

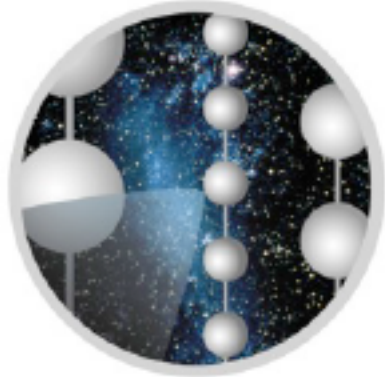
Astroparticle Physics

2022/23

1. **Historical introduction - basic properties of cosmic rays**
2. **Hadronic interactions and accelerator data**
3. **Cascade equations**
4. **Electromagnetic cascades**
5. **Extensive air showers**
6. **Detectors for extensive air showers**
7. **High-energy cosmic rays and the knee in the energy spectrum of cosmic rays**
8. **Radio detection of extensive air showers**
9. **Acceleration, Astrophysical accelerators and beam dumps**
10. **Extragalactic propagation of cosmic rays**
11. **Ultra-high-energy energy cosmic rays**
12. **Astrophysical gamma rays and neutrinos**
13. **Neutrino astronomy**
14. **Gamma-ray astronomy**

Neutrino astronomy
based on a lecture by Francis Halzen
(given at the International School of Cosmic-Ray Astrophysics, Erice)





ICECUBE

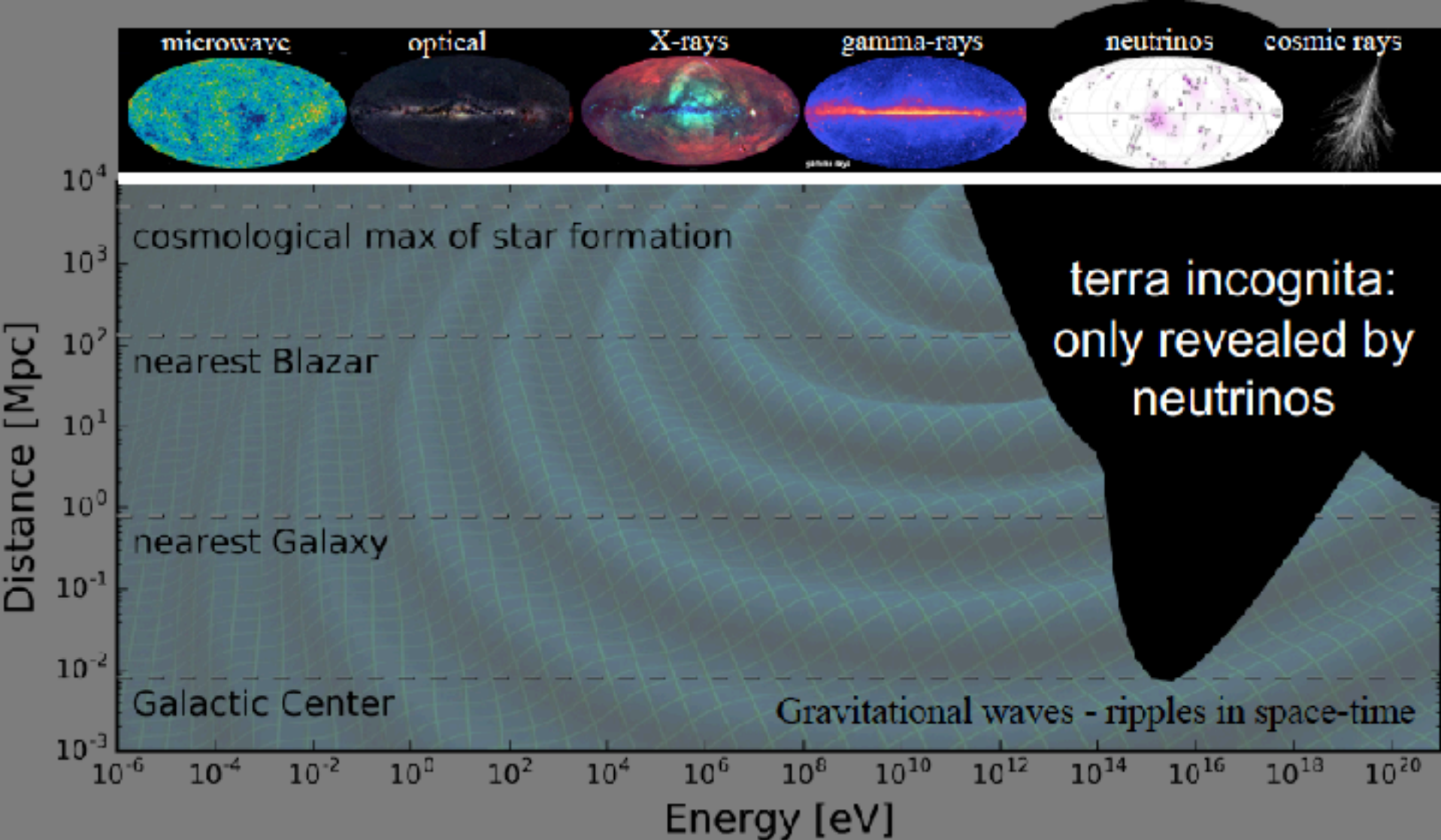


IceCube:

Building a New Window on the Universe

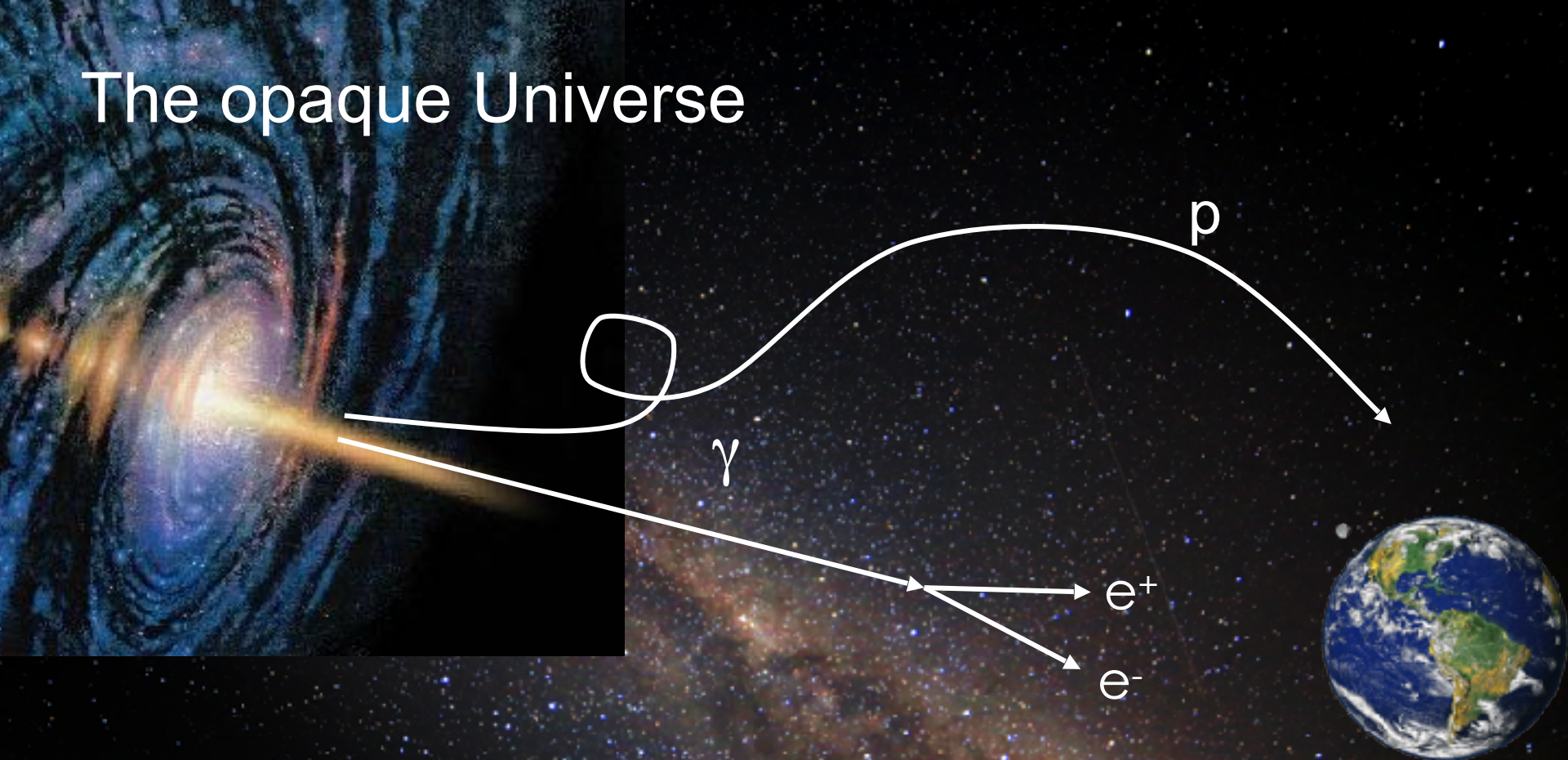
francis halzen

- 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
- the first high-energy cosmic ray accelerator
- what next?



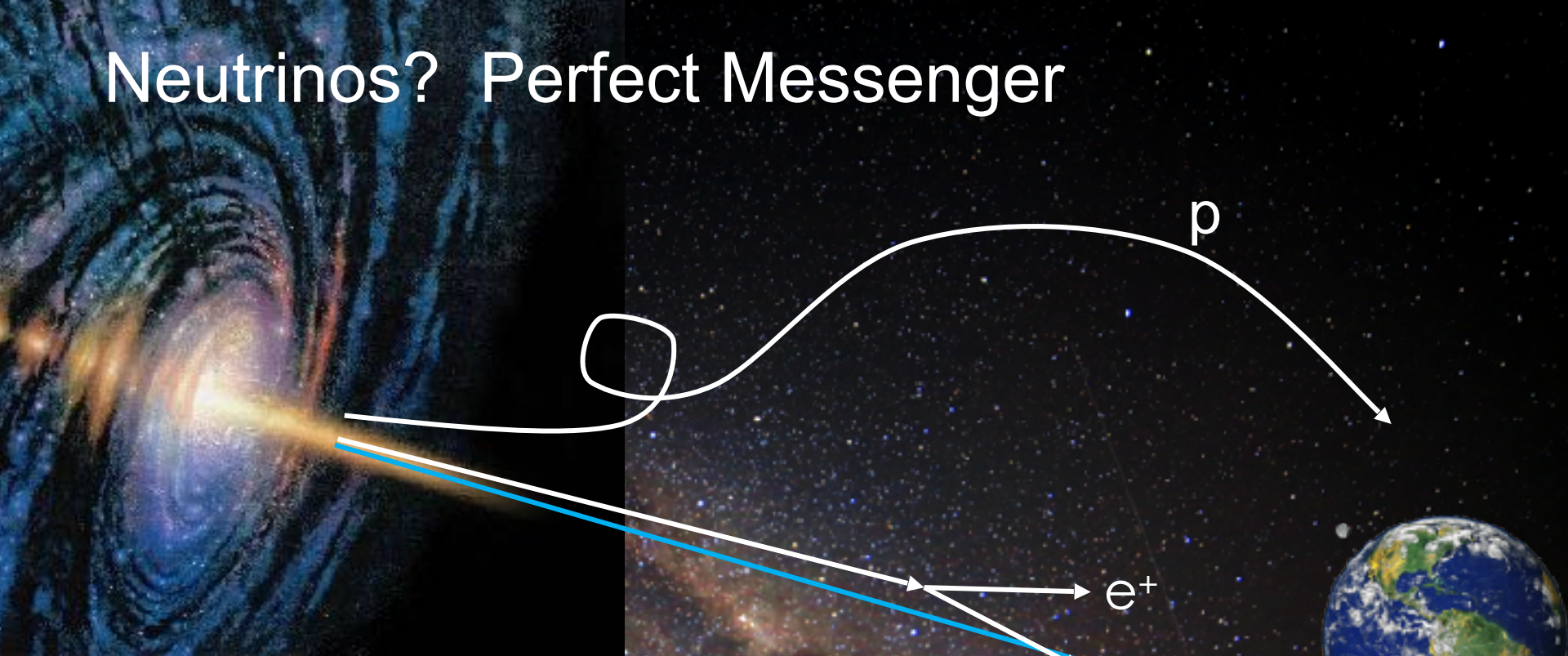
- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

The opaque Universe



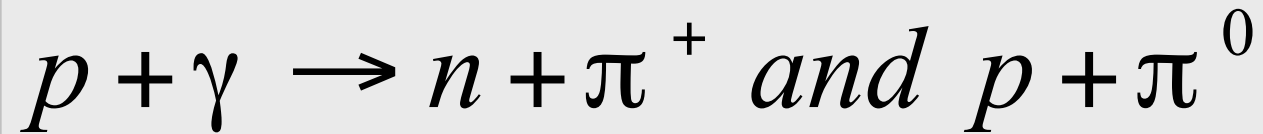
PeV photons interact with microwave photons ($411/\text{cm}^3$) before reaching our telescopes
enter: neutrinos

Neutrinos? Perfect Messenger

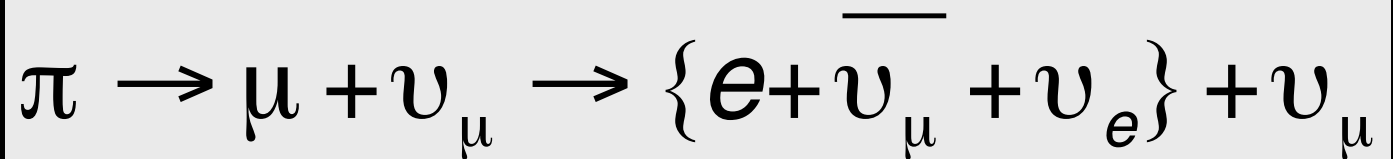


- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays
- ... but difficult to detect: how large a detector?

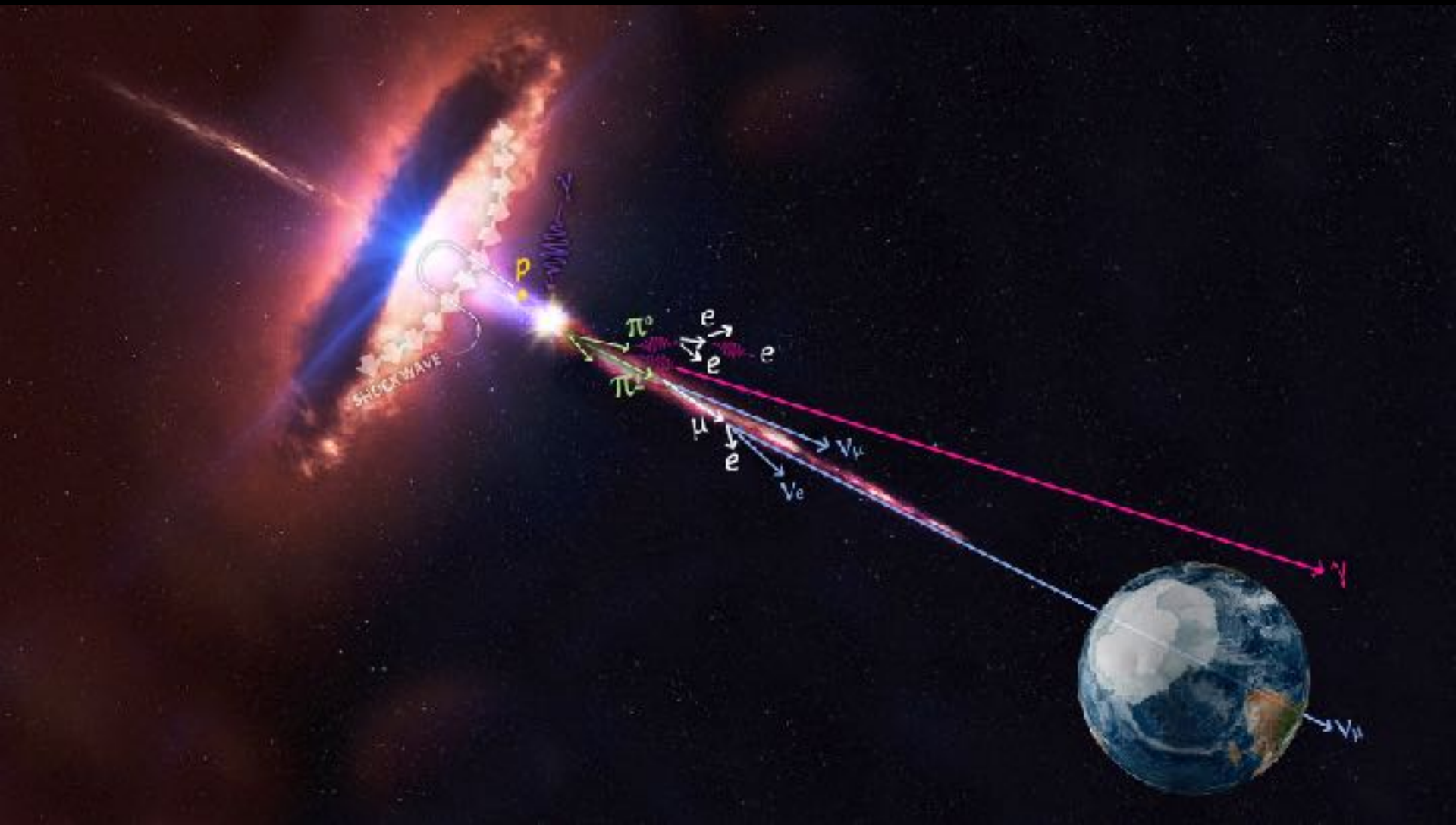
cosmic rays interact with the
microwave background



cosmic rays disappear, neutrinos with
EeV (10⁶ TeV) energy appear

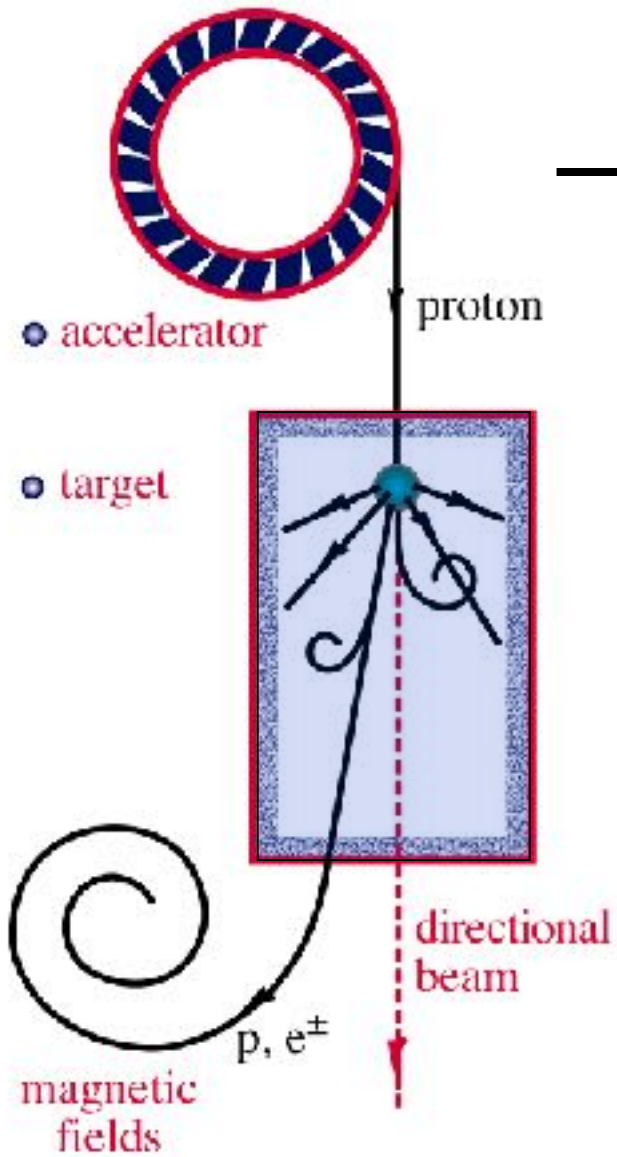


1 event per cubic kilometer per year
...but it points at its source!



blazar geometry

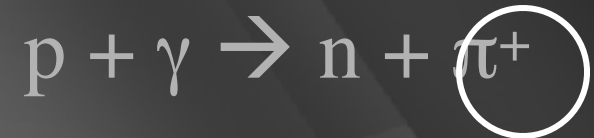
ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation
and dust



~ cosmic ray + neutrino



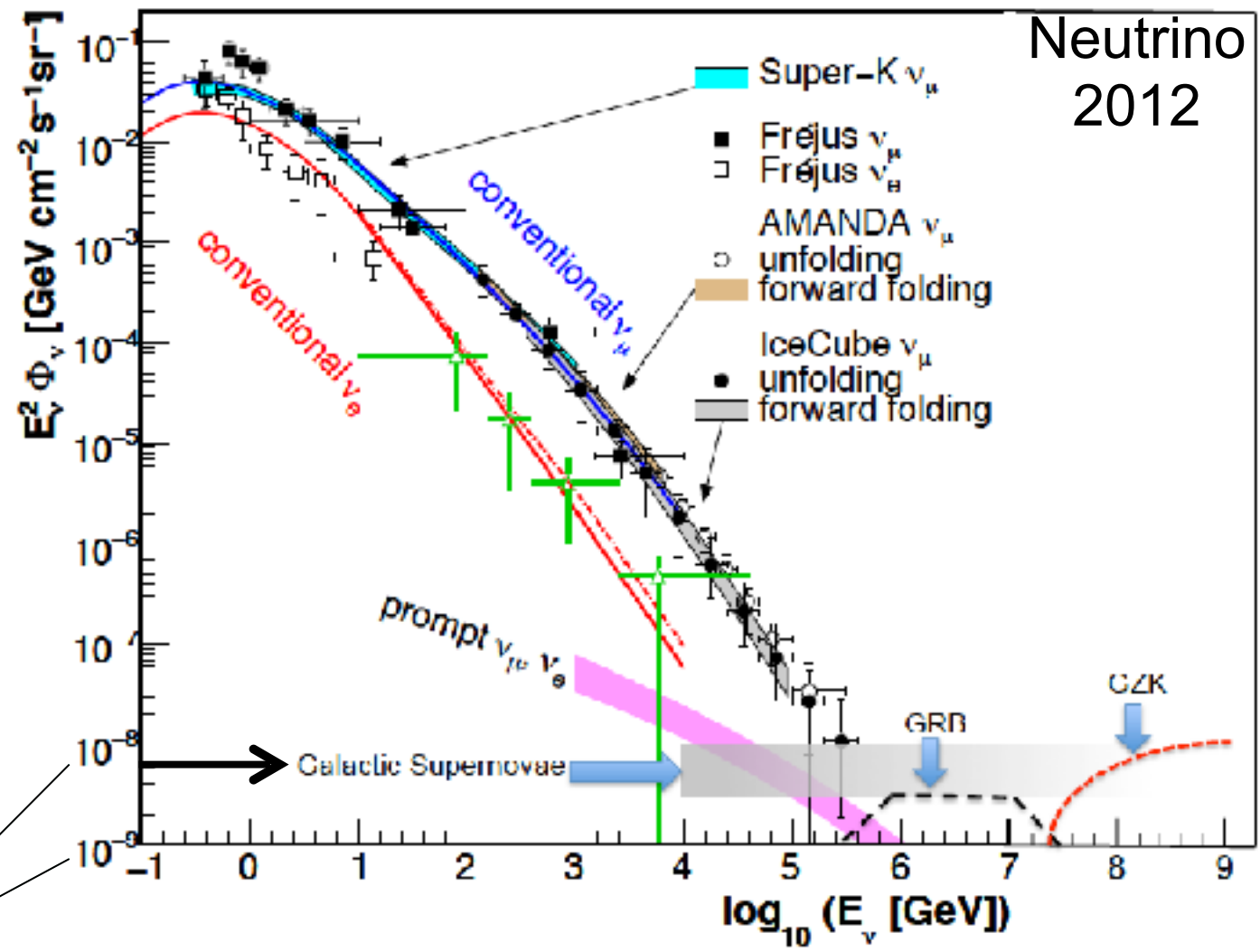
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

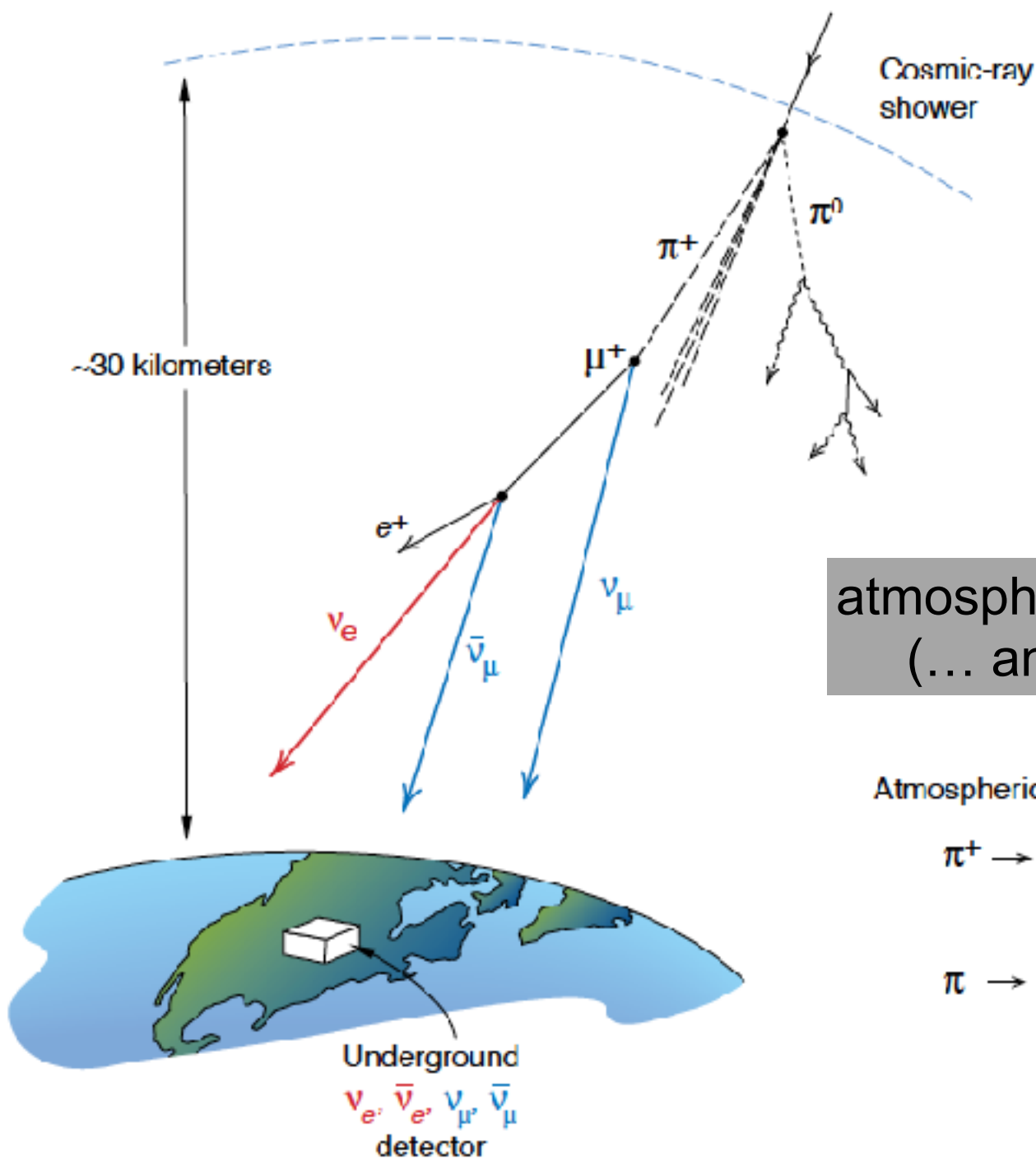
10—100 events per year for fully efficient detector



atmospheric

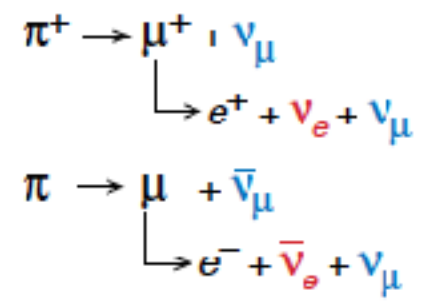
cosmic

↑
100 TeV

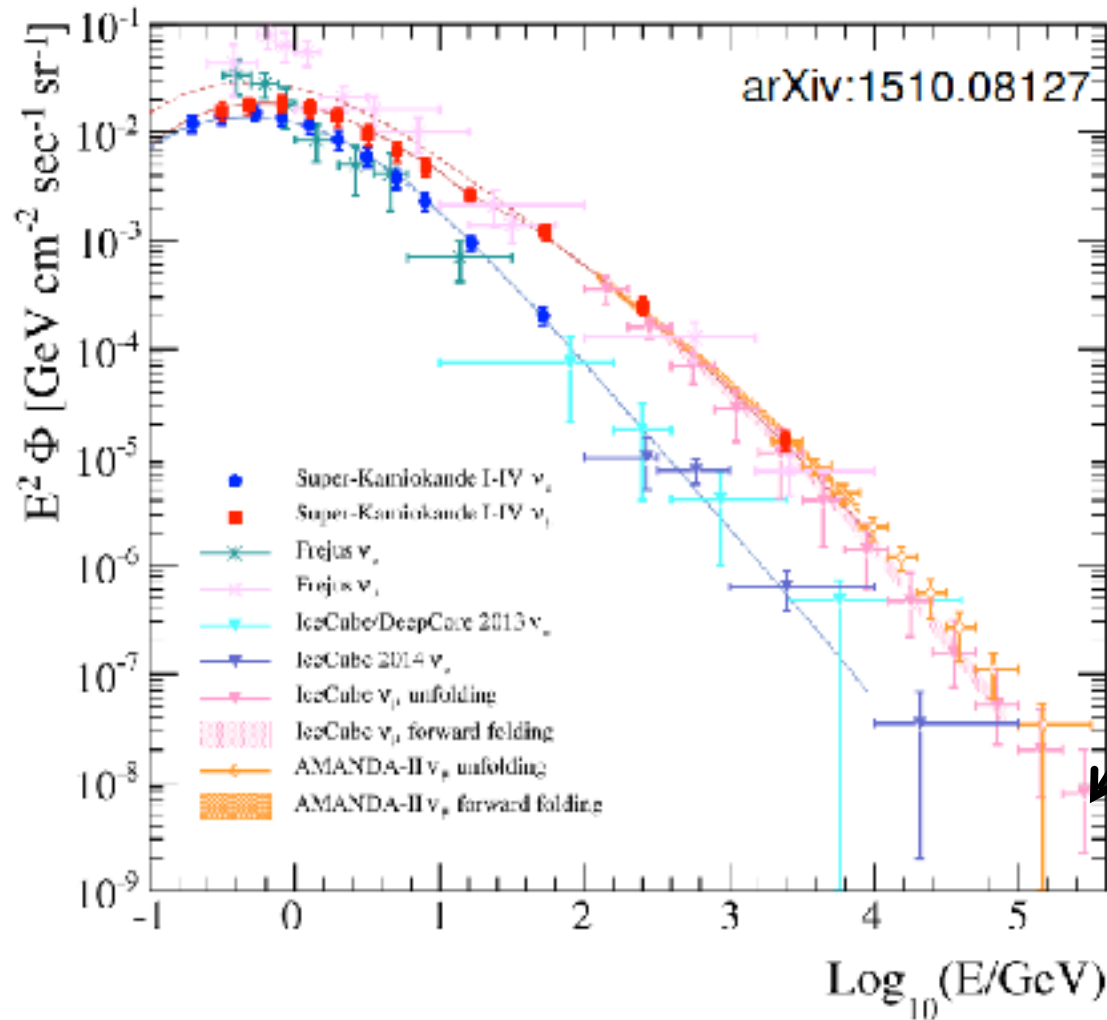


atmospheric neutrinos
(... and muons!)

Atmospheric neutrino source



Underground
 $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$
detector



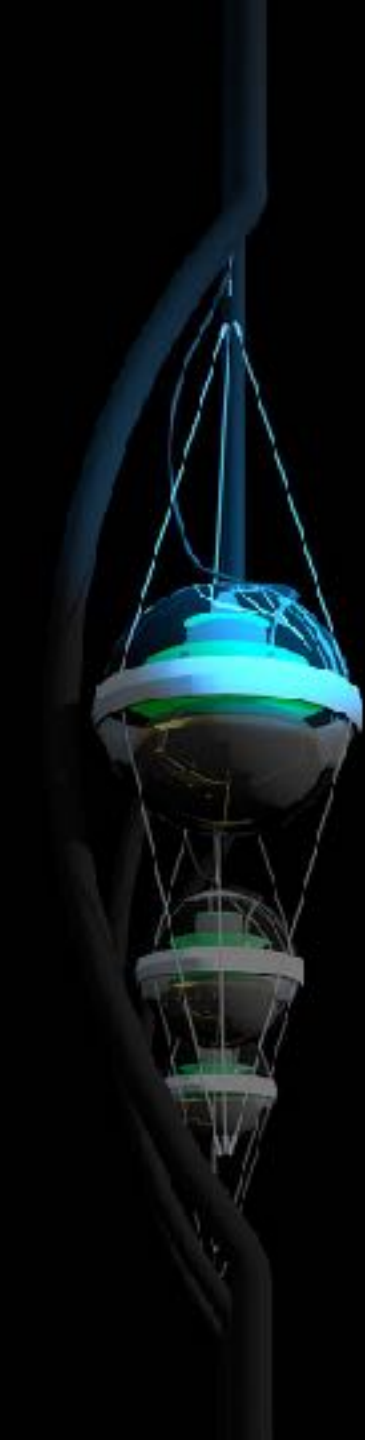
< 1 atmospheric neutrino event per cubic kilometer per year

atmospheric neutrino spectrum (energy measurement) well understood

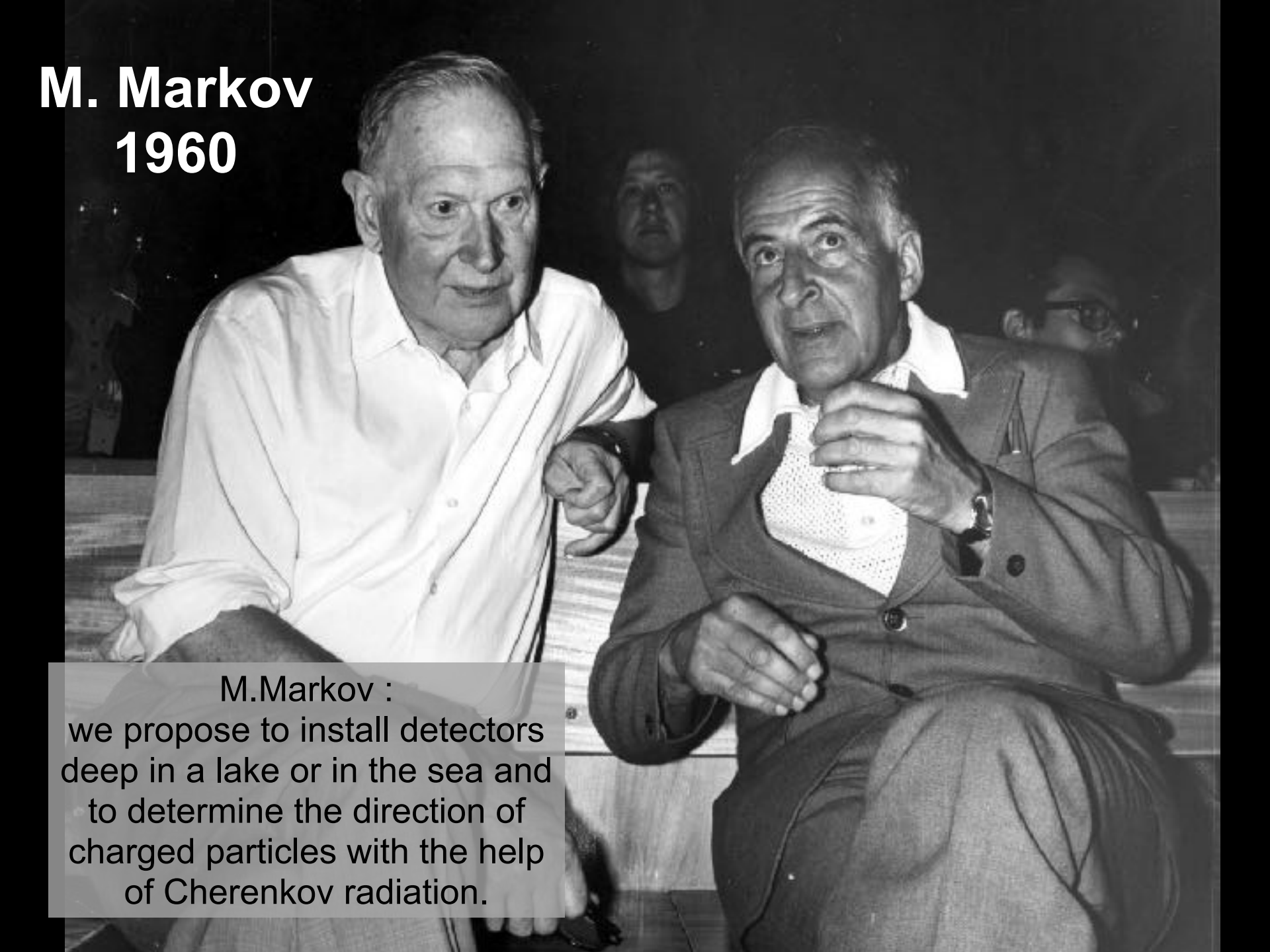
IceCube

francis halzen

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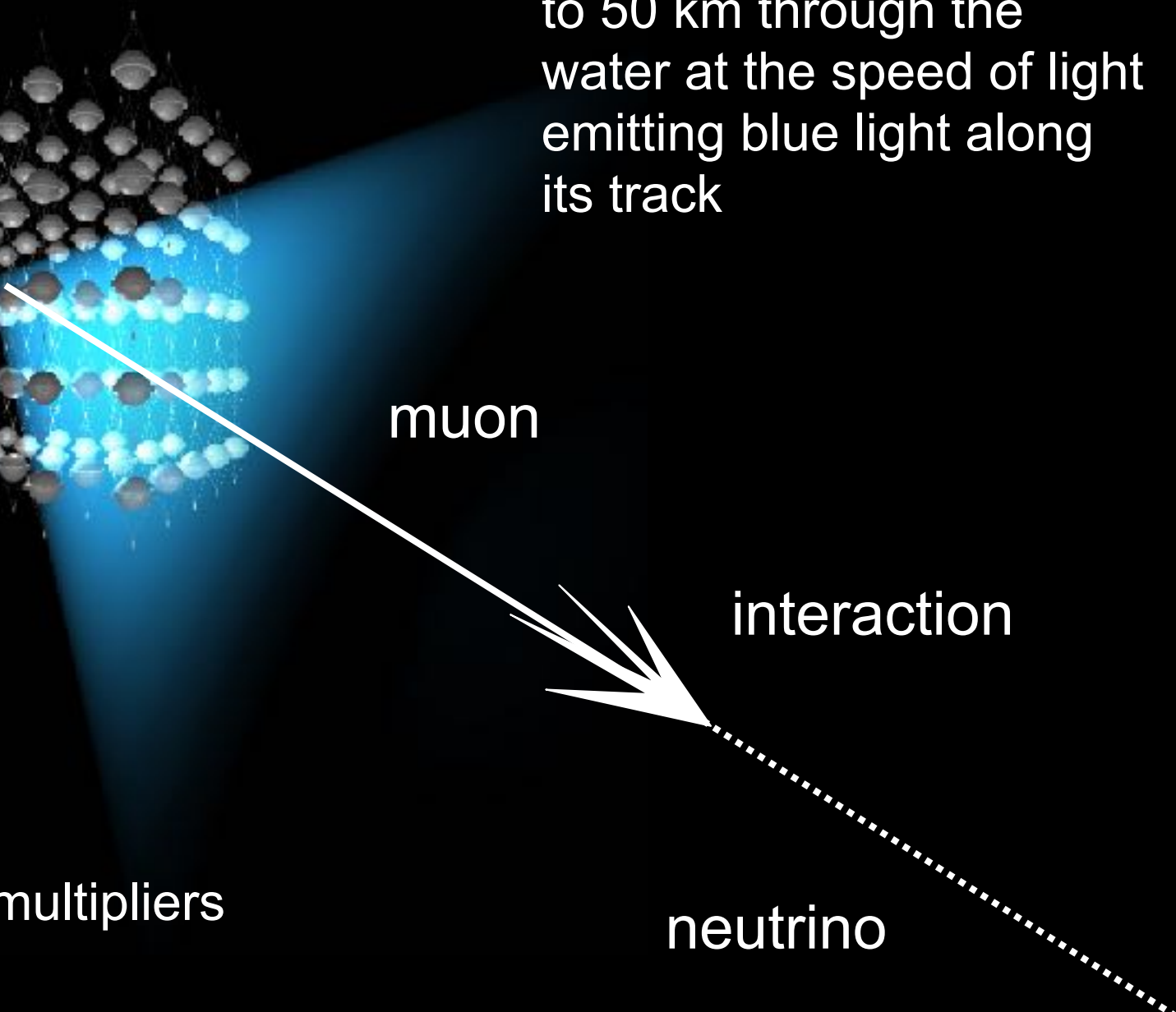
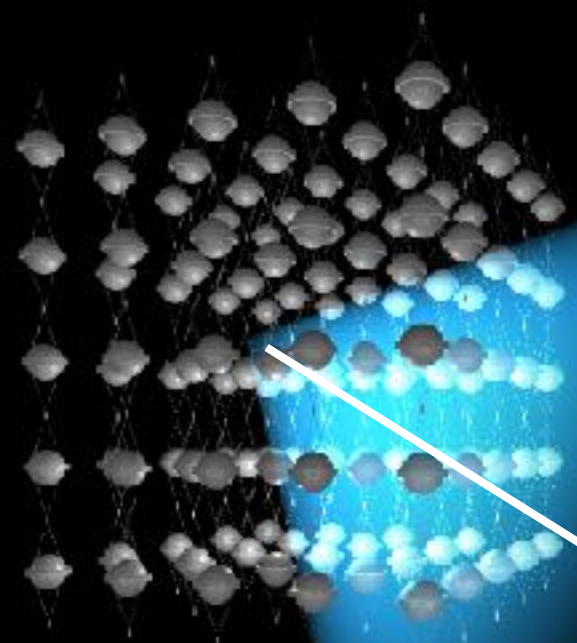


M. Markov 1960

A black and white photograph showing two men in the foreground. The man on the left is older, with thinning hair, wearing a light-colored, long-sleeved button-down shirt. He is looking towards the right. The man on the right is younger, wearing a dark suit jacket over a light-colored, patterned shirt. He is looking towards the camera with a slight smile and has his hands clasped in front of him. In the background, several other people are visible, including a man with glasses on the right and another man in the center. The setting appears to be an indoor event or conference.

M.Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.

- speed of light in water $< c$
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



muon

interaction

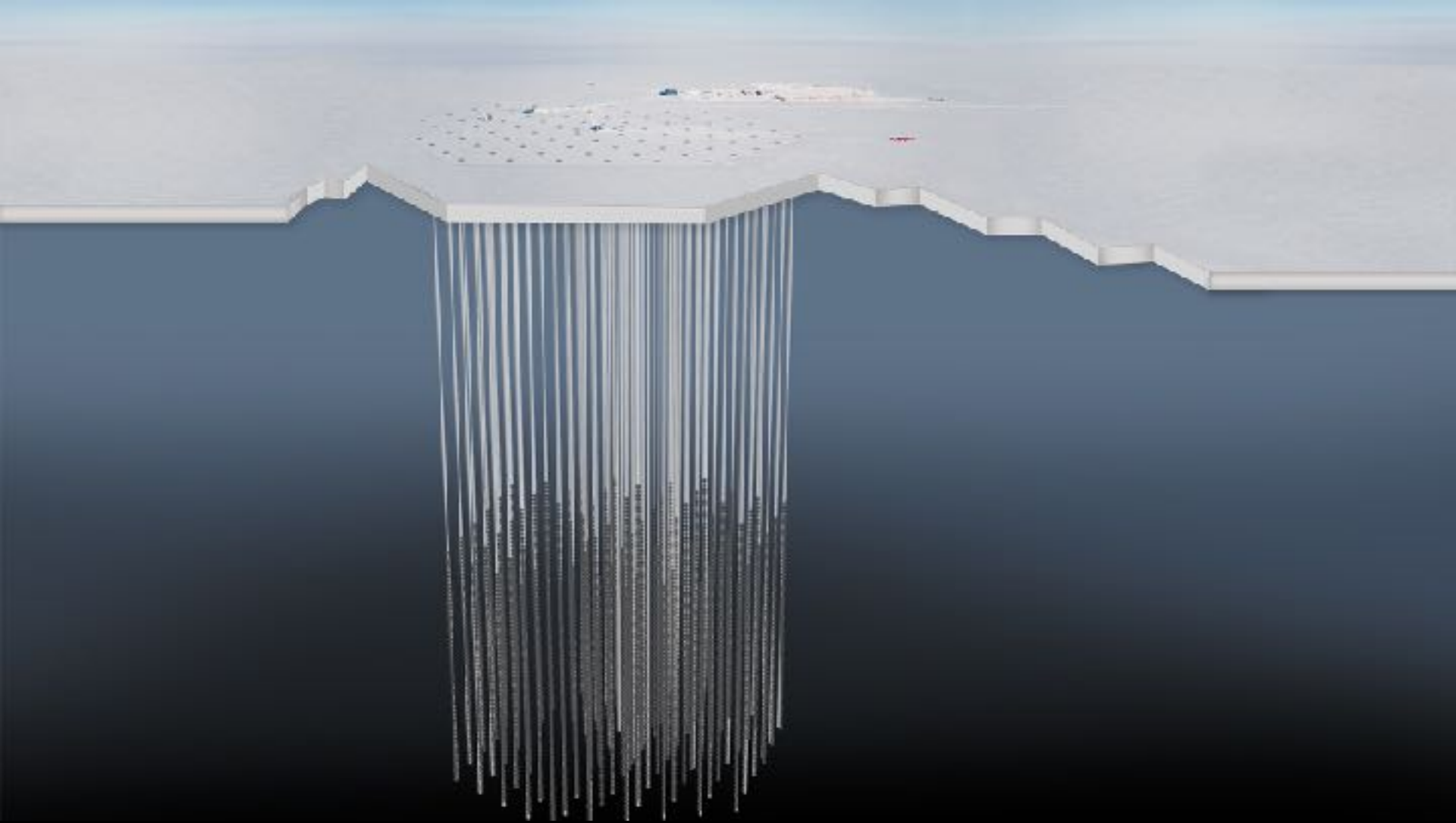
neutrino

• lattice of photomultipliers



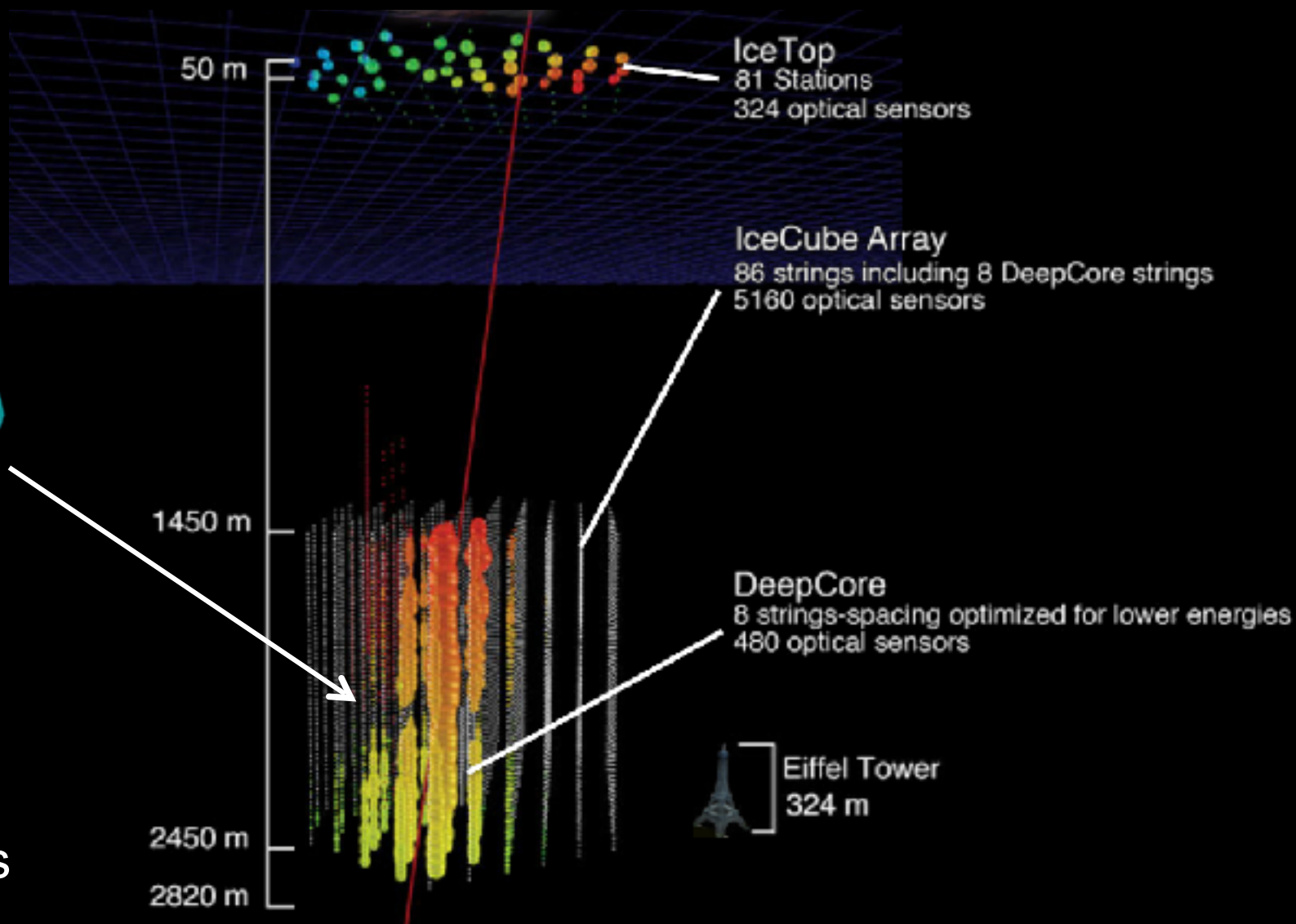
ultra-transparent ice below 1.5 km

instrument 1 cubic kilometer of natural ice below 1.45 km



IceCube

5160 PMs
in 1 km³



photomultiplier
tube -10 inch

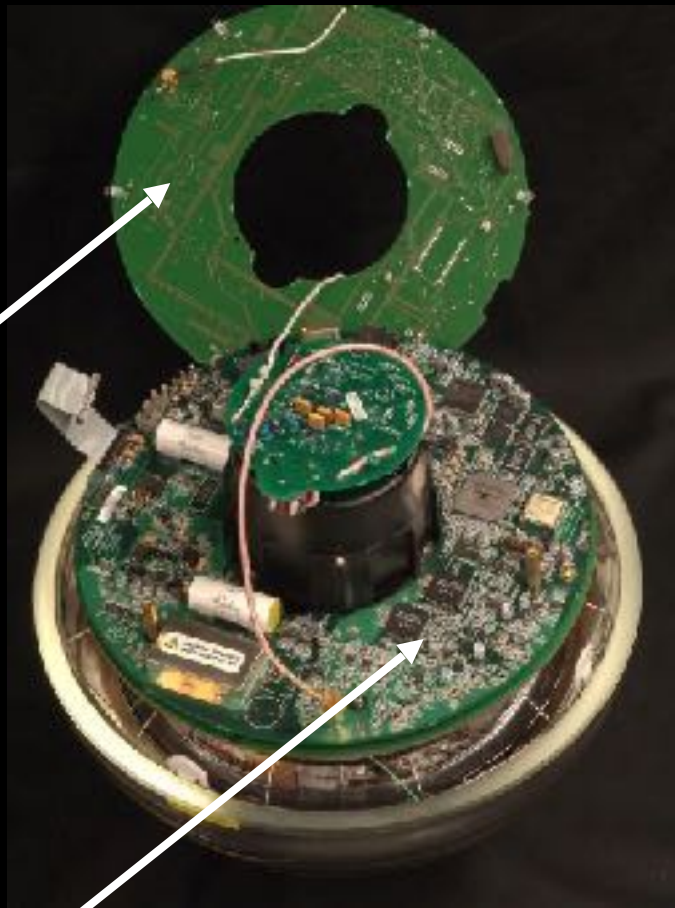


architecture of independent DOMs

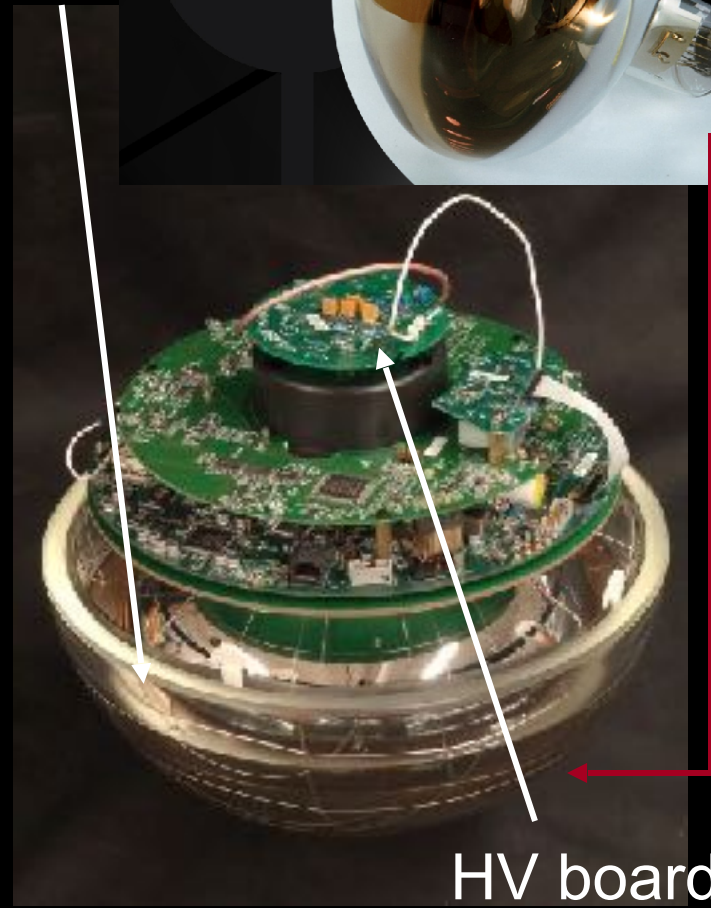
10 inch pmt



LED
flasher
board

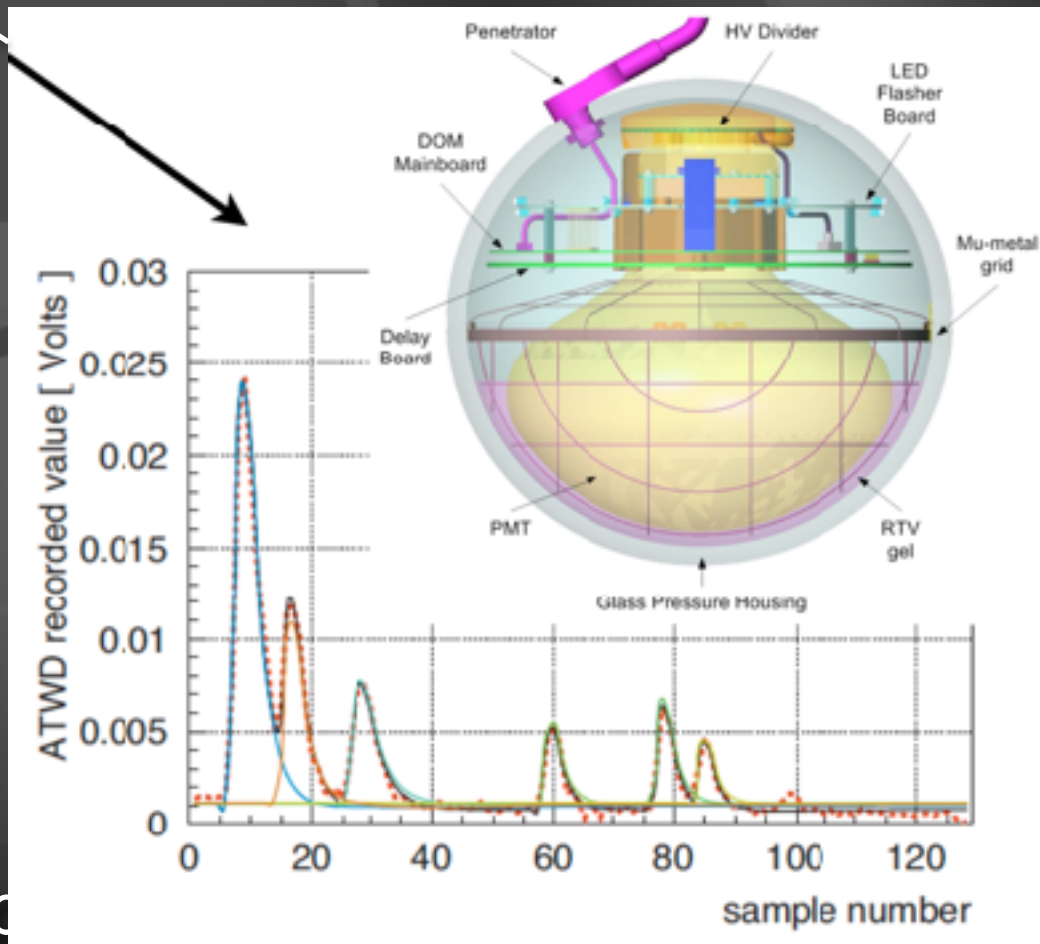


main
board



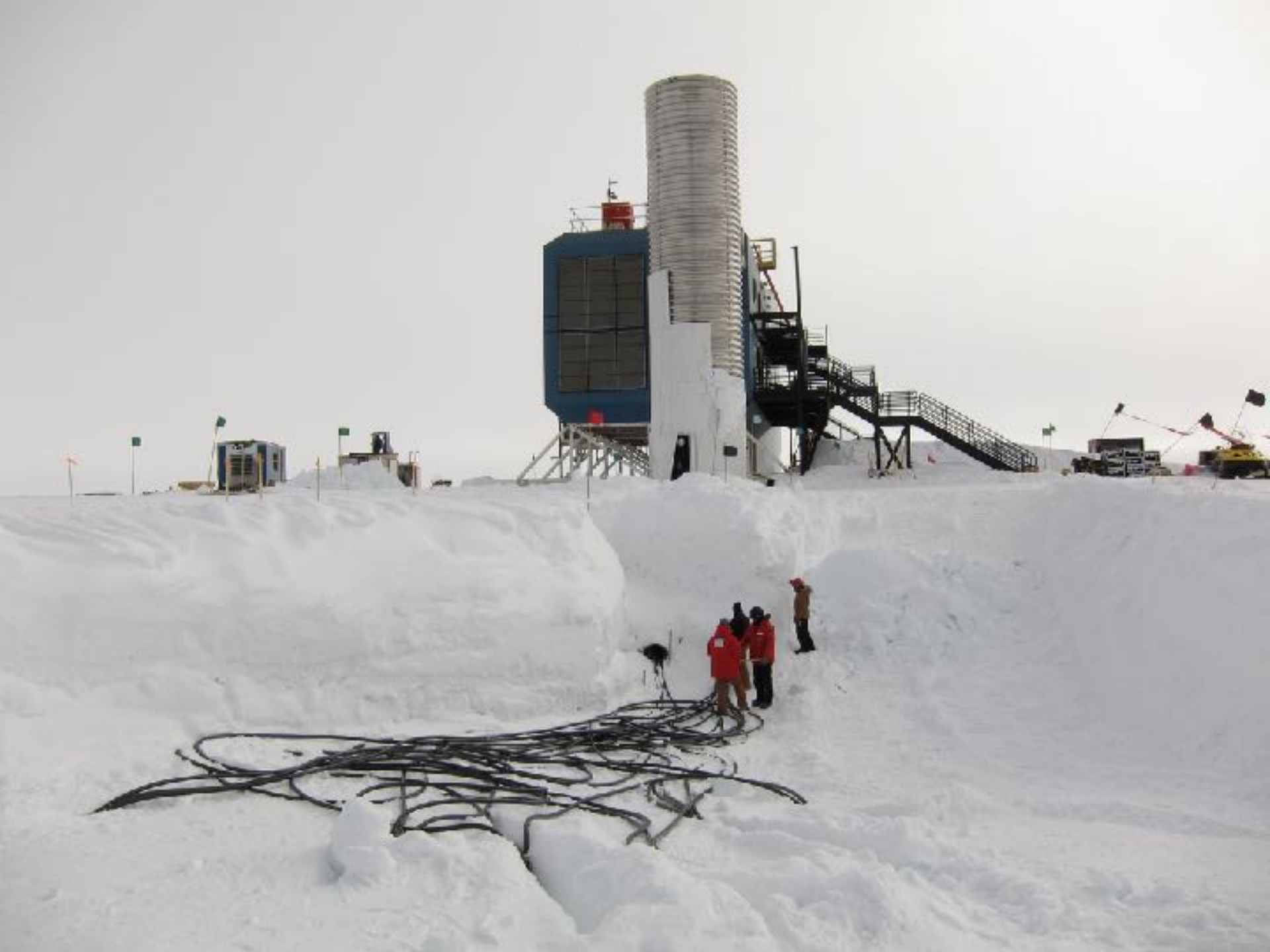
HV board

... each Digital Optical Module independently collects light signals like this, digitizes them,

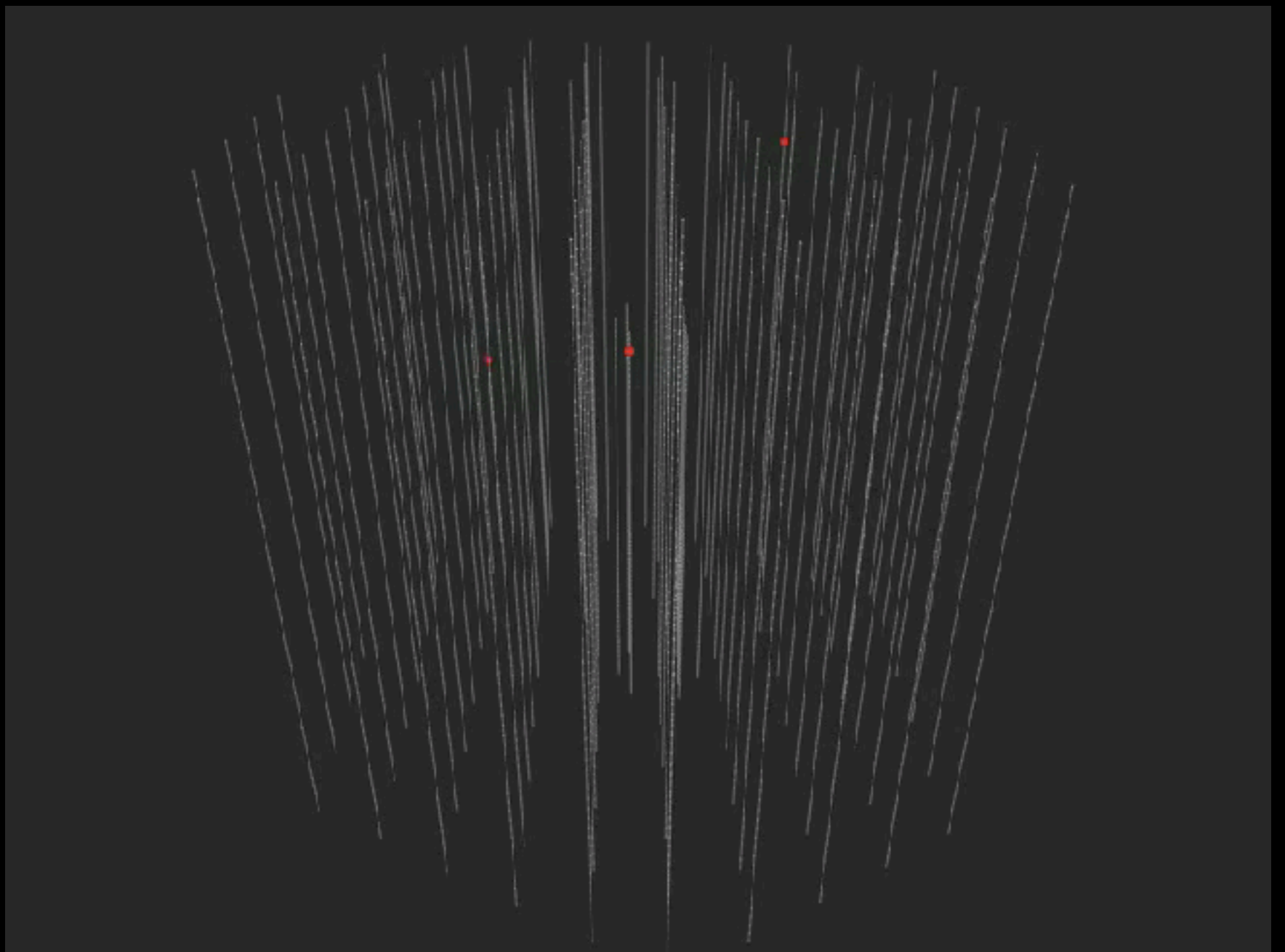


...time stamp each event with precision, and sends them to a computer that sorts them into events...



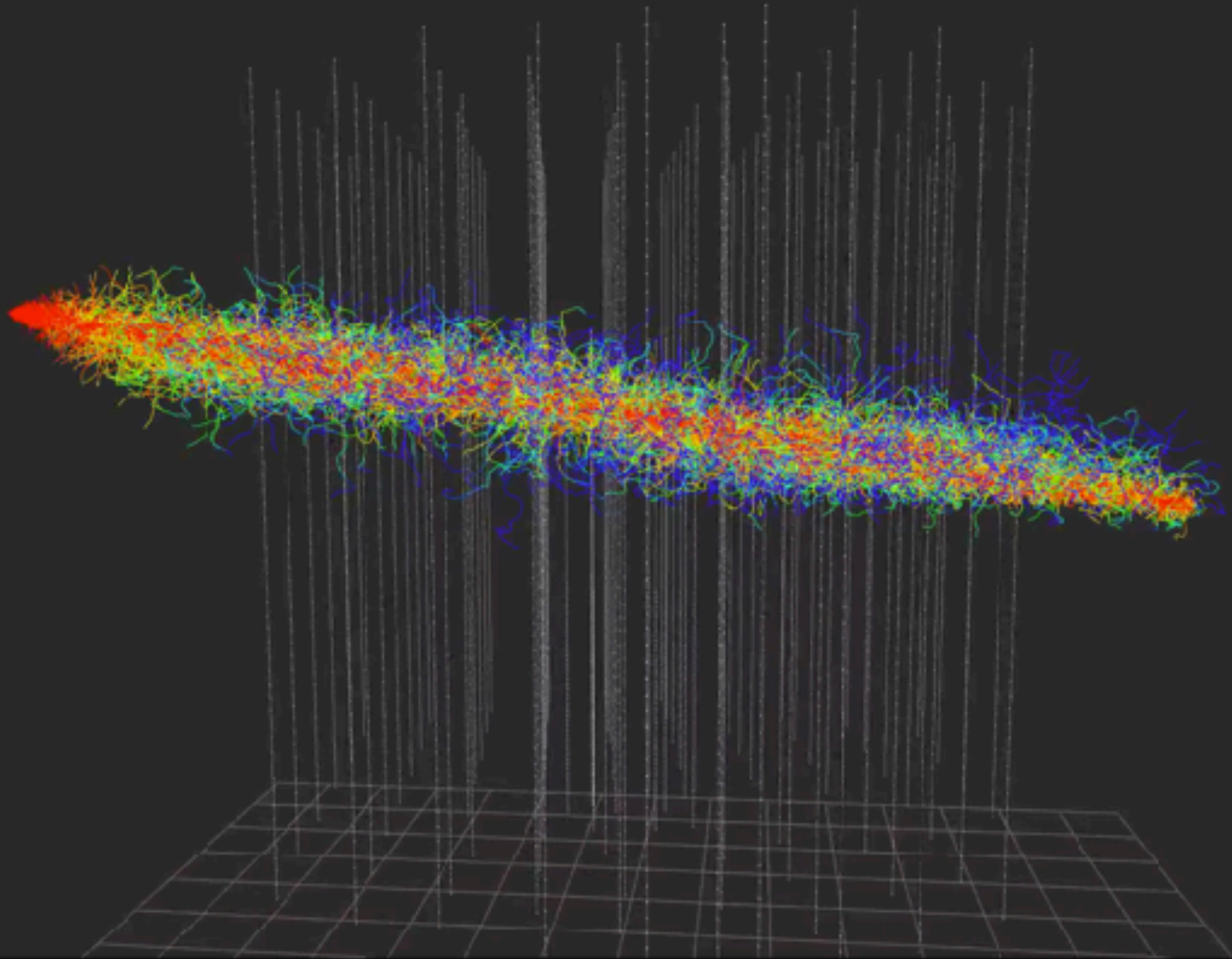


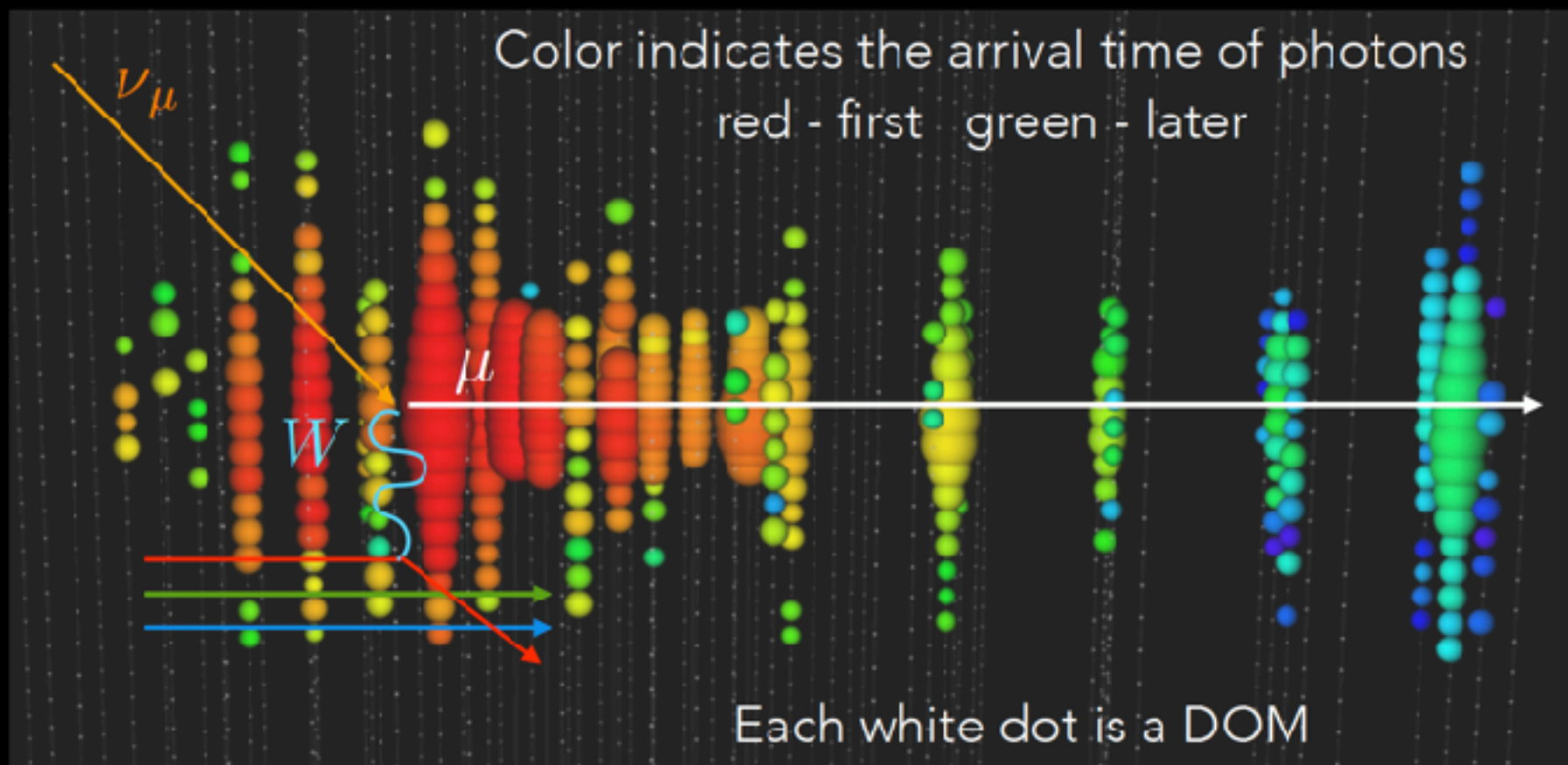




muon track: color is time; number of photons is energy

neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



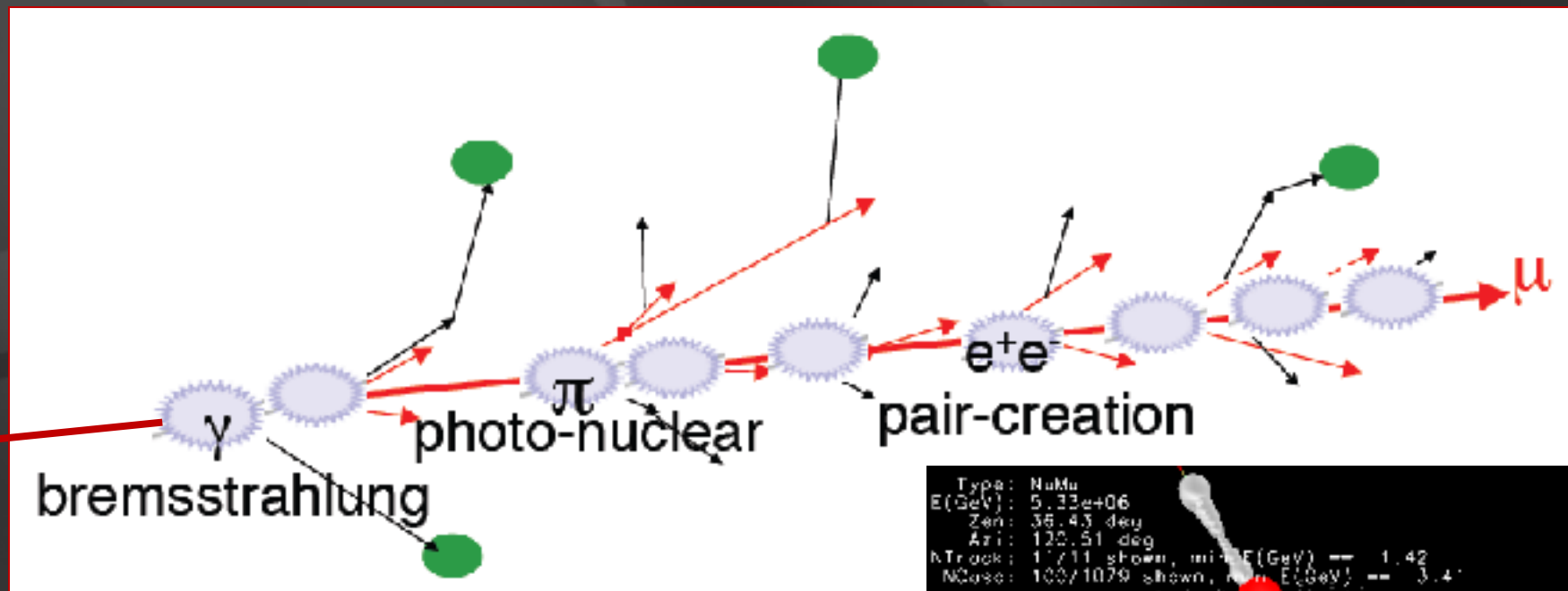


Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

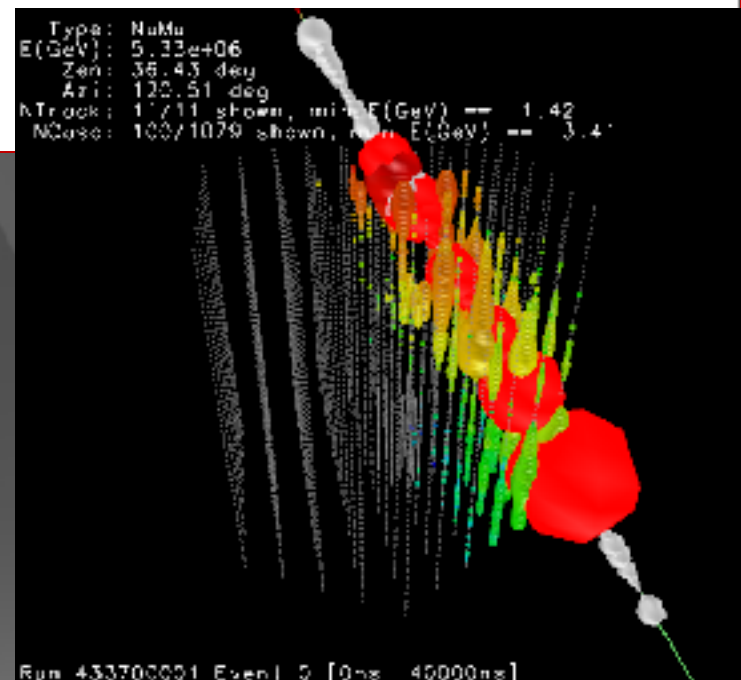
93 TeV muon: light ~ energy

```
Type: NuMu  
E (GeV): 9.30e+04  
Zen: 40.45 deg  
Azi: 192.12 deg  
NT:uck: 1/1 shown, min E(GeV) == 93026.46  
NCasc: 100/427 shown, min E(GeV) == 7.99
```

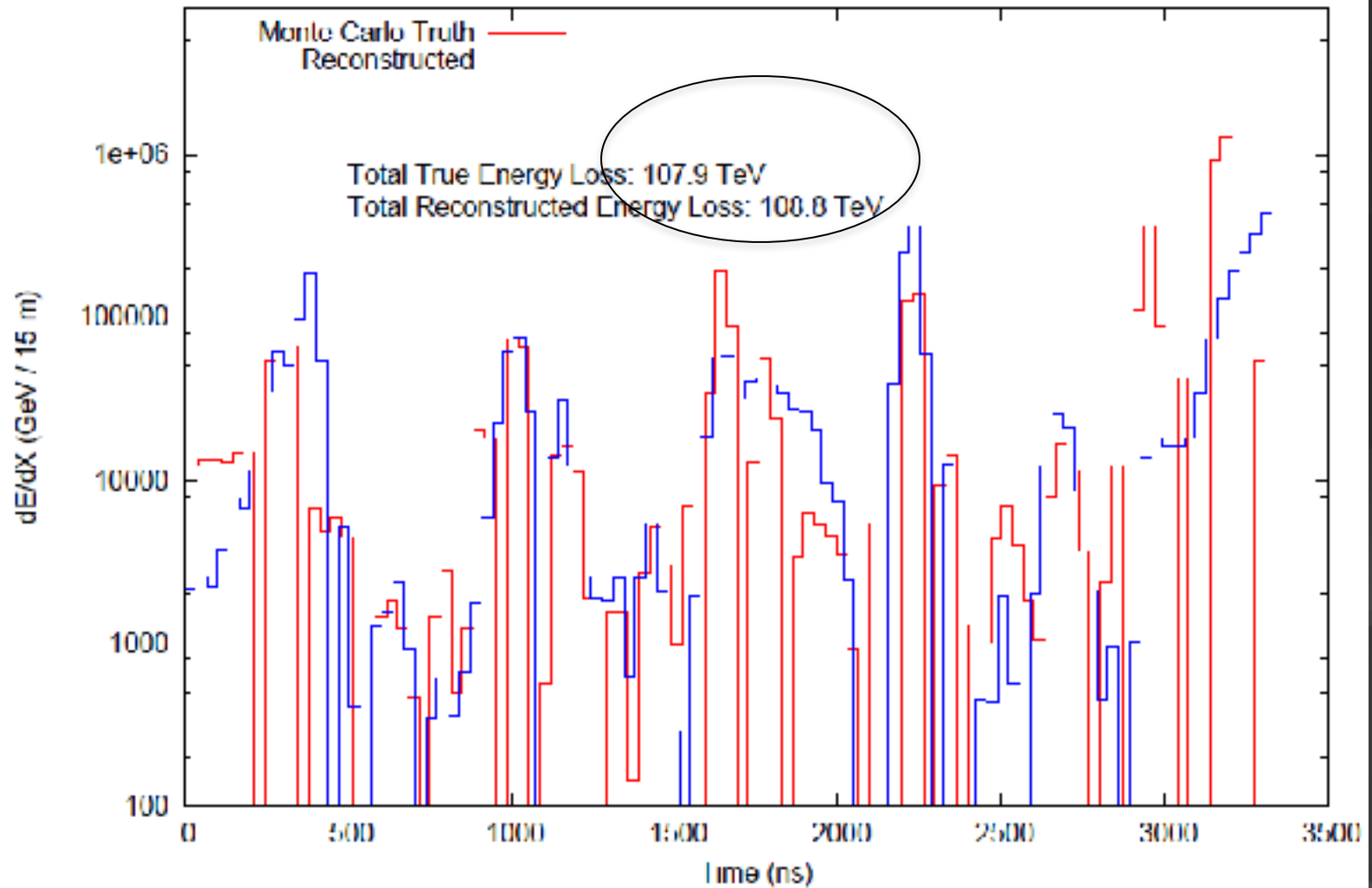
energy measurement (> 1 TeV)



convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx , ...)



Differential Energy Reconstruction of 5 PeV Muon in IC-86

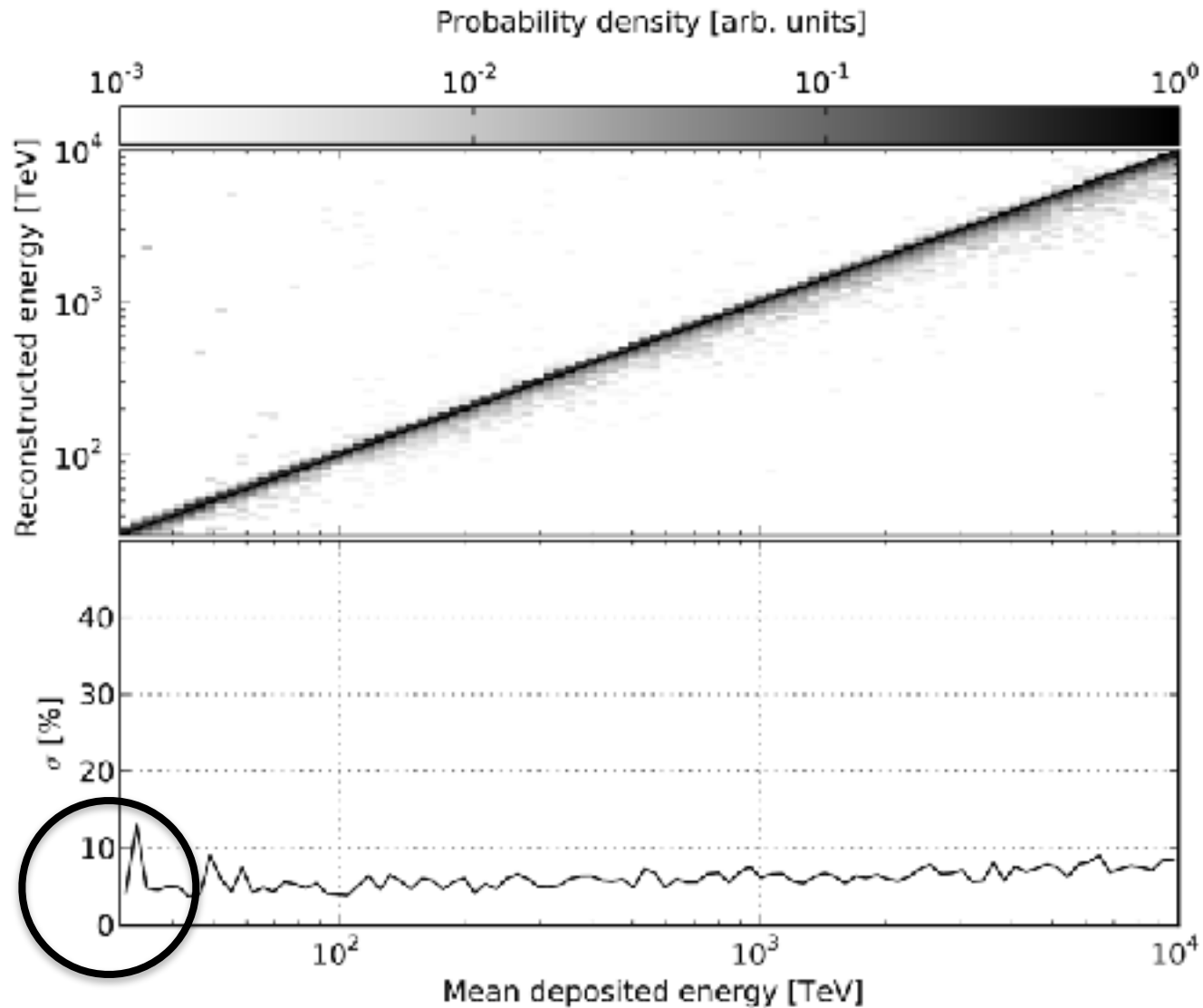


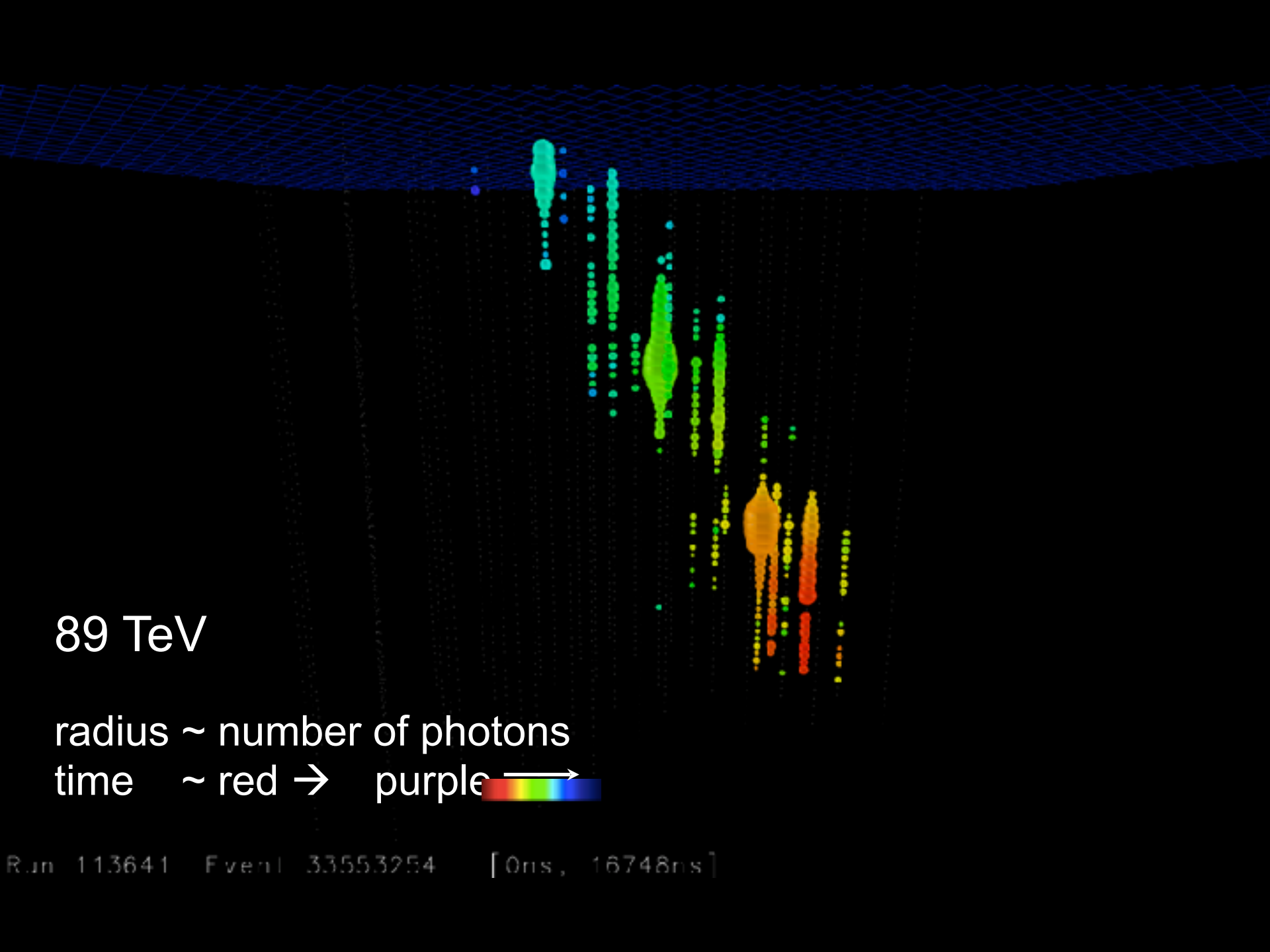
1.1 km



limited angular and energy resolution: computing \rightarrow ice properties

energy reconstruction of electromagnetic showers



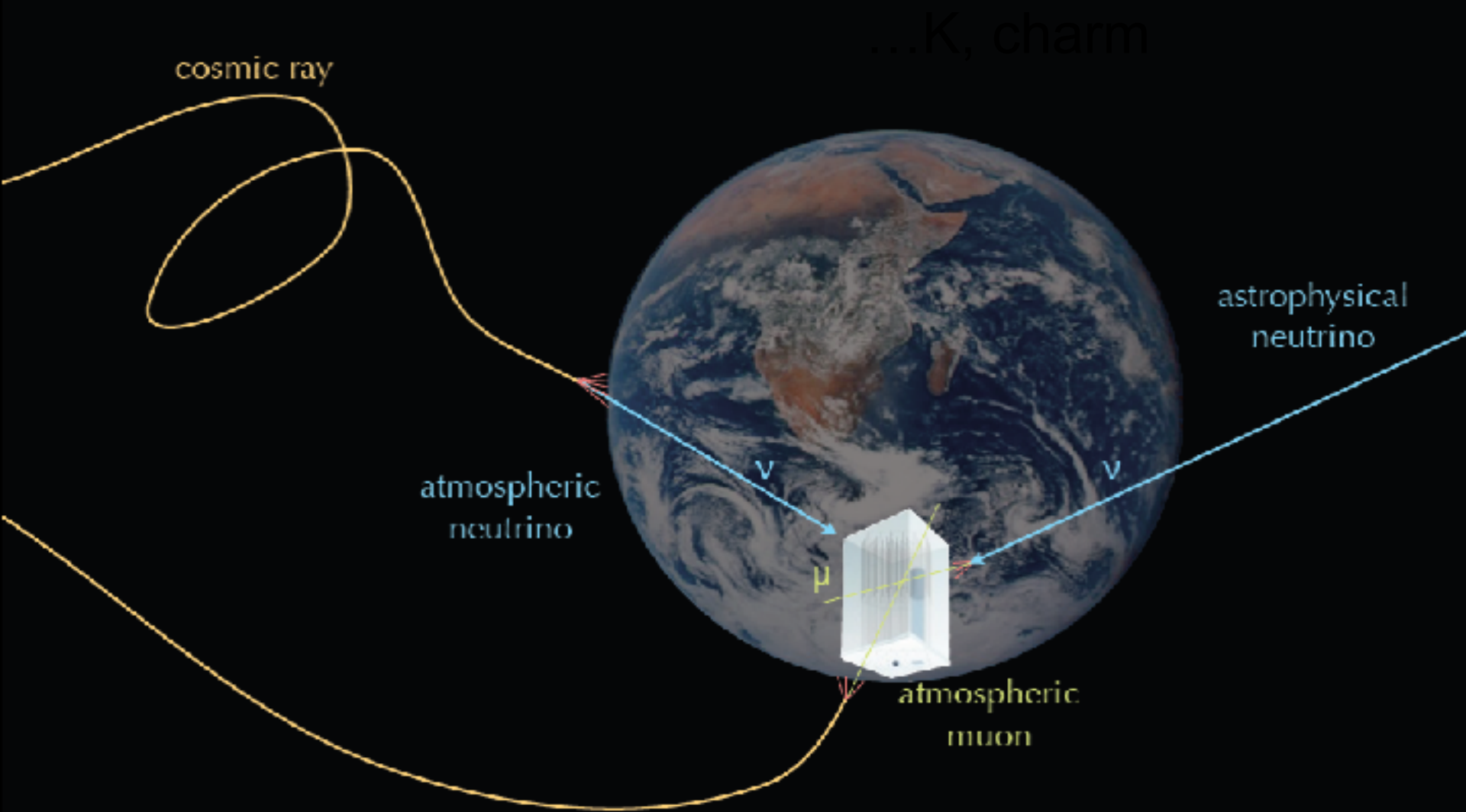


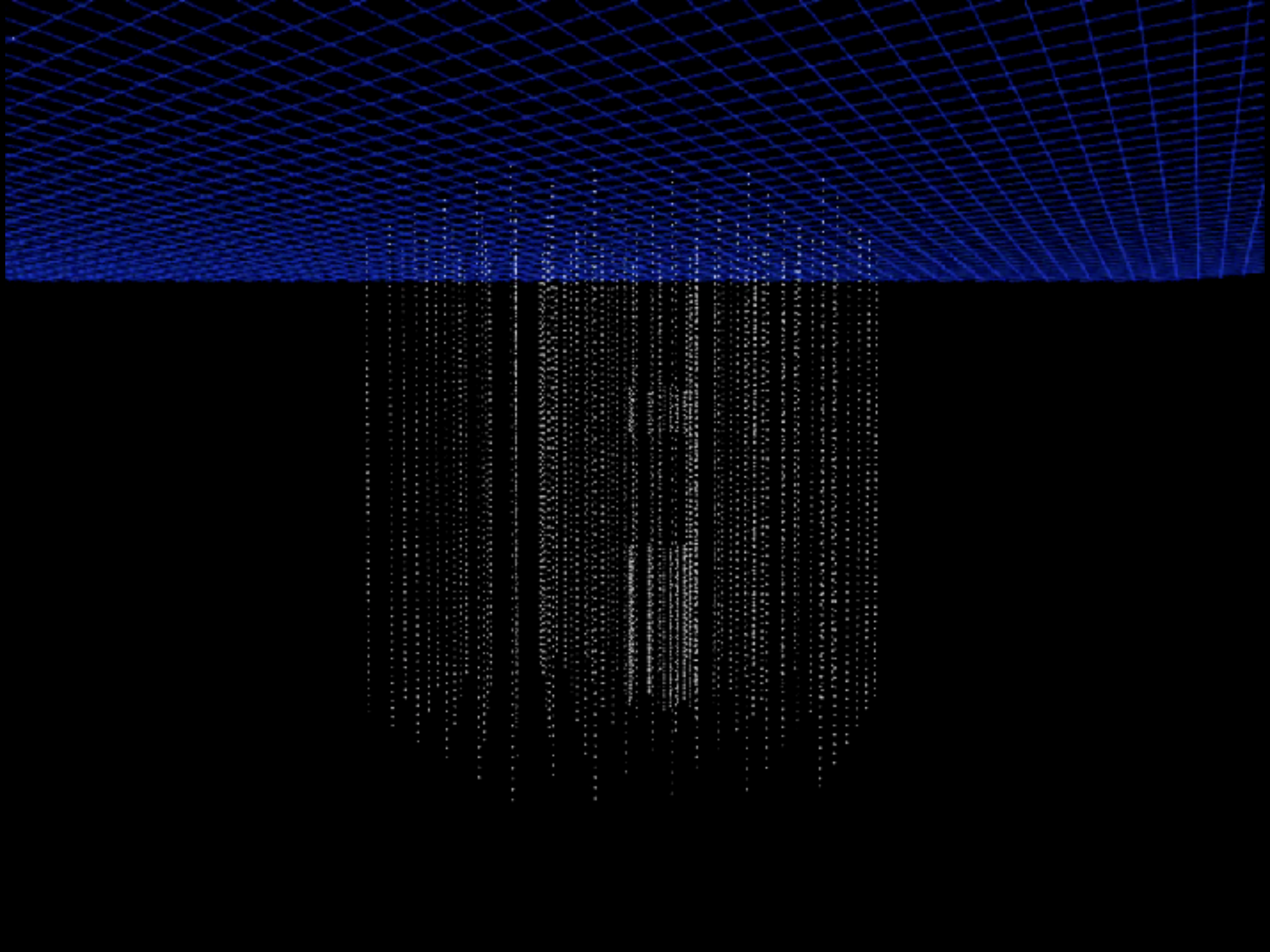
89 TeV

radius \sim number of photons

time \sim red \rightarrow purple \rightarrow

Signals and Backgrounds





... you looked at 10msec of data !

muons detected per year:

• atmospheric* μ $\sim 10^{11}$

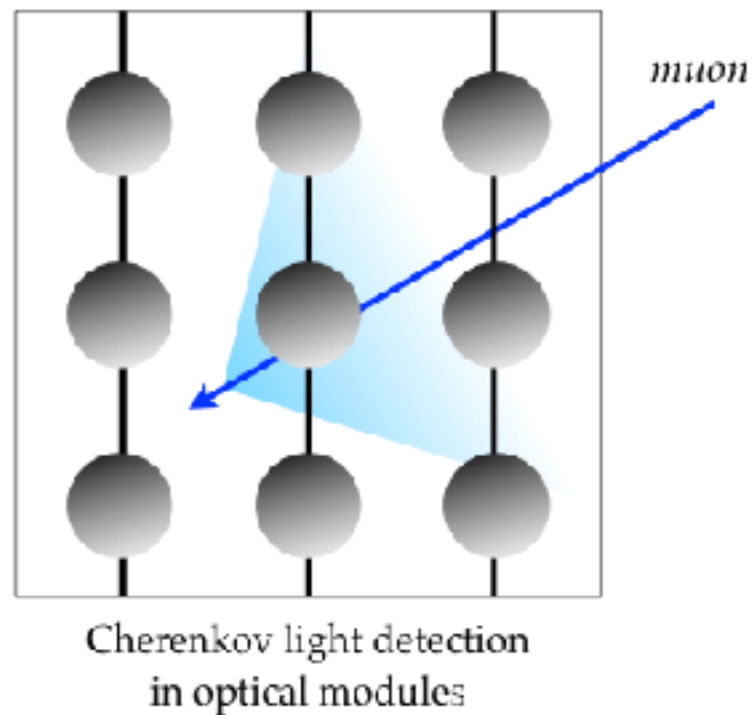
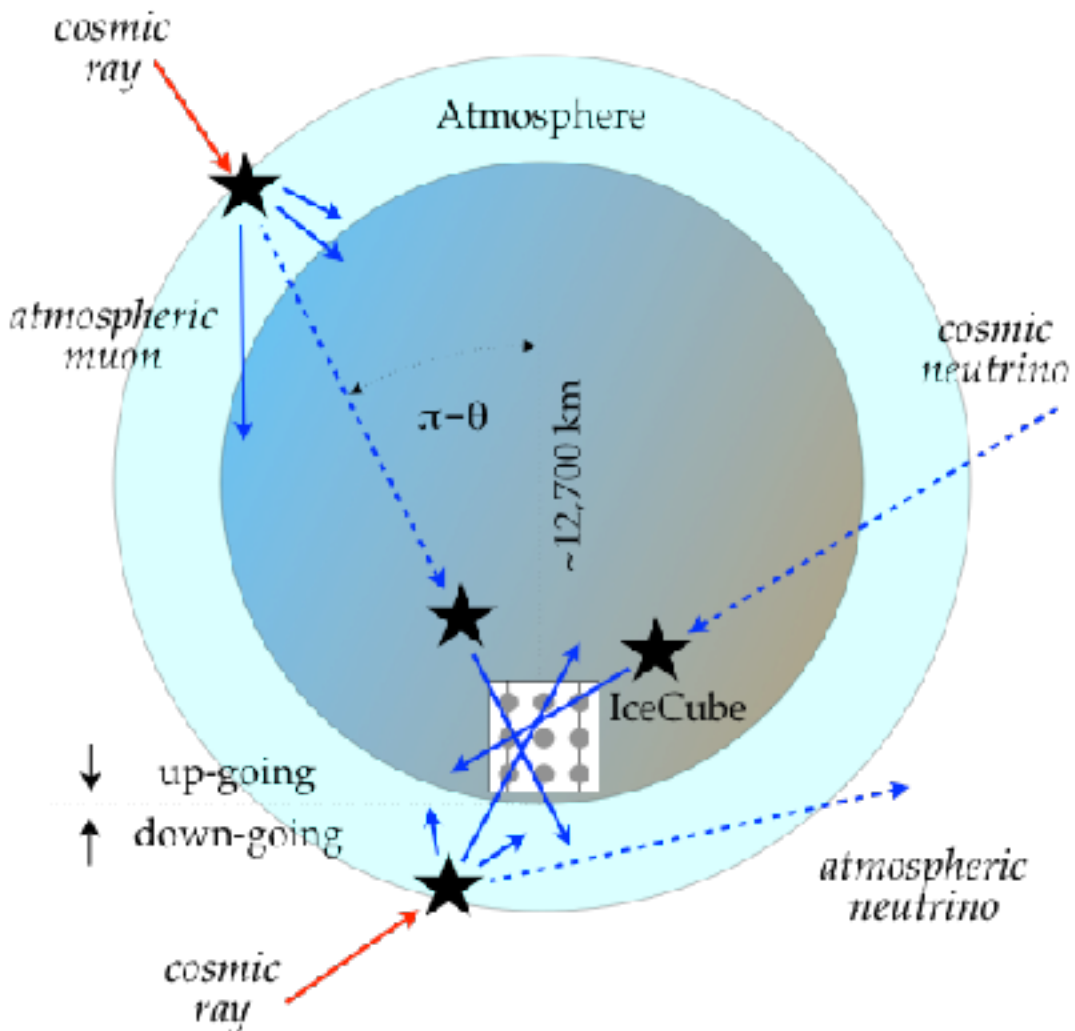
• atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$

• cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

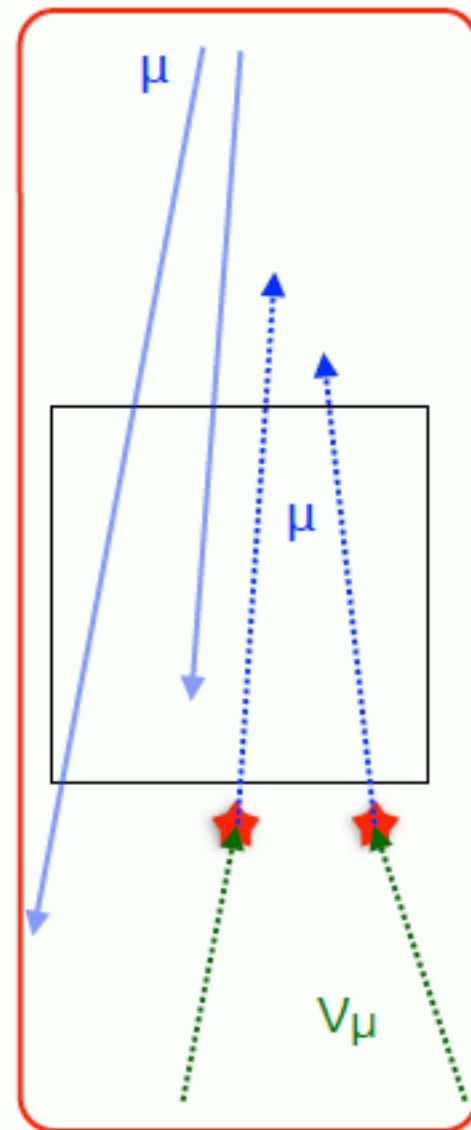
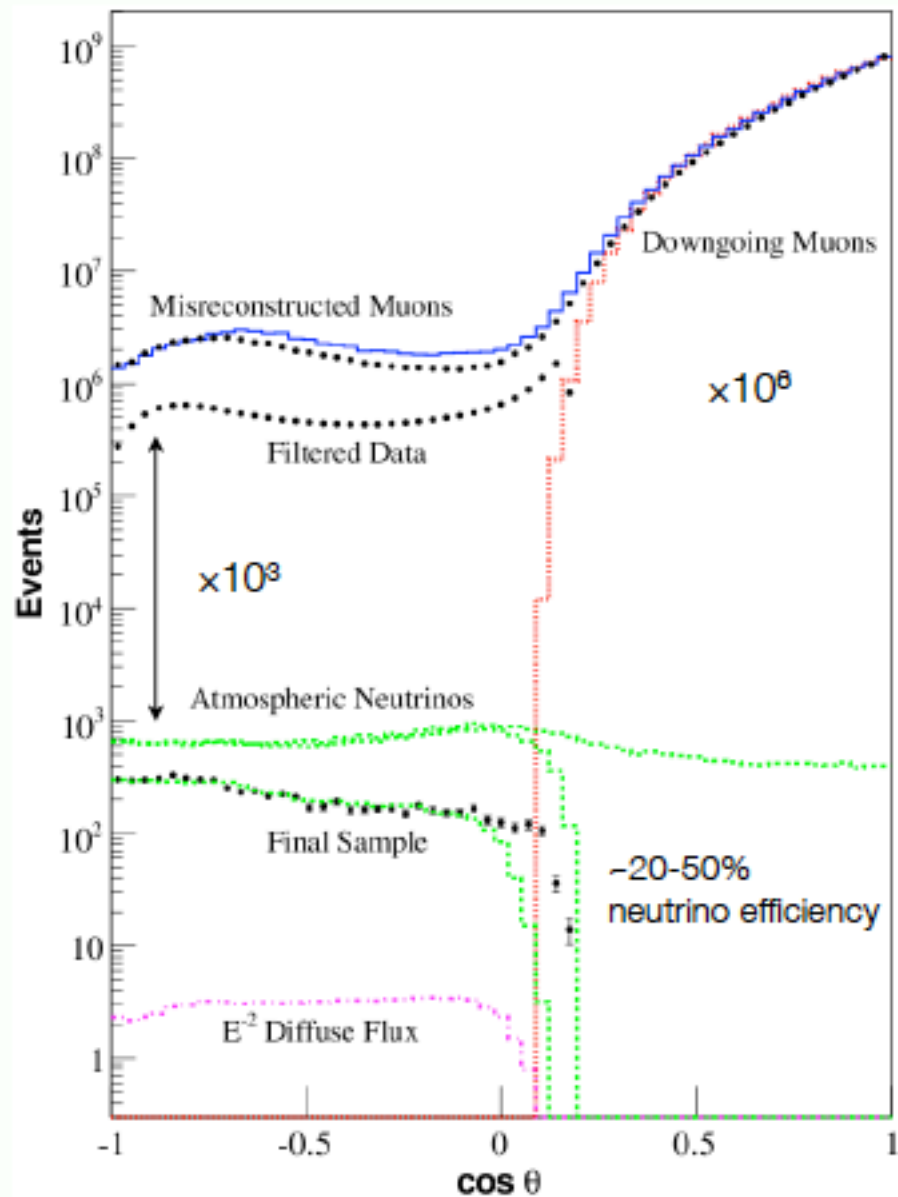
** 1 every 6 minutes

- rejecting atmospheric muons

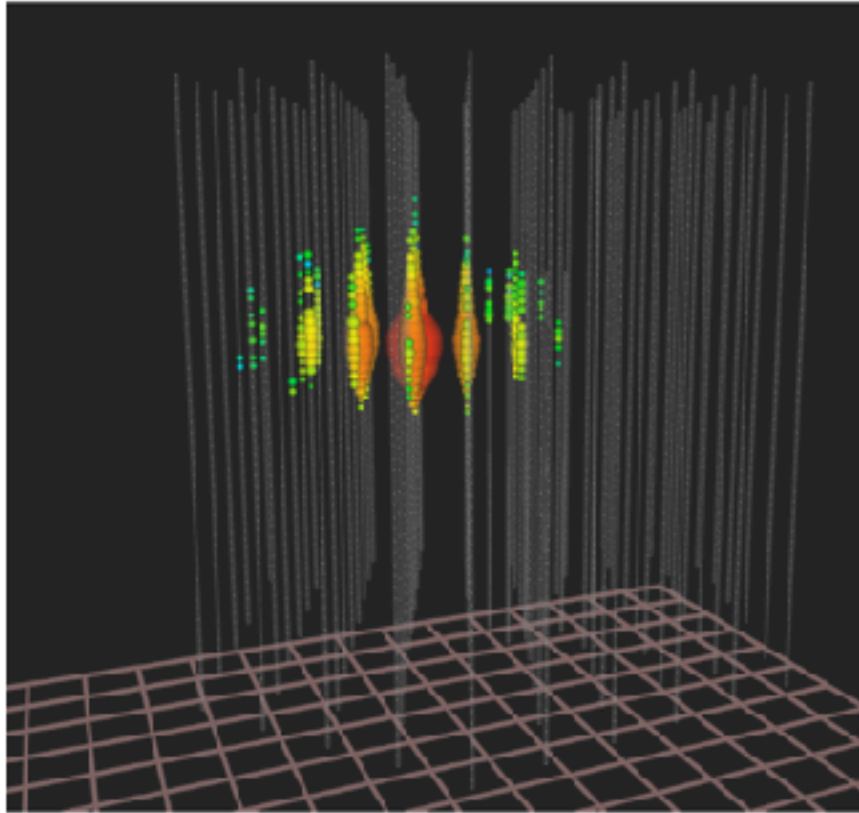


- rejecting atmospheric neutrinos

through-going
(tracks)

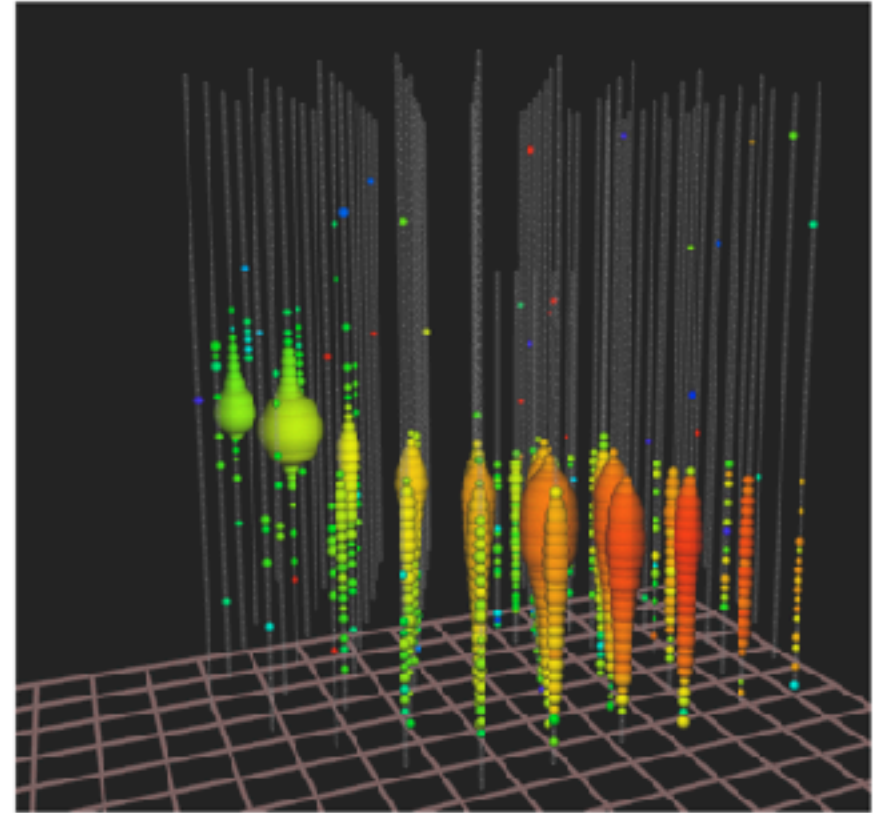


isolated neutrinos interacting
inside the detector (HESE)



total energy measurement
all flavors, all sky

up-going muon tracks
(UPMU)



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

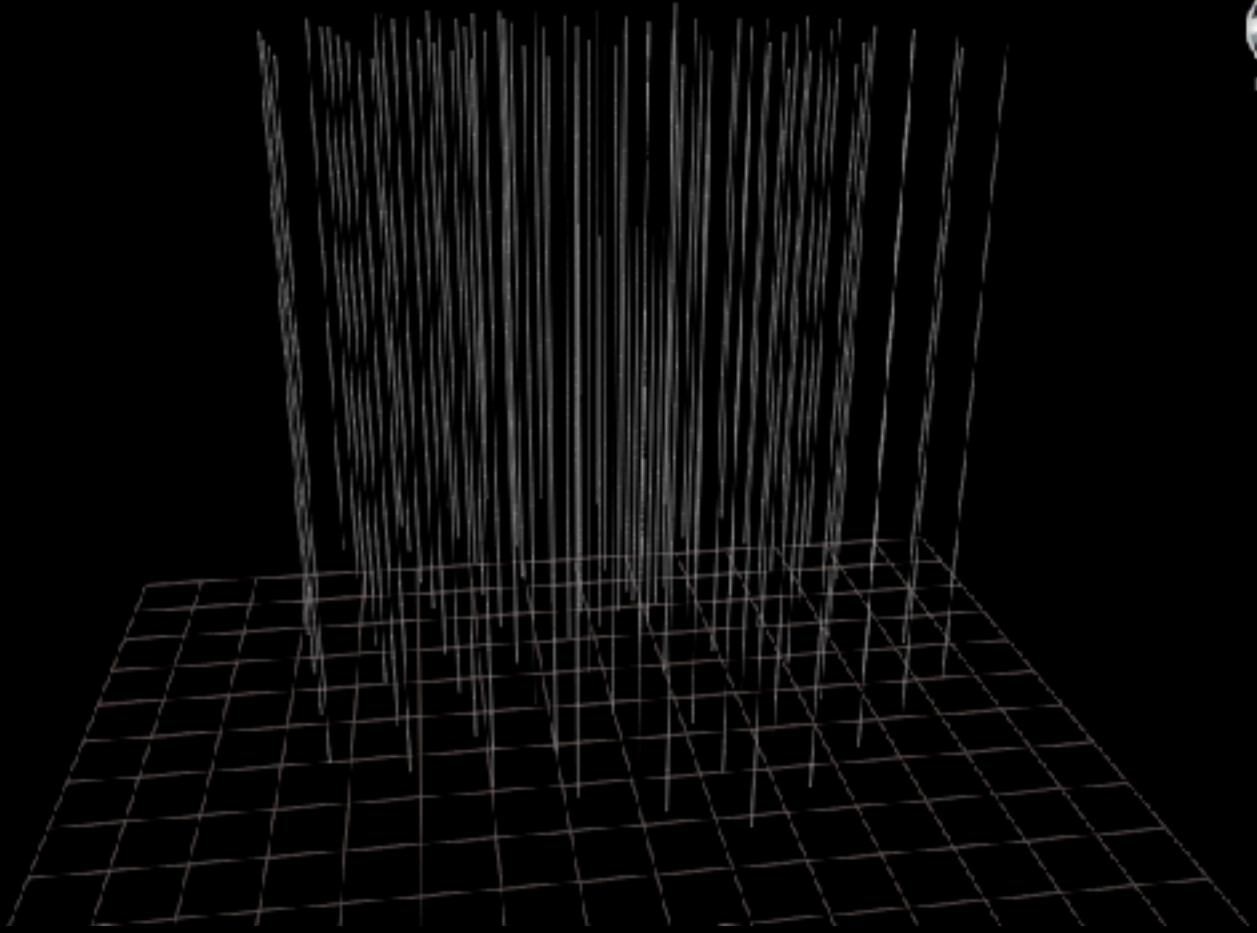
IceCube

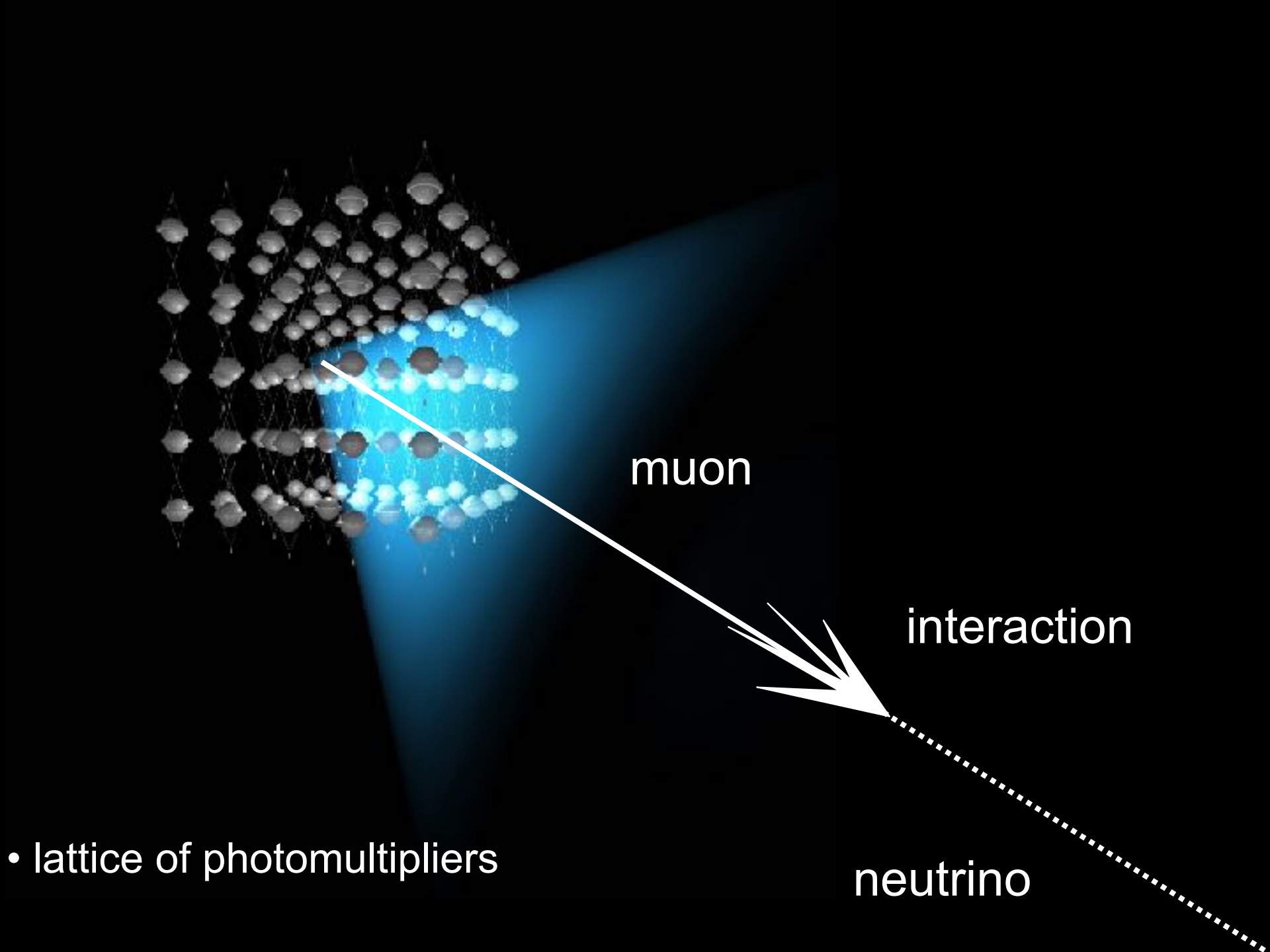
francis halzen

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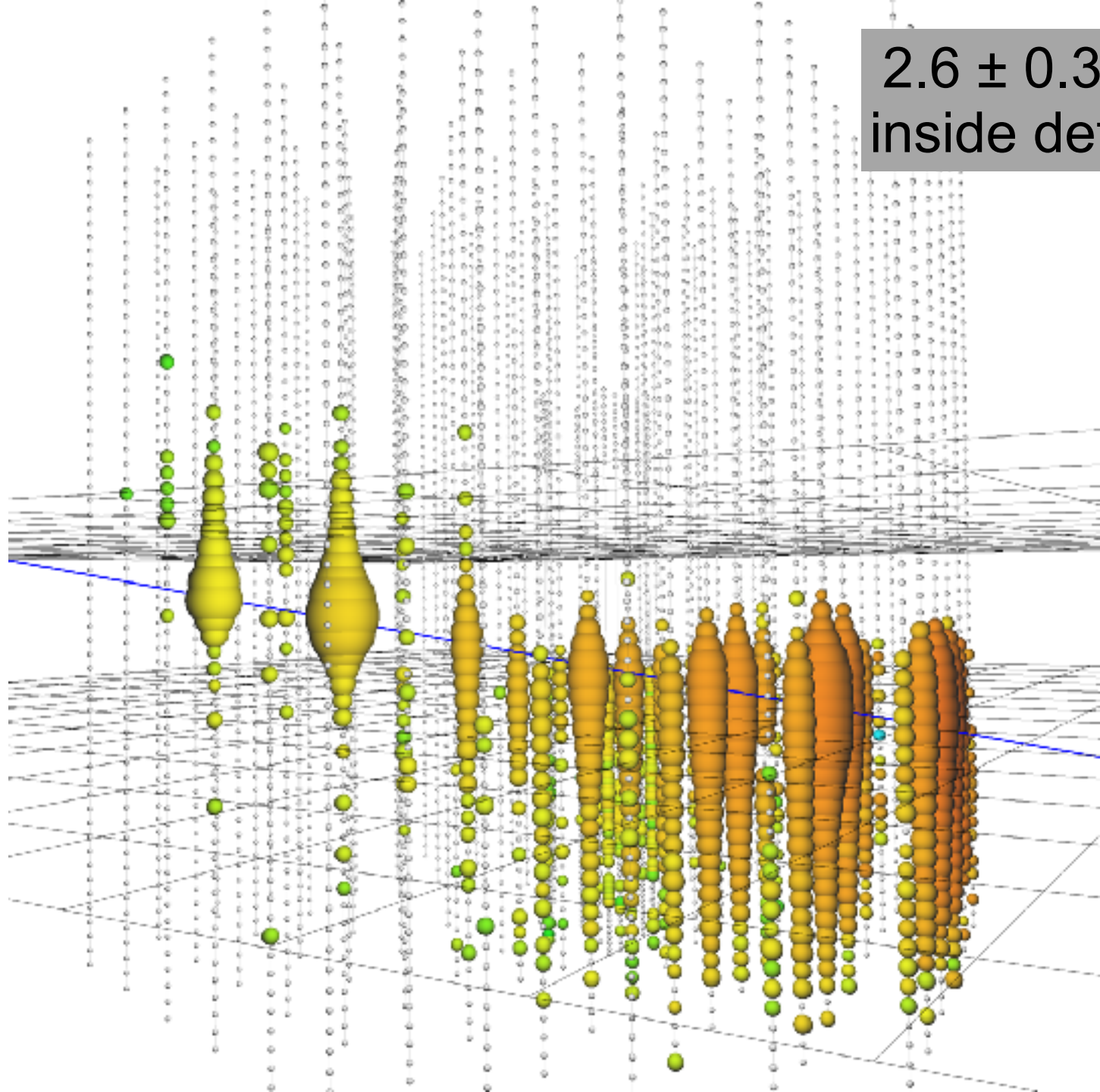


University of Queensland

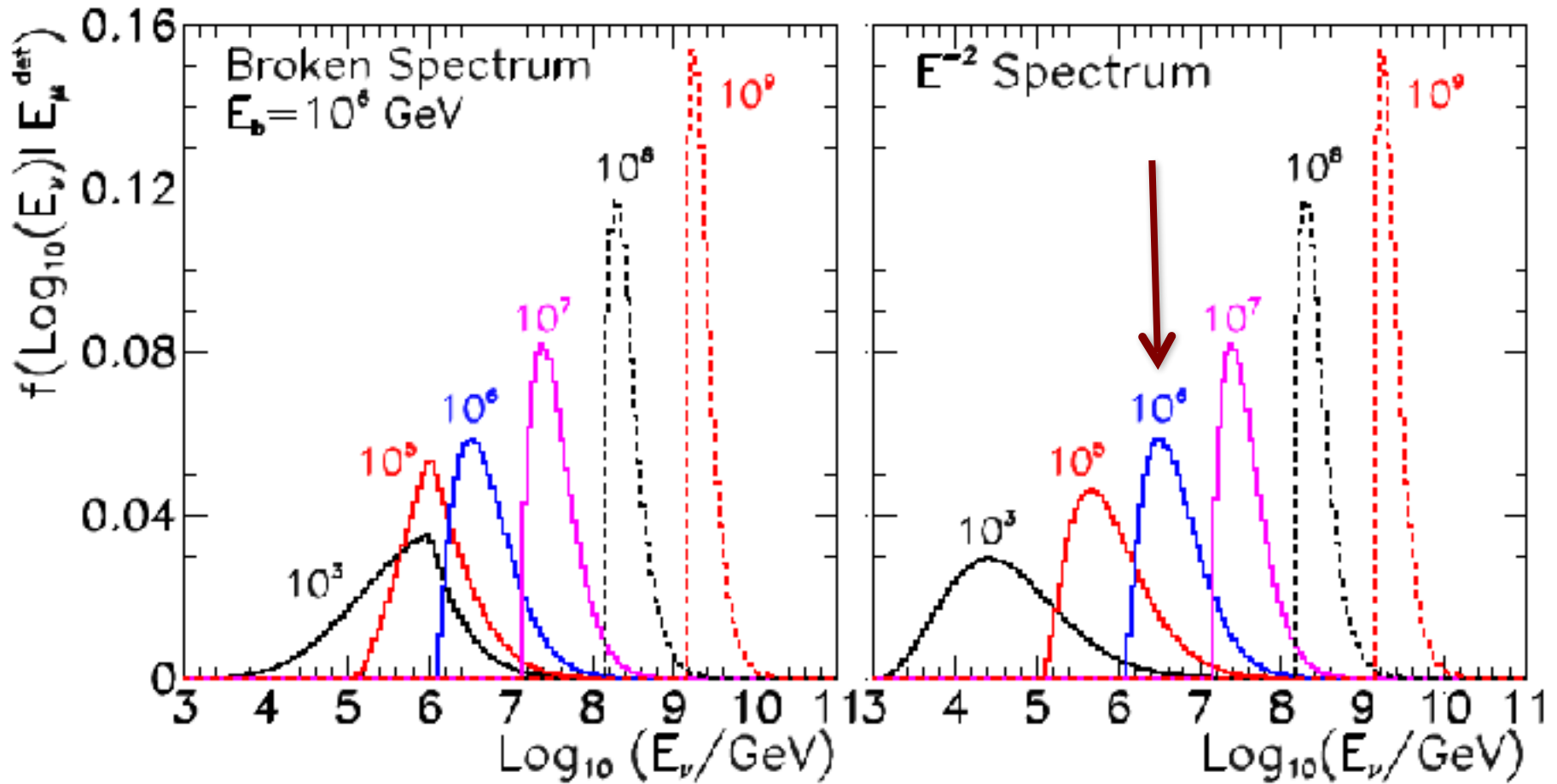




2.6 ± 0.3 PeV
inside detector



distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube



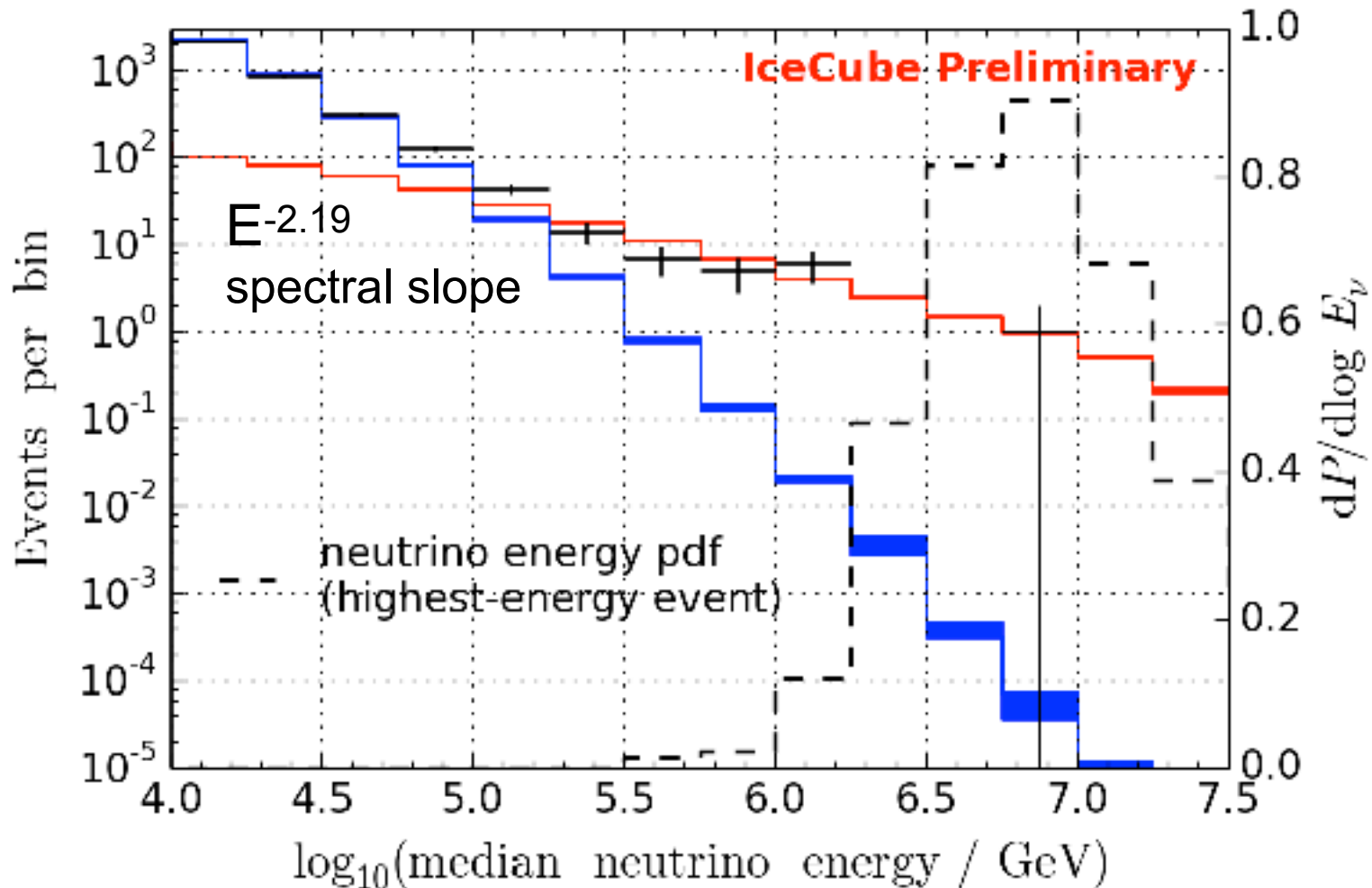
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric
atmospheric background: less than one event/deg²/year

Assuming best-fit power law:

+++ Unfolding

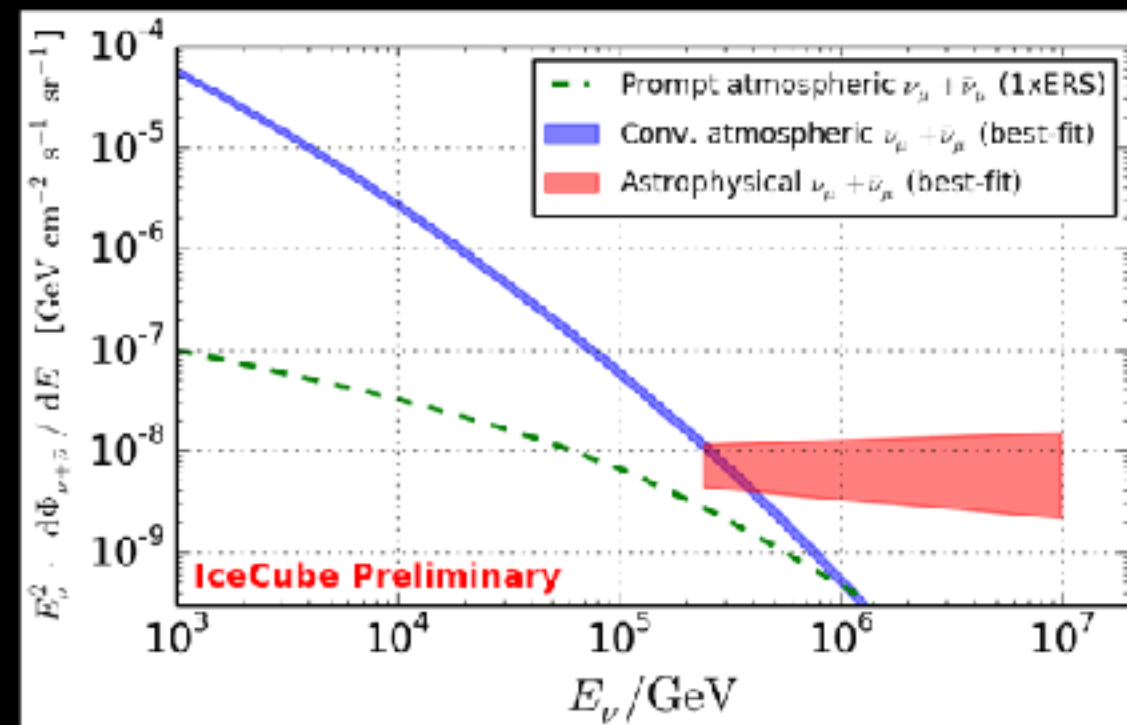
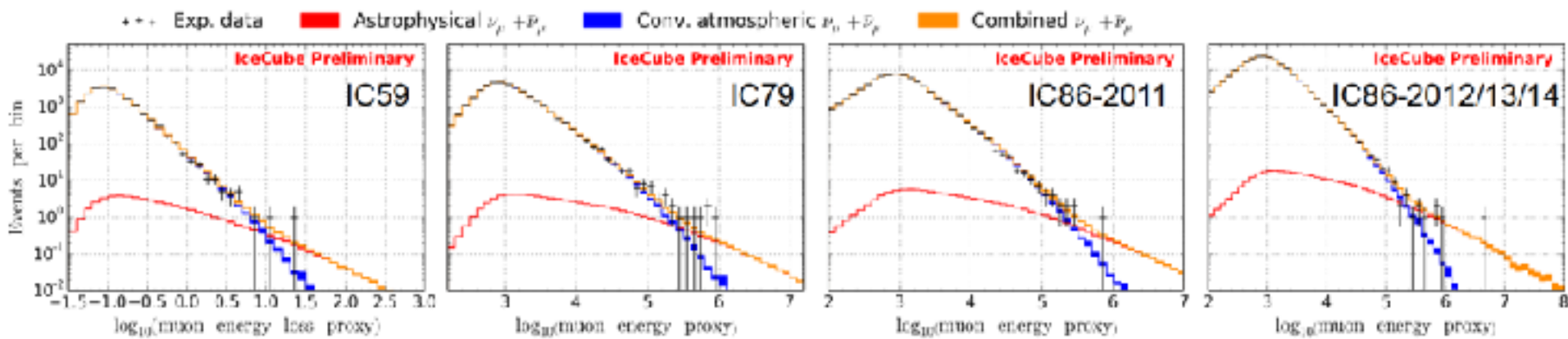
■ Conv. atmospheric ν_μ | $\bar{\nu}_\mu$

■ Astrophysical ν_μ | $\bar{\nu}_\mu$



after 7 years \rightarrow 6.4 sigma

120 cosmic neutrinos/year/flavor



■ Best-fit astrophysical normalization:

$$0.97^{+0.27}_{-0.25} \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

■ Best-fit spectral index:

$$\gamma_{\text{astro}} = 2.16 \pm 0.11$$

■ Energy ranges:

$$240 \text{ TeV} - 10 \text{ PeV}$$

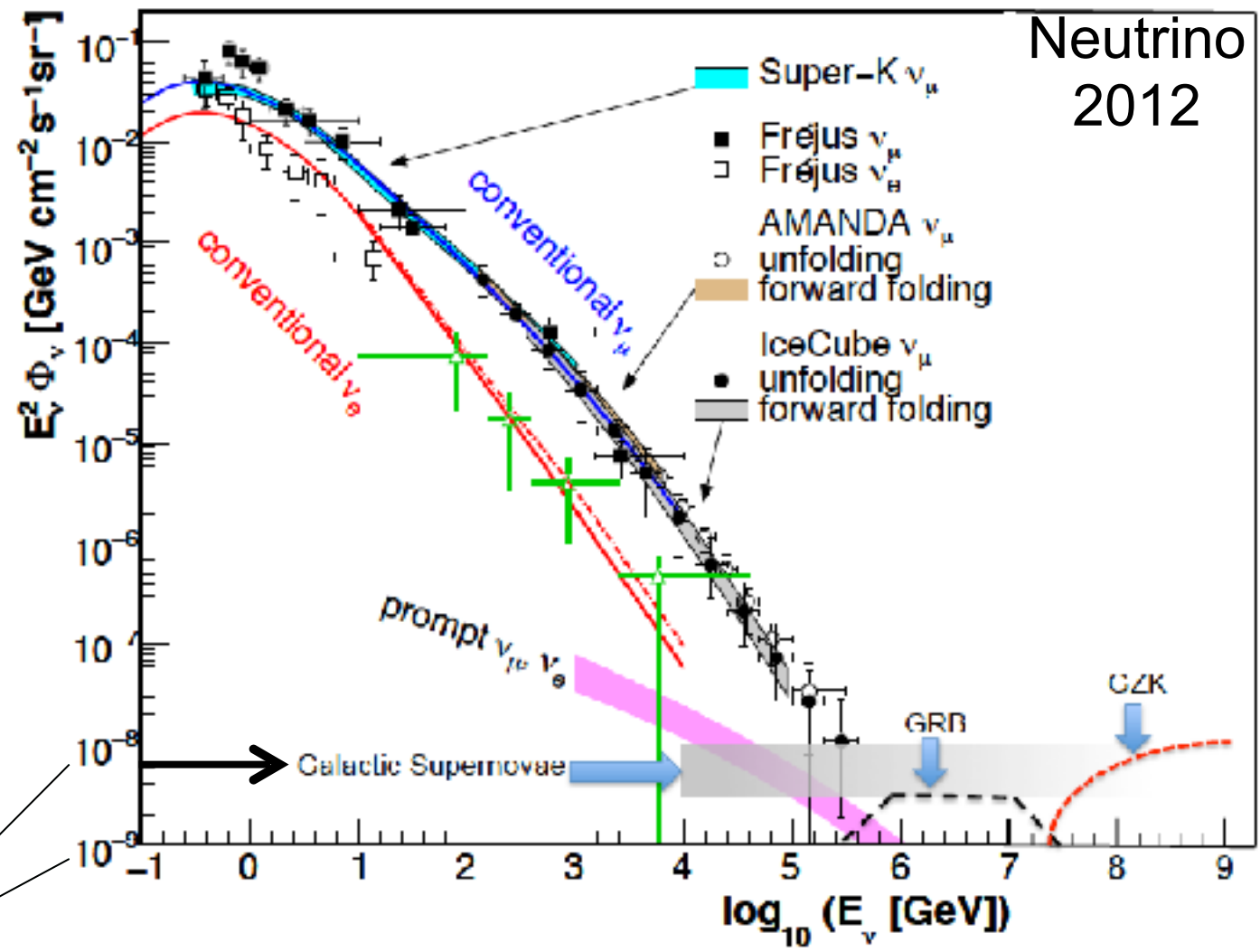
■ Atmospheric-only hypothesis excluded by 6.0σ

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector



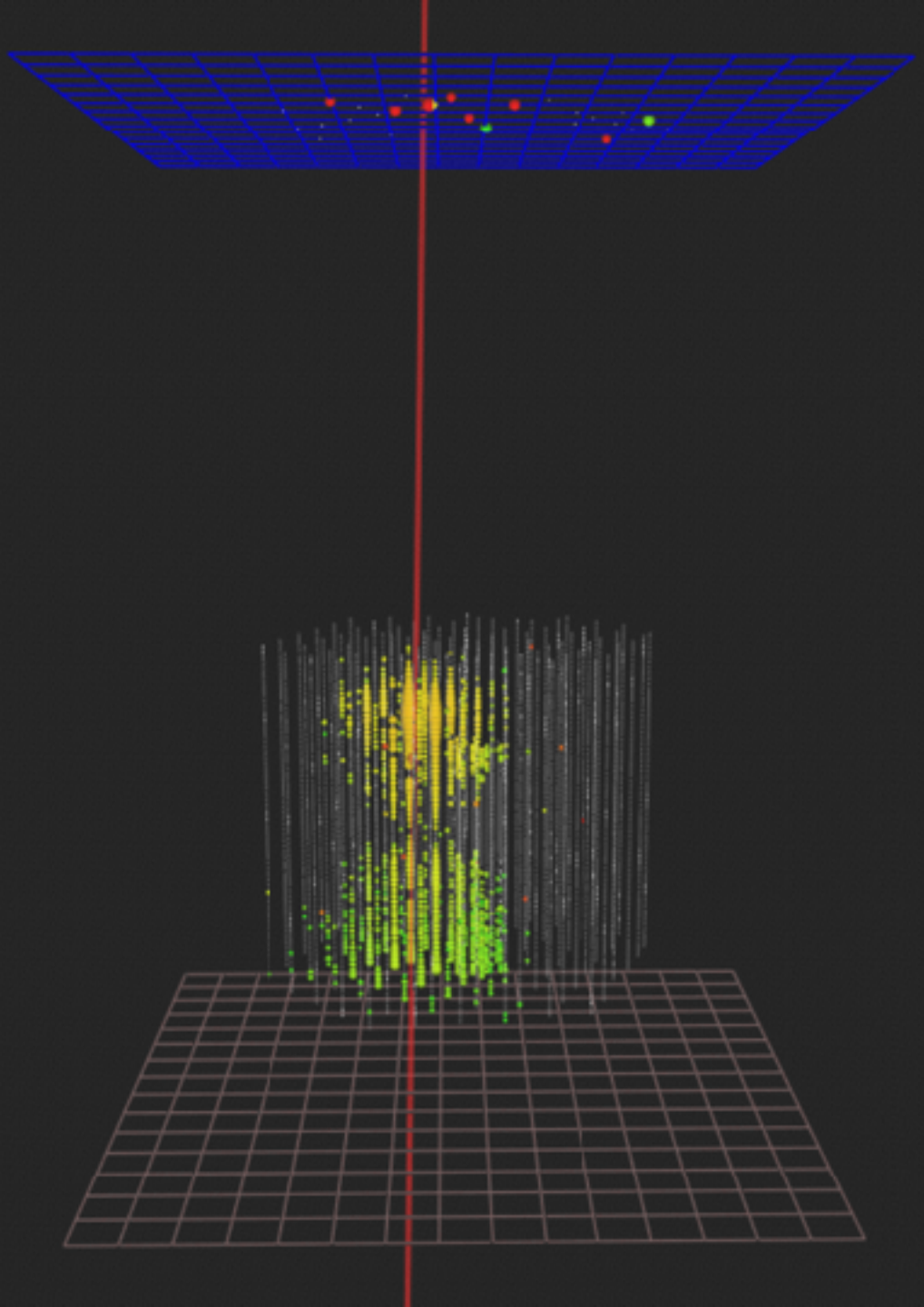
atmospheric

cosmic

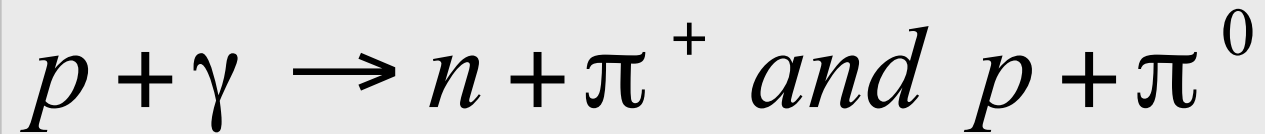
↑
100 TeV

430 TeV inside
detector
PeV ν_μ
no air shower

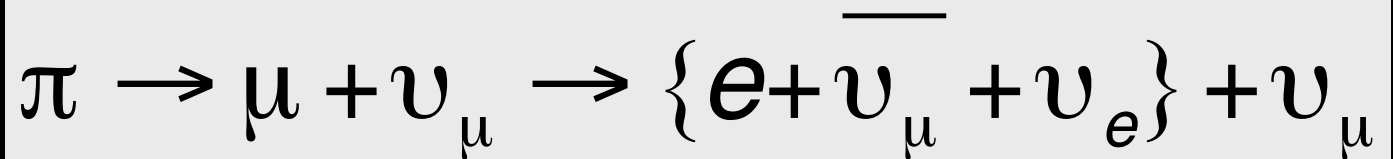
all cosmic
neutrinos are
isolated by
self-veto



cosmic rays interact with the
microwave background



cosmic rays disappear, neutrinos with
EeV (10⁶ TeV) energy appear



1 event per cubic kilometer per year
...but it points at its source!

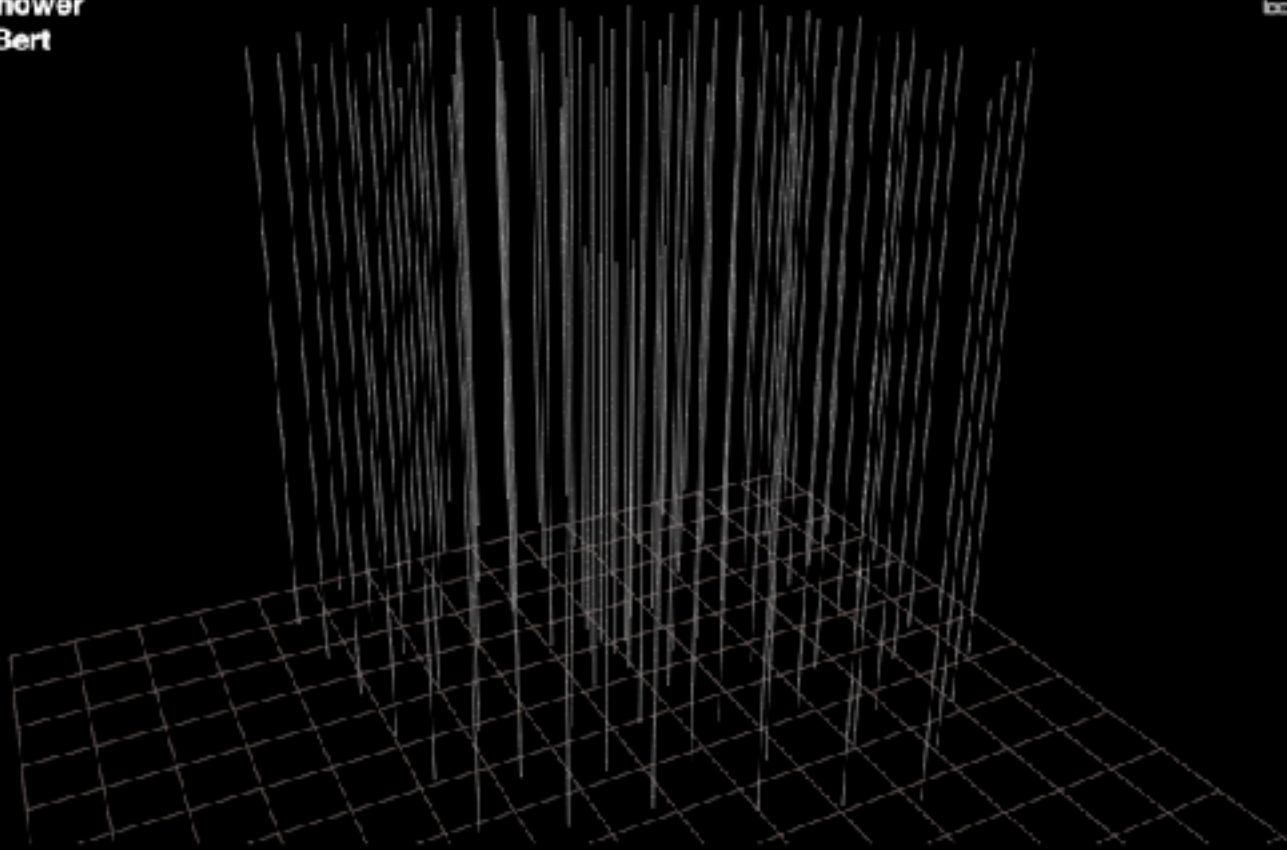
GZK neutrino search: two neutrinos with $> 1,000$ TeV

date: **August 9, 2011**

energy: **1.04 PeV**

topology: **shower**

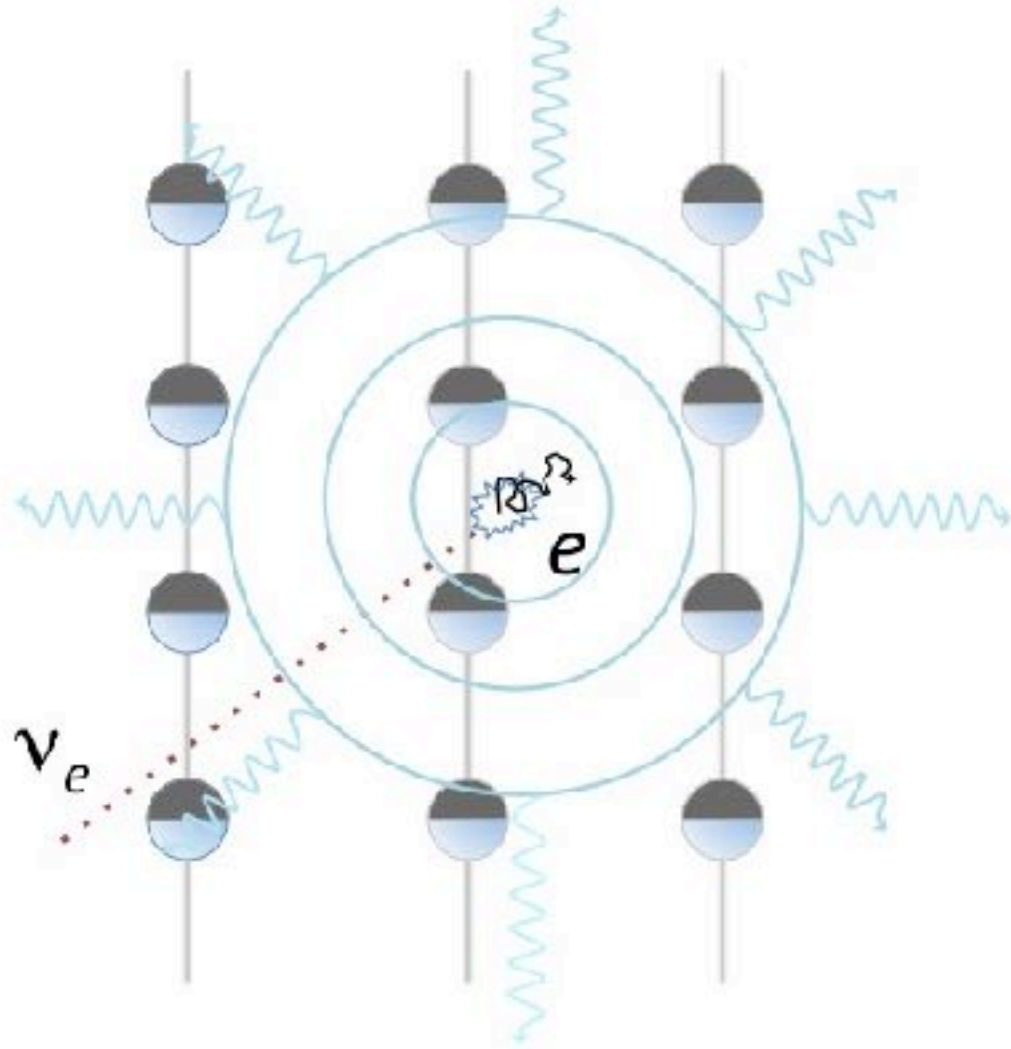
nickname: **Bert**

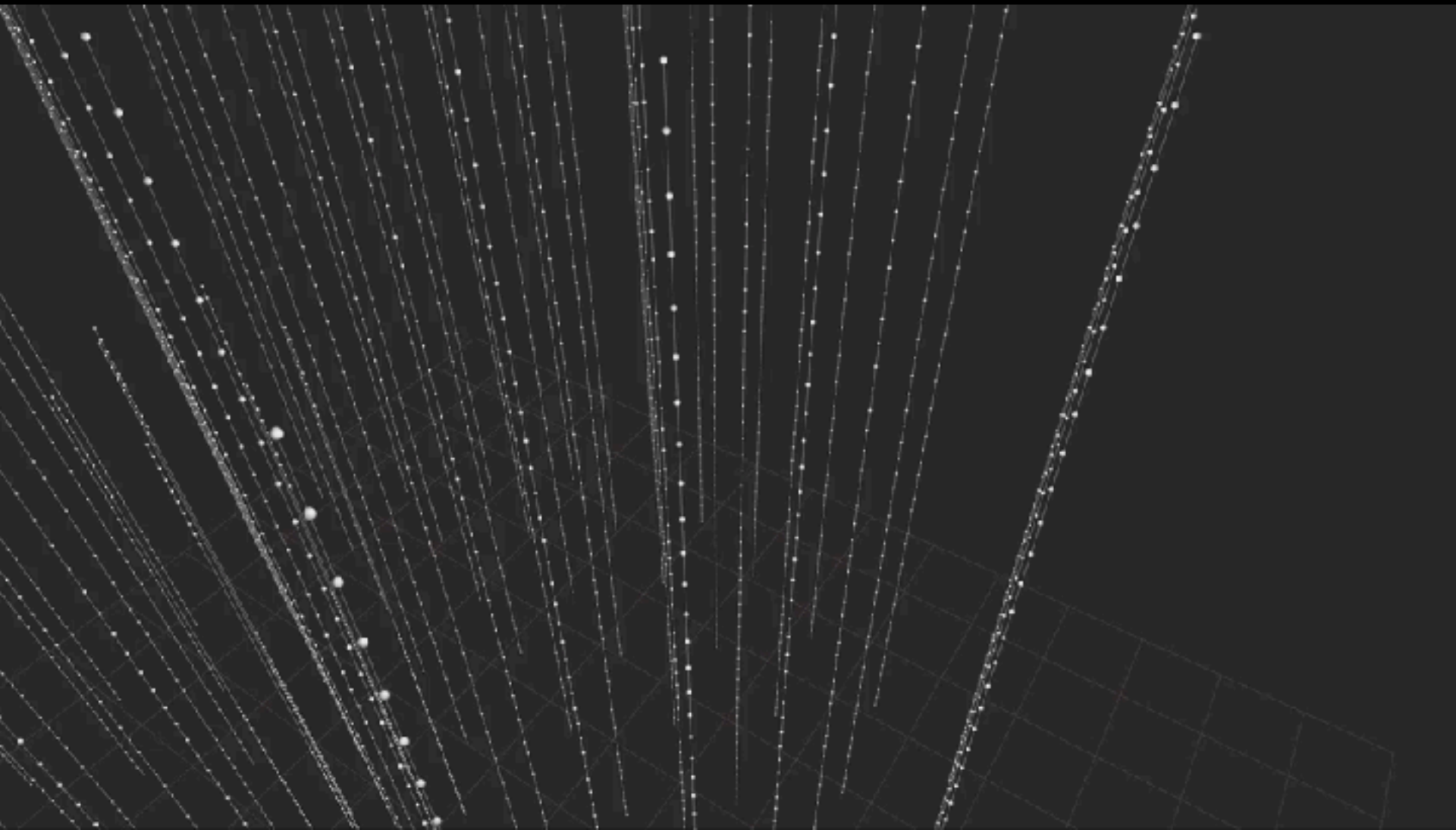


electron showers versus muon tracks

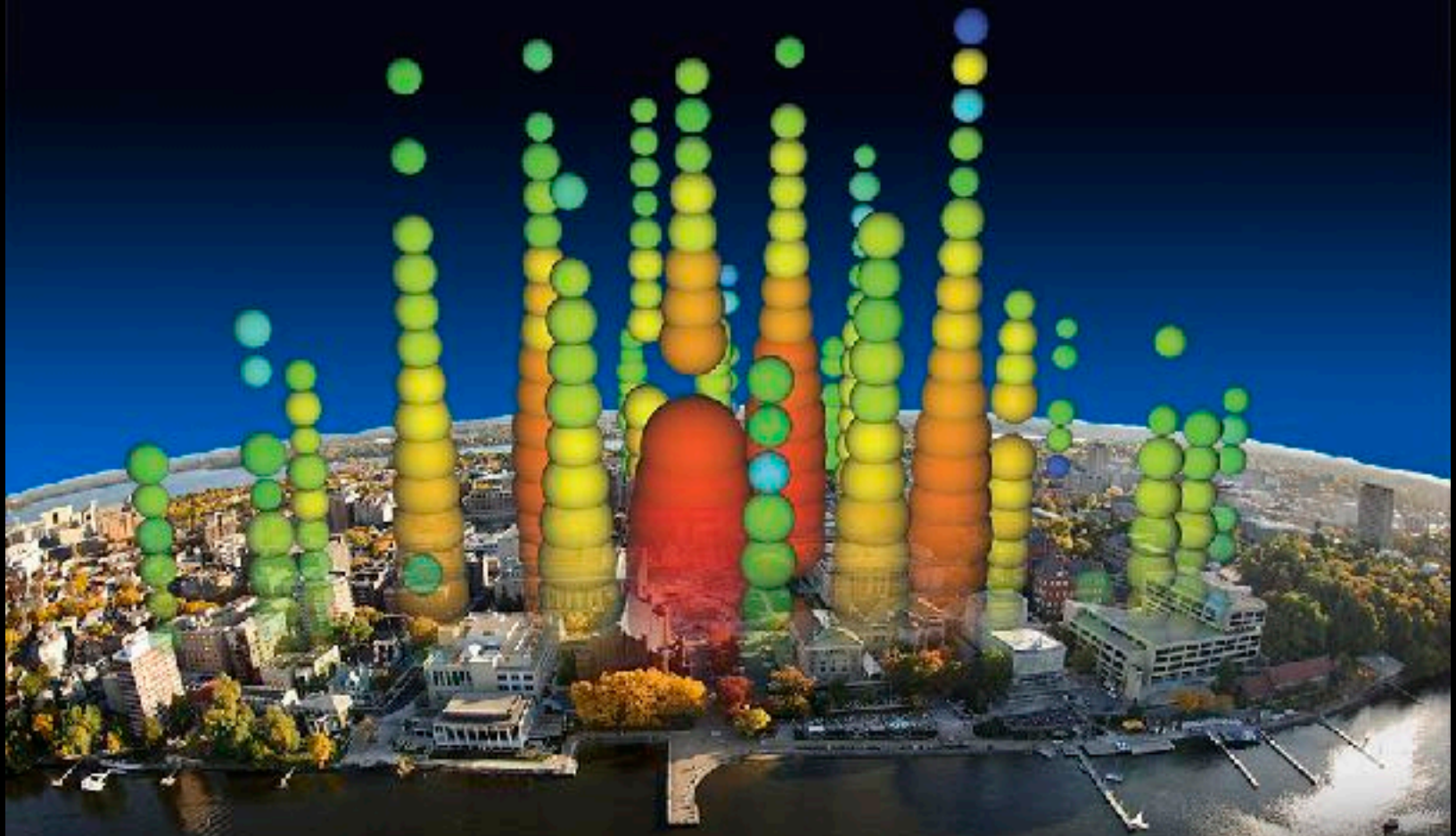
PeV ν_e and ν_τ
showers:

- 10 m long
- volume $\sim 5 \text{ m}^3$
- isotropic after 25~50 m





size = energy & color = time = direction

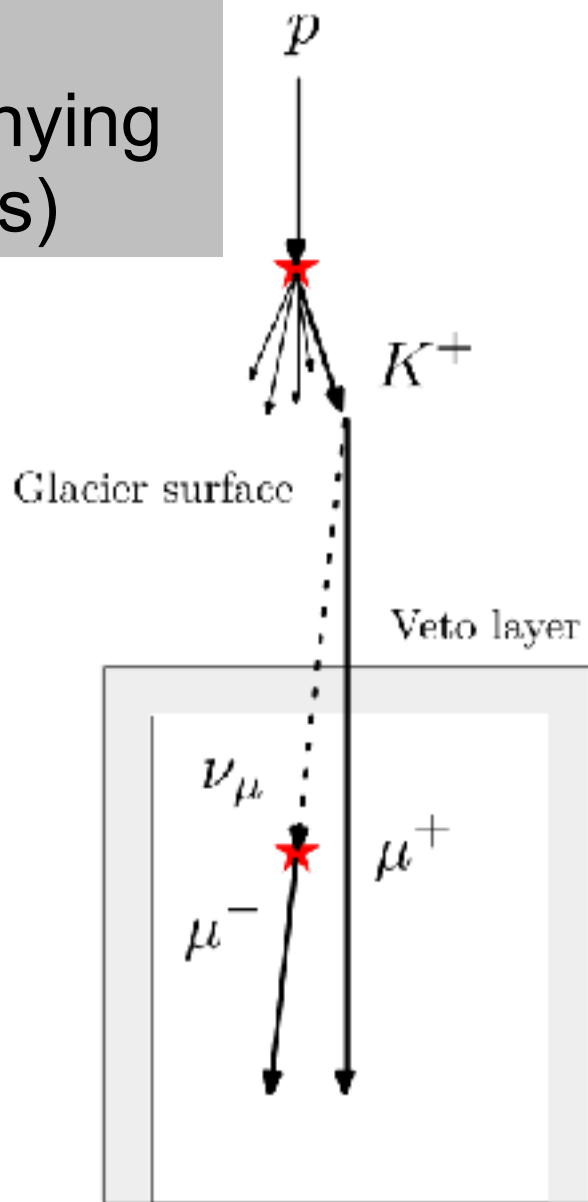


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

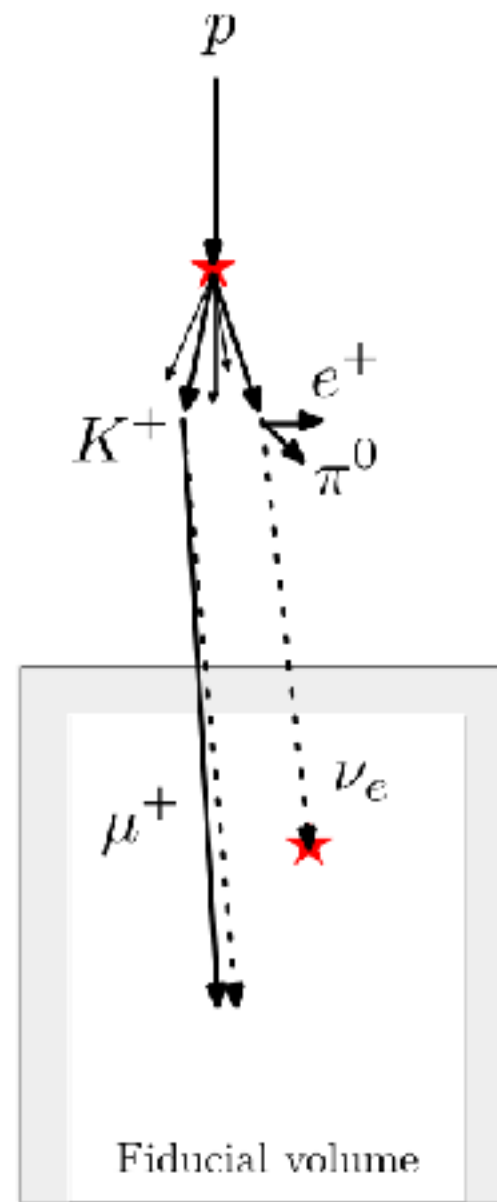
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



no
accompanying
muon(s)

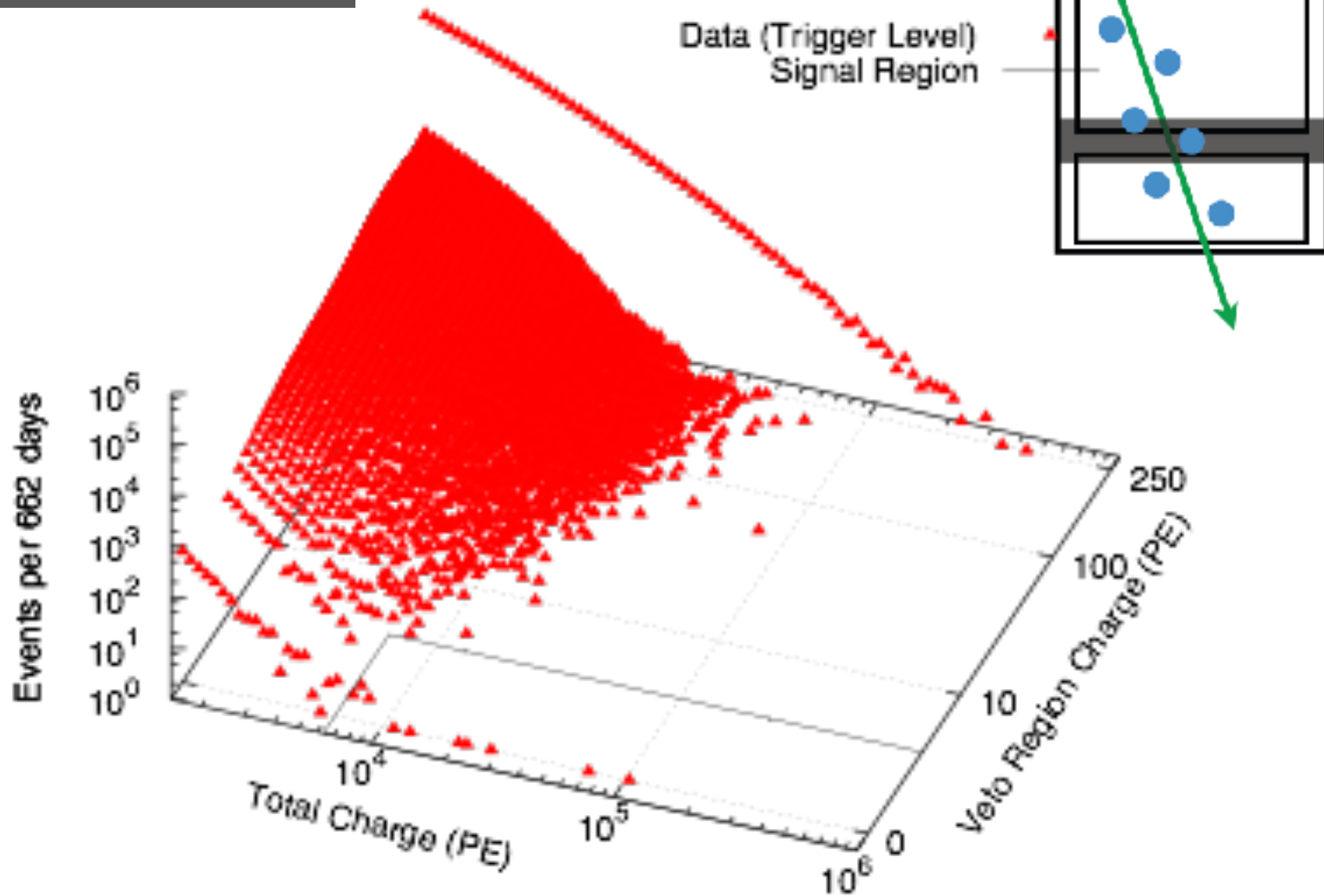


Veto by correlated muon



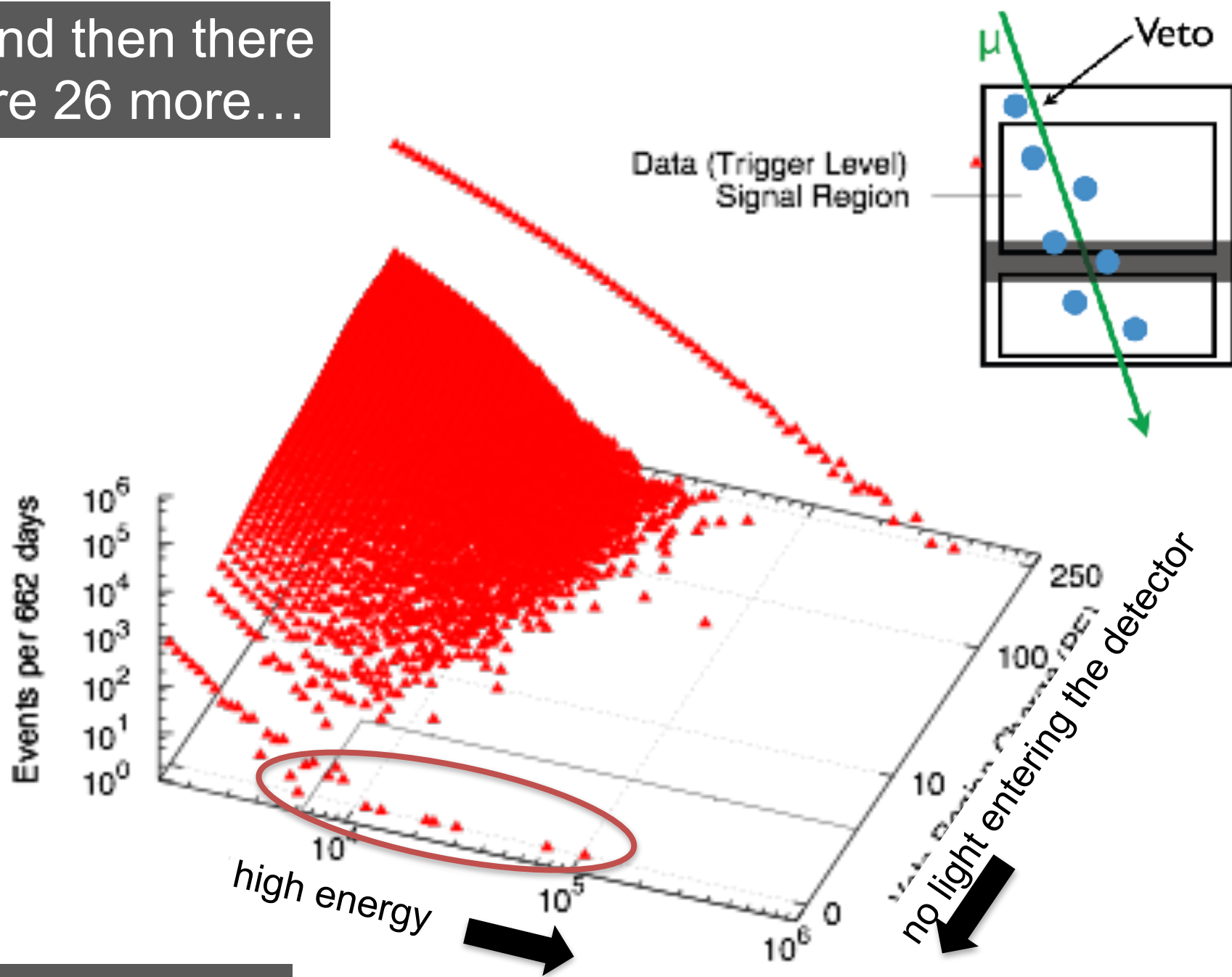
Veto by uncorrelated muon

...and then there were 26 more...



data: 86 strings one year

...and then there were 26 more...



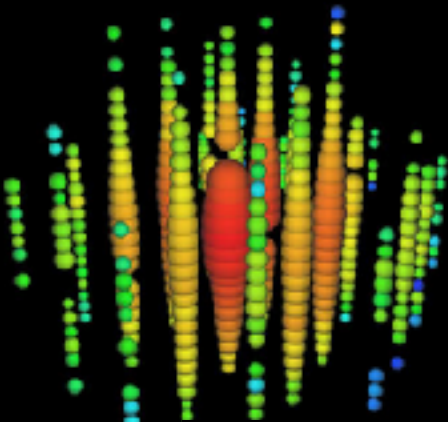
data: 86 strings one year

2 old + 26 new events

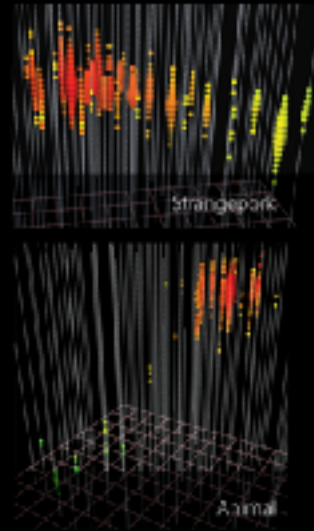
RESEARCH

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration



28 High Energy Events



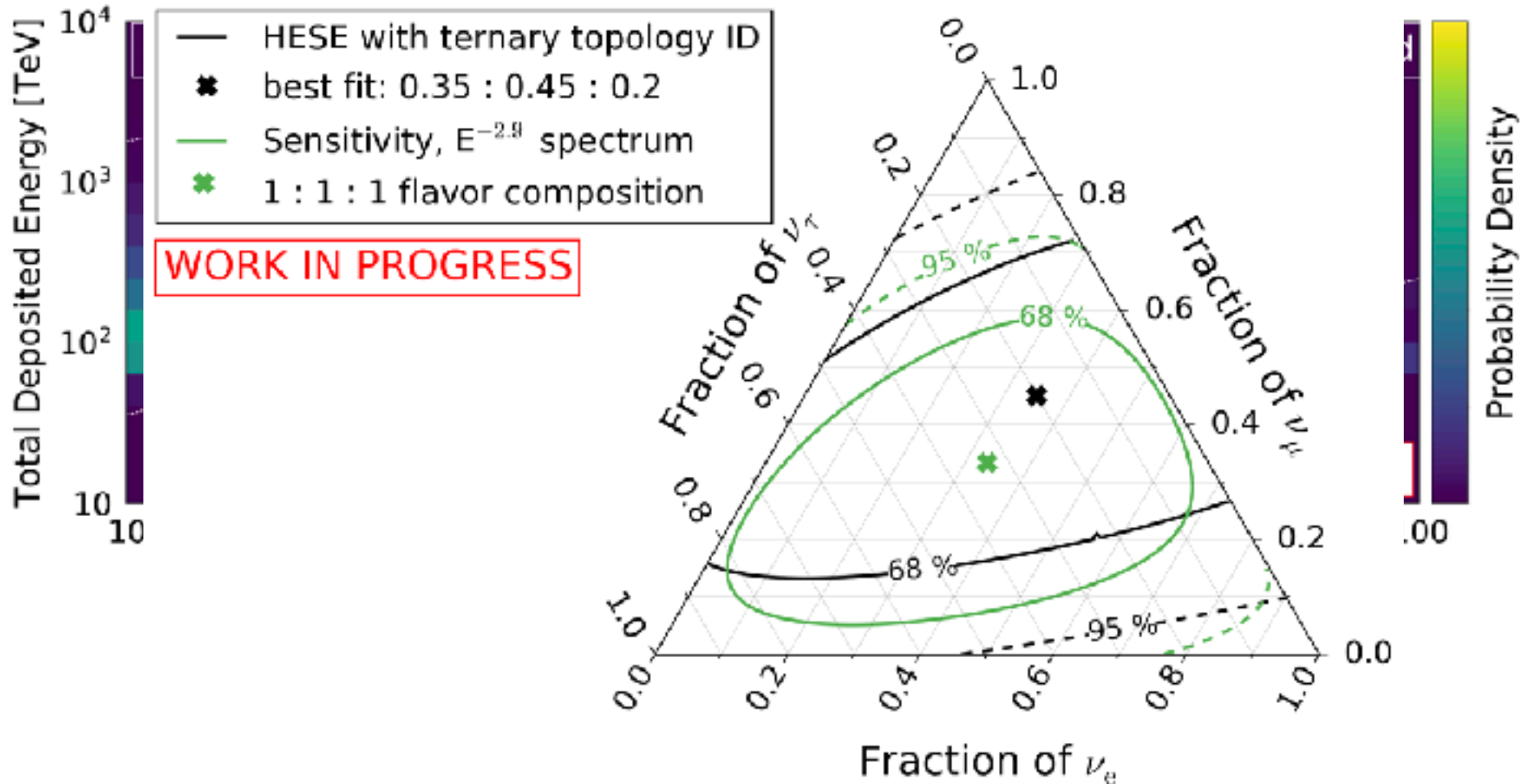
High-energy neutrinos at the IceCube detector

A 200 TeV neutrino interaction by the IceCube detector, a large multi-colored event in the detector, the direction of the neutrino is original neutrino.

The IceCube and IceCube-Gen2 Collaboration. Copyright 2013. C. Köpcke et al.

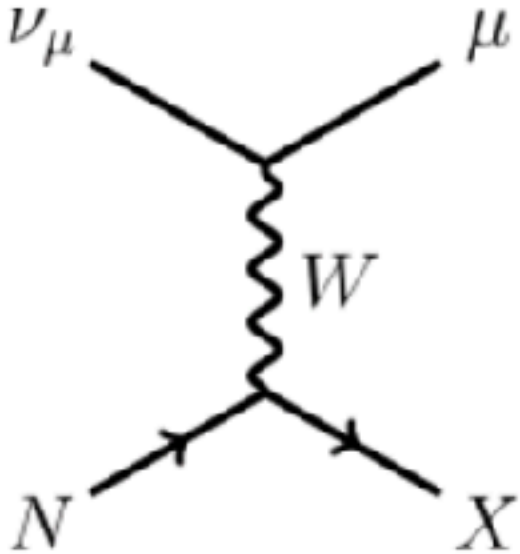
2000 TeV event in year 3

high-energy starting events – 7.5 yr

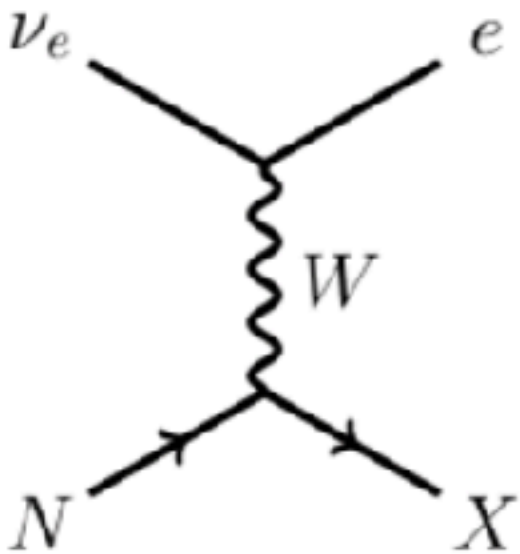
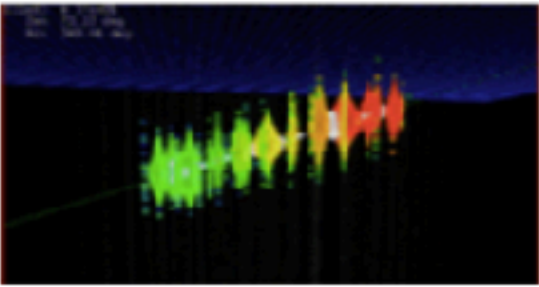


oscillations of PeV neutrinos over cosmic distances to 1:1:1

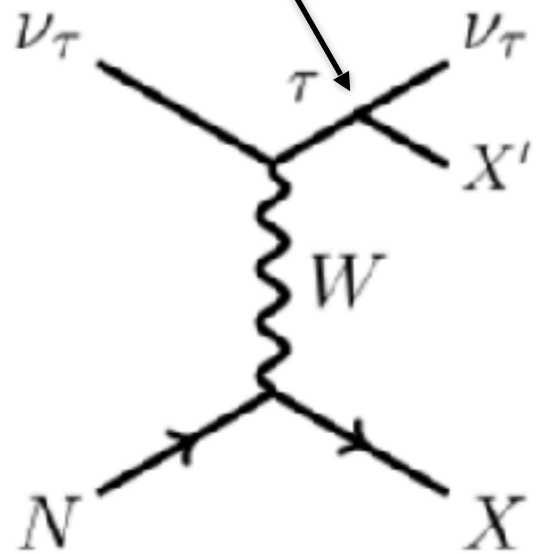
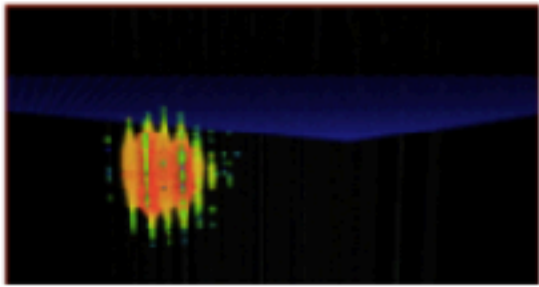
tau decay length:
50m per PeV



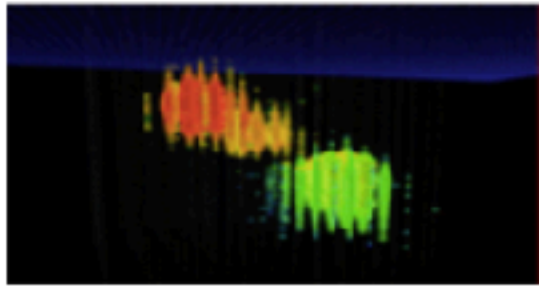
track



shower

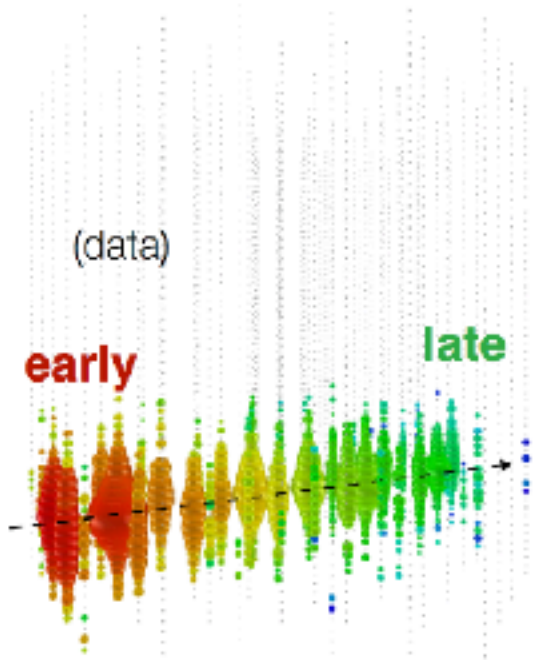


double bang*



event topologies

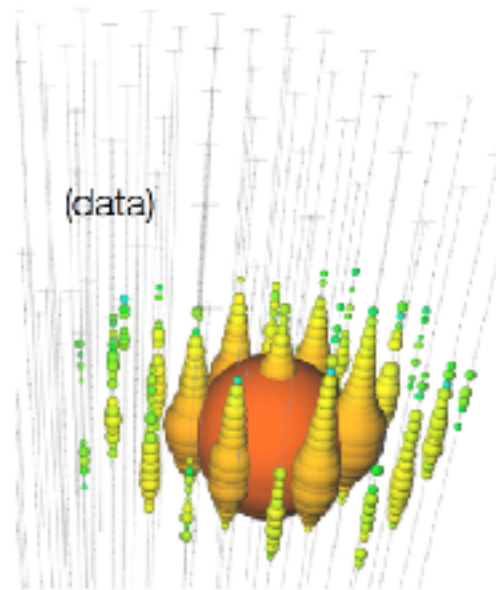
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

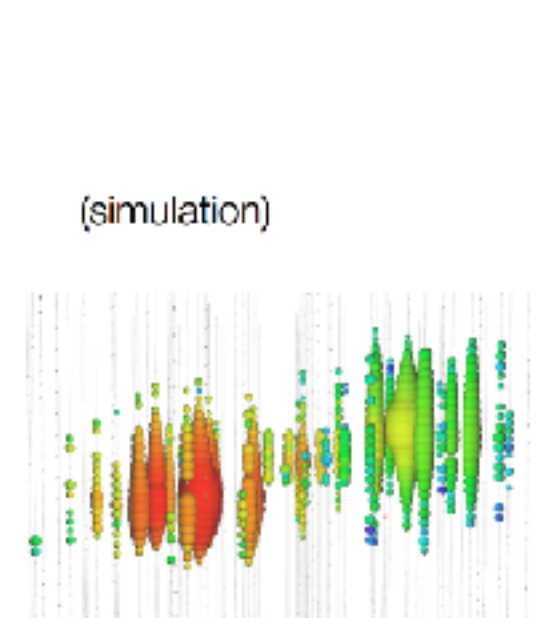
Neutral-current / ν_e



Isolated energy
deposition (cascade)
with no track

15% deposited energy resolution
10 degree angular resolution (above
100 TeV)

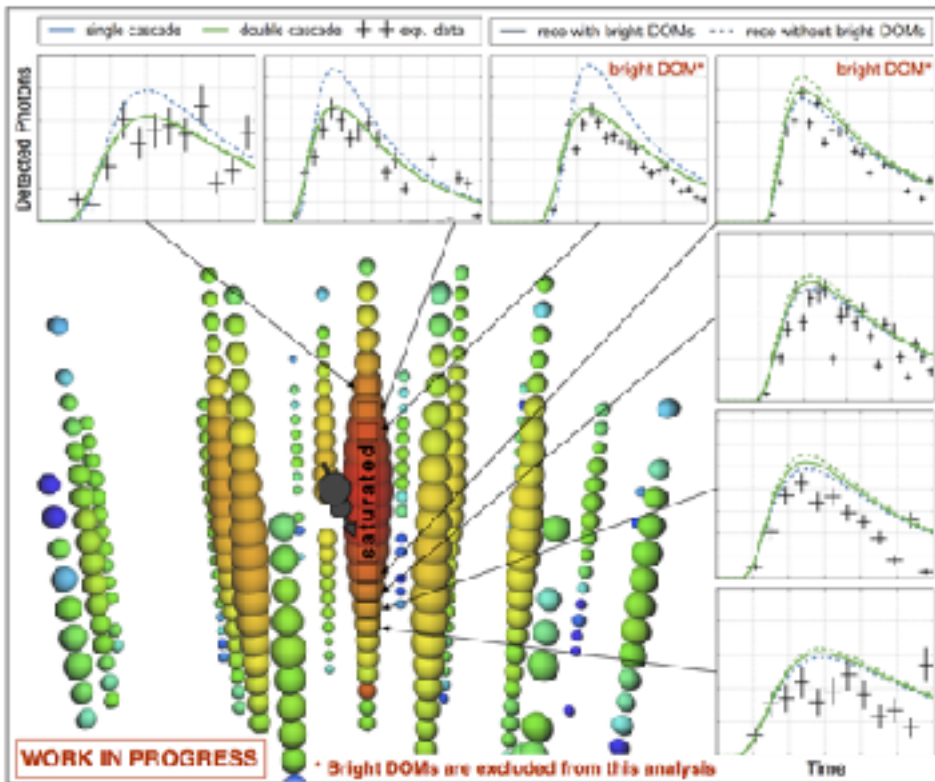
Charged-current ν_τ



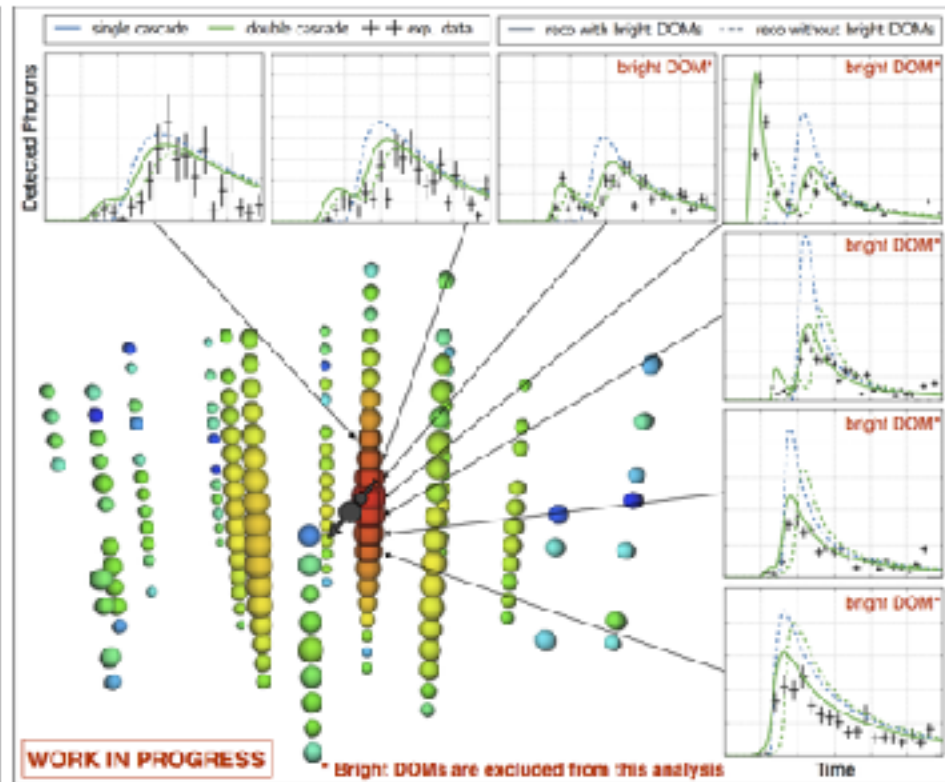
Double cascade

(resolvable above ~100 TeV
deposited energy)

high-energy starting events (starting) – 7.5 yr



Double cascade Event #1



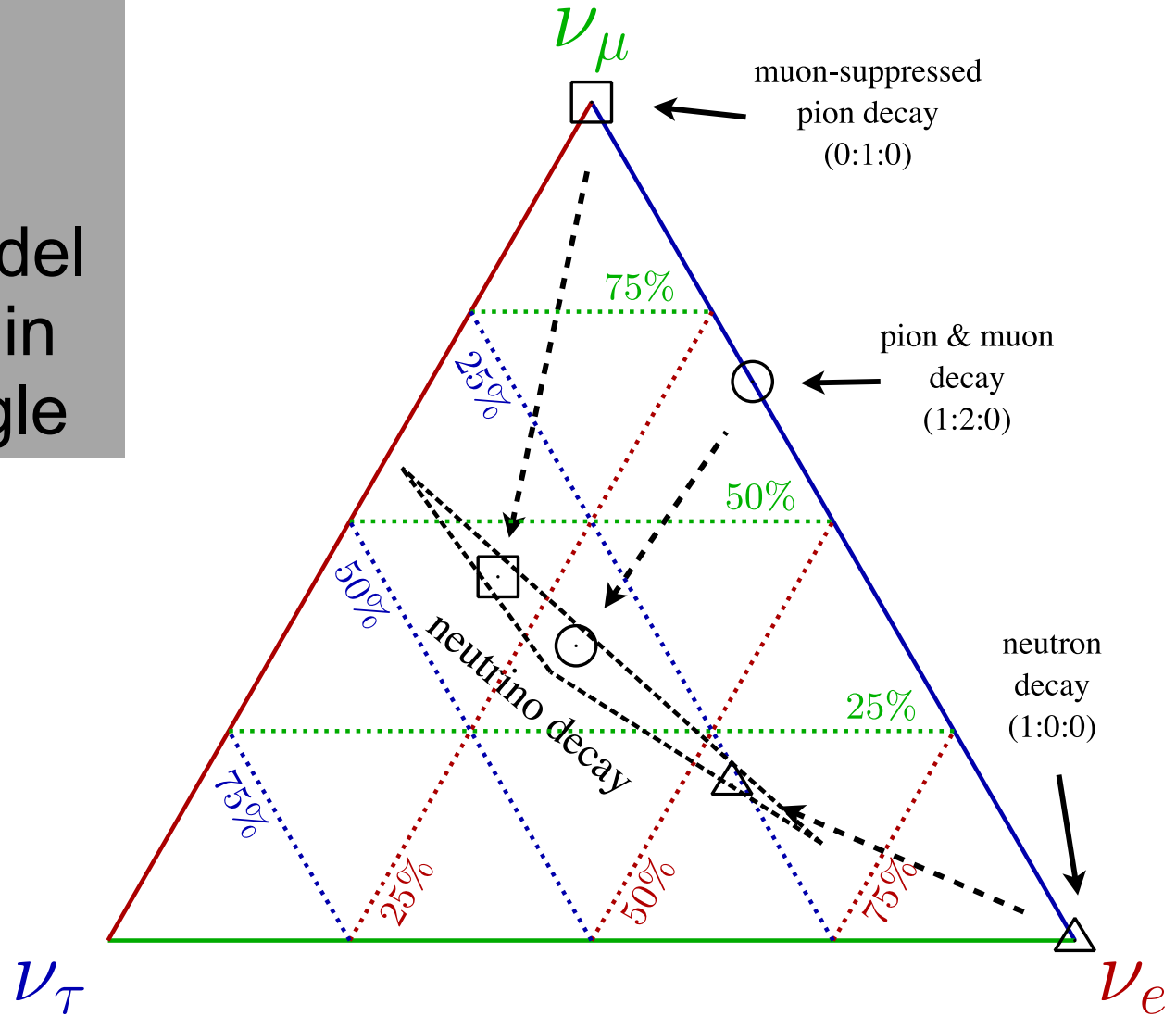
Double cascade Event #2

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

new physics ?

if not...

every model
ends up in
the triangle

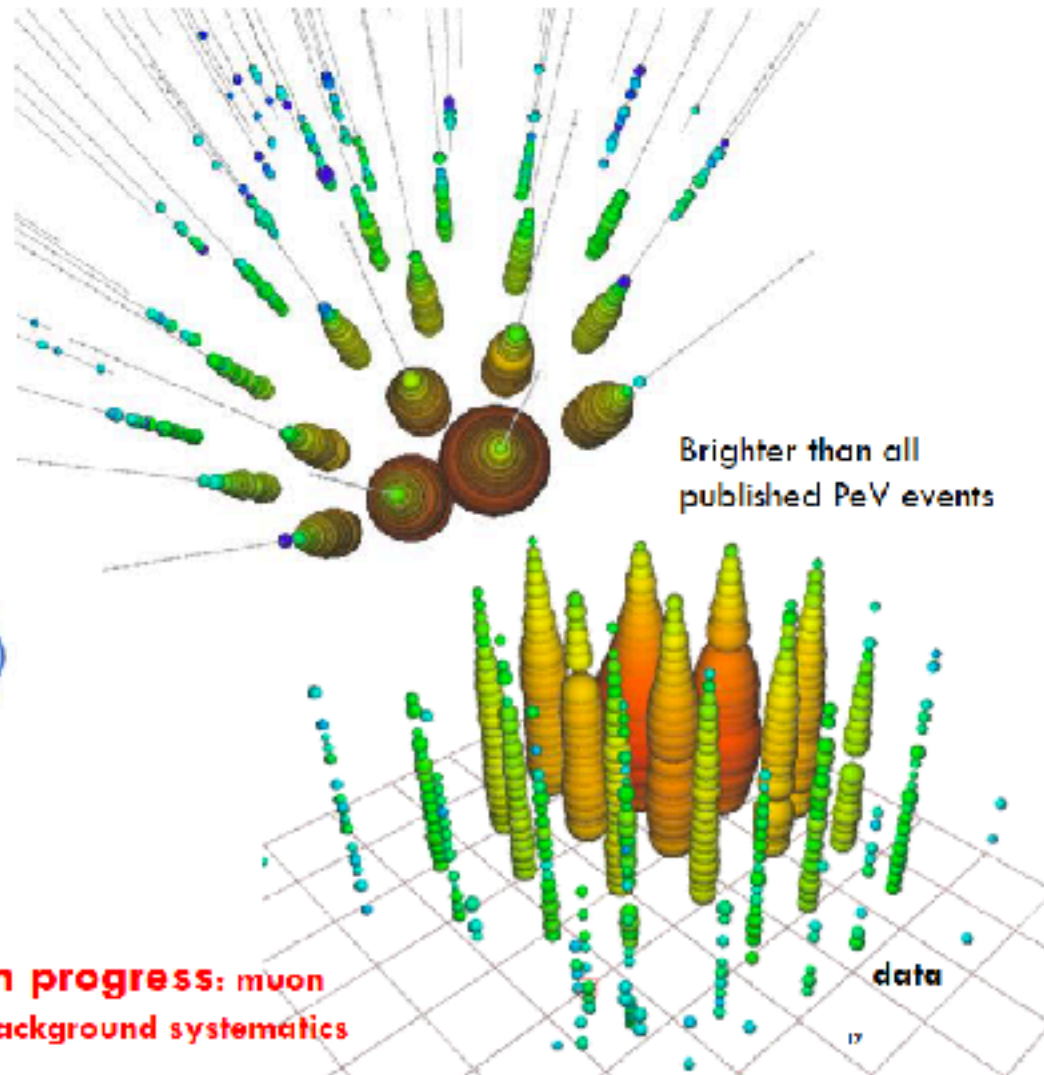
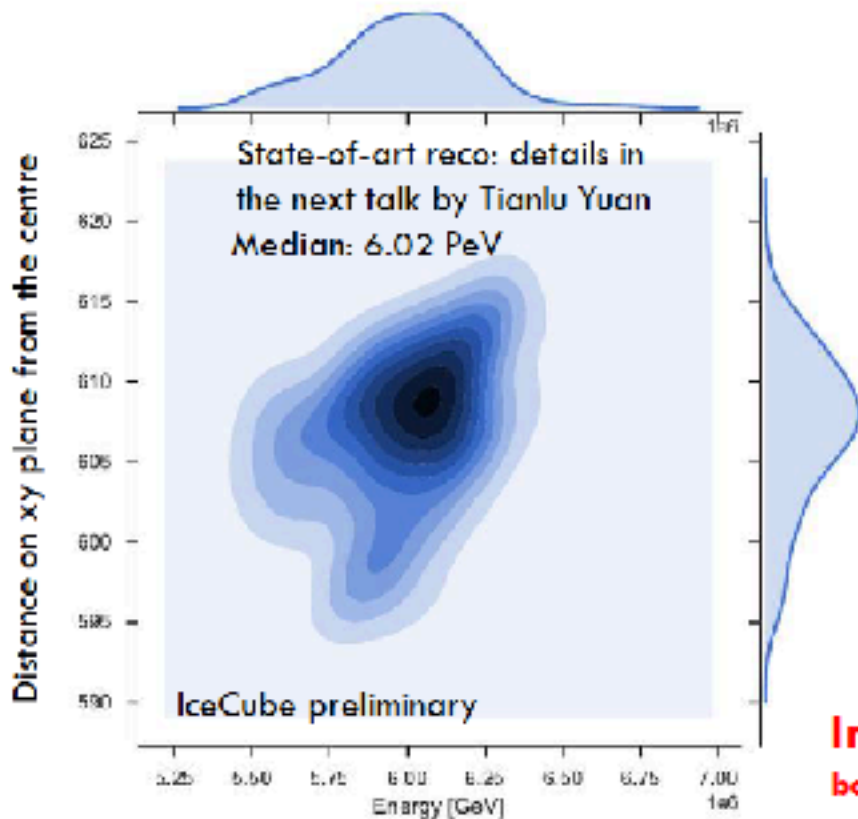


the first Glashow resonance event:

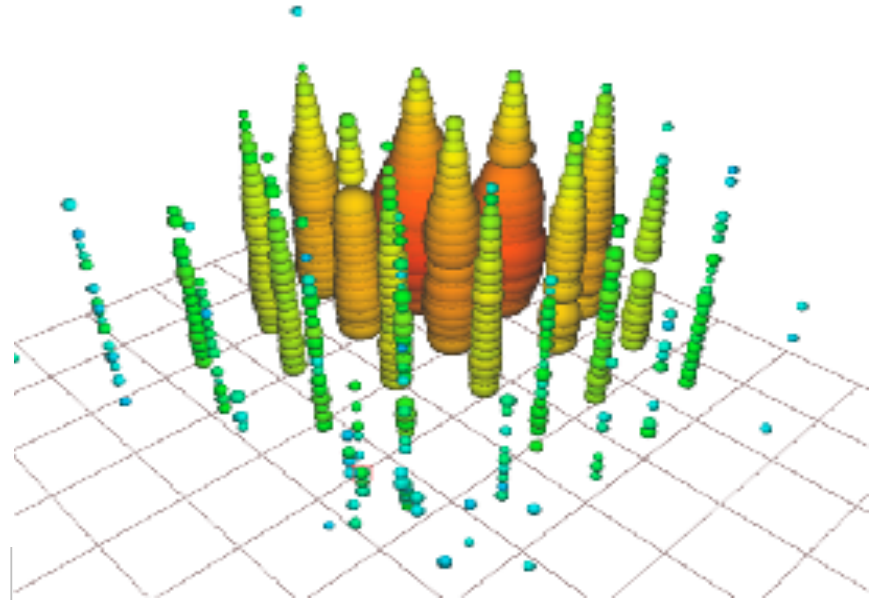
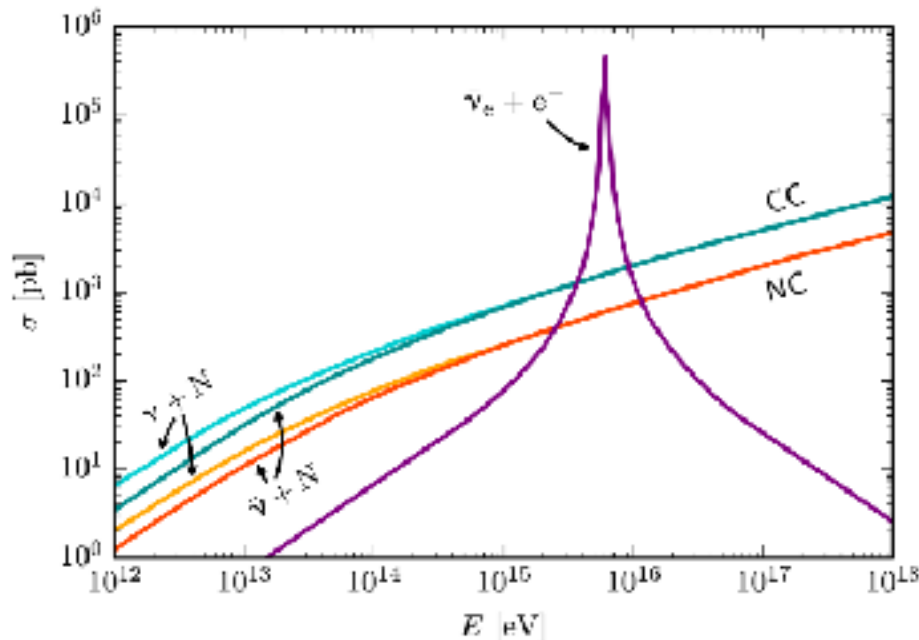
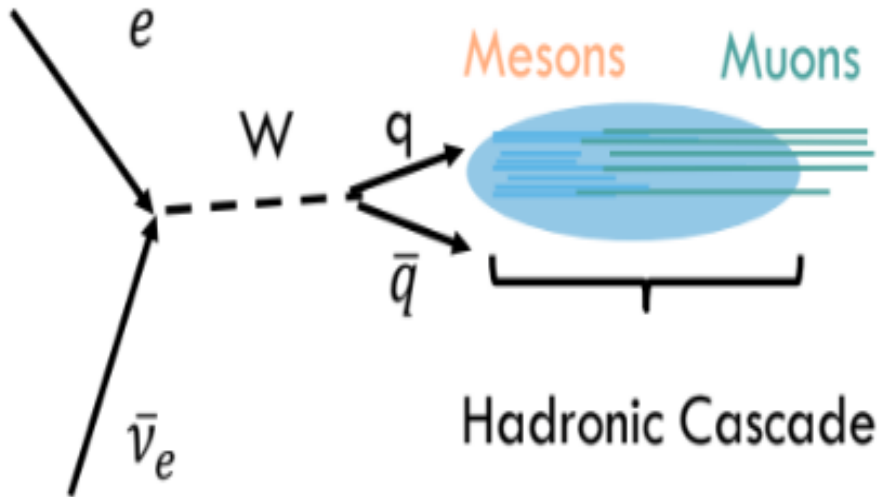
anti- ν_e + atomic electron \rightarrow real W at 6.3 PeV

Partially contained event with energy ~ 6 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE



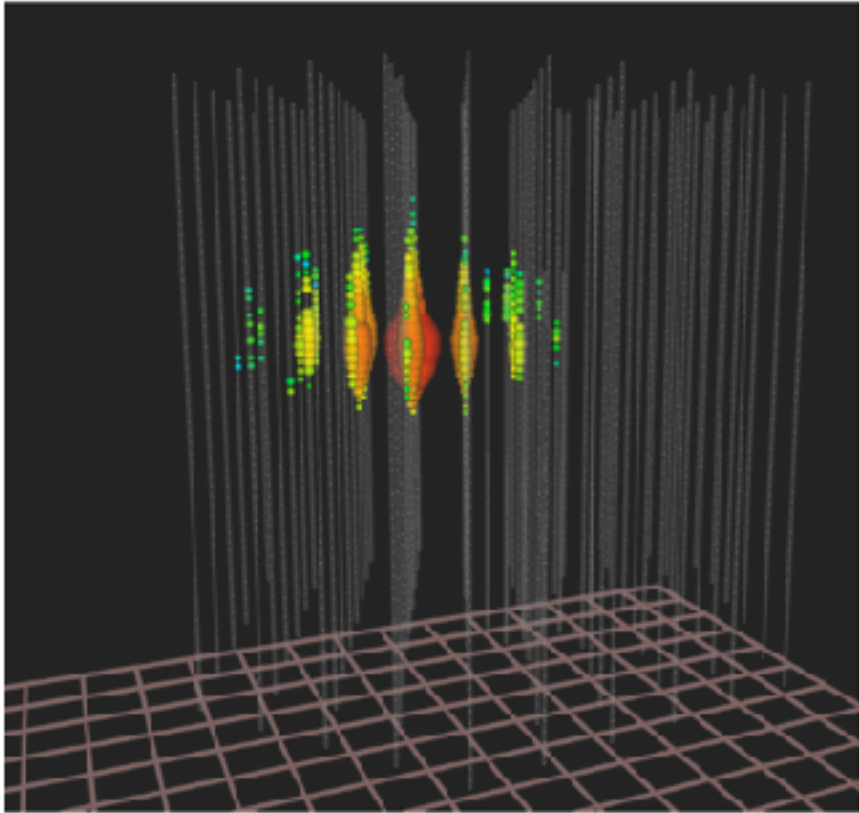
Glashow resonance: anti- ν_e + atomic electron \rightarrow real W



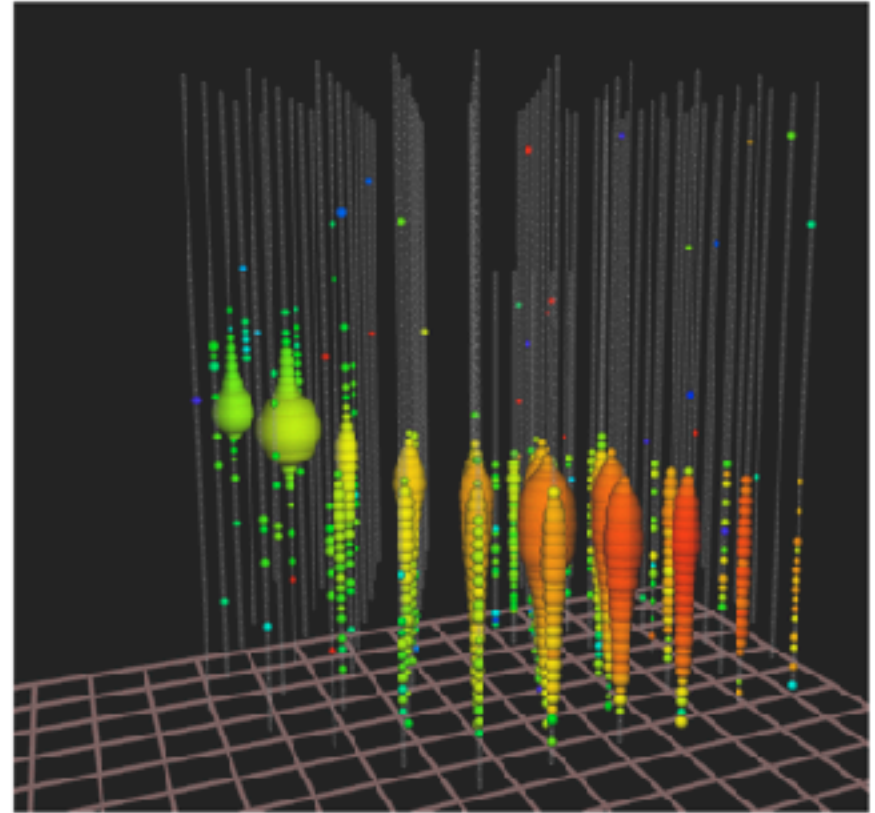
- partially-contained PeV search
- deposited energy: 5.9 ± 0.18 PeV
- typical visible energy is 93%
- \rightarrow resonance: $E_\nu = 6.3$ PeV

work on-going

are the two observations consistent?

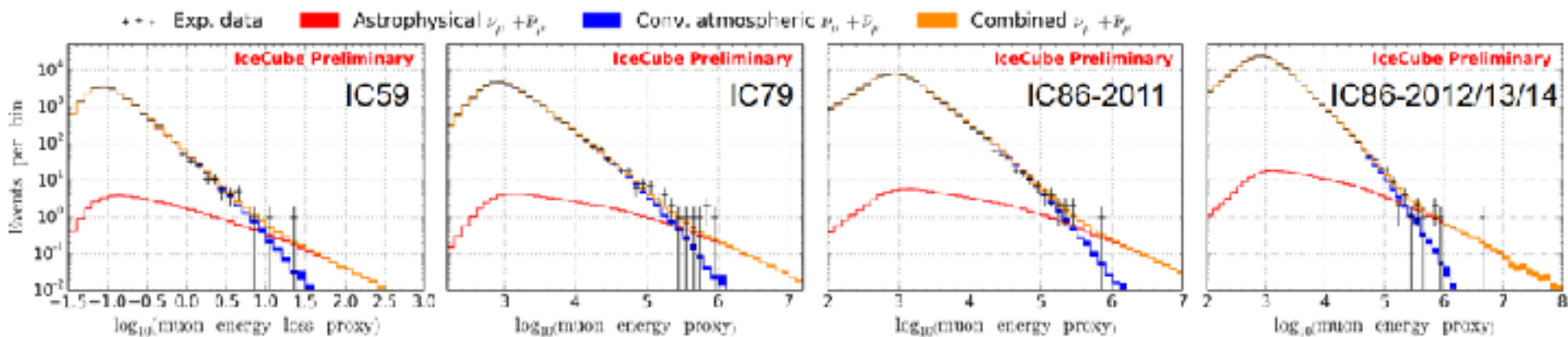


total energy measurement
all flavors, all sky



astronomy: angular resolution
superior ($<0.4^\circ$)

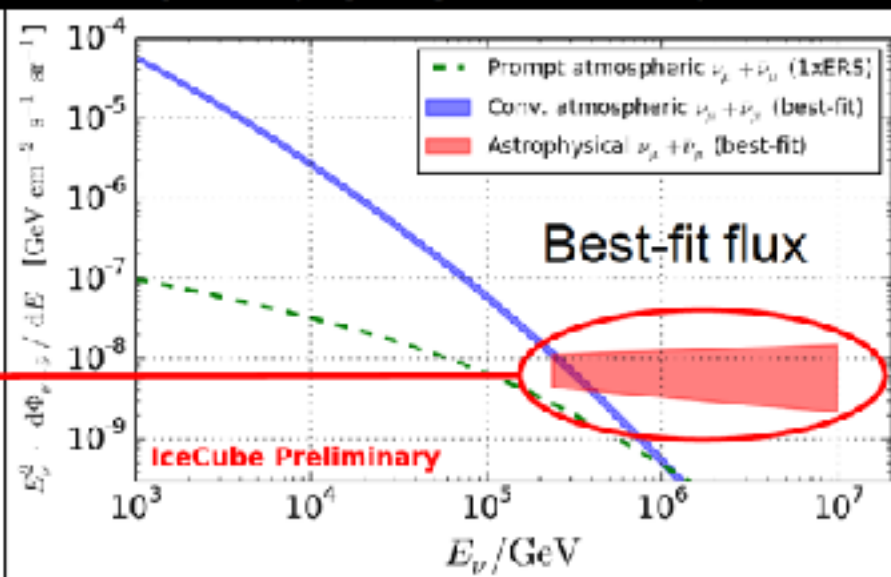
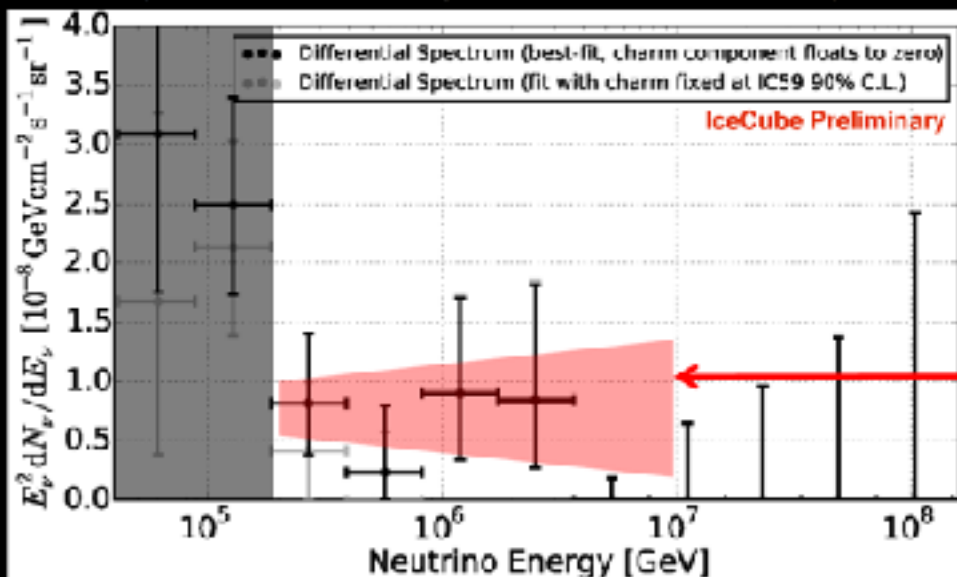
after 6 years: 3.7 \rightarrow 6.0 sigma



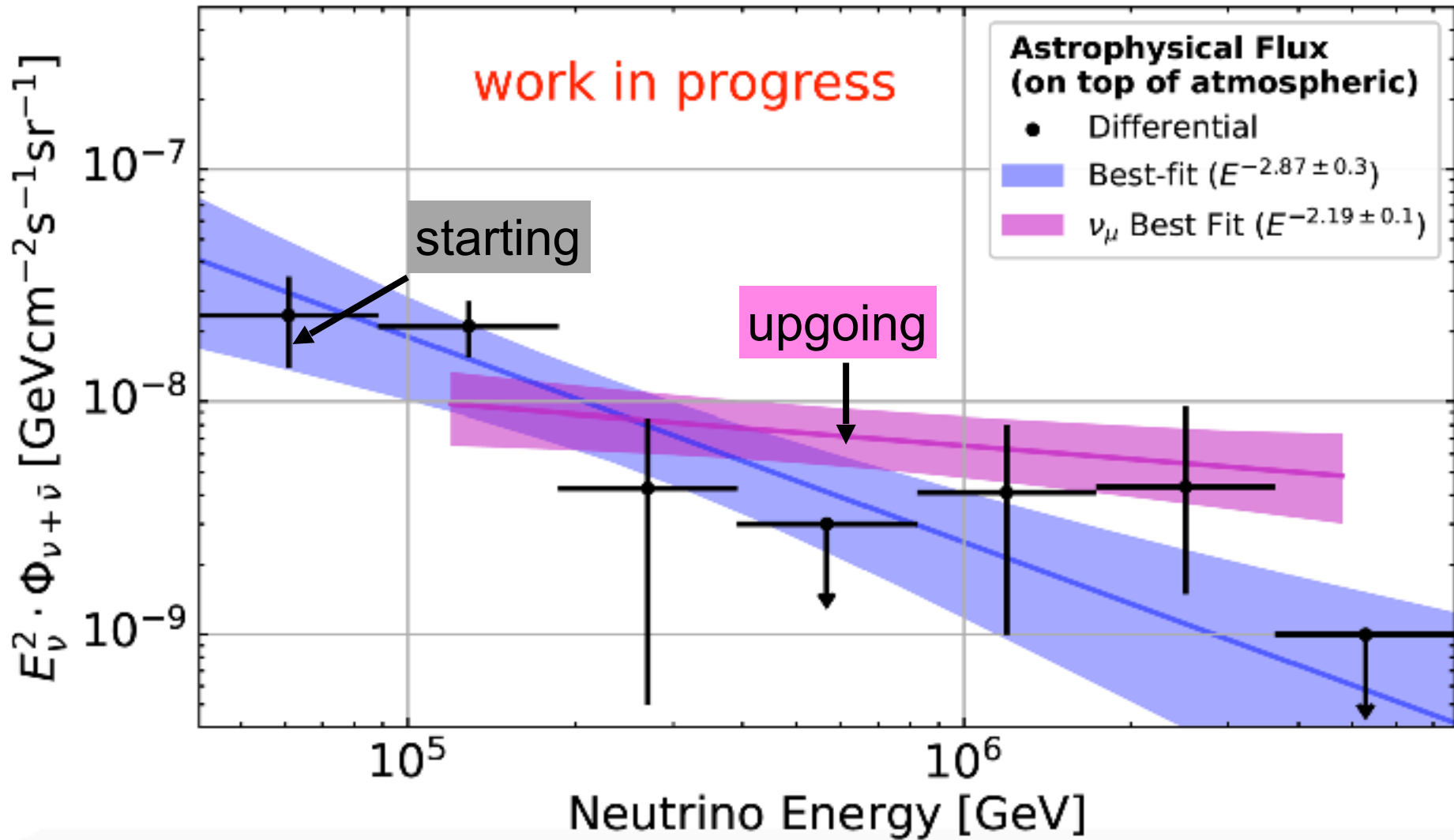
HESE 4 year unfolding

(\rightarrow dominated by shower-like events)

6 year up-going numu analysis

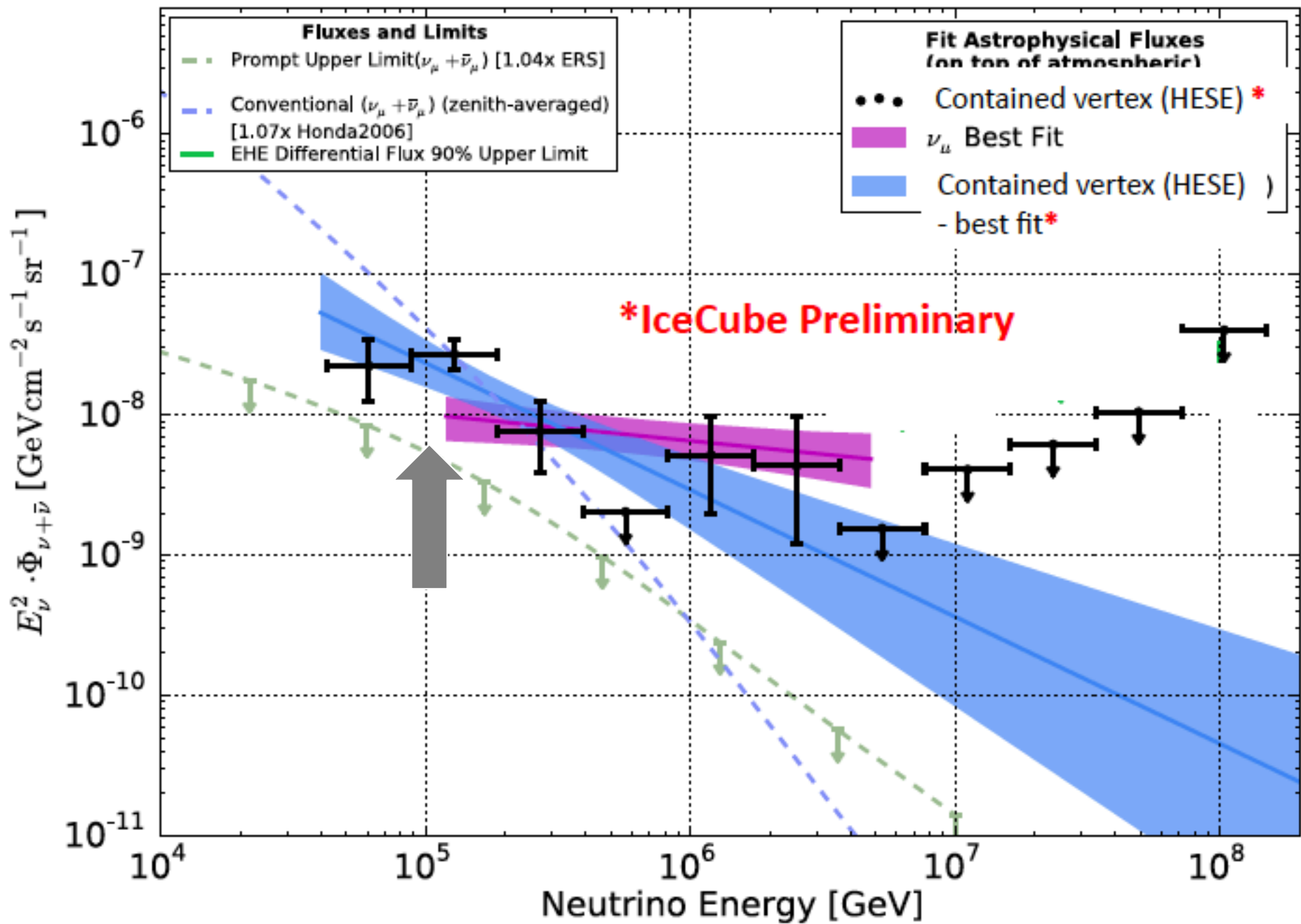


high-energy starting events – 7.5 yr

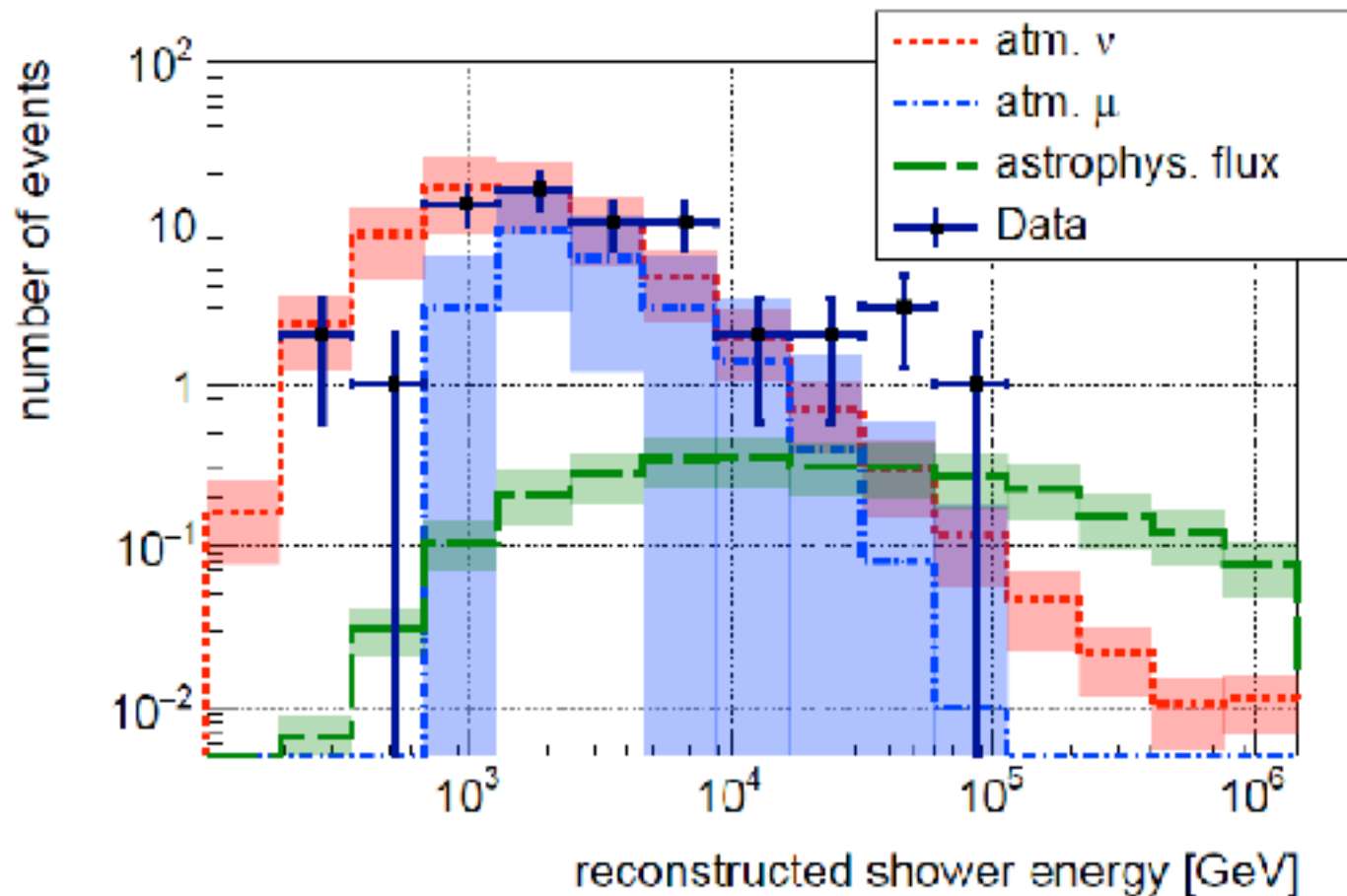


- two methods are consistent
- excess cosmic flux < 100 TeV?

- cosmic neutrinos below 100 TeV ?



ANTARES

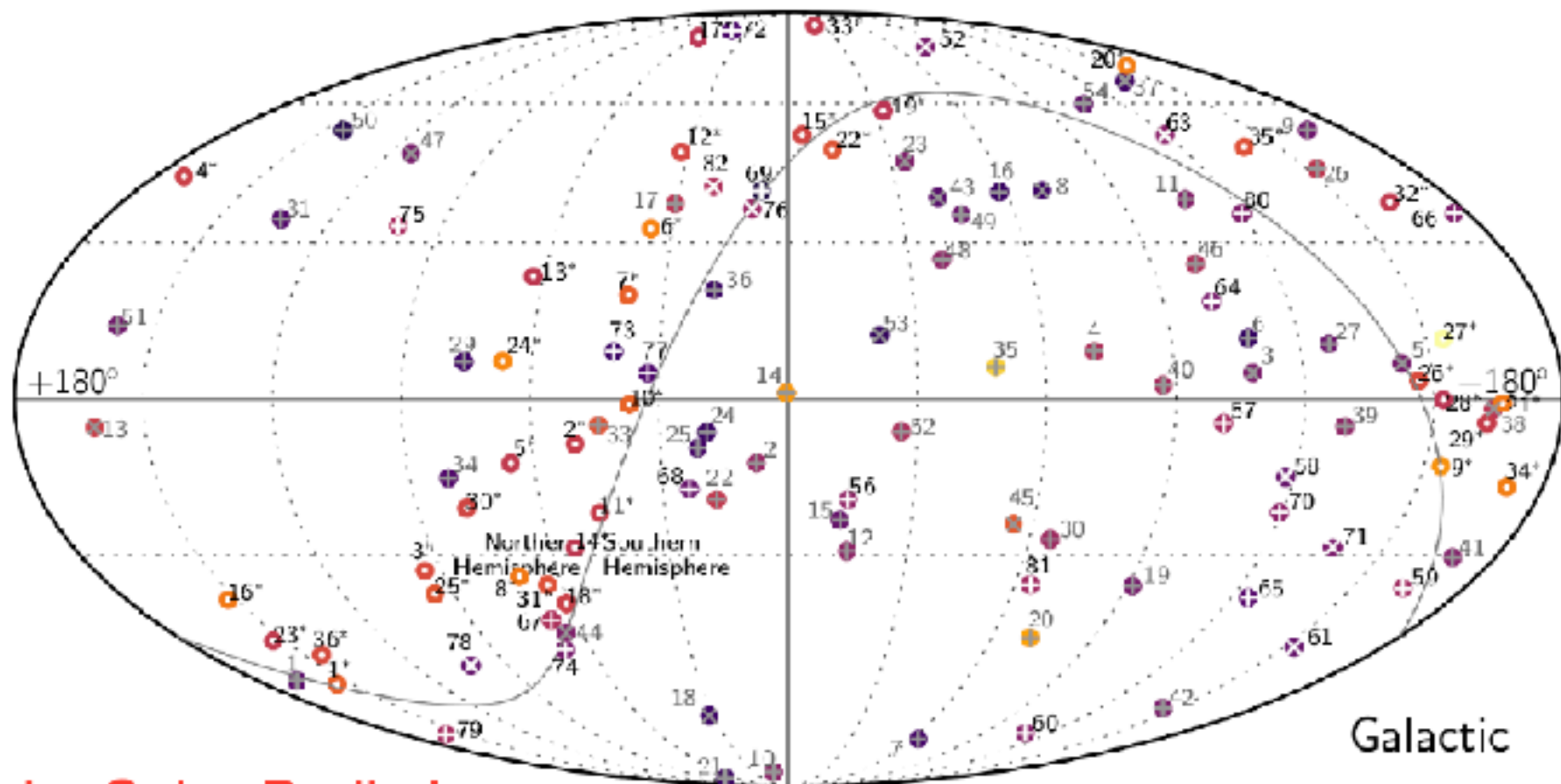




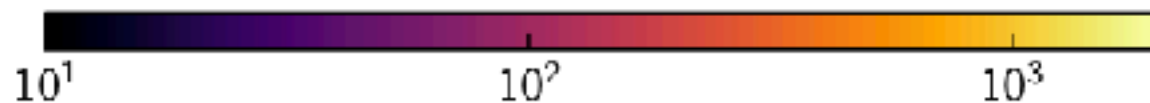
IceCube

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
- the first high-energy cosmic ray accelerator
- what next?



IceCube Preliminary



Deposited Energy or Muon Energy Proxy [TeV]

- ⊗ N New Starting Tracks
- ⊗ N Earlier Starting Tracks
- ⊕ N New Starting Cascades
- ⊕ 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)
- [decay of halo dark matter particles?]

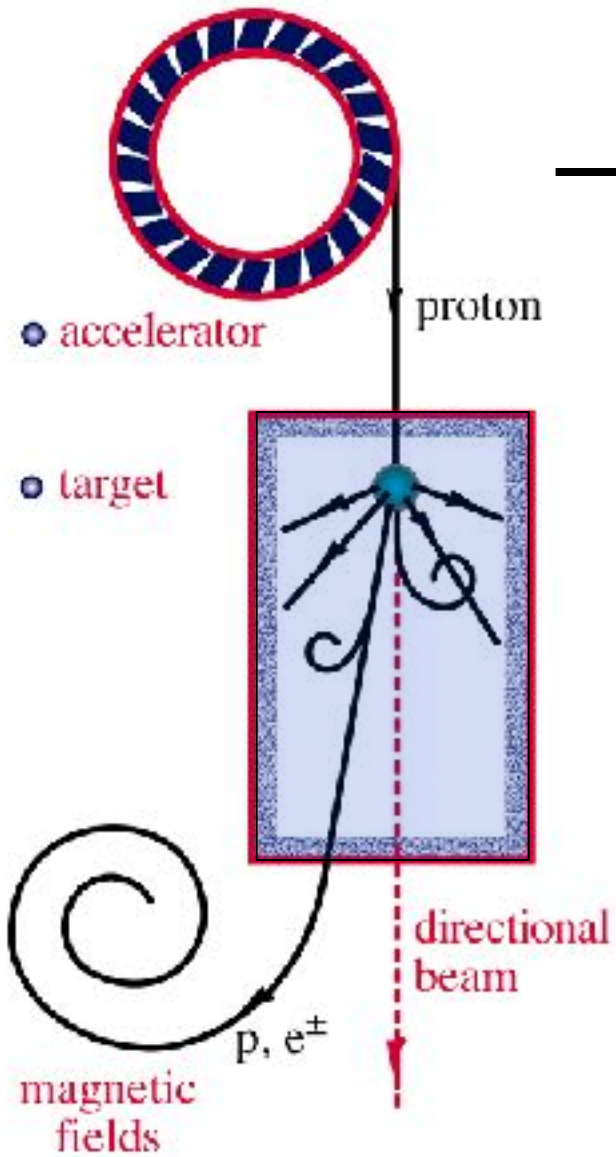


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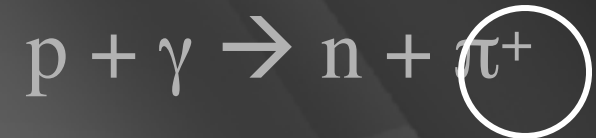
ν and γ beams : heaven and earth



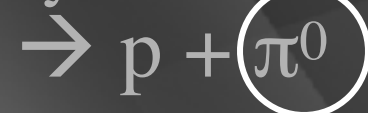
accelerator is powered by large gravitational energy

black hole
neutron star

radiation
and dust



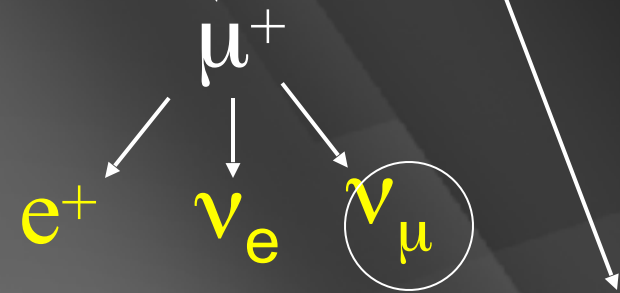
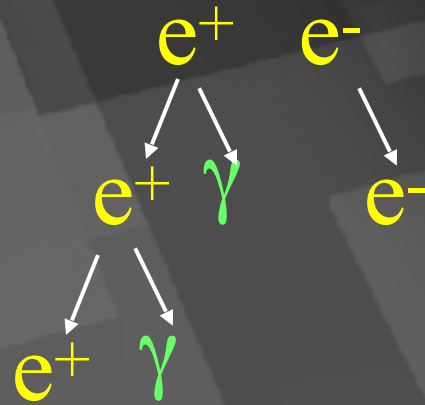
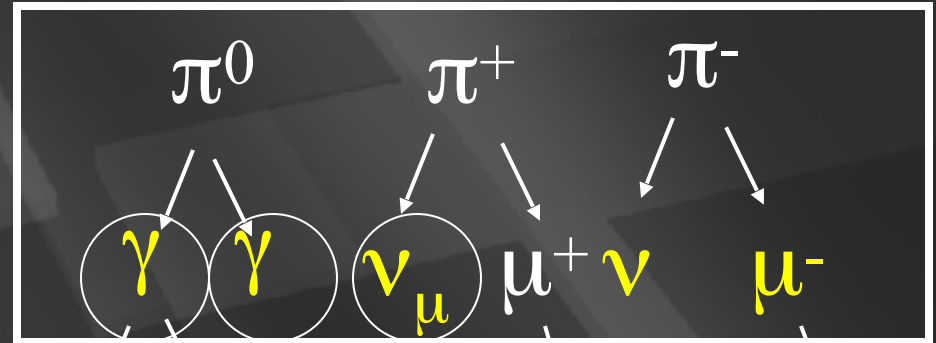
~ cosmic ray + neutrino



~ cosmic ray + gamma

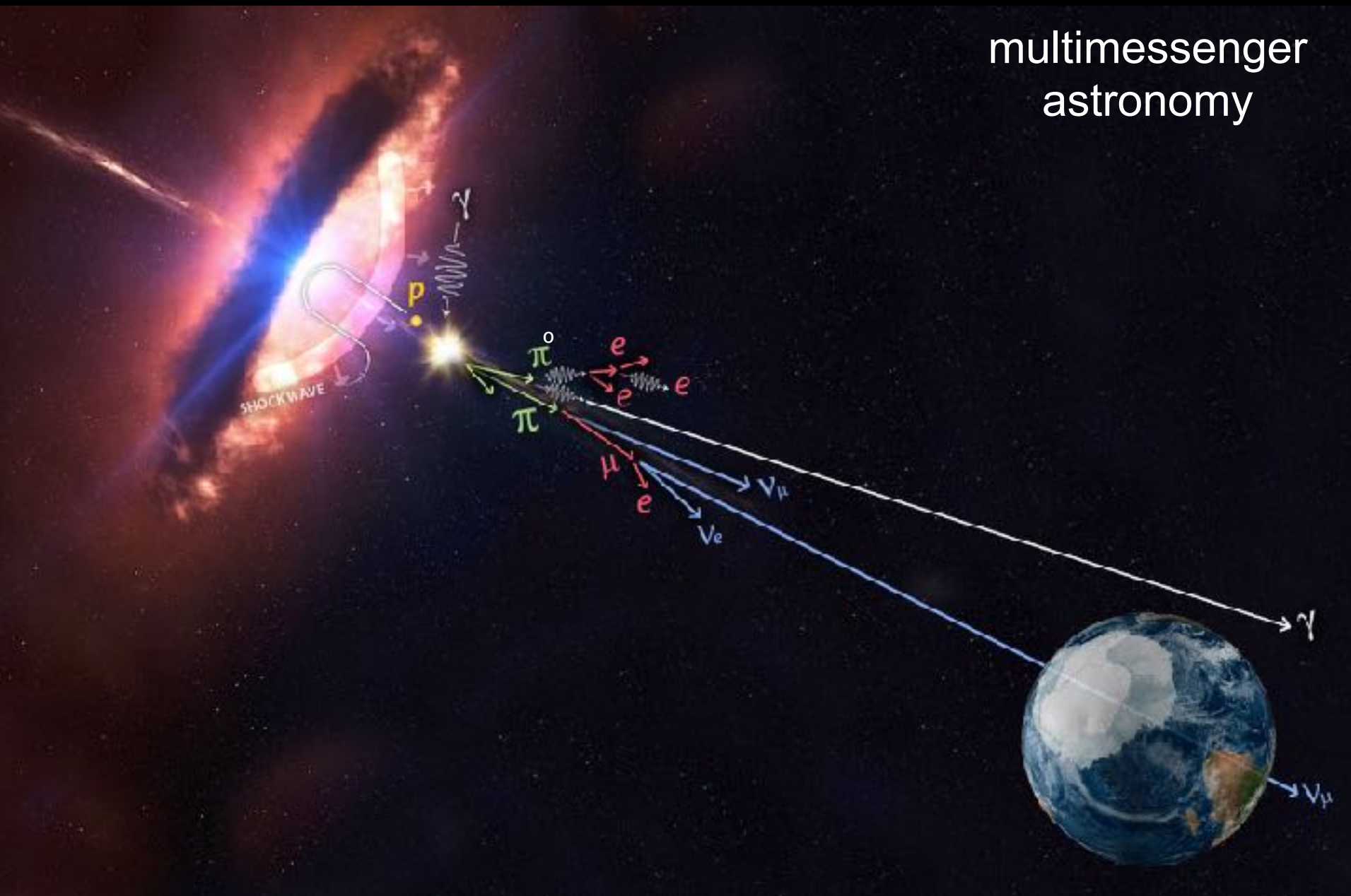
neutral pions
are observed as
gamma rays

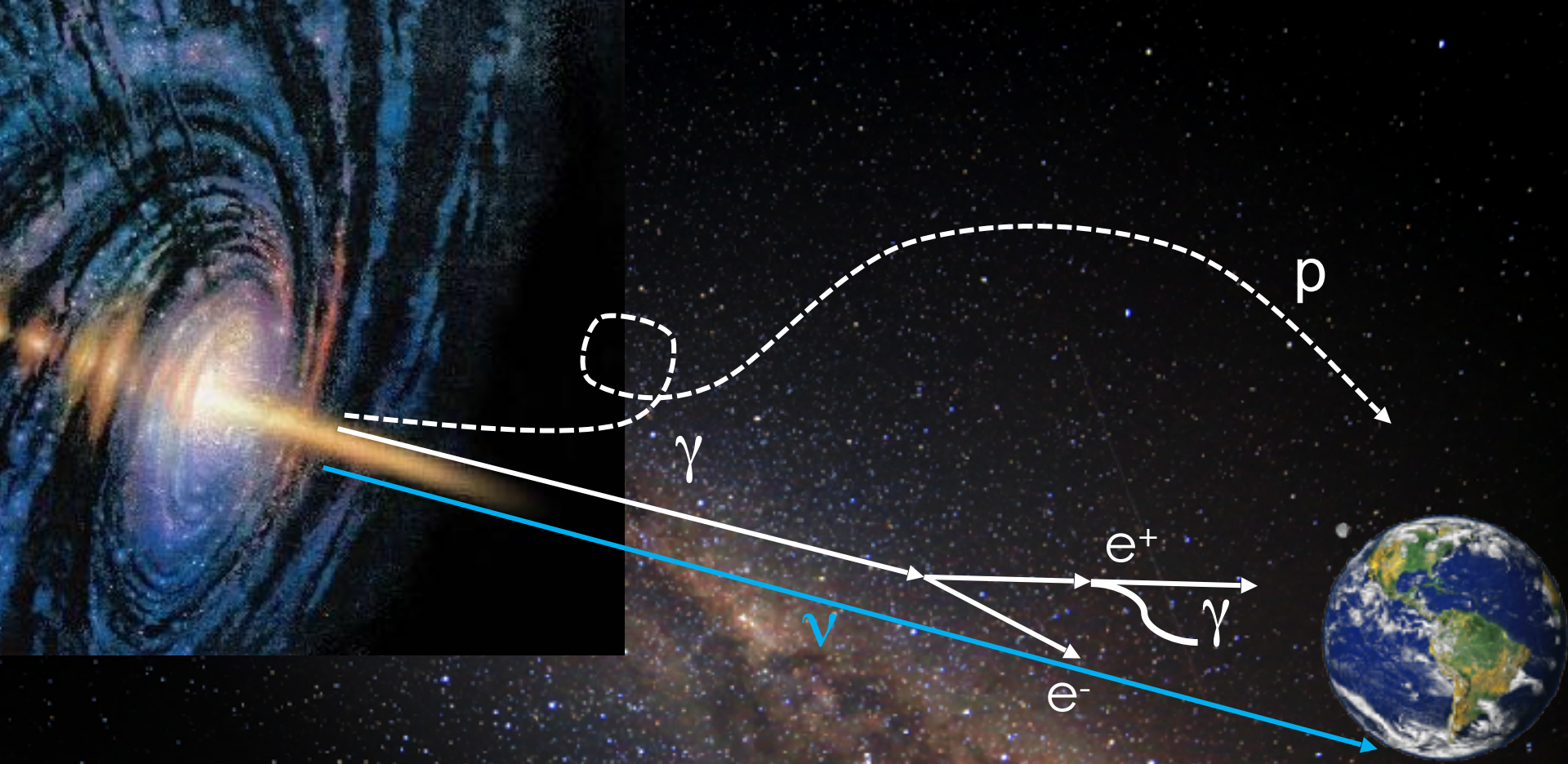
charged pions
are observed as
neutrinos



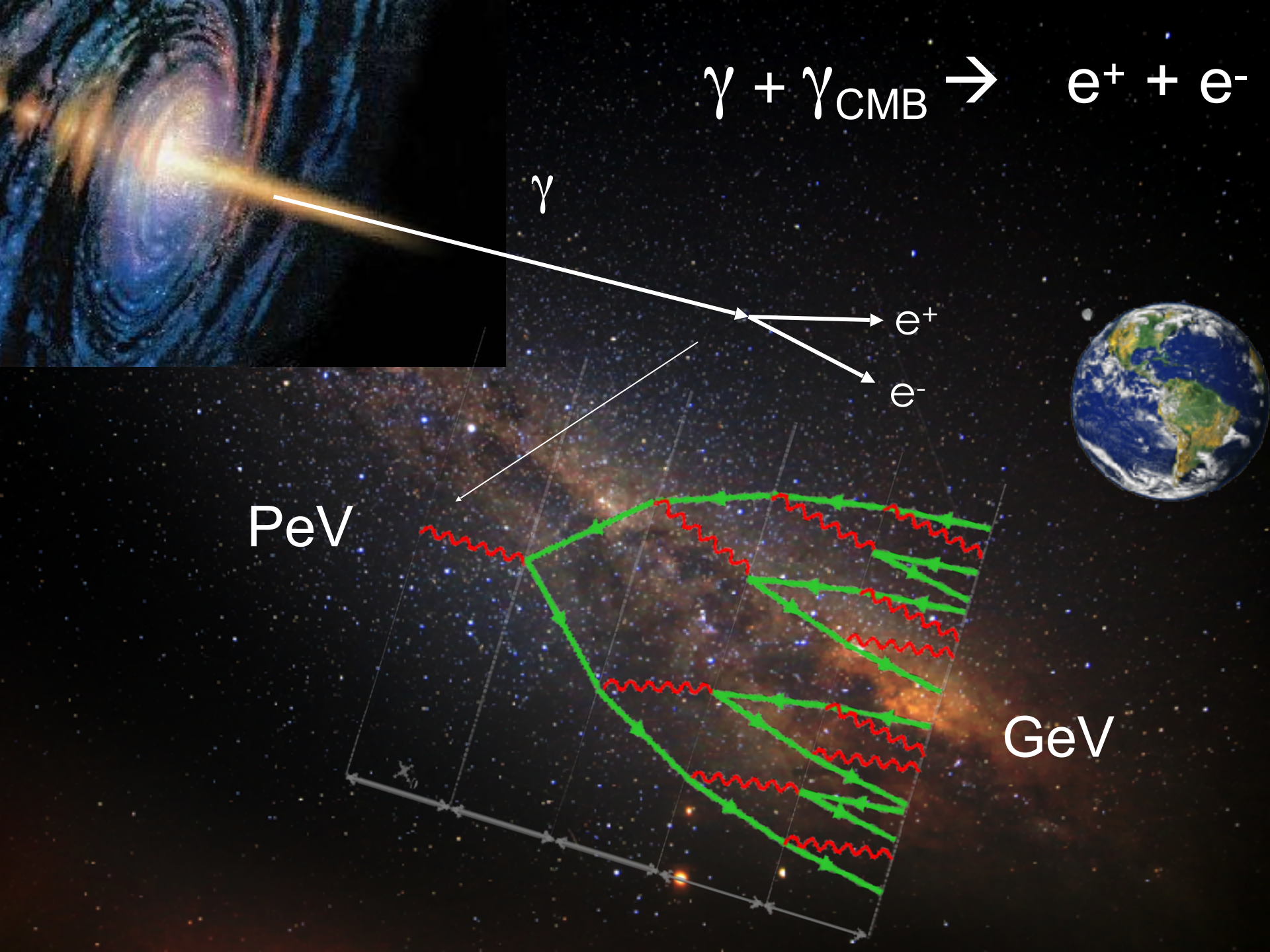
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

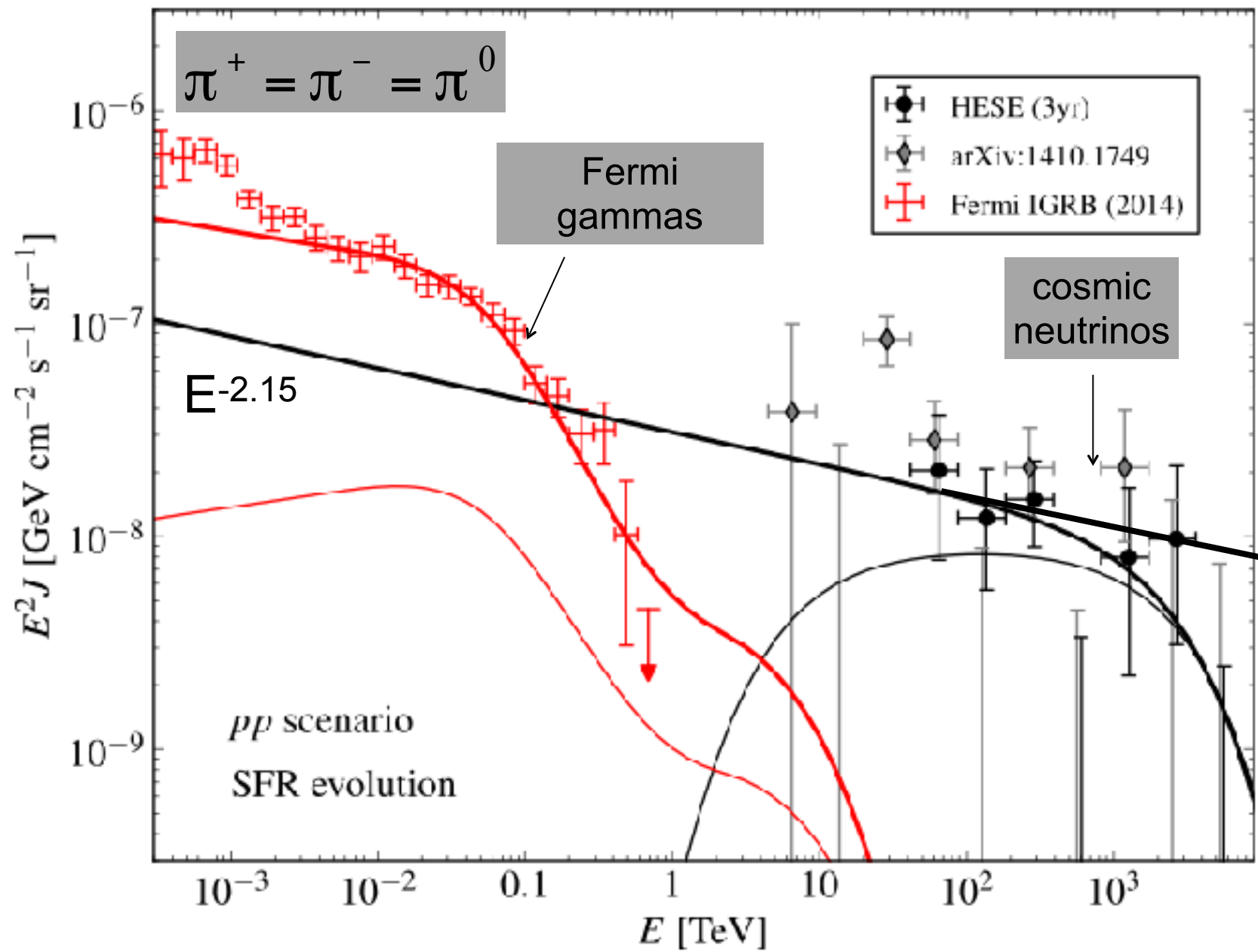
multimessenger
astronomy



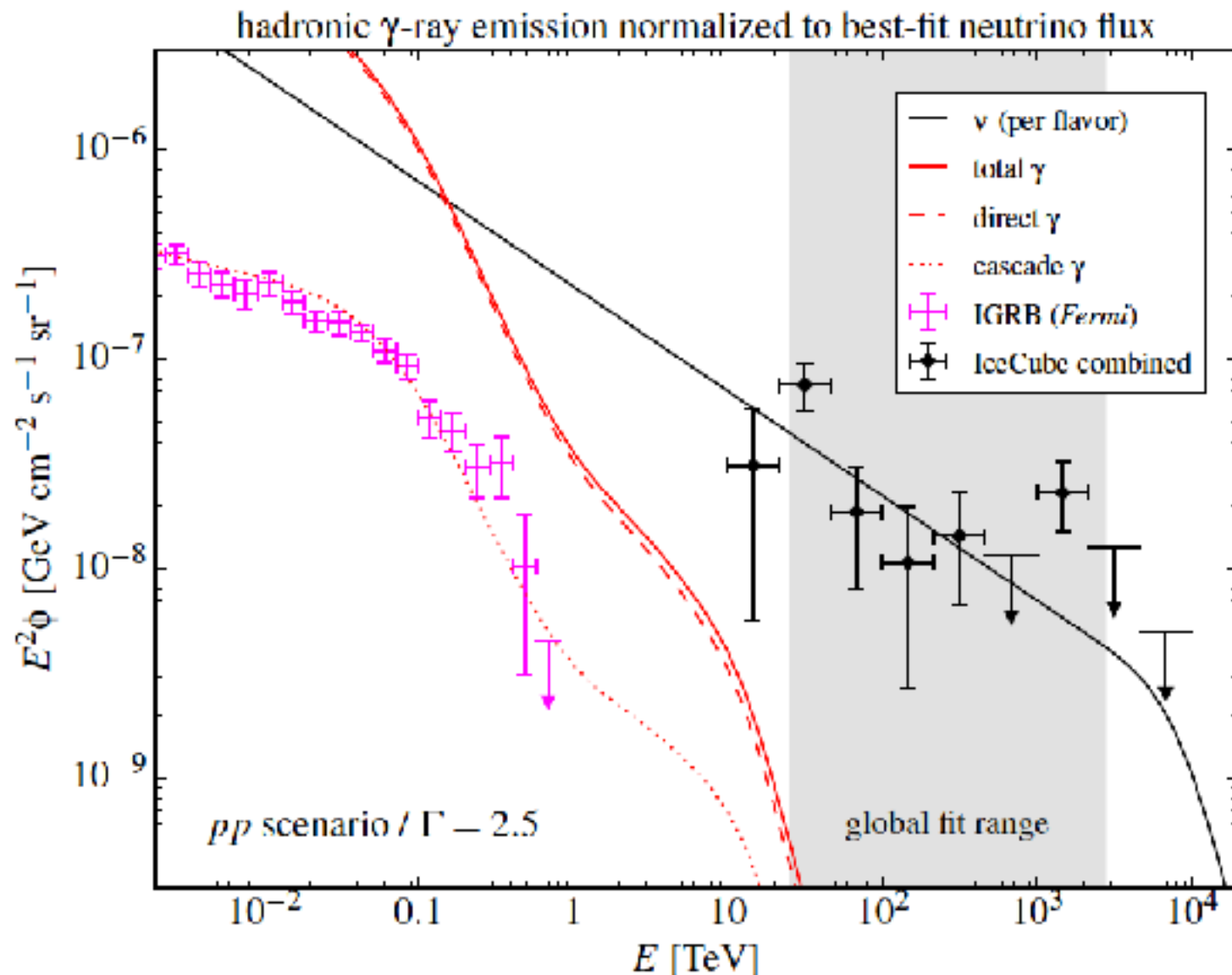


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

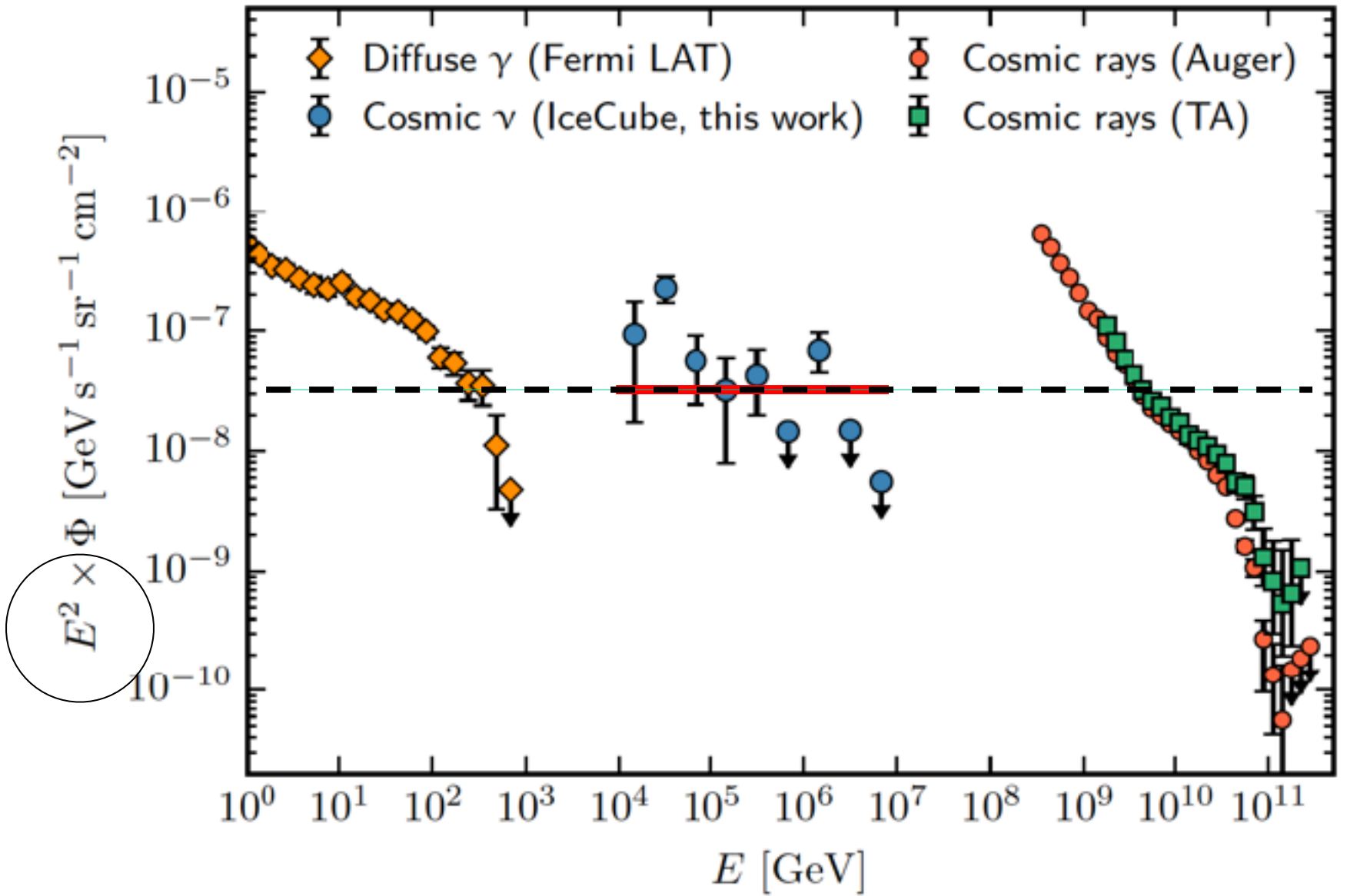




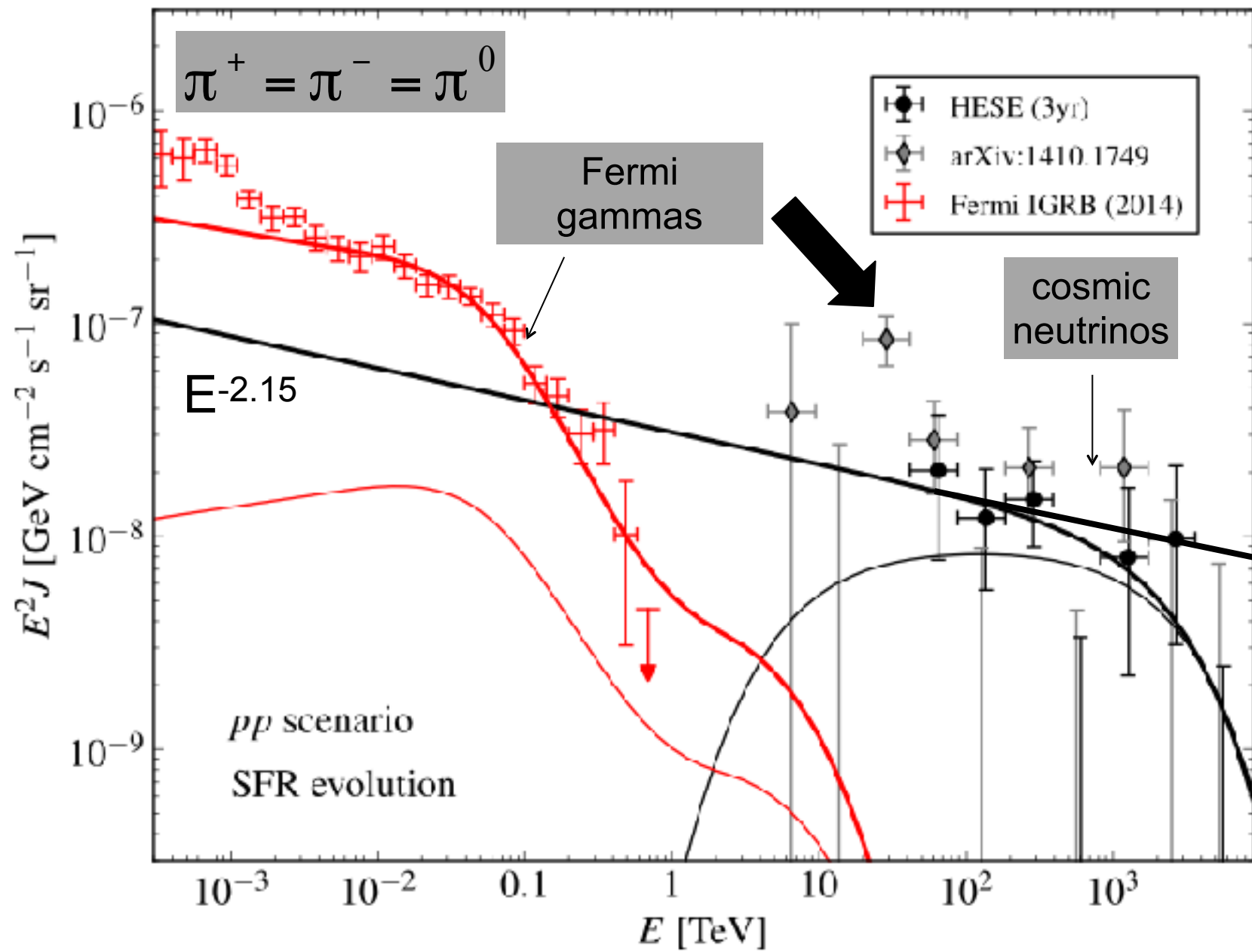
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



dark sources: a “problem” ?
 gamma rays cascade in the source to $< \text{GeV}$ energy

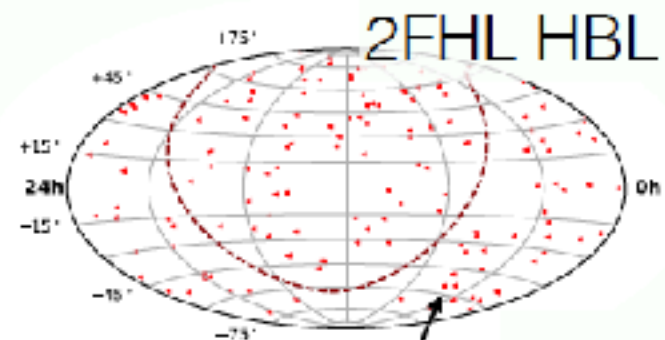
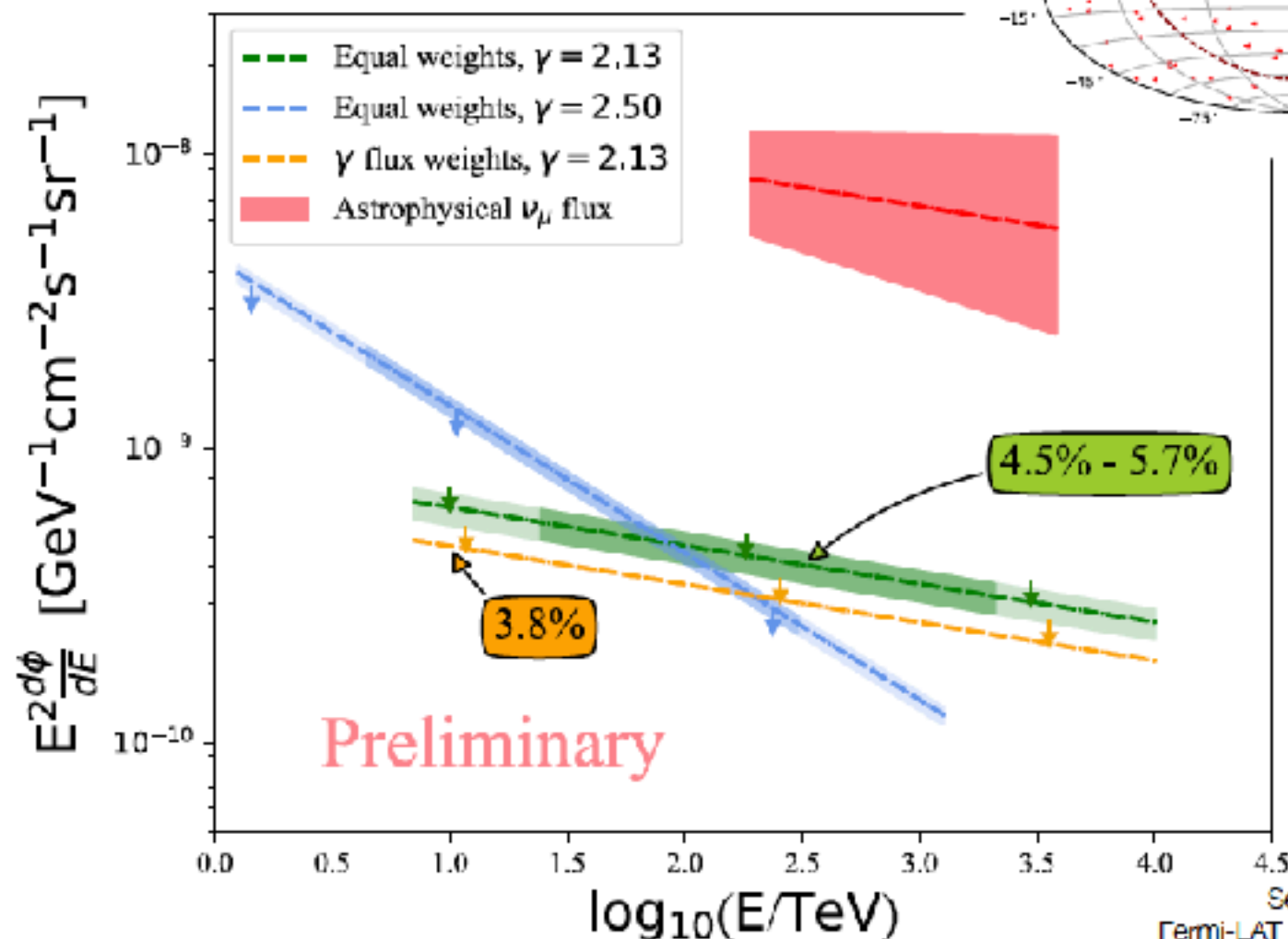


energy in the Universe in gamma rays, neutrinos and cosmic rays

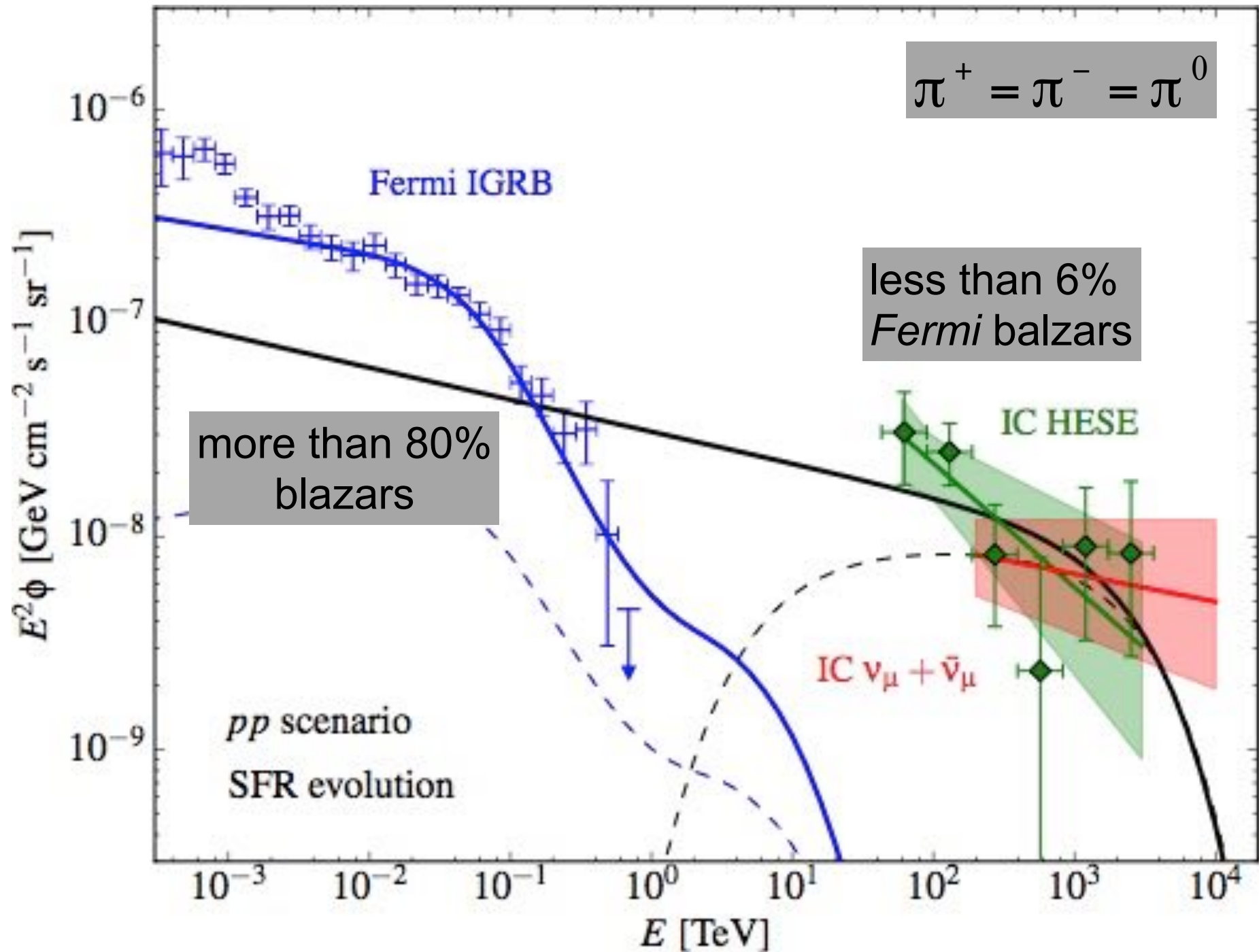


Population studies: blazar catalog search

Blazars account for
 85% of extragalactic γ background
 < 6-27% of the IceCube neutrino flux



<1% of the sky

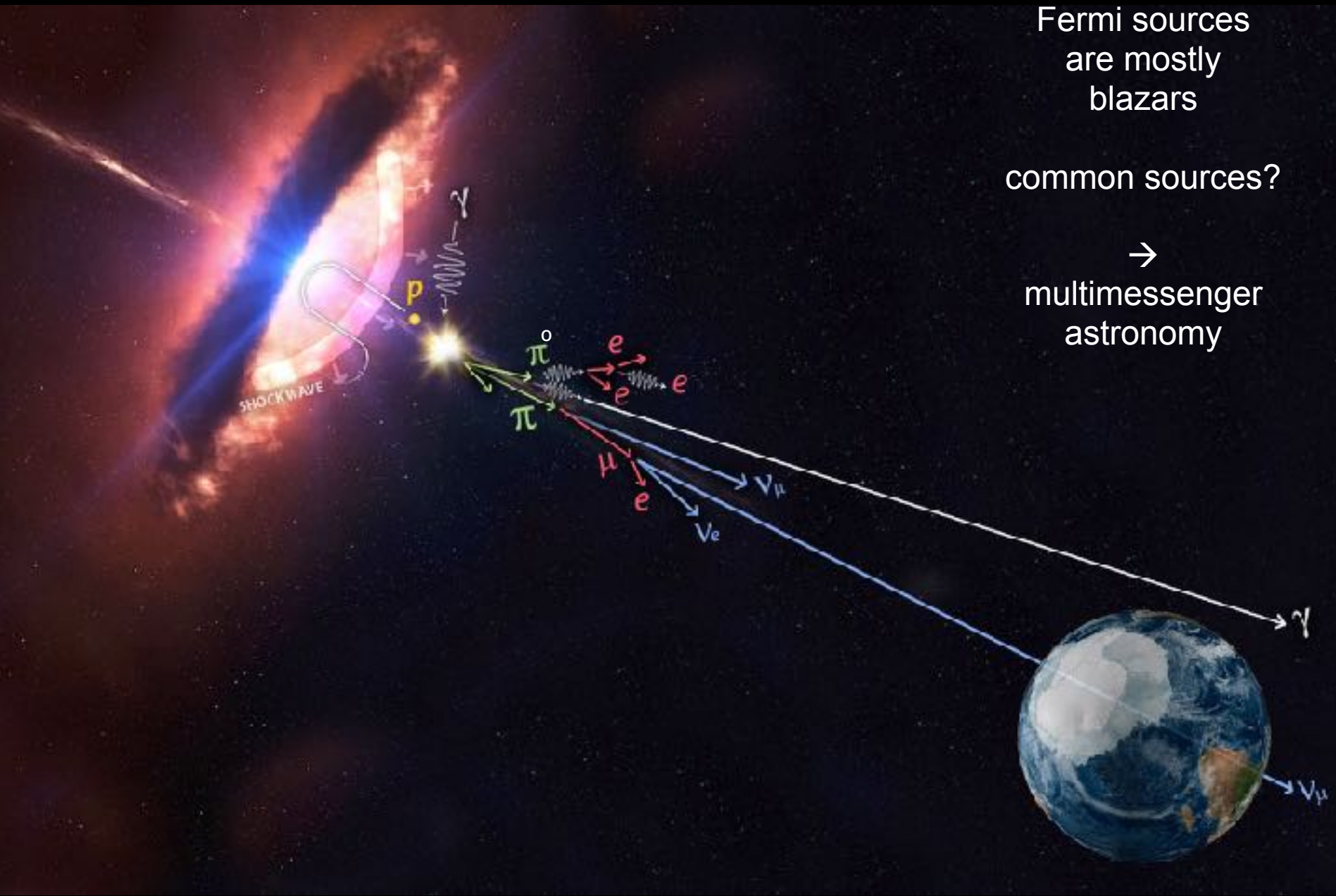


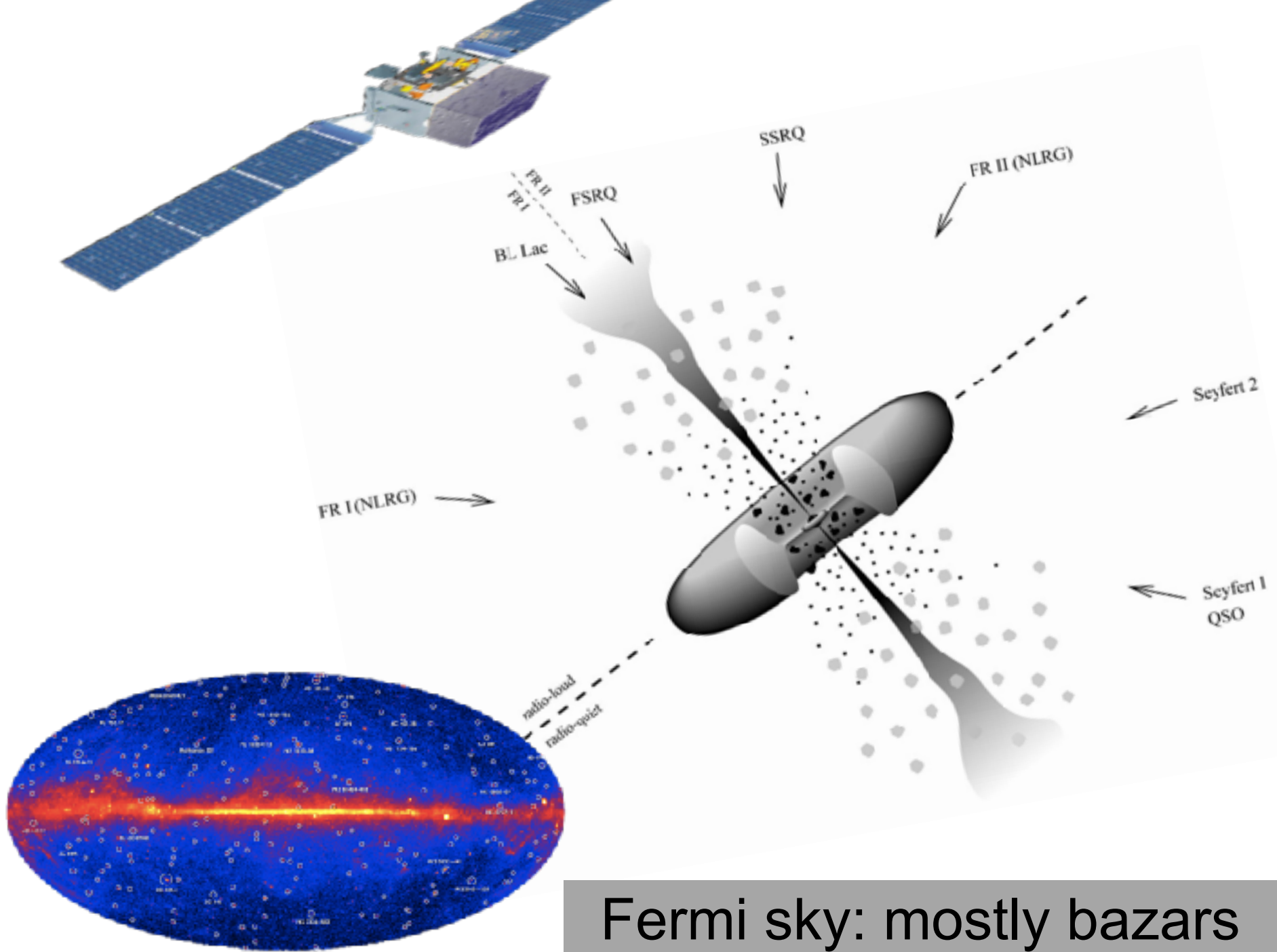
note that the gammas rays accompanying < 100 TeV neutrinos are not seen suggesting a hidden source(s)

Fermi sources
are mostly
blazars

common sources?

→
multimessenger
astronomy



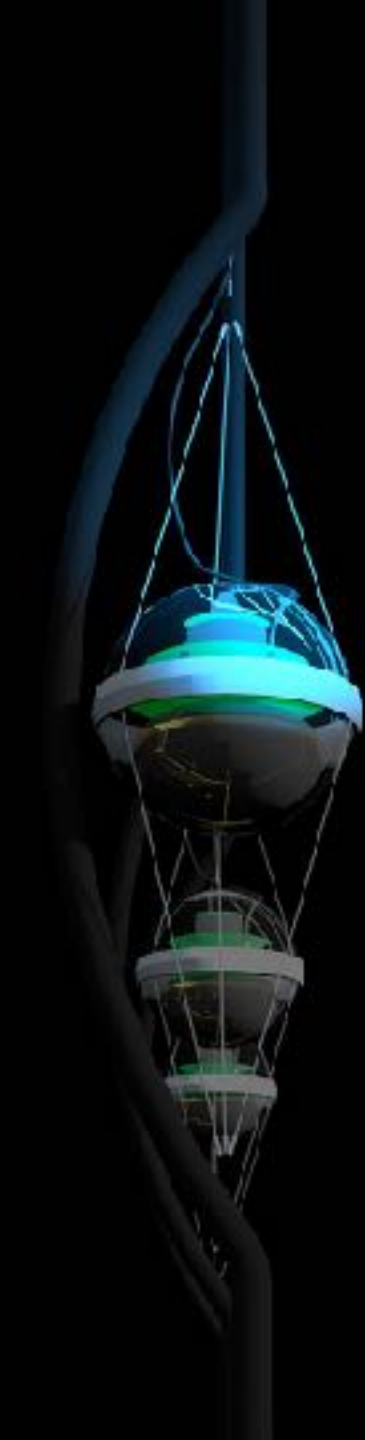


Fermi sky: mostly bazars

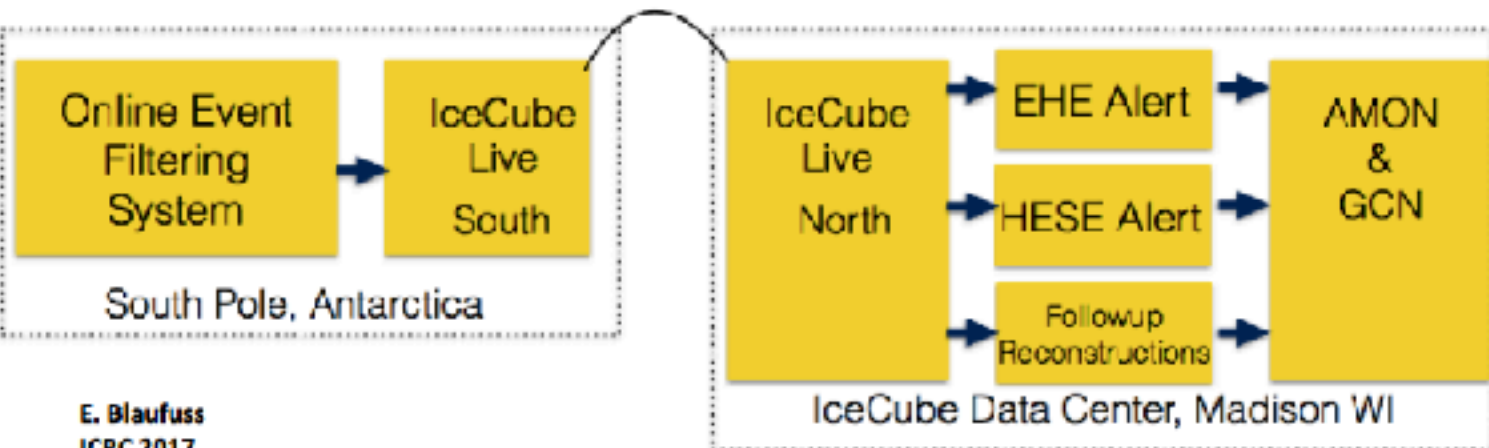
IceCube

francis halzen

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 - muon neutrinos through the Earth
 - starting neutrinos: all flavors
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- what next?



Realtime alerts from IceCube



E. Blaufuss
ICRC 2017

Median alert latency: 33 seconds

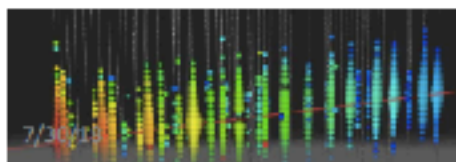
Upcoming improvements:

- New starting event selections
- Cascades
- Higher astrophysical purity
- Improved event information in alerts

13 alerts sent since 2016

First alert sent within 1 minute

Detailed follow-ups after a few hours



	Starting Tracks	Throughgoing tracks
Energy	> 60 TeV	> 500 TeV
Alerts per year	4.8	4 - 5
Signal events per year	1.1	2.5 - 4

Williams - RICH 2018 - IceCube

IceCube Coll.: *Astropart. Phys.*, 92, 30 (2017) 13



HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

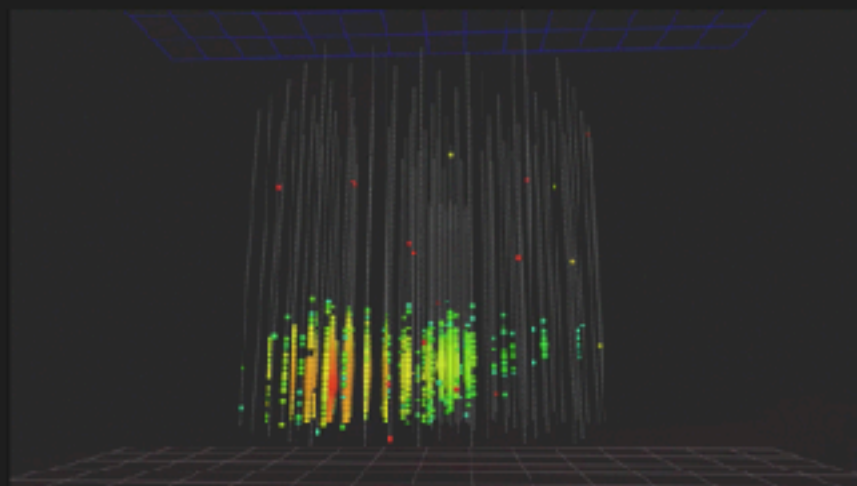
47

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

GCN notice for starting track sent Apr 27

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

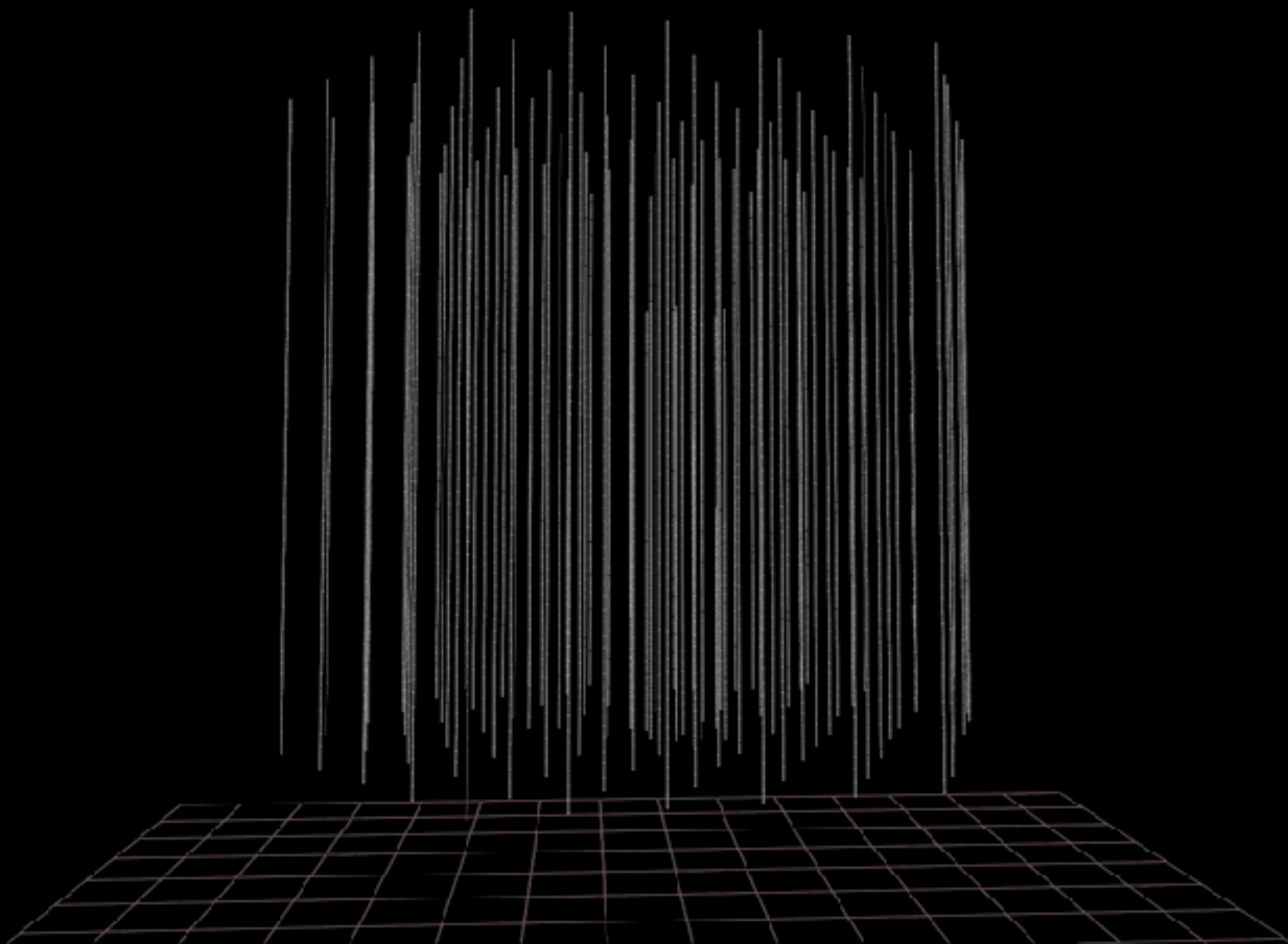
```
TITLE: GCN/AMON NOTICE
NOTICE_DATE: Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE: AMON ICECUBE HESE
RUN_NUM: 127853
EVENT_NUM: 67093193
SRC_RA: 240.5683d {+16h 02m 16s} (J2000),
240.7644d {+16h 03m 03s} (current),
239.9678d {+15h 59m 52s} (1950)
SRC_DEC: +9.3417d {+09d 20' 30"} (J2000),
+9.2972d {+09d 17' 50"} (current),
+9.4798d {+09d 28' 47"} (1950)
SRC_ERROR: 35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERRORS0: 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"}
```



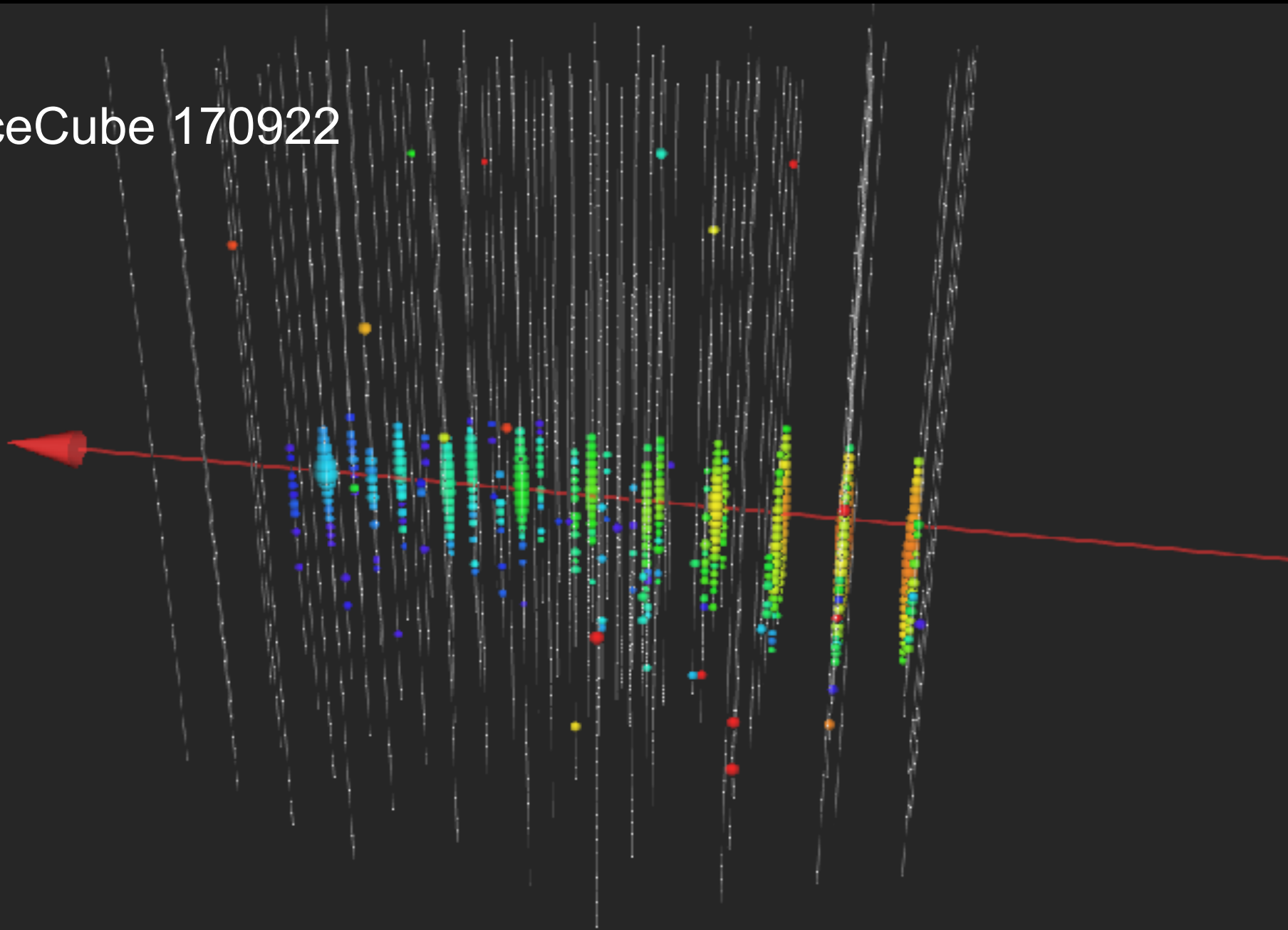
IceCube Trigger

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



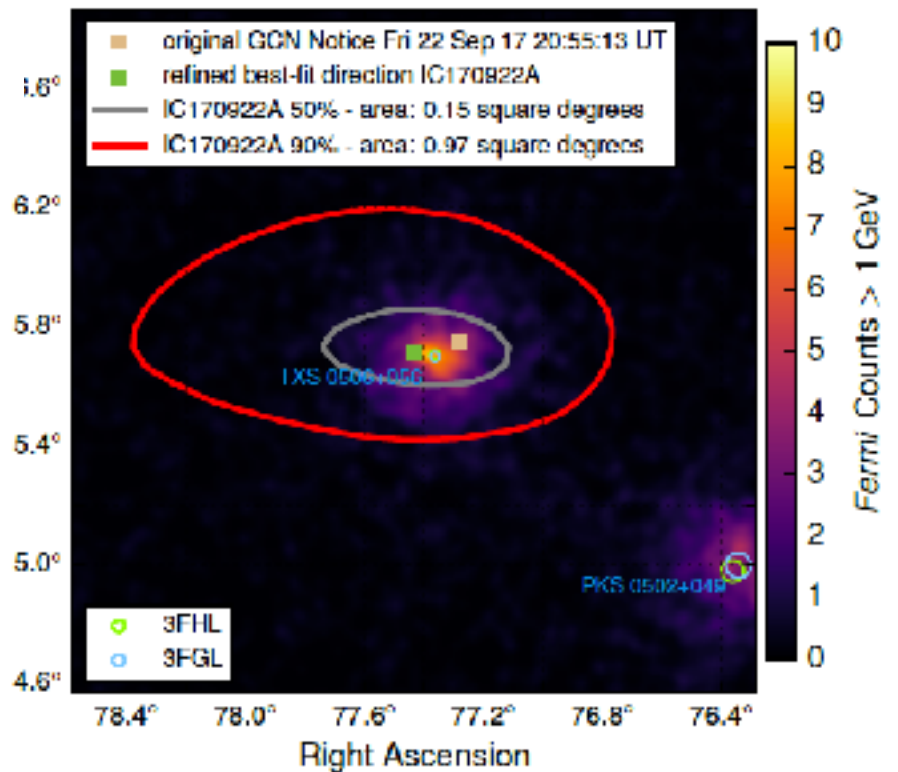
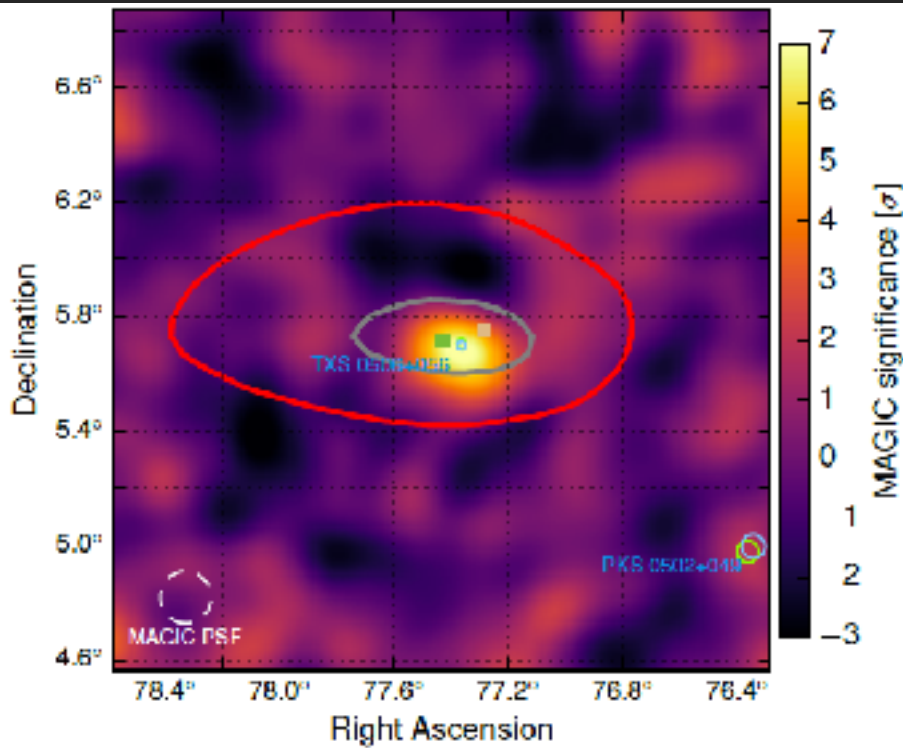
multiwavelength campaign launched by IC 170922

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

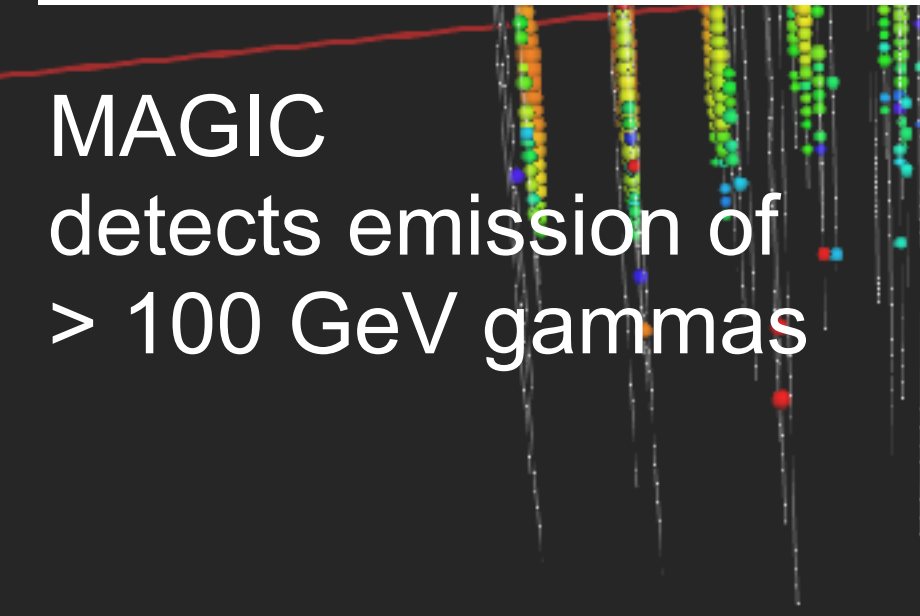
- neutrino: time 22.09.17, 20:54:31 UTC
energy 290 TeV
direction RA 77.43° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.1° (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

IceCube 170922

Fermi
detects a flaring
blazar within 0.1°



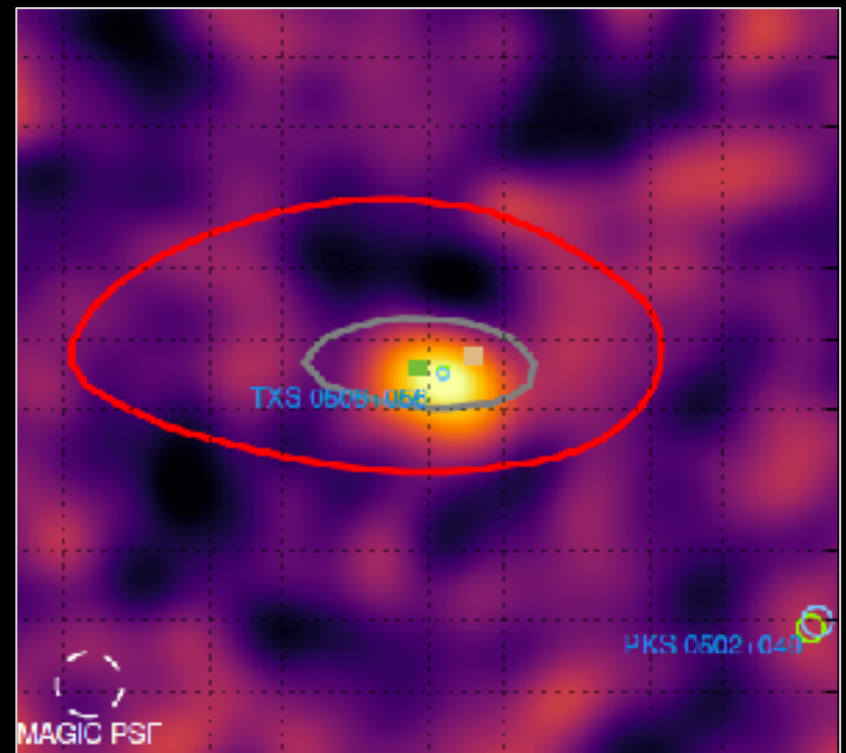
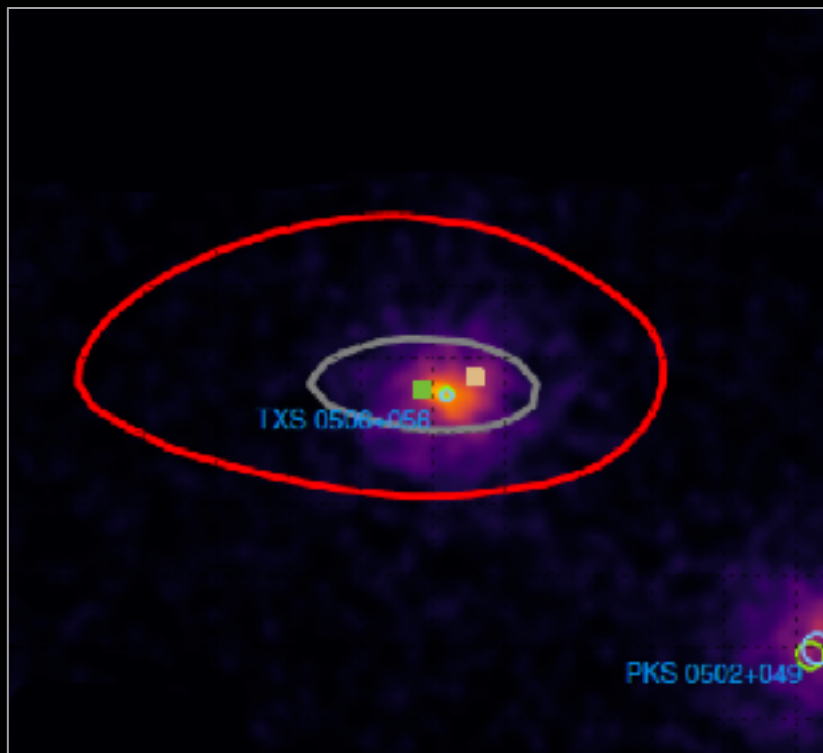
MAGIC
detects emission of
> 100 GeV gammas





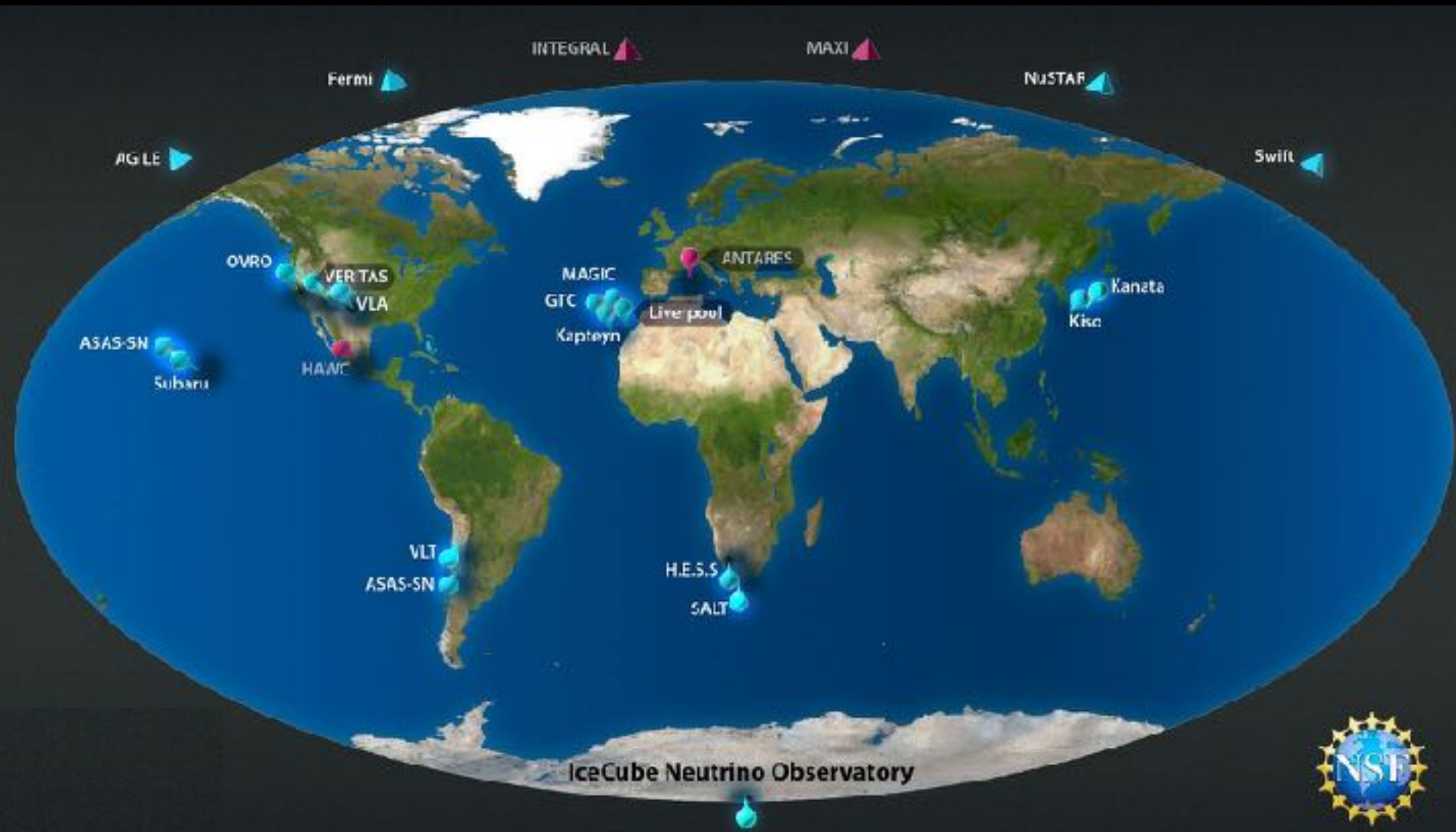
Neutrino points within 0.06° of
a known Fermi blazar

MAGIC detects emission of
>100 GeV gammas



MAGIC atmospheric Cherenkov telescope





multiwavelength campaign launched by IC 170922

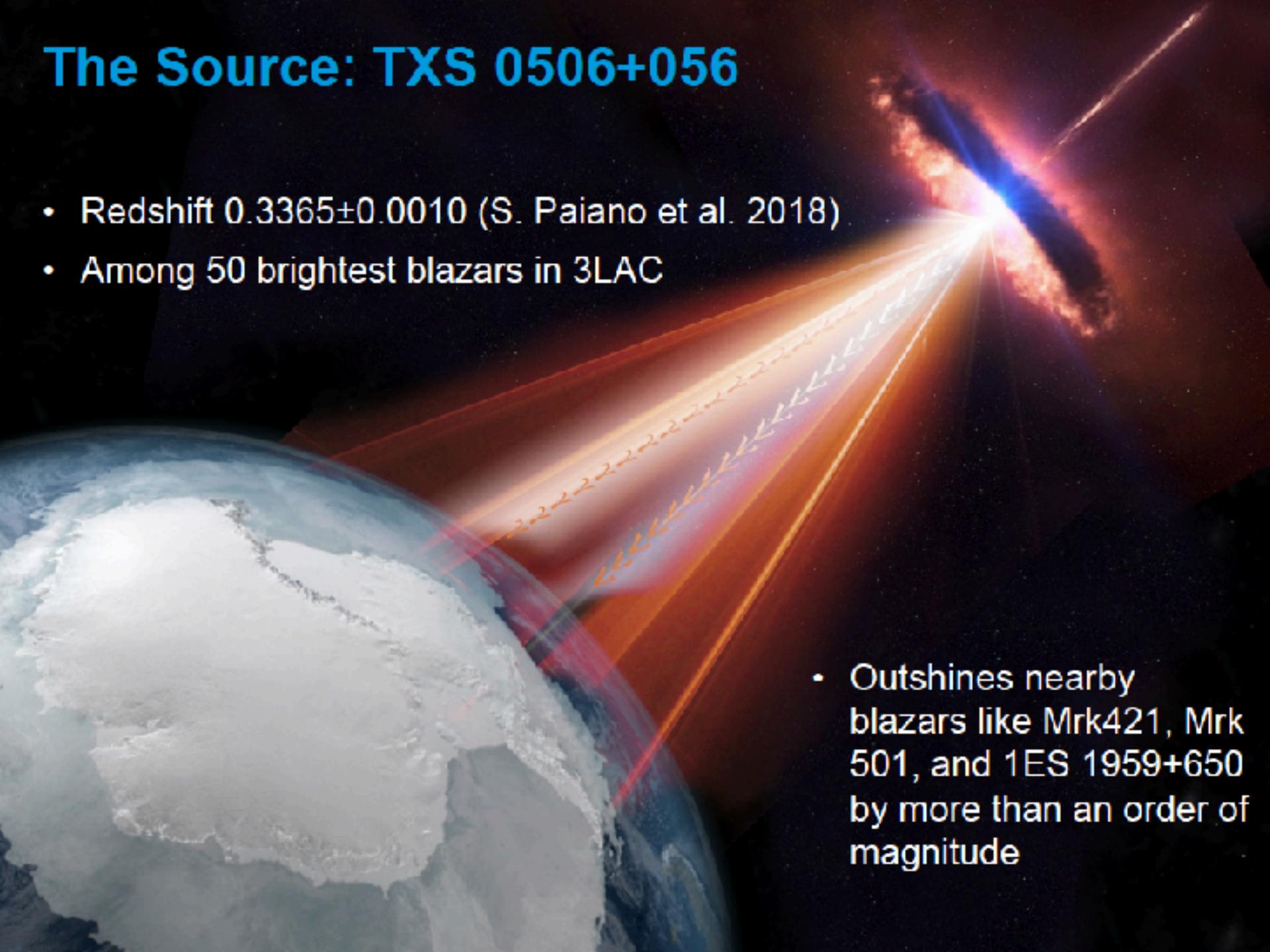
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL,
Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

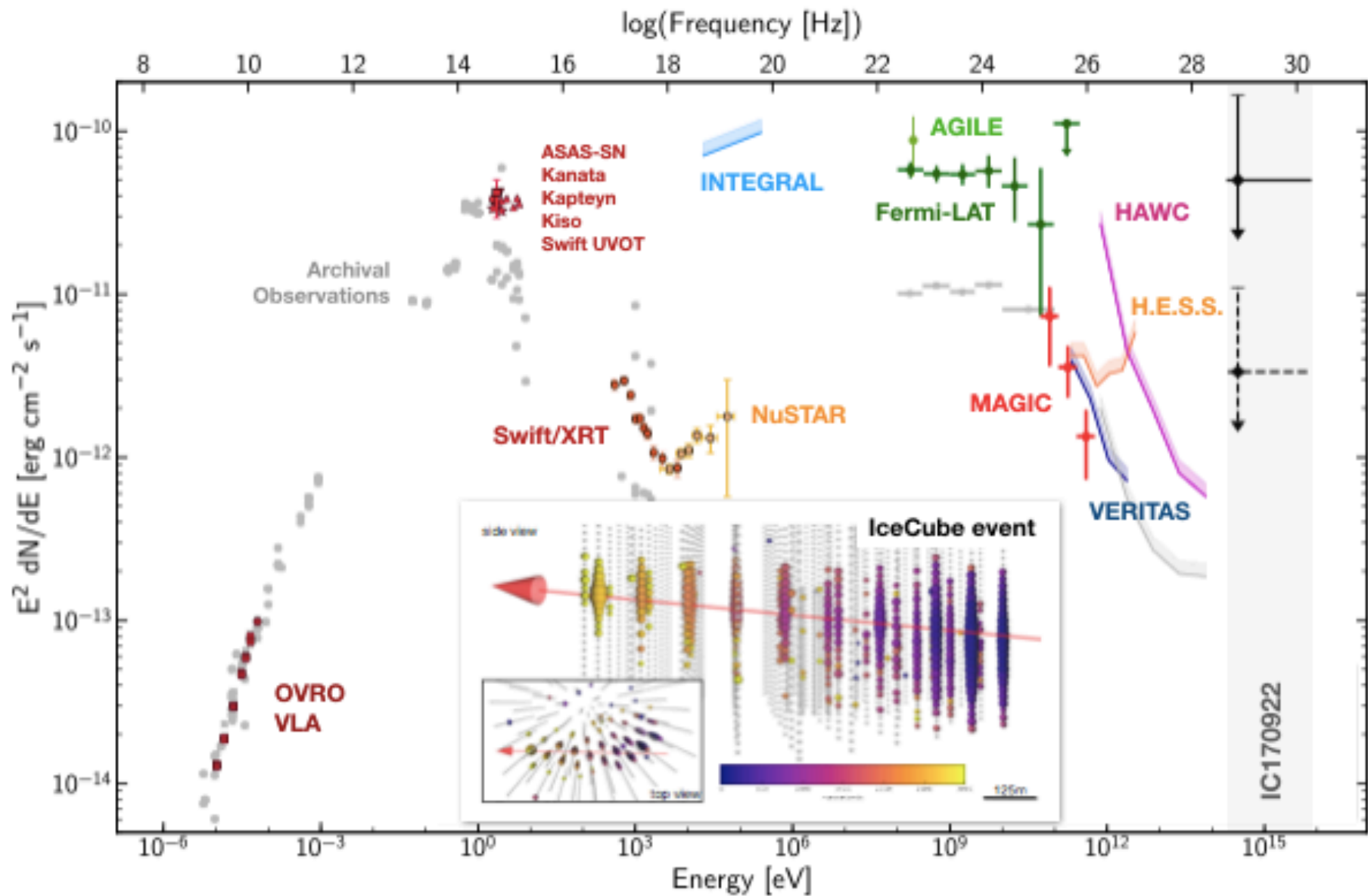
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- → Fermi-LAT archival data

The Source: TXS 0506+056

- Redshift 0.3365 ± 0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC

- Outshines nearby blazars like Mrk421, Mrk 501, and 1ES 1959+650 by more than an order of magnitude





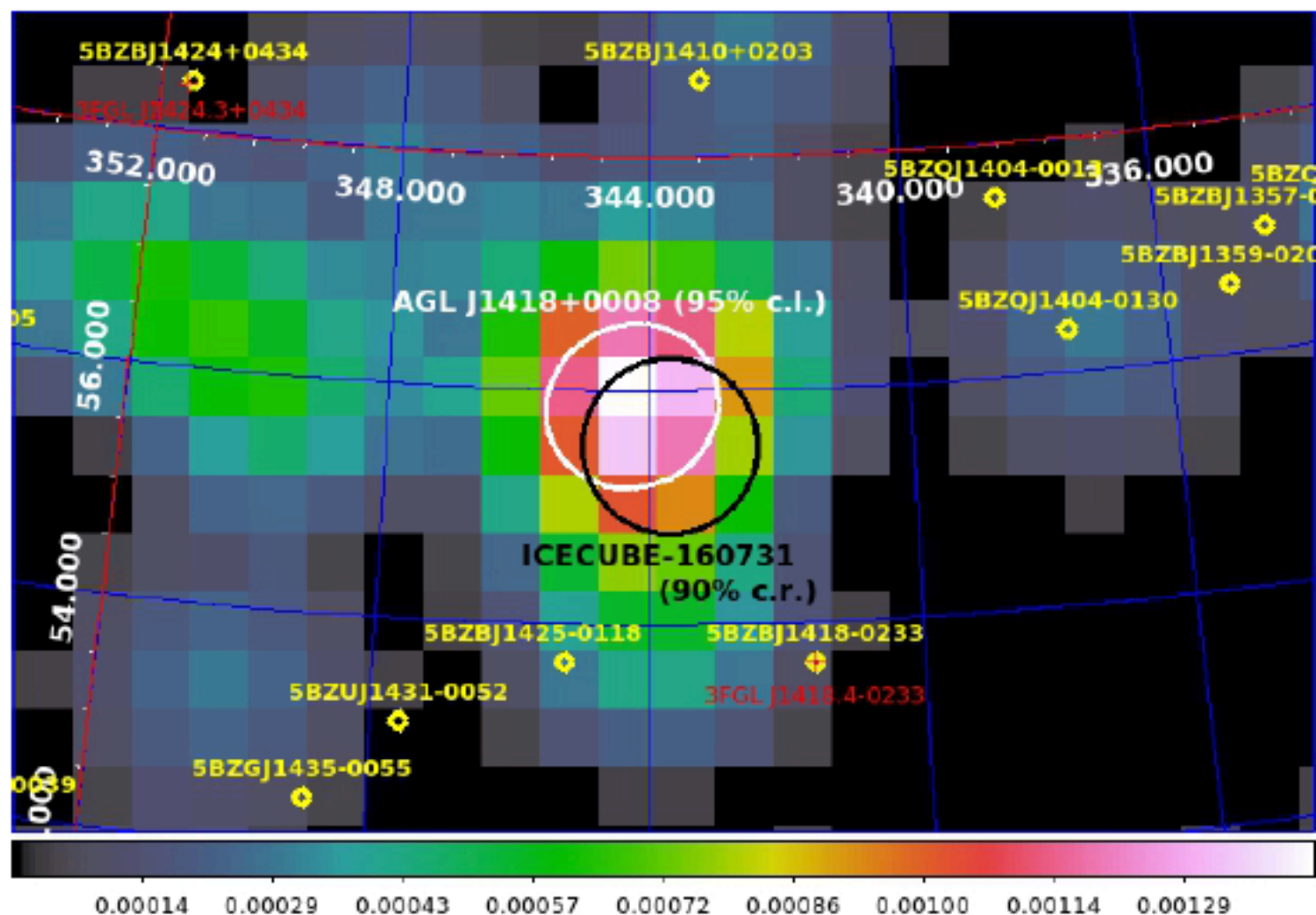
we identified a source of high energy cosmic rays:

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

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

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

F. LUCARELLI,^{1,2} C. FITTORI,^{1,2} F. VERRECCHIA,^{1,2} I. DONNARUMMA,³ M. TAVANI,^{4,5,6} A. BUIGABELLI,⁷ A. GIULIANI,⁸
L. A. ANTONELLI,^{1,2} P. CARAVED,⁸ P. W. CATTANEO,⁹ S. COLAFRANCESCO,^{10,2} F. LONGO,¹¹ S. MEREGHETTI,³
A. MORSELLI,¹² L. PACCIANI,⁴ G. PIANO,⁴ A. FELLIZZONI,¹³ M. PLIA,¹³ A. RAPPOLDI,⁹ A. TROIS,¹³ AND S. VERCELLONE¹⁴



Corresponding author: Fabrizio Lucaelli
fabrizio.lucaelli@asdc.asi.it