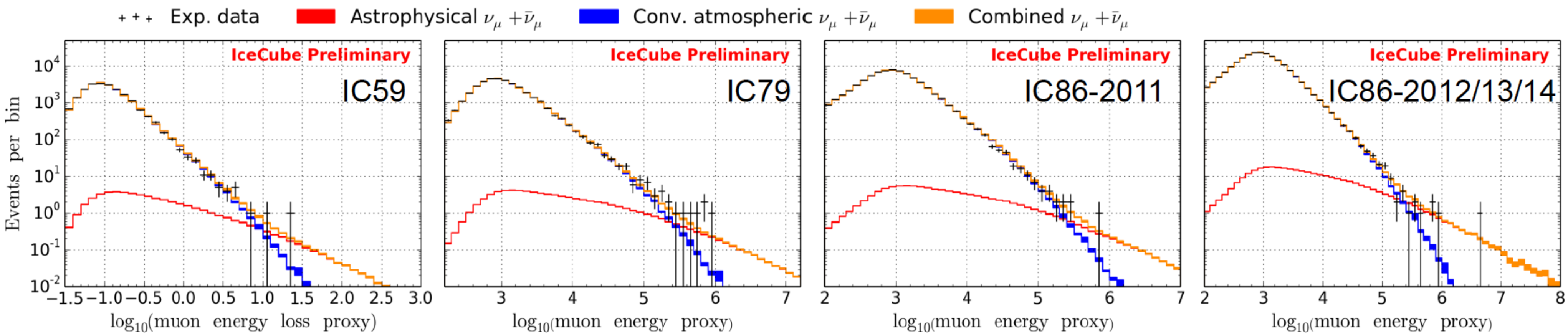


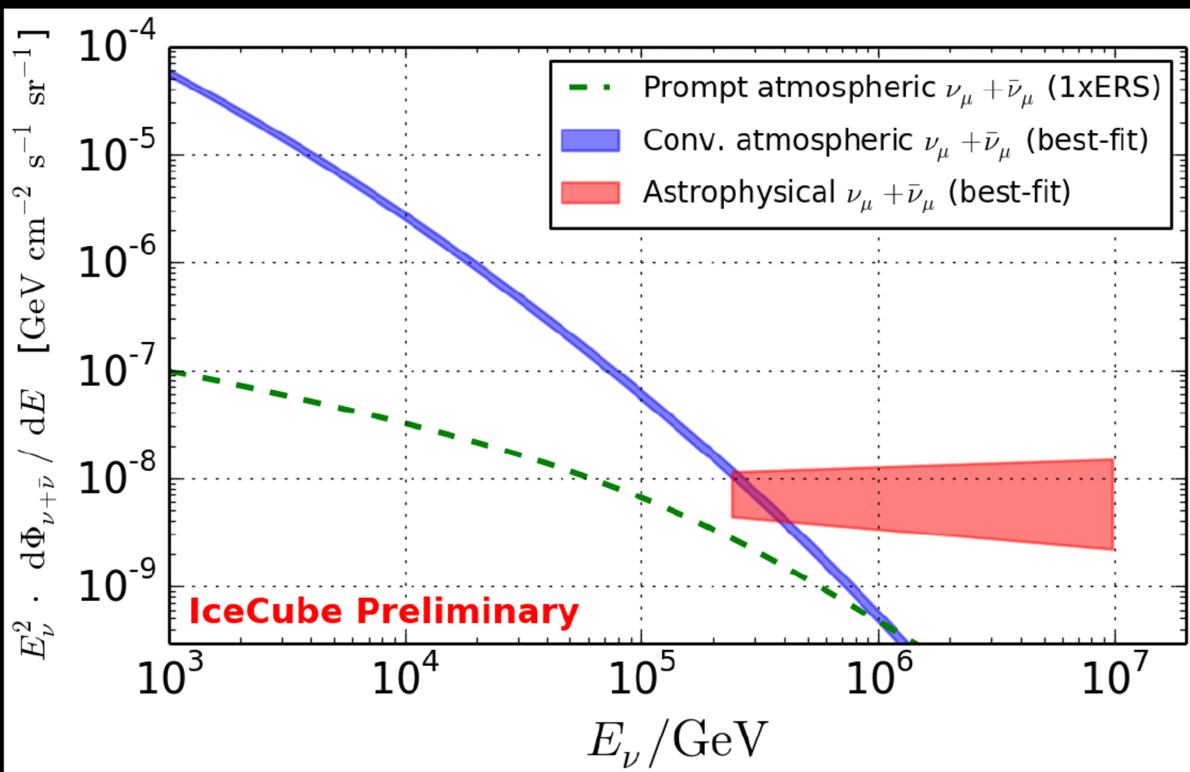
atmospheric

cosmic

100 TeV

after 7 years → 6.4 sigma





- Best-fit astrophysical normalization:

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

- Best-fit spectral index:

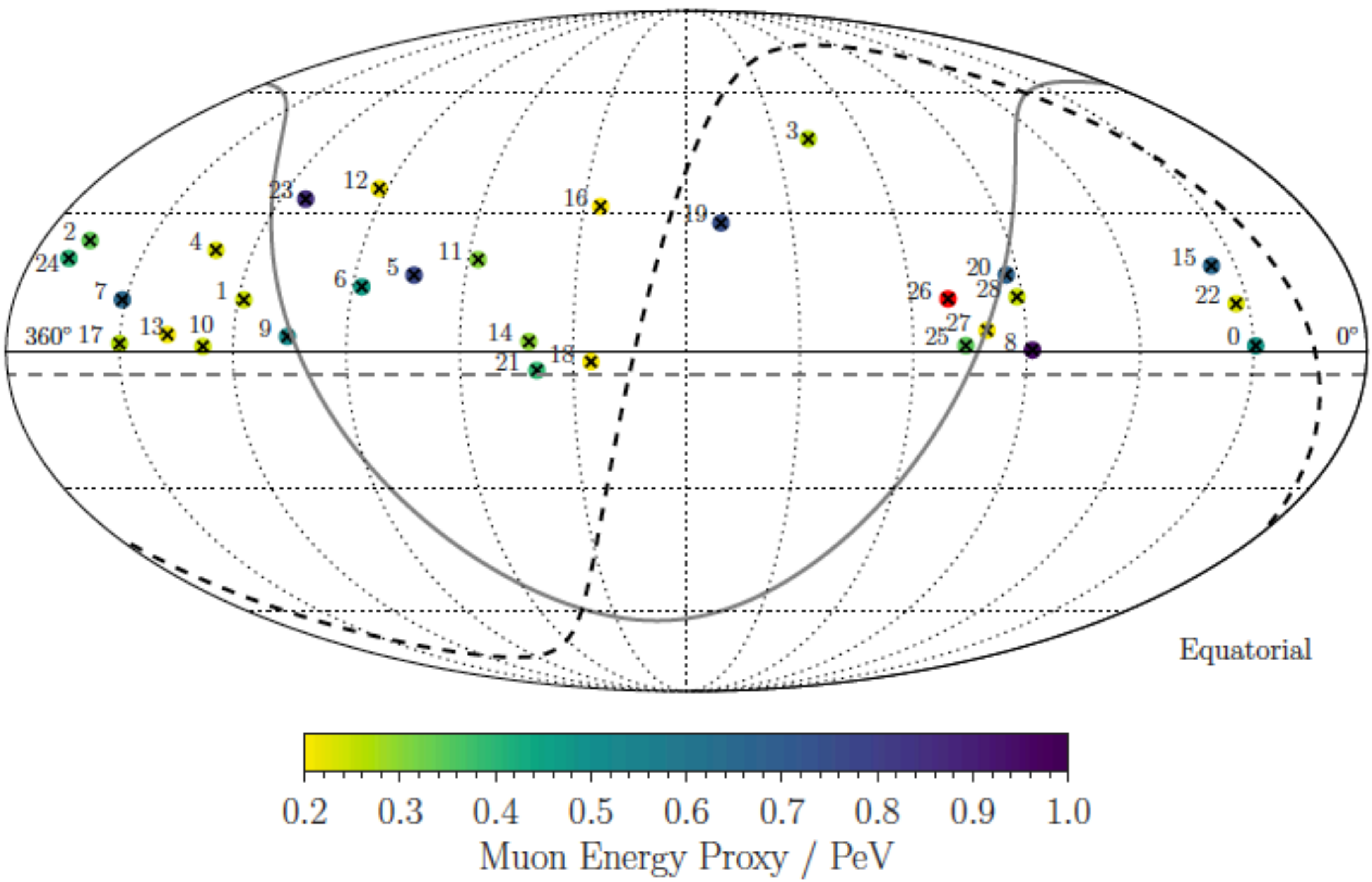
γ_{astro} = 2.16 ± 0.11

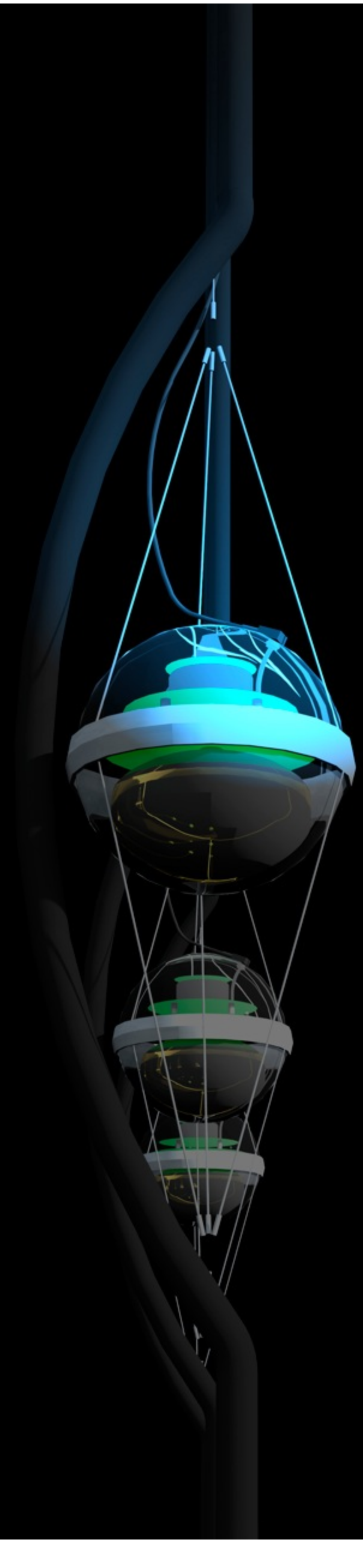
- Energy ranges:

240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ

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





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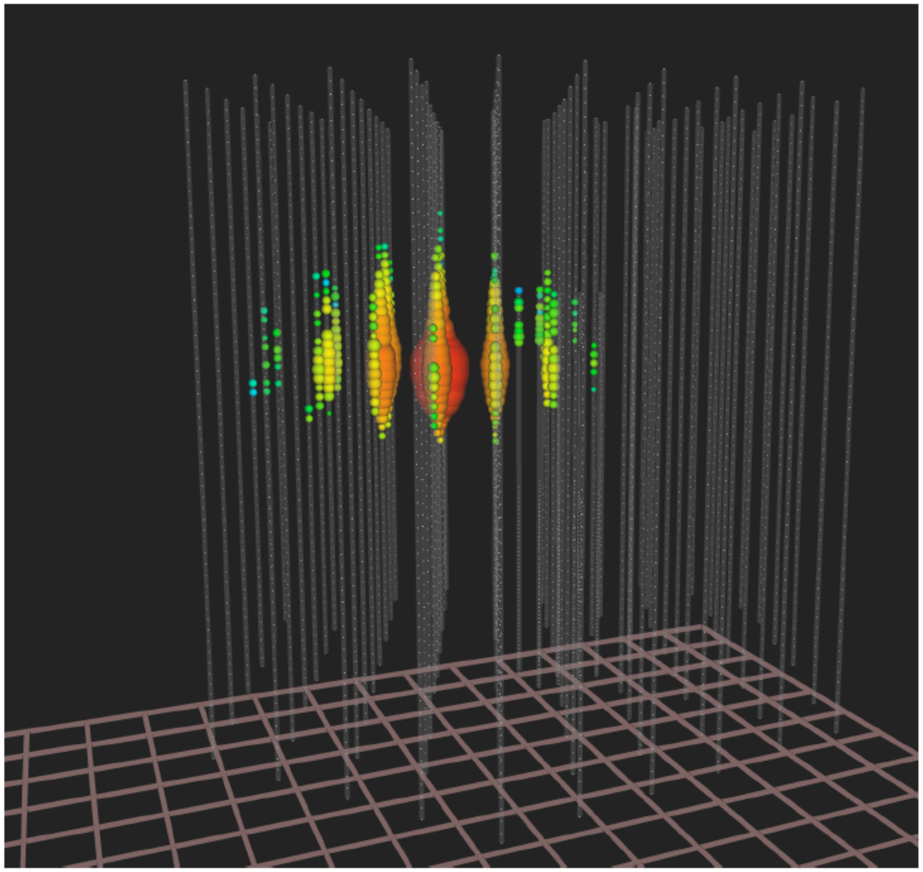
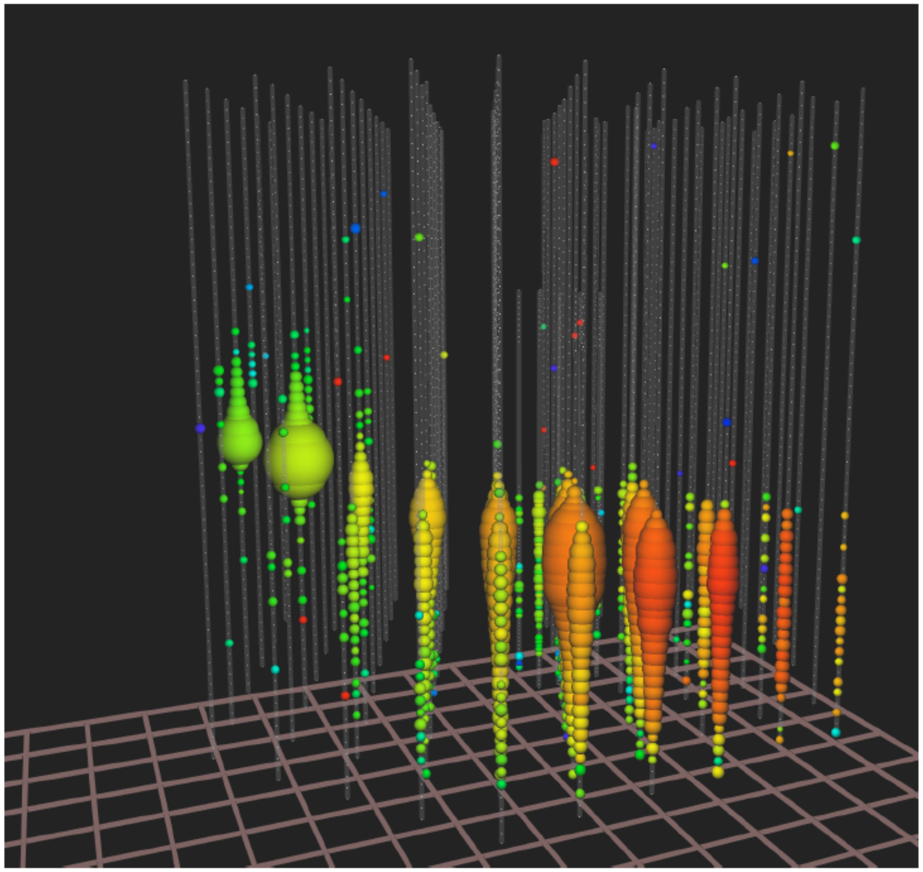
isolated neutrinos interacting inside the detector

up-going muon tracks

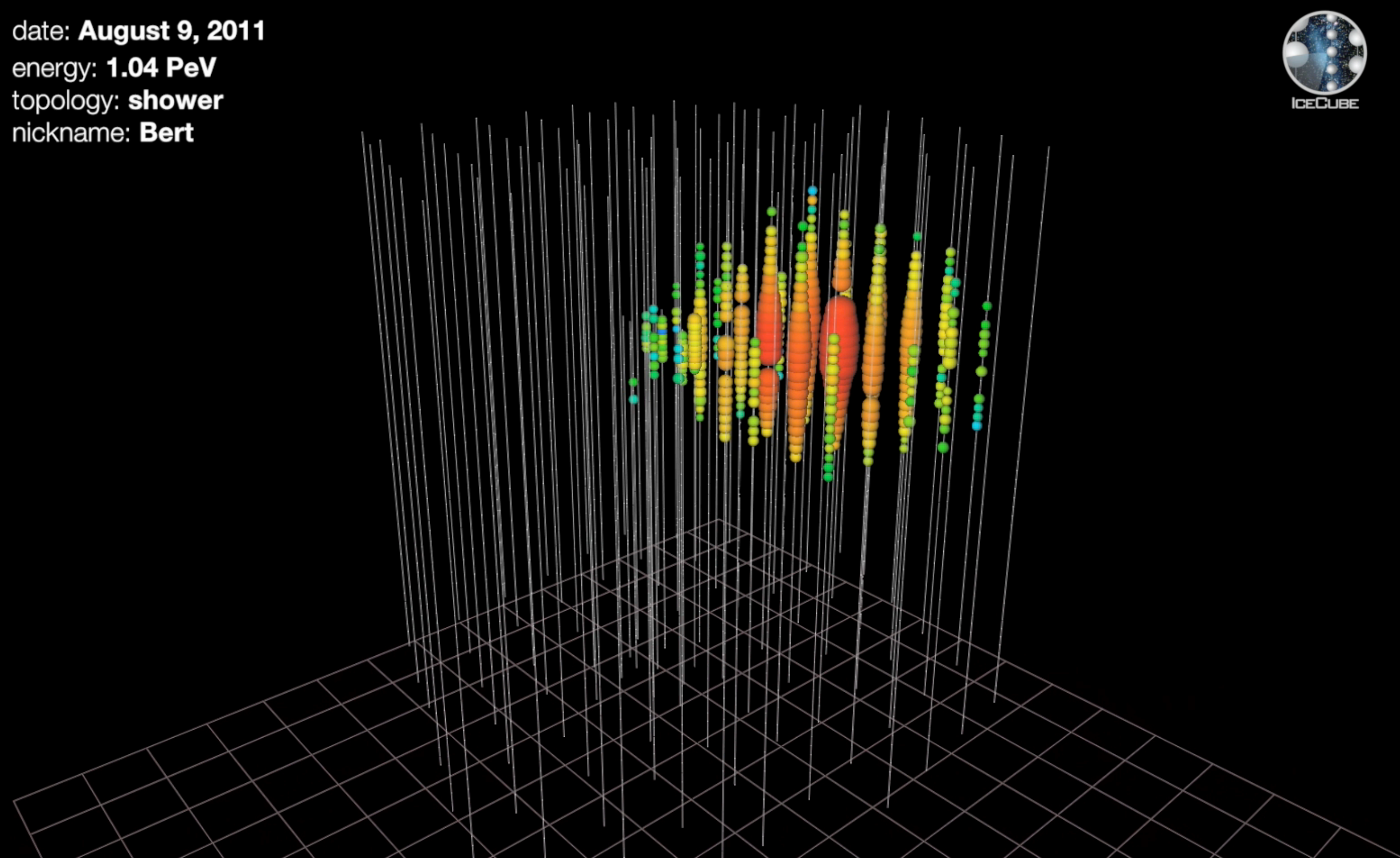




calorimetry: direct energy measurement; all flavors

astronomy: angular resolution superior

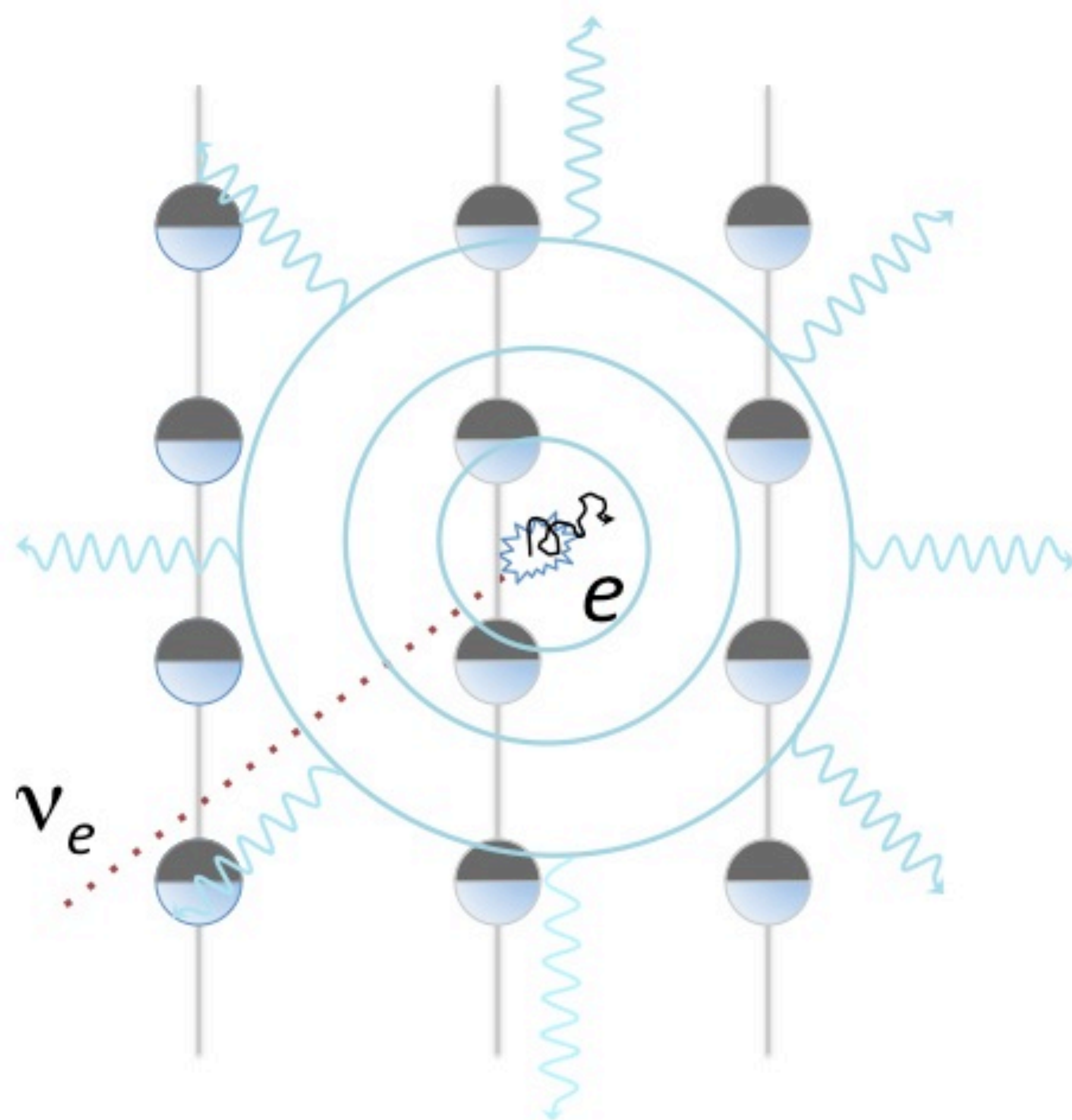
GZK neutrino search: two neutrinos with > 1,000 TeV

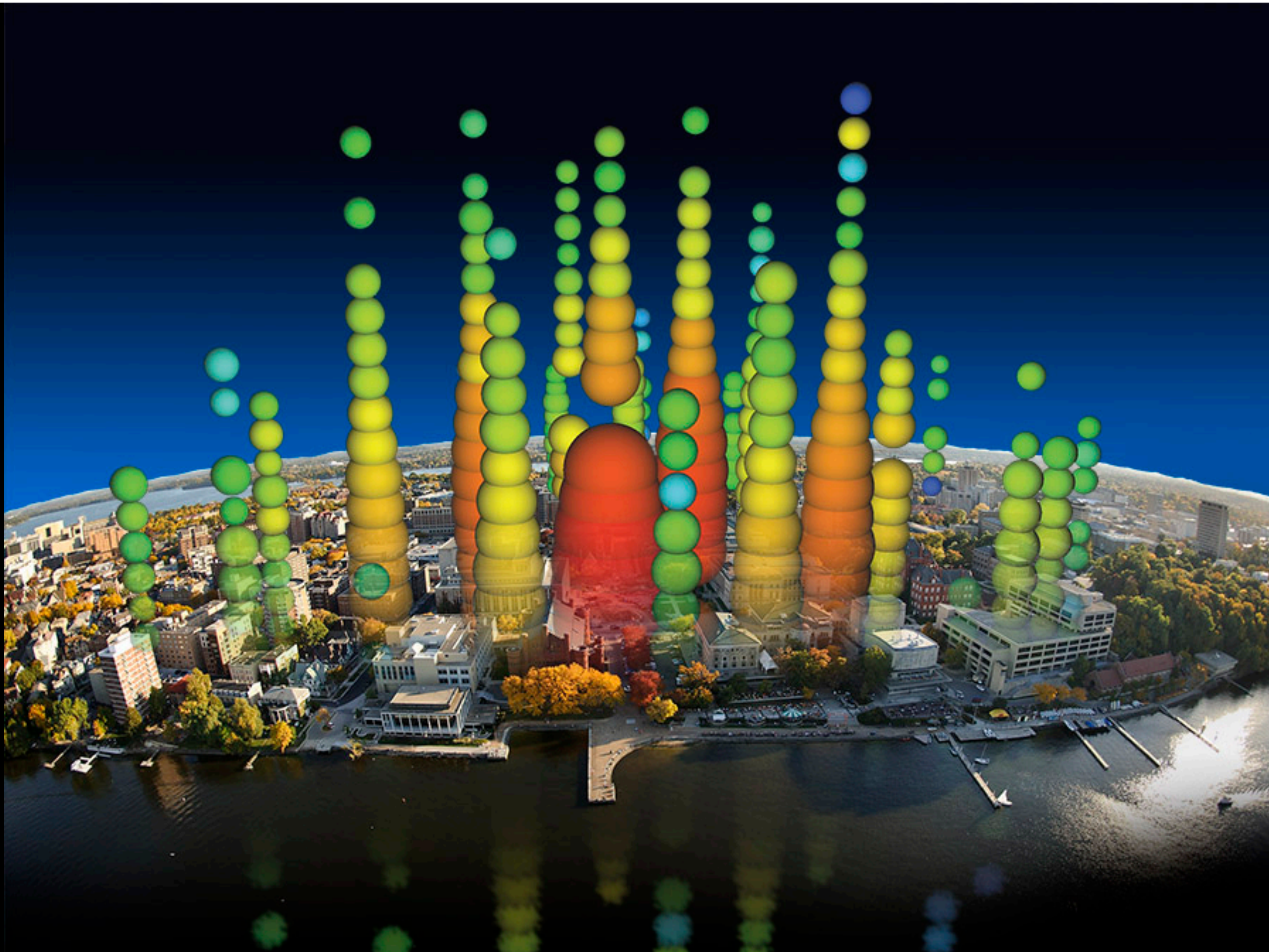


electron showers versus muon tracks

PeV ν_e and ν_τ showers:

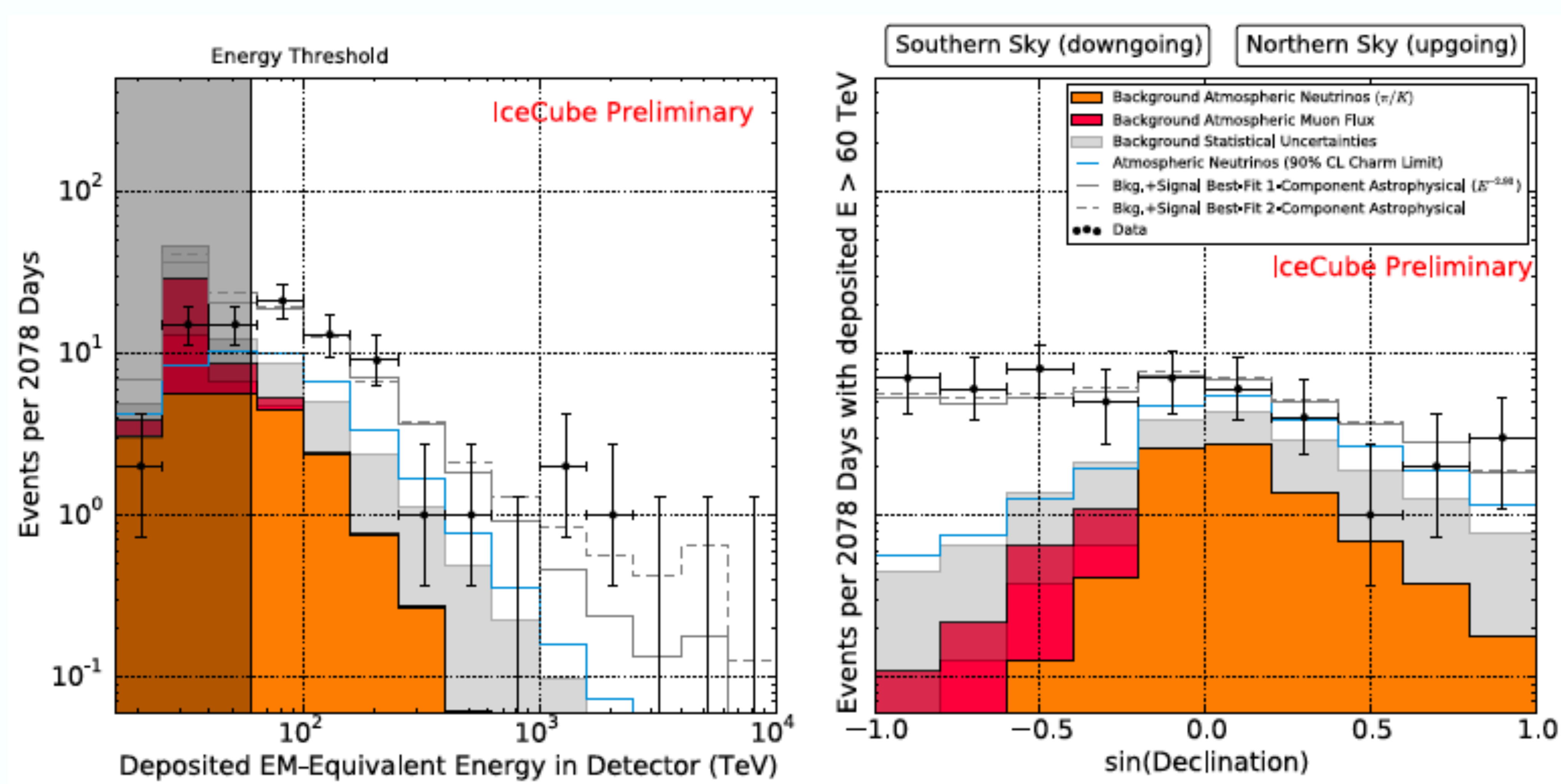
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m

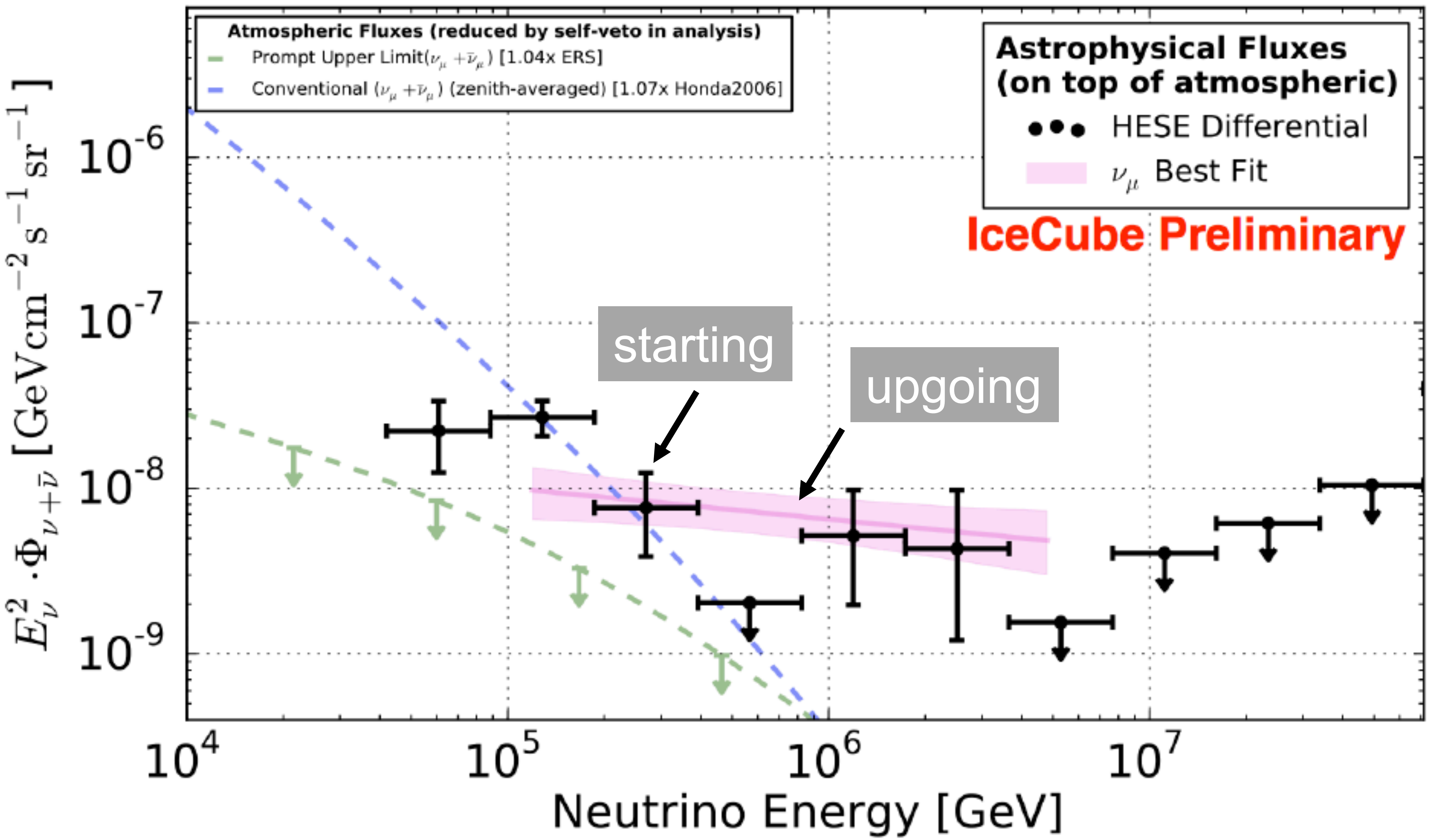




- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

starting events: now 6 years → 8σ

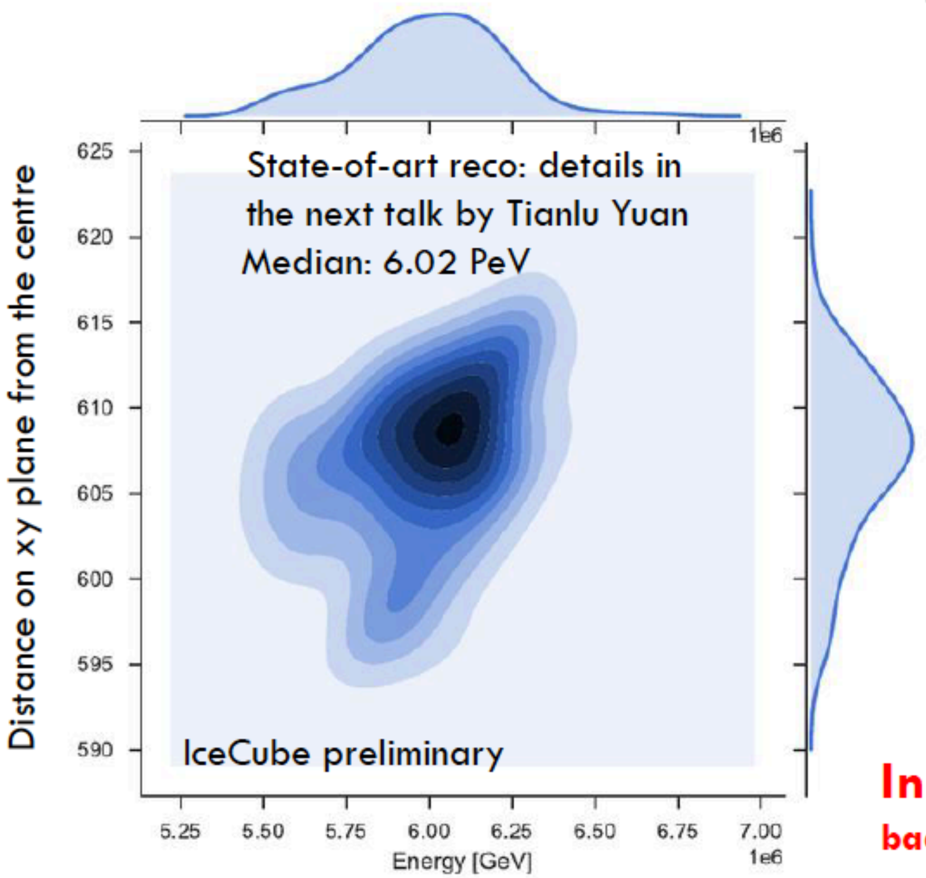


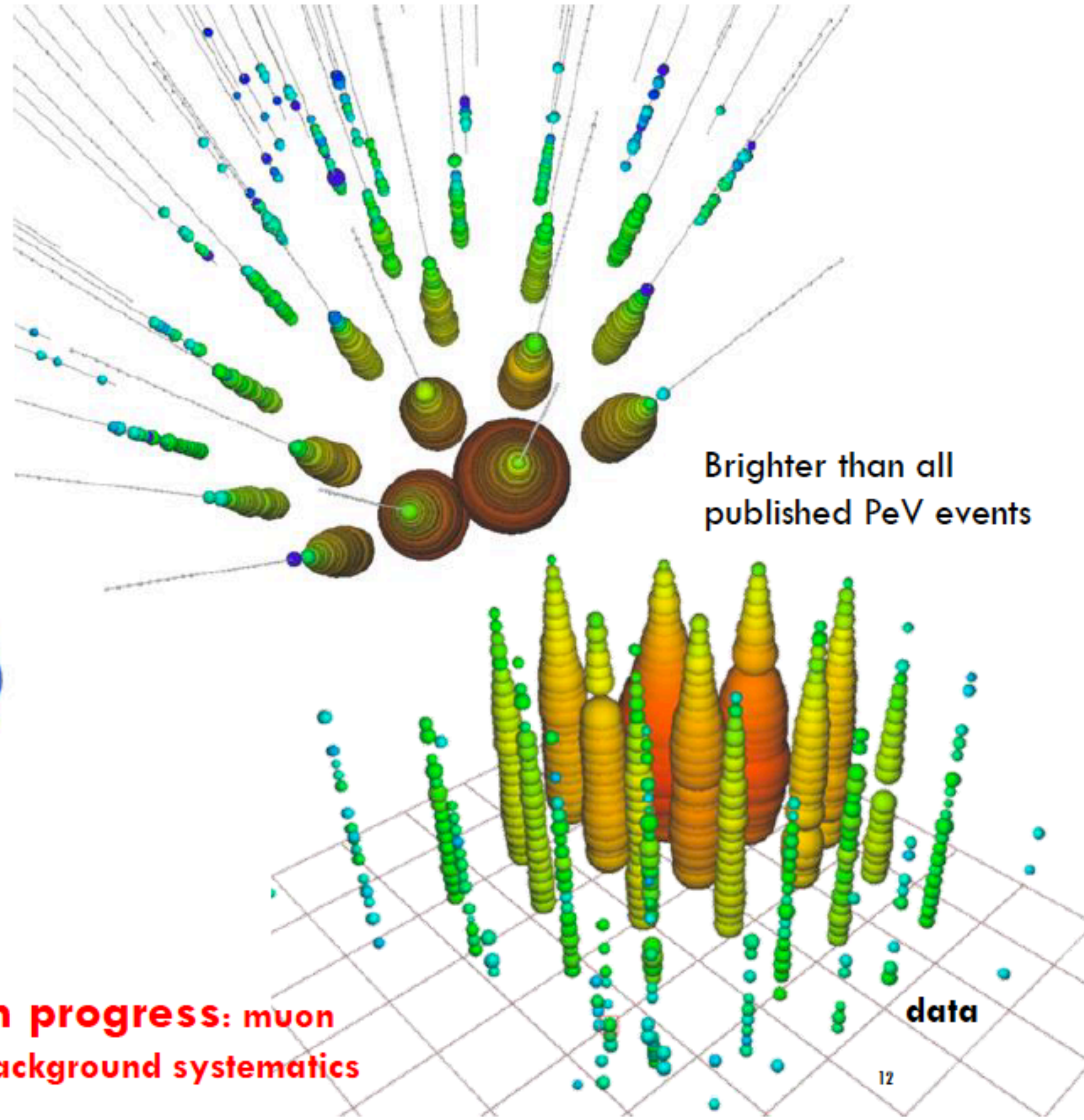


two methods are consistent

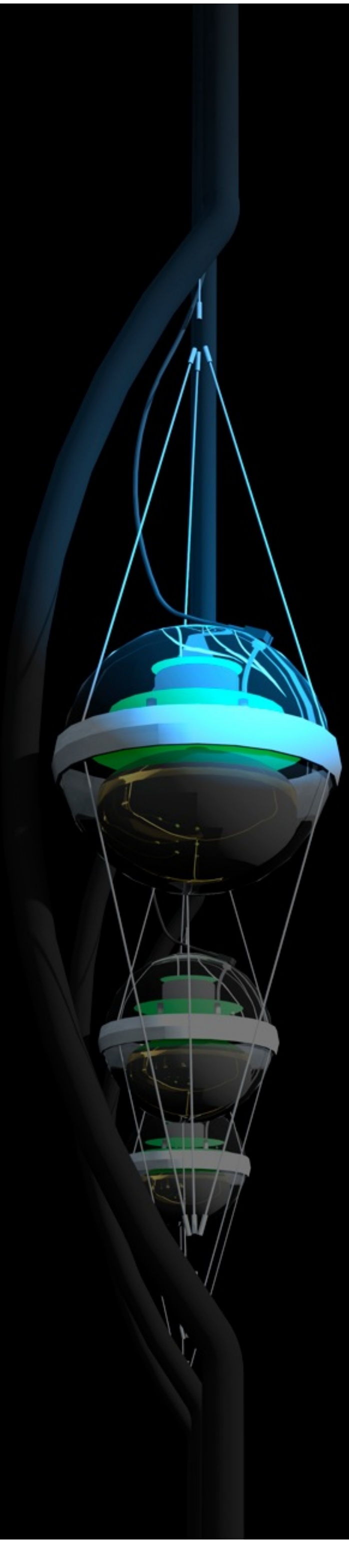
Partially contained event with energy ~ 6 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE





In progress: muon background systematics



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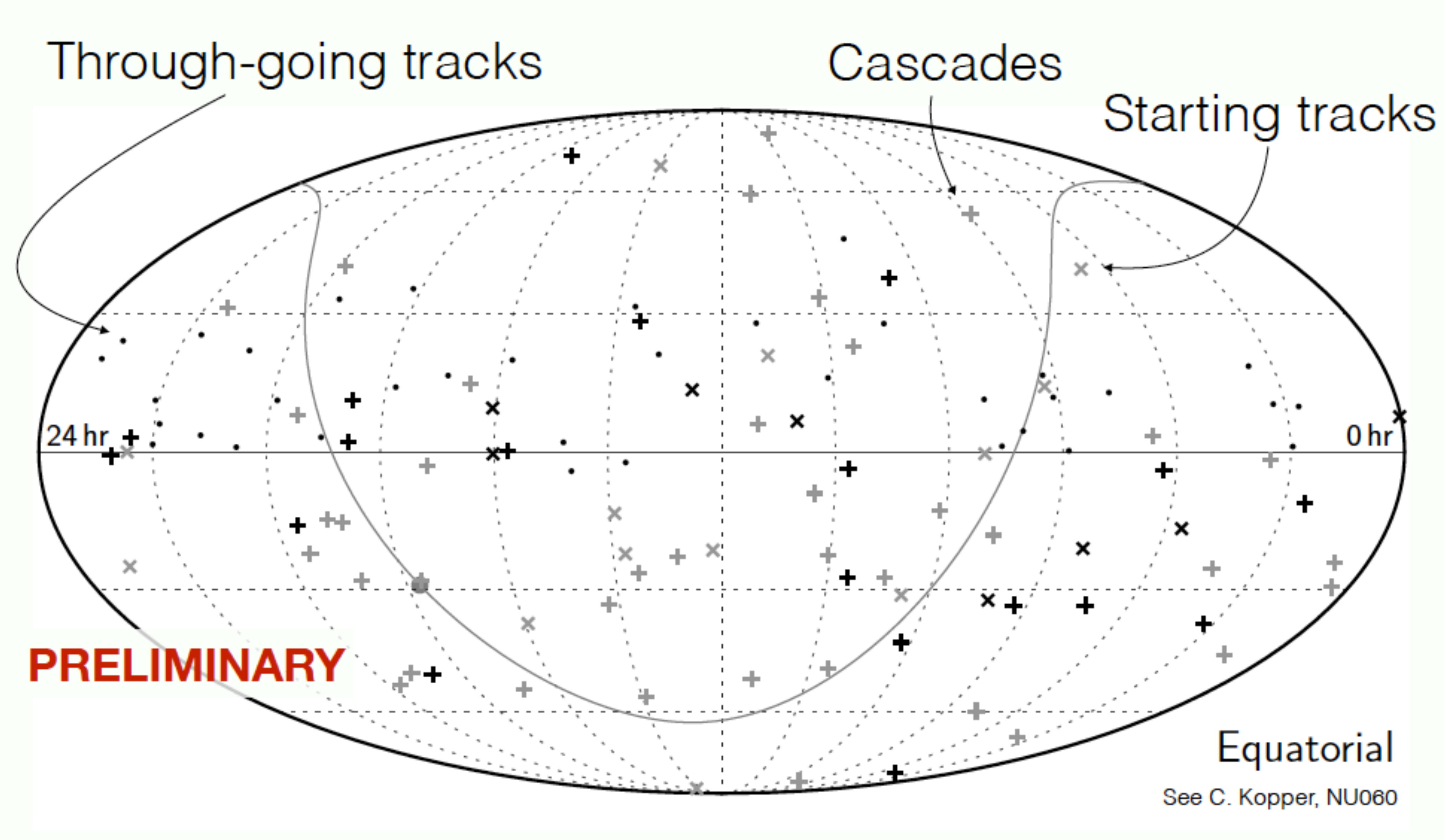
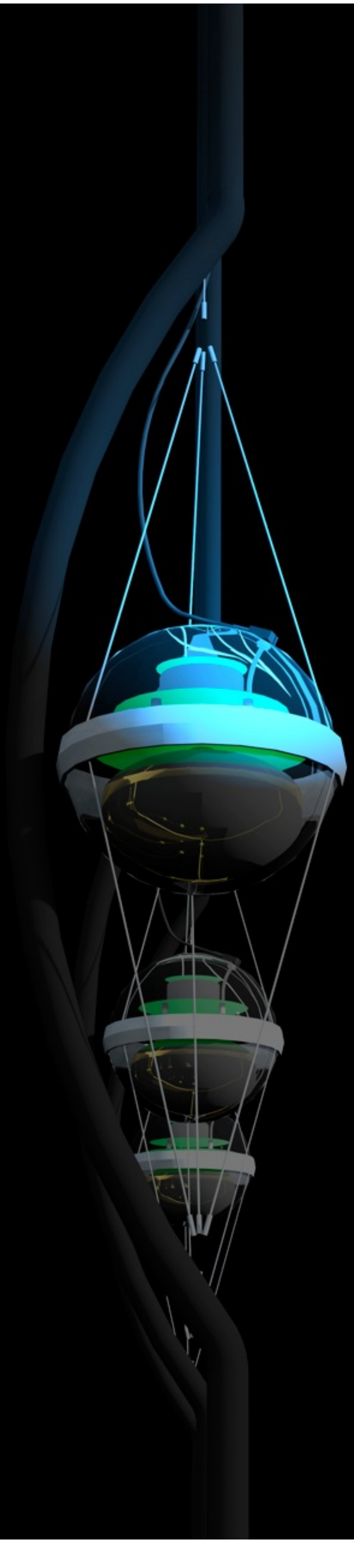


Through-going tracks
Cascades
Starting tracks
24 hr
0 hr
PRELIMINARY
Equatorial
See C. Kopper, NU060

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)
- [decay of halo dark matter particles?]



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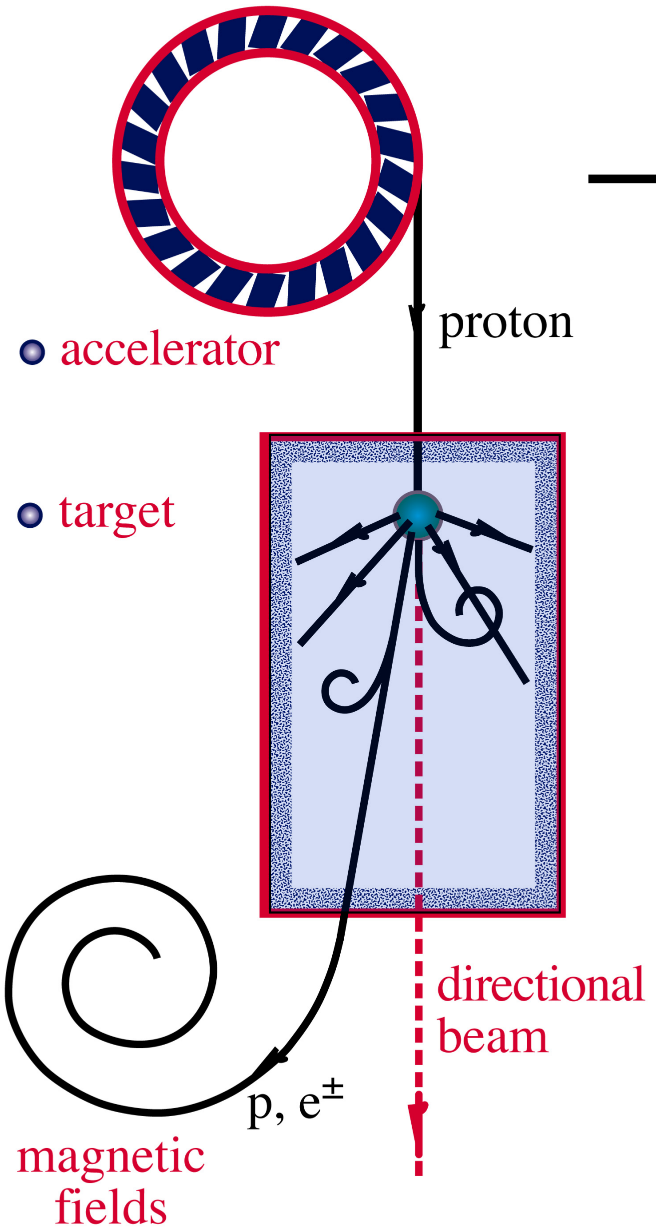
ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

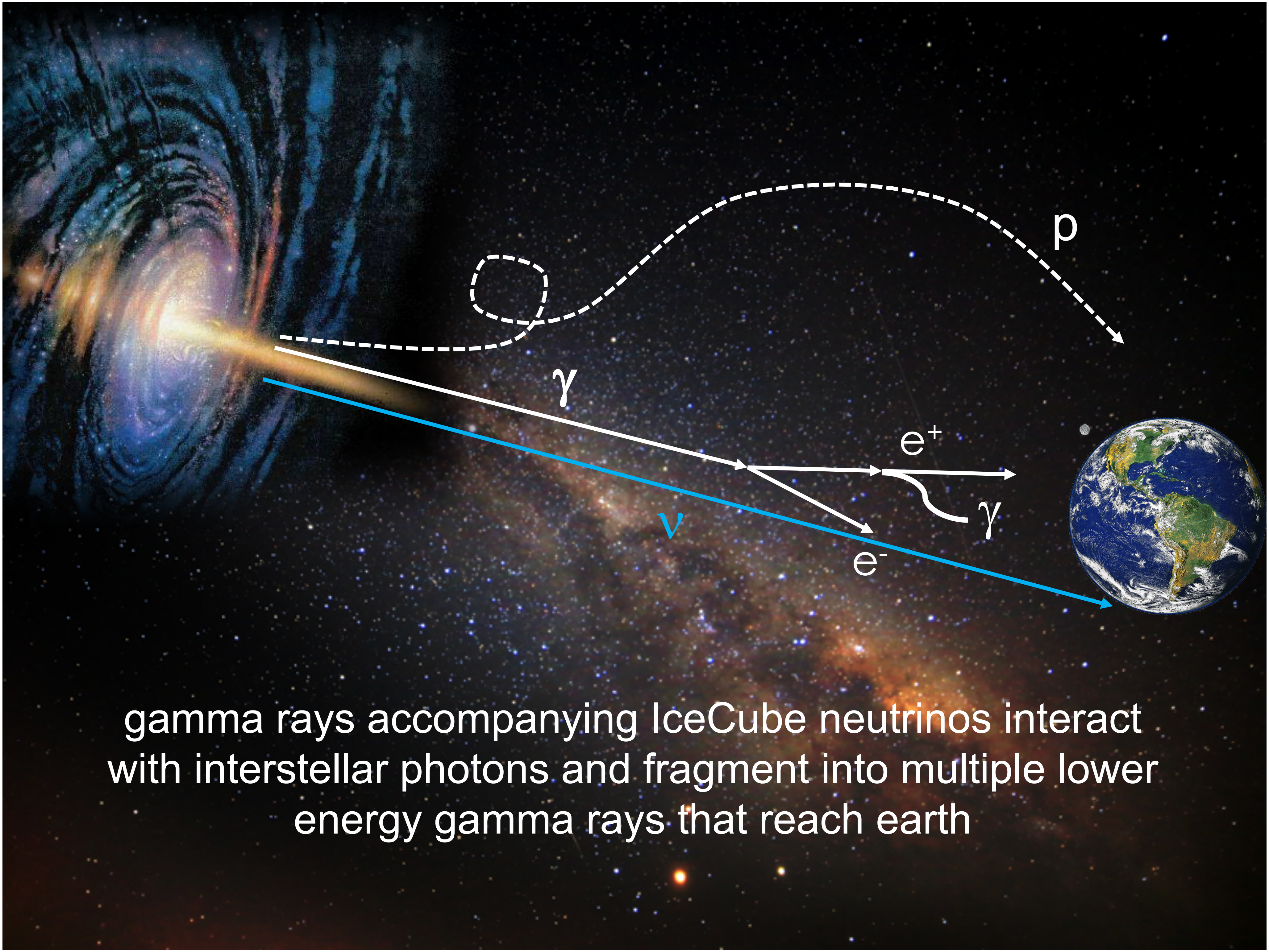
radiation
and dust

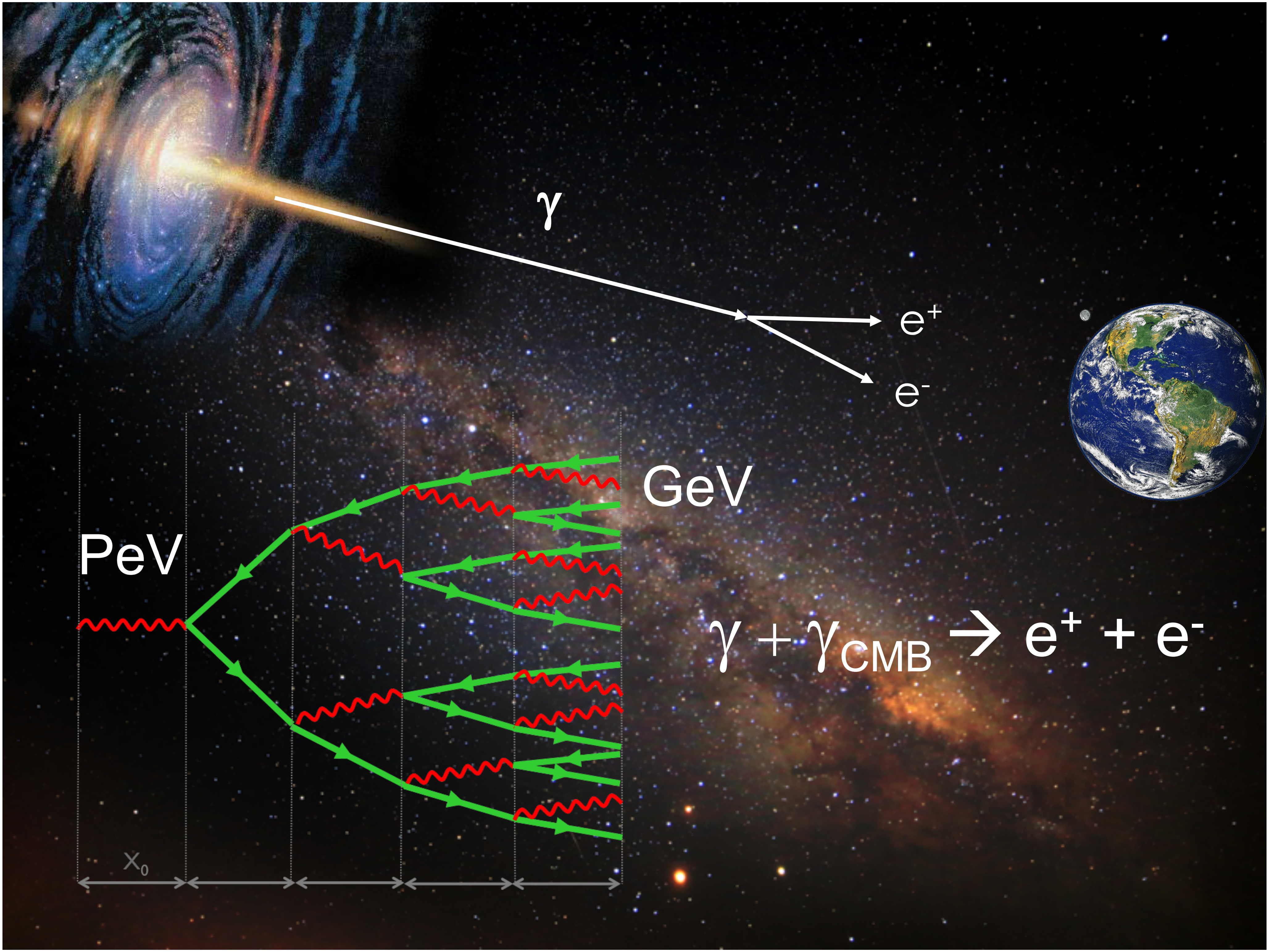
$$p + \gamma \rightarrow n + \pi^{+}$$

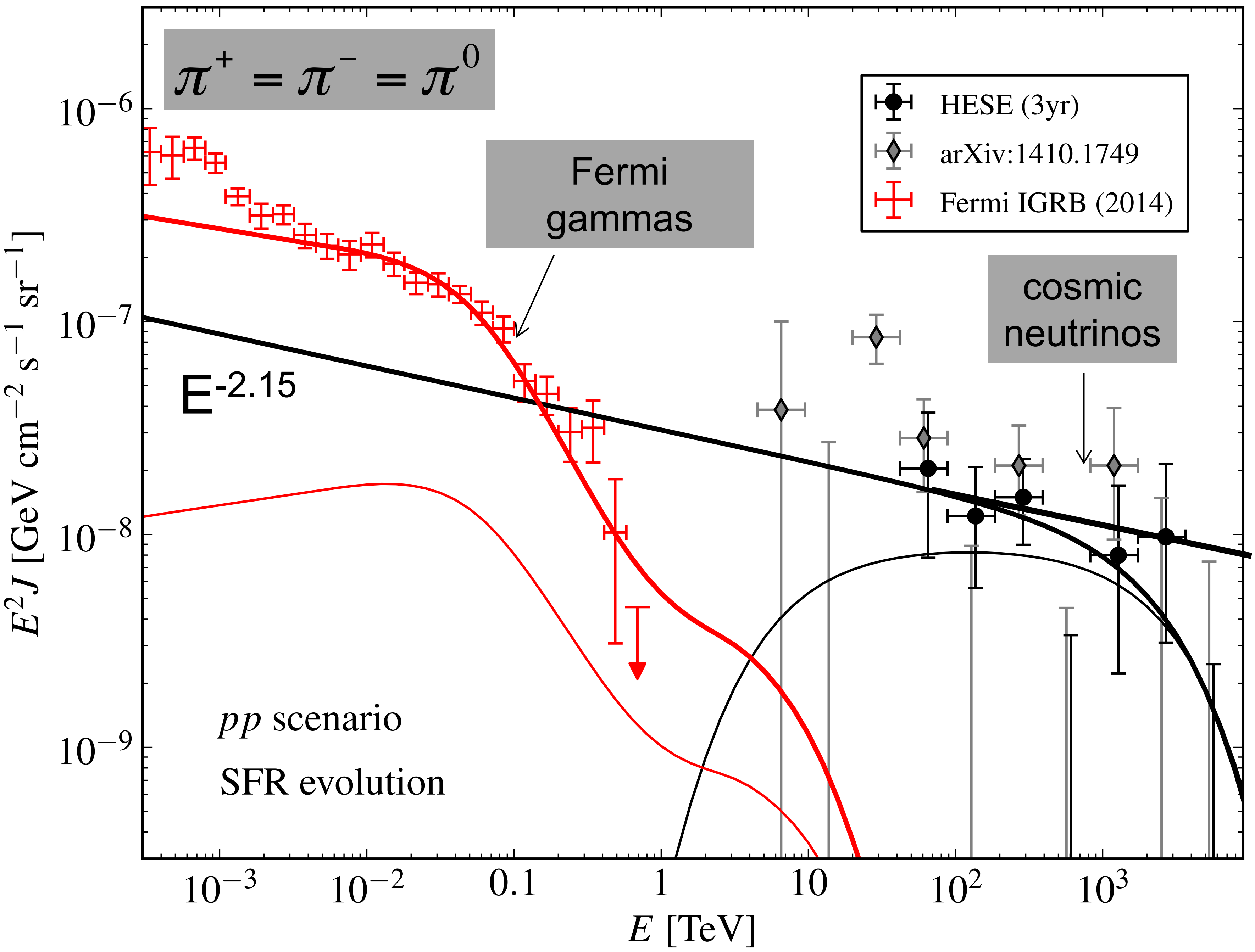
~ cosmic ray + neutrino

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

~ cosmic ray + gamma

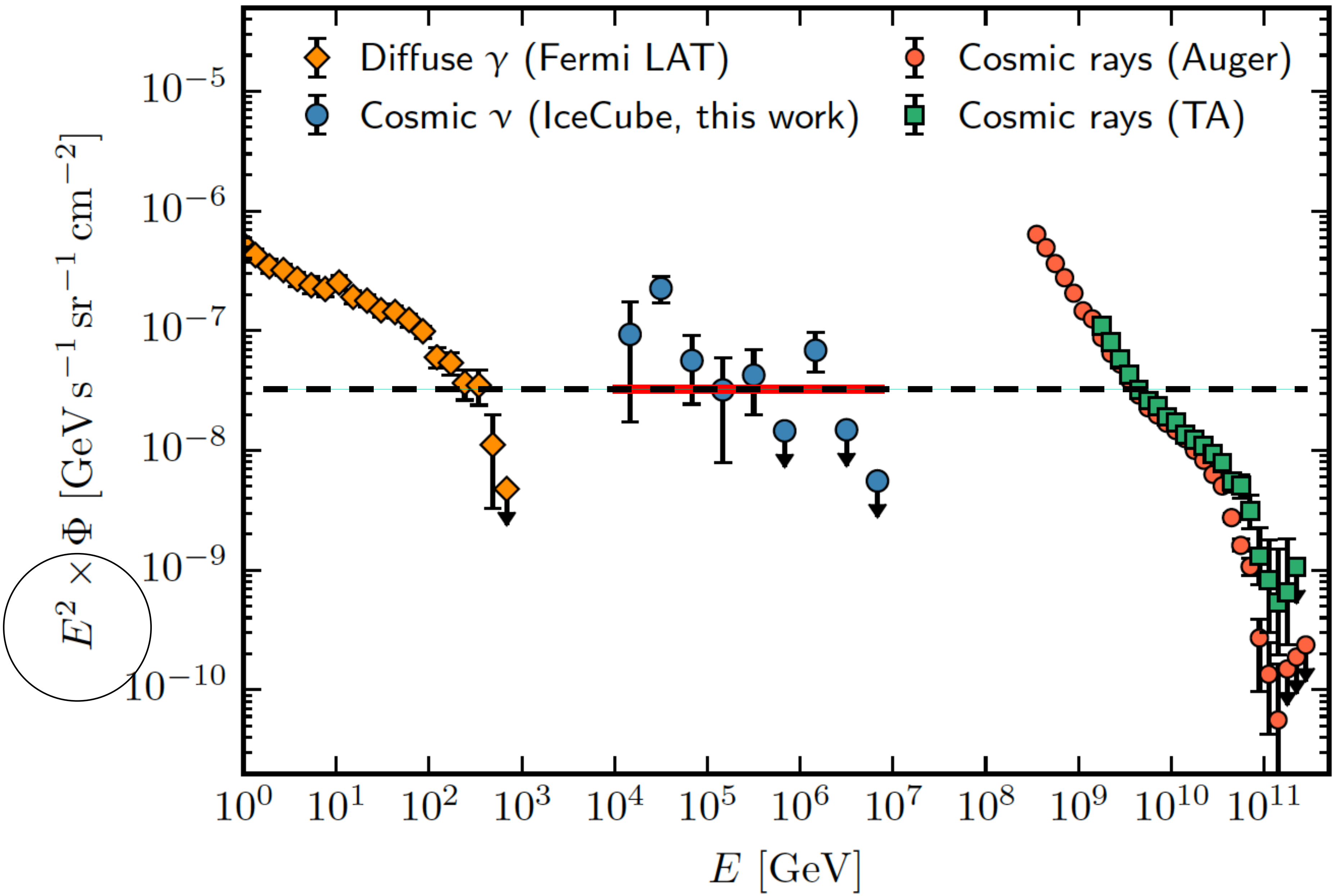

p
γ
e+
γ
ν
e-
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


γ
e+
e-
GeV
PeV
γ + γCMB → e+ + e-
X0



$\pi^+ = \pi^- = \pi^0$
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



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

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

- common sources?

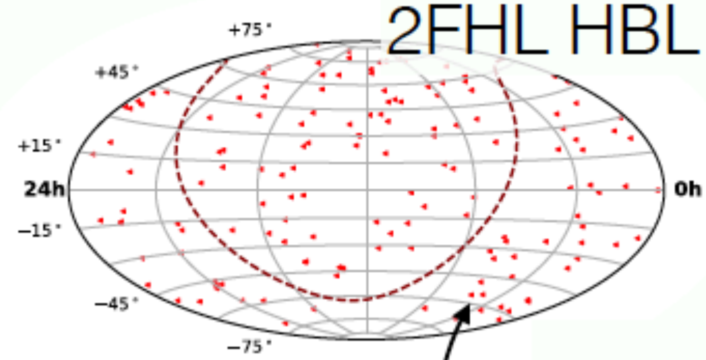
  Fermi: mostly blazars

  IceCube: at least, not the same blazars

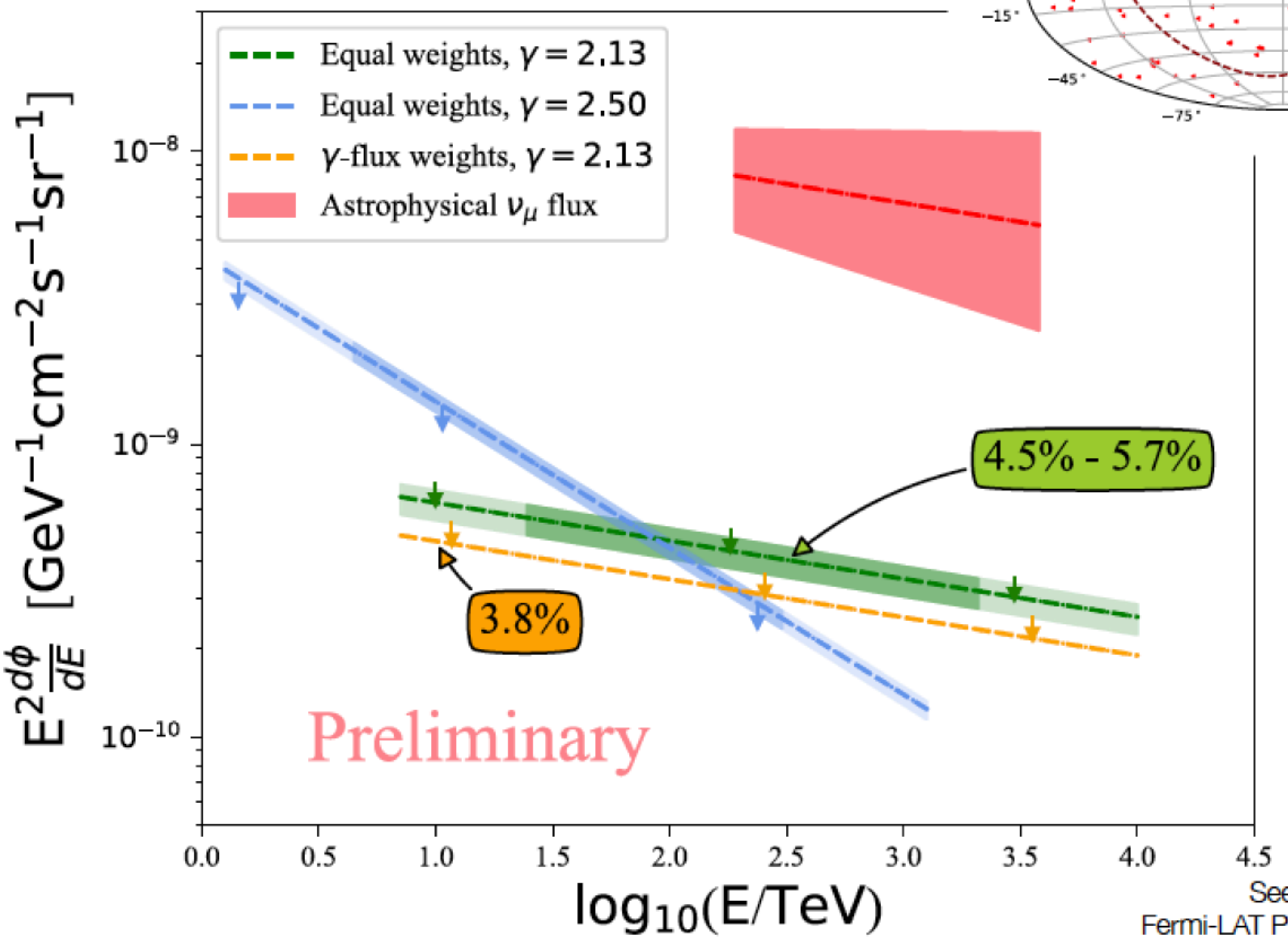
Population studies: blazar catalog search

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

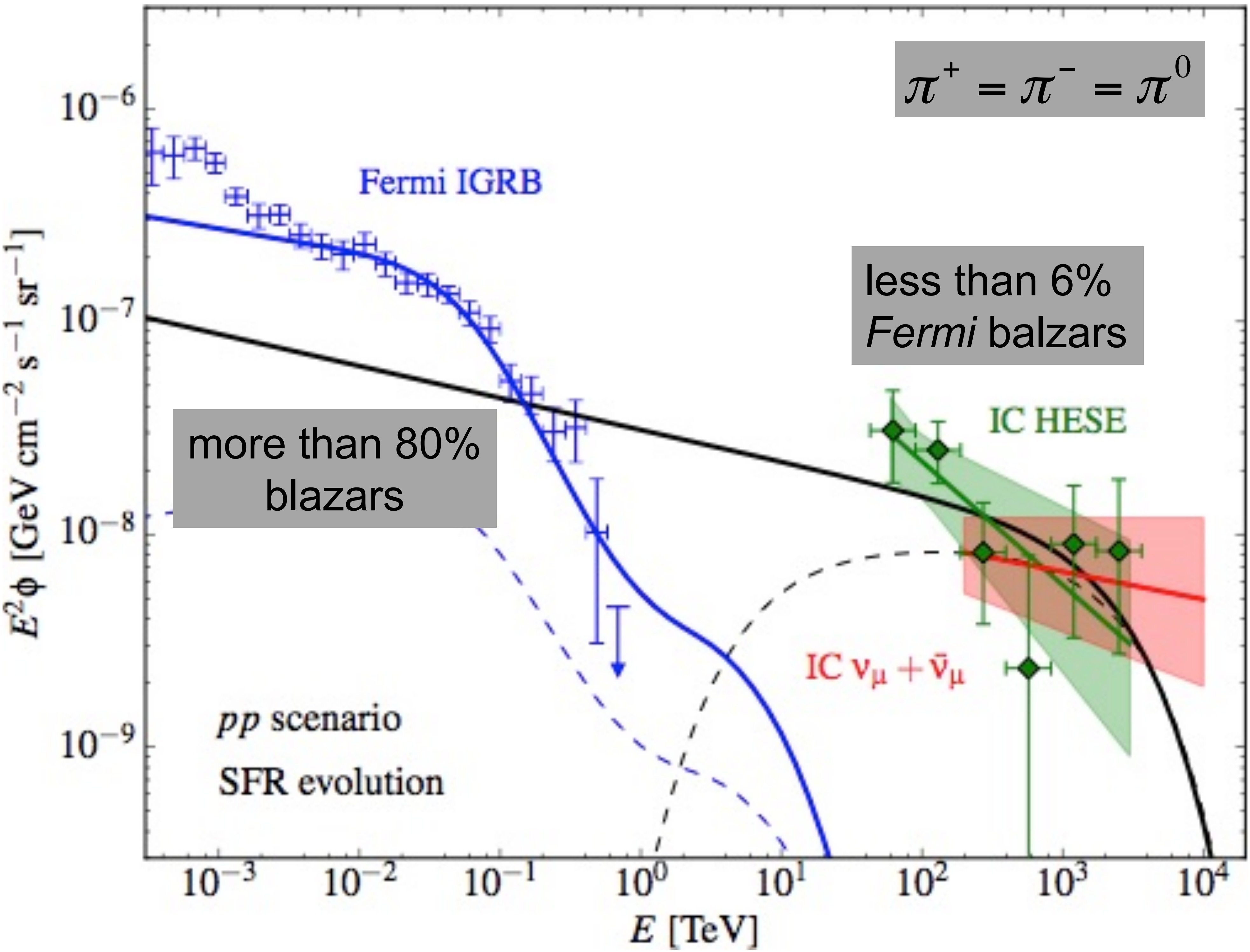
2FHL HBL



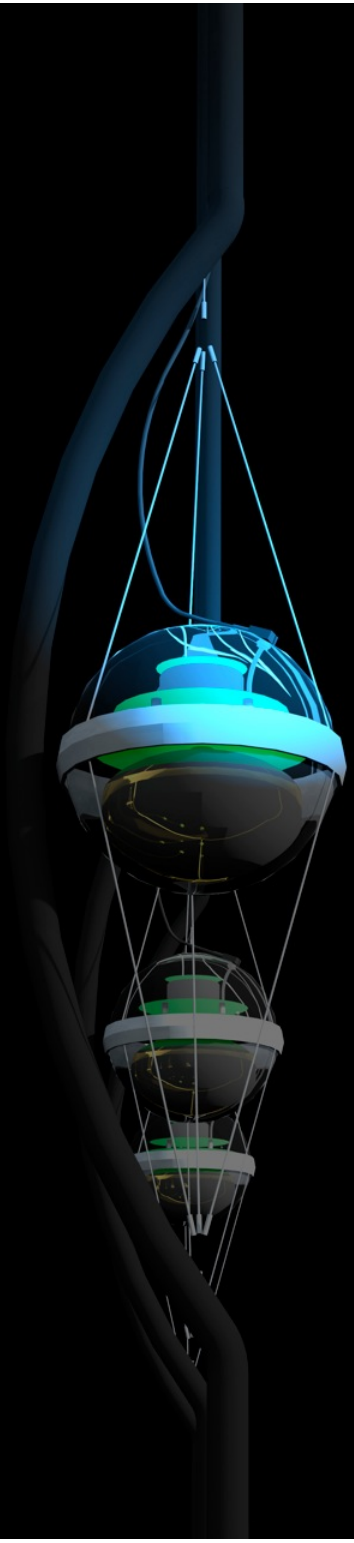
<1% of the sky



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



$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
less than 6%
Fermi balzars
IC HESE
more than 80%
blazars
IC $\nu_\mu + \bar{\nu}_\mu$
pp scenario
SFR evolution
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



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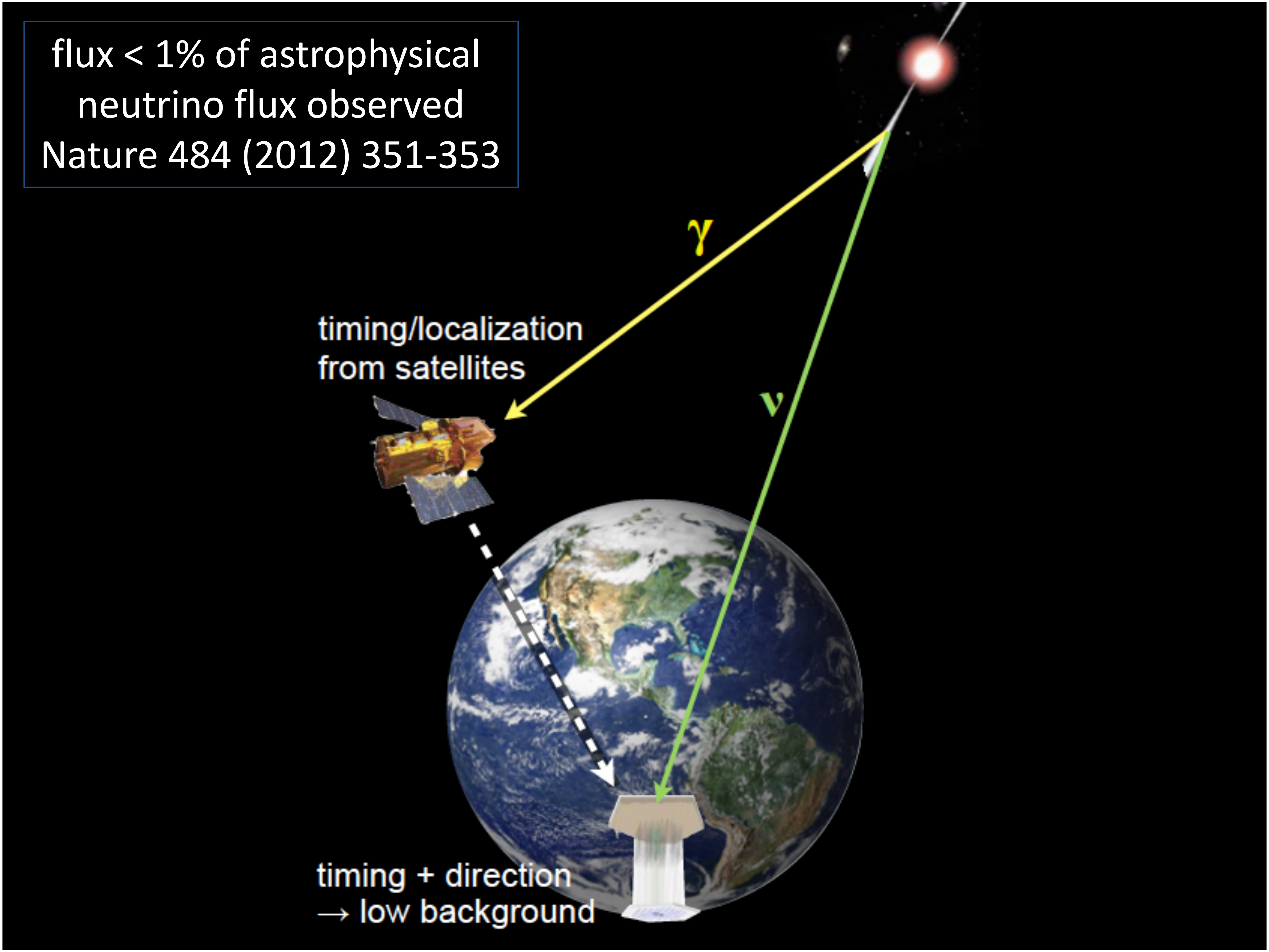

flux < 1% of astrophysical
neutrino flux observed
Nature 484 (2012) 351-353
γ
ν
timing/localization
from satellites
timing + direction
→ low background

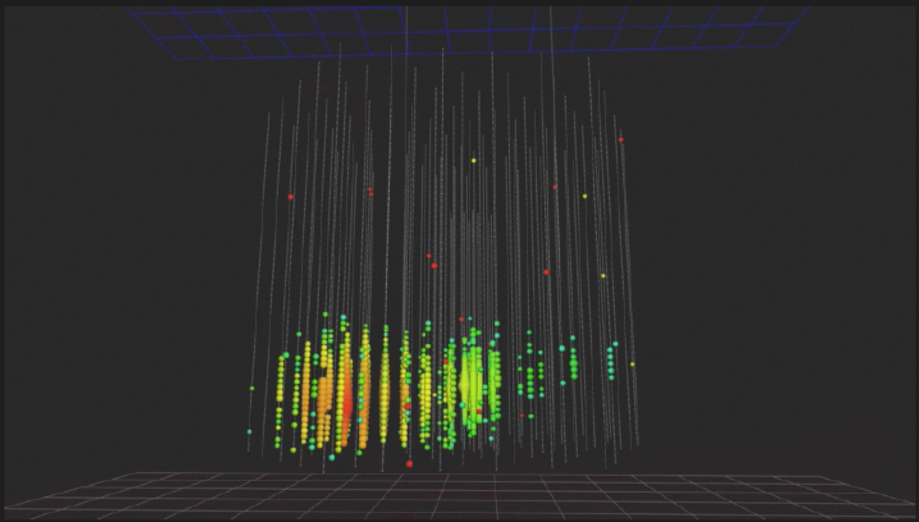
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

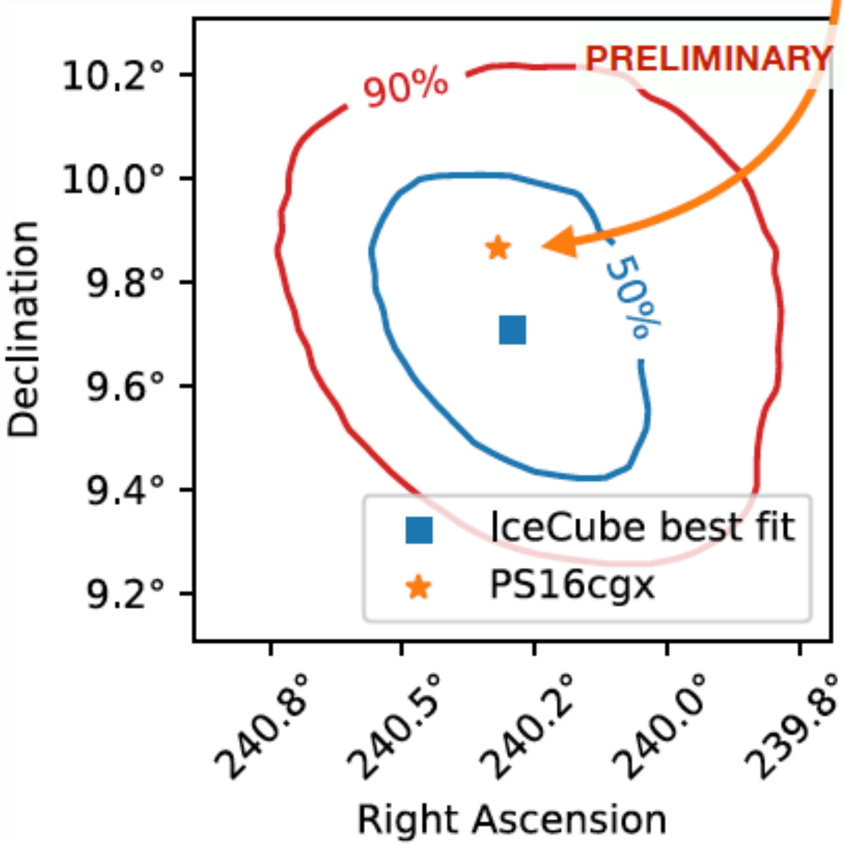
We send **rough reconstructions first** and then **update them.**

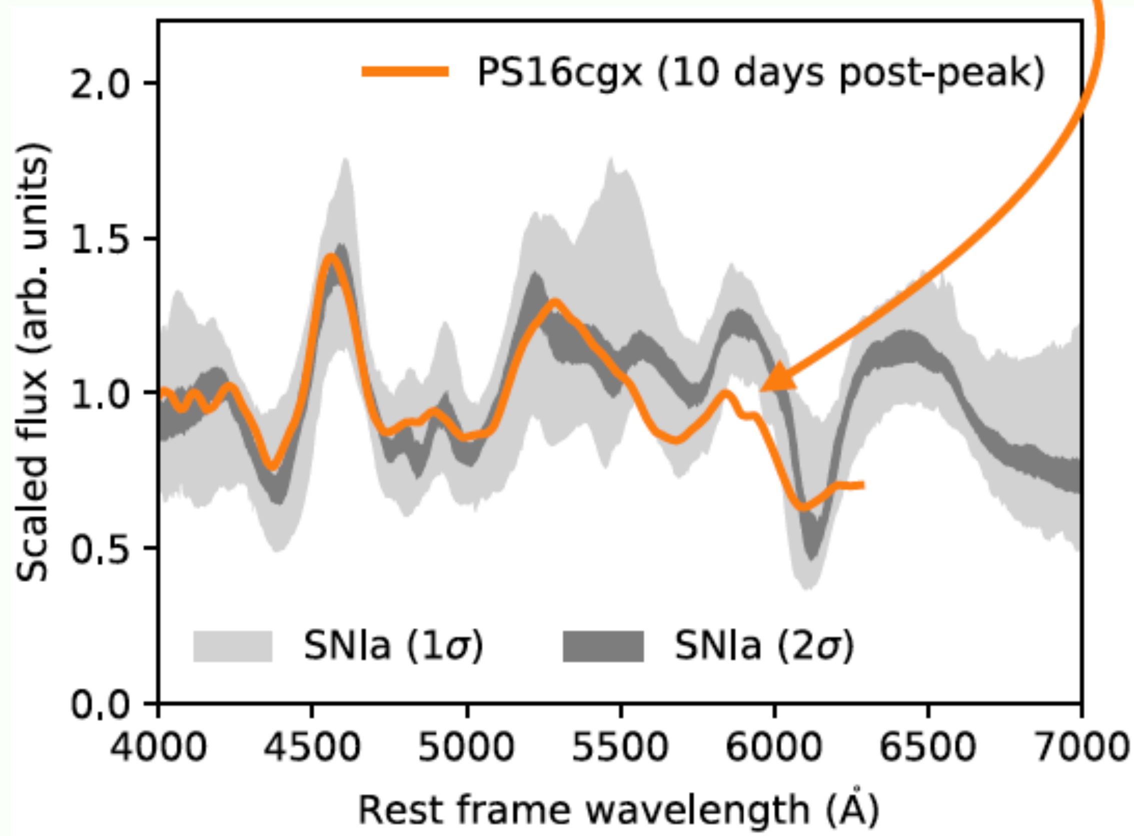


PS16cgx: a young supernova in the field of a HESE neutrino

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

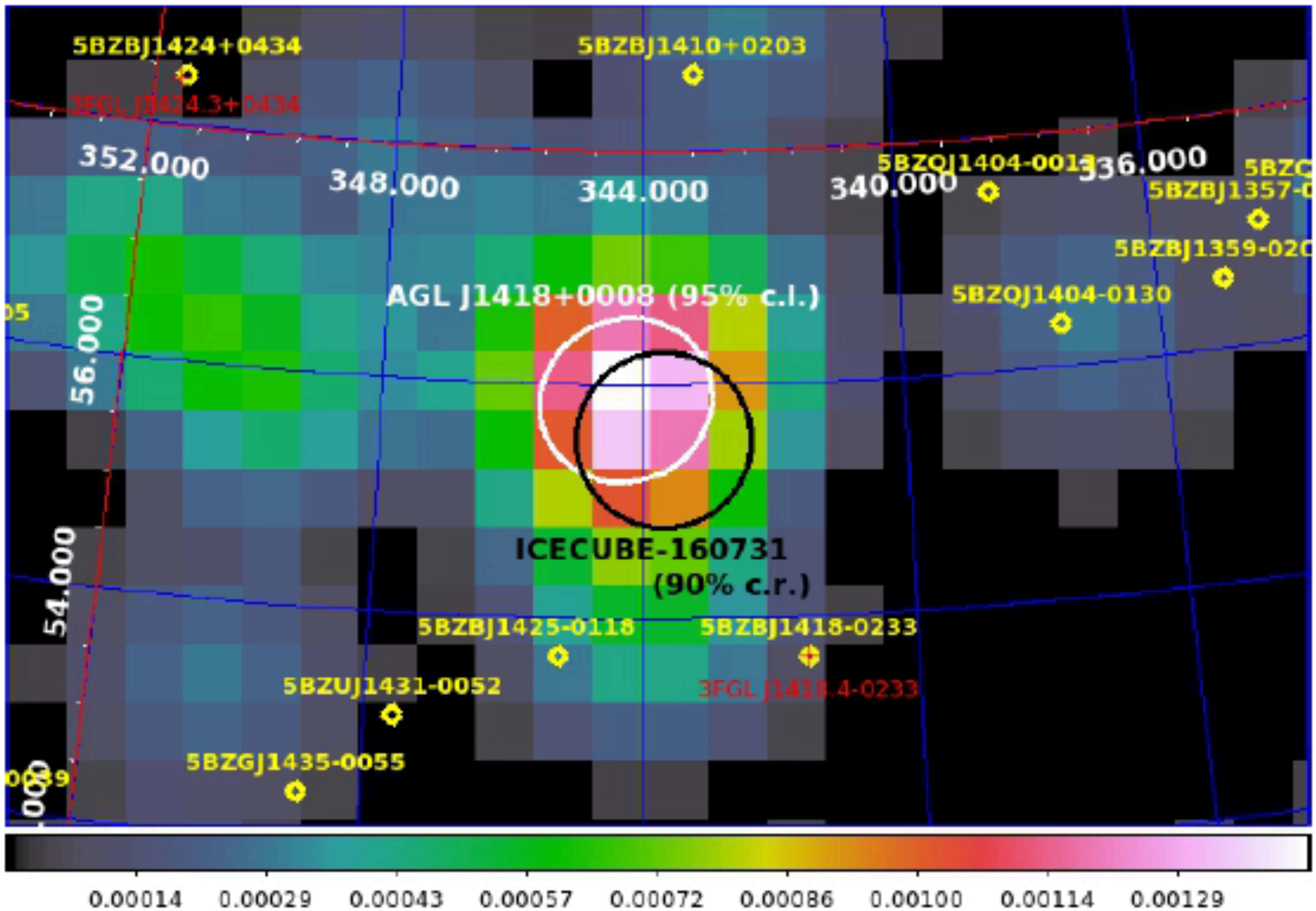




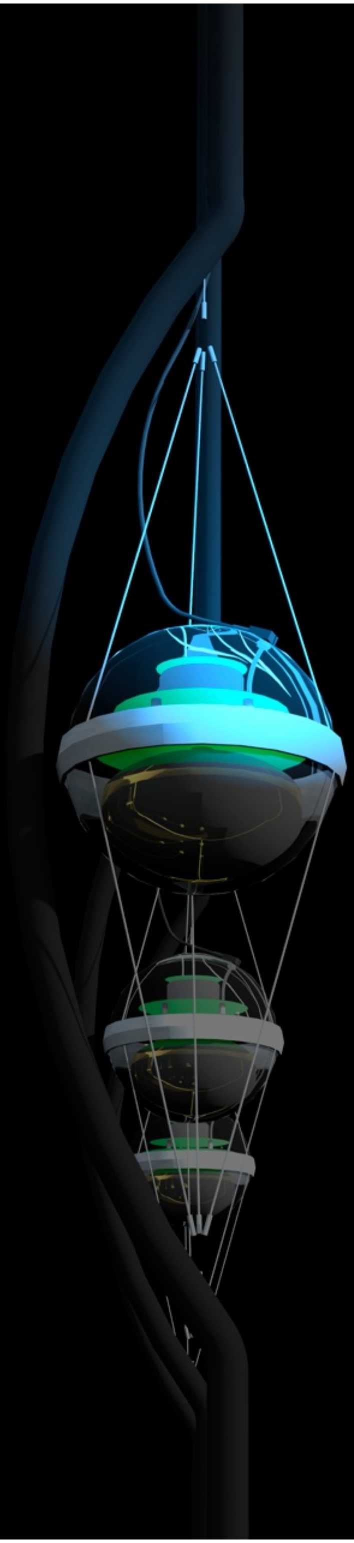
Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

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



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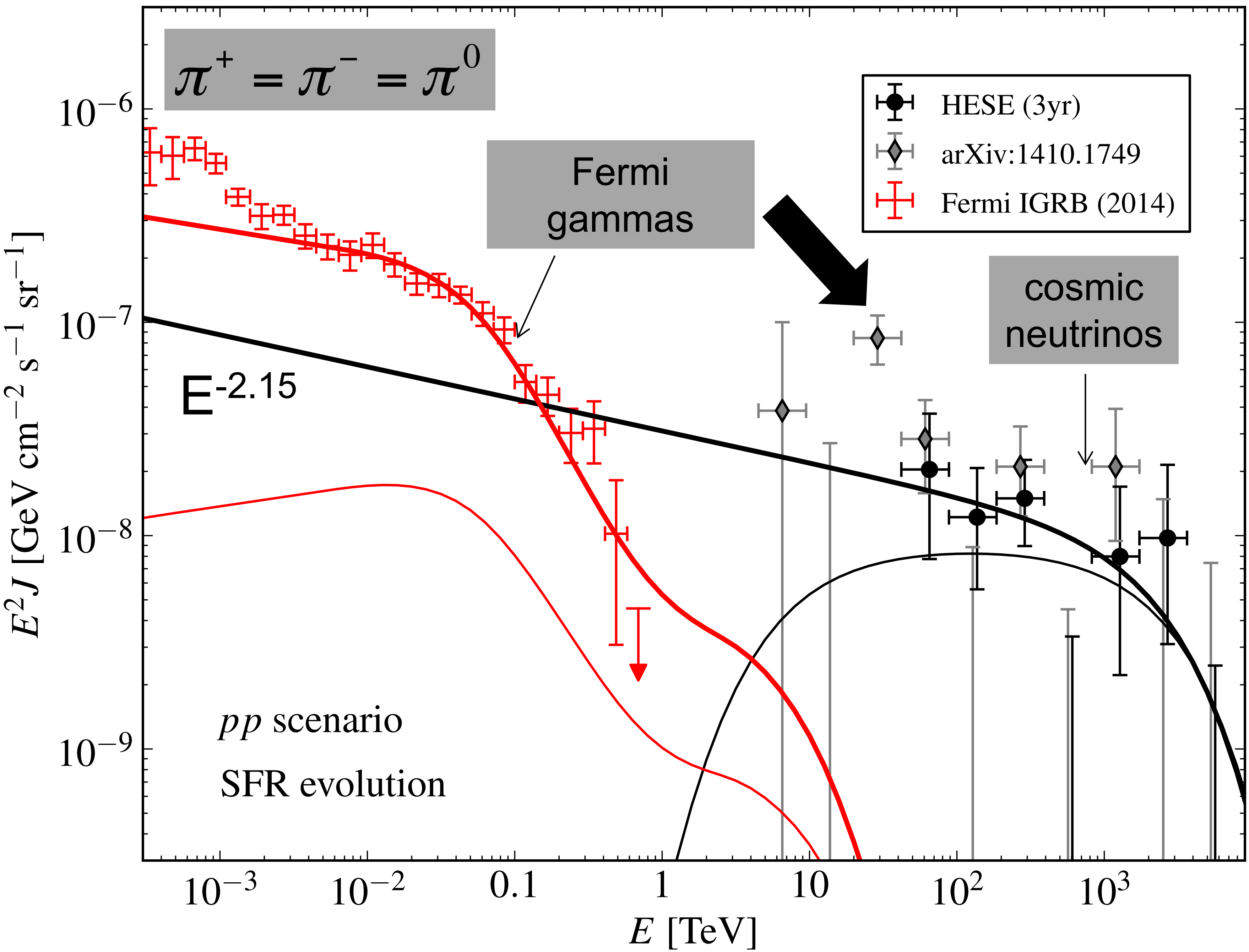

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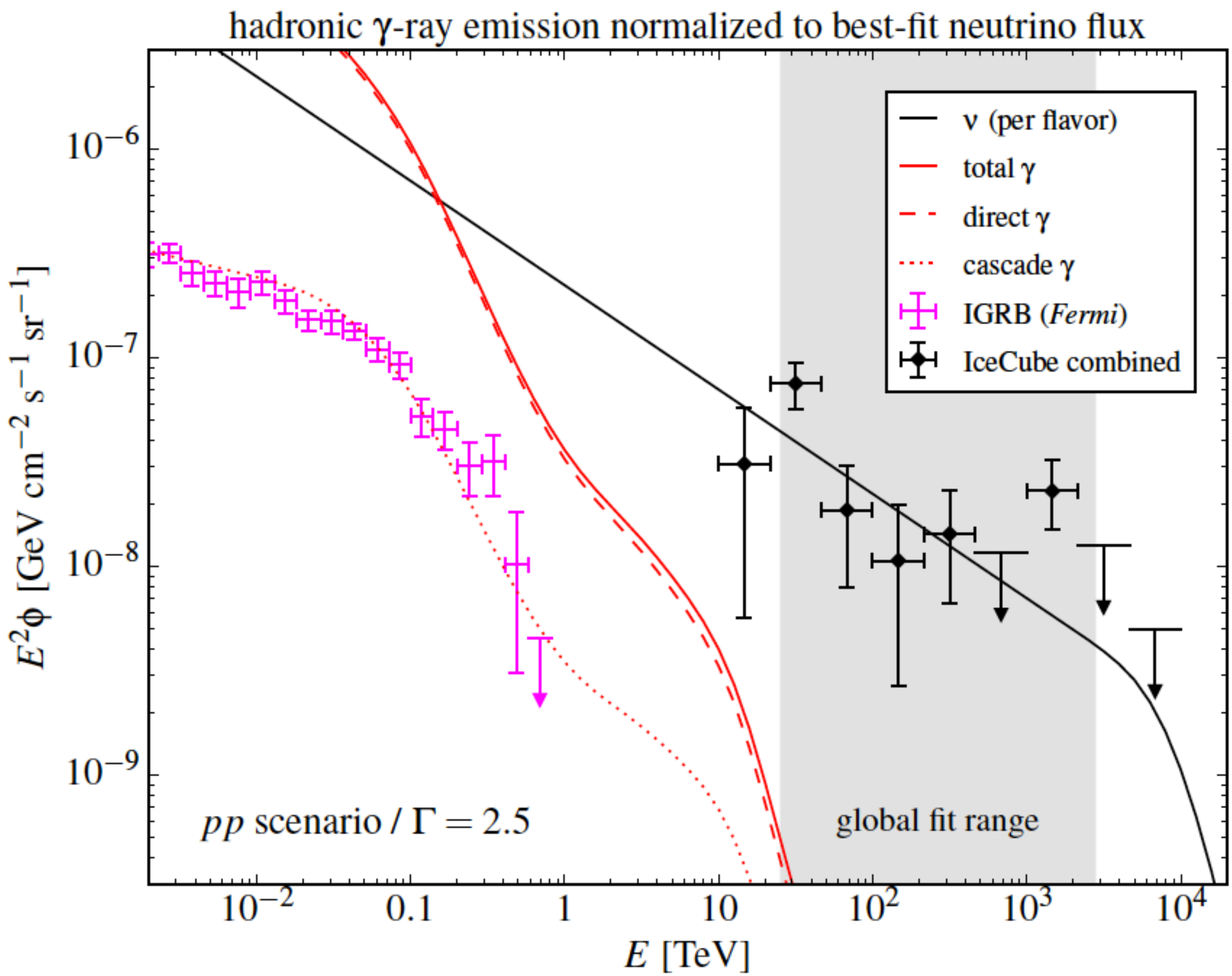
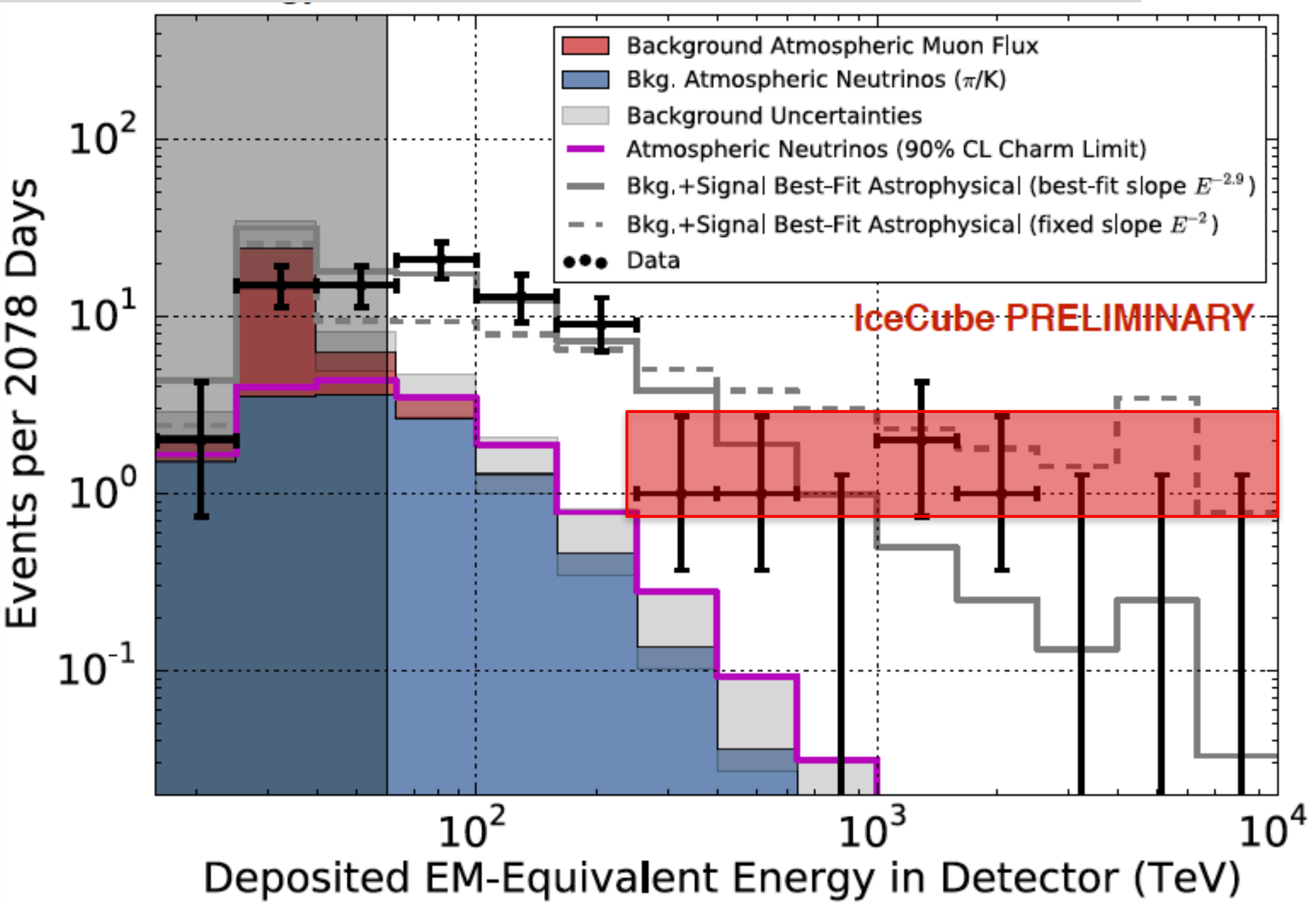
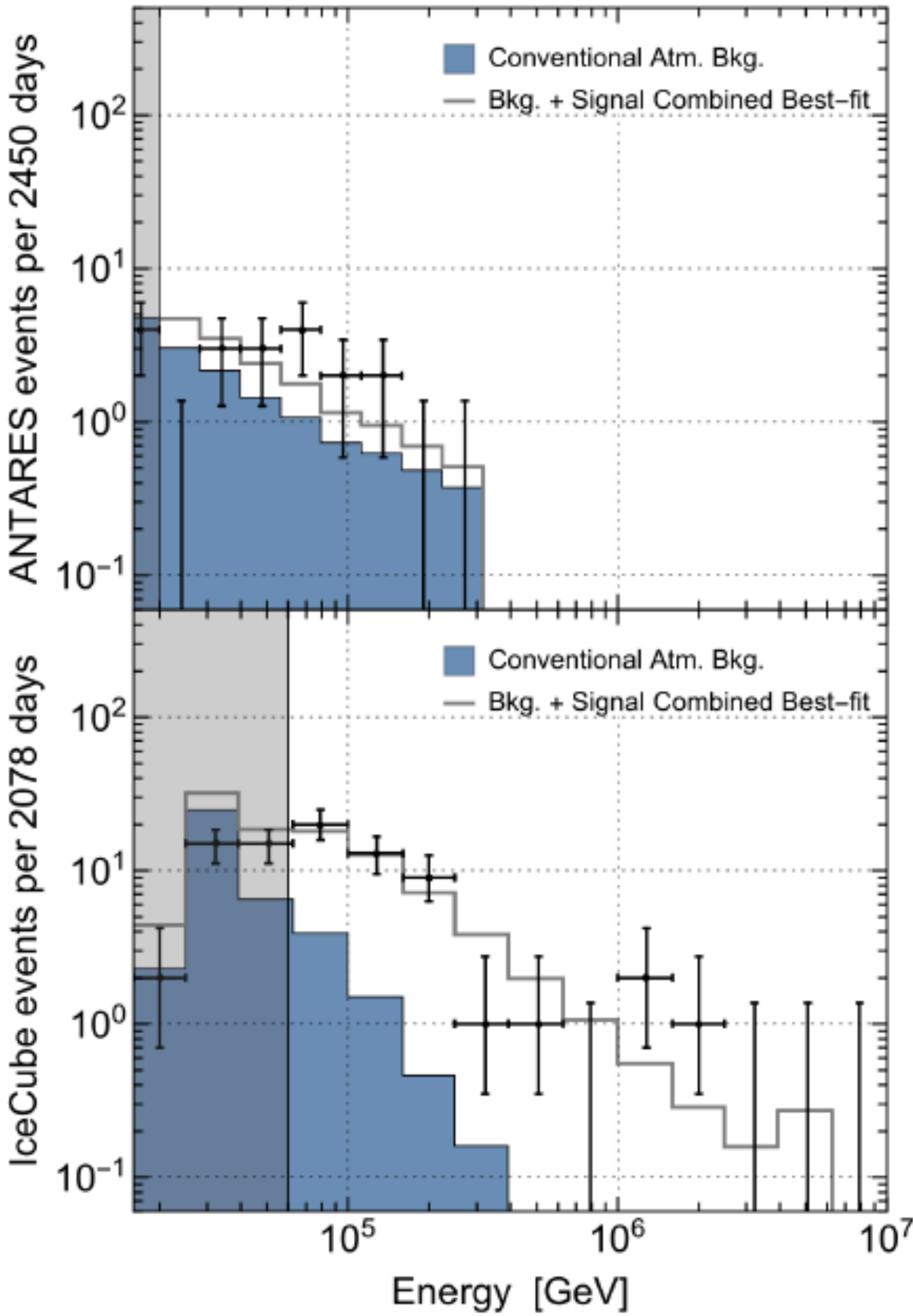
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3



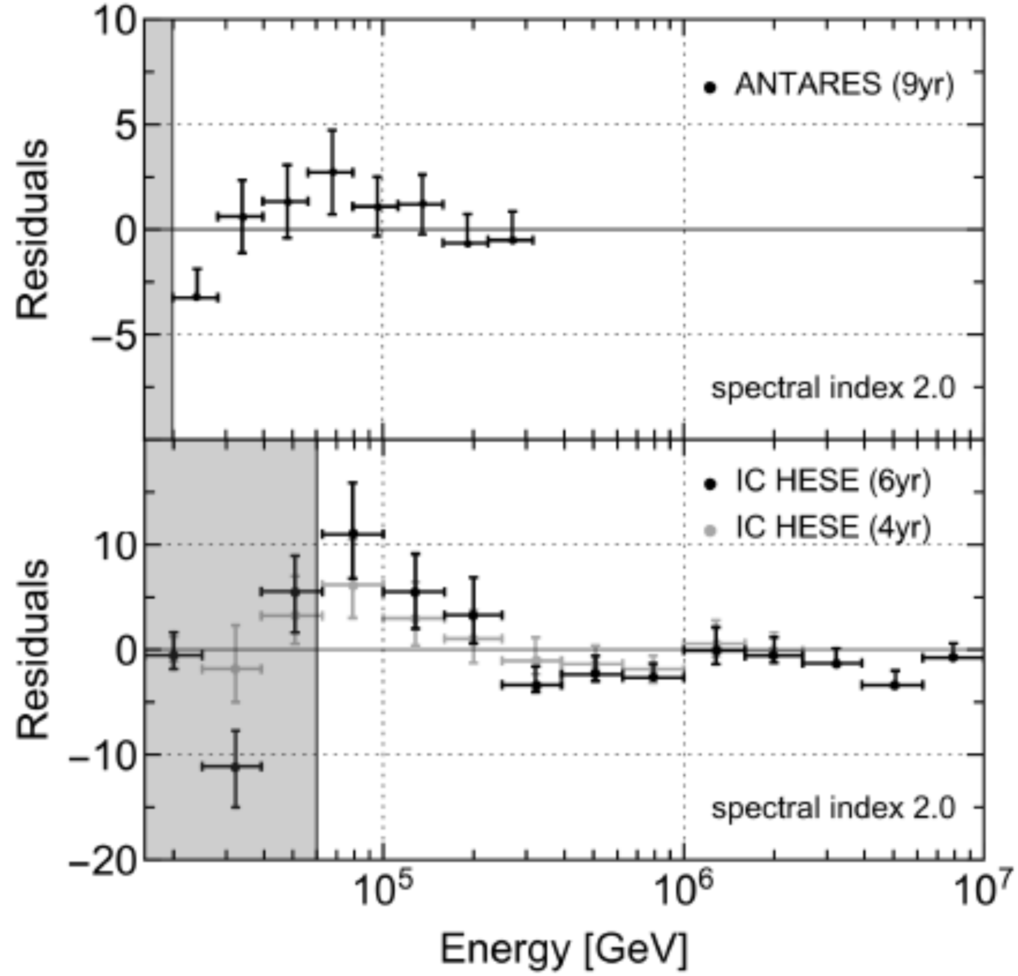
a "problem" ?
gamma rays cascade in the source to < GeV energy

comparison HESE and muon neutrino results (red overlay)



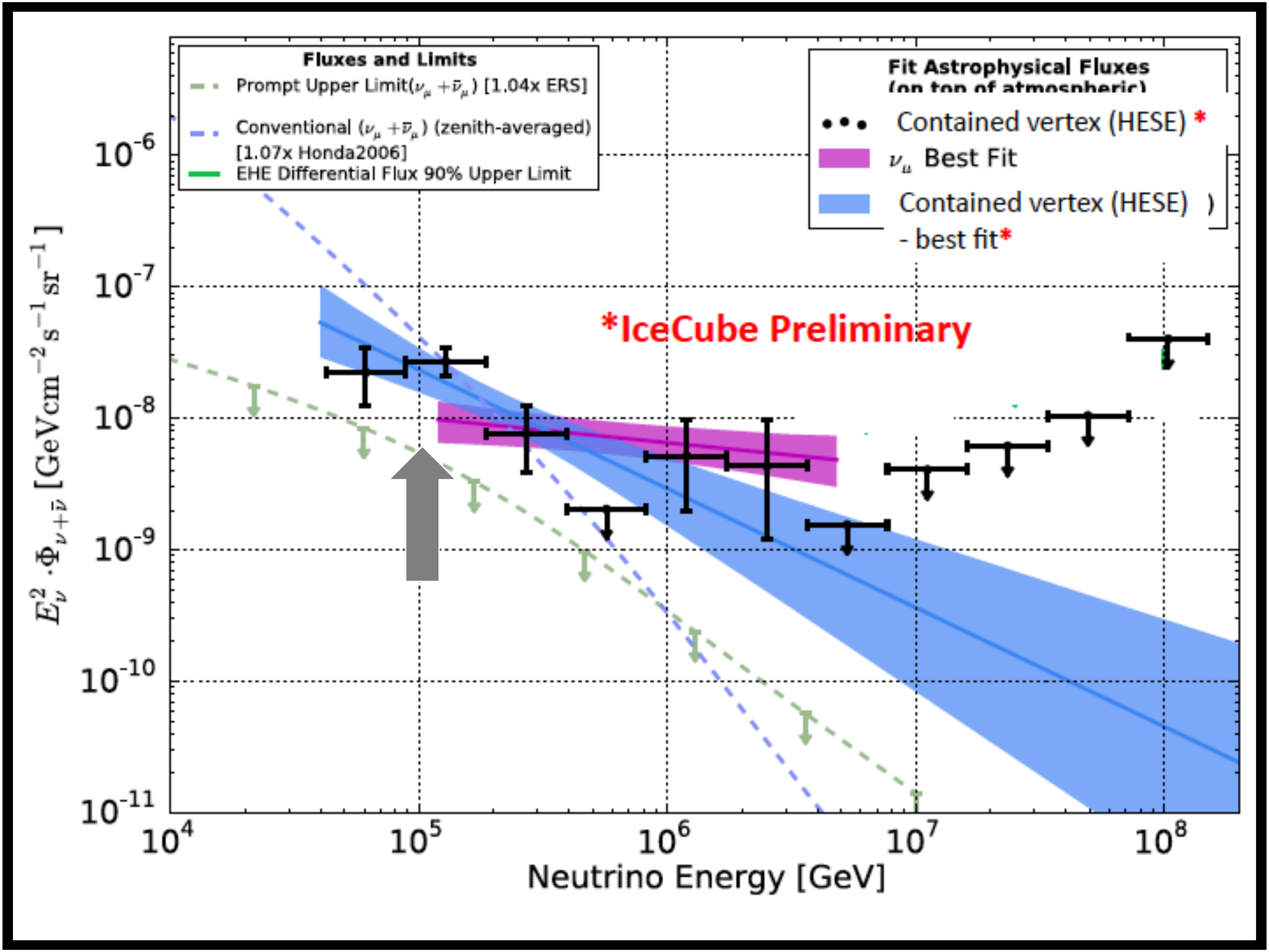


Residuals for E^{-2} spectrum



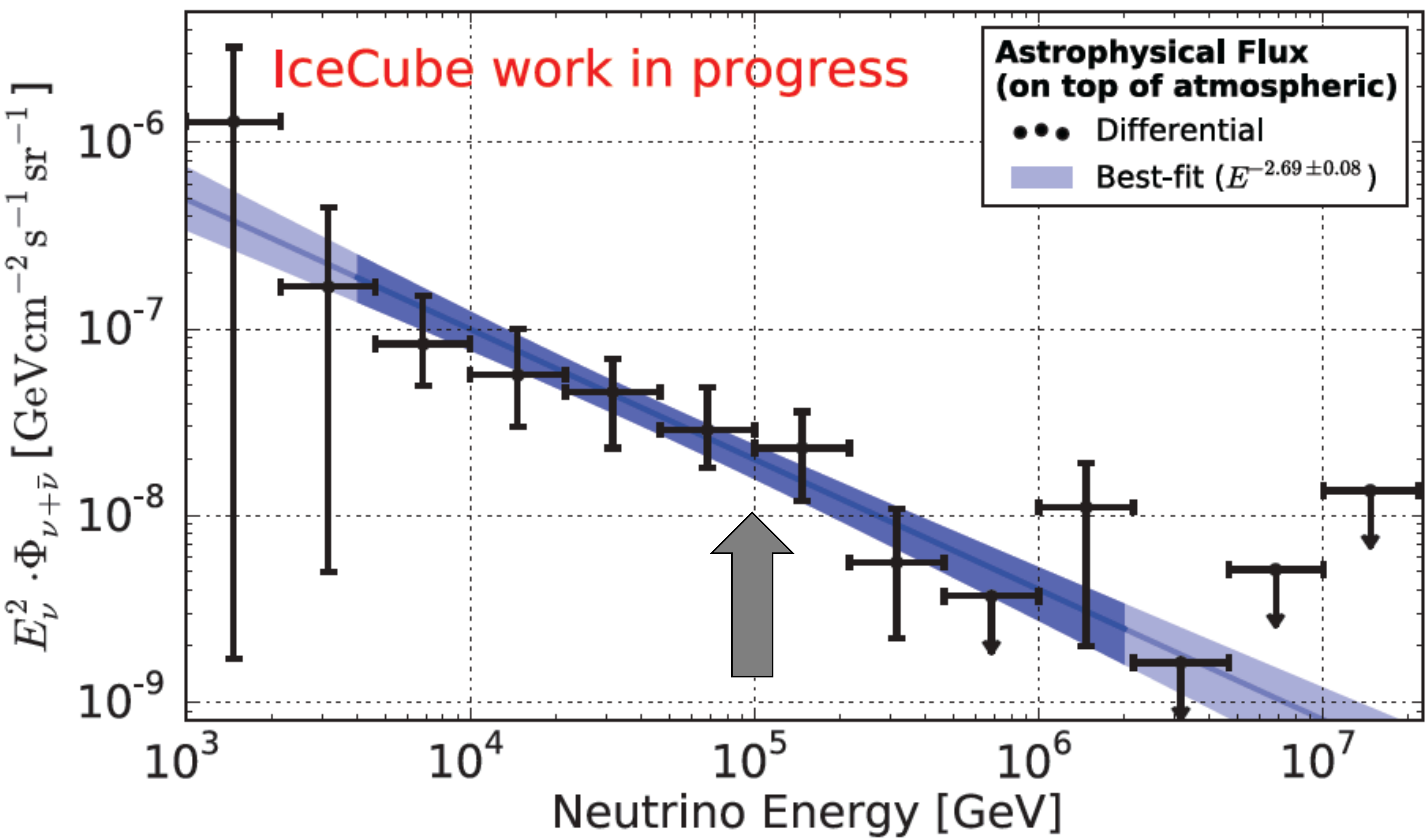
Marco Chianese et al.

- almost 3σ, but appears in every analysis
- the lower the threshold, the steeper the power

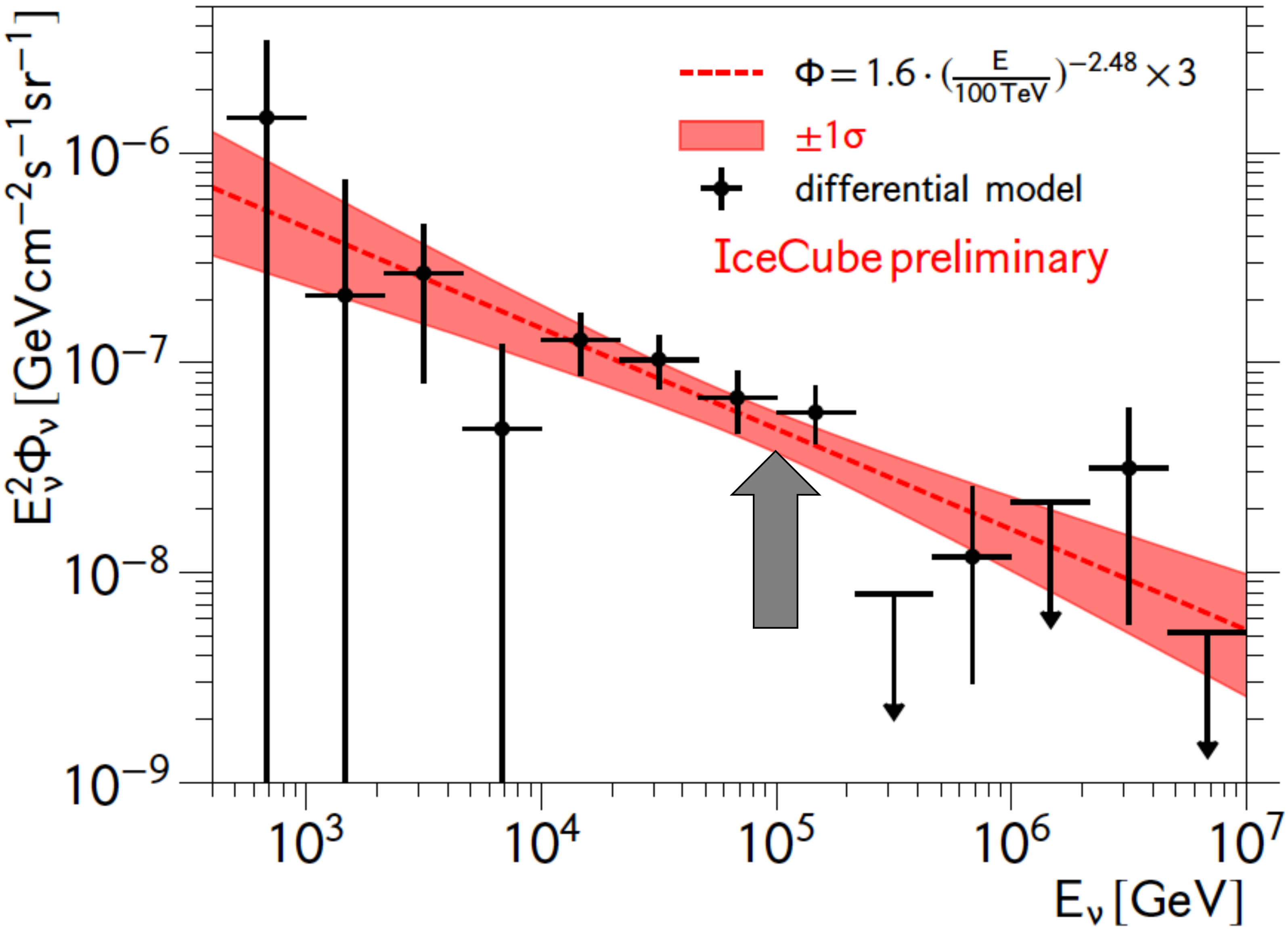


Fluxes and Limits
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
EHE Differential Flux 90% Upper Limit
Fit Astrophysical Fluxes (on top of atmospheric)
Contained vertex (HESE) *
ν_μ Best Fit
Contained vertex (HESE) - best fit*
*IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [$\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^4
10^5
10^6
10^7
10^8

low threshold starting event analysis; 7 years

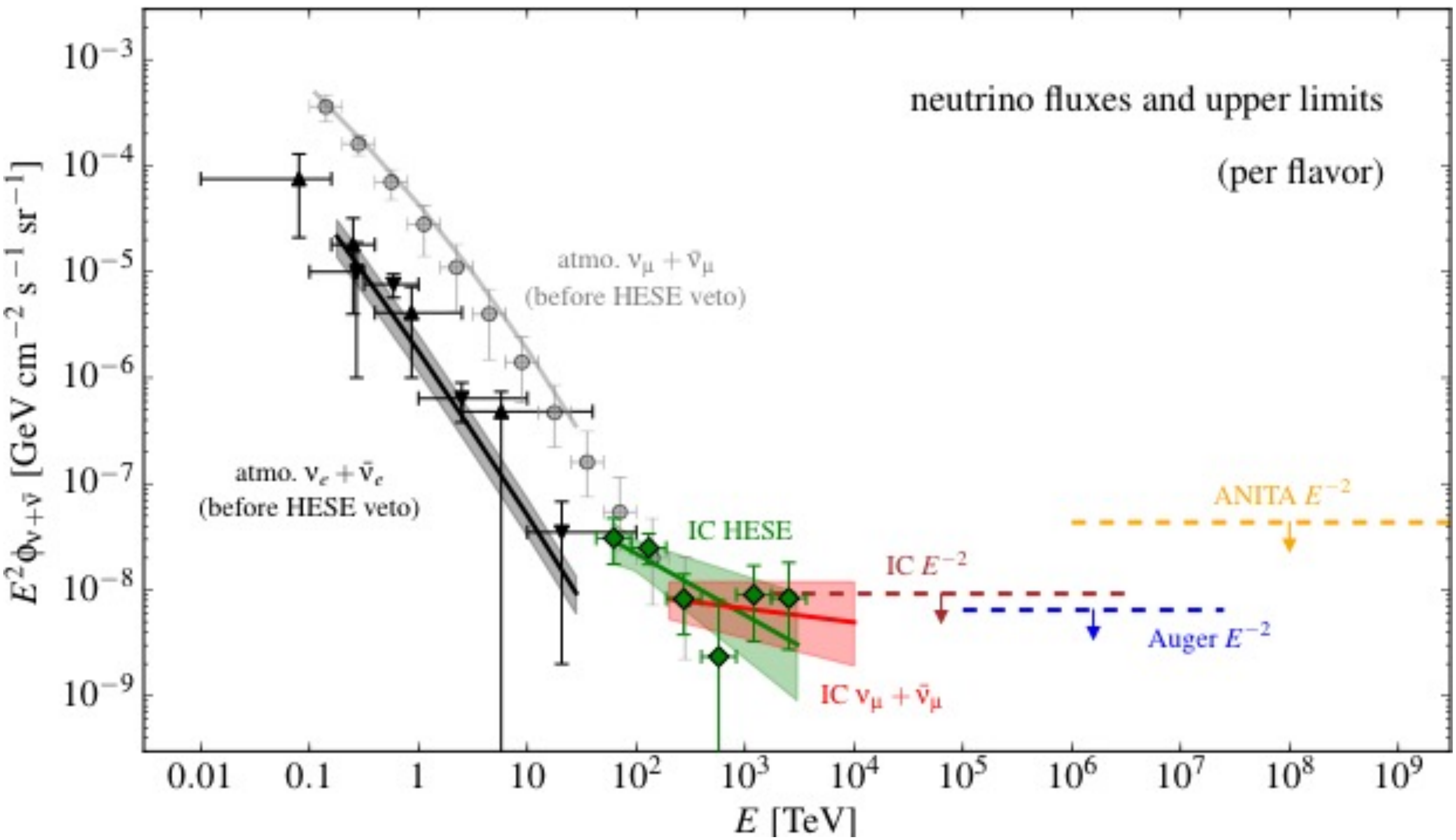


shower events only: cosmic flux dominates > 20 TeV



- 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



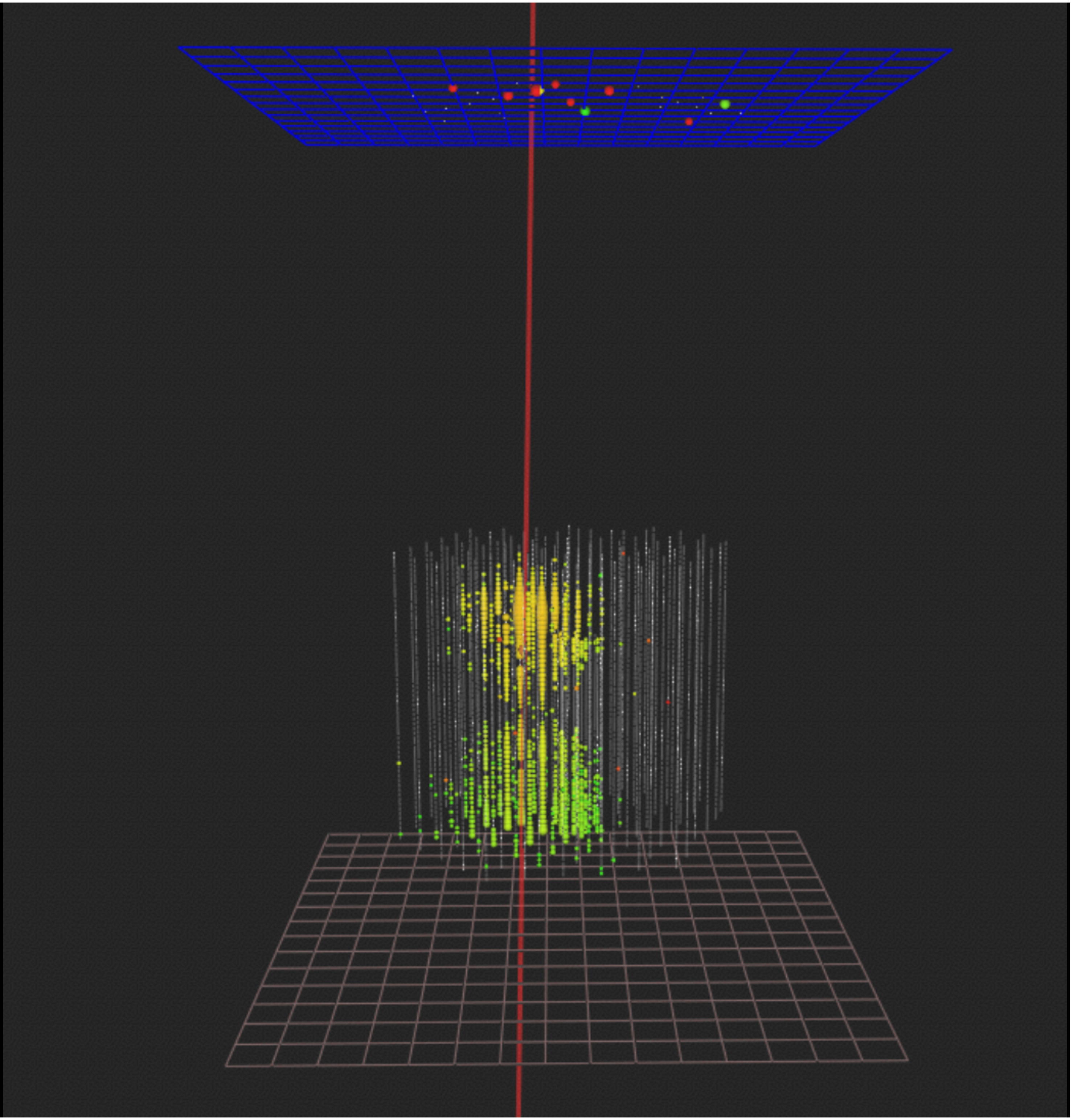
- tracks cosmic ray flux in energy, isotropic in zenith, normalization unknown: does not fit the data
- neutrino events are isolated
- incompatible with observes atmospheric *electron* neutrino spectrum

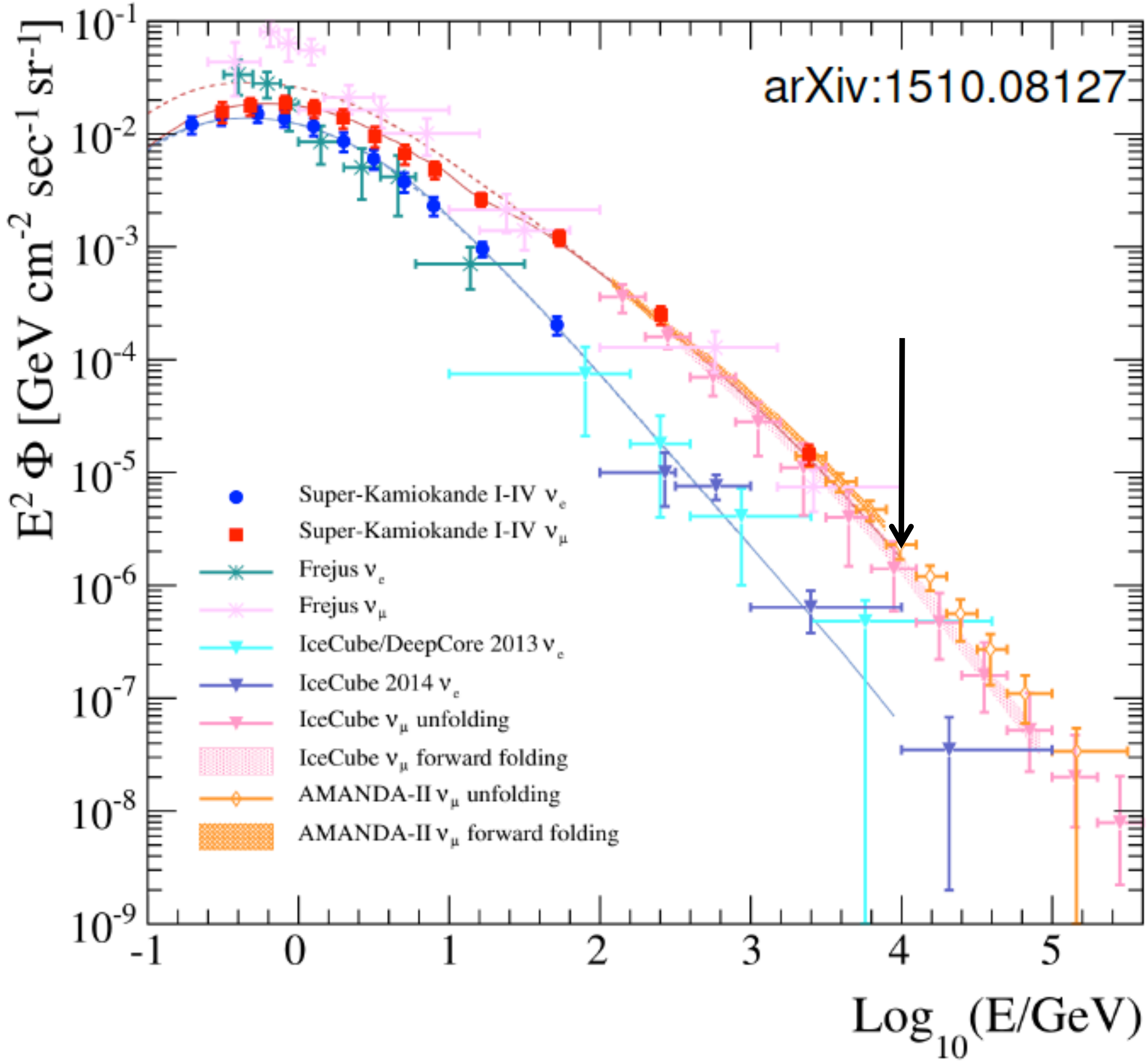
430 TeV inside detector

PeV ν_μ

no air shower

all cosmic neutrinos are isolated by self-veto

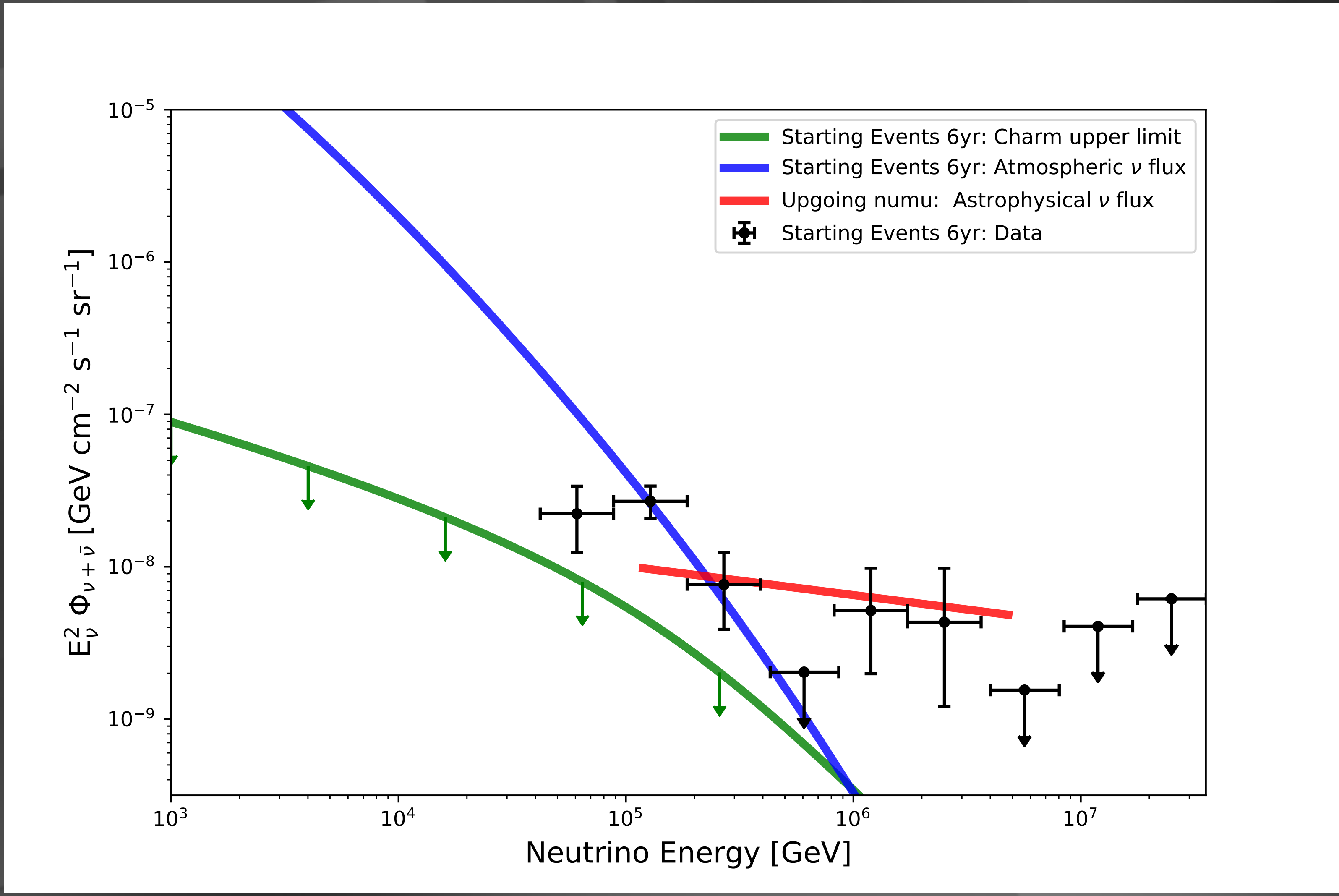




atmospheric neutrino spectrum (energy measurement) well understood at 10 TeV in terms of conventional neutrinos; charm contribution is small

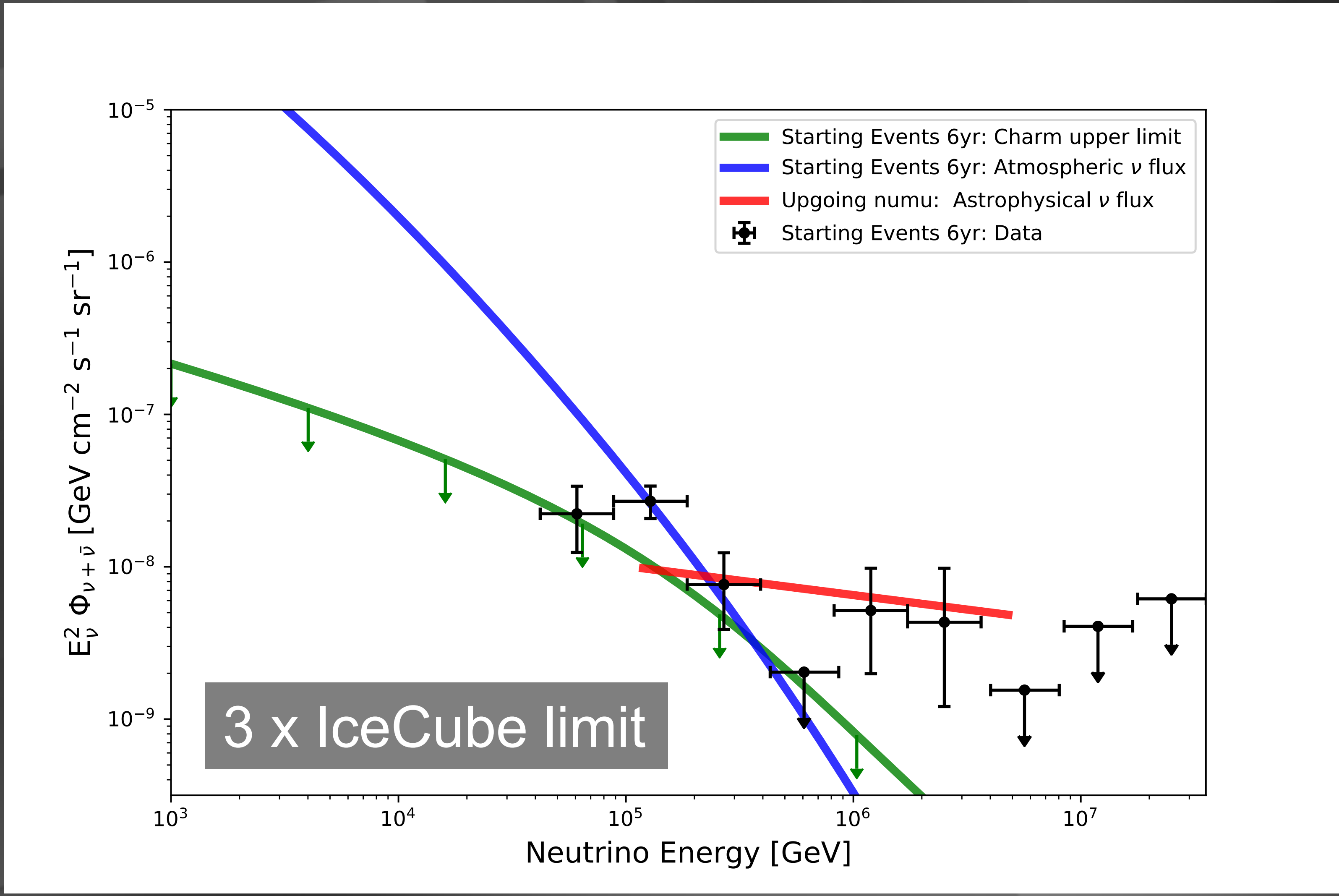
not background: prompt decay of charm particles produced in the atmosphere

- tracks cosmic ray flux in energy, isotropic in zenith (normalization unknown): does not fit the data
- neutrino events are isolated
- constrained by atmospheric *electron* neutrino spectrum

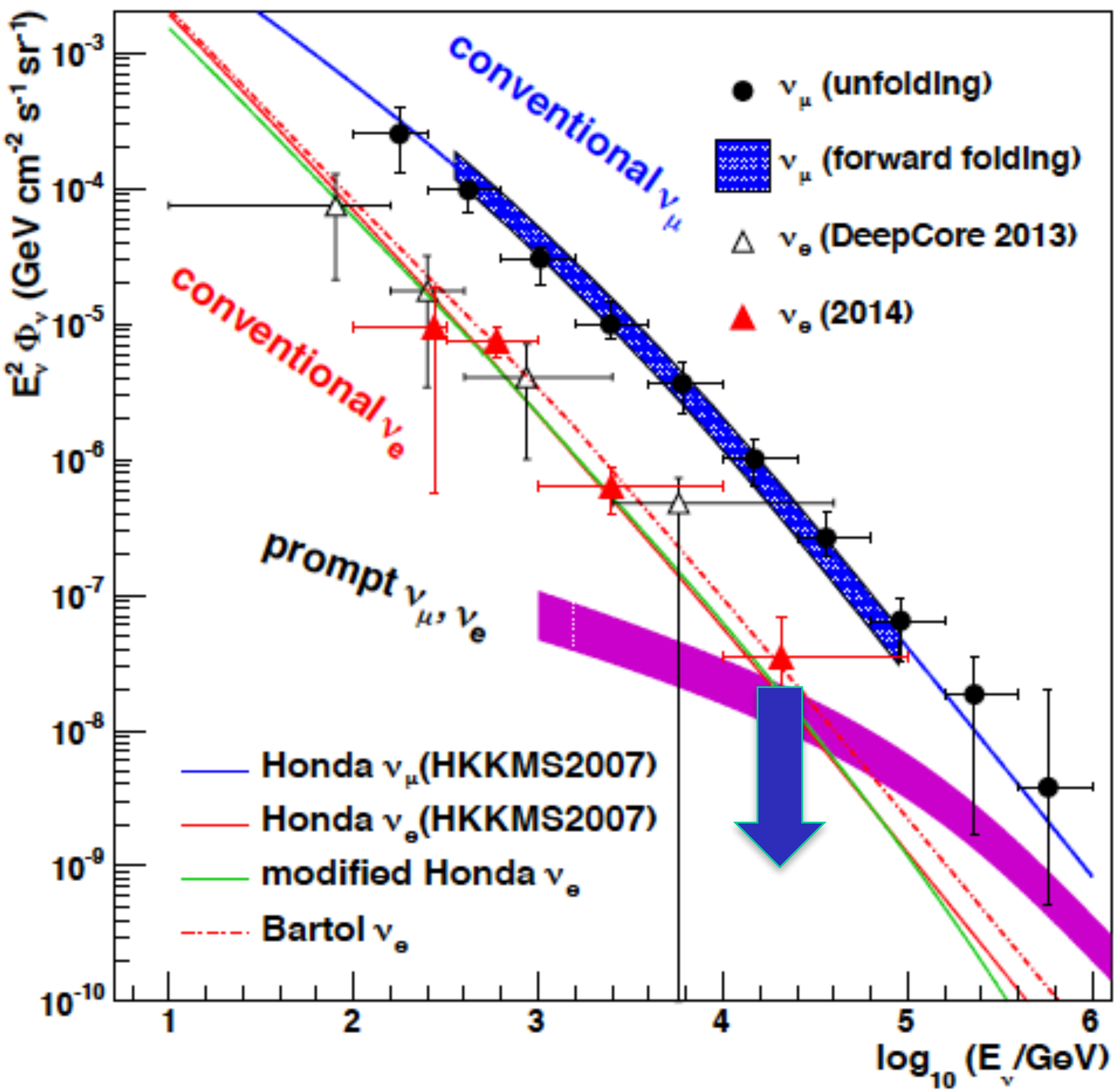


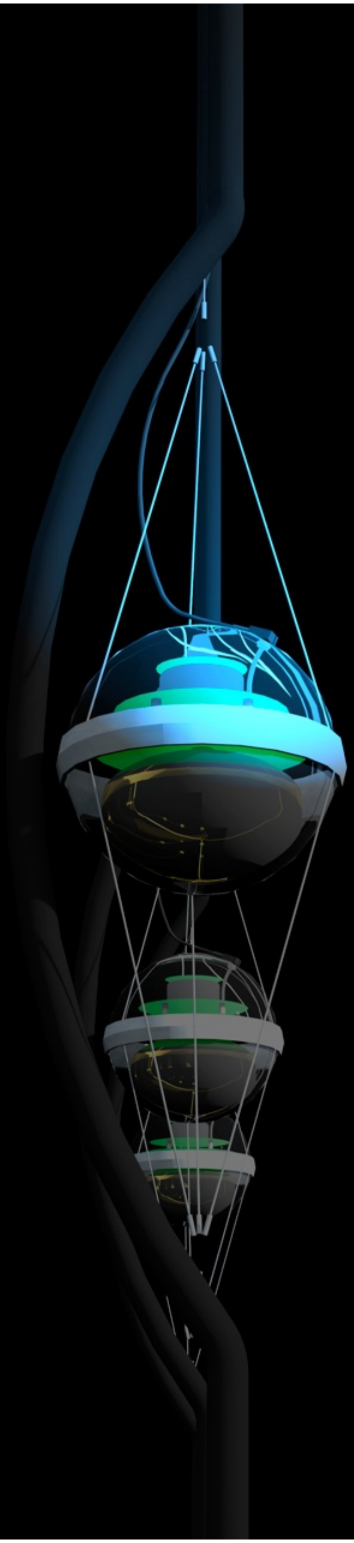
not background: prompt decay of charm particles produced in the atmosphere

- tracks cosmic ray flux in energy, isotropic in zenith (normalization unknown): does not fit the data
- neutrino events are isolated
- constrained by atmospheric *electron* neutrino spectrum



charm limited by atmospheric electrons



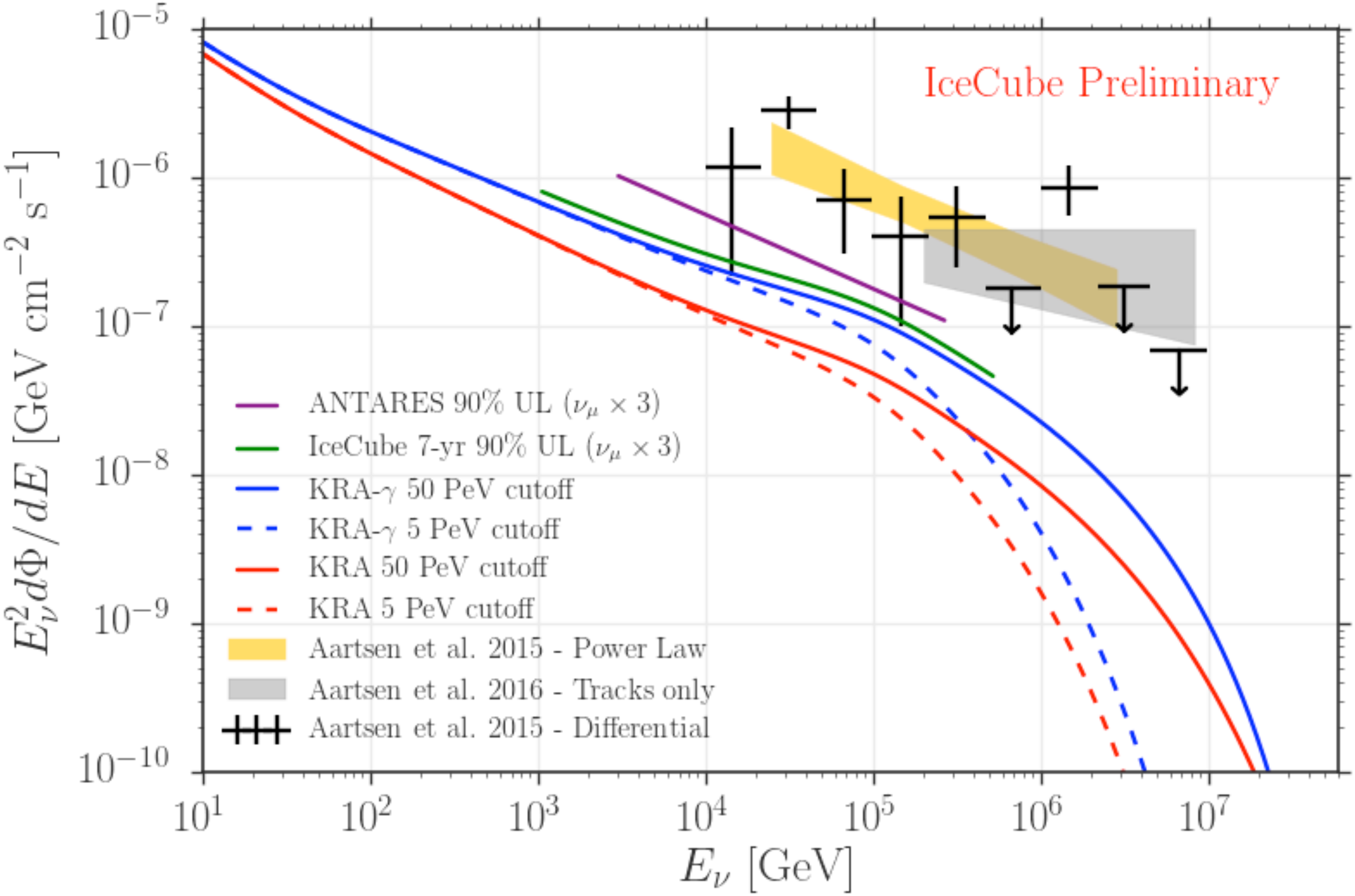


IceCube and Multimessenger Astronomy

francis halzen

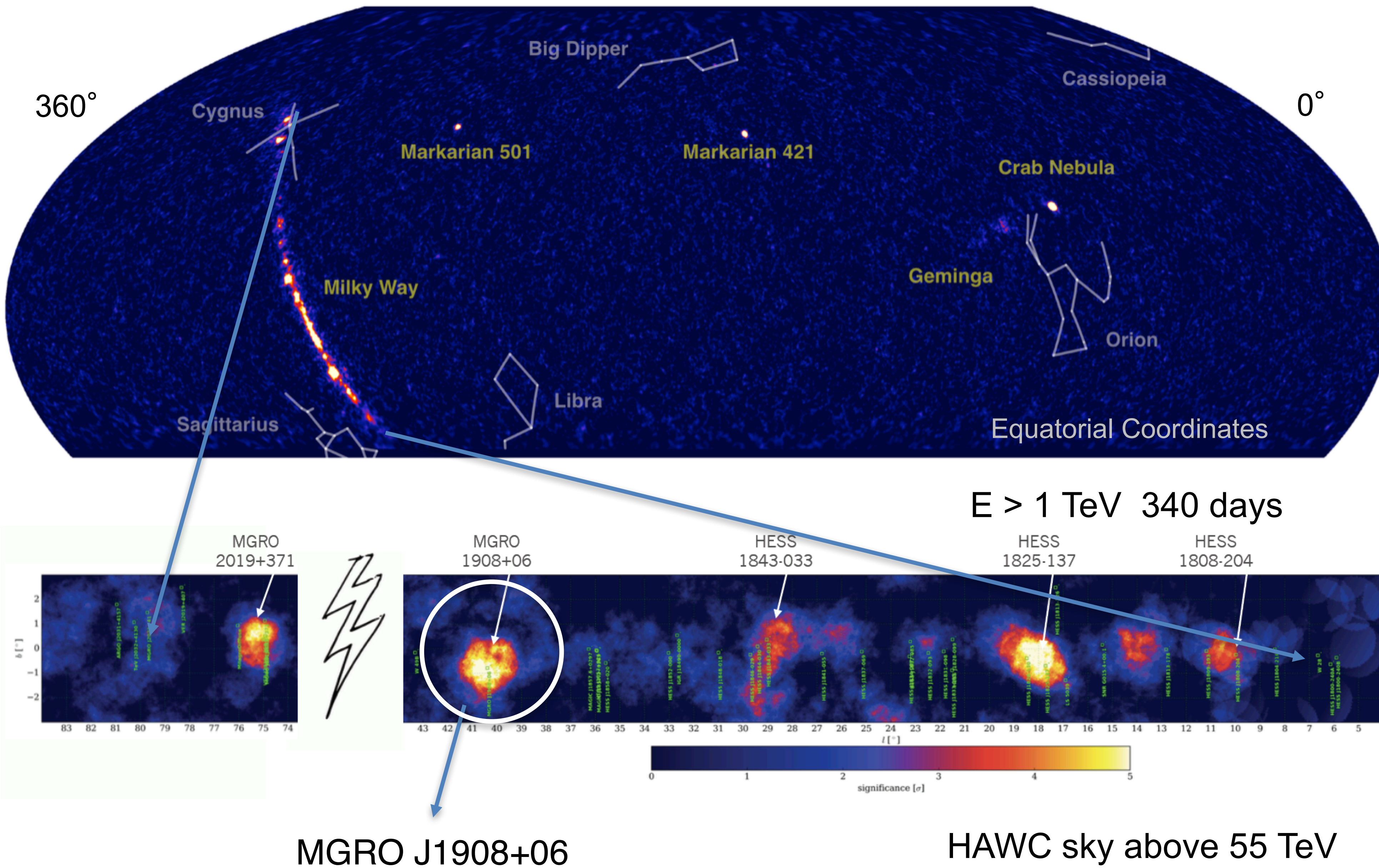
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- other multiwavelength observations
- cosmic neutrinos below 100 TeV?
- the Galaxy

IceCube.wisc.edu



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

HAWC View of Gamma Ray Sky



neutral pions

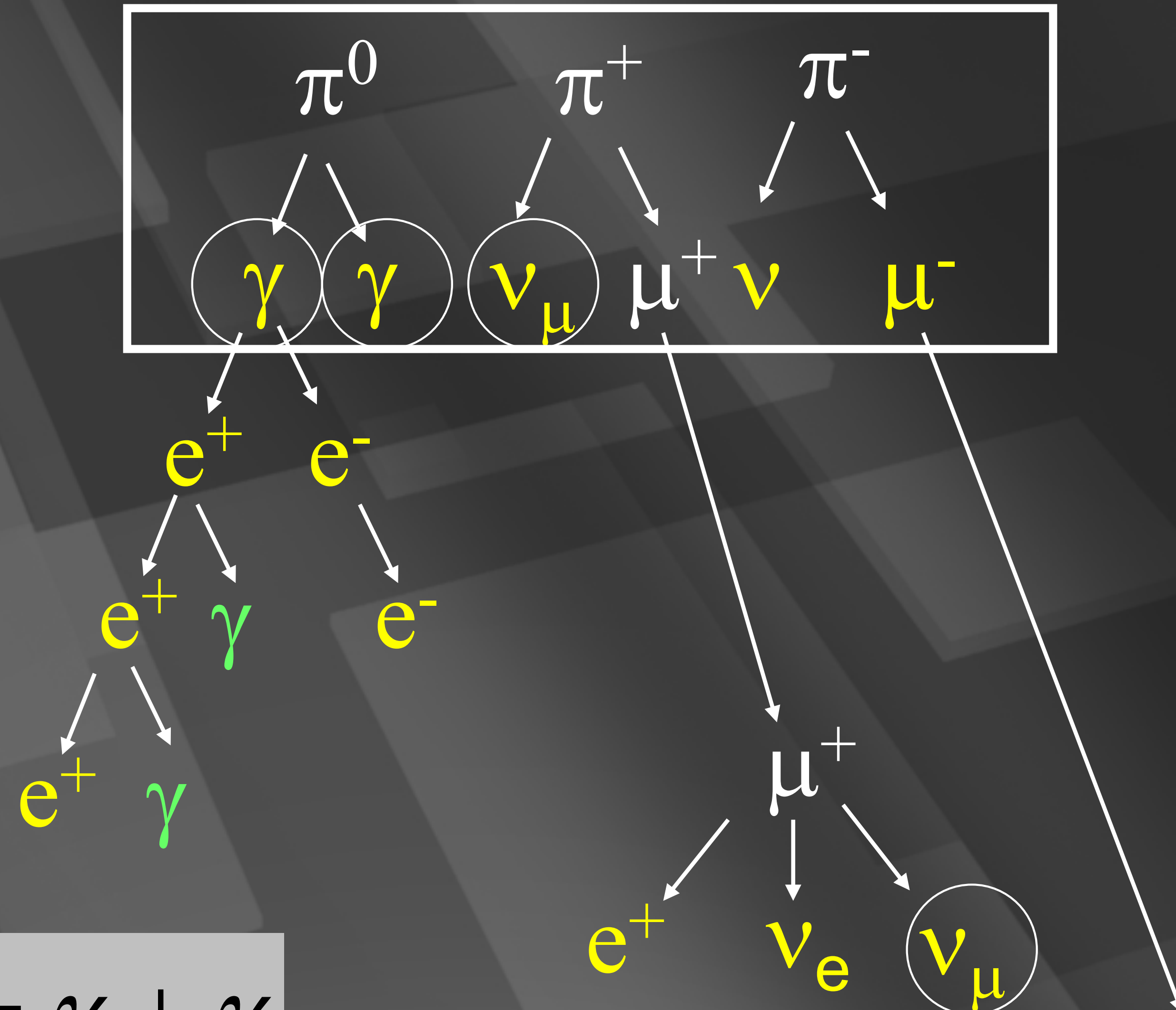
are observed as

gamma rays

charged pions

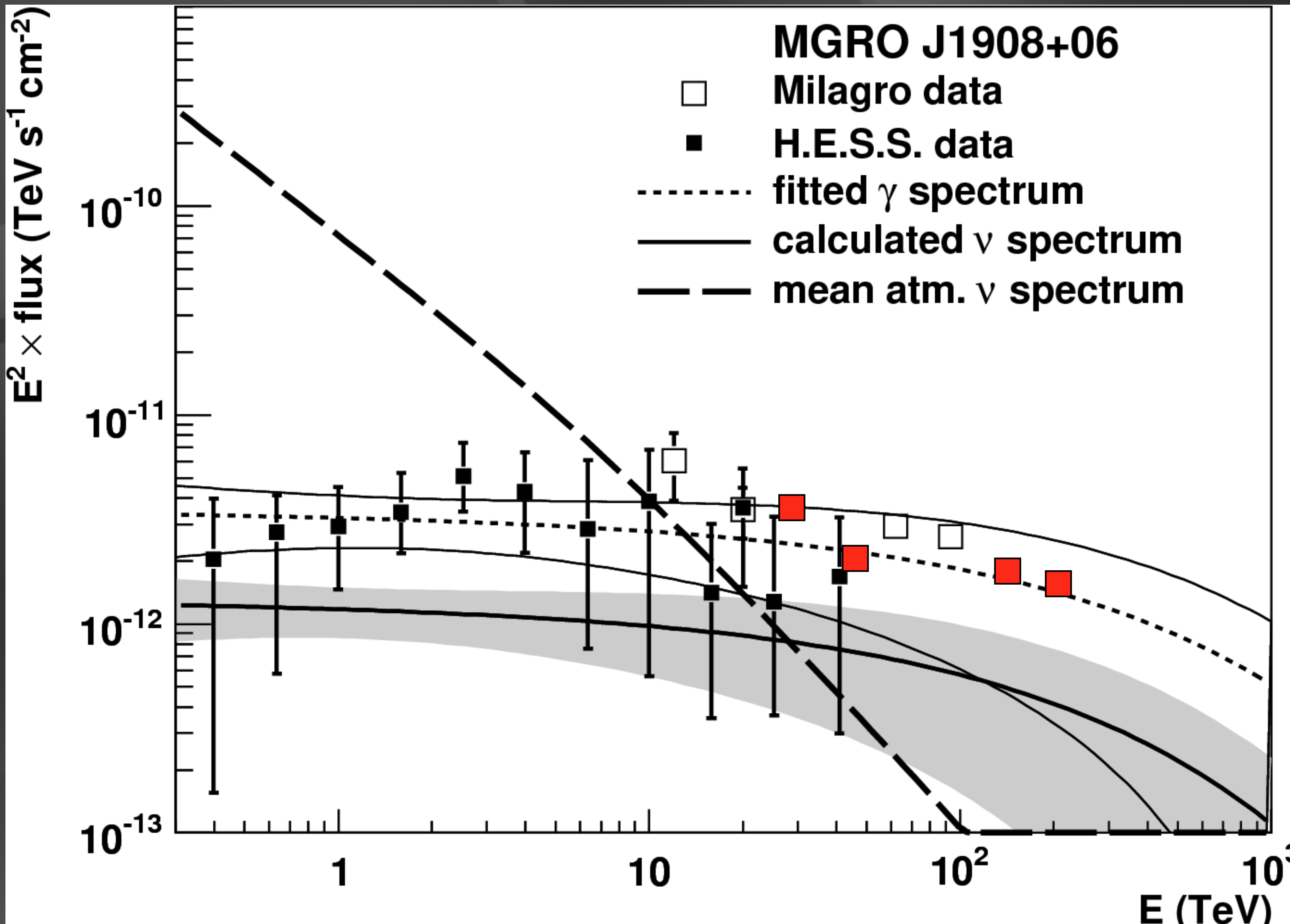
are observed as

neutrinos

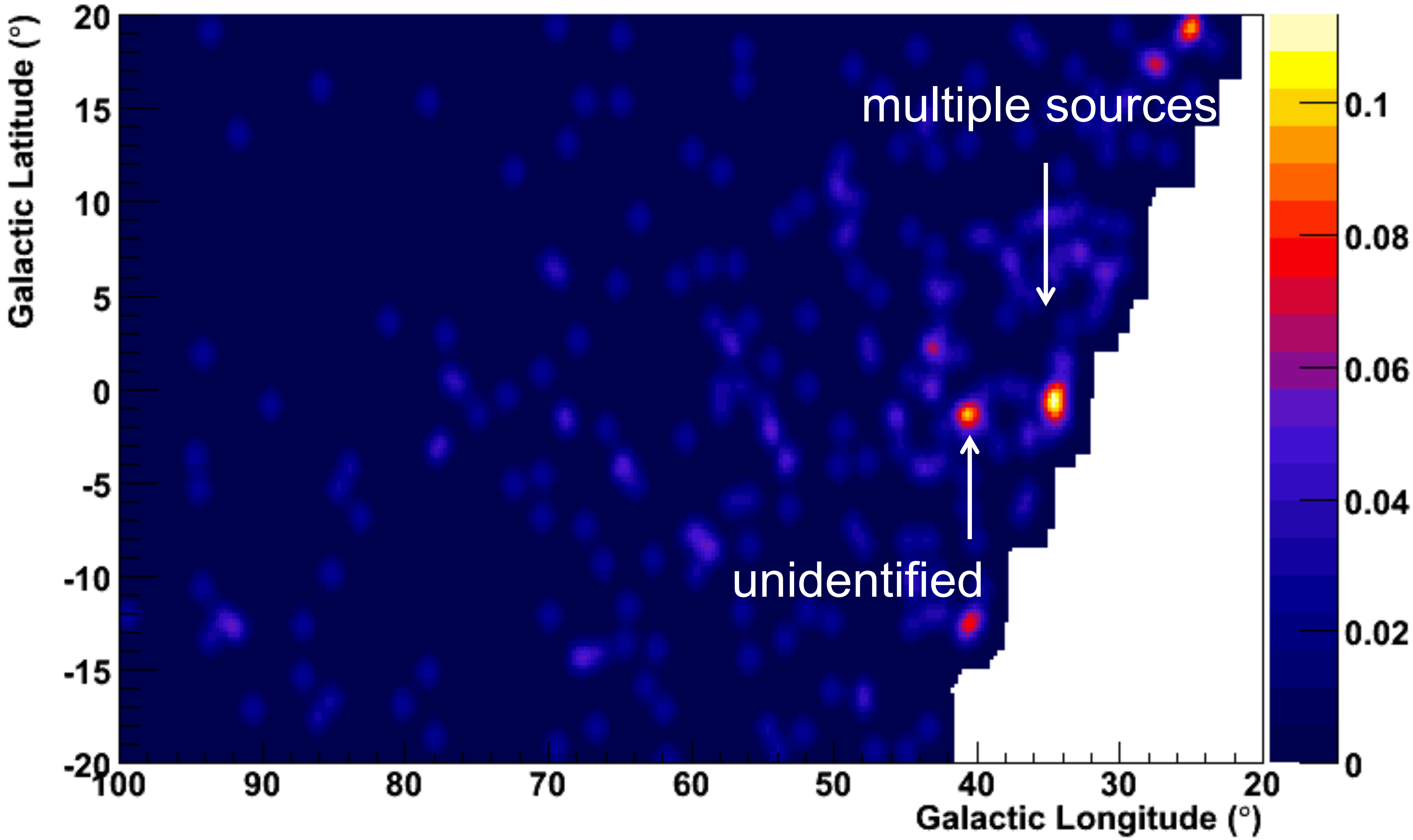


$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

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



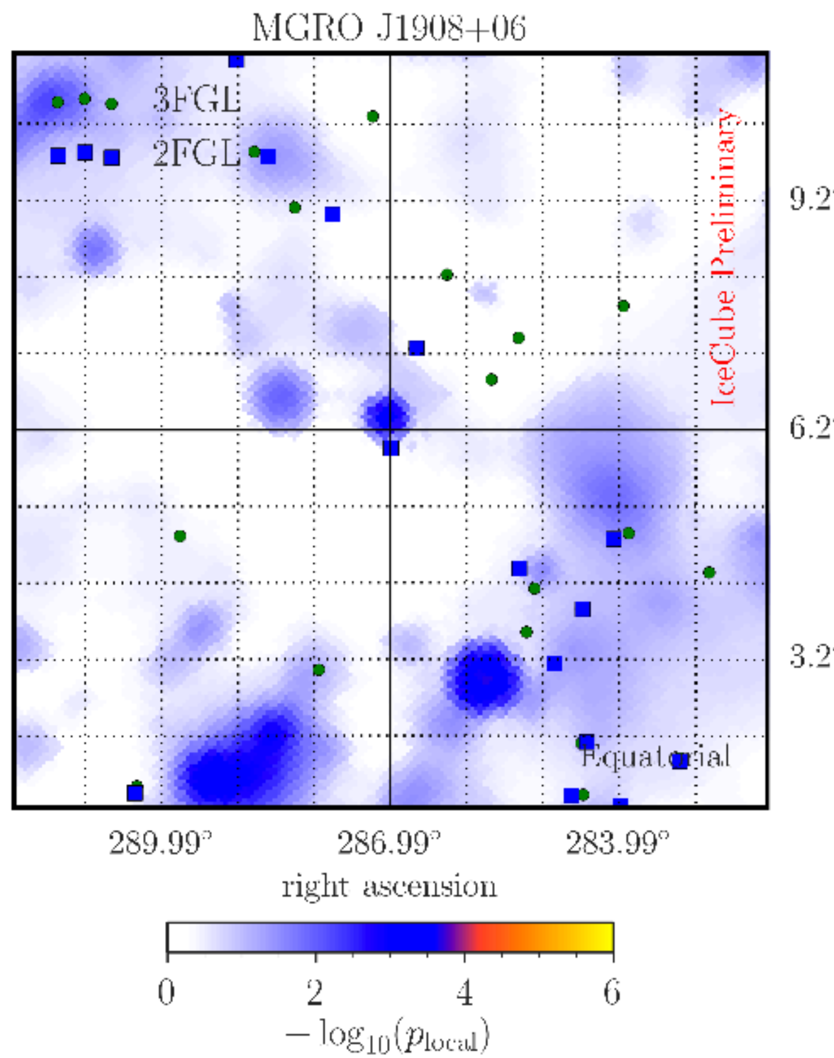
2007 simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.



- 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	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [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	0.2069	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.[illegible]3	0.0055	5.[illegible]86	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	[illegible]	-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	$1.01 \cdot 10^{-12}$



Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos are essential for understanding the non-thermal universe.
- from discovery to astronomy: more events, more telescopes IceCube-Gen2, KM3NeT and GVD (Baikal)
- 10 years of IceCube data -pass 2 (detector geometry with individual DOMs, more photons in reconstruction, better calibration)

THE ICECUBE COLLABORATION

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Universiteit Gent
Vrije Universiteit Brussel

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Knut and Alice Wallenberg Foundation
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
South Pole Neutrino Observatory

overflow slides

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

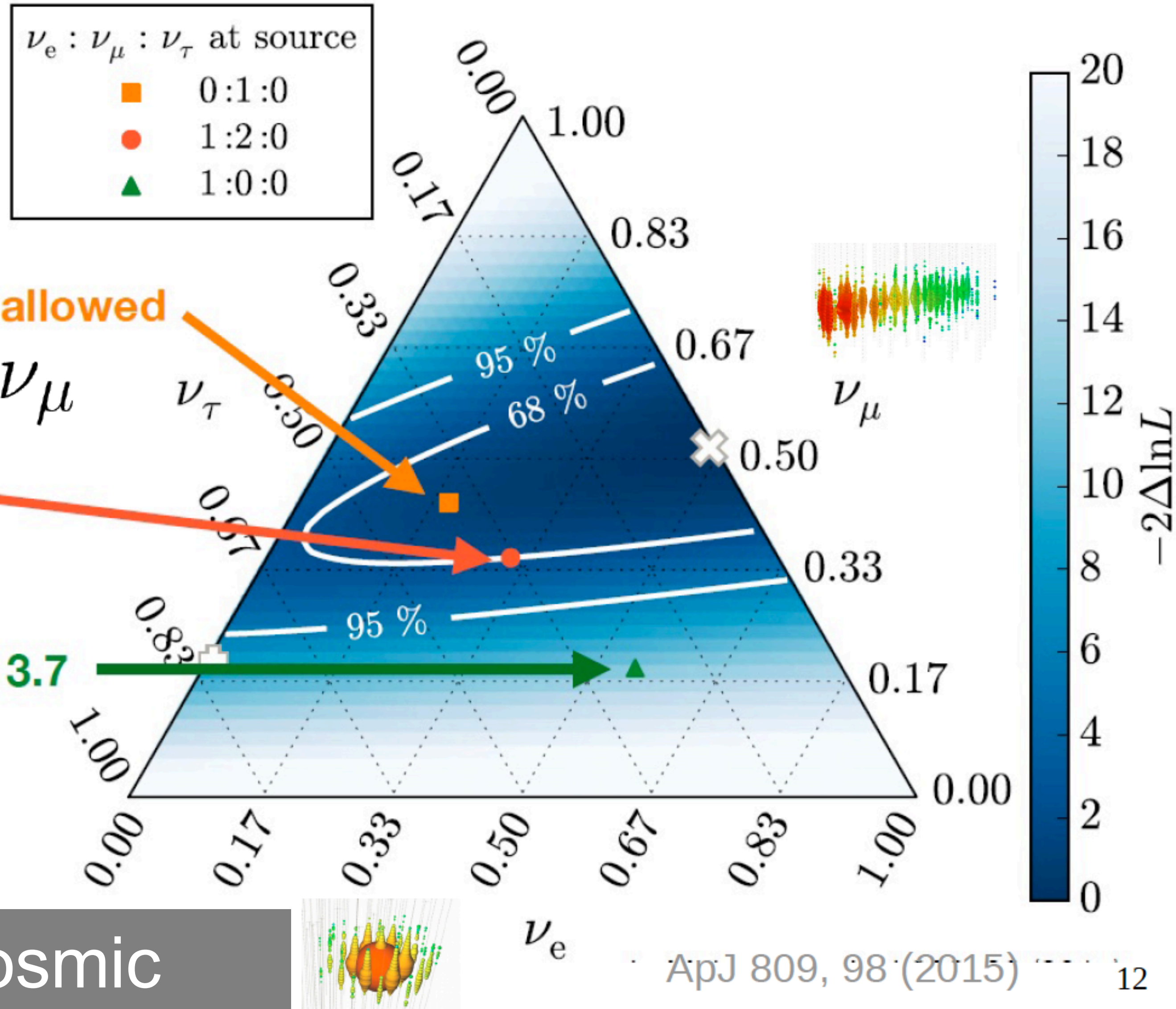
Muon-damped pion decay: allowed

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

Pion decay: allowed

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

Neutron decay: rejected at 3.7



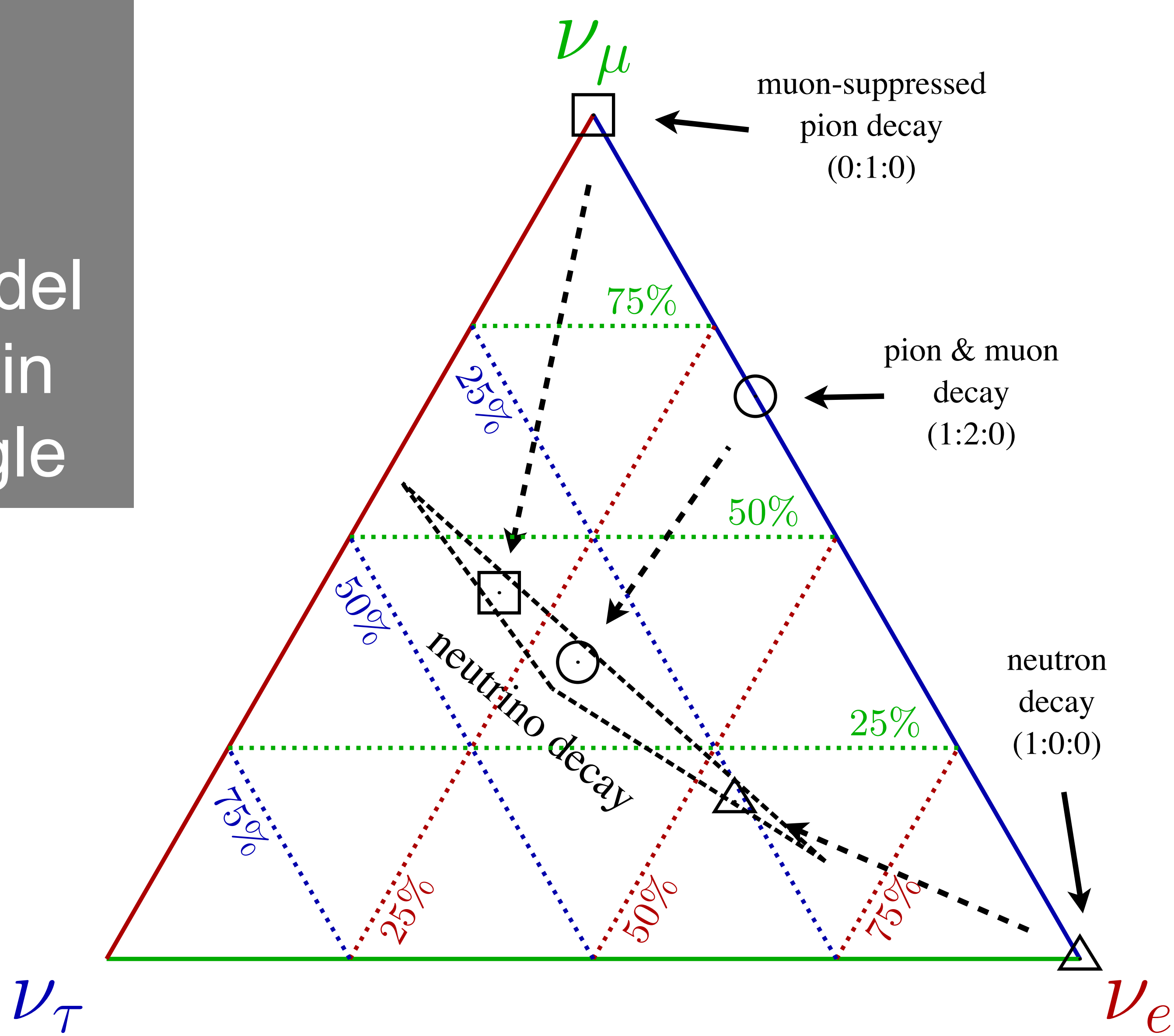
oscillate over cosmic distances to 1:1:1

ApJ 809, 98 (2015)

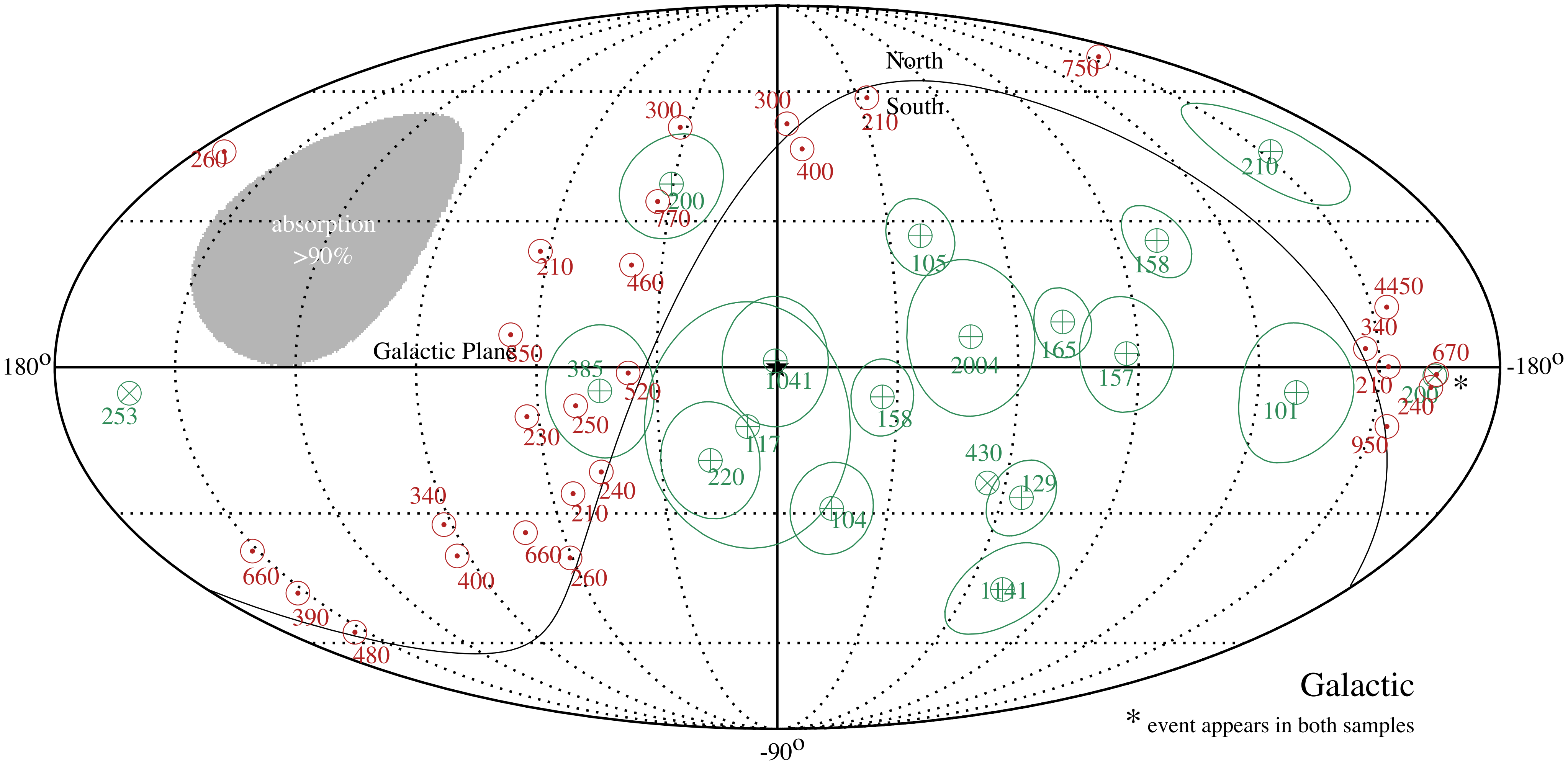
new physics ?

if not…

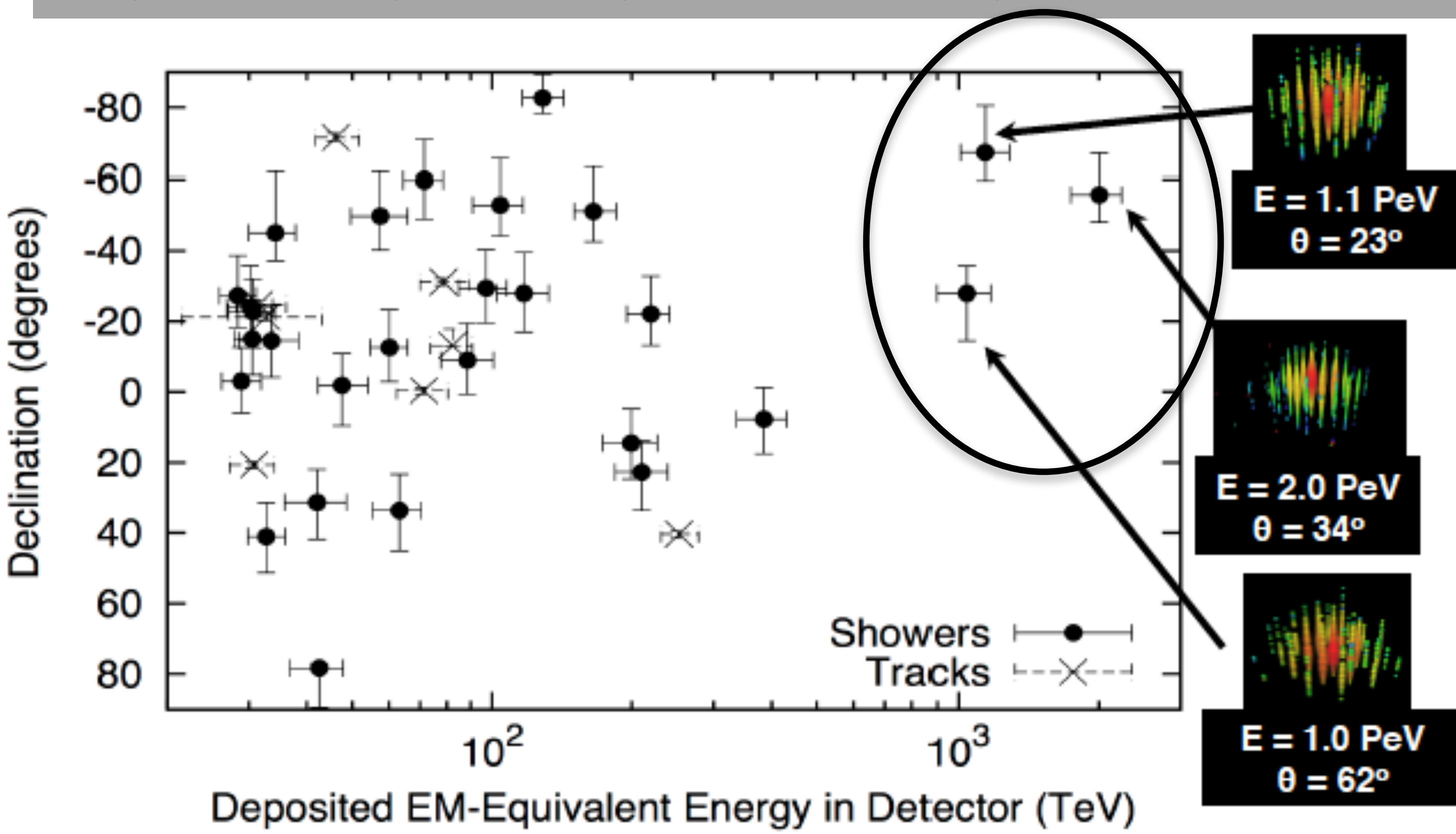
every model ends up in the triangle



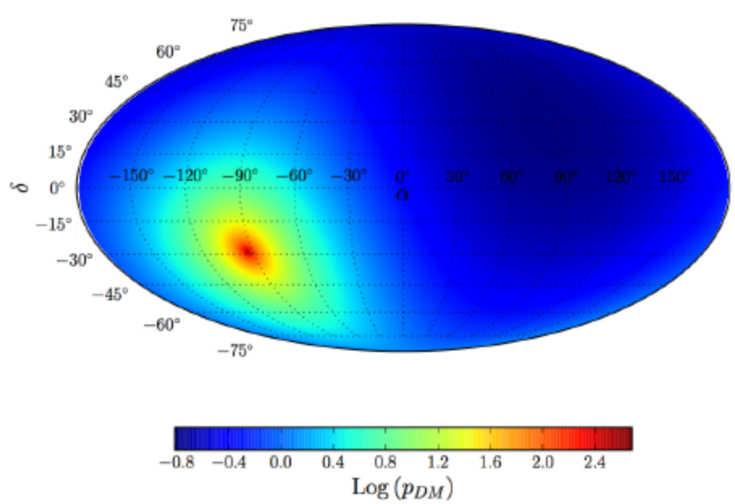
HESE 4yr with $E_{\mathrm{dep}} > 100$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with $E_\mu > 200$ TeV (red)

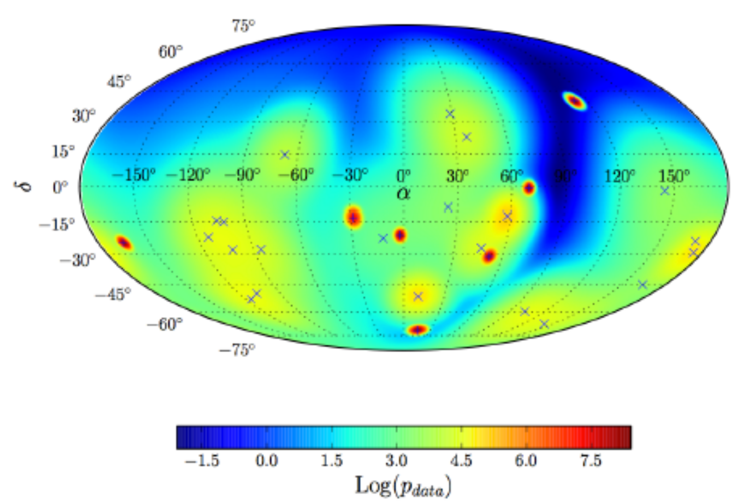


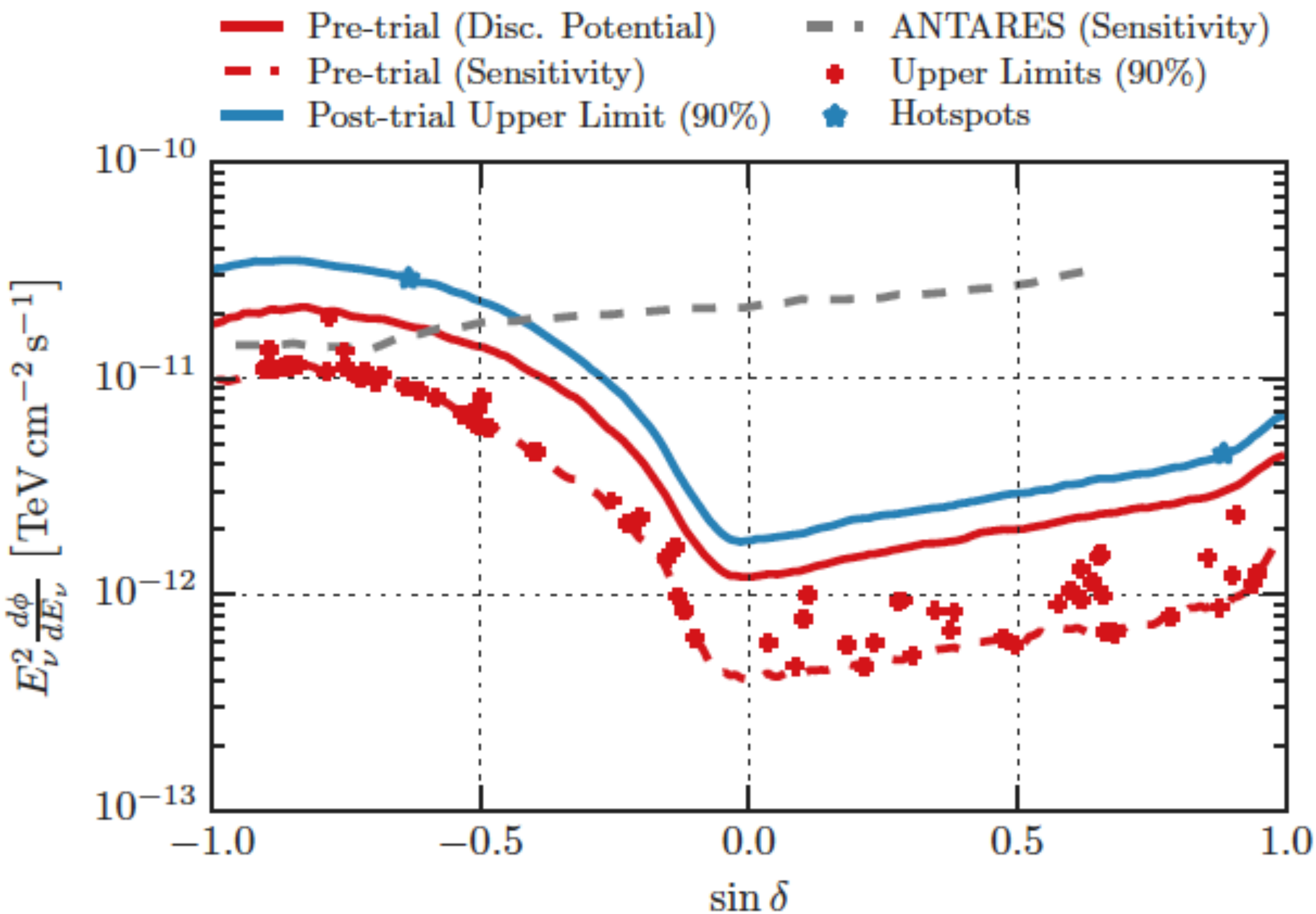
expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle







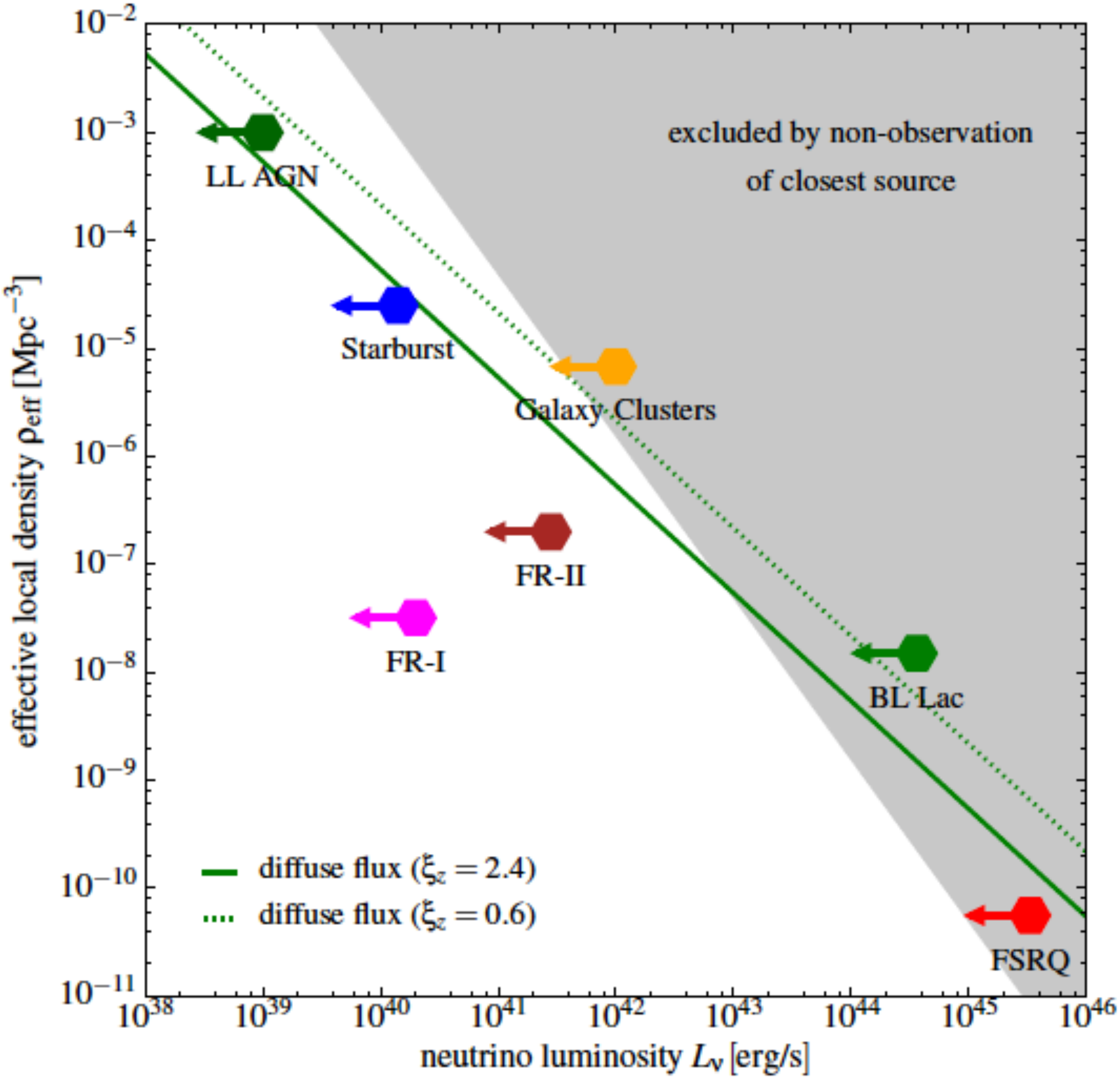
when resolved point sources?

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

Olbers paradox

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

blazars, FSRQ…



Olbers paradox

$$\phi_{\rm diff} = \int d^3r \frac{L_\nu}{4\pi r^2} \cdot \rho$$

diffuse flux is measured

nearest source

$$\frac{4}{3}\pi d_{ns}^3 \cdot \rho = 1$$

and

$$d_{\rm ns} \sim \rho^{-1/3}$$

$$\phi_{\rm ns} = \frac{L_\nu}{4\pi d_{\rm ns}^2} \sim (L_\nu \cdot \rho)\, d_{\rm ns} \sim \phi_{\rm diff} \cdot \rho^{-1/3}$$

lower density of sources → easier to pick out closest source

total number of events required to observe
n-events multiplets from the closest sources is

$$740 \times \left[\frac{n}{2}\right] \times \left[\frac{\rho_0}{10^{-5}}\right]^{\frac{1}{3}} \text{ events}$$

for a observed diffuse cosmic flux and 0.4 degrees angular resolution

examples of local source densities (per Mpc^3):

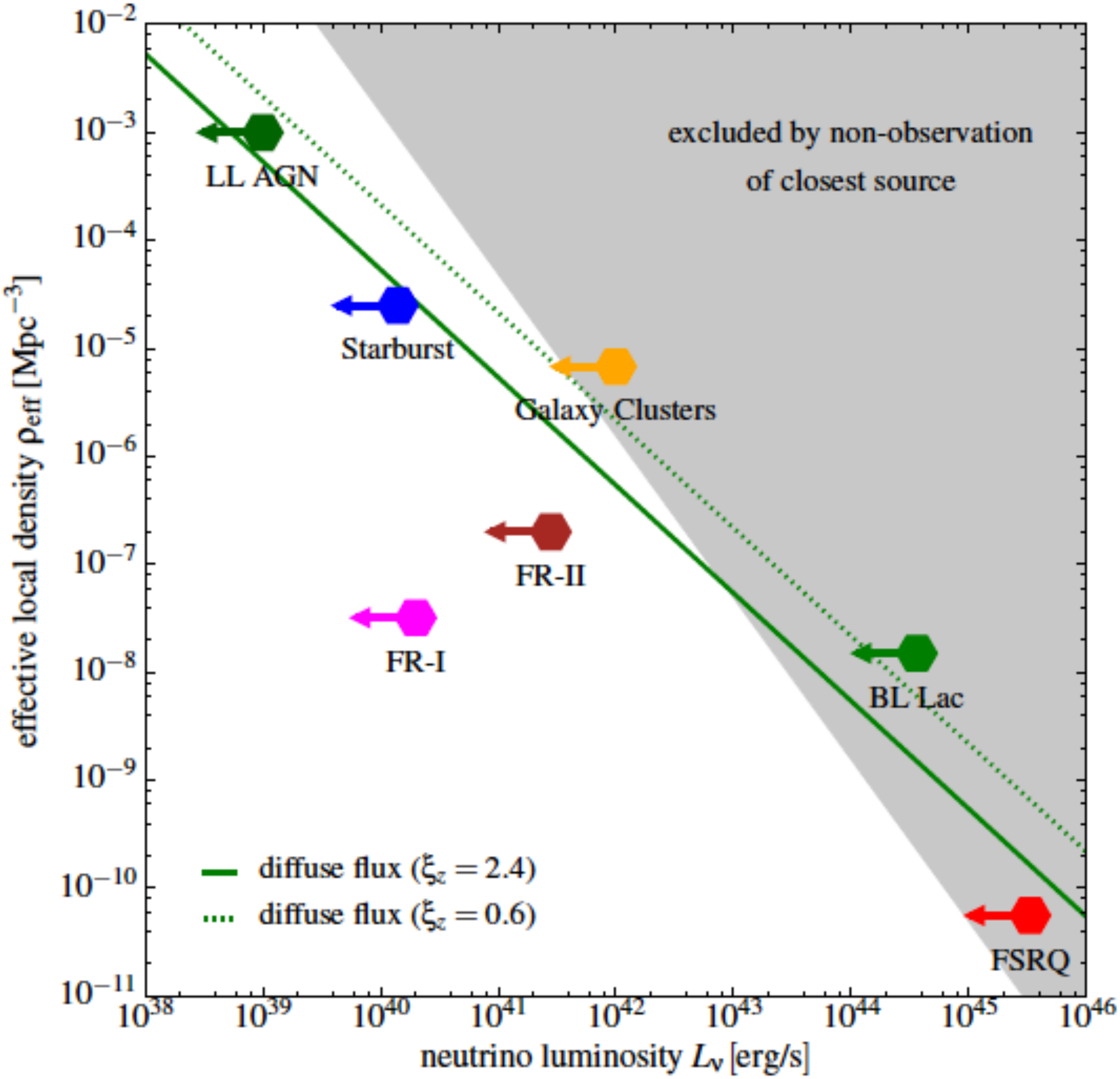
- $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\mathrm{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\mathrm{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**

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

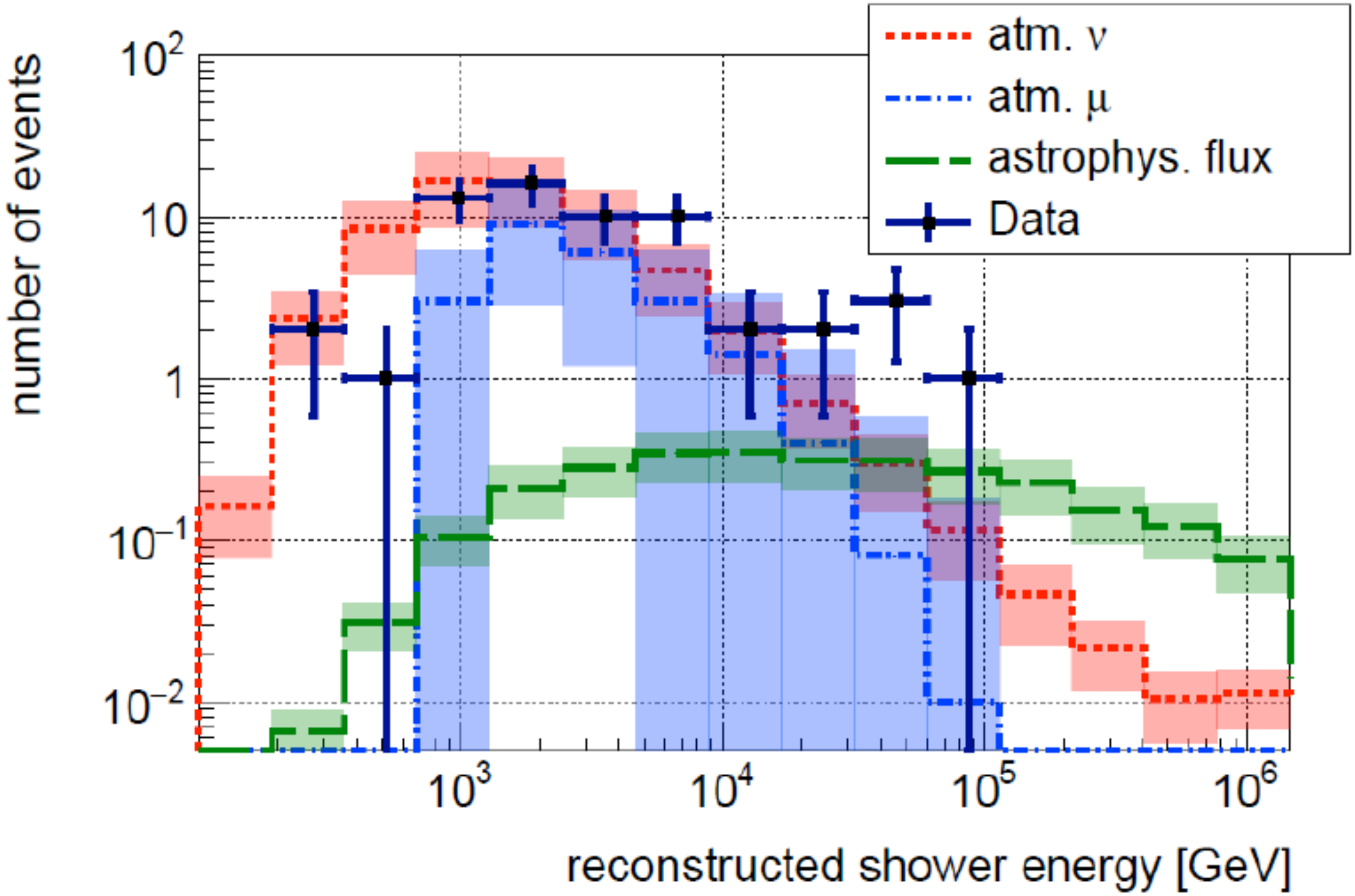
Olbers paradox

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

blazars, FSRQ…



ANTARES



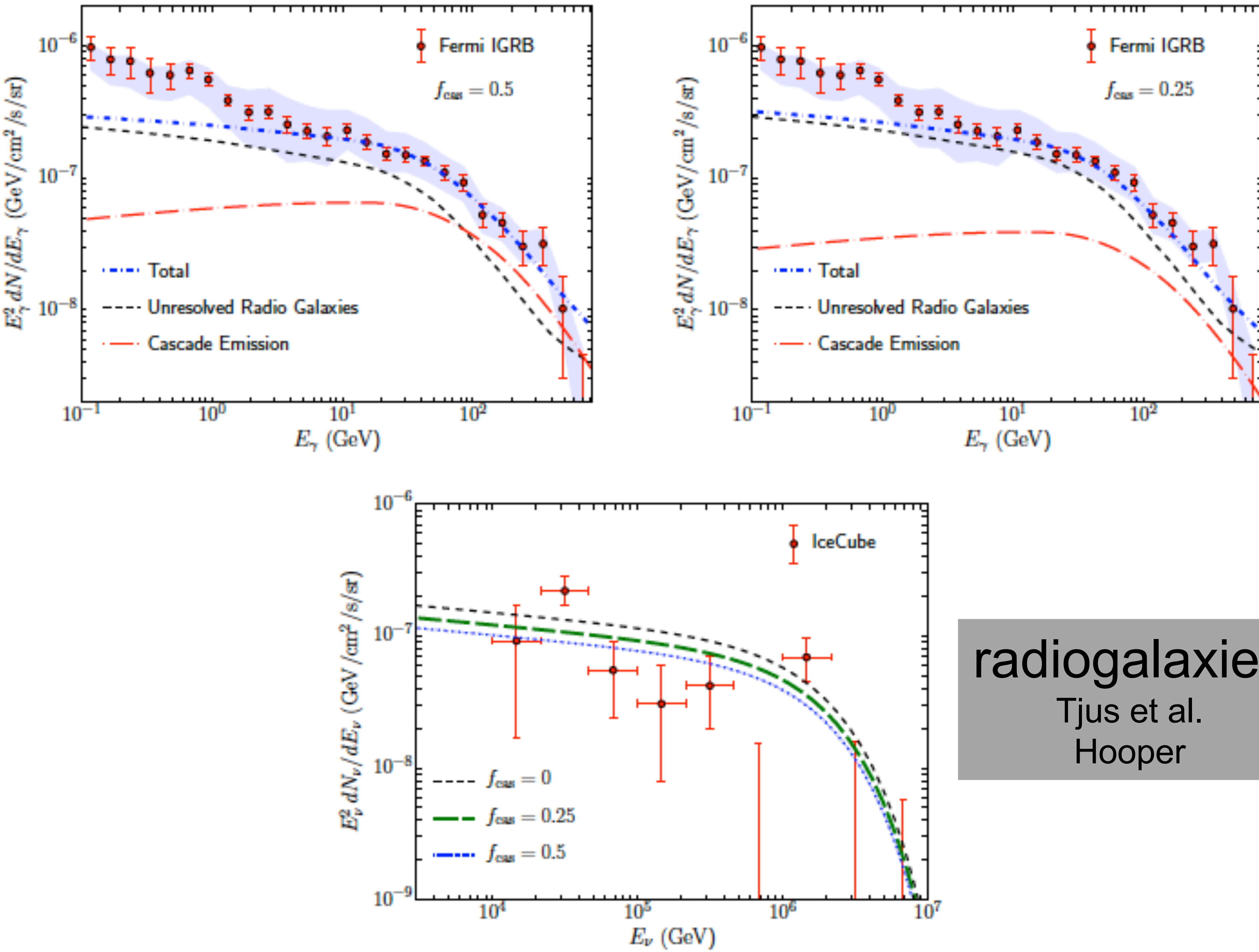
atm. ν
atm. μ
astrophys. flux
Data
number of events
10^2
10
1
10^{-1}
10^{-2}
10^3
10^4
10^5
10^6
reconstructed shower energy [GeV]

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?)

What are the sources of cosmic neutrinos?

- observations accommodated by *radiogalaxies* that also accommodate the Fermi flux
- sources soon?

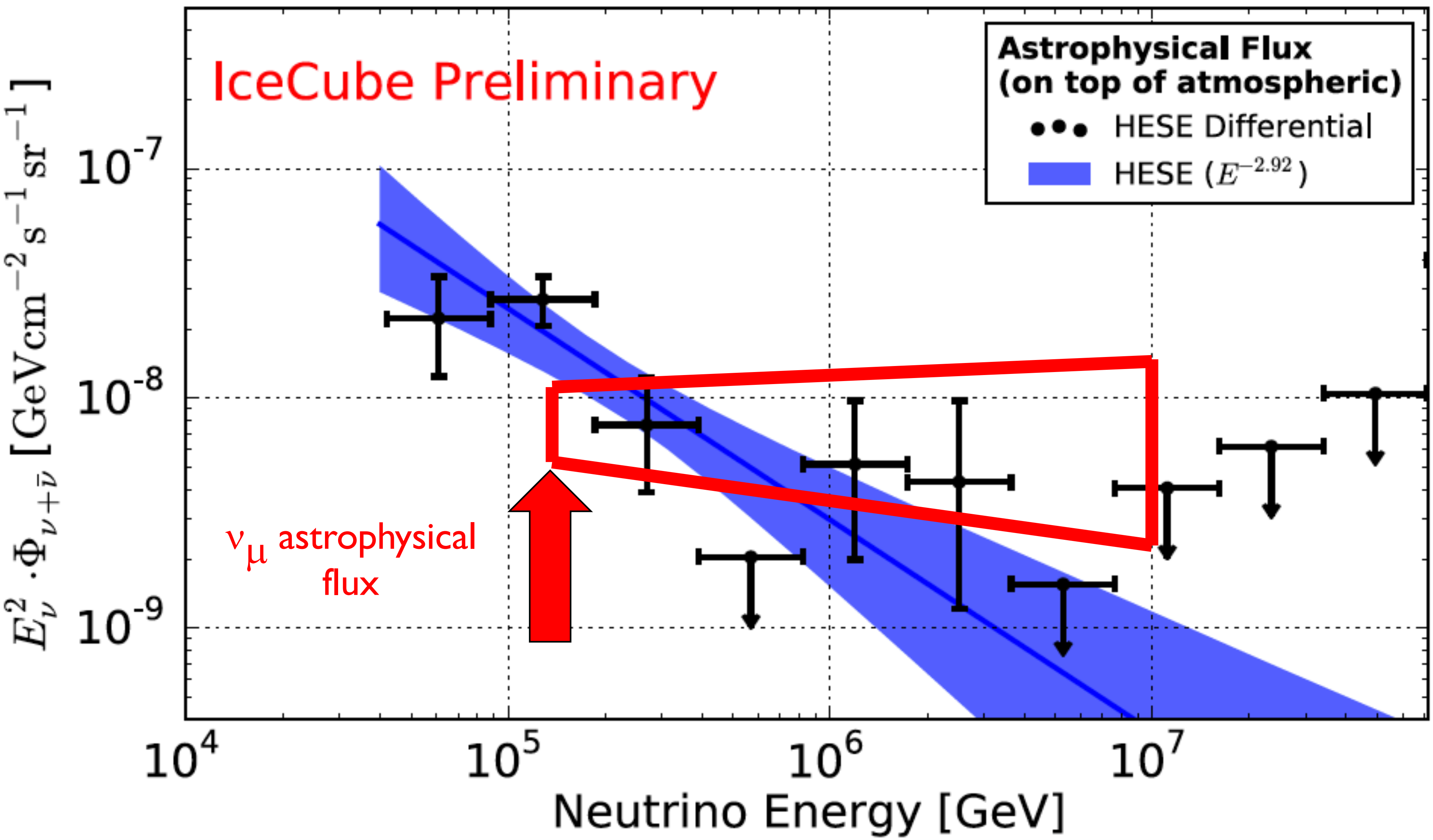


radiogalaxies

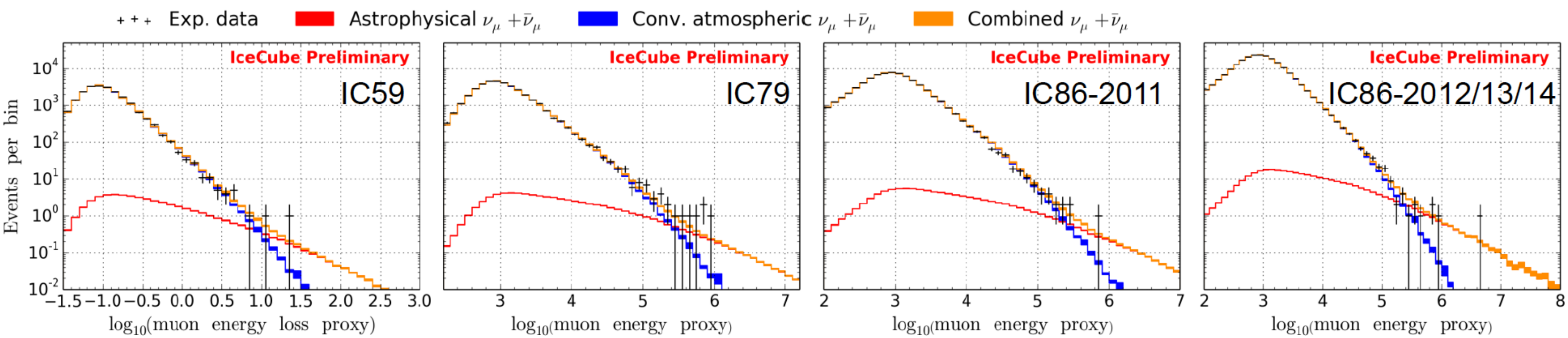
Tjus et al.

Hooper

two methods consistent above 100 TeV



after 6 years: 3.7→ 6.0 sigma



HESE 4 year unfolding
(→ dominated by shower-like events)

6 year up-going numu analysis