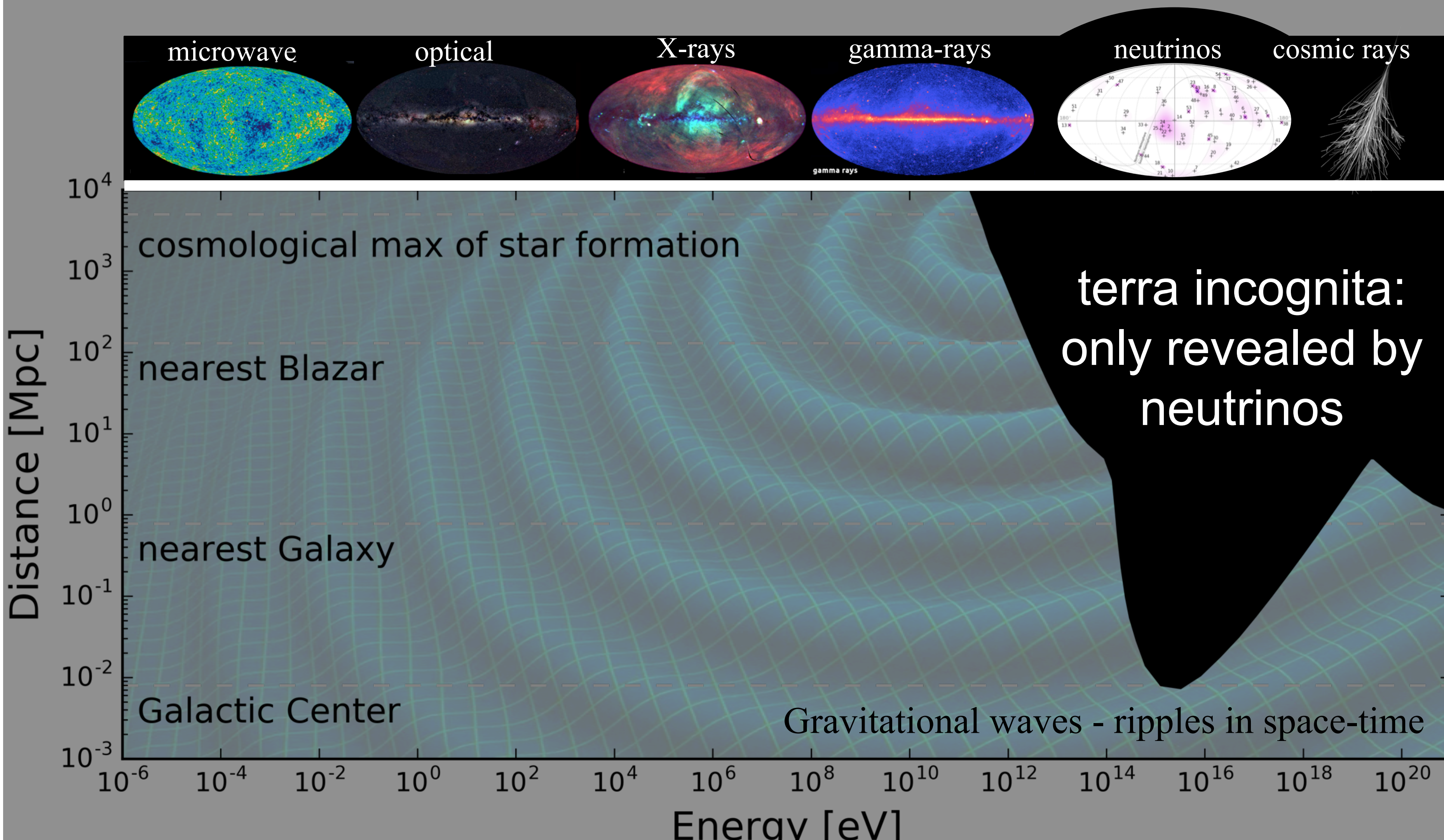
IceCube: the discovery of cosmic neutrinos

francis halzen

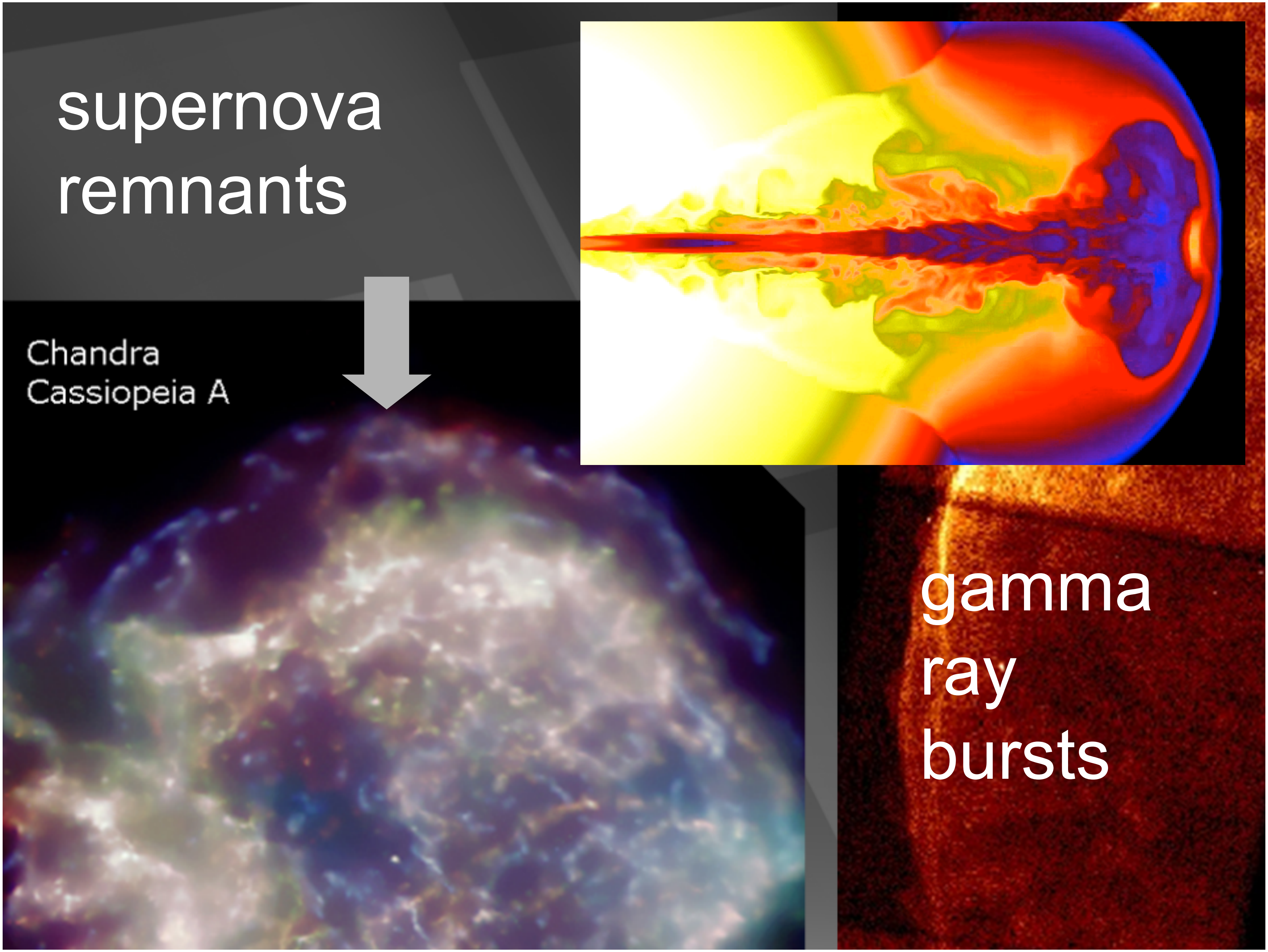
- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

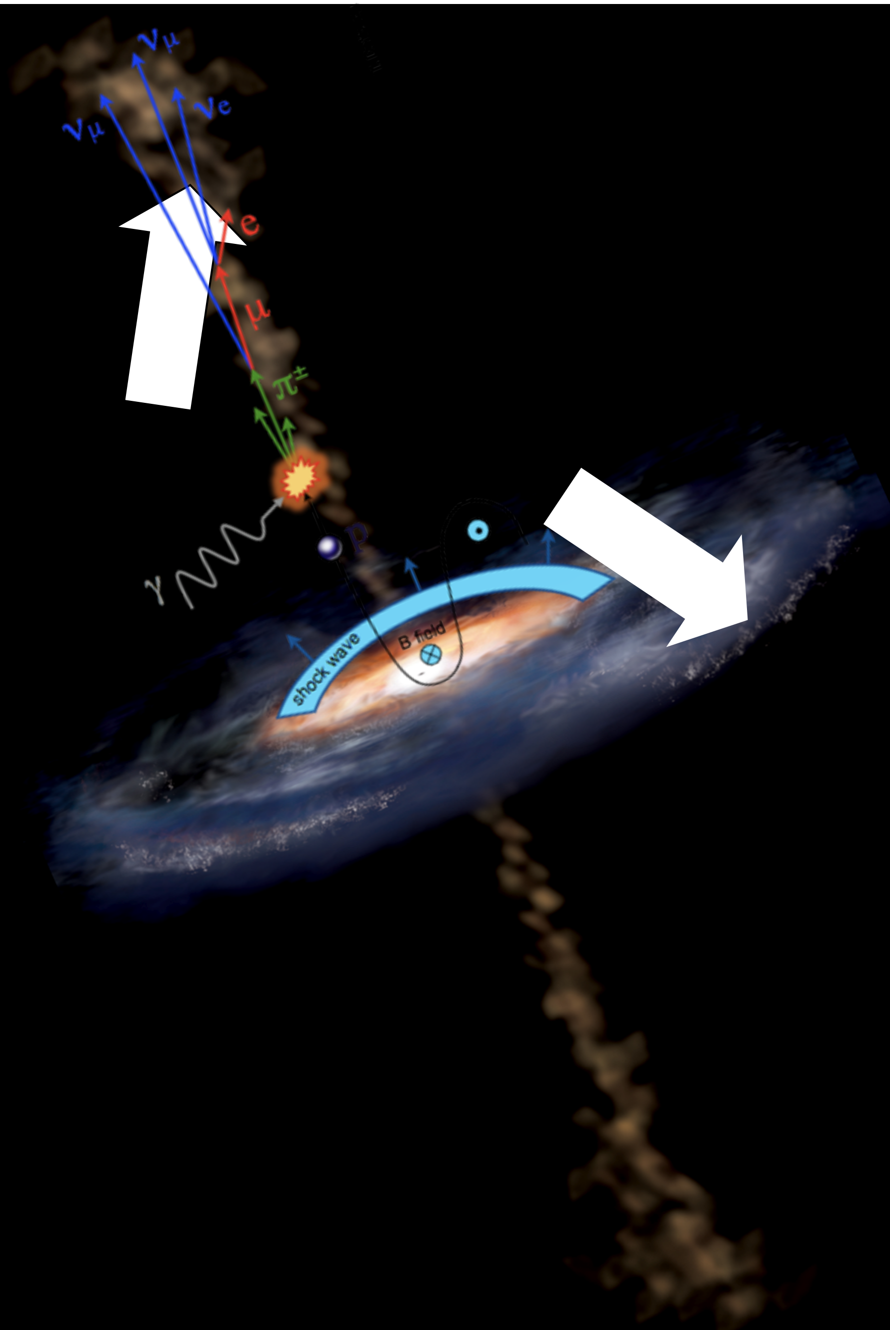
IceCube.wisc.edu

Multi-Messenger Astronomy



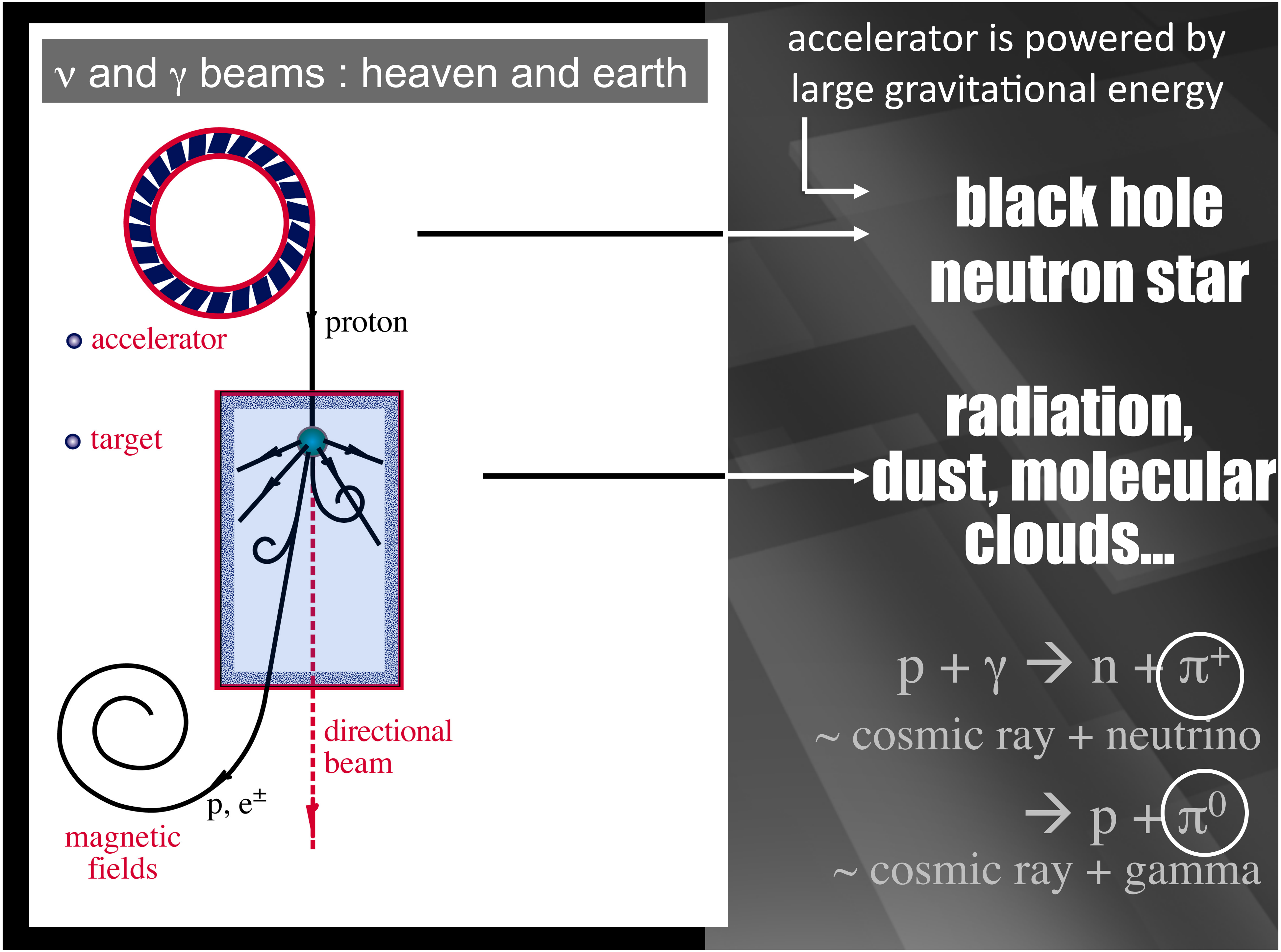
20% of the Universe is opaque to the EM spectrum


supernova
remnants
Chandra
Cassiopeia A
gamma
ray
bursts



active galaxy

particle flows near supermassive black hole


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

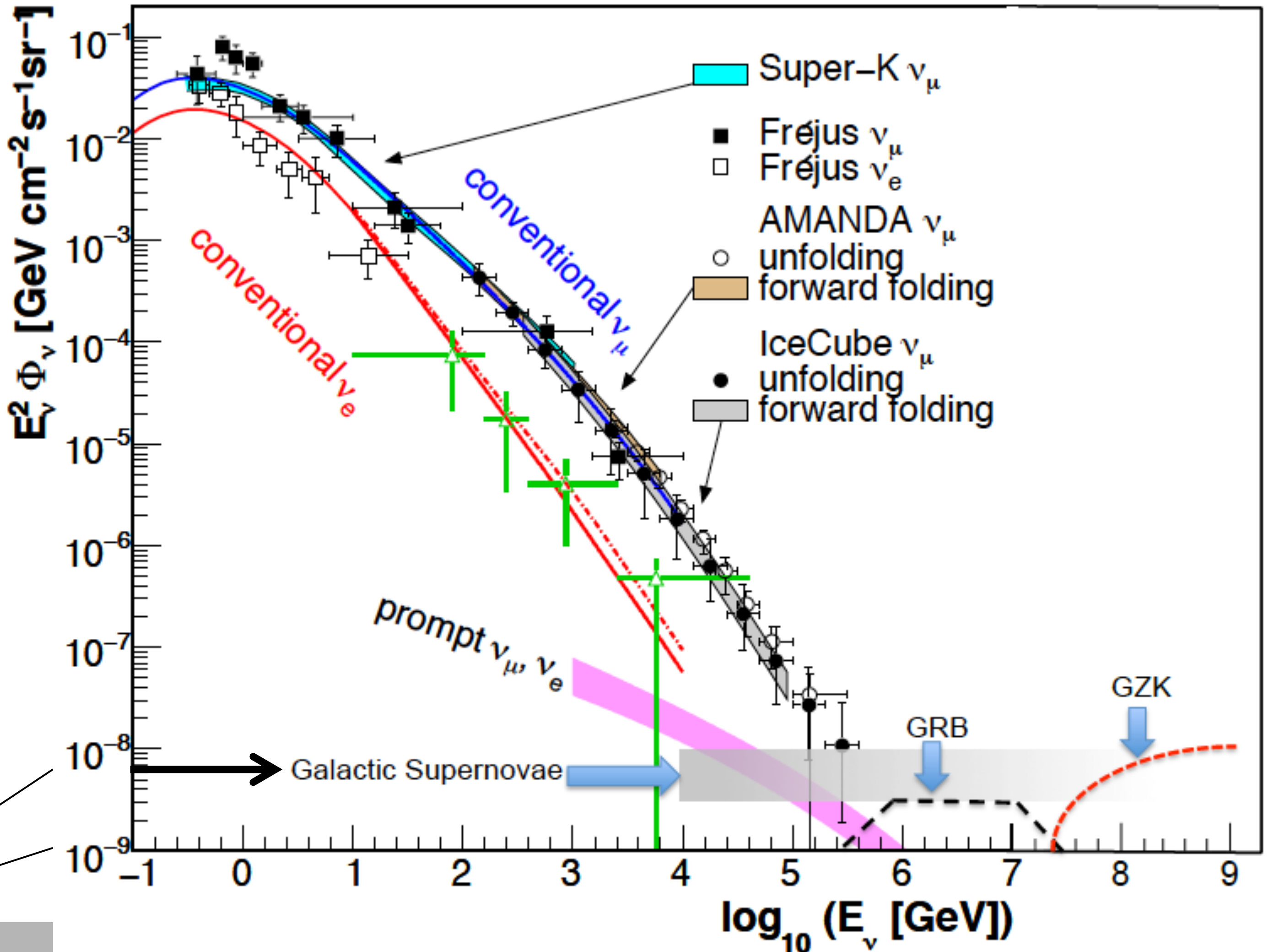
above 100 TeV

• cosmic neutrinos:

• atmospheric background disappears

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

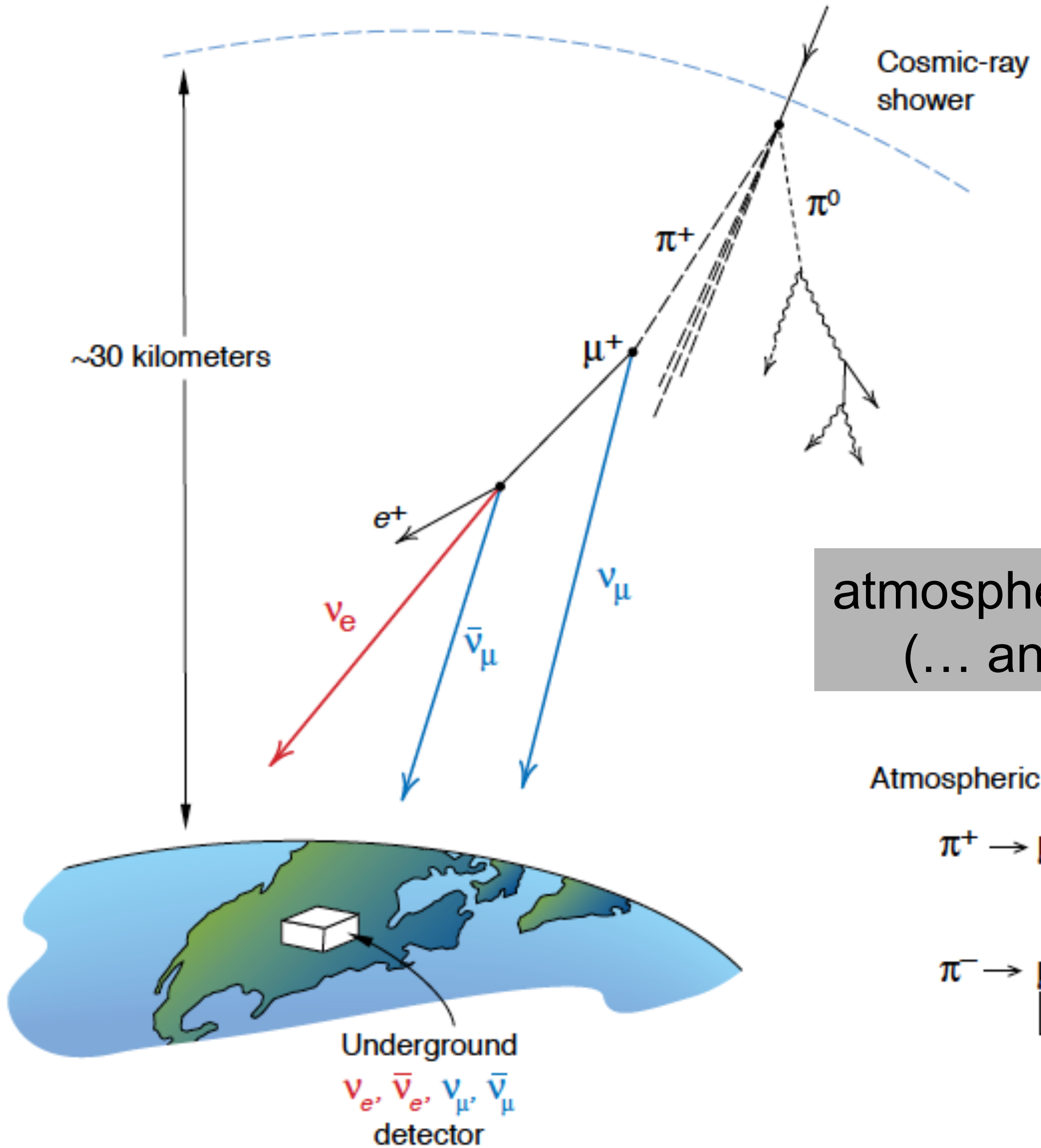
10—100 events per year for fully efficient 1 km³ detector



atmospheric

cosmic

100 TeV

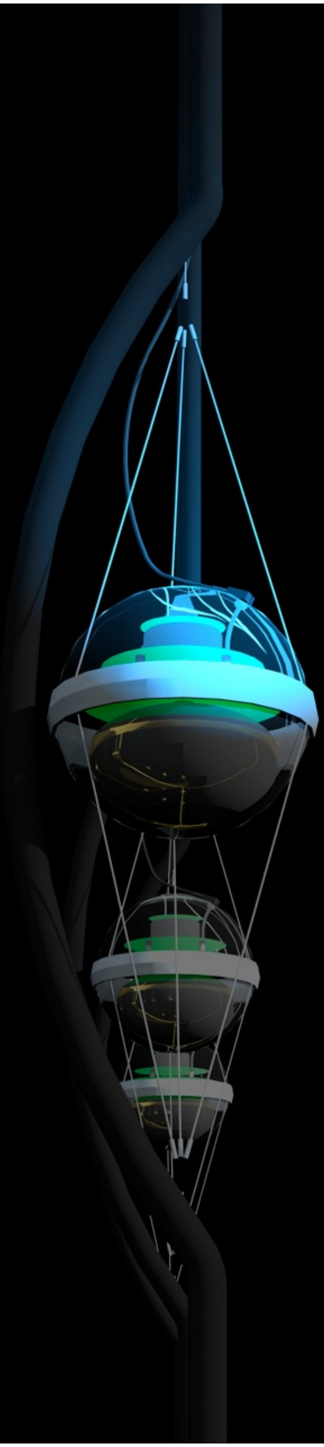


atmospheric neutrinos (… and muons!)

Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



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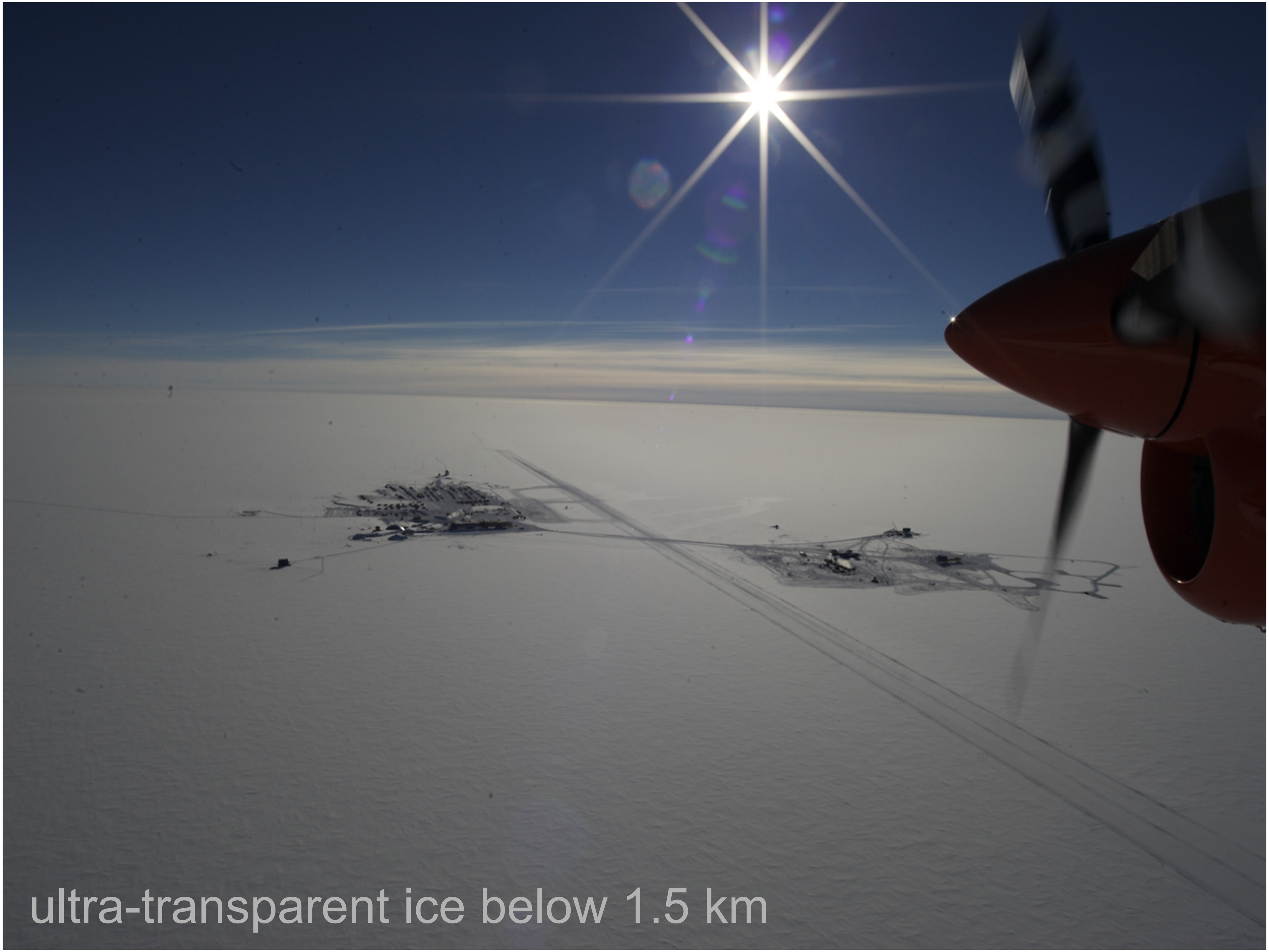
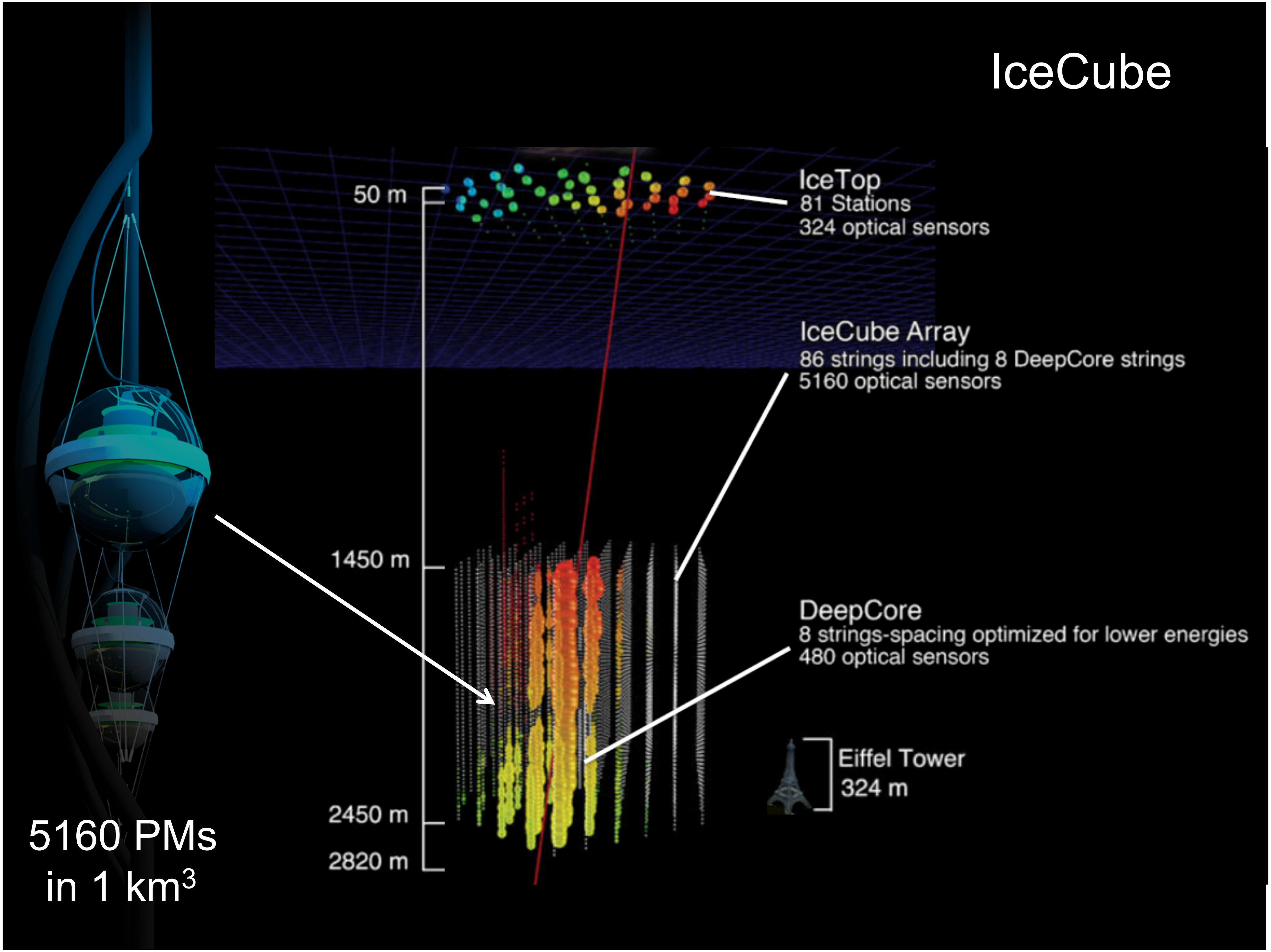
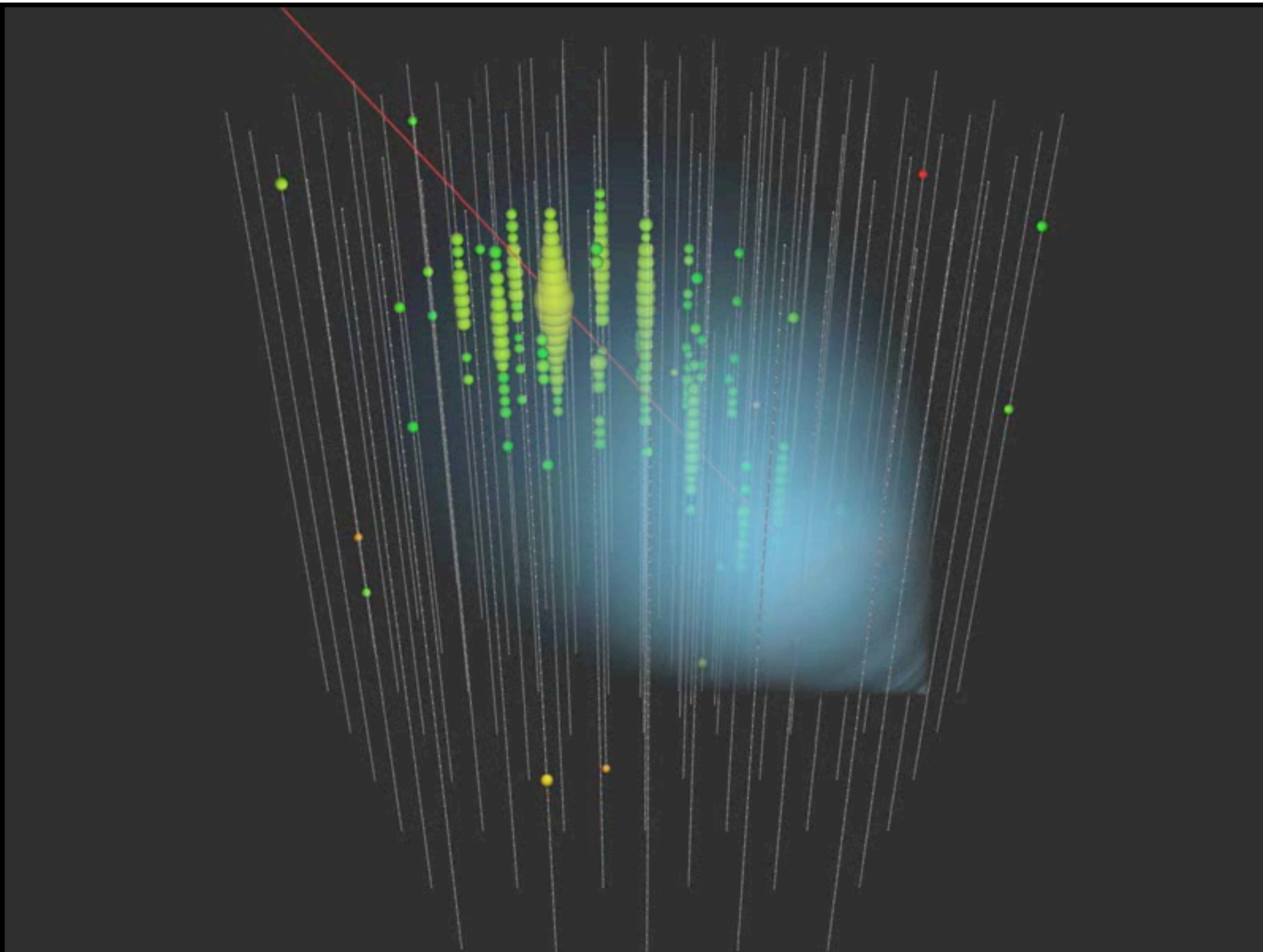

ultra-transparent ice below 1.5 km

IceCube


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

photomultiplier tube -10 inch



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

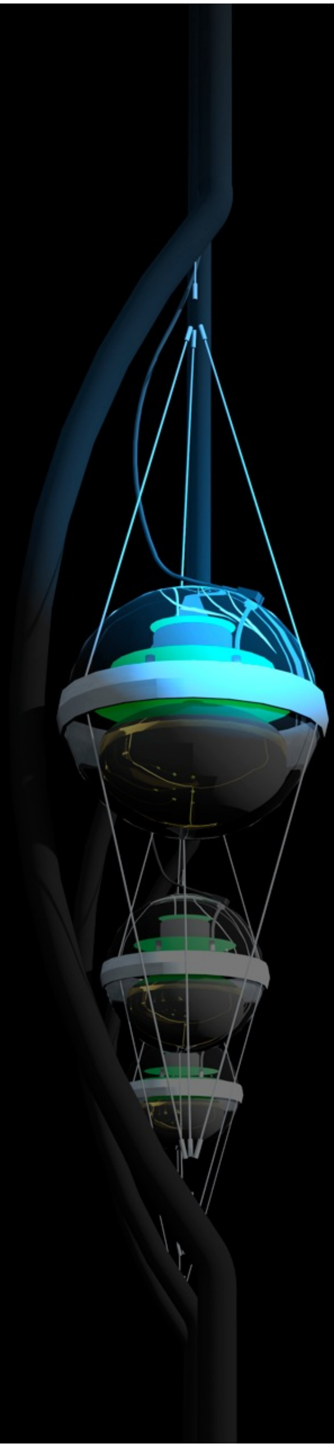
separating signal and "background"

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



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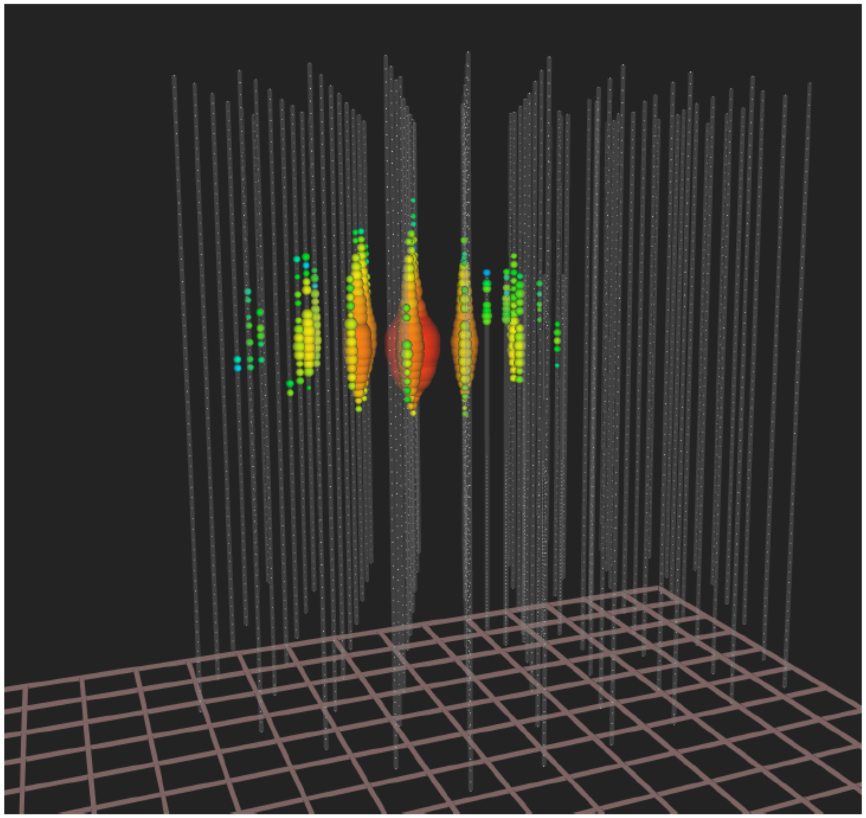
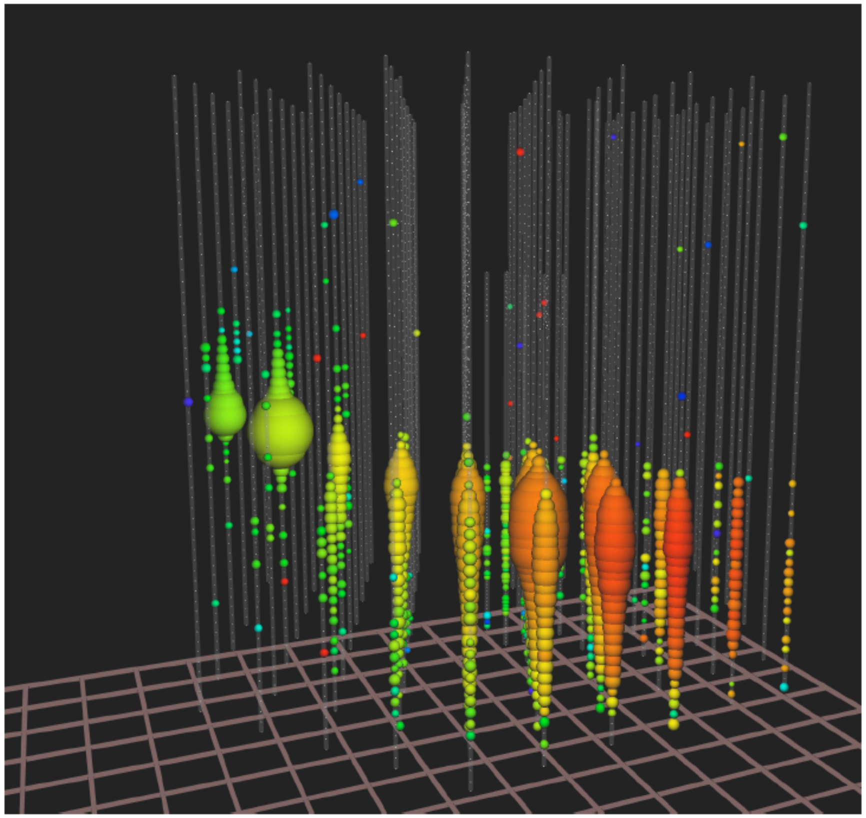
isolated neutrinos interacting inside the detector

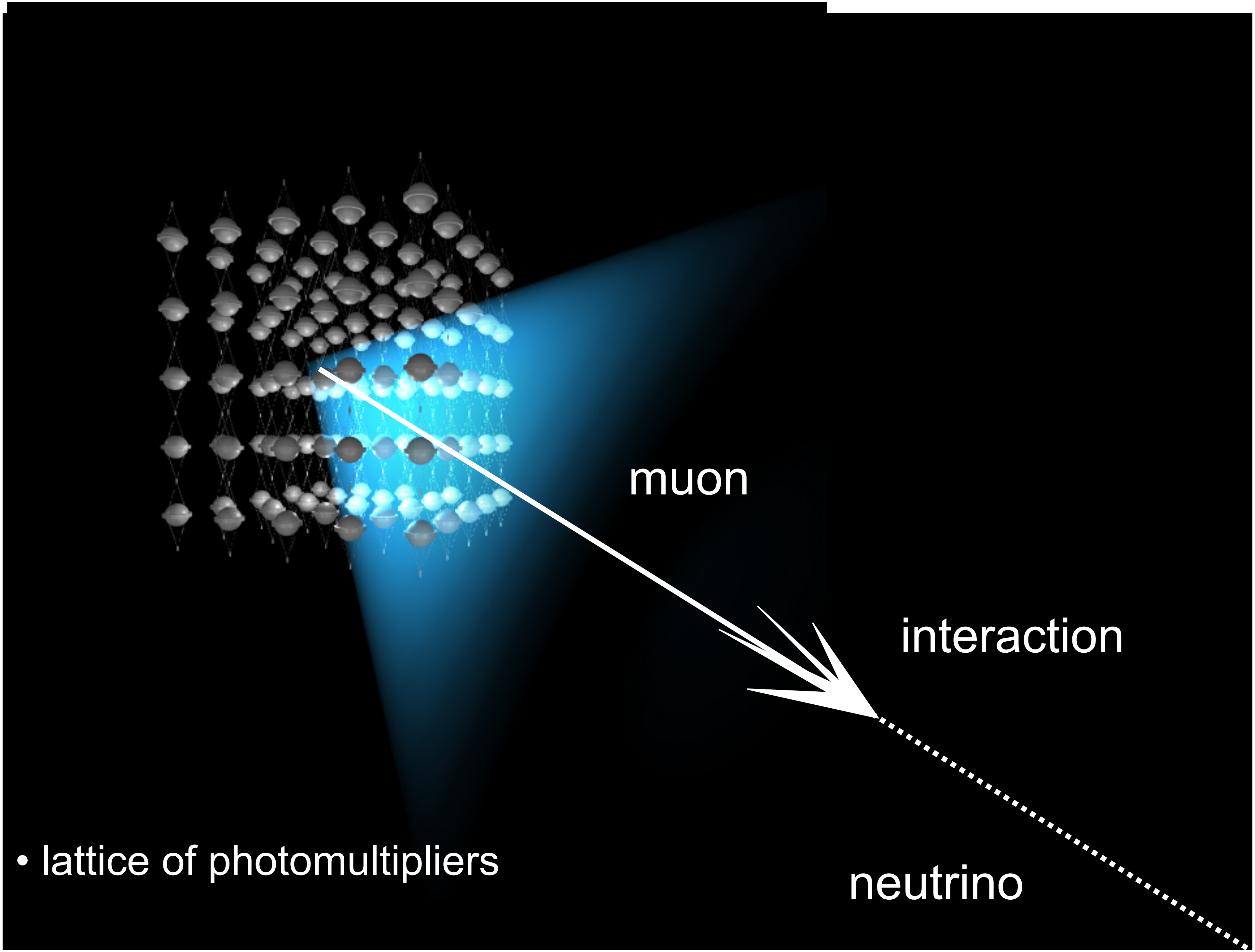
up-going muon tracks



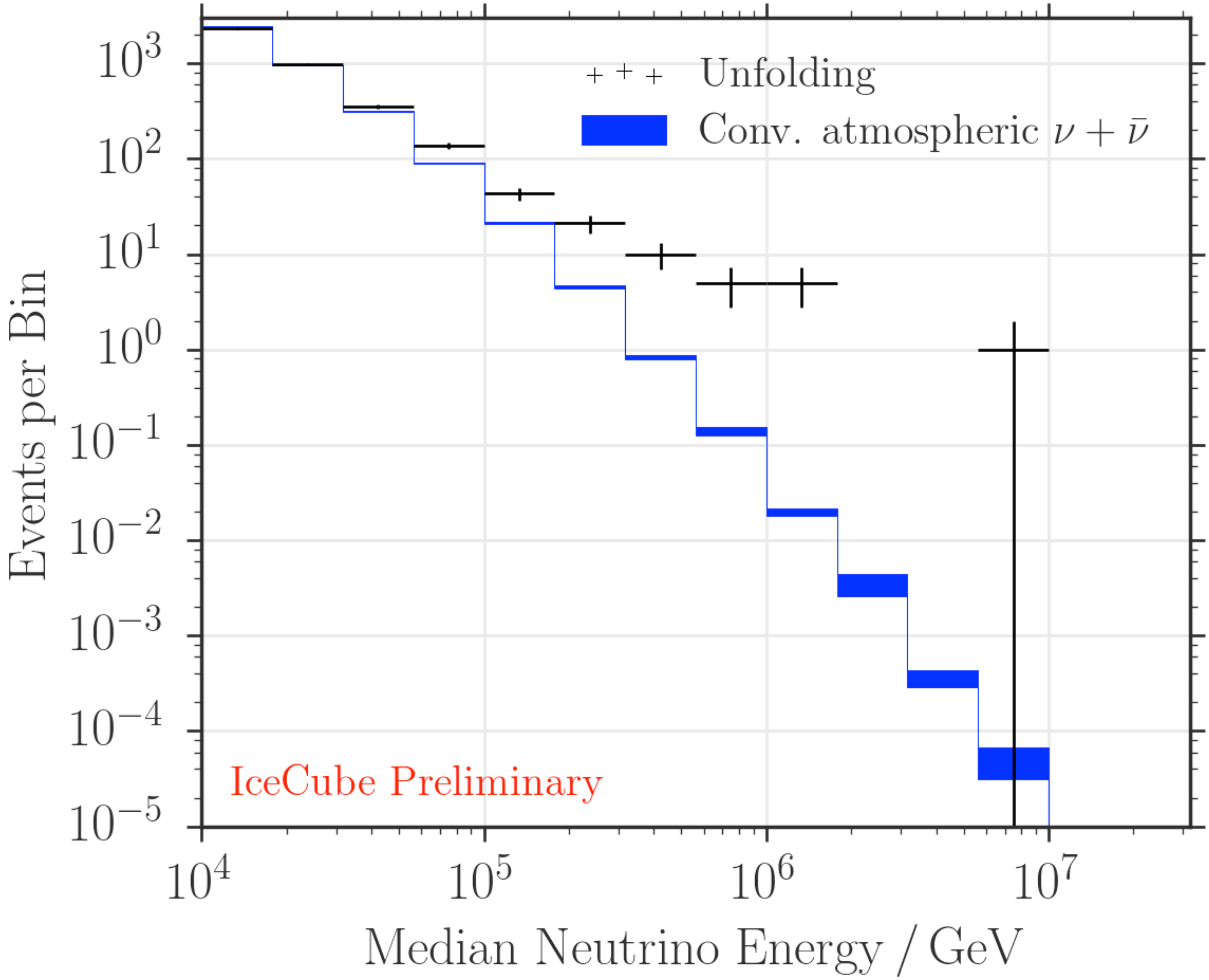


calorimetry: direct energy measurement; all flavors

astronomy: angular resolution superior


muon
interaction
neutrino
• lattice of photomultipliers

muon neutrinos through the Earth → 6 sigma

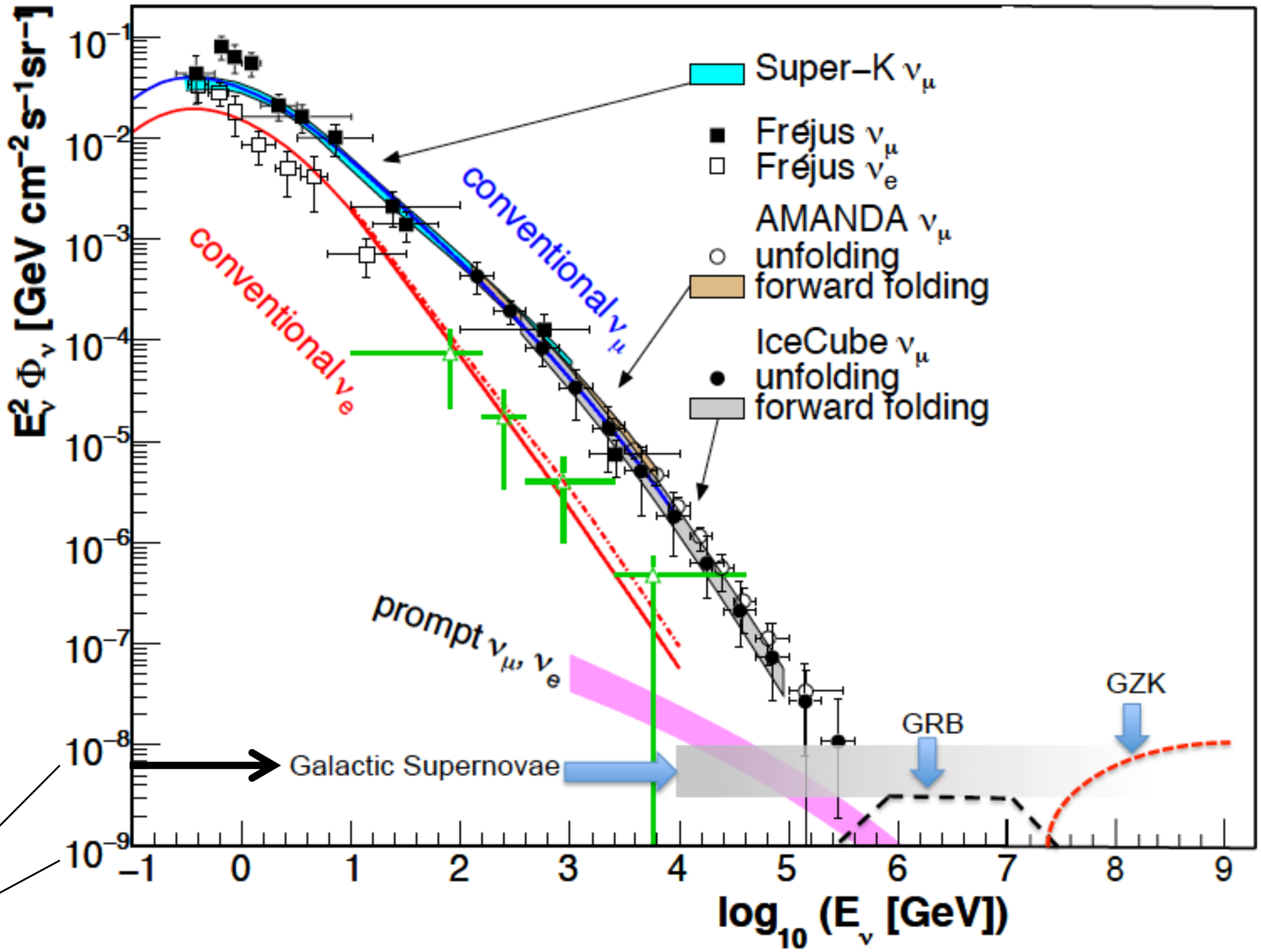


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

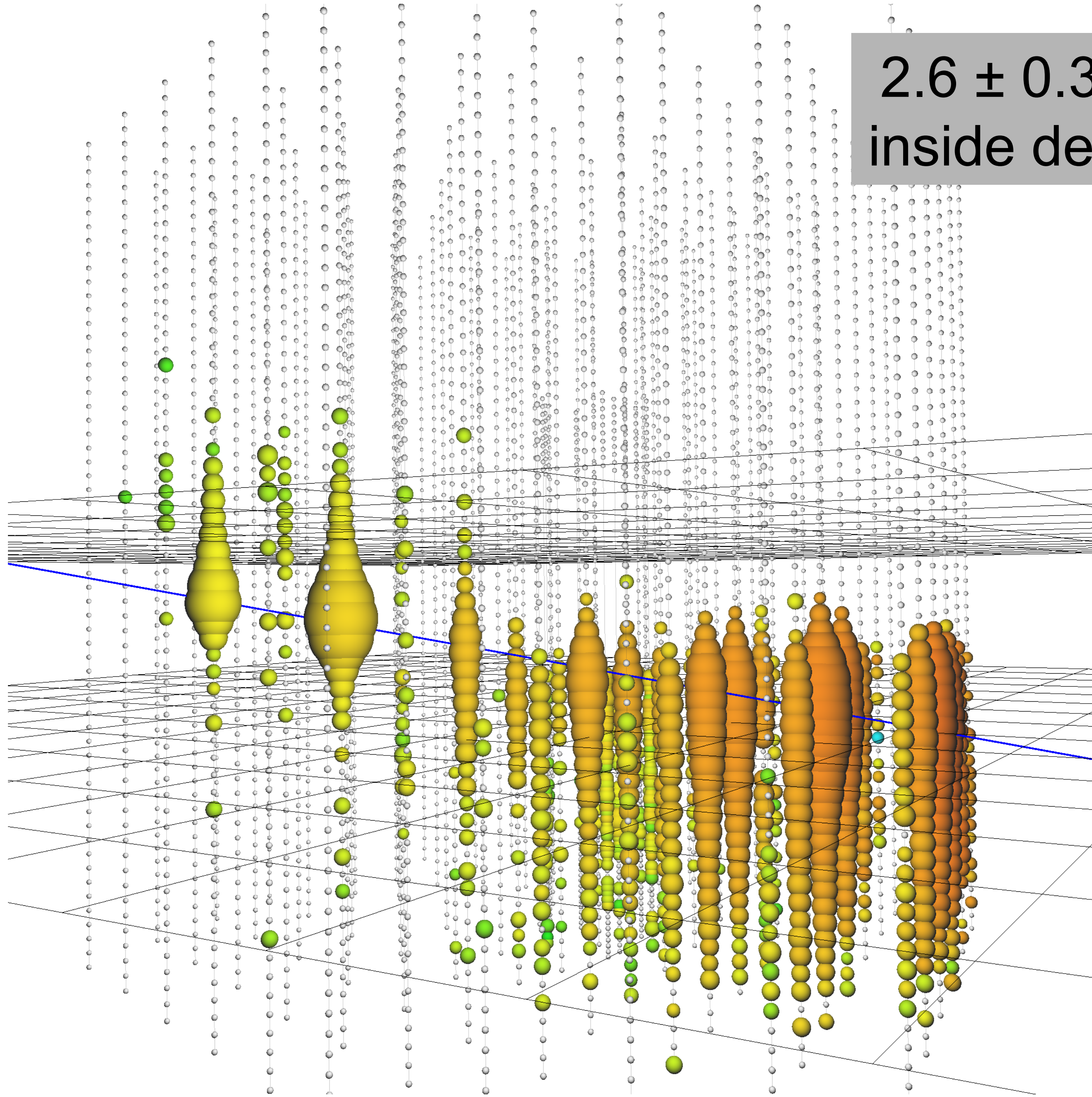
10—100 events per year for fully efficient detector

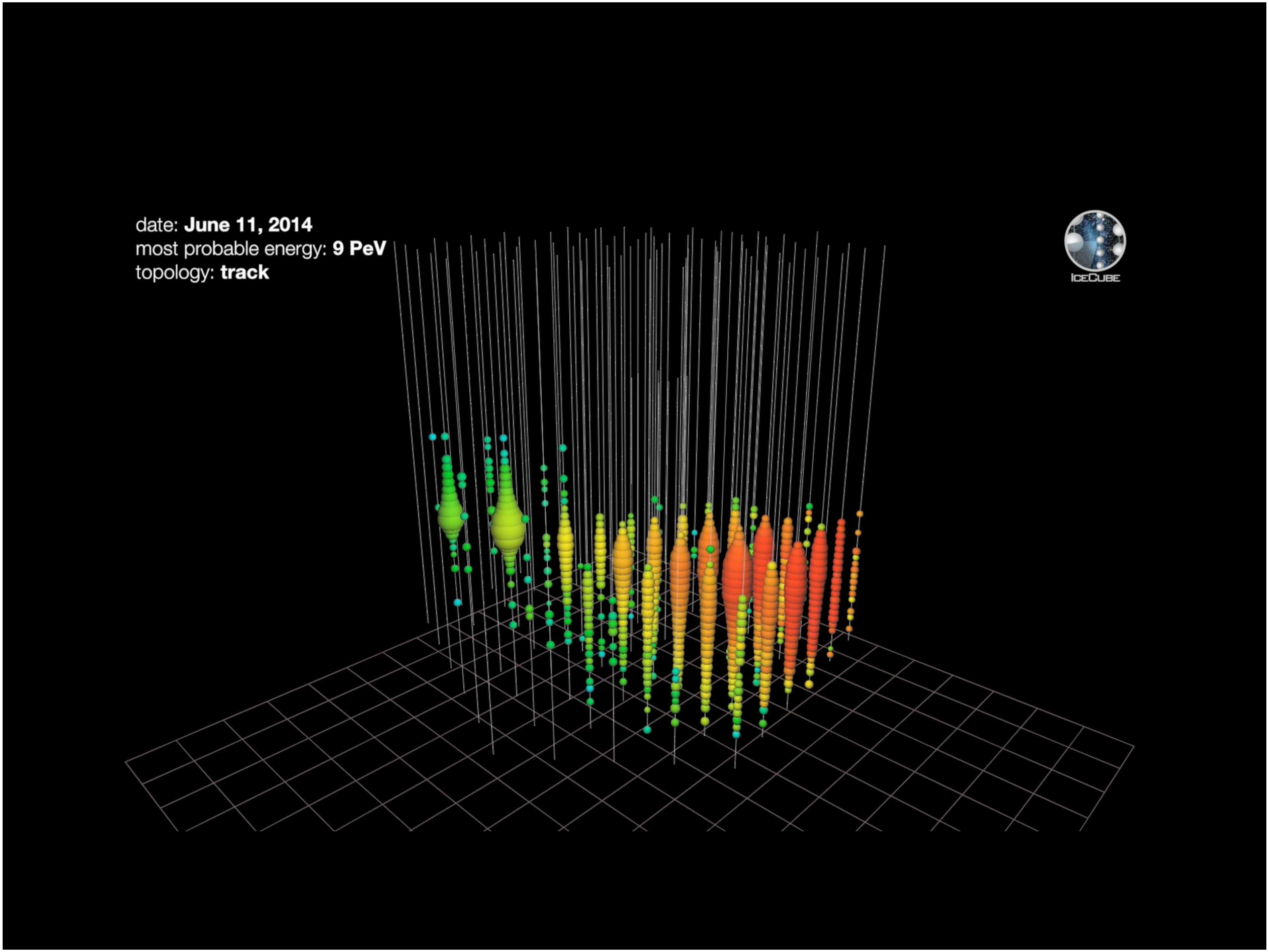


atmospheric

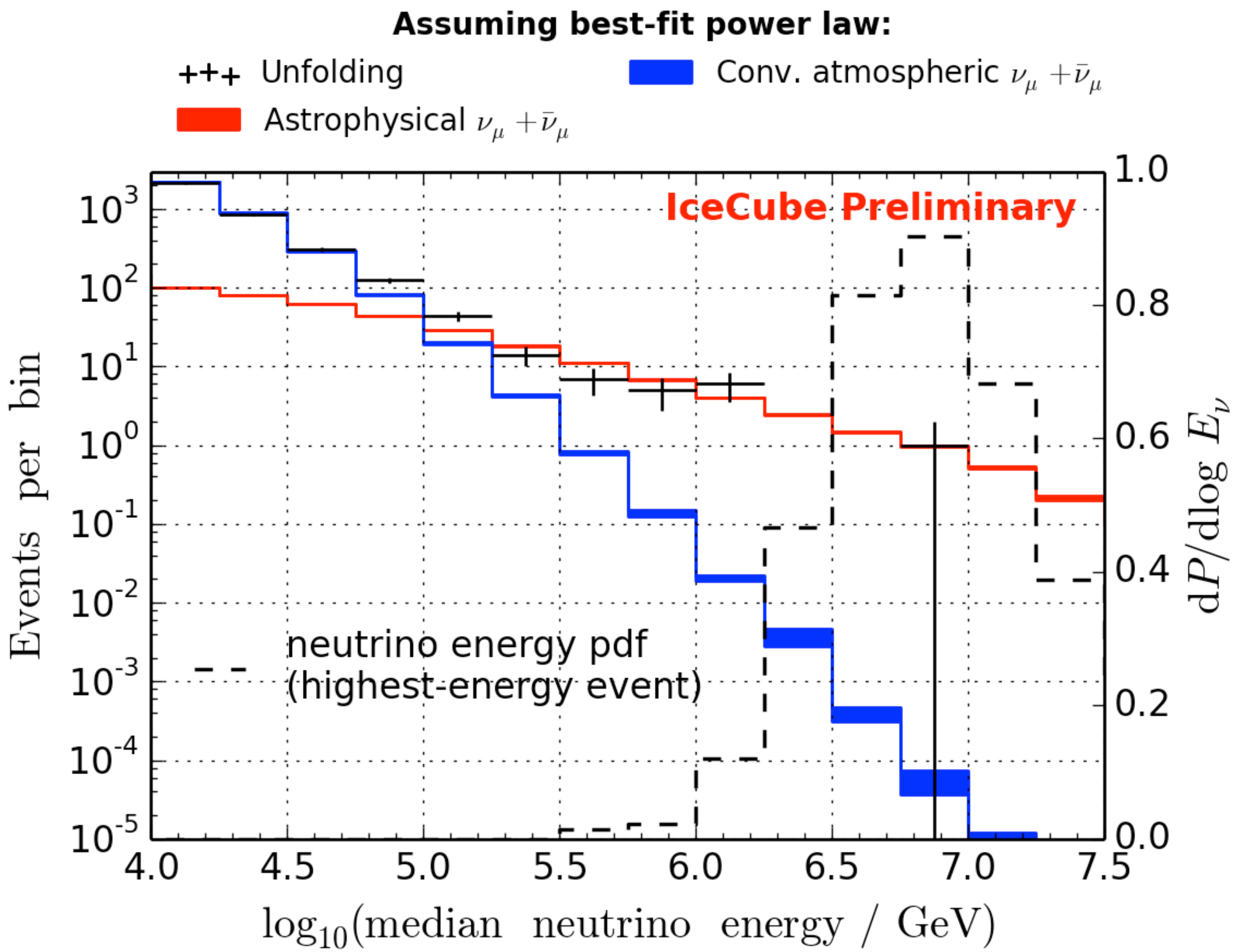
cosmic

100 TeV

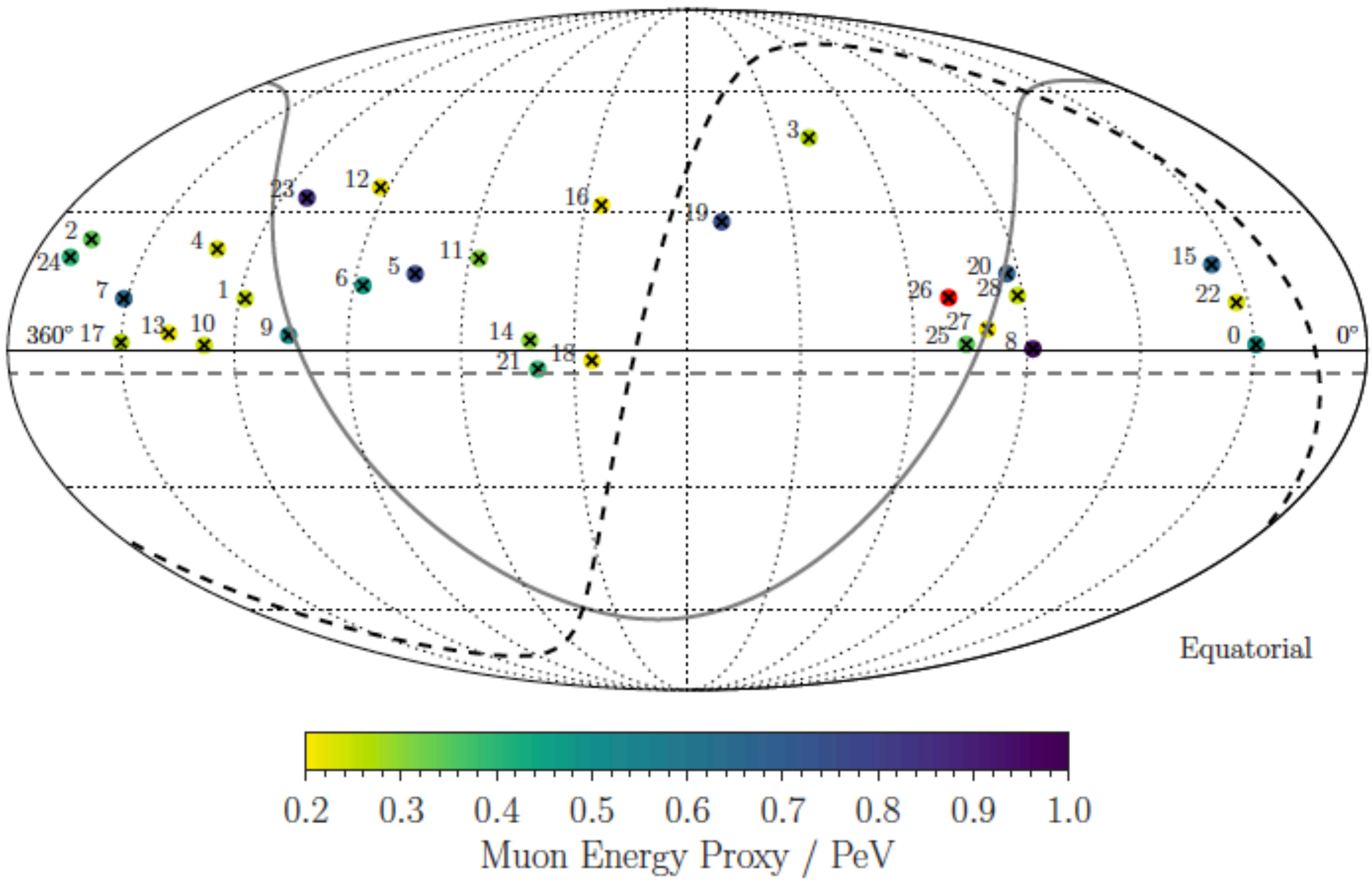

2.6 ± 0.3 PeV
inside detector


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

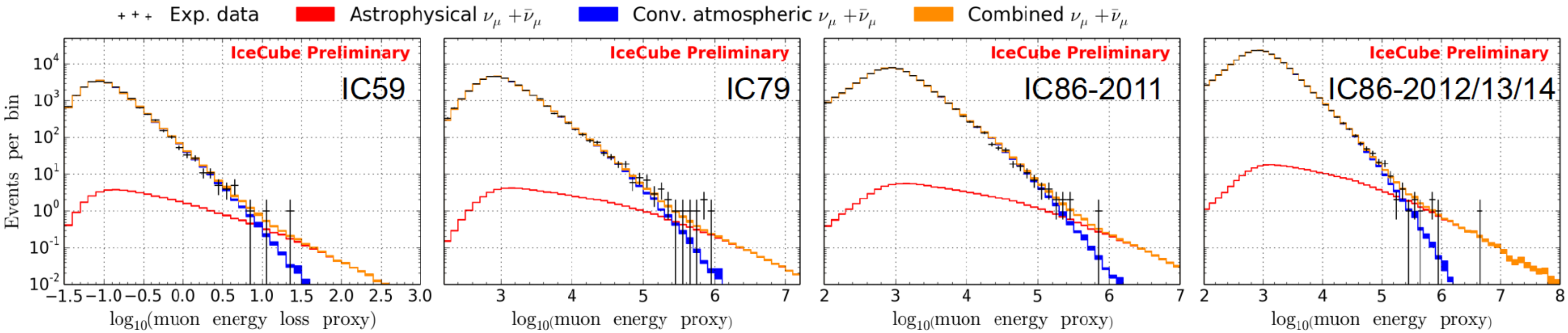
~550 cosmic neutrinos in a background of ~340,000 atmospheric

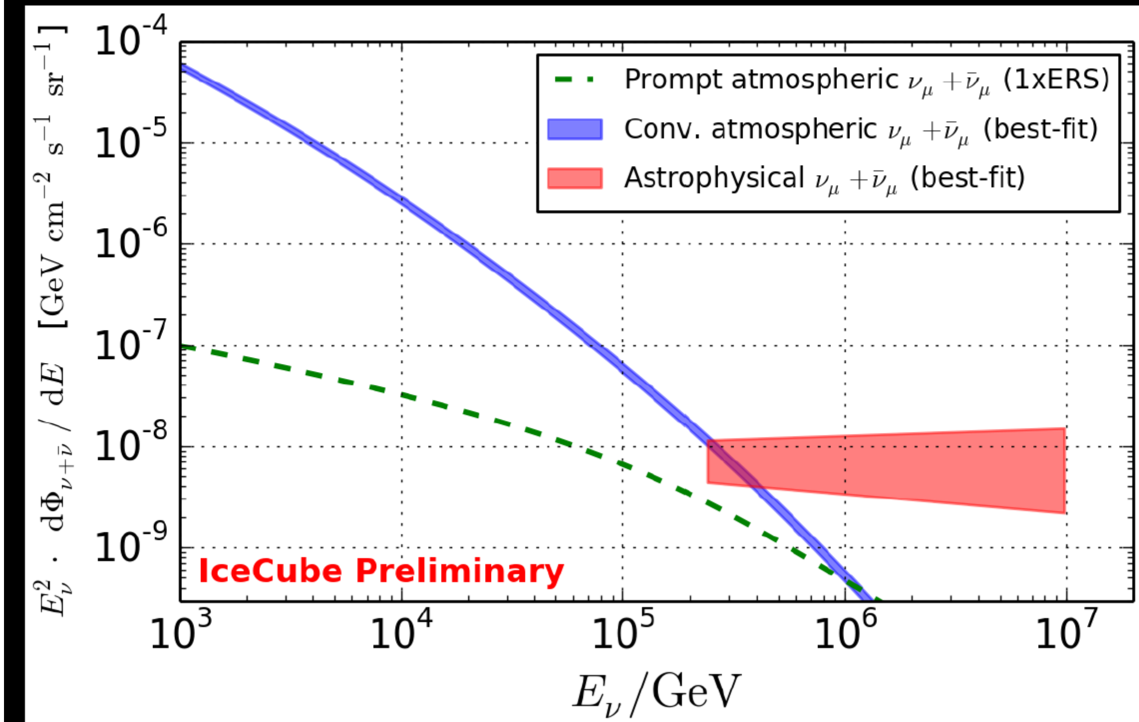


highest energy ν_μ: astronomy with 0.2-0.4 degree resolution !
events above 200 TeV only



after 7 years → 6 sigma





- Best-fit astrophysical normalization:

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

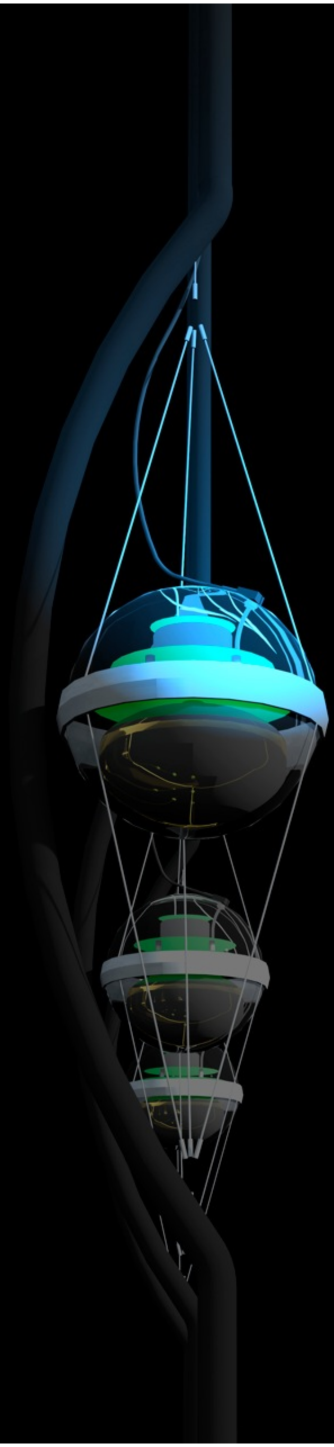
- Best-fit spectral index:

  γ_{astro} = 2.16 ± 0.11

- Energy ranges:

  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ



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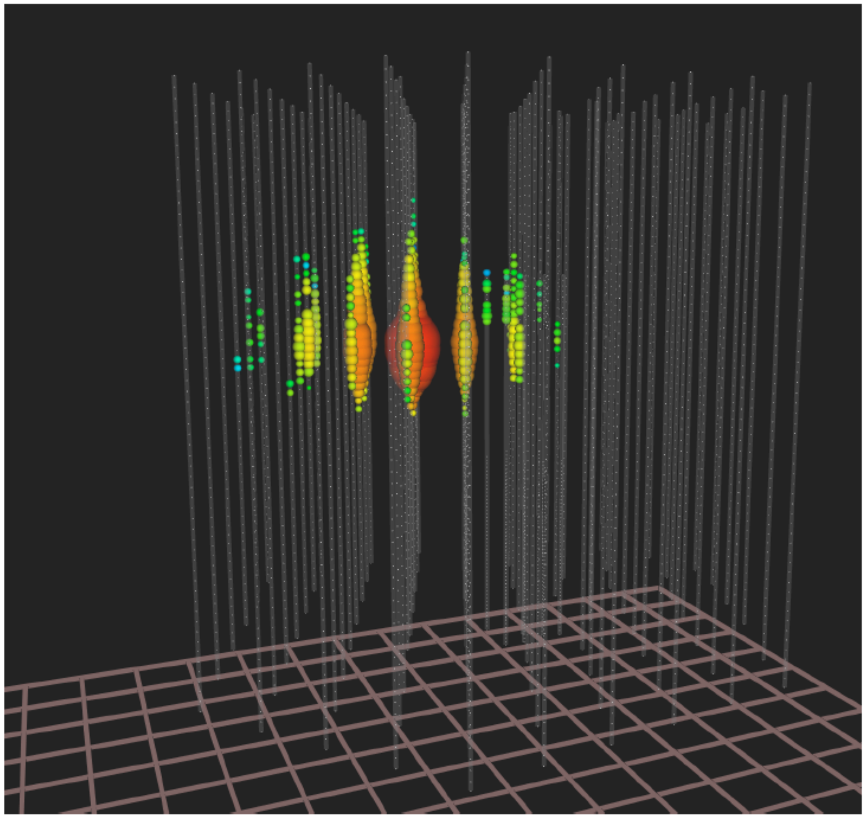
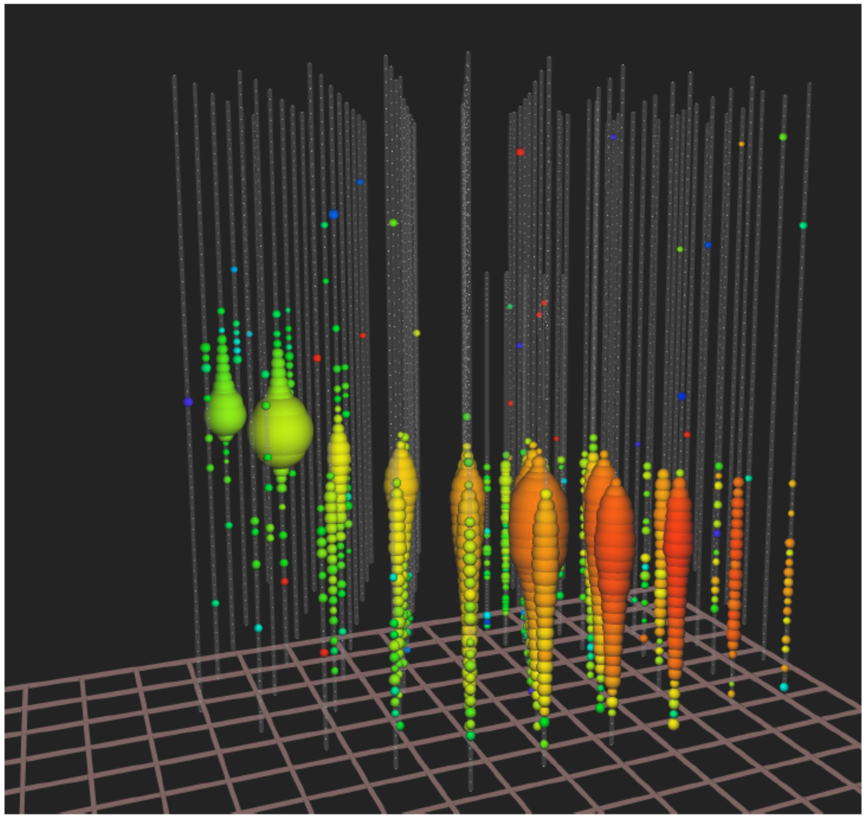
isolated neutrinos interacting inside the detector

up-going muon tracks



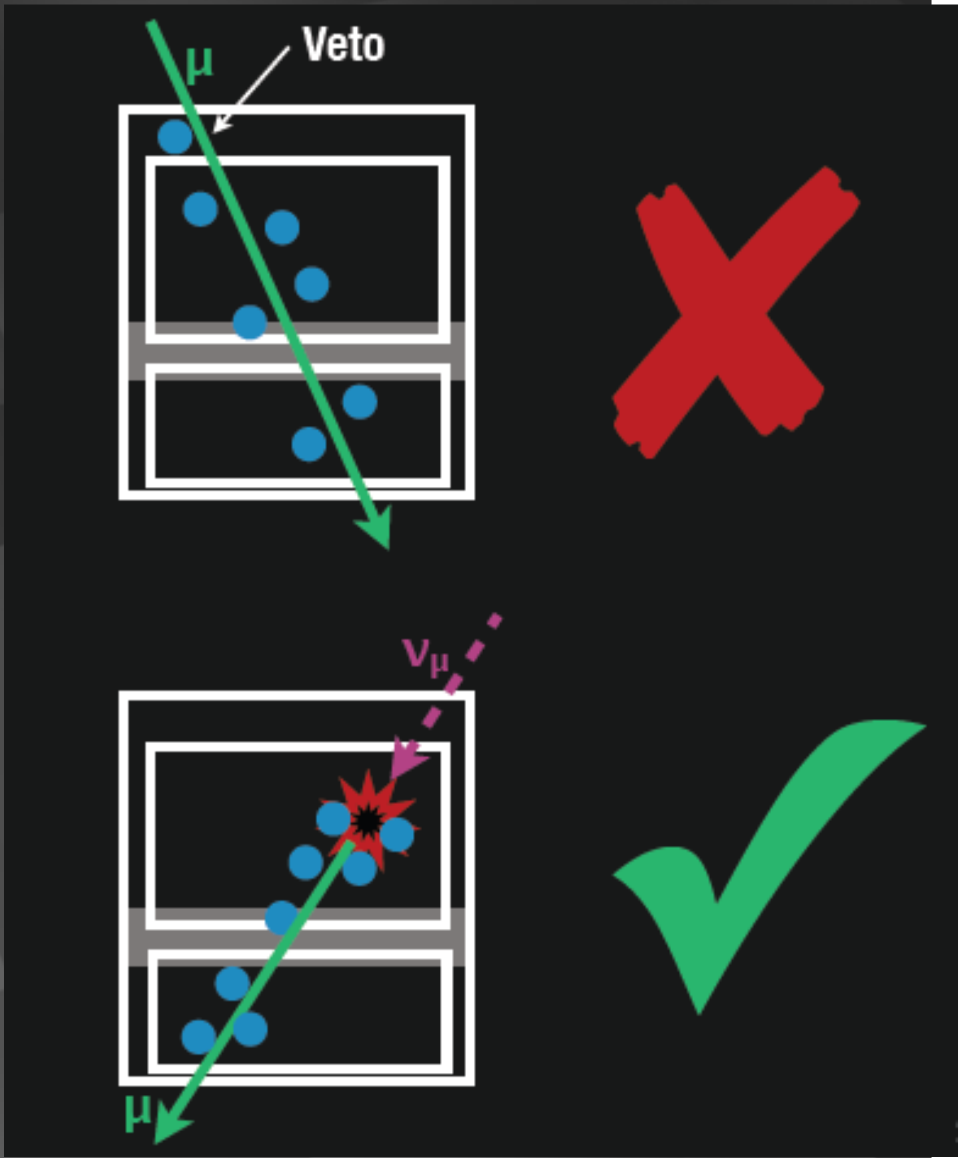


calorimetry: direct energy measurement; all flavors

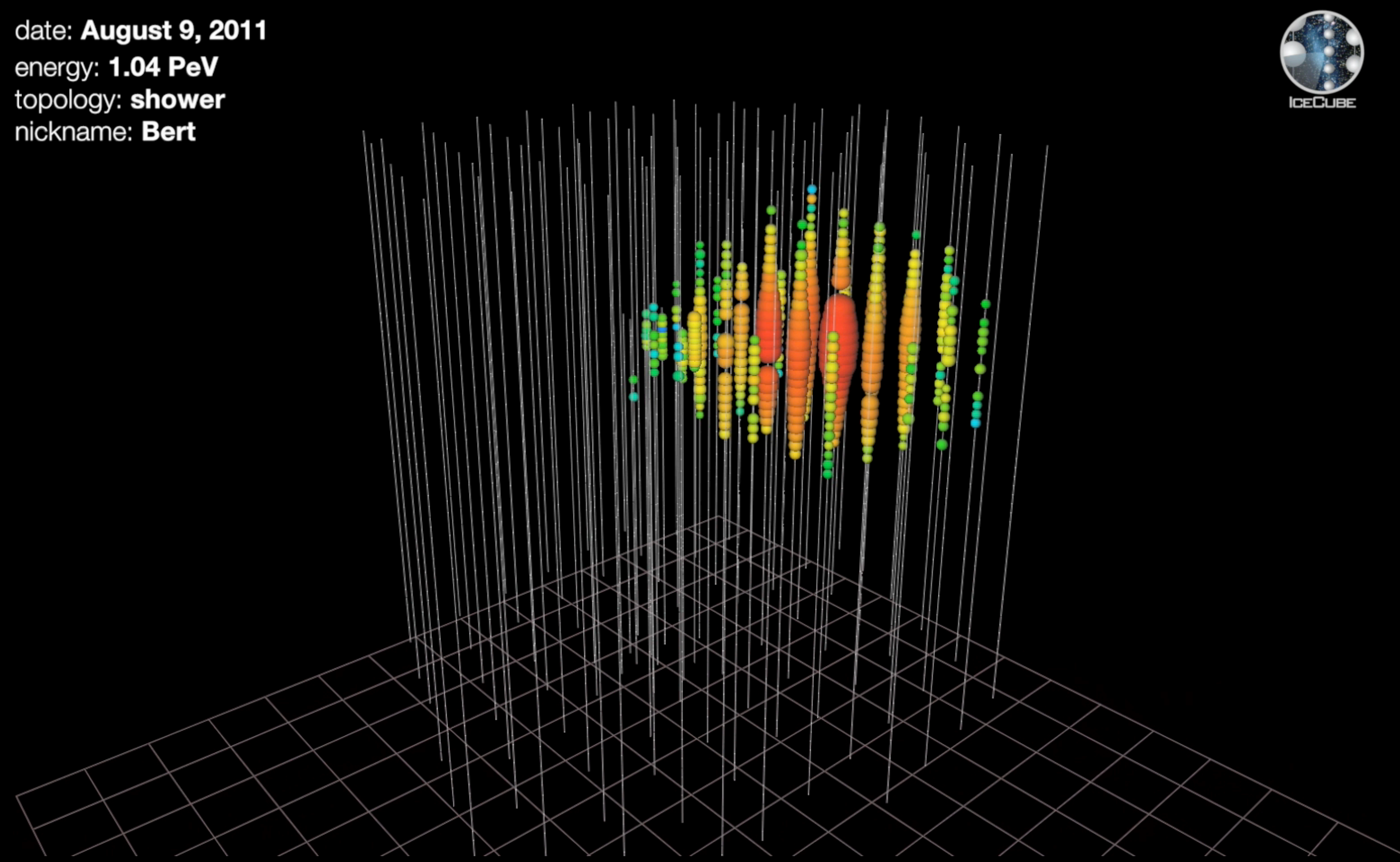
astronomy: angular resolution superior

neutrinos starting inside the detector

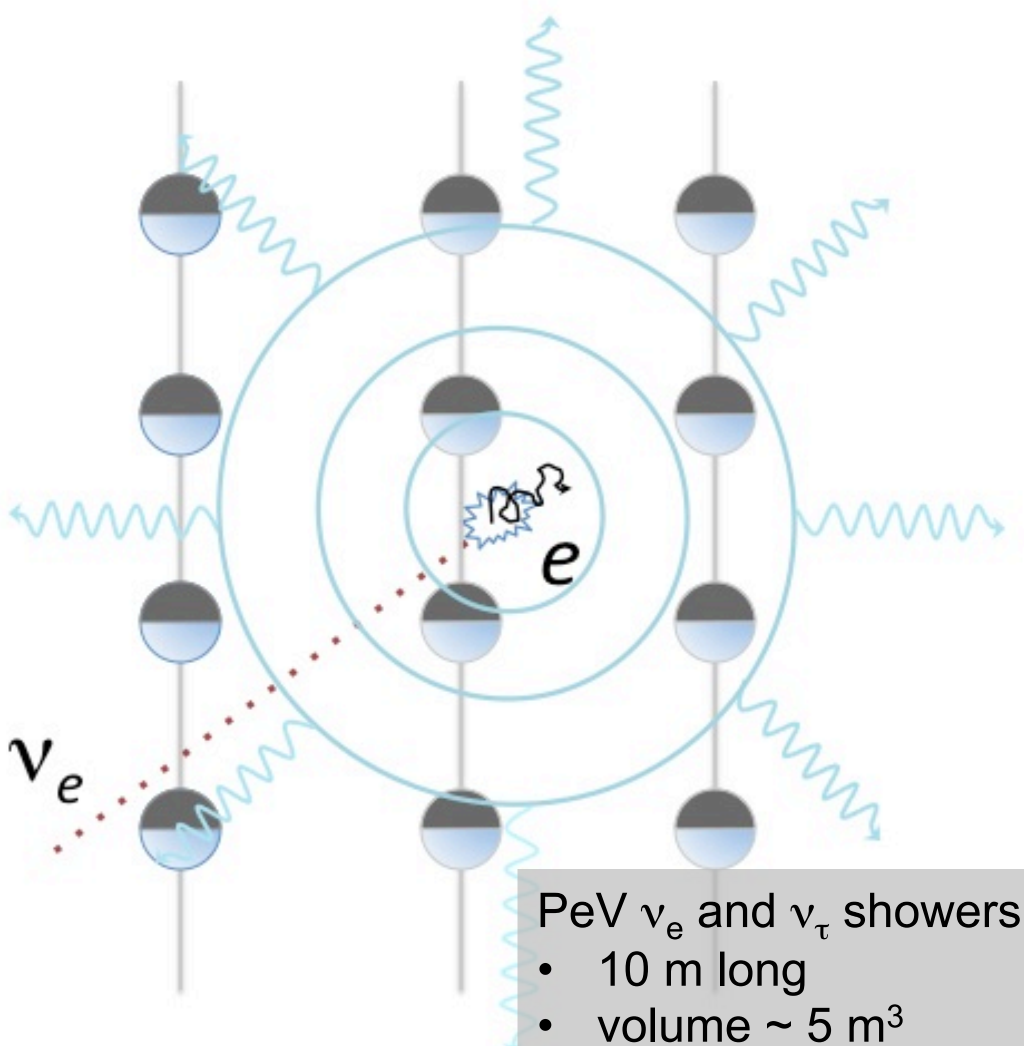
- ✓ no light in the veto region
- ✓ veto for atmospheric neutrinos that are typically accompanied by muons
- ✓ energy measurement: to-tal absorption calorimetry
- ✓ all sky, all flavors



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

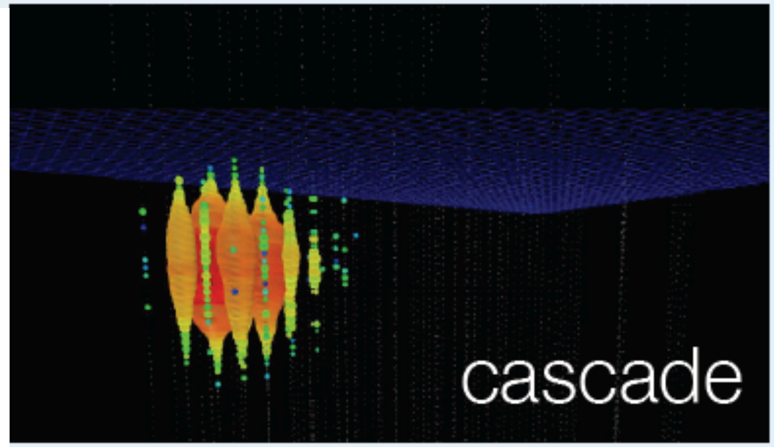


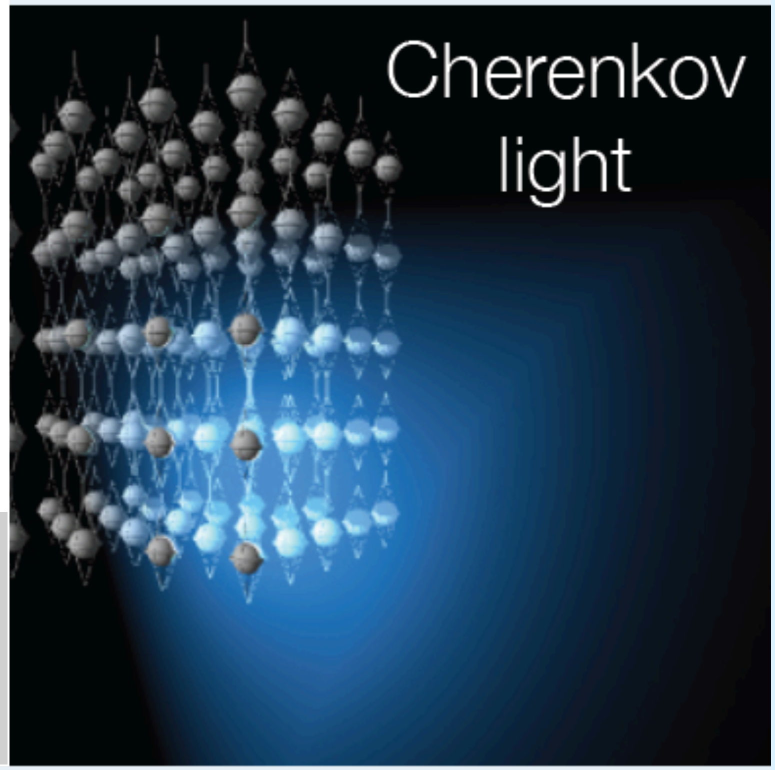
tracks and showers

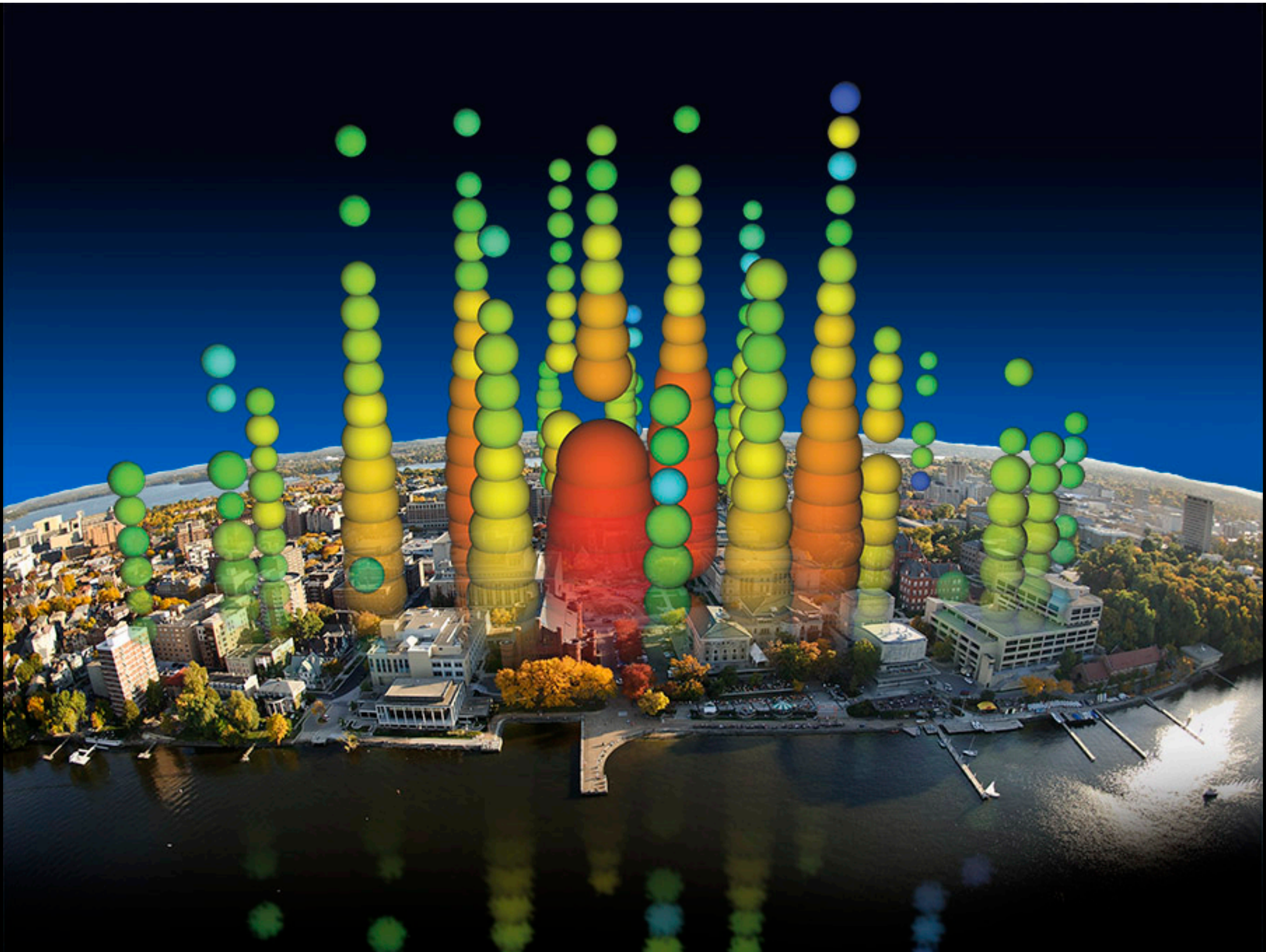


PeV ν_e and ν_τ showers:

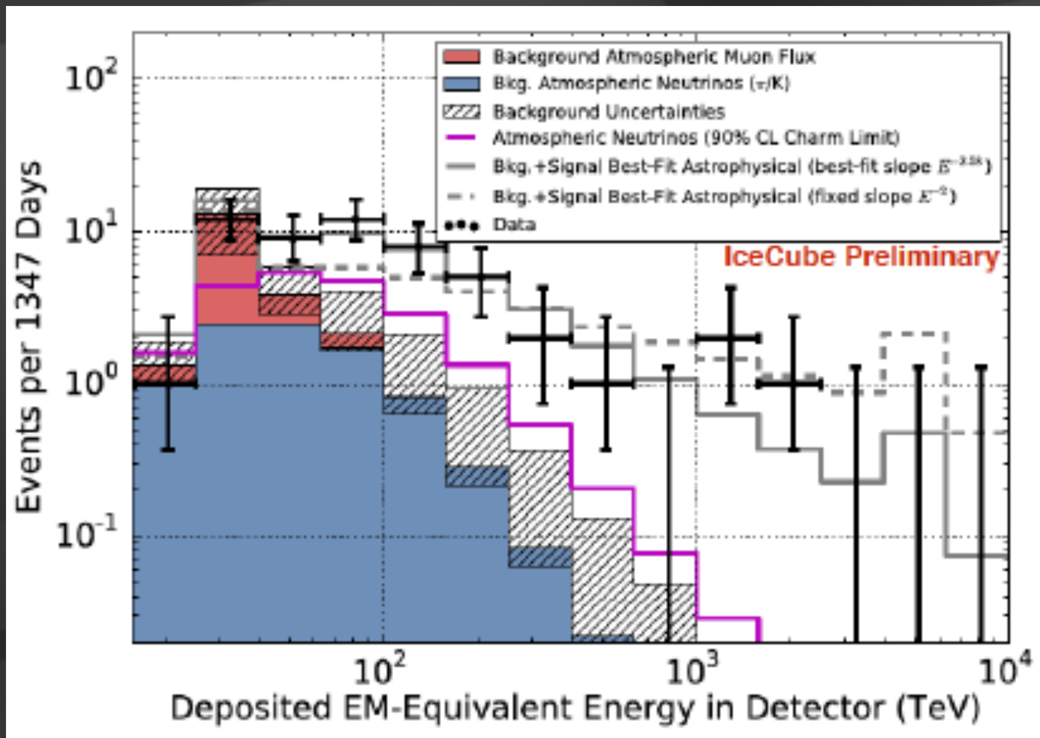
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



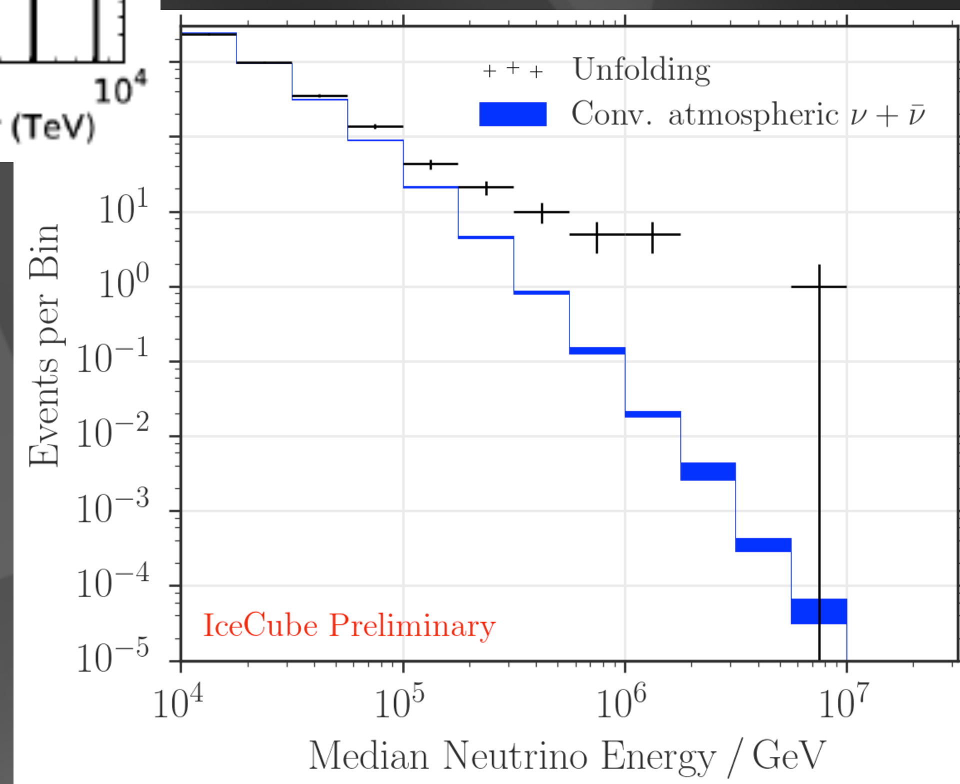




- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

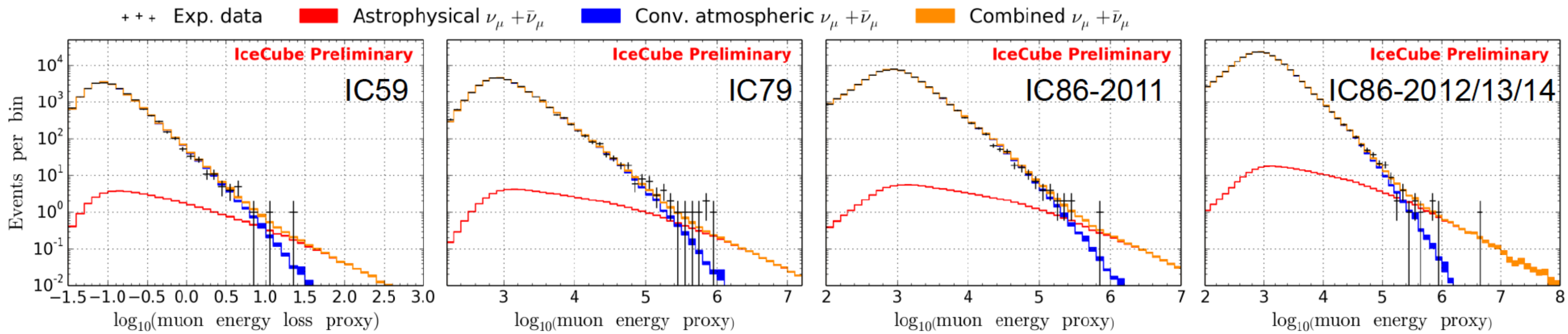


confirmation!
flux of muon neutrinos
through the Earth (6σ)



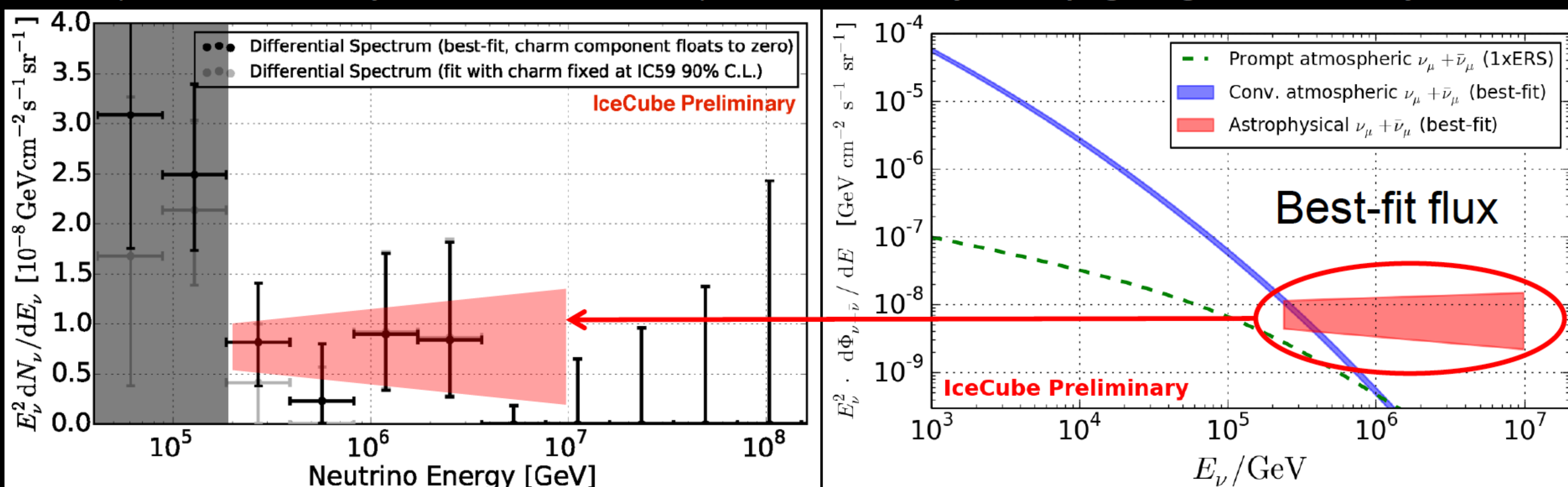
neutrinos of all flavors
interacting inside
IceCube (7σ)

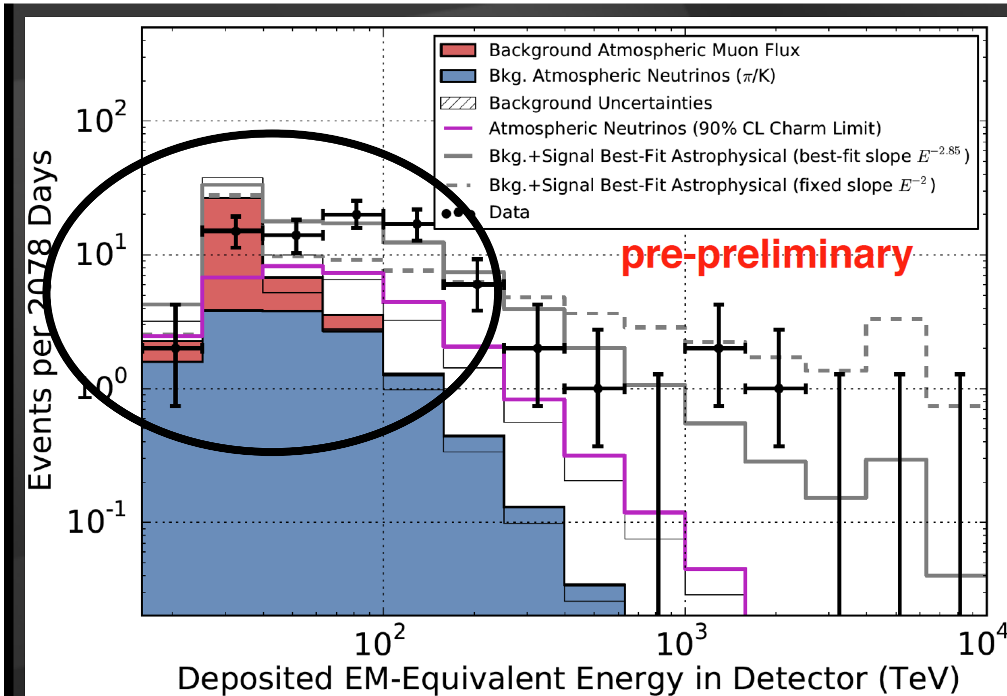
after 6 years: 3.7→ 6.0 sigma



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

6 year up-going numu analysis





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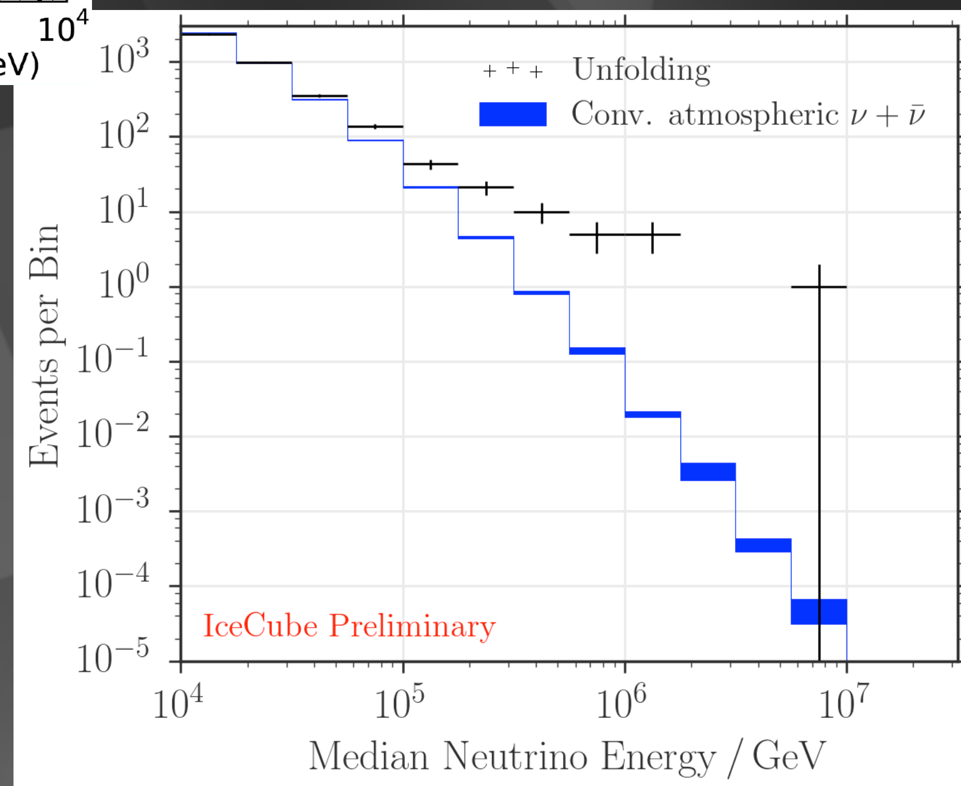
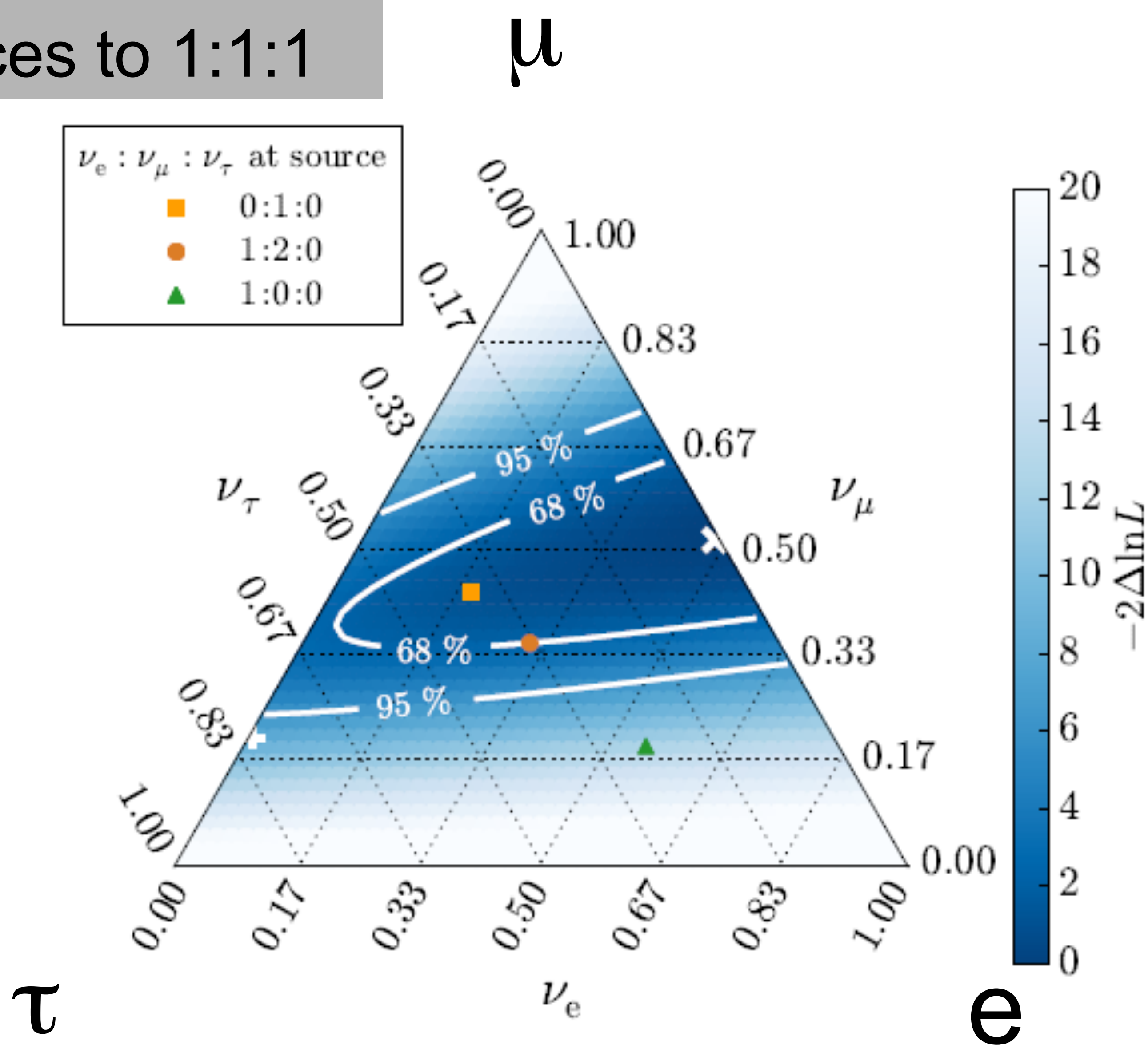
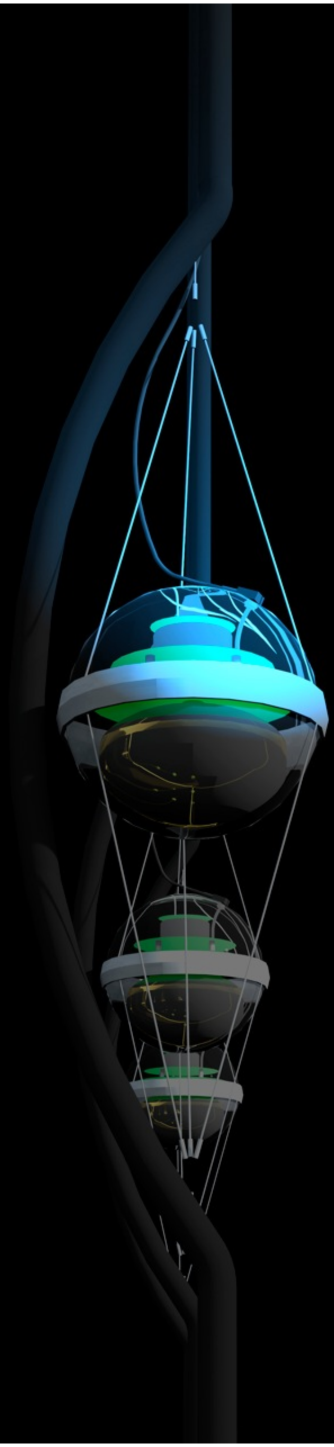


neutrinos of all flavors
interacting inside
IceCube

oscillate over cosmic distances to 1:1:1





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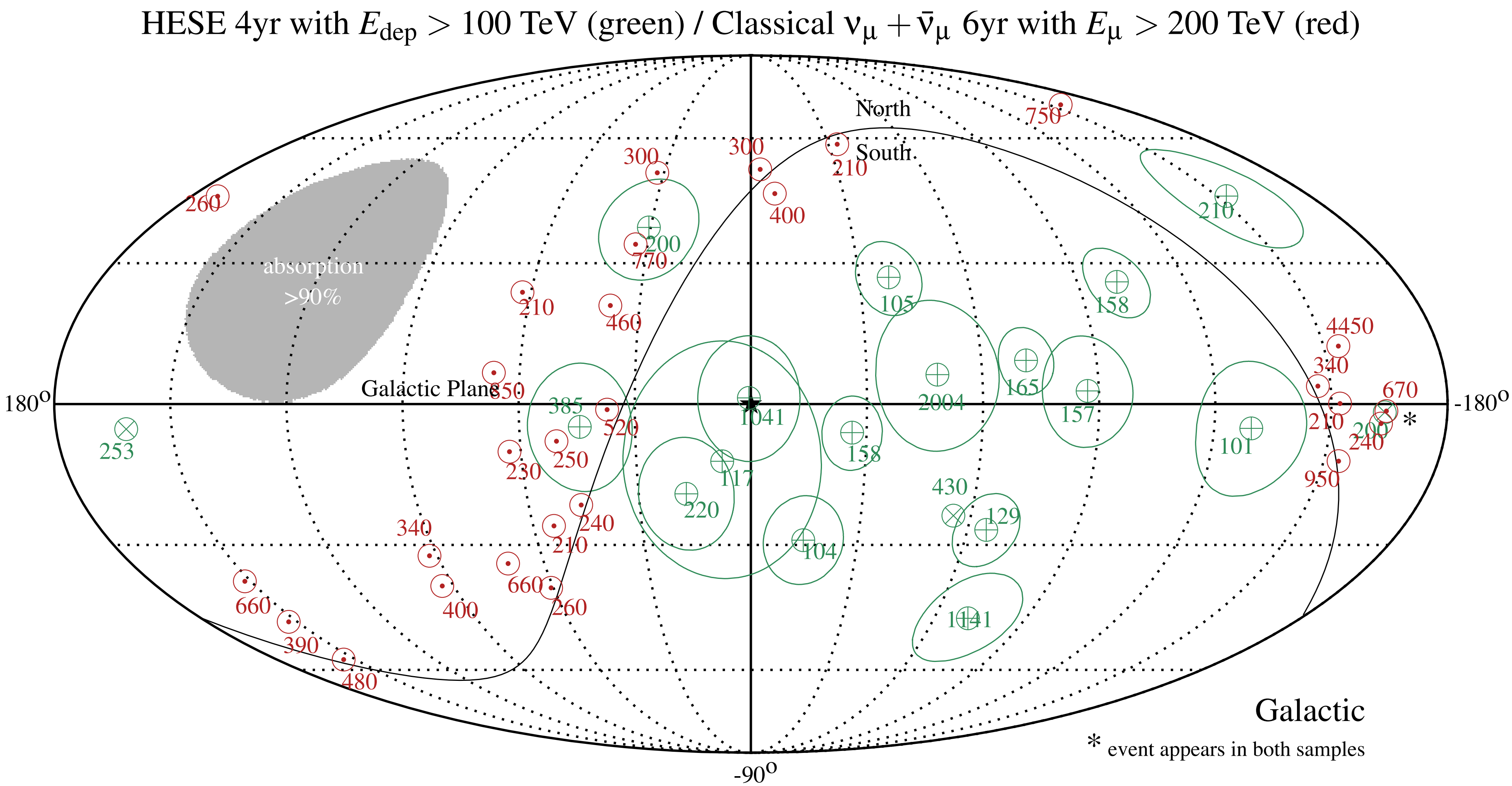
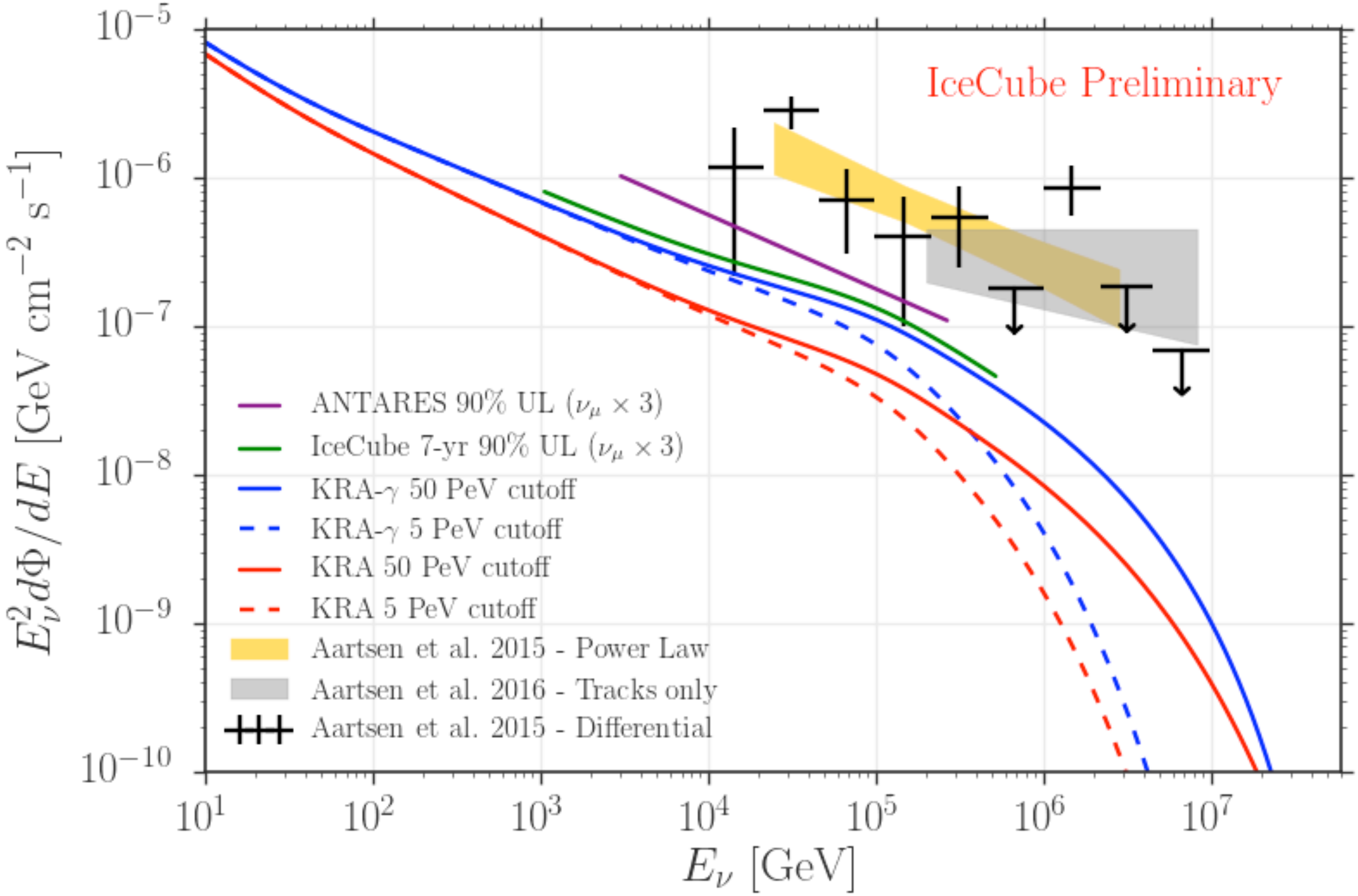


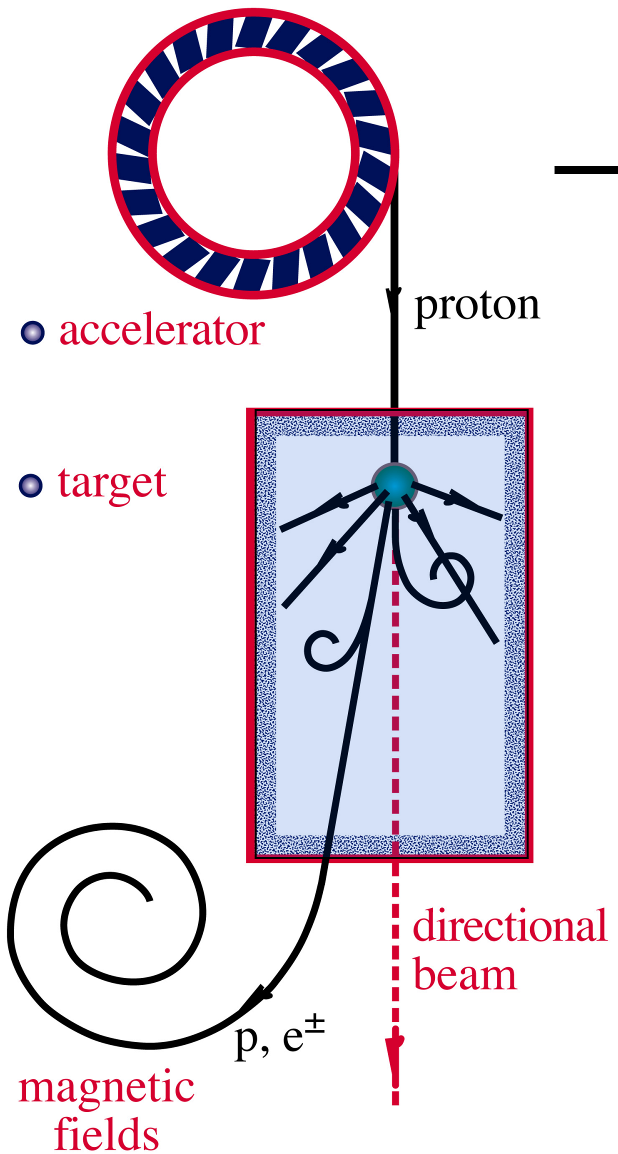
HESE 4yr with $E_{dep} > 100$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with $E_\mu > 200$ TeV (red)
North
South
absorption
>90%
Galactic Plane
180°
-180°
-90°
Galactic
* event appears in both samples



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

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)
- where are the PeV gamma rays that accompany PeV neutrinos?

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

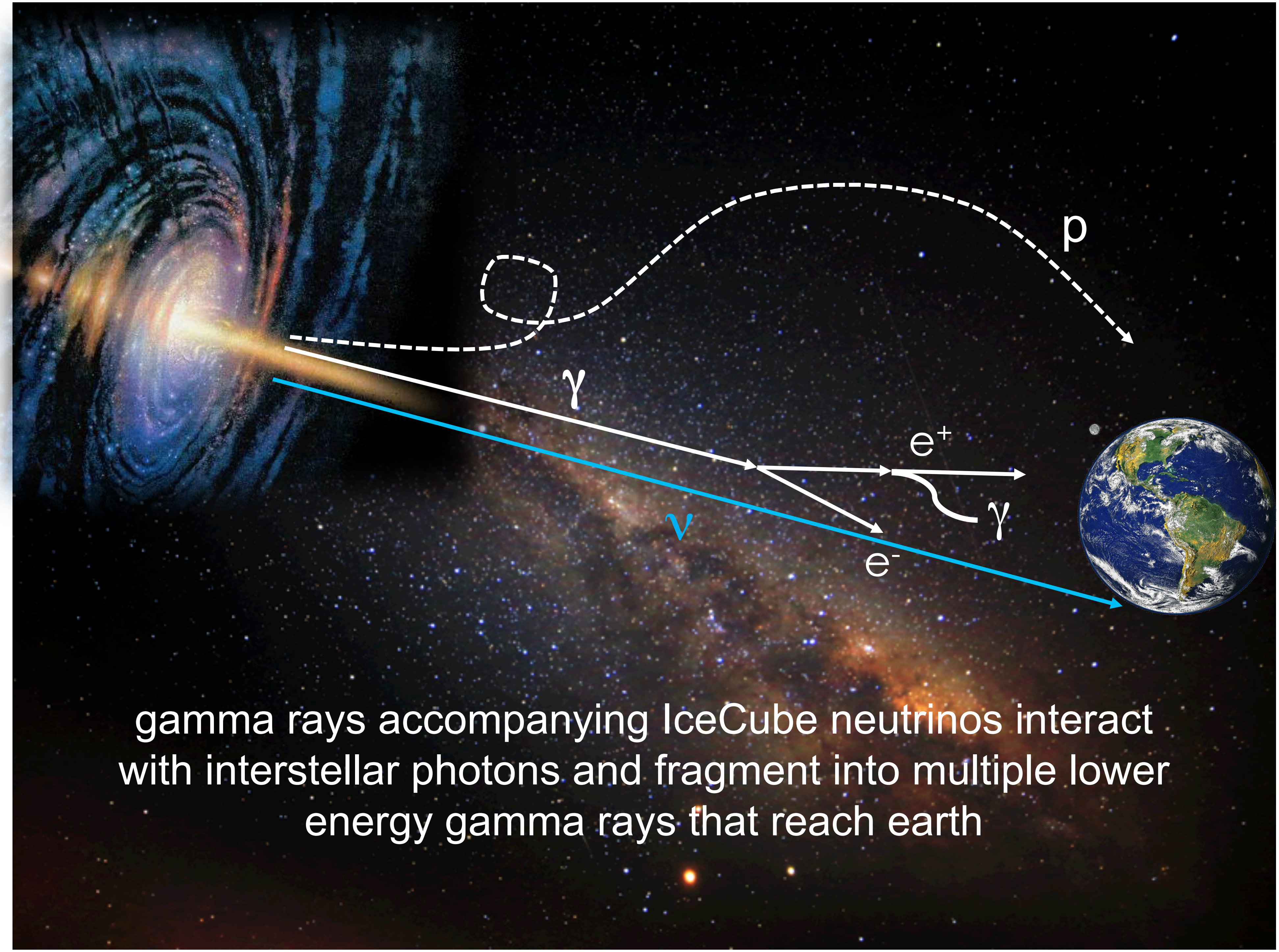
radiation and dust

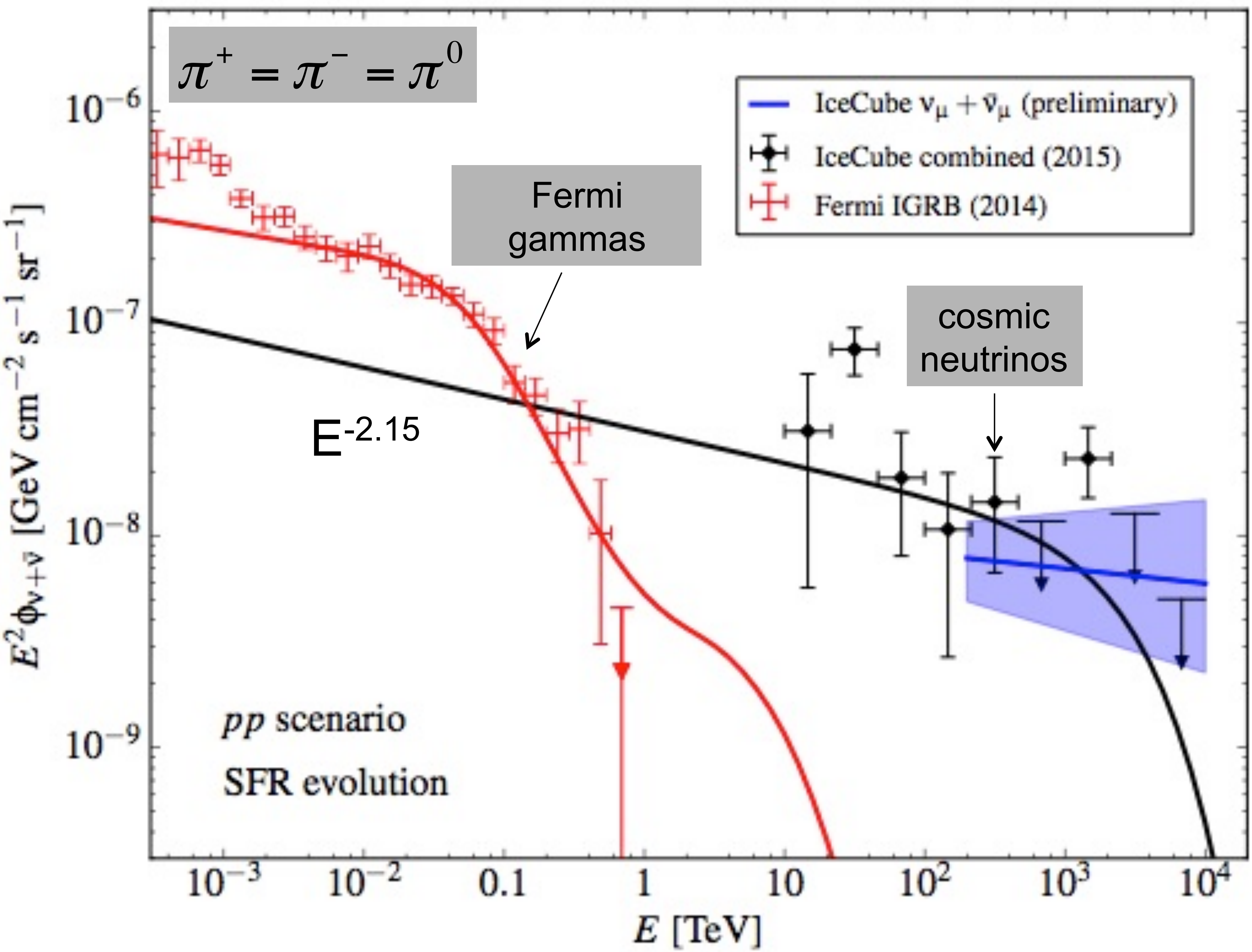
$$p + \gamma \rightarrow n + \pi^{+}$$

~ cosmic ray + neutrino

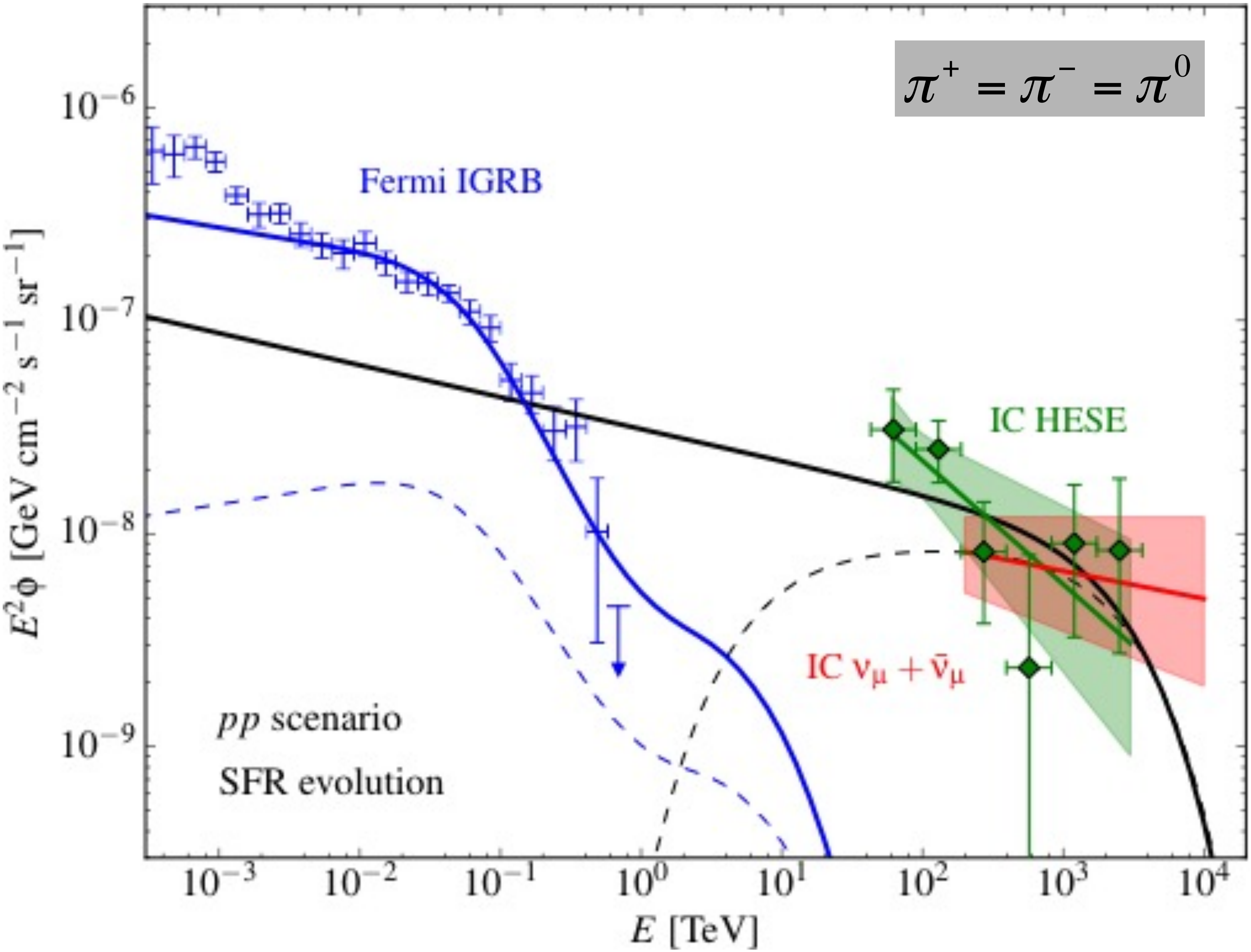
$$\rightarrow p + \pi^{0}$$

~ cosmic ray + gamma

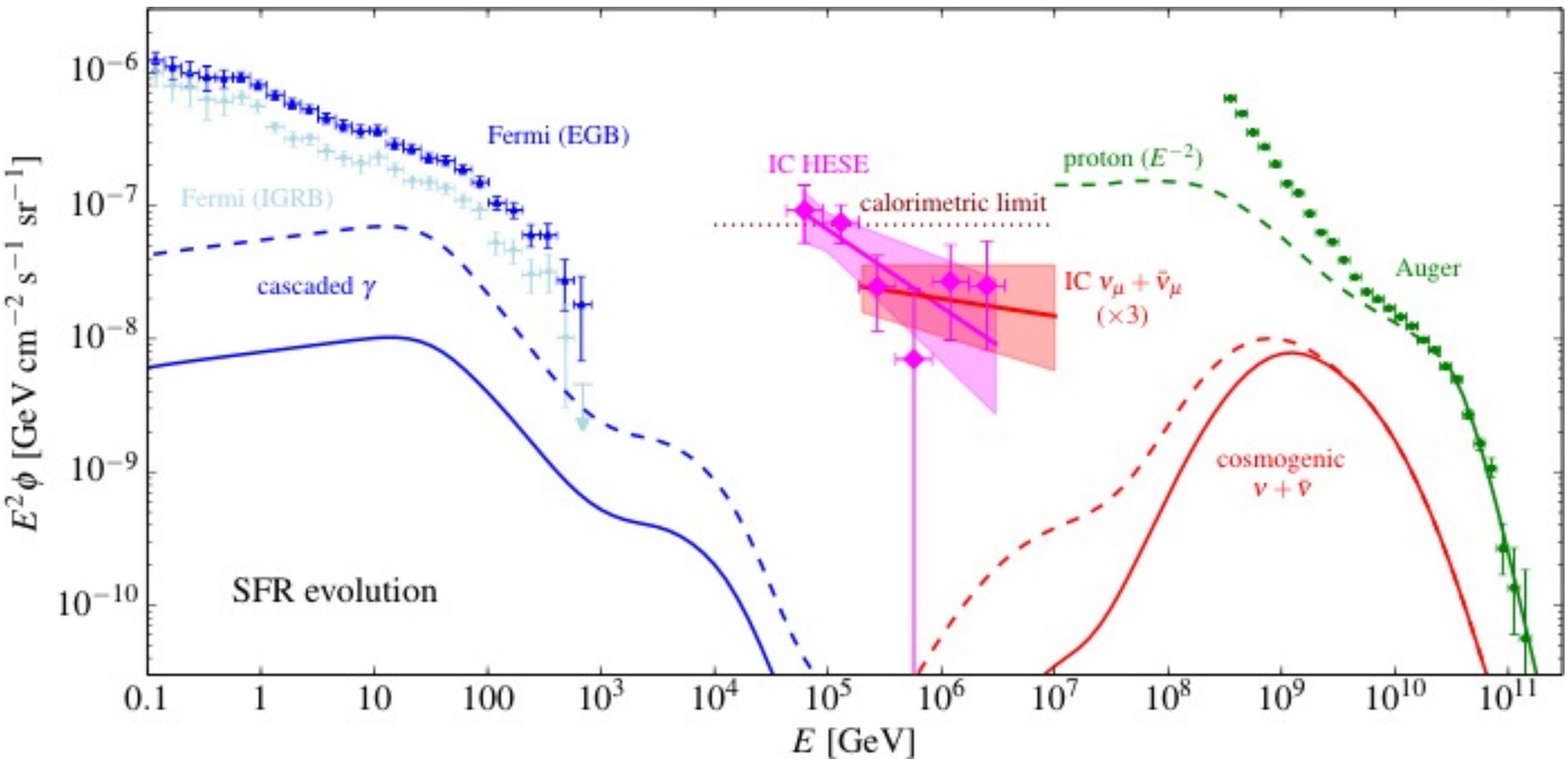

p
γ
e+
γ
ν
e-
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 \phi_{\nu+\bar{\nu}}$ [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
10^4



$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
IC HESE
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}

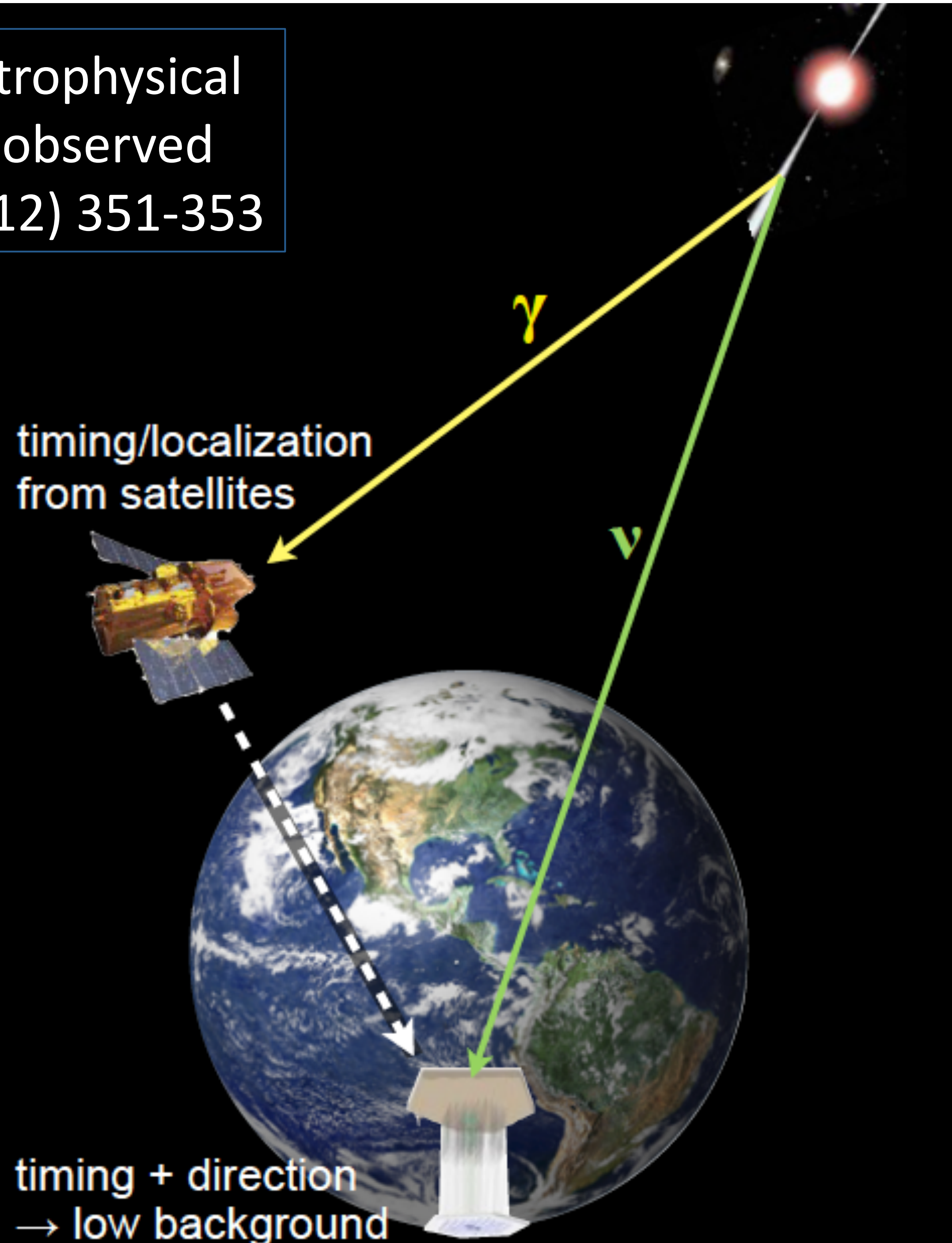


Fermi (EGB)
Fermi (IGRB)
cascaded γ
IC HESE
calorimetric limit
IC $\nu_\mu + \bar{\nu}_\mu$
($\times 3$)
proton (E^{-2})
Auger
cosmogenic
$\nu + \bar{\nu}$
SFR evolution
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
100
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}

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

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

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



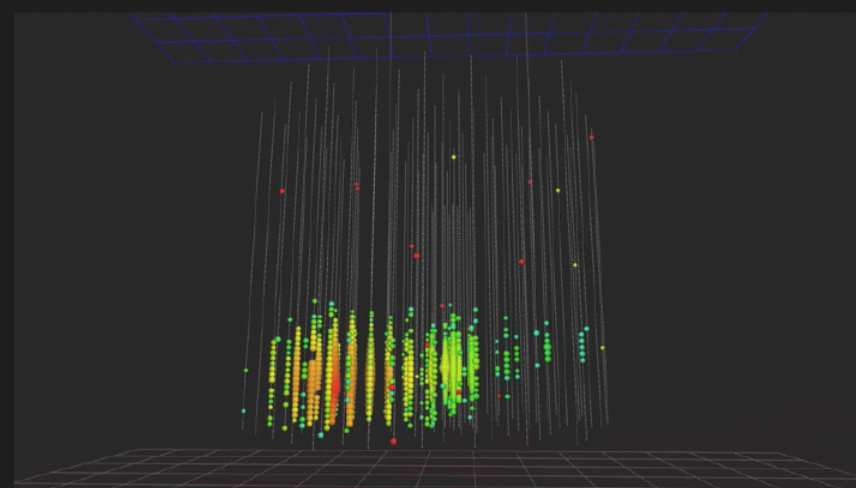
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

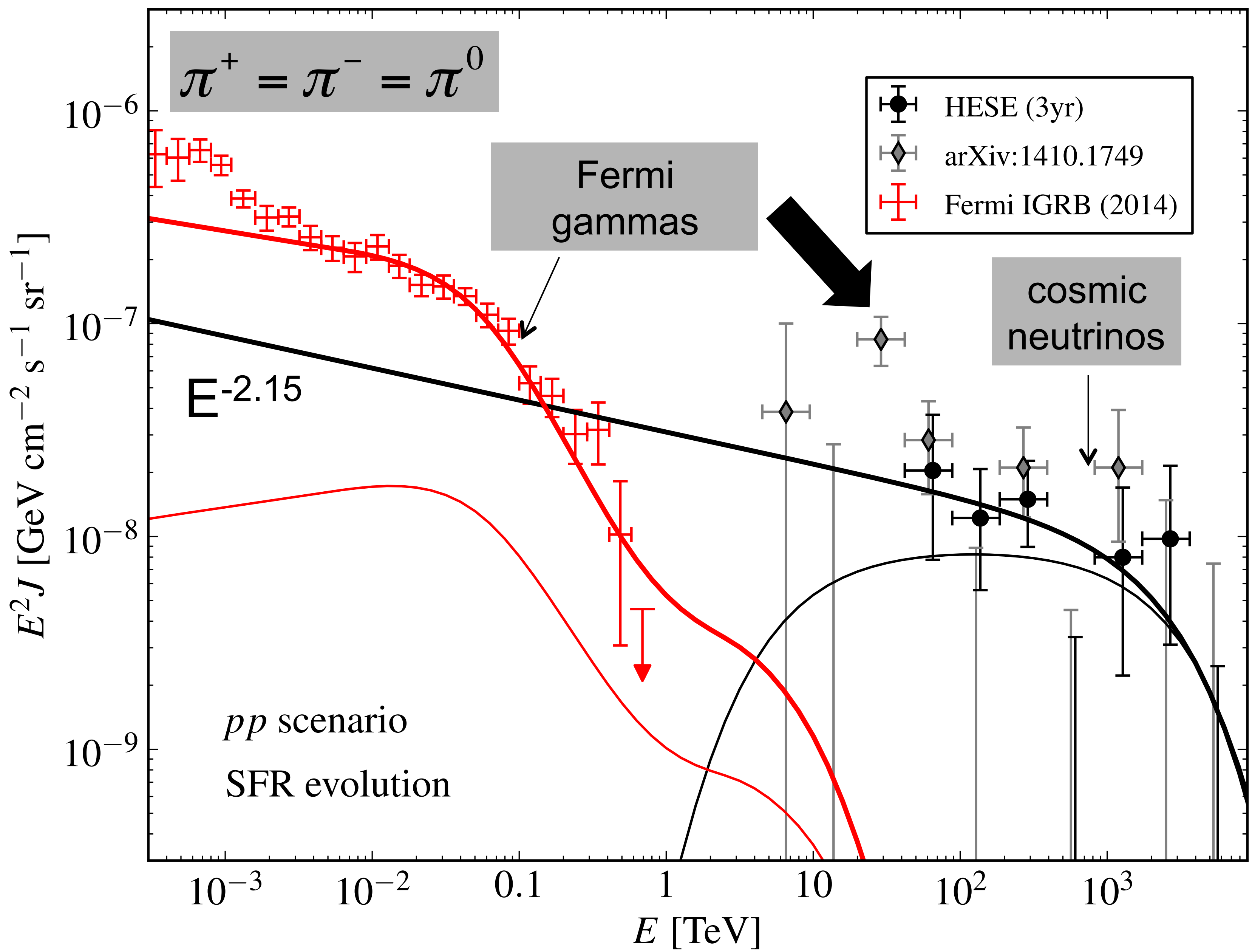
We send our high-energy events in real-time as public GCN alerts now!

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

GCN notice for starting track sent Apr 27

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

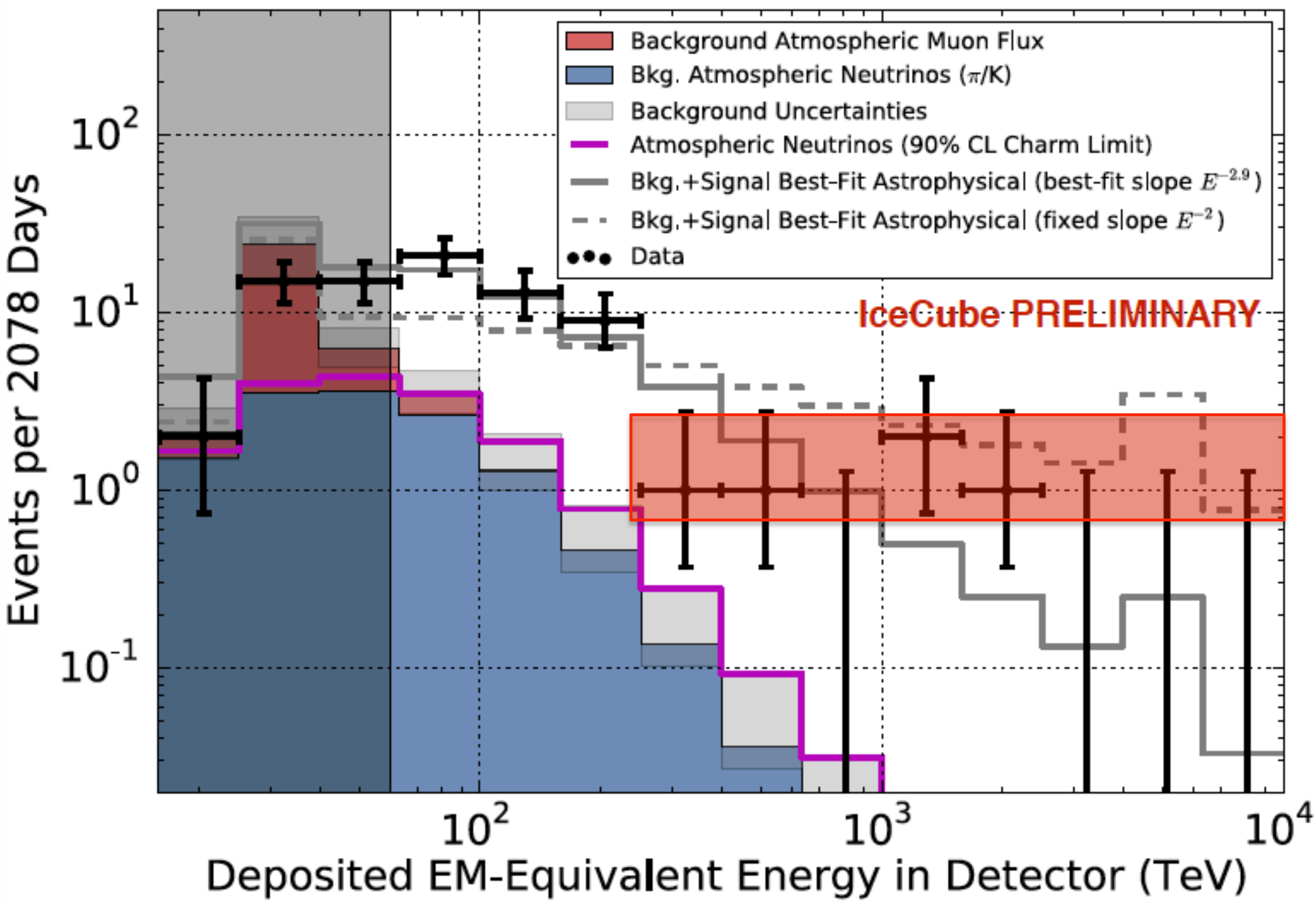




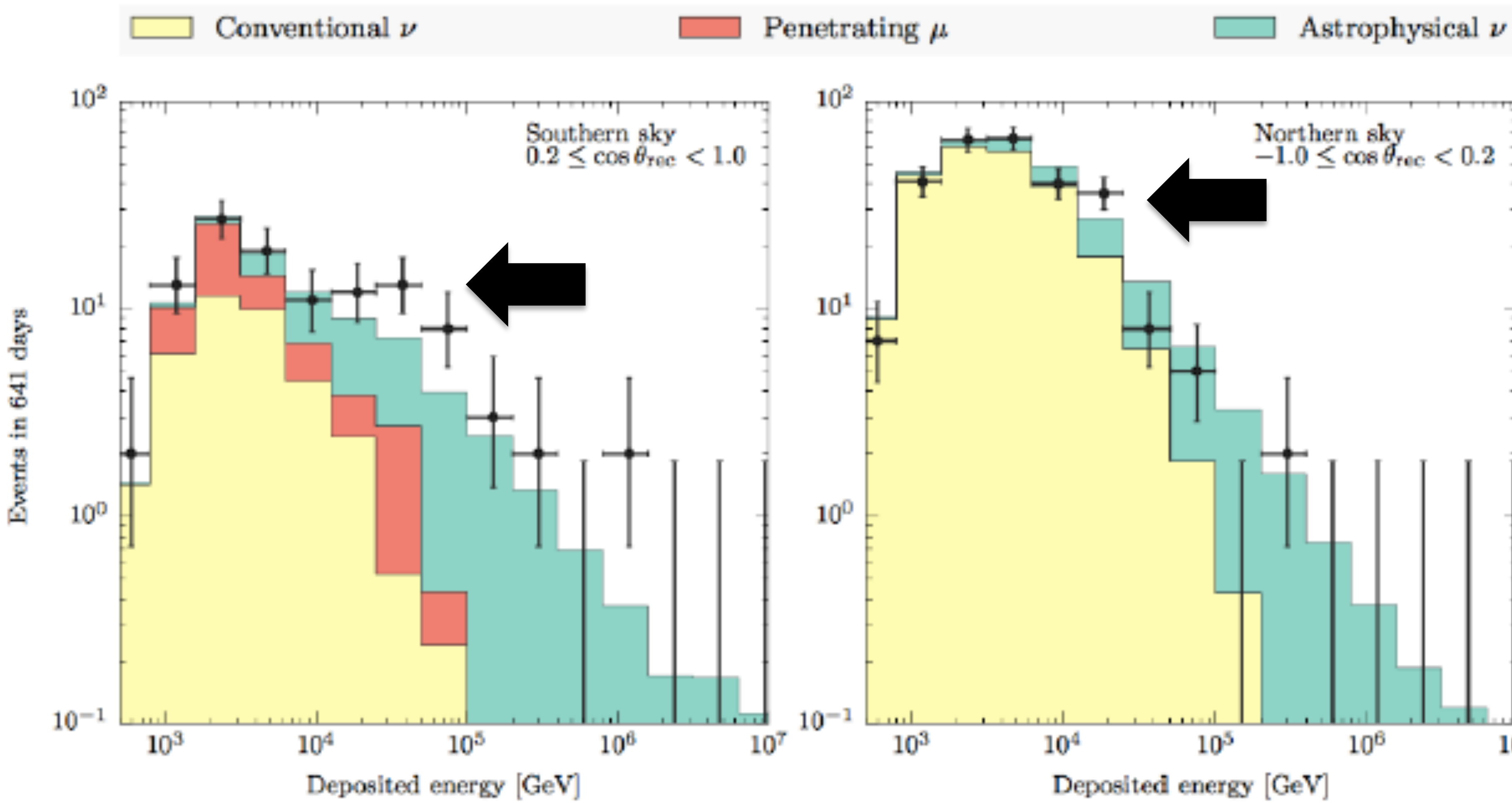
$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]

- there is more

comparison HESE and muon results (red overlay)



towards lower energies: a second component?



warning:

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

PeV neutrinos absorbed in the Earth

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

- Galactic sources?

Detector Complementarity

Wide-field / Continuous Operation

VHE Sensitivity

Fermi, AGILE, EGRET

HAWC, ARGO, Milagro

VERITAS, HESS, MAGIC

Space-Based

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

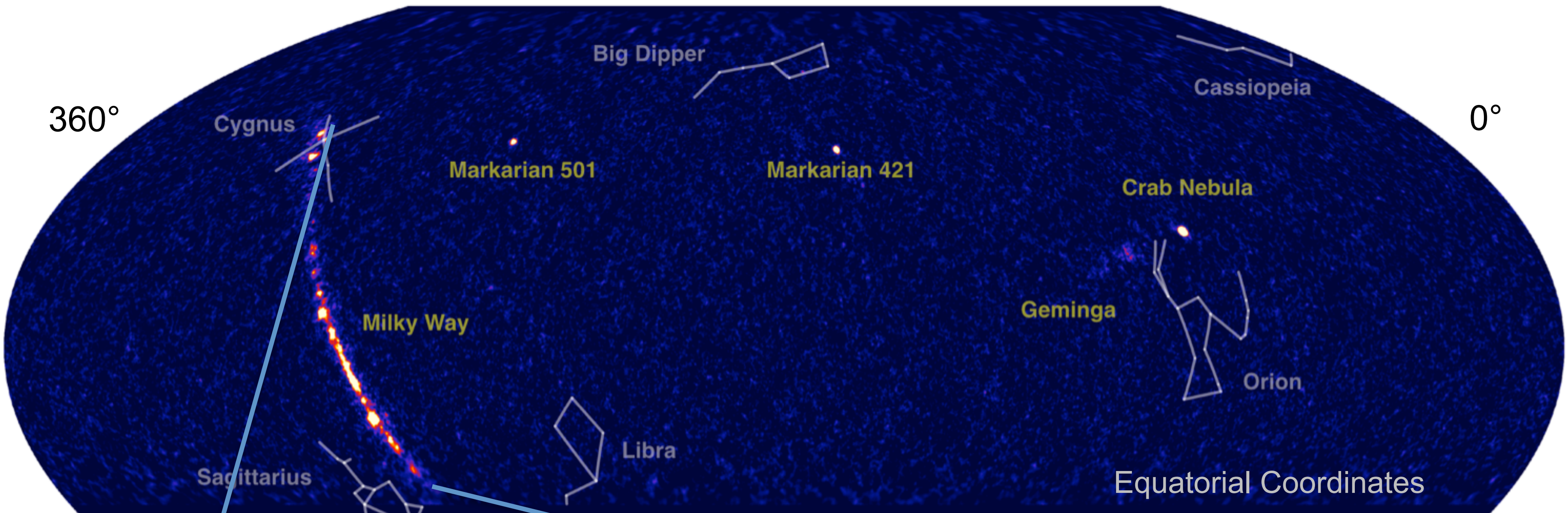
Ground Arrays

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

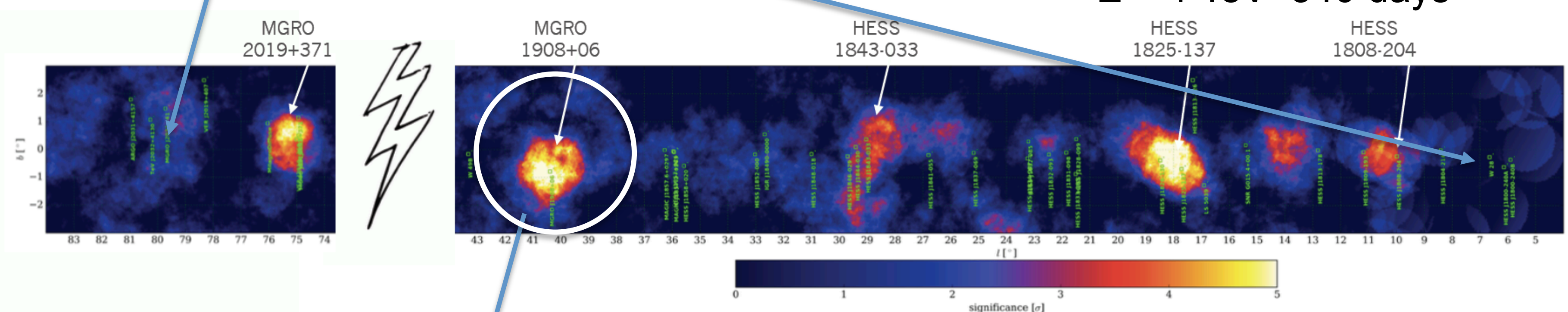
IACTs

- Excellent pointing
- Highest energies
- Surveys limited

HAWC View of Gamma Ray Sky



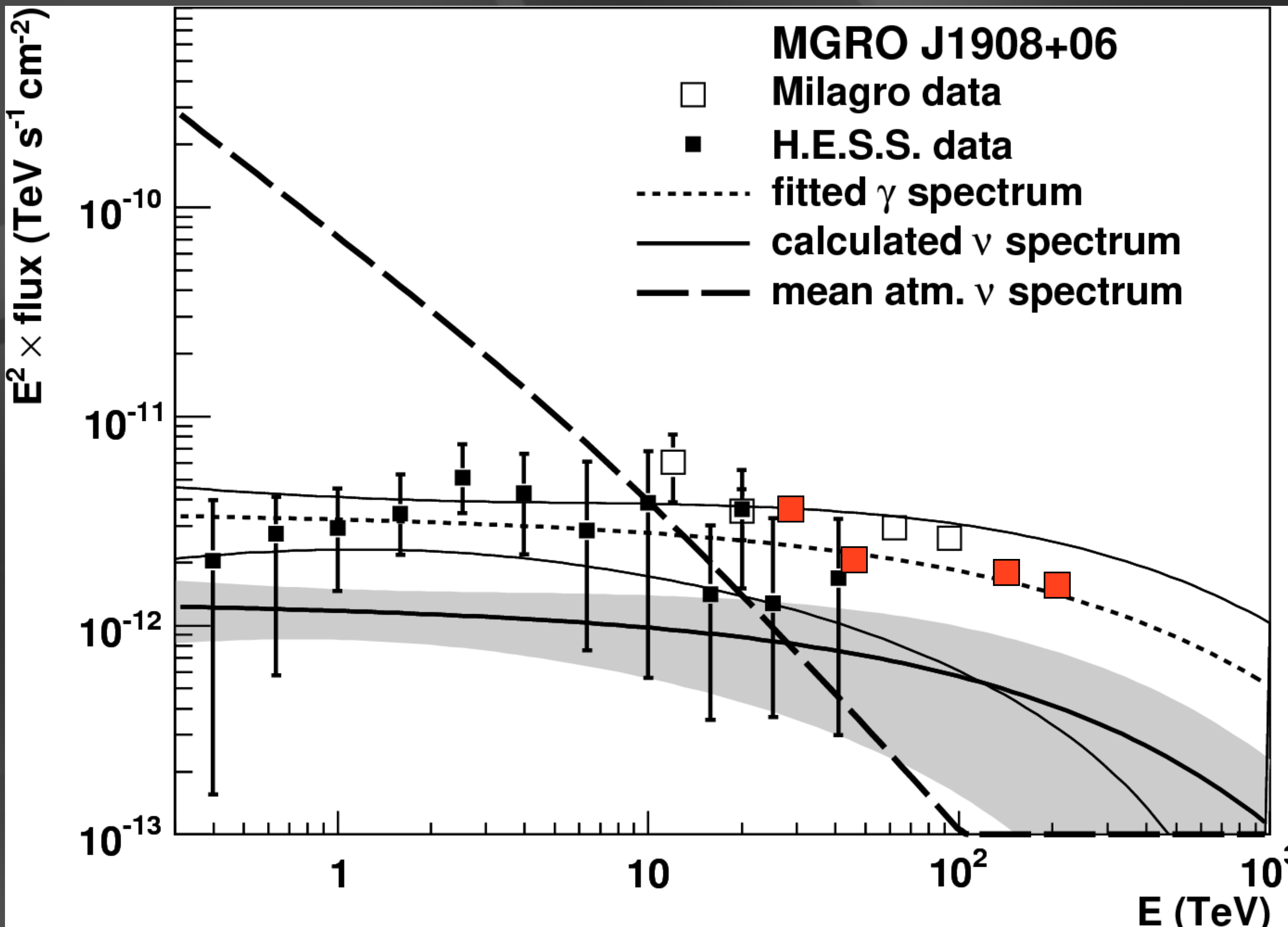
E > 1 TeV 340 days



MGRO J1908+06

HAWC sky above 55 TeV

MGRO J1908+06: the first Pevatron? (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.

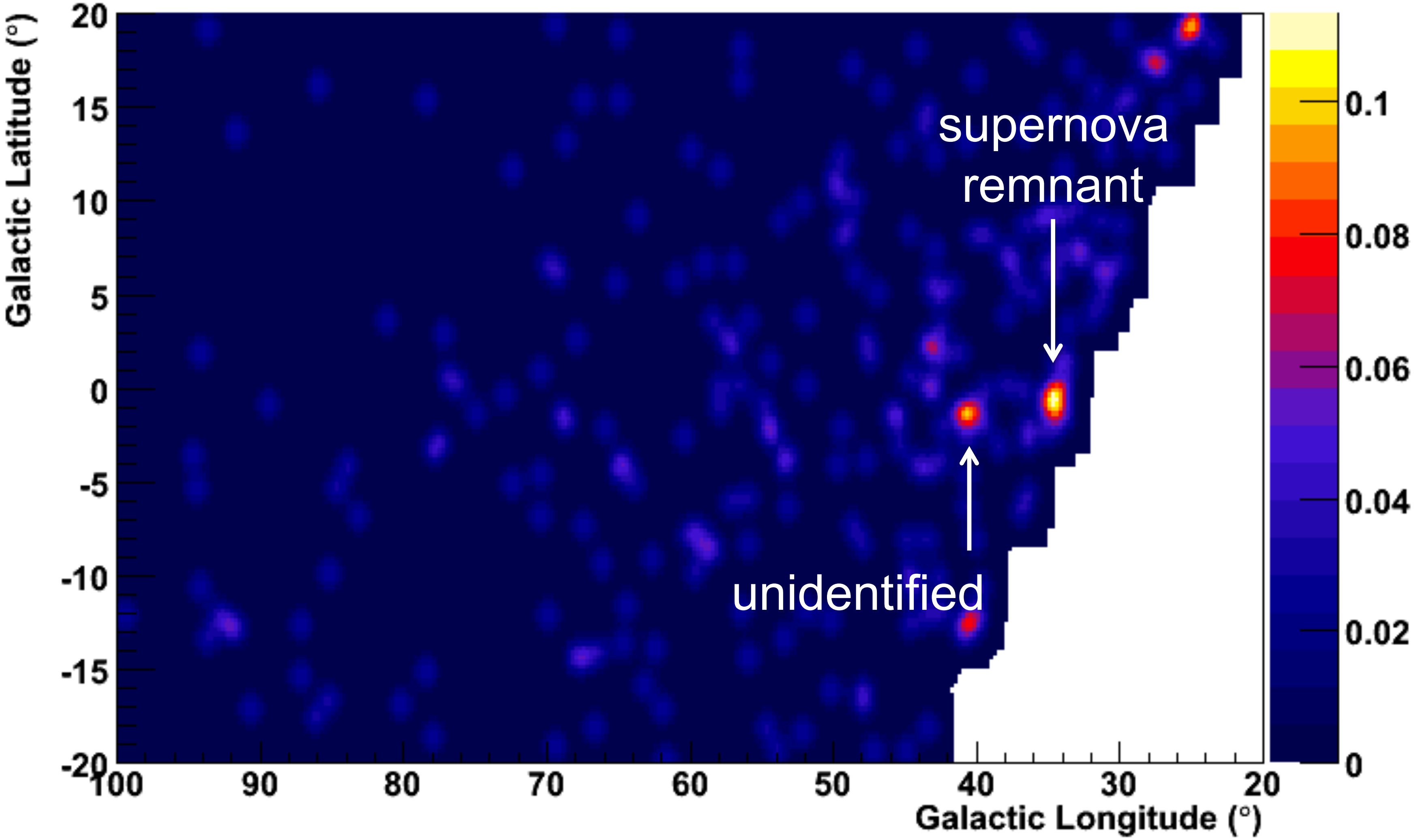
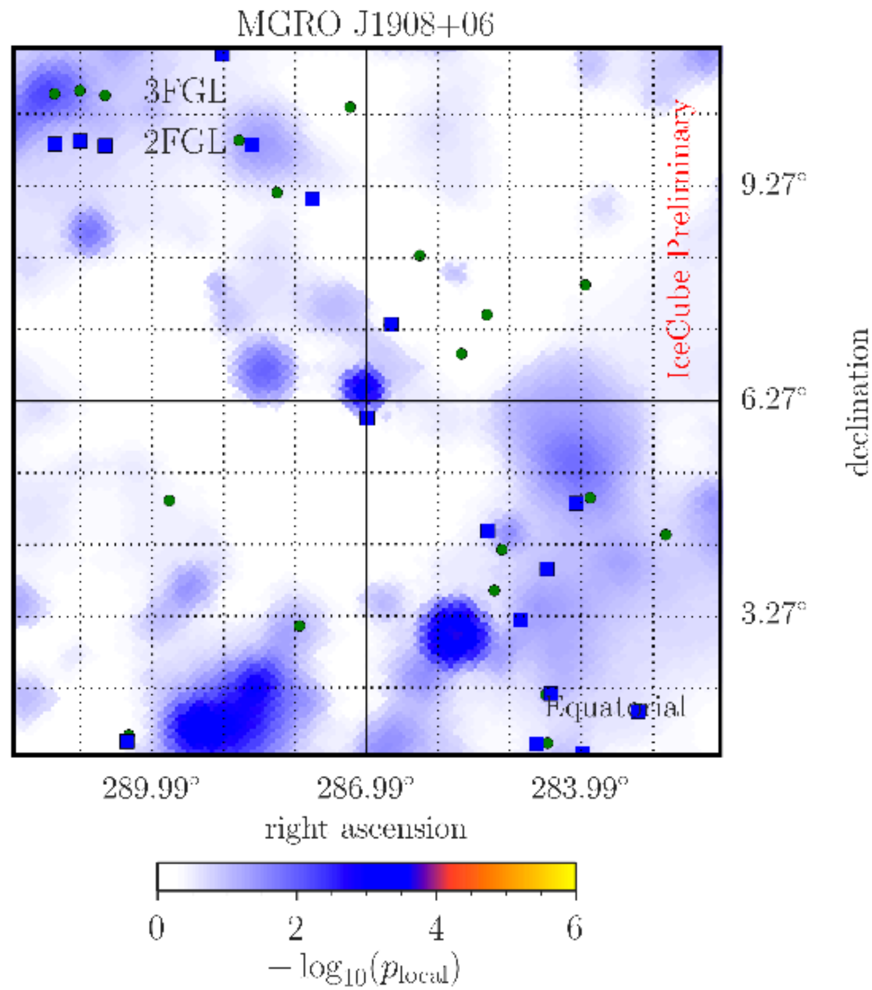
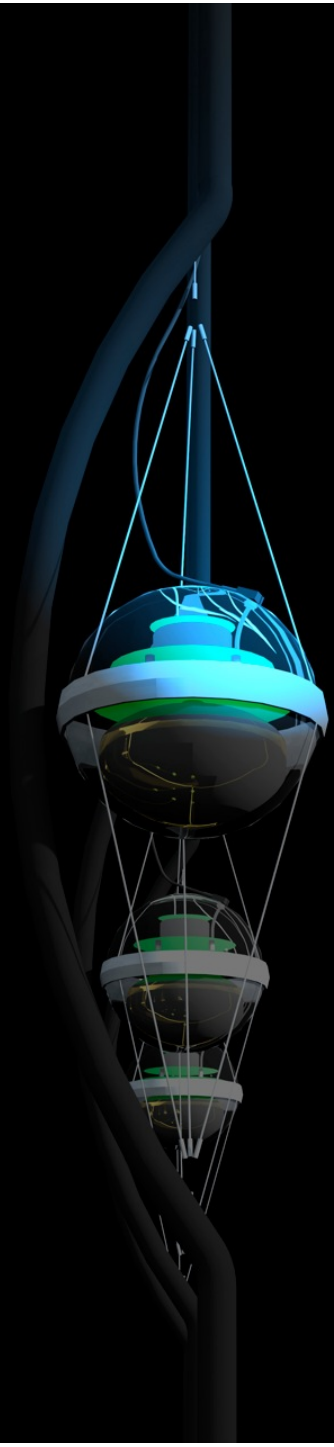


Table 1: Results of the pre-defined source list.

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	38.13	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	$1.01 \cdot 10^{-12}$





IceCube: the discovery of cosmic neutrinos

francis halzen

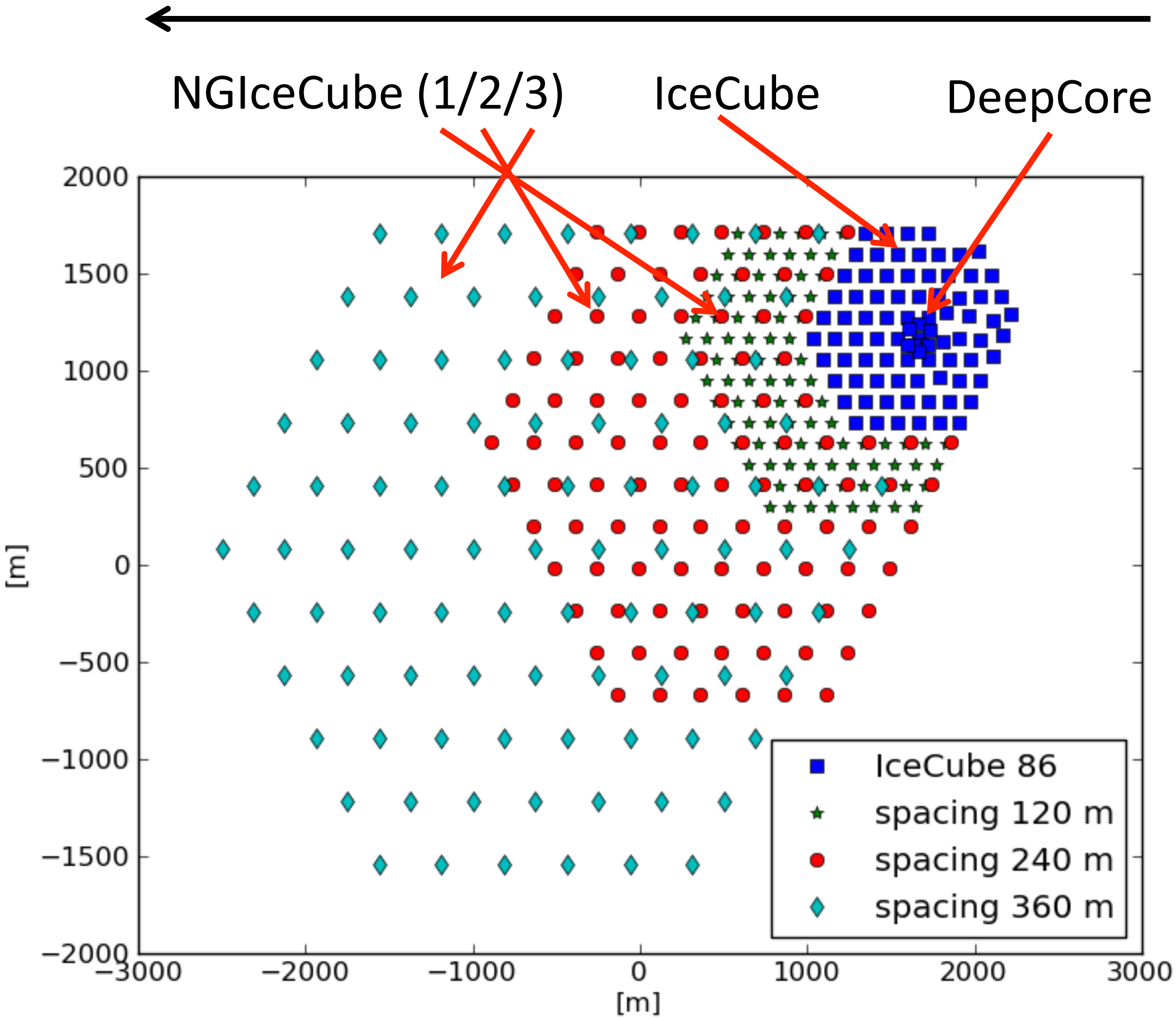
- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

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

measured optical properties → twice the string spacing

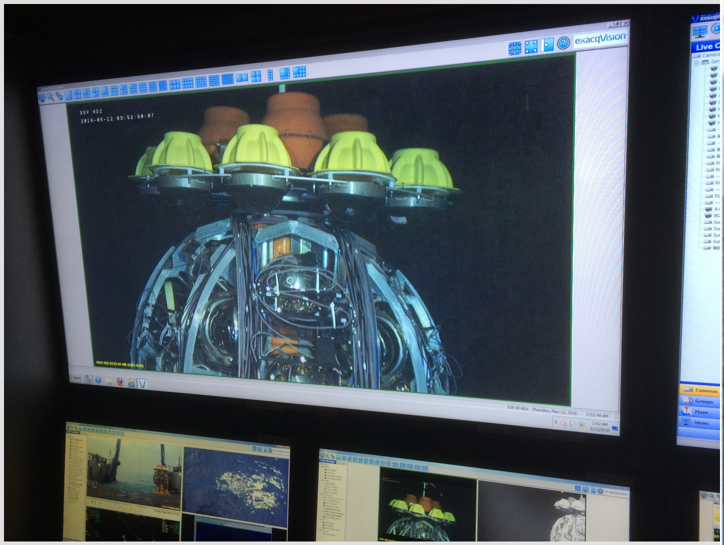
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

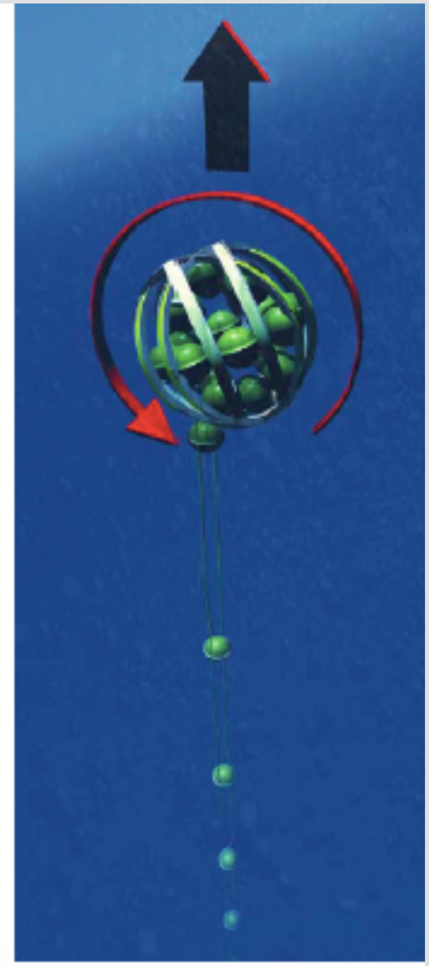


Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³





also GVD
in lake Baikal

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

Conclusions

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

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

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

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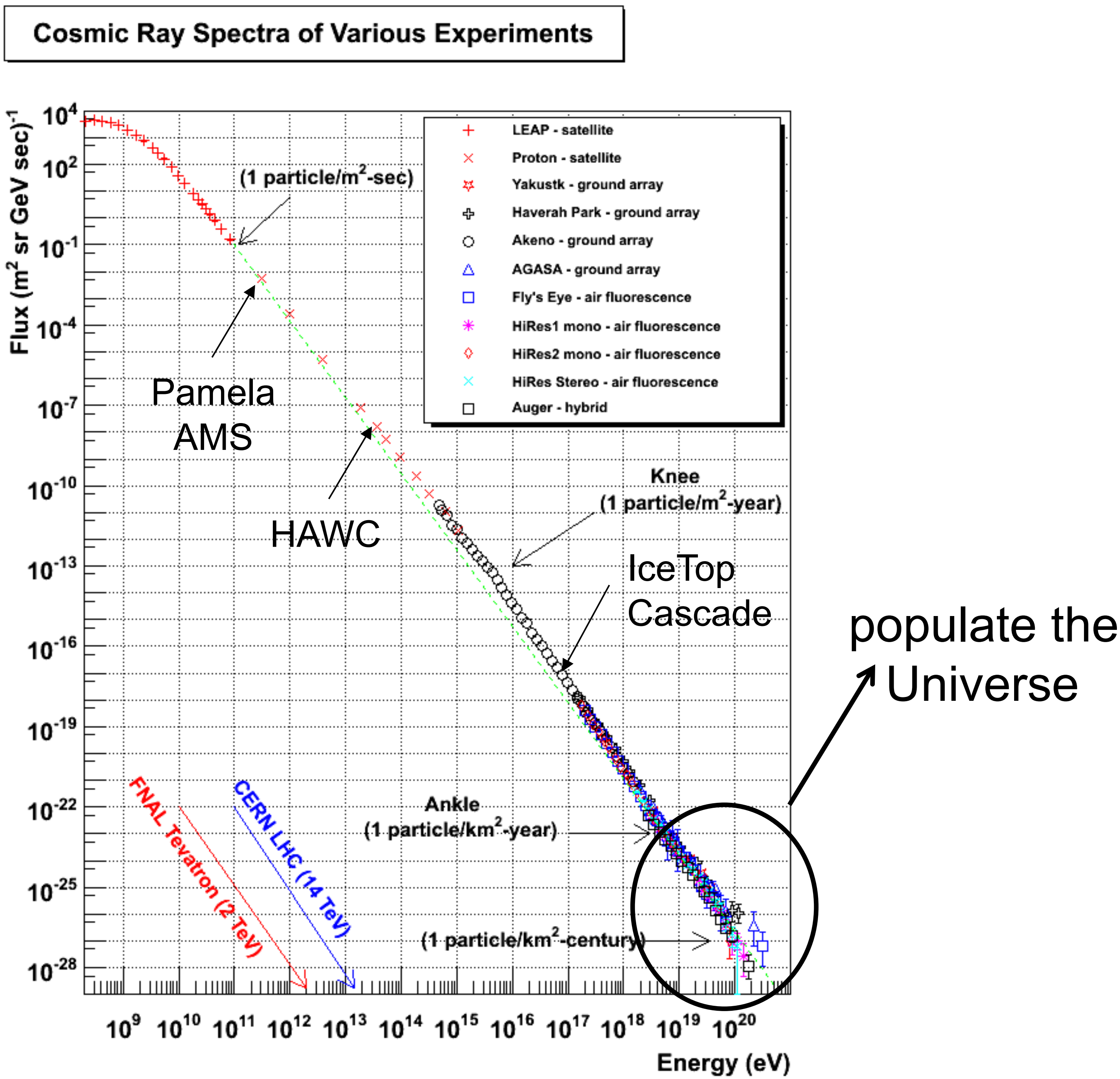
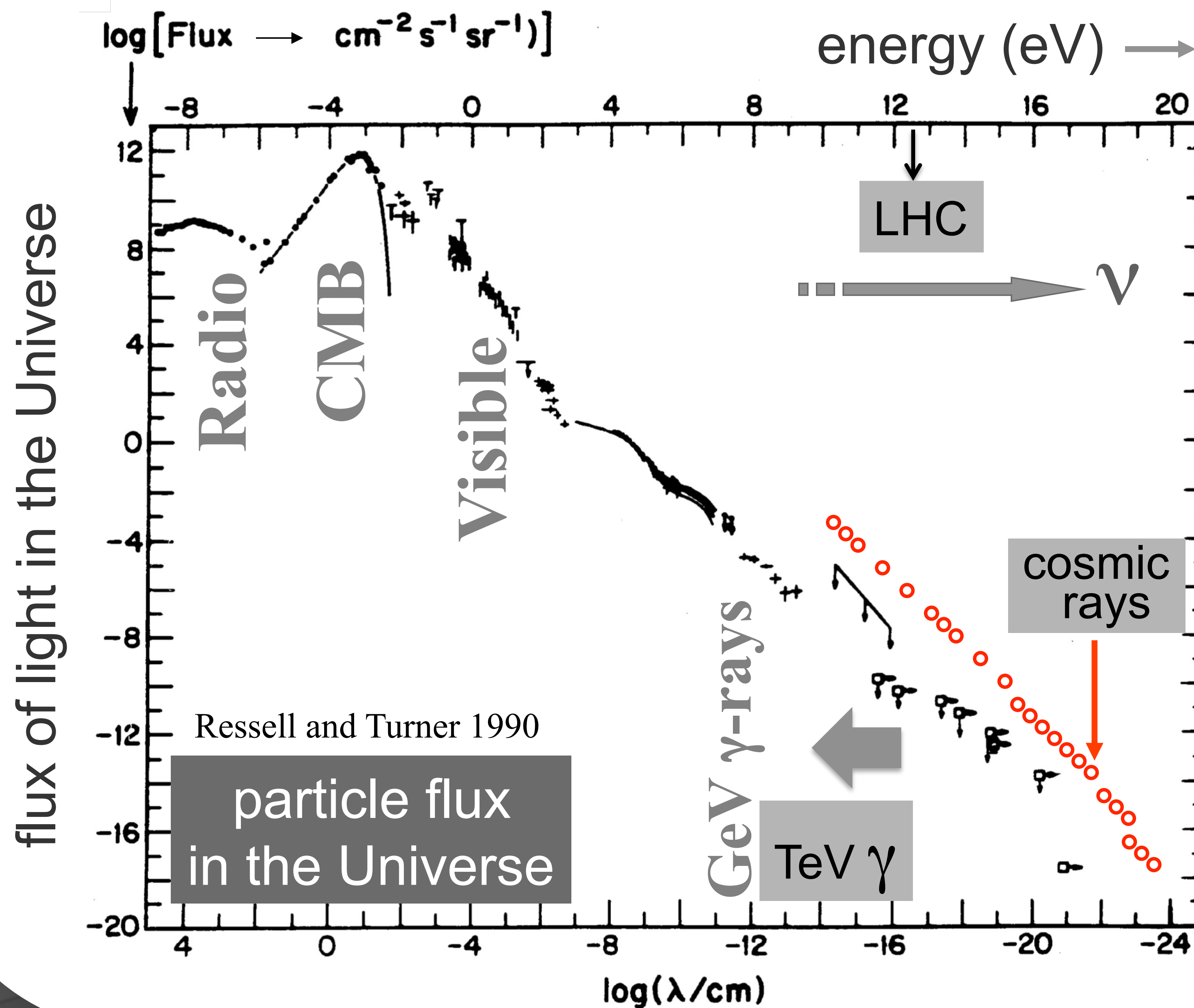
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

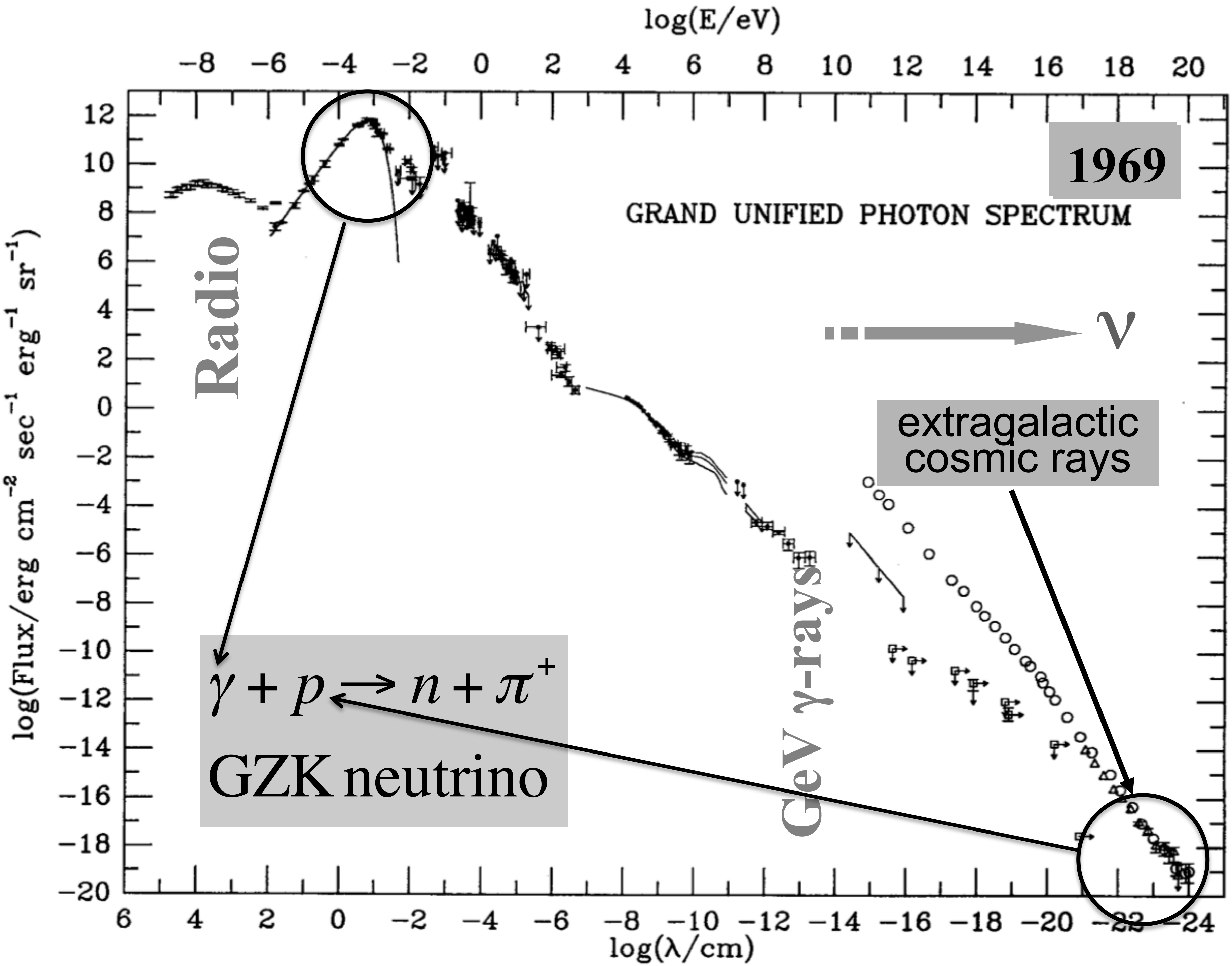
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

overflow slides


Cosmic Ray Spectra of Various Experiments
Flux (m^2 sr GeV sec)^-1
10^4
10^2
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
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/m^2-sec)
Pamela
AMS
HAWC
Knee
(1 particle/m^2-year)
IceTop
Cascade
Ankle
(1 particle/km^2-year)
(1 particle/km^2-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
populate the
Universe



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


log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
extragalactic
cosmic rays
γ + p → n + π⁺
GZK neutrino
GeV γ-rays
log(Flux/erg cm⁻² sec⁻¹ erg⁻¹ sr⁻¹)
log(λ/cm)

cosmic rays interact with the microwave background

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

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

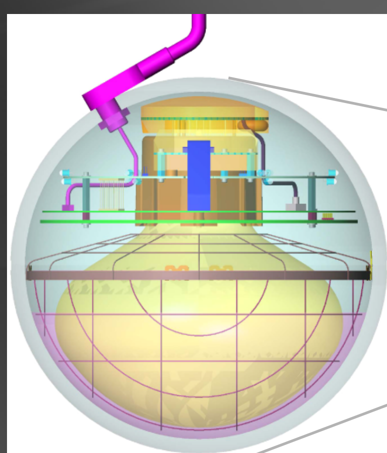
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

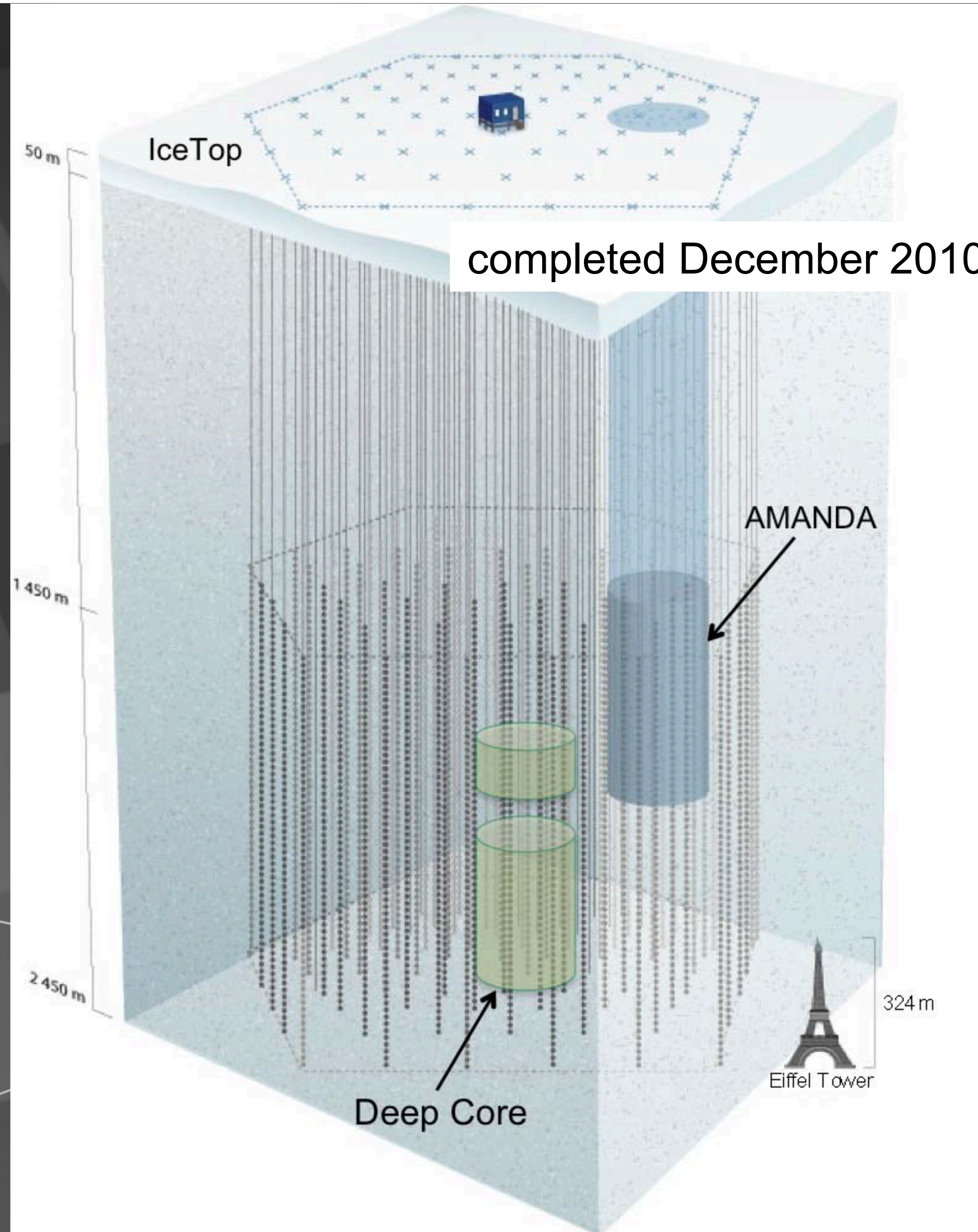
...but it points at its source!

IceCube / Deep Core

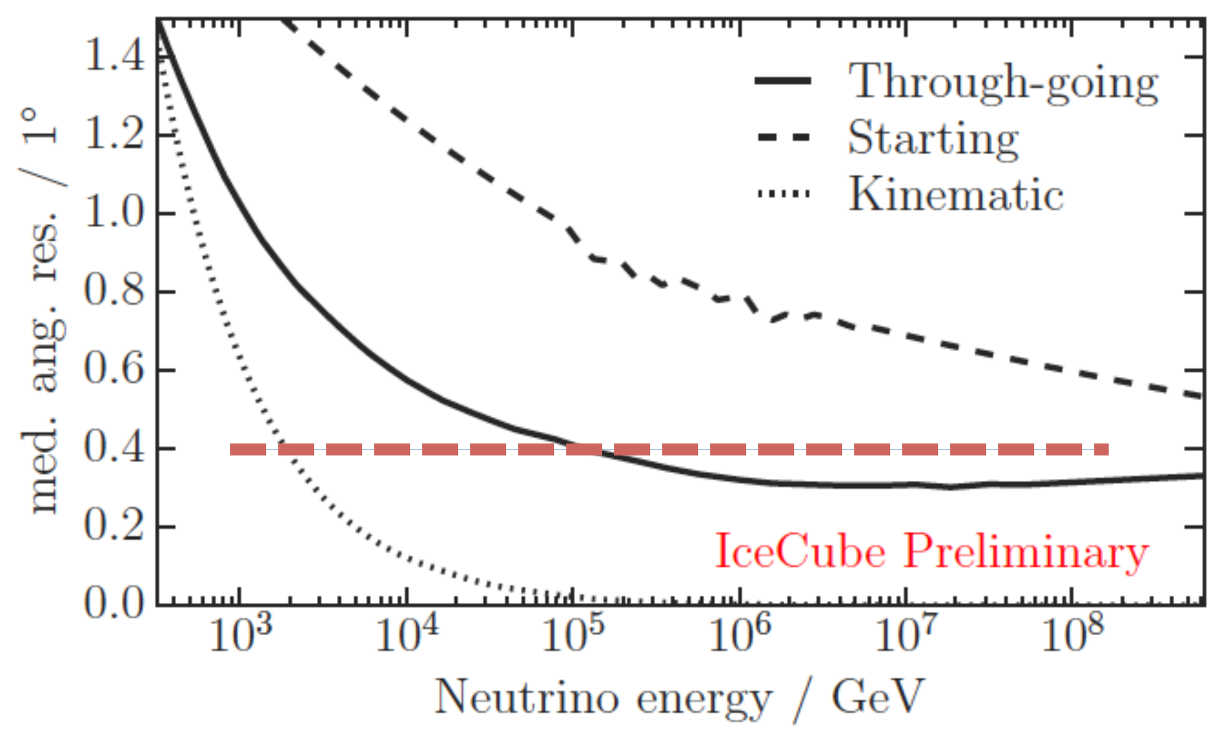
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.4 degree muon track ~ 10 degree shower
- < 15% energy resolution



Digital Optical Module (DOM)



astronomy here: through-going muons with resolution 0.2~0.4^0



GZK neutrinos: cosmic rays interact with the microwave background

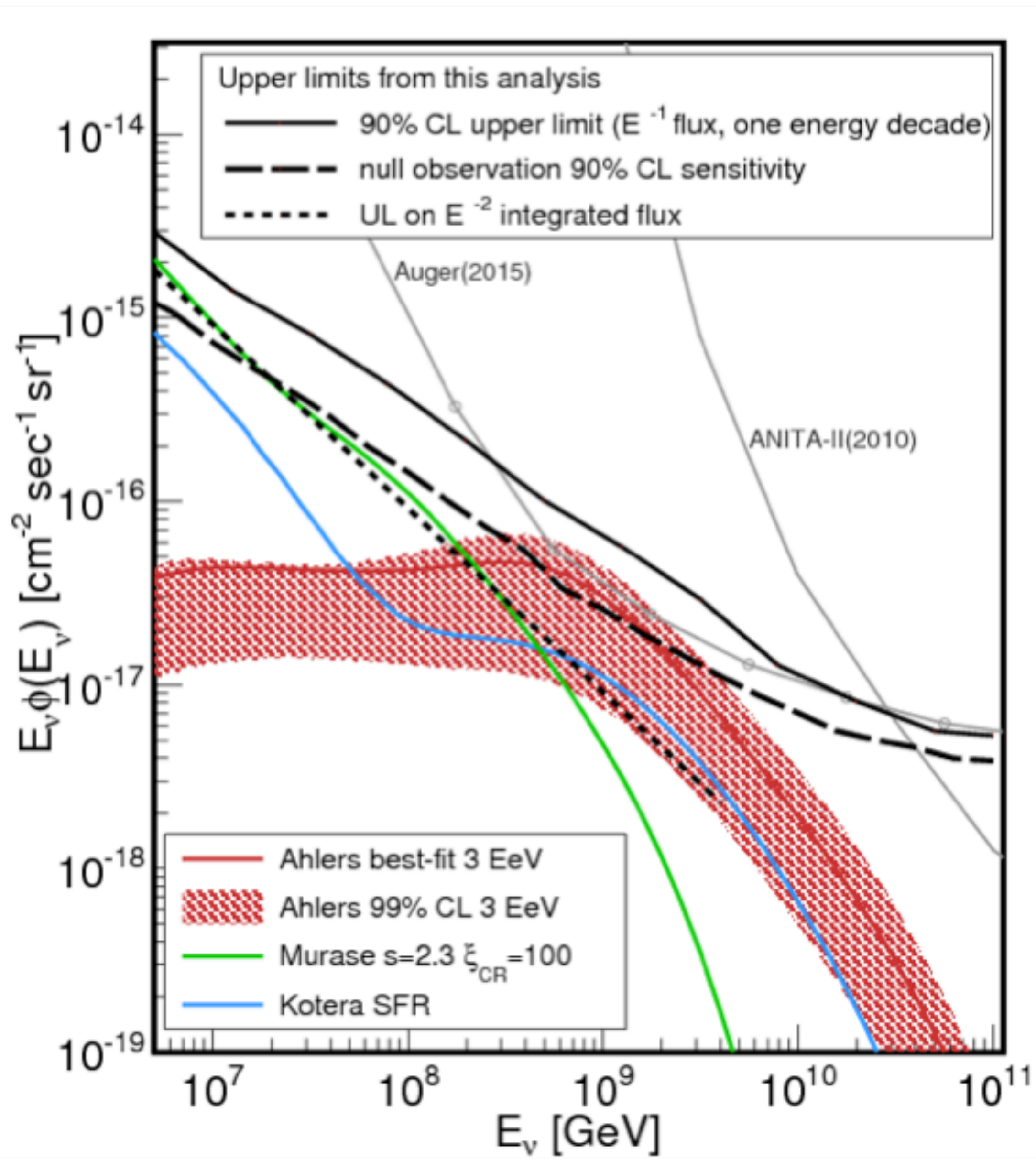
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

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

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

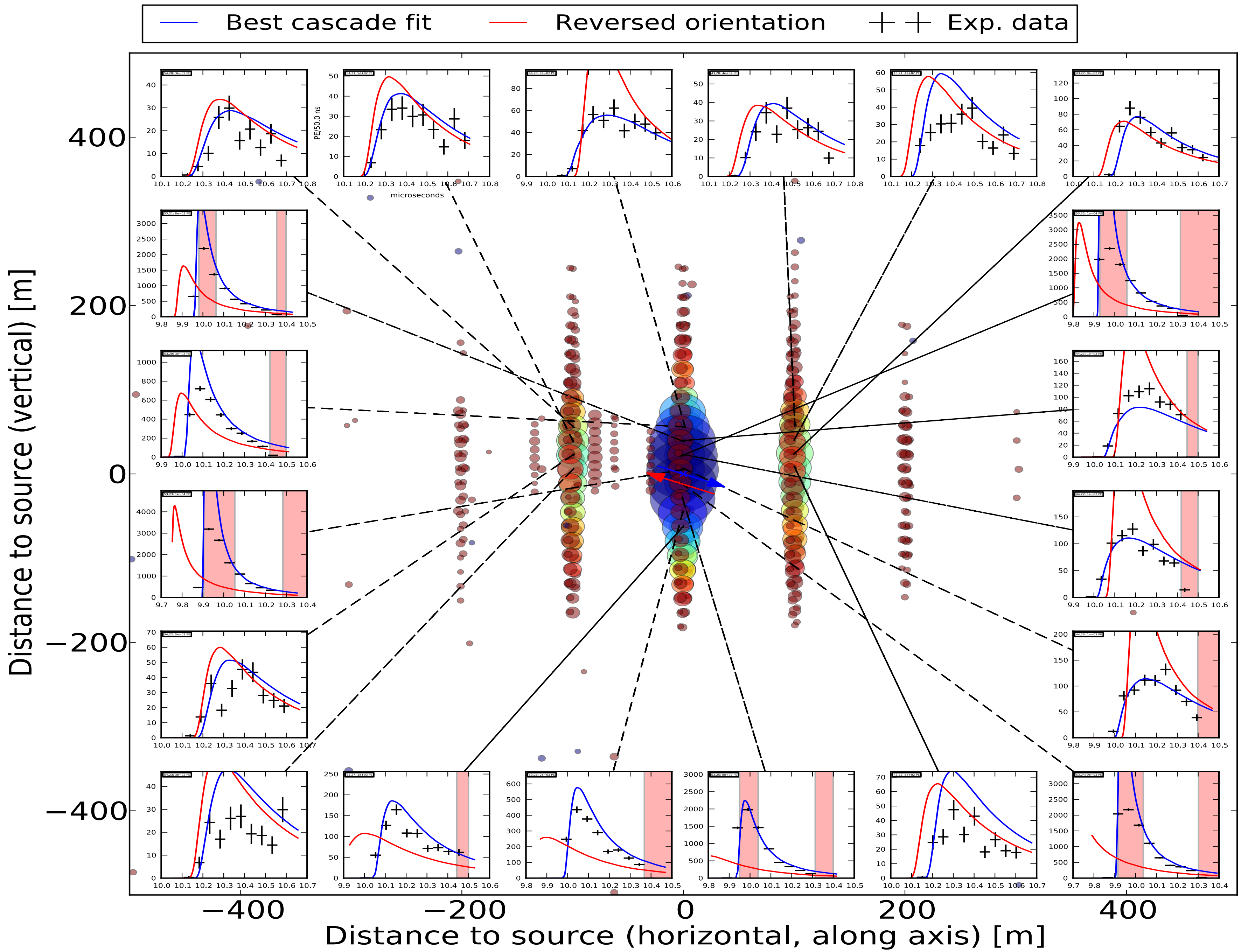
0.7 events per year in IceCube

...but it points at its source!

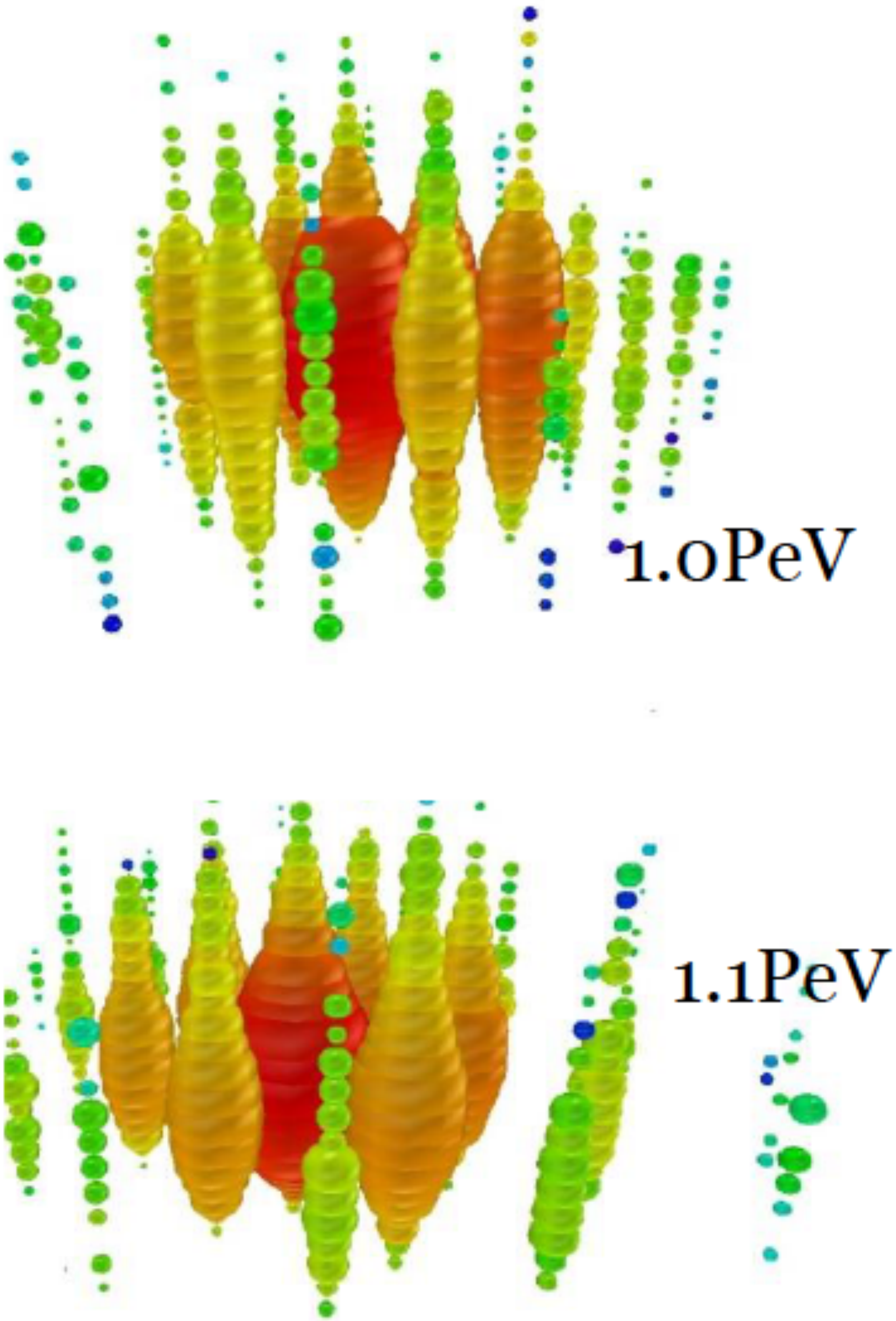


Upper limits from this analysis
90% CL upper limit (E -1 flux, one energy decade)
null observation 90% CL sensitivity
UL on E -2 integrated flux
Auger(2015)
ANITA-II(2010)
Ahlers best-fit 3 EeV
Ahlers 99% CL 3 EeV
Murase s=2.3 ξCR=100
Kotera SFR
10-14
10-15
10-16
10-17
10-18
10-19
10^7
10^8
10^9
10^10
10^11
Eν [GeV]
Eνφ(Eν) [cm-2 sec-1 sr-1]

1607.05886



Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds



- energy

  1,041 TeV
  1,141 TeV

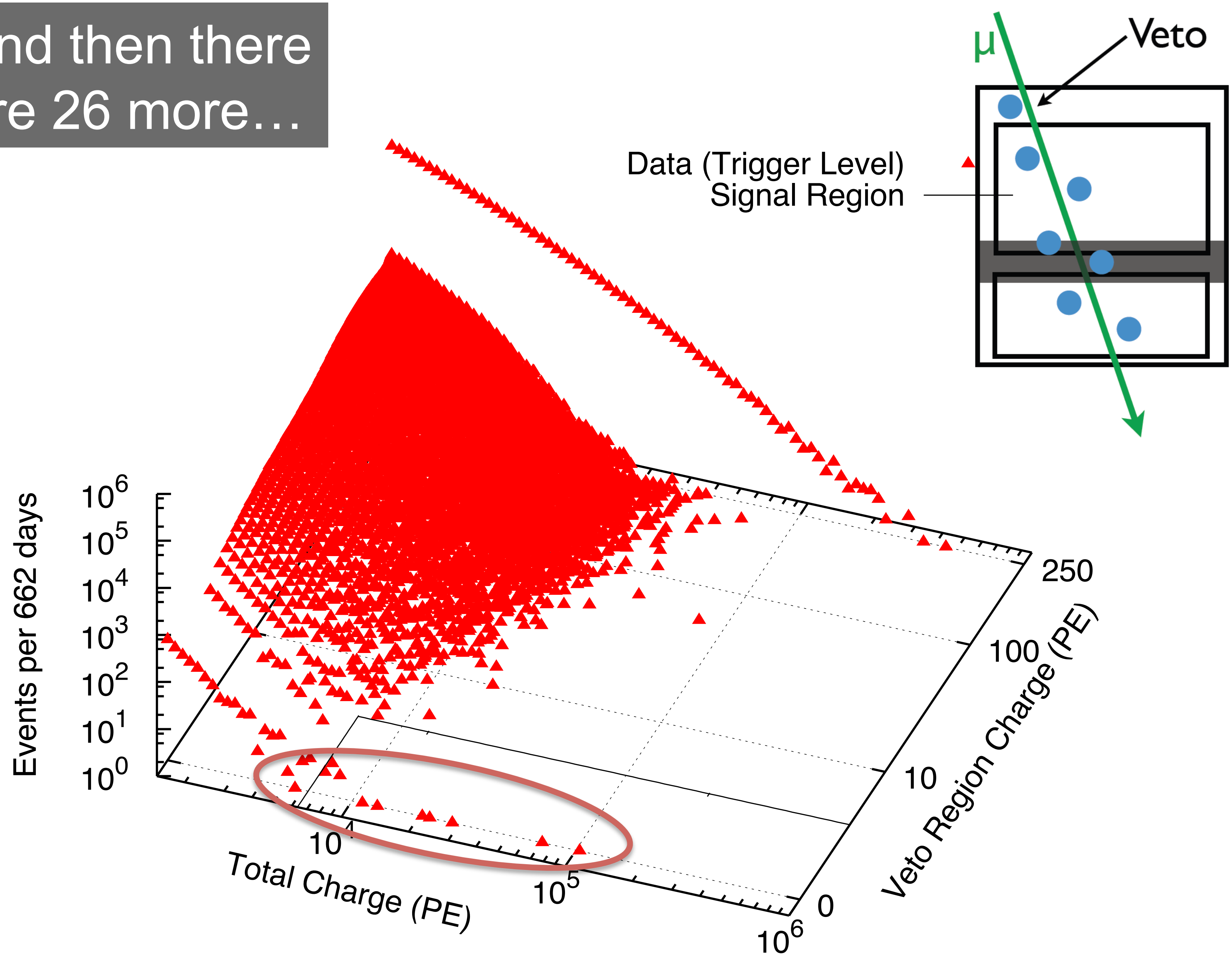
  (15% resolution)

- not atmospheric at 3σ

- no muons from accompanying atmospheric shower

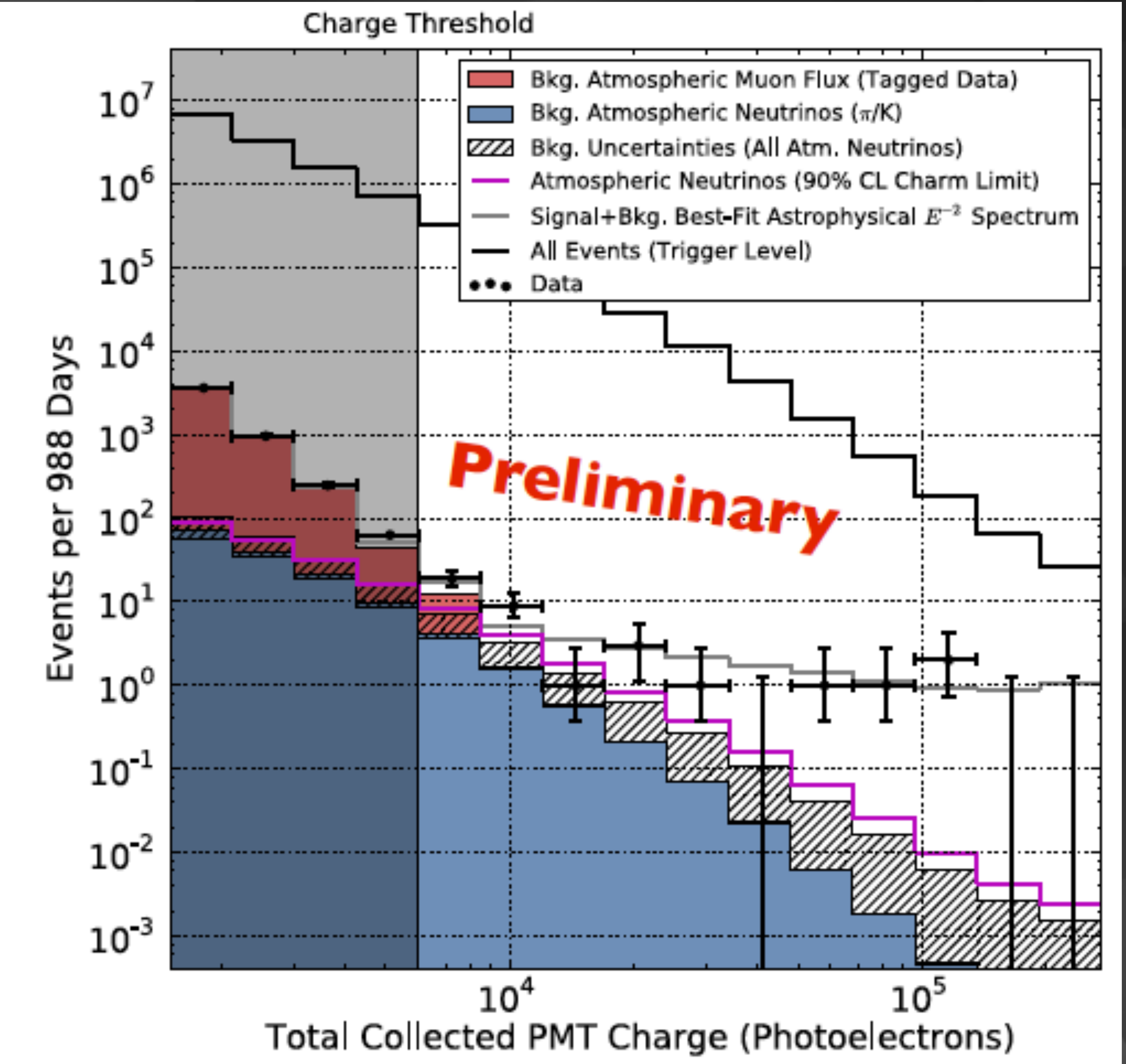
- look for more

…and then there were 26 more…



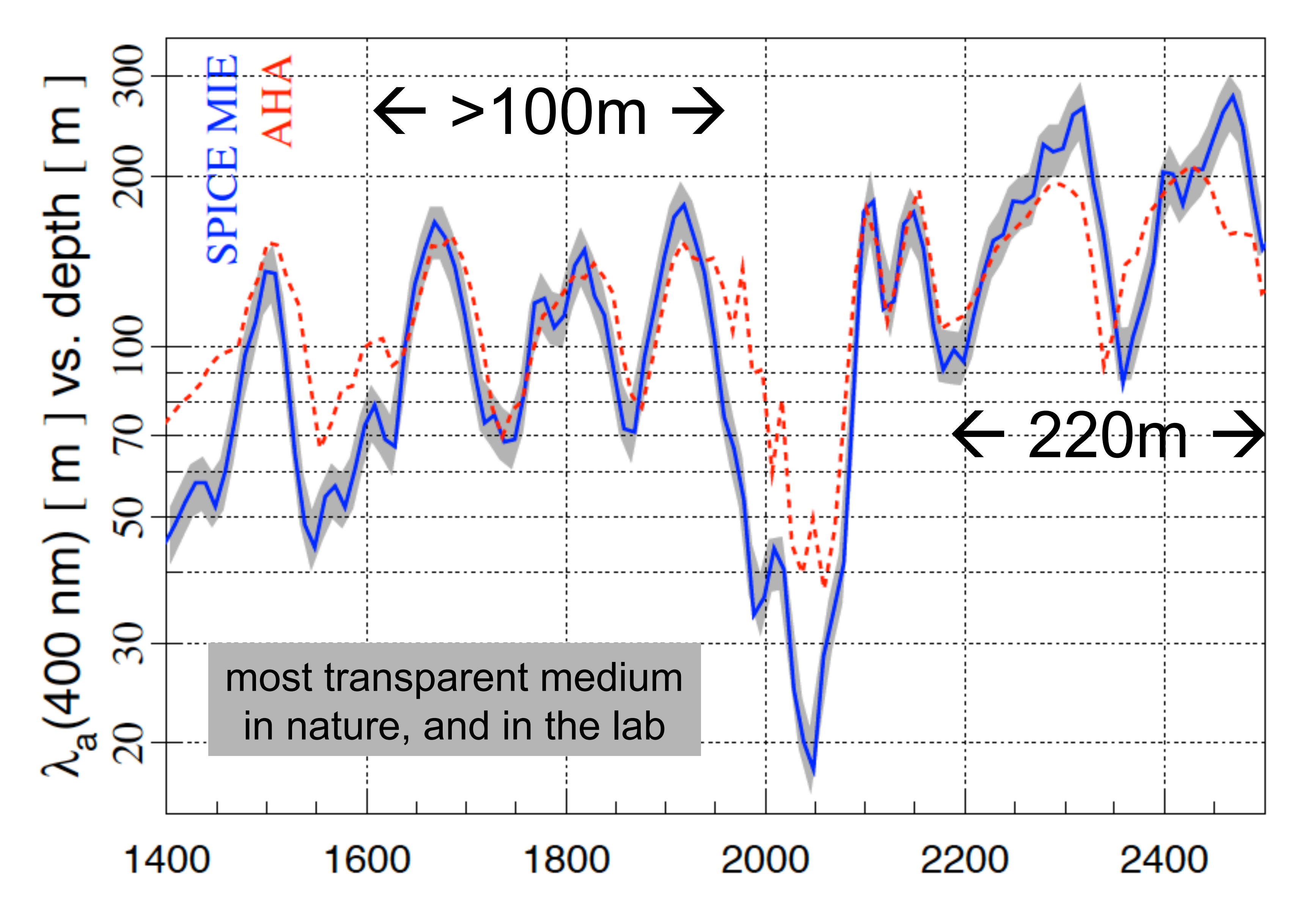
data: 86 strings one year

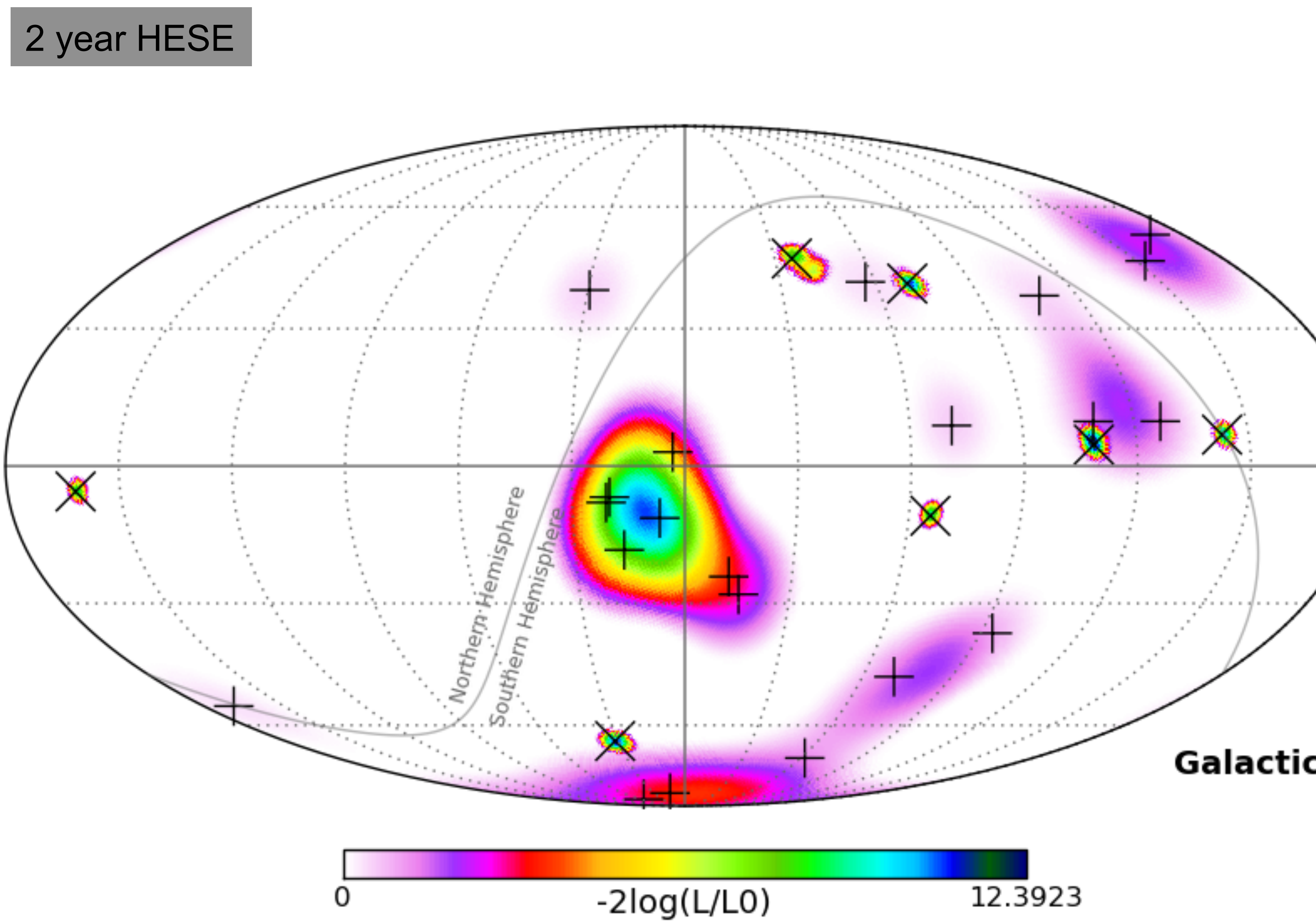
total charge collected by PMTs of events with interaction inside the detector



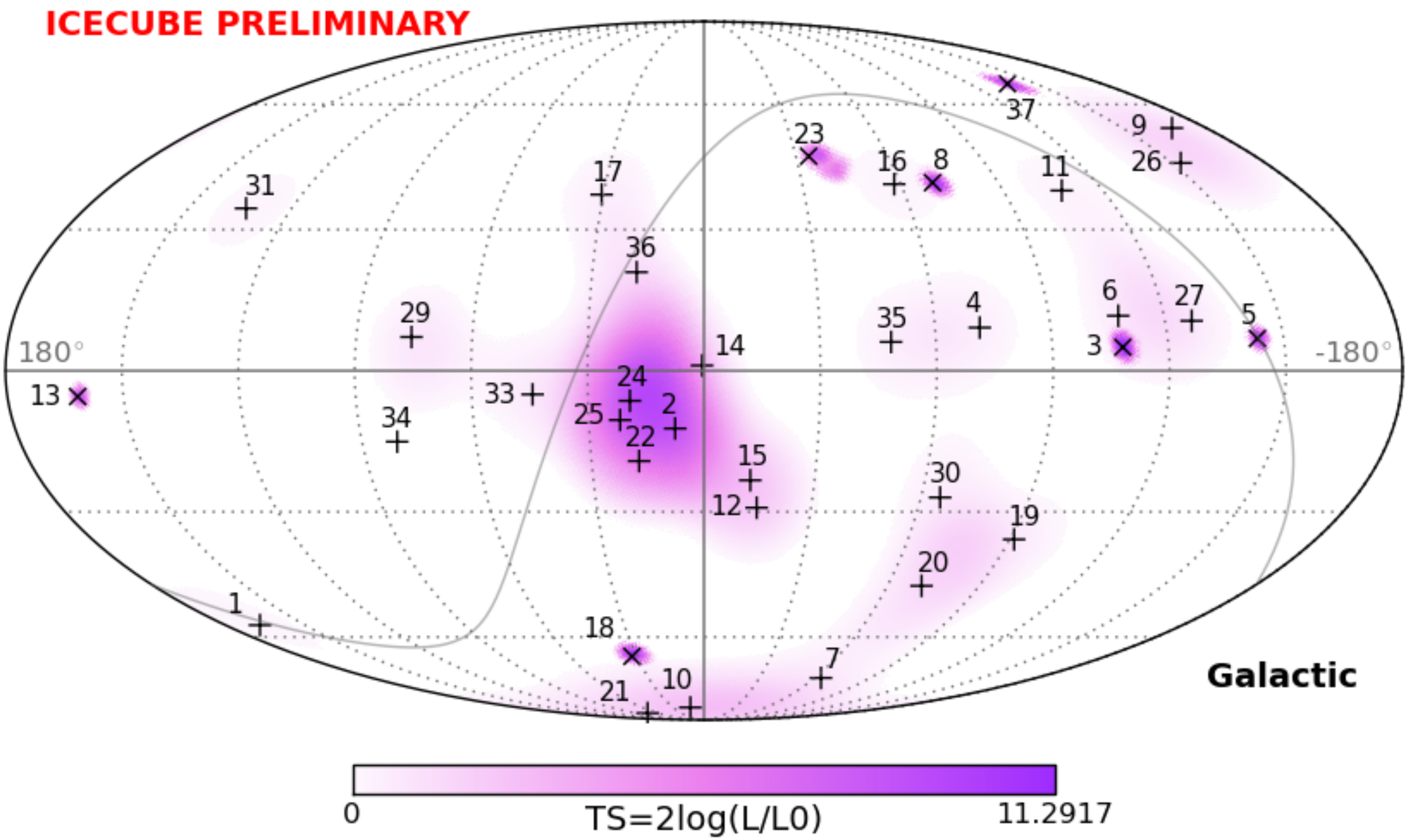
Science 342 (2013) 1242856

absorption length of Cherenkov light

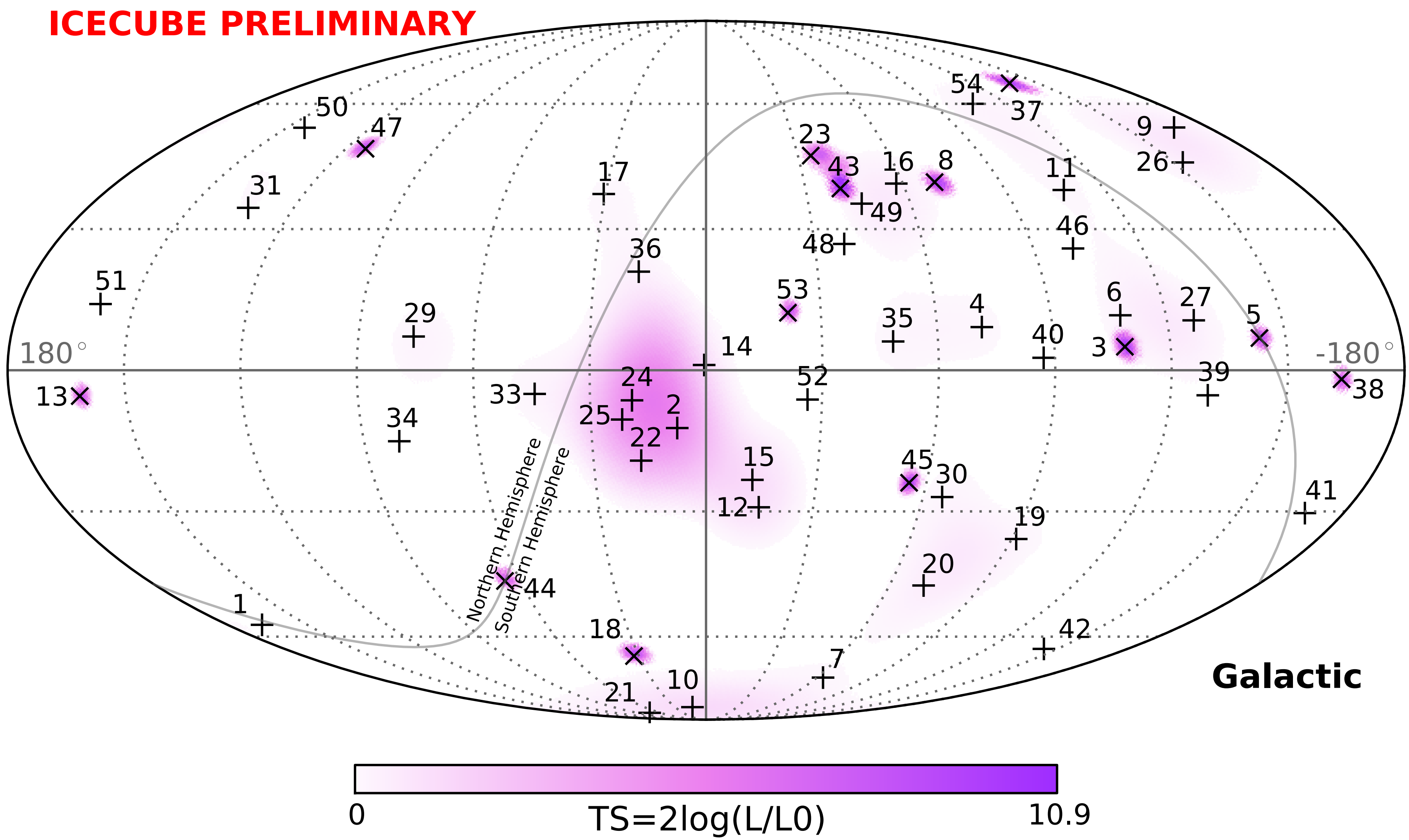



2 year HESE
Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

3 year HESE

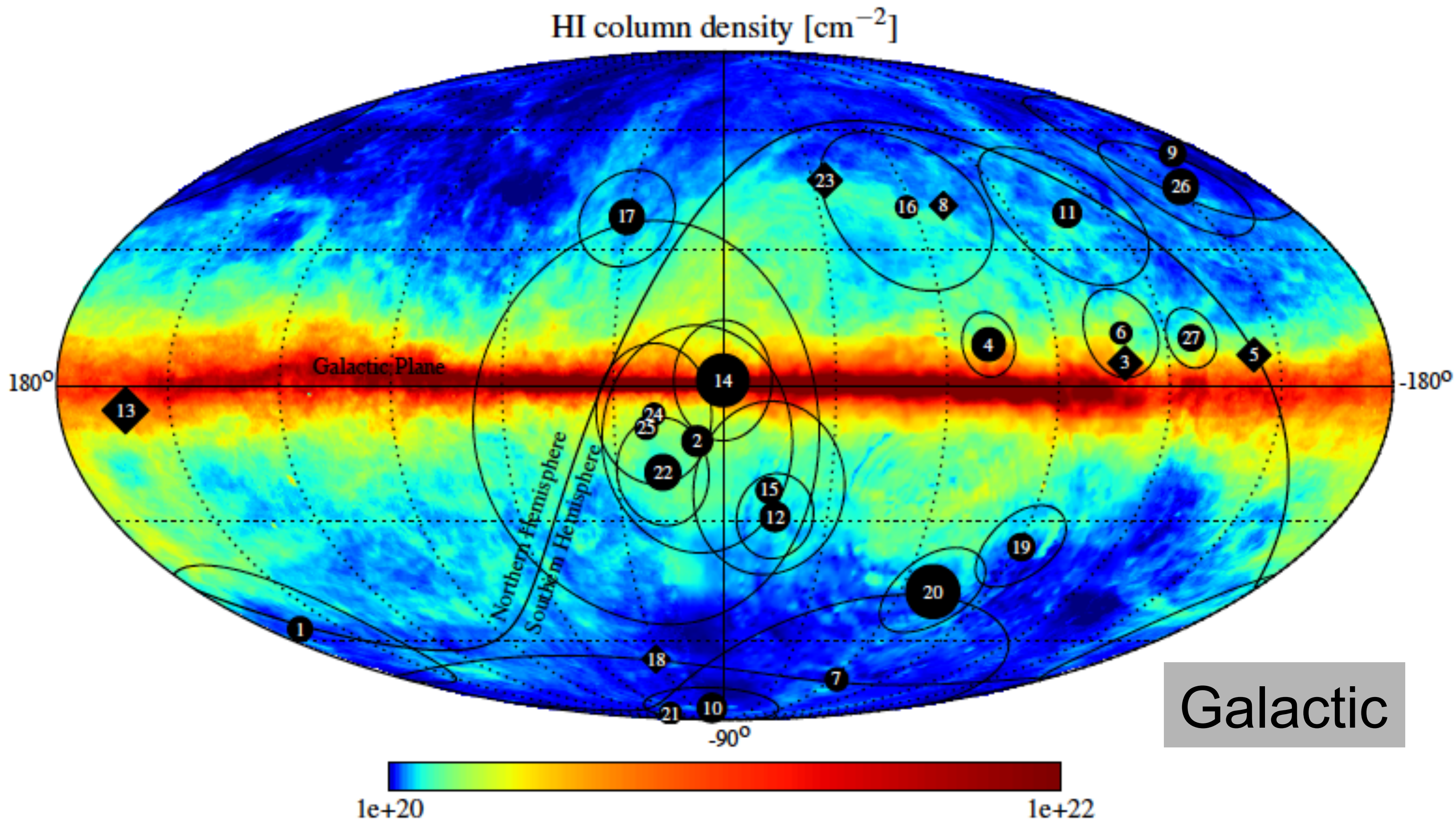

ICECUBE PRELIMINARY
180°
-180°
Galactic
0
TS=2log(L/L0)
11.2917
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
29
30
31
33
34
35
36
37

4 year HESE

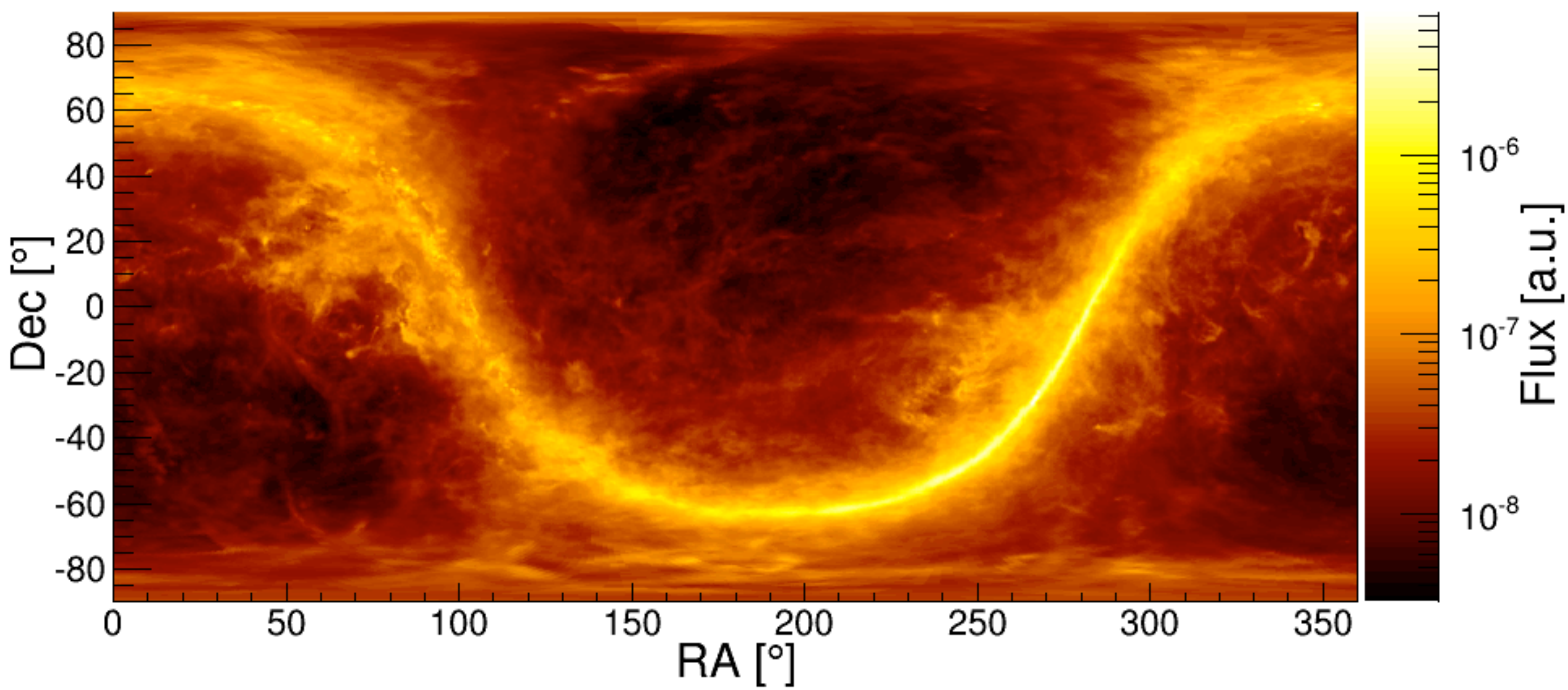


where do they come from?

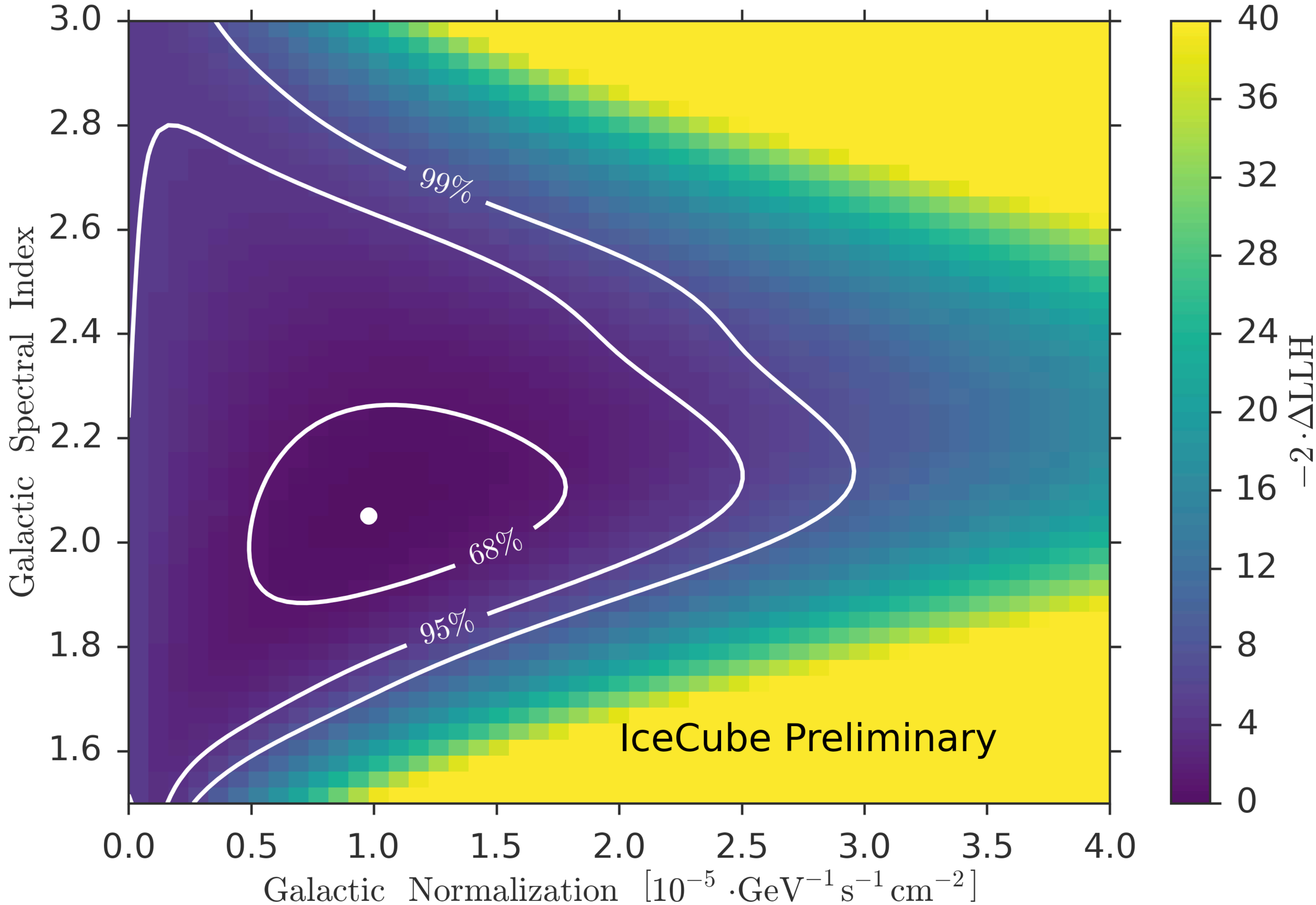
correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg



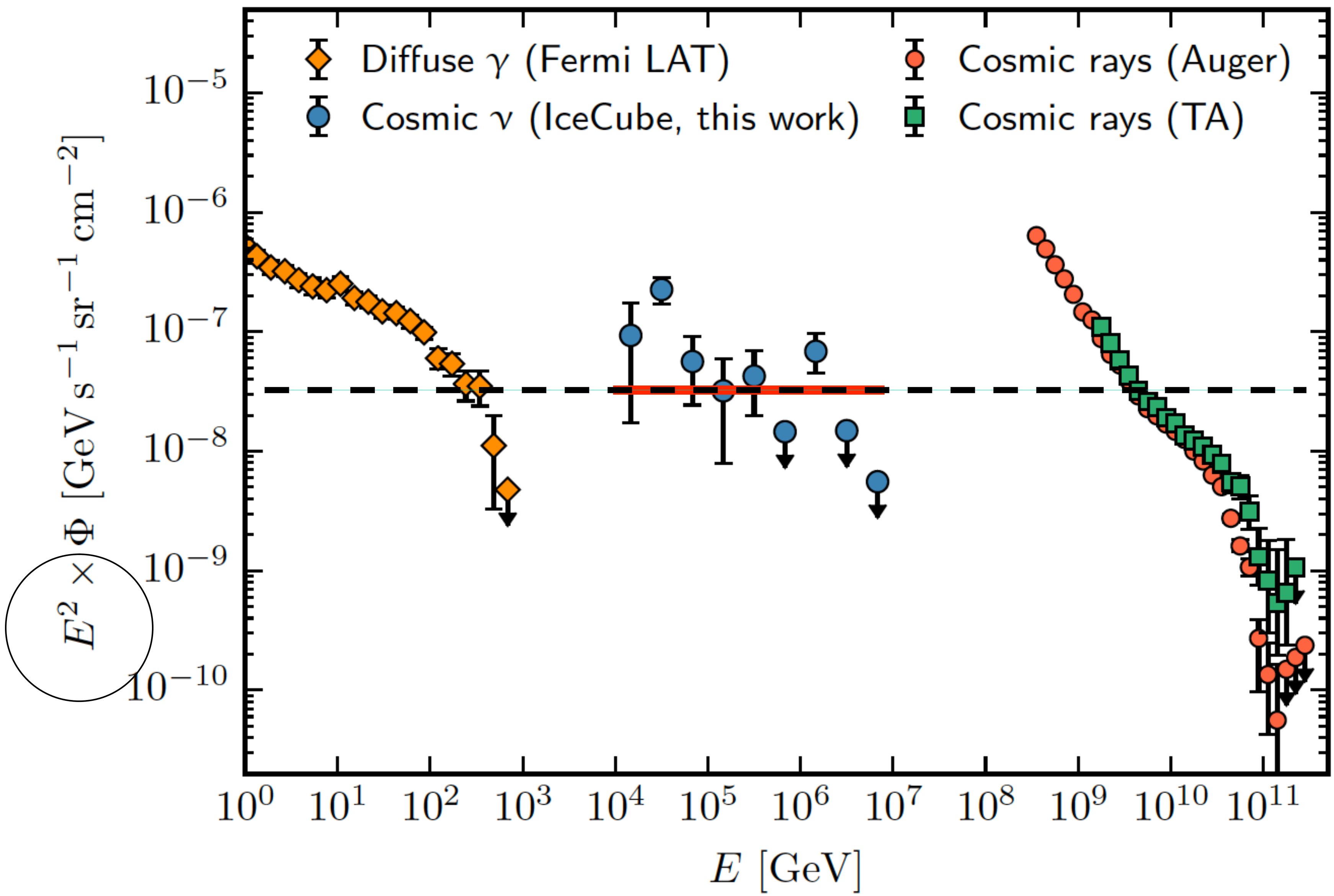
Galactic



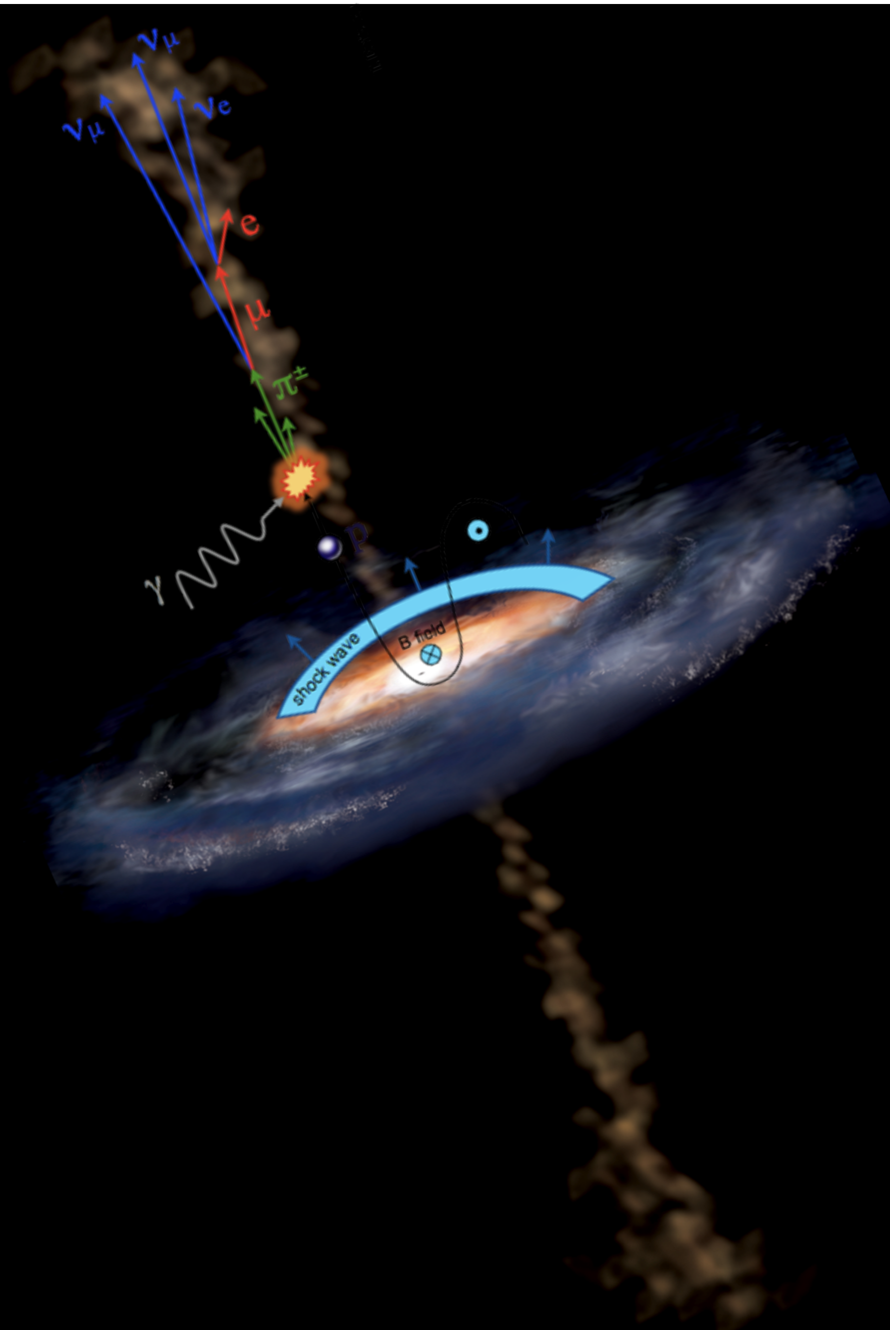
80
60
40
20
0
-20
-40
-60
-80
Dec [°]
0
50
100
150
200
250
300
350
RA [°]
10^{-6}
10^{-7}
10^{-8}
Flux [a.u.]



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

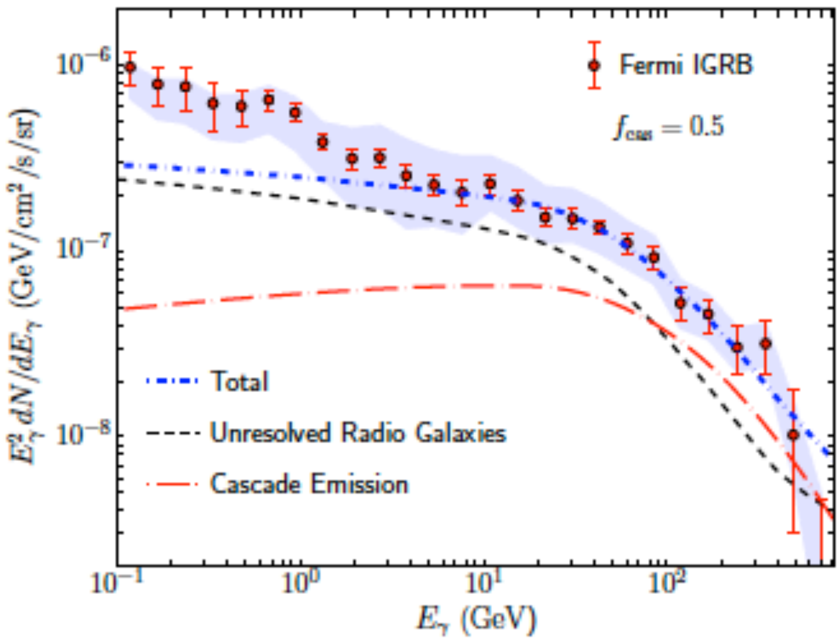


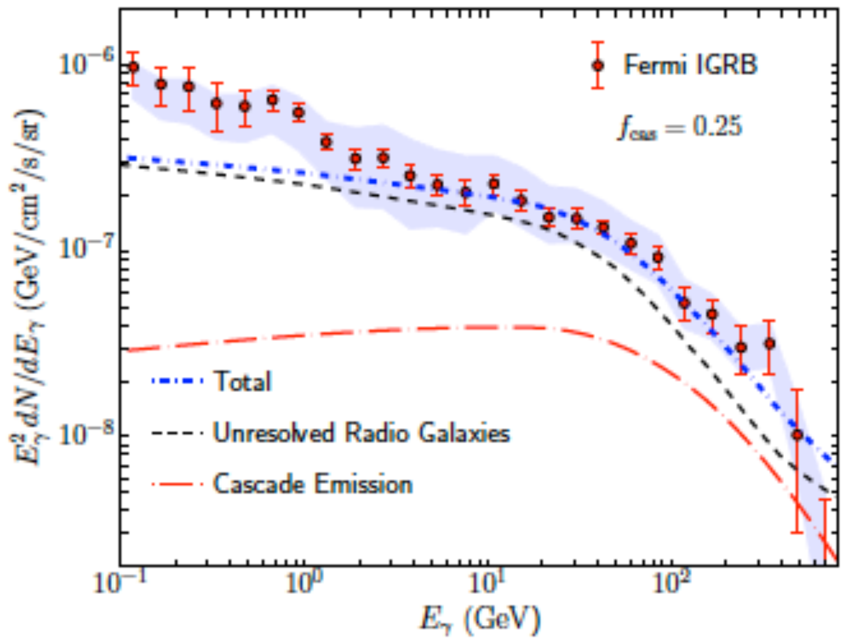
energy in the Universe in gamma rays, neutrinos and cosmic rays

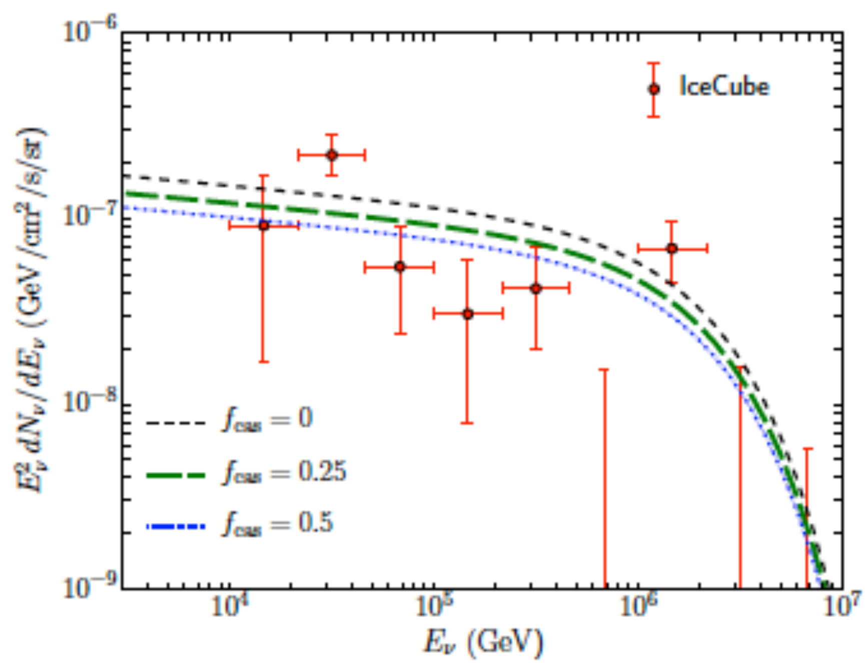


active galaxy

particle flows near
supermassive
black hole



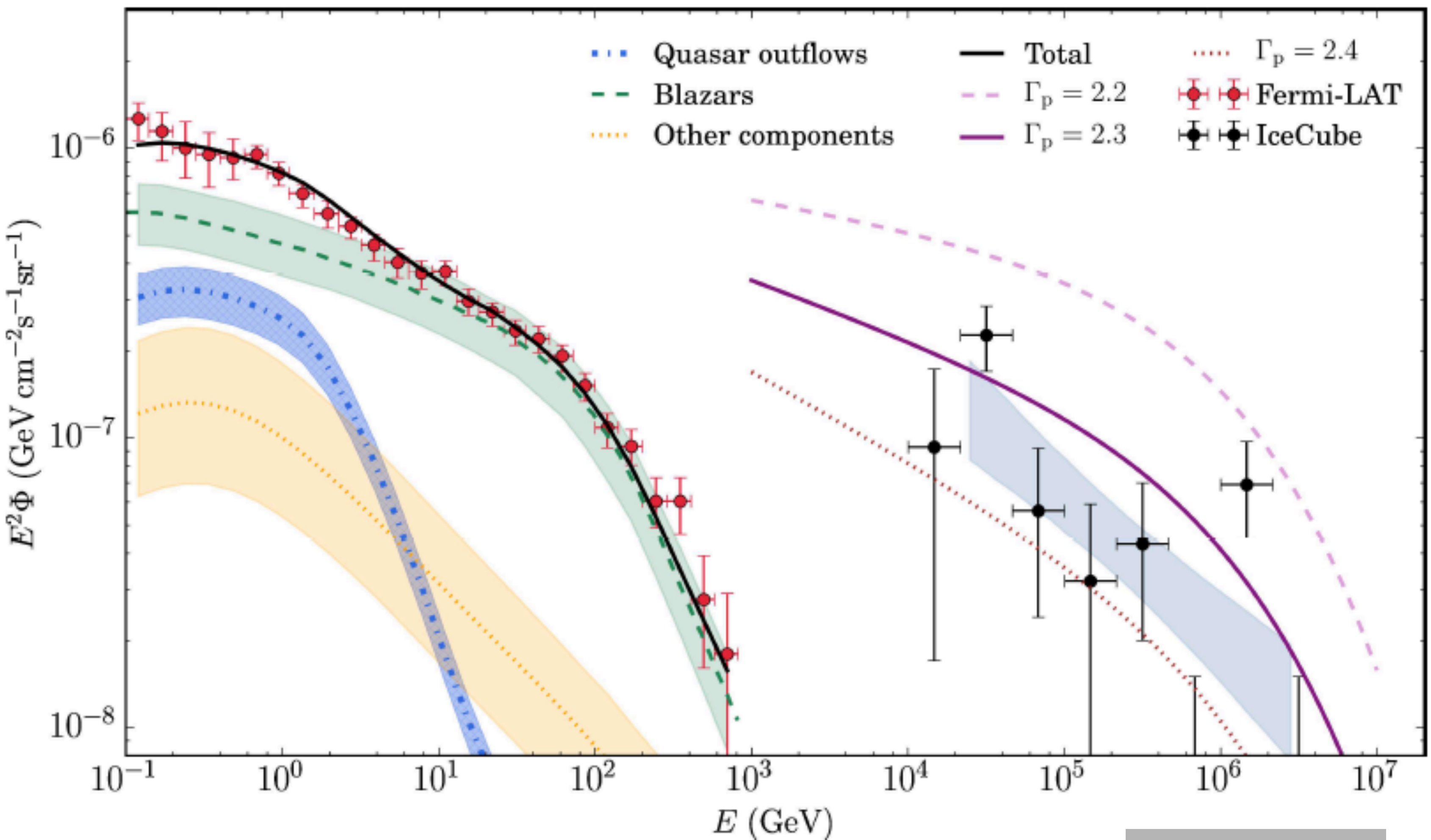




radiogalaxies

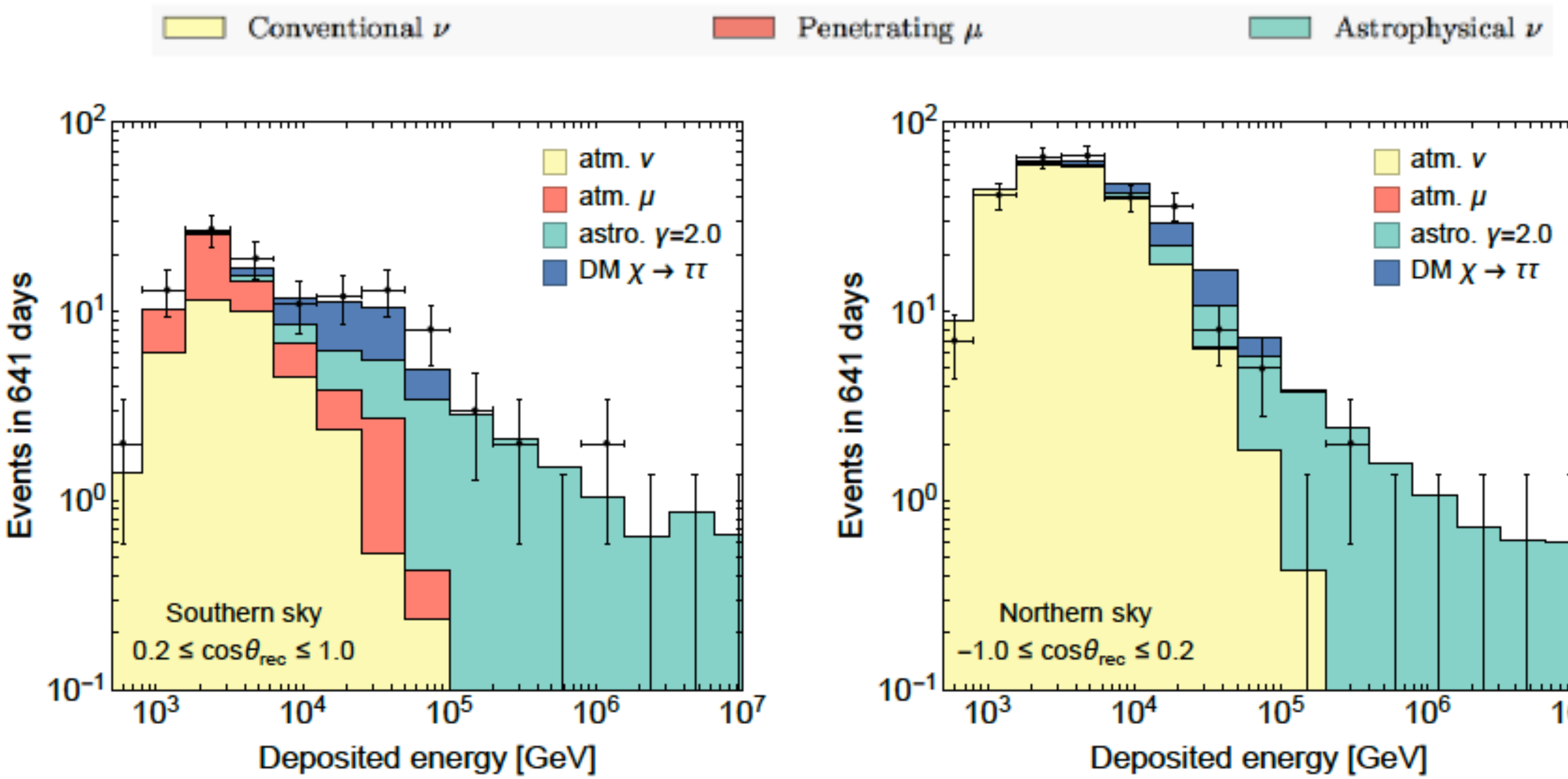
Tjus et al.

Hooper



quasars
Loeb

towards lower energies: a second component?



warning:

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

PeV neutrinos absorbed in the Earth

neutrinos from supernova remnants :

molecular clouds as beam dumps → pion production