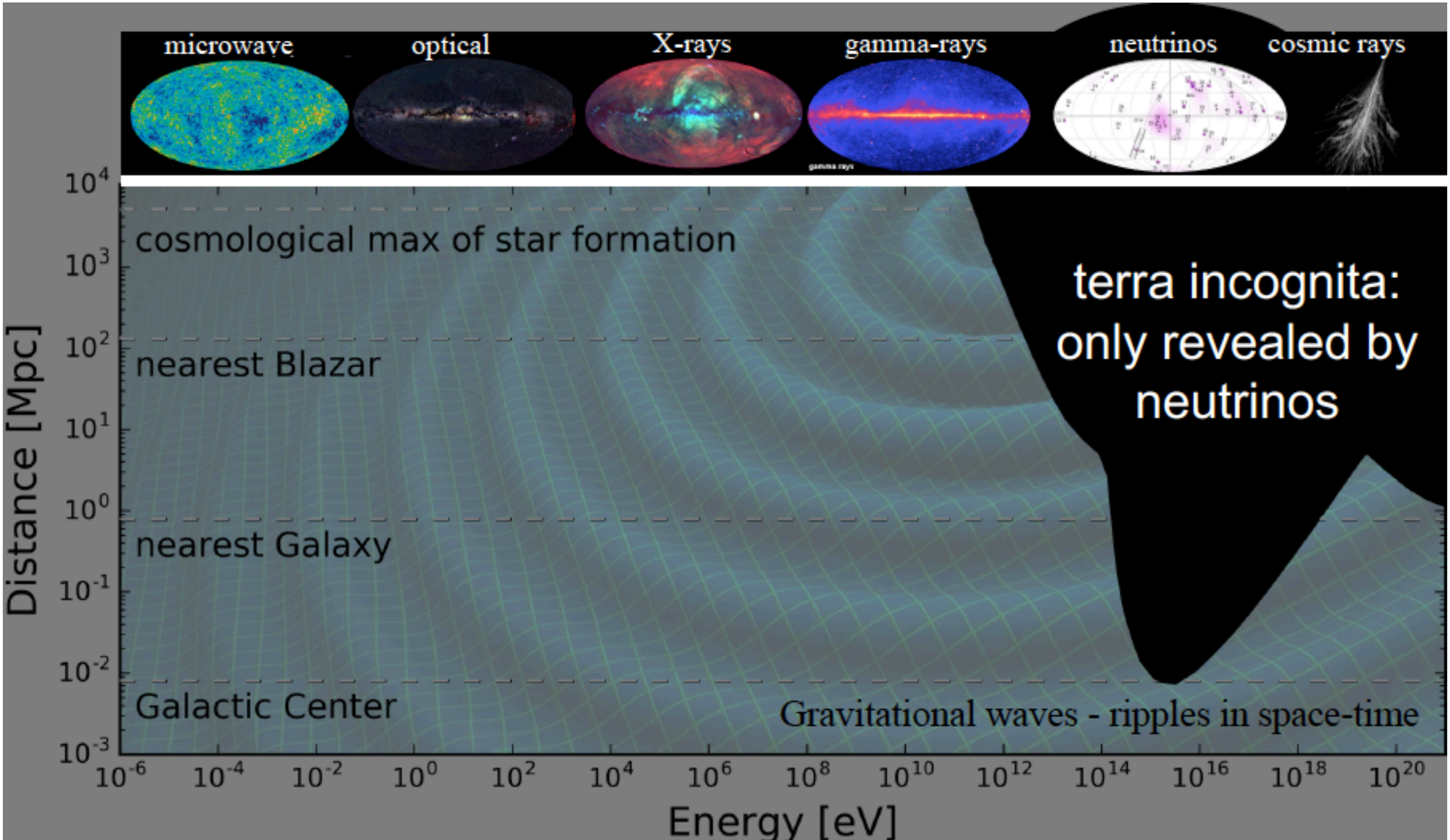
IceCube:
Building a New Window on the Universe

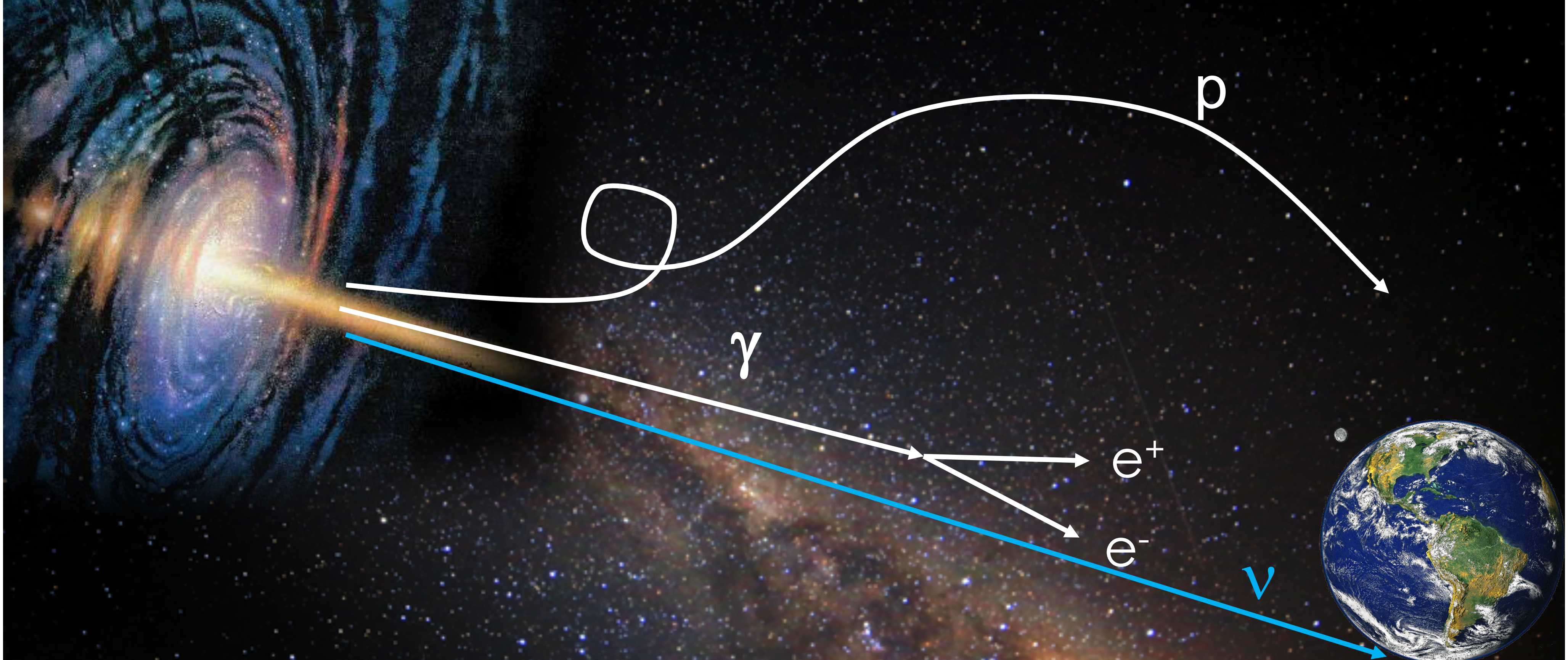
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- other multiwavelength observations
- cosmic neutrinos below 100 TeV?
- the Galaxy

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

Cosmic Rays? Charged – Do not point

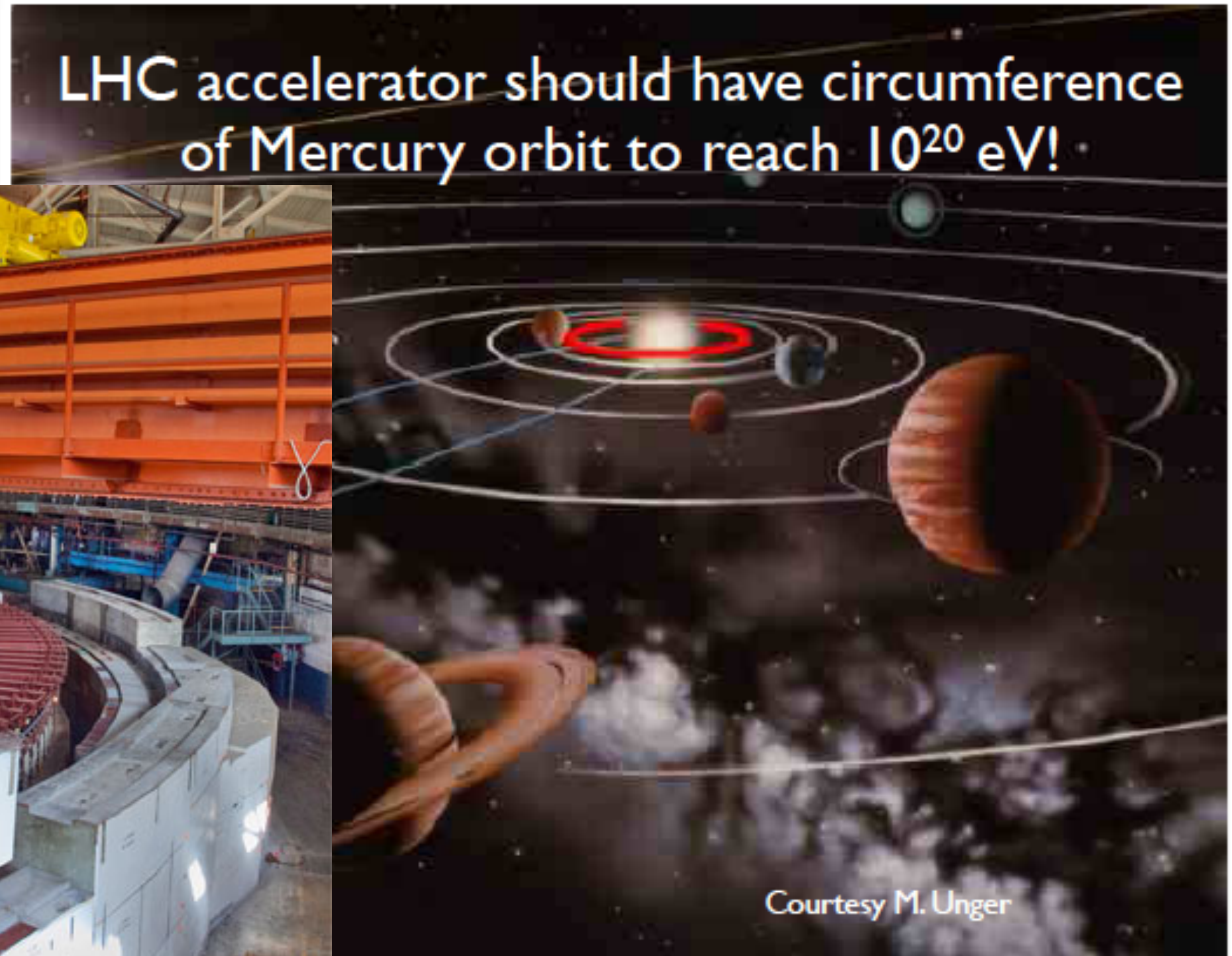


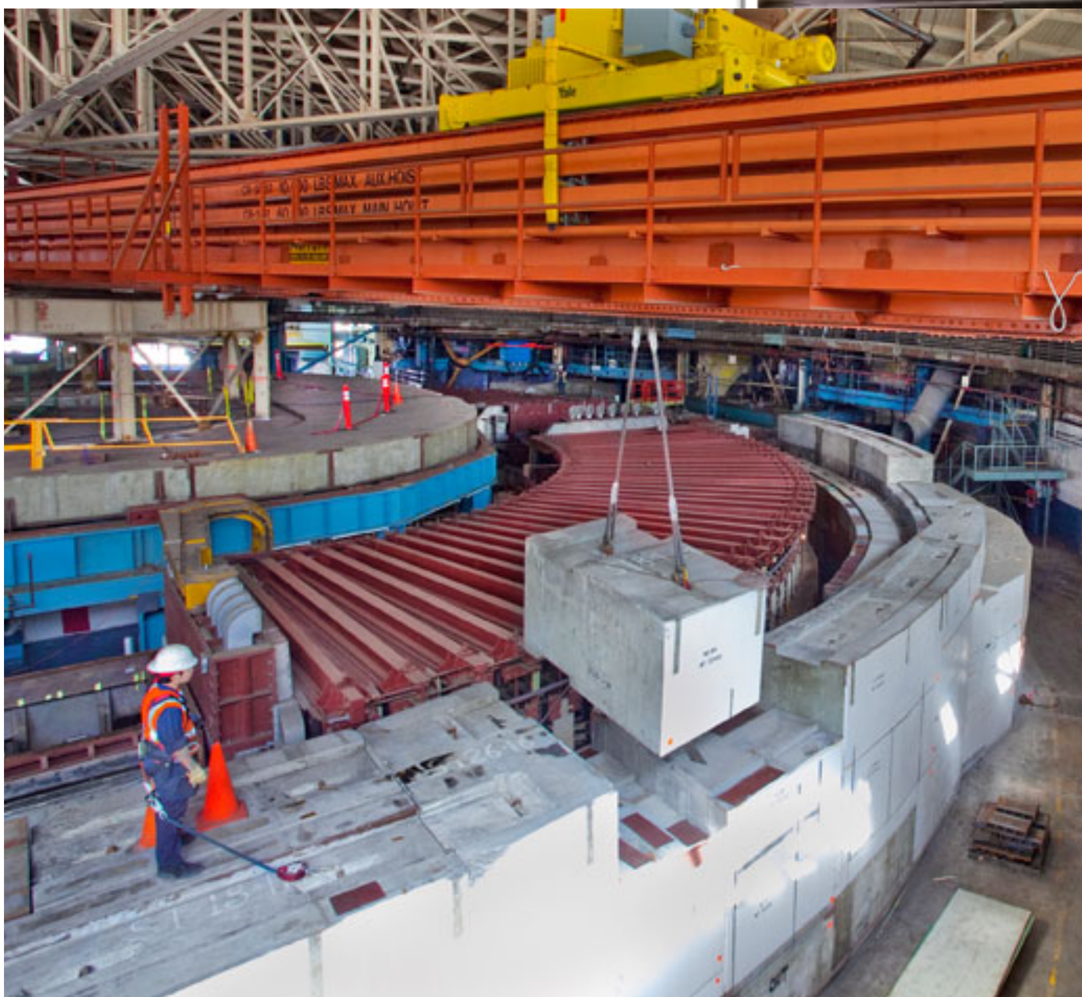
- PeV gamma rays are absorbed by cosmic microwave photons:

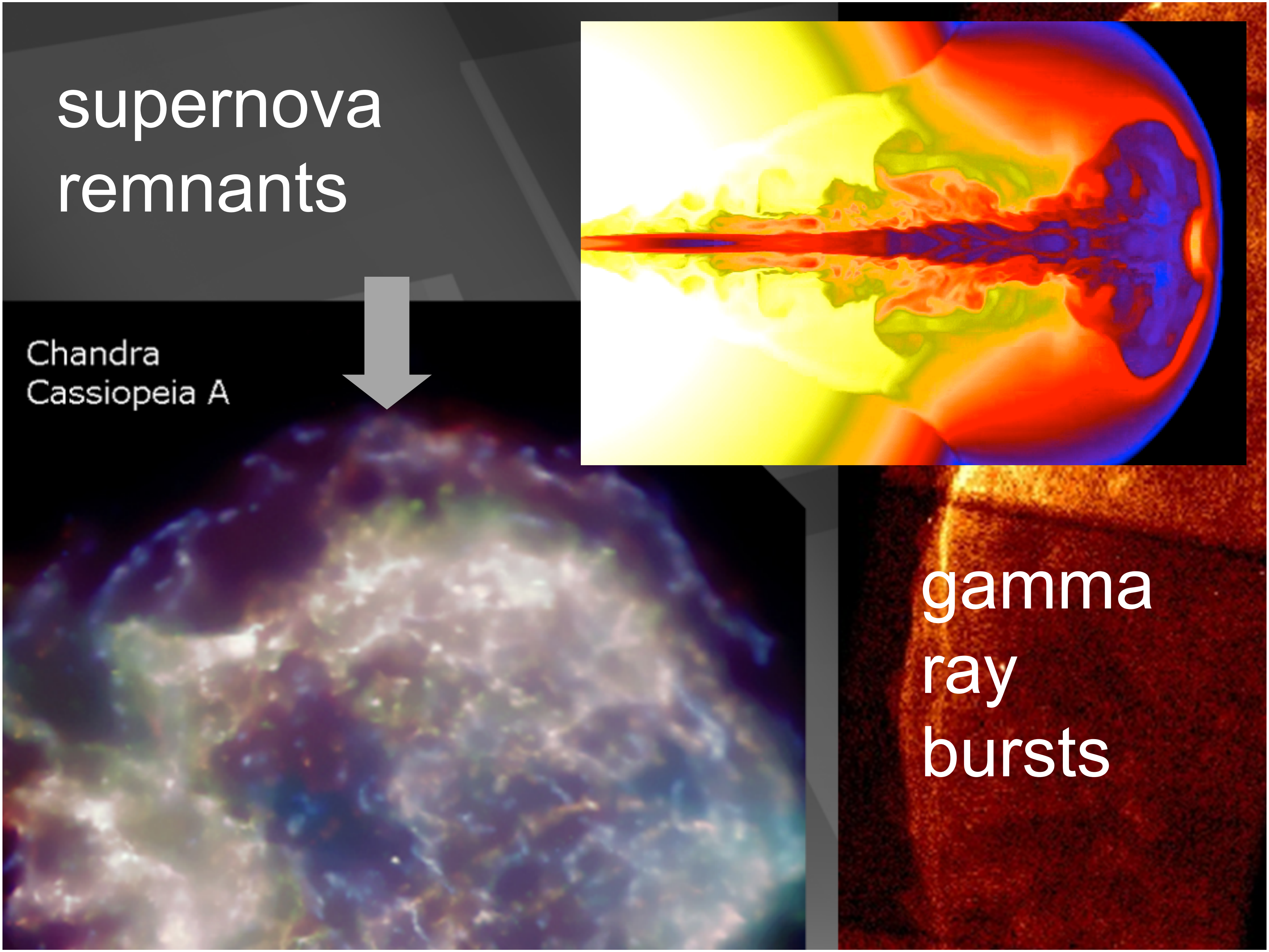
$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

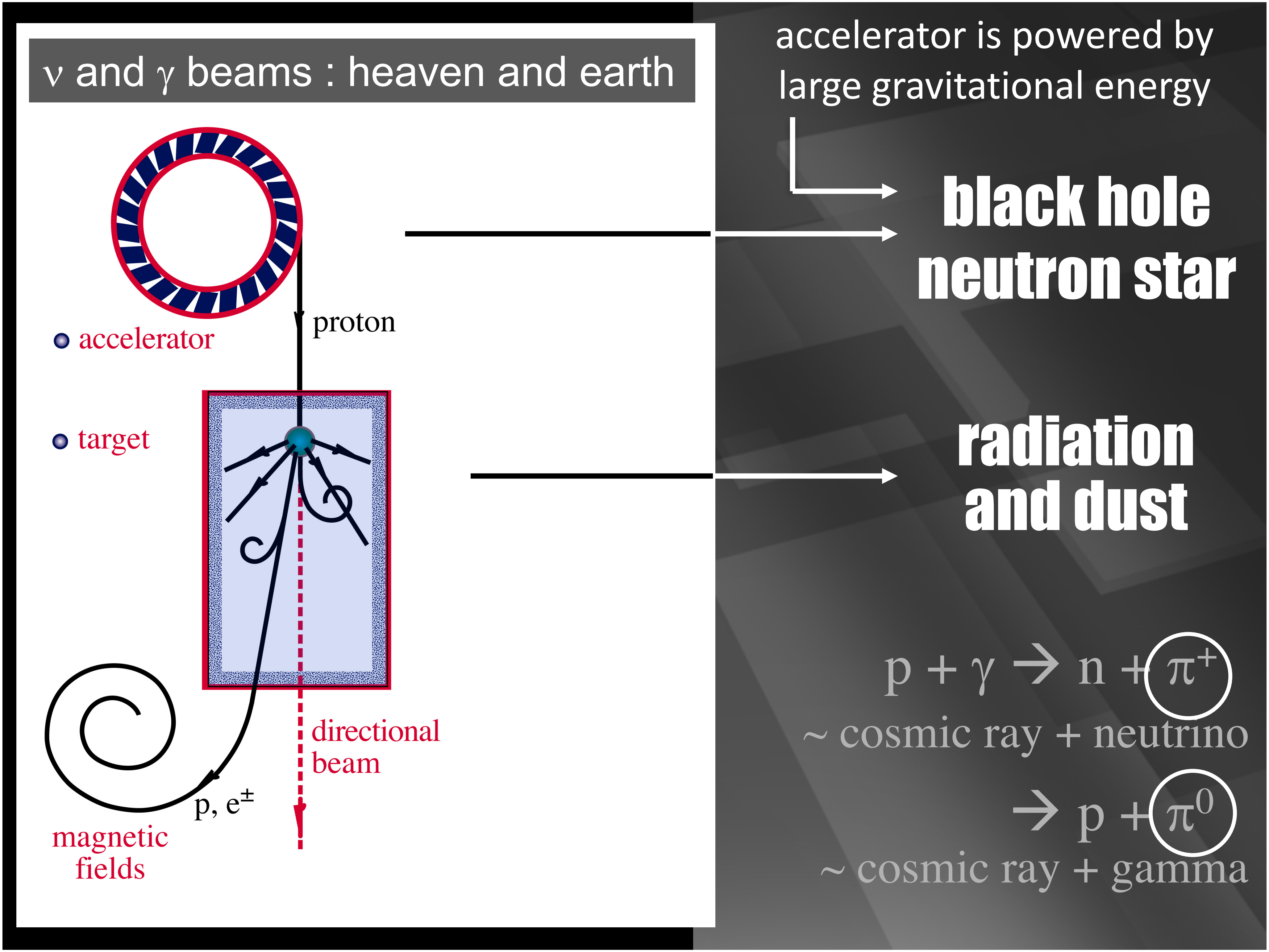
- neutrinos: perfect messengers; do not interact and image the sky in regions from which even X-rays cannot escape

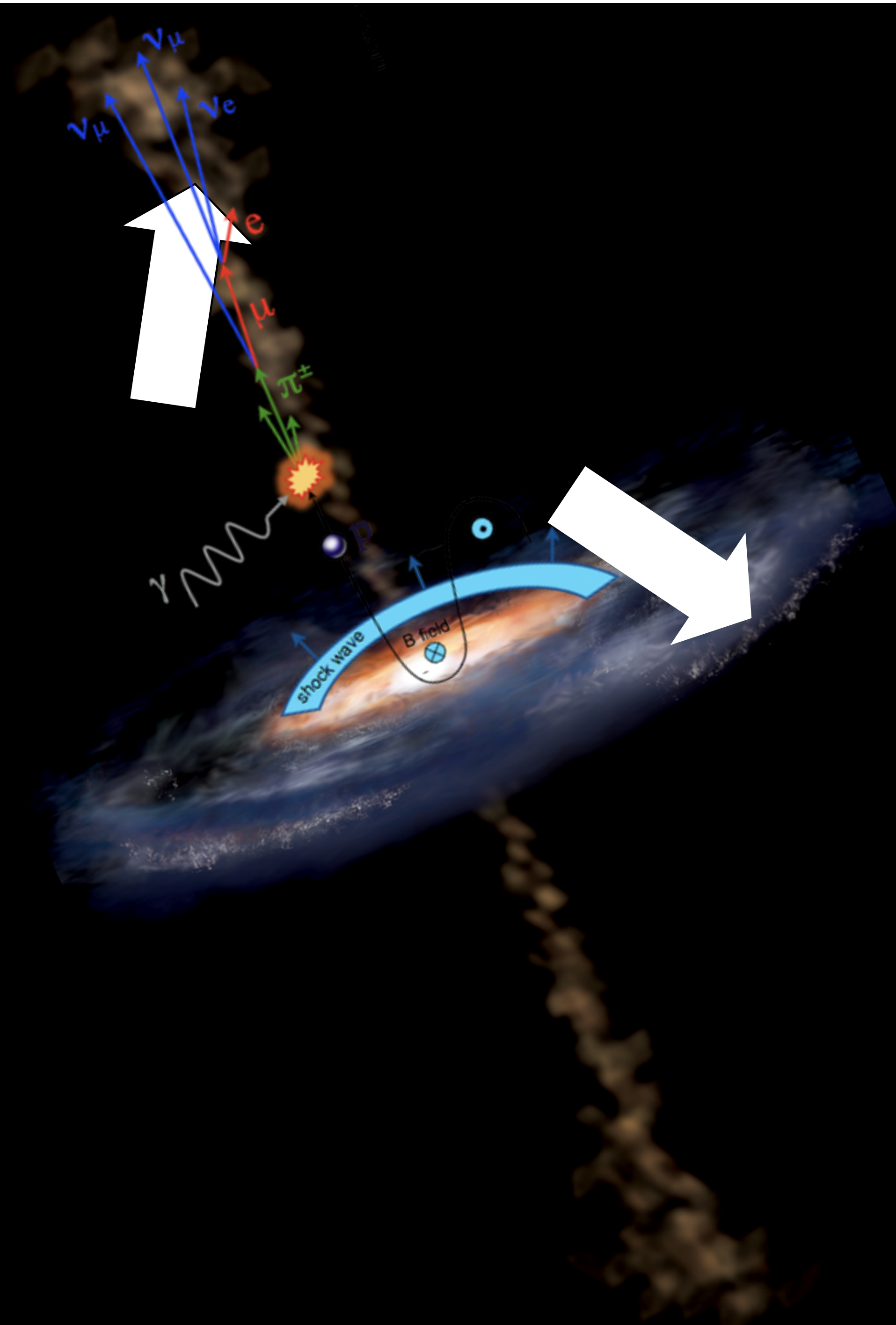
Energy ~ [magnetic field B] x [accelerator's size R]






supernova remnants
Chandra
Cassiopeia A
gamma ray bursts


ν and γ beams : heaven and earth
accelerator is powered by large gravitational energy
black hole
neutron star
proton
accelerator
target
radiation and dust
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma
directional beam
p, e±
magnetic fields



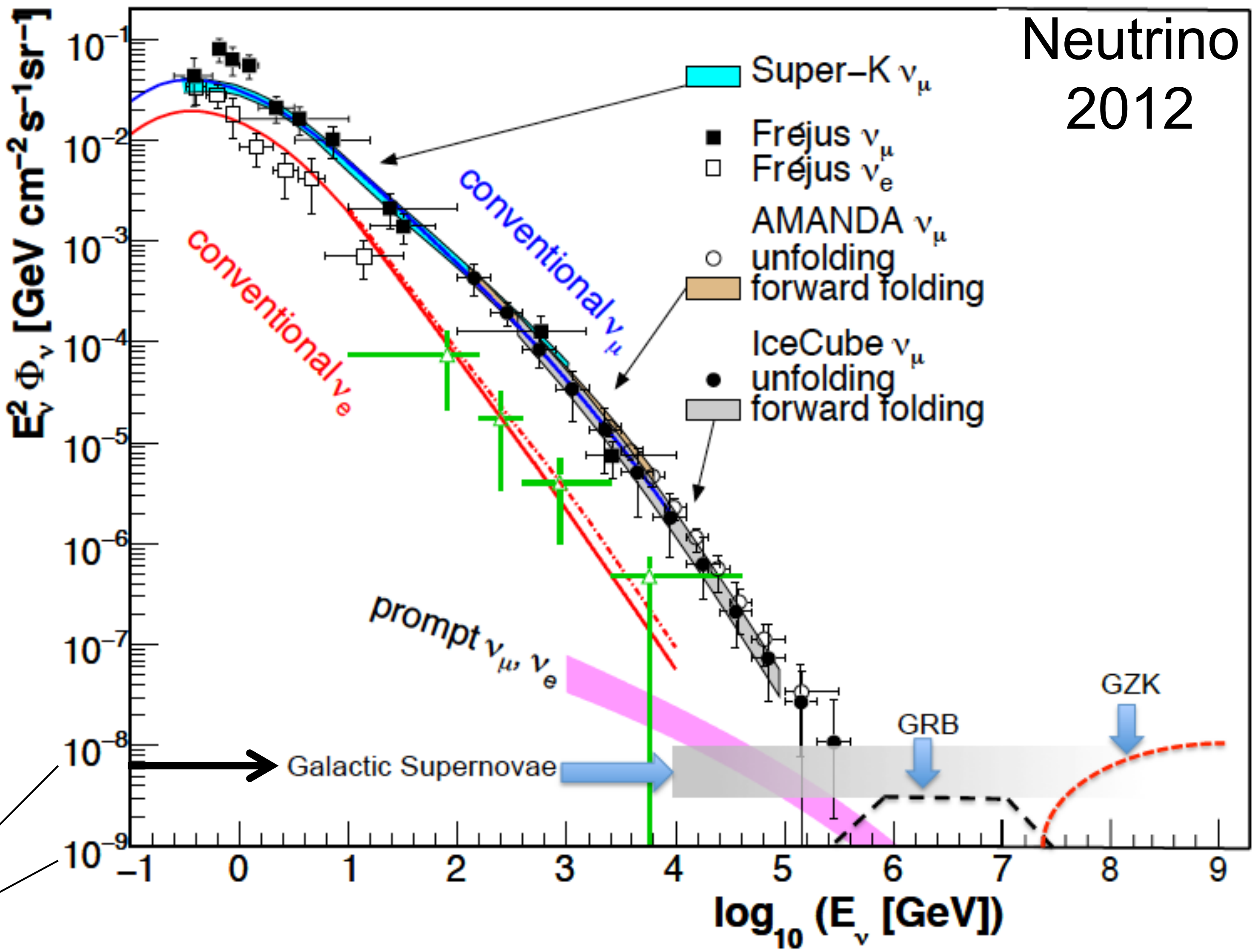
active galaxy

particle flows near supermassive black hole above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

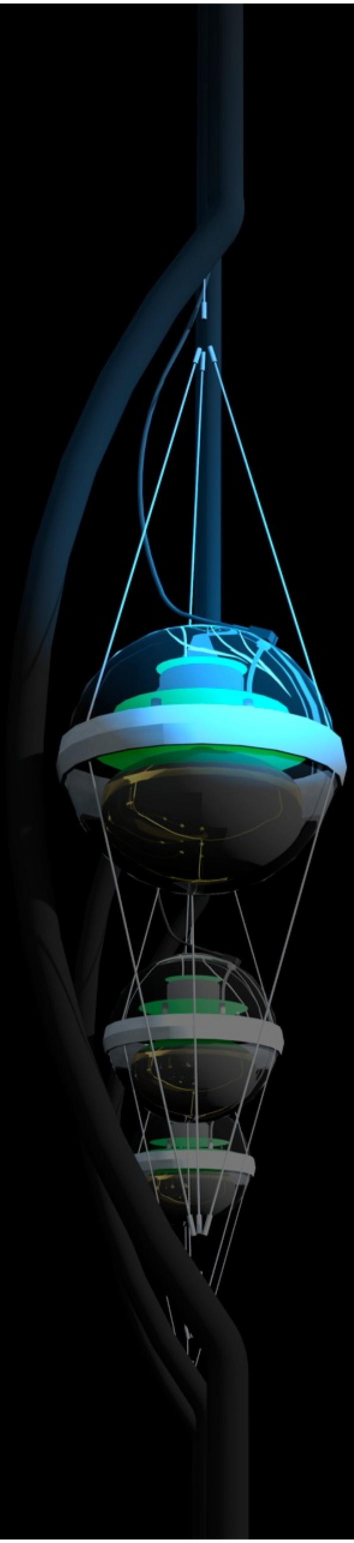
10—100 events per year for fully efficient detector



atmospheric

cosmic

100 TeV



IceCube and Multimessenger Astronomy

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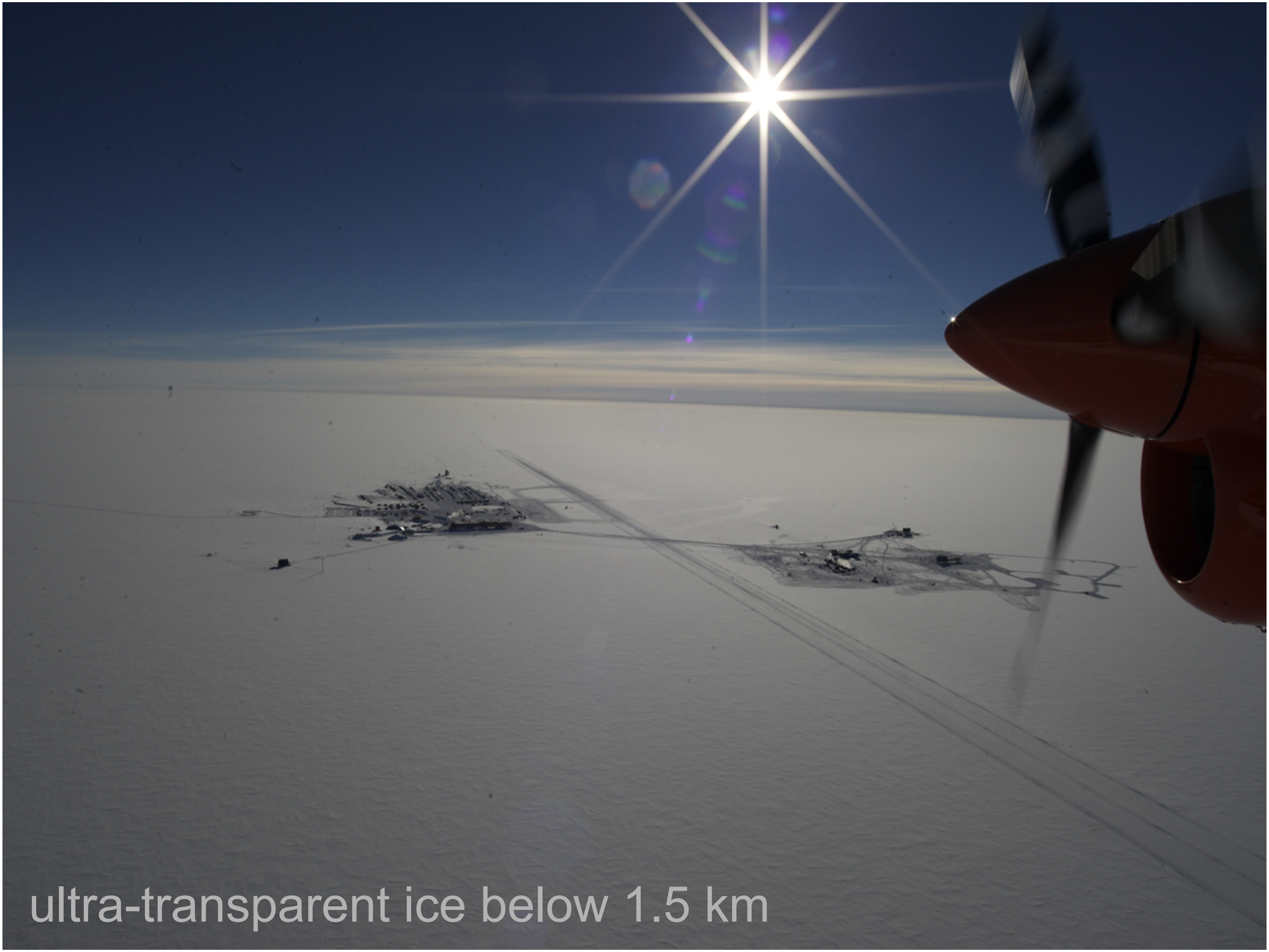
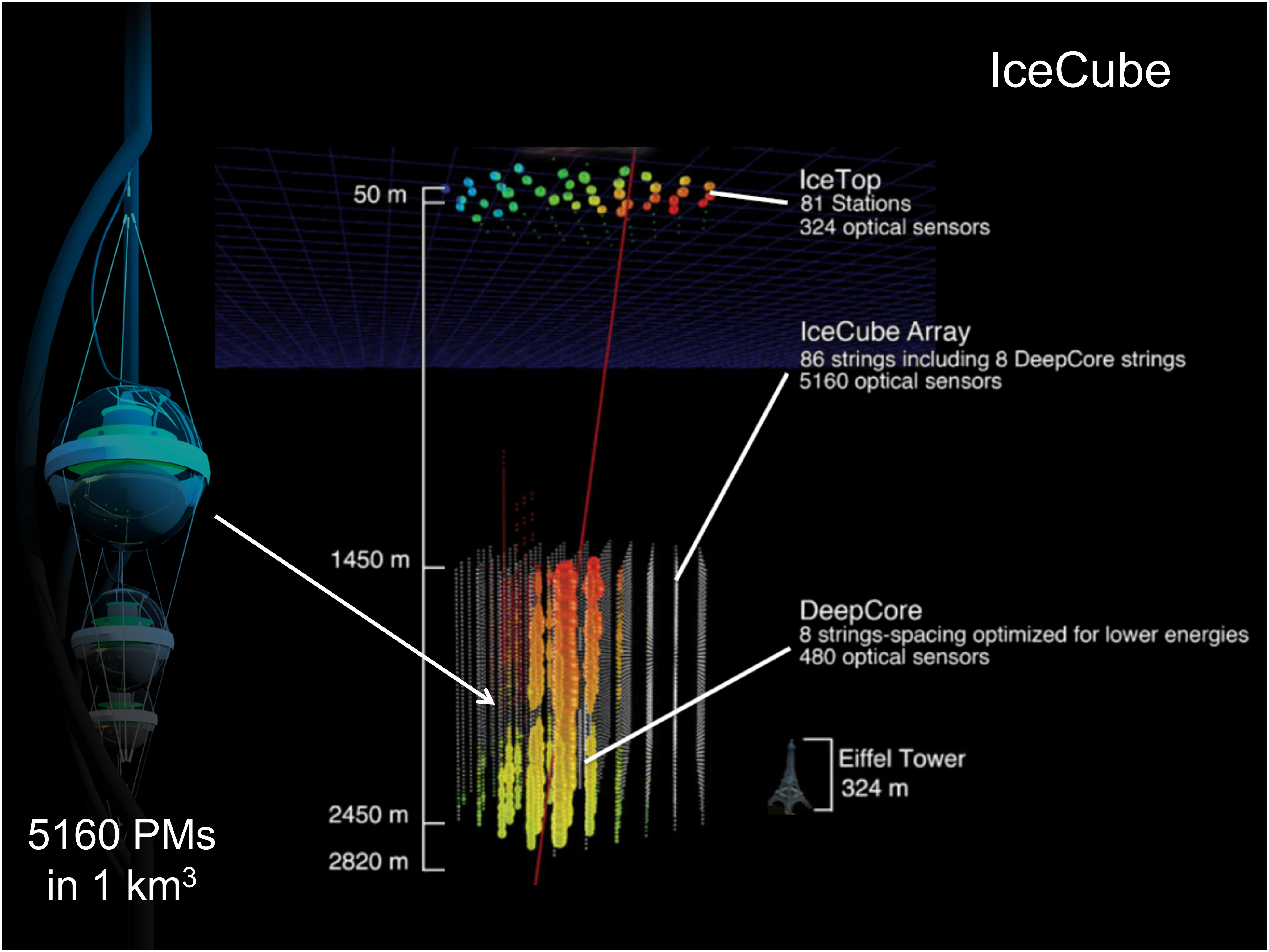
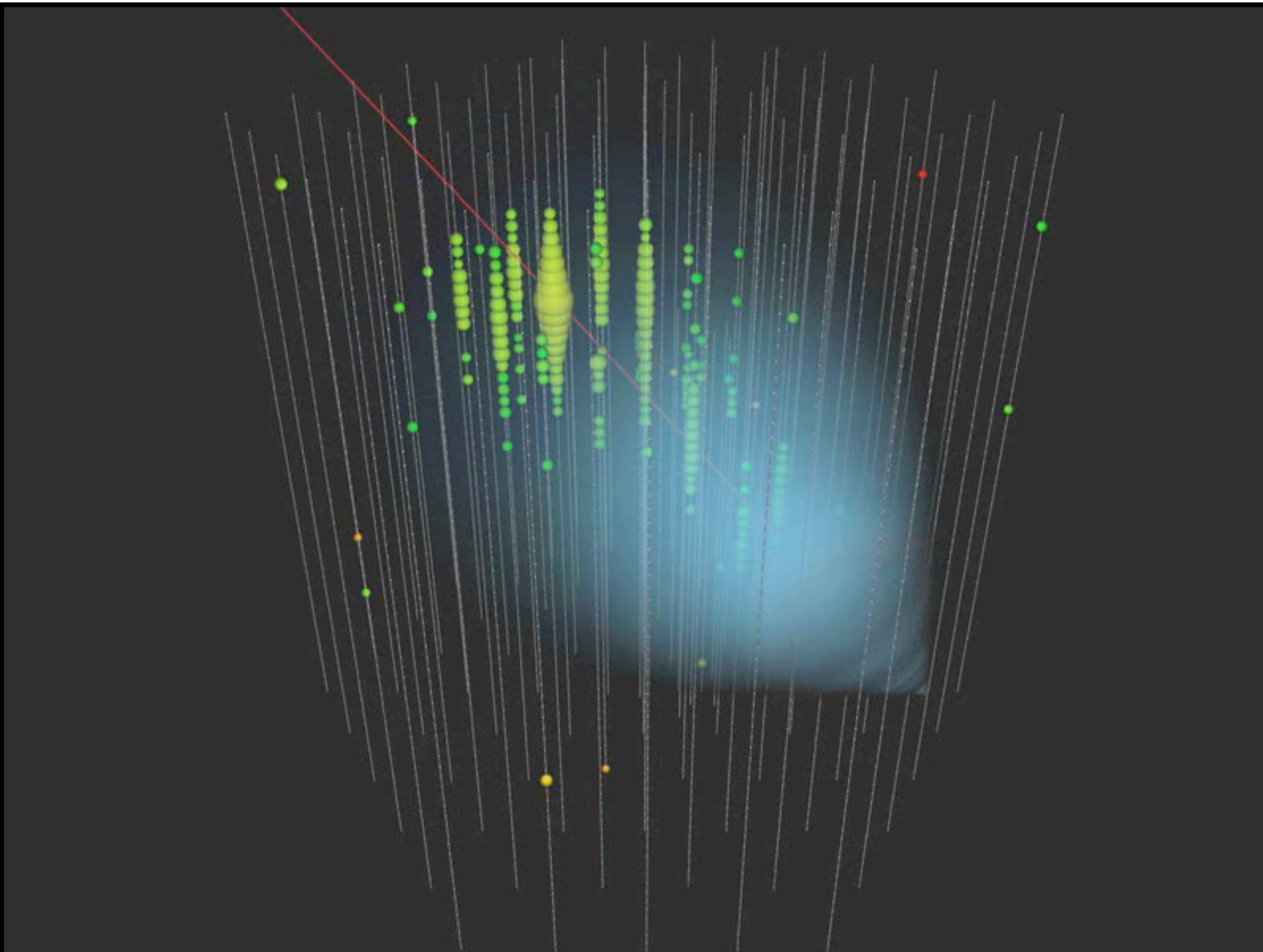

ultra-transparent ice below 1.5 km

IceCube



5160 PMs in 1 km^3



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

separating signal and "background"

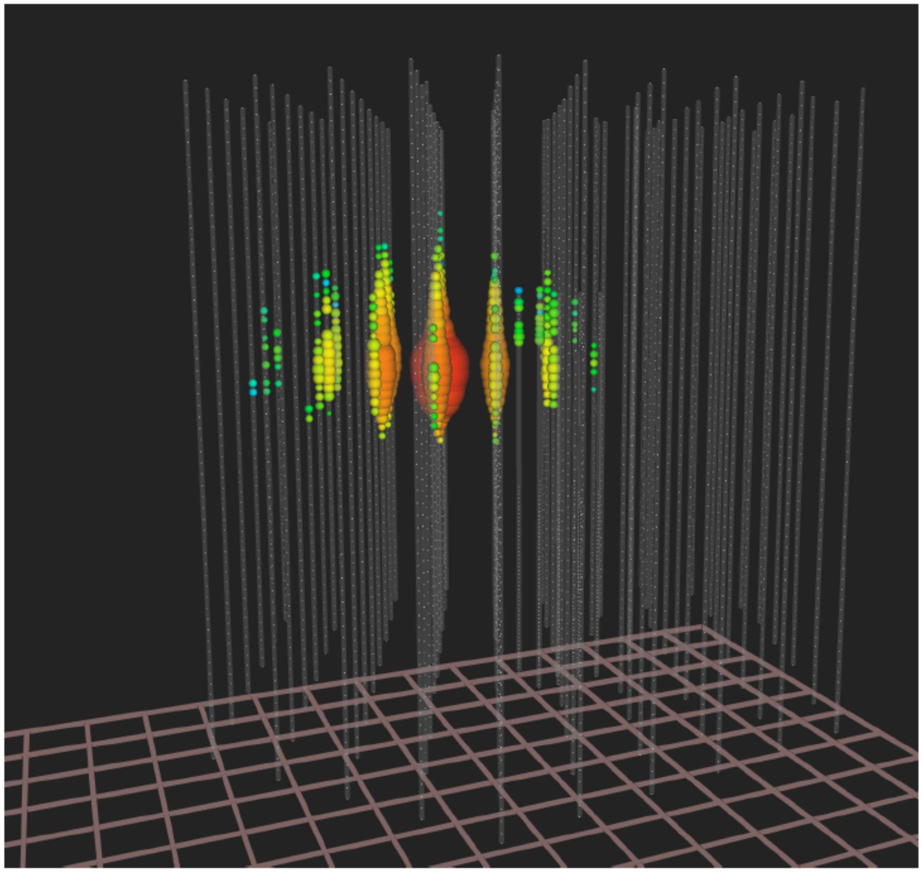
muons detected per year:

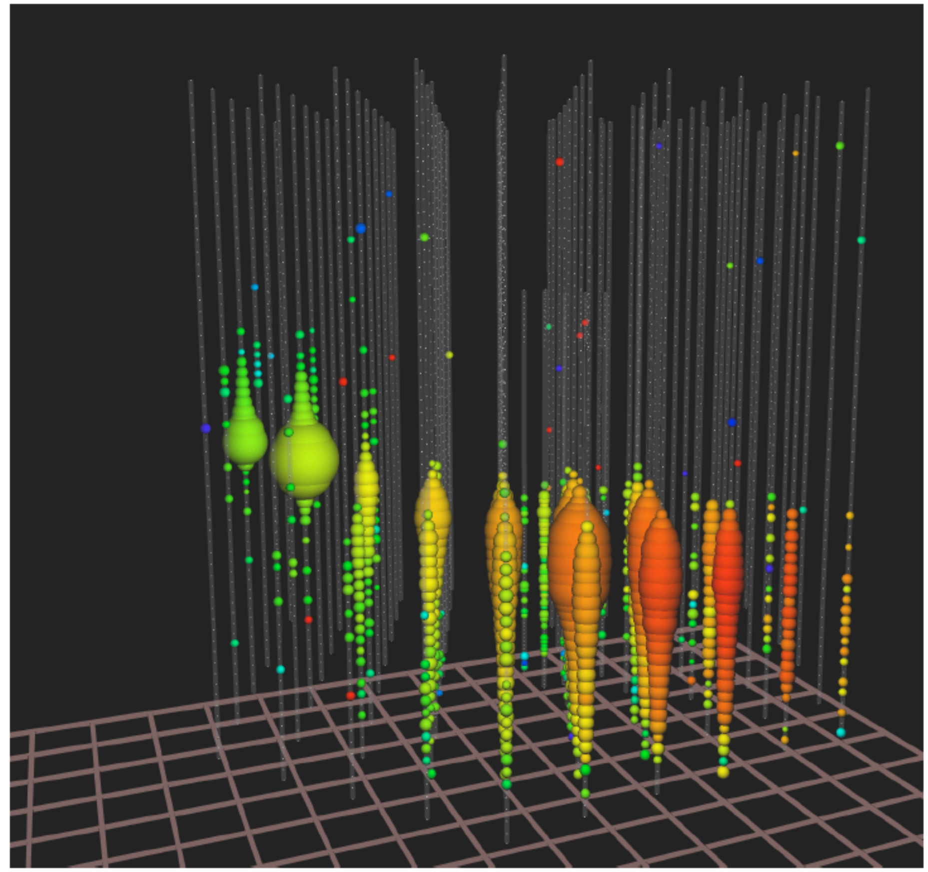
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^5
- cosmic $\nu \rightarrow \mu$ ~ $10\text{-}10^2$

* 3000 per second ** 1 every 6 minutes

isolated neutrinos interacting *inside* the detector (HESE)

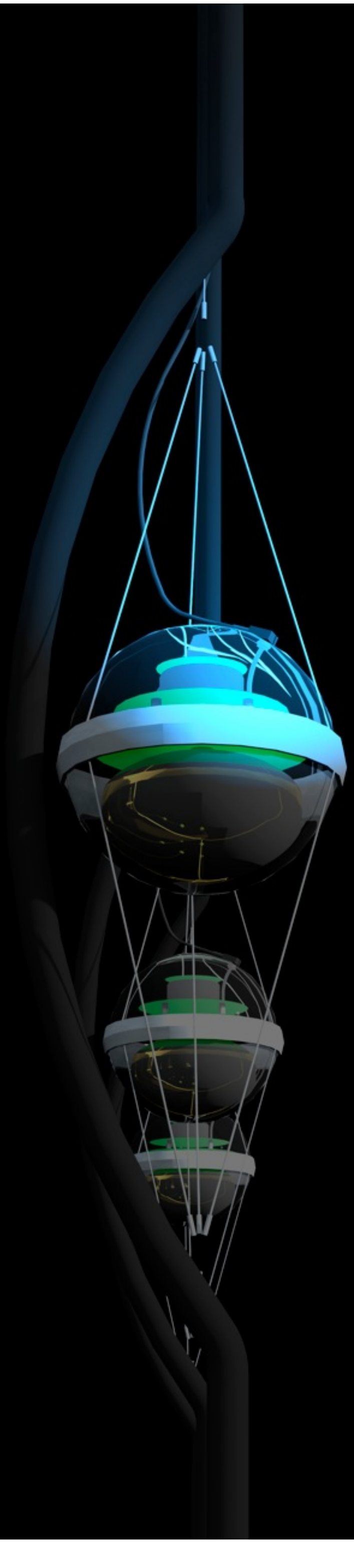
up-going muon tracks (UPMU)





total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5°)



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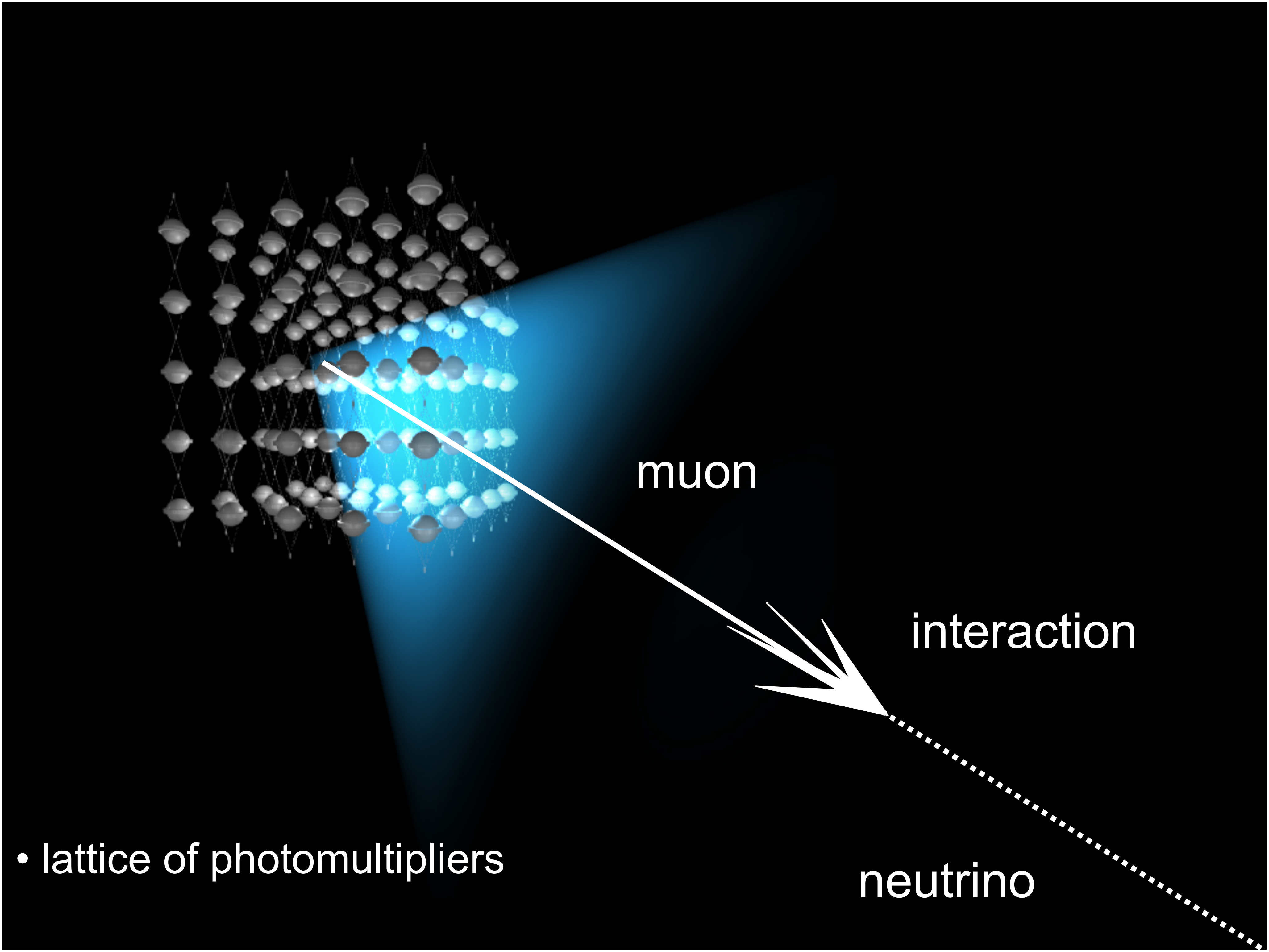
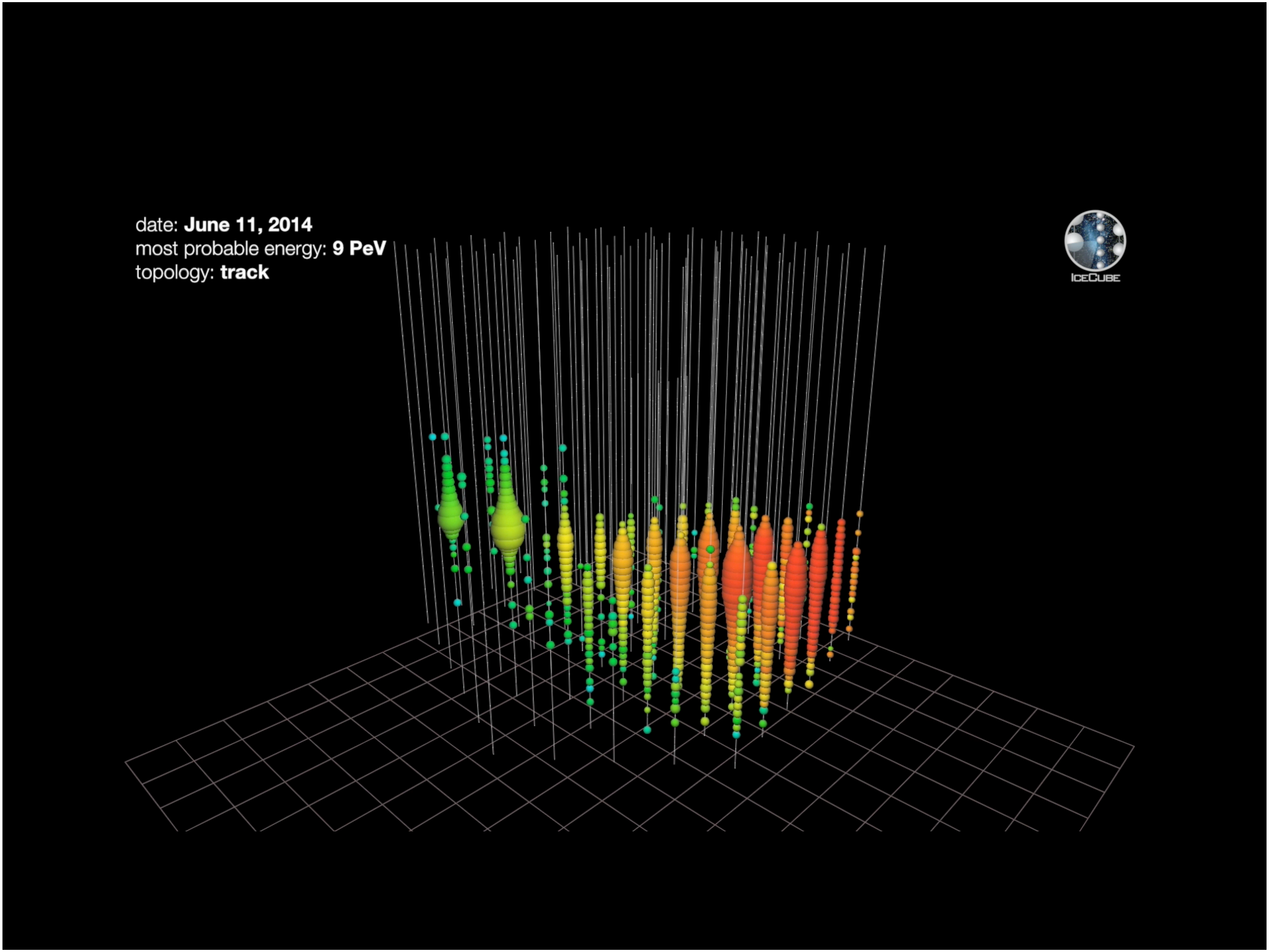
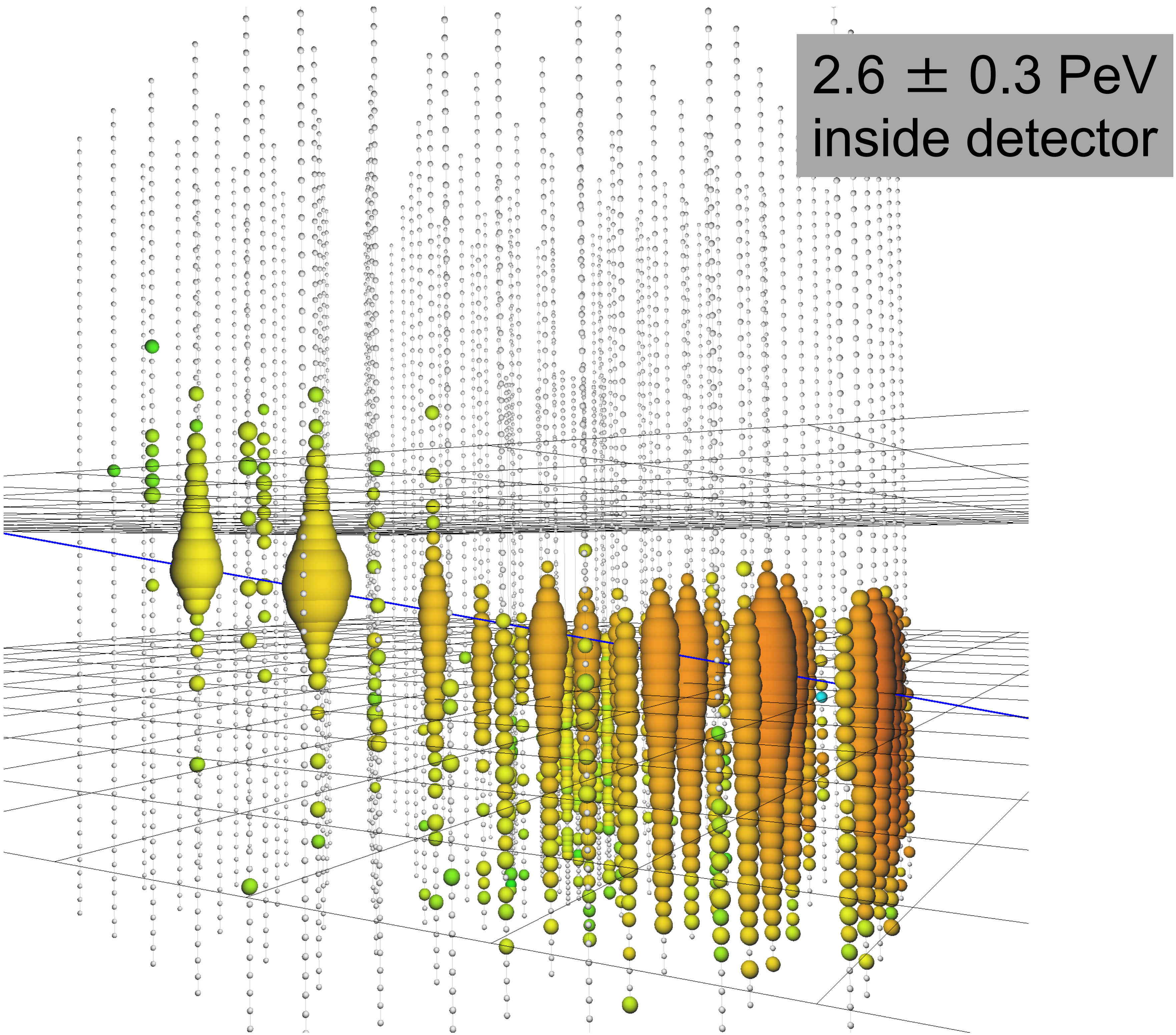
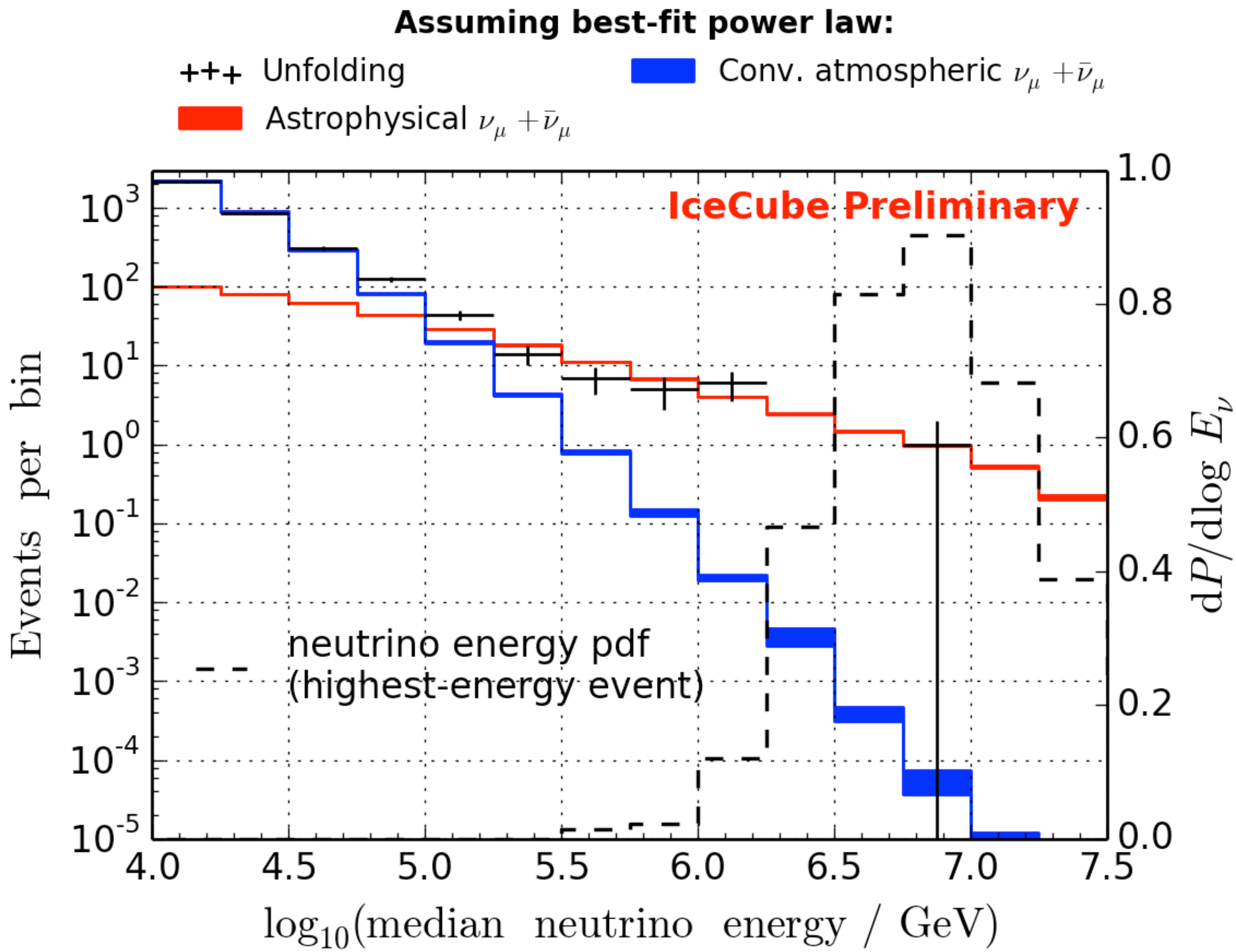

muon
interaction
neutrino
• lattice of photomultipliers


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

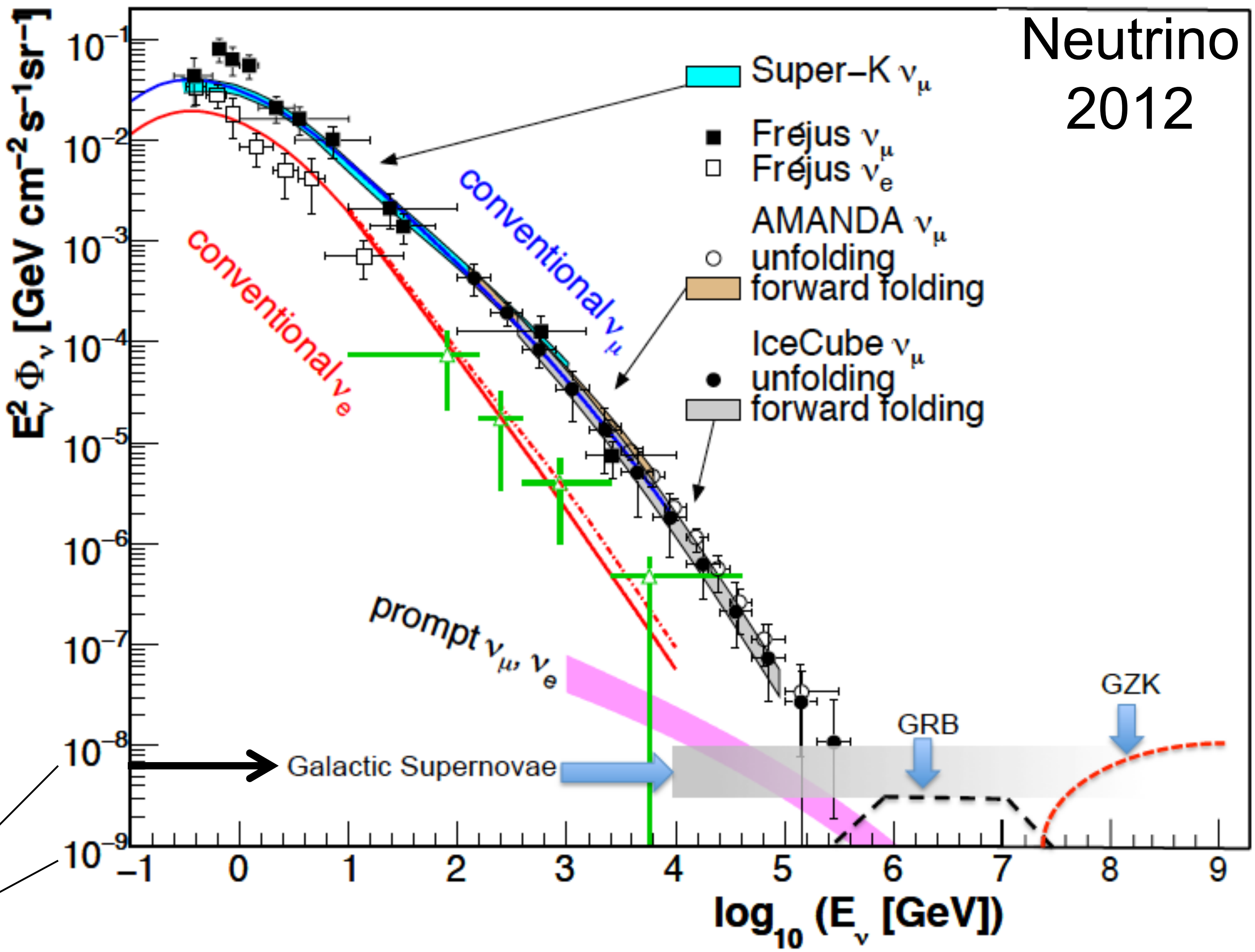
atmospheric background: less than one event/deg^2/year



above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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



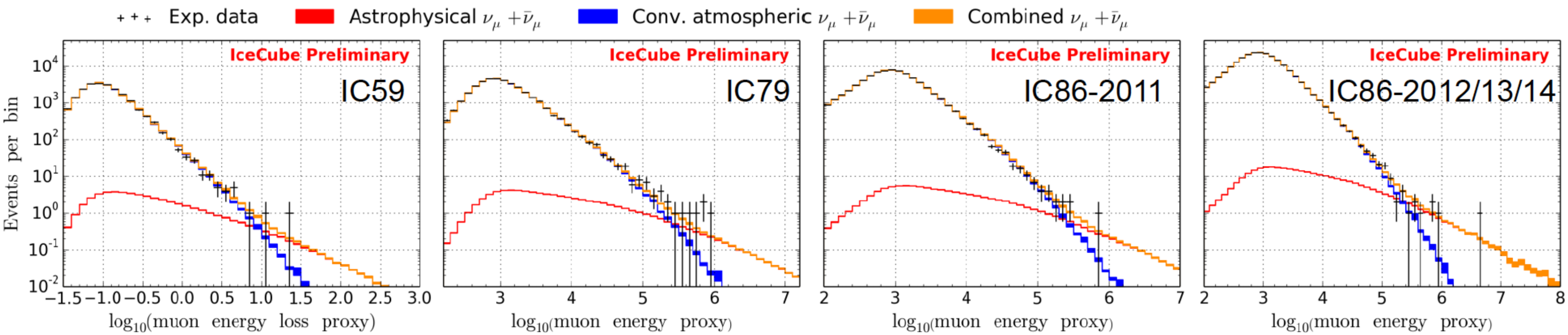
10—100 events per year for fully efficient detector

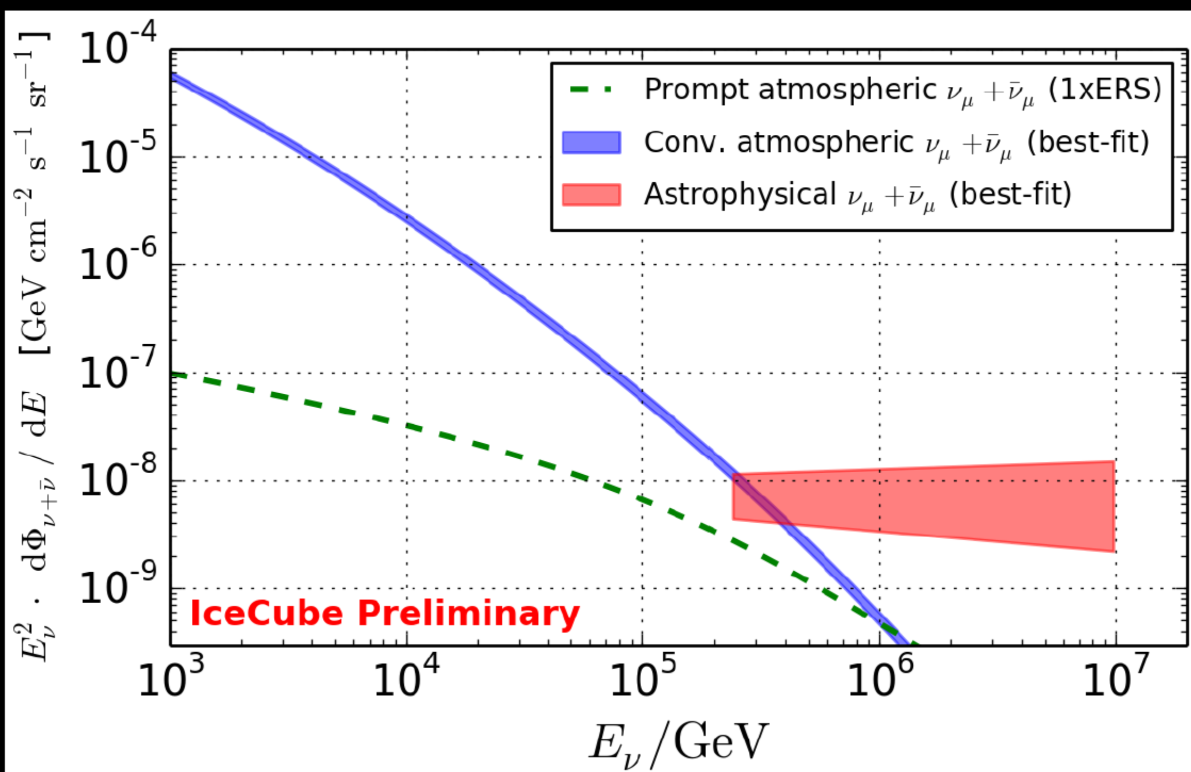
atmospheric

cosmic

100 TeV

after 7 years → 6.4 sigma





- Best-fit astrophysical normalization:

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

- Best-fit spectral index:

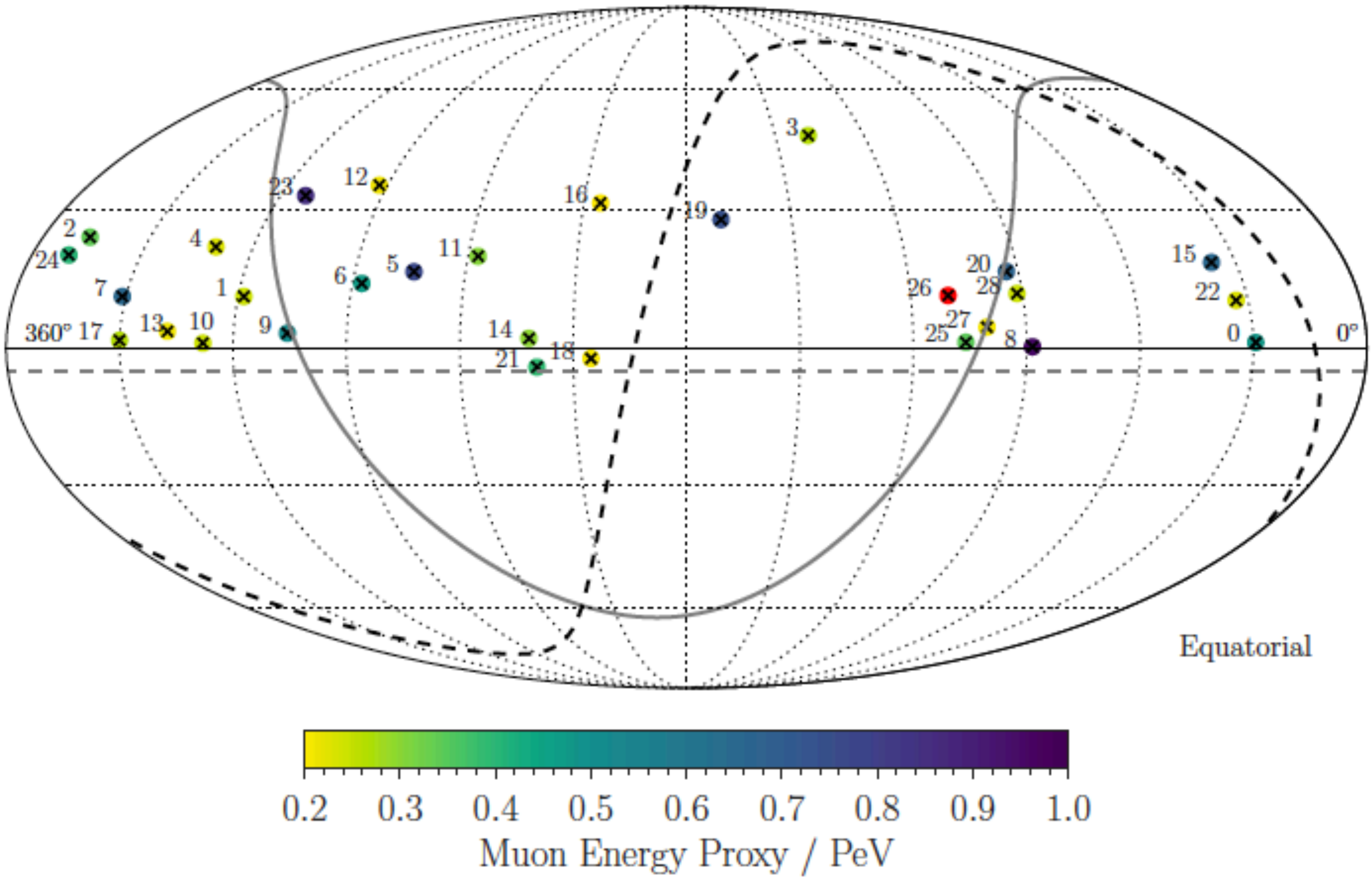
  γ_{astro} = 2.16 ± 0.11

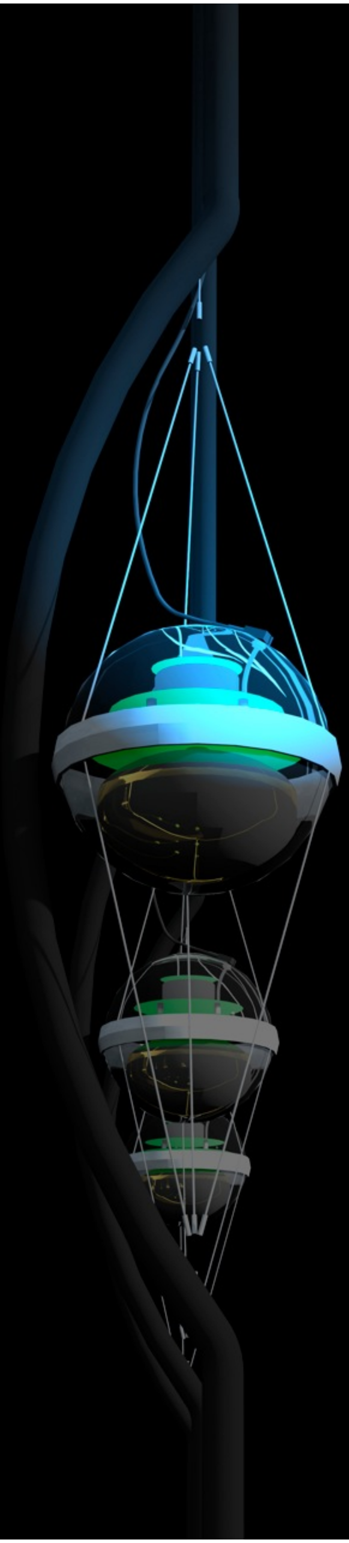
- Energy ranges:

  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ

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





IceCube and MultimessengerAstronomy

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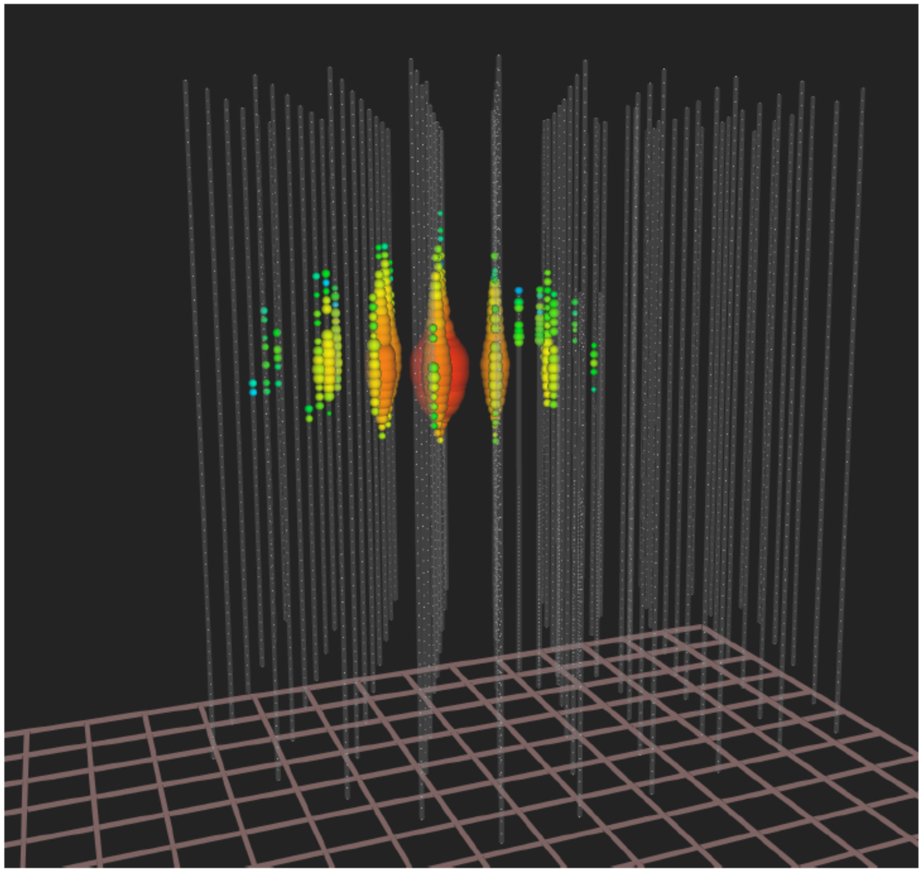
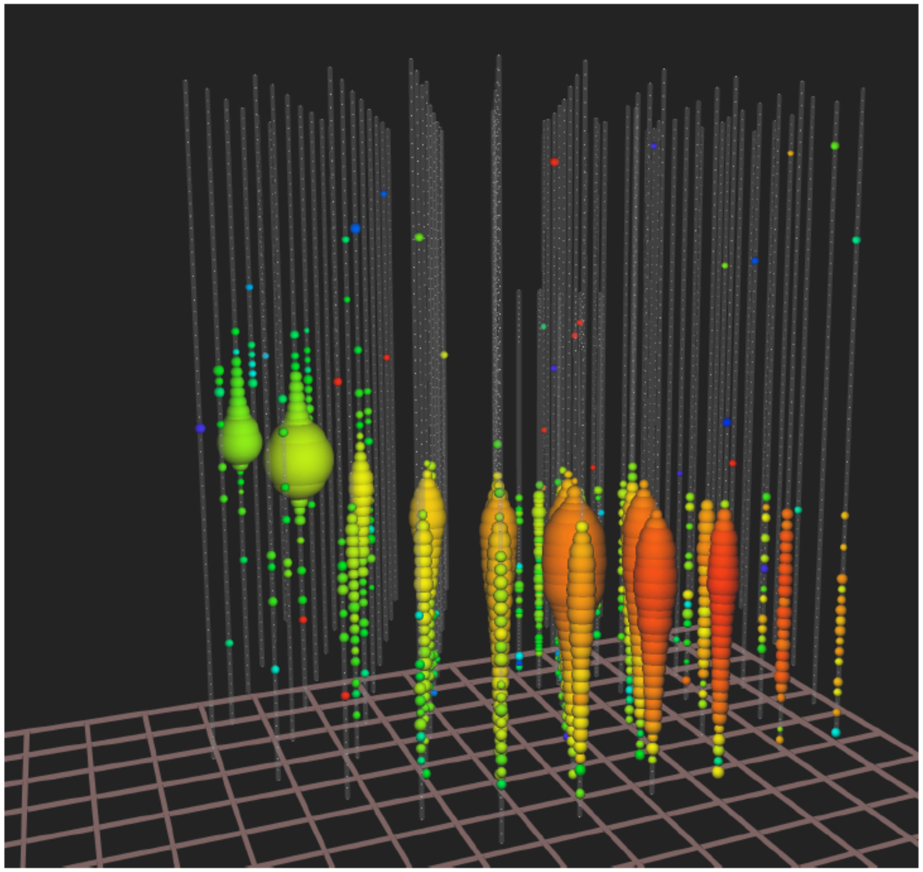
isolated neutrinos interacting inside the detector

up-going muon tracks

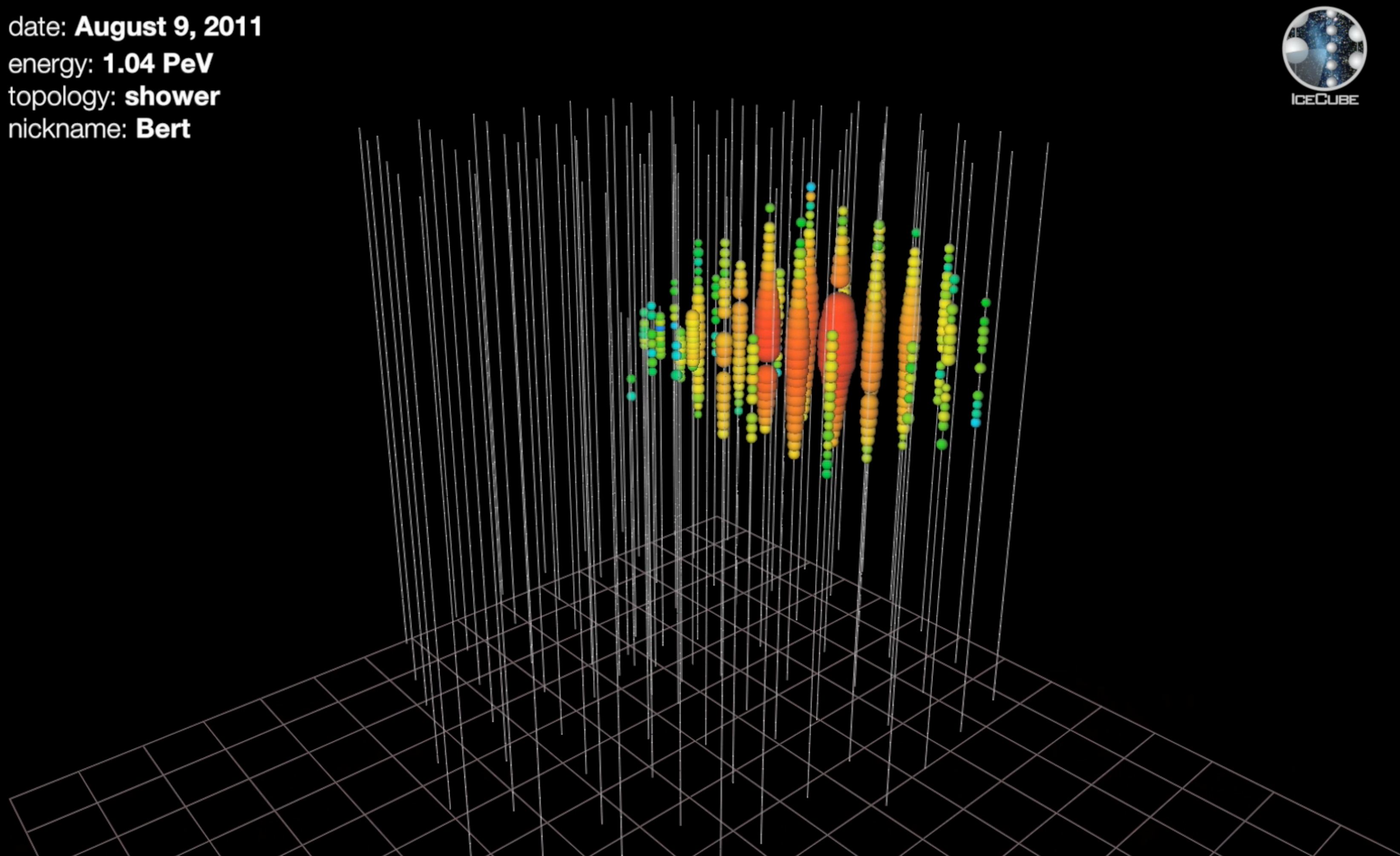




calorimetry: direct energy measurement; all flavors

astronomy: angular resolution superior

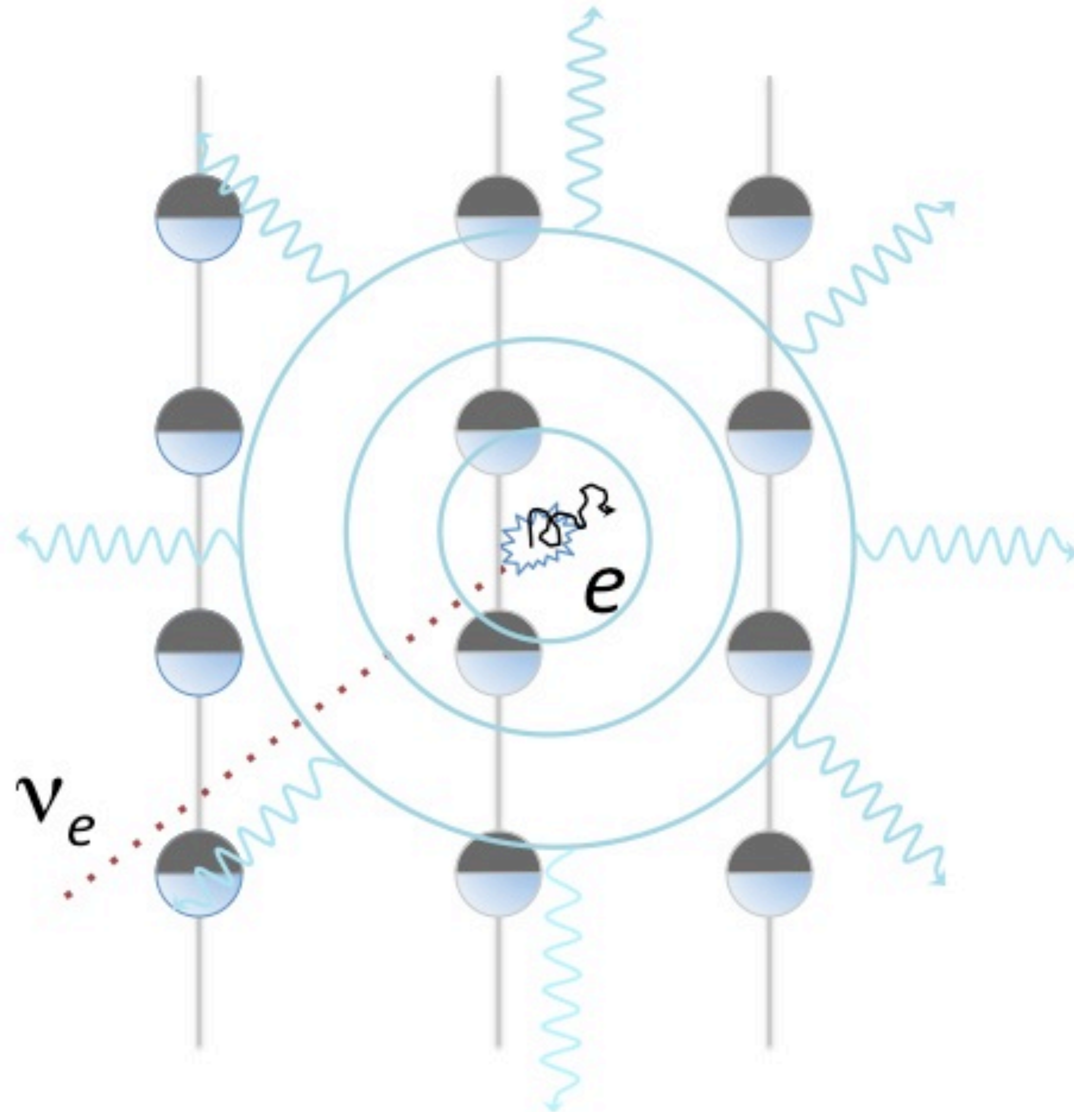
GZK neutrino search: two neutrinos with > 1,000 TeV

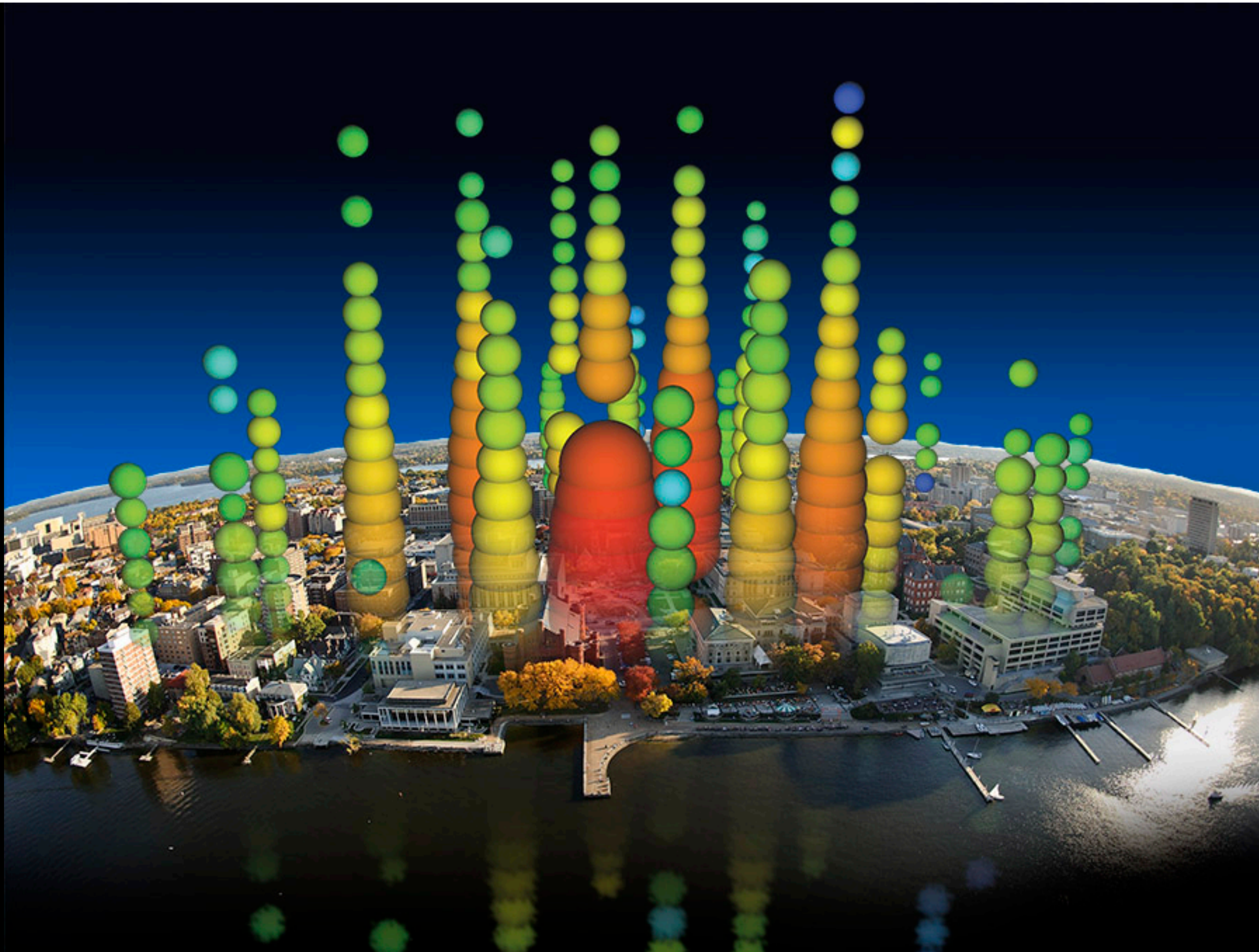


electron showers versus muon tracks

PeV ν_e and ν_τ showers:

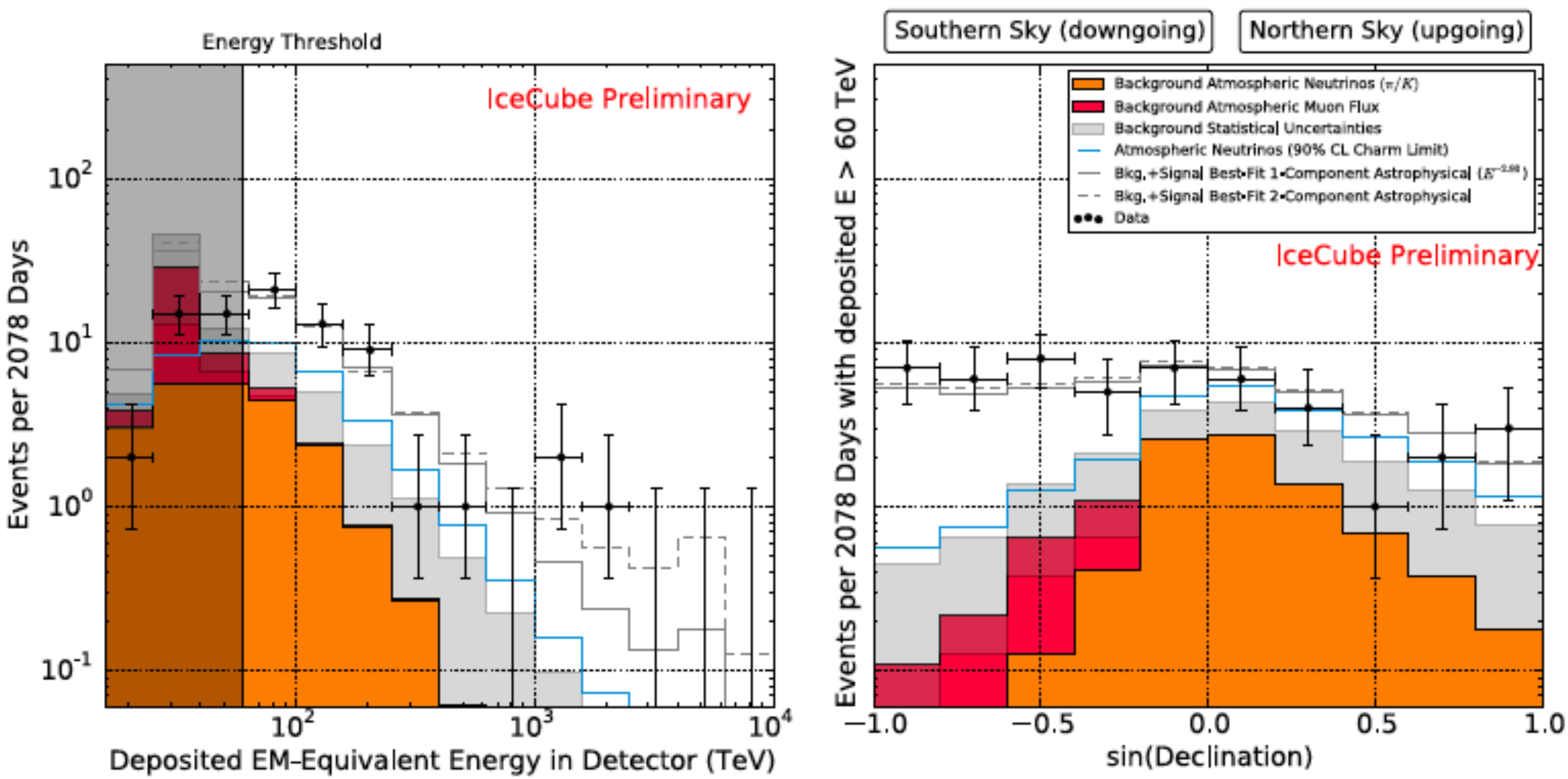
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m





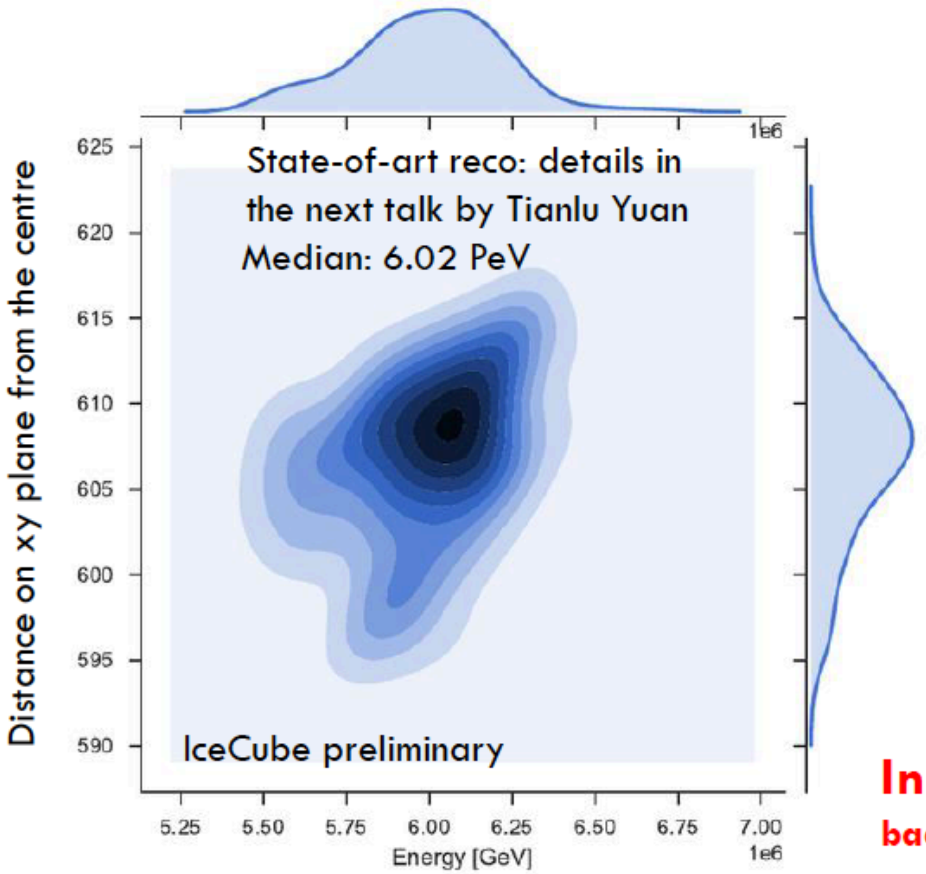
- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

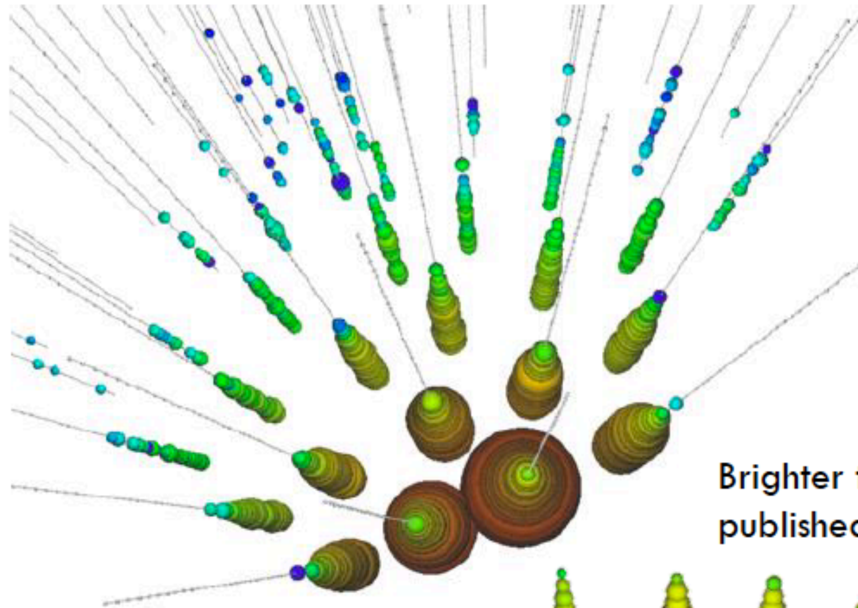
starting events: now 6 years → 8σ



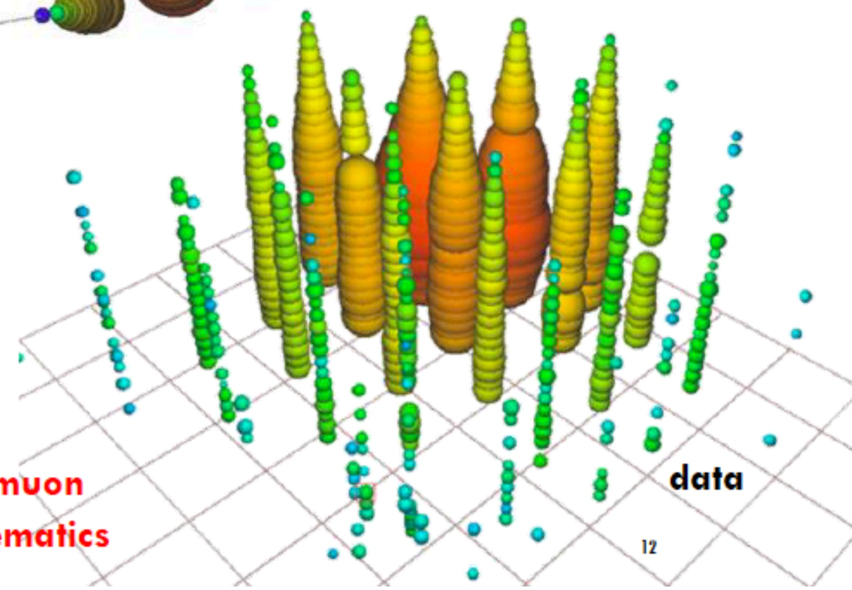
Partially contained event with energy ~ 6 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE



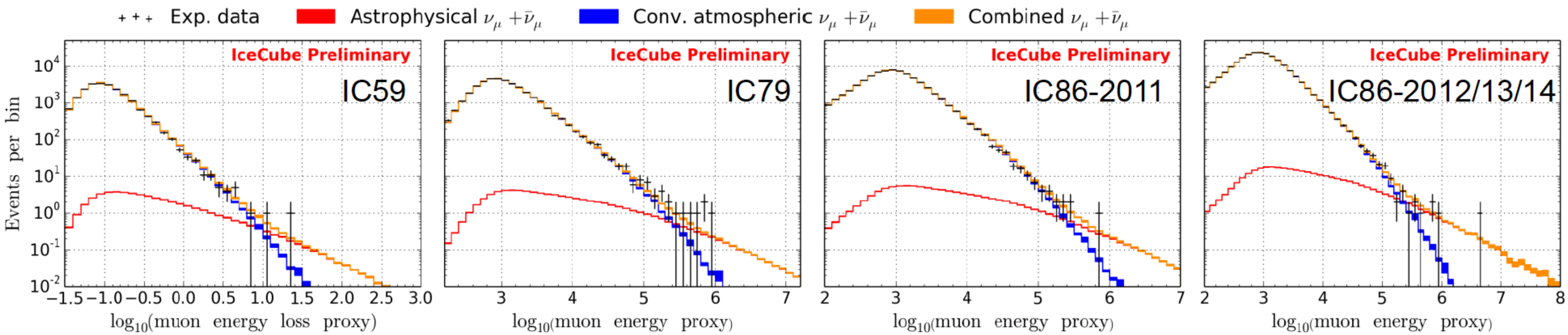


Brighter than all published PeV events



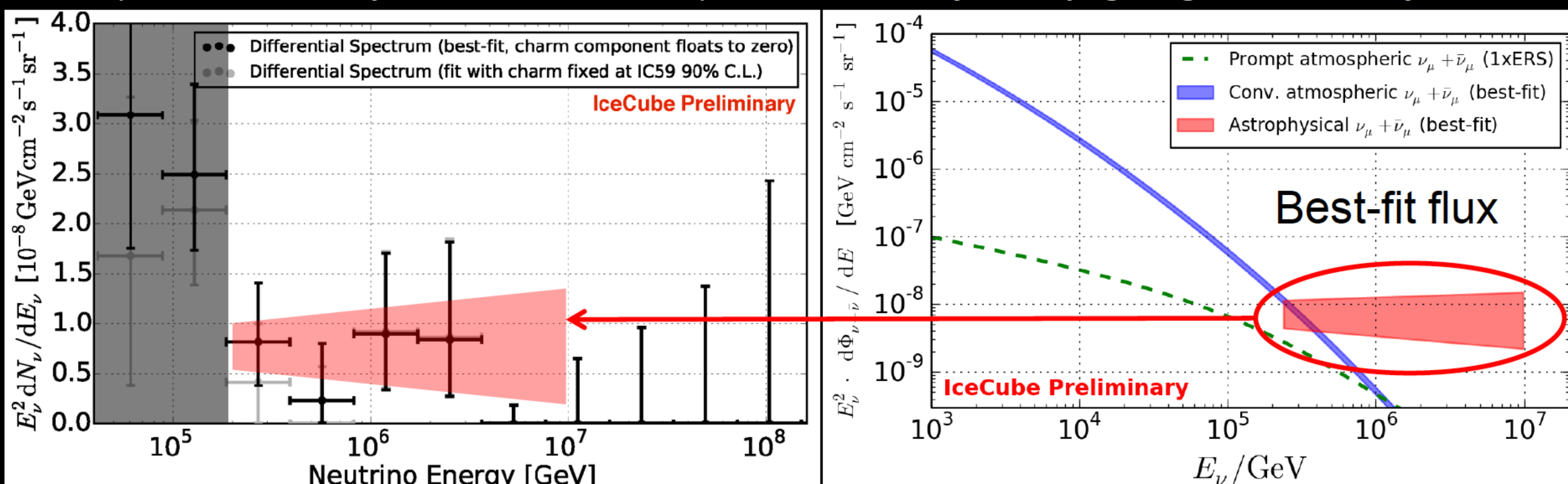
In progress: muon background systematics

after 6 years: 3.7→ 6.0 sigma

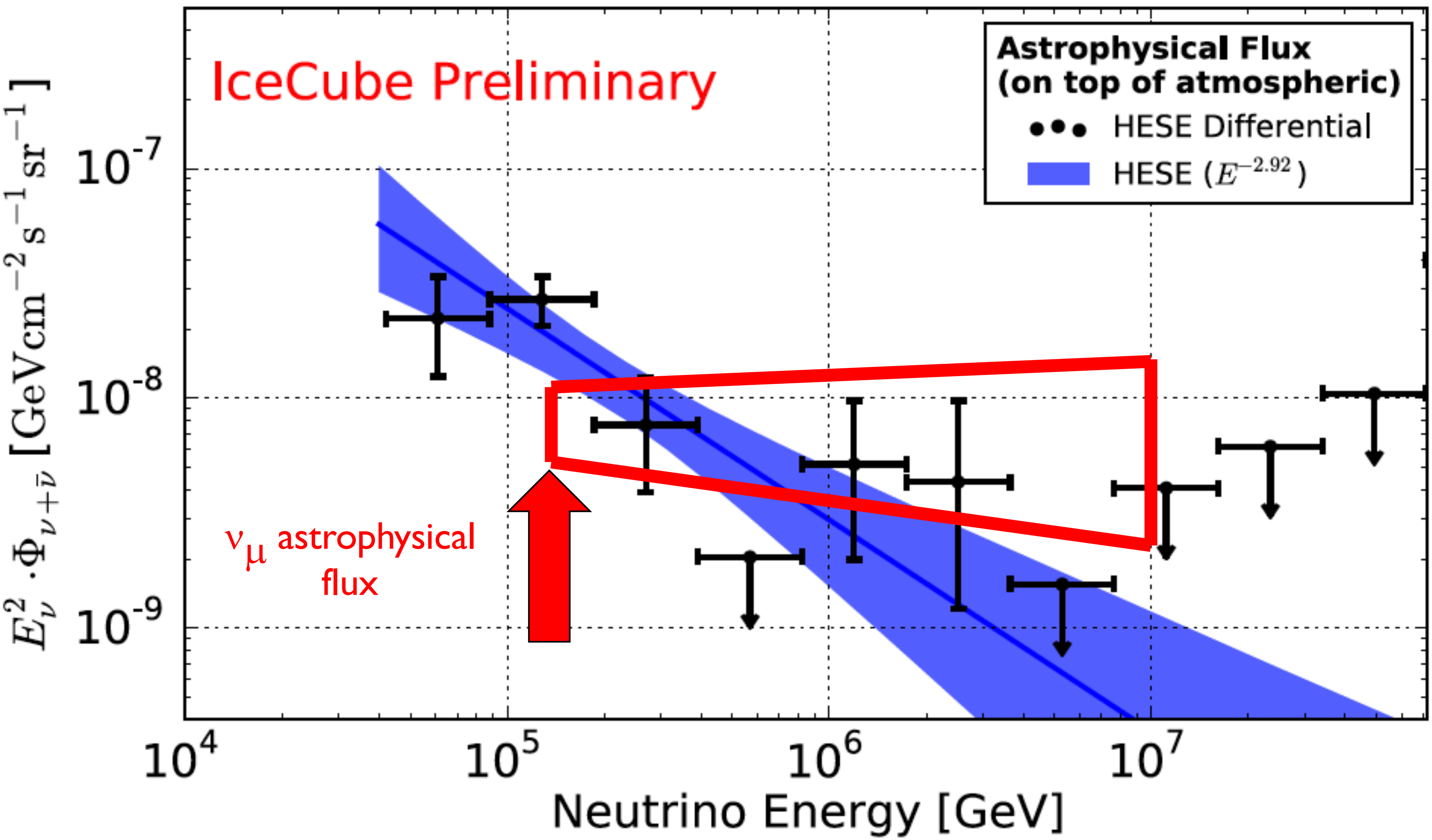


HESE 4 year unfolding
(→ dominated by shower-like events)

6 year up-going numu analysis



two methods consistent above 100 TeV



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

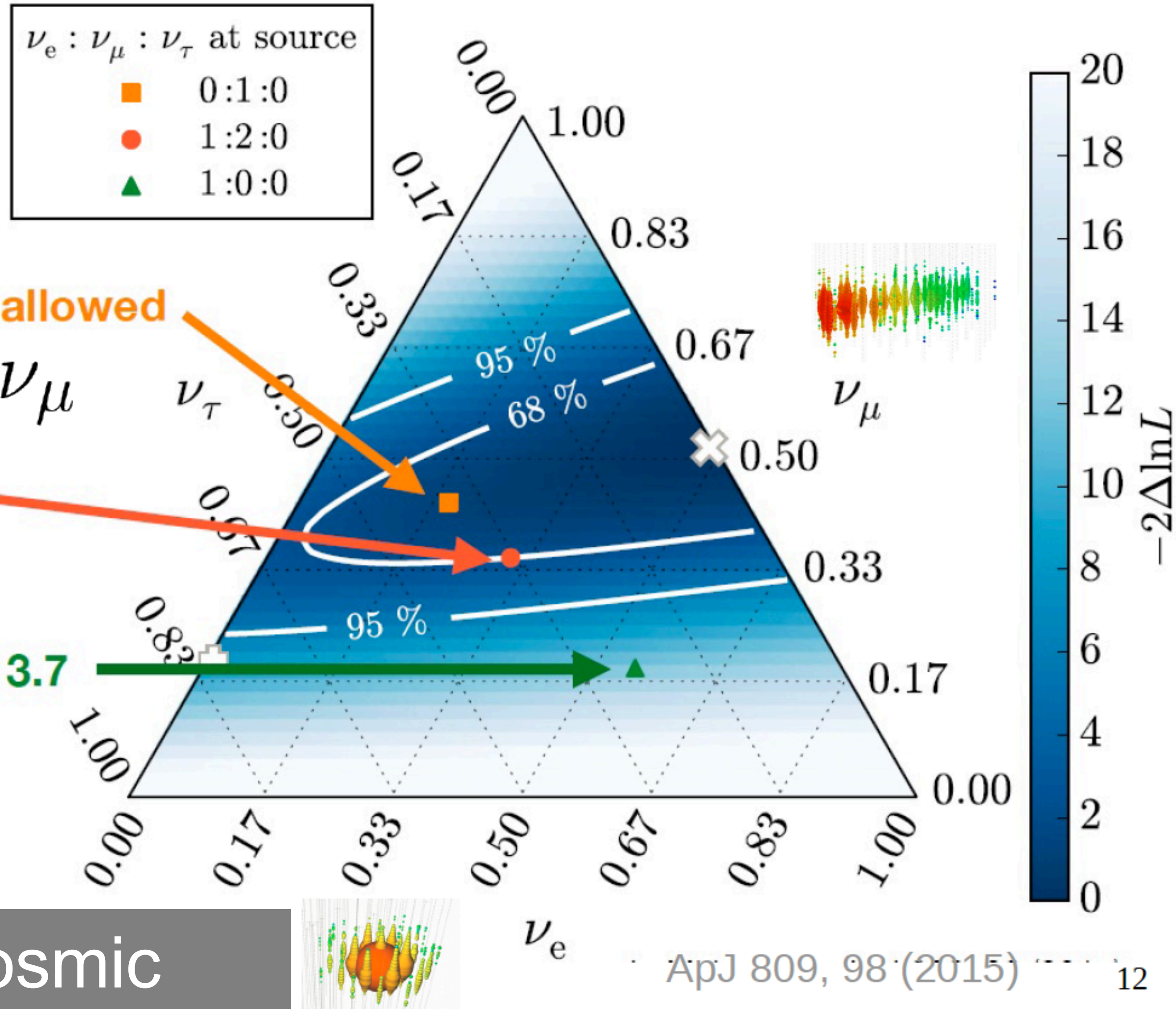
Muon-damped pion decay: allowed

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

Pion decay: allowed

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

Neutron decay: rejected at 3.7



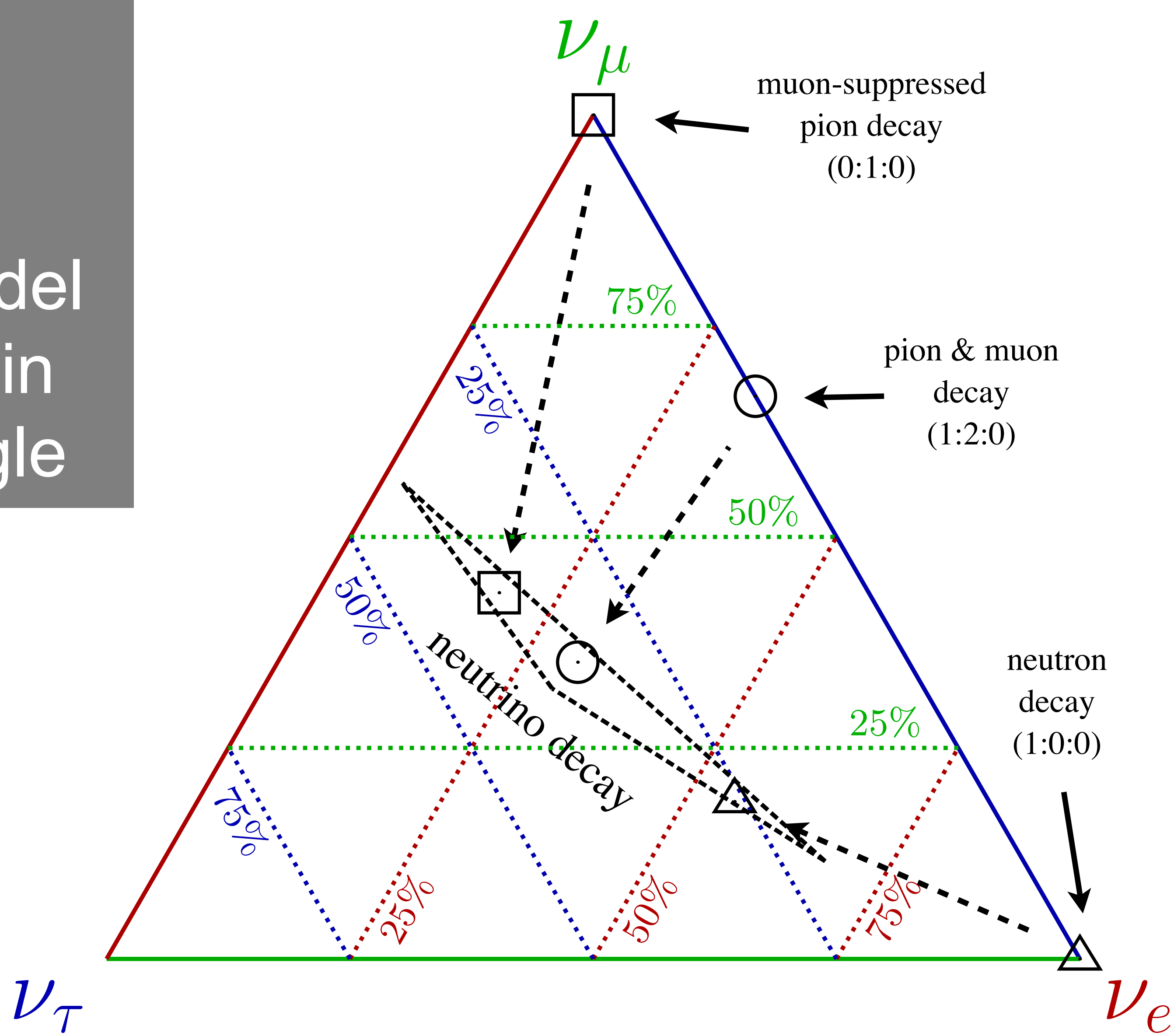
oscillate over cosmic distances to 1:1:1

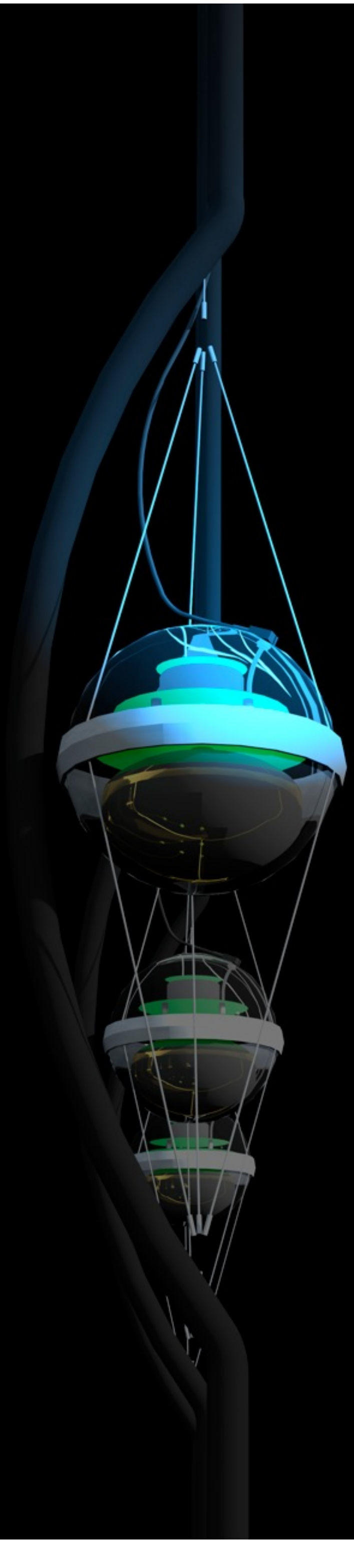
ApJ 809, 98 (2015)

new physics ?

if not…

every model ends up in the triangle





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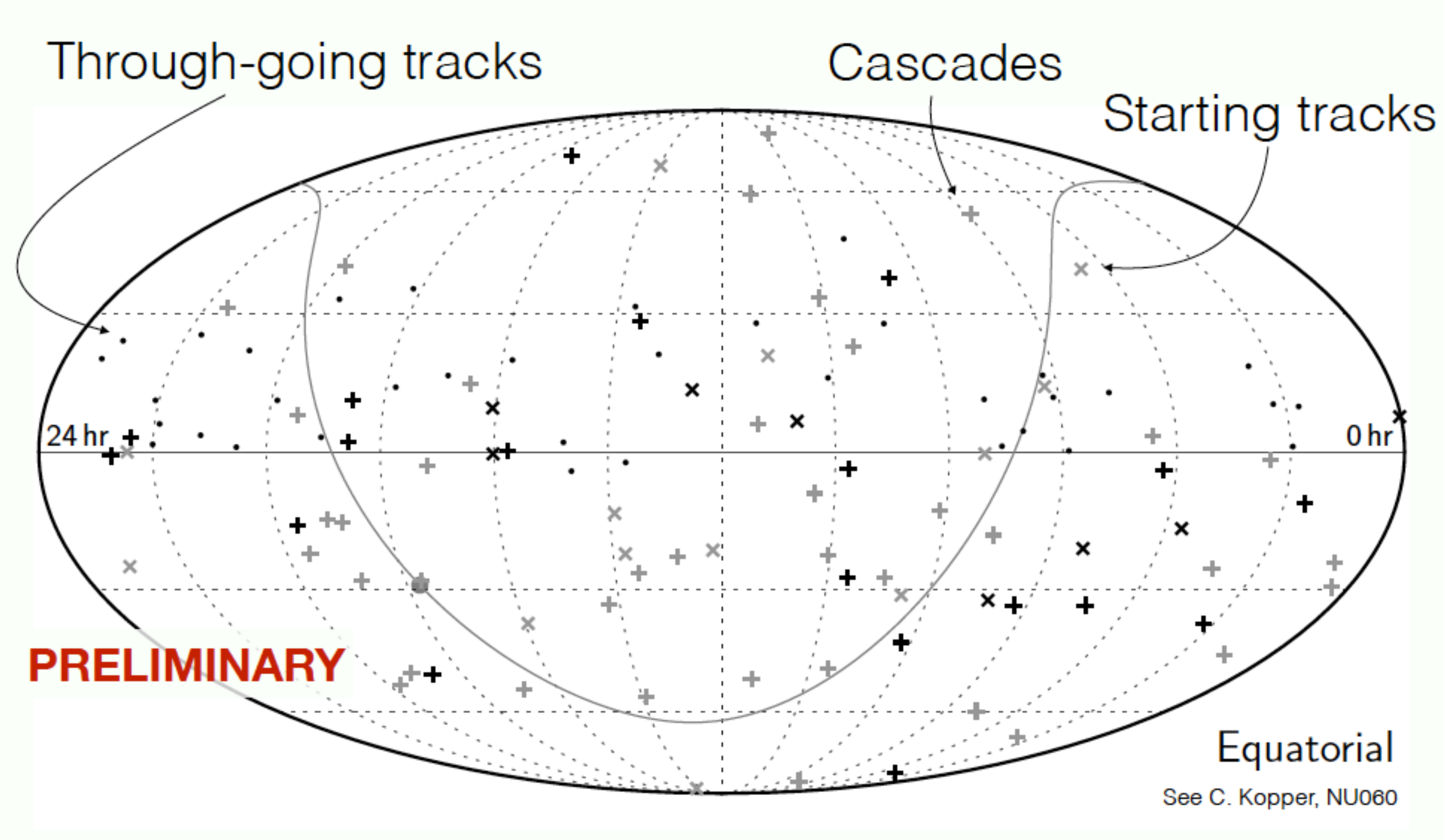
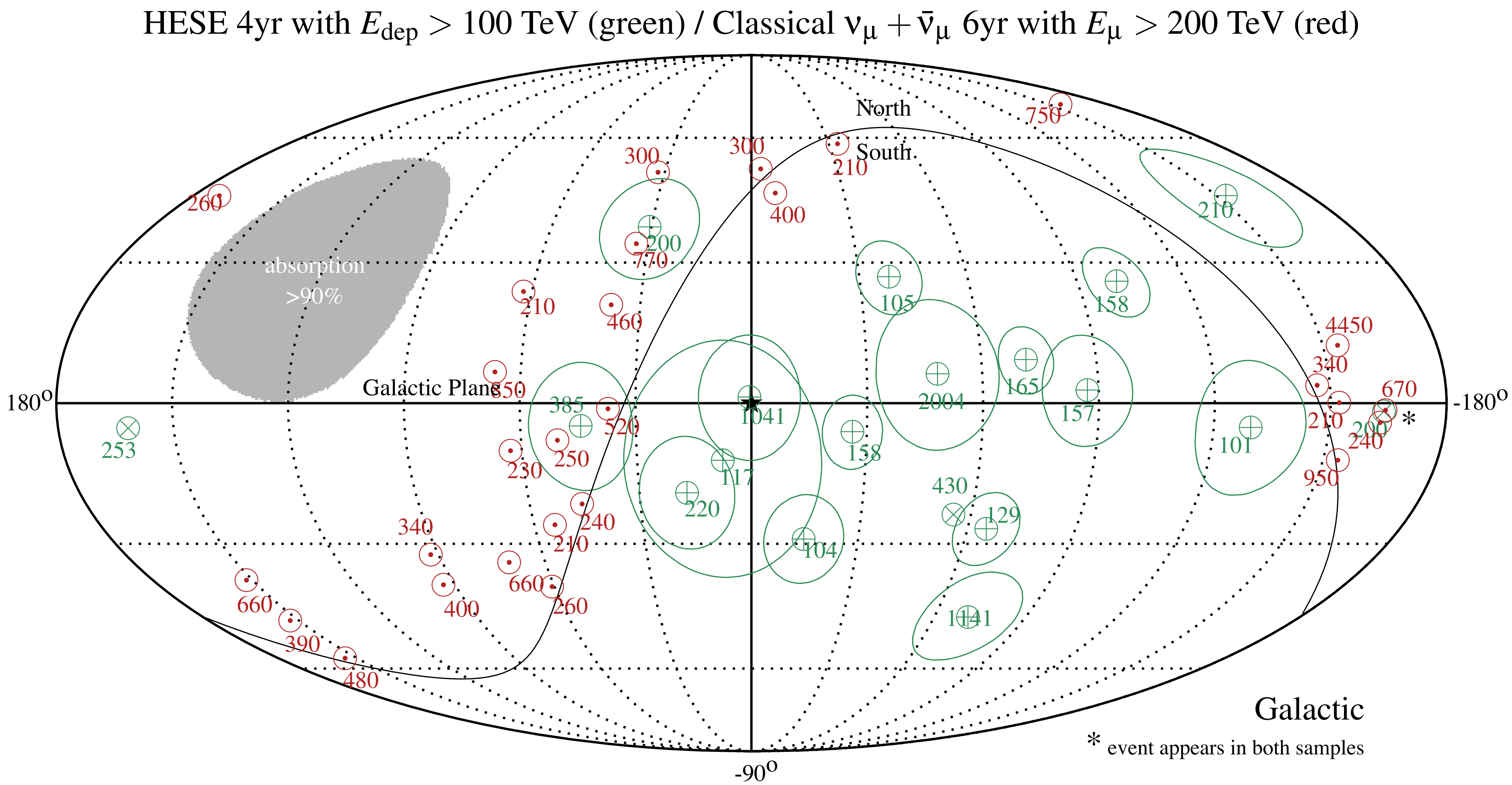
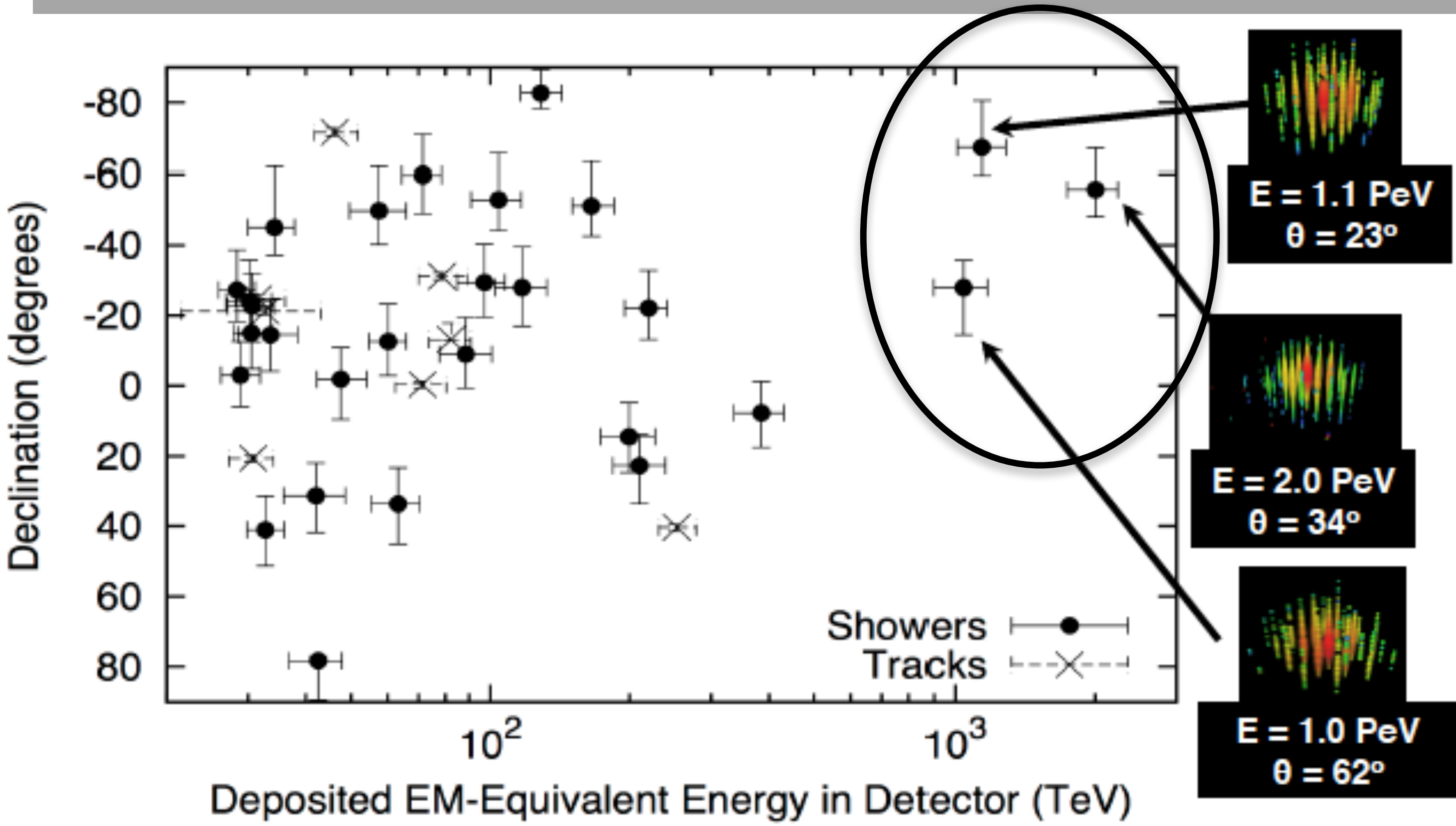

Through-going tracks
Cascades
Starting tracks
24 hr
0 hr
PRELIMINARY
Equatorial
See C. Kopper, NU060

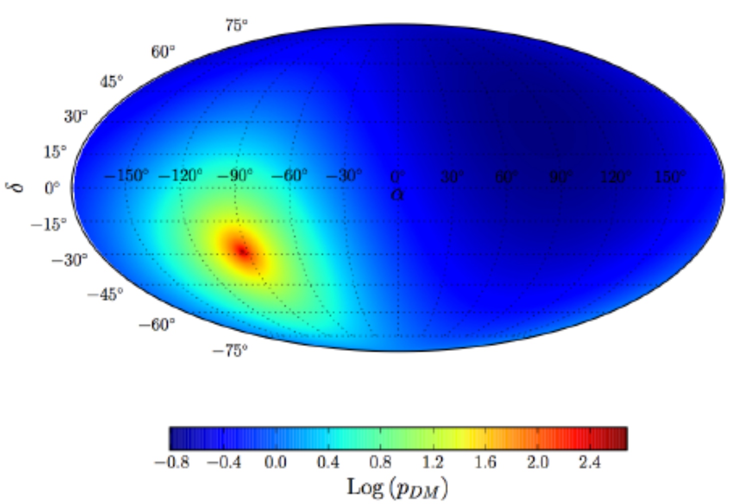

HESE 4yr with E_{dep} > 100 TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with E_μ > 200 TeV (red)
North
South
absorption
>90%
Galactic Plane
180°
-180°
-90°
Galactic
* event appears in both samples
750
300
300
210
400
260
200
770
210
460
105
158
210
4450
340
670
250
385
520
1041
2004
165
157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

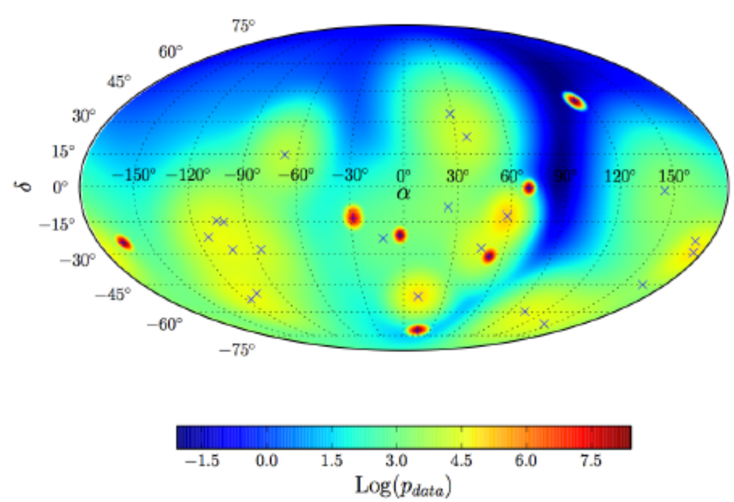
- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)
- [decay of halo dark matter particles?]

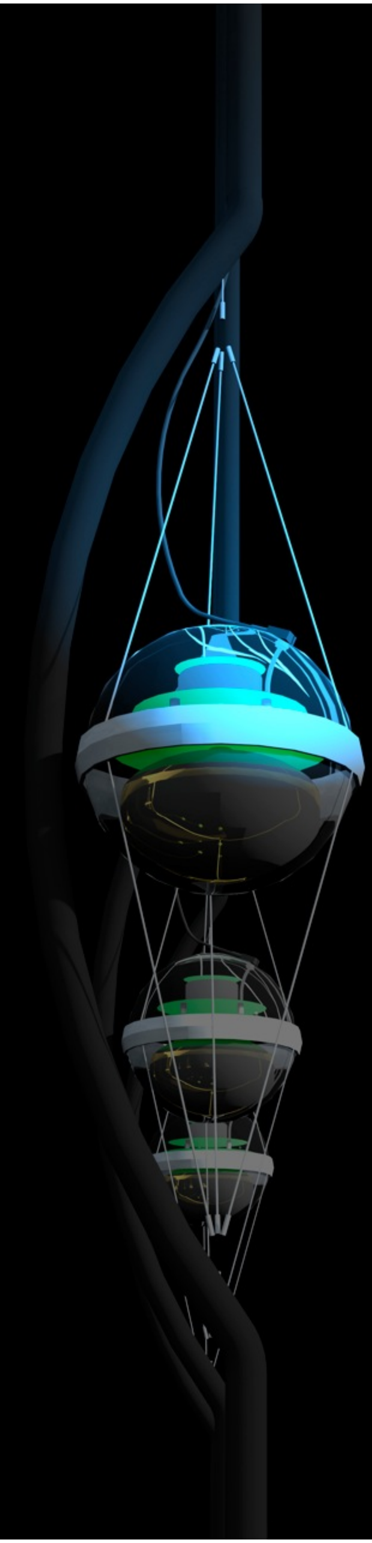
expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle







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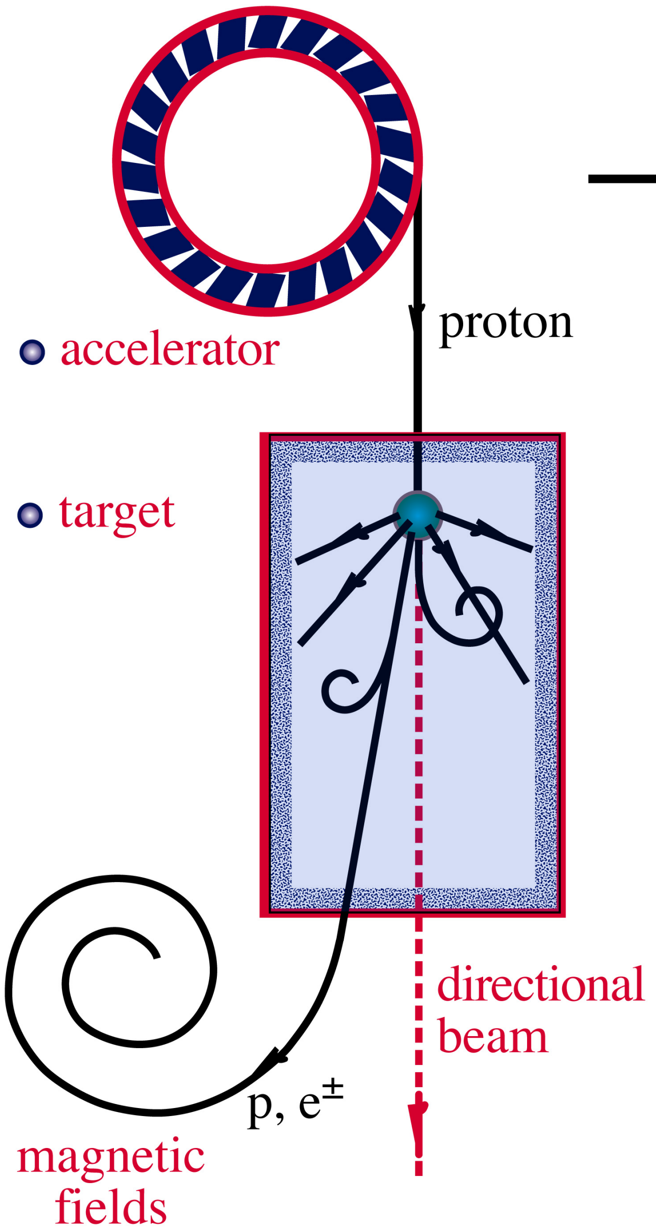
ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

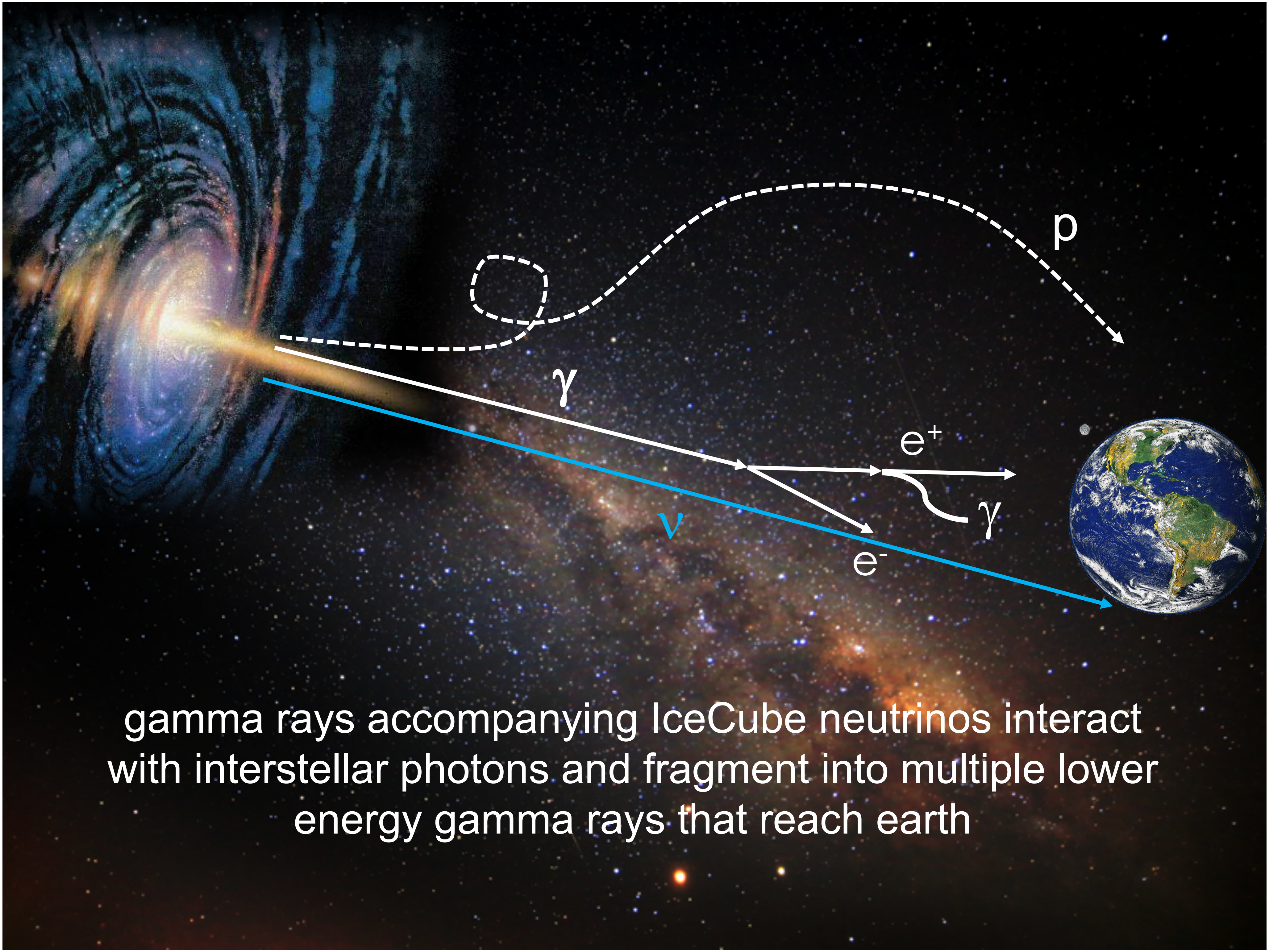
radiation and dust

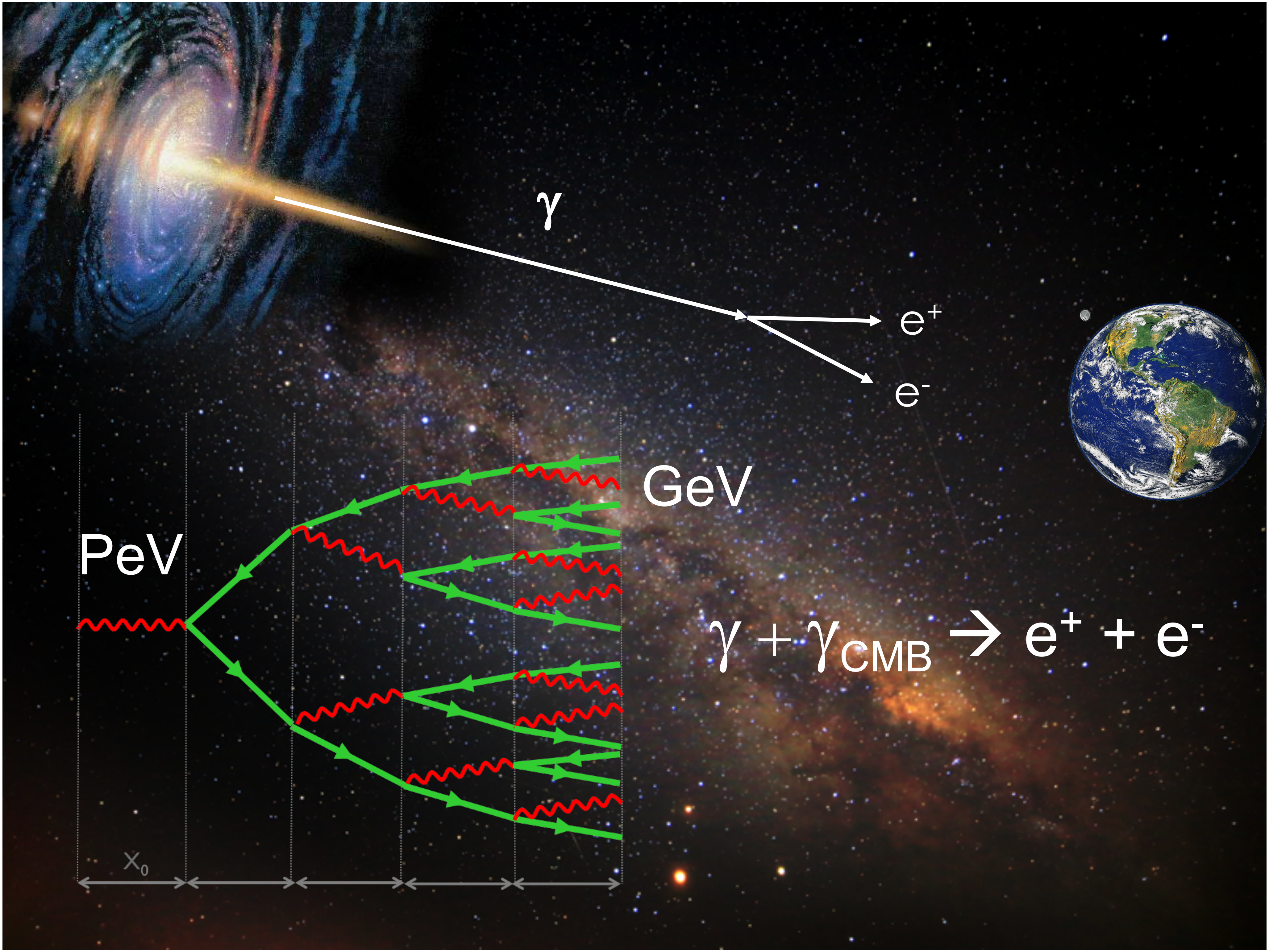
$p + \gamma \rightarrow n + \pi^+$

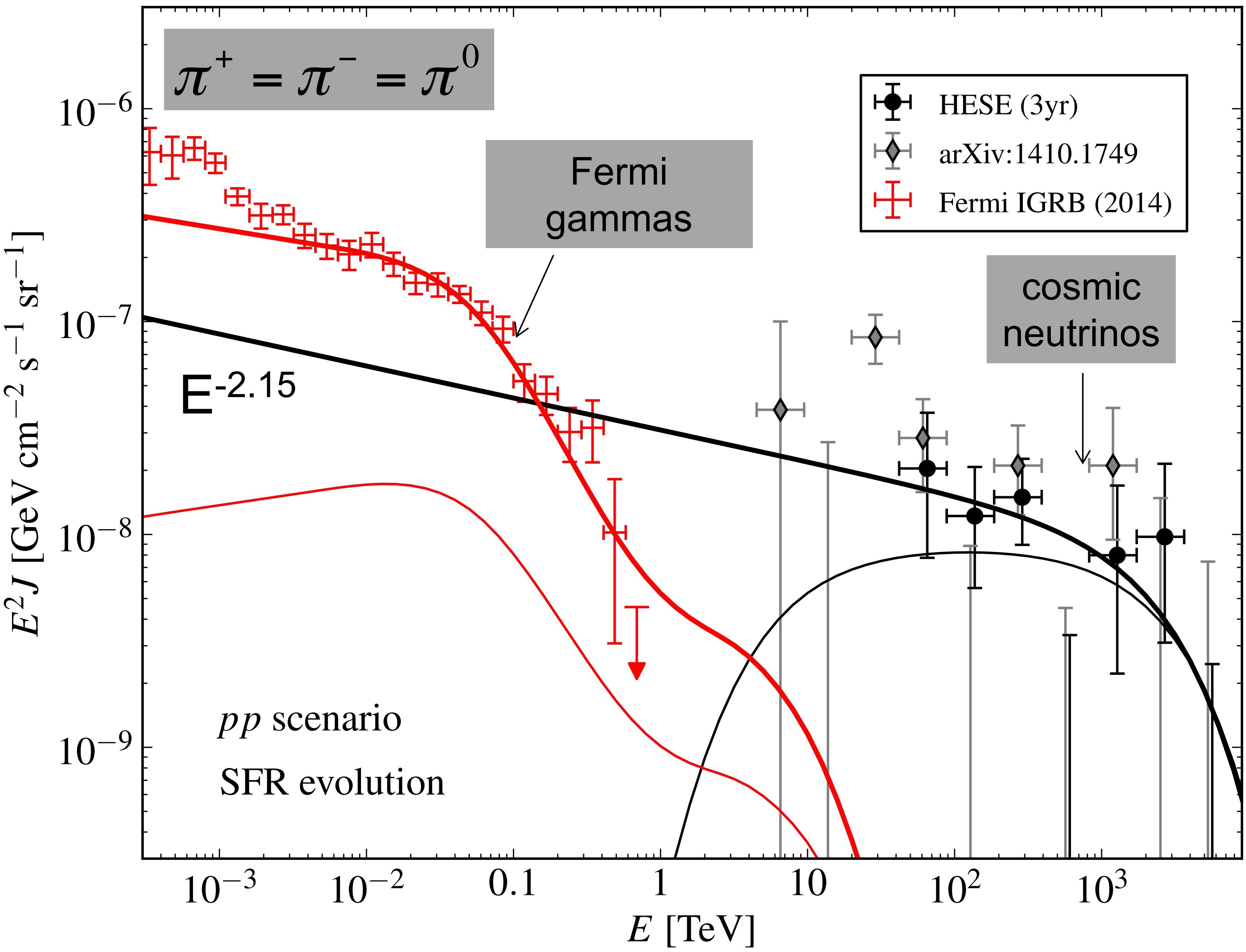
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

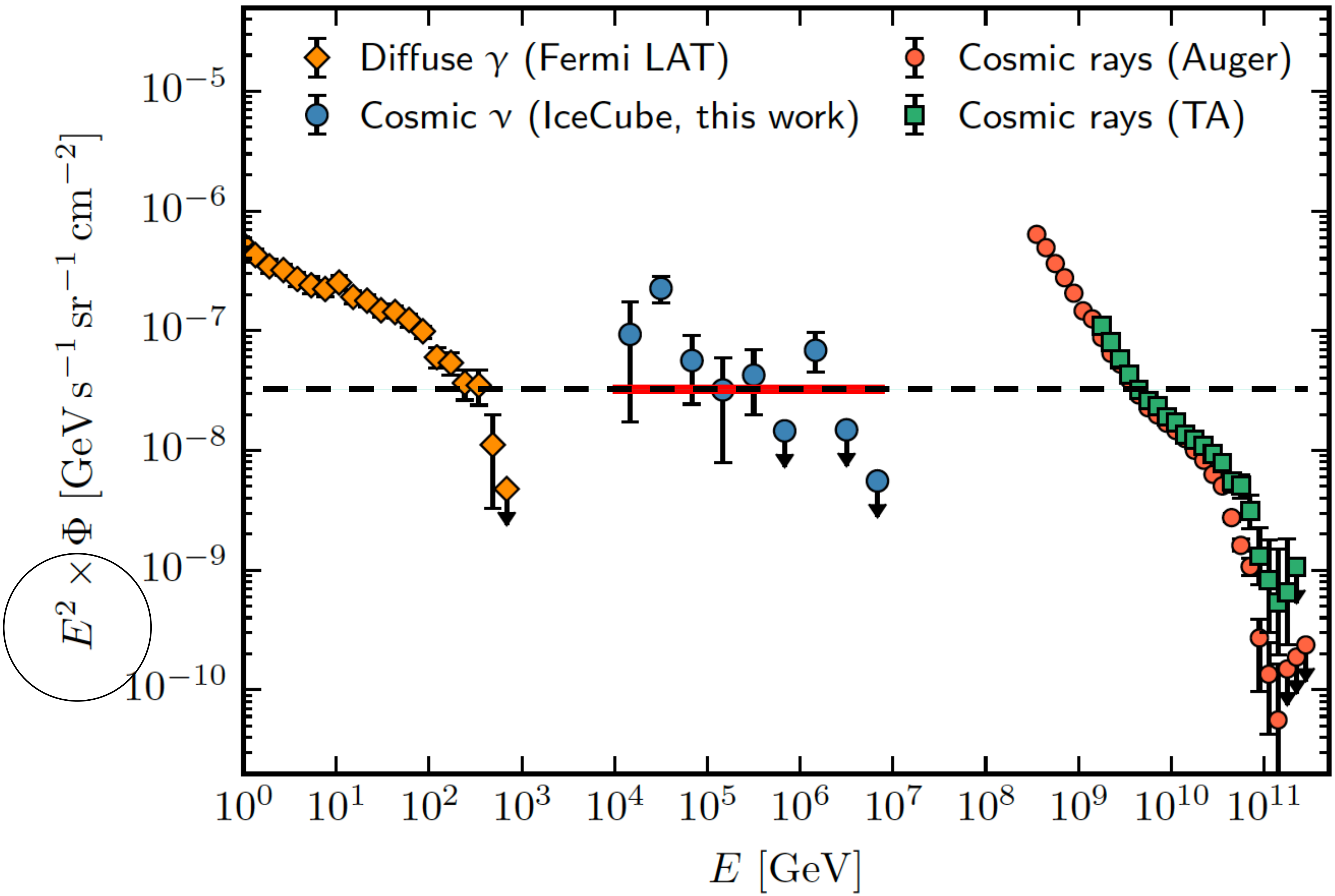

p
γ
e+
γ
ν
e-
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


γ
e+
e-
GeV
PeV
γ + γCMB → e+ + e-
X0



$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
$E^{-2.15}$
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

- 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

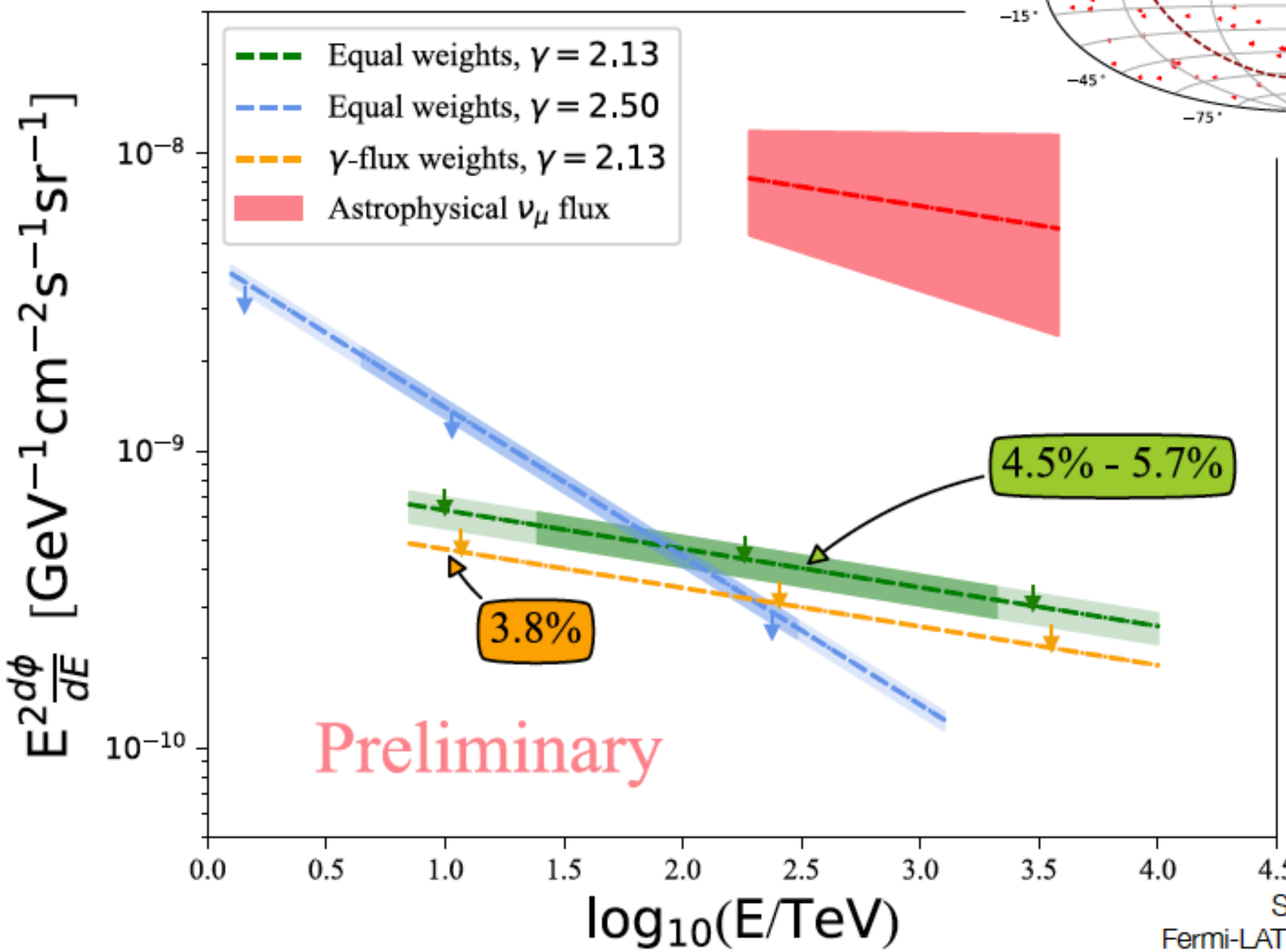
- common sources?

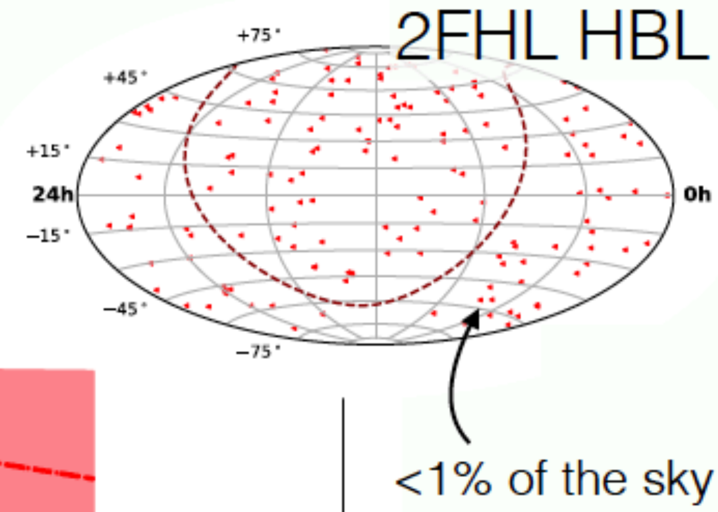
  Fermi: mostly blazars

  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





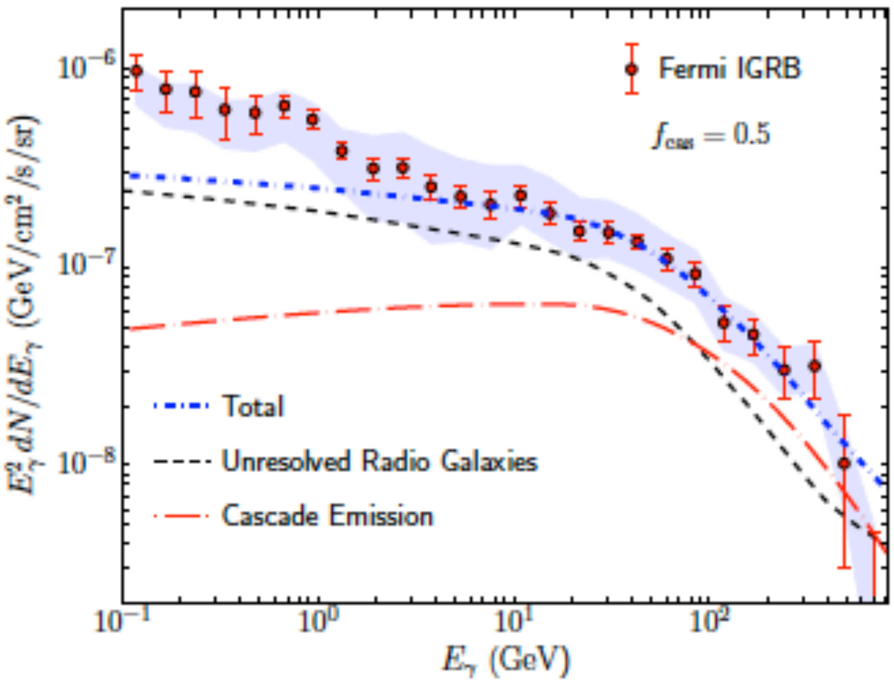
See: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

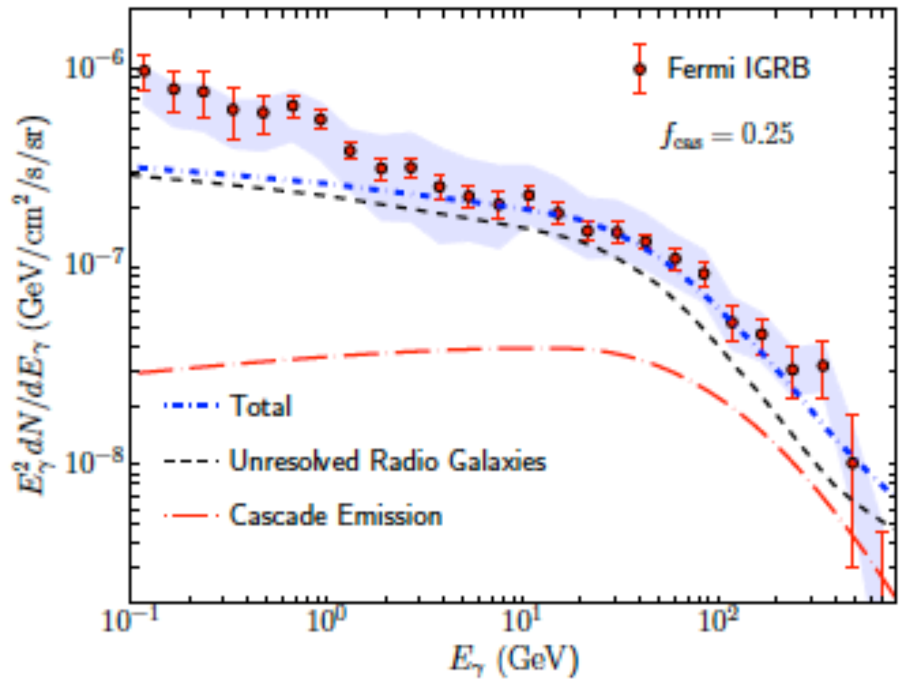
blazars? not the resolved Fermi blazars, but…

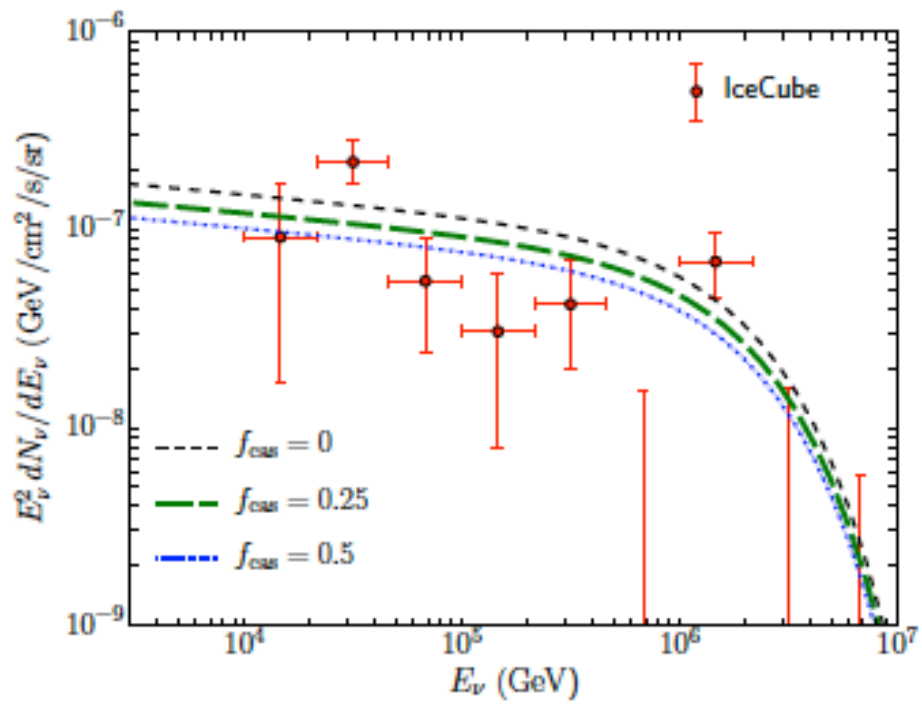
- neutrinos originate from a larger volume
- 50% of blazars *not* identified
- sources transparent to high energy gamma rays may not have the target density to produce neutrinos (GRB?)

What are the sources of cosmic neutrinos?

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



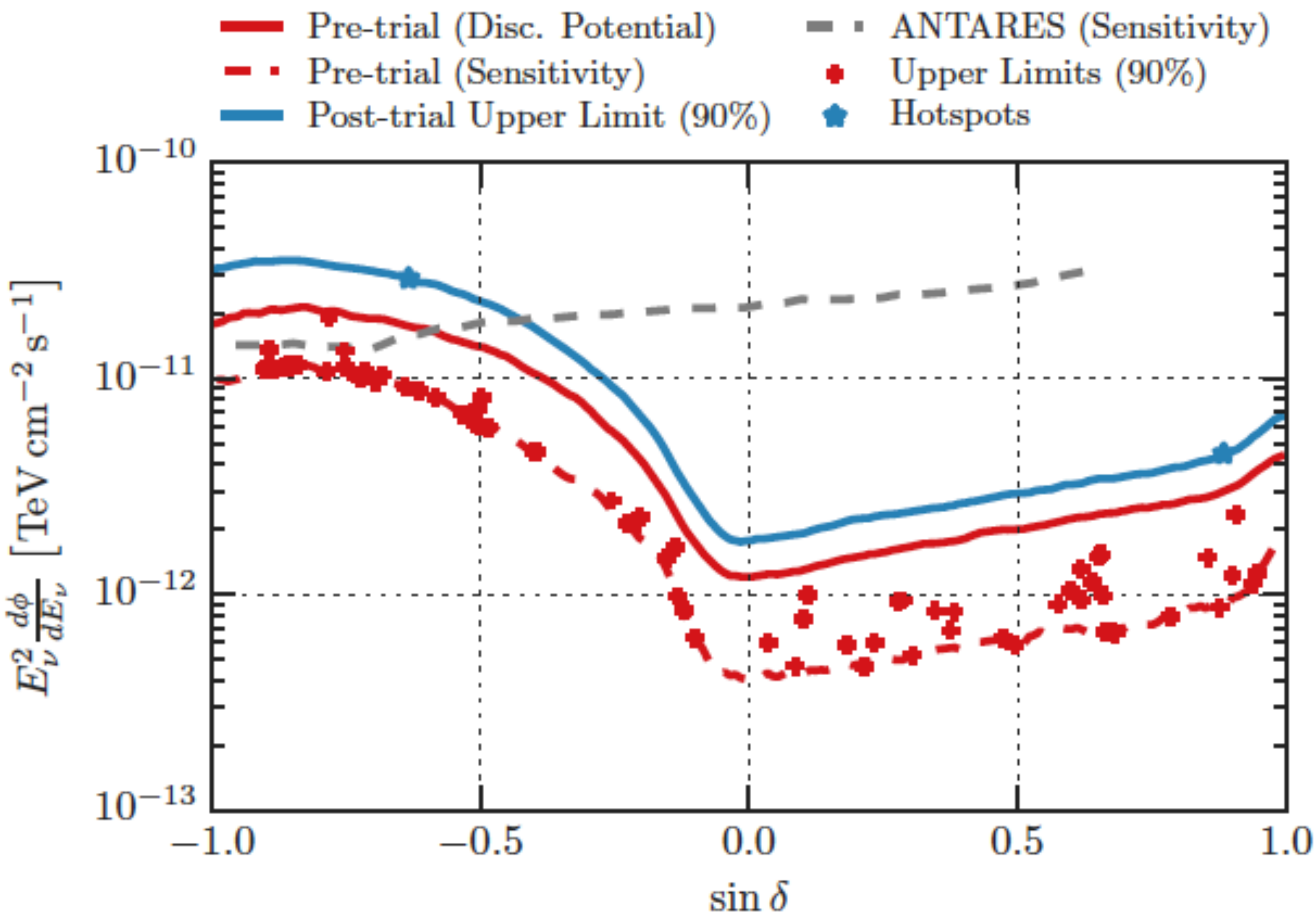




radiogalaxies

Tjus et al.

Hooper



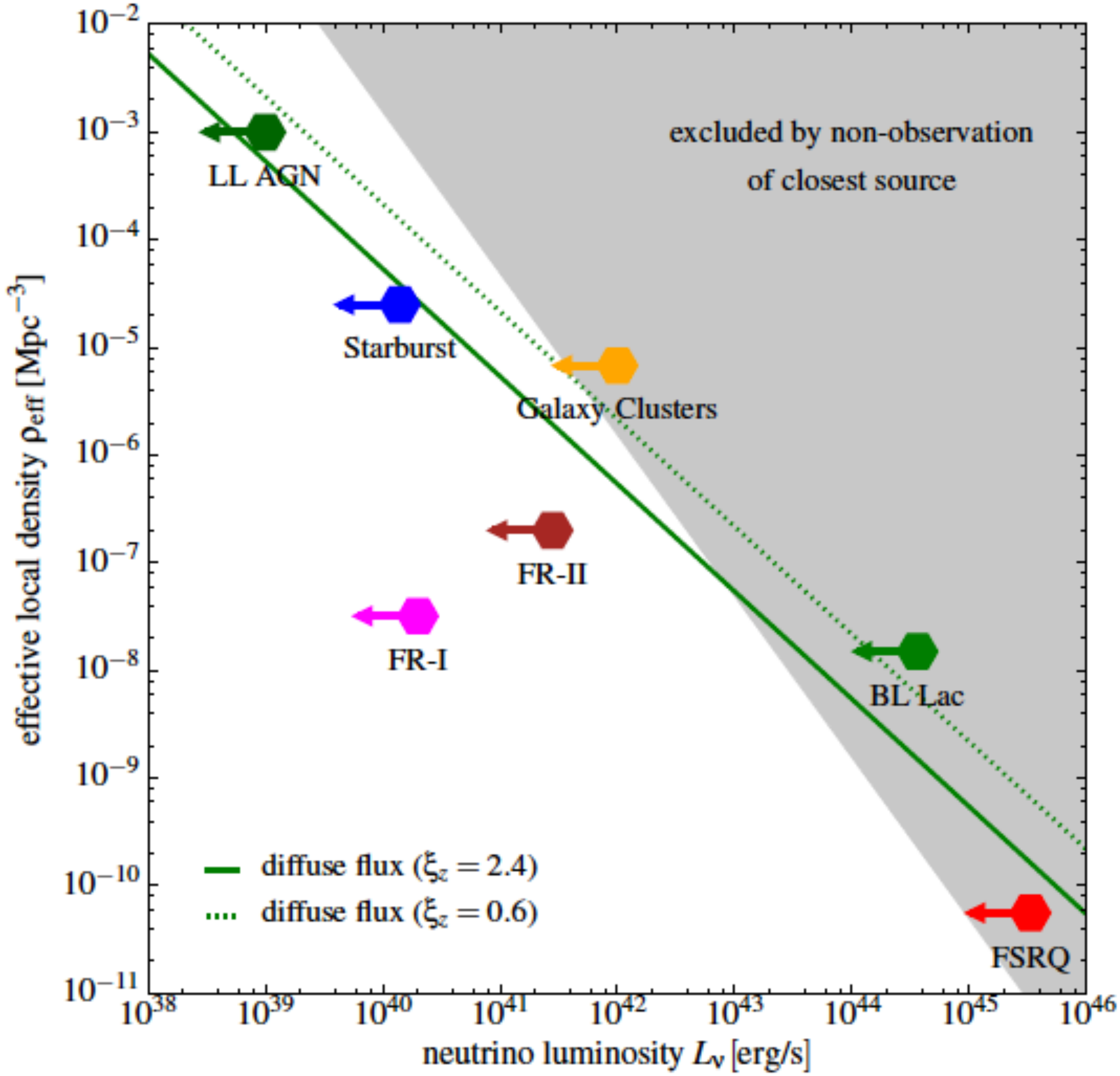
when resolved point sources?

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

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

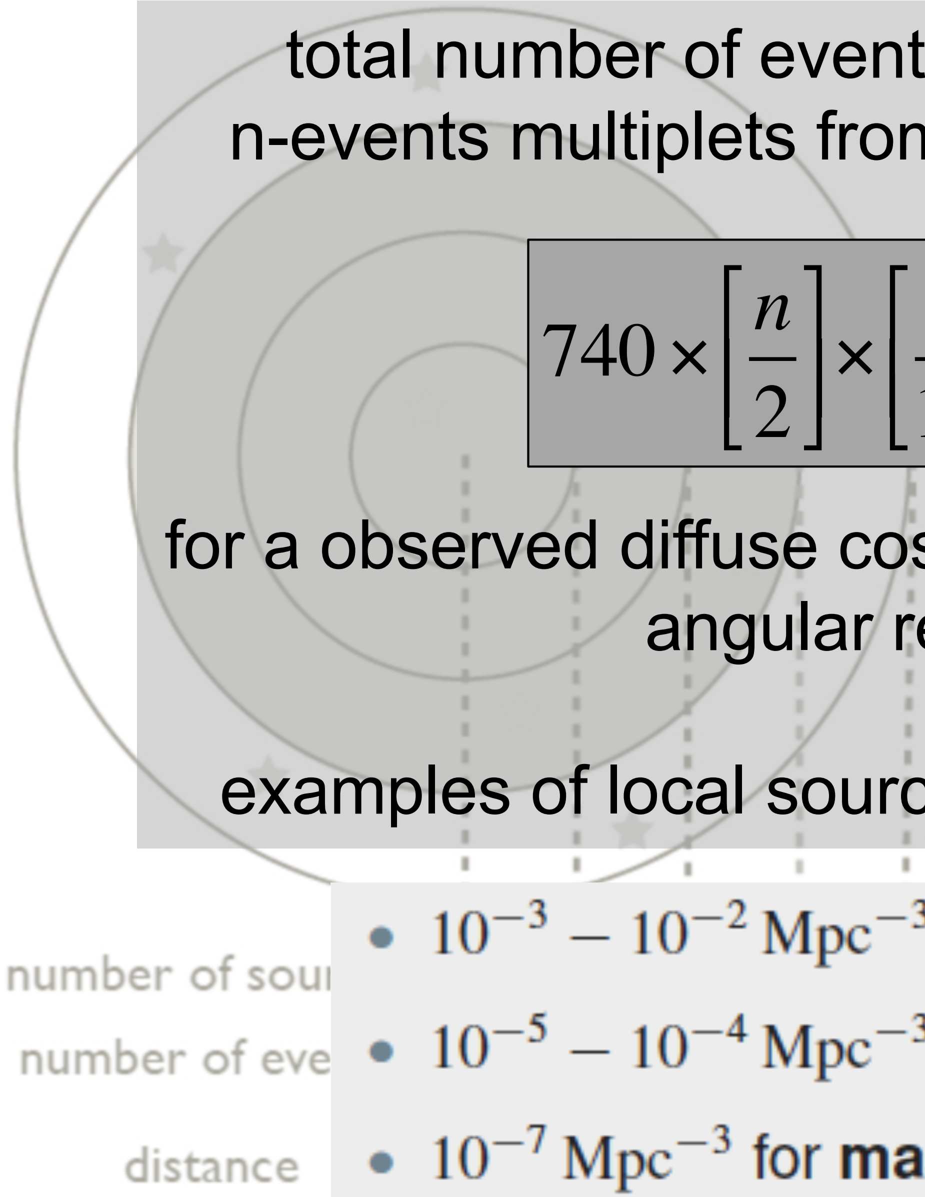
$$\phi_{\rm ns} = \frac{L_\nu}{4\pi d_{\rm ns}^2} \sim (L_\nu \cdot \rho) d_{\rm ns} \sim \phi_{\rm diff} \cdot \rho^{-1/3}$$

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):

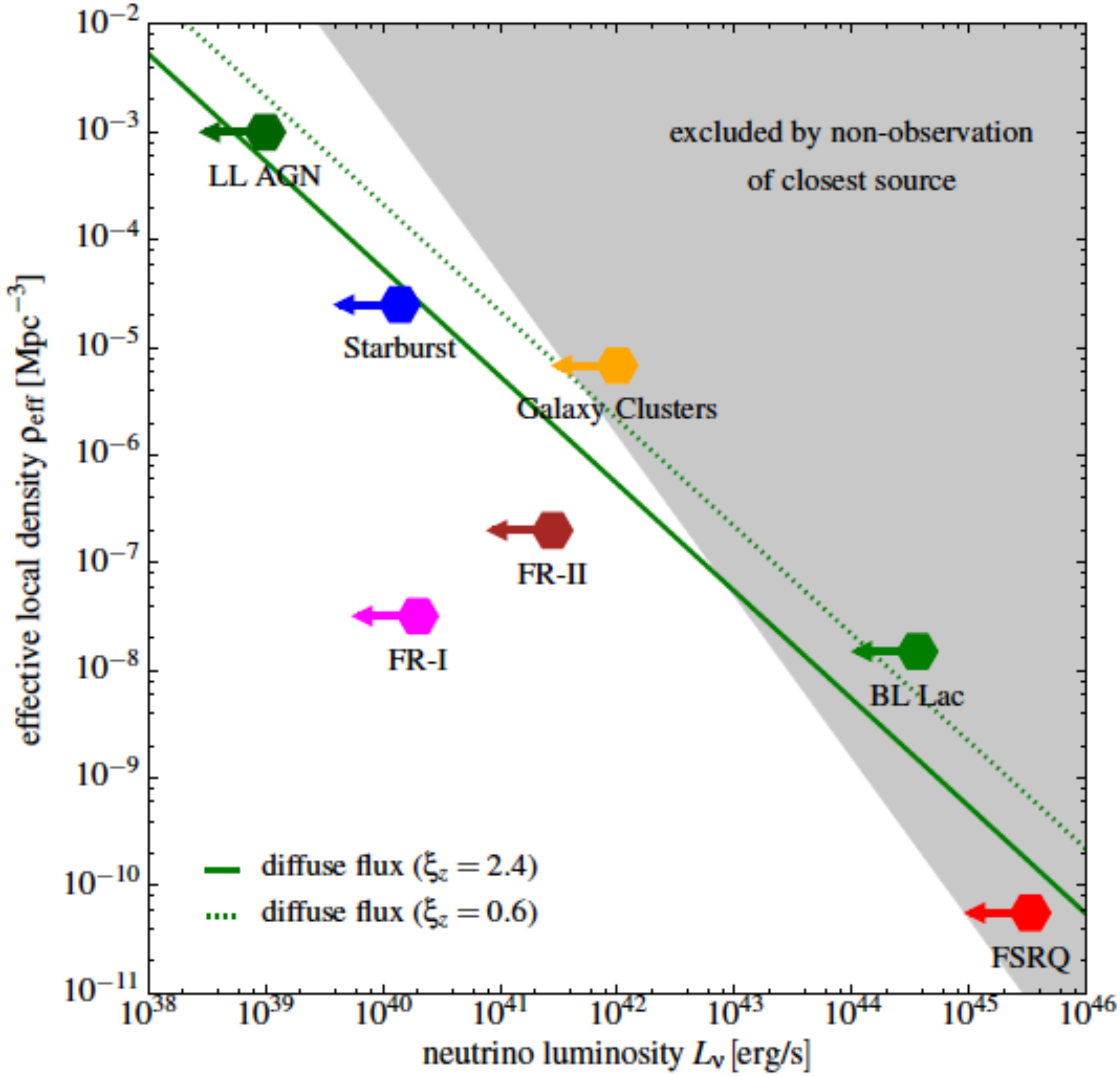
- $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\mathrm{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\mathrm{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**

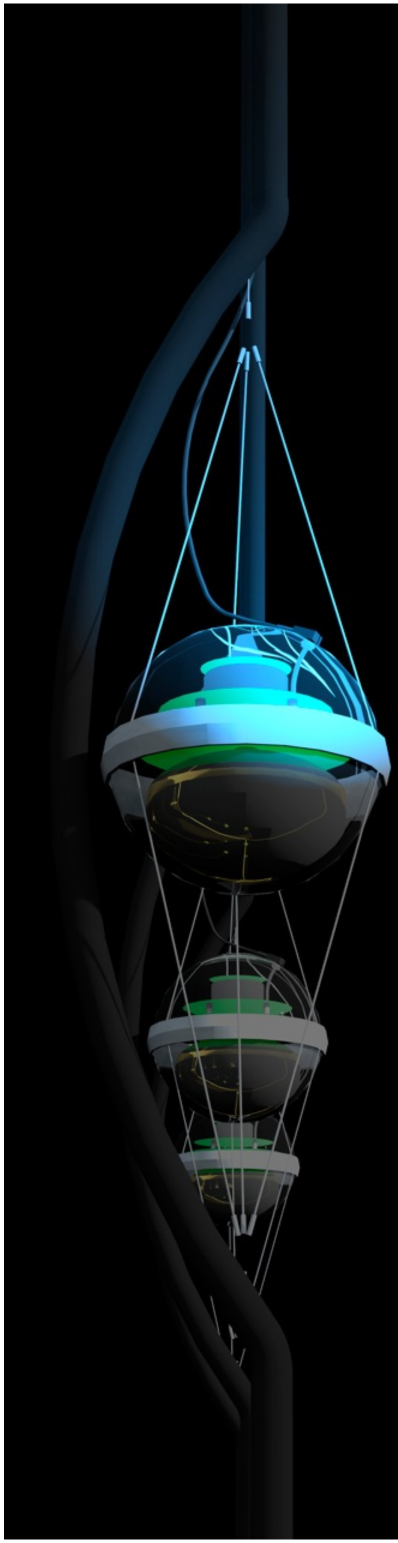
flux nearest source = (diffuse flux observed)(density of sources)$^{-1/3}$

Olbers paradox

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

blazars, FSRQ…





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francis halzen

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- cosmic neutrinos: two independent observations
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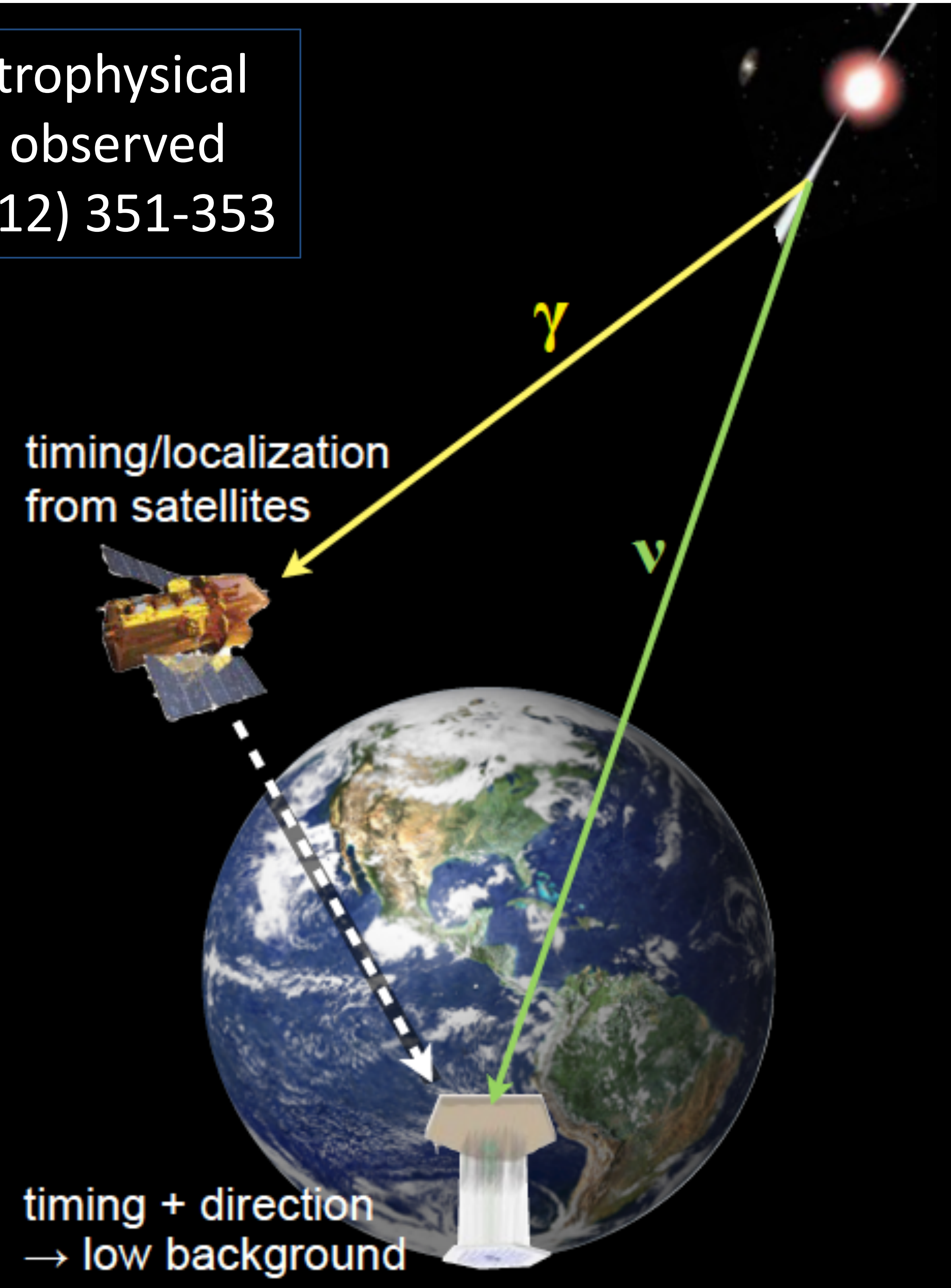
flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353



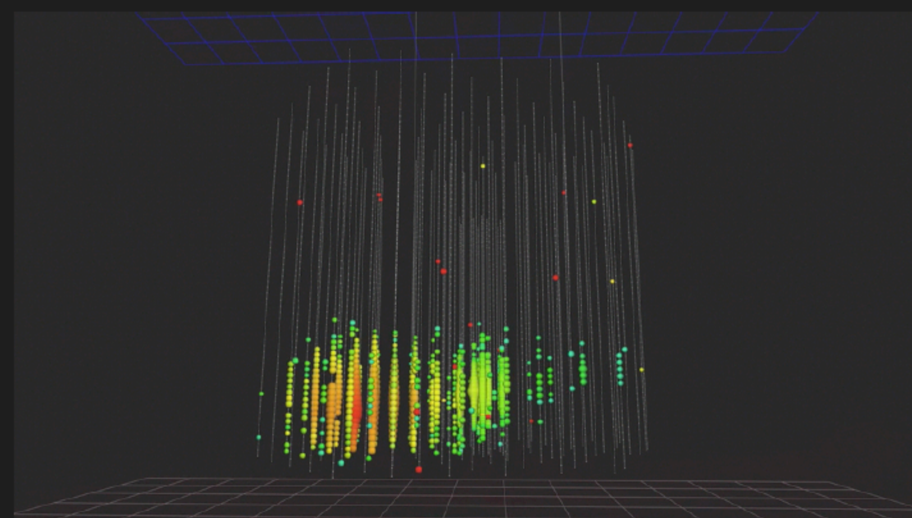
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

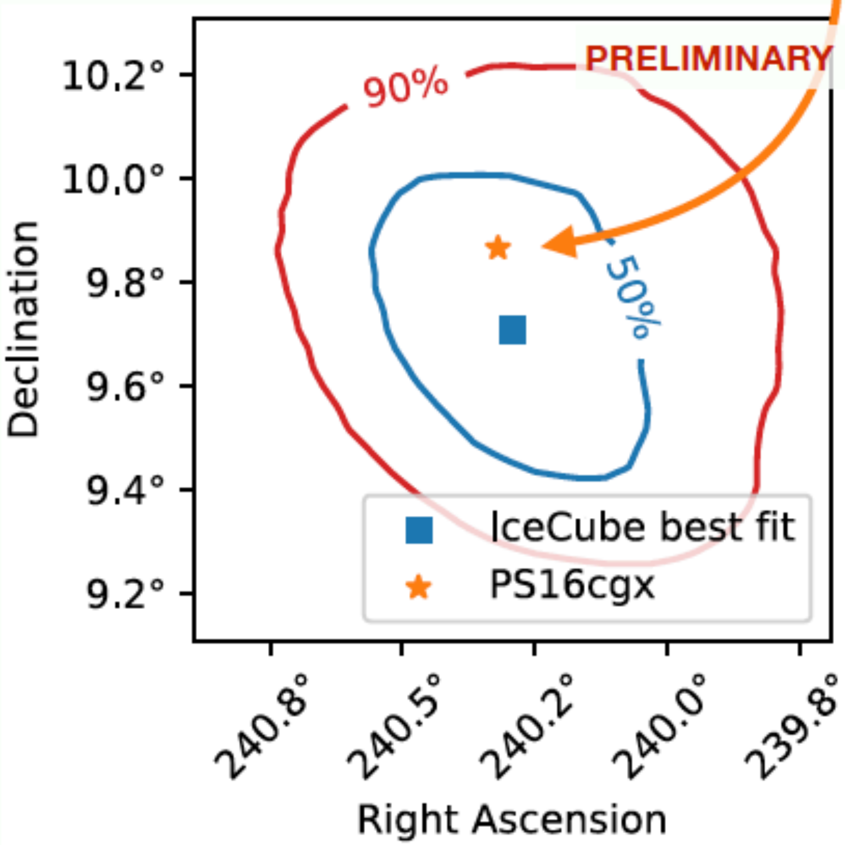
We send **rough reconstructions first** and then **update them.**

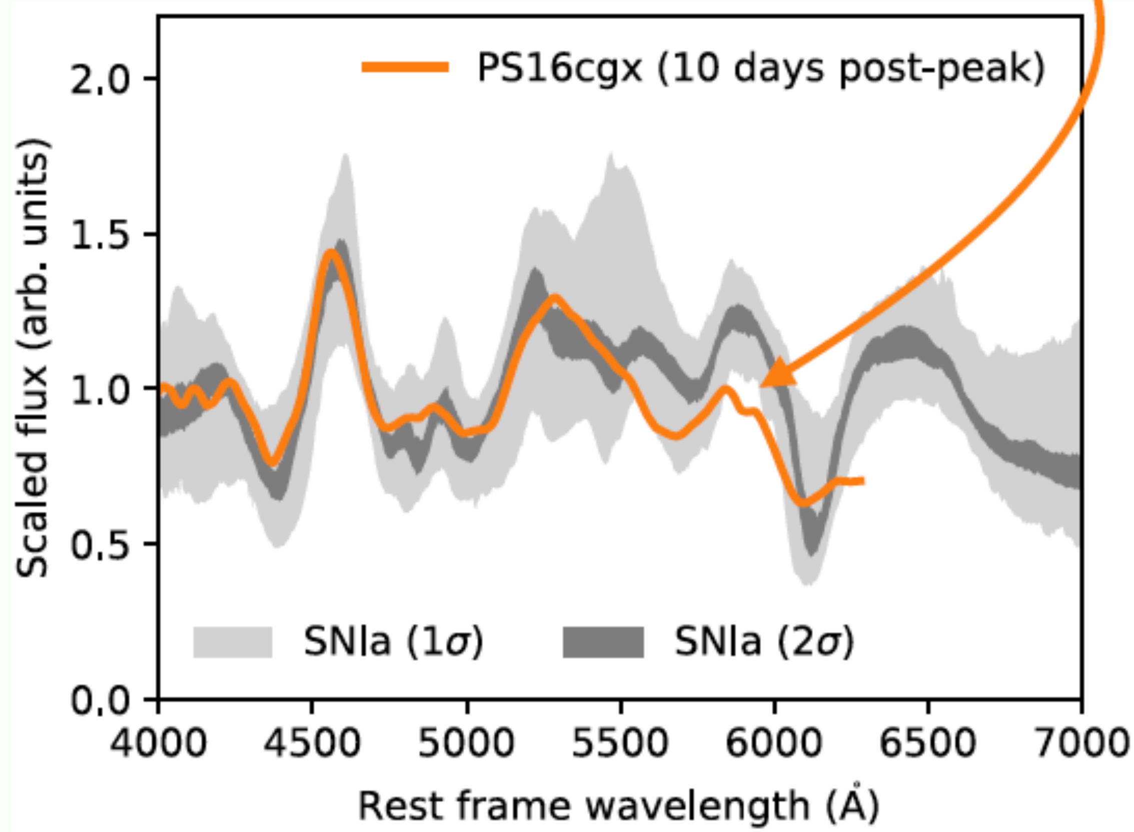


PS16cgx: a young supernova in the field of a HESE neutrino

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

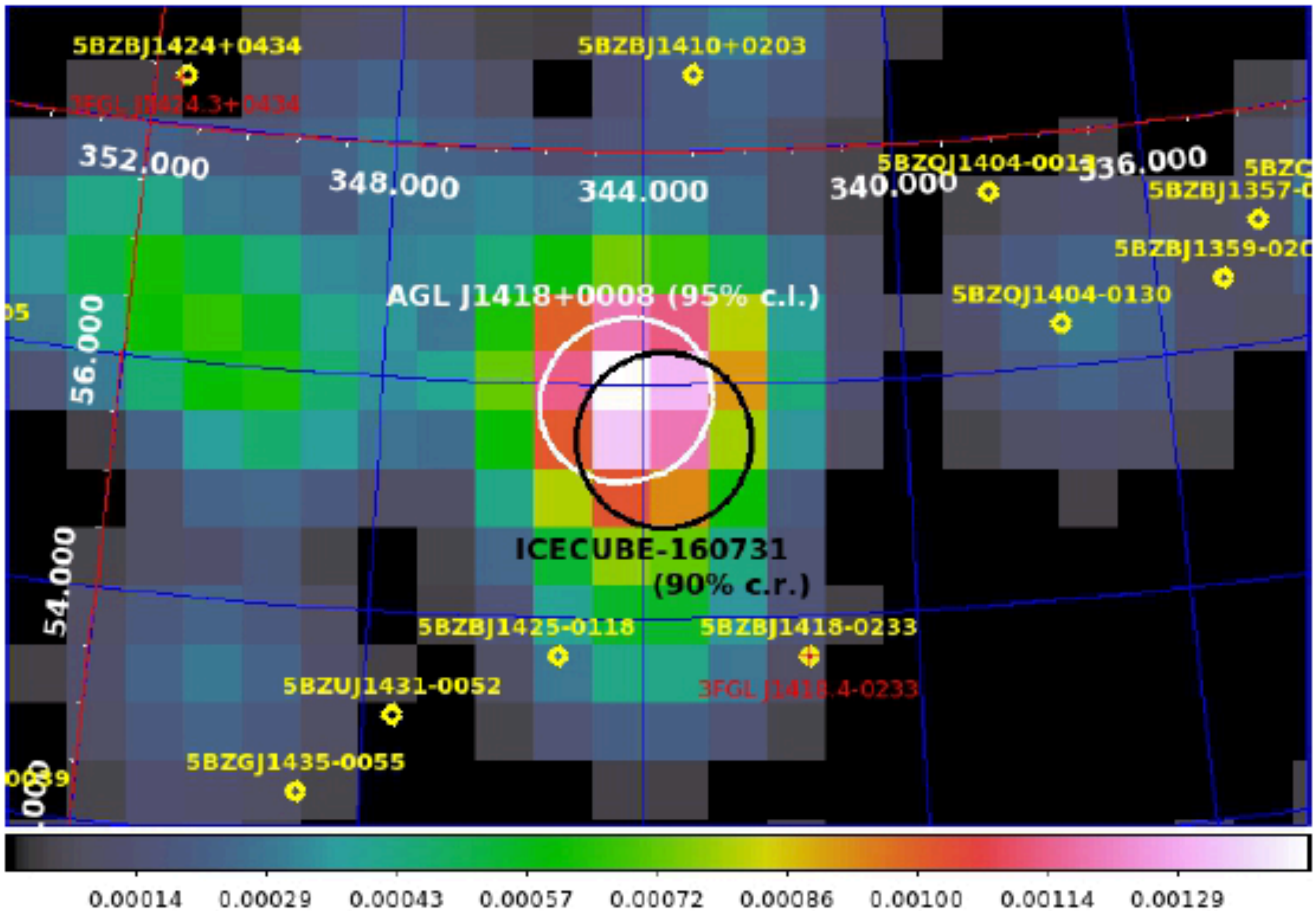




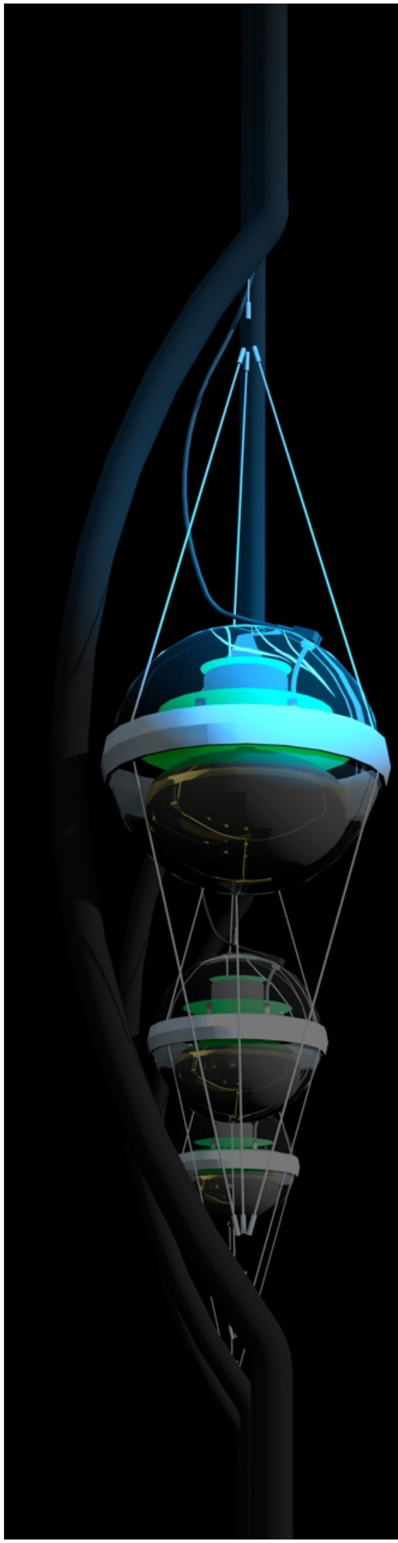
Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

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



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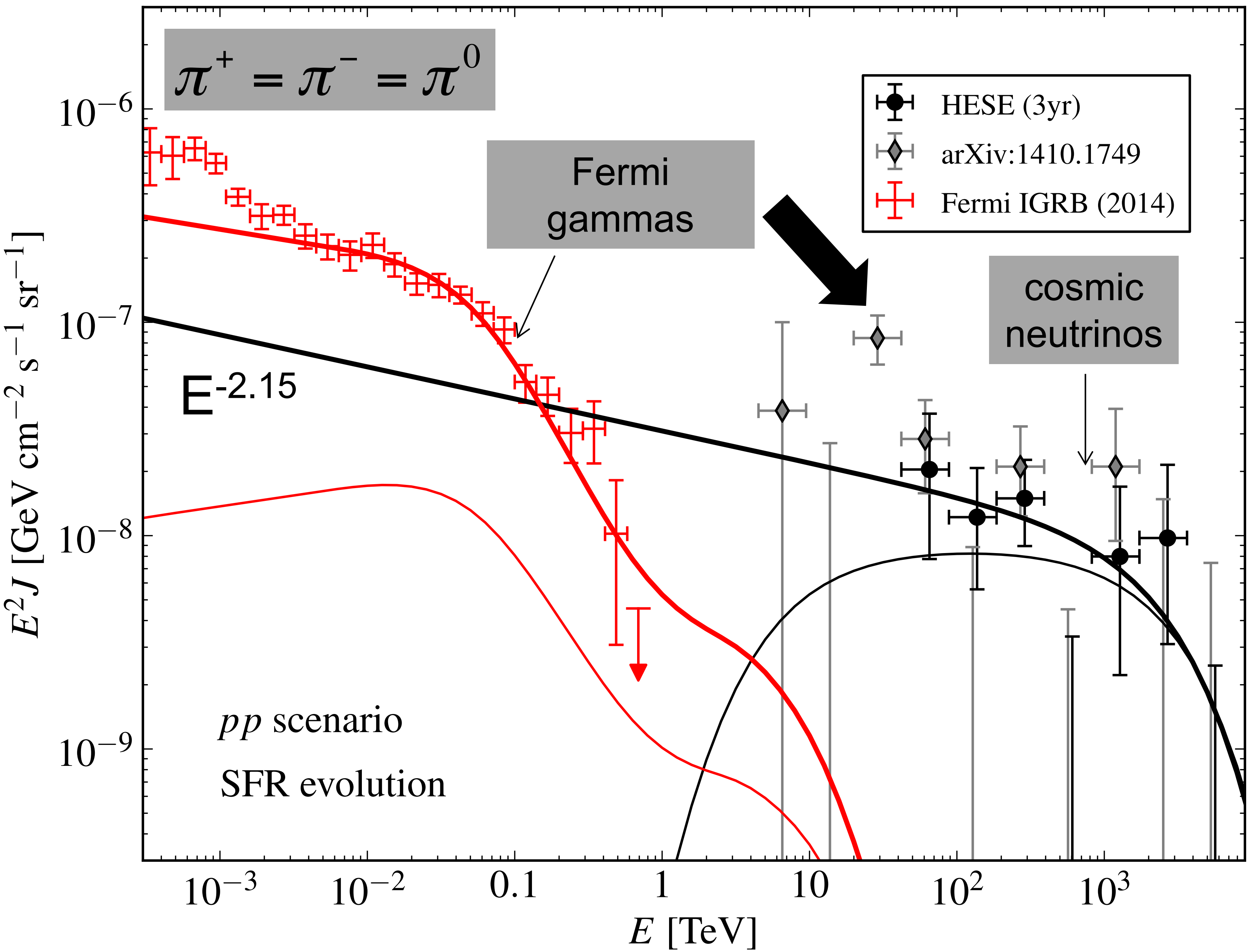
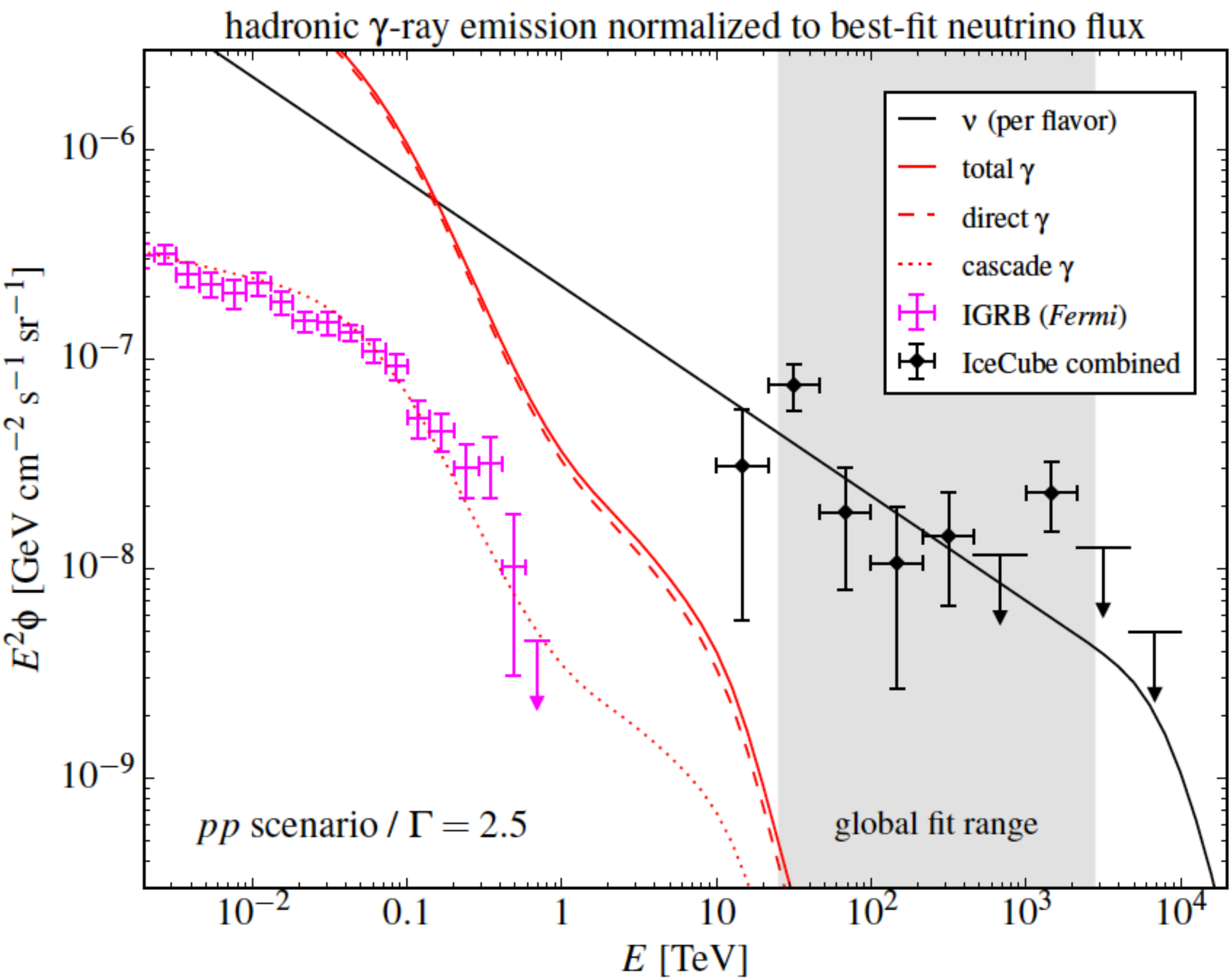
- cosmic neutrinos below 100 TeV ?

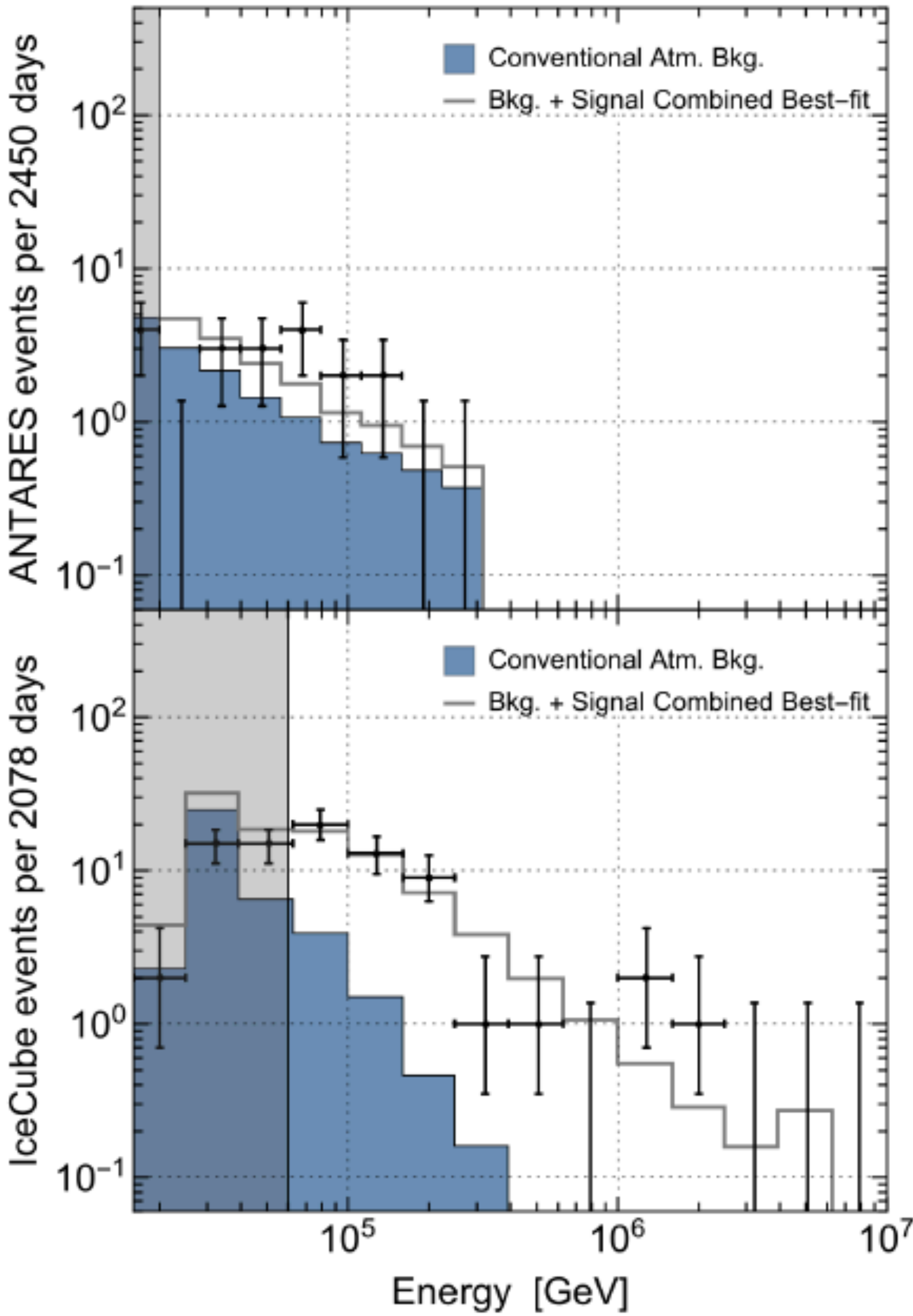


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

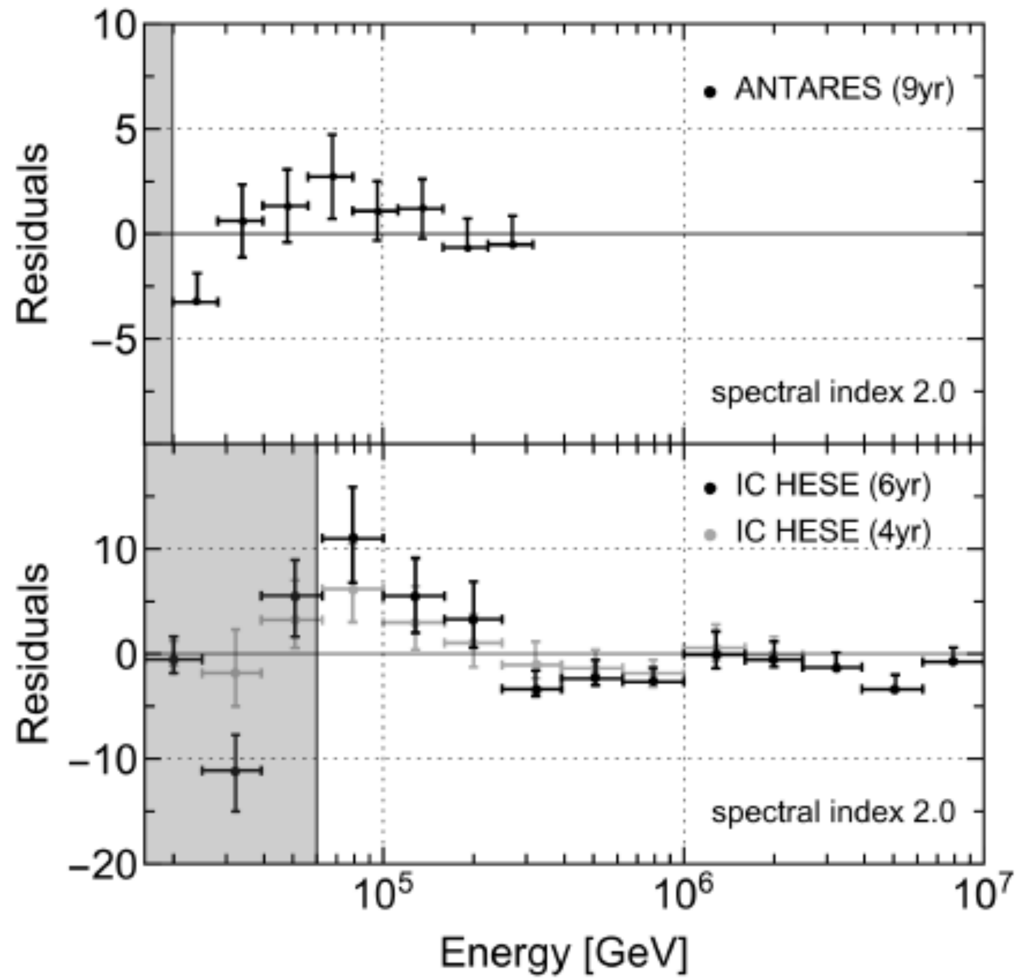


a “problem” ?

gamma rays cascade in the source to < GeV energy

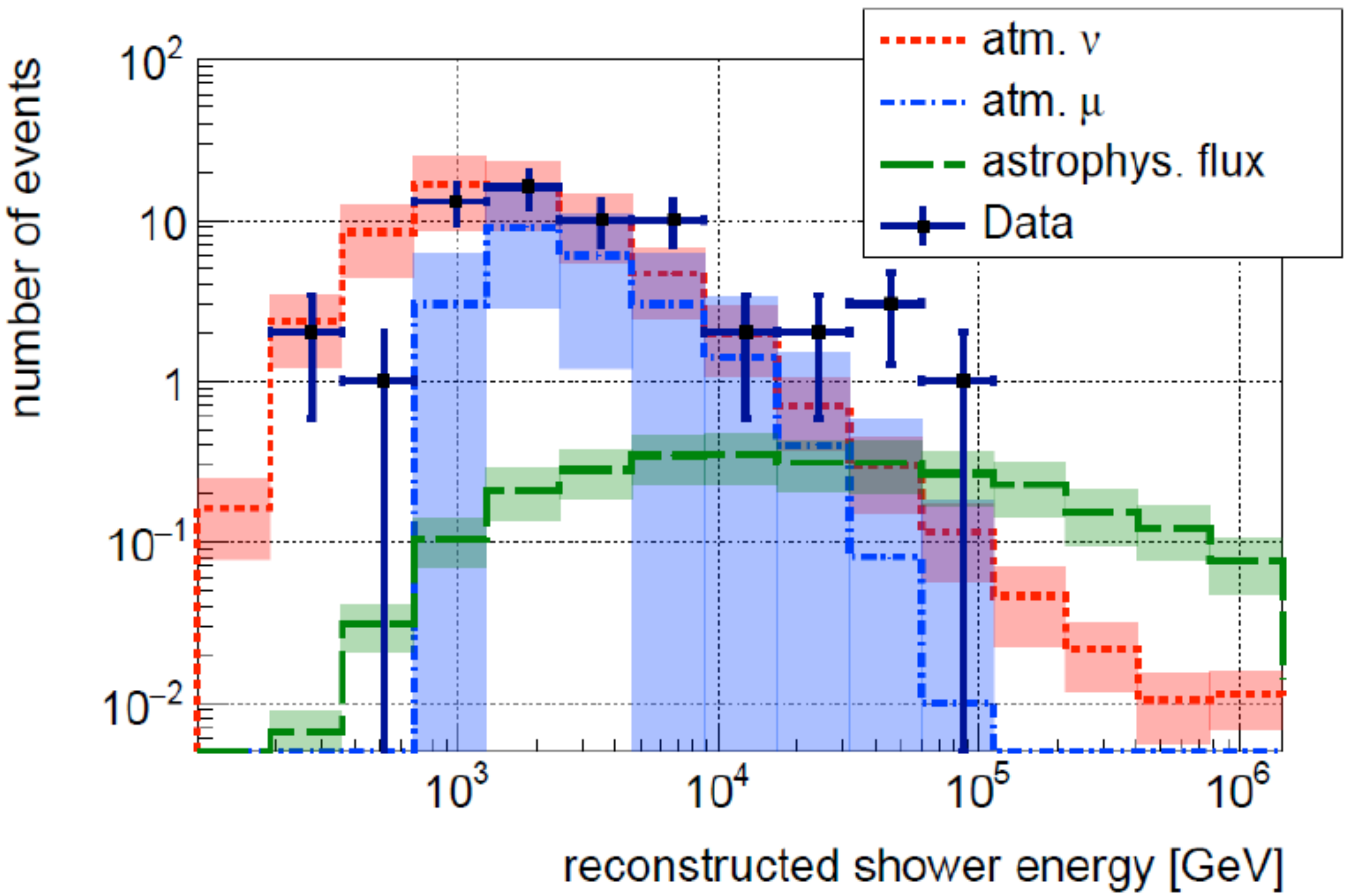


Residuals for E^{-2} spectrum



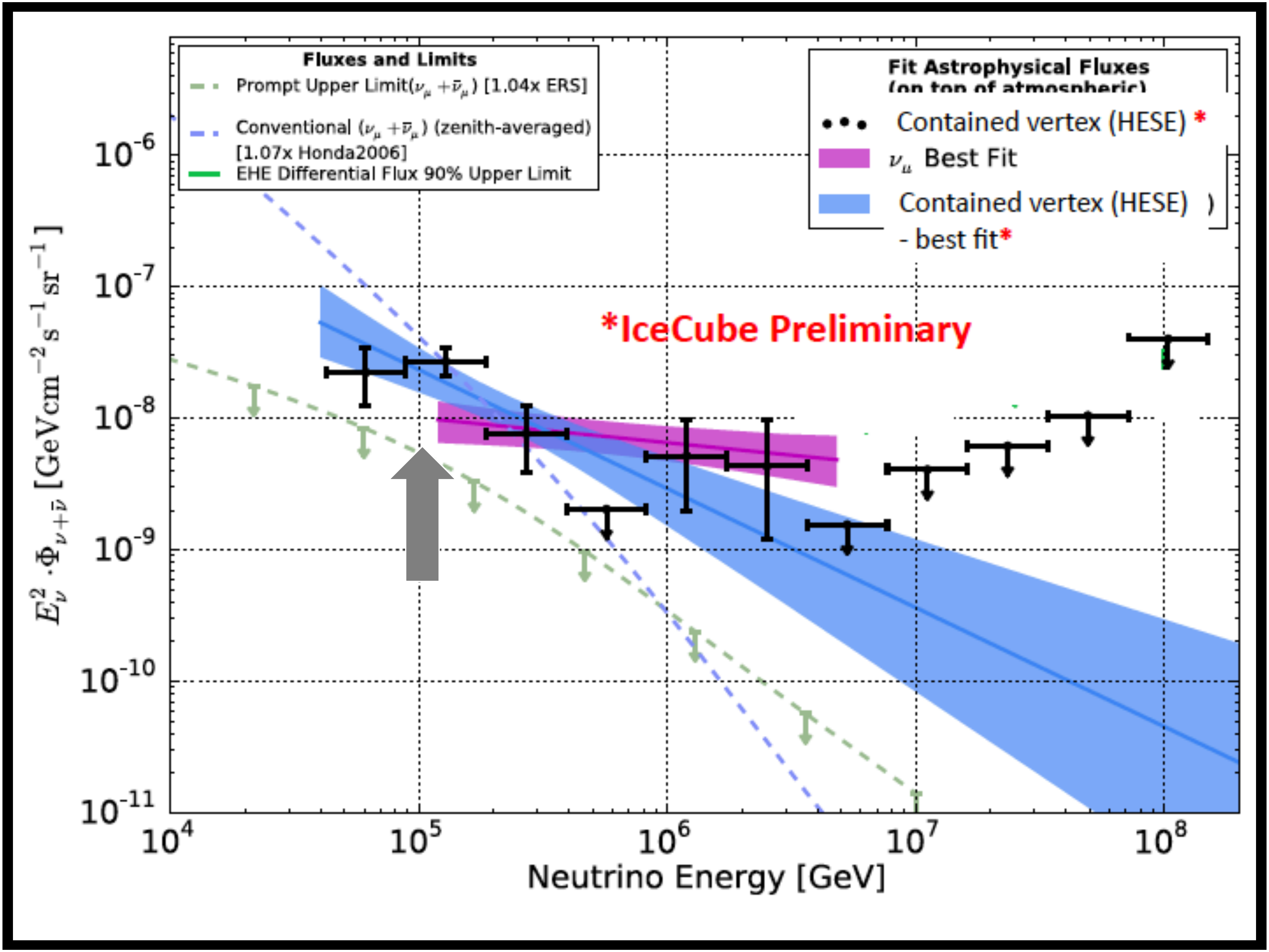
Marco Chianese et al.

ANTARES



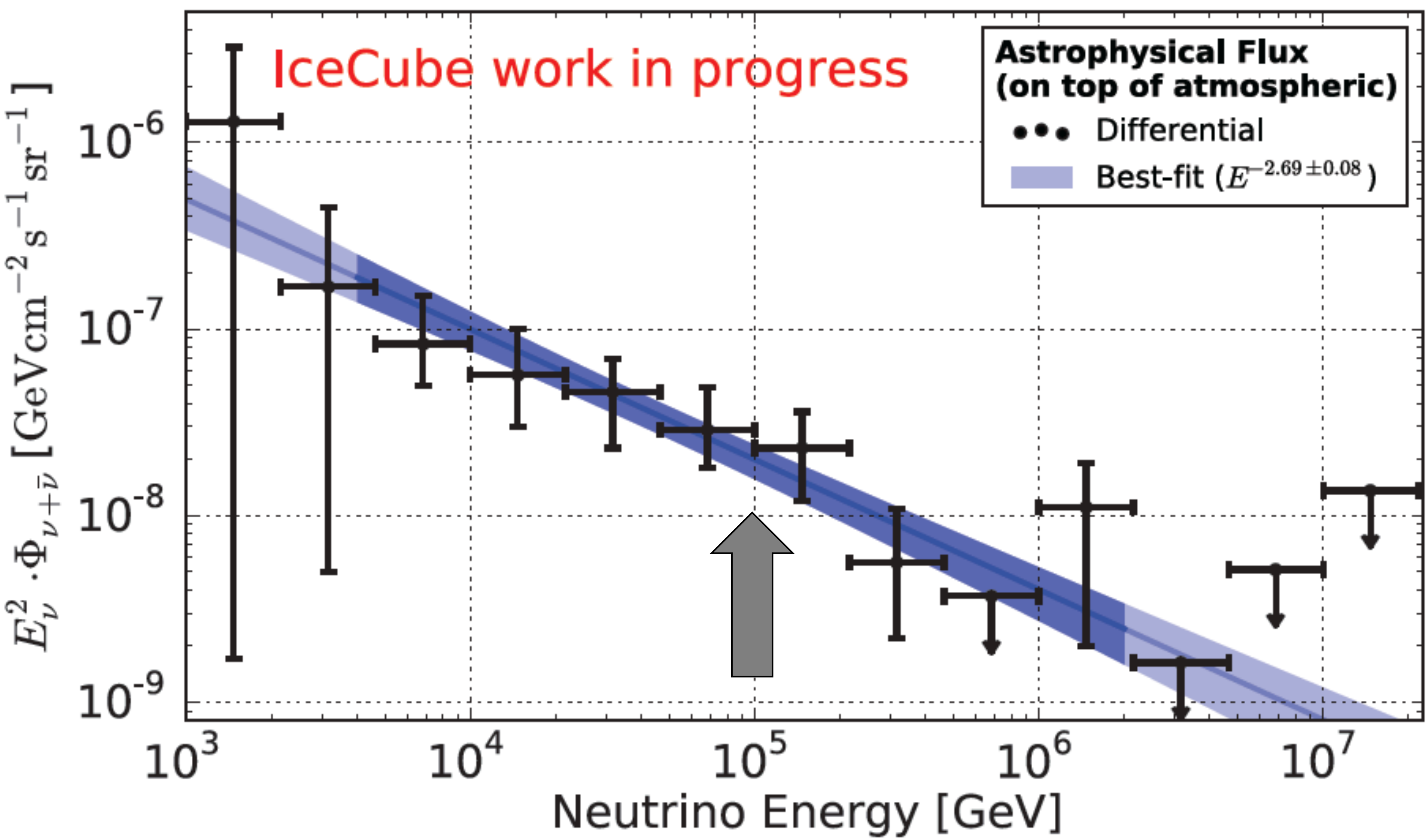
number of events
reconstructed shower energy [GeV]
atm. ν
atm. μ
astrophys. flux
Data

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

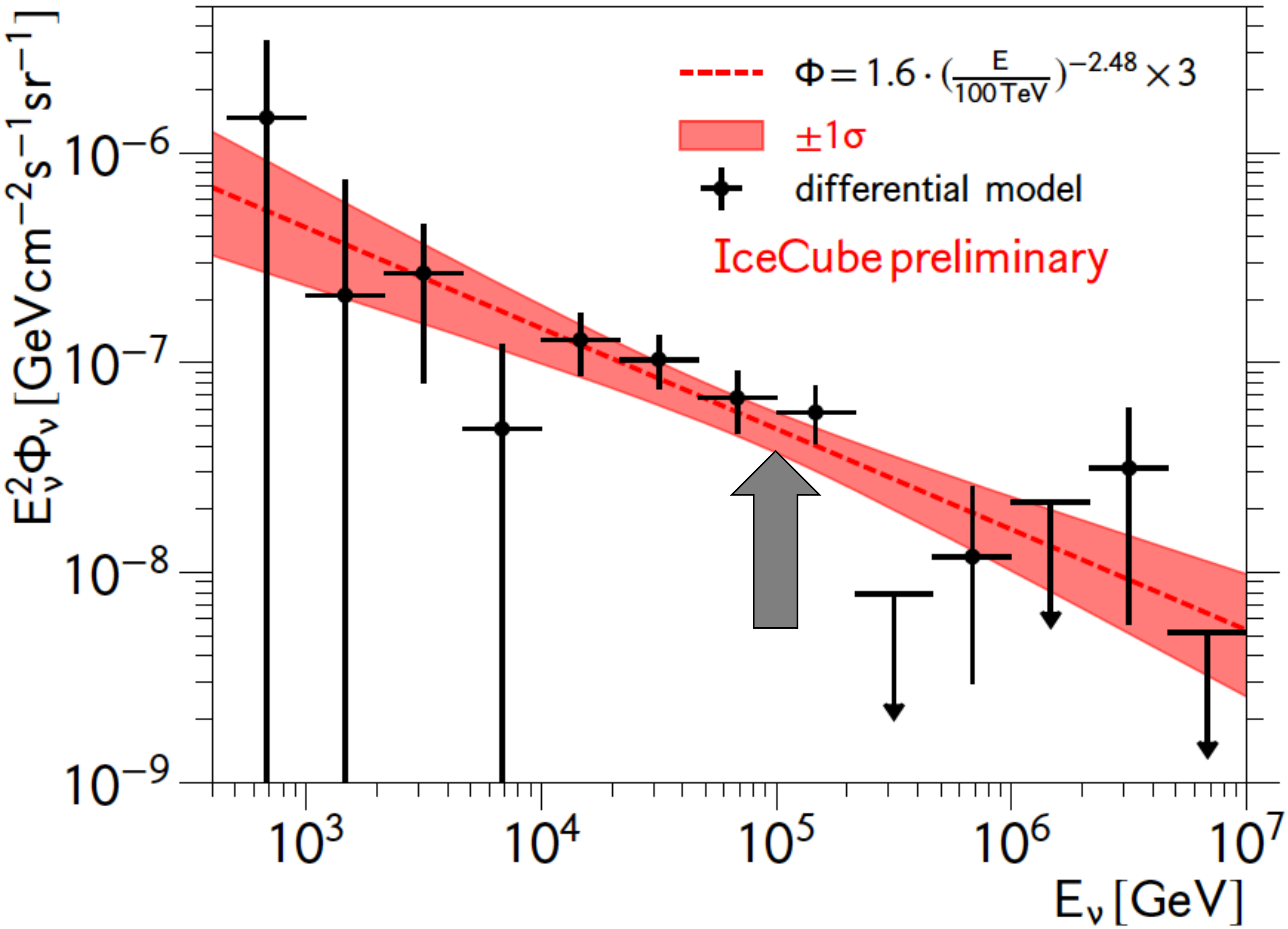


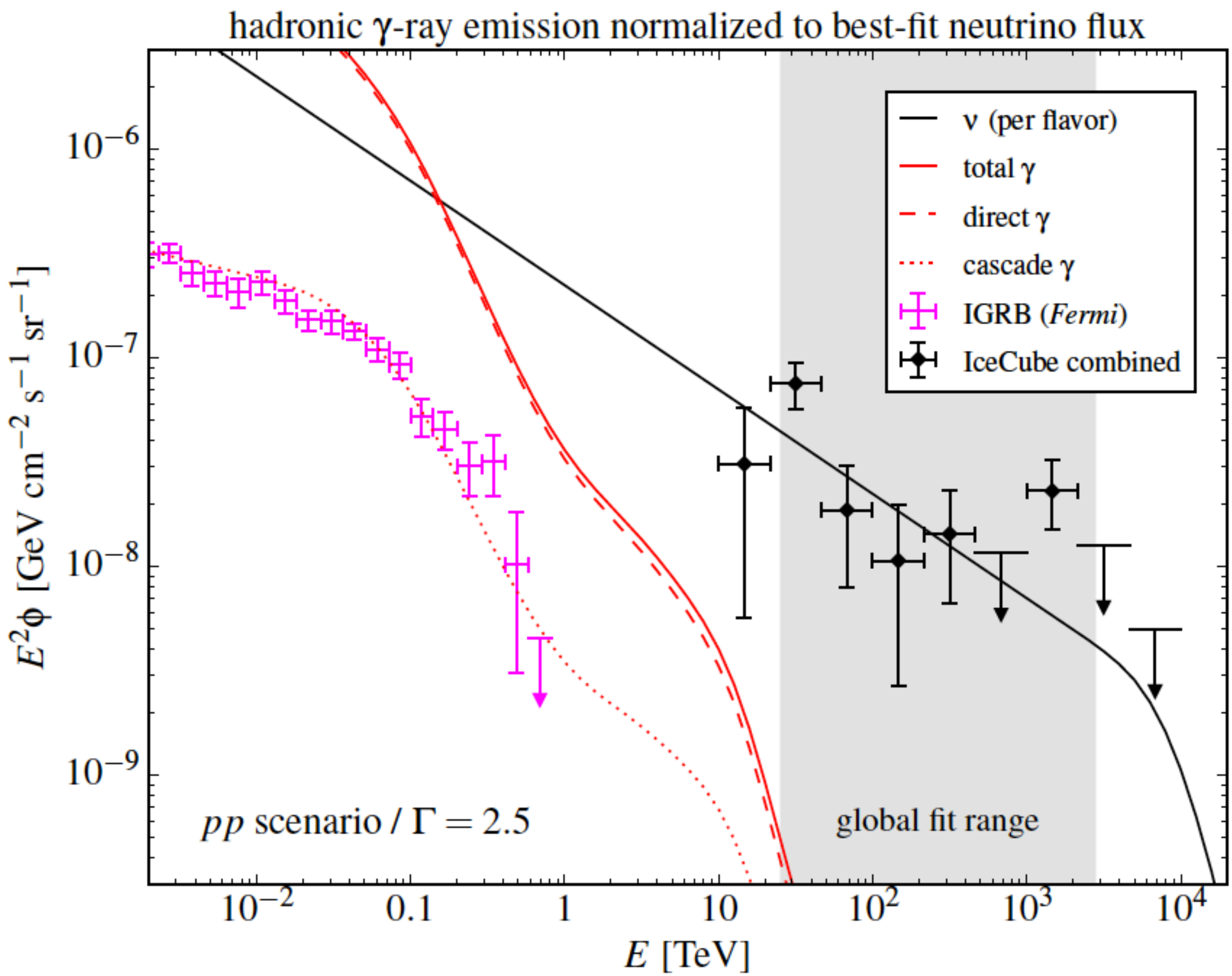
Fluxes and Limits
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
EHE Differential Flux 90% Upper Limit
Fit Astrophysical Fluxes (on top of atmospheric)
Contained vertex (HESE) *
ν_μ Best Fit
Contained vertex (HESE)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

low threshold starting event analysis; 7 years



shower events only: cosmic flux dominates > 20 TeV





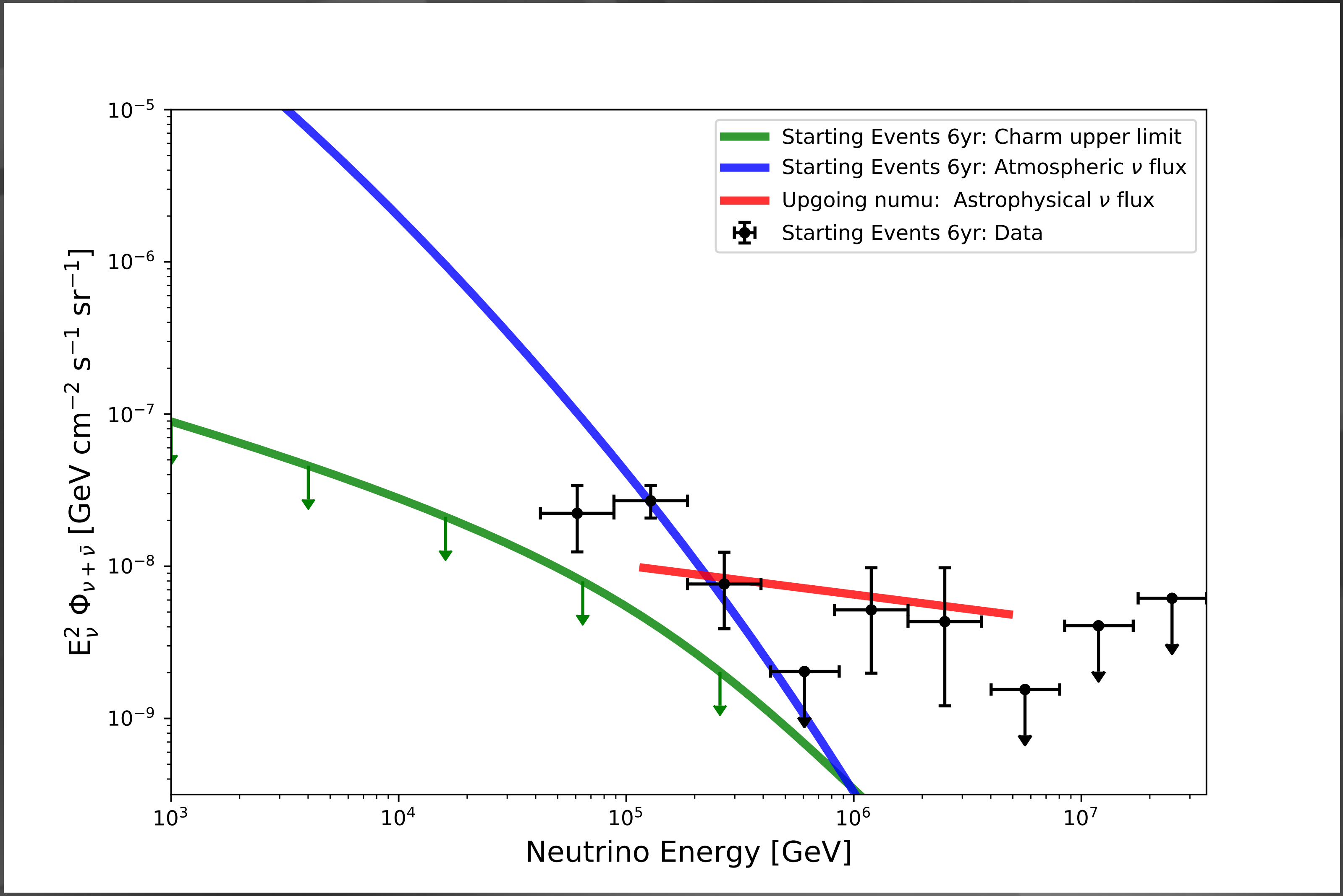
a "problem" ?

gamma rays cascade in the source to < GeV energy

- 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
- constrained by atmospheric *electron* neutrino spectrum



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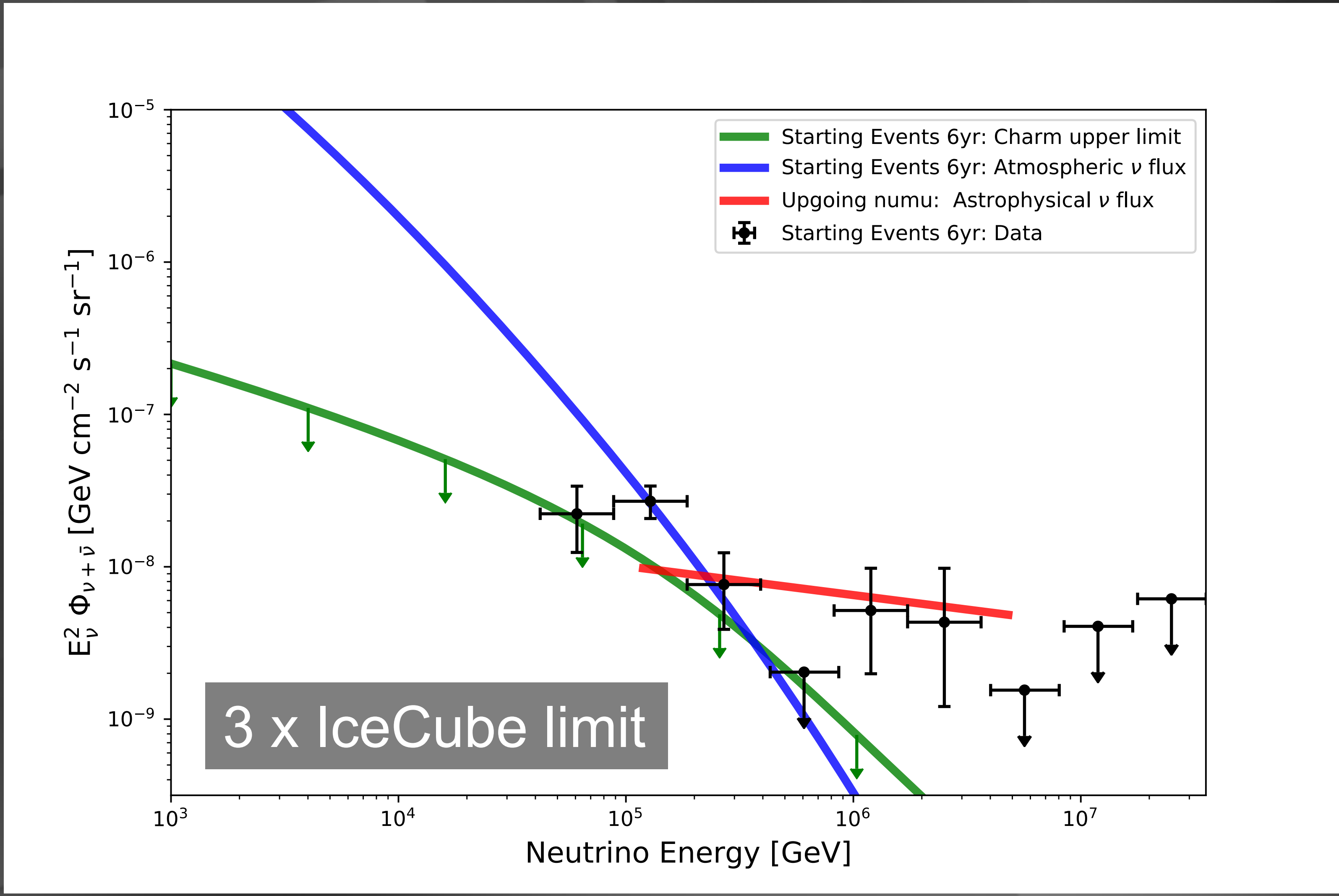
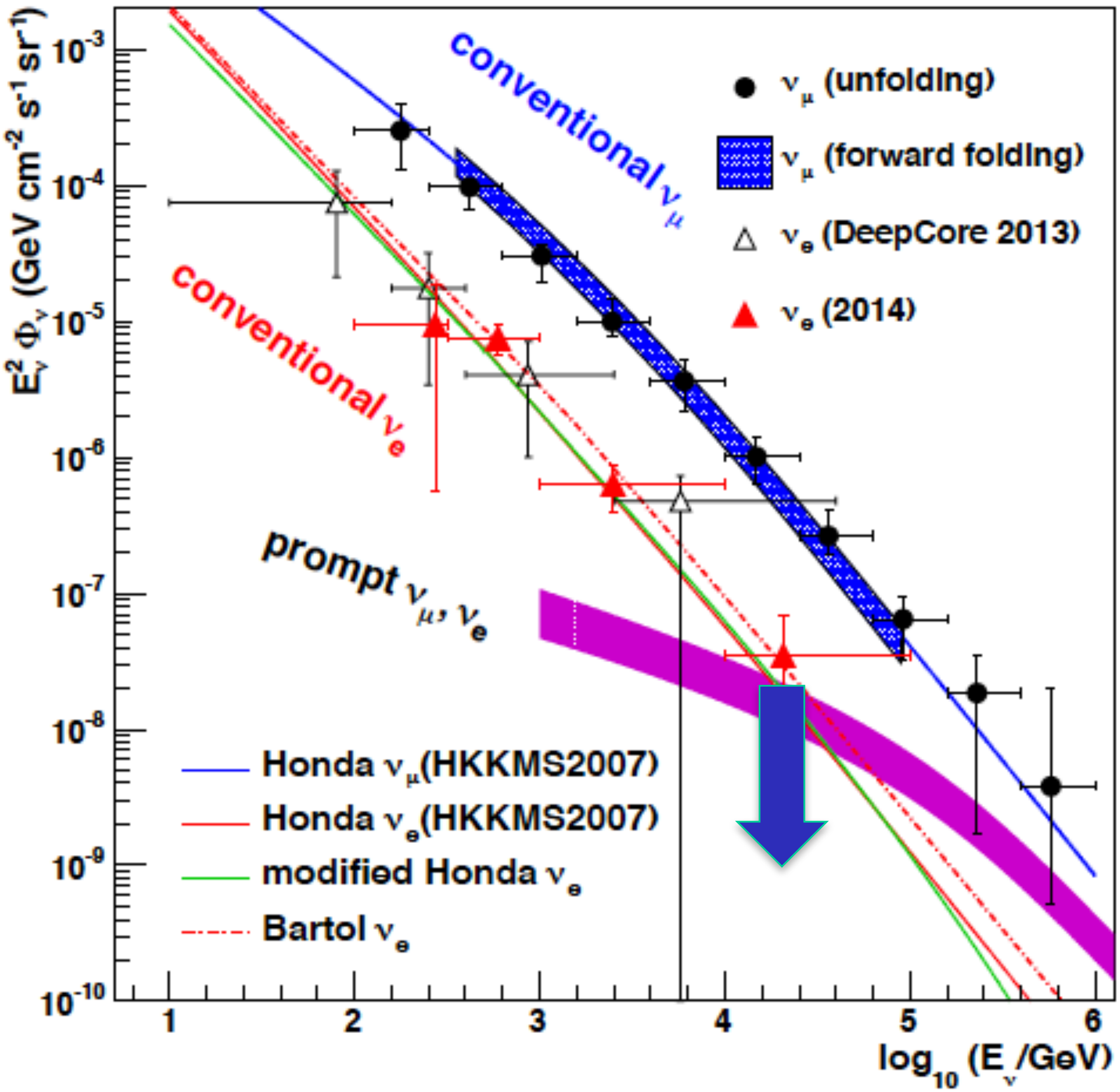
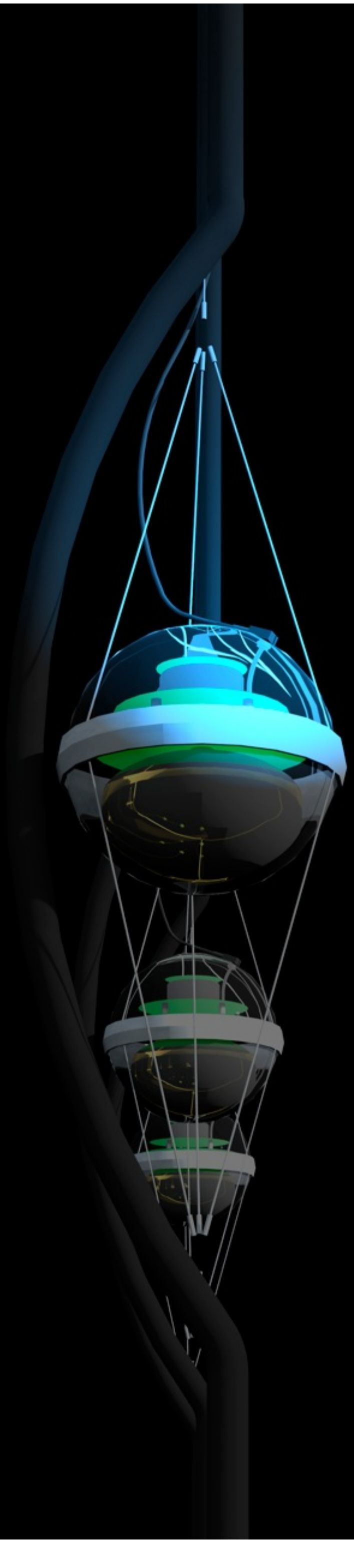


charm limited by atmospheric electrons





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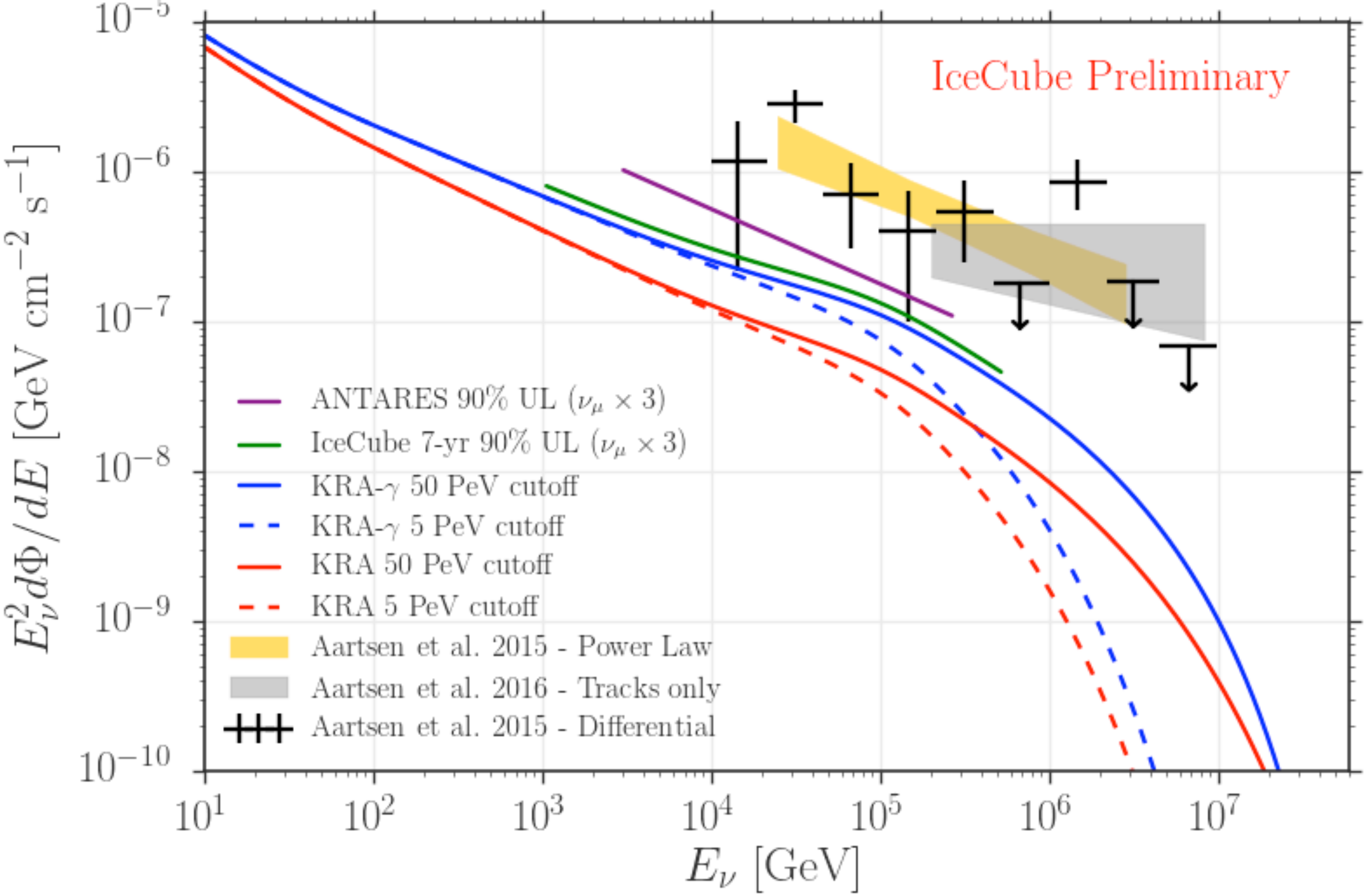
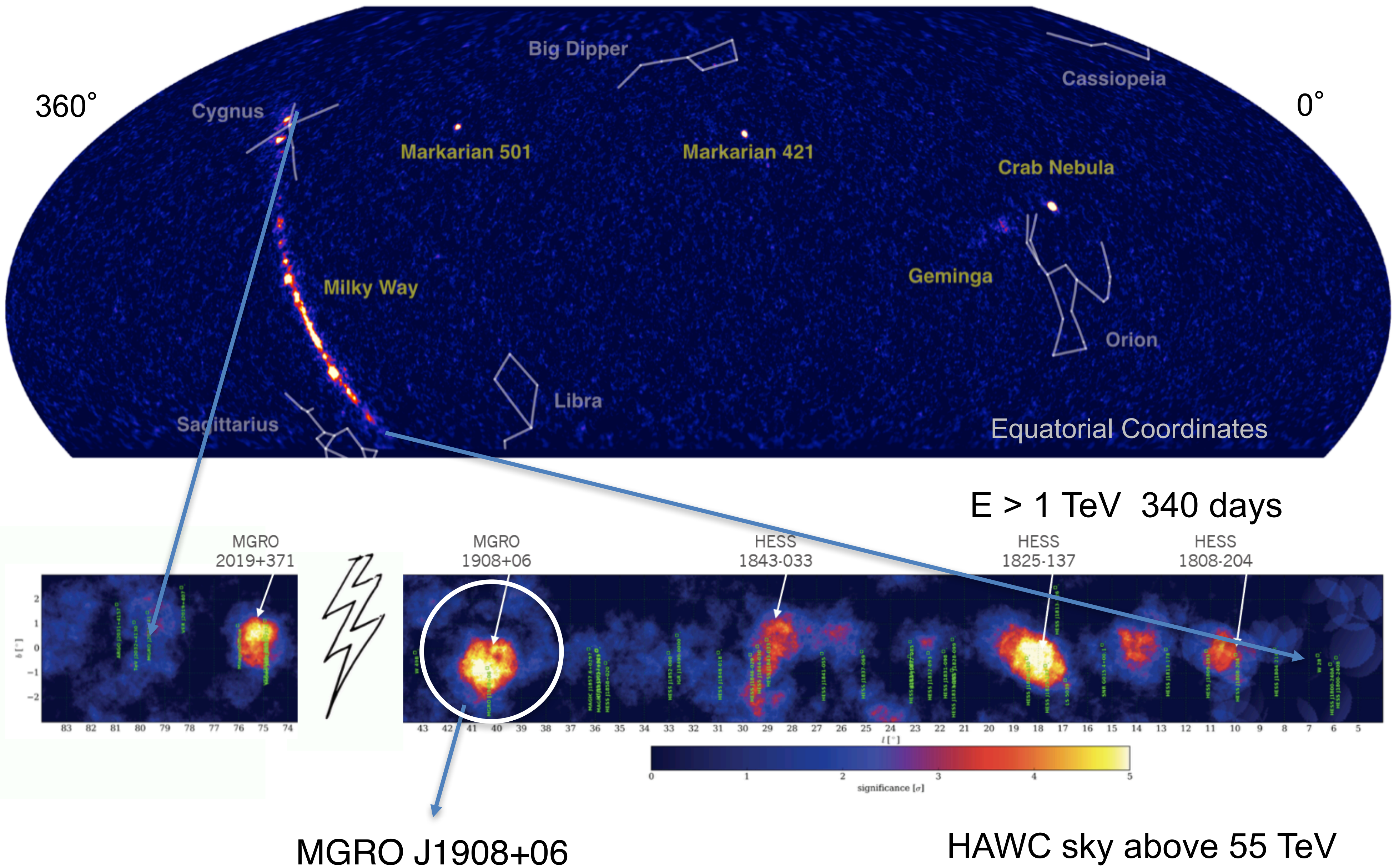


at most ~10% of the events are Galactic in origin

HAWC View of Gamma Ray Sky



neutral pions

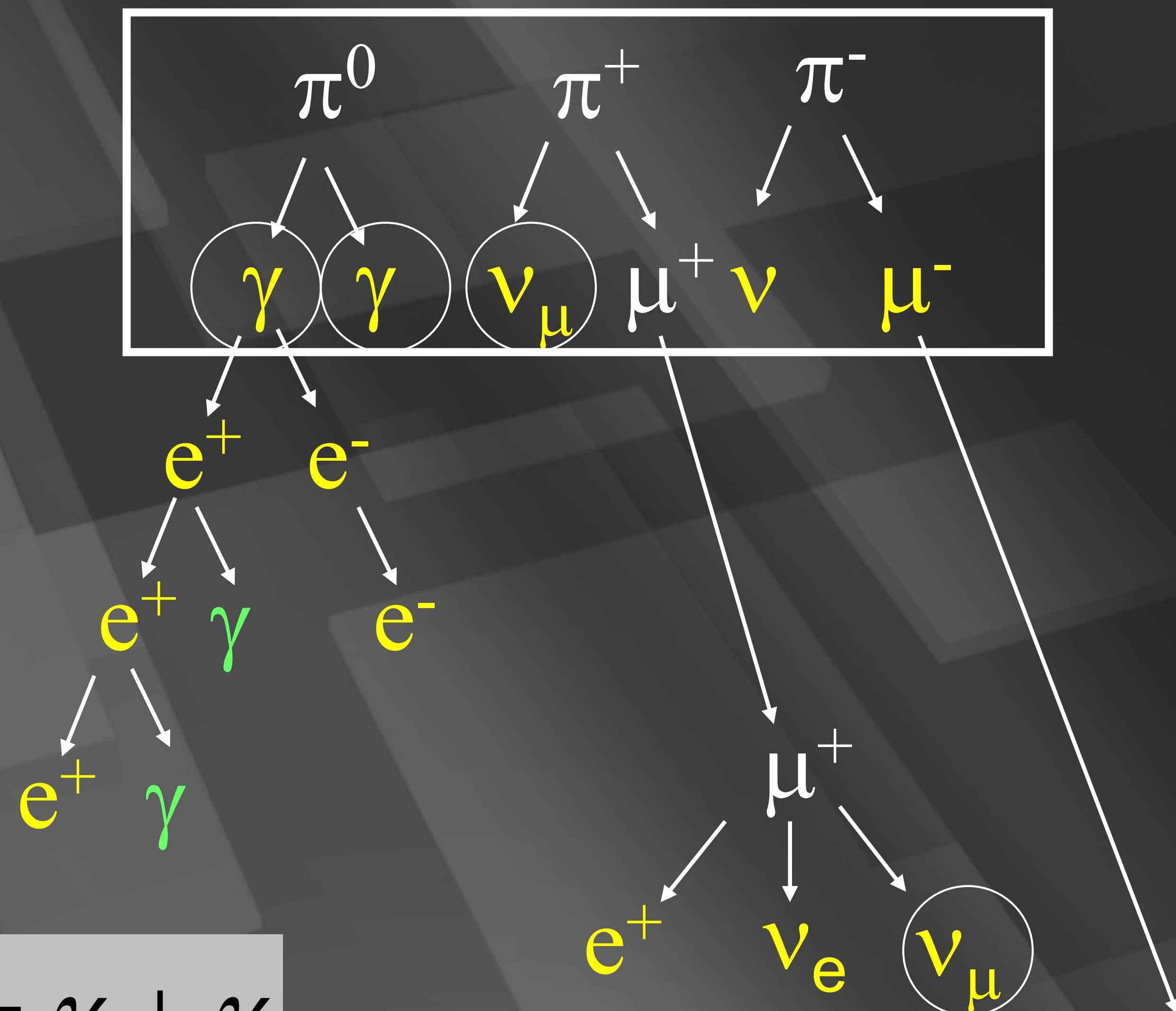
are observed as

gamma rays

charged pions

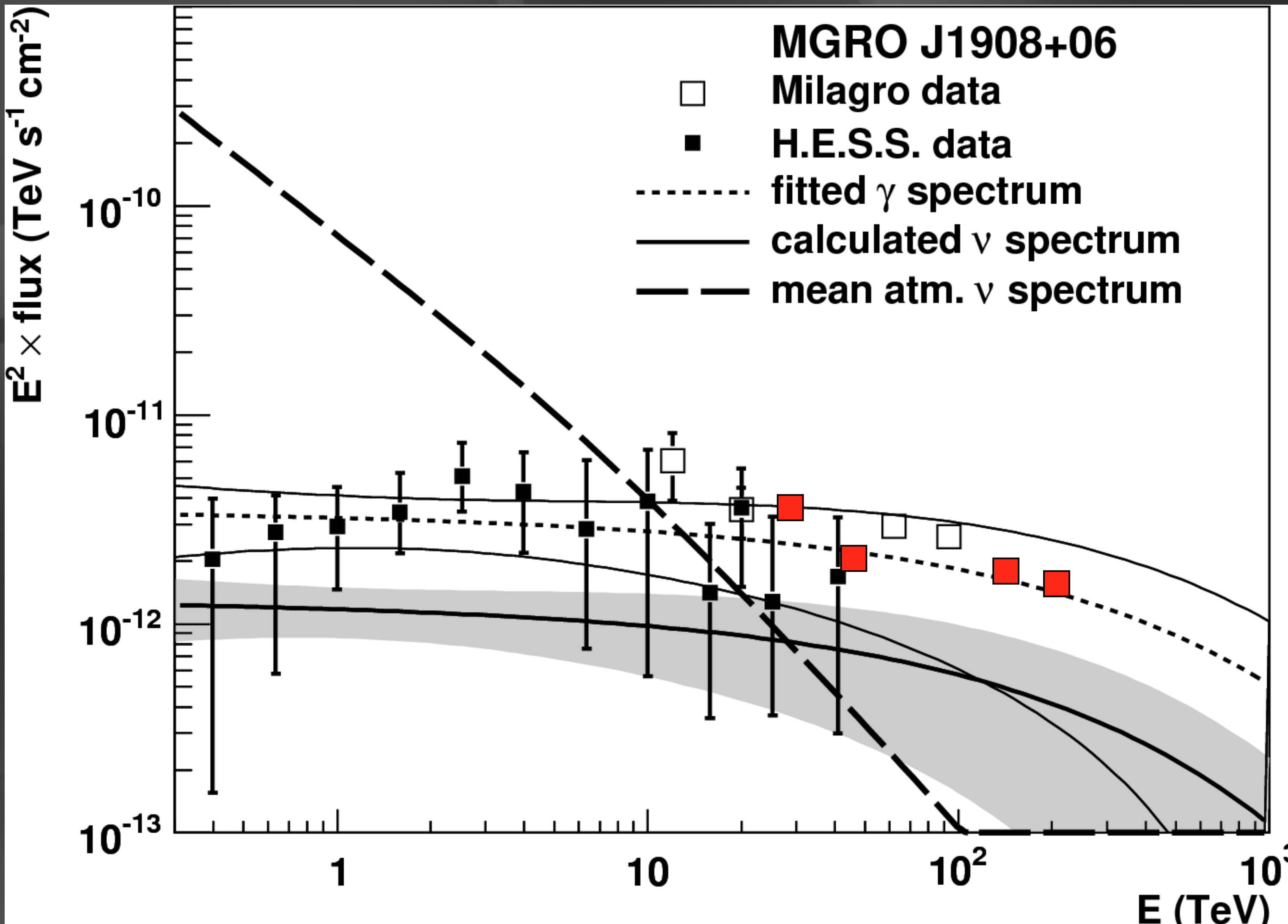
are observed as

neutrinos

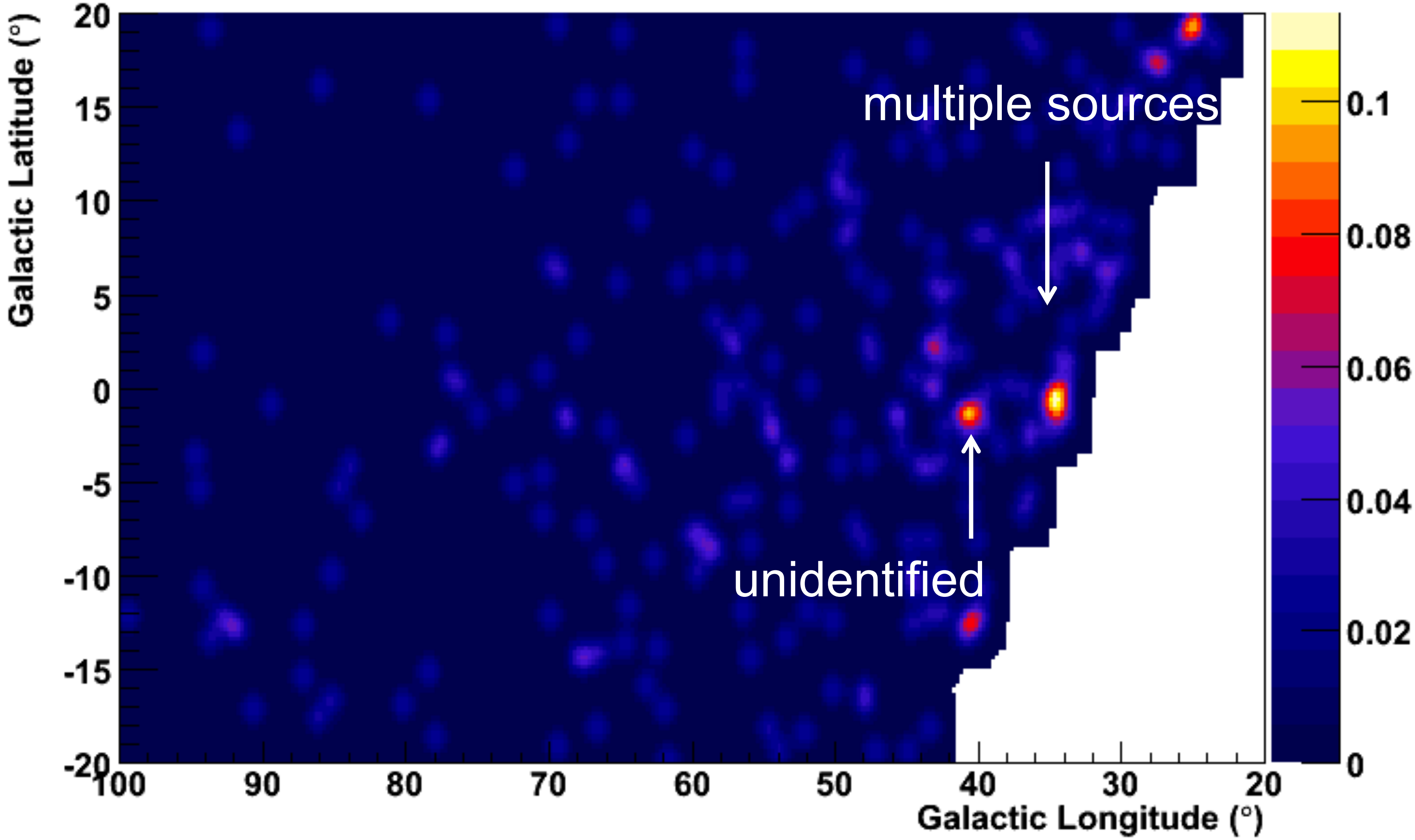


$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

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



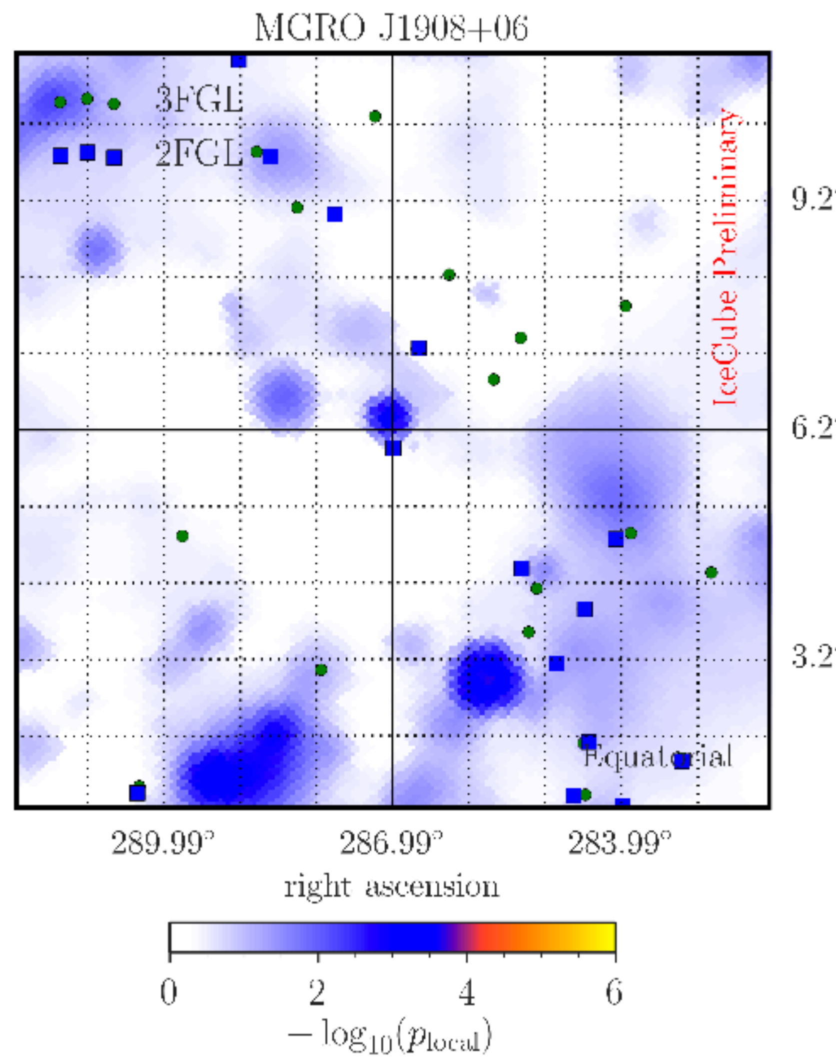
2007 simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.



- 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	16.1[illegible]	0.0072	[illegible].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	6.2[illegible]	0.0032	6.[illegible]84	3.28	$1.13 \cdot 10^{-12}$
Geminga	PWN	98.48	17.7[illegible]	0.9754	-[illegible].424	0.00	$1.16 \cdot 10^{-13}$
Crab Nebula	PWN	83.63	22.01	0.1188	[illegible]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 (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

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SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
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RWTH Aachen
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Yale University

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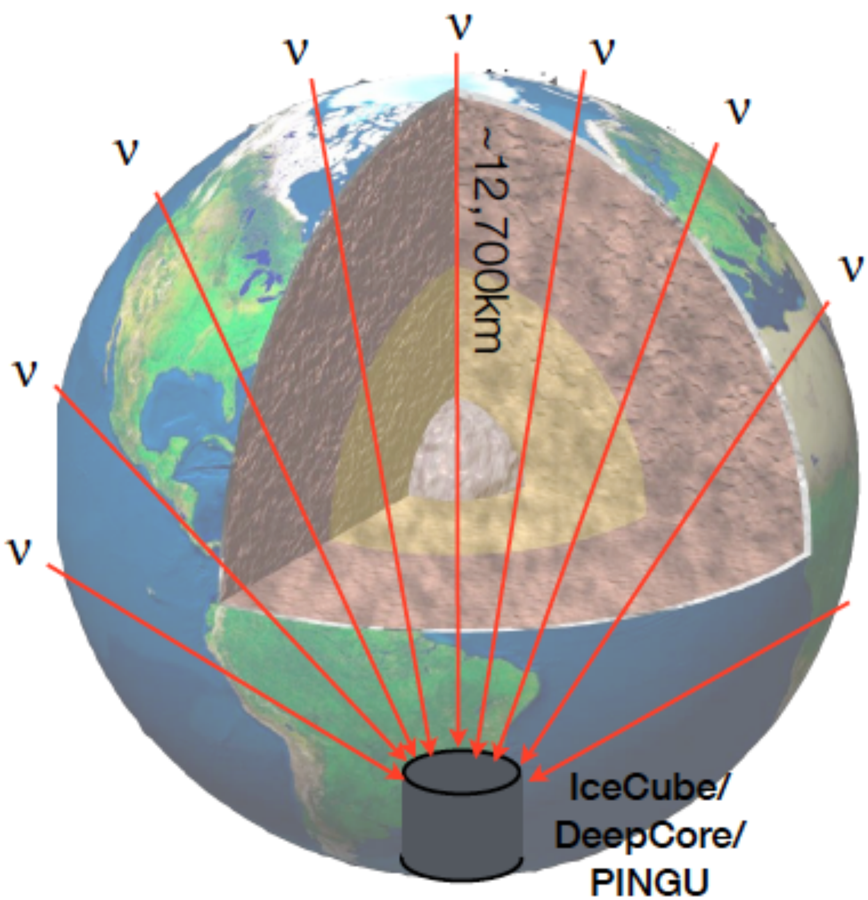
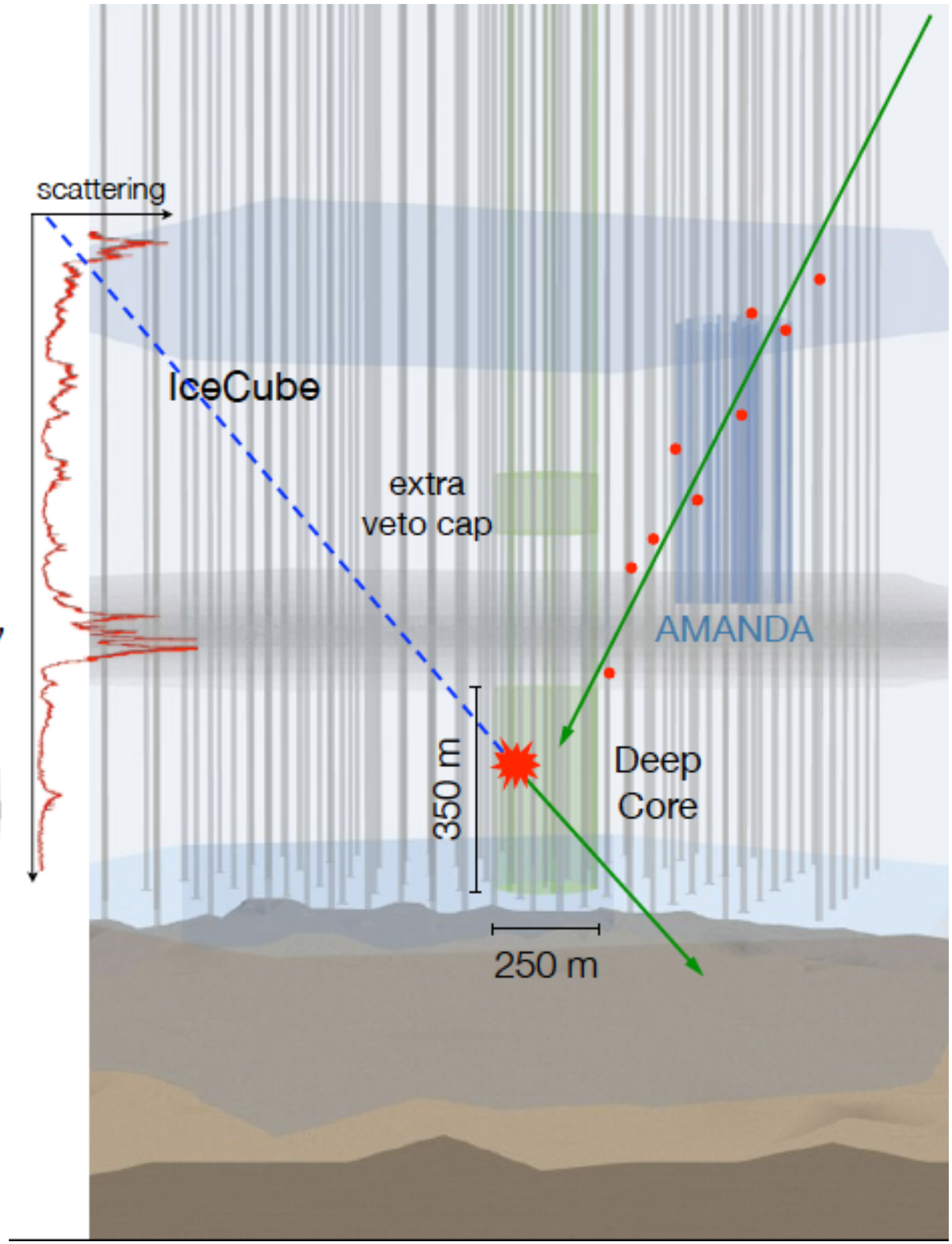
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

overflow slides

one half million atmospheric neutrinos…





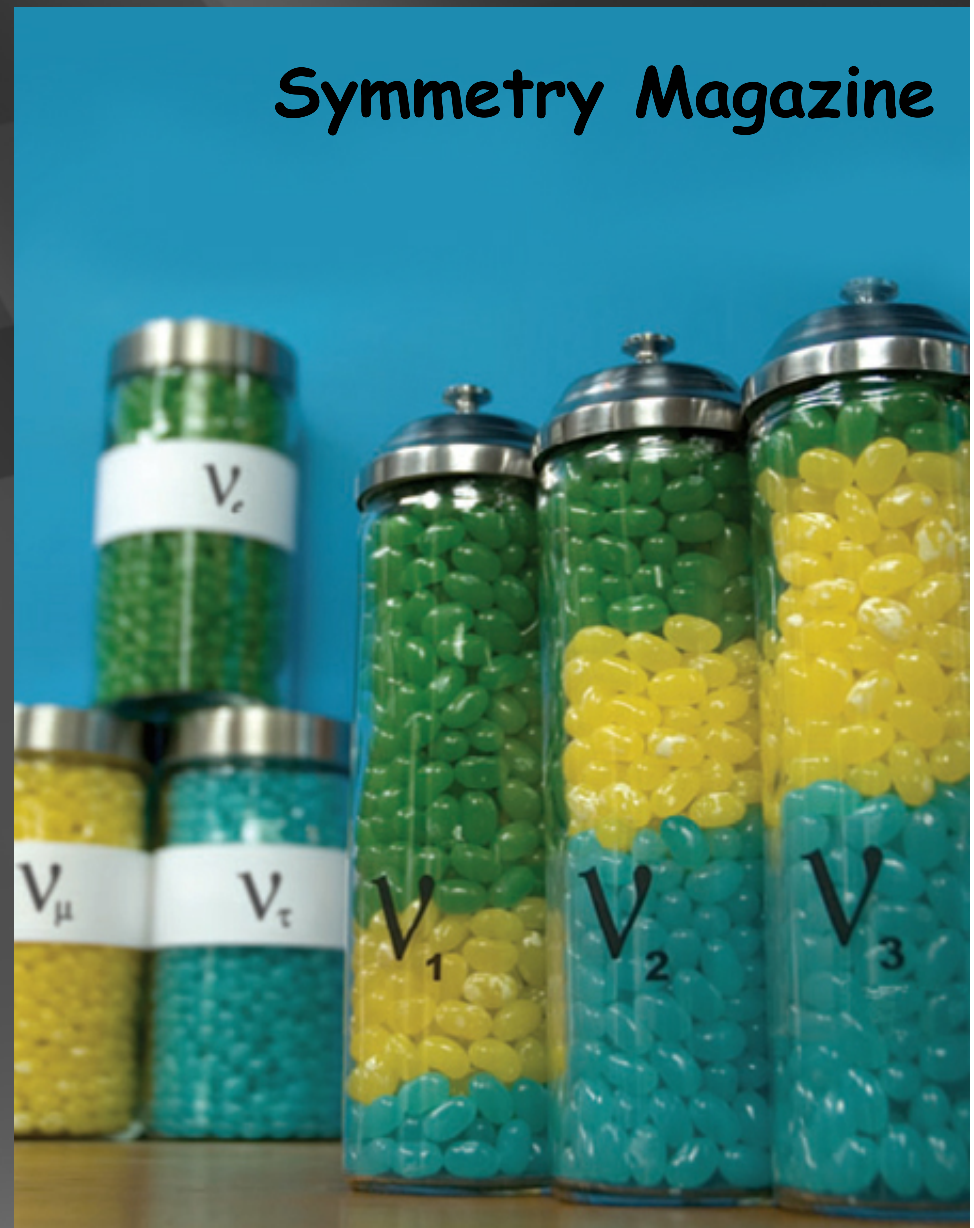
neutrinos: the sun and the atmophere

- beyond the Standard Model
- its symmetry is incomplete
- hierarchy problem $m_\nu/m_e \sim 10^{-6}$

$$\nu_1 = \left(\frac{\nu_\mu + \nu_\tau}{\sqrt{2}}\right)$$

$$\nu_2 = \sin\theta_\odot \nu_e + \cos\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

$$\nu_3 = -\cos\theta_\odot \nu_e + \sin\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

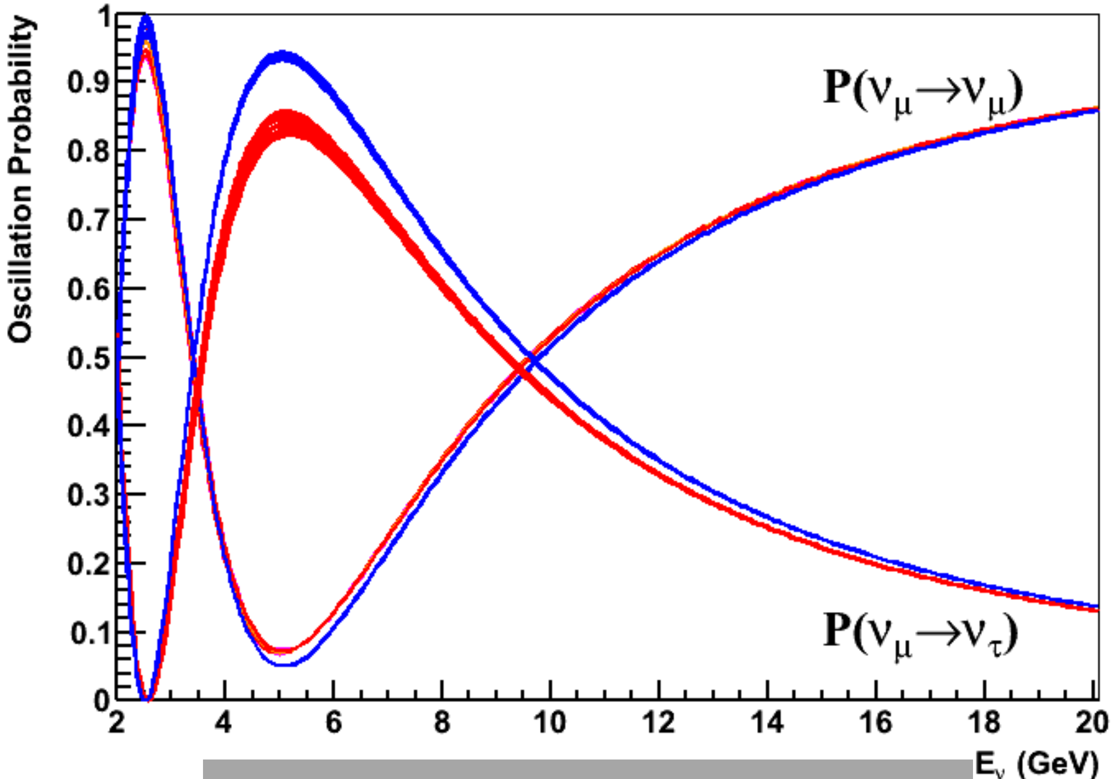


IceCube

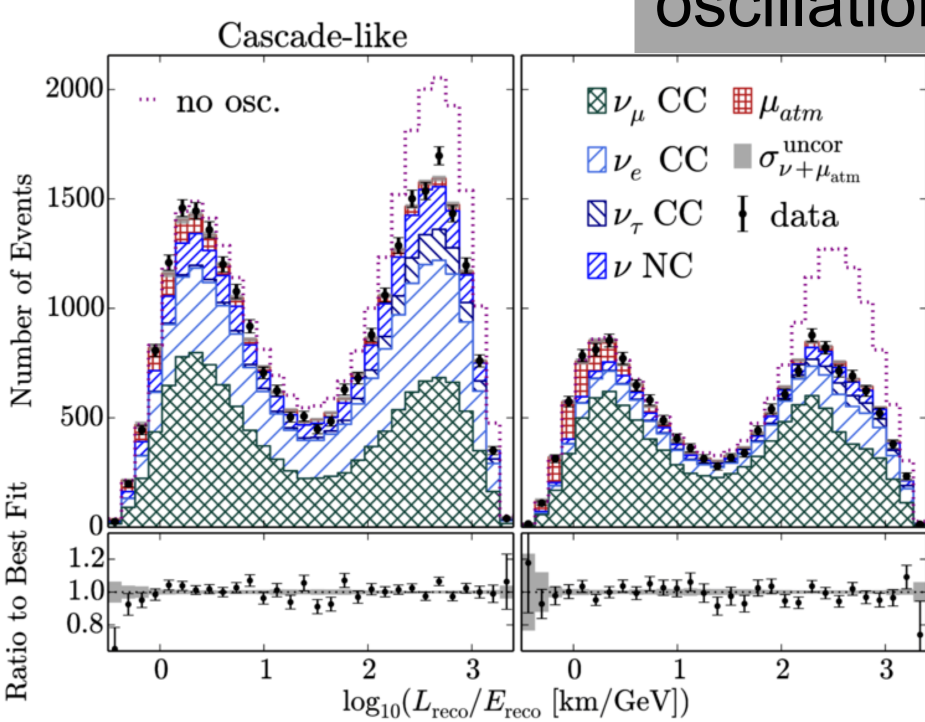
DeepCore

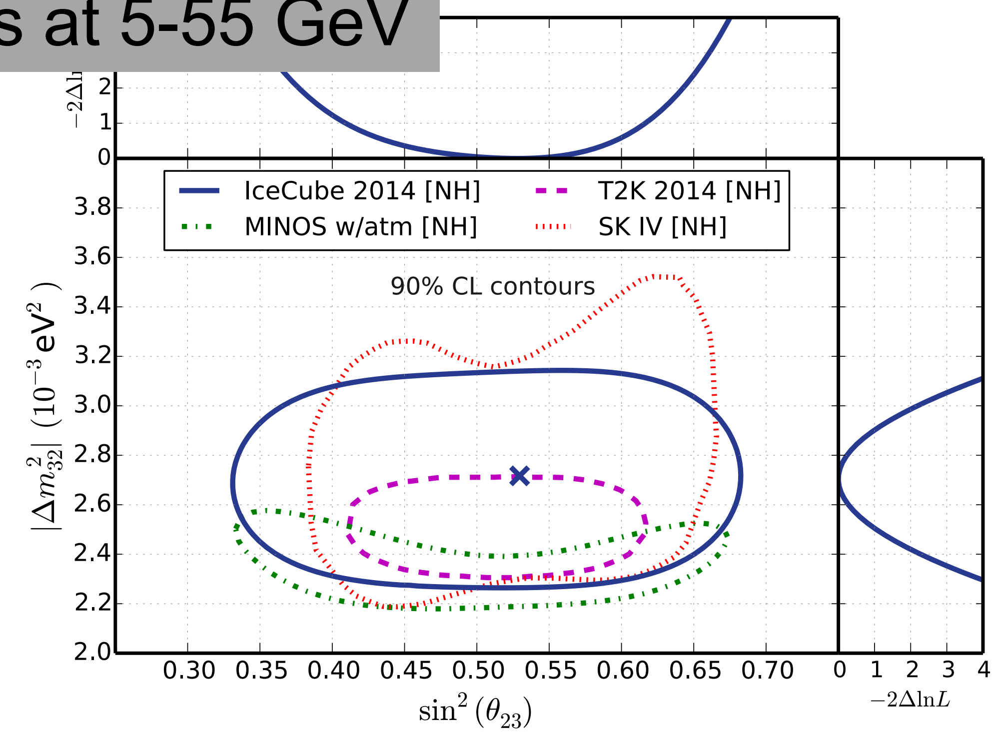
Phase 1

one year only!



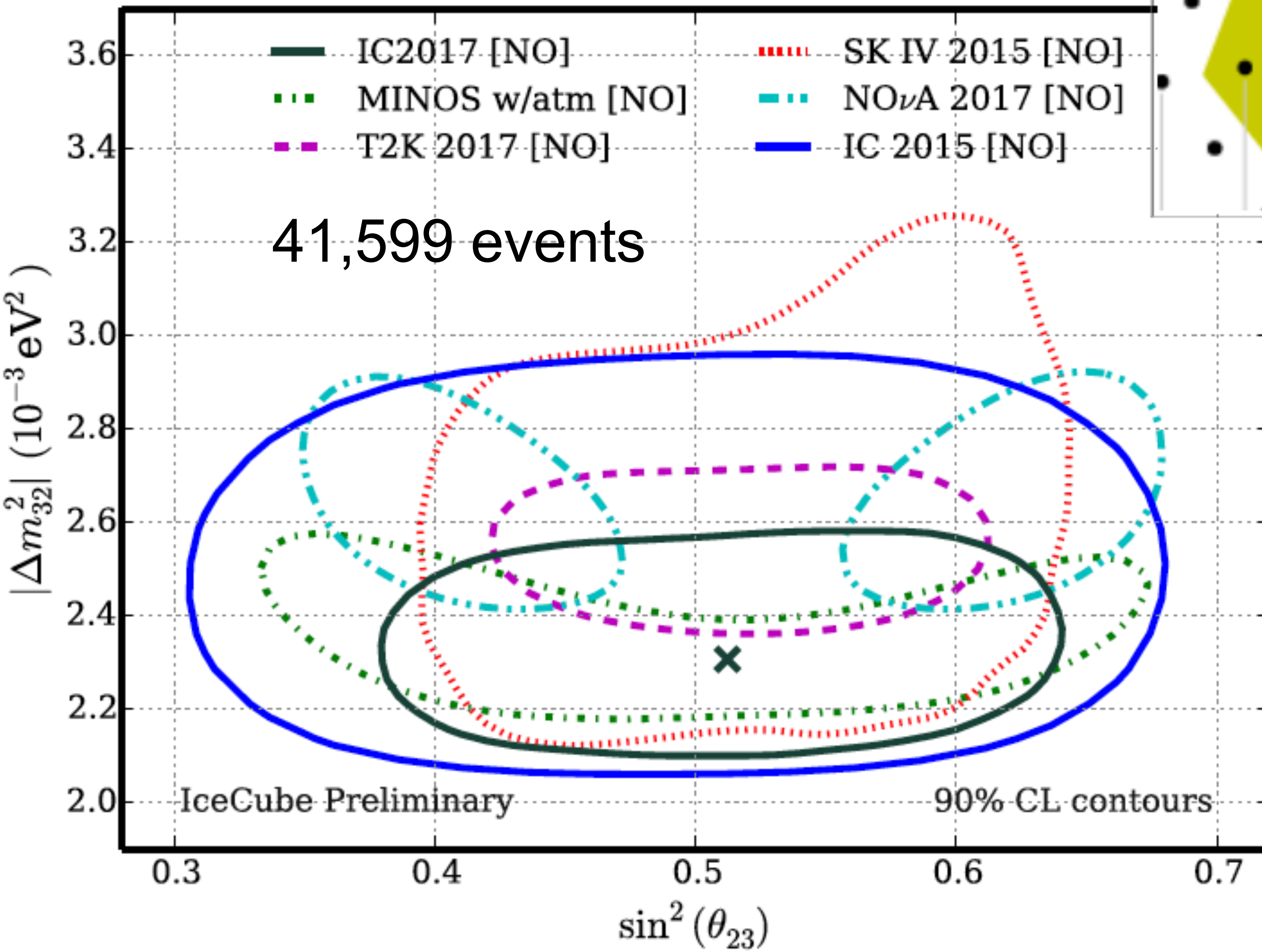
oscillations at 5-55 GeV

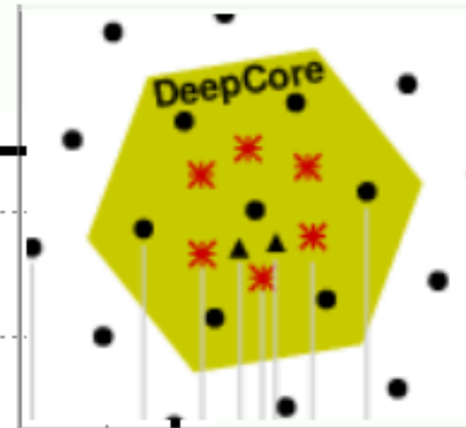




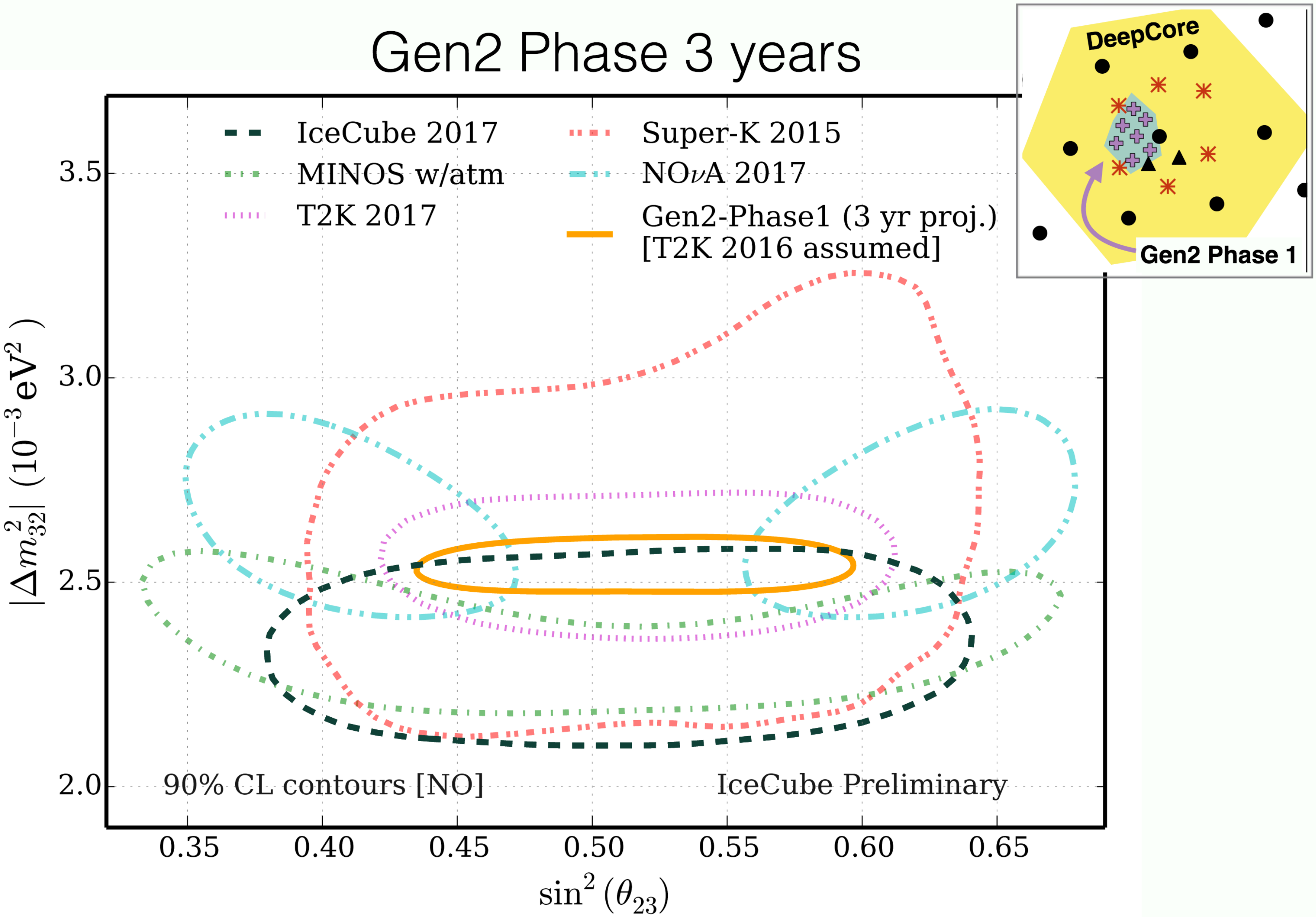
IceCube DeepCore: 3 years

41,599 events

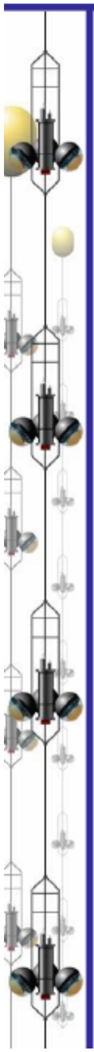




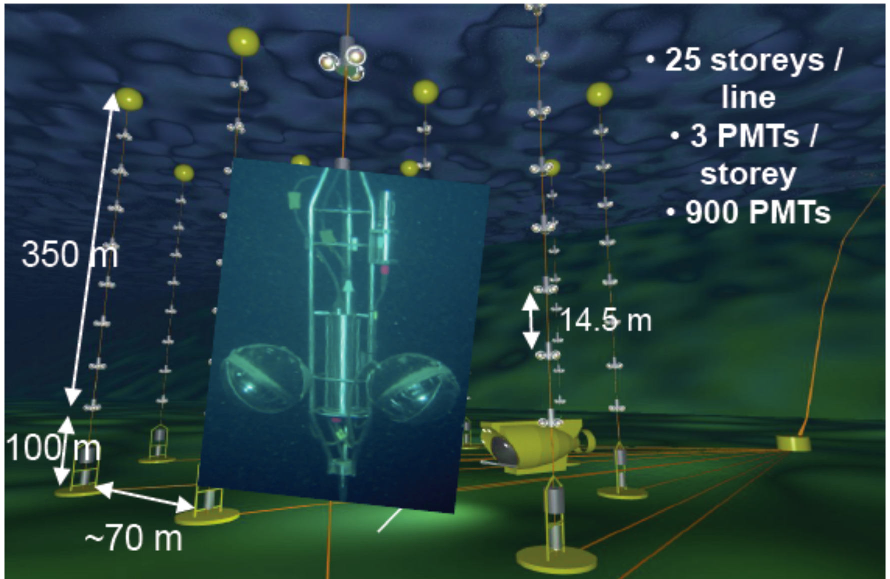
Gen2 Phase 3 years



Mediterranean Detectors



ANTARES Complete since 2008



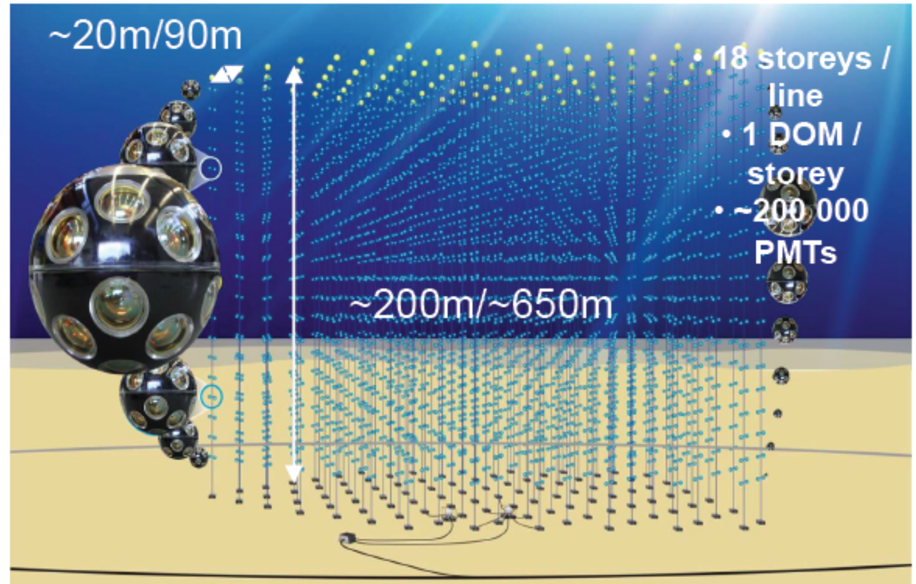
~10 Mton

12 lines

First Generation

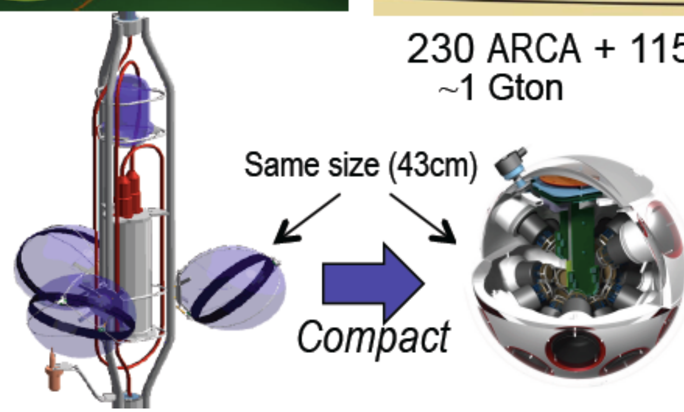
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

~1 Gton ~6 Mton

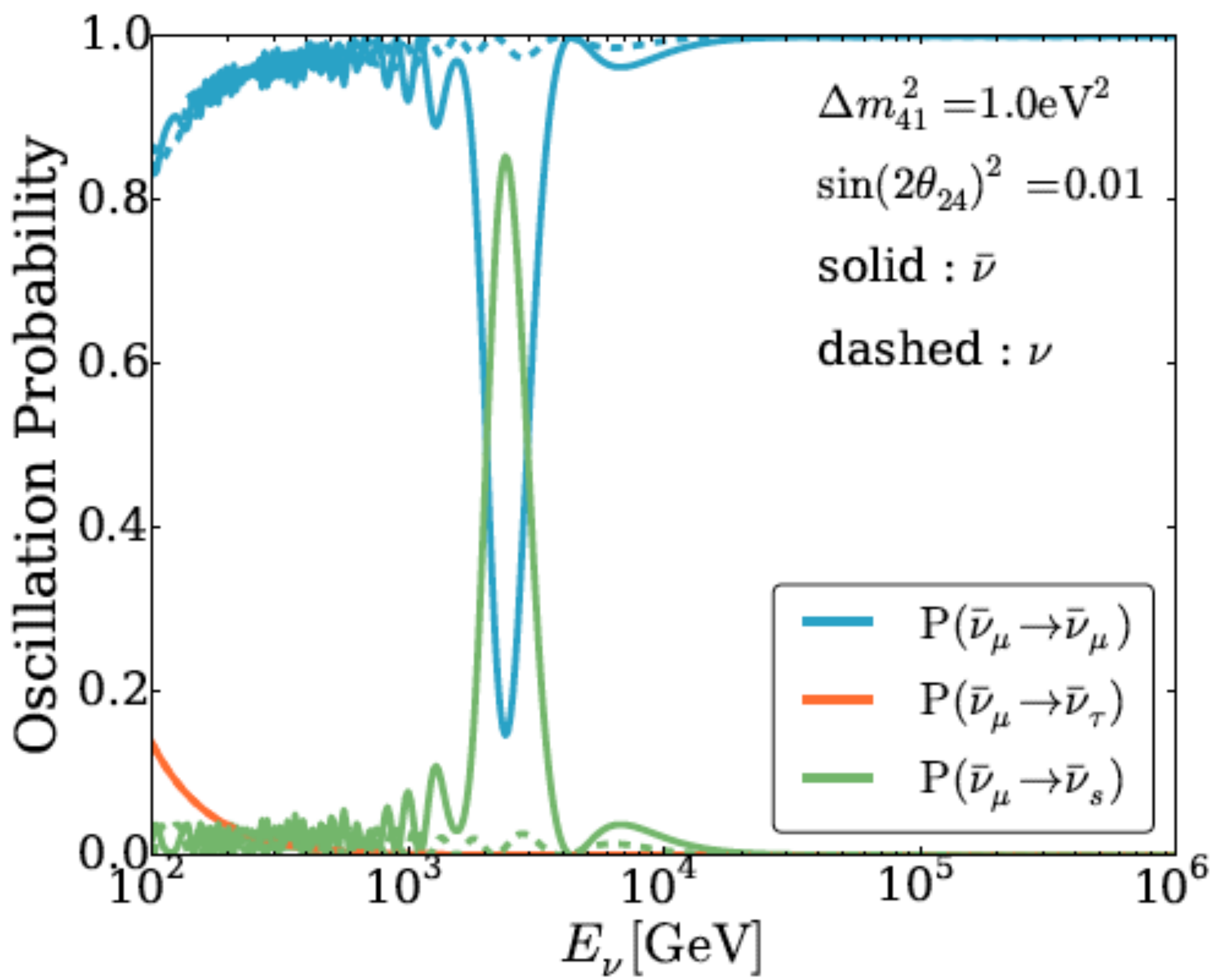


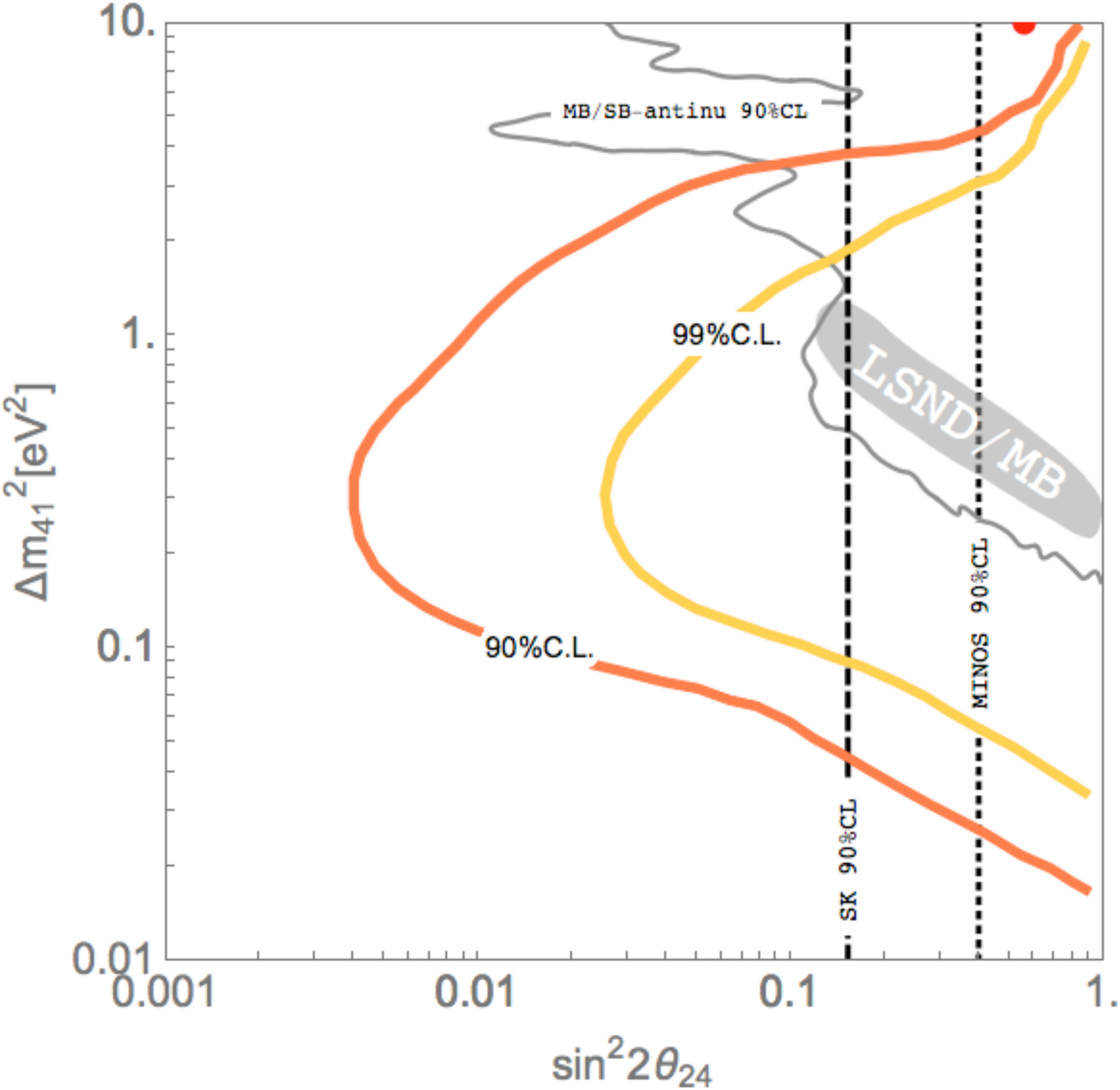
• DOM: 31 3" PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

eV sterile neutrino → Earth MSW resonance for TeV neutrinos

In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$





10.
1.
0.1
0.01
0.001
0.01
0.1
1.
$\Delta m_{41}{}^2$[eV^2]
$\sin^2 2\theta_{24}$
MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL