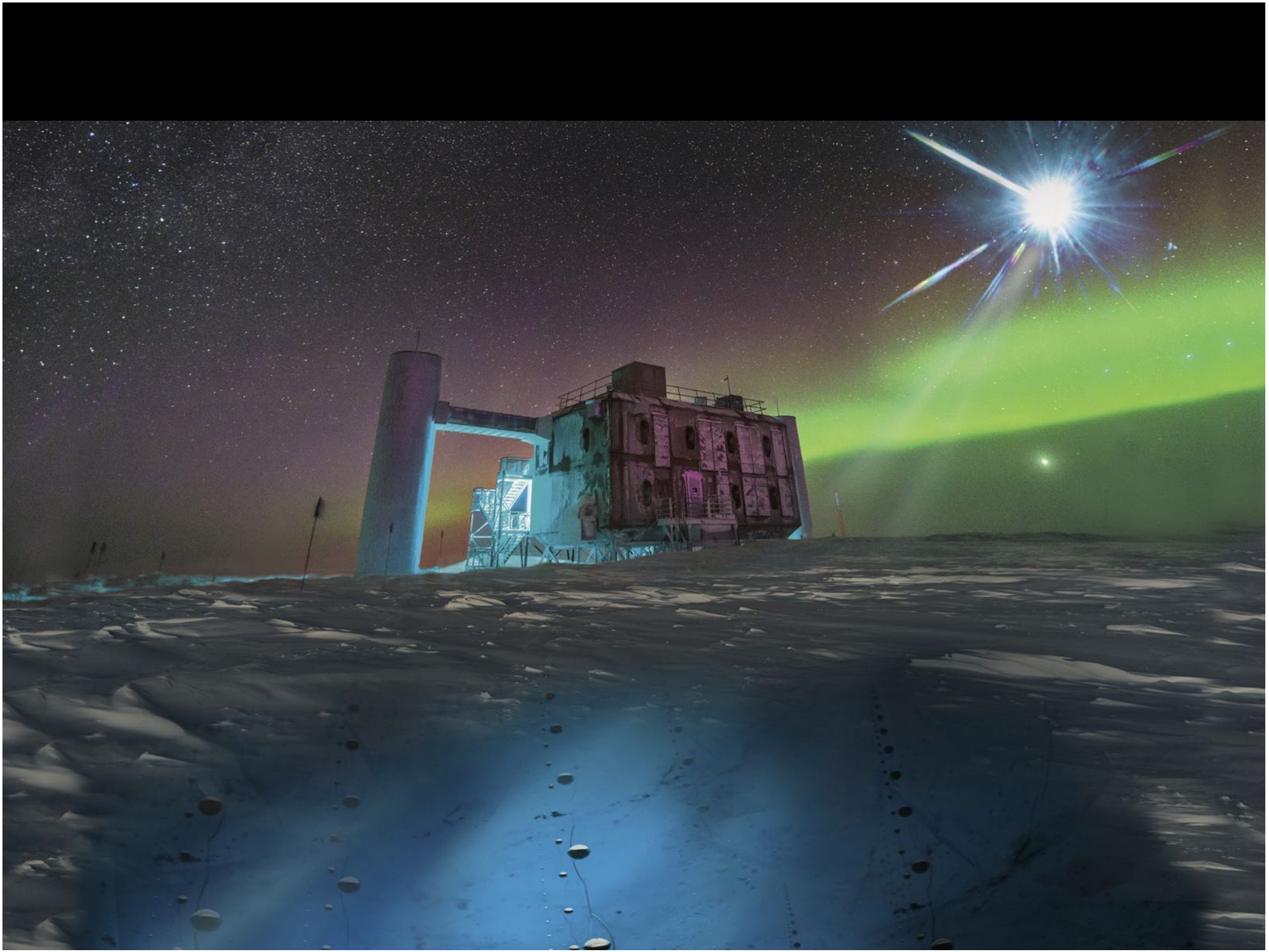


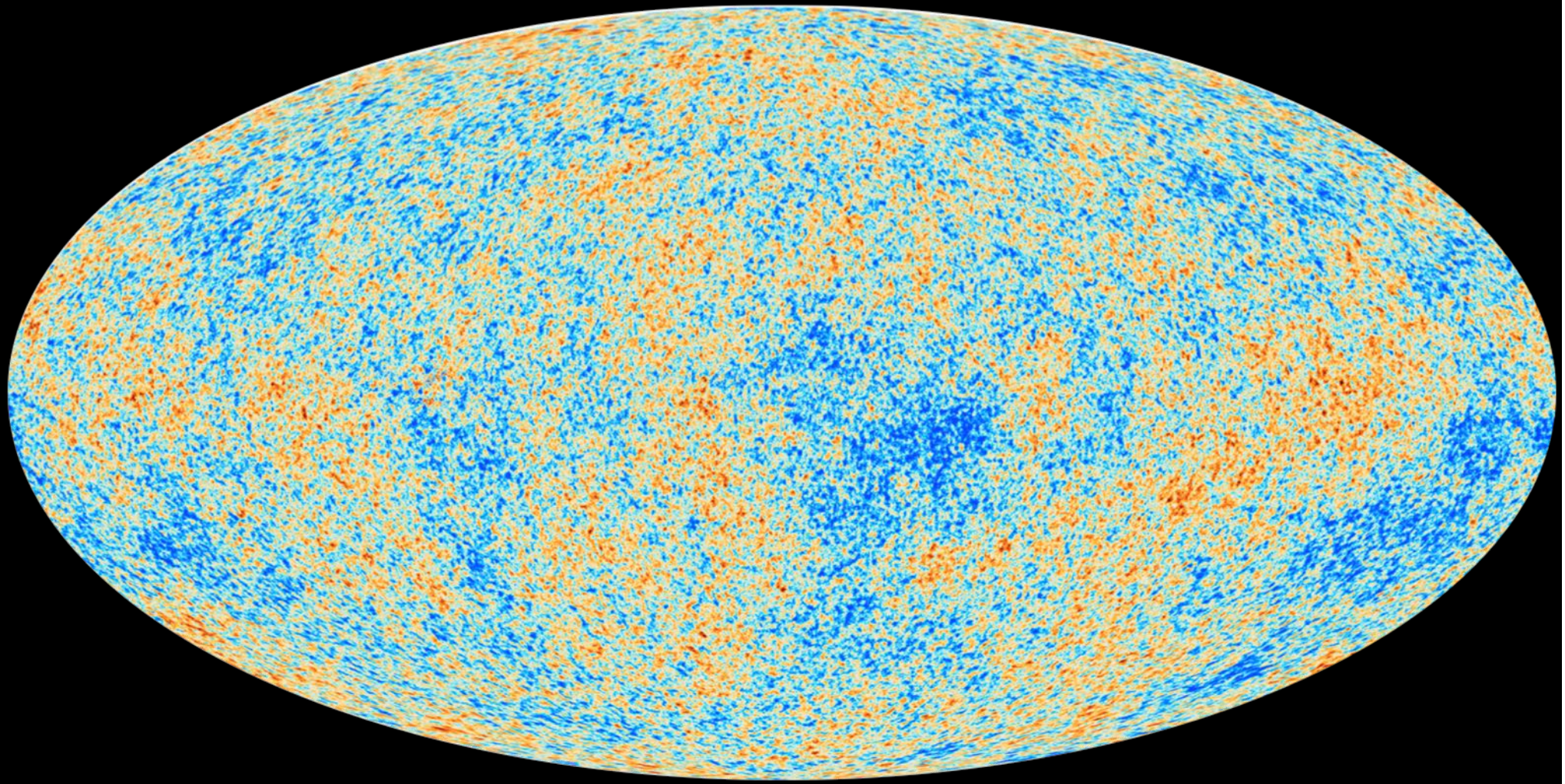
IceCube:
Building a New Window on the Universe

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?

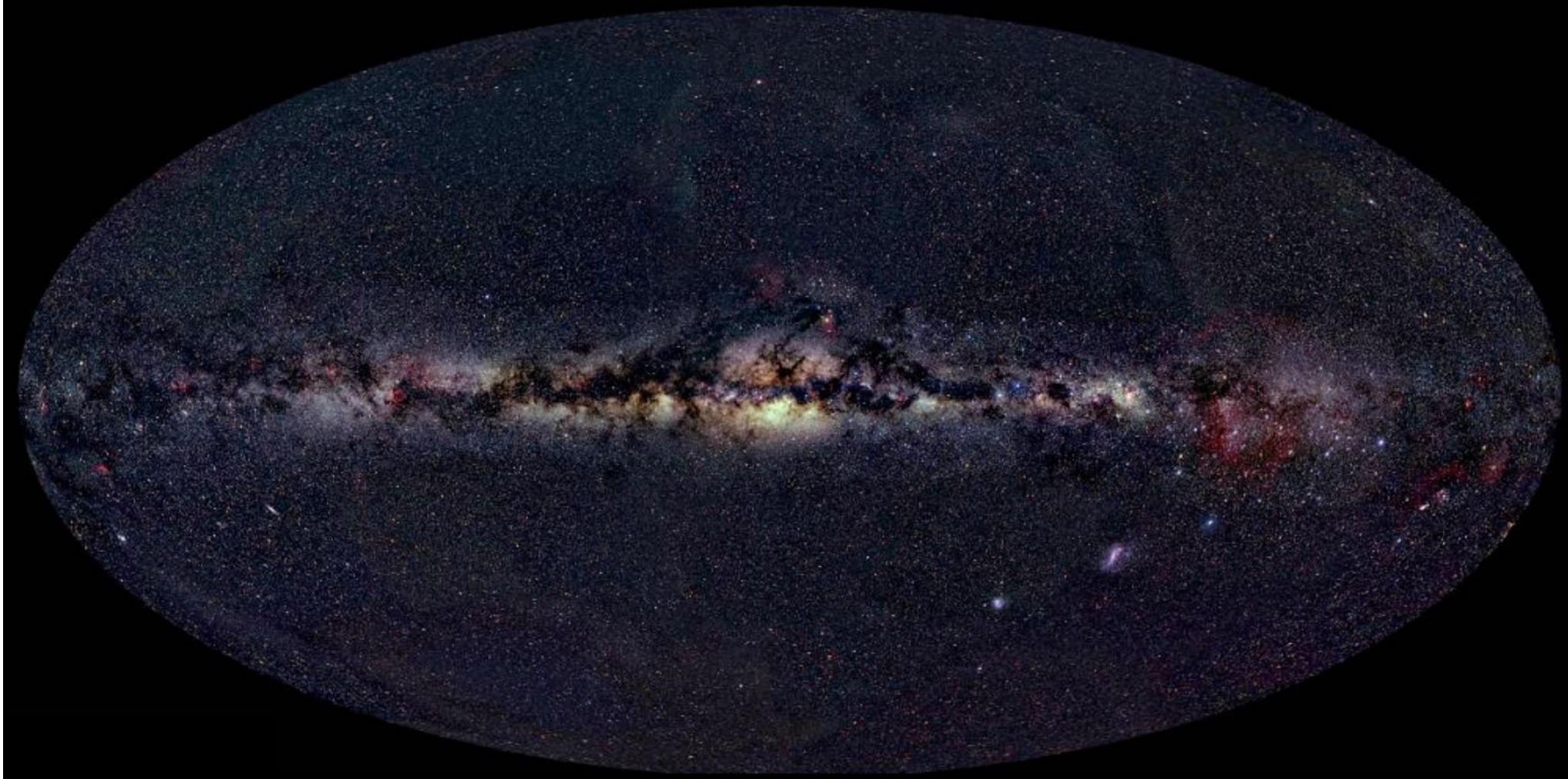
icecube.wisc.edu

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



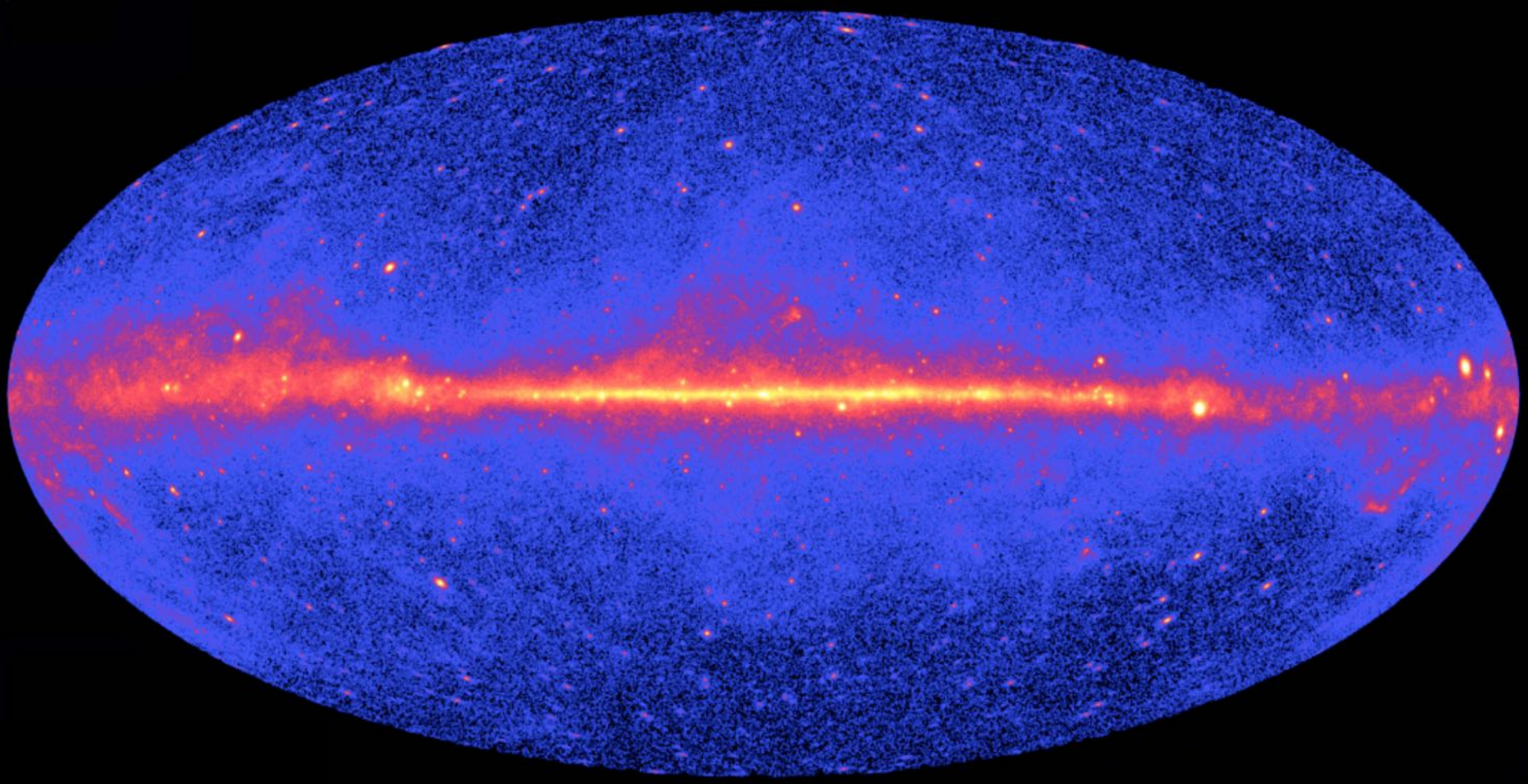
wavelength = 10^{-3} m $\Leftrightarrow$ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m ⇔ energy = 1 eV

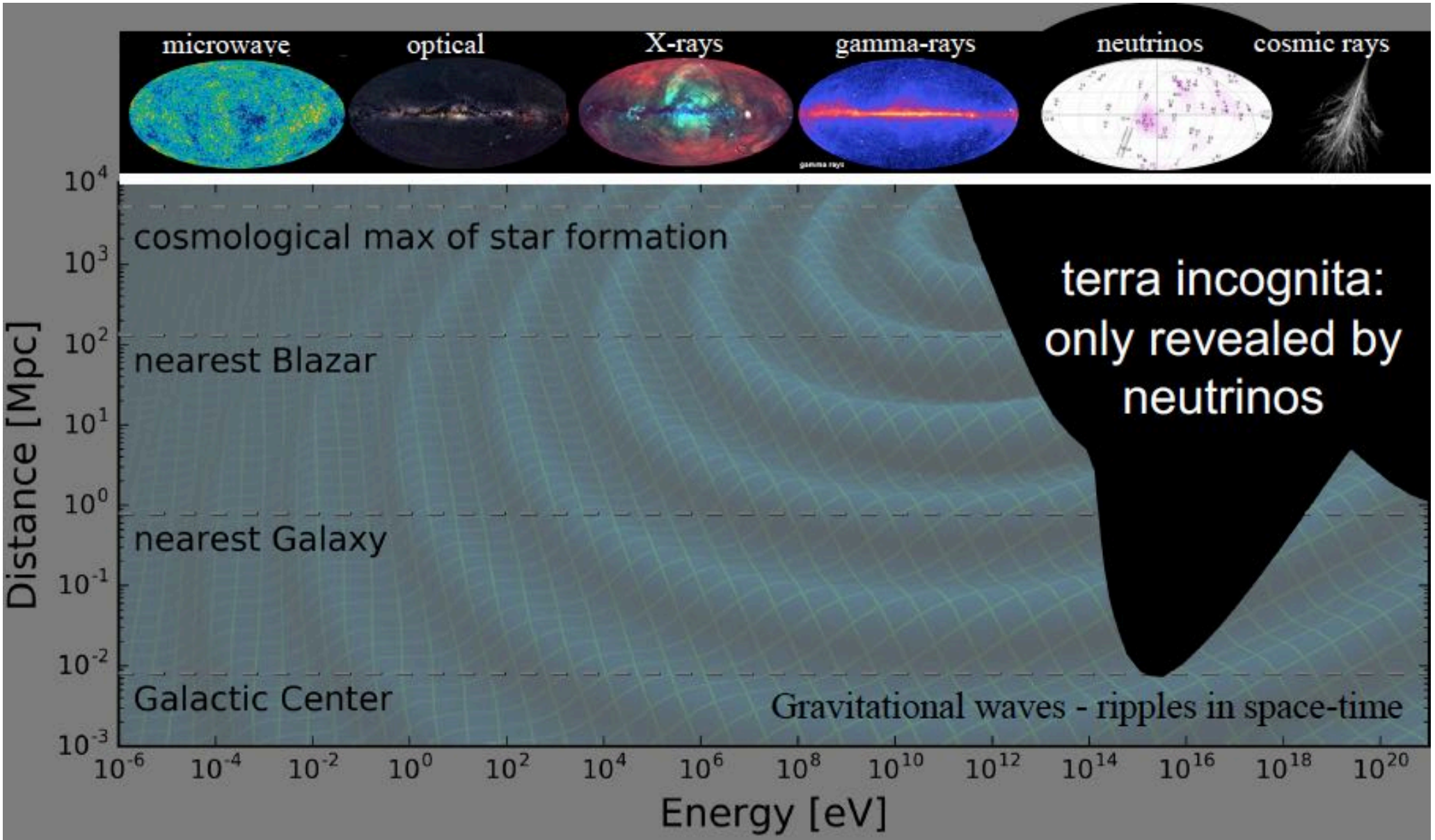
Cosmic Horizons – Gamma Radiation



wavelength = 10^{-15} m ⇔ energy = 1 GeV

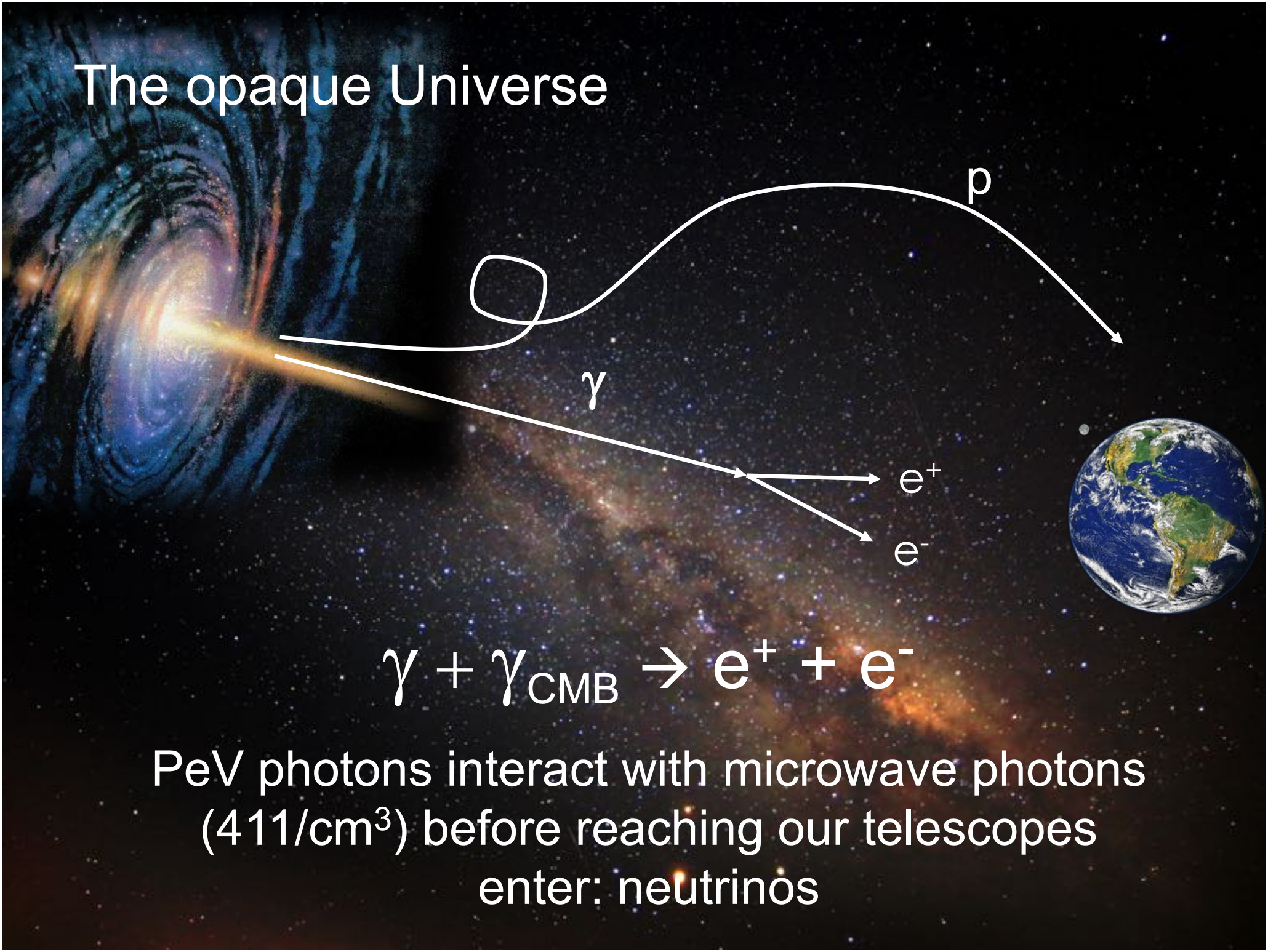
Cosmic Horizons – Gamma Radiation

wavelength = 10^{-21} m $\Leftrightarrow$ energy = 10^{3} TeV



- 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

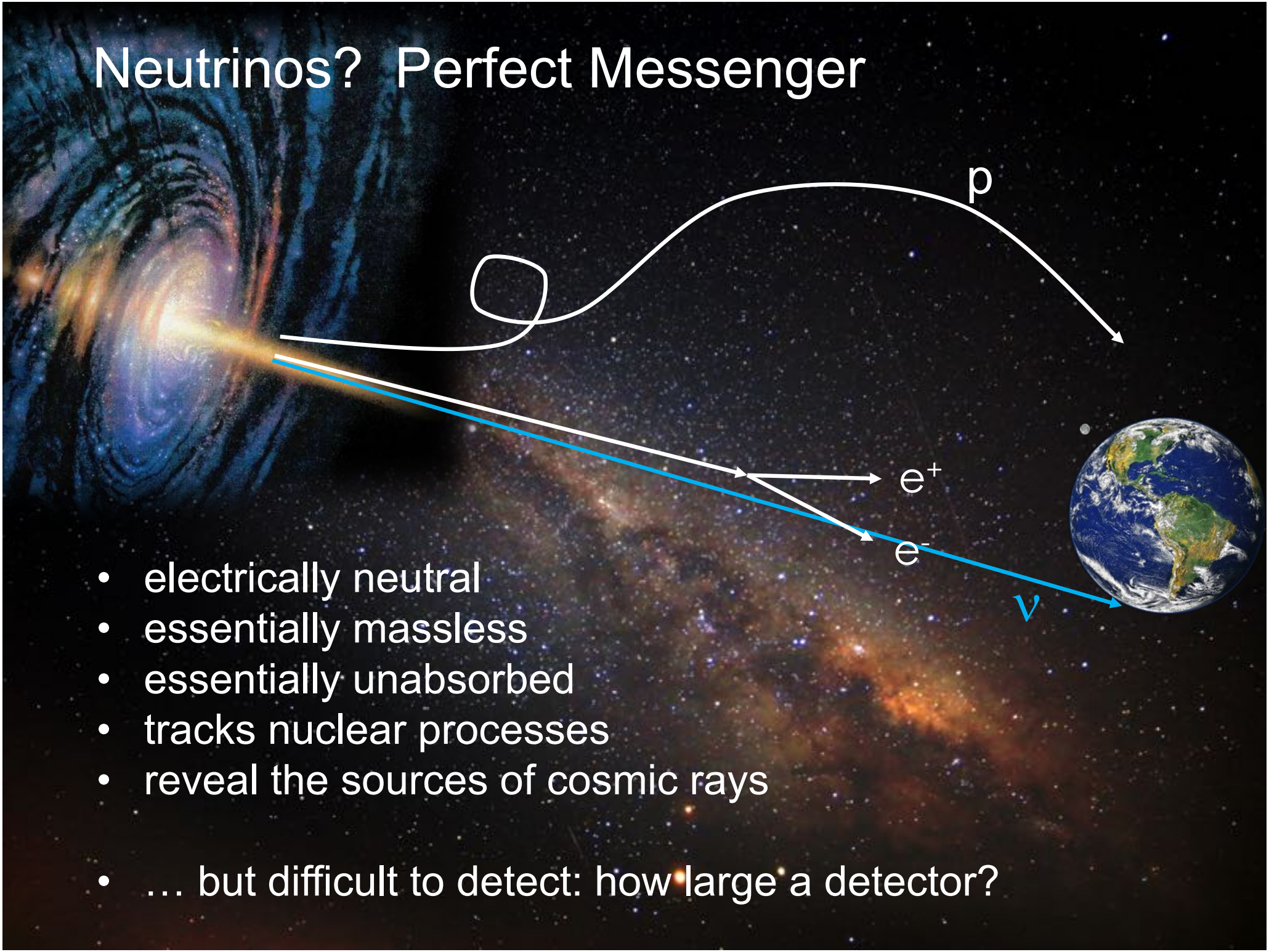


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

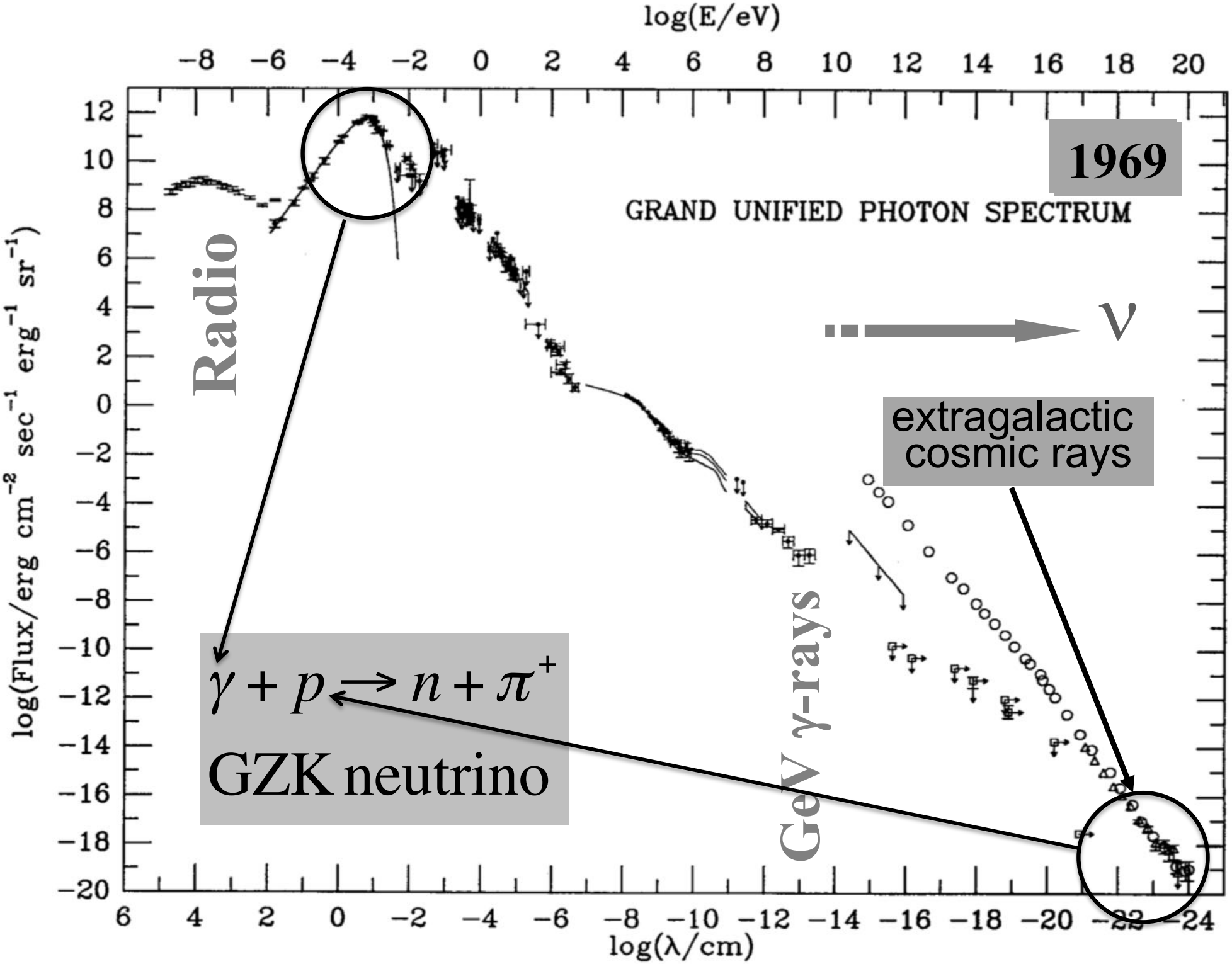
enter: neutrinos

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?


log(E/eV)
−8 −6 −4 −2 0 2 4 6 8 10 12 14 16 18 20
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
extragalactic
cosmic rays
GeV γ-rays
$\gamma + p \rightleftharpoons n + \pi^+$
GZK neutrino
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
12 10 8 6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20
6 4 2 0 −2 −4 −6 −8 −10 −12 −14 −16 −18 −20 −22 −24
log(λ/cm)

cosmic rays interact with the microwave background

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

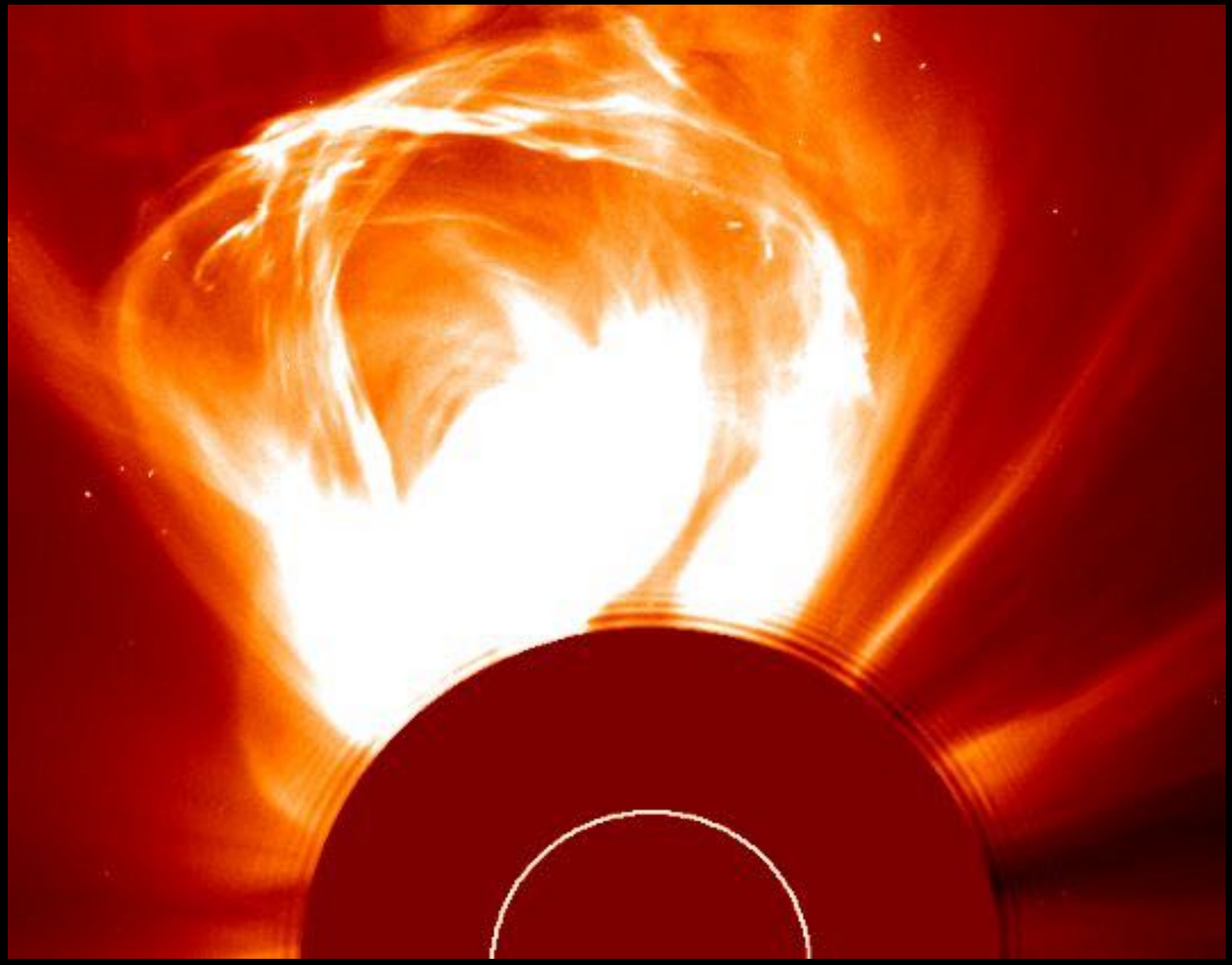
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

nonthermal universe: cosmic accelerators



- accelerator must contain the particles

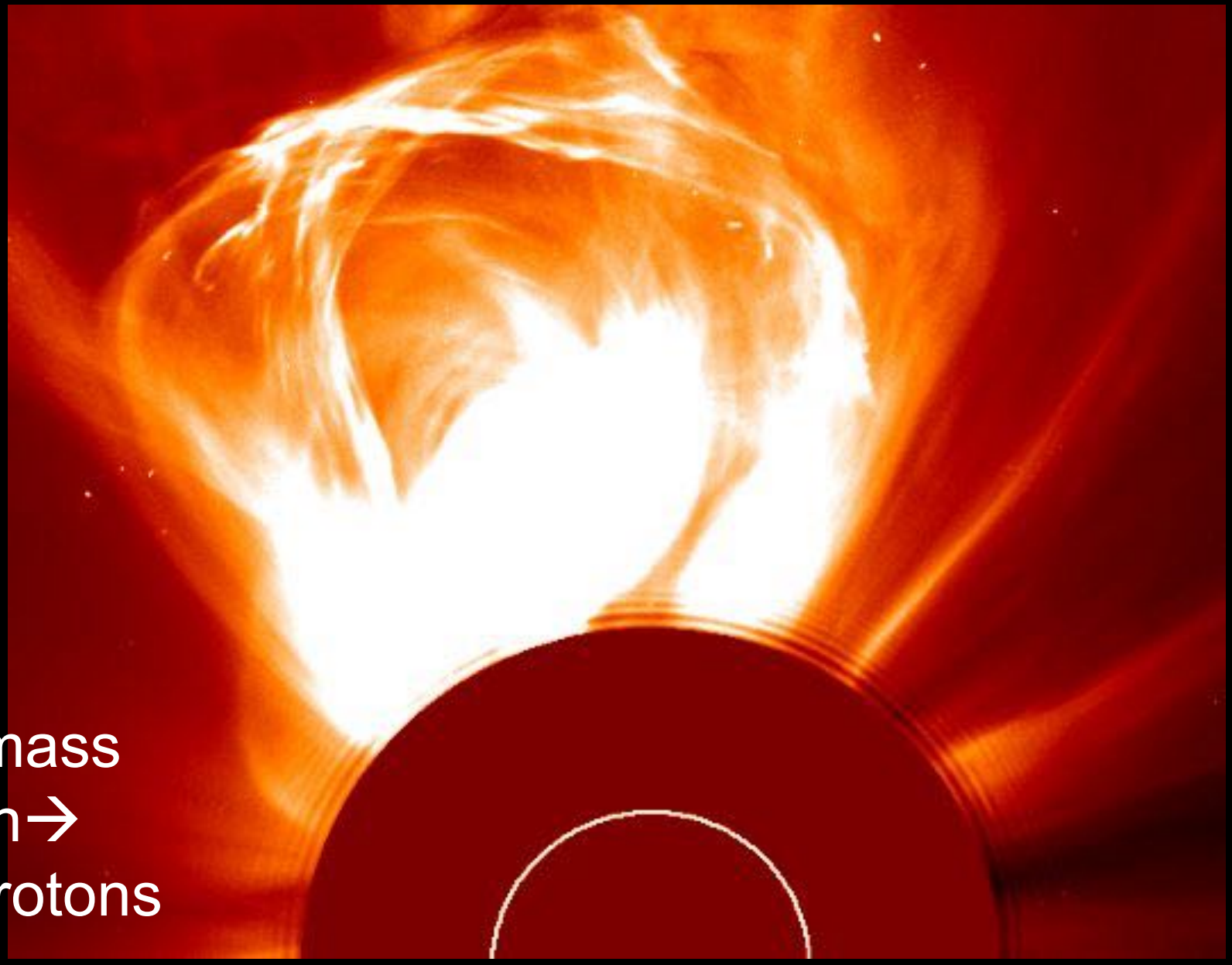
$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

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

challenges of cosmic ray astrophysics:

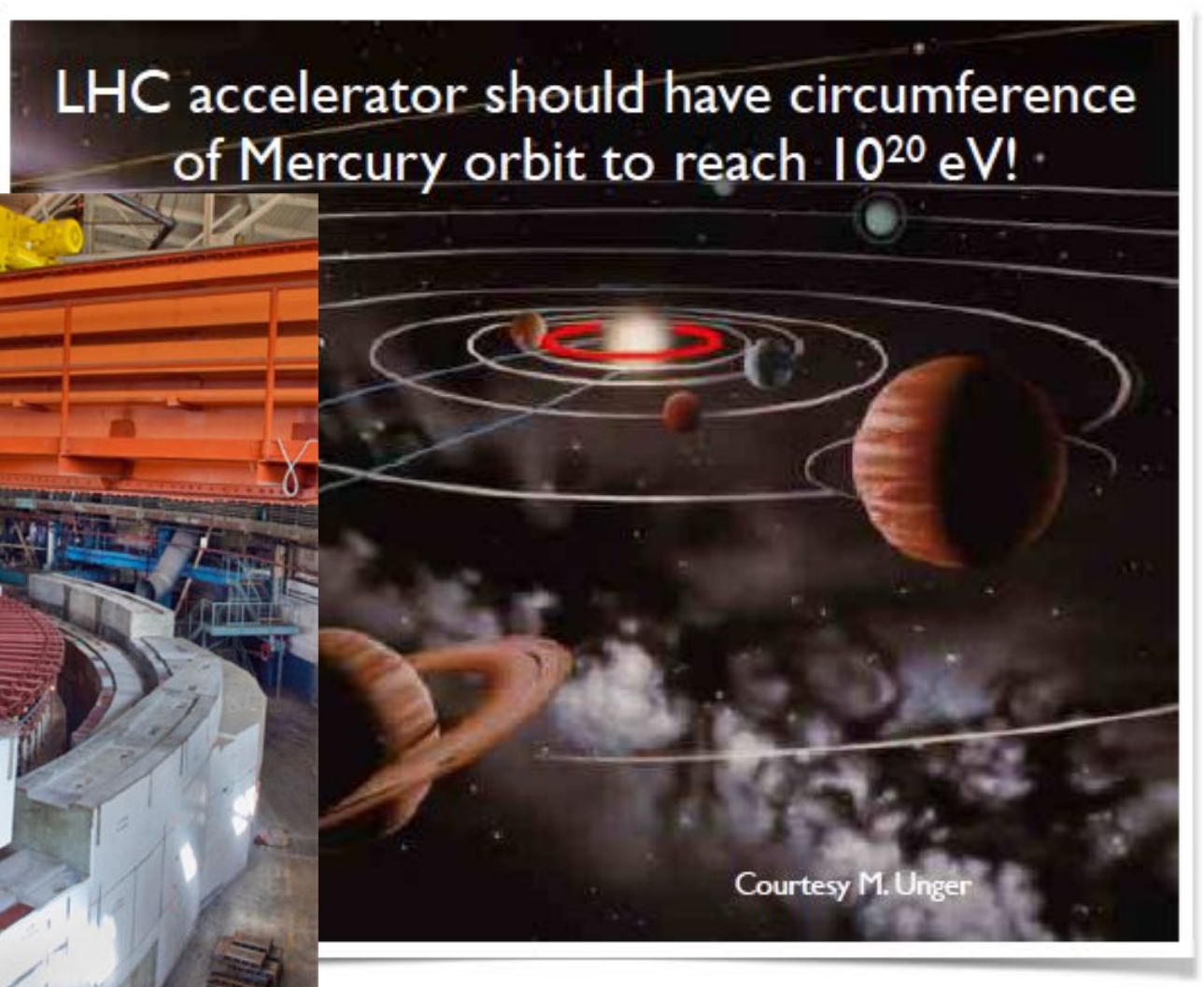
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

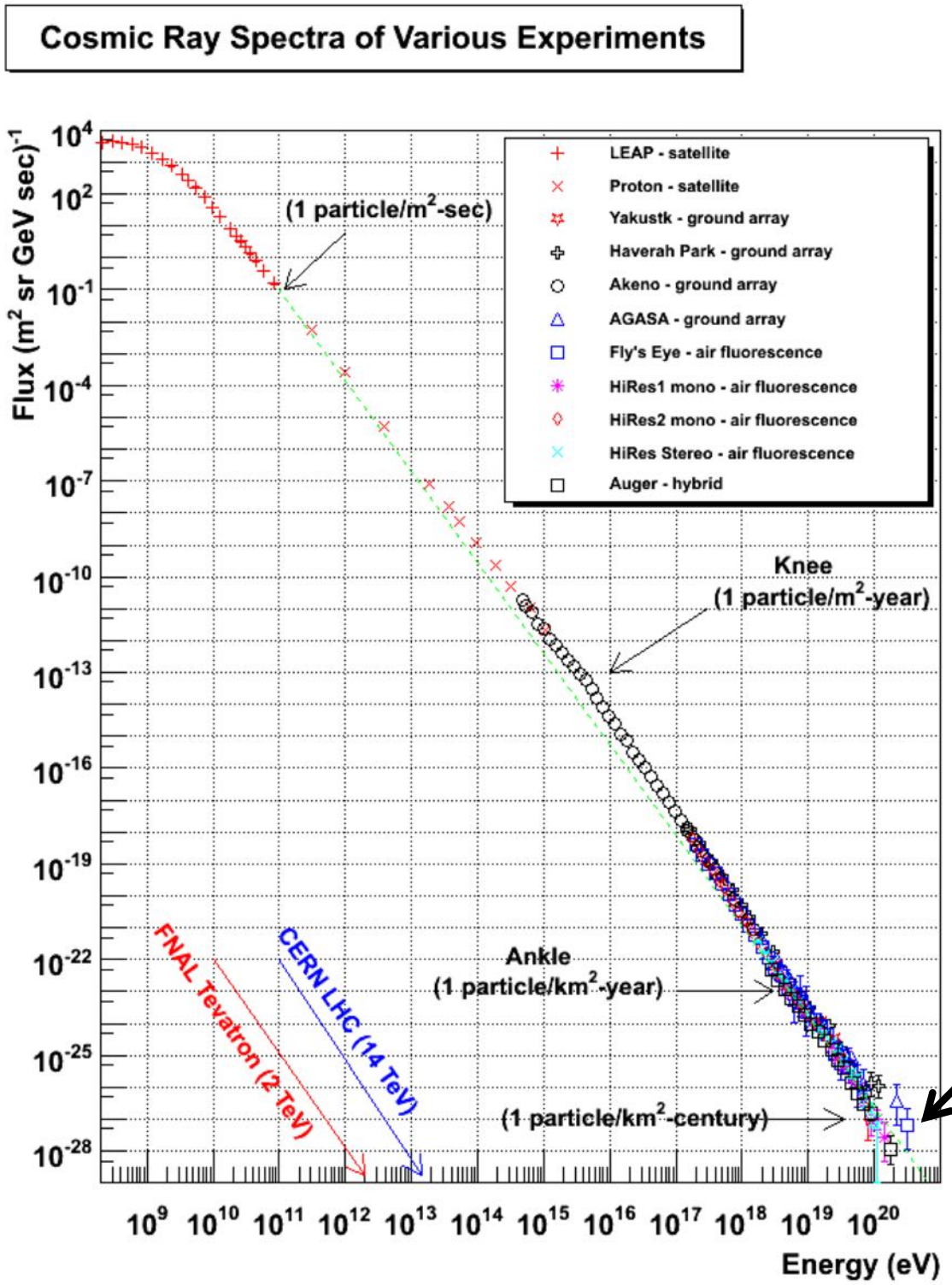
the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

accomodating energy and luminosity are challenging





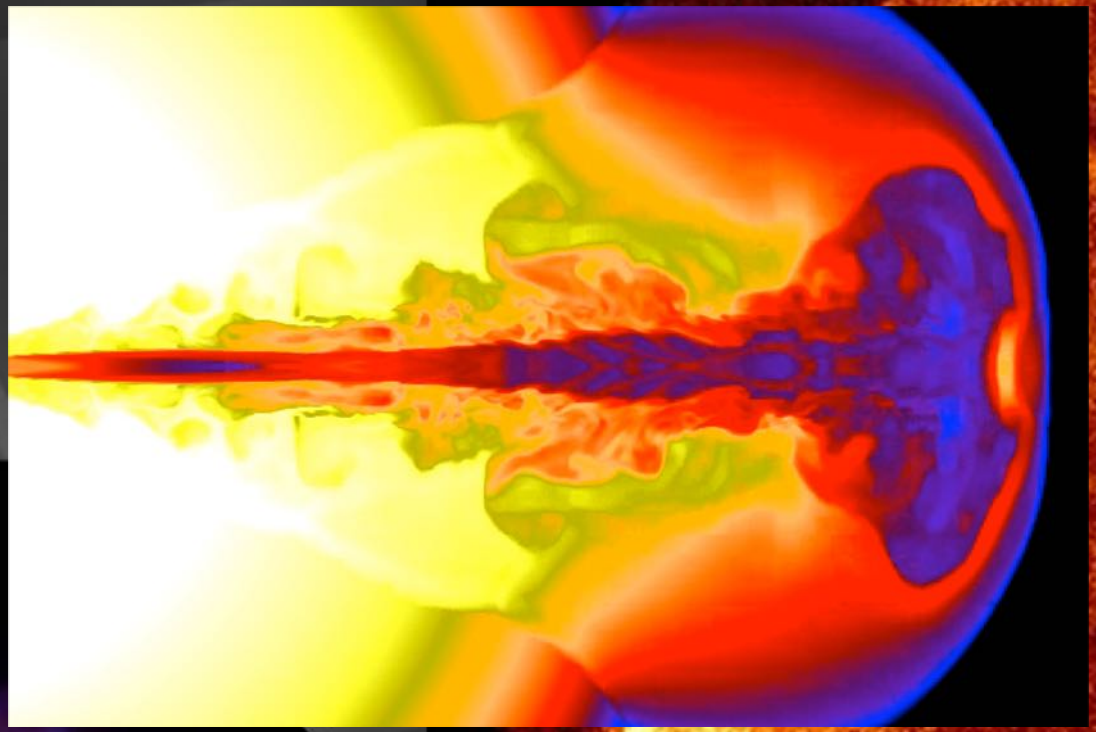
cosmic ray accelerators:
where, how?

gravitational energy from collapsing star converted into particle acceleration

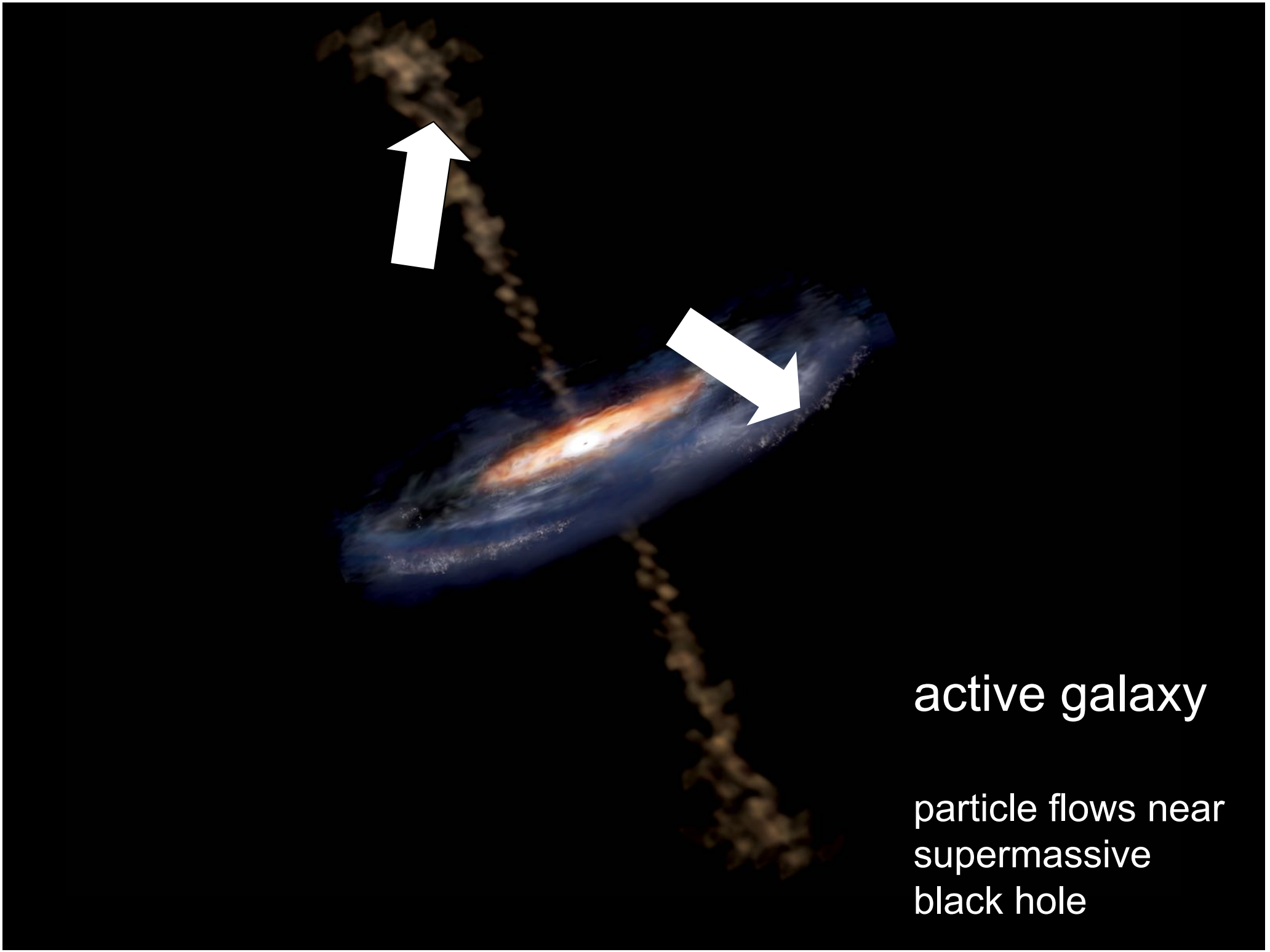
LHC filling the orbit of Mercury

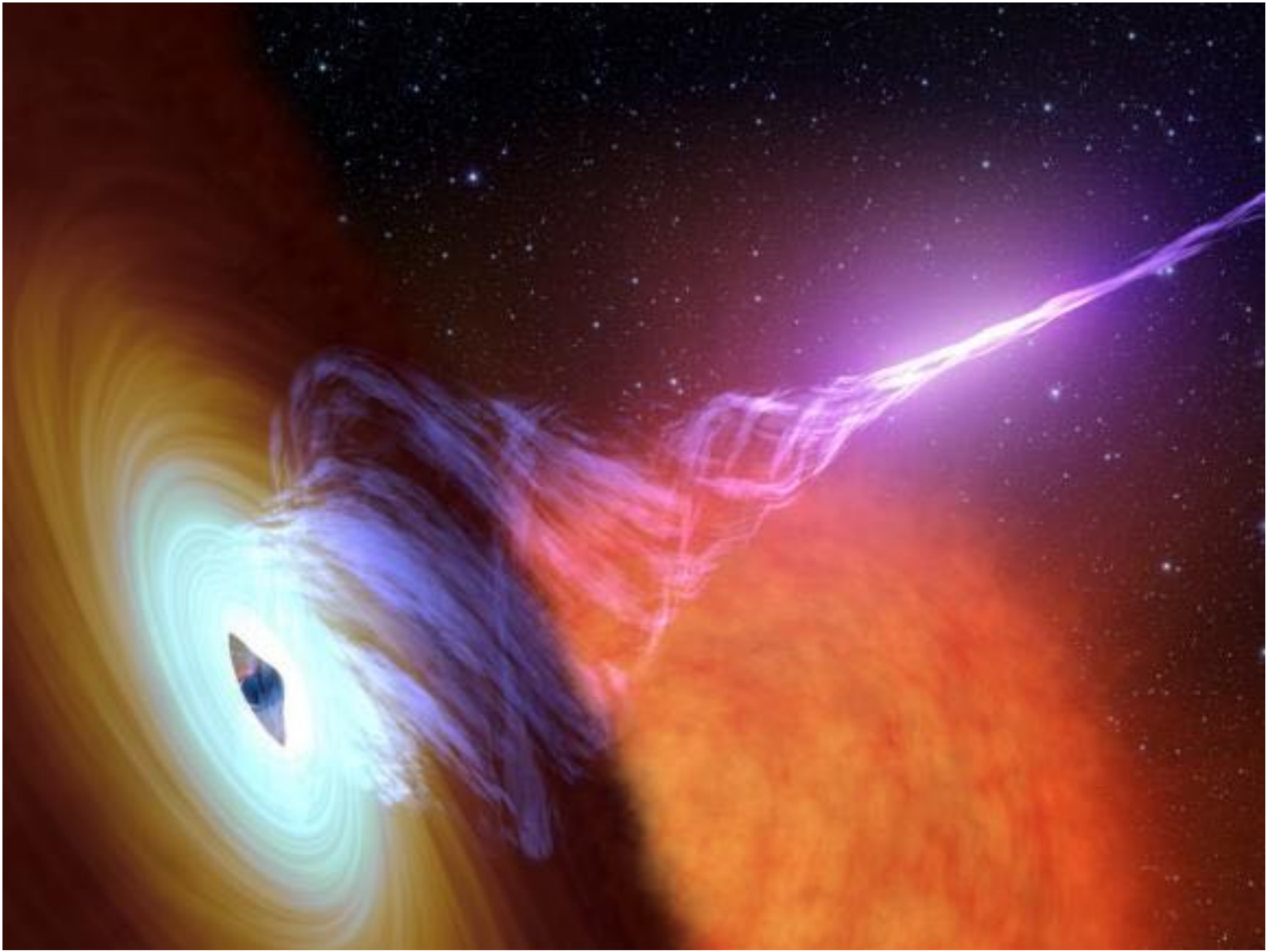
supernova remnants

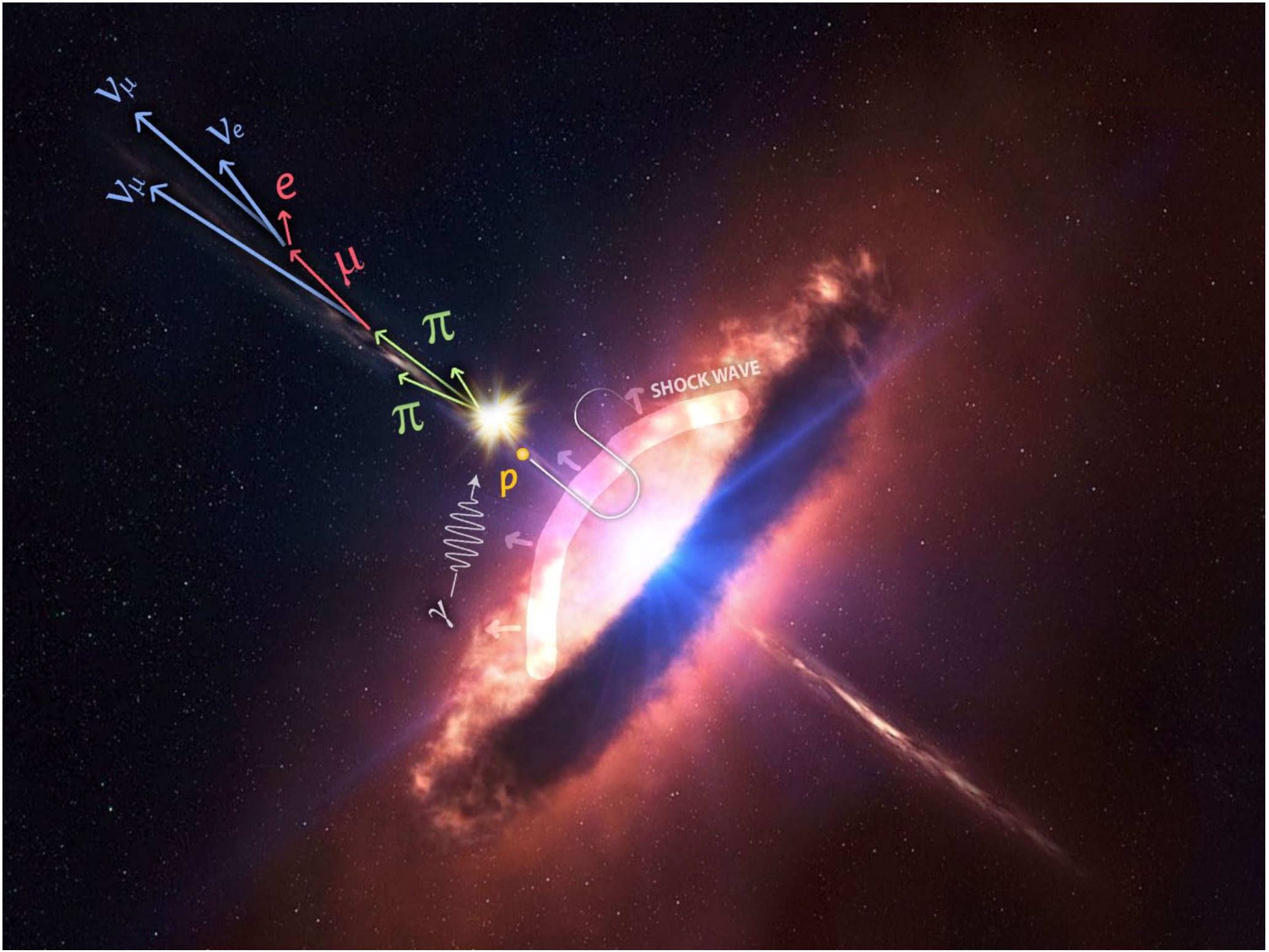
Chandra
Cassiopeia A

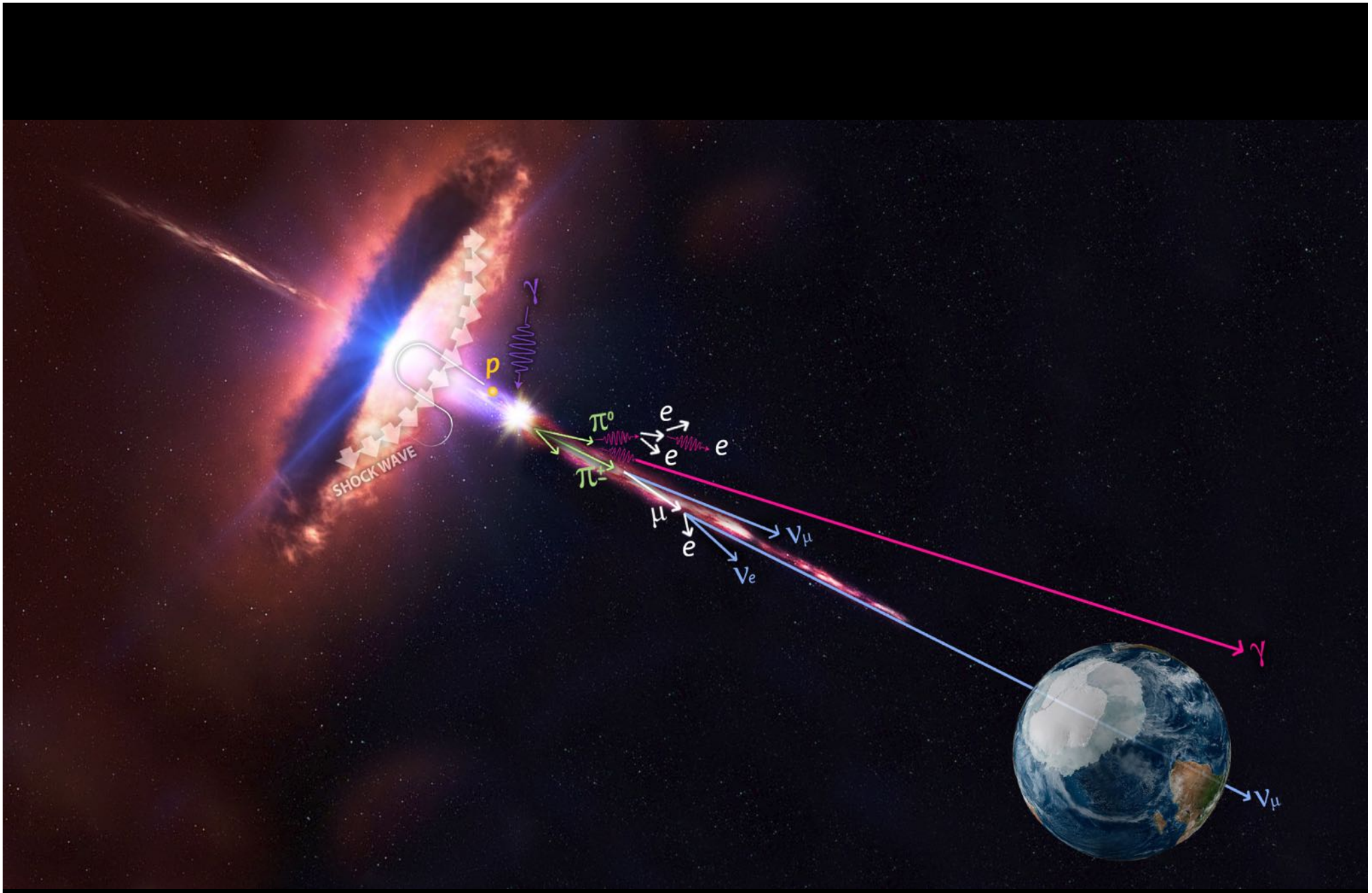


gamma ray bursts


active galaxy
particle flows near
supermassive
black hole

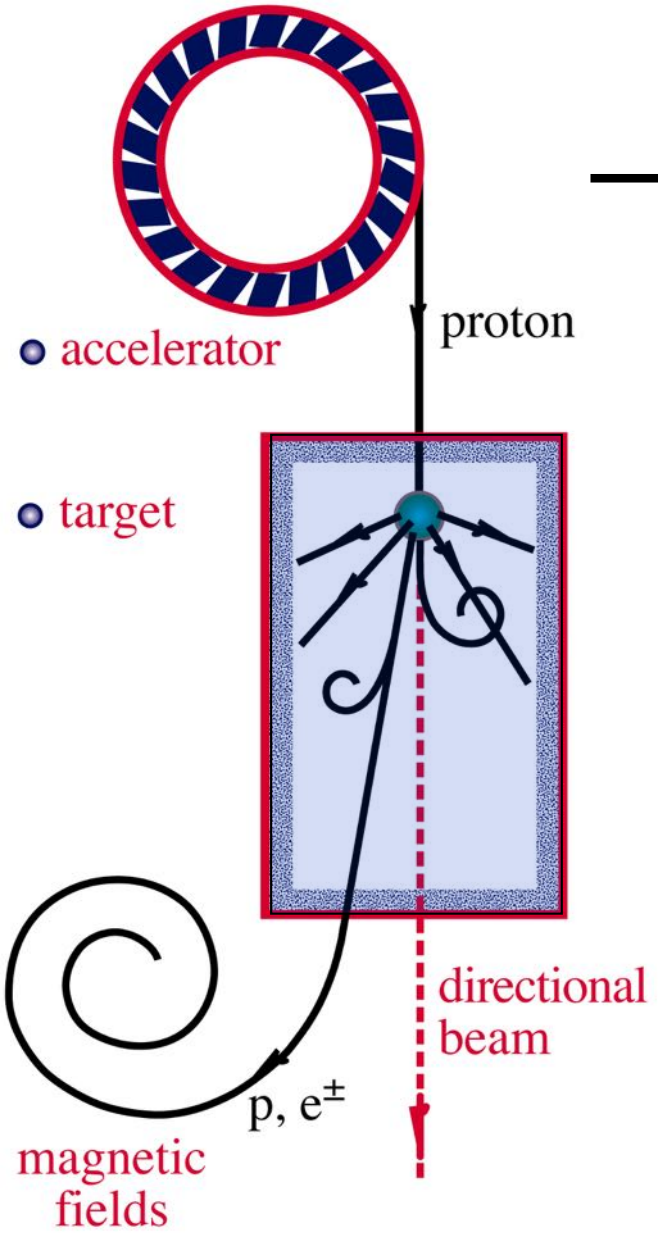



ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE



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

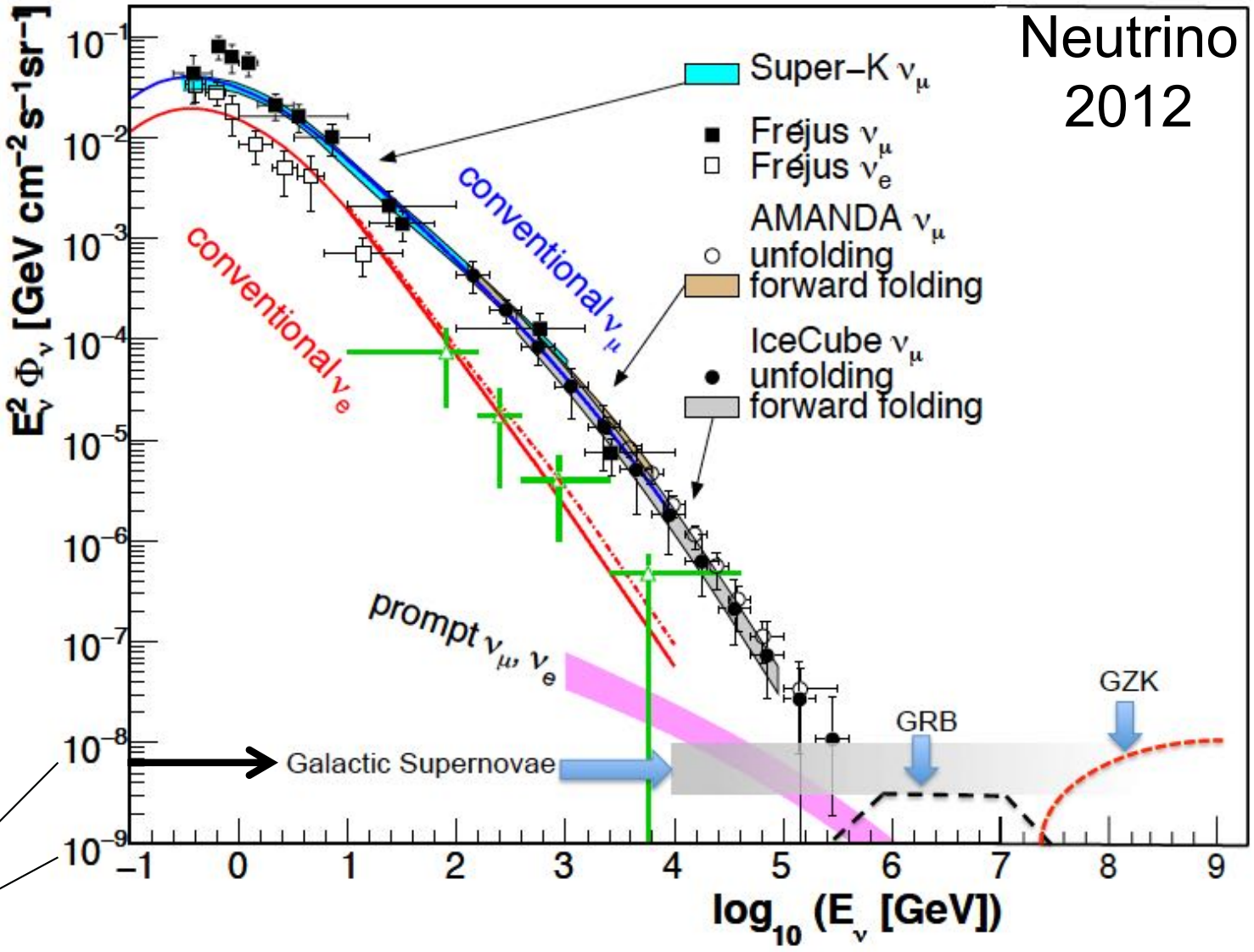
$\rightarrow p + \pi^0$

~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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

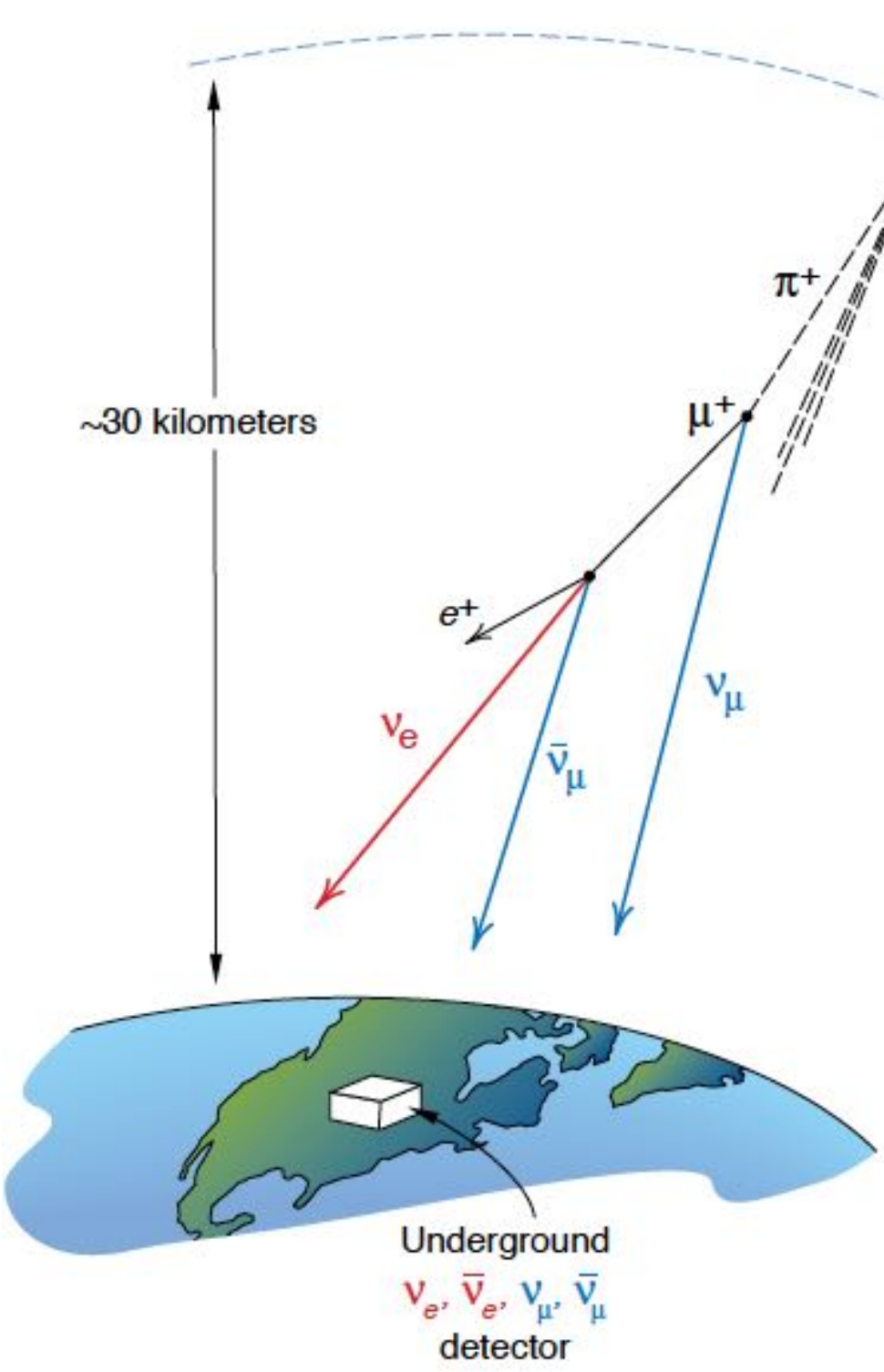


10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV

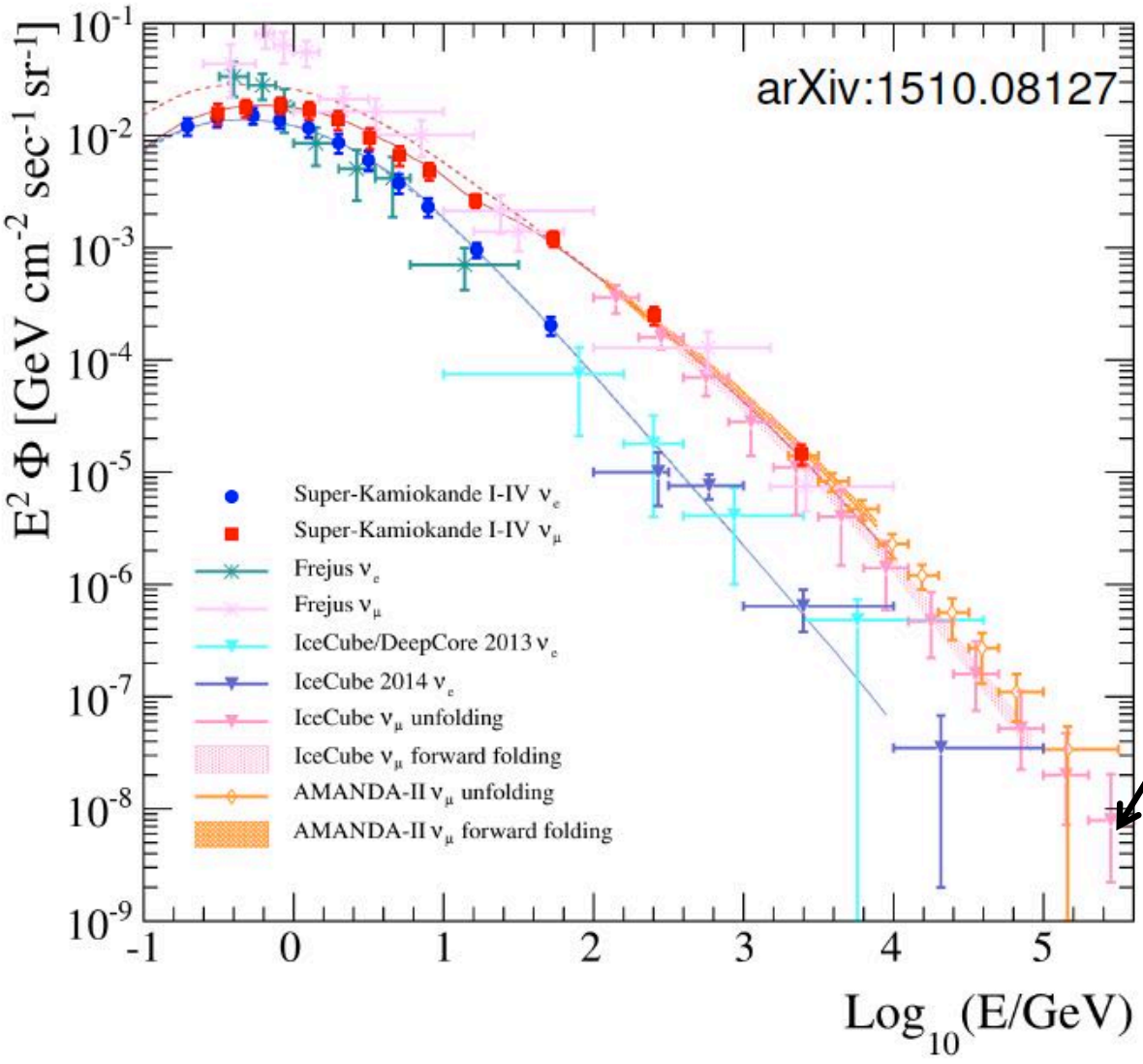


atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

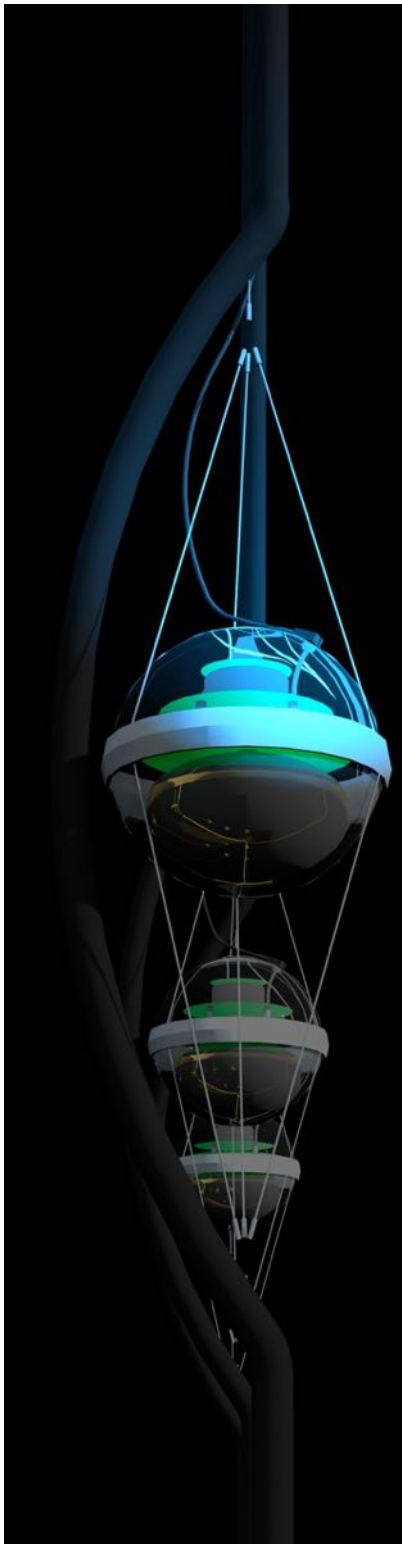
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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



< 1 atmospheric neutrino event per cubic kilometer per year

atmospheric neutrino spectrum (energy measurement) well understood



IceCube

francis halzen

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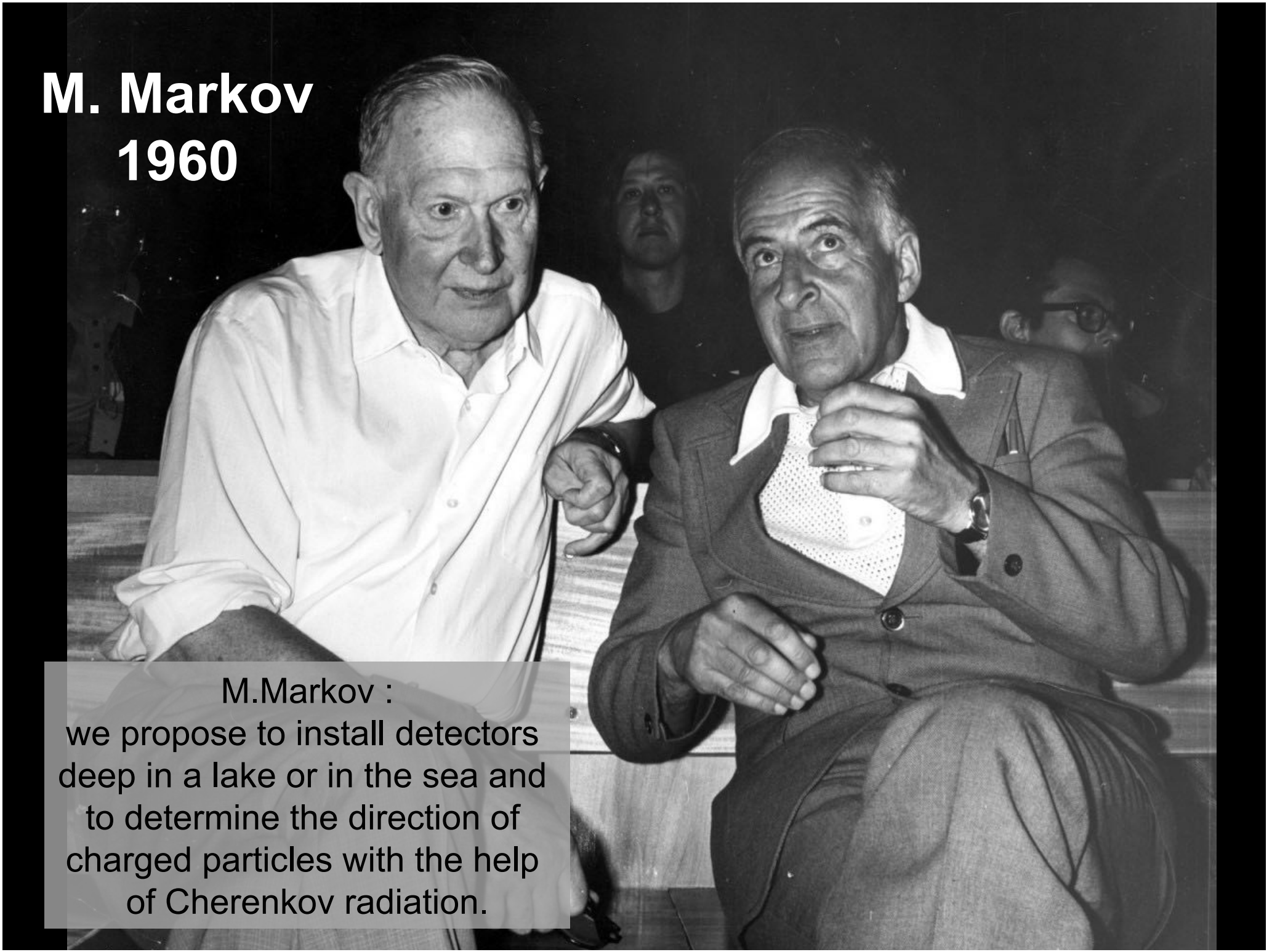
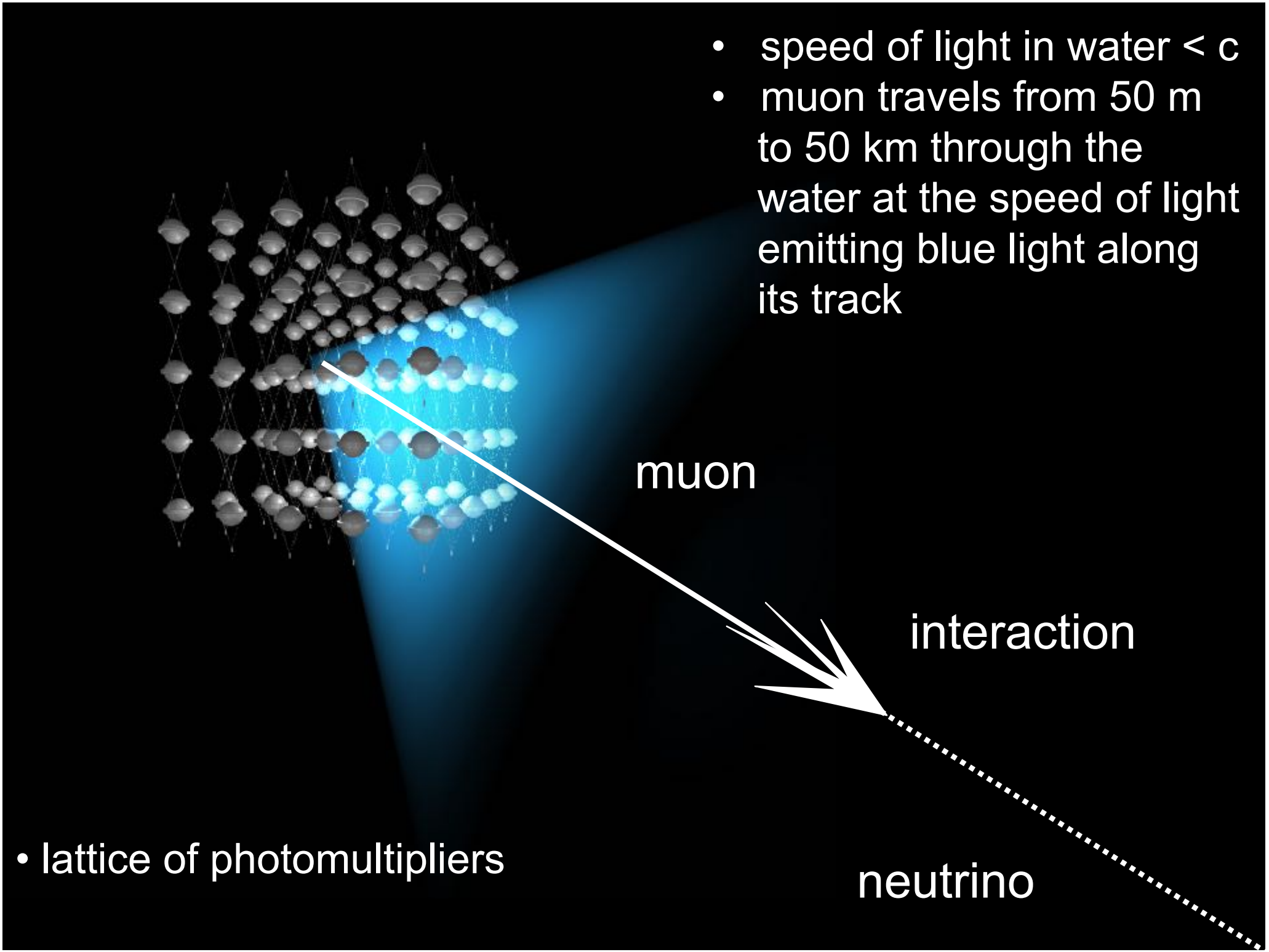
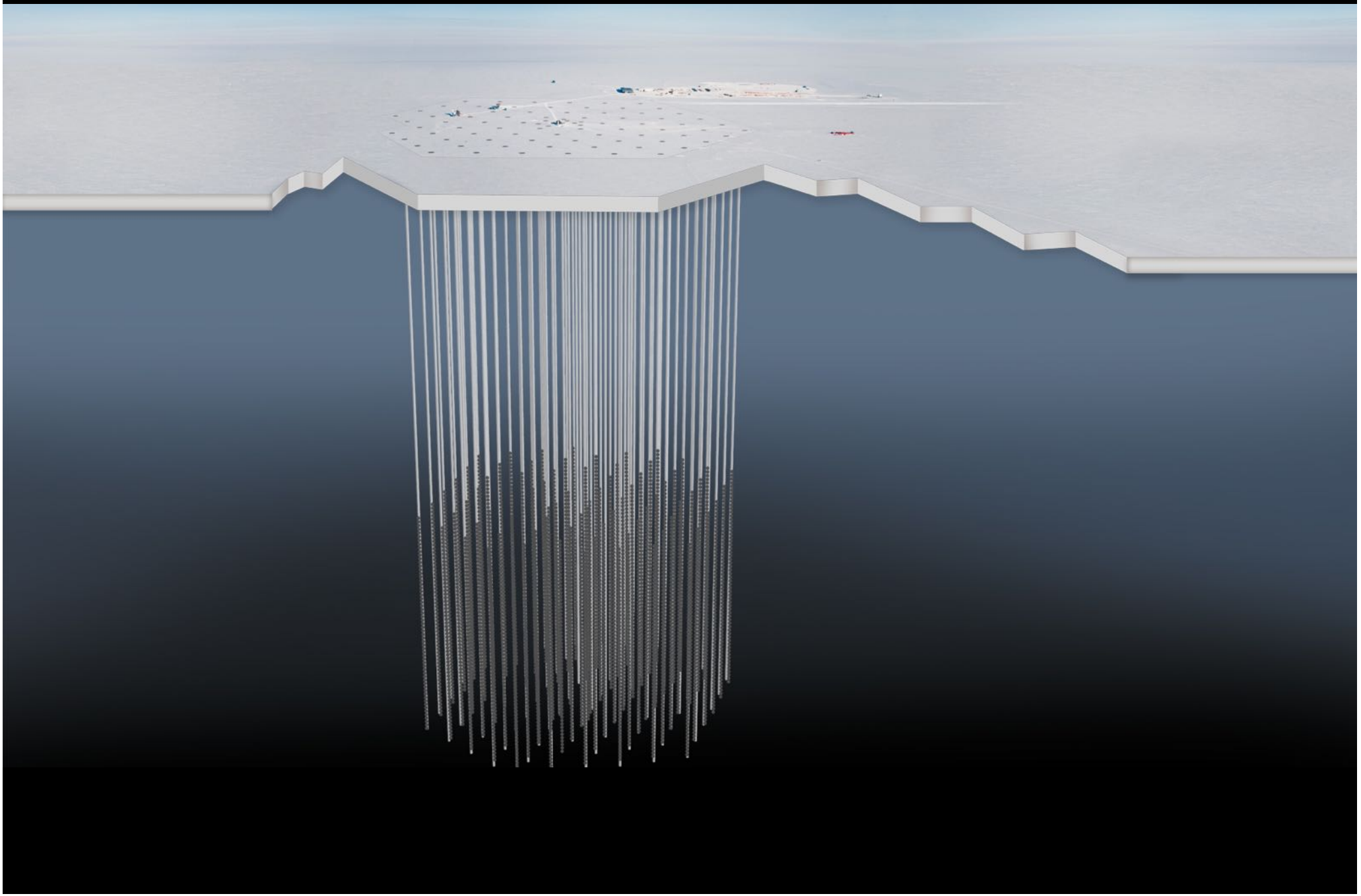
iceCube.wisc.edu

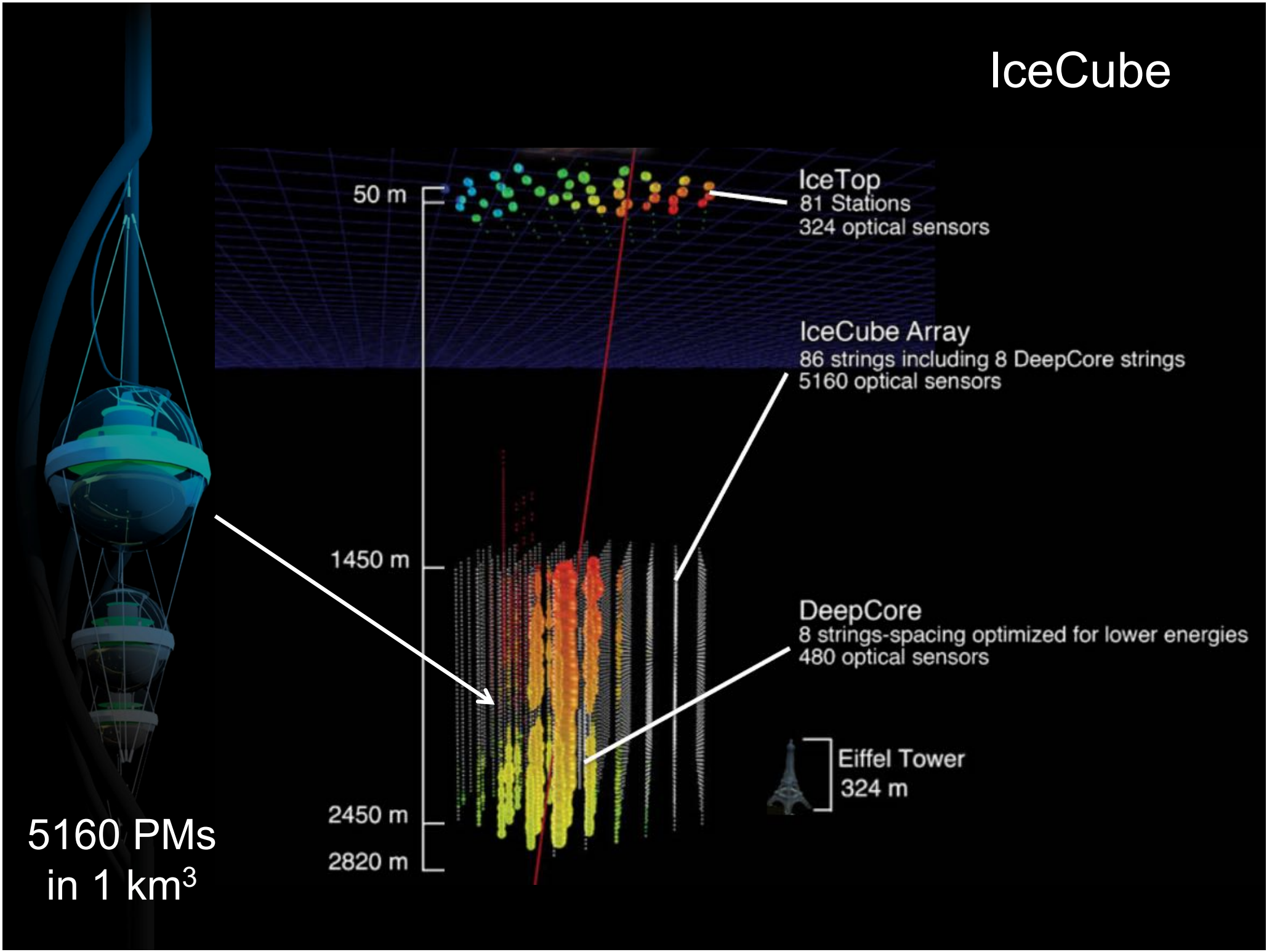

M. Markov
1960
M.Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.


• 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

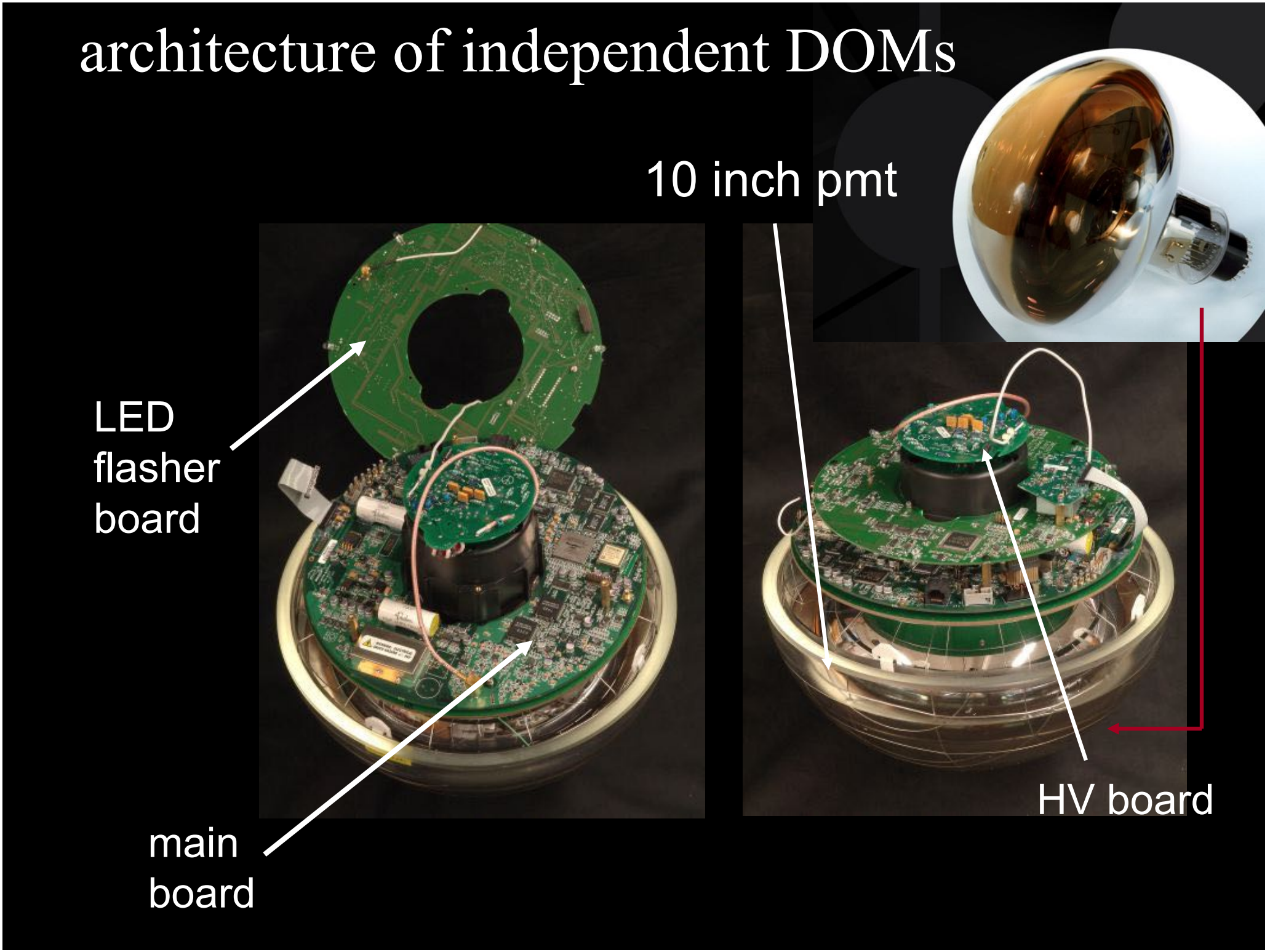
instrument 1 cubic kilometer of natural ice below 1.45 km



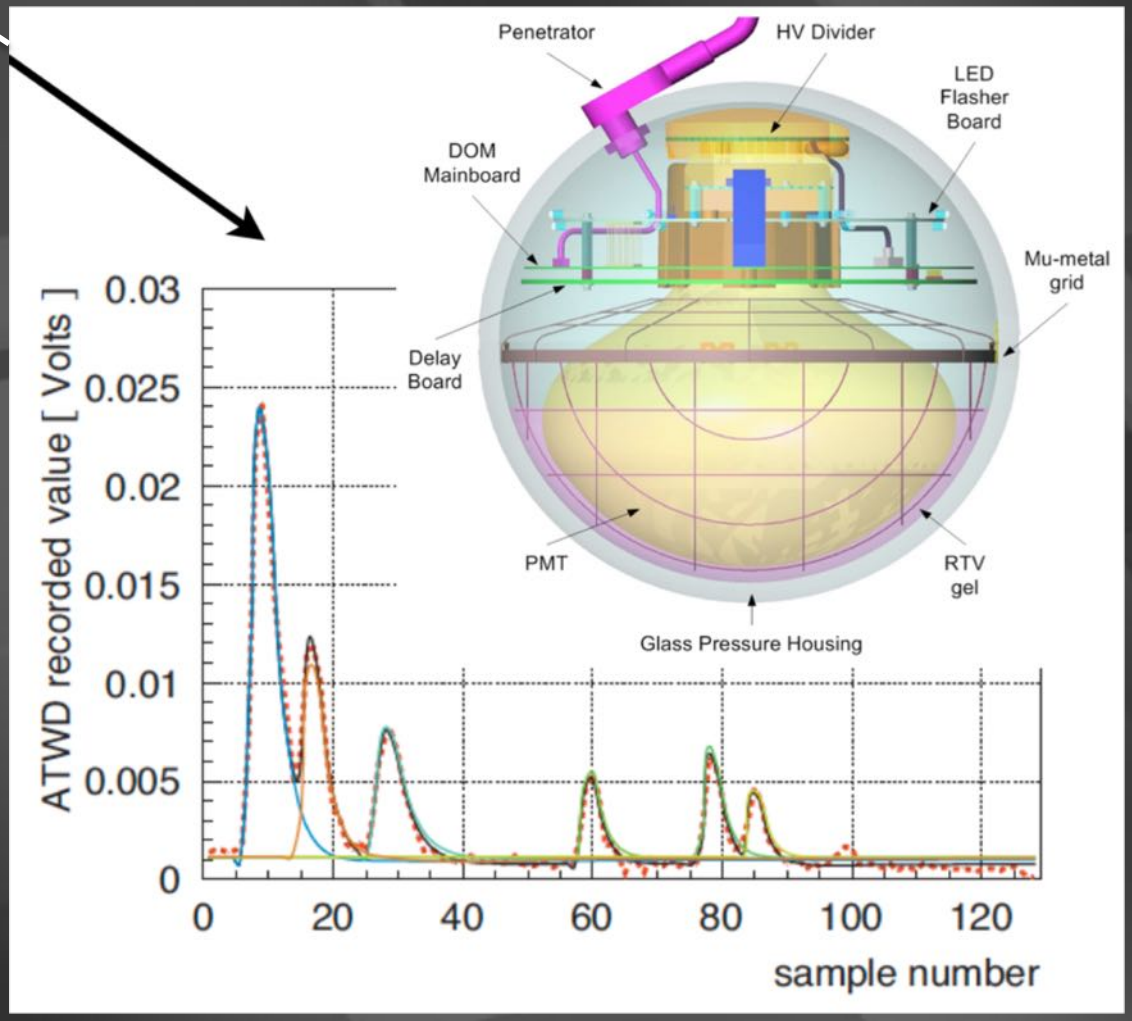

IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

photomultiplier tube -10 inch

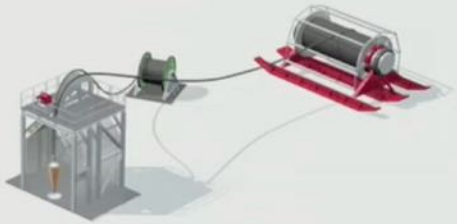
architecture of independent DOMs

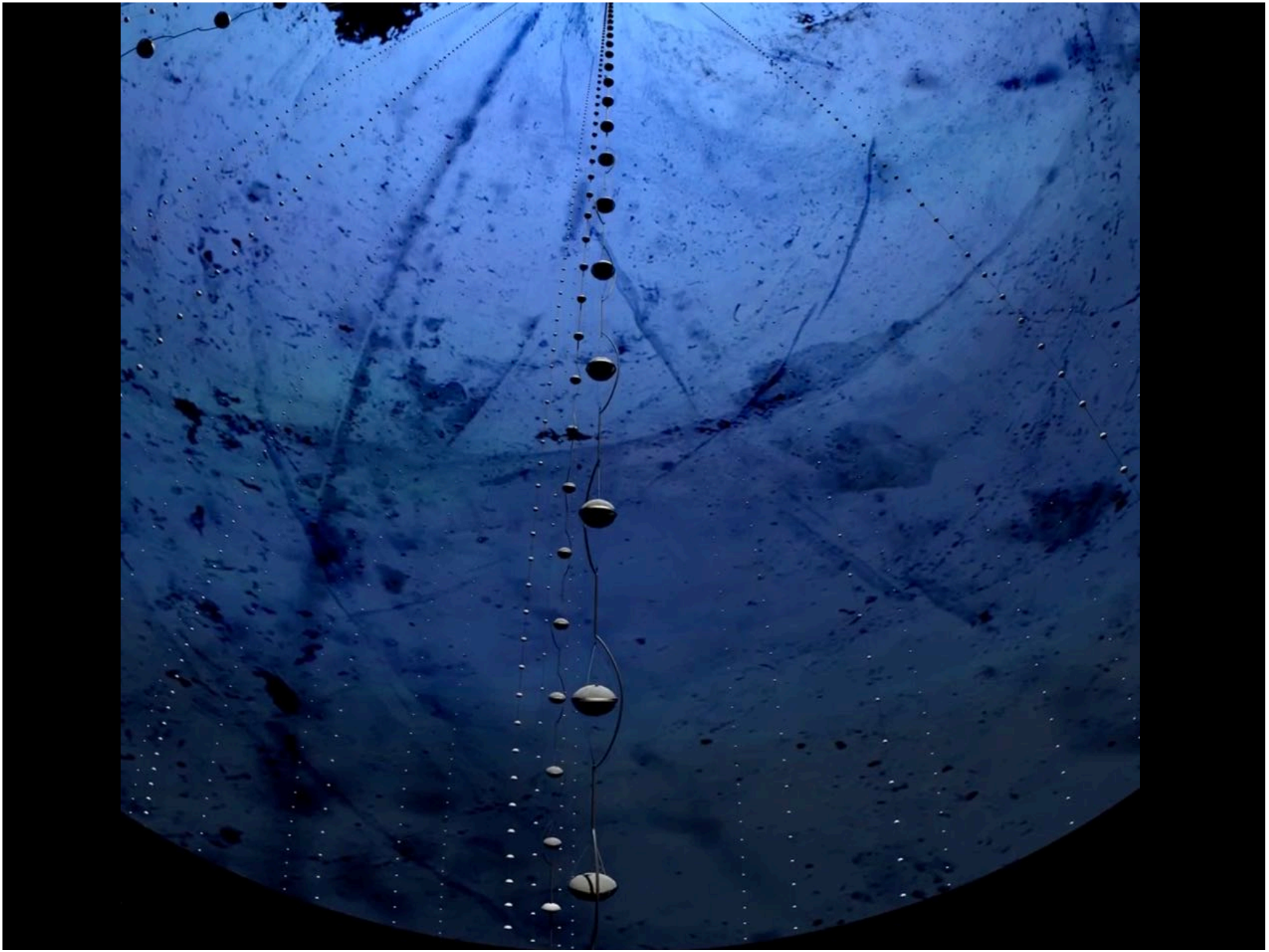


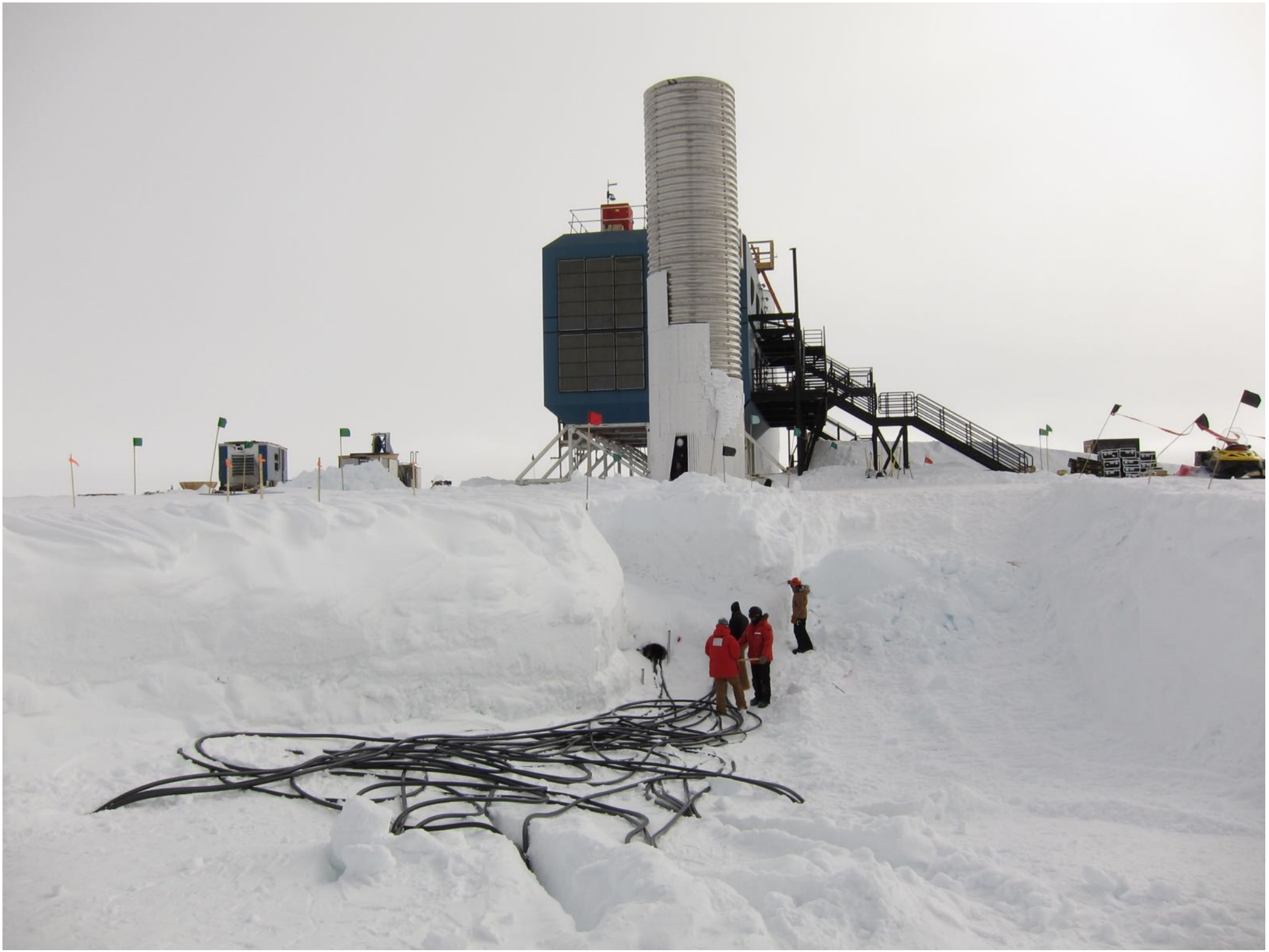
… each Digital Optical Module independently collects light signals like this, digitizes them,

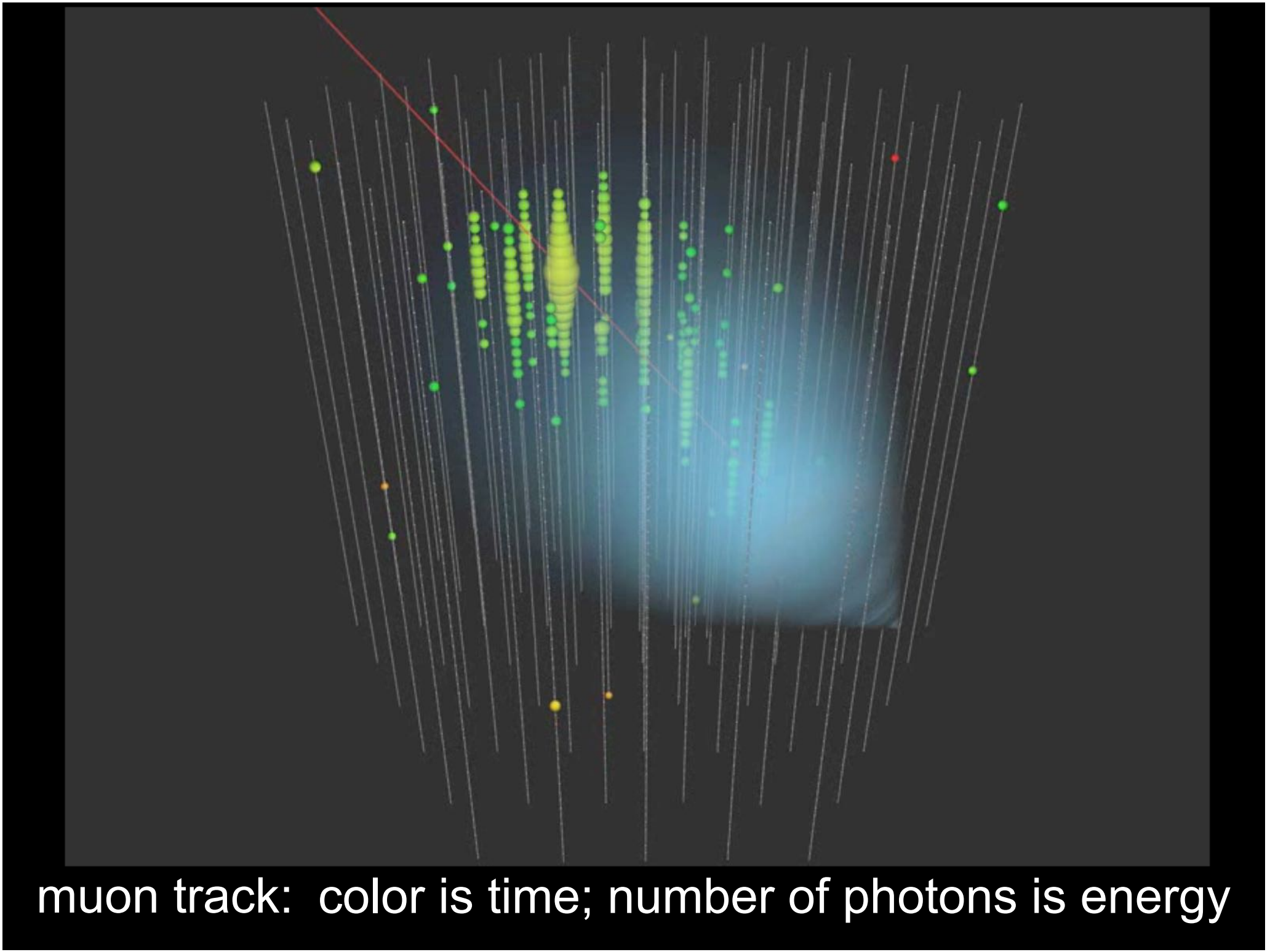


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…

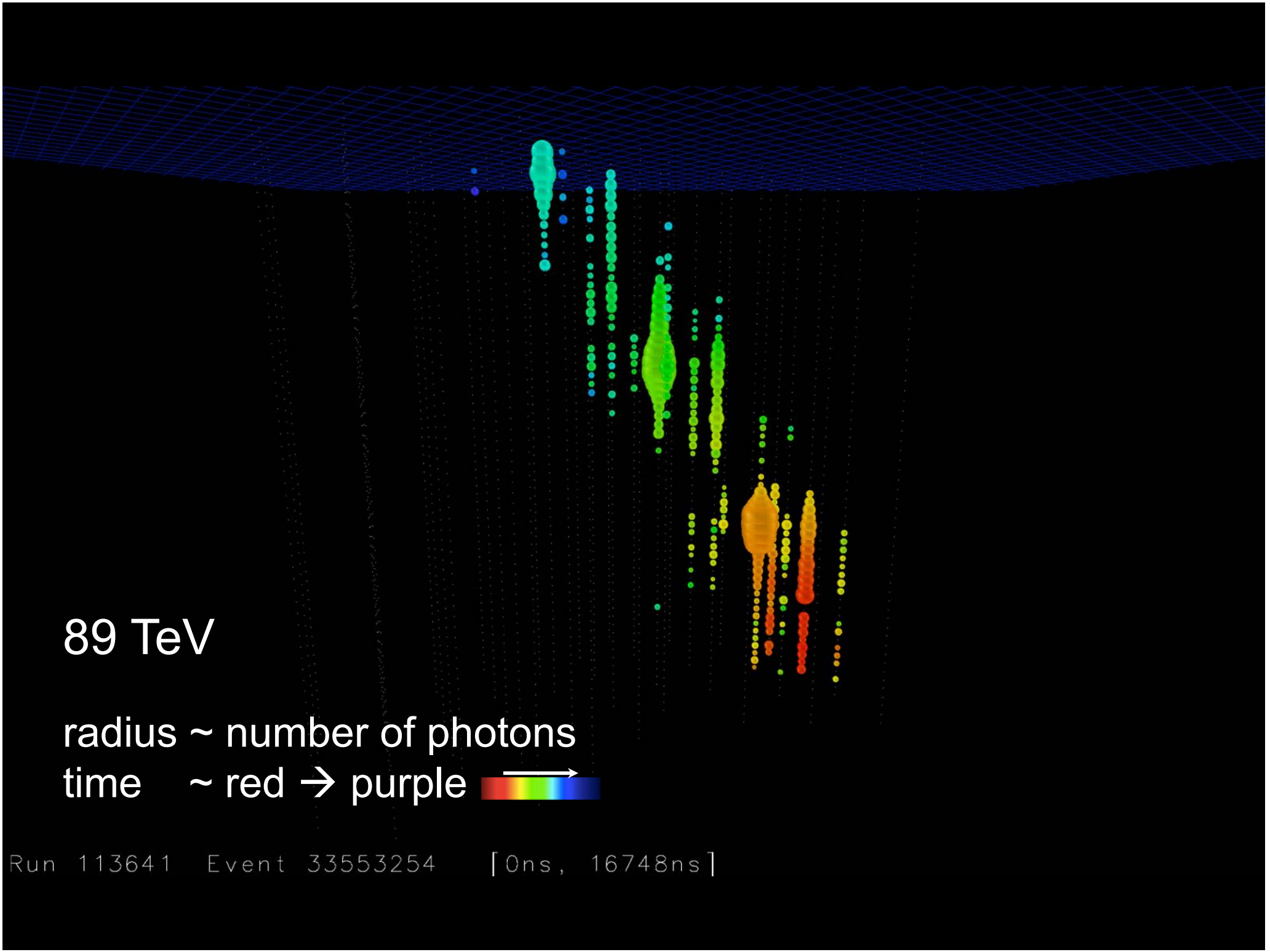




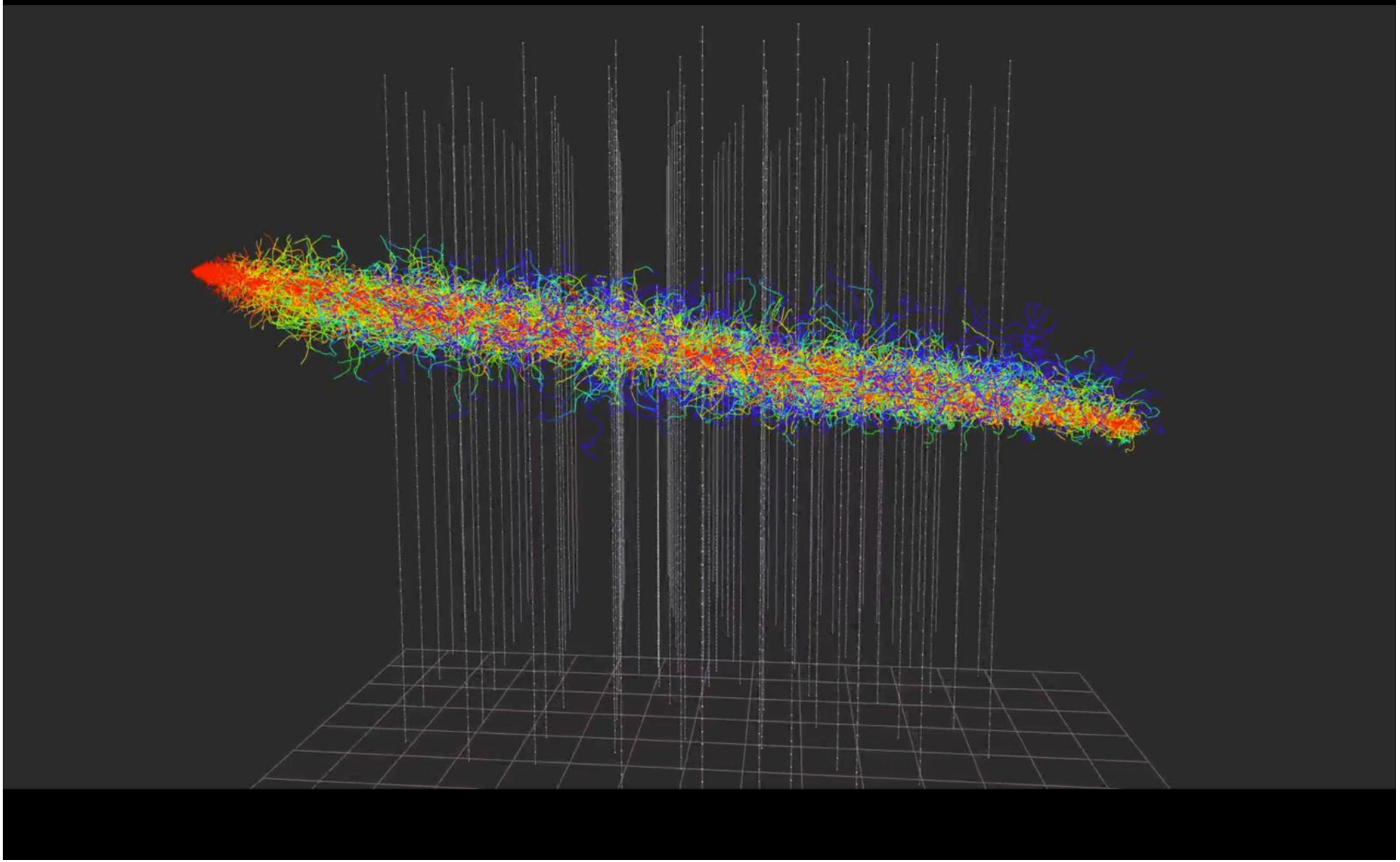




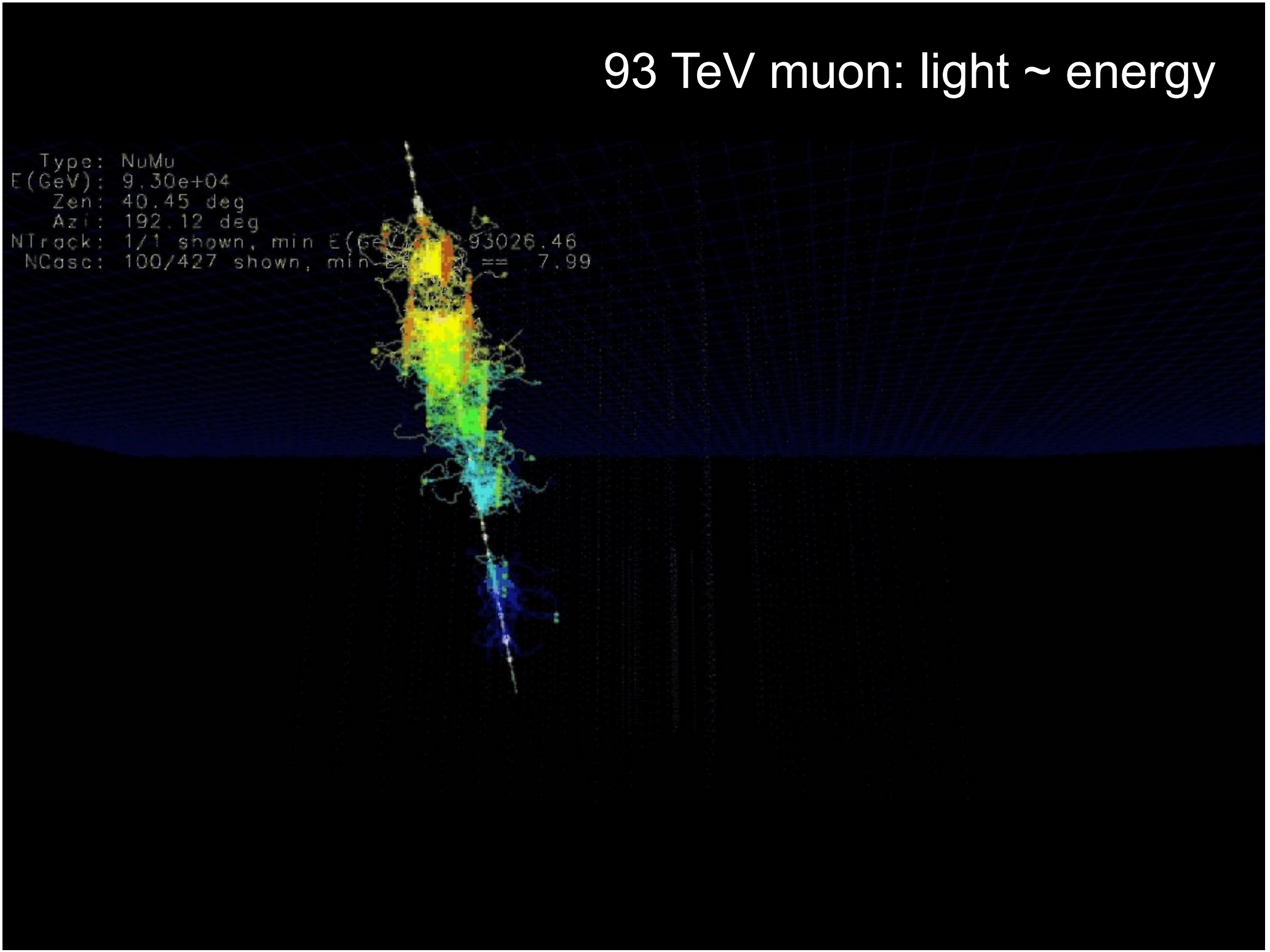
muon track: color is time; number of photons is energy

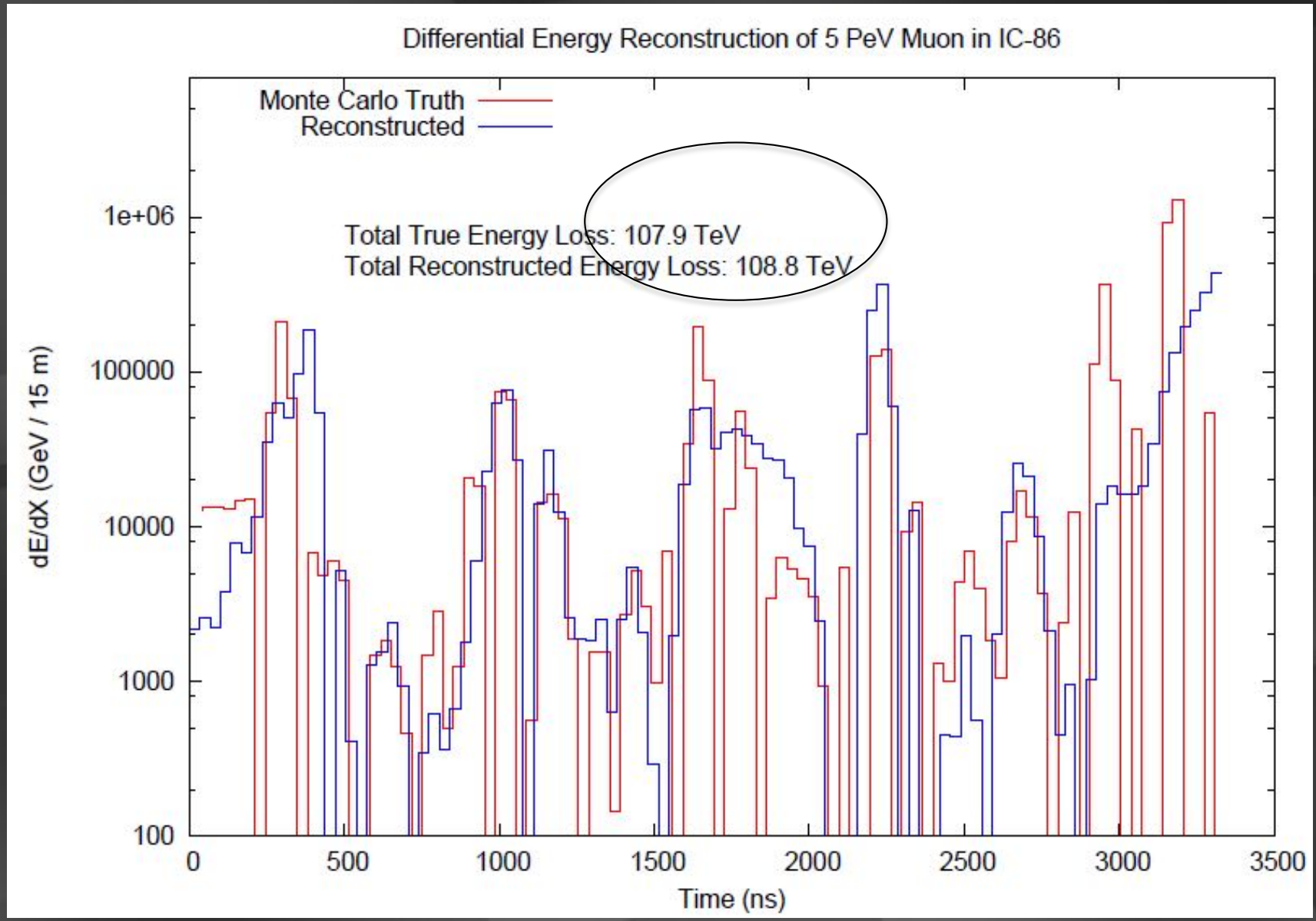

89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]

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



93 TeV muon: light ~ energy

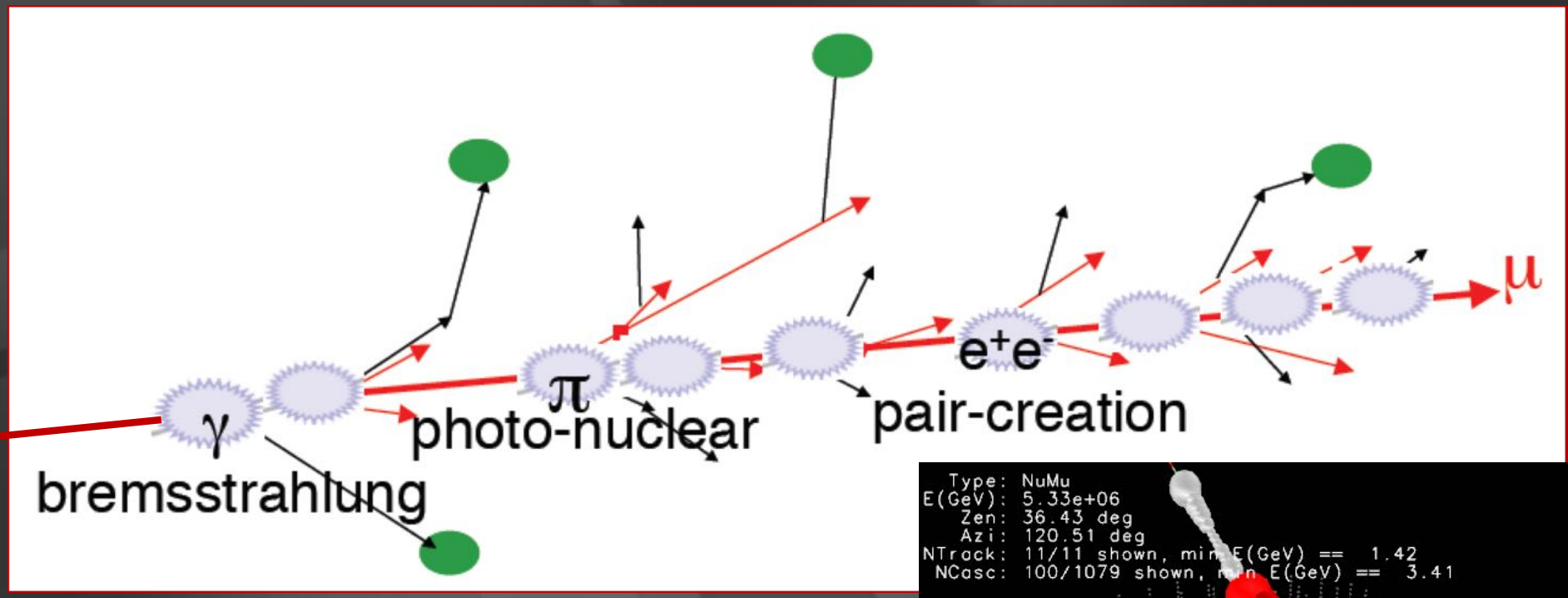


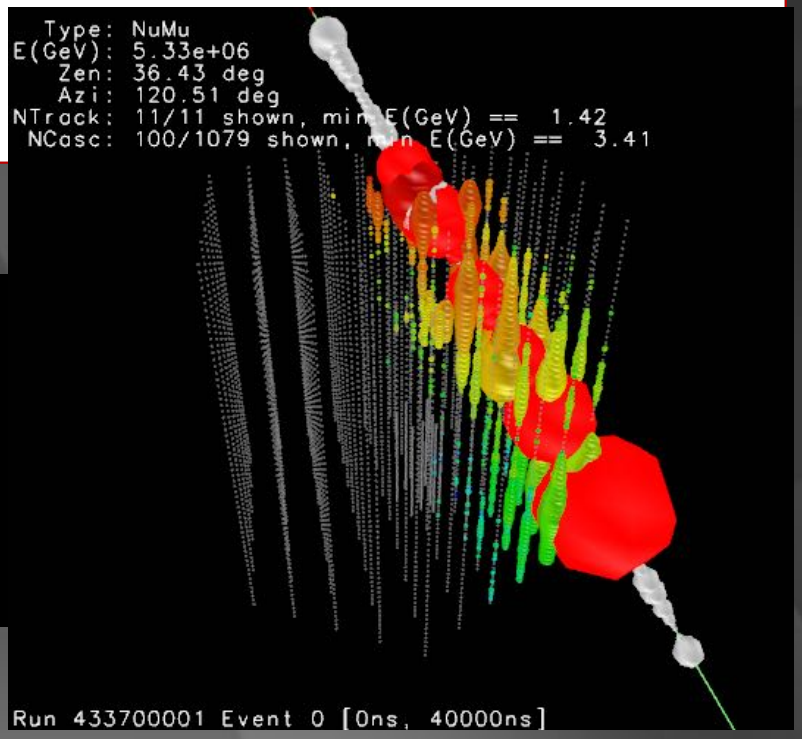


1.1 km

limited angular and energy resolution: computing → ice properties

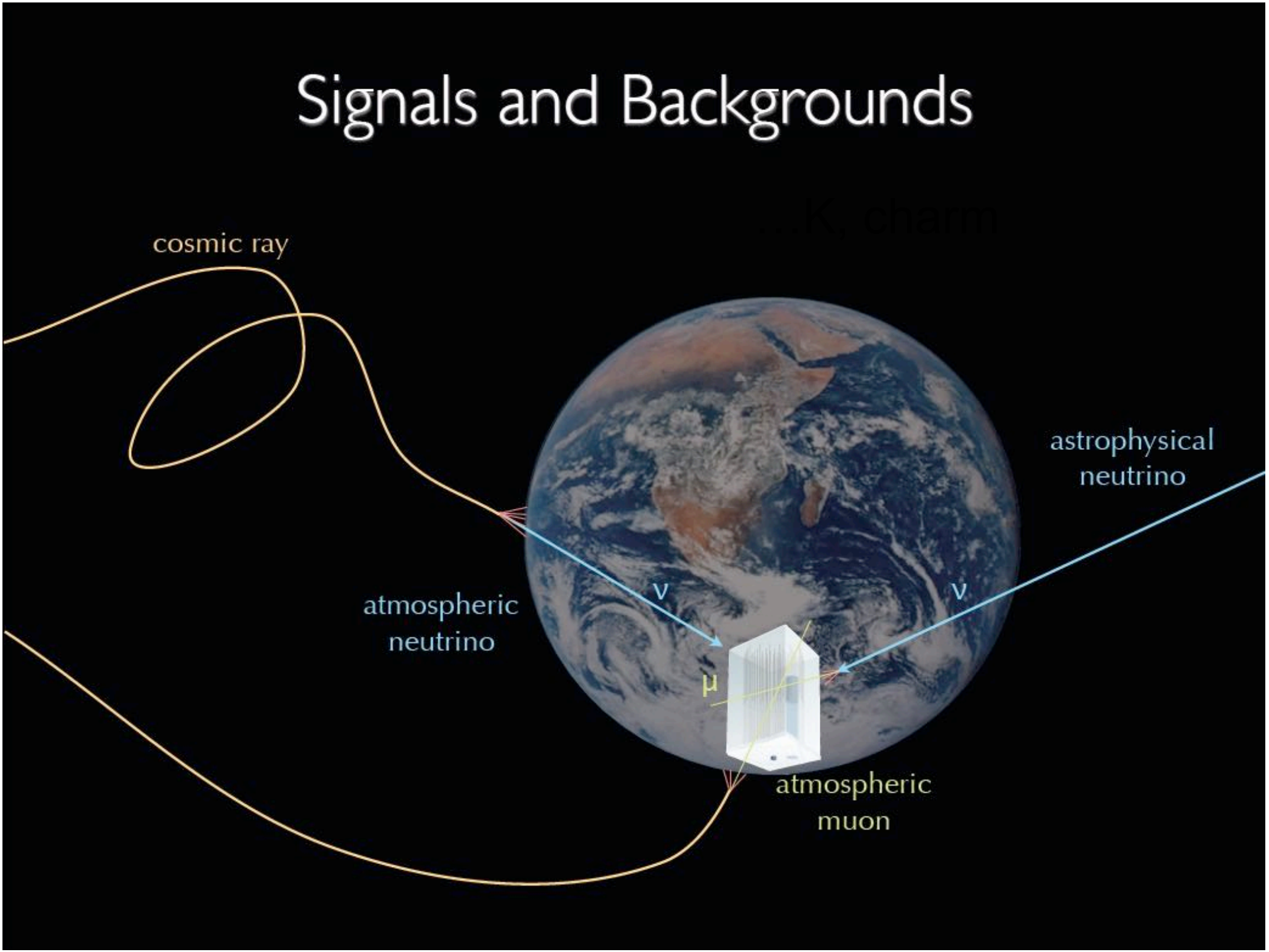
energy measurement (> 1 TeV)

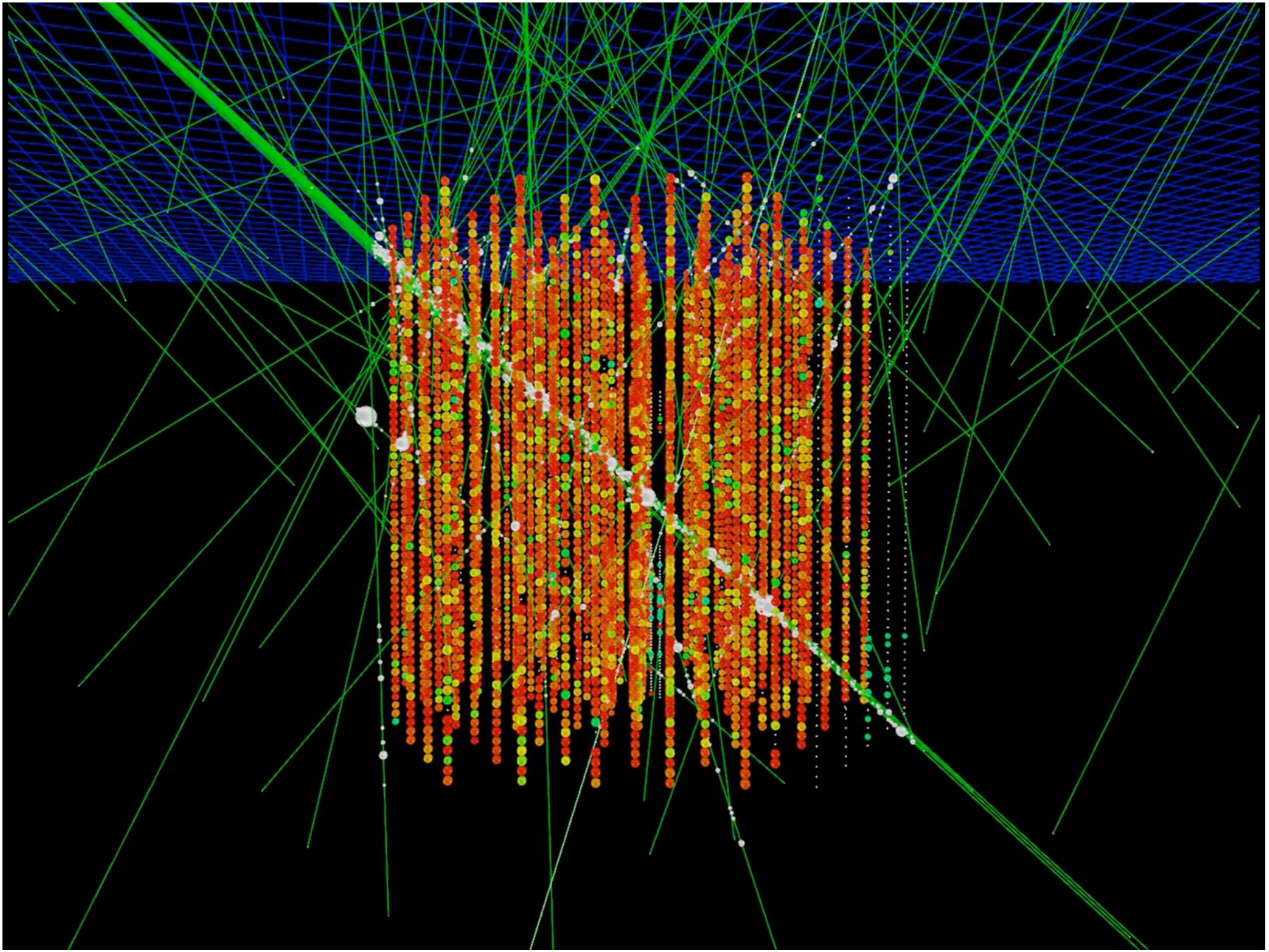




convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

Signals and Backgrounds





… you looked at 10msec of data !

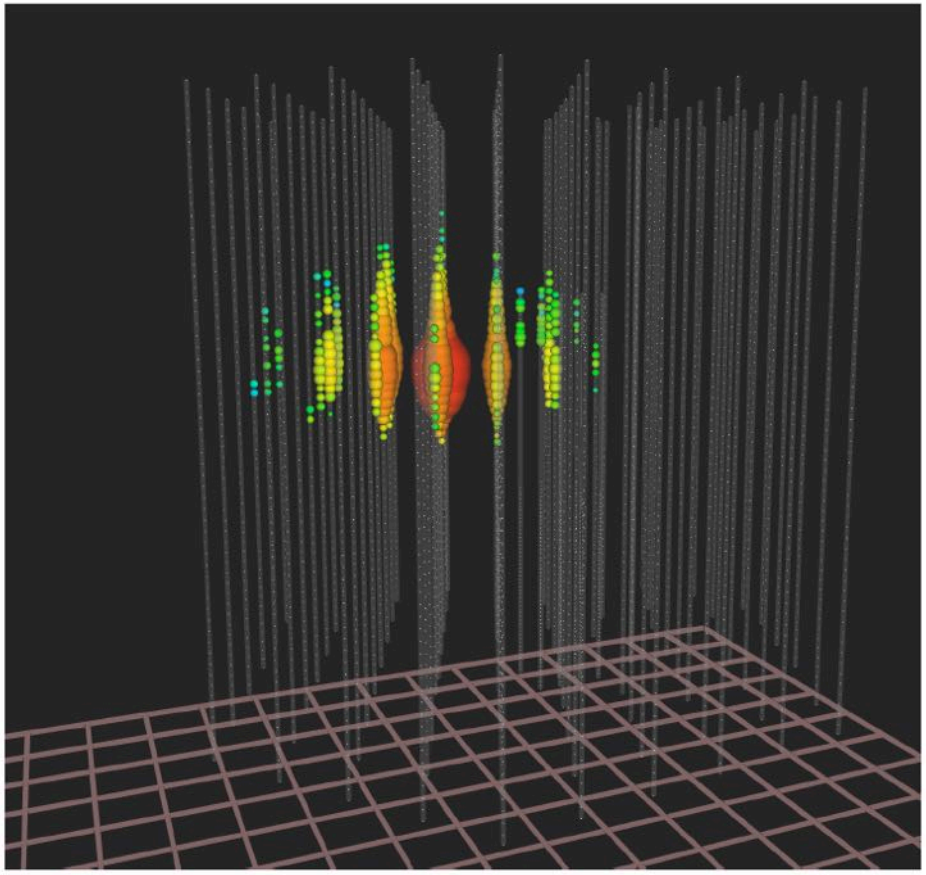
muons detected per year:

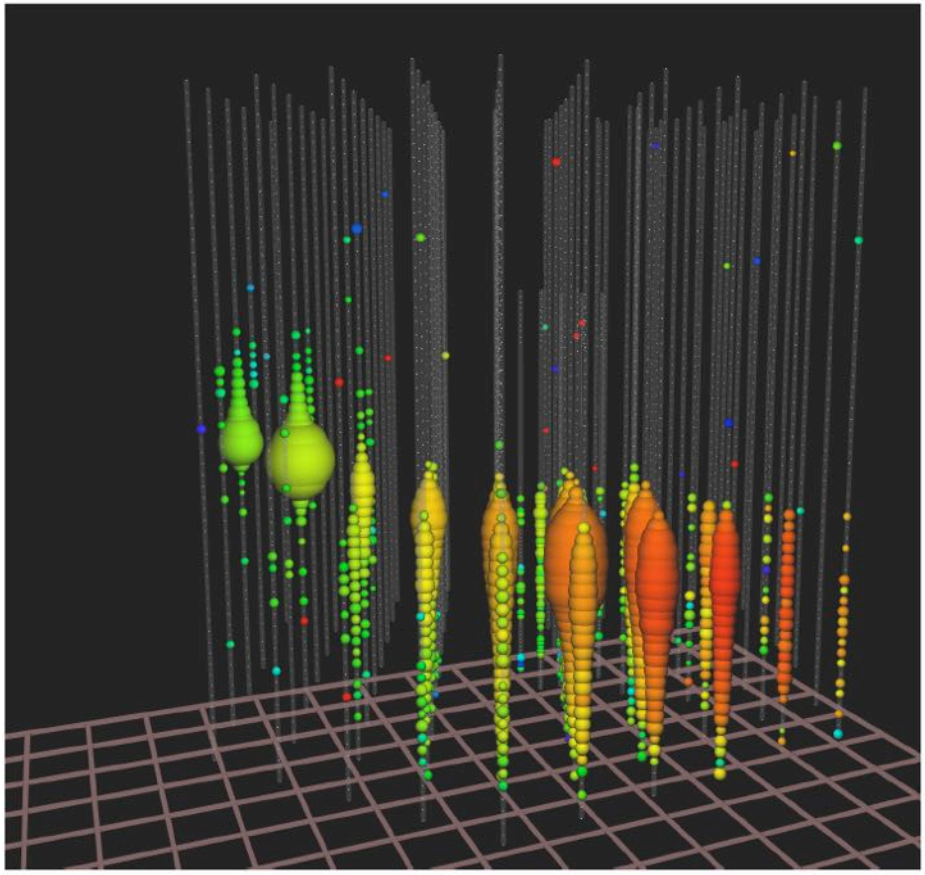
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second ** 1 every 6 minutes

isolated neutrinos interacting *inside* the detector (HESE)

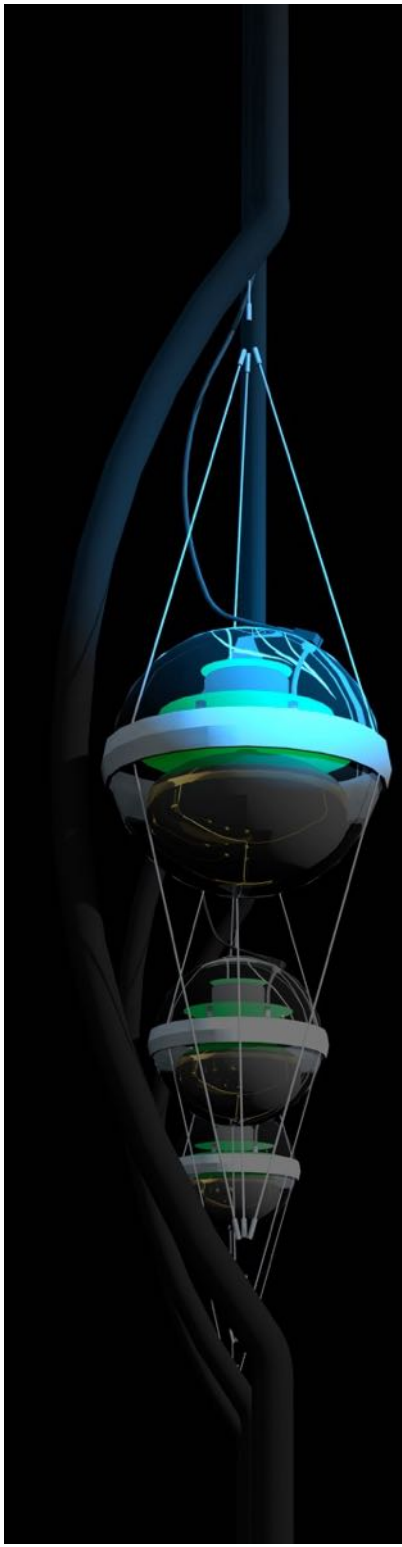
up-going muon tracks (UPMU)





total energy measurement all flavors, all sky

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



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francis halzen

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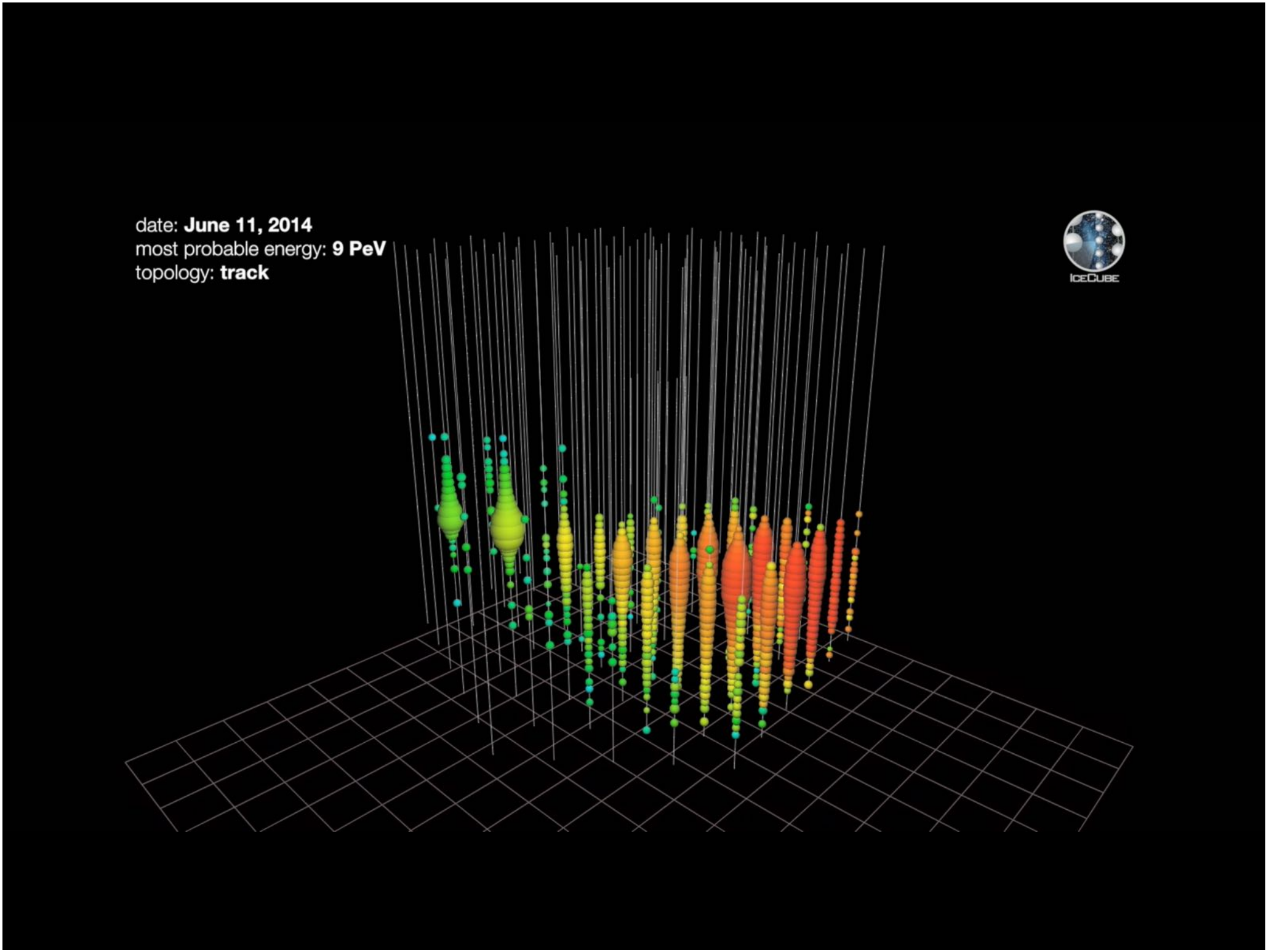
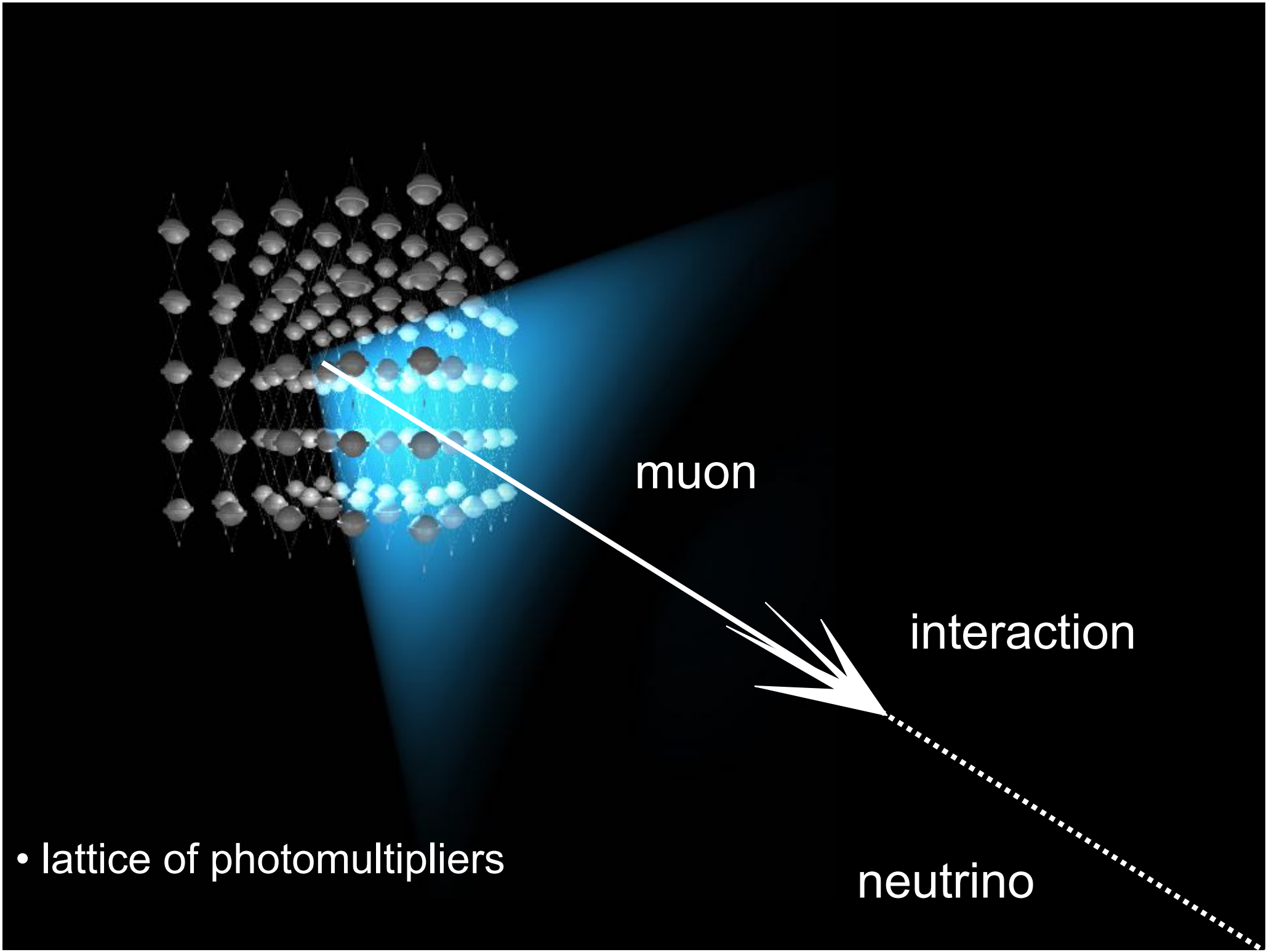
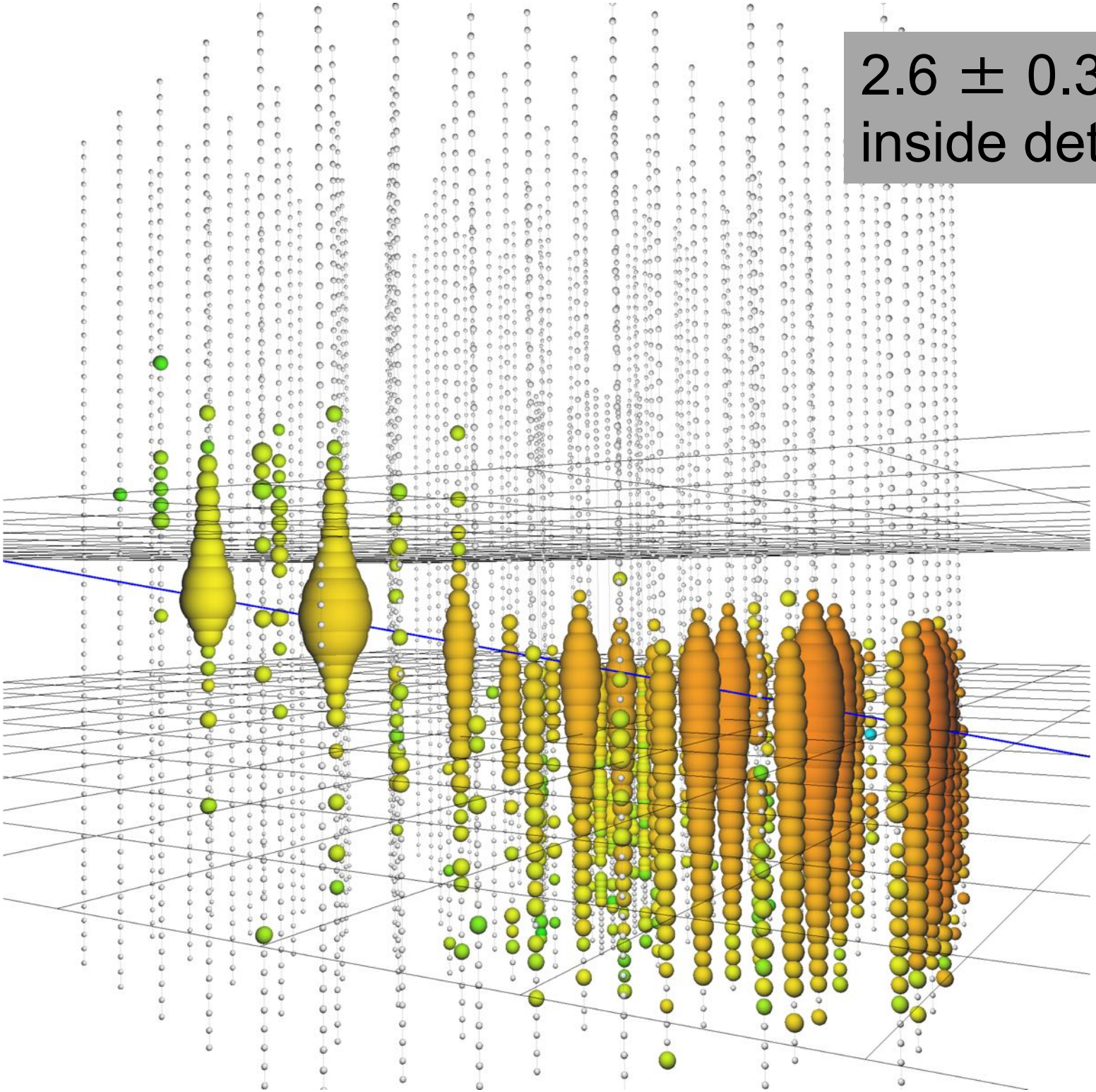
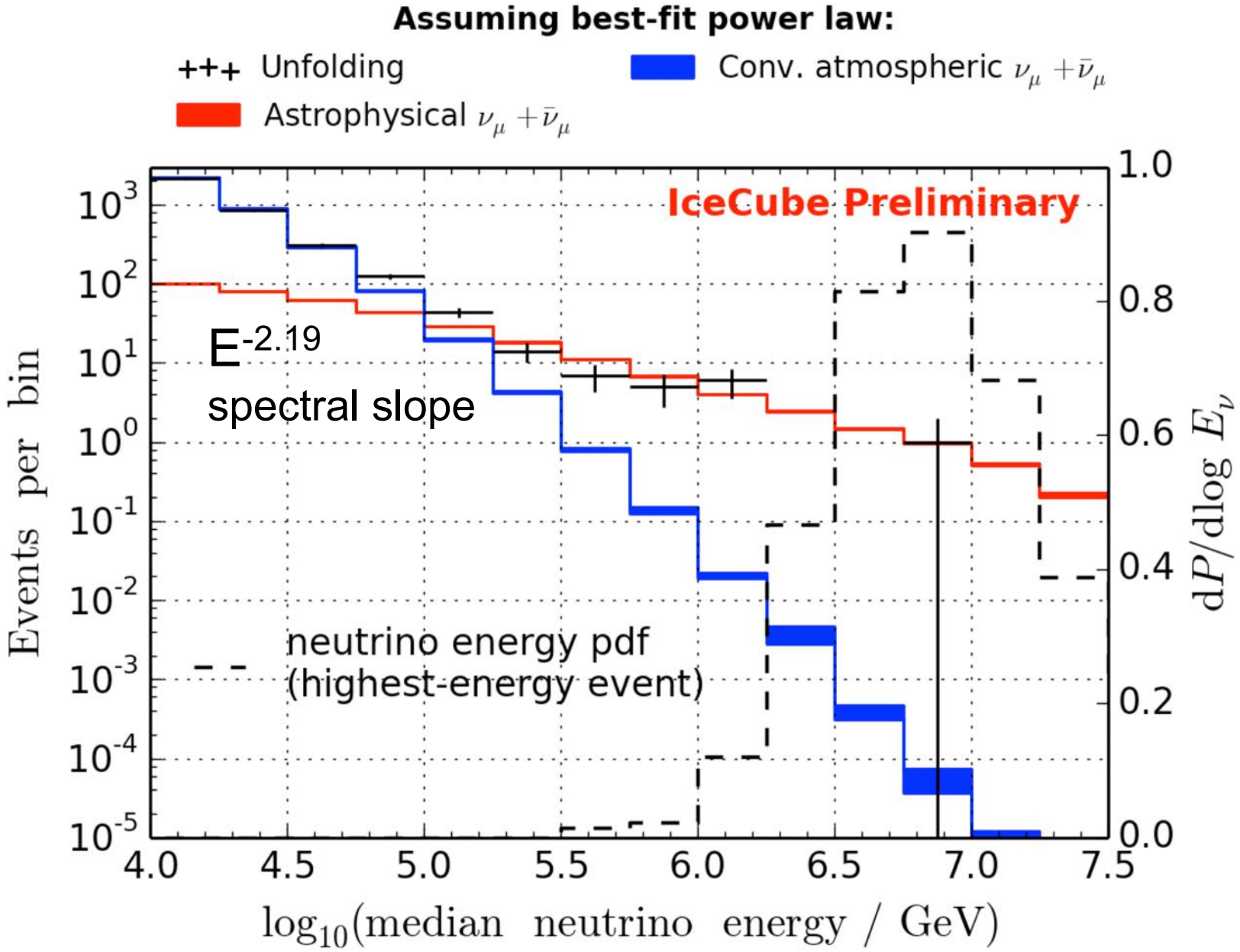
IceCube.wisc.edu


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


muon
interaction
neutrino
• lattice of photomultipliers


2.6 ± 0.3 PeV
inside detector

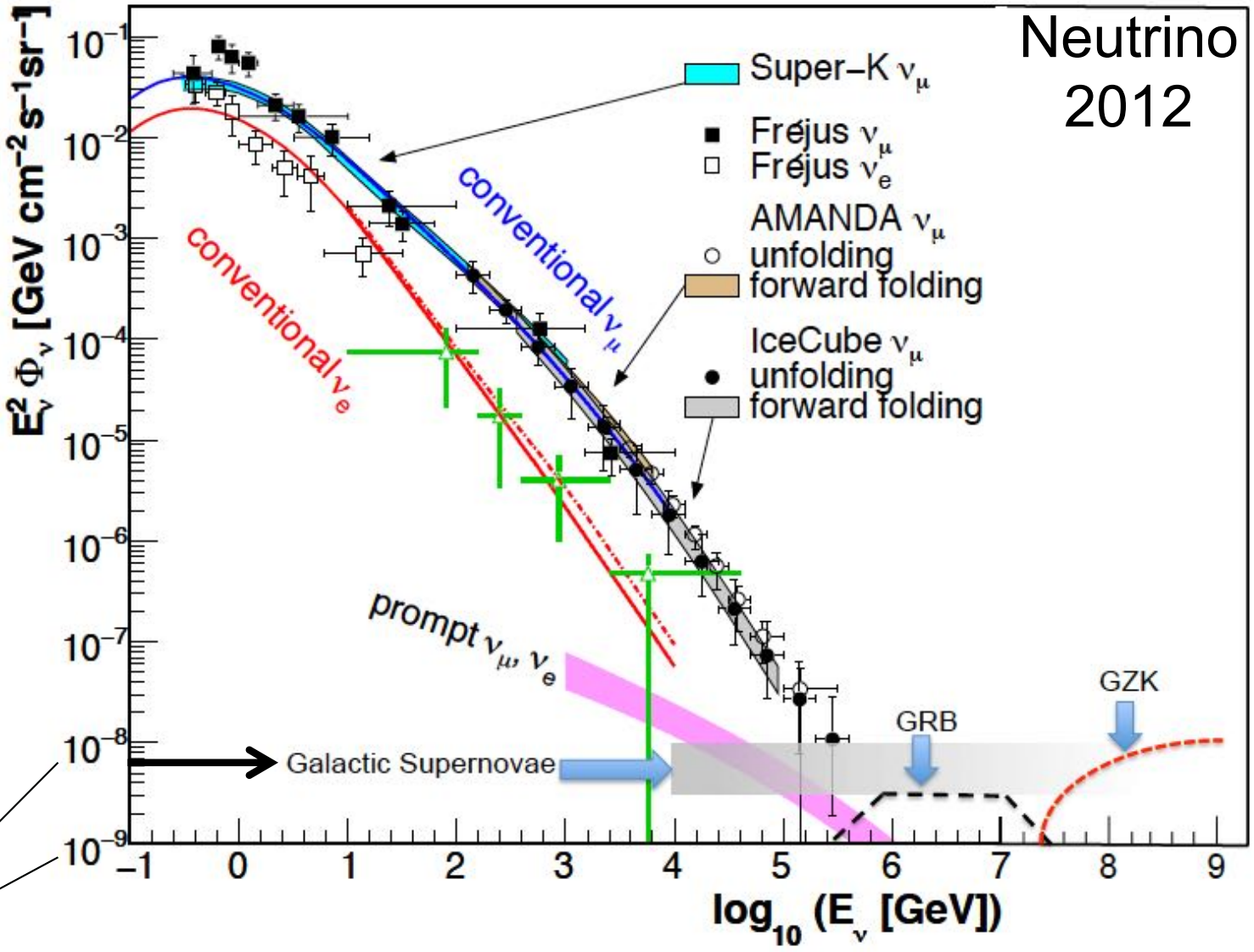
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric
atmospheric background: less than one event/deg^2/year



above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

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



10—100 events per year for fully efficient detector

atmospheric

cosmic

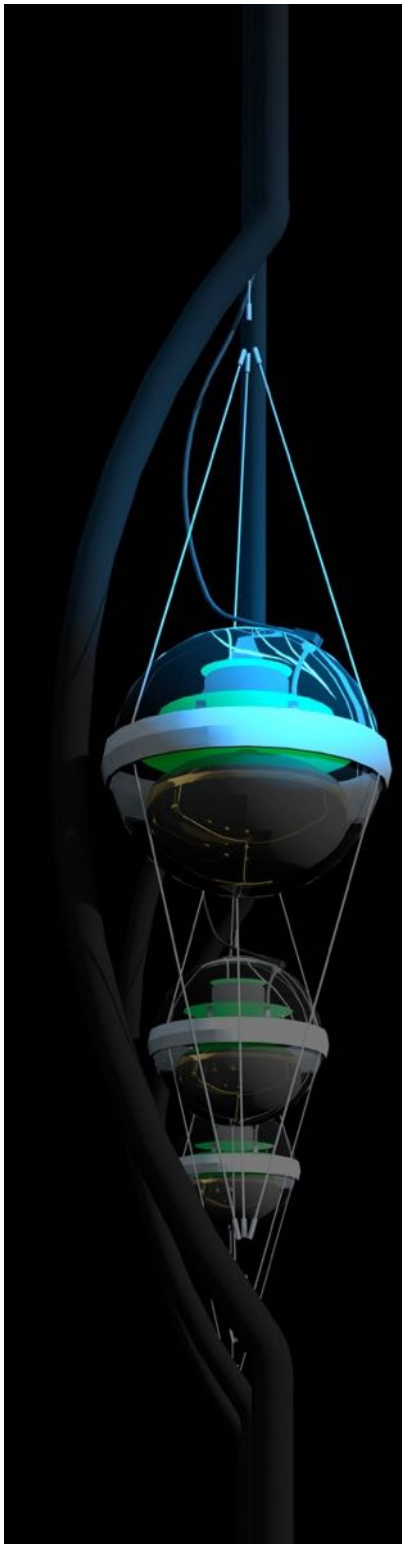
100 TeV

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



IceCube

francis halzen

- IceCube
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iceCube.wisc.edu

cosmic rays interact with the microwave background

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

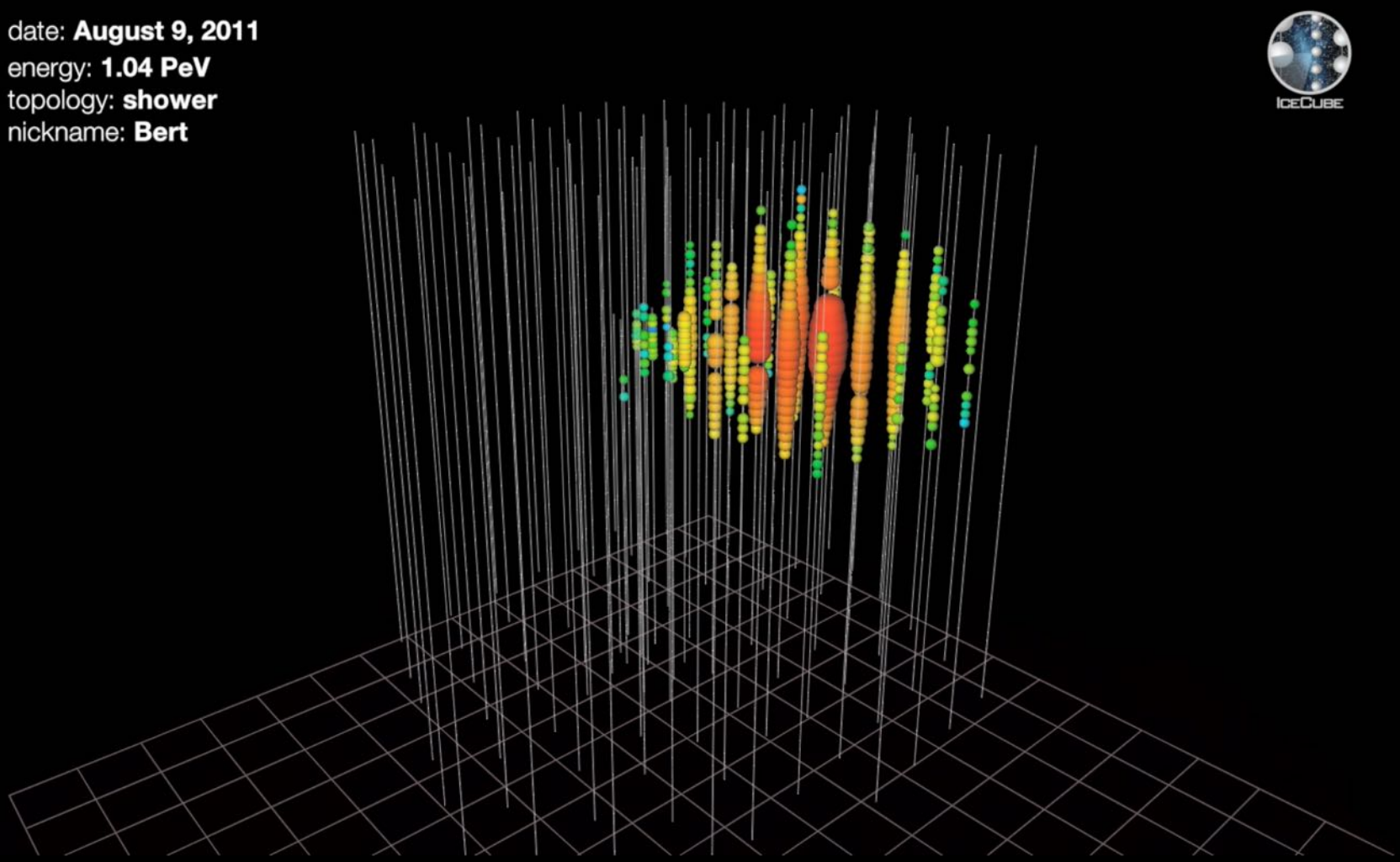
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

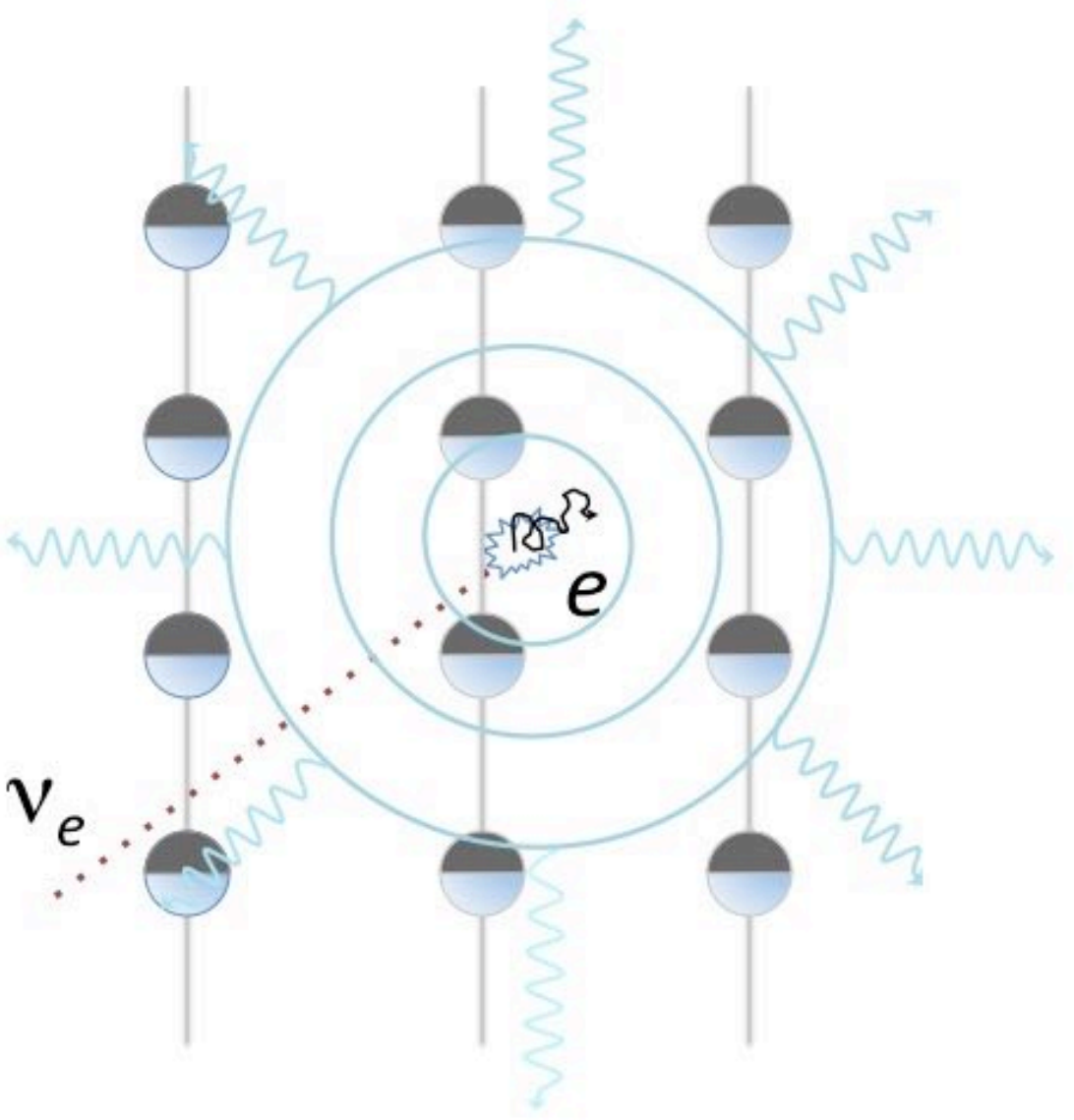
GZK neutrino search: two neutrinos with > 1,000 TeV

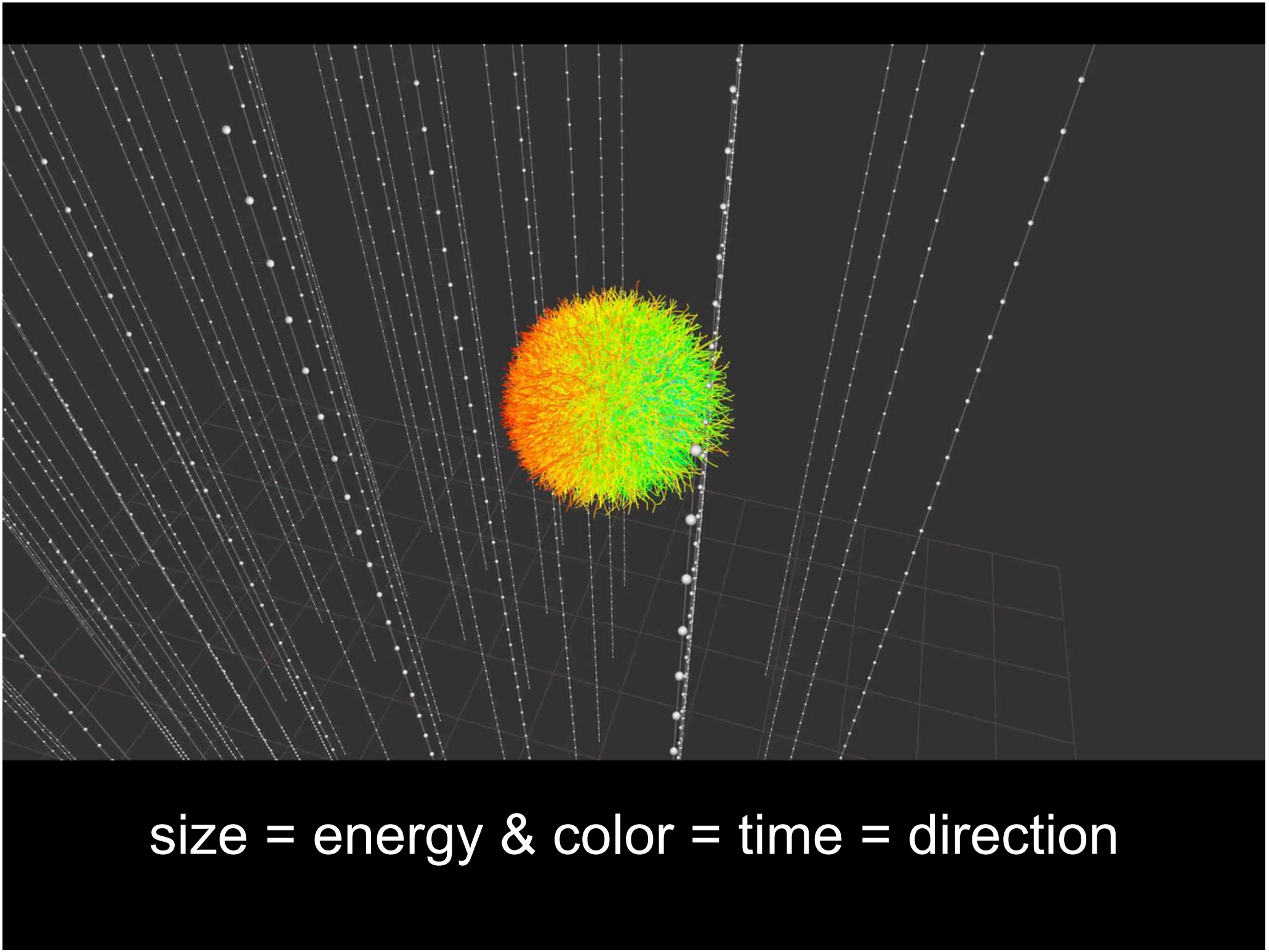


electron showers versus muon tracks

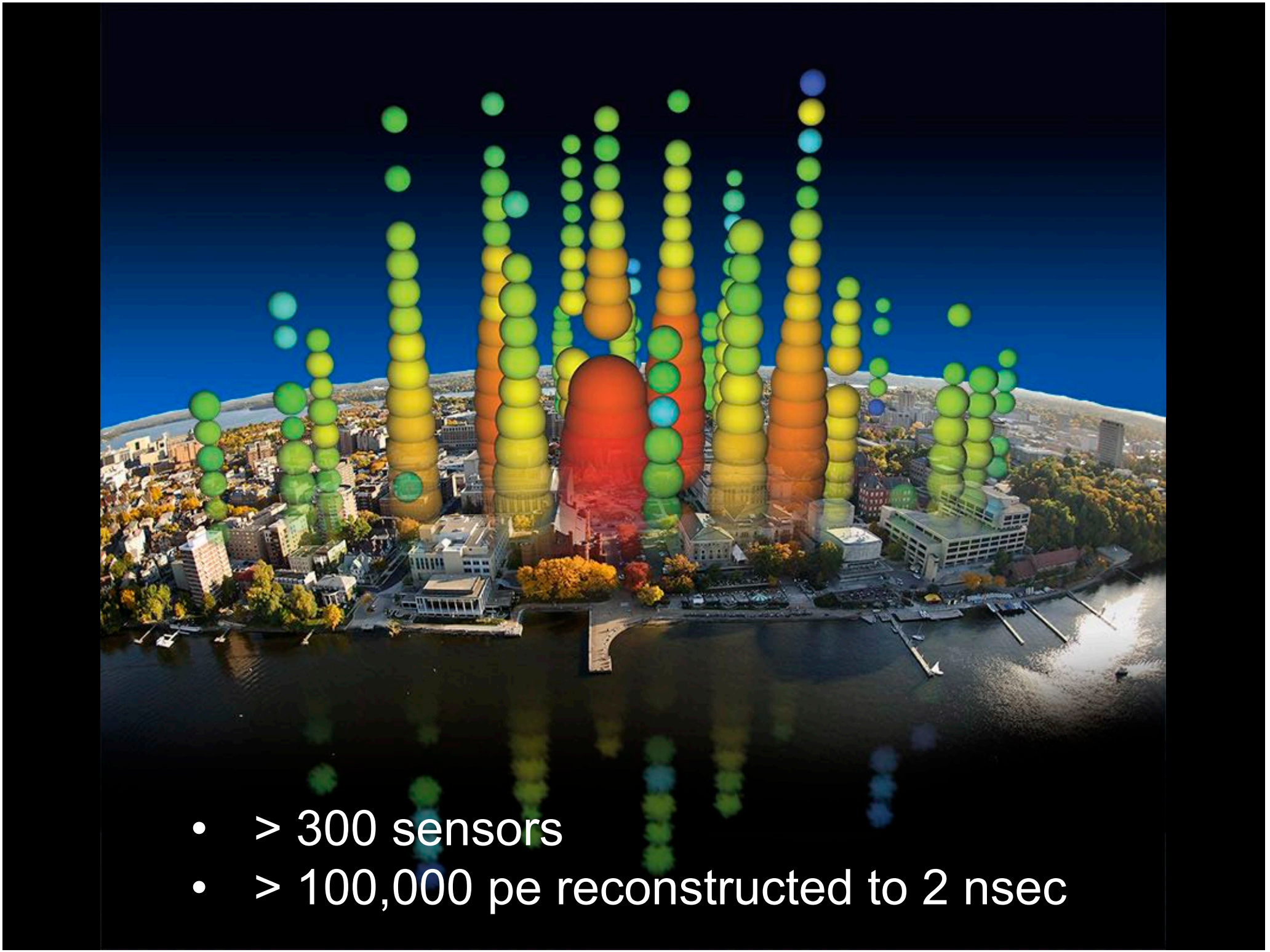
PeV ν_e and ν_τ showers:

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



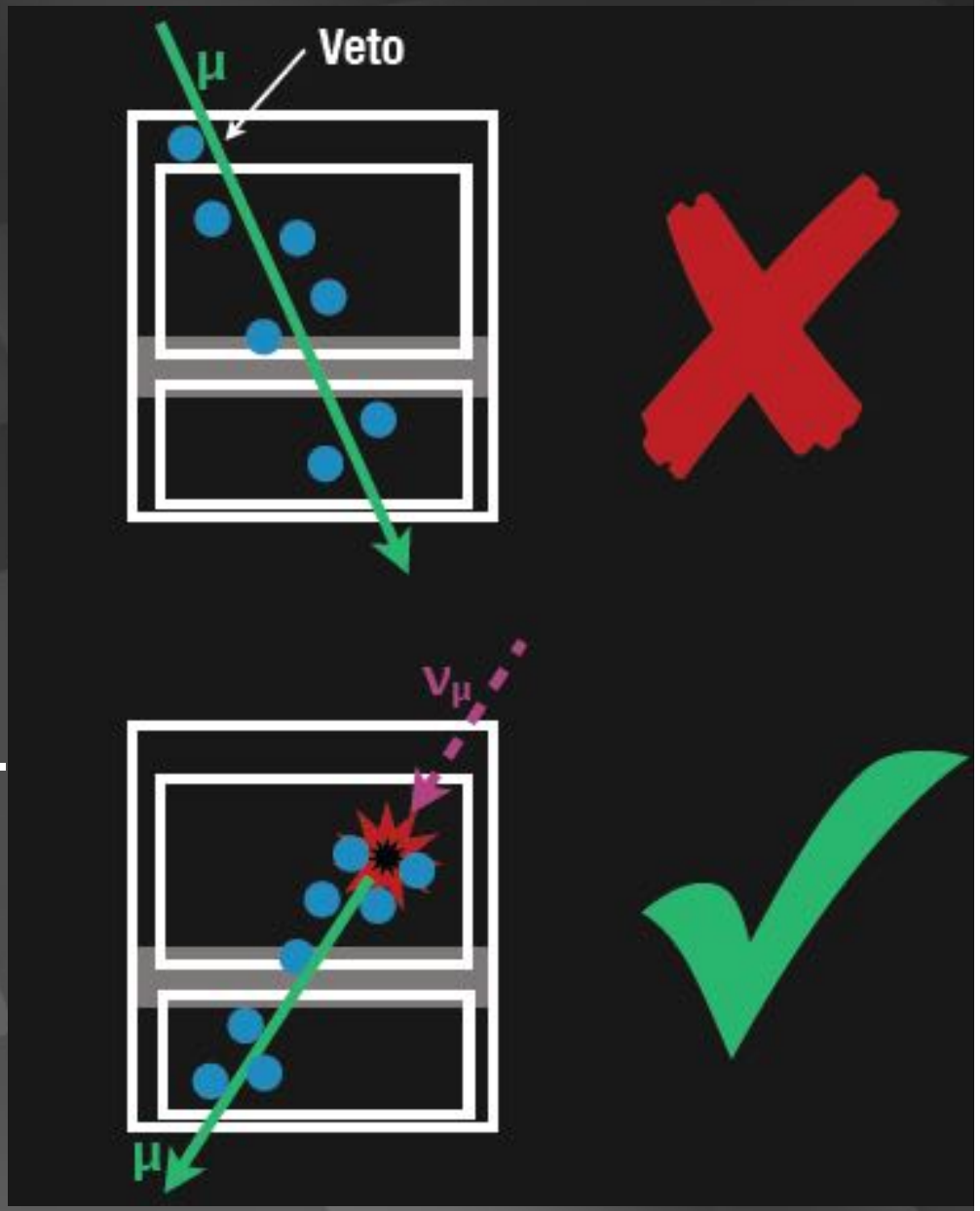


size = energy & color = time = direction

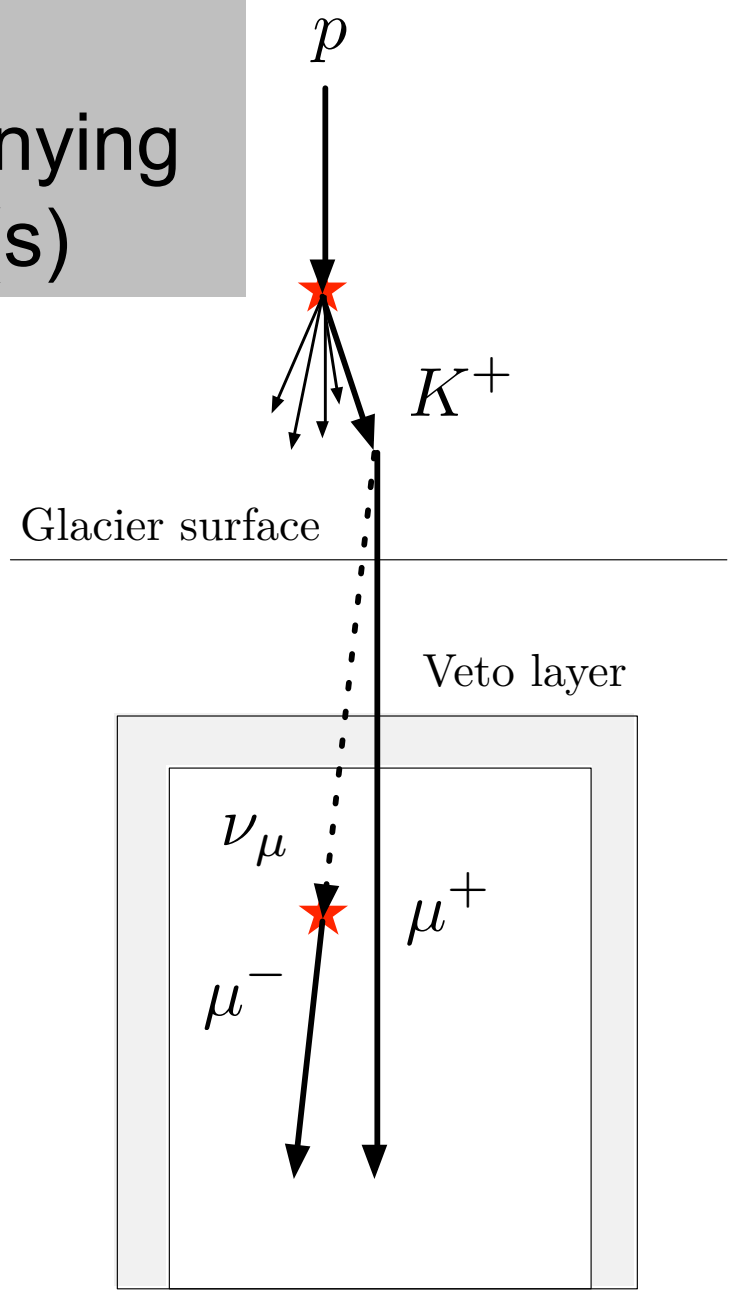


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

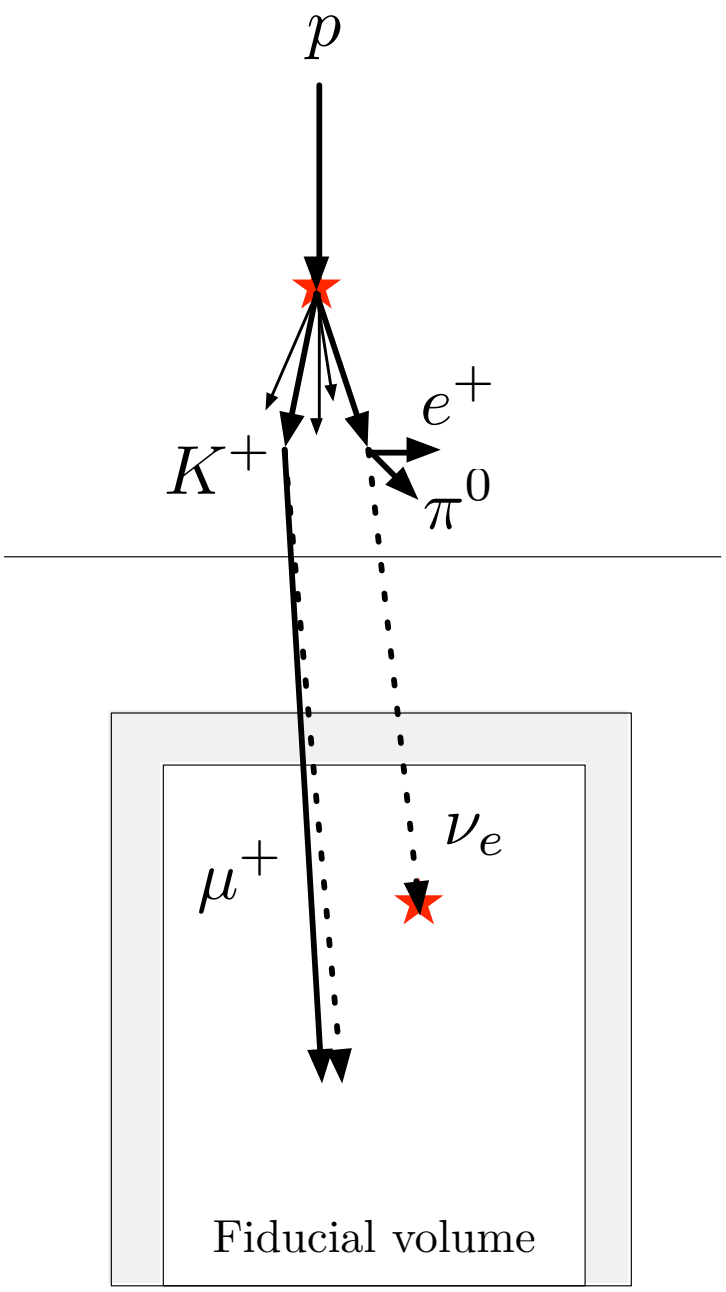
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



no accompanying muon(s)

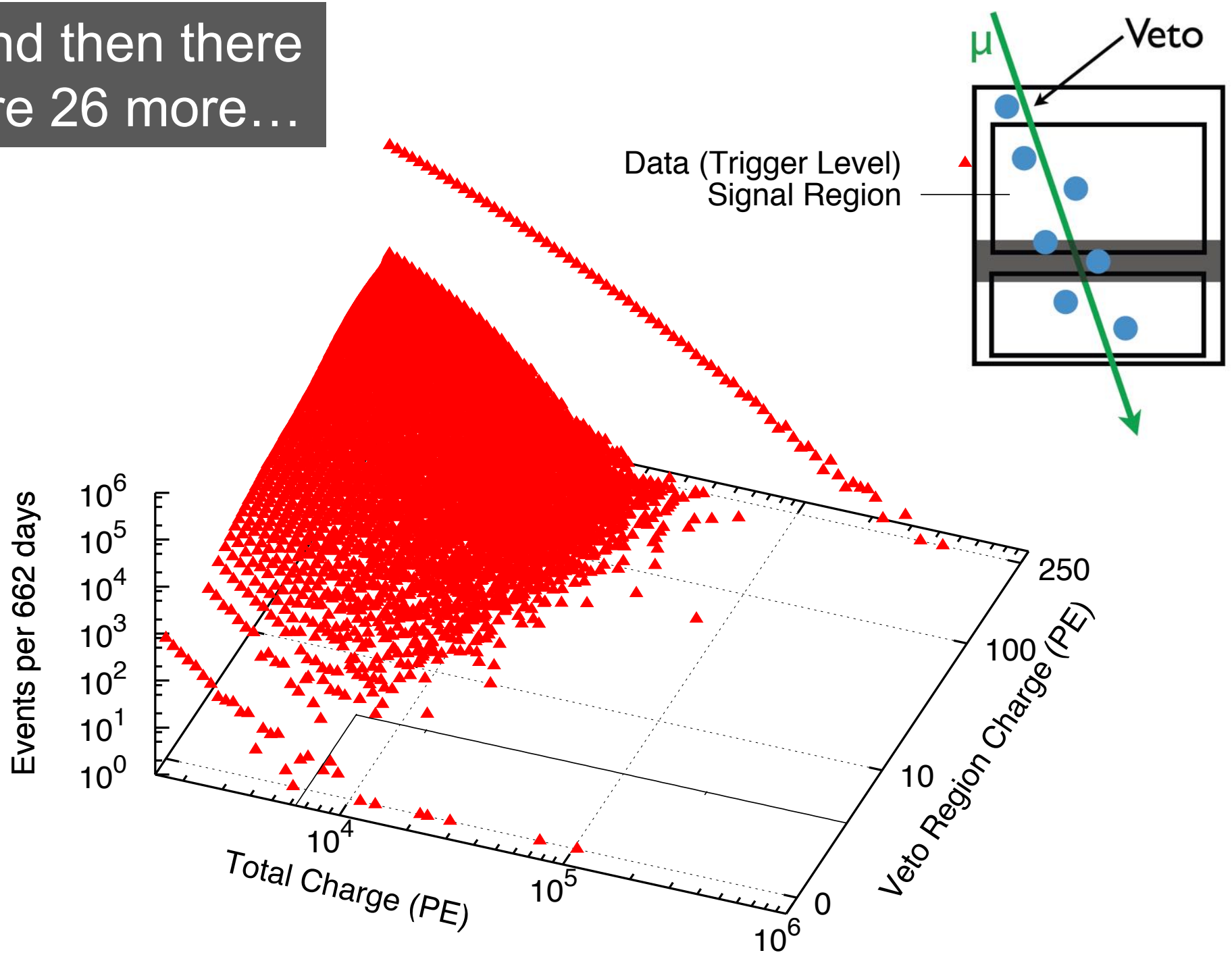


Veto by correlated muon



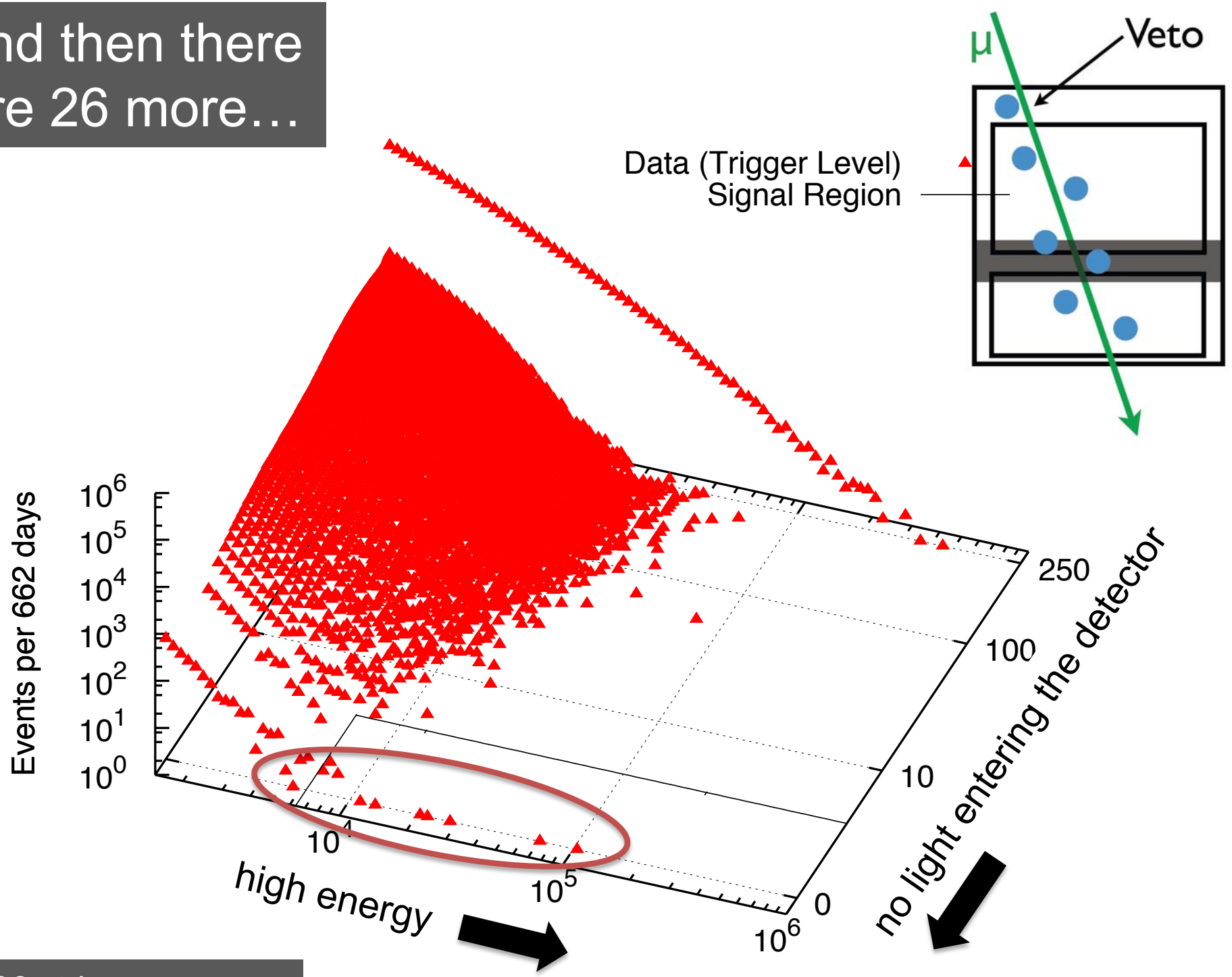
Veto by uncorrelated muon

…and then there were 26 more…



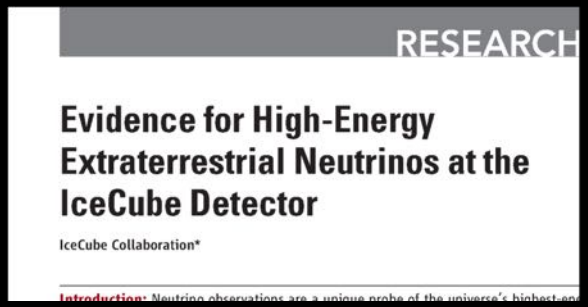
data: 86 strings one year

…and then there were 26 more…



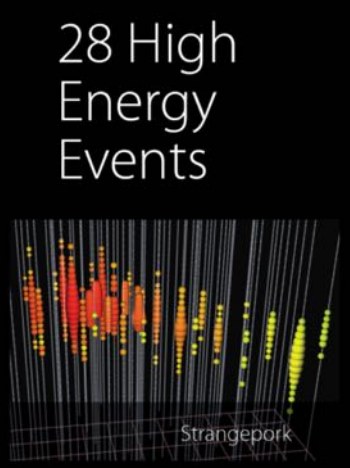
data: 86 strings one year

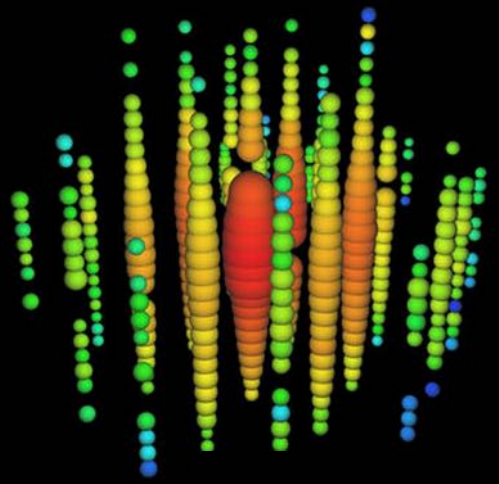
2 old + 26 new events

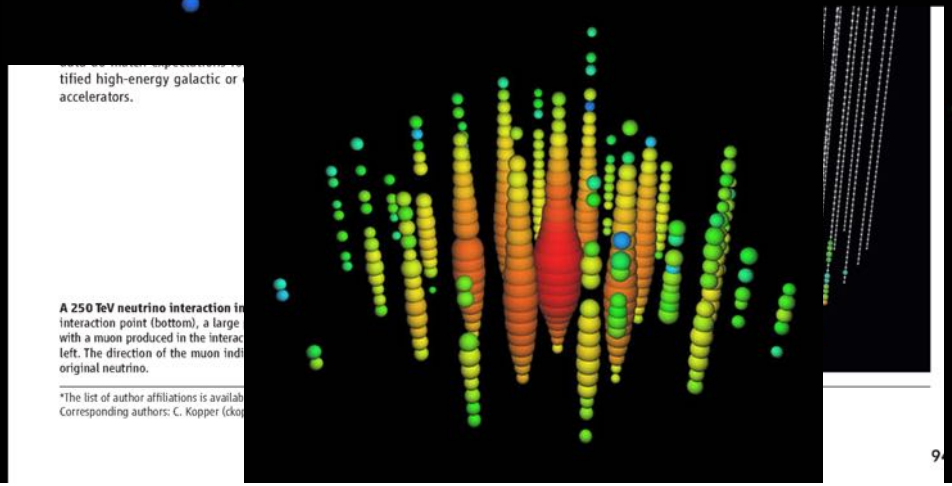

RESEARCH

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

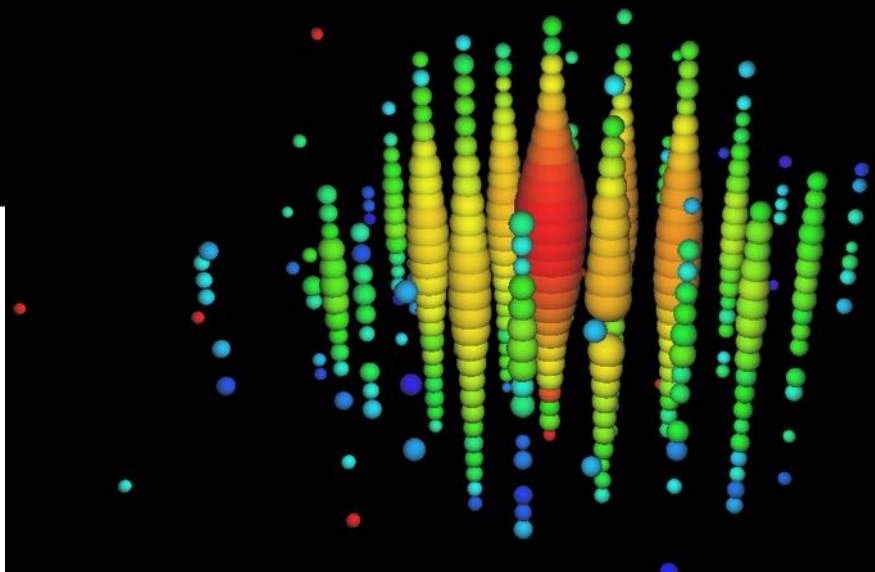





tified high-energy galactic or
accelerators.

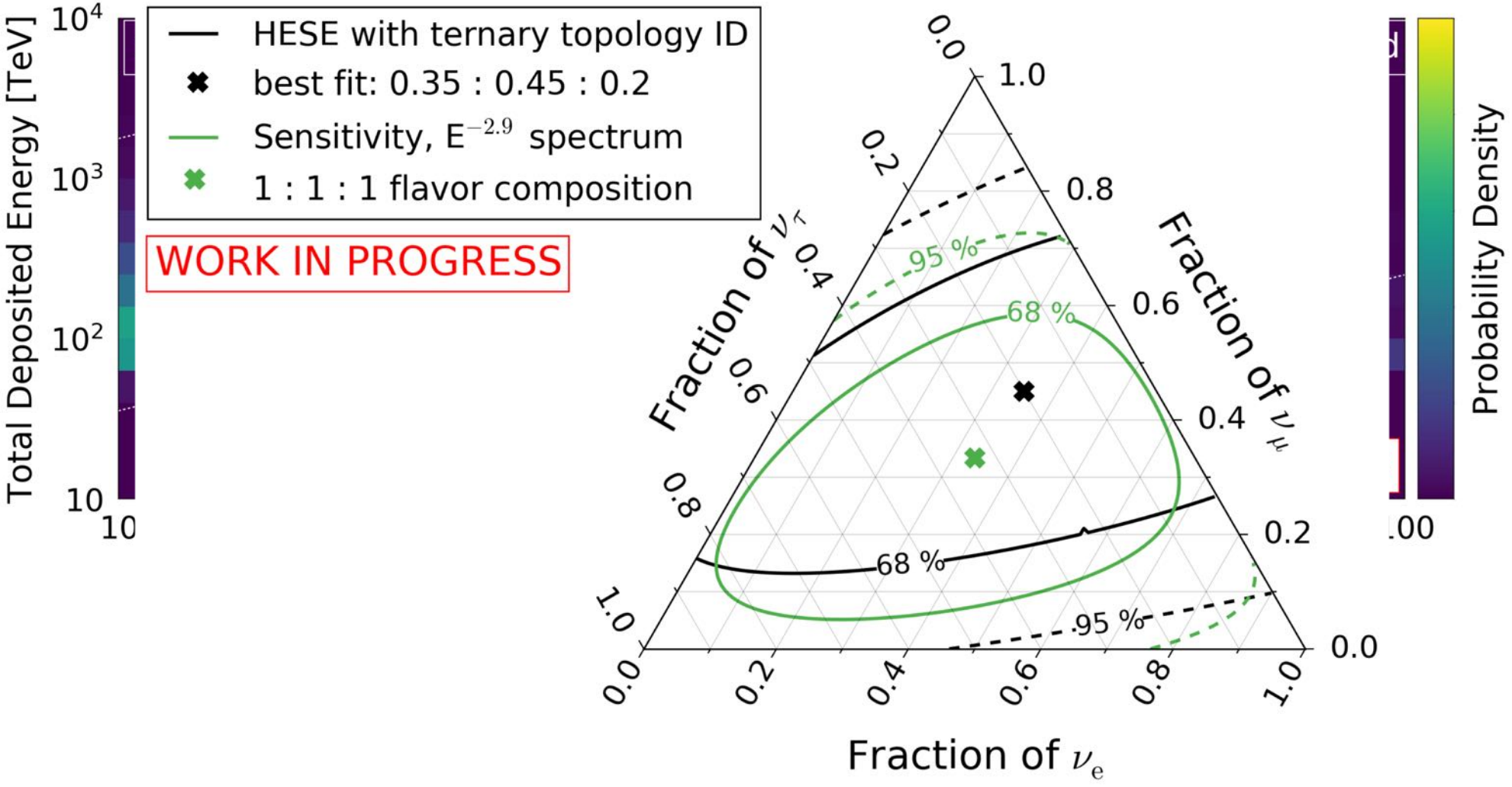
A 250 TeV neutrino interaction in
interaction point (bottom), a large
with a muon produced in the interac
left. The direction of the muon indi
original neutrino.

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



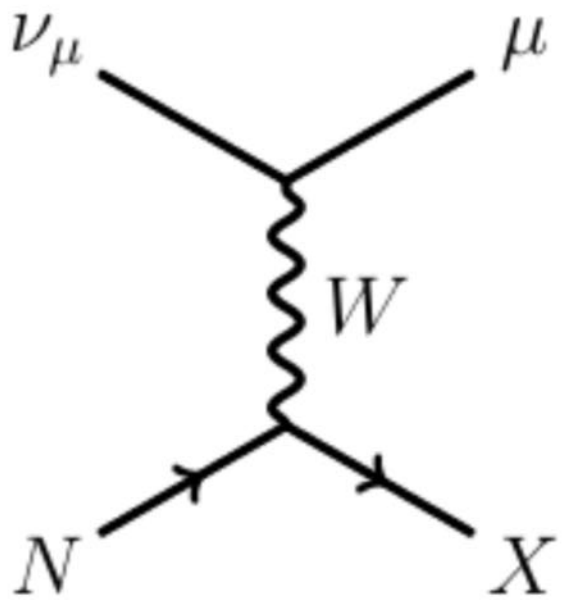
2000 TeV event in year 3

high-energy starting events – 7.5 yr

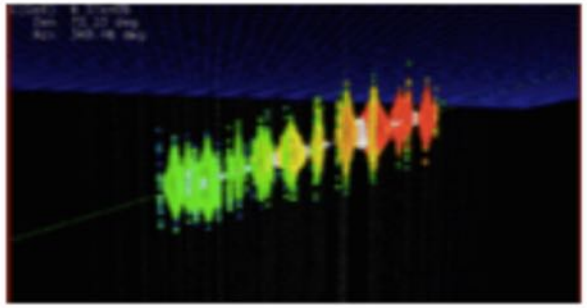


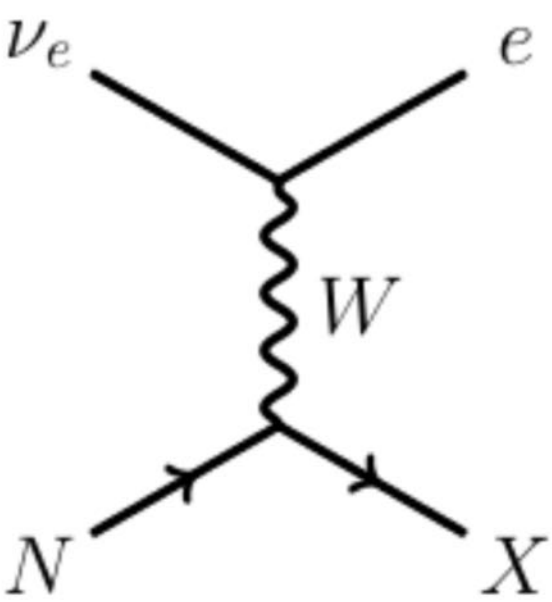
oscillations of PeV neutrinos over cosmic distances to 1:1:1

tau decay length:
50m per PeV

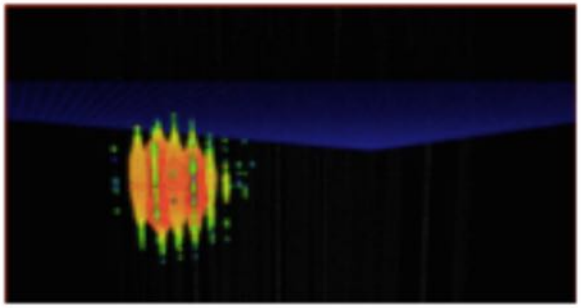


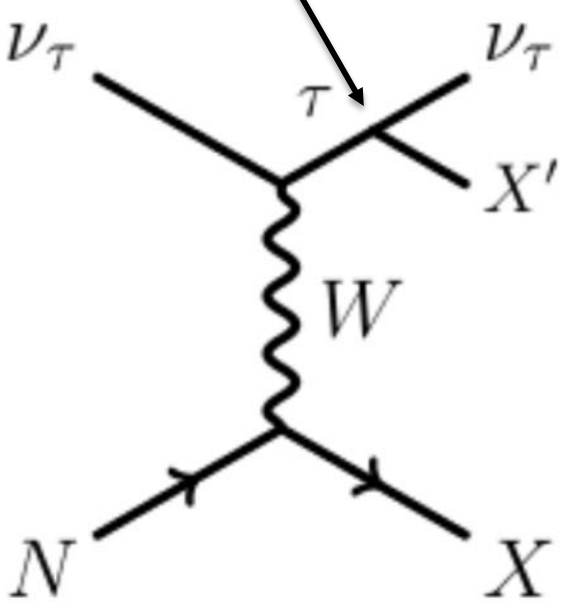
track



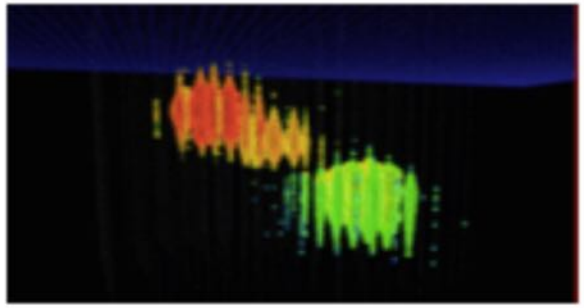


shower

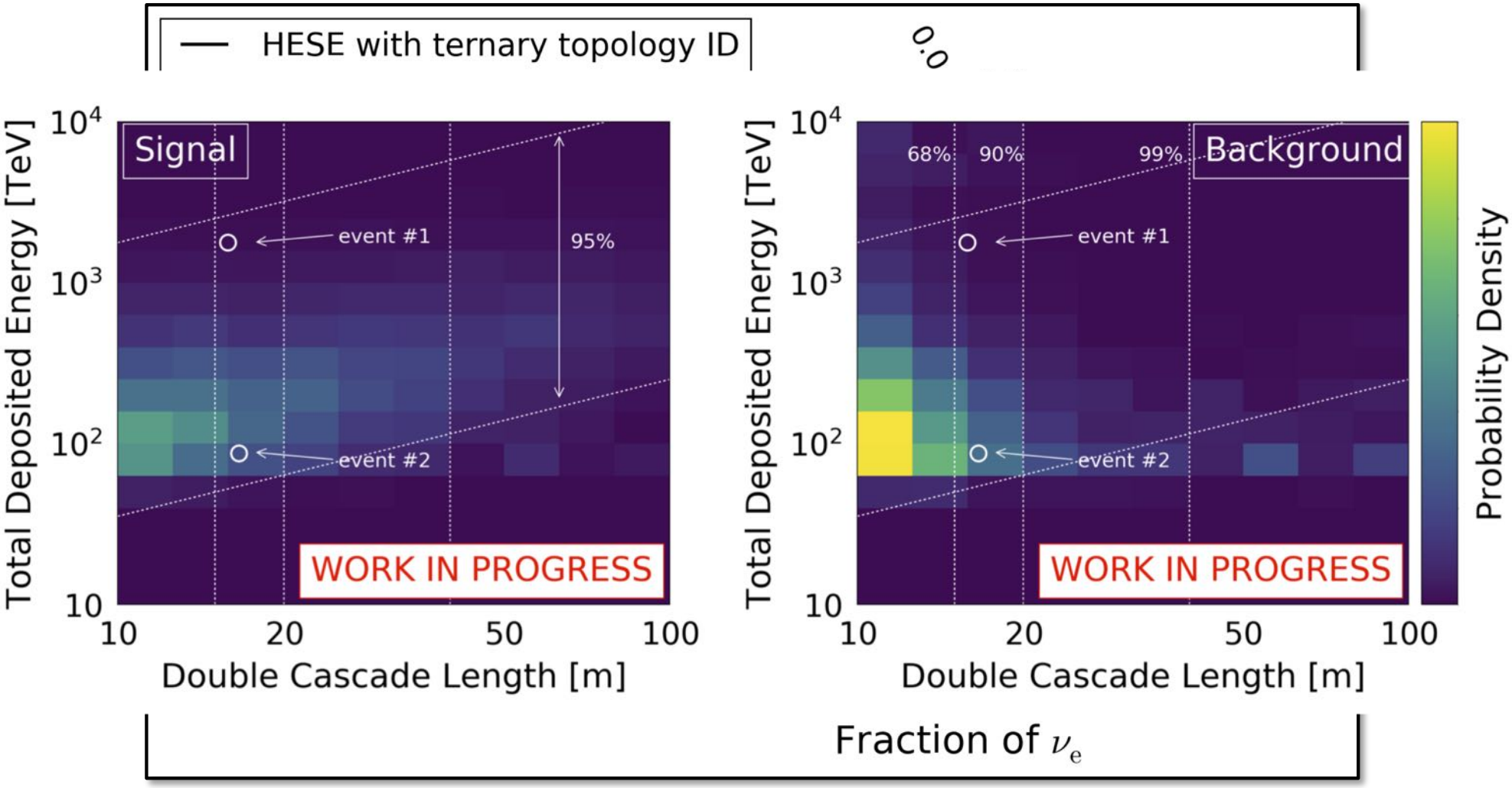




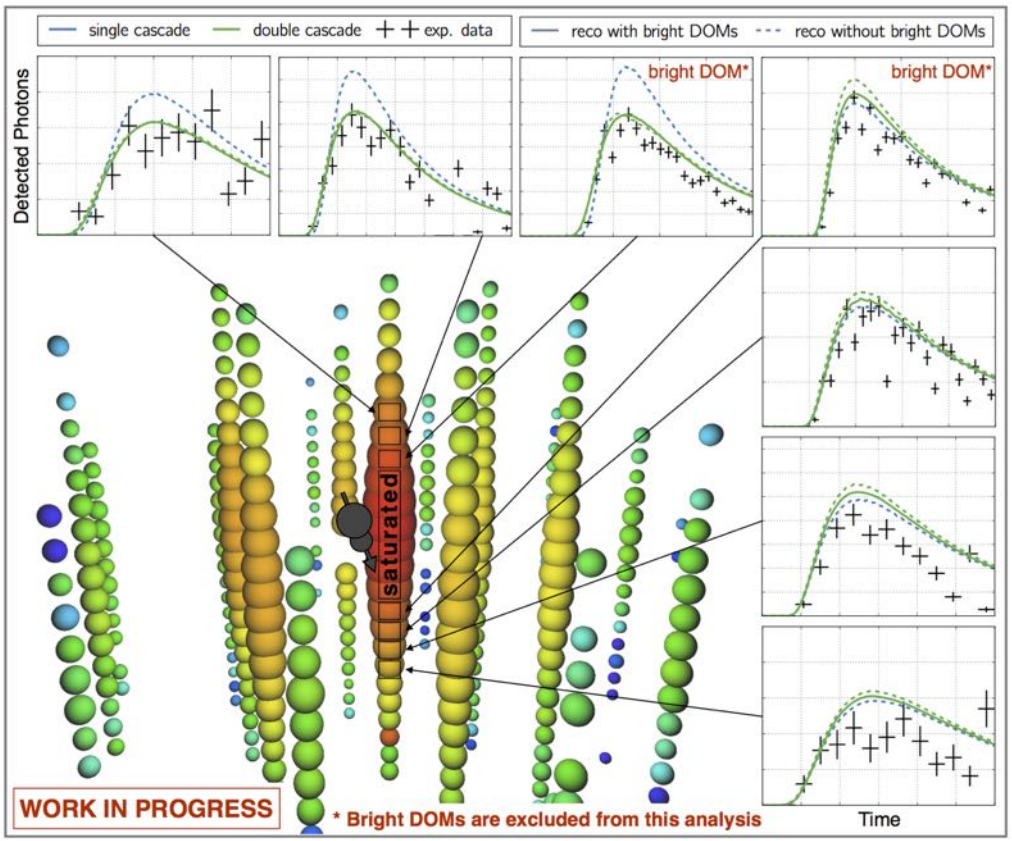
double bang*



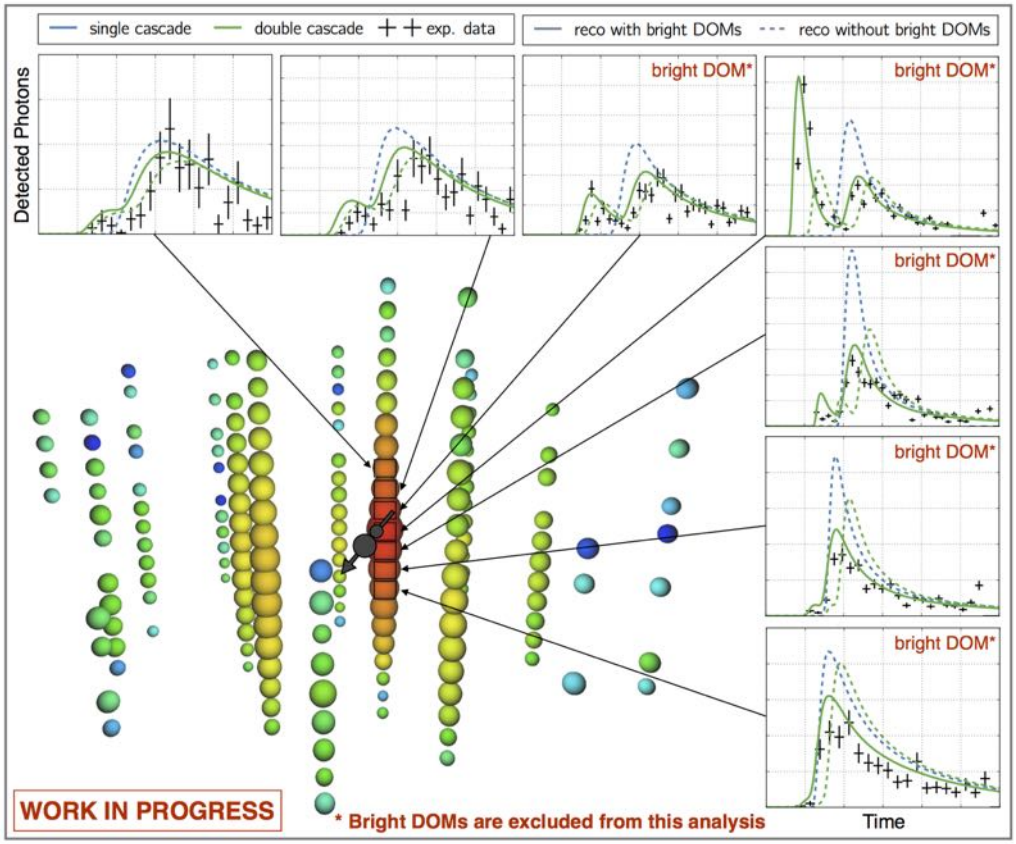
high-energy starting events – 7.5 yr



high-energy starting events (starting) – 7.5 yr



Double cascade Event #1



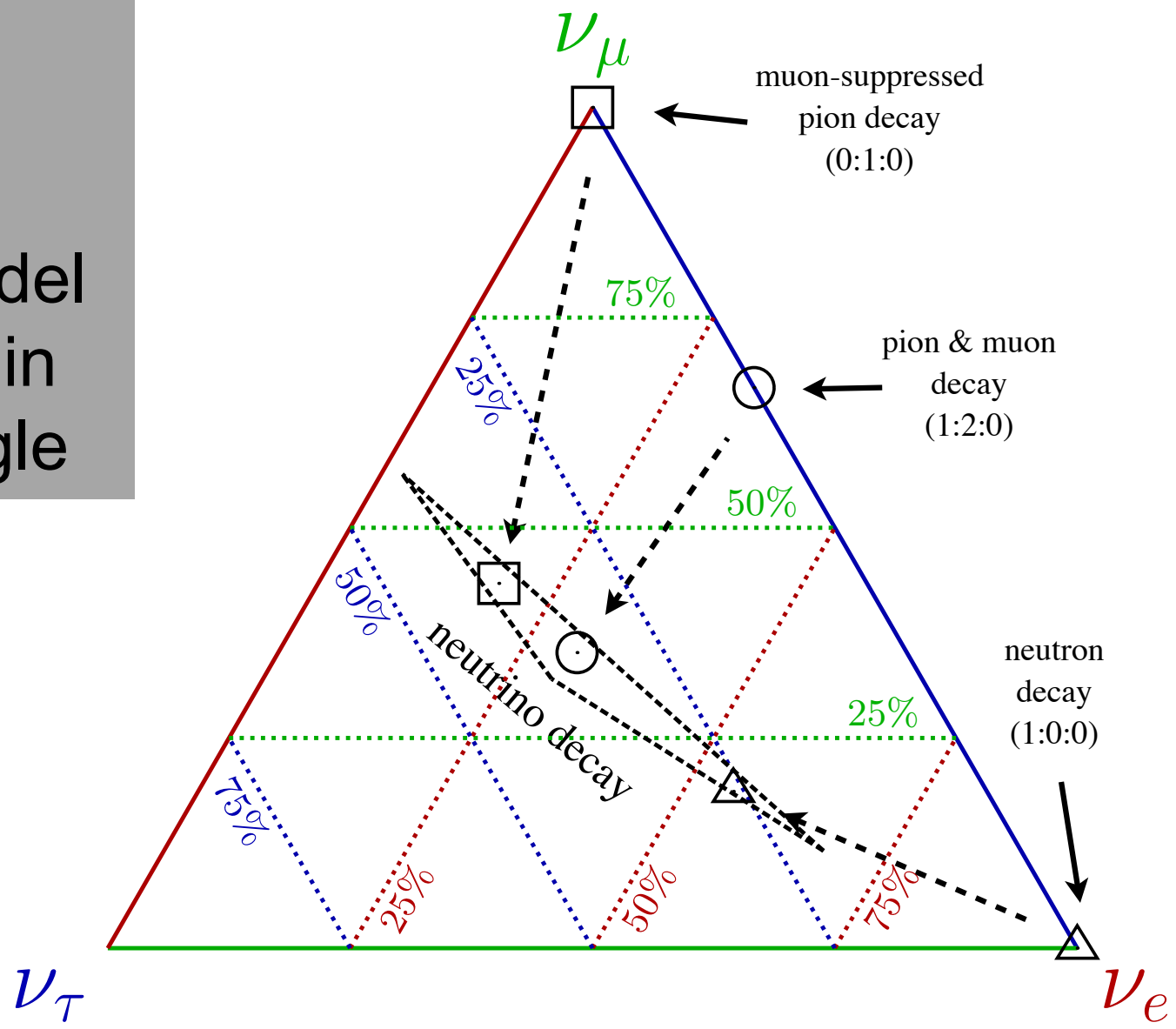
Double cascade Event #2

"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

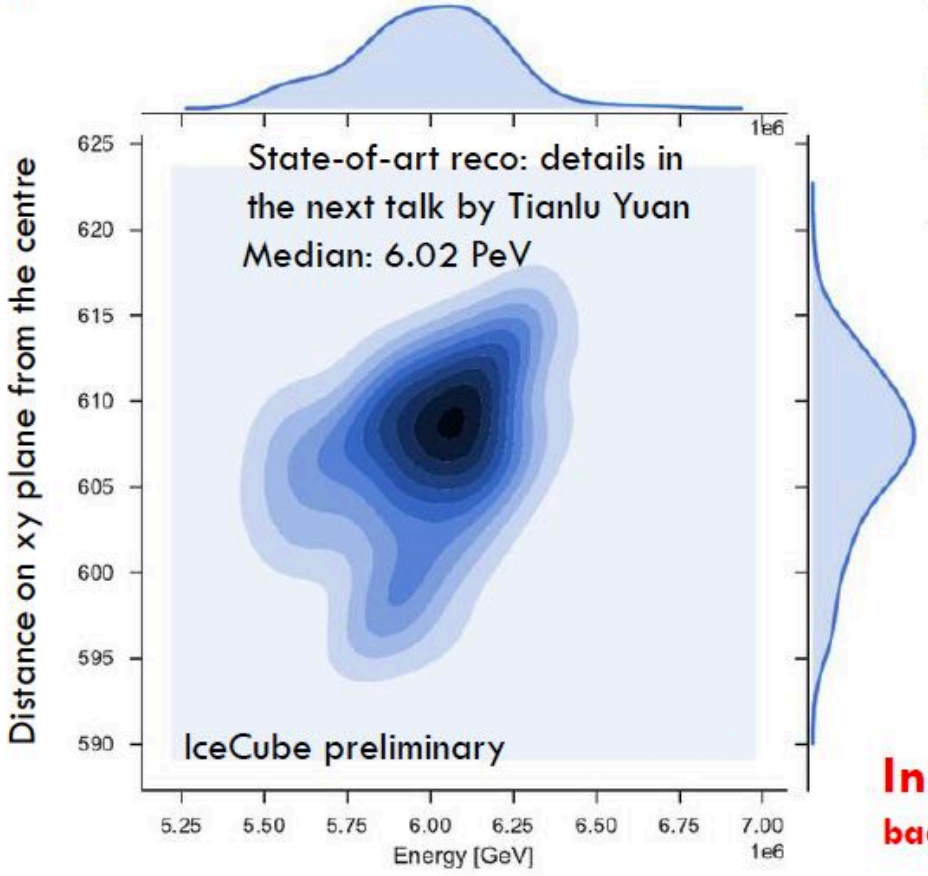


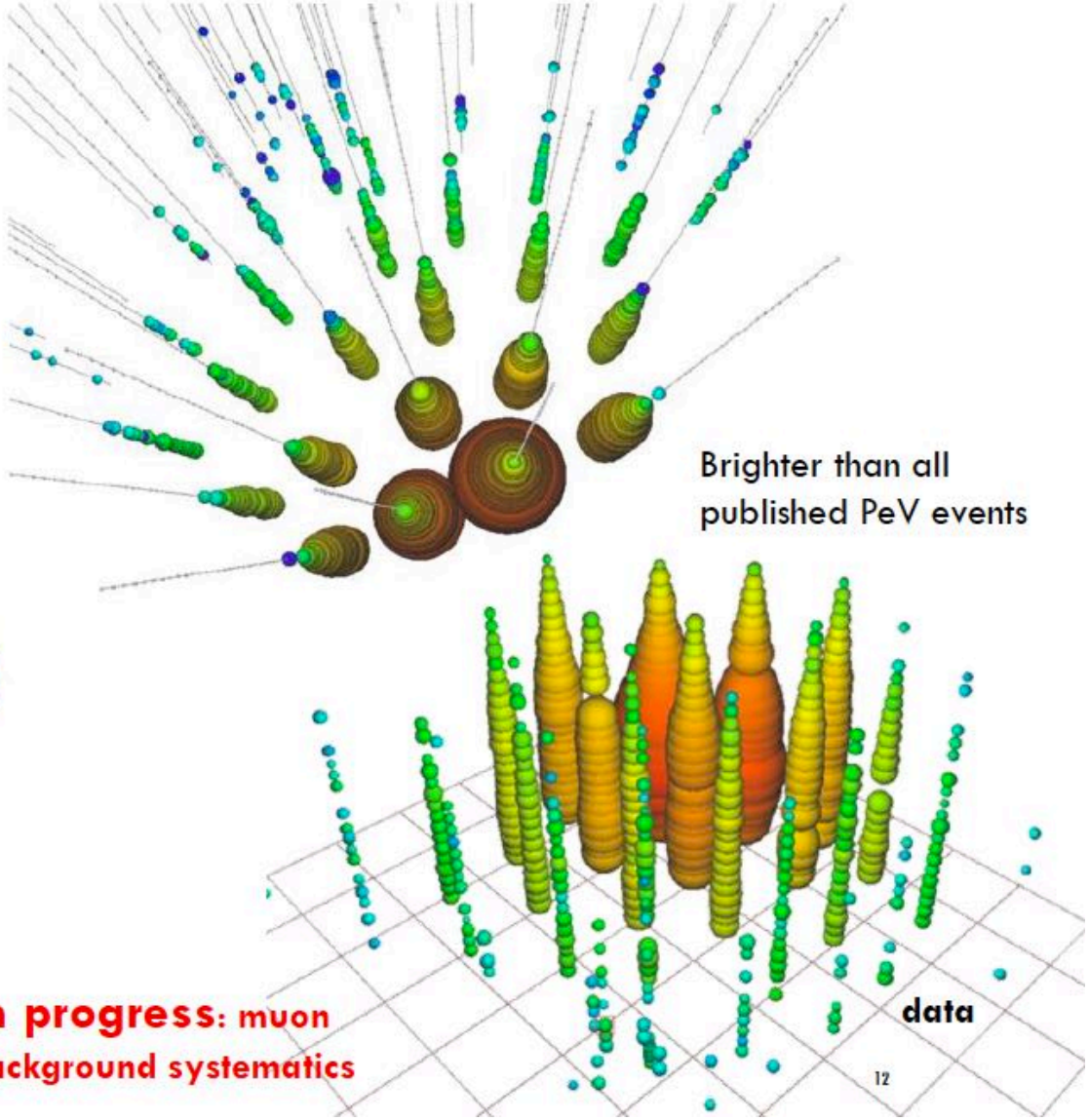
the first Glashow resonance event:

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

Partially contained event with energy ~ 6 PeV

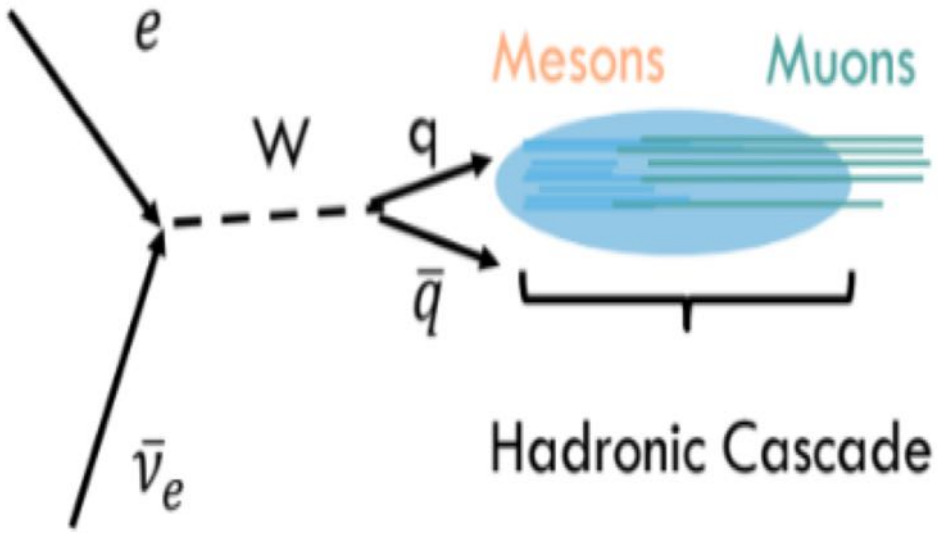
HIGHEST-ENERGY NEUTRINO CANDIDATE

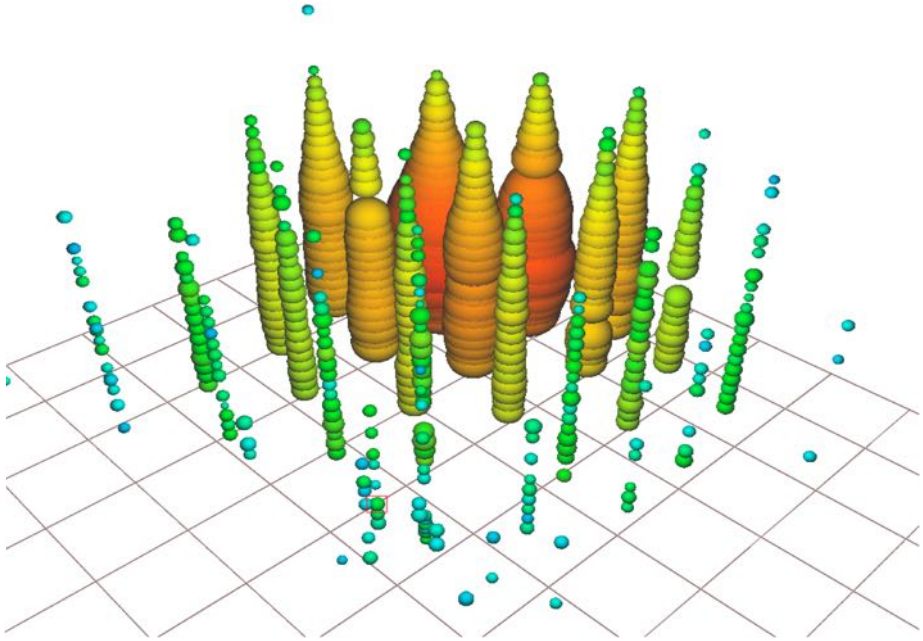


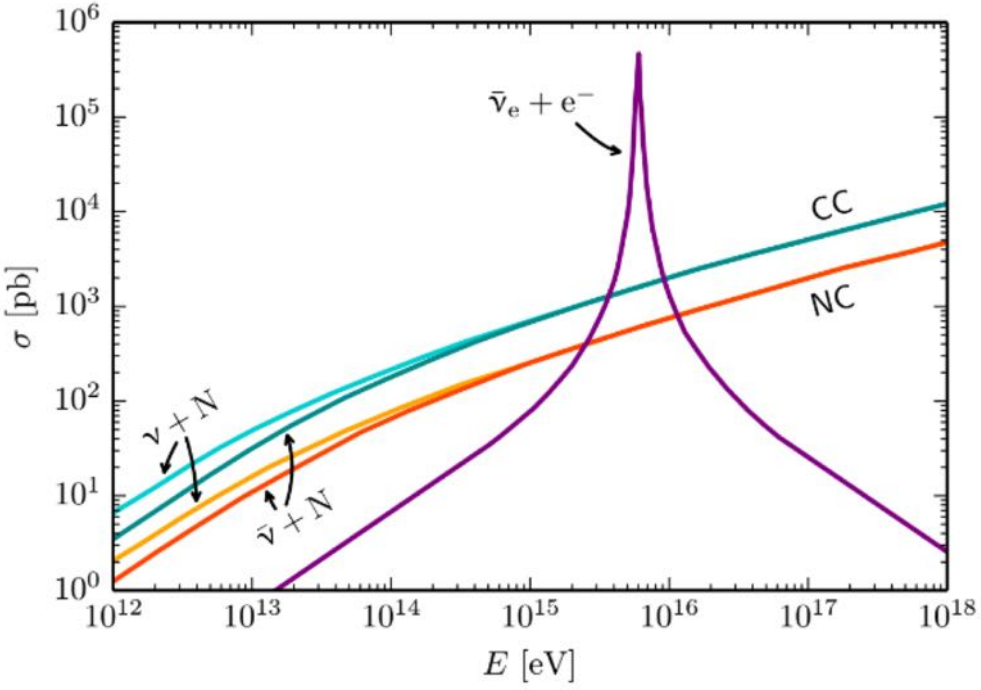


In progress: muon background systematics

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





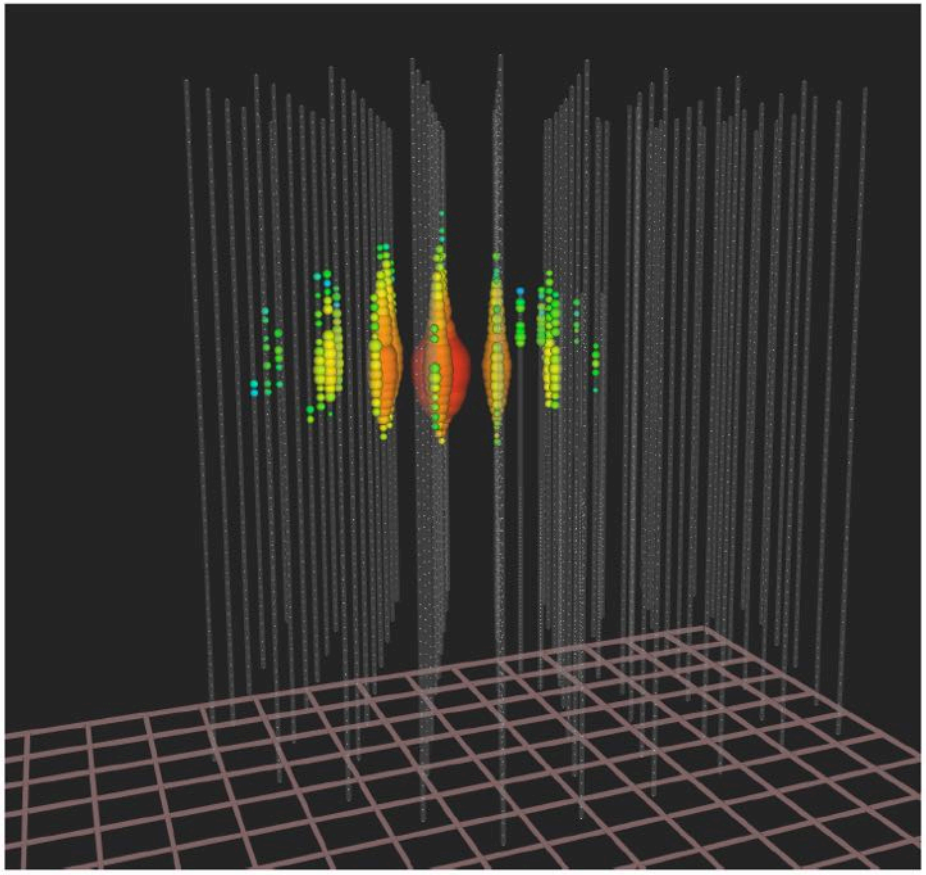


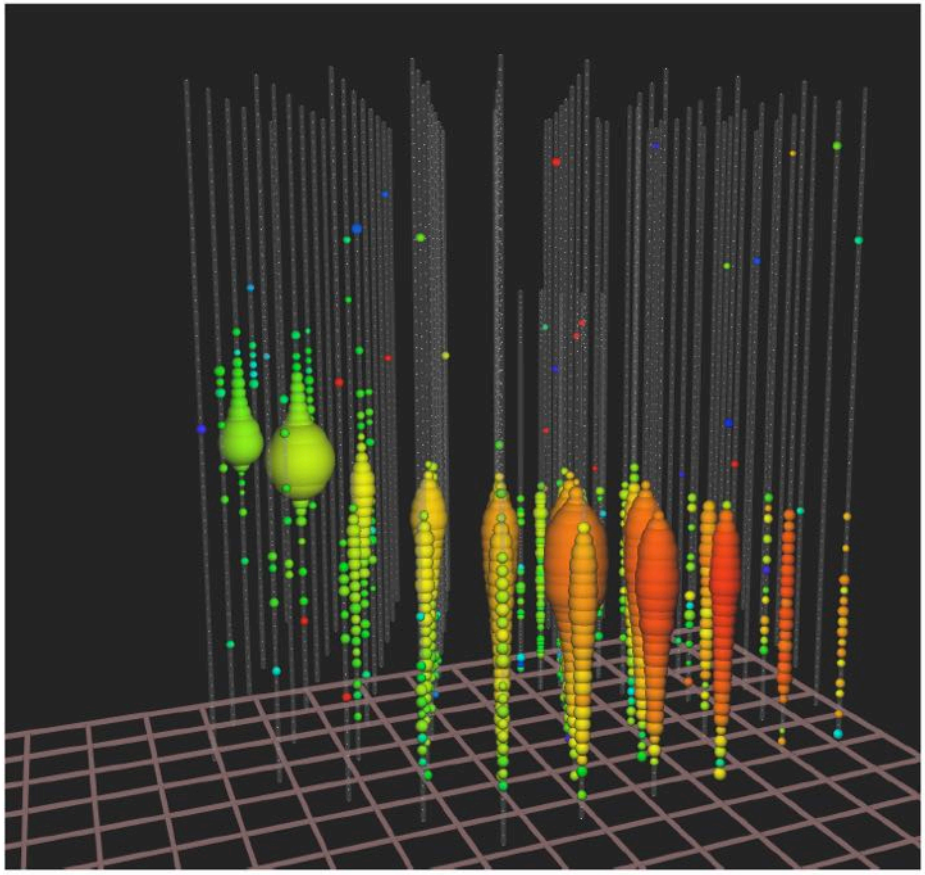
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

are the two observations consistent?

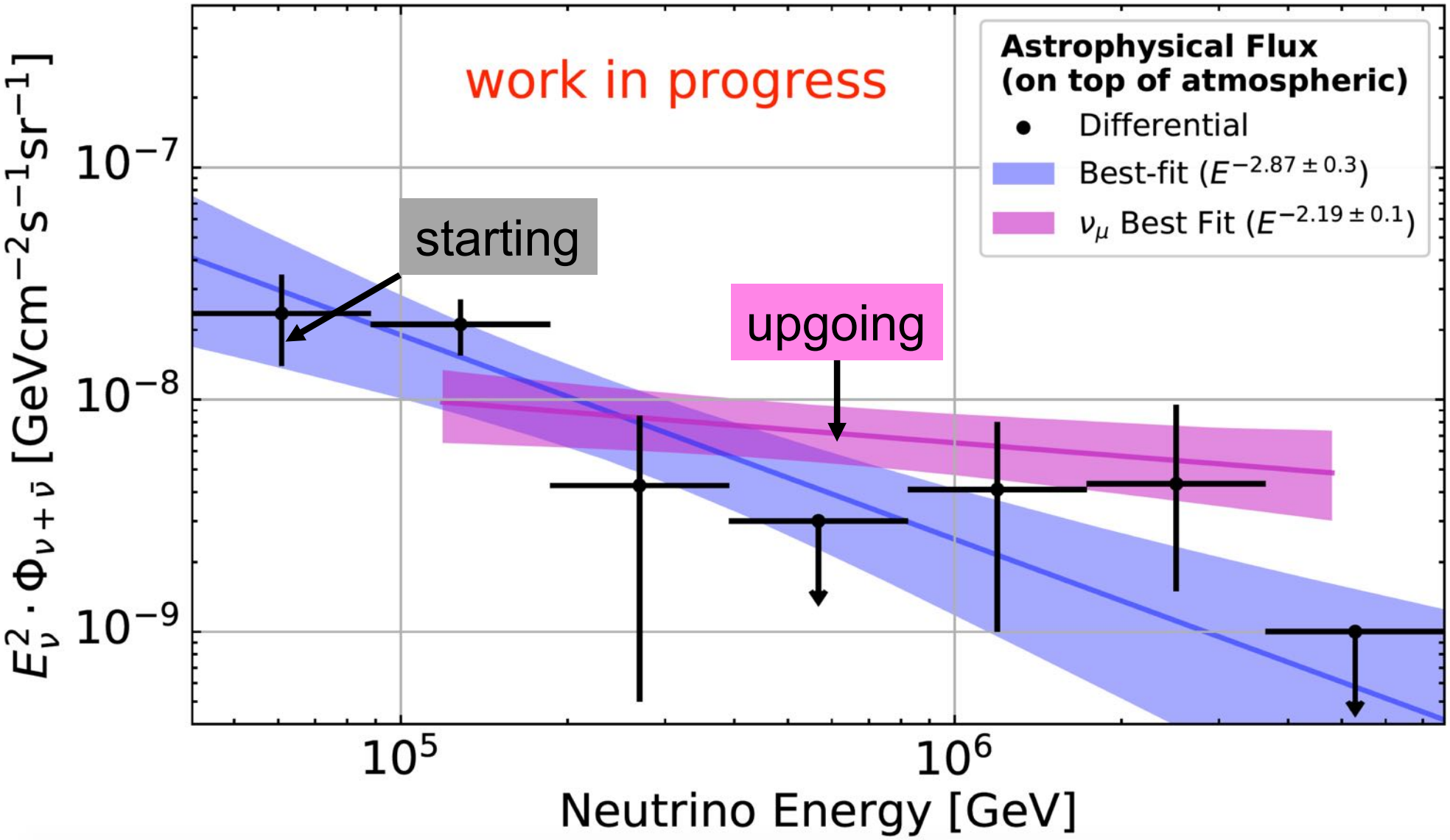




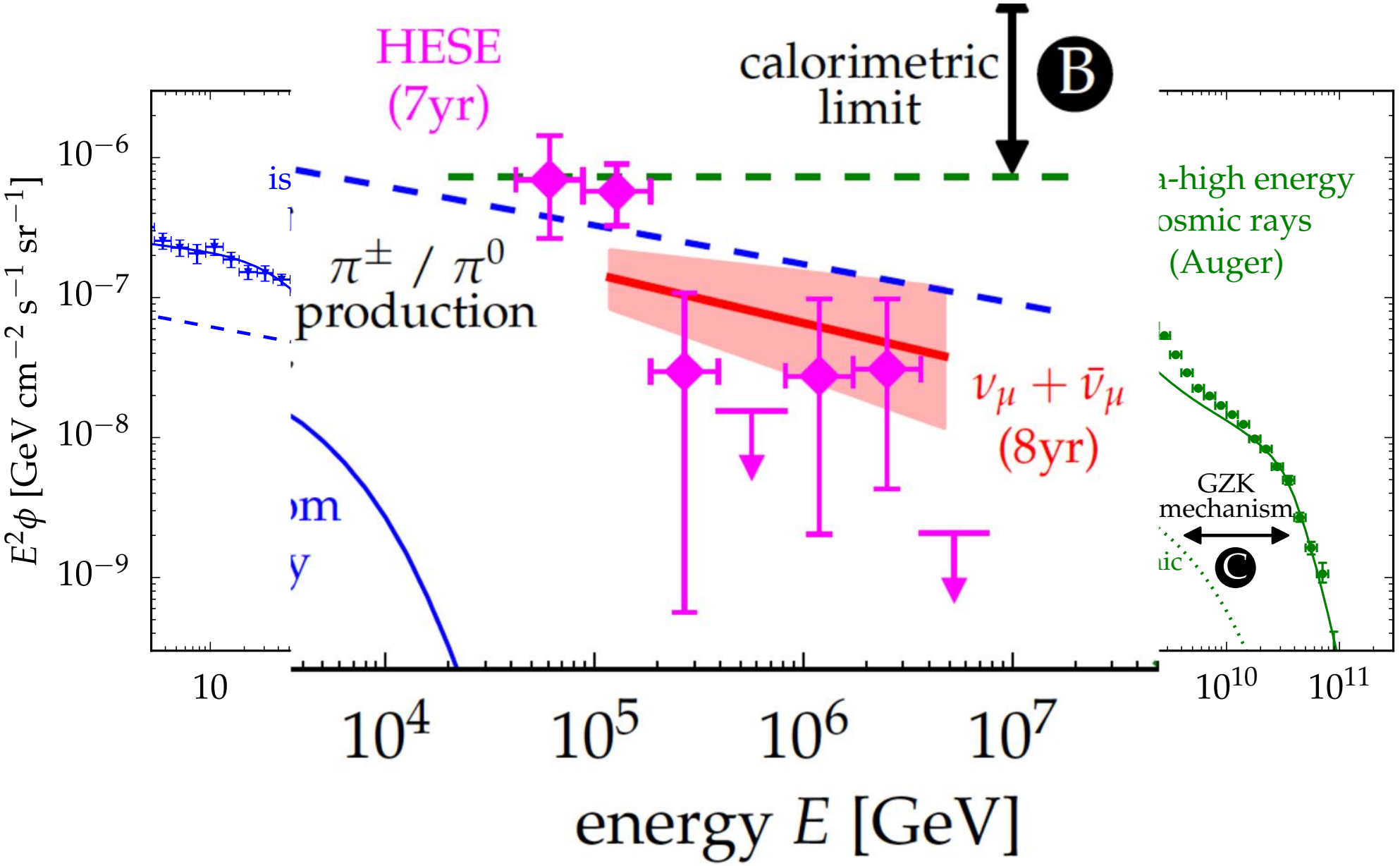
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4°)

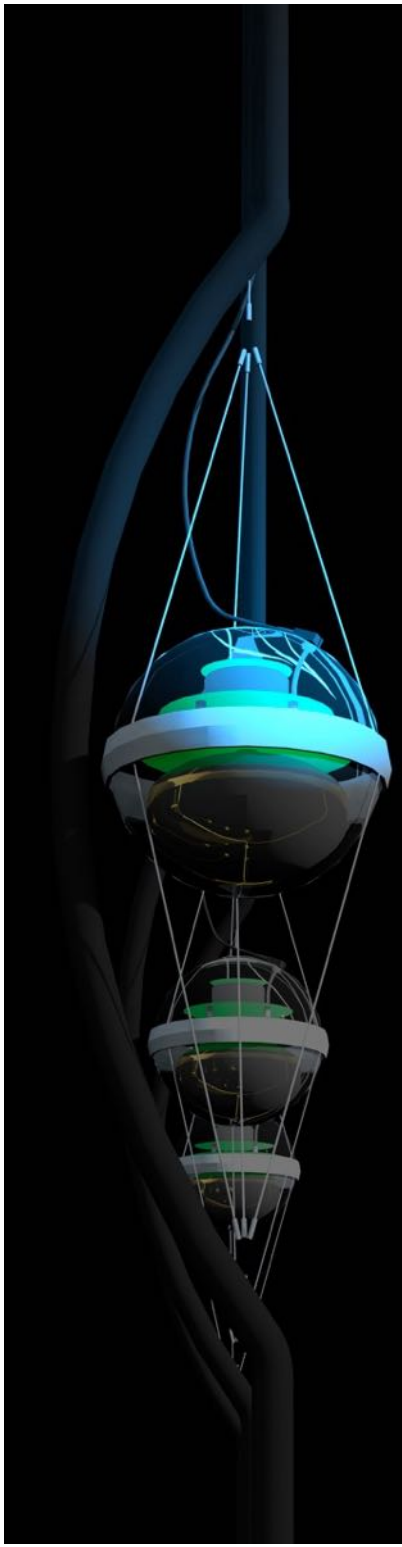
high-energy starting events – 7.5 yr



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


HESE
(7yr)
calorimetric
limit
B
$\pi^{\pm}$ / π^0
production
$\nu_\mu + \bar{\nu}_\mu$
(8yr)
GZK
mechanism
C
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
10^4
10^5
10^6
10^7
10^{10}
10^{11}
energy E [GeV]

- cosmic neutrinos below 100 TeV ?



IceCube

francis halzen

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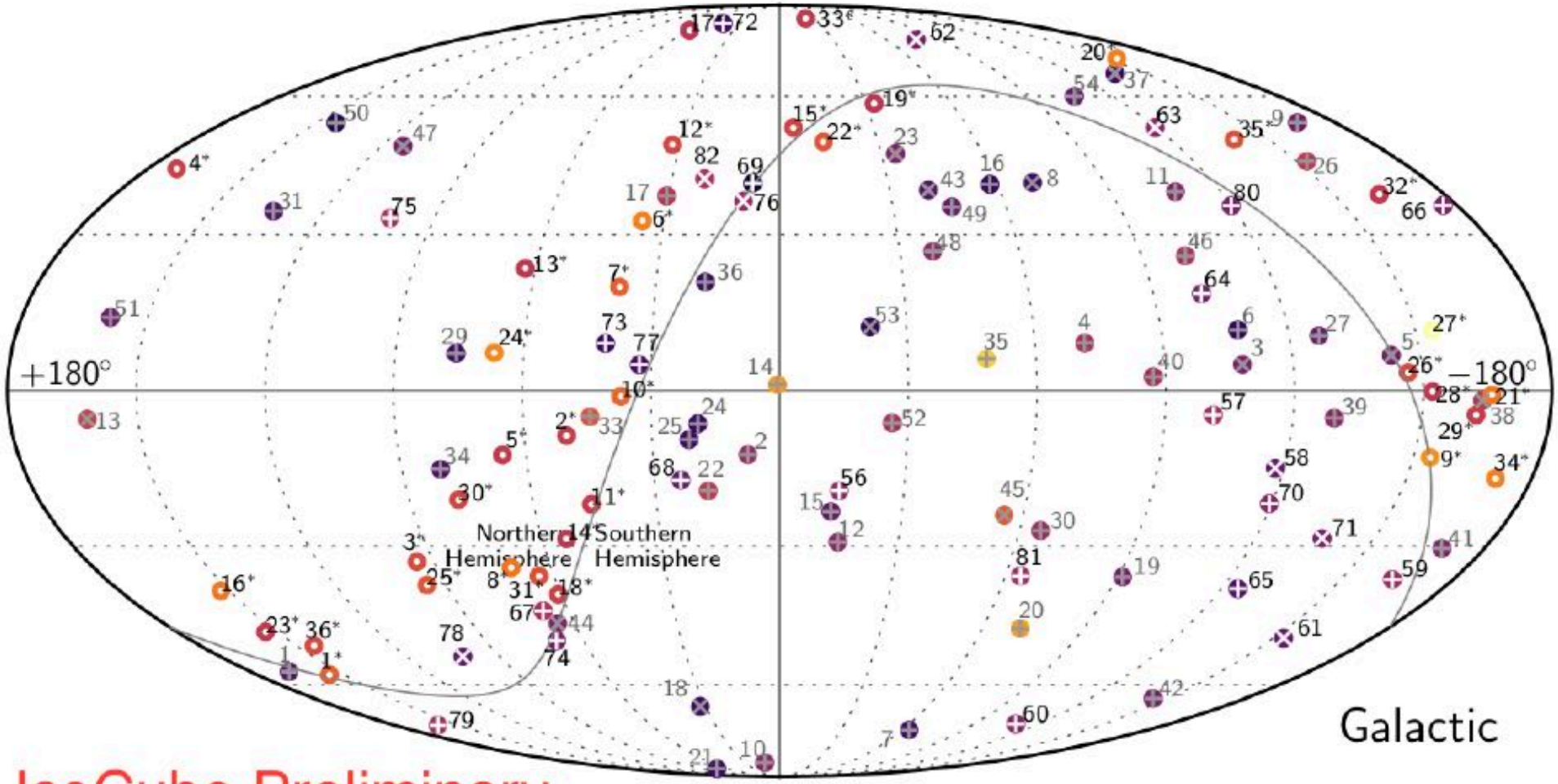


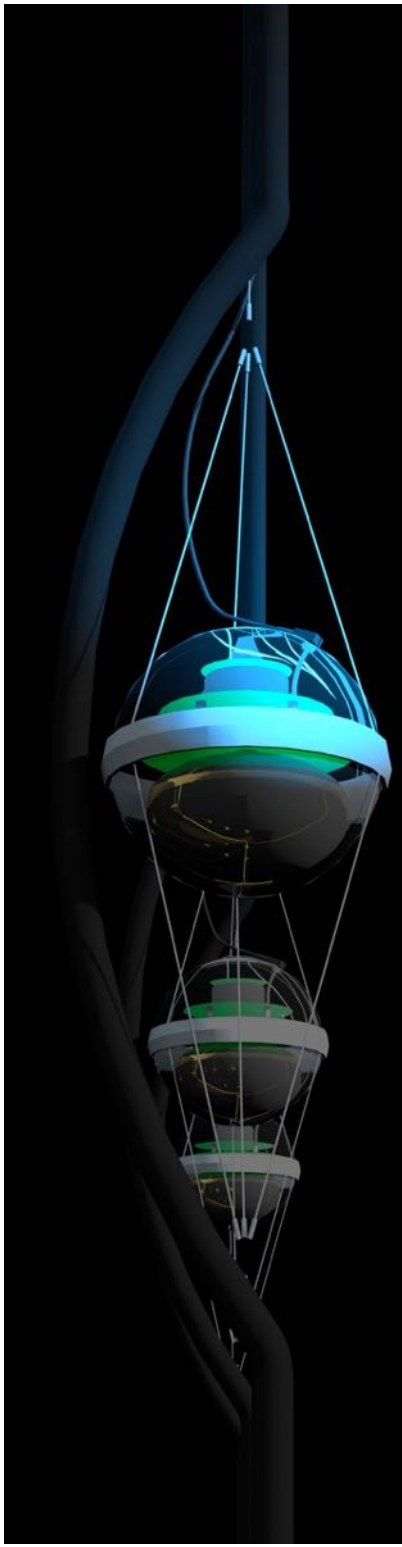
IceCube Preliminary

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)
- dark sources < 100 TeV ?



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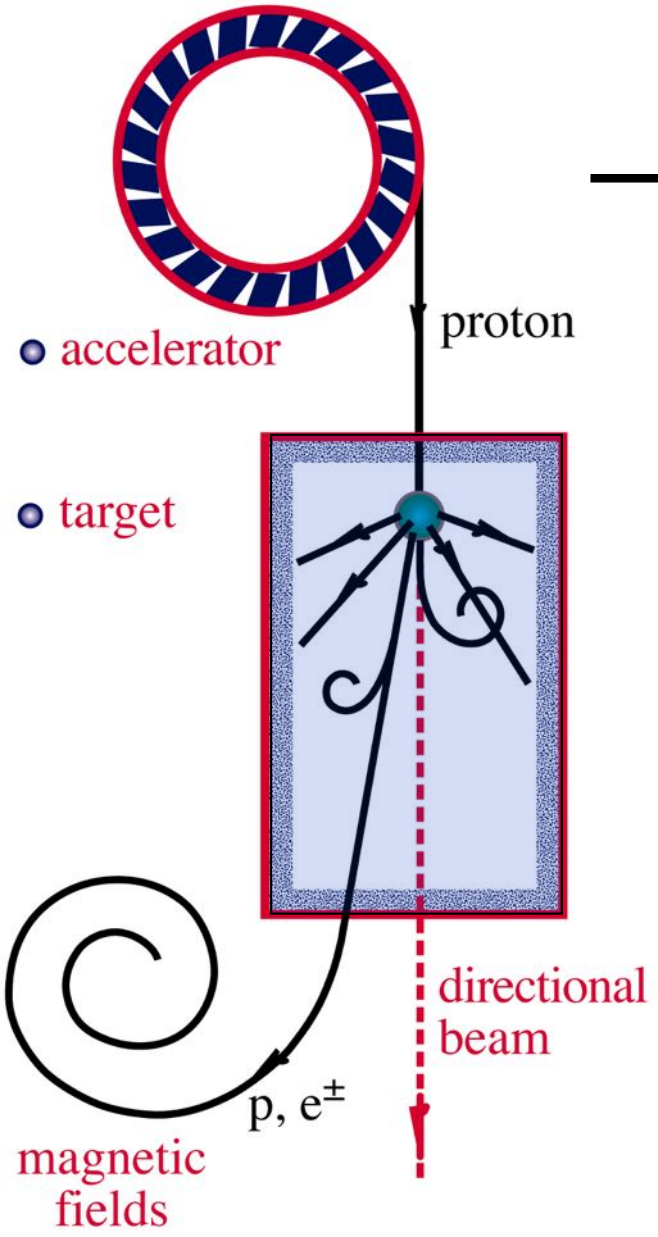
- cosmic neutrinos below 100 TeV?

iceCube.wisc.edu

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

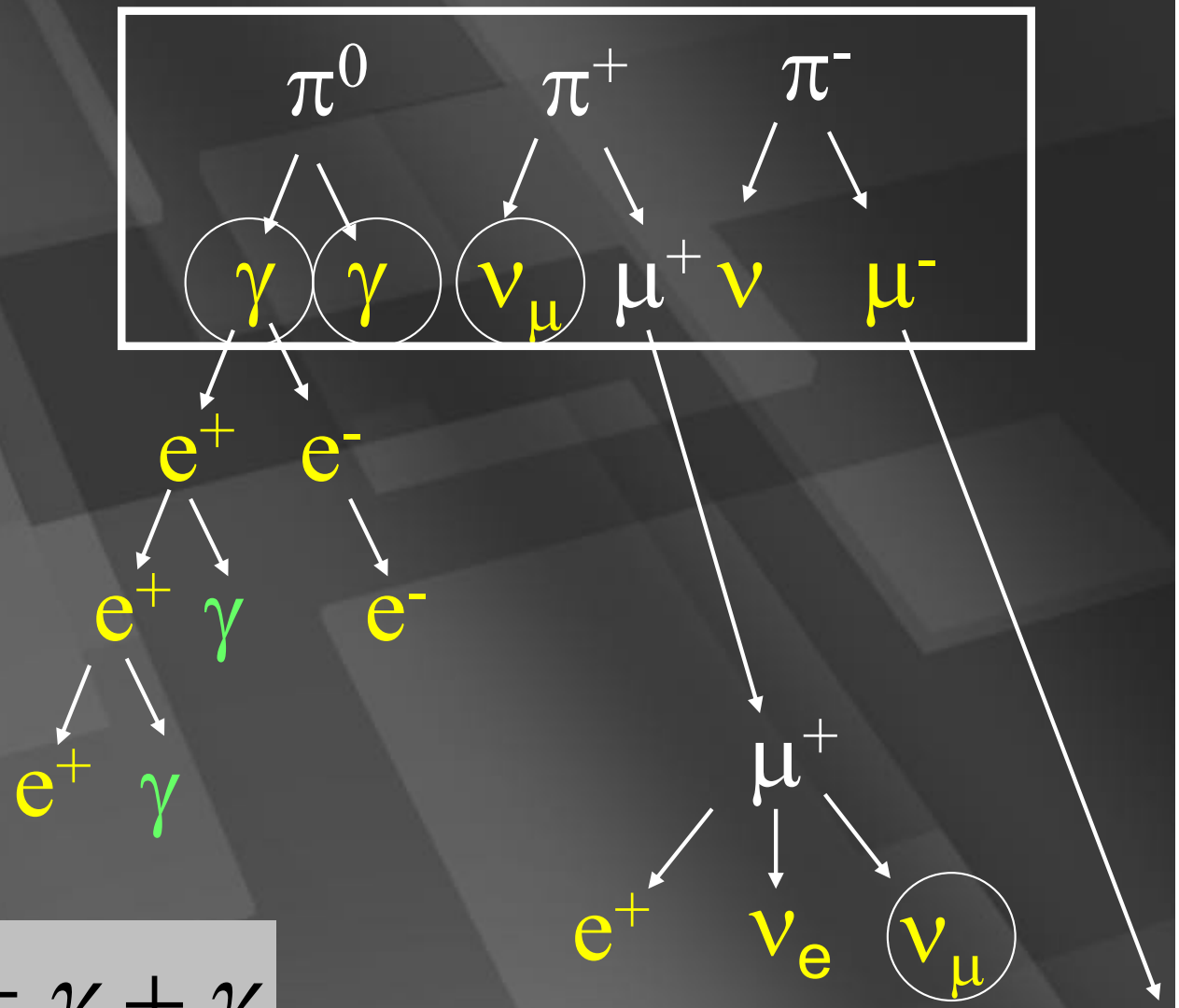
are observed as

gamma rays

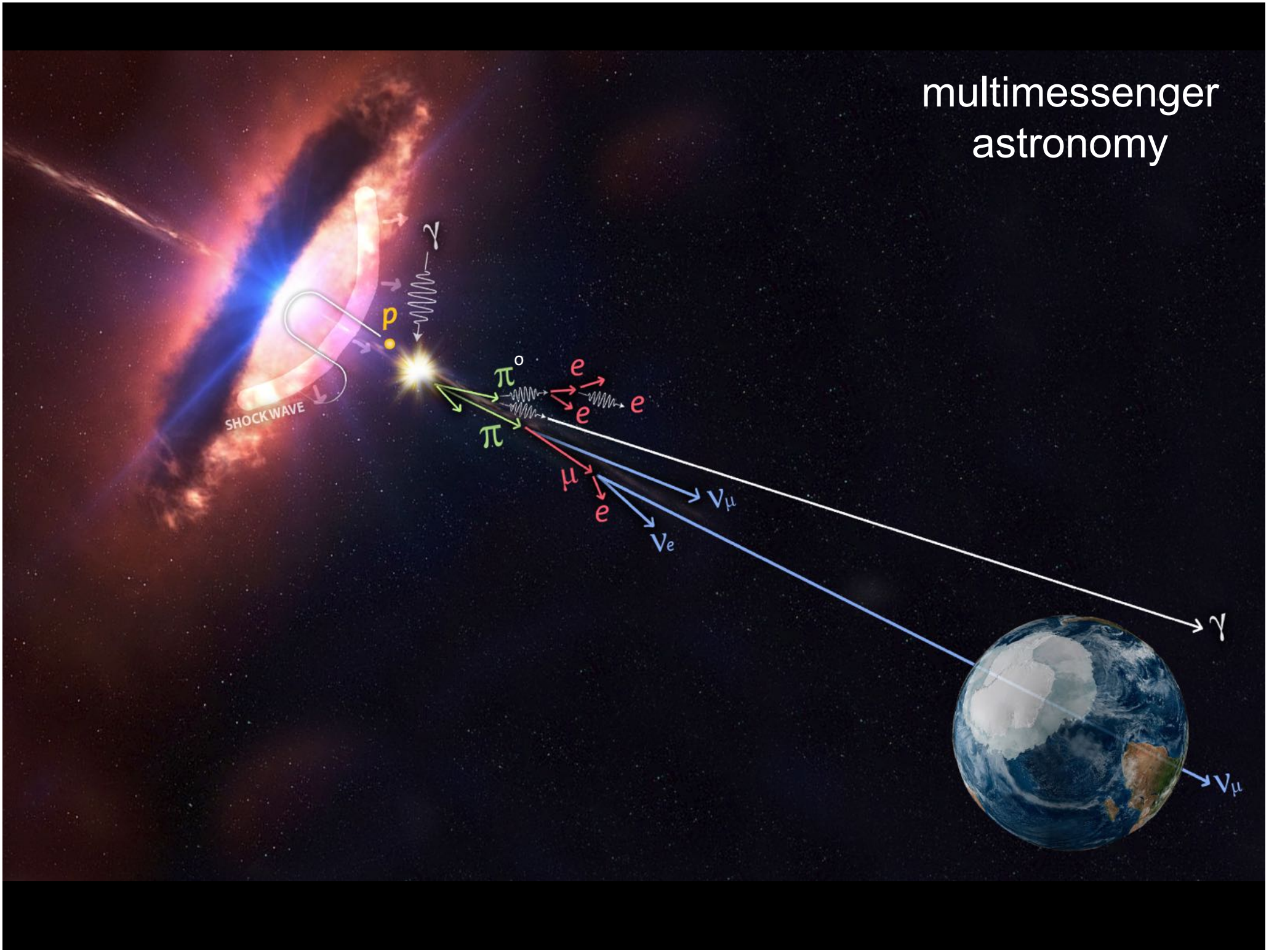
charged pions

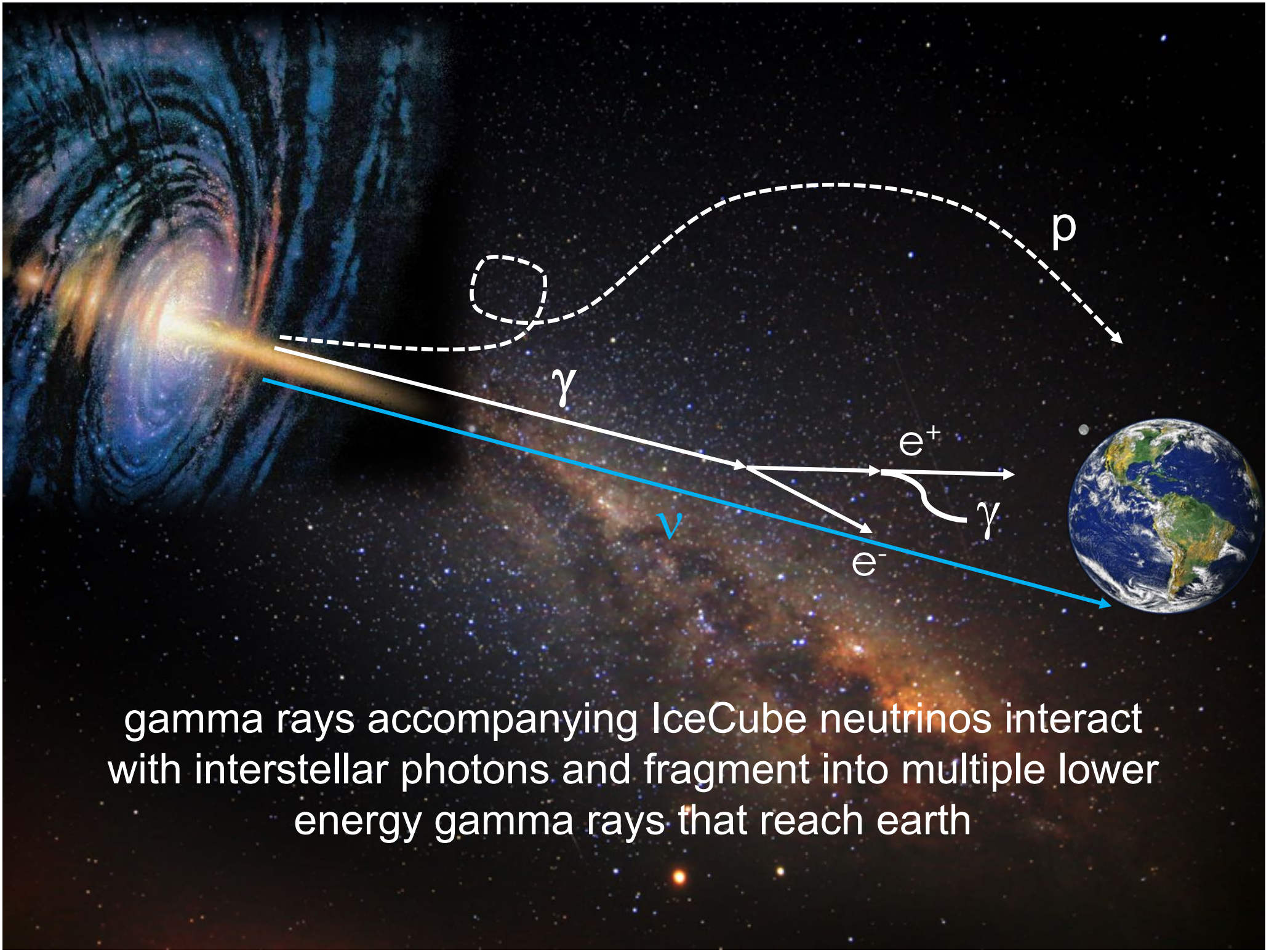
are observed as

neutrinos

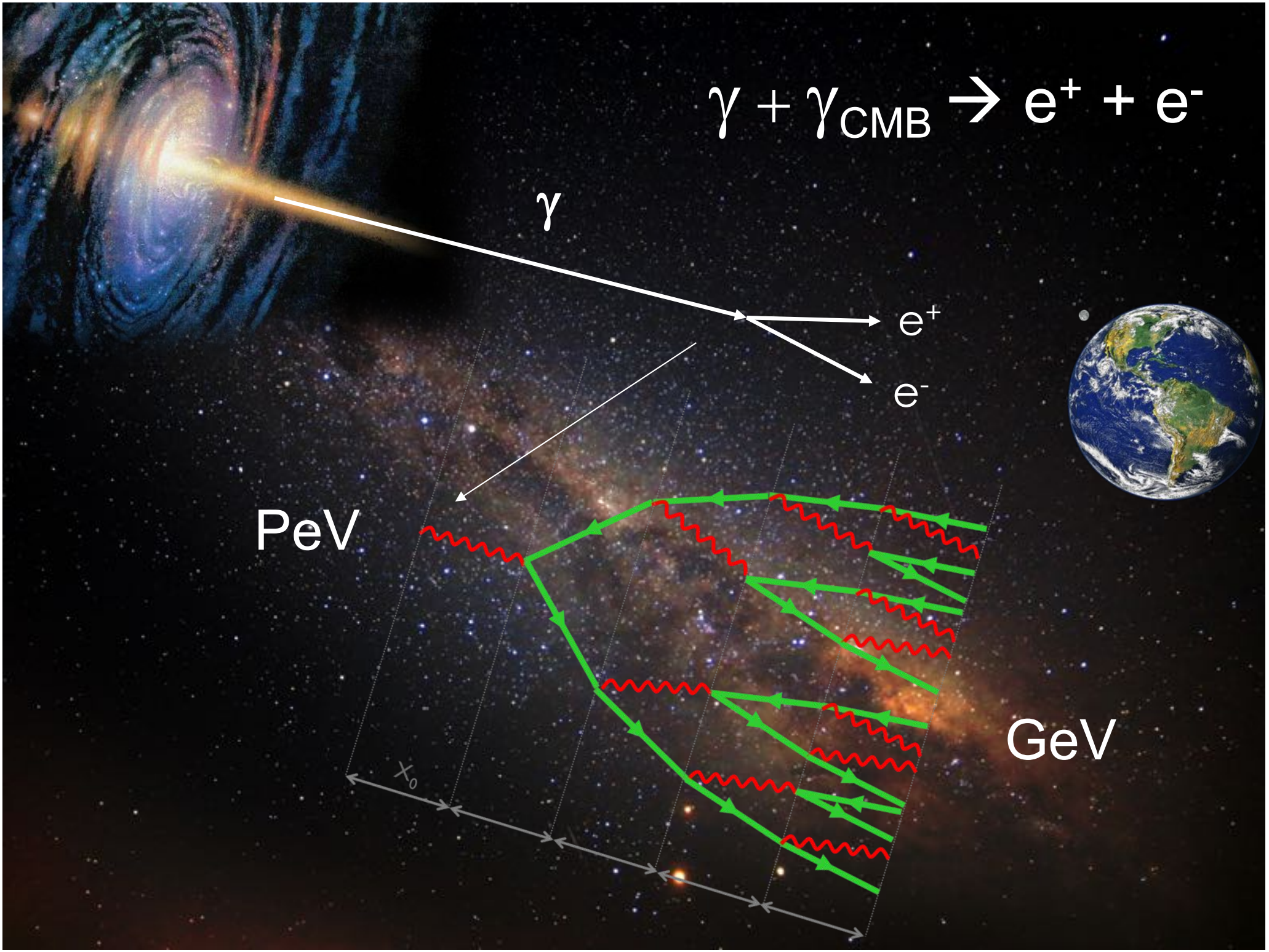


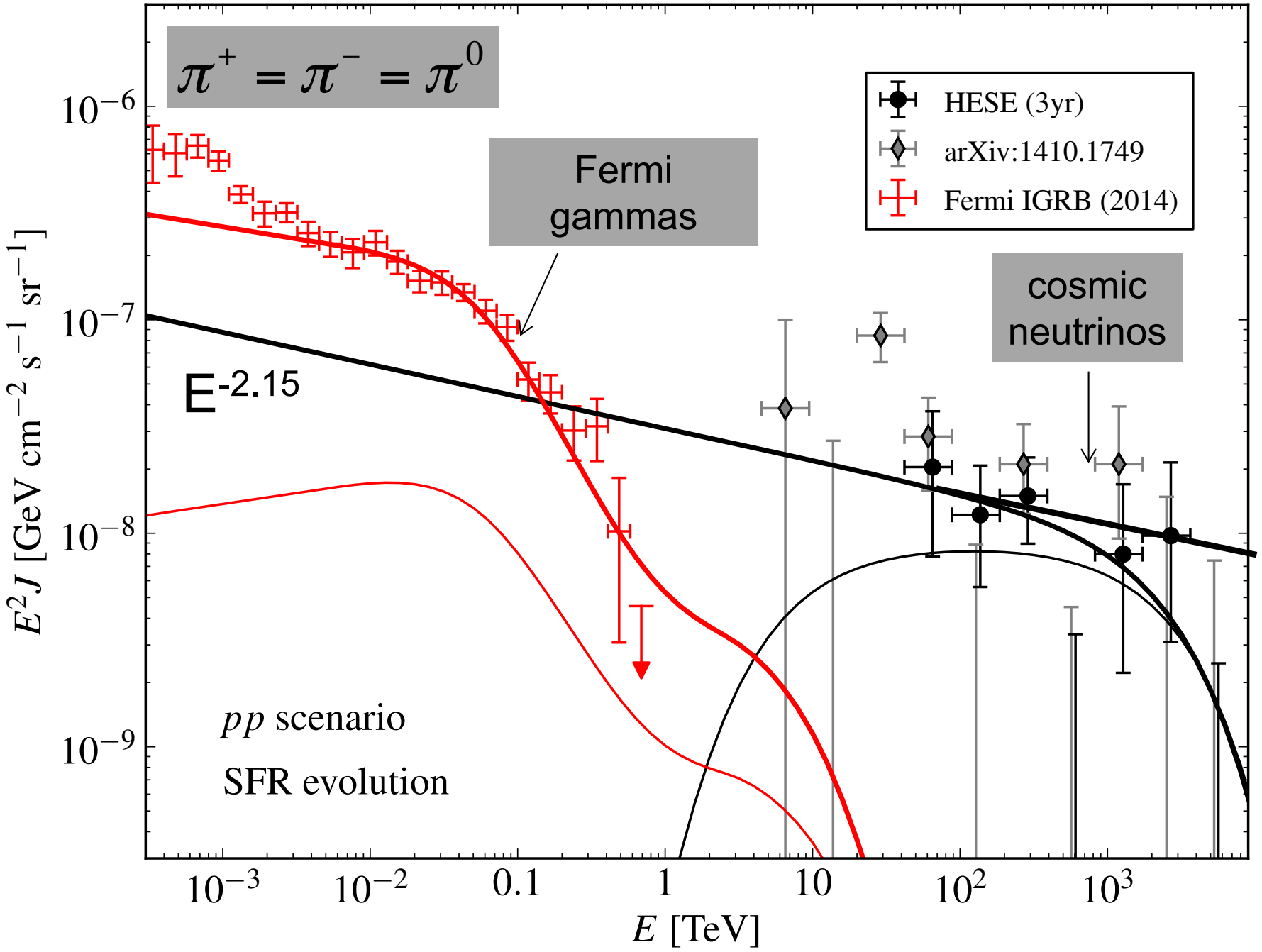
$$\nu_\mu + \overline{\nu}_\mu = \gamma + \gamma$$


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

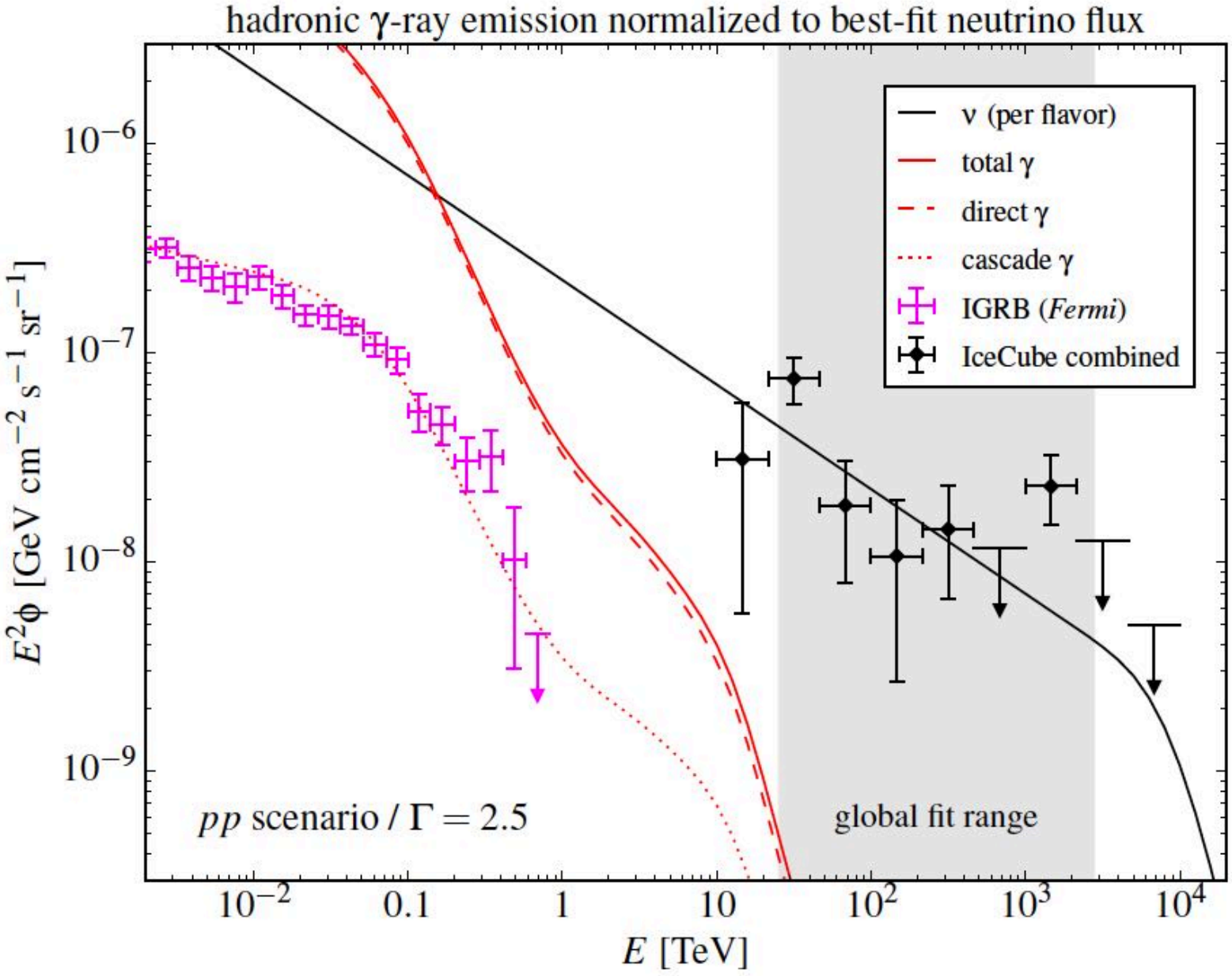


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

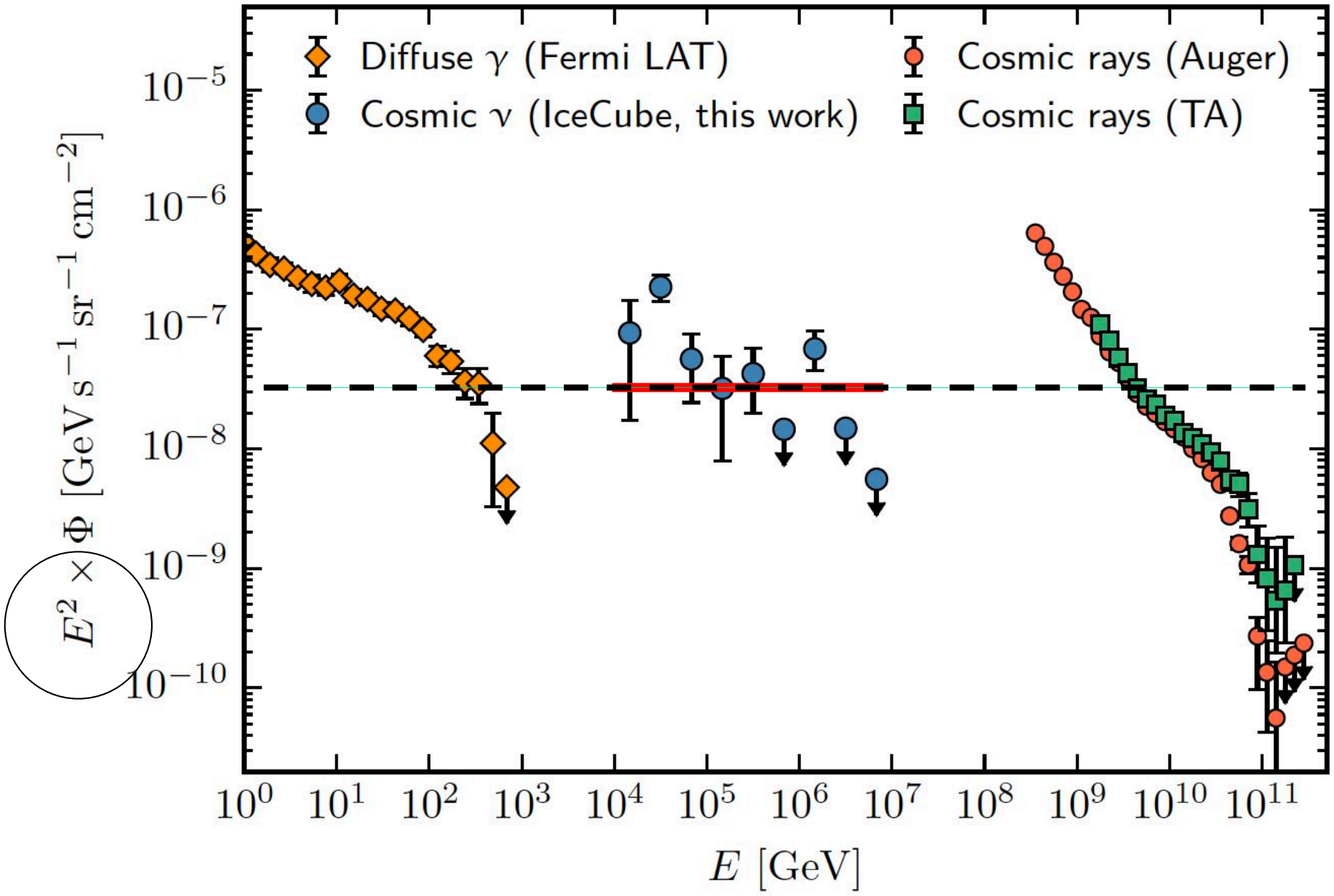

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0


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

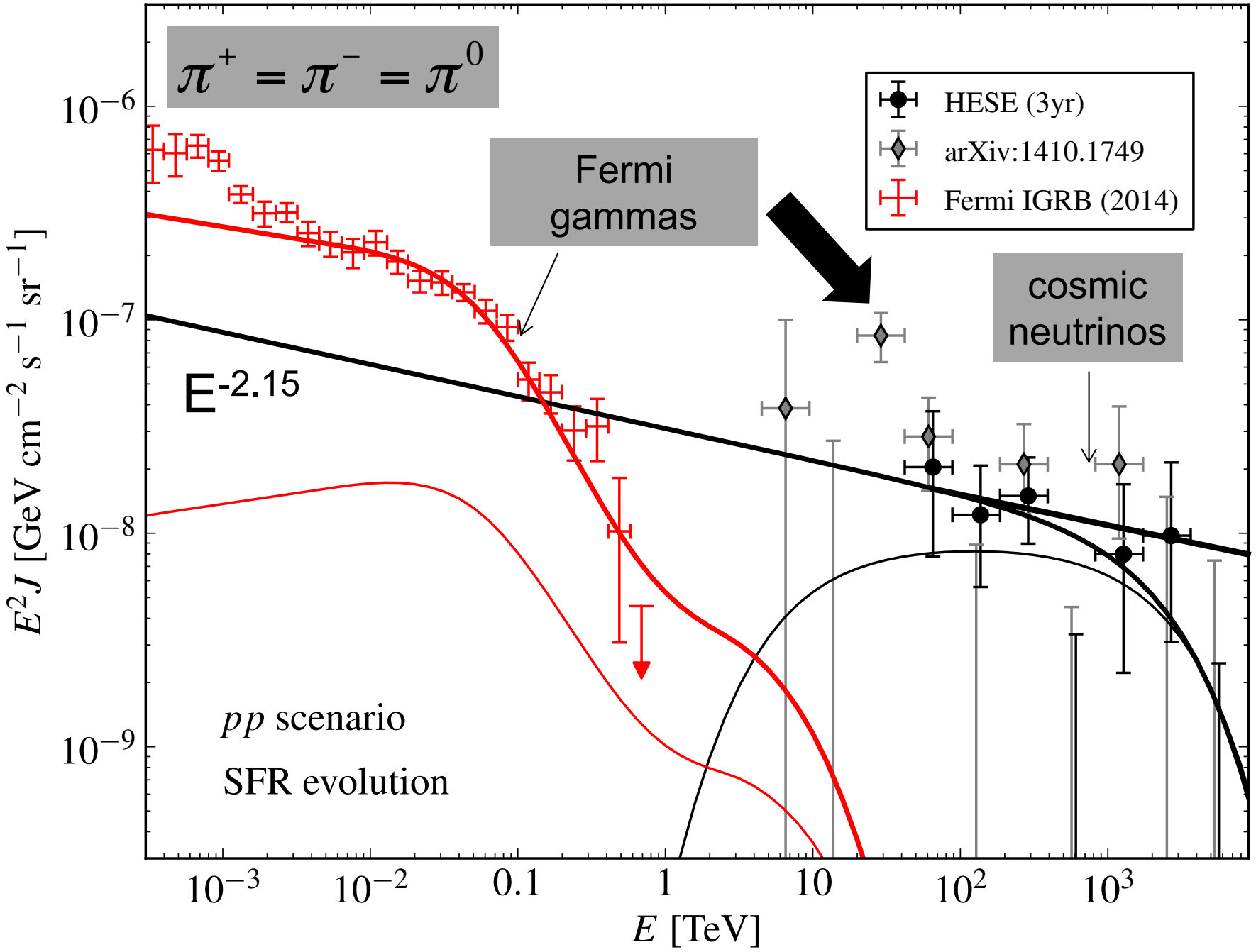
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays

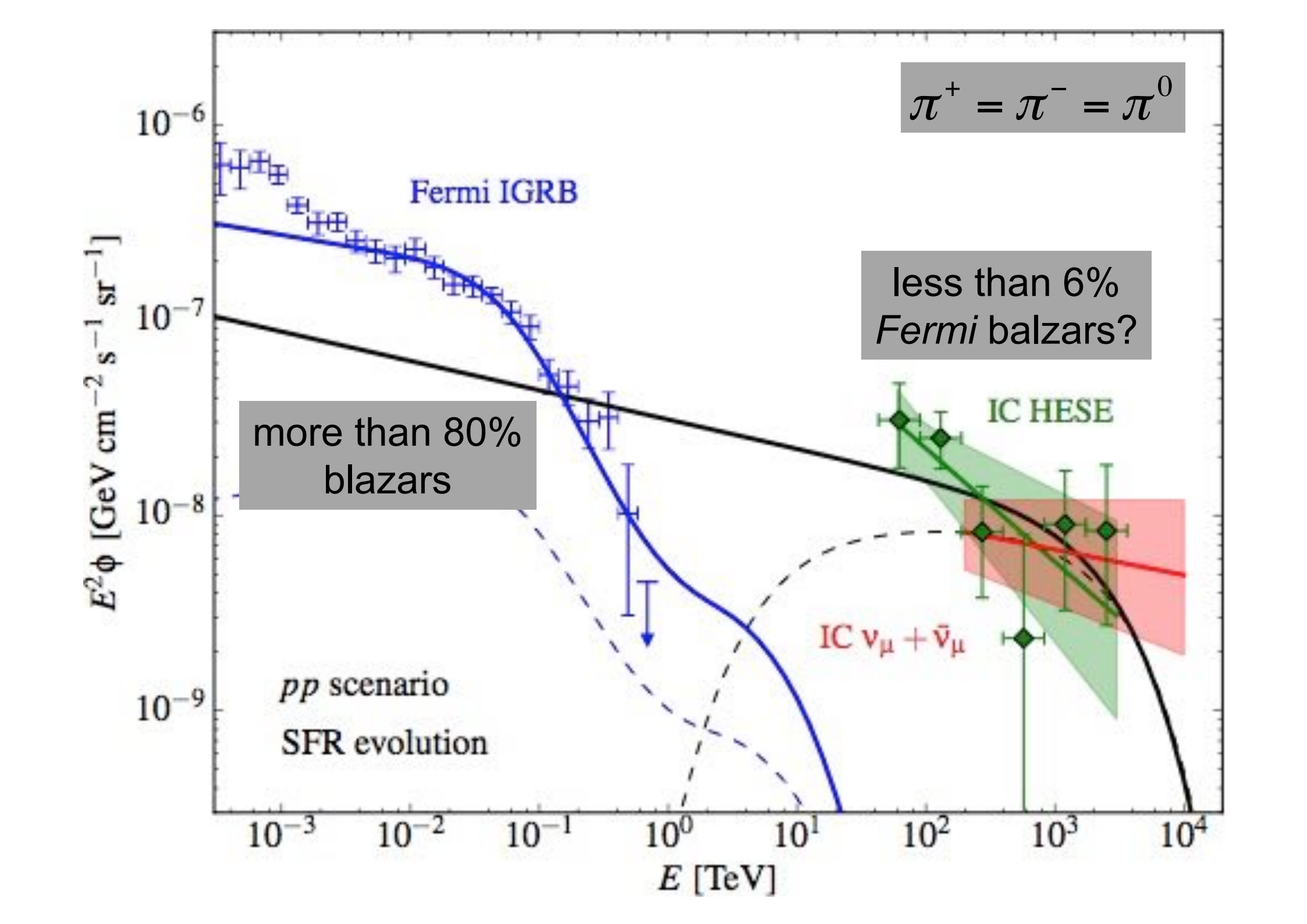


dark sources: a “problem” ?
gamma rays cascade in the source to < GeV energy

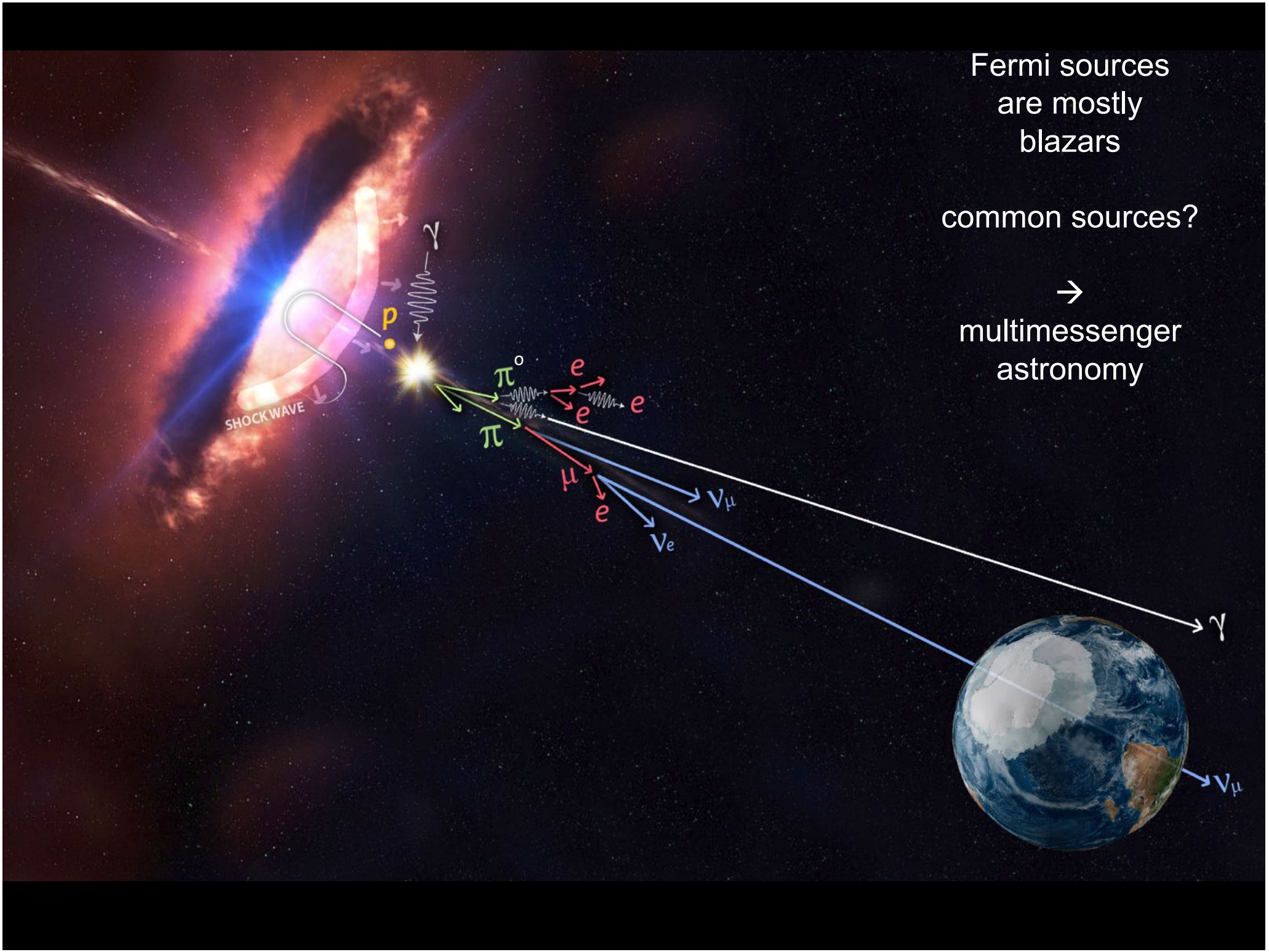


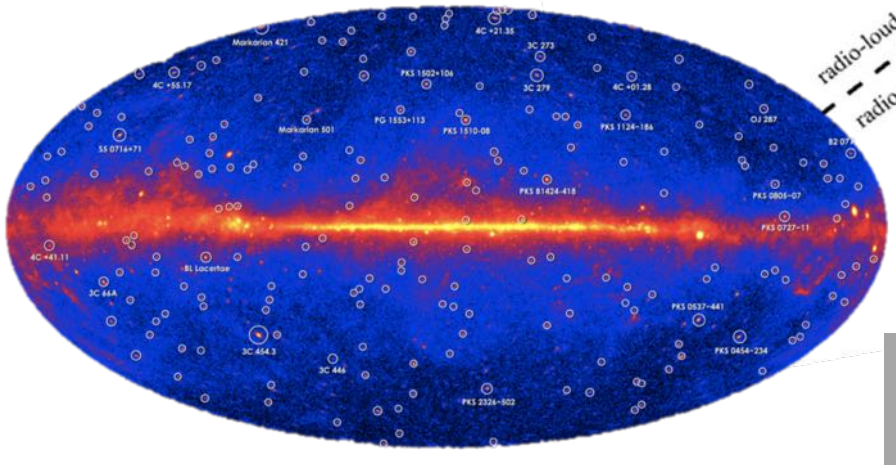
energy in the Universe in gamma rays, neutrinos and cosmic rays


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
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

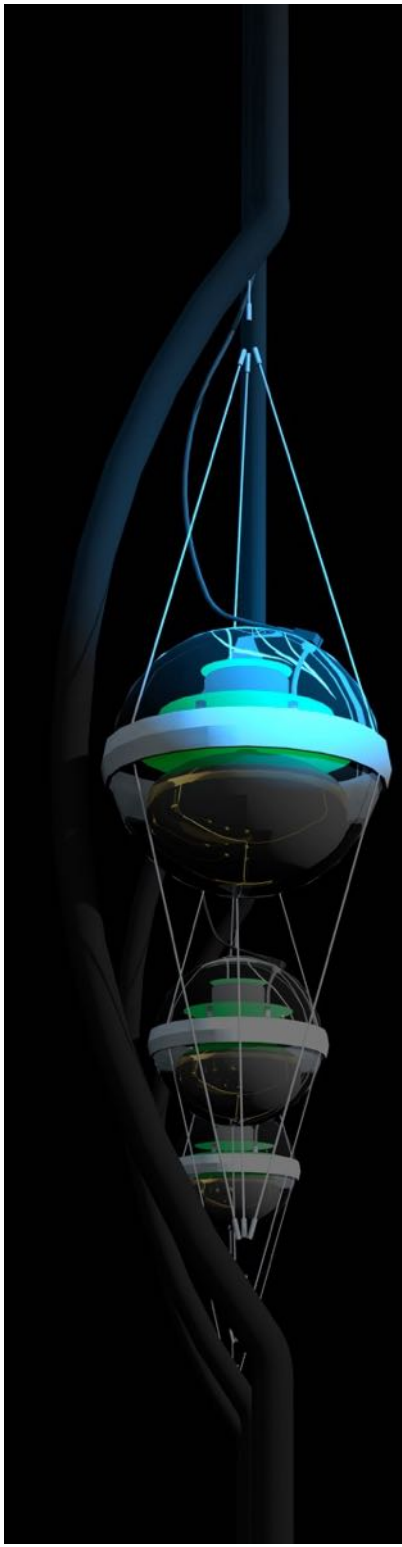

$\pi^+ = \pi^- = \pi^0$
Fermi IGRB
less than 6%
Fermi balzars?
more than 80%
blazars
IC HESE
IC $\nu_\mu + \bar{\nu}_\mu$
pp scenario
SFR evolution
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

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?

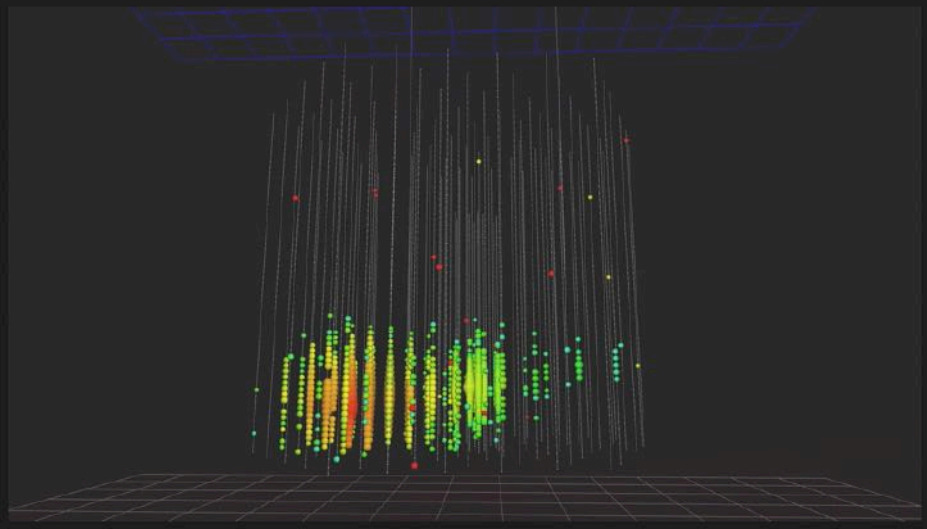
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

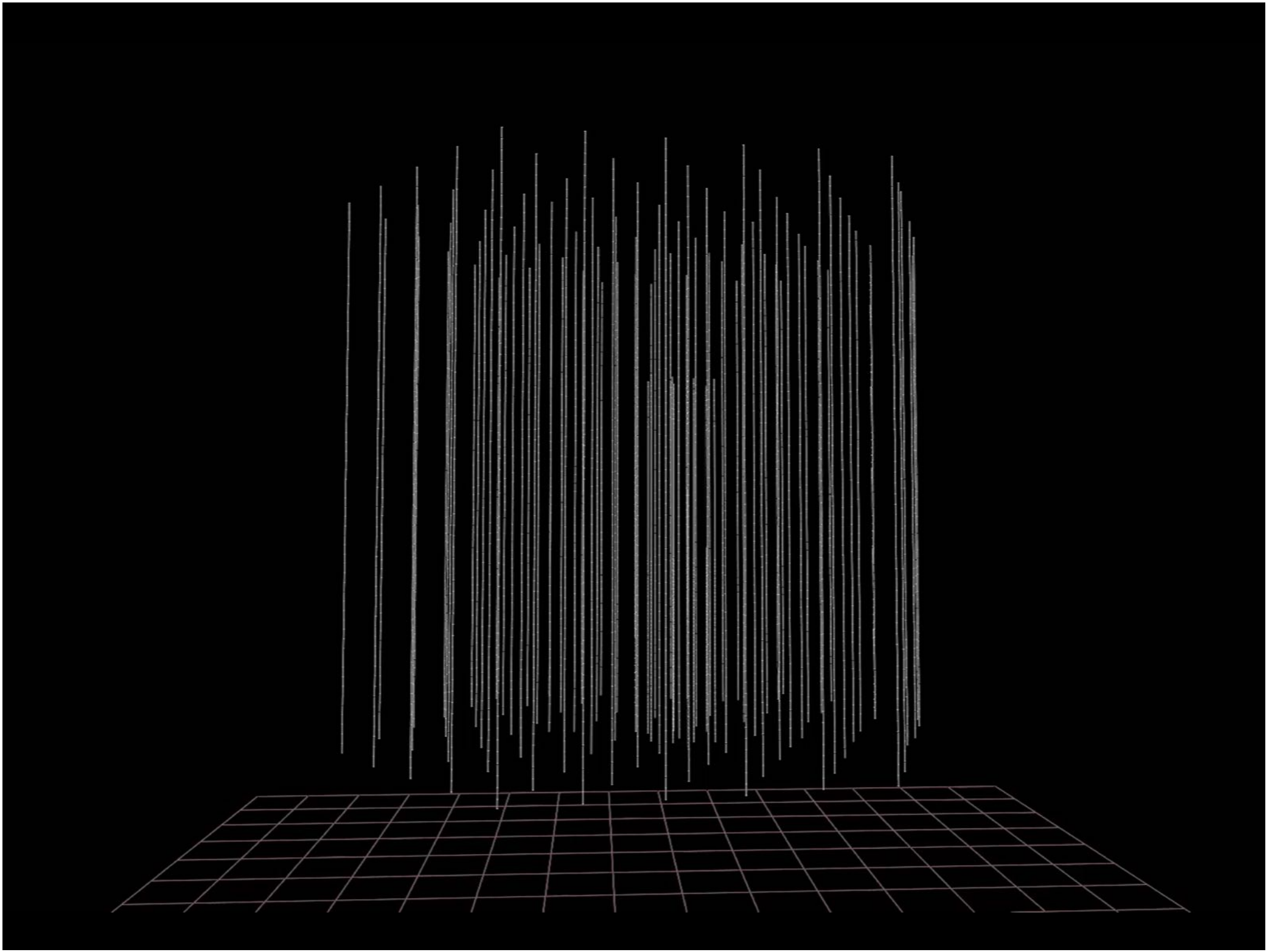
We send **rough reconstructions first** and then **update them.**

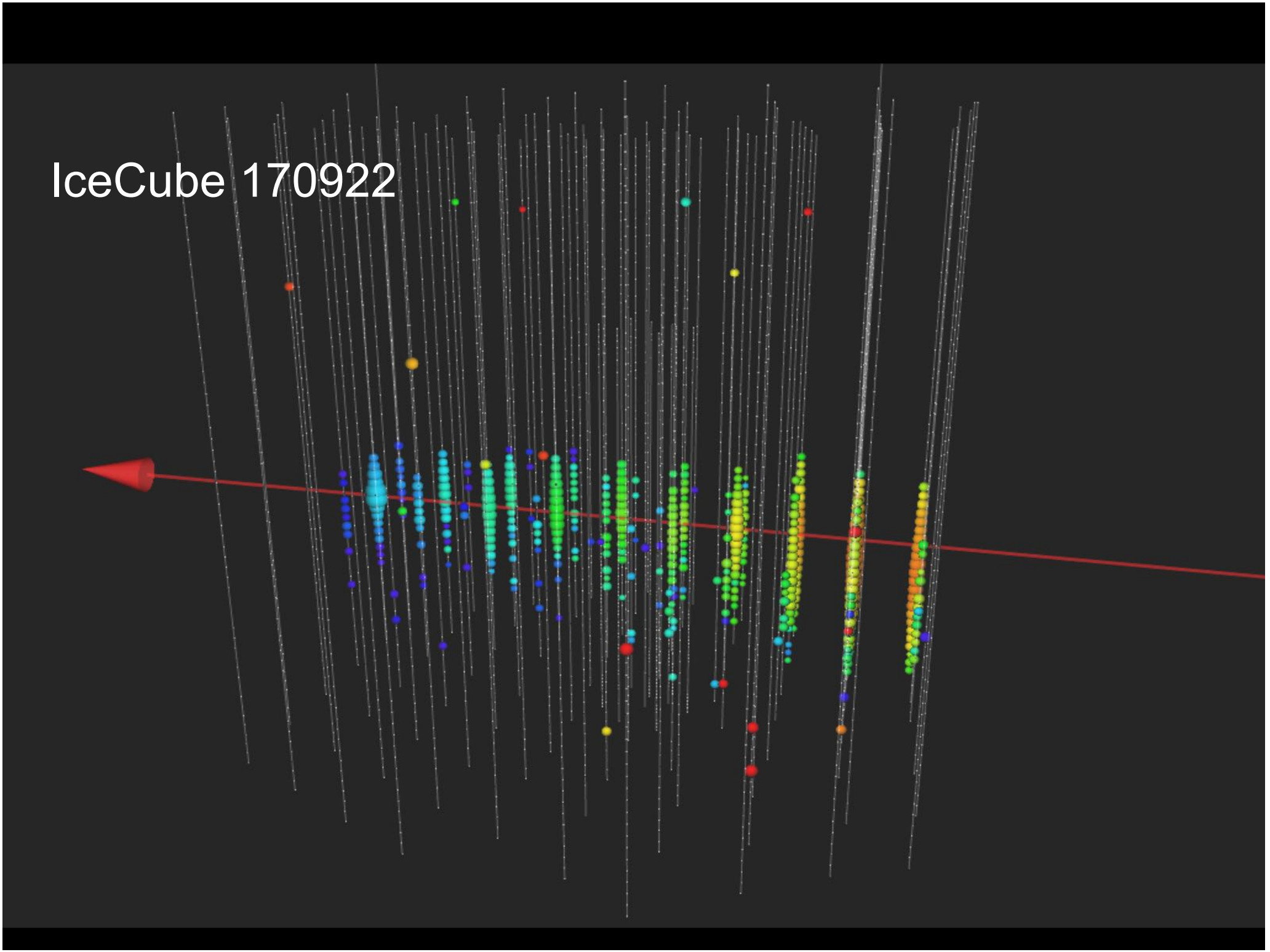


IceCube Trigger

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]
```

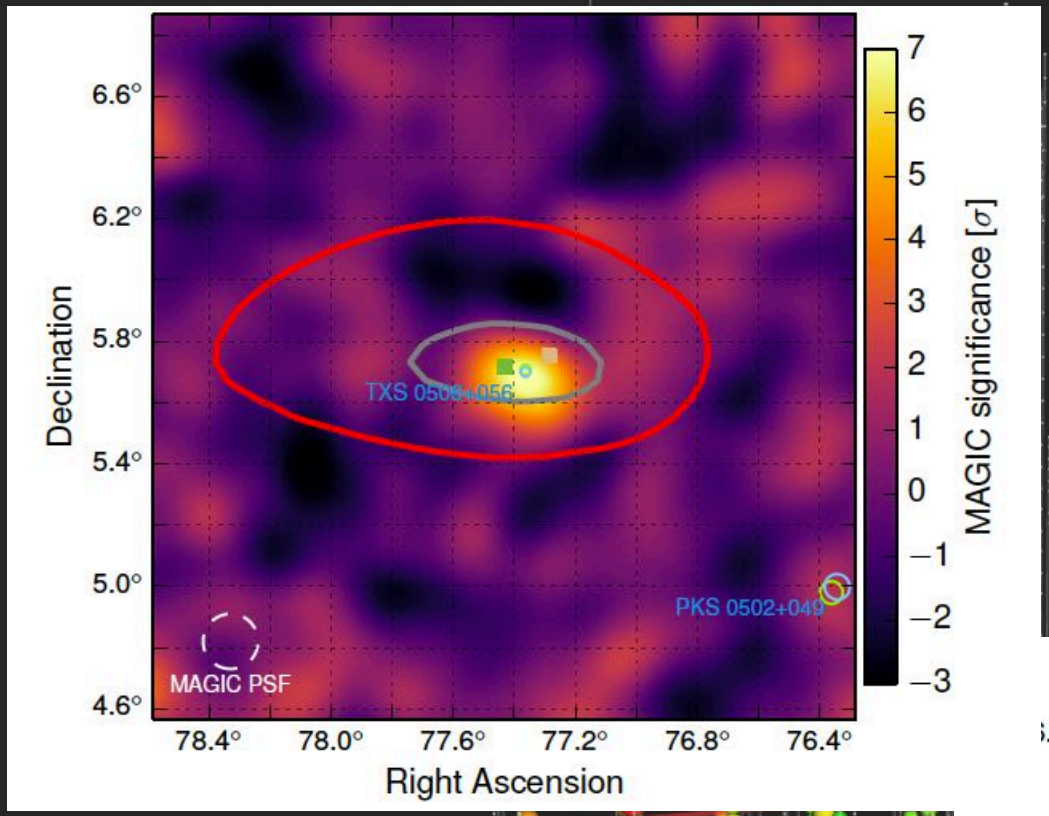



IceCube 170922

multiwavelength campaign launched by IC 170922

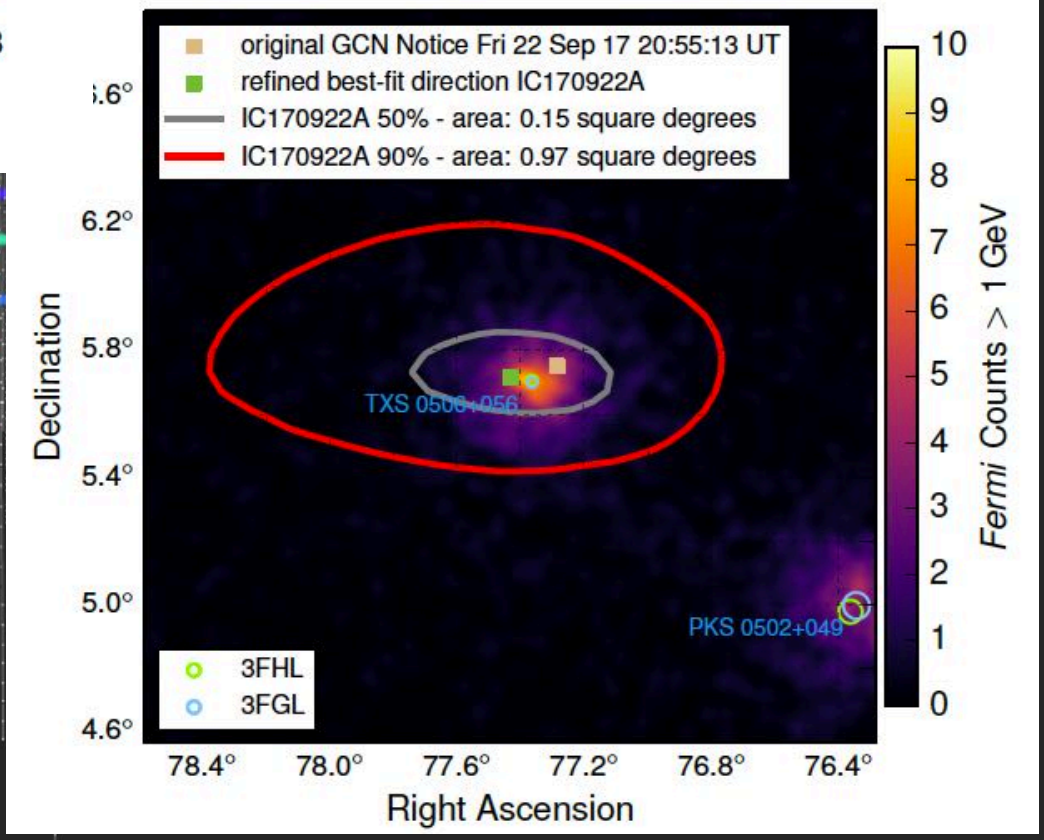
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- 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



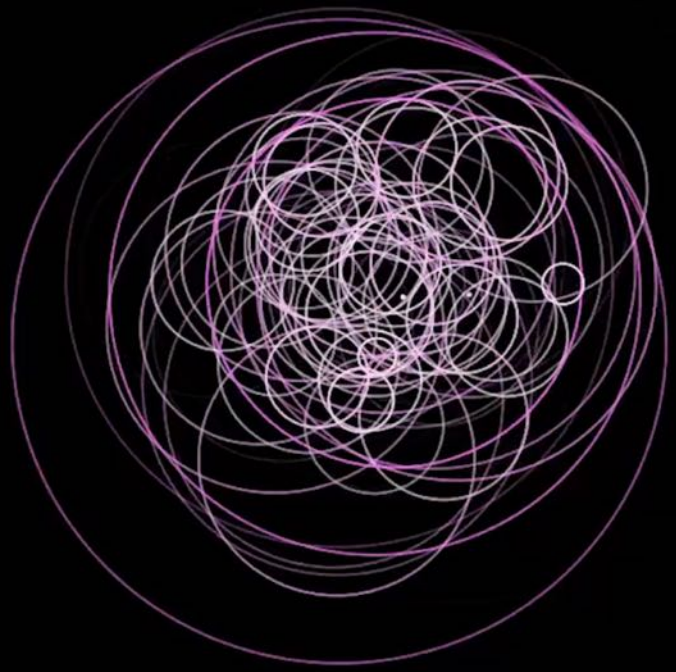
IceCube 170922

Fermi
detects a flaring
blazar within 0.1°

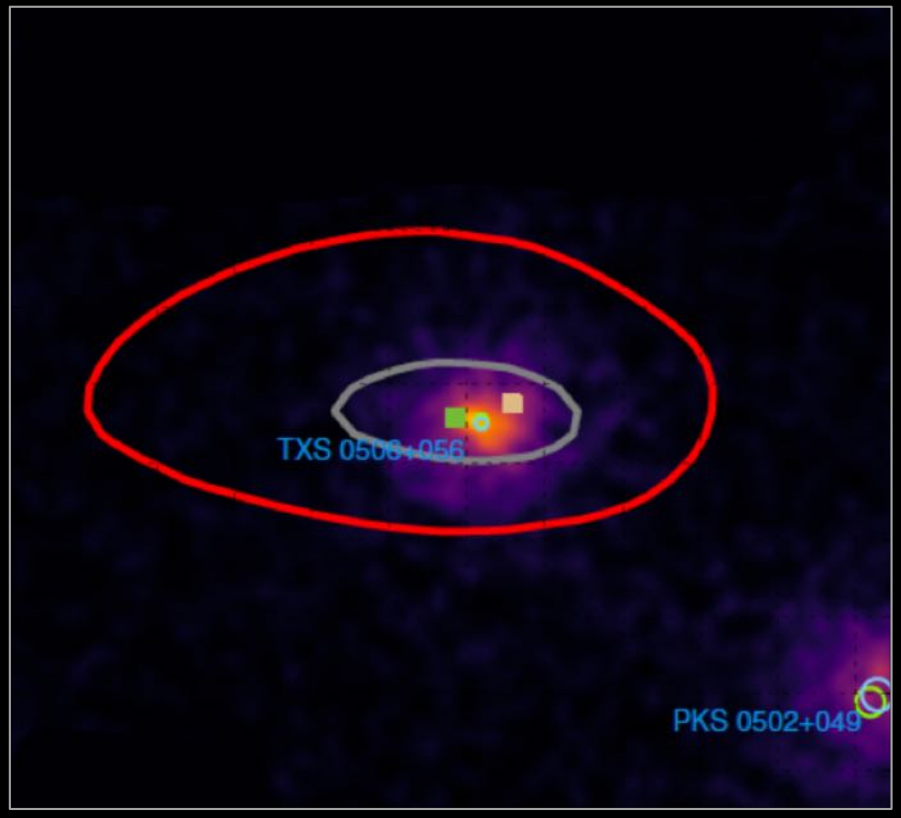


MAGIC
detects emission of
> 100 GeV gammas

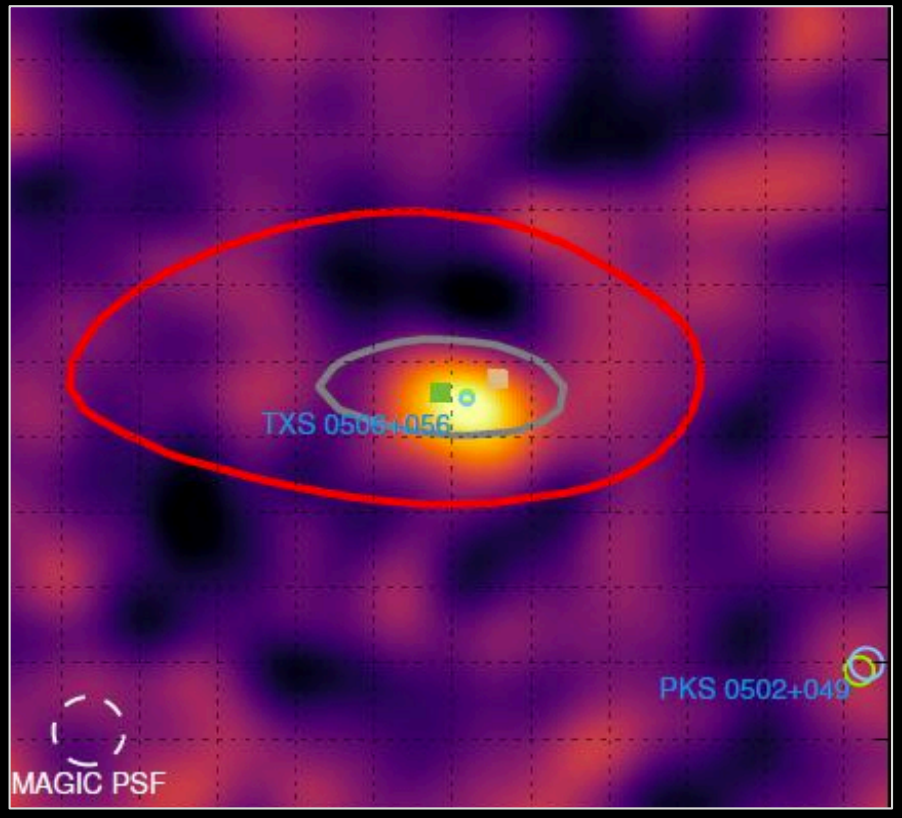
build-up over several months followed by rapid daily variability



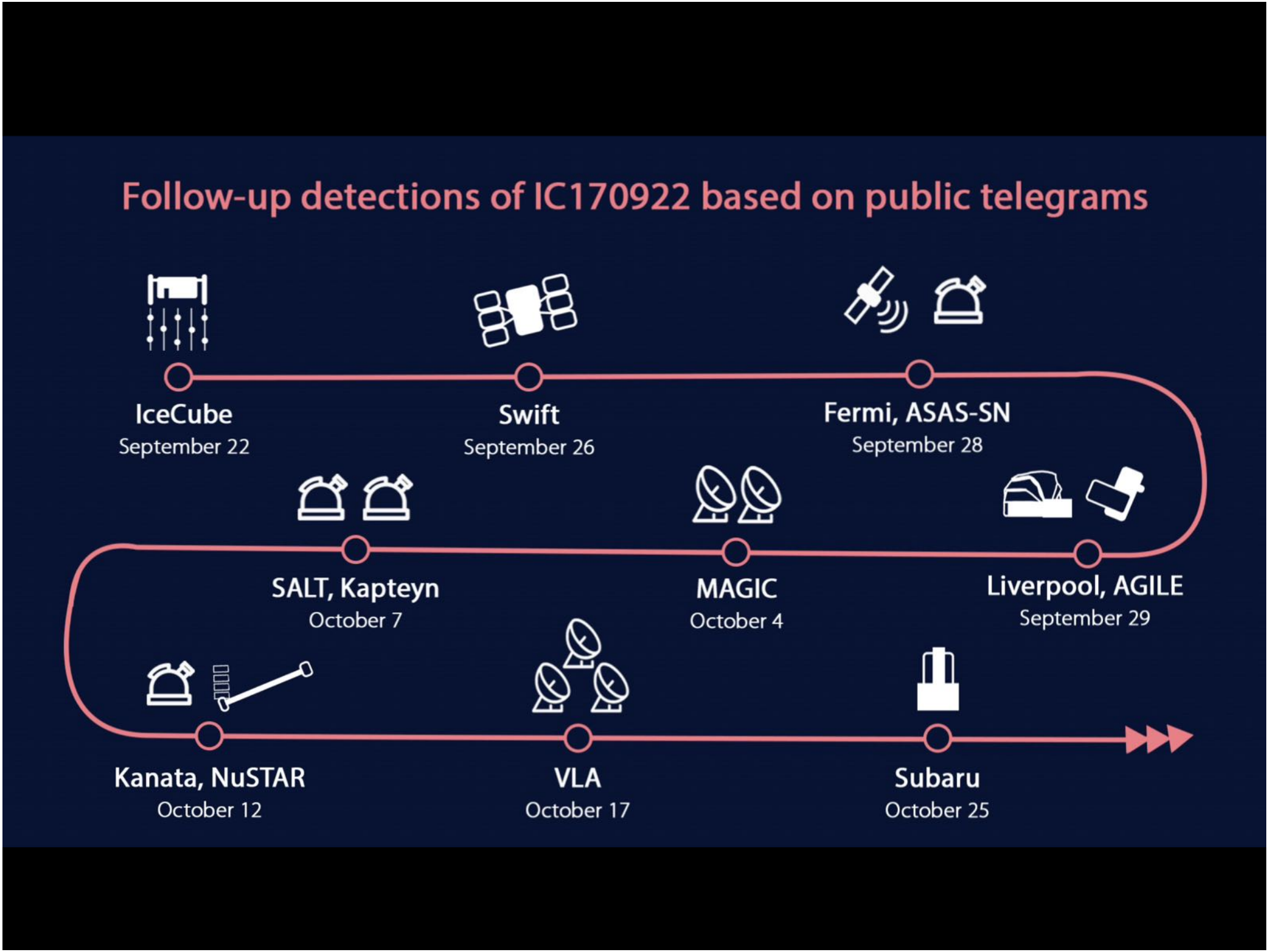
Neutrino points within 0.06^{o}
of a known Fermi blazar

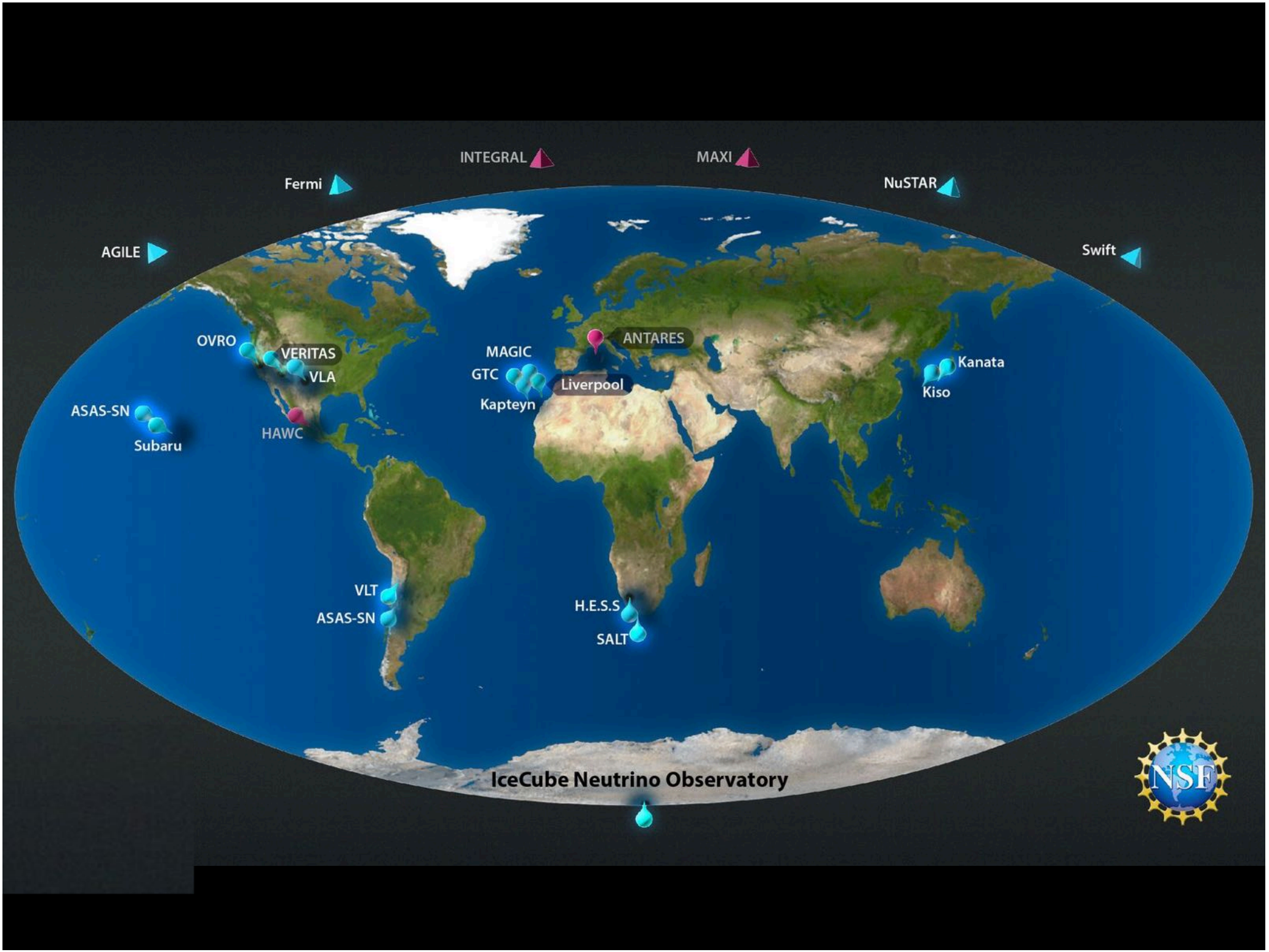


MAGIC detects emission of
>100 GeV gammas



MAGIC atmposheric Cherenkov telescope


Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
Liverpool, AGILE
September 29
MAGIC
October 4
SALT, Kapteyn
October 7
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25


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

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

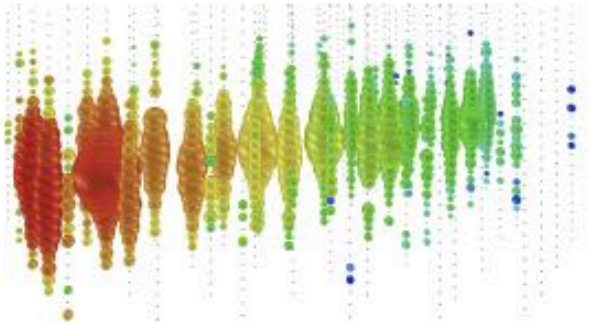
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.1^{o} (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT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

The Source: TXS 0506+056

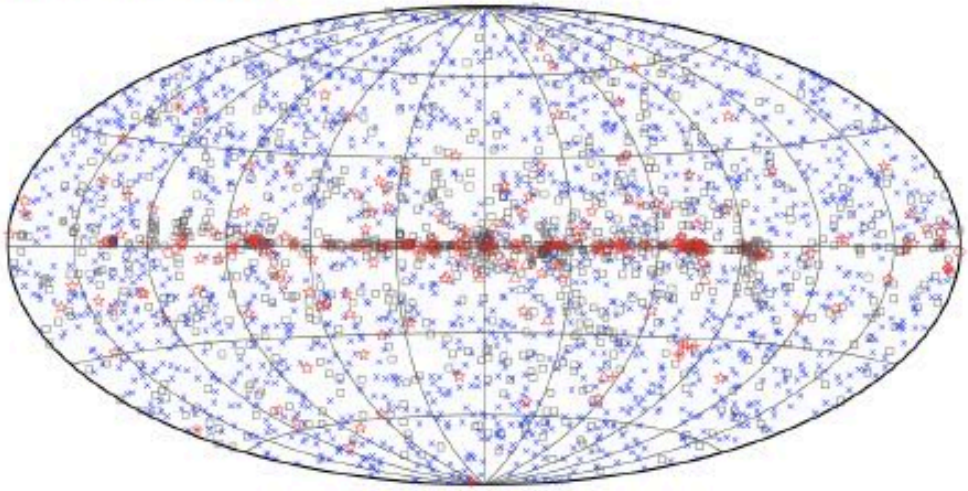
- Redshift 0.3365±0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC

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

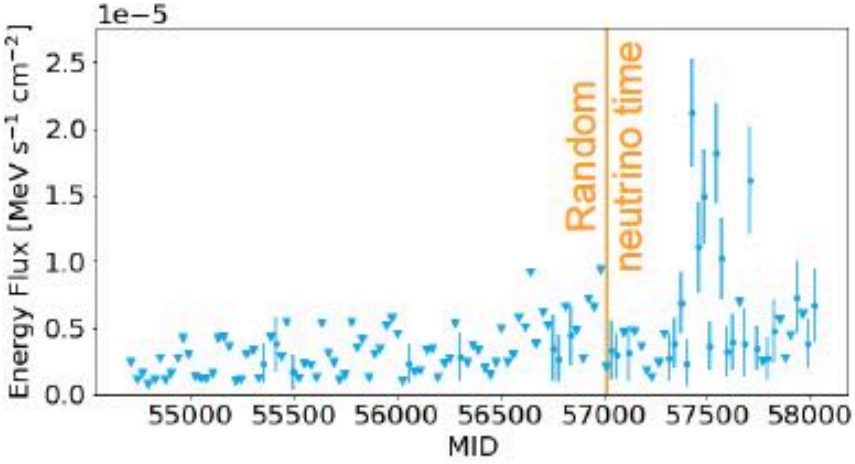
How Likely is it a Chance Probability?



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?

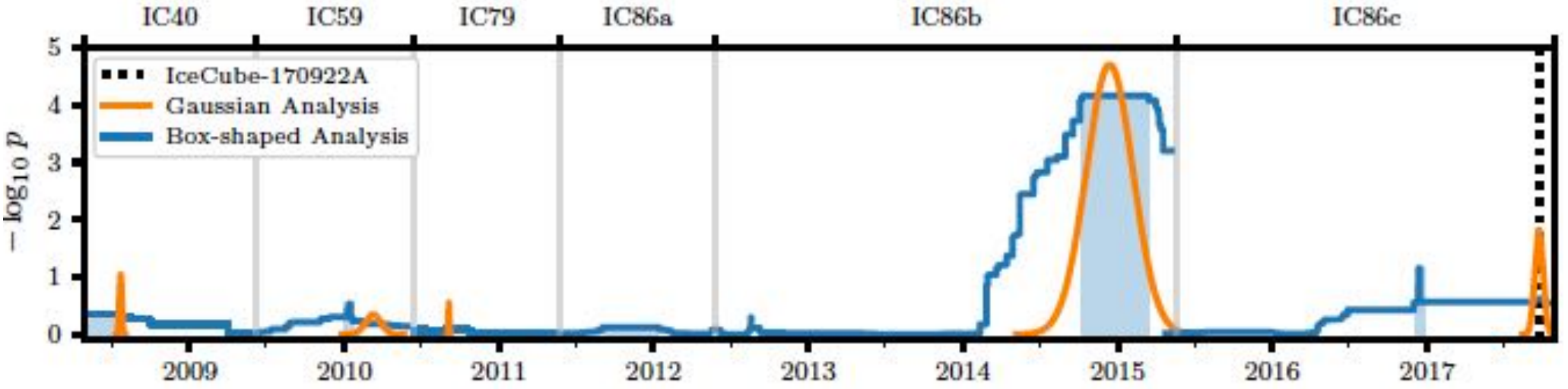


Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?

multiwavelength campaign launched by IC 170922

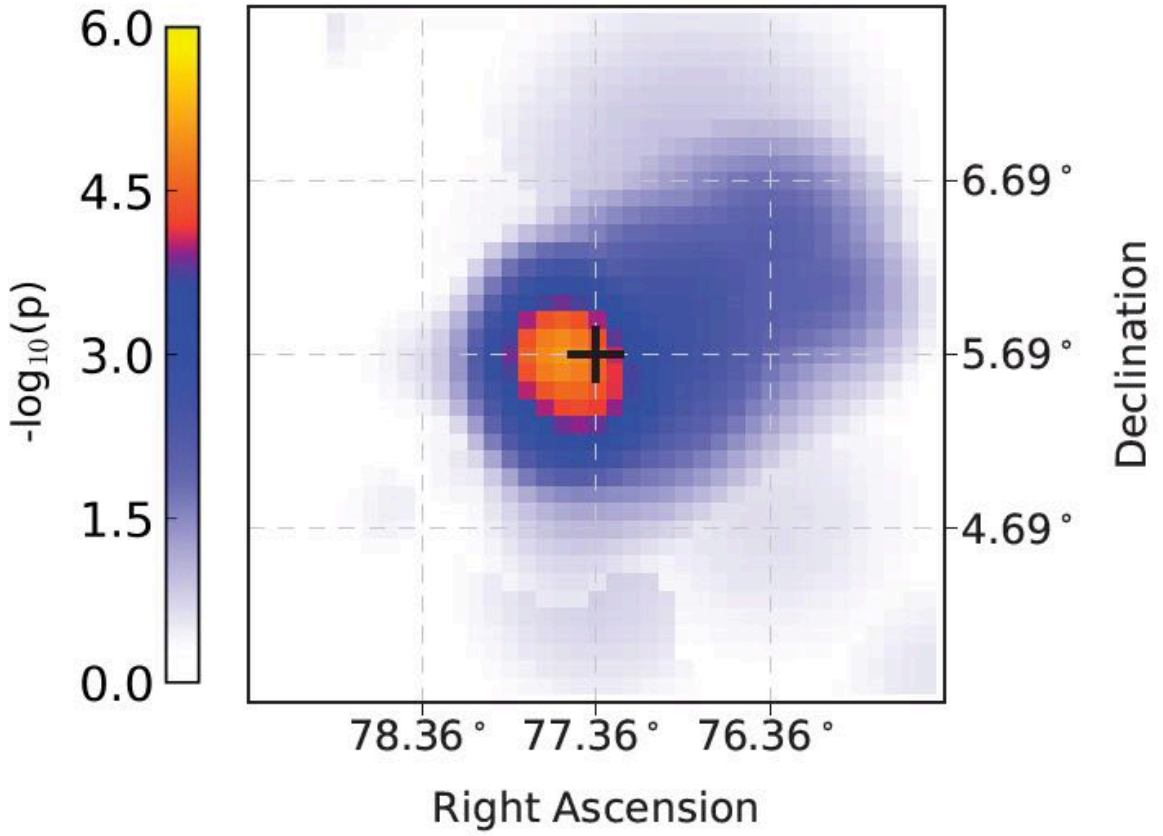
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

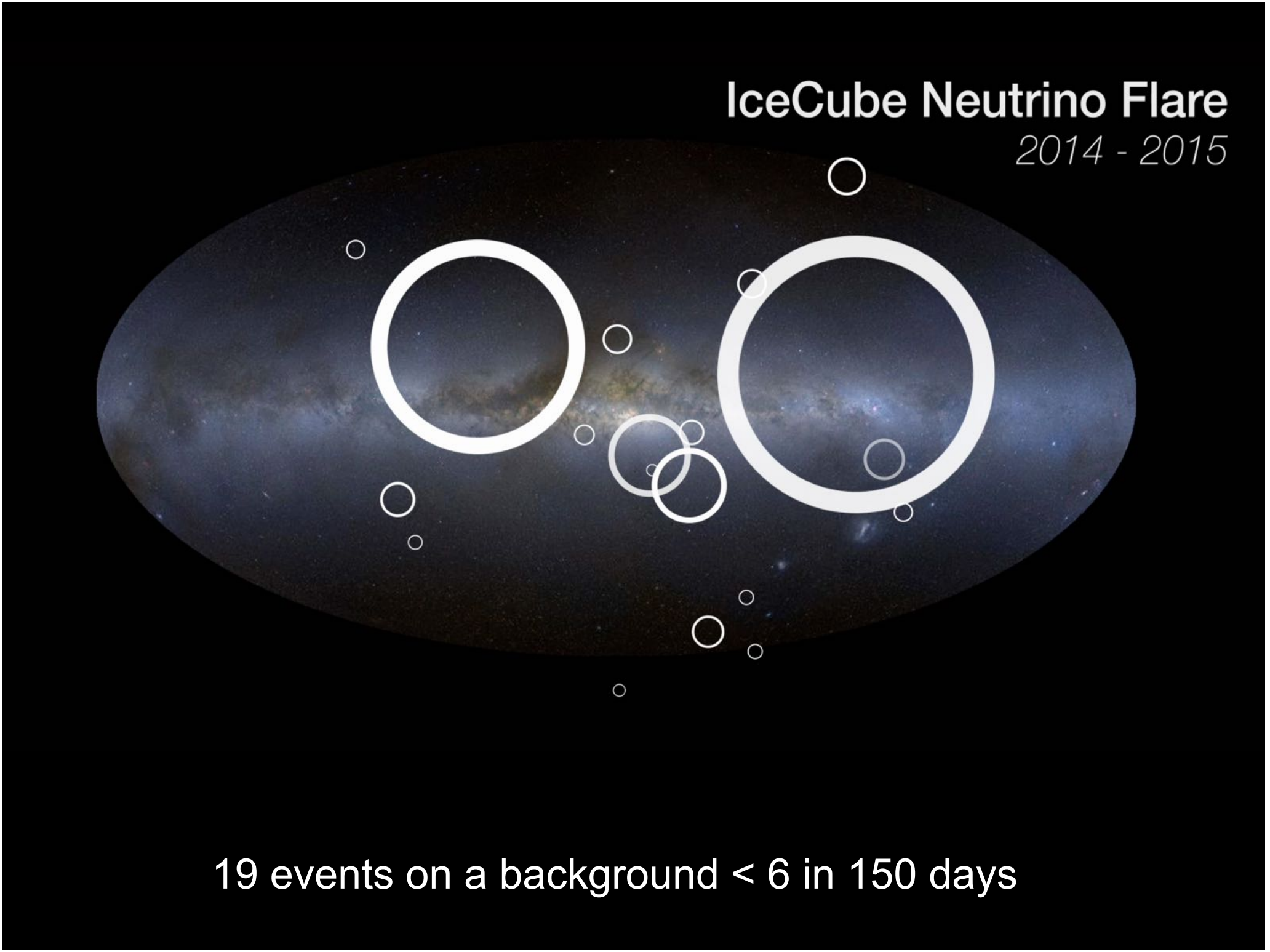
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.1^{o} (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

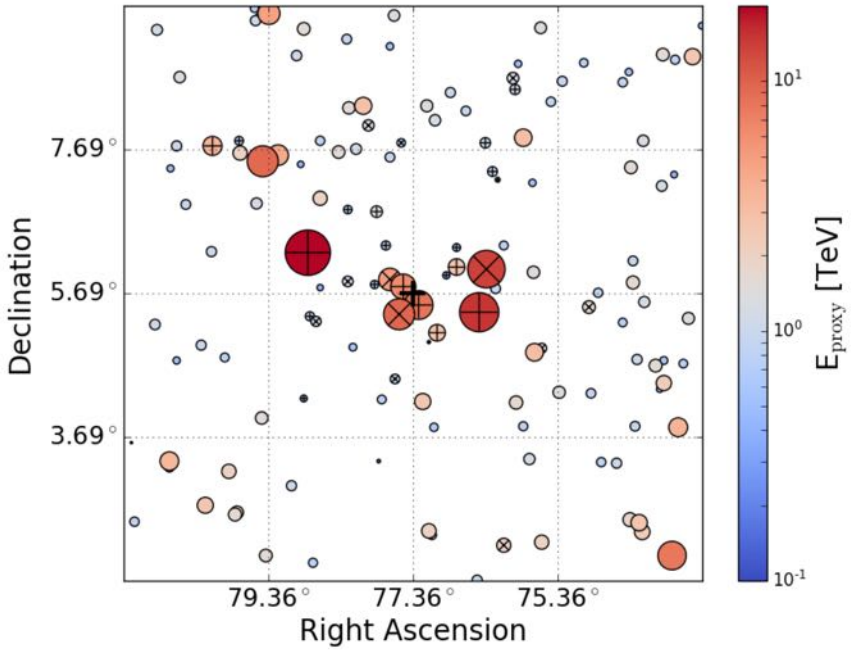


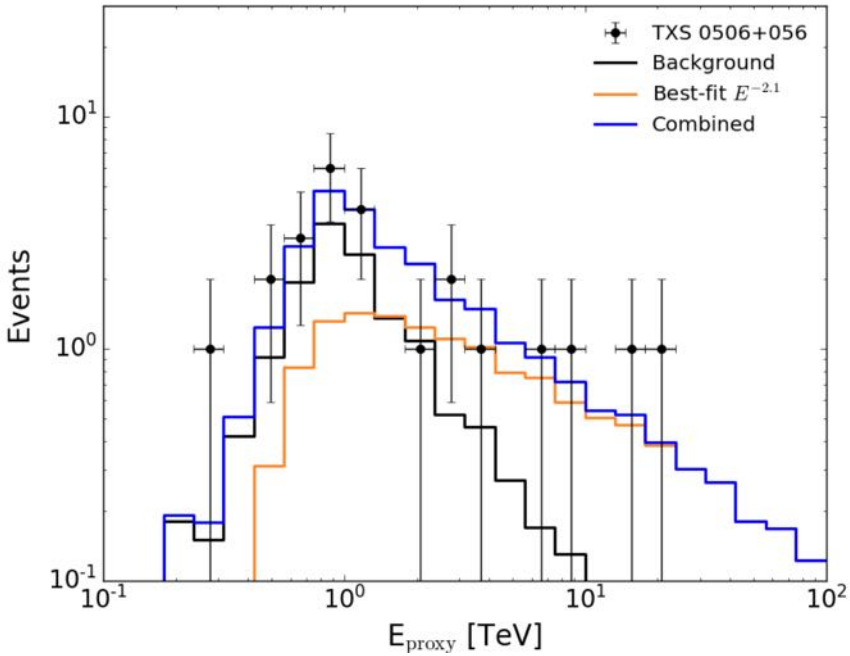
search in archival IceCube data:

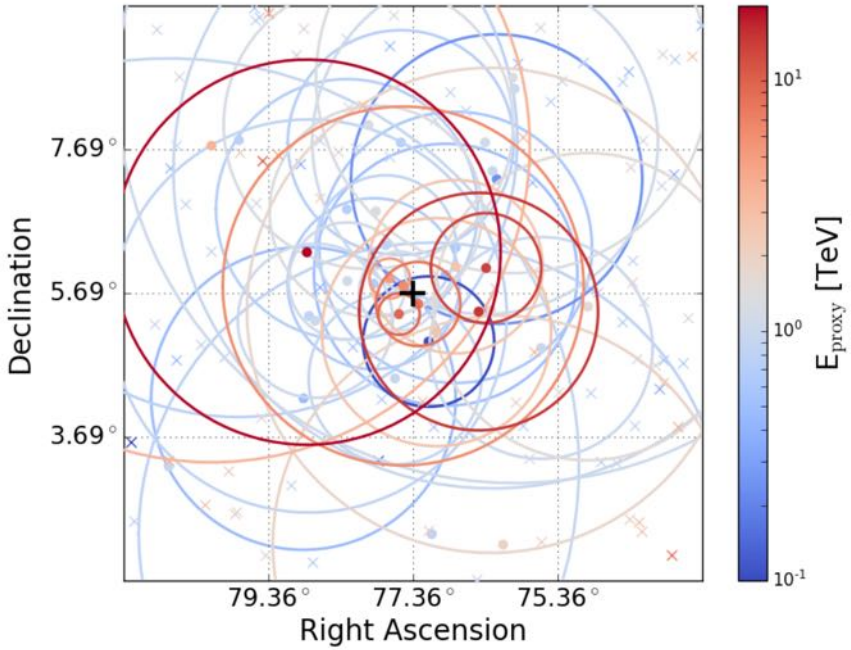
- ~150 day flare in December 2014: 19 events (6 bkg)
- accompanied by hardest photon spectrum in 10 yrs

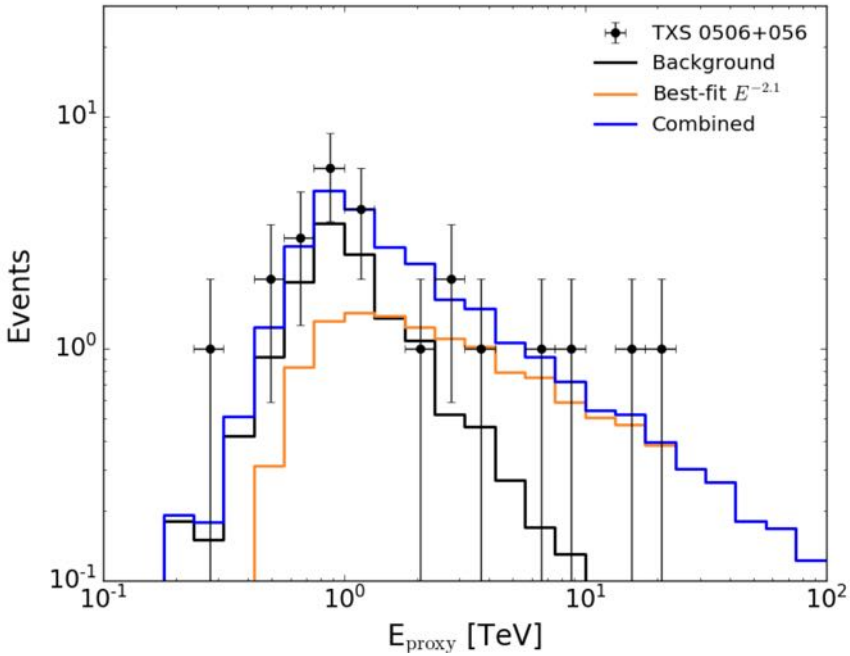



IceCube Neutrino Flare
2014 - 2015
19 events on a background < 6 in 150 days


Declination
7.69°
5.69°
3.69°
79.36°
77.36°
75.36°
Right Ascension
10^1
10^0
10^{-1}
E_{proxy} [TeV]


TXS 0506+056
Background
Best-fit $E^{-2.1}$
Combined
Events
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
10^2
E_{proxy} [TeV]

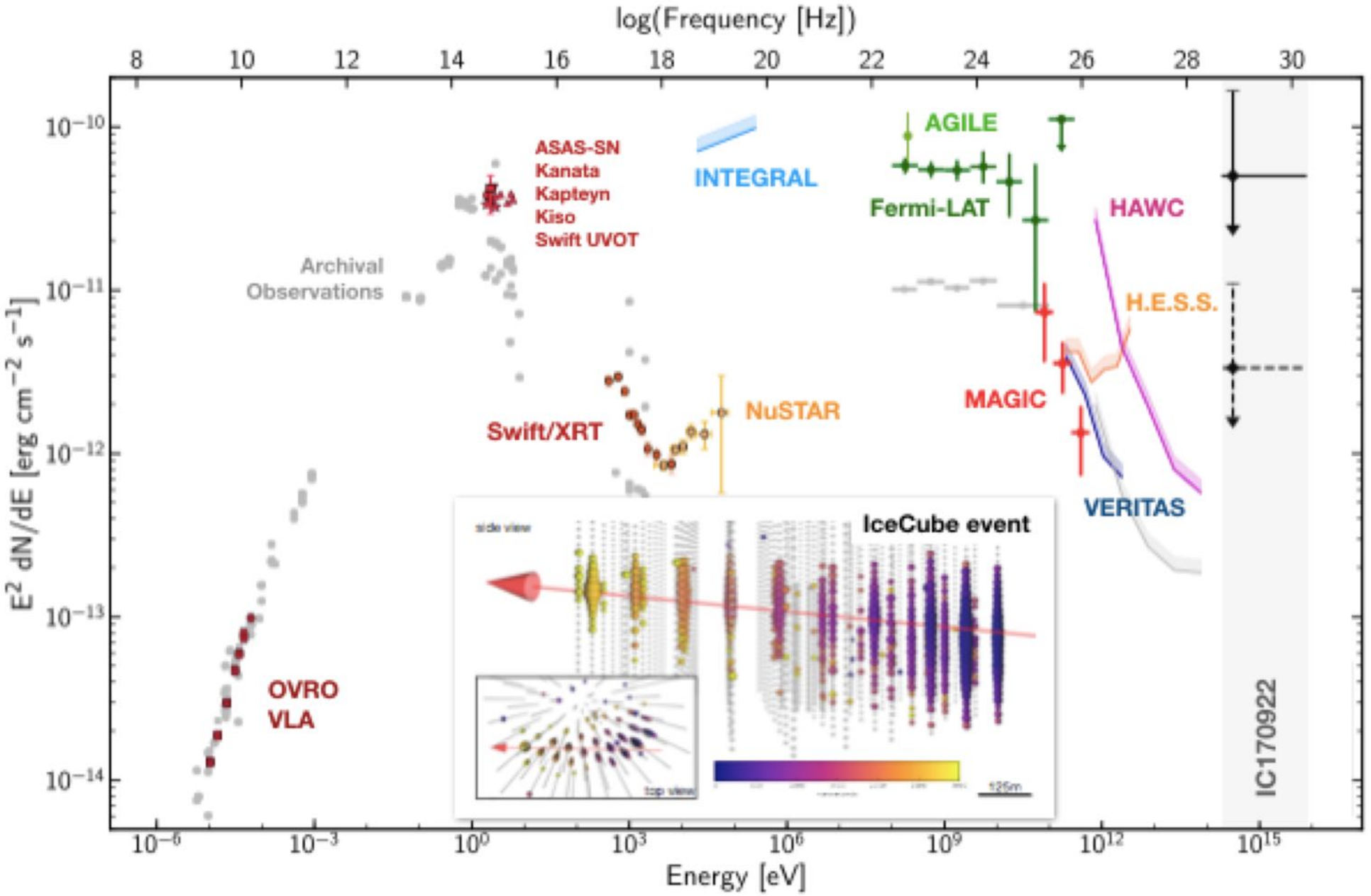

Declination
7.69°
5.69°
3.69°
79.36°
77.36°
75.36°
Right Ascension
10^1
10^0
10^{-1}
E_{proxy} [TeV]


TXS 0506+056
Background
Best-fit $E^{-2.1}$
Combined
Events
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
10^2
E_{proxy} [TeV]

we identified a source of high energy cosmic rays:

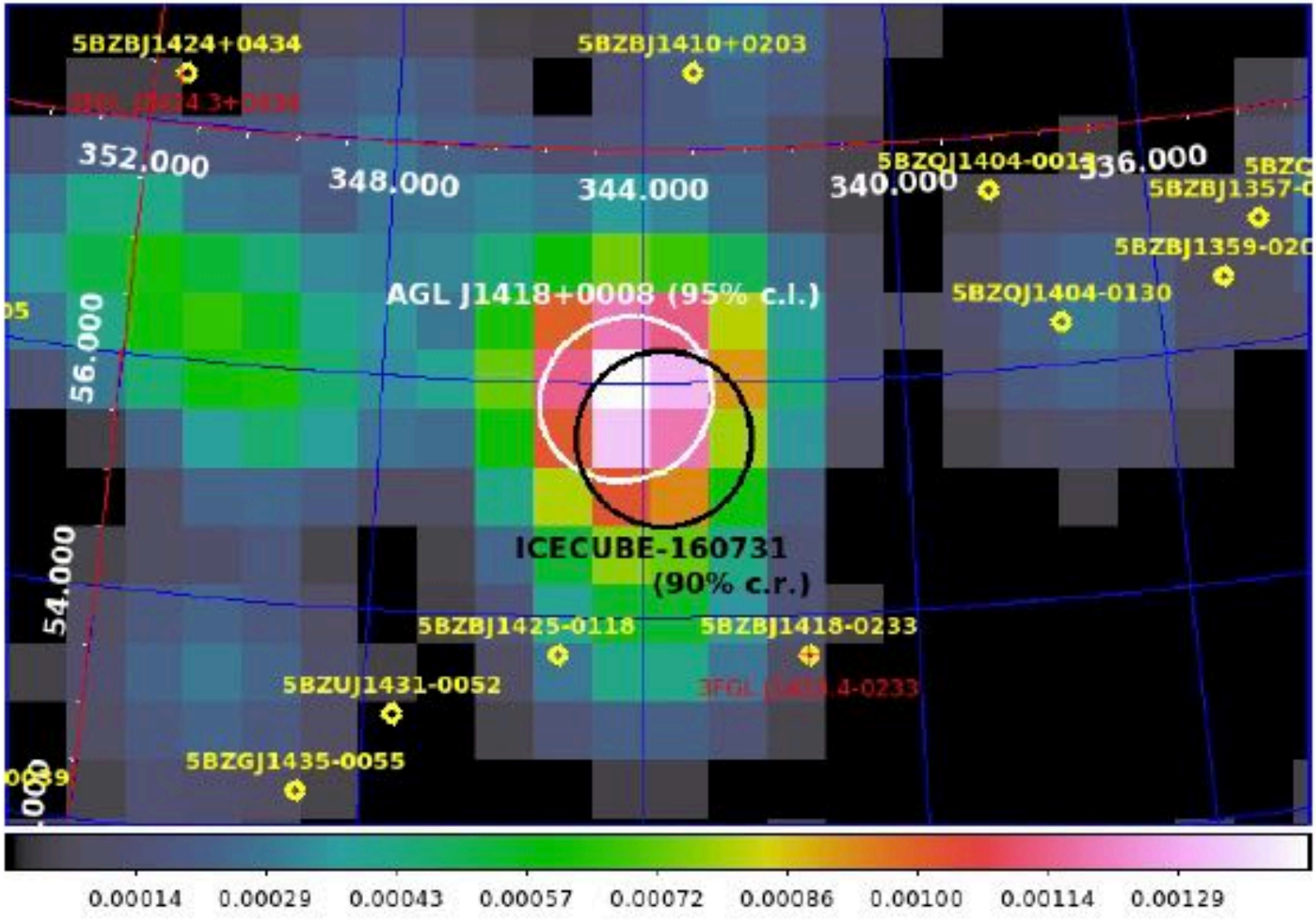
the active galaxy (blazar) TXS 0506+056 at a redshift of 0.33

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


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}]
ASAS-SN
Kanata
Kapteyn
Kiso
Swift UVOT
INTEGRAL
AGILE
Fermi-LAT
HAWC
Archival
Observations
H.E.S.S.
NuSTAR
Swift/XRT
MAGIC
VERITAS
IceCube event
side view
top view
125m
OVRO
VLA
IC170922
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]

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

F. Lucarelli,[1,2] C. Pittori,[1,2] F. Verrecchia,[1,2] I. Donnarumma,[3] M. Tavani,[4,5,6] A. Bulgarelli,[7] A. Giuliani,[8] L. A. Antonelli,[1,2] P. Caraveo,[8] P. W. Cattaneo,[9] S. Colafrancesco,[10,2] F. Longo,[11] S. Mereghetti,[8] A. Morselli,[12] L. Pacciani,[4] G. Piano,[4] A. Pellizzoni,[13] M. Pilia,[13] A. Rappoldi,[9] A. Trois,[13] and S. Vercellone[14]



Corresponding author: Fabrizio Lucarelli
fabrizio.lucarelli@asdc.asi.it

TANAMI blazars in the IceCube PeV neutrino fields

F. Krauß[1,2], M. Kadler[2], K. Mannheim[2], R. Schulz[1,2], J. Trüstedt[1,2], J. Wilms[1], R. Ojha[3,4,5], E. Ros[6,7,8], G. Anton[9], W. Baumgartner[3], T. Beuchert[1,2], J. Blanchard[10], C. Bürkel[1,2], B. Carpenter[5], T. Eberl[9], P.G. Edwards[11], D. Eisenacher[2], D. Elsässer[2], K. Fehn[9], U. Fritsch[9], N. Gehrels[3], C. Gräfe[1,2], C. Großberger[12], H. Hase[13], S. Horiuchi[14], C. James[9], A. Kappes[2], U. Katz[9], A. Kreikenbohm[1,2], I. Kreykenbohm[1], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], J.E.J. Lovell[15], C. Müller[1,2], C. Phillips[11], C. Plötz[13], J. Quick[16], T. Steinbring[1,2], J. Stevens[11], D. J. Thompson[3], and A.K. Tzioumis[11]

(Affiliations can be found after the references)

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

Brenda L. Dingus[1] & David L. Bertsch[2]

(1) Physics Department, University of Wisconsin, Madison, WI 53711
dingus@physics.wisc.edu
(2)NASA Goddard Space Flight Center, Greeenbelt, MD 20771

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

Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos are essential for understanding the non-thermal universe.
- identified the first high-energy cosmic ray accelerator
- from discovery to astronomy: more events, more telescopes IceCube-Gen2, KM3NeT and GVD (Baikal)
- 10 years of IceCube data -pass 2 (detector geometry for individual DOMs, use more photons in reconstruction, better optics of ice)

THE ICECUBE COLLABORATION

ISTRALIA 1

NGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory

- Galactic sources?

neutral pions

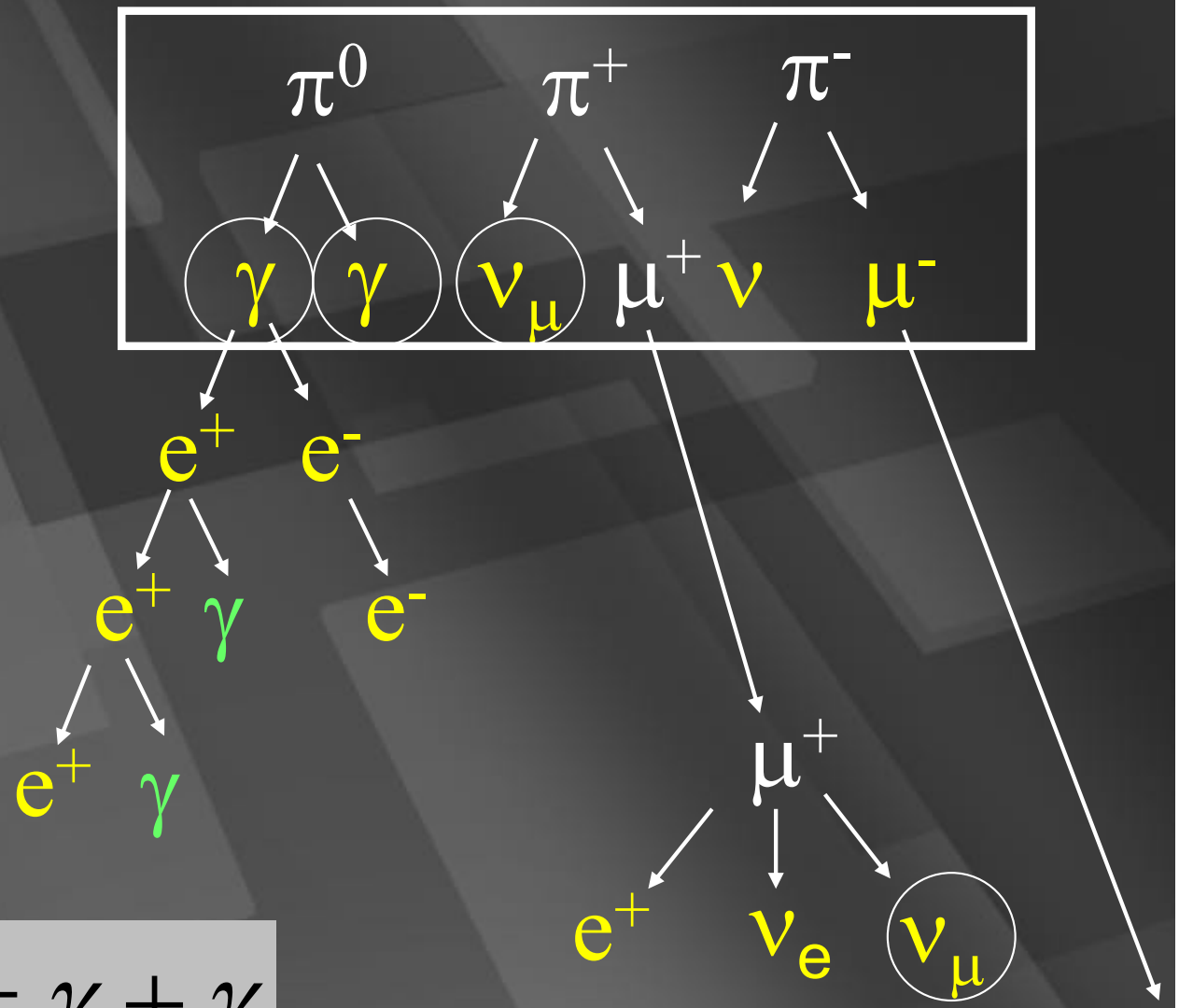
are observed as

gamma rays

charged pions

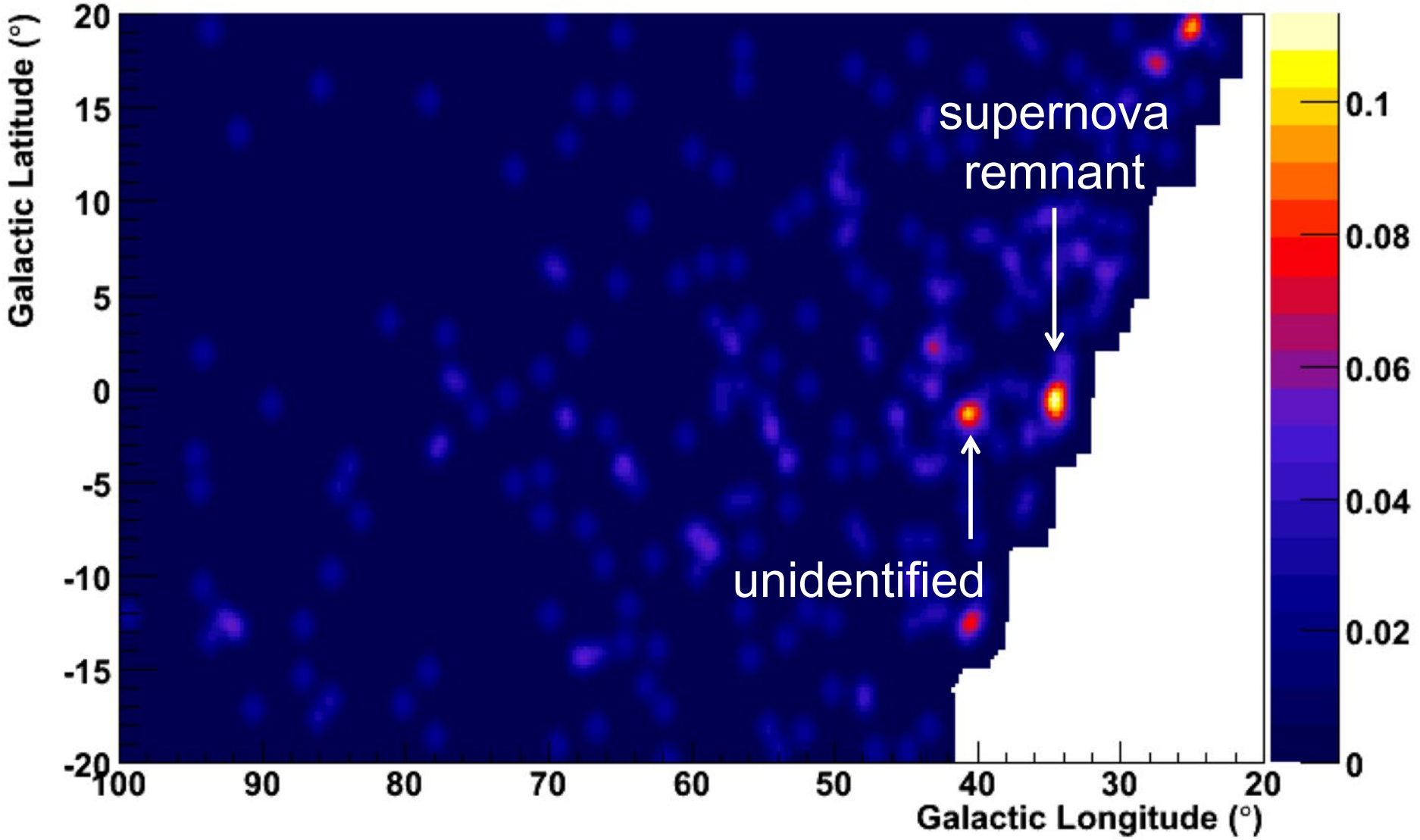
are observed as

neutrinos

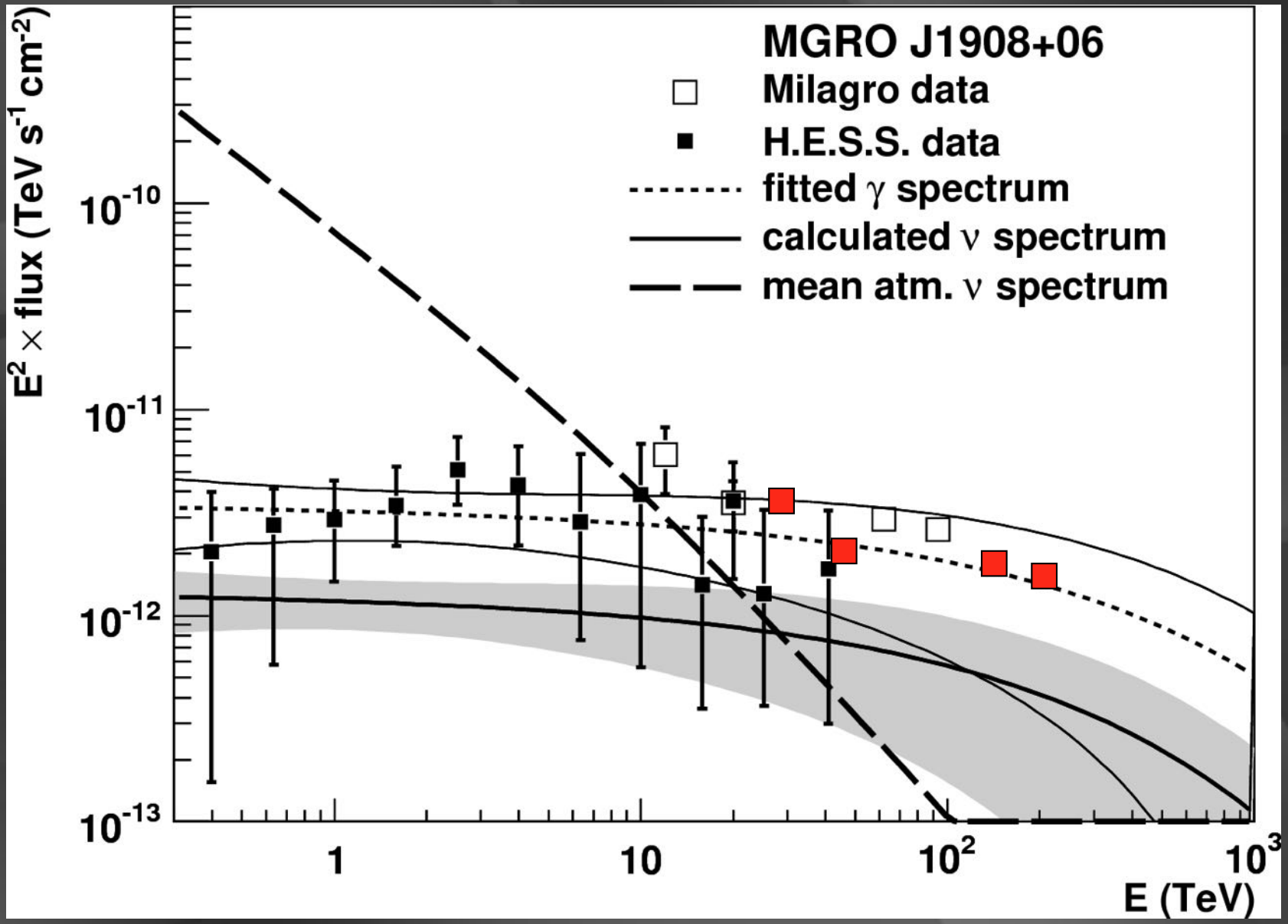


$$\nu_\mu + \overline{\nu}_\mu = \gamma + \gamma$$

2007 simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.



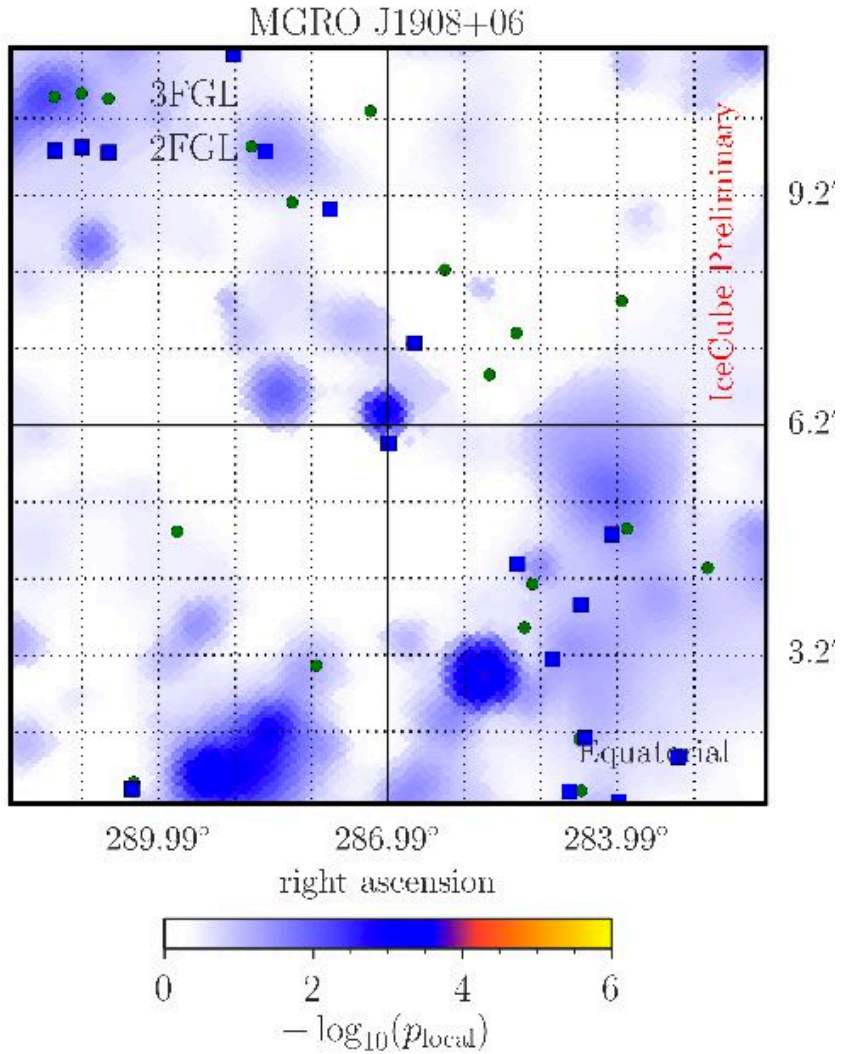
MGRO J1908+06: the first Pevatron? (2007!)



- most significant source in pre-defined list (p-value 0.003 pretrial)
- joined HAWC-IceCube analysis in progress using photon templates

Table 1: Results of the pre-defined source list.

Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04 \cdot 10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.059	0.00	$4.47 \cdot 10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.055	0.00	$5.37 \cdot 10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68 \cdot 10^{-13}$
Mrk 501	BL Lac	253.47	39.76	0.6847	-0.172	0.00	$3.51 \cdot 10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58 \cdot 10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7890	-0.243	0.00	$1.96 \cdot 10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50 \cdot 10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58 \cdot 10^{-13}$
1ES 1959+650	BL Lac	300.00	65.15	0.2069	0.124	1.69	$1.17 \cdot 10^{-12}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84 \cdot 10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42 \cdot 10^{-13}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98 \cdot 10^{-13}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.74 \cdot 10^{-13}$
3C454.3	FSRQ	343.50	16.15	0.0072	5.503	5.98	$1.26 \cdot 10^{-12}$
4C 38.41	FSRQ	248.81	38.13	0.0055	5.586	6.62	$1.72 \cdot 10^{-12}$
MGRO J1908+06	NI	286.99	6.27	0.0032	6.784	3.28	$1.13 \cdot 10^{-12}$
Geminga	PWN	98.48	17.77	0.9754	-3.424	0.00	$1.16 \cdot 10^{-13}$
Crab Nebula	PWN	83.63	22.01	0.1188	0.709	4.32	$8.65 \cdot 10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	0.9884	-3.191	0.00	$1.39 \cdot 10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53 \cdot 10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22 \cdot 10^{-13}$
Cas A	SNR	350.85	58.81	0.2069	0.033	0.88	$1.05 \cdot 10^{-12}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14 \cdot 10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85 \cdot 10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30 \cdot 10^{-13}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78 \cdot 10^{-12}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31 \cdot 10^{-13}$
M82	SRG	148.97	69.68	0.8887	-0.888	0.00	$1.83 \cdot 10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01 \cdot 10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01 \cdot 10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93 \cdot 10^{-13}$
Cyg X-3	XB/mqso	308.11	40.96	0.3230	-0.003	0.00	$7.28 \cdot 10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01 \cdot 10^{-12}$

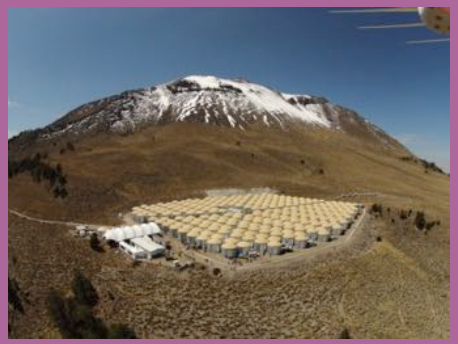


Detector Complementarity

Wide-field / Continuous Operation

VHE Sensitivity

Fermi, AGILE, EGRET



HAWC, ARGO, Milagro

VERITAS, HESS, MAGIC

Space-Based

- All sky coverage
- GeV range (area->flux limited)

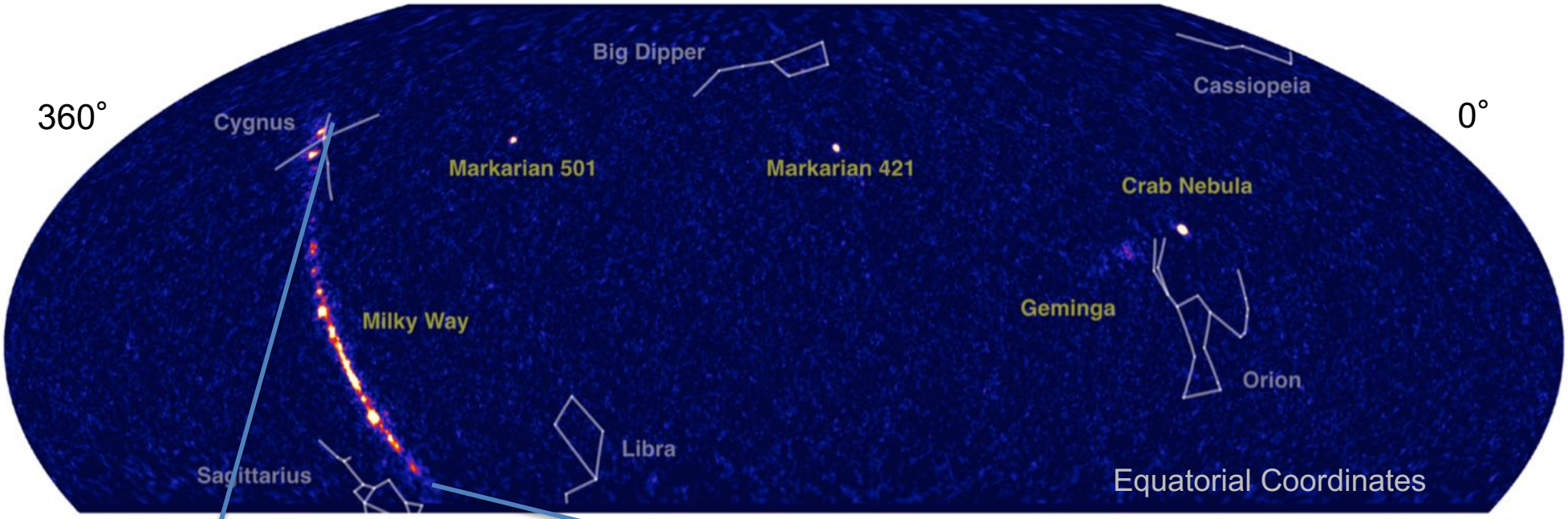
Ground Arrays

- 95% duty cycle, ~2 sr f.o.v.
- Daily coverage of $2/3$ sky
- Unbiased surveys
- Highest energies, E > 100 GeV

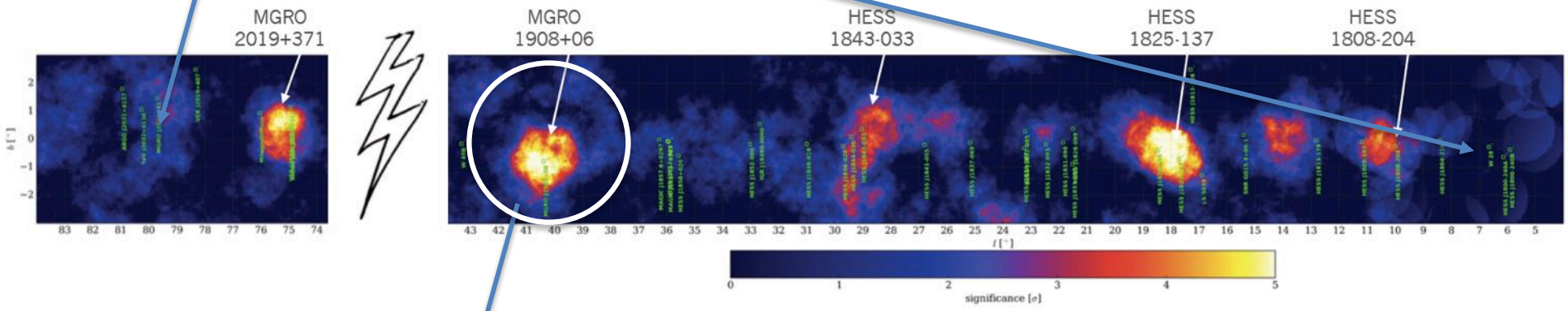
IACTs

- Excellent pointing
- Highest energies
- Surveys limited

HAWC View of Gamma Ray Sky

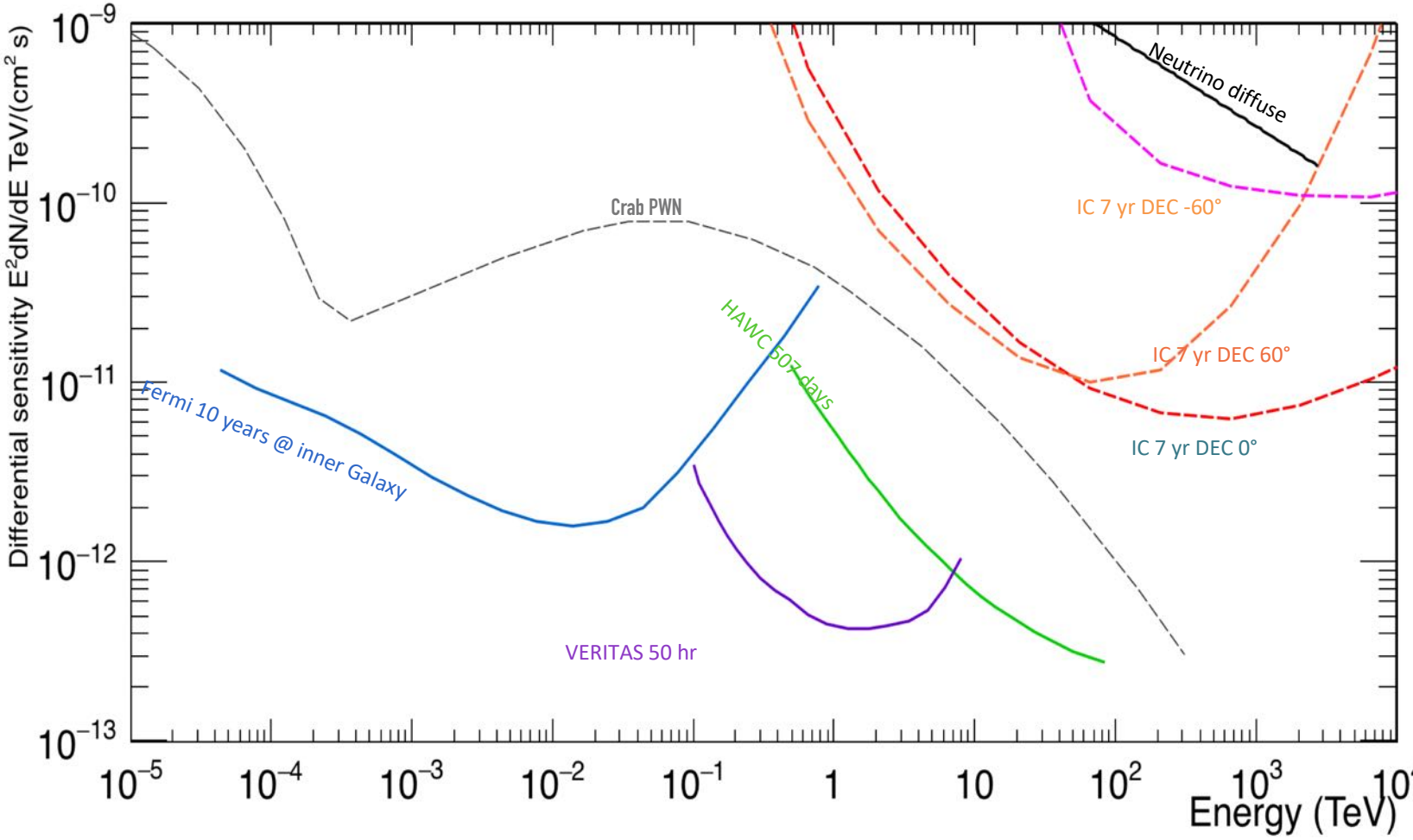


E > 1 TeV 340 days



MGRO J1908+06

HAWC sky above 55 TeV

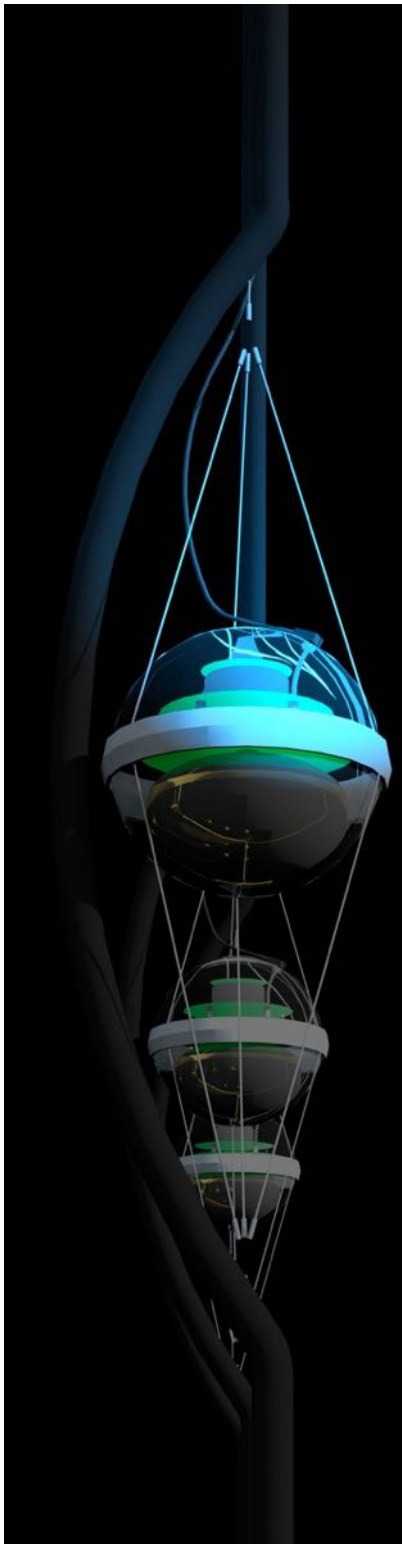


Comparisons with HAWC

- HAWC is better at detecting very large emission regio
  HAWC is also a survey instrument, so they are accumulating exposure in ~40% of all sky they are surveying.
  This is especially important for E> a few TeV energy range.
- VERITAS is better at detecting gamma-rays with E<a few TeV with moderate exposure w/ source size < 1 degree.
  Much better instantaneous sensitivity for E< a few tens of TeV with moderate exposure.
  Better angular resolution, energy resolution.

Detected sources are largely SNR/PWNs (2 blazars)

Detected various sources (40 extragalactic sources, 33 galactic sources)



IceCube

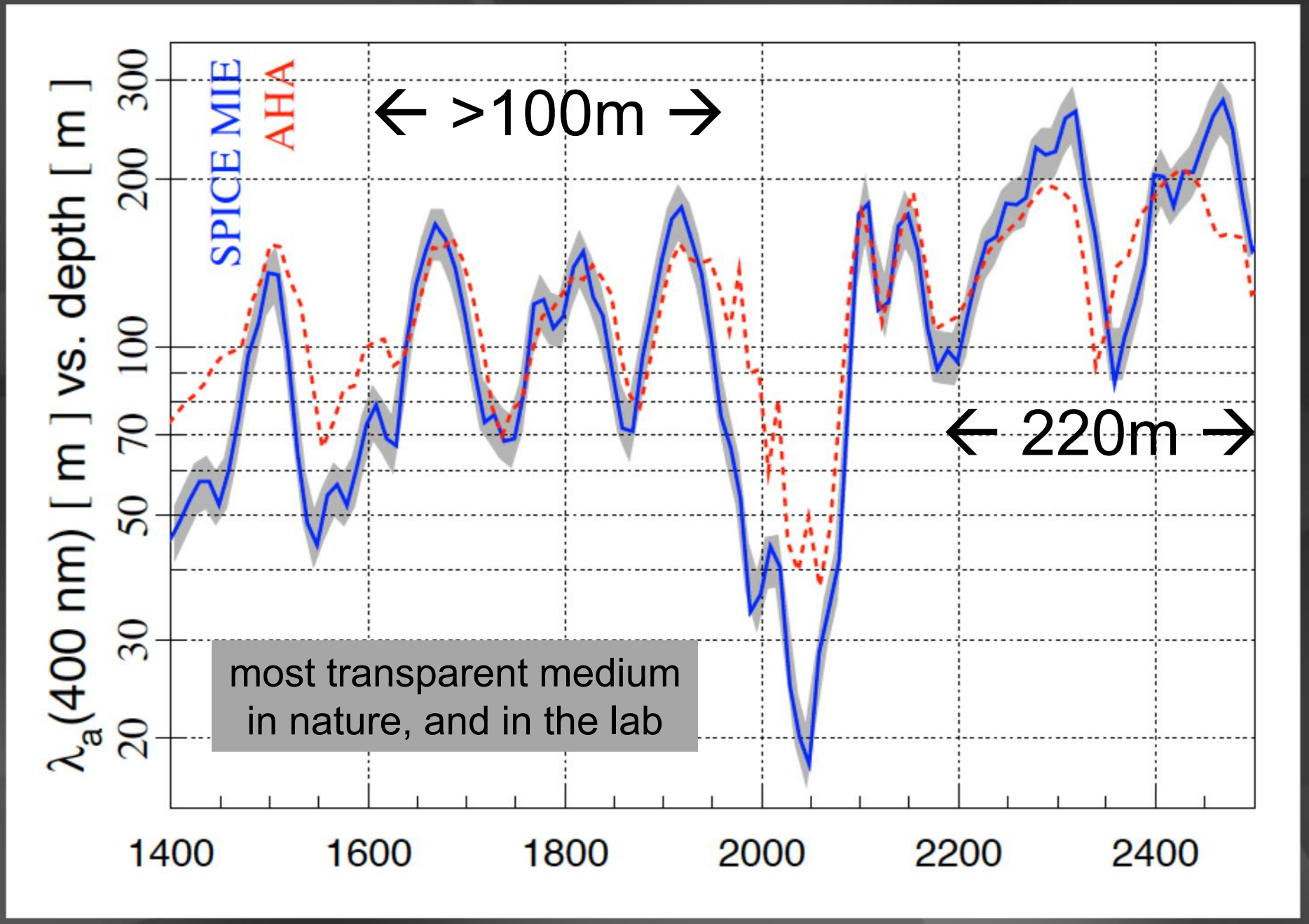
francis halzen

- 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?

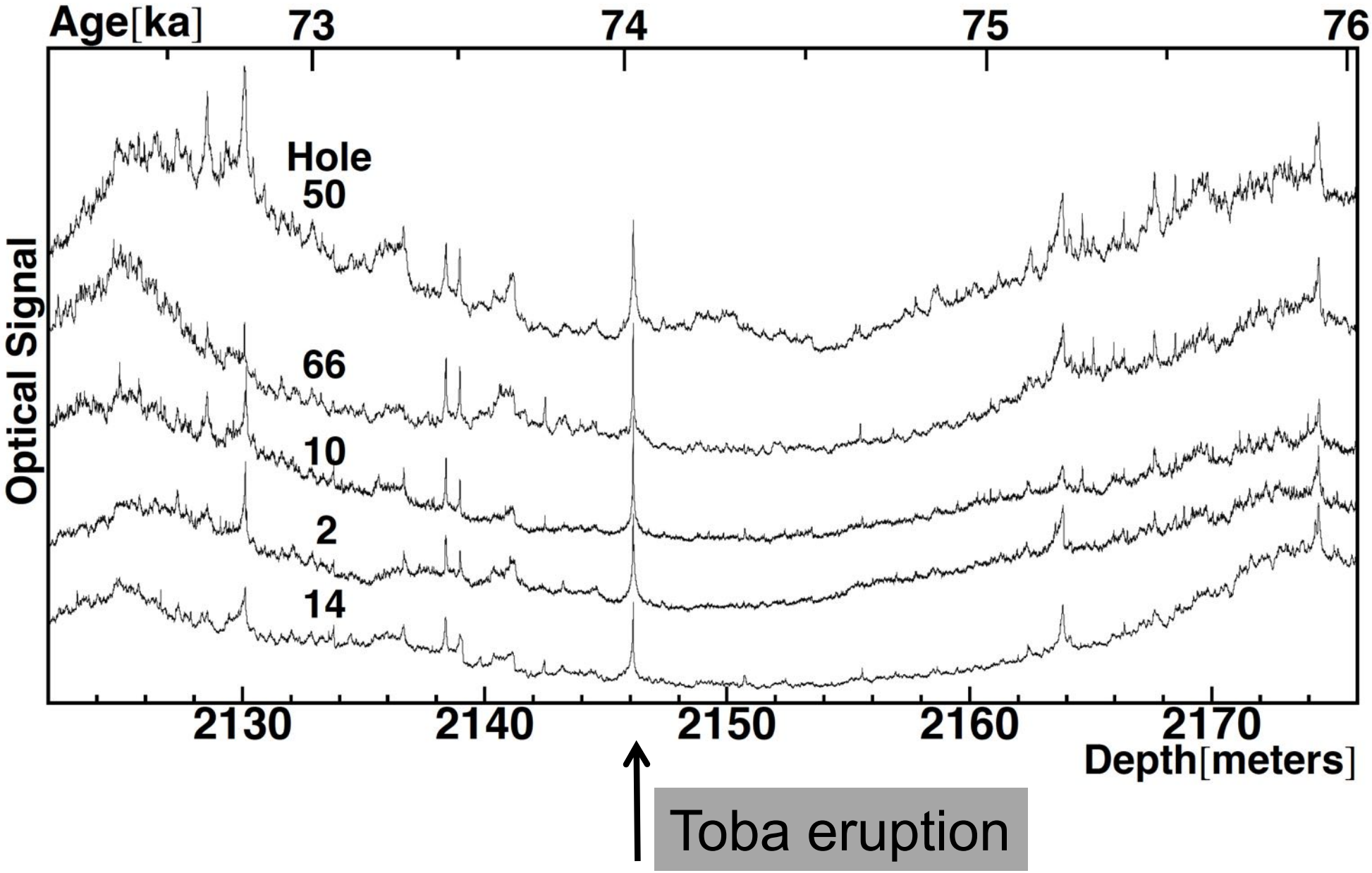
IceCube.wisc.edu

- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of ~ 0.1 degree will see multiple neutrinos from single sources and identify the sources
- need 1,000 events versus 100 now in a few years
- discovery instrument → astronomical telescope

absorption length of Cherenkov light

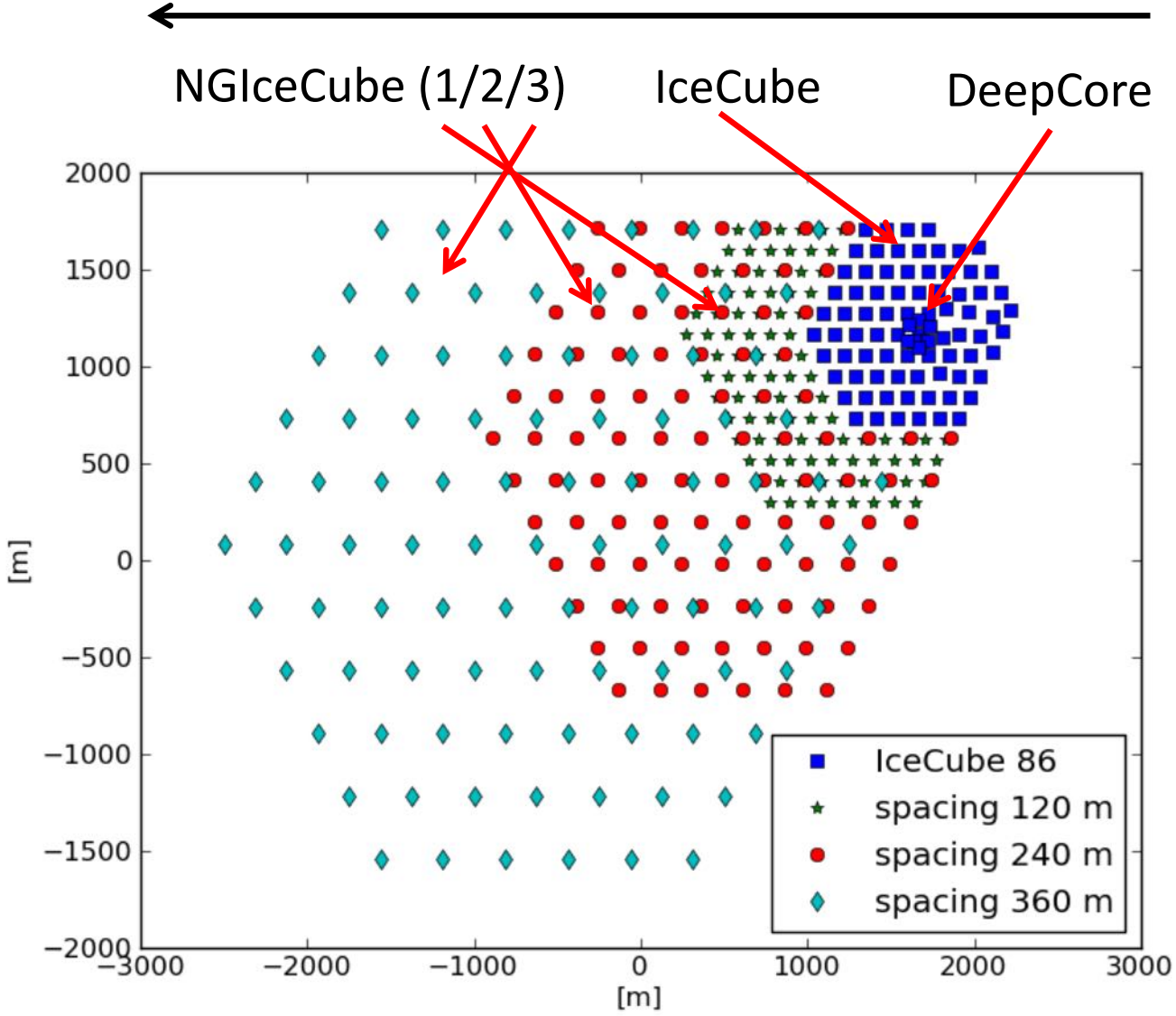


we are limited by computing, not the optics of the ice



measured optical properties → twice the string spacing

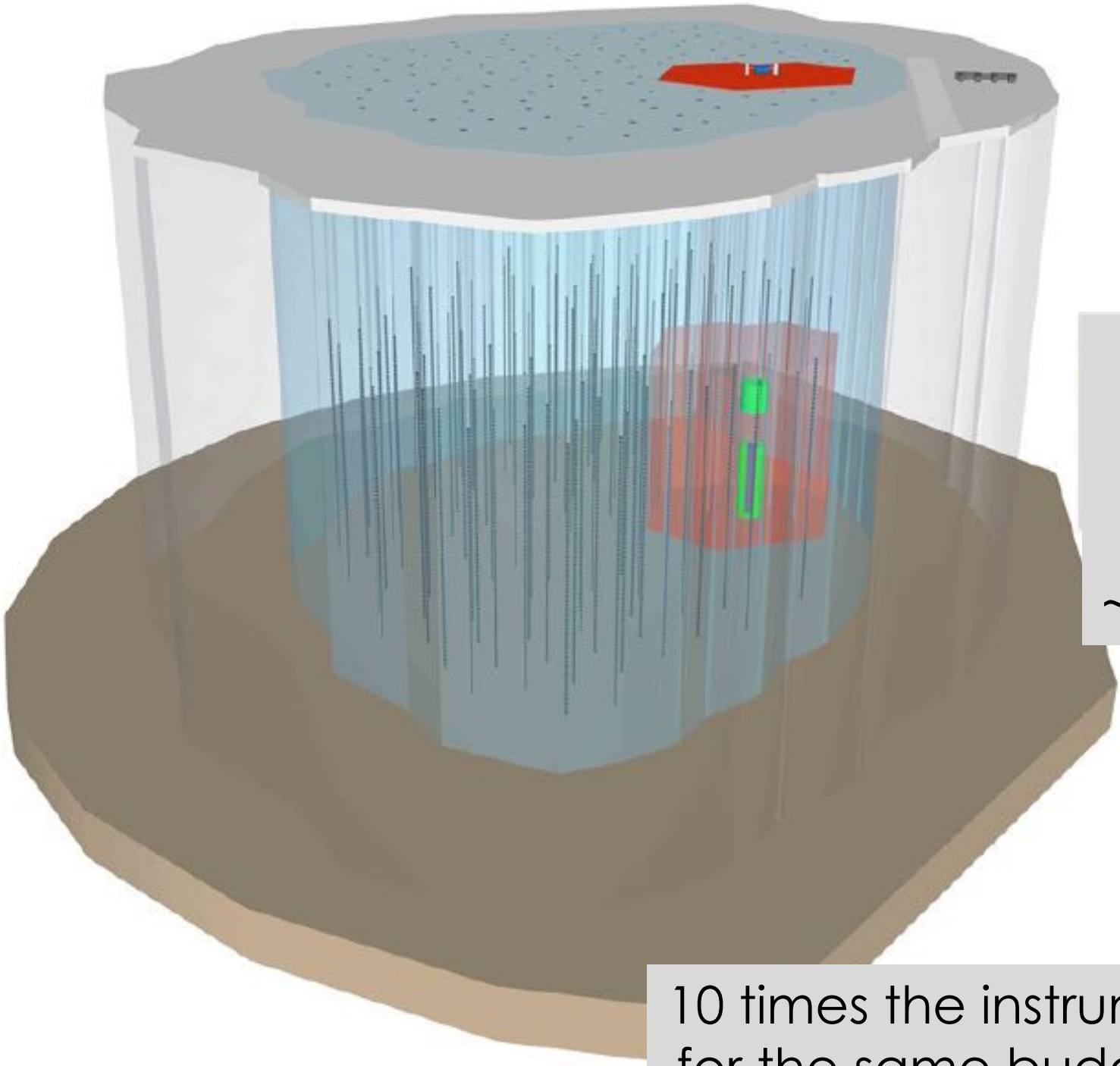
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

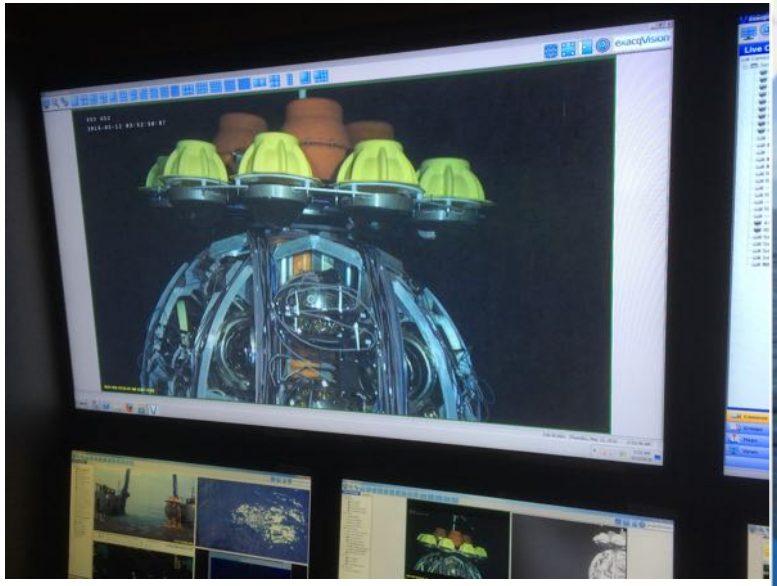
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

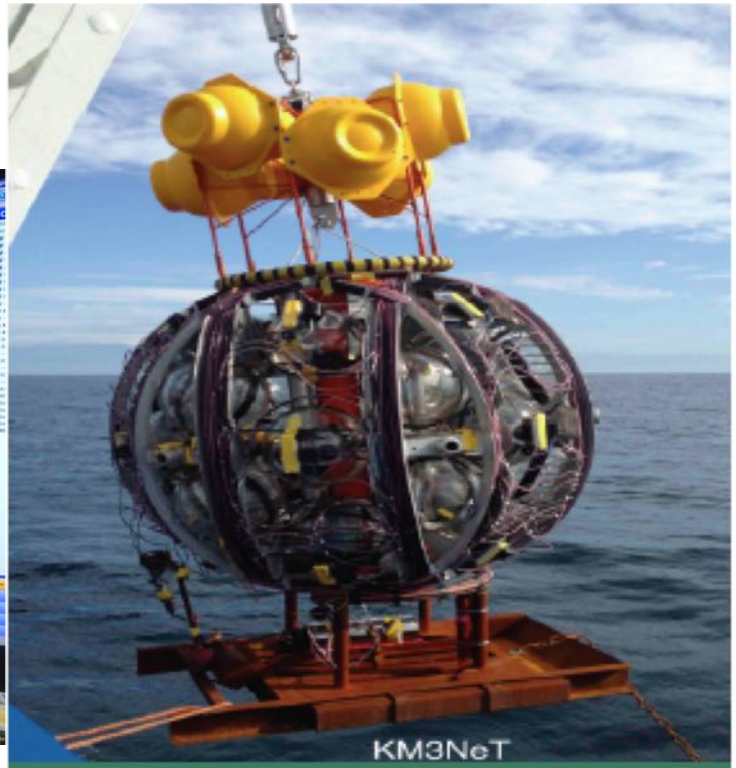
Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3



120 strings
depth 1.35 to
2.7 km
80 DOM/string
~250 m spacing

10 times the instrumented volume
for the same budget as IceCube

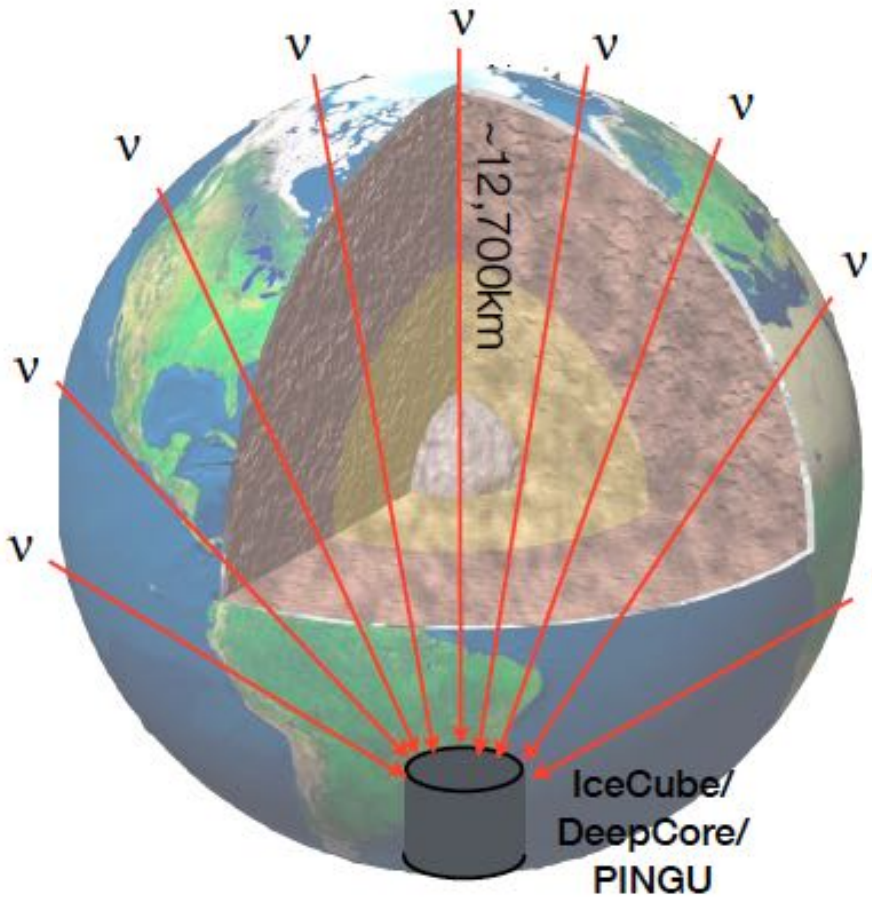


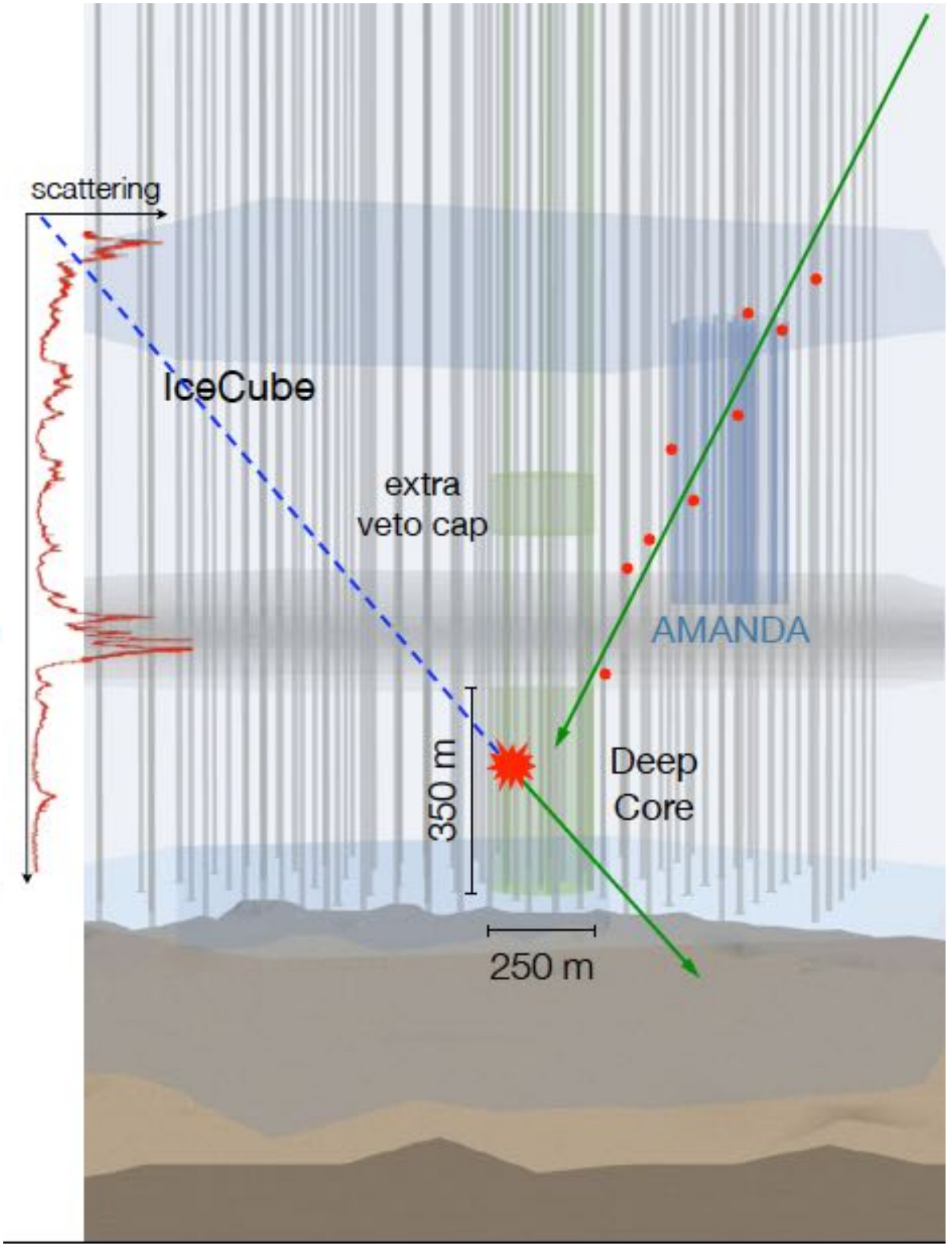


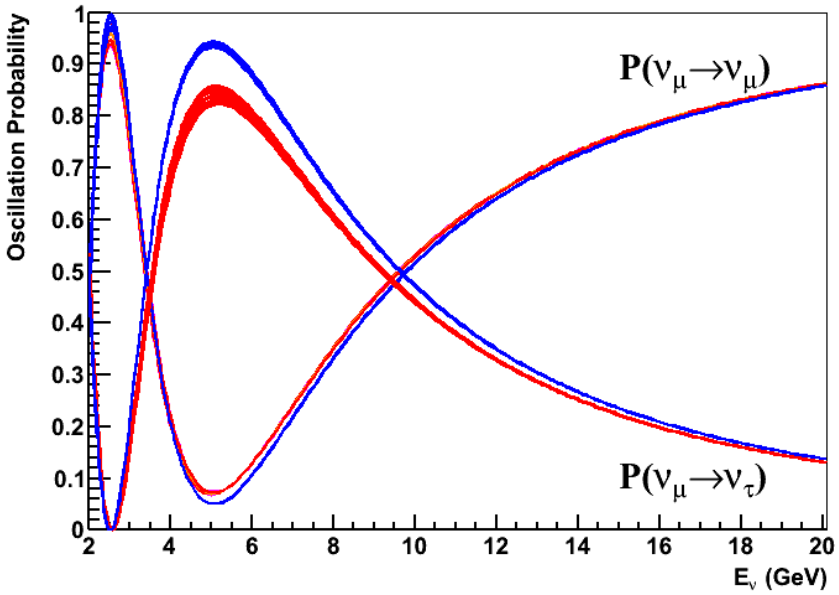
rapid deployment
autonomous unfurling
recoverable

KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf

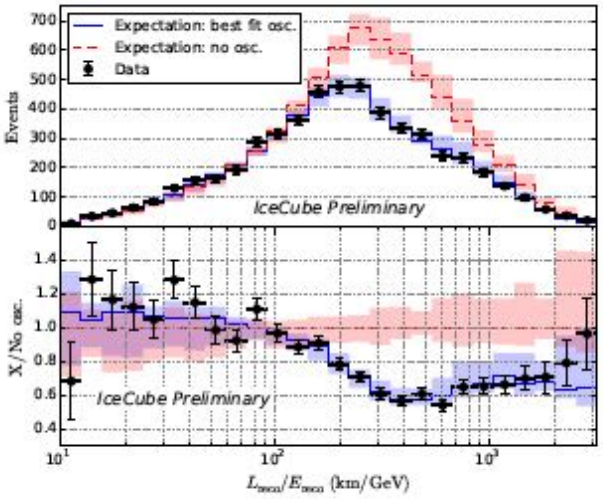
one half million atmospheric neutrinos…

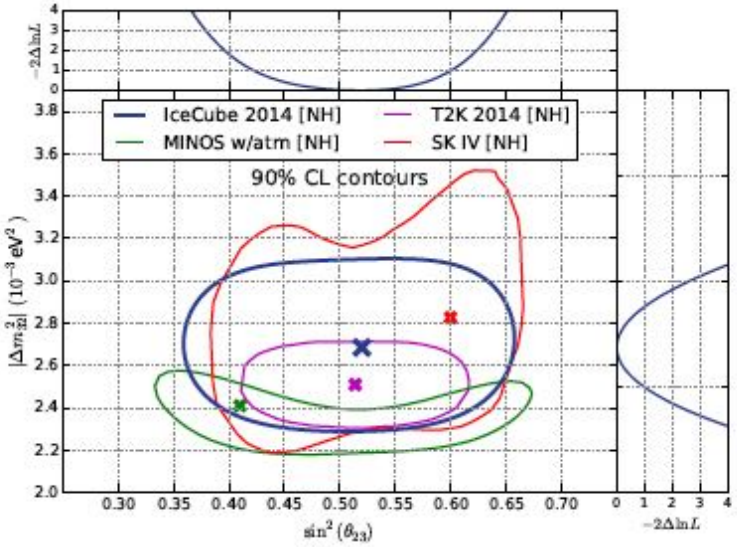






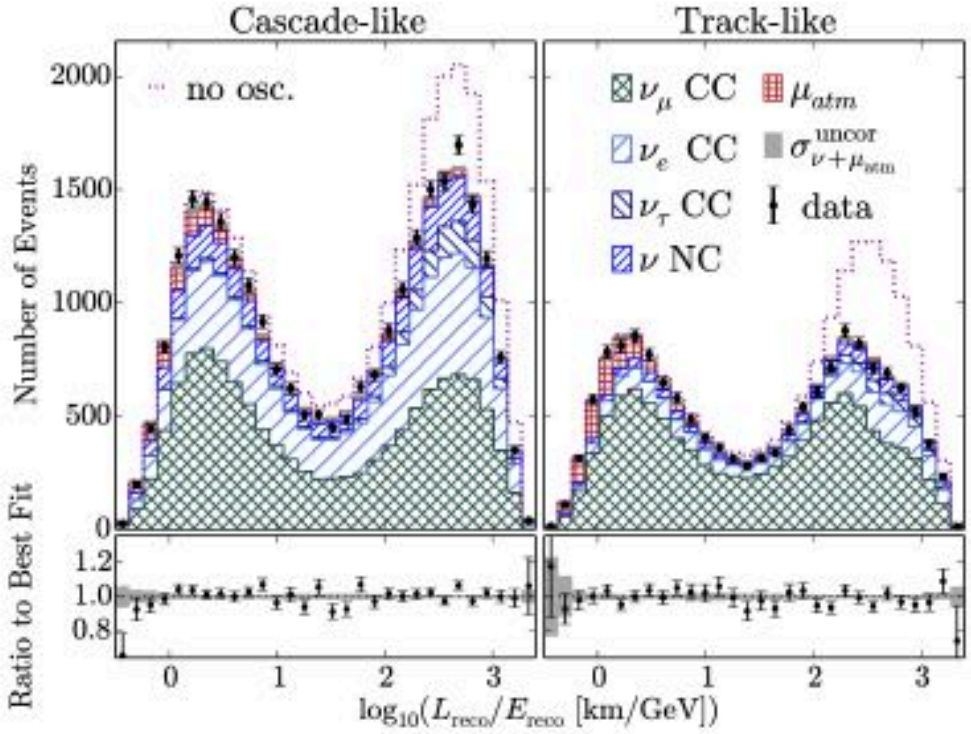
oscillations at 20 GeV



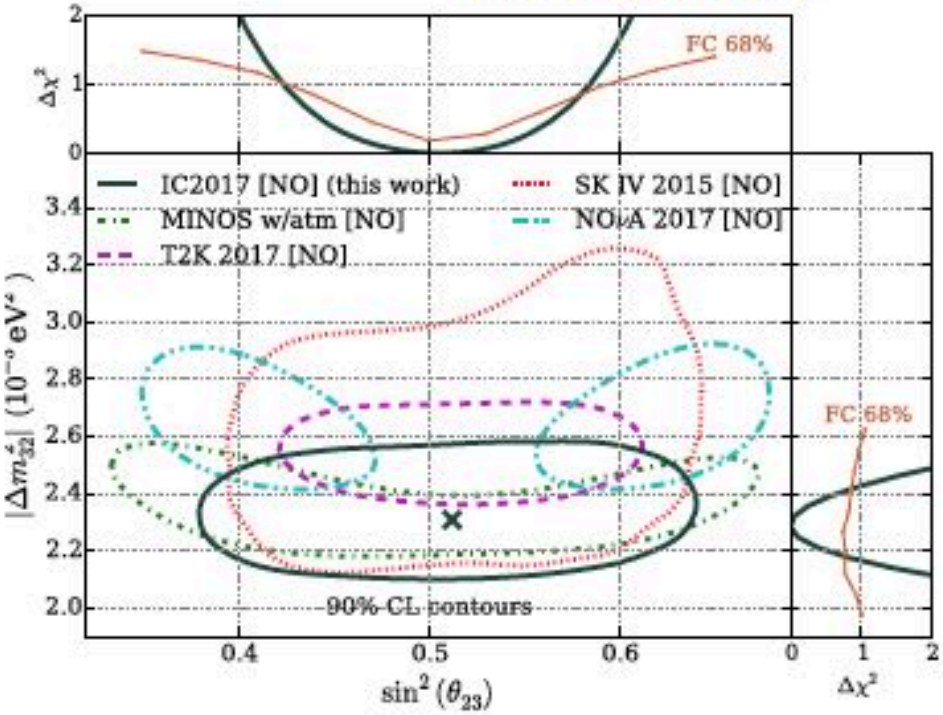


DeepCore: mapping the first oscillation dip at 10X higher energy
new physics?

Neutrino Oscillation



IceCube, PRL 2018

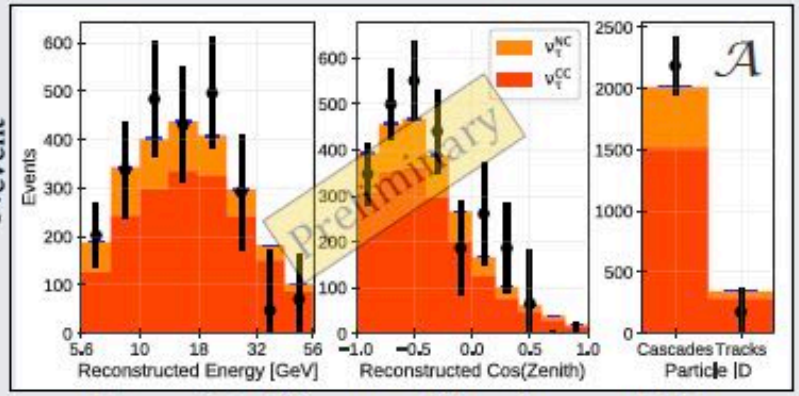


- 3 years of IceCube Deep Core data
- measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

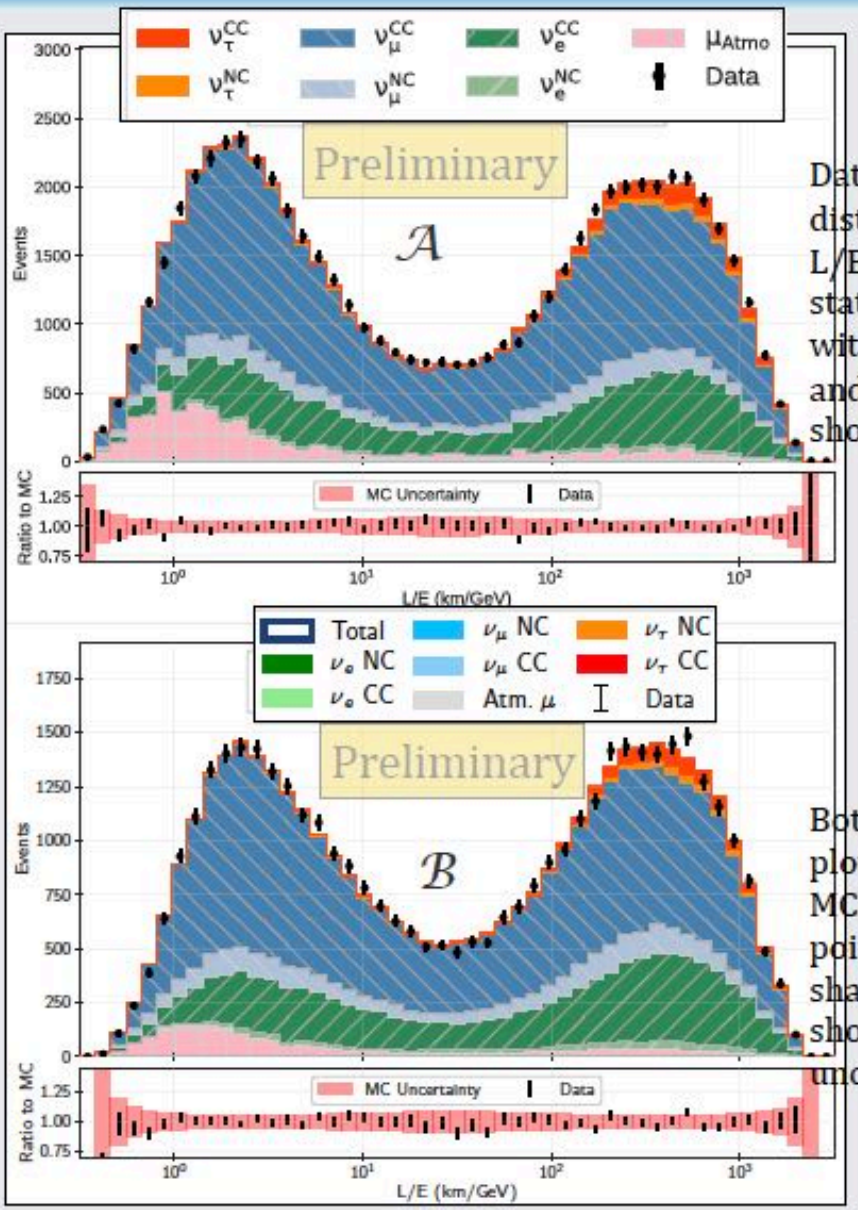
$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\text{eV}^2$$

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

Data distributions with best-fit $\nu_e+\nu_\mu$ and μ backgrounds subtracted (points with stat. error bars), overlaid with best fit ν_τ hypotheses.



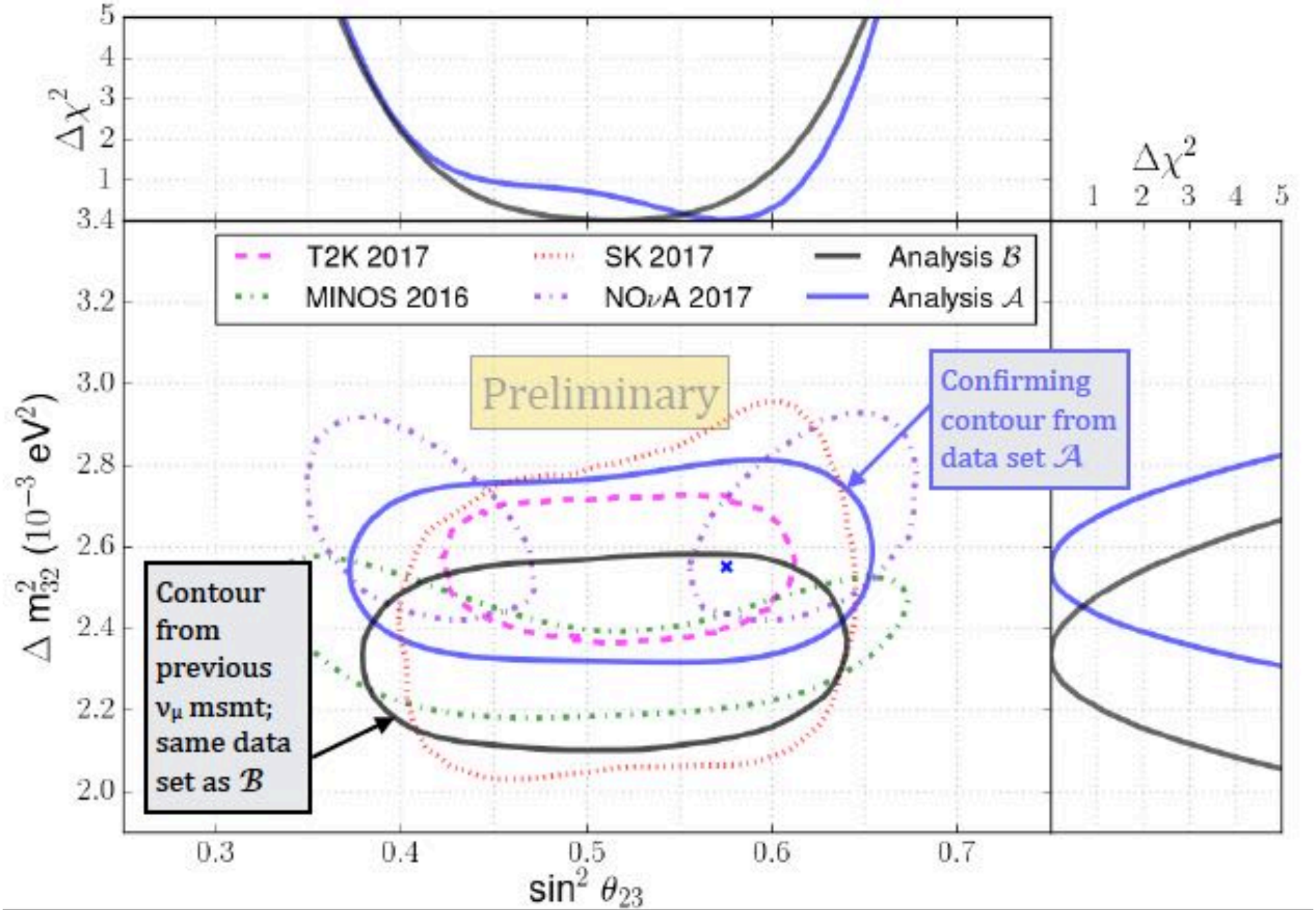
E_{reco} (GeV) $\cos(\theta_{zen})_{reco}$ PID_{reco}



$(L/E)_{reco}$ (km/GeV)

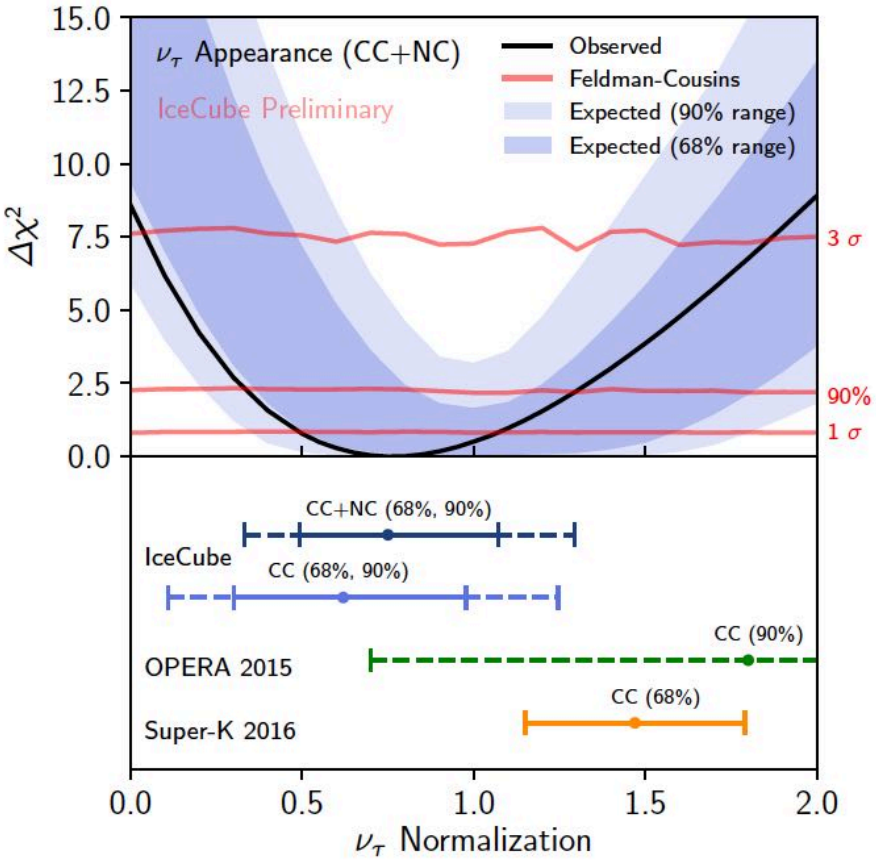
Data distributions vs. L/E (points with stat. error bars), with best-fit ν and μ bkgds. shown (hists.).

Bottom of each plot shows data/MC at best fit point, with shaded region showing stat. unc. of best fit.


$\Delta\chi^2$
$\Delta\chi^2$
T2K 2017
MINOS 2016
SK 2017
NOνA 2017
Analysis $\mathcal{B}$
Analysis $\mathcal{A}$
Preliminary
Confirming contour from data set $\mathcal{A}$
Contour from previous ν_μ msmt; same data set as $\mathcal{B}$
$\Delta\, m^2_{32}$ (10^{-3} eV^2)
$\sin^2\theta_{23}$

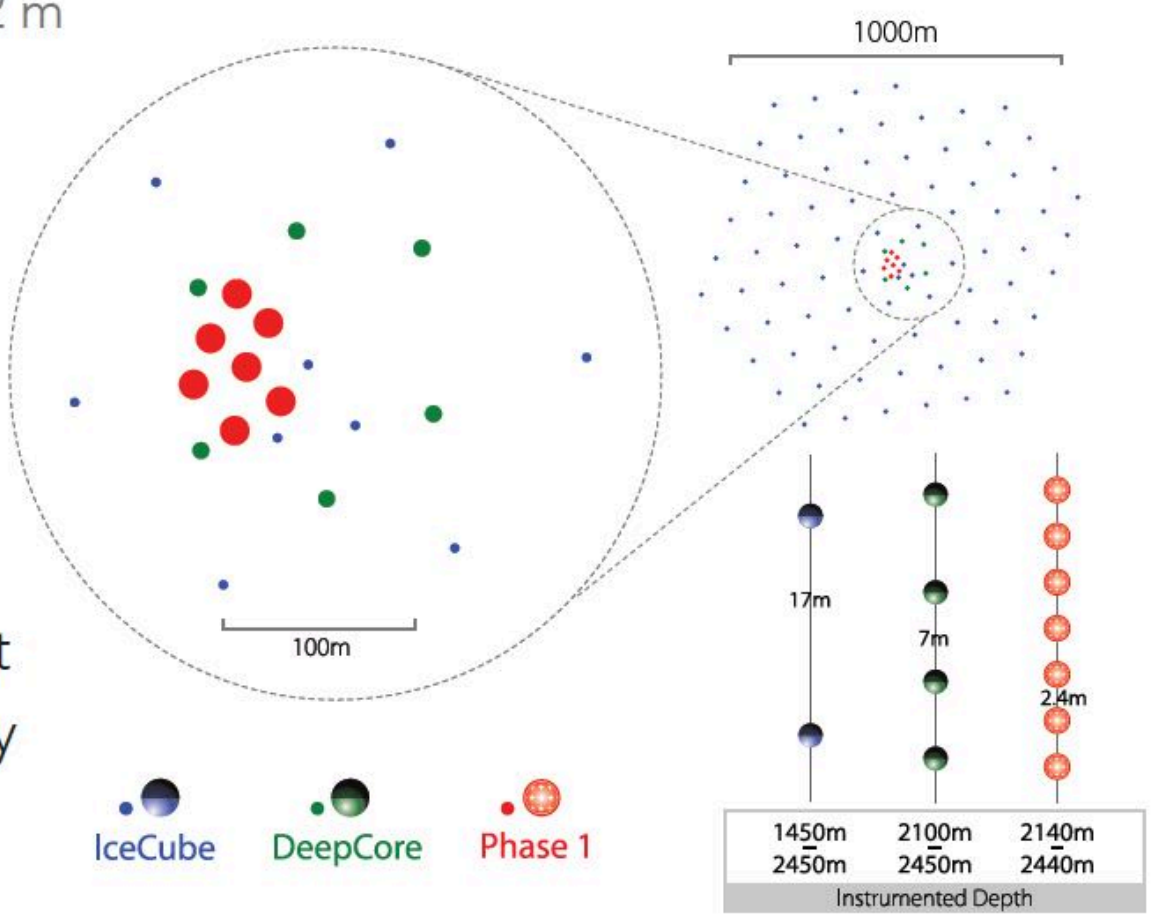
Tau Appearance and PMNS Unitarity

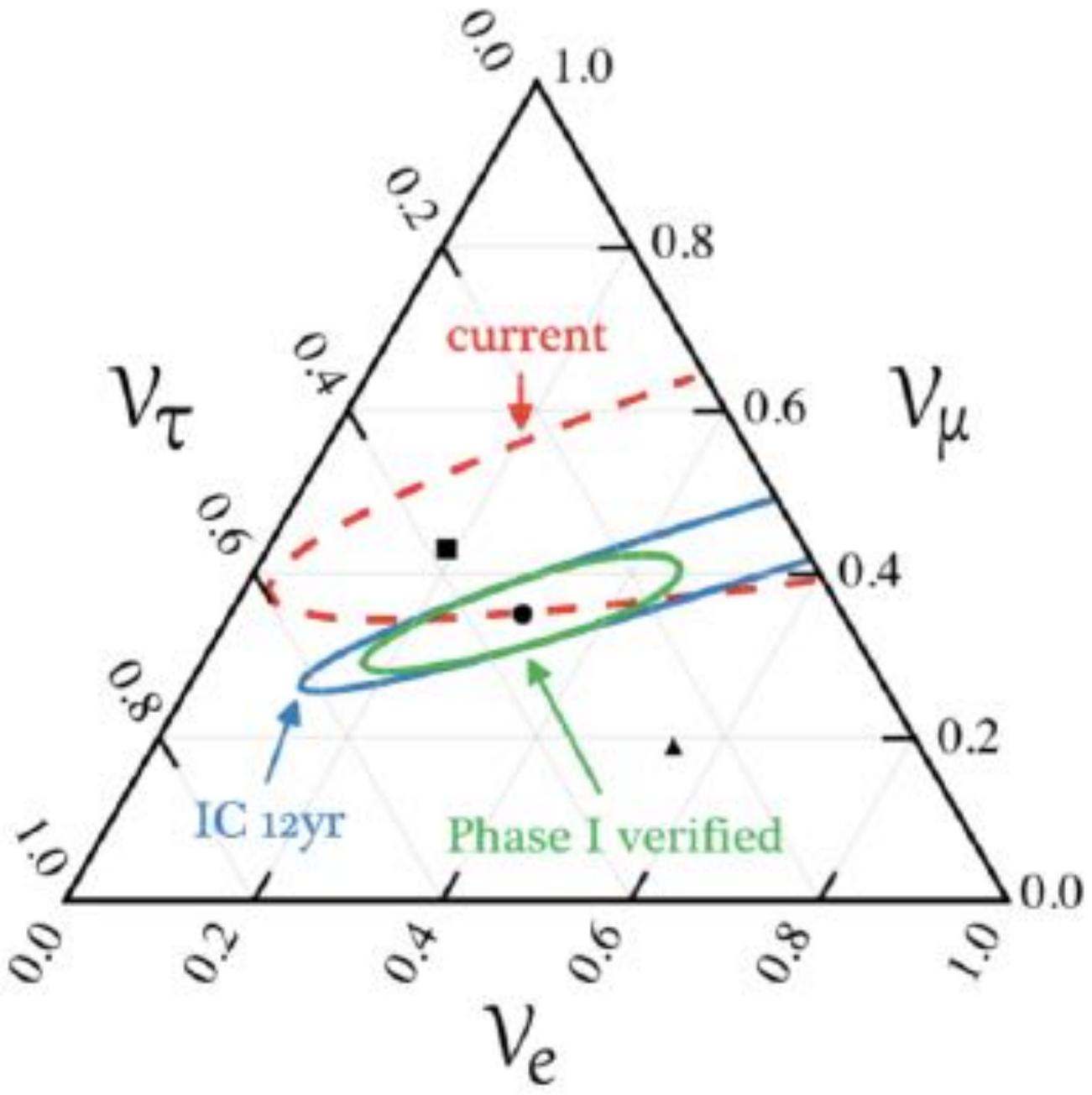
- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix



Next Step: the IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy

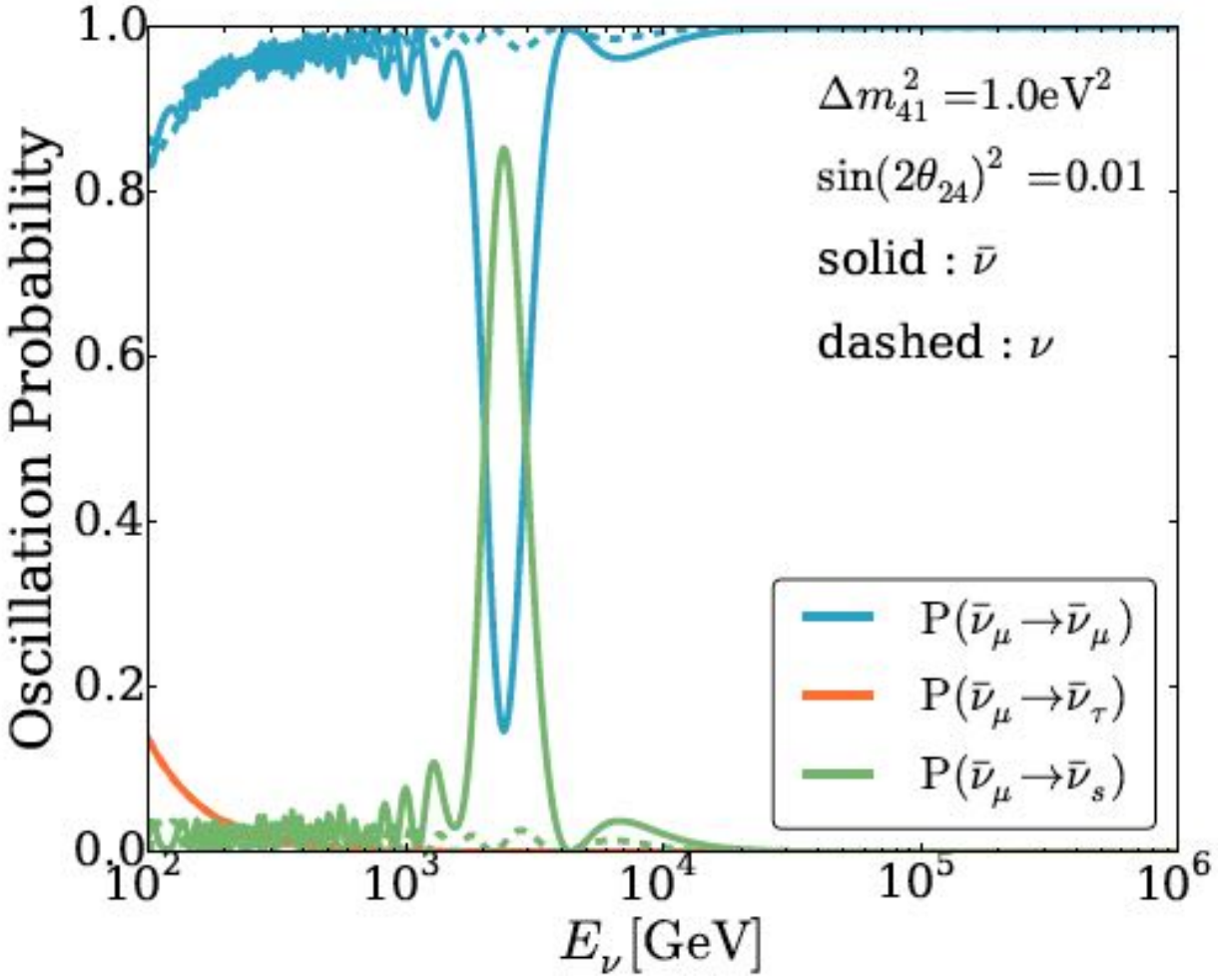


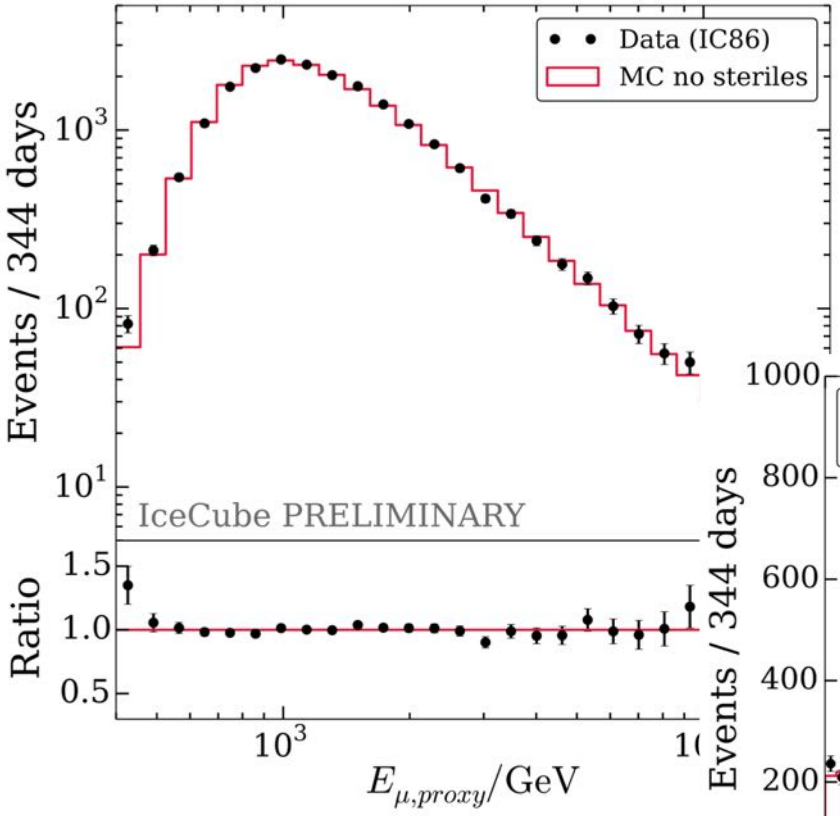

ν_τ
ν_μ
ν_e
current
IC 12yr
Phase I verified
0.0
0.2
0.4
0.6
0.8
1.0

eV sterile neutrino → Earth MSW resonance for TeV neutrinos

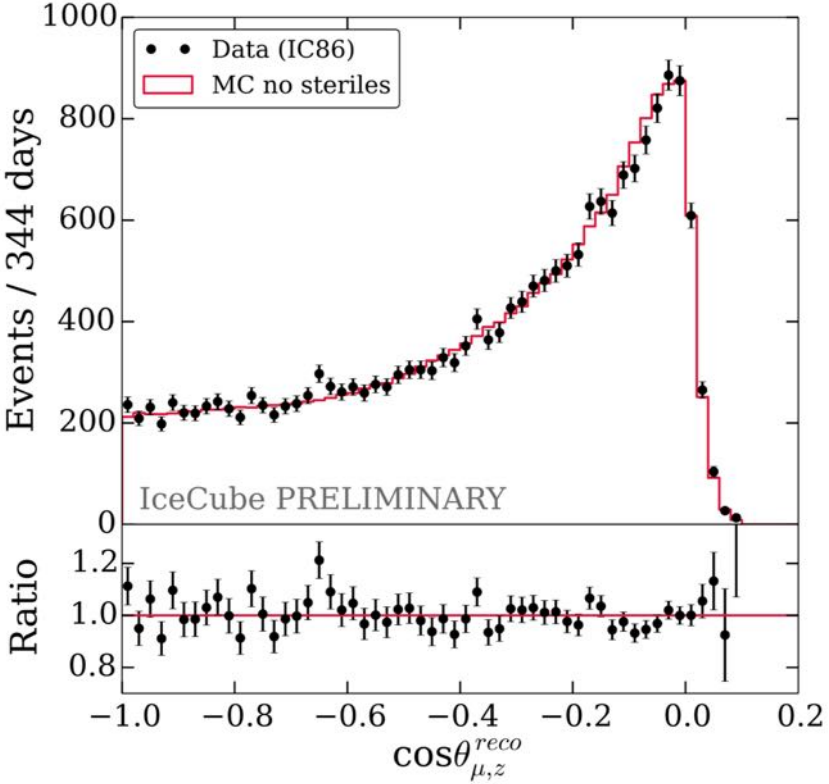
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

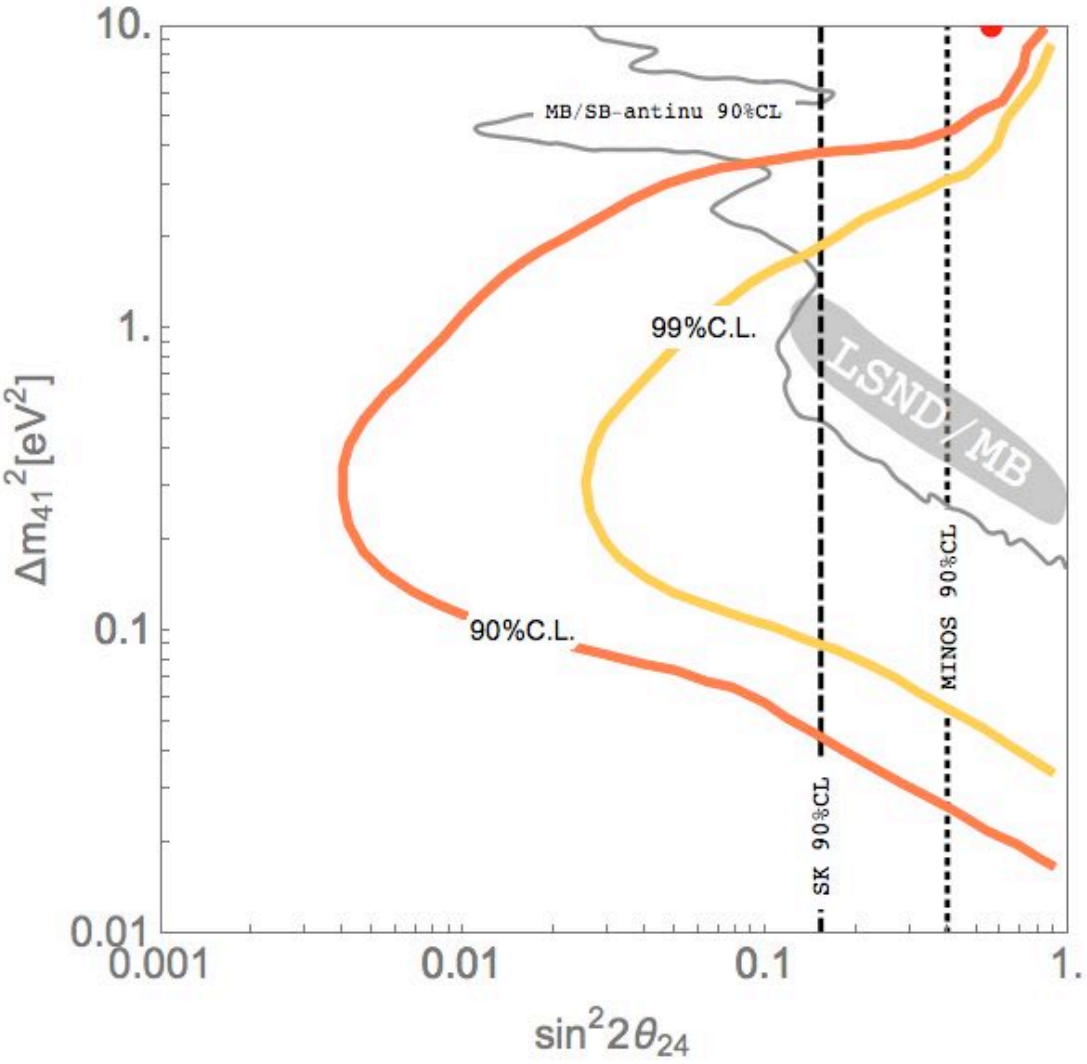
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$





no telltale structure in the zenith angle distribution

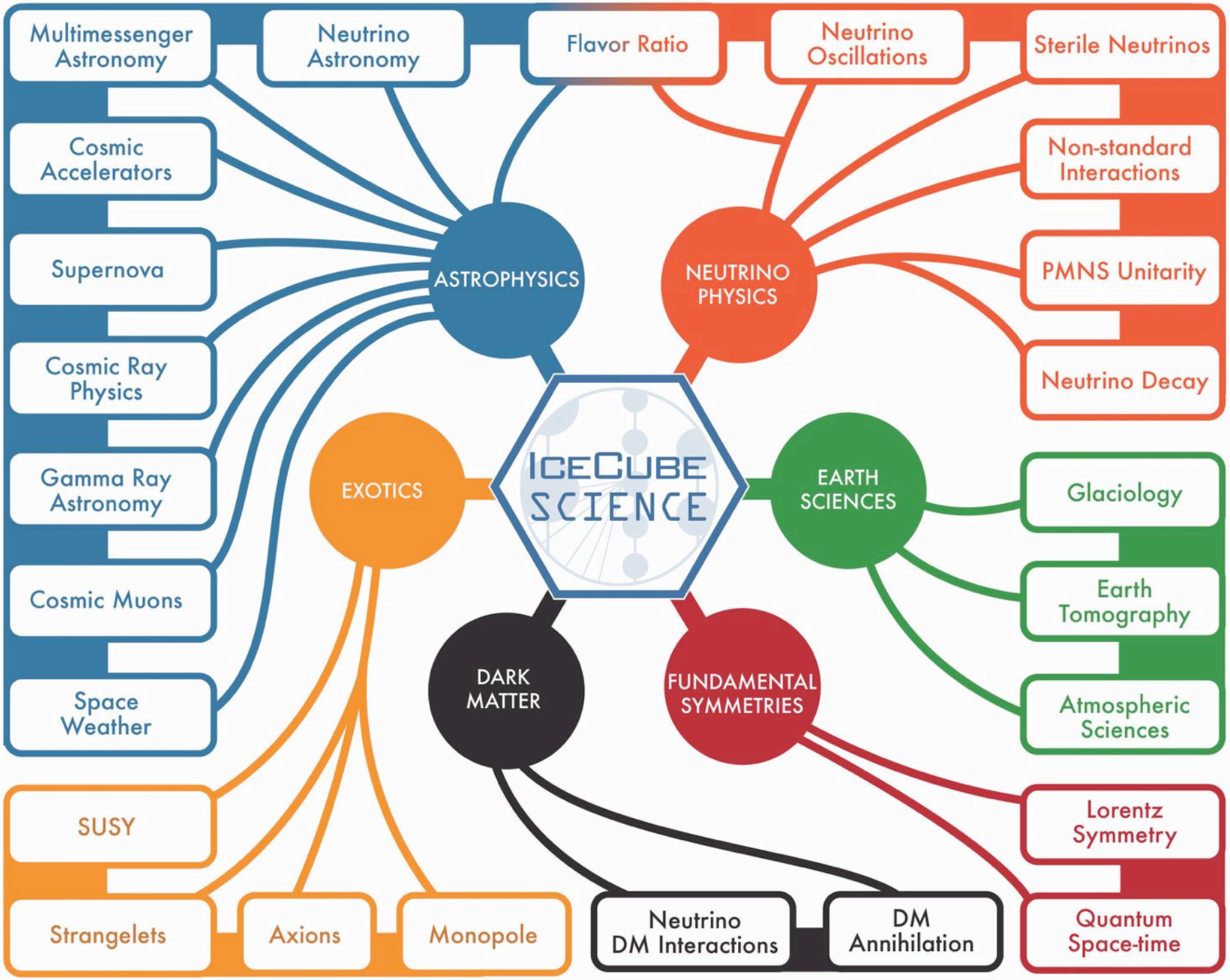




from 1 → 7 years of data soon

did not talk about:

- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- cosmic ray physics, muon maps,…
- PINGU/ORCA
- ….


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

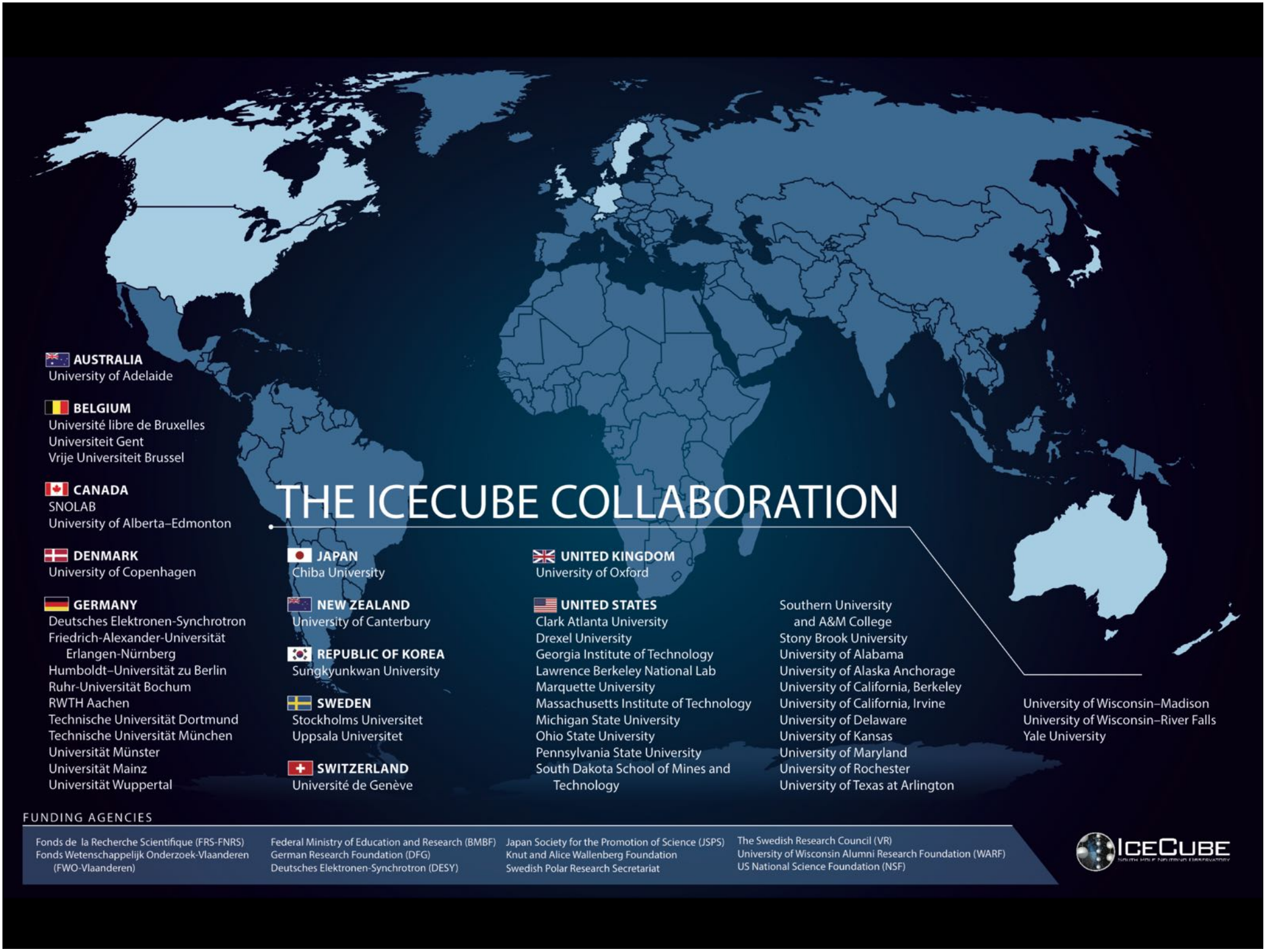
THE ICECUBE COLLABORATION

ISTRALIA 1

NGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory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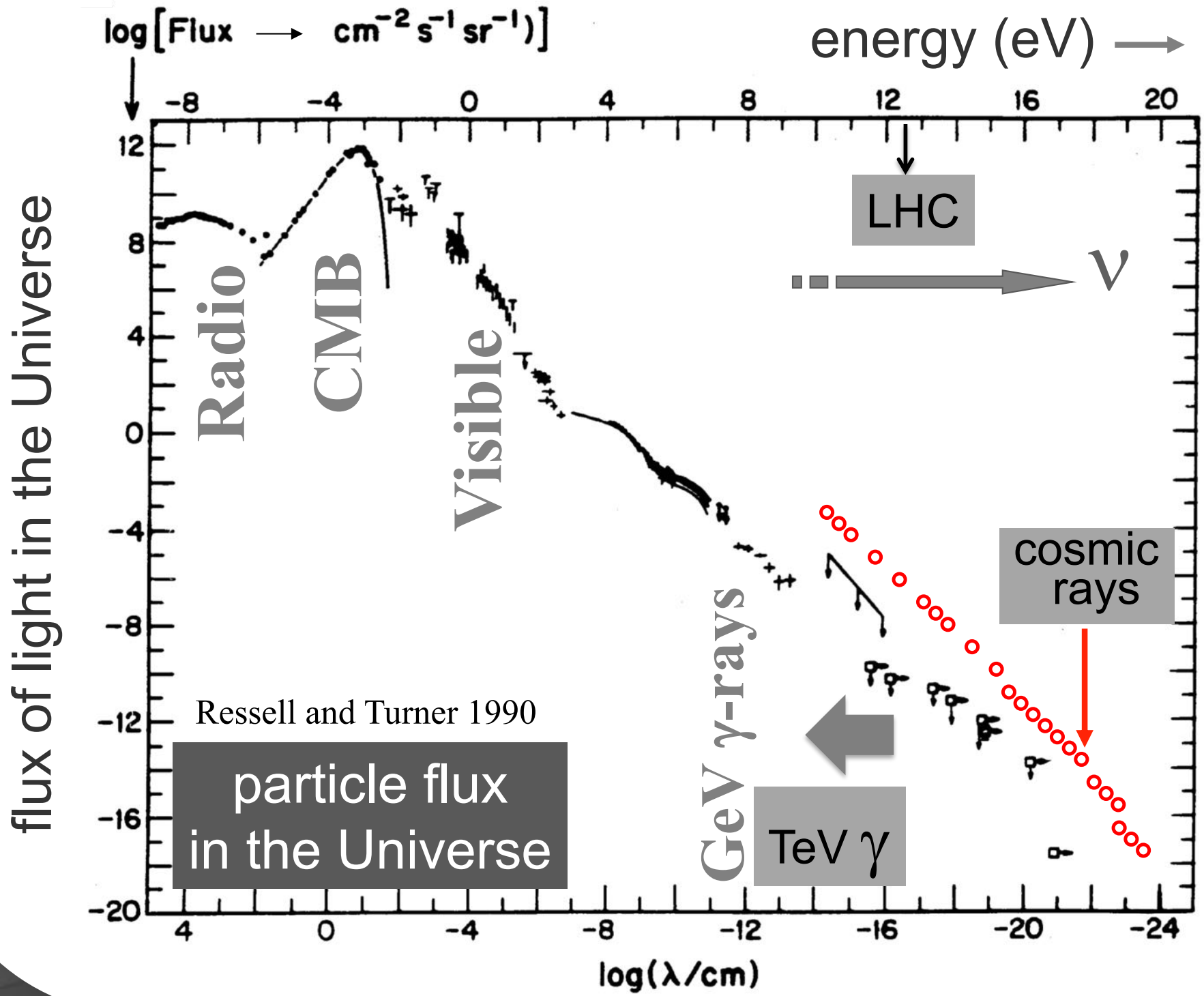
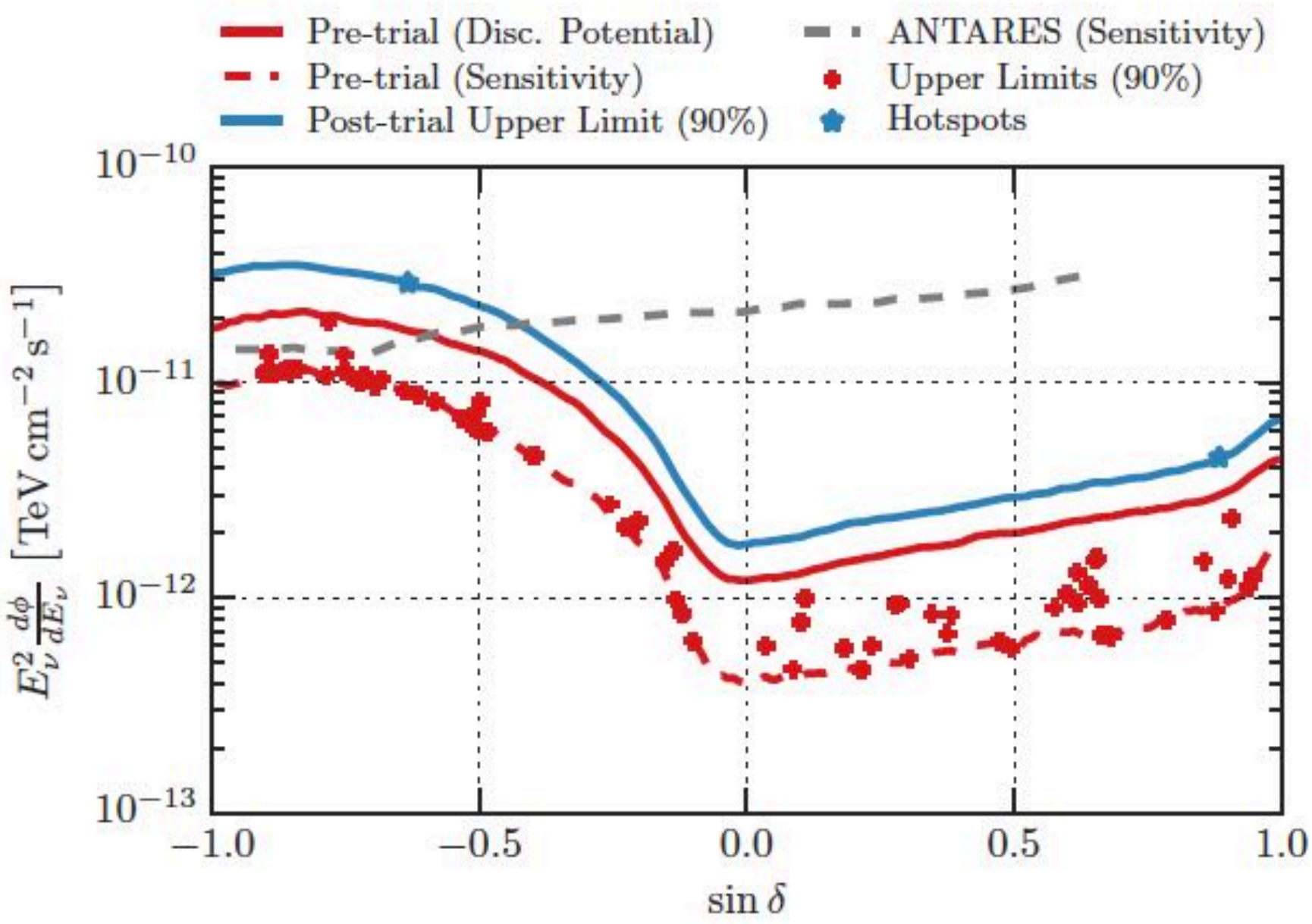
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University
FUNDING AGENCIES
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
IceCube

overflow slides


log[Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux of light in the Universe
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
LHC
ν
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe



when resolved point sources?

Olbers paradox

$$\phi_{\rm diff} = \int d^3 r \frac{L_\nu}{4\pi r^2} \cdot \rho$$

diffuse flux is measured

nearest source

$$\frac{4}{3}\pi d_{ns}^3 \cdot \rho = 1 \qquad \text{and} \qquad d_{\rm ns} \sim \rho^{-1/3}$$

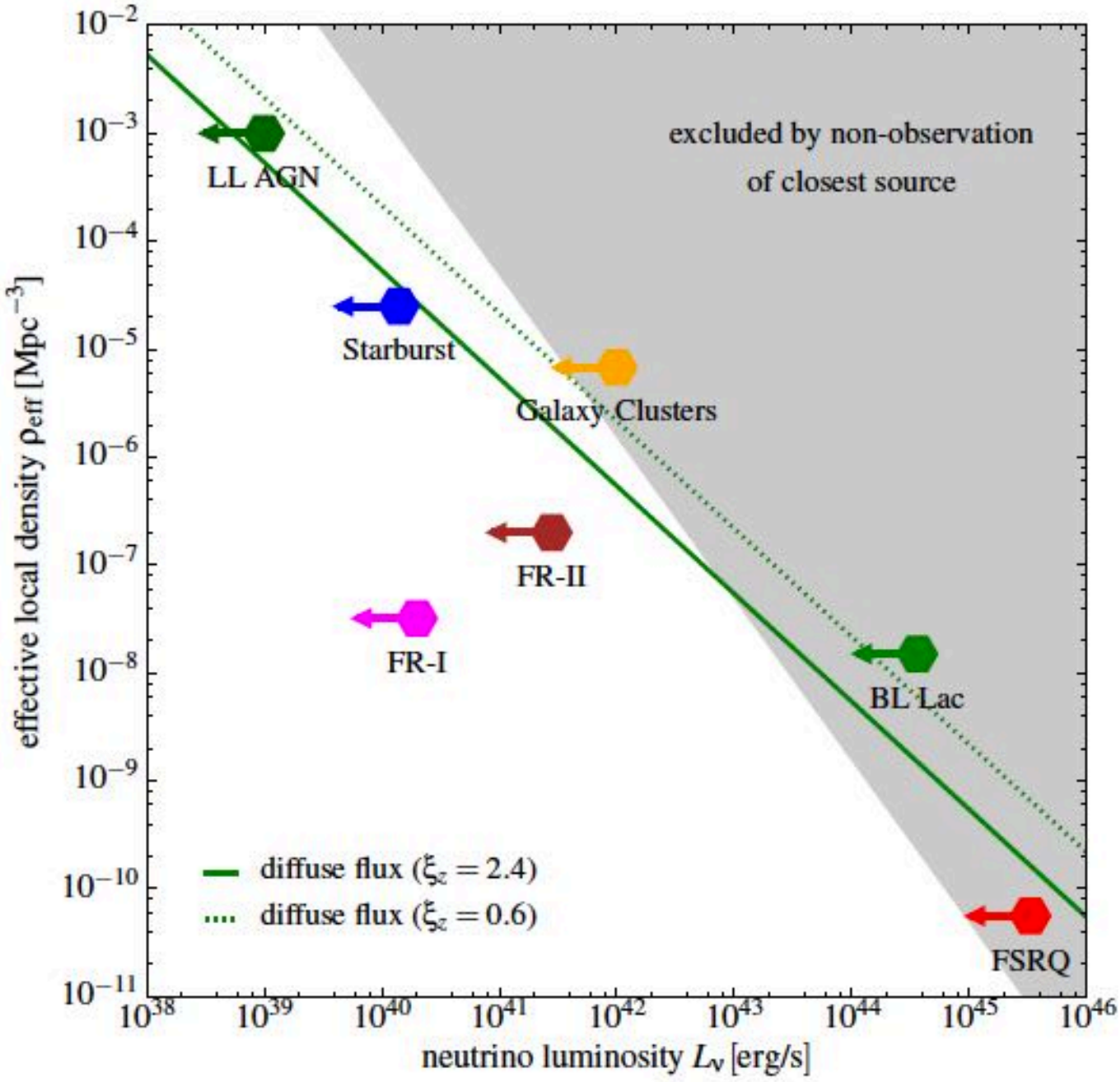
$$\phi_{\rm ns} = \frac{L_\nu}{4\pi d_{\rm ns}^2} \sim (L_\nu \cdot \rho) d_{\rm ns} \sim \phi_{\rm diff} \cdot \rho^{-1/3}$$

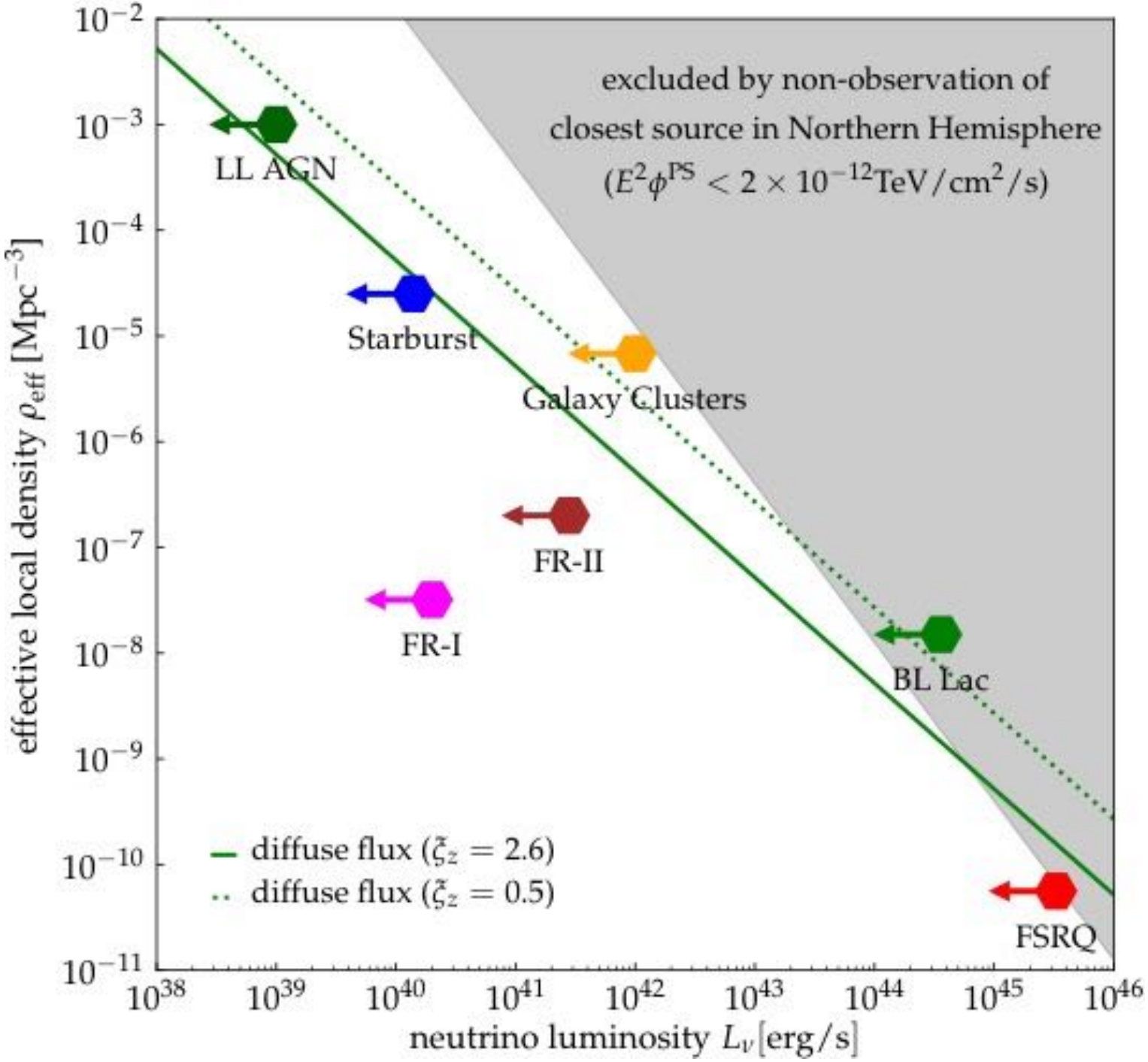
flux nearest source = (diffuse flux observed)(density of sources)$^{-1/3}$

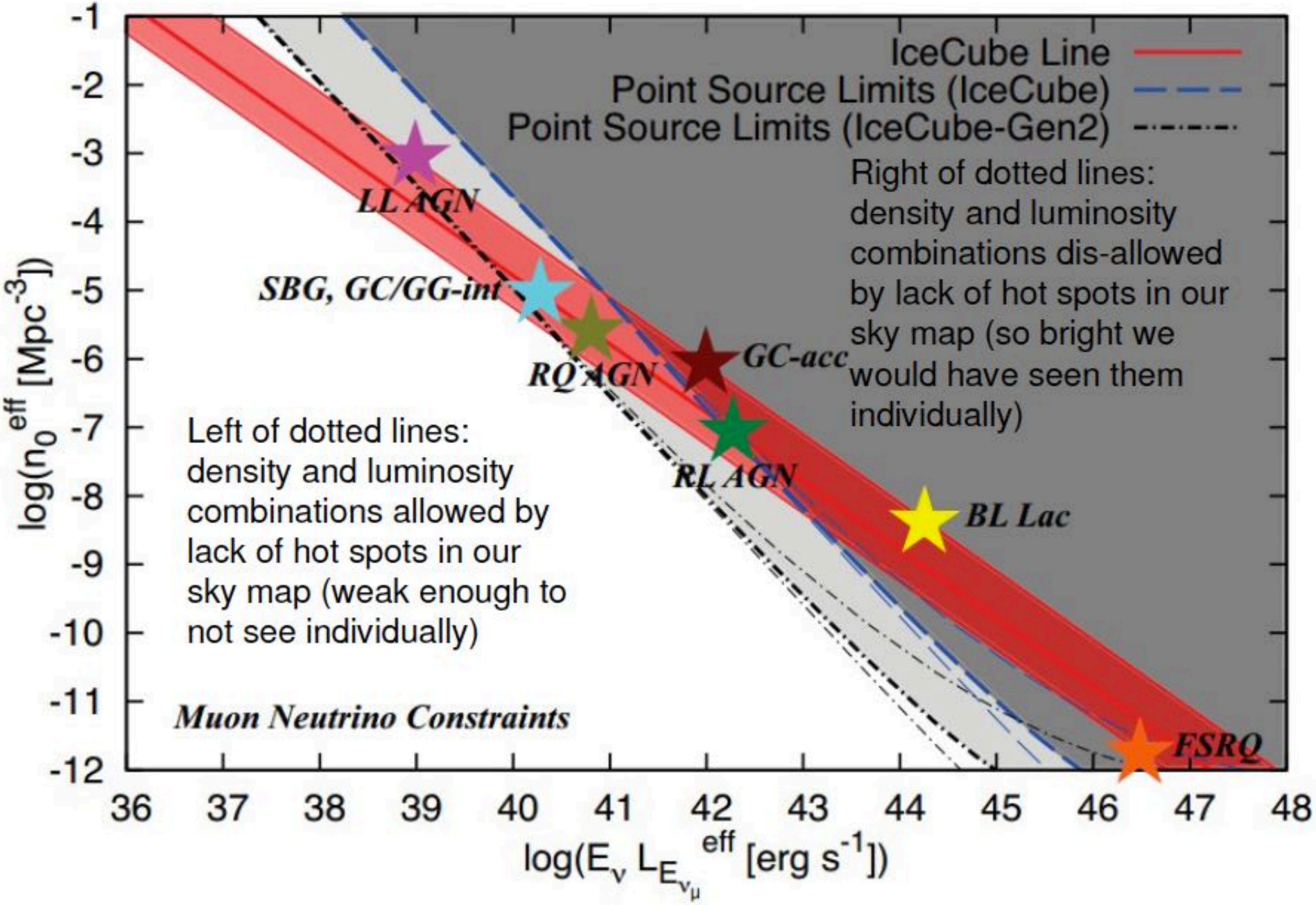
Olbers paradox

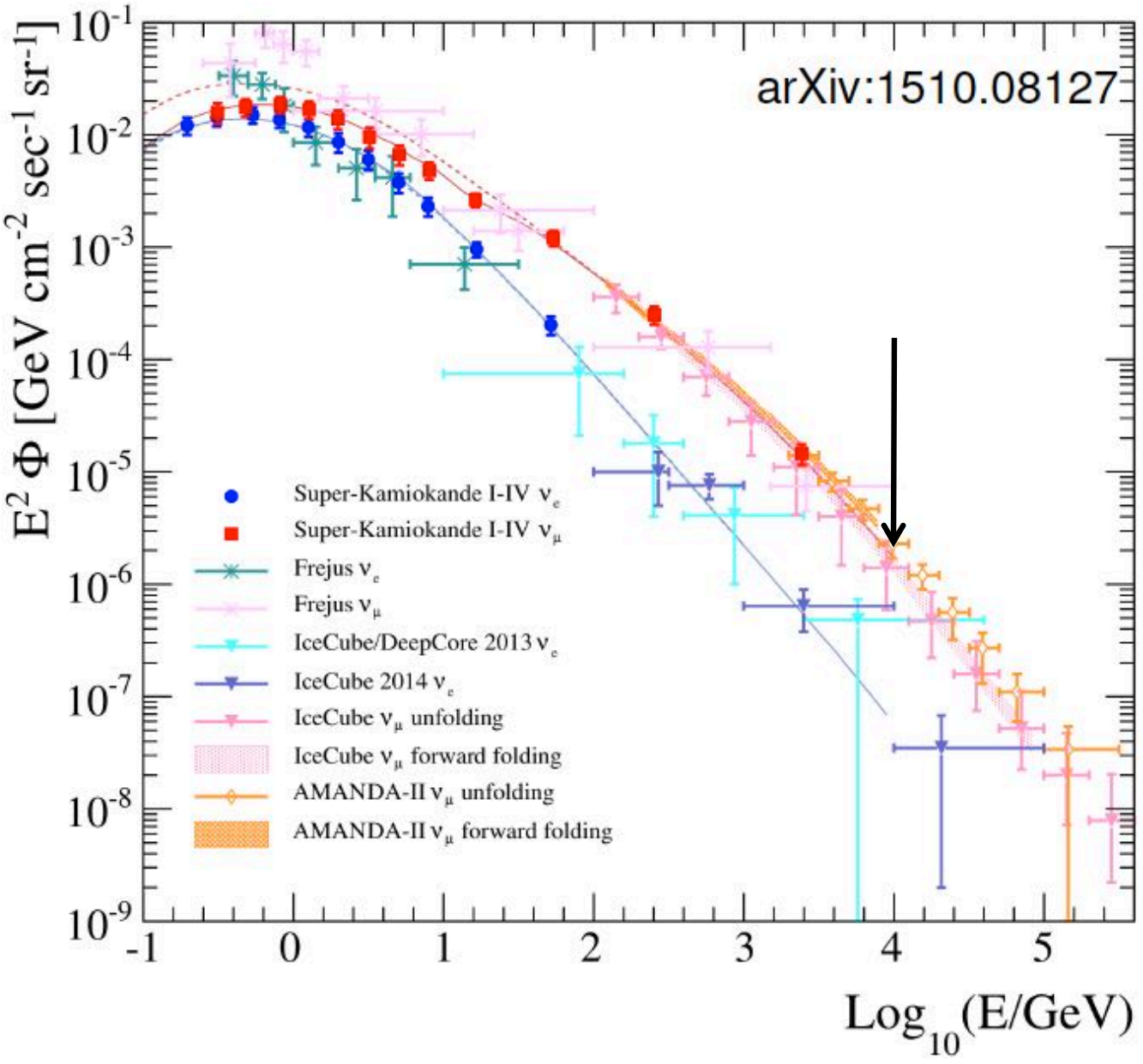
density 10^{-7} Mpc^{-3} soon !

blazars, FSRQ…




excluded by non-observation of
closest source in Northern Hemisphere
($E^2\phi^{PS} < 2 \times 10^{-12}$TeV/cm^2/s)
LL AGN
Starburst
Galaxy Clusters
FR-II
FR-I
BL Lac
FSRQ
diffuse flux ($\xi_z = 2.6$)
diffuse flux ($\xi_z = 0.5$)
effective local density $\rho_{\rm eff}$ [Mpc^{-3}]
neutrino luminosity L_ν[erg/s]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{38}
10^{39}
10^{40}
10^{41}
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}

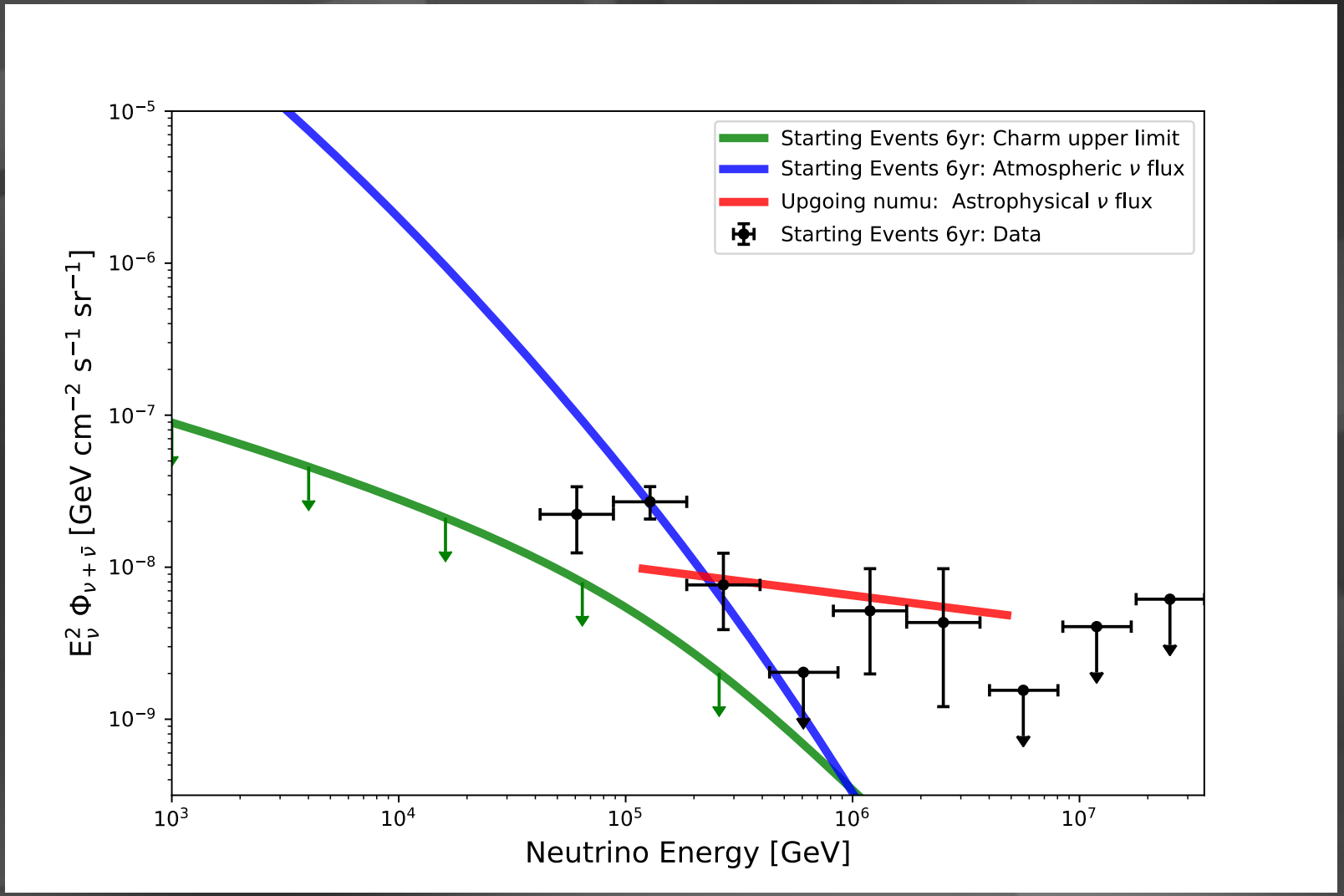

IceCube Line
Point Source Limits (IceCube)
Point Source Limits (IceCube-Gen2)
Right of dotted lines: density and luminosity combinations dis-allowed by lack of hot spots in our sky map (so bright we would have seen them individually)
Left of dotted lines: density and luminosity combinations allowed by lack of hot spots in our sky map (weak enough to not see individually)
LL AGN
SBG, GC/GG-int
RQ AGN
GC-acc
RL AGN
BL Lac
FSRQ
Muon Neutrino Constraints
log(n0 eff [Mpc-3])
log(Eν Lν eff [erg s-1])
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
36
37
38
39
40
41
42
43
44
45
46
47
48



atmospheric neutrino spectrum (energy measurement) well understood at 10 TeV in terms of conventional neutrinos; charm contribution is small

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

- tracks cosmic ray flux in energy, isotropic in zenith (normalization unknown): does not fit the data
- neutrino events are isolated
- constrained by atmospheric *electron* neutrino spectrum



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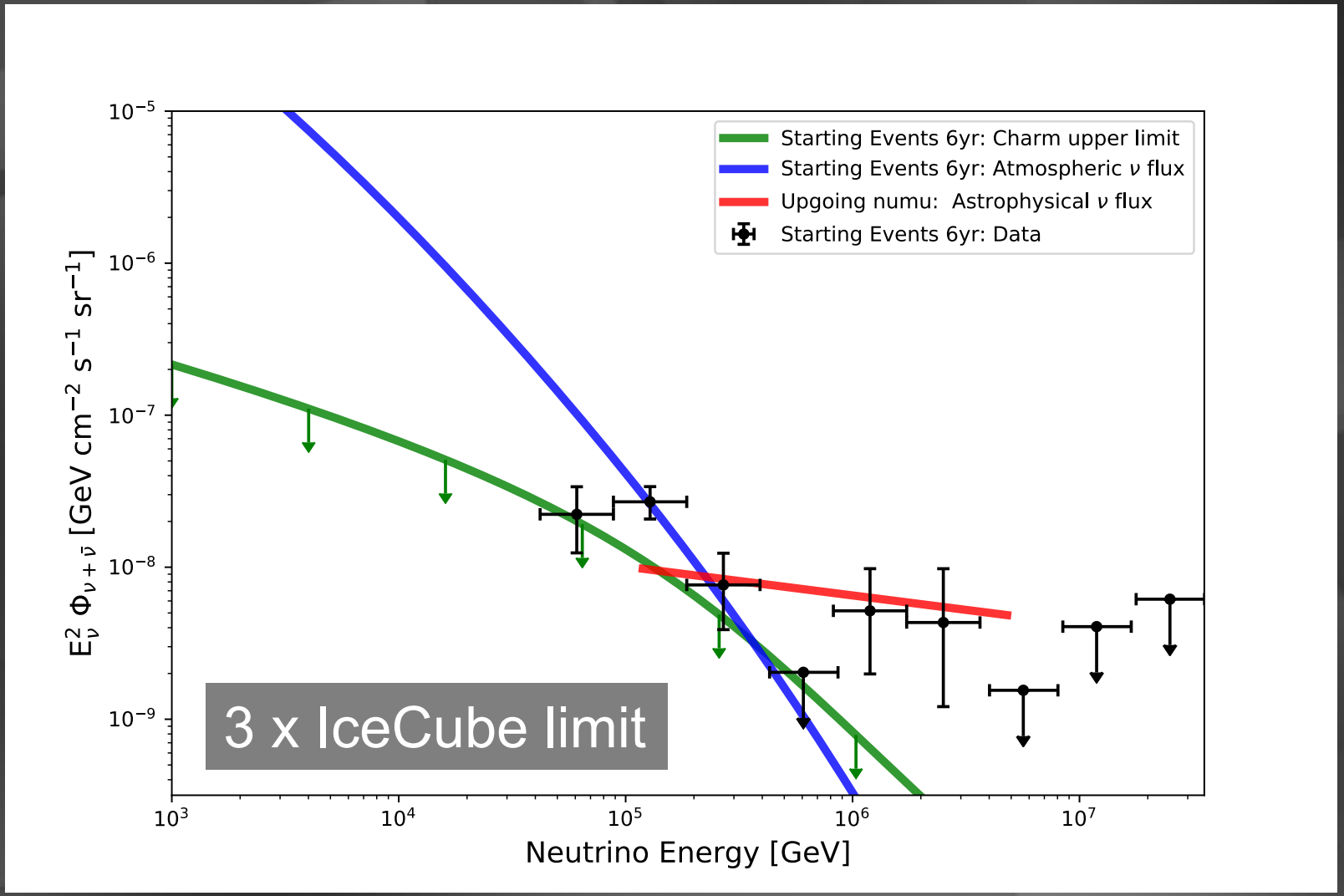
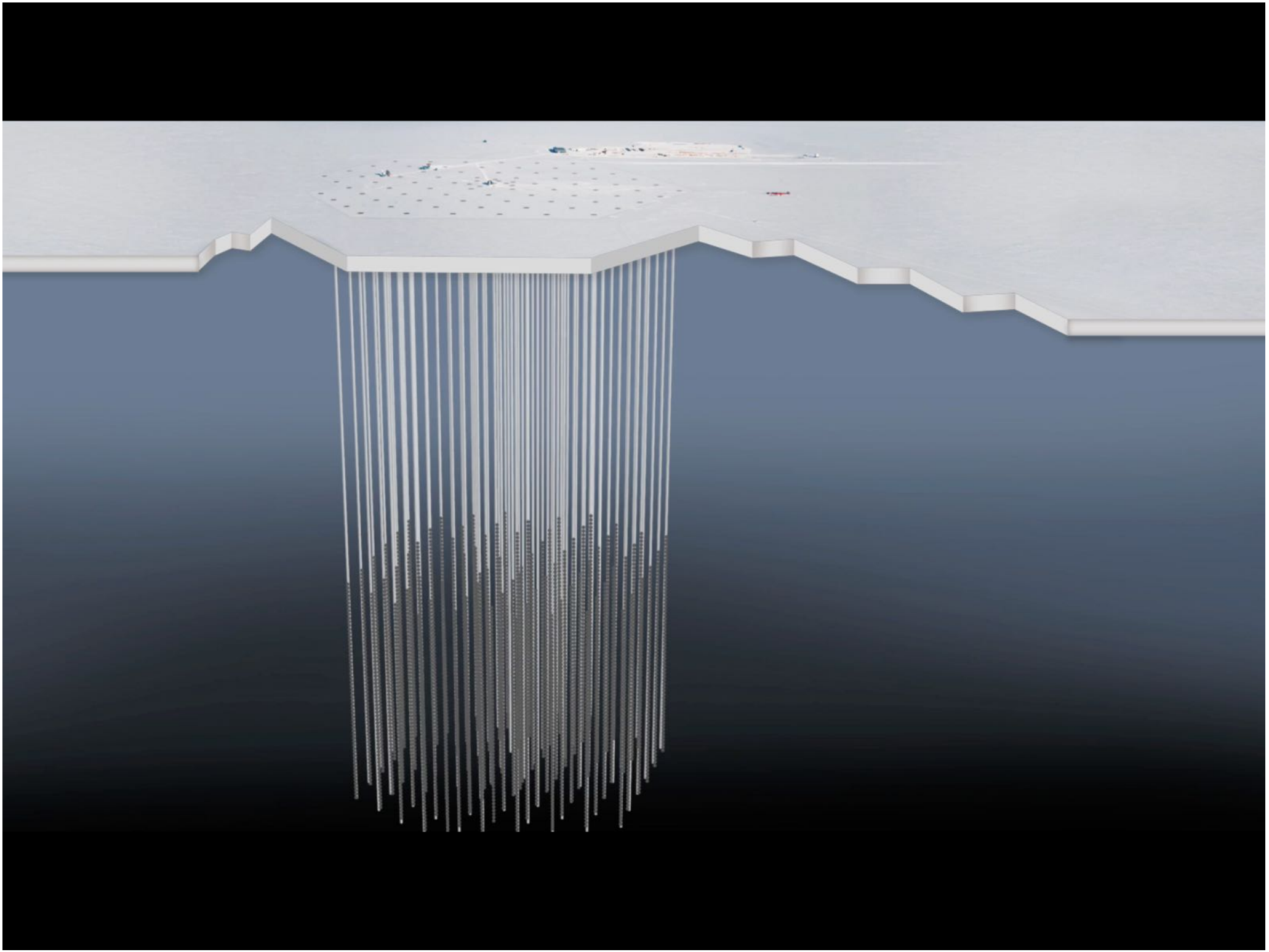
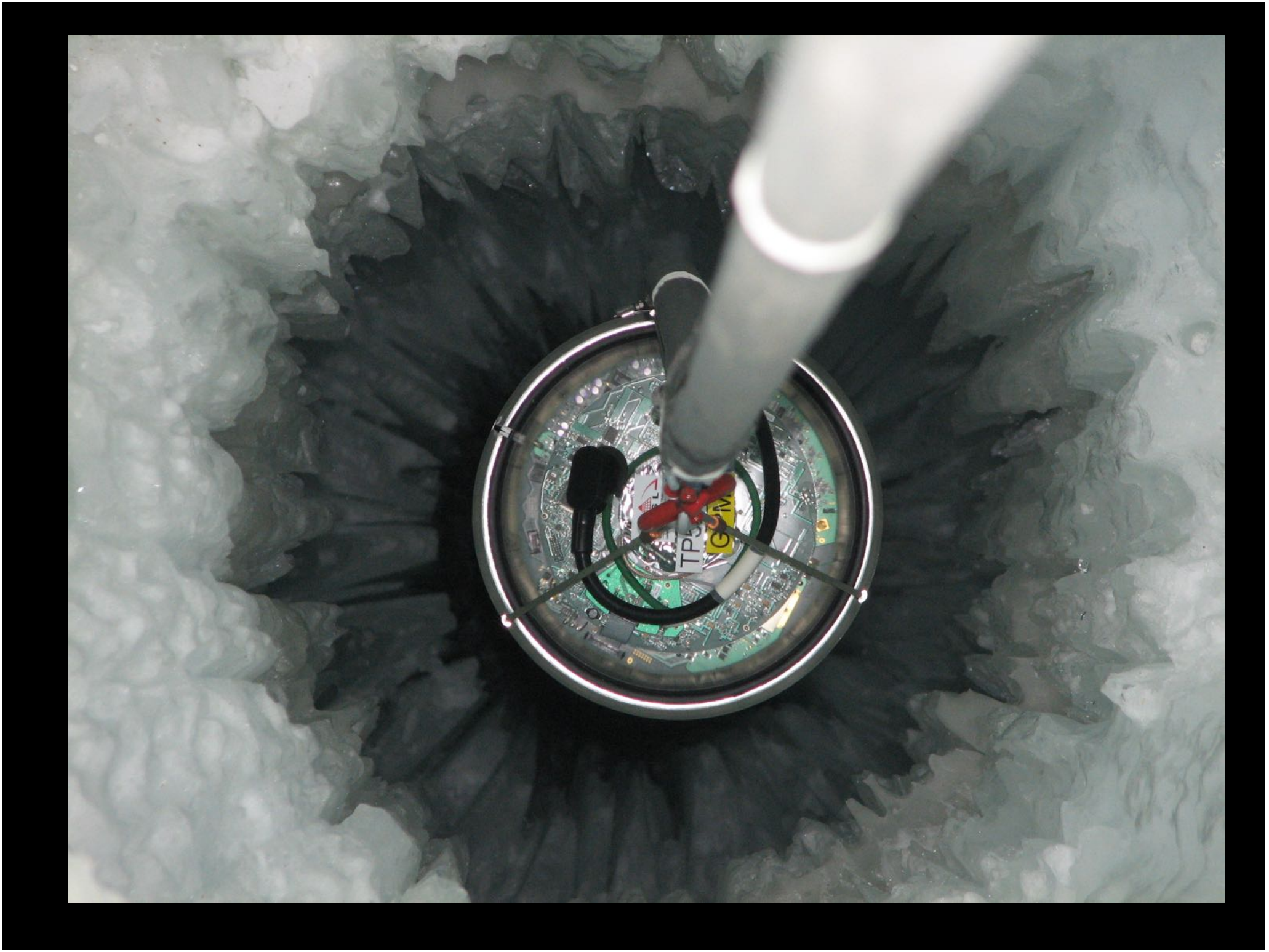
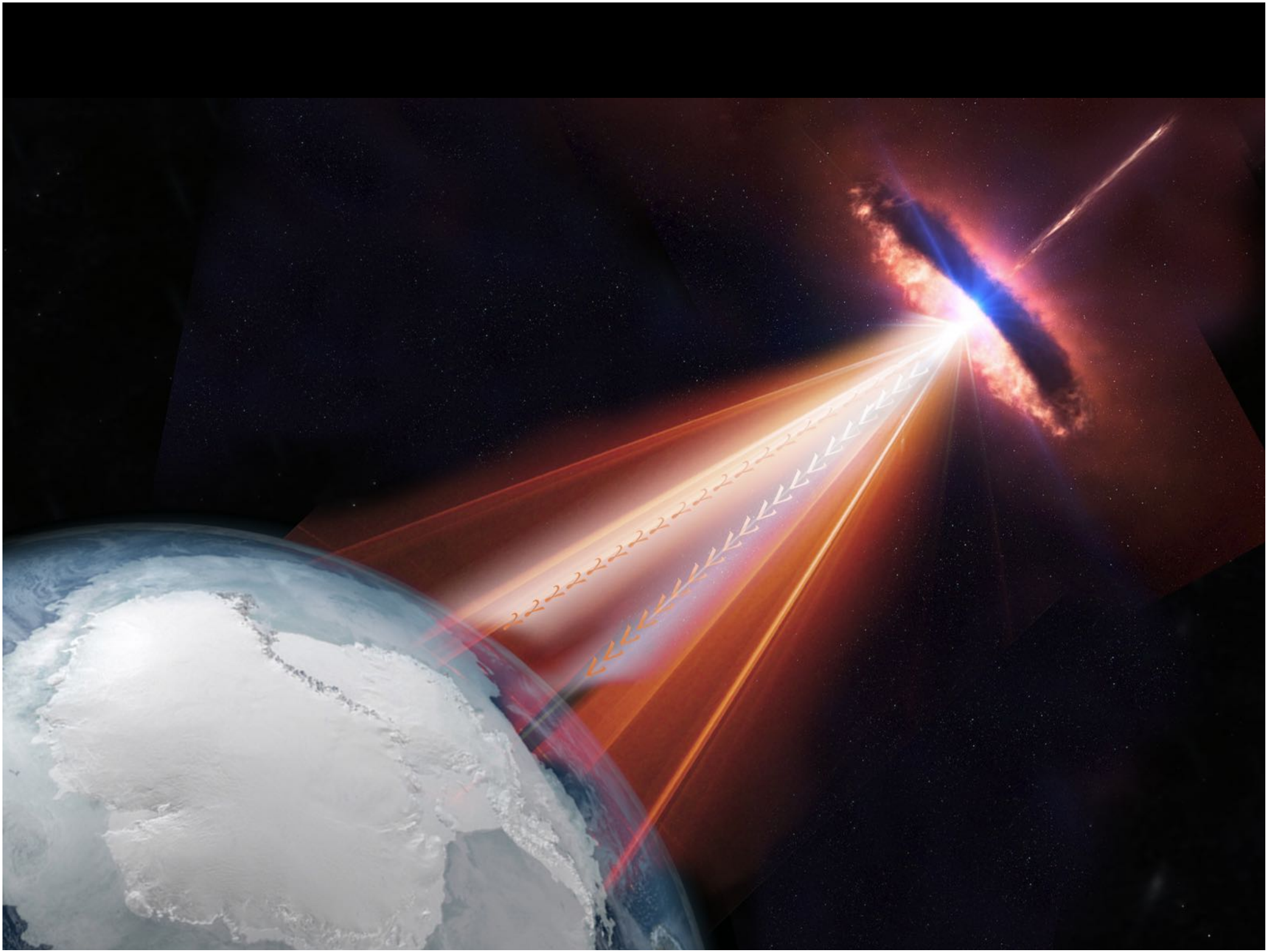
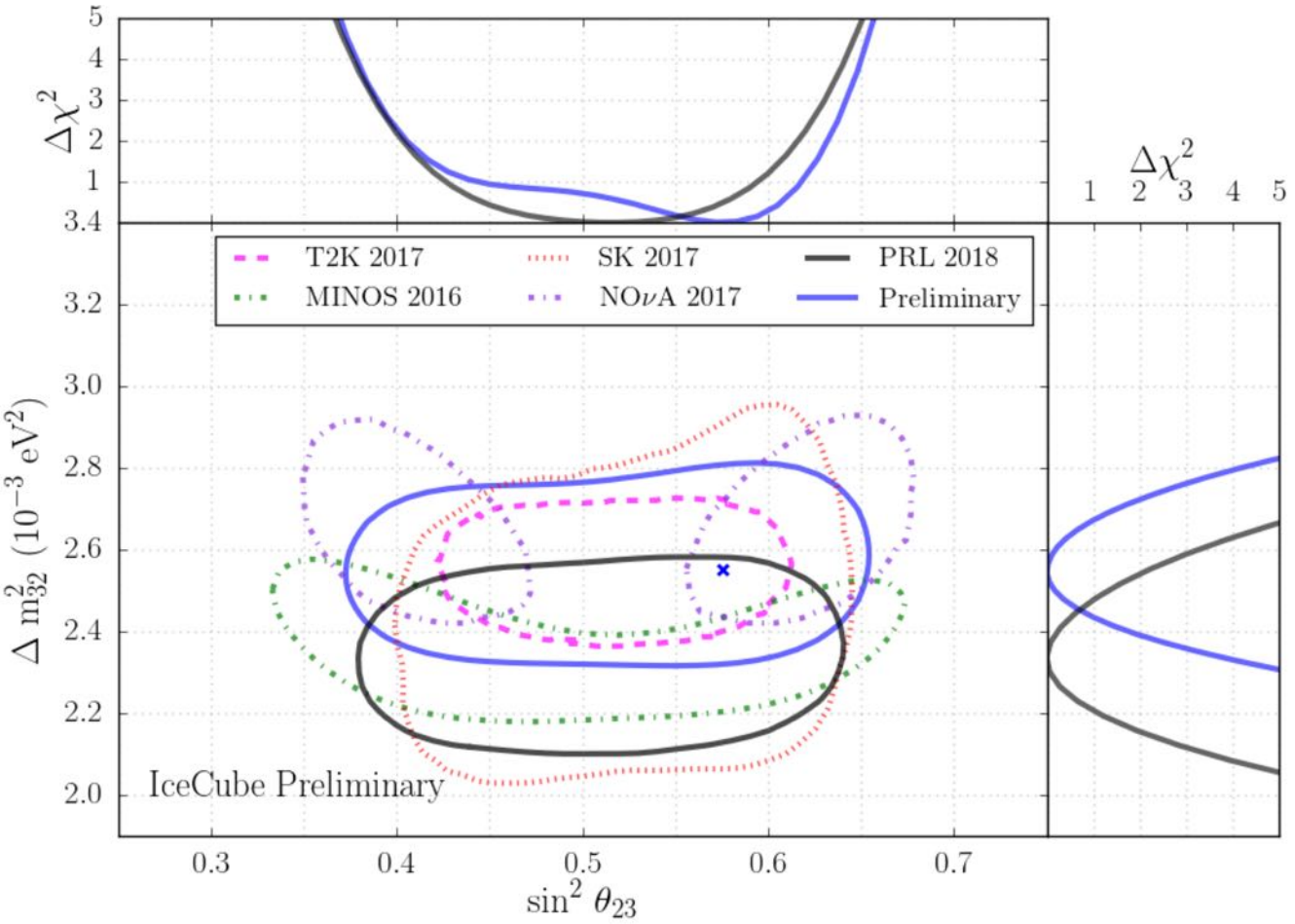



Victor Hess
1912
Archive Victor Francis Hess Society, Schloss Pöllau, Austria



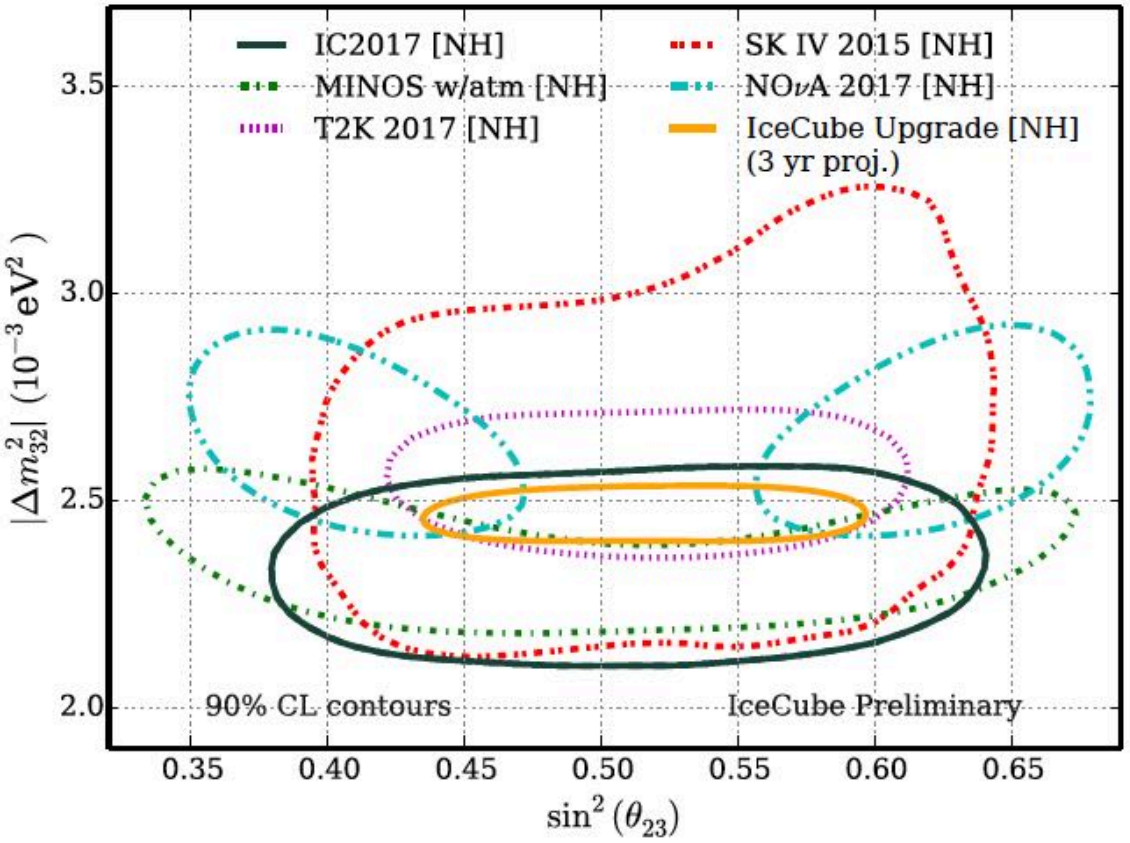





$\Delta\chi^2$
$\Delta\chi^2$
T2K 2017
MINOS 2016
SK 2017
NOνA 2017
PRL 2018
Preliminary
IceCube Preliminary
$\Delta\ m^2_{32}\ (10^{-3}\ eV^2)$
$\sin^2\theta_{23}$

Atmospheric Oscillation Parameters

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



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