Title: Particle/Astro Observations 3

Date: Jul 10, 2018 11:00 AM

URL: http://pirsa.org/18070004

Abstract:

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

… you looked at 10msec of data !

muons detected per year:

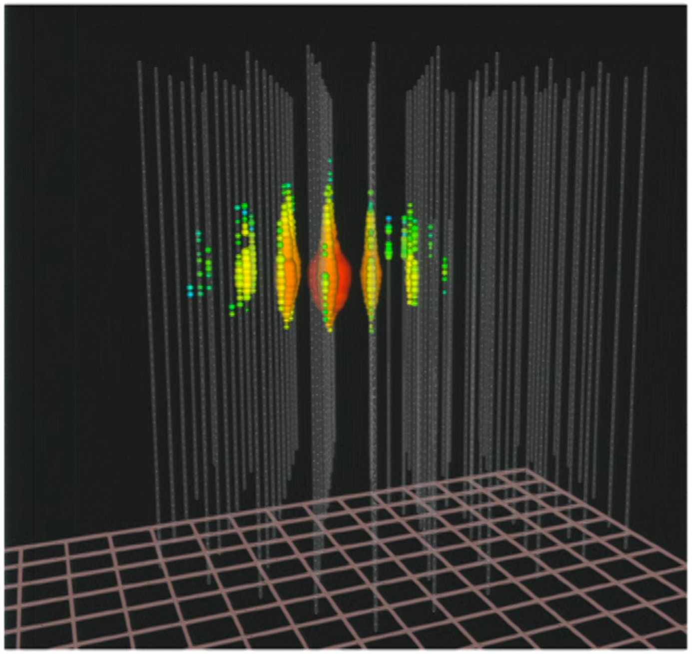
• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	~ 10

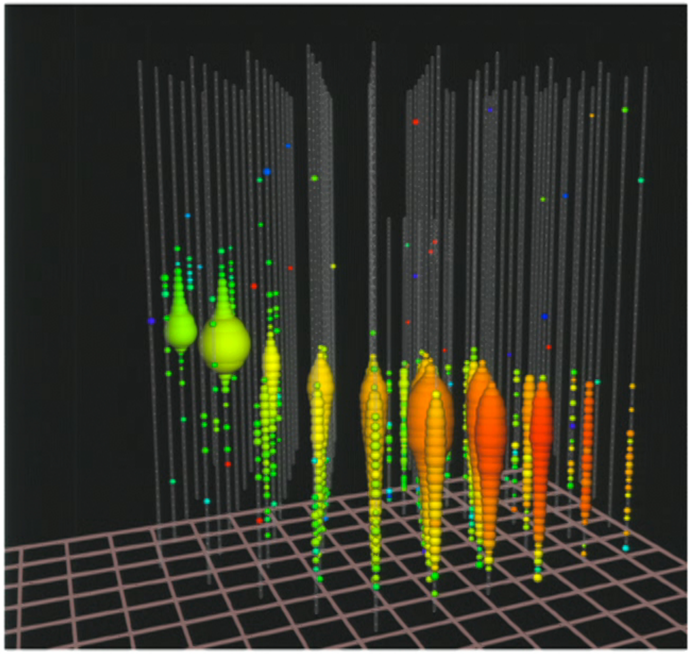
* 3000 per second

** 1 every 6 minutes

isolated neutrinos interacting *inside* the detector (HESE)

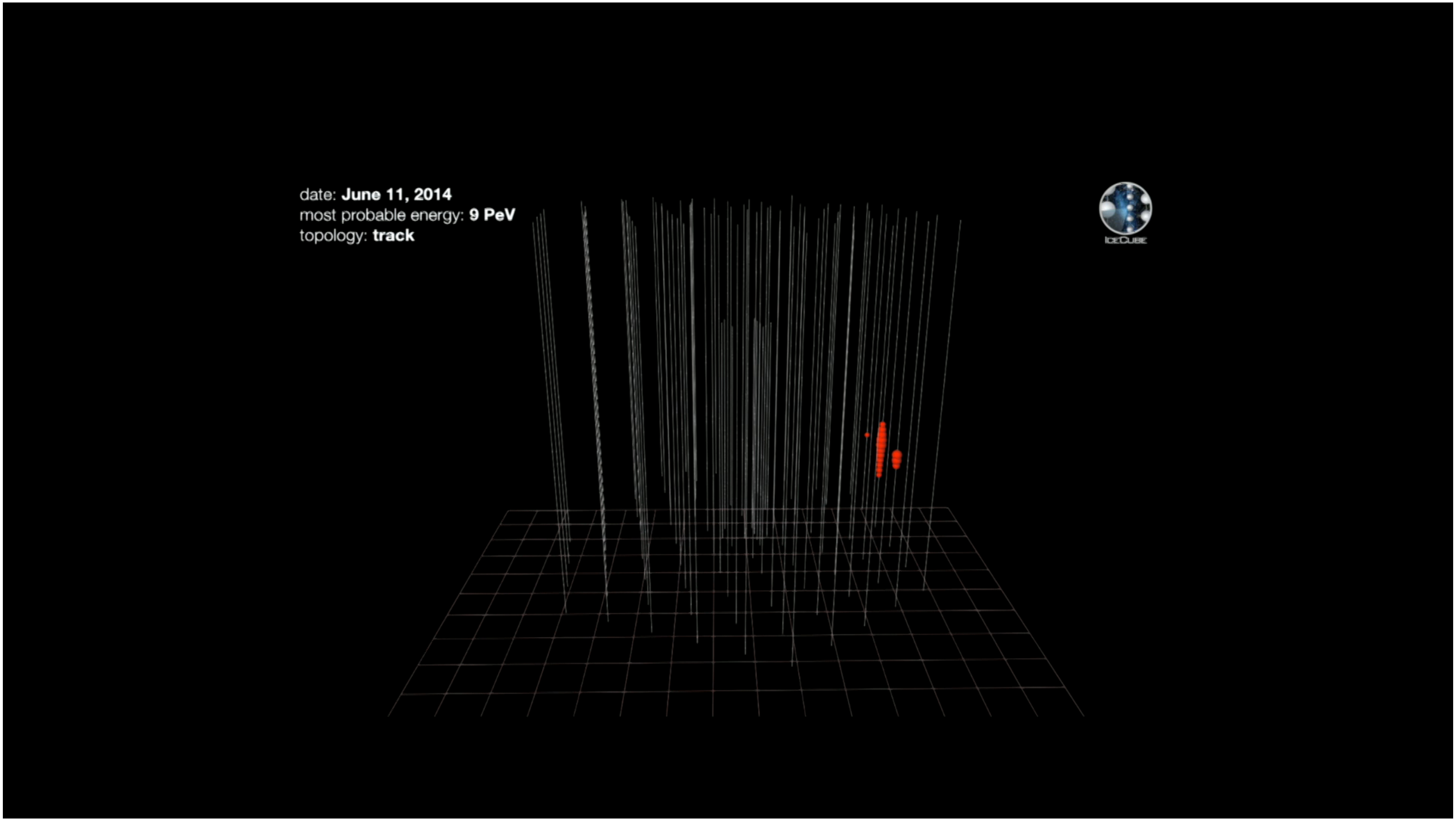
up-going muon tracks (UPMU)

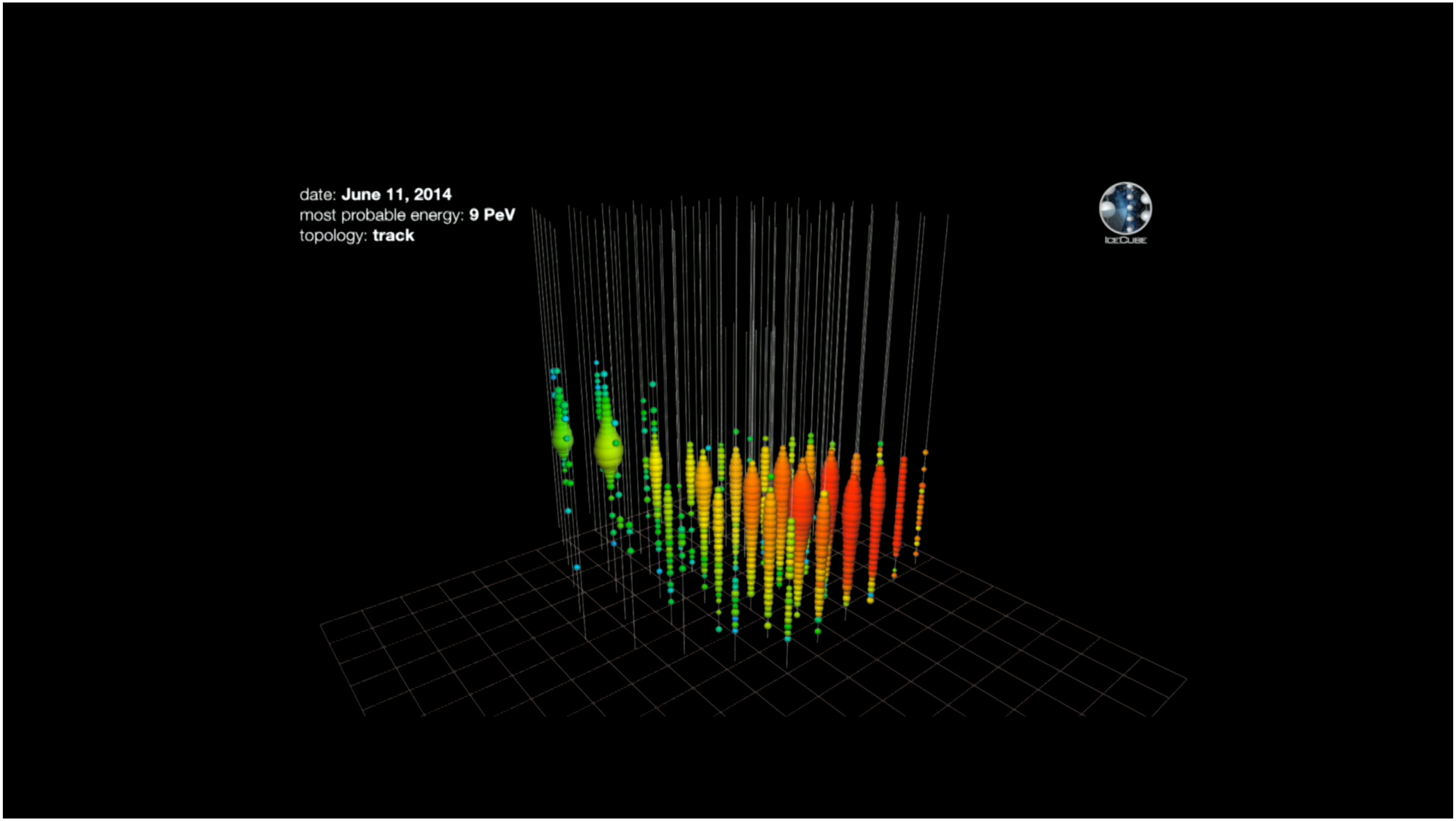




total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5°)


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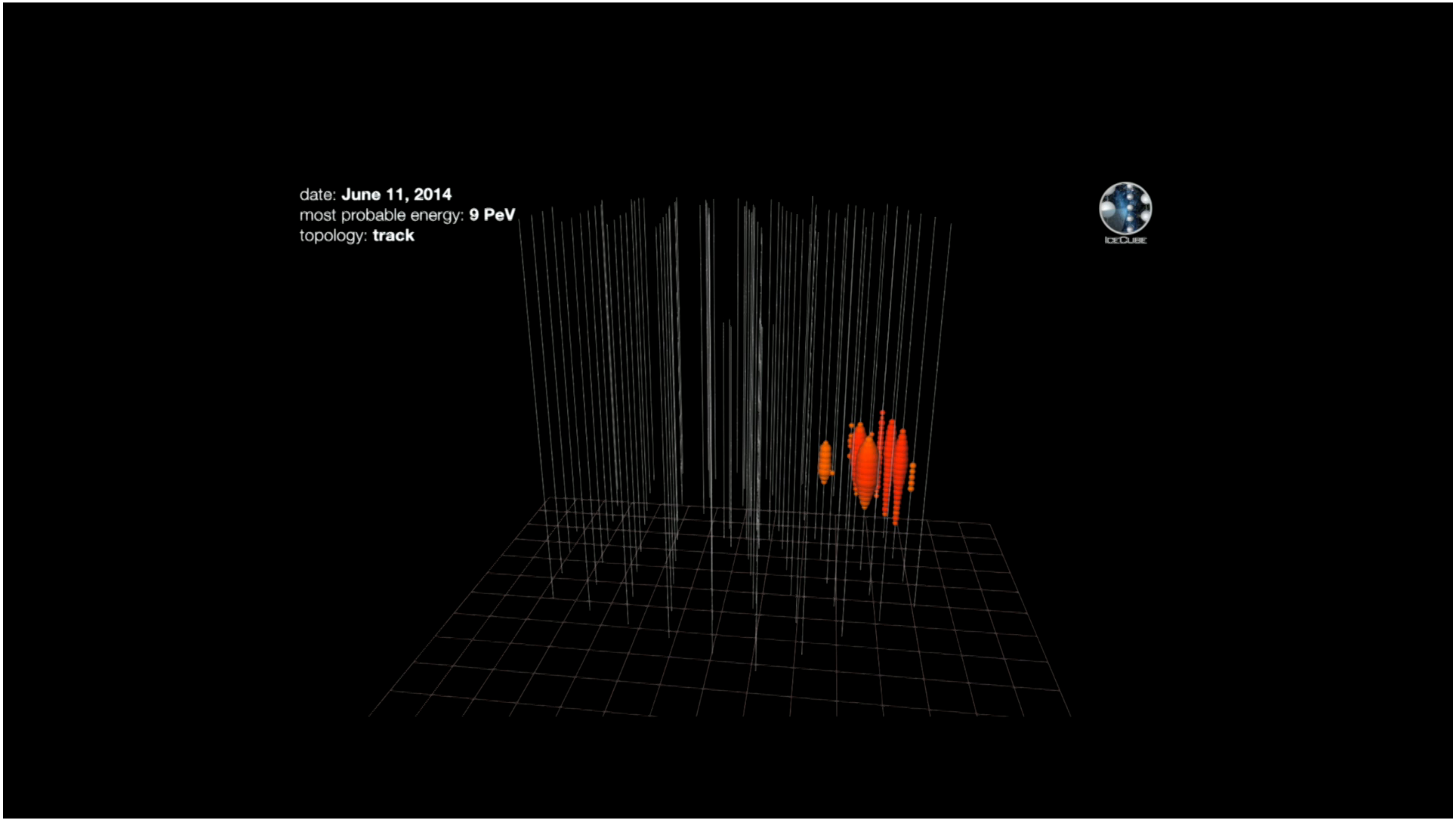
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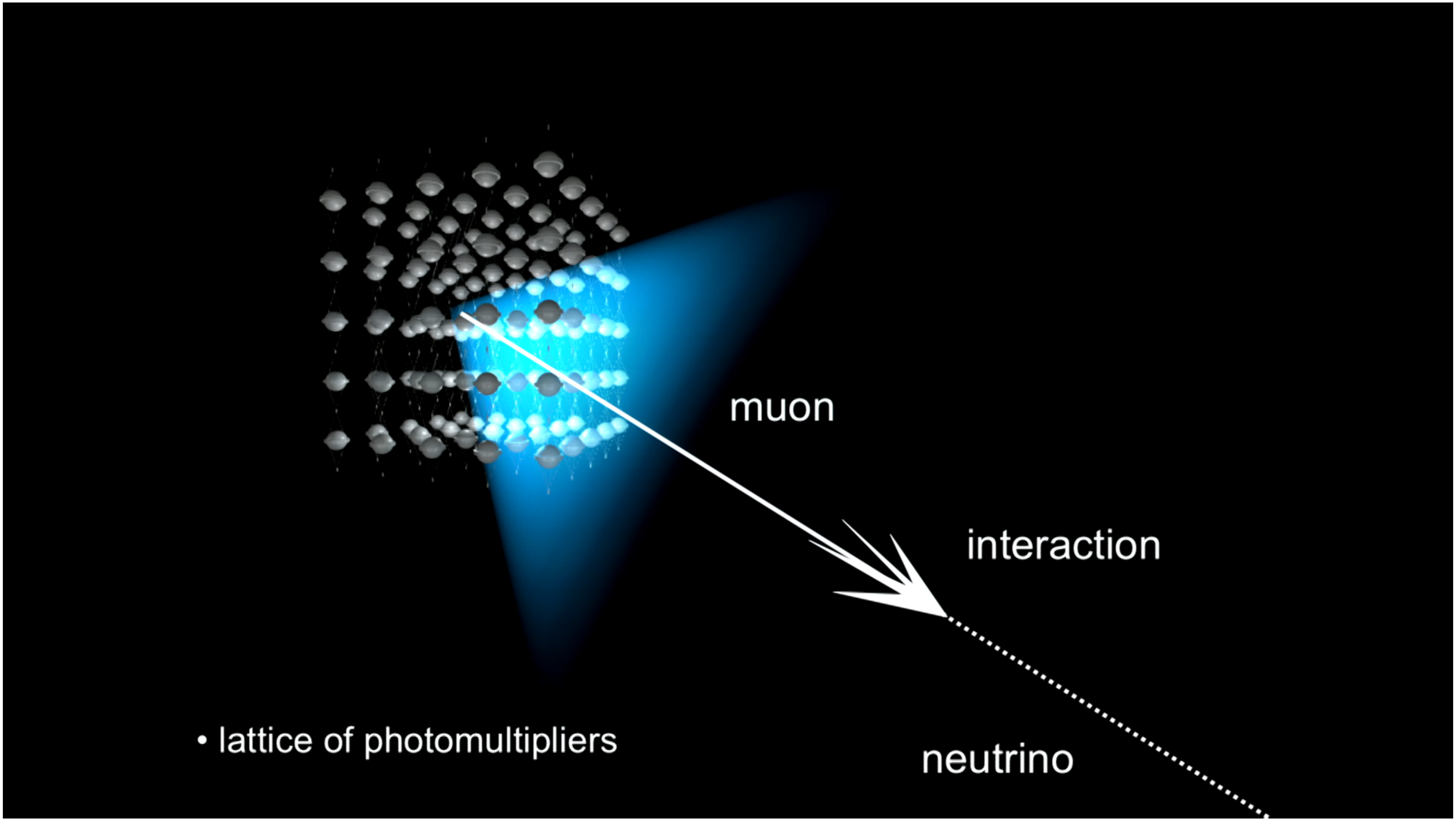
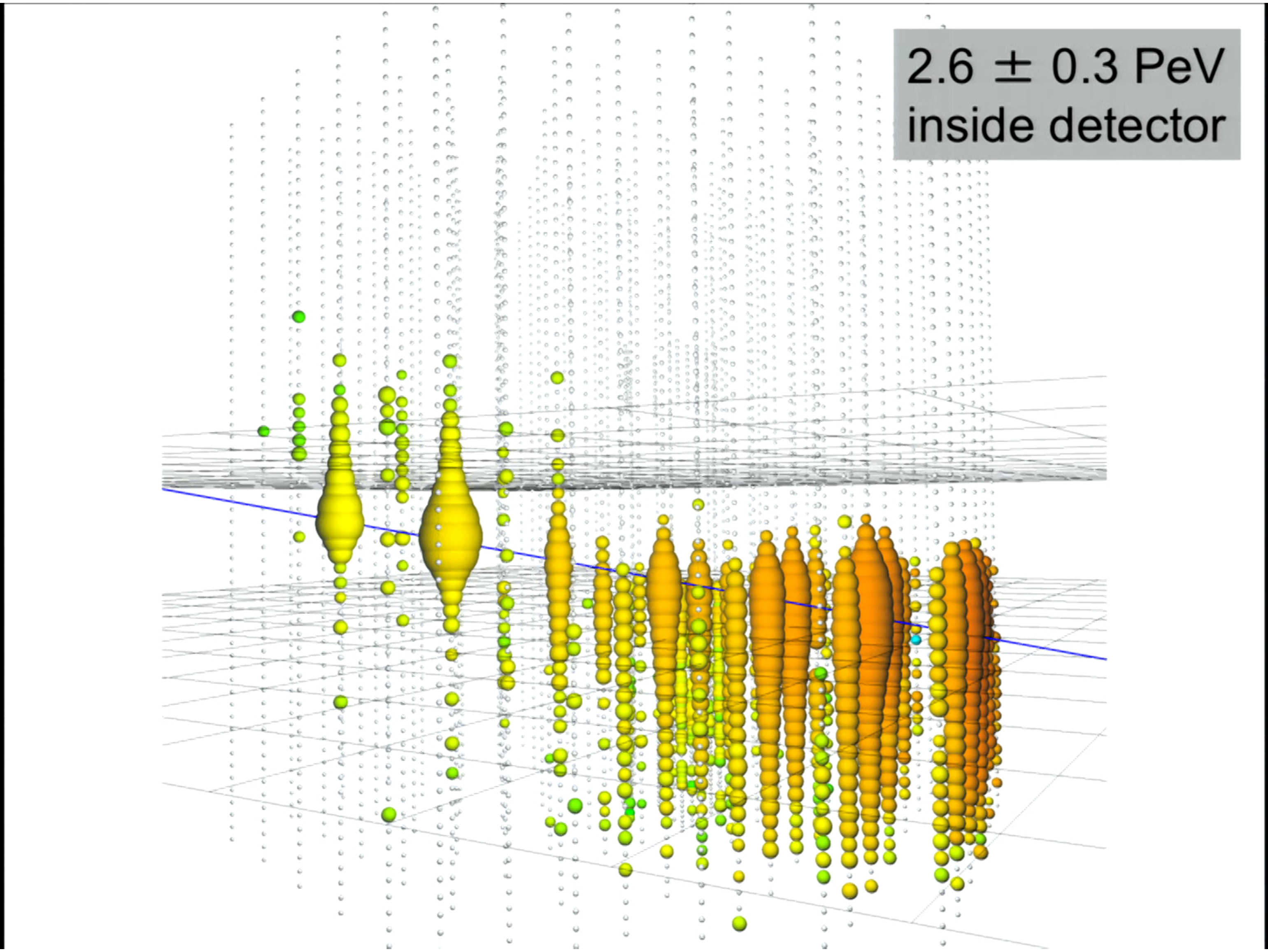
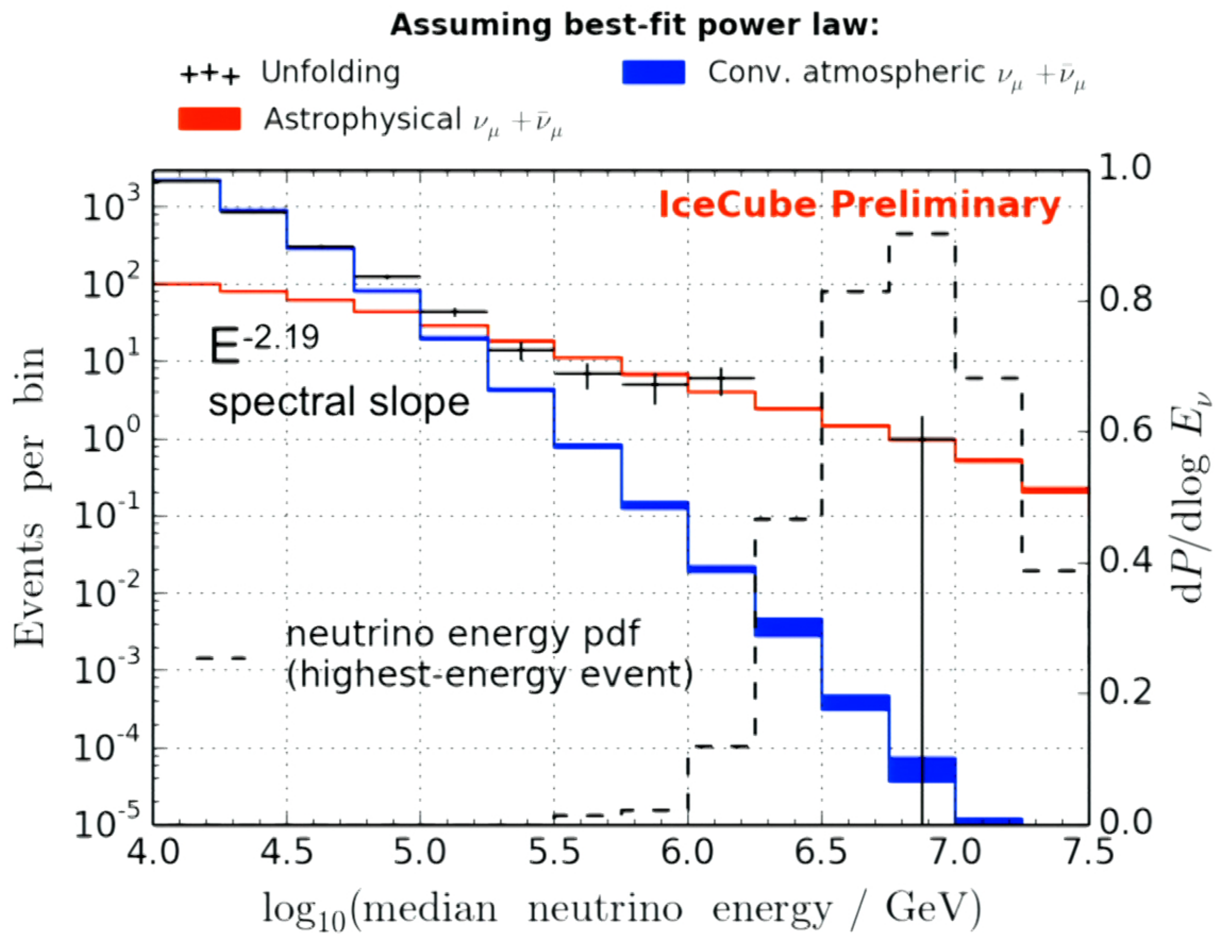

muon
interaction
neutrino
• lattice of photomultipliers

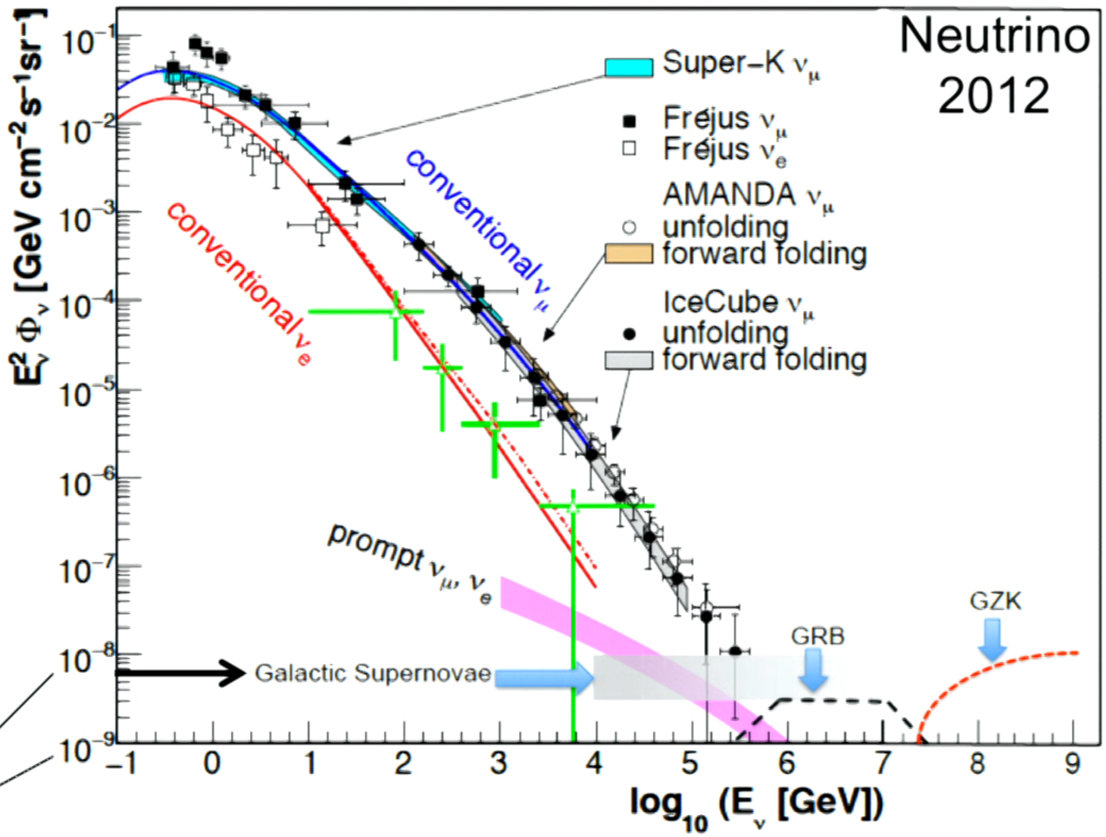

2.6 ± 0.3 PeV
inside detector

~ 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

cosmic rays interact with the microwave background

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

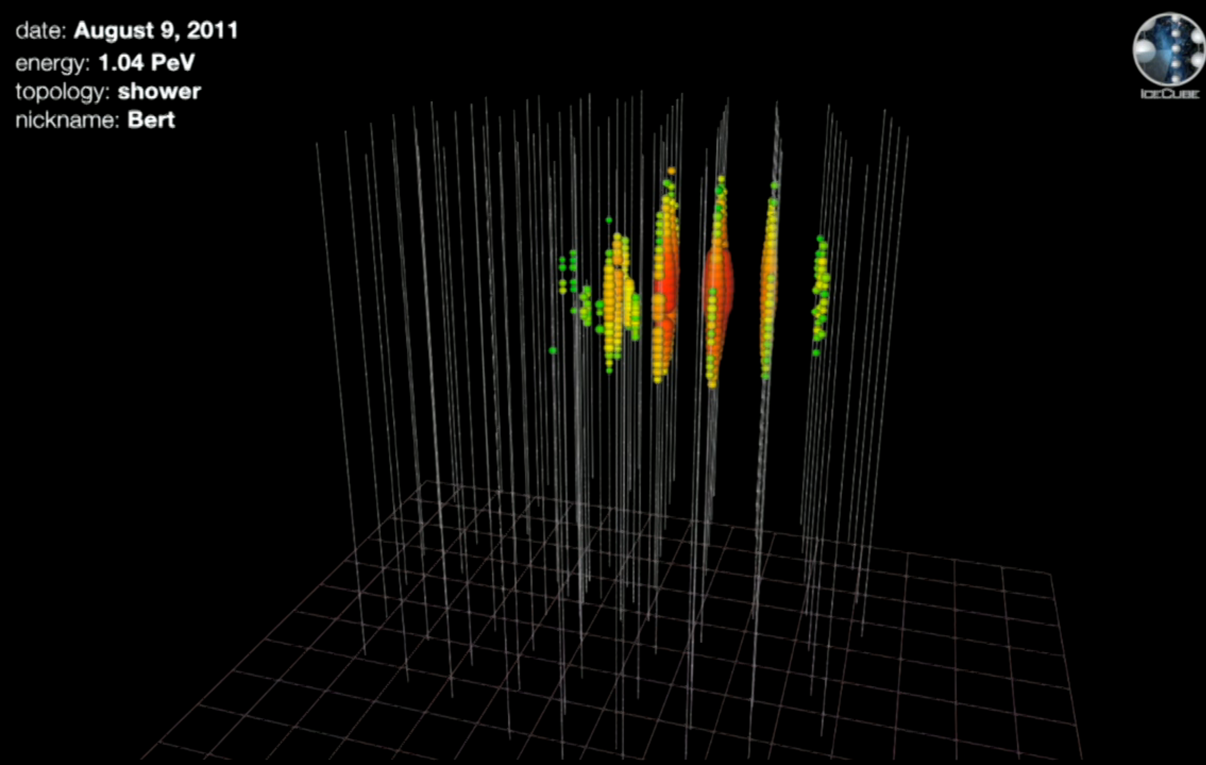
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

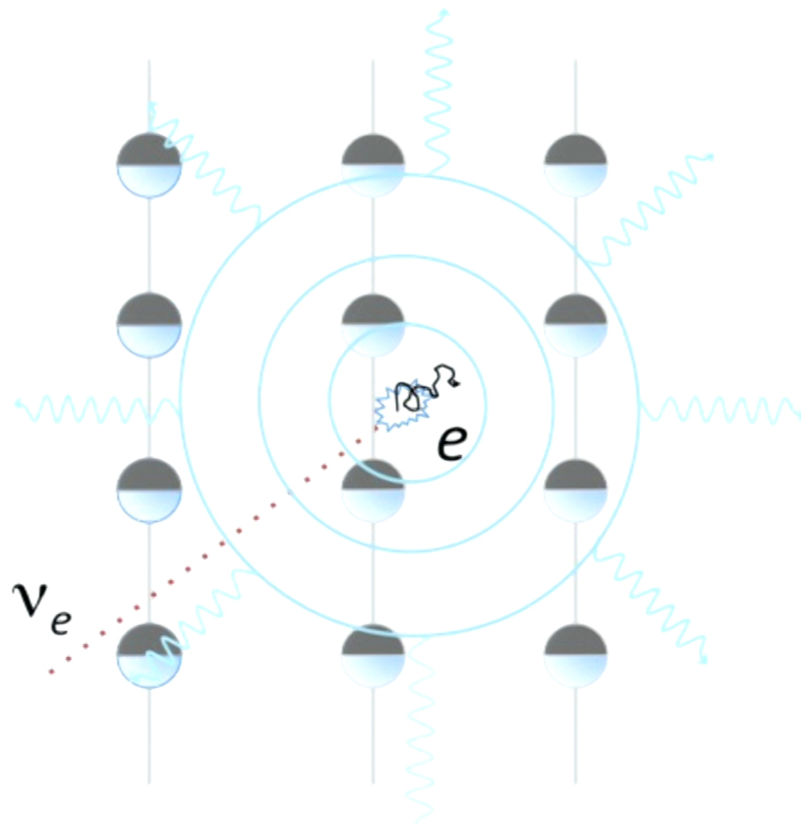
GZK neutrino search: two neutrinos with > 1,000 TeV

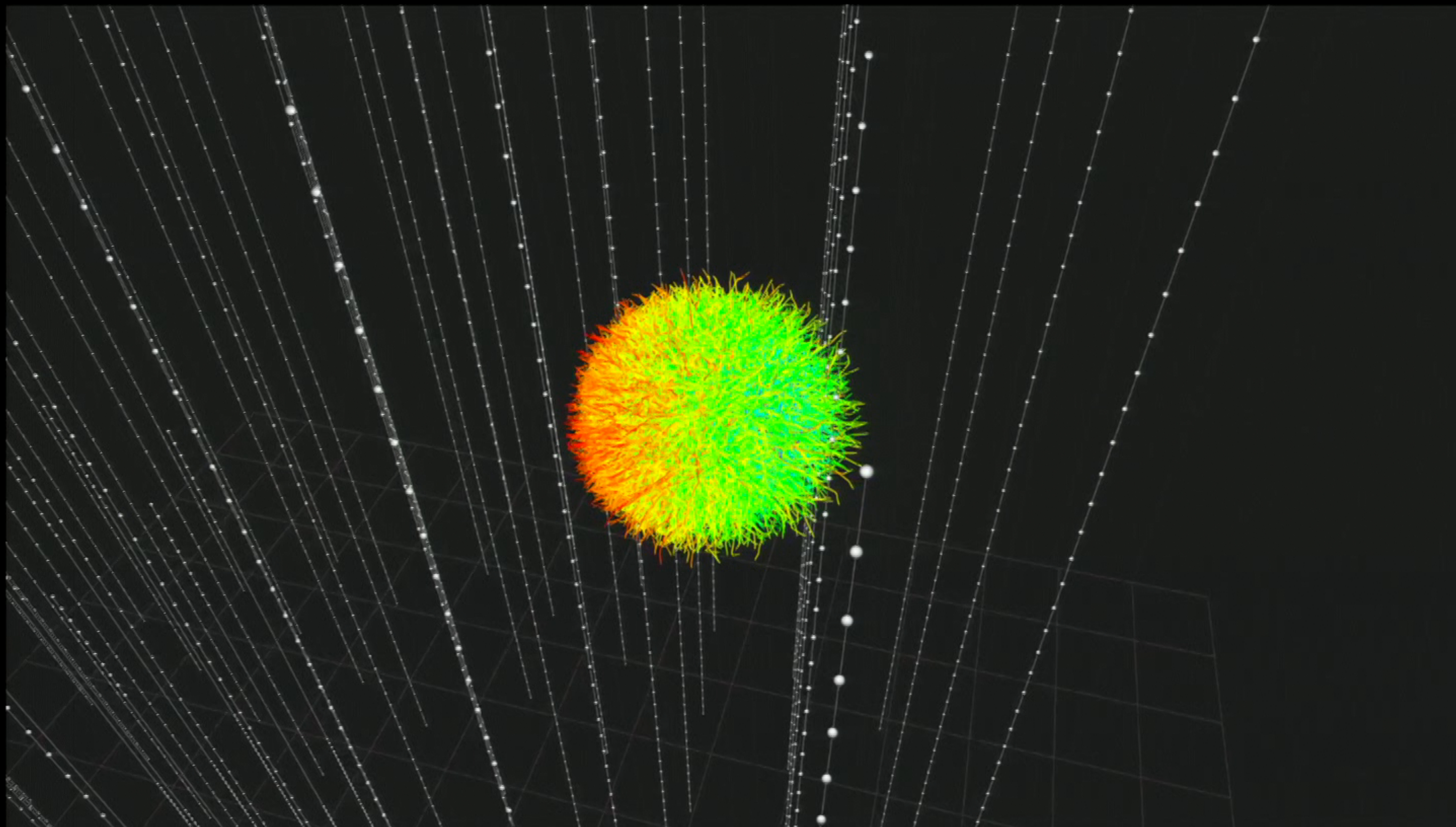


electron showers versus muon tracks

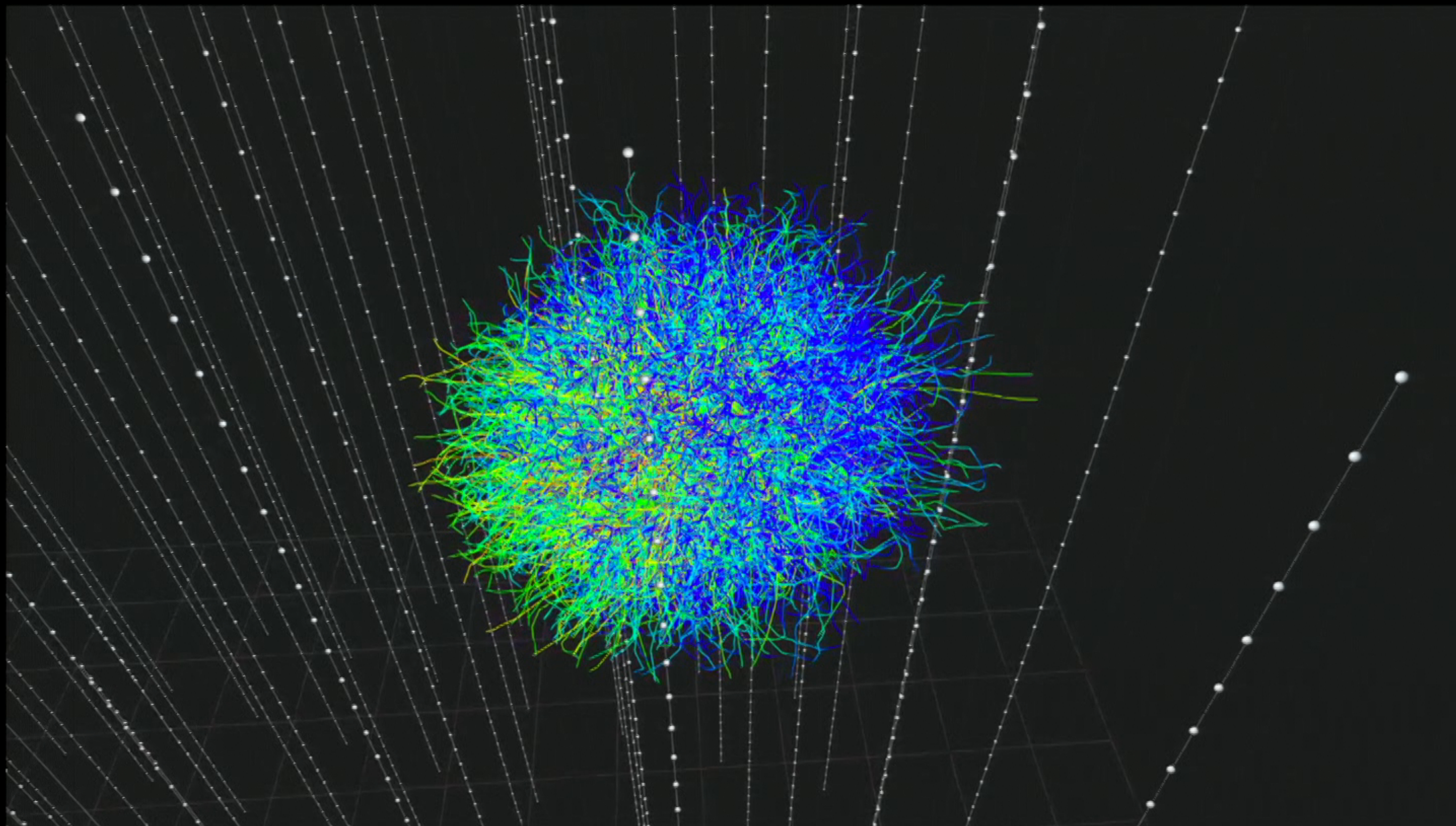
PeV ν_e and ν_τ showers:

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





size = energy & color = time = direction



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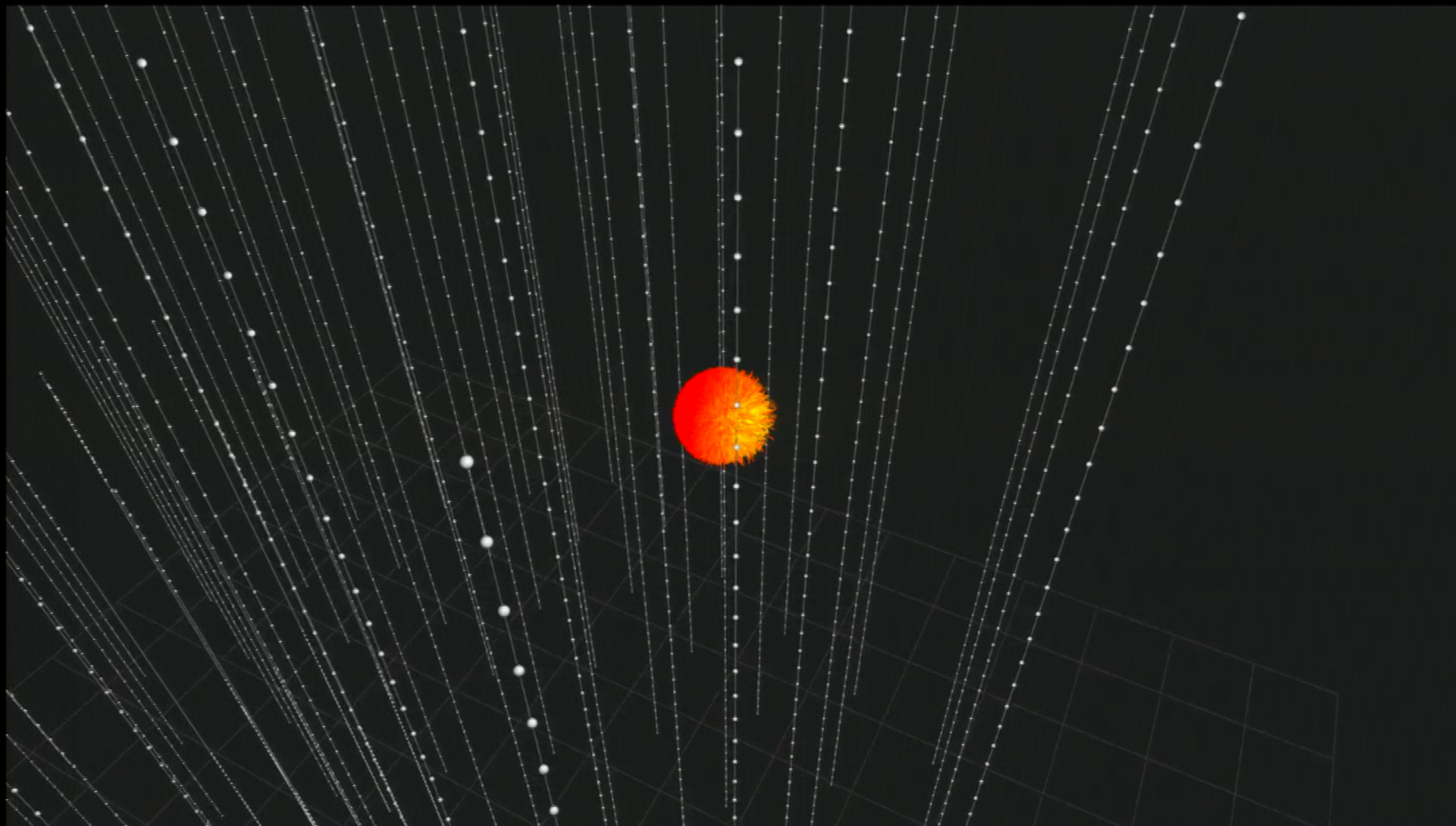

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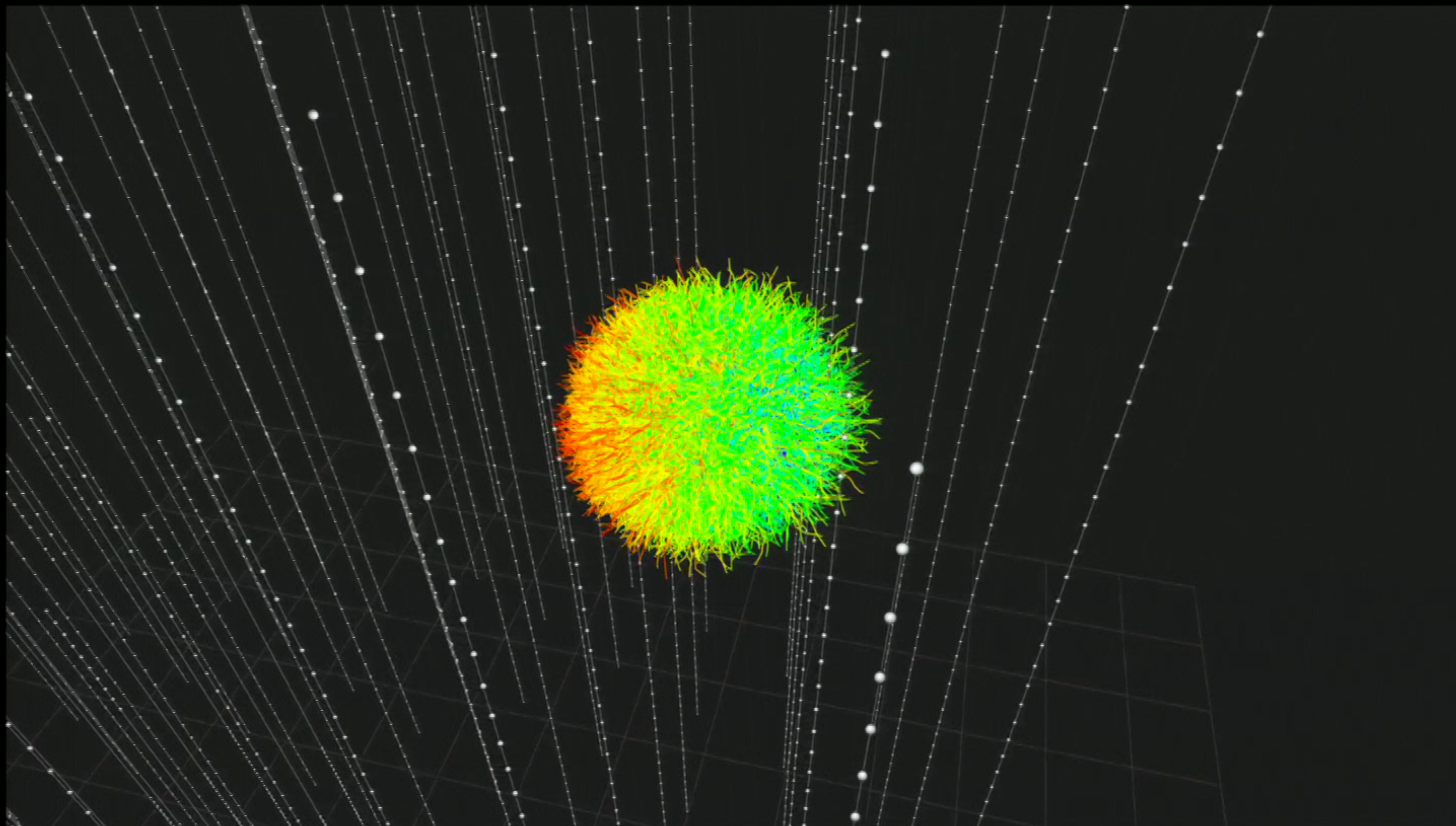

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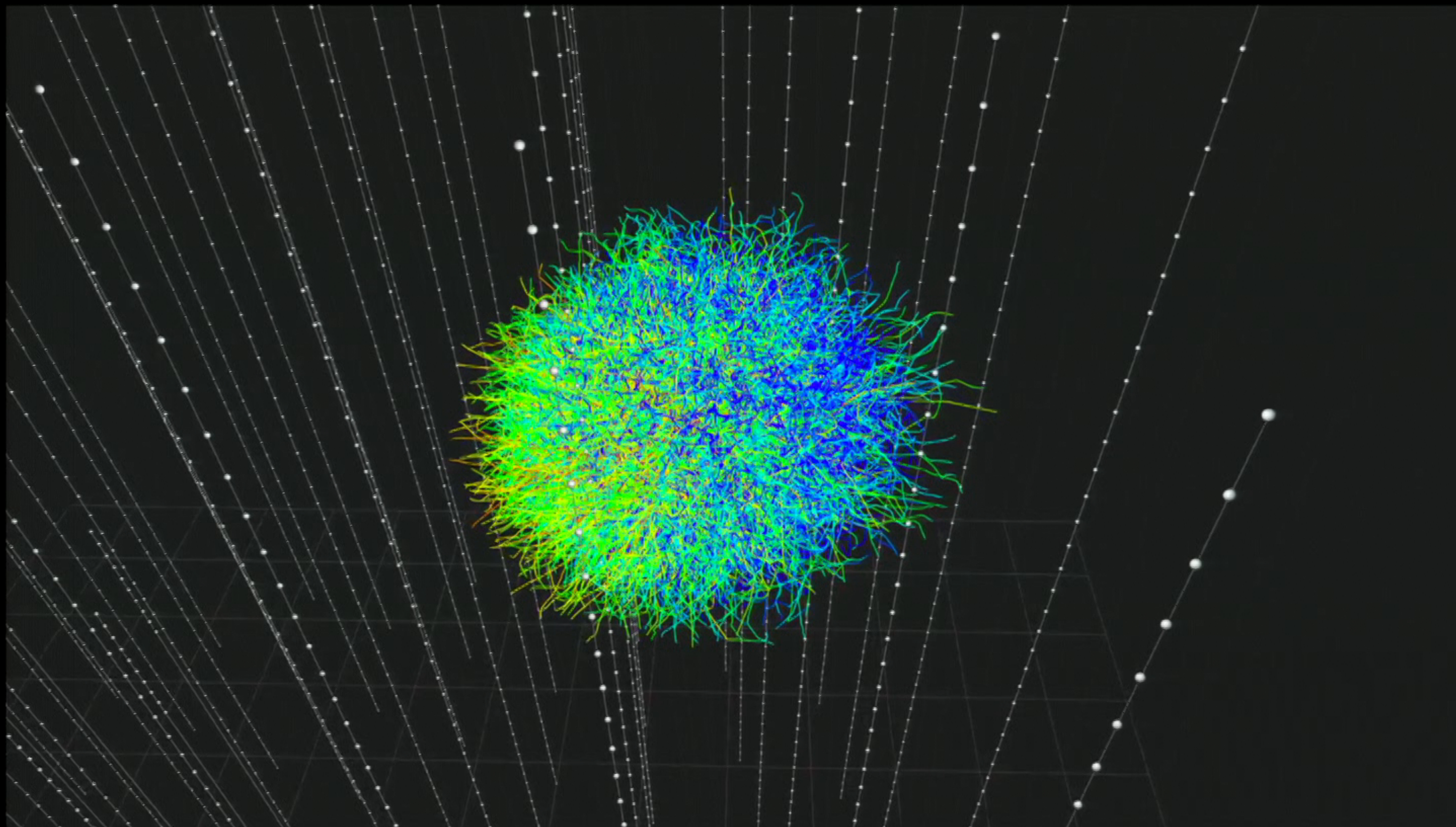

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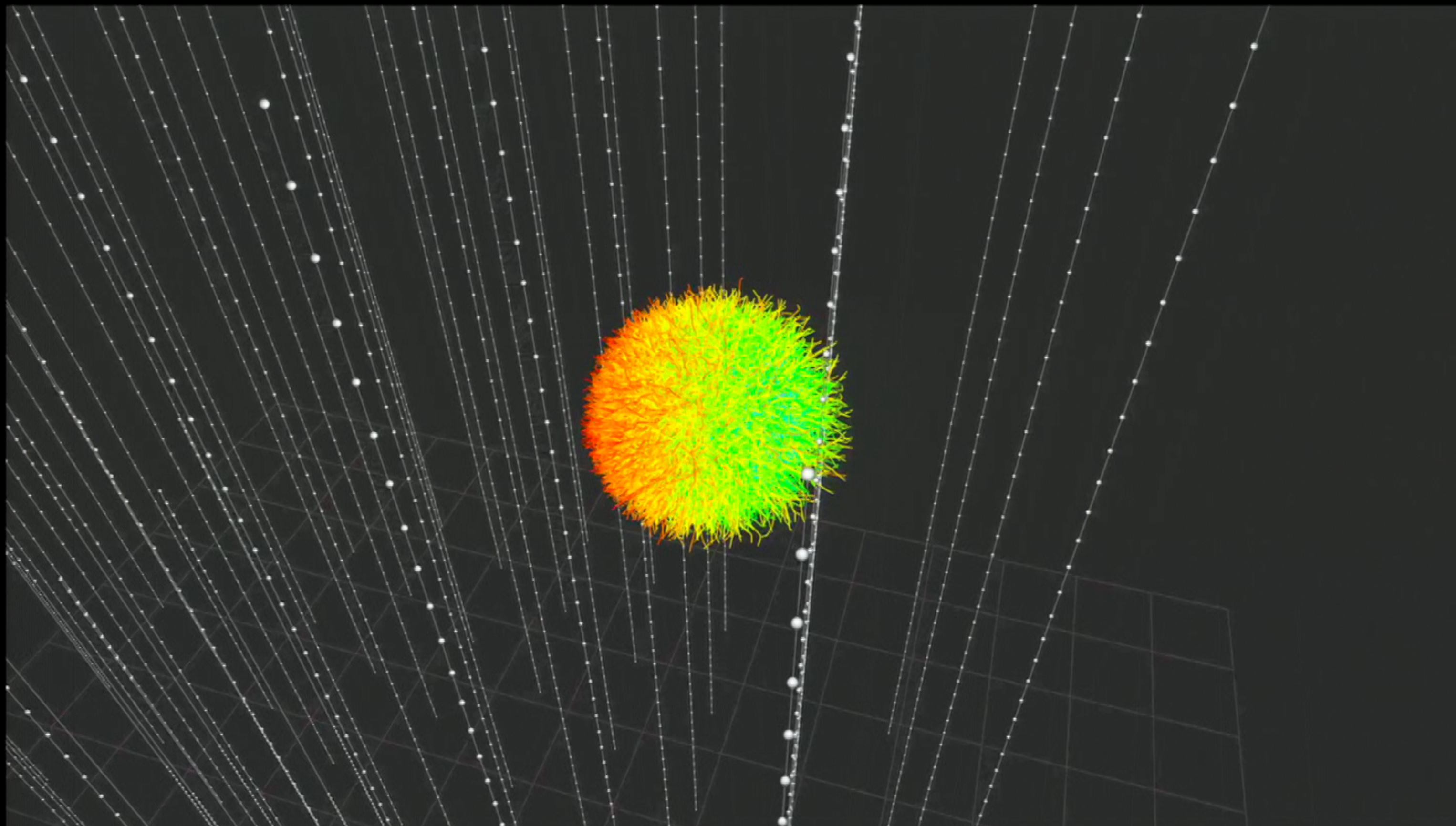

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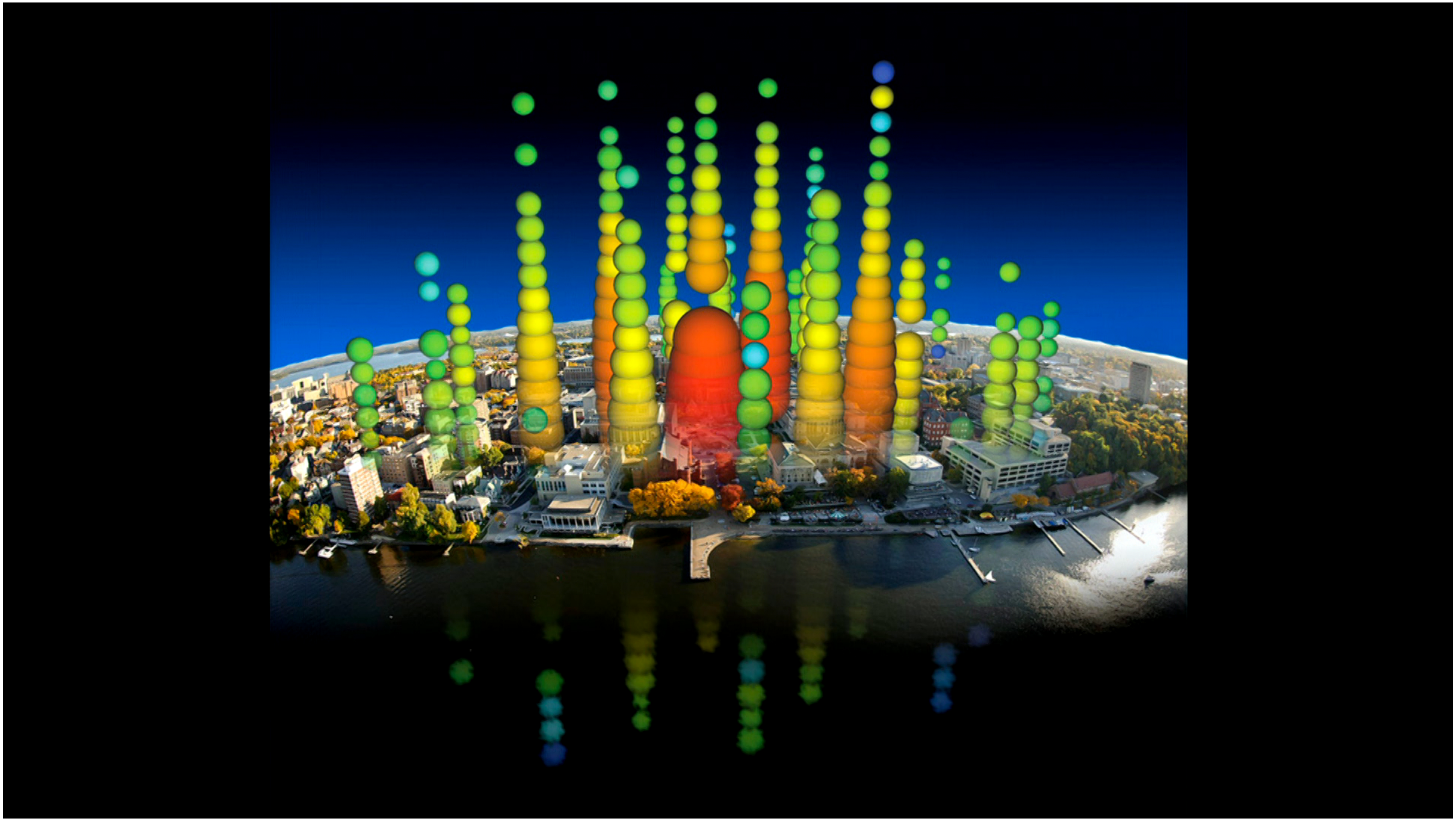
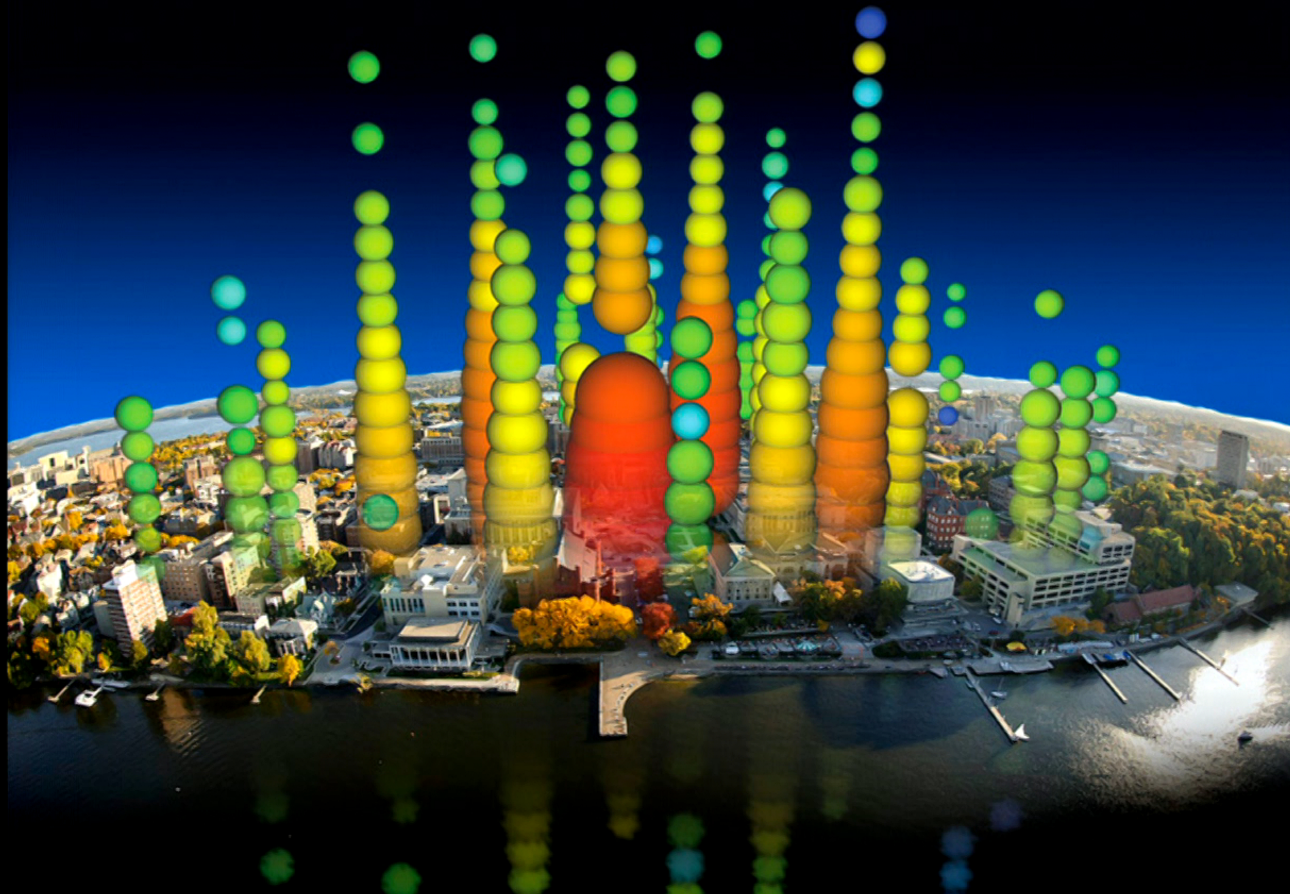
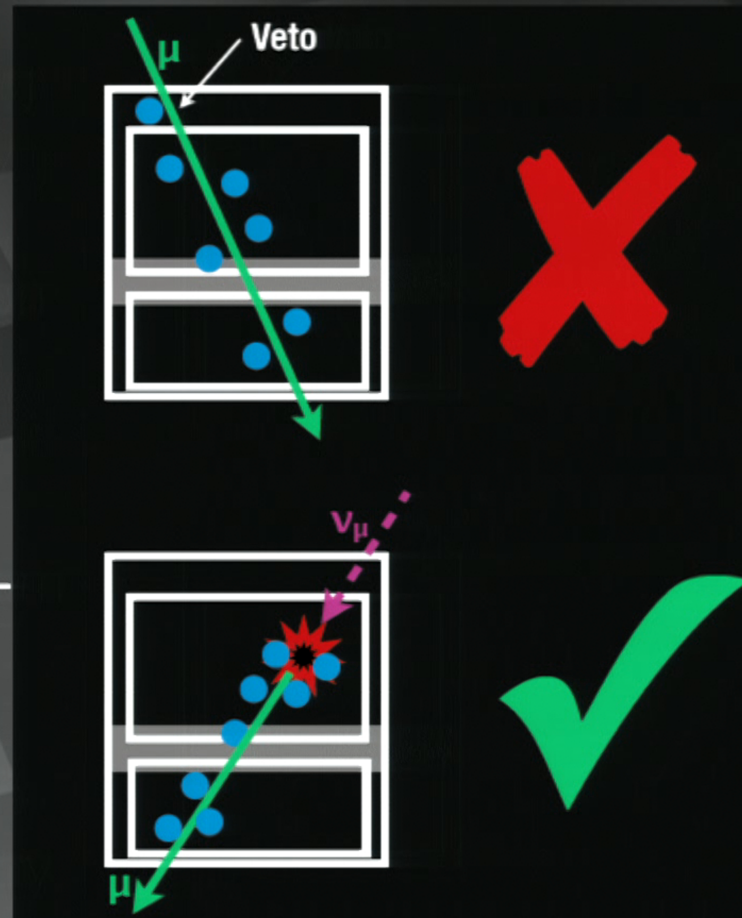


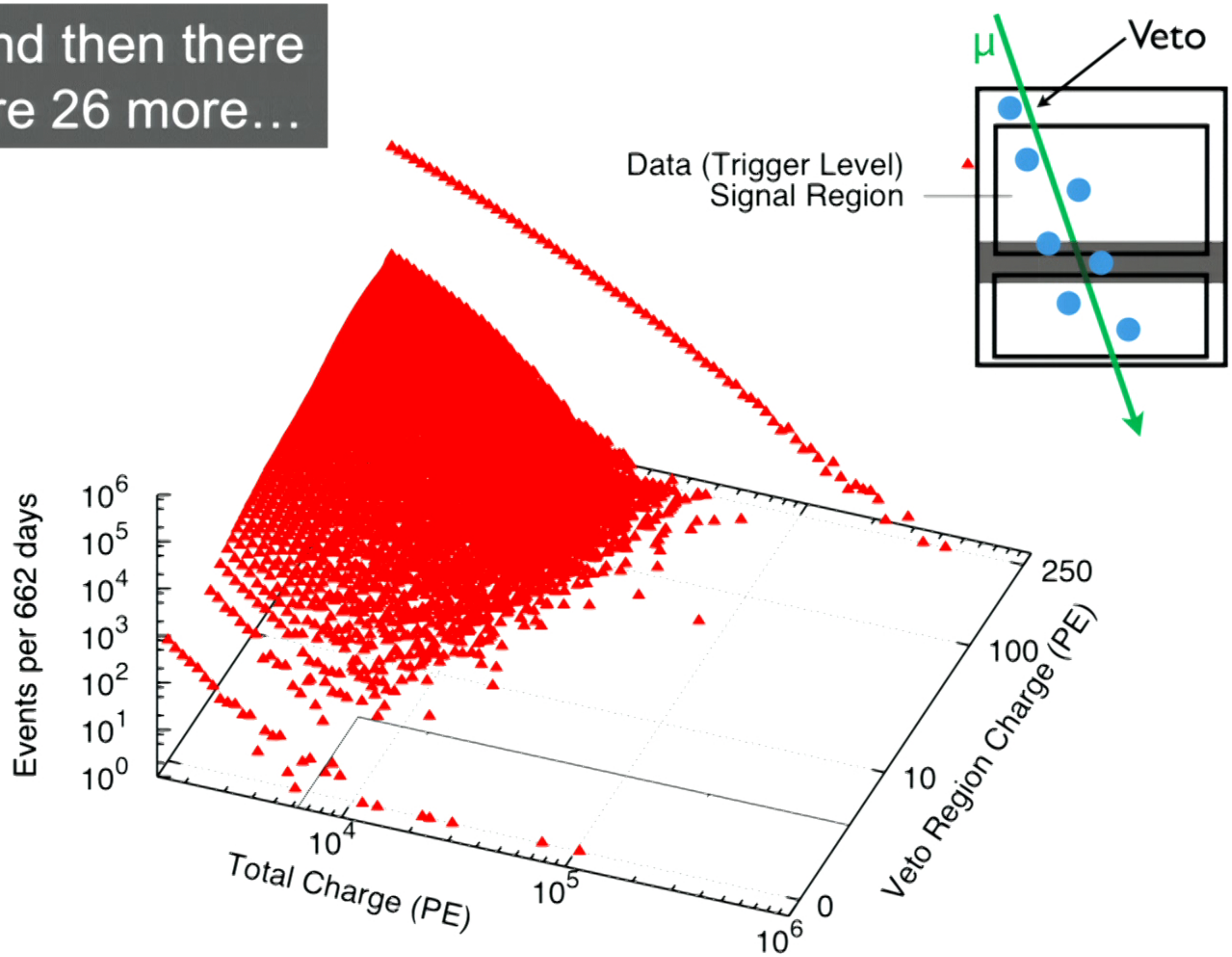


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

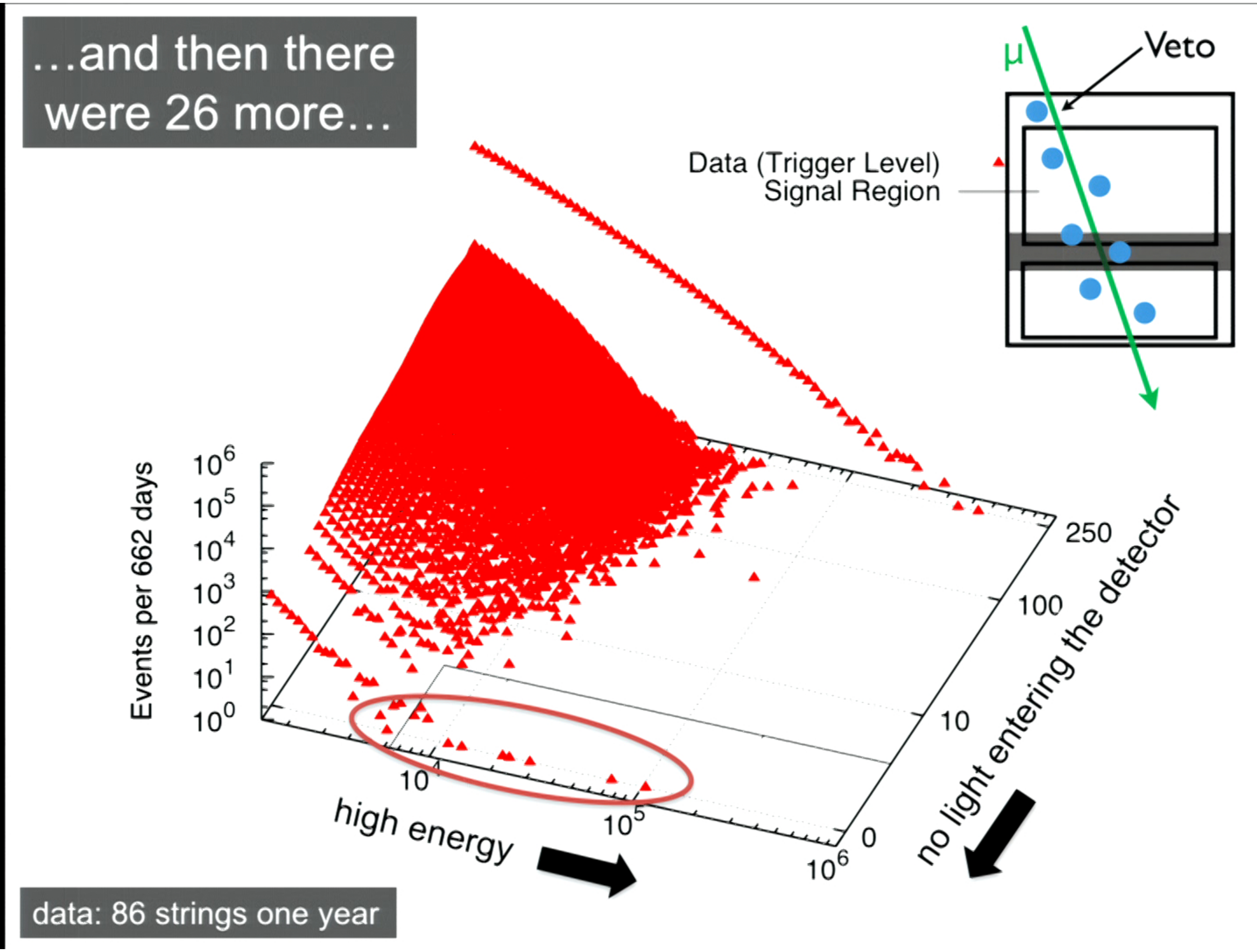
- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry



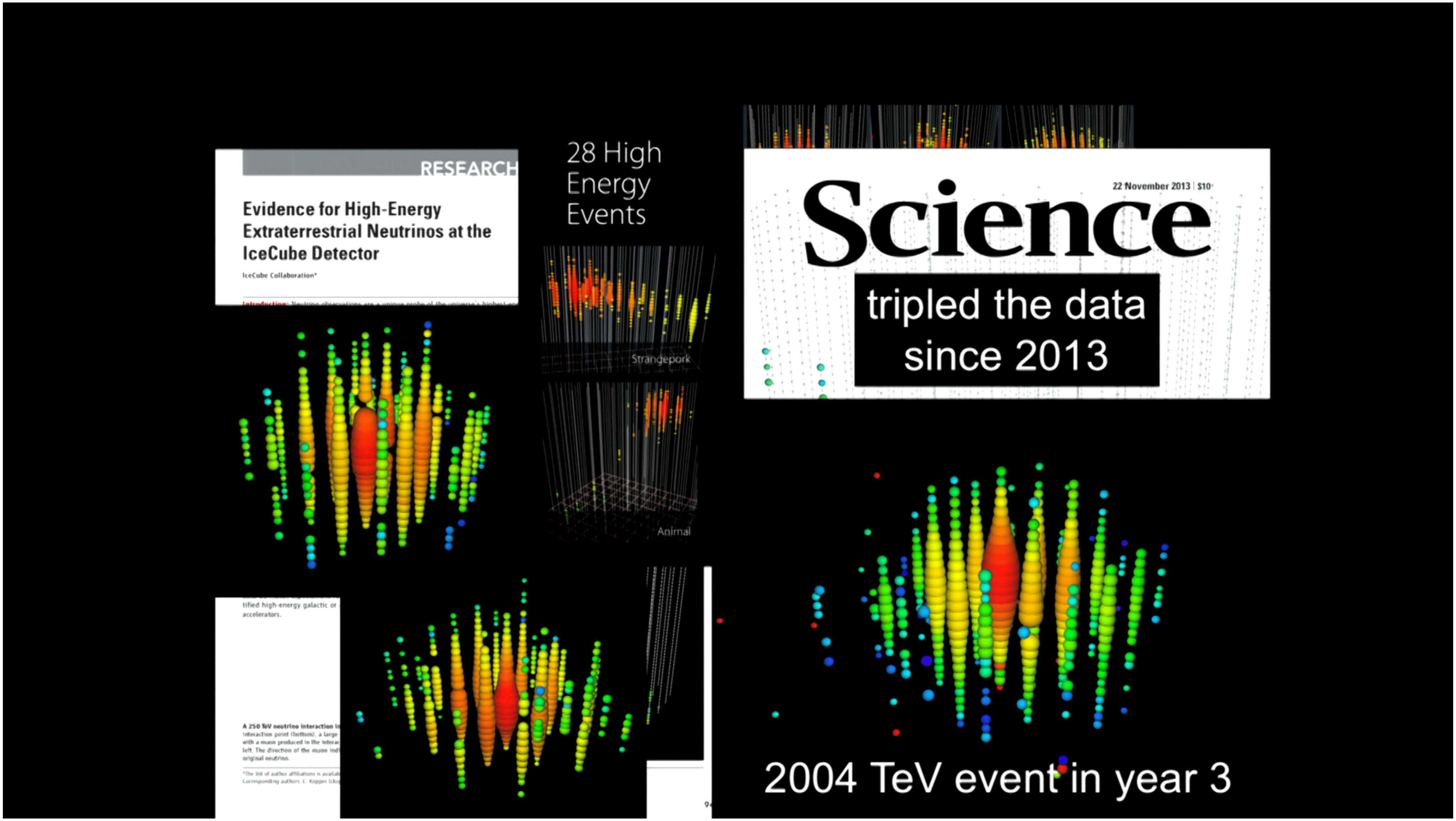
...and then there were 26 more...



data: 86 strings one year

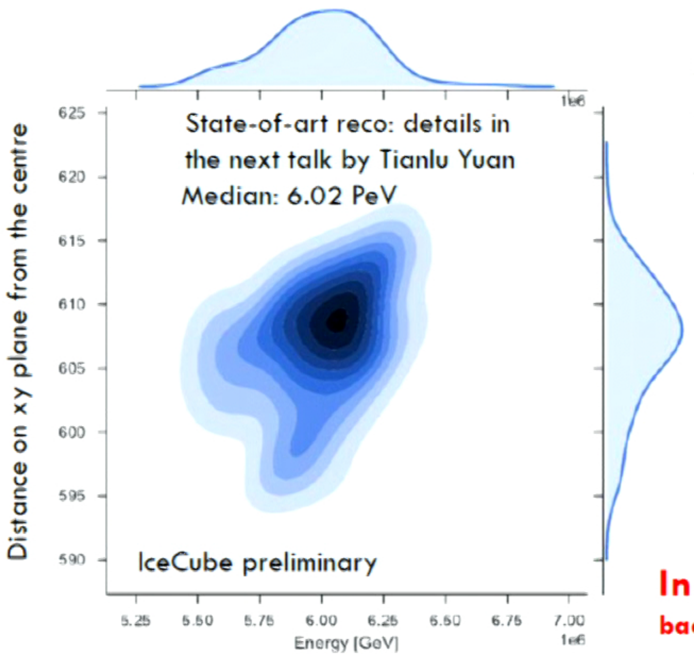


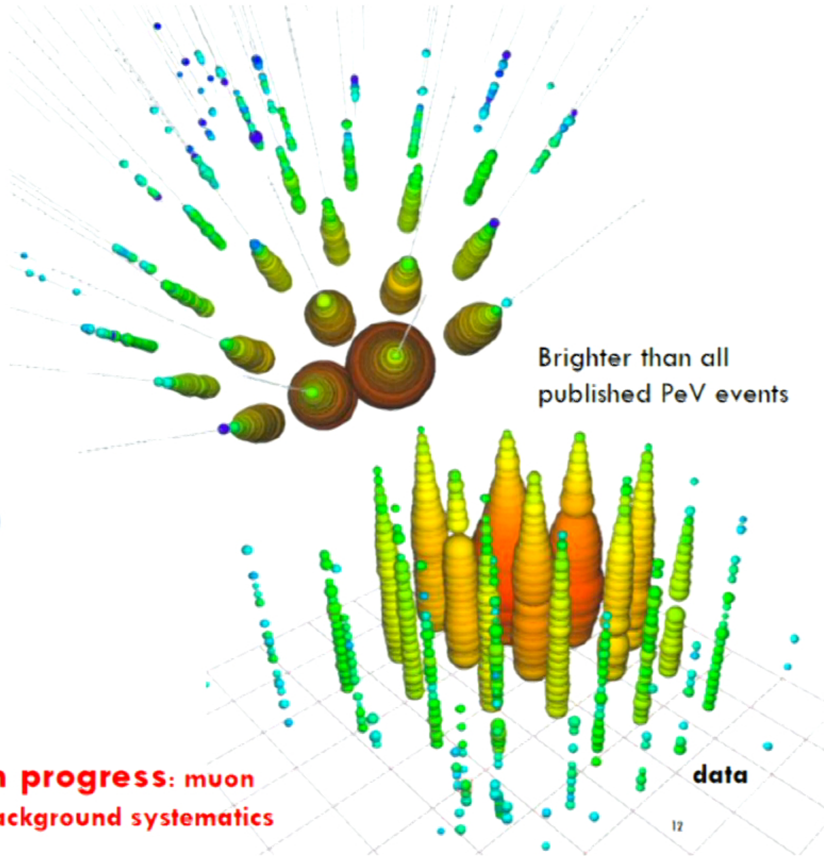
…and then there were 26 more…
Veto
μ
Data (Trigger Level)
Signal Region
Events per 662 days
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^4
10^5
10^6
high energy
250
100
10
0
no light entering the detector
data: 86 strings one year


RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
22 November 2013 | $10
Science
tripled the data since 2013
2004 TeV event in year 3

Partially contained event with energy ~ 6 PeV

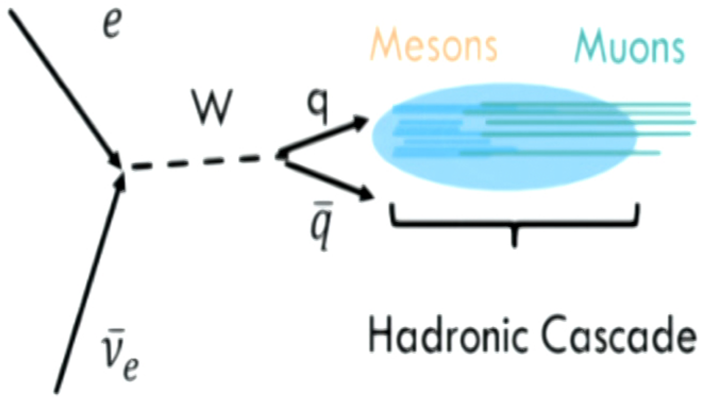
HIGHEST-ENERGY NEUTRINO CANDIDATE

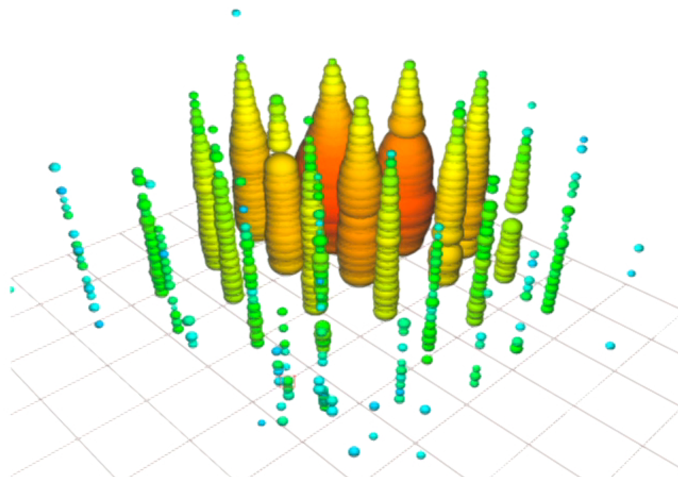


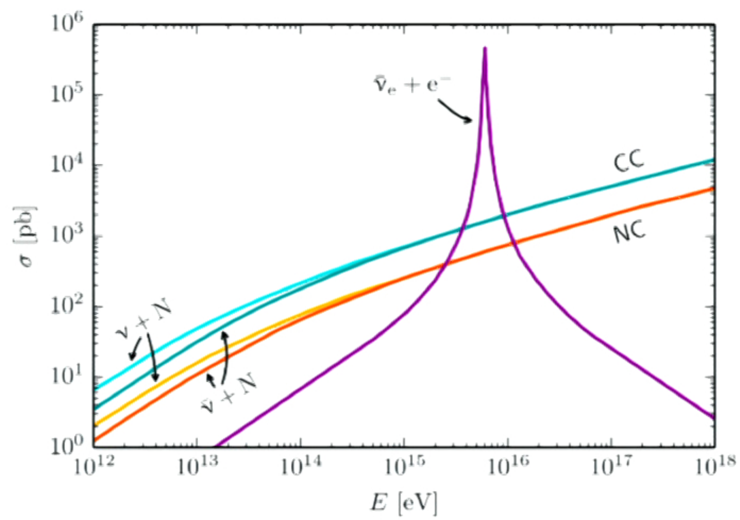


In progress: muon background systematics

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





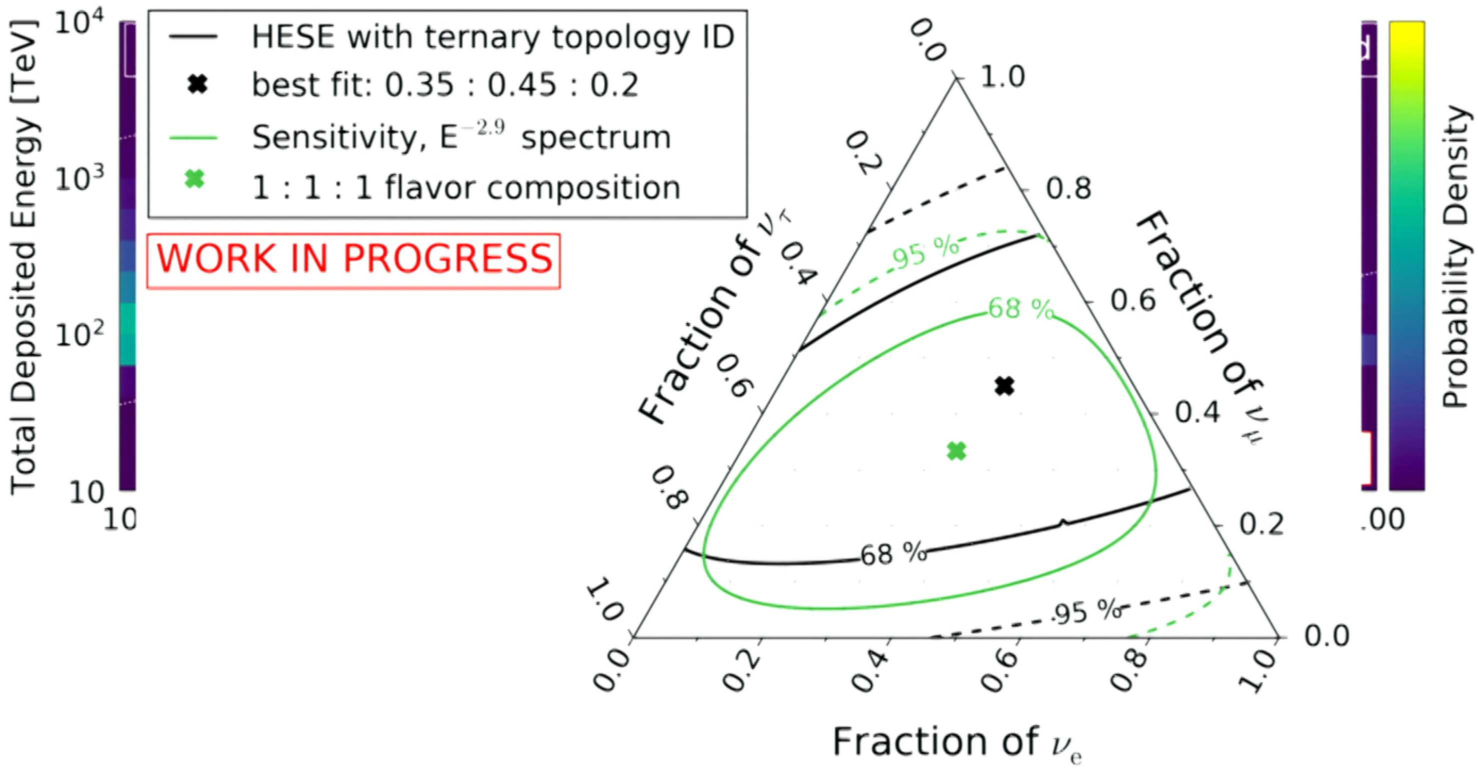


- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

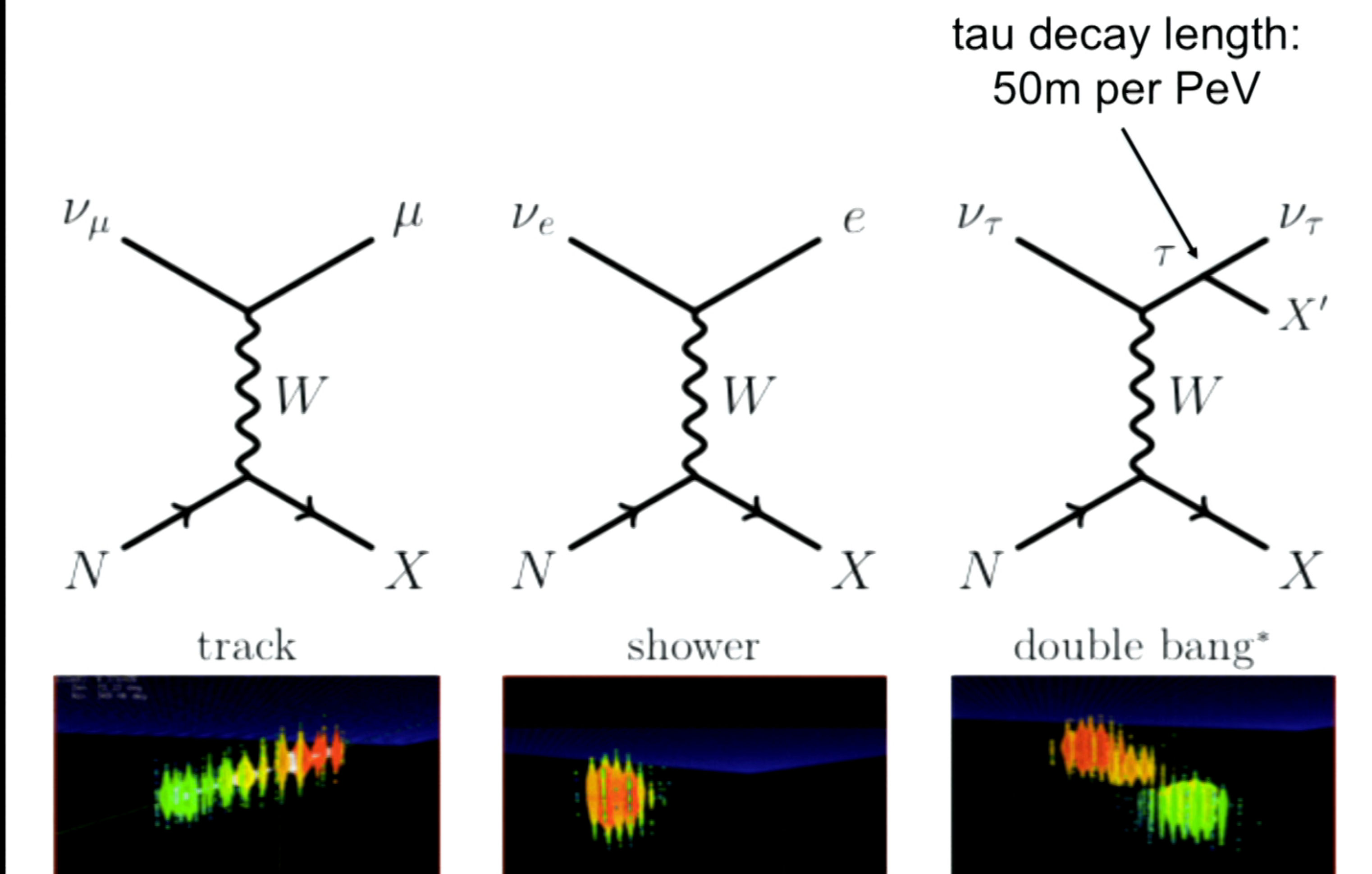
- → resonance: E_ν = 6.3 PeV

work on-going

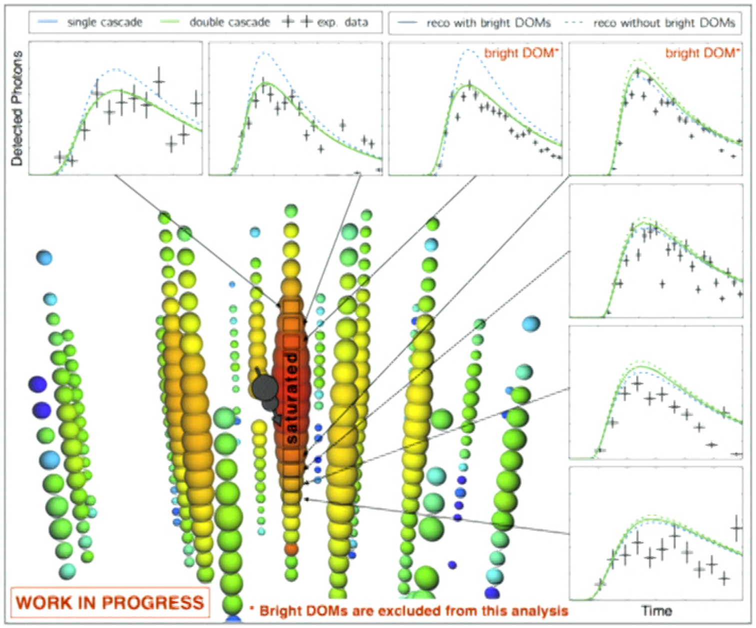
high-energy starting events – 7.5 yr



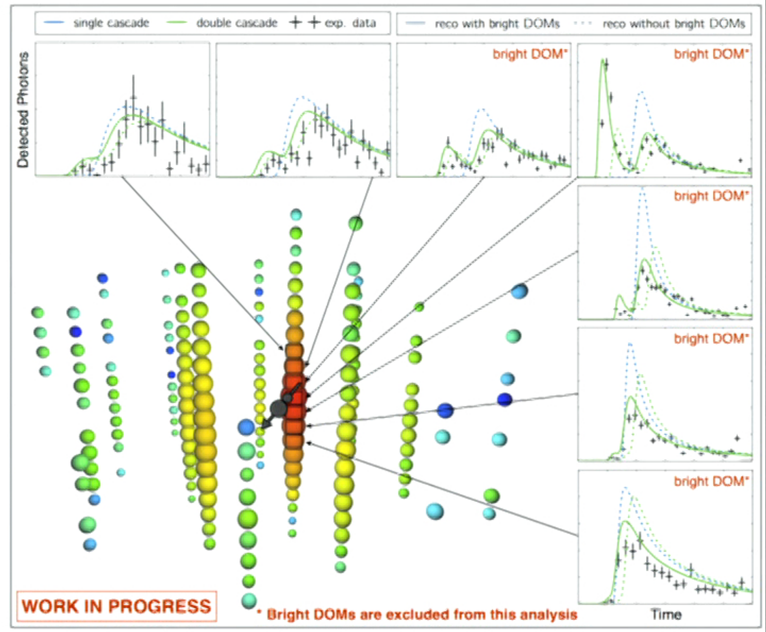
oscillations of PeV neutrinos over cosmic distances to 1:1:1


tau decay length:
50m per PeV
ν_μ
μ
W
N
X
ν_e
e
W
N
X
ν_τ
τ
ν_τ
X'
W
N
X
track
shower
double bang*

high-energy starting events (starting) – 7.5 yr



Double cascade Event #1

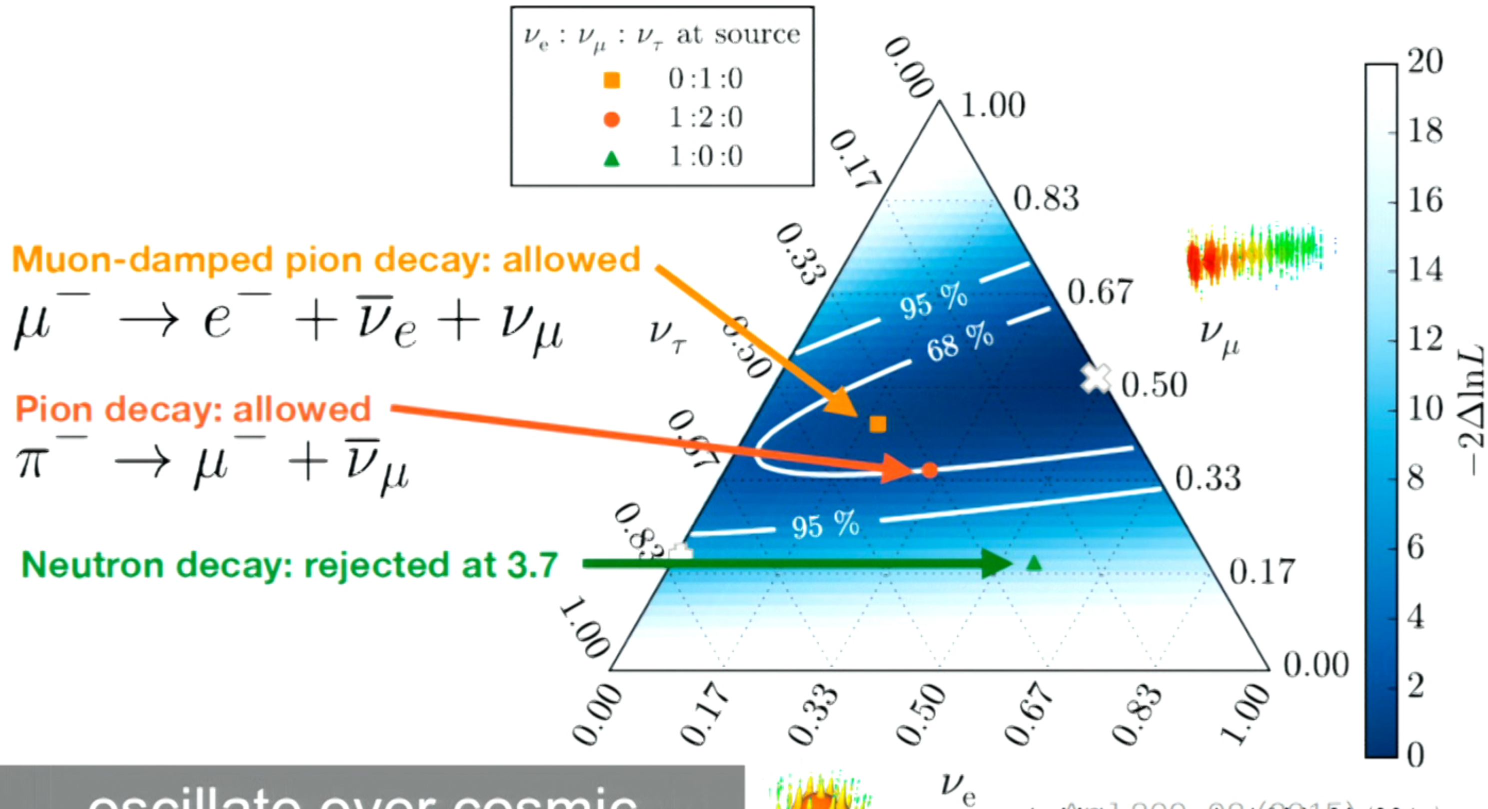


Double cascade Event #2

"Bright" DOMs not used in reconstruction

Direction and two reconstructed cascades shown in dark gray

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



oscillate over cosmic distances to 1:1:1

ApJ 809, 98 (2015)

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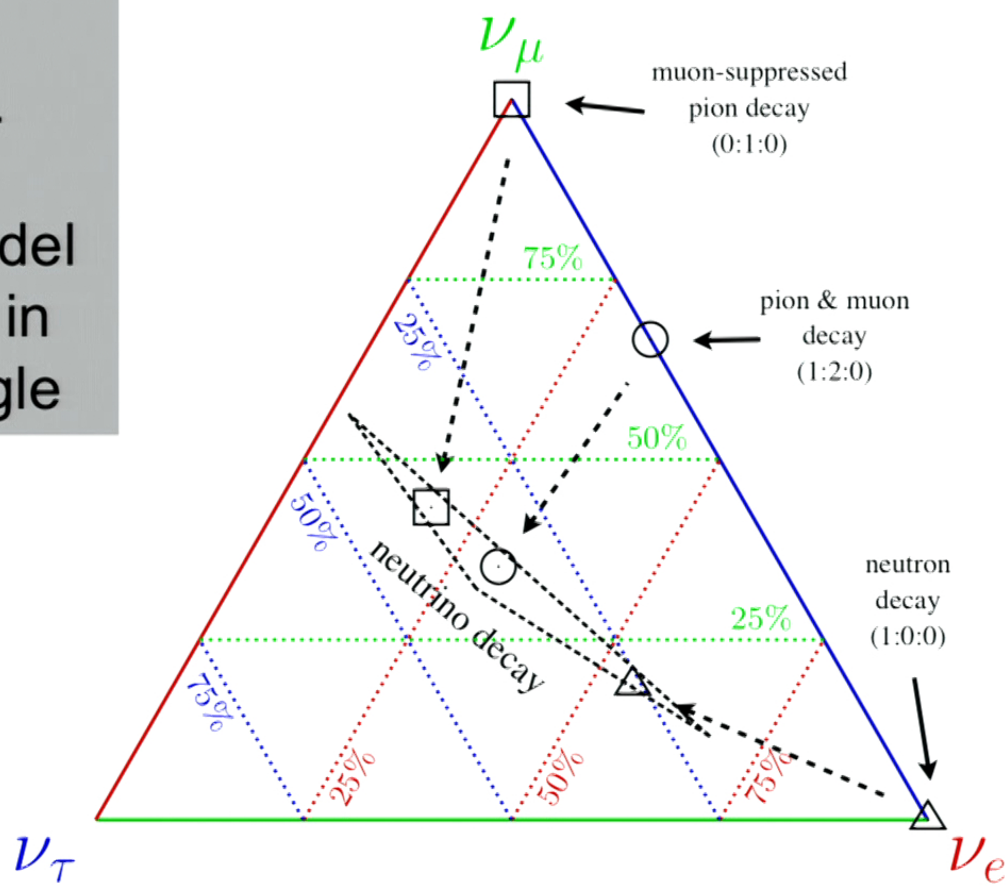
new physics ?

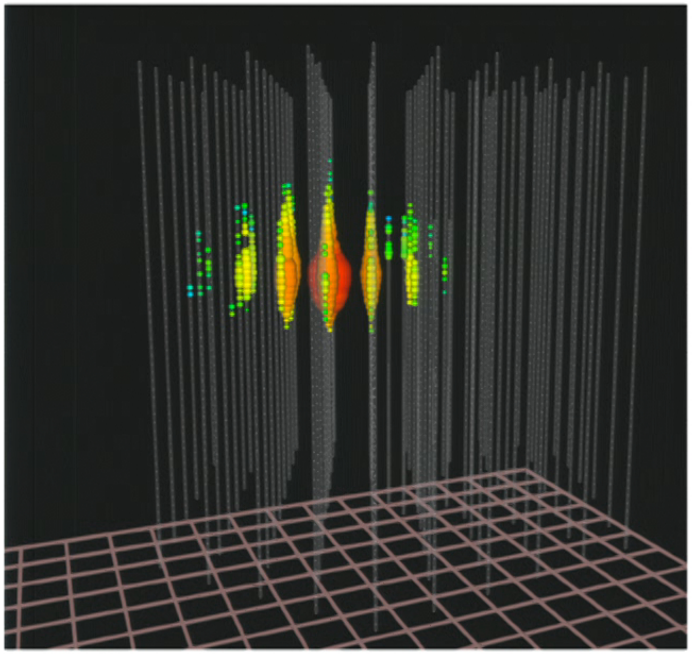
if not…

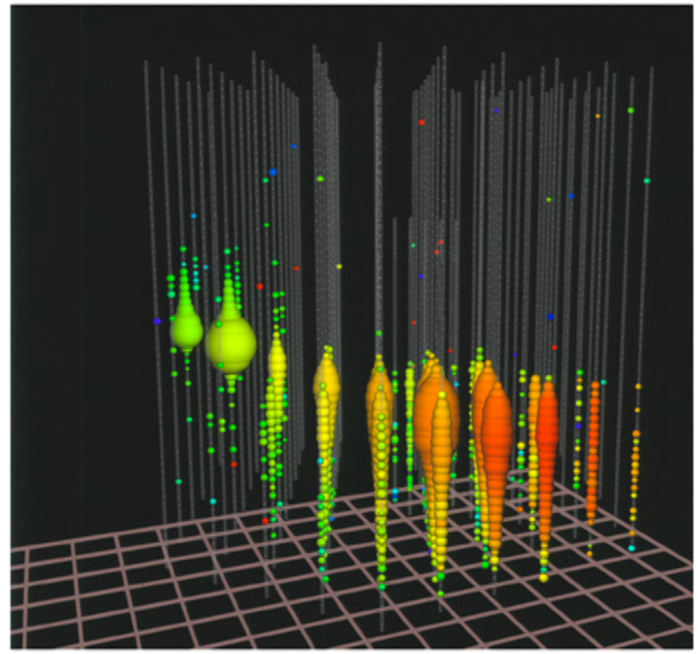
every model ends up in the triangle



isolated neutrinos interacting *inside* the detector (HESE)

up-going muon tracks (UPMU)

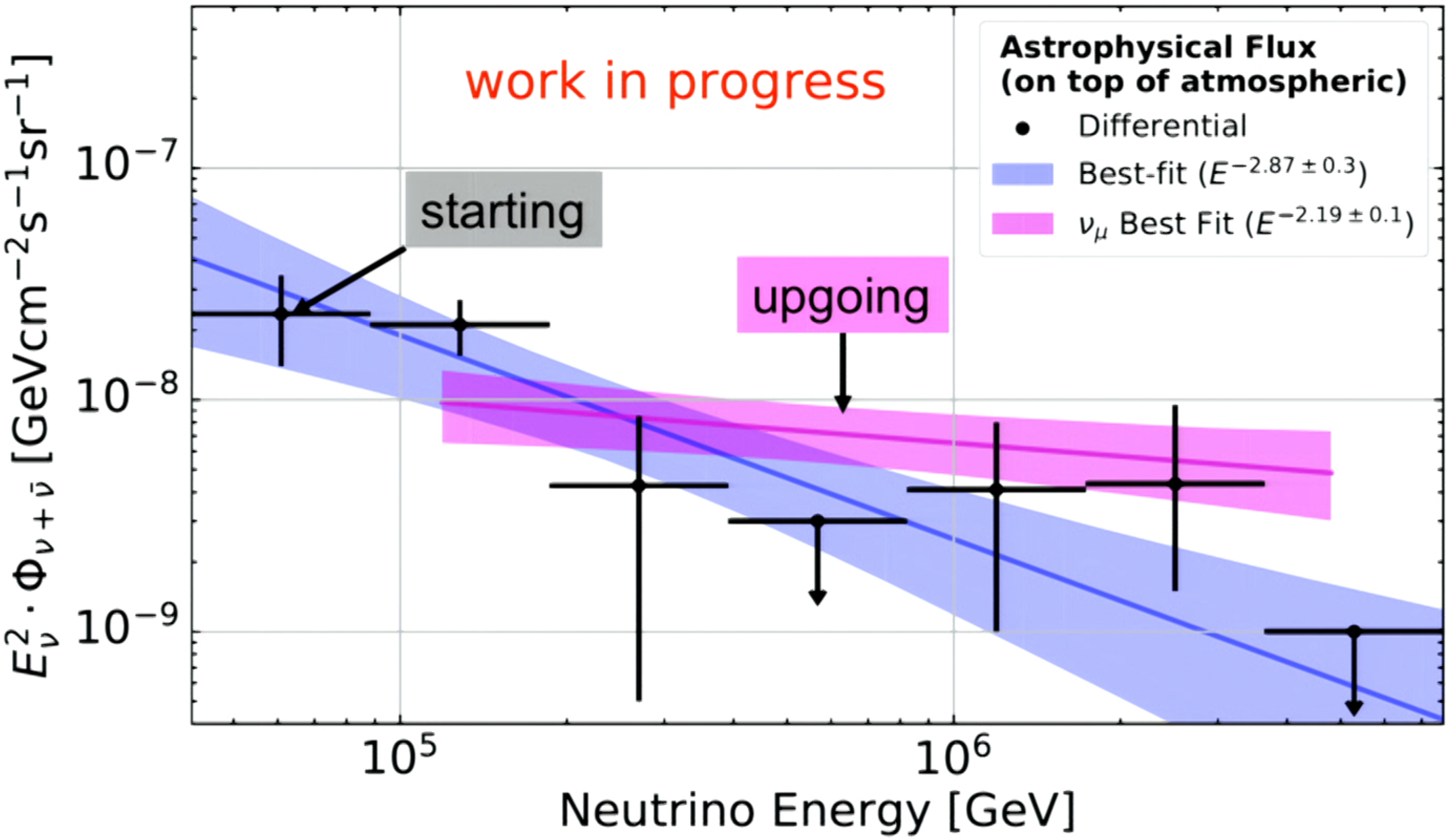




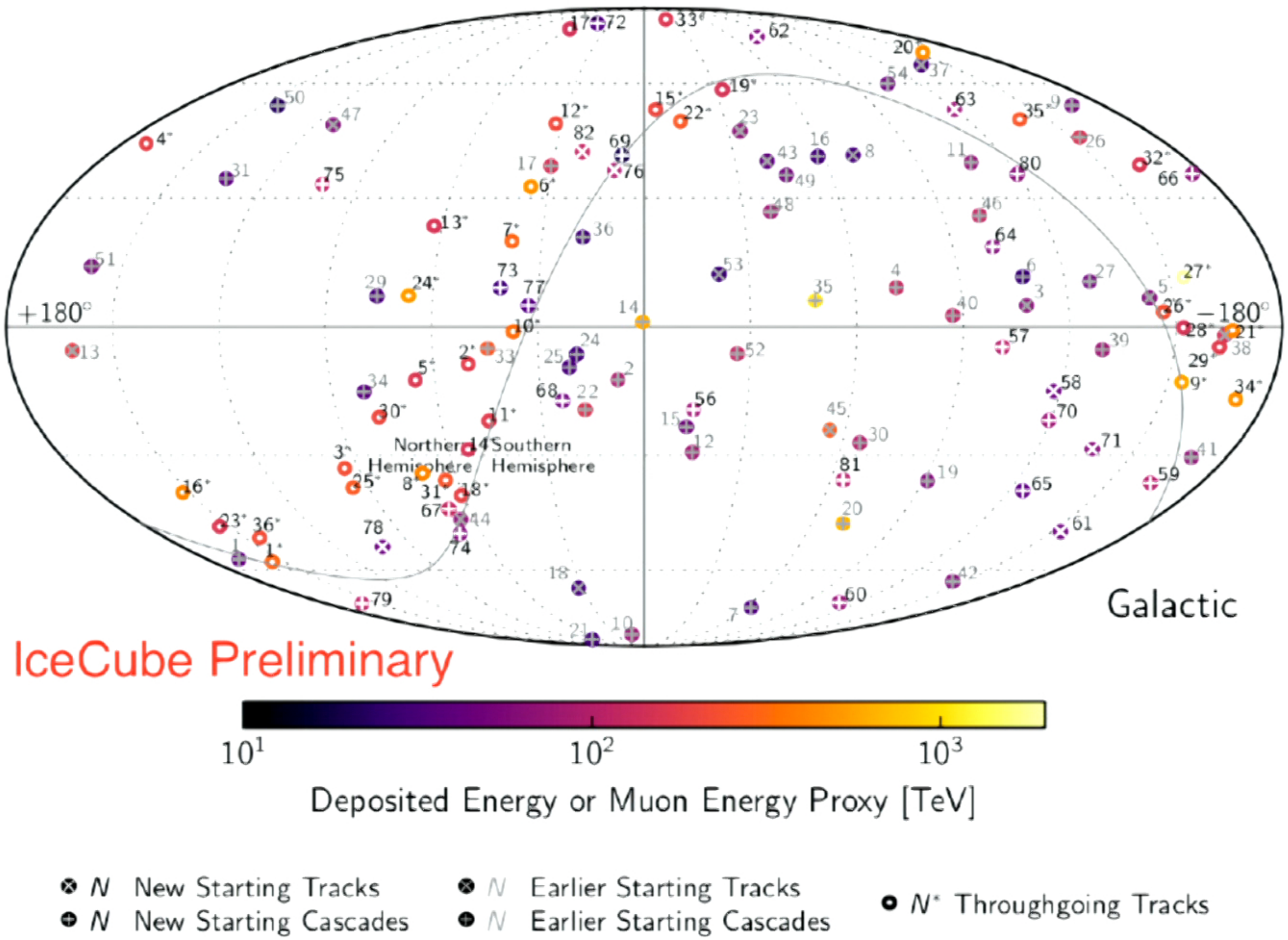
total energy measurement all flavors, all sky

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

high-energy starting events – 7.5 yr



two methods are consistent

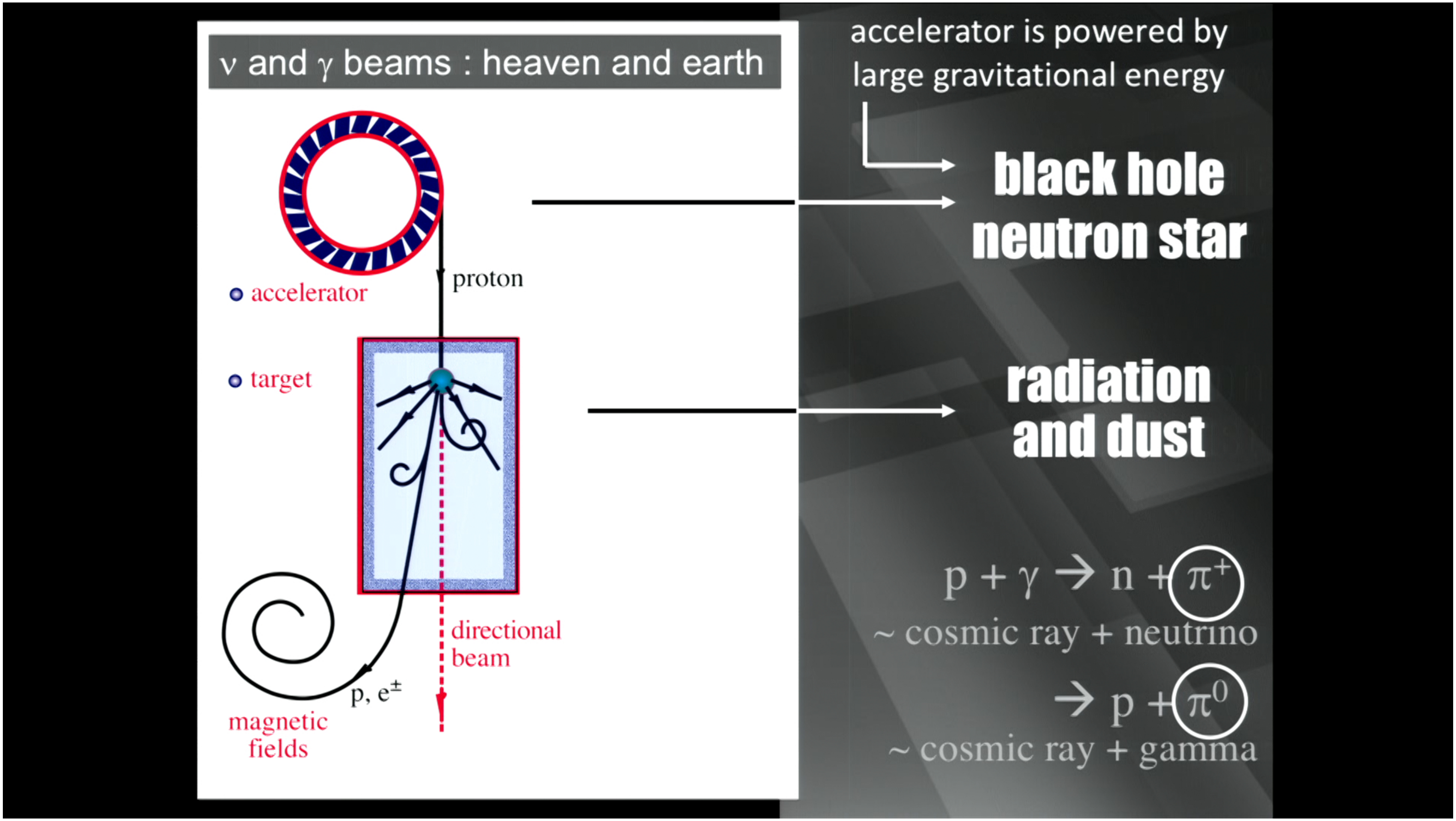


+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

- 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?]

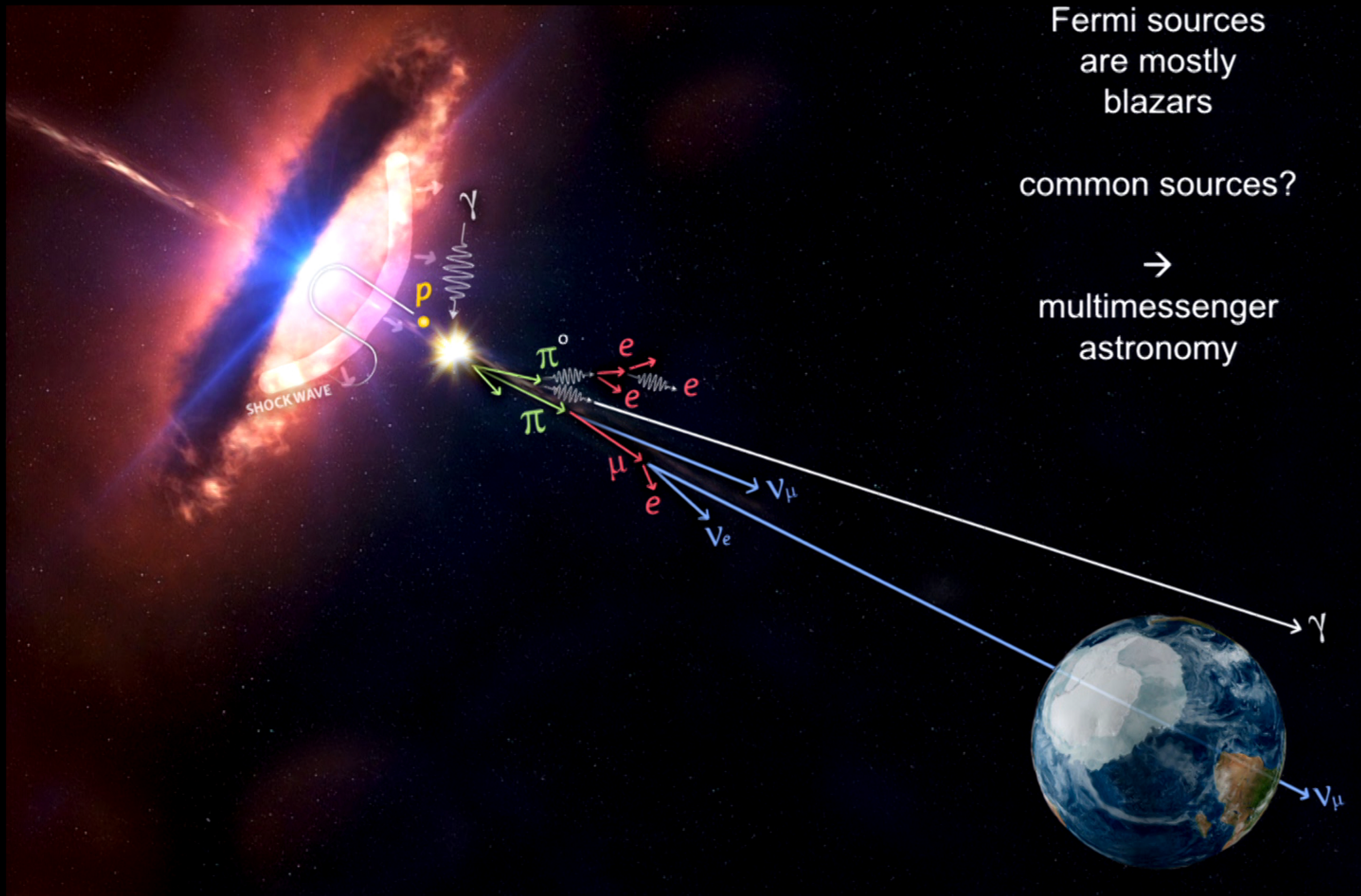

ν and γ beams : heaven and earth
accelerator
target
proton
magnetic fields
p, e±
directional beam
accelerator is powered by large gravitational energy
black hole
neutron star
radiation and dust
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma

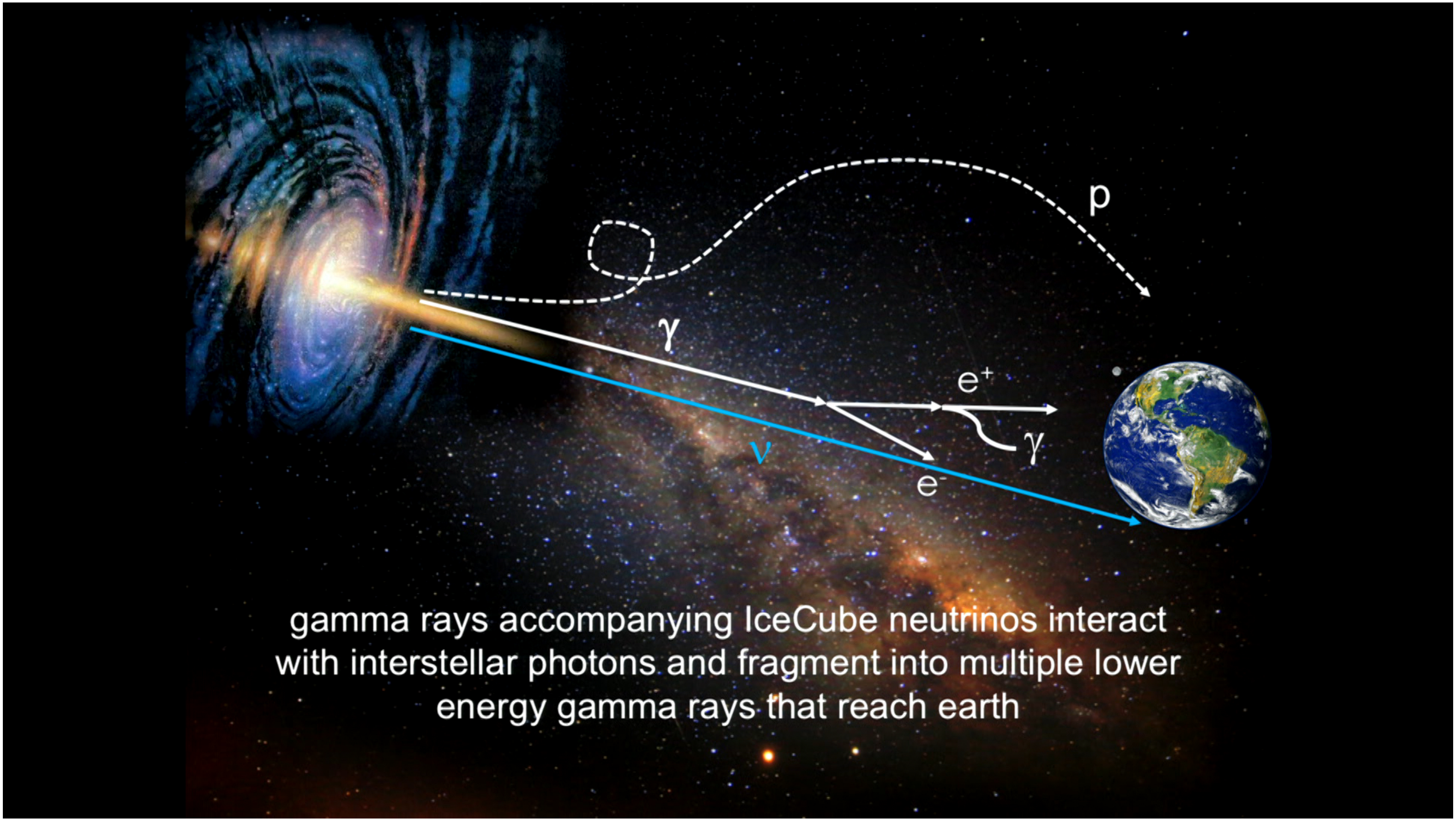
Fermi sources are mostly blazars

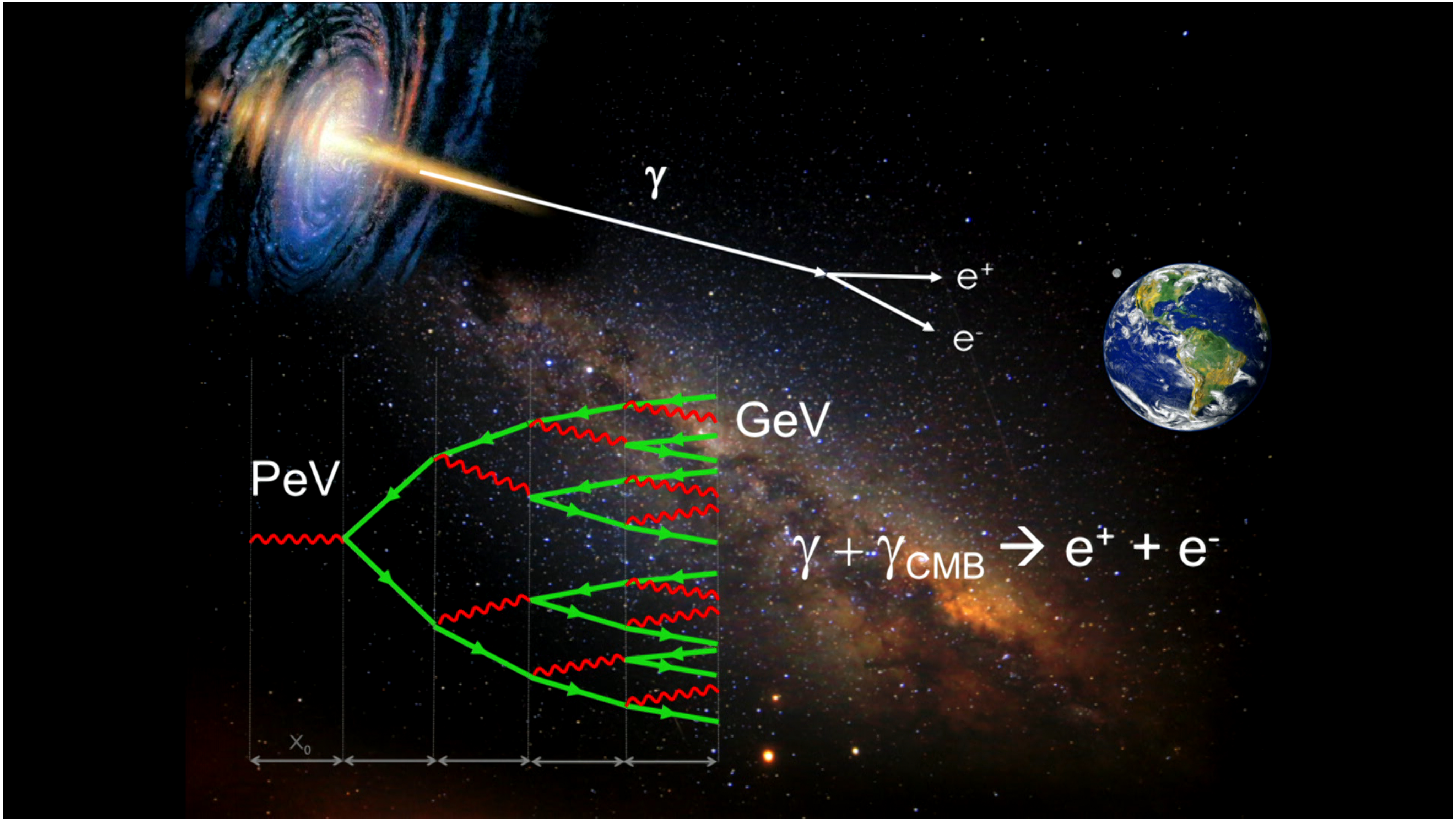
common sources?

→

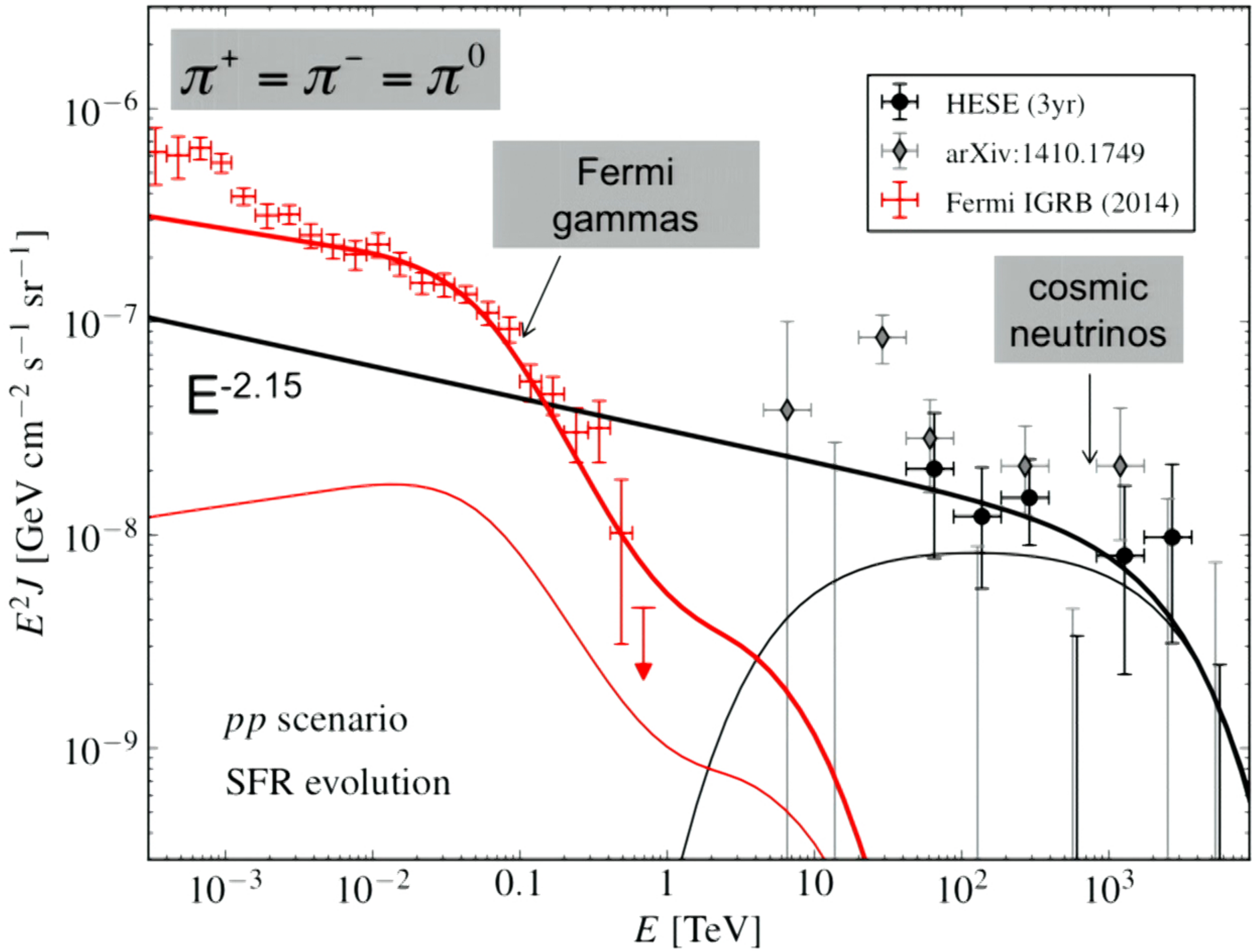
multimessenger astronomy



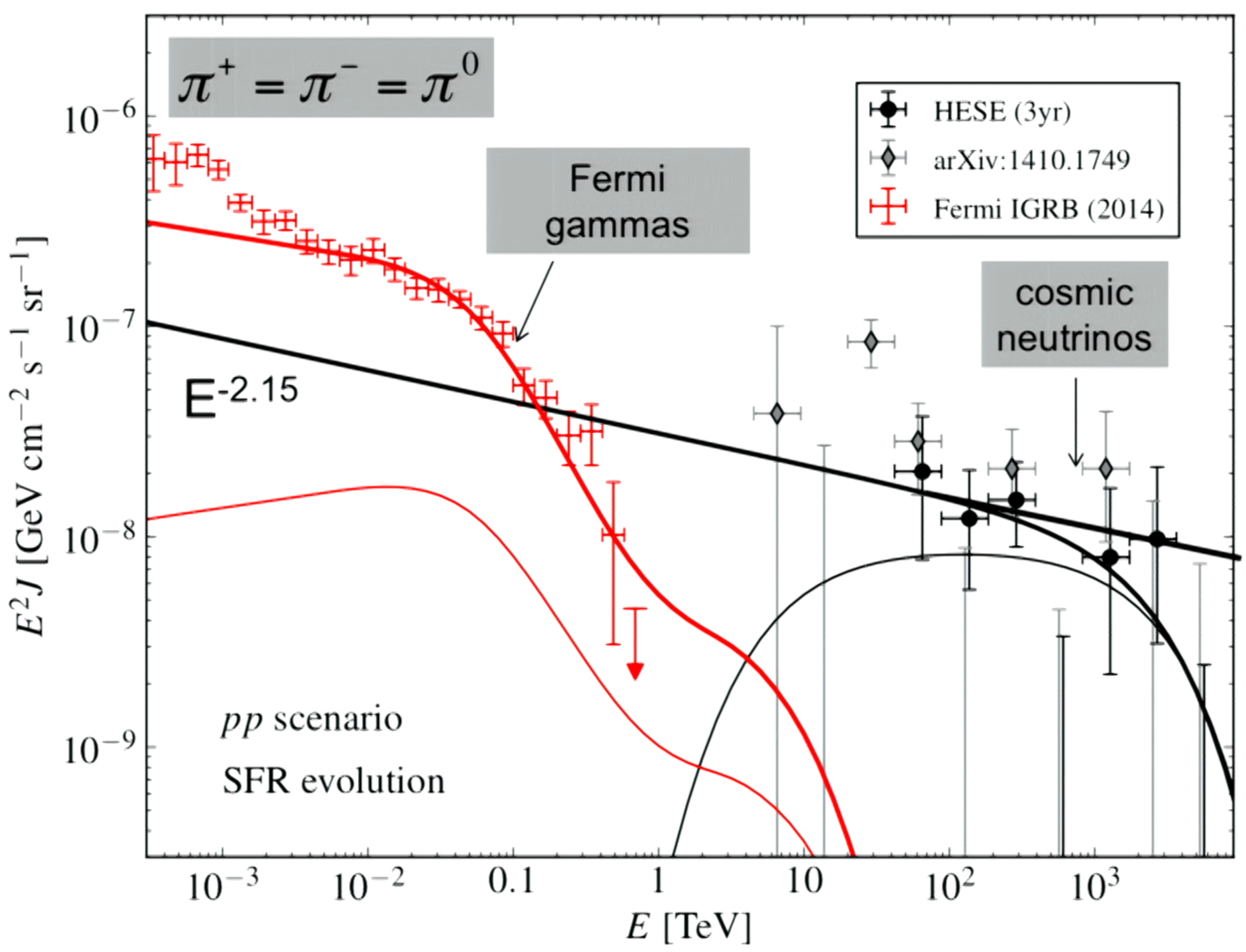

p
γ
e+
γ
ν
e-
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



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

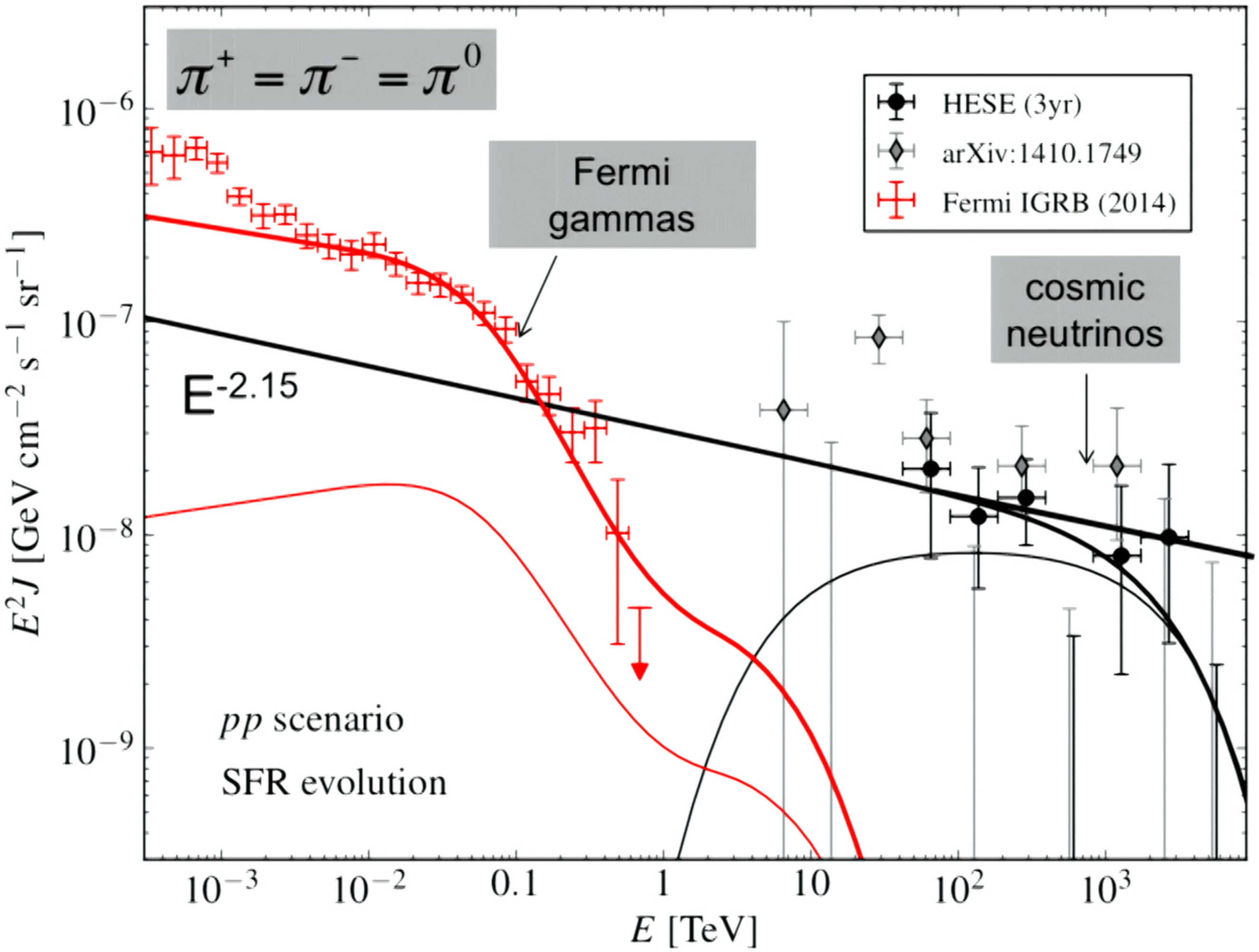


π⁺ = π⁻ = π⁰
Fermi gammas
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
cosmic neutrinos
E-2.15
pp scenario
SFR evolution
E²J [GeV cm⁻² s⁻¹ sr⁻¹]
E [TeV]



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

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



$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
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Fermi IGRB (2014)
Fermi gammas
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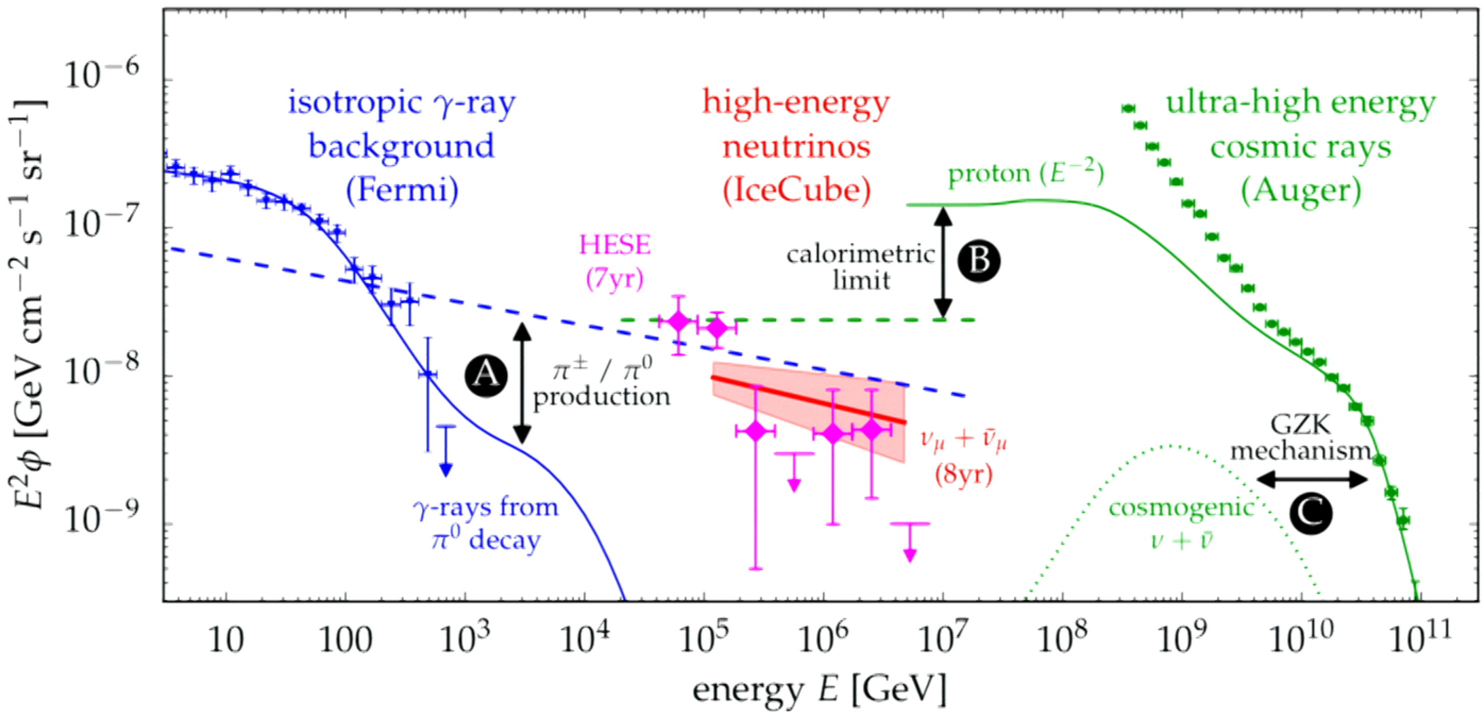
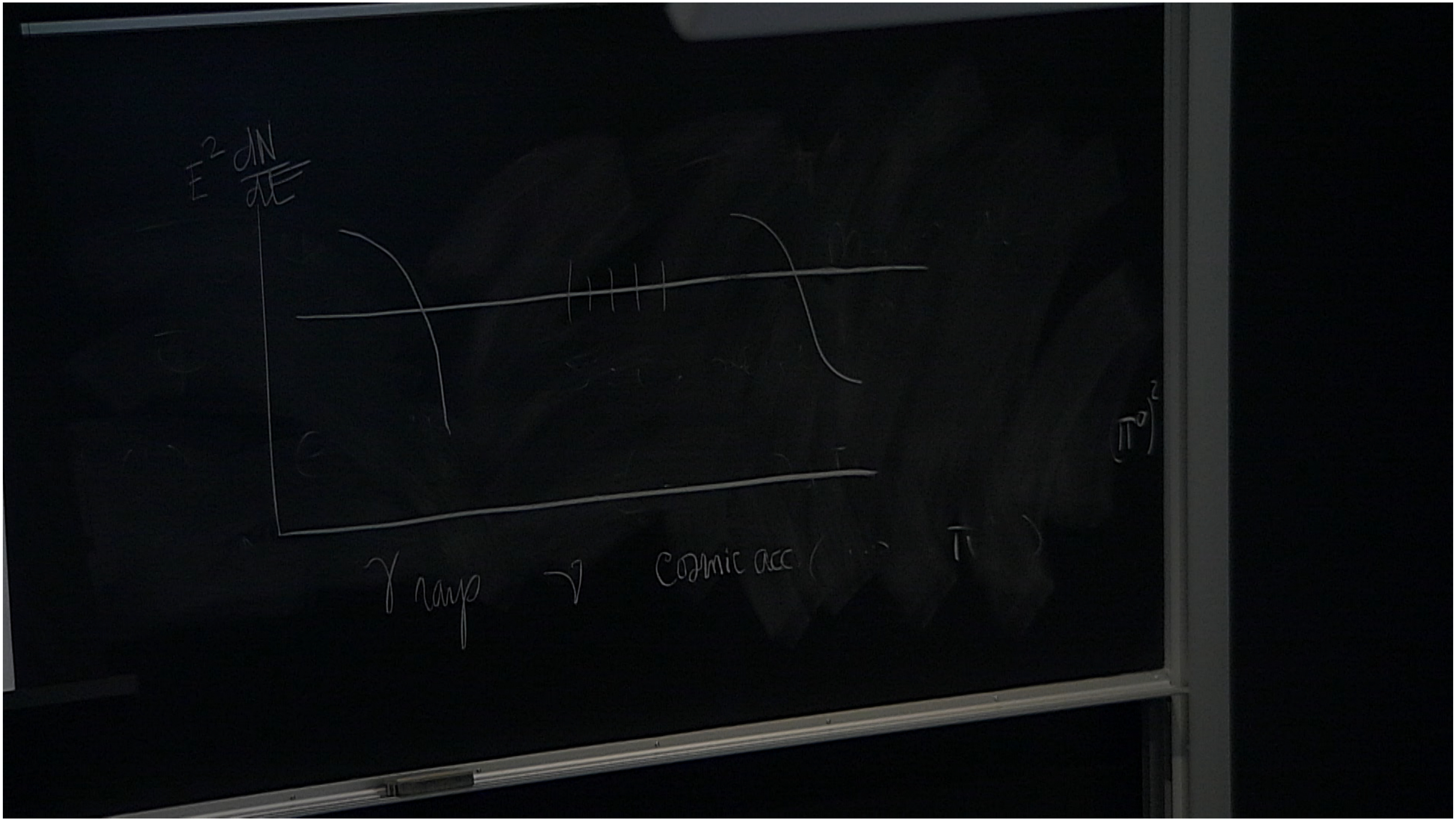
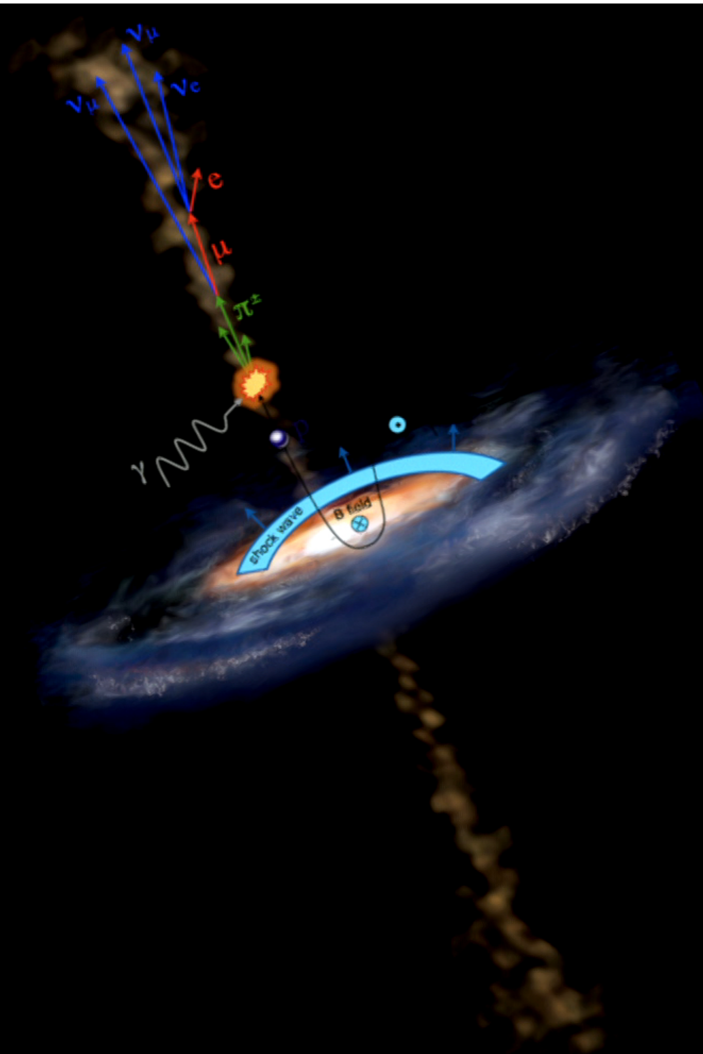
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]



similar energy density in the Universe in extragalactic cosmic rays



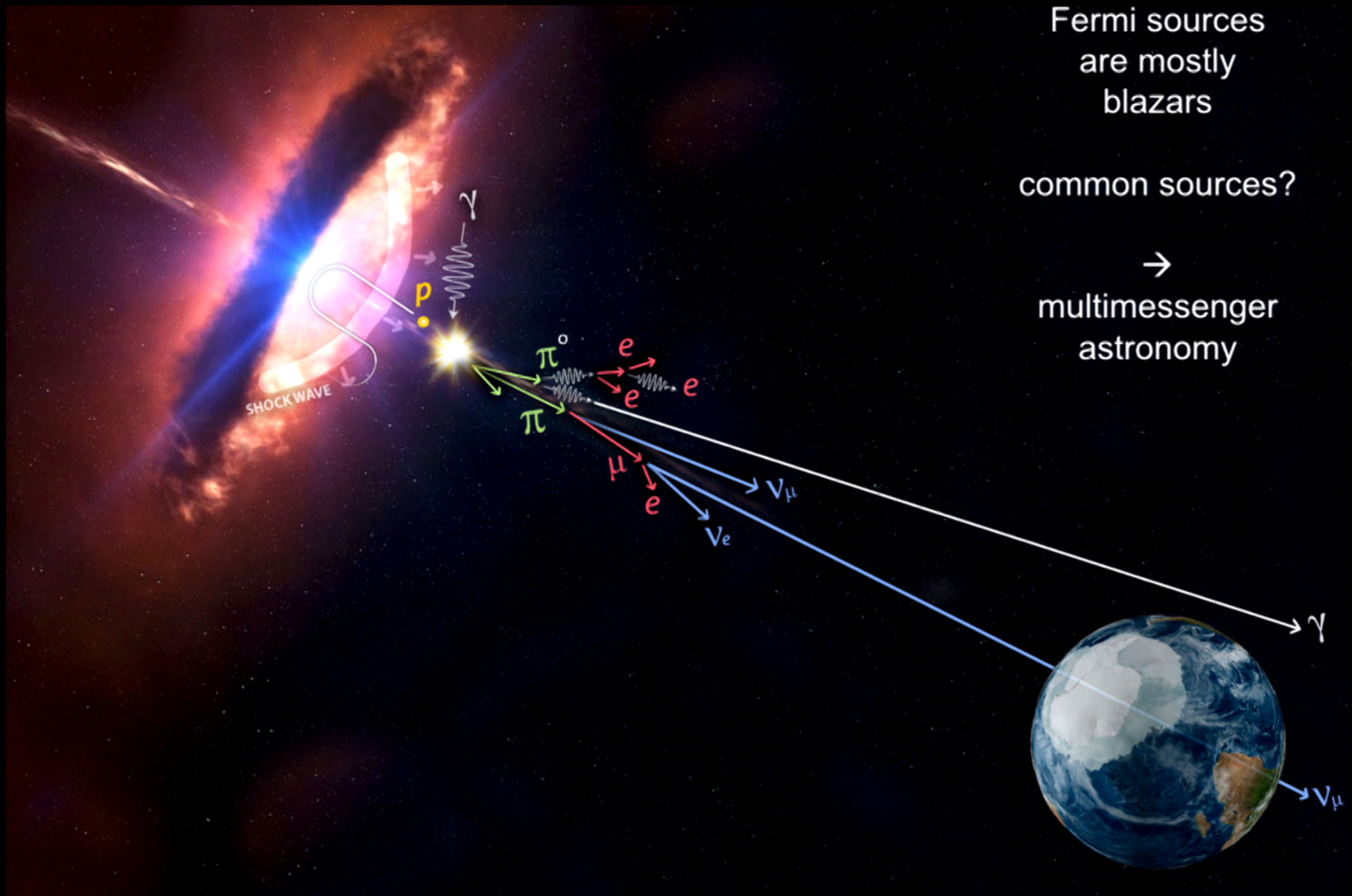
$E^2 \frac{dN}{dE}$
$(\pi^0)^2$
γ ray
ν
cosmic acc



Fermi sources
are mostly
blazars

common sources?

→
multimessenger
astronomy



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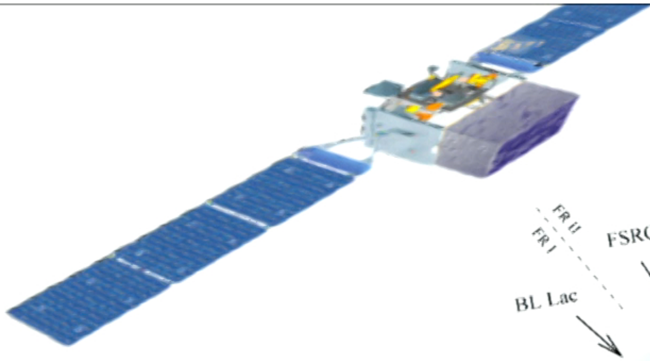
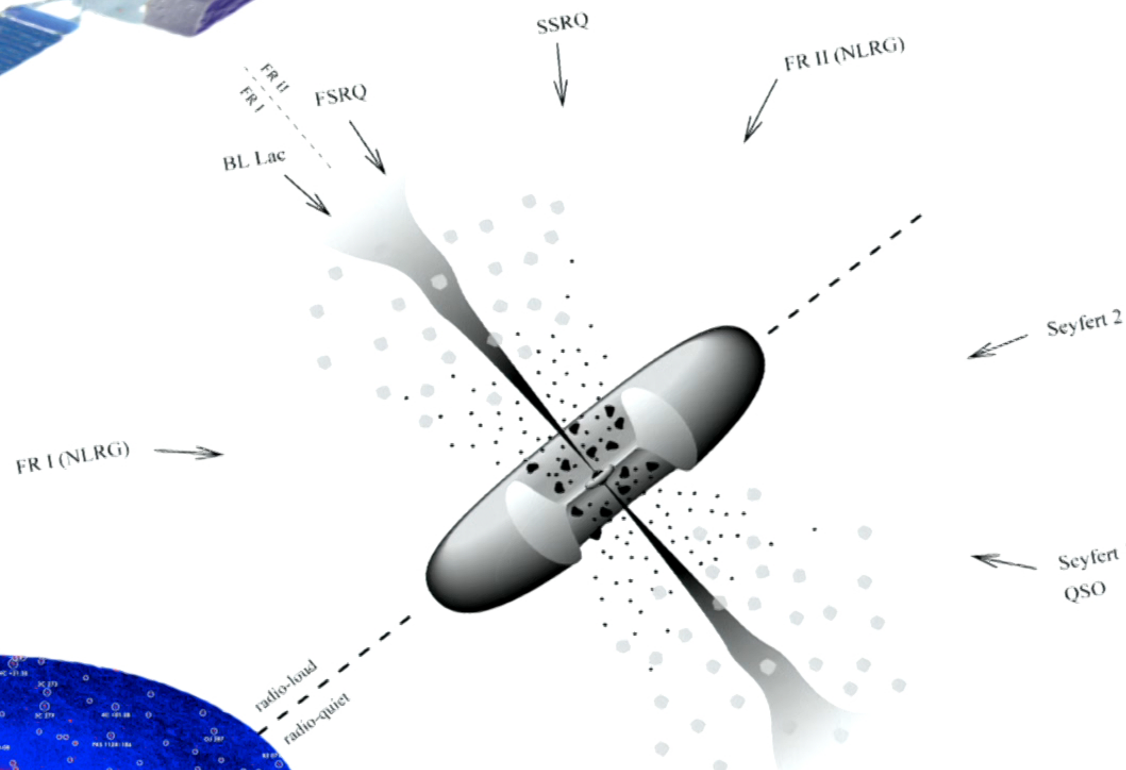
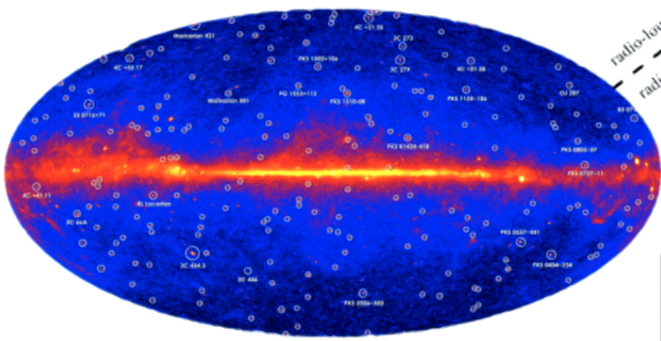
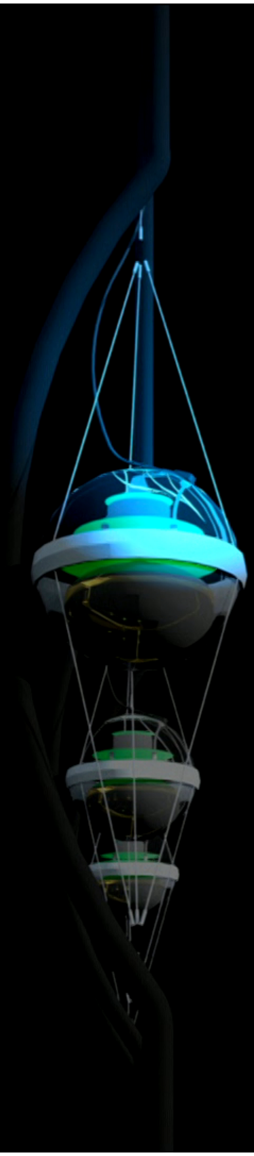






Fermi sky: mostly bazars



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?

iceCube.wisc.edu

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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

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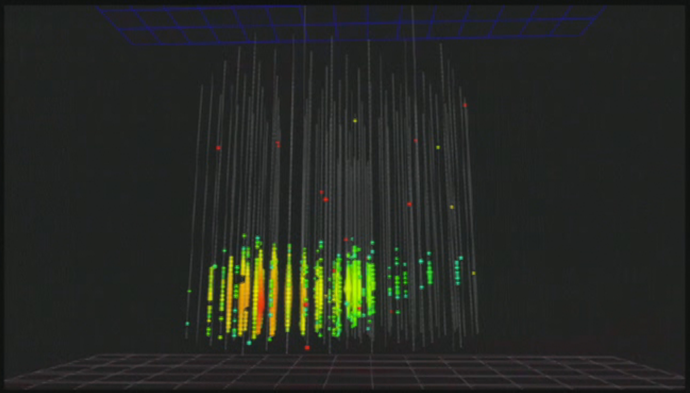
```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+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

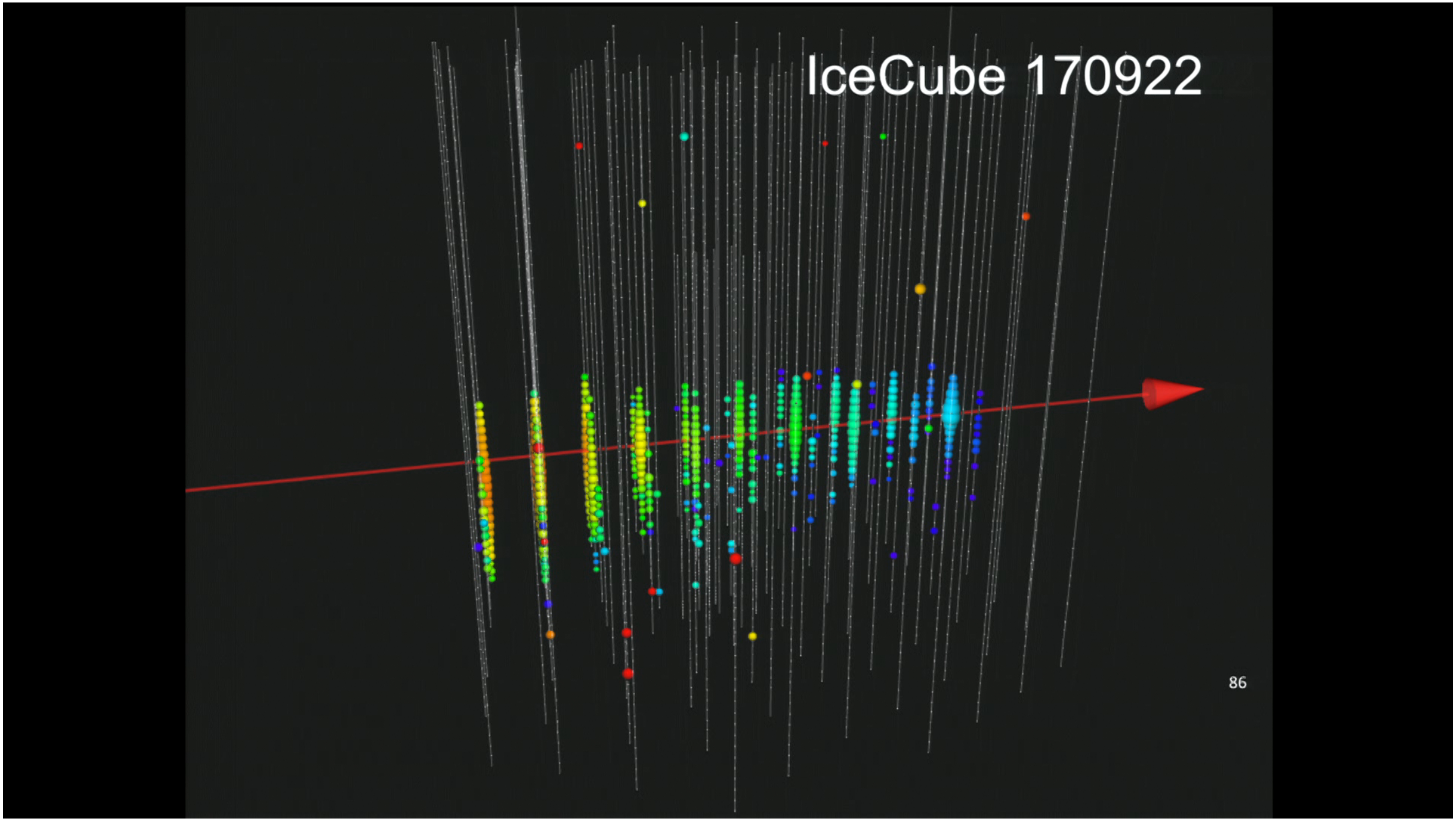
```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   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]
```

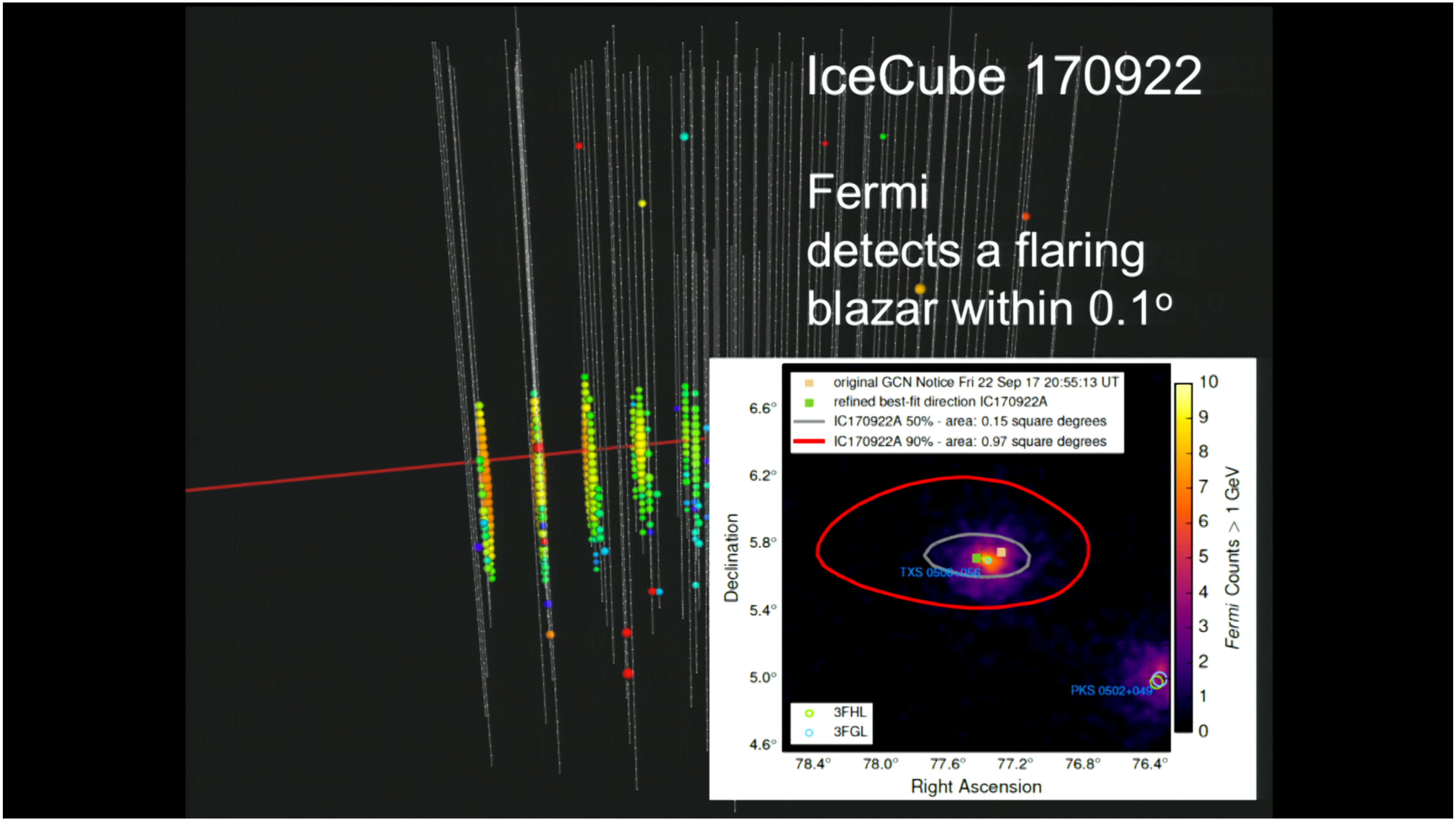
multiwavelength campaign launched by IC 170922

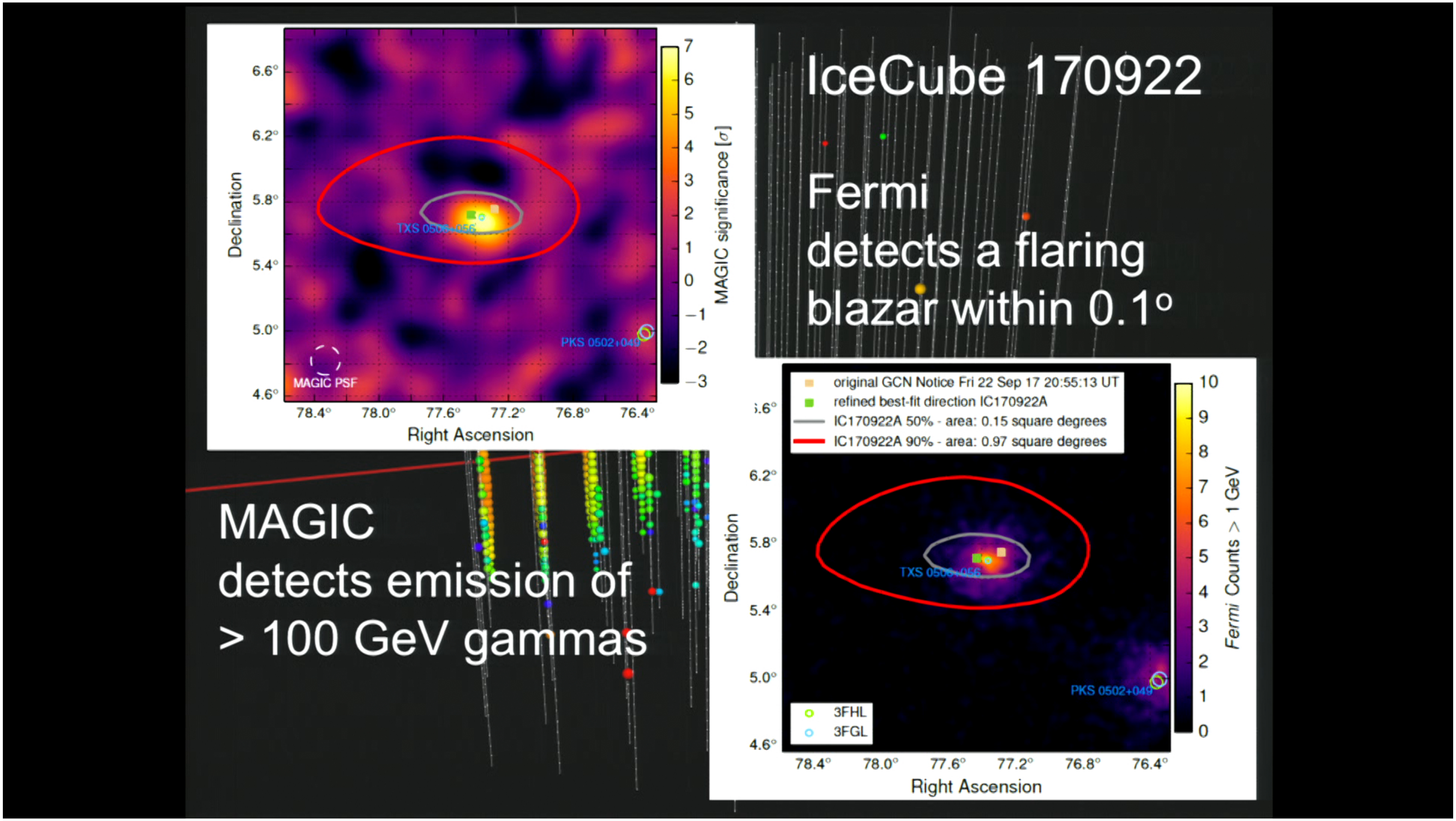
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

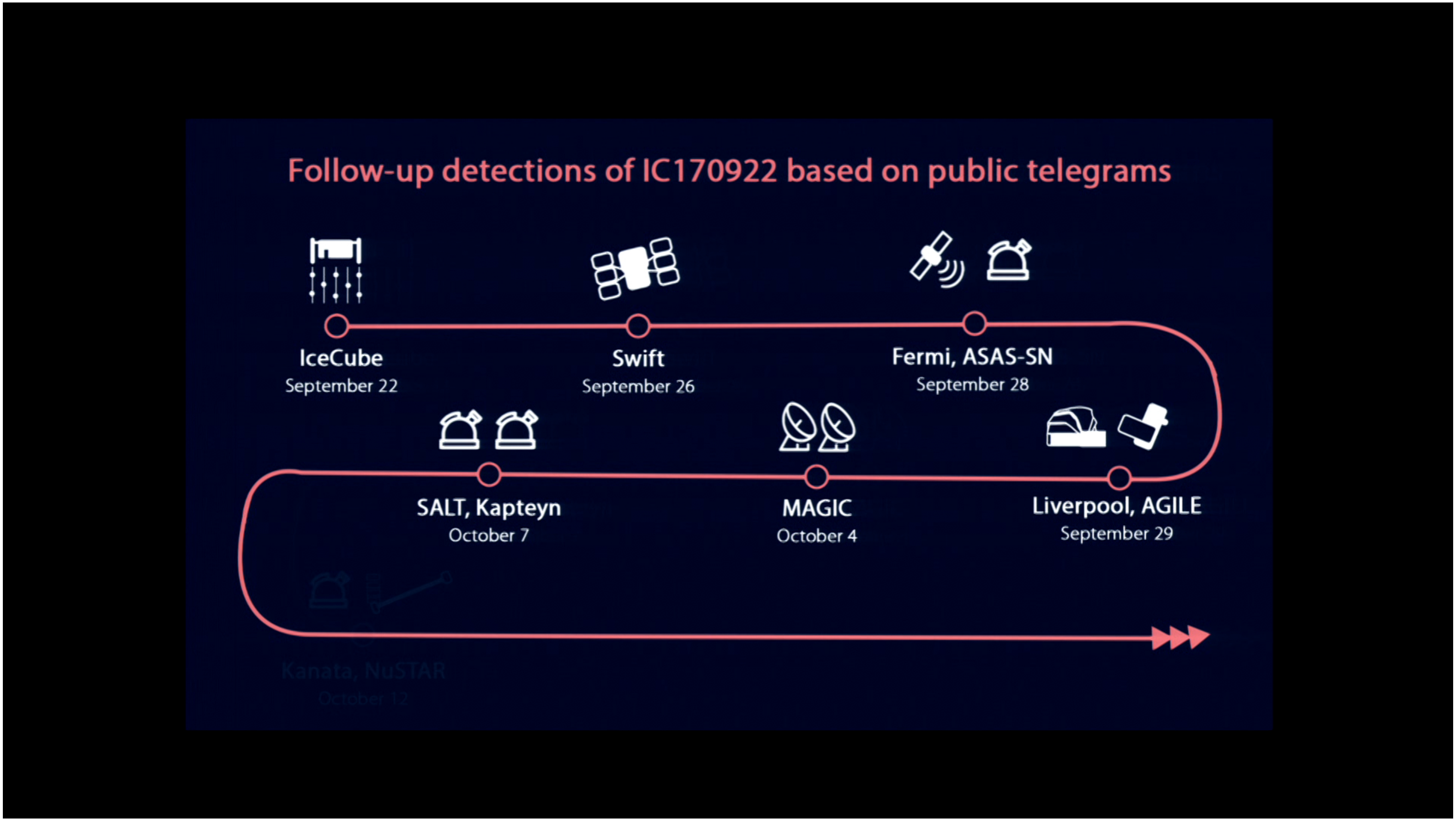
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.1^{o} (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT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

MAGIC atmposheric Cherenkov telescope

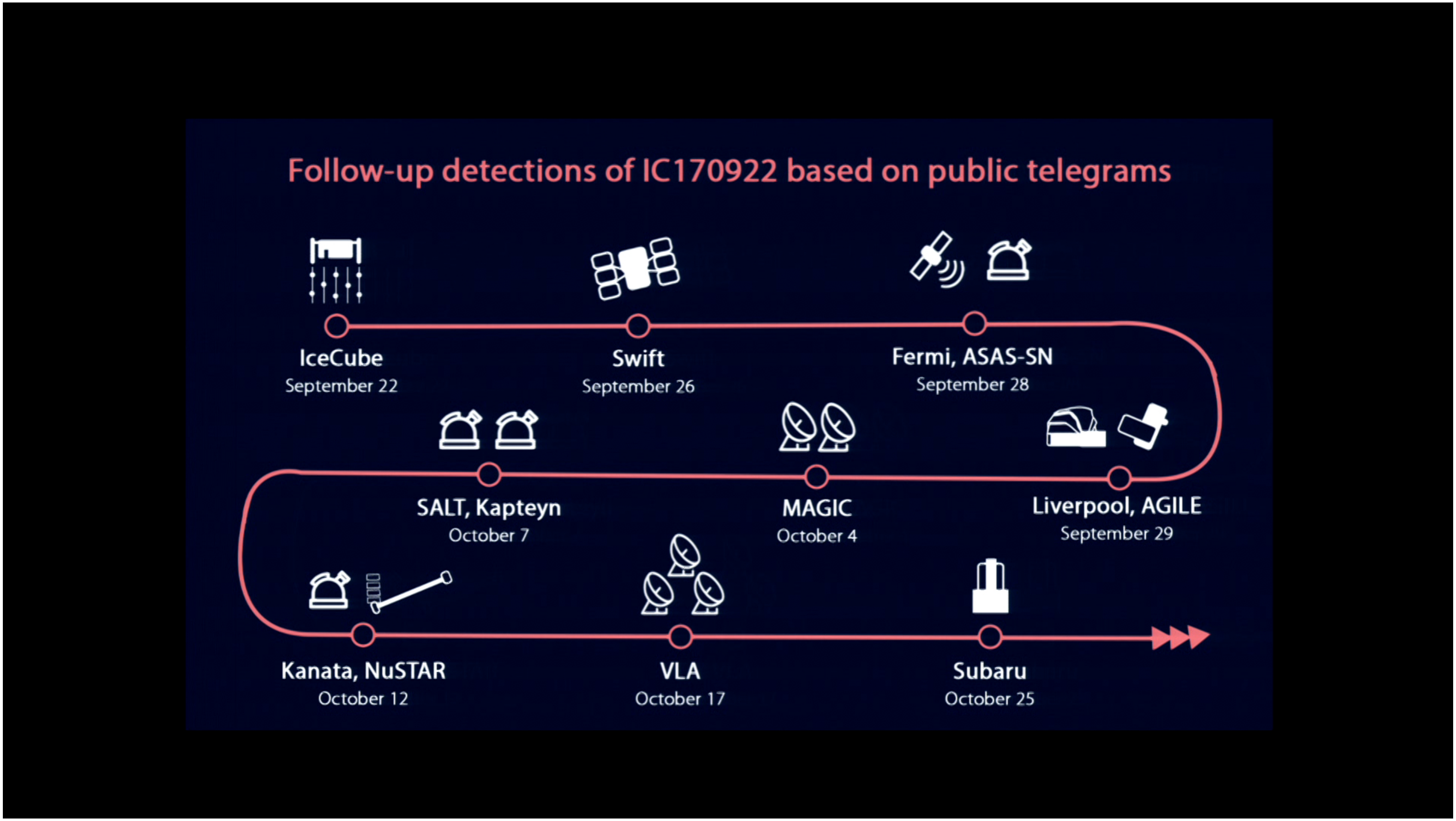

IceCube 170922
86


IceCube 170922
Fermi
detects a flaring
blazar within 0.1°
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
TXS 0506+056
PKS 0502+049
3FHL
3FGL
Declination
Right Ascension
Fermi Counts > 1 GeV

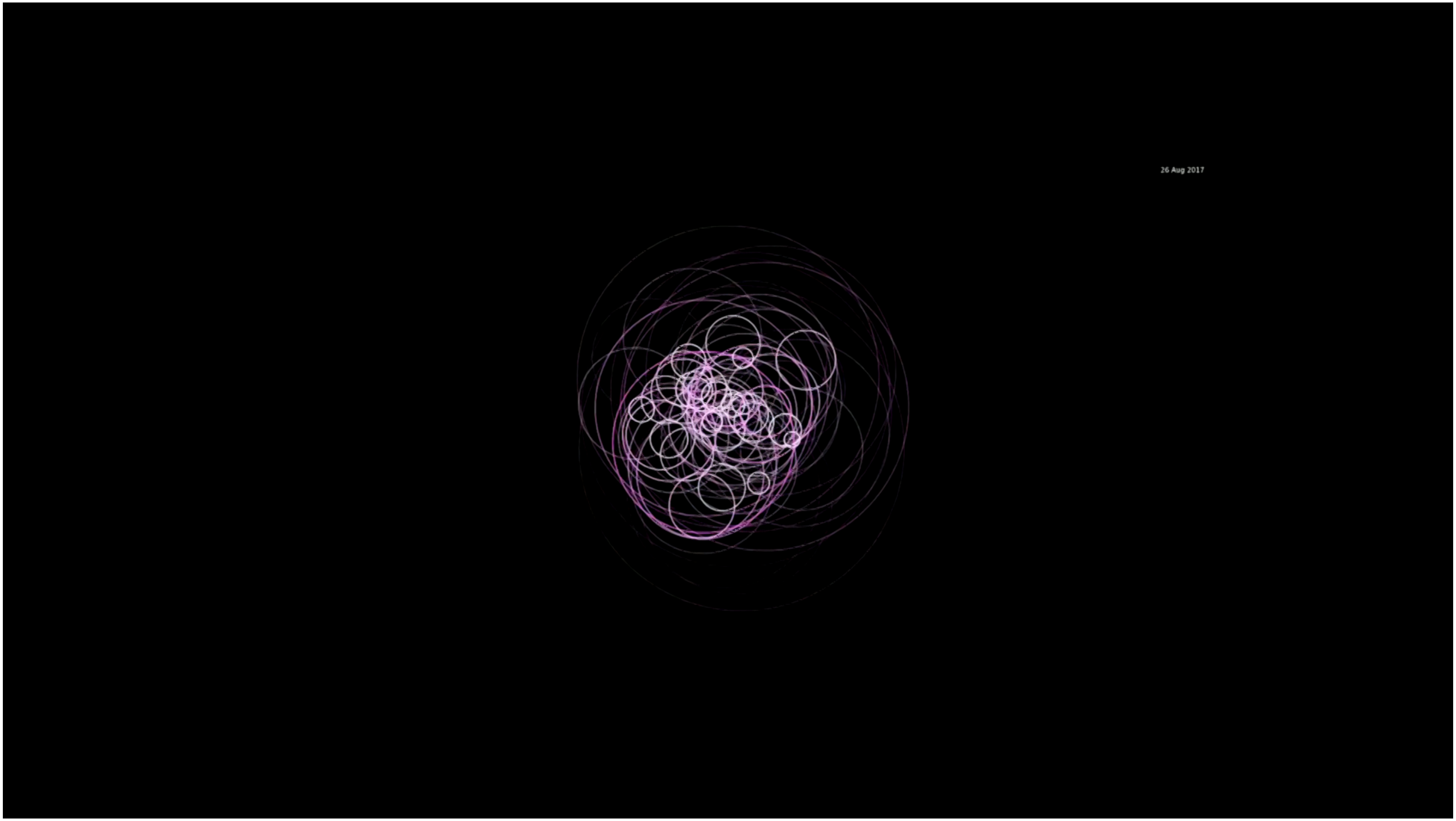

IceCube 170922
Fermi
detects a flaring
blazar within 0.1°
MAGIC
detects emission of
> 100 GeV gammas
MAGIC significance [σ]
Declination
Right Ascension
TXS 0506+056
PKS 0502+049
MAGIC PSF
original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
3FHL
3FGL
Fermi Counts > 1 GeV

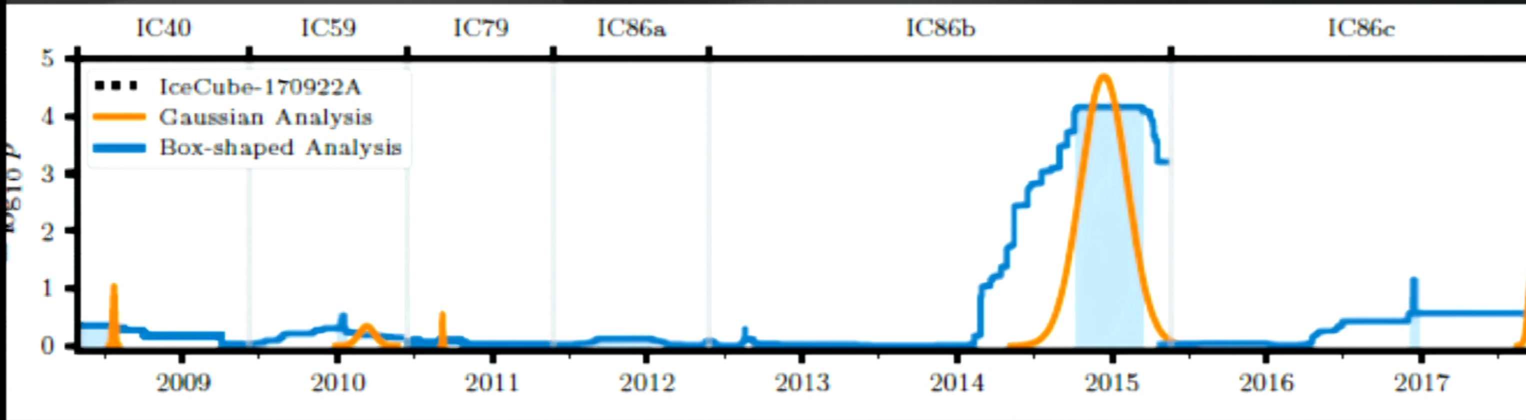


Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
Liverpool, AGILE
September 29
MAGIC
October 4
SALT, Kapteyn
October 7
Kanata, NuSTAR
October 12



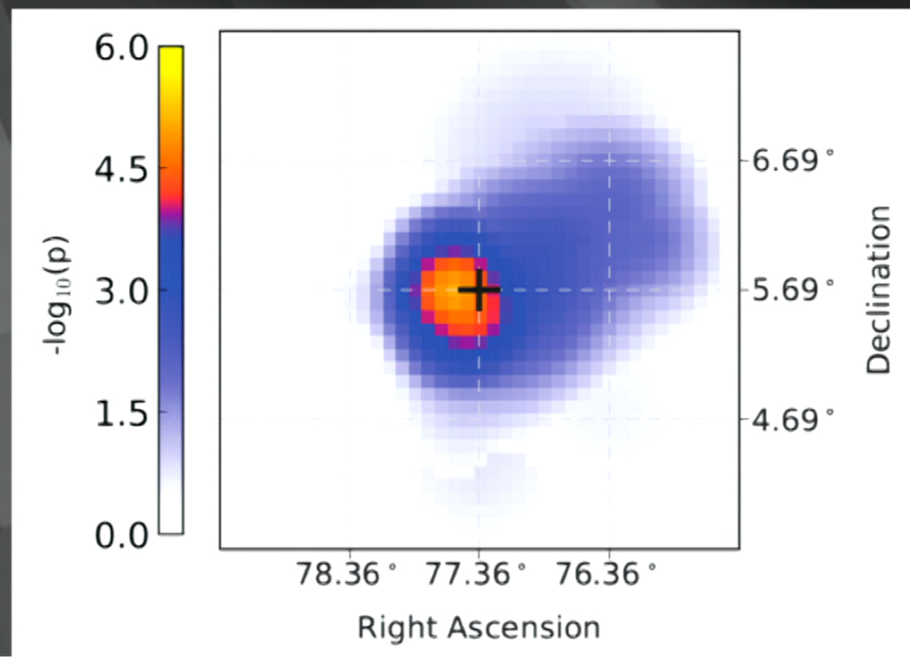
Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
SALT, Kapteyn
October 7
MAGIC
October 4
Liverpool, AGILE
September 29
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25

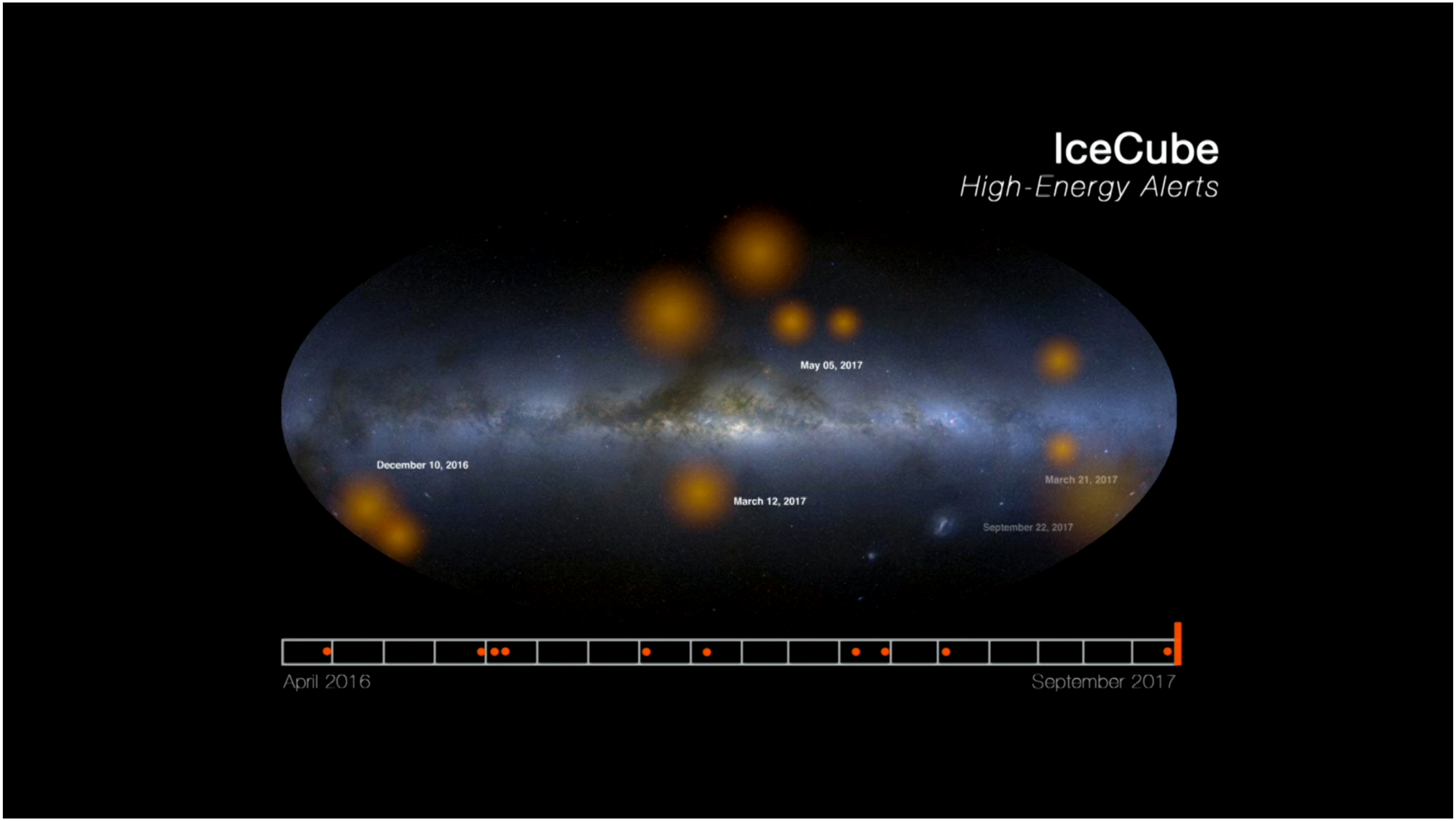

26 Aug 2017

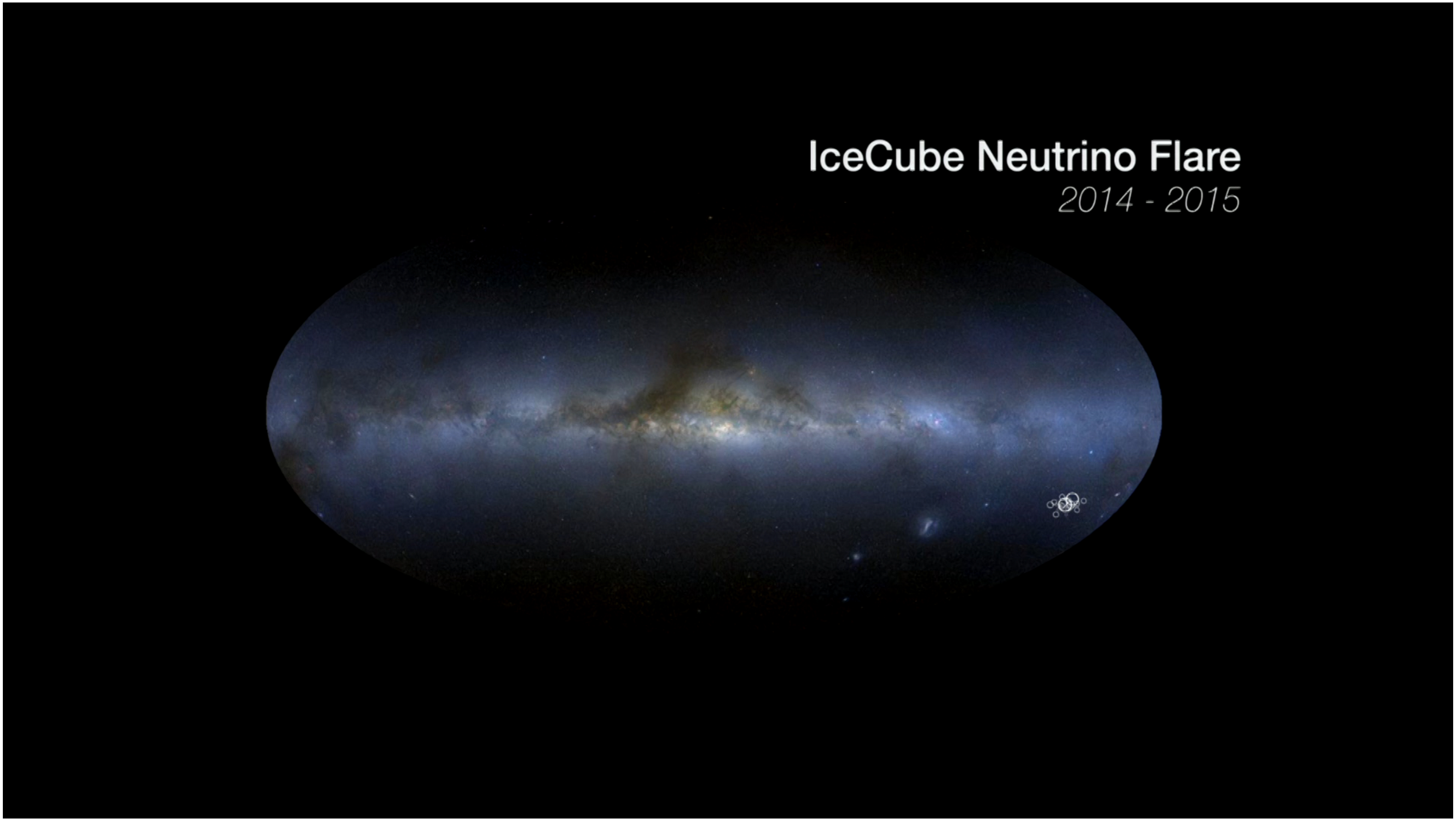


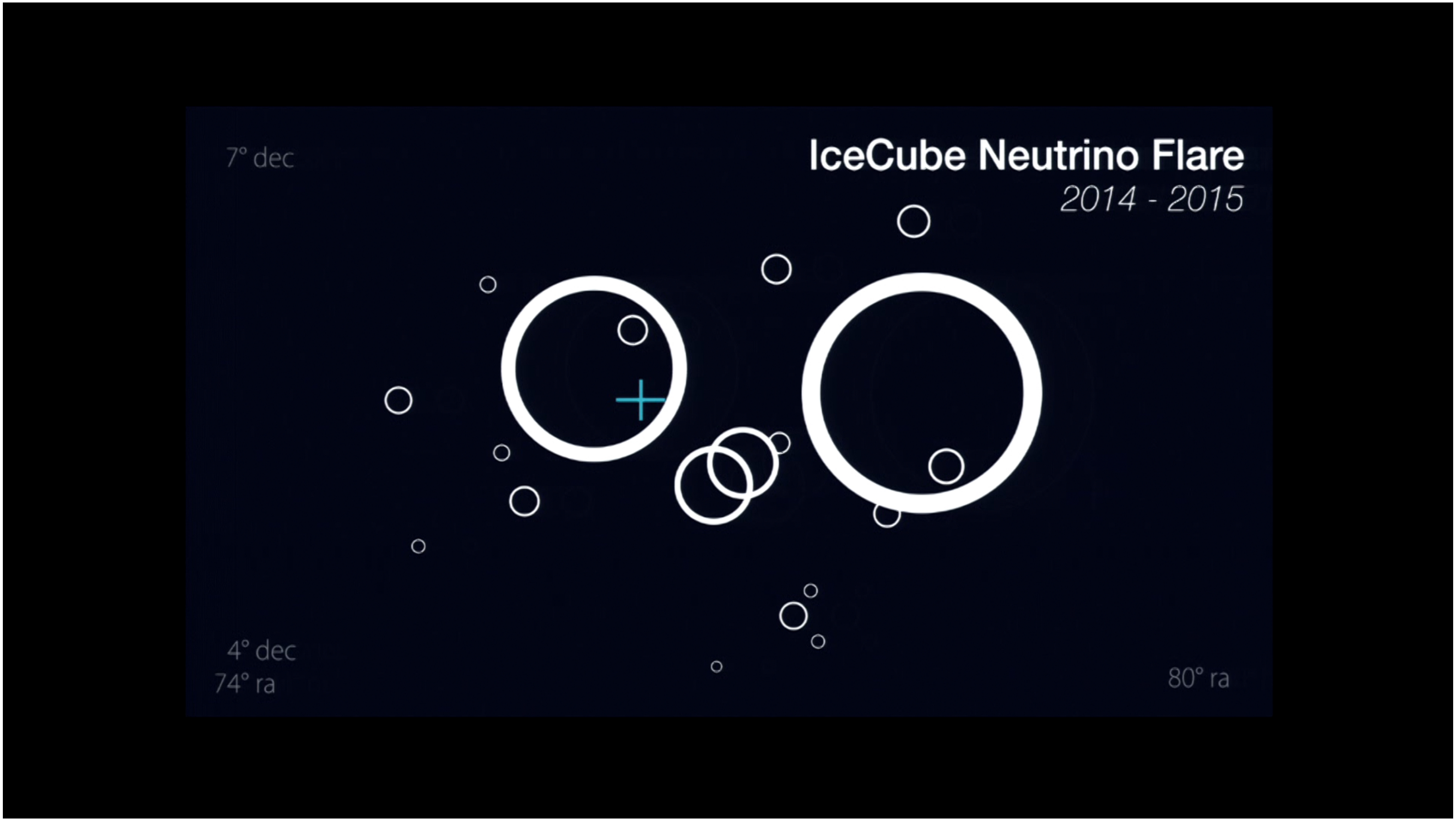
search in archival IceCube data:

- ~100 day flare in December 2014
- accompanied by hardening of the Fermi spectrum




IceCube
High-Energy Alerts
May 05, 2017
December 10, 2016
March 12, 2017
March 21, 2017
September 22, 2017
April 2016
September 2017


IceCube Neutrino Flare
2014 - 2015


7° dec
IceCube Neutrino Flare
2014 - 2015
4° dec
74° ra
80° ra

IceCube

South Pole Neutrino Observatory

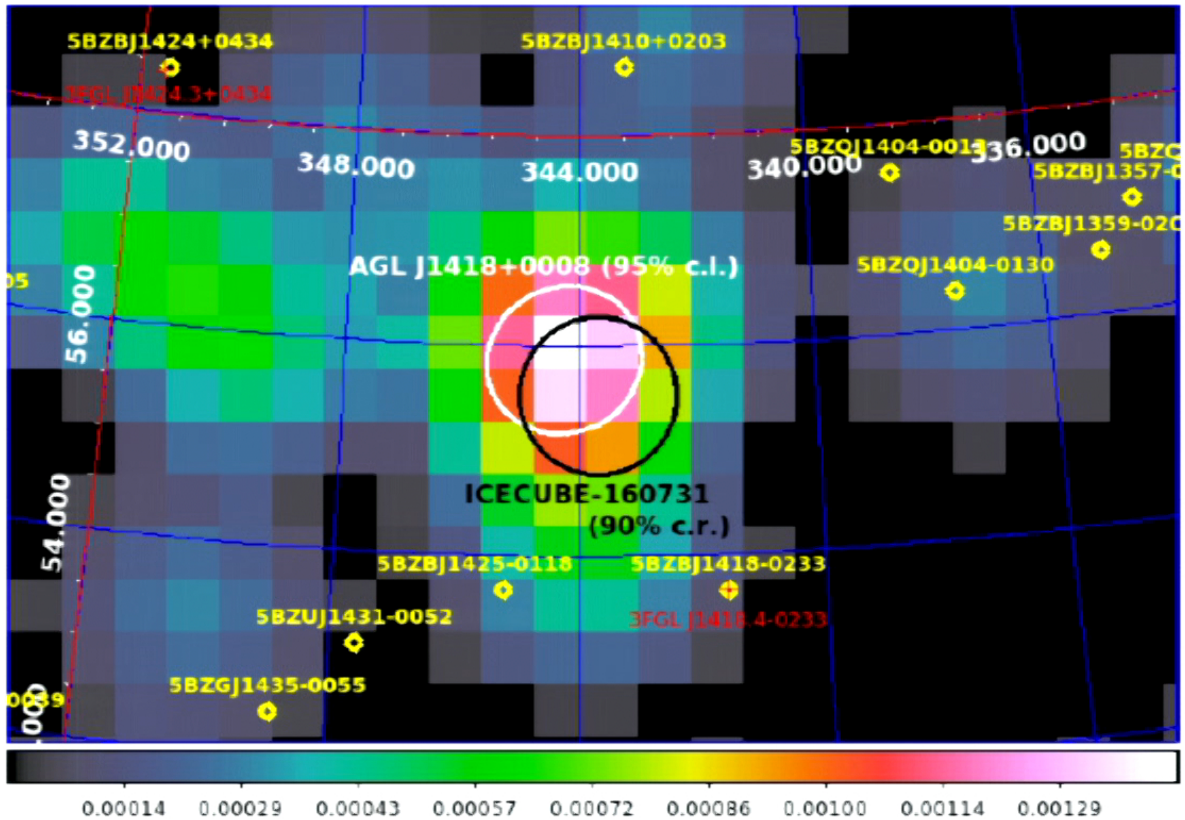
we identified a source of high energy cosmic rays:

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

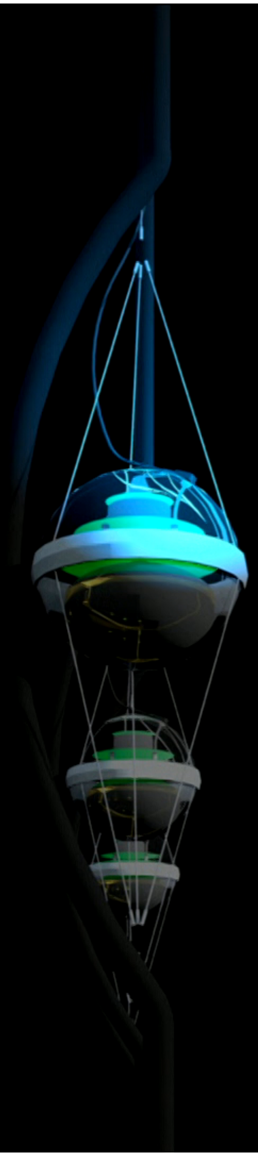
extensive multiwavelength campaign will allow us to study the first cosmic accelerator

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

F. Lucarelli,[1,2] C. 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



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