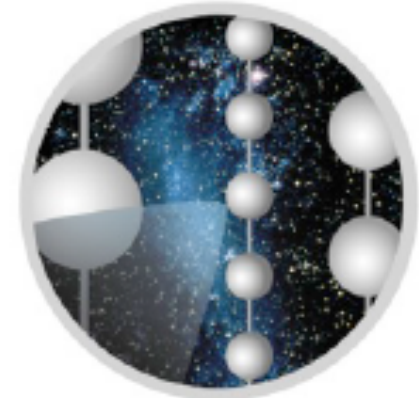


# Multimessenger Astronomy

francis halzen

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



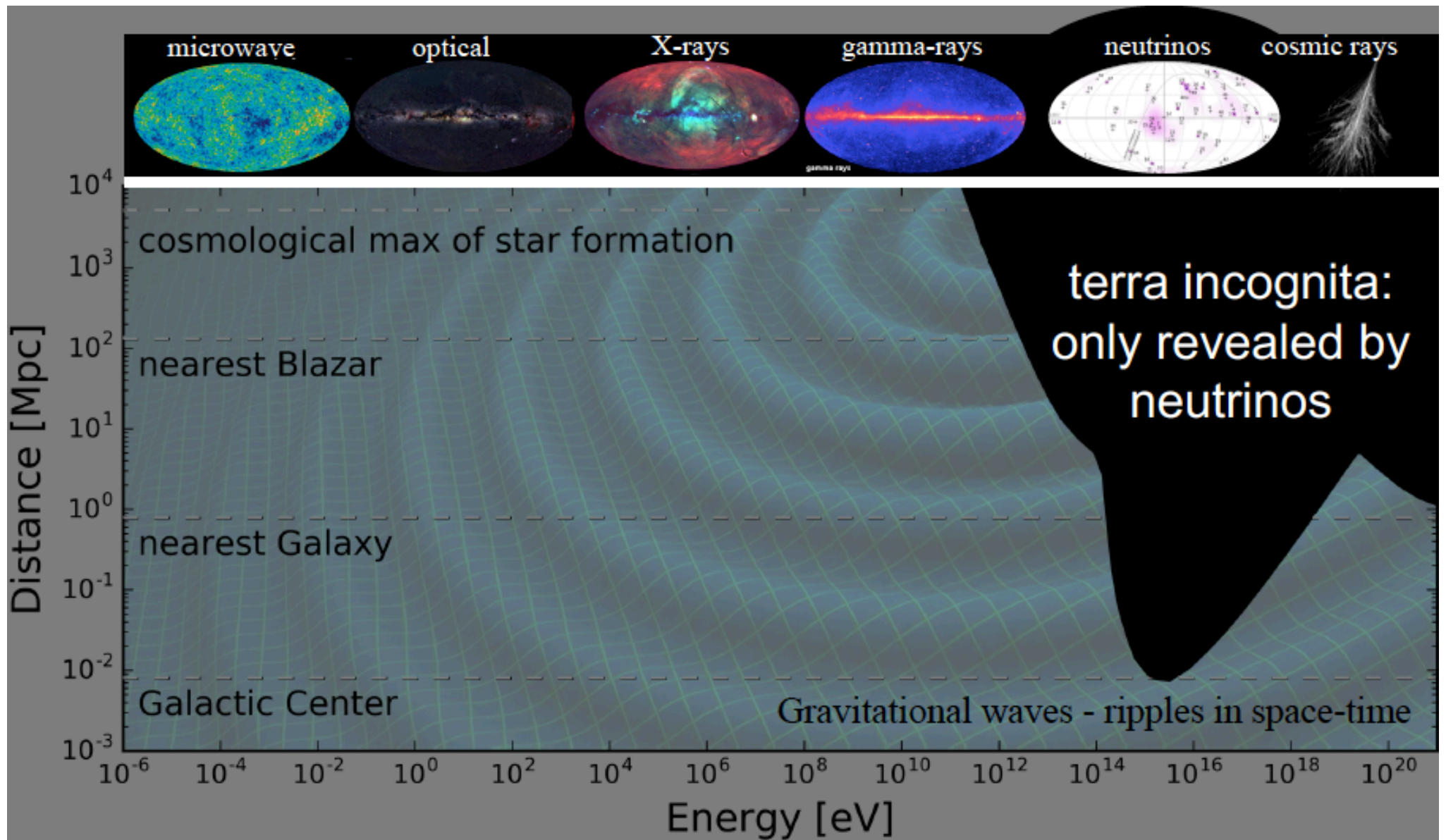
ICECUBE



[icecube.wisc.edu](http://icecube.wisc.edu)

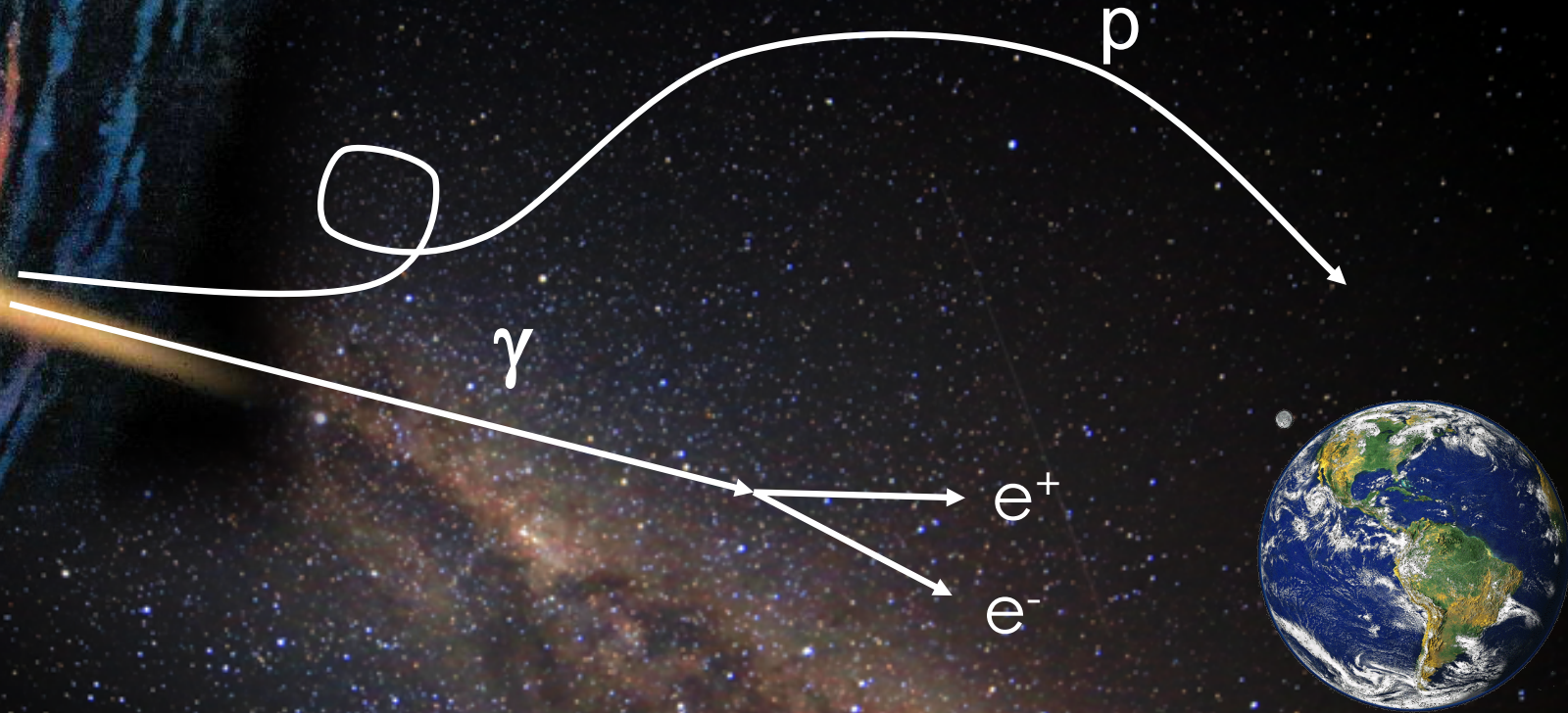
supernova 1987a: 24 neutrinos, thousands of papers





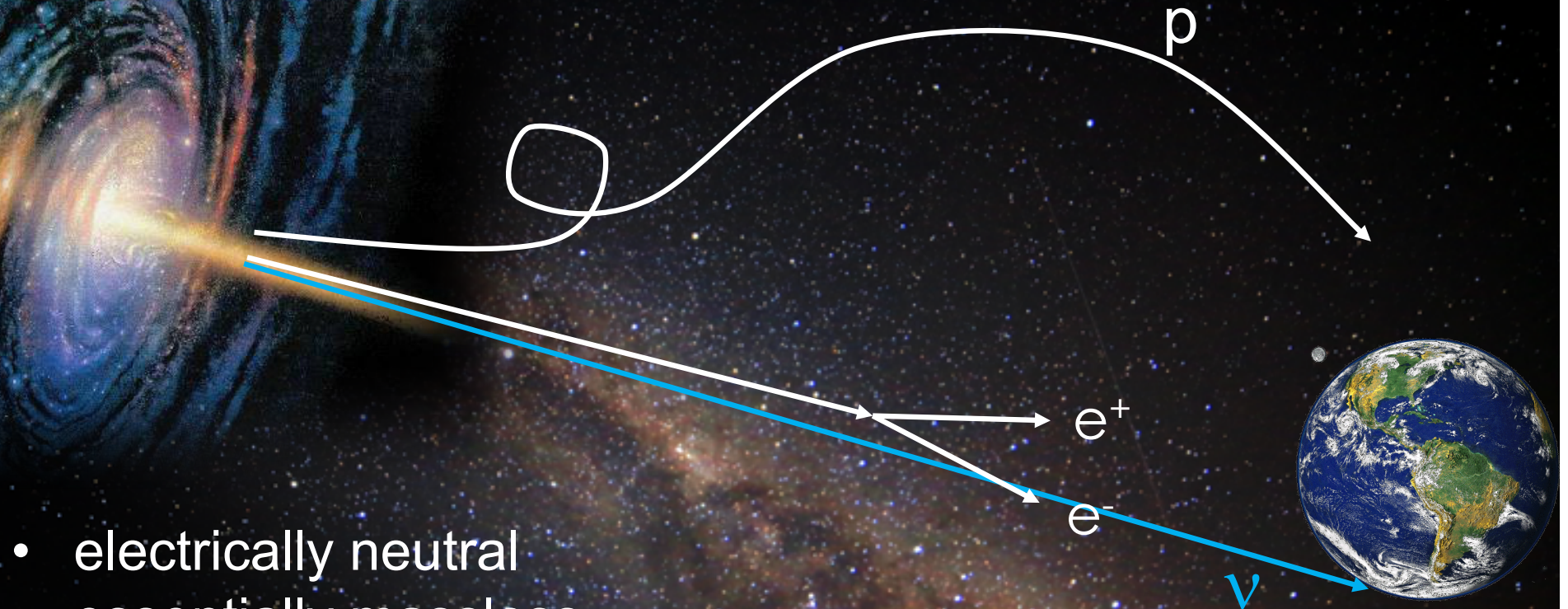
- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

# The opaque Universe



photons interact with microwave photons  
before reaching our telescopes

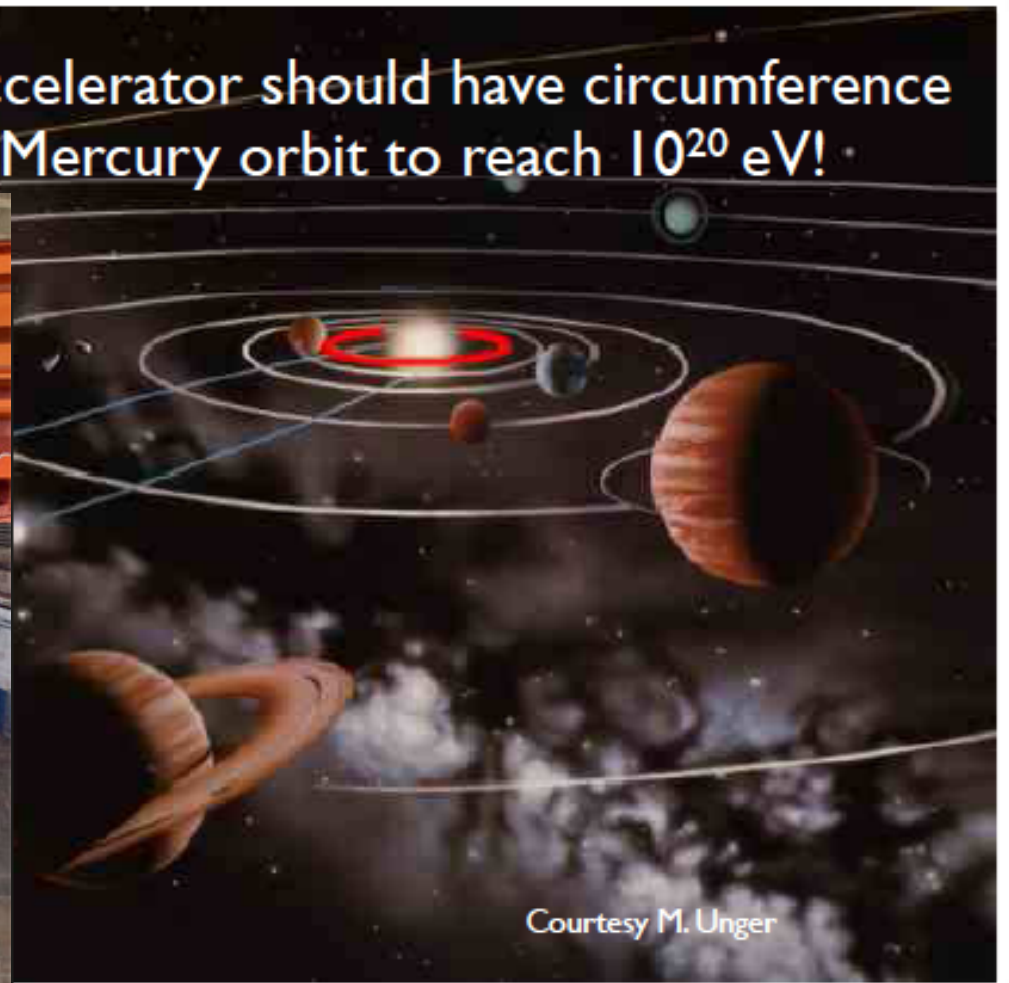
# Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays after 10<sup>5</sup> years
- ... but difficult to detect

- energy  $\sim$  [magnetic field  $B$ ] x [accelerator's size  $R$ ]

LHC accelerator should have circumference of Mercury orbit to reach  $10^{20}$  eV!



- luminosity  $\sim$  a few percent of gravitational energy of...

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

timing/localization  
from satellites



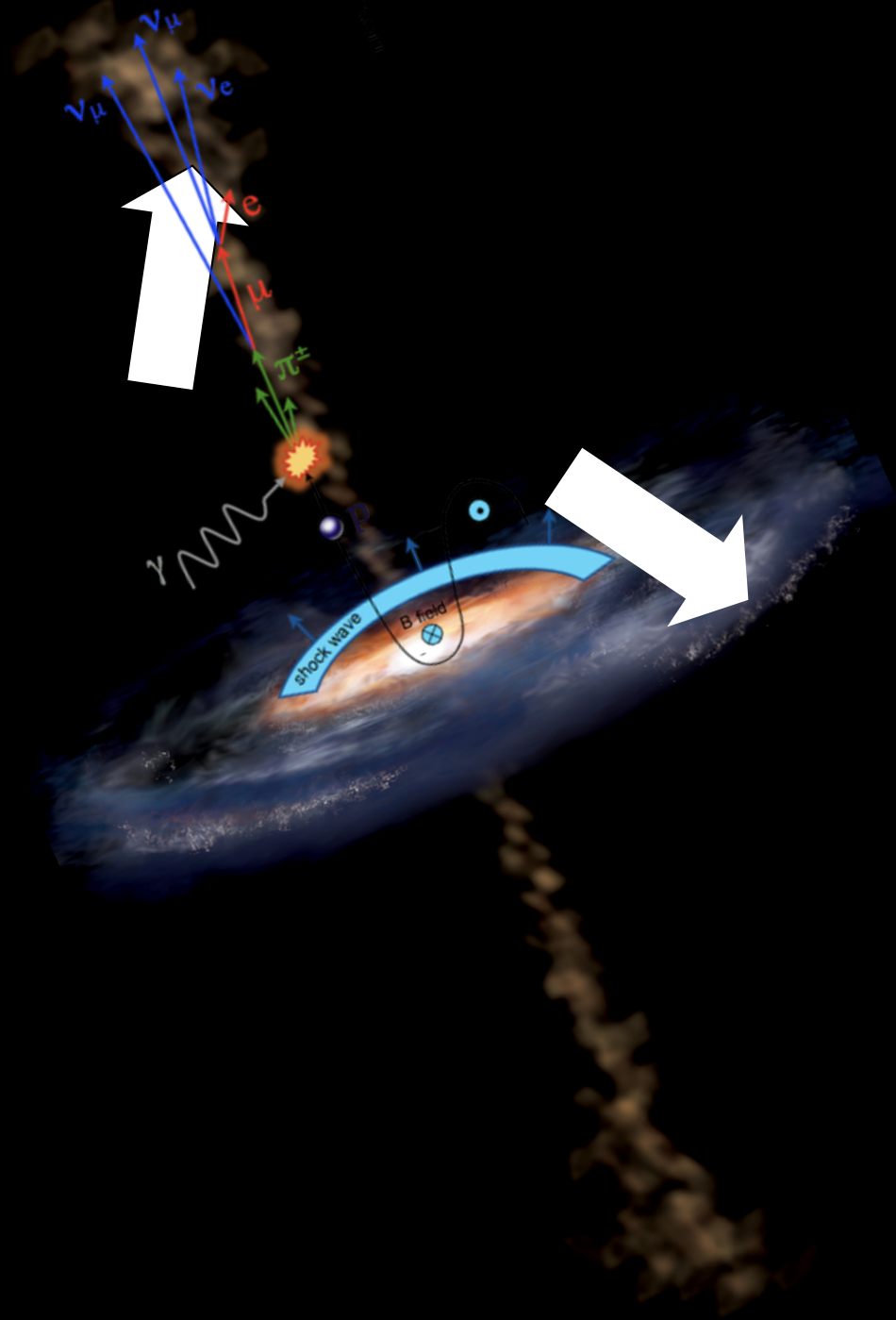
timing + direction  
→ low background



$\gamma$

$\nu$

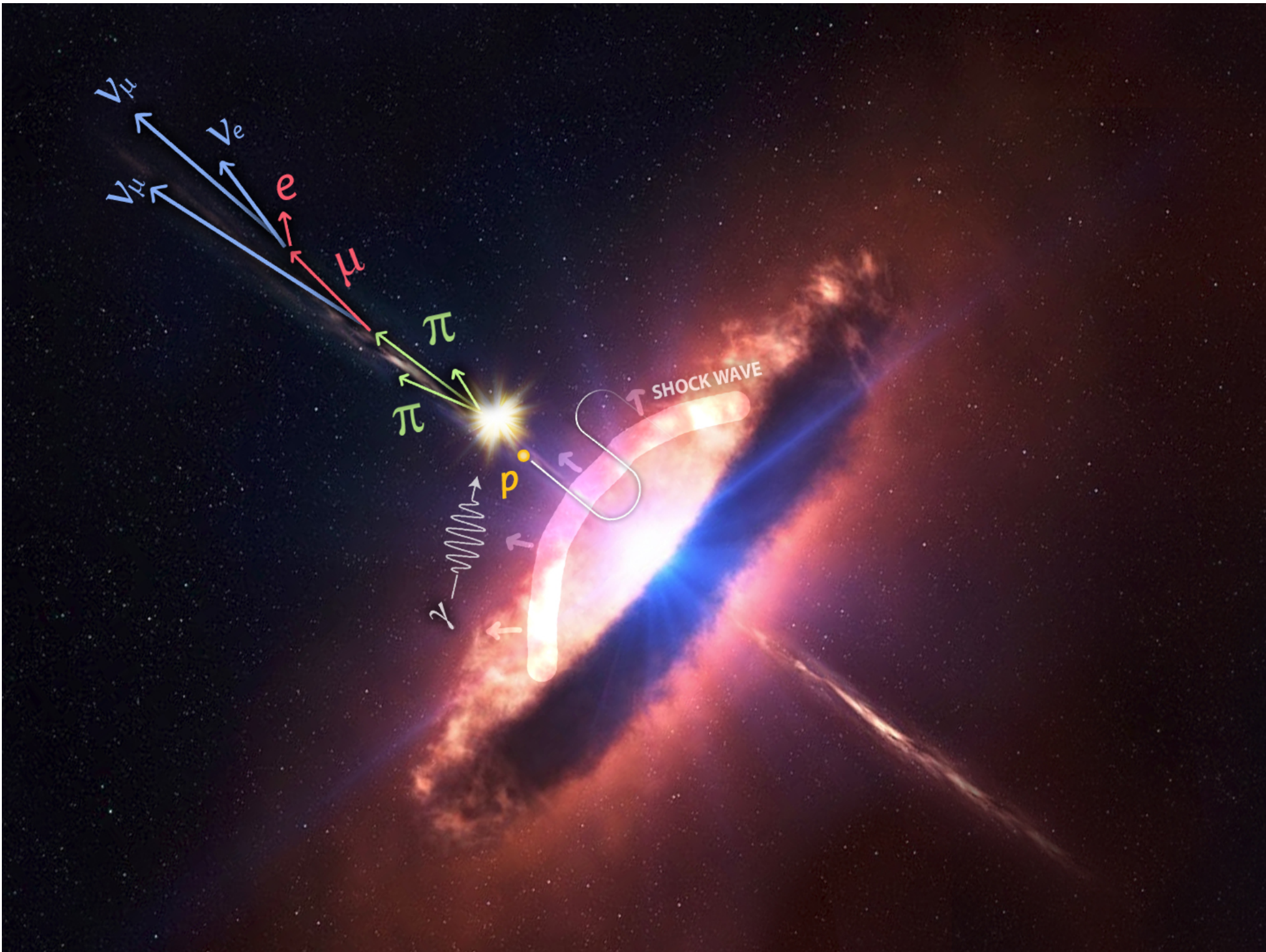




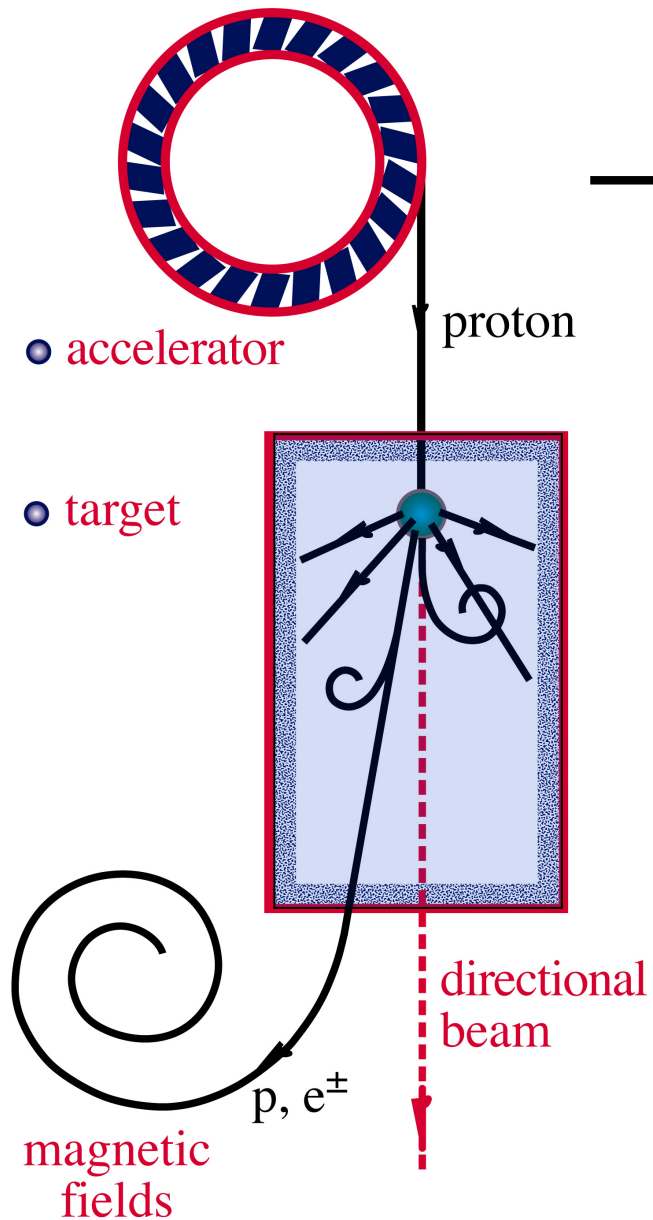
active galaxy

particle flows near  
supermassive  
black hole





# $\nu$ and $\gamma$ beams : heaven and earth



accelerator is powered by large gravitational energy

**black hole  
neutron star**

**radiation  
and dust**

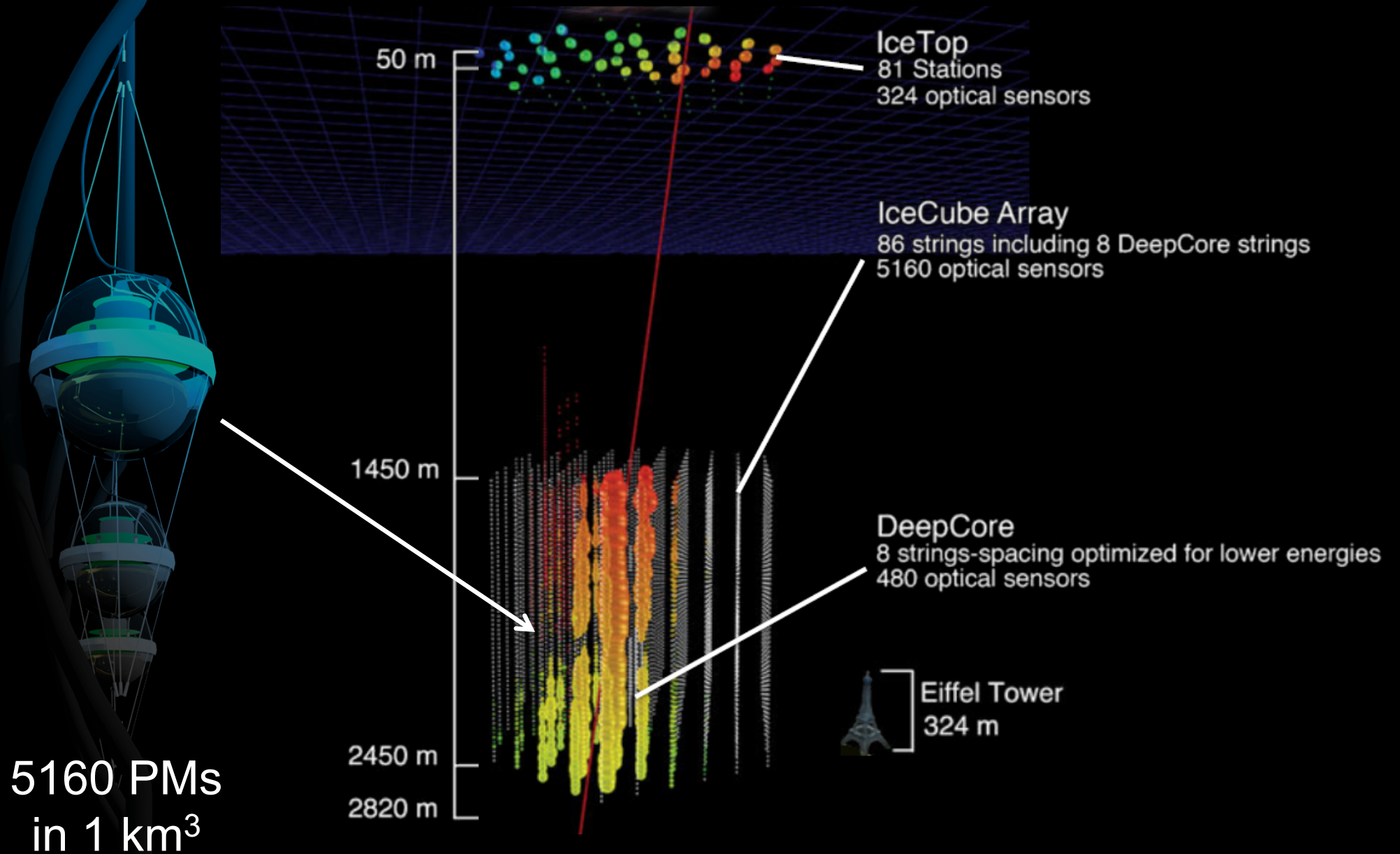


$\sim$  cosmic ray + neutrino



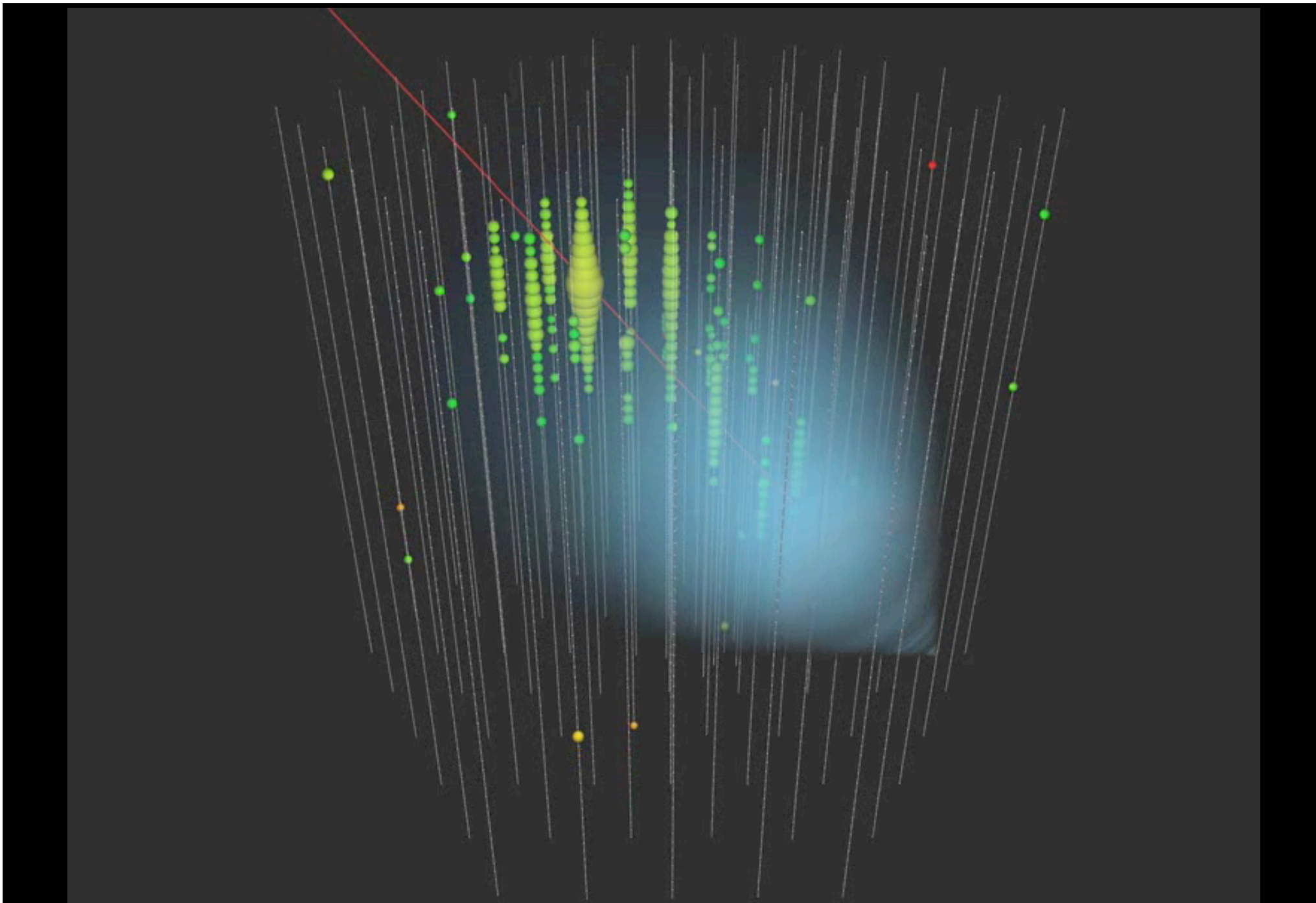
$\sim$  cosmic ray + gamma

# IceCube

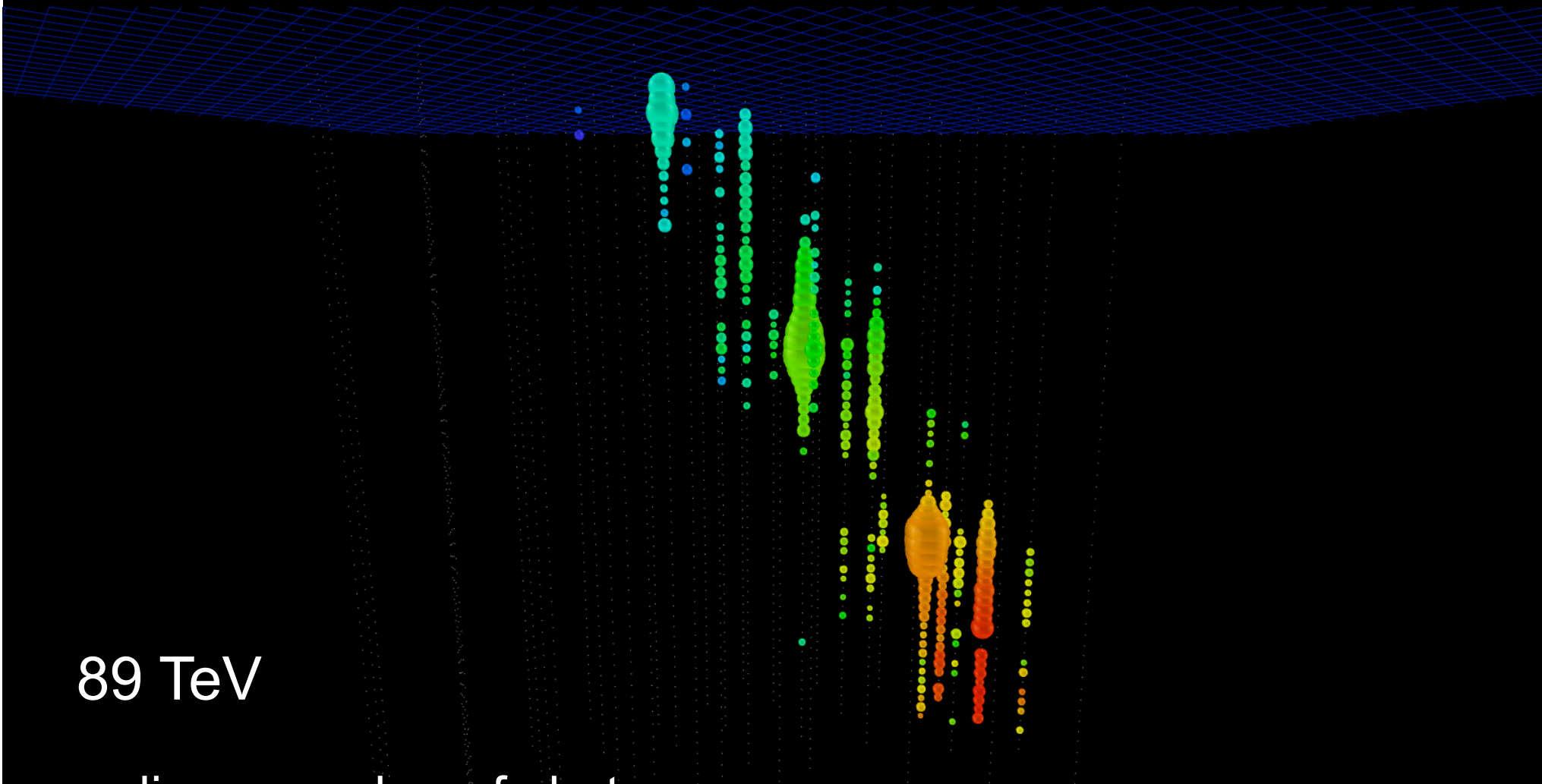


photomultiplier  
tube -10 inch





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

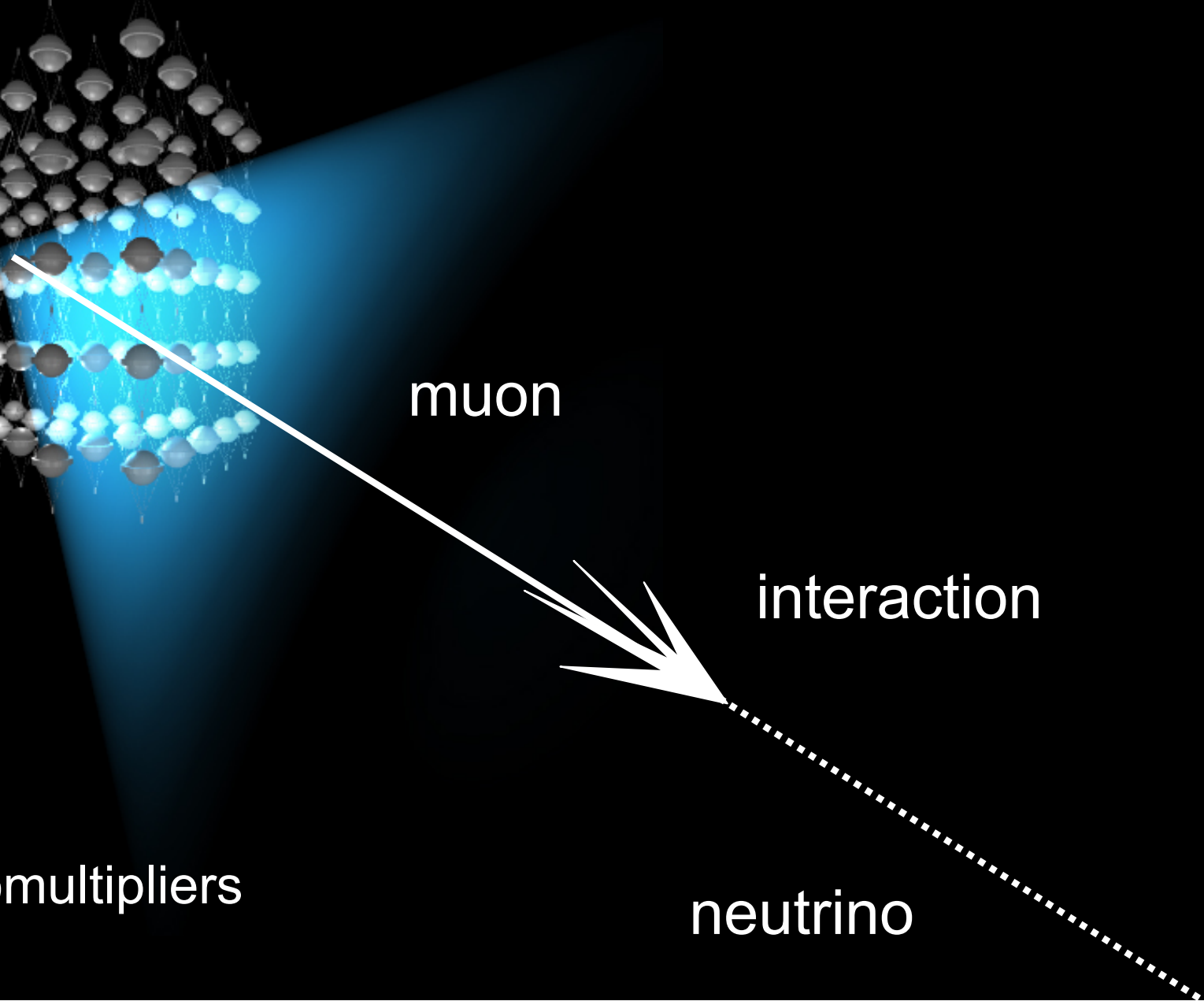
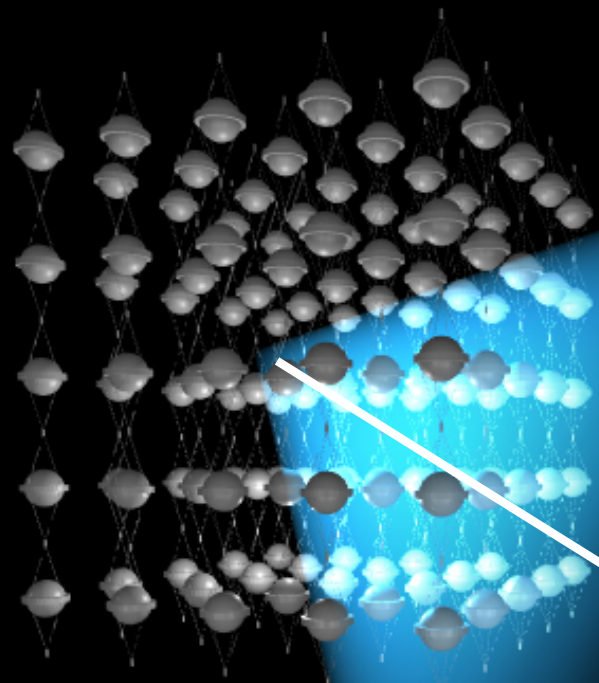


89 TeV

radius ~ number of photons

time ~ red → purple 

Run 113641 Event 33553254 [0ns, 16748ns]



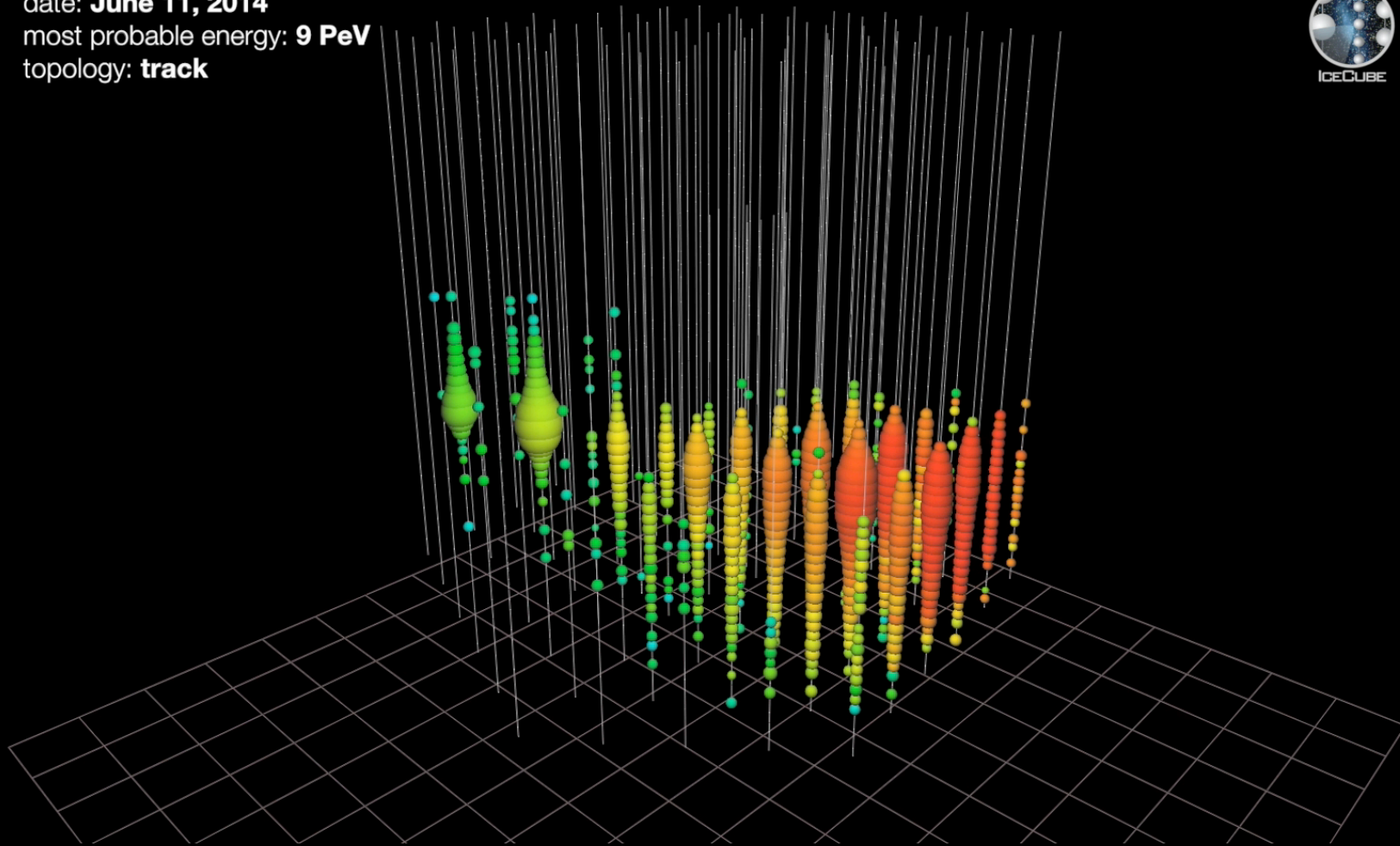
muon

interaction

• lattice of photomultipliers

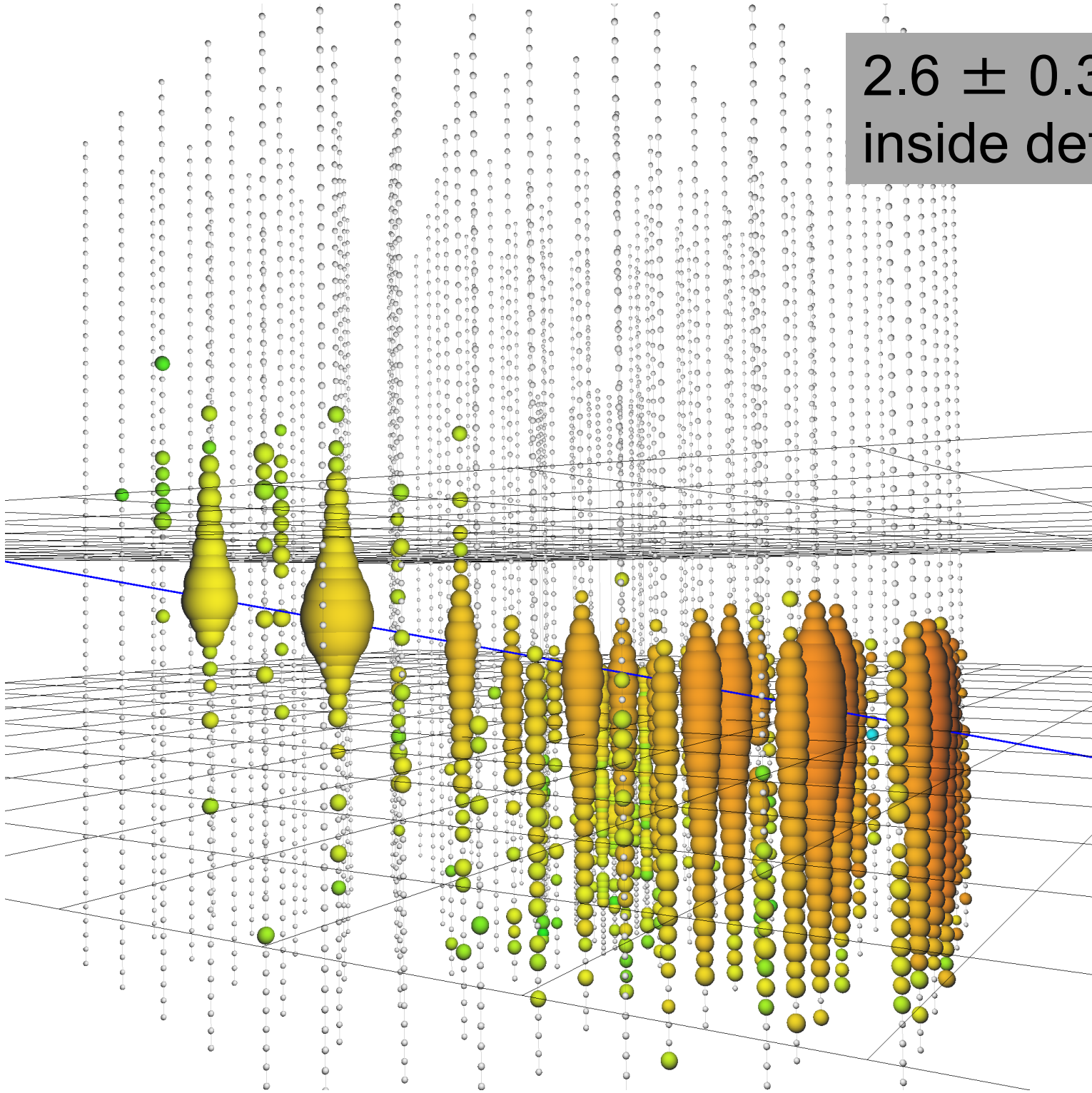
neutrino

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





$2.6 \pm 0.3$  PeV  
inside detector



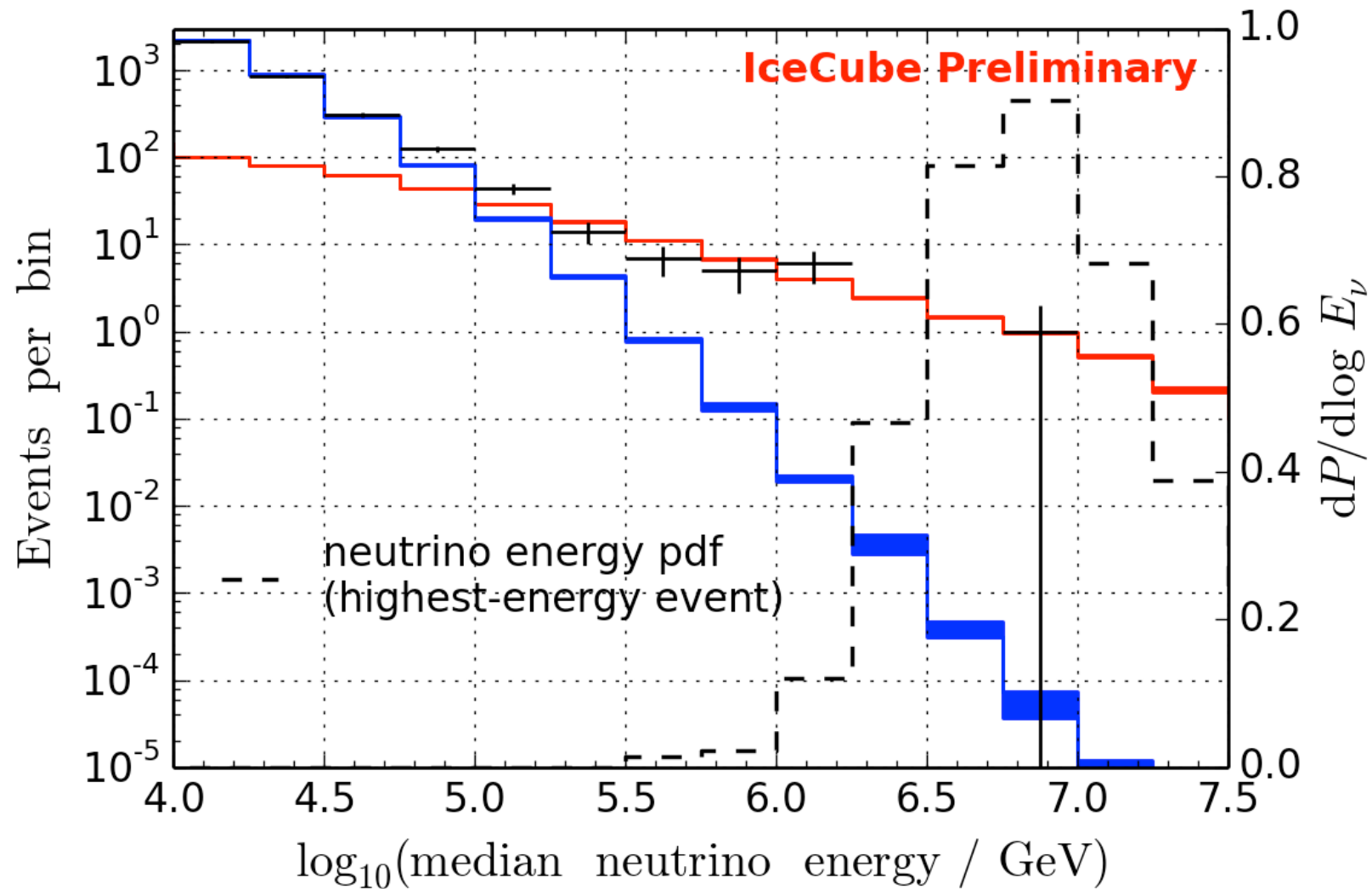
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric  
atmospheric background: less than one event/deg<sup>2</sup>/year

Assuming best-fit power law:

+++ Unfolding

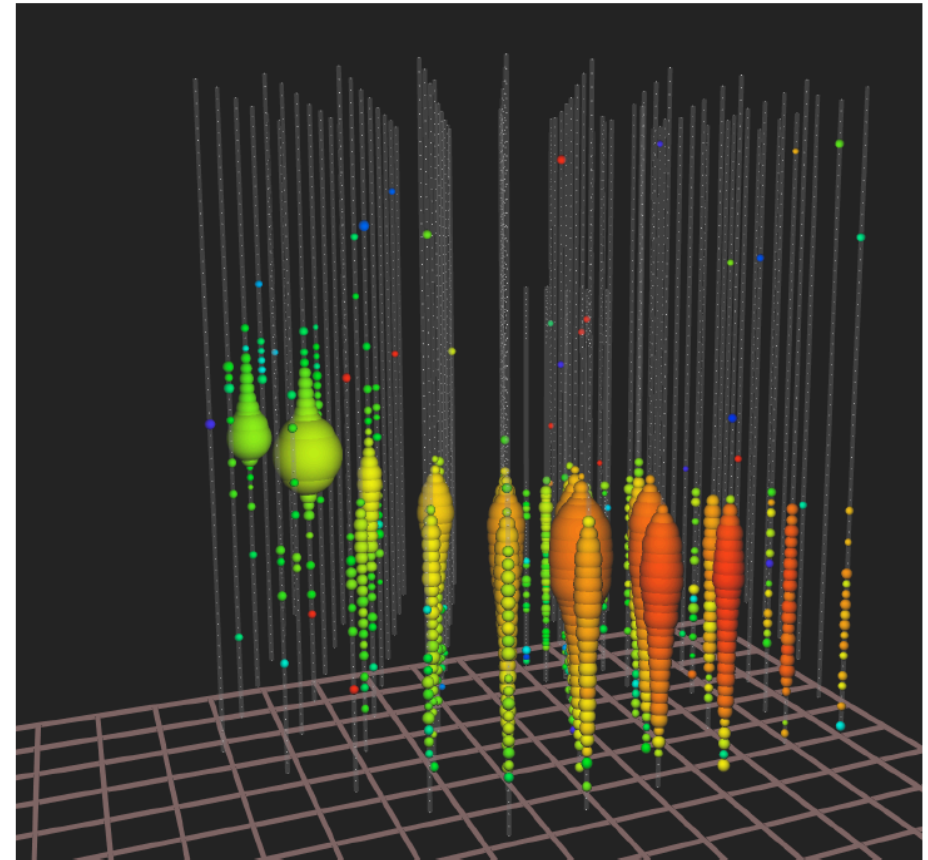
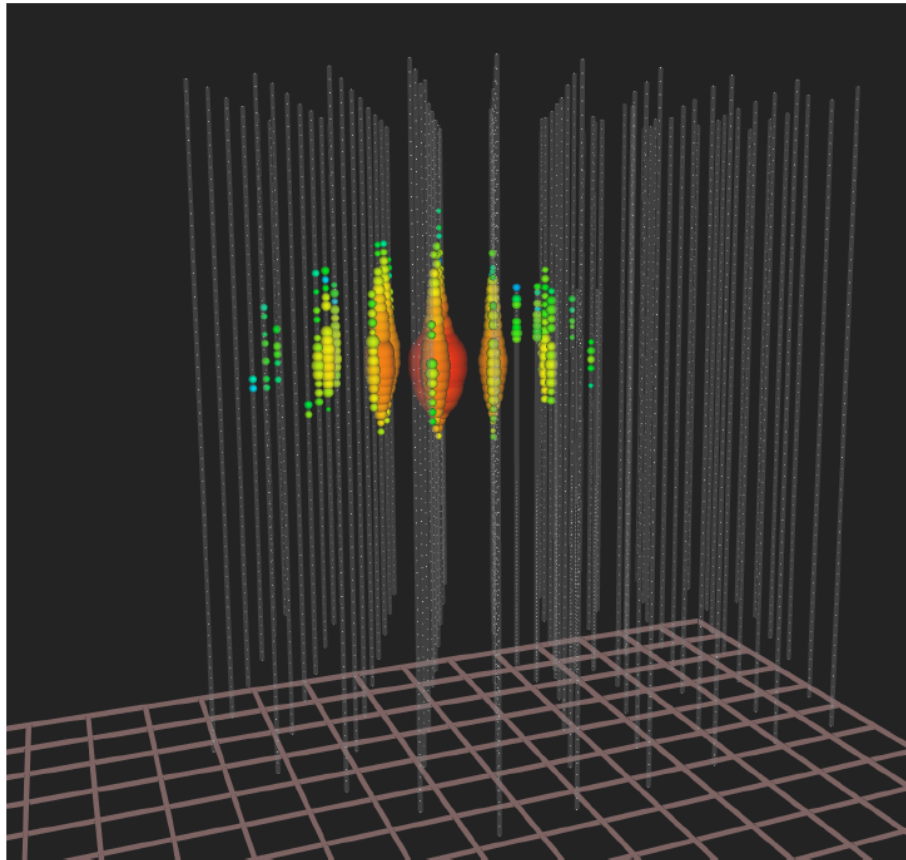
■ Conv. atmospheric  $\nu_\mu + \bar{\nu}_\mu$

■ Astrophysical  $\nu_\mu + \bar{\nu}_\mu$



*isolated* neutrinos interacting  
*inside* the detector (HESE)

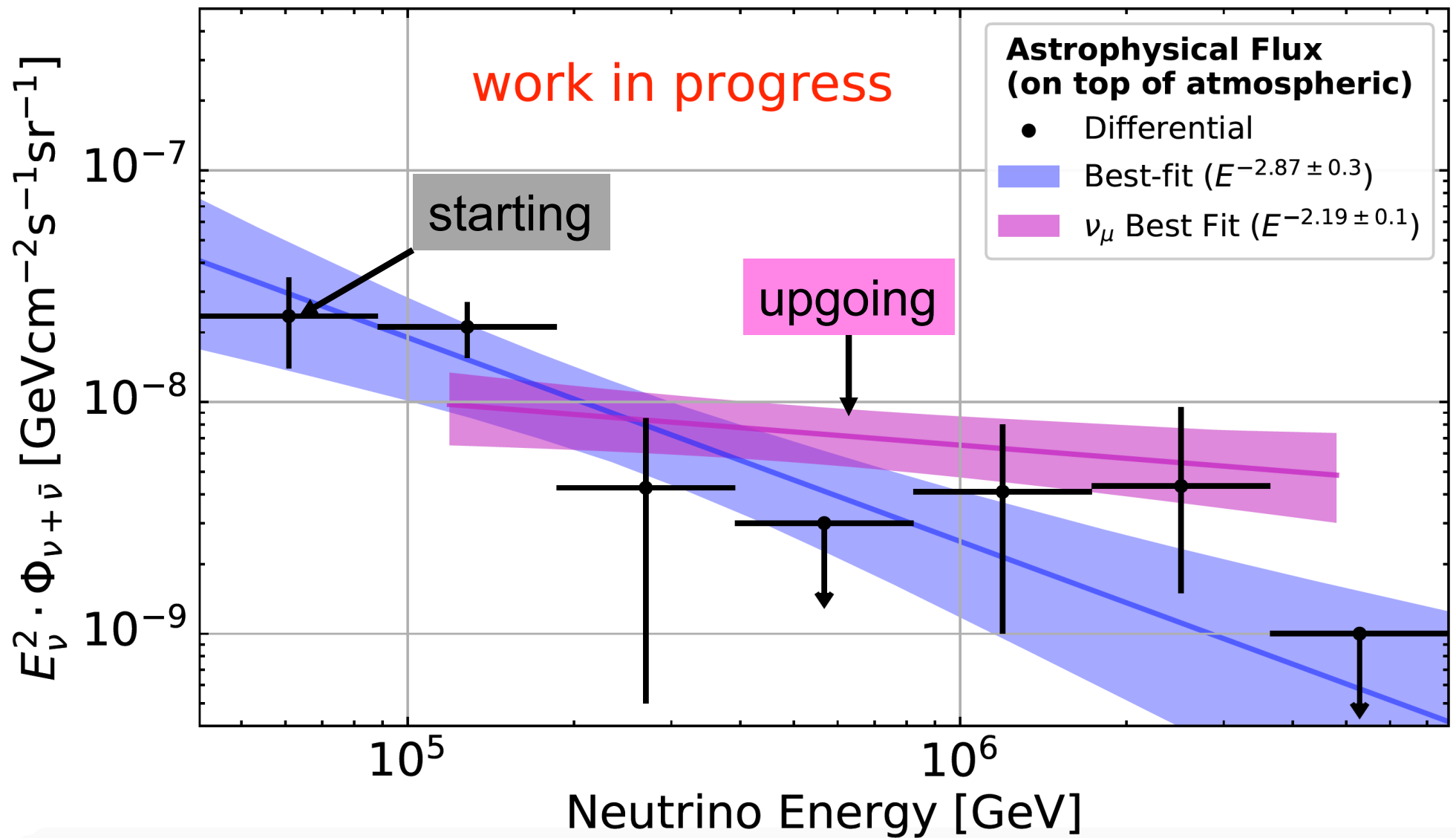
up-going muon tracks  
(UPMU)



total energy measurement  
all flavors, all sky

astronomy: angular resolution  
superior ( $<0.5^\circ$ )

# high-energy starting events – 7.5 yr

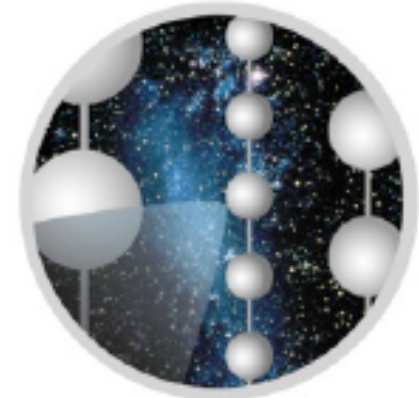


two methods are consistent

# Multimessenger Astronomy

francis halzen

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



ICECUBE

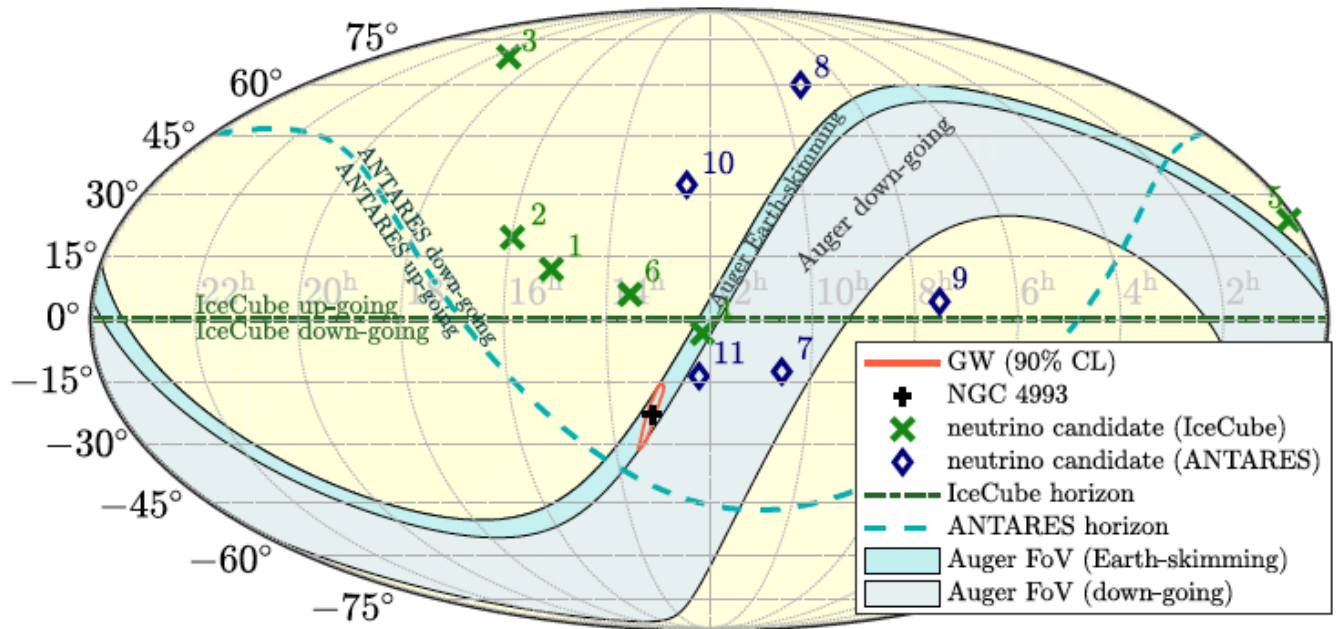


[icecube.wisc.edu](http://icecube.wisc.edu)

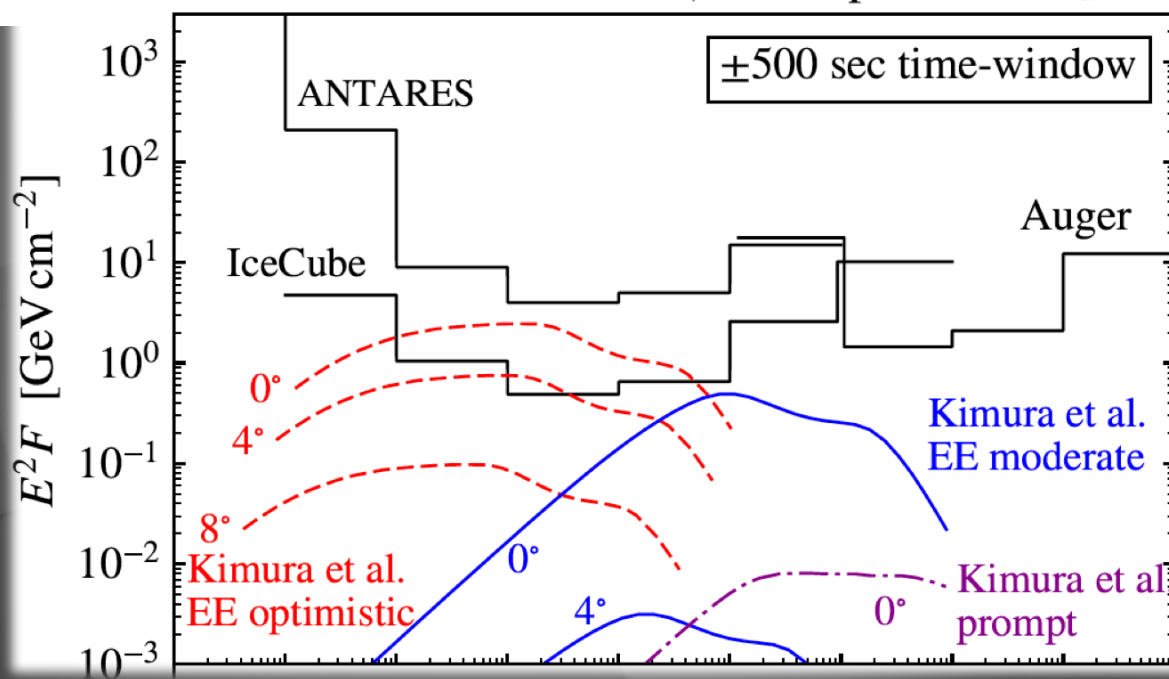
# neutron star-neutron star merger



LIGO-VIRGO



GW170817 Neutrino limits (fluence per flavor:  $\nu_x + \bar{\nu}_x$ )

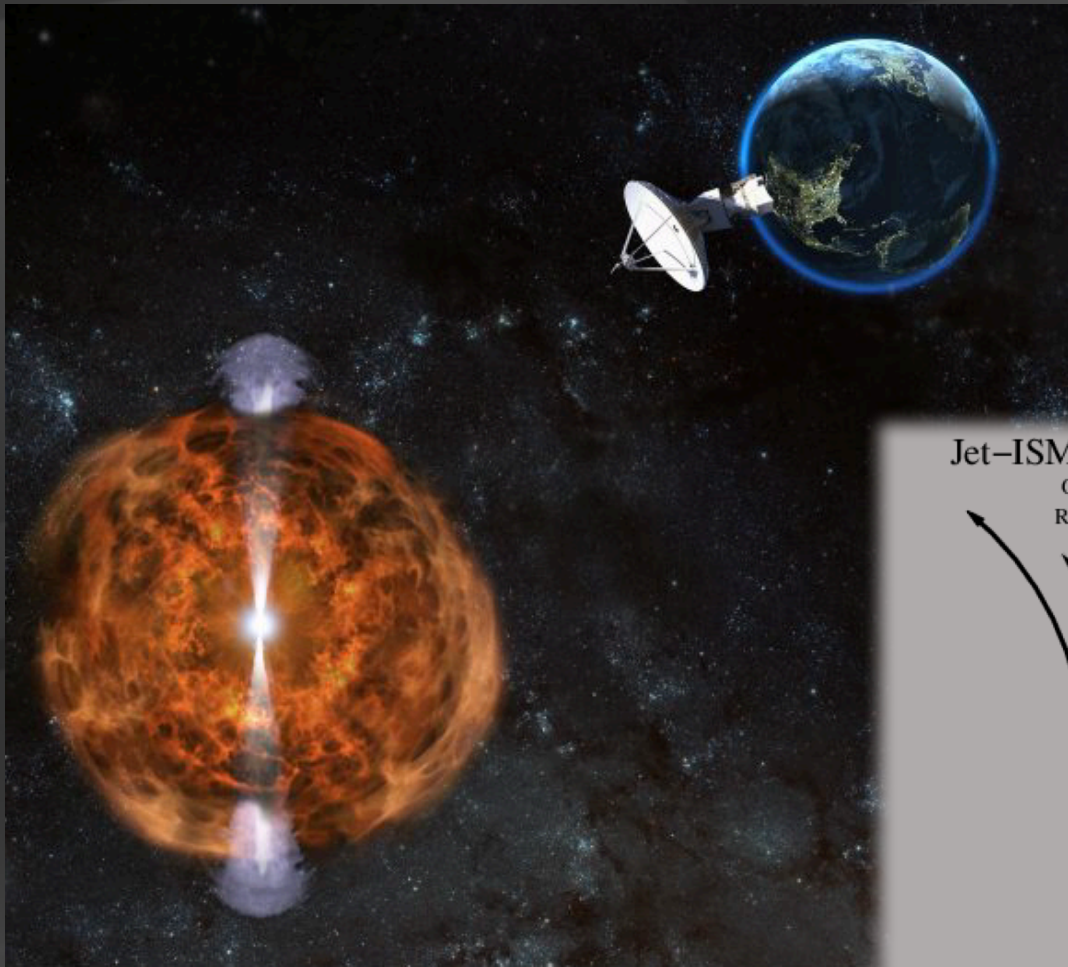




Rosswog and Ramirez-Ruiz

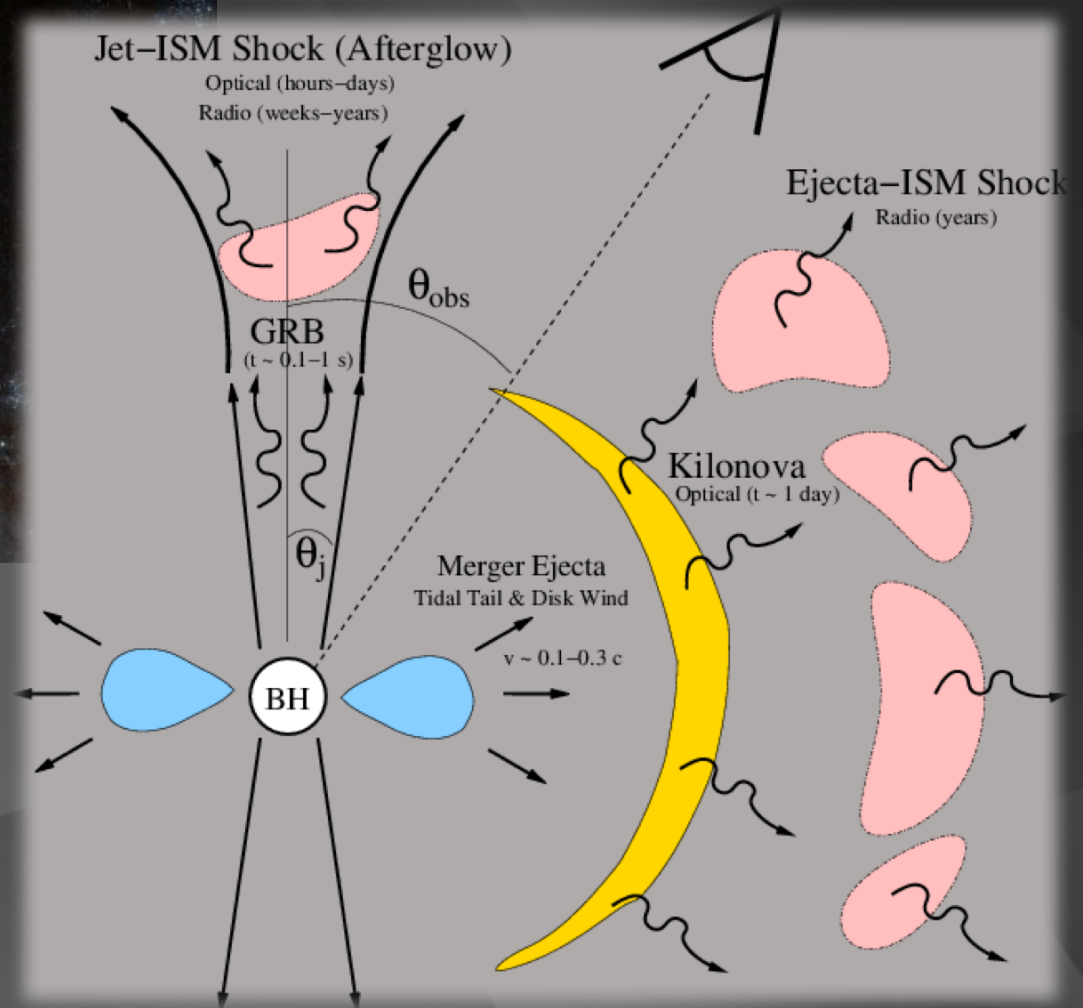
buildup of magnetic fields near merger launches jet

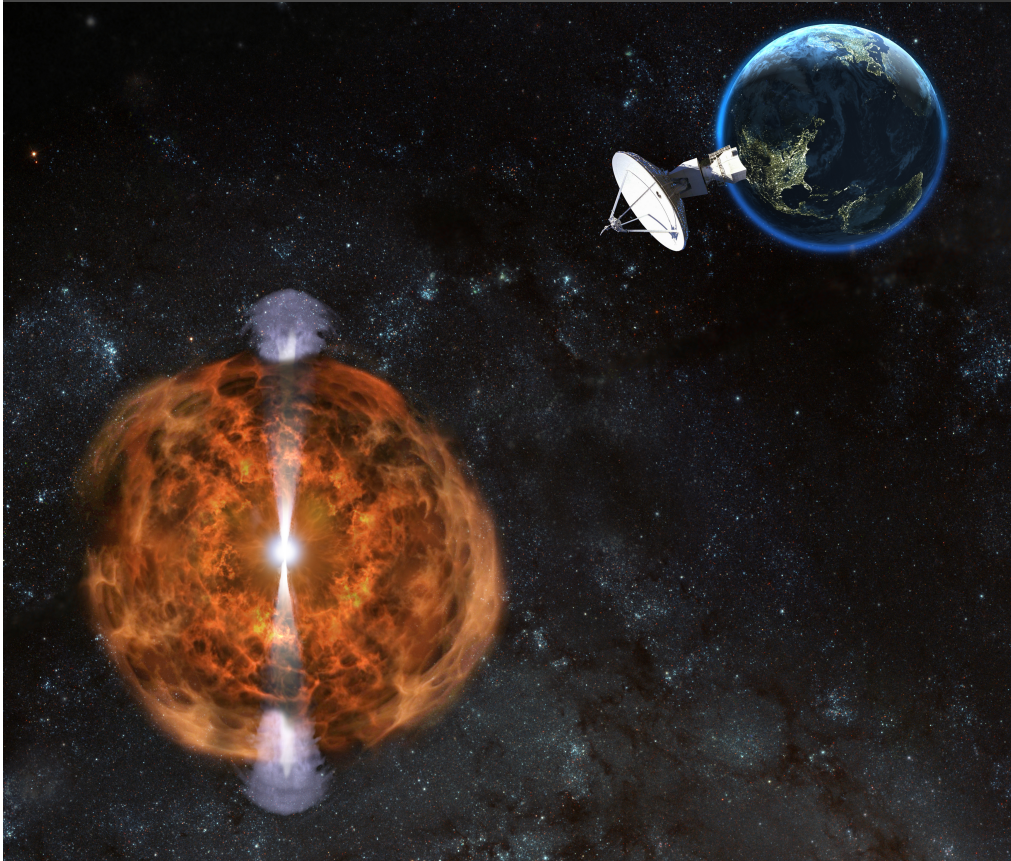




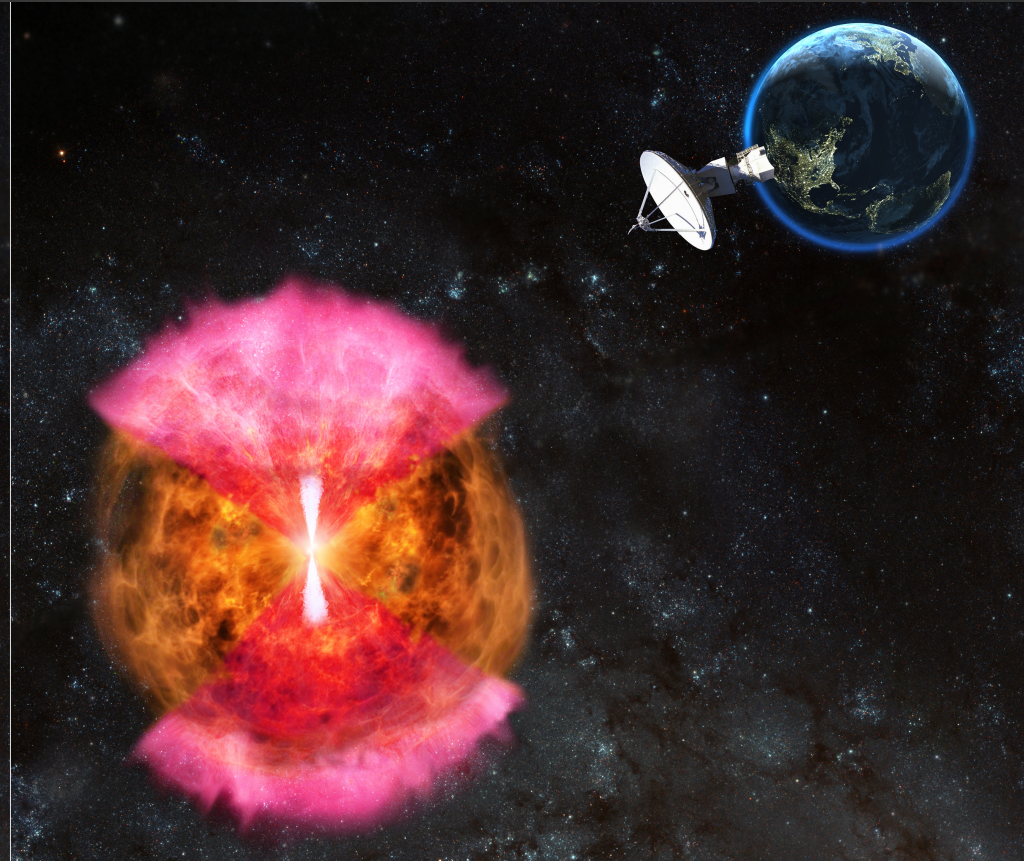
very weak short GRB  
seen by Fermi  
(off axis?)

- MeV neutrino emission:
- $\sim 0.01 M_{\text{sun}}$  material ejected
  - $\sim$  supernova

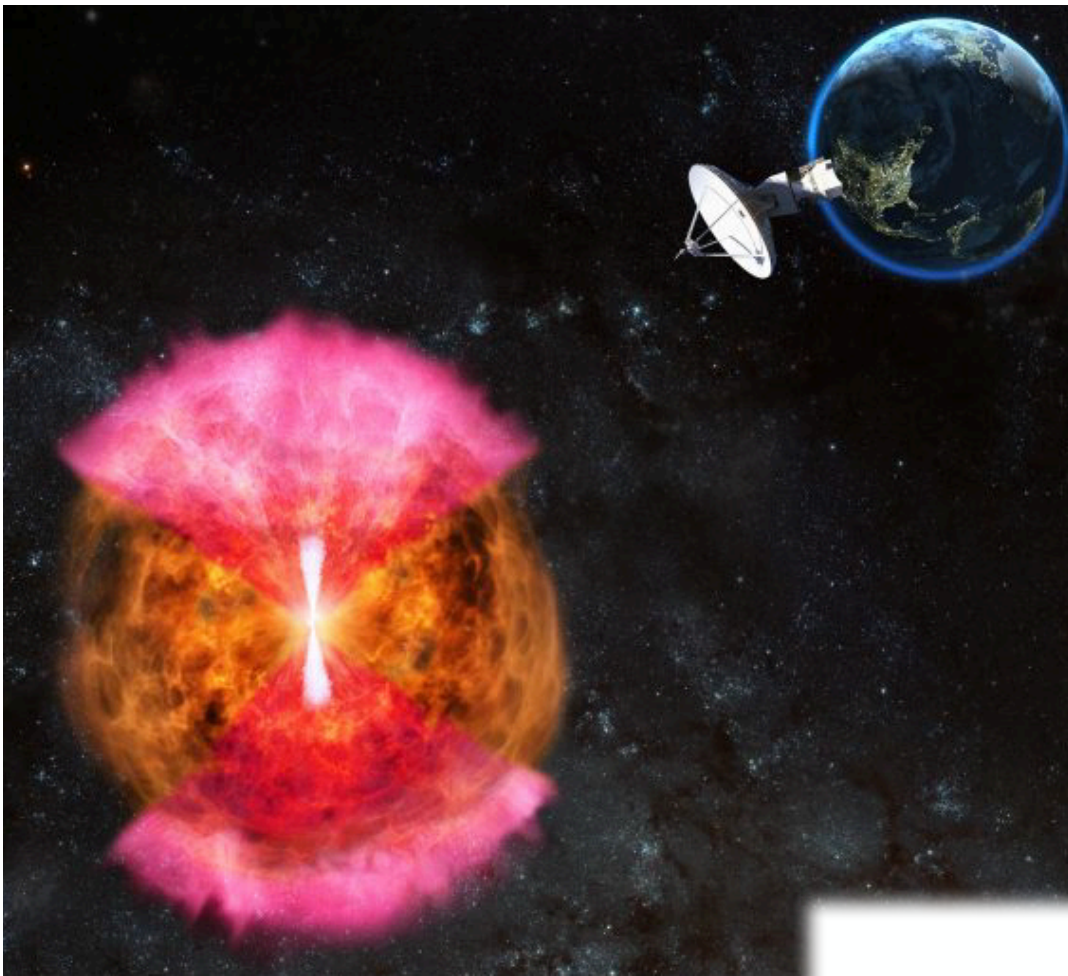




off-axis jet



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

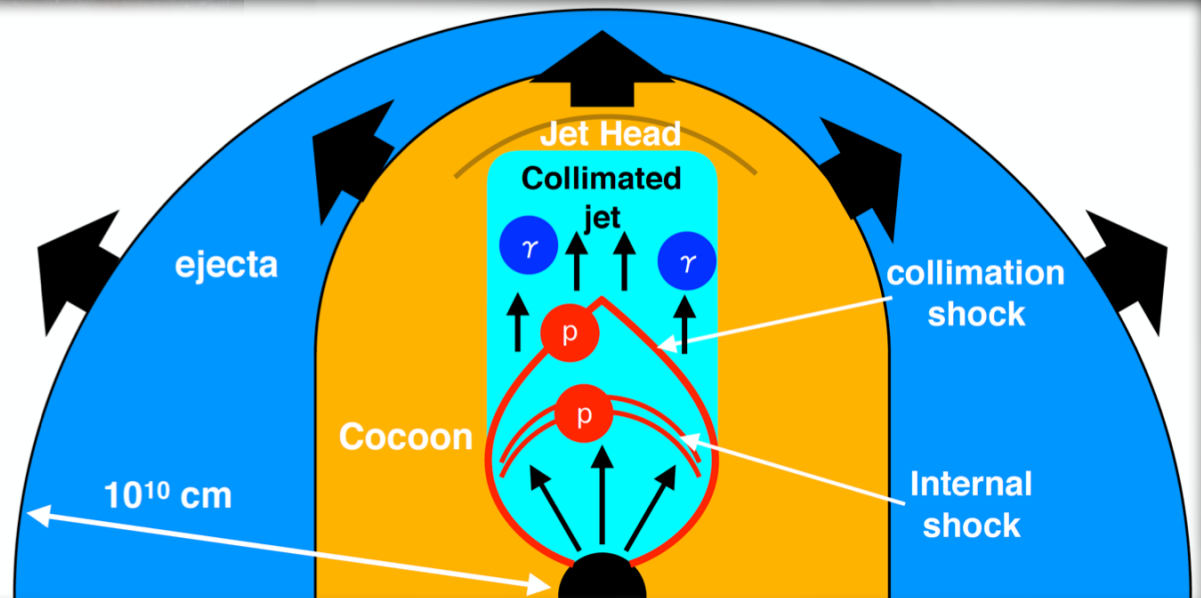


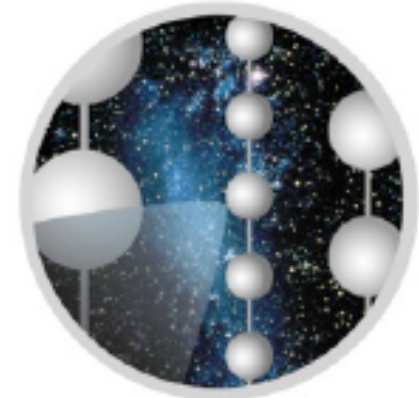
TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

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	$9.7 \times 10^{-3}$	0.52
B	$6.2 \times 10^{-3}$	$4.2 \times 10^{-4}$	0.027
GW+neutrino detection rate [ $\text{yr}^{-1}$ ]			
model	IceCube		Gen2
A	1.1		2.6
B	0.076		0.28

# Multimessenger Astronomy

francis halzen

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

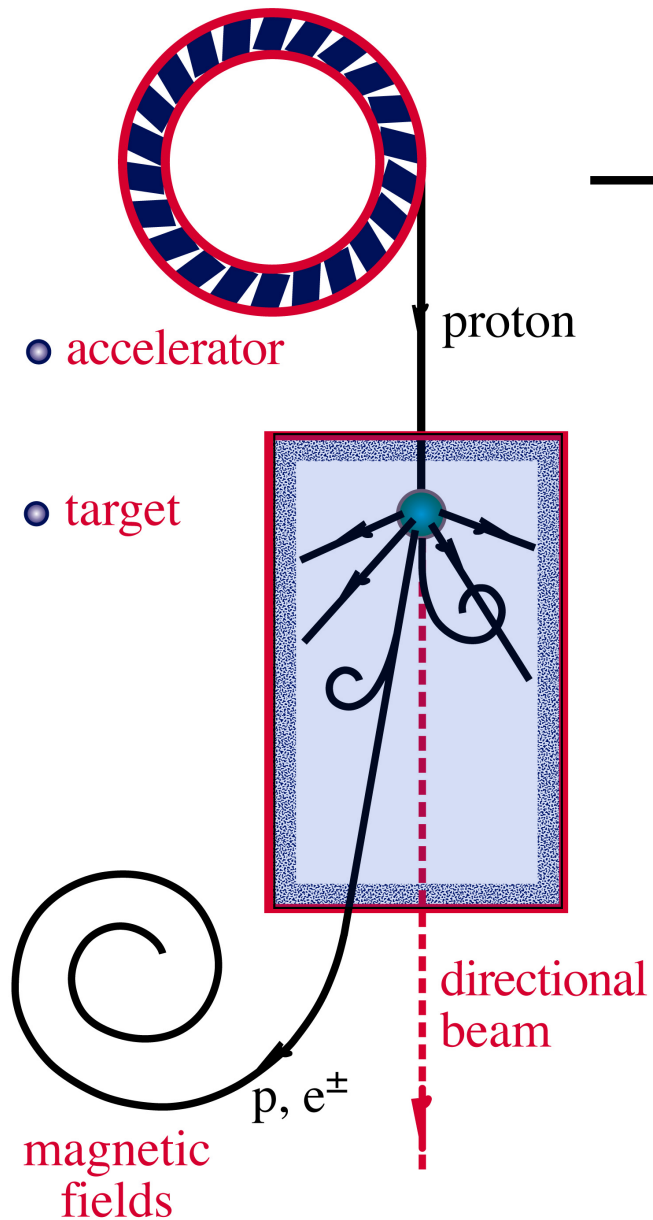


ICECUBE



[icecube.wisc.edu](http://icecube.wisc.edu)

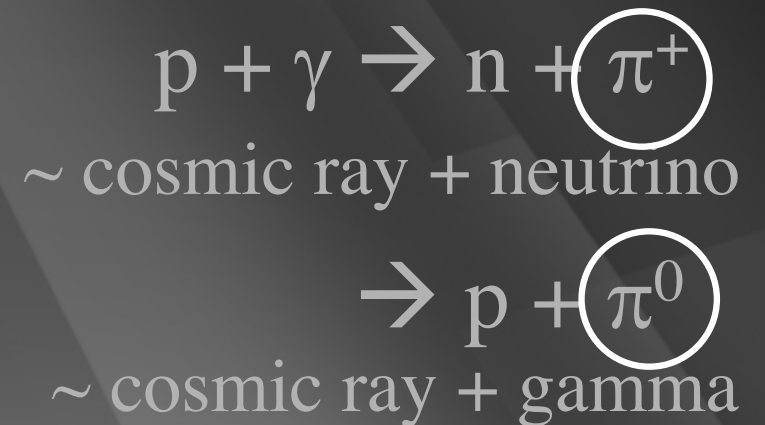
# $\nu$ and $\gamma$ beams : heaven and earth

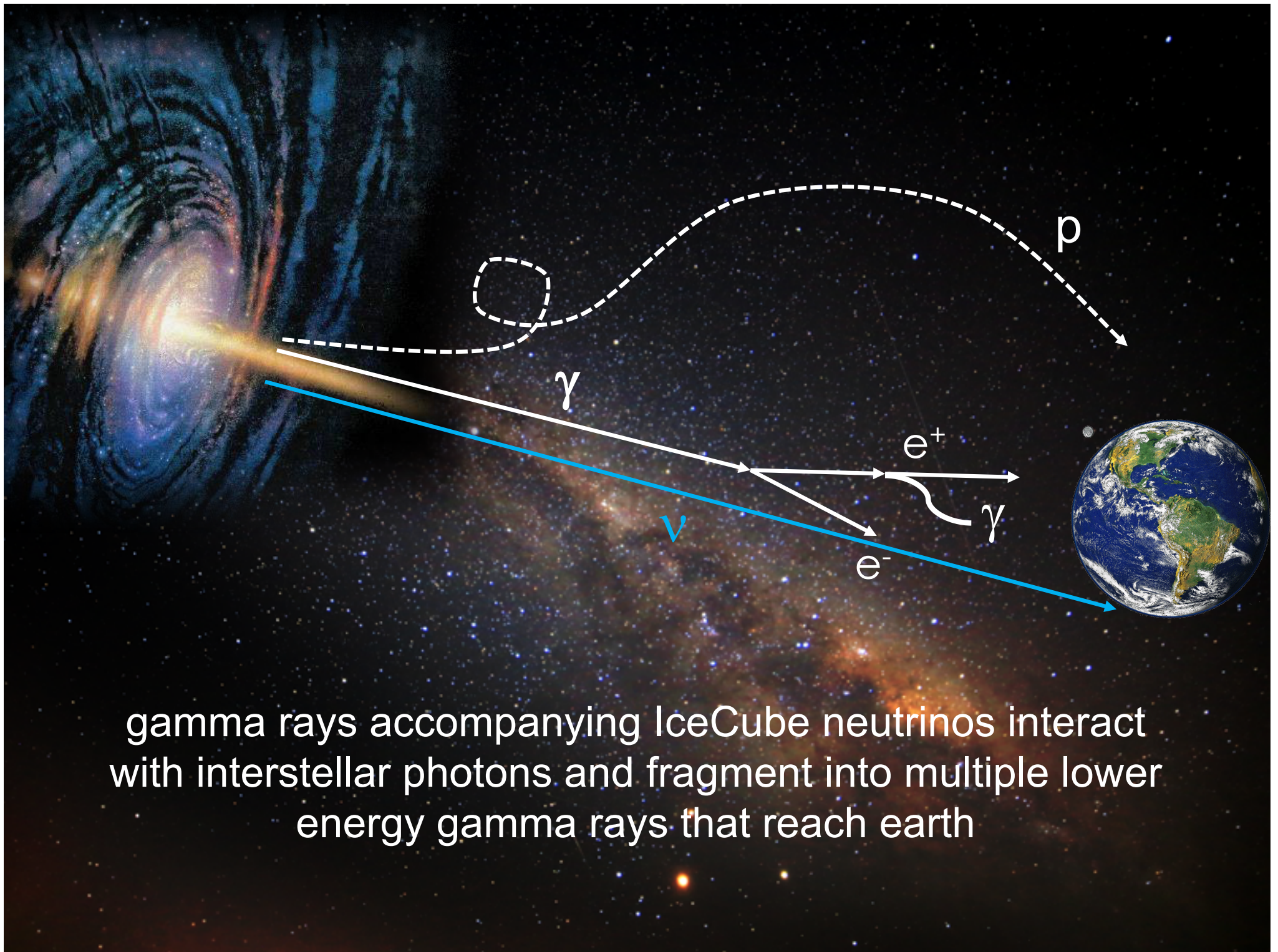


accelerator is powered by large gravitational energy

**black hole  
neutron star**

**radiation  
and dust**





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

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

$\gamma$

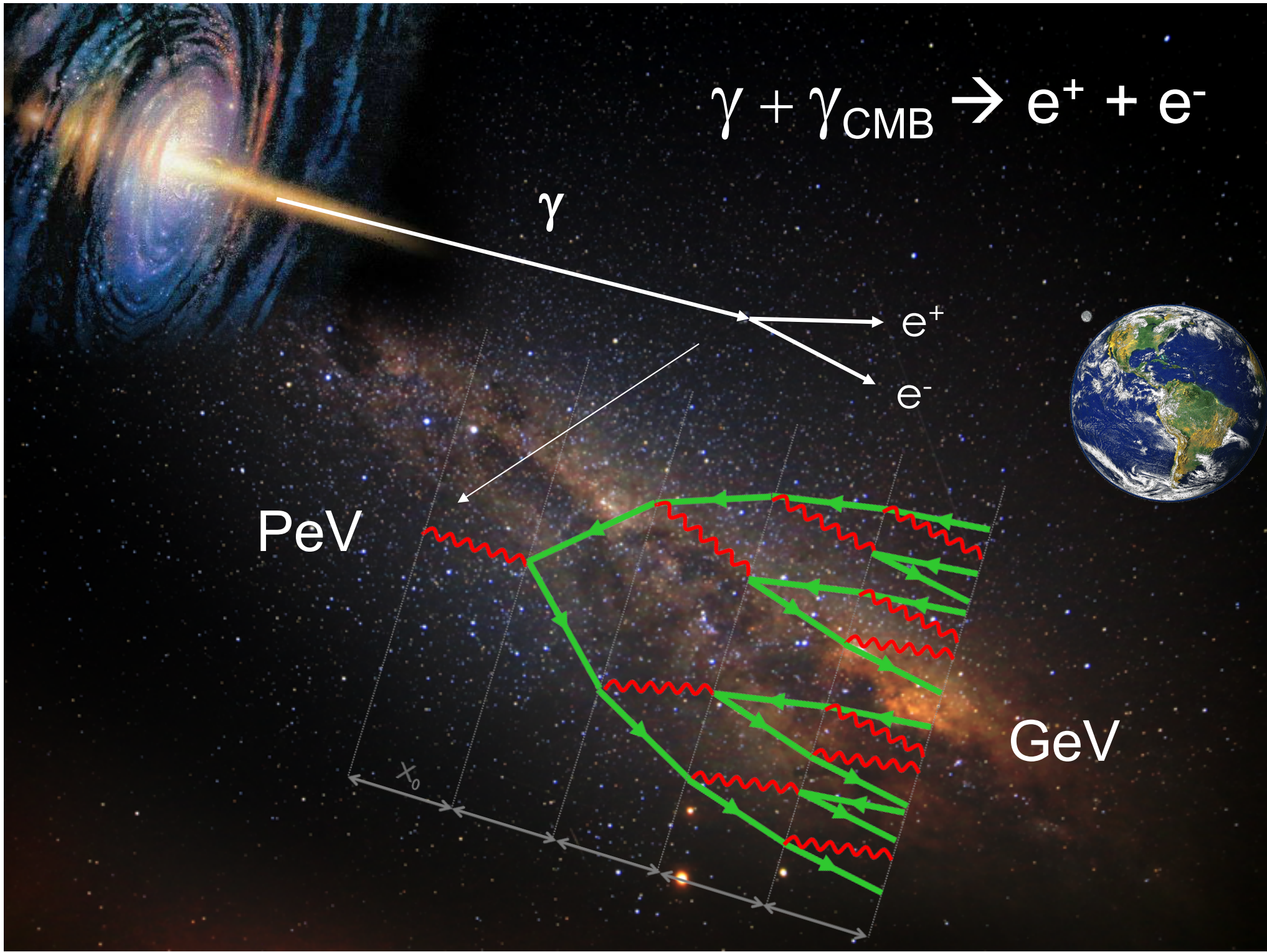
$e^+$

$e^-$

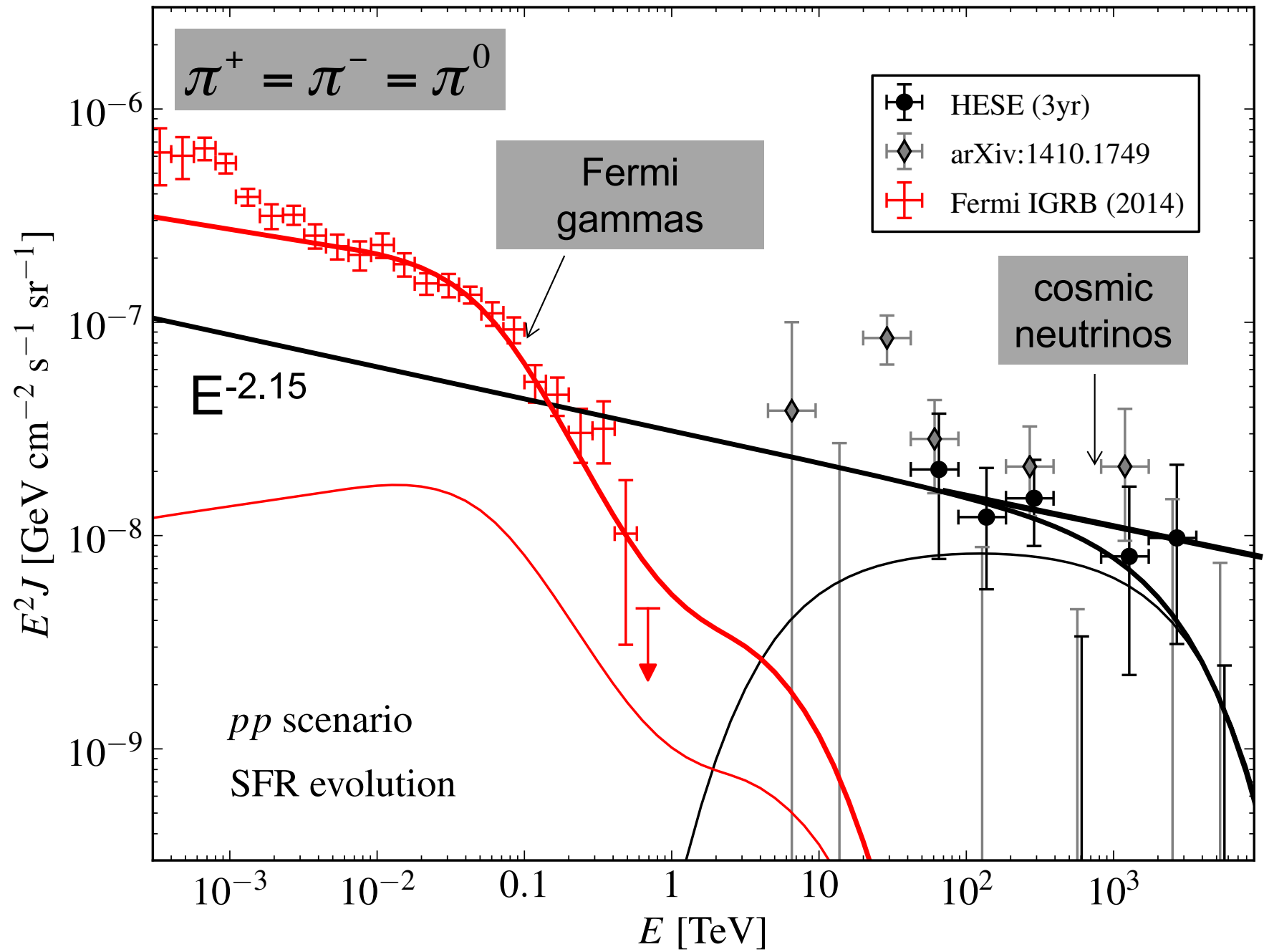
PeV

GeV

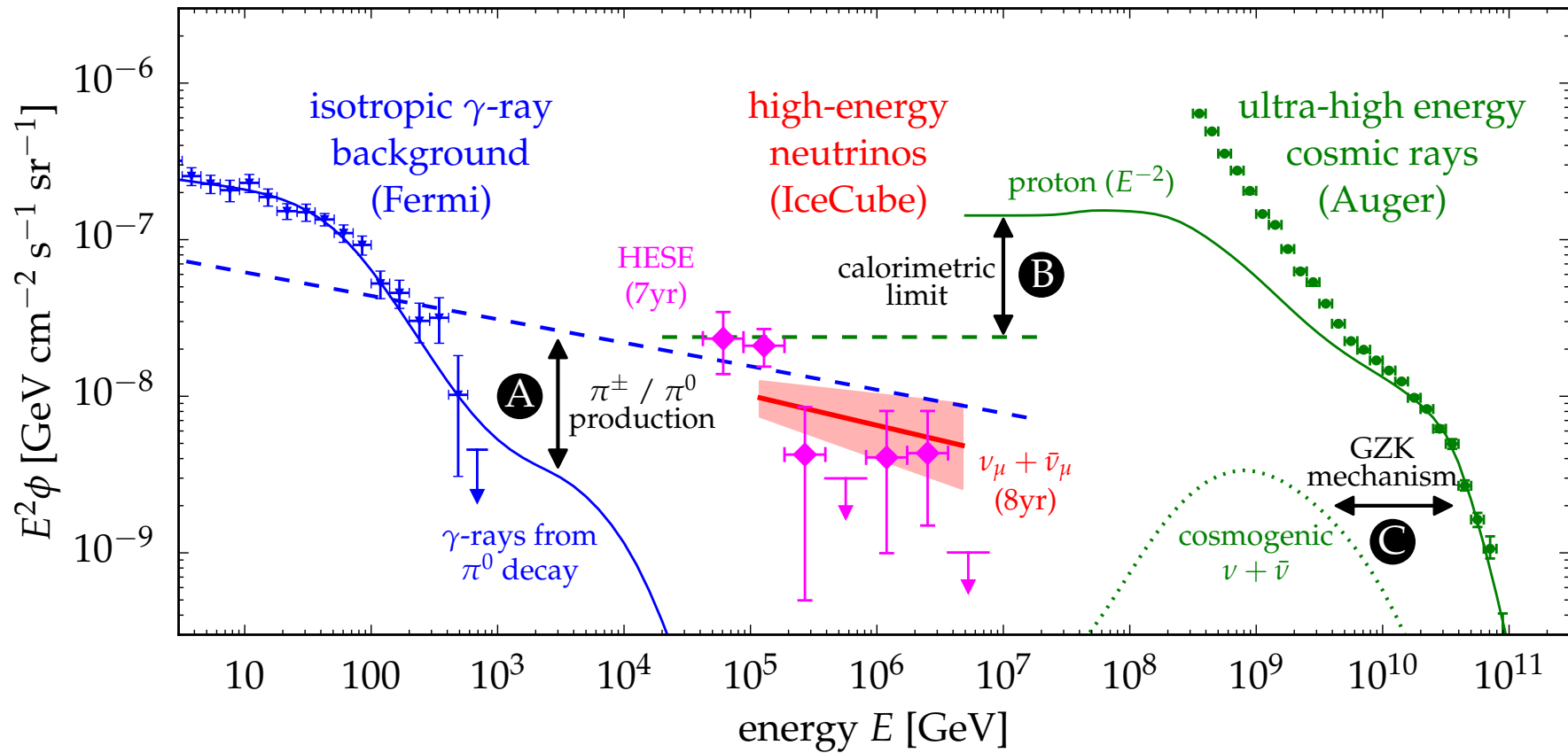
$x_0$



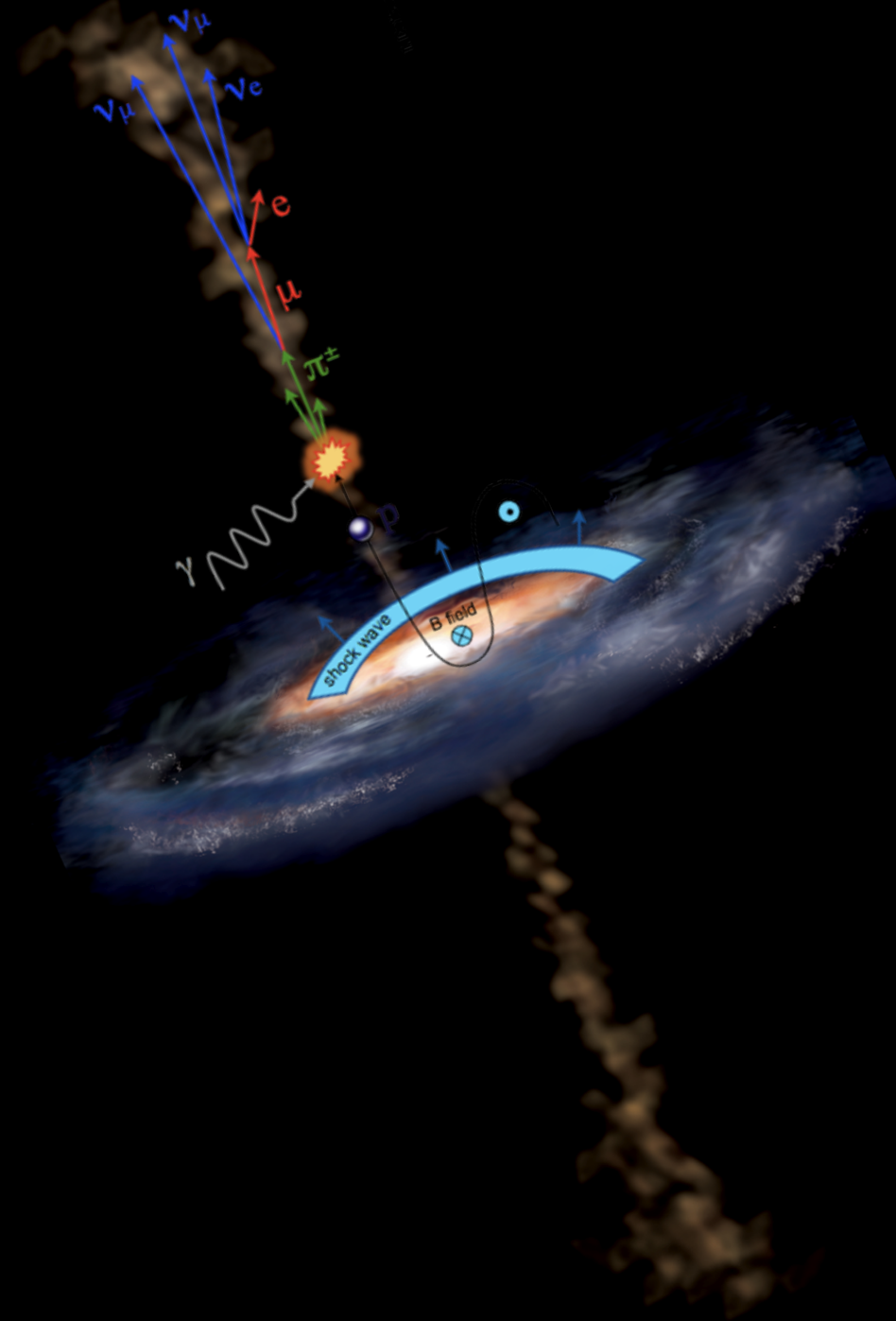




- energy density of neutrinos in the non-thermal Universe is similar as that in gamma-rays



similar energy density in the Universe in extragalactic cosmic rays

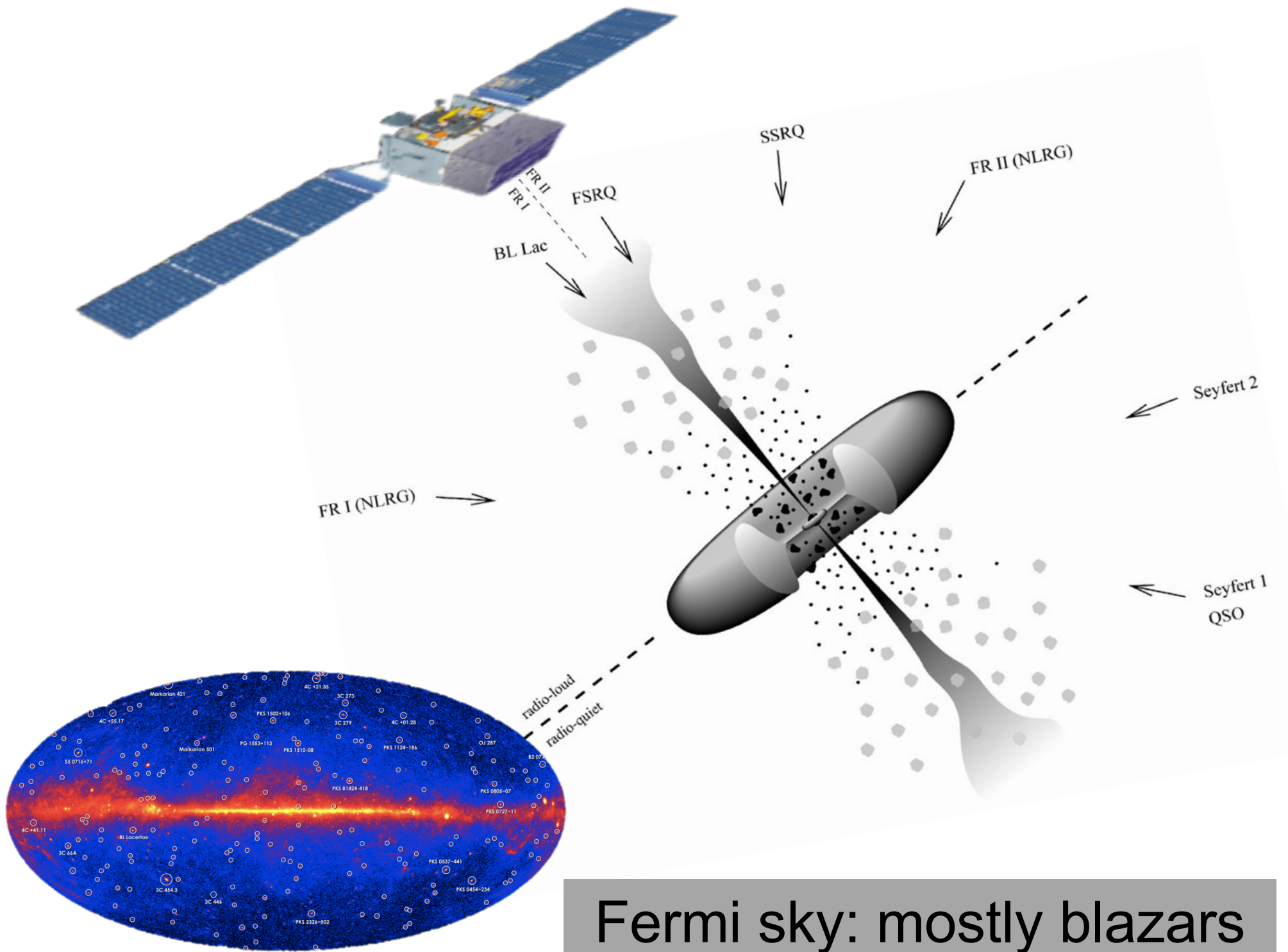


Fermi sources  
are mostly  
blazars

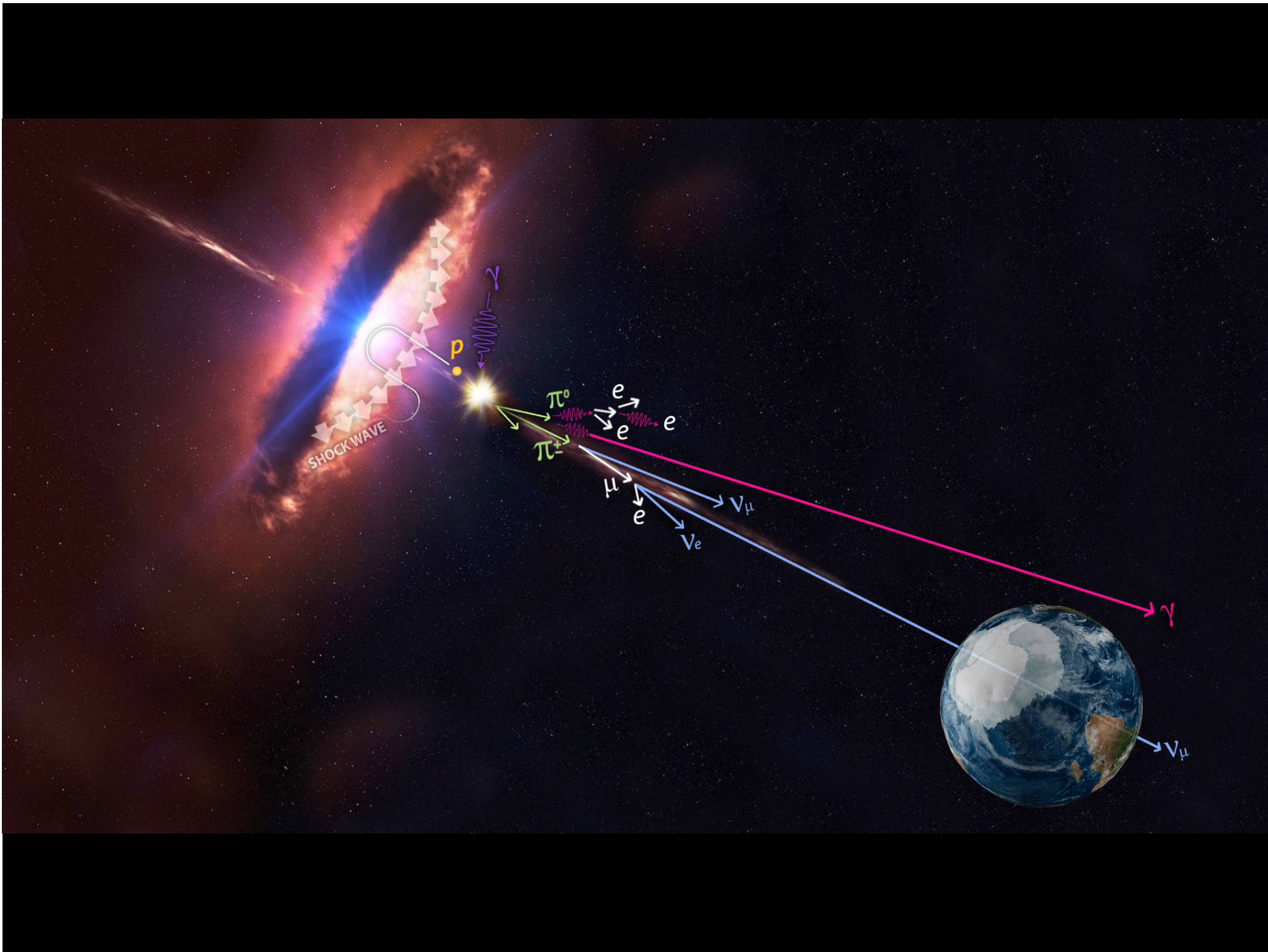
common sources?



multimessenger  
astronomy



Fermi sky: mostly blazars





# HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

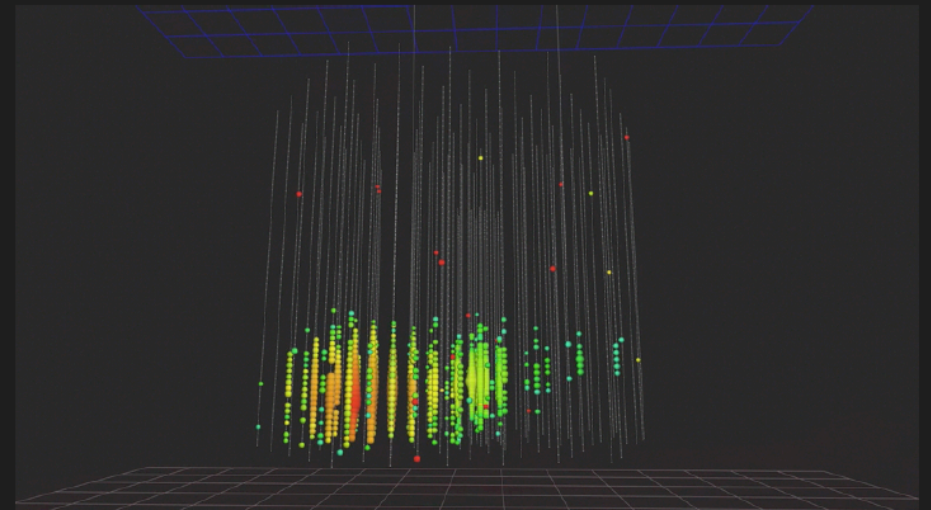
47

*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<sup>-1</sup> sr<sup>-1</sup>]  
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.



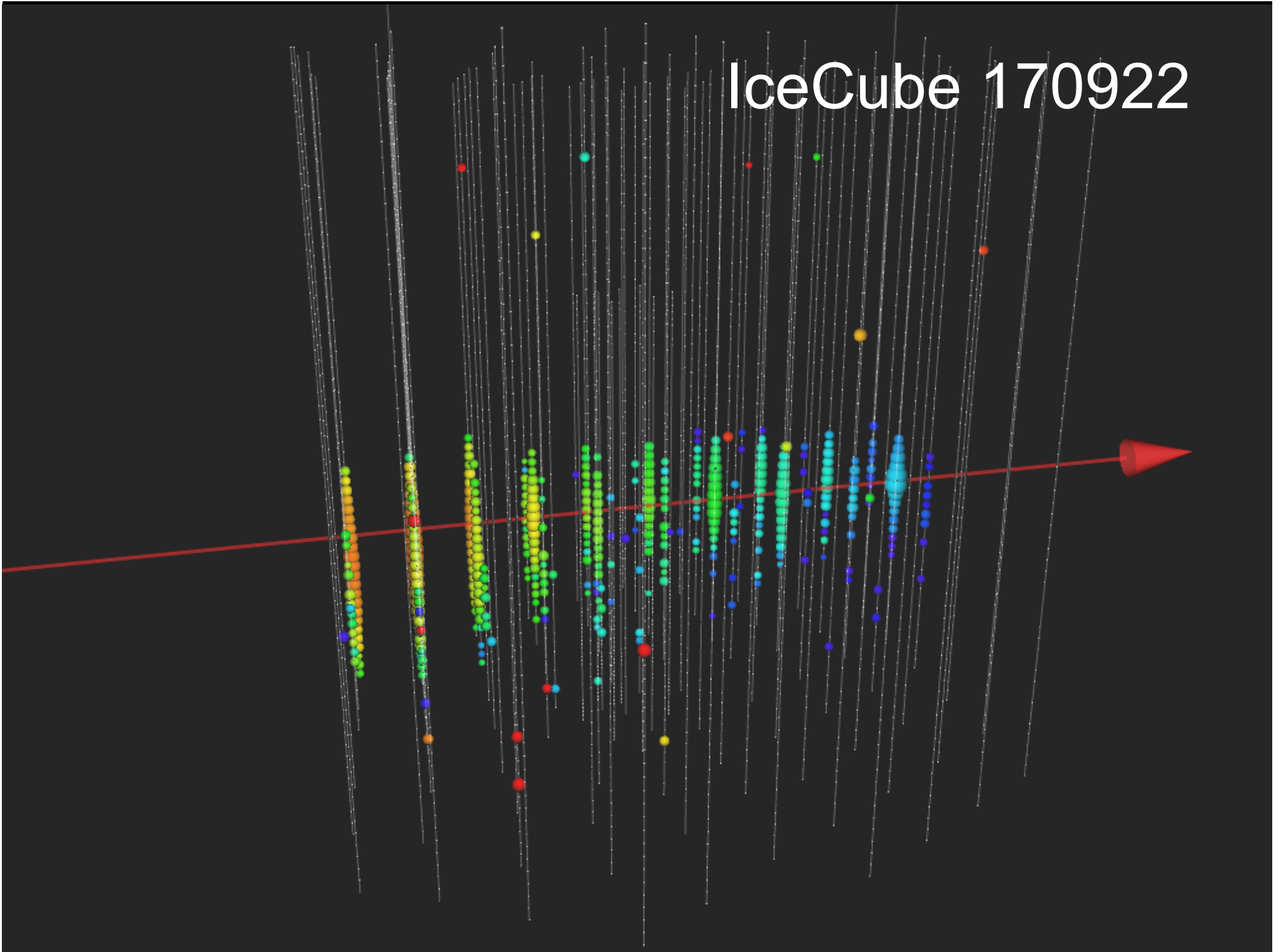
# IceCube Trigger

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]
```

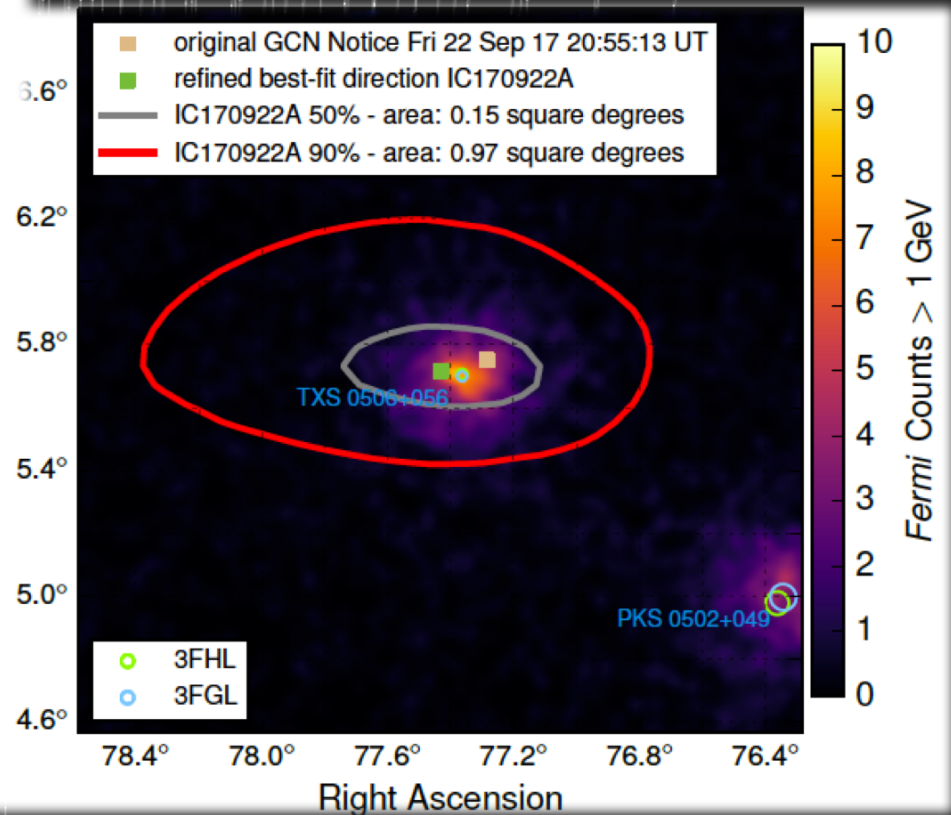
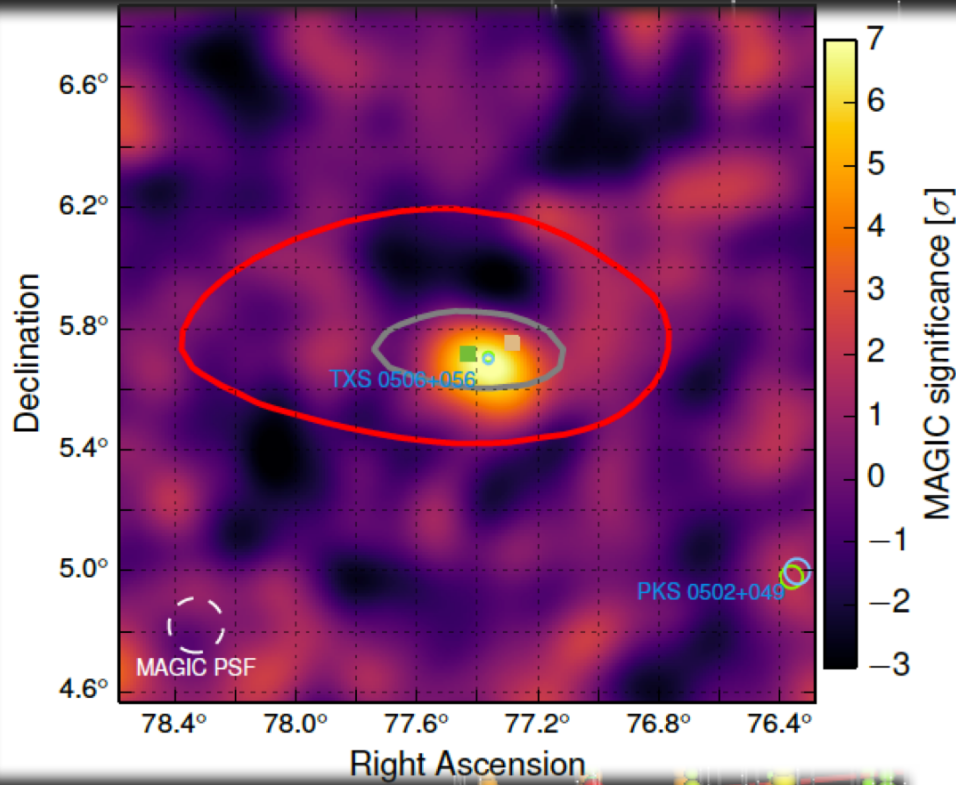


# IceCube 170922



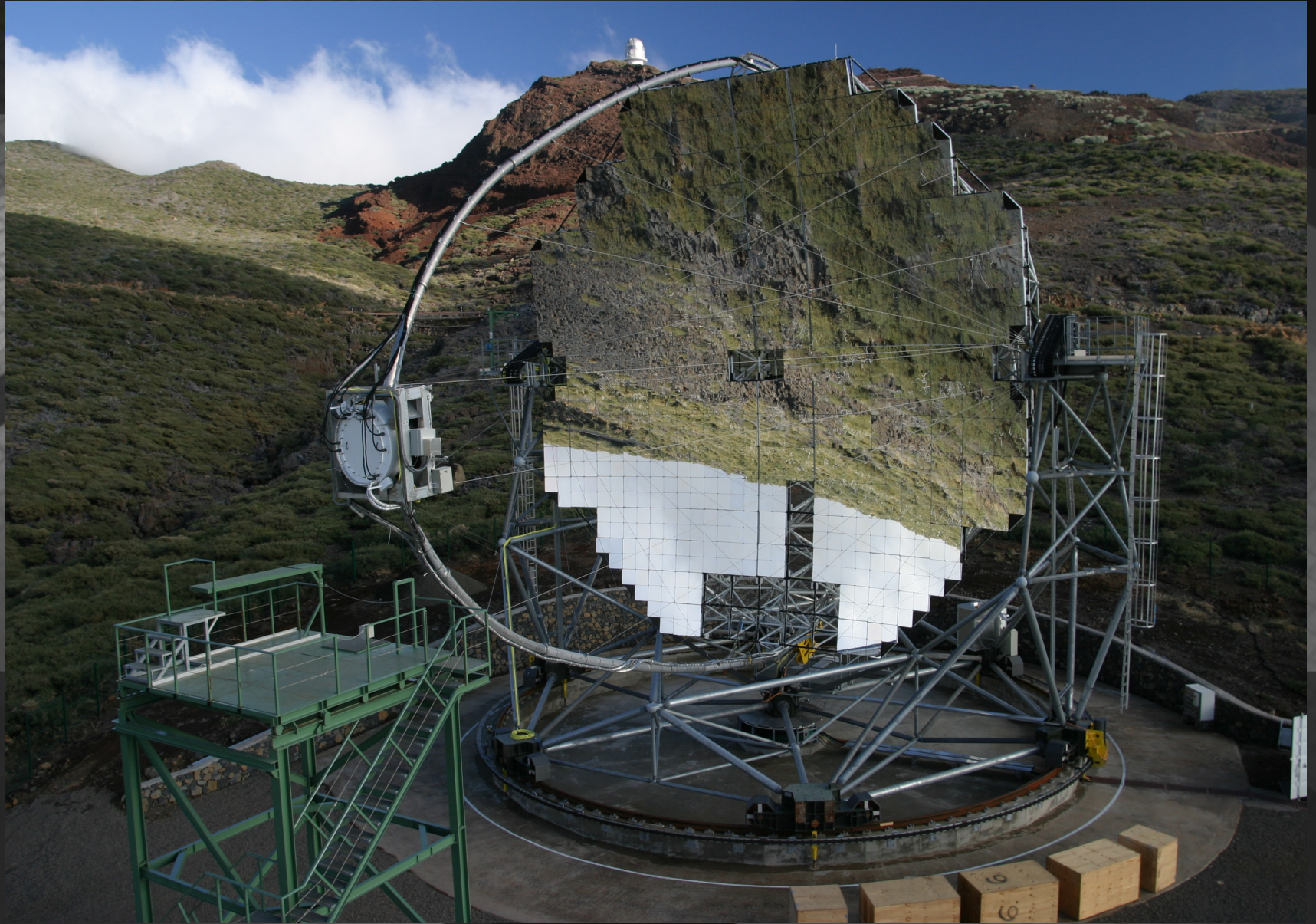
# IceCube 170922

Fermi  
detects a flaring  
blazar within  $0.1^\circ$



MAGIC  
detects emission of  
TeV gammas

# MAGIC



# 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. 28<sup>th</sup> till Oct. 3<sup>rd</sup>**
- 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  $\rightarrow z < 1.6$
- 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° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.1°
- 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 3.6 Gpc (redshift of 0.34)

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

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

SIMONA PAIANO,<sup>1,2</sup> RENATO FALOMO,<sup>1</sup> ALDO TREVES,<sup>3,4</sup> AND RICCARDO SCARPA<sup>5,6</sup>

<sup>1</sup>*INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5 I-35122 Padova - ITALY*

<sup>2</sup>*INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY*

<sup>3</sup>*Università degli Studi dell'Insubria, Via Valleggio 11 I-22100 Como - ITALY*

<sup>4</sup>*INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46 I-23807 Merate (LC) - ITALY*

<sup>5</sup>*Instituto de Astrofísica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN*

<sup>6</sup>*Universidad de La Laguna, Dpto. Astrofísica, 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  $z = 0.3365 \pm 0.0010$ .

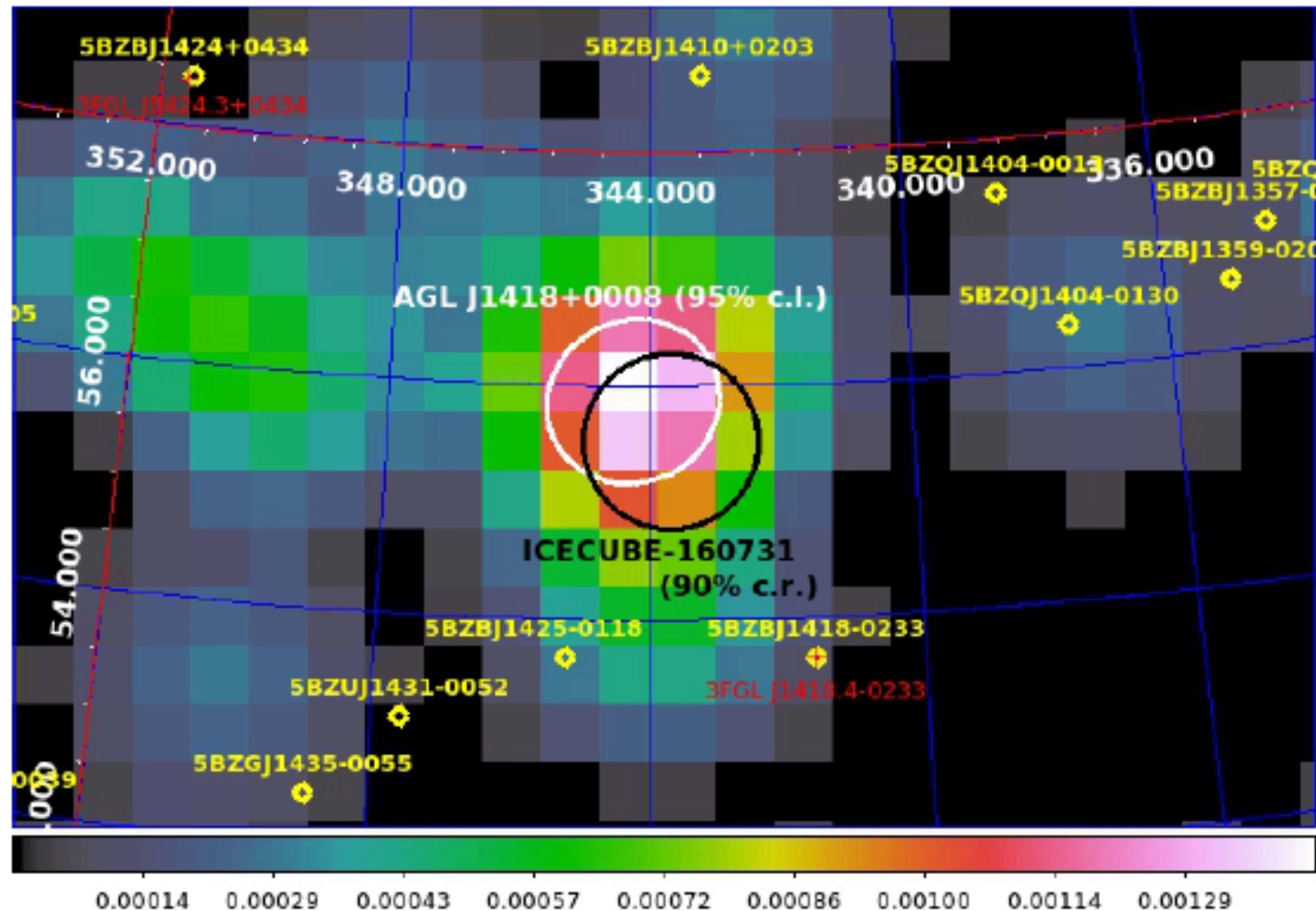
*Keywords:* galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

→ 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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# TANAMI blazars in the IceCube PeV neutrino fields

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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  $\gamma$ -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.

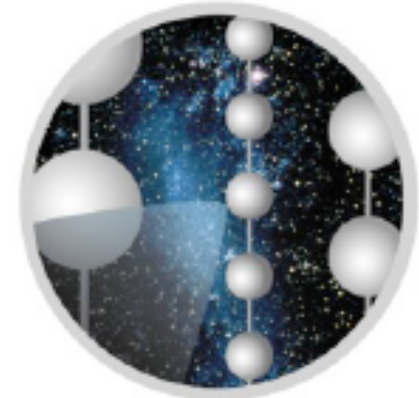
**Key words.** neutrinos – galaxies: active – quasars: general

neutrino astronomy was born with a supernova in 1987. After more than 30 years, the 172209 event unexpectedly involved neutrinos that are tens of million times more energetic from a source a million times more distant

# Multimessenger Astronomy

francis halzen

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- August 17, 2017
- September 22, 2017
- ....
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