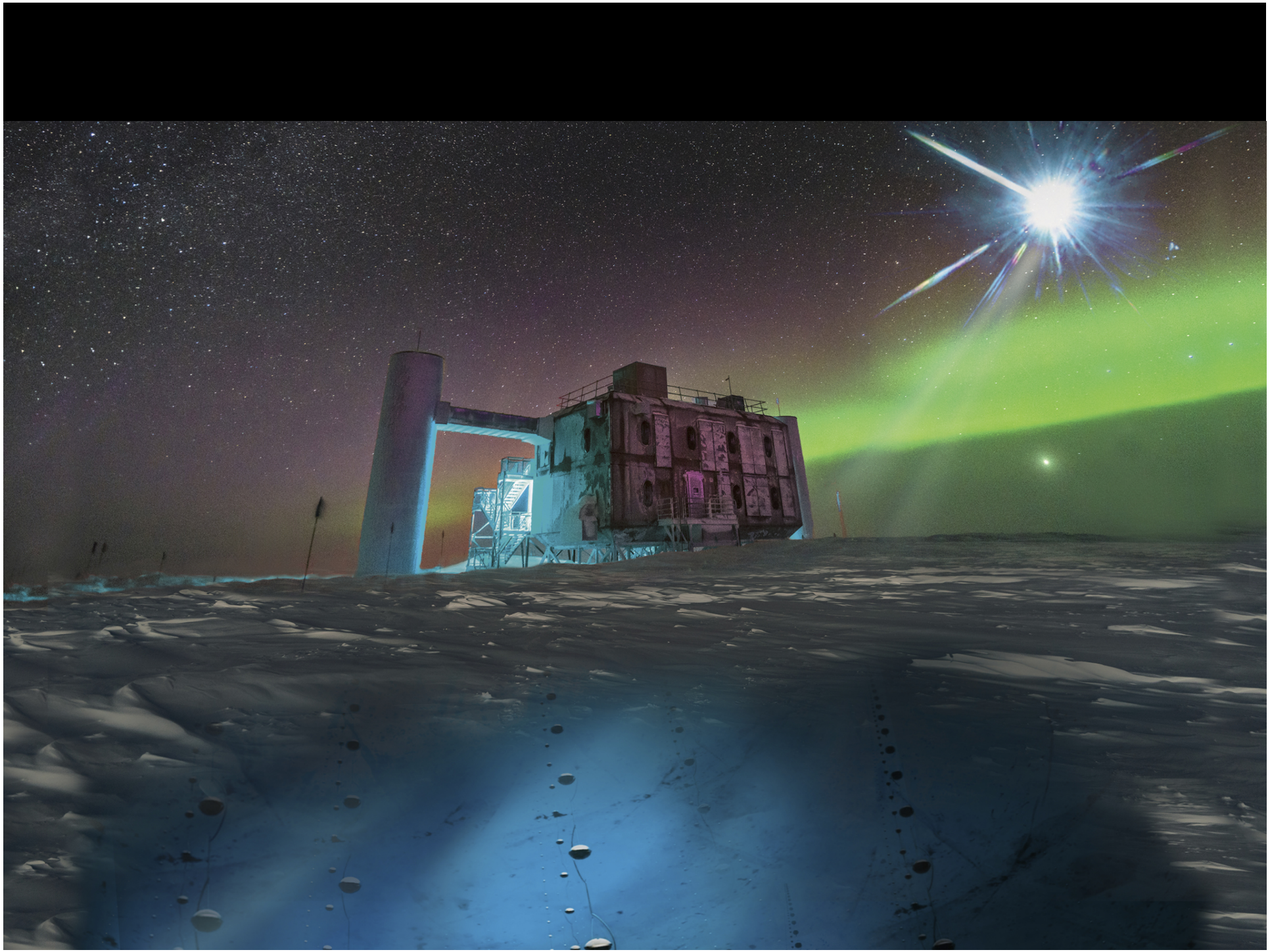


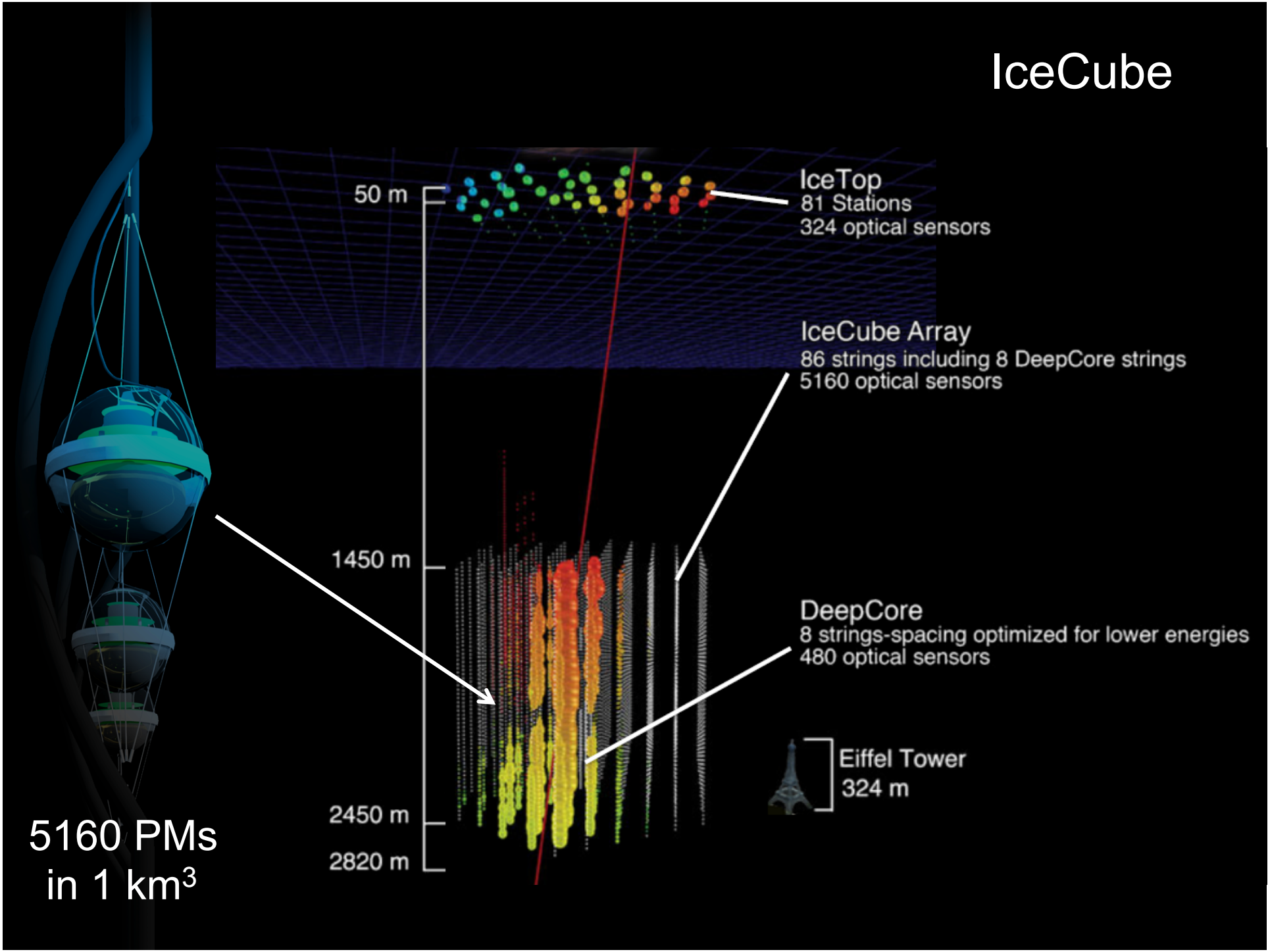
IceCube:

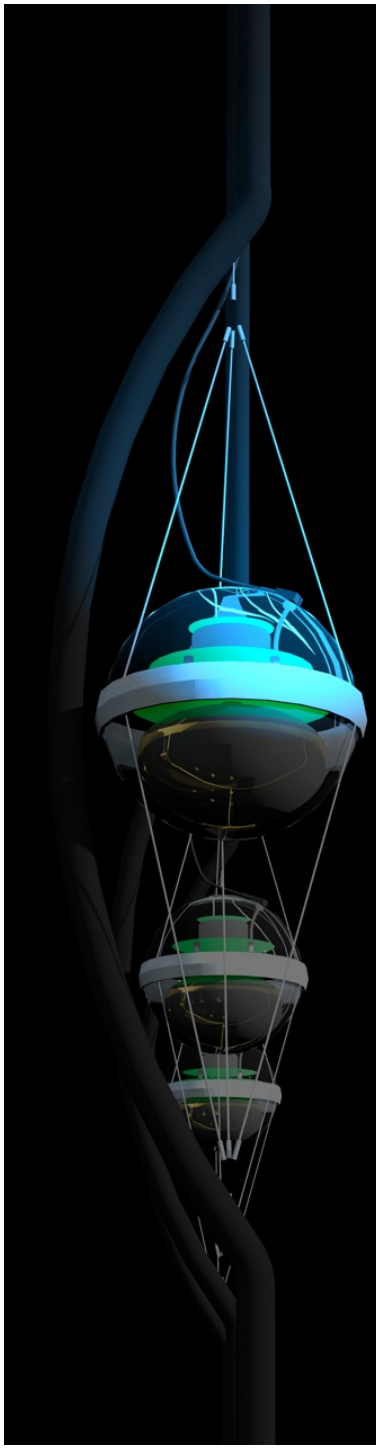
Building a New Window on the Universe

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
  - → tau neutrinos
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator

icecube.wisc.edu


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



IceCube

francis halzen

- IceCube
- cosmic neutrinos: three independent observations
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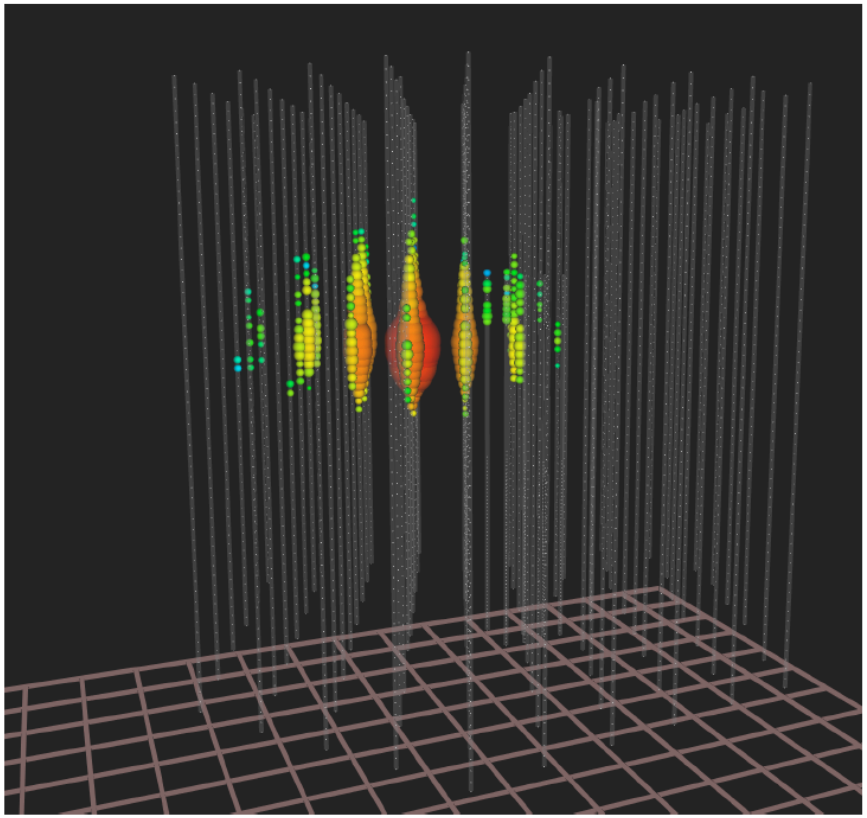
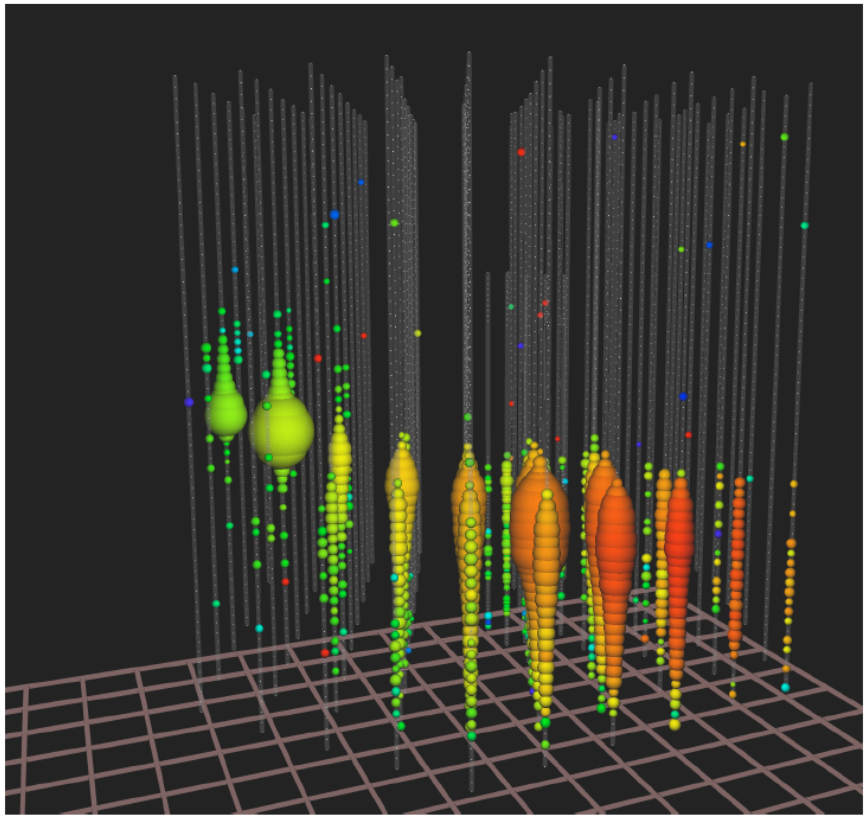
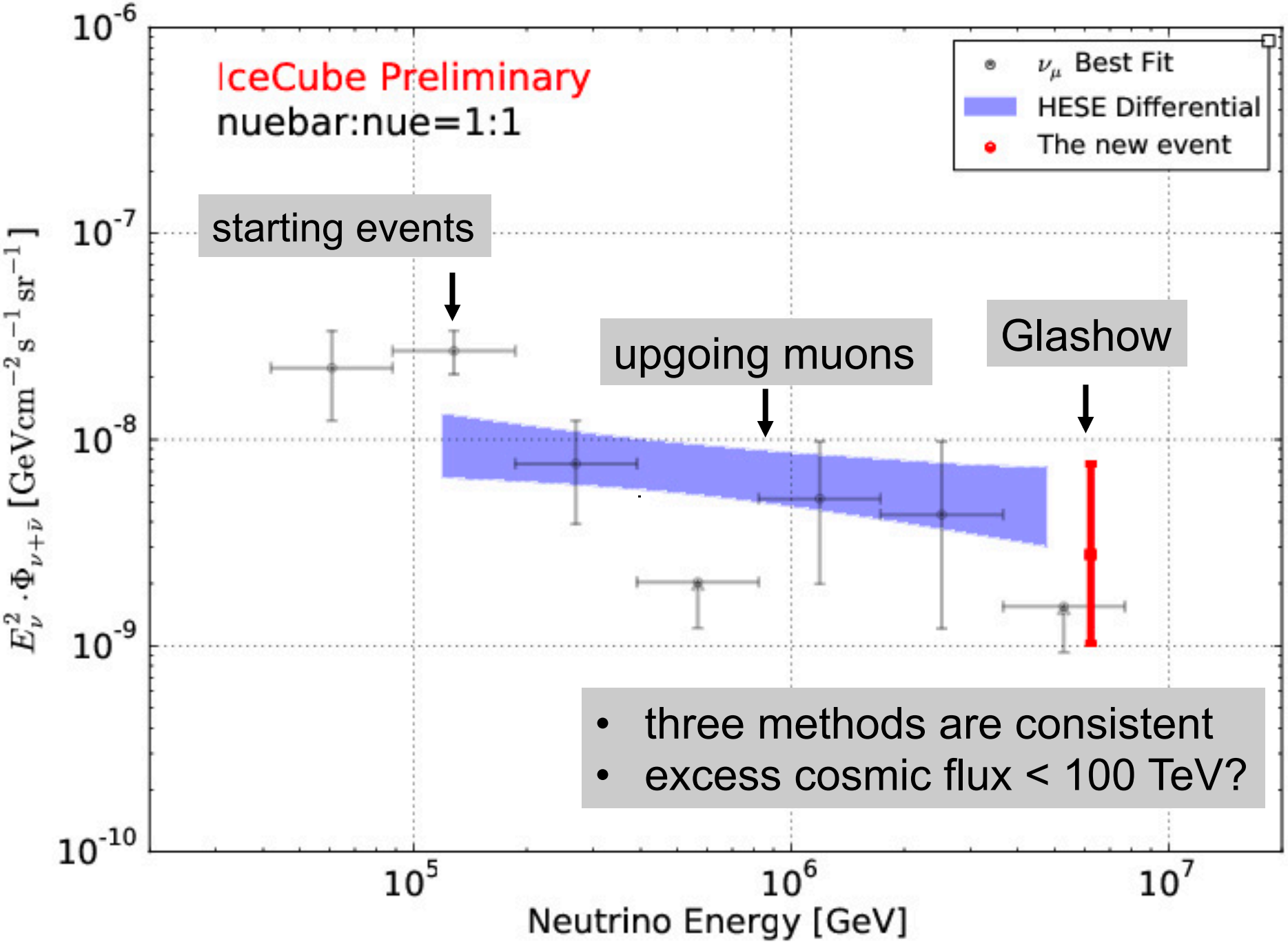
are the three observations consistent?



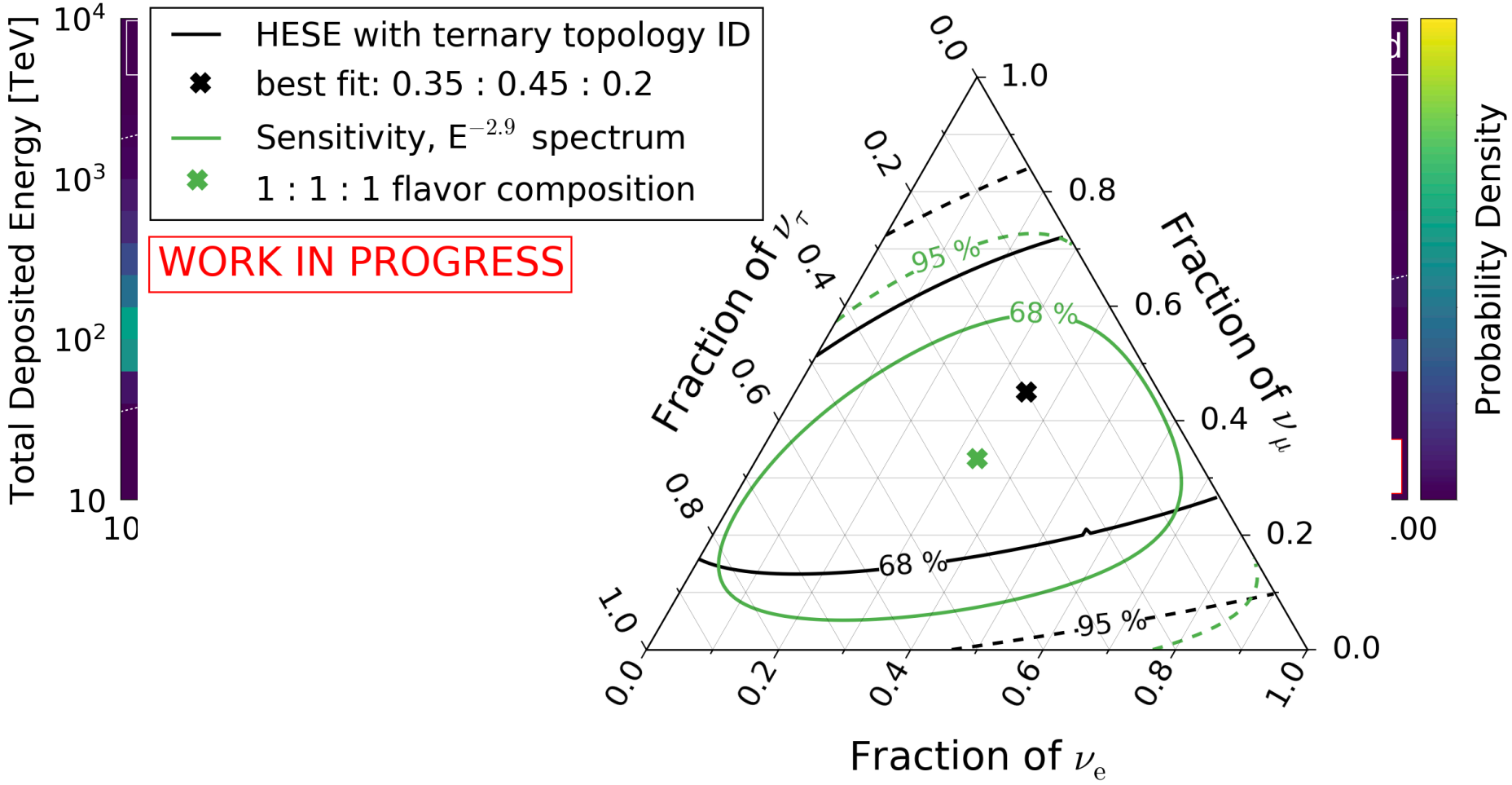


total energy measurement
all flavors, all sky

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

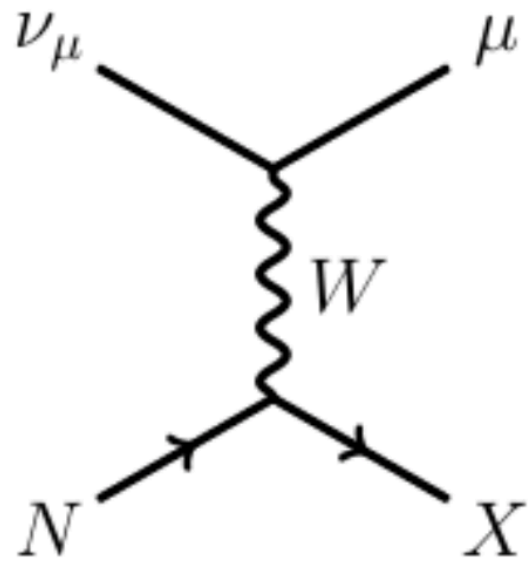

IceCube Preliminary
nuebar:nue=1:1
ν_μ Best Fit
HESE Differential
The new event
starting events
upgoing muons
Glashow
• three methods are consistent
• excess cosmic flux < 100 TeV?
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}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

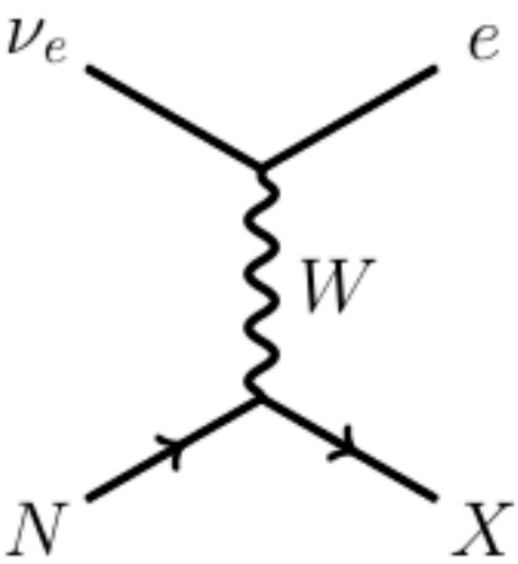
high-energy starting events – 7.5 yr

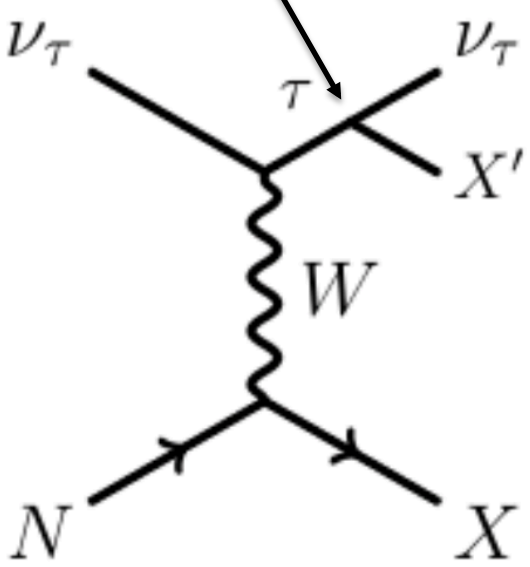


oscillations of PeV neutrinos over cosmic distances to 1:1:1

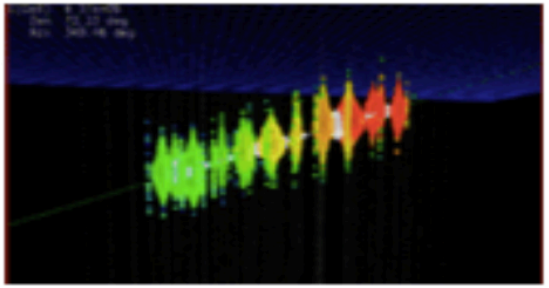
tau decay length:
50m per PeV



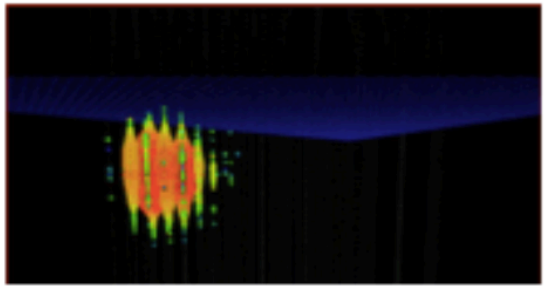




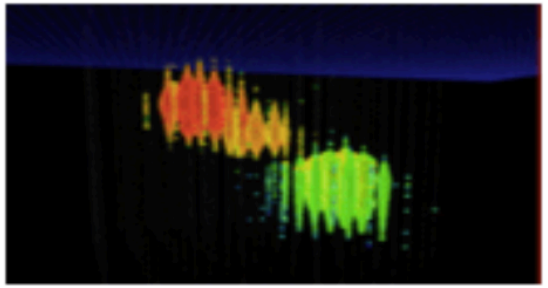
track



shower

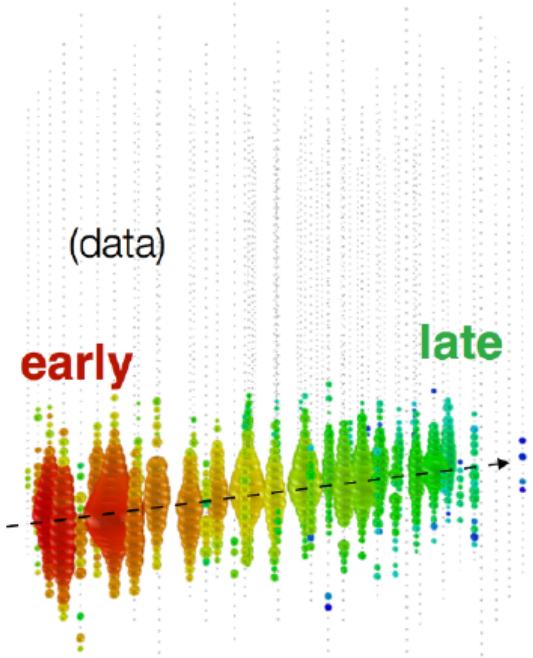


double bang*



event topologies

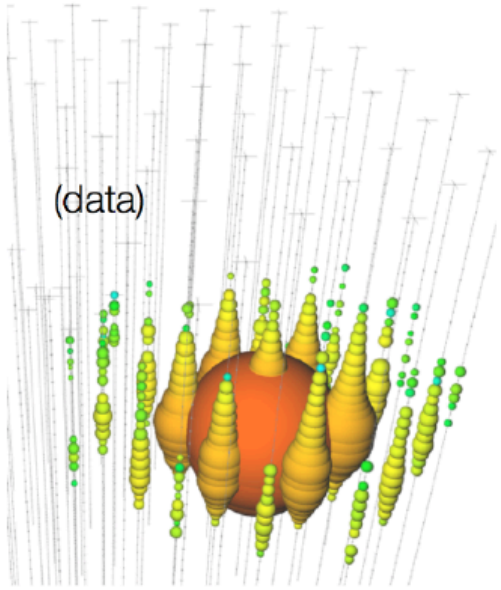
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

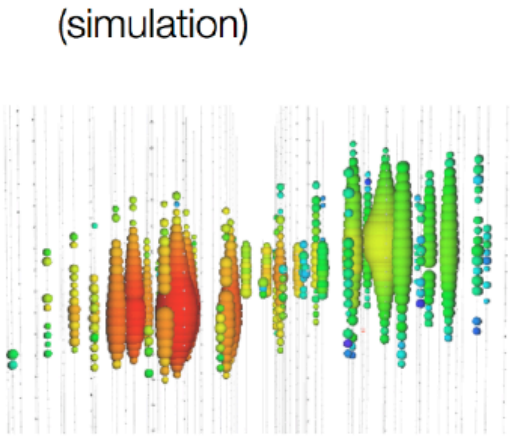
Neutral-current / ν_e



Isolated energy deposition (cascade) with no track

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

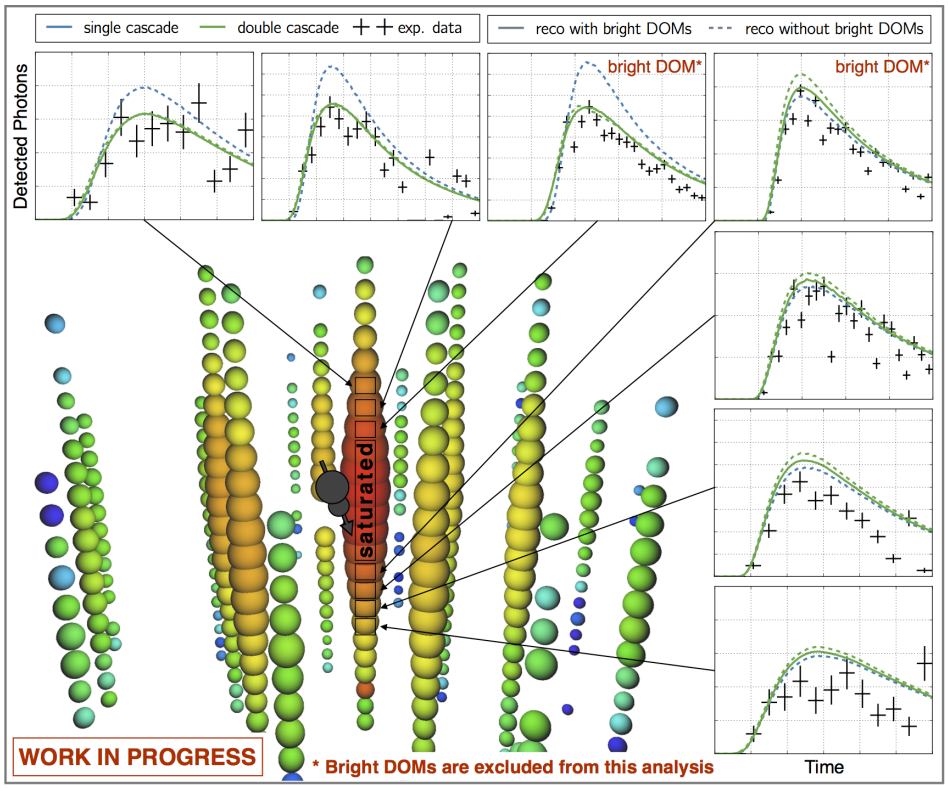
Charged-current ν_τ



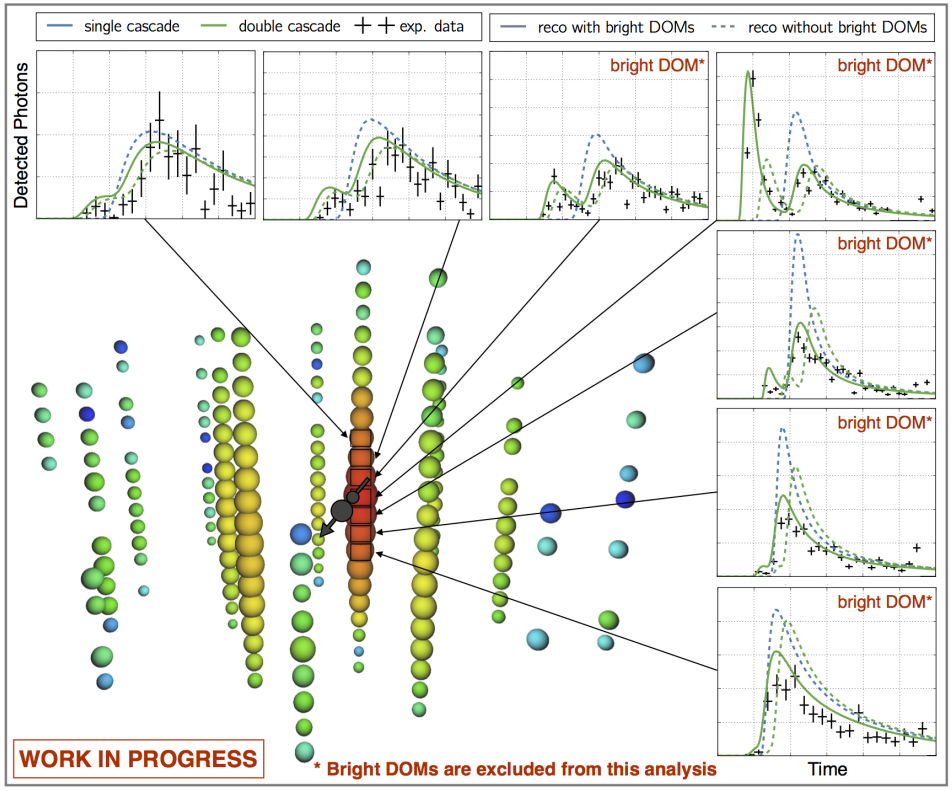
Double cascade

(resolvable above ~100 TeV deposited energy)

high-energy starting events (starting) – 7.5 yr



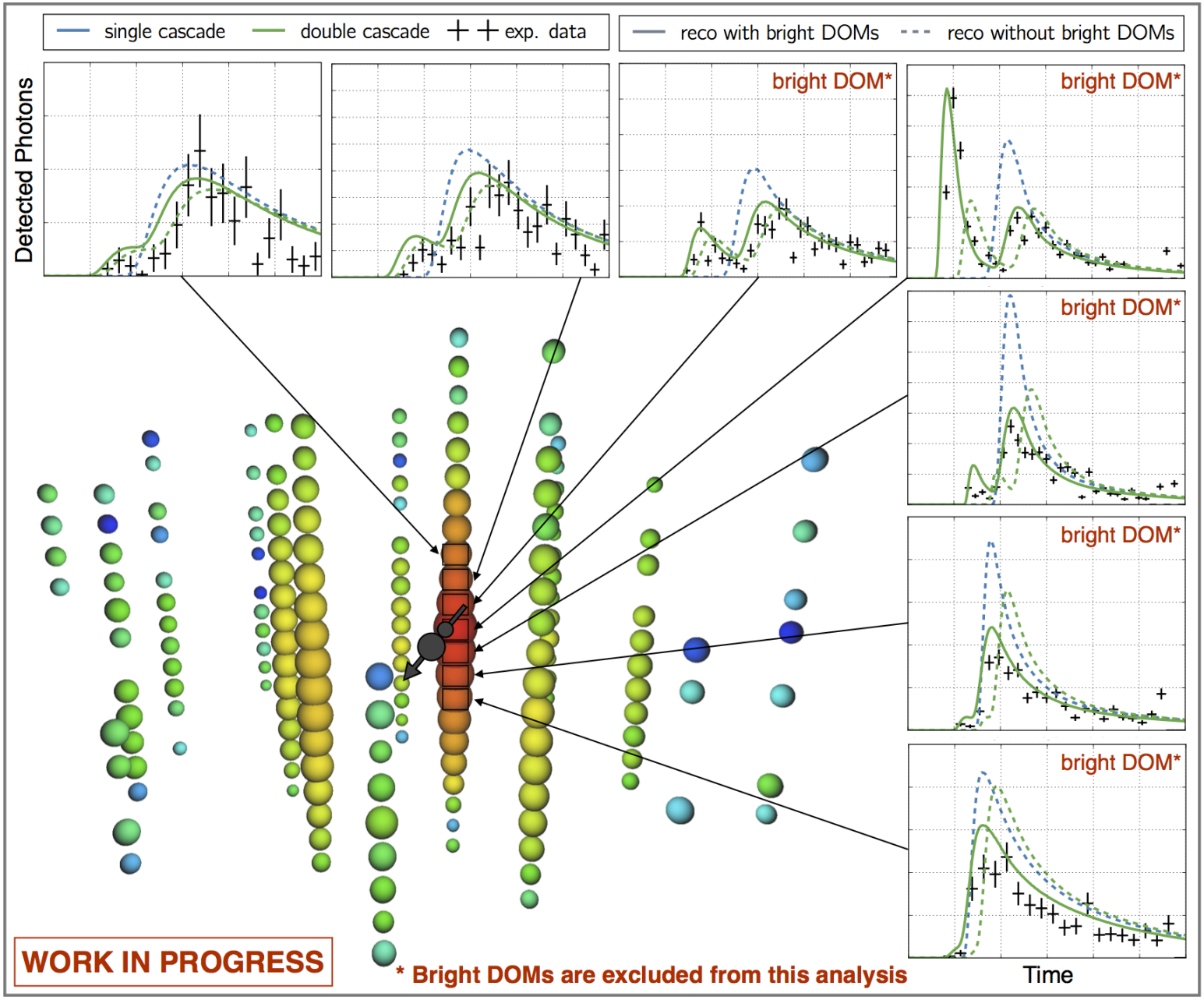
Double cascade Event #1

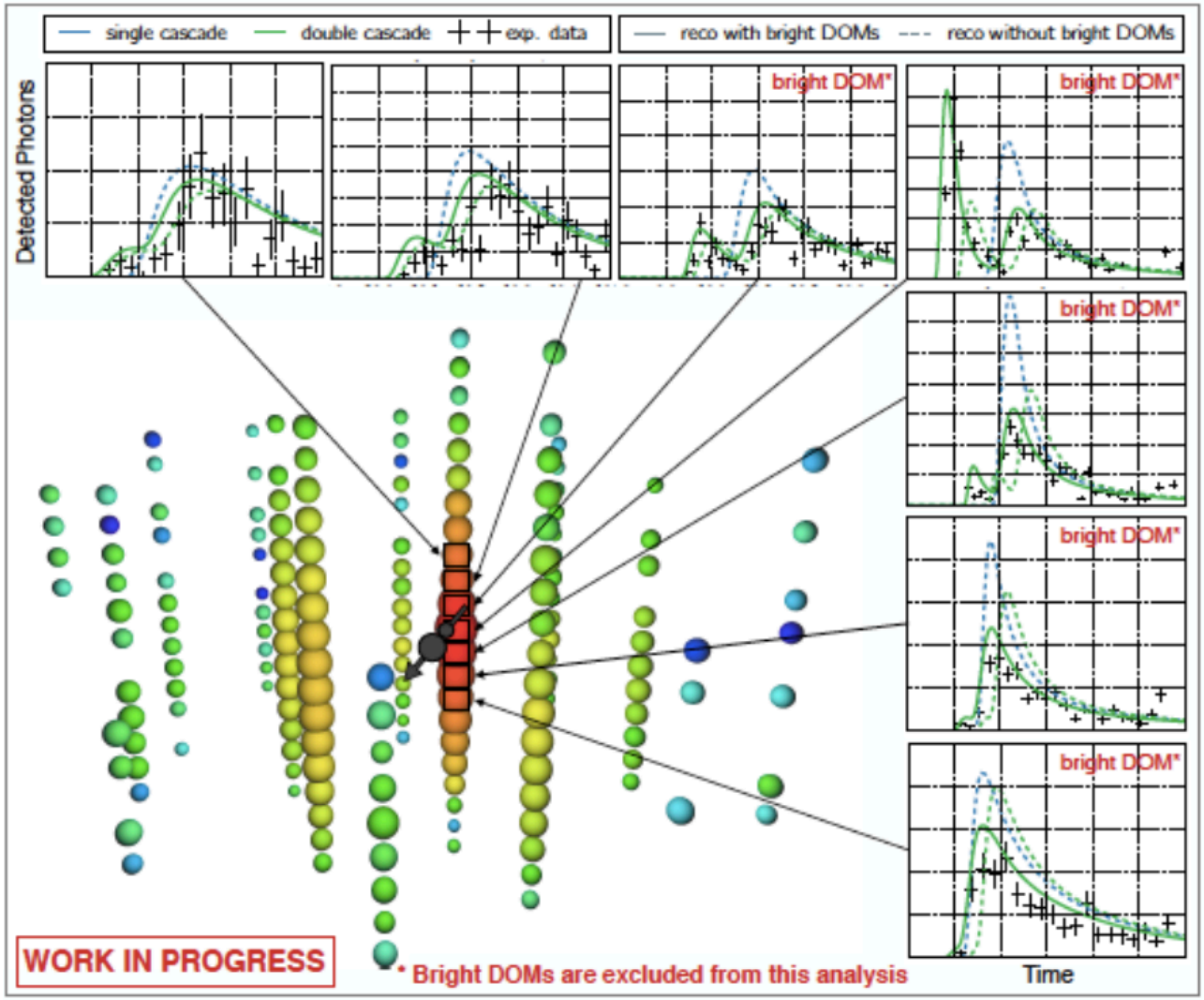


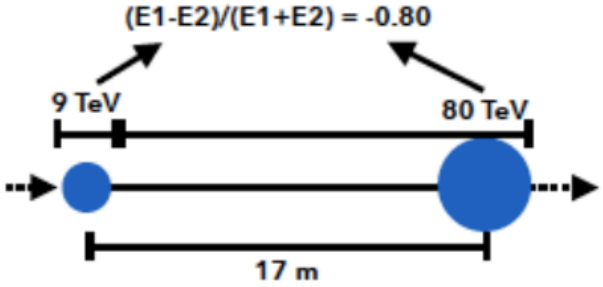
Double cascade Event #2

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

a cosmic tau neutrino: livetime 17m



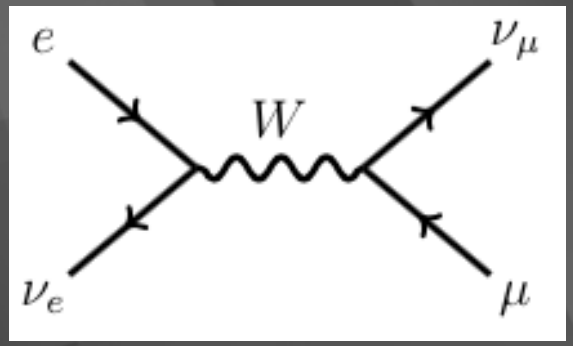




- Observed 2014
- Observed light arrival pattern clearly favors double cascade hypothesis

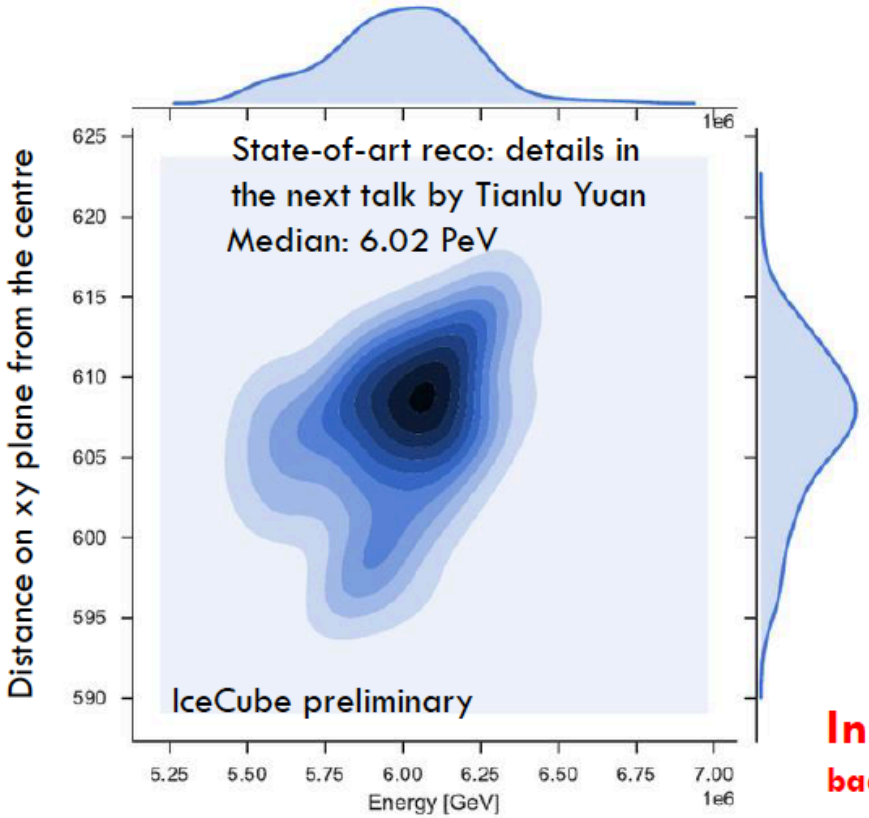
the first Glashow resonance event:

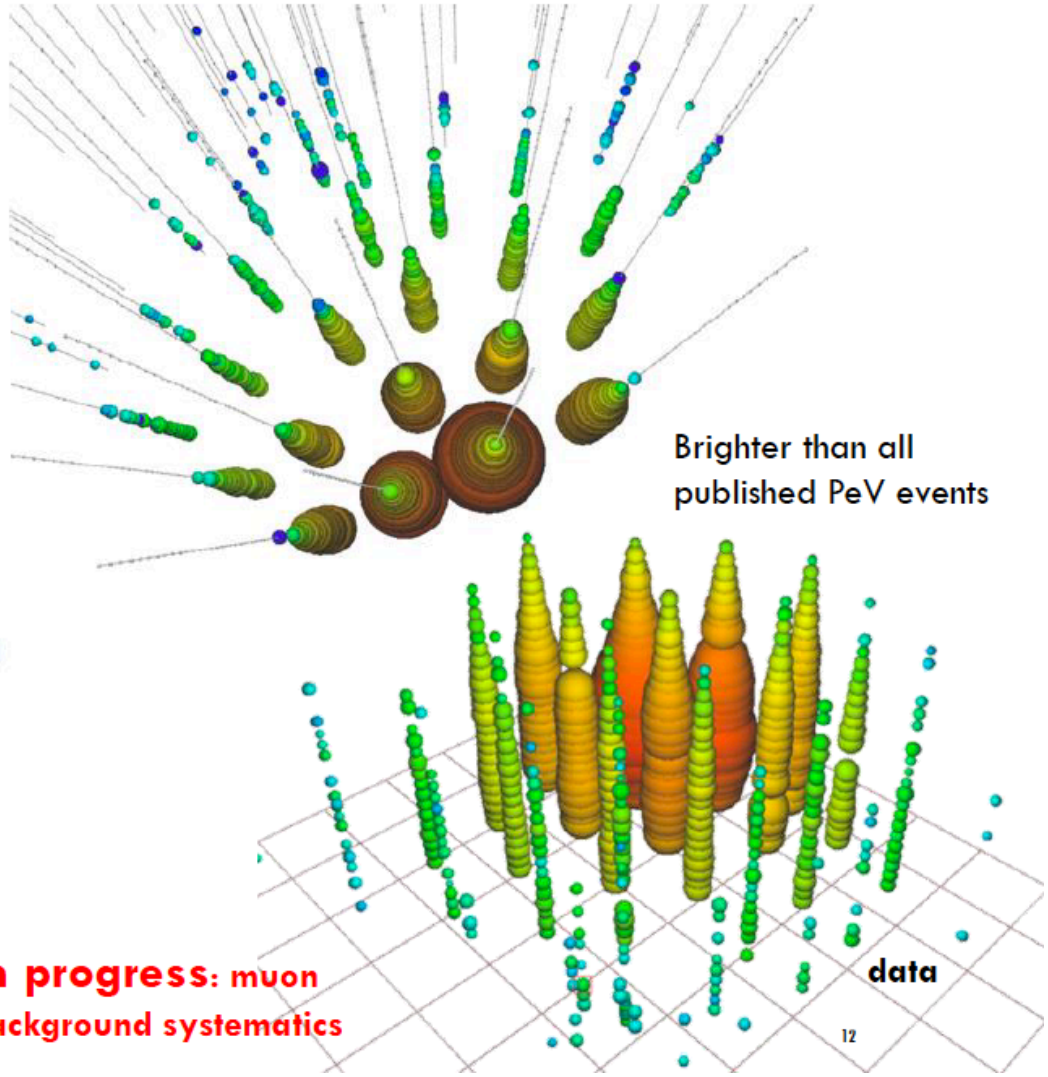
anti-ν_e + atomic electron → real W at 6.3 PeV



Partially contained event with energy ~ 6 PeV

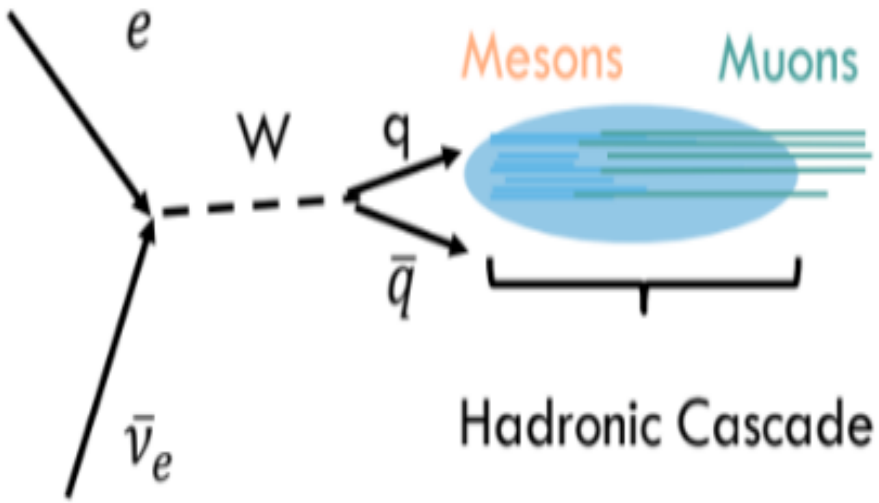
HIGHEST-ENERGY NEUTRINO CANDIDATE

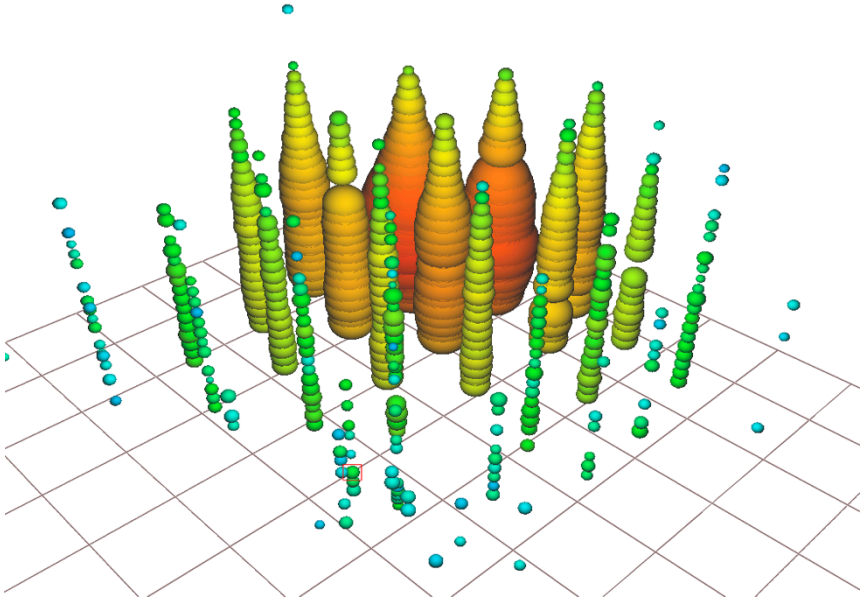


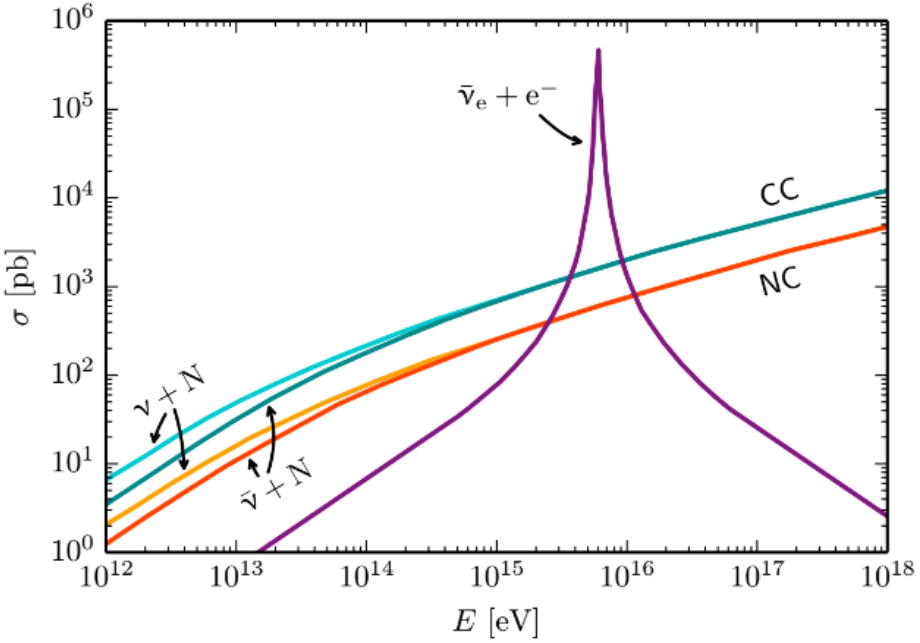


In progress: muon background systematics

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





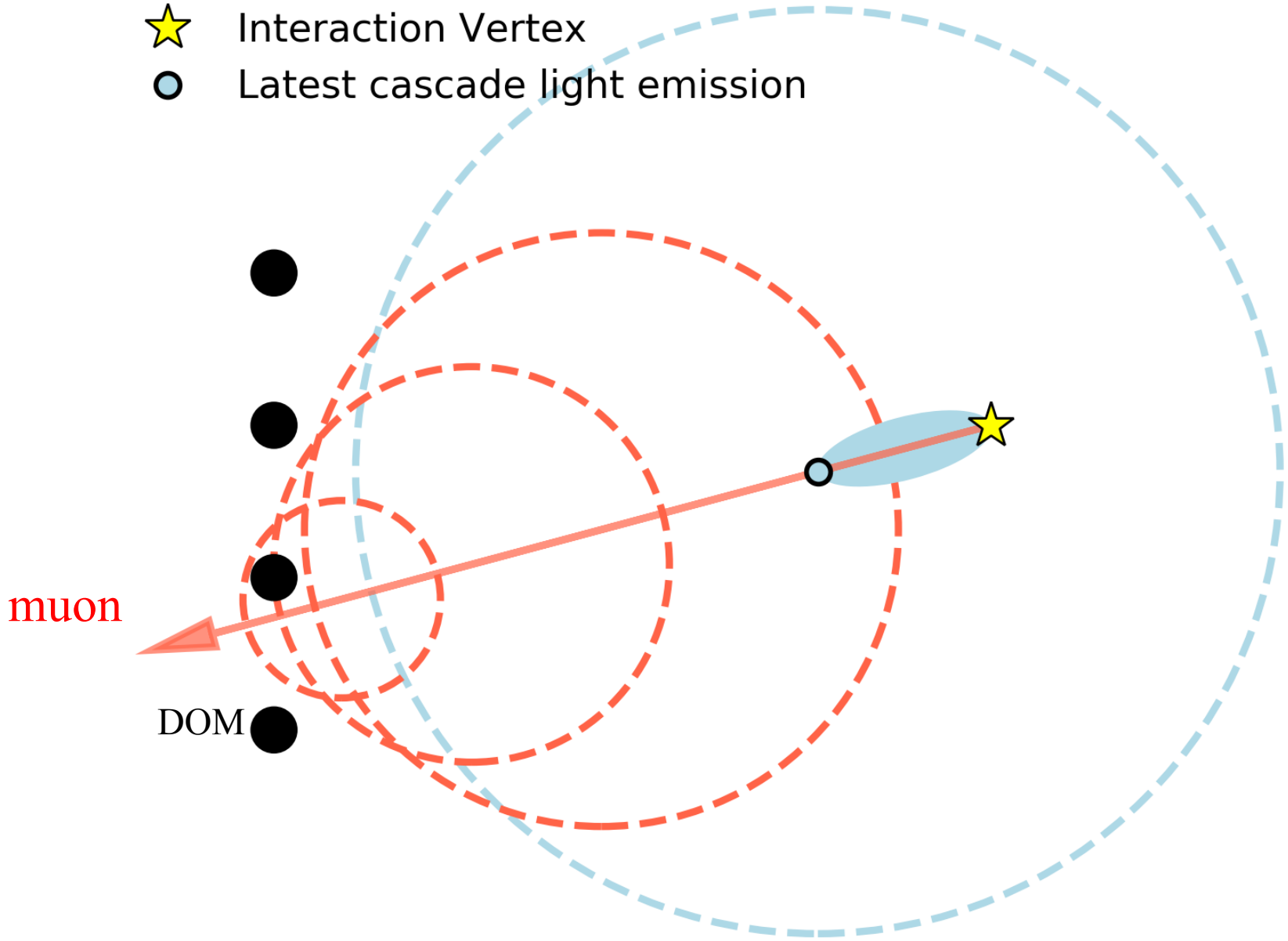


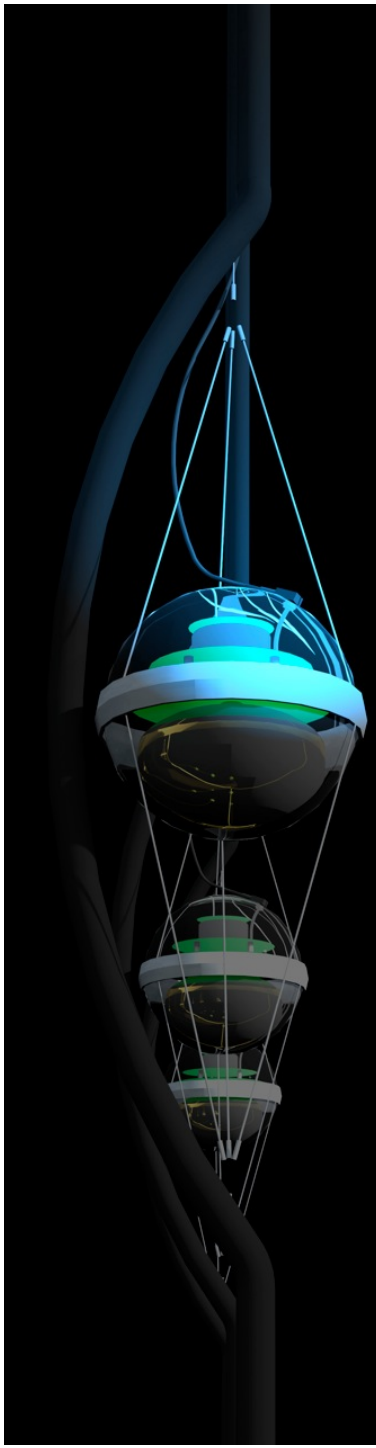
- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

muon (v=c) outraces the light propagating from the electromagnetic component (v<c)





IceCube

francis halzen

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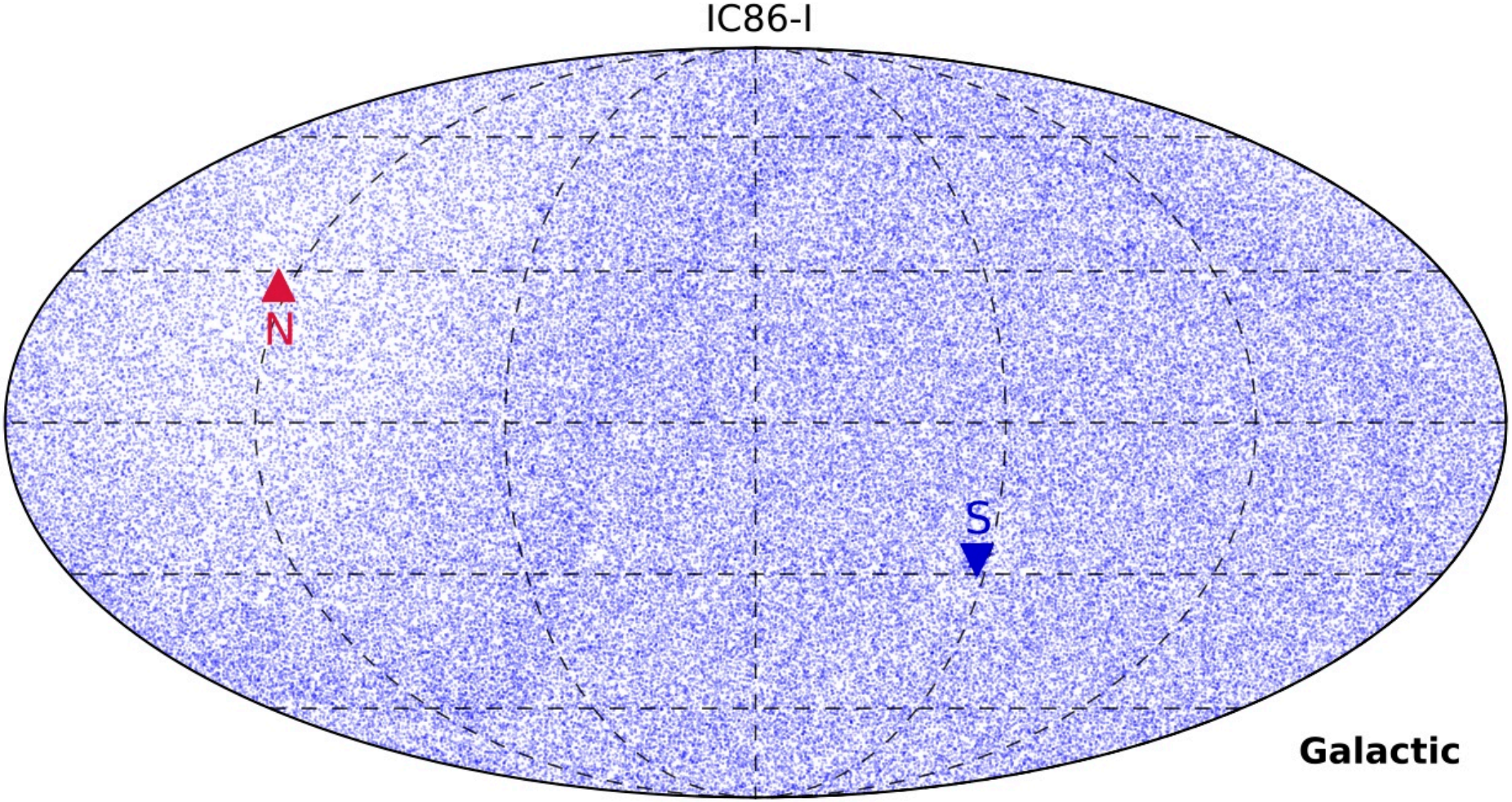
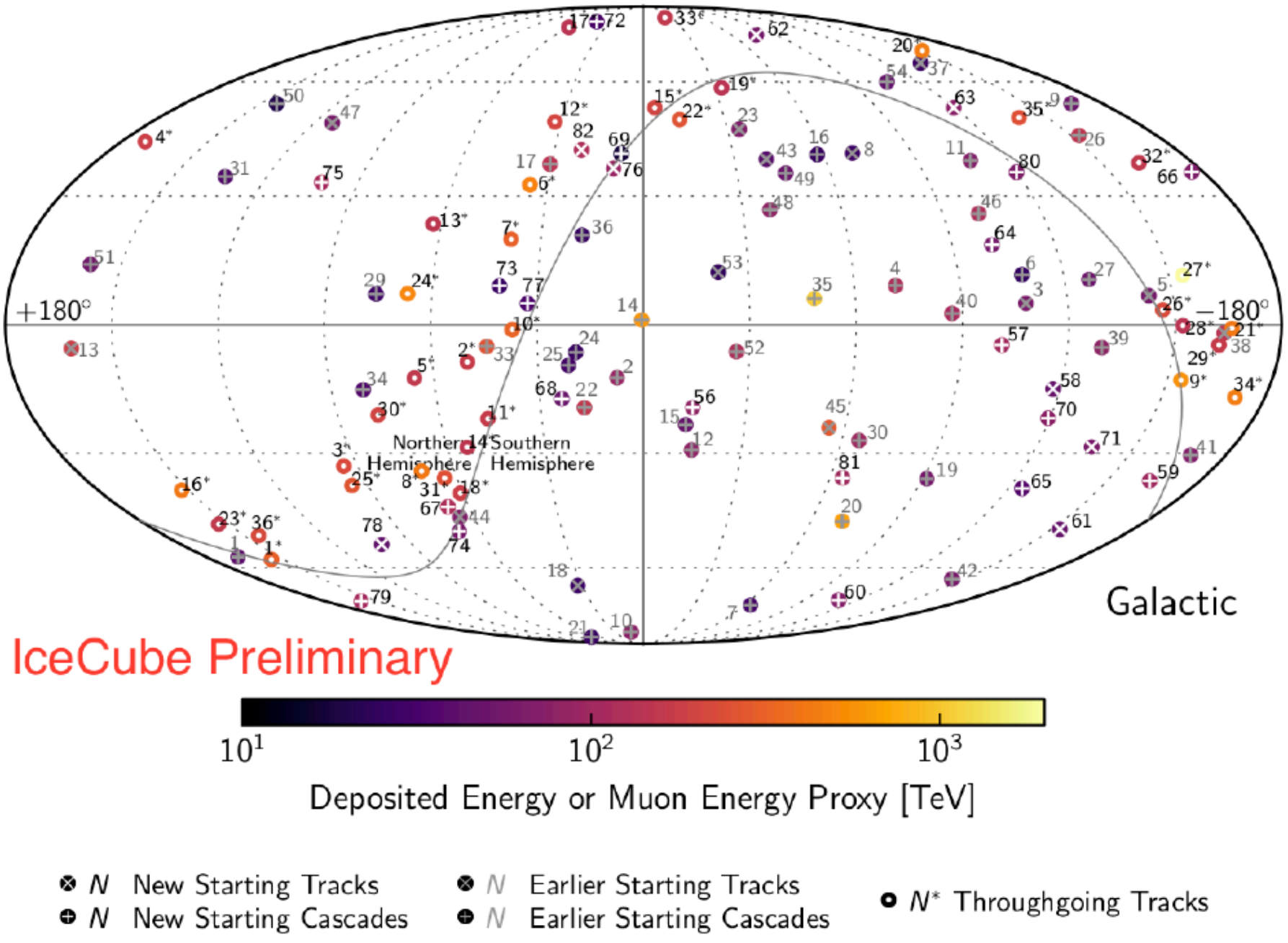


138322 neutrino candidates in one year

120 cosmic neutrinos

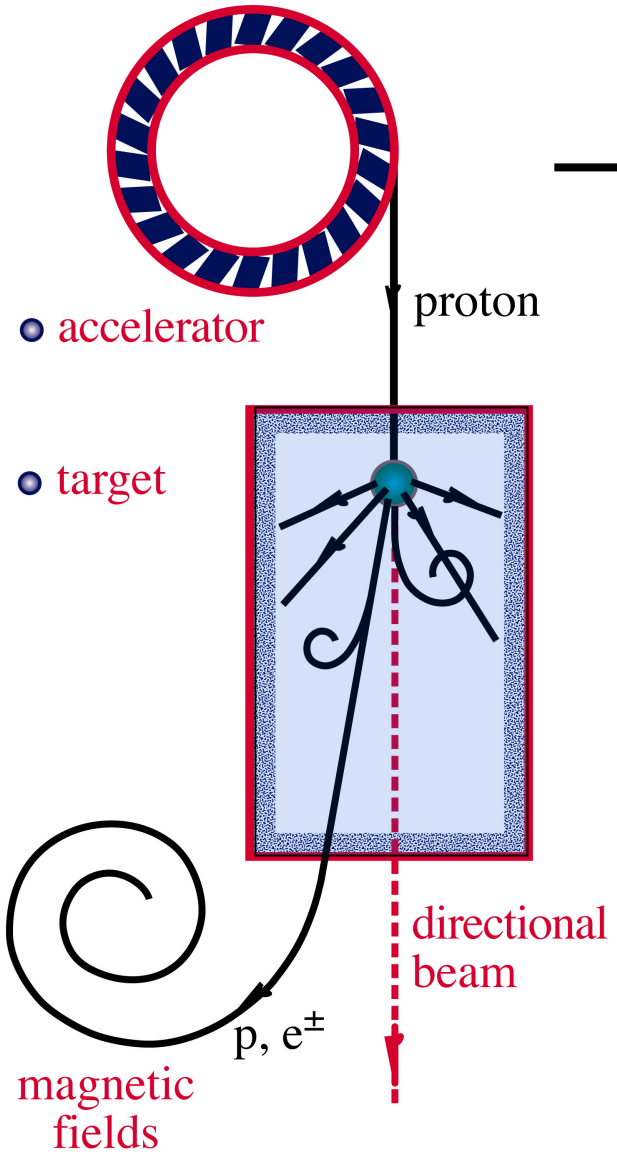
~12 separated from atmospheric background with E>60 TeV

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

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

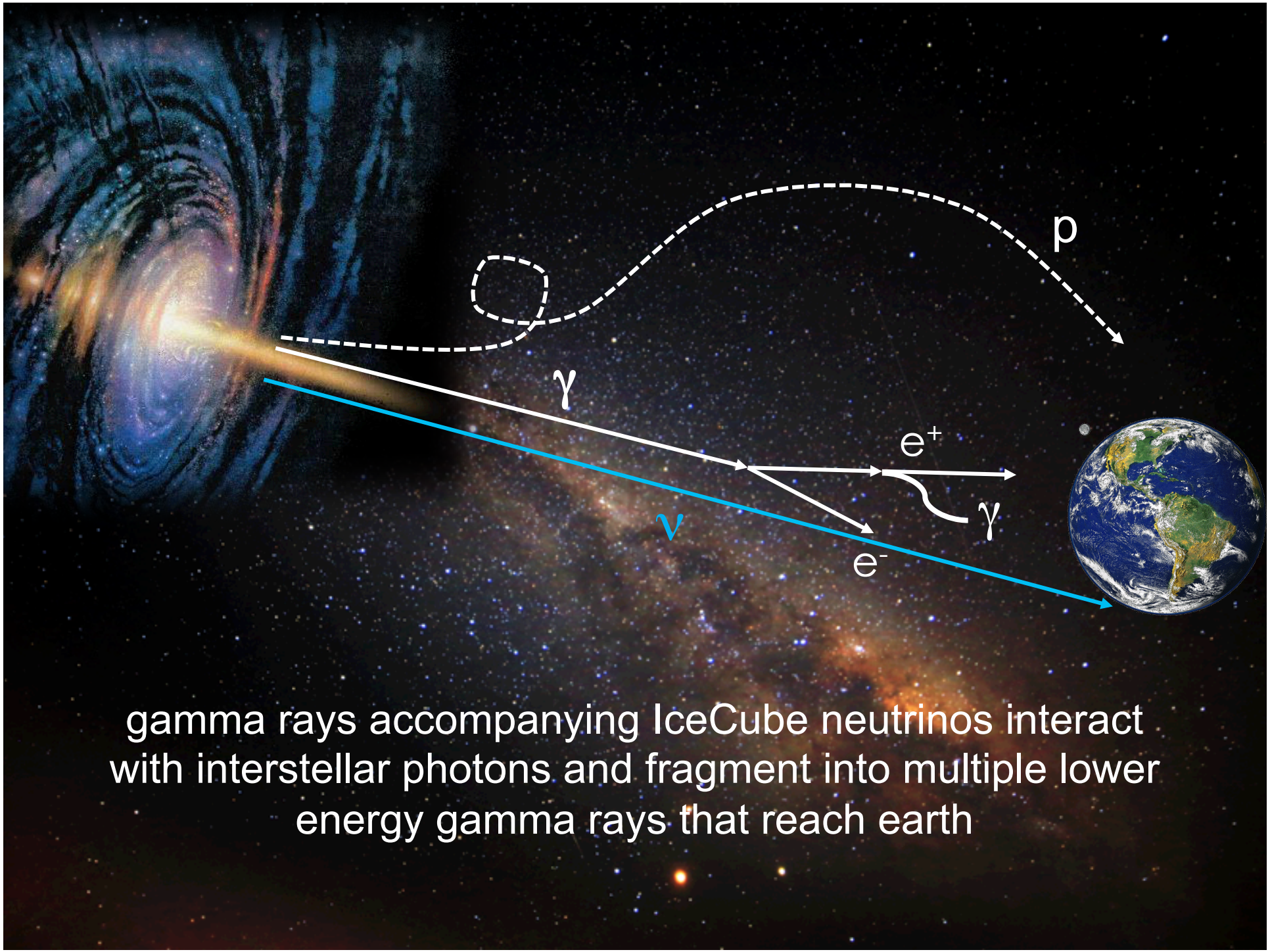
radiation
and dust

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

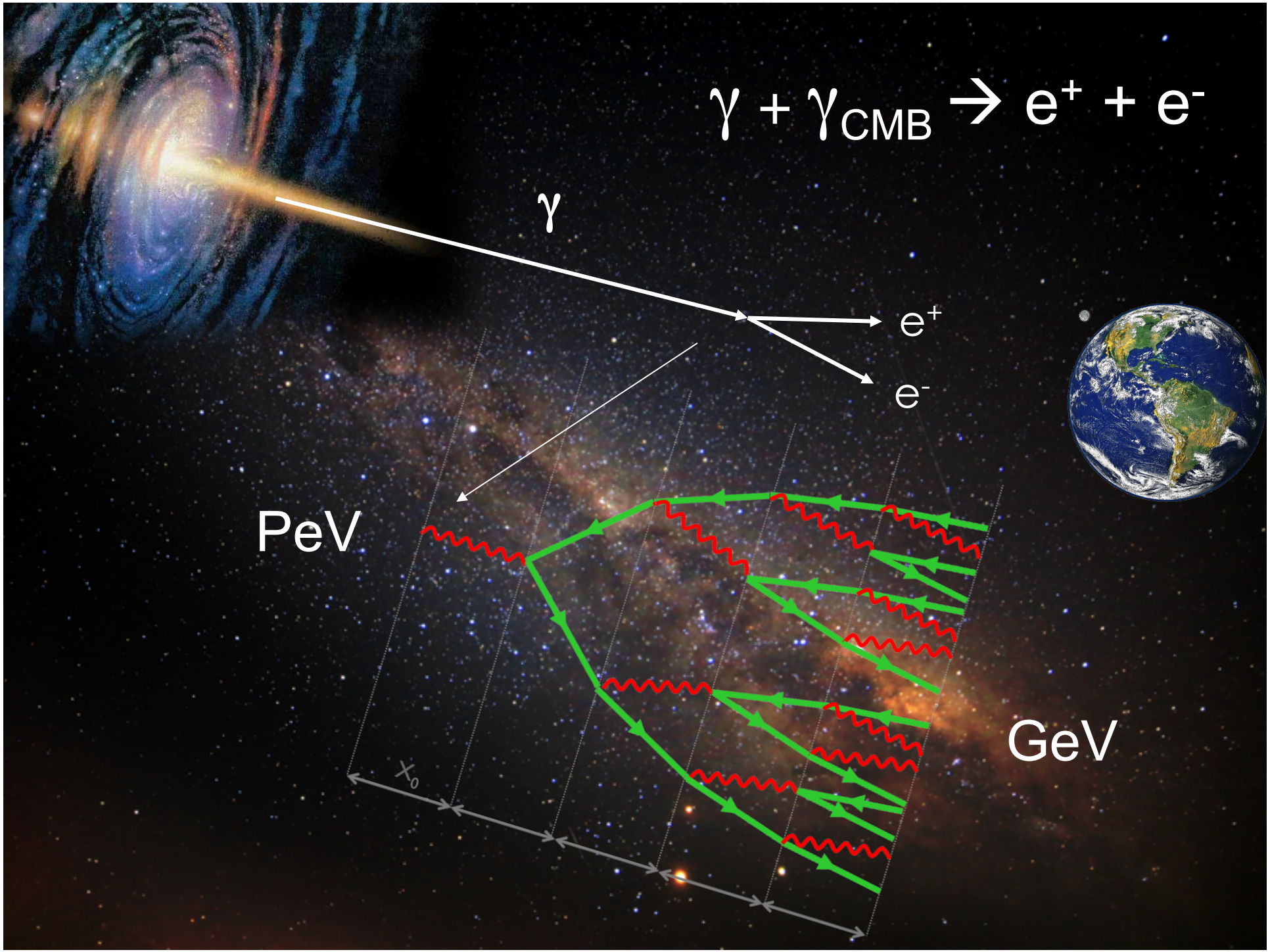
~ cosmic ray + neutrino

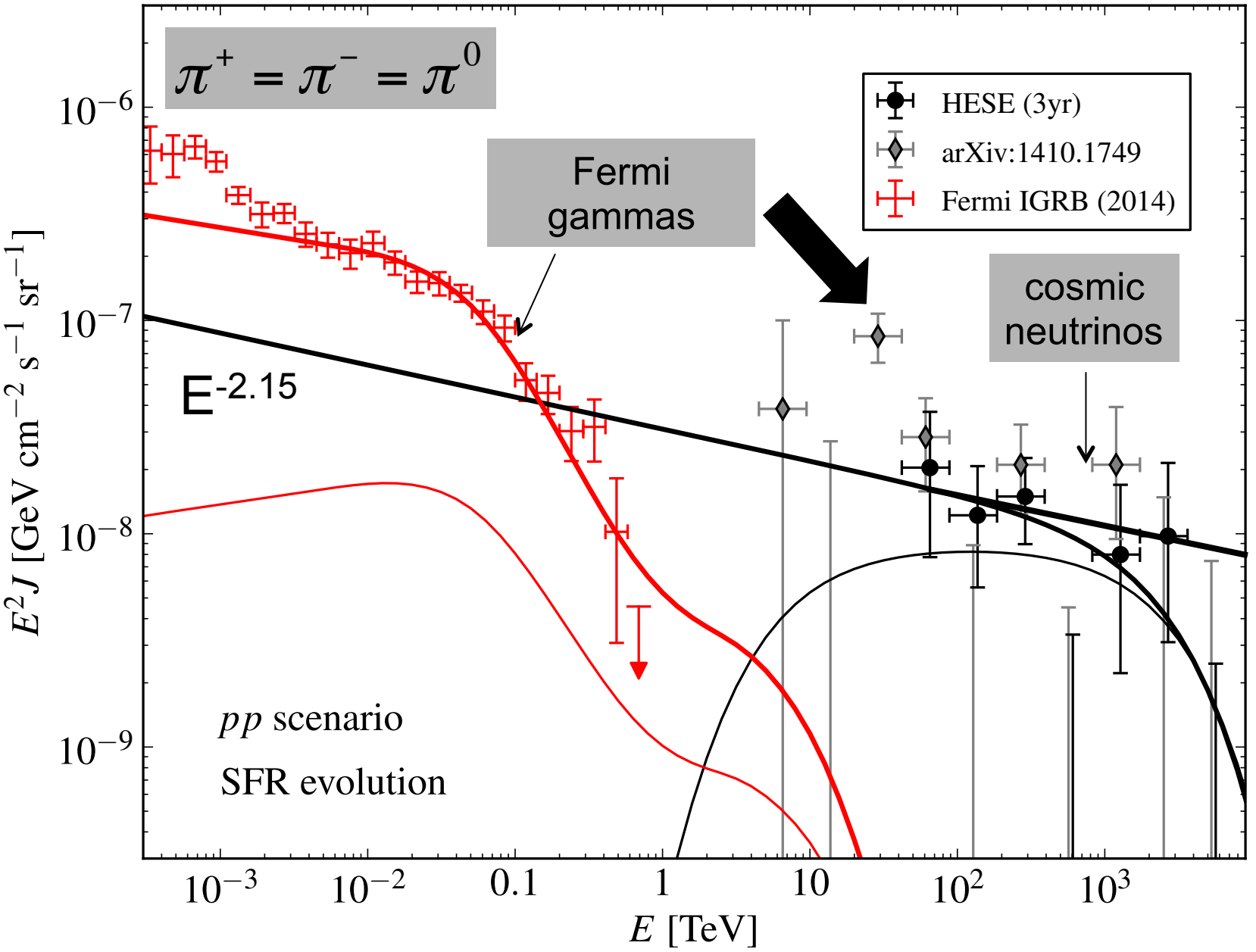
$\rightarrow p + \pi^0$

~ cosmic ray + gamma



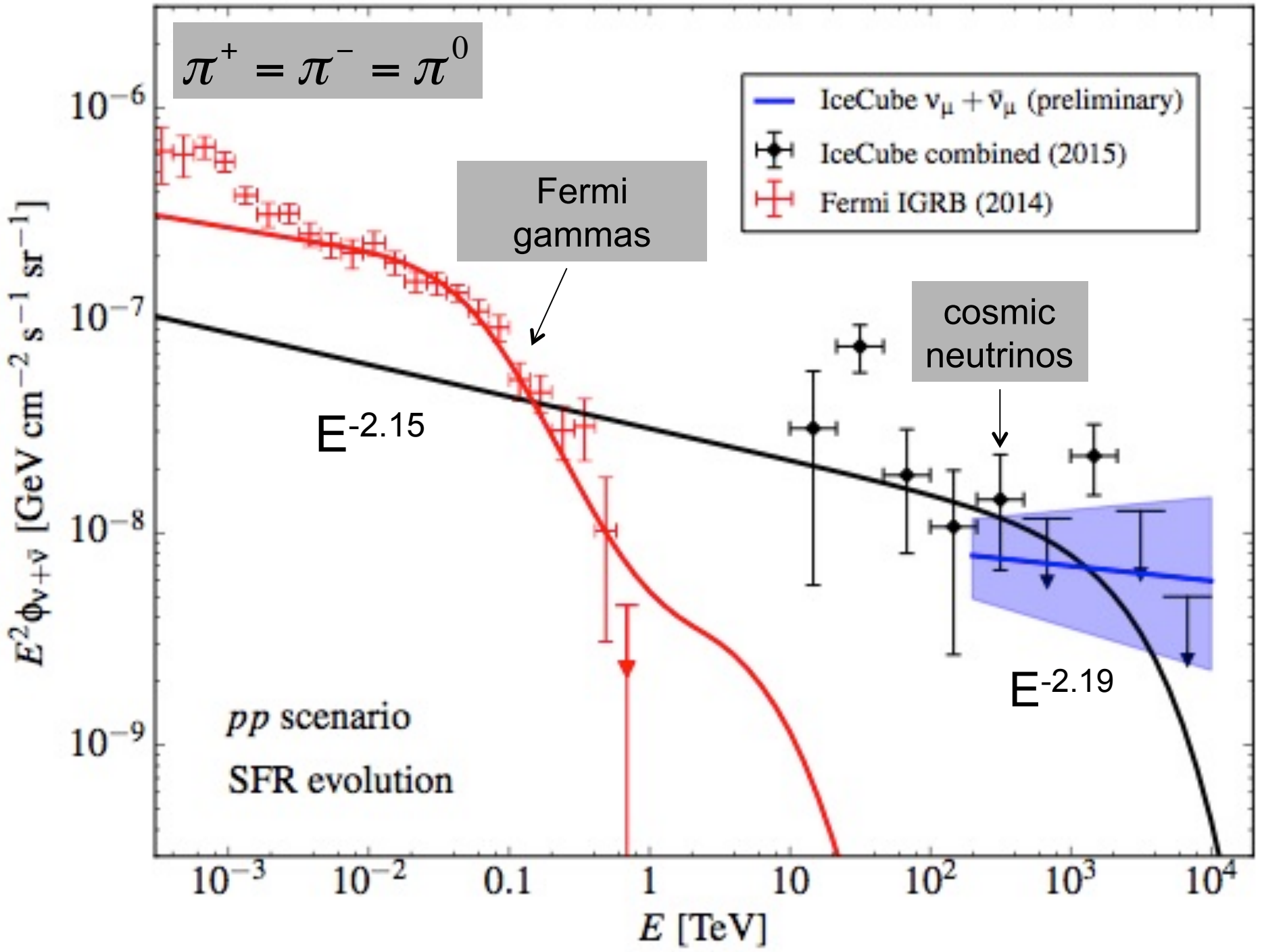
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth

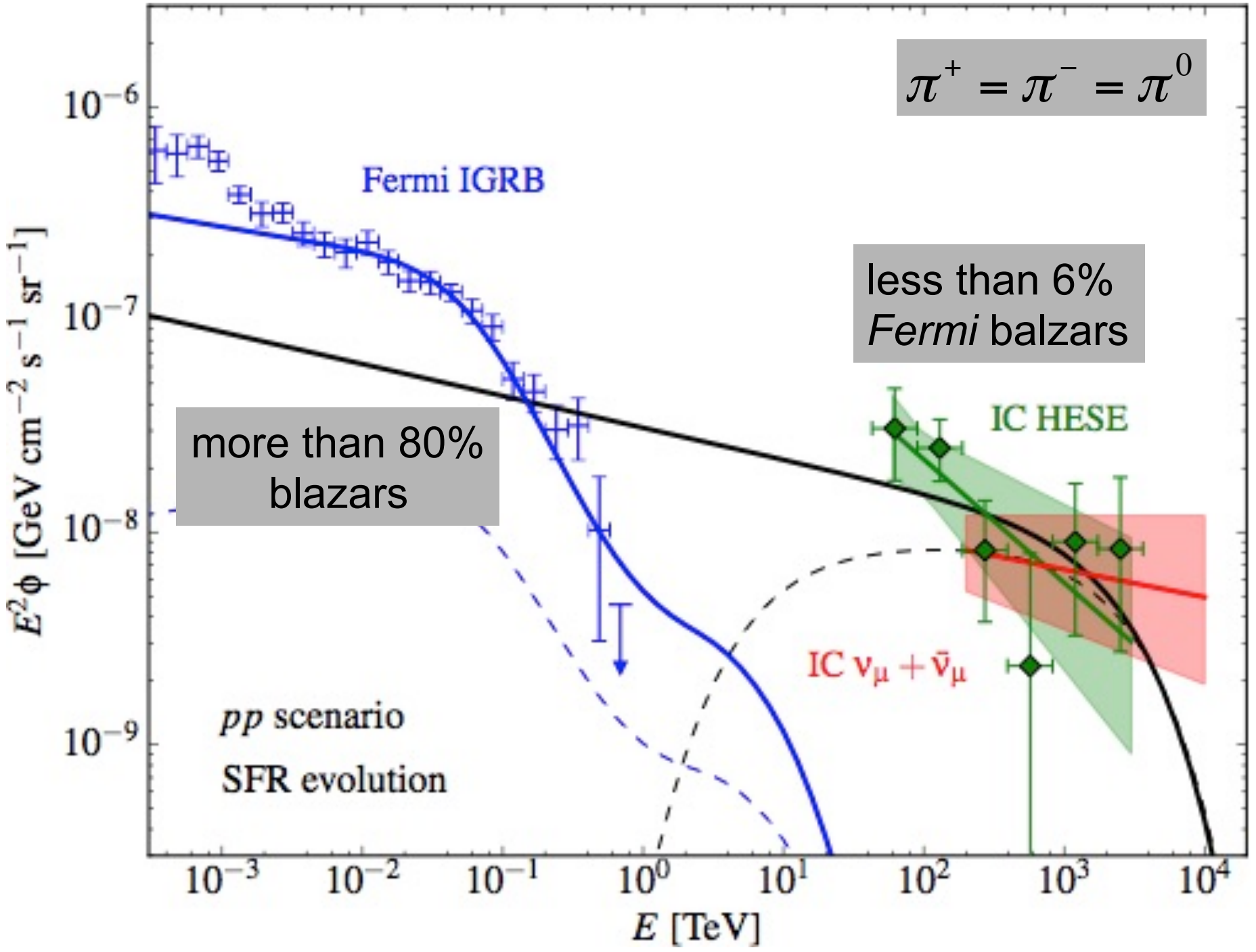

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0

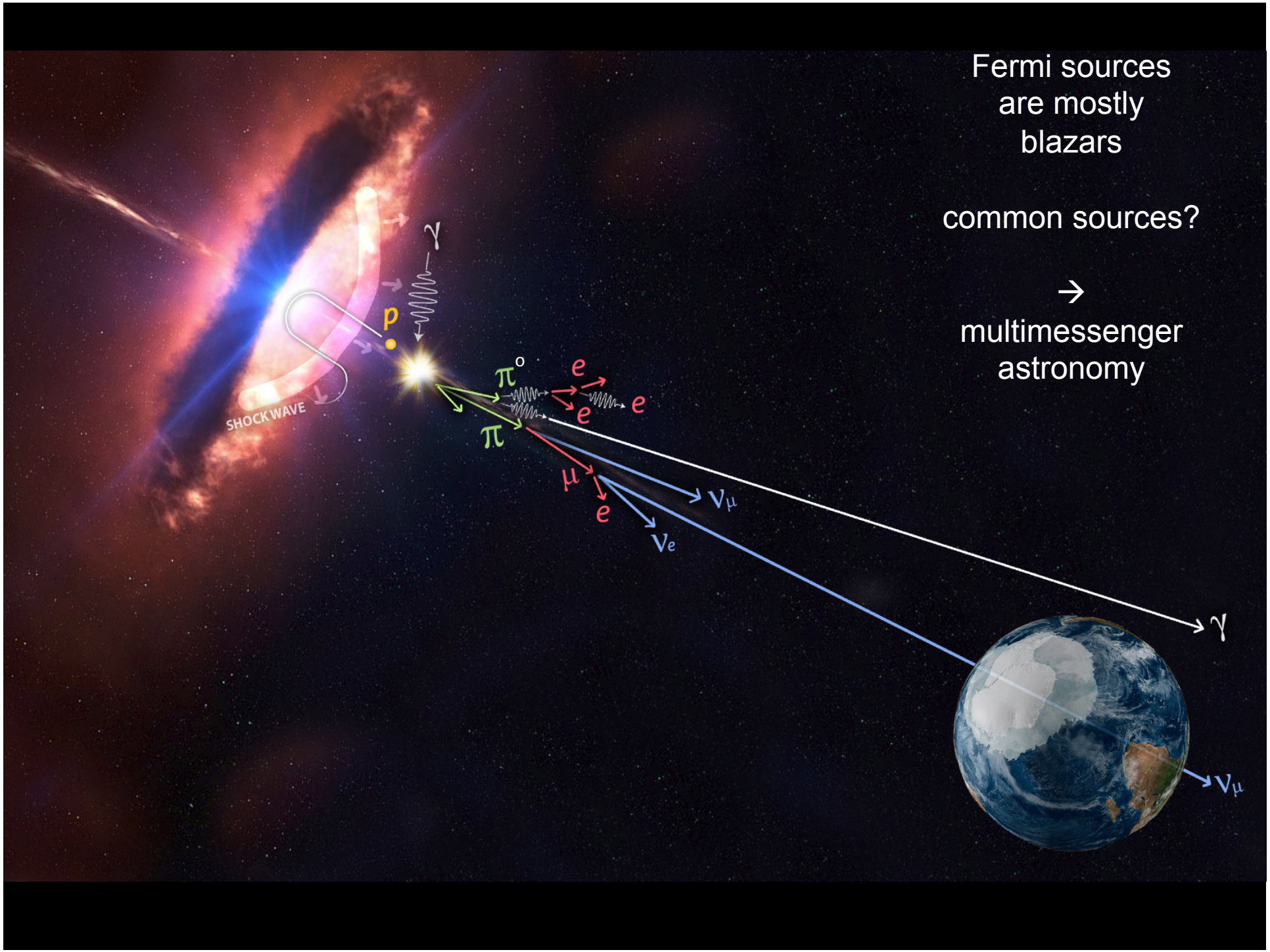

$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
E-2.15
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

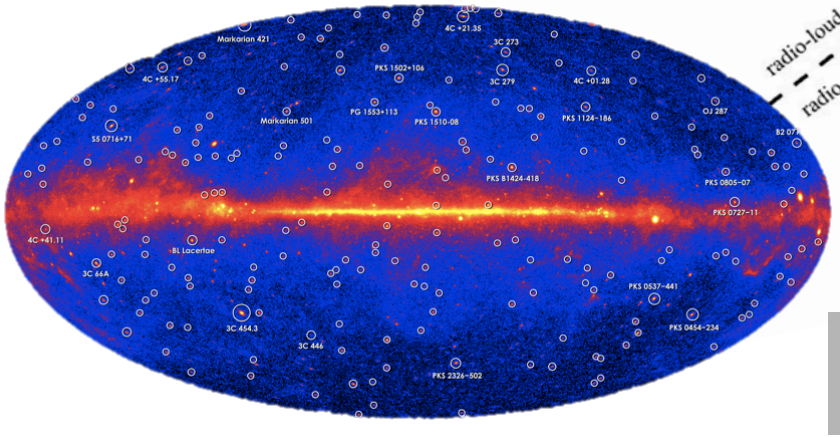
- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays

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

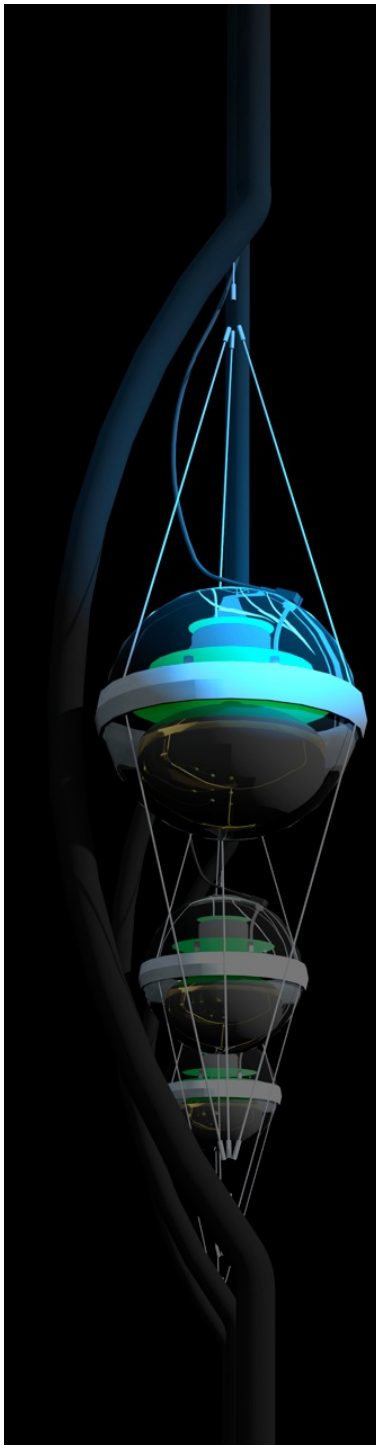

$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
$E^{-2.19}$
pp scenario
SFR evolution
$E^2\phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
10^4


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


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



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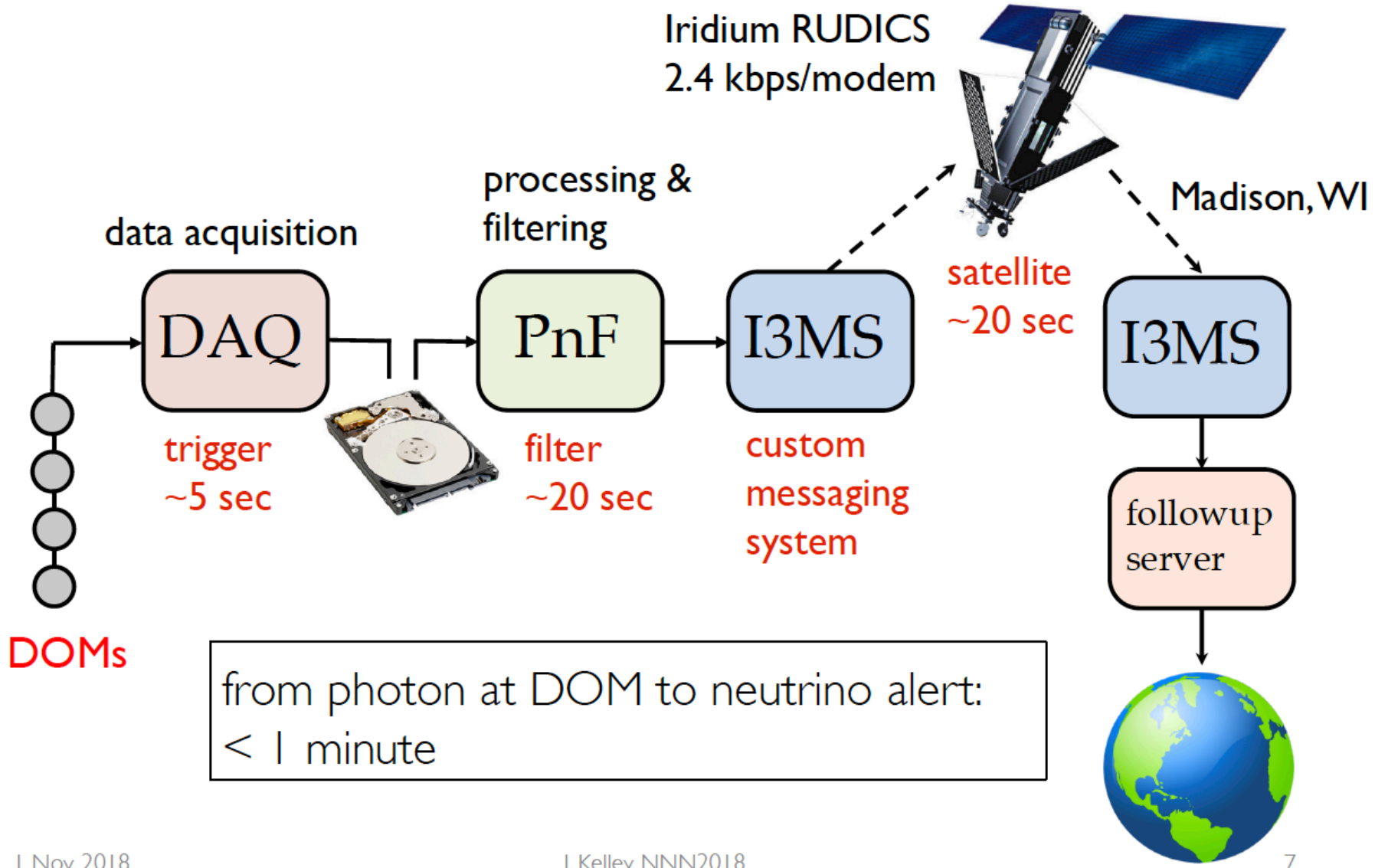
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

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



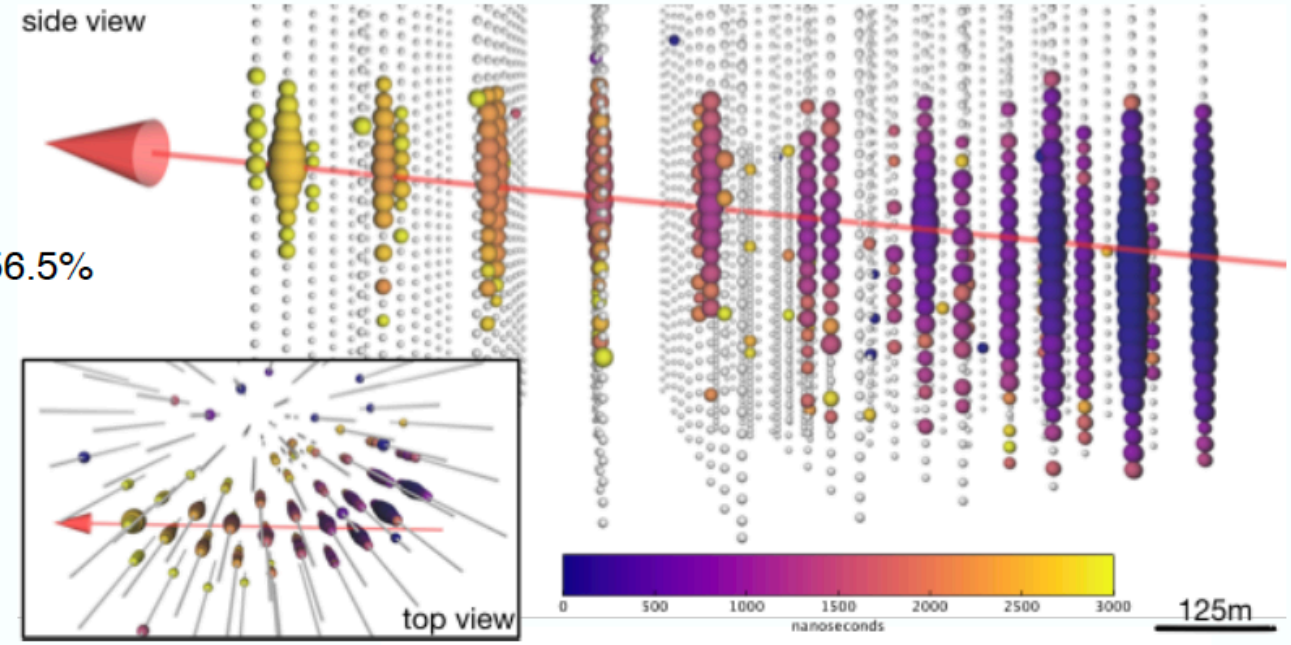
IceCube Trigger

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]
```

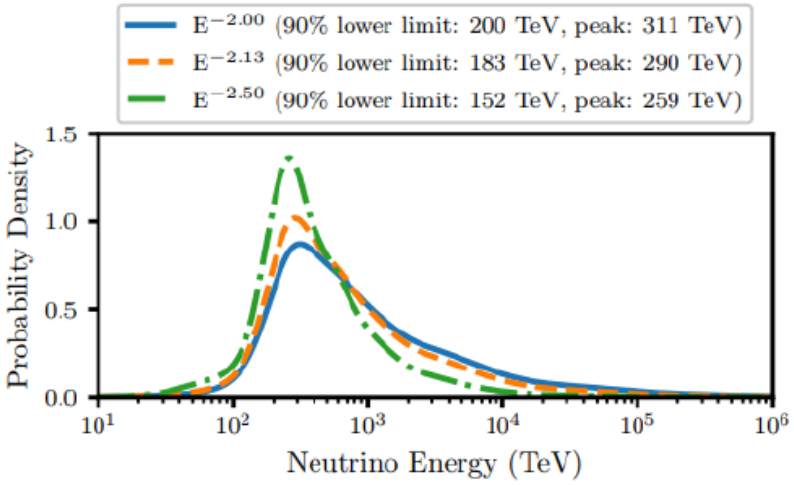
IC-170922A

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



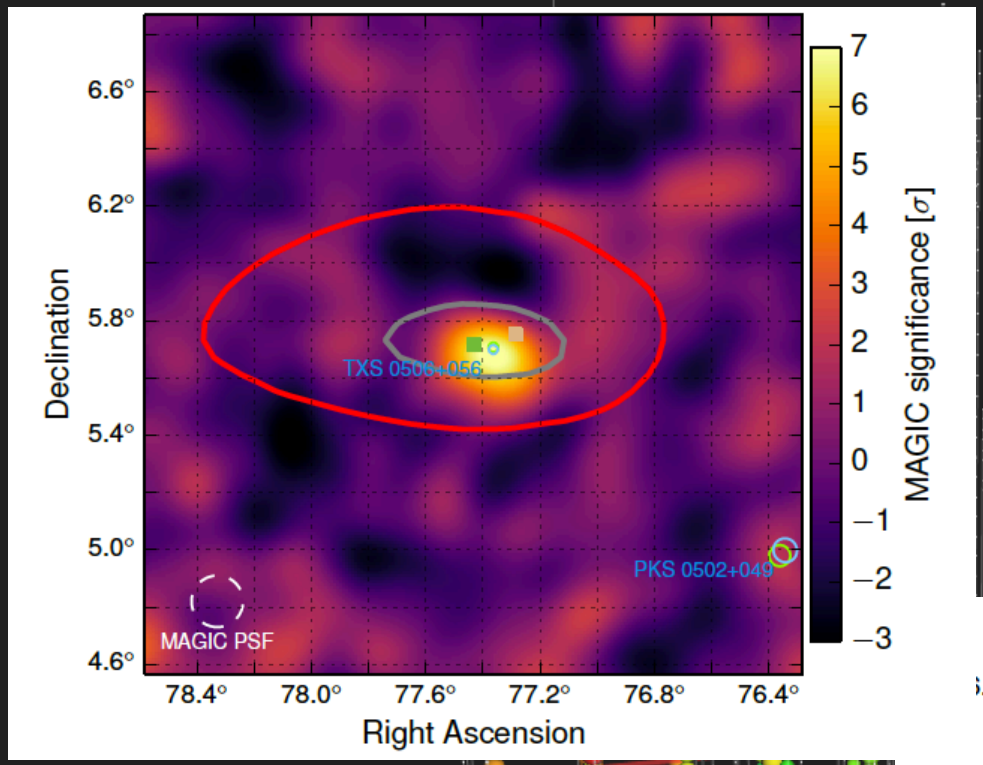
Signalness: 56.5%

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).



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

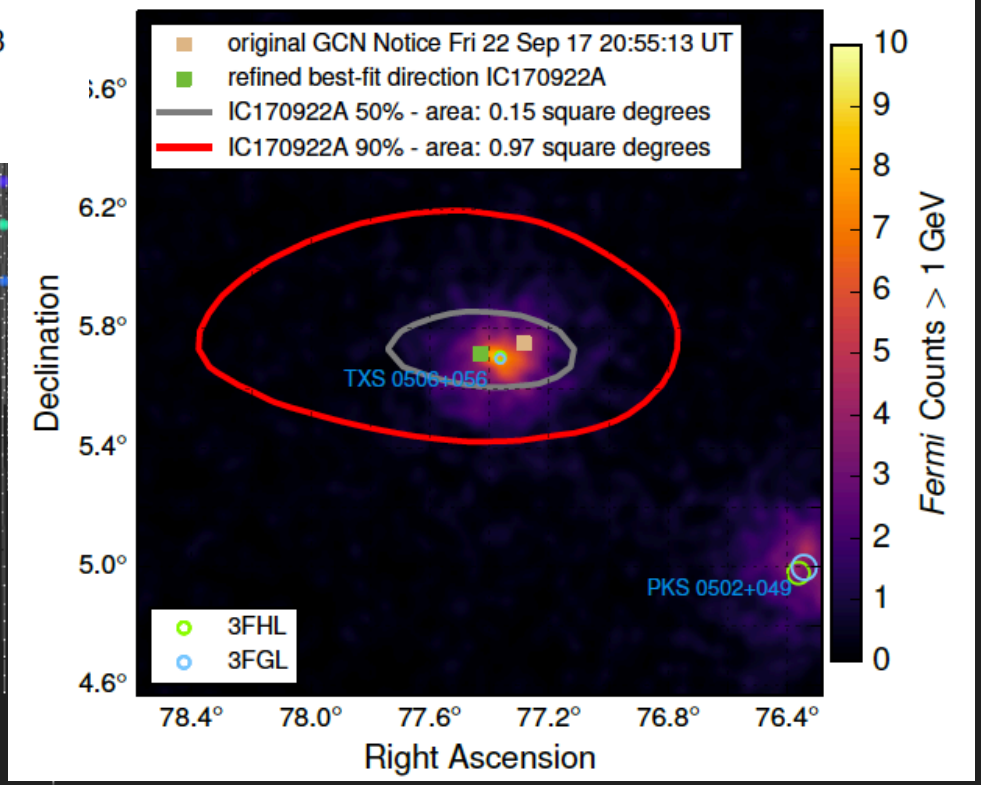
https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

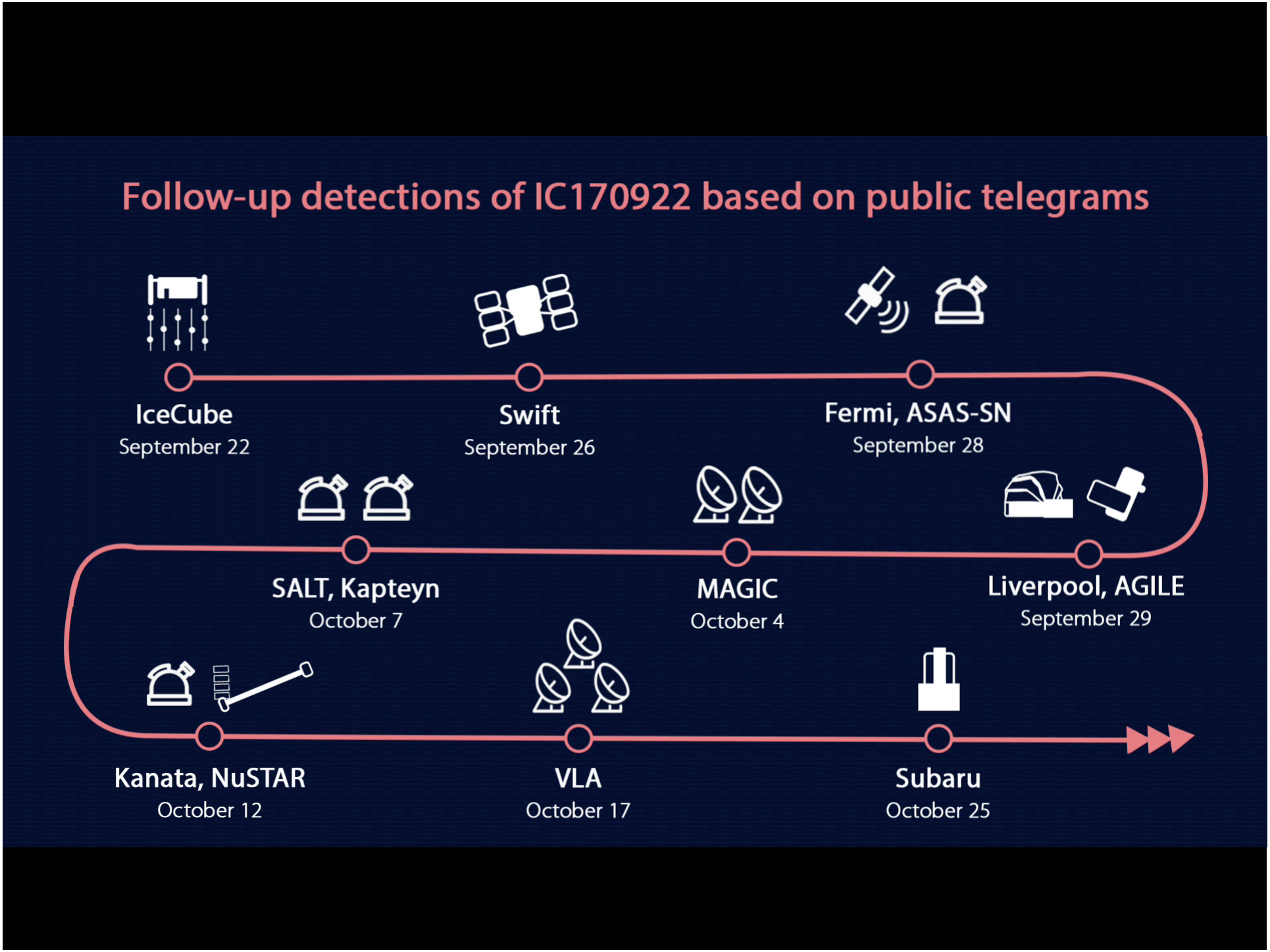


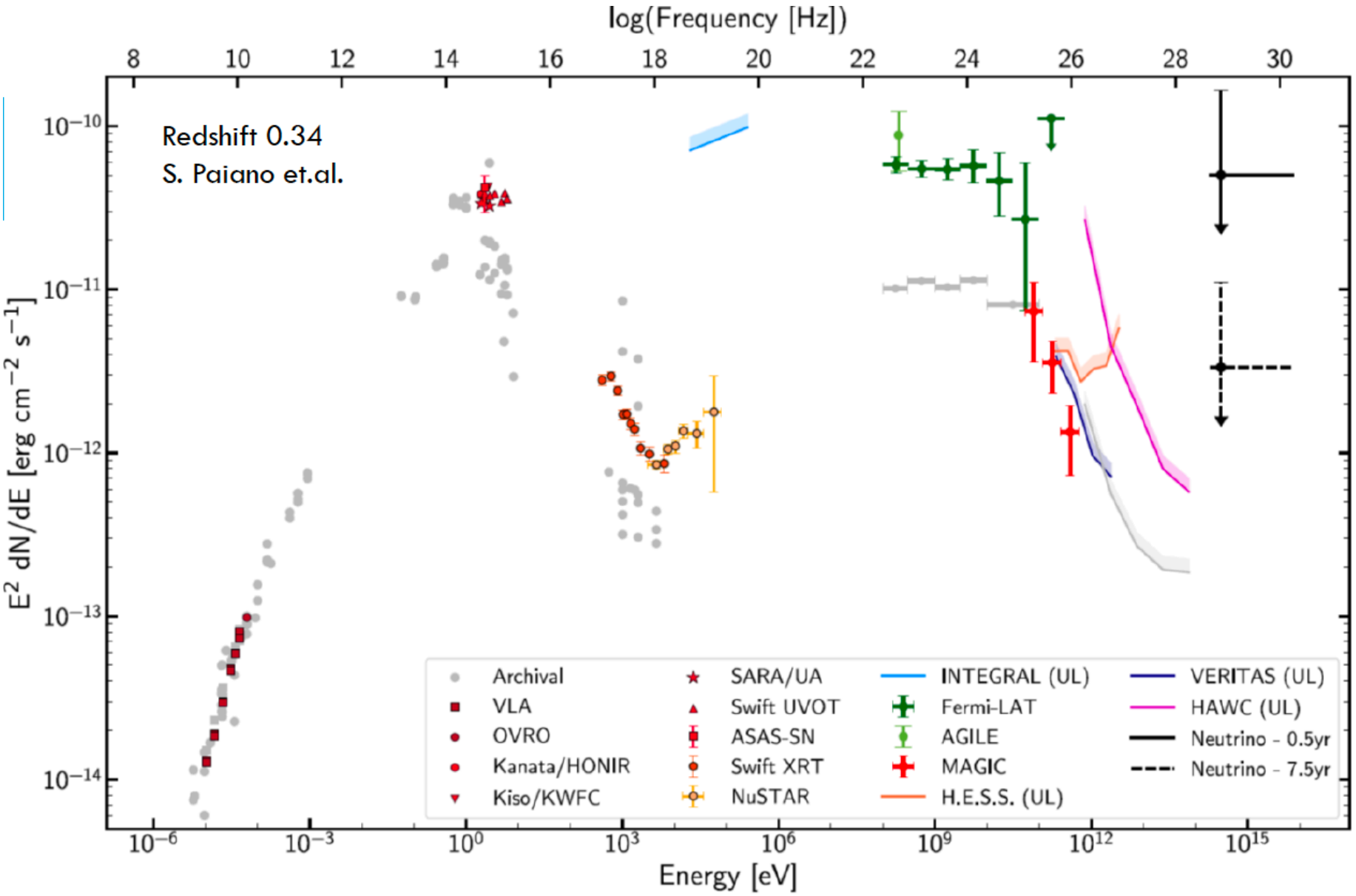
IceCube 170922

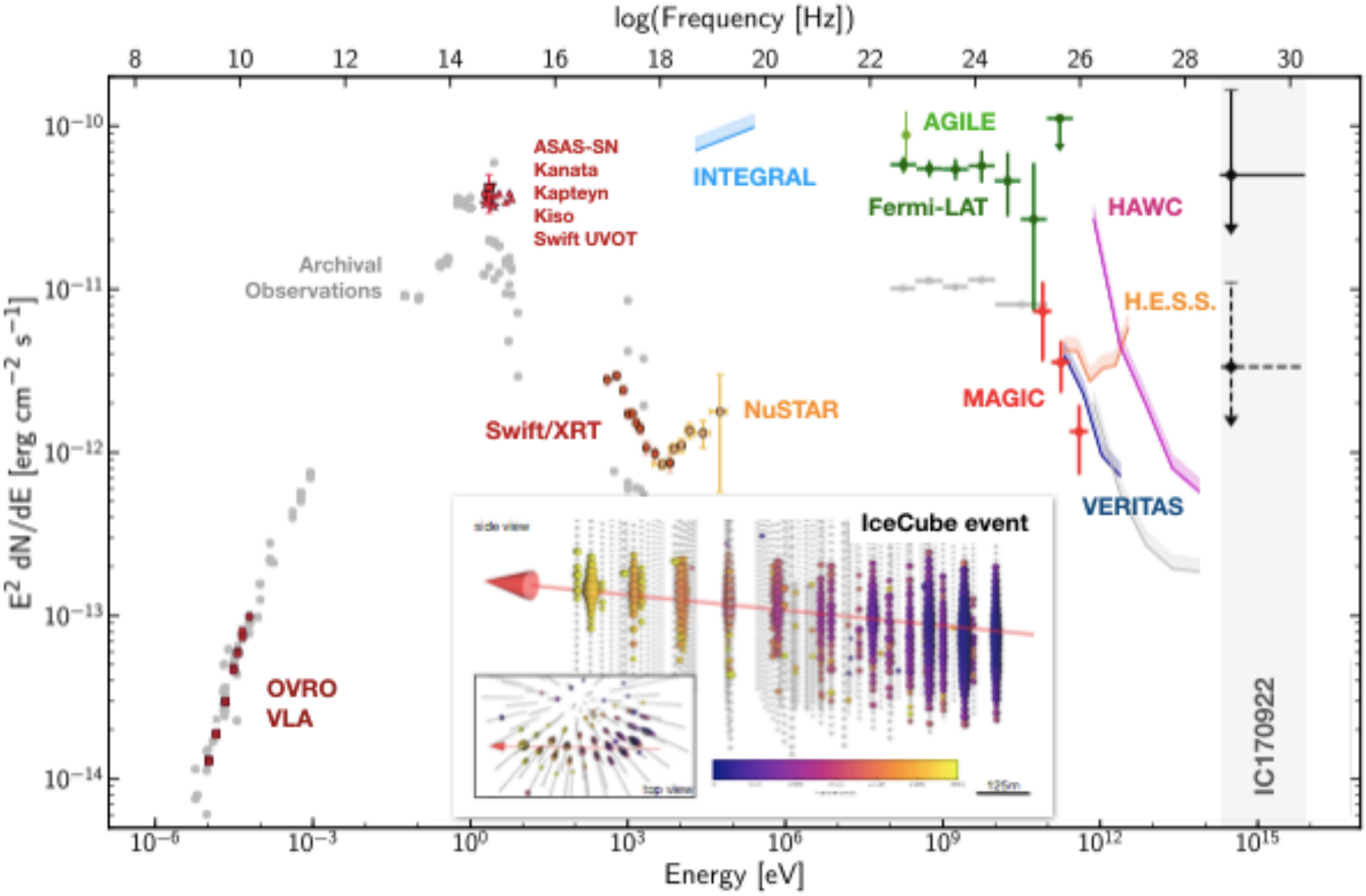
Fermi
detects a flaring
blazar within 0.1°

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


log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
Redshift 0.34
S. Paiano et.al.
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr



we know this one is hadronic

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

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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

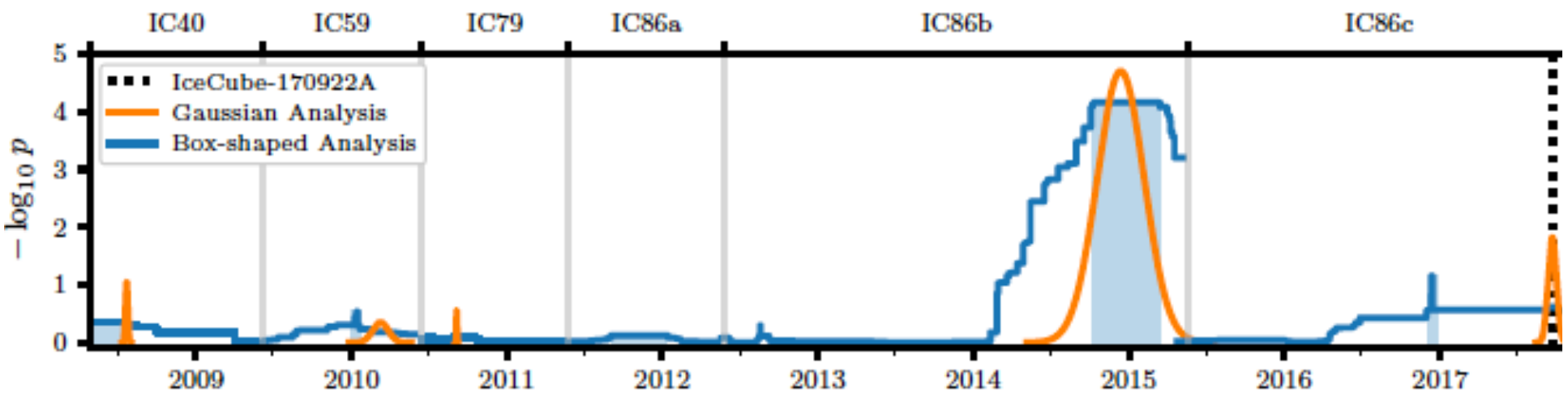
- we do not see our own Galaxy
- we do not see the nearest extragalactic sources
- we find a blazar at 4 billion lightyears!

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

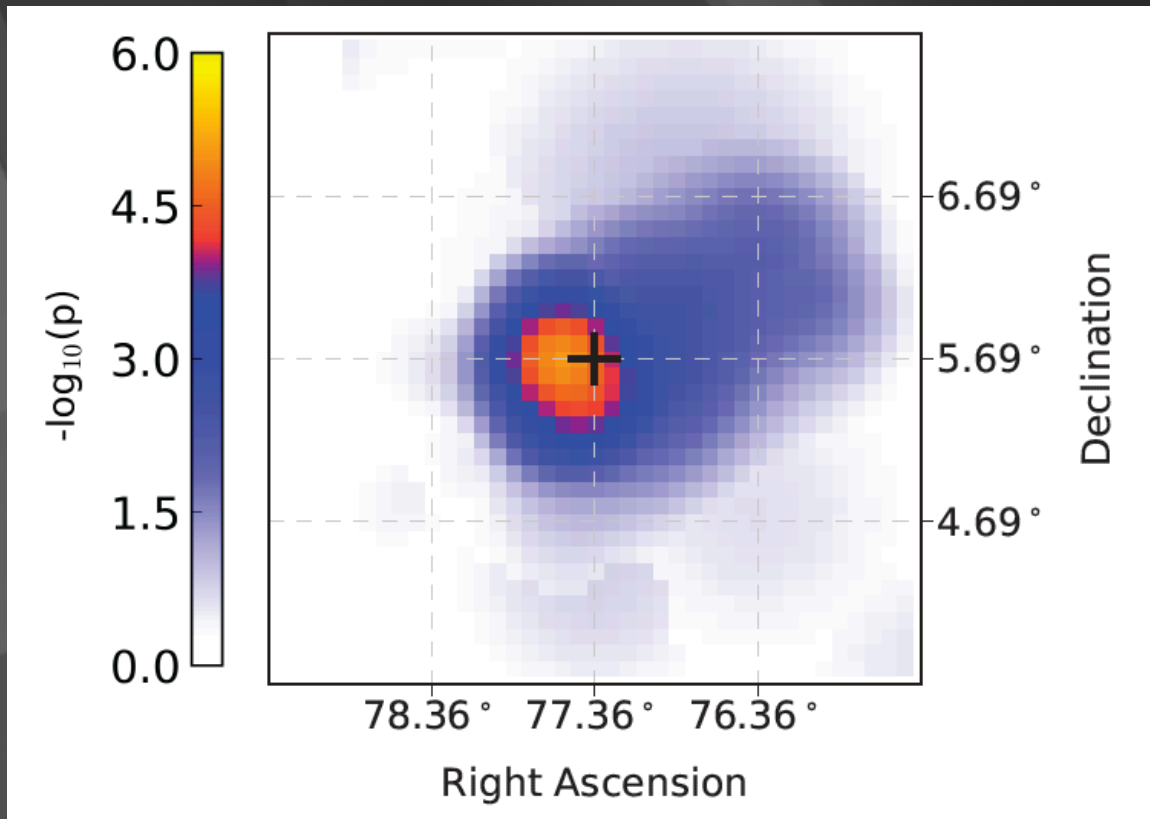
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^{o} Dec 5.72^{o}
- Fermi-LAT: flaring blazar within 0.1^{o} (7x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes

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

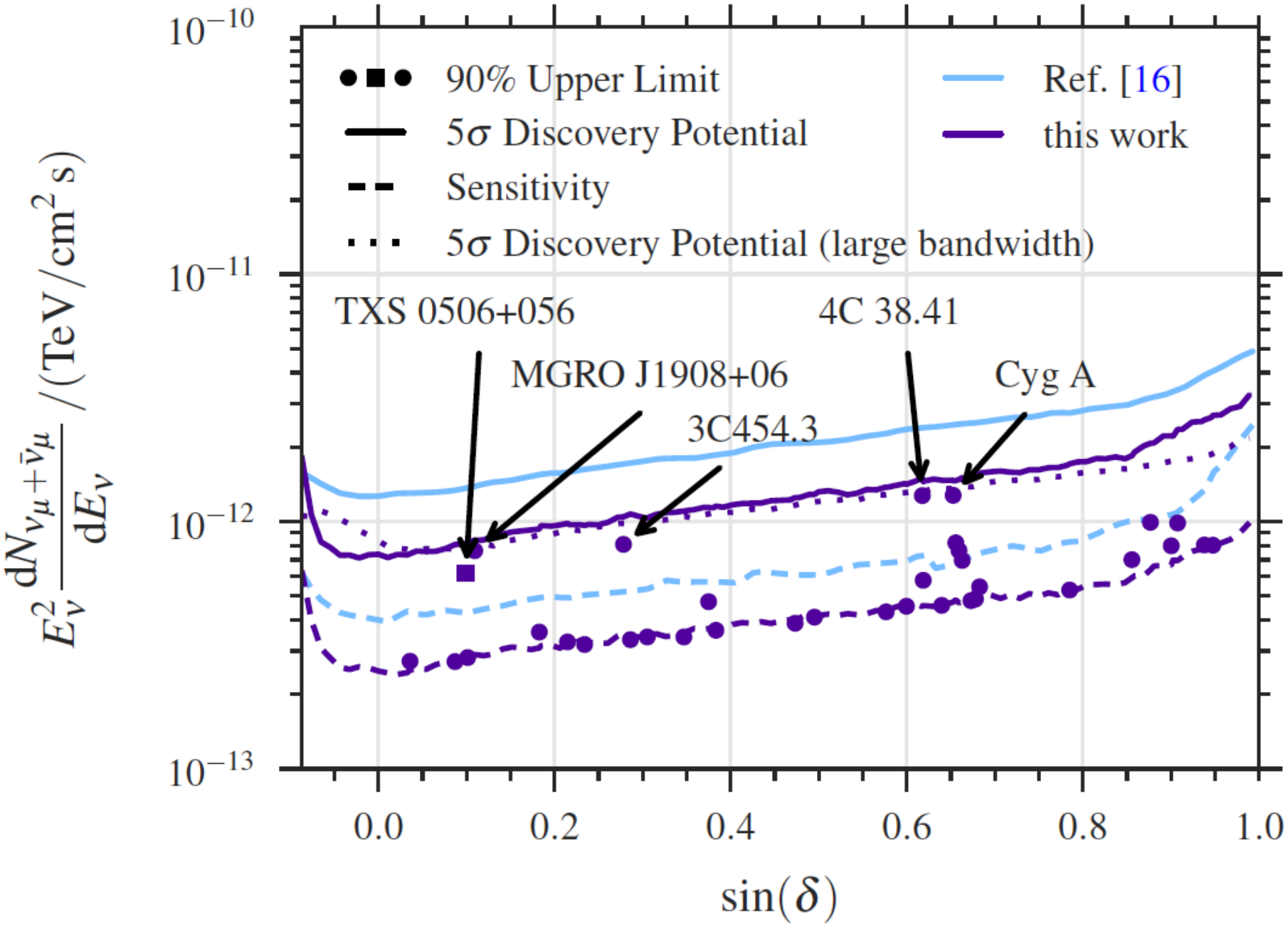


search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 10^{-5} bkg. probability
- accompanied by hardest Fermi spectrum in the 10 years of data ($E^{-1.7}$).



Why not seen before?



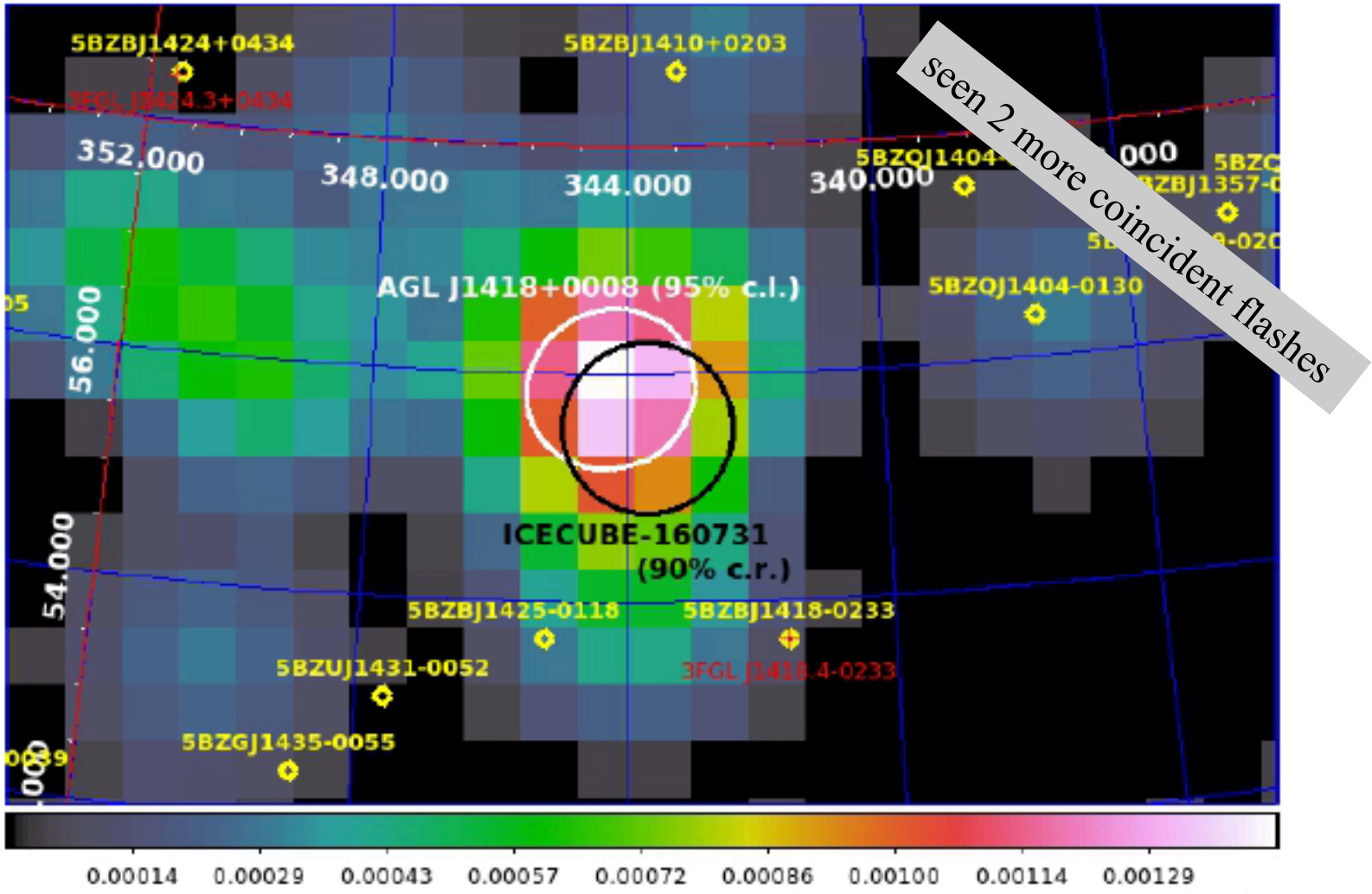
we identified a source of high energy cosmic rays:

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]



seen 2 more coincident flashes

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Flaring Sources and the Diffuse Neutrino Flux

Neutrino flux from episodic emission from a fraction of a source class

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

Adopting for the observation of 2014 neutrino burst for TXS:

$$\sum_{\alpha} E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{\mathcal{F}}{4\pi} \left(\frac{R_H}{3\,\mathrm{Gpc}}\right) \left(\frac{\xi_z}{0.7}\right) \left(\frac{L_\nu}{1.2 \times 10^{47}\,\mathrm{erg/s}}\right) \left(\frac{\rho}{1.5 \times 10^{-8}\,\mathrm{Mpc}^{-3}}\right) \left(\frac{\Delta t}{110\,\mathrm{d}} \frac{10\,\mathrm{yr}}{T}\right)$$

$$= 3 \times 10^{-11}\,\mathrm{TeV cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

$$\longrightarrow \mathcal{F} \sim 5\%$$

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.

https://arxiv.org/pdf/1811.07439.pdf

Relating to the Cosmic Rays

The equal energetics of cosmic rays and neutrinos dictates

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{8\pi}\left(1-e^{-f_\pi}\right)\frac{\xi_z}{H_0}\frac{dE}{dt}$$

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

Finding the pion production efficiency of the neutrino source ⟶ $f_\pi \gtrsim 0.4$

high opacity for p-gamma interaction. Expected for an efficient neutrino emitter!

Gamma ray opacity is connected to pion efficiency

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

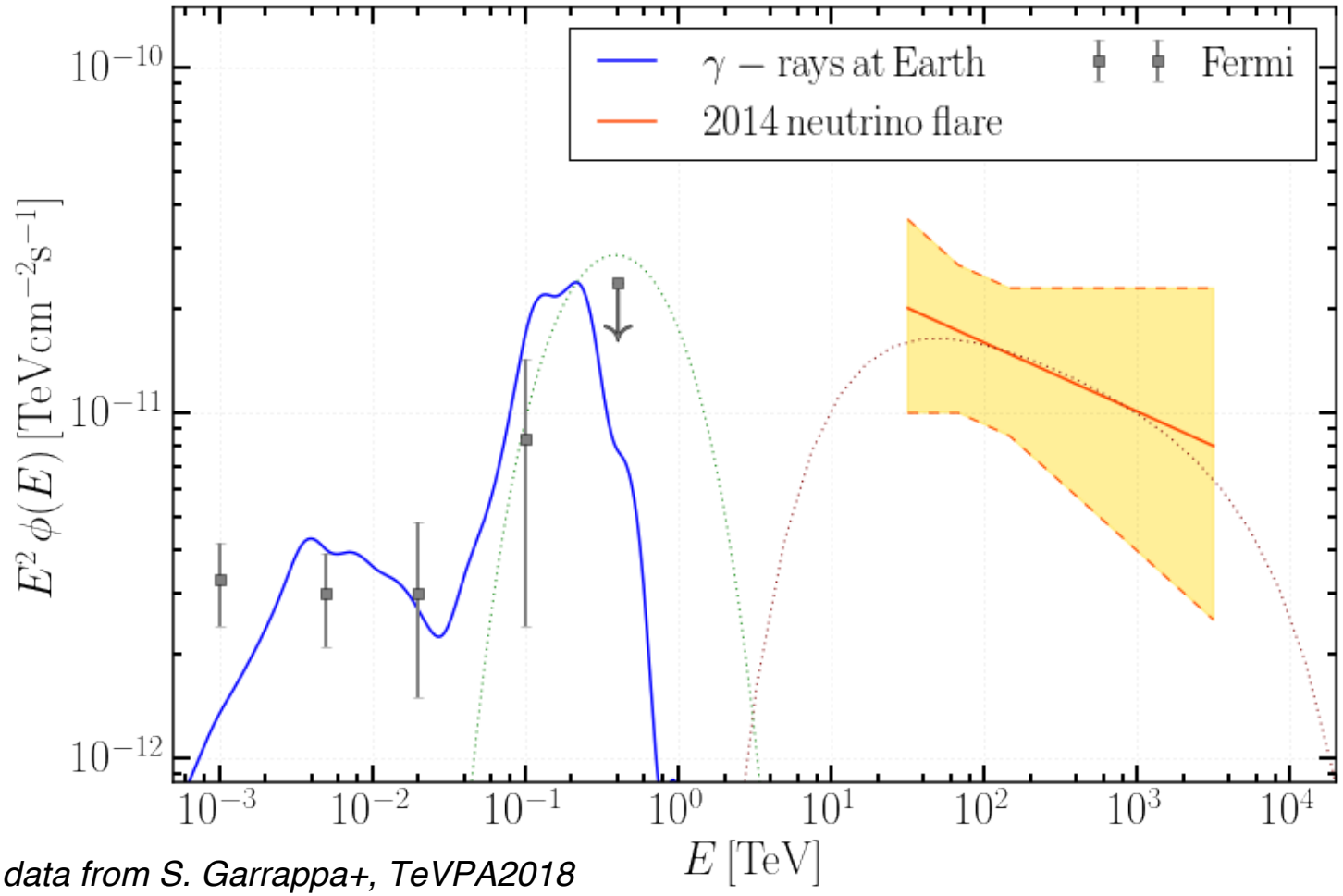
HE gamma rays will be absorbed at the source!

Is this compatible with the gamma ray observations?

https://arxiv.org/pdf/1811.07439.pdf

The Multimessenger Picture

Neutrino flux → energetics → Gamma ray flux outside the source shifted to lower energies → EBL Absorption → Observed flux @ Fermi



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

https://arxiv.org/pdf/1811.07439.pdf

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)

how large a detector?

beam

produces the observed cosmic rays

target

nearby radiation fields hydrogen/dust

generic theoretical framework

Generic Framework: Hadronic pion production *pp->π^0/±*

rate per energy per time

$$q_{\pi^\pm} = \frac{dN_\pi}{dE_\pi dt} = \int dE_p \int_0^\tau d\tau' \frac{dN_p}{dE_p} e^{-\tau'} \frac{dN_\pi}{dE_\pi}(E_\pi)$$
$$= (1 - exp(-\tau)) \int dE_p \frac{dN_p}{dE_p} n_\pi \delta(E_\pi - < E_\pi >)$$
$$= nl\sigma n_\pi \frac{1}{f_\pi} \frac{dN_p}{dE_p}(\frac{E_\pi}{f_\pi})$$

In most astrophysical situations the optical depth is small $1 - exp(-\tau) \to \tau$

energy fraction $f_\pi = \frac{< E_\pi >}{E_p}$

$$q_{\nu_i}(E_{\nu_i}) = q_\pi(4E_{\nu_i}) dE_\pi / dE_{\nu_i} = 4q_\pi(4E_{\nu_i})$$

Assume the total energy of pions is distributed equally among 4 decay leptons

$$q_{\nu_i}(E_{\nu_i}) = 4nl\sigma n_\pi \frac{1}{f_\pi} \frac{dN_p}{dE_p}(\frac{4E_{\nu_i}}{f_\pi})$$

Diffuse flux for nearby sources at Earth

$$\Phi = \frac{1}{4\pi} \int d^3 r \rho(r) \frac{q_\nu(E_\nu)}{4\pi r^2}$$

Point source flux

ρ is the source population density

Integrating over the Universe

$$dr \to cdt \to cdz(dt/dz) = cdz \frac{1}{H(z)}$$

$$\Phi = \frac{c}{4\pi} \int \frac{dz}{H(z)} \rho(z) q_\nu((1+z)E_\nu)$$

Number of Neutrinos from a source at zenith angle θ_z at the detector

$$N = t \int_{E_\nu^{th}} dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu} \times A_\nu^{eff}(E_\nu, \theta_z)$$

Correlate Gamma-ray Flux to Neutrino Flux

Relation between gamma-ray and Neutrino flux

$$E_\gamma J_\gamma(E_\gamma) \simeq e^{-\frac{d}{\lambda_{\gamma\gamma}}} \frac{2}{K} \frac{1}{3} \sum_{\nu_\alpha} E_\nu J_{\nu_\alpha}(E_\nu)$$

$$E_\gamma \simeq 2E_\nu$$

- K is the ratio of charged to neutral pions
- J is the differential flux
- d is the distance to the source
- $\lambda_{\gamma\gamma}$ is the interaction length accounting for the absorption of TeV-PeV gamma-rays in radiation backgrounds.

$p\gamma$ interaction → $K \simeq 1$

pp interaction → $K \simeq 2$

thought to be the main hadronic process for Galactic sources detected by gamma-ray observations.

Sources are optically thin, which is true for many Galactic CR sources. Thus the exponential term can be neglected.