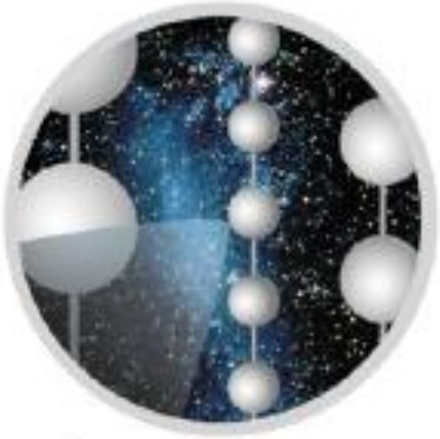


neutrino astronomy 2019

francis halzen

neutrino astronomy

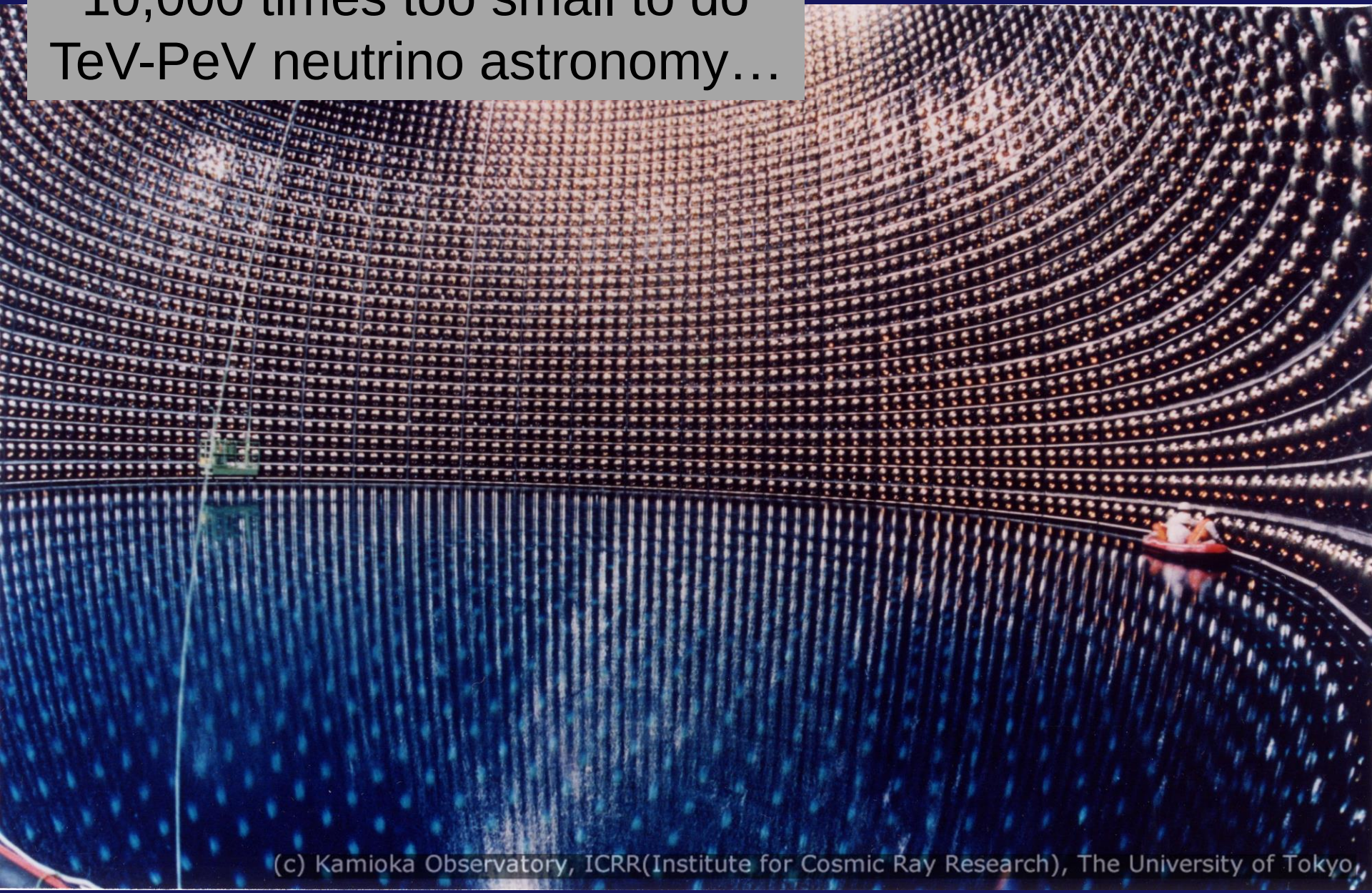
- cosmic neutrinos: four independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → tau neutrinos
  - → Glashow event

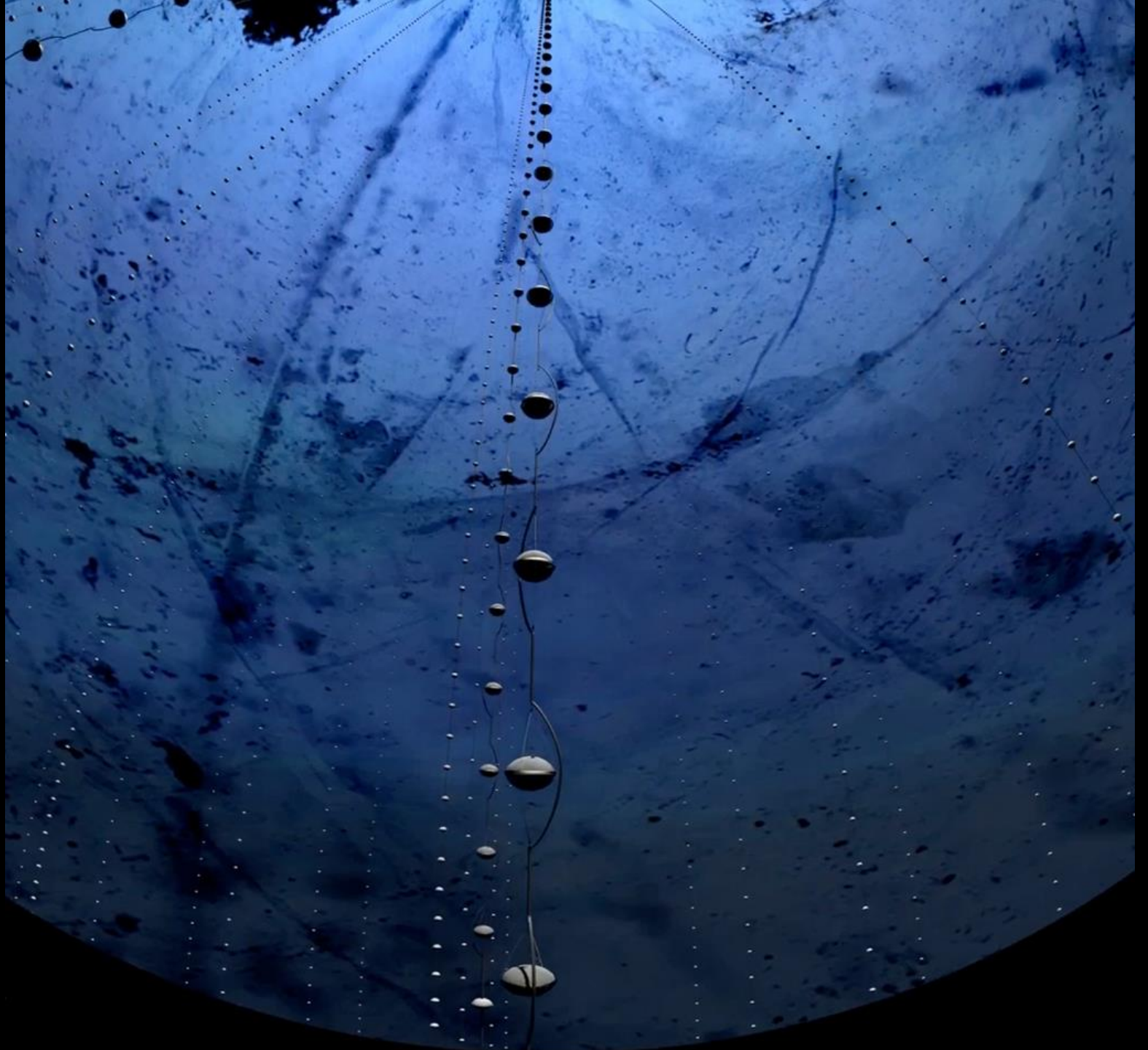
multimessenger astronomy

- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator

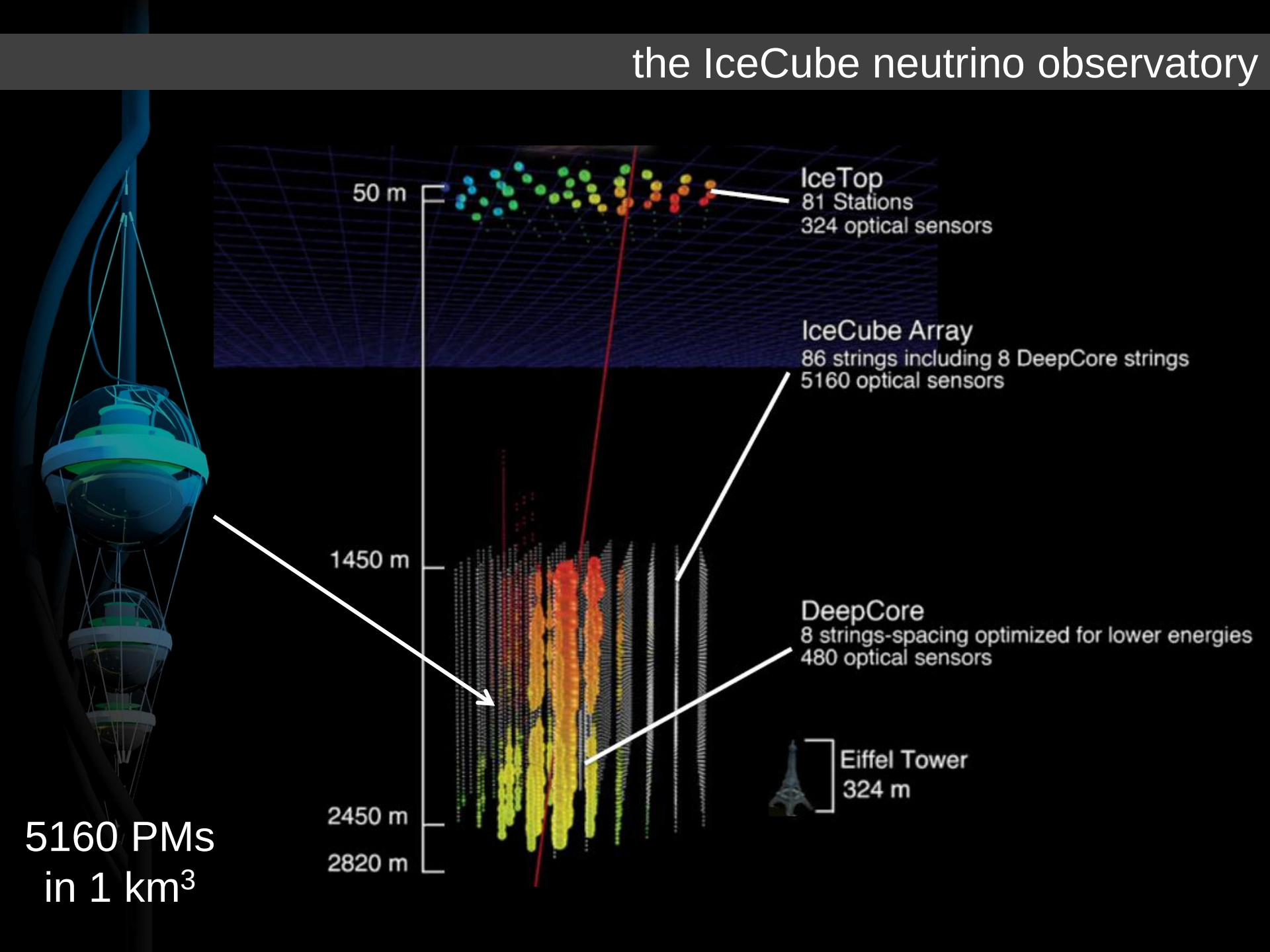
icecube.wisc.edu

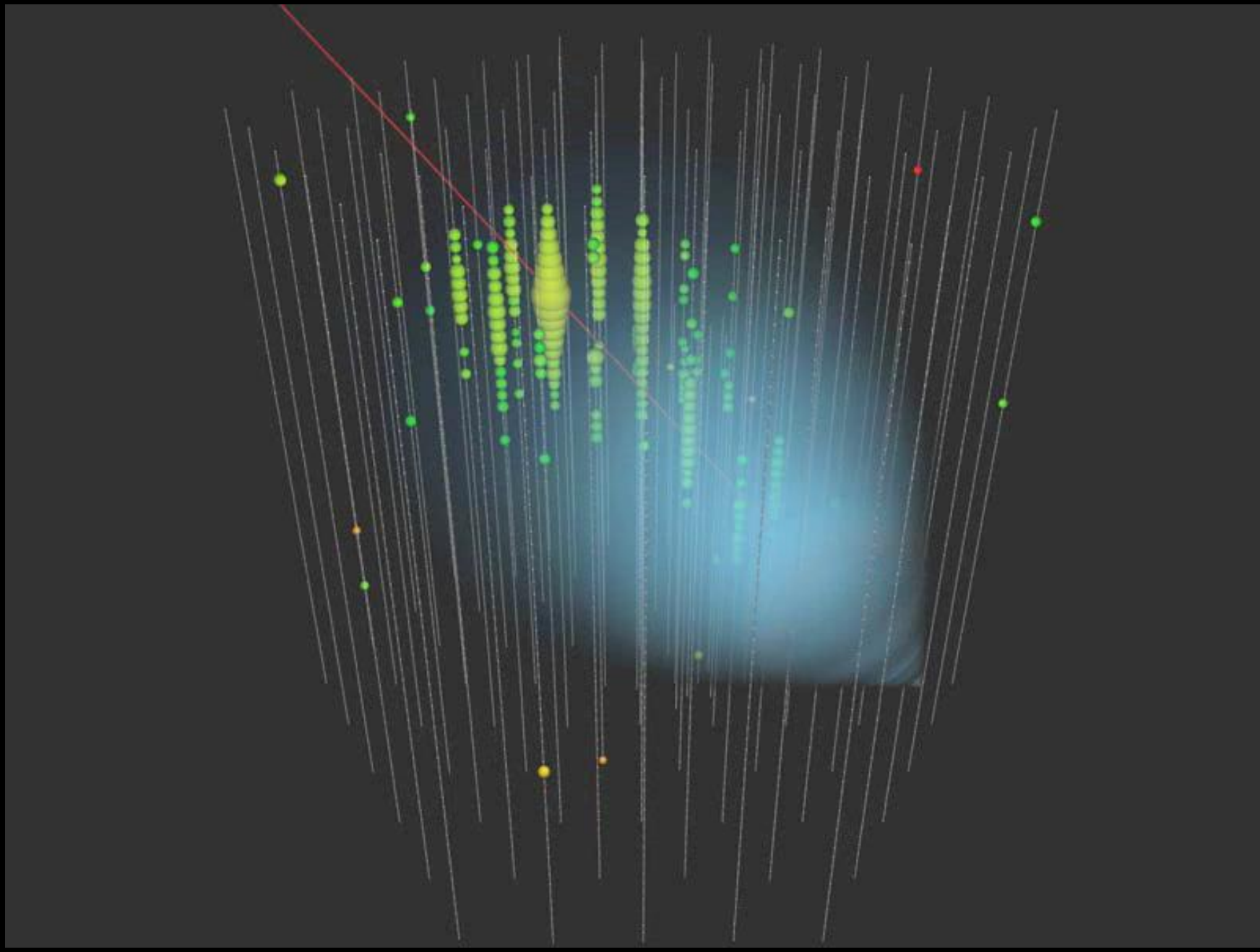
10,000 times too small to do TeV-PeV neutrino astronomy…





the IceCube neutrino observatory





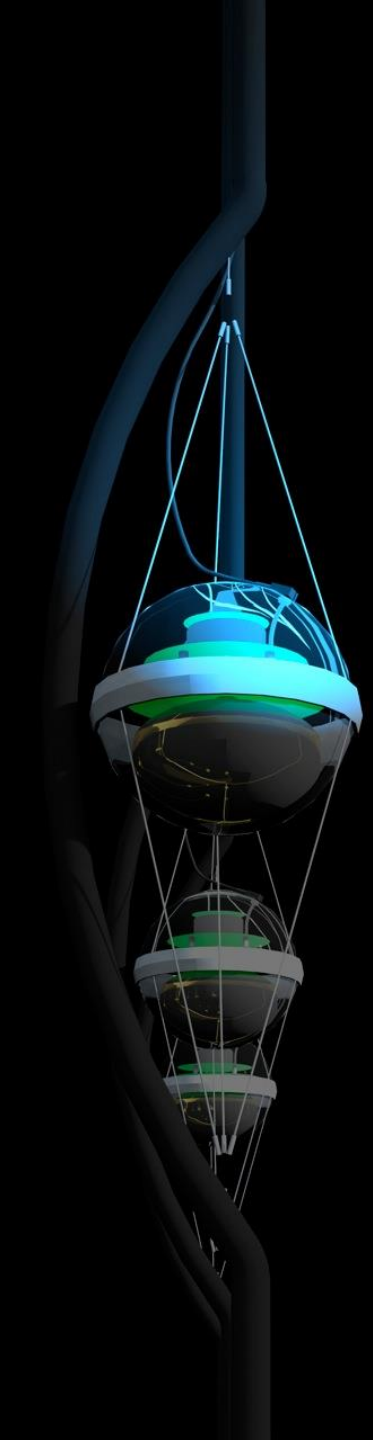
muon track: color is time; number of photons is energy

separating signal and “background”

muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $> 10^{5}$
- cosmic $\nu \rightarrow \mu$ ~ 120

* 3000 per second ** 1 every 5 minutes



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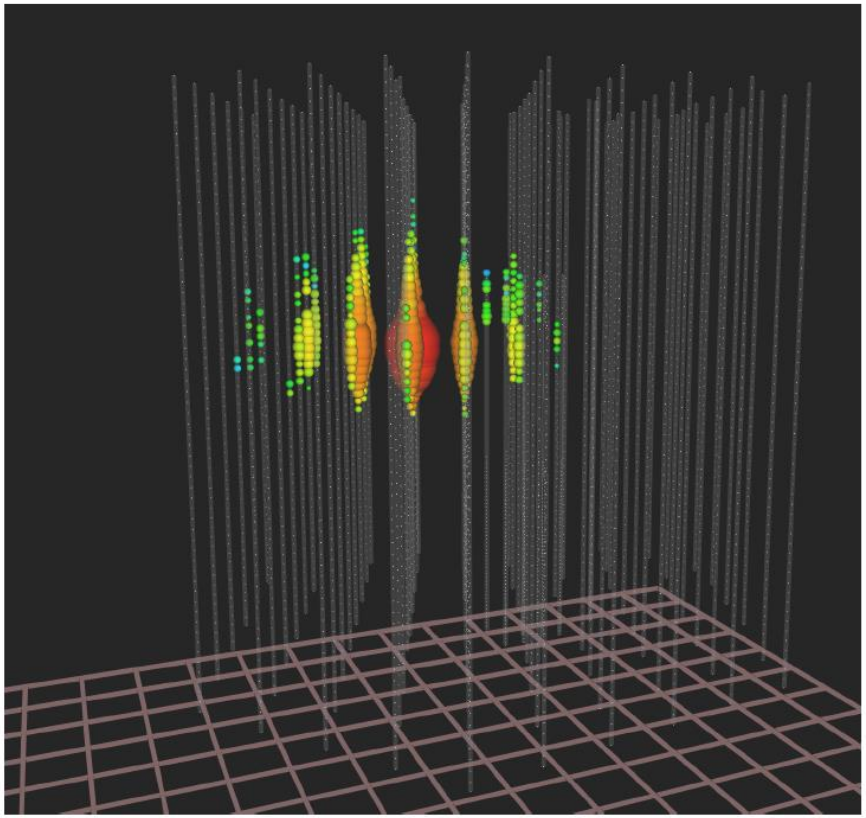
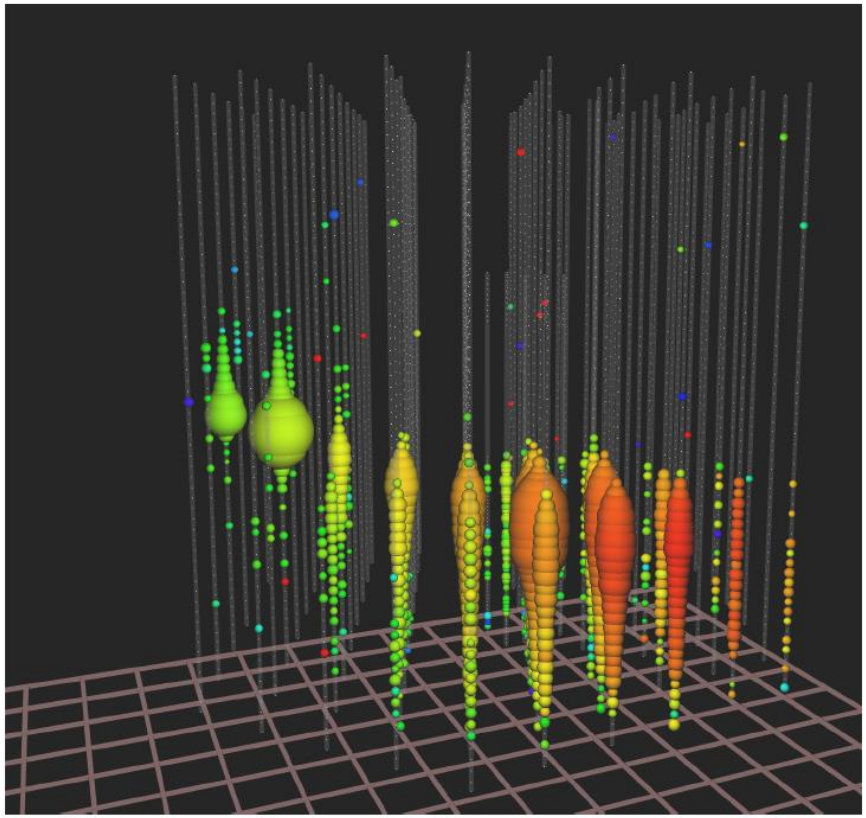
neutrinos interacting
inside the detector

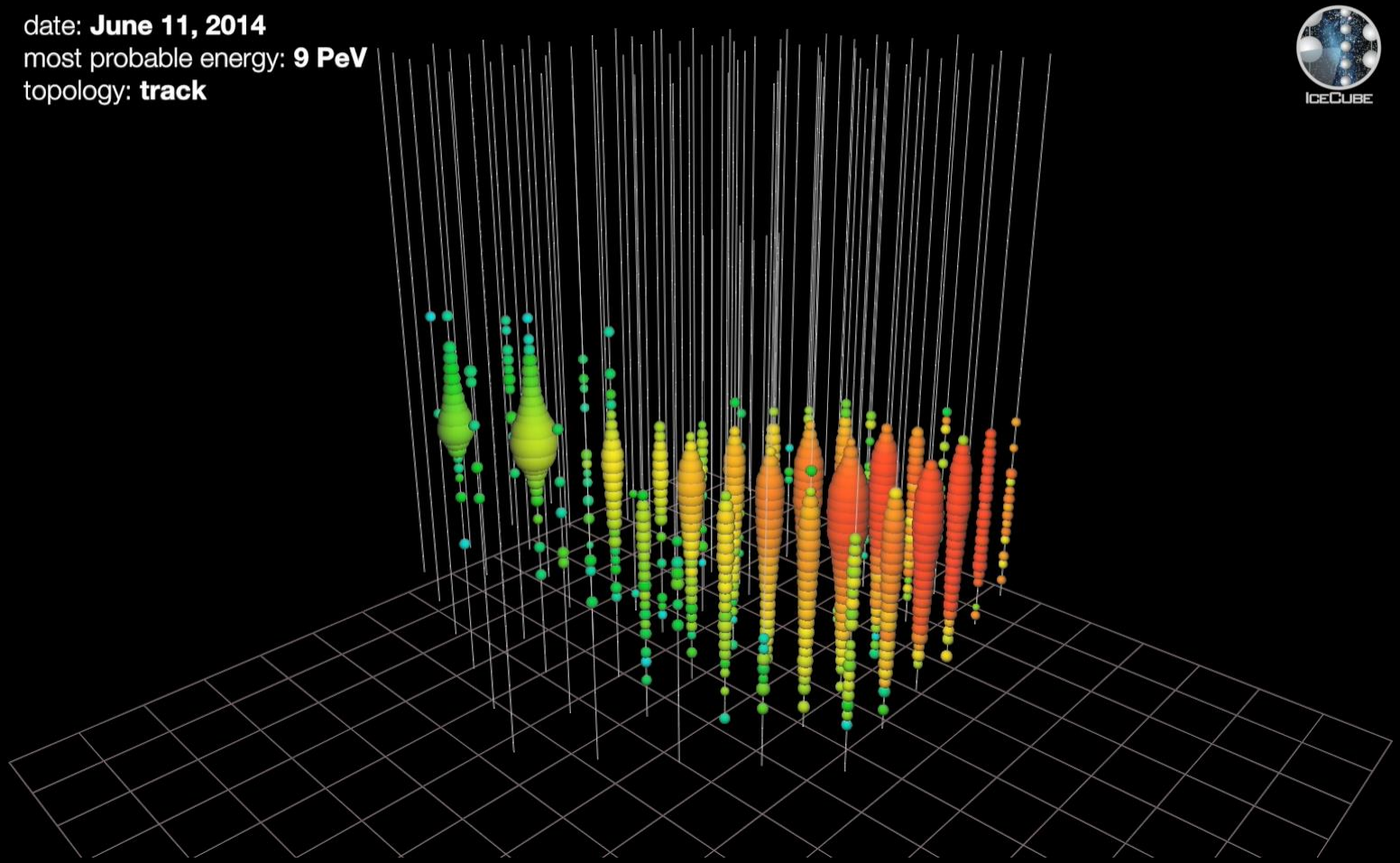


muon neutrinos
filtered by the Earth

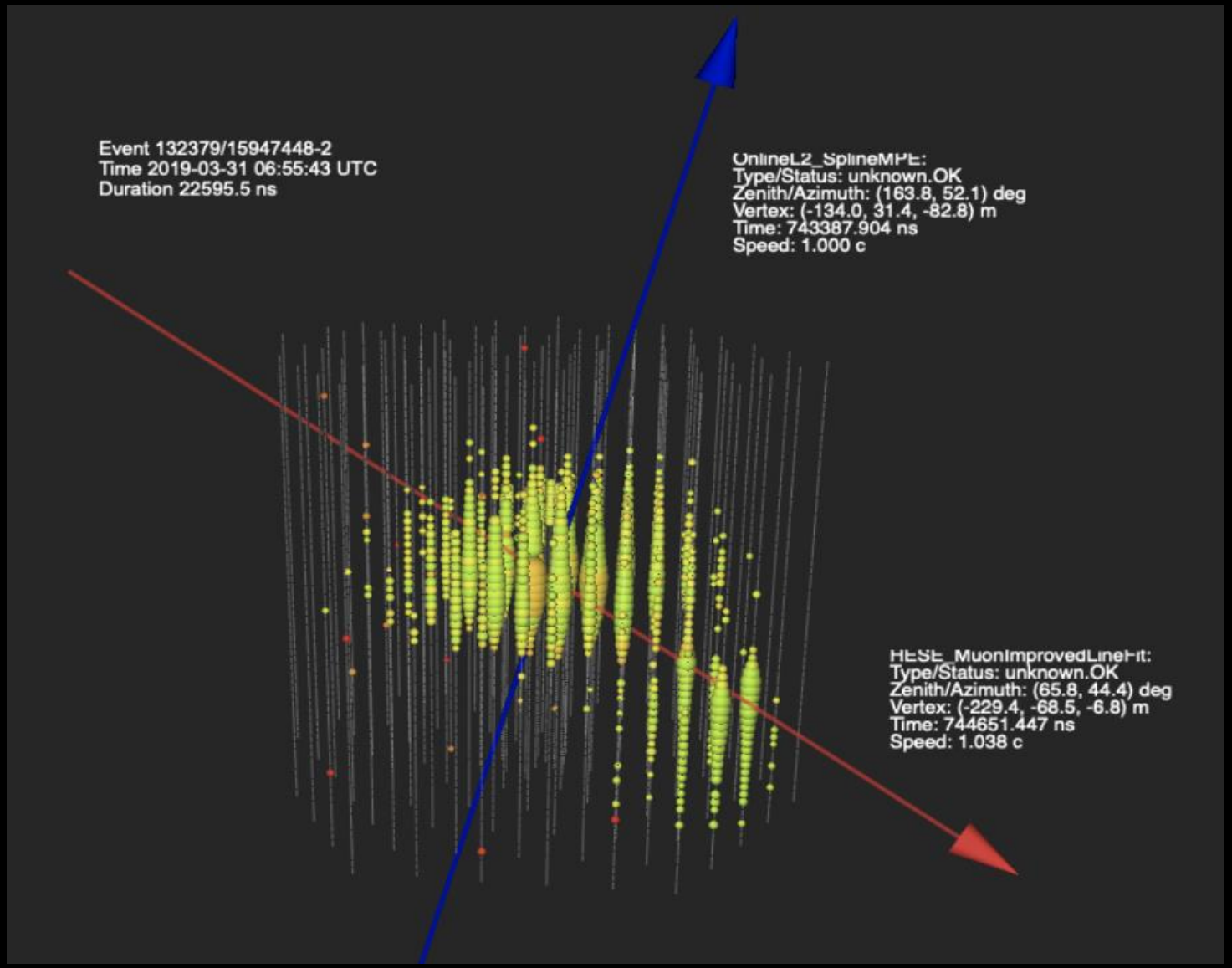


total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4º)

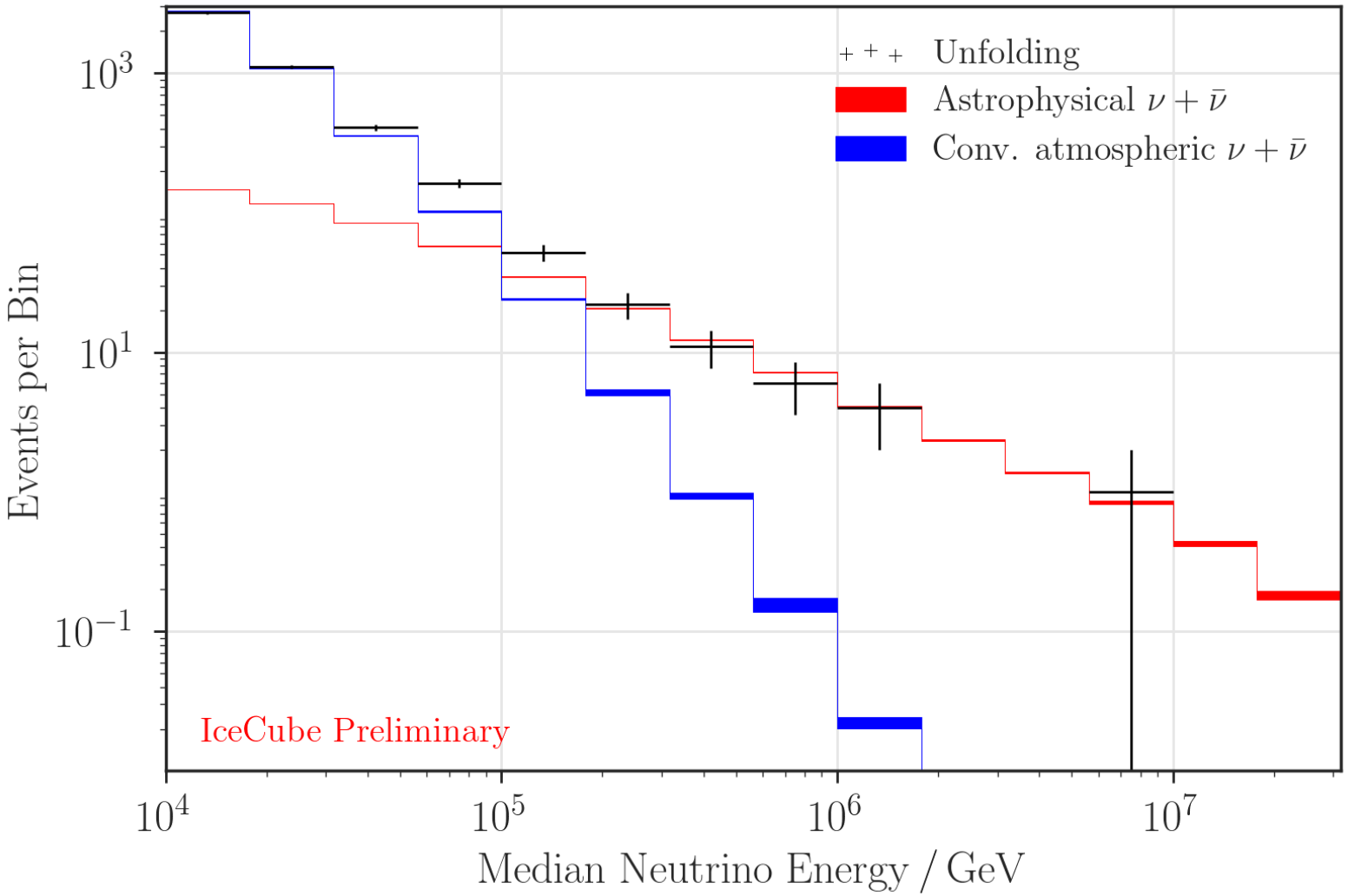

date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
IceCube

IC190331: 5300 TeV deposited inside the detector

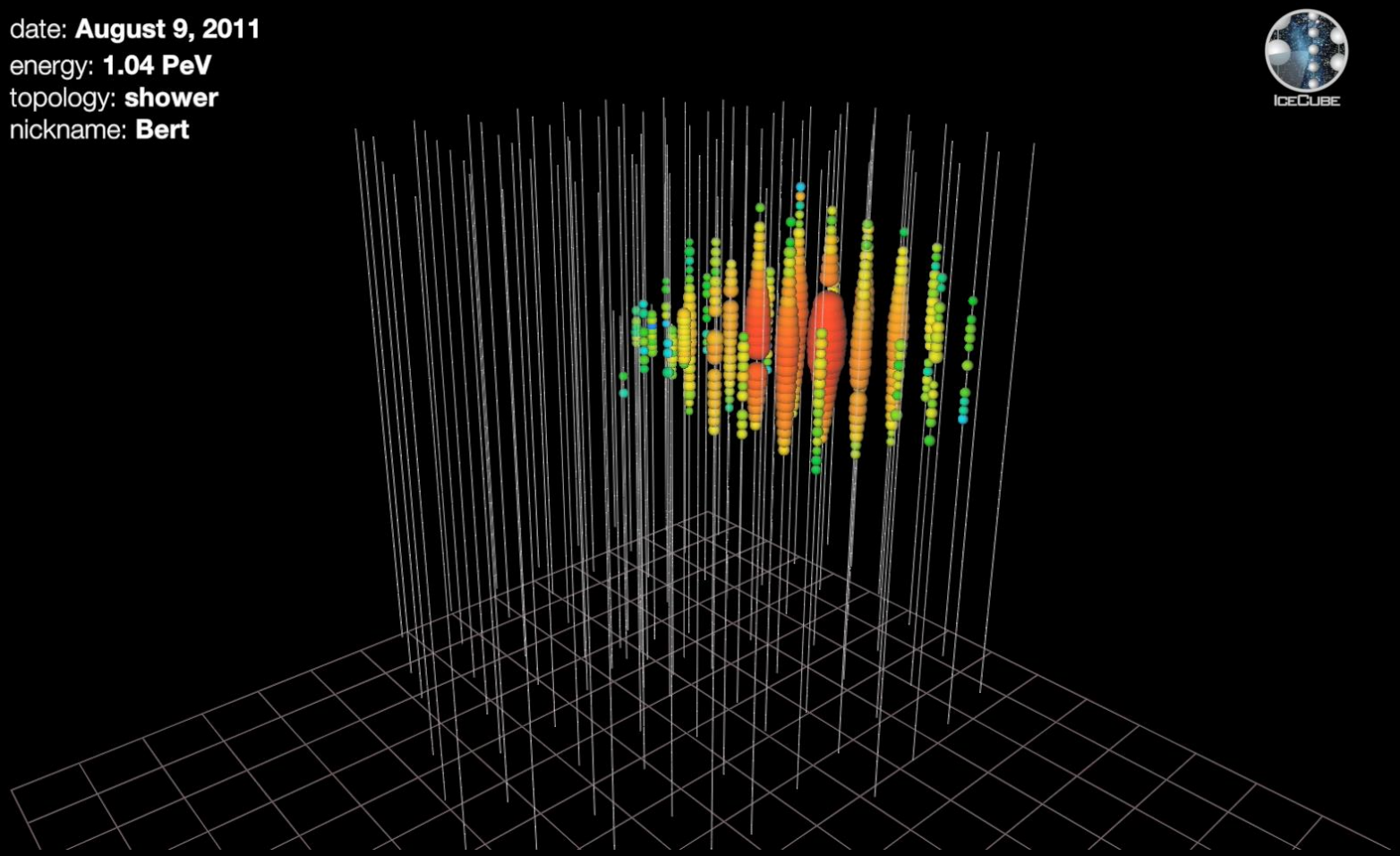


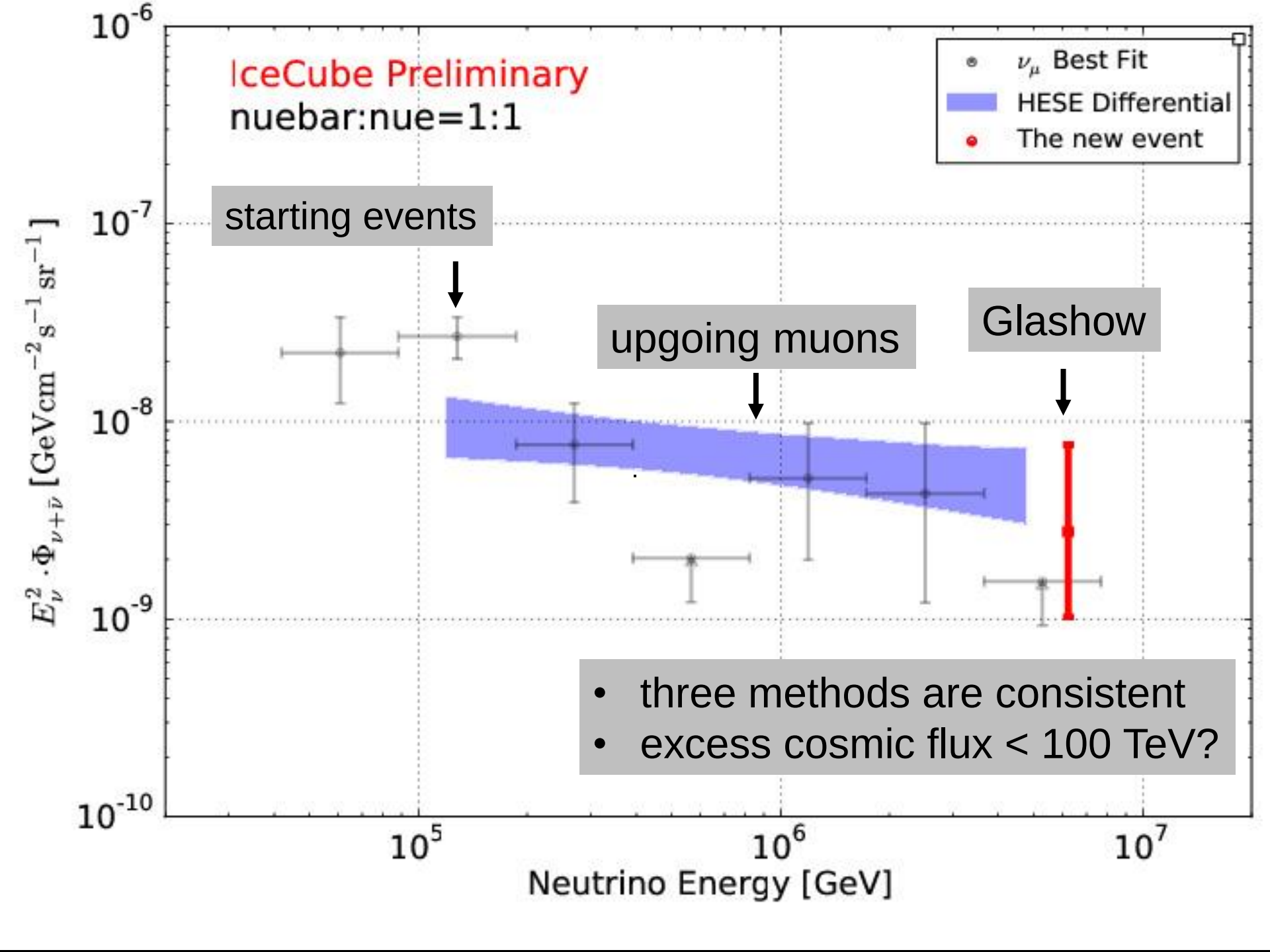
initial neutrino energy 10~20 PeV

atmospheric vs cosmic neutrinos

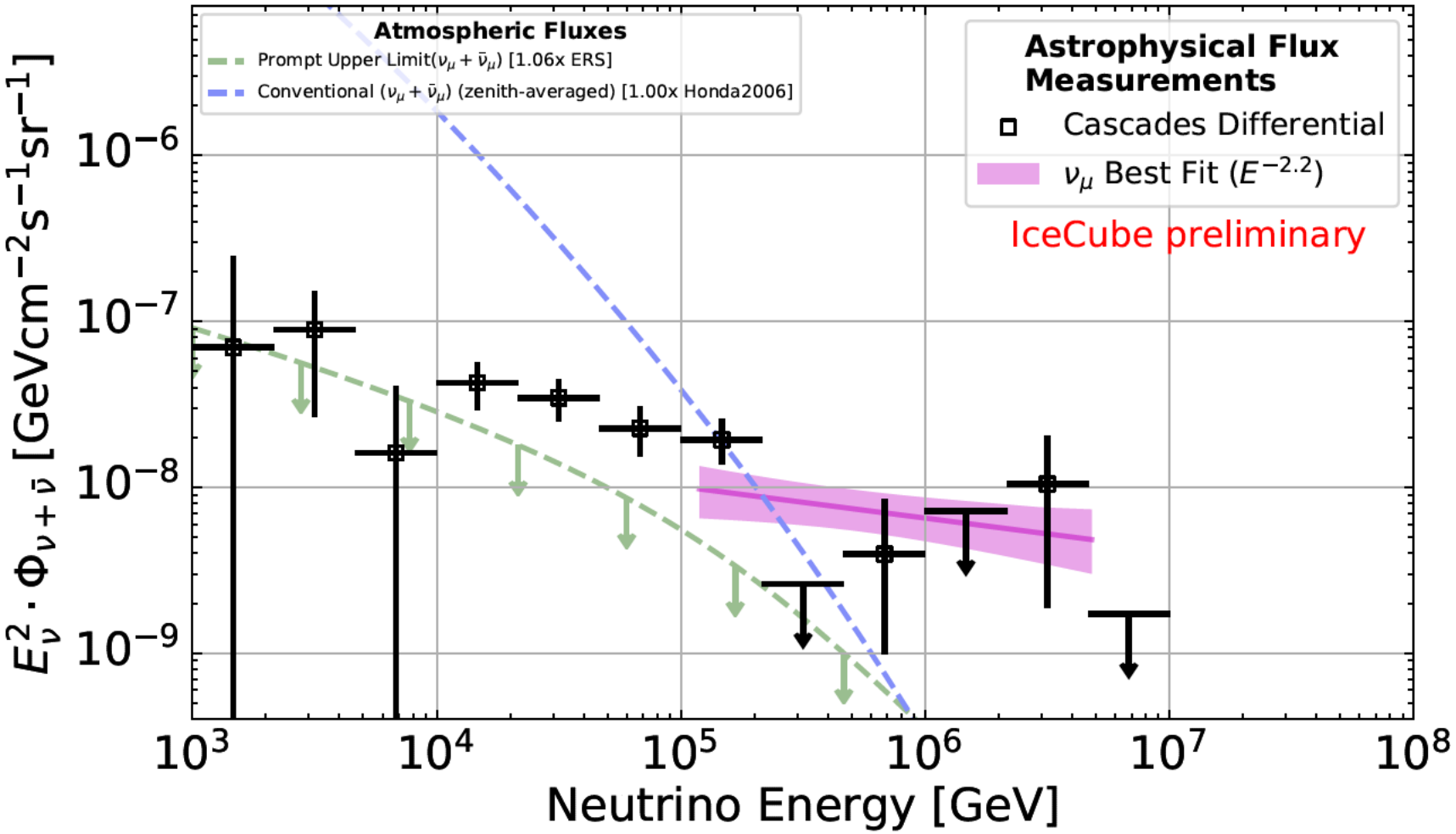


neutrinos interacting inside the instrumented volume

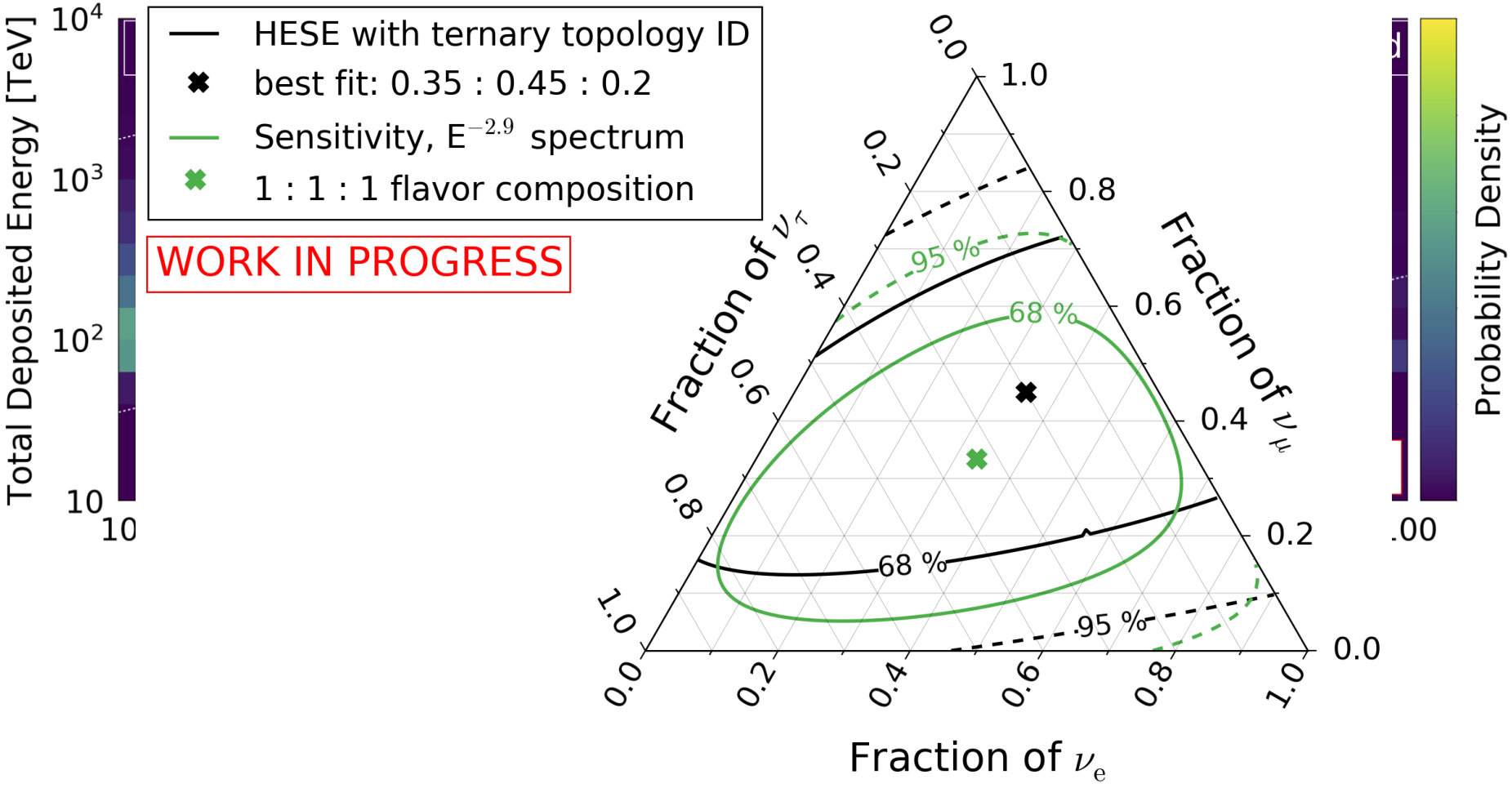



IceCube Preliminary
nuebar:nue=1:1
ν_μ Best Fit
HESE Differential
The new event
starting events
upgoing muons
Glashow
• three methods are consistent
• excess cosmic flux < 100 TeV?
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^5
10^6
10^7

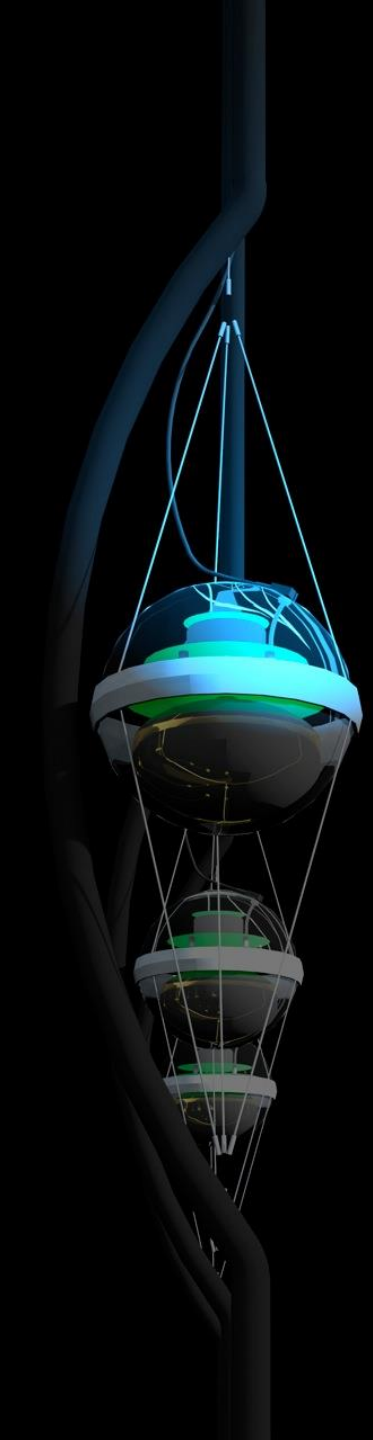
flux of electron and tau neutrinos



high-energy starting events – 7.5 yr



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



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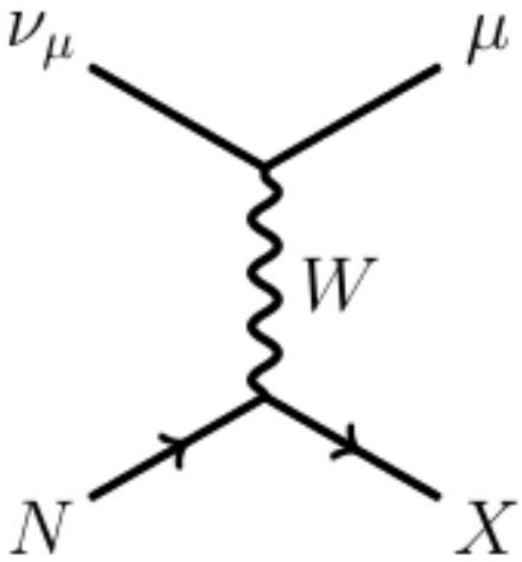
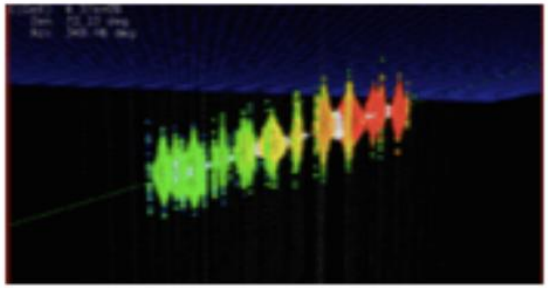
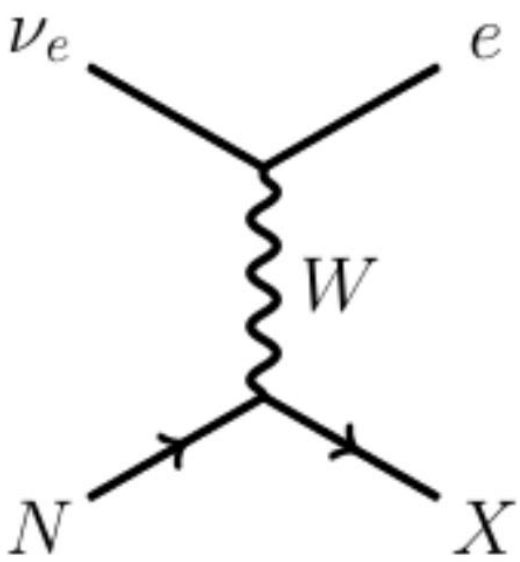
tau decay length:
50m per PeV

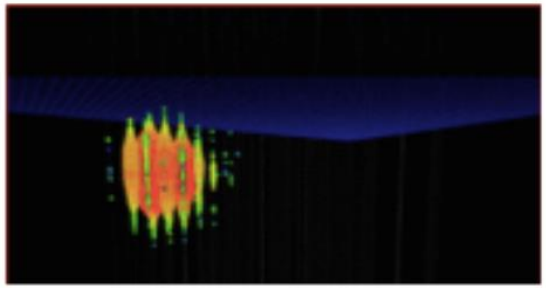


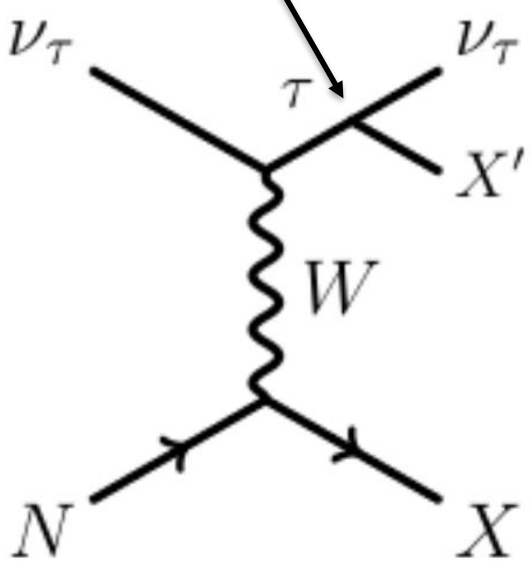
track



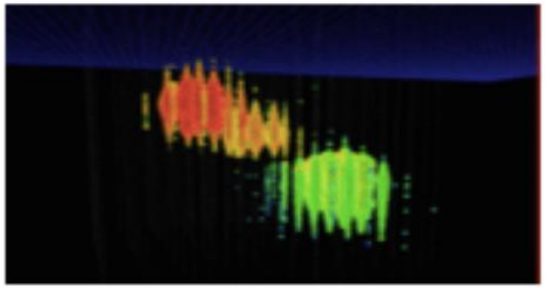


shower

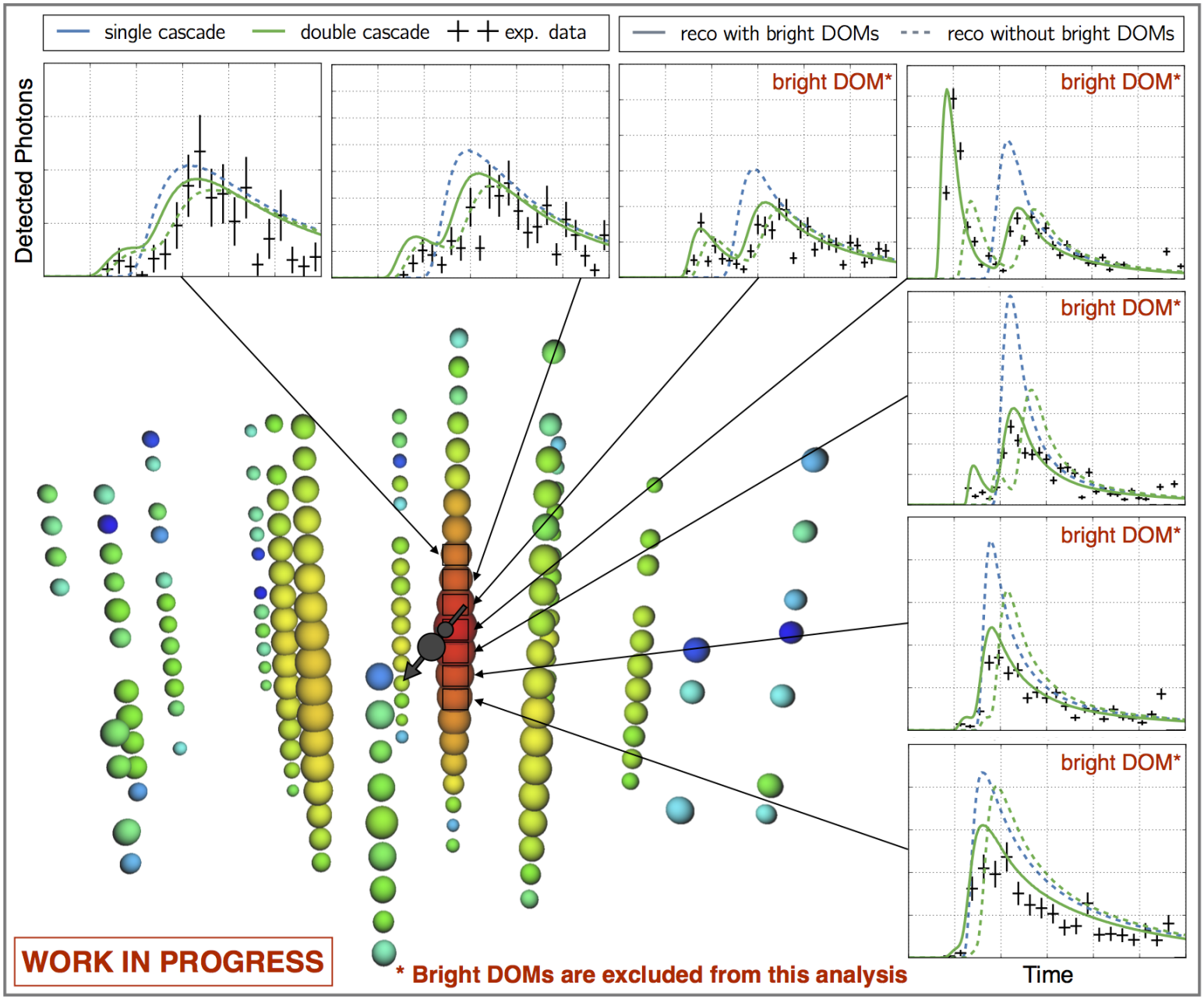




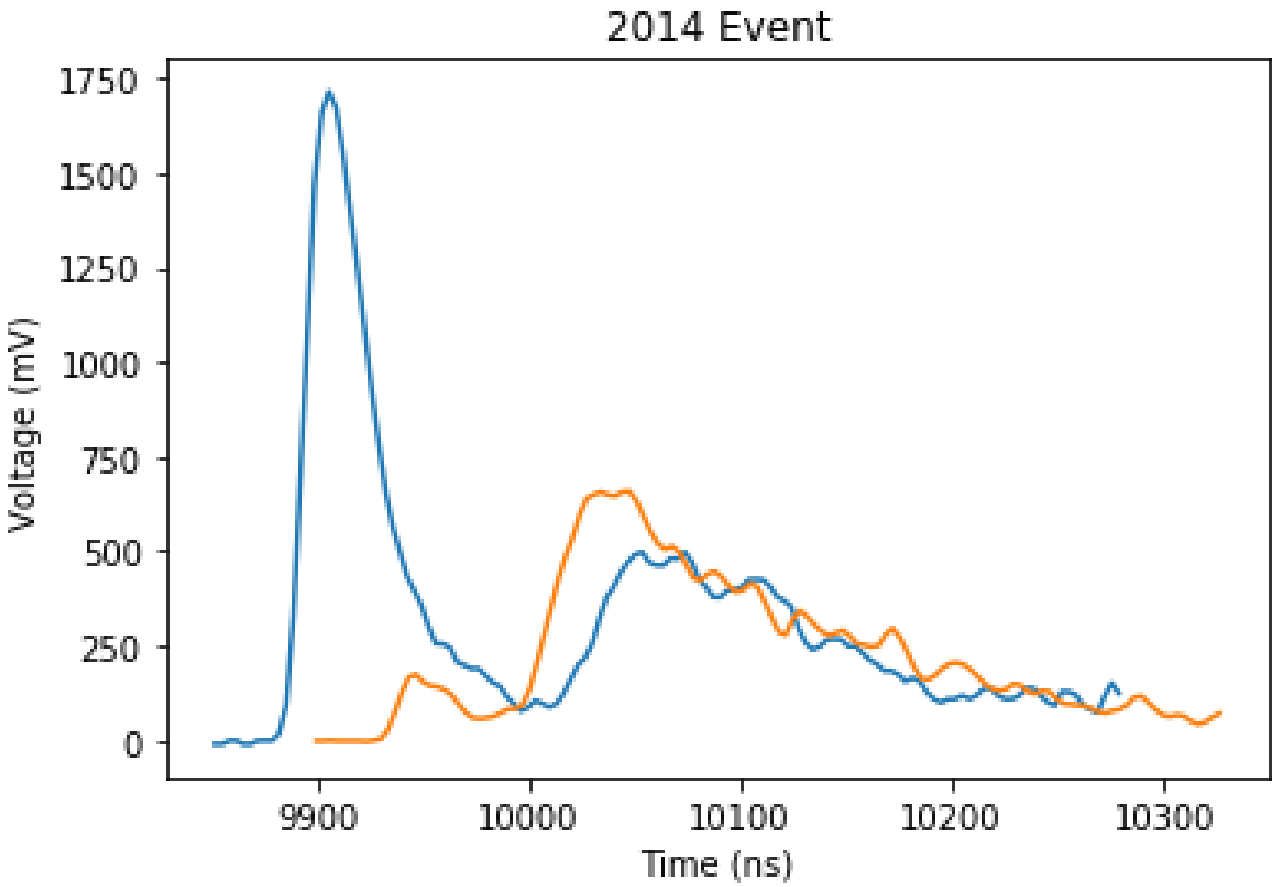
double bang*

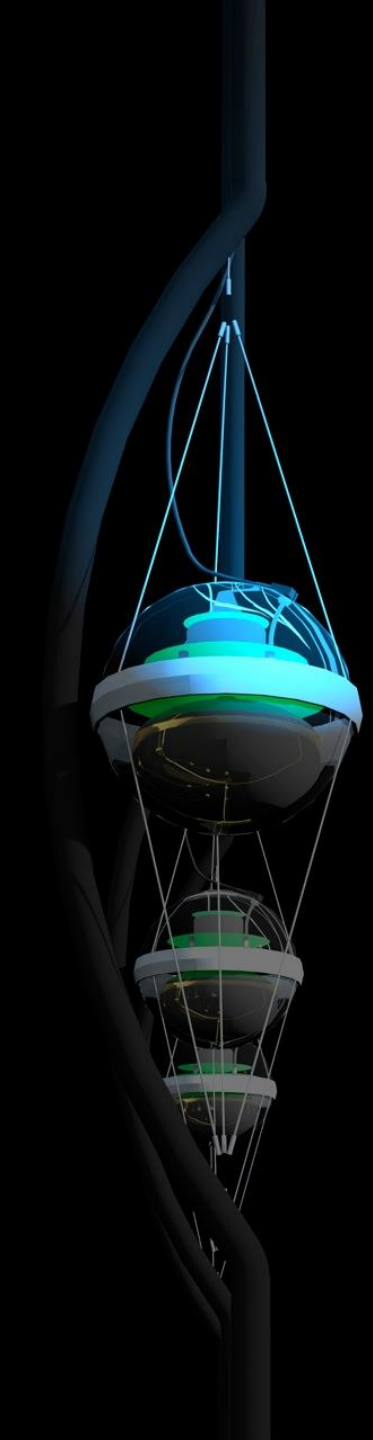


a cosmic tau neutrino: livetime 17m



event found in 3 different analyses





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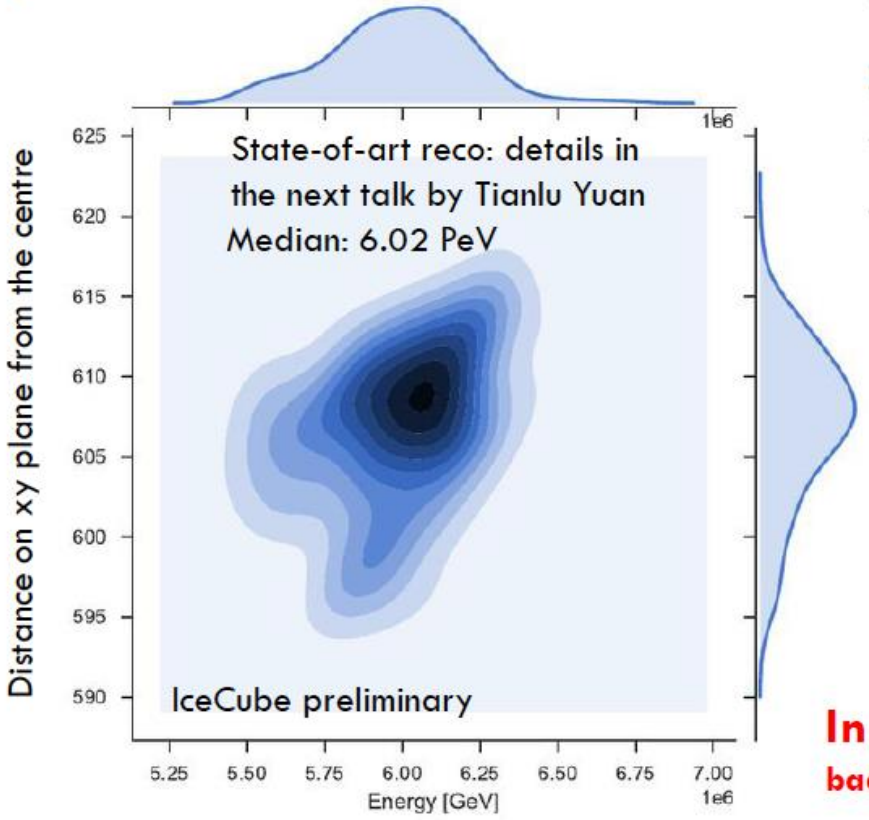
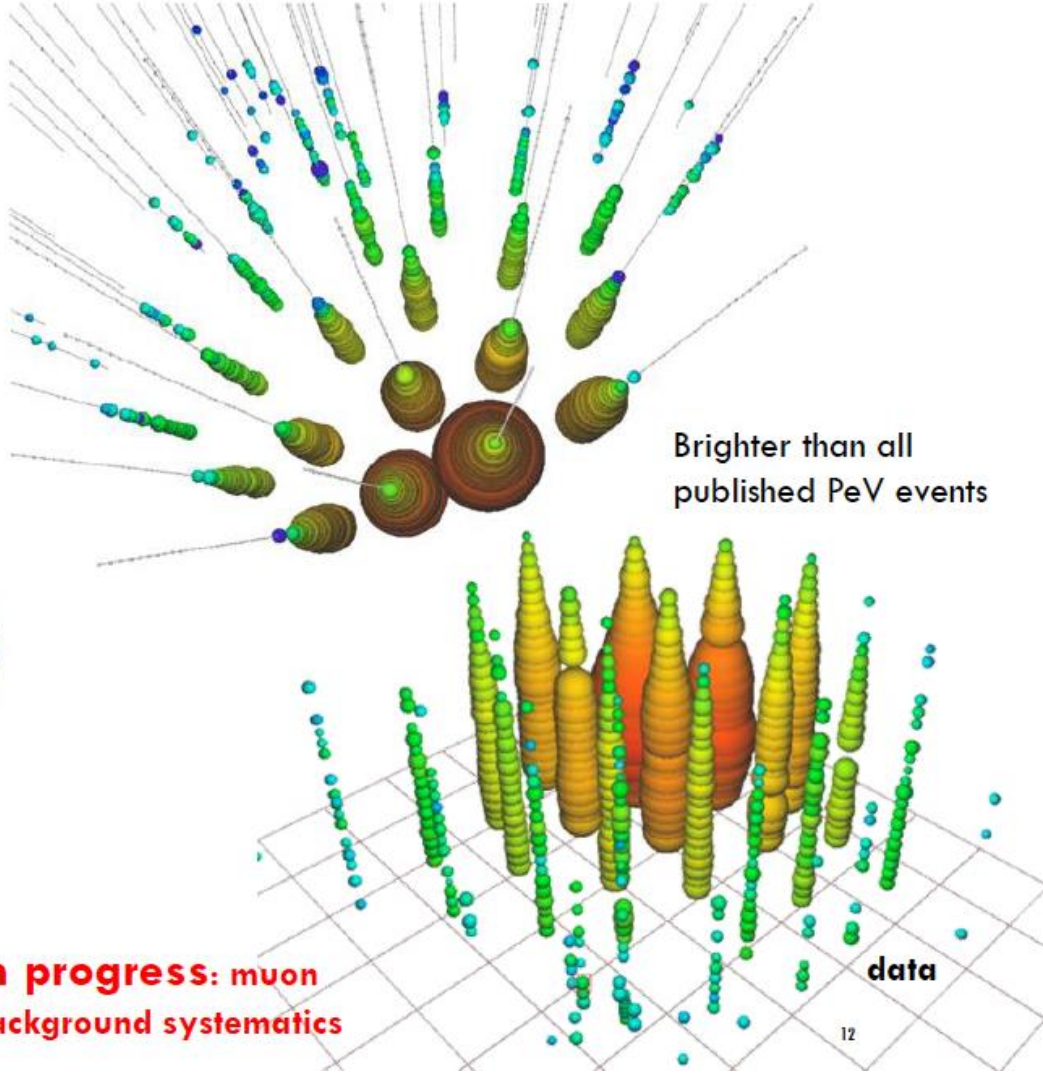
partially contained event with energy of 6.3 PeV

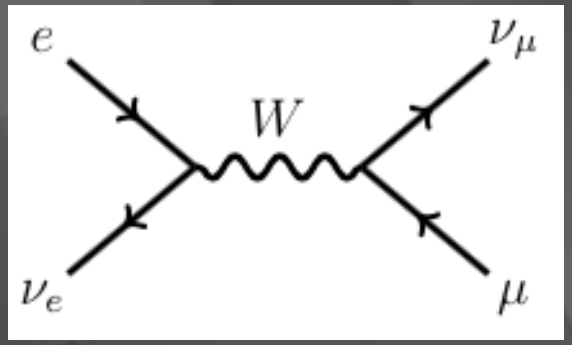
HIGHEST-ENERGY NEUTRINO CANDIDATE



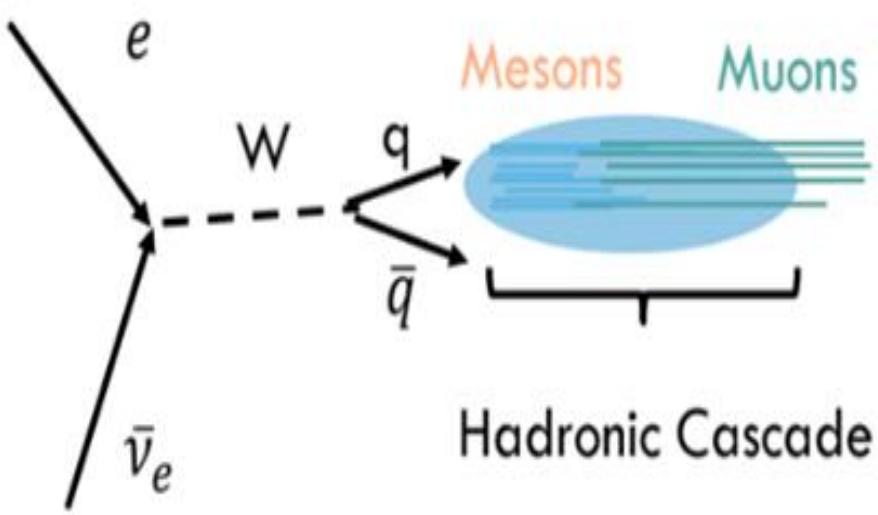


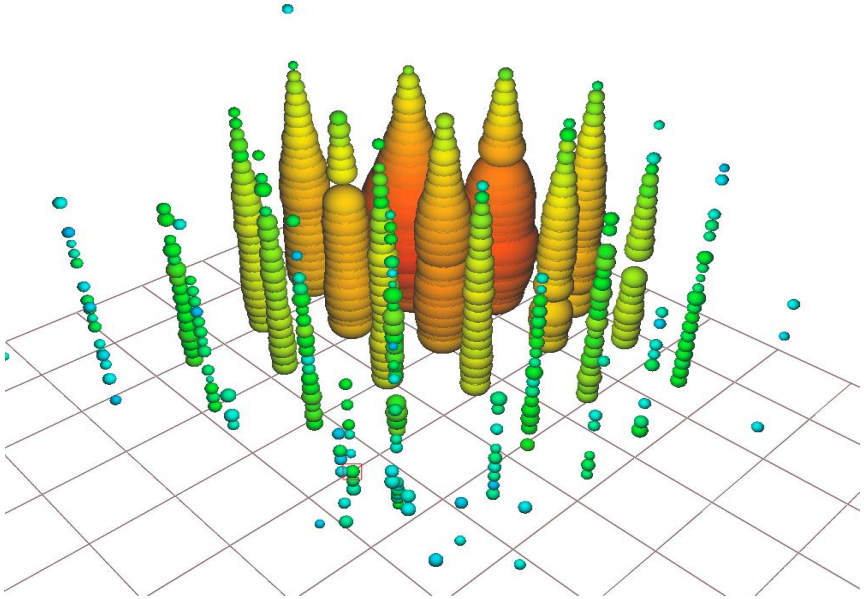
the first Glashow resonance event:

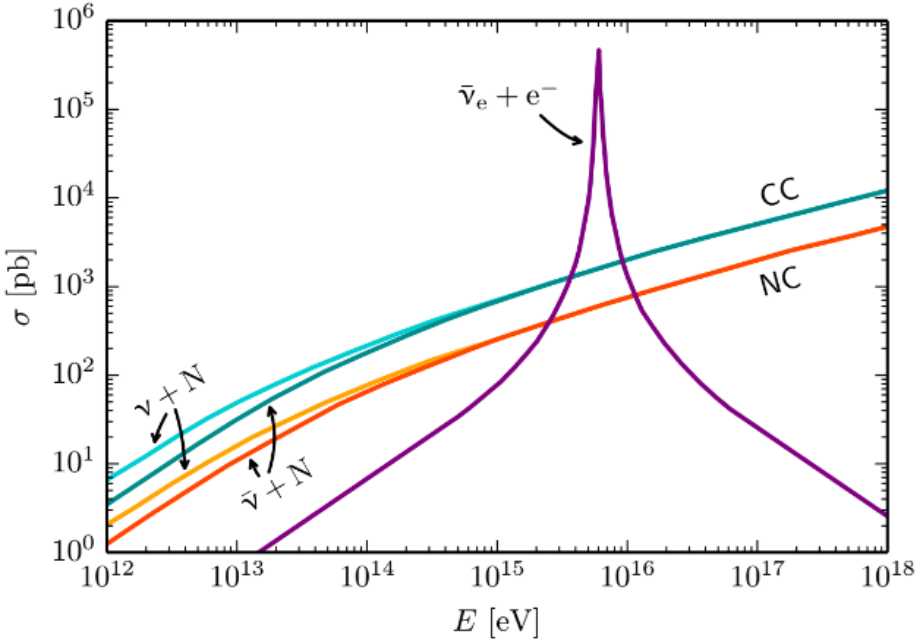
anti-ν_e + atomic electron → real W at 6.3 PeV



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



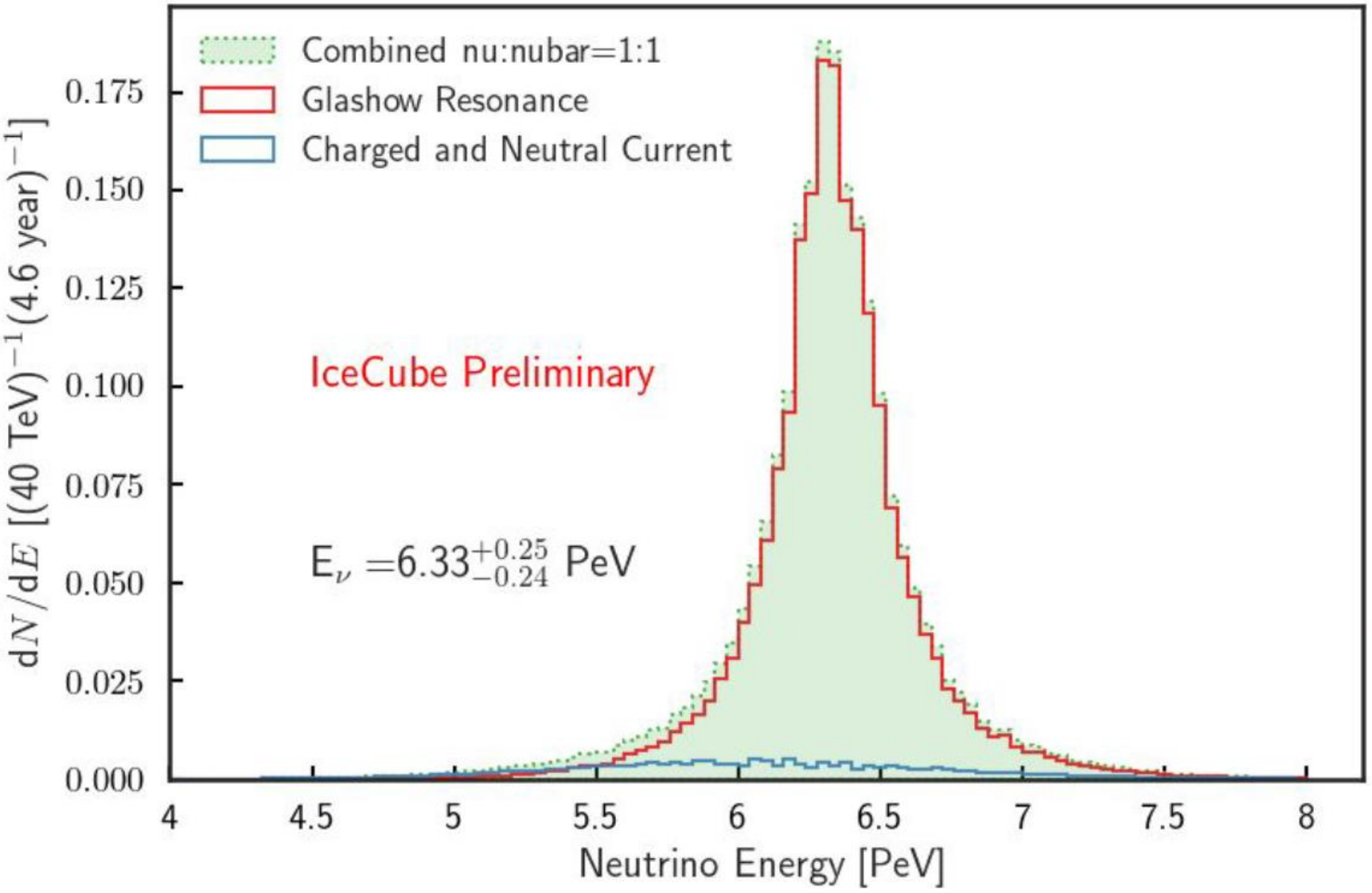




- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- visible energy is 93%

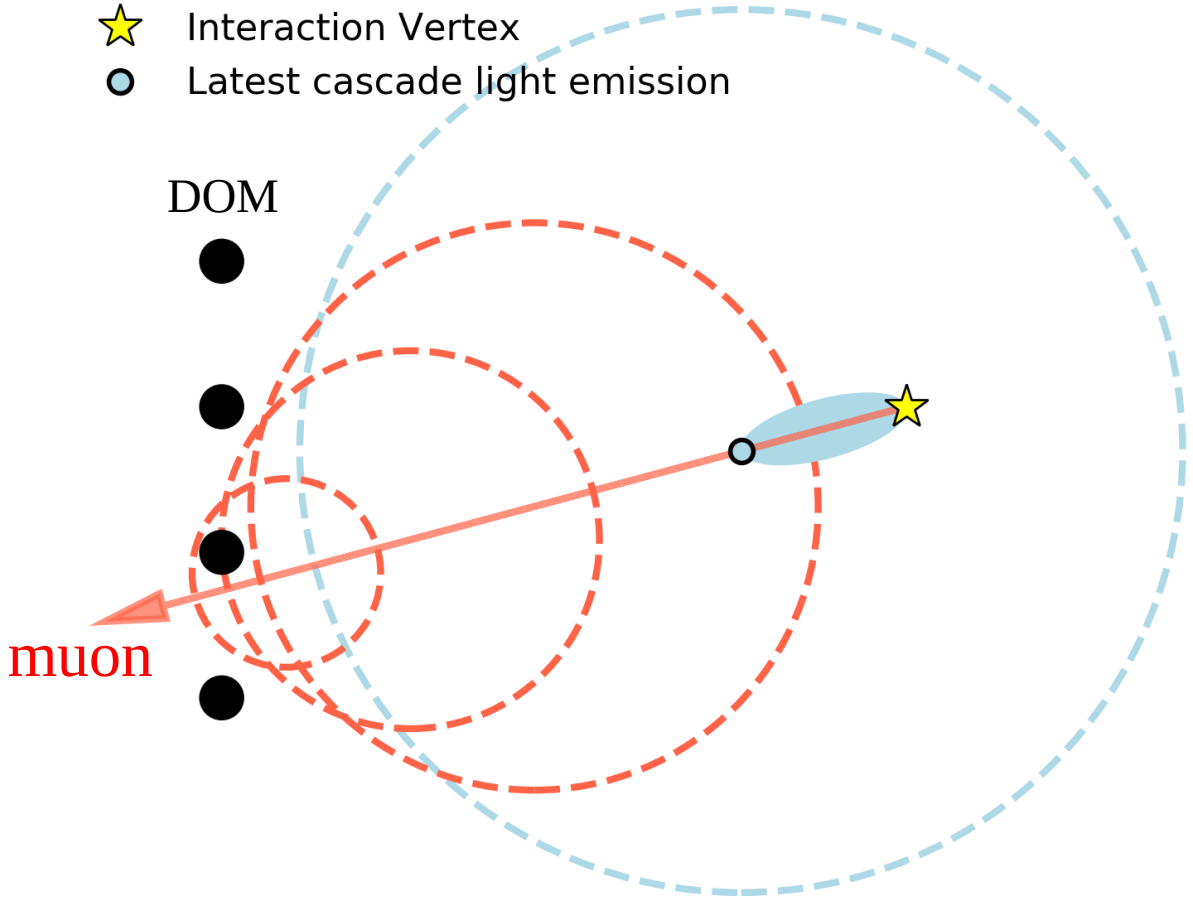
- → resonance: E_ν = 6.3 PeV

work on-going

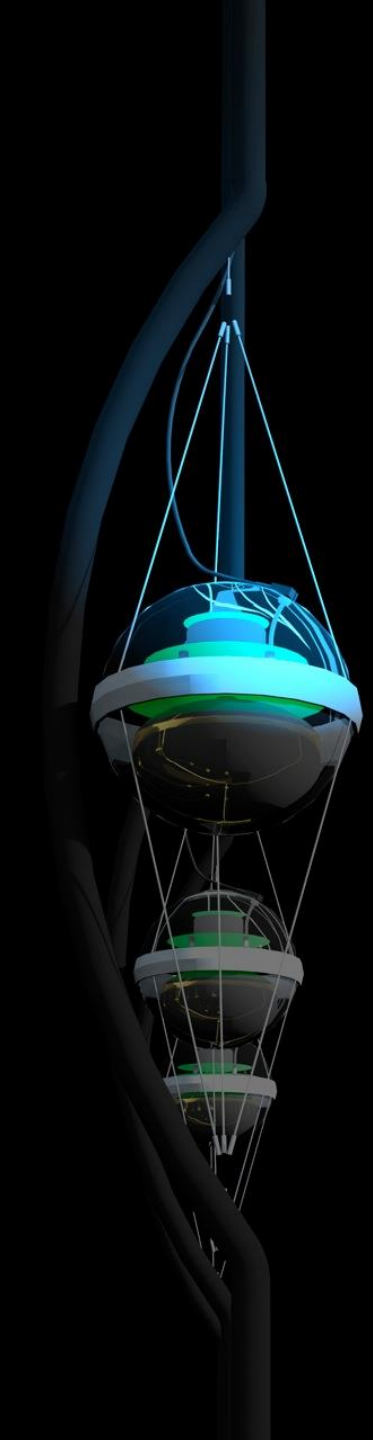

Combined nu:nubar=1:1
Glashow Resonance
Charged and Neutral Current
IceCube Preliminary
$E_\nu = 6.33^{+0.25}_{-0.24}$ PeV
dN/dE [(40 TeV)$^{-1}$(4.6 year)$^{-1}$]
0.175
0.150
0.125
0.100
0.075
0.050
0.025
0.000
4
4.5
5
5.5
6
6.5
7
7.5
8
Neutrino Energy [PeV]

- hadronic (quark-antiquark decay of the W) versus electromagnetic shower radiated by a high energy background cosmic ray muon?

- muons from pions (v=c) outrace the light propagating in ice that is produced by the electromagnetic component (v<c)



- IceCube observes a diffuse flux of neutrinos from extragalactic (see later) sources



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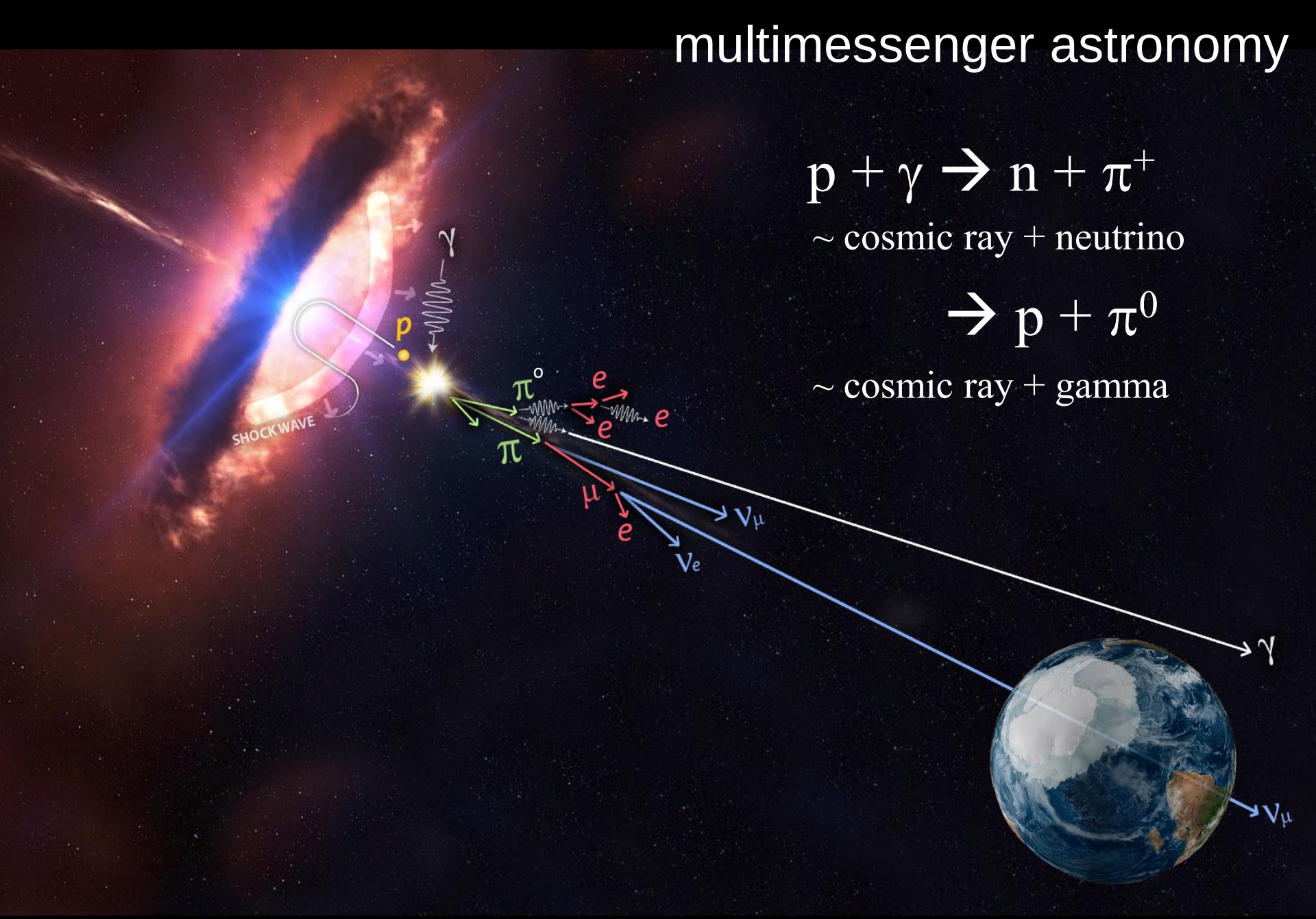
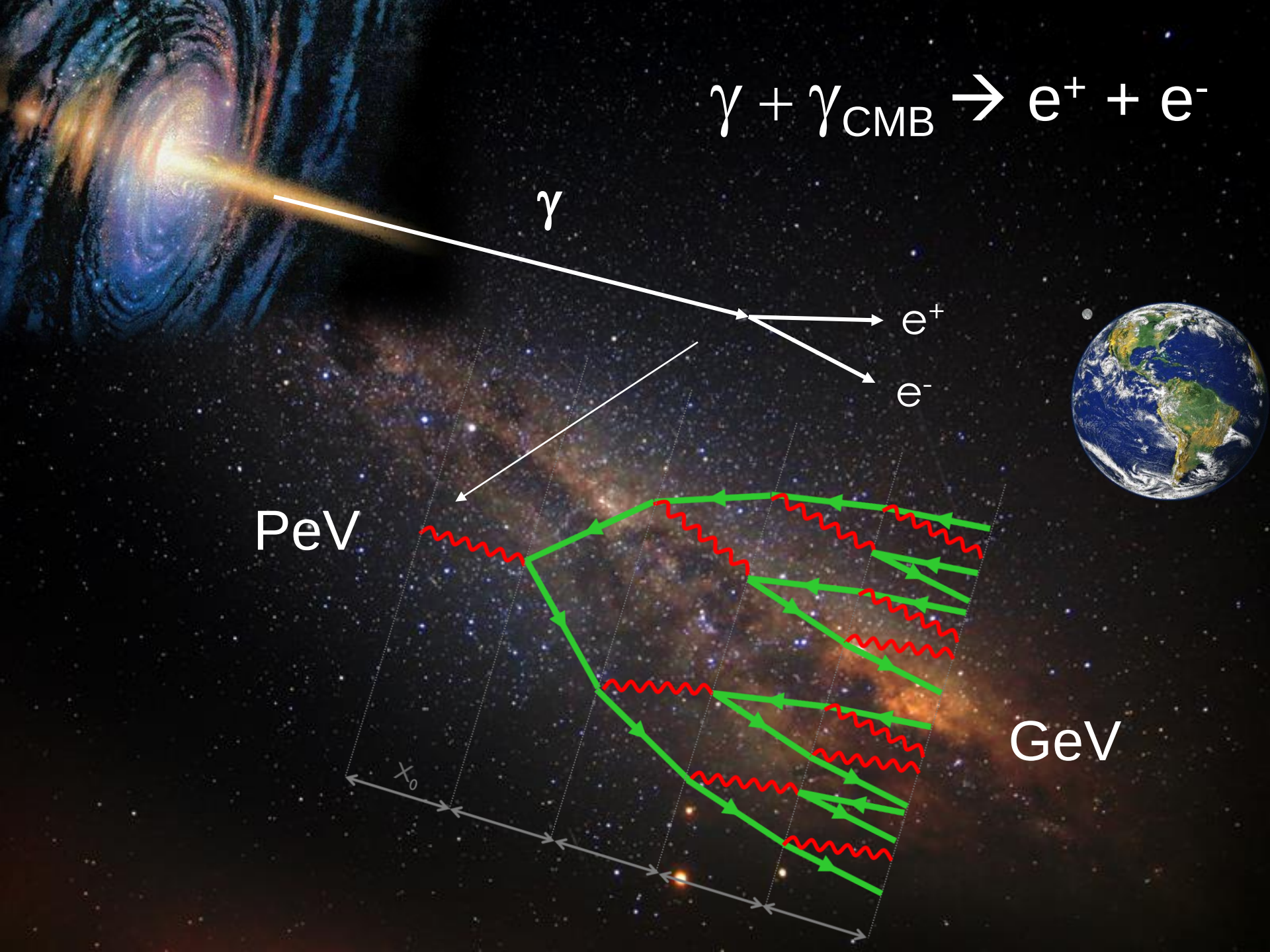
$p + \gamma \rightarrow n + \pi^+$

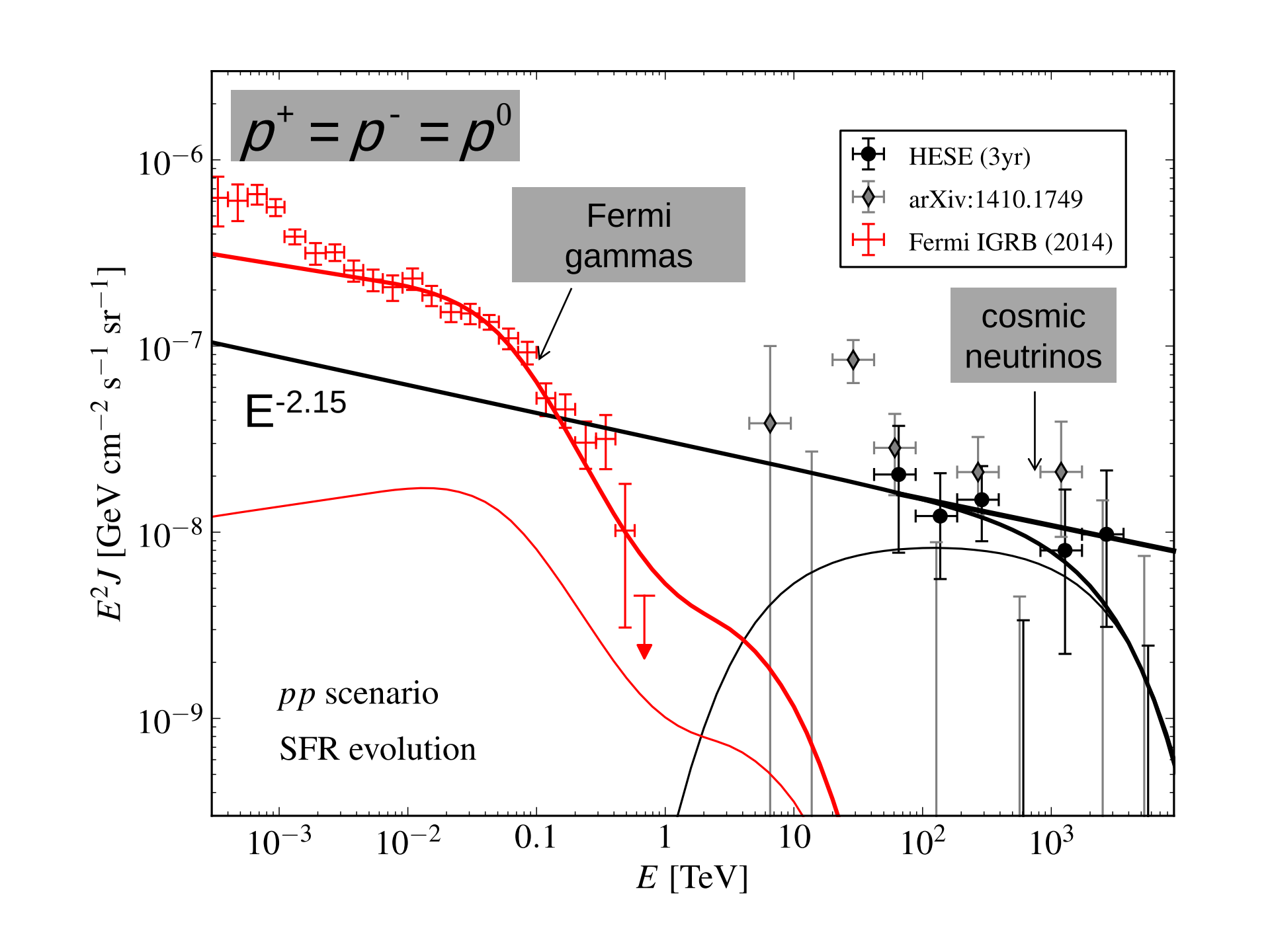
~ cosmic ray + neutrino

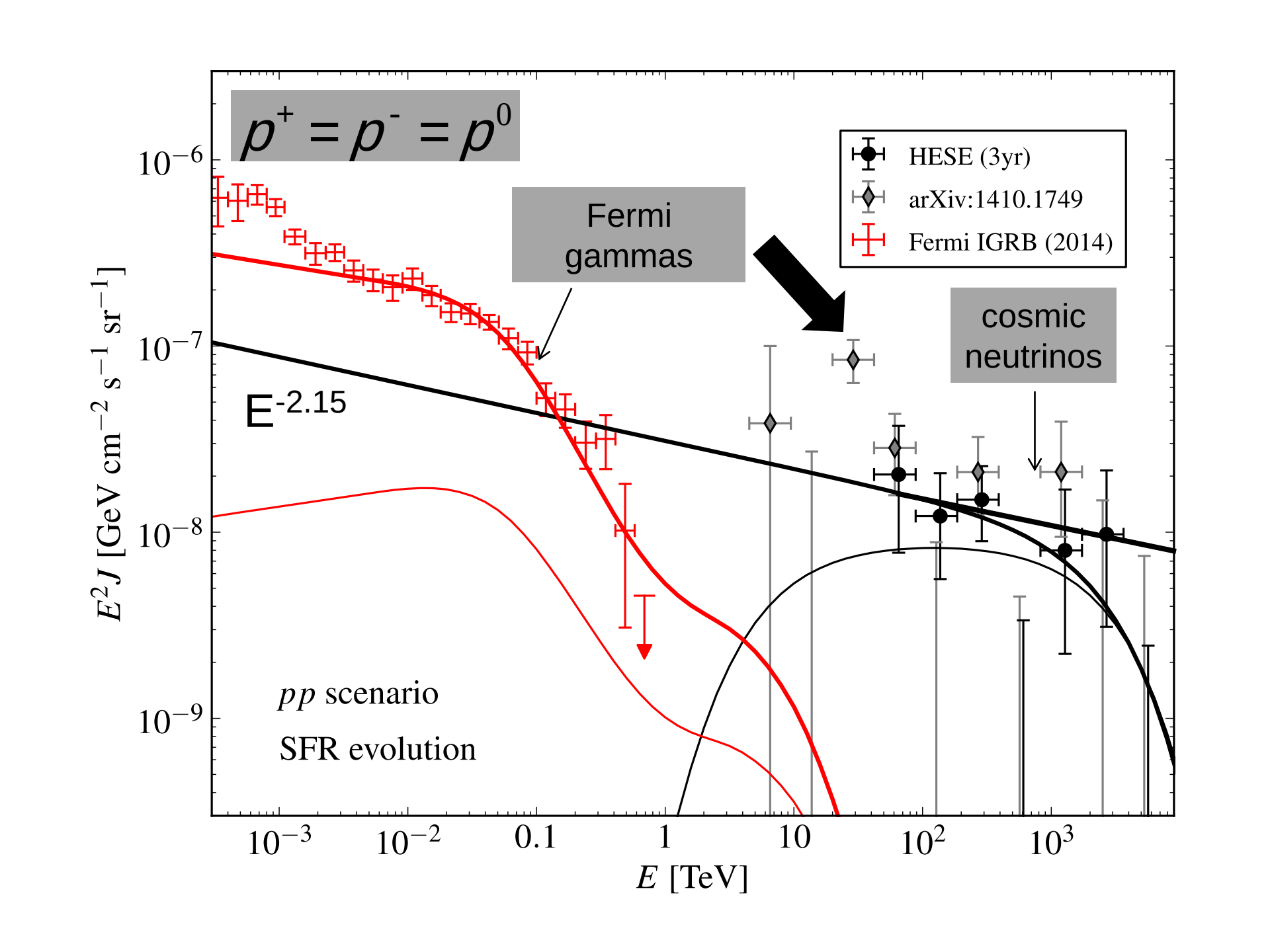
$\rightarrow p + \pi^0$

~ cosmic ray + gamma




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


$p^+ = p^- = p^0$
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]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3


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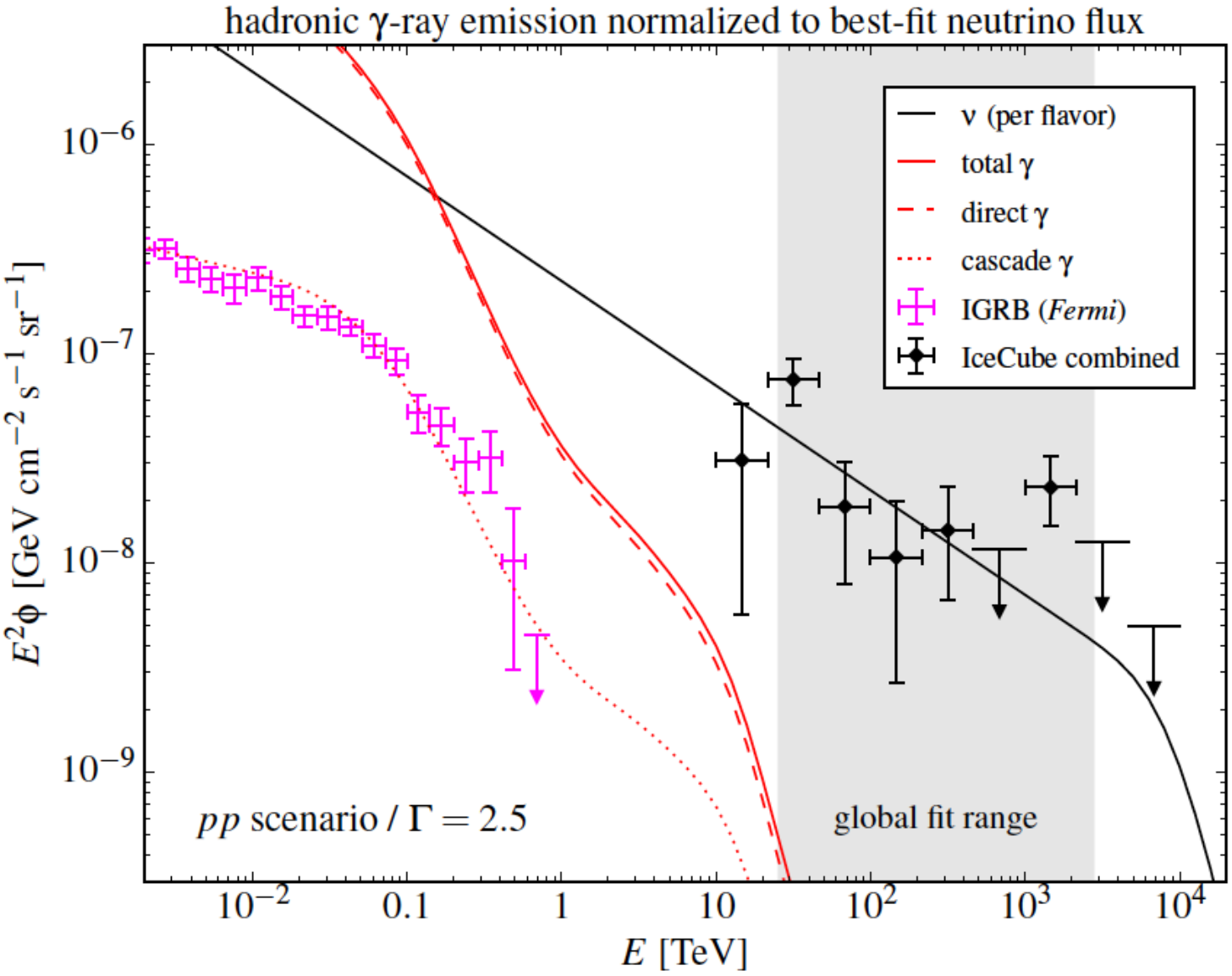
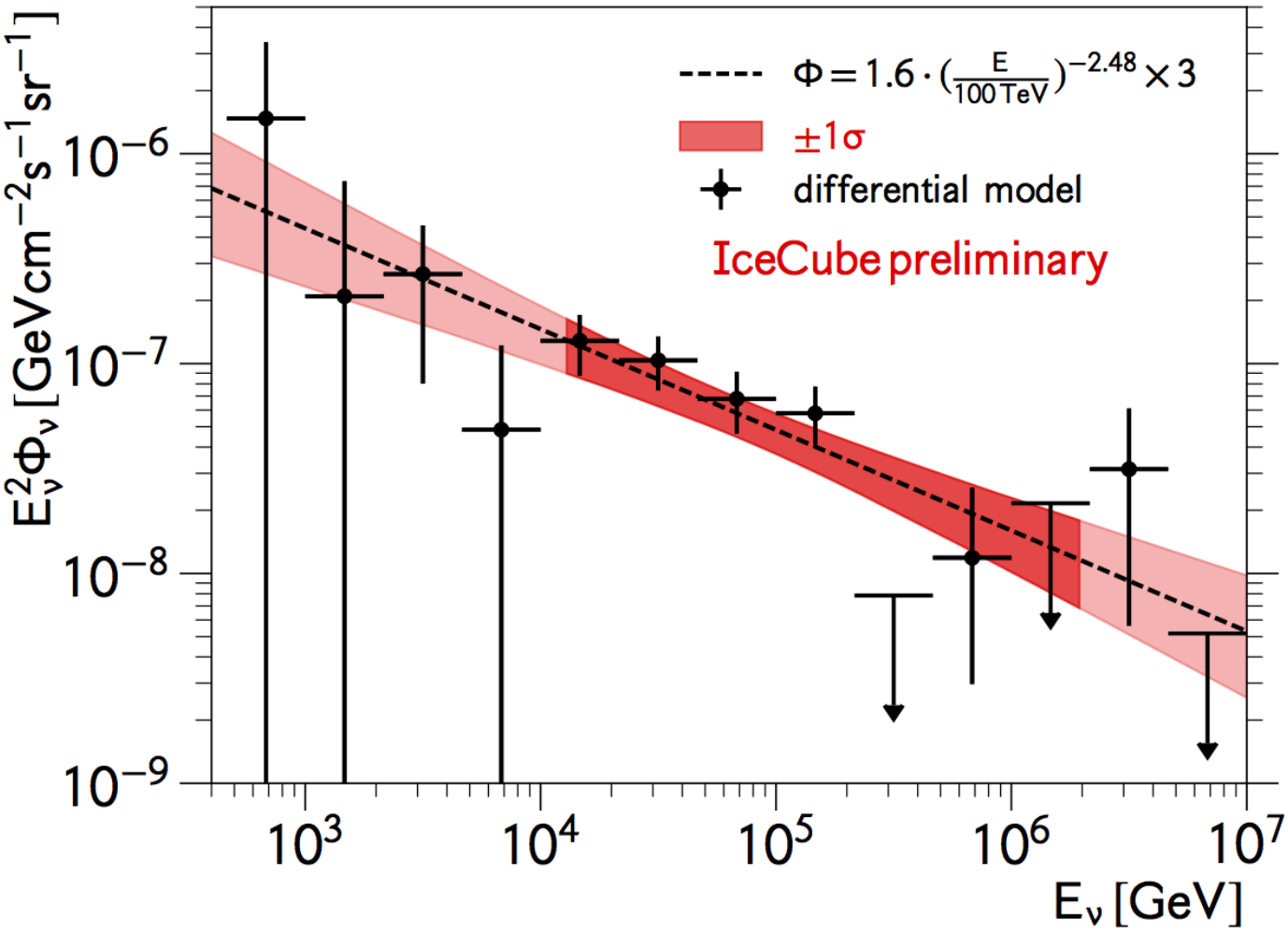
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3



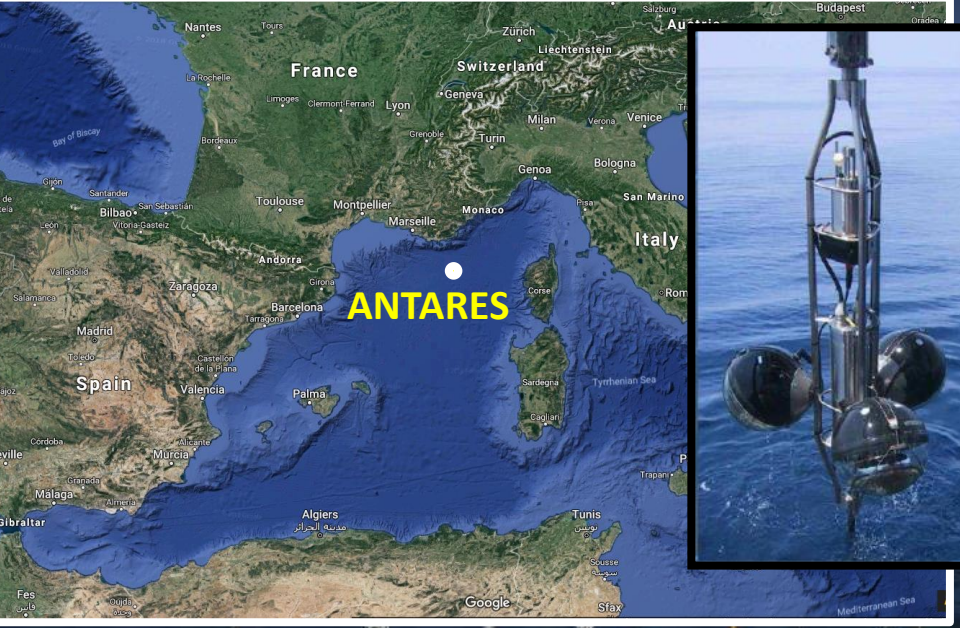
dark sources below 100 TeV not seen in γ's ?
gamma rays cascade in the source to lower energy

Multi-year cascade ($\nu_e+\nu_\tau$) analysis: dark sources ?



- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays
- origin of events from opaque sources < 100 TeV ?
- where do the comic neutrinos come from ?

ANTARES



Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep

450 m

40 km to shore

Junction Box

70 m

Interlink cables

ANTARES – Diffuse flux

Sample:
- 2007 – 2015, 2450 days of livetime
- All-flavour analysis (track+showers)

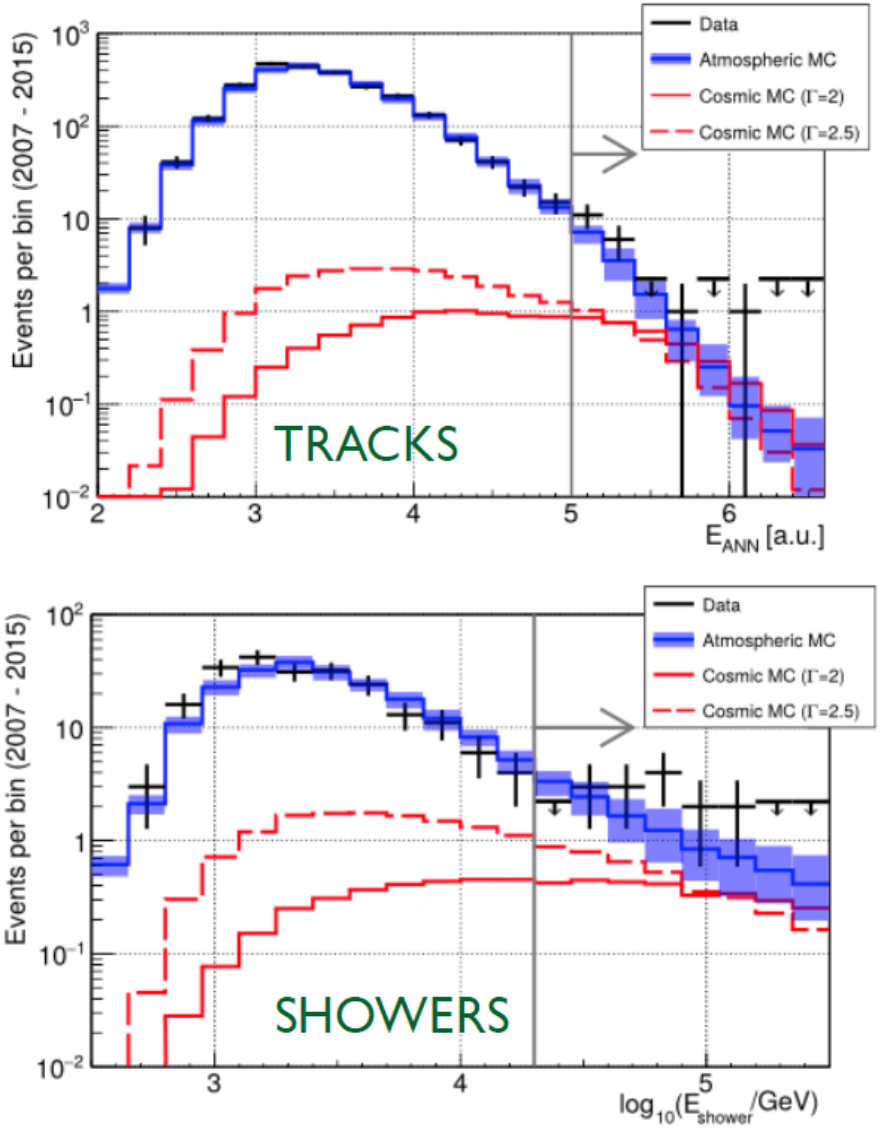
Event selection chain + energy-related cut applied to
- obtain a high-purity neutrino sample
- maximize sensitivity

Signal modeled according to the IceCube flux

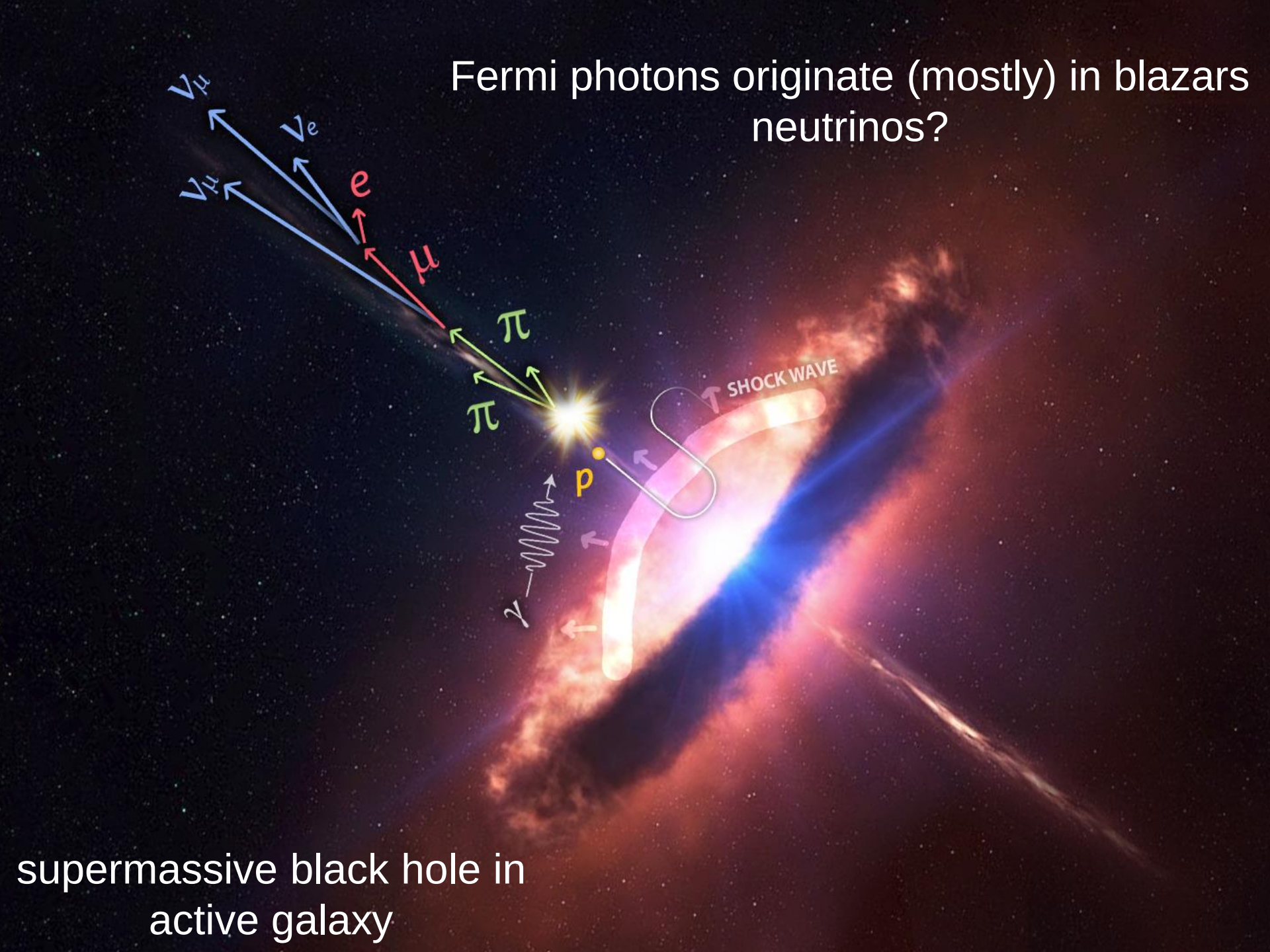
Result:
33 events (19 tracks + 14 showers) in data
24 ±7 (stat.+syst.) events background in MC

1.6σ excess, null cosmic rejected at 85% CL

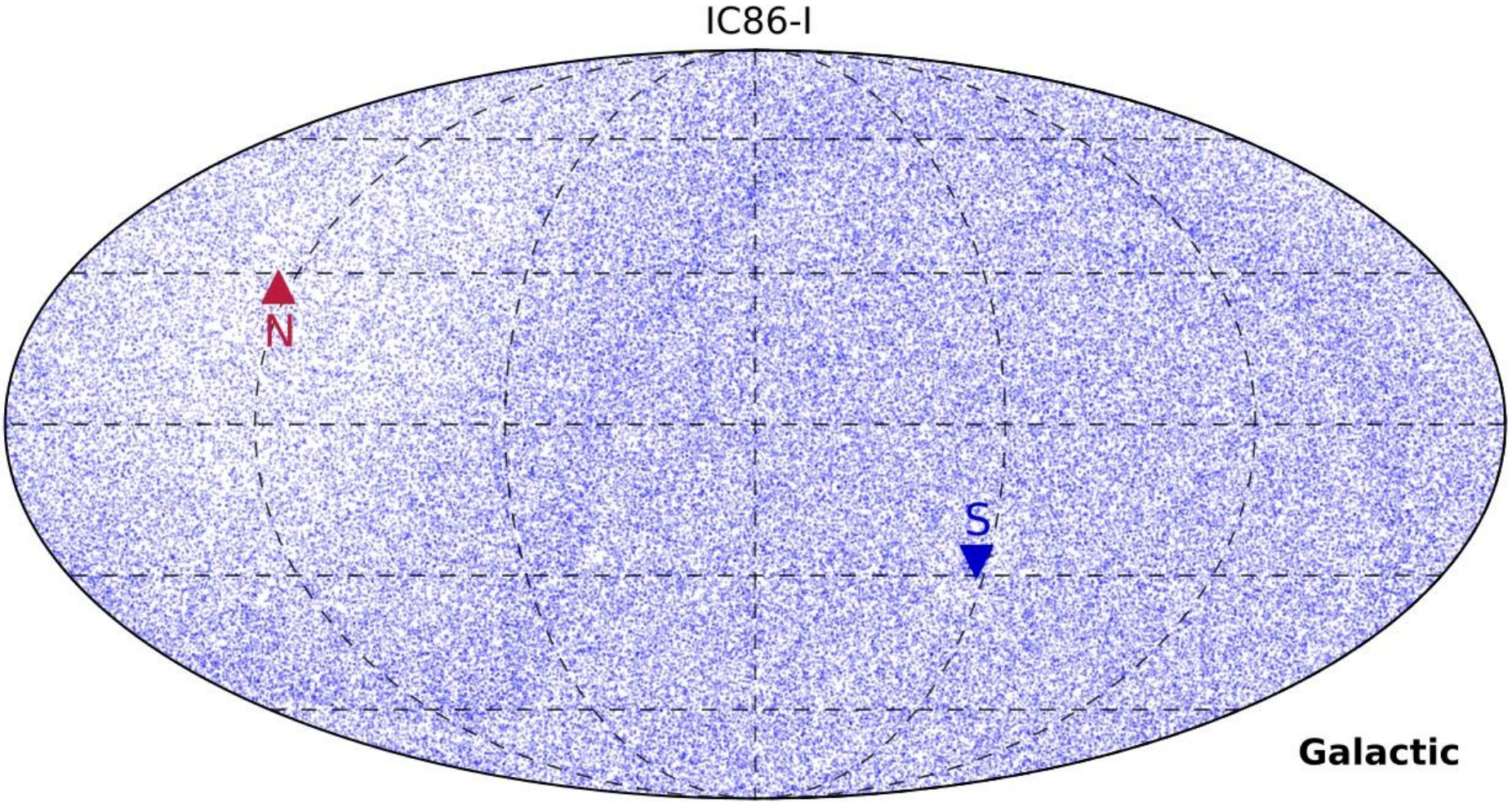
ApJ 853, (2018) L7



Fermi photons originate (mostly) in blazars
neutrinos?



supermassive black hole in
active galaxy

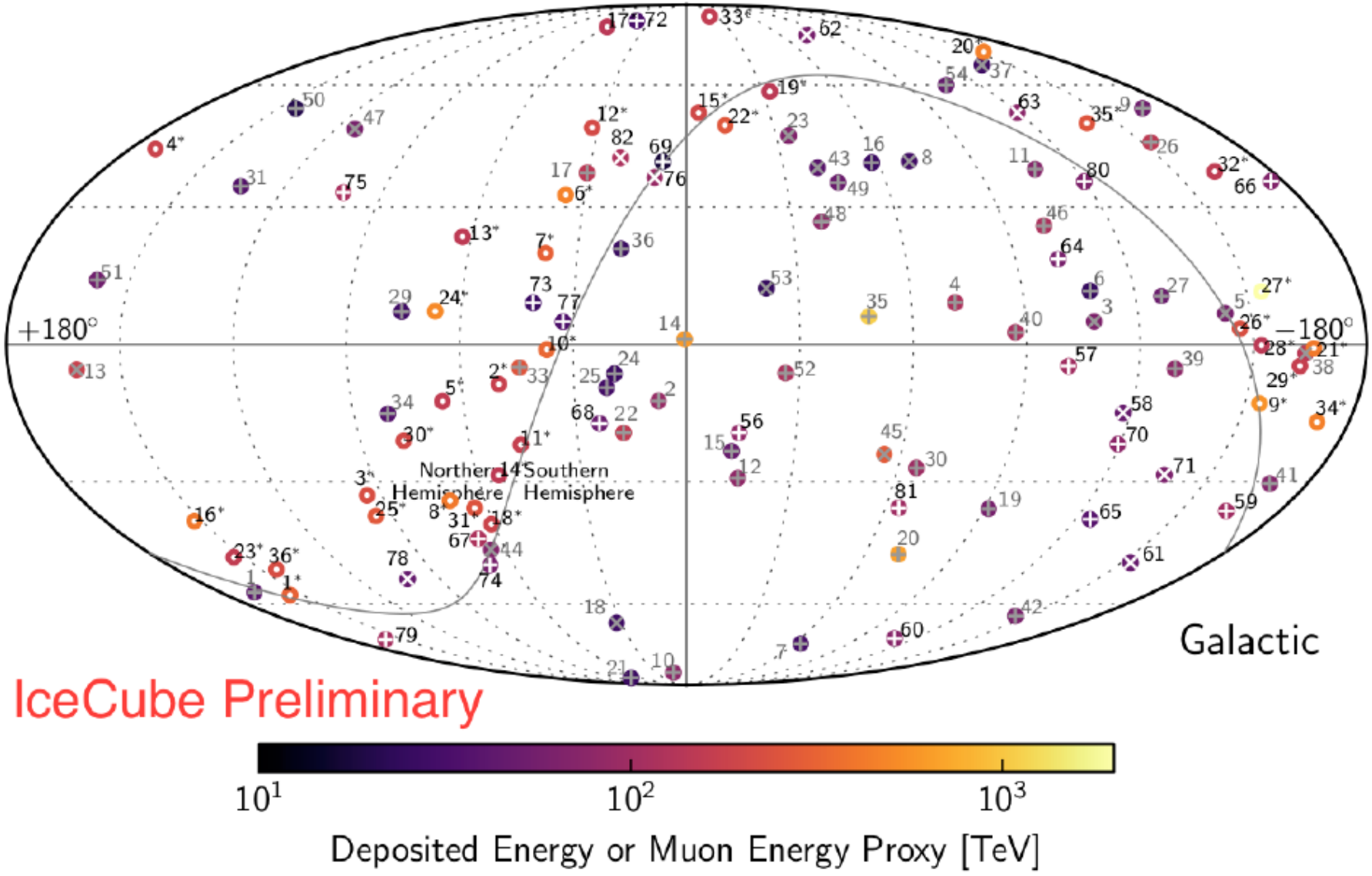


138322 neutrino candidates in one year

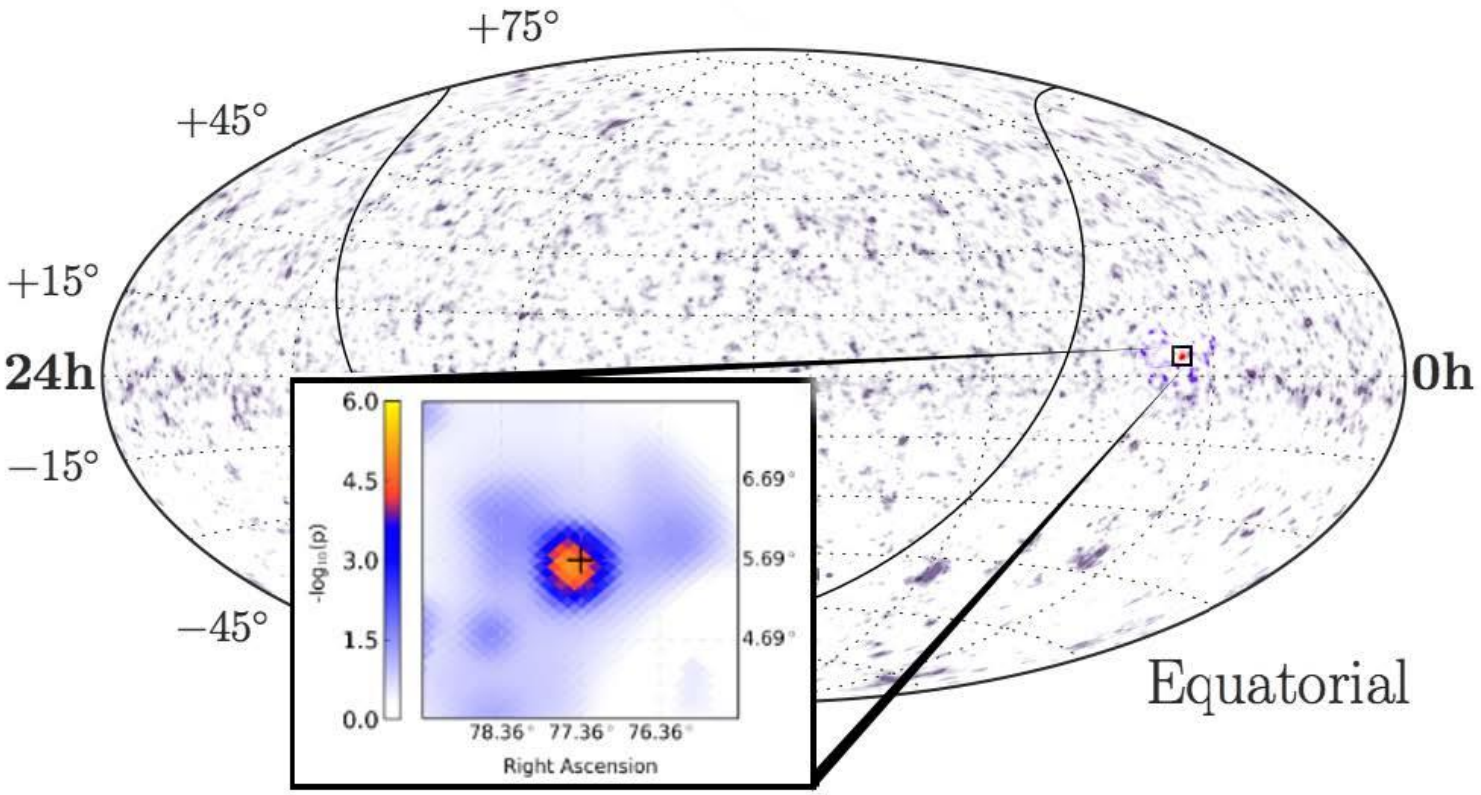
120 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV

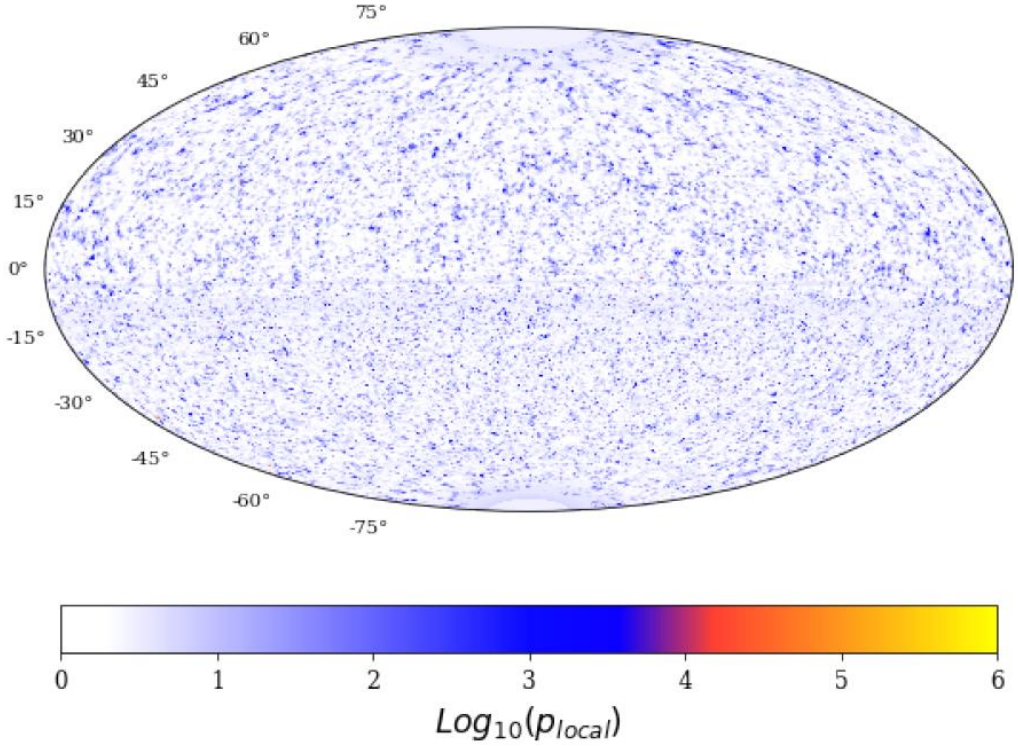
structure in the map results from neutrino absorption by the Earth

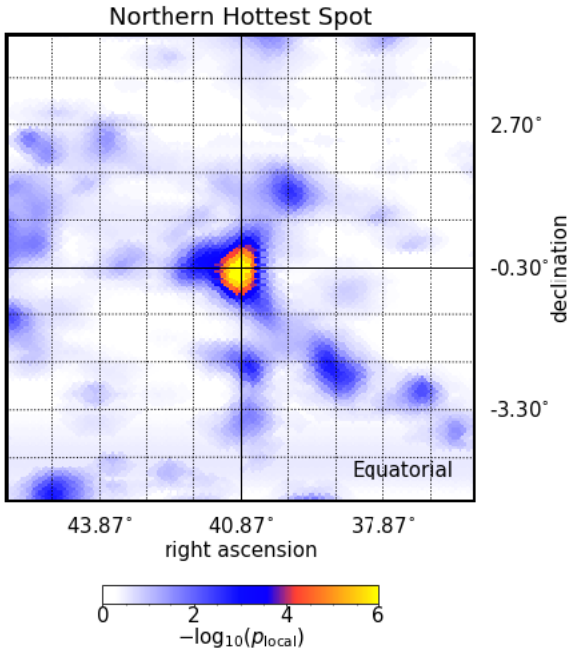

+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

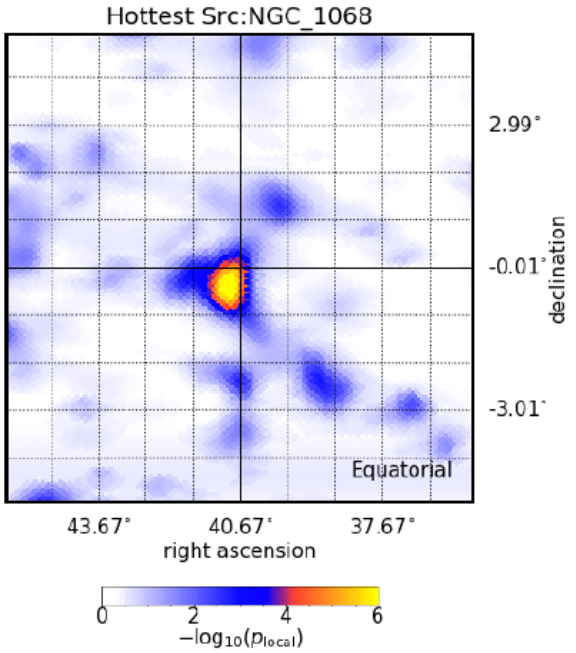
10 years of IceCube data: evidence non-uniform skymap, mostly resulting from 4 source candidates



10 years of muon neutrinos

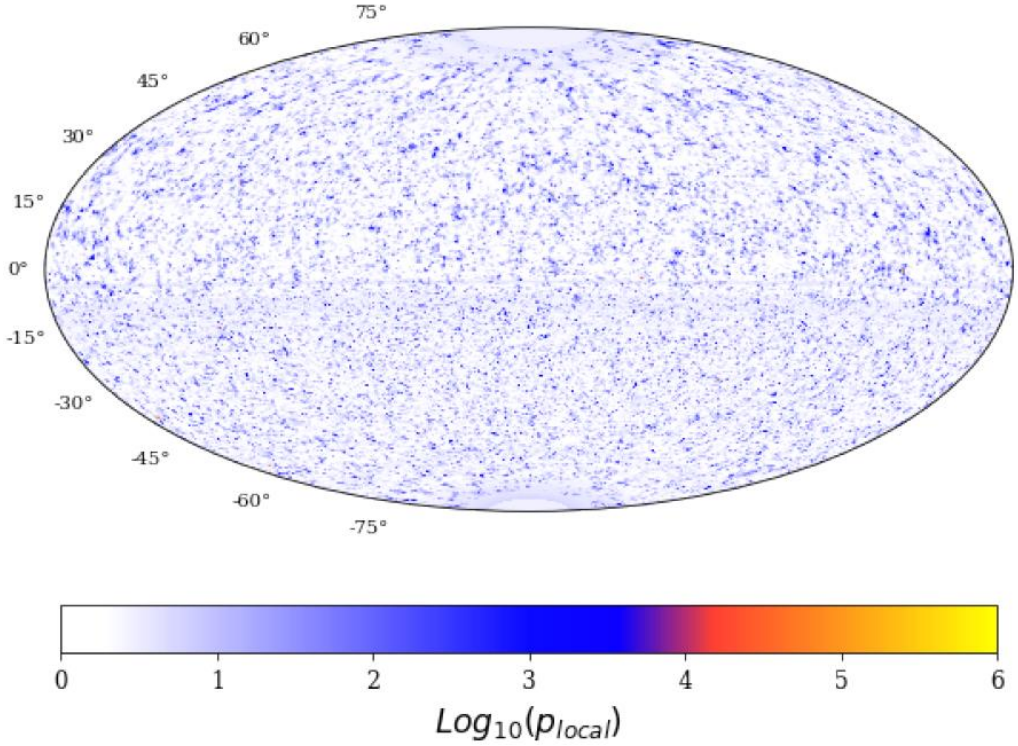


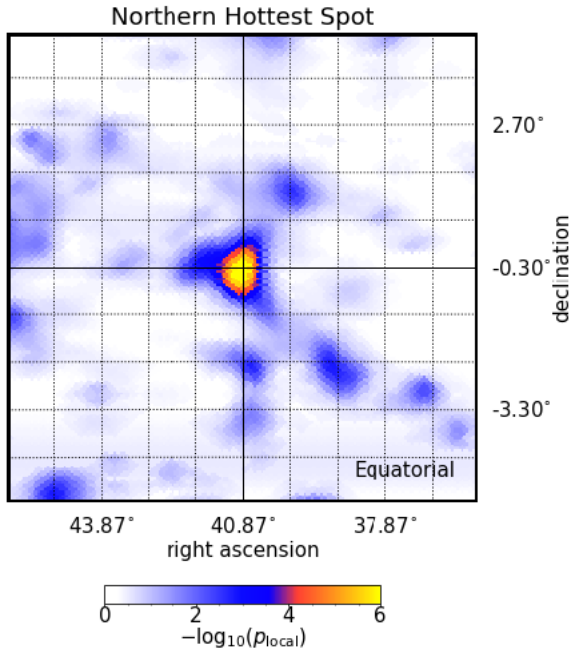


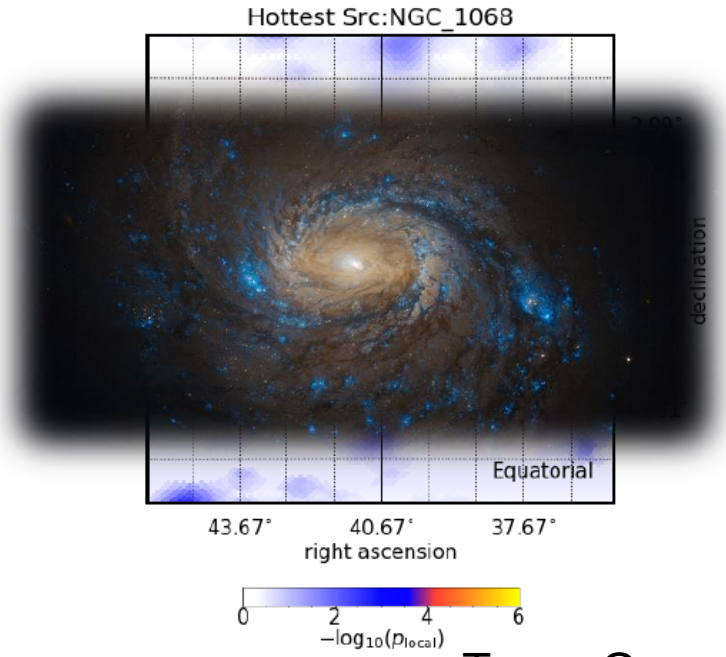


Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
All-Sky Scan	North	10**-6.45	0.09
	South	10**-5.37	0.476
Source List	North	10**-4.7 (4.1σ)	0.002 (2.875σ)
	South	0.0587	0.55
Src List Population	North	3.98σ	0.0005 (3.3σ)
	South	1.18σ	0.36
Stacking	SNR	0.475	0.475
	PWN	0.1	0.1
	UNID	0.496	0.496

10 years of muon neutrinos







Analysis	Hemisphere	Best Pre-trial Pvalue	Post-trial Pvalue
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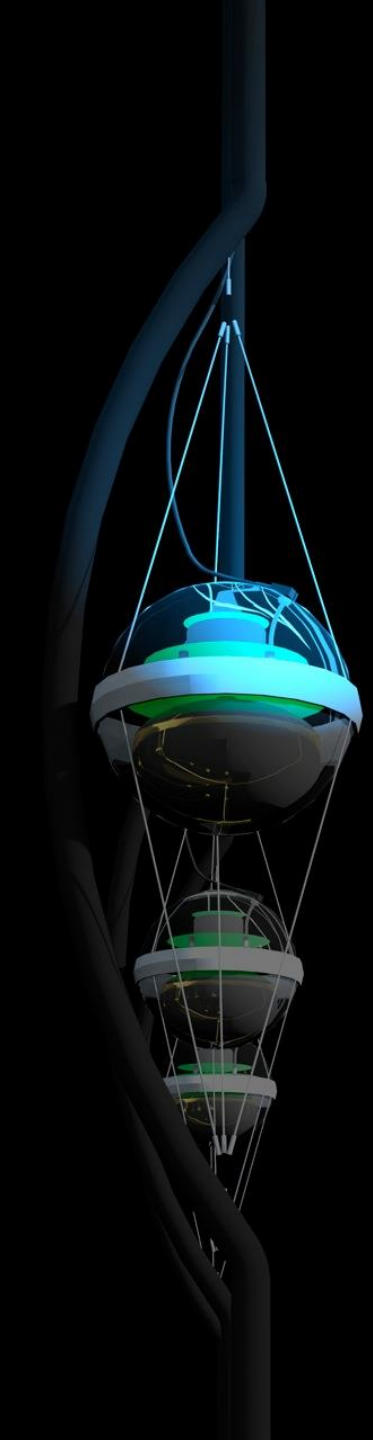
Tessa Carver

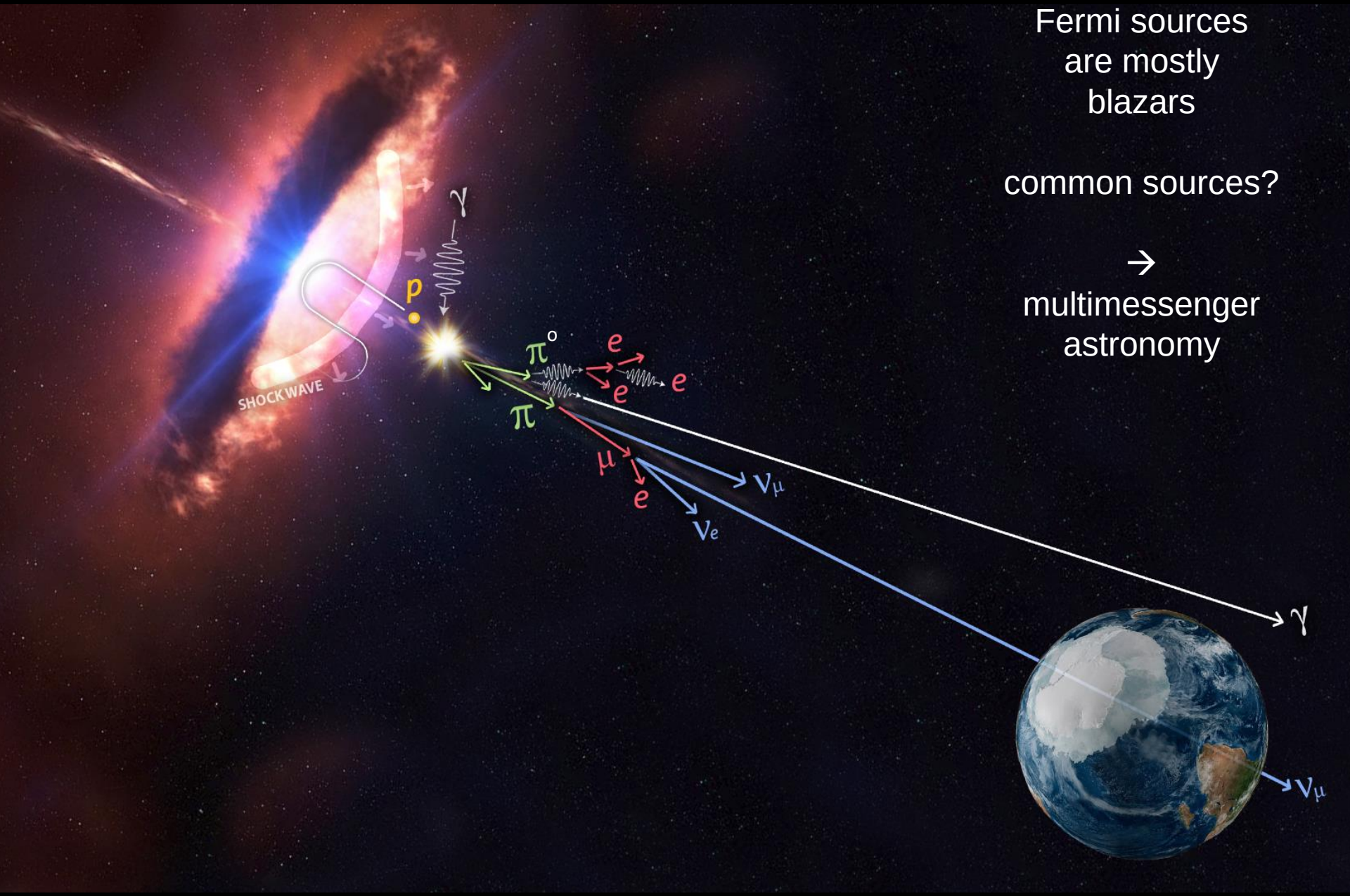


neutrino astronomy

- cosmic neutrinos: four independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → tau neutrinos
  - → Glashow event

multimessenger astronomy

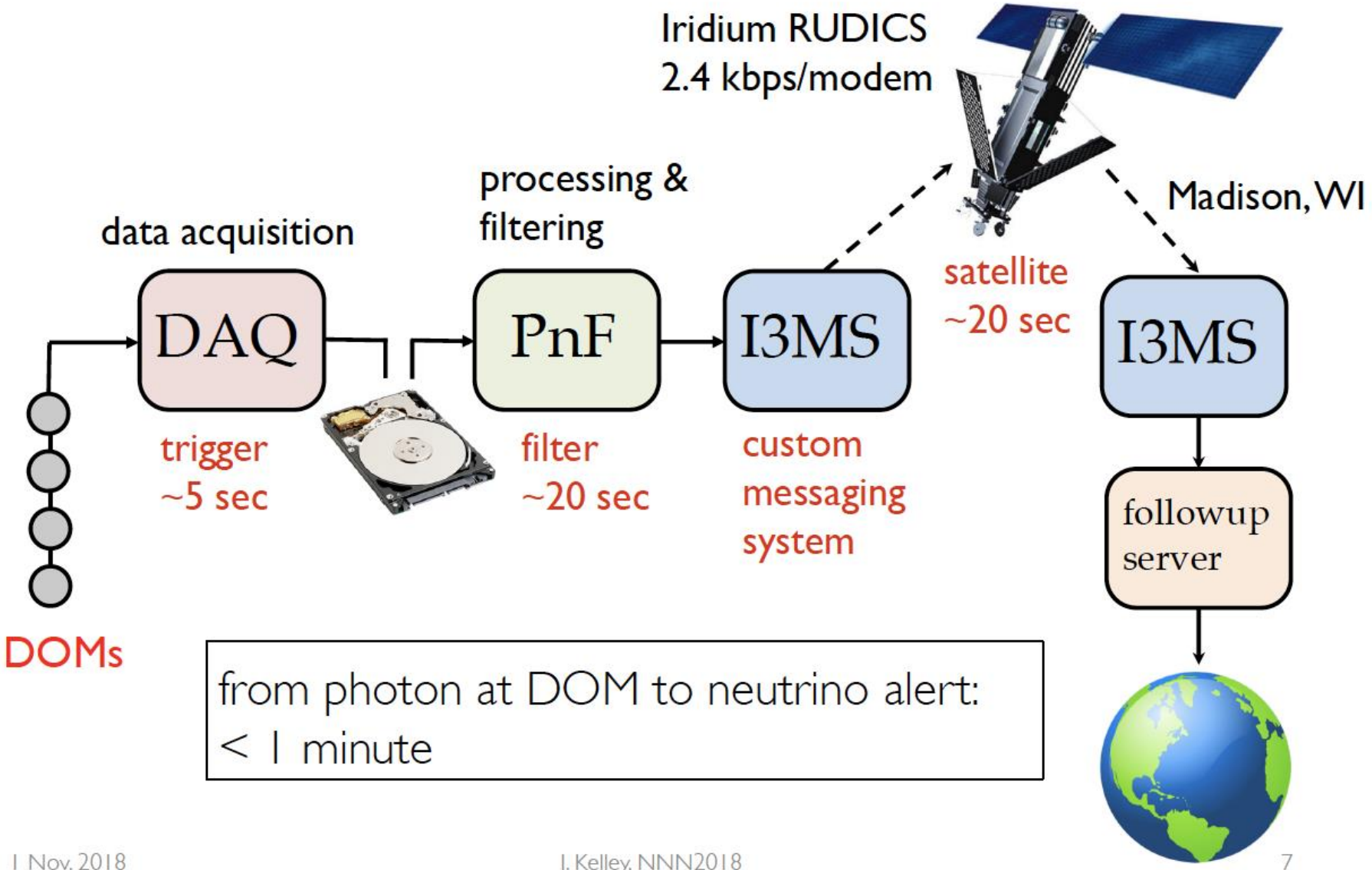
- Fermi photons and IceCube neutrinos
- the first extragalactic cosmic ray accelerator


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

HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

M. Richman

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



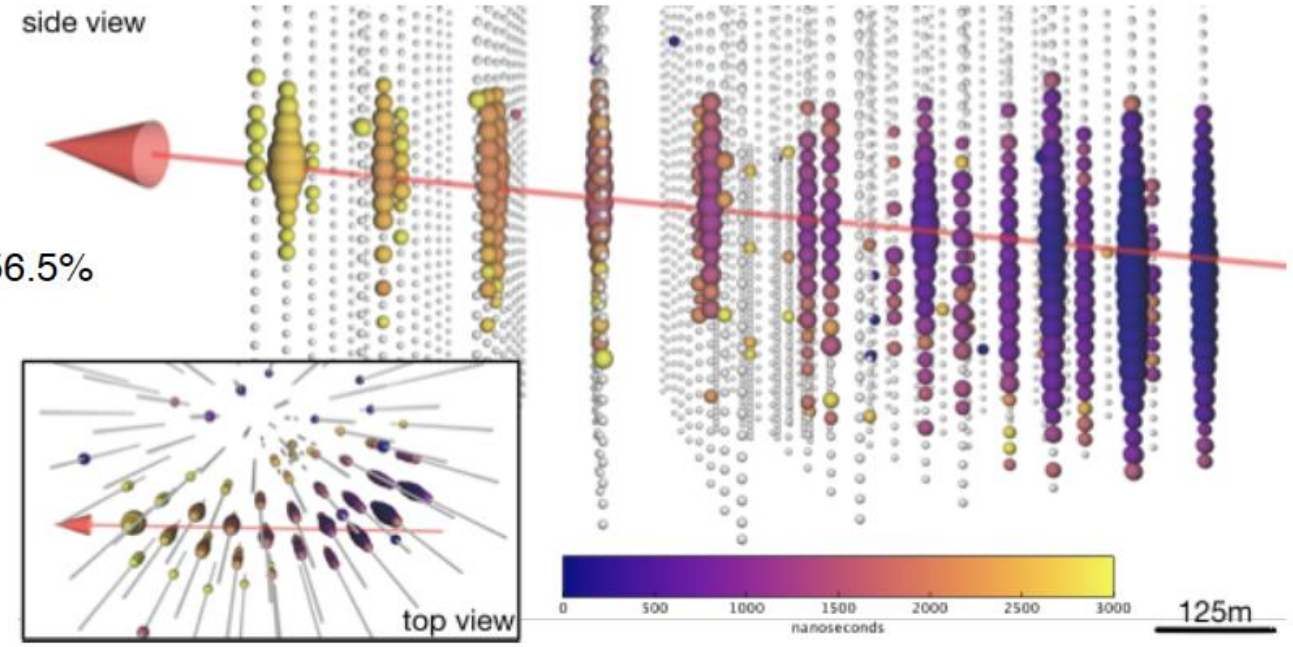
IceCube Trigger

43 seconds after trigger, GCN notice was sent

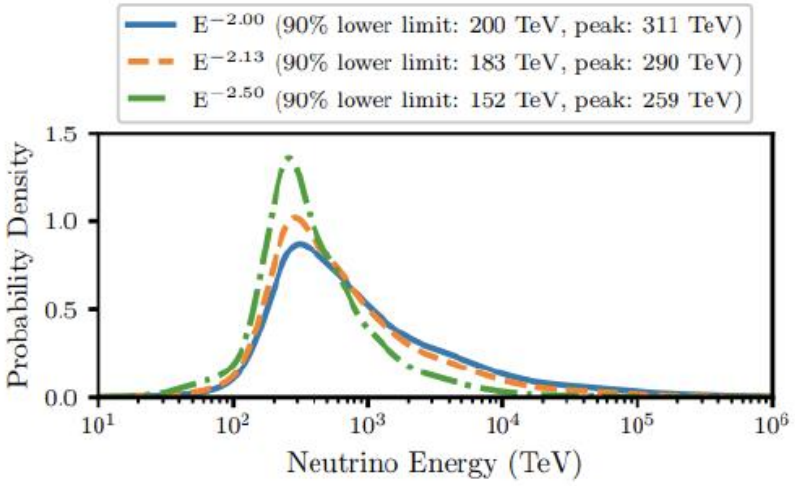
```
////////////////////////////////////////////////////////////////////////
TITLE:              GCN/AMON NOTICE
NOTICE_DATE:        Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:        AMON ICECUBE EHE
RUN_NUM:            130033
EVENT_NUM:          50579430
SRC_RA:              77.2853d {+05h 09m 08s} (J2000),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

IC-170922A

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)



Signalness: 56.5%

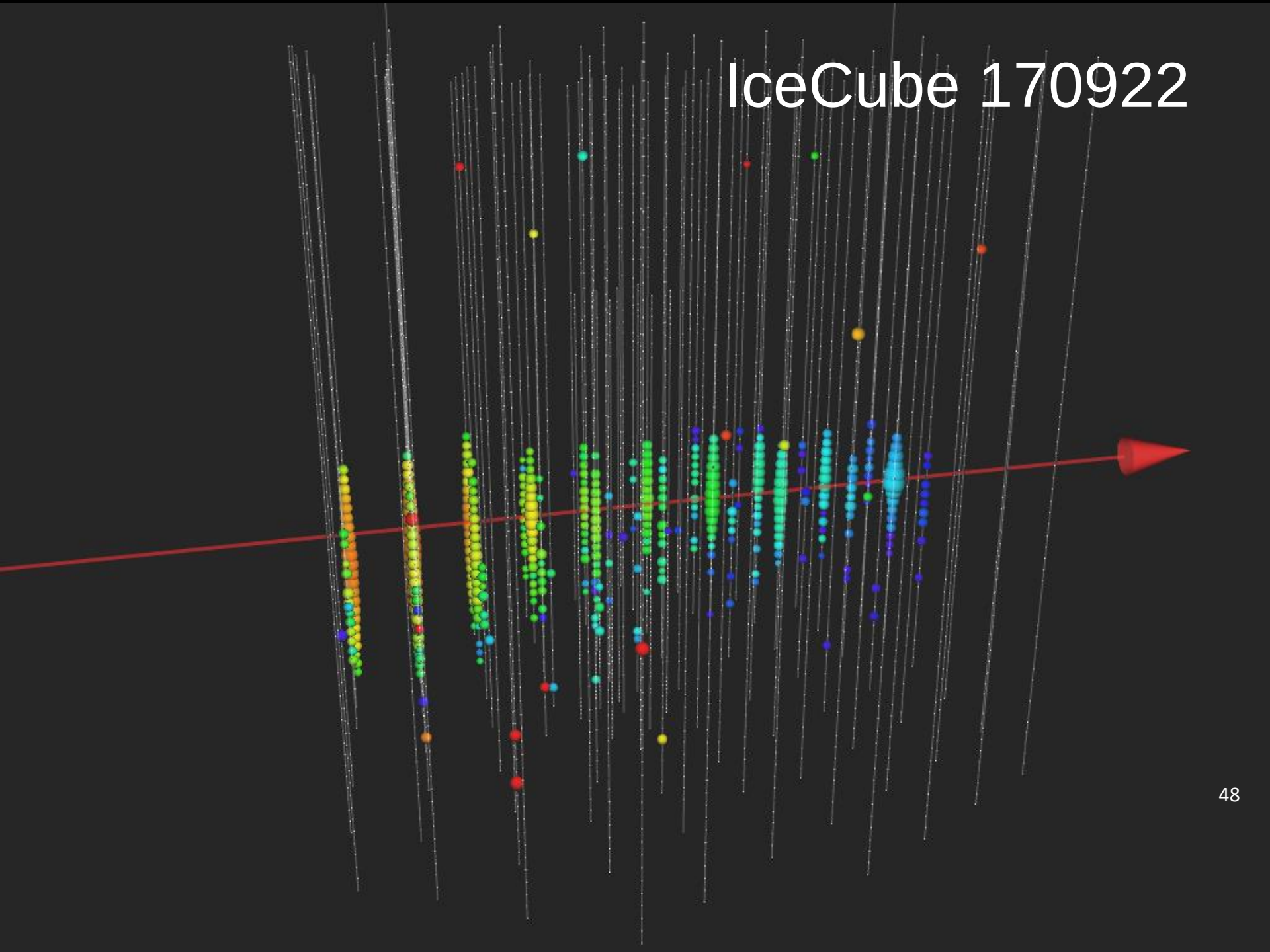


Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

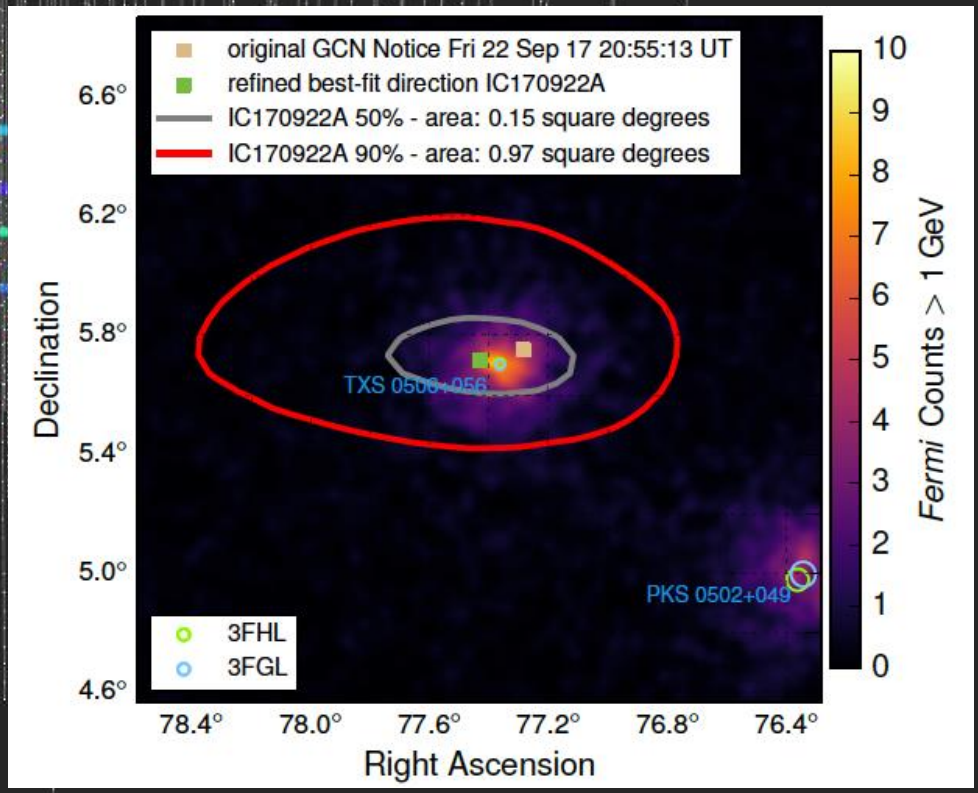
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

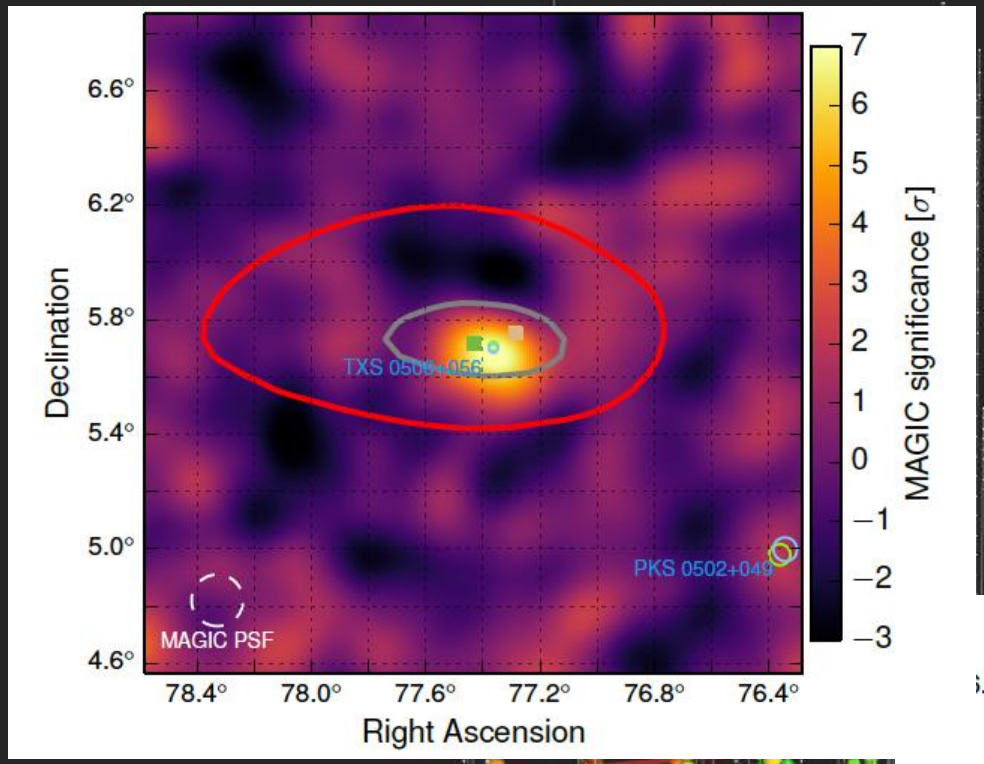
IceCube 170922



IceCube 170922

Fermi
detects a flaring
blazar within 0.1°

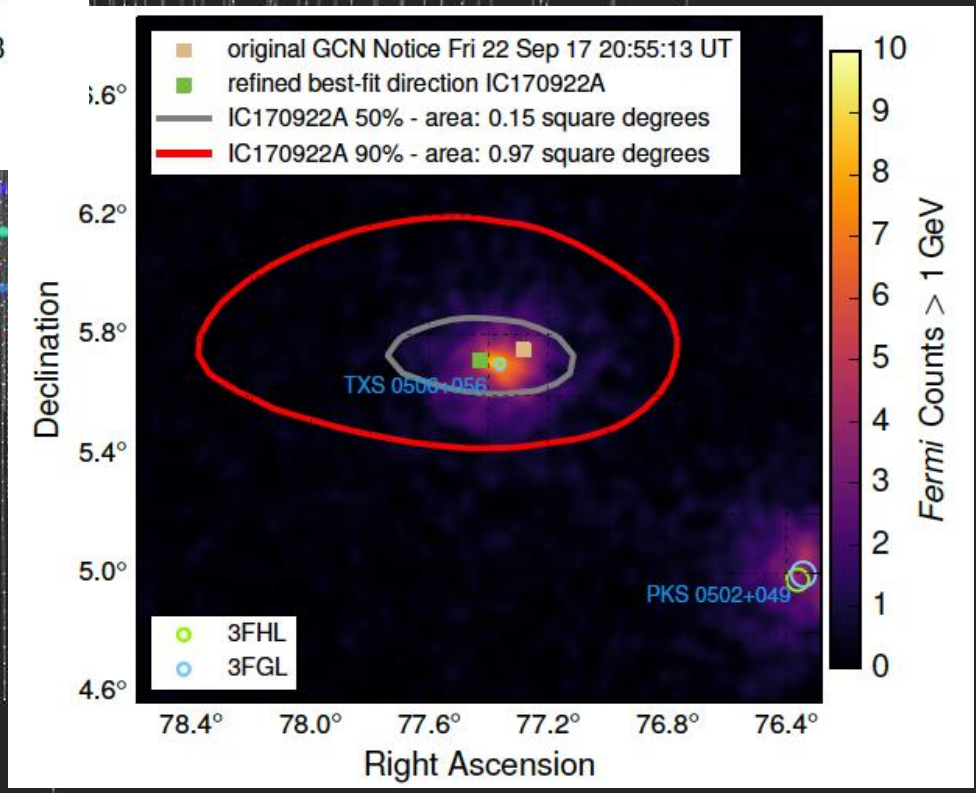


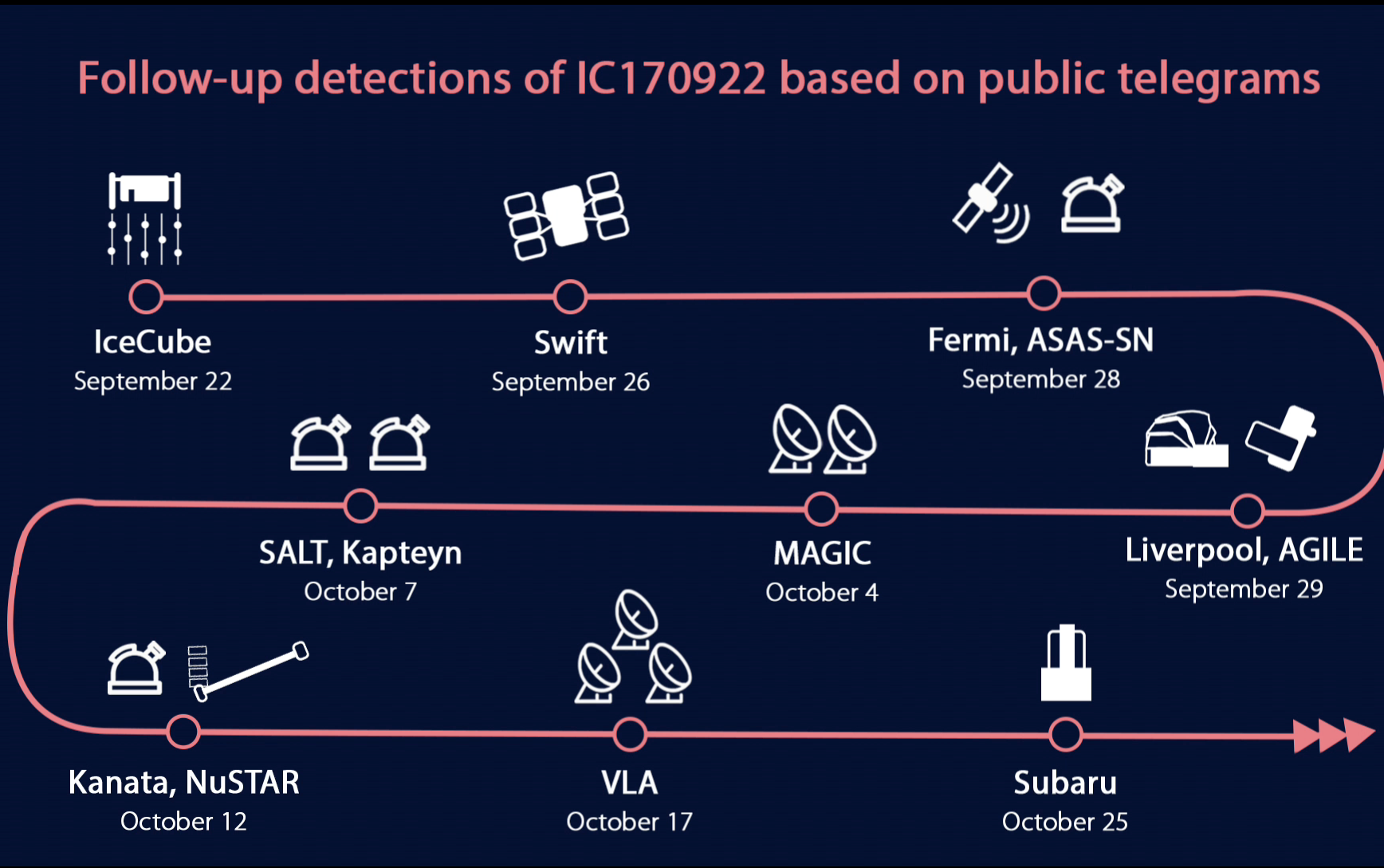


IceCube 170922

Fermi
detects a flaring
blazar within 0.1°

MAGIC
detects emission of
> 100 GeV gammas




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

THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

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[2] *INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova - ITALY*
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[5] *Instituto de Astrofisica de Canarias, C/O Via Lactea, s/n E38205 - La Laguna (Tenerife) - SPAIN*
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(Received February, 2018; Revised February 7, 2018; Accepted 2018)

Submitted to ApJL

ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW $\sim$ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift z = 0.3365±0.0010.

Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

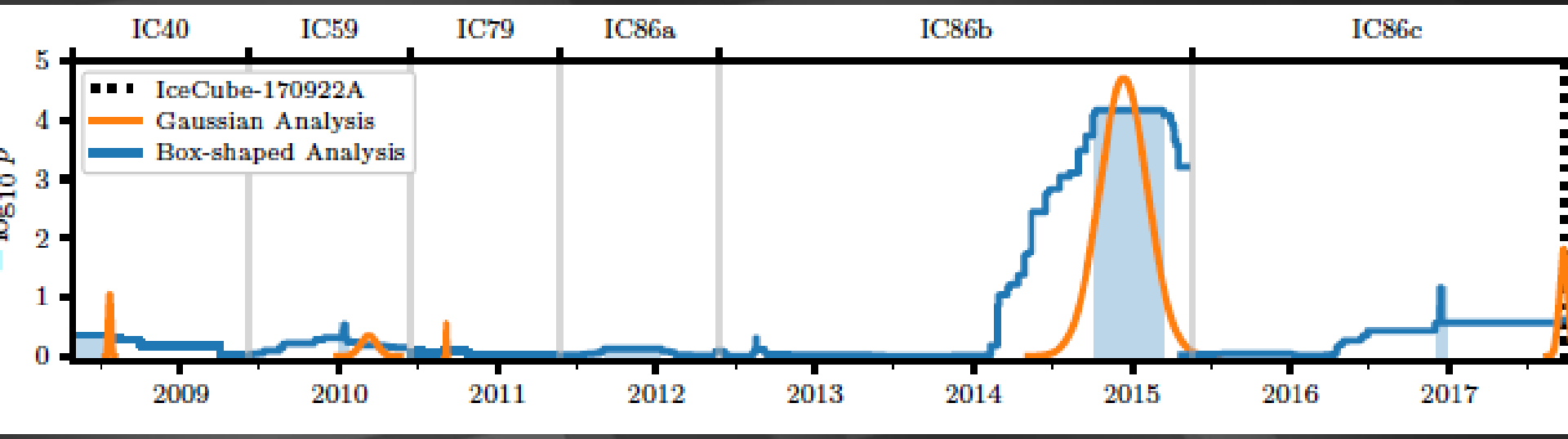
- we do not see our own Galaxy
- we do not see the nearest extragalactic sources
- we find a blazar at 4 billion lightyears!

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

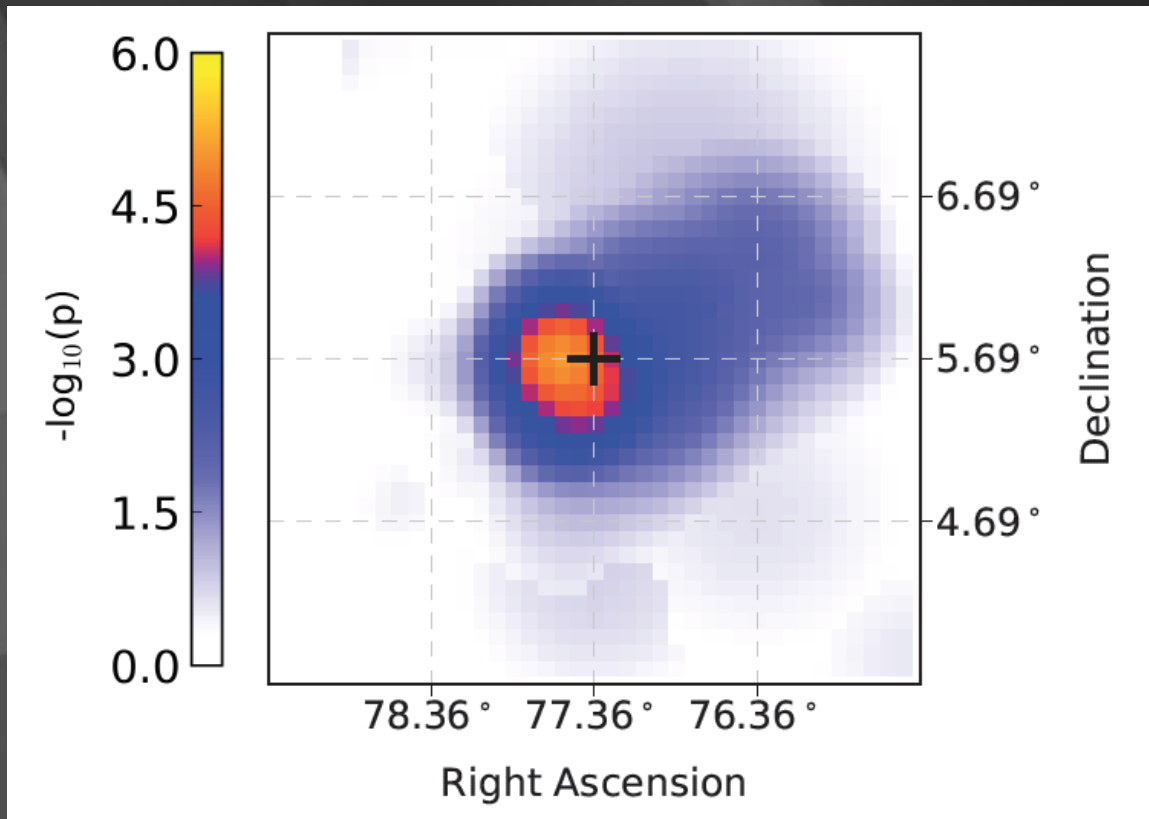
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.1^{o} (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes

- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

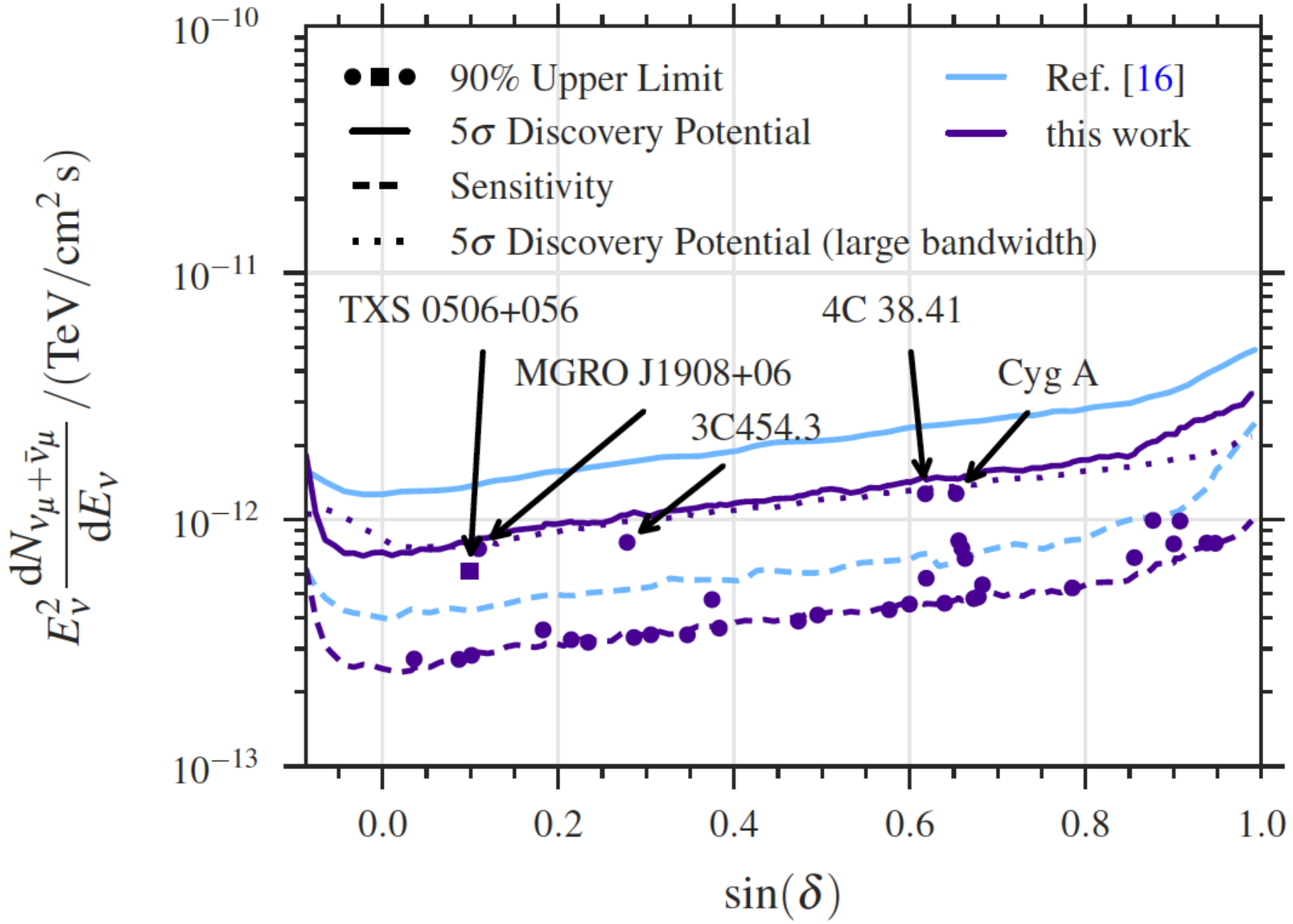


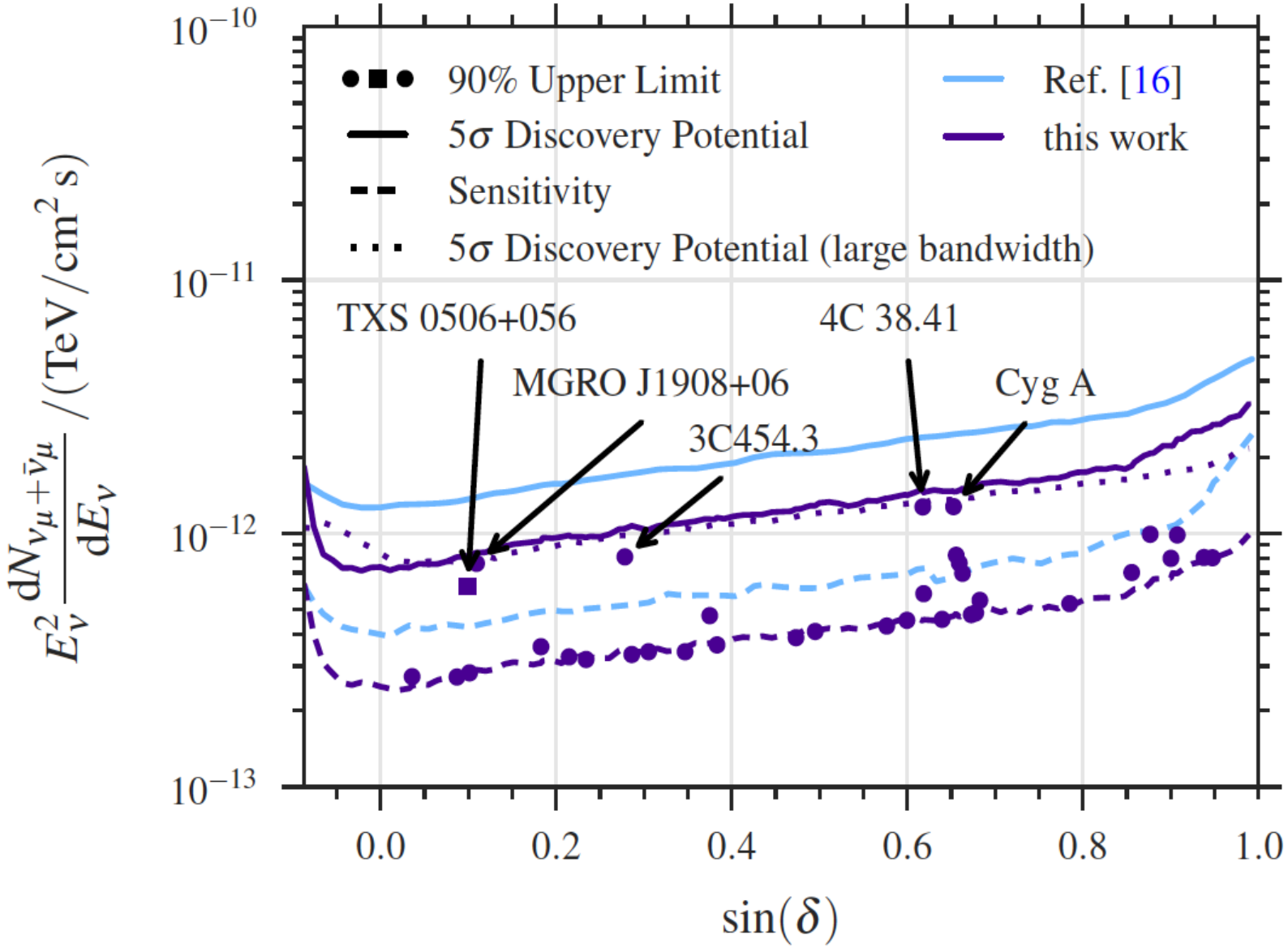
search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 2.10^{-5} bkg.probability
- spectrum $E^{-2.1}$



Why not seen before?





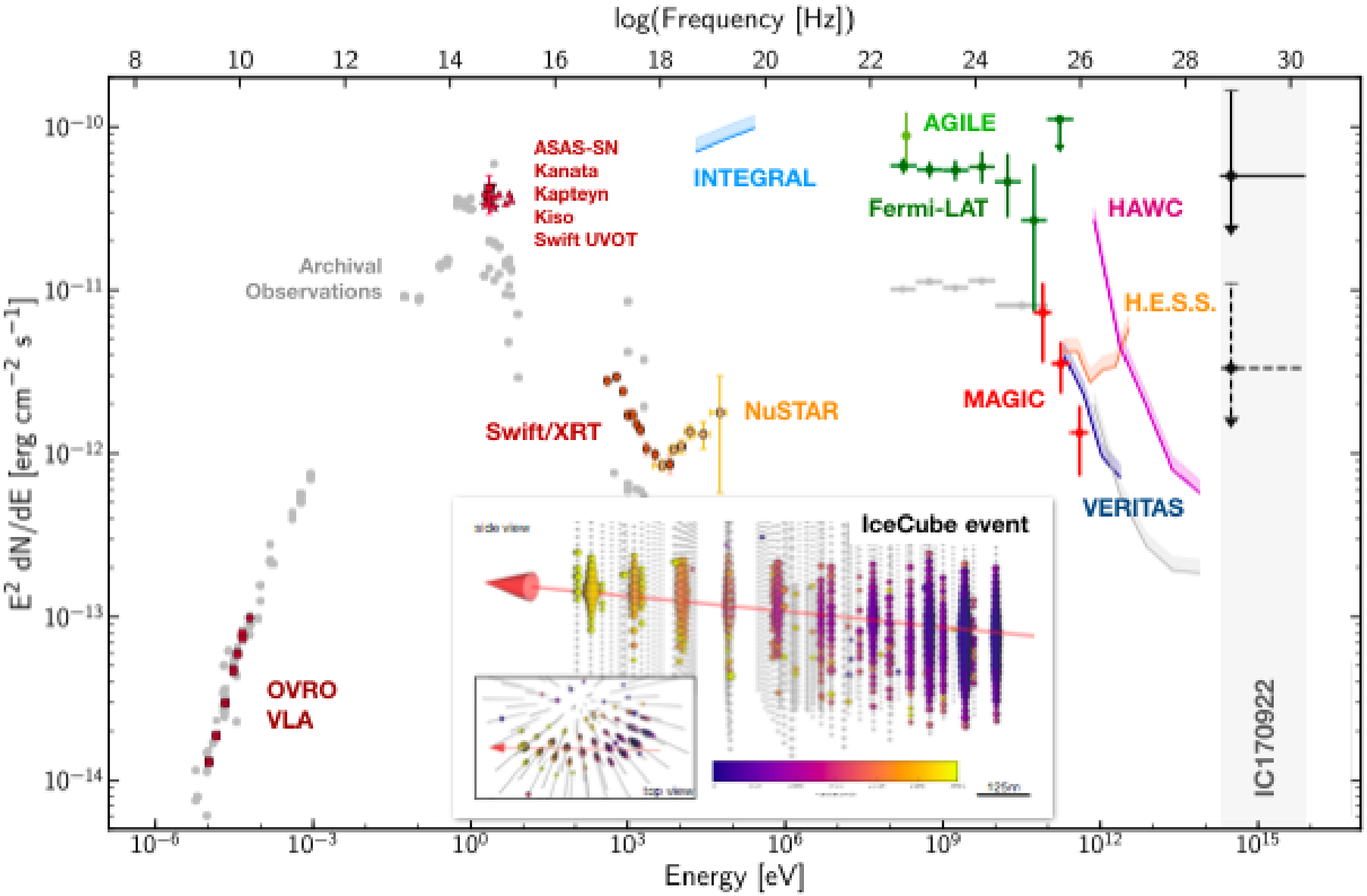
this is the case for larger detectors with better angular resolution

we identified a source of high energy cosmic rays:

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

at ten times further distance, it outshines nearby active galaxies: is it special?

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



we know that this one is a cosmic ray source

relation between flaring sources and the diffuse flux ?

diffuse ν_μ flux

TXS luminosity

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{4\pi} \frac{c}{H_0} \xi_z L_\nu \rho \mathcal{F} \frac{\Delta t}{T}$$

density of blazars

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq 7.4 \times 10^{-9}\,\mathrm{TeV cm^{-2} s^{-1} sr^{-1}} \times \left(\frac{\mathcal{F}}{4\pi}\right) \left(\frac{c/H_0}{4.3\,\mathrm{Gpc}}\right) \left(\frac{\xi_z}{0.7}\right) \left(\frac{L_\nu}{1.2 \times 10^{47}\,\mathrm{erg/s}}\right) \left(\frac{\rho}{1.5 \times 10^{-8}\,\mathrm{Mpc^{-3}}}\right) \left(\frac{\Delta t}{110\,\mathrm{d}}\right) \left(\frac{10\,\mathrm{yr}}{T}\right).$$

5%

a special class of blazars that undergo 110-day duration flares like TXS 0506+056 once every 10 years accommodates the observed diffuse flux of high-energy cosmic neutrinos (selected by evolution?)

a target that produces > 12 neutrinos in 110 days is opaque to gamma rays that lose energy in the source before entering the EBL

- the energetics of cosmic rays and neutrinos dictates

p-beam

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{4\pi}\left(\frac{1}{2}(1-e^{-\tau_{p\gamma}})\,\xi_z t_H \frac{dE}{dt}\right)$$

γ-target density

- observed CRs energy injection rate $\frac{dE}{dt} \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

- high opacity for p-gamma interactions $\longrightarrow$ $\tau_{p\gamma} \gtrsim 0.4$

- gamma ray opacity is connected to pion efficiency

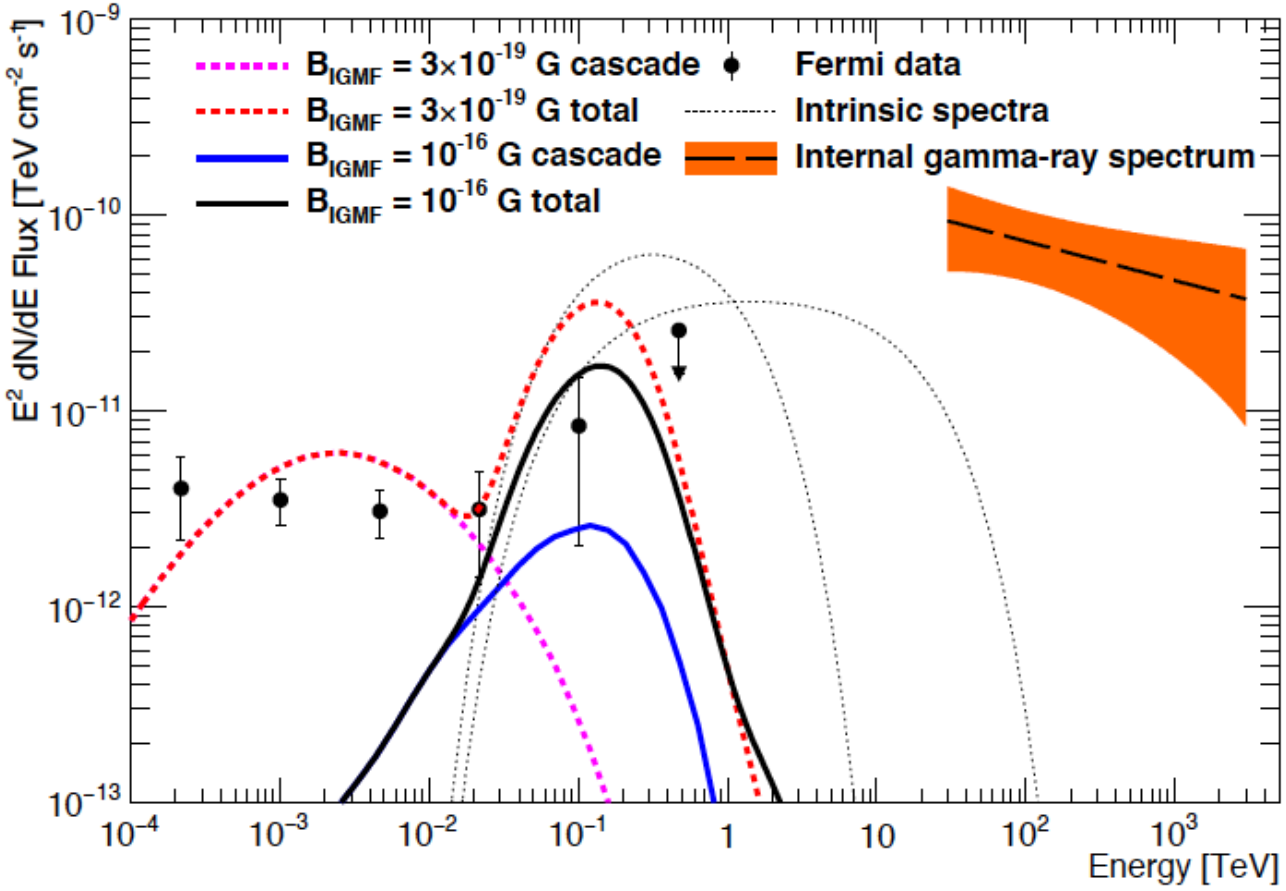
$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}}\tau_{p\gamma} \longrightarrow \tau_{\gamma\gamma} \simeq 100$$

the gamma rays that accompany the neutrinos lose energy in the source

- is this compatible with the gamma ray observations?

the multimessenger picture

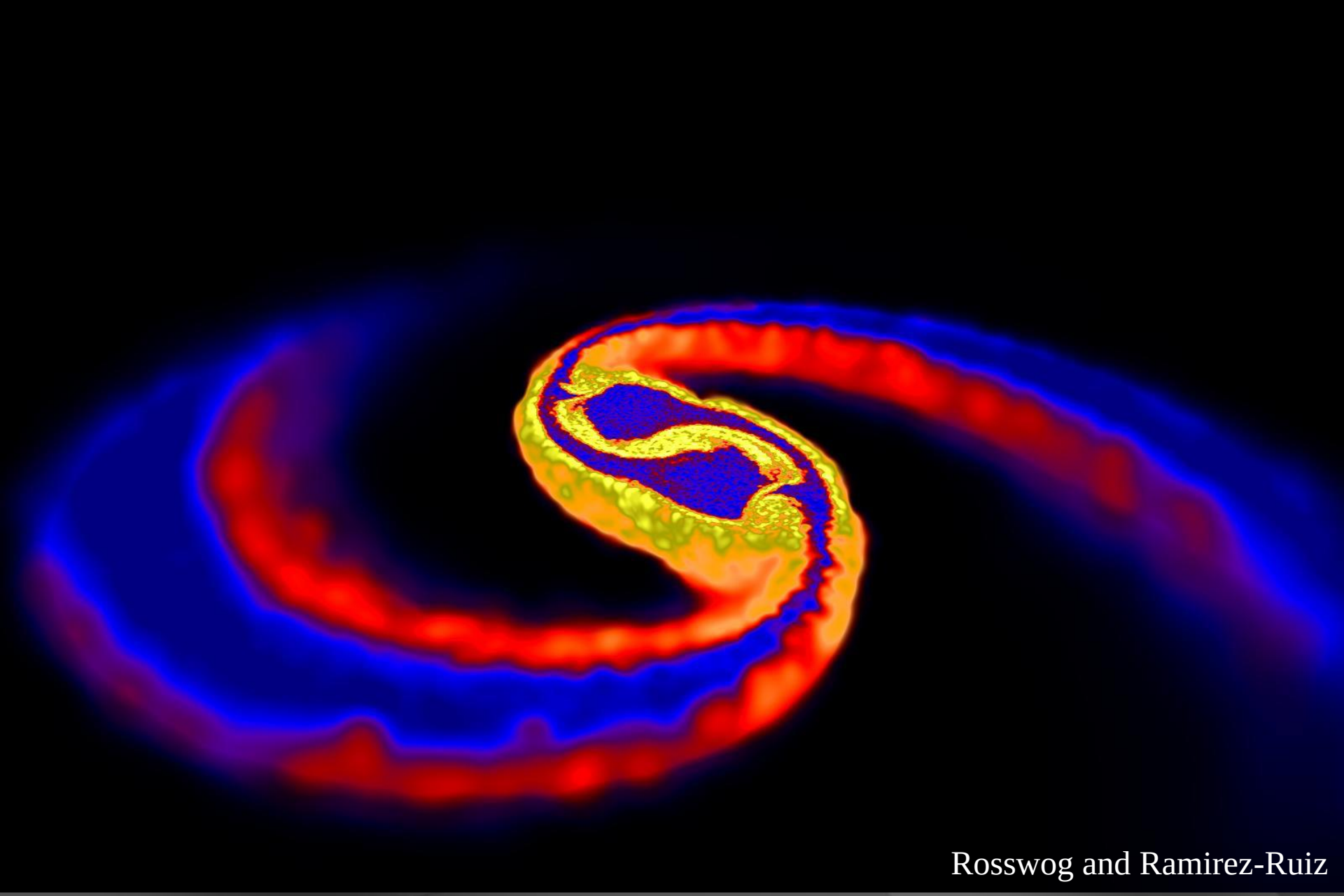
neutrino flux —(multimessenger relation)→ gamma ray flux cascades to lower energy in the source —(EBL absorption)→ observed flux @ Fermi



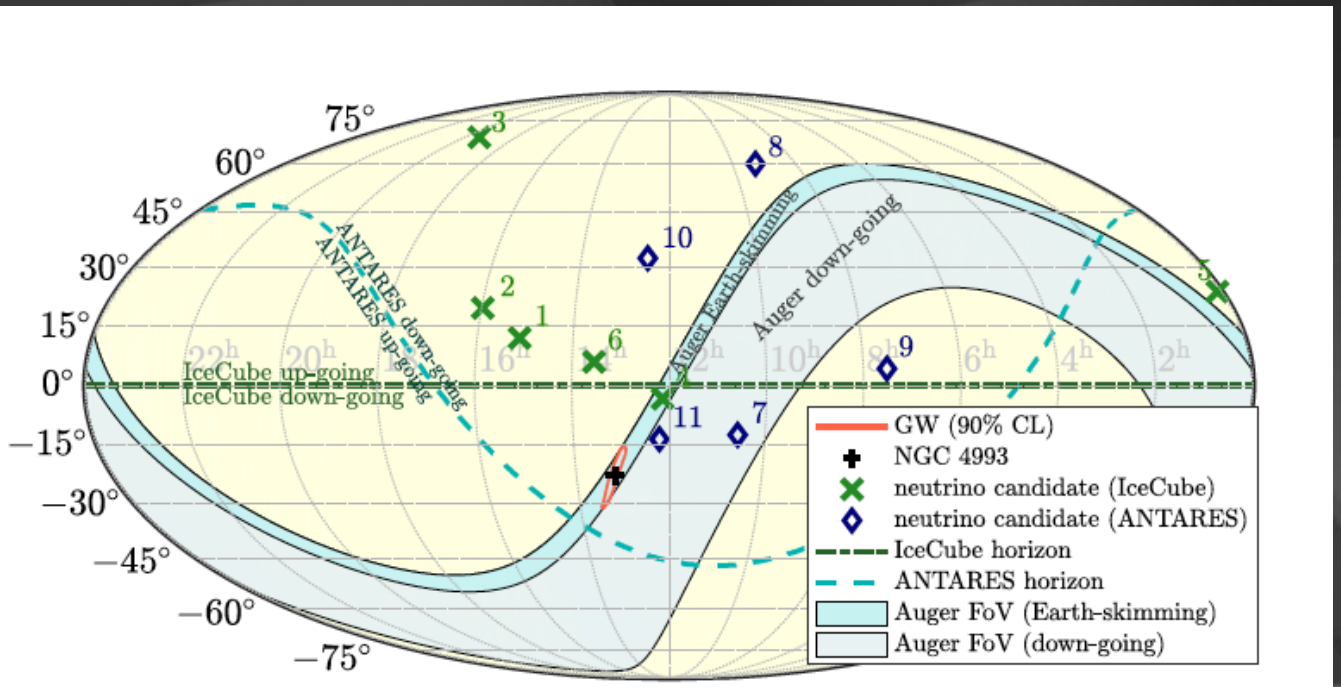
**Fermi data from S. Garrappa+, TeVPA2018*

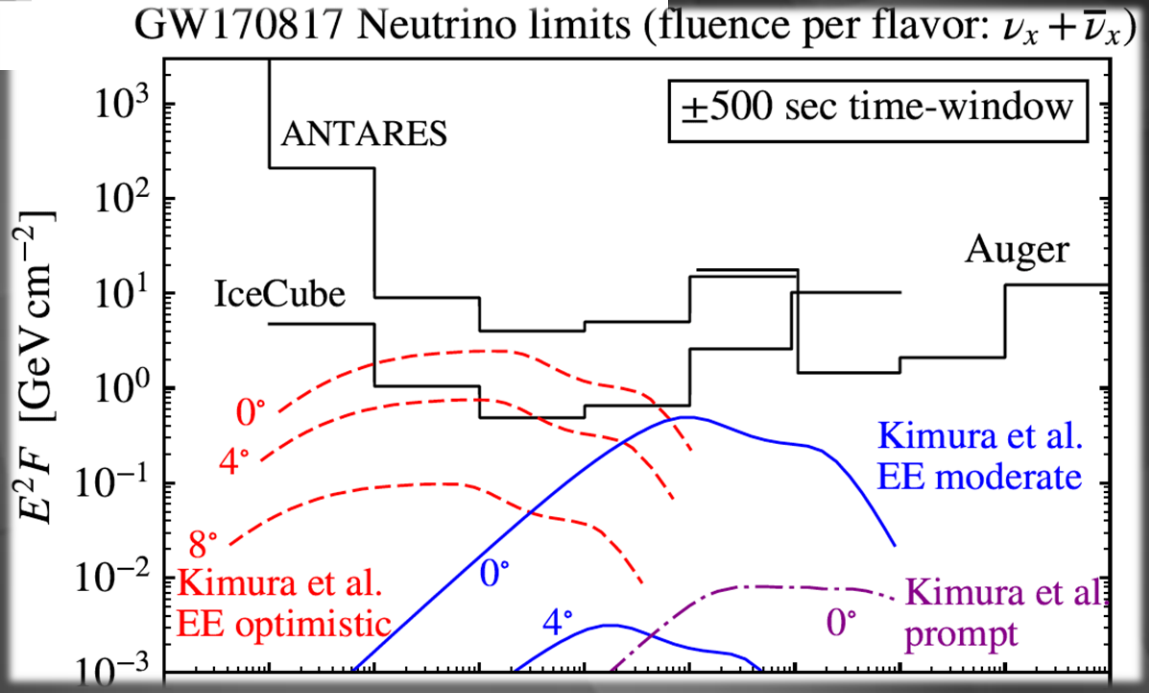
neutron star-neutron star merger

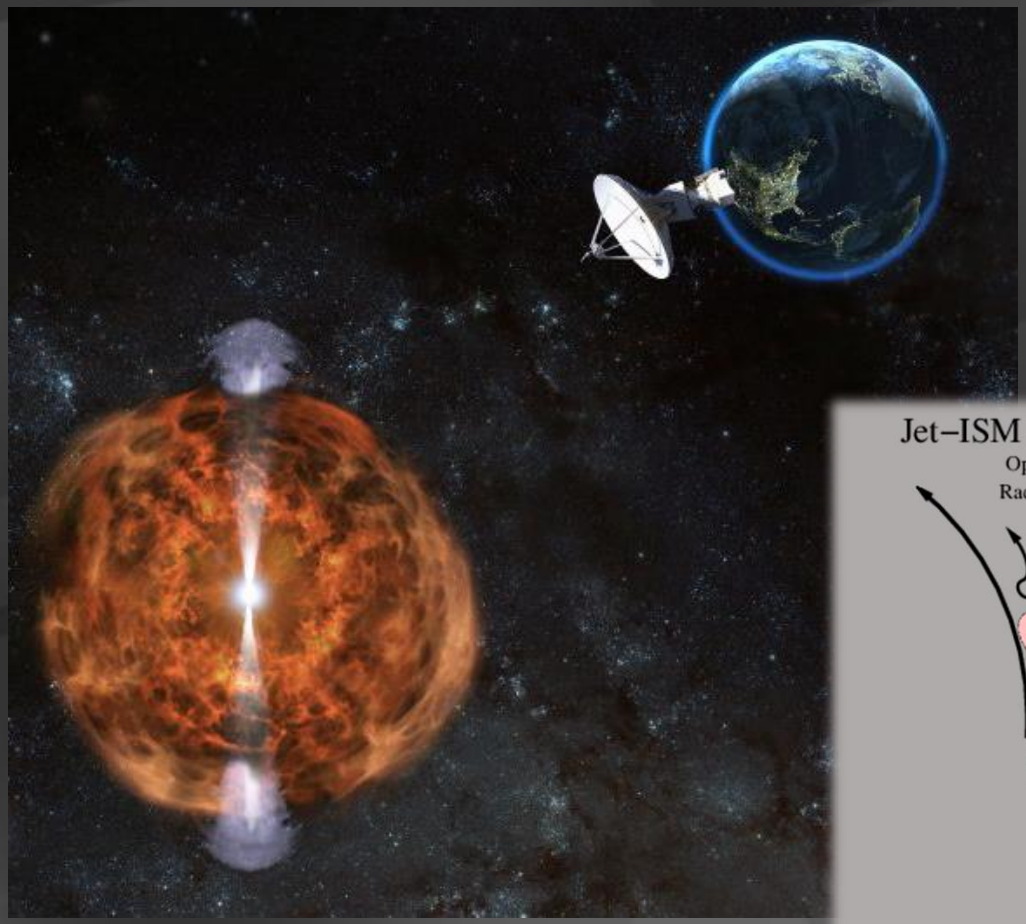
LIGO-VIRGO



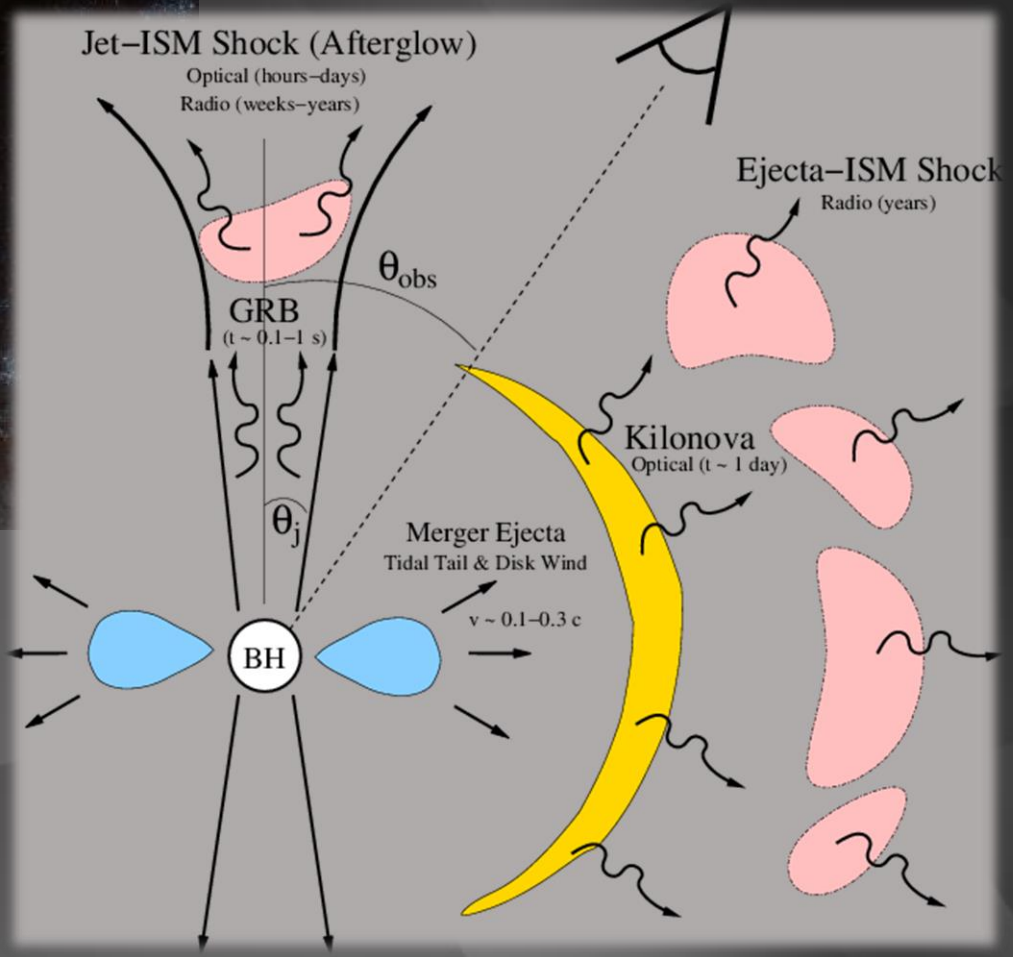
merger of neutron stars about to launch a jet


75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
22h
20h
16h
12h
8h
6h
4h
2h
IceCube up-going
IceCube down-going
ANTARES up-going
ANTARES down-going
Auger Earth-skimming
Auger down-going
1
2
3
4
5
6
7
8
9
10
11
GW (90% CL)
NGC 4993
neutrino candidate (IceCube)
neutrino candidate (ANTARES)
IceCube horizon
ANTARES horizon
Auger FoV (Earth-skimming)
Auger FoV (down-going)


GW170817 Neutrino limits (fluence per flavor: $\nu_x + \overline{\nu}_x$)
±500 sec time-window
ANTARES
IceCube
Auger
E^2F [GeV cm^{-2}]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0°
4°
8°
Kimura et al.
EE optimistic
Kimura et al.
EE moderate
0°
4°
0°
Kimura et al.
prompt

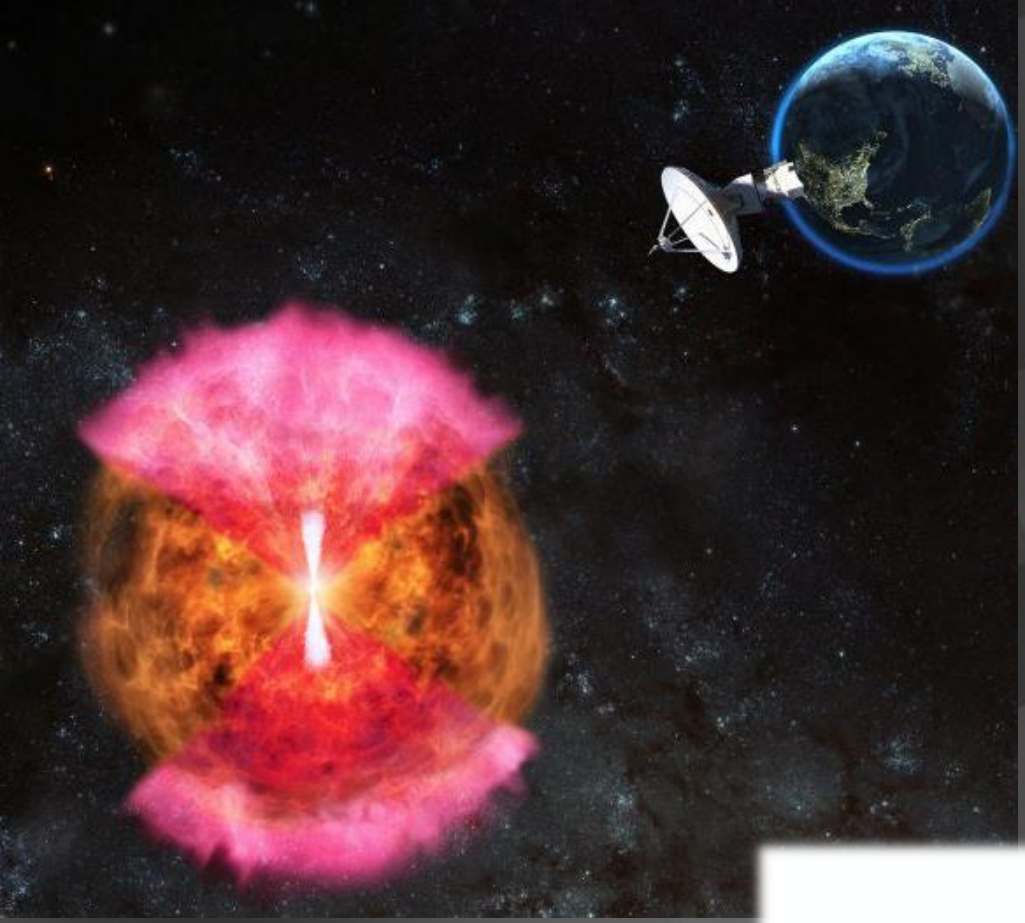


very weak short GRB seen by Fermi (off axis? choked jet?)



MeV neutrino emission:

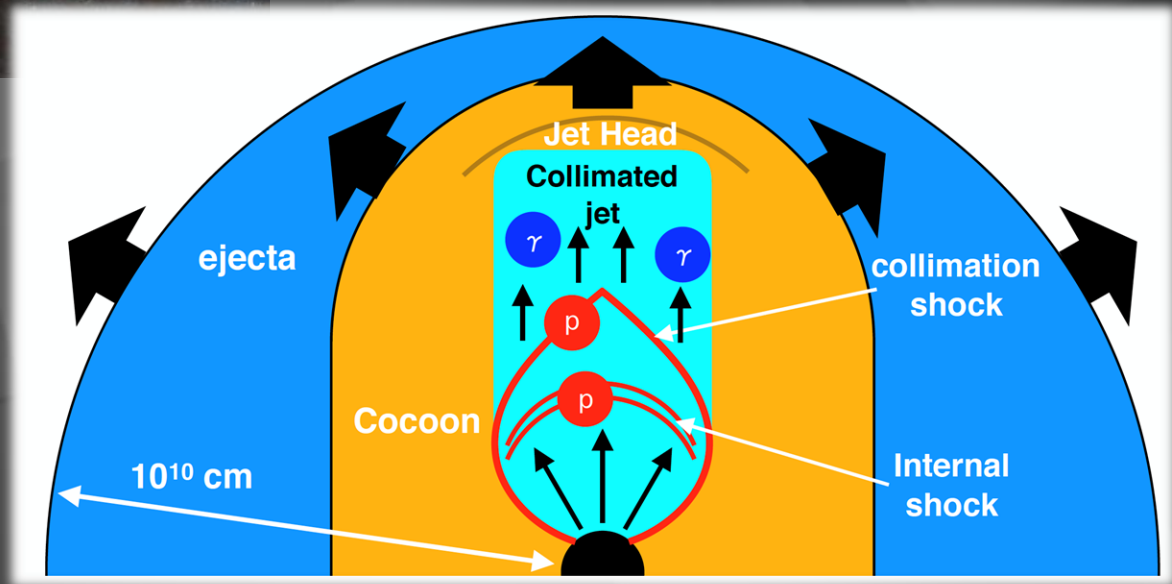
- ~ 0.01 M_{sun} material ejected
- ~ supernova



high-energy neutrinos: from collimation (TeV) and internal shocks (PeV):

protons photoproduce neutrinos

- on photons from leakage of the collimated jet
- on synchrotron photons from electrons (internal shock)



Kimura et al.

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

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

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

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

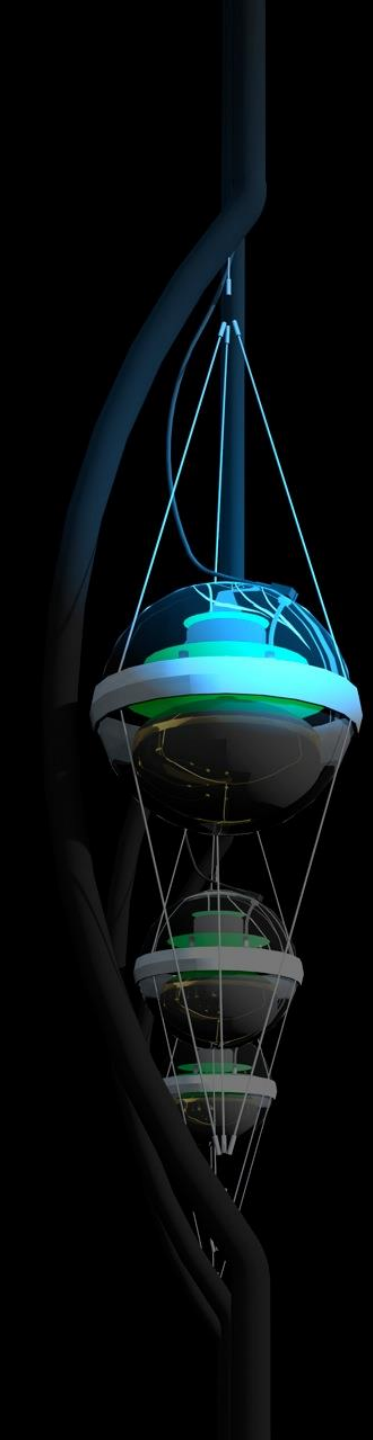
THE ICECUBE COLLABORATION

ISTRALIA 1

NGDOM 1

UNITED STATES 25

IceCube
South Pole Neutrino Observatory



neutrino astronomy 2019

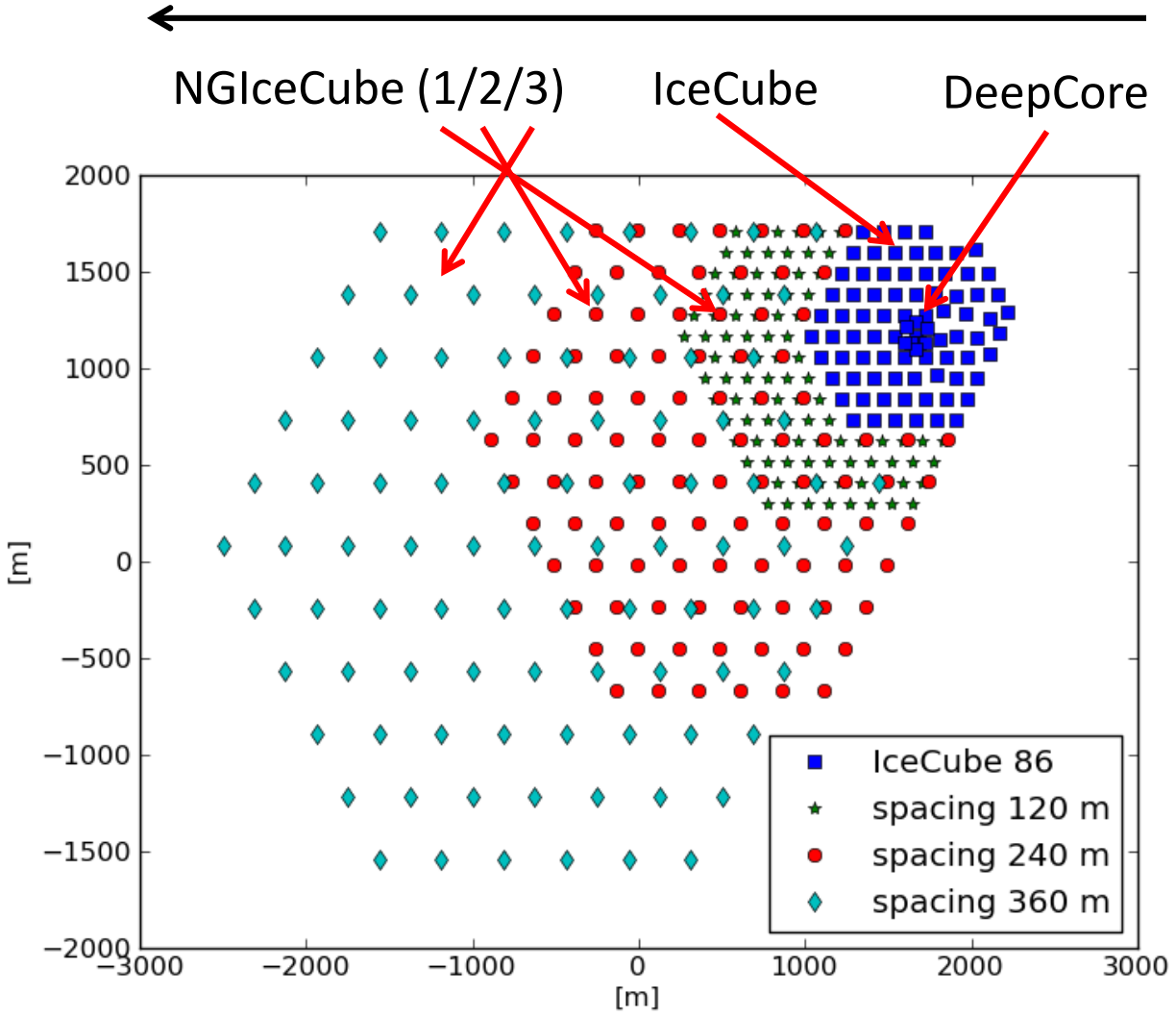
- it exists
- more neutrinos
- more telescopes

icecube.wisc.edu

overflow slides

measured optical properties → twice the string spacing

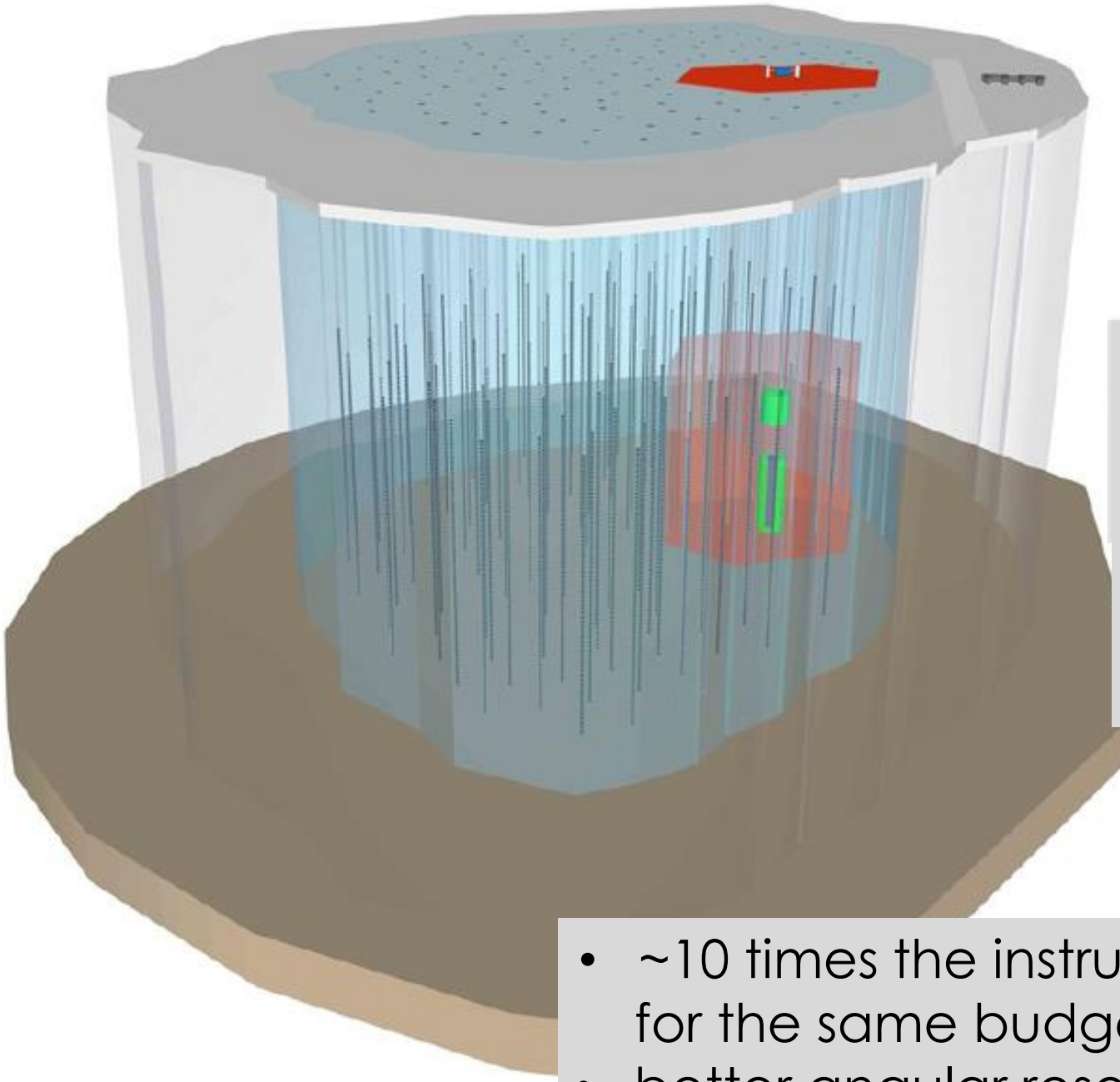
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



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

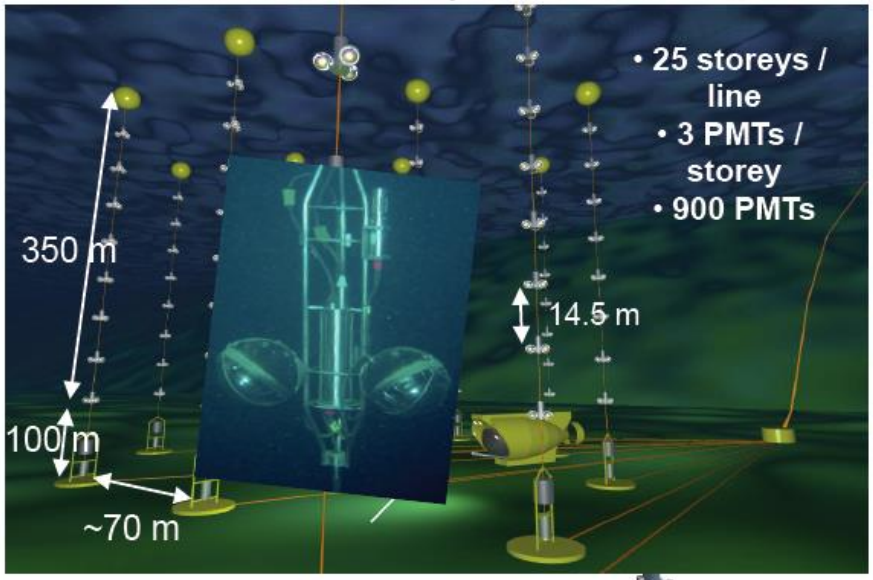


120 strings
depth 1.35 to
2.7 km
80 DOM/string
~250 m spacing
(Claudio Kopper)

- ~10 times the instrumented volume for the same budget as IceCube
- better angular resolution

Mediterranean Detectors

ANTARES Complete since 2008



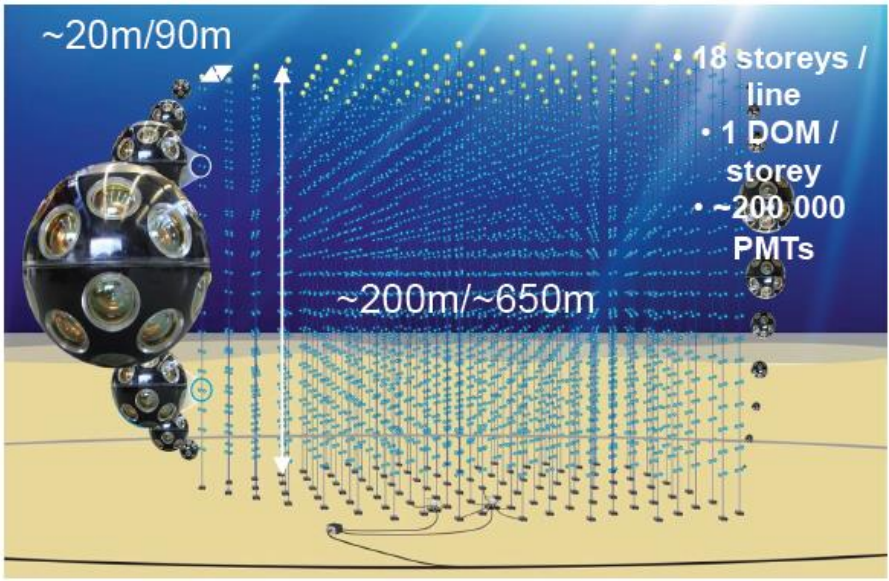
~10 Mton

12 lines

First Generation

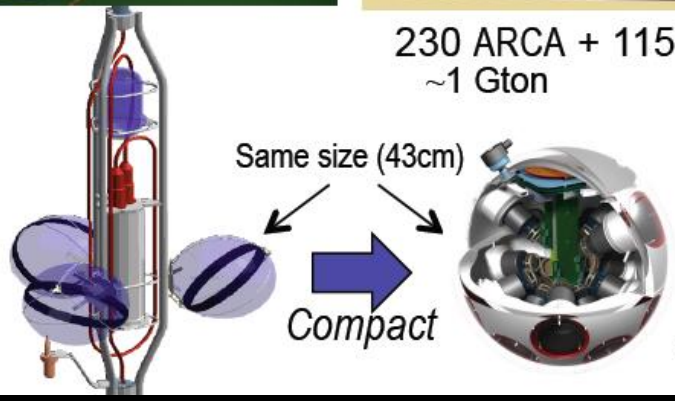
First line since 10 years

KM3NeT Under Construction

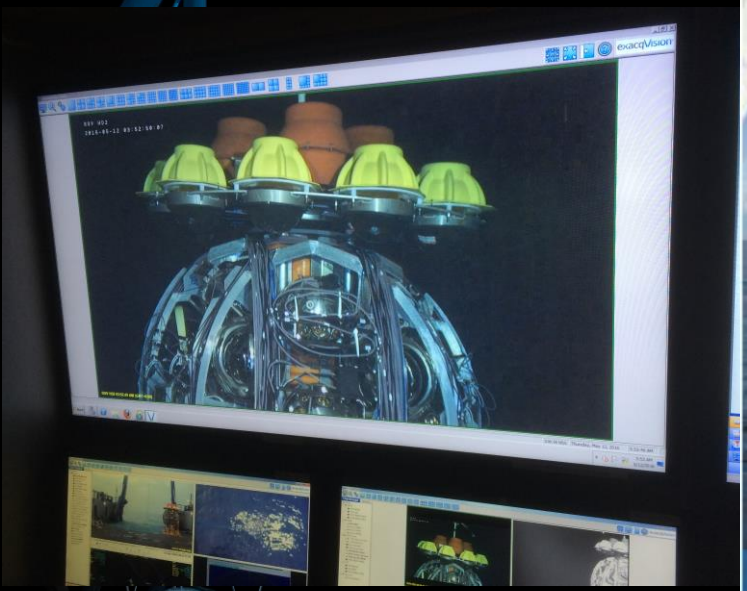


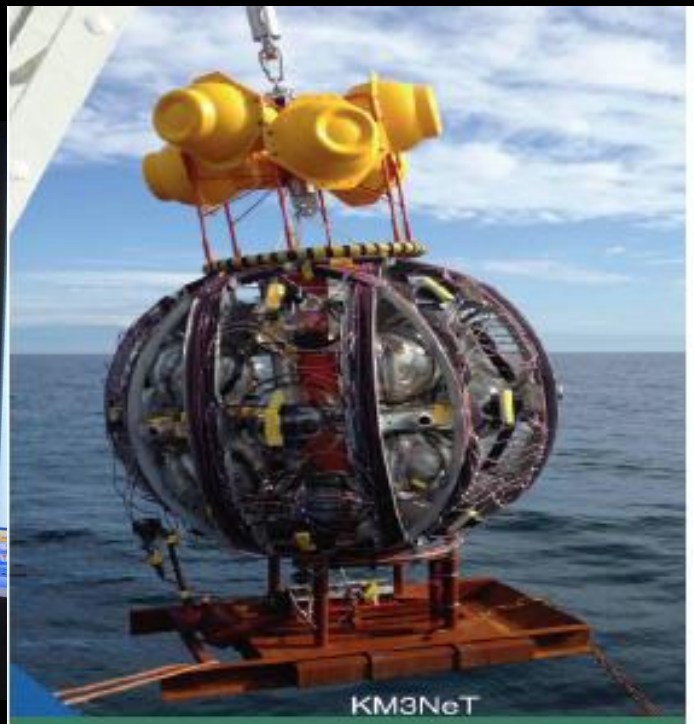
230 ARCA + 115 ORCA lines New Generation

~1 Gton ~6 Mton



- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

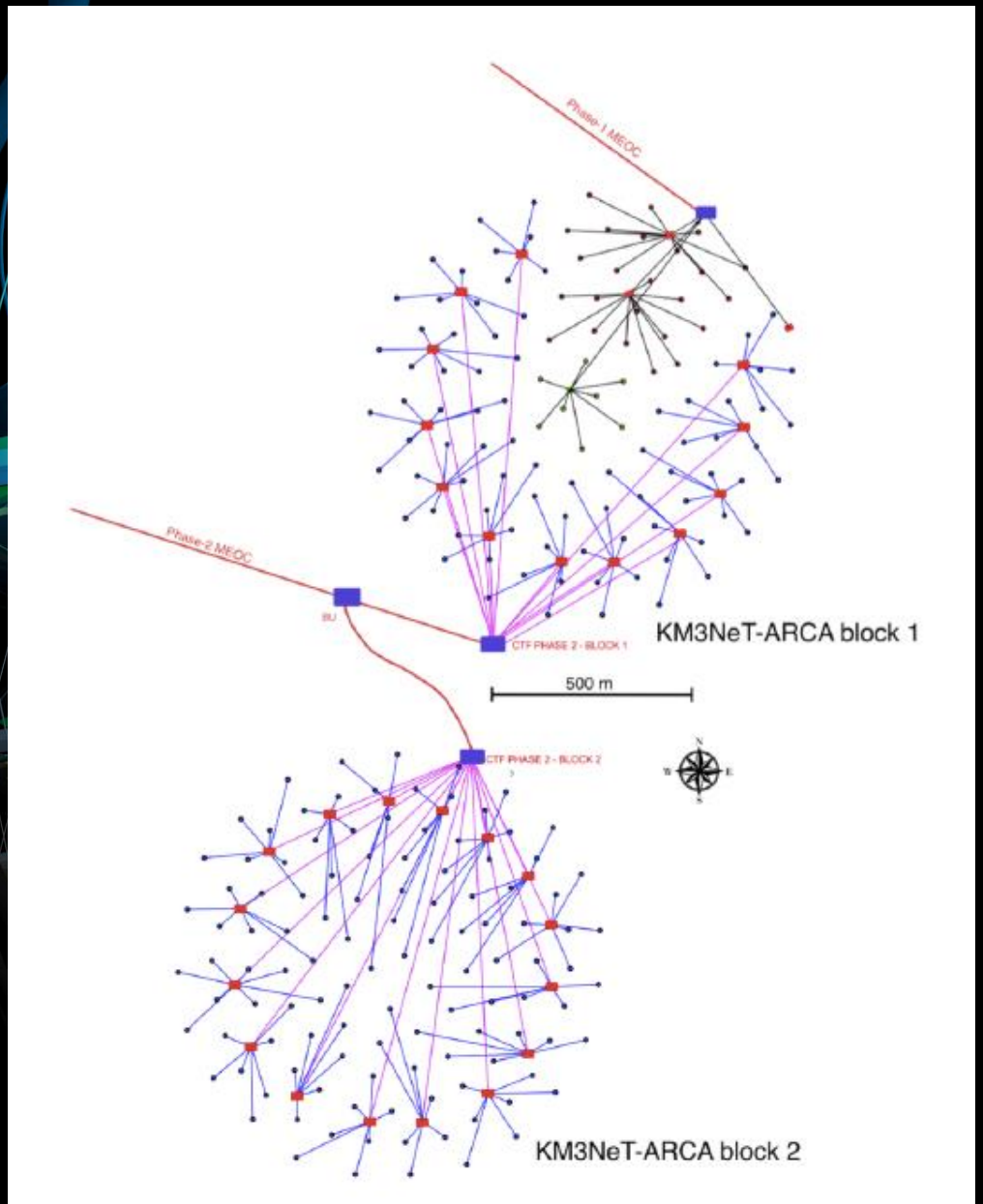


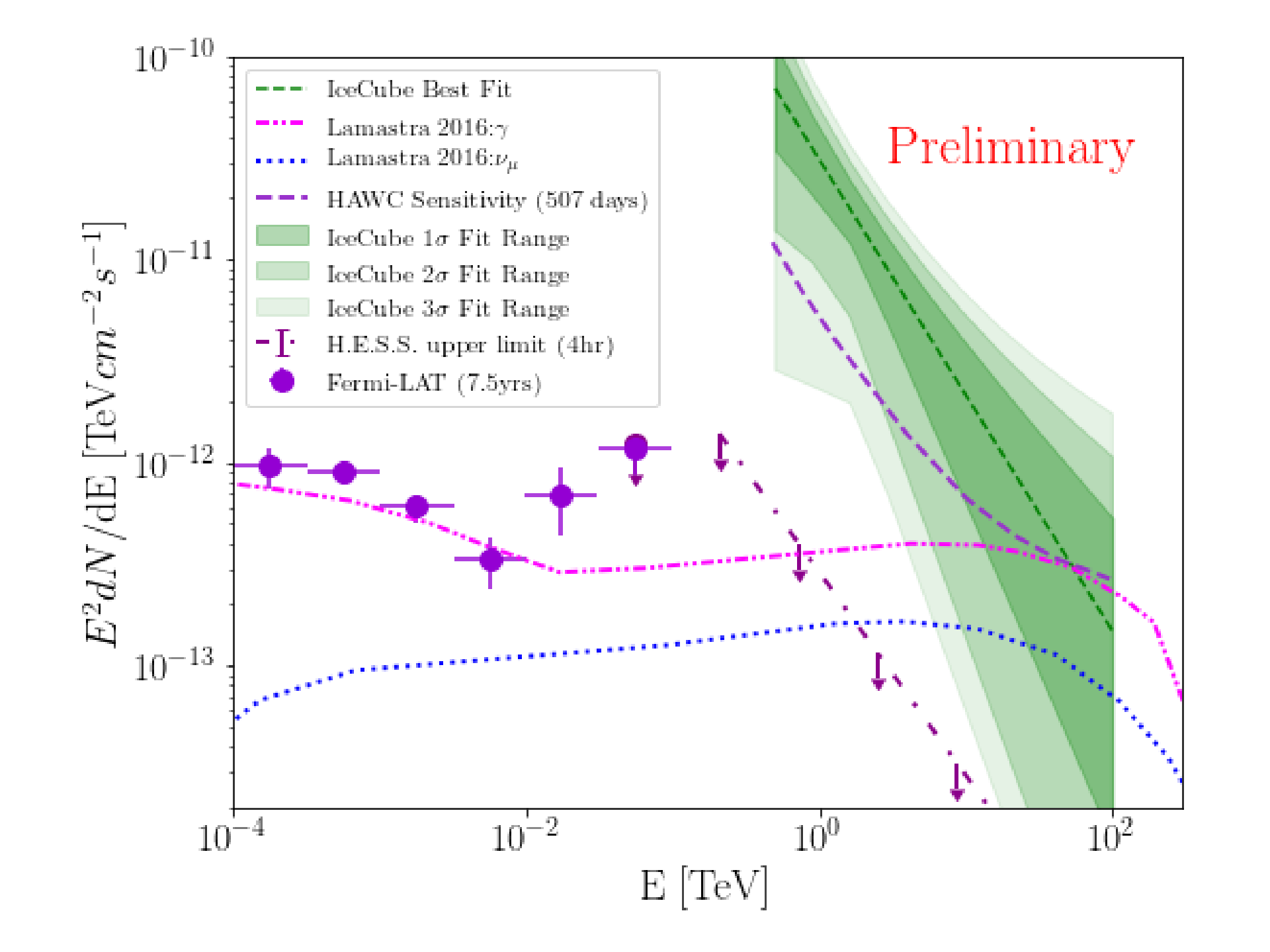


rapid deployment
autonomous unfurling
recoverable

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

High energies ARCA

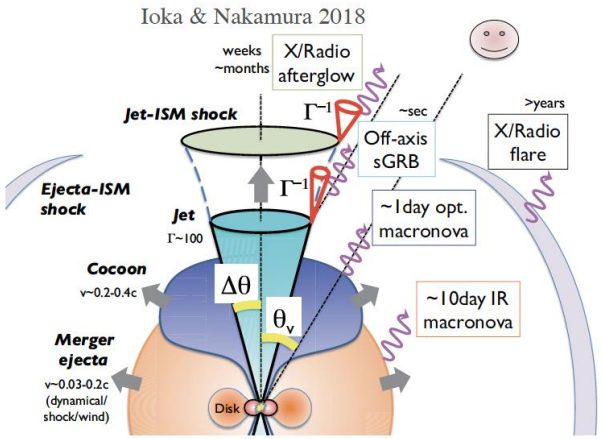


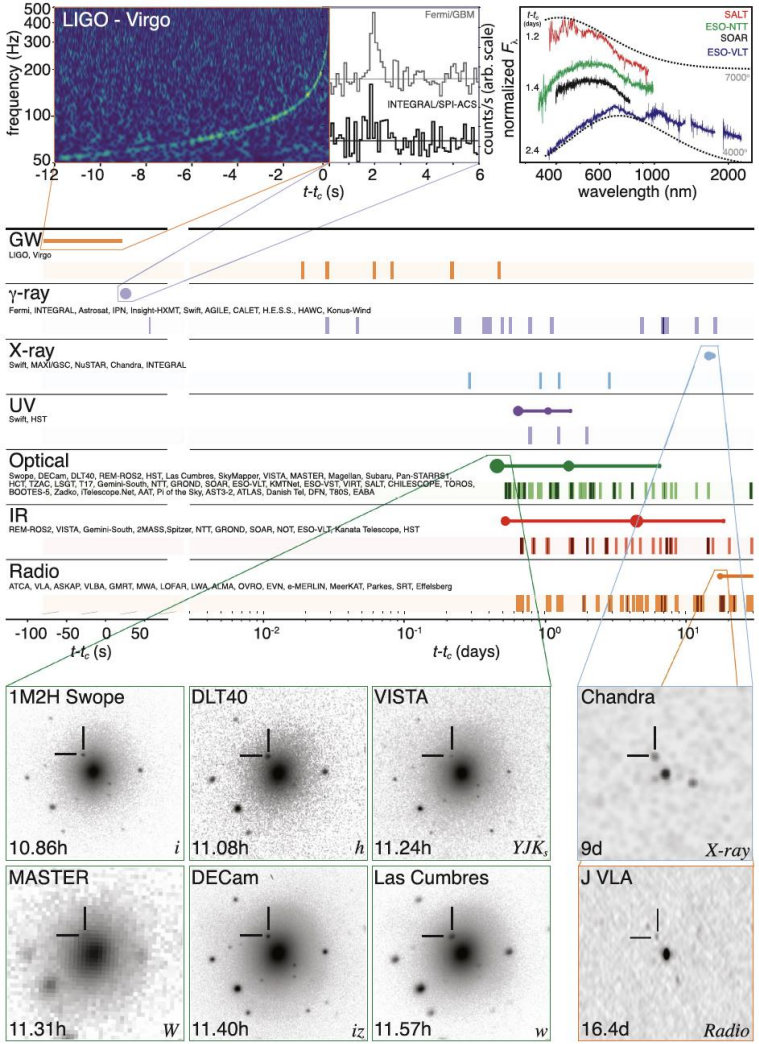

IceCube Best Fit
Lamastra 2016:γ
Lamastra 2016:ν_μ
HAWC Sensitivity (507 days)
IceCube 1σ Fit Range
IceCube 2σ Fit Range
IceCube 3σ Fit Range
H.E.S.S. upper limit (4hr)
Fermi-LAT (7.5yrs)
Preliminary
E^2dN/dE [TeV$cm^{-2}s^{-1}$]
E [TeV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-4}
10^{-2}
10^{0}
10^{2}

GW170817

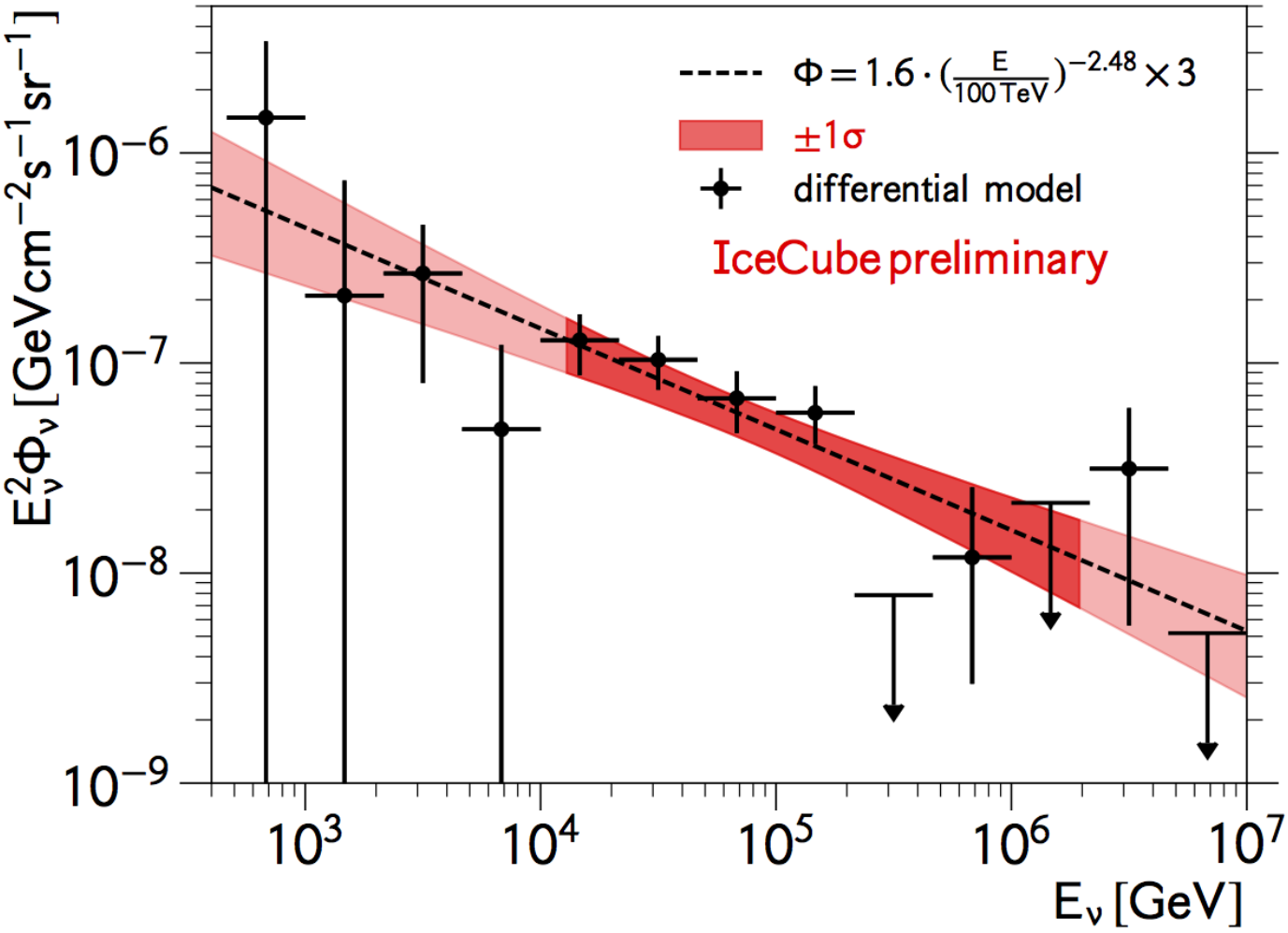
LIGO 2017 (Multi-messenger paper)

- The first detection of NS-NS merger event
- **GeV-TeV gamma-rays are not observed, but NS mergers are expected to emit them.**

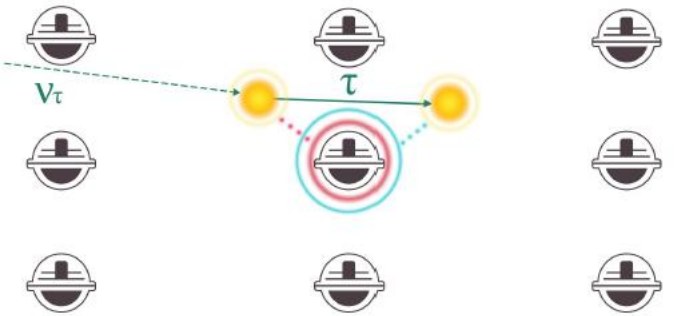


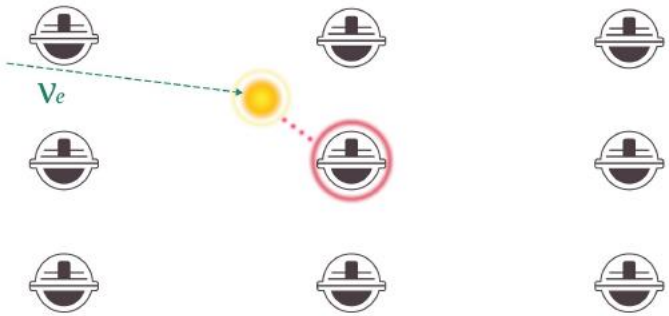


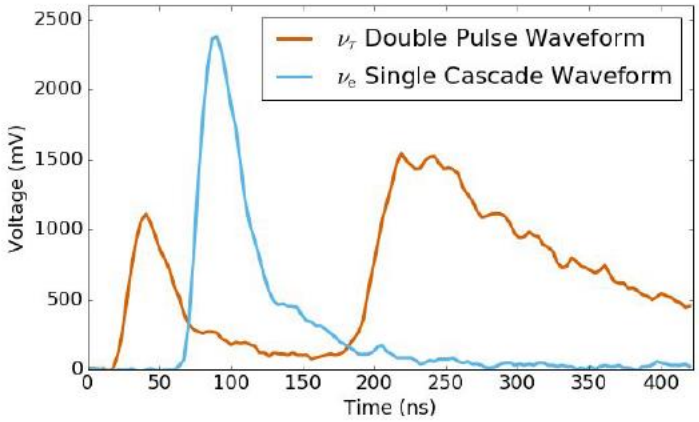
Multi-year cascade ($\nu_e+\nu_\tau$) analysis

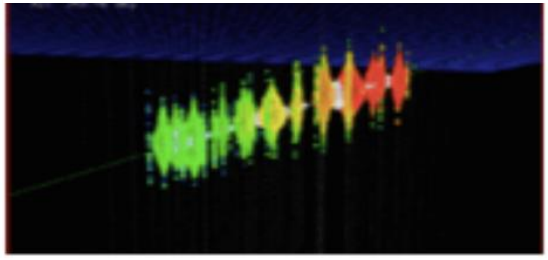


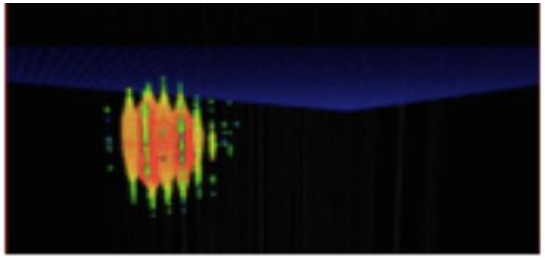
tau decay length:
50m per PeV

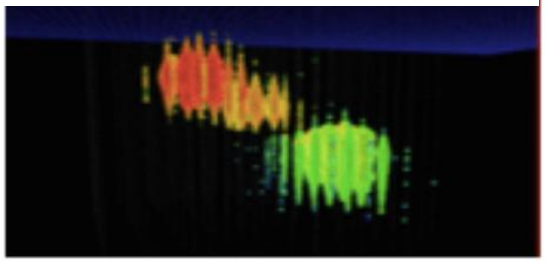












ongoing upgrade

- neutrino oscillation at PeV energy
- test of the 3-neutrino scenario
- neutrino physics BSM