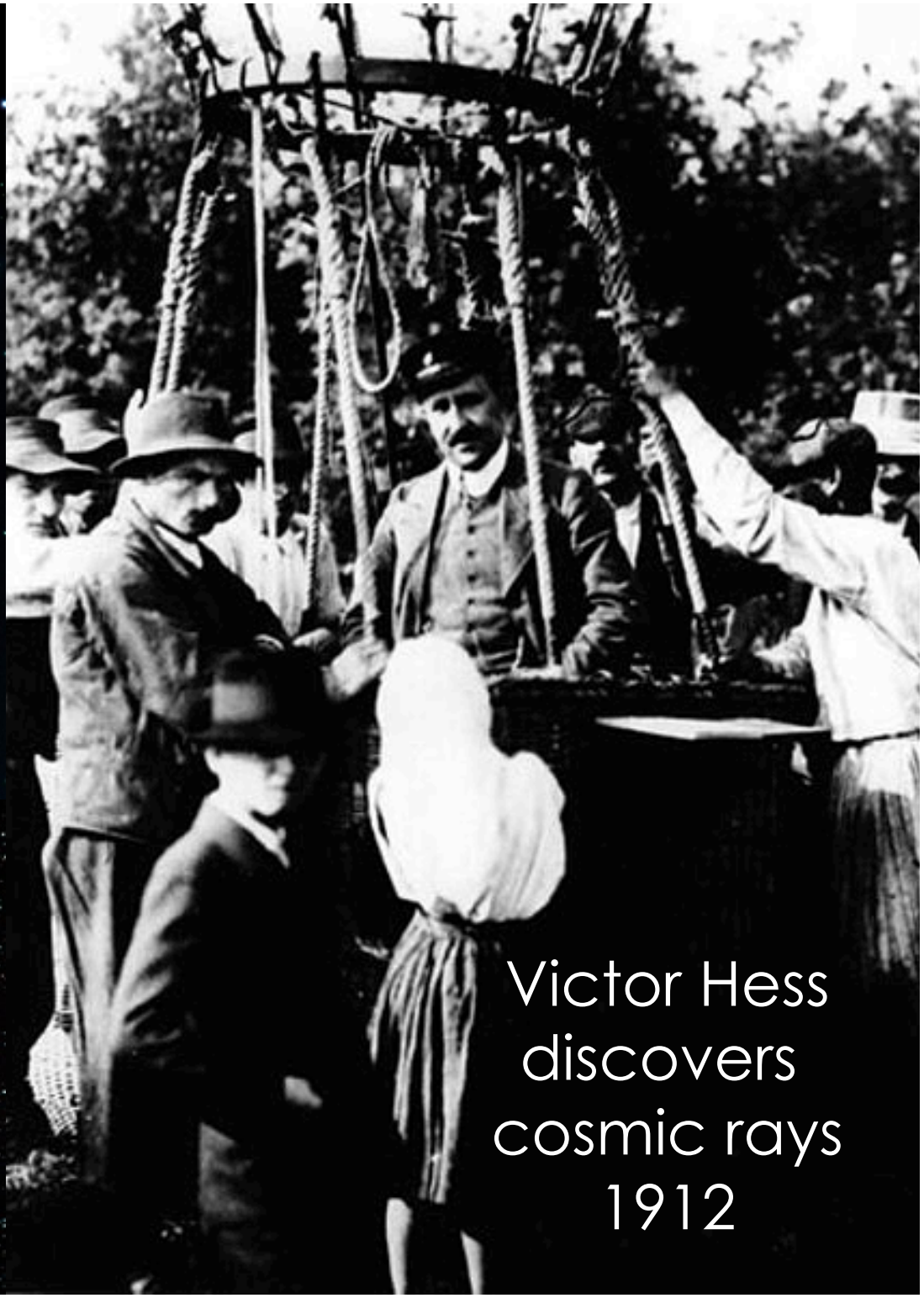
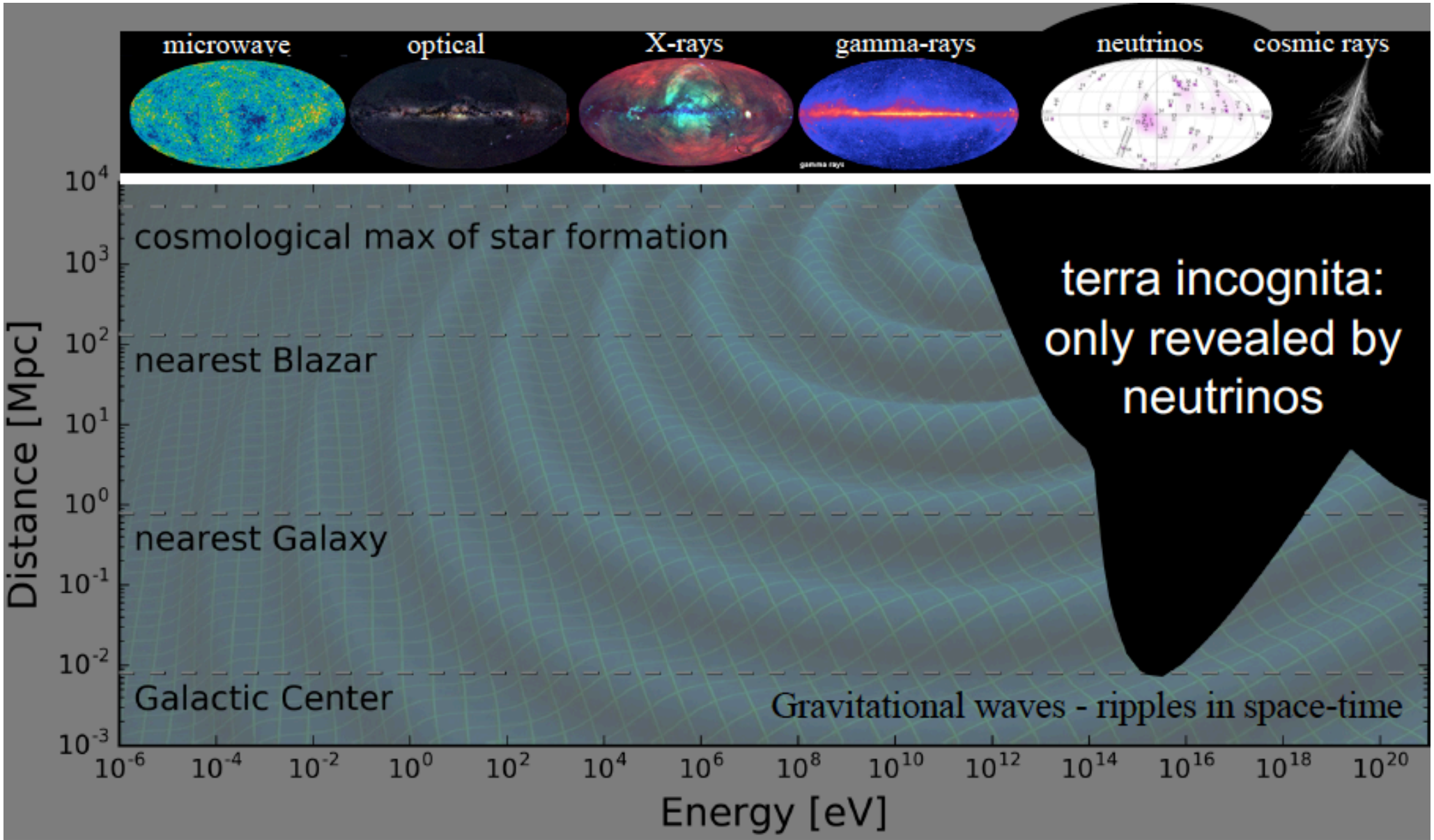
IceCube:
Building a New Window on the Universe

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

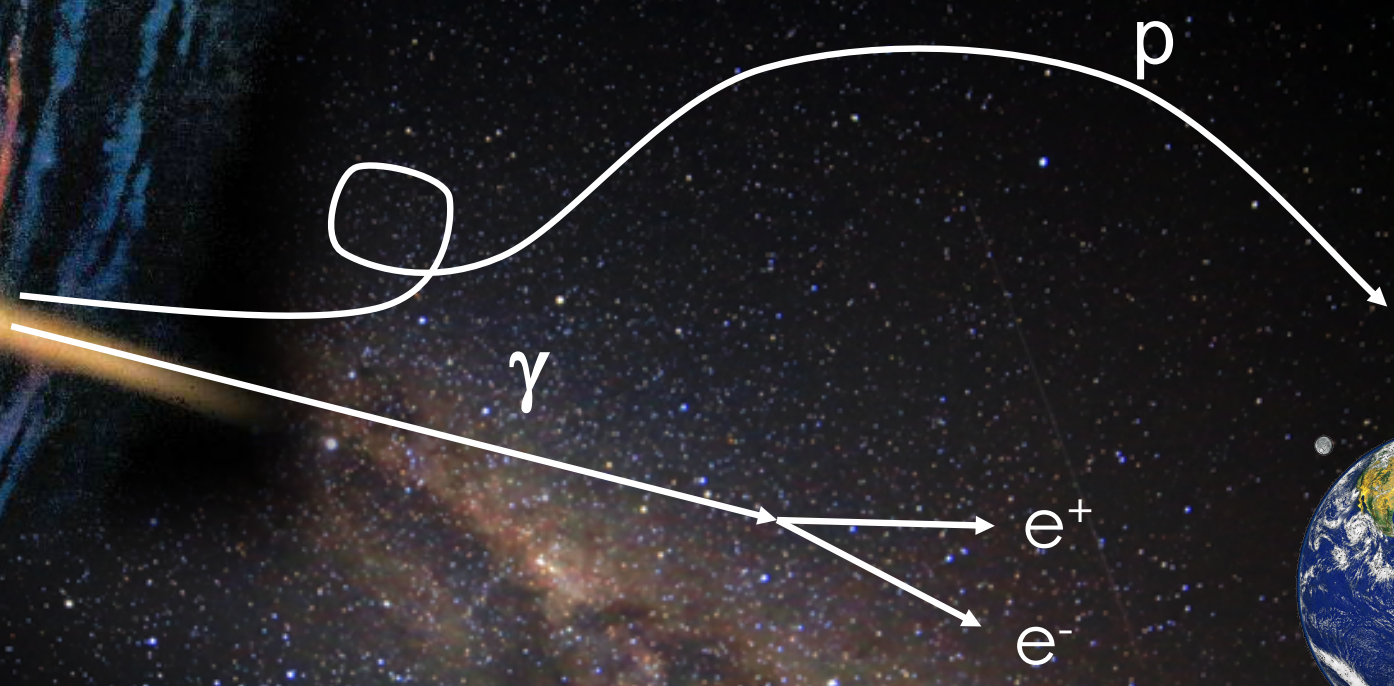

galactic sources?
extragalactic sources?
Fly's Eye 1991
300,000,000 TeV


Victor Hess
discovers
cosmic rays
1912



- 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

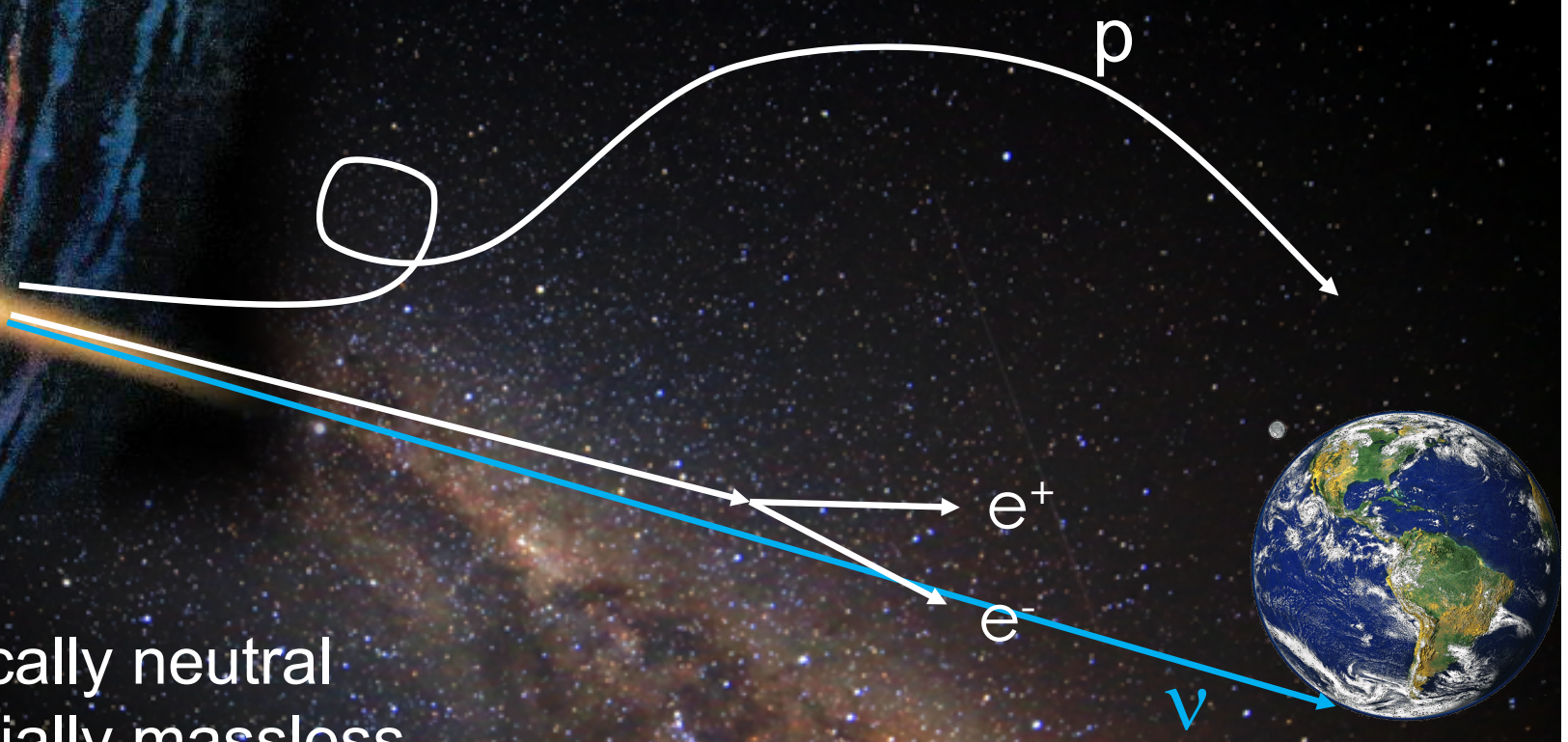
The opaque Universe



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

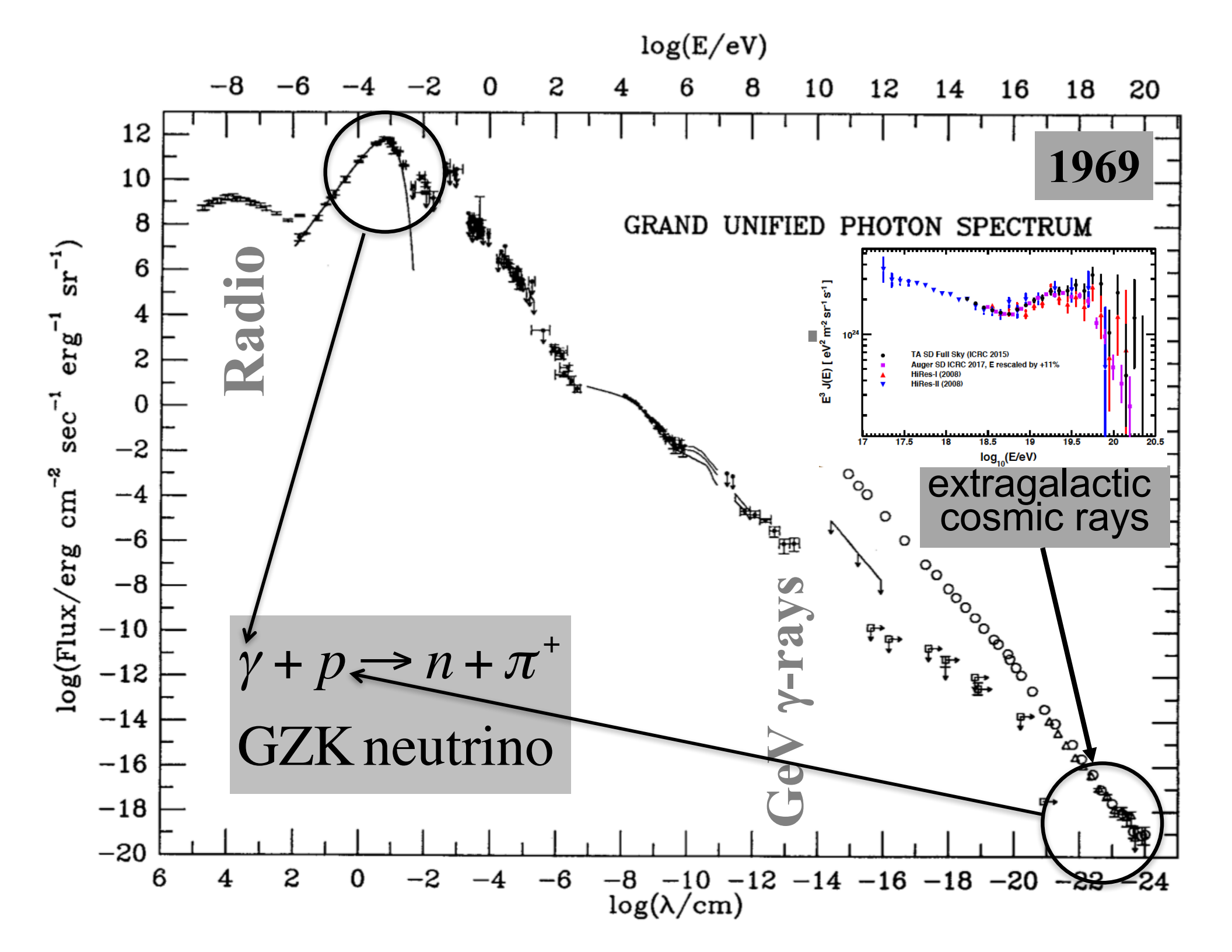
photons interact with microwave photons
before reaching our telescopes

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?


log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
GeV γ-rays
extragalactic cosmic rays
$\gamma + p \rightleftharpoons n + \pi^+$
GZK neutrino
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)
E^3 J(E) [eV^2 m^{-2} sr^{-1} s^{-1}]
TA SD Full Sky (ICRC 2015)
Auger SD ICRC 2017, E rescaled by +11%
HiRes-I (2008)
HiRes-II (2008)
log$_{10}$(E/eV)

cosmic rays interact with the microwave background

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

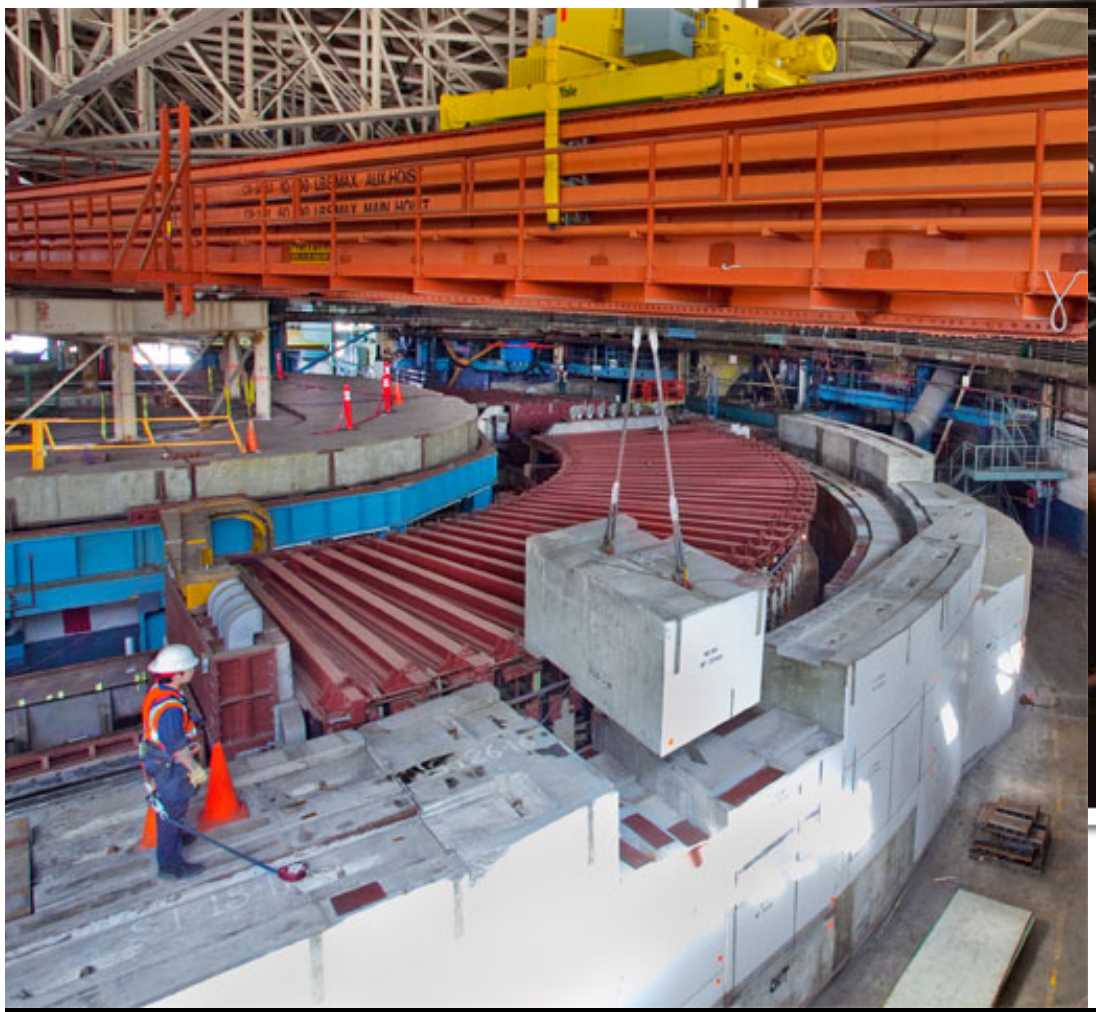
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

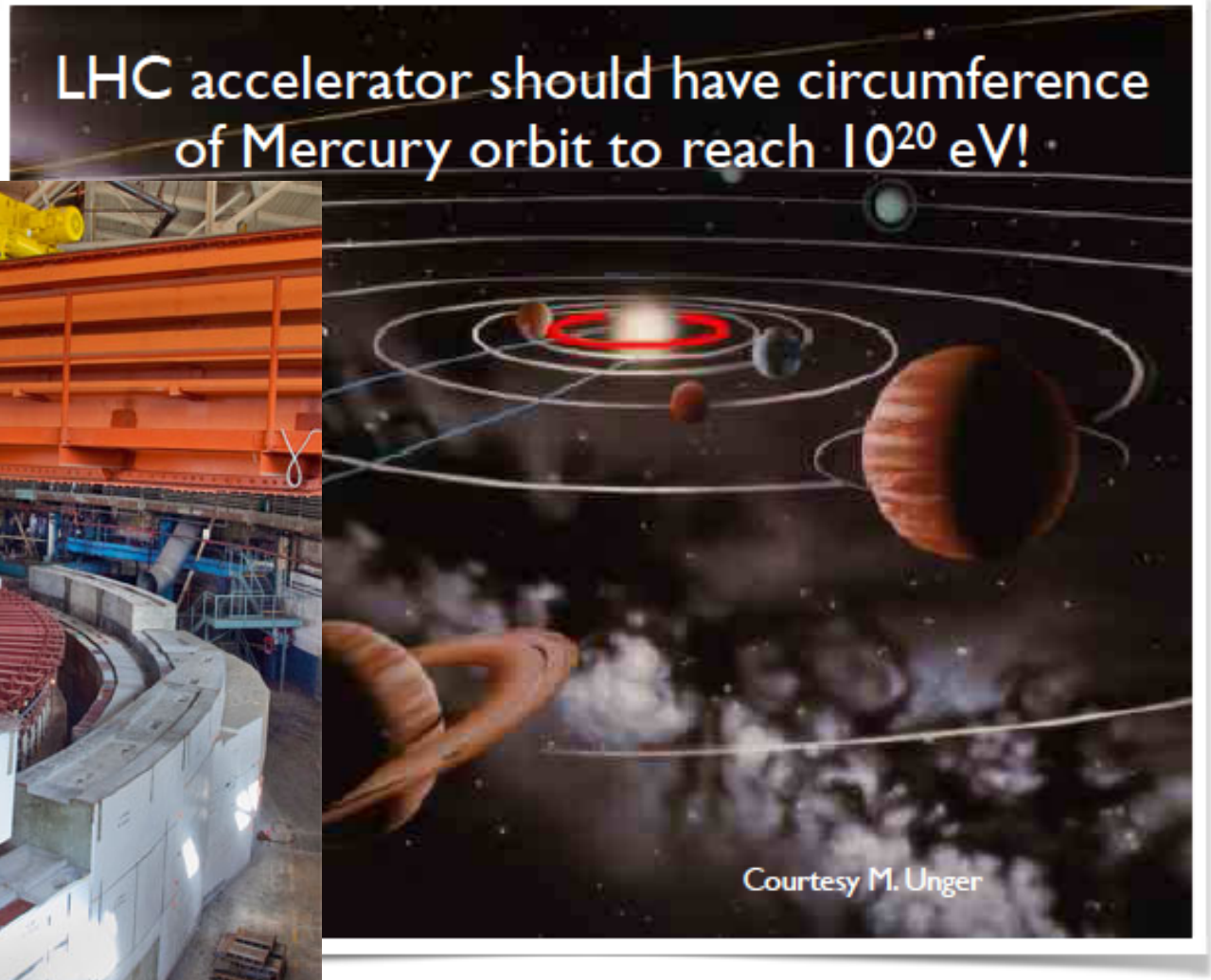
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source!

transform gravitational energy into the acceleration of particles





the sun constructs an accelerator

accelerator must contain the particle orbit

$$R_{gyro}\ (= \frac{E}{\mathrm{v}qB}) \leq R$$

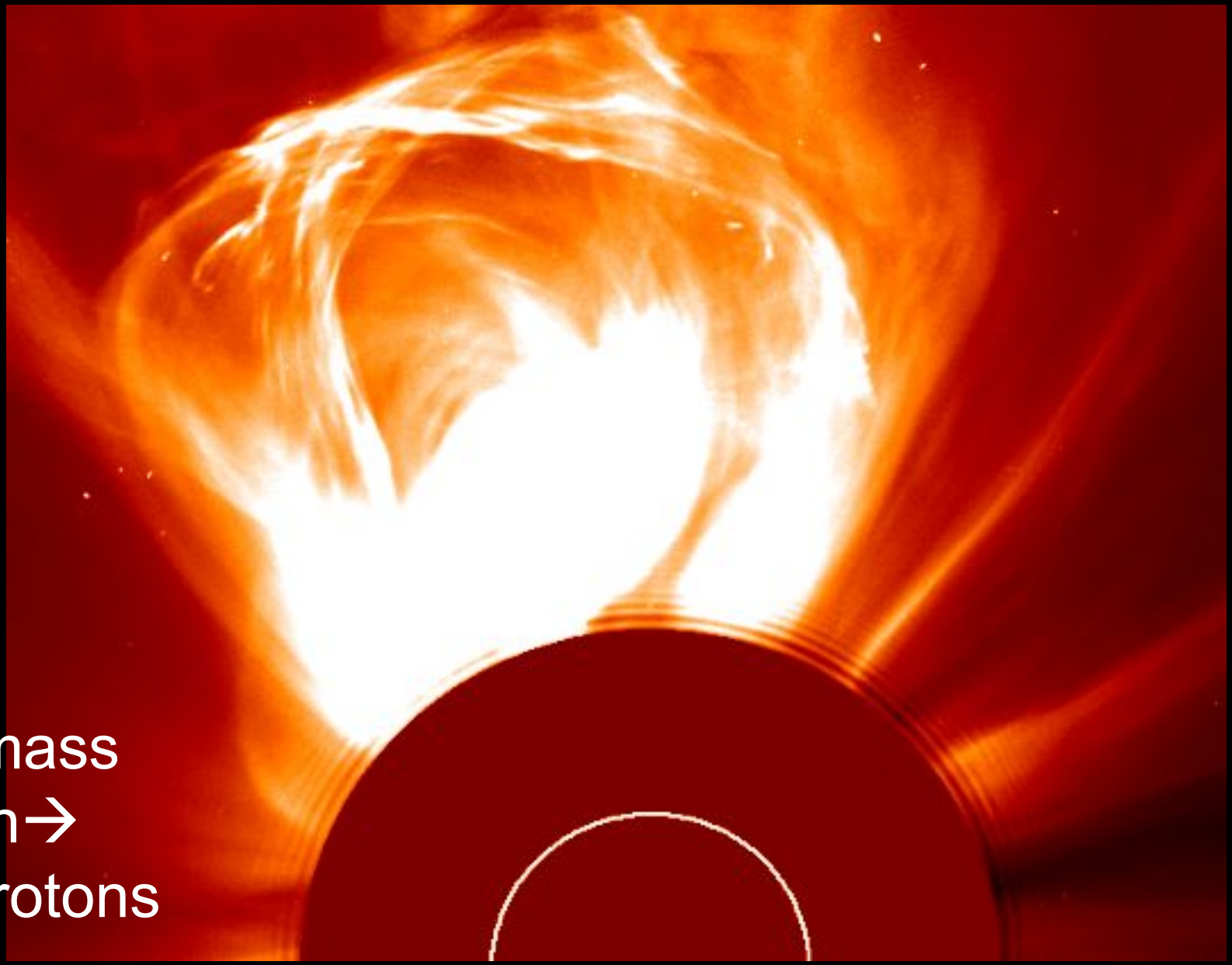
$$E \leq \mathrm{v}\ qBR$$

challenges of cosmic ray astrophysics:

- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

→ convert a few percent of gravitational energy into particle acceleration (shocks)

the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

accelerator must contain the particle orbit

$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

$$E \leq \mathrm{v}\, qBR$$

challenges of cosmic ray astrophysics:

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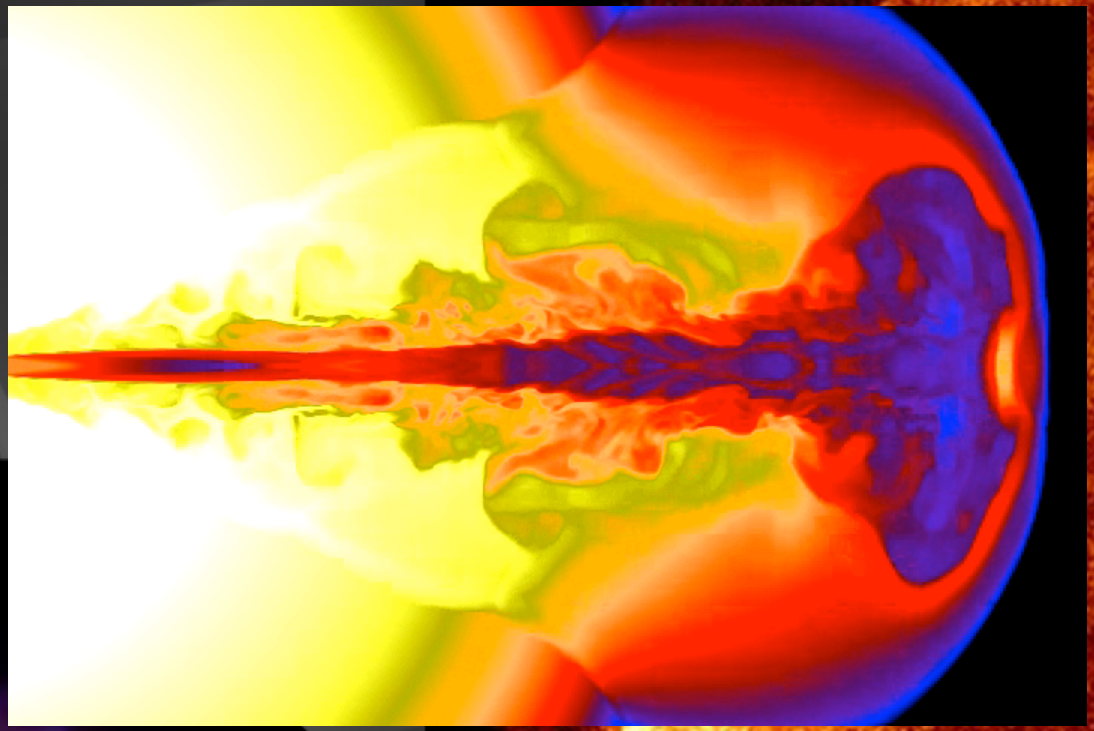
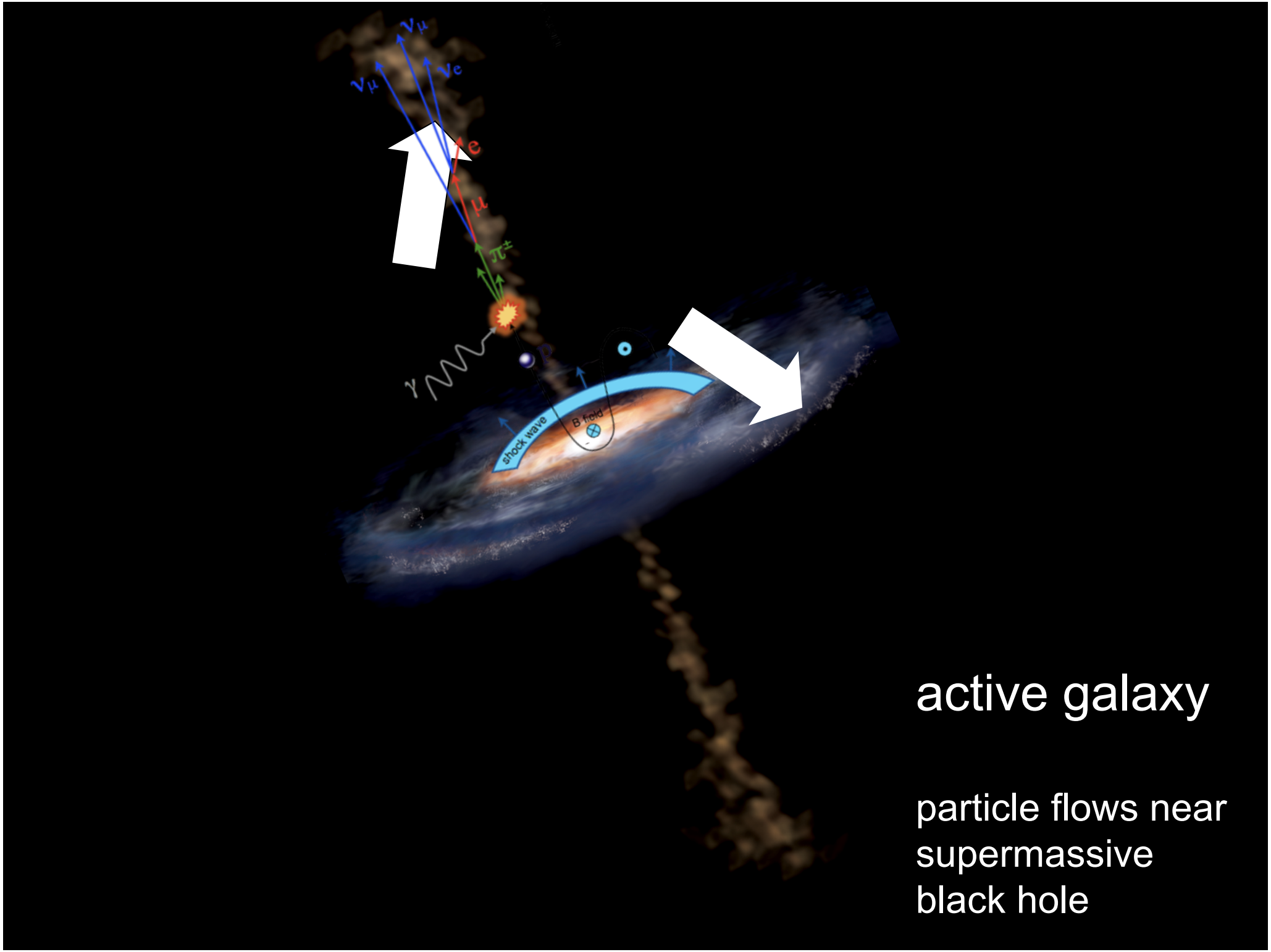
supernova remnants

Chandra
Cassiopeia A

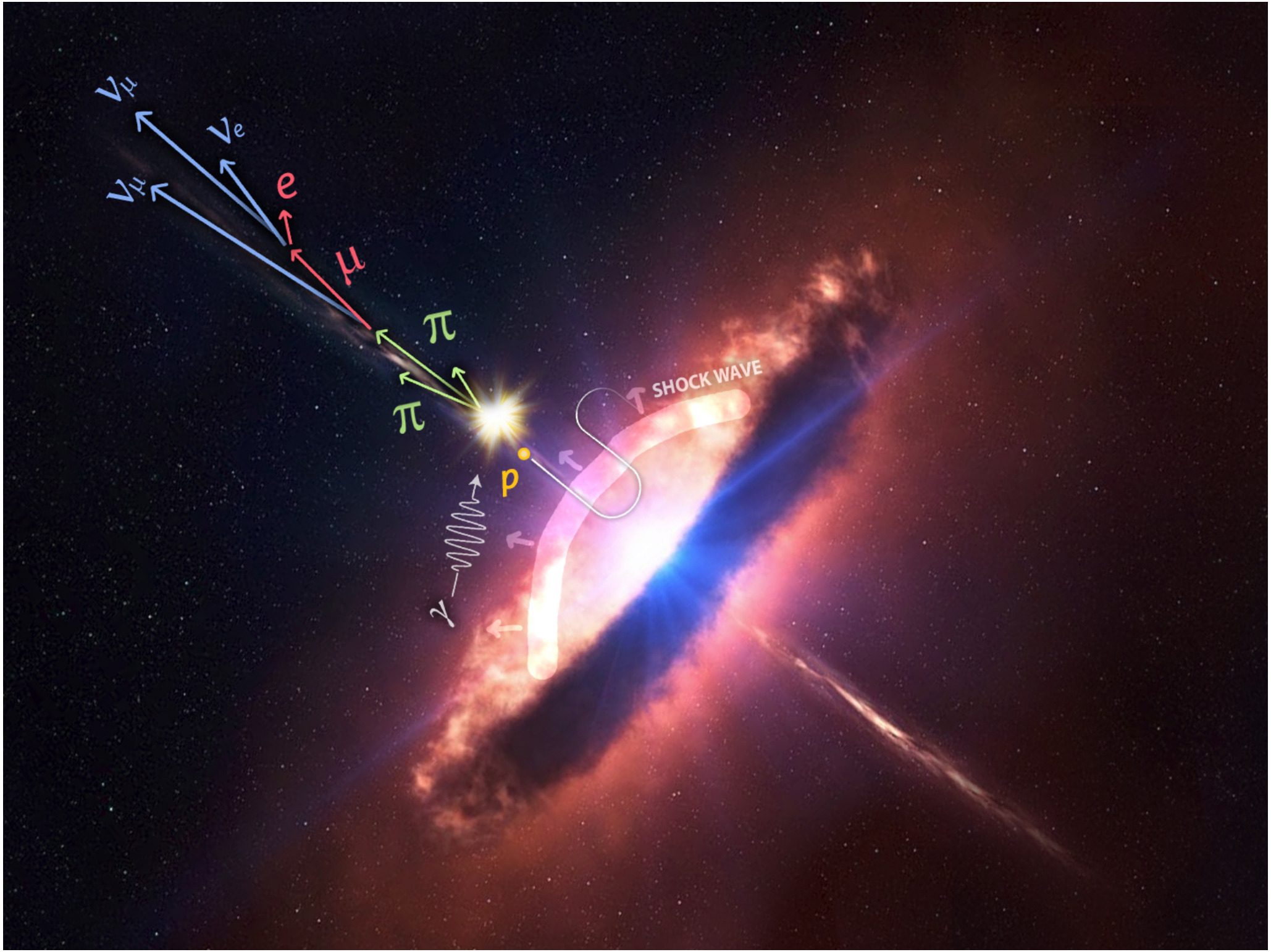


gamma ray bursts

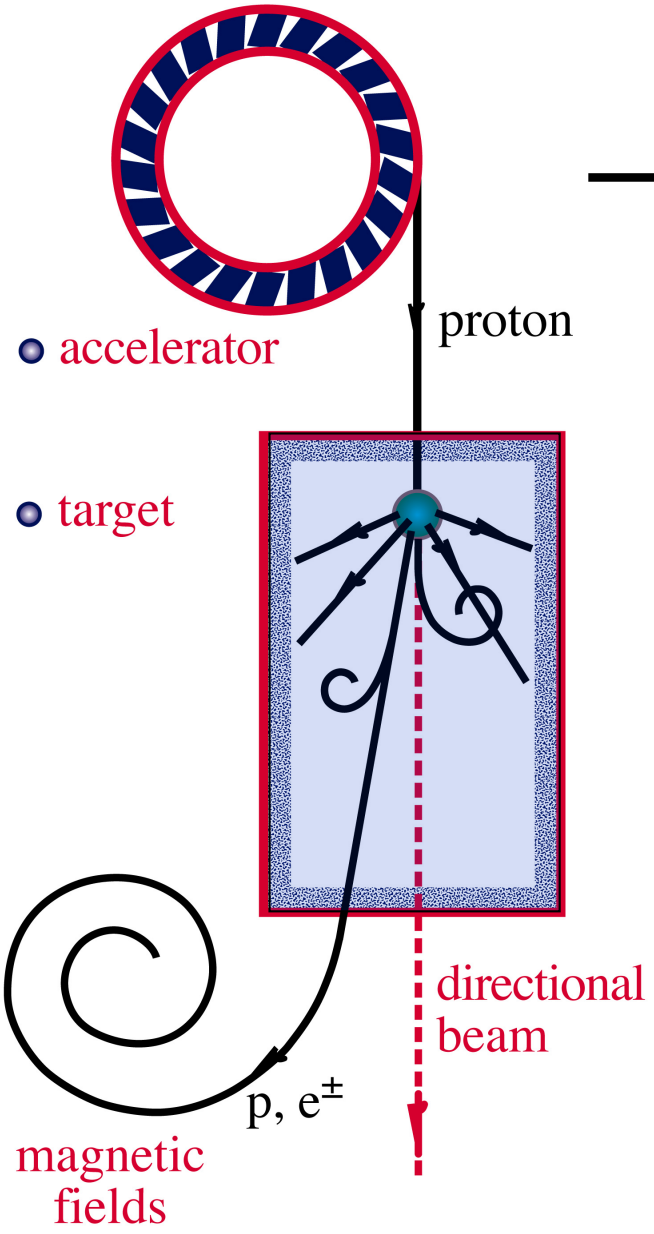


active galaxy

particle flows near supermassive black hole


ν_μ
ν_e
ν_μ
e
μ
π
π
SHOCK WAVE
p
γ

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

$\rightarrow p + \pi^0$

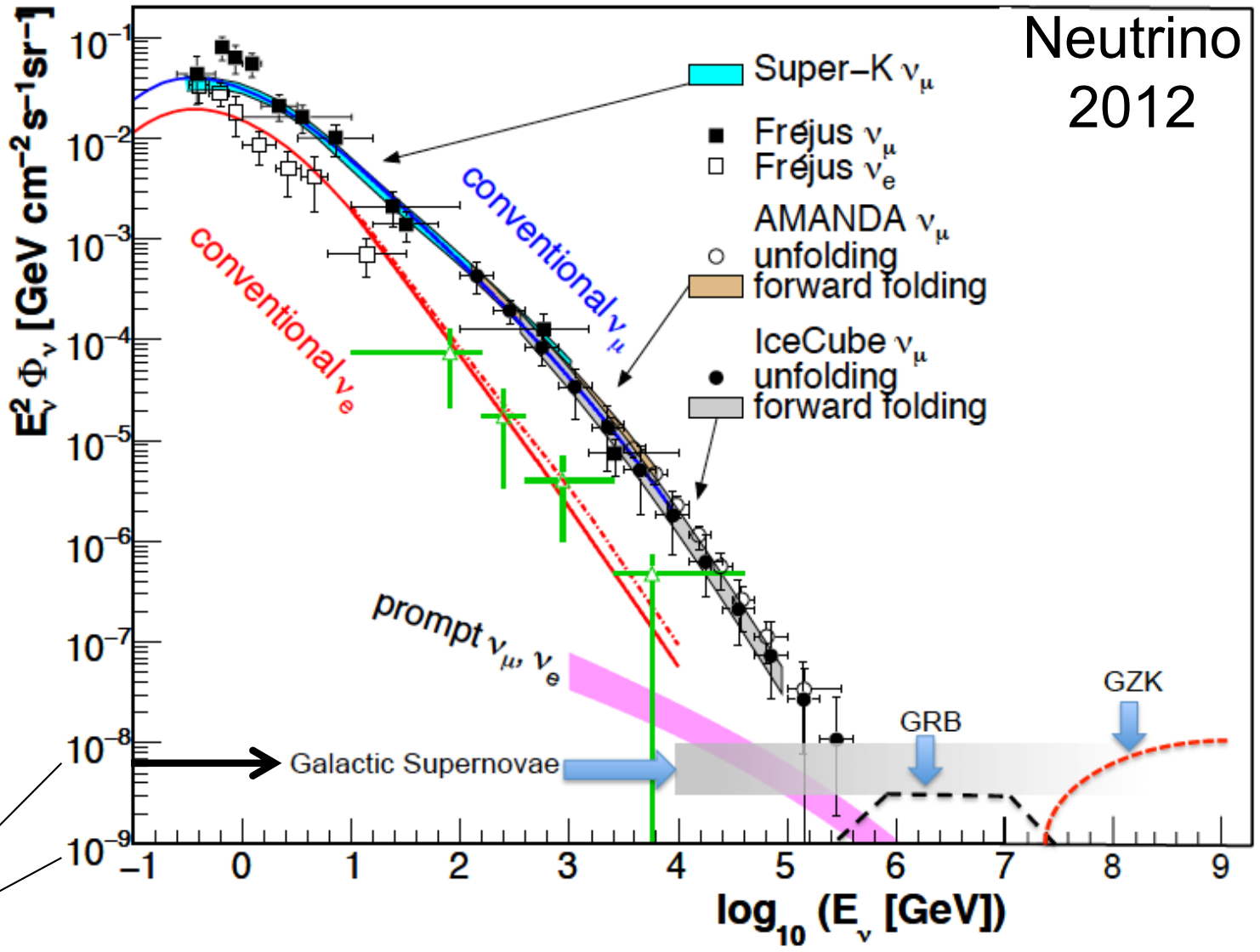
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

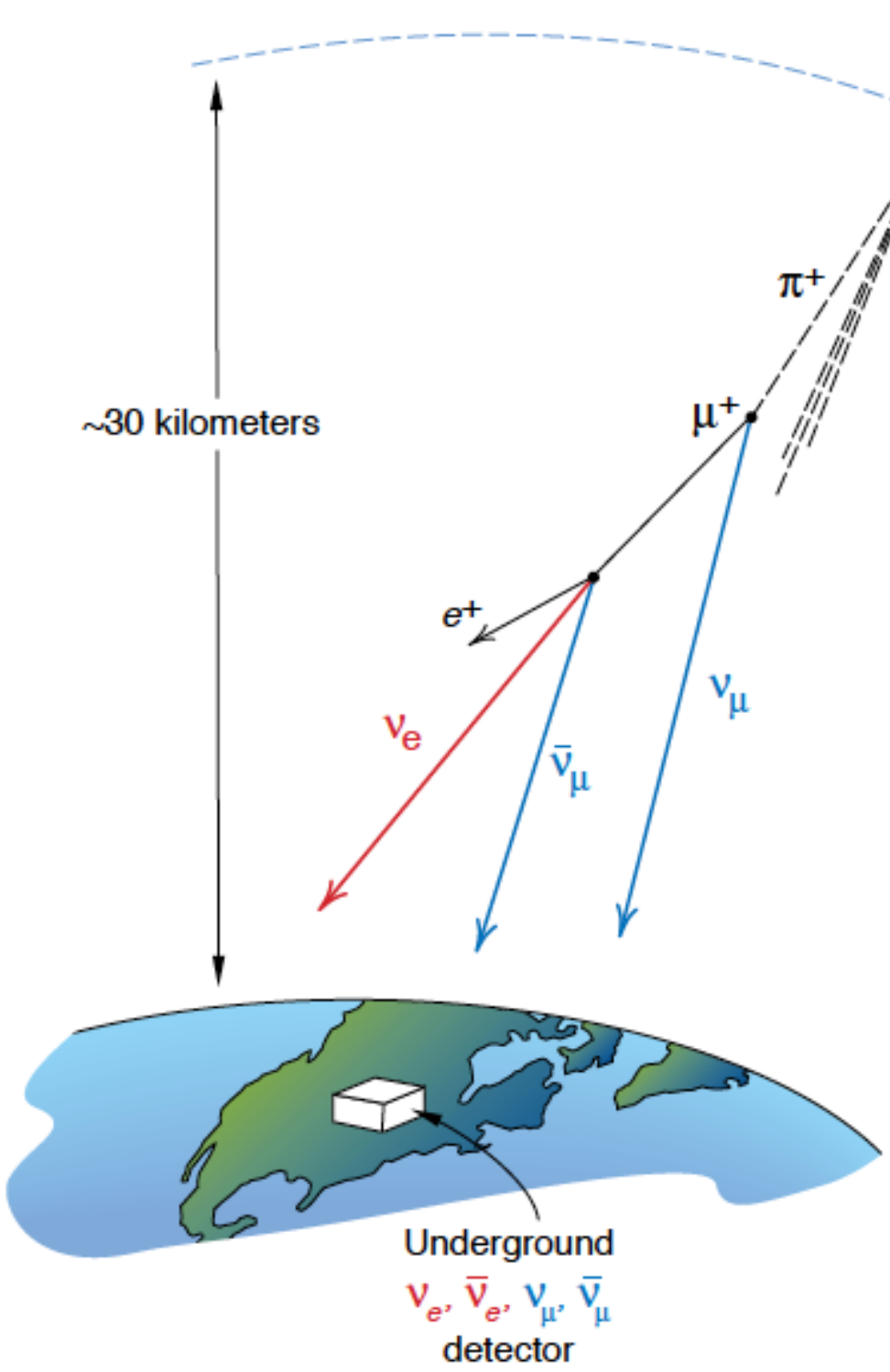
$dN/dE \sim E^{-2}$

10—100 events per year for fully efficient detector



atmospheric ⇑ cosmic

100 TeV

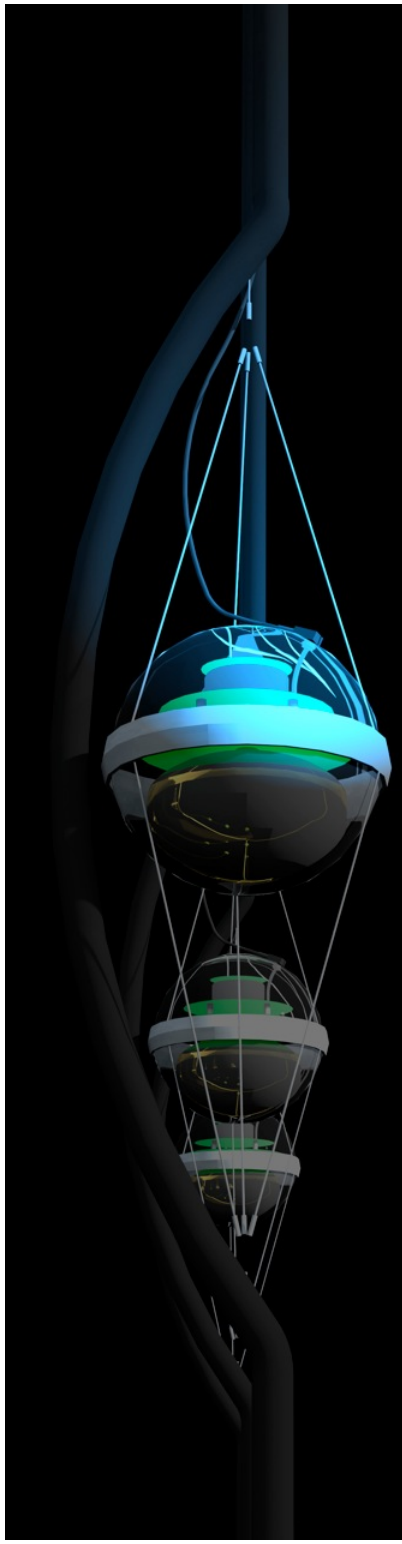


atmospheric neutrinos
(… and muons!)

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

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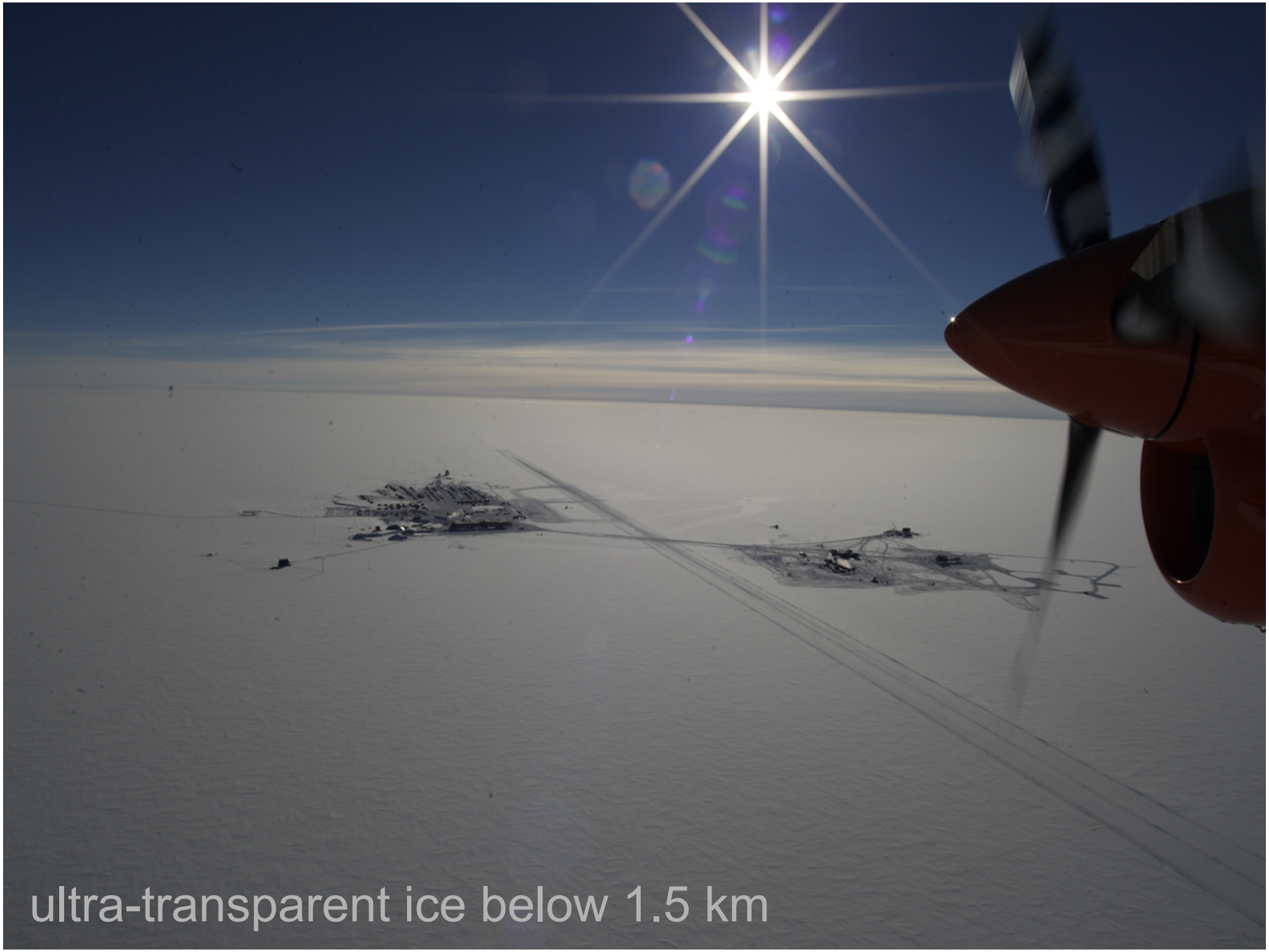
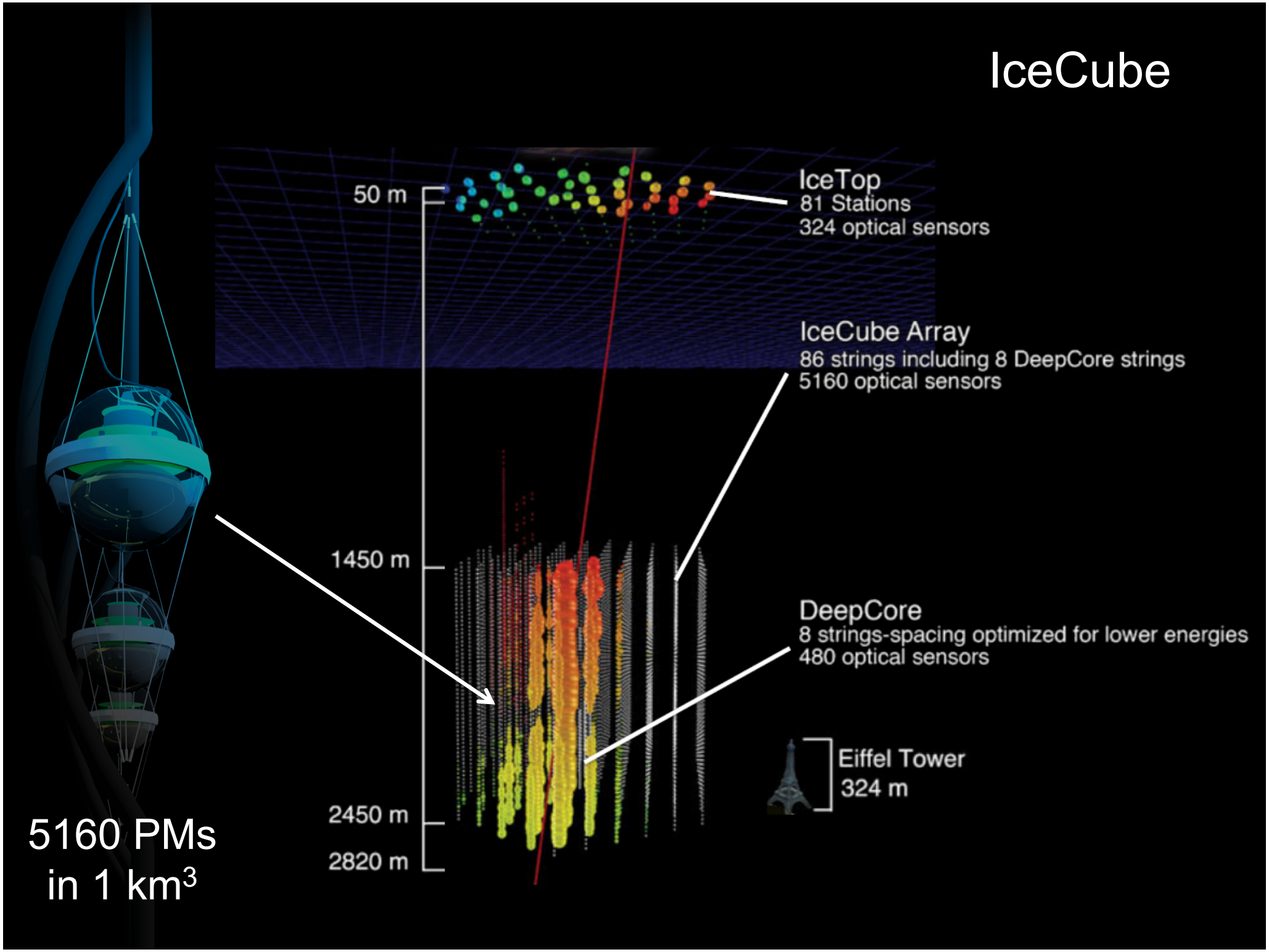
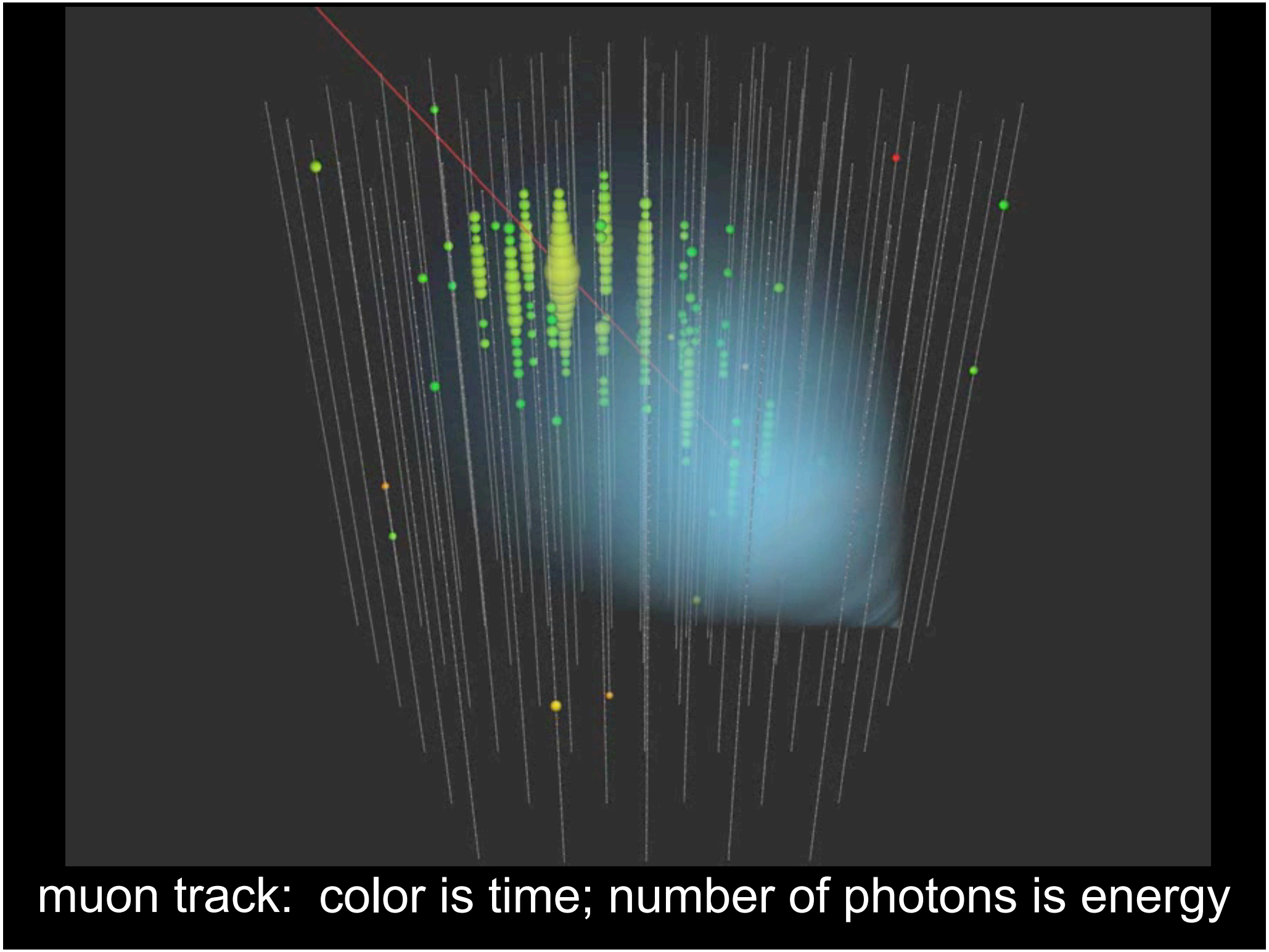
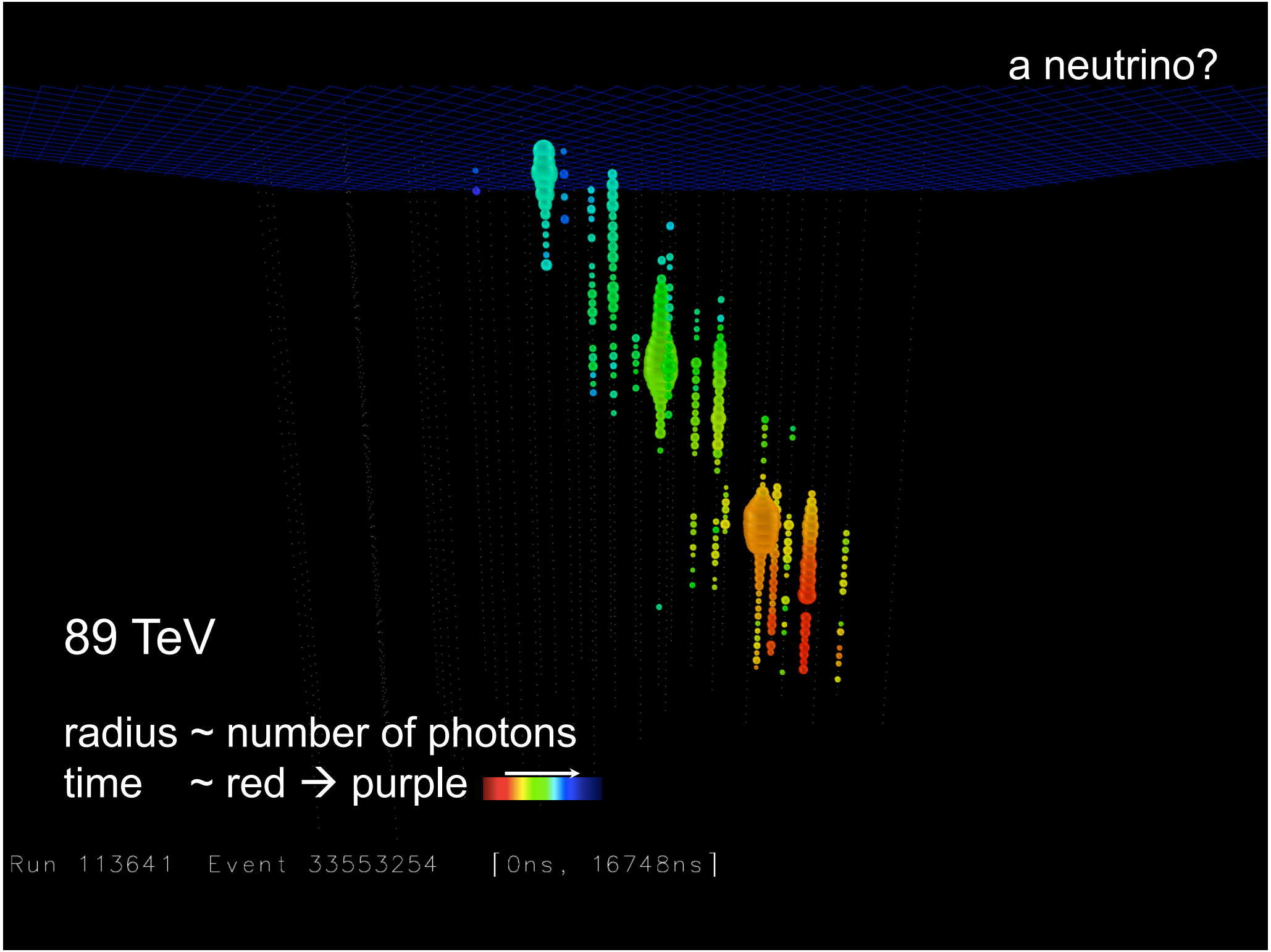

ultra-transparent ice below 1.5 km

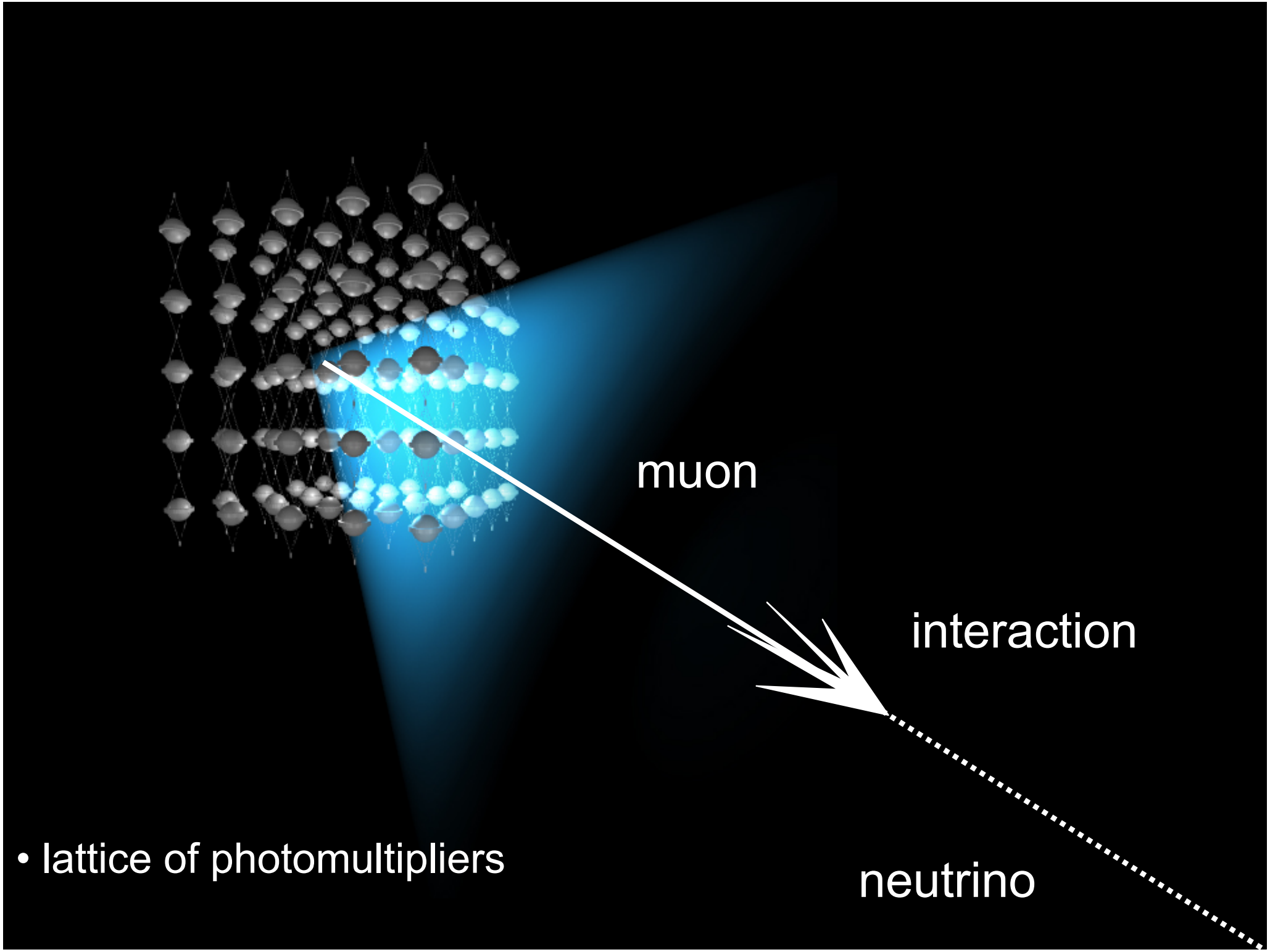

IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

photomultiplier tube -10 inch

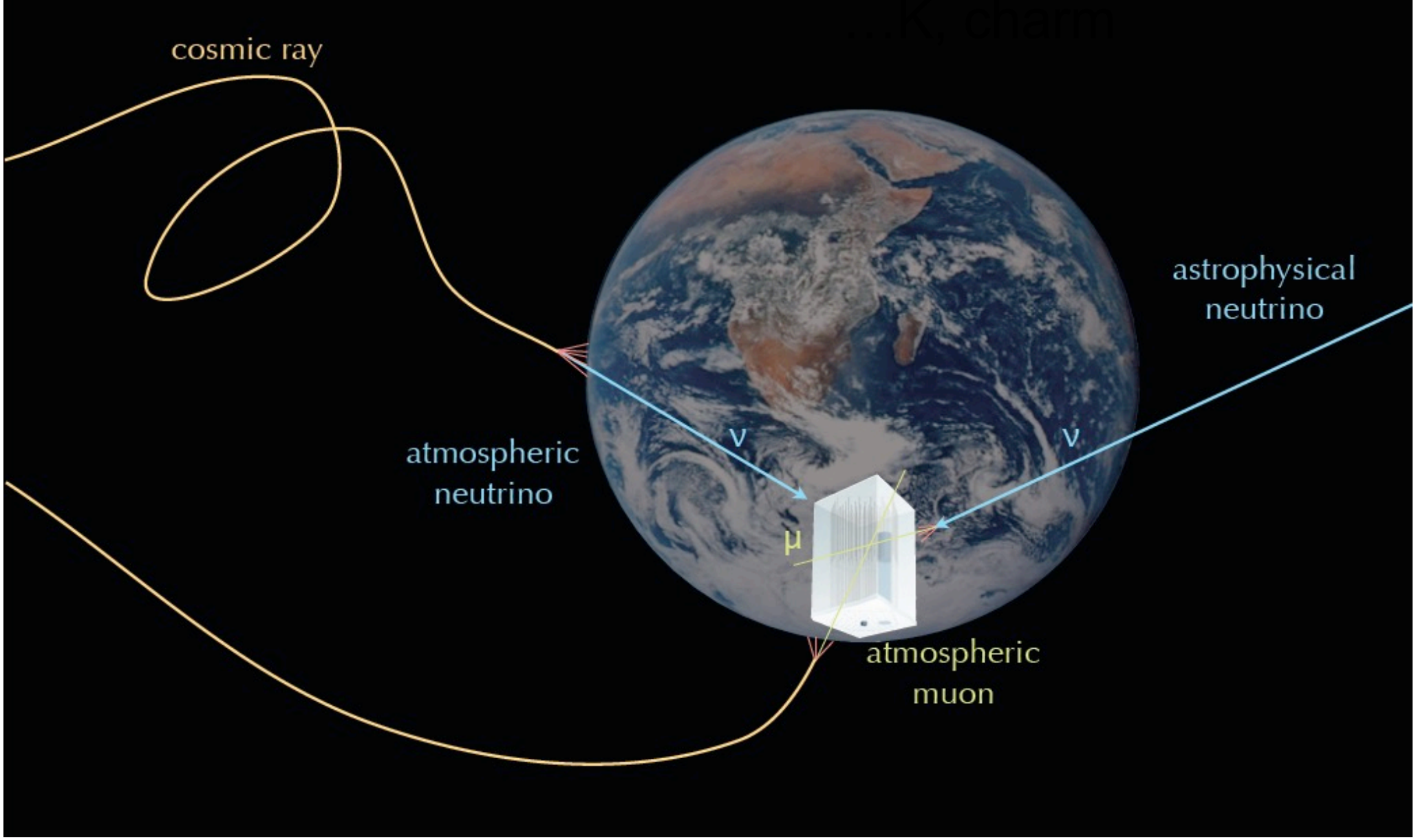


muon track: color is time; number of photons is energy


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


muon
interaction
neutrino
• lattice of photomultipliers

Signals and Backgrounds



separating signal and "background"

muons detected per year:

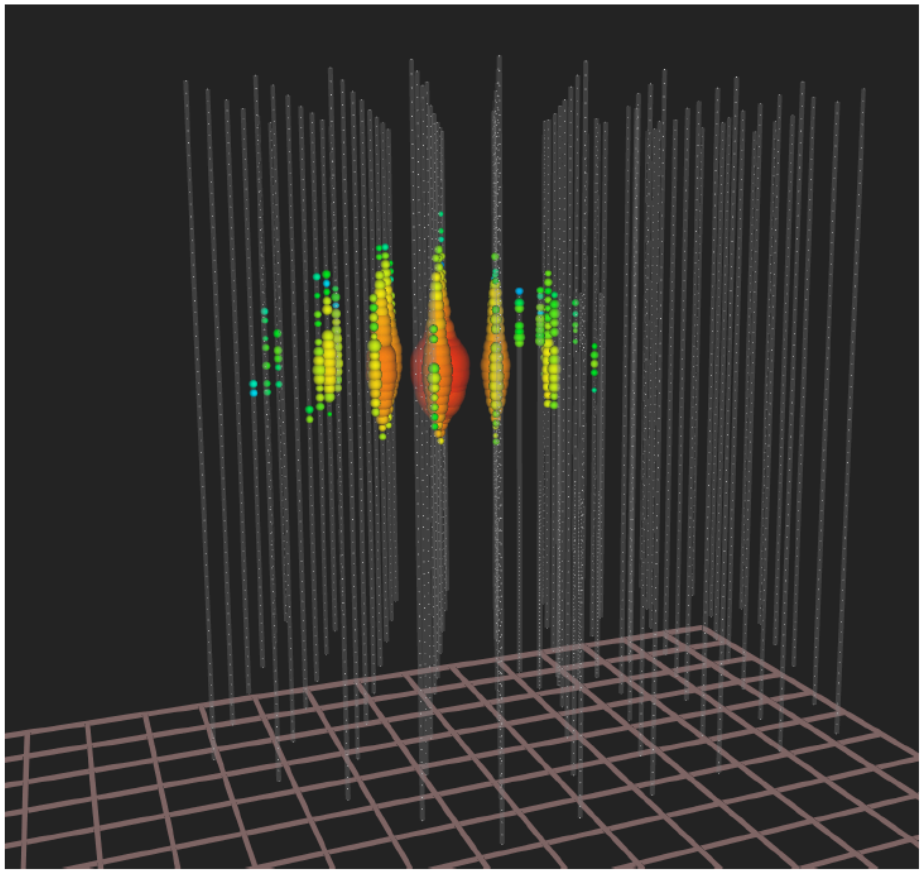
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ $10\text{-}10^{2}$

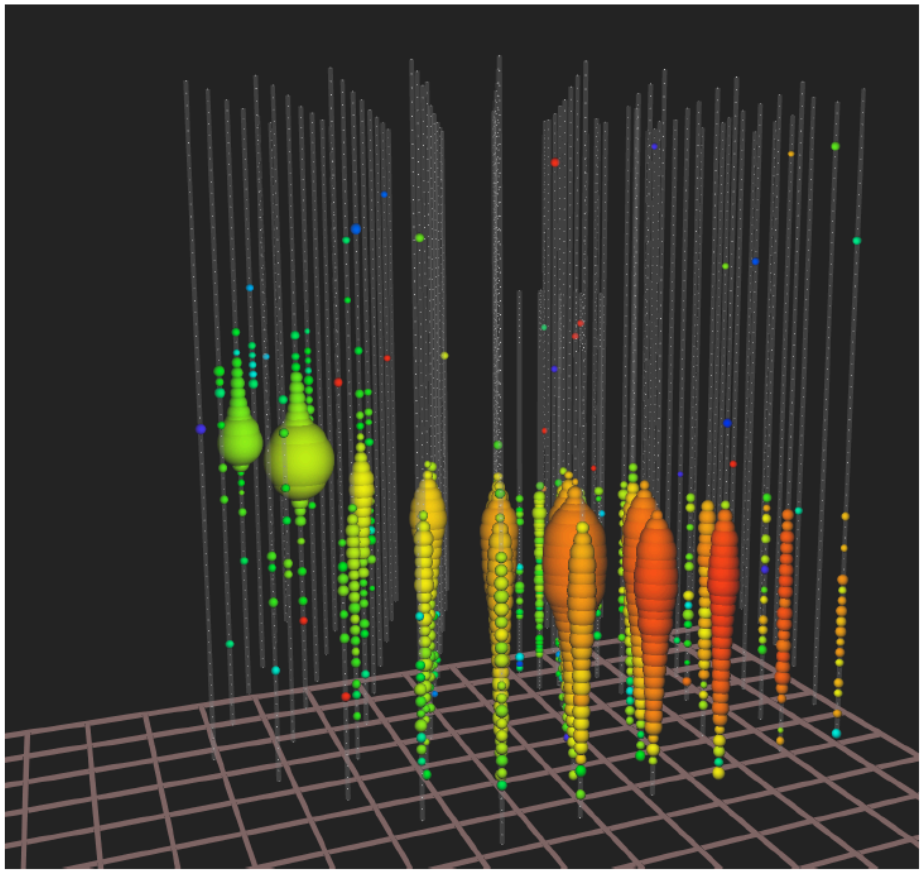
* 3000 per second

** 1 every 6 minutes

isolated neutrinos interacting *inside* the detector (HESE)

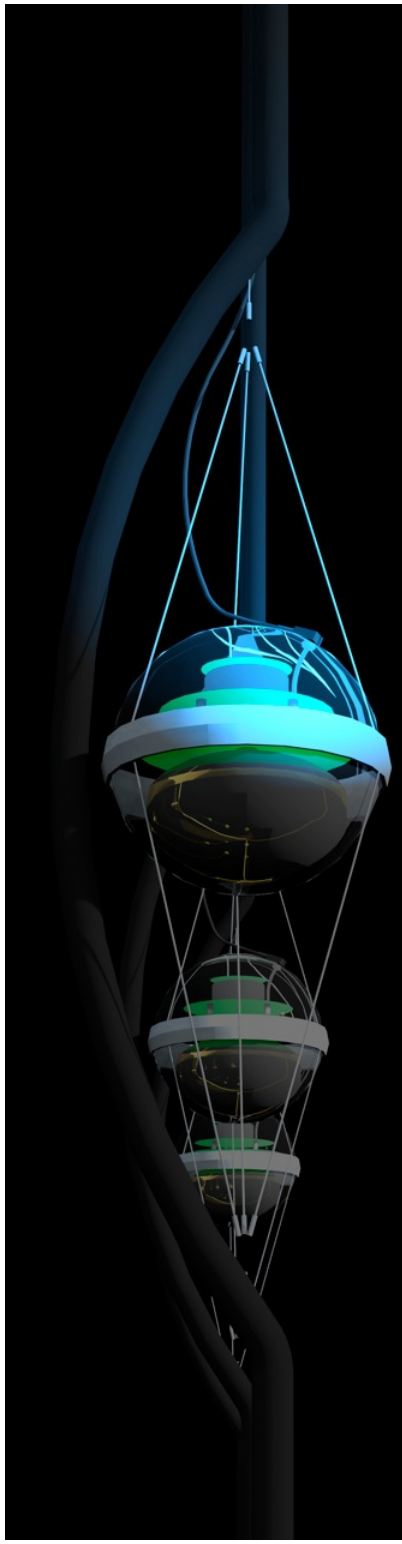
up-going muon tracks (UPMU)





total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.5^{o})



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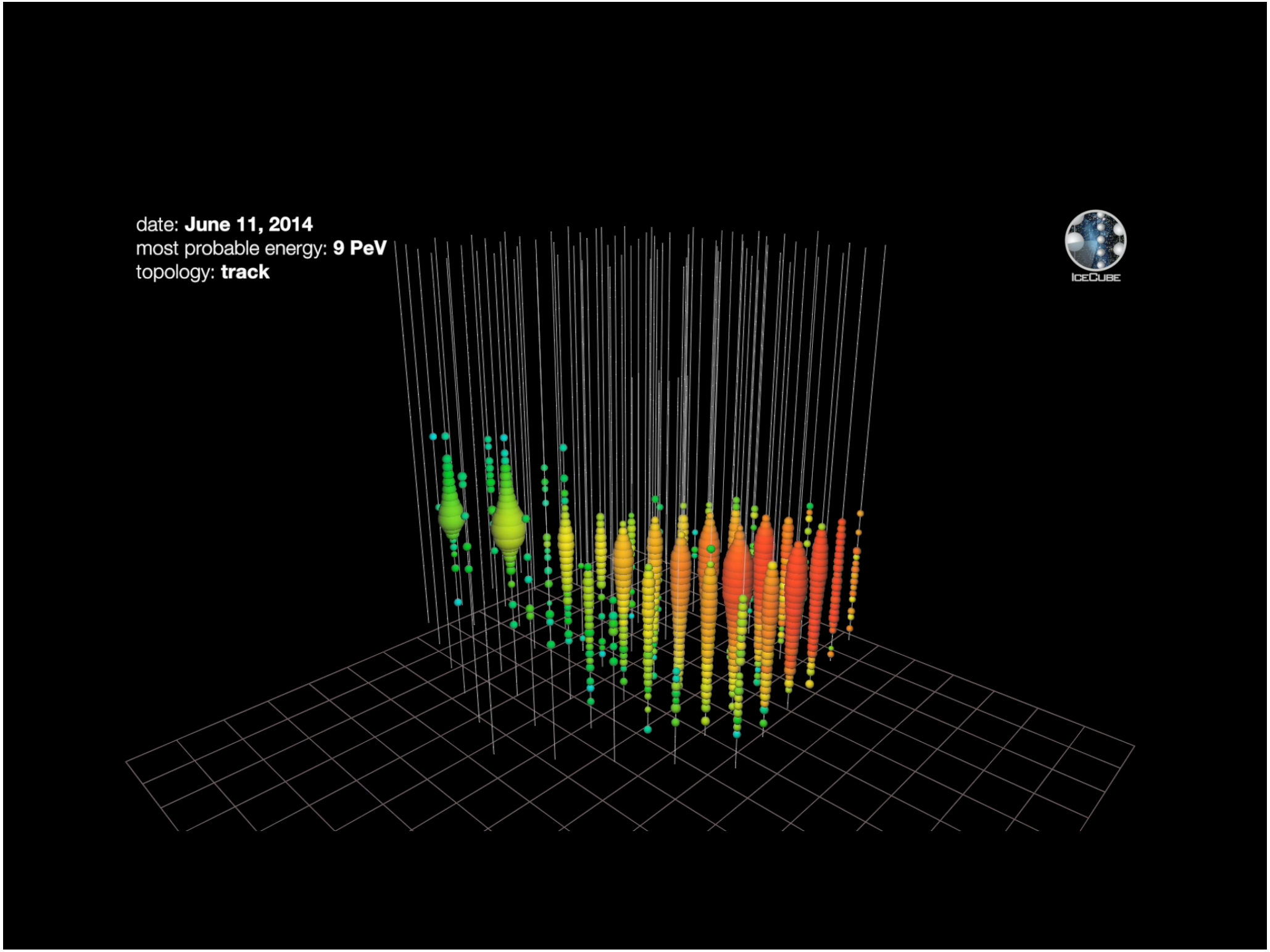
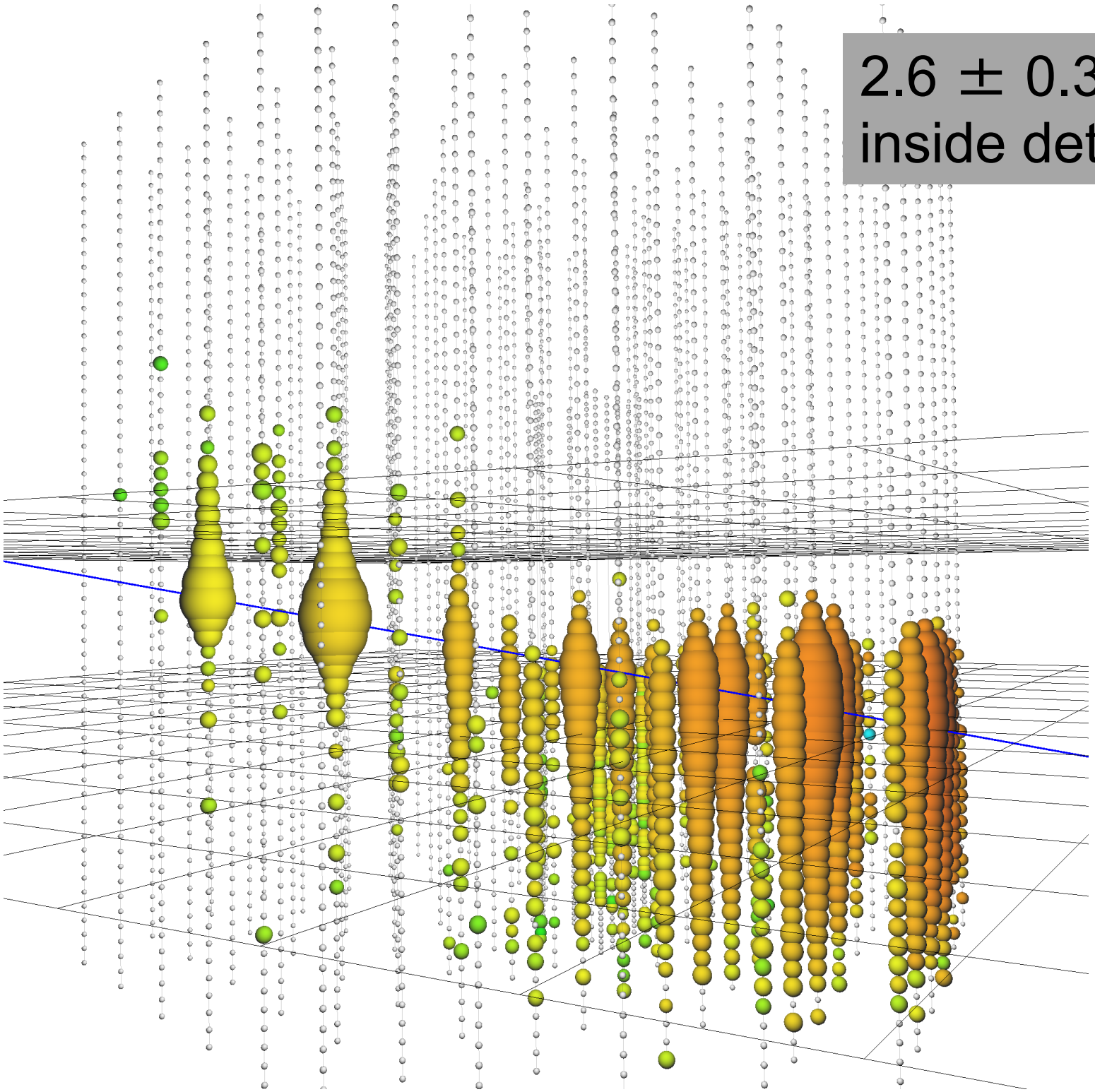
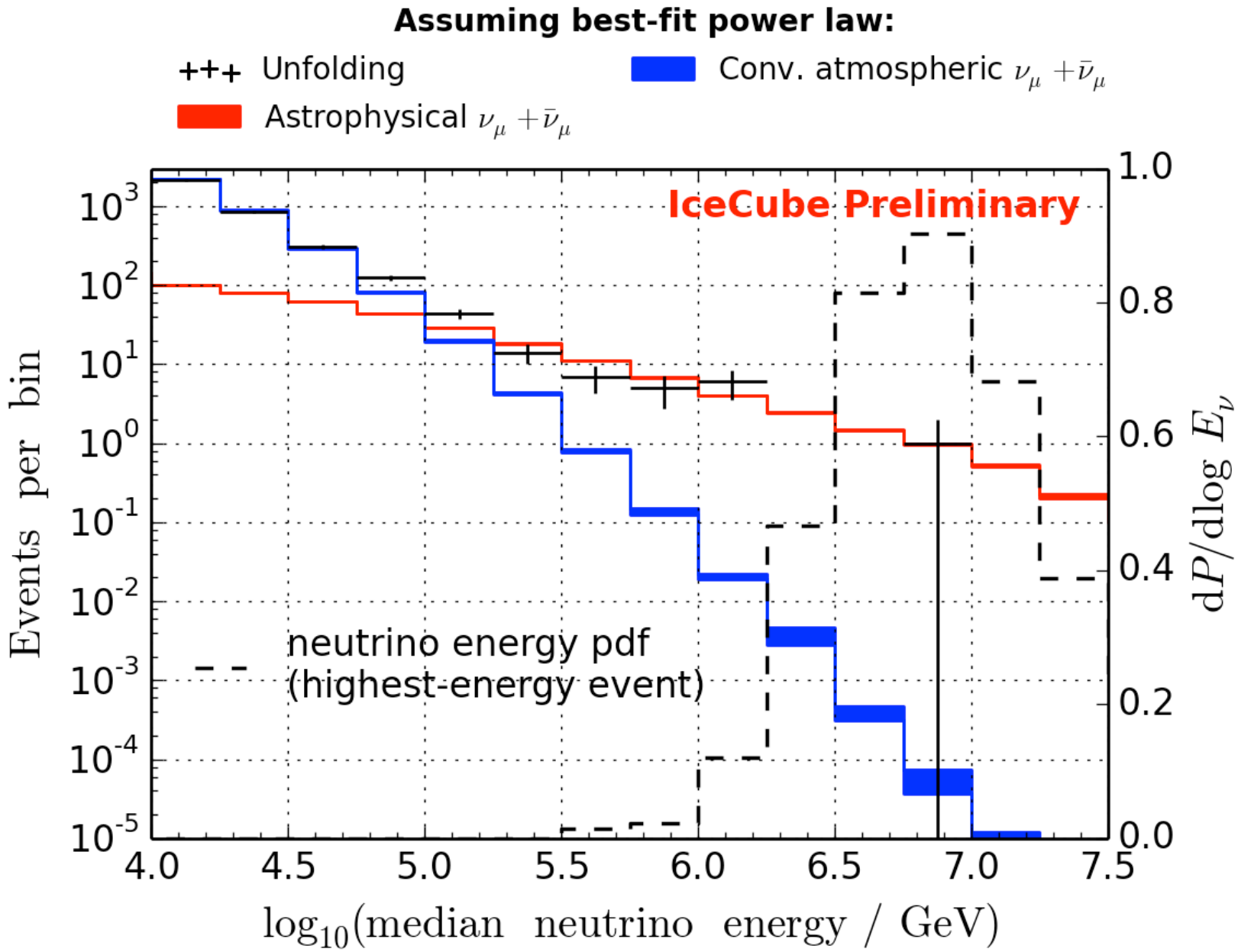
IceCube.wisc.edu


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

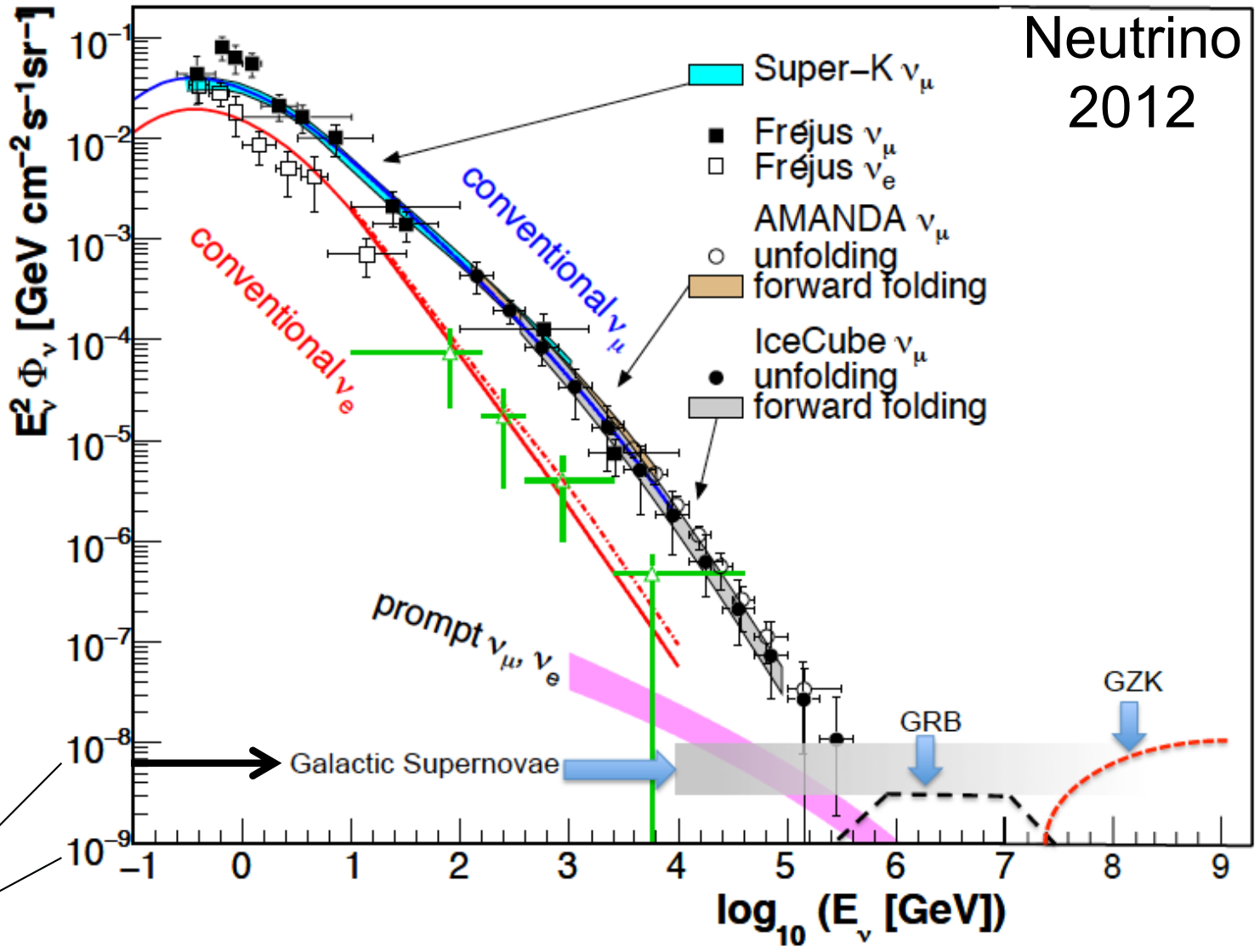


above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

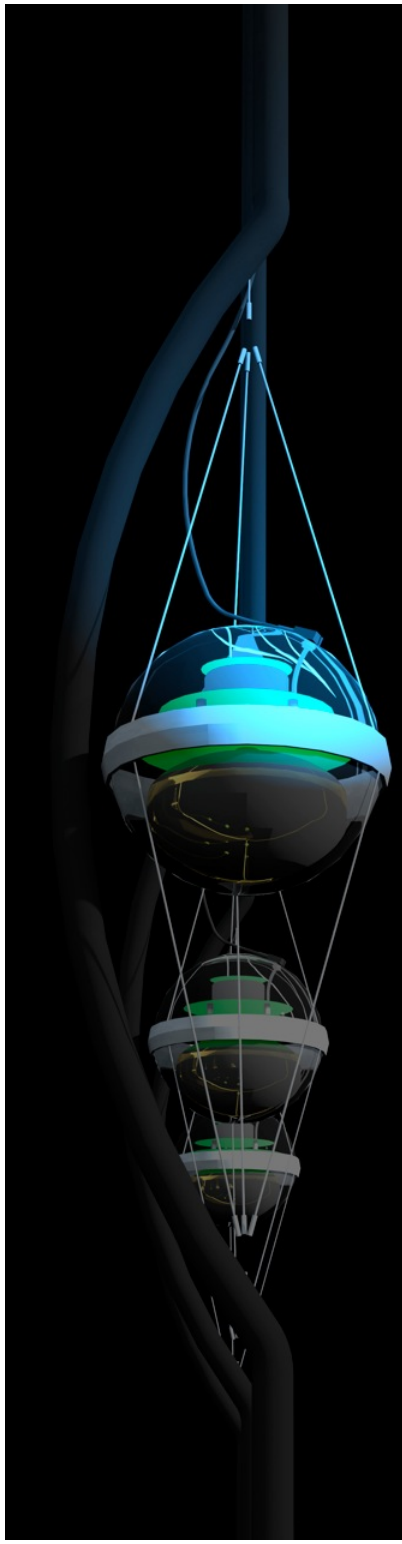
$dN/dE \sim E^{-2}$

10—100 events per year for fully efficient detector



atmospheric ⇑ cosmic

100 TeV



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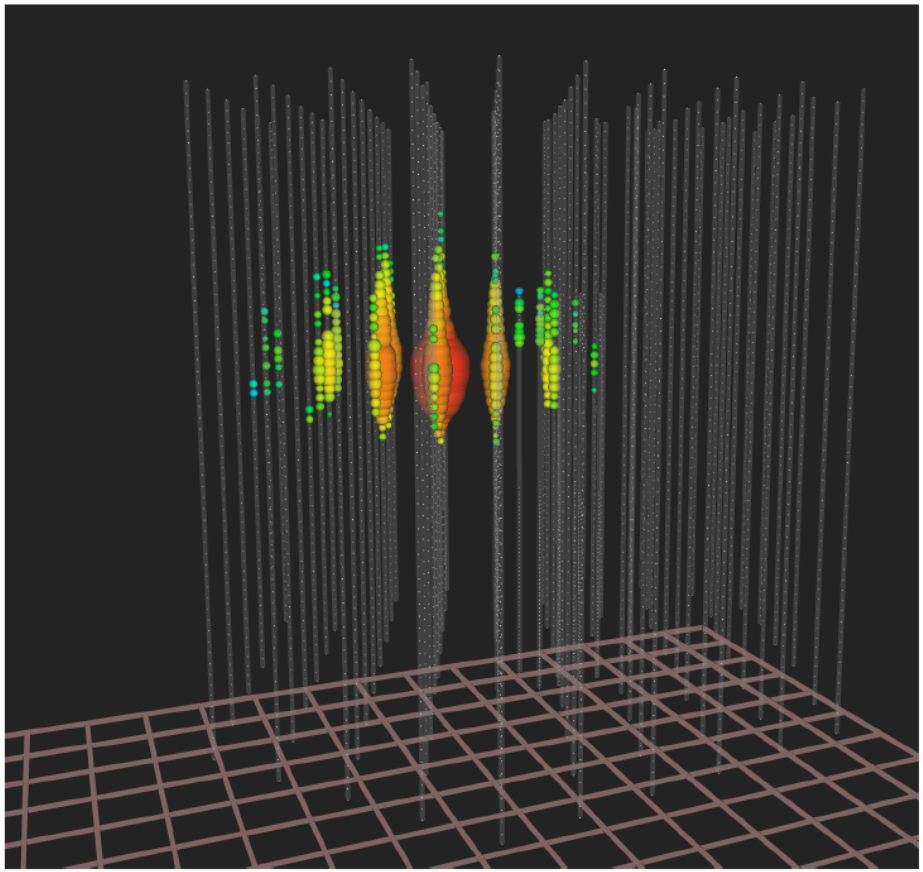
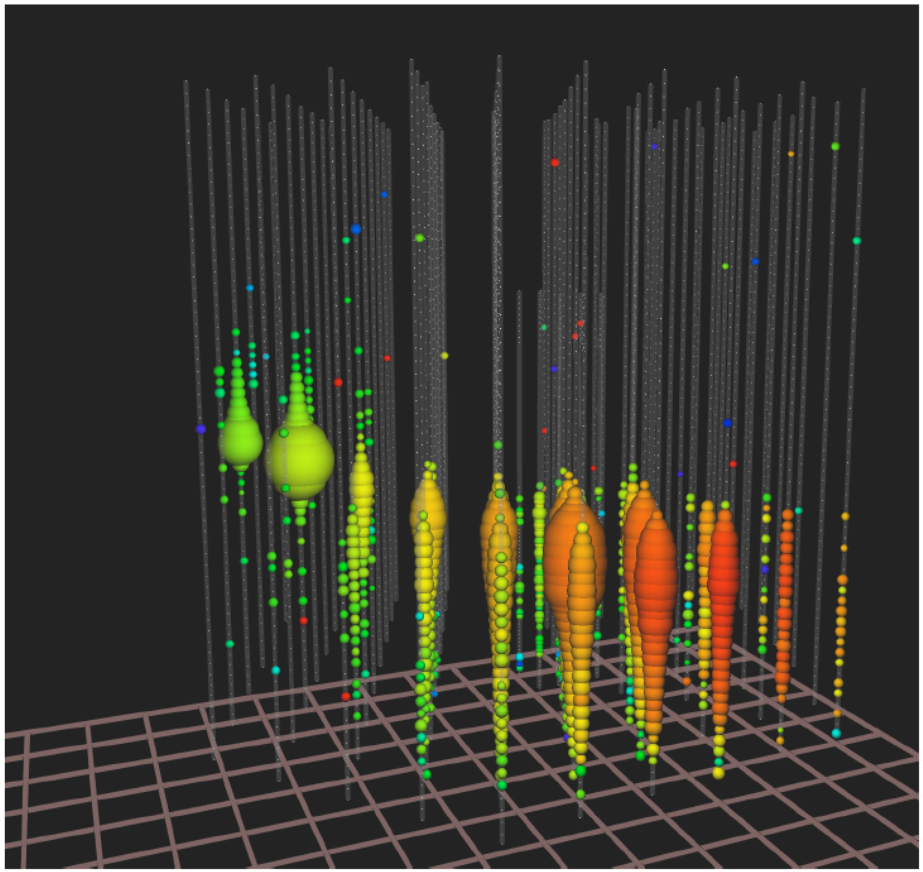
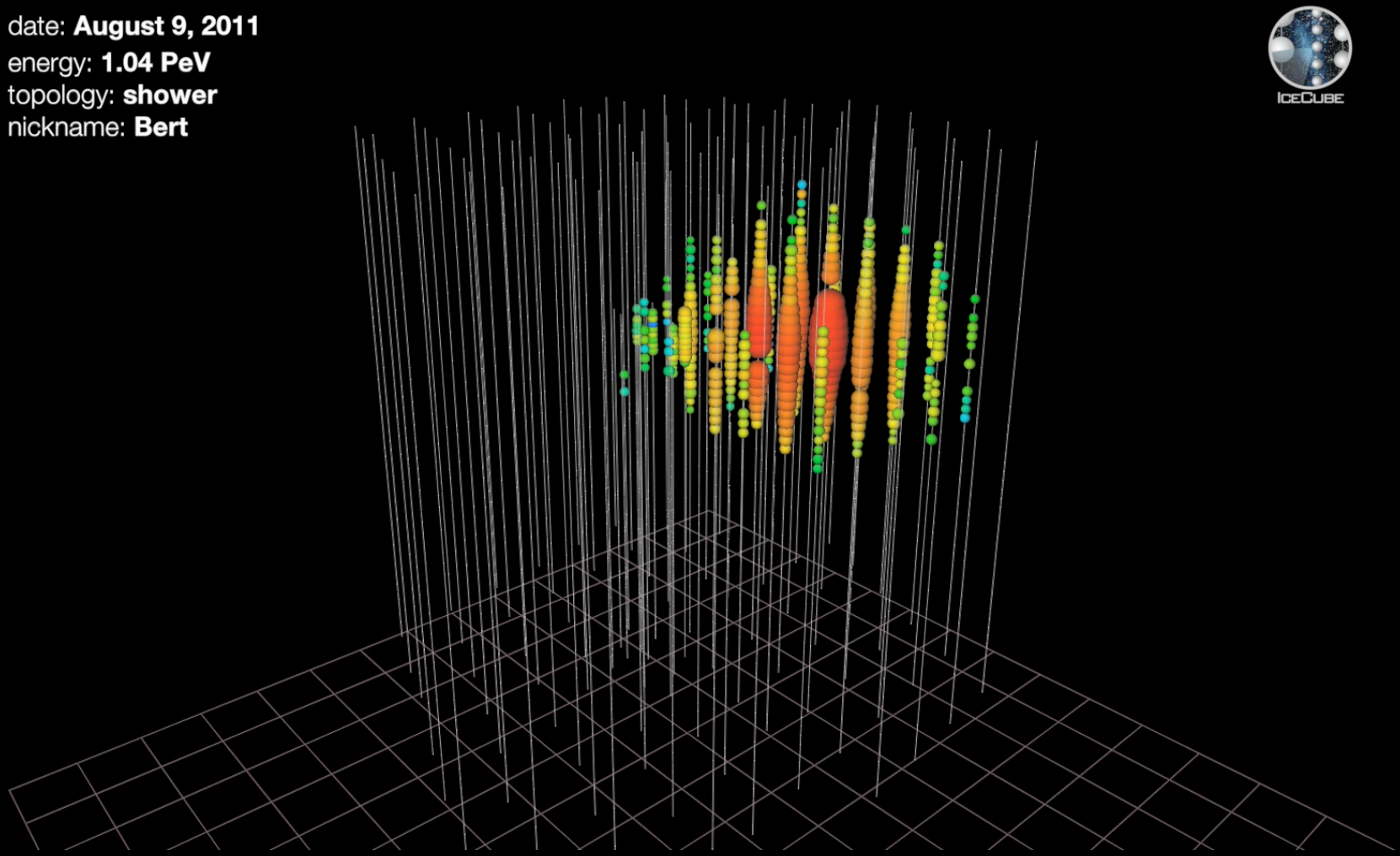




total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.5^{o})

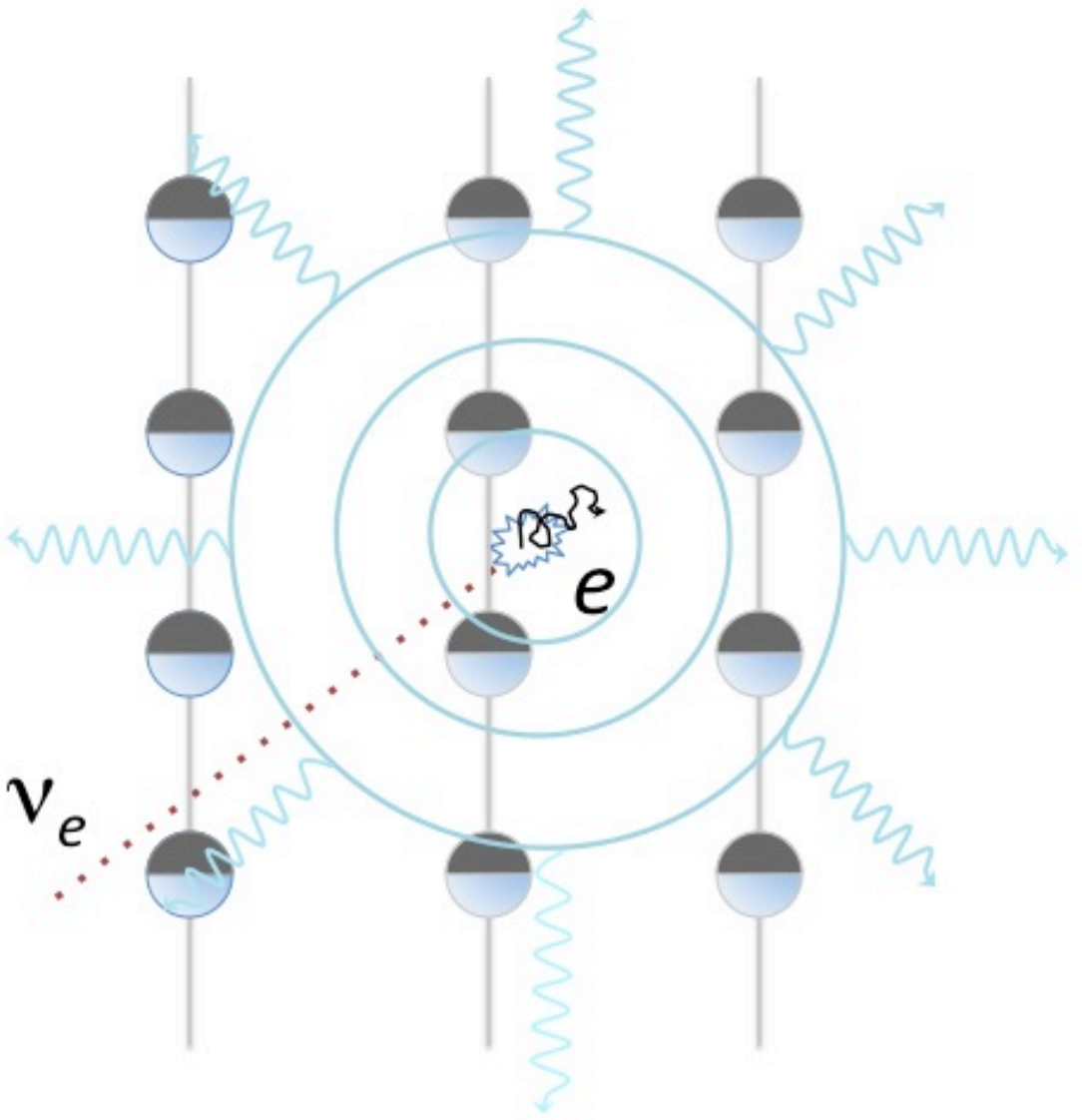
GZK neutrino search: two neutrinos with > 1,000 TeV

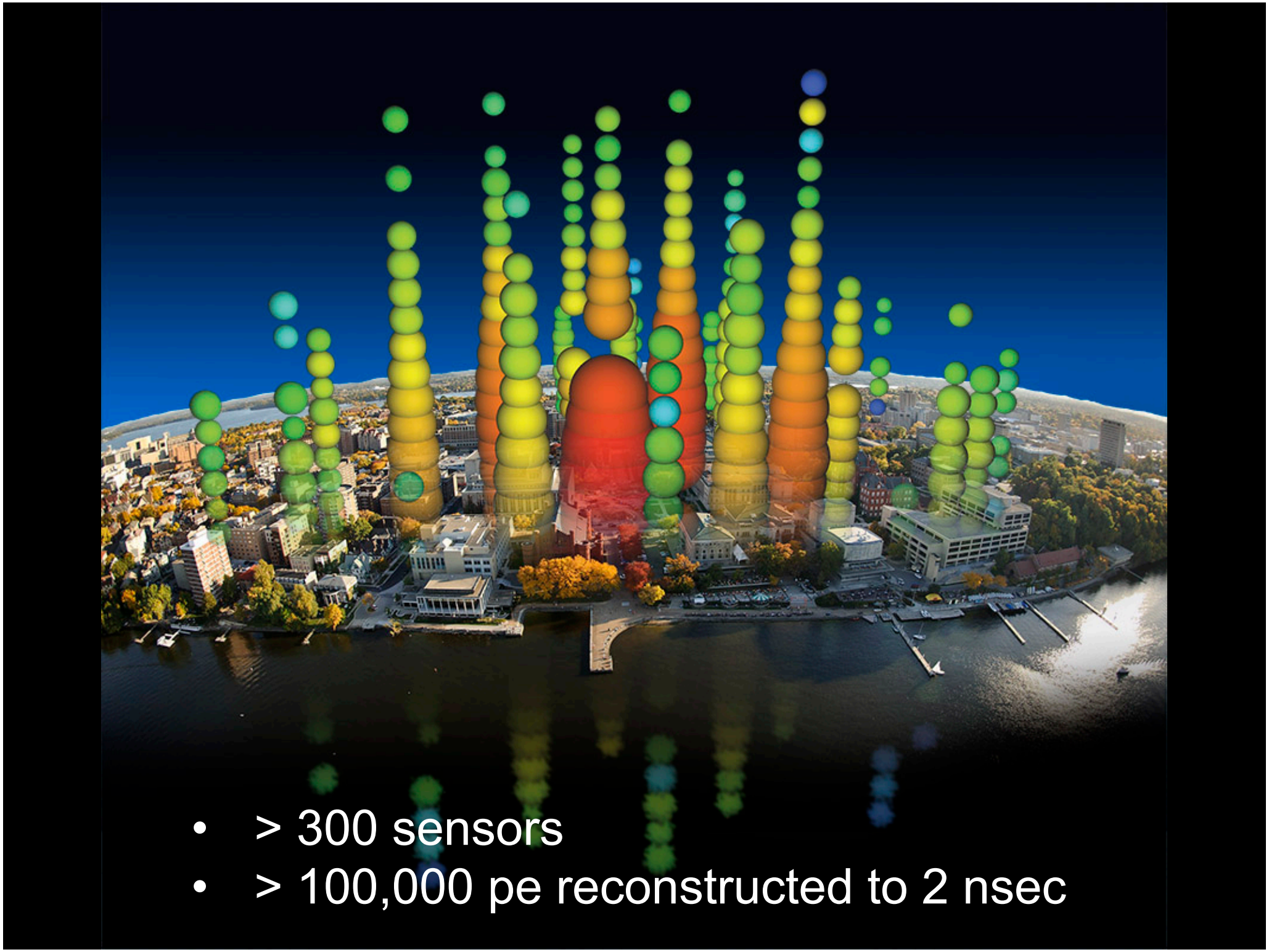


electron showers versus muon tracks

PeV ν_e and ν_τ showers:

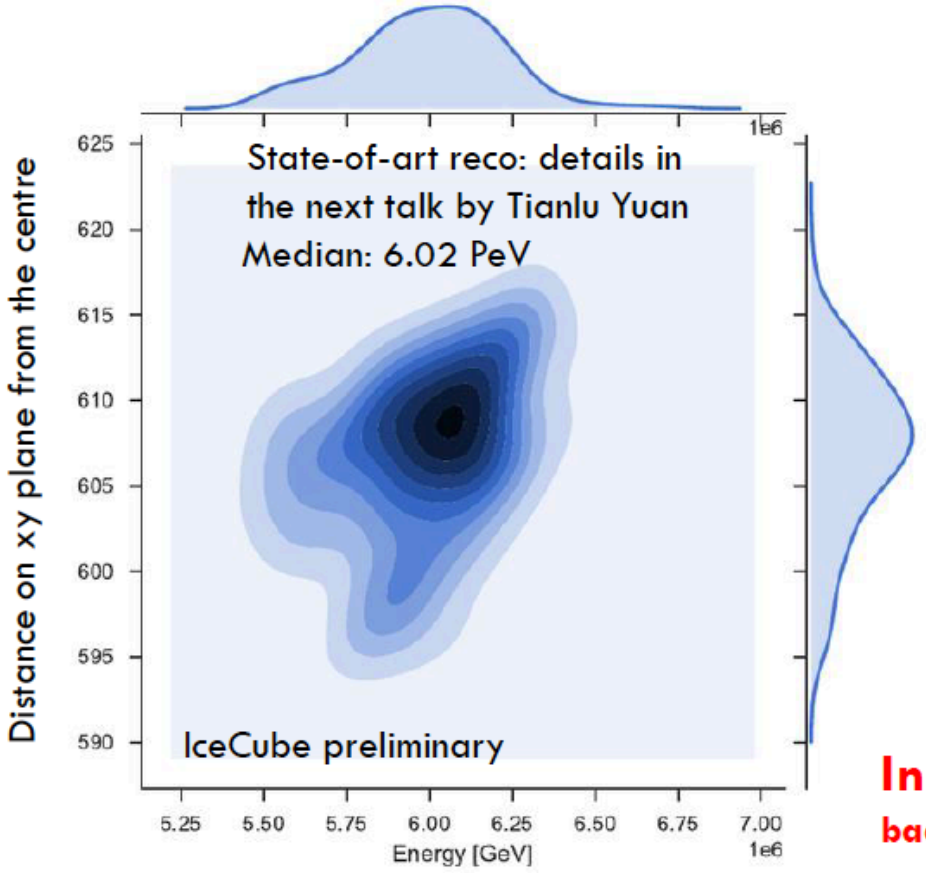
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m

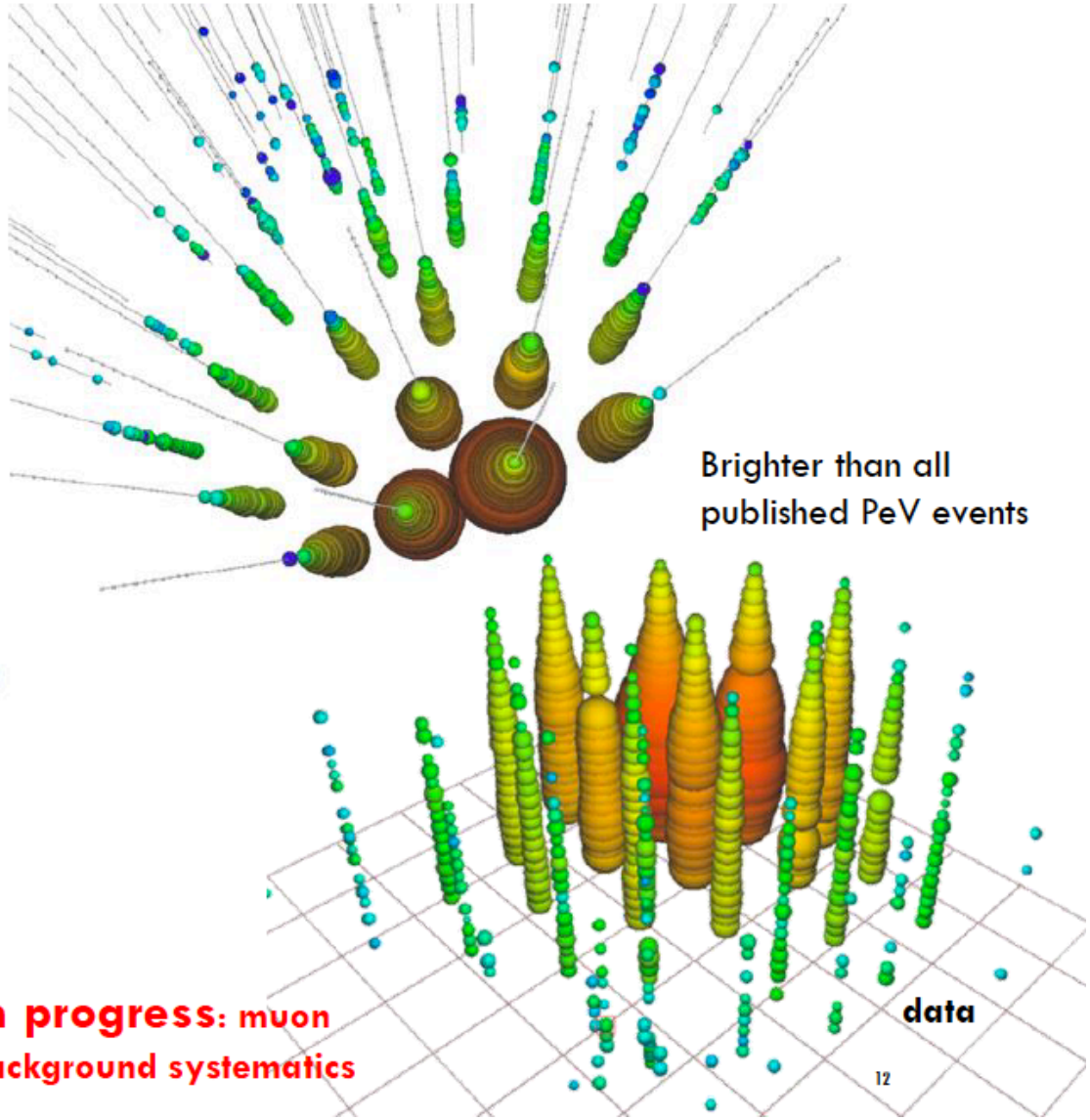



• > 300 sensors
• > 100,000 pe reconstructed to 2 nsec

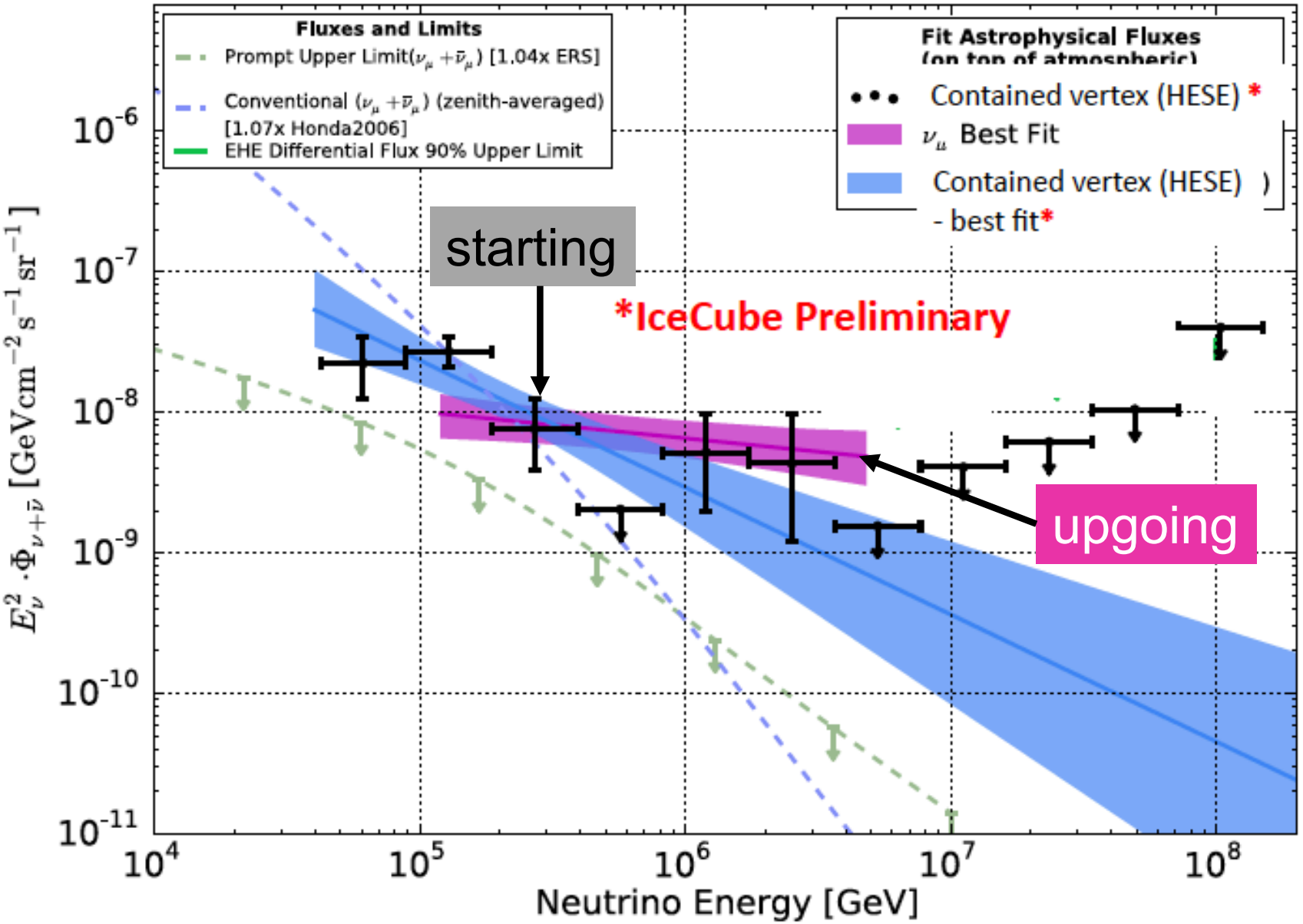
Partially contained event with energy ~ 6 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE

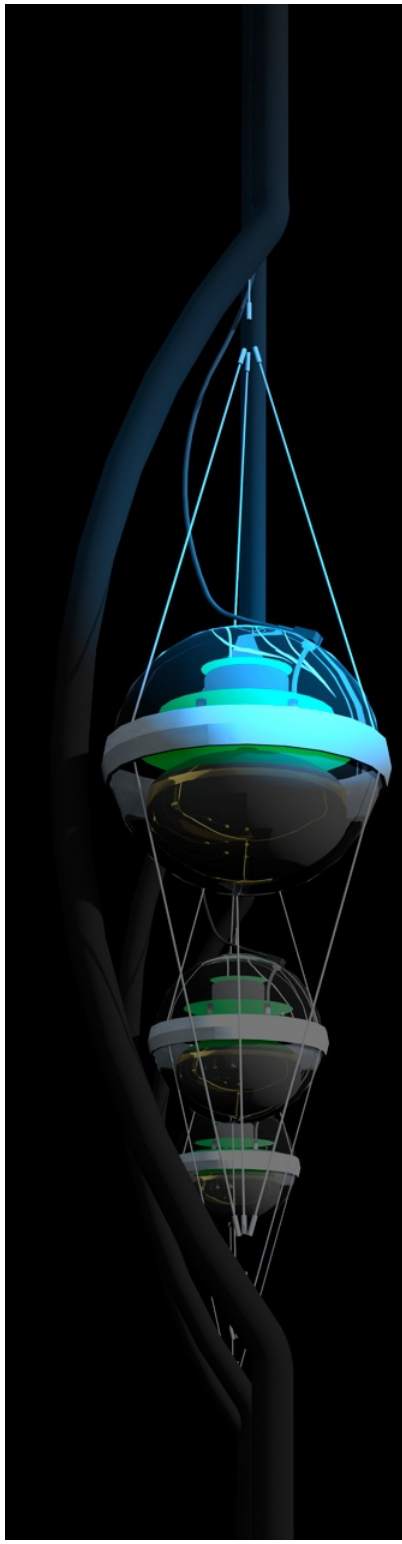




In progress: muon background systematics



two methods are consistent



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- where do they come from?
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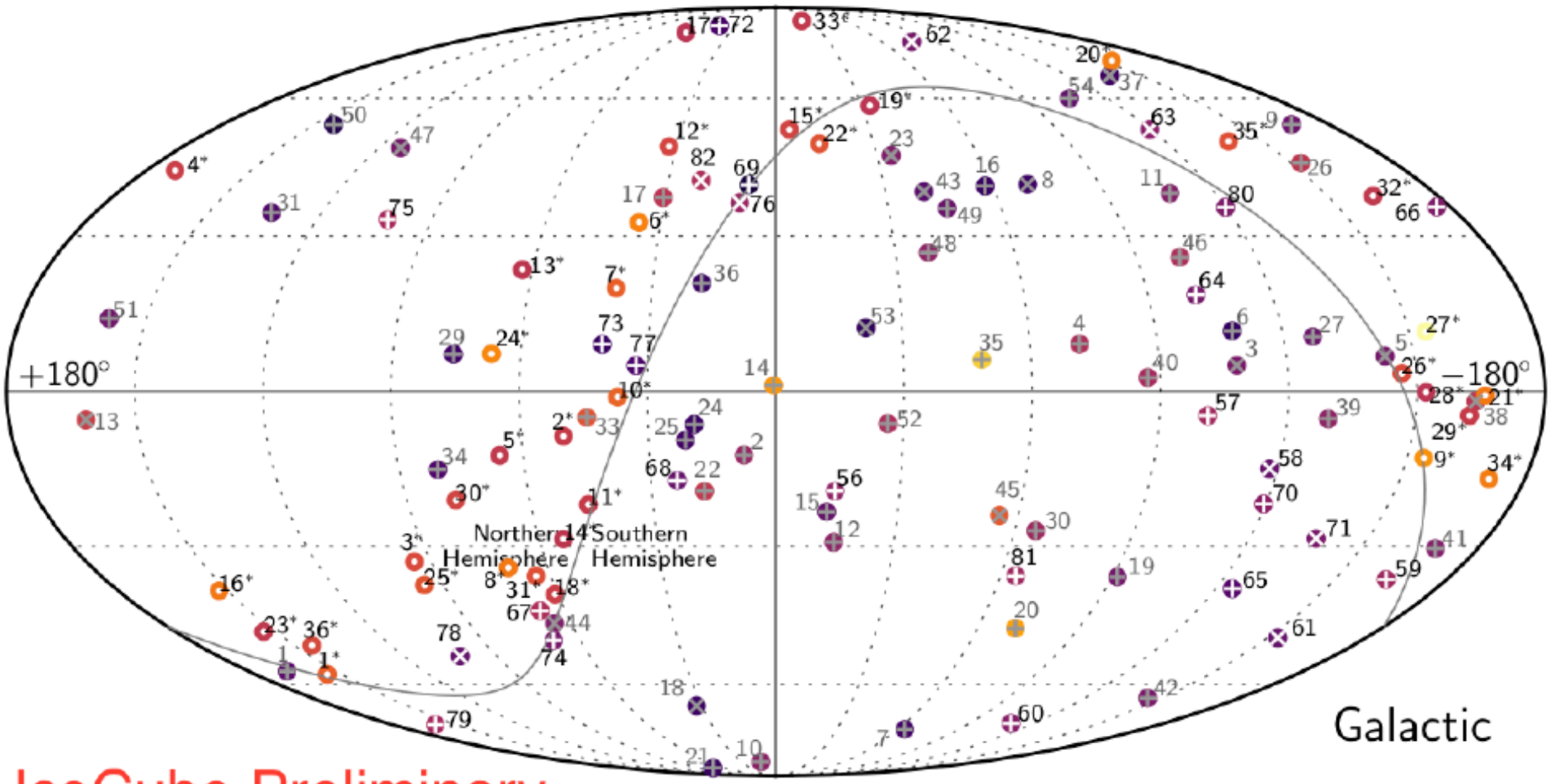
- the first high-energy cosmic ray accelerator
- what next?

iceCube.wisc.edu



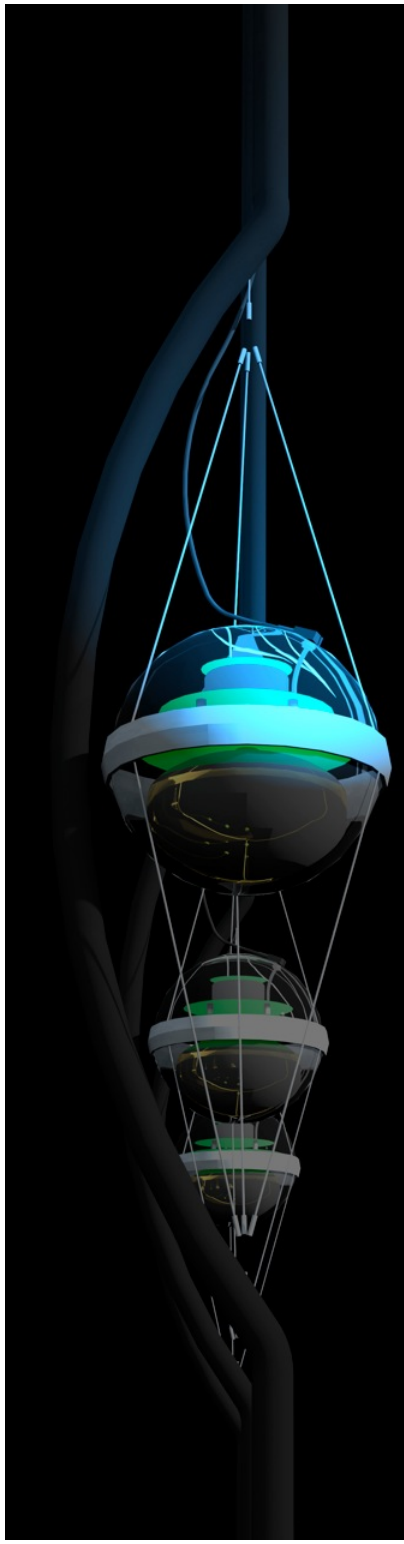
IceCube Preliminary

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

- 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 photons accompanying PeV neutirnos?



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- cosmic neutrinos below 100 TeV?

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neutral pions

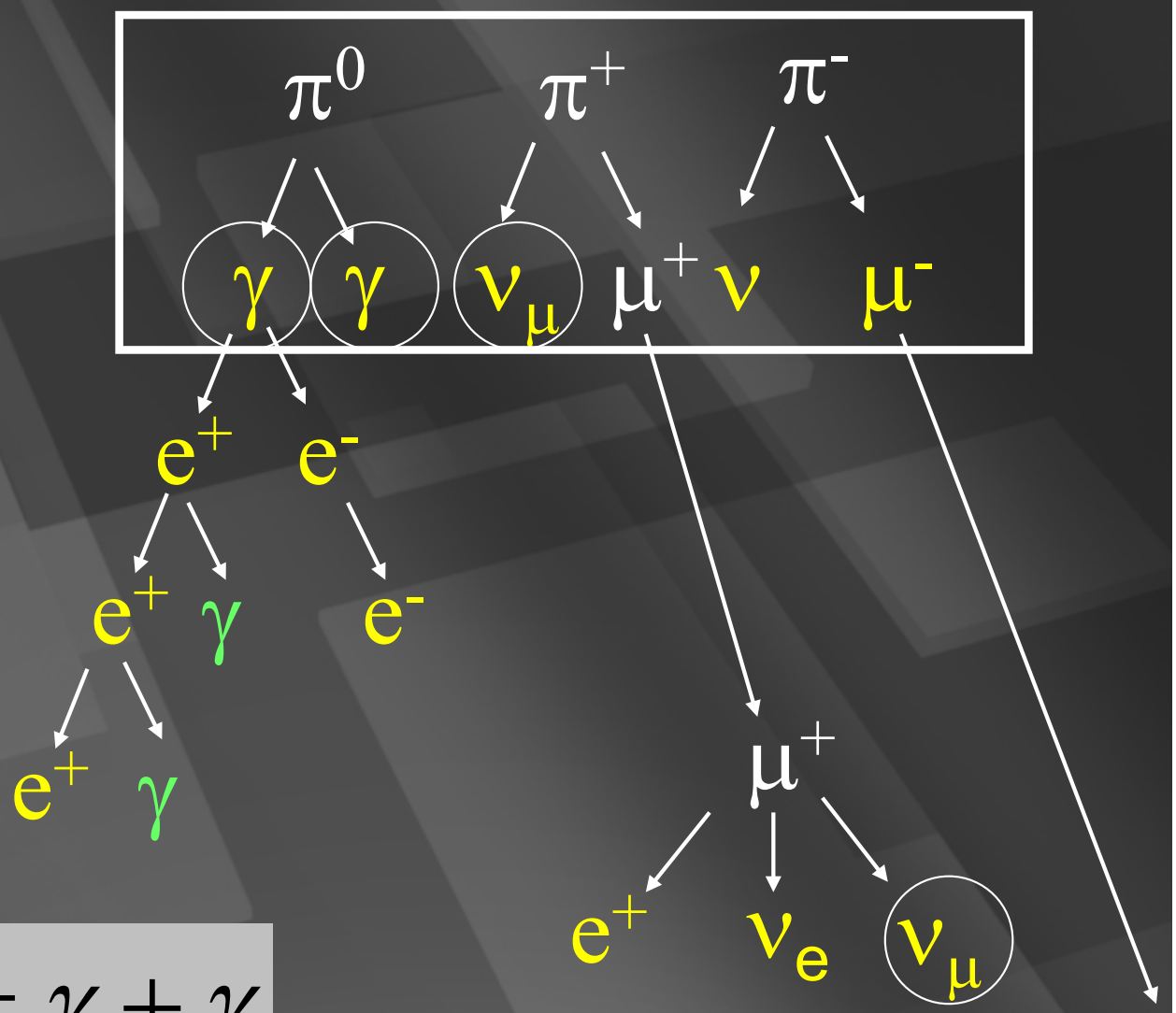
are observed as

gamma rays

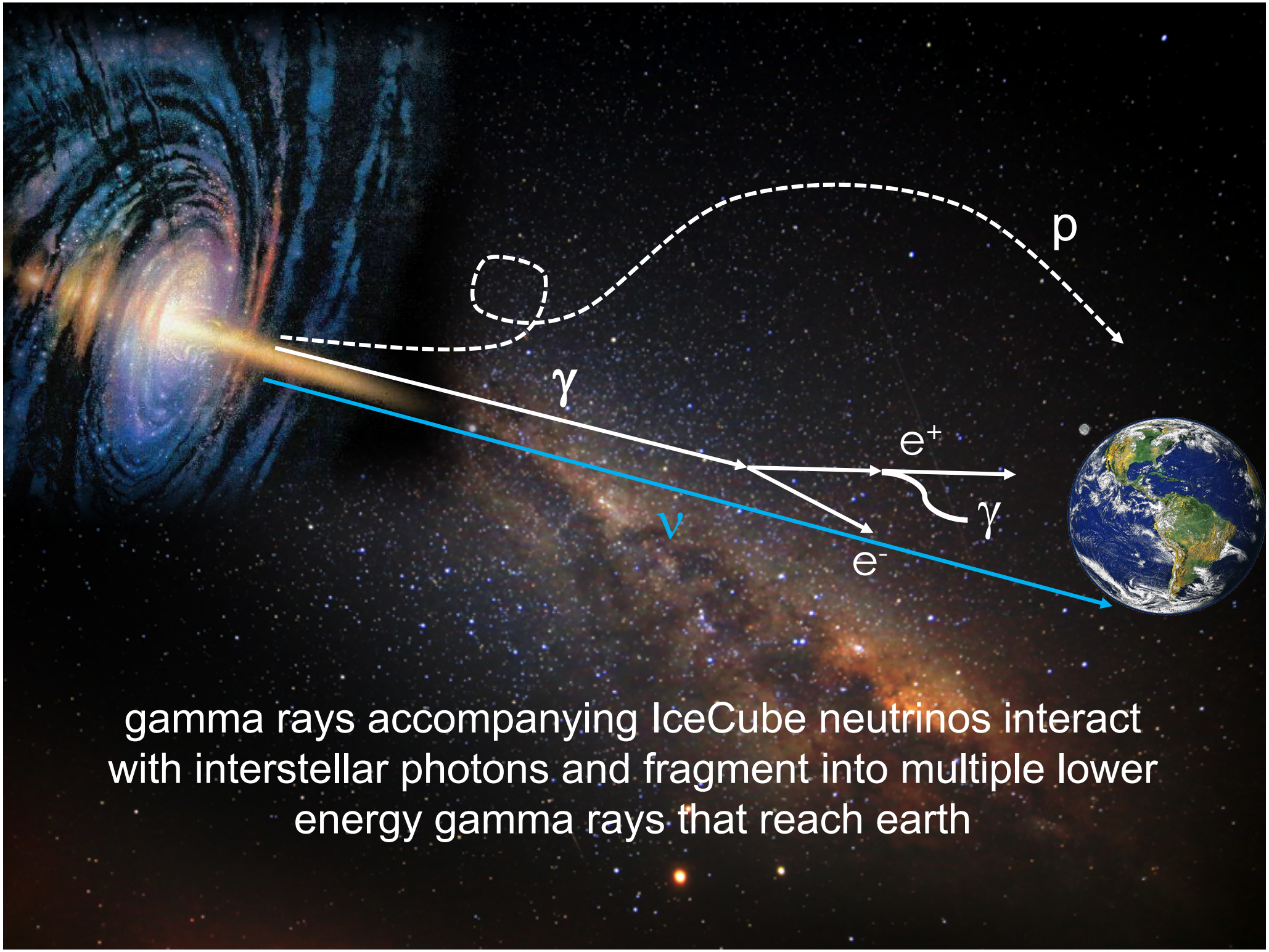
charged pions

are observed as

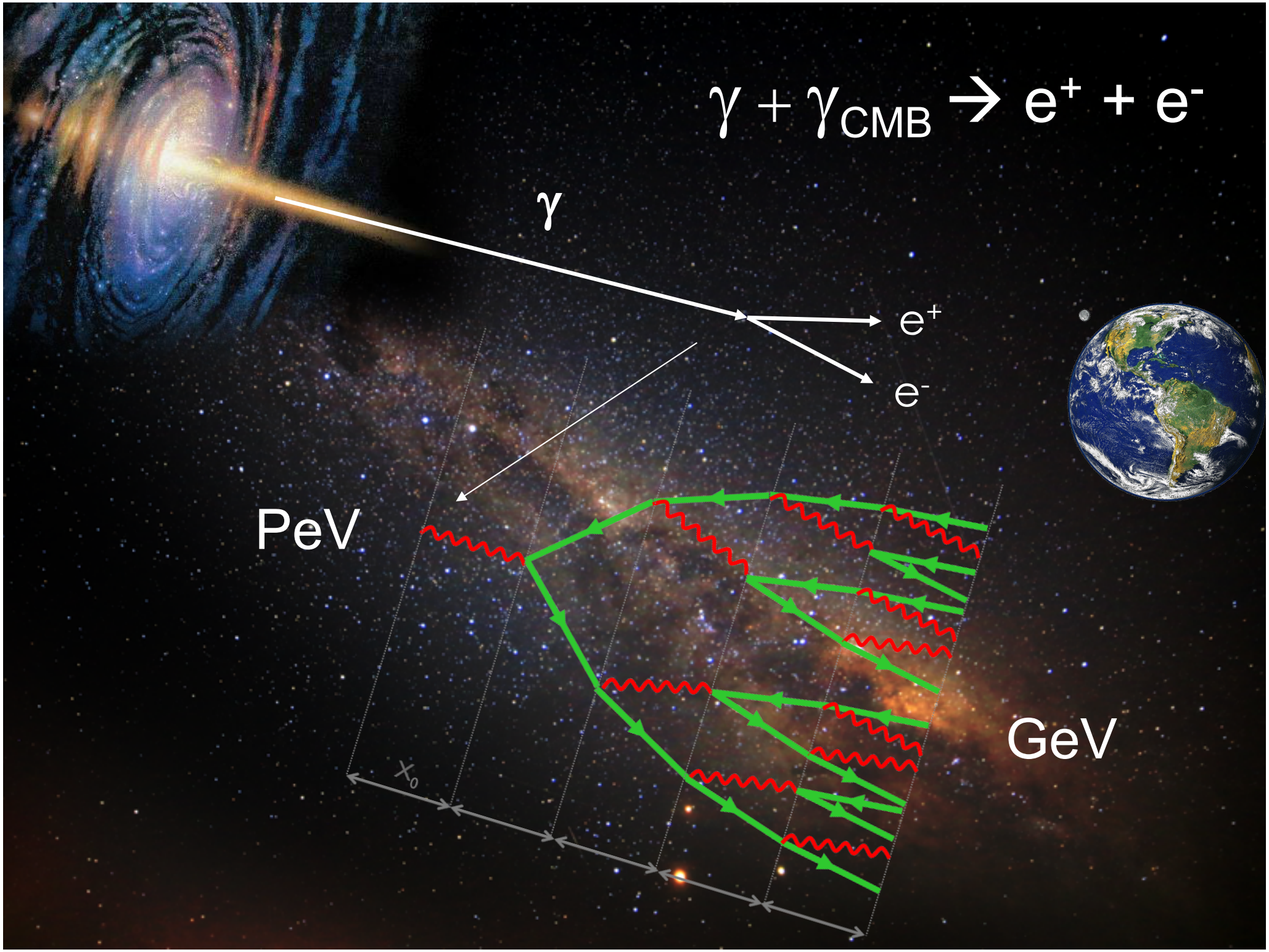
neutrinos

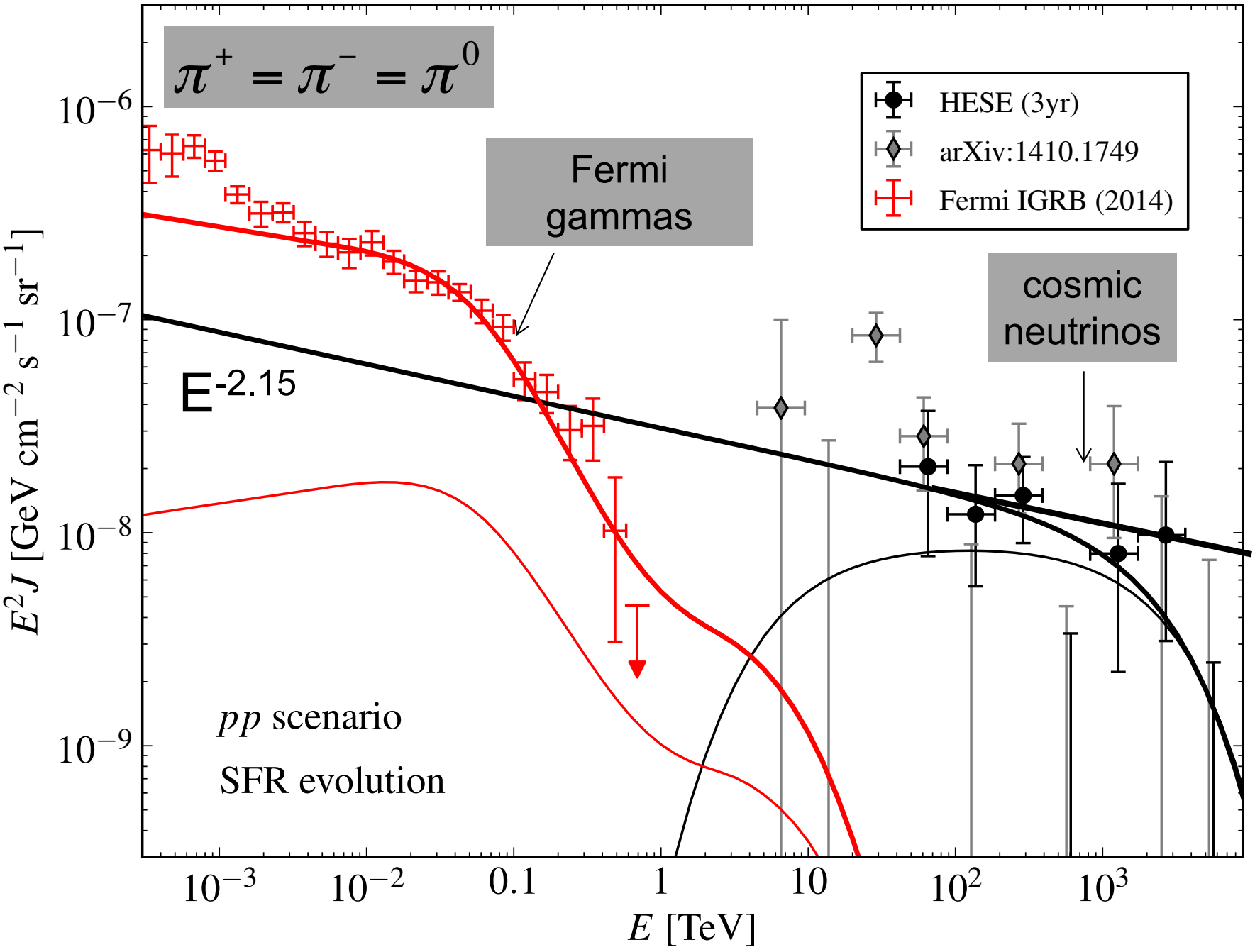


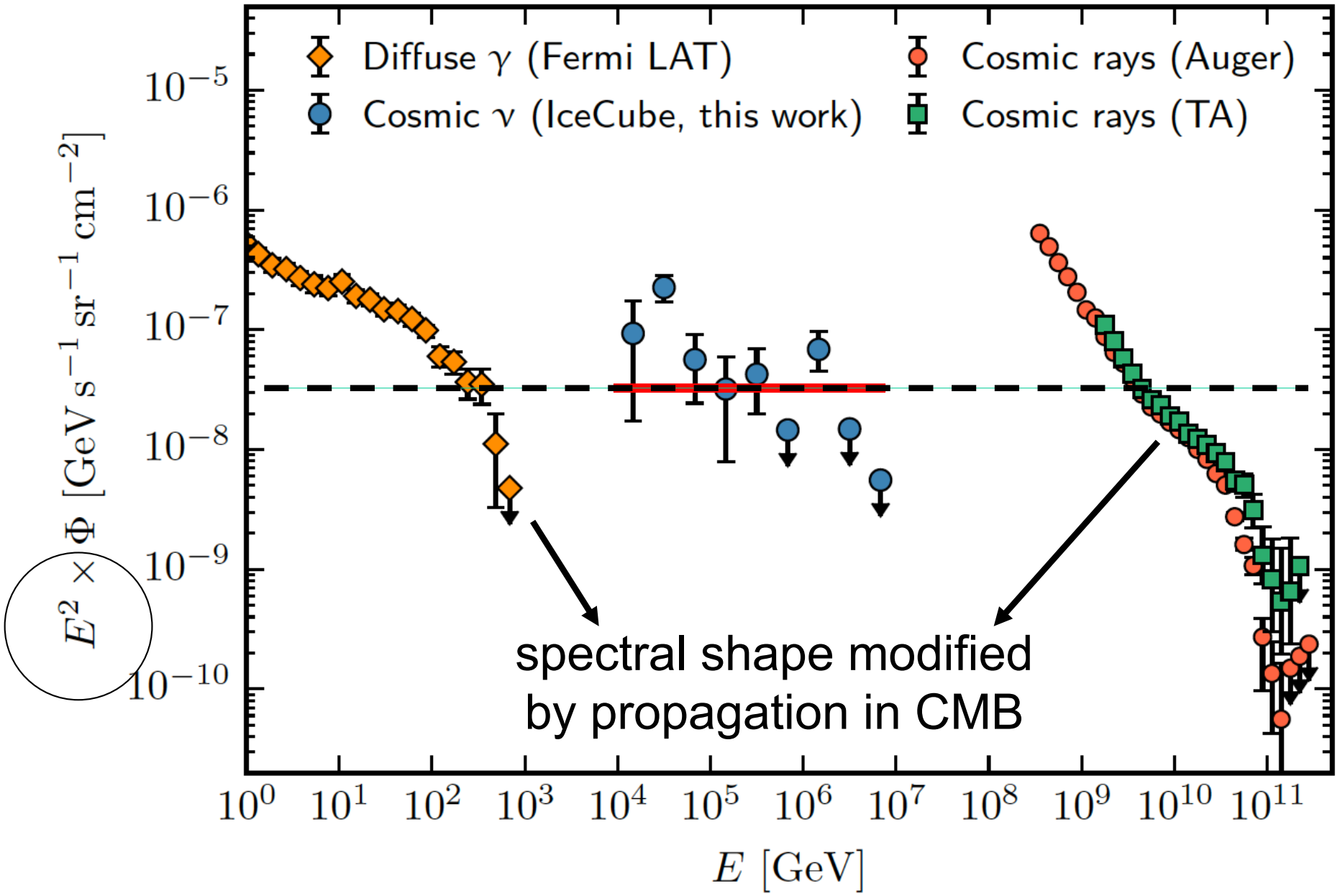
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$



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

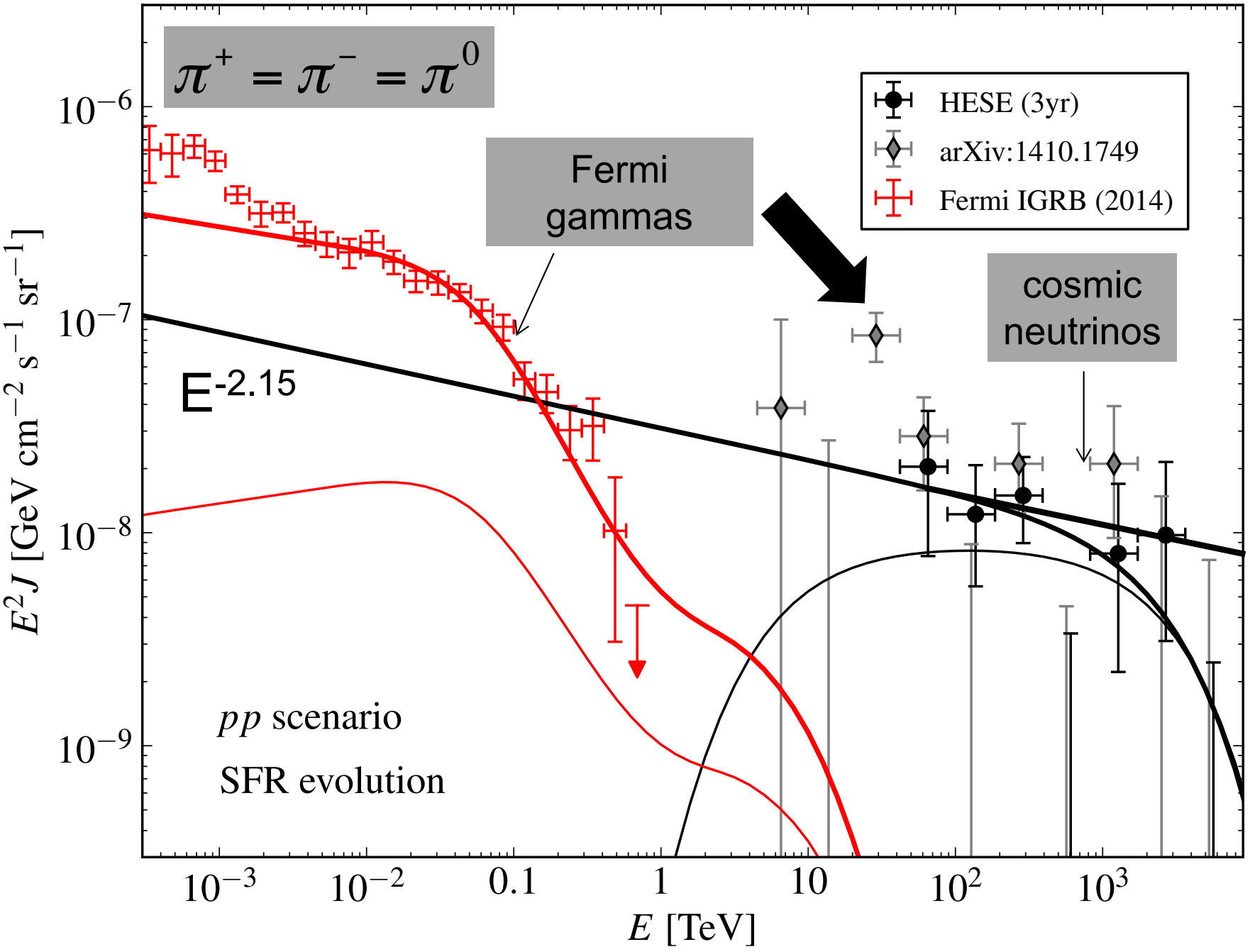

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0

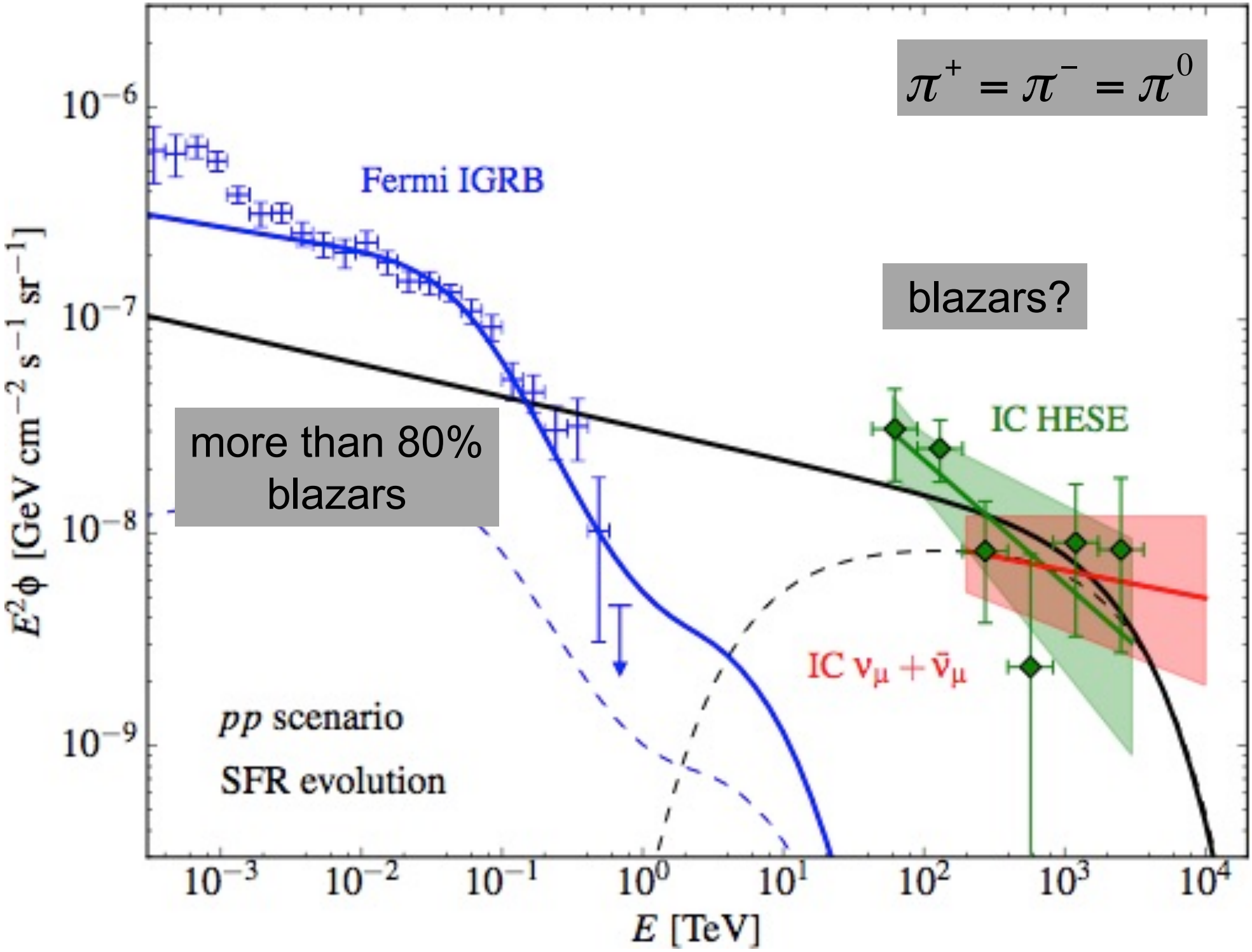

$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
E-2.15
pp scenario
SFR evolution
E^2J [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

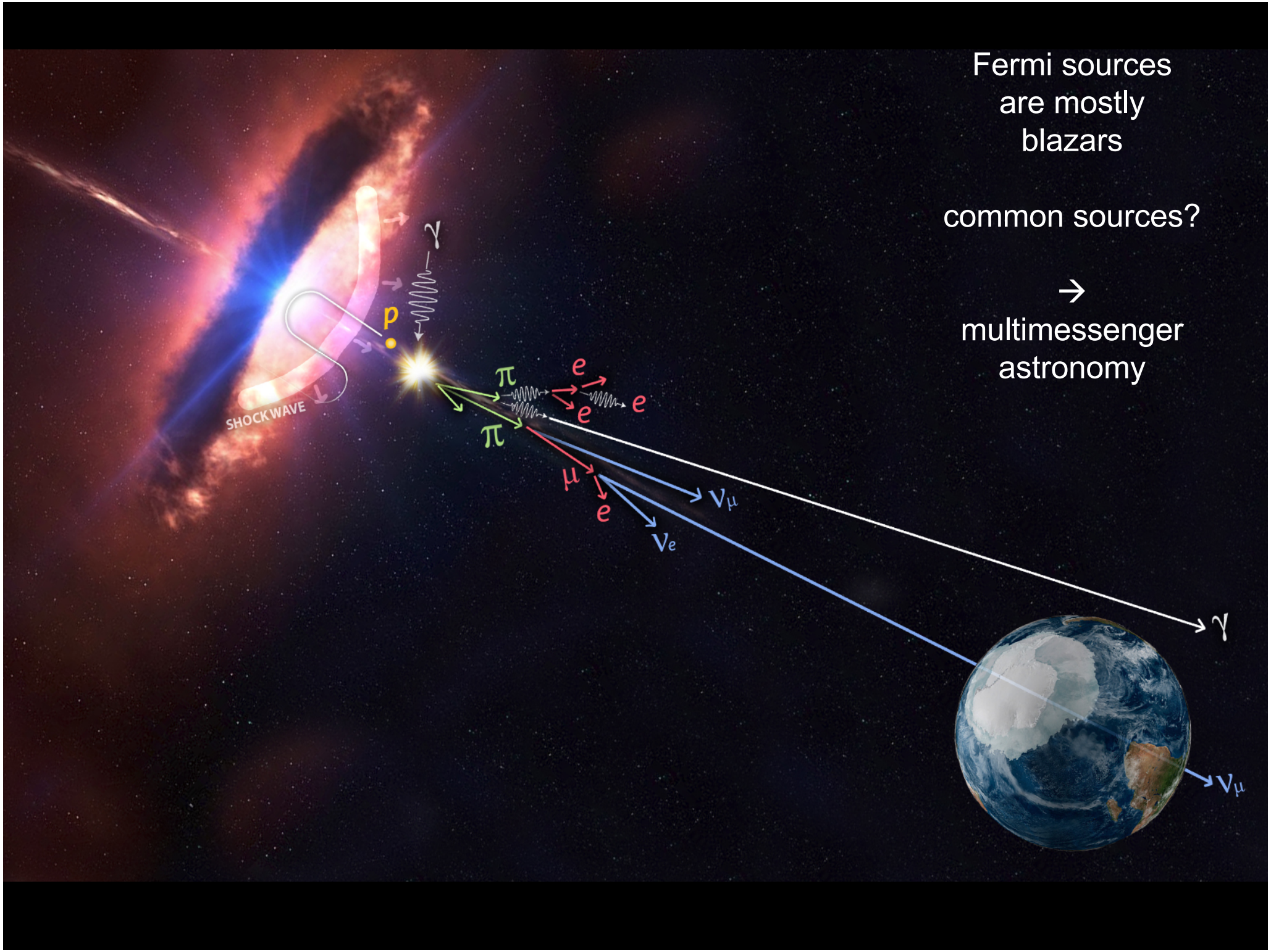


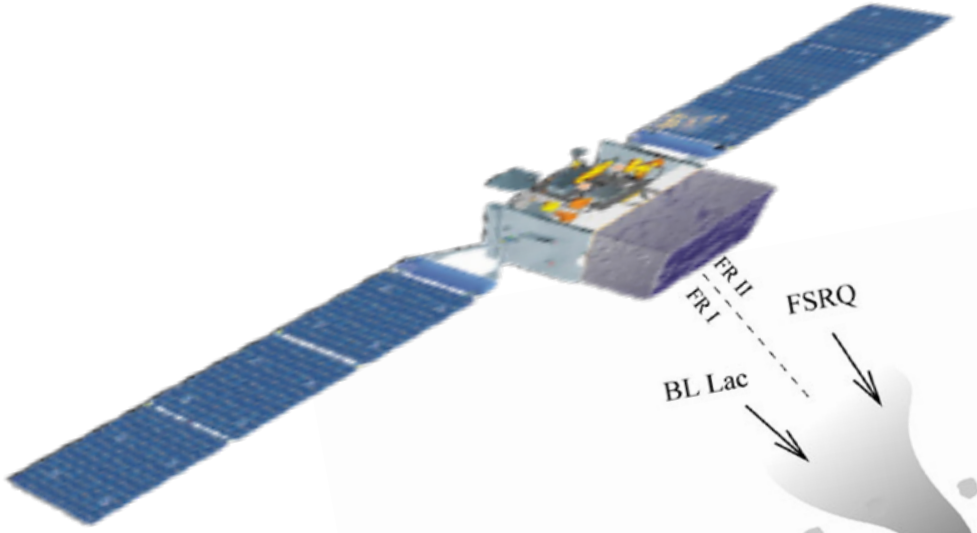
energy in the Universe in gamma rays, neutrinos and cosmic rays

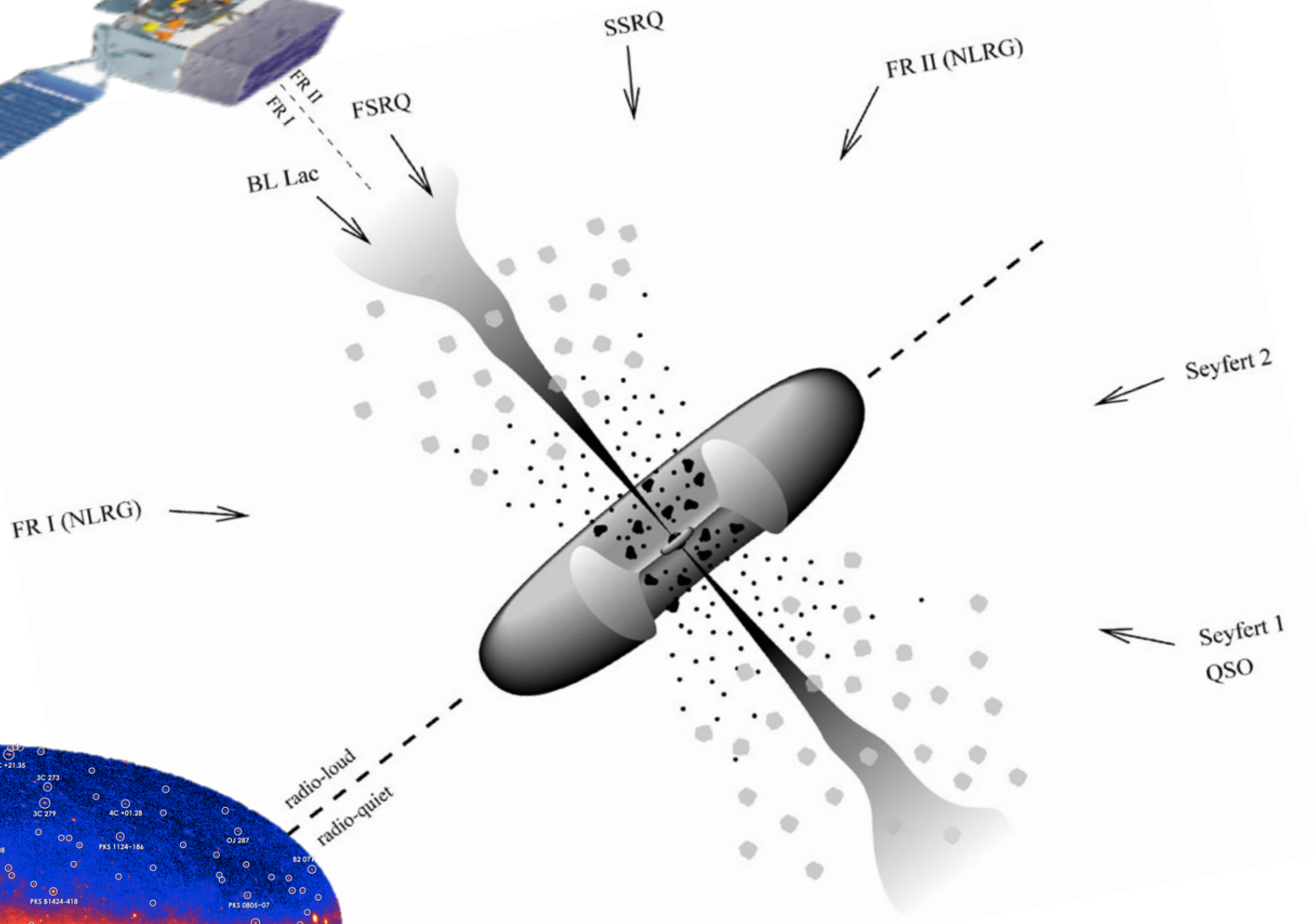
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays (and cosmic rays!)

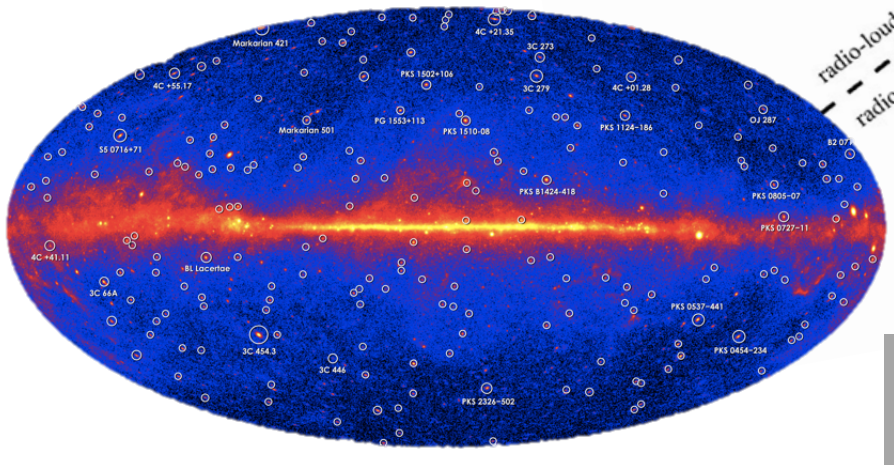

$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
E-2.15
pp scenario
SFR evolution
E^2J [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3


$\pi^+ = \pi^- = \pi^0$
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}

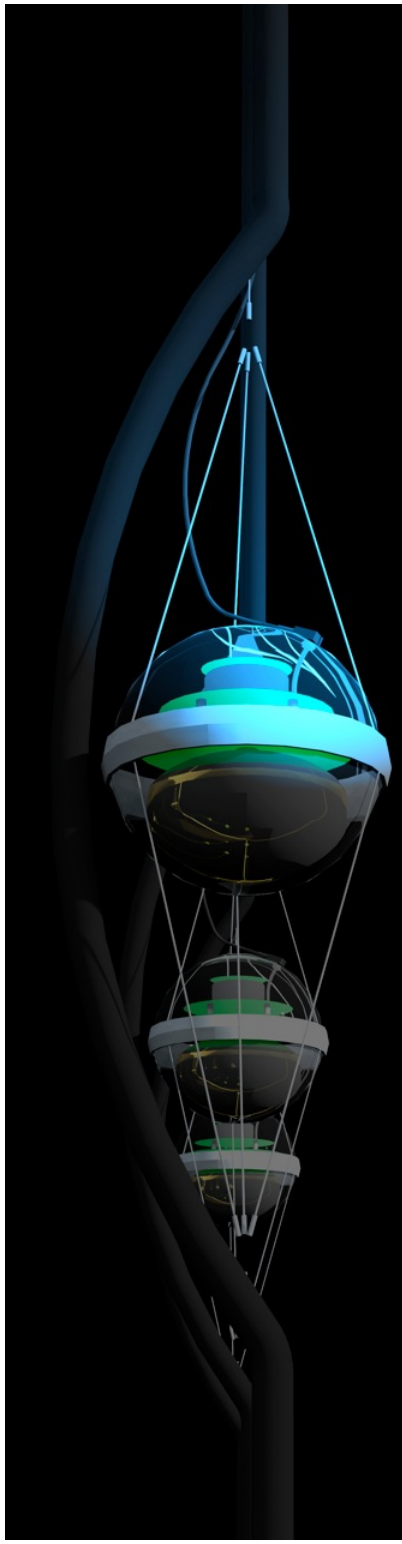

Fermi sources
are mostly
blazars
common sources?
→
multimessenger
astronomy
γ
p
SHOCK WAVE
π
e
e
e
π
μ
e
ν_μ
ν_e
γ
ν_μ







Fermi sky: mostly blazars

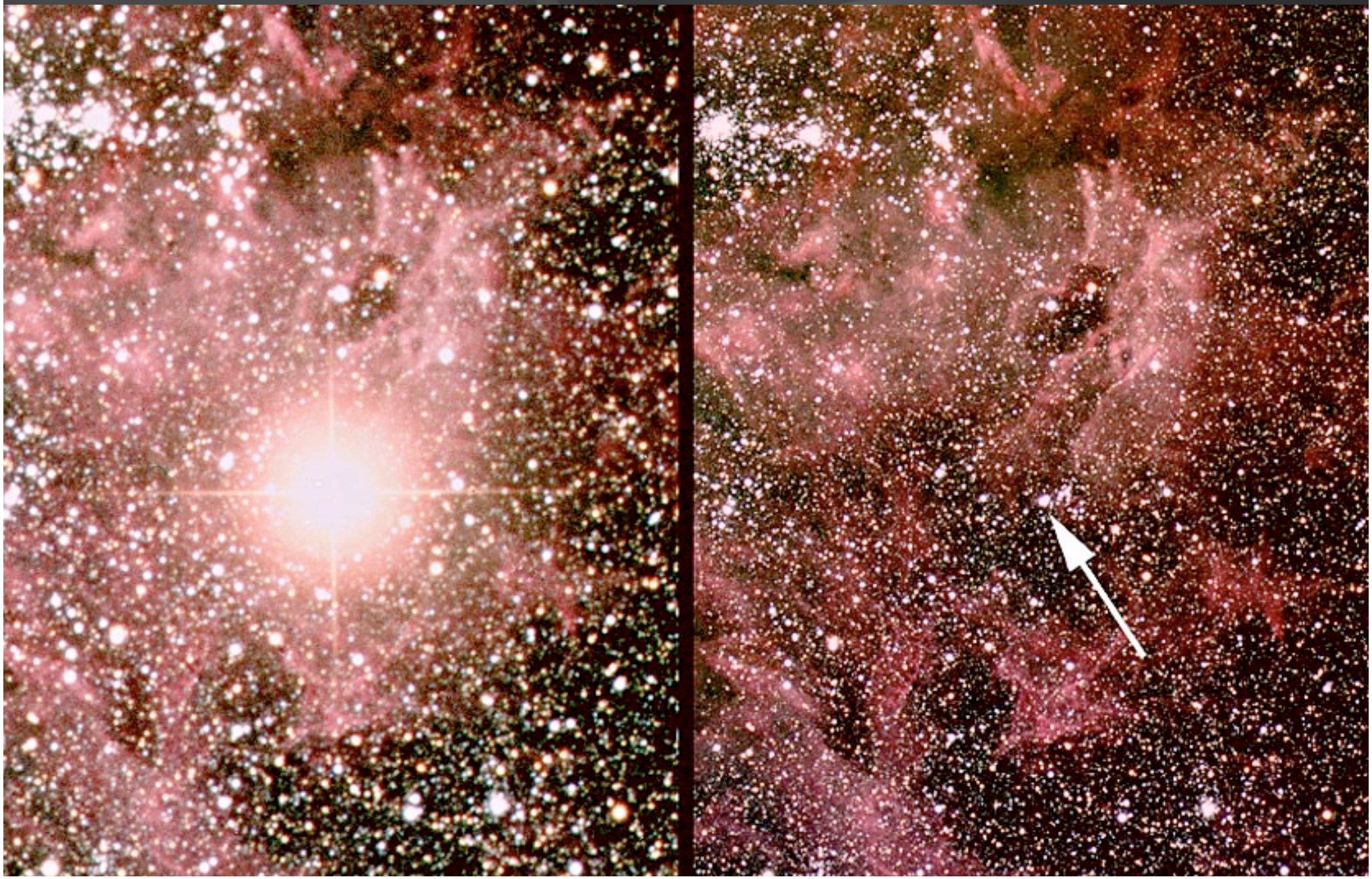


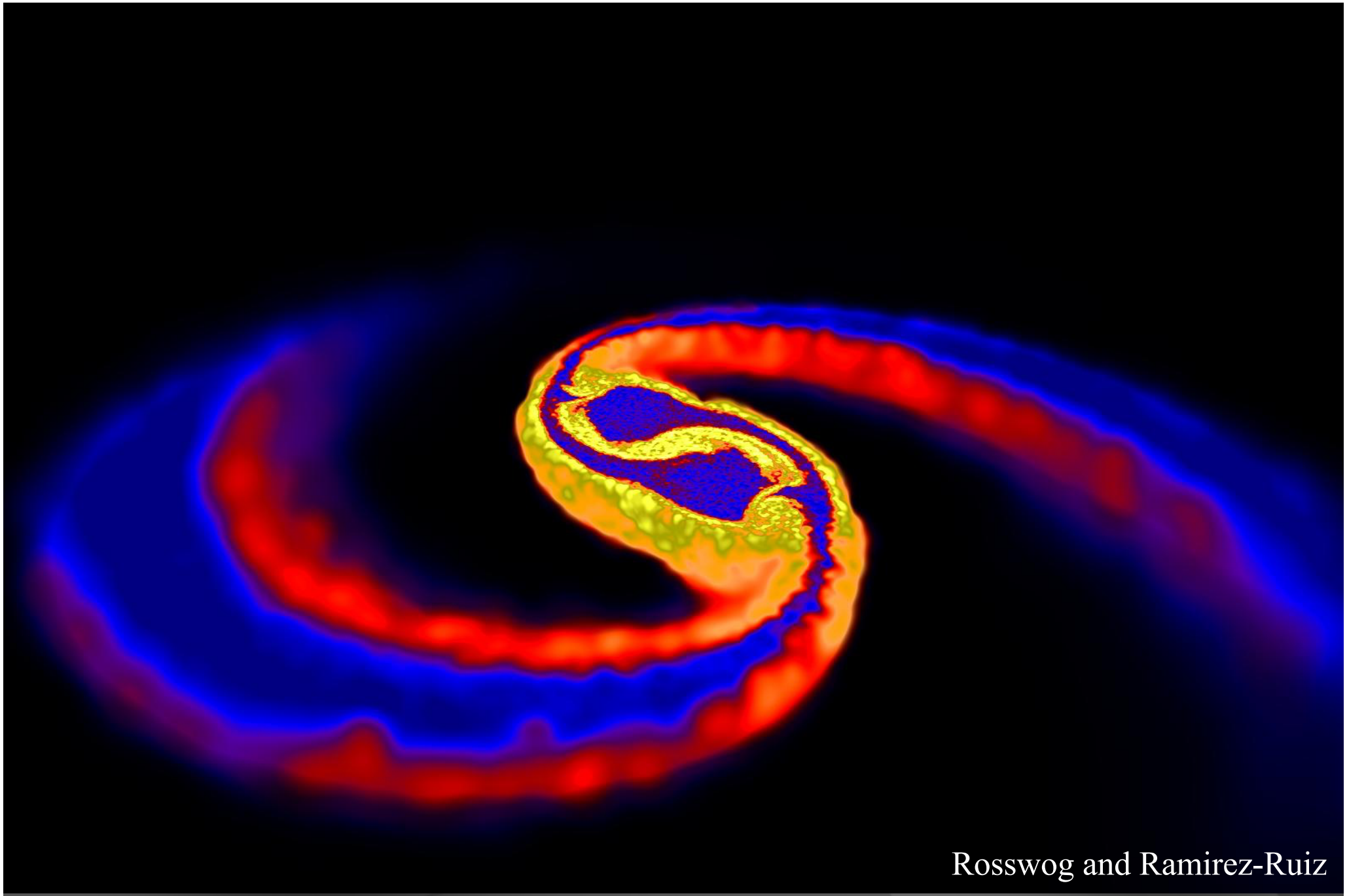
IceCube

francis halzen

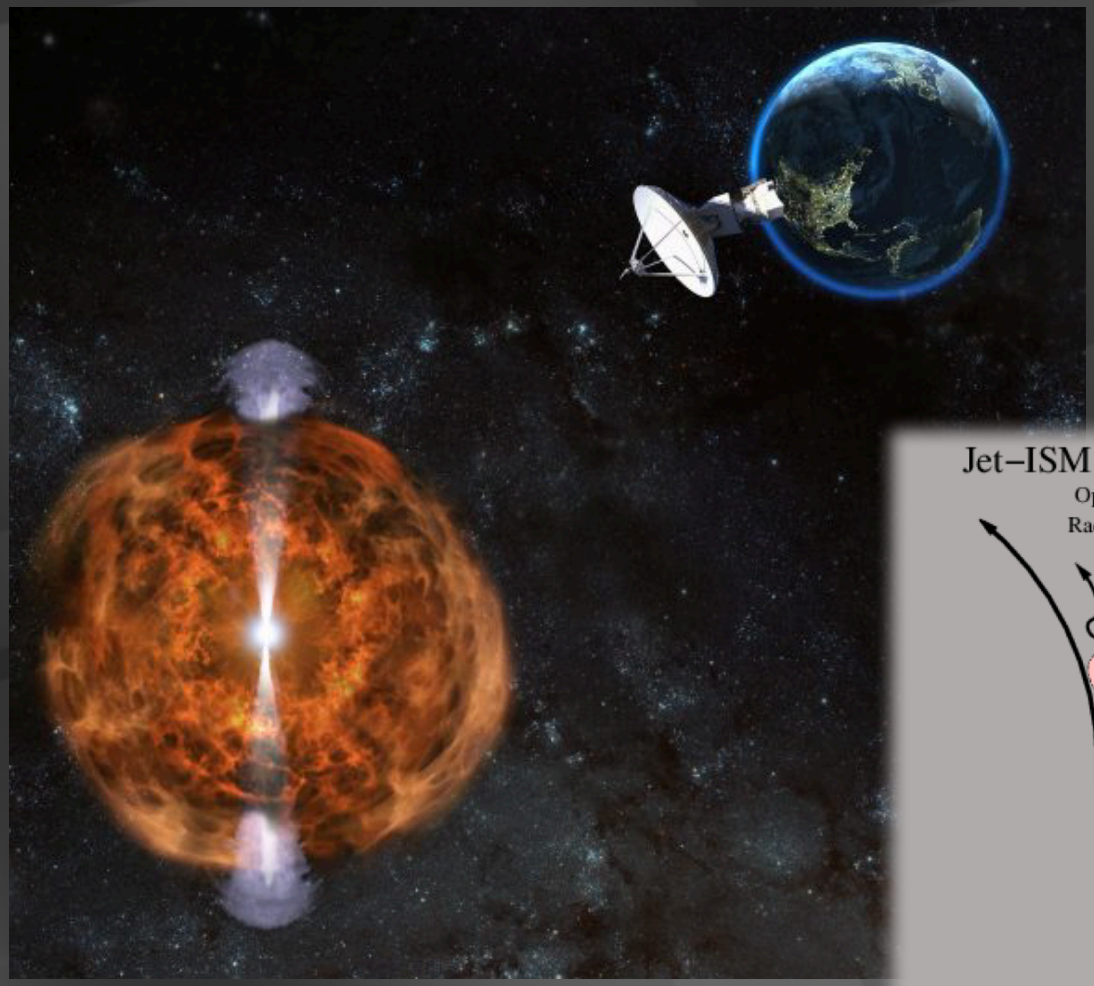
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- multimessenger astronomy

supernova 1987a: 24 neutrinos, thousands of papers

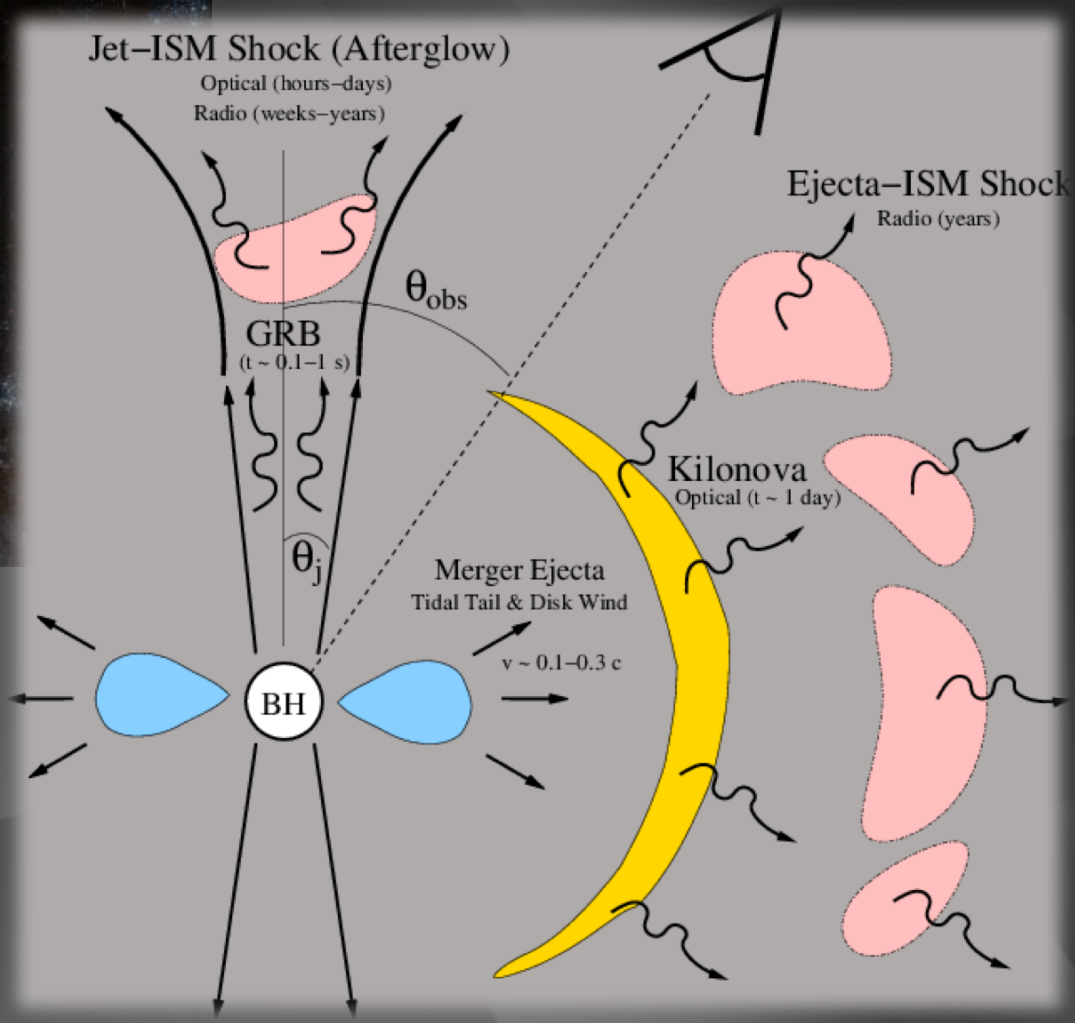




buildup of magnetic fields near merger launches jet



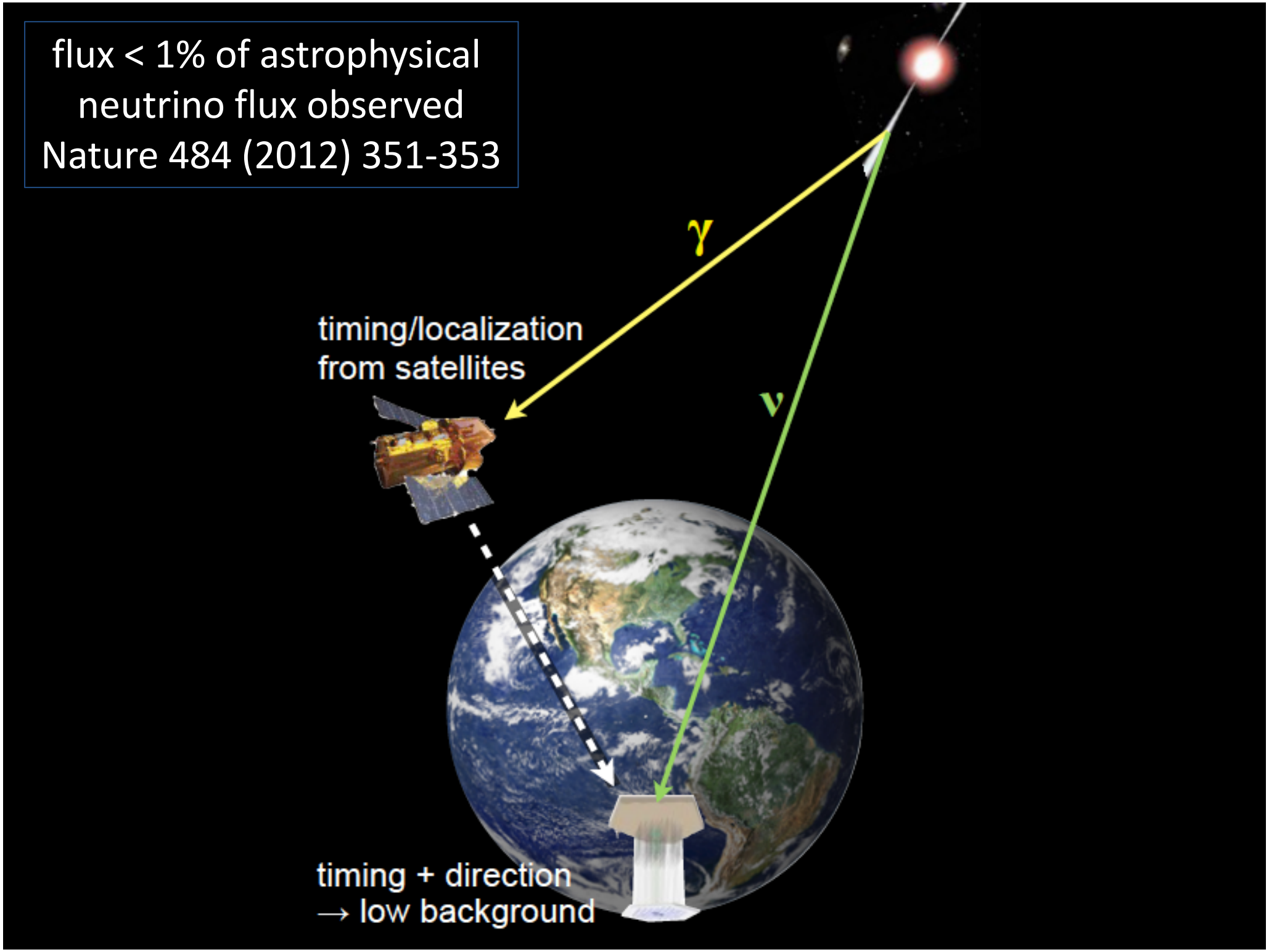
very weak short GRB seen by Fermi (off axis?)



MeV neutrino emission:

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

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



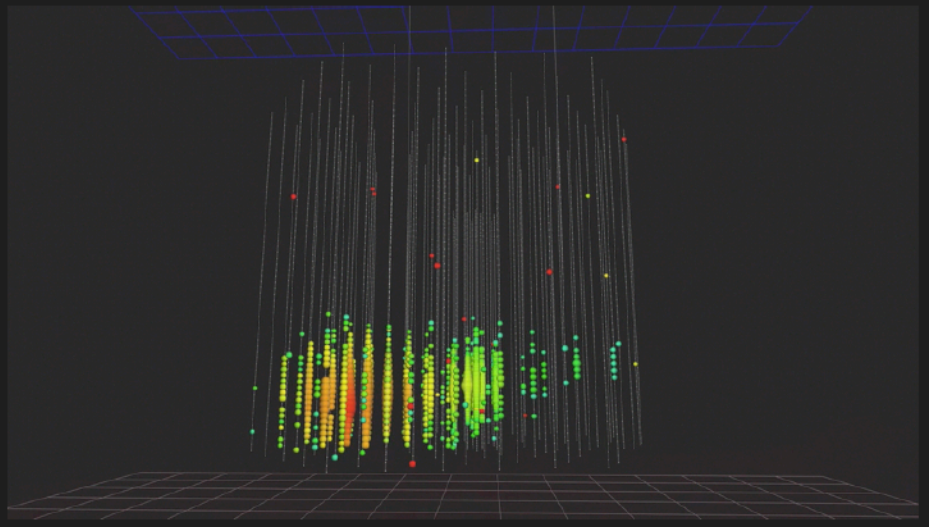
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

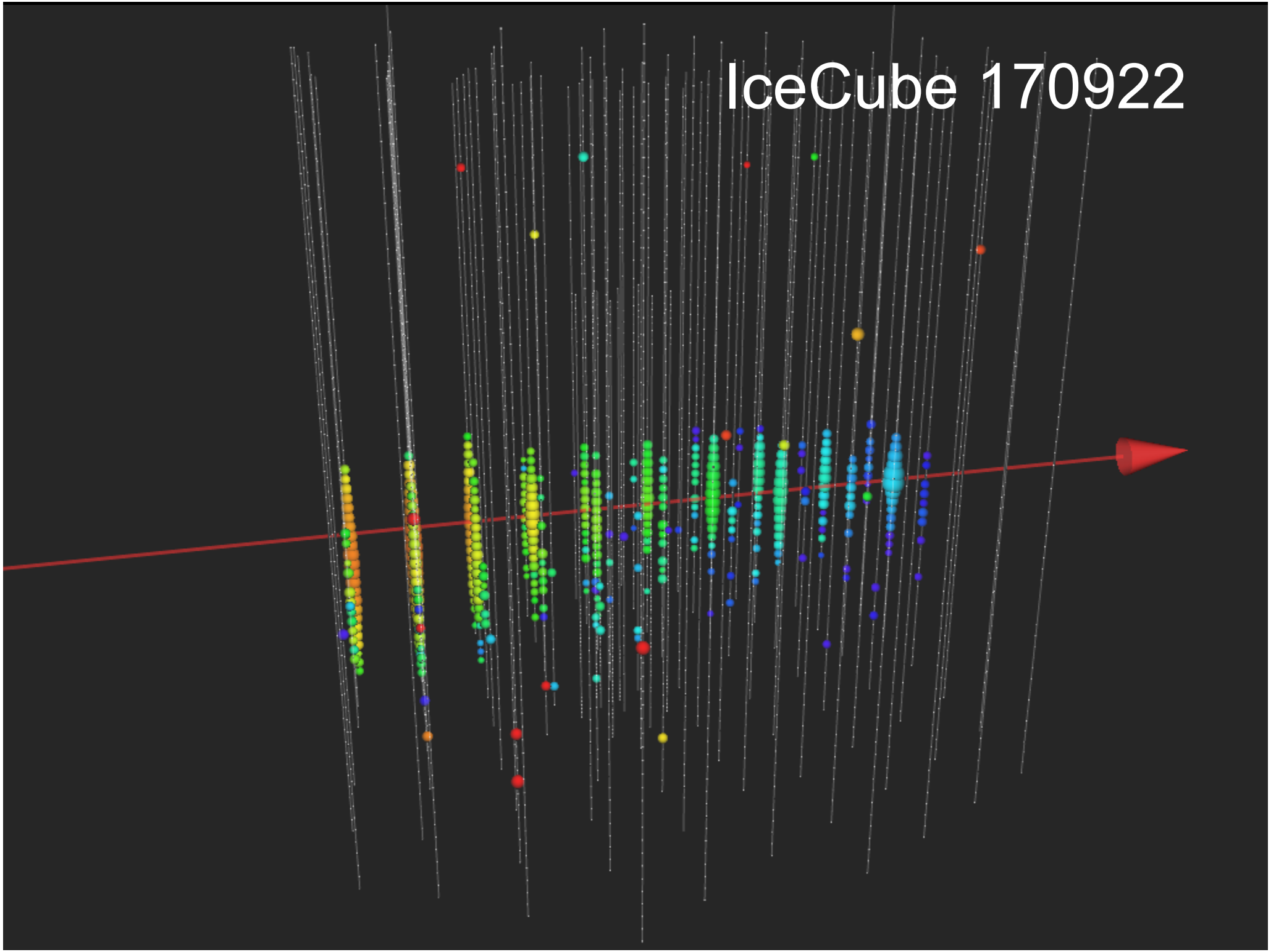
We send **rough reconstructions first** and then **update them.**



IceCube Trigger

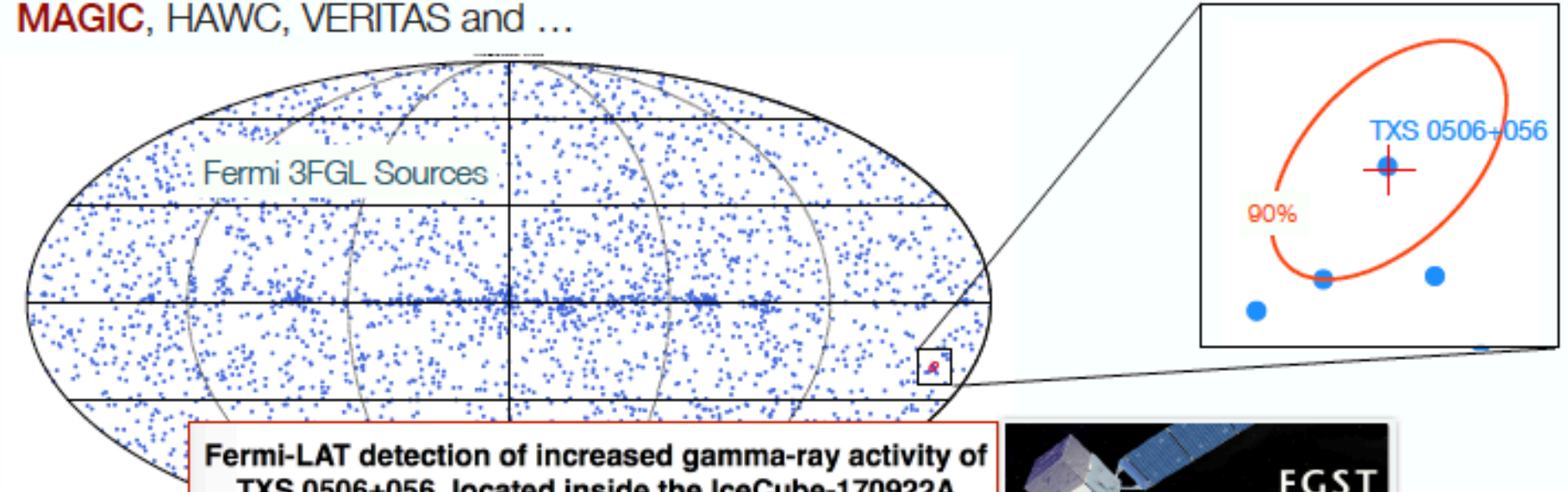
43 seconds after trigger, GCN notice was sent

```
////////////////////////////////////////////////////////////////////////
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

IC 170922A

- IceCube issued an alert on September 22, 2017.
- Follow up observations by ANTARES, H.E.S.S. , **Fermi-LAT**, **Swift**, AGILE, **MAGIC**, HAWC, VERITAS and …



Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2
Credential Certification: David J. Th

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

- *updates coming soon!*

multiwavelength campaign launched by IC 170922

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} (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

MAGIC atmposheric Cherenkov telescope

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

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*
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(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

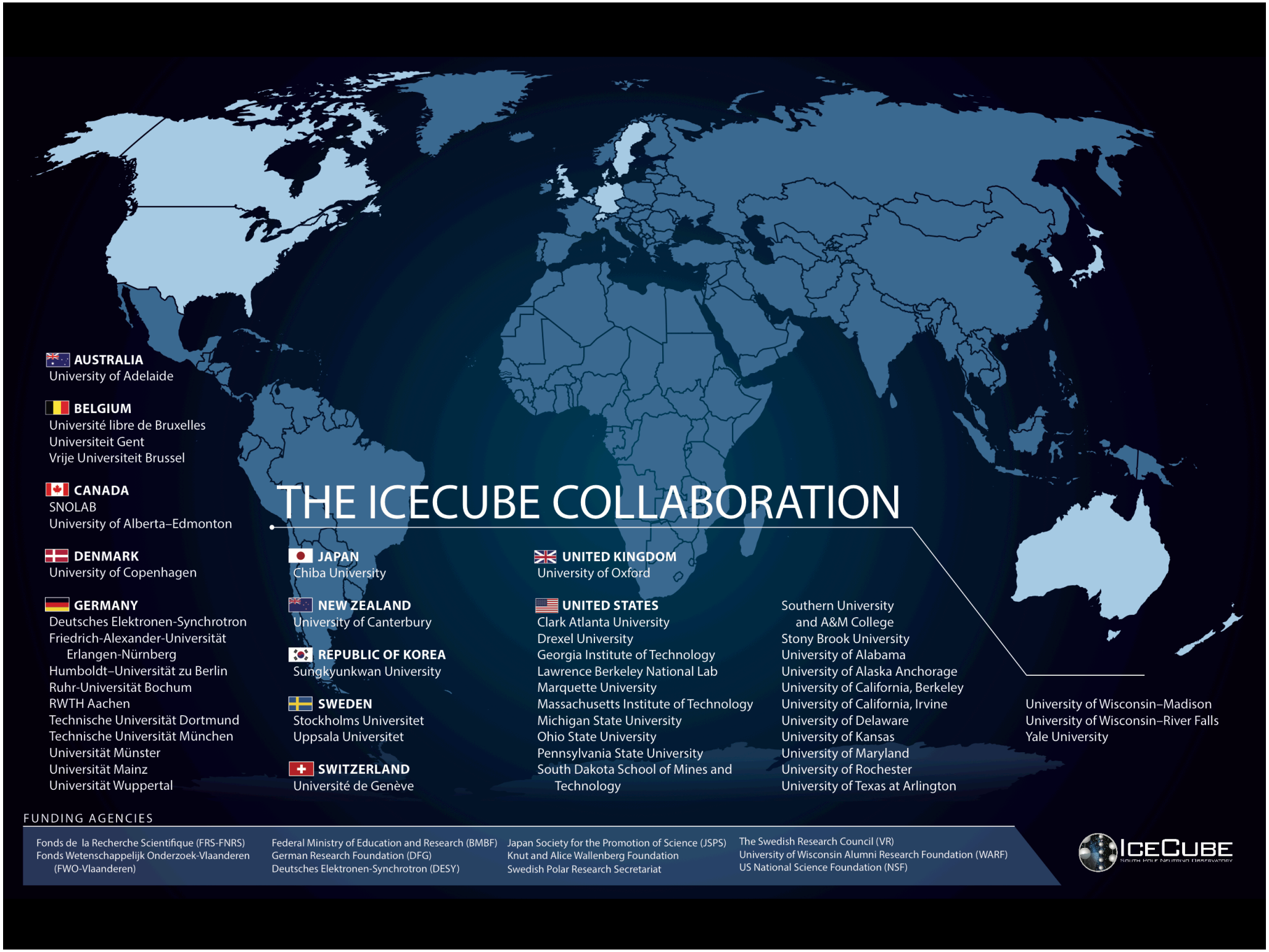
→ although at 10 times larger redshift than nearby blazars (like the Markarian sources), TXS 0506+056 has the same flux → probably special subclass

extensive multiwavelength campaign centered on the active galaxy (blazar) TXS 0506+056 at a redshift of 0.33

analysis of the data in progress

Conclusions

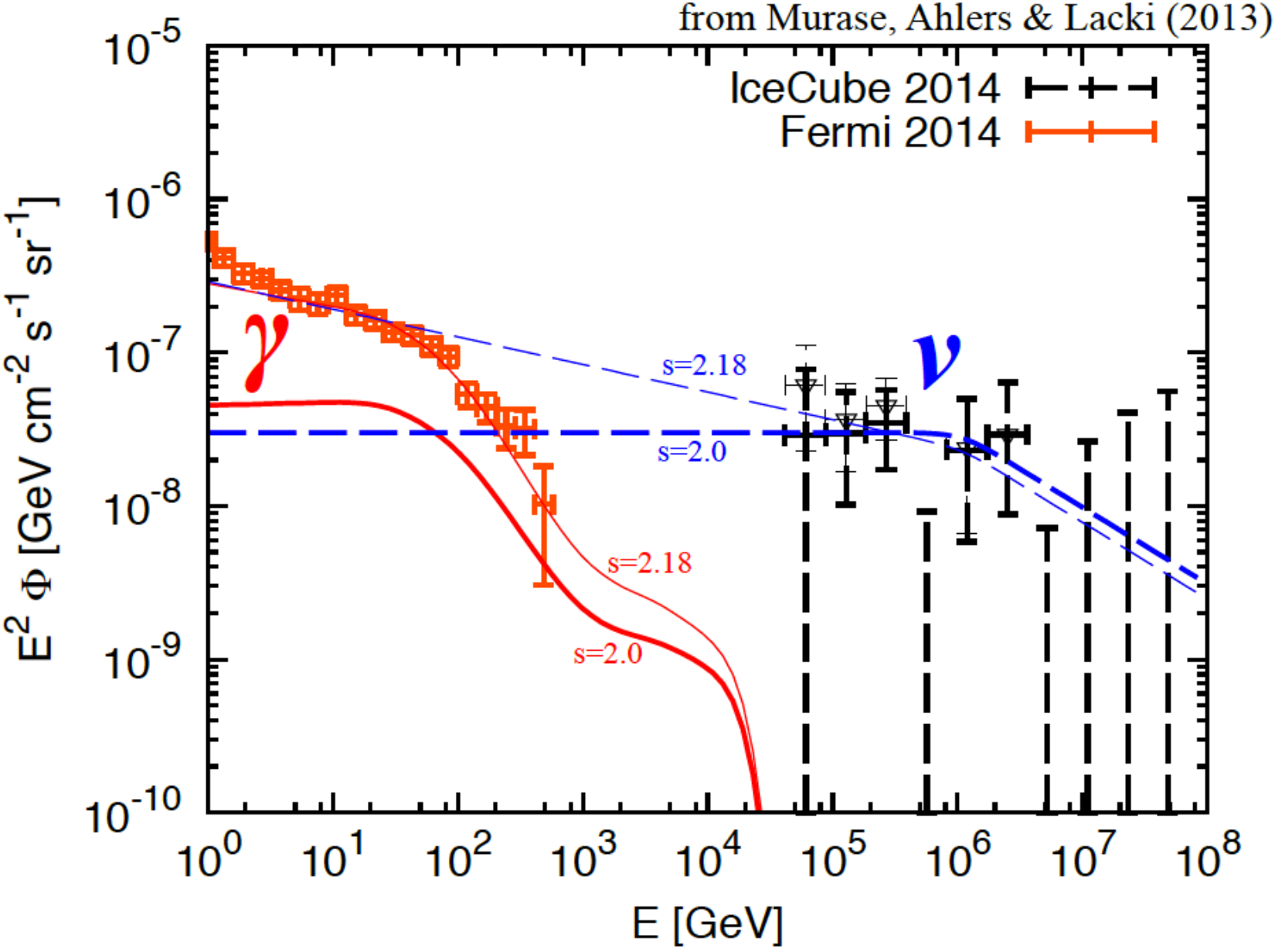
- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos (protons and nuclei) are essential for understanding the non-thermal universe.
- results of multimessenger campaign involving neutrinos forthcoming
- from discovery to astronomy: more events, more telescopes IceCube-Gen2 (phase 1 approved), KM3NeT and GVD (Baikal)

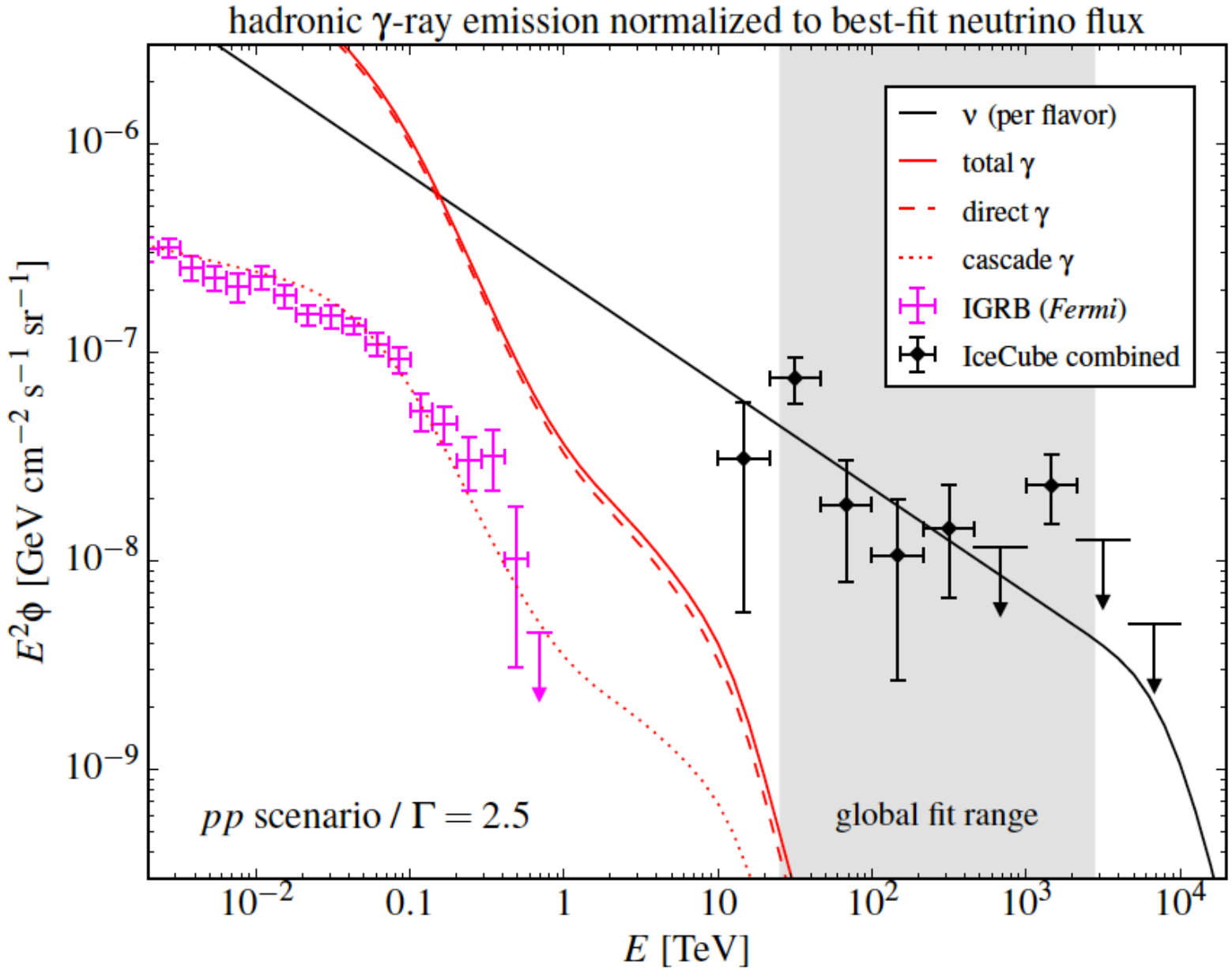


FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

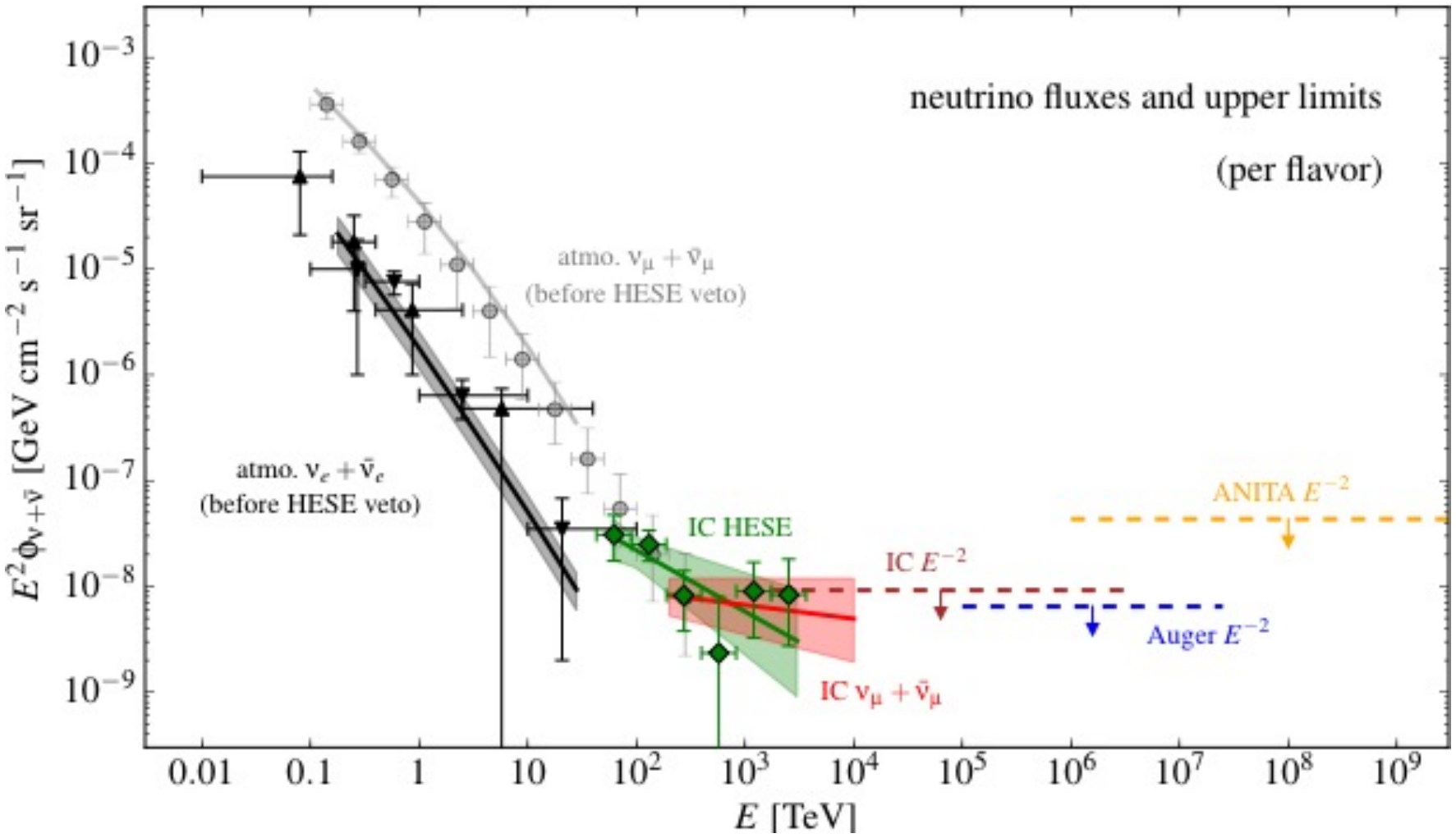
overflow slides


from Murase, Ahlers & Lacki (2013)
IceCube 2014
Fermi 2014
γ
ν
s=2.18
s=2.0
s=2.18
s=2.0
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸



dark sources below 100 TeV not seen in γ's ?
gamma rays cascade in the source to < GeV energy

not background: prompt decay of charm particles produced in the atmosphere



- tracks cosmic ray flux in energy, isotropic in zenith, normalization unknown: does not fit the data
- neutrino events are isolated
- incompatible with observes atmospheric *electron* neutrino spectrum

Kimura et al.

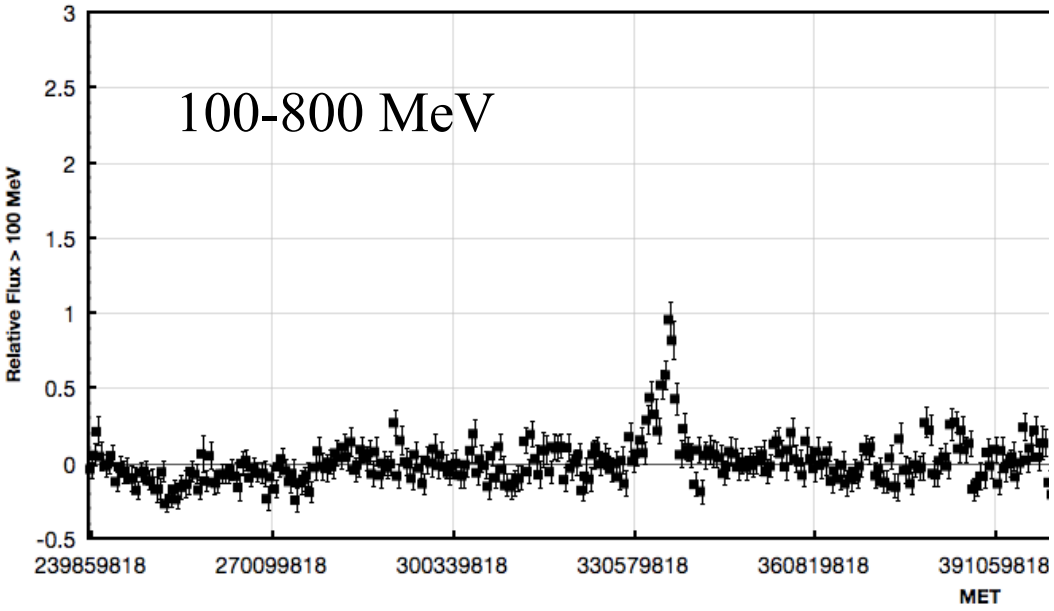
TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

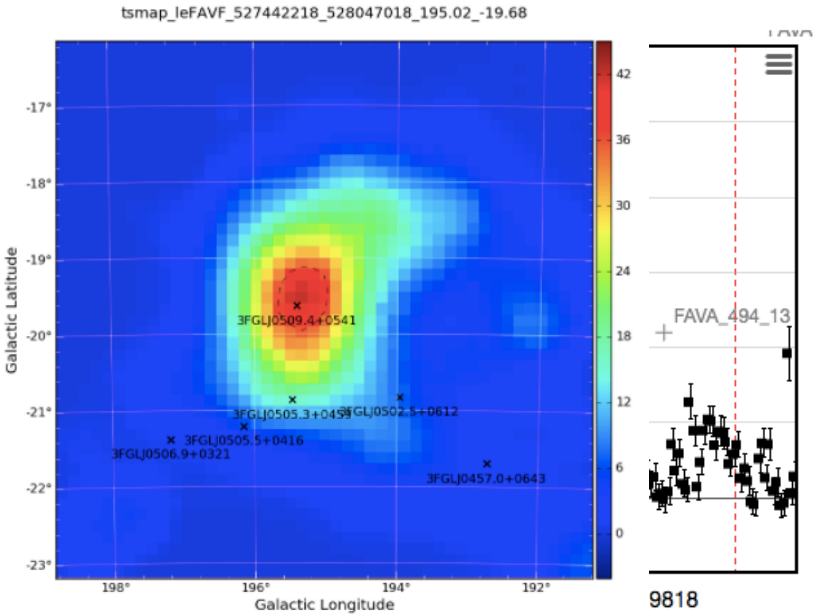
Number of detected neutrinos from single event at 40 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	6.6	0.55	29
B	0.36	0.023	1.5

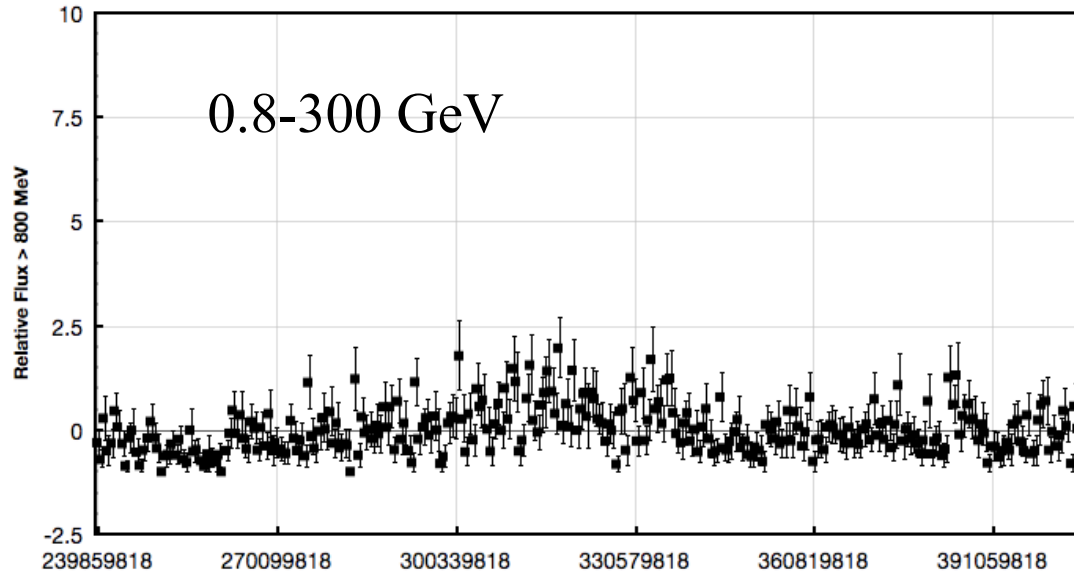
Number of detected neutrinos from single event at 300 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

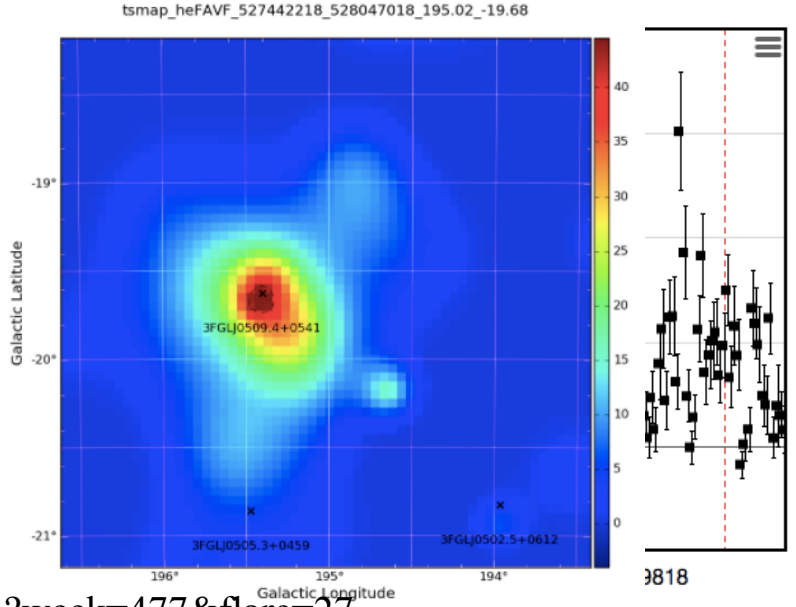
GW+neutrino detection rate [yr^{-1}]		
model	IceCube	Gen2
A	1.1	2.6
B	0.076	0.28

Fermi Large Area Telescope (LAT)







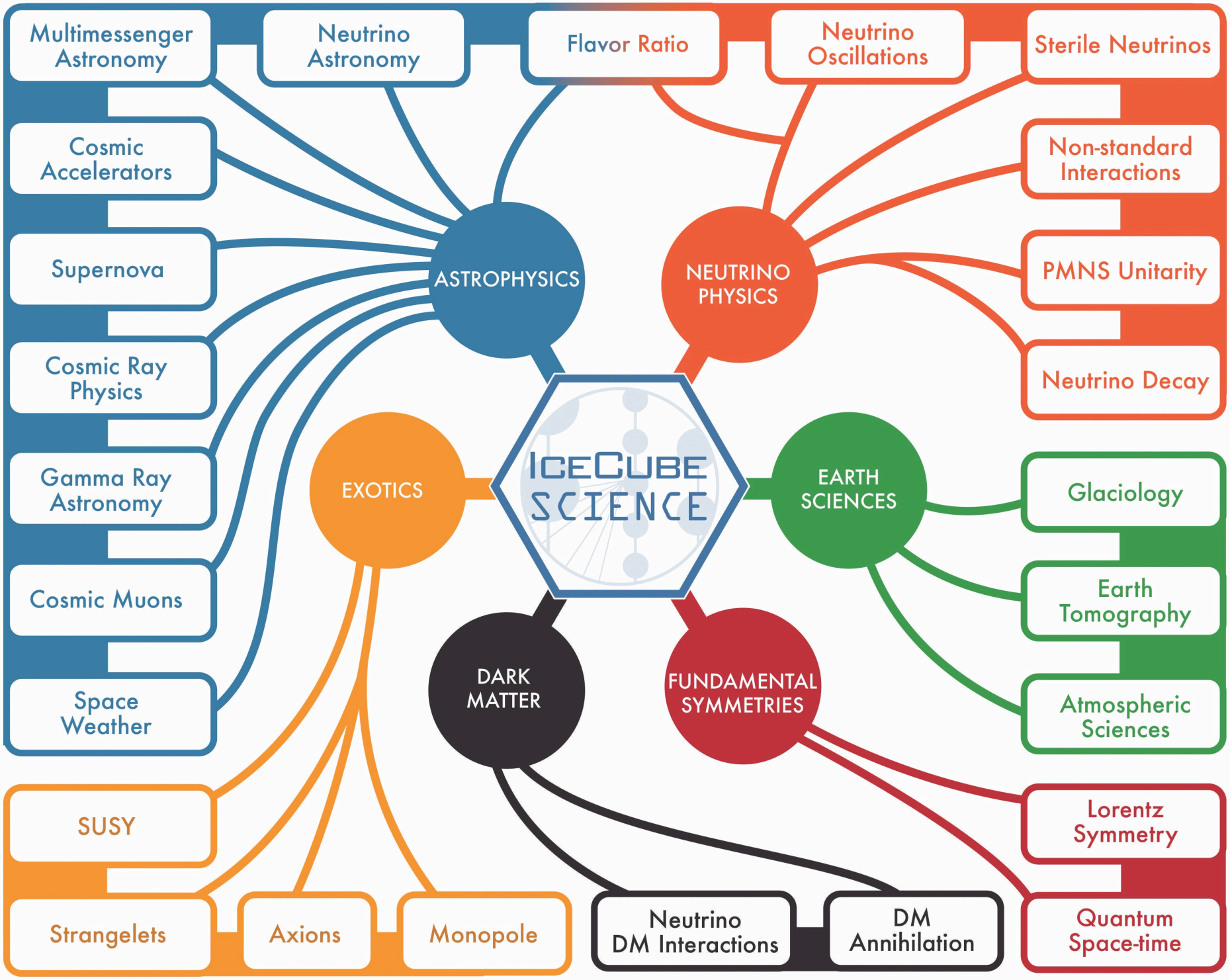


https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27

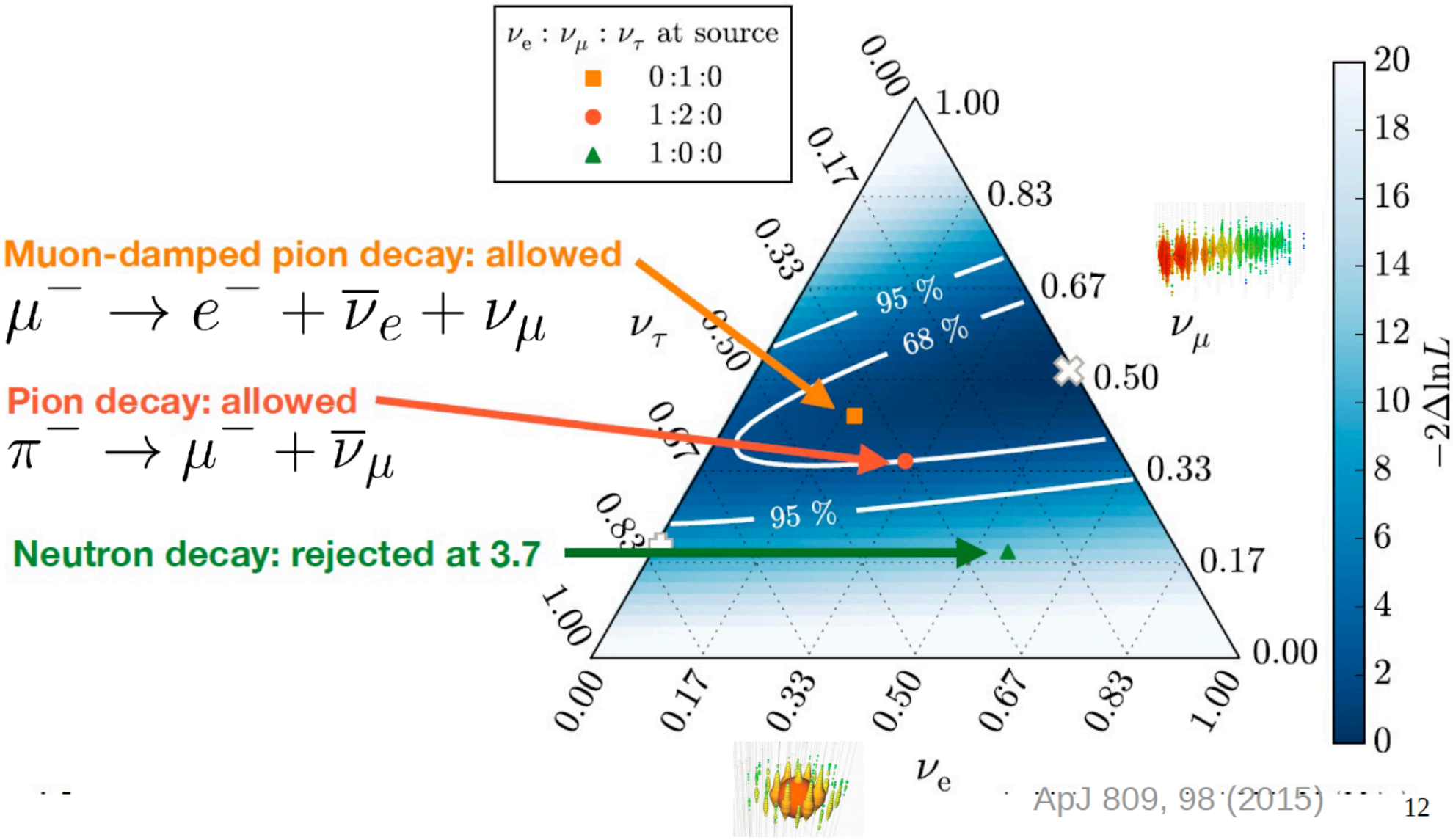
IceCube – Update Information

4h later, GCN circular was sent

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of  Maryland) report on
behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability
of being of astrophysical origin. The event was identified by the  Extremely High Energy
(EHE) track event selection. The IceCube detector was in a normal operating state. EHE events
typically have a neutrino interaction vertex that is outside the detector, produce a muon
that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert
(https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the direction refined
to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible
astrophysical source for the candidate neutrino.
```


ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
EXOTICS
EARTH SCIENCES
DARK MATTER
FUNDAMENTAL SYMMETRIES
Multimessenger Astronomy
Neutrino Astronomy
Cosmic Accelerators
Supernova
Cosmic Ray Physics
Gamma Ray Astronomy
Cosmic Muons
Space Weather
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Non-standard Interactions
PMNS Unitarity
Neutrino Decay
Glaciology
Earth Tomography
Atmospheric Sciences
SUSY
Strangelets
Axions
Monopole
Neutrino DM Interactions
DM Annihilation
Lorentz Symmetry
Quantum Space-time

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

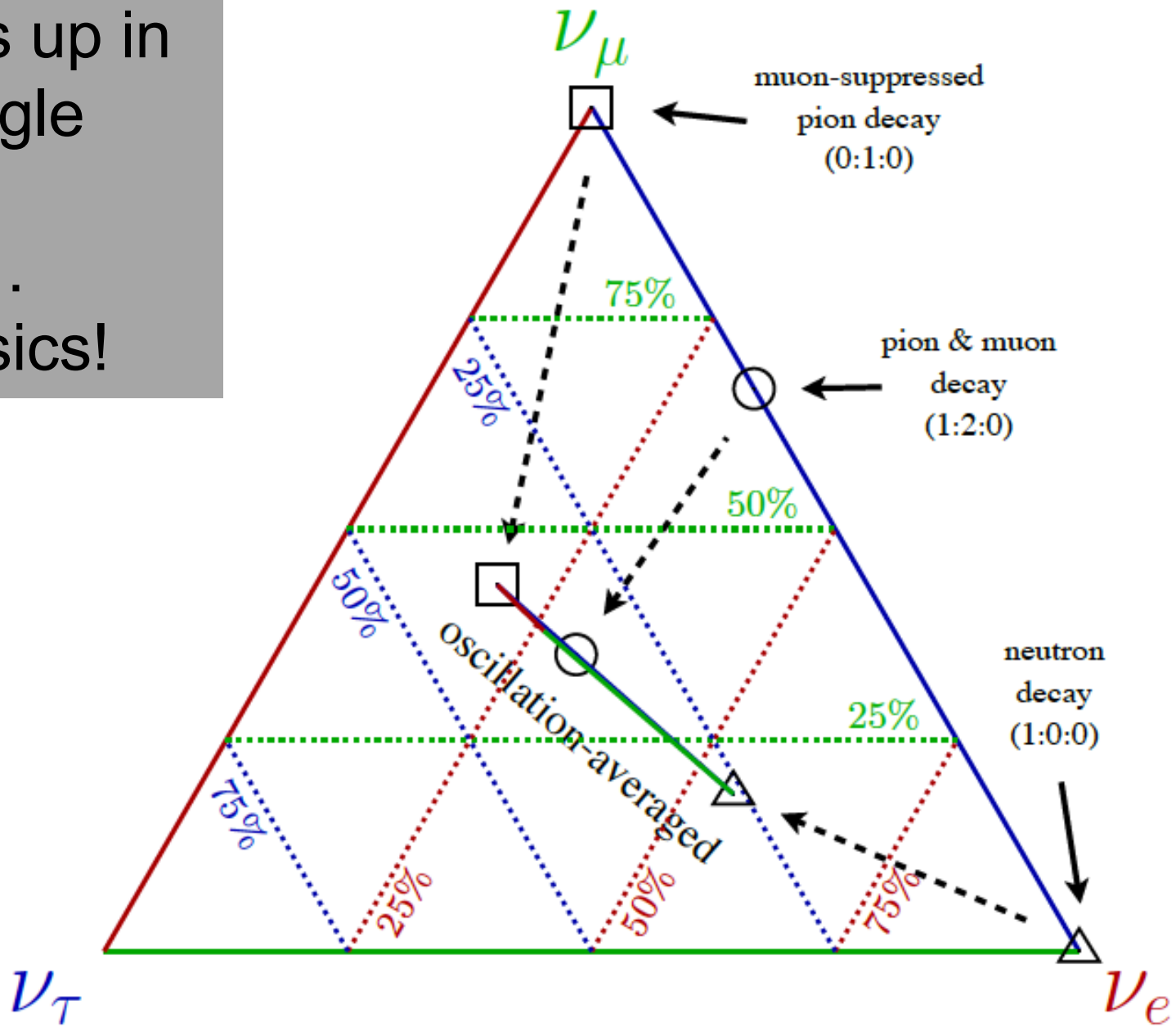


ApJ 809, 98 (2015)

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

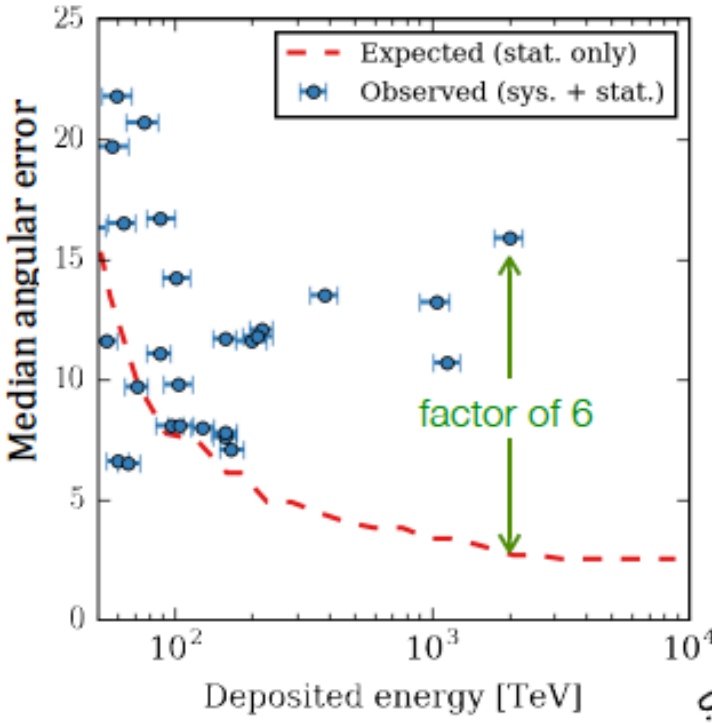
every astrophysical model ends up in the triangle

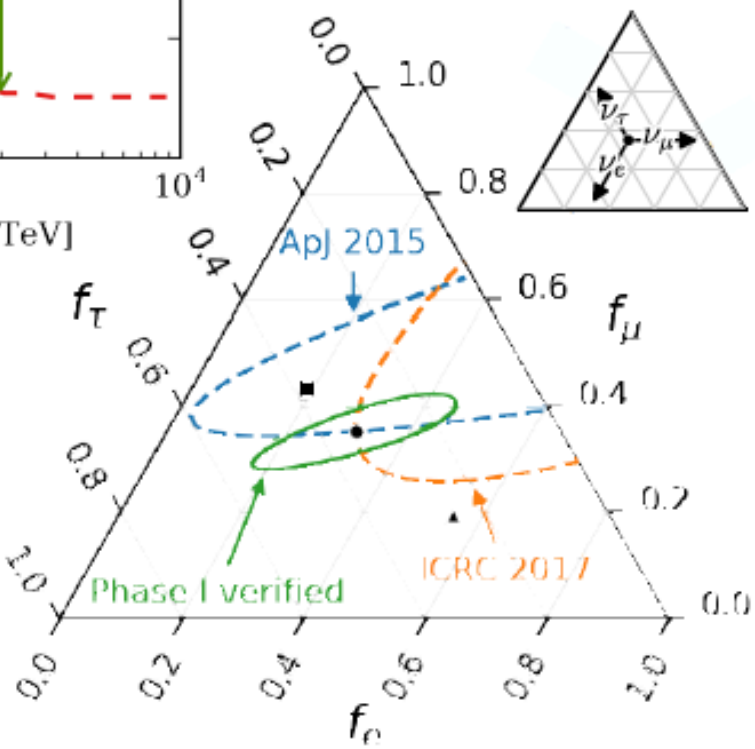
if not…
new physics!



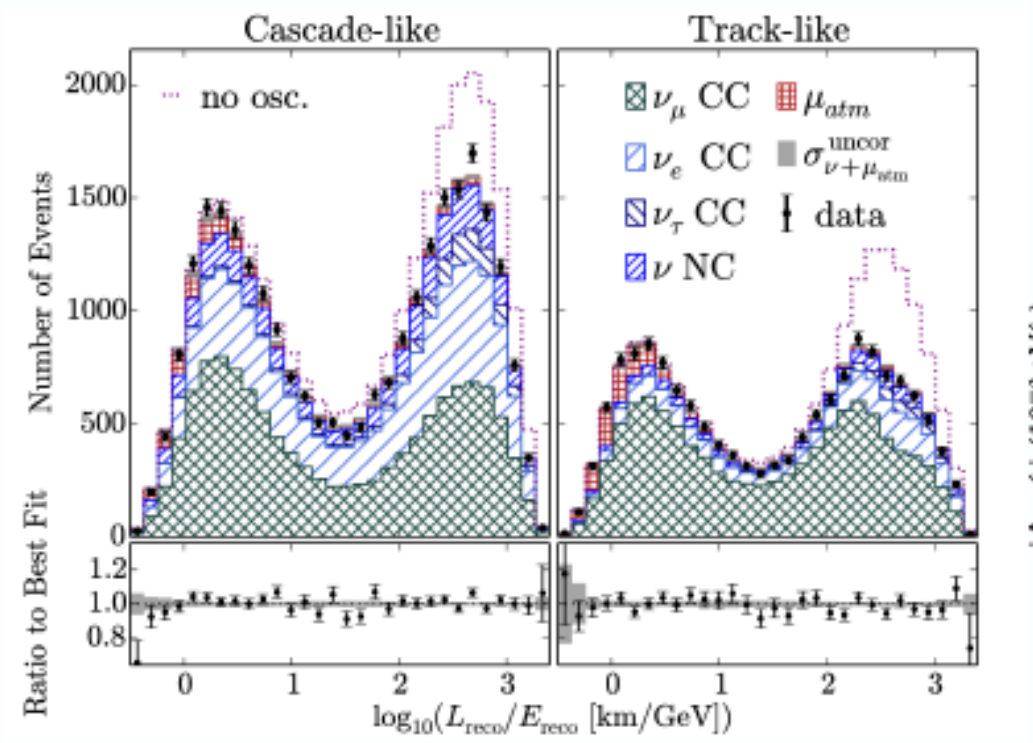
Ongoing upgrade and reanalysis of 10-year data

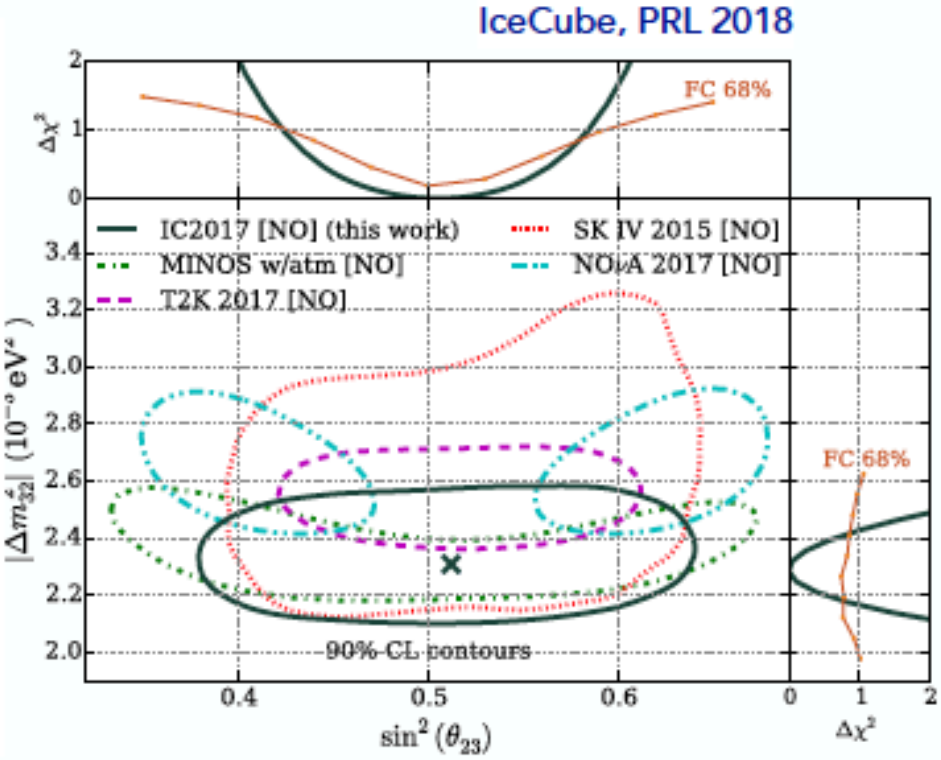
- Angular resolution of high energy events dominated by ice optical uncertainties
  - Stat. limit is 0.1-0.2° (ν_μ) and 3-5° (ν_e, ν_τ) rather than 0.5-1°/10-15°
- Ability to identify ν_τ limited by ice anisotropy
- Ice is complex but stable – existing data can be reprocessed with improved calibrations





Neutrino Oscillation





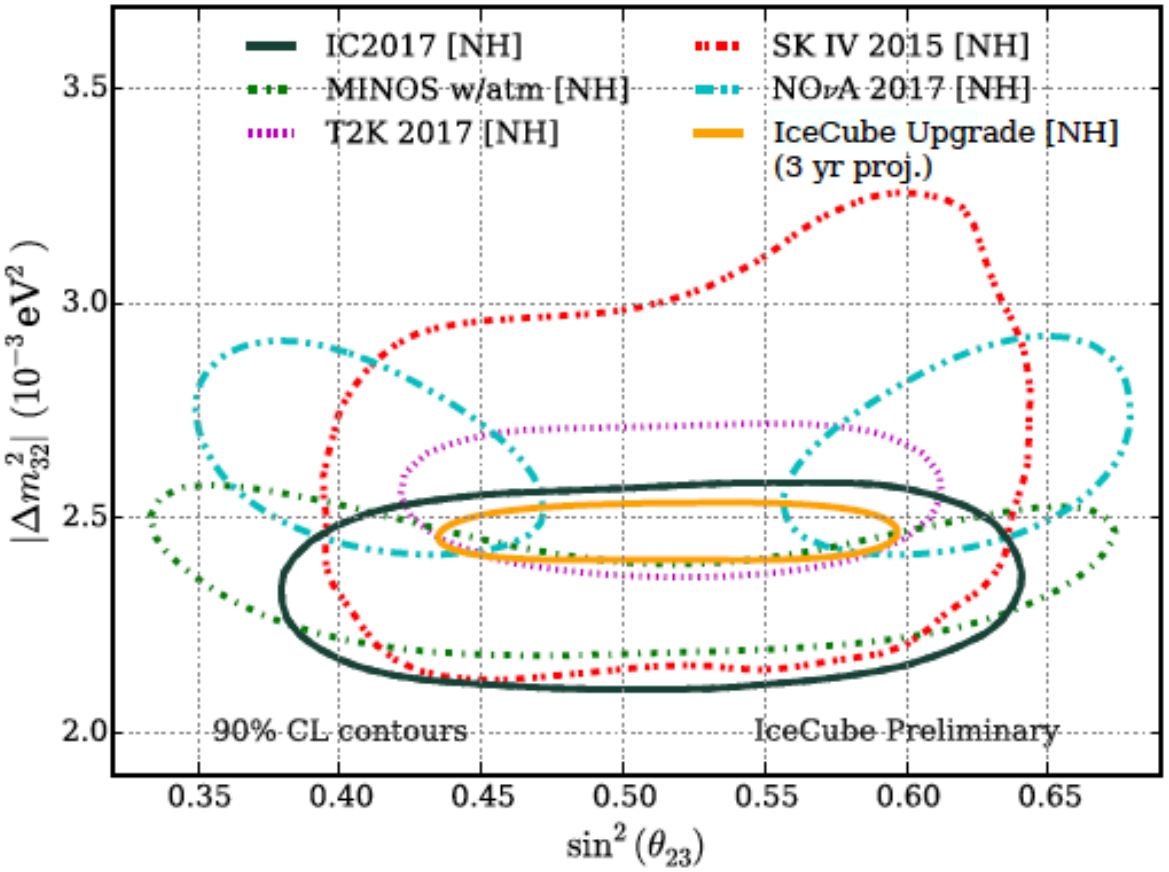
- 3 years of IceCube Deep Core data
- measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

Atmospheric Oscillation Parameters

- Currently unclear whether $\sin^2 \theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6σ*



- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)