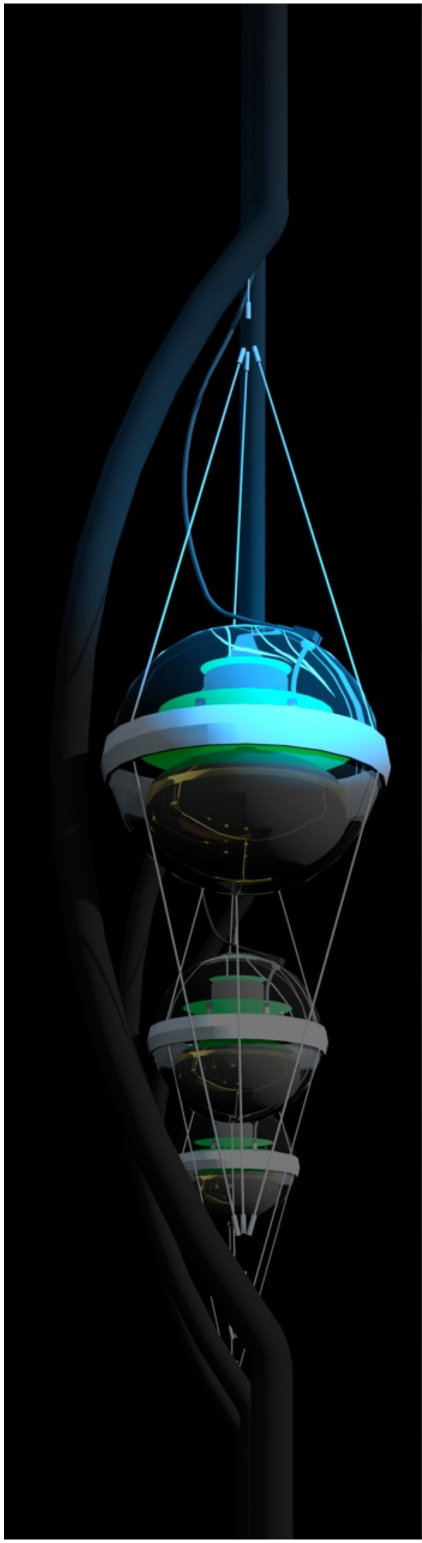


Multimessenger Astronomy

francis halzen

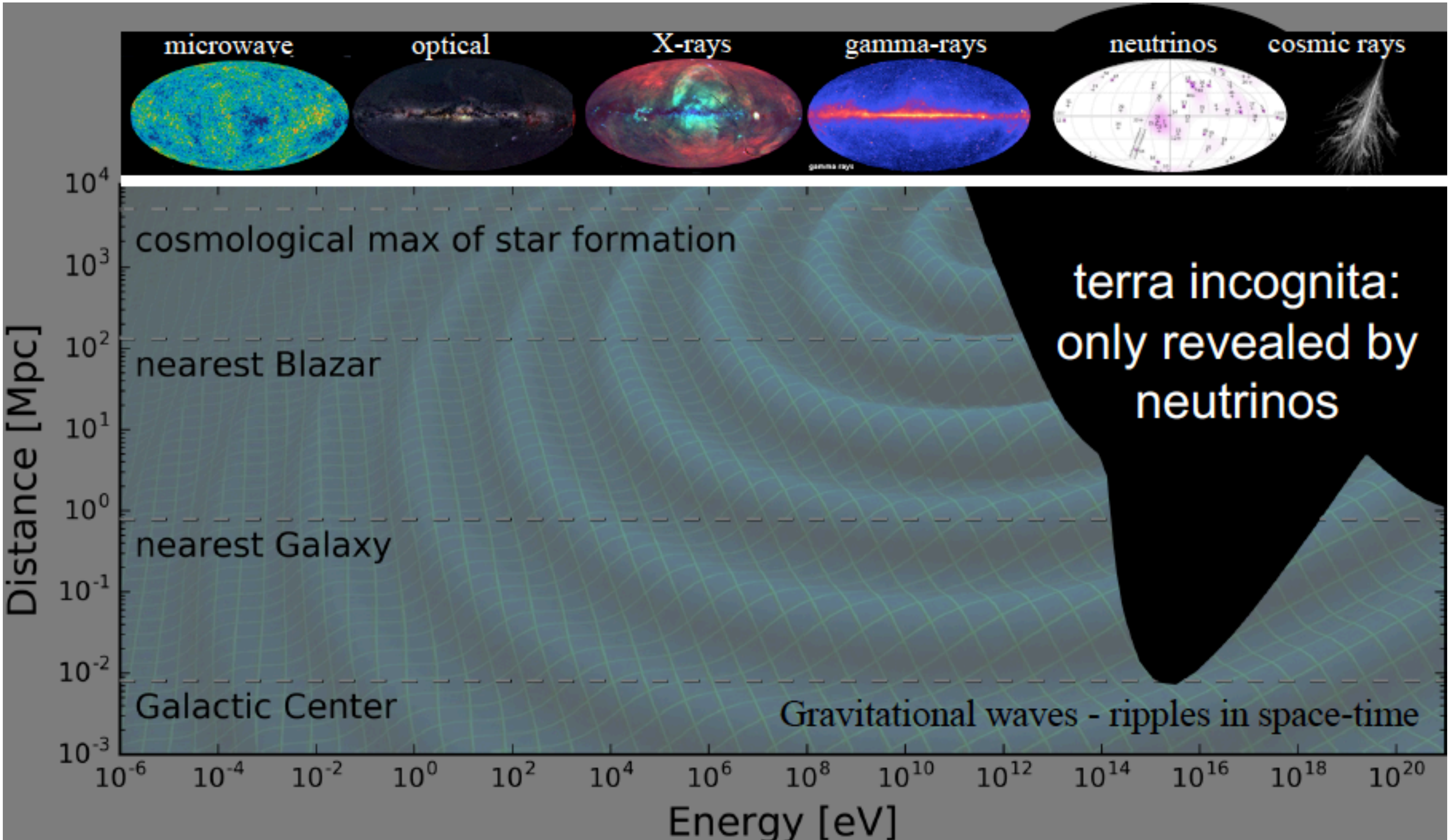
- February 23, 1987
- August 17, 2017
- September 22, 2017
- ….

ICECUBE

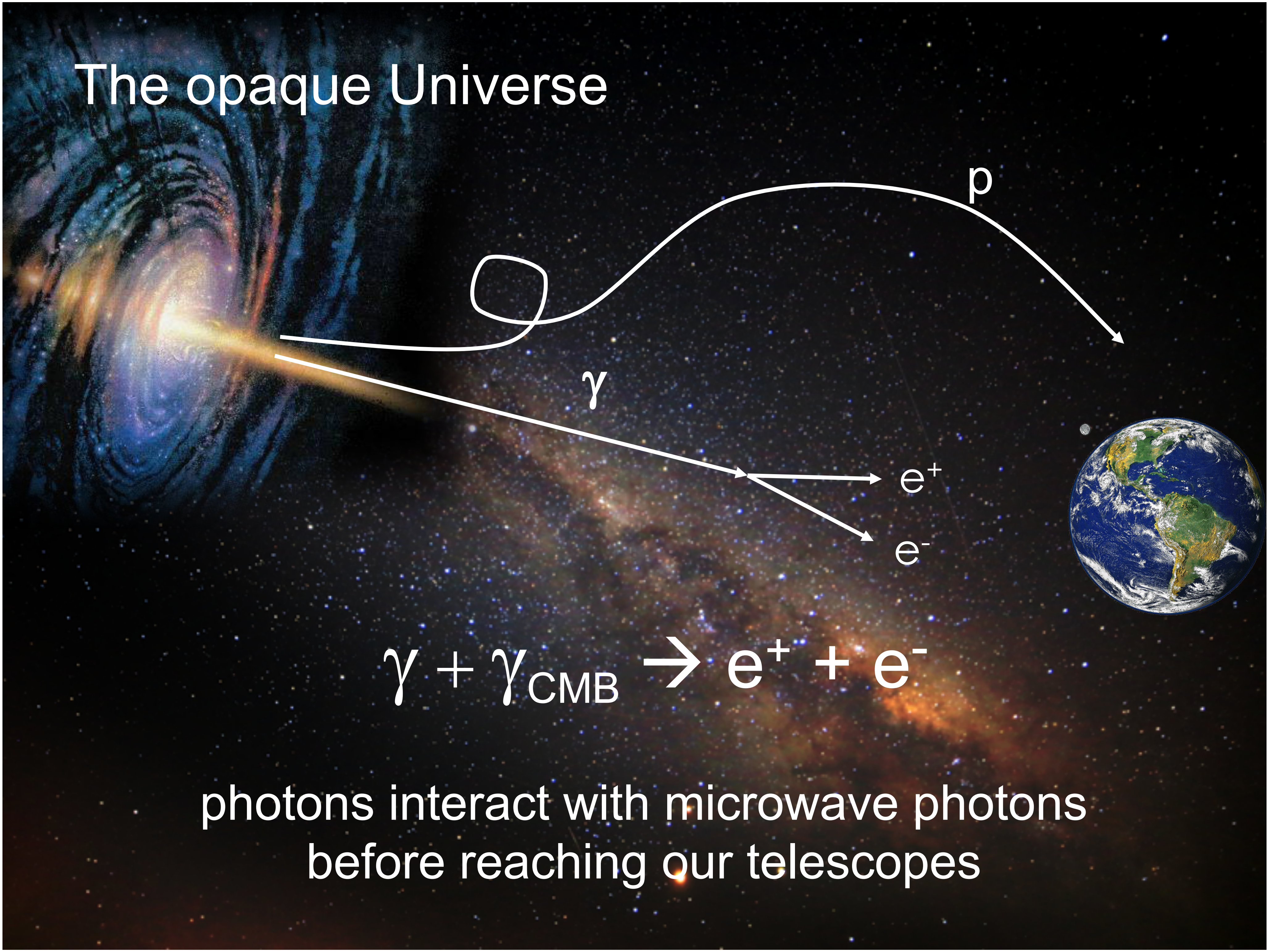
NSF

icecube.wisc.edu

supernova 1987a: 24 neutrinos, thousands of papers

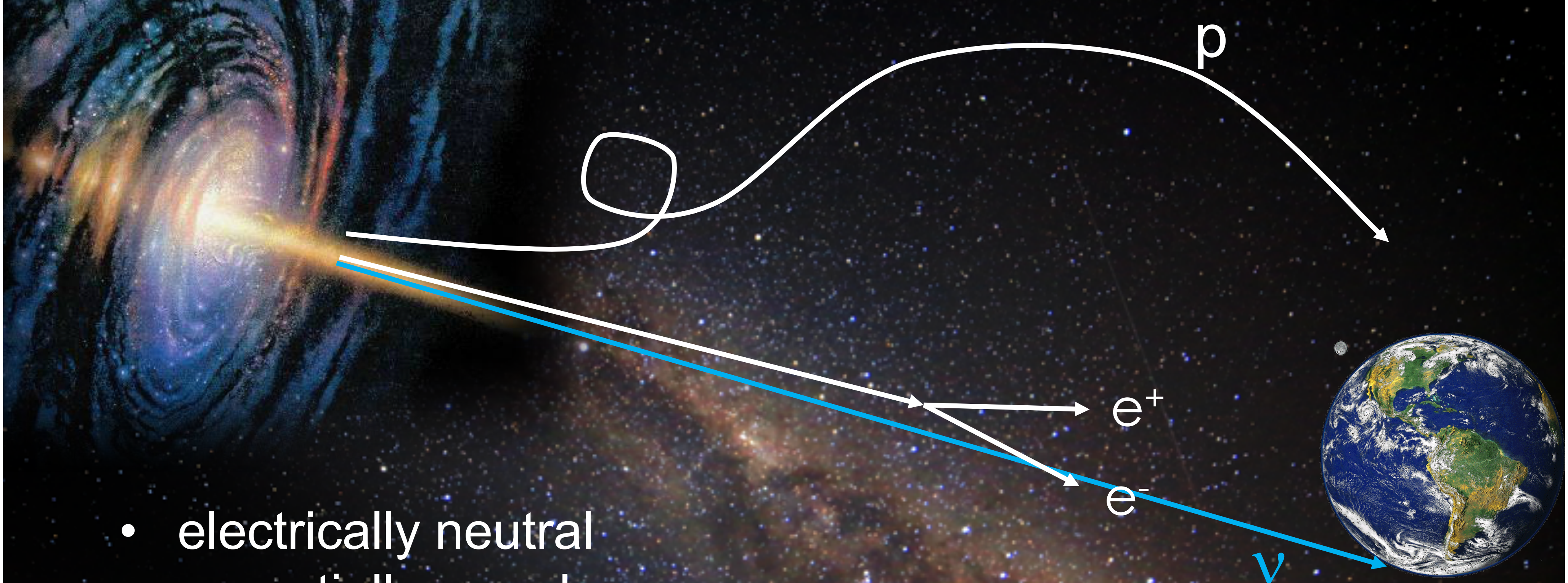


- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays



The opaque Universe
p
γ
e+
e-
γ + γCMB → e+ + e-
photons interact with microwave photons
before reaching our telescopes

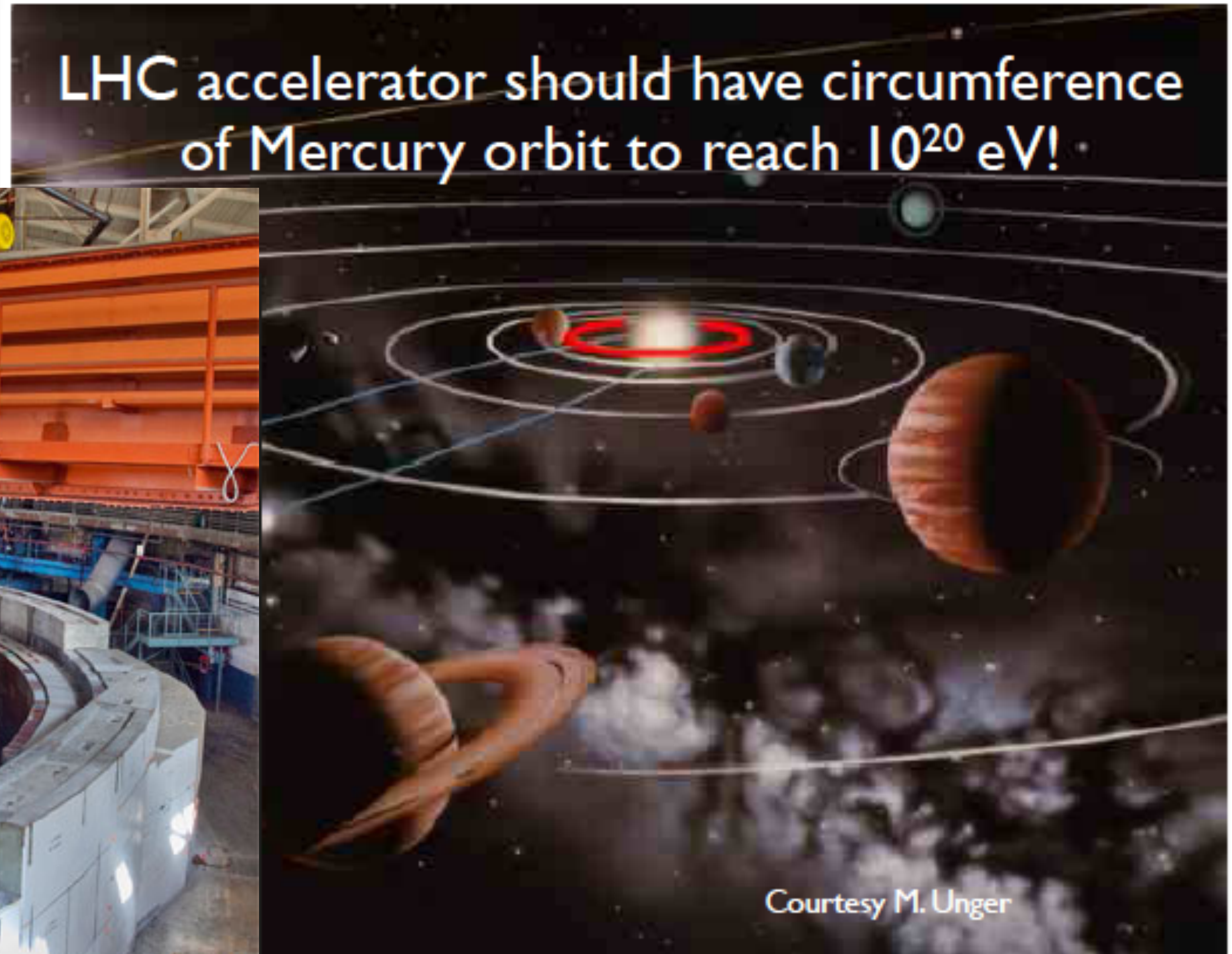
Neutrinos? Perfect Messenger



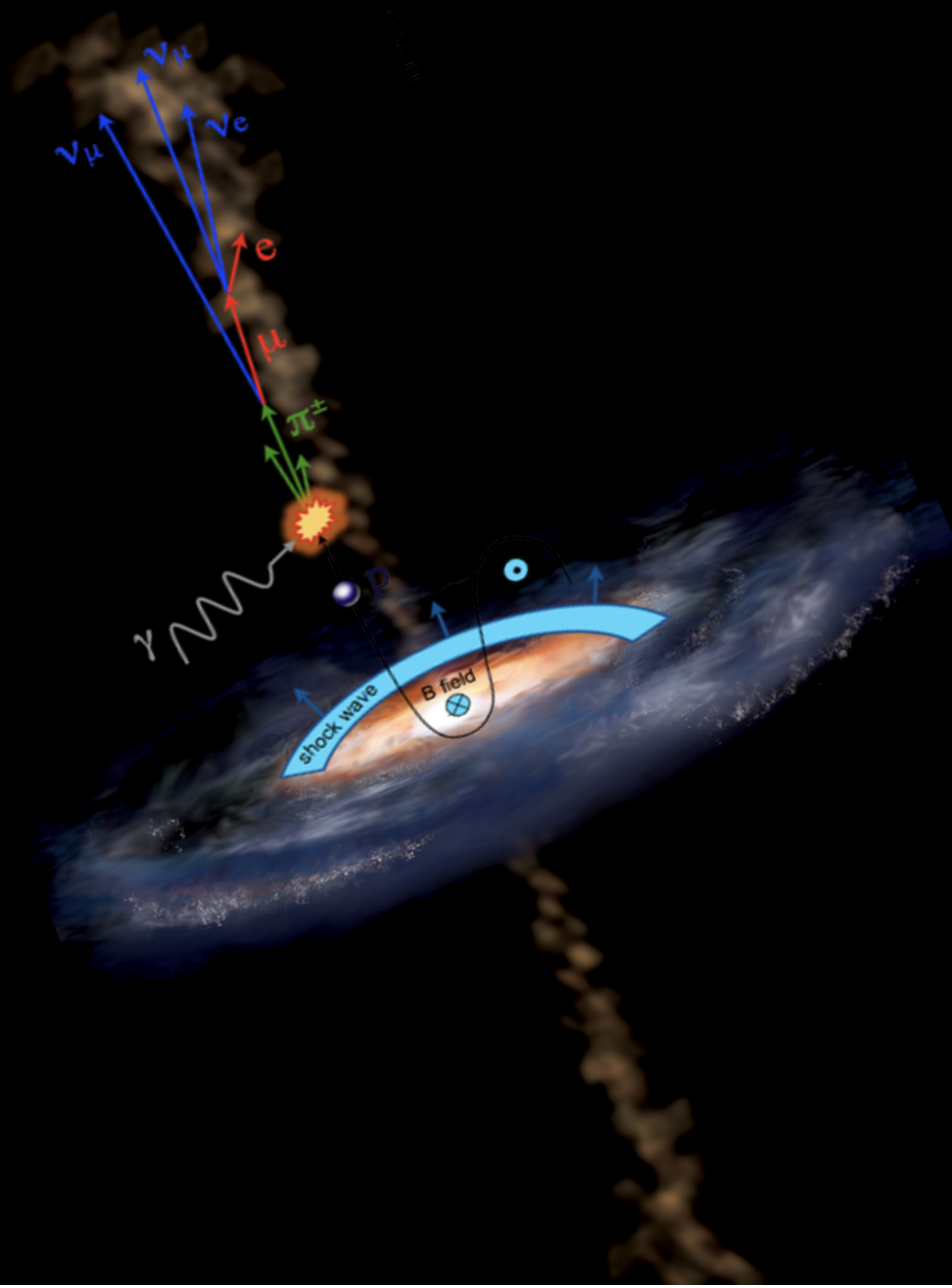
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays after 105 years

- … but difficult to detect

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

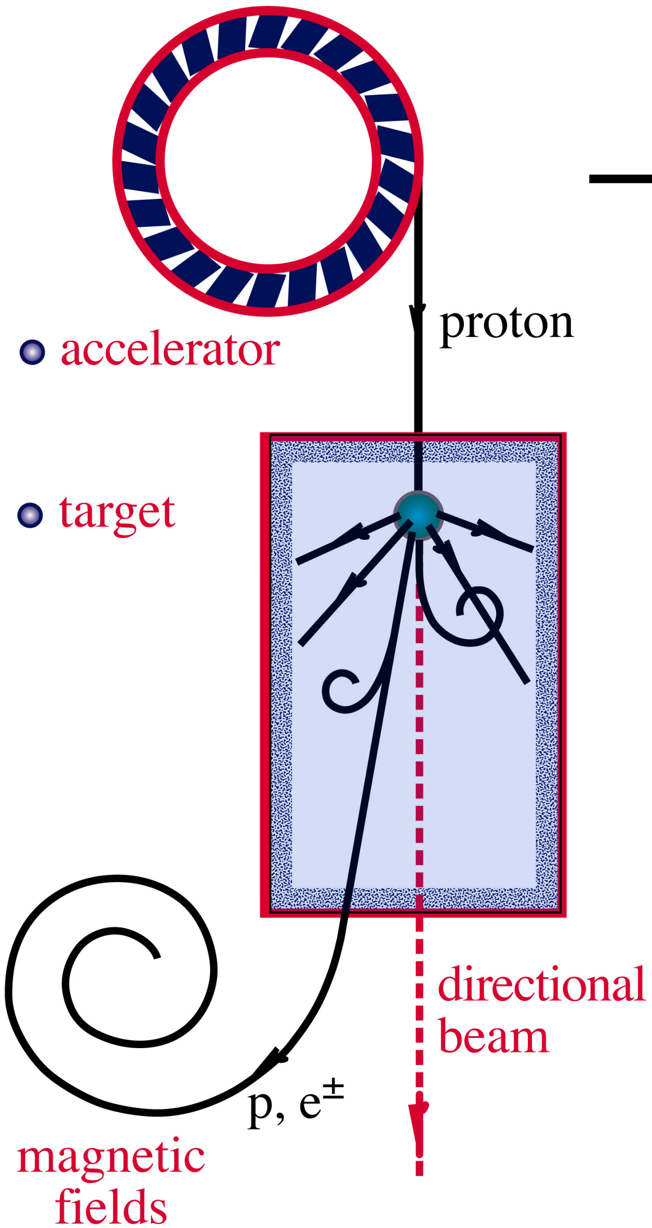


- luminosity ~ a few percent of gravitational energy of…



supermassive black hole in active galaxy

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

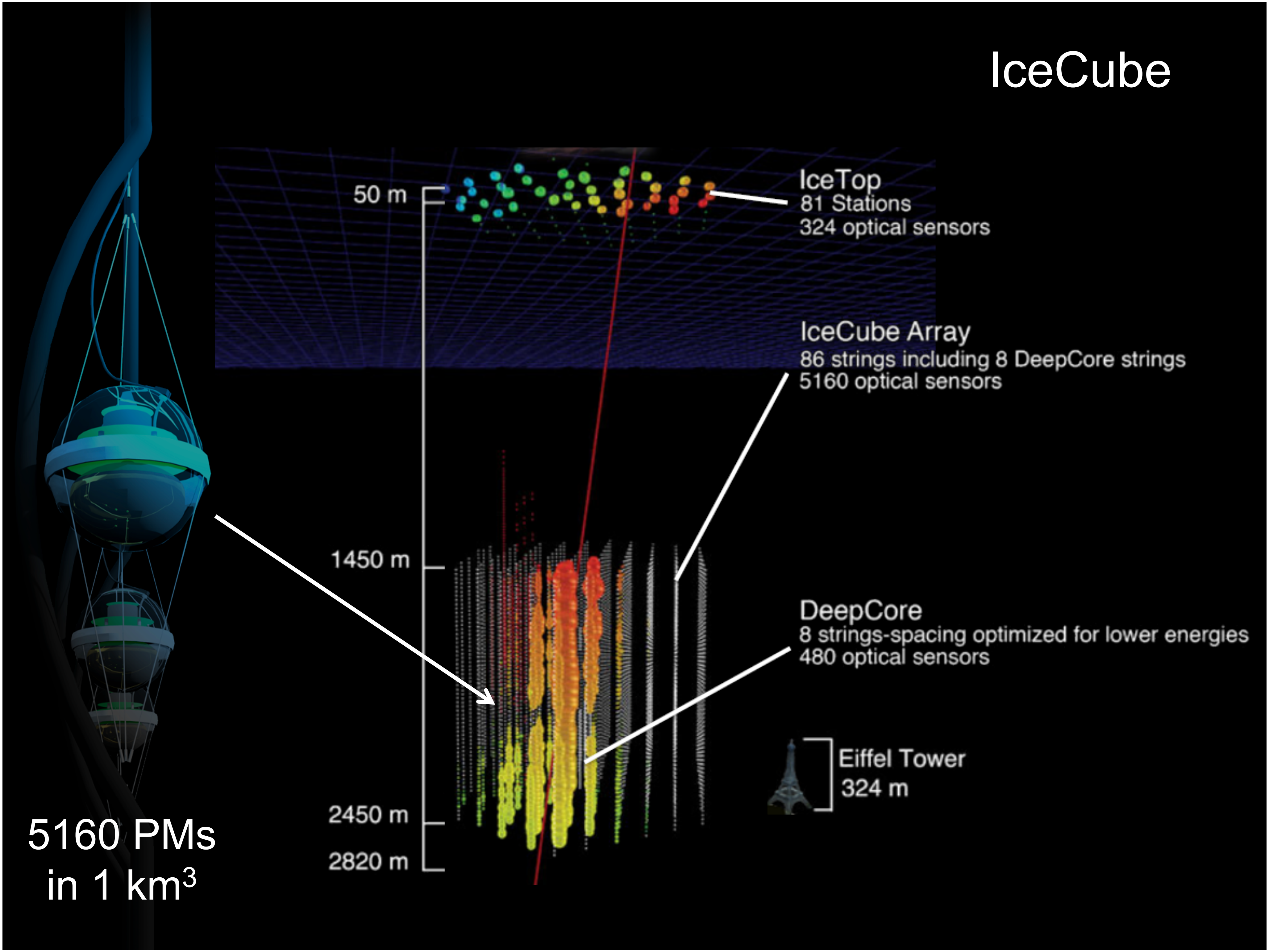
$$p + \gamma \rightarrow n + \pi^{+}$$

~ cosmic ray + neutrino

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

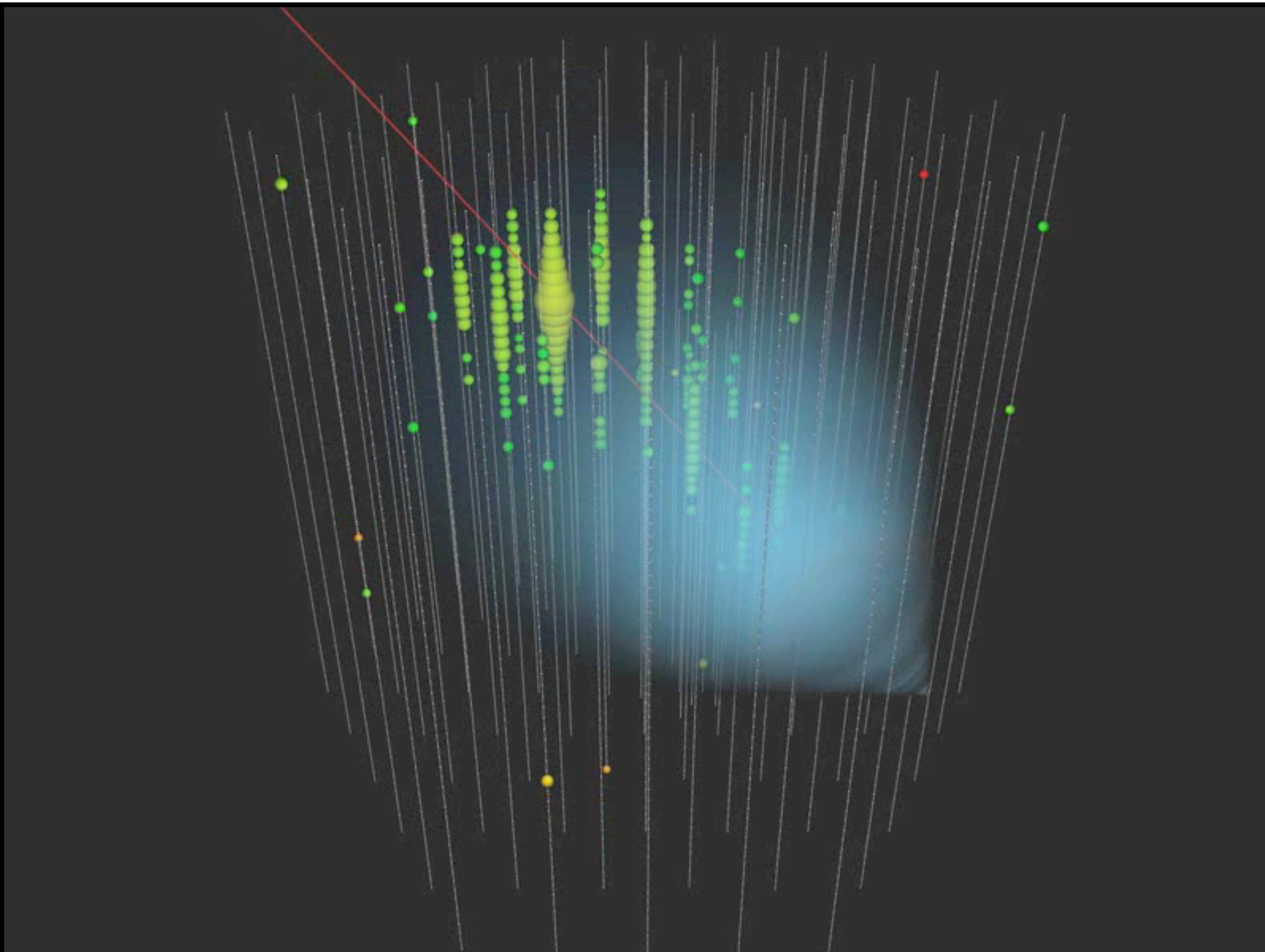
~ cosmic ray + gamma

IceCube

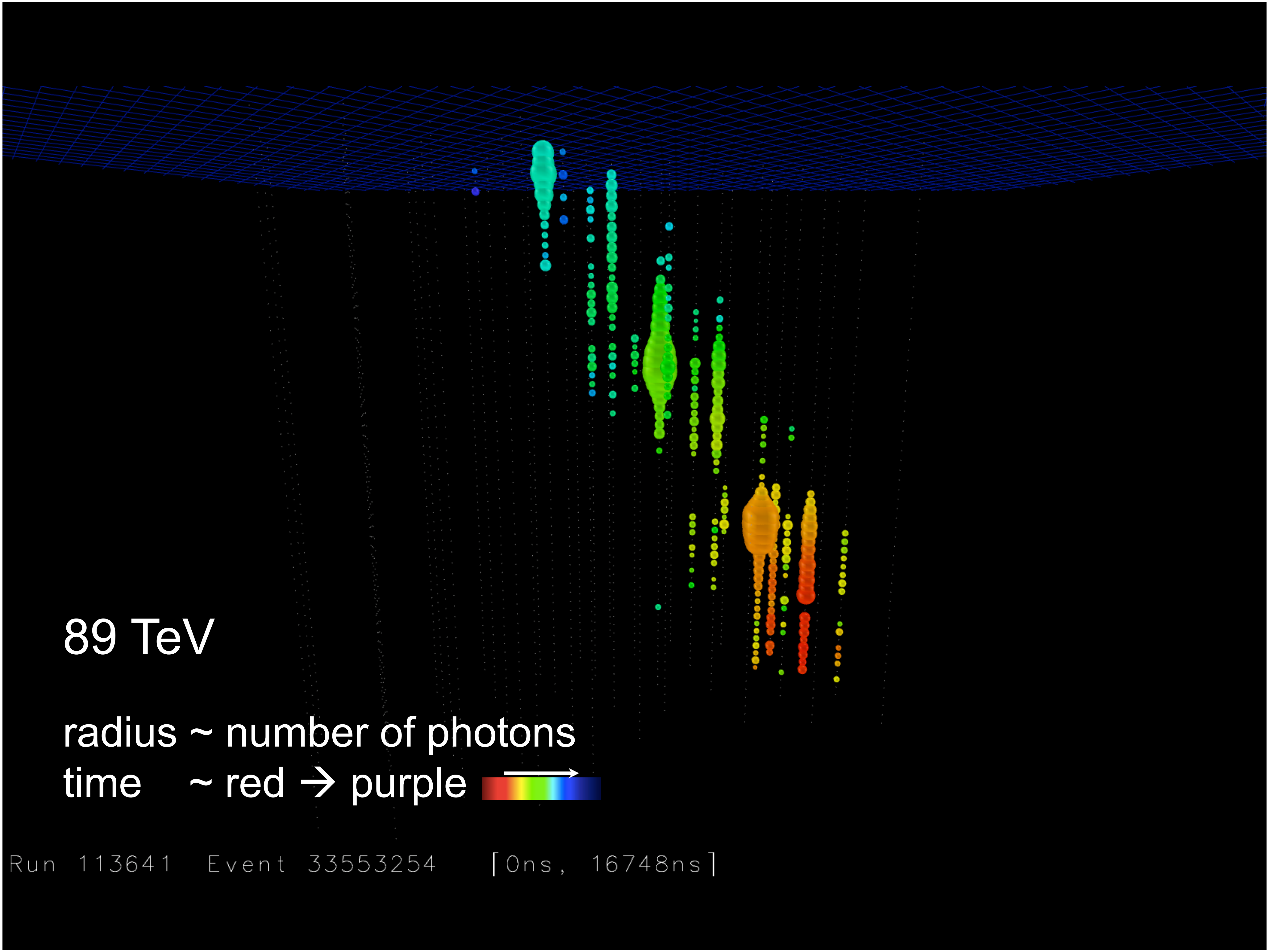


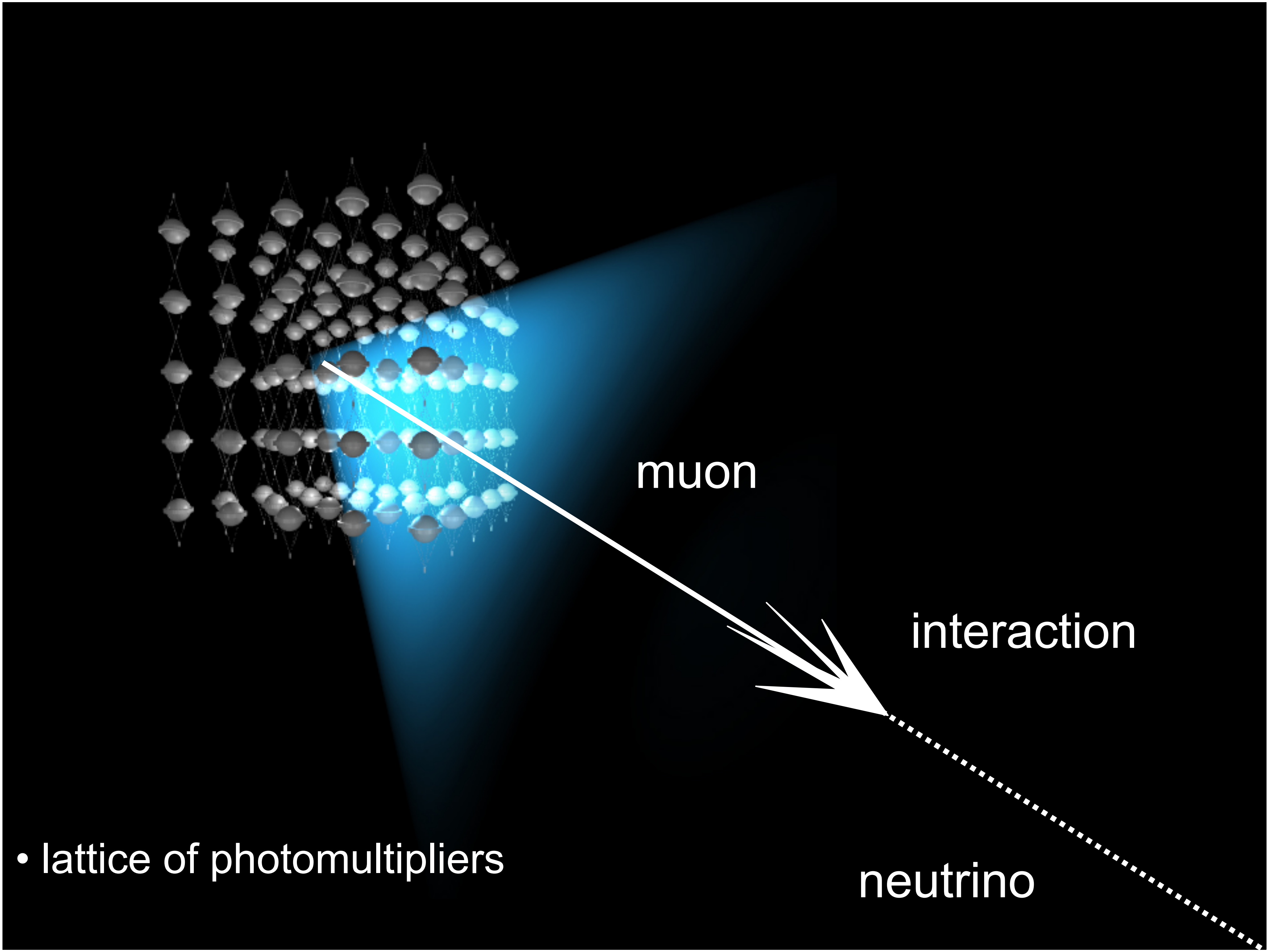
5160 PMs
in 1 km^3

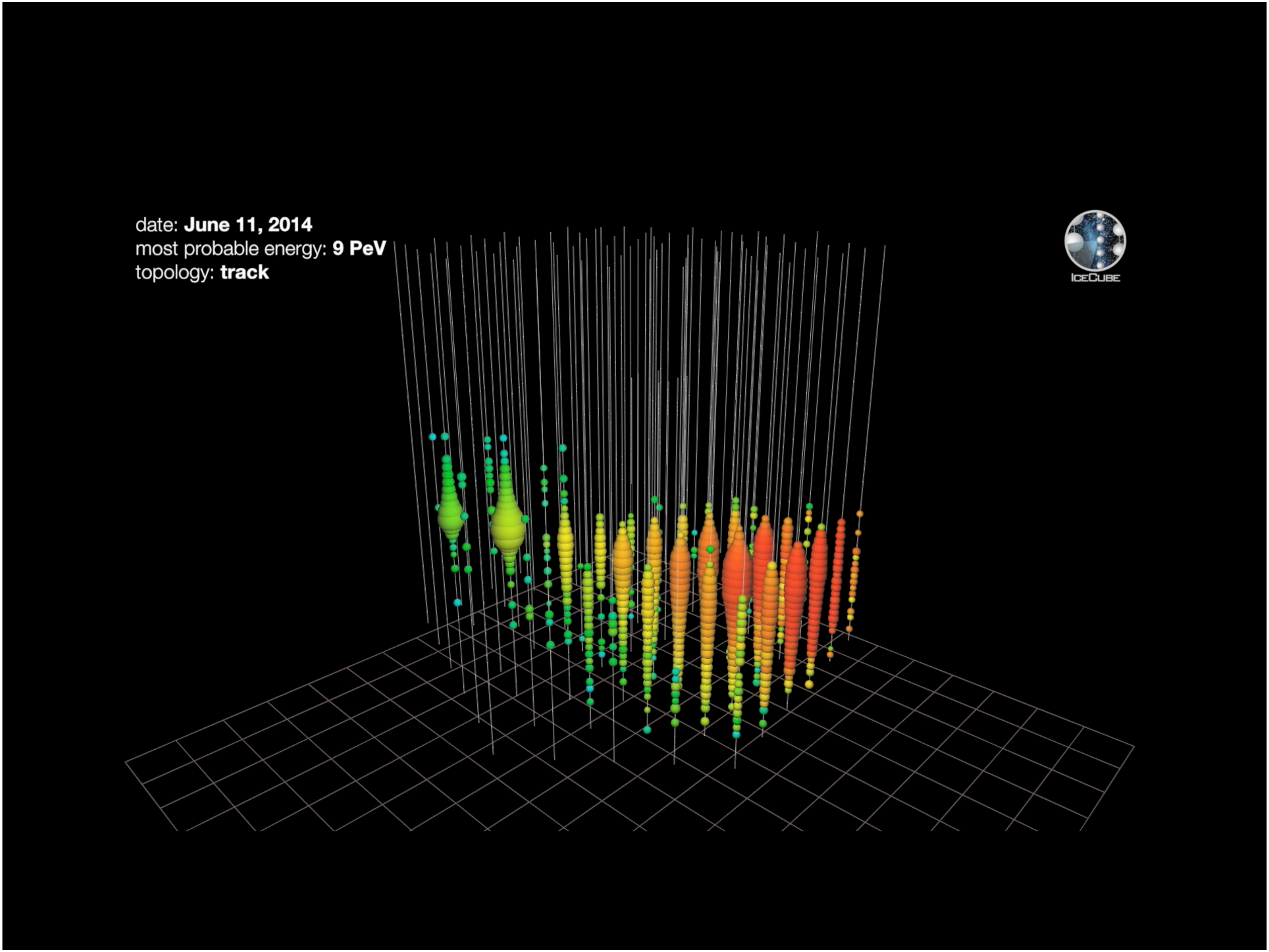
photomultiplier
tube -10 inch

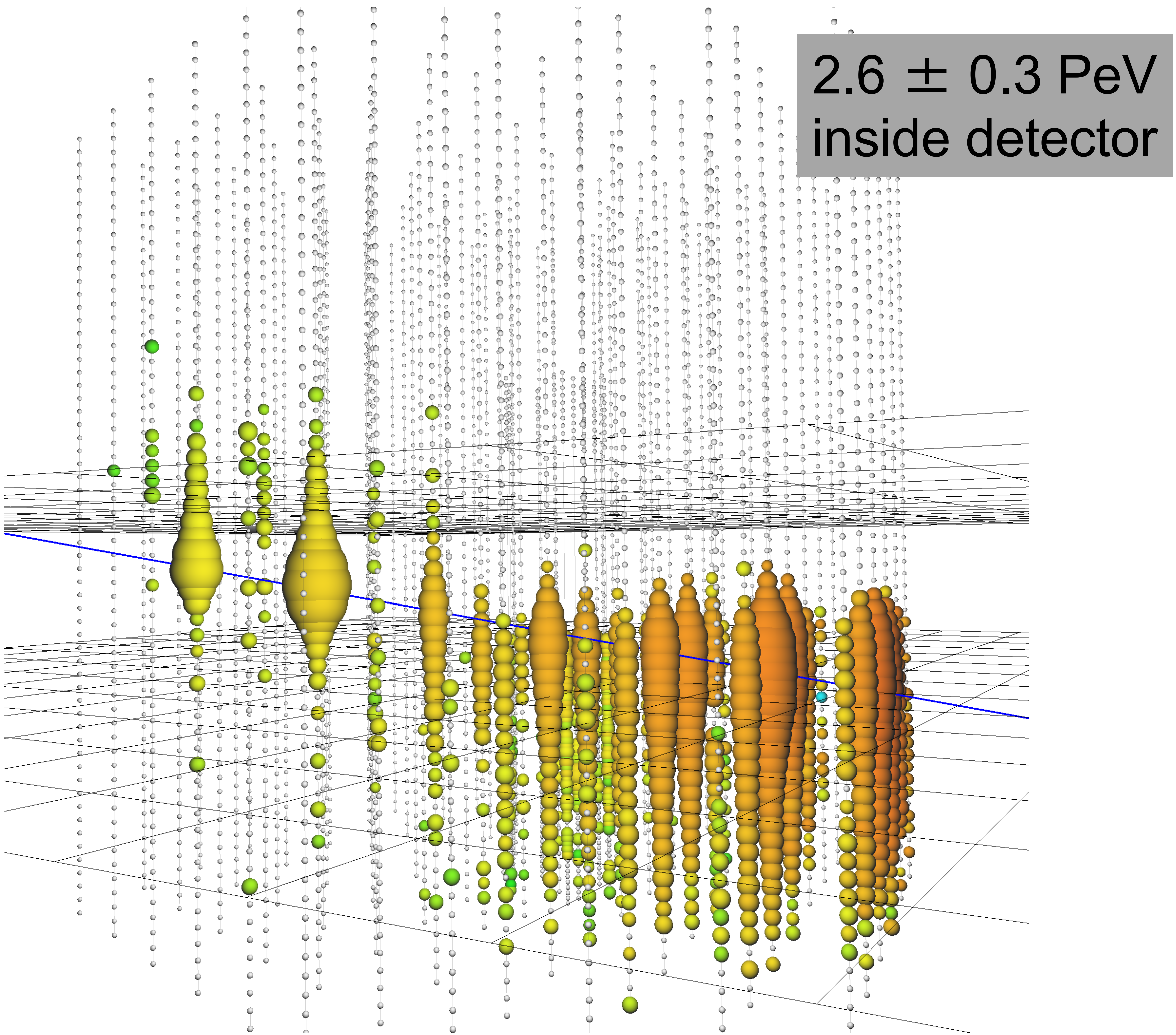


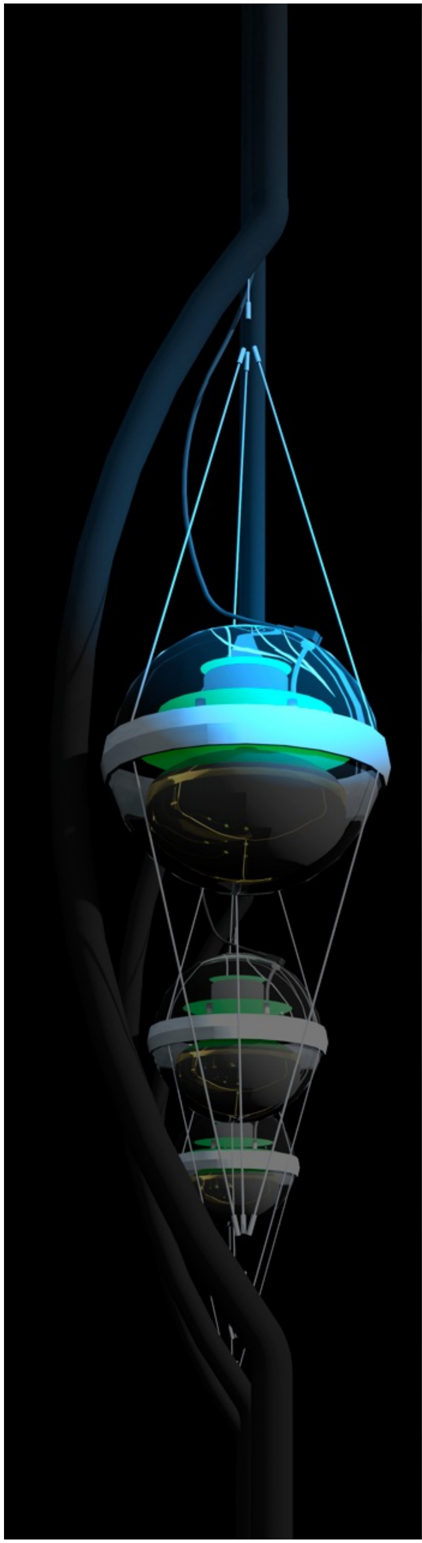
muon track: color is time; number of photons is energy


89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]


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



Multimessenger Astronomy

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- ….

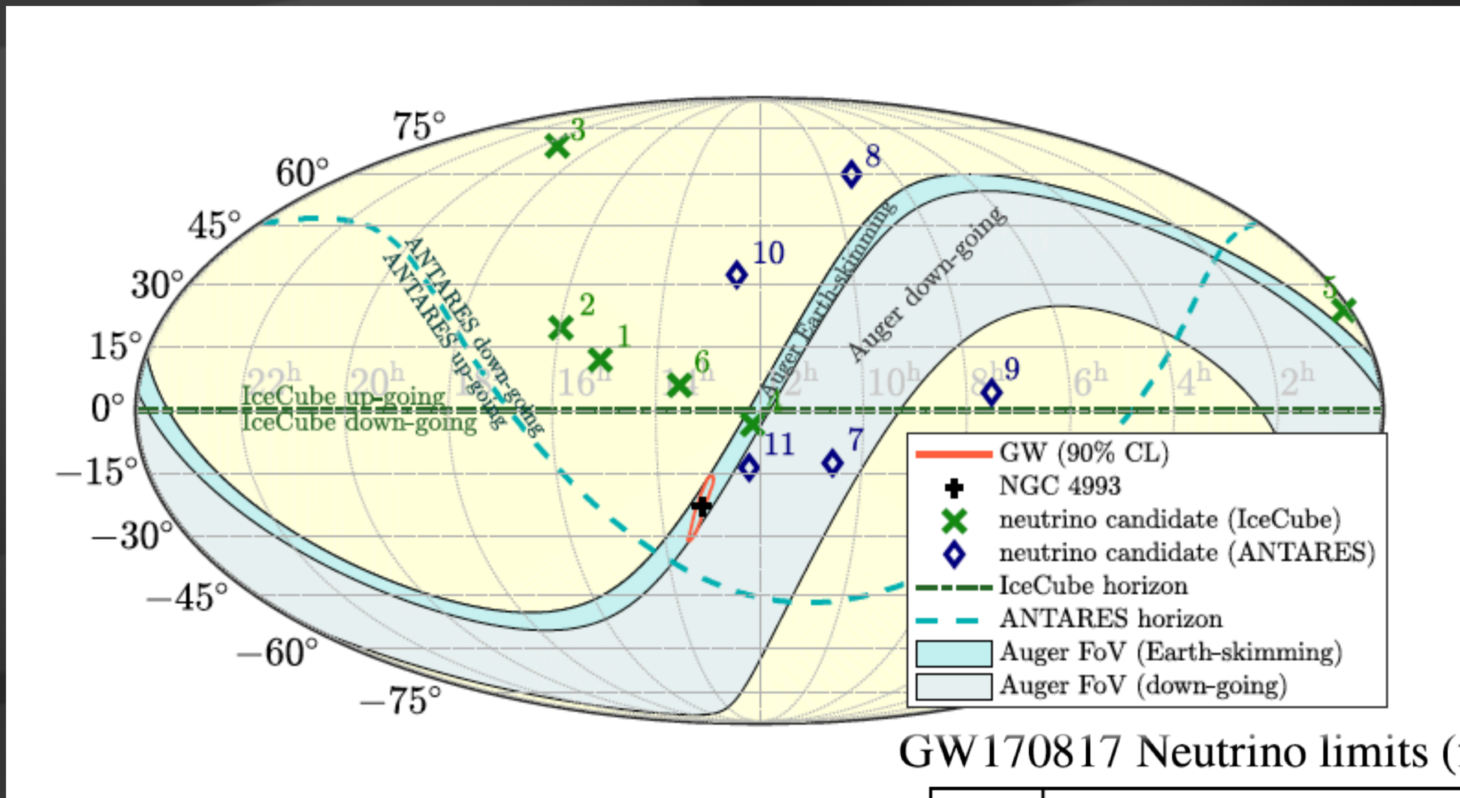
ICECUBE

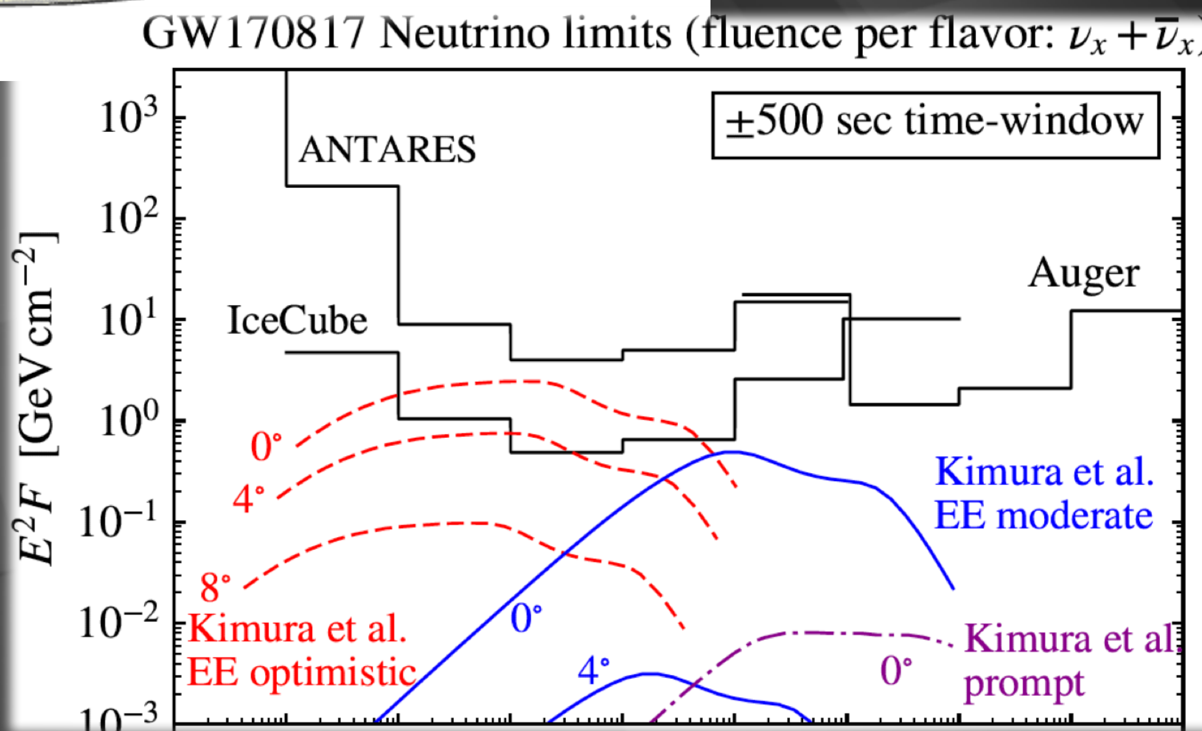
NSF

icecube.wisc.edu

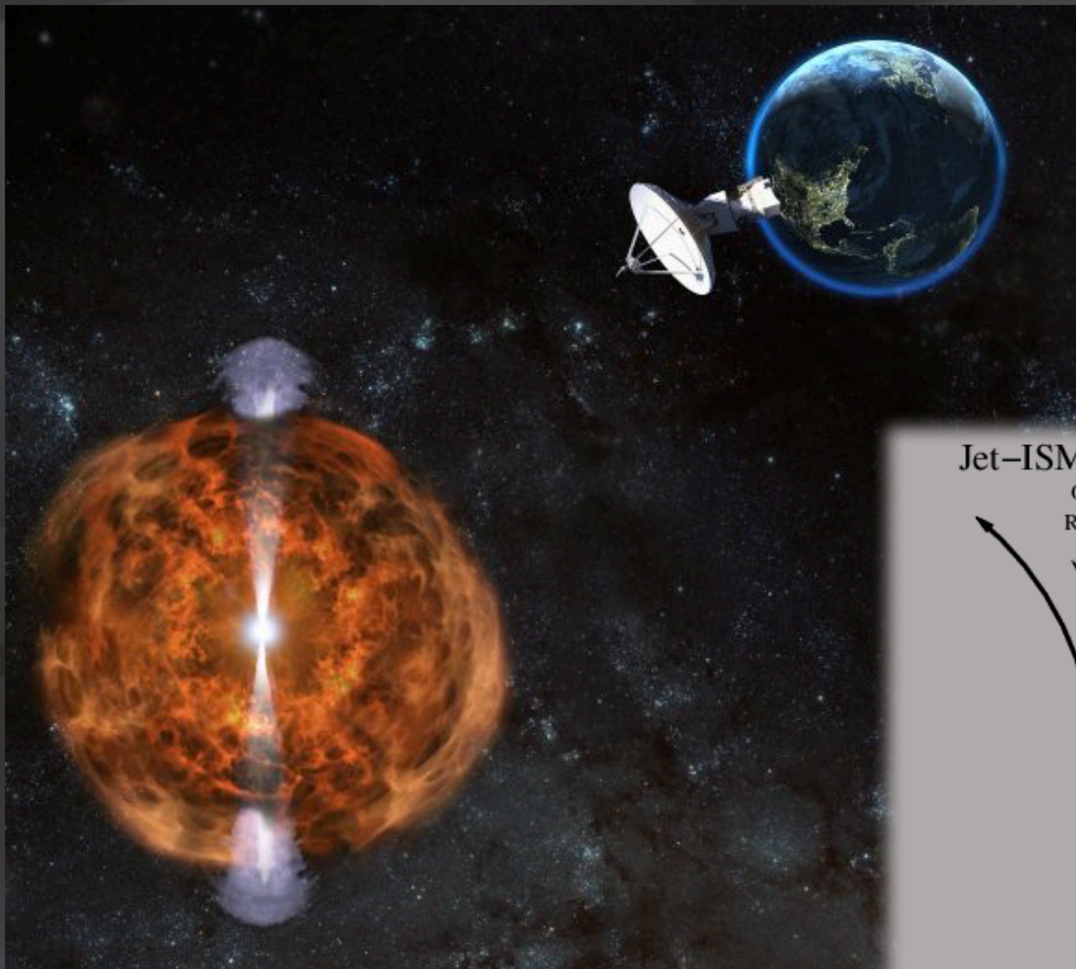
neutron star-neutron star merger

LIGO-VIRGO

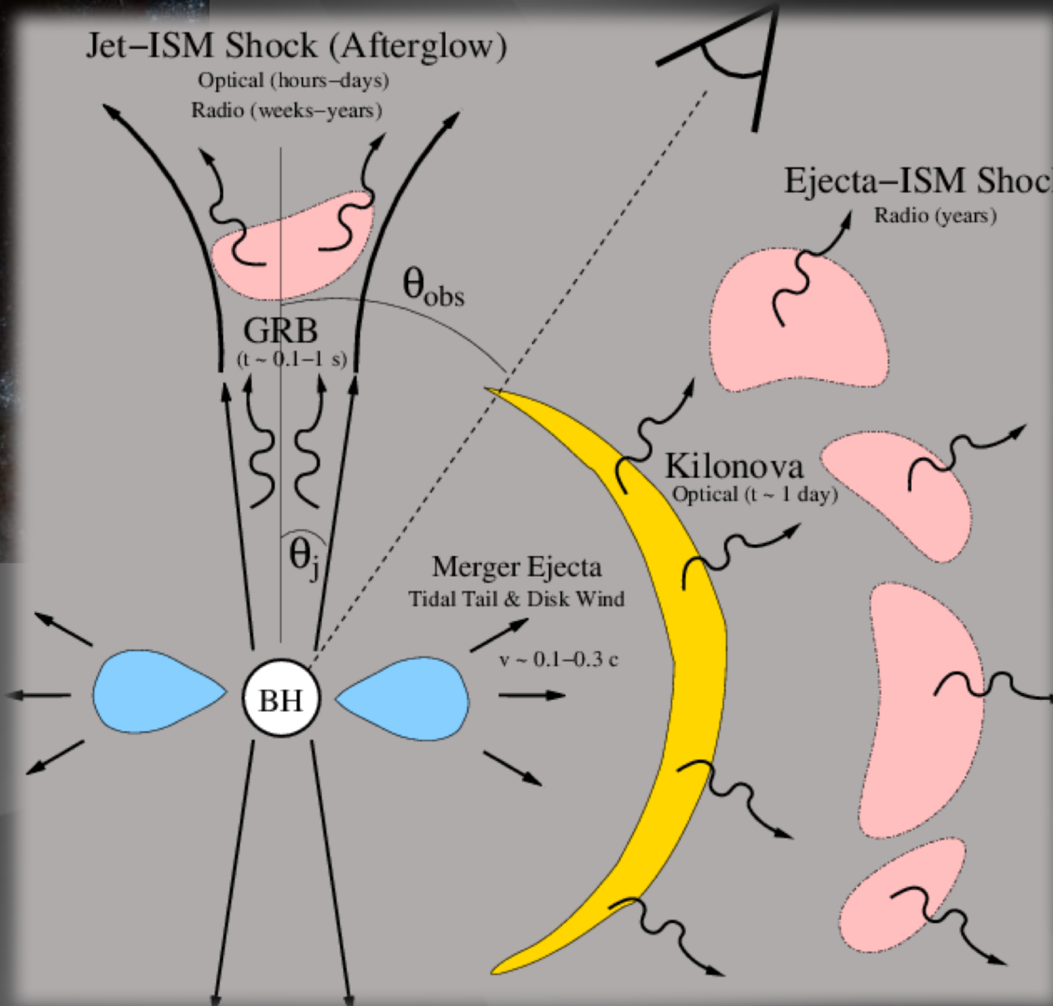

75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
22h 20h 16h 14h 12h 10h 8h 6h 4h 2h
ANTARES down-going
ANTARES up-going
IceCube up-going
IceCube down-going
Auger Earth-skimming
Auger down-going
1 2 3 4 5 6 7 8 9 10 11
GW (90% CL)
NGC 4993
neutrino candidate (IceCube)
neutrino candidate (ANTARES)
IceCube horizon
ANTARES horizon
Auger FoV (Earth-skimming)
Auger FoV (down-going)


GW170817 Neutrino limits (fluence per flavor: $\nu_x + \overline{\nu}_x$)
±500 sec time-window
ANTARES
IceCube
Auger
E^2F [GeV cm^{-2}]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0°
4°
8°
Kimura et al.
EE optimistic
Kimura et al.
EE moderate
Kimura et al.
prompt

buildup of magnetic fields near merger launches jet

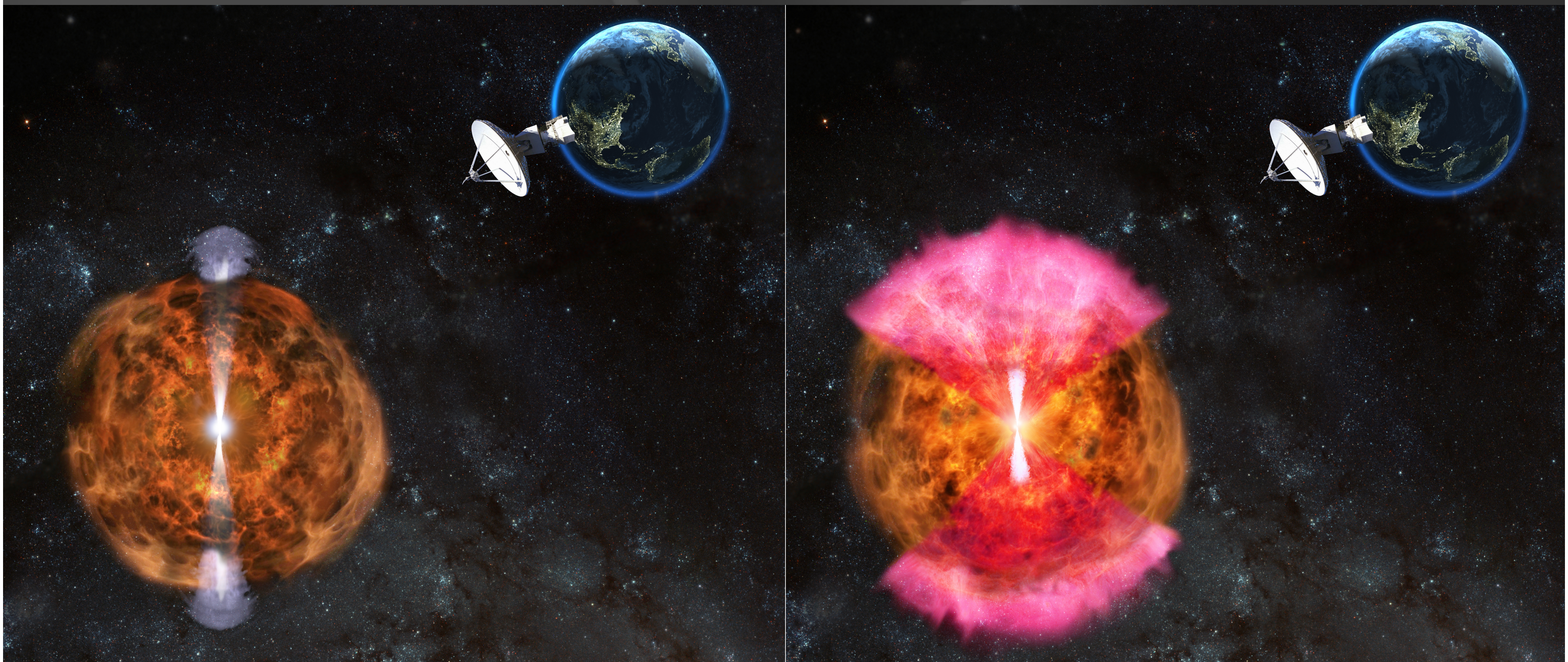


very weak short GRB seen by Fermi (off axis?)



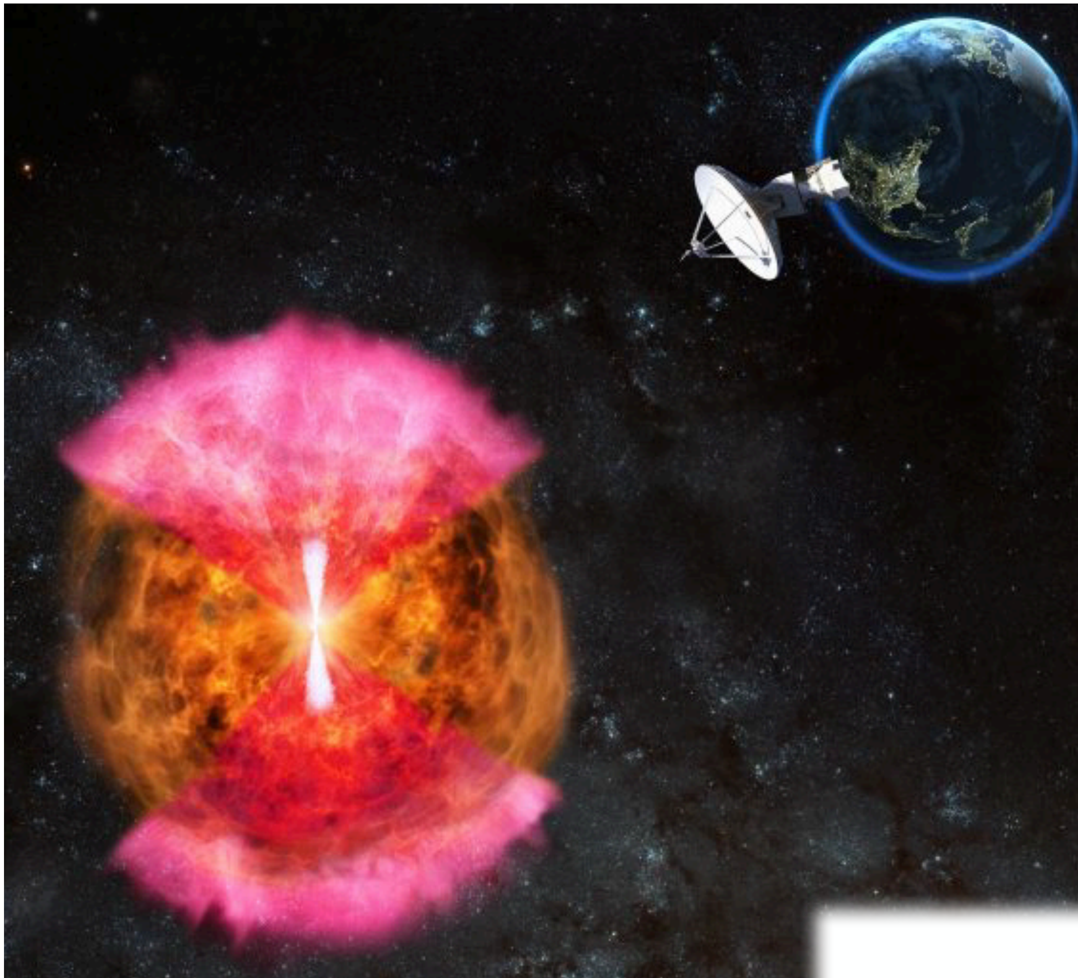
MeV neutrino emission:

- ~ 0.01 M_{sun} material ejected
  - ~ supernova



off-axis jet

choked jet cocoon



high-energy neutrinos from internal shocks:

protons interact with photons

- from leakage of the collimation jet
- from bremsstrahlung by accelerated electrons

to produce pions and neutrinos

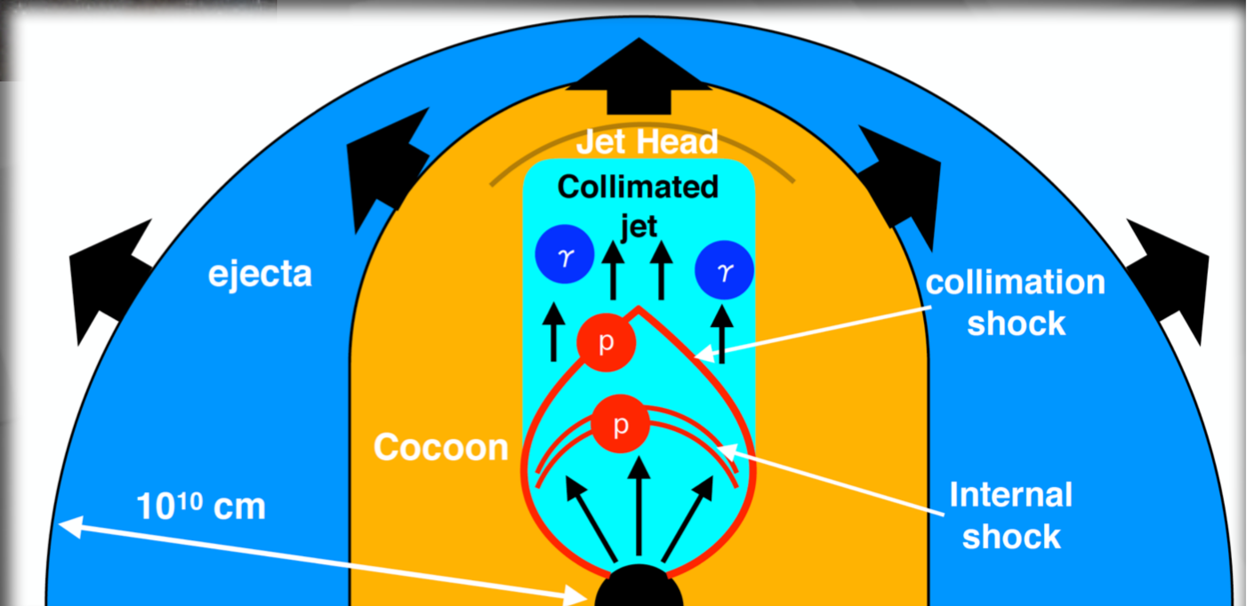
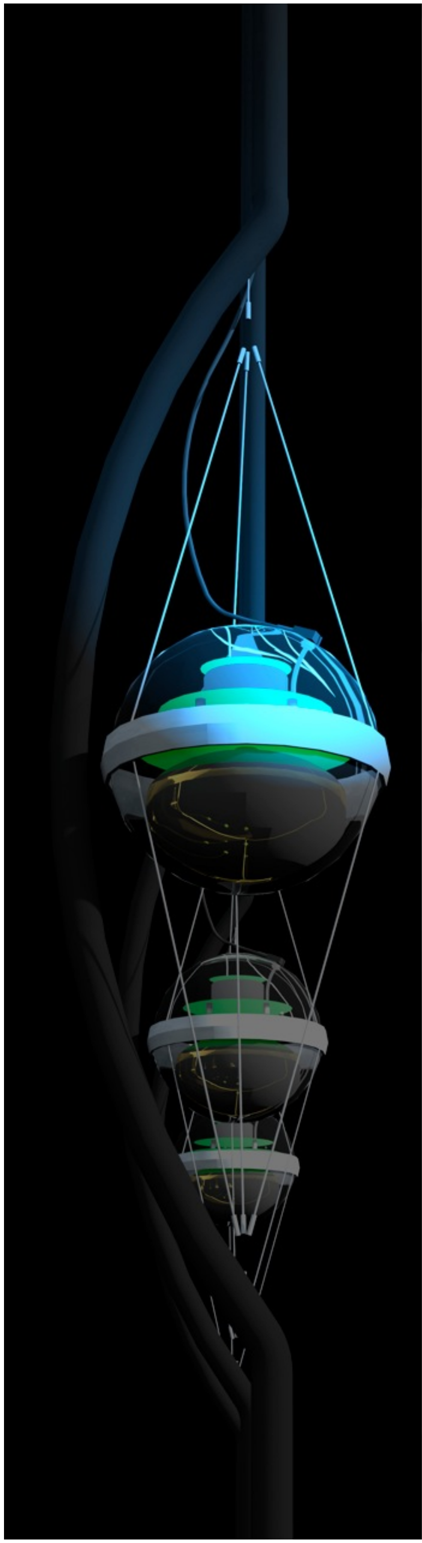


TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

Number of detected neutrinos from single event at 40 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	6.6	0.55	29
B	0.36	0.023	1.5

Number of detected neutrinos from single event at 300 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

GW+neutrino detection rate [yr^{-1}]		
model	IceCube	Gen2
A	1.1	2.6
B	0.076	0.28



Multimessenger Astronomy

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- February 23, 1987
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- ….

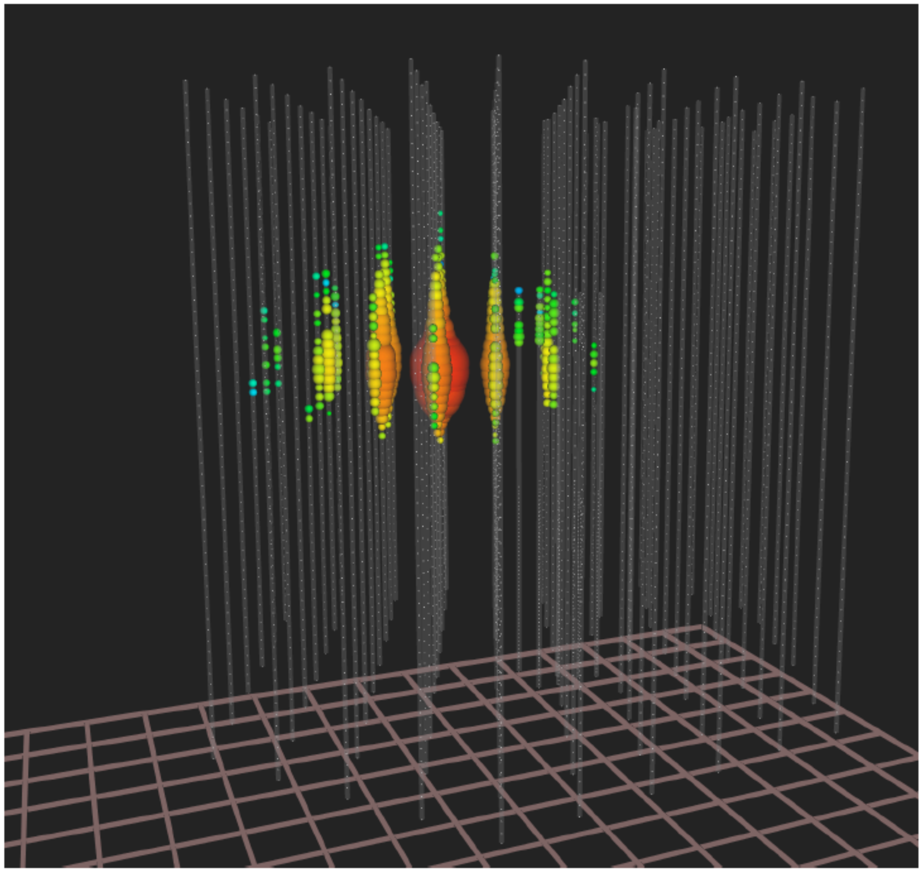
ICECUBE

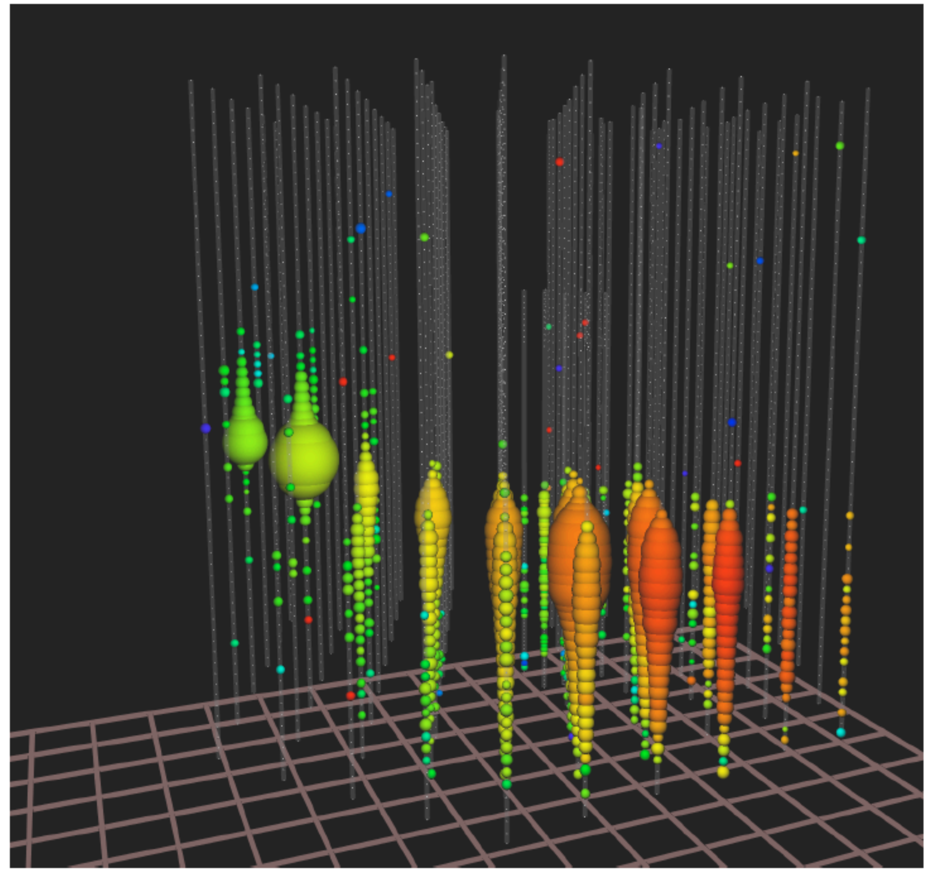
NSF

icecube.wisc.edu

isolated neutrinos interacting *inside* the detector (HESE)

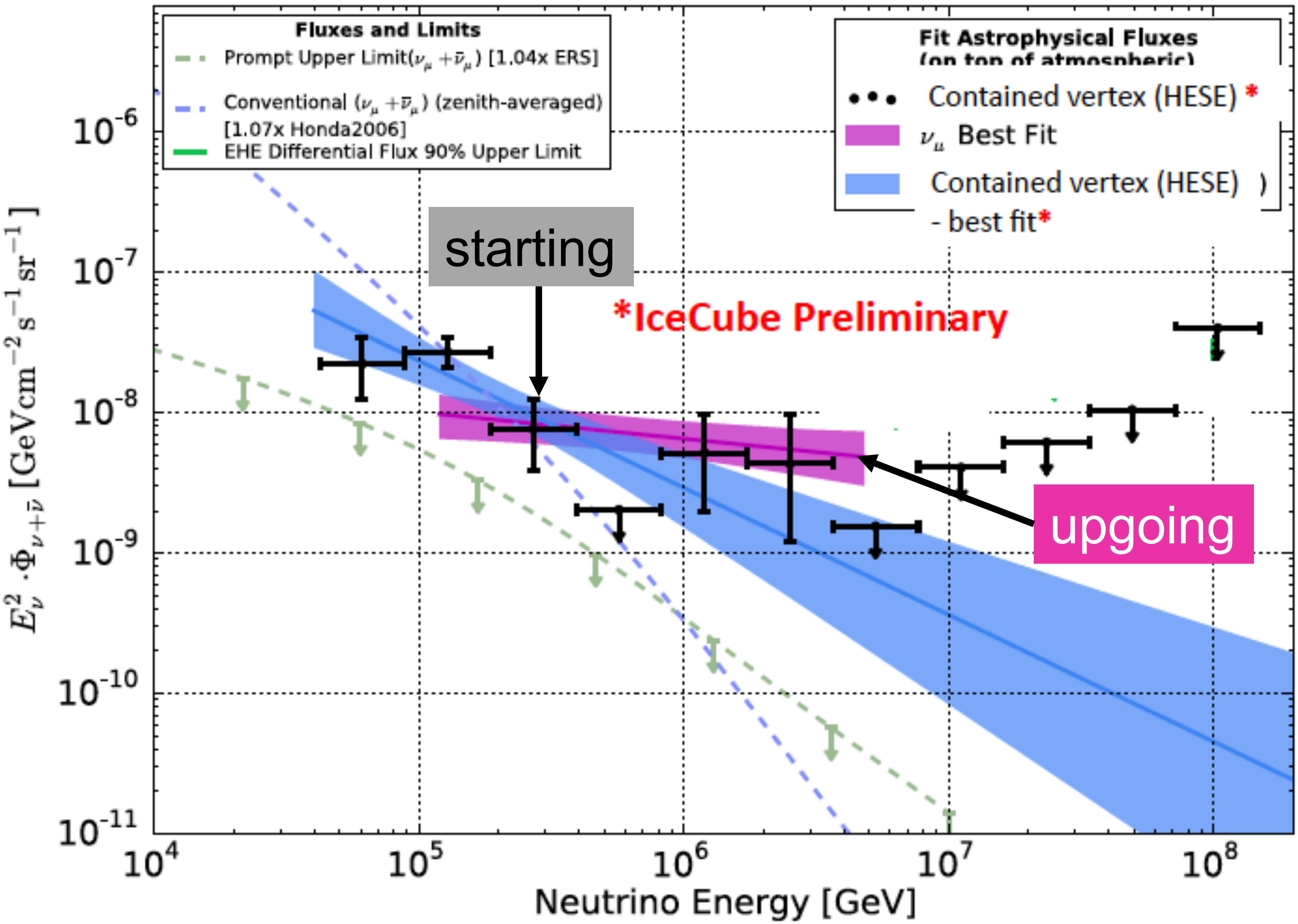
up-going muon tracks (UPMU)





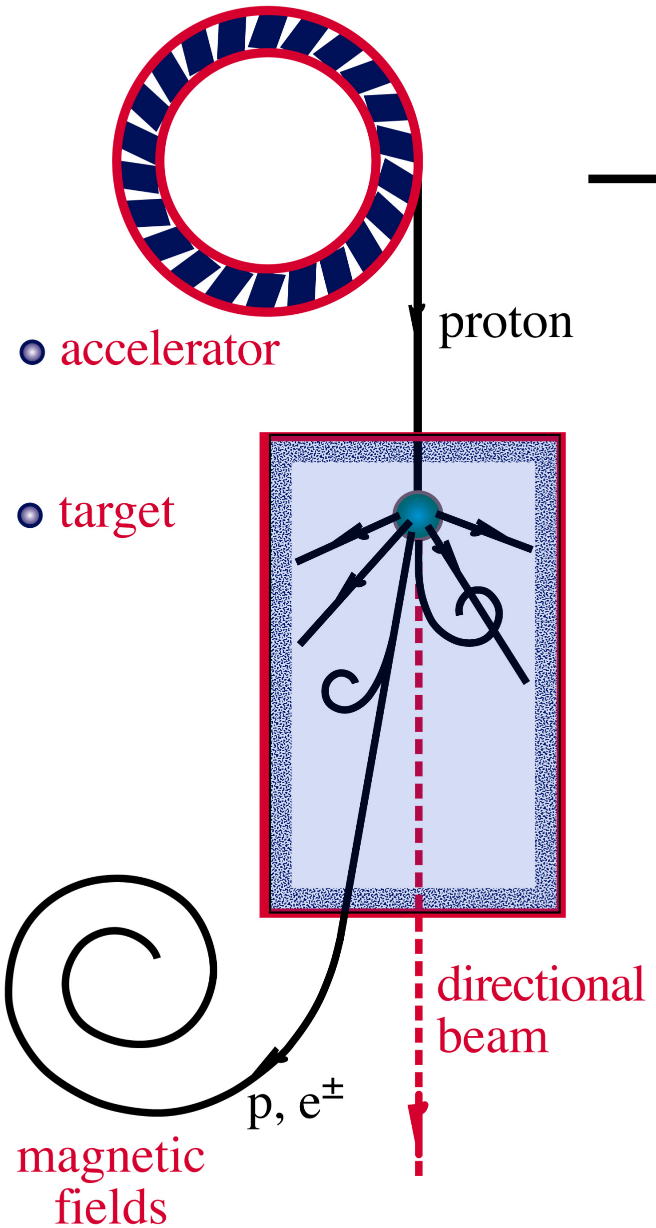
total energy measurement
all flavors, all sky

astronomy: angular resolution superior (<0.5°)



two methods are consistent

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

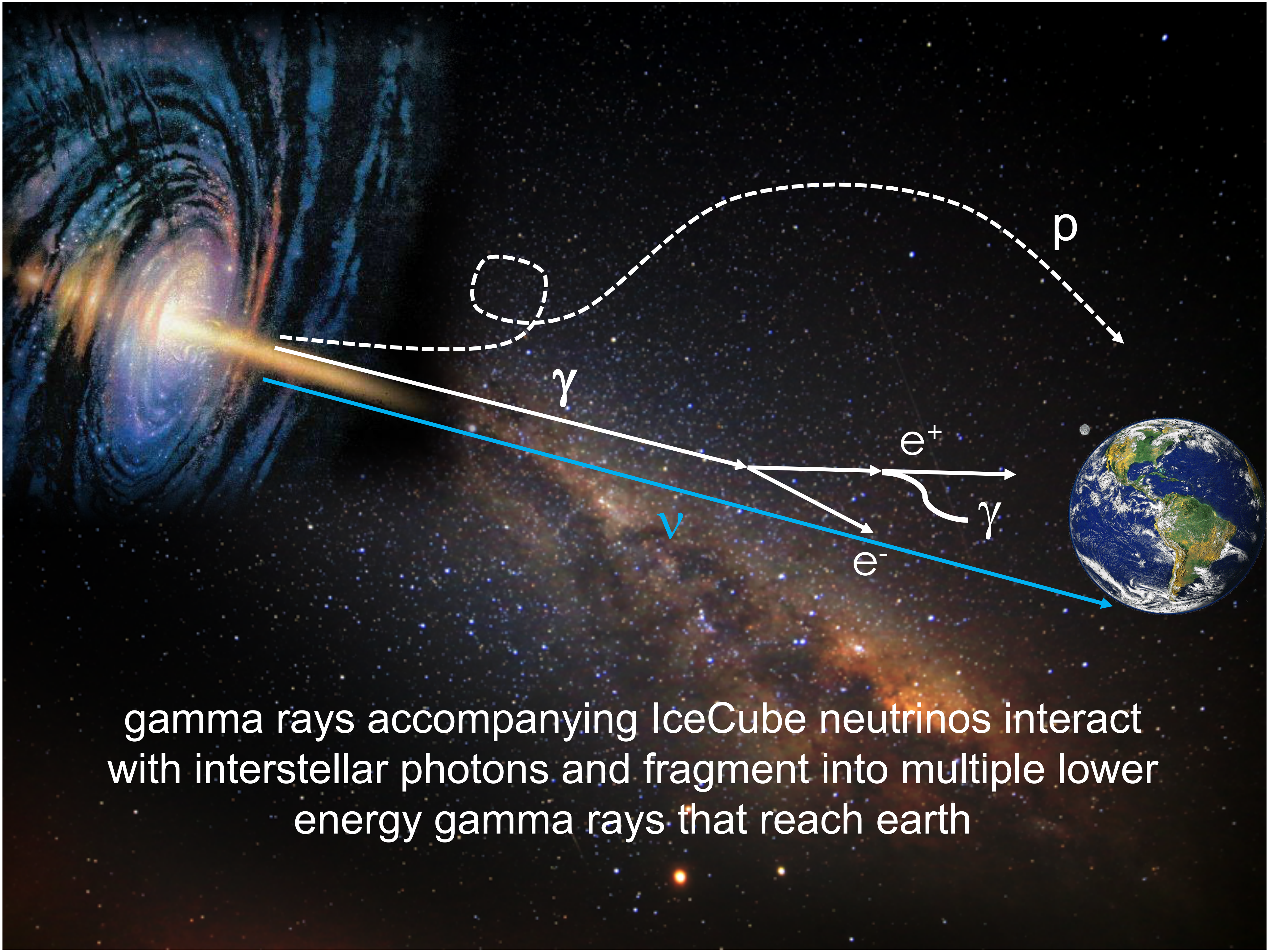
radiation and dust

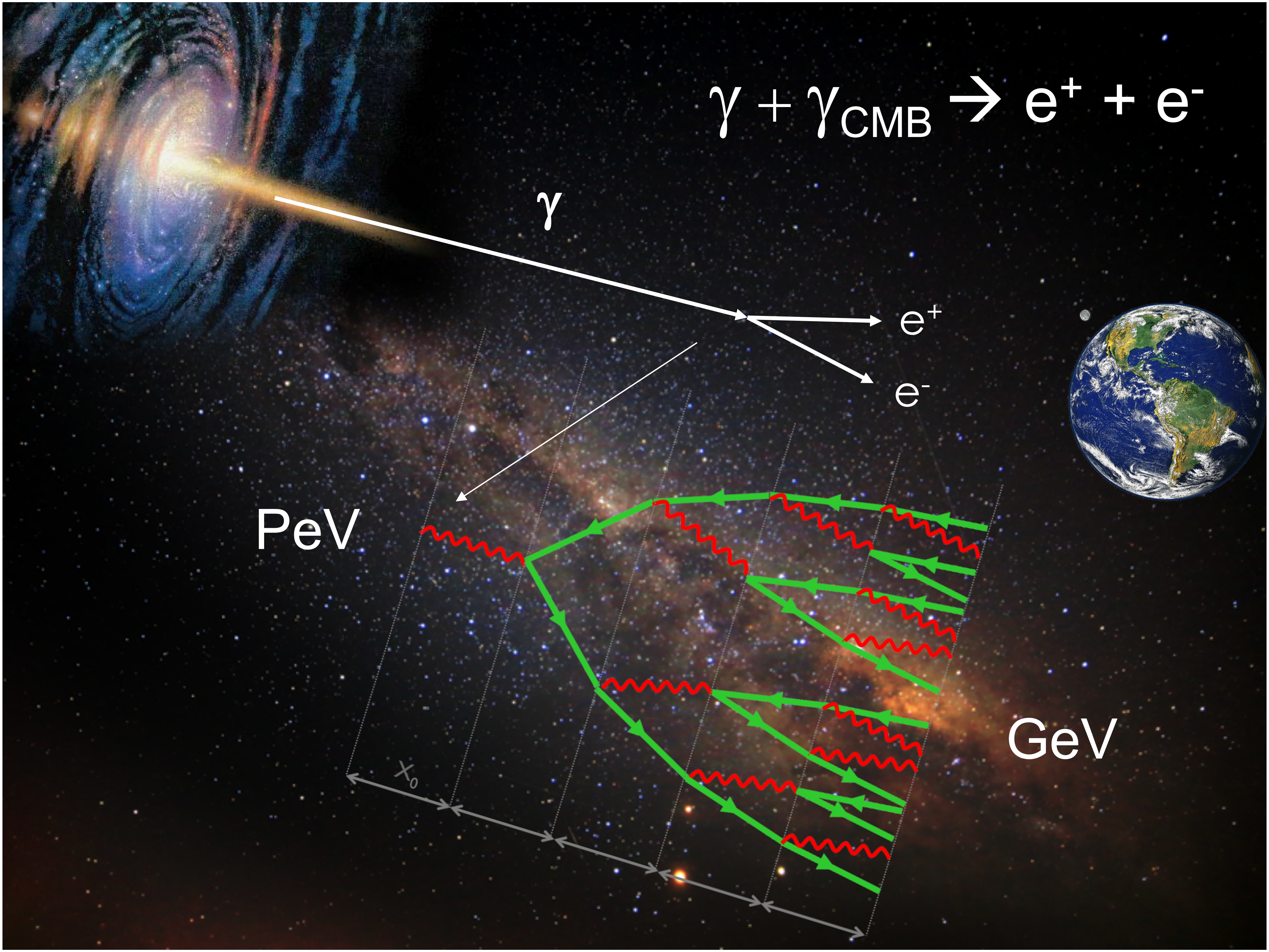
$p + \gamma \rightarrow n + \pi^+$

~ cosmic ray + neutrino

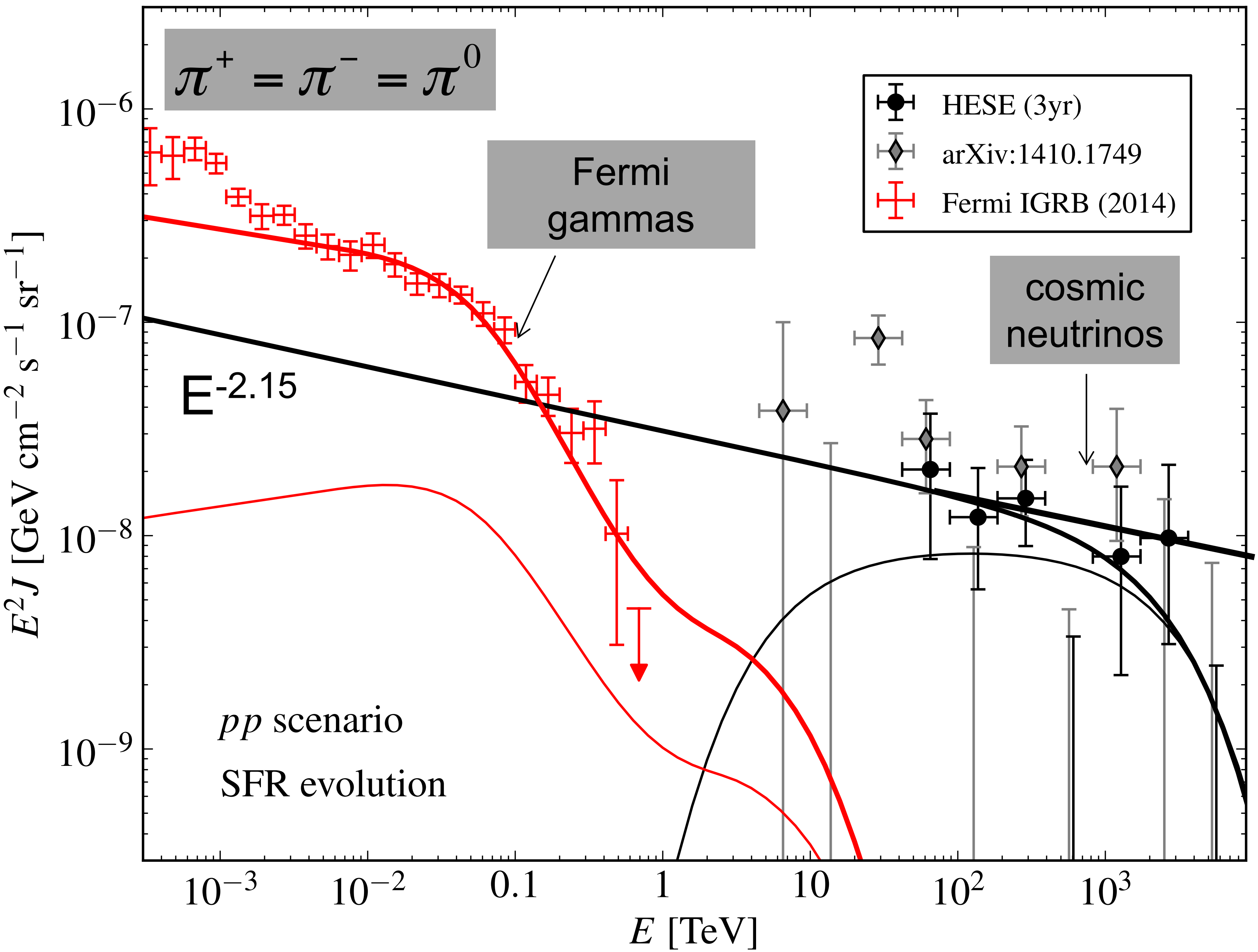
$\rightarrow p + \pi^0$

~ 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

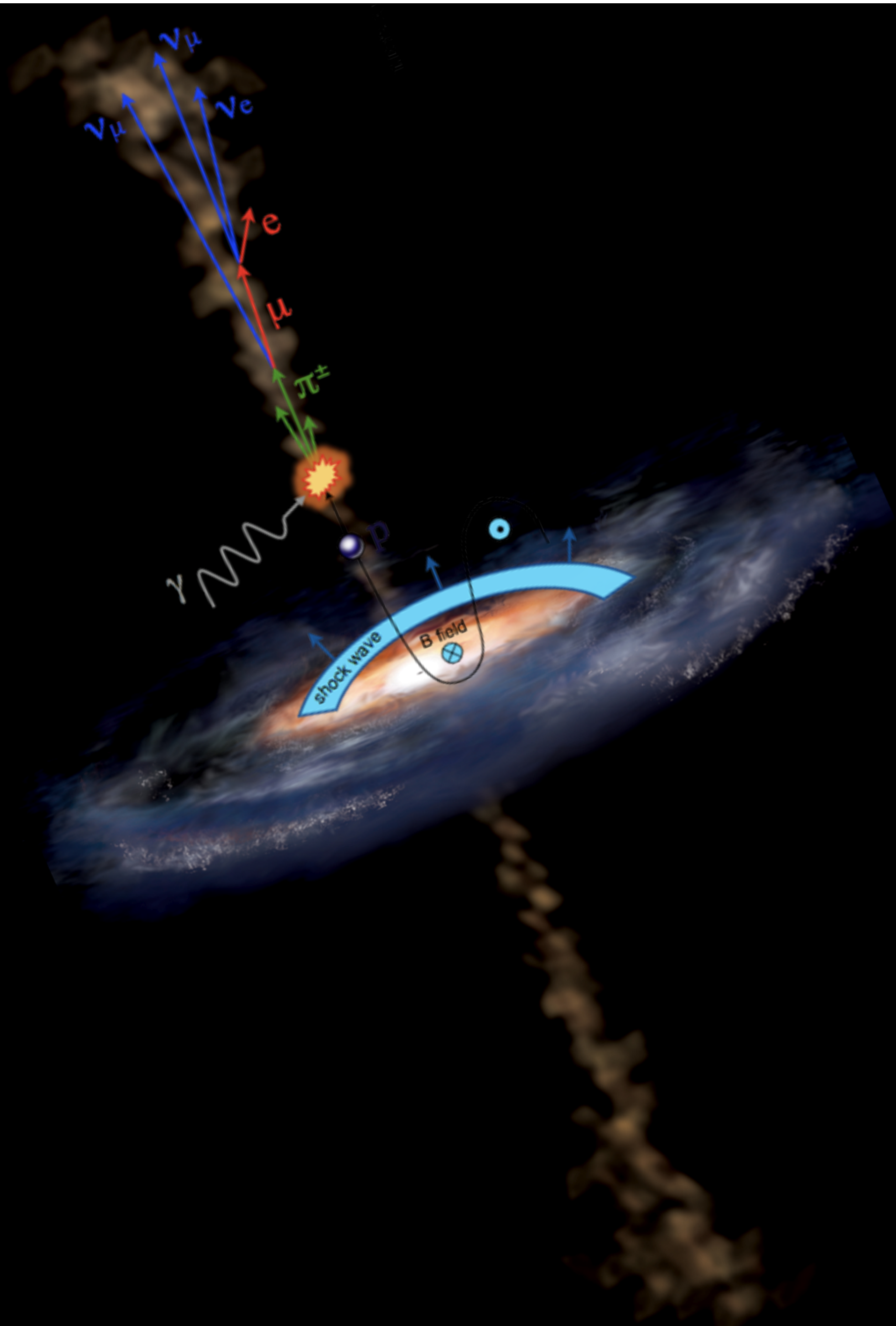


$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0



$\pi^+ = \pi^- = \pi^0$
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}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
E [TeV]

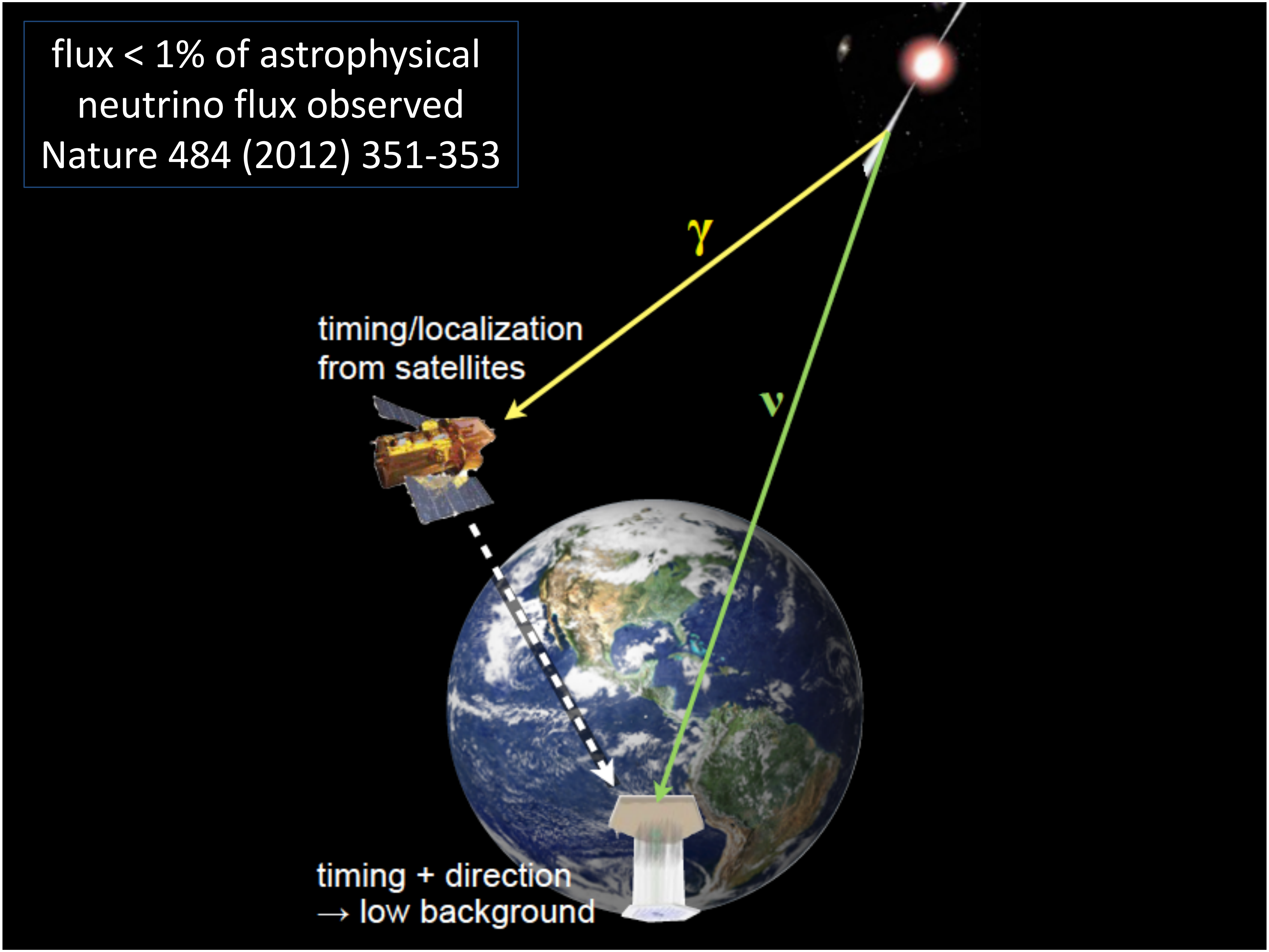
- energy density of neutrinos in the non-thermal Universe is similar as that in gamma-rays



Fermi sources
are mostly
blazars

common sources?

→
multimessenger
astronomy


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

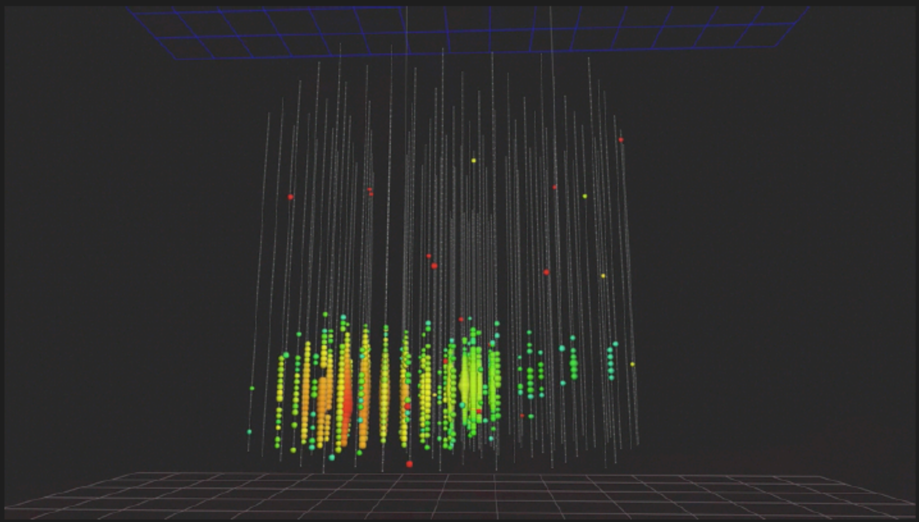
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

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

GCN notice for starting track sent Apr 27

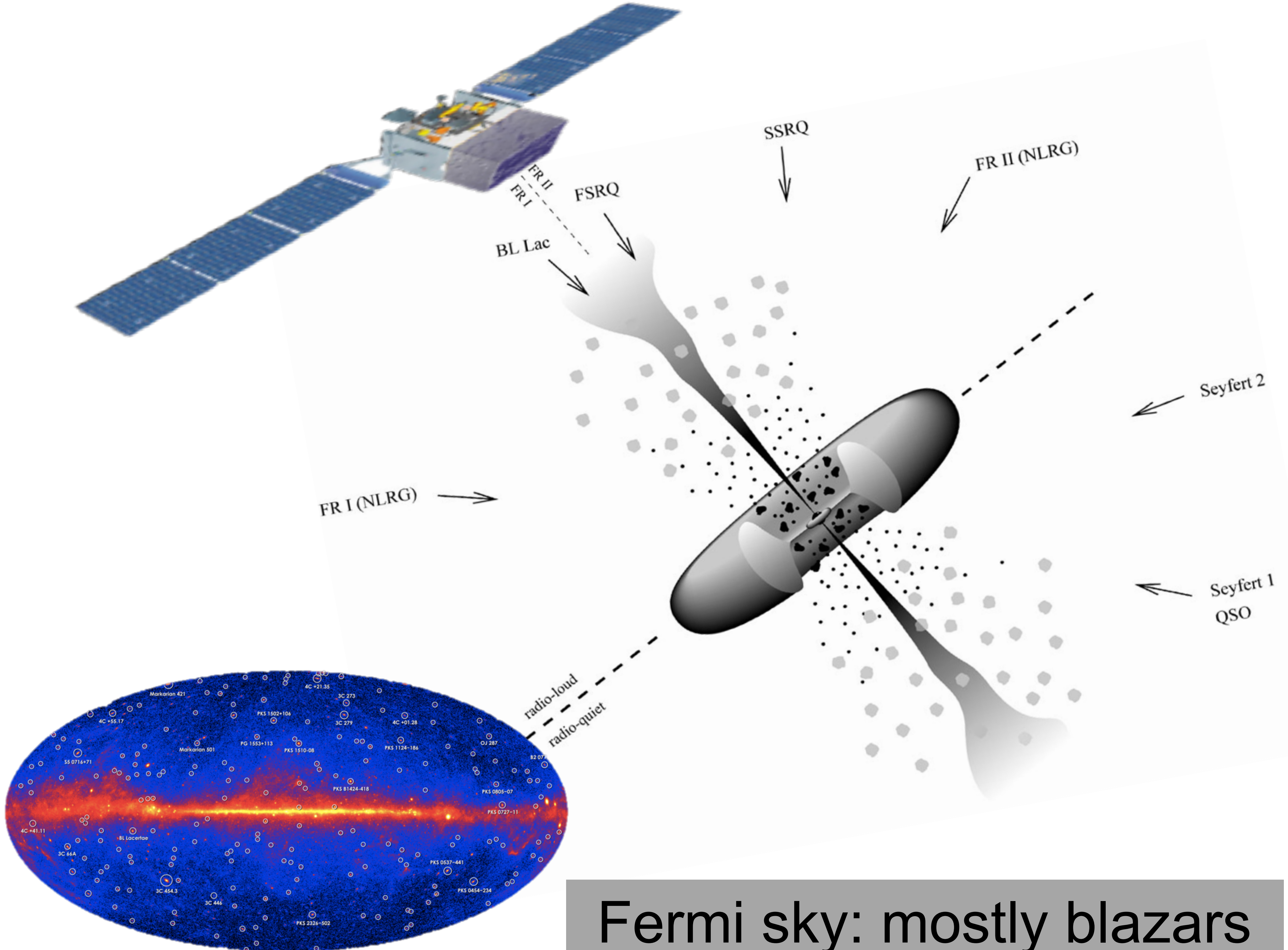
We send **rough reconstructions first** and then **update them.**



IceCube Trigger

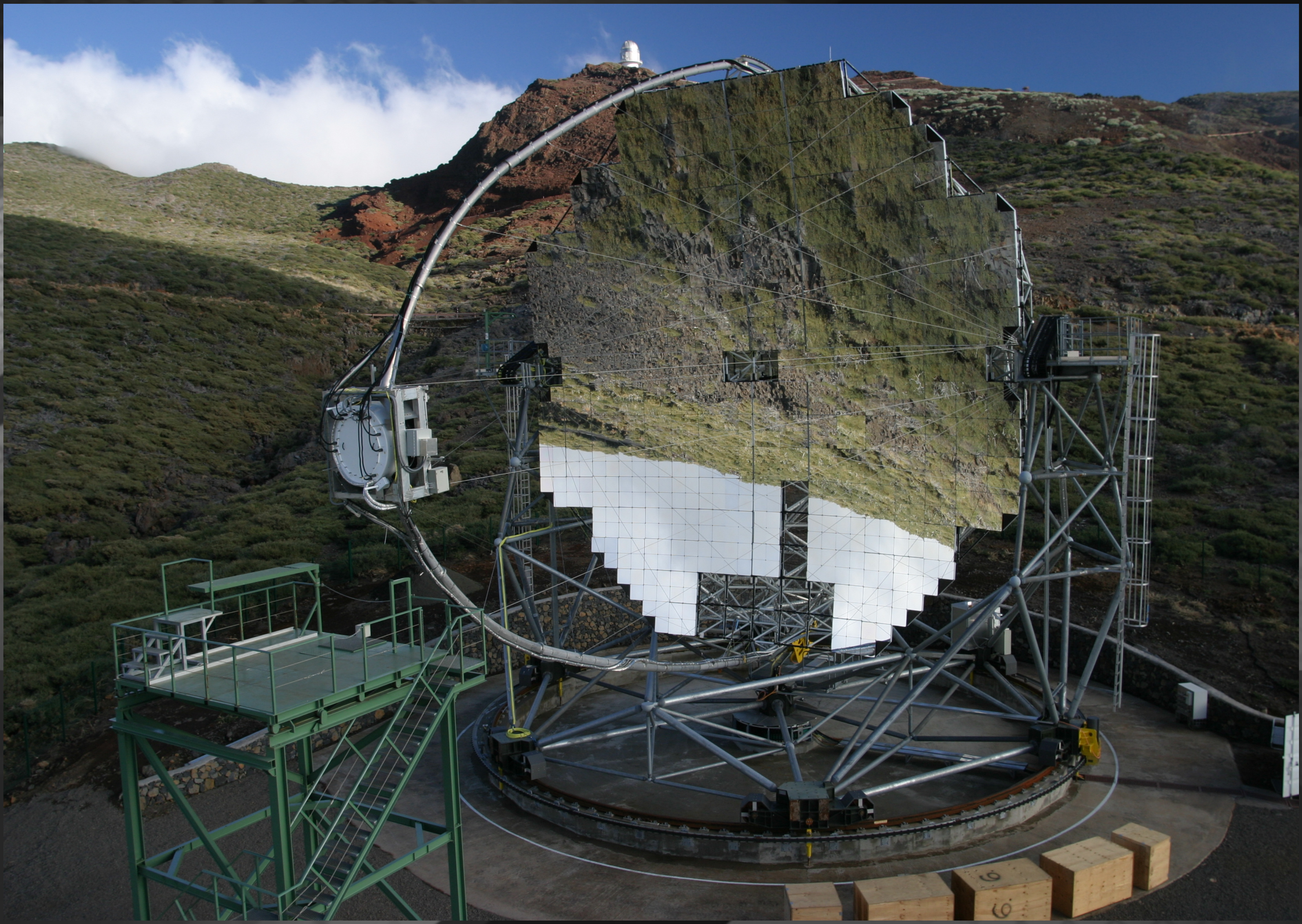
43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
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]
```



Fermi sky: mostly blazars

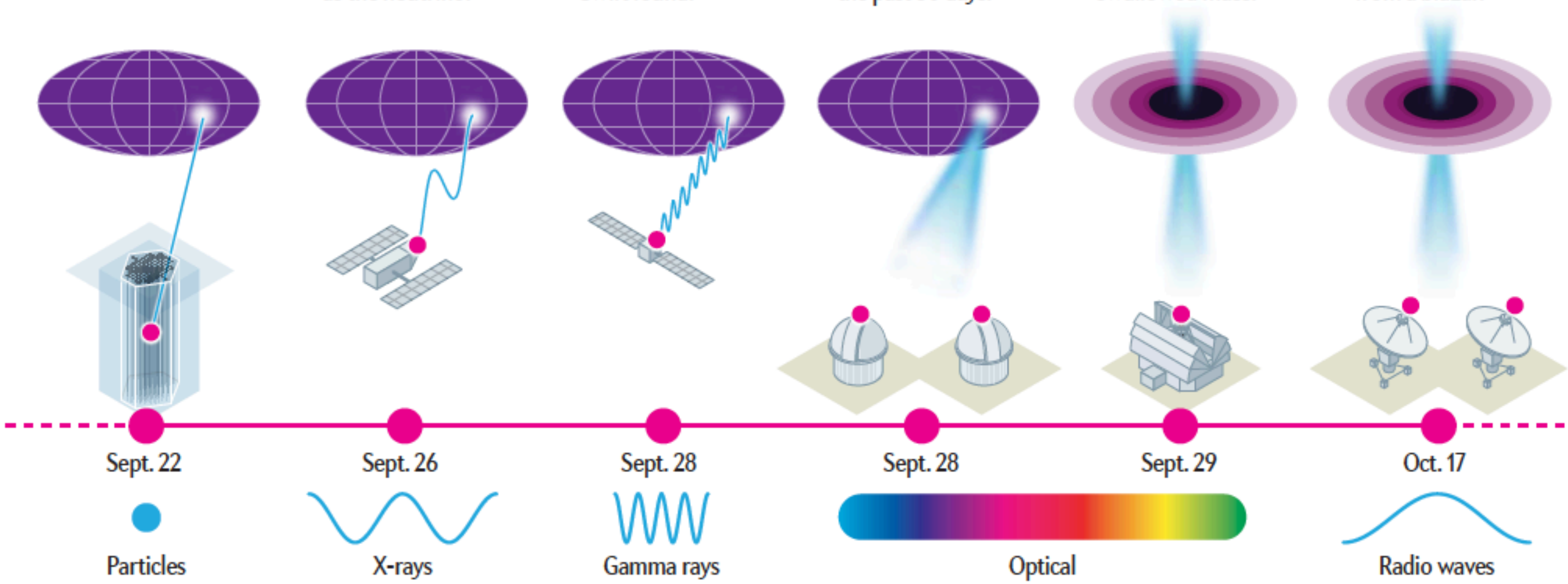
MAGIC



Many Messengers

Over three and a half weeks in 2017, astronomers observed the same celestial event—what they believe to be a flare-up from matter falling into a supermassive black hole—through multiple wavelengths of light, as well as particles called neutrinos. The combined observations offer scientists much more information about these mysterious phenomena than any measurement alone.

1. First, the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino and issued an alert.
2. The orbiting Swift x-ray telescope reported finding nine sources of x-rays coming from the same area of the sky as the neutrino.
3. Two days later the Fermi space telescope identified gamma rays coming from one of the same sources Swift found.
4. A network of ground-based optical telescopes called ASAS-SN announced that this source had been brightening over the past 50 days.
5. Another optical telescope found evidence that the source was a blazar—a huge black hole emitting jets as it swallowed mass.
6. The Very Large Array in New Mexico, observing in radio light, confirmed that the source of all these signals was a jet from a blazar.



Finkbeiner (Scientific American)

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

Multi-wavelength observations of a flaring blazar coincident with an IceCube high-energy neutrino

IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^o Dec 5.72^o
- Fermi-LAT: flaring blazar within 0.1^o
- MAGIC: TeV source in follow-up observations
- …
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

we identified a source of high energy cosmic rays:

the active galaxy (blazar) TXS 0506+056 at a distance of 1.8 Gpc (redshift of 0.33)

extensive multiwavelength campaign will allow us to study the first cosmic accelerator

Draft version February 7, 2018
Typeset using LaTeX preprint2 style in AASTeX61

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

Simona Paiano,[1,2] Renato Falomo,[1] Aldo Treves,[3,4] and Riccardo Scarpa[5,6]

[1] INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5 I-35122 Padova - ITALY
[2] INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY
[3] Università degli Studi dell'Insubria, Via Valleggio 11 I-22100 Como - ITALY
[4] INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46 I-23807 Merate (LC) - ITALY
[5] Instituto de Astrofisica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN
[6] Universidad de La Laguna, Dpto. Astrofisica, s/n E-38206 La Laguna (Tenerife) - SPAIN

(Received February, 2018; Revised February 7, 2018; Accepted 2018)

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

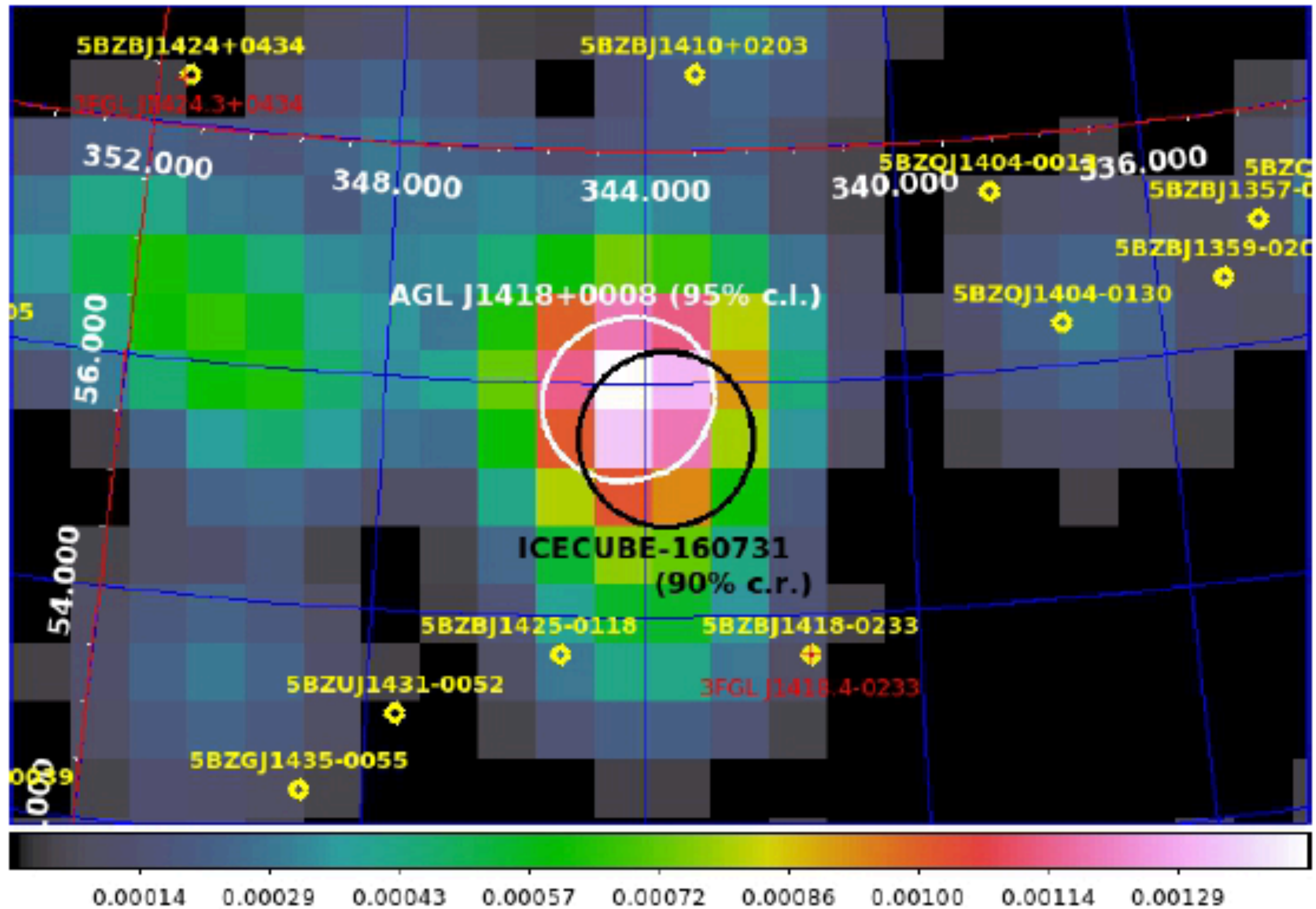
→ although at 10 times larger redshift than nearby blazars (like the Markarian sources), TXS 0506+056 has the same flux → probably special subclass

- flare buildup ~100 days
- neutrinos emitted during period of
- rapid variation ~days

→ previous evidence?

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

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)

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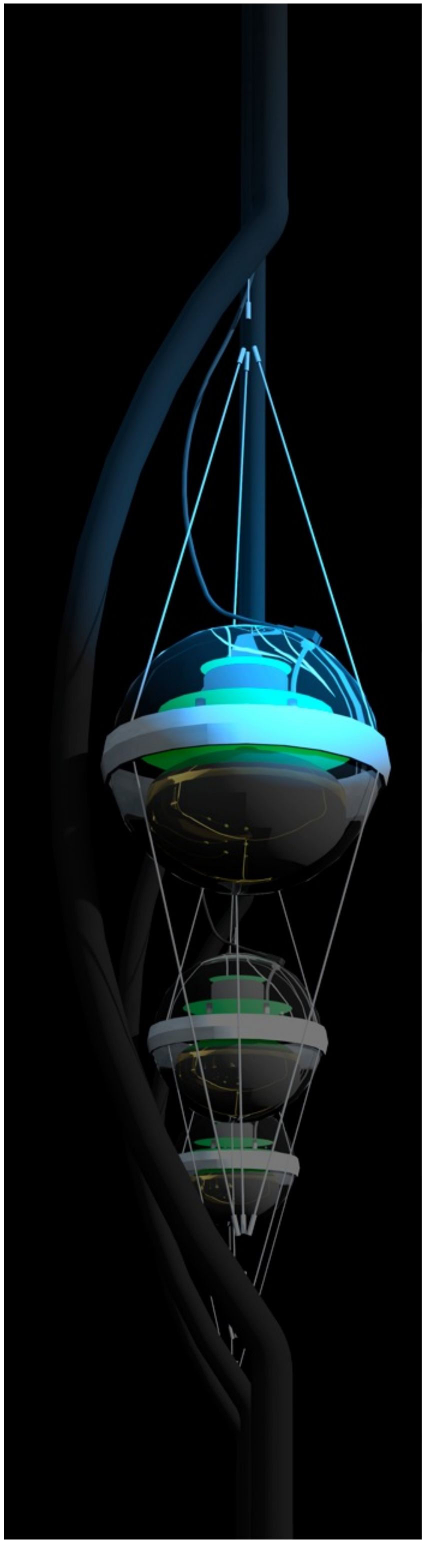
ABSTRACT

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



Multimessenger Astronomy

francis halzen

- February 23, 1987
- August 17, 2017
- September 22. 2017
- ….
- *the future is now*

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