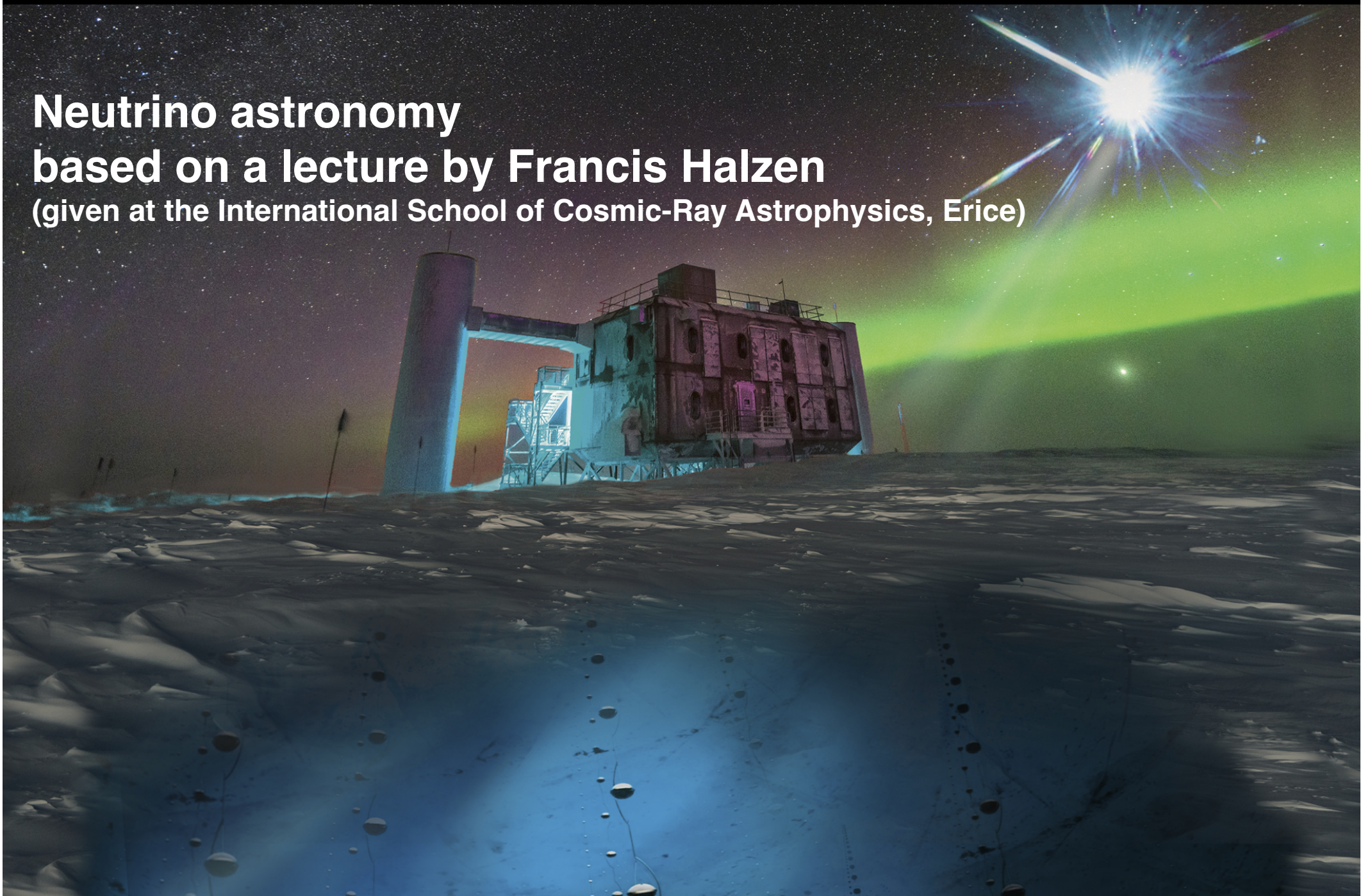
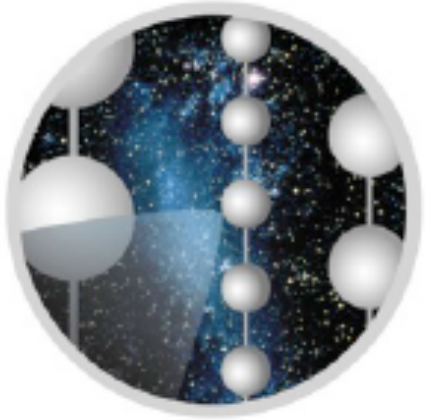
Astroparticle Physics 2021/22

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)





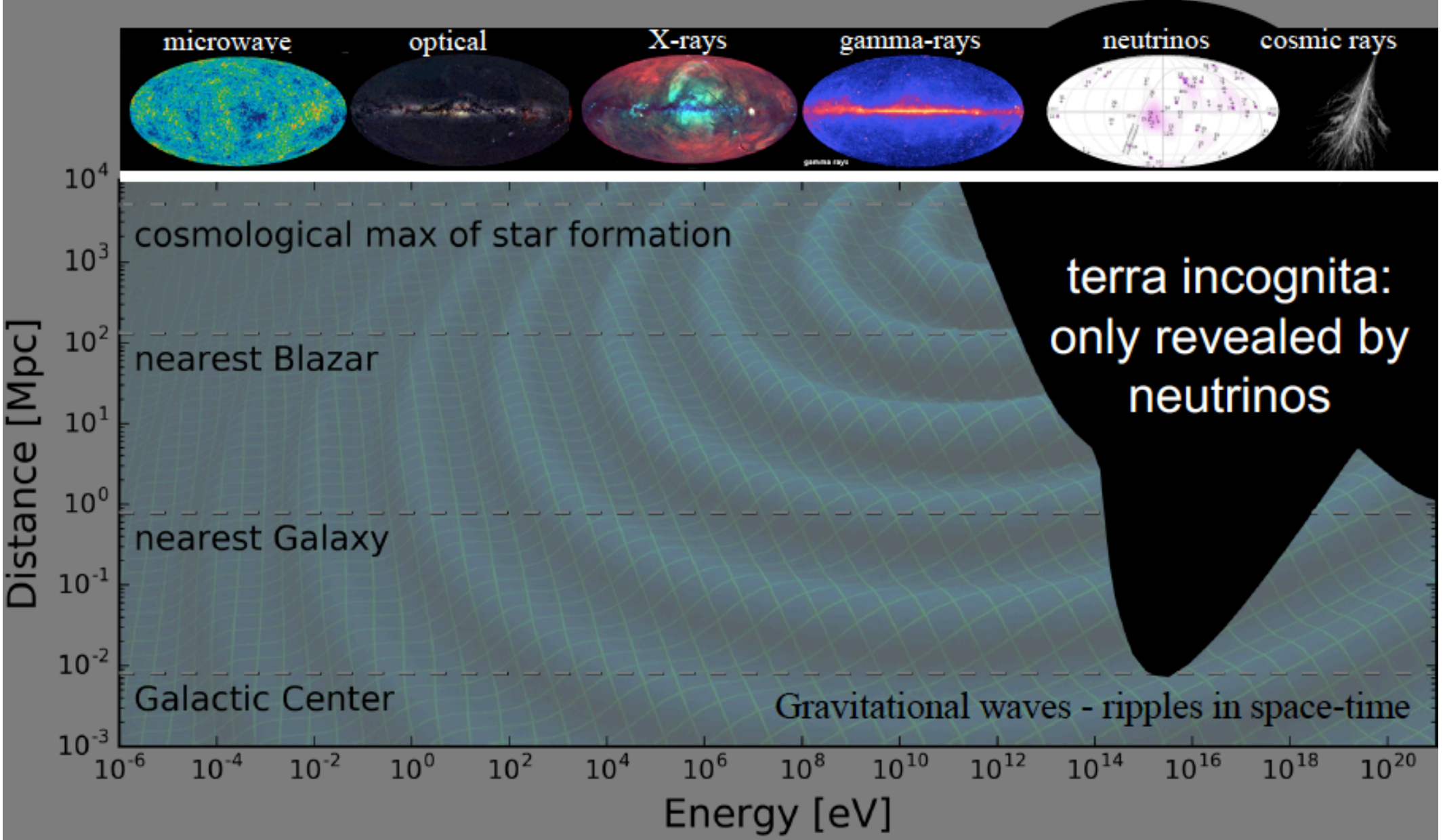
IceCube:

Building a New Window on the Universe

francis halzen

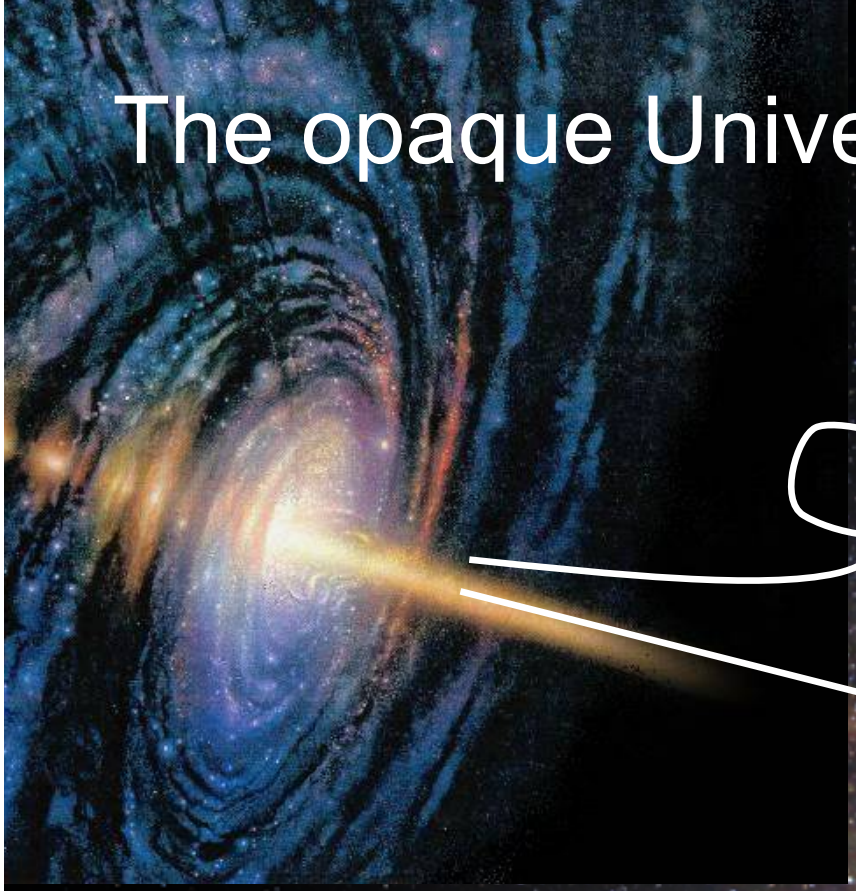
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

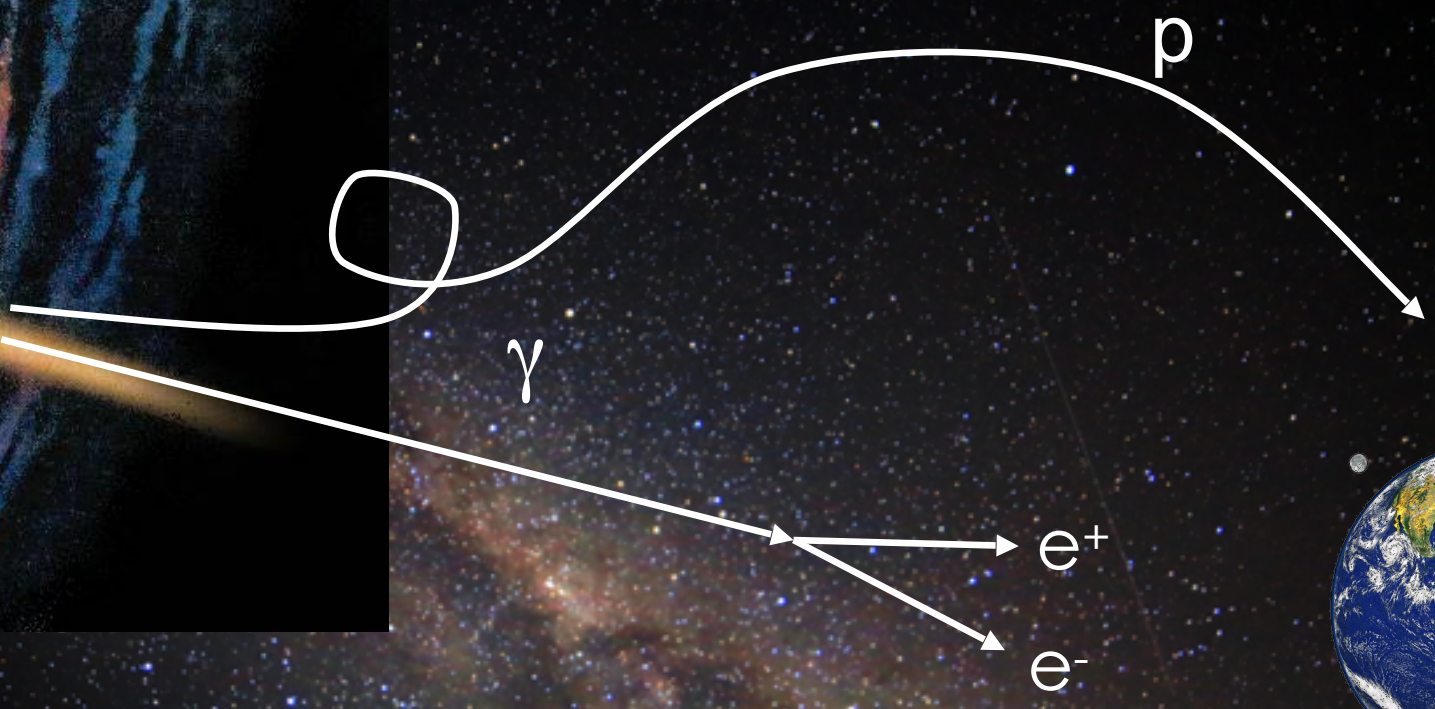
icecube.wisc.edu



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

The opaque Universe

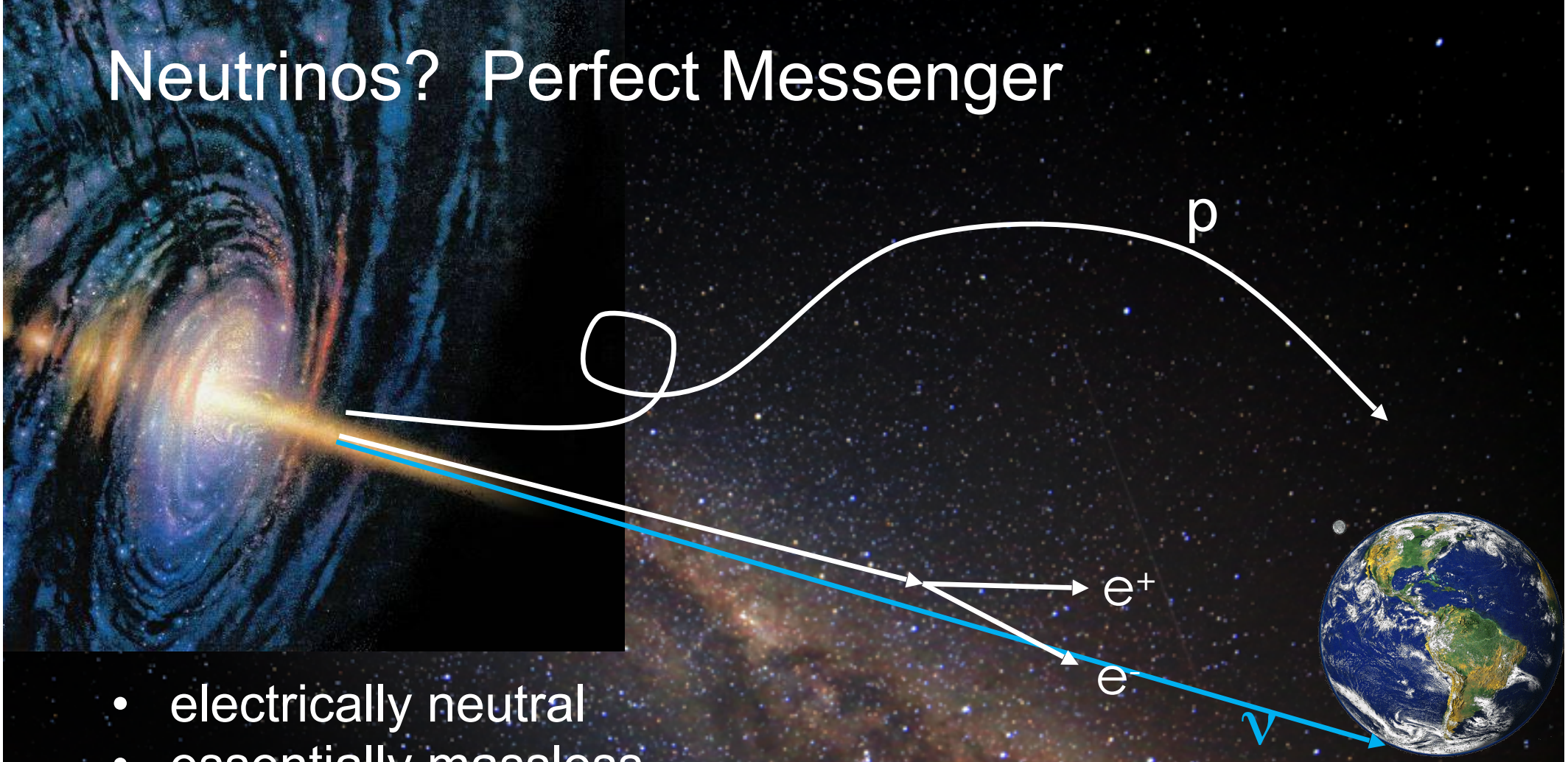




$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons (411/ 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

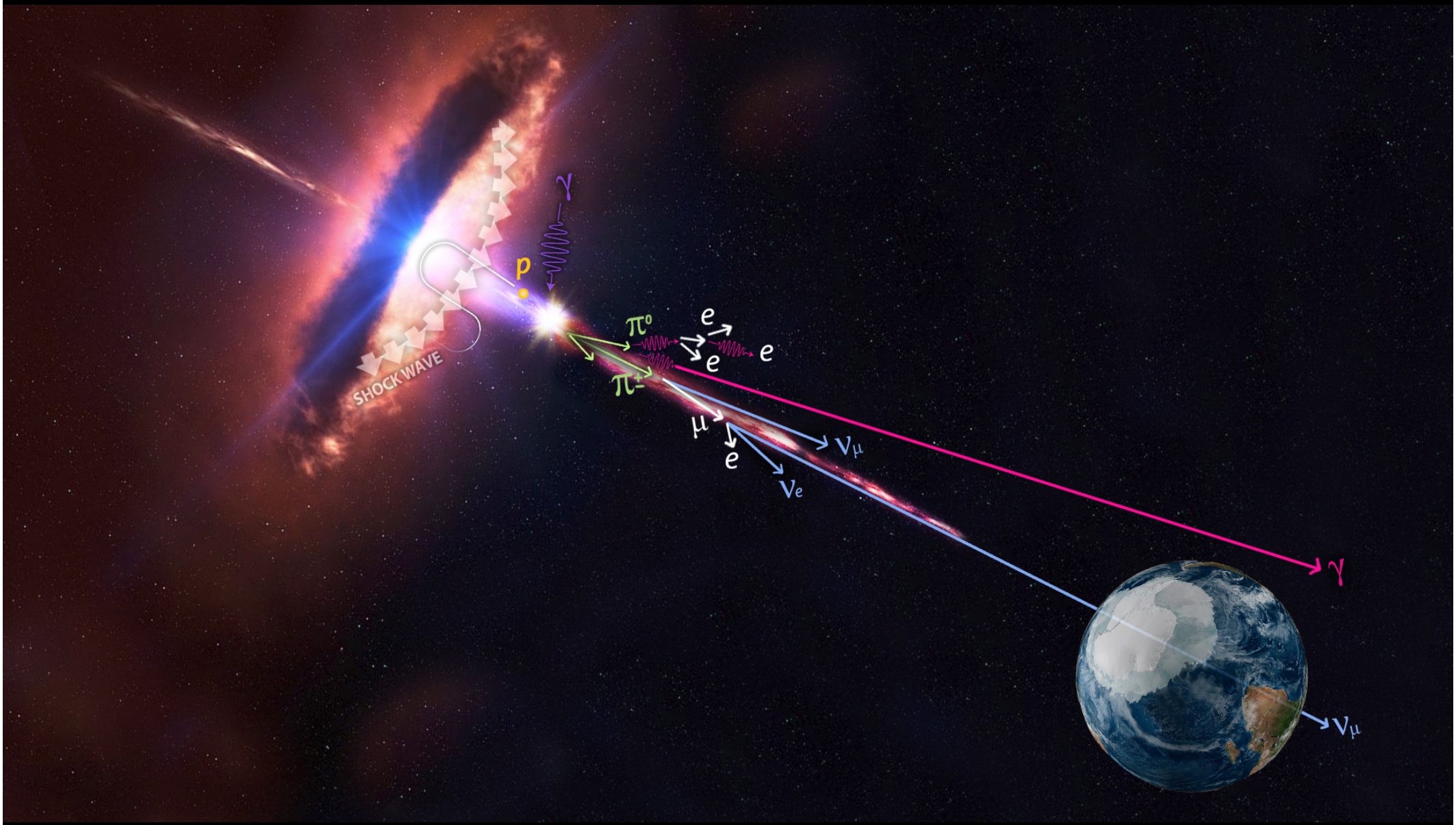
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

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

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

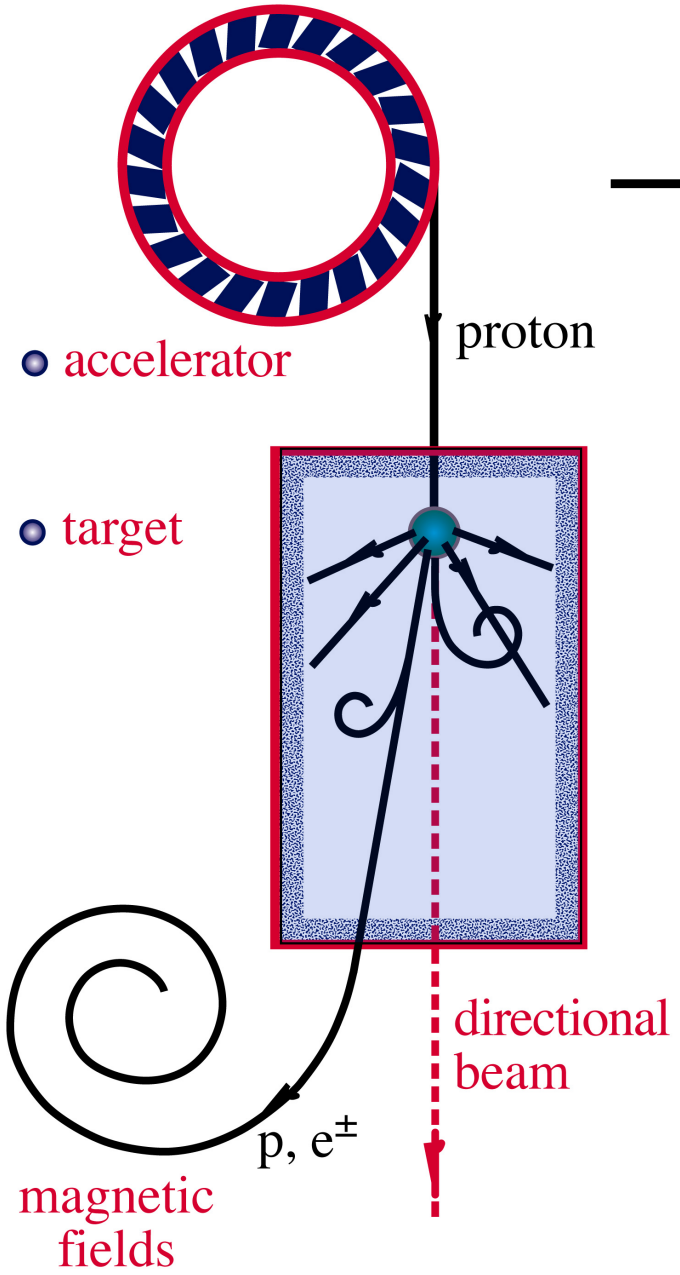
1 event per cubic kilometer per year

...but it points at its source!



blazar geometry

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

$\rightarrow p + \pi^0$

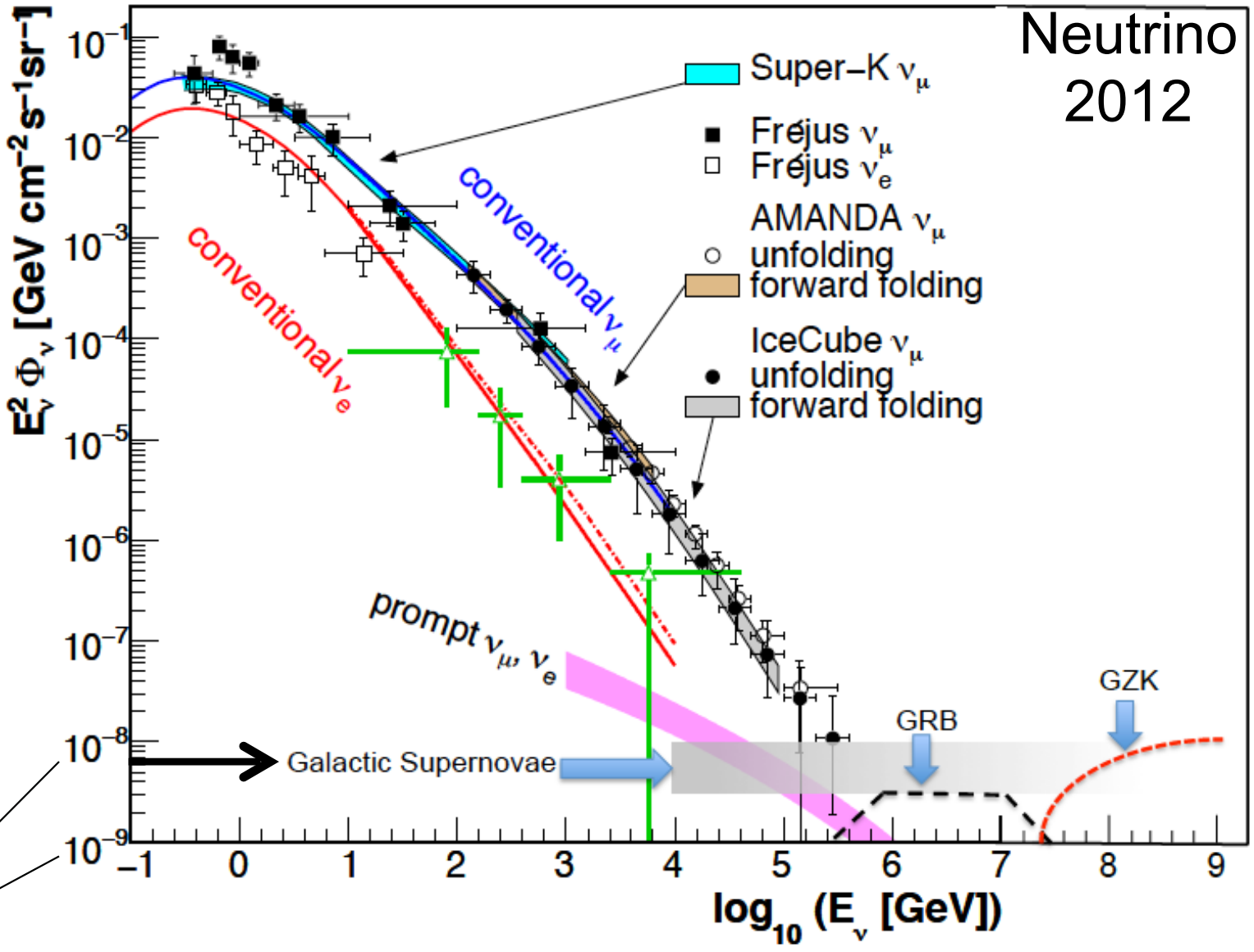
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

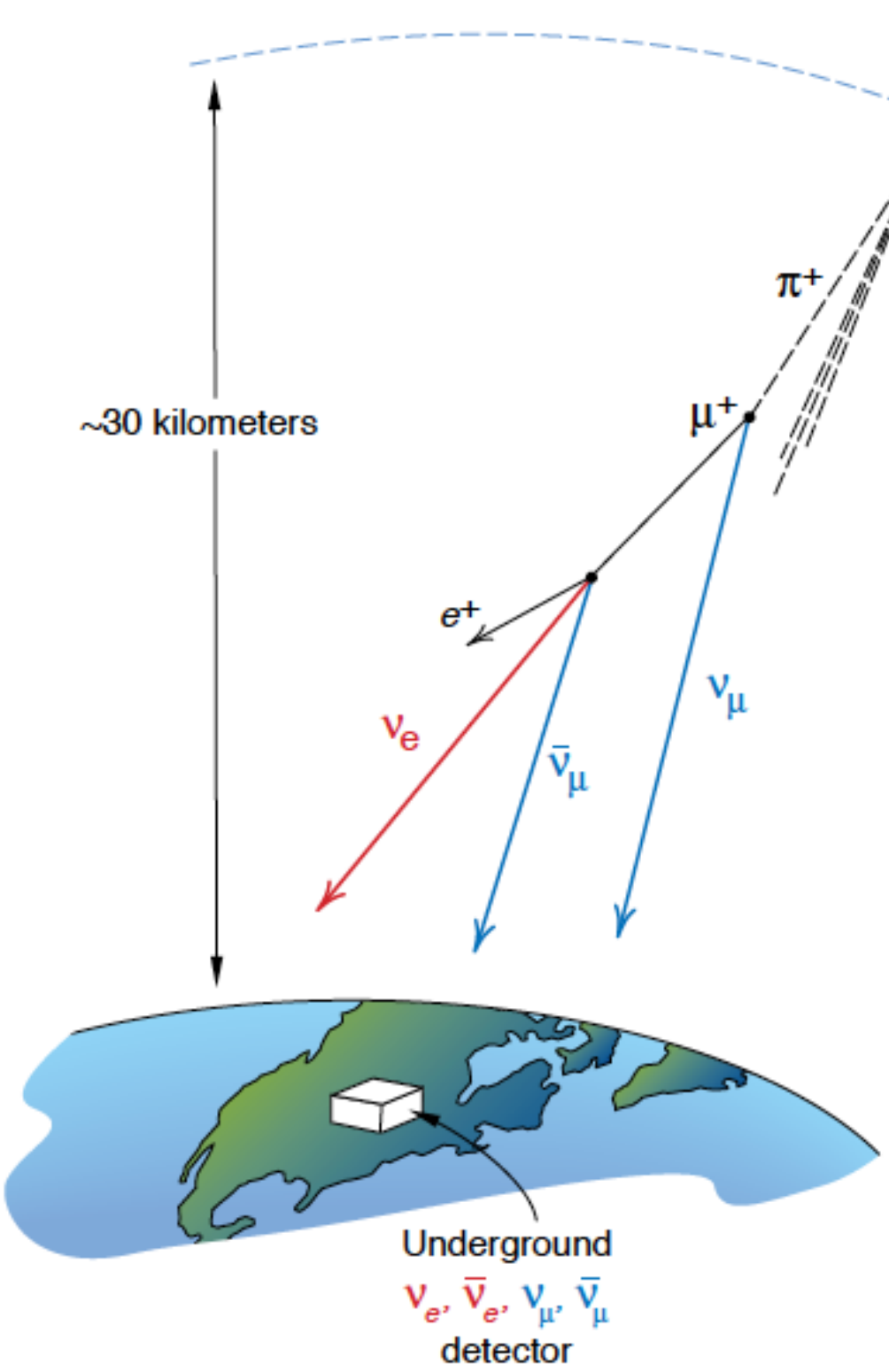
10—100 events per year for fully efficient detector



atmospheric

cosmic

100 TeV

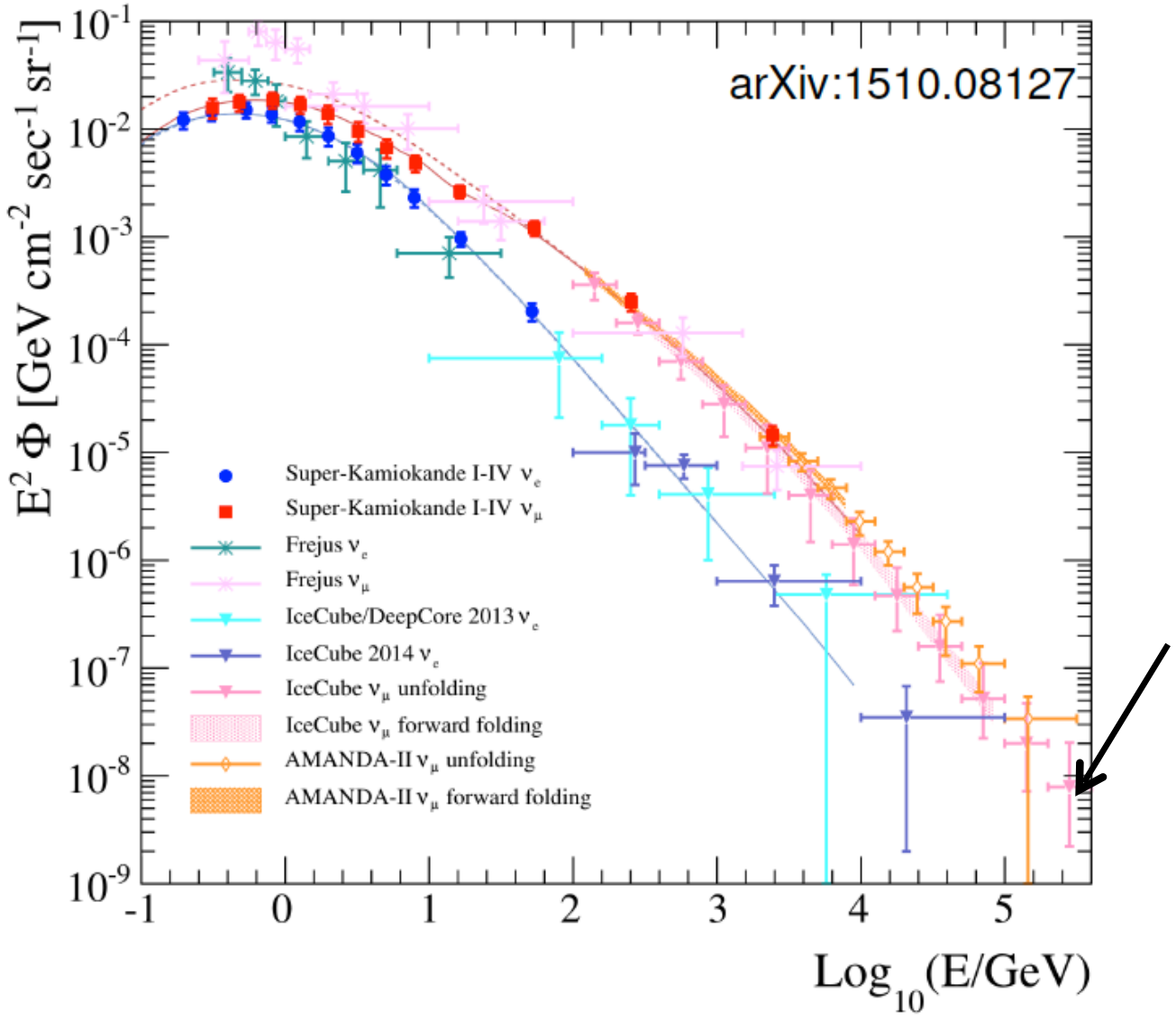


atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

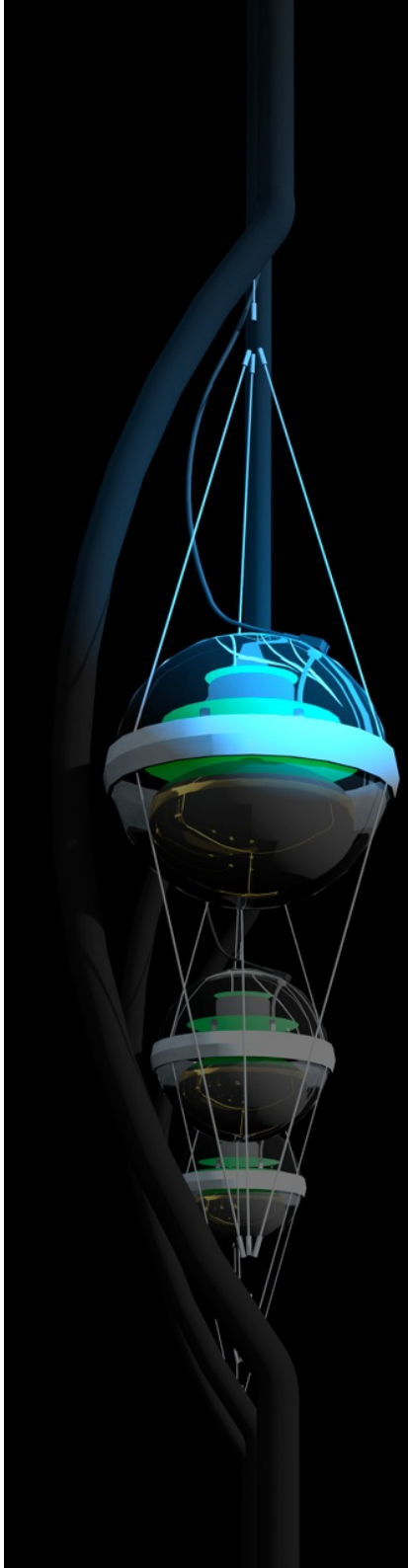
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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



< 1 atmospheric neutrino event per cubic kilometer per year

atmospheric neutrino spectrum (energy measurement) well understood



IceCube

francis halzen

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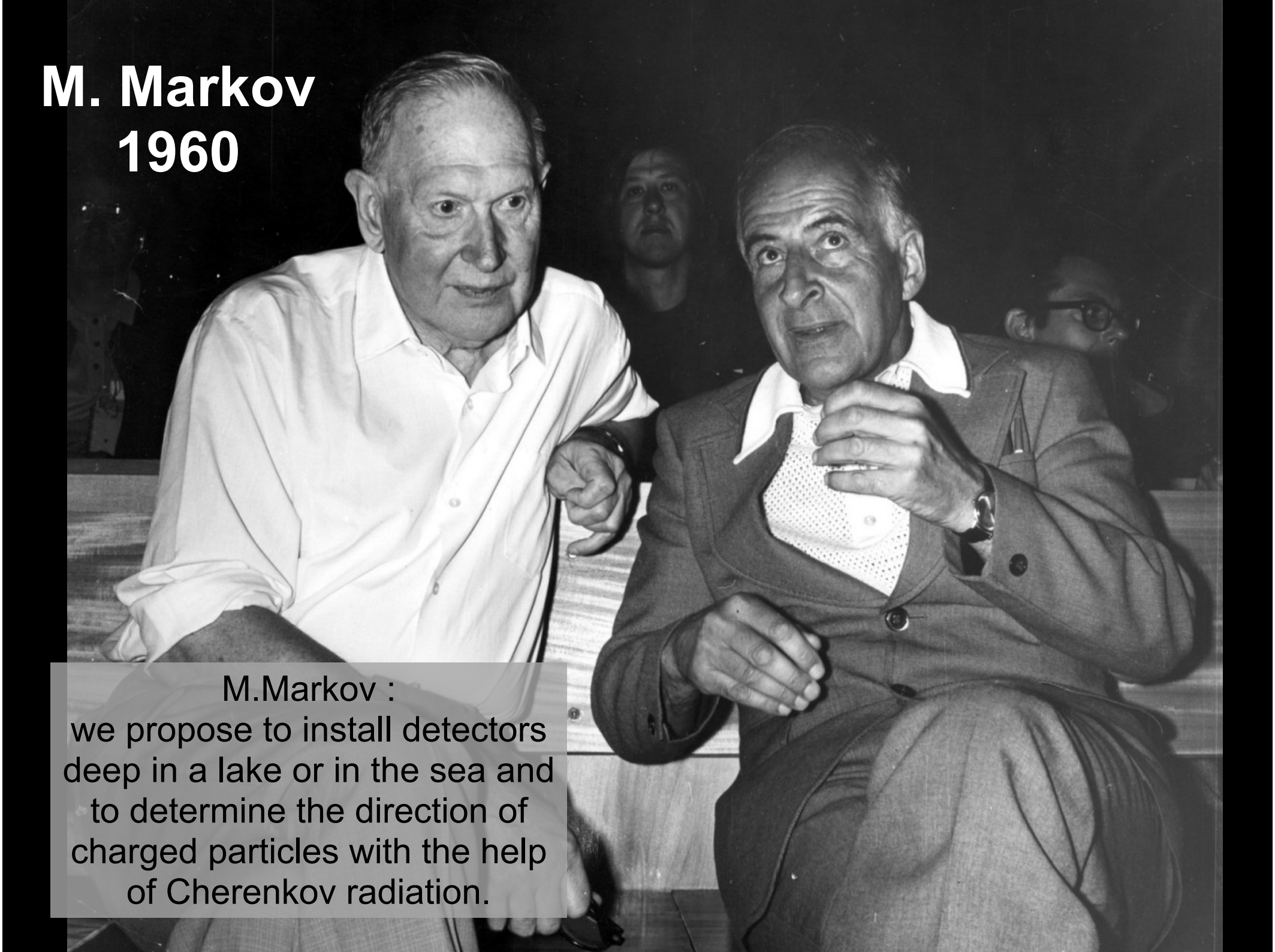
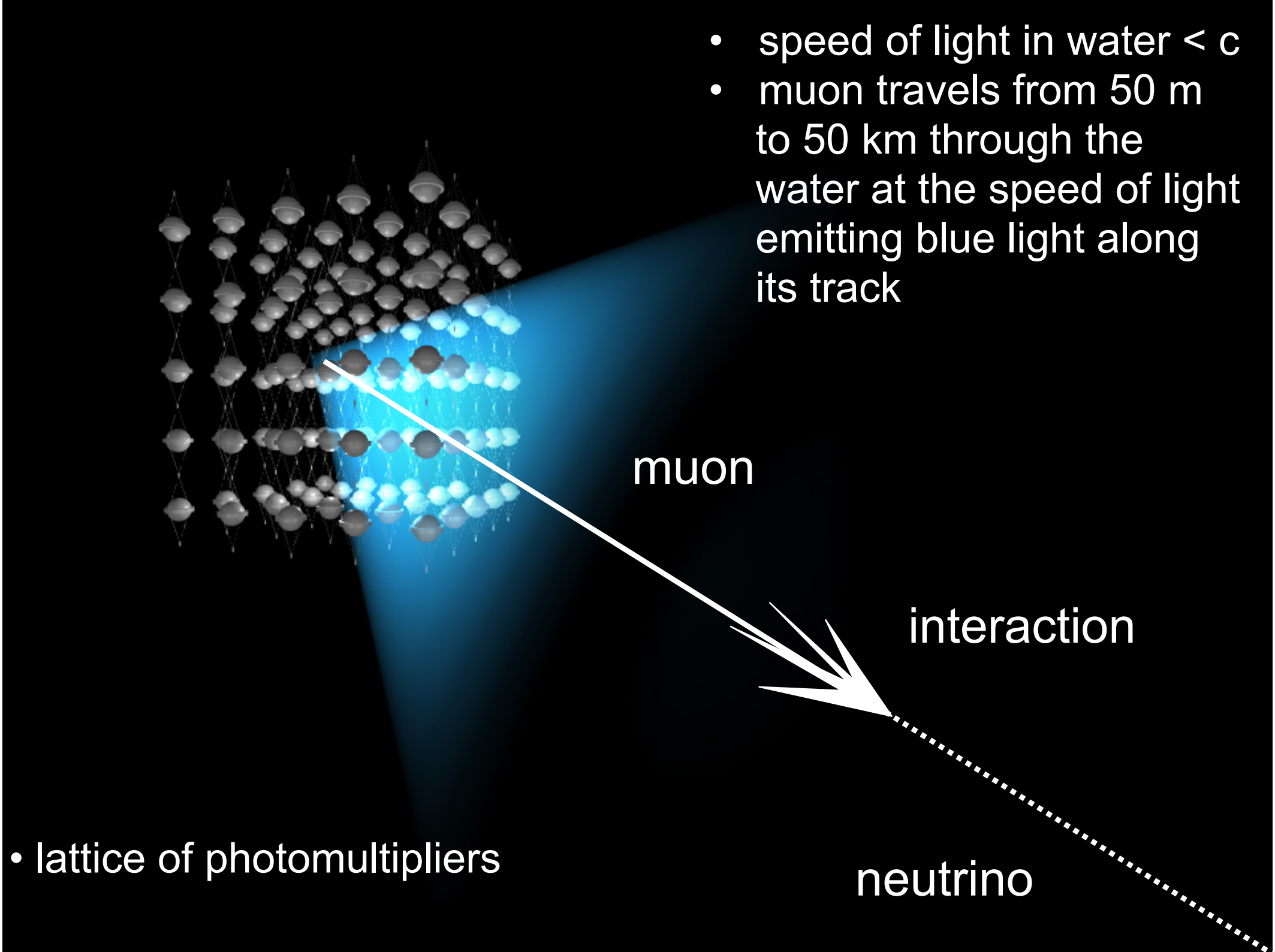
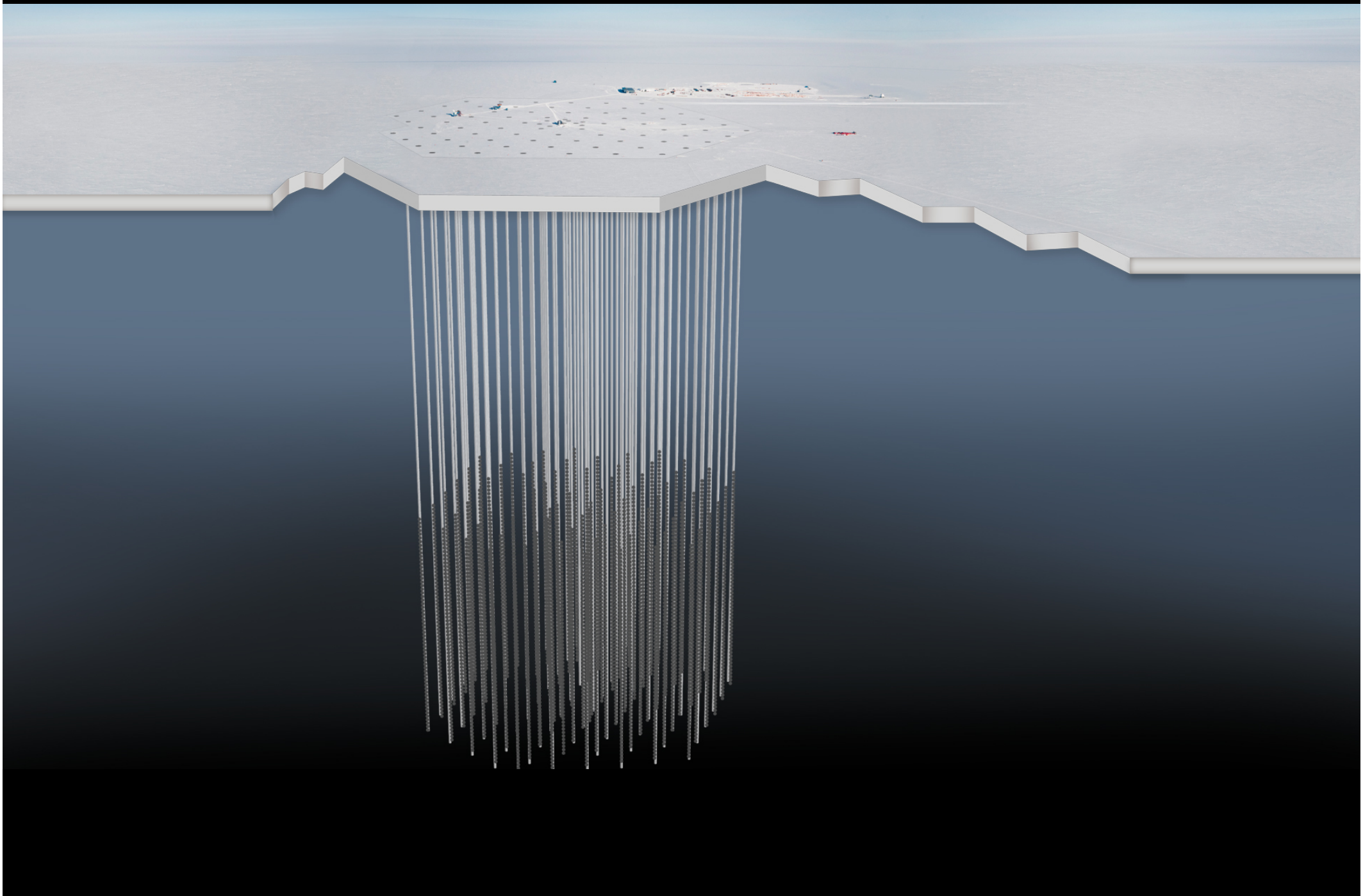
M. Markov 1960

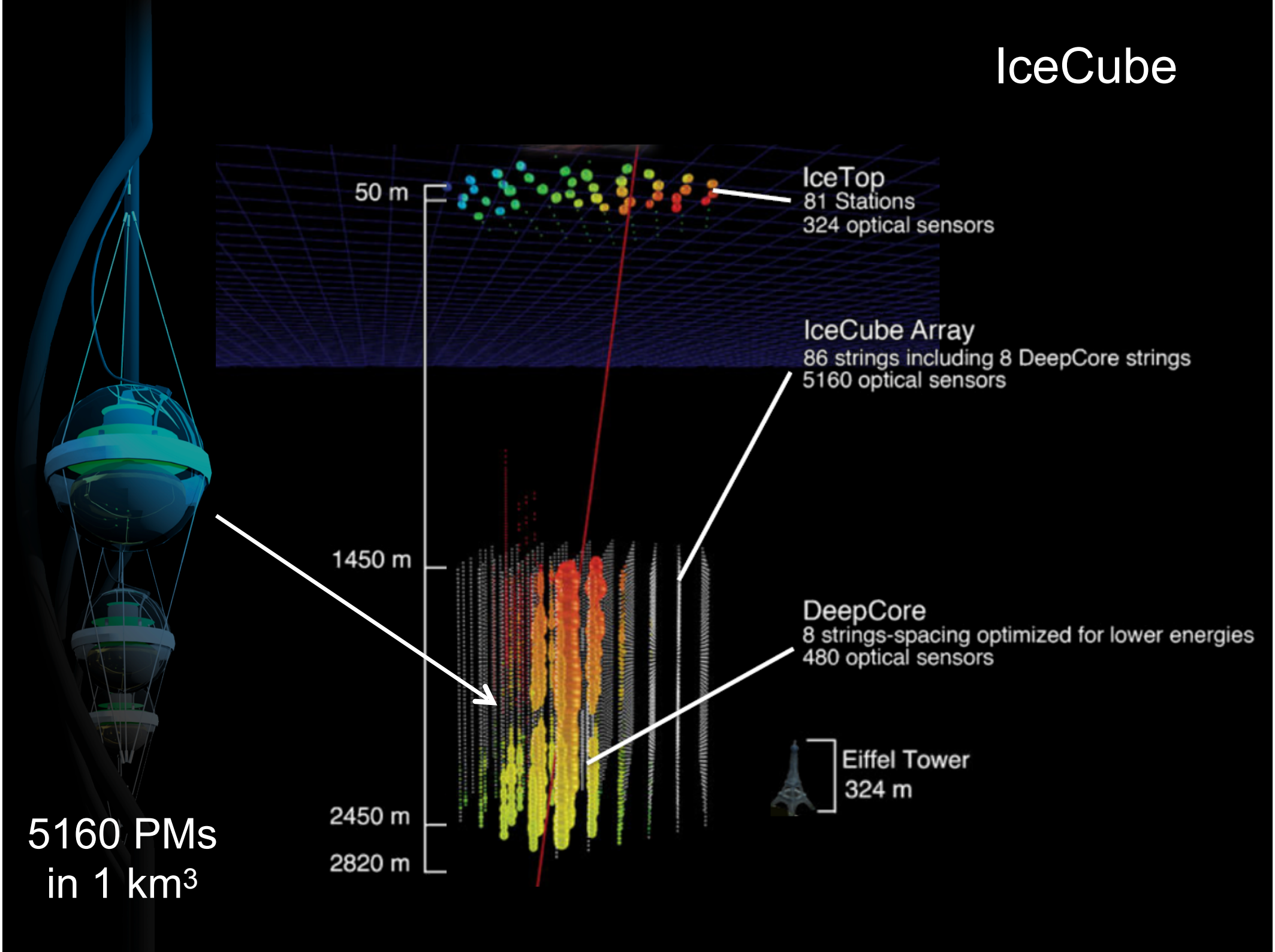


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.


• 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

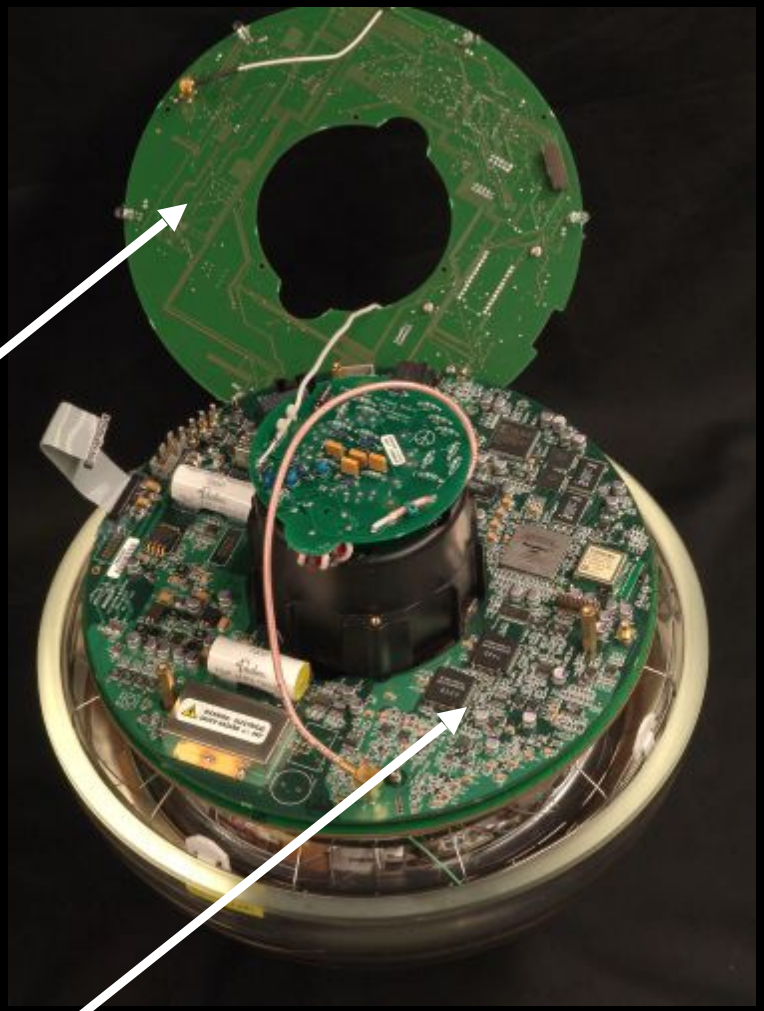

instrument 1 cubic kilometer of natural ice below 1.45 km


IceCube
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

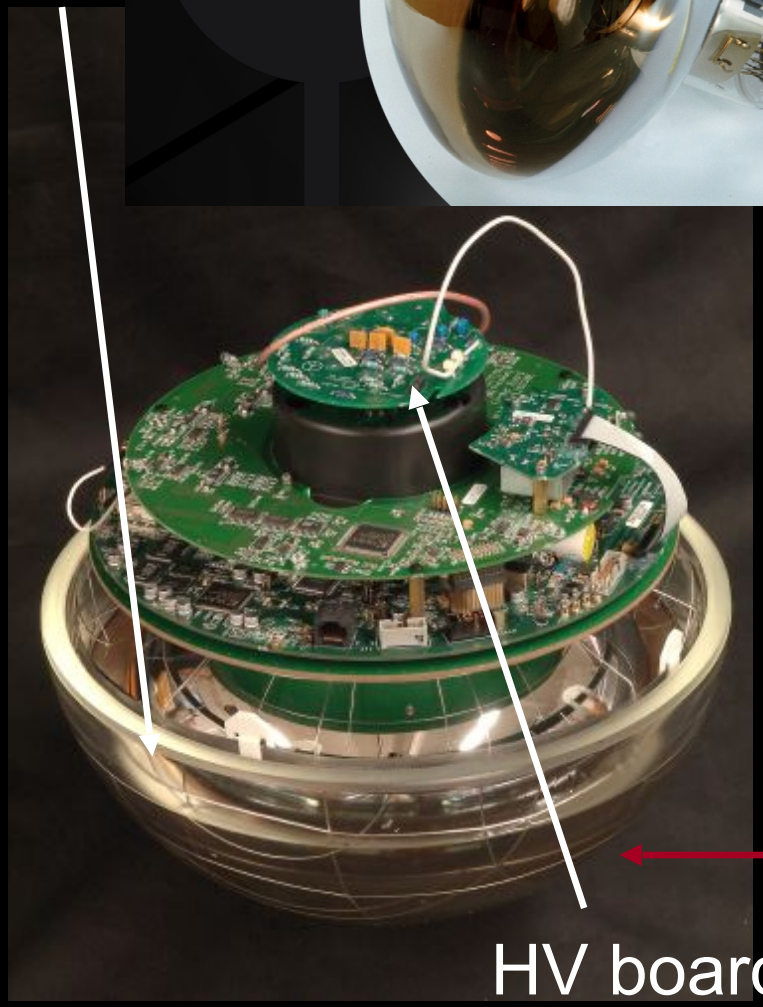
architecture of independent DOMs

10 inch pmt



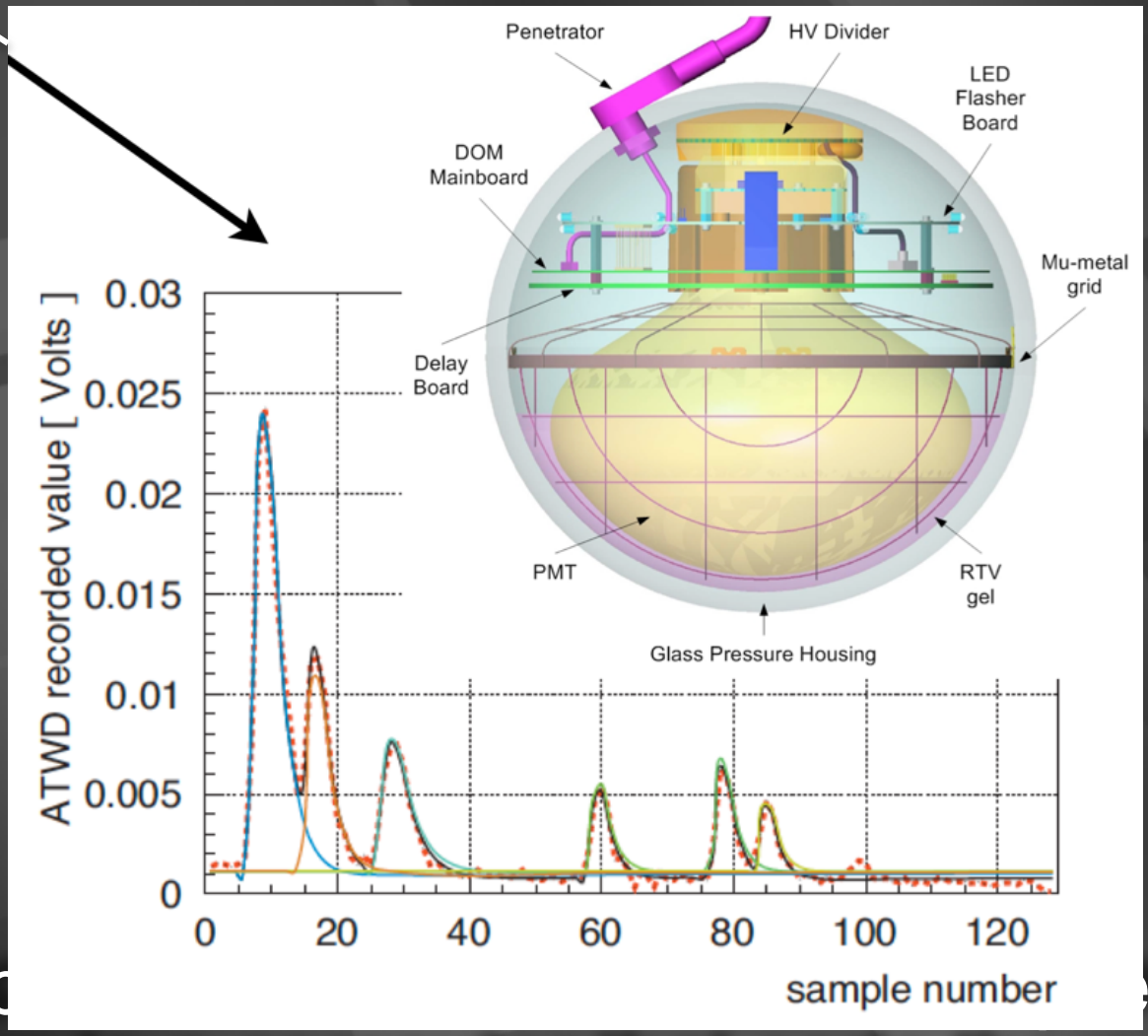
LED
flasher
board

main
board

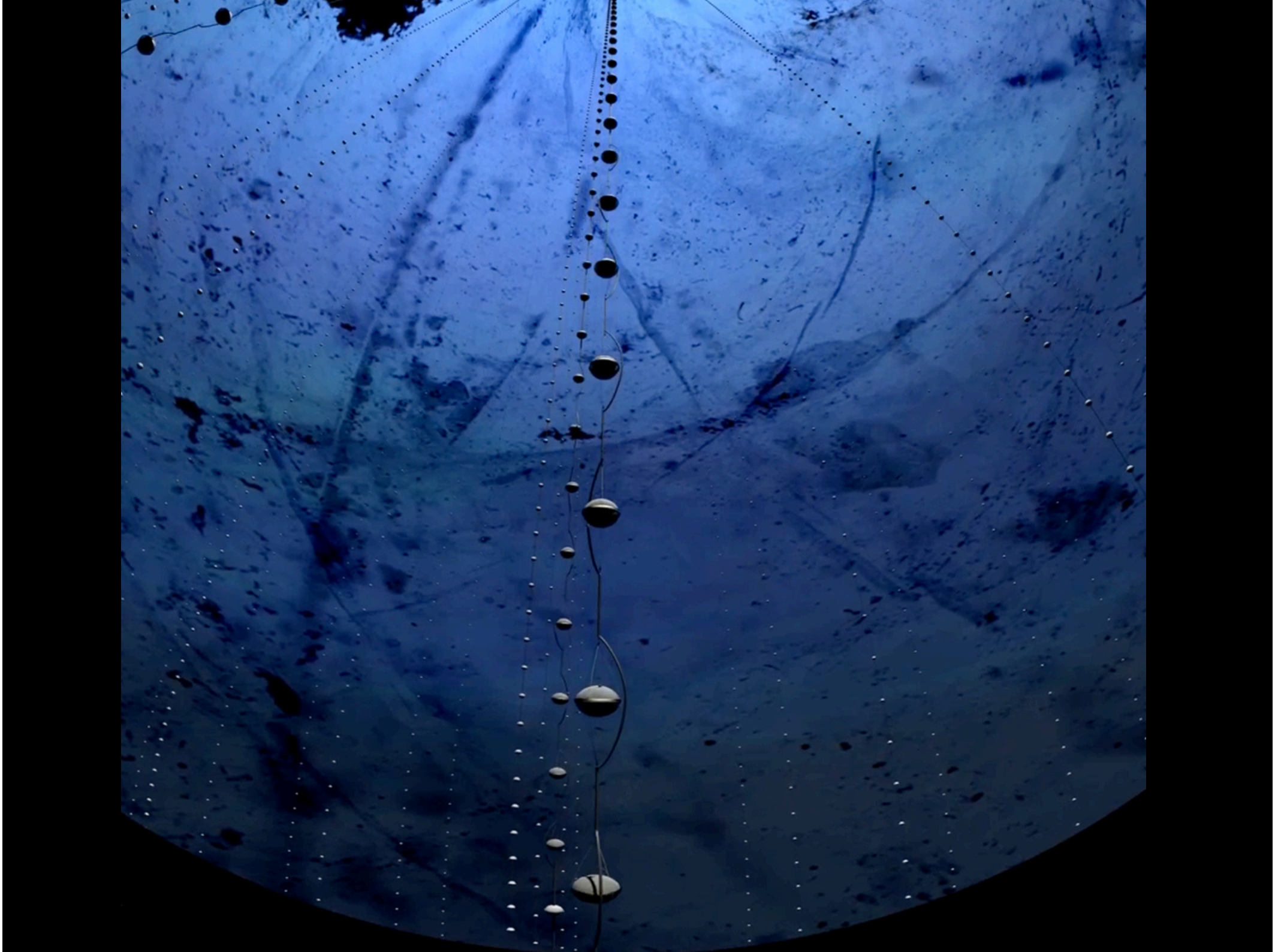


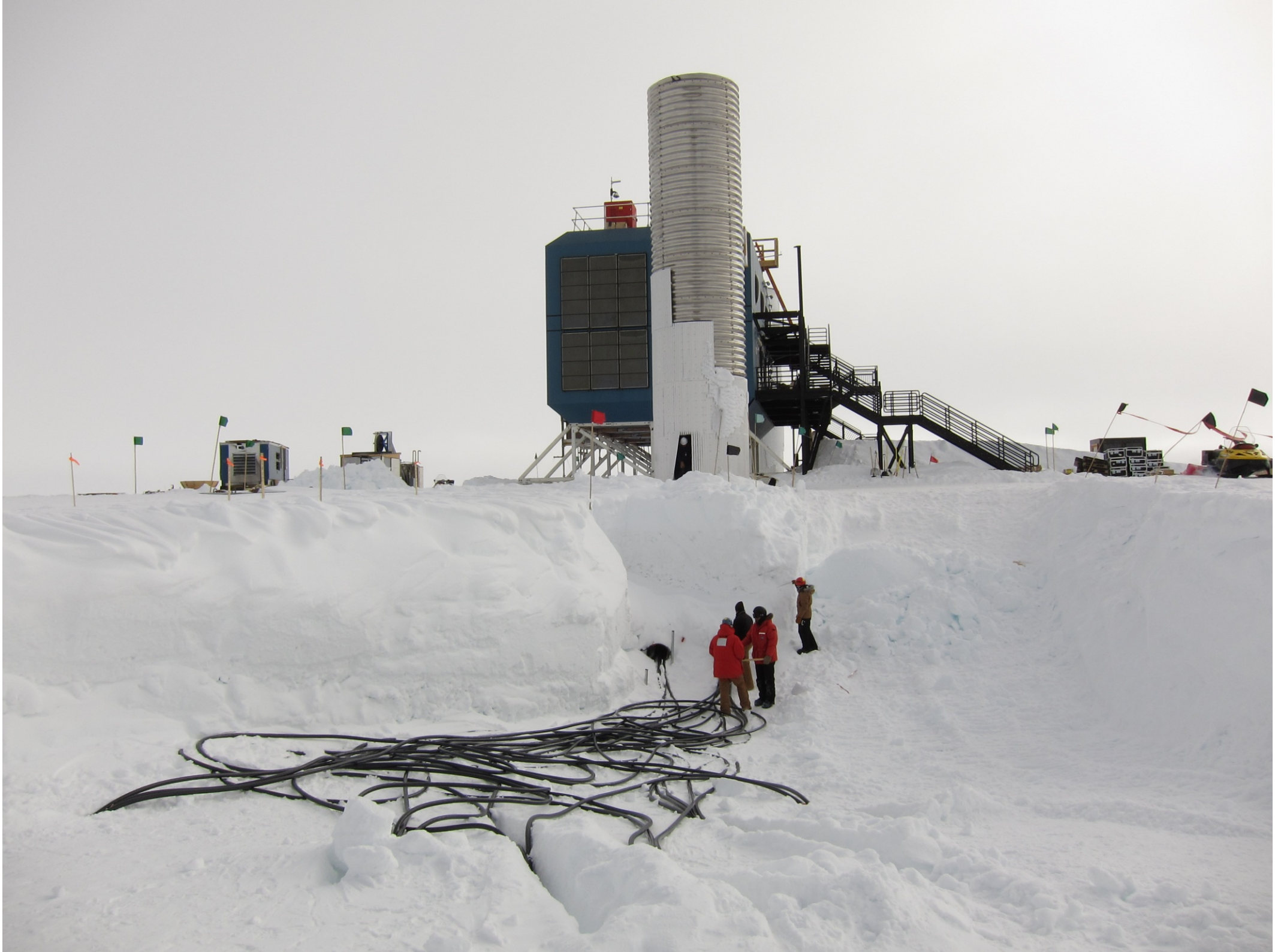
HV board

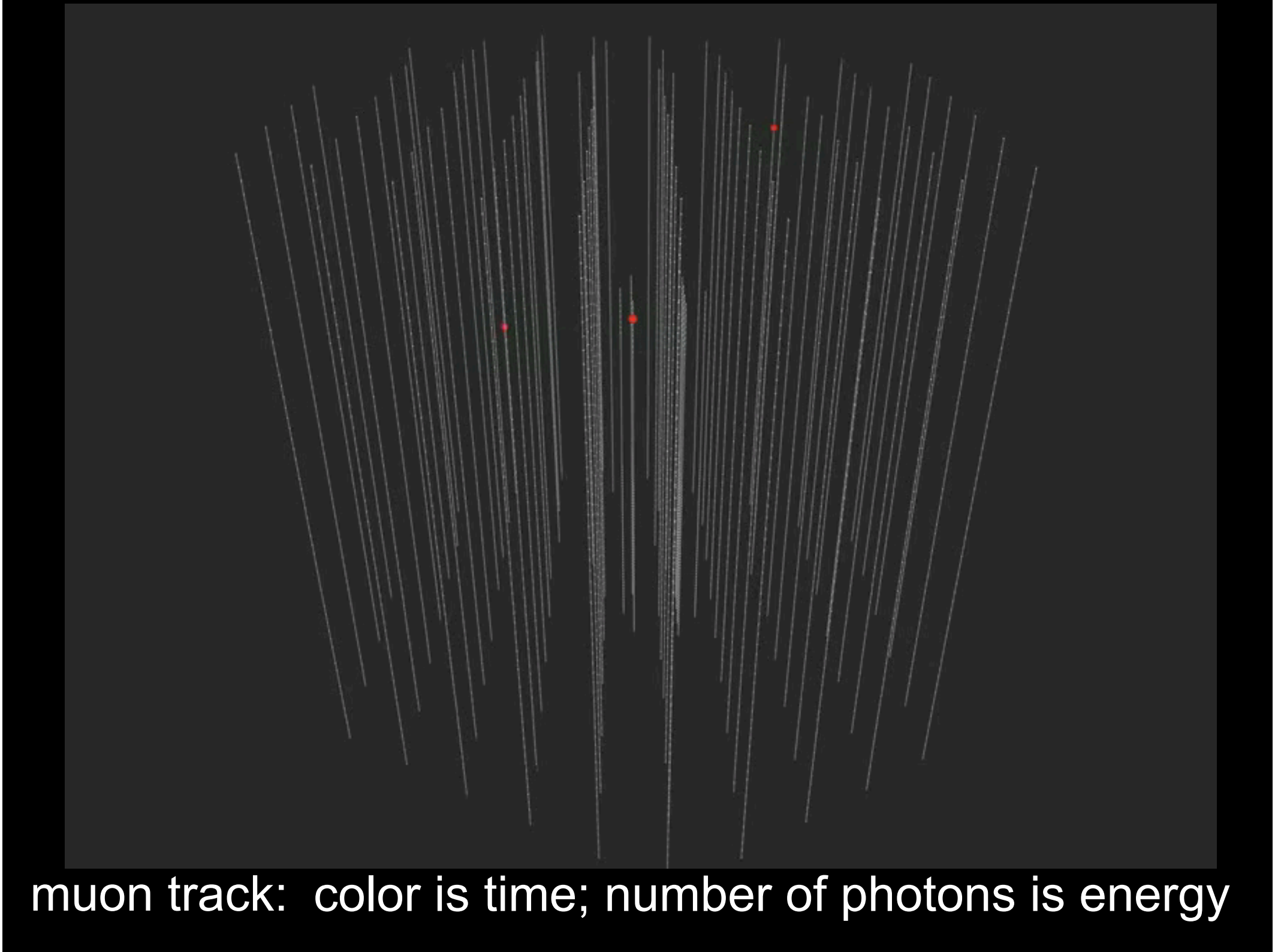
… each Digital Optical Module independently collects light signals like this, digitizes them,



…time stamp ecision, and sends them to a computer that sorts them events…

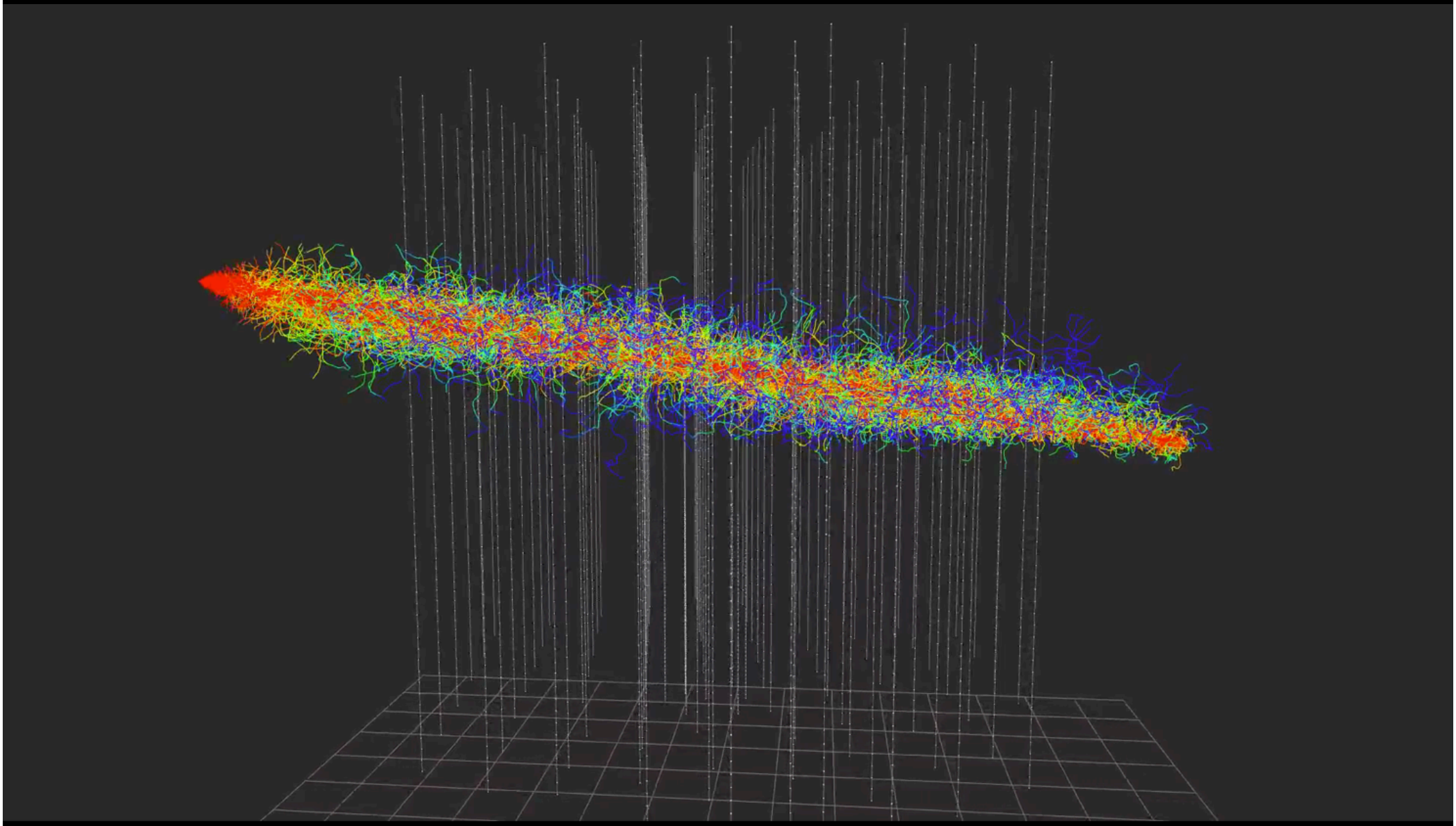


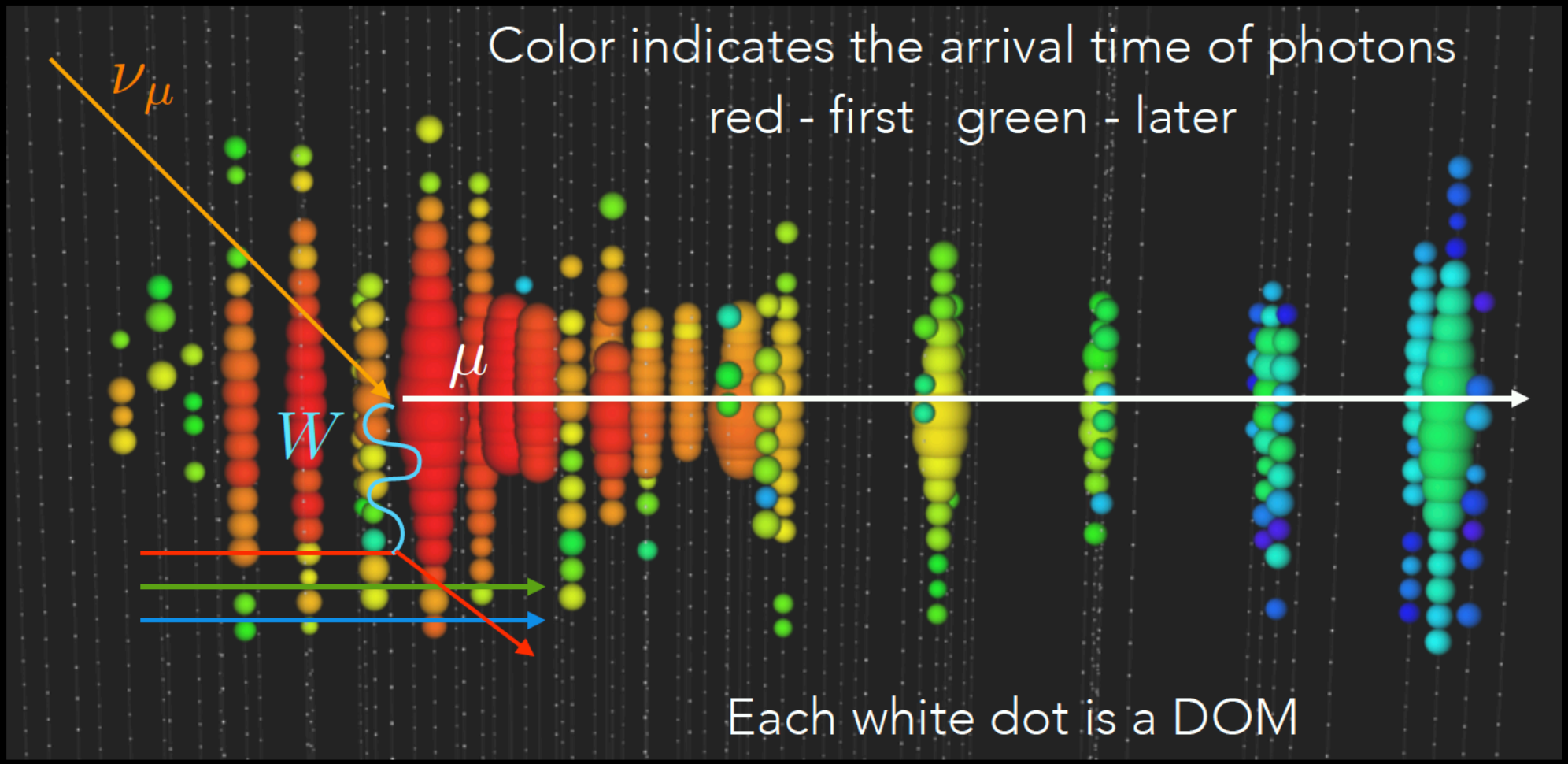




muon track: color is time; number of photons is energy

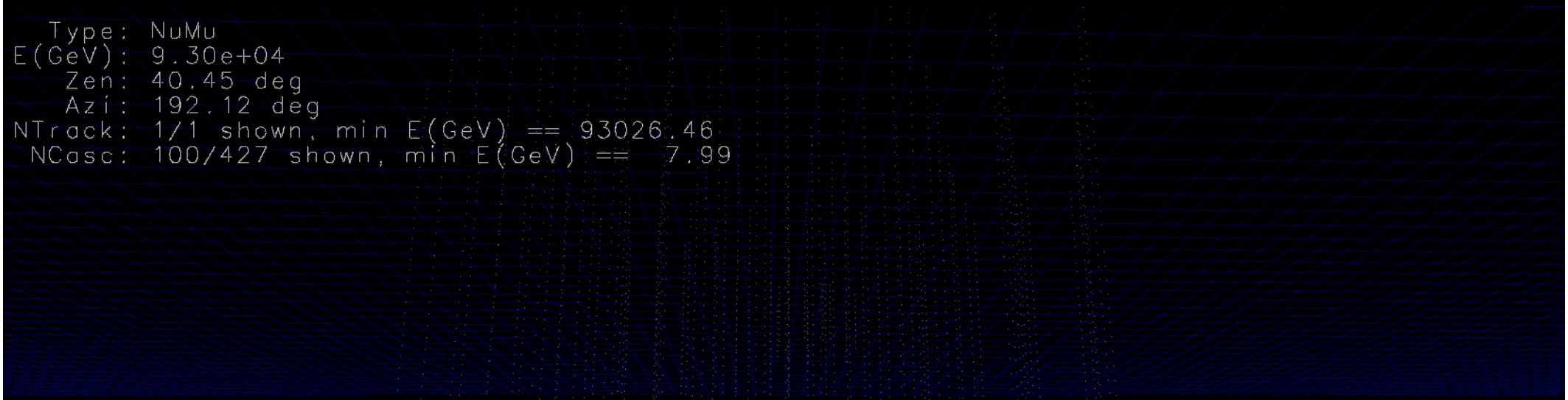
neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



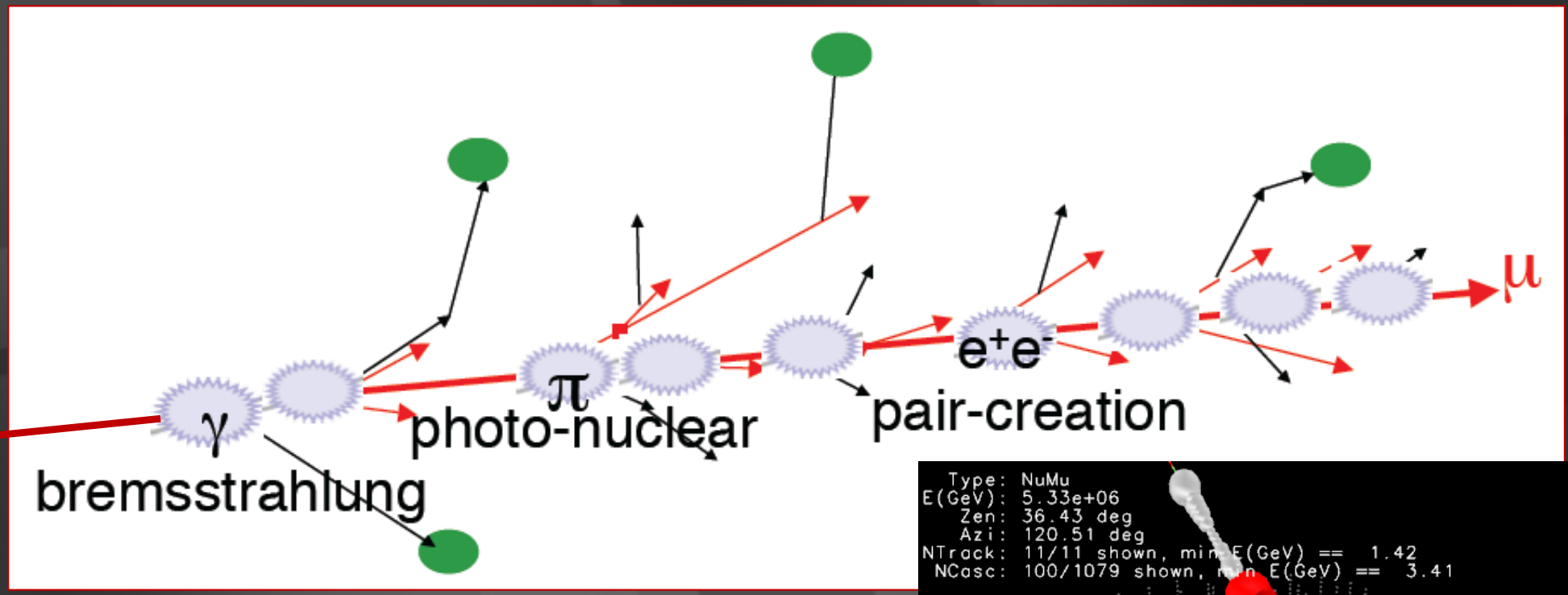


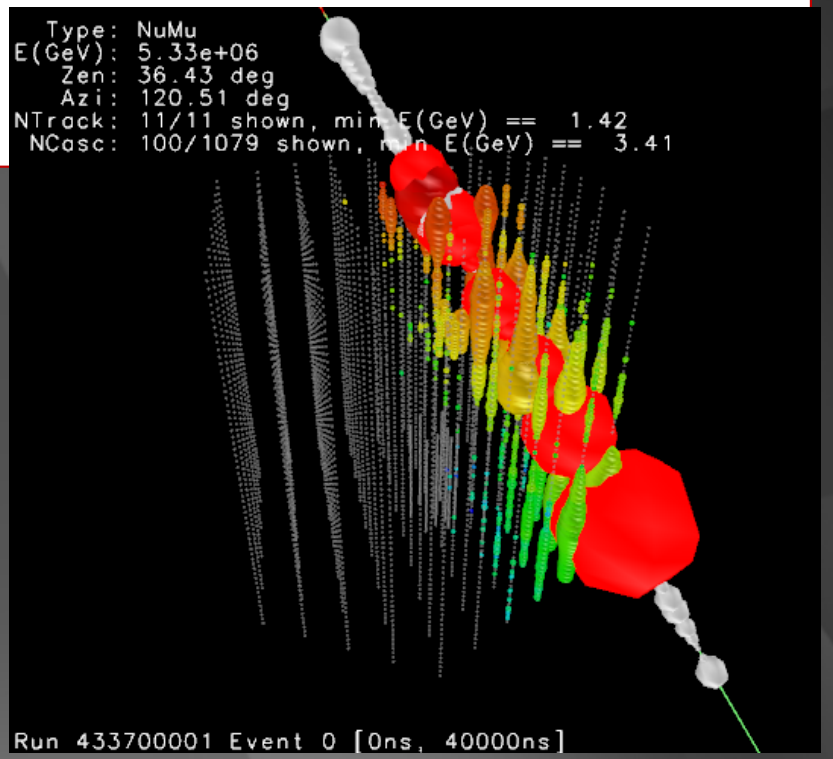
Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

93 TeV muon: light ~ energy

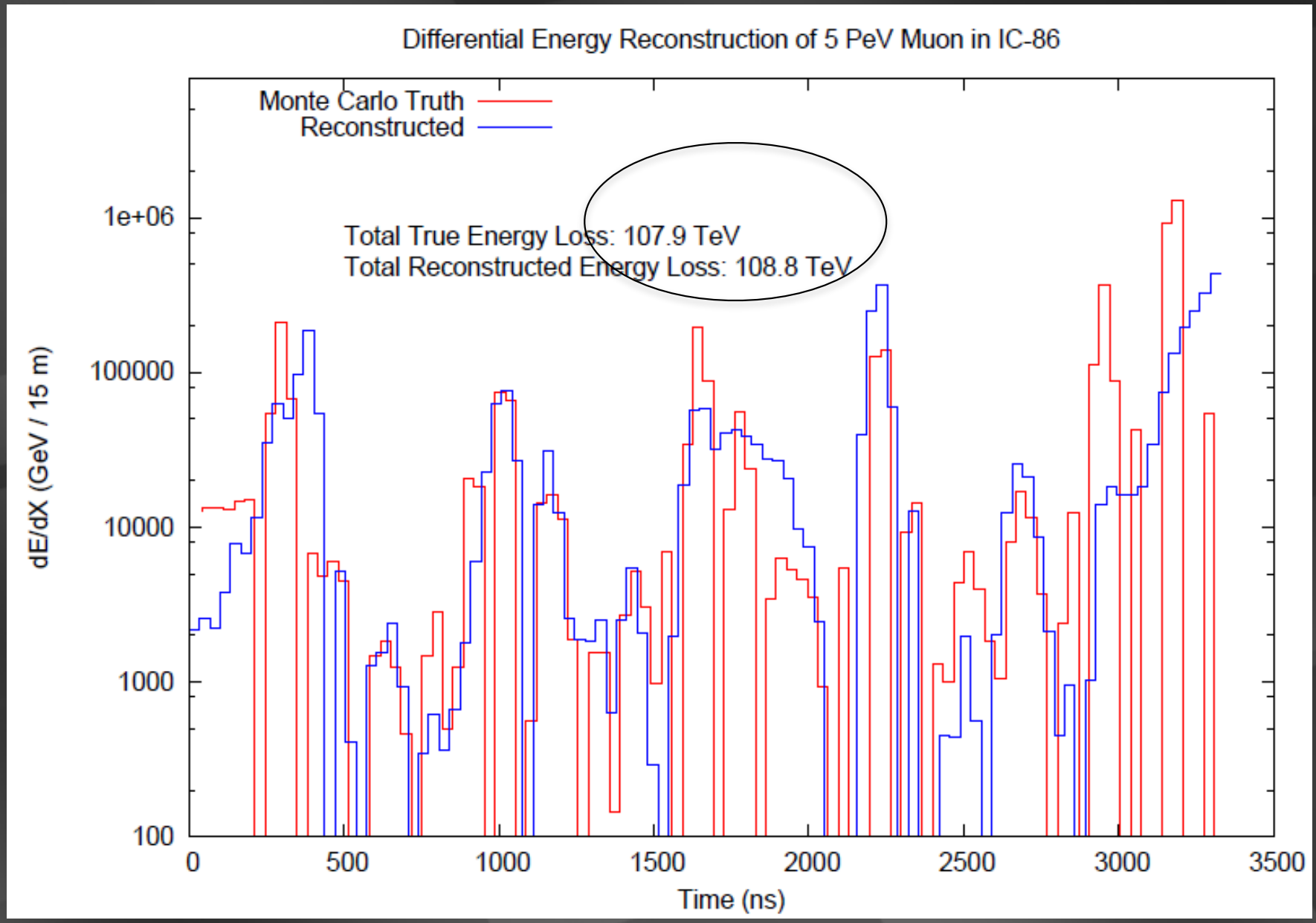


energy measurement (> 1 TeV)





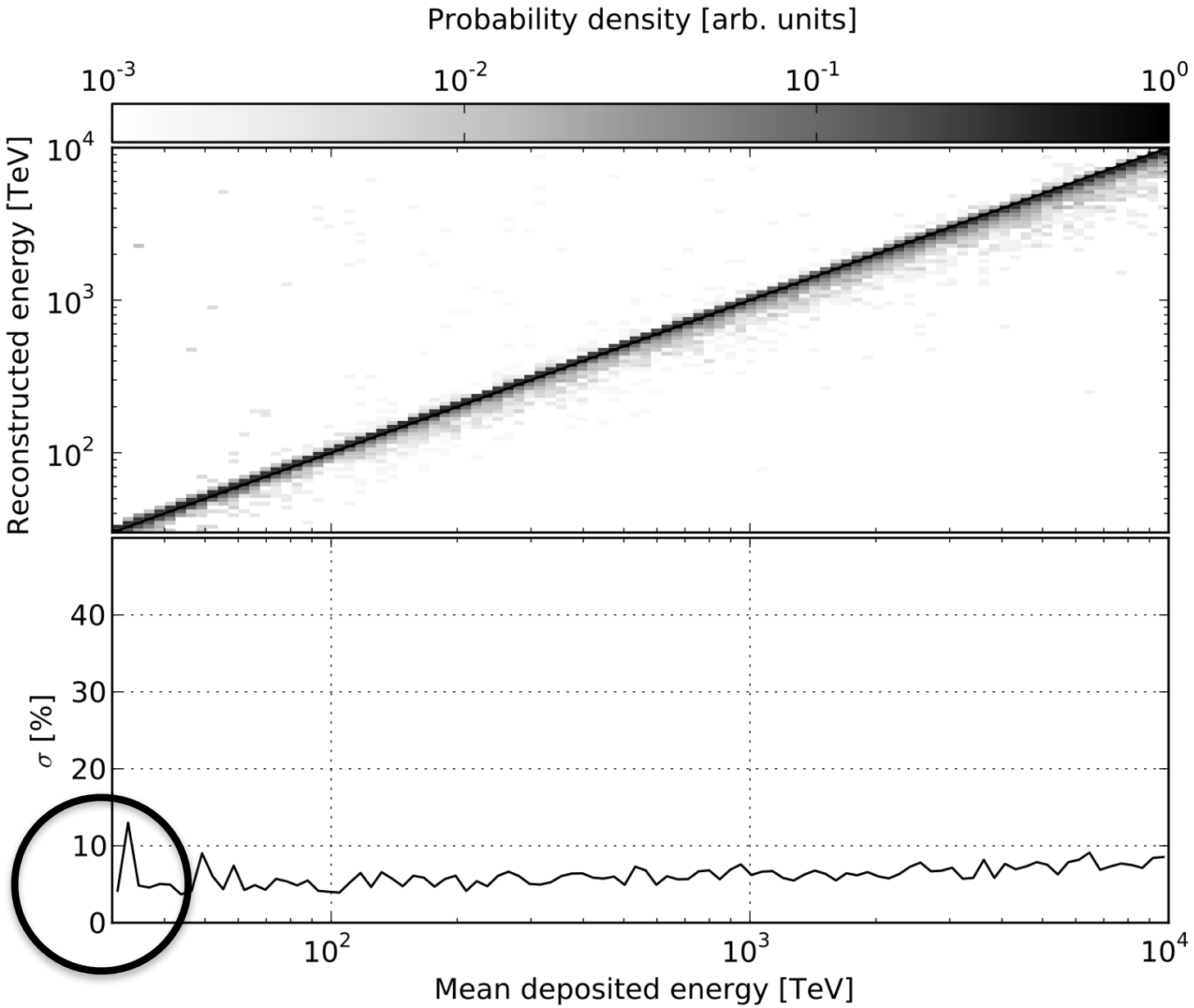
convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

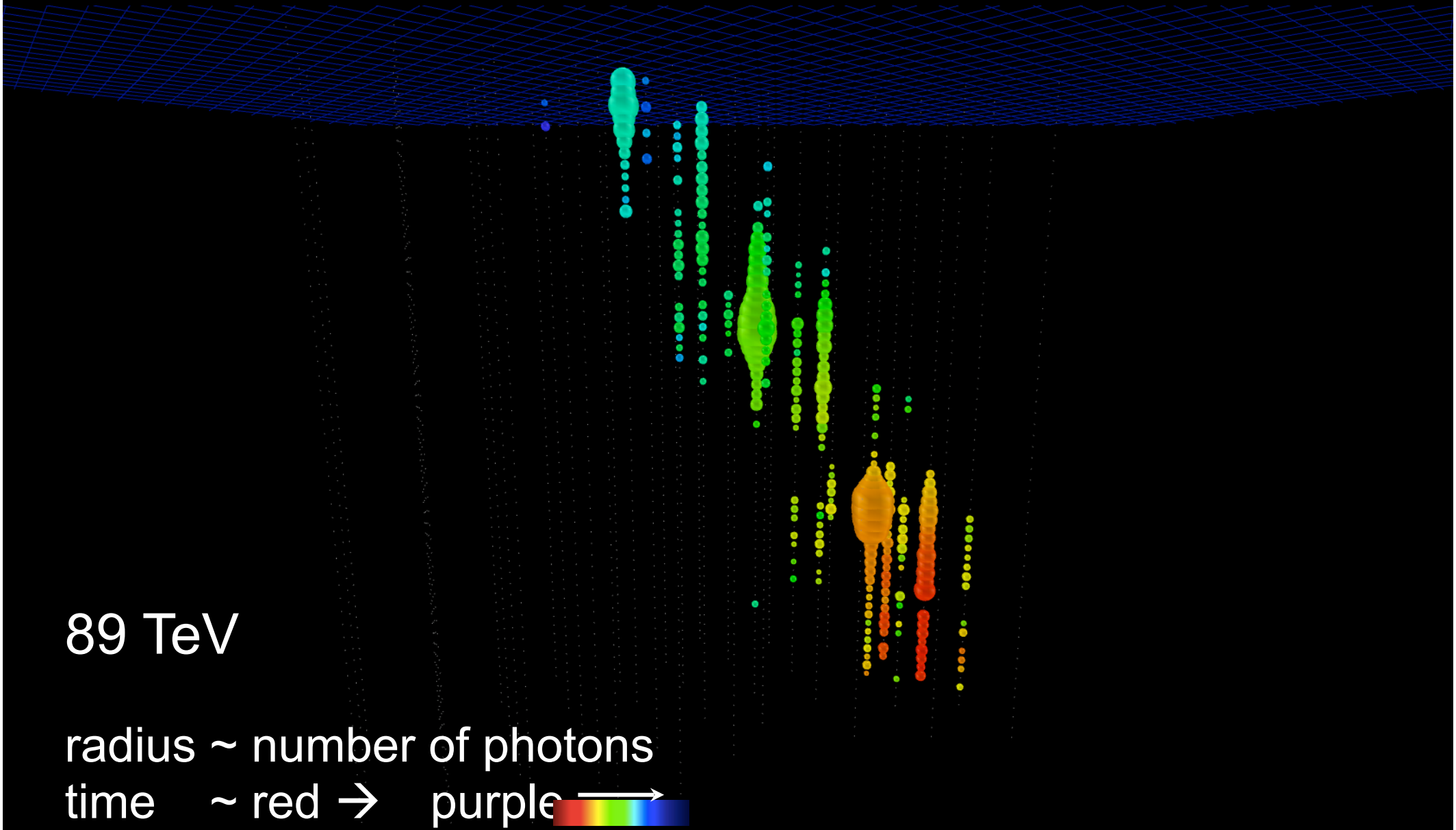


1.1 km

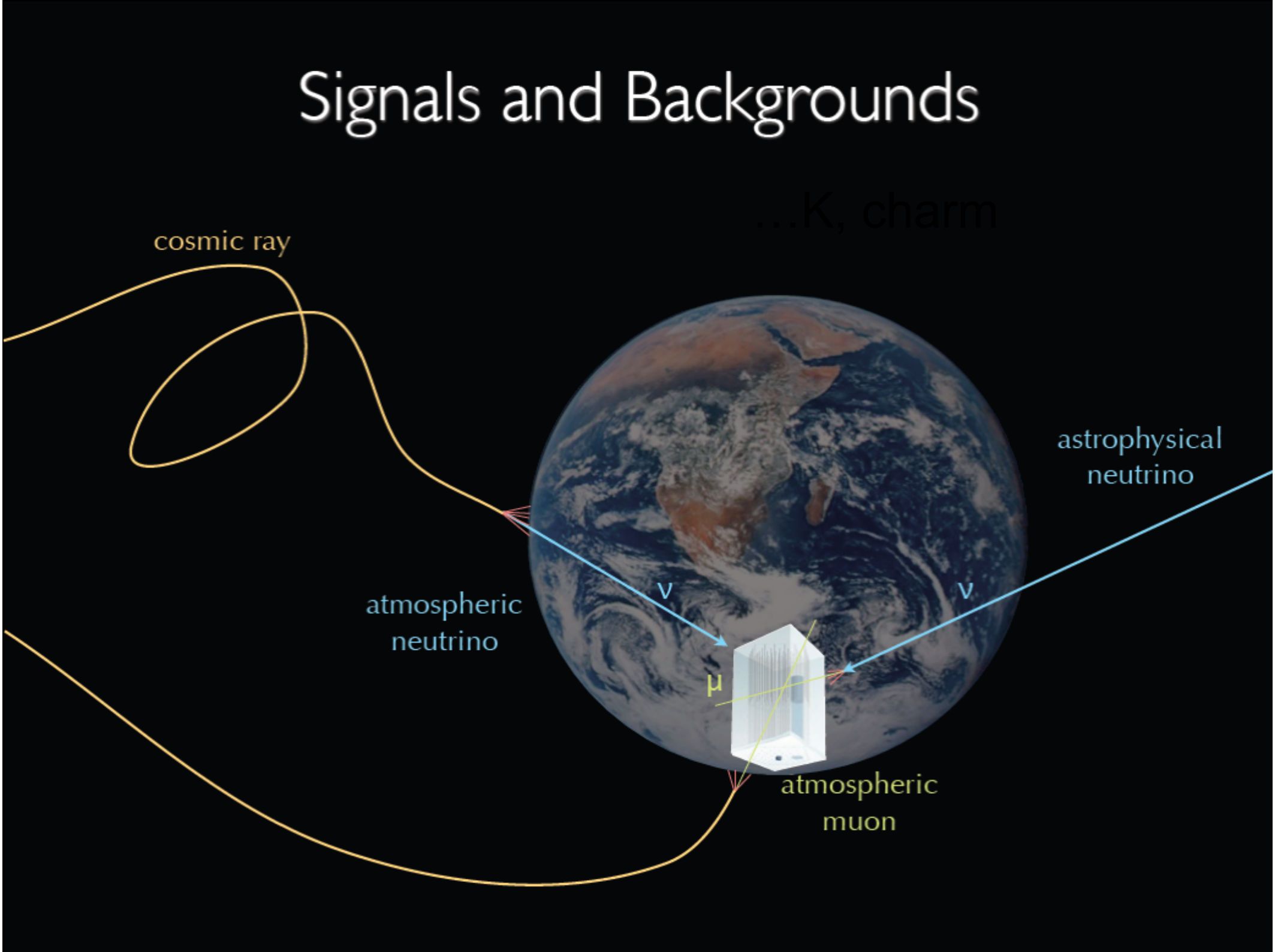
limited angular and energy resolution: computing → ice properties

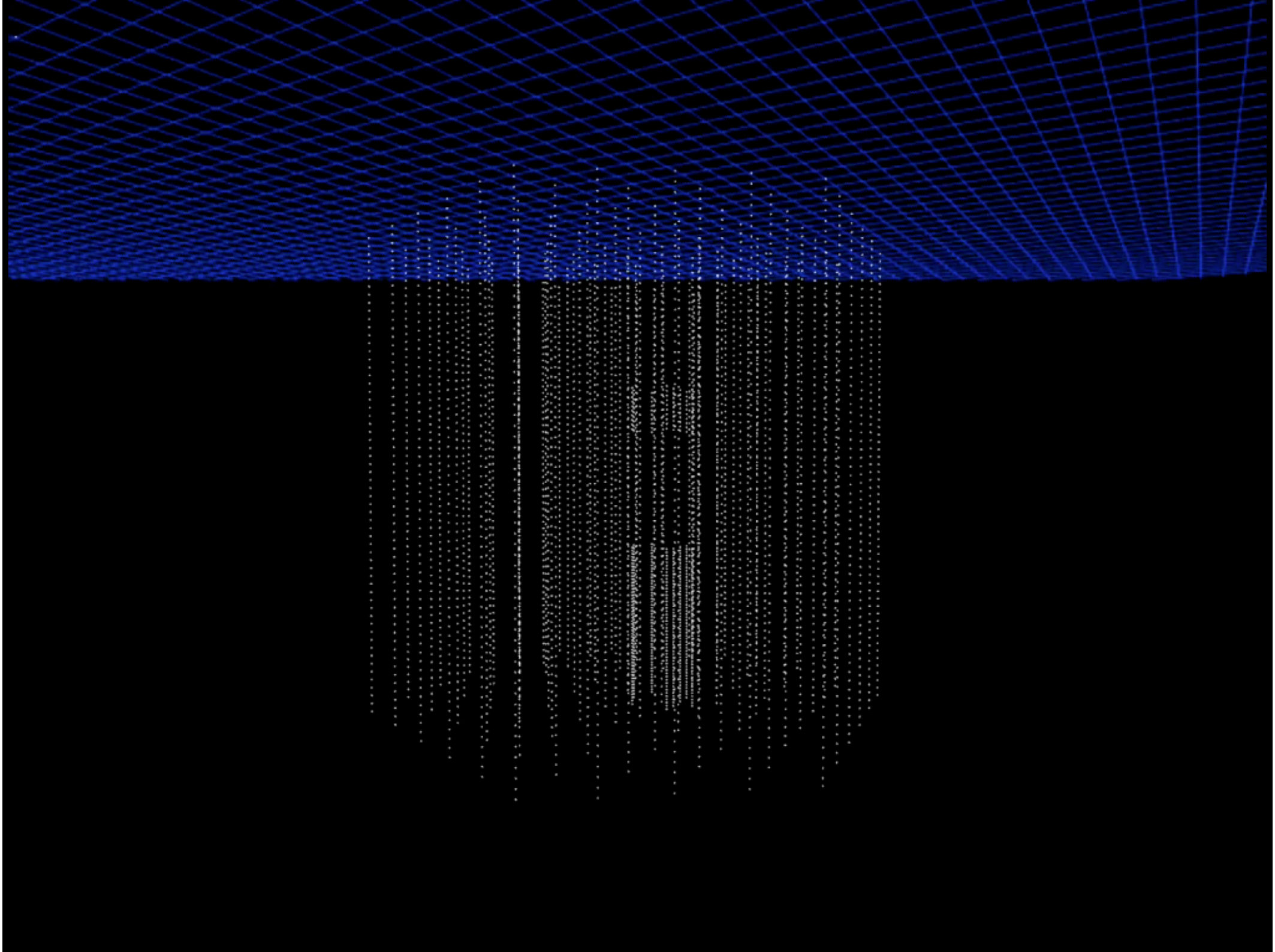
energy reconstruction of electromagnetic showers




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

Signals and Backgrounds





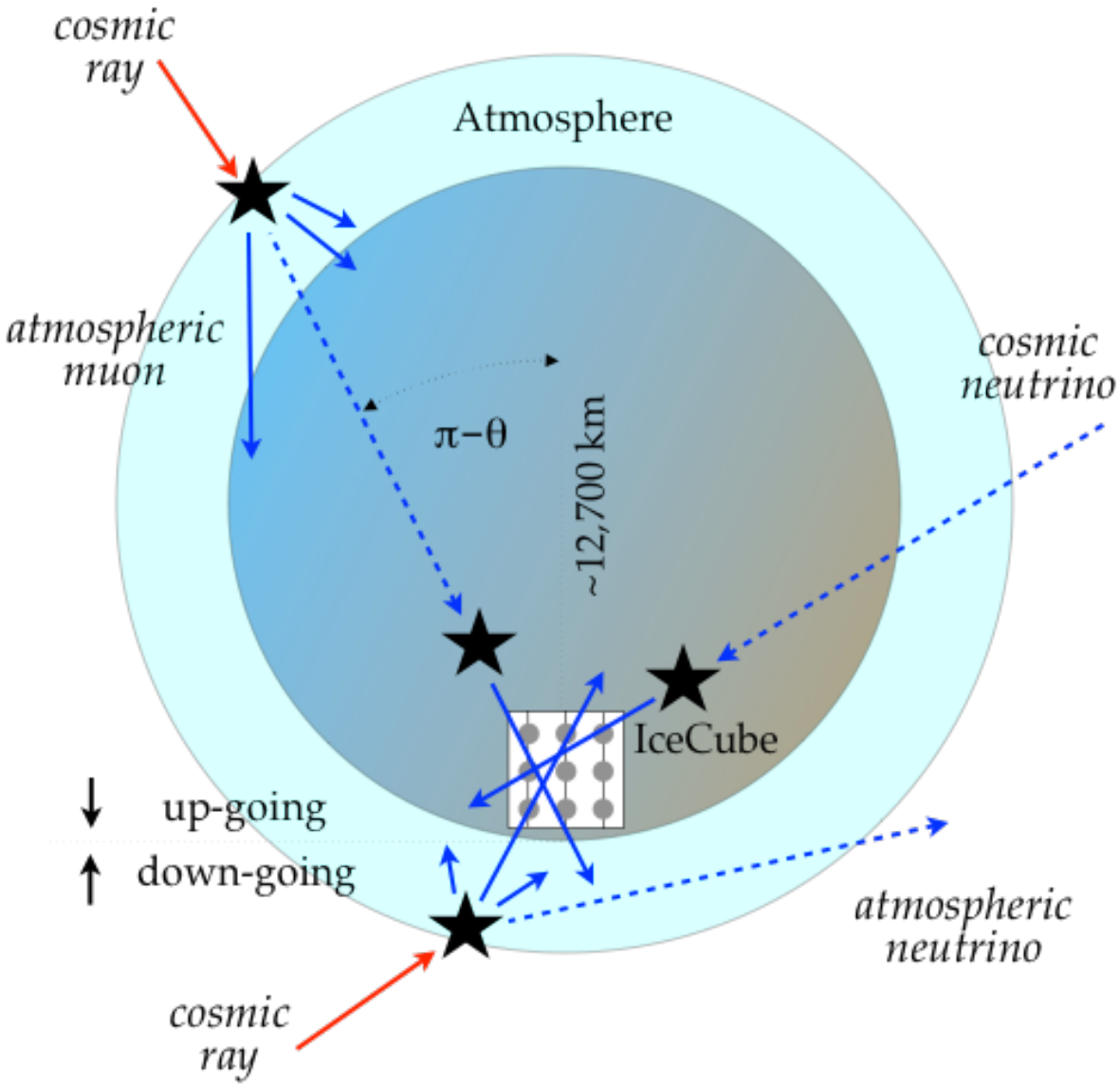
… you looked at 10msec of data !

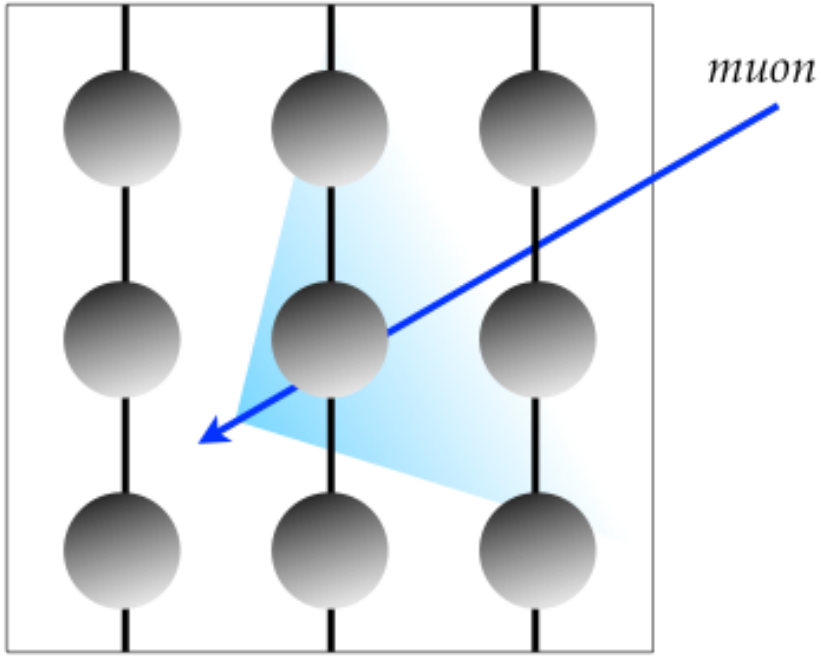
muons detected per year:

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

* 3000 per second ** 1 every 6 minutes

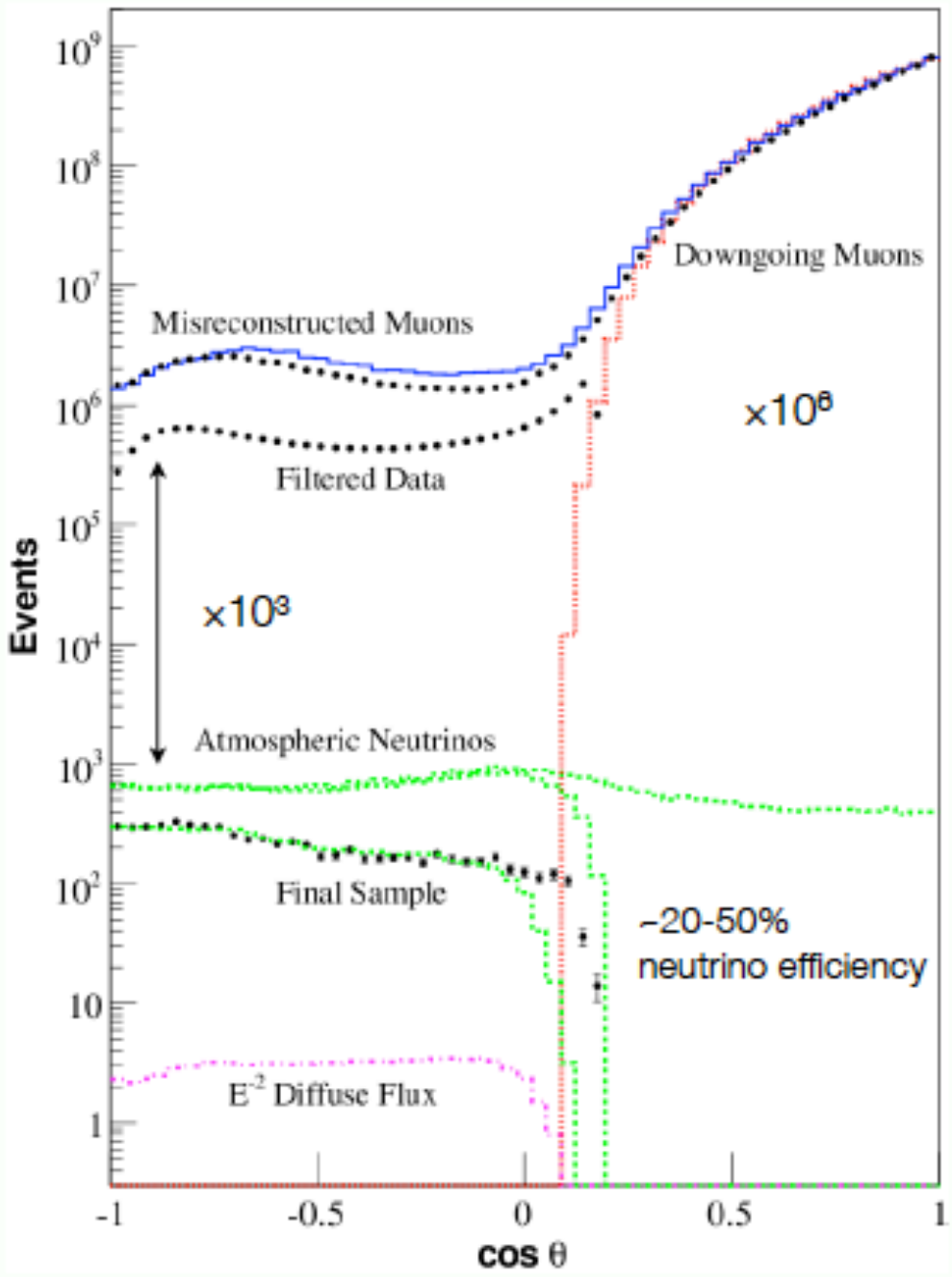
- rejecting atmospheric muons

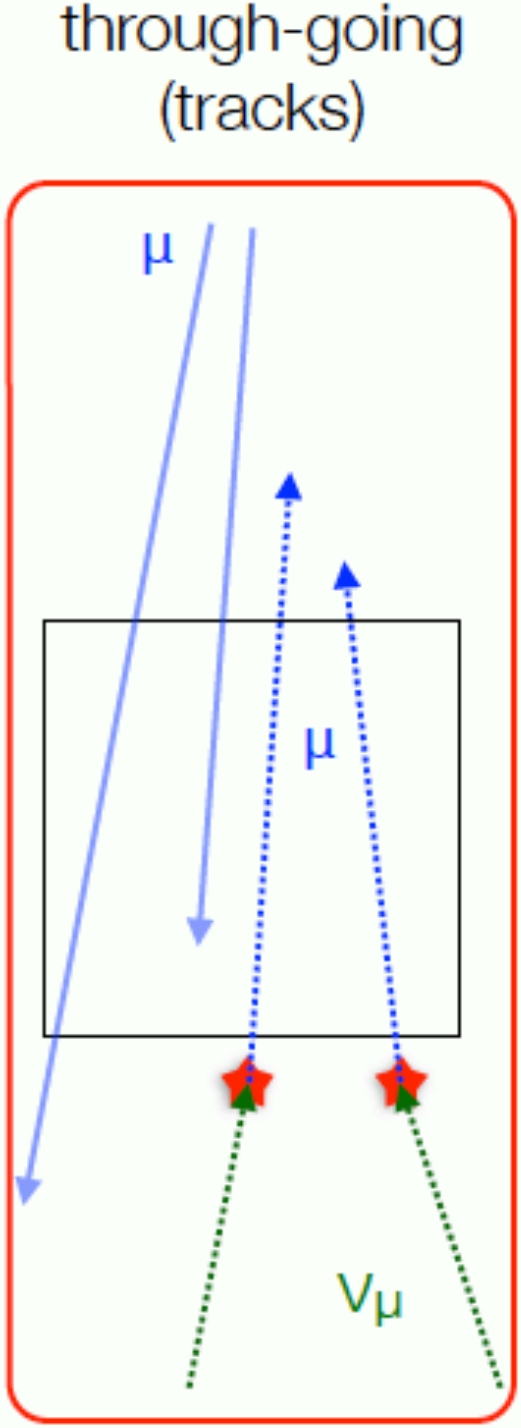




Cherenkov light detection in optical modules

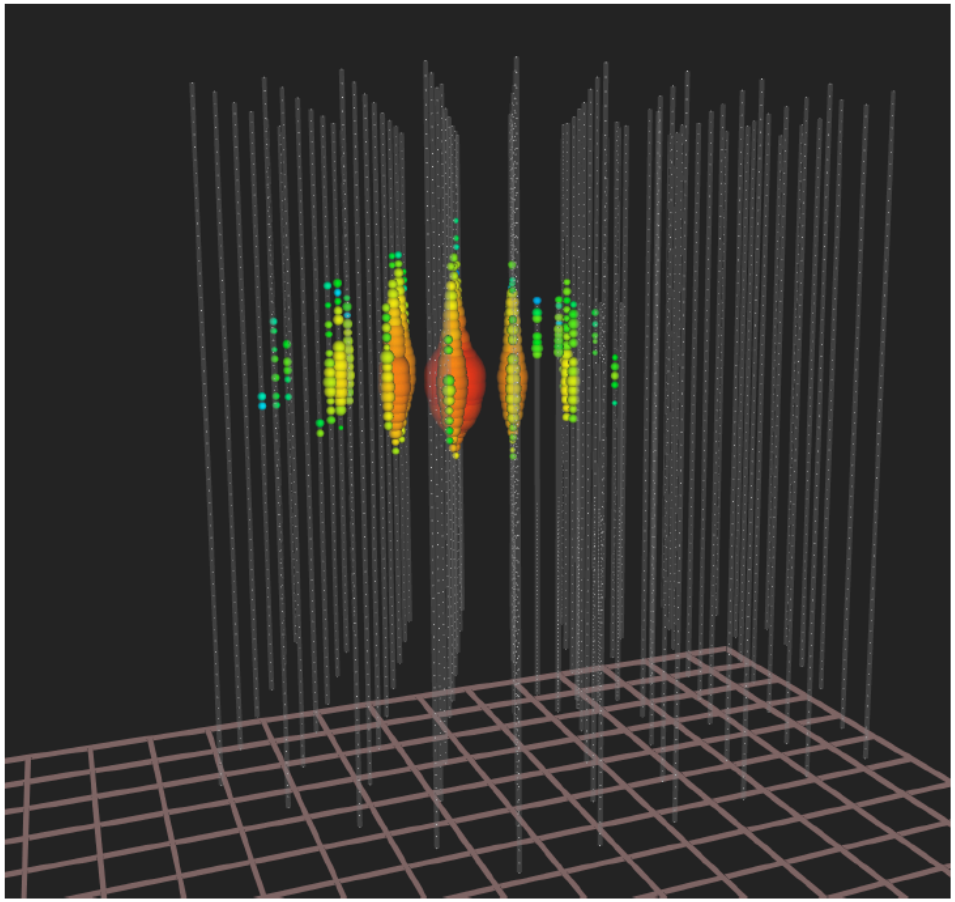
- rejecting atmospheric neutrinos

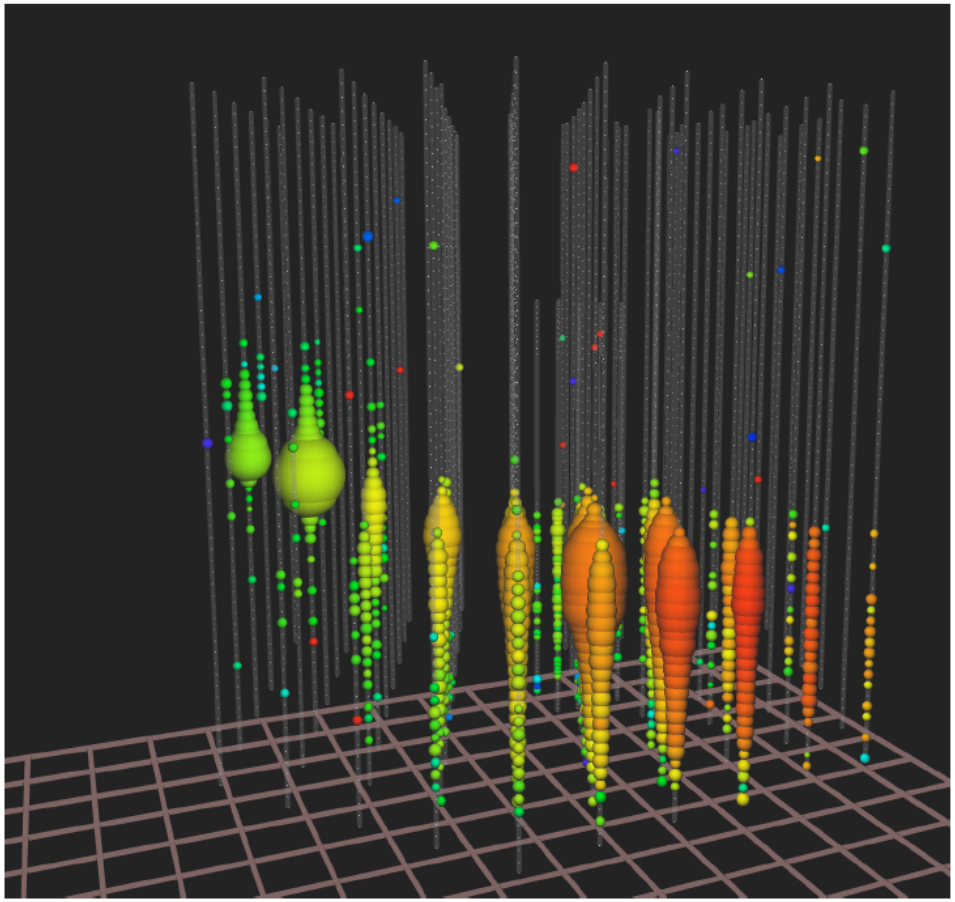

Events
cos θ
Misreconstructed Muons
Downgoing Muons
×10⁶
Filtered Data
×10³
Atmospheric Neutrinos
Final Sample
~20-50%
neutrino efficiency
E⁻² Diffuse Flux


through-going
(tracks)
μ
μ
νμ

isolated neutrinos interacting *inside* the detector (HESE)

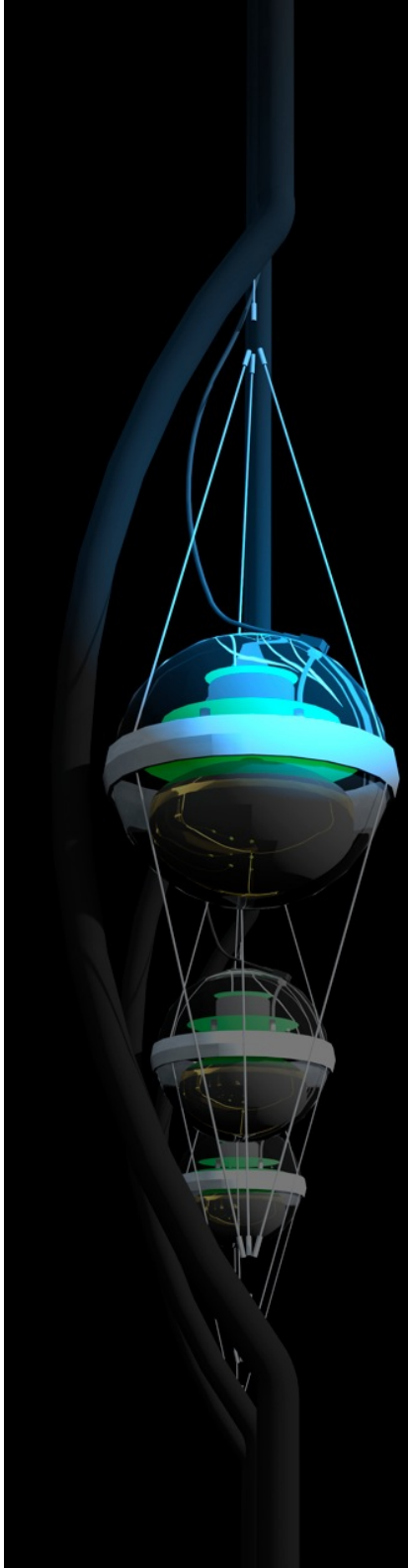
up-going muon tracks (UPMU)





total energy measurement
all flavors, all sky

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



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francis halzen

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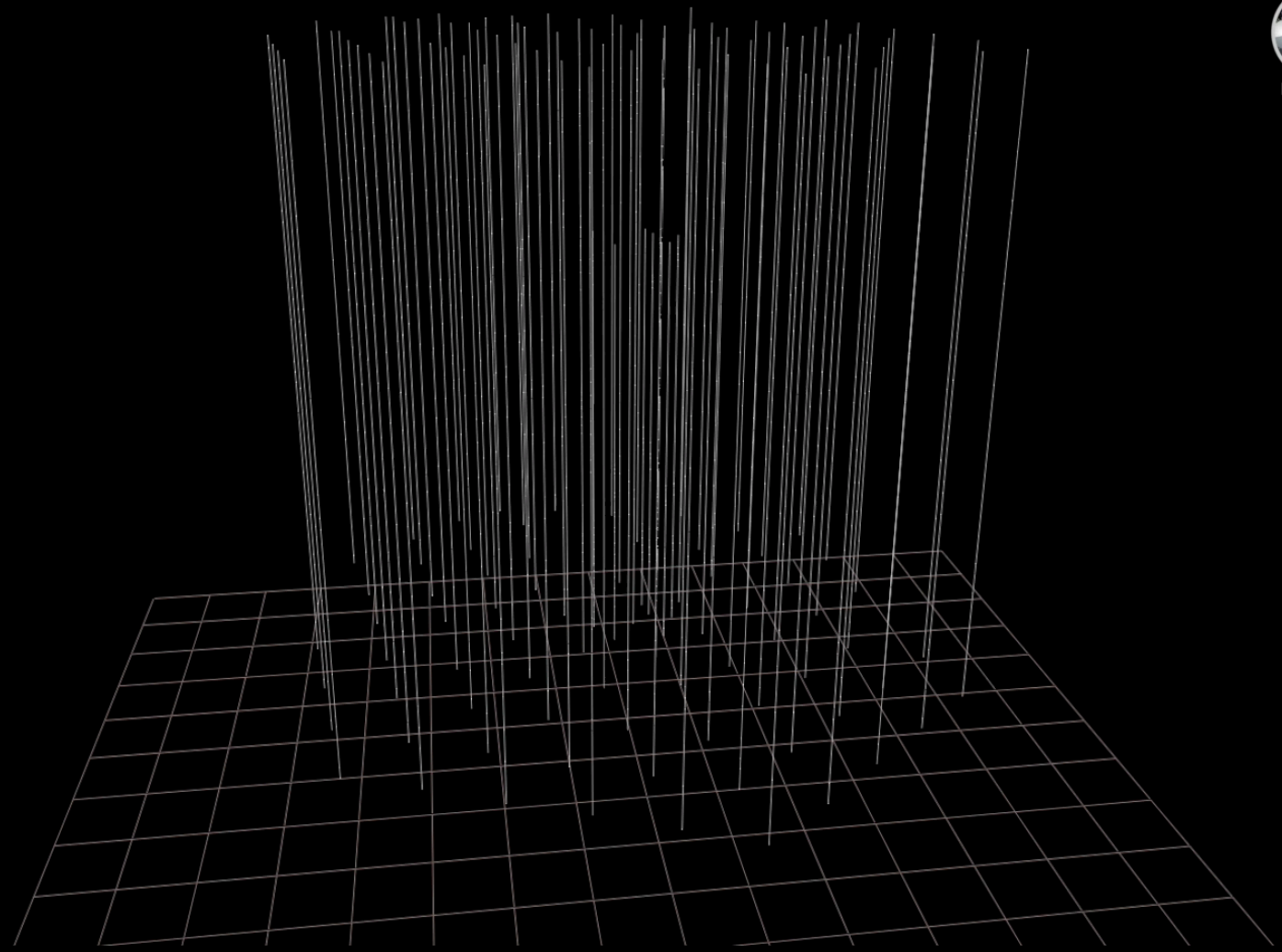
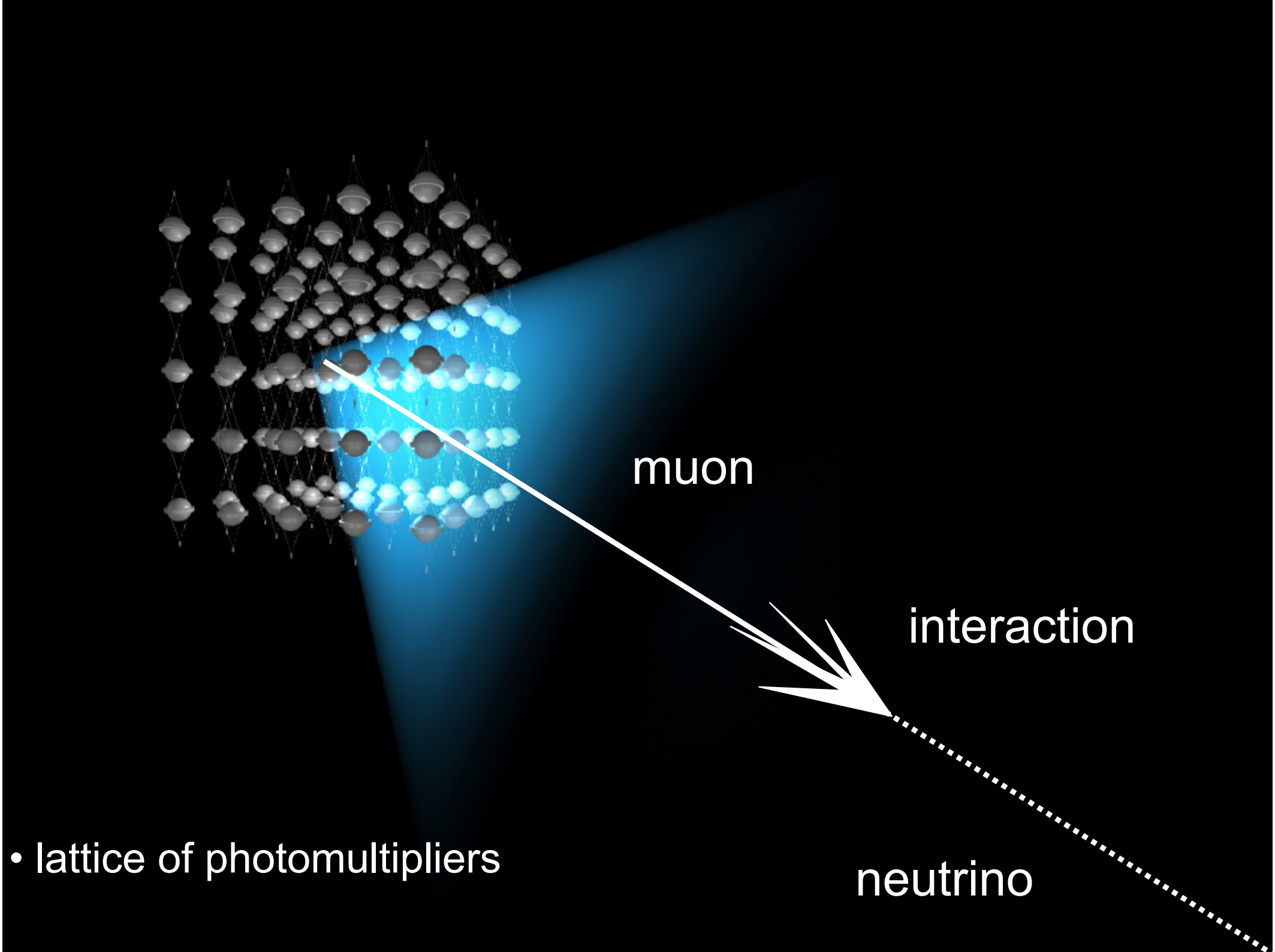
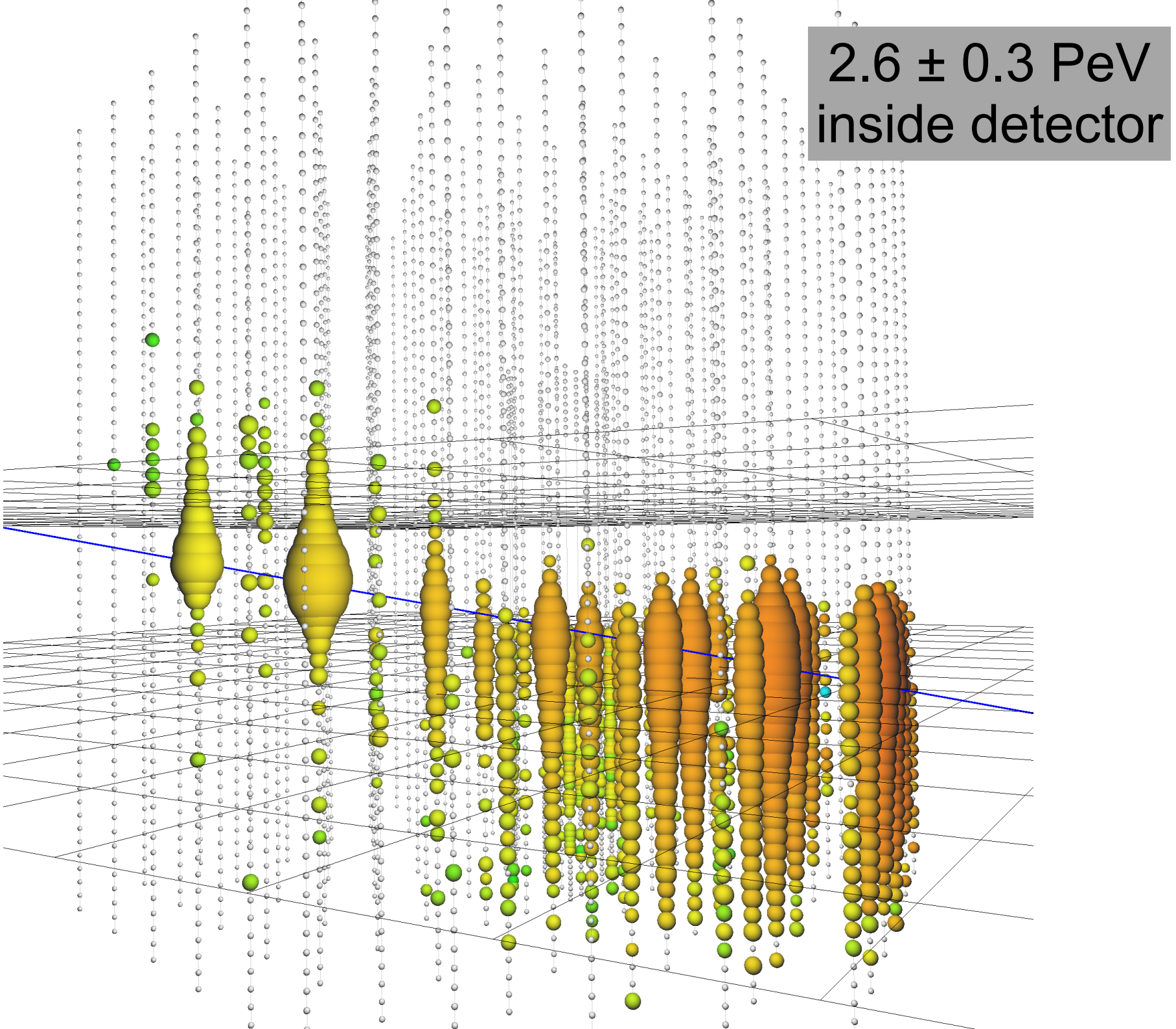
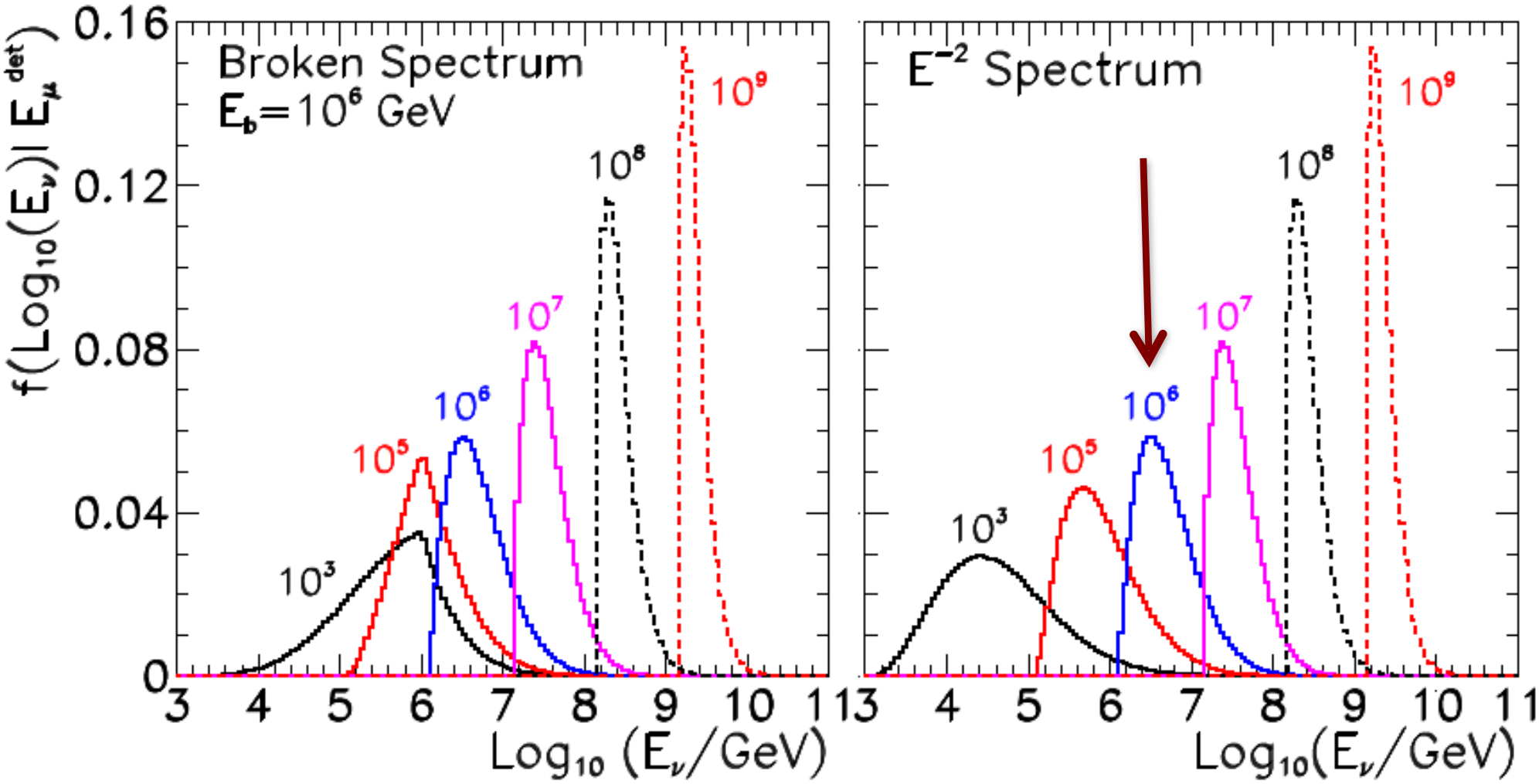
IceCube.wisc.edu


IceCube


muon
interaction
neutrino
• lattice of photomultipliers

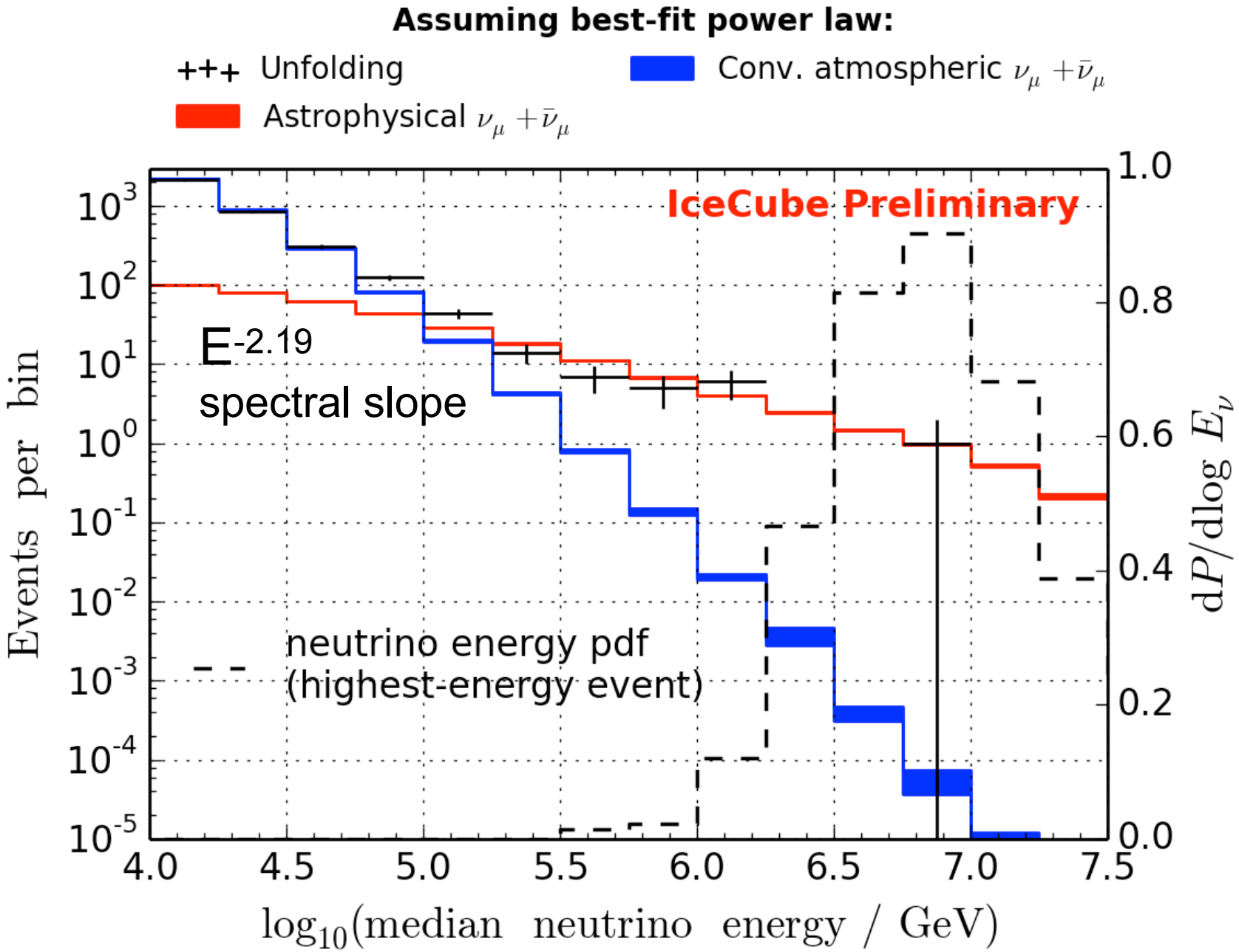

2.6 ± 0.3 PeV
inside detector

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

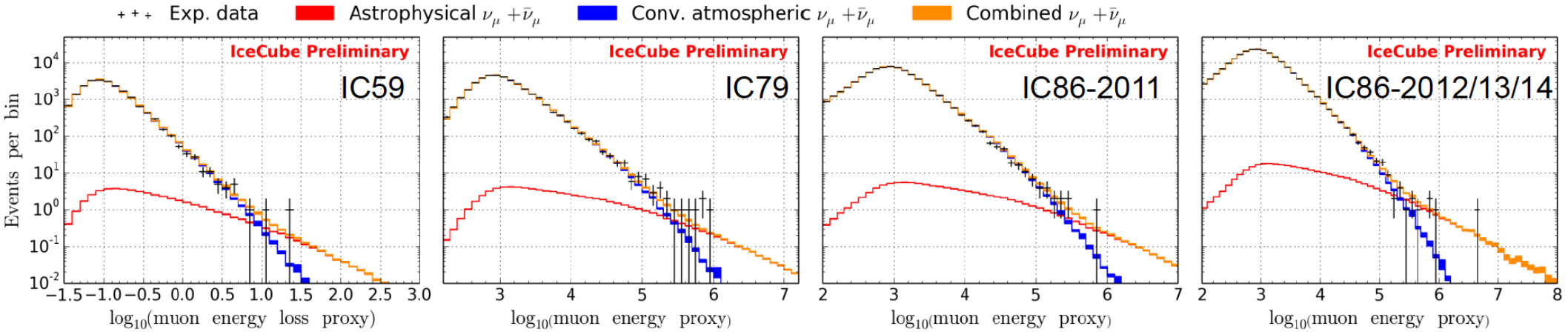


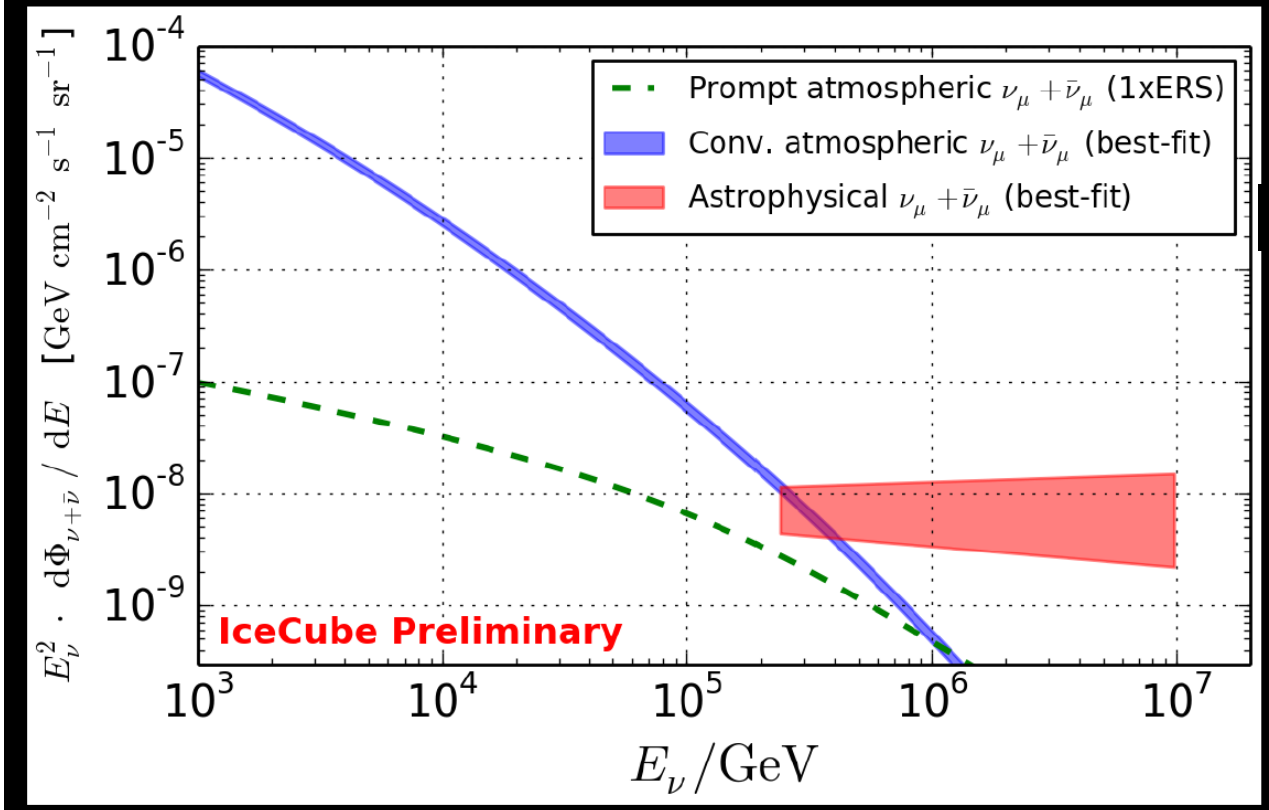
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric

atmospheric background: less than one event/deg^2/year



after 7 years → 6.4 sigma 120 cosmic neutrinos/year/flavor





- Best-fit astrophysical normalization:

$0.97^{+.27}_{-.25} \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

- Best-fit spectral index:

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

- Energy ranges:

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

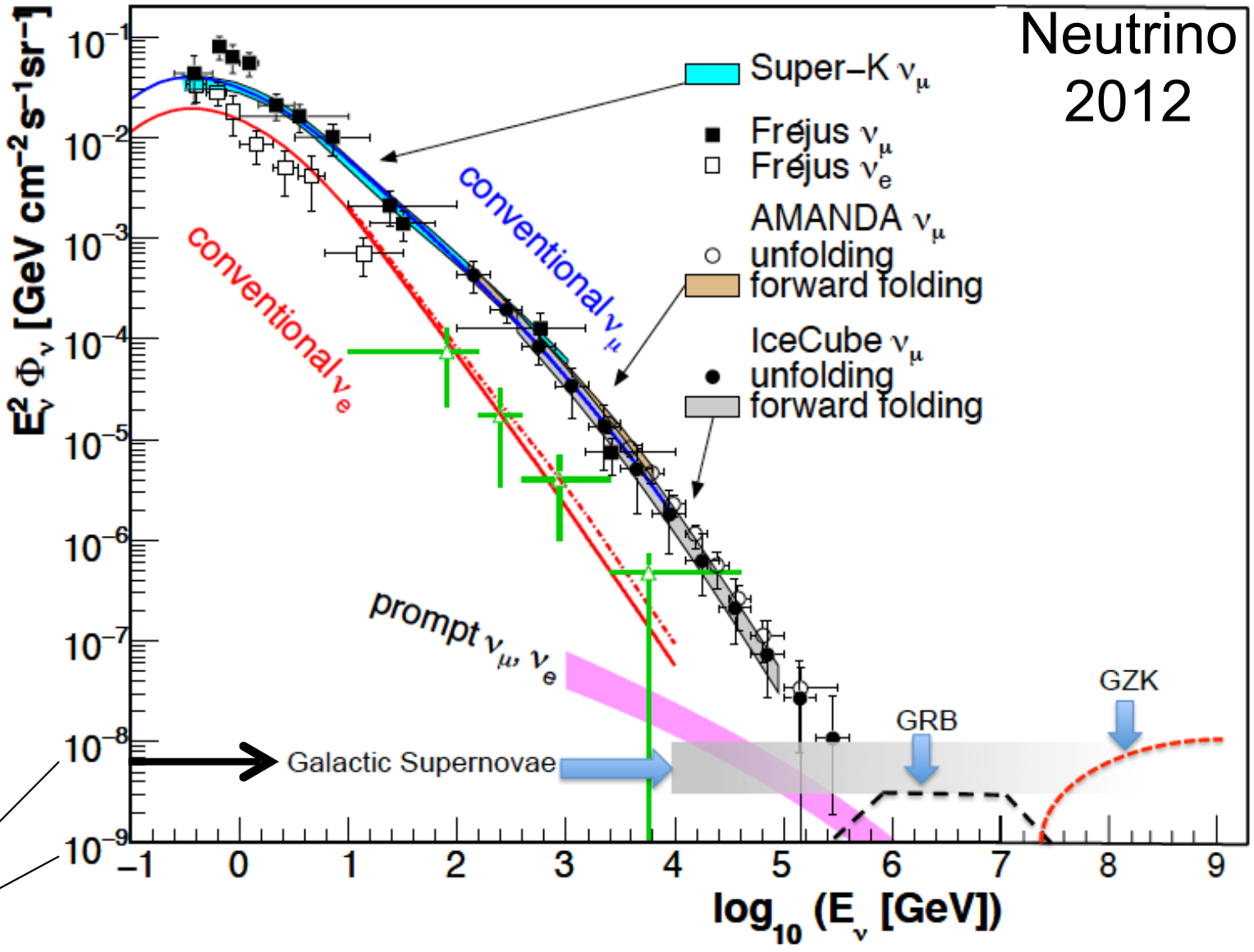
- Atmospheric-only hypothesis excluded by 6.0σ

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

10—100 events per year for fully efficient detector



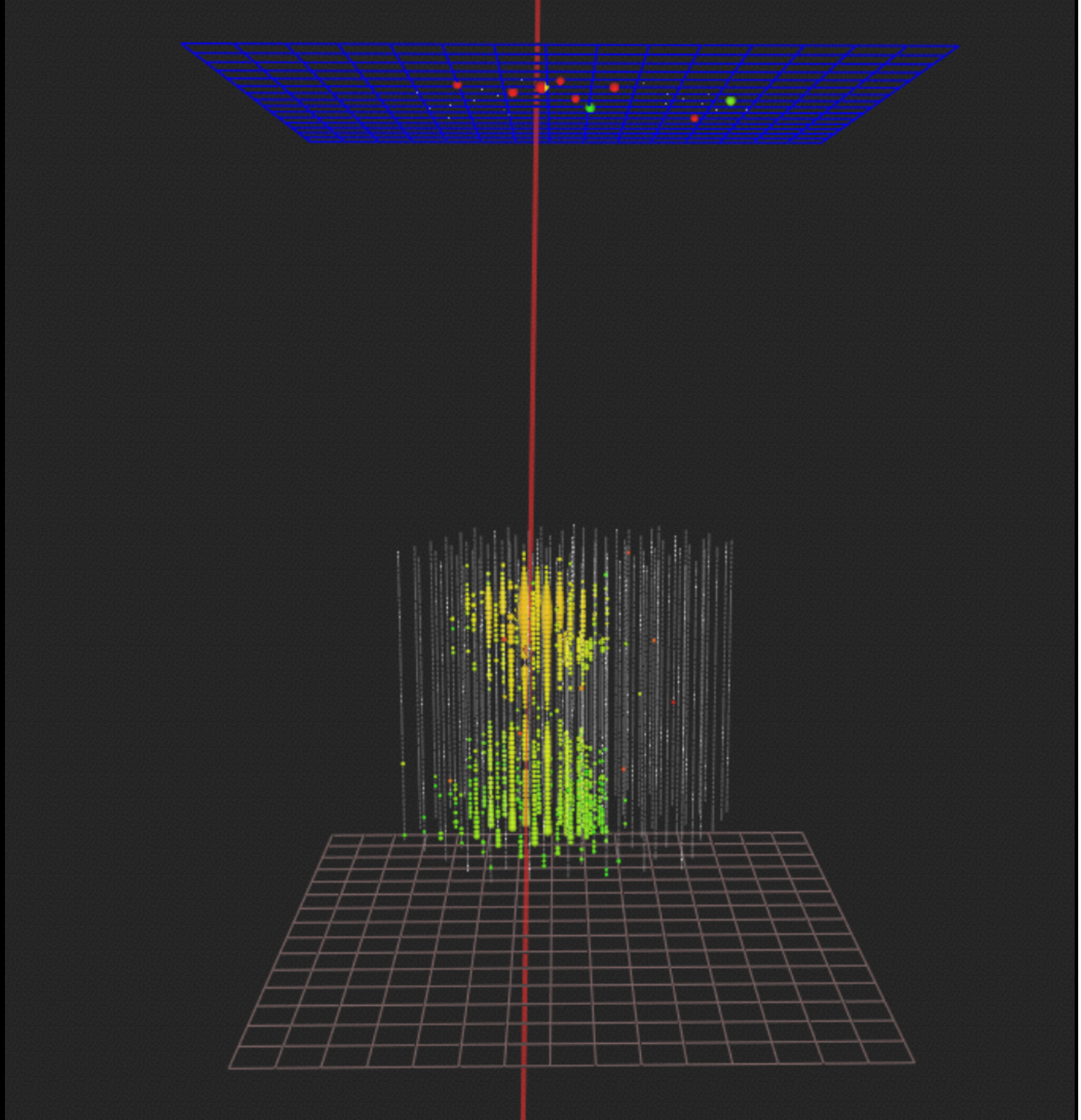
atmospheric

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

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

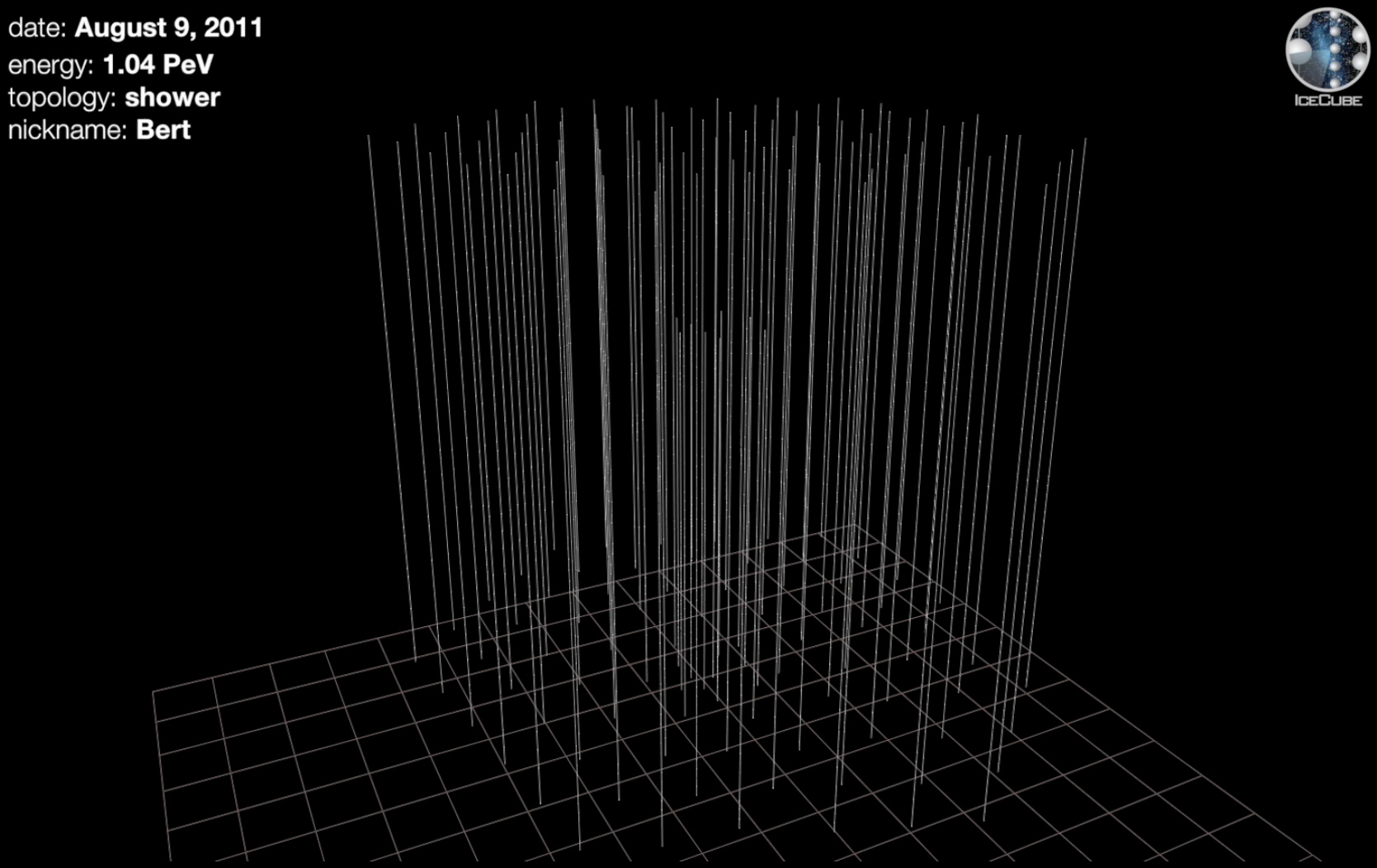
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

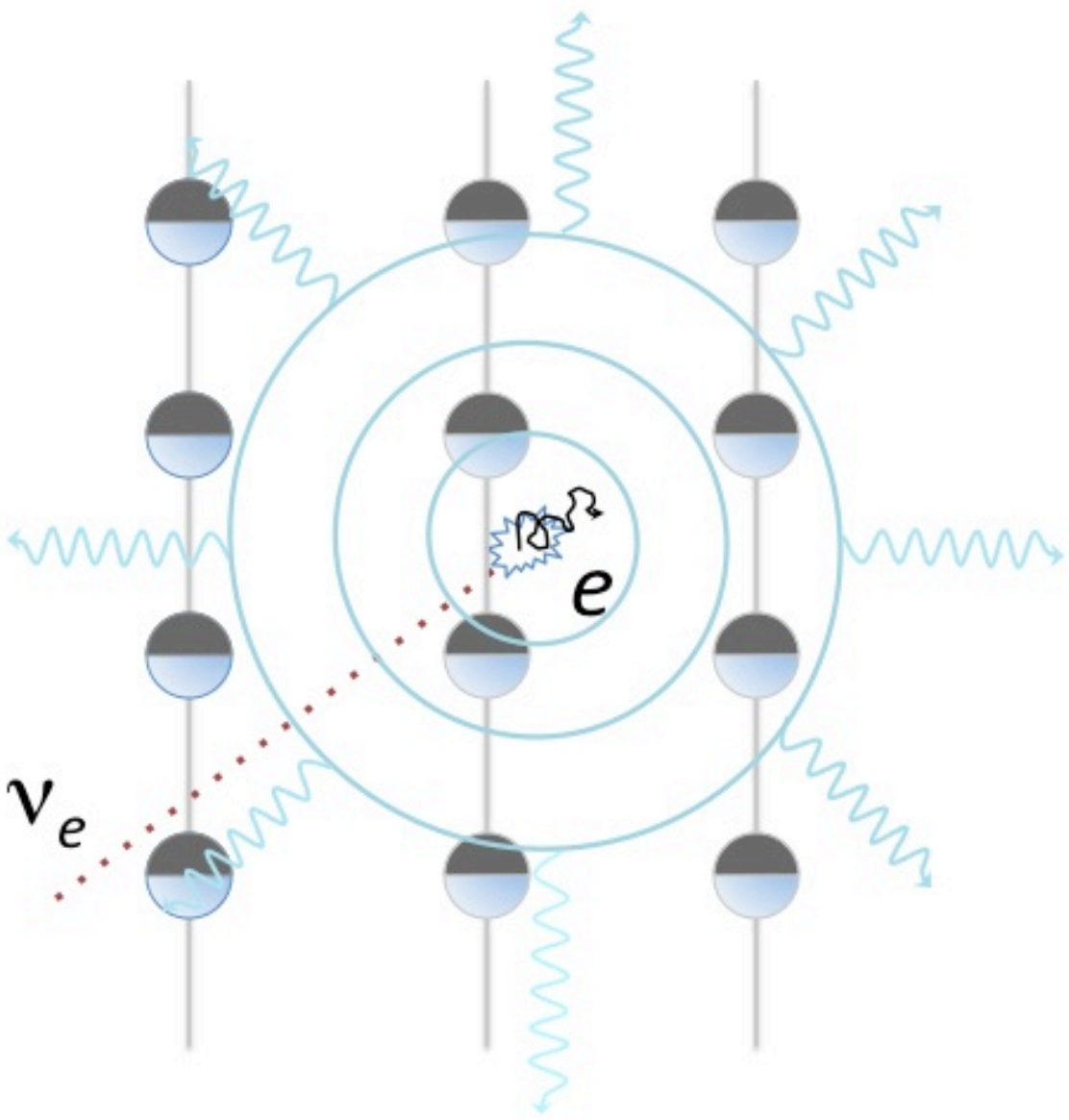
GZK neutrino search: two neutrinos with > 1,000 TeV

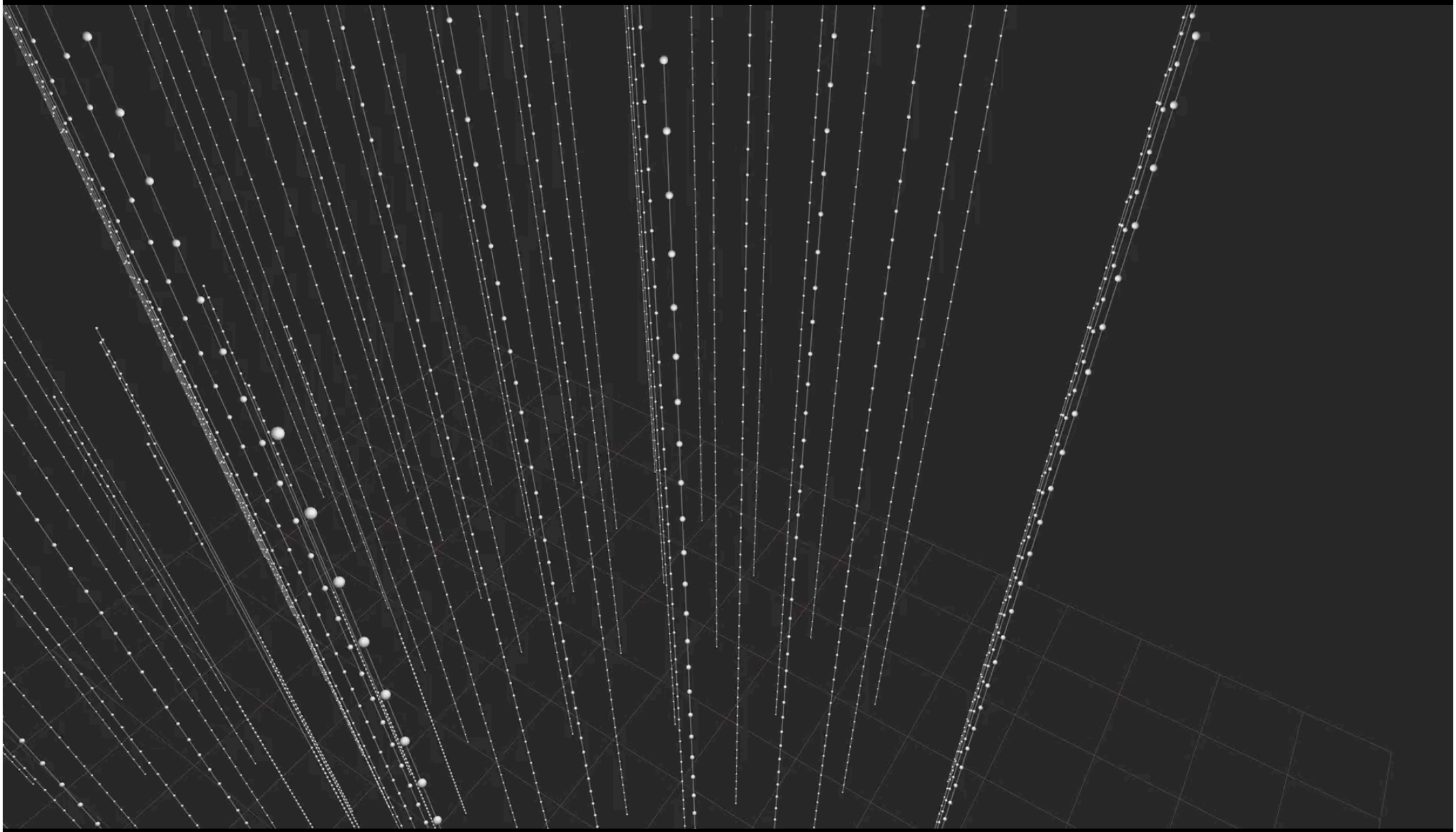


electron showers versus muon tracks

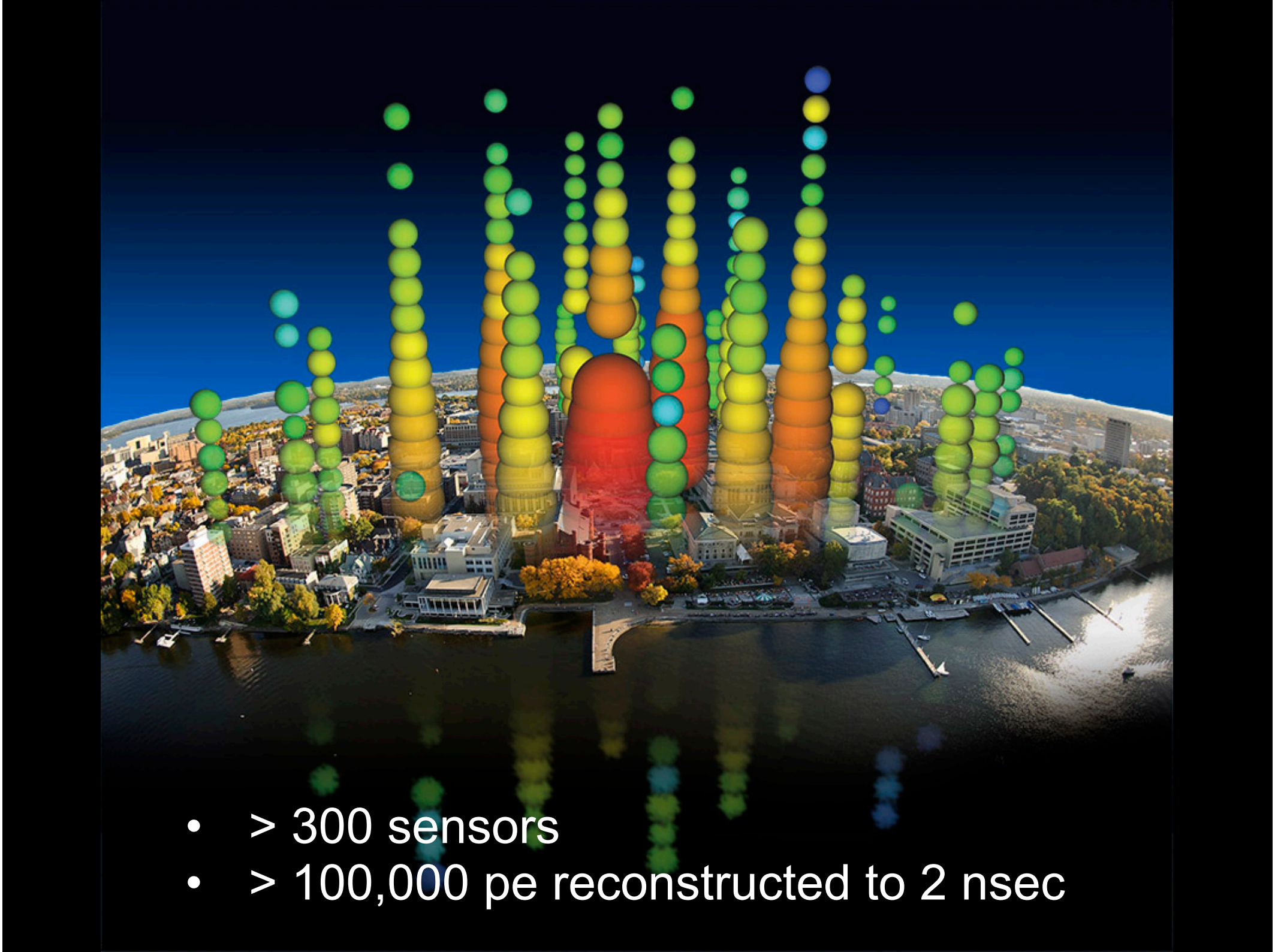
PeV ν_e and ν_τ showers:

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



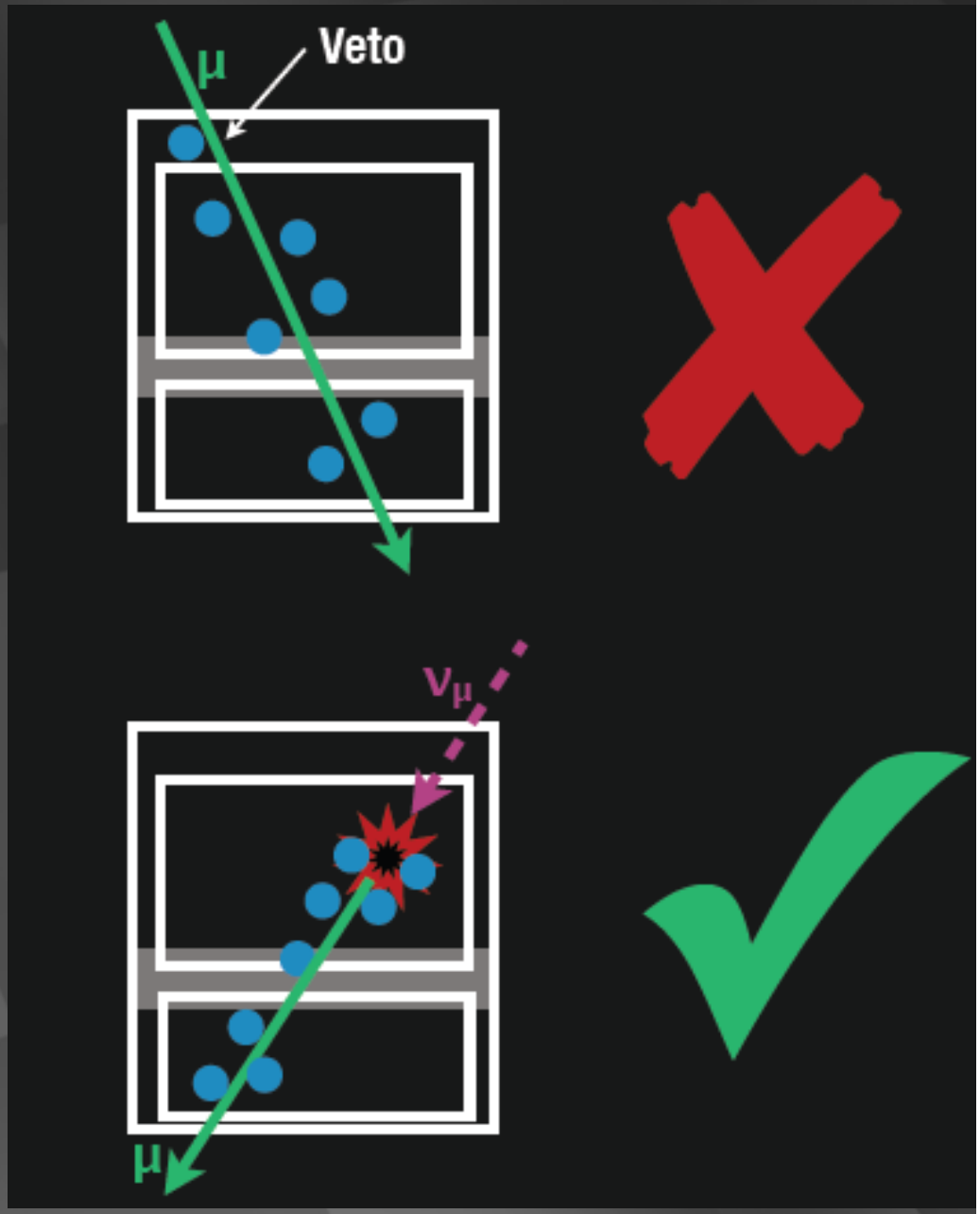


size = energy & color = time = direction

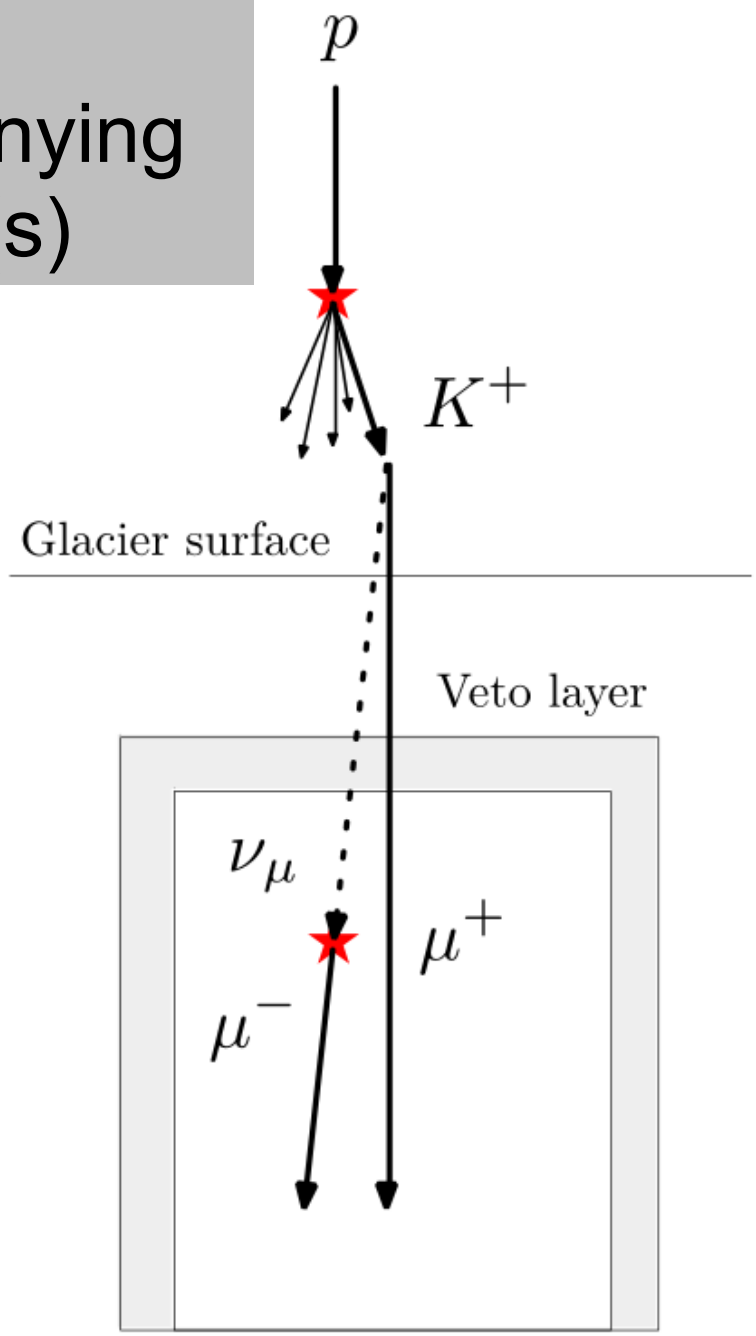


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

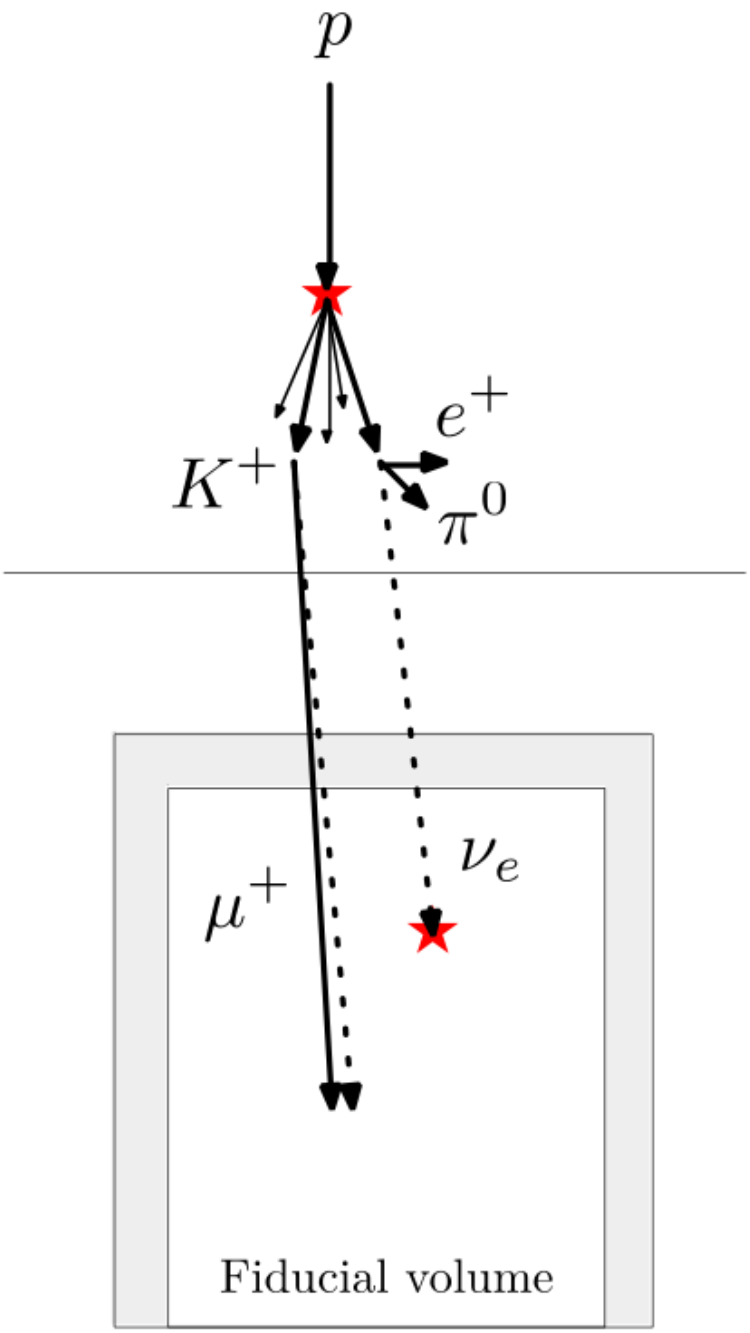
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



no accompanying muon(s)

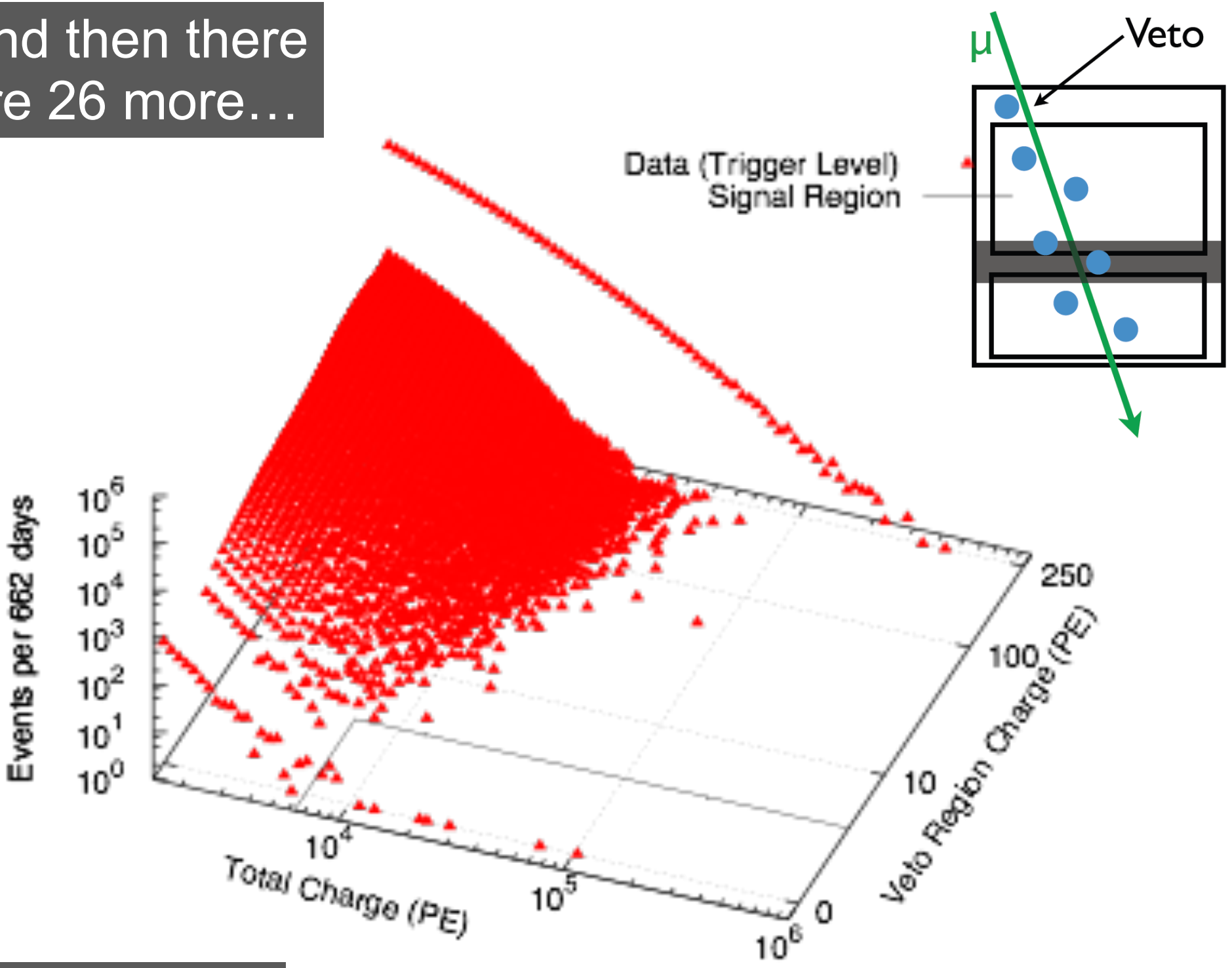


Veto by correlated muon



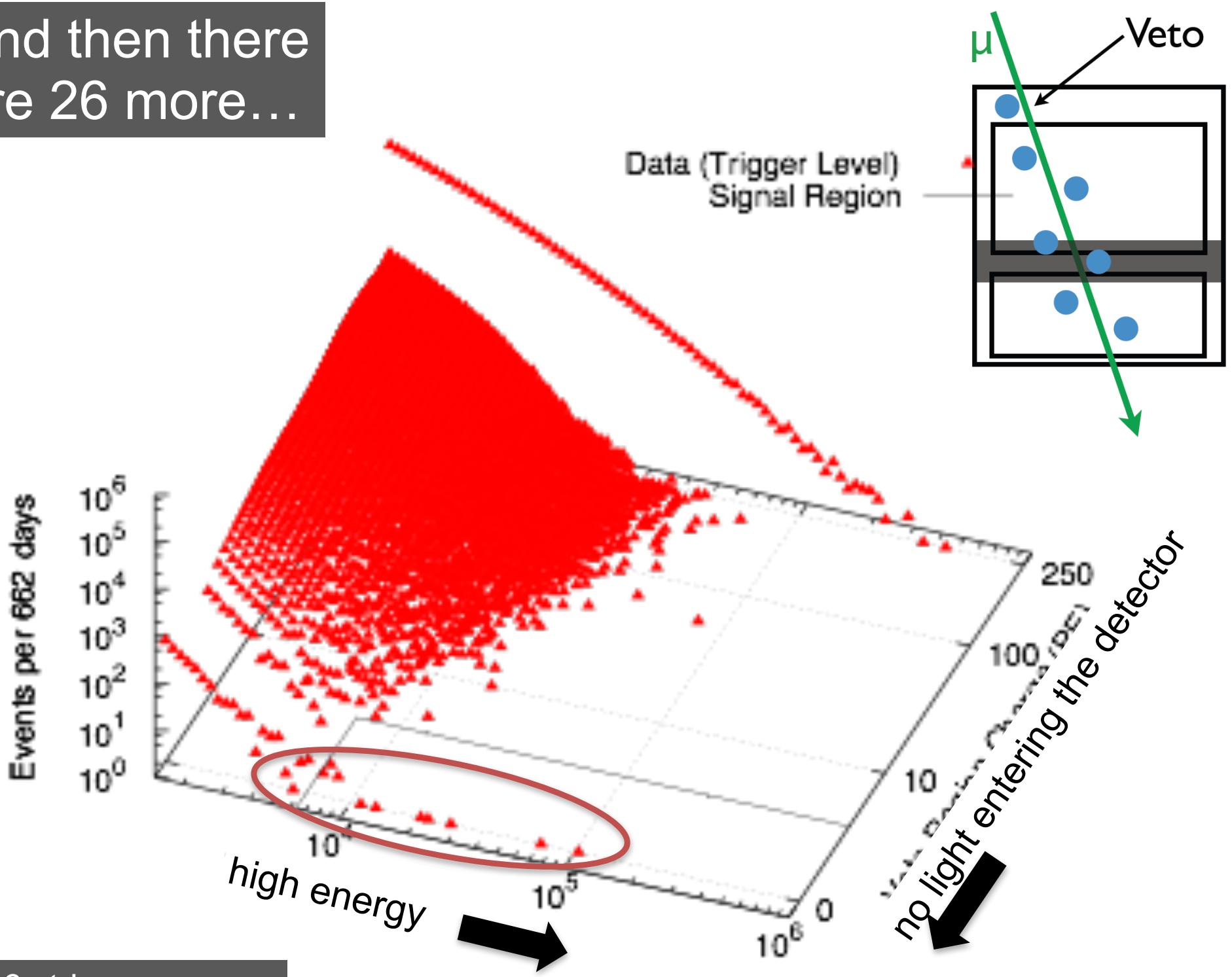
Veto by uncorrelated muon

…and then there were 26 more…



data: 86 strings one year

…and then there were 26 more…



data: 86 strings one year

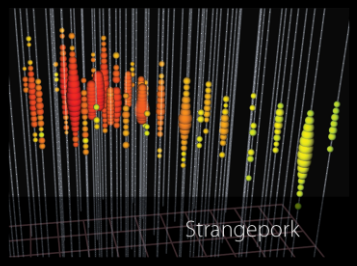
2 old + 26 new events

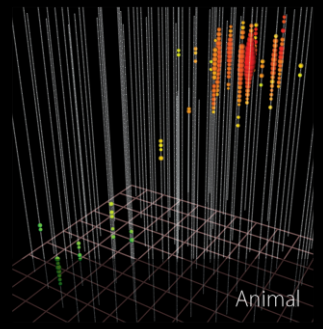
RESEARCH

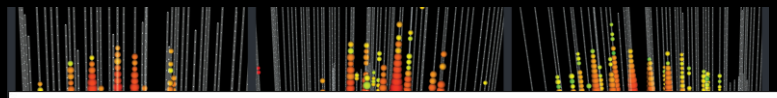
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

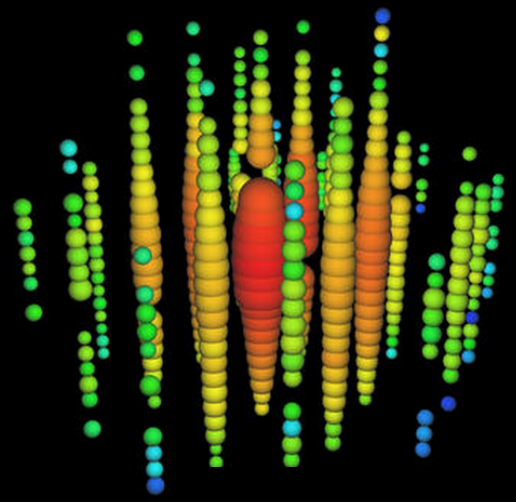
IceCube Collaboration*

28 High Energy Events





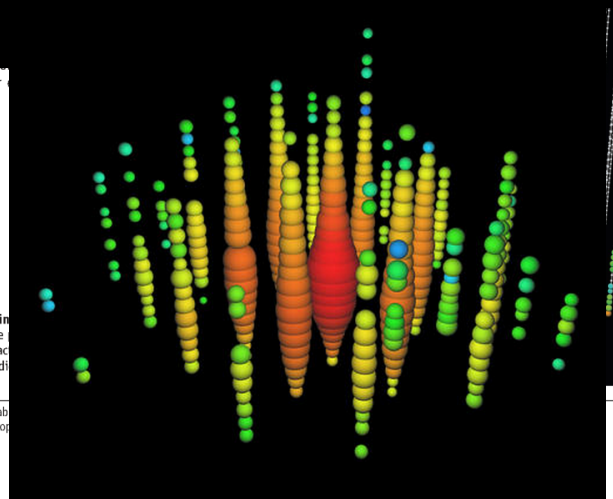


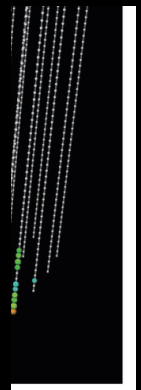


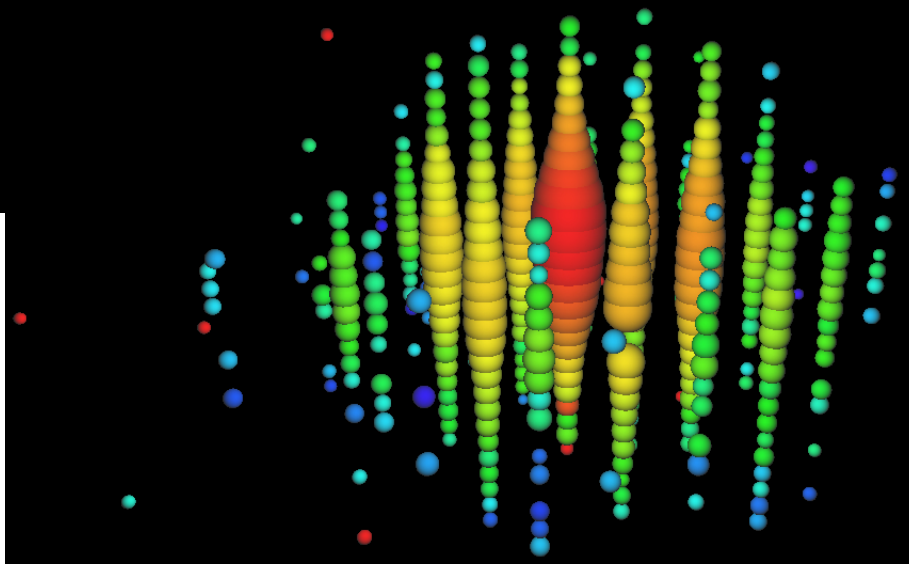
tified high-energy galactic or
accelerators.

A 250 TeV neutrino interaction in
interaction point (bottom), a large
with a muon produced in the interac
left. The direction of the muon indi
original neutrino.

*The list of author affiliations is availab
Corresponding authors: C. Kopper (ckop

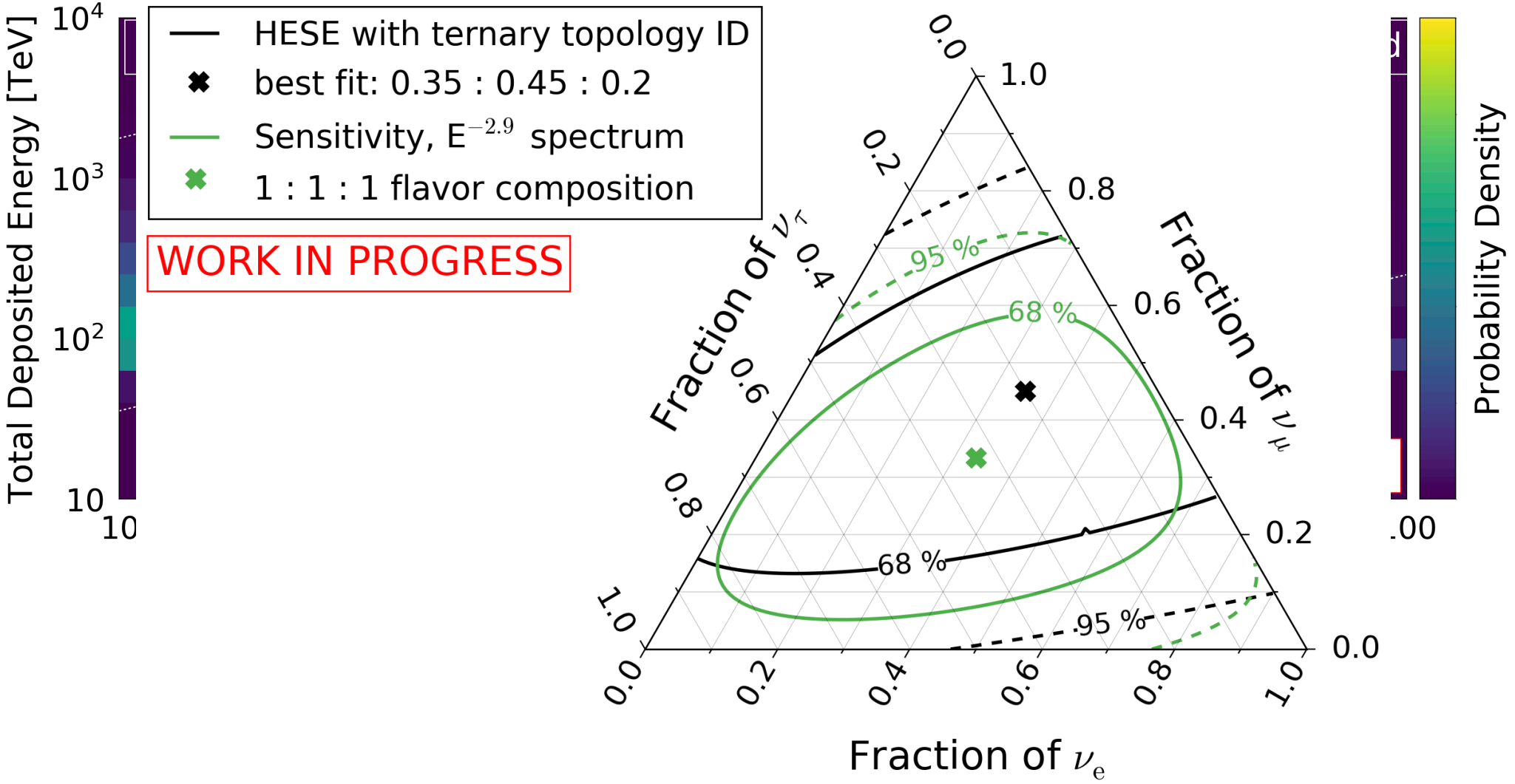






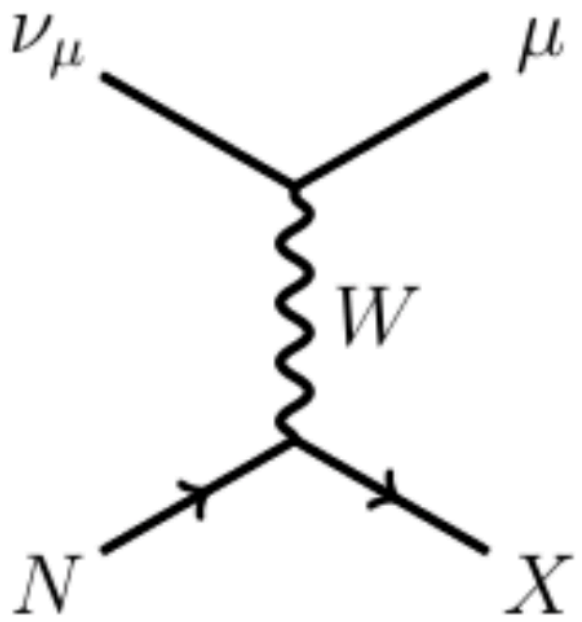
2000 TeV event in year 3

high-energy starting events – 7.5 yr

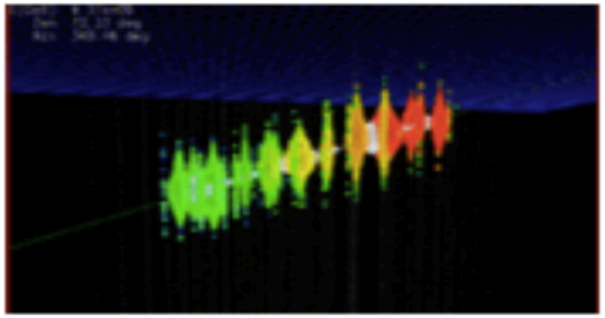


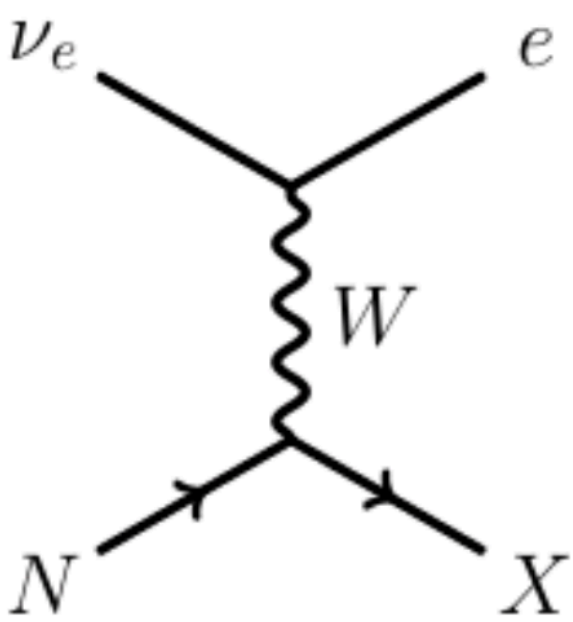
oscillations of PeV neutrinos over cosmic distances to 1:1:1

tau decay length:
50m per PeV

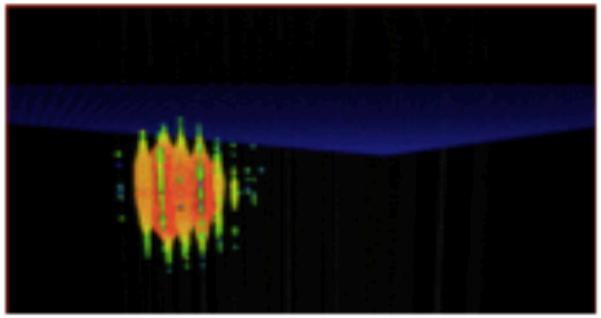


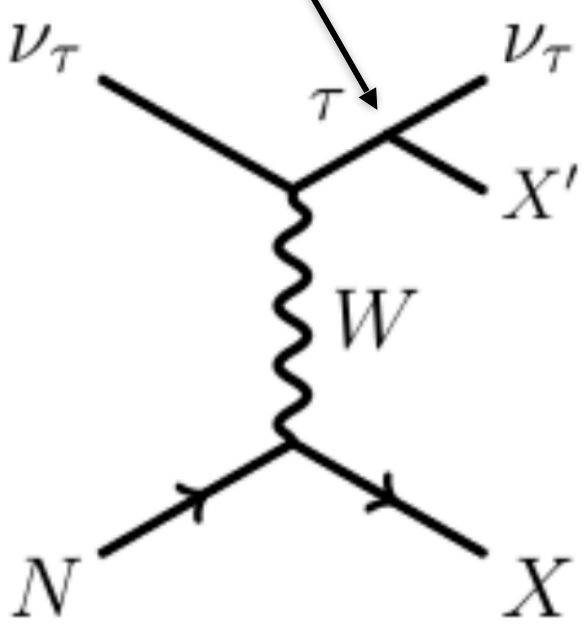
track



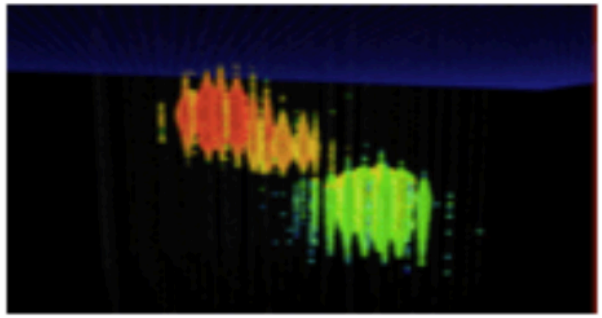


shower



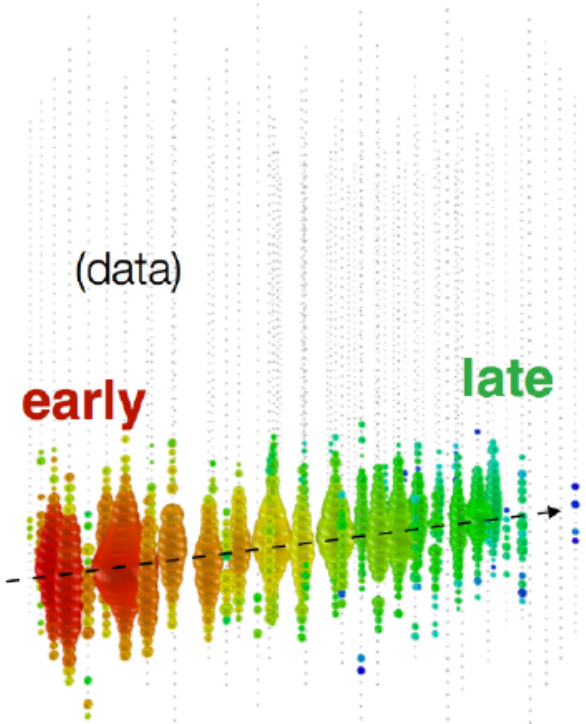


double bang*



event topologies

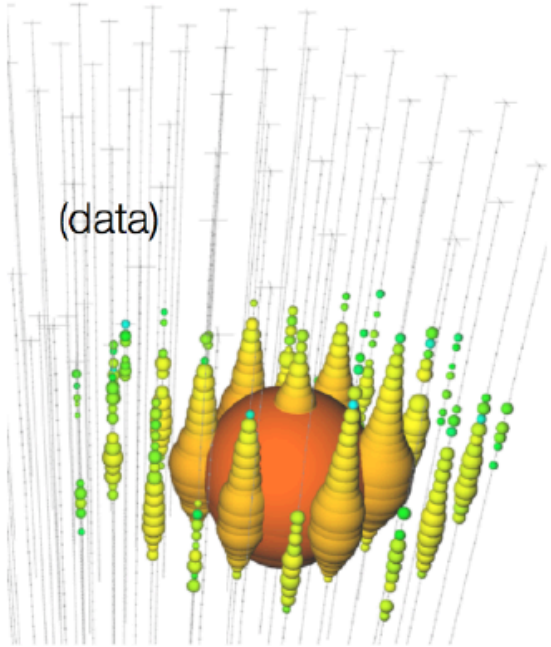
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

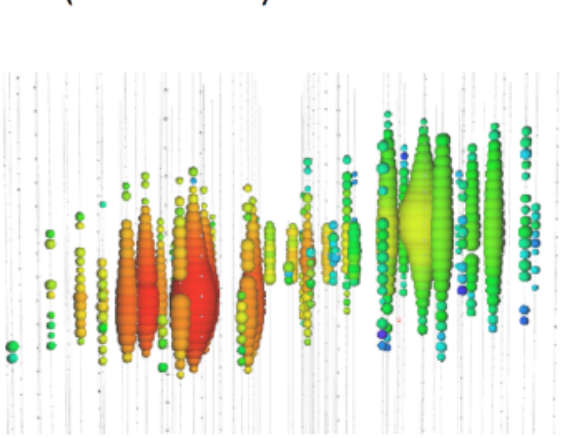
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

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

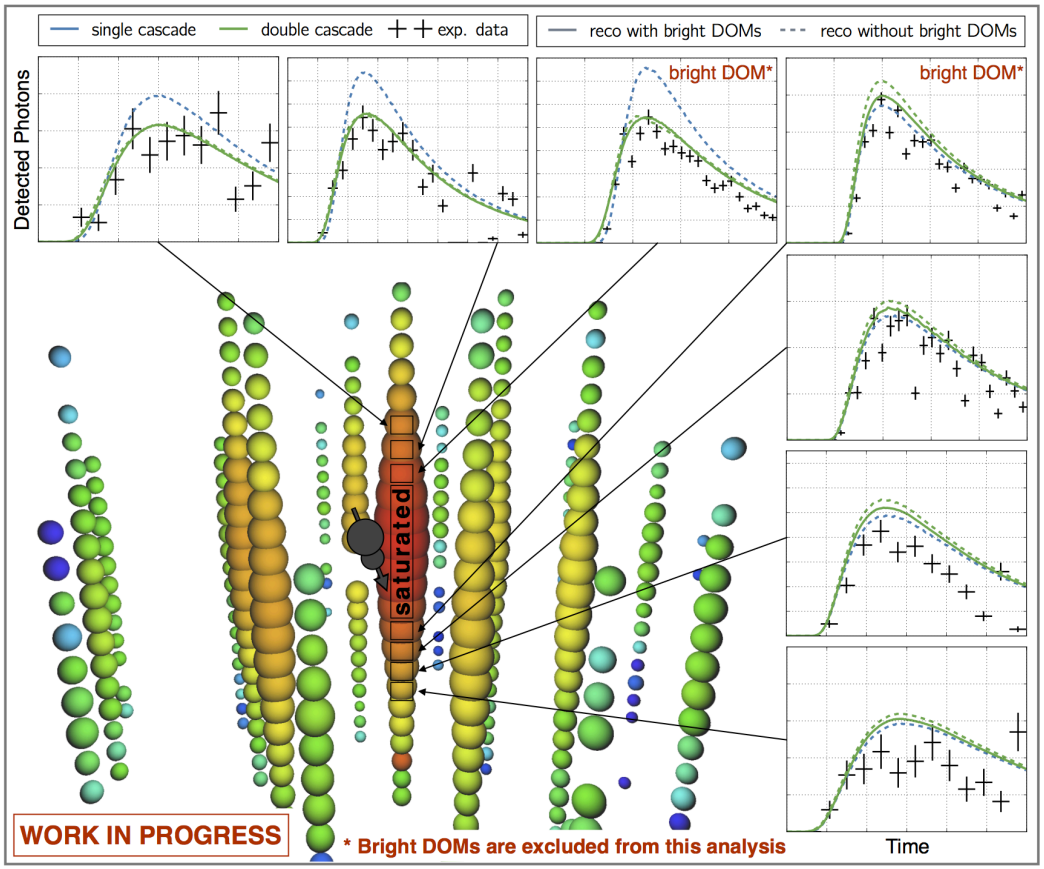
Charged-current ν_τ



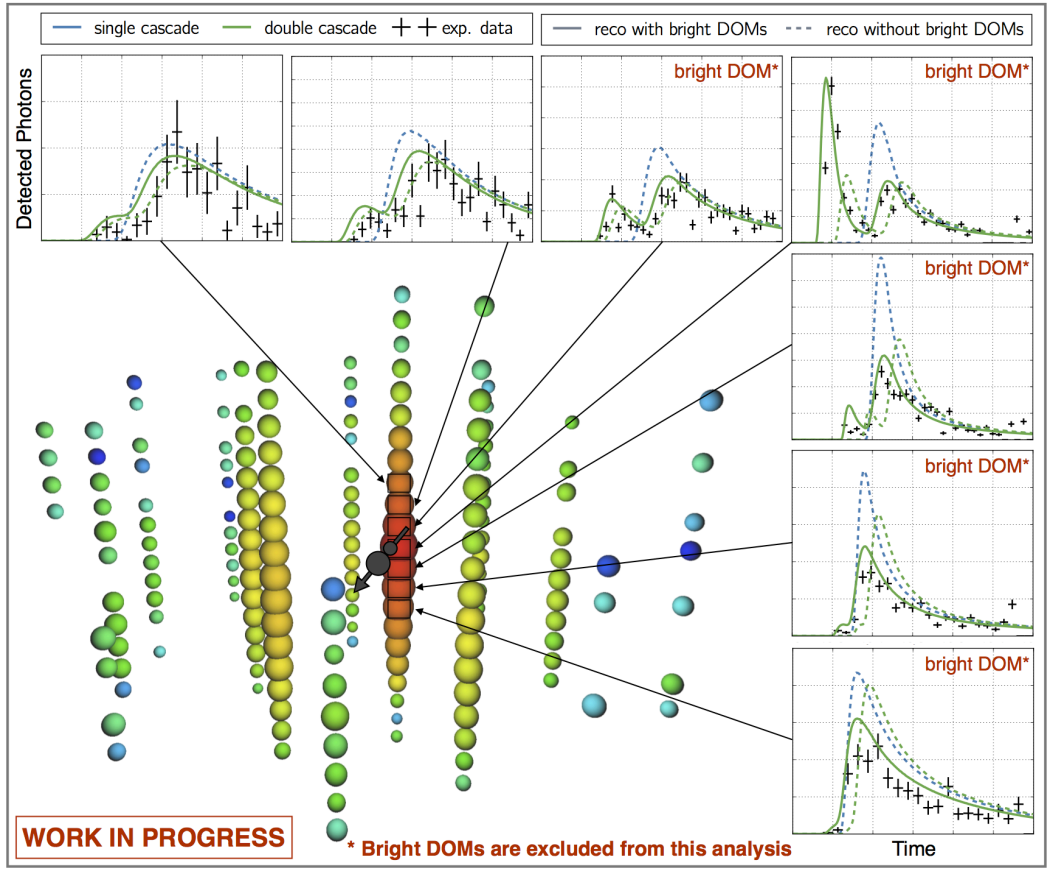
Double cascade

(resolvable above ~100 TeV deposited energy)

high-energy starting events (starting) – 7.5 yr



Double cascade Event #1



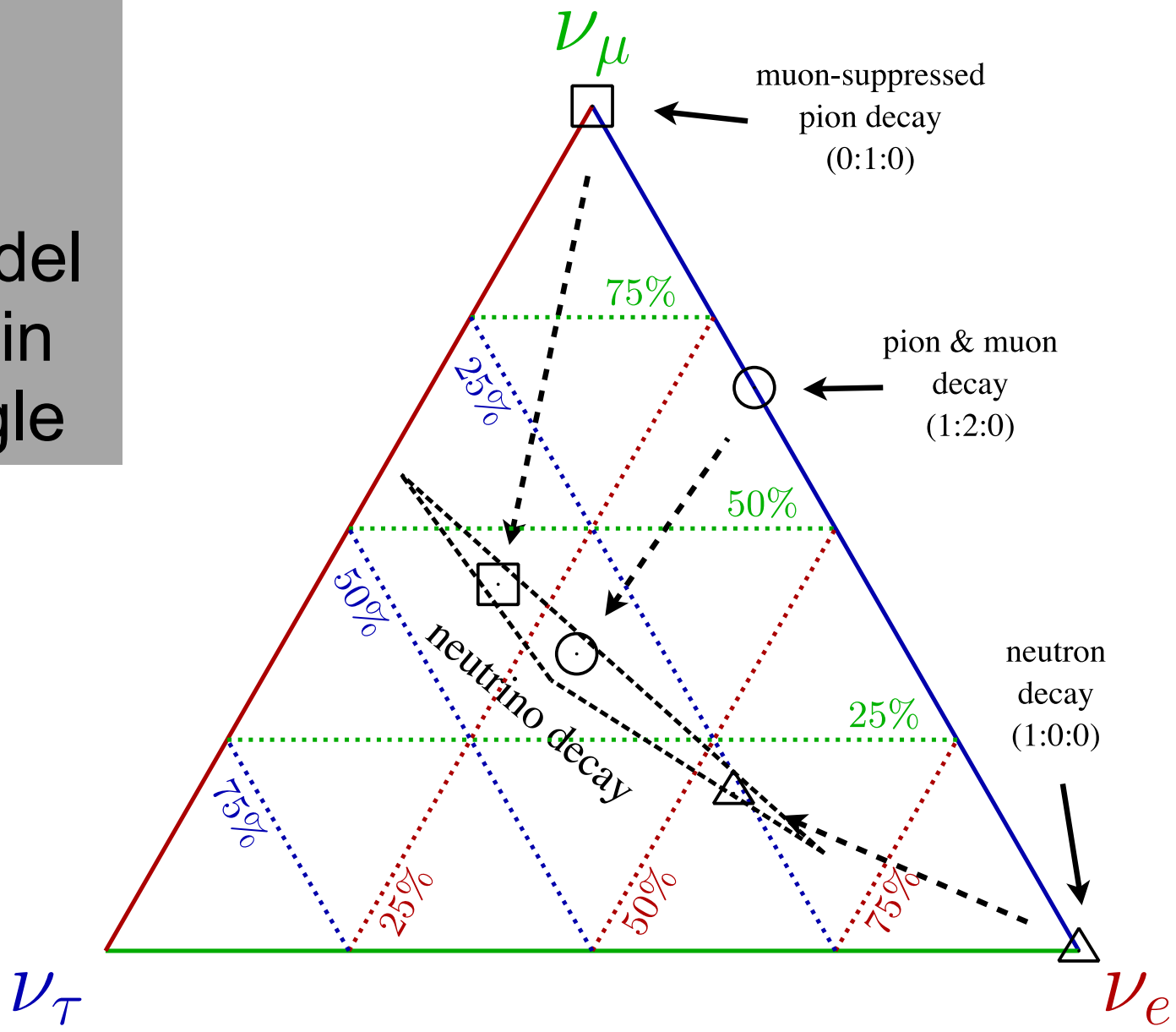
Double cascade Event #2

"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

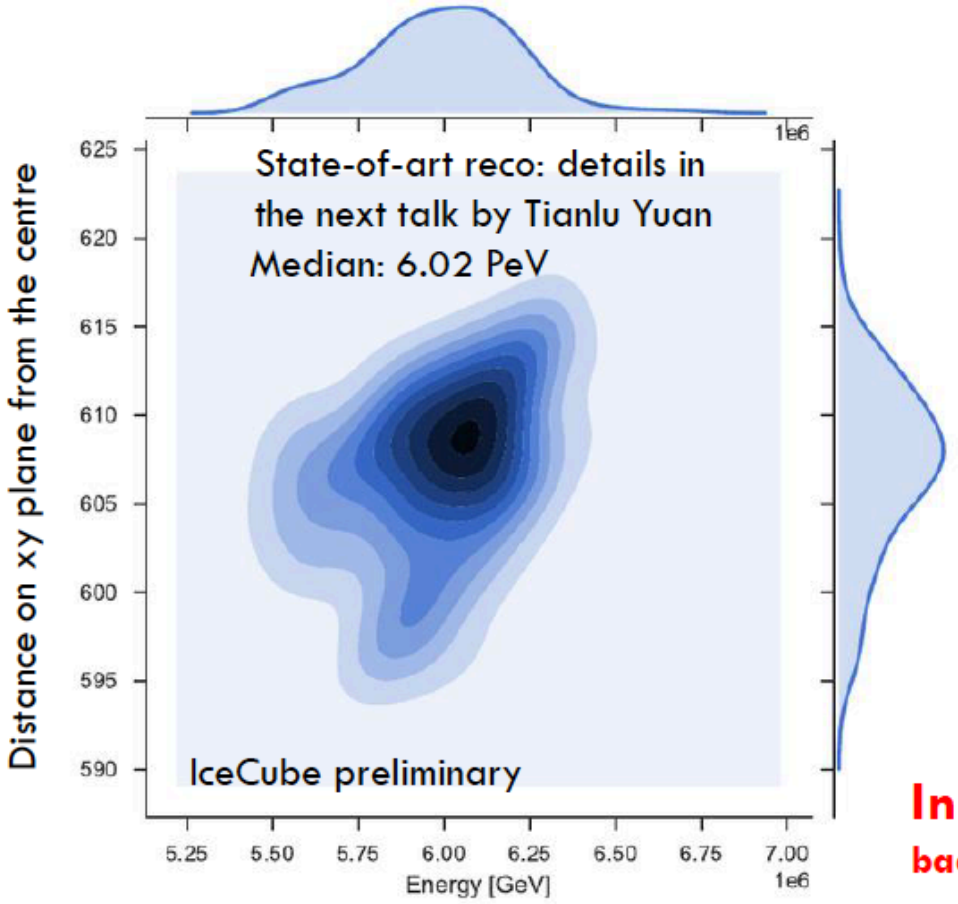


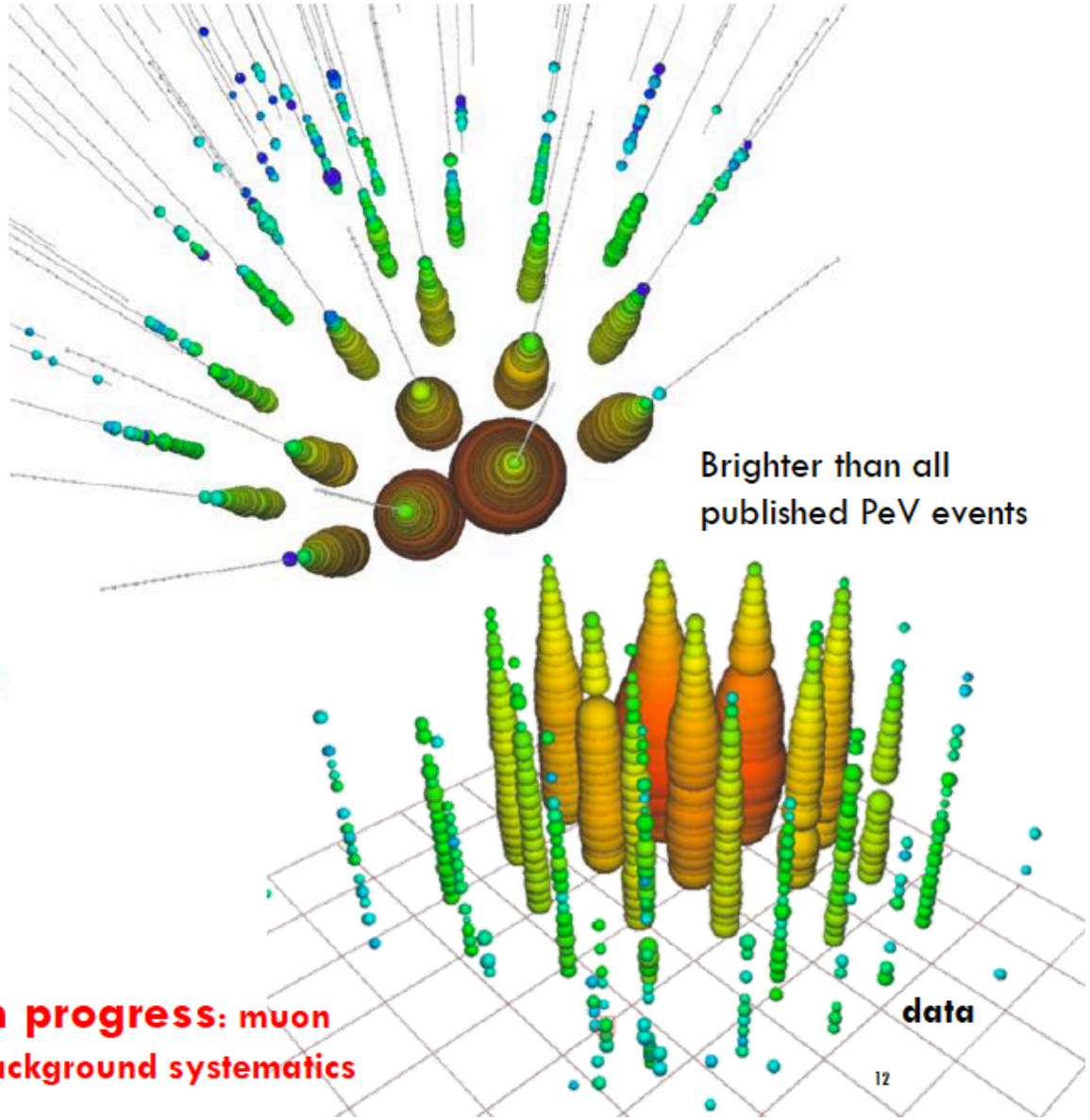
the first Glashow resonance event:

anti-ν_e + atomic electron → real W at 6.3 PeV

Partially contained event with energy ~ 6 PeV

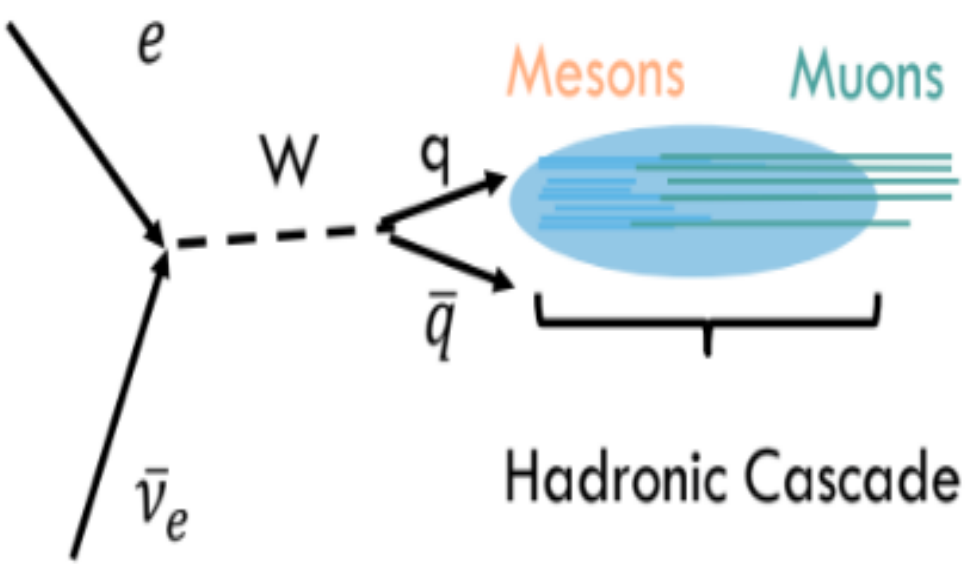
HIGHEST-ENERGY NEUTRINO CANDIDATE

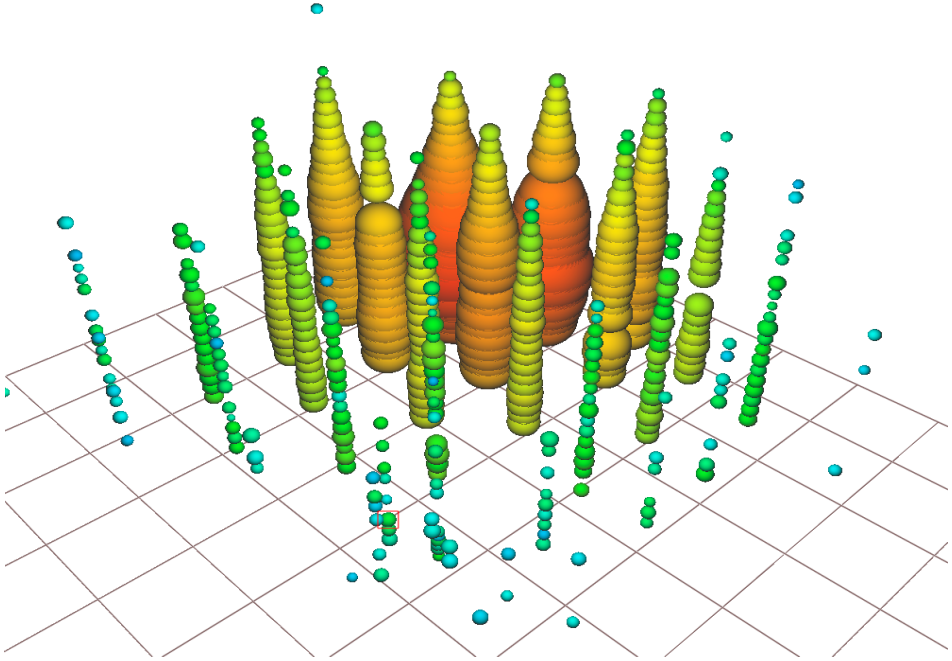


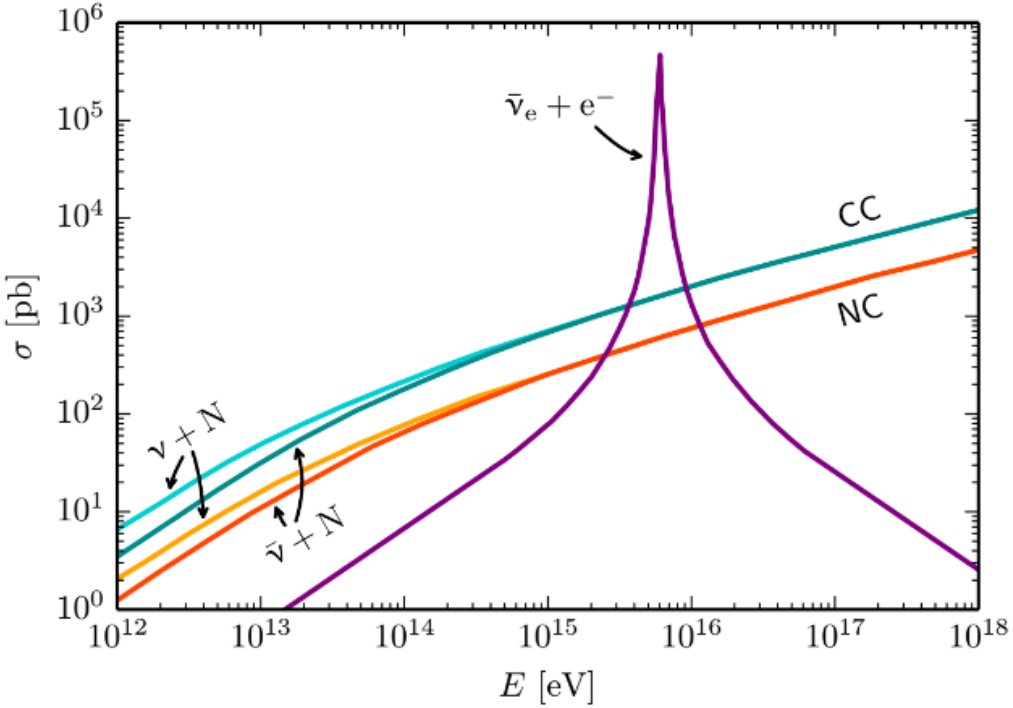


In progress: muon background systematics

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





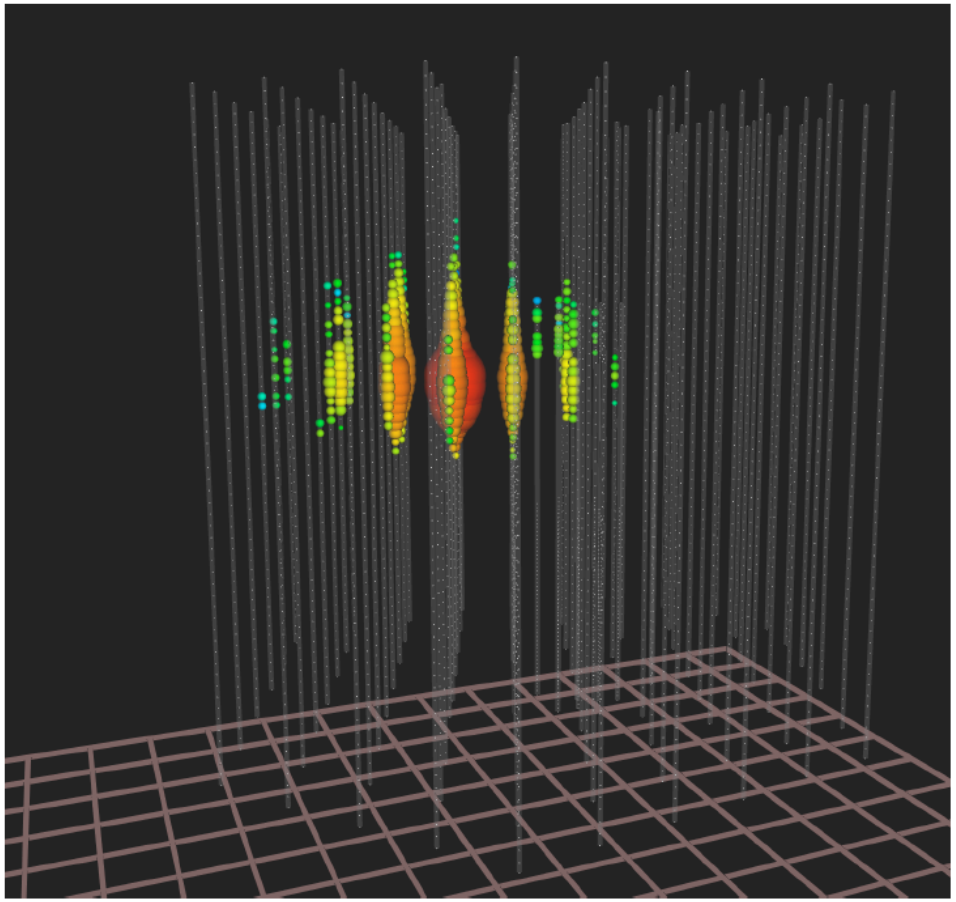


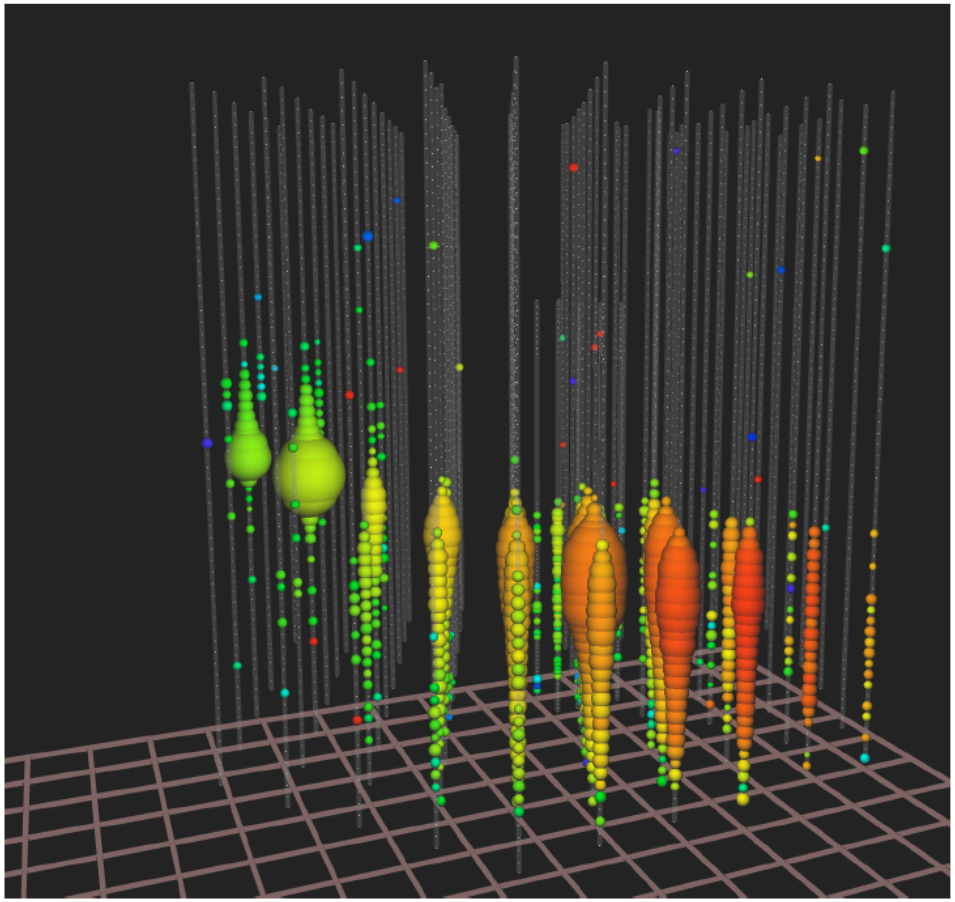
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

are the two observations consistent?

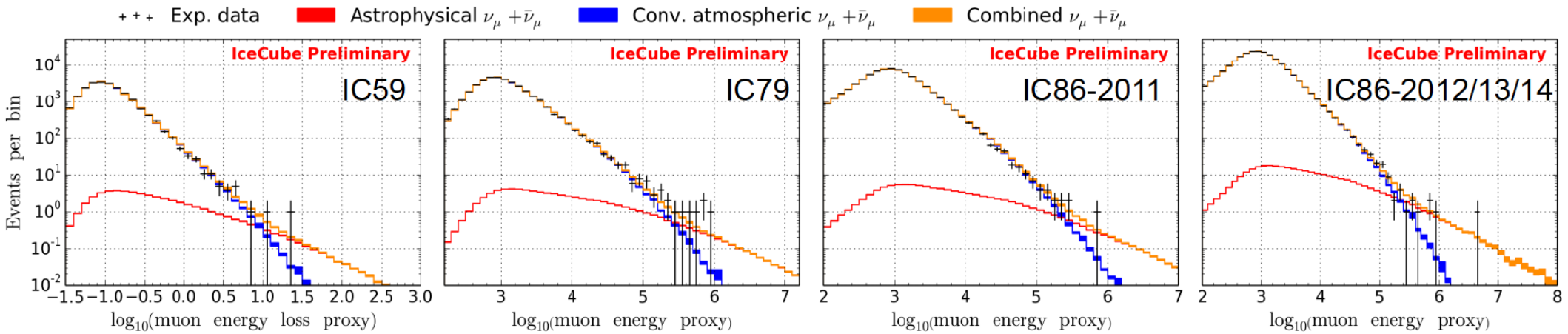




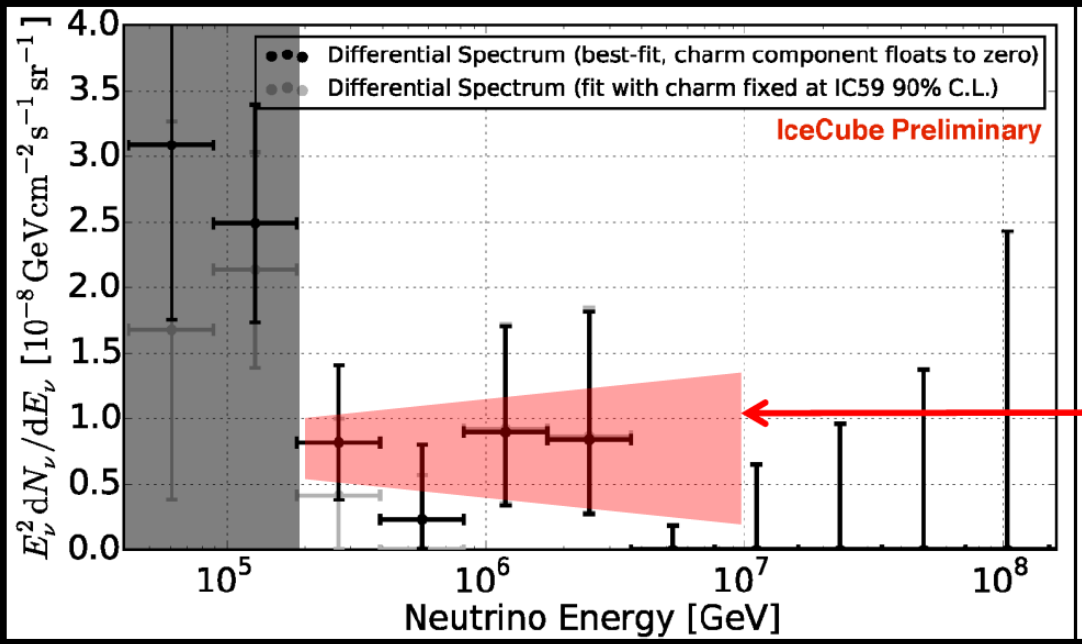
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4^{o})

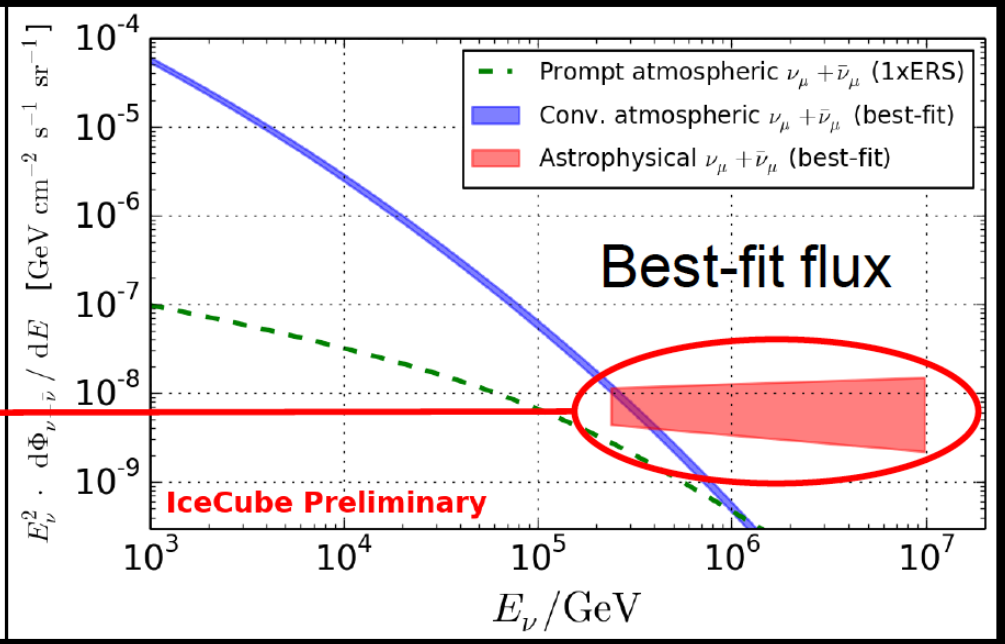
after 6 years: 3.7→ 6.0 sigma



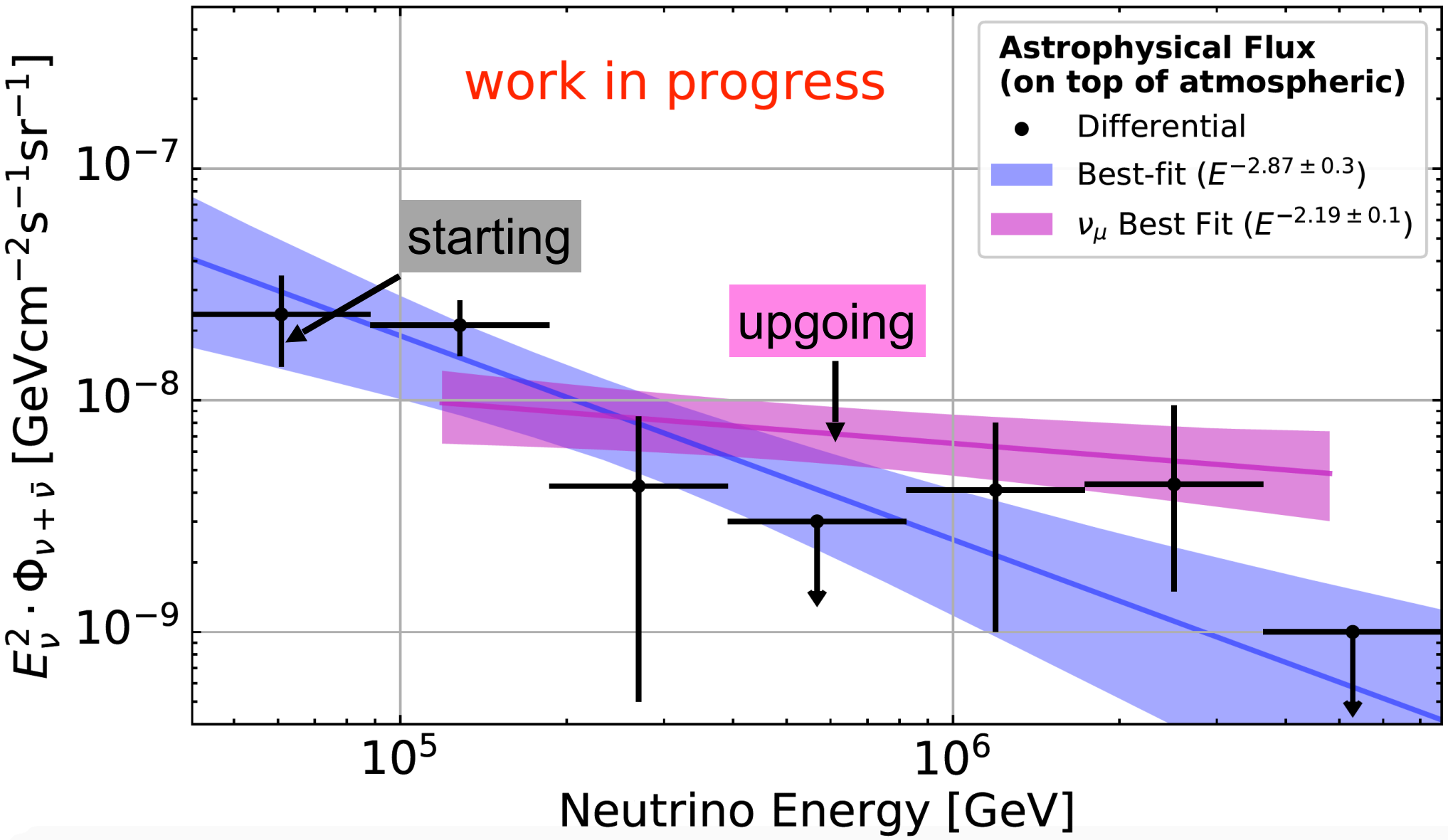
HESE 4 year unfolding
(→ dominated by shower-like events)



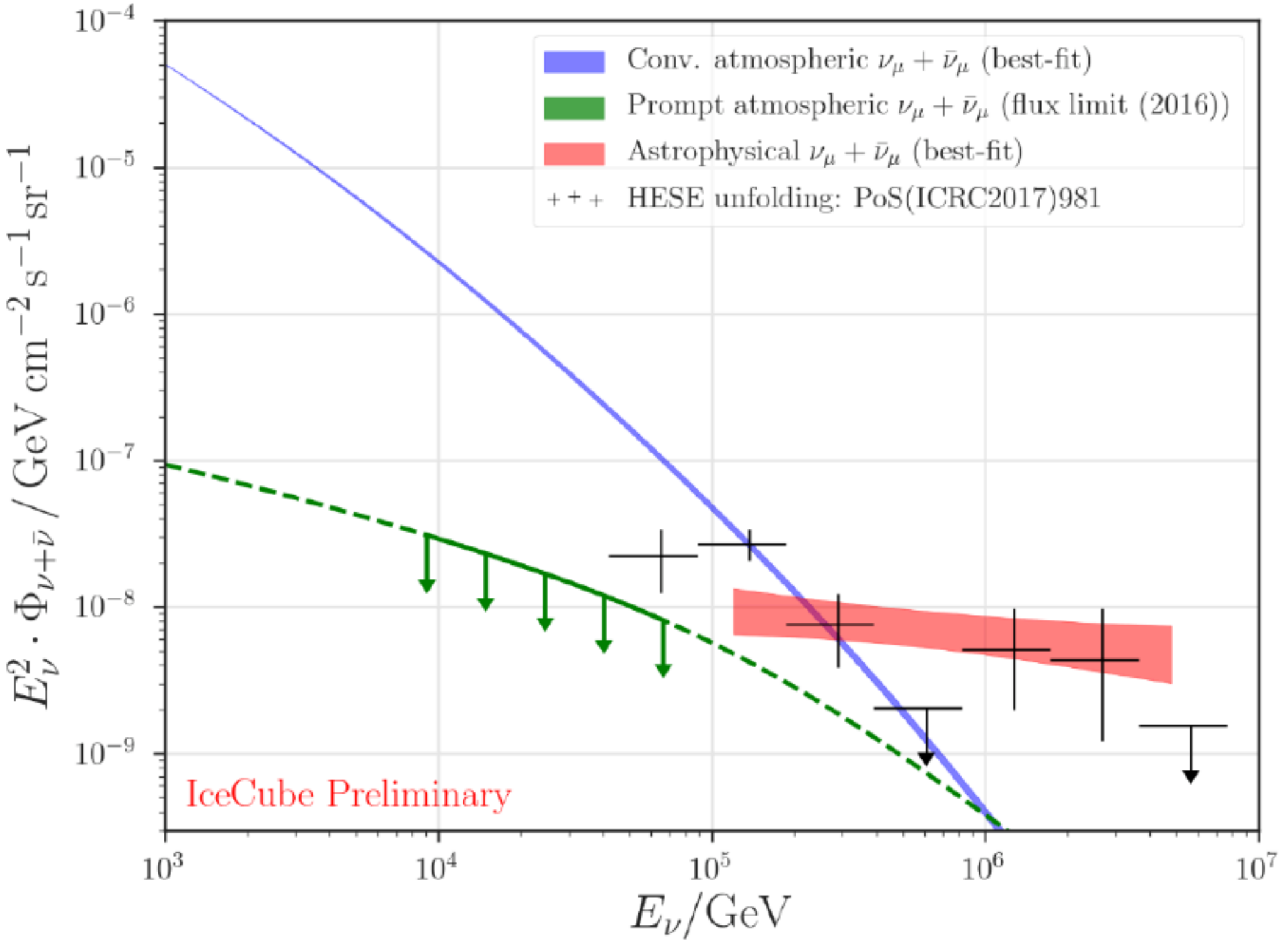
6 year up-going numu analysis



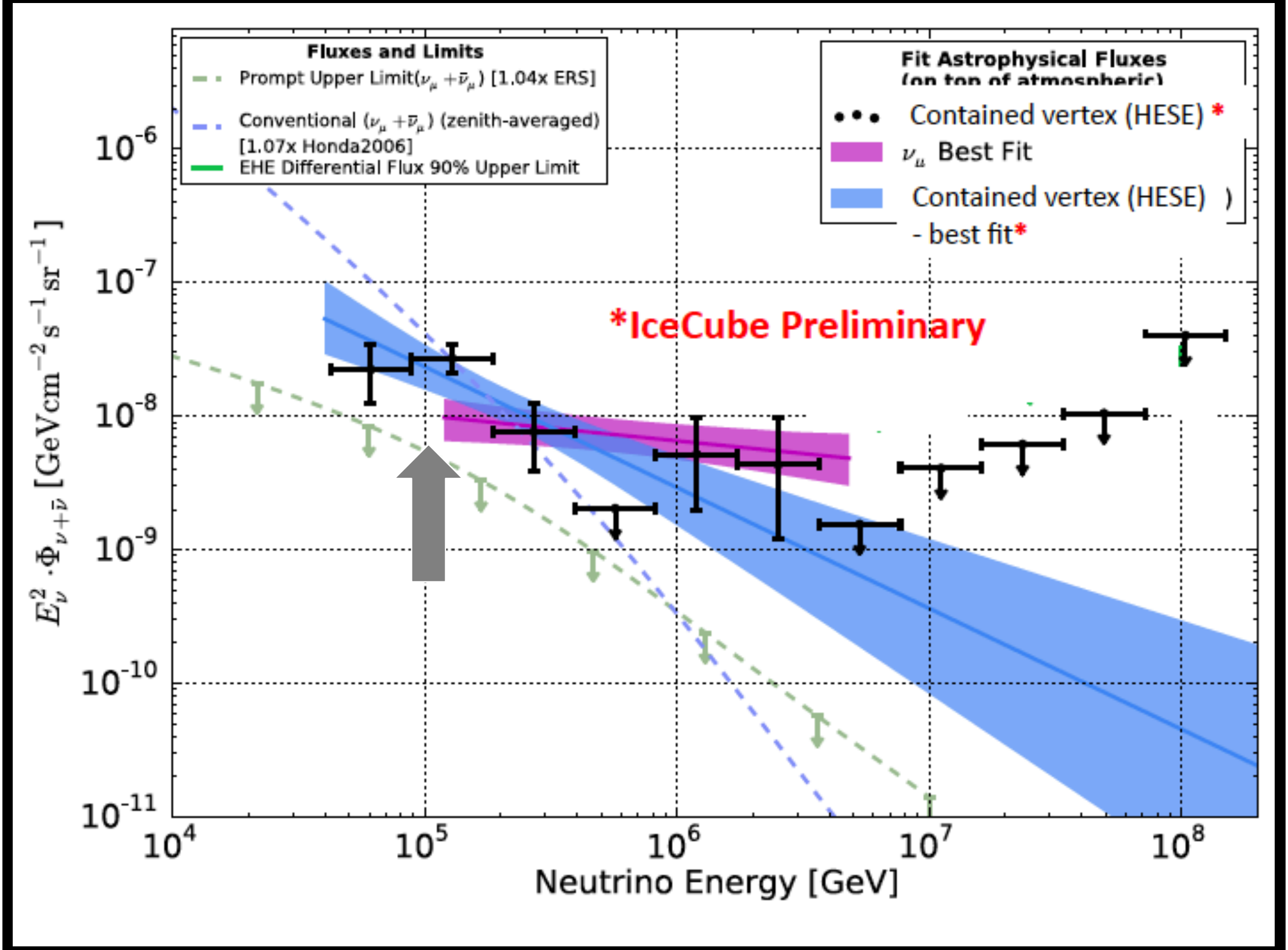
high-energy starting events – 7.5 yr



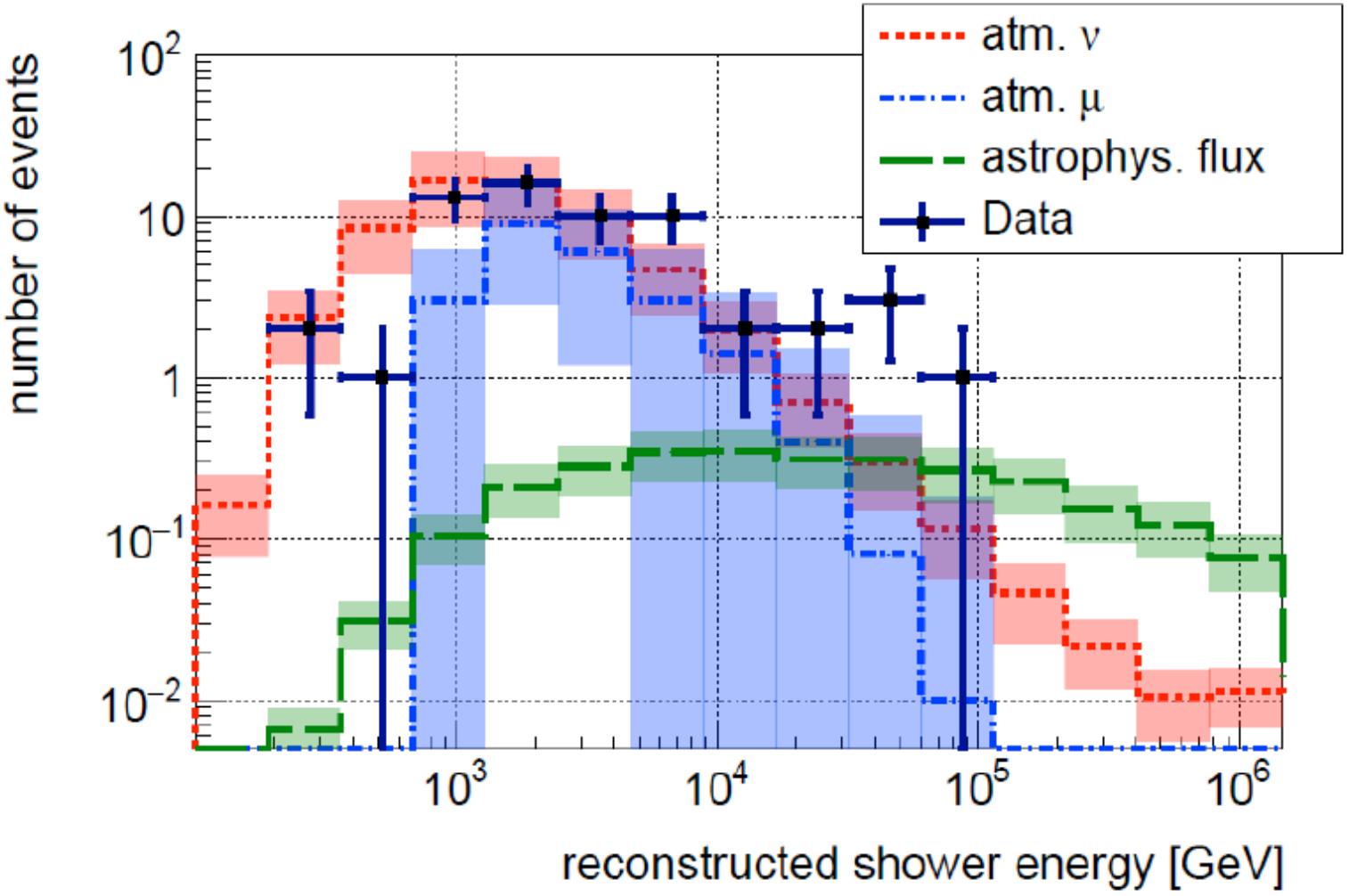
- two methods are consistent
- excess cosmic flux < 100 TeV?

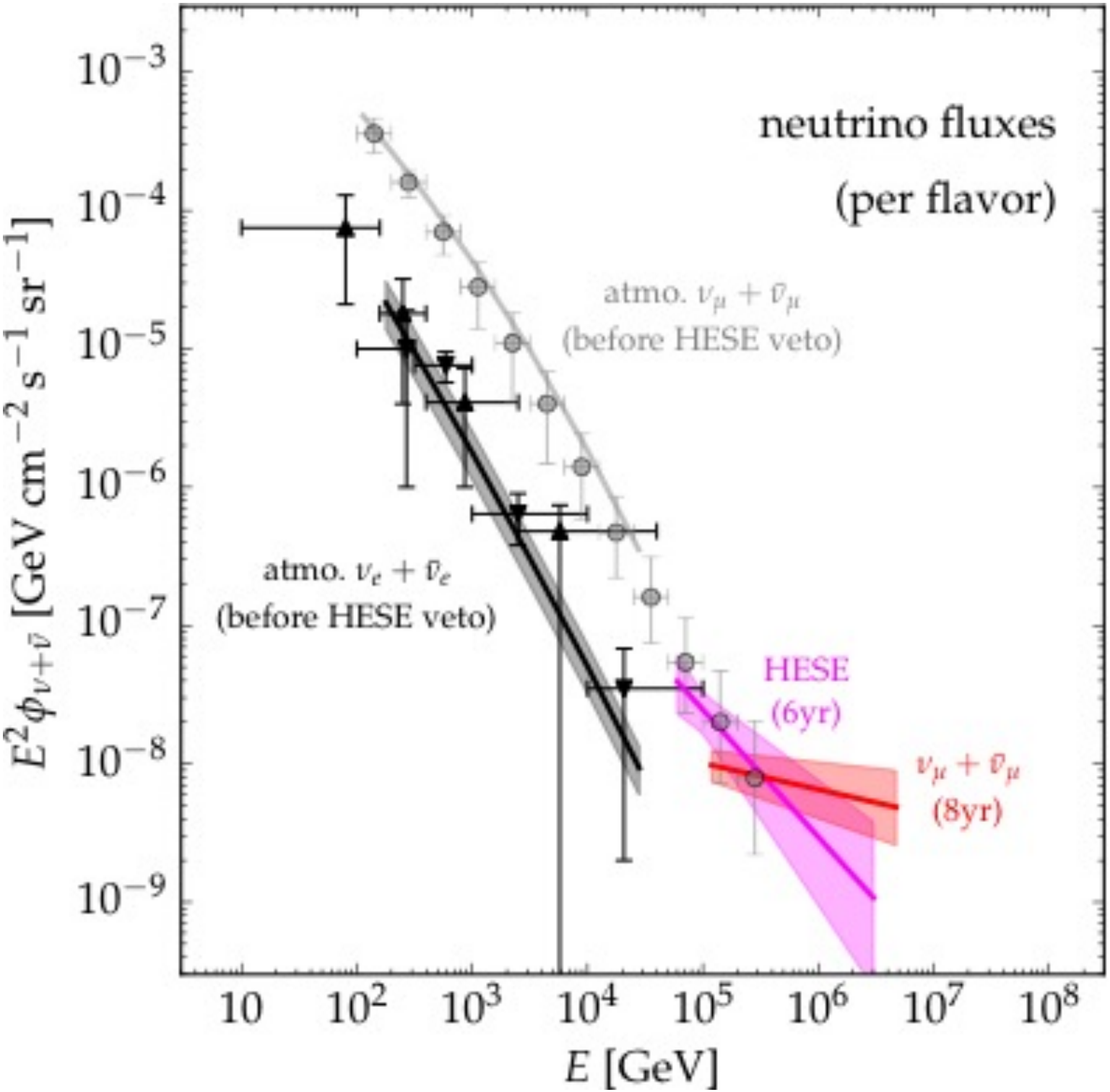

Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
Prompt atmospheric $\nu_\mu + \bar{\nu}_\mu$ (flux limit (2016))
Astrophysical $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
HESE unfolding: PoS(ICRC2017)981
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ / GeV cm^{-2} s^{-1} sr^{-1}
E_ν/GeV
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7

- cosmic neutrinos below 100 TeV ?

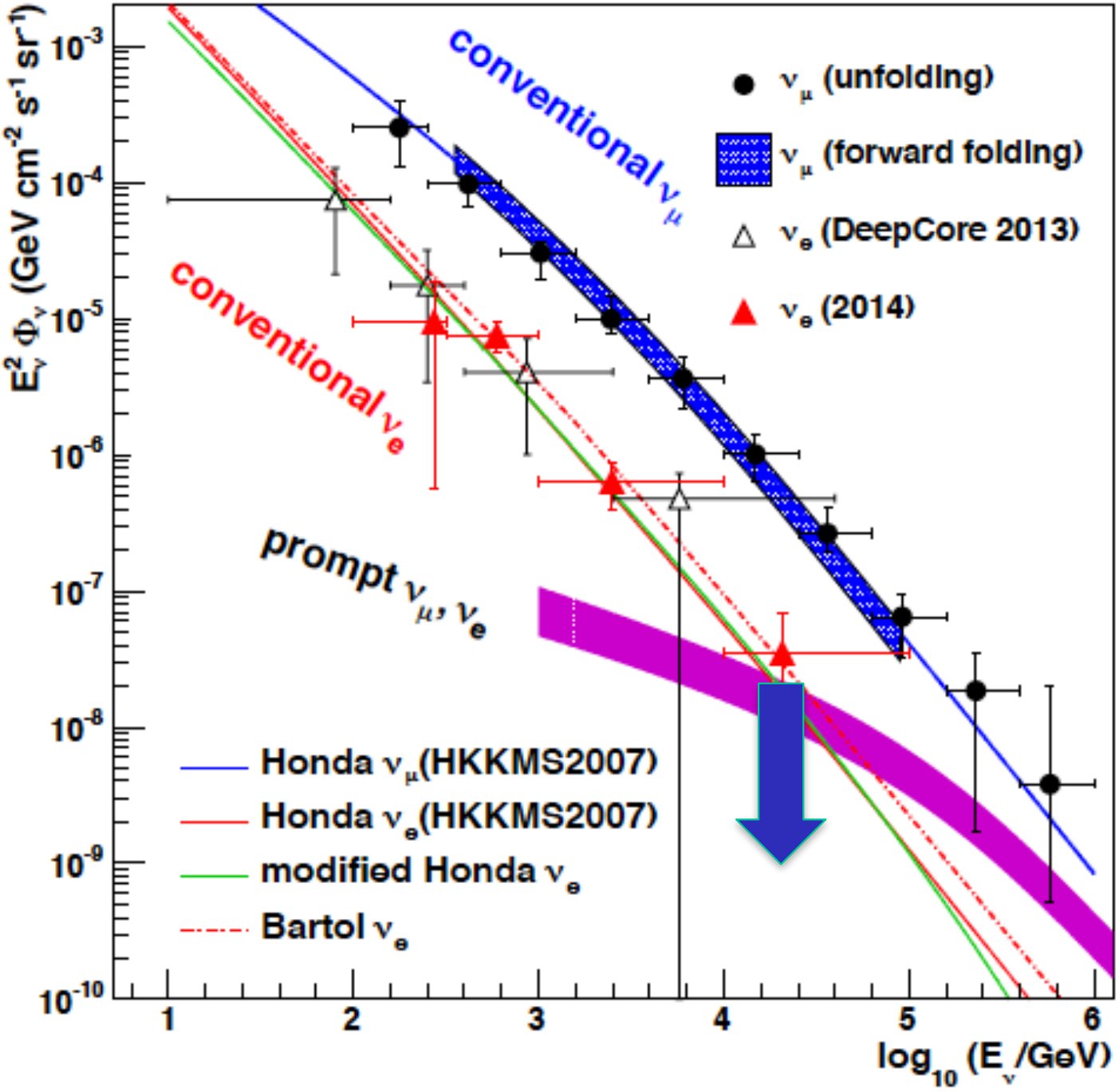

Fluxes and Limits
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]
EHE Differential Flux 90% Upper Limit
Fit Astrophysical Fluxes
Contained vertex (HESE) *
ν_μ Best Fit
Contained vertex (HESE) - best fit*
*IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^4
10^5
10^6
10^7
10^8

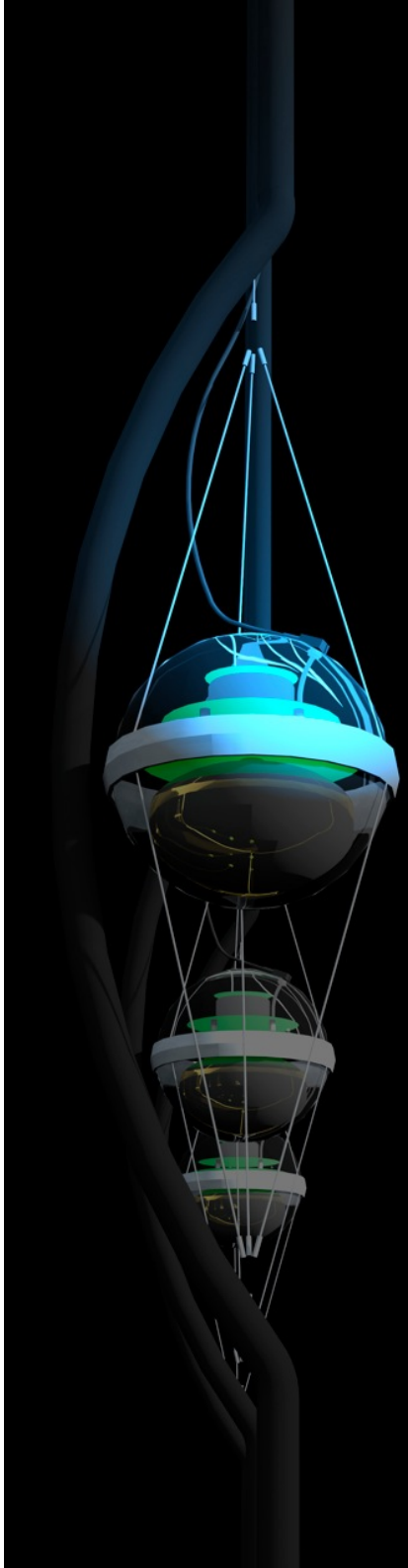
ANTARES


atm. ν
atm. μ
astrophys. flux
Data
number of events
10^2
10
1
10^{-1}
10^{-2}
10^3
10^4
10^5
10^6
reconstructed shower energy [GeV]


neutrino fluxes
(per flavor)
atmo. $\nu_\mu + \bar{\nu}_\mu$
(before HESE veto)
atmo. $\nu_e + \bar{\nu}_e$
(before HESE veto)
HESE
(6yr)
$\nu_\mu + \bar{\nu}_\mu$
(8yr)
$E^2\phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8

charm limited by atmospheric electrons

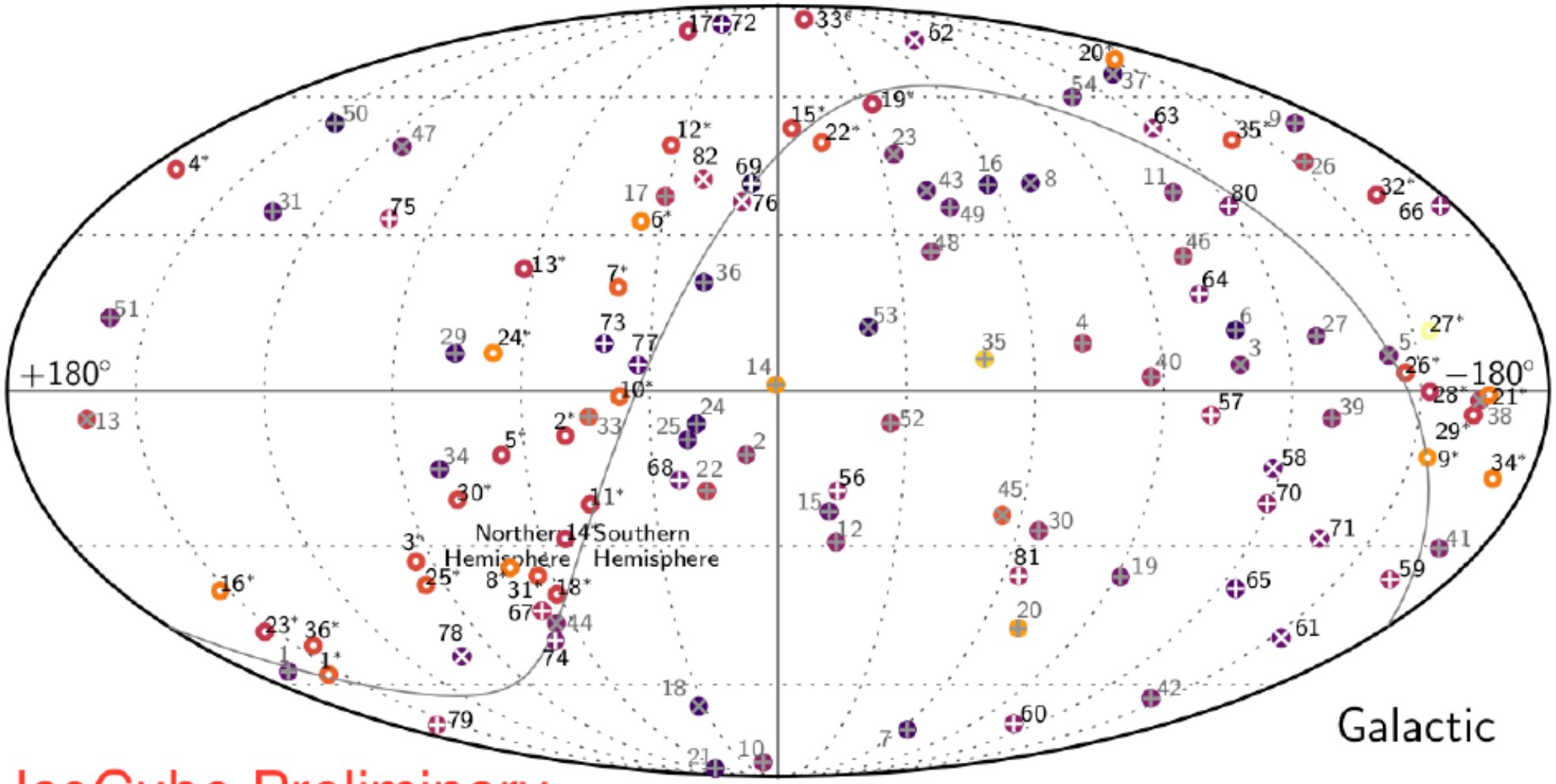




IceCube

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?



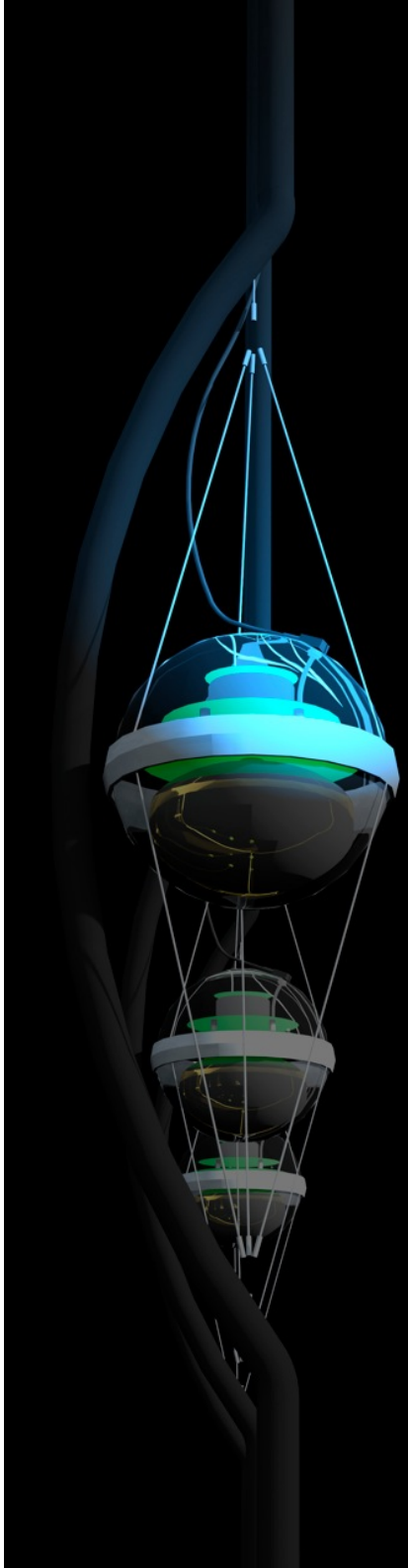
IceCube Preliminary

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)
- [decay of halo dark matter particles?]

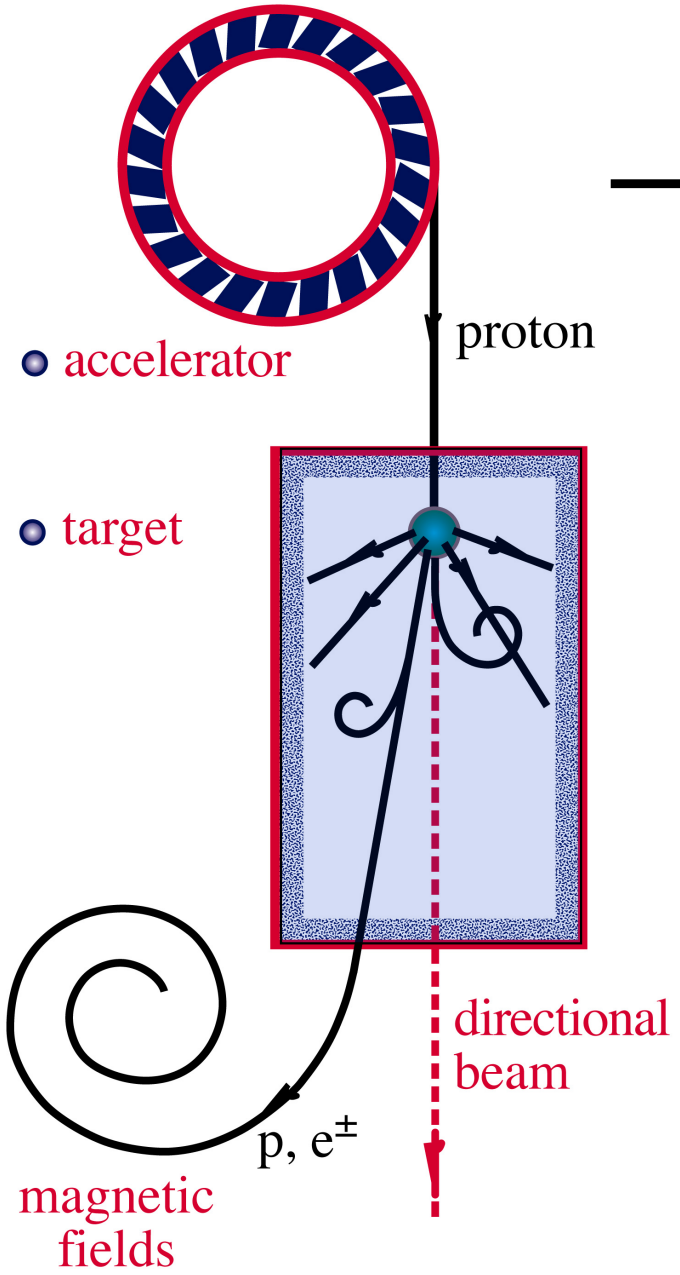


IceCube

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
- cosmic neutrinos below 100 TeV?

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

neutral pions

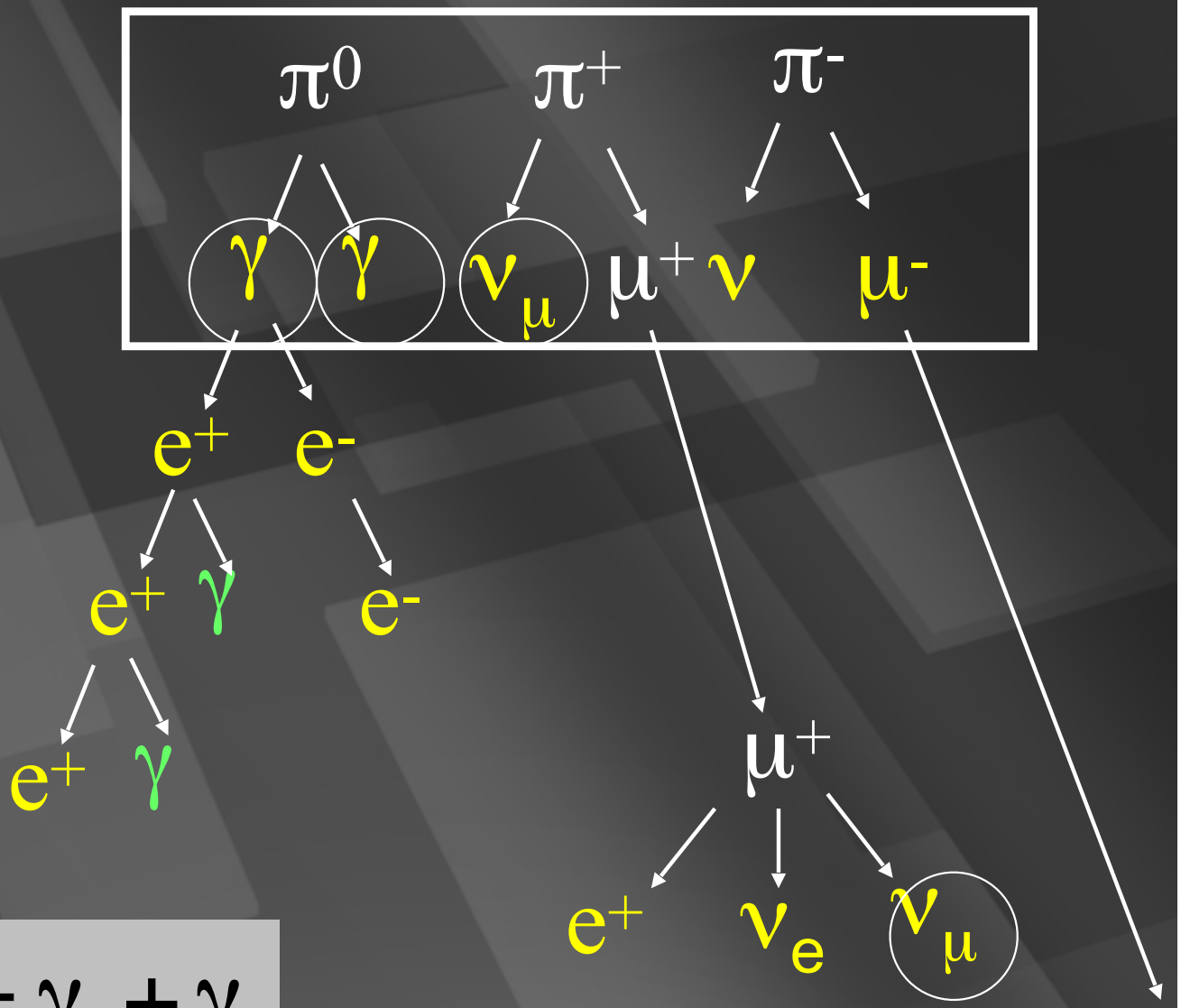
are observed as

gamma rays

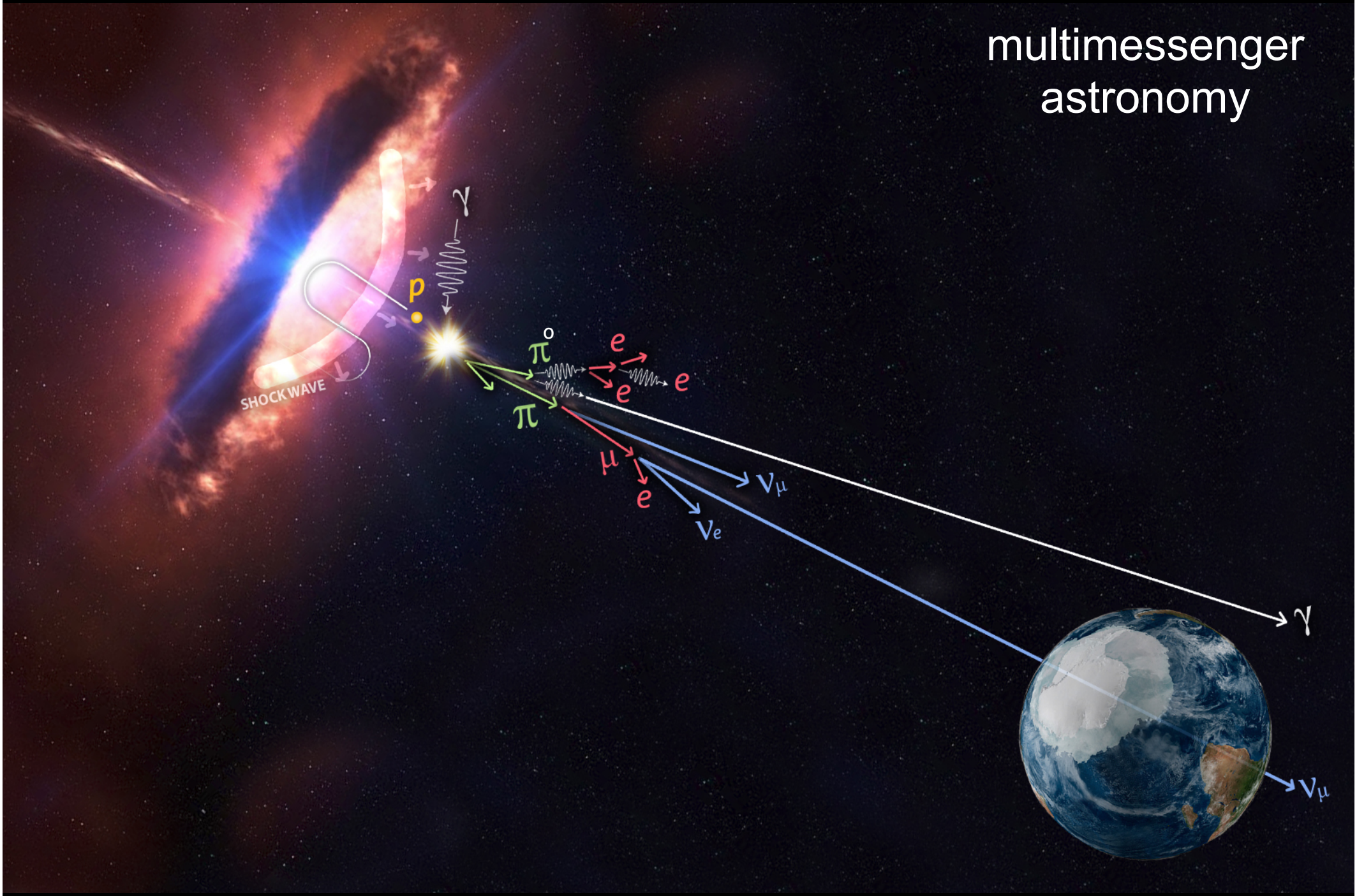
charged pions

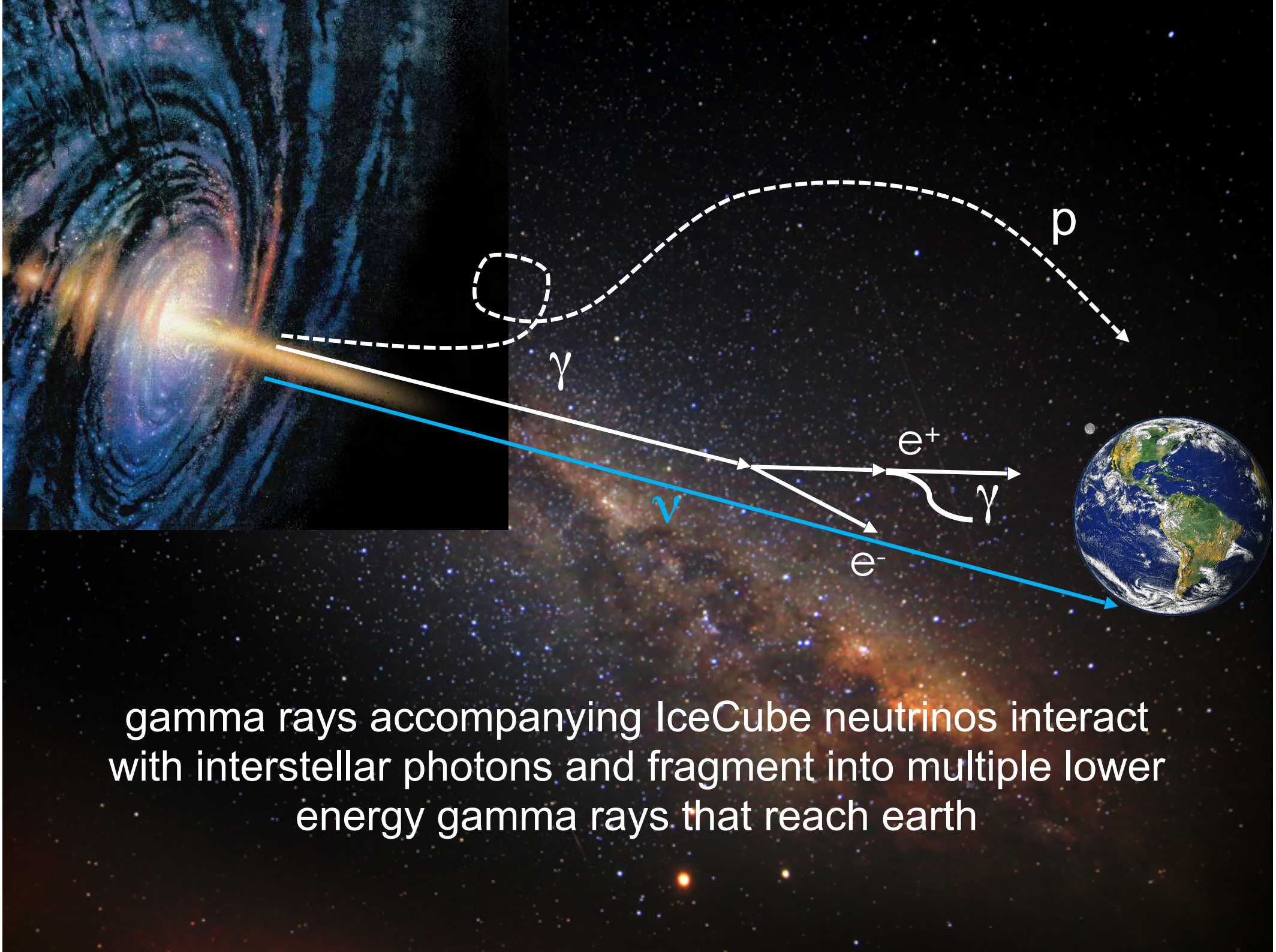
are observed as

neutrinos

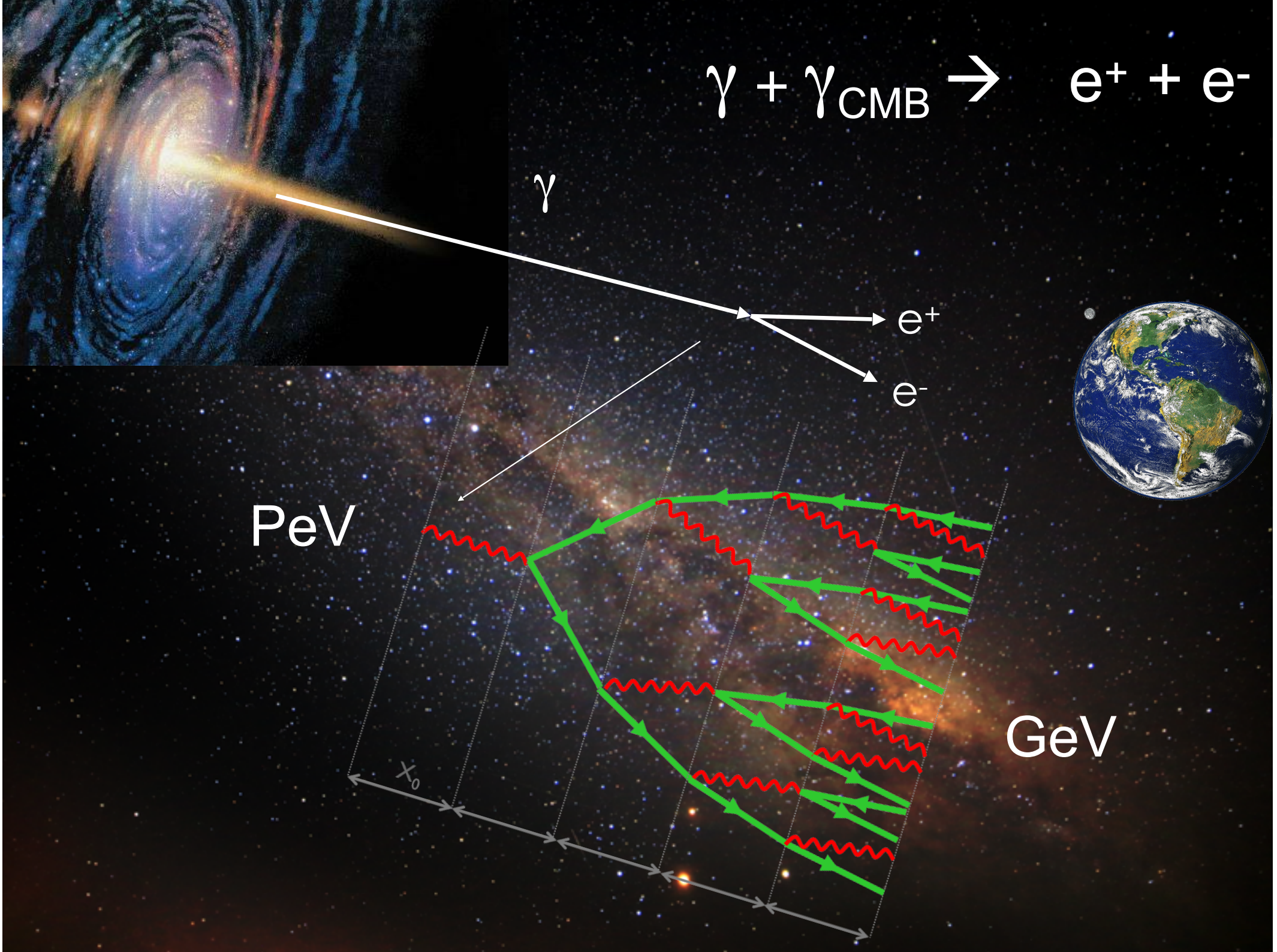


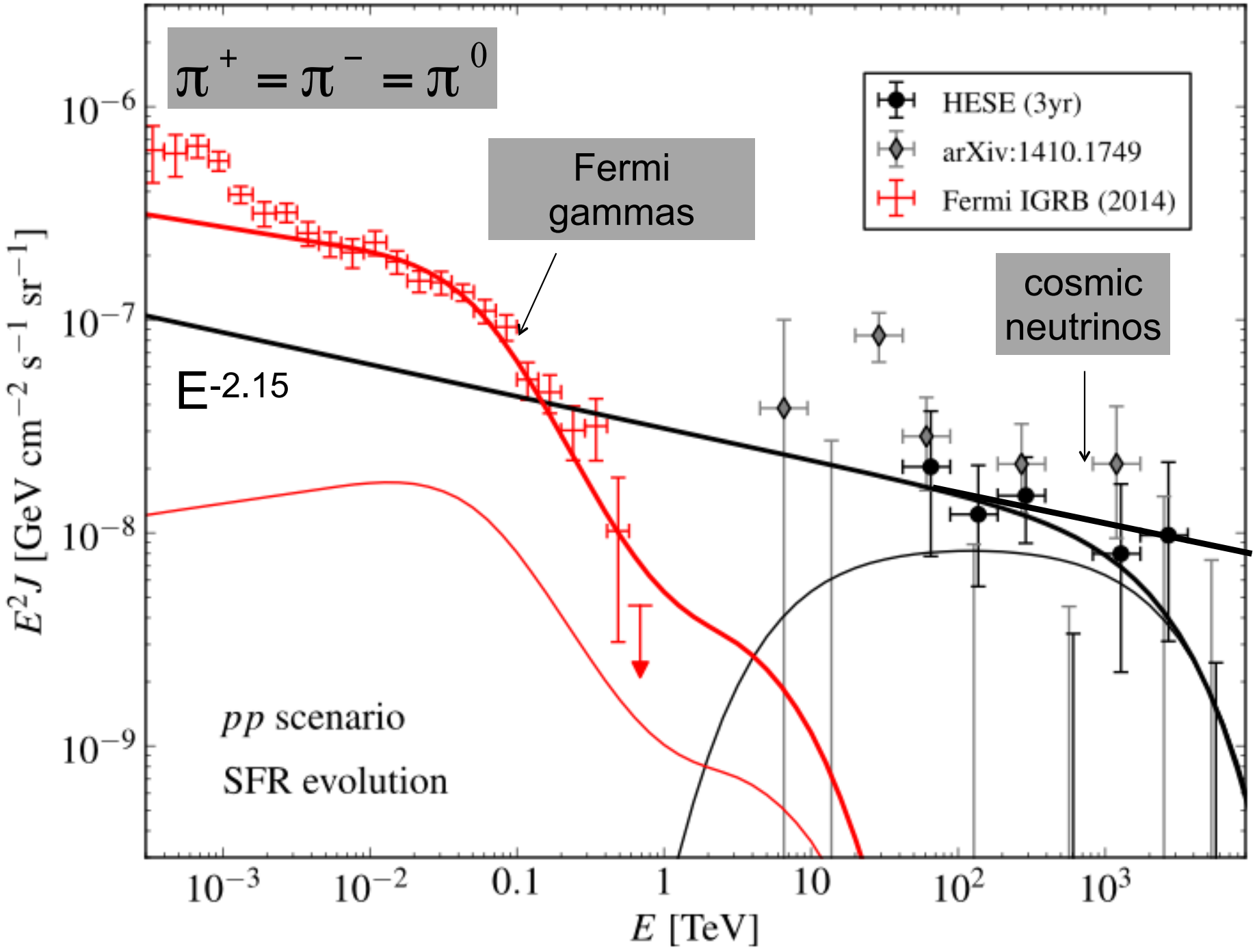
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$


multimessenger
astronomy
γ
p
SHOCK WAVE
π
o
e
e
e
π
μ
e
νμ
νe
γ
νμ

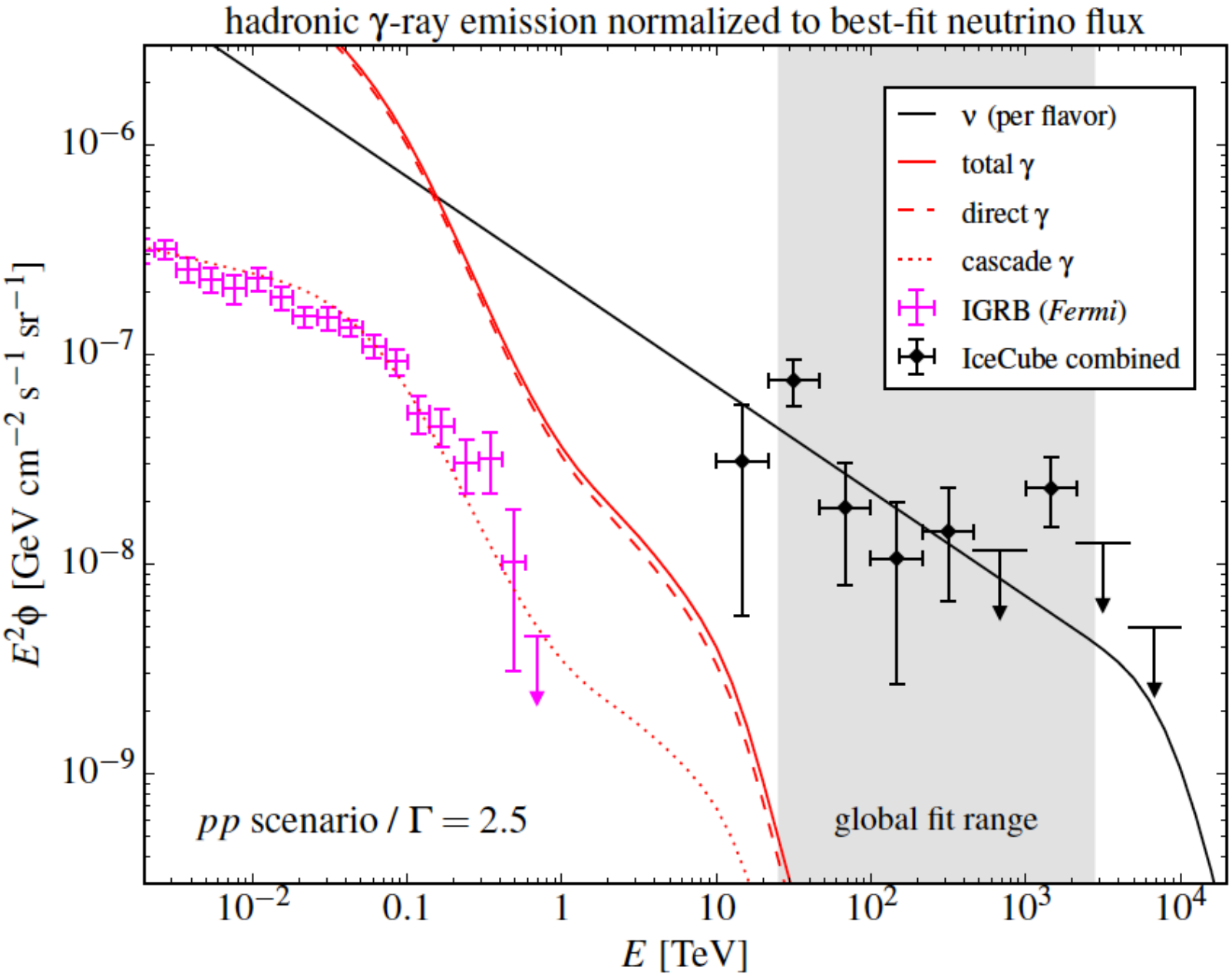


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

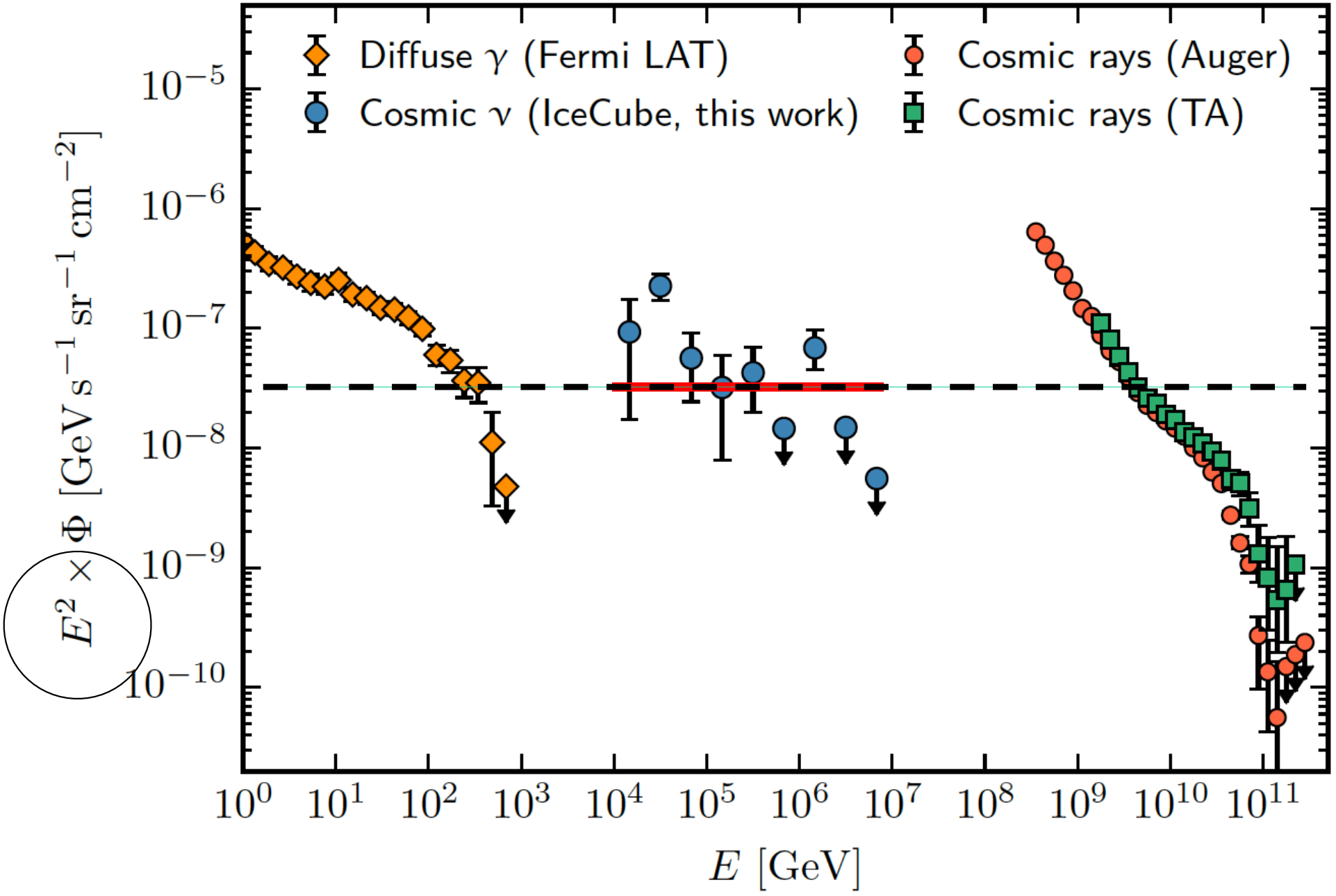

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0


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

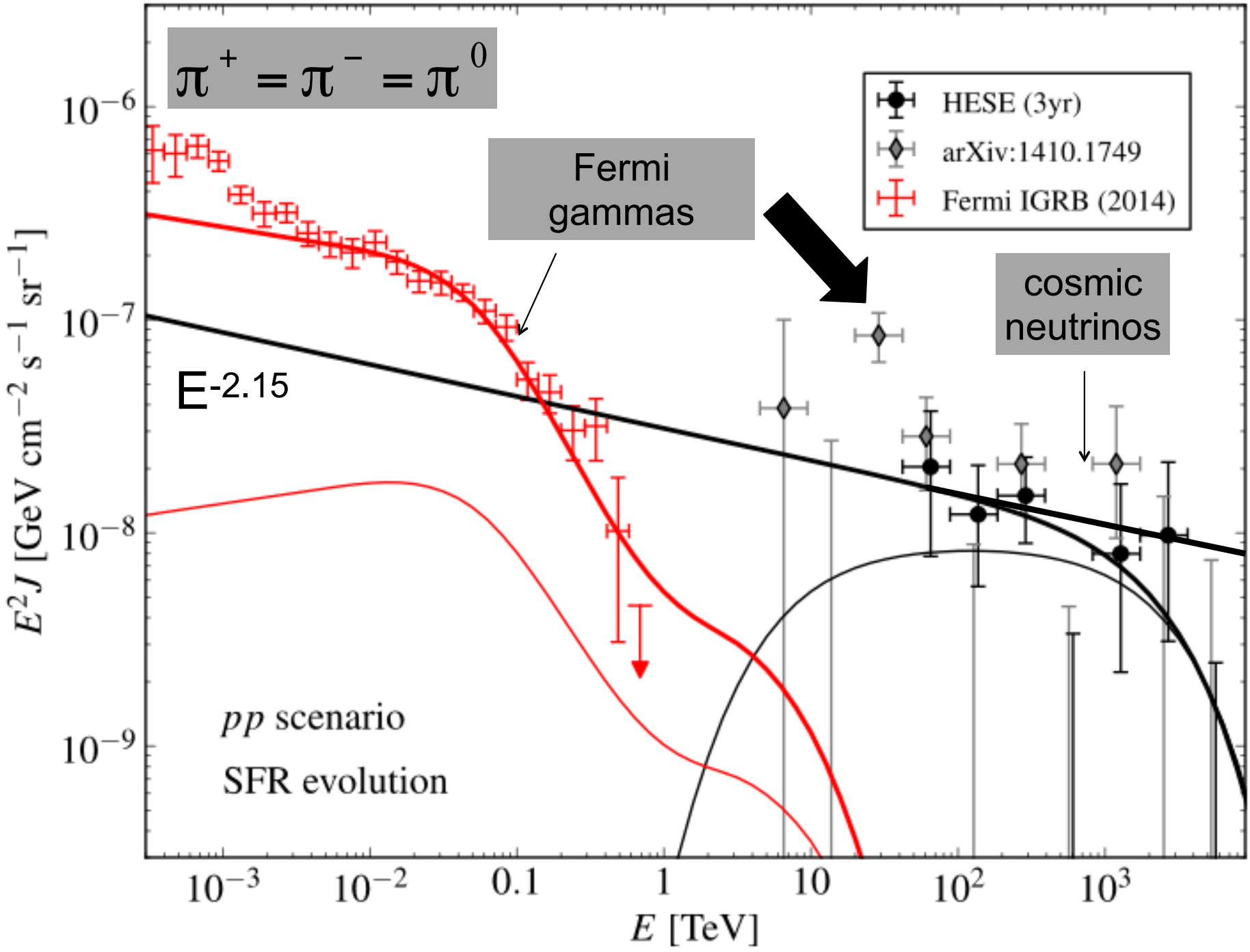
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



dark sources: a “problem” ?
gamma rays cascade in the source to < GeV energy



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


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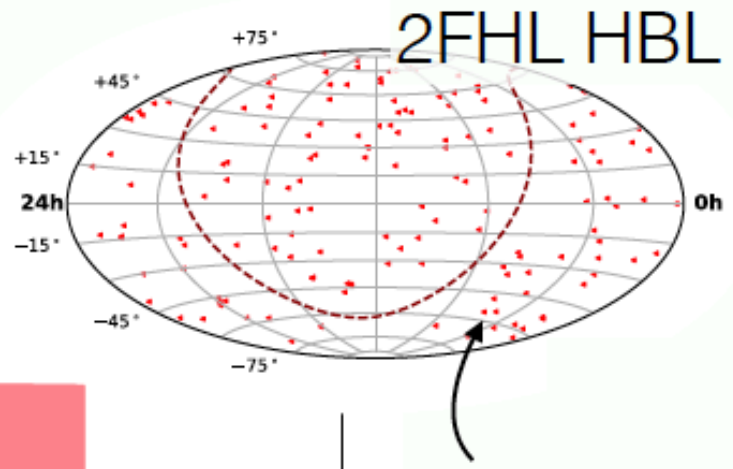
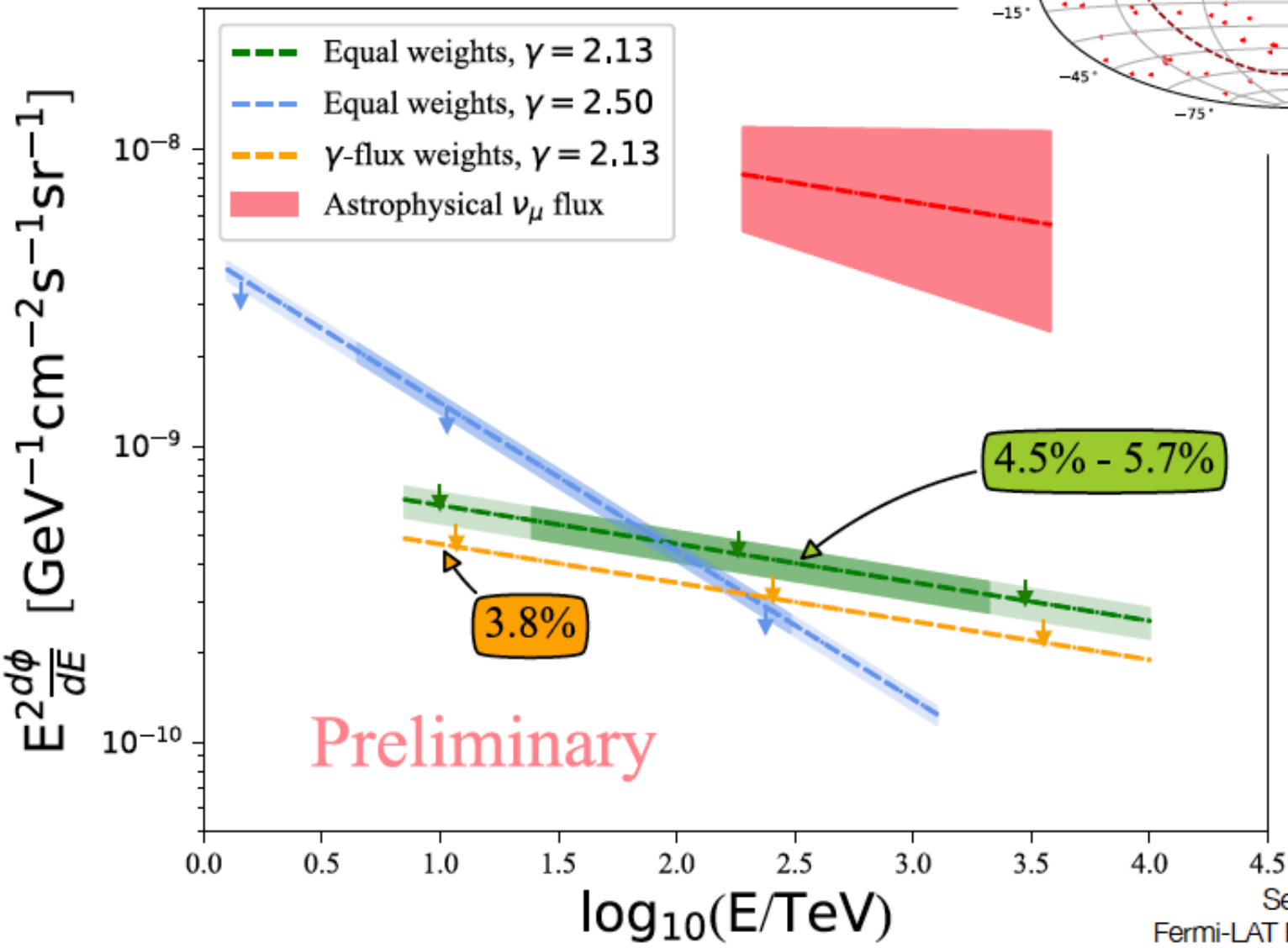
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

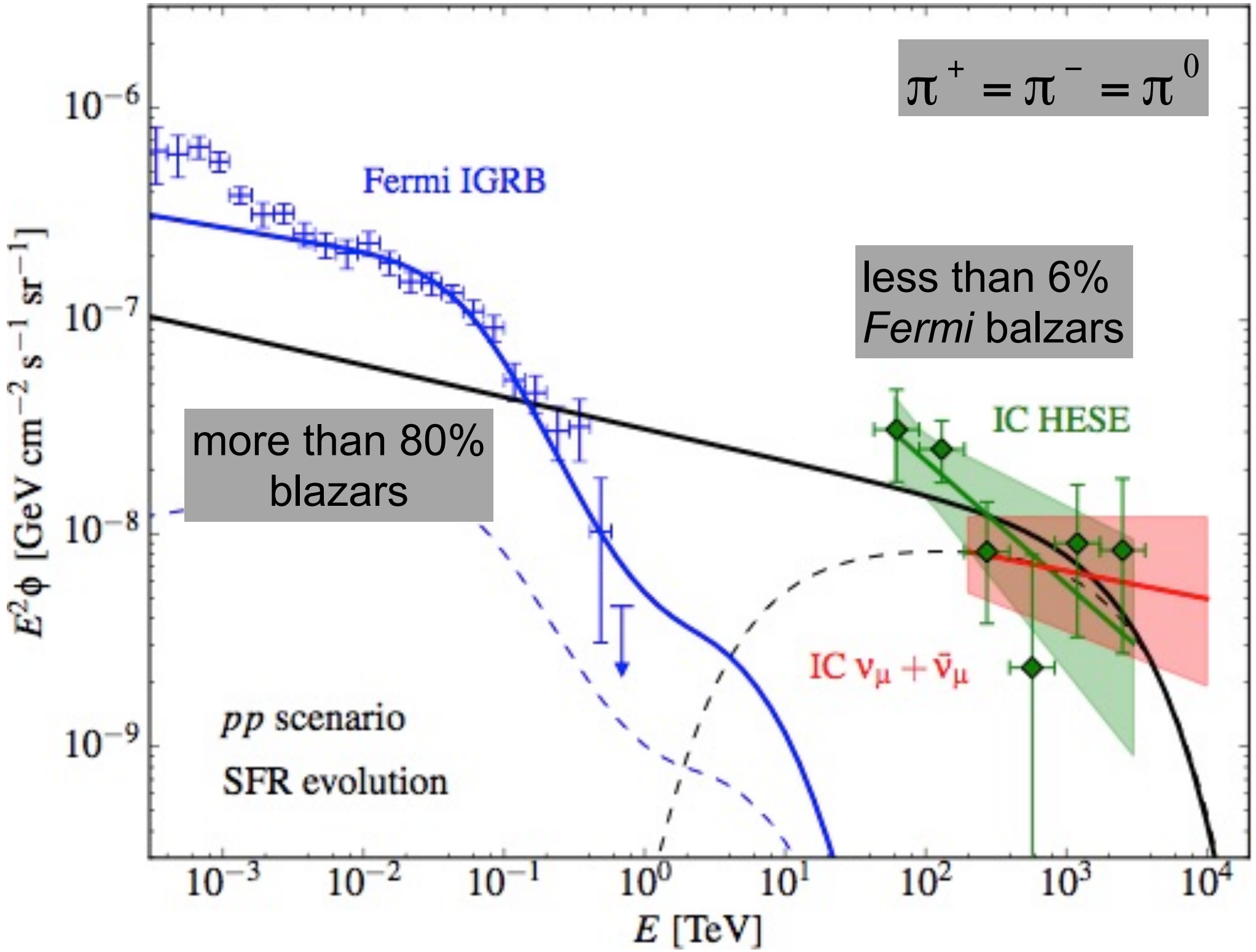
Population studies: blazar catalog search

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

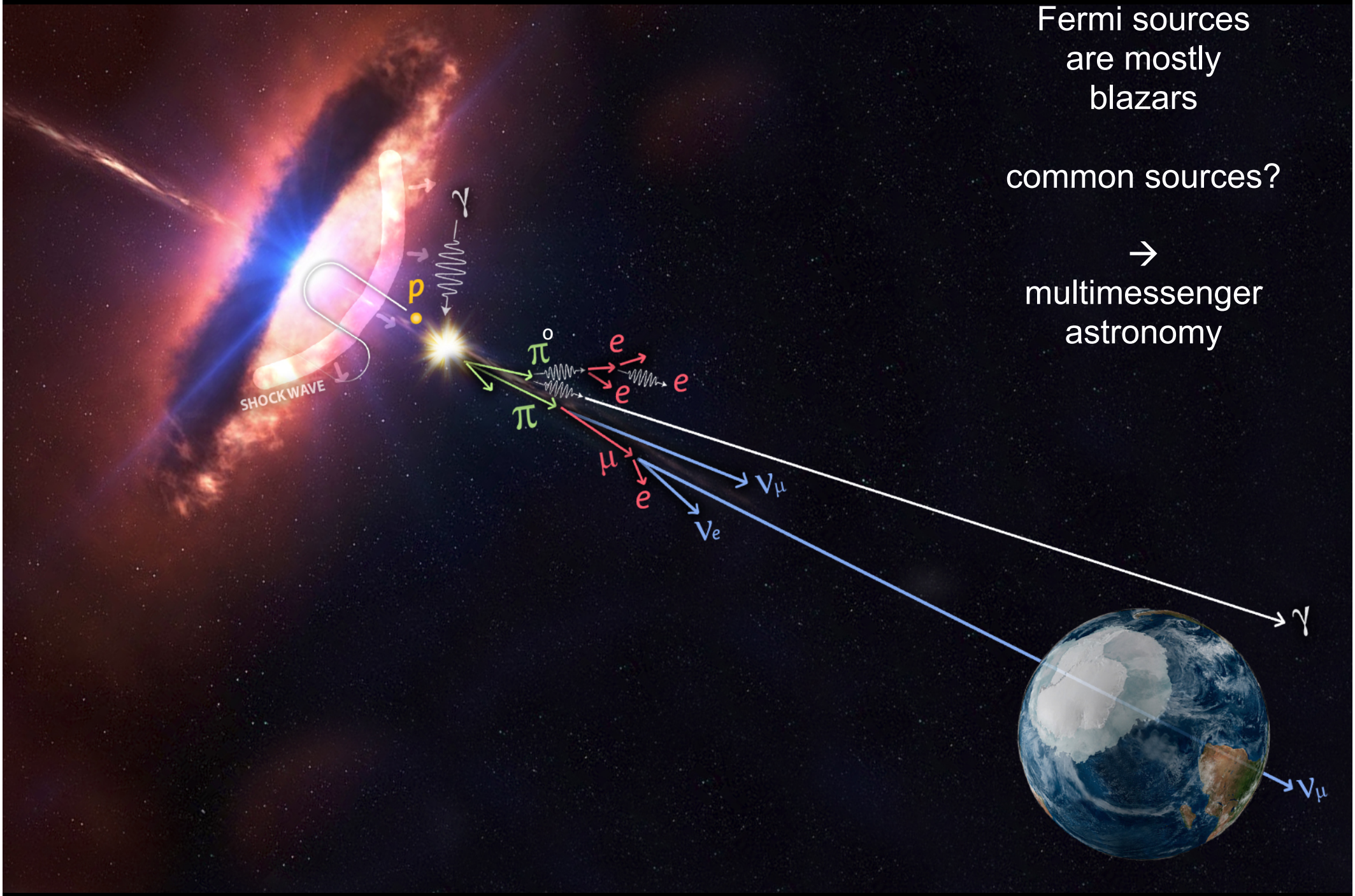


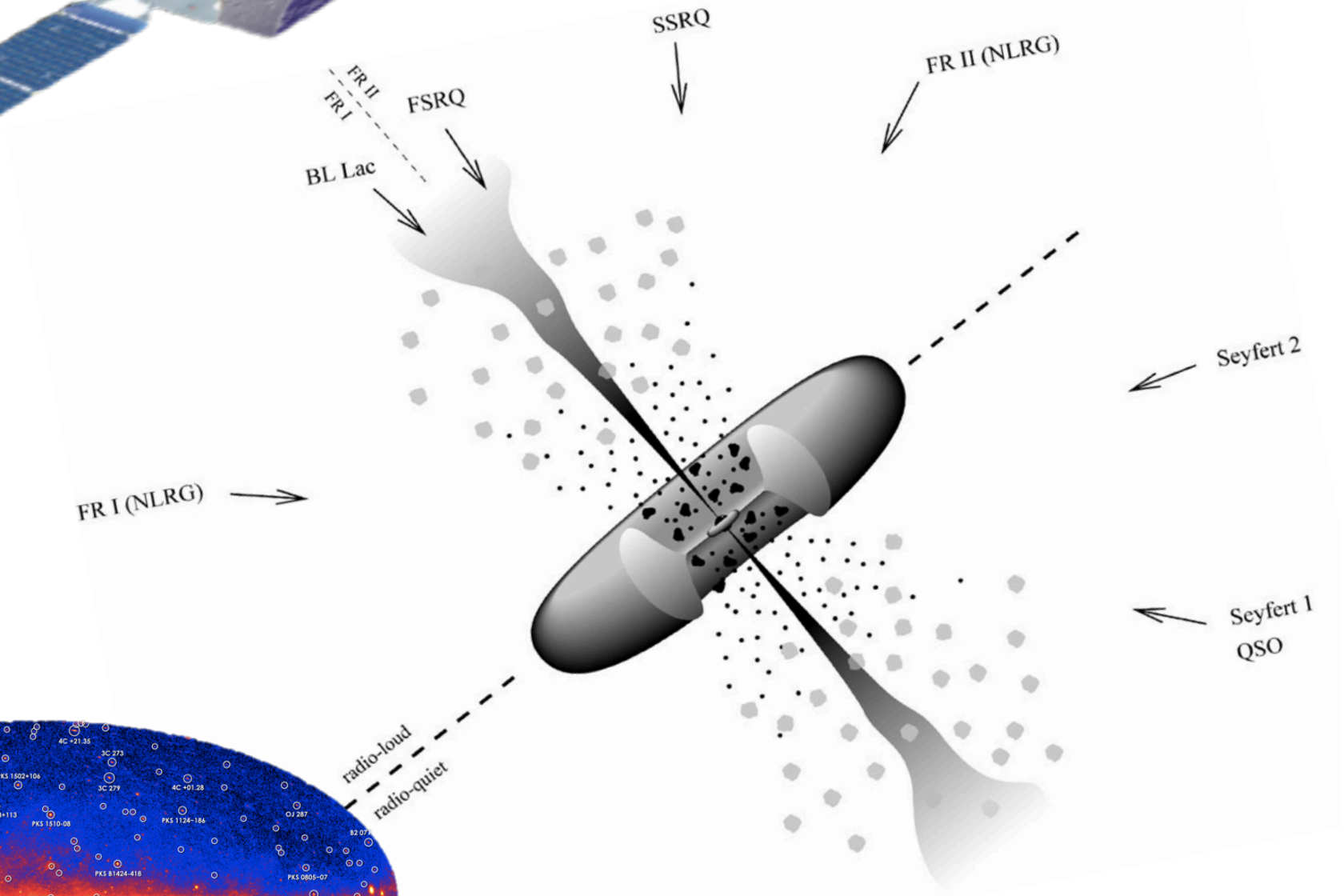


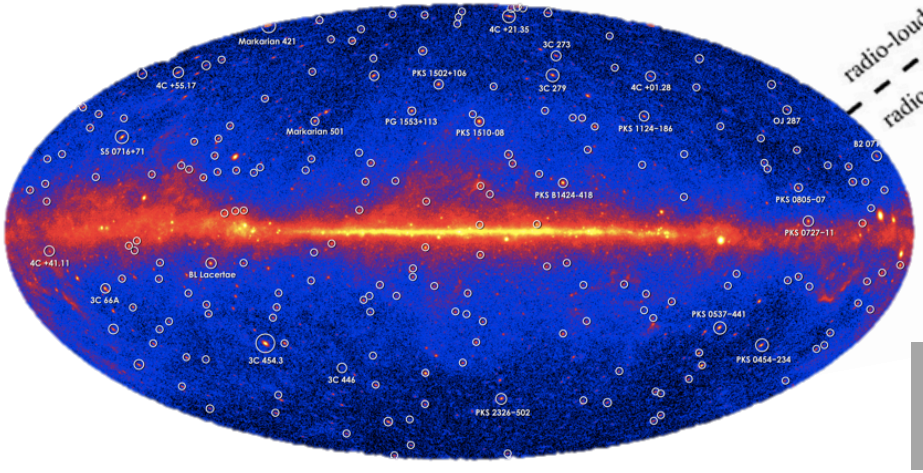
See: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45


$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
less than 6%
Fermi balzars
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}

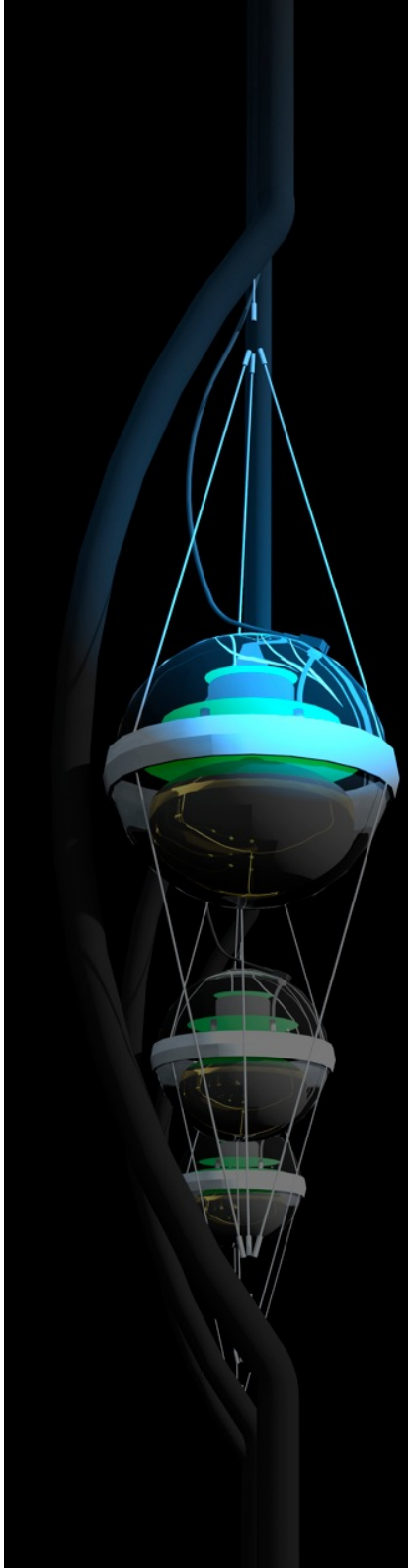
note that the gammas rays accompanying < 100 TeV neutrinos are not seen suggesting a hidden source(s)


Fermi sources
are mostly
blazars
common sources?
→
multimessenger
astronomy
γ
p
SHOCK WAVE
π°
e
e
e
π
μ
e
νμ
νe
γ
νμ





Fermi sky: mostly bazars

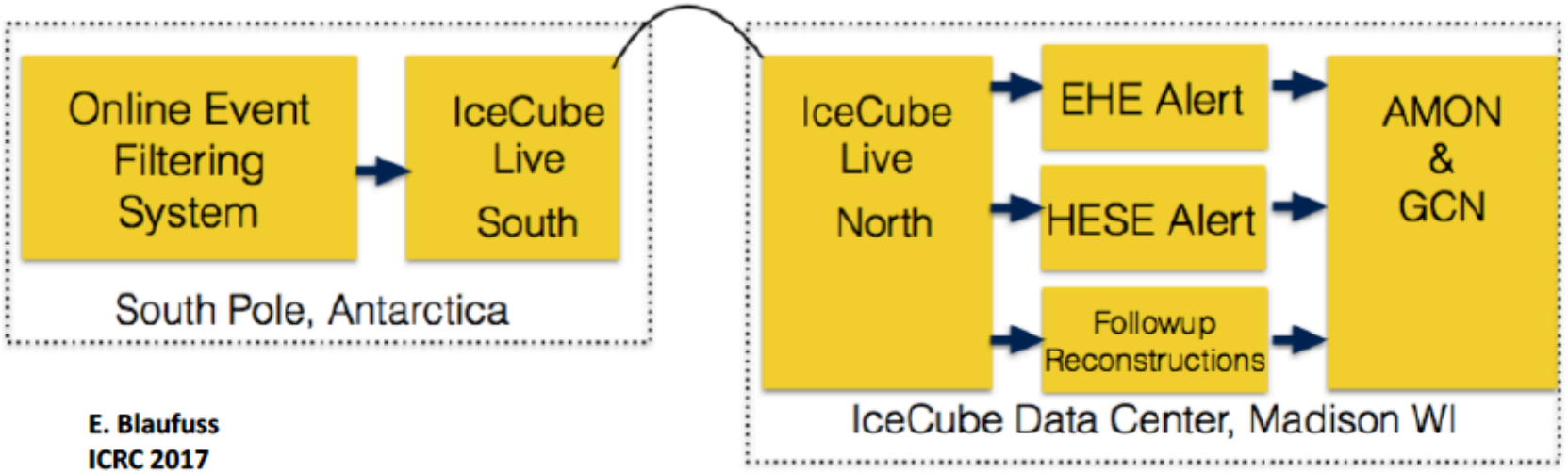


IceCube

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?

Realtime alerts from IceCube



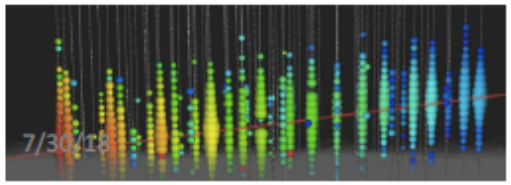
E. Blaufuss
ICRC 2017

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**

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

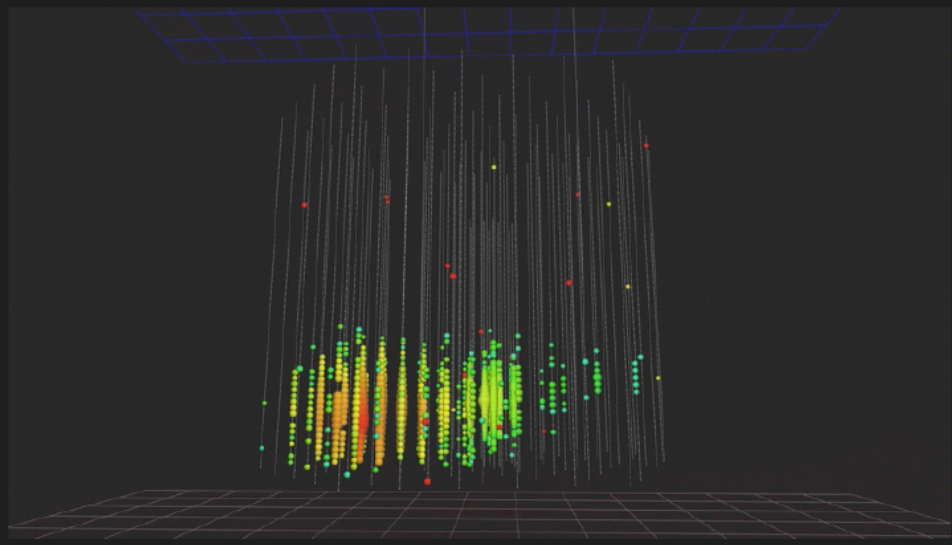
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

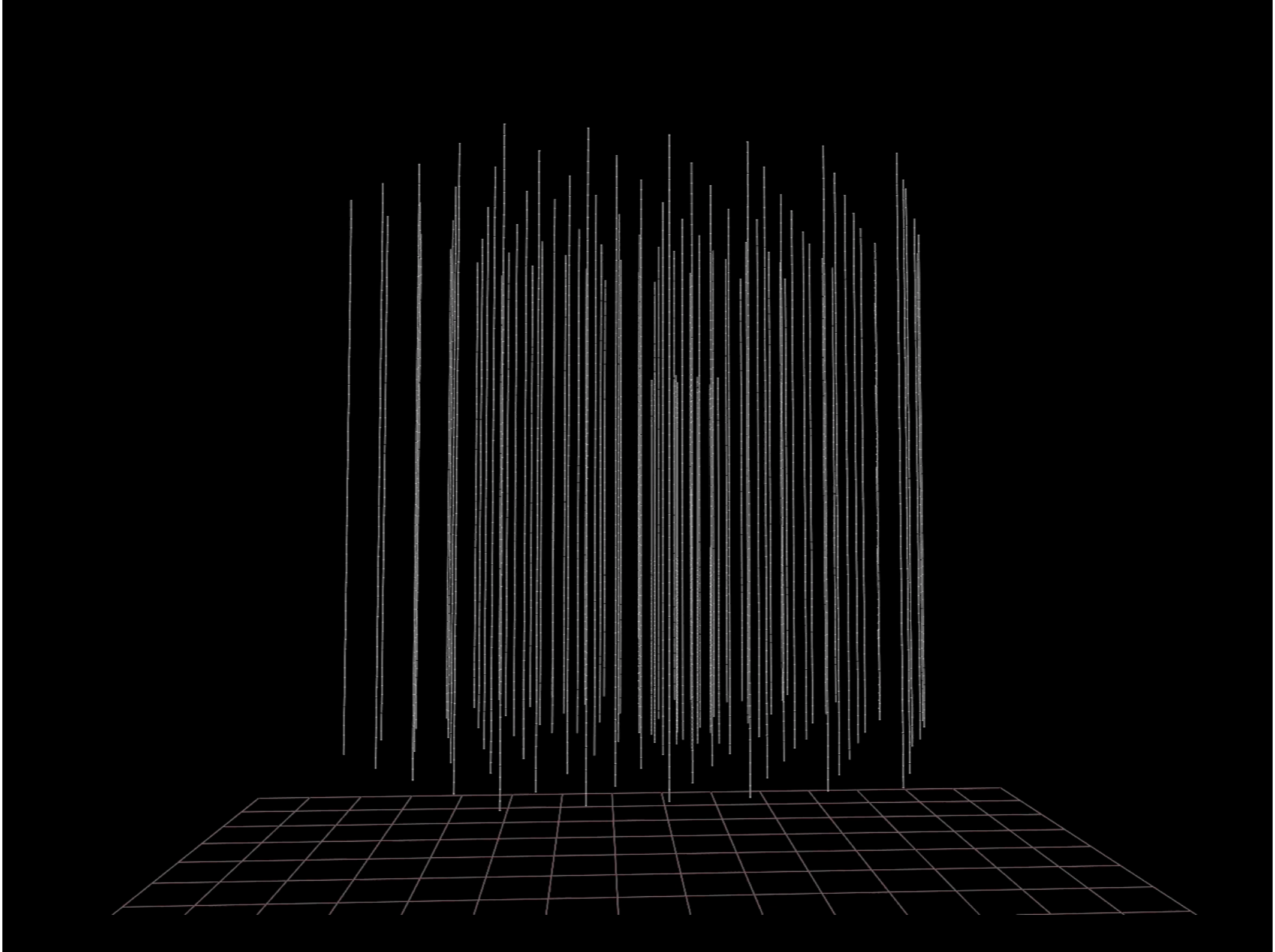
We send **rough reconstructions first** and then **update them.**

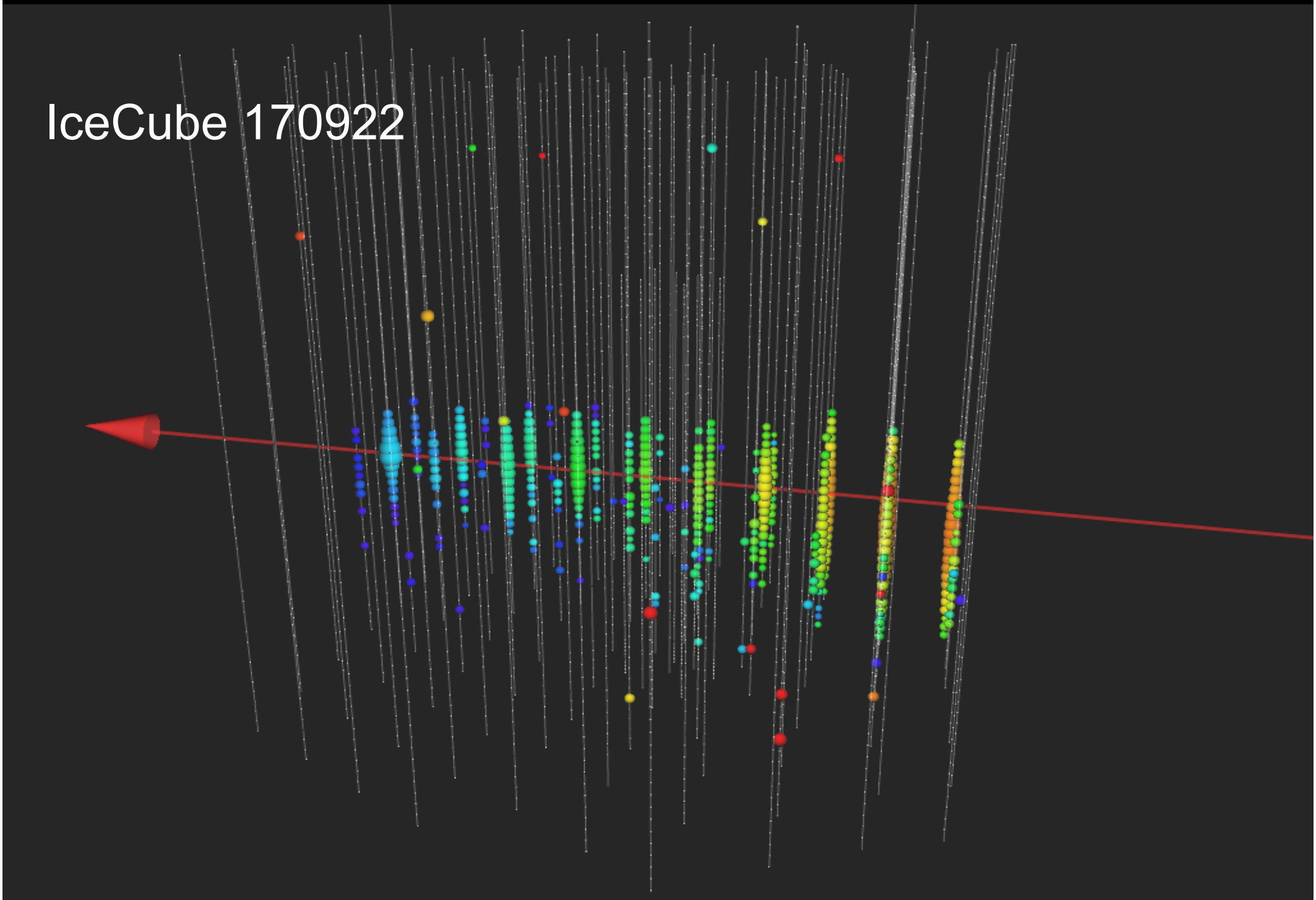


IceCube Trigger

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

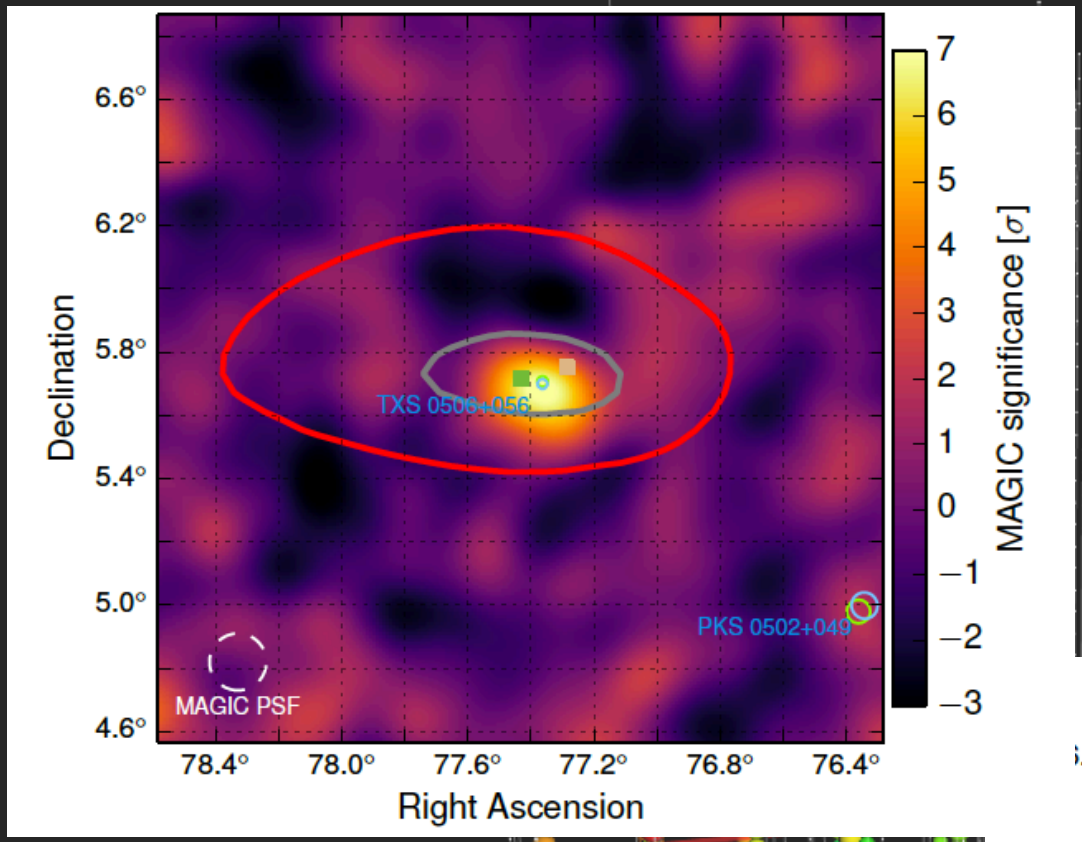
multiwavelength campaign launched by IC 170922

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

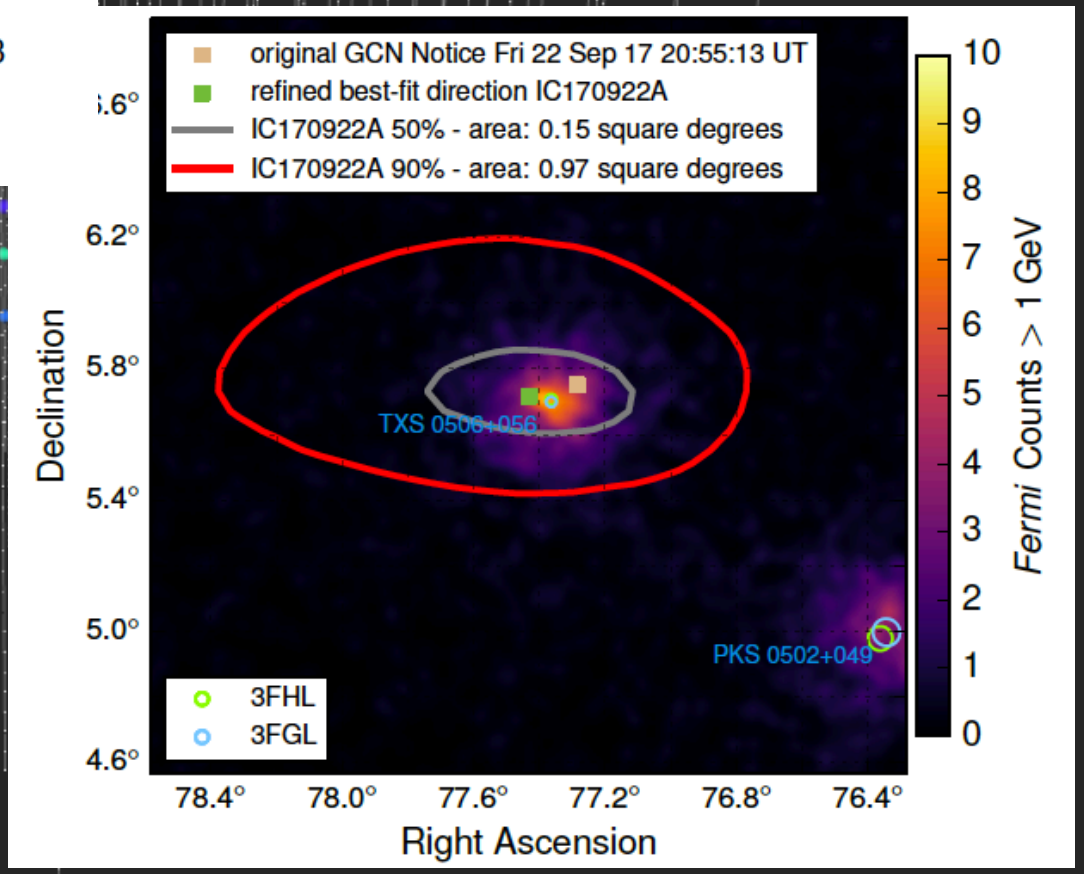
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.1^{o} (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT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

IceCube 170922

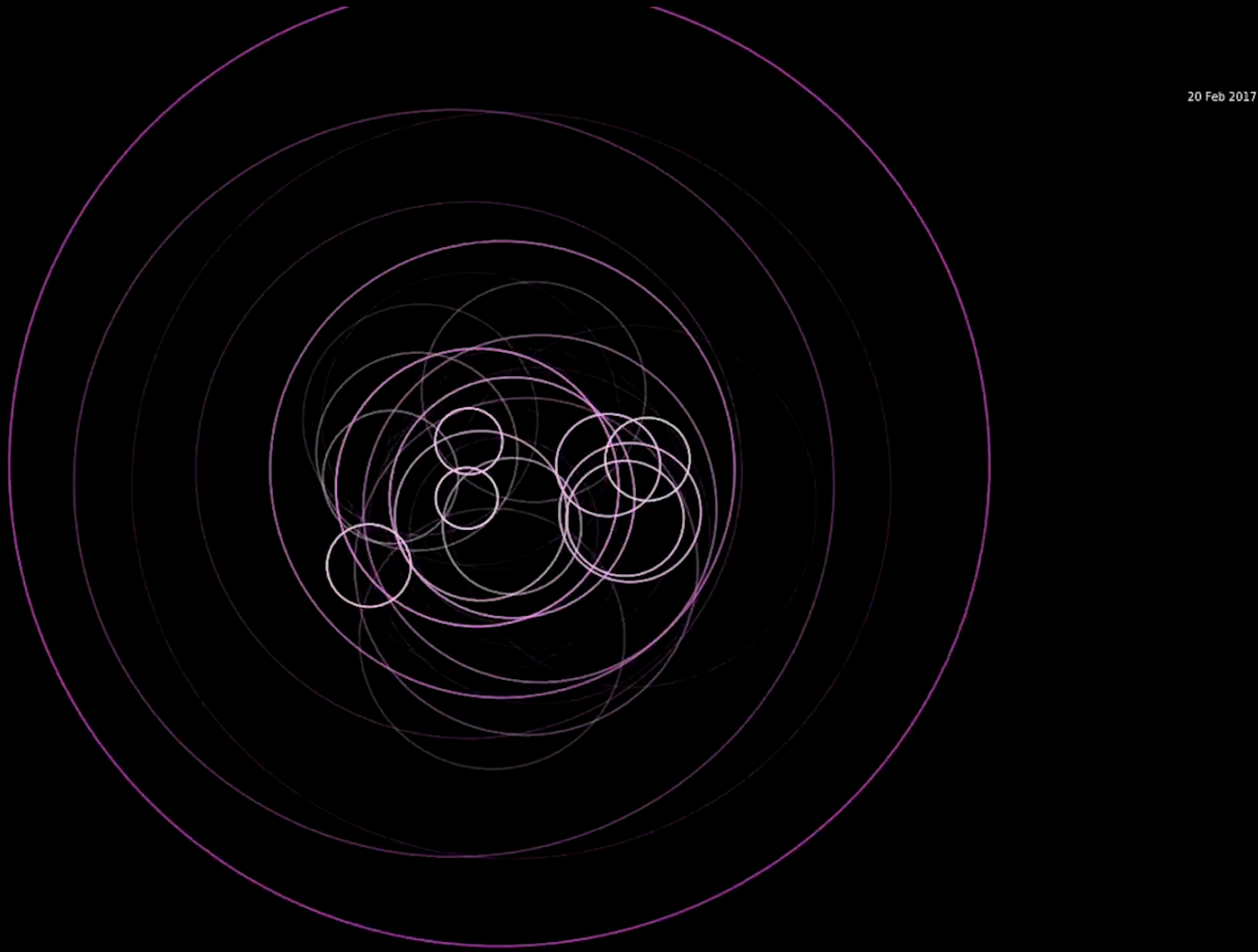
Fermi
detects a flaring
blazar within 0.1°



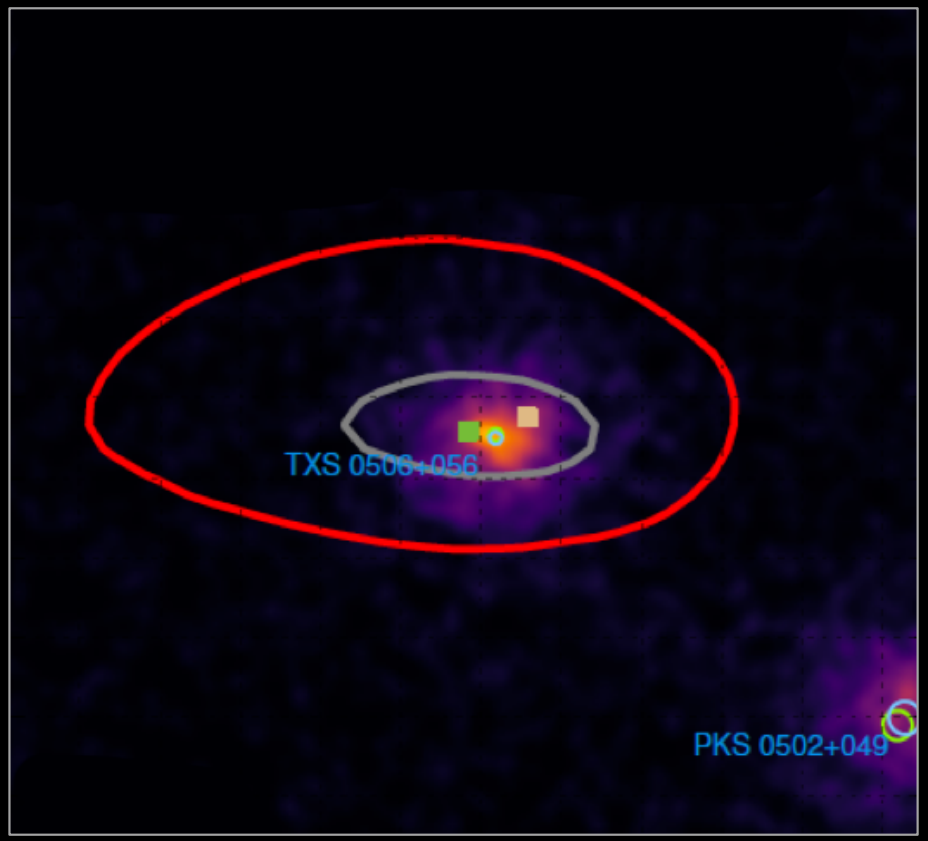
MAGIC
detects emission of
> 100 GeV gammas



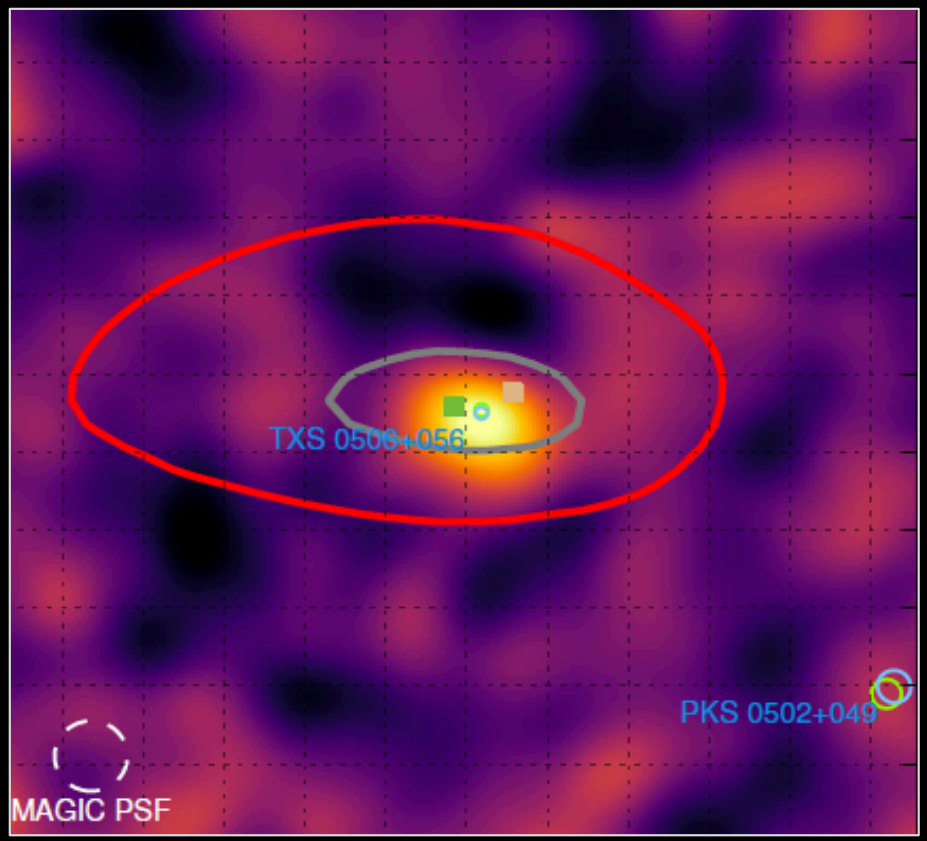
build-up over several months followed by rapid daily variability



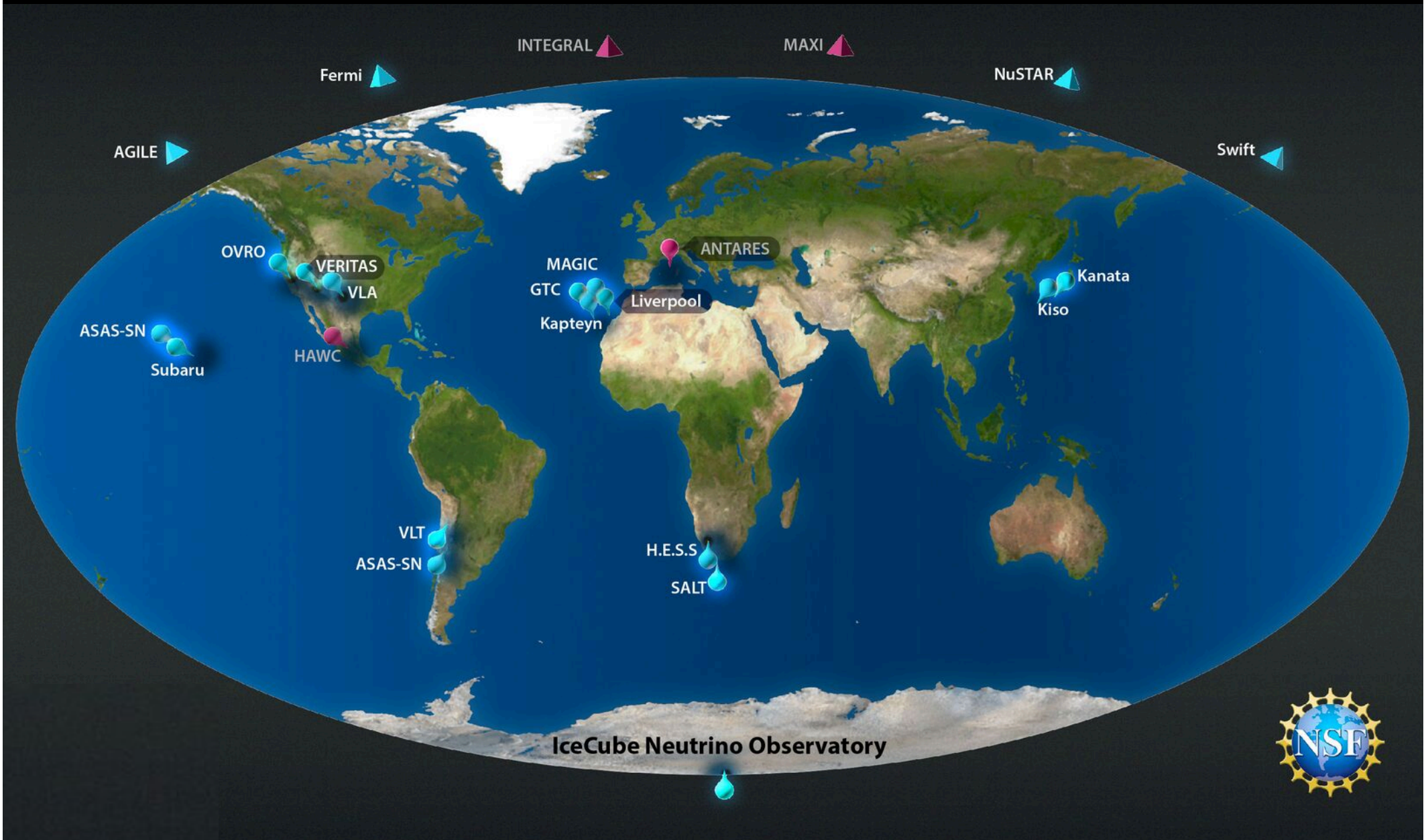
Neutrino points within 0.06° of a known Fermi blazar



MAGIC detects emission of >100 GeV gammas



MAGIC atmposheric Cherenkov telescope


INTEGRAL
MAXI
Fermi
NuSTAR
AGILE
Swift
OVRO
VERITAS
VLA
ANTARES
MAGIC
GTC
Liverpool
Kapteyn
Kanata
Kiso
ASAS-SN
Subaru
HAWC
VLT
ASAS-SN
H.E.S.S
SALT
IceCube Neutrino Observatory
NSF

multiwavelength campaign launched by IC 170922

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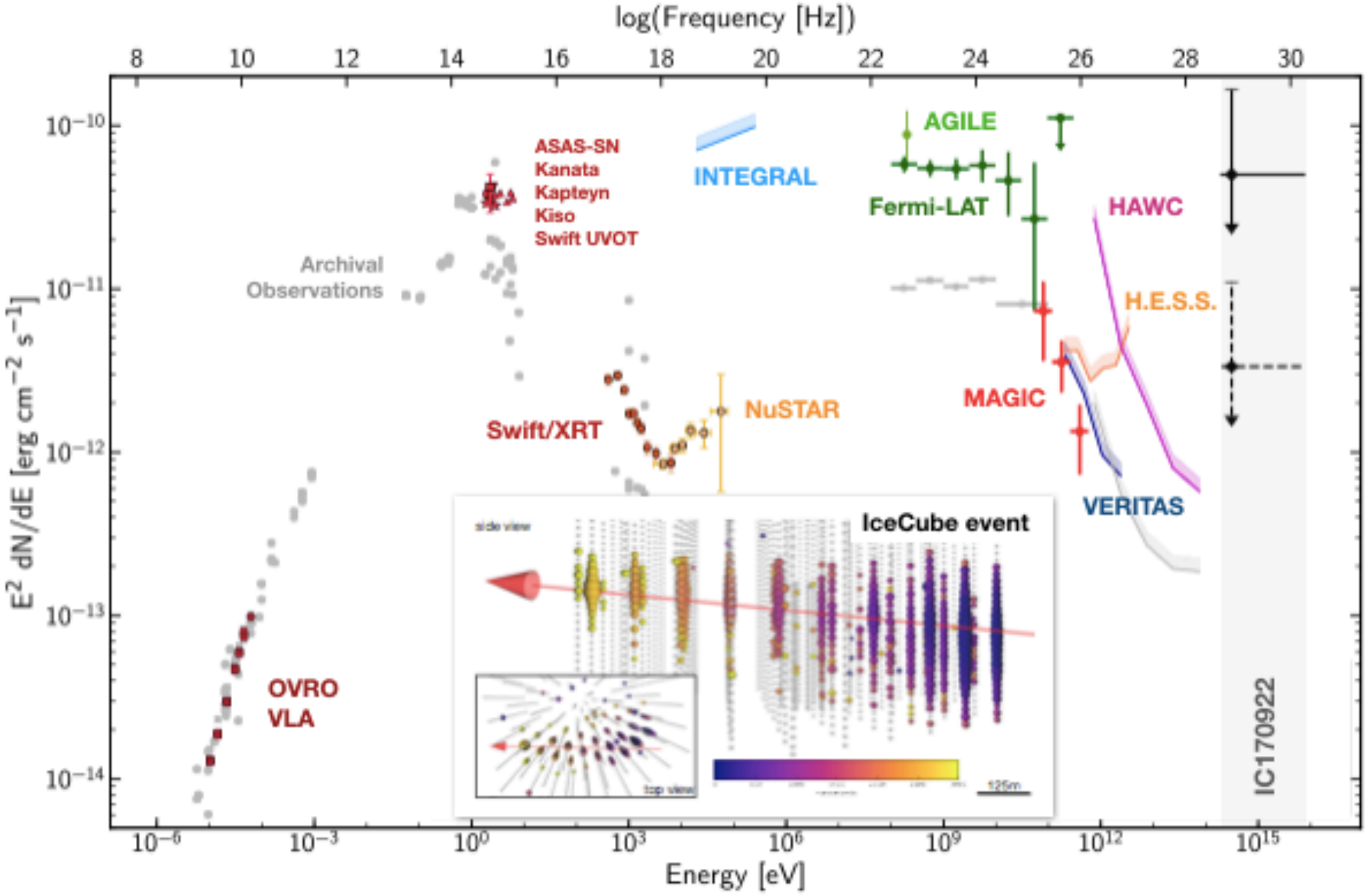
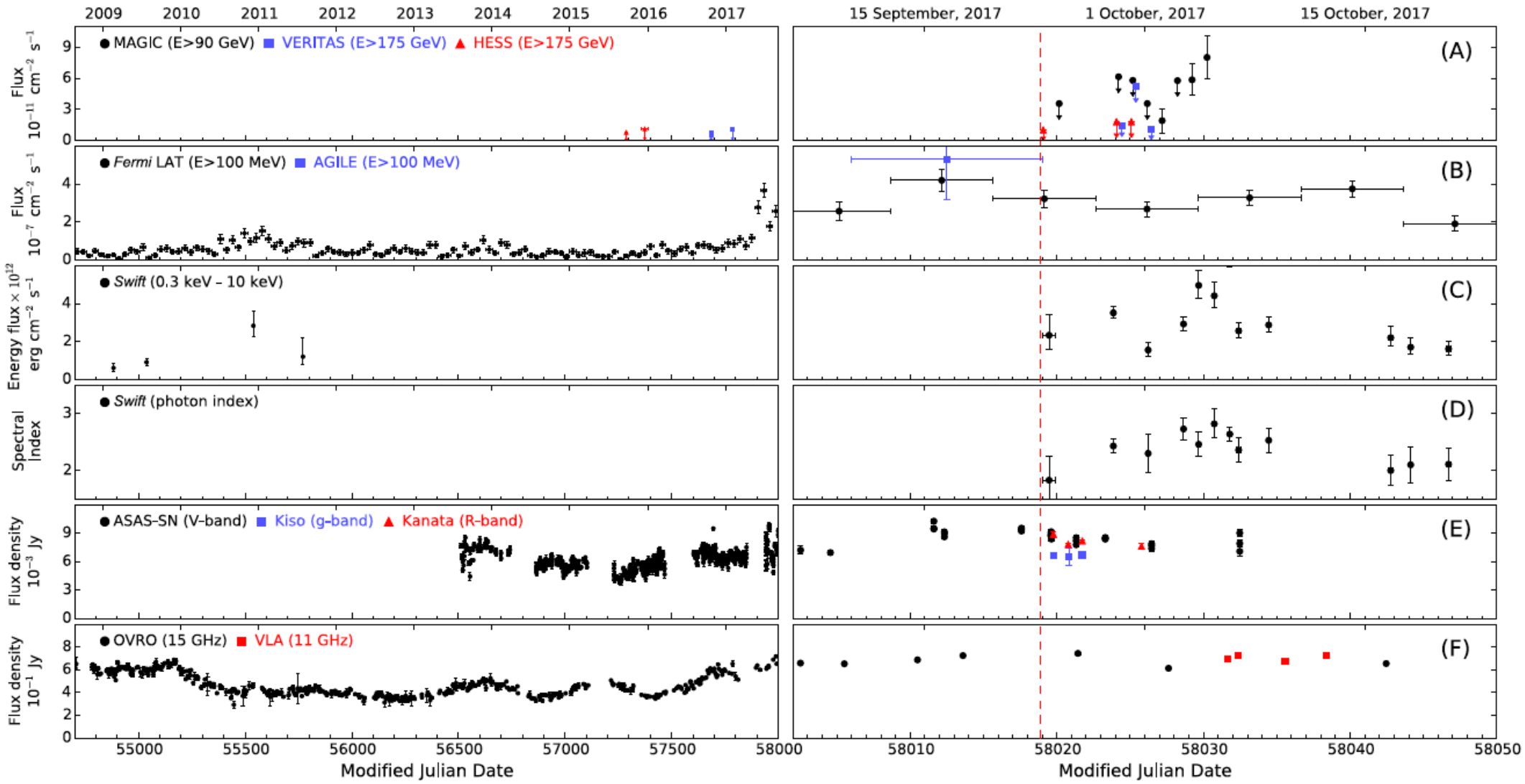
- → Fermi-LAT archival data

The Source: TXS 0506+056

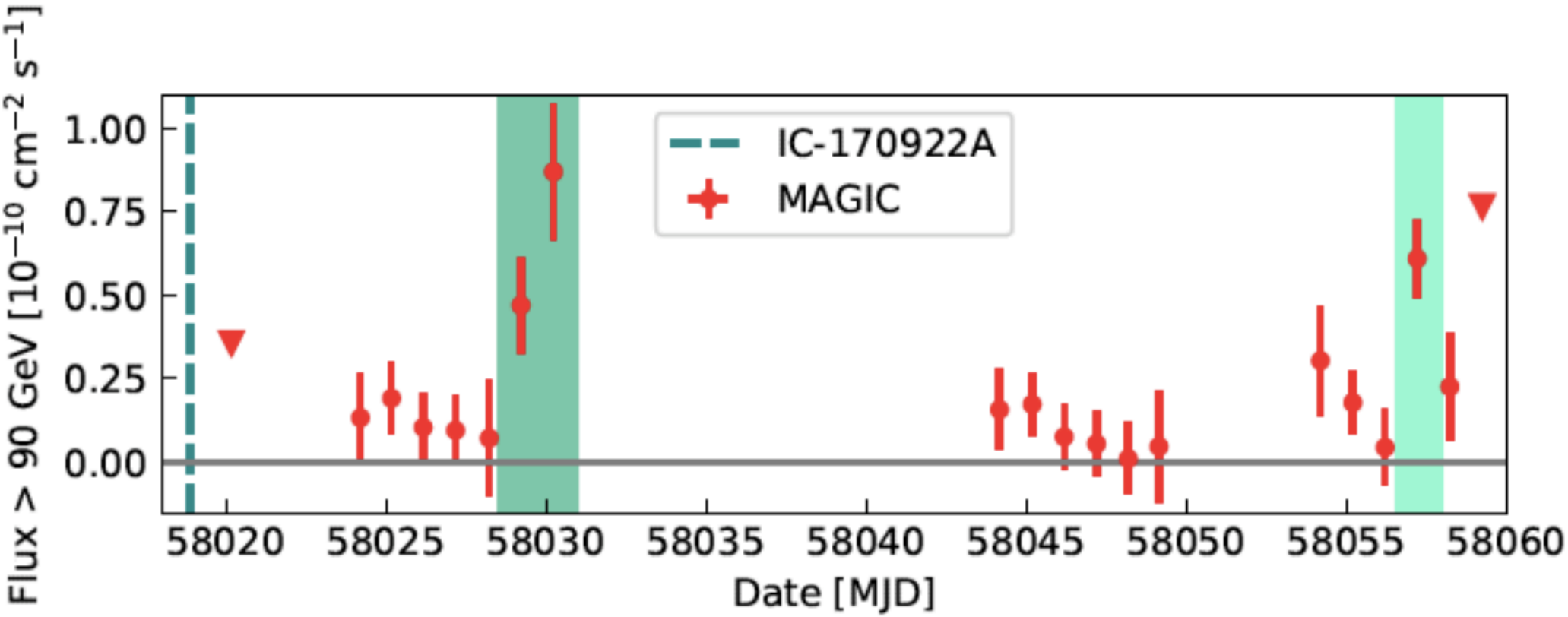
- Redshift 0.3365±0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC

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

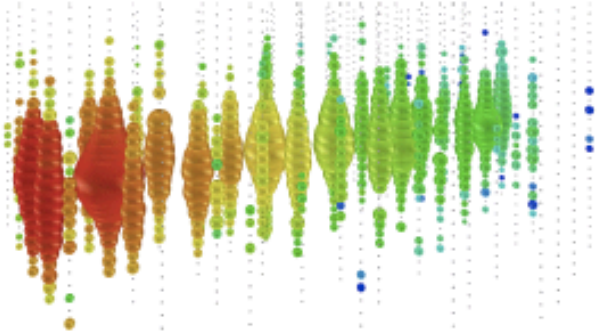

log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
ASAS-SN
Kanata
Kapteyn
Kiso
Swift UVOT
Archival
Observations
INTEGRAL
AGILE
Fermi-LAT
HAWC
H.E.S.S.
MAGIC
VERITAS
Swift/XRT
NuSTAR
OVRO
VLA
IceCube event
side view
top view
125m
IC170922


2009
2010
2011
2012
2013
2014
2015
2016
2017
15 September, 2017
1 October, 2017
15 October, 2017
MAGIC (E>90 GeV) VERITAS (E>175 GeV) HESS (E>175 GeV)
Flux 10^{-11} cm^{-2} s^{-1}
(A)
Fermi LAT (E>100 MeV) AGILE (E>100 MeV)
Flux 10^{-7} cm^{-2} s^{-1}
(B)
Swift (0.3 keV – 10 keV)
Energy flux $\times 10^{12}$ erg cm^{-2} s^{-1}
(C)
Swift (photon index)
Spectral Index
(D)
ASAS-SN (V-band) Kiso (g-band) Kanata (R-band)
Flux density 10^{-3} Jy
(E)
OVRO (15 GHz) VLA (11 GHz)
Flux density 10^{-1} Jy
(F)
55000
55500
56000
56500
57000
57500
58000
58010
58020
58030
58040
58050
Modified Julian Date
Modified Julian Date

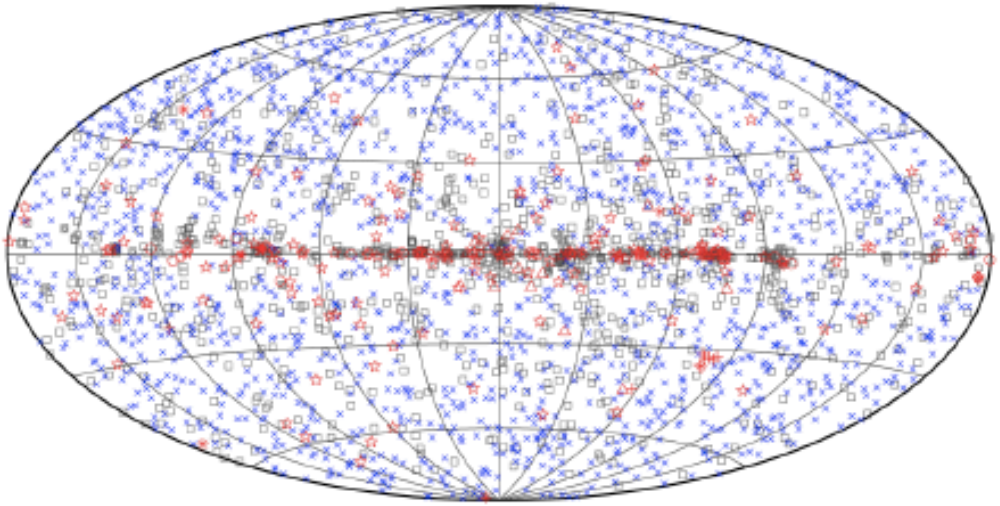
MAGIC finds variability on a 1-day scale
→ compact emission region



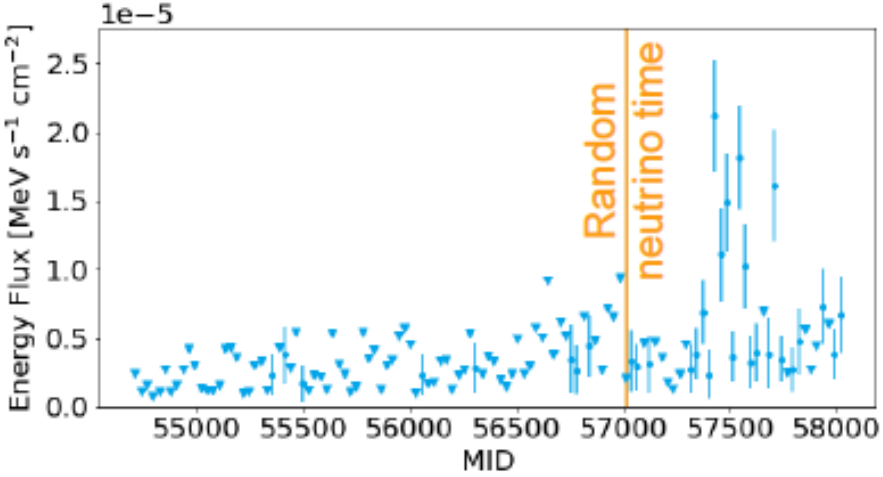
How Likely is it a Chance Probability?



Step I: Draw a random neutrino from a representative sample of high-energy muon-track events



Step II: Are there any extra-galactic Fermi source close in space to the neutrinos?



Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?

Neutrino emission correlates with

1. gamma-ray energy flux in the range 1-100 GeV

$$w_s(t) = \phi_E(t) = \int_{1\ \mathrm{GeV}}^{100\ \mathrm{GeV}} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

2. relative gamma-ray flux variations in the range 1-100 GeV

$$w_s(t) = \phi_\gamma(t) / \langle \phi_\gamma \rangle$$

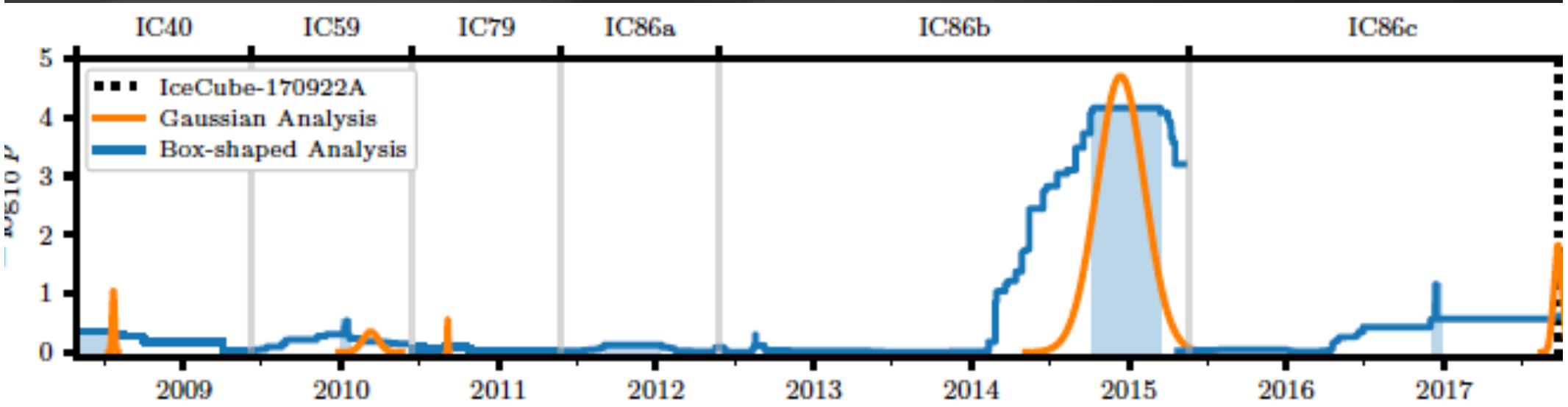
3. very high-energy gamma-ray energy flux in the range 100GeV-1TeV (extrapolated from Fermi energy range)

$$w_s(t) = \phi_E(t) = \int_{100\ \mathrm{GeV}}^{1\ \mathrm{TeV}} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

multiwavelength campaign launched by IC 170922

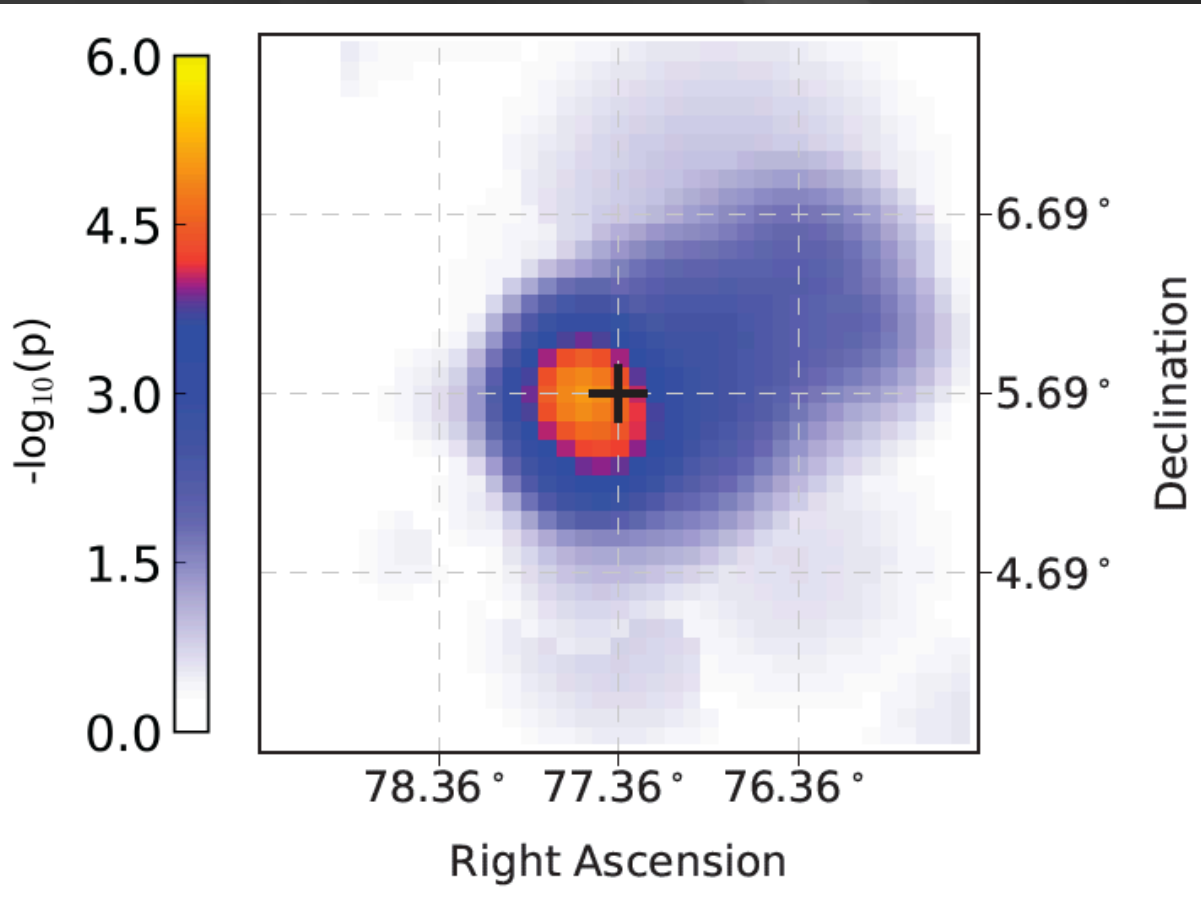
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- 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} (7x 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



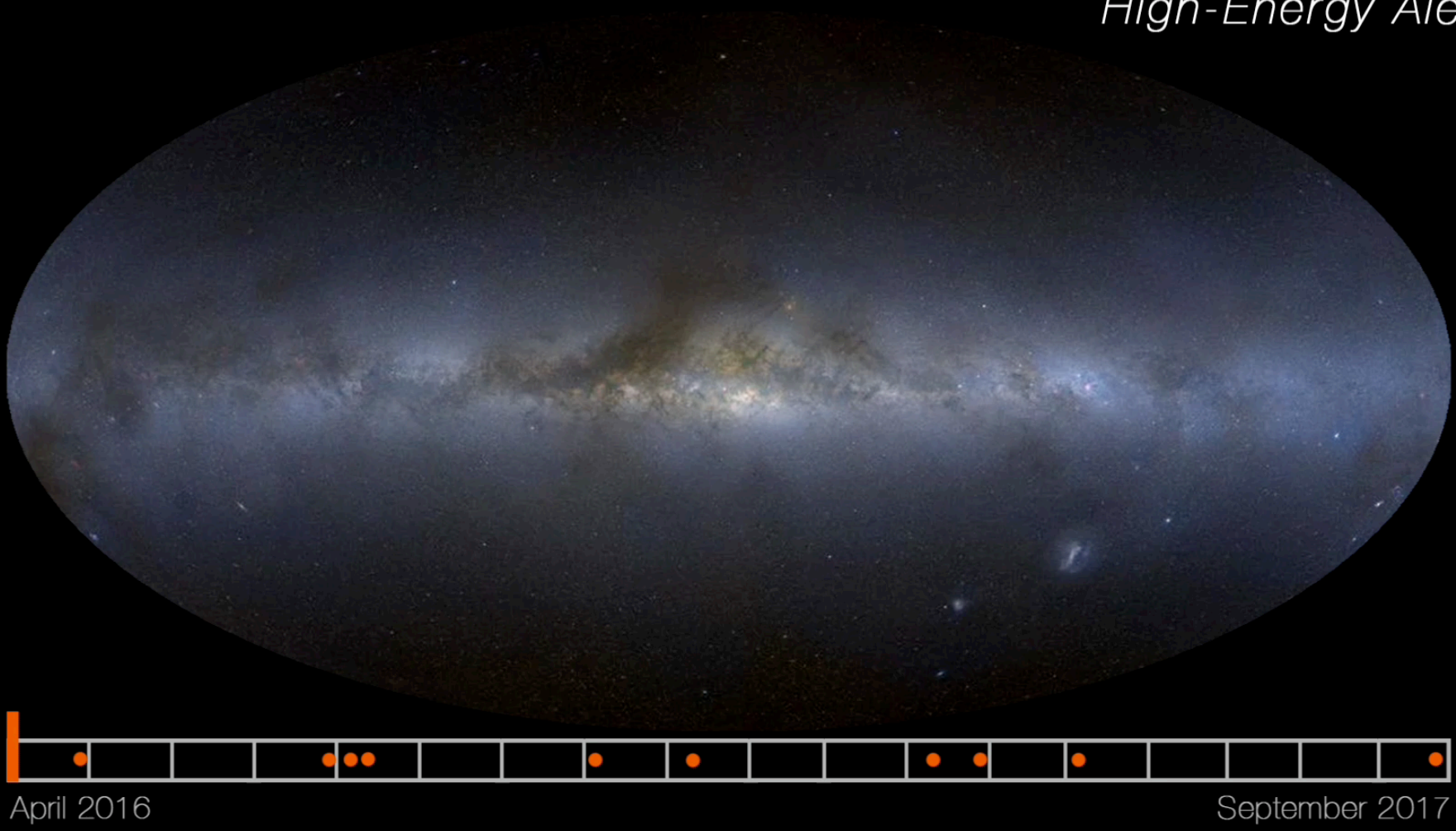
search in archival IceCube data:

- ~100 day flare in December 2014
- accompanied by hardest Fermi spectrum in 10 yrs ($E^{-1.7}$)



IceCube

High-Energy Alerts



19 events on a background < 6 in 150 days

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

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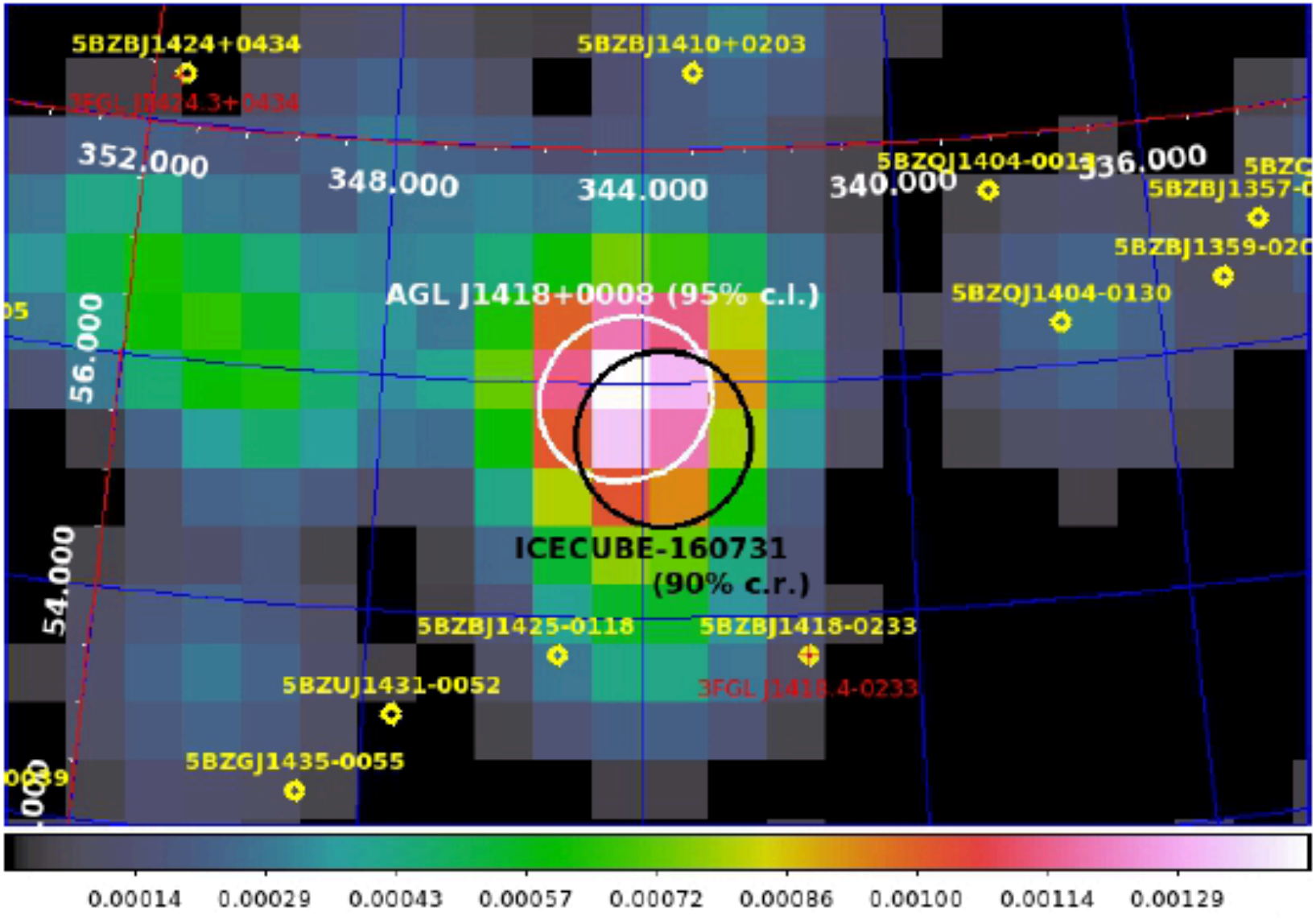

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TANAMI blazars in the IceCube PeV neutrino fields

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Received 15 May 2014 / Accepted 2 June 2014

ABSTRACT

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

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

The Highest Energy Emission Detected by EGRET from Blazars

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Abstract. Published EGRET spectra from blazers extend only to 10 GeV, yet EGRET has detected approximately 2000 γ-rays above 10 GeV of which about half are at high Galactic latitude. We report a search of these high-energy γ-rays for associations with the EGRET and TeV detected blazers. Because the point spread function of EGRET improves with energy, only ~2 γ-rays are expected to be positionally coincident with the 80 blazars searched, yet 23 γ-rays were observed. This collection of > 10 GeV sources should be of particular interest due to the improved sensitivity and lower energy thresholds of ground-based TeV observatories. One of the blazers, RGB0509+056, has the highest energy γ-rays detected by EGRET from any blazar with 2 > 40 GeV, and is a BL Lac type blazar with unknown redshift.

Victor Hess 1912