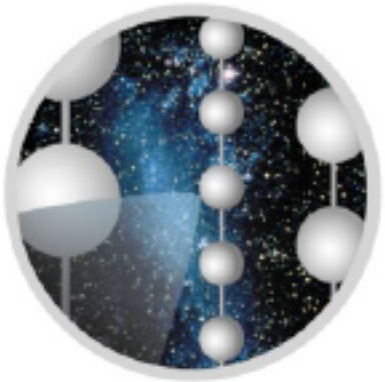


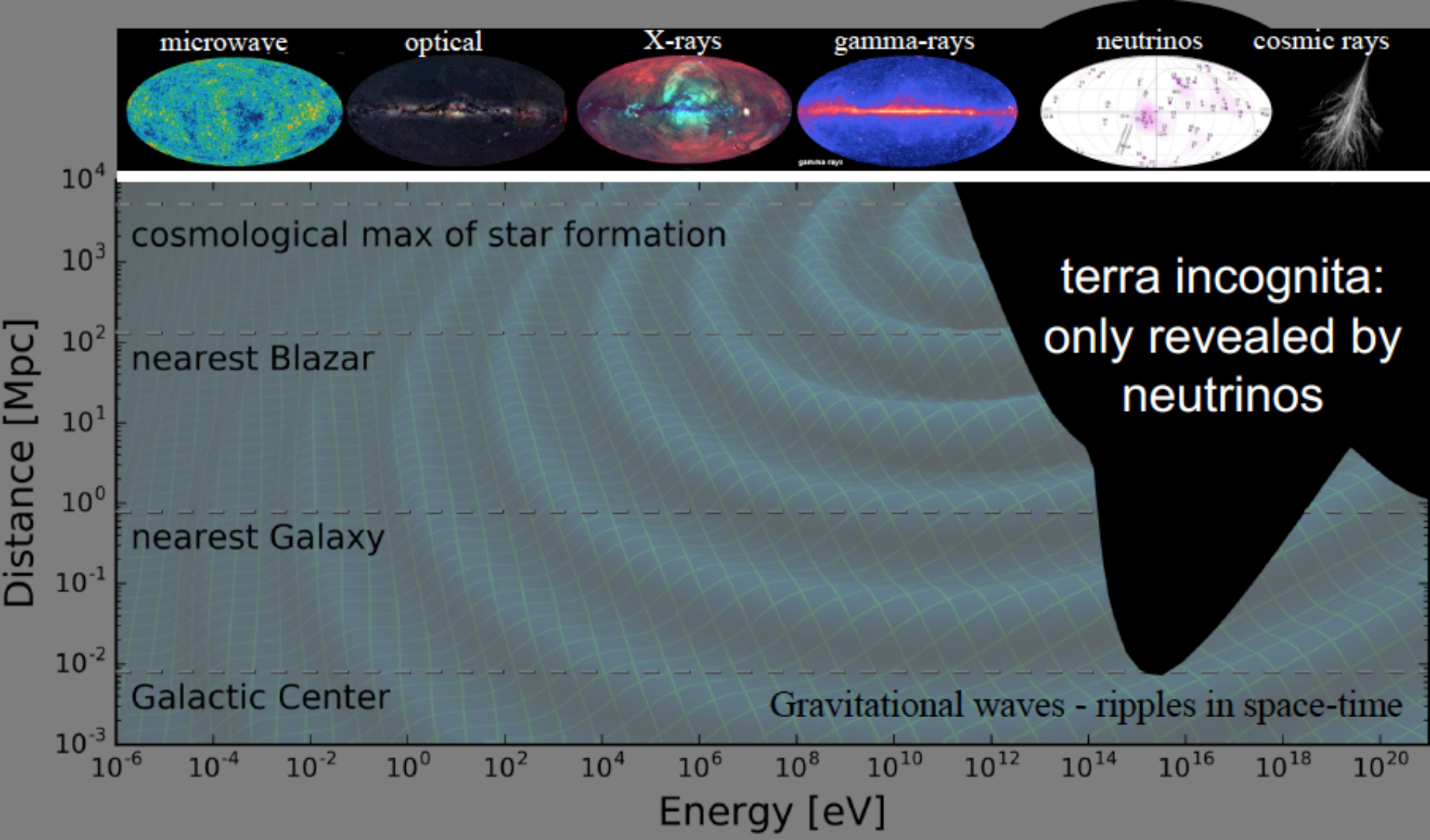
IceCube:

Building a New Window on the Universe

francis halzen

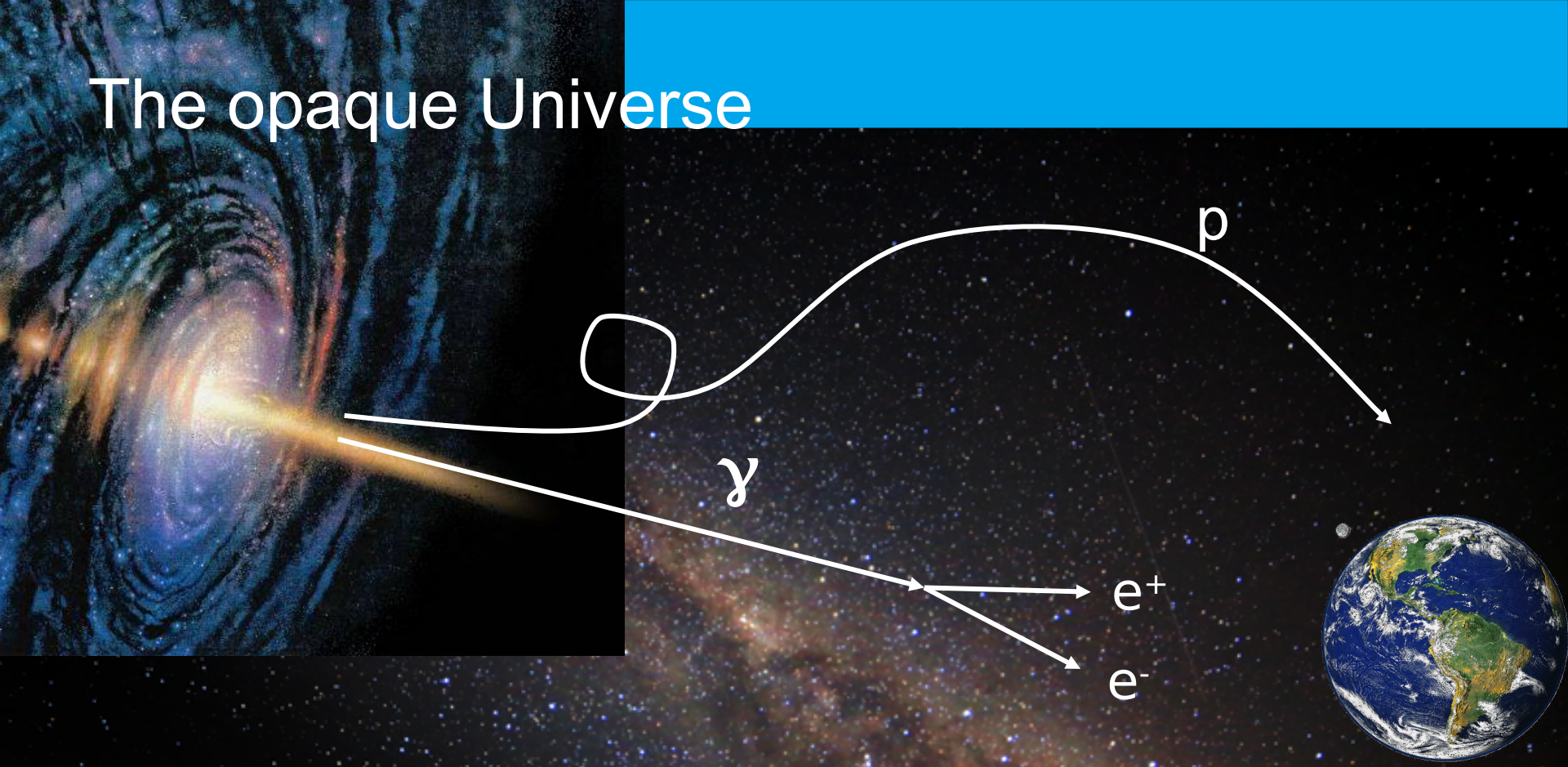
- IceCube
- cosmic neutrinos: two independent observations
  - muon neutrinos through the Earth
  - starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- multimessenger astronomy

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

The opaque Universe



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

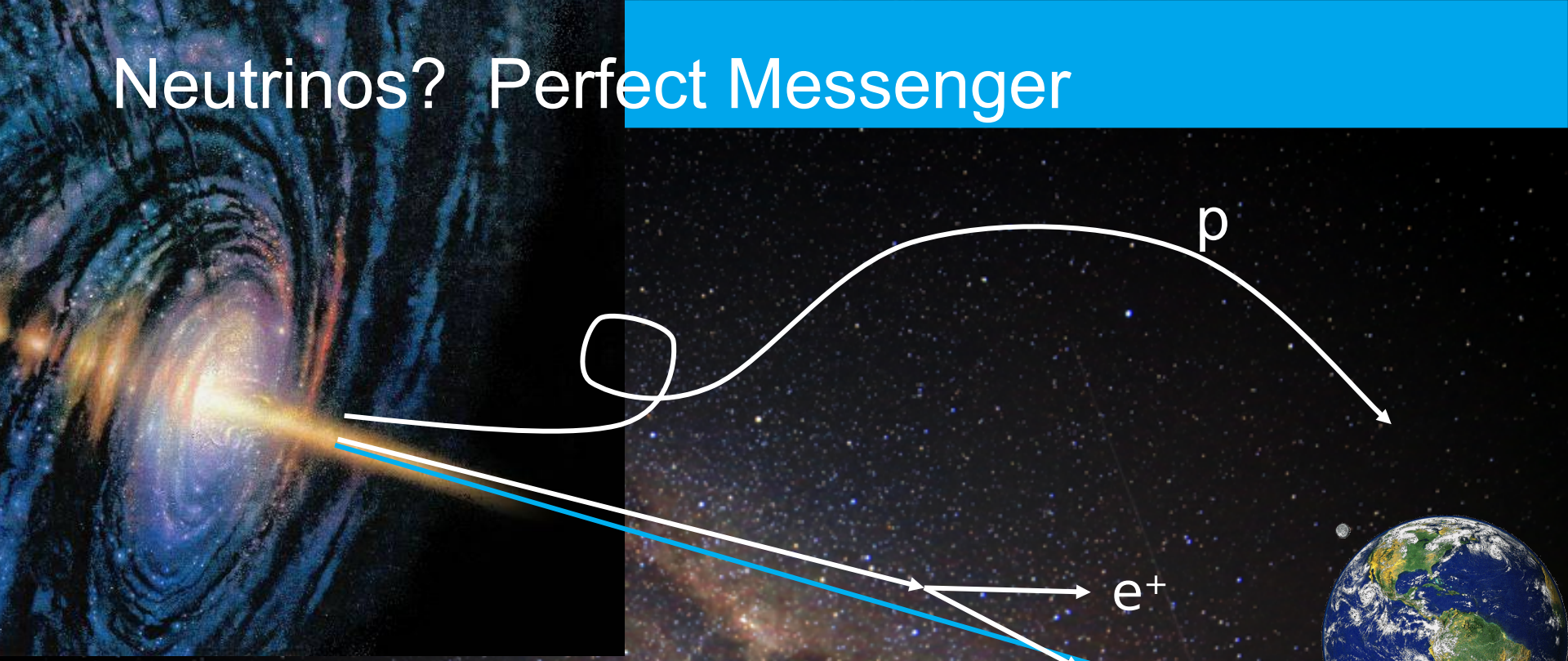
photons interact with microwave photons ($410/cm^3$) before reaching our telescopes

enter: neutrinos

HELMHOLTZ ASSOCIATION

DESY

Neutrinos? Perfect Messenger



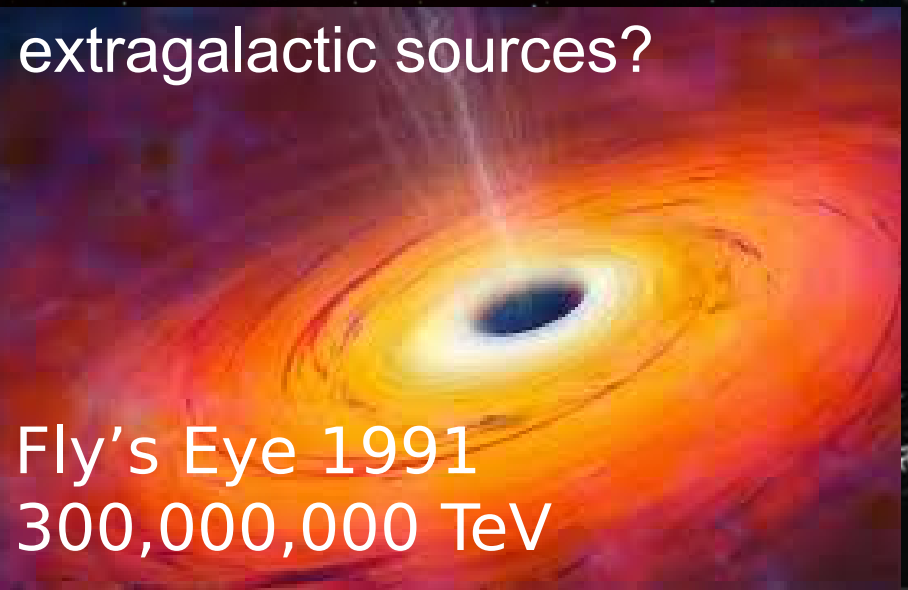
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector

HELMHOLTZ ASSOCIATION

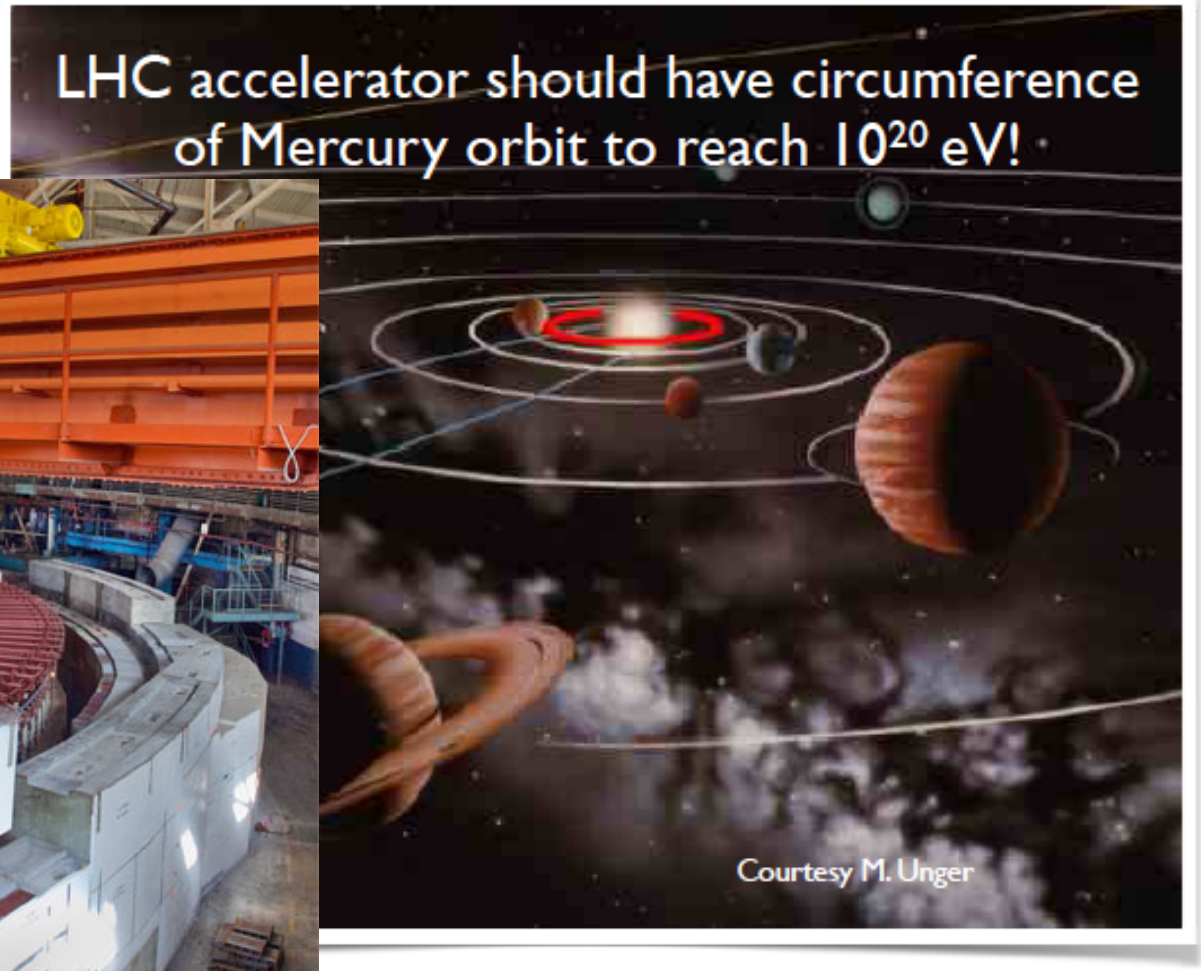
DESY

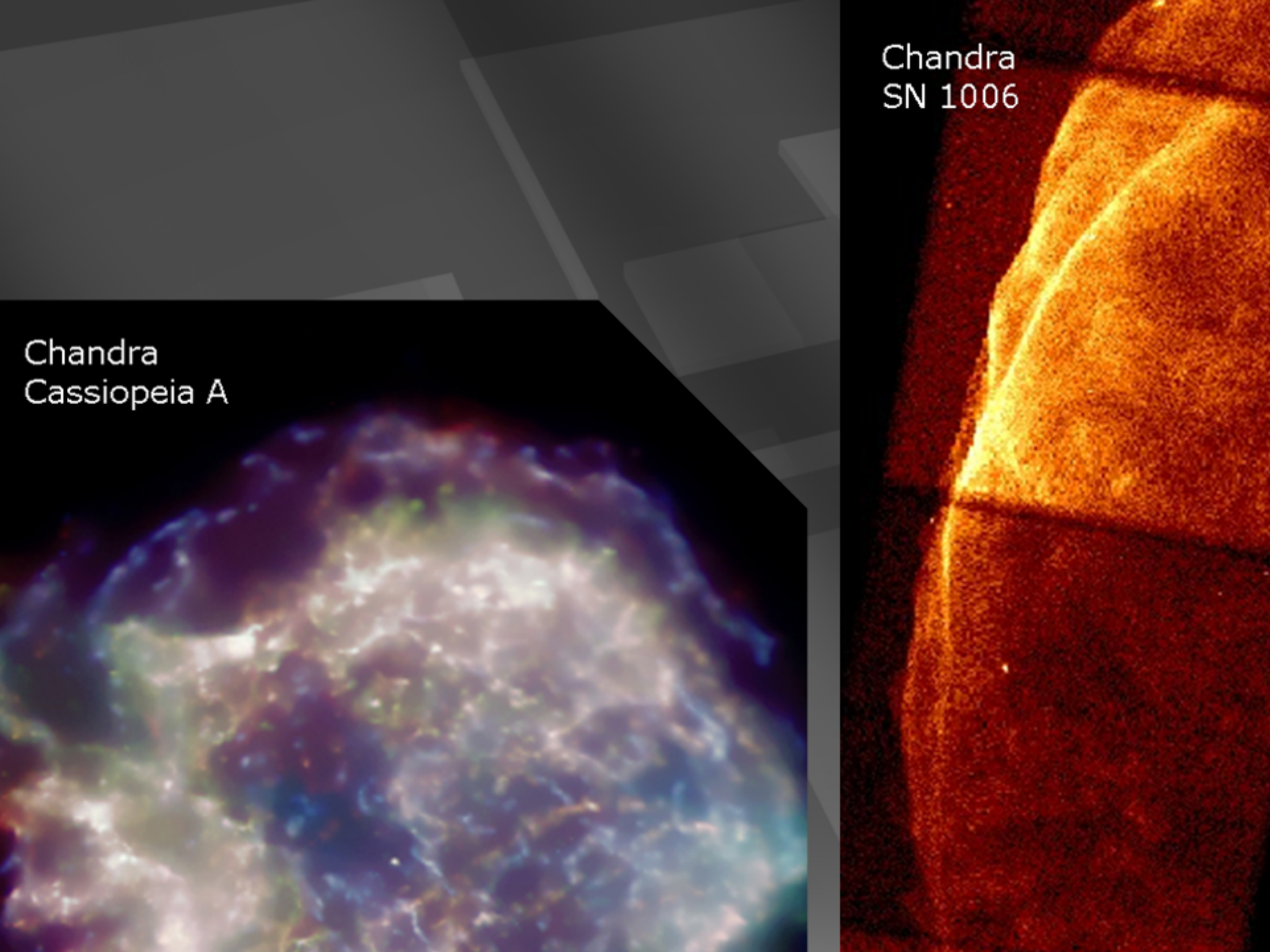
galactic sources?


extragalactic sources?
Fly’s Eye 1991
300,000,000 TeV

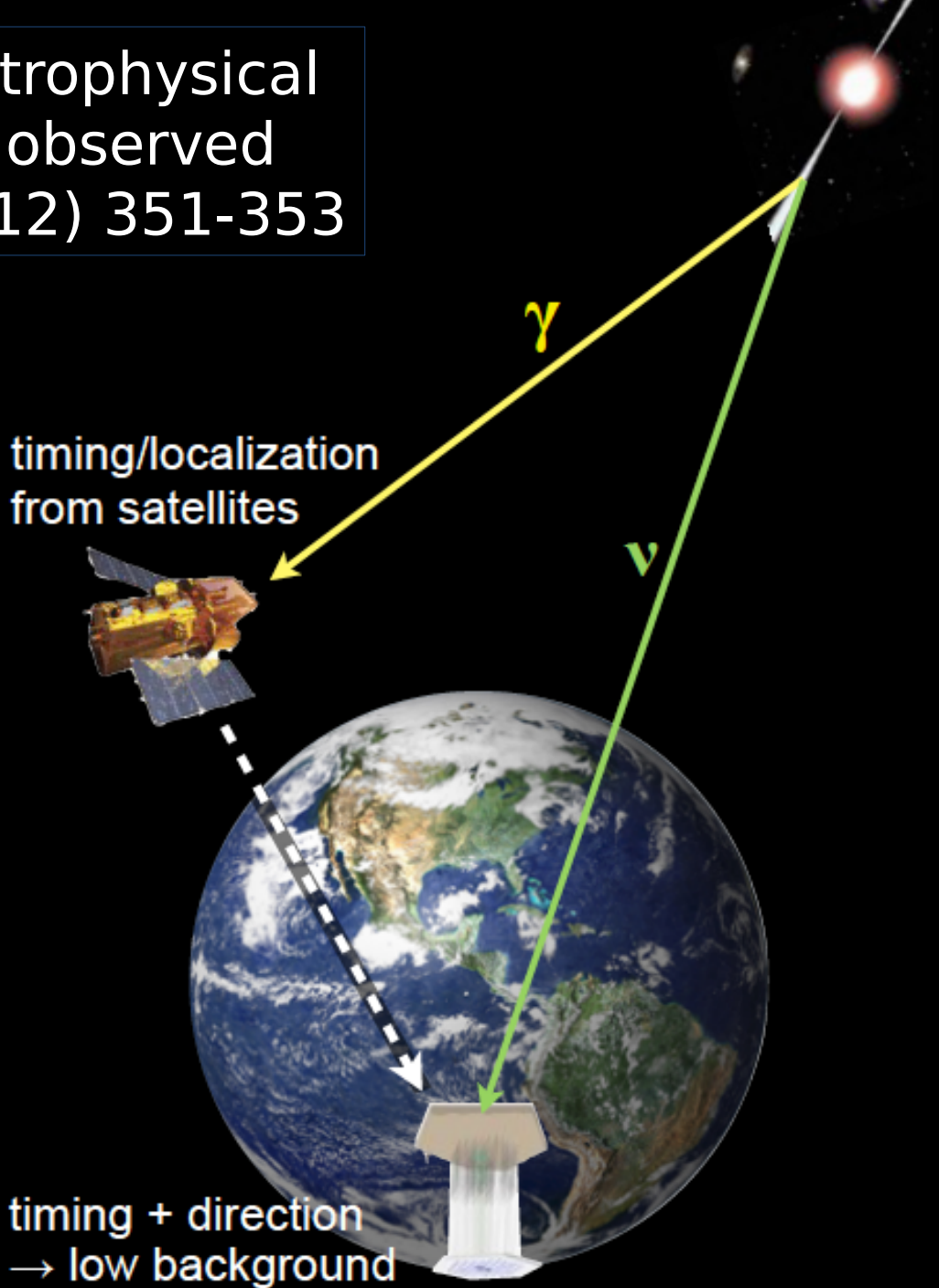
Victor Hess
discovers
cosmic rays
1912

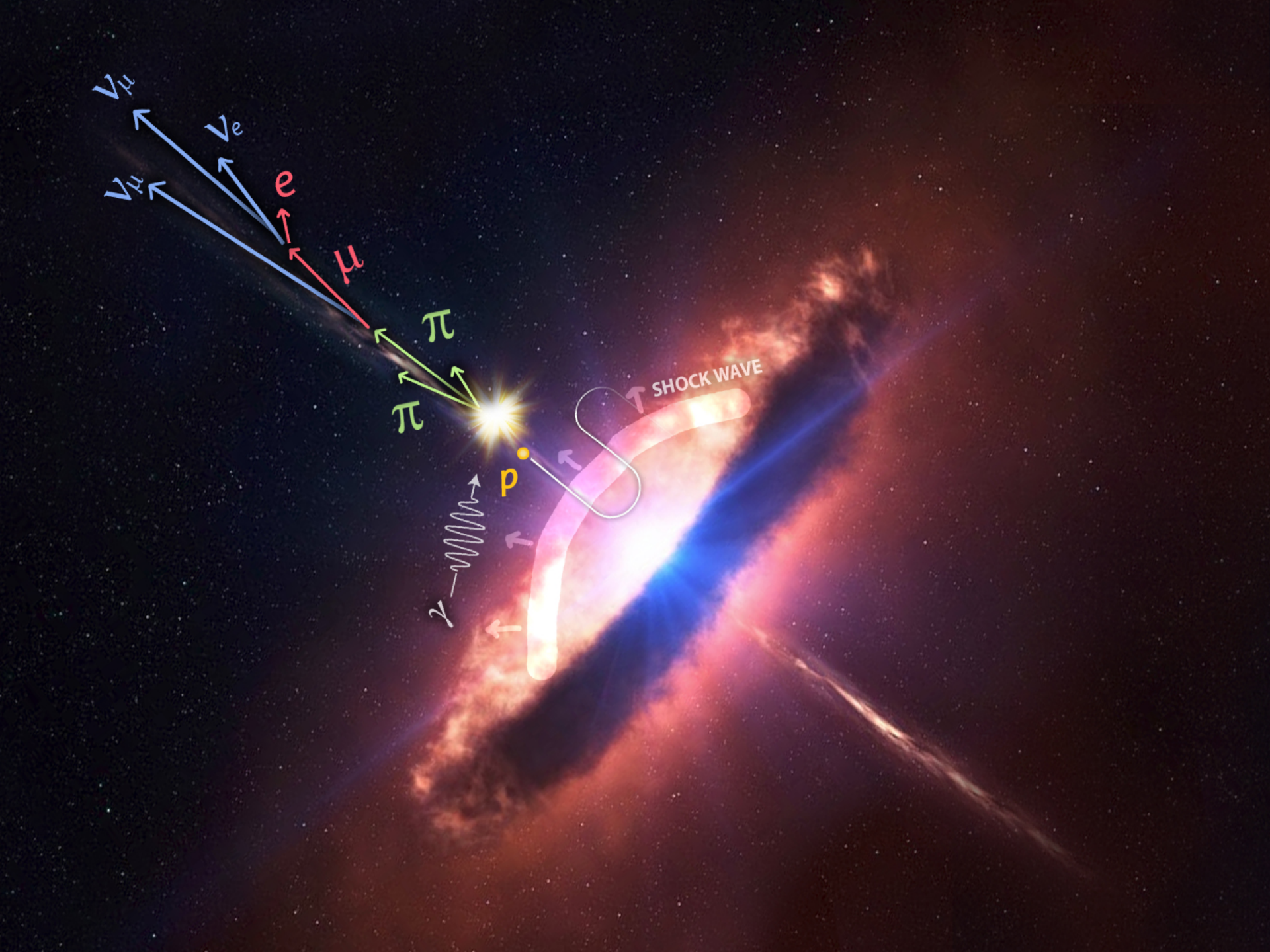
transform gravitational energy into the acceleration of particles




Chandra
Cassiopeia A
Chandra
SN 1006

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

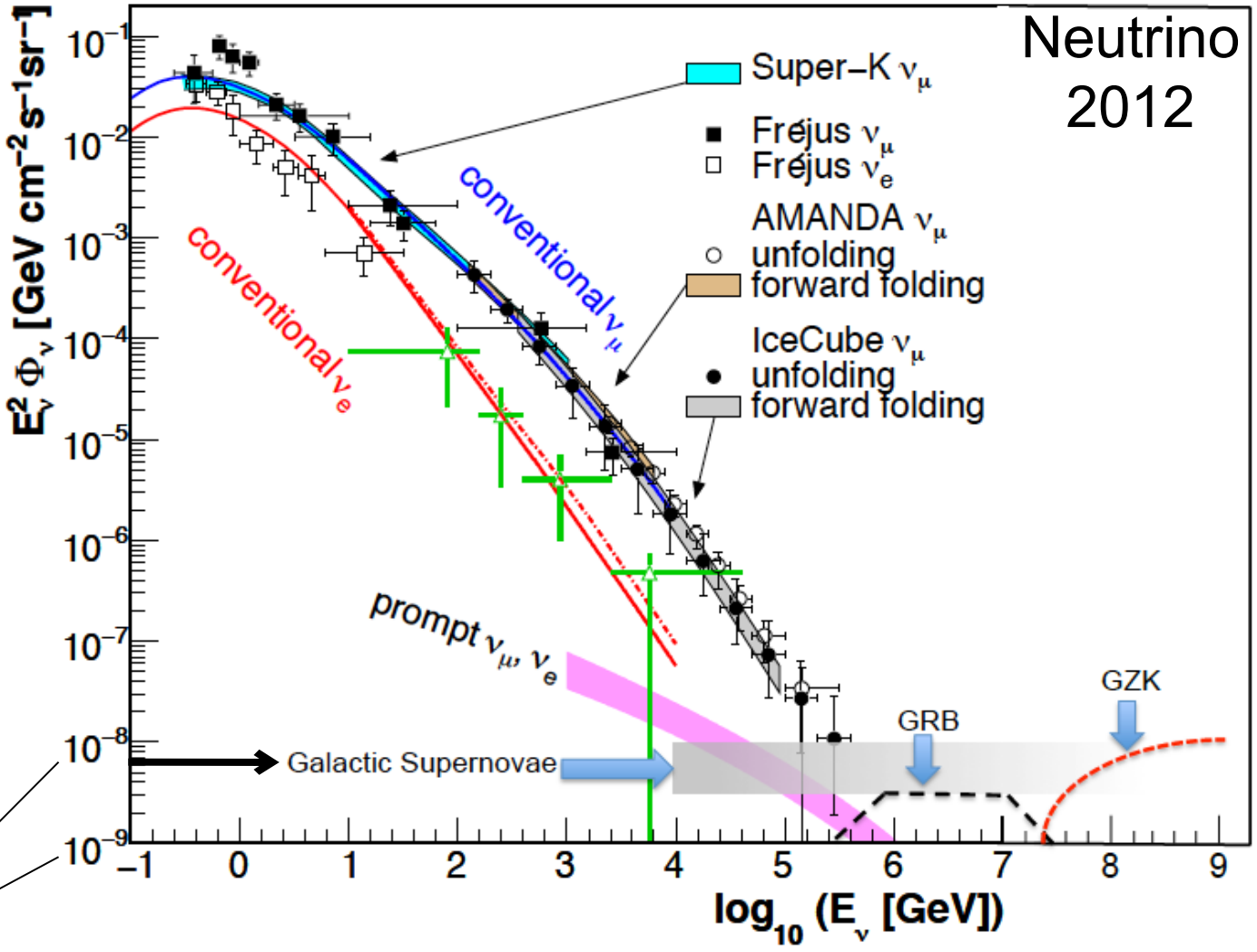



ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

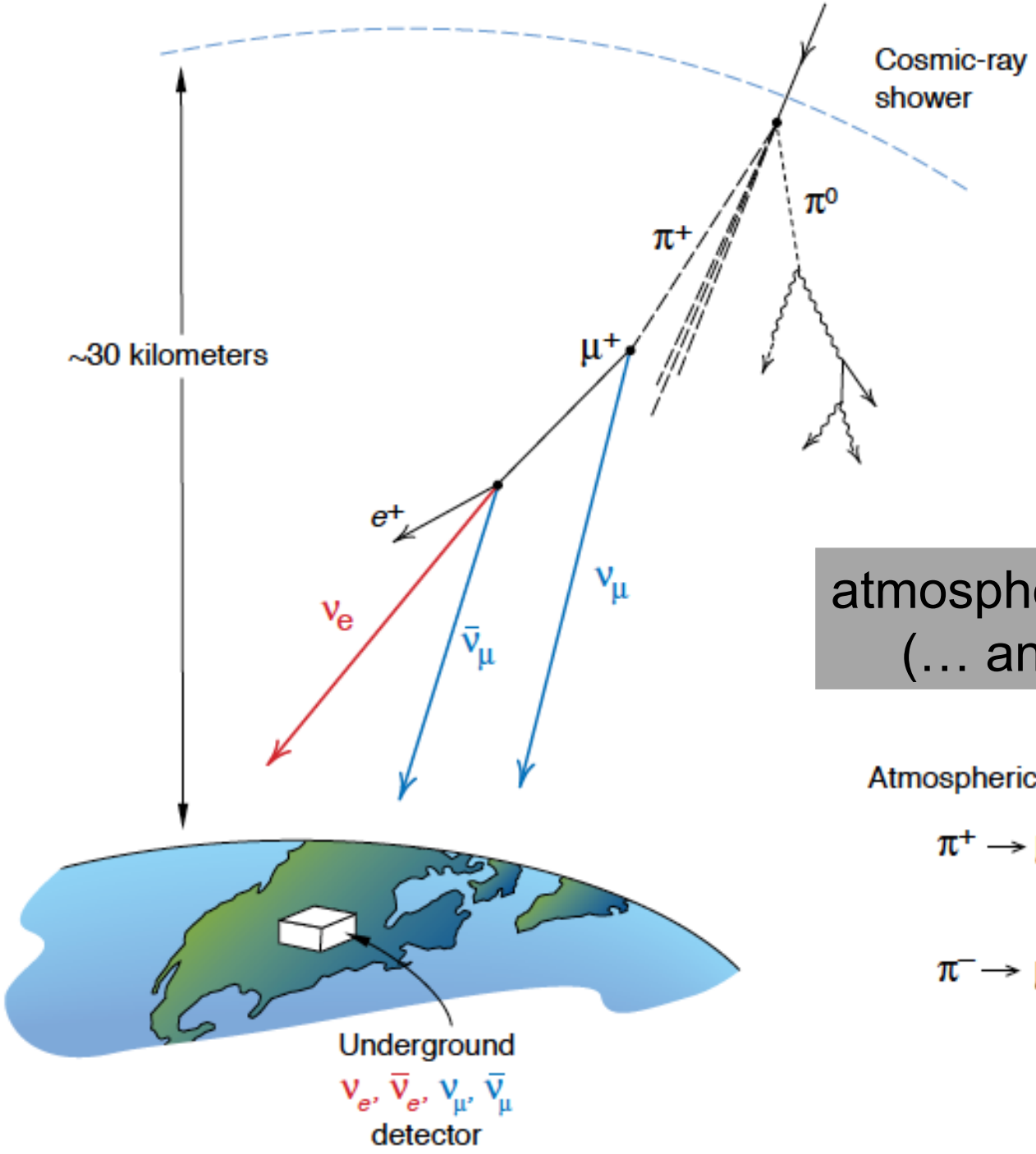


10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV

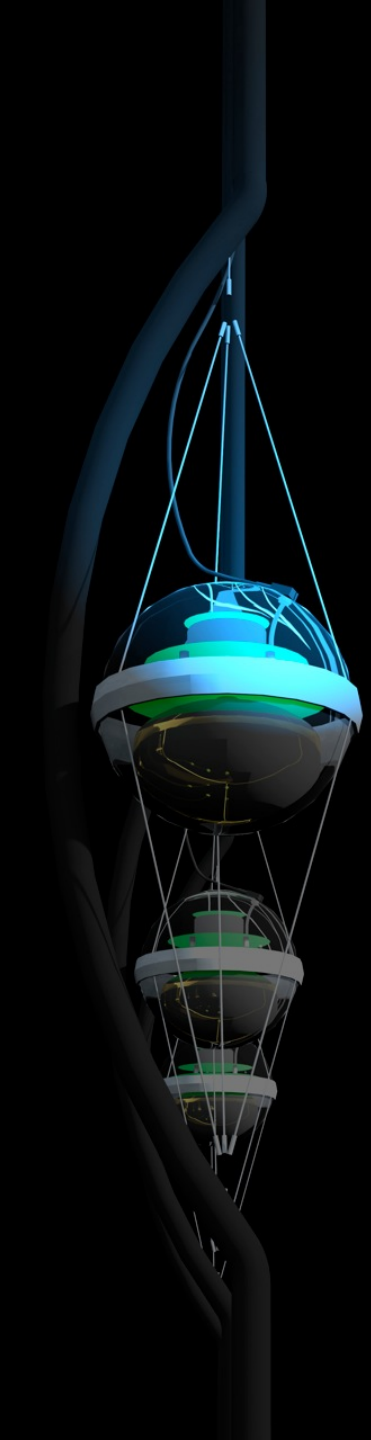


atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

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

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



IceCube

francis halzen

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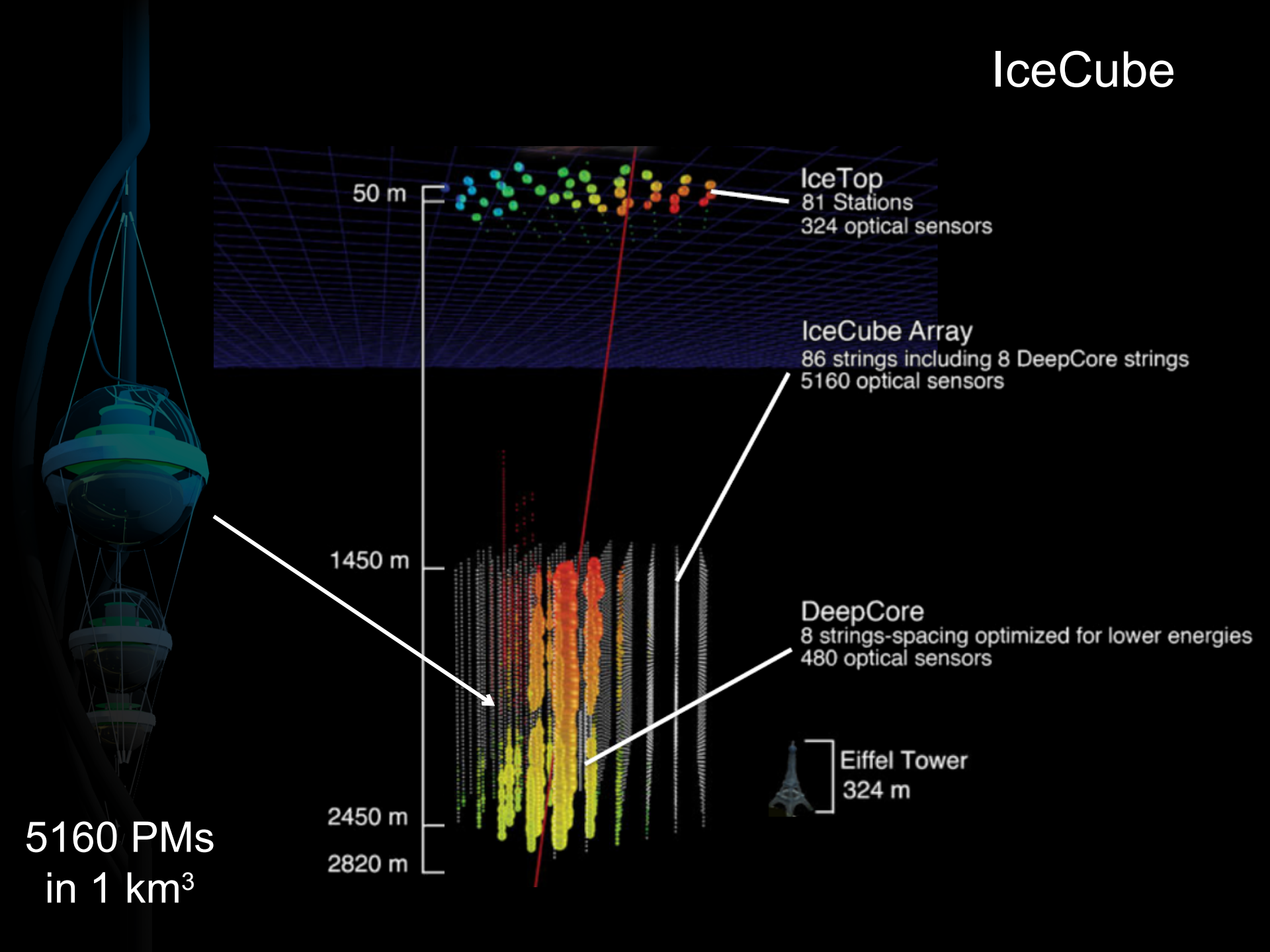
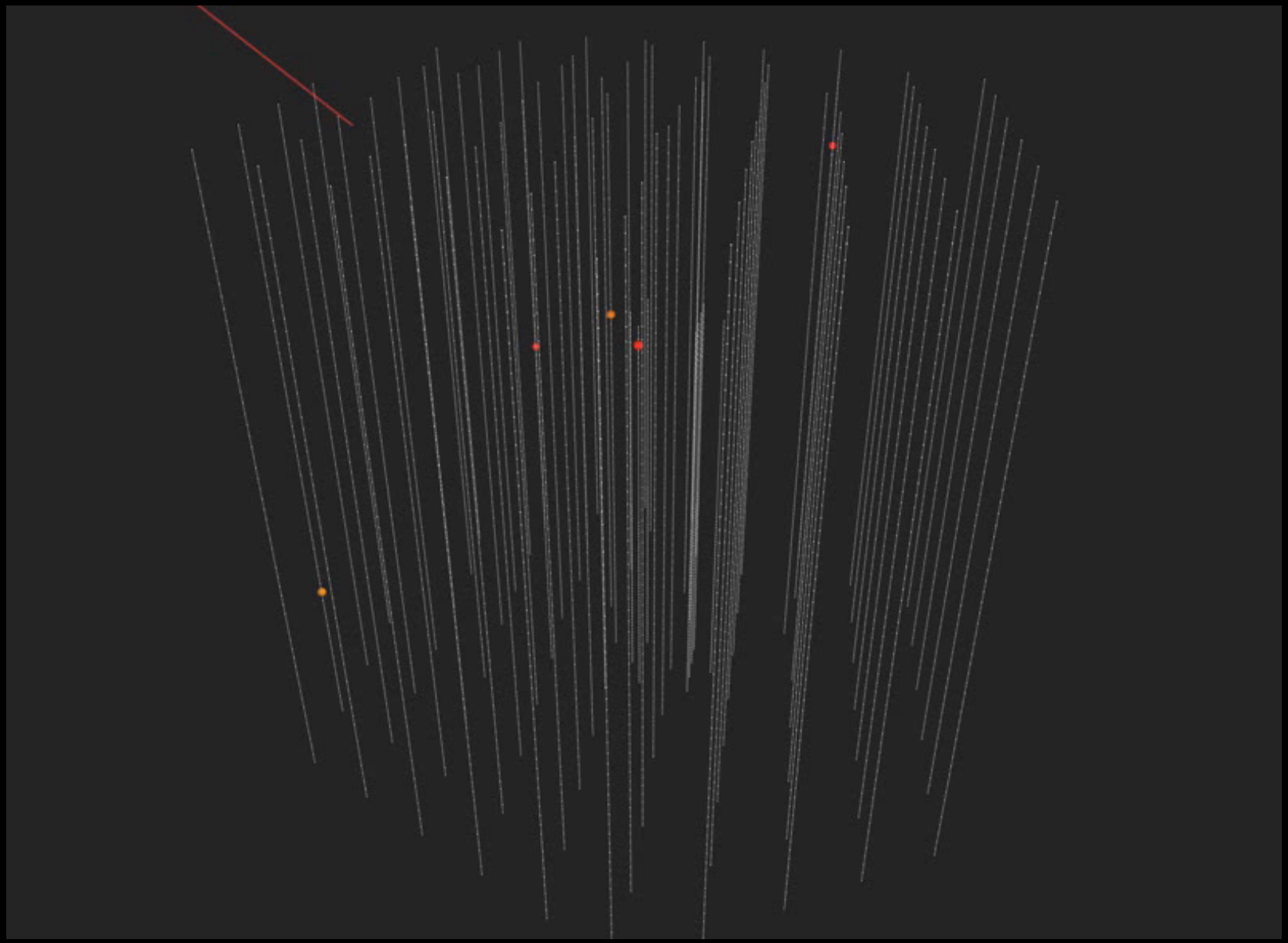
ultra-transparent ice below 1.5 km

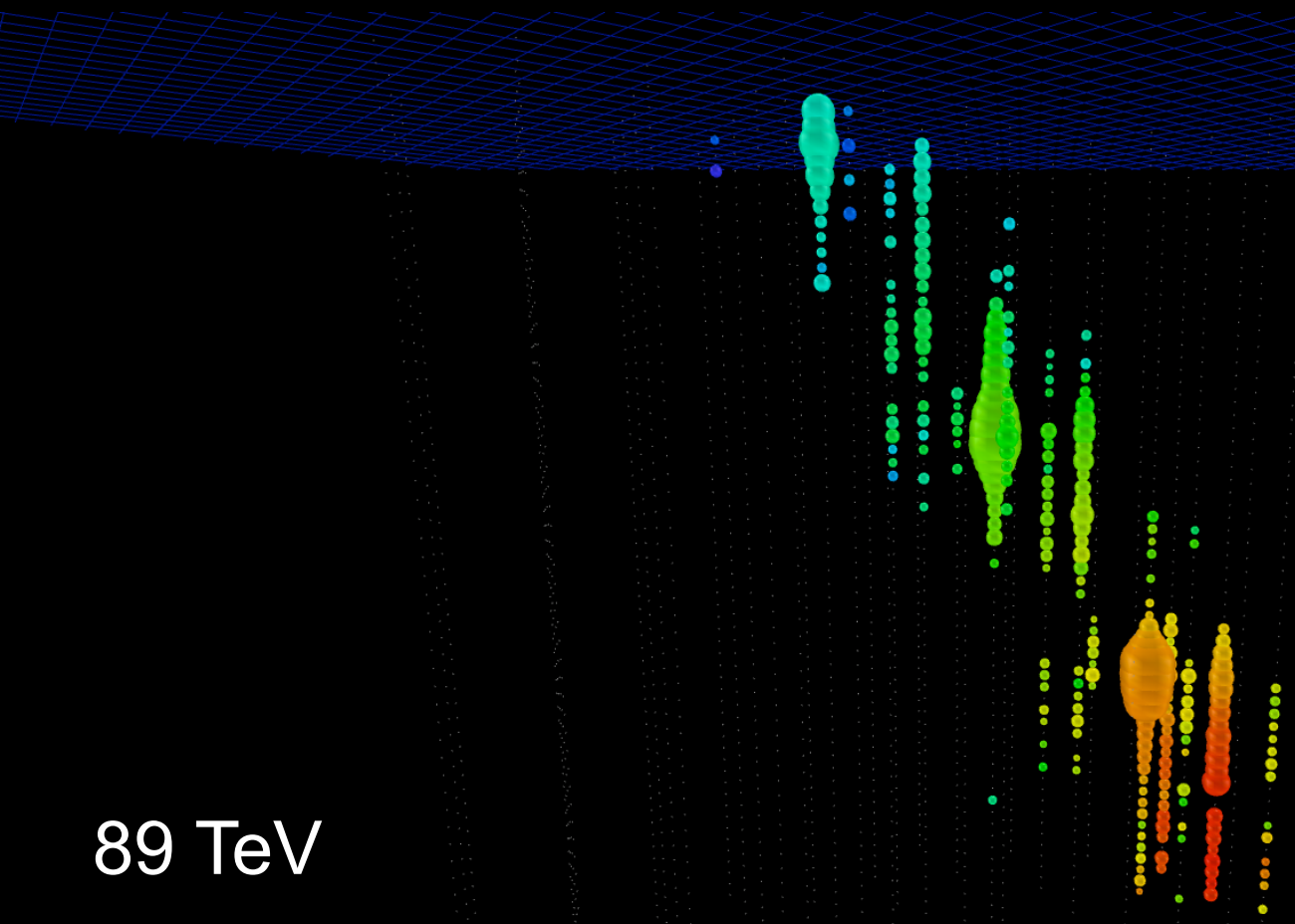
IceCube


50 m
IceTop
81 Stations
324 optical sensors
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 km3



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

a neutrino?

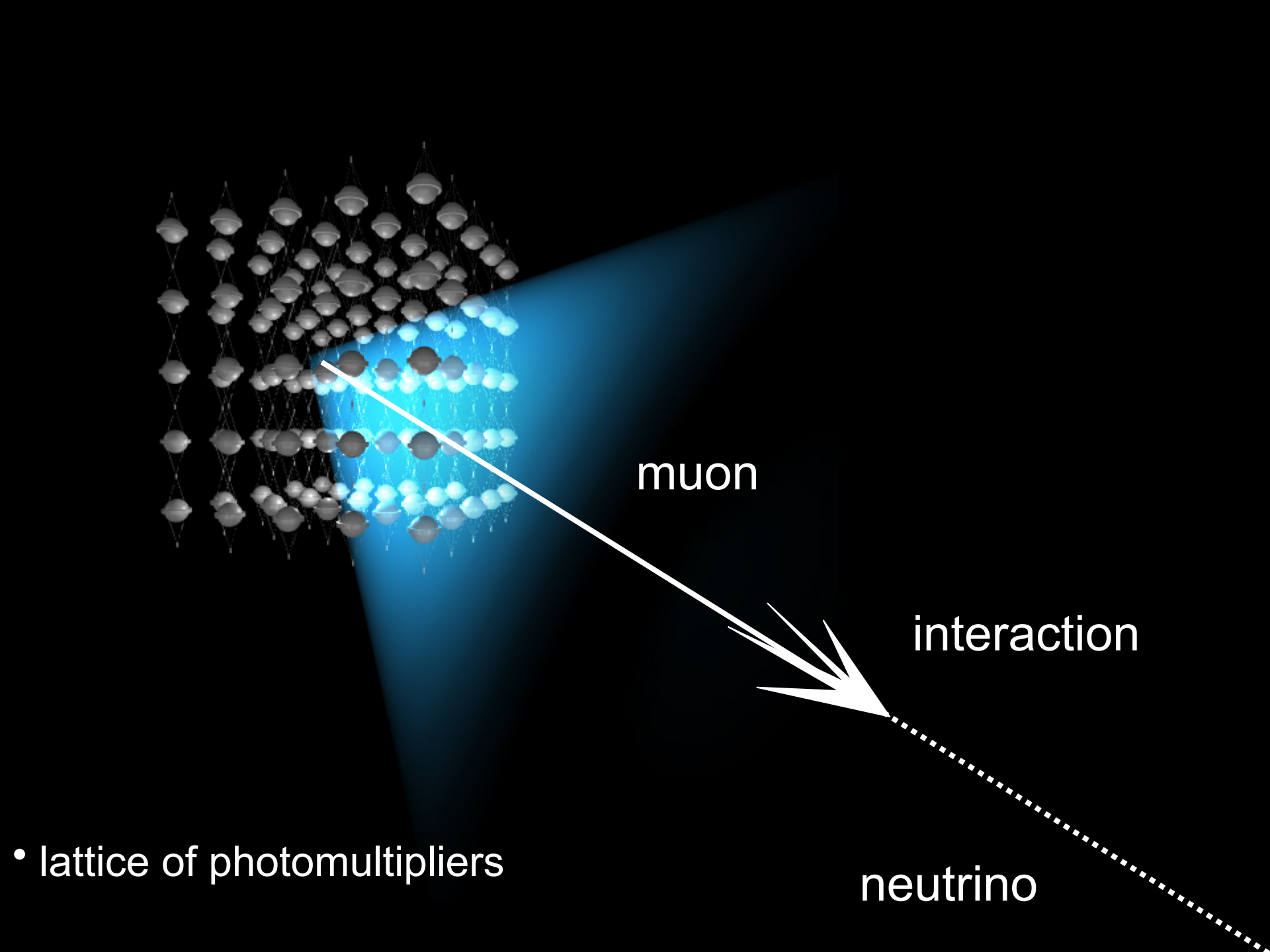


89 TeV

radius ~ number of photons

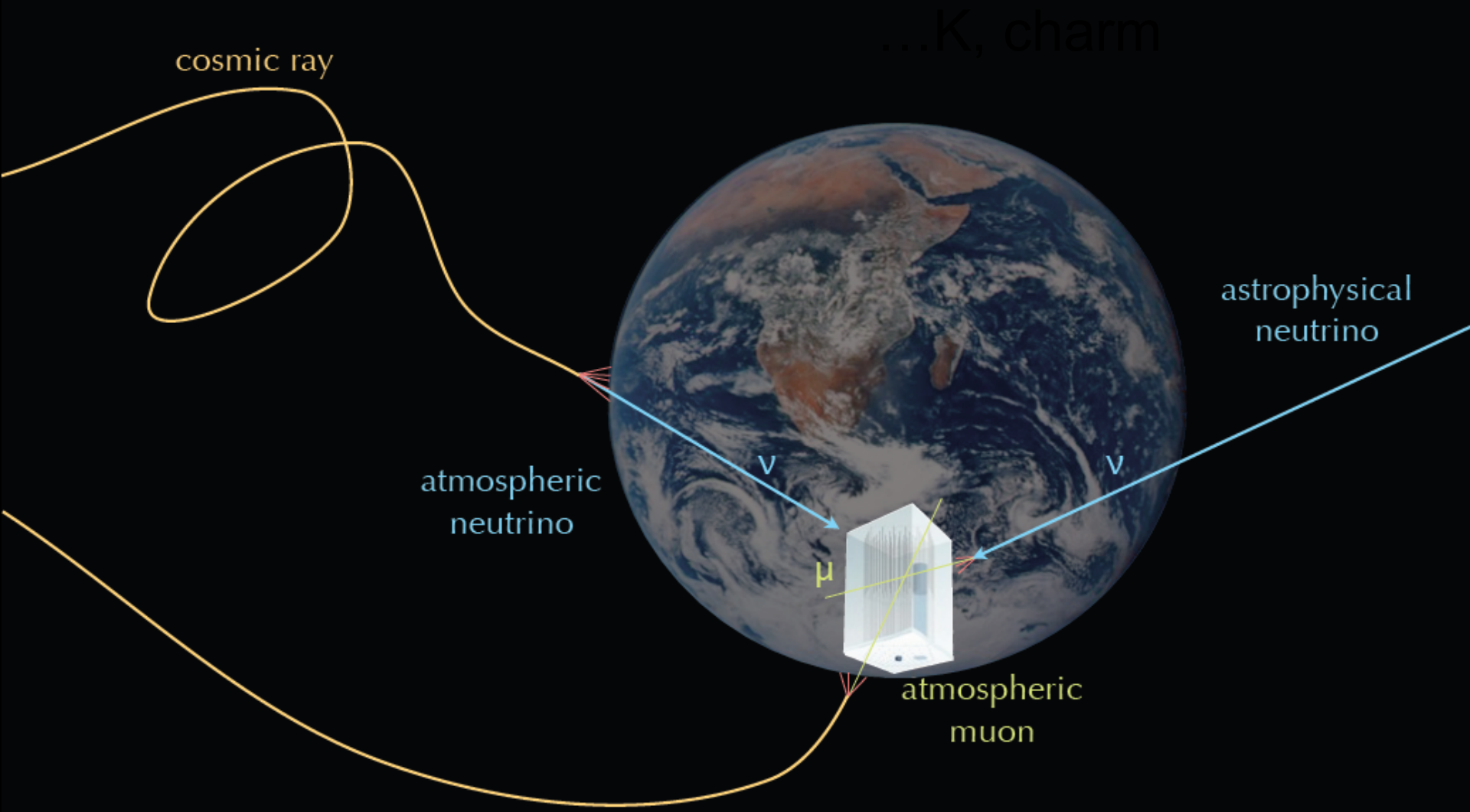
time ~ red purple

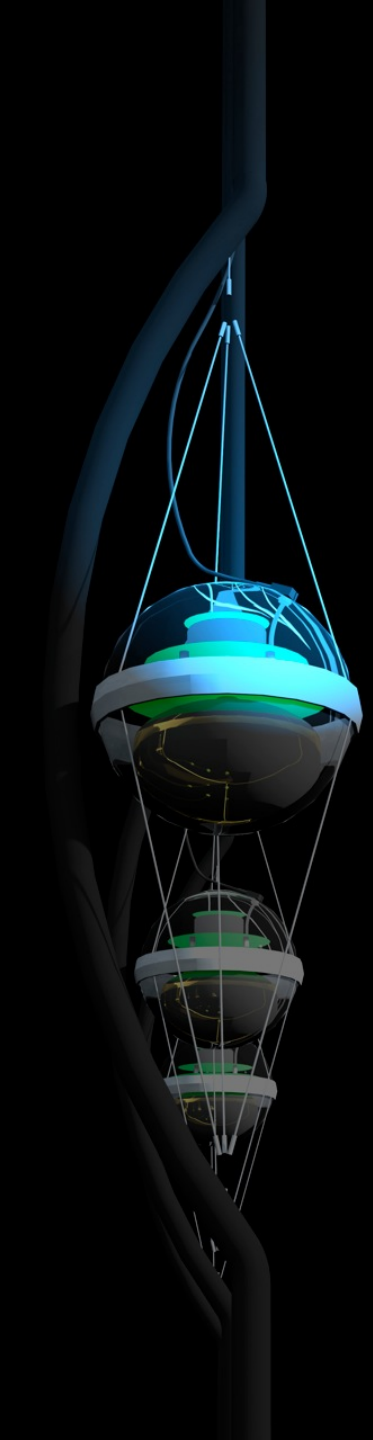
Run 113641 Event 33553254 [0ns, 16748ns]



- lattice of photomultipliers

Signals and Backgrounds





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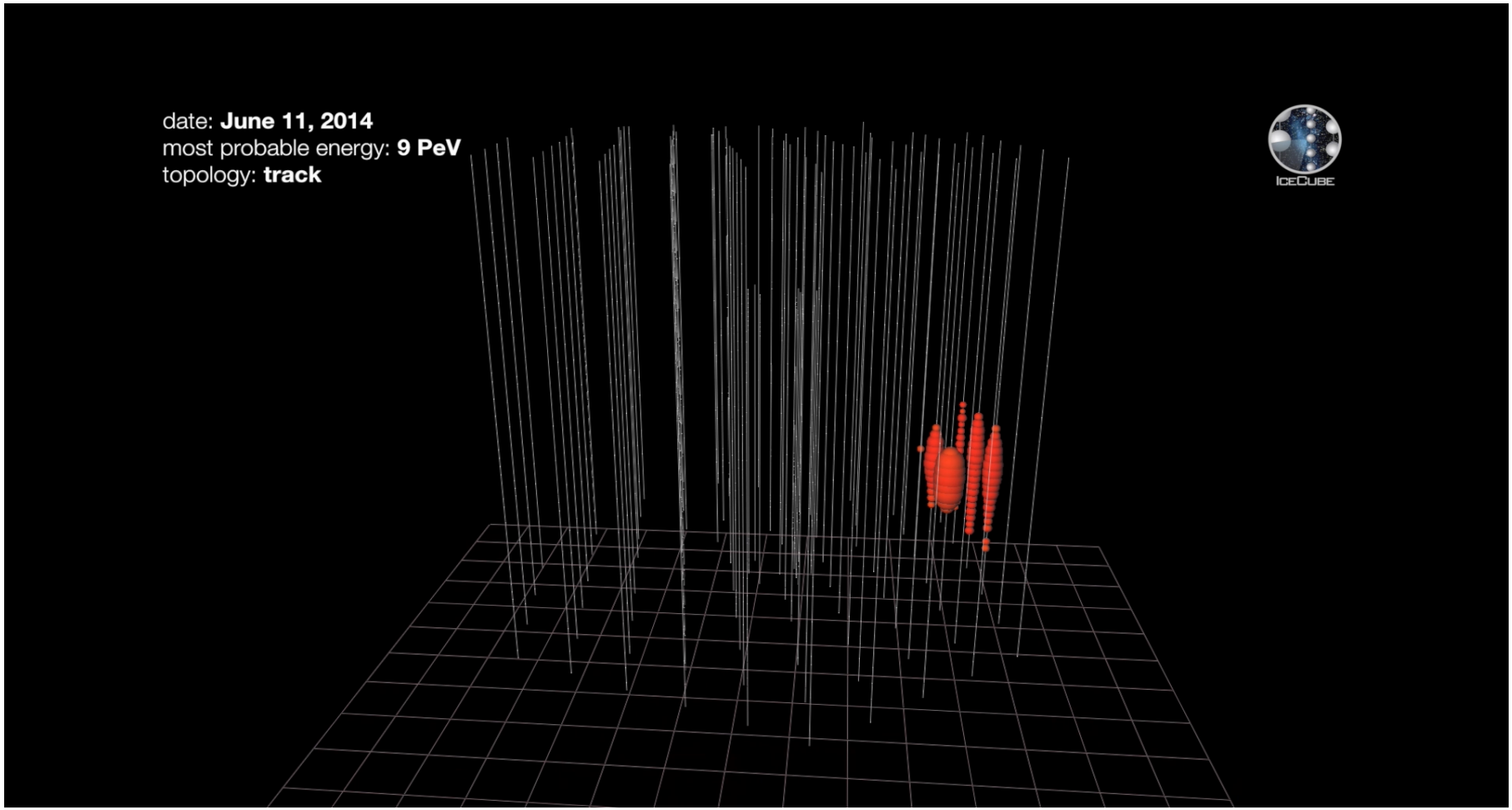
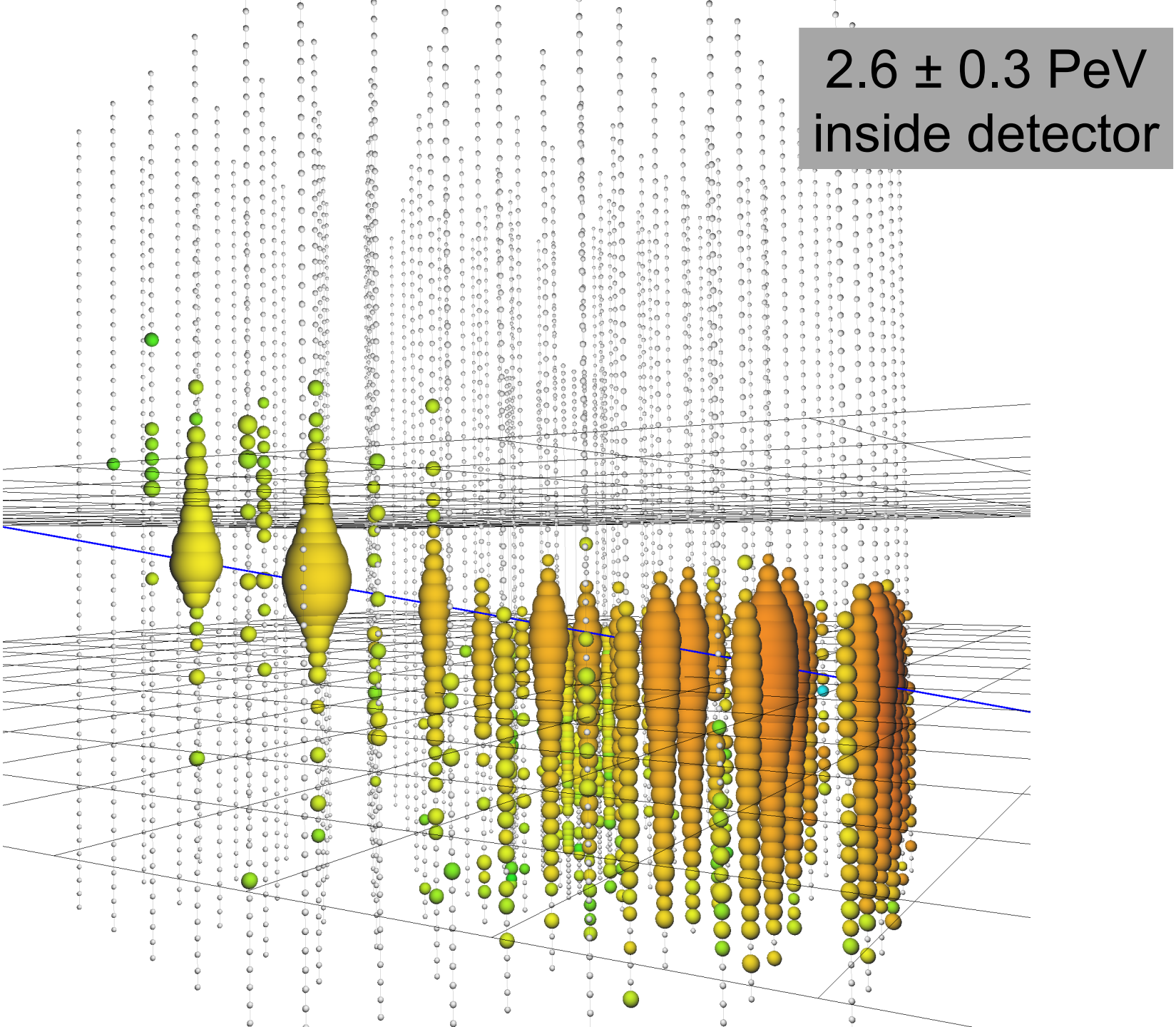
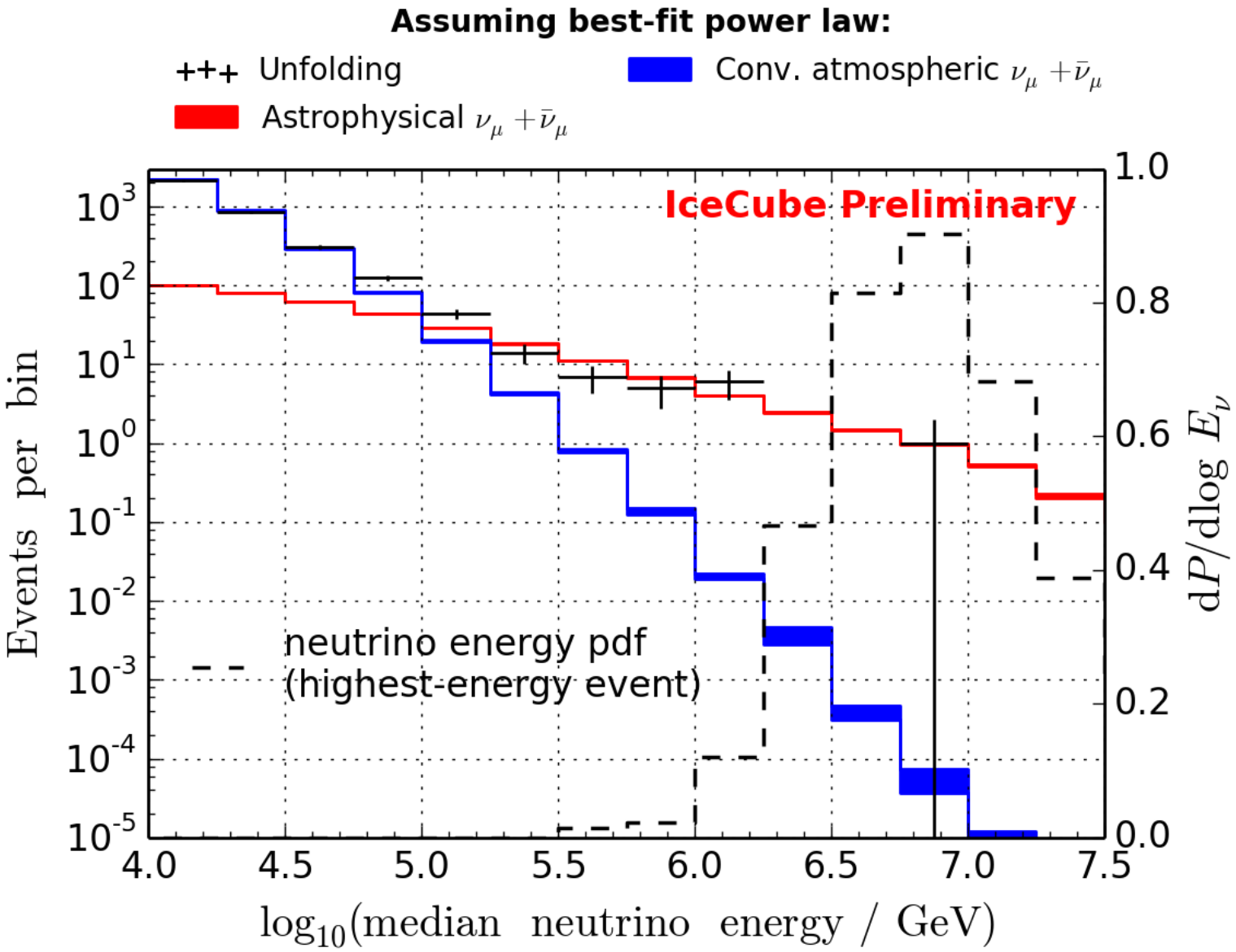

date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
IceCube


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

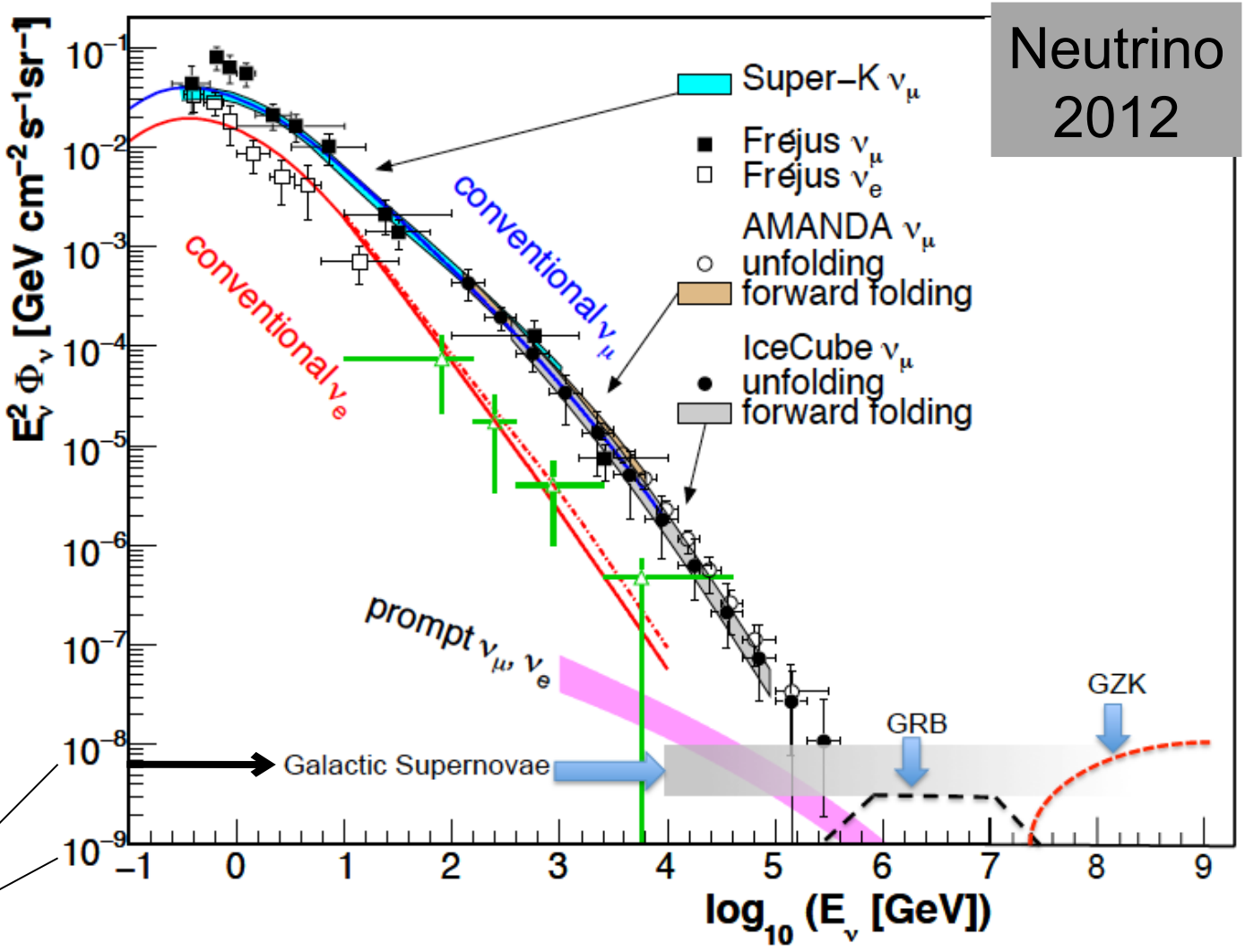


above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

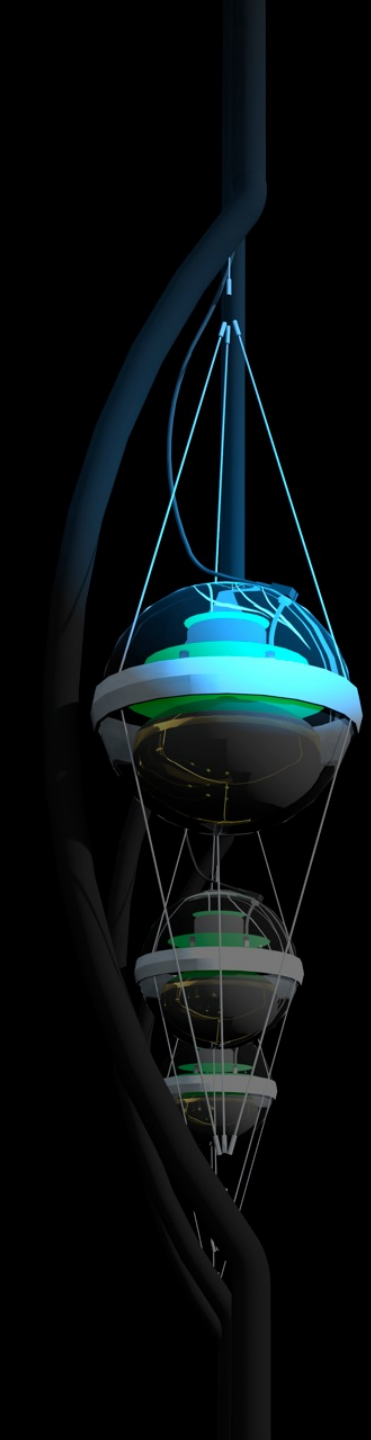
10—100 events per year for fully efficient detector



atmospheric

cosmic

100 TeV



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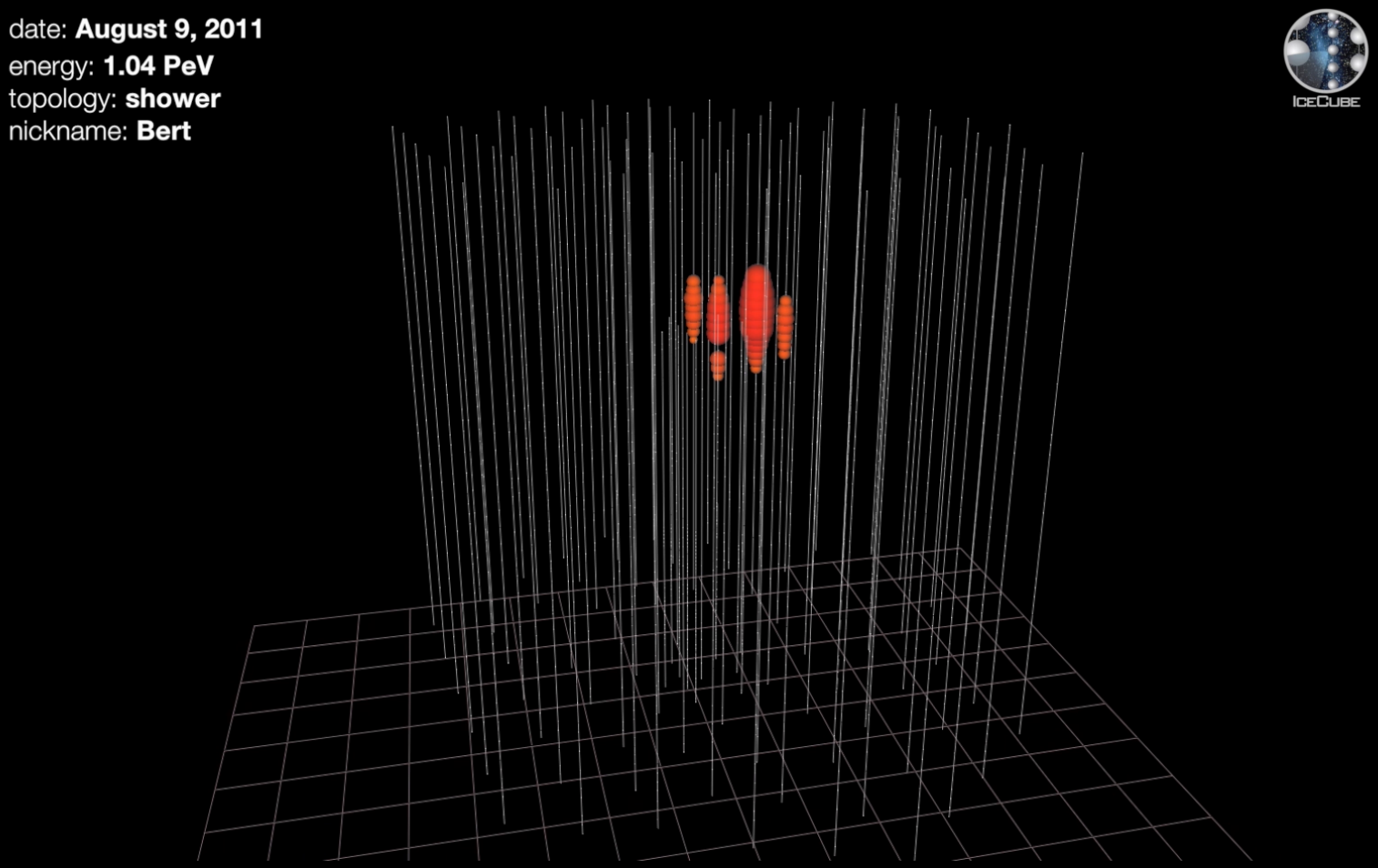
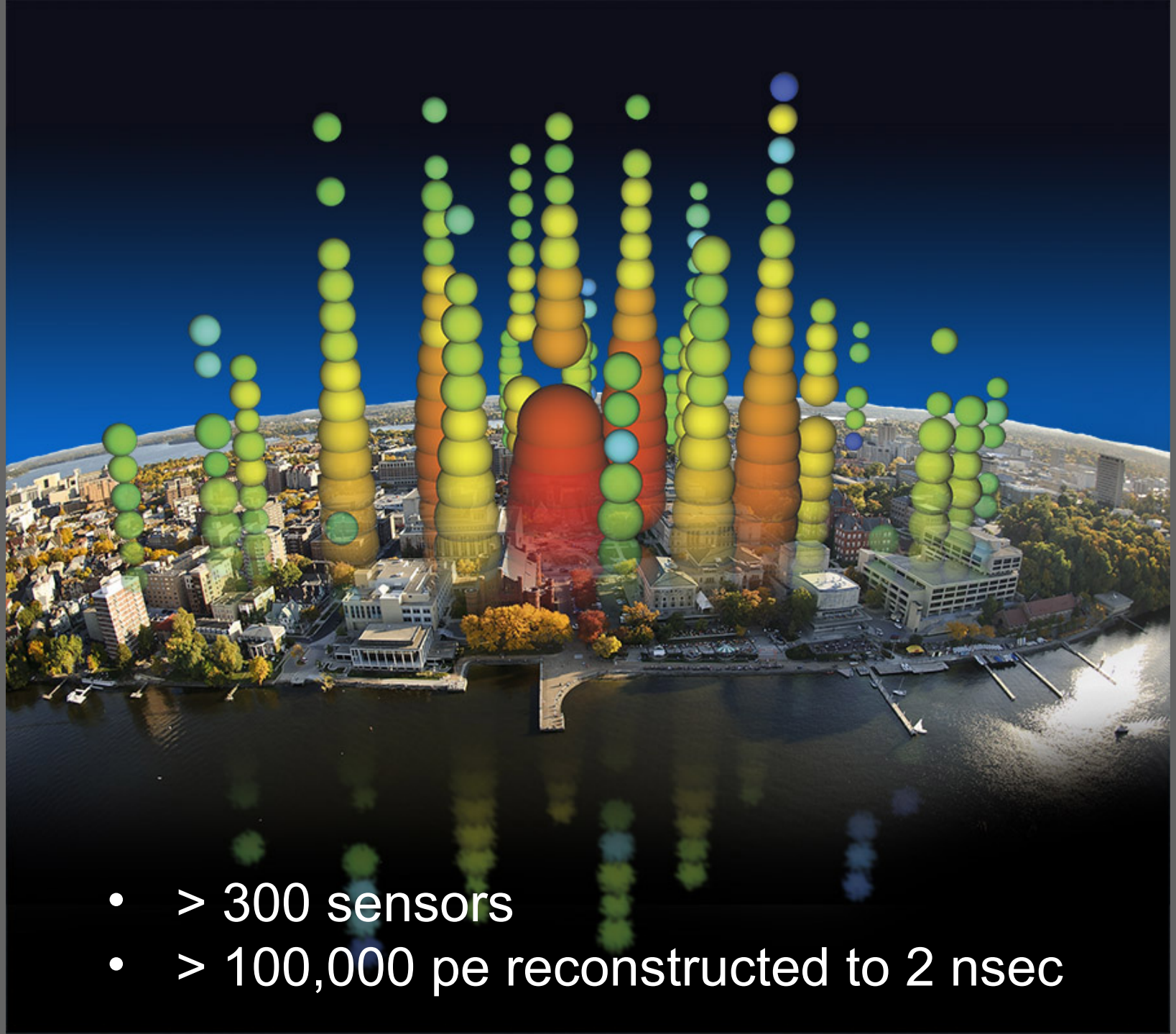
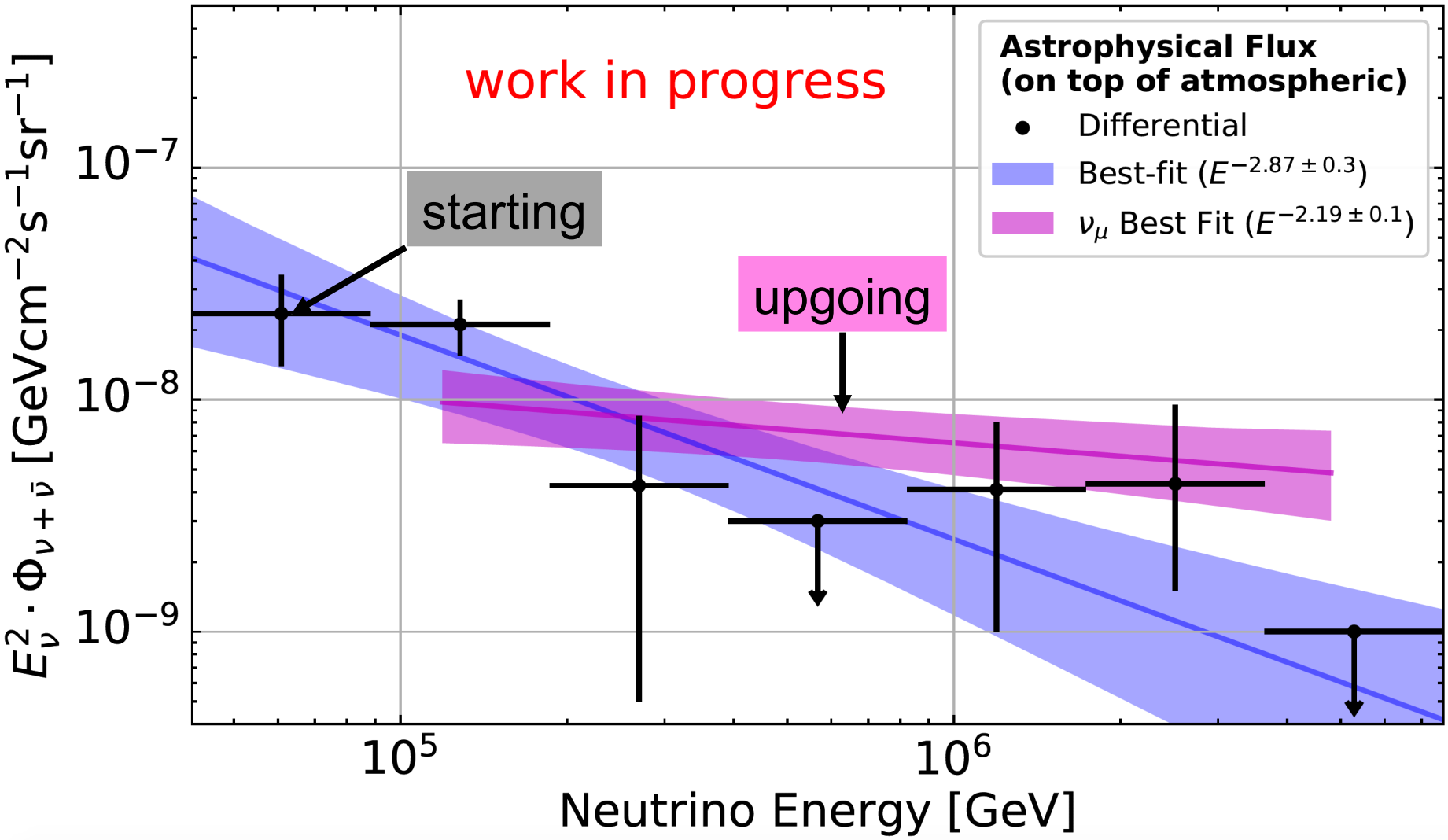
GZK neutrino search: two neutrinos with > 1,000 TeV





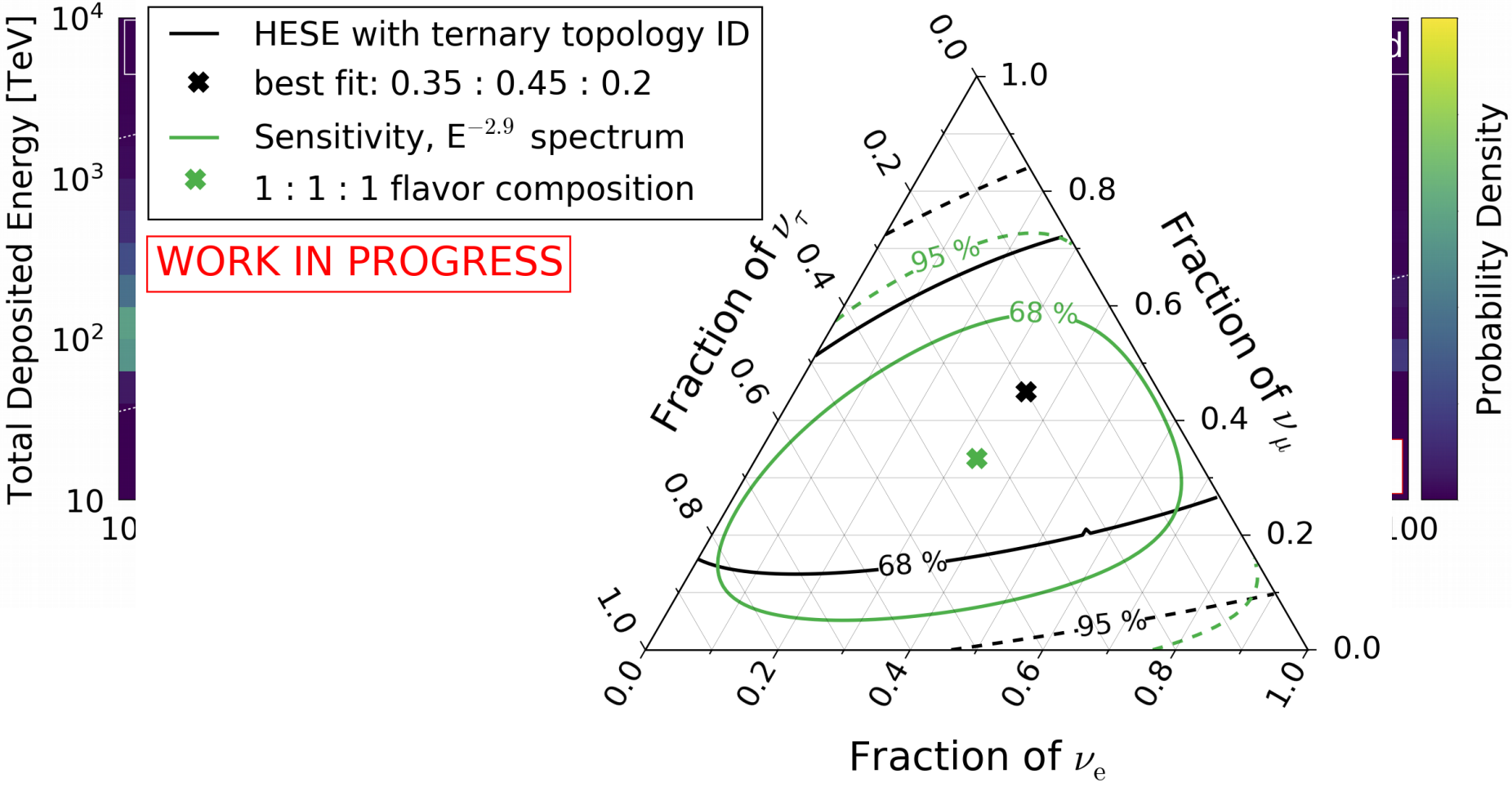
- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

high-energy starting events – 7.5 yr



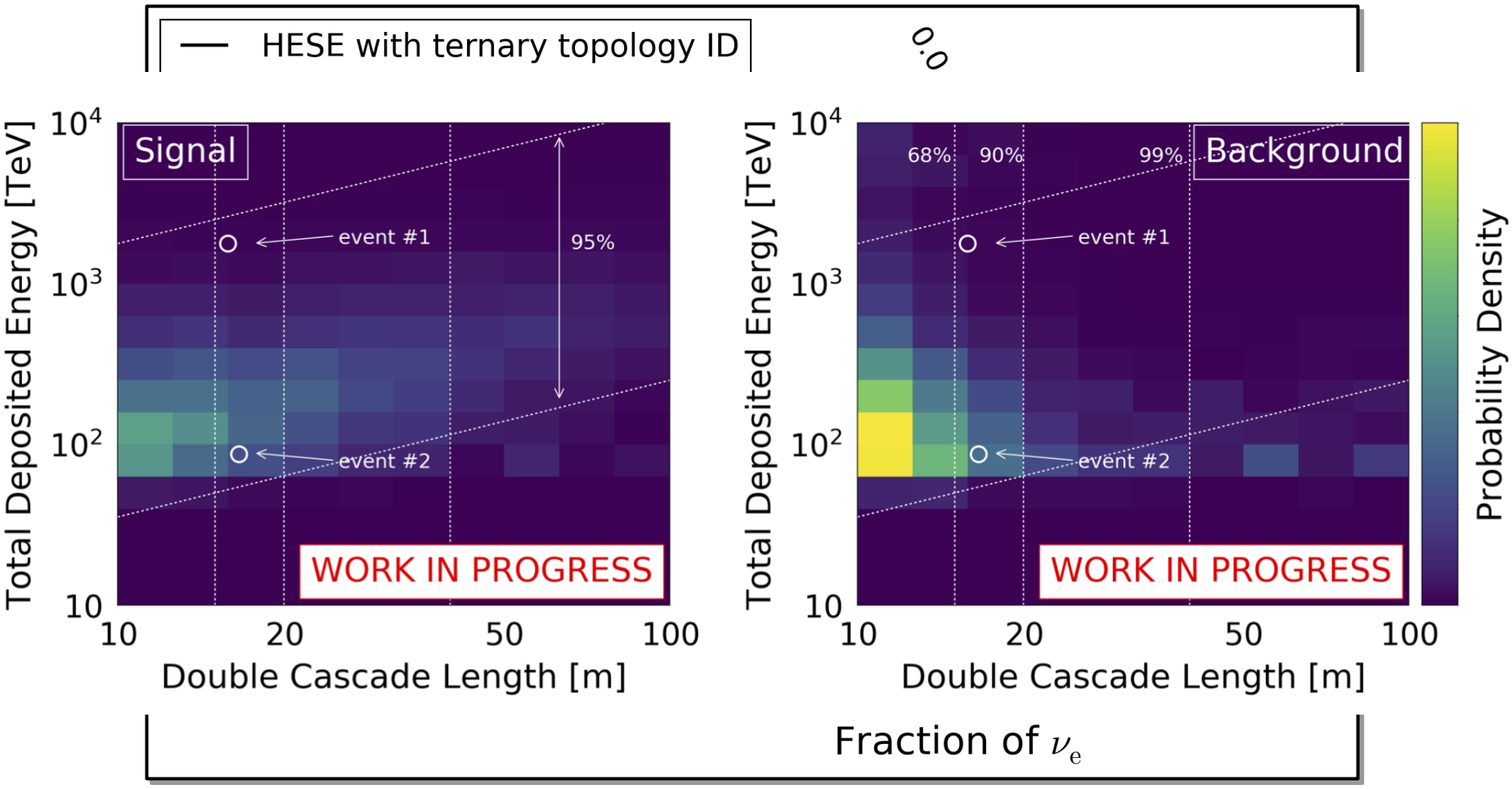
two methods are consistent

high-energy starting events – 7.5 yr

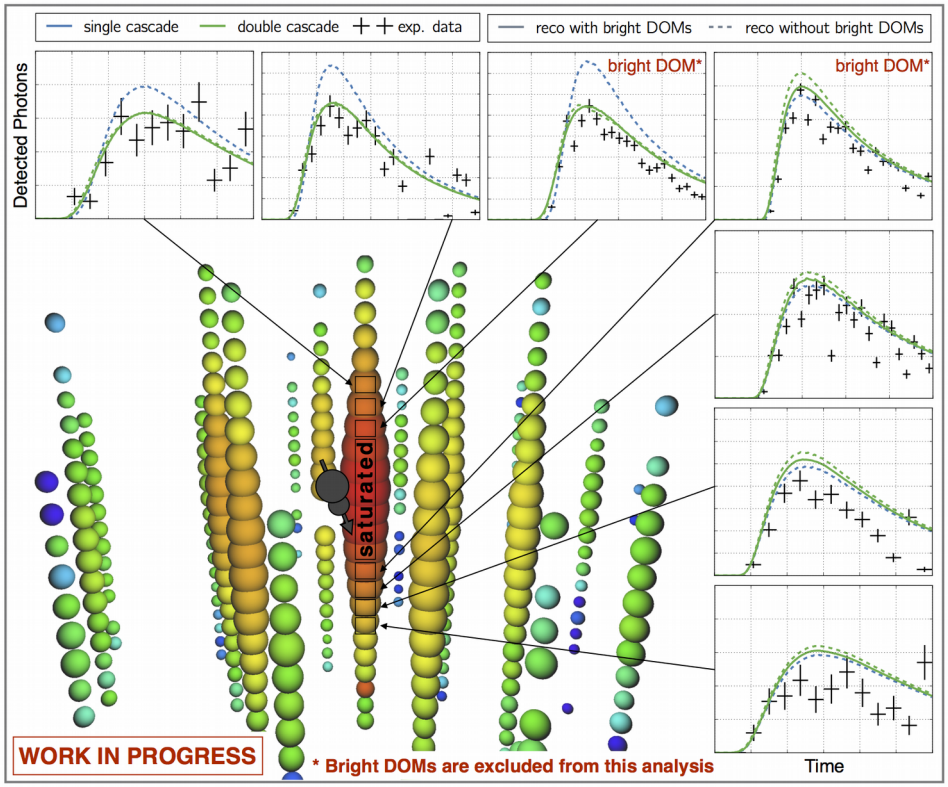


oscillations of PeV neutrinos over cosmic distances to 1:1:1

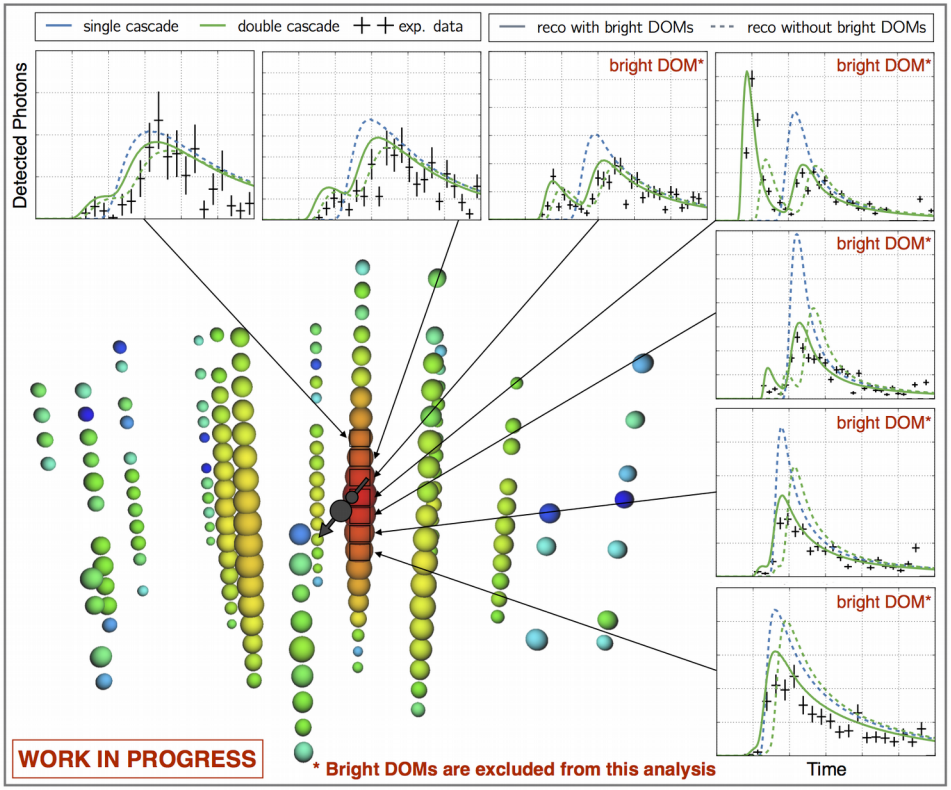
high-energy starting events – 7.5 yr



high-energy starting events (starting) – 7.5 yr



Double cascade Event #1

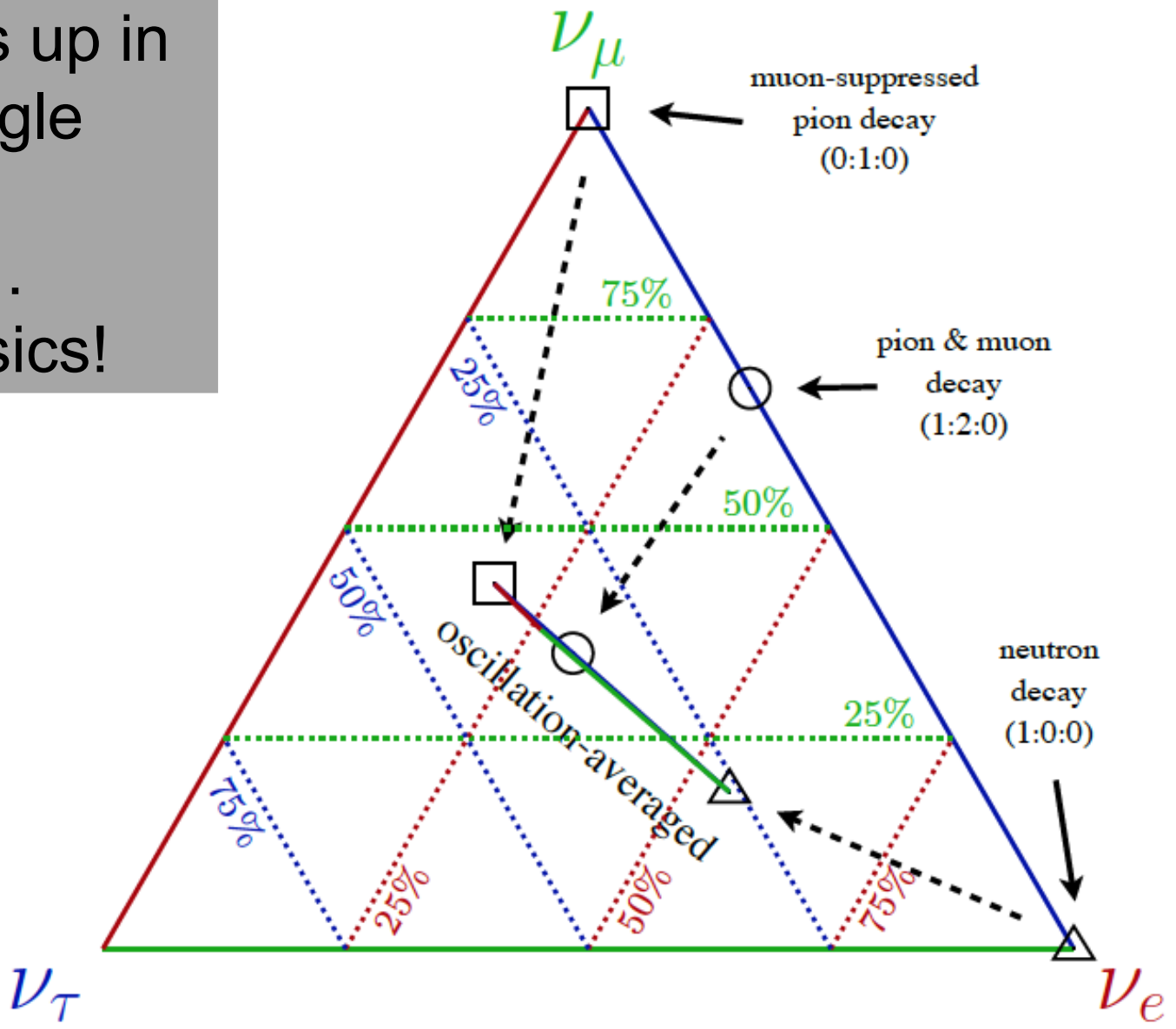


Double cascade Event #2

“Bright” DOMs not used in reconstruction
Direction and two reconstructed cascades shown in dark gray

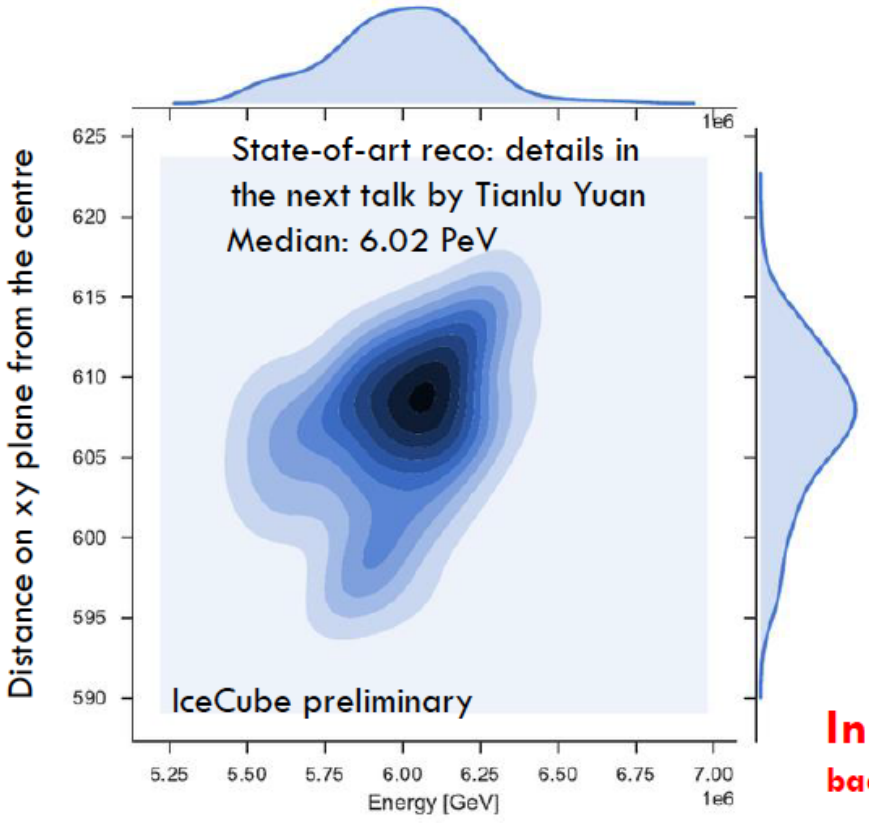
every astrophysical model ends up in the triangle

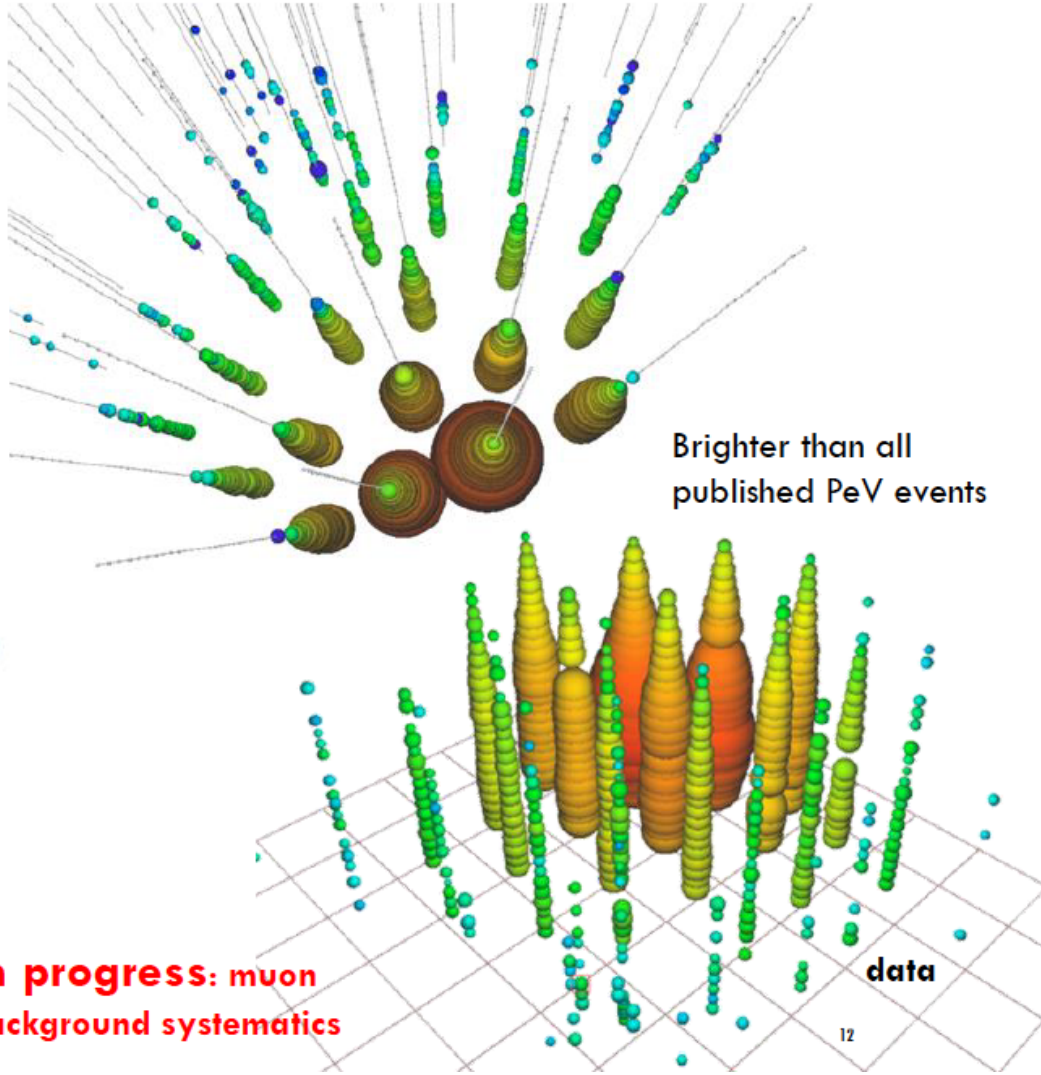
if not…
new physics!



Partially contained event with energy 5.9 PeV

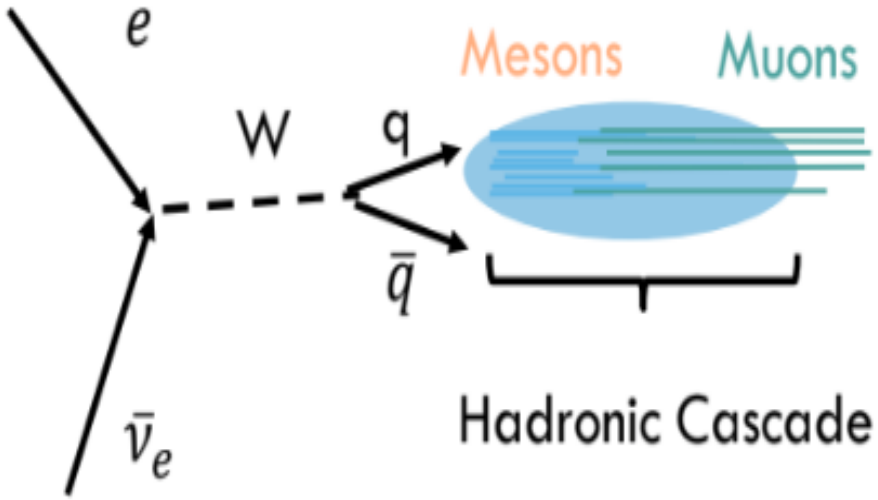
HIGHEST-ENERGY NEUTRINO CANDIDATE

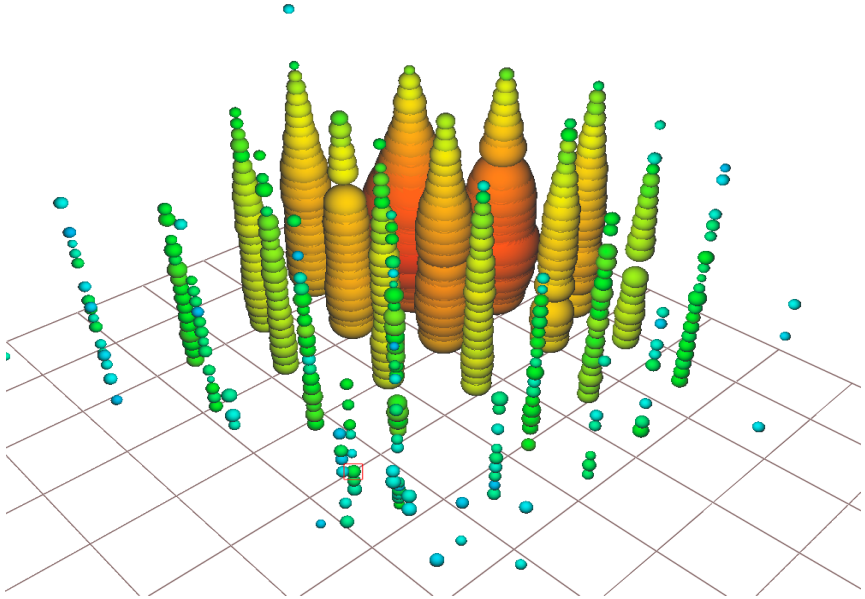


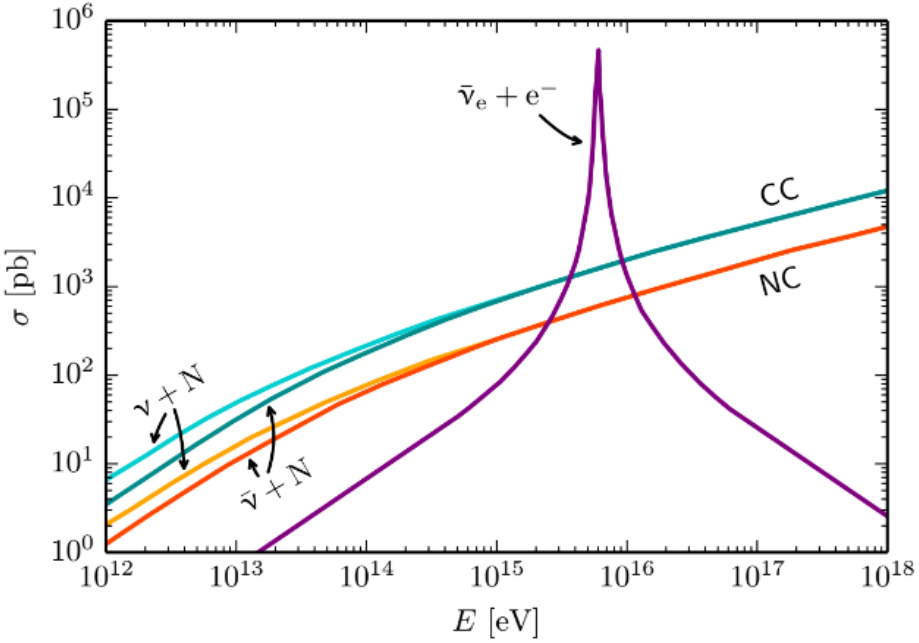


In progress: muon background systematics

Glashow resonance: anti-ν_e + atomic electron ☾ real W



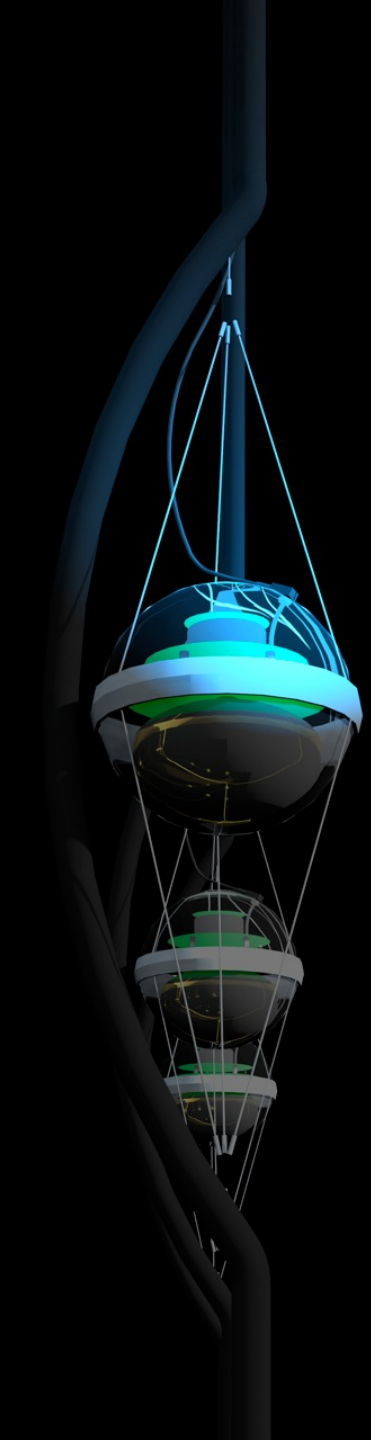




- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- ☾ resonance: E_ν = 6.3 PeV

work on-going



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francis halzen

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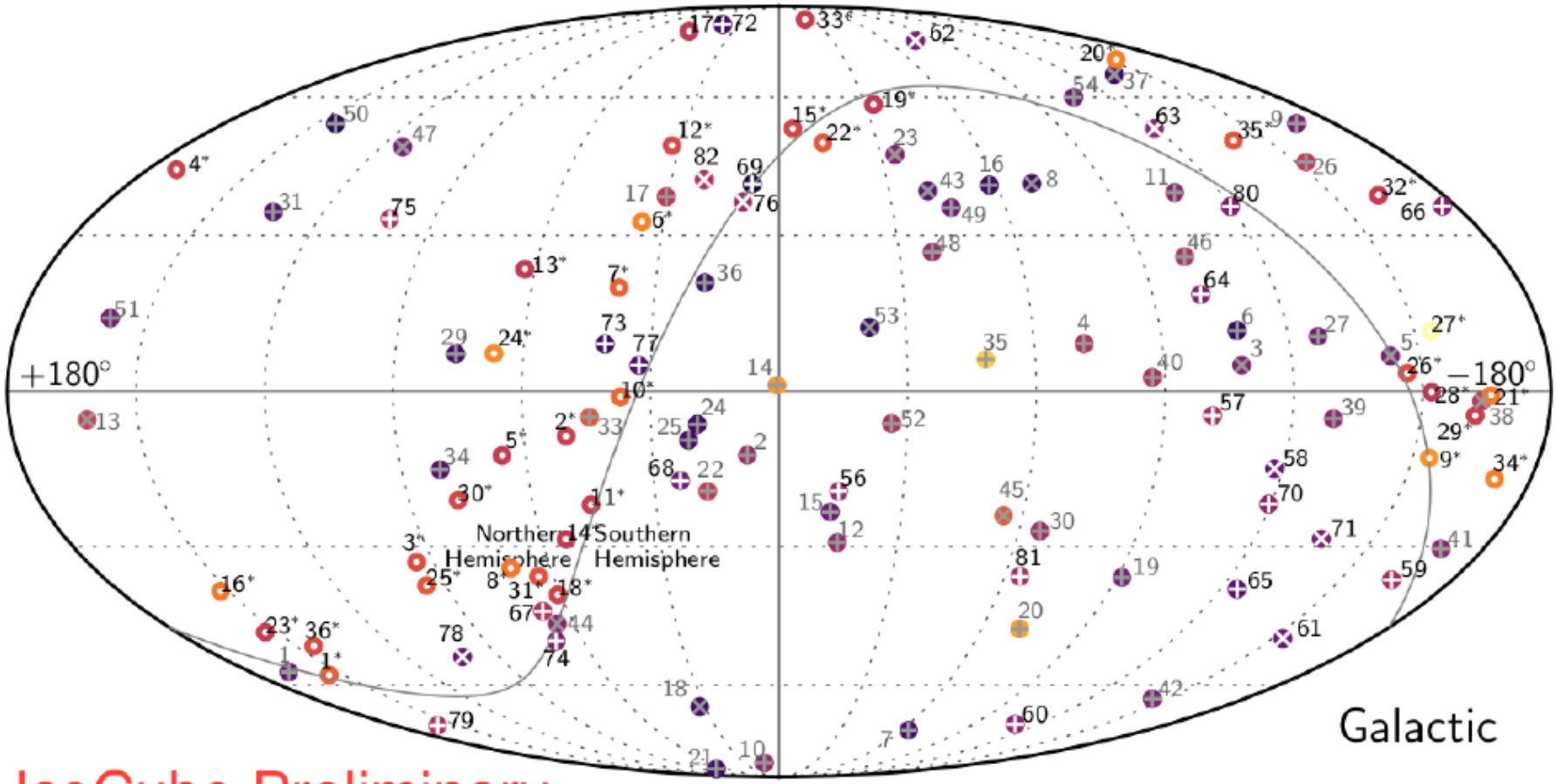
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

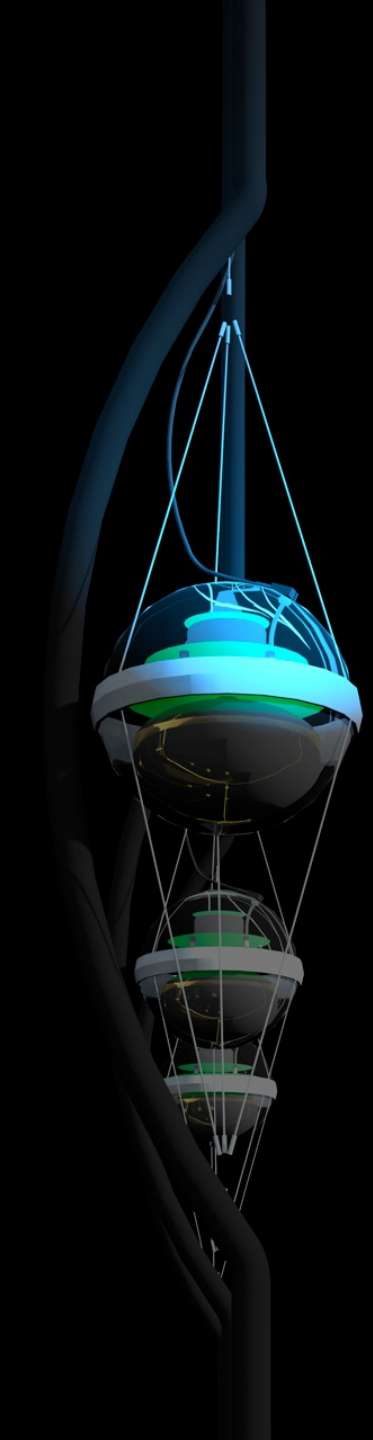


IceCube Preliminary

10^1 10^2 10^3

Deposited Energy or Muon Energy Proxy [TeV]

- ⊗ *N* New Starting Tracks
- ⊕ *N* New Starting Cascades
- ⊗ *N* Earlier Starting Tracks
- ⊕ *N* Earlier Starting Cascades
- ○ *N** Throughgoing Tracks



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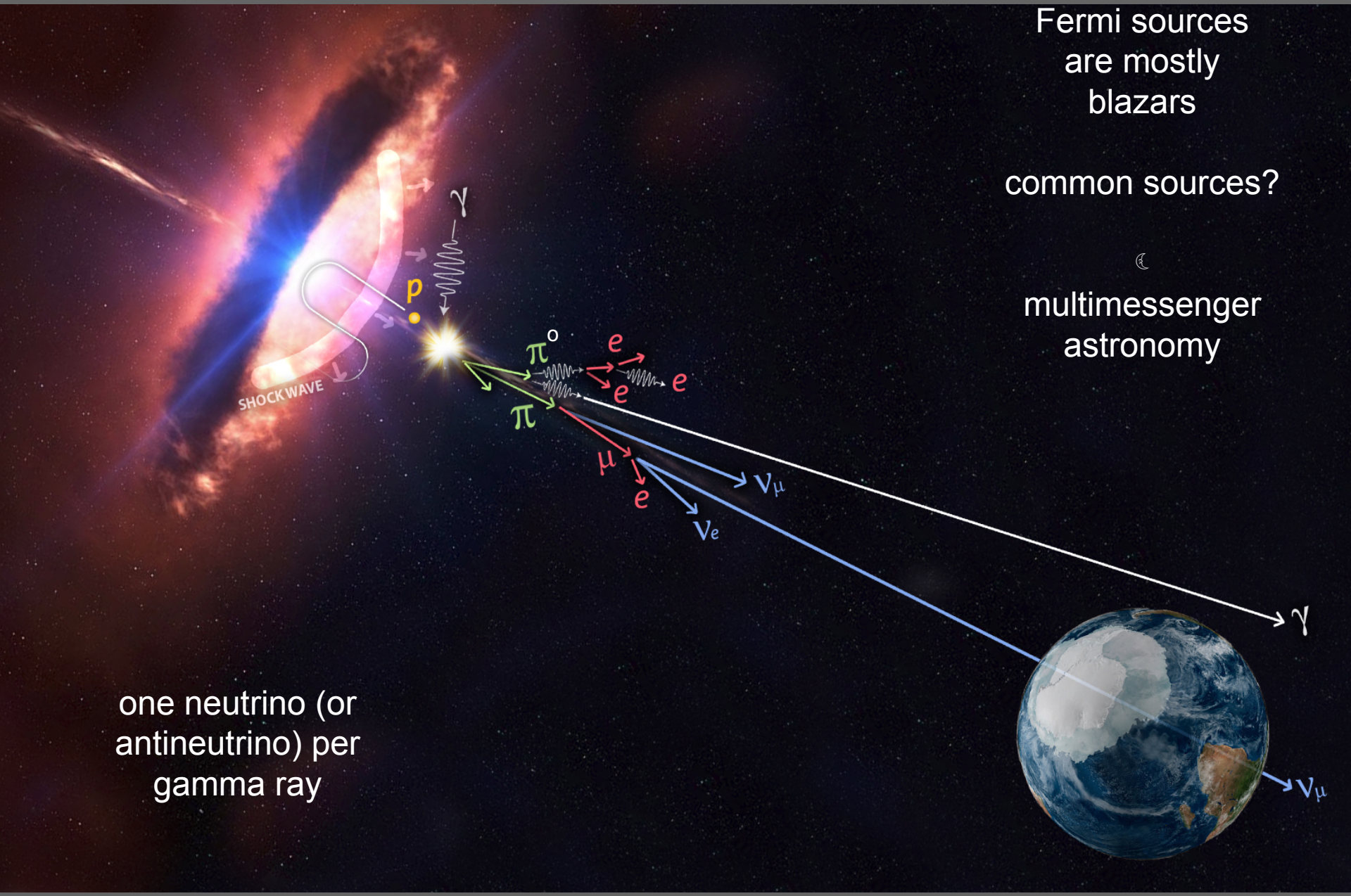
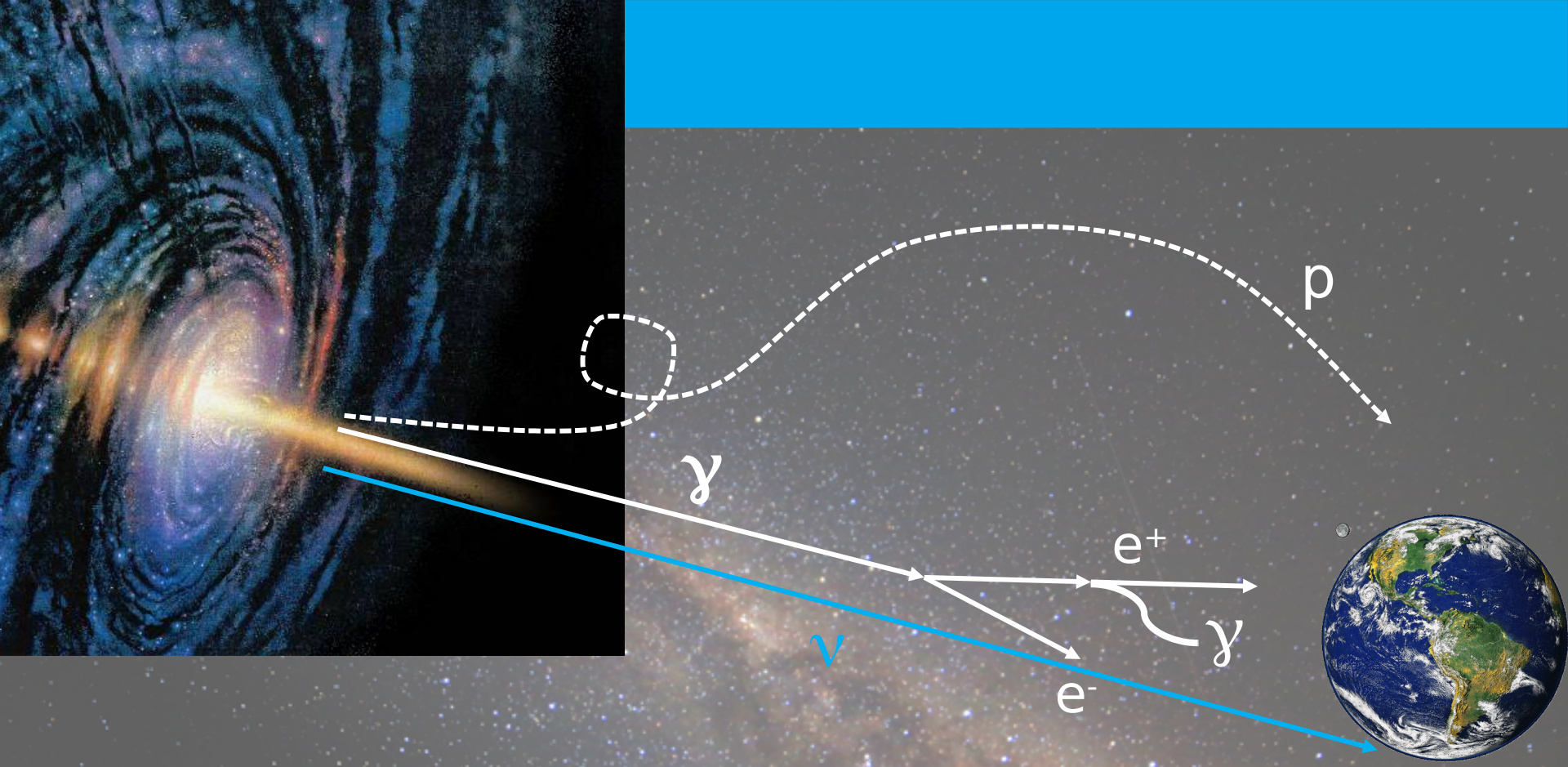
- cosmic neutrinos below 100 TeV?


Fermi sources
are mostly
blazars
common sources?
multimessenger
astronomy
one neutrino (or
antineutrino) per
gamma ray
SHOCK WAVE
p
γ
π
o
e
e
e
π
μ
e
νμ
νe
γ
νμ

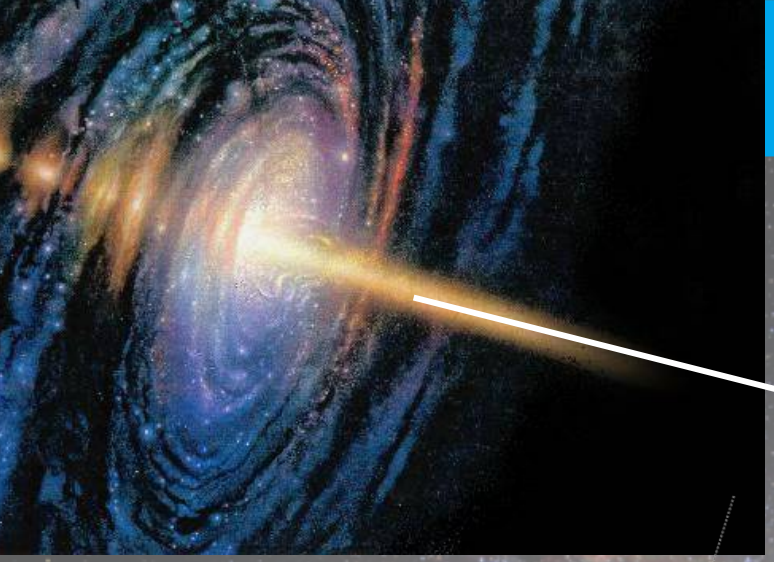
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$



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

HELMHOLTZ ASSOCIATION

DESY



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

γ

e^+

e^-

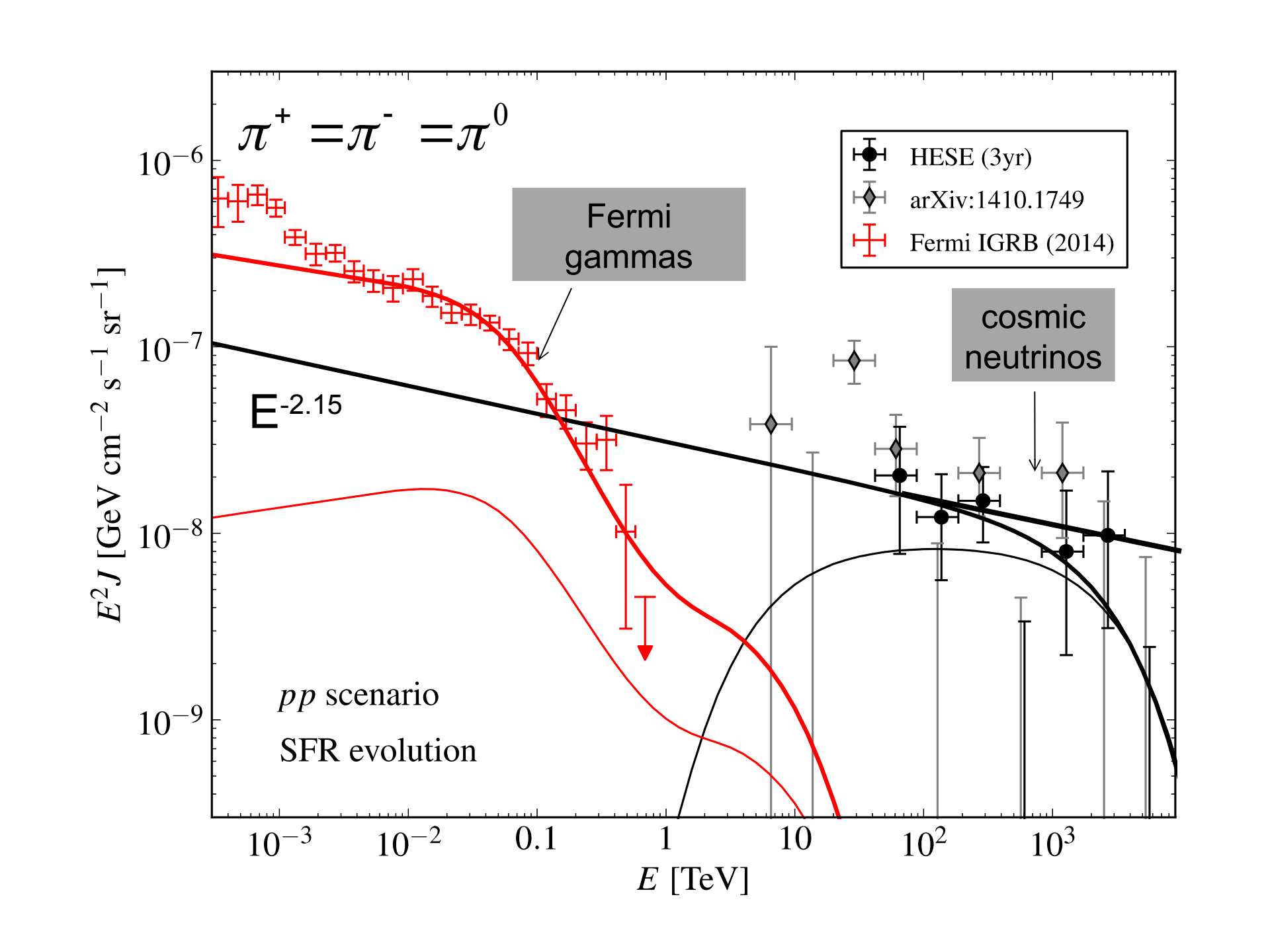
PeV

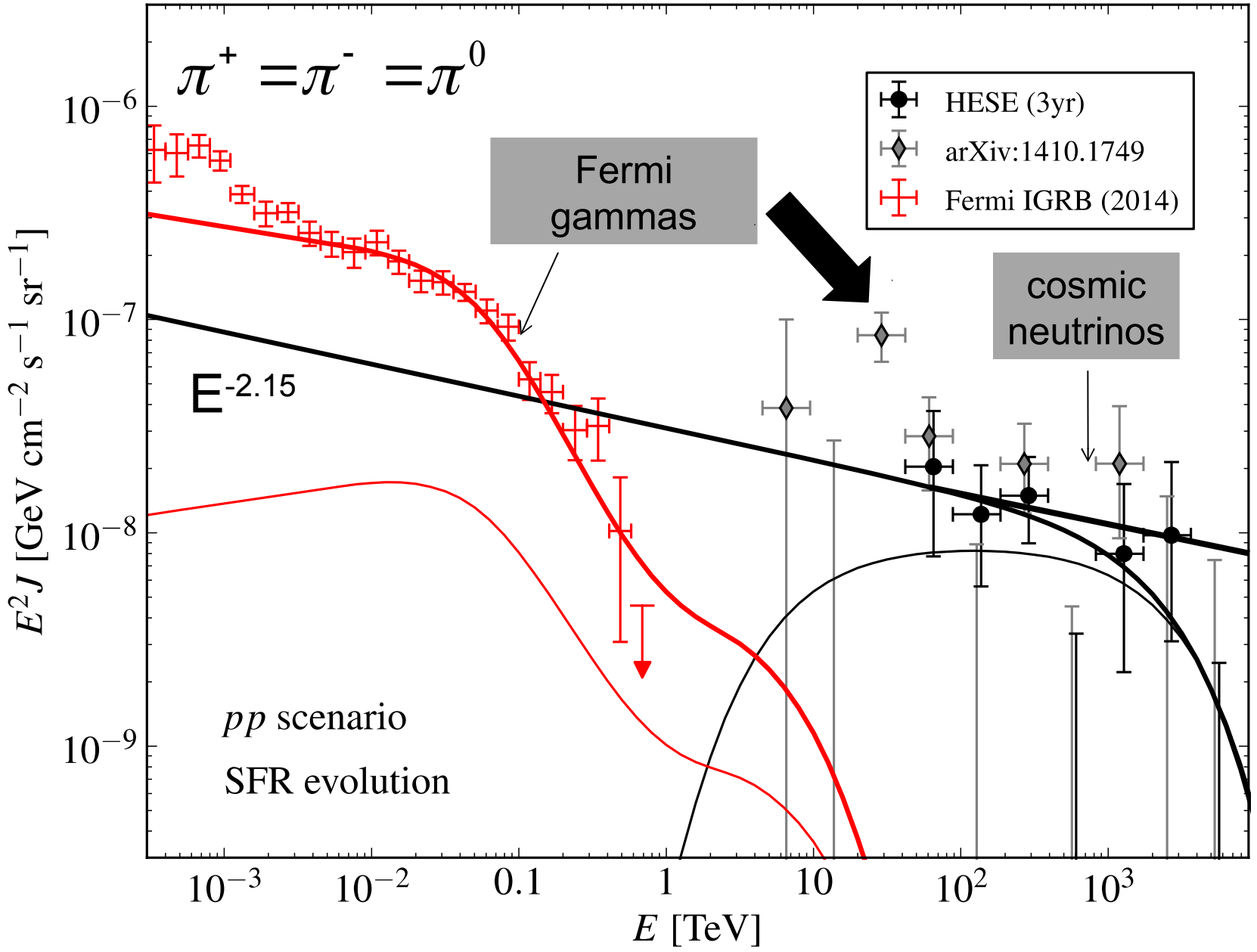
GeV

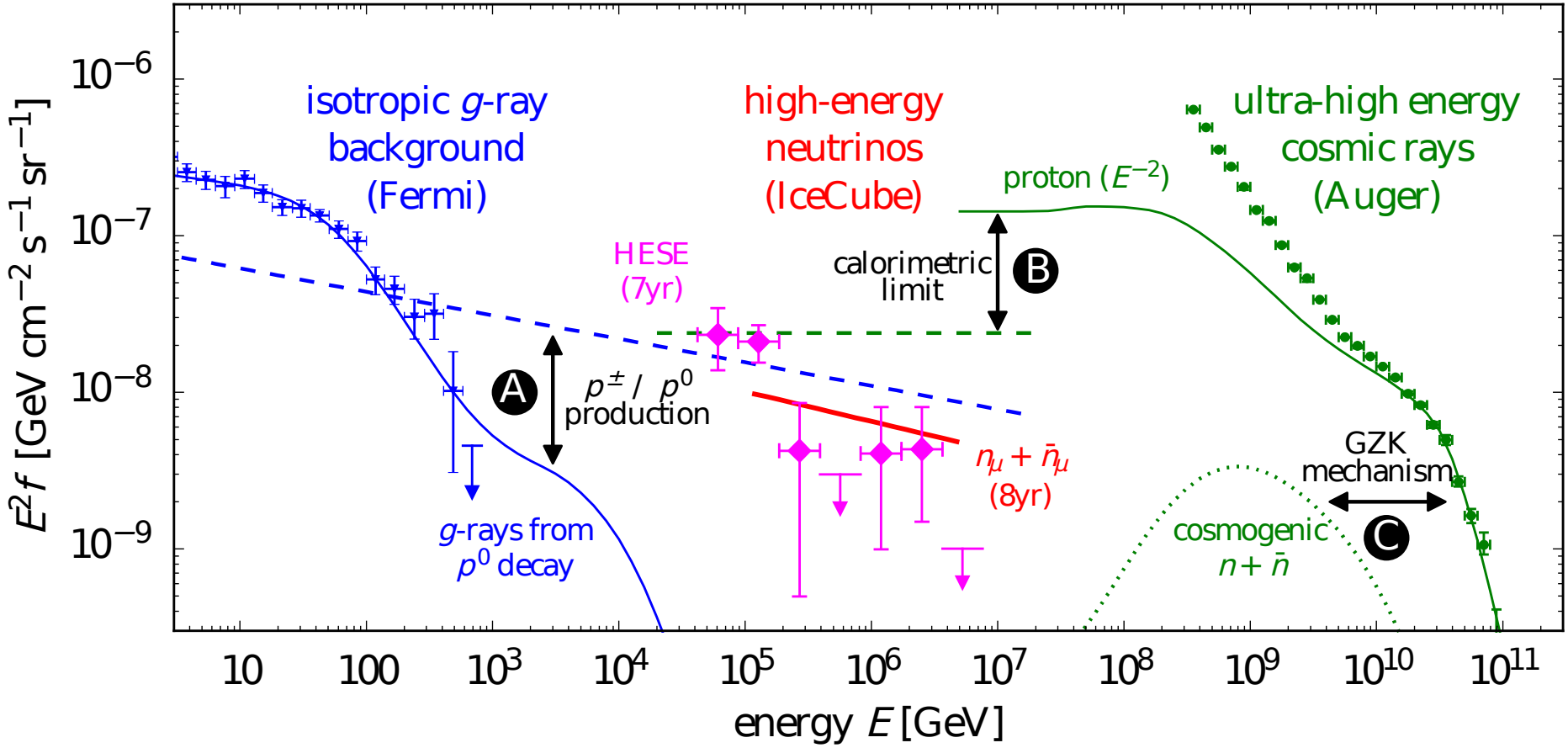
X_0

HELMHOLTZ ASSOCIATION

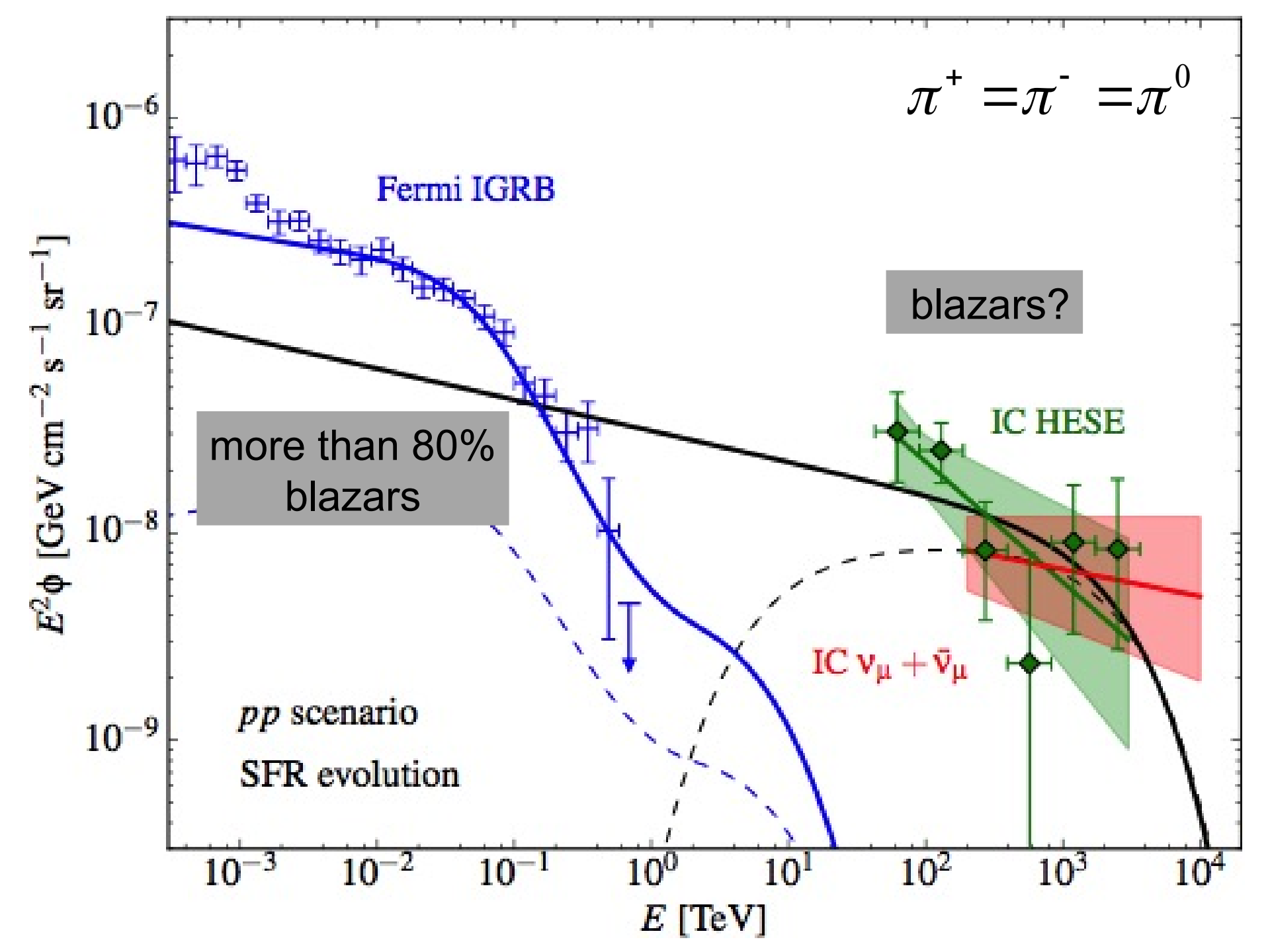
DESY

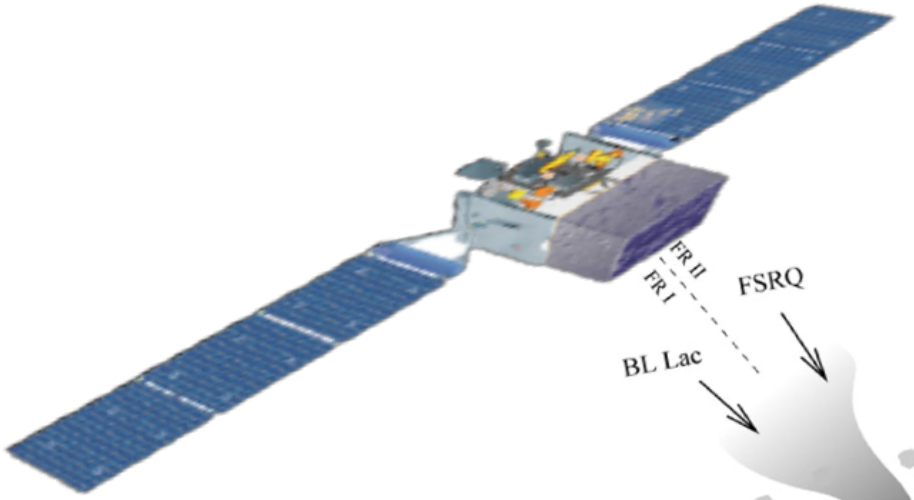

$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

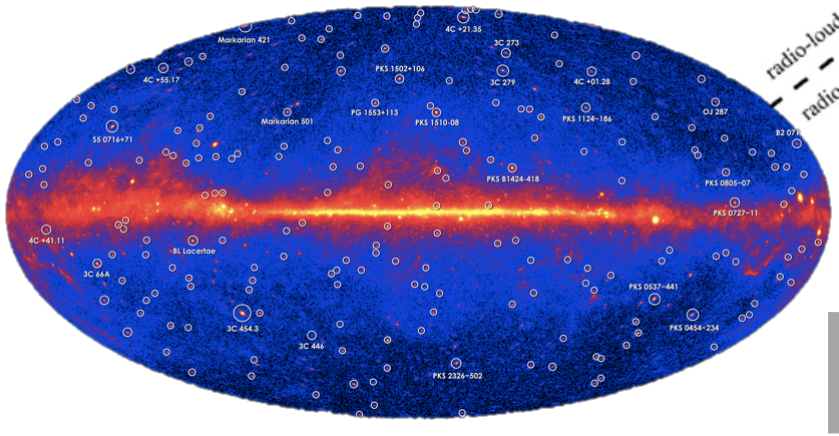

$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

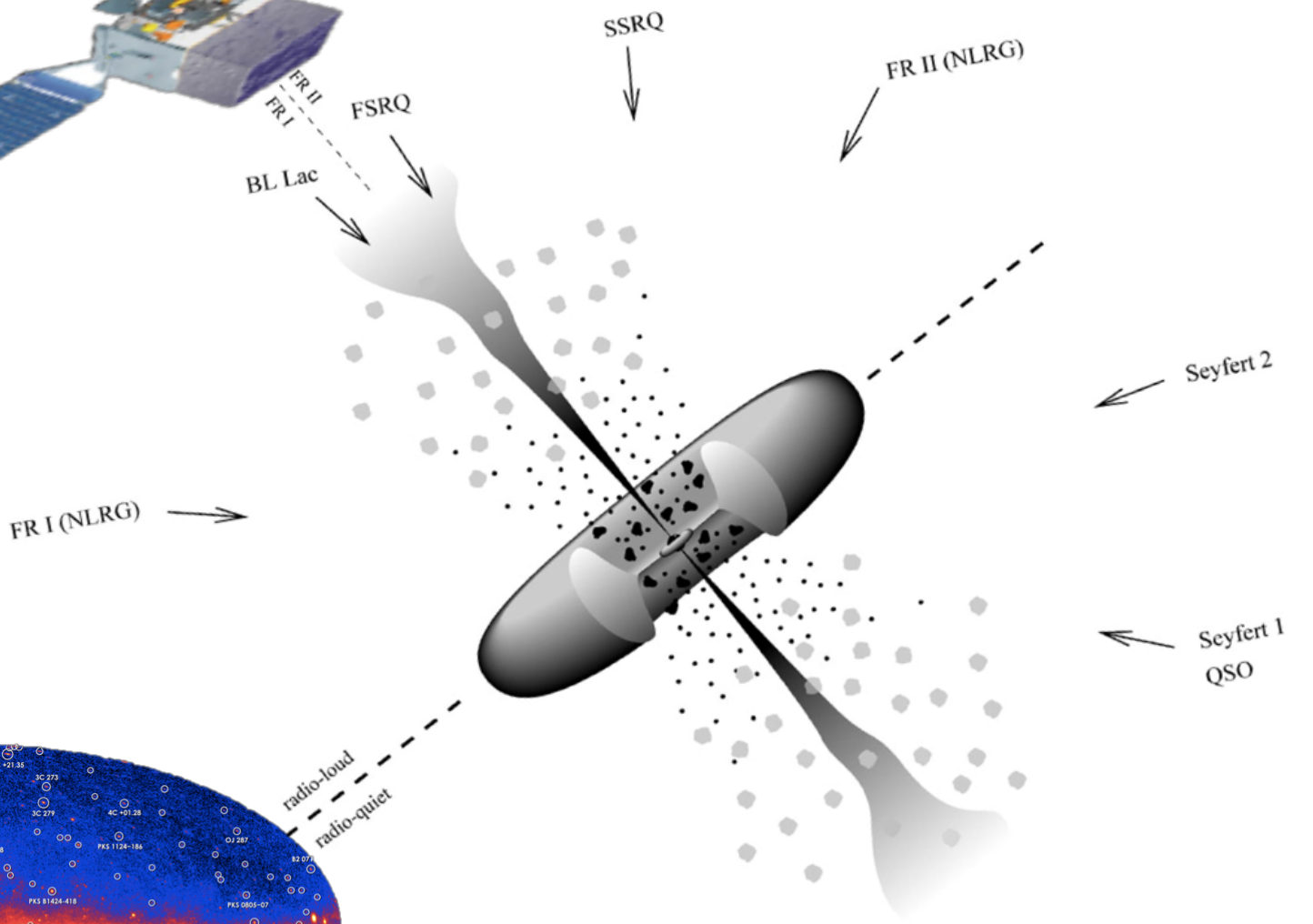


similar energy density in the Universe in extragalactic cosmic rays


$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
blazars?
more than 80% blazars
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 sky: mostly blazars

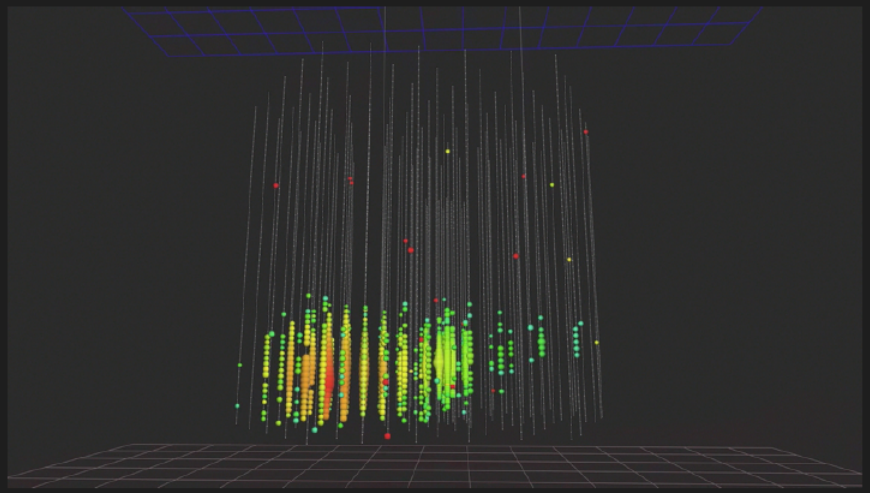
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

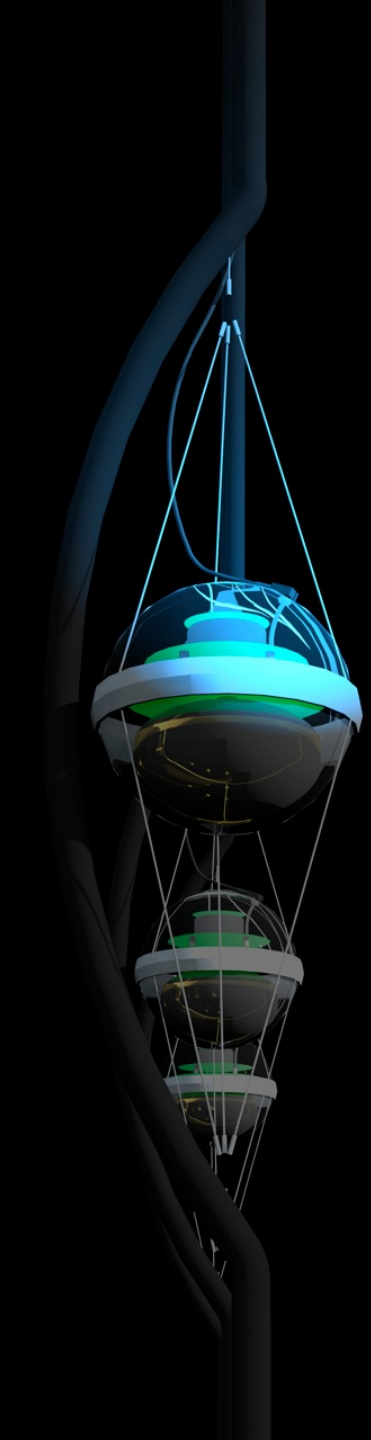
We send our high-energy events in real-time as public GCN alerts now!

```
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.**





IceCube

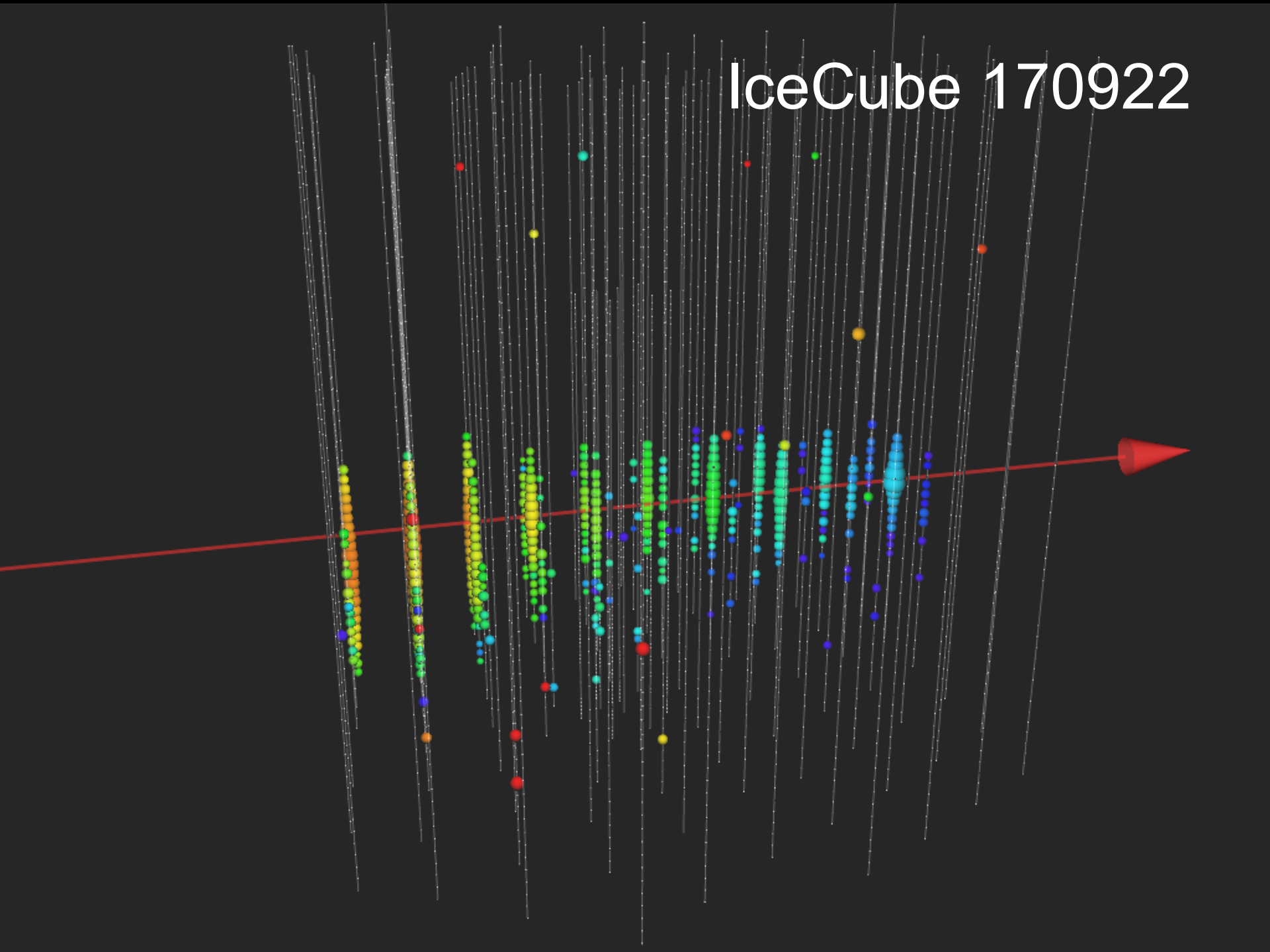
francis halzen

- 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
- multimessenger astronomy

IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
////////////////////////////////////////////////////////////////////////
TITLE:              GCN/AMON NOTICE
NOTICE_DATE:        Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:        AMON ICECUBE EHE
RUN_NUM:            130033
EVENT_NUM:          50579430
SRC_RA:              77.2853d {+05h 09m 08s} (J2000),
                     77.5221d {+05h 10m 05s} (current),
                     76.6176d {+05h 06m 28s} (1950)
SRC_DEC:             +5.7517d {+05d 45' 06"} (J2000),
                     +5.7732d {+05d 46' 24"} (current),
                     +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:          14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:     18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:     75270 SOD {20:54:30.43} UT
REVISION:           0
N_EVENTS:           1 [number of neutrinos]
STREAM:             2
DELTA_T:            0.0000 [sec]
SIGMA_T:            0.0000e+00 [dn]
ENERGY :            1.1998e+02 [TeV]
SIGNALNESS:         5.6507e-01 [dn]
CHARGE:             5784.9552 [pe]
```


IceCube 170922

Further Observations I

- 17/09/23 09:31:27 GMT (GCN 21917), INTEGRAL, upper limit
- 17/09/24 19:34:55 GMT (GCN 21923), ANTARES, upper limit (+/-1h, +/-1d)
- 17/09/25 01:55:22 GMT (GCN 21924), HAWC, upper limit
- **17/09/26 14:34:30 GMT (GCN 21930), Swift (3.25h after the neutrino trigger, 800s per field, 19-point tiling), 9 sources identified**
- 17/09/27 14:33 GMT (ATel 10787), HESS, observation 4h after neutrino trigger (for ~1h) and consecutive night (1h), no detection
- **17/09/28 10:10 GMT (ATel 10791), Fermi-LAT, known gamma-ray source TXS 0506+056 (3FGL J0509.4+0541) in error circle, in flaring state, redshift unknown**
- 17/09/28 11:58:48 GMT (GCN 21941), further Swift observations, additional 5ks of TXS position, possible spectral evolution
- 17/09/28 18:00 GMT (ATel 10794): ASAS-SN finds enhanced optical flux of TXS 0506+056
- 17/09/29 13:00 GMT (ATel 10799): Liverpool telescope takes optical spectrum, no redshift measurement possible
- 17/09/29 15:41 GMT (ATel 10801): AGILE confirms gamma-ray flare
- 17/09/30 02:10 GMT (ATel 10802): HAWC, no detection in 12day window

Further Observations II

- **17/10/04 17:17 GMT (ATel 10817): MAGIC, VHE gamma-ray detection, 5 sigma detection above 100 GeV was achieved after 12 h of observations from Sept. 28th till Oct. 3rd**
- 17/10/07 13:26 GMT (ATel 10830): SALT-HRS, optical spectrum, no redshift measurement possible
- 17/10/07 18:58 GMT (ATel 10831): Kapteyn optical telescope, decline of the flare reported from ASAS-SN data continues
- 17/10/09 22:32 GMT (ATel 10833): VERITAS, observations started 12.2h after neutrino trigger, total time of 5h, no detection
- 17/09/11 02:36 GMT (ATel 10838): MAXI/GSC, no significant X-ray enhancement
- 17/09/11 08:44 GMT (ATel 10840): VLT/X-Shooter spectrum, no lines, non-detection of Lyman alpha absorption ☾ $z<1.6$
- 17/09/12 15:50 GMT (ATel 10844): Kanata optical follow-up, intrinsic polarization
- 17/09/12 16:54 GMT (ATel 10845): Joint Swift and NuSTAR observations, Jointly analyzed, the spectra are not consistent with any single power-law fit
- 17/09/17 14:08 GMT (ATel 10861): VLA radio observations, significant variability, radio spectrum is typical of emission from a compact jet
- 17/09/25 04:36 GMT (ATel 10890): Subaru/FOCAS, spectrum, no redshift measurement possible

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arXiv:1802.01939v1 [astro-ph.GA] 6 Feb 2018

THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

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Submitted to ApJL

ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW $\sim$ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift z = 0.3365±0.0010.

Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

☾ although at 10 times larger redshift than nearby blazars (like the Markarian sources), TXS 0506+056 has the same flux ☾ probably special subclass

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

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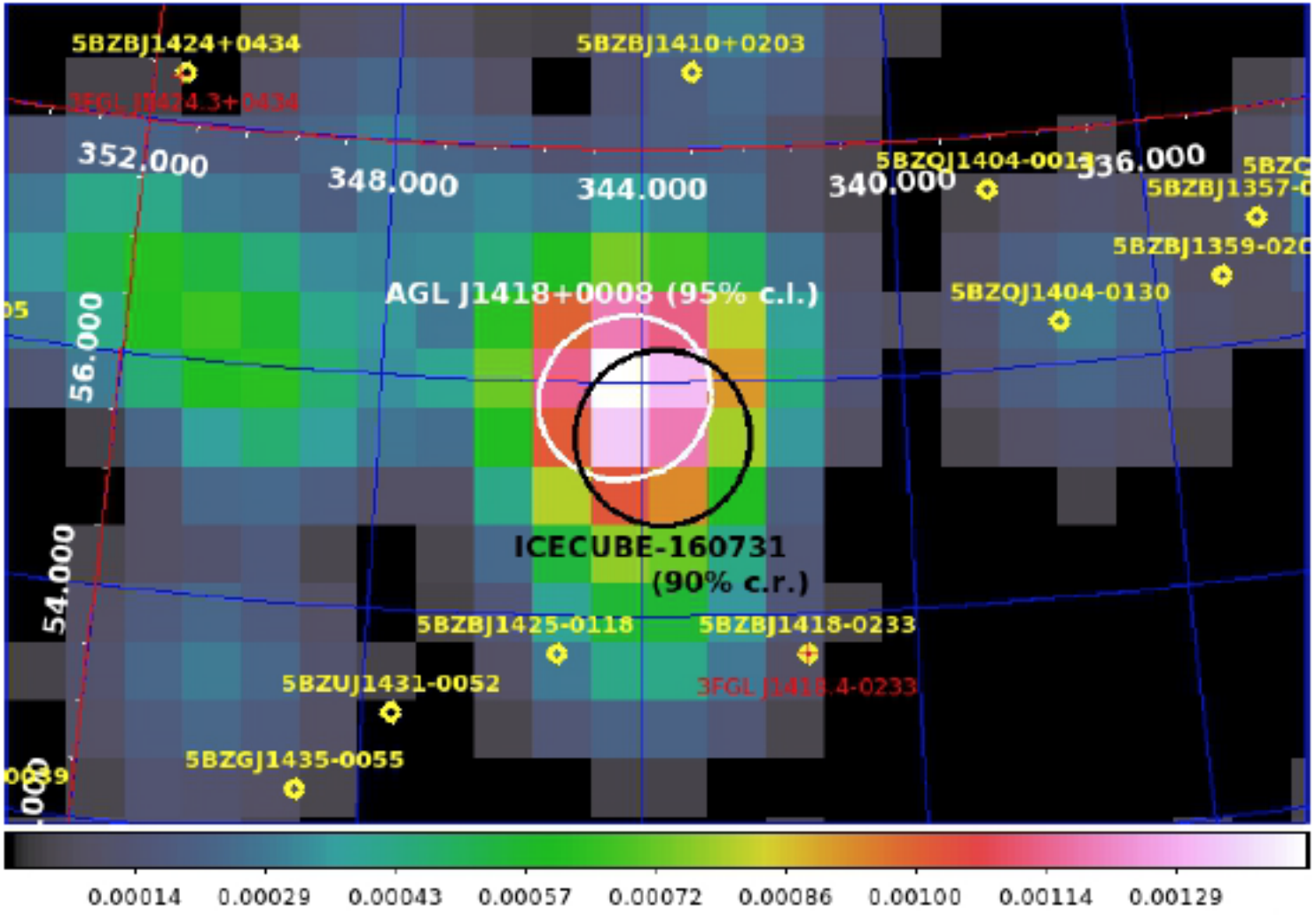

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TANAMI blazars in the IceCube PeV neutrino fields

F. Krauß[1,2], M. Kadler[2], K. Mannheim[2], R. Schulz[1,2], J. Trüstedt[1,2], J. Wilms[1], R. Ojha[3,4,5], E. Ros[6,7,8], G. Anton[9], W. Baumgartner[3], T. Beuchert[1,2], J. Blanchard[10], C. Bürkel[1,2], B. Carpenter[5], T. Eberl[9], P.G. Edwards[11], D. Eisenacher[2], D. Elsässer[2], K. Fehn[9], U. Fritsch[9], N. Gehrels[3], C. Gräfe[1,2], C. Großberger[12], H. Hase[13], S. Horiuchi[14], C. James[9], A. Kappes[2], U. Katz[9], A. Kreikenbohm[1,2], I. Kreykenbohm[1], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], J.E.J. Lovell[15], C. Müller[1,2], C. Phillips[11], C. Plötz[13], J. Quick[16], T. Steinbring[1,2], J. Stevens[11], D. J. Thompson[3], and A.K. Tzioumis[11]

(Affiliations can be found after the references)

Received 15 May 2014 / Accepted 2 June 2014

ABSTRACT

The IceCube Collaboration has announced the discovery of a neutrino flux in excess of the atmospheric background. Owing to the steeply falling atmospheric background spectrum, events at PeV energies most likely have an extraterrestrial origin. We present the multiwavelength properties of the six radio-brightest blazars that are positionally coincident with these events using contemporaneous data of the TANAMI blazar sample, including high-resolution images and spectral energy distributions. Assuming the X-ray to γ-ray emission originates in the photoproduction of pions by accelerated protons, the integrated predicted neutrino luminosity of these sources is high enough to explain the two detected PeV events.

Key words. neutrinos – galaxies: active – quasars: general

FUNDING AGENCIES

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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)

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South Pole Neutrino Observatory
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