Multi-messenger Astrophysics with high energy neutrinos and photons

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Vikram Discussion on Neutrino Astrophysics
March 19-21, 2025
PRL , Ahmedabad

Neutrinos and Gamma rays

2017 : A year of Multi-messenger events

ATel #10791: Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region. - Mozilla Firefox

www.astronomerstelegram.org/?read=10791

[Previous | Next | ADS]

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on *28 Sep 2017; 10:10 UT*
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons cm-2 s-1 (errors are statistical only), increased by a factor of ~6 compared to the 3FGL flux, with nearly the same power-law index of 2.0+/-0.1. We strongly encourage multiwavelength observations of this source. We also encourage optical spectroscopy for this source, because the redshift is still unknown. According

Related

- 10890 Subaru/FOCAS Optical Spectroscopy for a possible IceCube-170922A counterpart TXS 0506+056
- 10861 VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event
- 10845 Joint Swift XRT and NuSTAR Observations of TXS 0506+056
- 10844 Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
- 10840 VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
- 10838 MAXI/GSC observations of IceCube-170922A and TXS 0506+056
- 10833 VERITAS follow-up observations of IceCube neutrino event 170922A
- 10831 Optical photometry of TX0506+056
- 10830 SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
- 10817 First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
- 10802 HAWC gamma ray data prior to IceCube-

ATel #10817: First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A - Moz

www.astronomerstelegram.org/?read=10817

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First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on *4 Oct 2017; 17:17 UT*
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

Related

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A minor(?) event got overshadowed by the big event of Gravitational waves and its EM counterpart

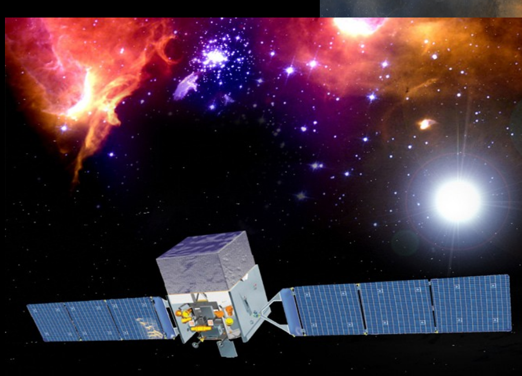
Multi-messenger Astrophysics

Origin of cosmic rays

PeV Neutrino astronomy

Gamma ray astronomy

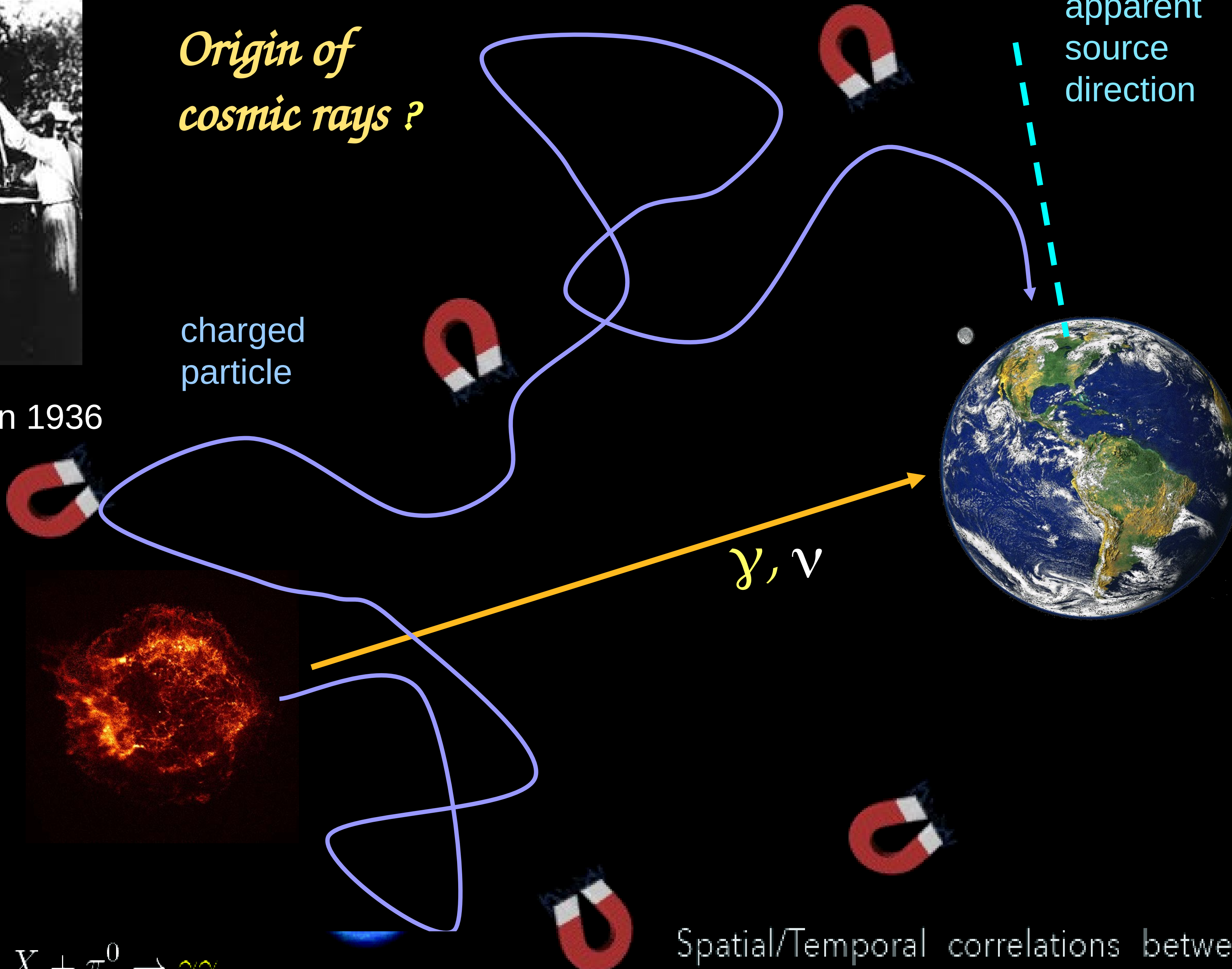
Optical and X-rays



Active Galactic Nuclei (blazars)

Origin of cosmic rays ?

Nobel Prize in 1936



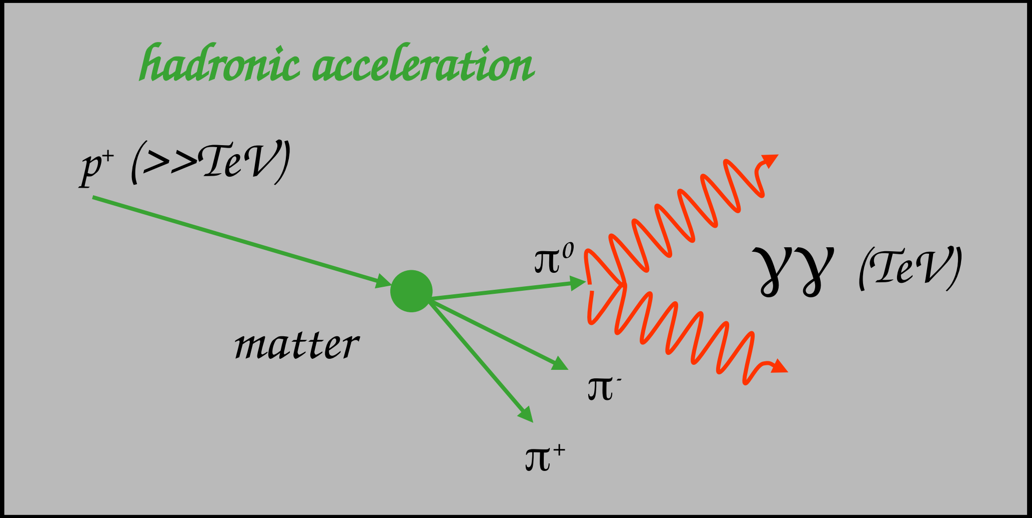
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Spatial/Temporal correlations between neutrinos and gamma rays can trace cosmic-ray acceleration/interaction sites

γ-ray astrophysics and cosmic rays (CR)

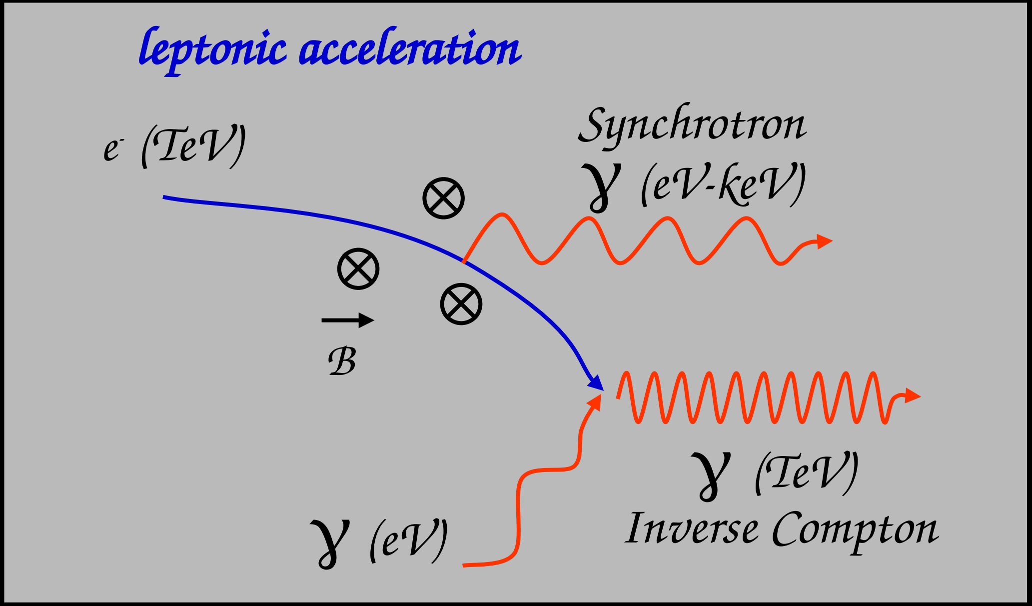
Study origin of CRs,

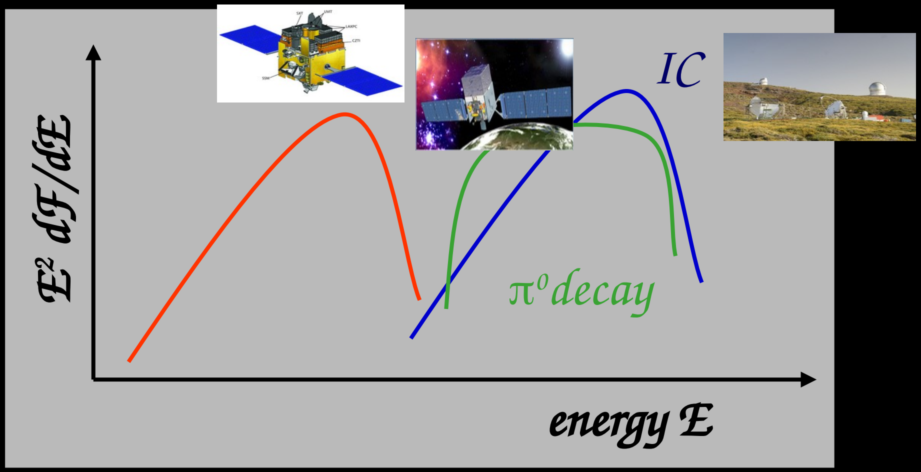
=> search for γ-rays produced by CRs close to source



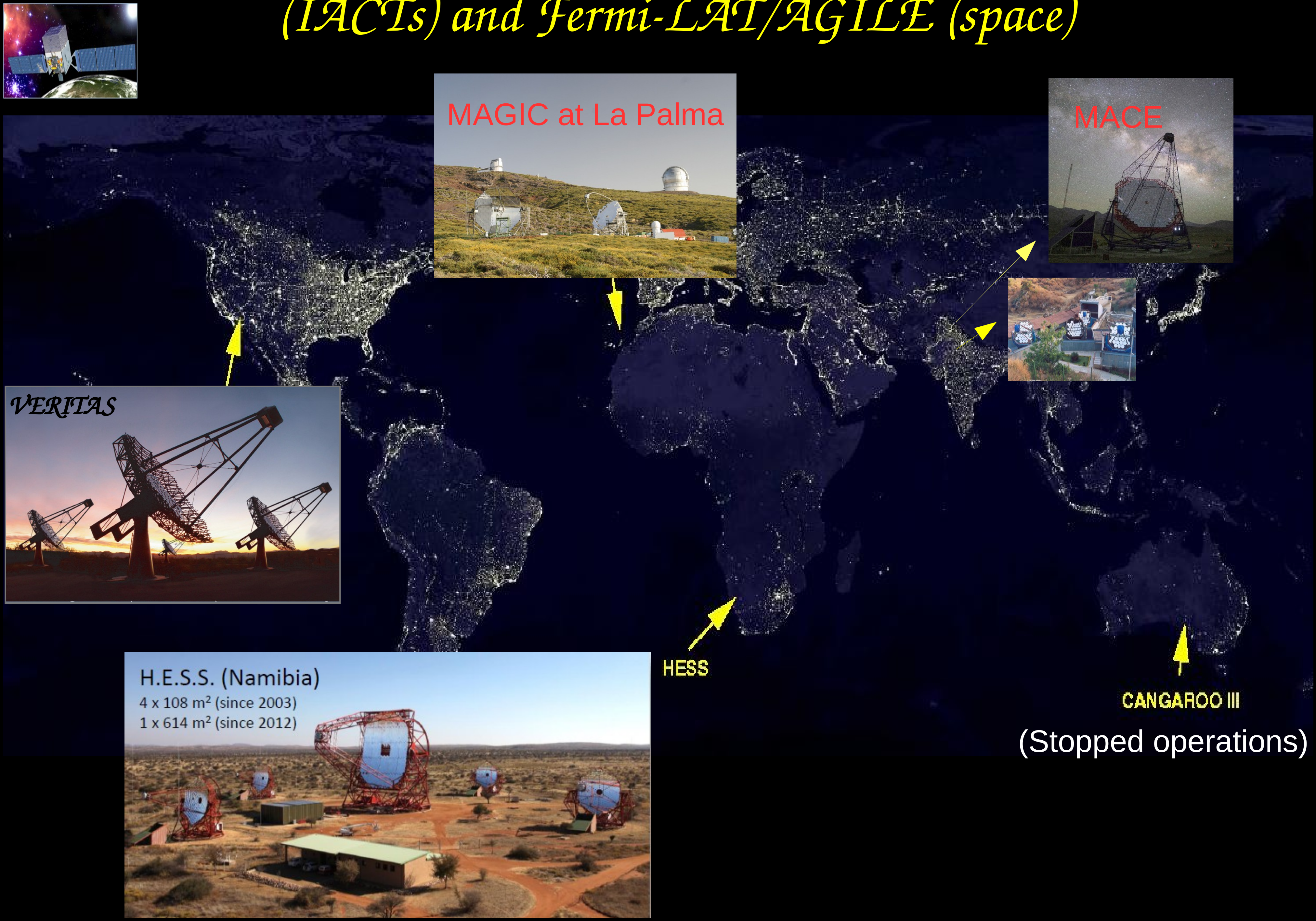
- *discriminate hadronic vs leptonic acceleration*

=> shape of spectrum





Current Generation of high energy gamma-ray detectors (IACTs) and Fermi-LAT/AGILE (space)



Fermi-LAT Observatory (100 MeV – 300 GeV)

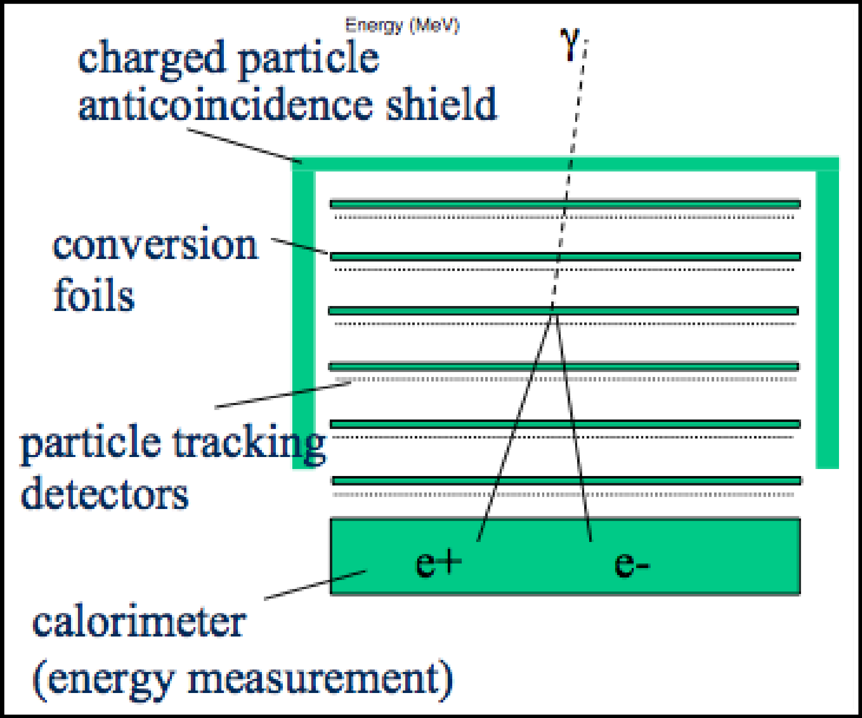
Revolutoinised the field of gamma-ray astrophysics with magnificent and variety of observations

Three main parts:

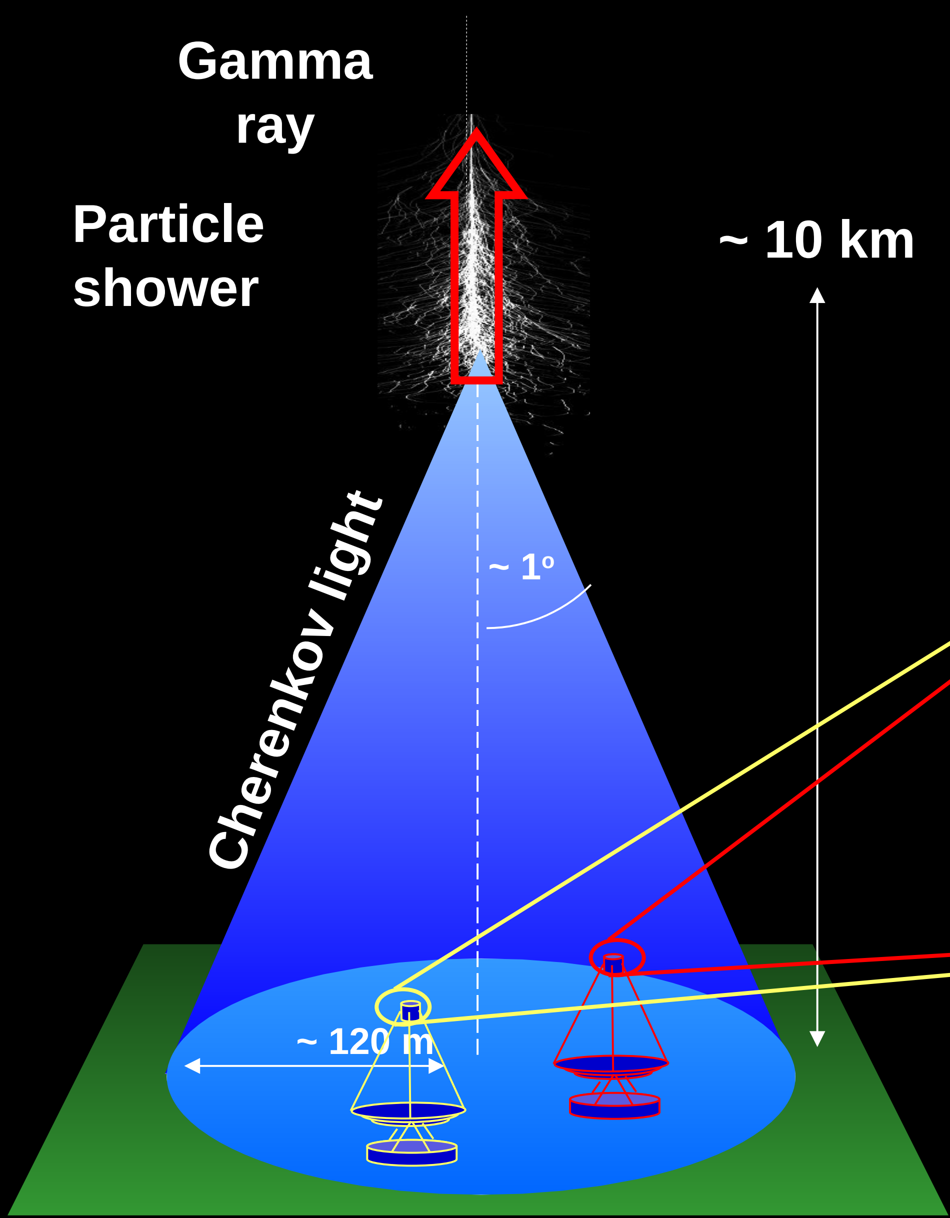
A tracker to determine the trajectory of the $e^{\pm}$

A calorimeter for measuring the energy

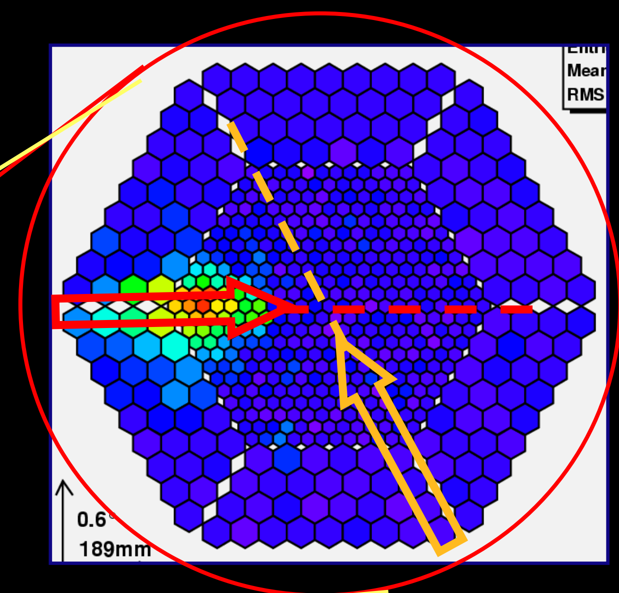
An "active shield" against charged cosmic rays (particle detector set in anti-coincidence)



Imaging Air Cherenkov Telescopes > 50 GeV

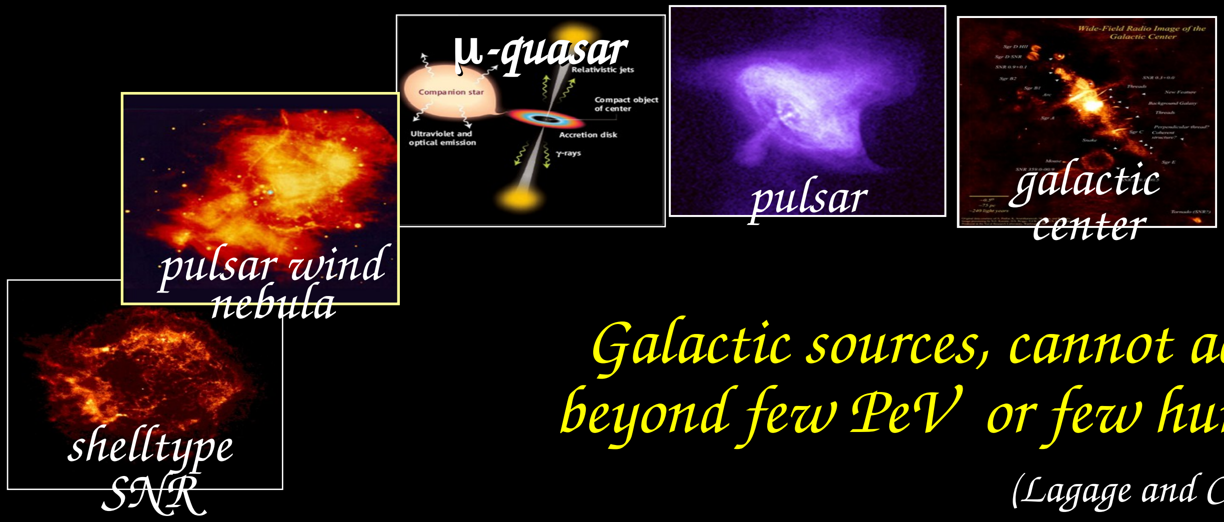


Cherenkov light Image of particle shower in telescope camera



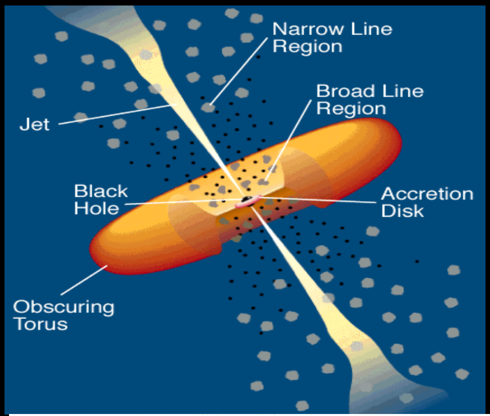
reconstruct:
arrival direction, energy
have to reject hadron background (based on various image shape parameters)

Sources of cosmic rays/high energy gamma rays

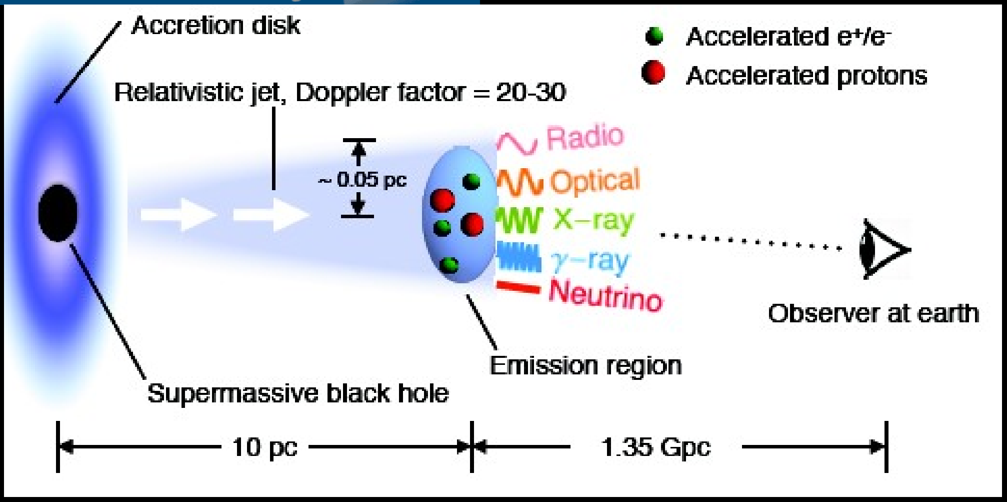


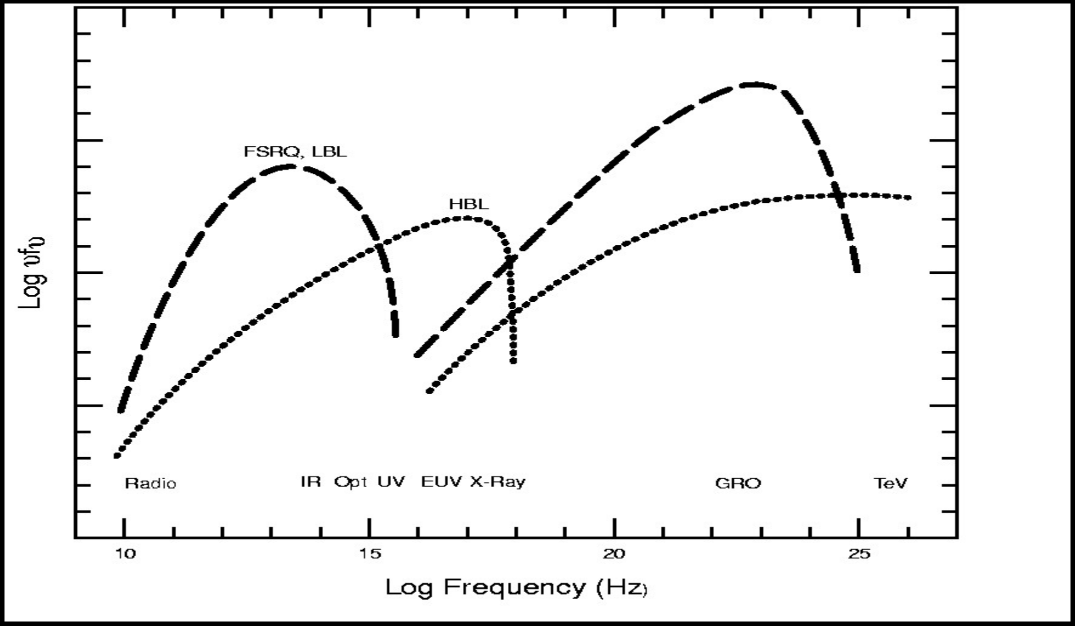
Galactic sources, cannot accelerate beyond few PeV or few hundred TeV

(Lagage and Cesarky (1983) and others)



Blazars : sub class of AGN, highly variable and can accelerate particles to ultra high energies



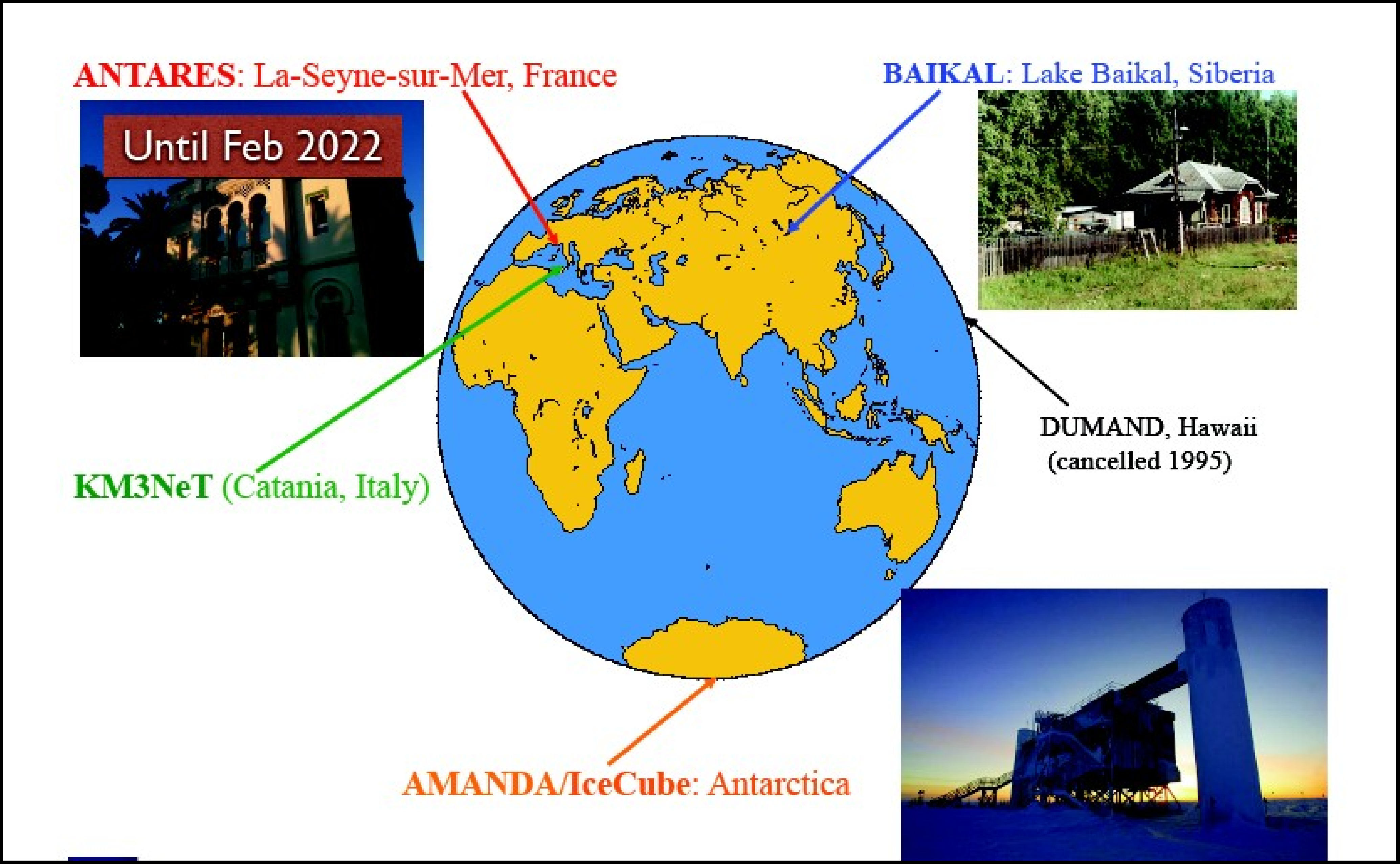


Very High Energy γ-ray Astronomy

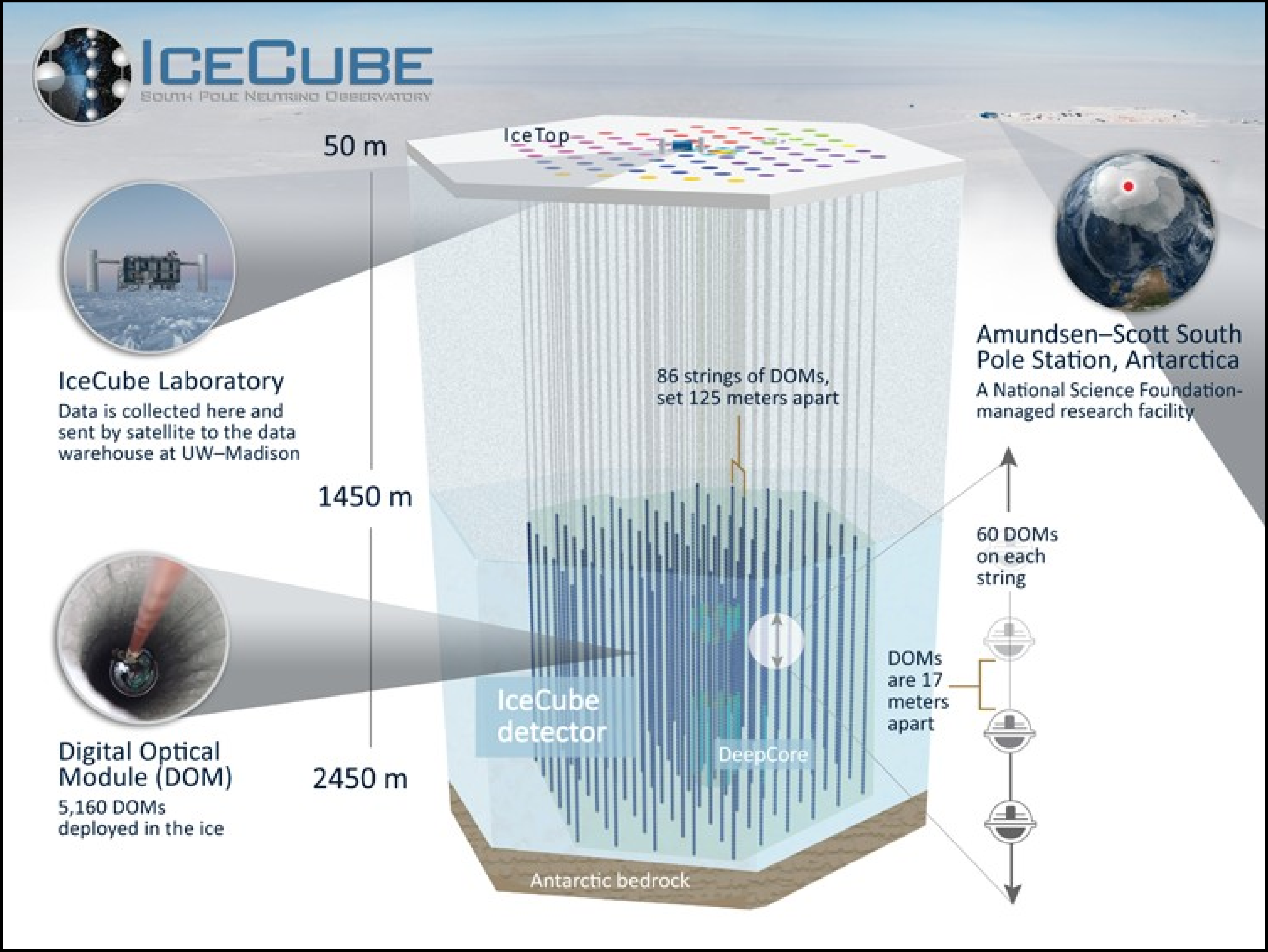
- One of the Youngest astronomic disciplines
- First significant measurement of TeV γ-ray emission from Crab Nebula by Whipple telescope in 1989
- > 50 hrs for 9 sigma detection

- Current generation since 2004
- 1% of Crab nebula flux
- You can now see TeV gamma rays from Crab nebula in < 2 mins
- SINP and several other institutes are members of MAGIC since 2015

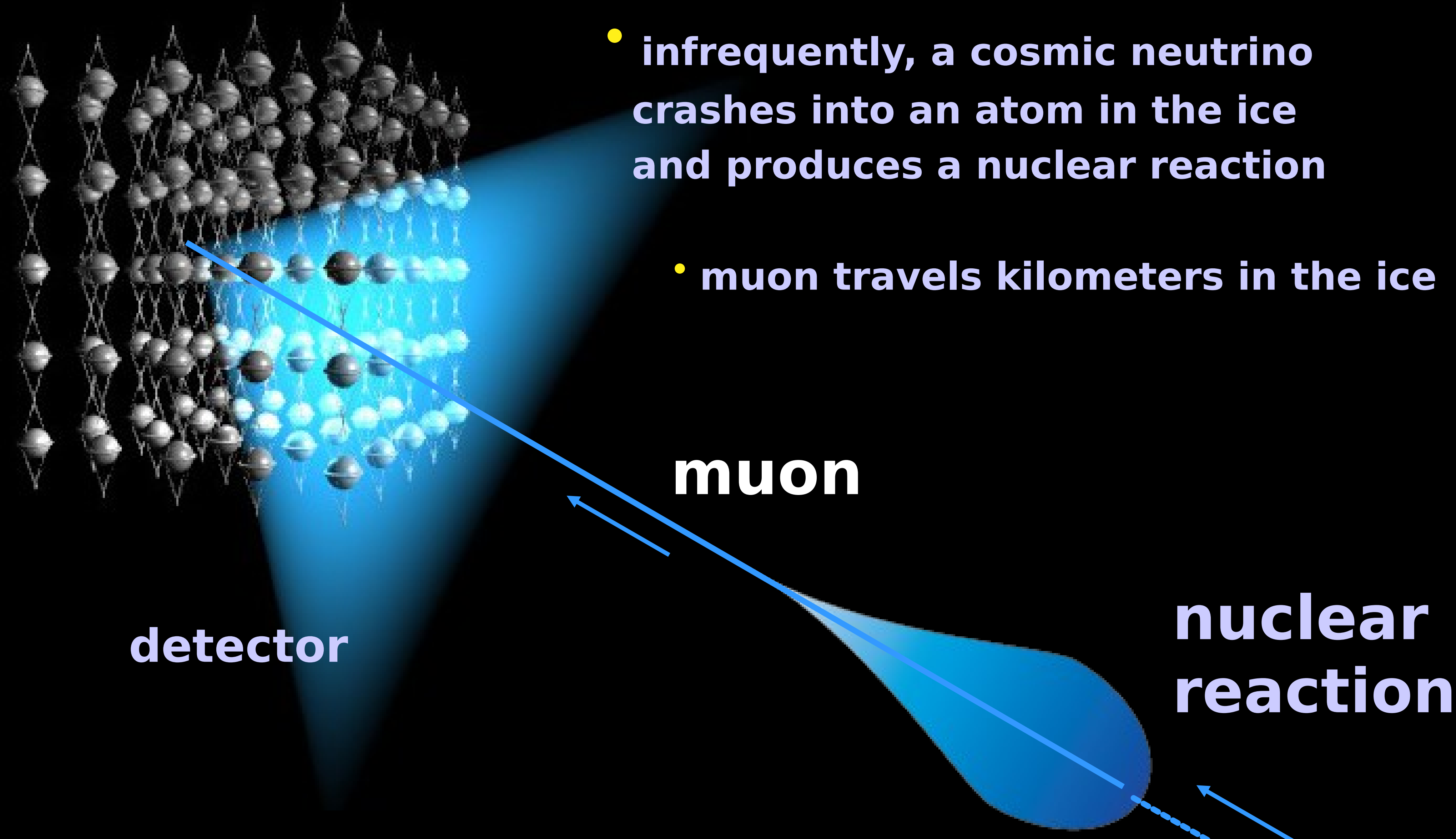
Neutrino Telescopes around the world



IceCube Neutrino Telescope at South Pole



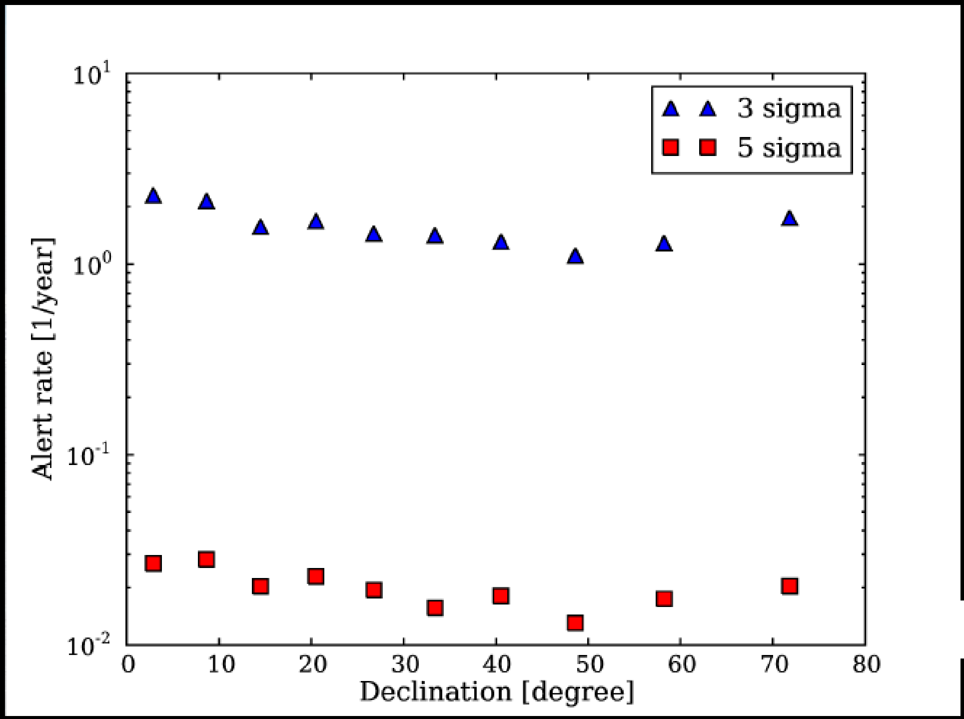
- infrequently, a cosmic neutrino crashes into an atom in the ice and produces a nuclear reaction
  - muon travels kilometers in the ice



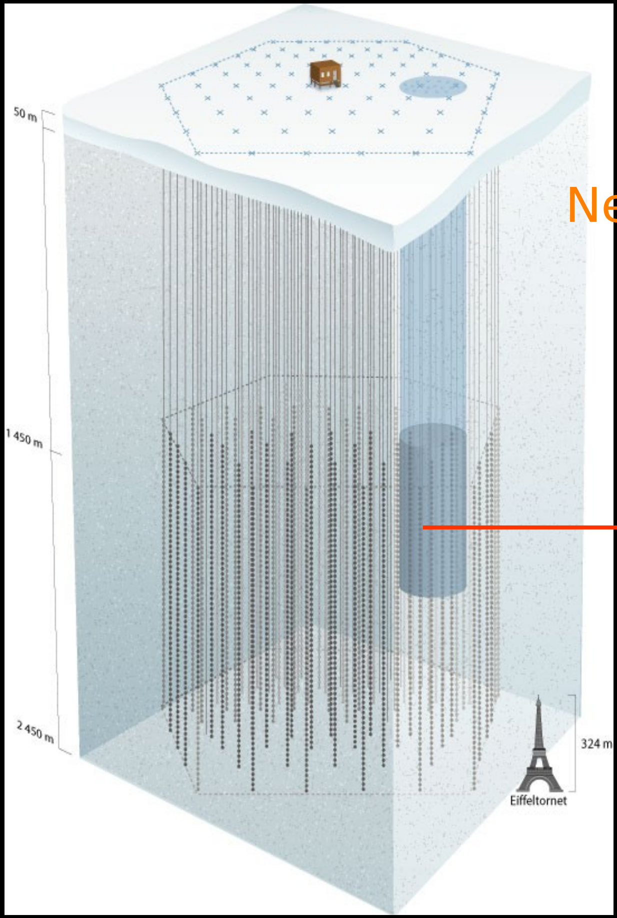
- Cerenkov light produced as the muon moves with relativistic speeds
  - optical sensors capture (and map) the light

Neutrino ToO Program with IceCube/MAGIC
A pioneering effort by MAGIC since 2007

- *NToO program to follow ups of real time alerts and look for correlations : smoking gun for cosmic ray acceleration*
- *Implementation of the program started in 2007*
- *Compute alert rate from background*
- *Alert to MAGIC/IACTs well-tested by 2010*



[M. Ackermann et al. arXiv:0709.2640]



Neutrino Trigger

E.Bernardini (PI), R.Franke, PM
K.Satalecka, W.Bhattacharyya

Real Time Alerts from IceCube

- Since April 2016, the IceCube collaboration began releasing real-time alerts of detections of high-energy (>100 TeV) neutrinos

Search for neutrinos correlated with gamma-ray blazars :

No clear detection

Sporadic claims of TeV " orphaned flares"

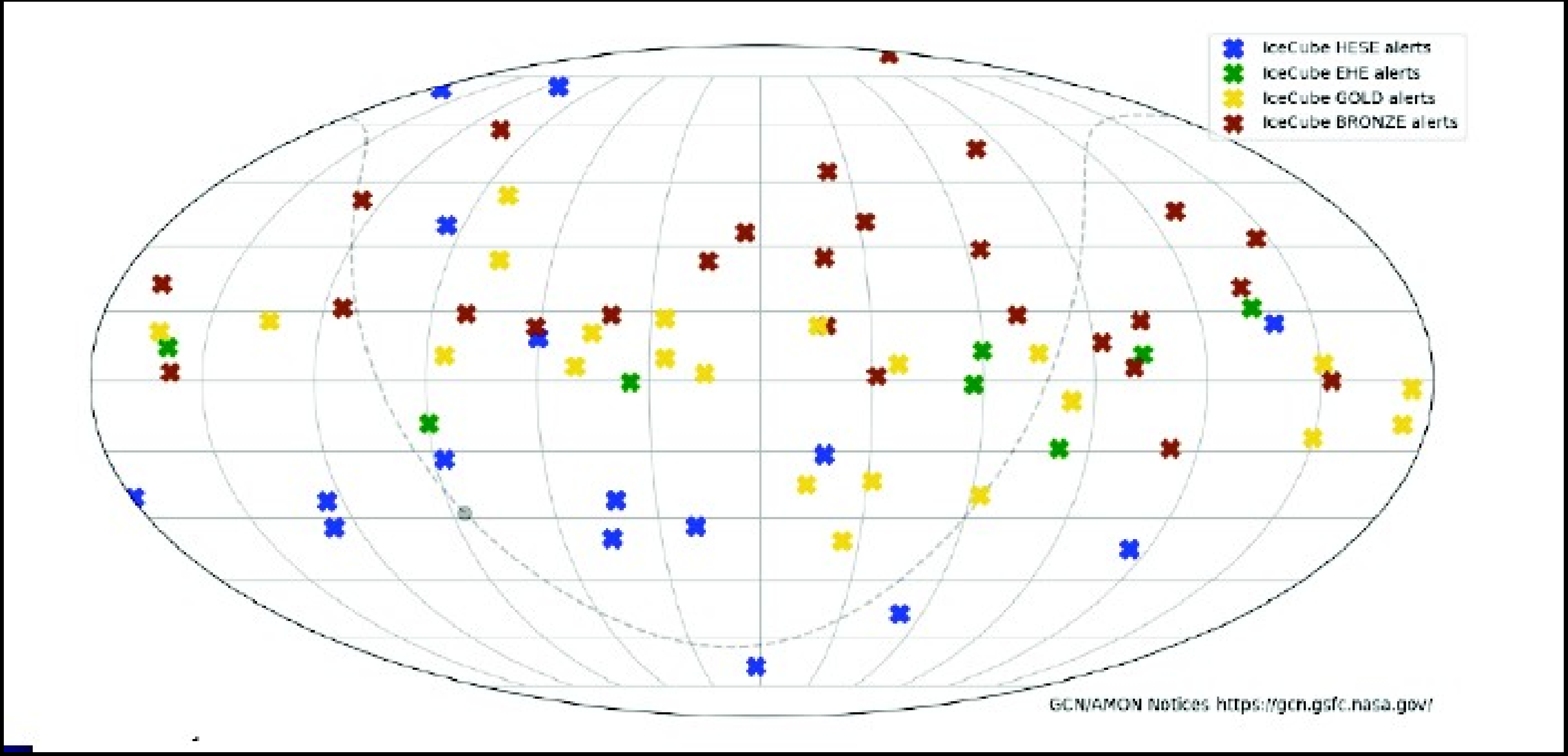
ApJ, 807, 46 2015

Till 2017, no clear detection of a neutrino event with other wavelengths

ID	E_{dep} (TeV)	Time (MJD)	Decl. (deg.)	R.A. (deg.)	Ang. Err. (deg.)	Topology
55	— — —	56798.73029	— — —	— — —	— — —	Coincident
56	$104.2^{+9.7}_{-10.0}$	56817.38958	-50.1	280.5	6.5	Shower
57	$132.1^{+18.1}_{-16.8}$	56830.52665	-42.2	123.0	14.4	Shower
58	$52.6^{+5.2}_{-5.7}$	56859.75882	-32.4	102.1	<1.3	Track
59	$124.6^{+11.6}_{-11.7}$	56922.58530	-3.9	63.3	8.8	Shower
60	$93.0^{+12.9}_{-11.7}$	56931.93110	-37.9	32.7	13.3	Shower
61	$53.8^{+7.2}_{-6.3}$	56970.20736	-16.5	55.6	<1.2	Track
62	$75.8^{+6.7}_{-7.1}$	56987.77219	13.3	187.9	<1.3	Track
63	$97.4^{+9.6}_{-9.6}$	57000.14311	6.5	160.0	<1.2	Track
64	$70.8^{+8.1}_{-7.7}$	57036.74378	-27.3	144.5	10.6	Shower
65	$43.3^{+5.9}_{-5.2}$	57051.66378	-33.5	72.8	17.5	Shower
66	$84.2^{+10.7}_{-9.9}$	57053.12727	38.3	128.7	18.3	Shower
67	$165.7^{+16.5}_{-15.5}$	57079.96532	3.0	335.7	7.0	Shower
68	$59.1^{+8.0}_{-6.0}$	57081.53526	-15.7	294.3	11.7	Shower
69	$18.0^{+2.2}_{-2.0}$	57133.79007	0.3	236.2	15.7	Shower
70	$98.8^{+12.0}_{-11.1}$	57134.39812	-33.5	93.9	12.3	Shower
71	$73.5^{+10.0}_{-10.5}$	57140.47276	-20.8	80.7	<1.2	Track
72	$35.3^{+4.6}_{-4.1}$	57144.29607	28.3	203.2	19.5	Shower
73	$26.2^{+2.6}_{-2.3}$	57154.83679	11.1	278.4	6.9	Shower
74	$71.3^{+9.1}_{-8.1}$	57157.00077	-0.9	341.0	12.7	Shower
75	$164.0^{+20.7}_{-21.4}$	57168.40450	70.5	259.0	13.1	Shower
76	$126.3^{+12.0}_{-12.7}$	57276.56530	-0.4	240.2	<1.2	Track
77	$39.5^{+3.8}_{-3.7}$	57285.01732	2.1	278.4	7.2	Shower
78	$56.7^{+7.0}_{-6.9}$	57363.44233	7.5	0.4	<1.2	Track
79	$158.2^{+20.3}_{-19.8}$	57365.75249	-11.1	24.6	14.6	Shower
80	$85.6^{+11.1}_{-10.6}$	57386.35877	-3.6	146.6	16.1	Shower
81	$151.8^{+13.9}_{-21.6}$	57480.64736	-79.4	45.0	13.5	Shower
82	$159.3^{+15.5}_{-15.3}$	57505.24482	9.4	240.9	<1.2	Track

IceCube Alert Streams

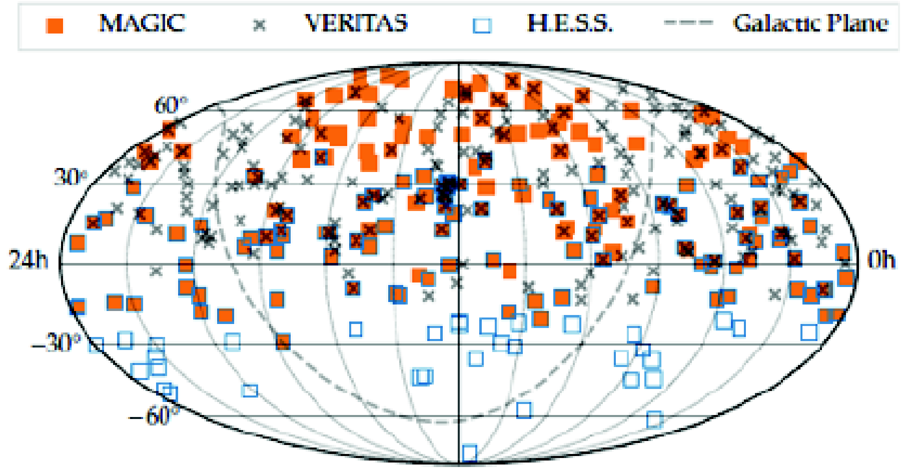
- Upgrade in 2019: Bronze/Gold alert streams (30%/50% astrophysical probability)
- Publicly distributed via AMON/GCN => follow-up observations by all IACTs
- Aim: identify a plausible EM counterpart to the neutrino event



F.Schussler et al, Moriond, VHEPU (2022)

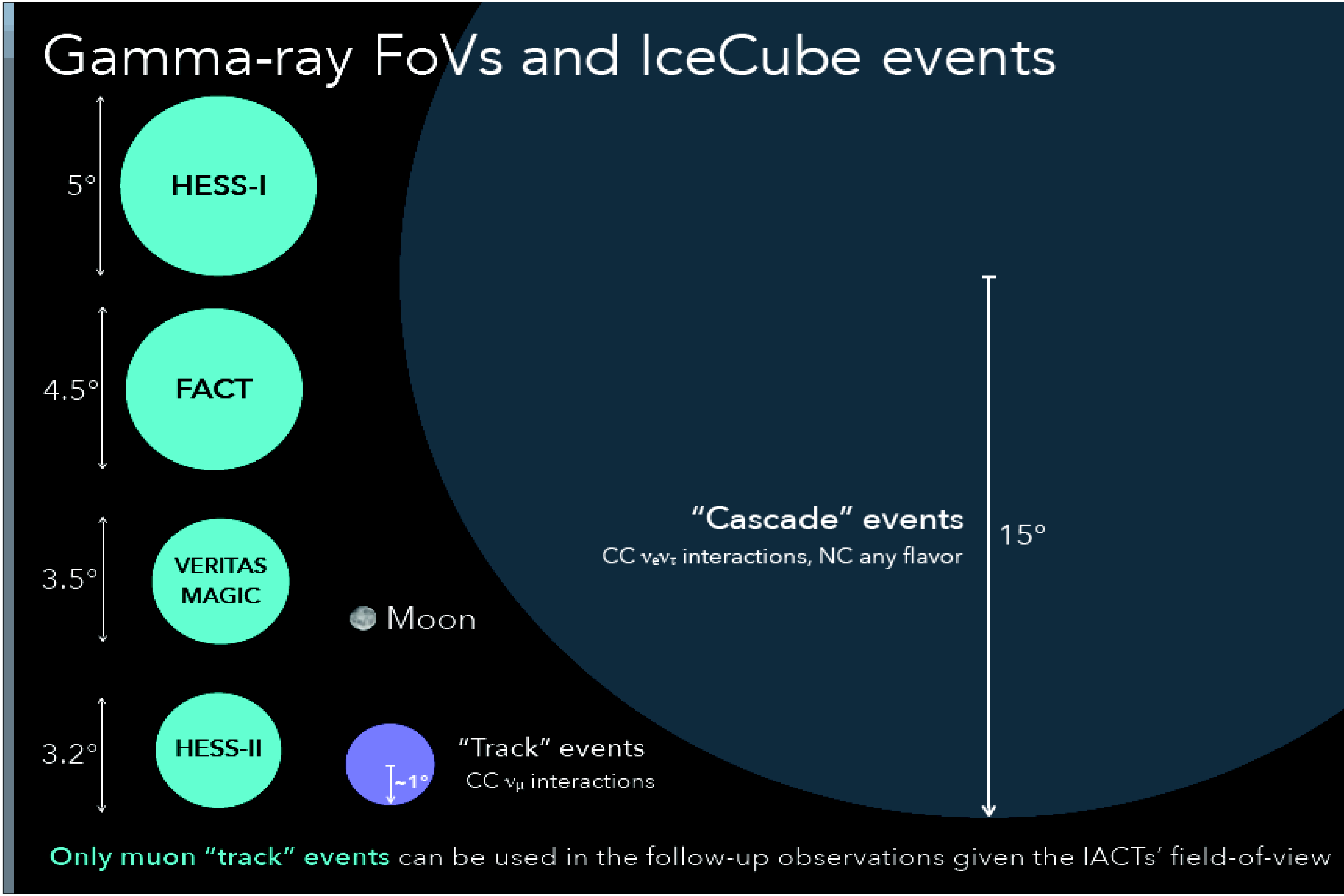
IceCube alert streams (I): Gamma-ray follow-up ("GFU")

- Searches for neutrino multiplets ("flares") in the IC online data stream
  - Time periods ranging from seconds to 180days
- Predefined targets + all-sky search (in preparation)
- Alerts distributed privately under MoU
  - Northern Sky: MAGIC & VERITAS since 2012
  - Southern Sky: H.E.S.S. since 2019
- Source selection based on 3LAC/3FHL/TeVCat; variability; distance; visibility
- Aim: determine the state of the source (quiescence vs flaring state; spectral changes)



Since October 2024, Icecube will discontinue private alerts and make all of them public
Discussion ongoing on preparing new source list (E. Bernardini, S. Mangano, C.Bosco Mengelo, PM and others)

Which events can be ToO for EM telescopes ?



The Story of EHE IC-170922A and a Blazar

September 22nd

```
////////////////////////////////////////
TITLE:         GCN/AMON NOTICE
NOTICE_DATE:  Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:  AMON ICECUBE EHE
[…]
SRC_RA:        77.2853d {+05h 09m 08s}
SRC_DEC:       +5.7517d {+05d 45' 06"}
[…]
SRC_ERROR:     14.99 [arcmin radius,
               stat+sys, 50%
containment]
[…]
DISCOVERY_TIME: ...{20:54:30.43} UT
N_EVENTS:        1 [number of
neutrinos]
[…]
ENERGY :         1.1998e+02 [TeV]
SIGNALNESS:      5.6507e-01 [dn]
CHARGE:          5784.9552 [pe]
[…]
////////////////////////////////////////
```

→ Better energy and direction reconstruction followed

September 27th

Fermi-LAT Collaboration followed-up the EHE-170922A error circle

They found that TXS 0506+056 was showing brightening in the GeV band

Hard spectrum in HE band → ask for triggering VHE observations

Flare detected by *Fermi*-LAT in HE γ rays

Since September 24th

ATEL

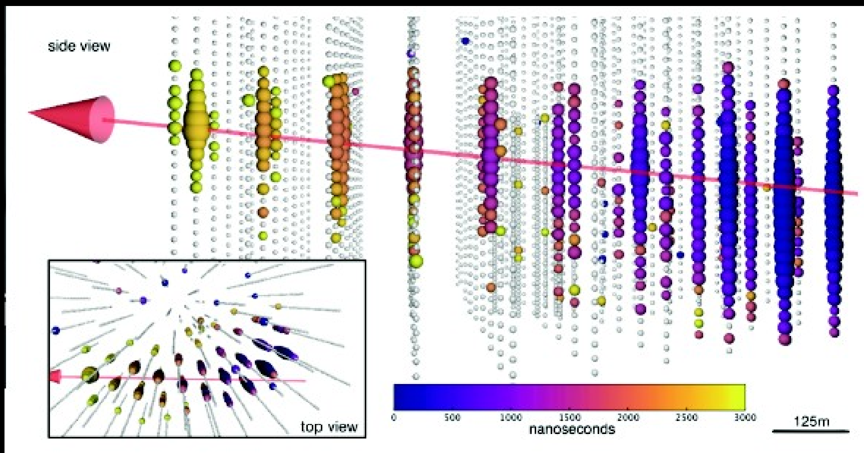
Day	Preliminary cumulative significance (LE)	Weather
24/09/2017		(yellow)
28/09/2017	1.89	(green)
29/09/2017	2.78	(green)
30/09/2017	2.37	(green)
1/10/2017	3.12	(green)
2/10/2017	3.88	(green)
3/10/2017	4.92	(green)
4/10/2017	6.22	(green)
Moon-break		

(green) : all data used
(yellow) : weather cuts used

Flare detected by MAGIC in VHE γ rays

Several other observatories were also alerted

The Story of EHE IC-170922A and a Blazar



Flurry of ATELs in next days

ICECUBE

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:*
on 28 Sep 2017; 11:57 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

...anckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson ... Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)

...irmation of gamma-ray activity from the ...ceCube-170922A error region

...relli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.

...tection of VHE gamma rays by MAGIC from ... consistent with the recent EHE neutrino event IceCube-170922A

...0817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT

...wift XRT and NuSTAR Observations of TXS 0506+056

...B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans ..., C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. ... (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)

...GSC observations of IceCube-170922A and TXS 0506+056

...; *H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara, ... Shimomukai (JAXA), T. Mihara, M. Sugizaki, S. Nakahira, W. Iwakiri, ...tsu, F. Yatabe, T. Takao, M. Matsuoka (RIKEN), N. Kawai, S. Sugita, T. Tachibana, S. Harita, K. Morita (Tokyo Tech), A. Yoshida, T. Sakamoto, Y. Kawakubo, Y. Kitaoka, T. Hashimoto (AGU), H. Tsunemi, T. Yoneyama ..., M. Nakajima, T. Kawase, A. Sakamaki (Nihon U.), Y. Ueda, T. Hori, A.*

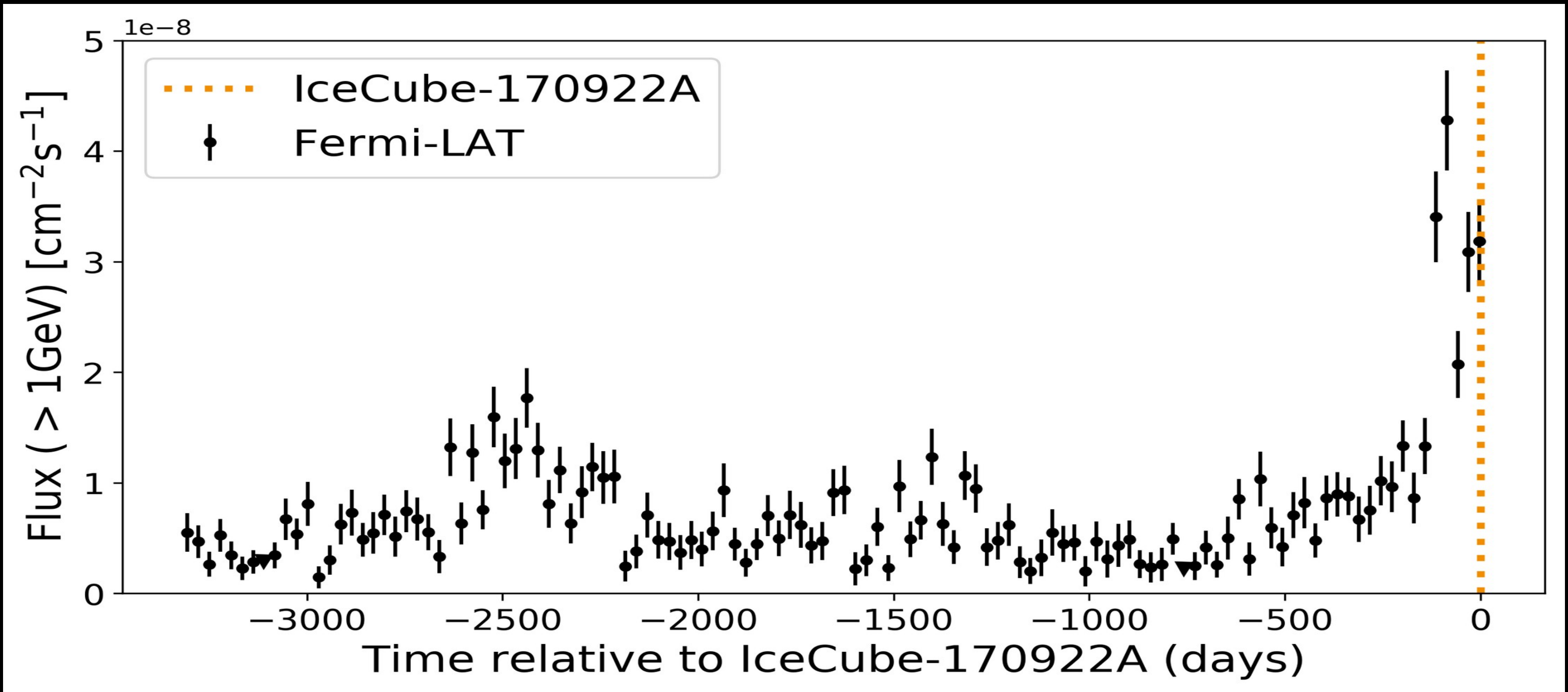
...A Radio Observations of the blazar TXS 0506+056 ...sociated with the IceCube-170922A neutrino event

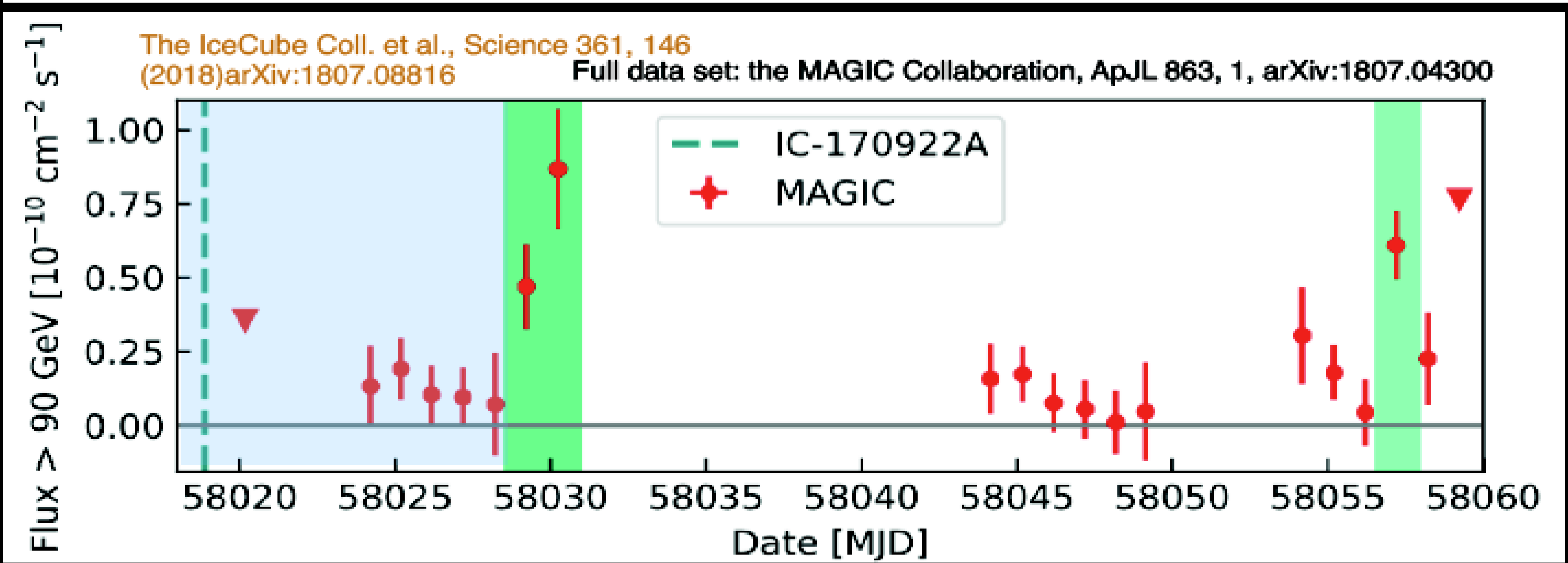
...10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C. A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT

```
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]
```

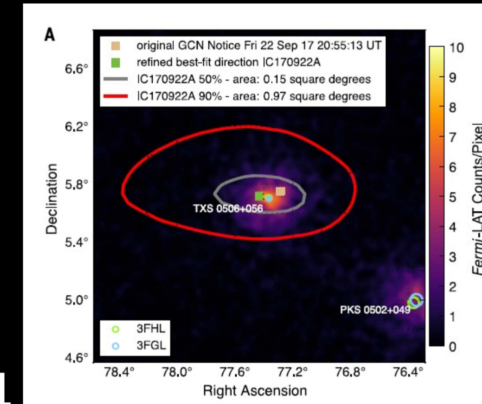
Y. Tanaka pointed out that a KANATA object consistent the neutrino was a Fermi-LAT blazars

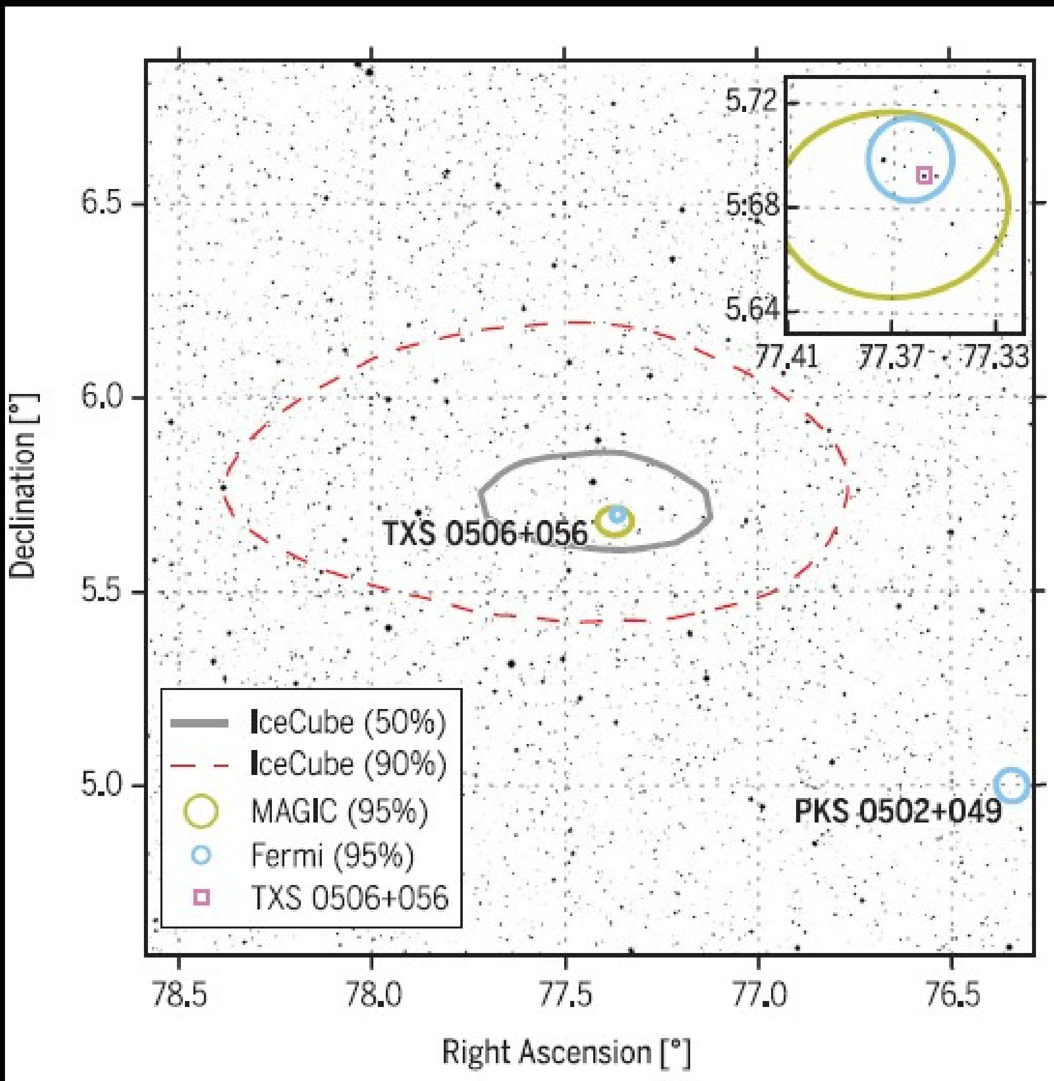
Fermi-LAT, MAGIC and others find a flaring blazar





IceCube, Fermi-LAT and MAGIC events came from the direction of a source TXS0506+056, a blazar





Redshift ~ 0.34

Distance ~ 1.75 Gpc

(5.7 billion light-years)

Chance coincidence prob. estimated through a Likelihood ratio test

$$\mathcal{L} = \prod_{i}^{N} \left(\frac{n_s}{N} \mathcal{S} + (1 - \frac{n_s}{N}) \mathcal{B} \right)$$

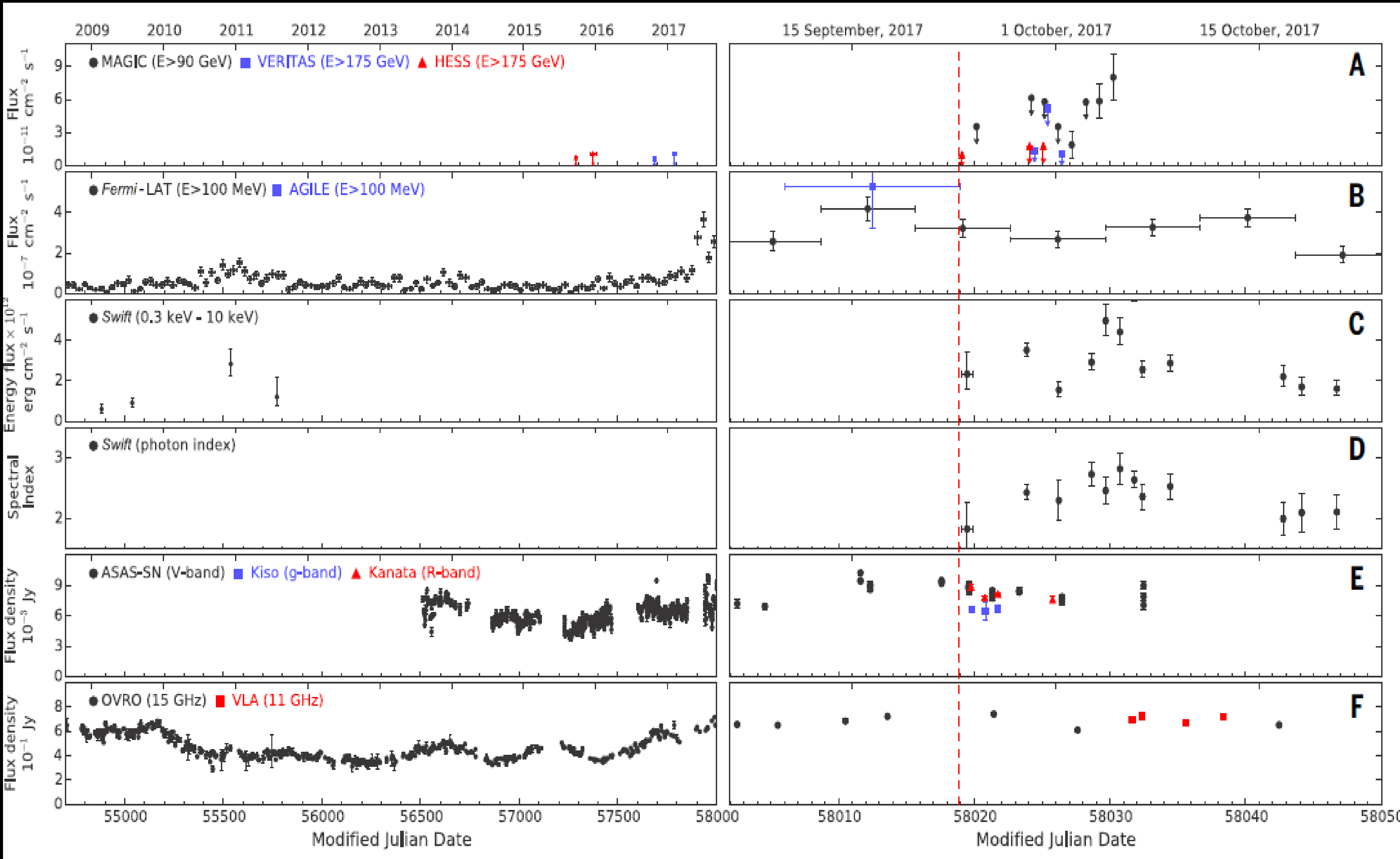
$$\mathcal{S}(\vec{x}, t) = \sum_{s} \frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)} \, w_s(t) \, w_{\text{acc}}(\theta_s)$$

Fluctuation disfavoured at 3 sigma

Energy of the neutrino ~ 290 TeV , 90% CL lower limit ~ 183 TeV

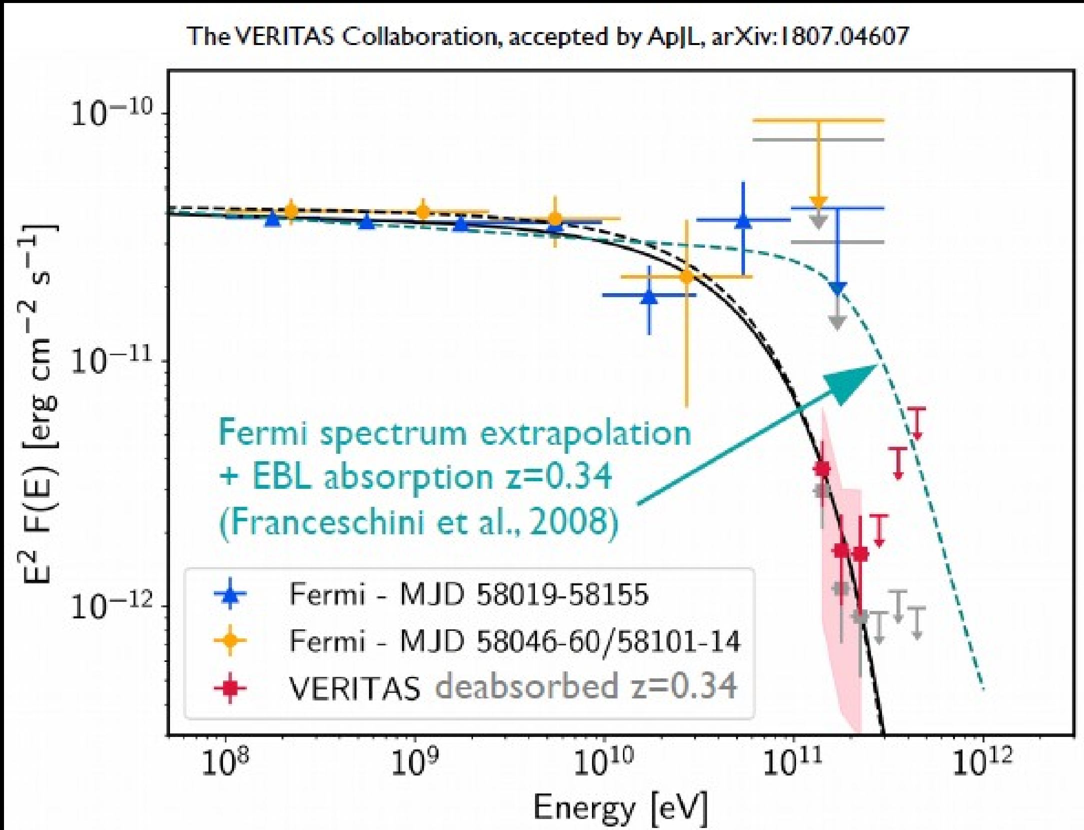
Upper limit of 4.5 PeV , depends on the assumed spectrum

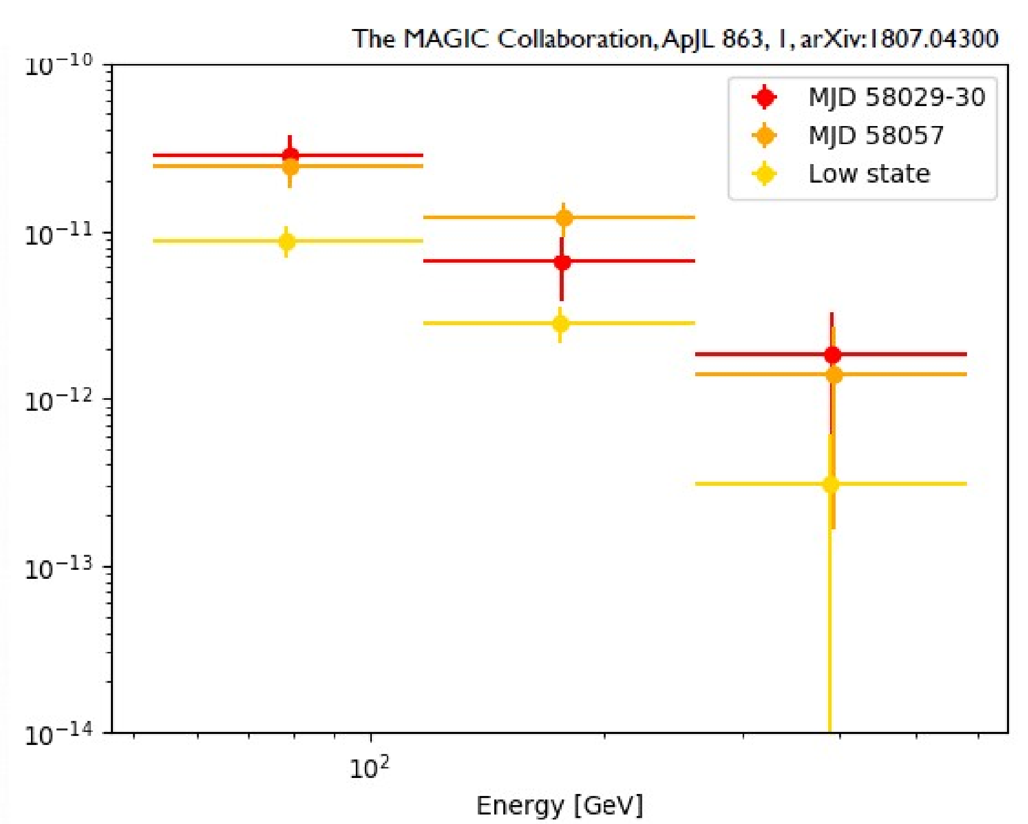
Long Term Multiwavelength Light curve

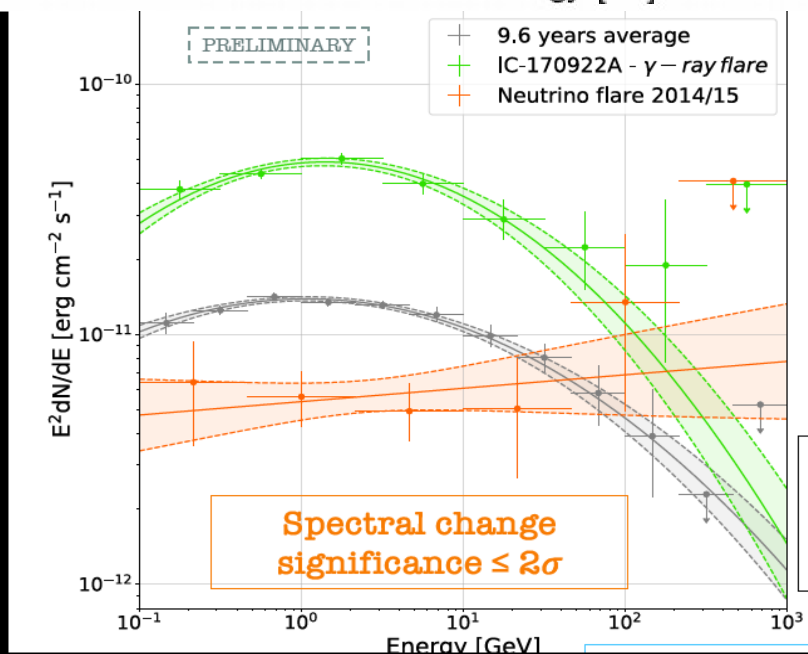


The IceCube Collaboration *et al.*, *Science* **361**, 146 (2018)

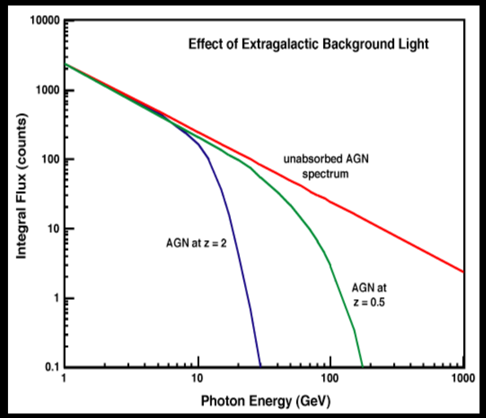
Spectral Shapes in HE and VHE







S.Buson
S.Gariappa
TeVPA 2018

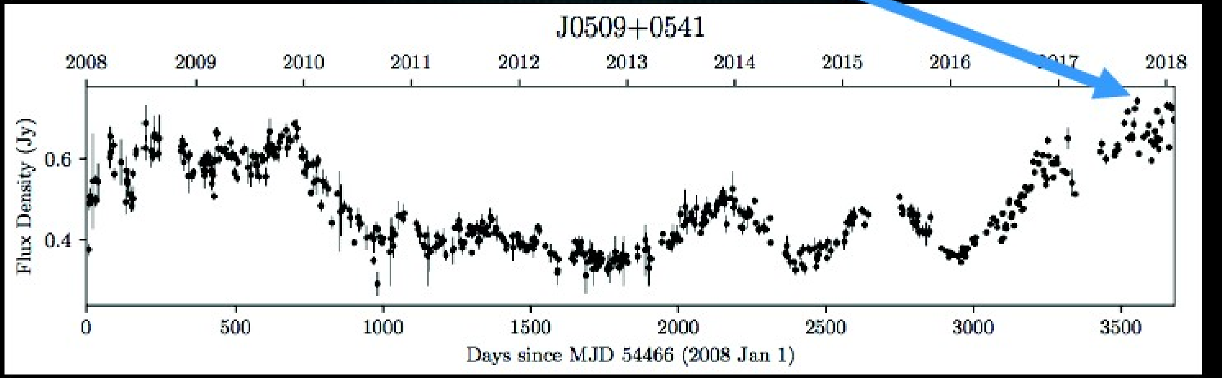


No clear spectral variability
MAGIC + VERITAS : simple PL
Spectral index very soft, typical of a blazar at high redshift
Strong curvature at > 50 GeV

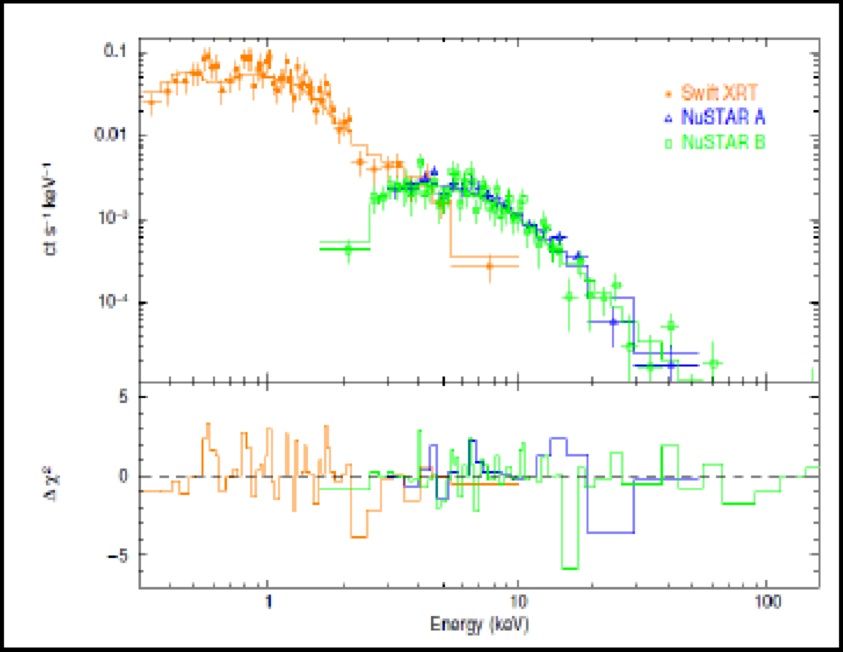
Observations in Radio, X-rays, optical

The Karl G. Jansky Very Large Array (VLA) (*37*) observed TXS 0506+056 starting 2 weeks after the alert in several radio bands from 2 to 12 GHz (*38*), detecting significant radio flux variability

TXS 0506+056 was detected significantly in all bands/epochs.



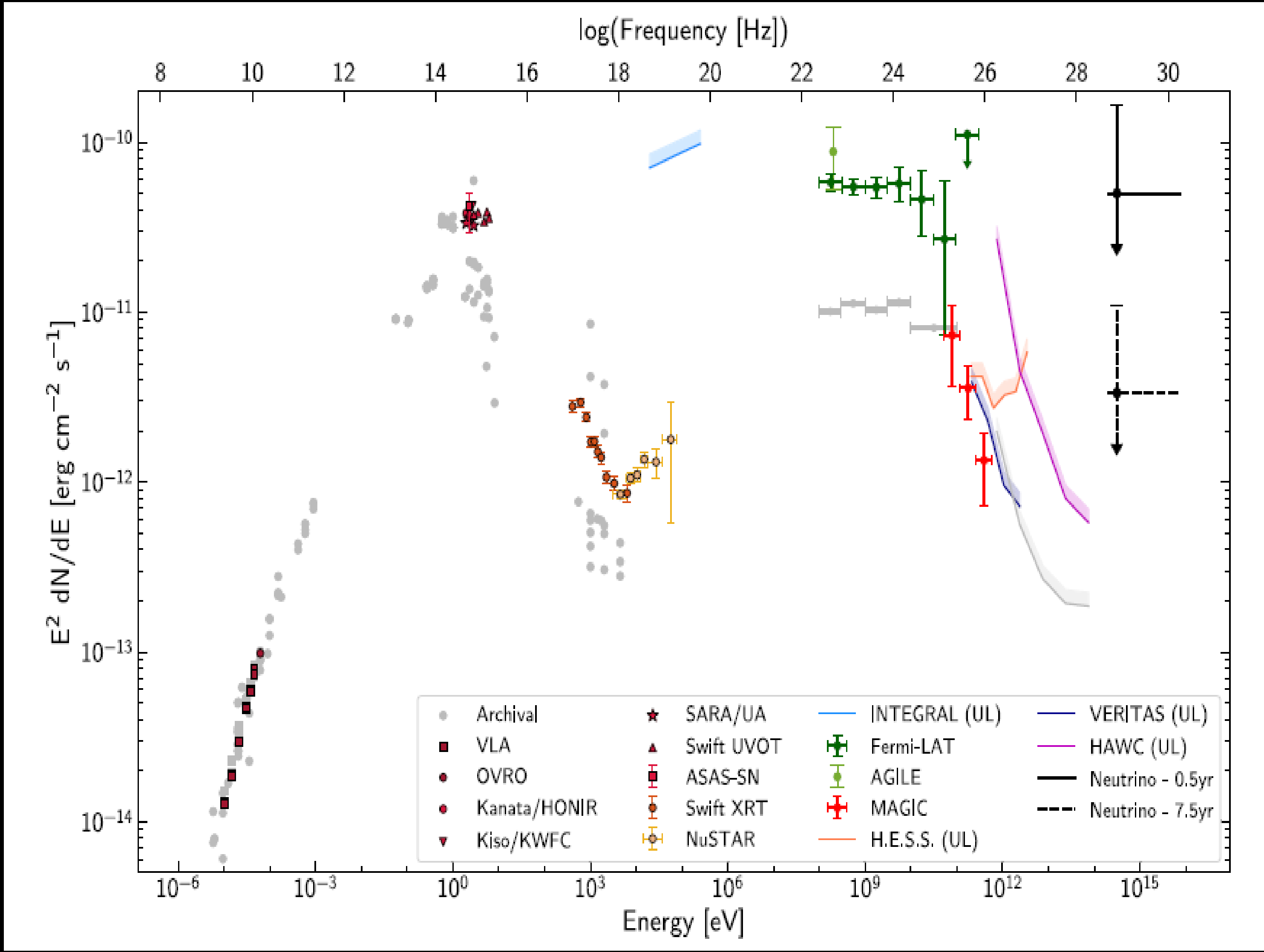
OVRO 40m Telescope (15 GHz)



Marginal spectral variations In X-rays seen, When compared with historical flux, an enhancement of flux also reported

Redshift measurement using Gran Telescopio Canarias, Paiano et al, ApJL (2018)

IceCube, Fermi-LAT and MAGIC events came from the direction of a distant blazar TXS0506+056

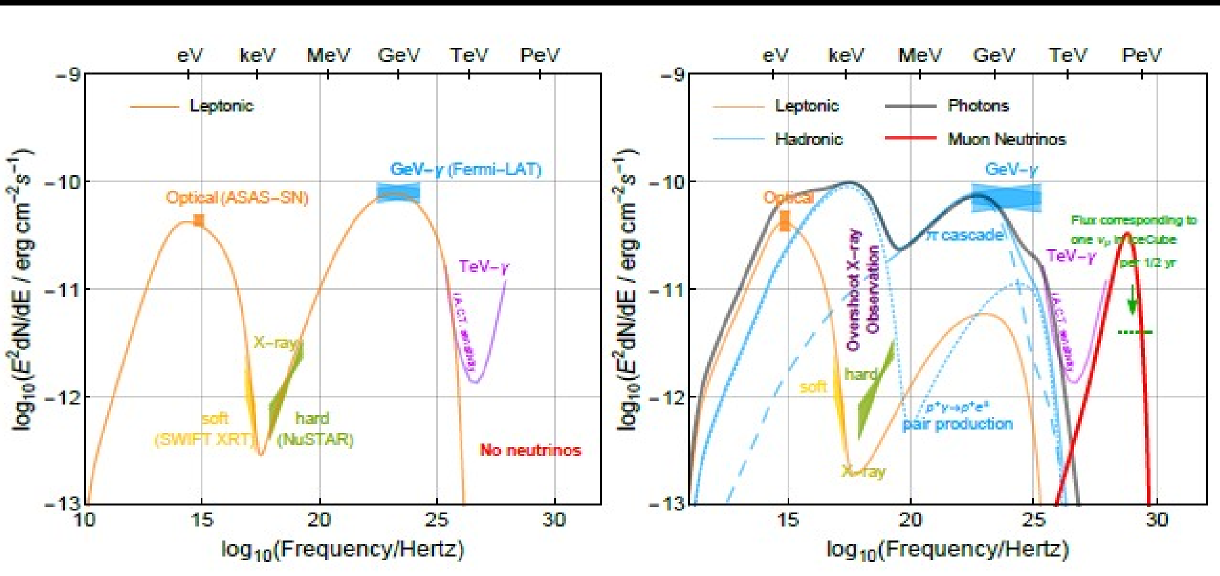


Photohadronic models
Gao et al. (1807.04275)
Righi, Tavecchio & Pacciani (1807.04299)
Ansoldi et al. for MAGIC (1807.04300)
Cerruti et al. (1807.04335)
Keivani, KM et al. for AMON (1807.04537)
KM, Oikonomou & Petropoulou (1807.04748)

Hadronuclear models
KM, Oikonomou & Petropoulou (1807.04748)
Liu et al. (1807.05113)
He et al. (1808.04330)
Sahakyan (1808.05651)

Explosion of theoretical papers in the archive in the next days

Modelling the Spectral Energy Distributions

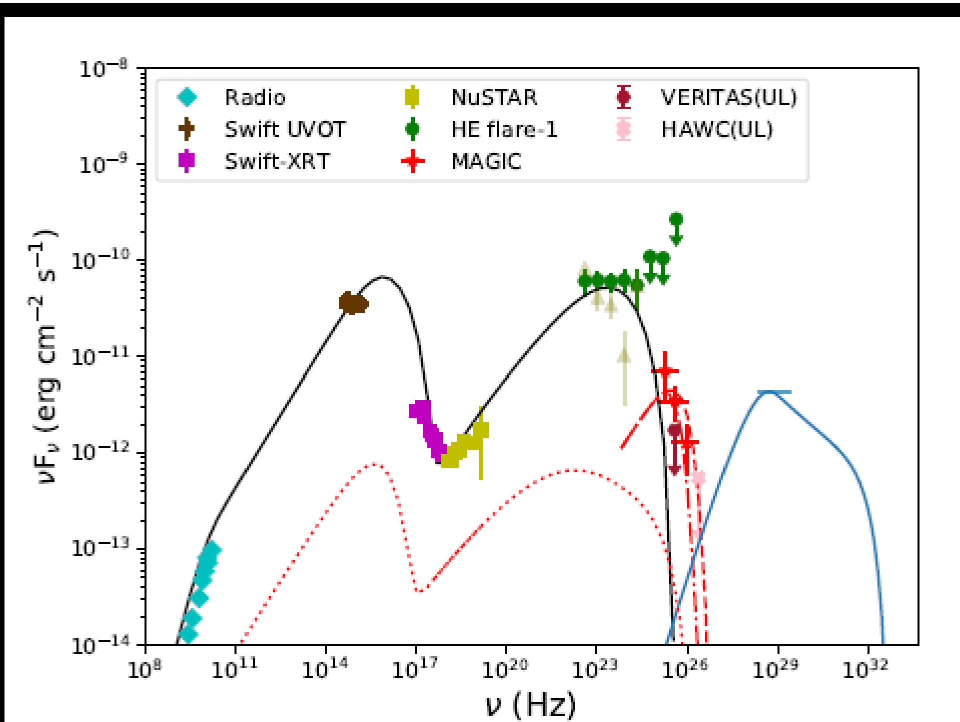


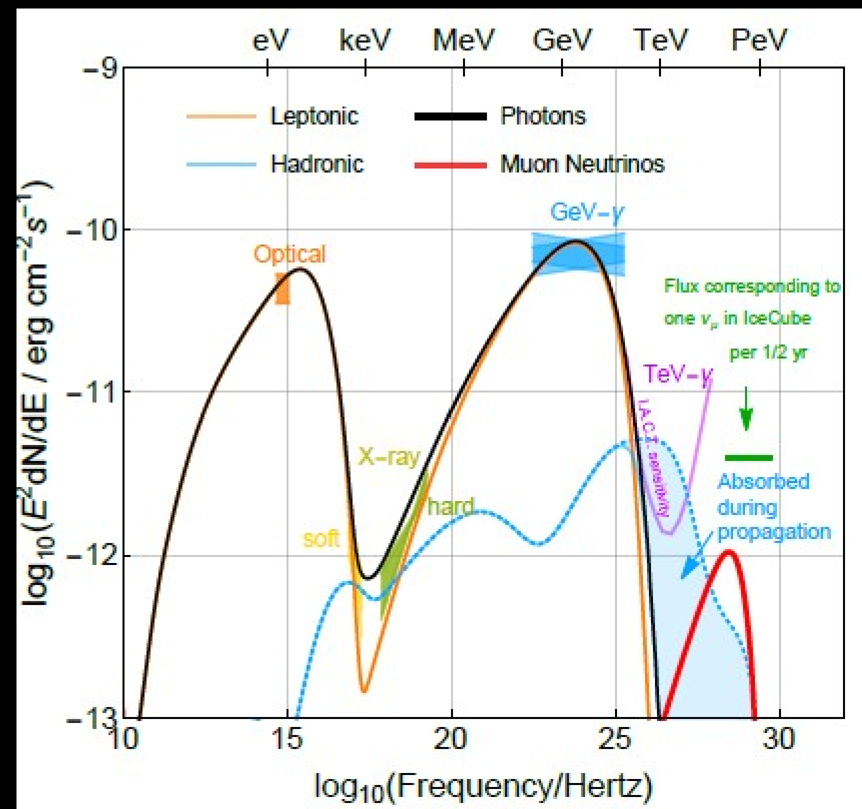
A pure leptonic model seems to fit all data ==> no neutrinos

Hadronic contribution tuned not to overproduce X-rays

Proton synchrotron model

Jet power in excess of L(Eddington)

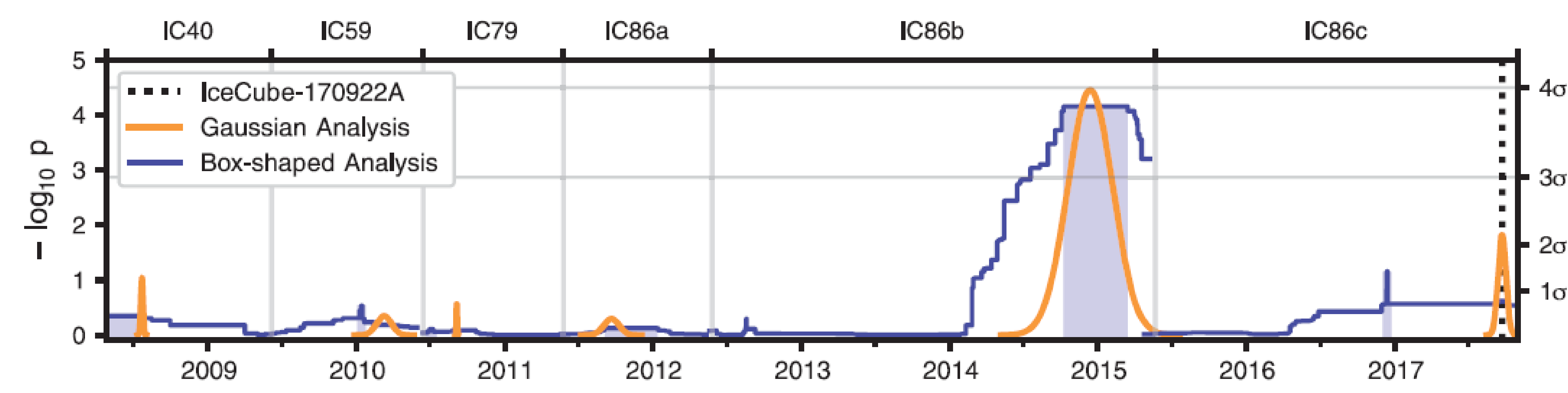




S.Gao et al, Nature Astronomy (2019), MAGIC Collaboration , ApJL (2018)
Sunanda, R.Moharana and PM (2022)

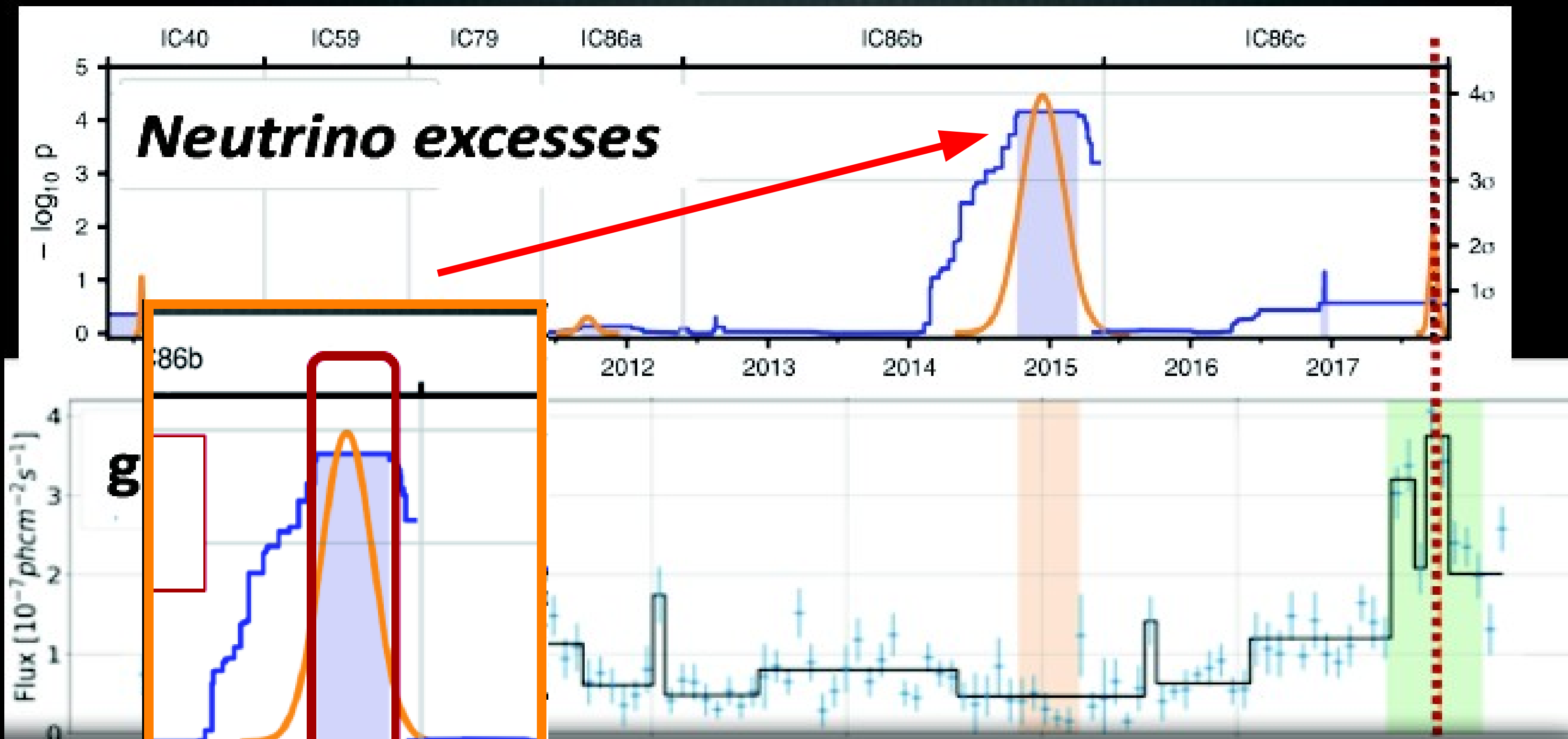
Something more interesting from IceCube data Archives

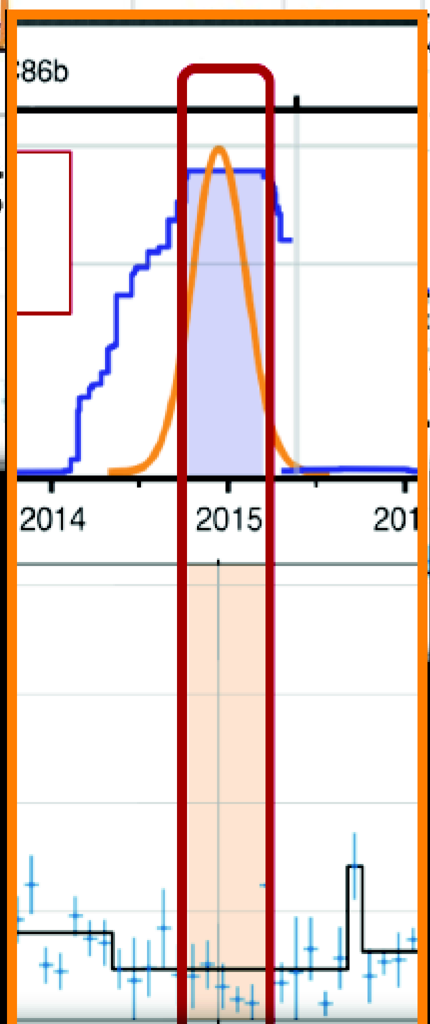
A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5**σ** evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.



IceCube Collaboration, *Science* **361**, 147–151 (2018)

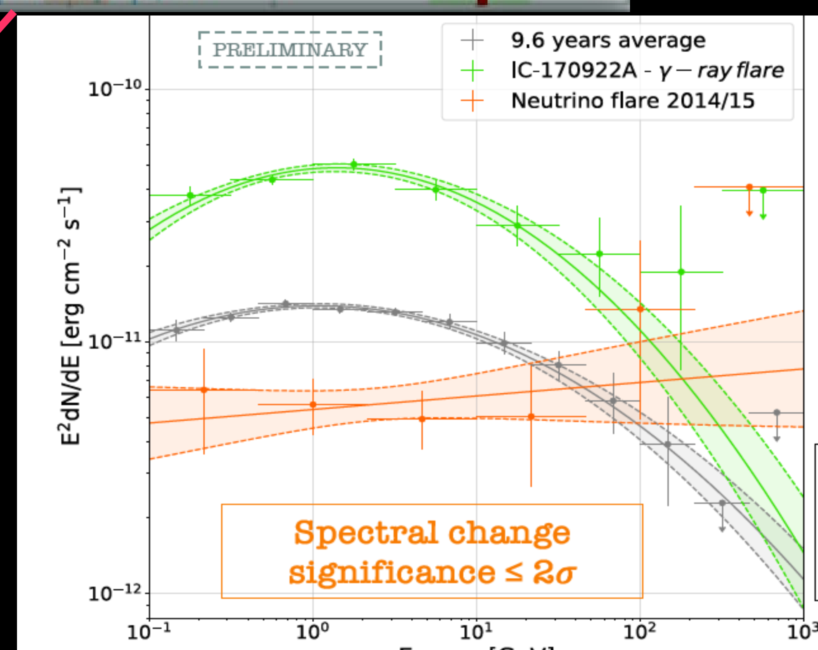
Neutrino and Gamma-ray Light curve/Spectrum





One gamma bright and one gamma dim

No significant change in spectral slope



S.Buson
S.Gariappa
TeVPA 2018

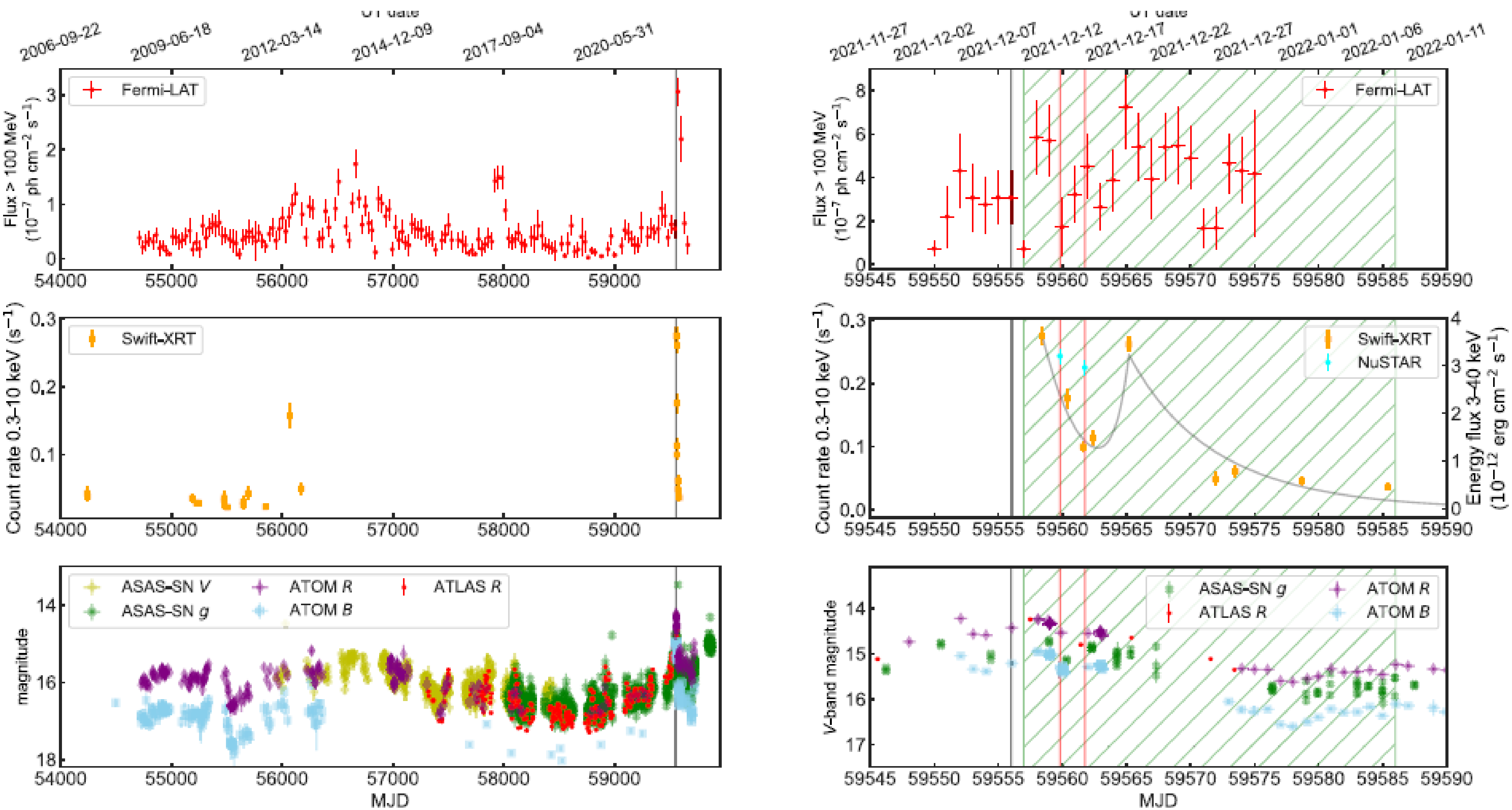
Some more Neutrino-photon blazar coincidence story

- IceCube-190730A, another very-high-energy neutrino (GCN Circular #25225, ATel #12967), Coincident with blazar PKS 1502+106 (4FGL J1504.4+1029 and 3FHL): 0.31°offset, within 50% CL region of neutrino, FSRQ at z=1.84
- OVRO 40m telescope: a 15 GHz flare started 5 years ago and now reaching all-time high 4 Jy (similar to TXS 0506+056)
- Models predict a substantial neutrino flux that is correlated with the gamma-ray and soft X-ray fluxes (Rodriguez et al, ApJ 912(2021))
- There were a few others in the last 2-3 years, however not very significant detections in other wavelengths.
- BZB J0955+3551, observed coincident with IC-200107A, X-ray flare in NuStar and NICER, however, probably not connected to neutrino emission (Paliya et al, ApJ 902 (2020))

PKS 0735 + 178 (z = 0.45) associated with IC-211208A ?

Source lies about 2.2 deg from the IceCube best fit position

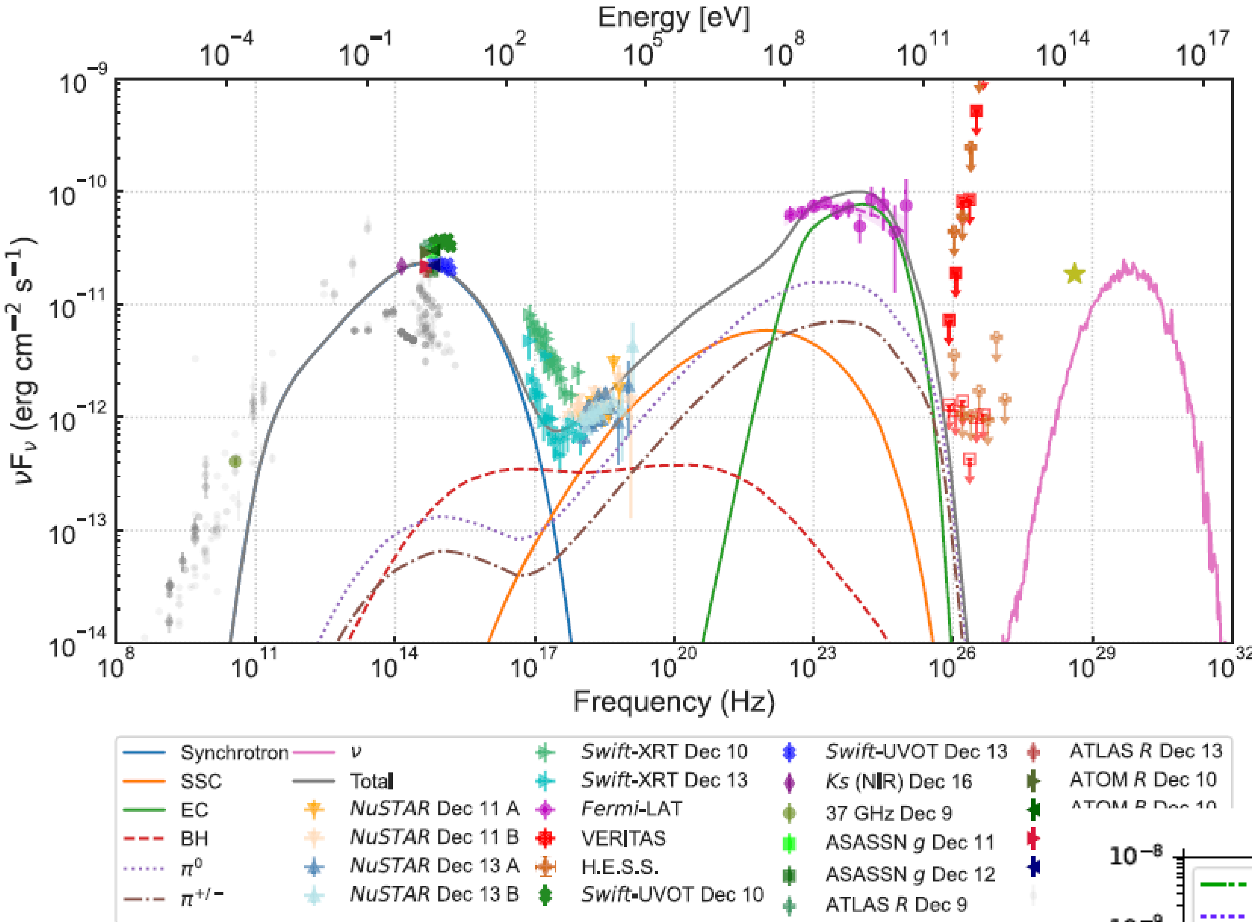
Baksan, KM3Net also reported detection of high energy neutrinos



(a) (b)

Energy of the neutrino event ~ 170 TeV, Elevated state in optical to gamma rays, No detection in VHE gamma rays by VERITAS and H.E.S.S.

Broad Band SED modelling

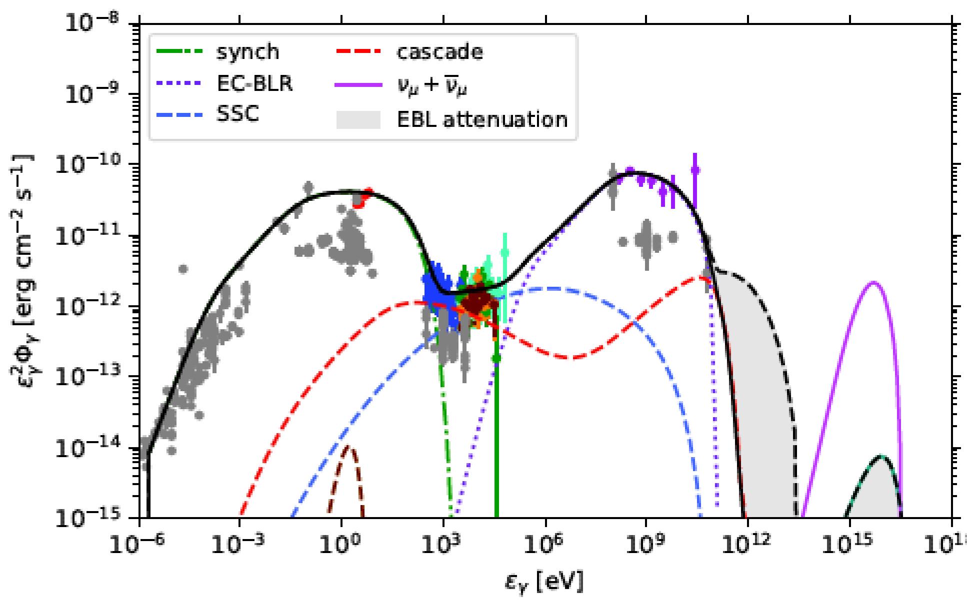


VERITAS Collaboration,
Acharyya et al, ApJ 953 (2023)

SSC+EC provides strong curvature ?
Intrinsic cut-off at > 100 GeV ?
Is the redshift higher ?

R.Prince, S.Das, N.Gupta, PM, C. Bozena
Published in MNRAS (2024)

Neutrino energy of 0.1 PeV
Constraints from cascade emission in X-rays



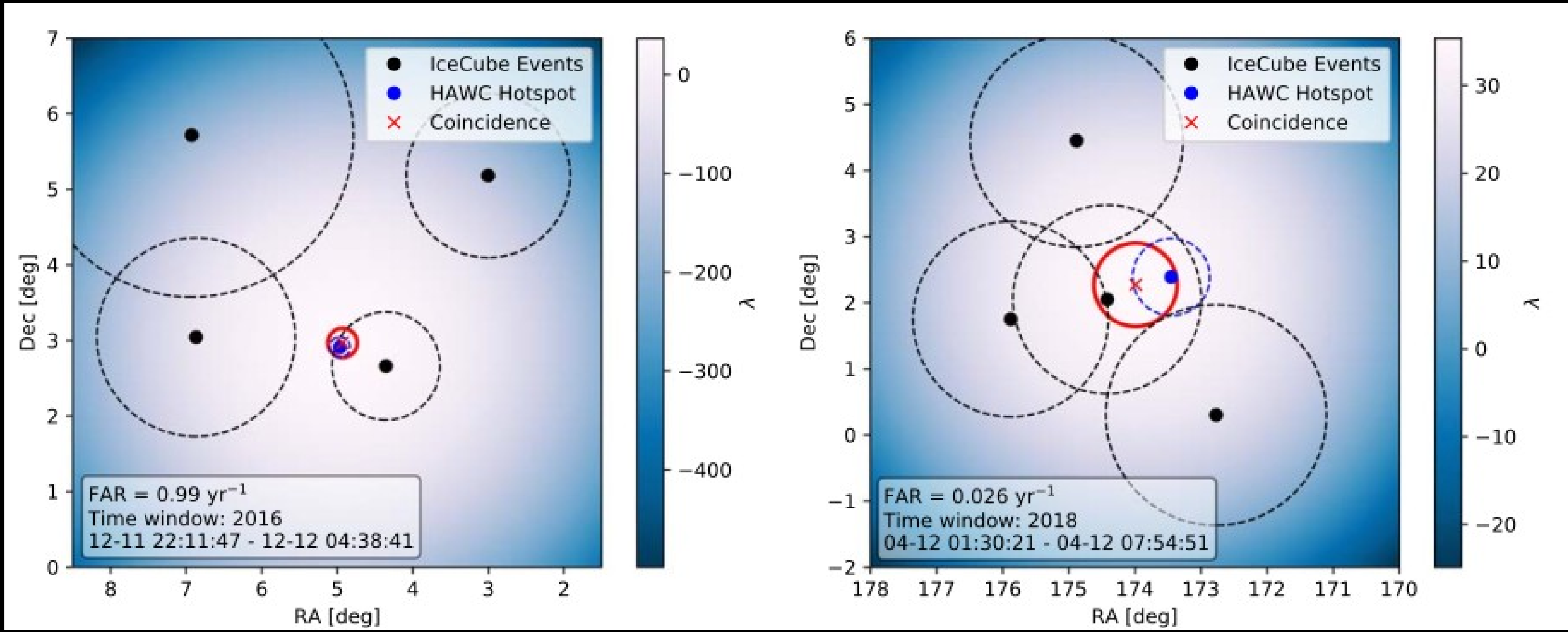
Search for coincident sub-threshold events in HAWC and IceCube

Temporal selection requiring IceCube events
to come within the transit time of HAWC hotspot.

A statistic to rank the coincident events
(Fischer's method)

Overlap of spatial uncertainties estimated
through a Maxm Likelihood method

Two coincident events found

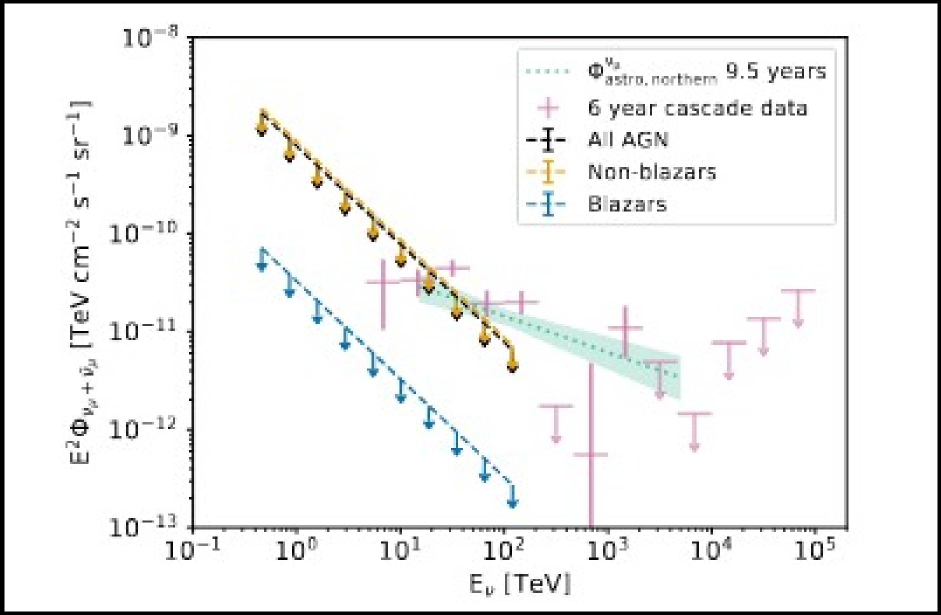


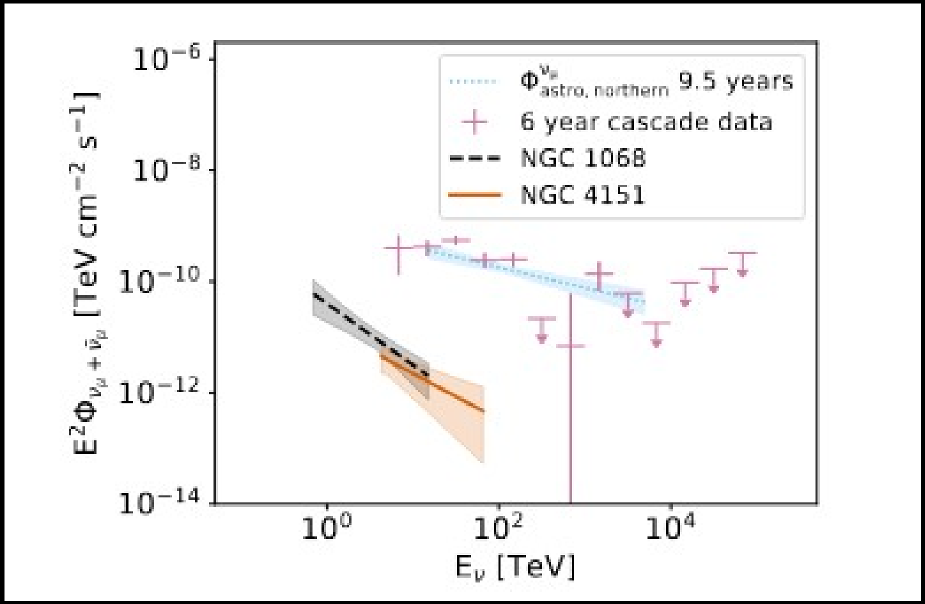
HAWC and IceCube Collaboration, THE ASTROPHYSICAL JOURNAL, 906:63 (10pp), 2021 January 1

Search for neutrinos in hard X-ray AGNs

Environments in which neutrinos can escape
But gamma rays interact with low energy photons
to cascade to lower energies.

BASS catalog, stacked search and individual source
search





NGC1068 and NGC 4151 are 2 significant sources. (however hidden in gamma rays)
Stacking analysis of non-blazar AGN show no significant emission

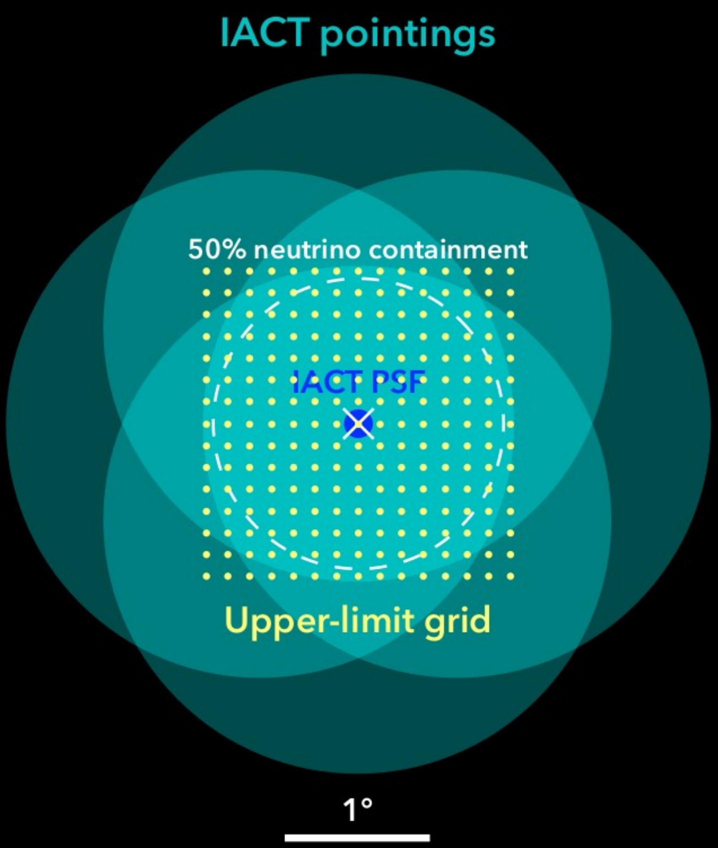
http://arxiv.org/pdf/2406.06684

Follow Up Observations in the multimessenger context

Since a few years, our group has conducted electromagnetic follow-ups of interesting high energy neutrino events :

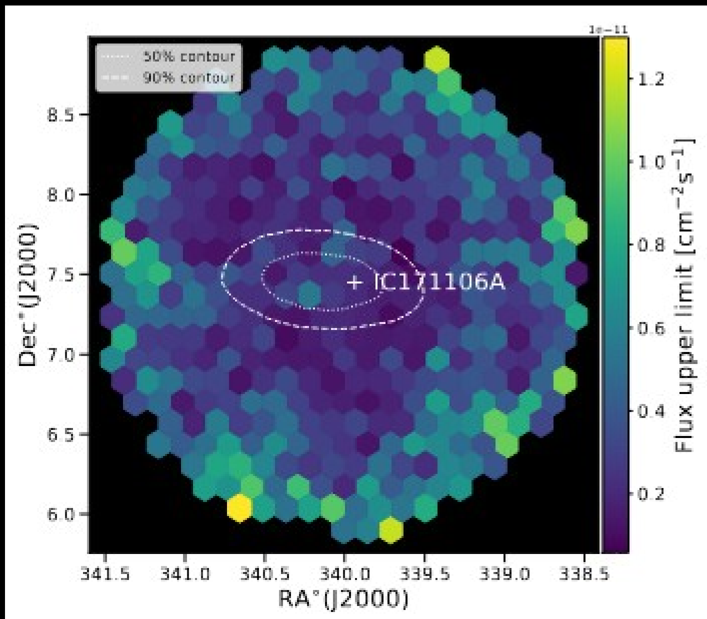
An anticipated proposal through HCT and DOT (Nainital)

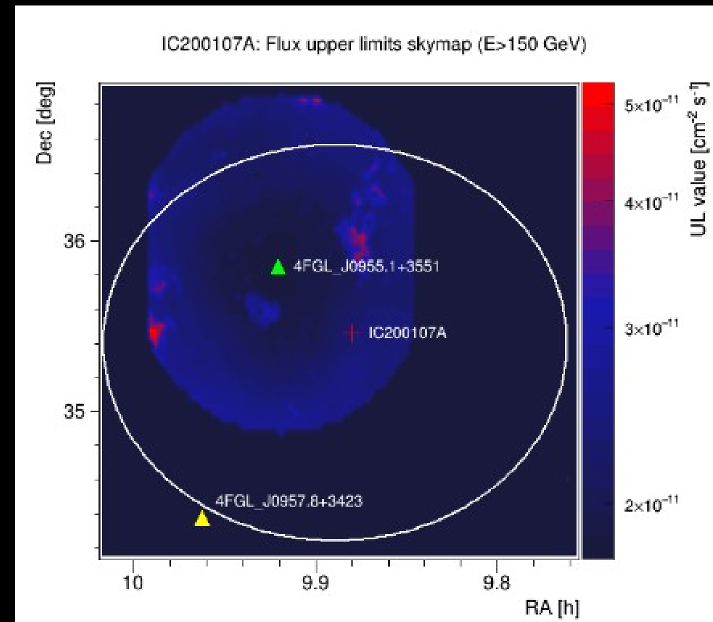
Occasional ToOs sent to ASTROSAT, not very successful as there is quite some latency

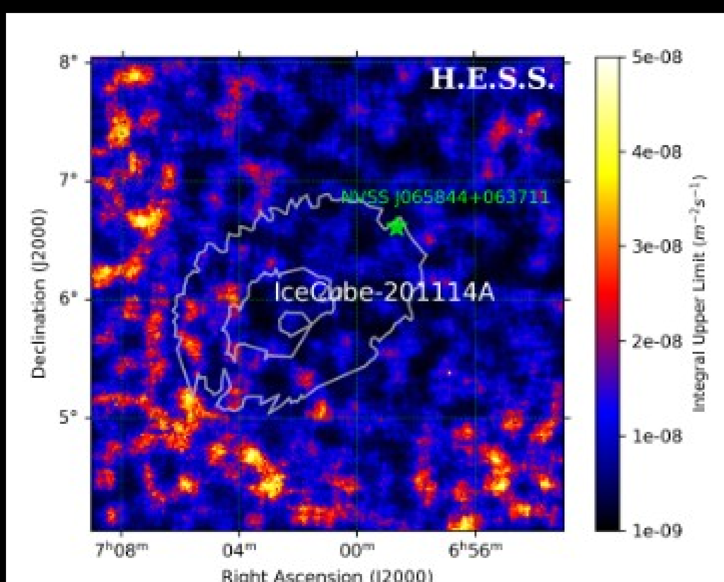


- The neutrino angular uncertainty is much larger than the IACT PSF.
- The IACT observations give us good coverage of the 50% containment region of the neutrino events.
- **We calculate integral upper limits (95% CL) above an energy threshold for a E^{-2} spectrum on a regular grid.**
- These ULs give constraints on any nearby gamma-ray excess or on potential electromagnetic counterparts.

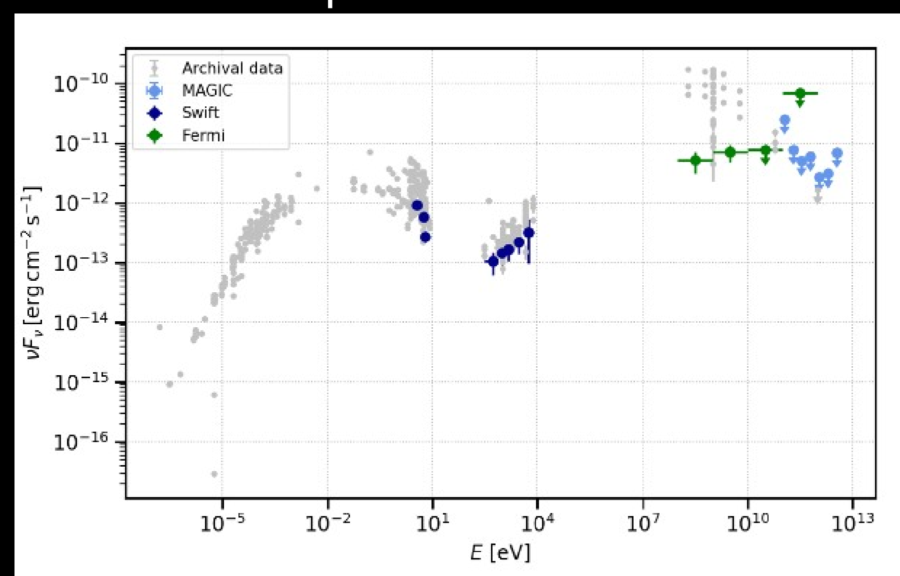
Follow Up Observations in the multimessenger context







Flux ULs computed from these observations



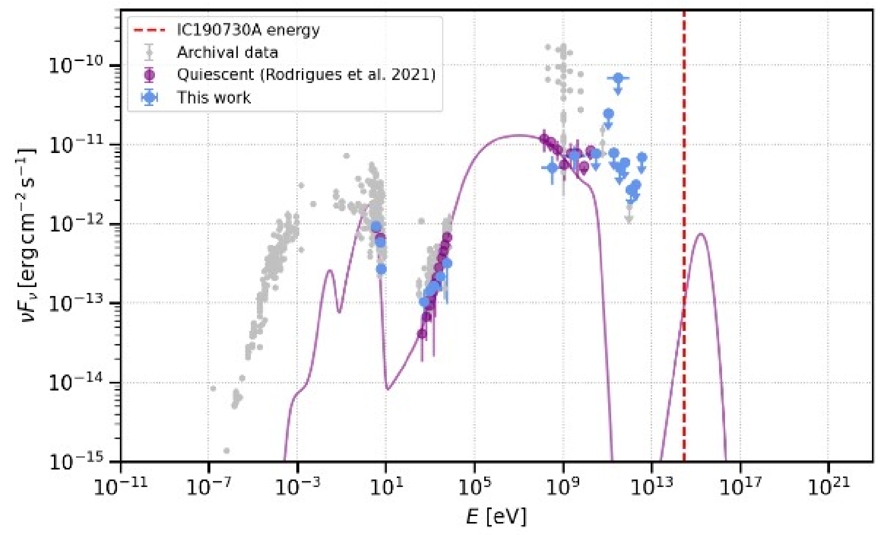
(b) IceCube-190730A/PKS 1502+106 (Section 6.5)

IceCube, MAGIC, VERITAS, H.E.S.S. Coll (in preparation)

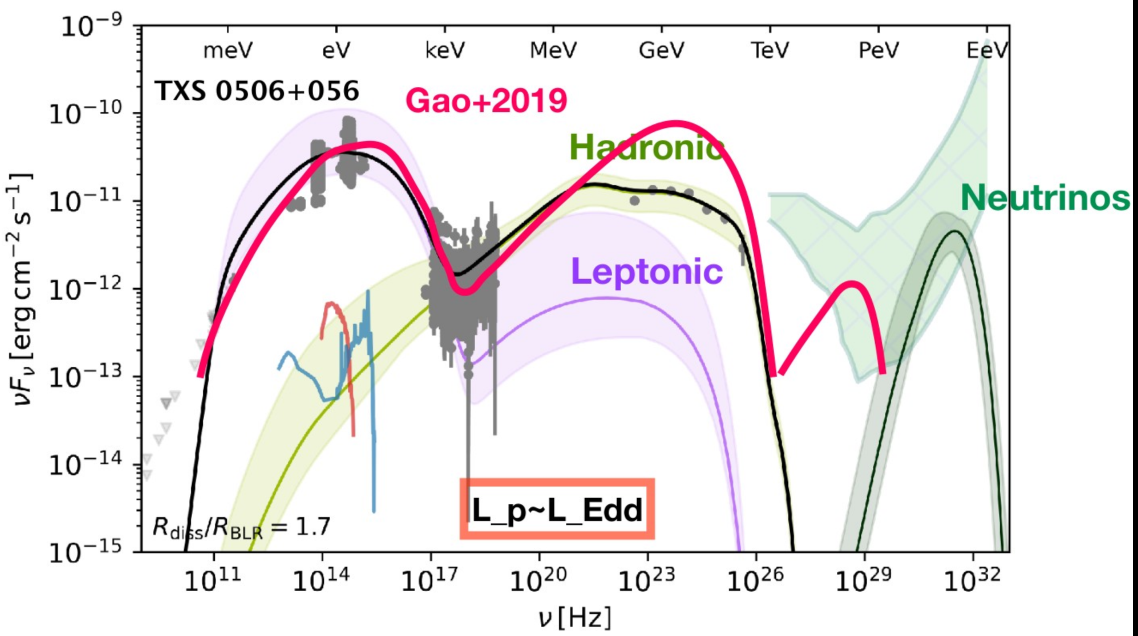
Follow Up Observations in the multimessenger context

Multiwavelength and multi-messenger modelling using JetSet (leptonic) Code and AM3 (leptohadronic) code
These are publicly available and we interact with the authors regularly to understand the codes and use them for specific source cases (work in progress)

Tramacere et al 2011, ApJ 739
Klinger, Rudolph, XR, et al 2024, ApJS 275



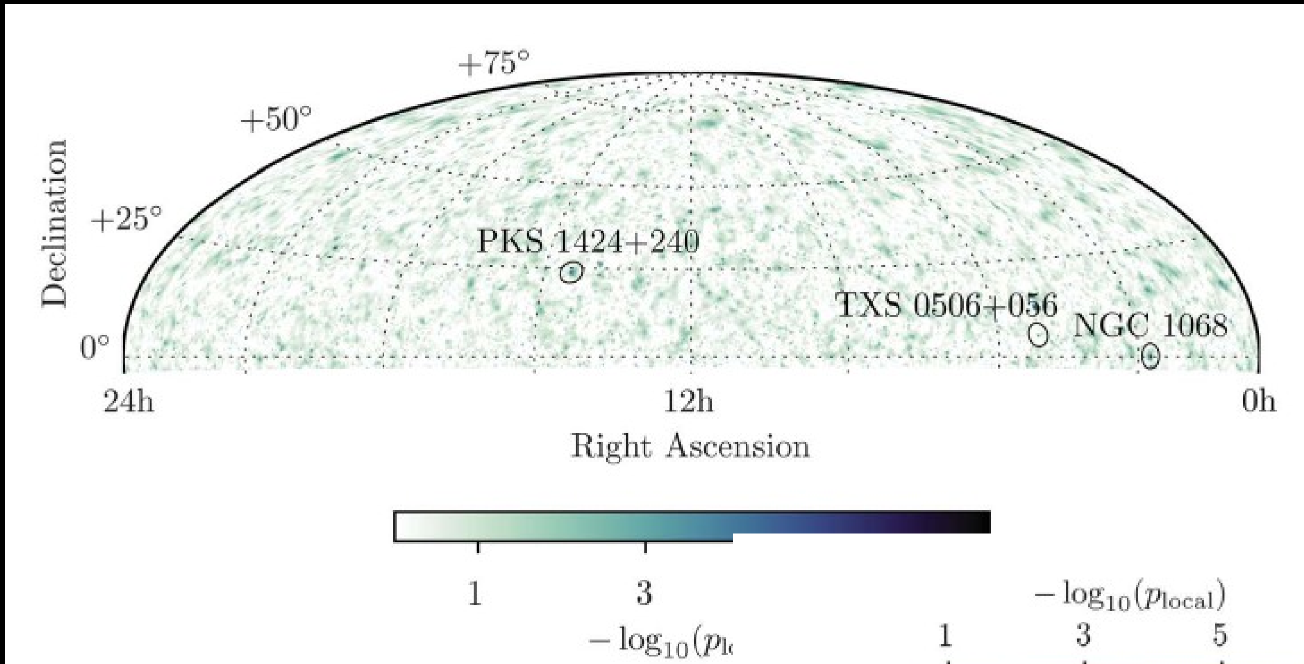
(d) IceCube-190730A/PKS1502+106, comparison with model from Rodrigues et al. (2021b) (Section 6.5)



X.Rodriguez et al , A&A 689 (2024)

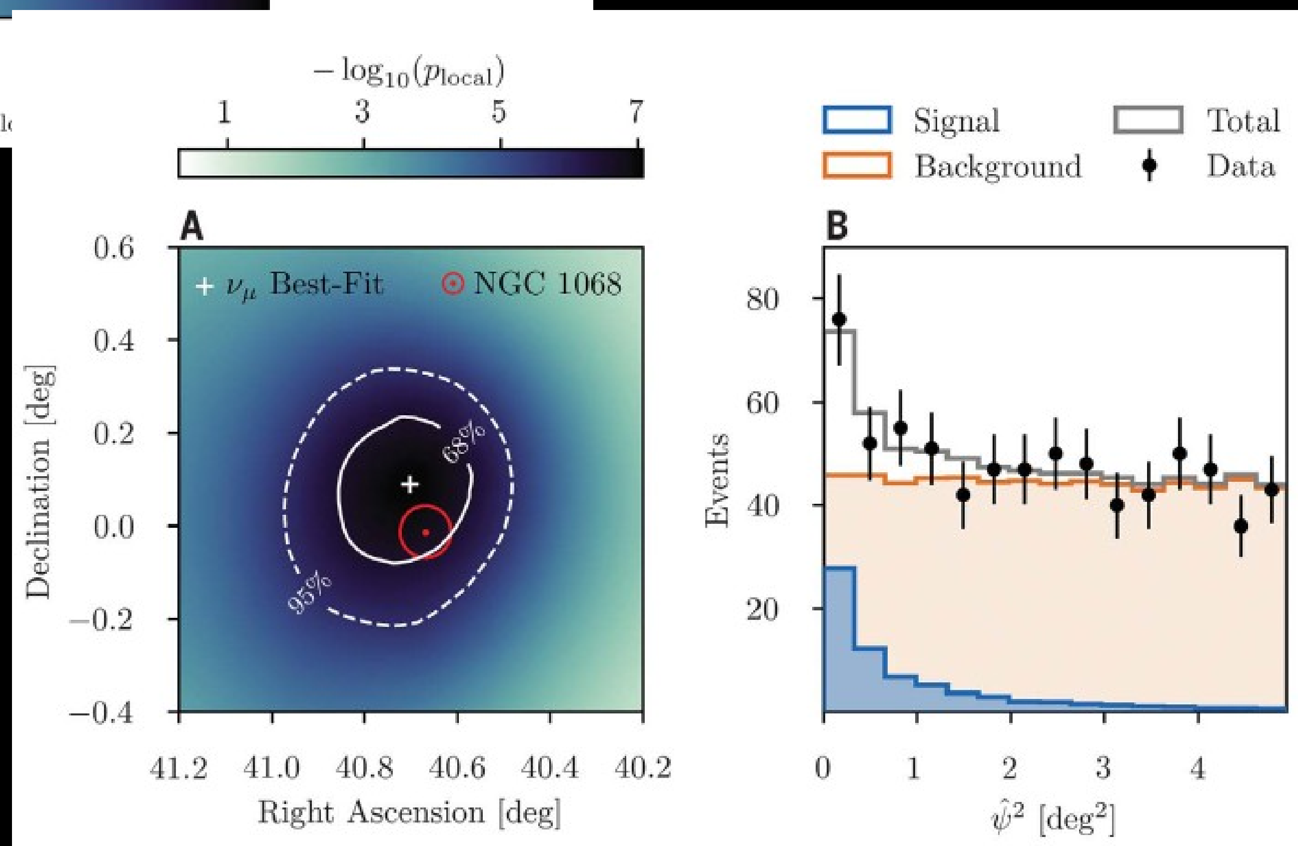
IceCube, MAGIC, VERITAS, H.E.S.S. Coll (in preparation)

Some more recent news on neutrinos and gamma rays from IceCube



9 yr search
yielded 2 more sources,
NGC1068 the most
significant,
global significance of
4.2 sigma

IceCube Collab, Science 6619 (2022)
Padovani et al MNRAS 510 (2022)

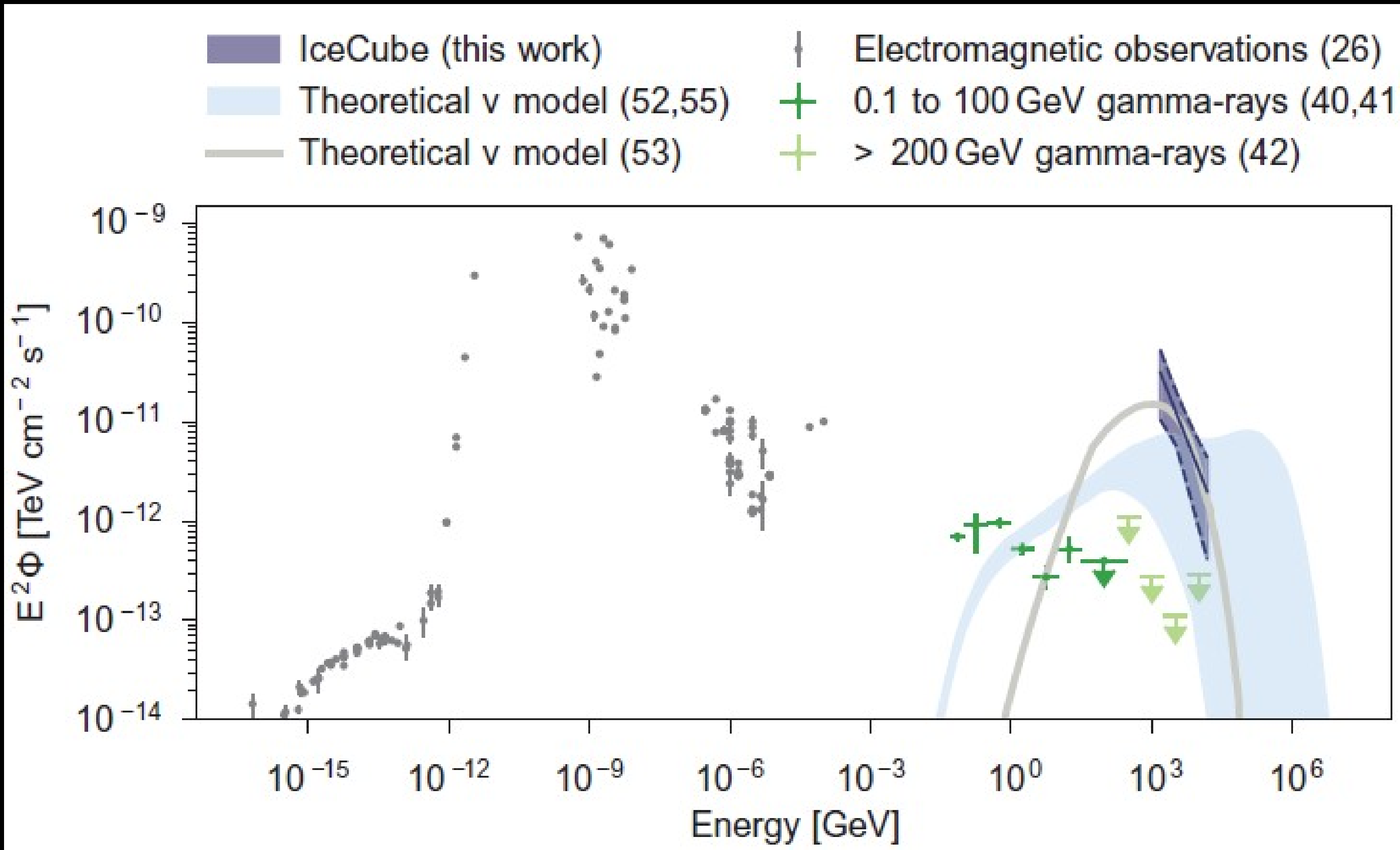


PKS1424 : HBL detected
by VERITAS (2009)

Acciari, V.A. et al., ApJ 708 (2010)

NGC1068 : Seyfert II
Galaxy, detected in HE
by Fermi-LAT
But no VHE detection

Non simultaneous Multifrequency Observations



IceCube Collab, Science (2022)

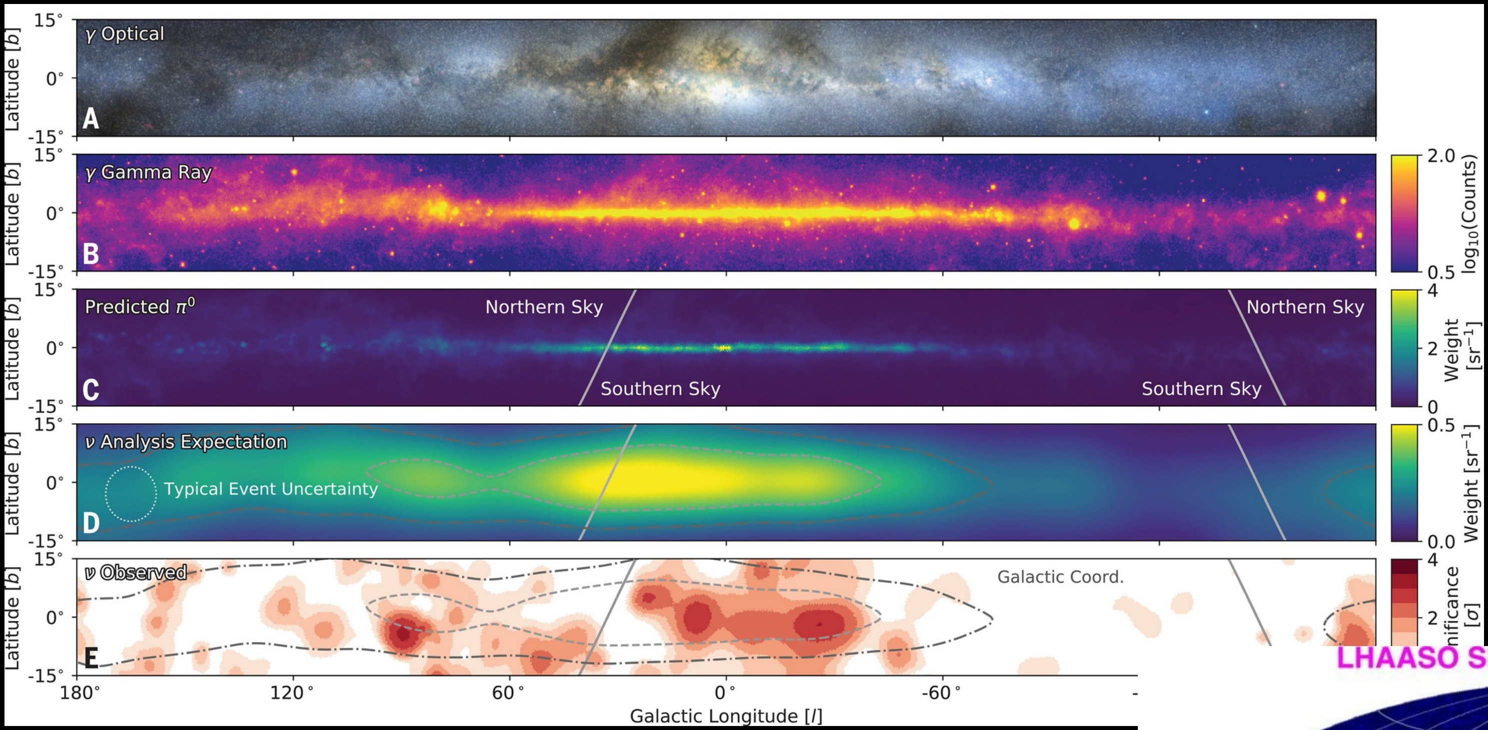
NGC 1068 is a Seyfert II galaxy, has vigorous starburst activity Hosts a Compton thick AGN

$$\Phi^{1\ \mathrm{TeV}}_{\nu_\mu+\bar{\nu}_\mu} = (5.0 \pm 1.5_{\mathrm{stat}}) \times 10^{-11}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

All flavor neutrino flux a factor 3 higher

Adopting a distance of 14.4 Mpc, the neutrino luminosity is about 1.5 higher than that of the gamma-ray luminosity as determined from Fermi.

More news on gamma rays and neutrinos

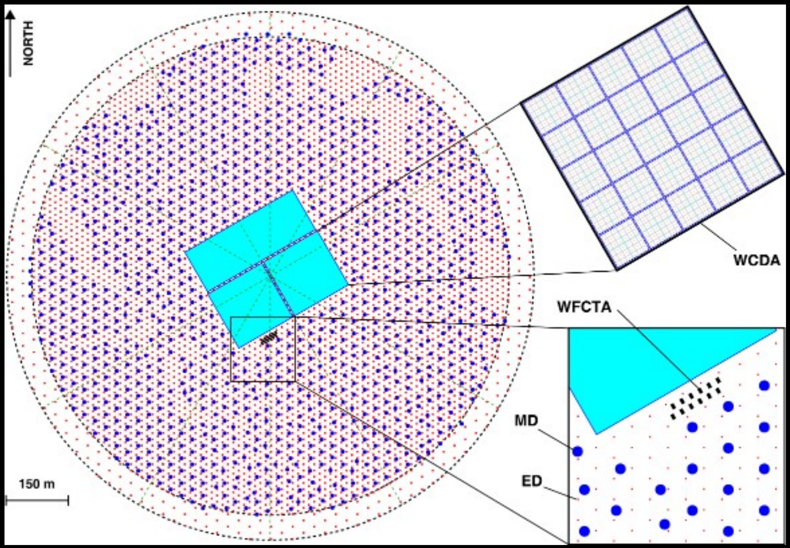


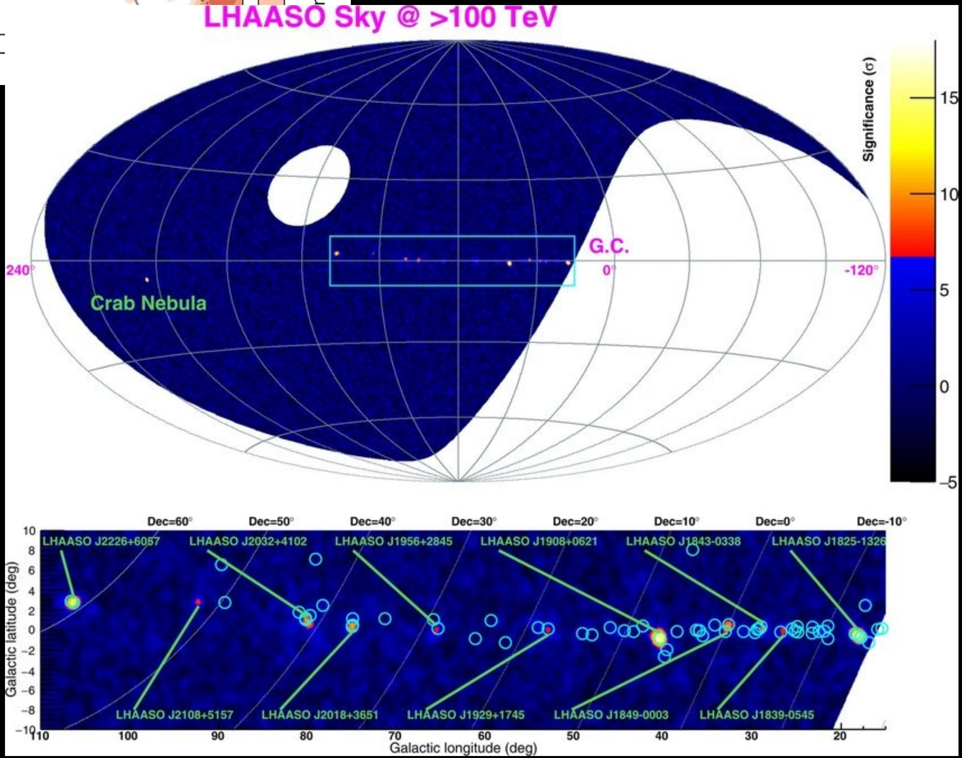
IceCube Collab, Science (2023)

Neutrinos from our Milky Way

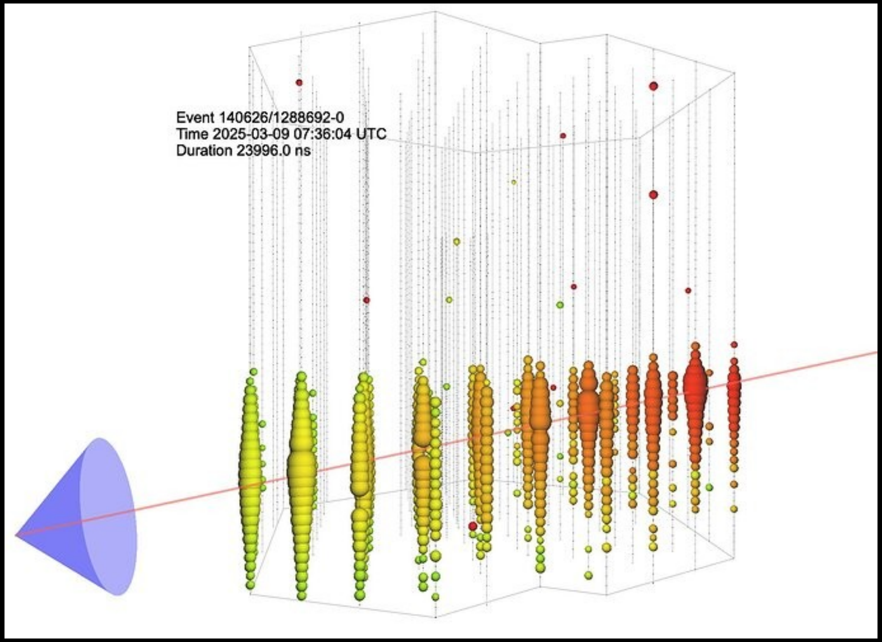
Neutrinos from LHAASO sources not found

arXiv : 2211.14184v1





Latest News on possible candidate GRB in IceCube alert



IceCube-250309A - IceCube observation of a high-energy neutrino candidate track-like event coincident with GRB 250309B

ATel #17070; *Anna Franckowiak (Ruhr-University Bochum), Lu Lu (University of Wisconsin_Madison), Giacomo Sommani (Ruhr-University Bochum), Tianlu Yuan (University of Wisconsin-Madison), Angela Zegarelli (Ruhr-University Bochum), Justin Vandenbroucke (University of Wisconsin-Madison), Marcos Santander (University of Alabama)*
on ***9 Mar 2025; 14:18 UT***
Credential Certification: Anna Franckowiak (anna.franckowiak@desy.de)

Subjects: Neutrinos, Gamma-Ray Burst

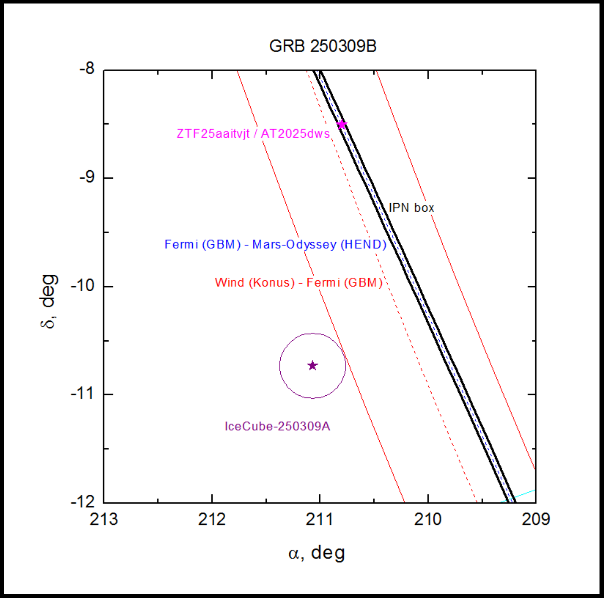
𝕏 Post

The IceCube Collaboration (http://icecube.wisc.edu/) reports:

On 2025-03-09 at 07:36:04.75 UT IceCube detected a track-like event with a high probability of being of astrophysical origin. The event was selected by the ICECUBE_Astrotrack_GOLD alert stream. This alert has an estimated false alarm rate of 0.18 events per year due to atmospheric backgrounds. The IceCube detector was in a normal operating state at the time of detection.

GCN : 39631
The alert coincides with the Fermi GRB250309B (Fermi-GBM trigger 763198715 at 07:38:30.66 on 09 March 2025;
https://gcn.gsfc.nasa.gov/other/763198715.fermi
) with a time delay of 145.91 seconds relative to the GRB trigger time. The angular distance to the most updated reconstruction released by the GBM team, which has a 1σ statistical error of 1.60 deg, is 0.77 degrees. An alternative algorithm results in a shifted direction (https://gcn.nasa.gov/circulars/39629) with an angular distance from the best fit neutrino direction of 3.18 degrees and has a 1σ statistical error of 1.3 degree and a systematic error of 1 degree.

The estimated energy is~4 PeV.

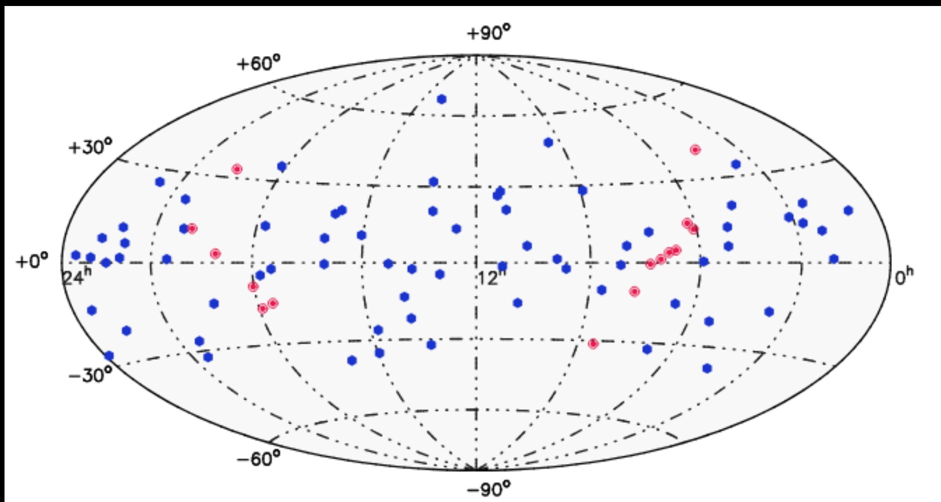


Using data from 4 satellites (Fermi, Konus-Wind, Mars-Odyssey, and GECAM-B), allowed to triangulate the position of GRB 250309B to a small strip that includes the optical event AT 2025dws but that is incompatible with the localization of the neutrino IceCube-250309A

Details in GCN # 39652

Fabian Schussler : https://forum.astro-colibri.science/t/neutrino-grb-coincidence/346/5

Is the growing evidence for blazar connection ?



P. Giommi et al, MNRAS 497 (2020) 1, 865-878

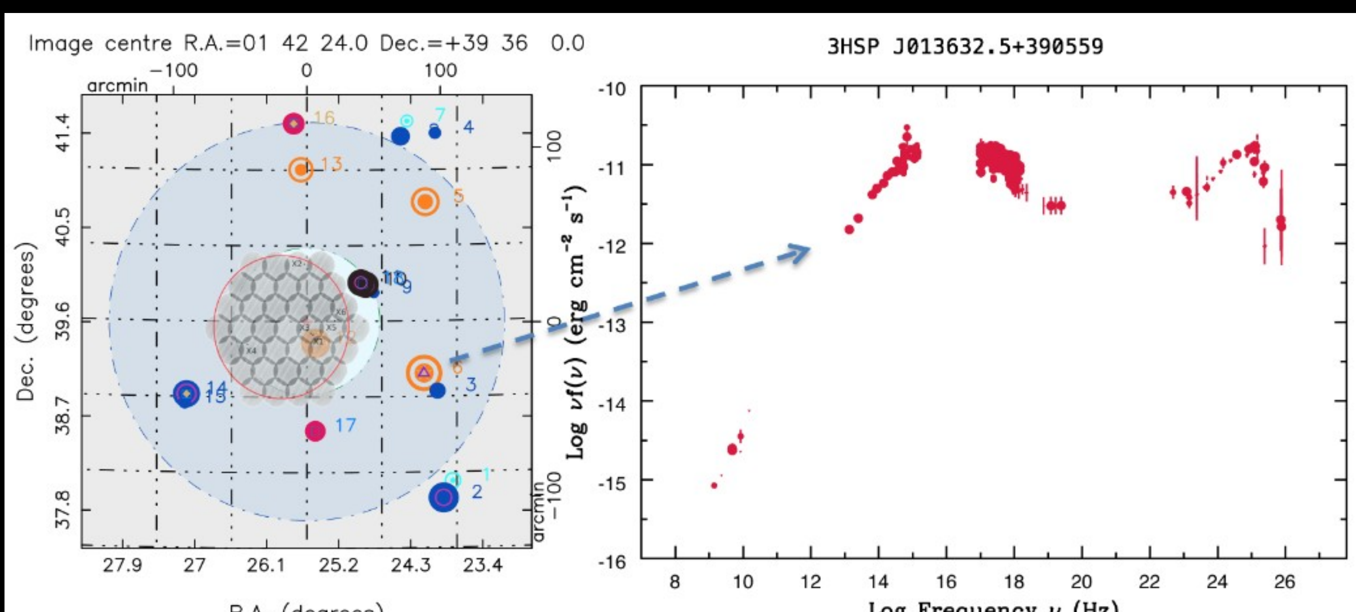
Fermi catalogs and 3HSP catalog sources in IceCube error regions (90%). 70 well recontructed track like events studied

Find number of sources lying inside error-box of IceCube and compare with randomised samples

29 sources from HSP catalog (no gamma-ray counterpart) at 2.79 sigma excess

Construct MWL SEDs using VOU-Blazars software package (using a much larger set of catalog)

About 20 gamma-ray blazars in IceCube 90% error region : Post trial p-value: 6.2 × 10−4 (3.23 σ)



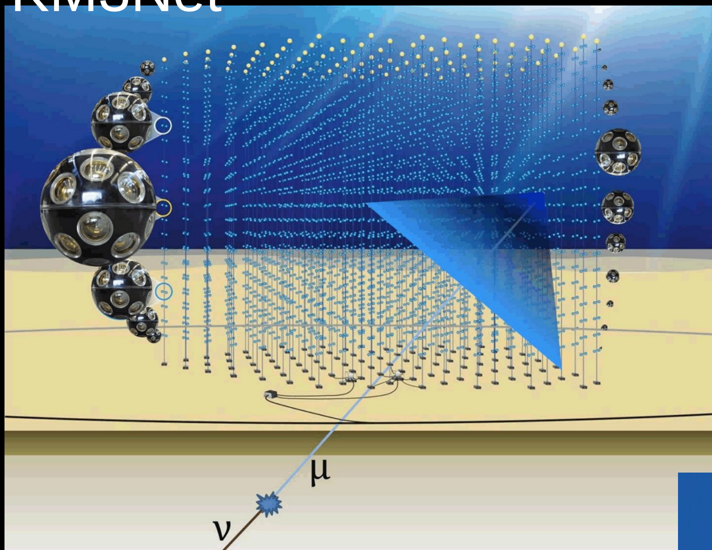
Growing consensus that blazars are counterparts of a fraction of IceCube neutrino alerts

Refined this analysis using different samples =>
we see a similar TS for blazars

Paper in preparation
S.Giri, C.Bakshi, PM et al

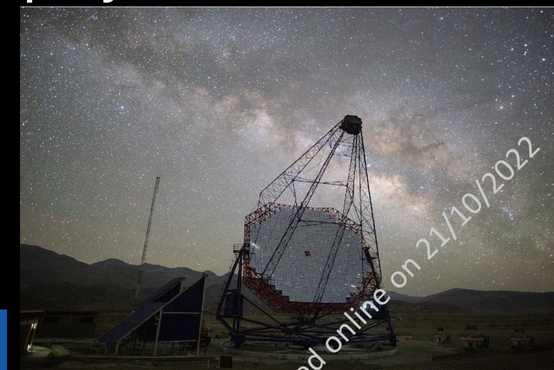
High energy Neutrino detection to Gamma-Neutrino Astronomy

KM3Net

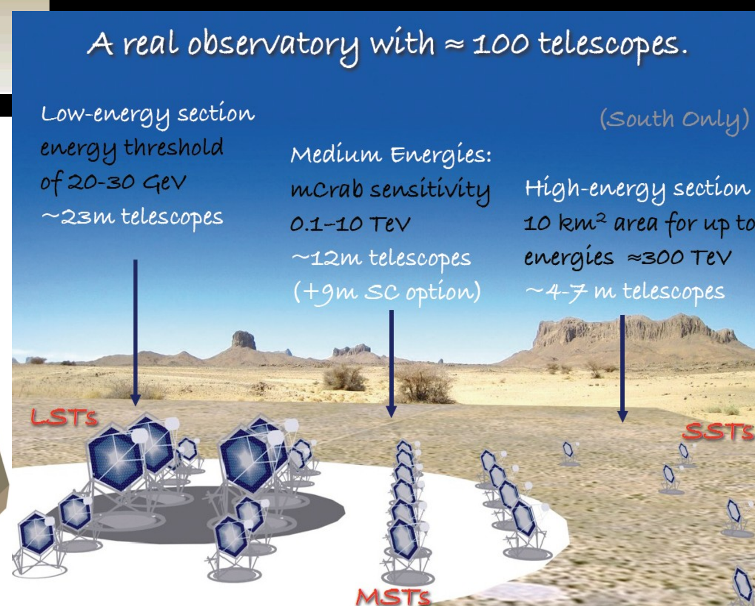


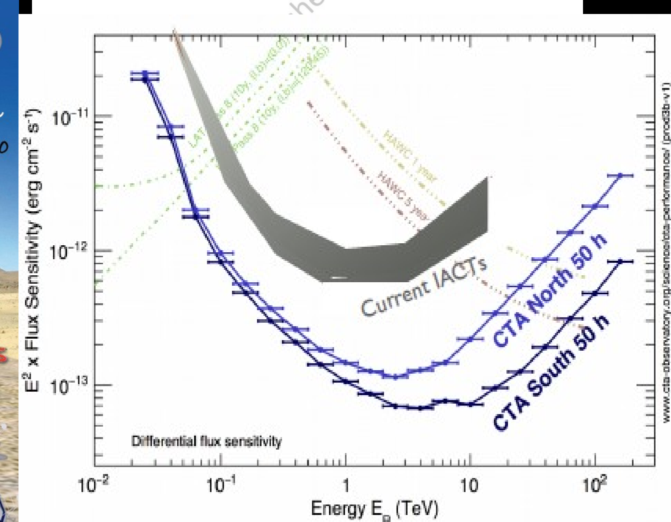
Multi-Km3 neutrino telescope in the Mediterranean
First strings have been deployed

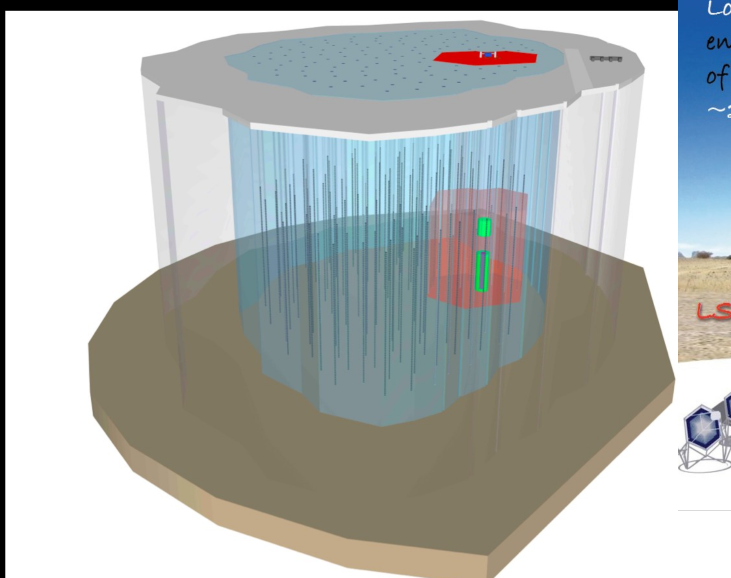
MACE
@Hanle



CTA







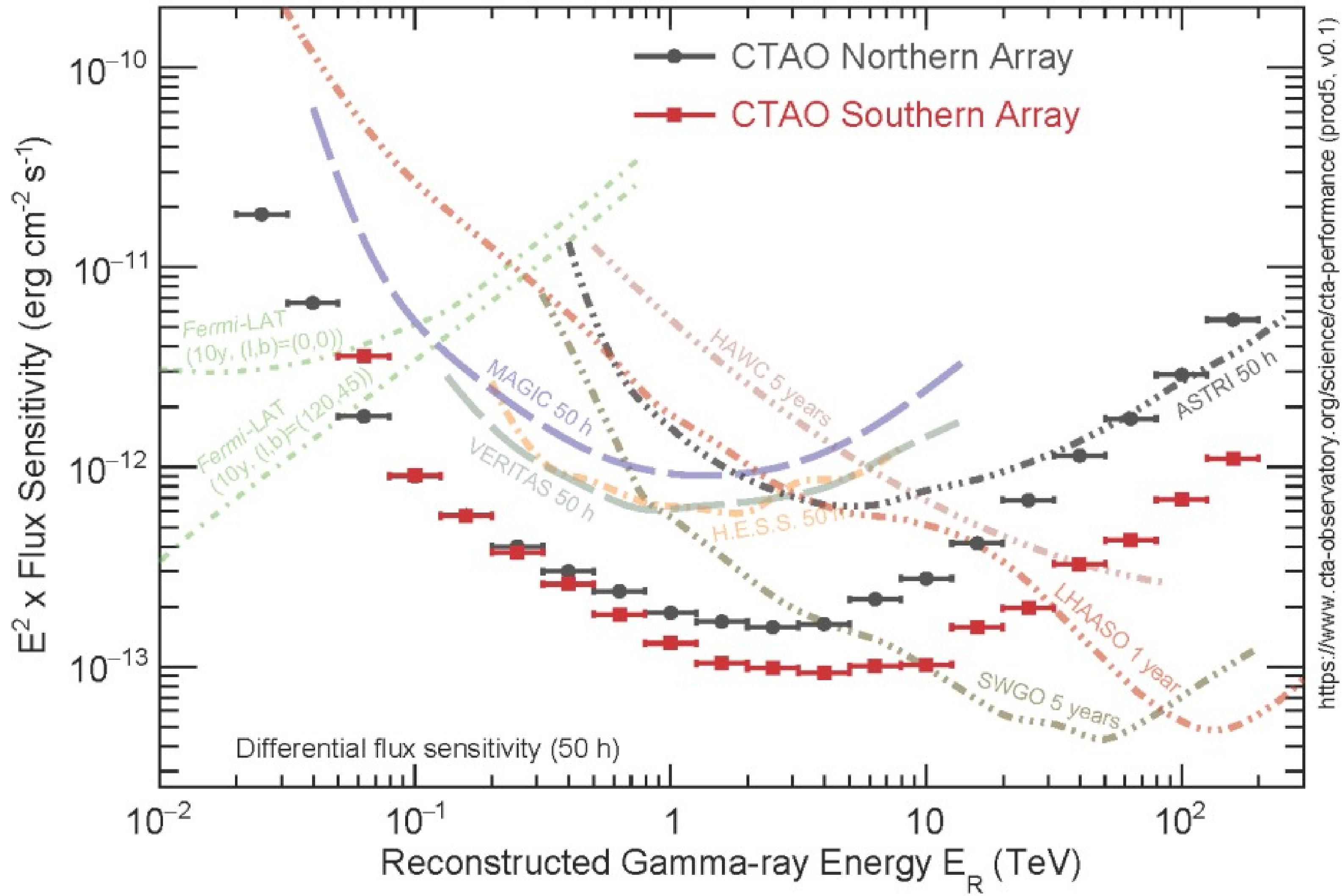
Partial array of CTA telescopes ready by 2026
at La Palma, CDR of LST completed

IceCube-Gen2, Extension of
IceCube

ToOs with Astrosat, optical telescopes in India

Cerenkov Telescope Array Observatory

CTAO Sensitivities



https://www.cta-observatory.org/science/cta-performance/

Prototype Large Size Telescope at La Palma (23 mt)

CTA-LST : Big International Effort
BR(Brazil), CH(Switzerland), DE(Germany), ES(Spain), FR(France), IN(India), IT(Italy), HR(Croatia), JP(Japan), SE(Sweden)

Focal Plane Instr.
Electronics (JP/IT/ES)
Camera body (ES)

Camera Supporting Structure (FR/IT)

UPS (JP)
Computers, network (JP)
INFRA (ES)

Construction almost finished : To be inaugurated 2nd week of October

Mirror (JP)
Interface Plate(DE/BR/JP)
Actuator (JP/CH)

Star Guider (SE)
Calibration Box (IN/IT)

Structure (DE/ES)
Access Tower (DE/ES)

Drive (ES/FR)
Bogie (ES/DE/IT)
Rail (ES/DE)
Foundation (ES)

Conclusions

Blazars are plausible sources of very high energy cosmic rays beyond several tens of PeV : $10^{(15)}$ to $10^{(17)}$ eV
Definitely not (yet) UHECRs

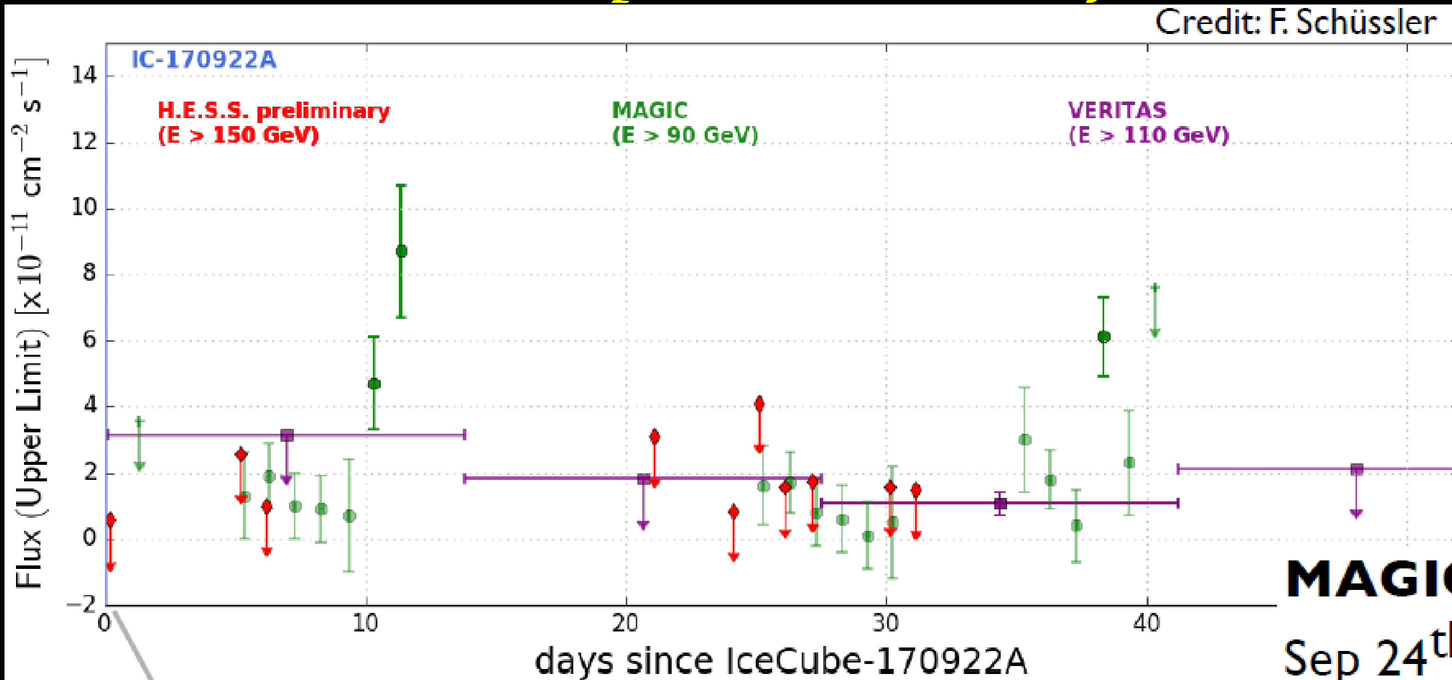
Detection of a blazar in flaring state in gamma rays in connection with a HE neutrino event raises more questions than it answers : Are they happenning only during flares ?
What about temporal correlation ???

We are having quite a few multimessenger SEDs to play with

We need many more such events : in the last years we have been performing regular em (MAGIC, HCT, ARIES, Astrosat, Swift etc) observations of high energy neutrino events :
Requires Tighter cooperation between observatories :
Future is very bright with CTA, KM3NeT and other em observatories

Backup Slides

Follow up observations confirm detection by others



MAGIC: 41 h collected between Sep 24th - Nov 2nd

Day-scale variability

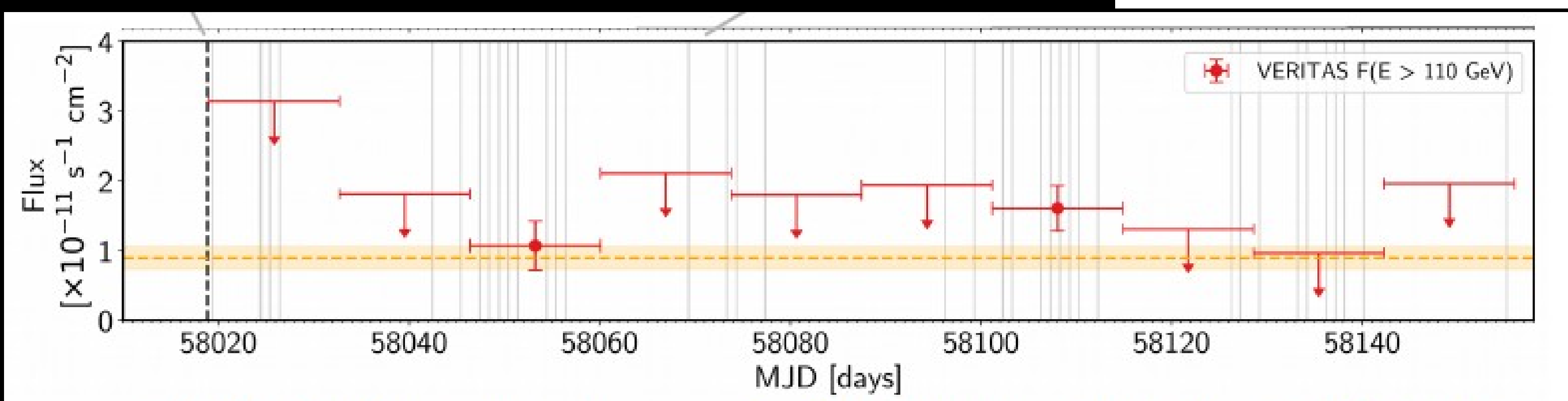
Probability of constant flux < 0.3%

2 flares (Oct 3rd-4th + Oct 31st) +

Lower state detected > 90 GeV

The MAGIC Collaboration, ApJL 863, 1, arXiv:1807.04300

The VERITAS Collaboration, accepted by ApJL, arXiv:1807.04607



VERITAS: 35 h collected between Sep 23rd – Feb 6th → **detection > 100 GeV**

High Energy Photon / Neutrino Production in Cosmic Ray sites

$$p + \gamma \rightarrow p + \pi^0, \quad \pi^0 \rightarrow \gamma\gamma, \quad e + \gamma \rightarrow e + \gamma$$

$$p + \gamma \rightarrow n + \pi^+, \quad \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

$$p_{\rm CR}\, p_{\rm ISM} \longrightarrow p\, p\, n \pi \,,$$

$$\pi \longrightarrow \gamma \,, \;\; \nu$$

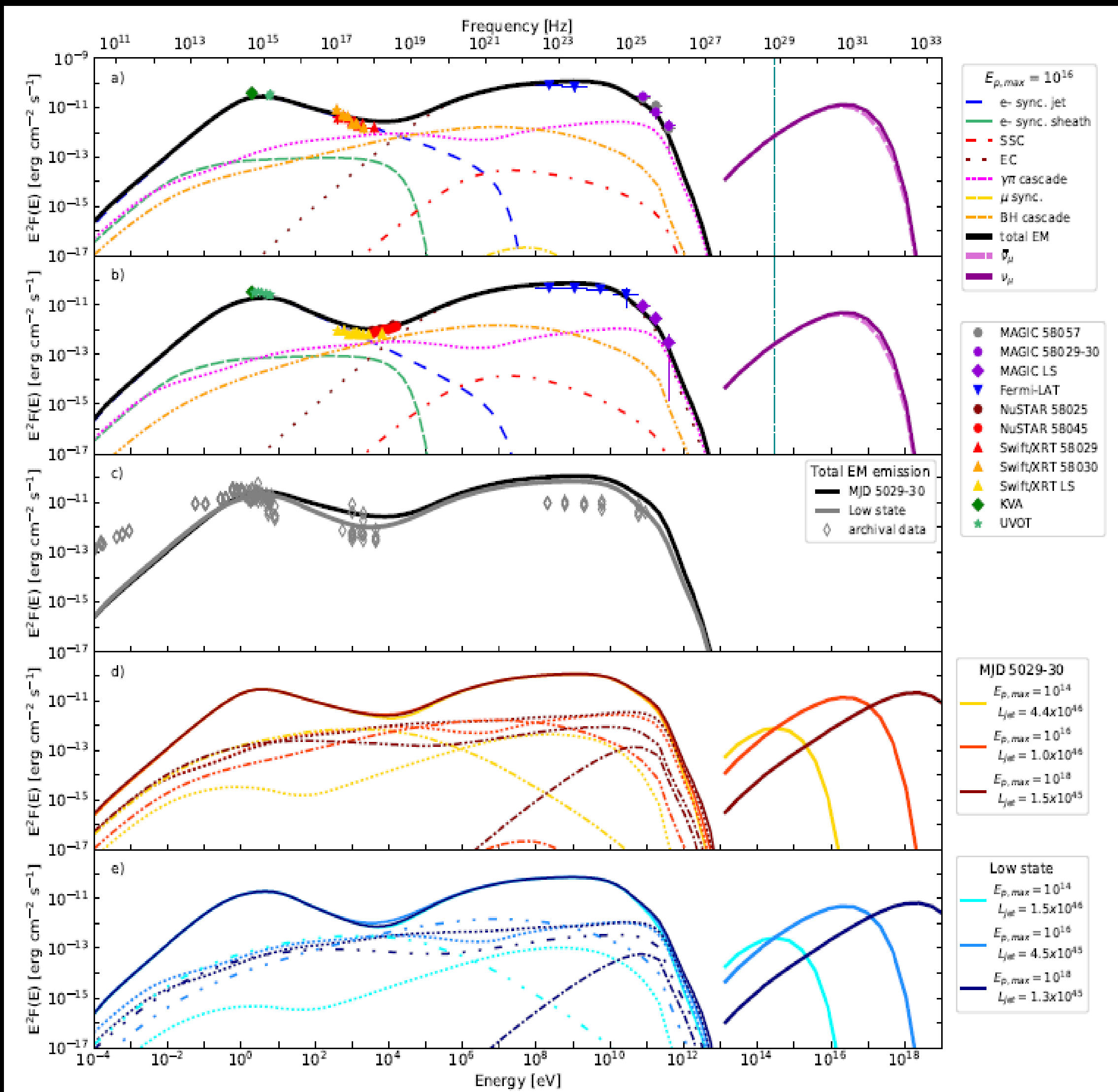
TeV γs can come from protons (thru π^0 decay) or from electrons (thru Inverse Compton)

But Tev νs can come only from proton interactions.

- γs and νs : Messangers from the cosmic accelerators. But Universe opaque to multi-TeV photons from distant extragalactic sources.
- ν's are the ultimate messangers from the highest energy accelerators at cosmic distance scales.

The pion takes on average 1/5th of proton's energy, and each neutrino takes about 1/4th of the pion energy. Thus the maximum neutrino energy is about 1/20th of the maximum proton energy.

Modelling the Spectral Energy Distribution



Detailed modelling to explain the Multimessenger connection

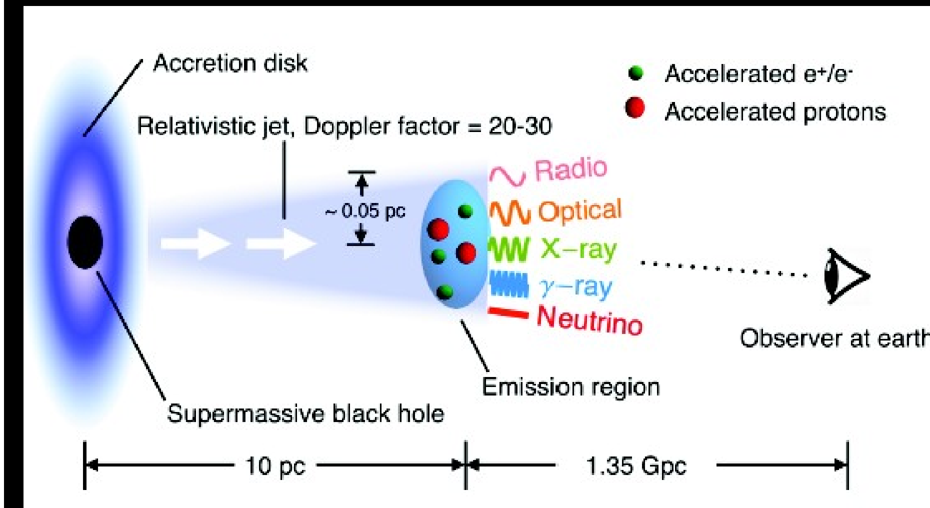


Photo-meson induced cascades, Bethe-Heitler pair cascades, synchrotron from protons and muons

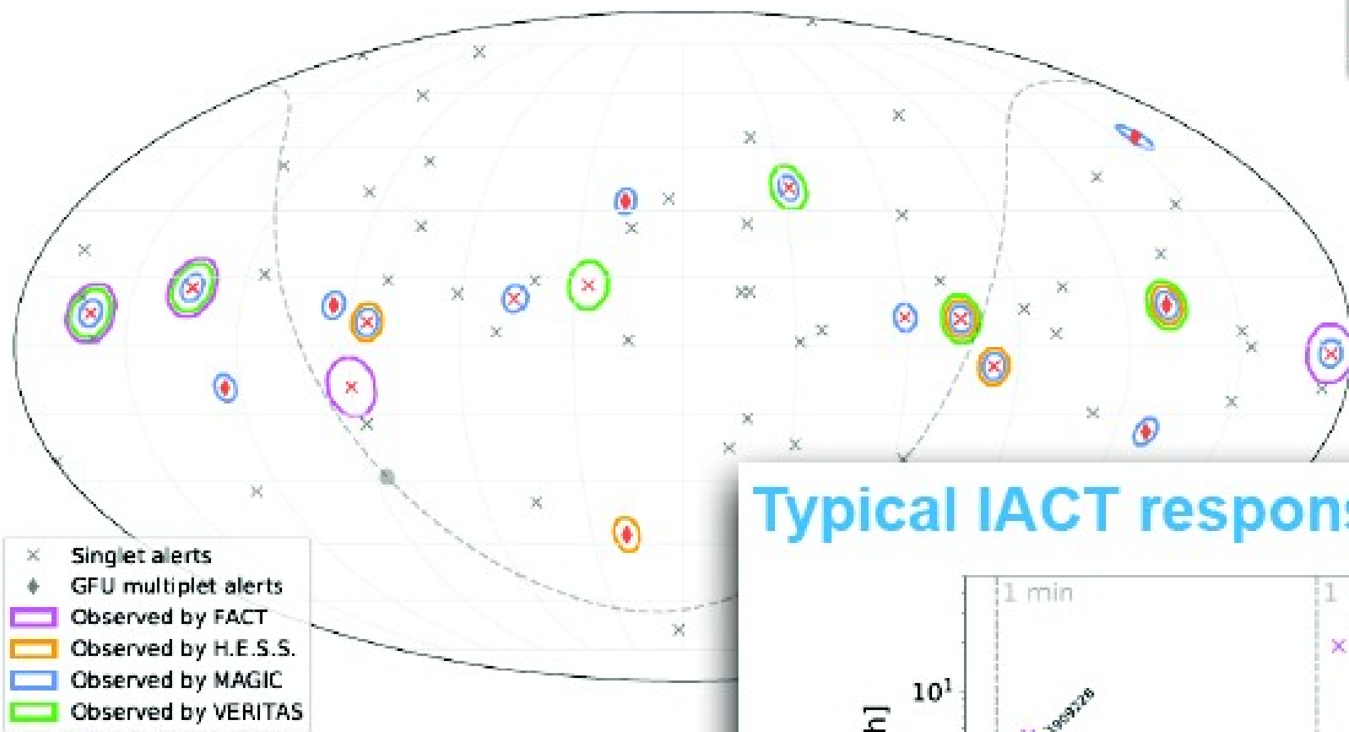
Synchrotron from electrons, SSC, EC

Maximum proton energy
~ 10 ^(16) eV

A one-zone model with external photons can explain both the low and high state of the source , MAGIC Collab, ApJL (2018)

Continued searches for additional correlations

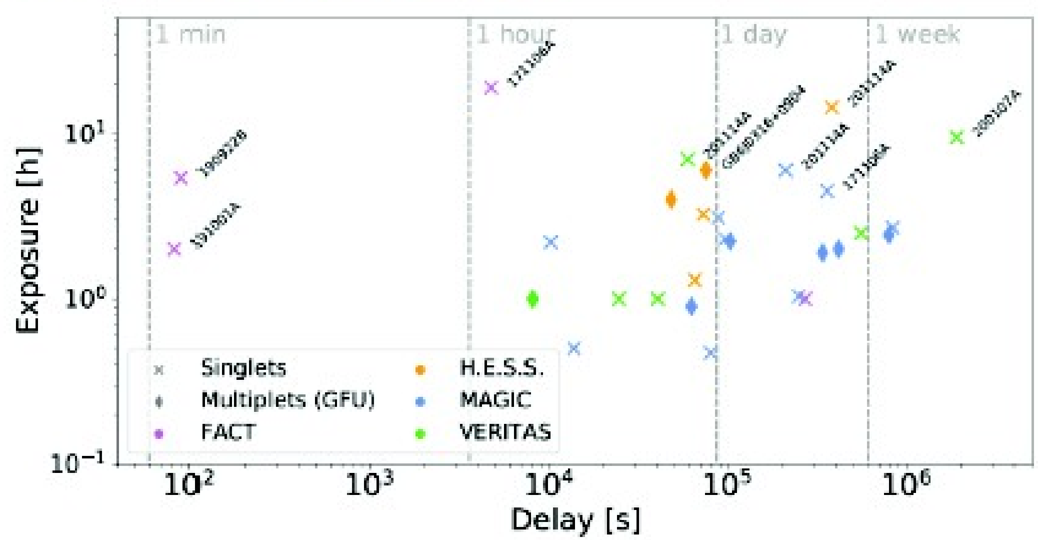
Alerts observed since October 2017



Alerts (Oct 2017 - Dec 2020):
62 singlets,
27 GFUs from 17 sources

Observed:
11 singlets,
GFUs from 7 sources

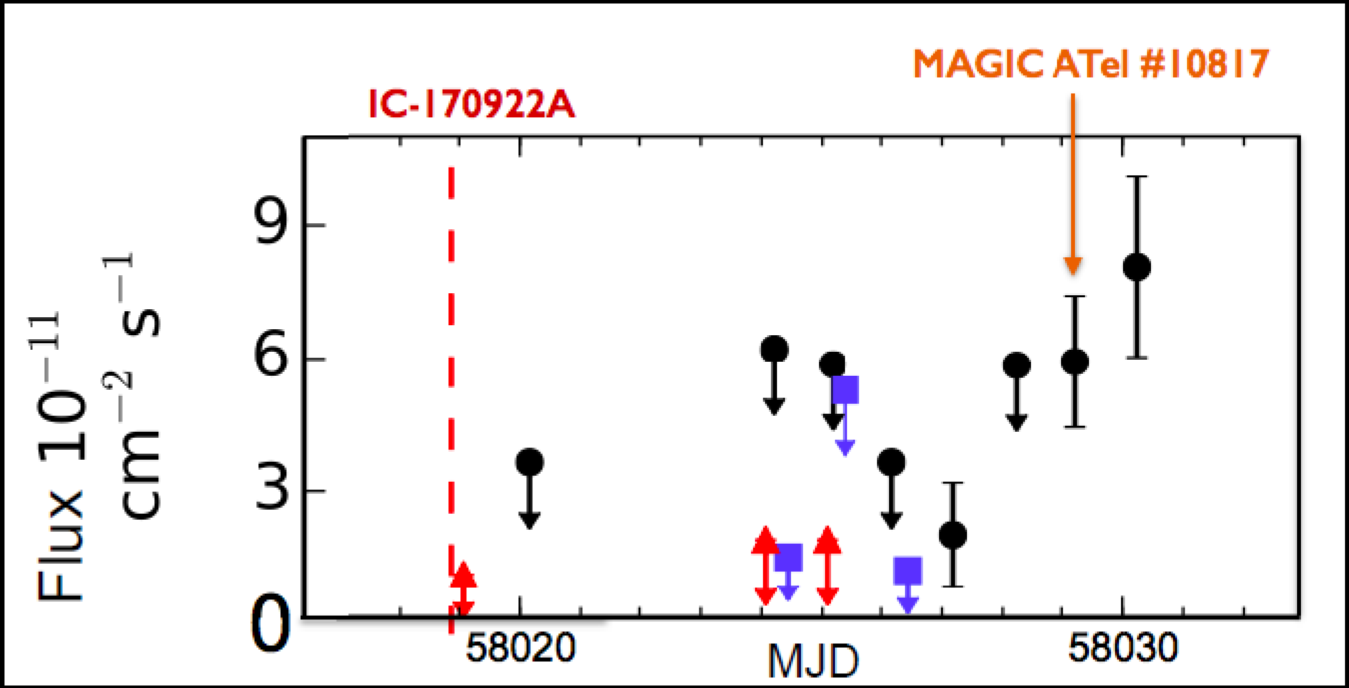
Typical IACT response



Joint effort by all IACTs

Santander et al. ICRC 2017
Satalecka et al., ICRC 2021

MAGIC detection of the flaring blazar



A low energy threshold Coupled with high sensitivity is essential for detection of high redshift sources.

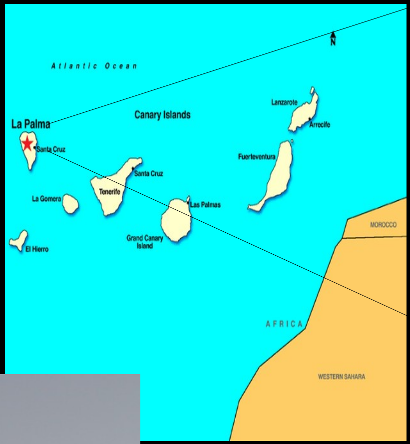
- **H.E.S.S**: fastest follow-up (~4 h delay), total 3.25 h/ 3 nights → no detection> 175 GeV
- **VERITAS**: first obs. ~12 h delay, total 5.5 h/ 3 nights → no detection > 175 GeV
- **MAGIC**: first obs. ~32 h delay (Sep 24th), 3.5h, weather non-optimal

  → 1h used for UL

  Sep 28th - Oct 4th: 13h collected/1 week → **detection > 90 GeV!** (Oct 3rd: ATel#10817)

MAGIC Telescopes (50 GeV-50 TeV)

- Low Energy threshold (~ 50 GeV), good overlap with Fermi.
- Most suited for high red-shift source observations with high sensitivity
- Fast movement to catch transients



- Operational since 2003
- 2 x 17 mt telescope in stereo mode since 2009
- < 1% of Crab nebula flux
- You can see TeV gamma rays from Crab nebula with MAGIC in < 2 mins
- Operate in moderate moonlight

Maximum Energy and Possible Sites

Maximum Energy:

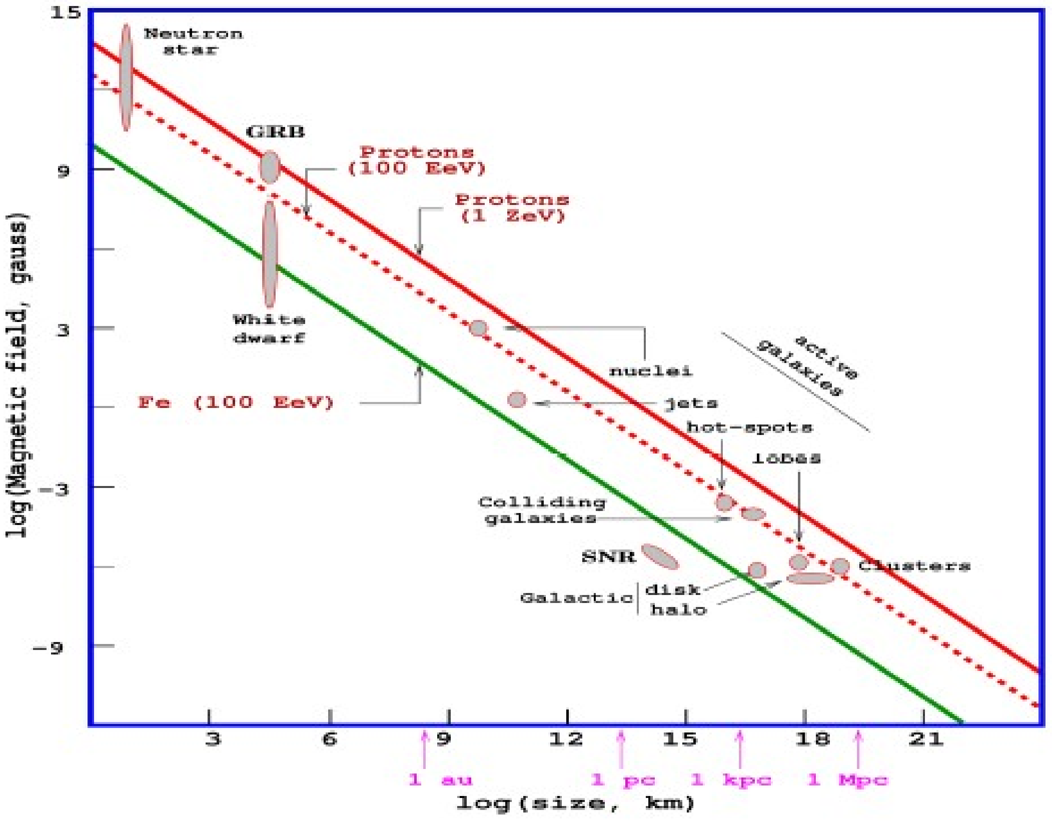
In general, Larmor confinement $\Rightarrow$

$$L \geq 2r_g = 2\frac{E}{ZeB}$$

$$r_g = 1.1\left(\frac{E}{10^{18}\,\text{eV}}\right)\left(\frac{10^{-6}\,\text{G}}{B_\perp}\right)Z^{-1}\,\text{kpc}$$

$$\Rightarrow E_{\max} \lesssim 0.5 B_{\mu\,\text{G}} L_{\text{kpc}} Z\,\text{EeV}$$

$$E_{\max} = \beta B_{\mu\,\text{G}} L_{\text{kpc}} Z\,\text{EeV} \quad (\beta \leq 1)$$

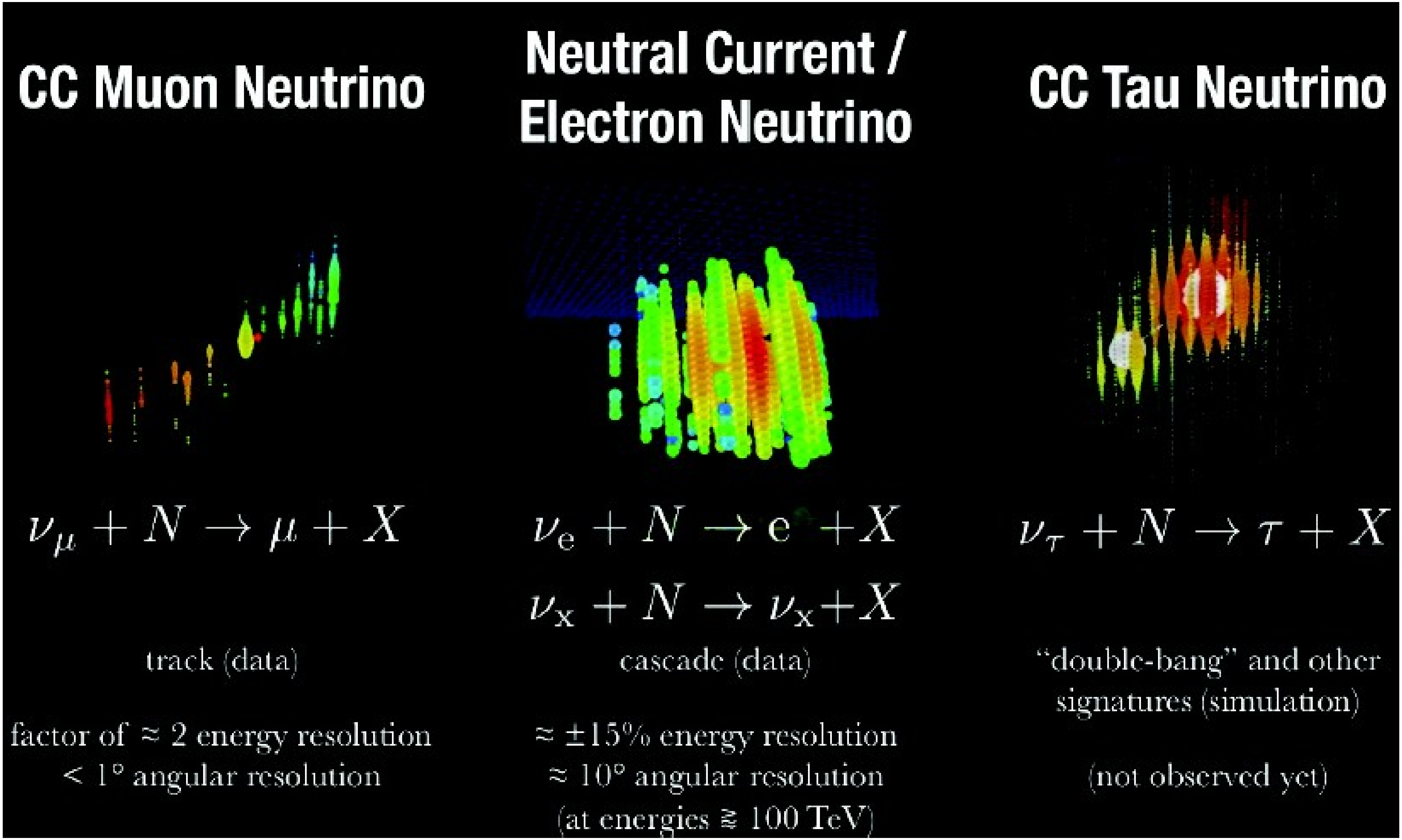


Gamma ray bursts, Active Galactic Nuclei, Clusters of Galaxies seem to be the best candidates for Very High Energy Cosmic rays

==>

Primarily sources which are extragalactic

Event Topologies in IceCube



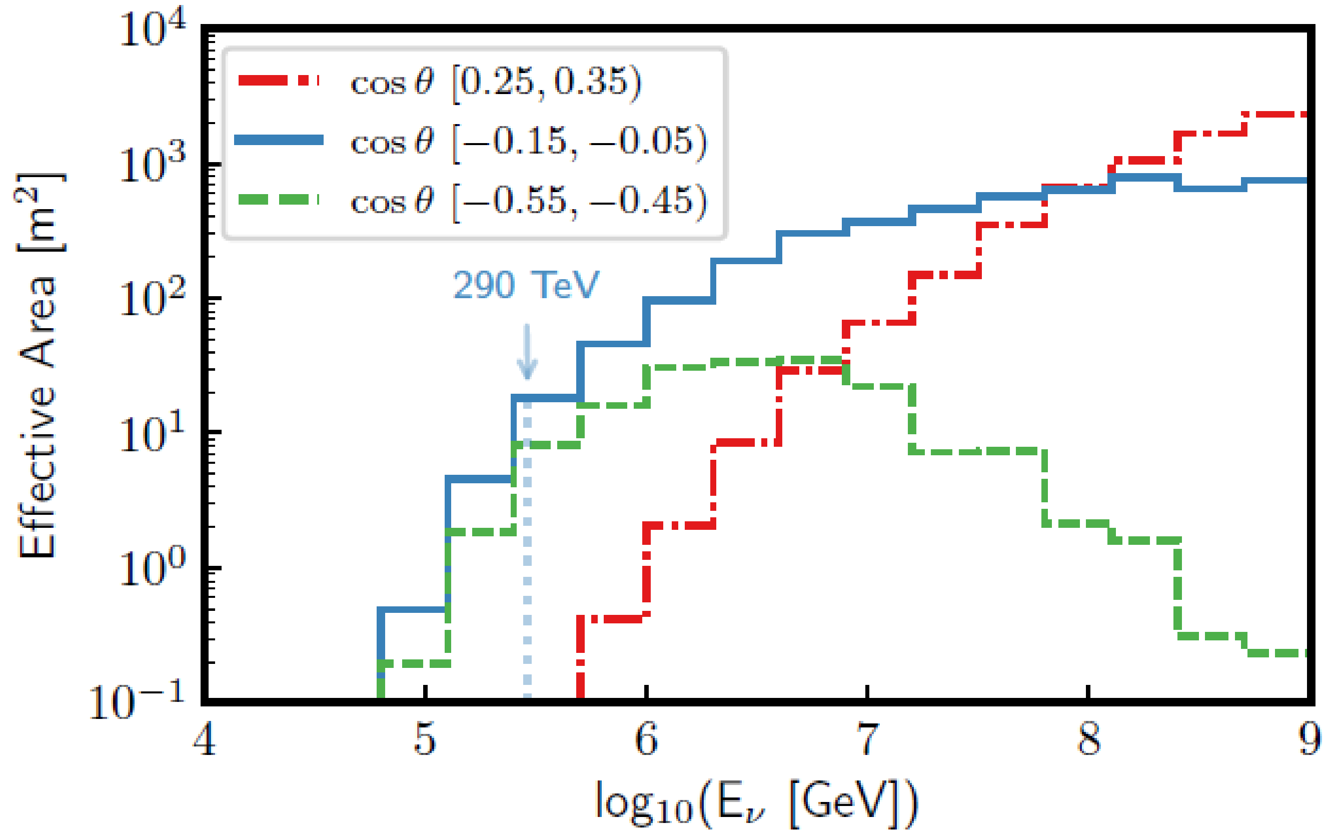
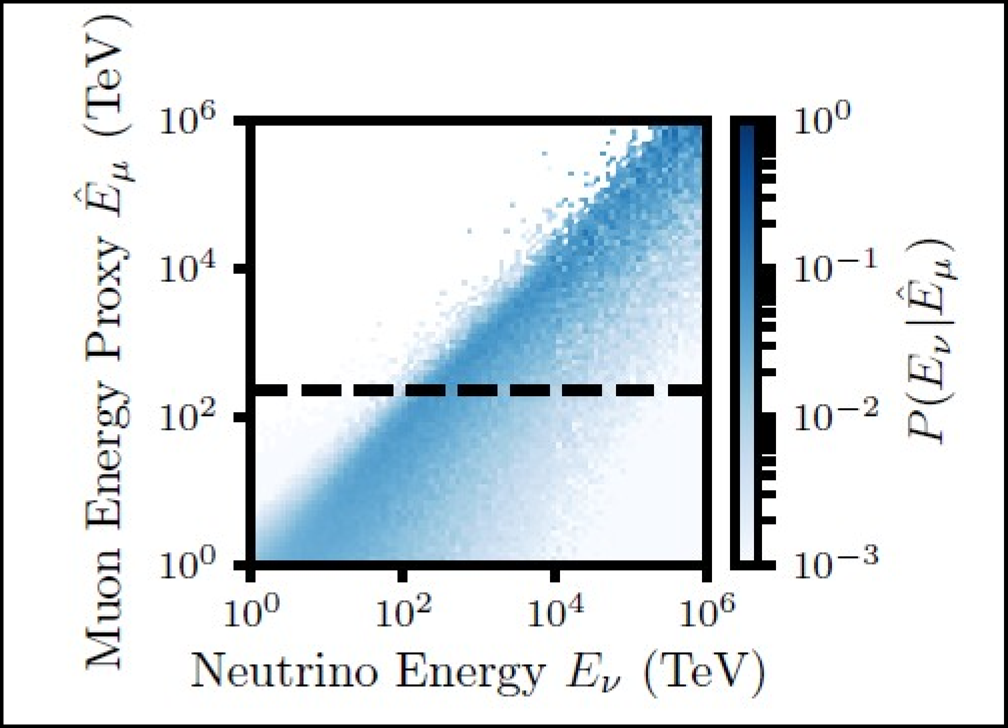
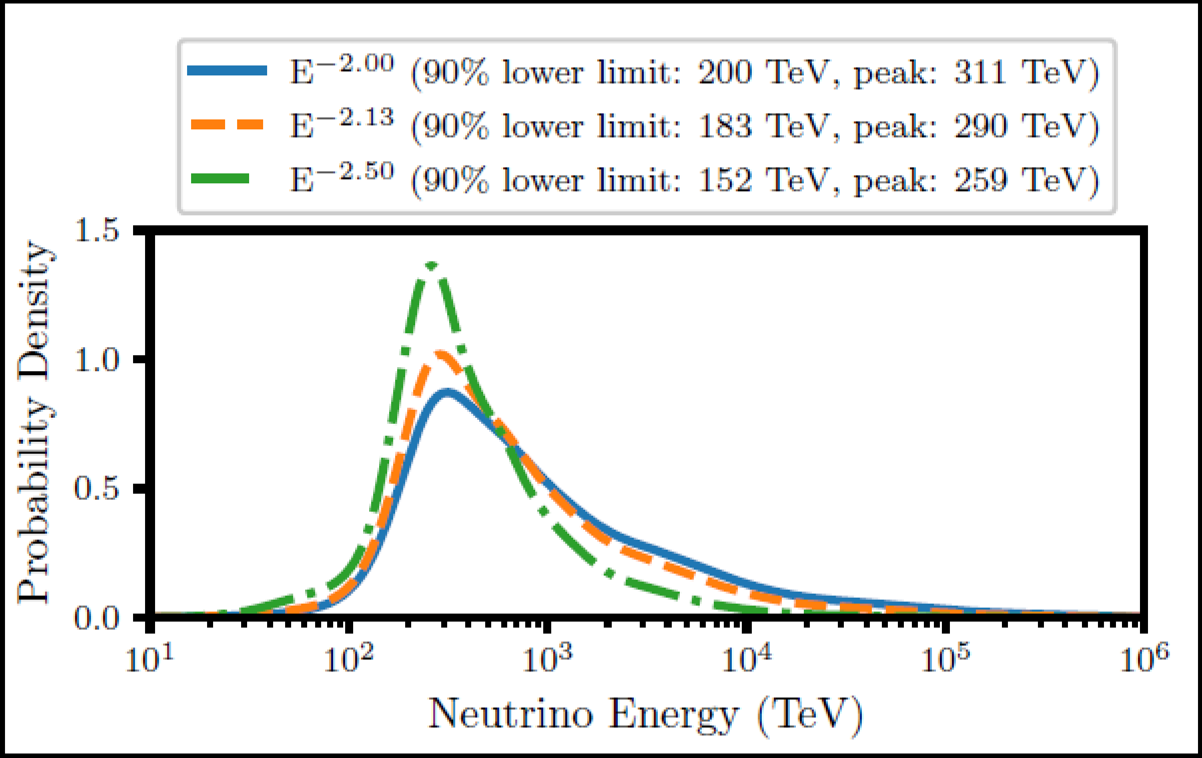


Figure S1: **Neutrino effective area for the through-going track alert channel.** Effective area for the online through-going track ("EHE") selection in three zenith angle ranges. The zenith angle of IceCube-170922A was cos(zenith) = −0.1, a preferred direction for this event selection. In the range −0.55 to −0.45 (∼30 deg below the horizon) a strong absorption by the Earth at the highest neutrino energies is seen, while in the interval 0.25 to 0.35 (∼20 deg above the horizon) strong cuts on track energy are needed to suppress the background from cosmic-ray muons, limiting sensitivity below 1 PeV. The most probable neutrino energy of 290 TeV is also



Muon Energy Proxy $\hat{E}_\mu$ (TeV)
Neutrino Energy E_ν (TeV)
$P(E_\nu|\hat{E}_\mu)$
10^0
10^2
10^4
10^6
10^{-1}
10^{-2}
10^{-3}



$E^{-2.00}$ (90% lower limit: 200 TeV, peak: 311 TeV)
$E^{-2.13}$ (90% lower limit: 183 TeV, peak: 290 TeV)
$E^{-2.50}$ (90% lower limit: 152 TeV, peak: 259 TeV)
Probability Density
Neutrino Energy (TeV)
0.0
0.5
1.0
1.5
10^1
10^2
10^3
10^4
10^5
10^6

Neutrino Blazar Coincidence

Perform several hypothesis tests based on spatial and temporal signal distribution and neutrino emission scenarios

For each hypothesis, create a TS in a likelihood ratio test to compare signal hypothesis to null hypothesis

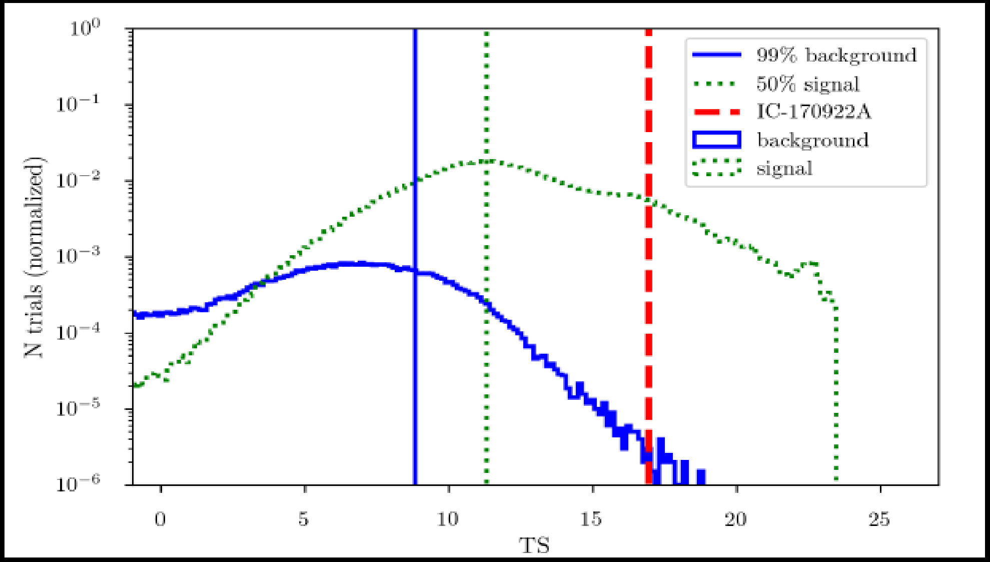
Null hypothesis assumes no correlation between gamma ray sources (catalog) and neutrino events

$$\mathcal{L} = \prod_i^N \left(\frac{n_s}{N}\mathcal{S} + (1 - \frac{n_s}{N})\mathcal{B} \right)$$

$$\mathcal{S}(\vec{x}, t) = \sum_s \frac{1}{2\pi\sigma^2} e^{-|\vec{x}_s - \vec{x}|^2/(2\sigma^2)}\, w_s(t)\, w_{\mathrm{acc}}(\theta_s)$$

Maximise Likelihood w.r.t n_s and other free parameters

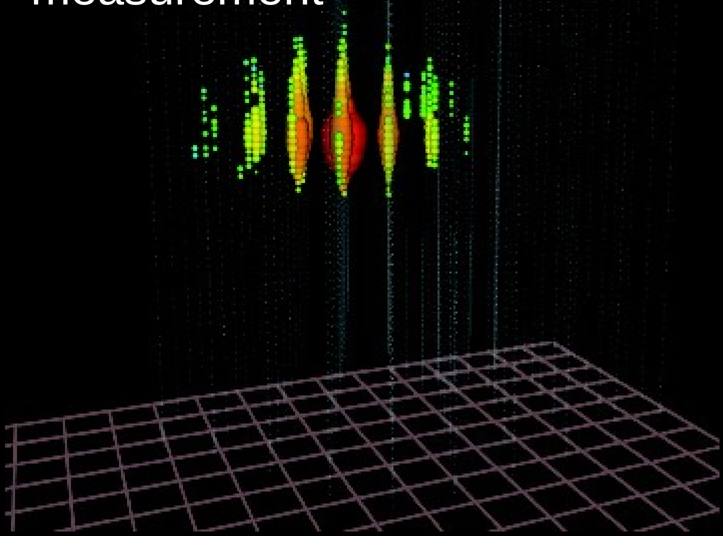
$$w_s(t) = \phi_E(t) = \int_{1\ \mathrm{GeV}}^{100\ \mathrm{GeV}} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$



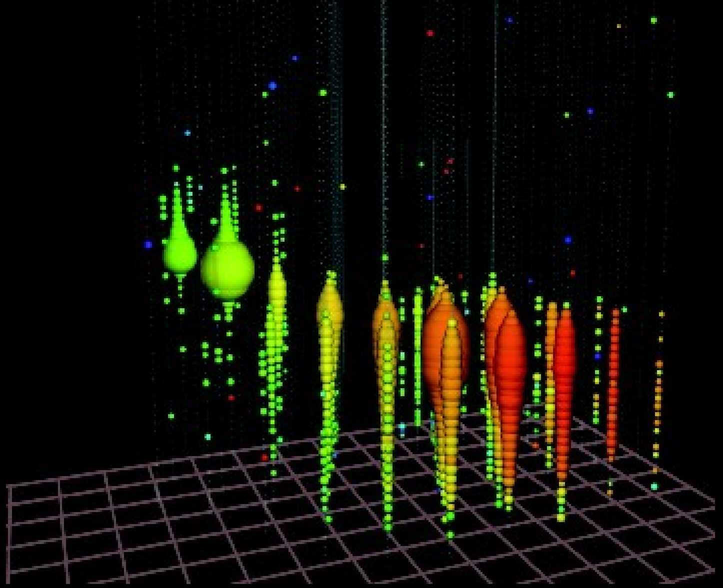
Pre-trial significance of 4.1 sigma
After trials reduces to 3 sigma

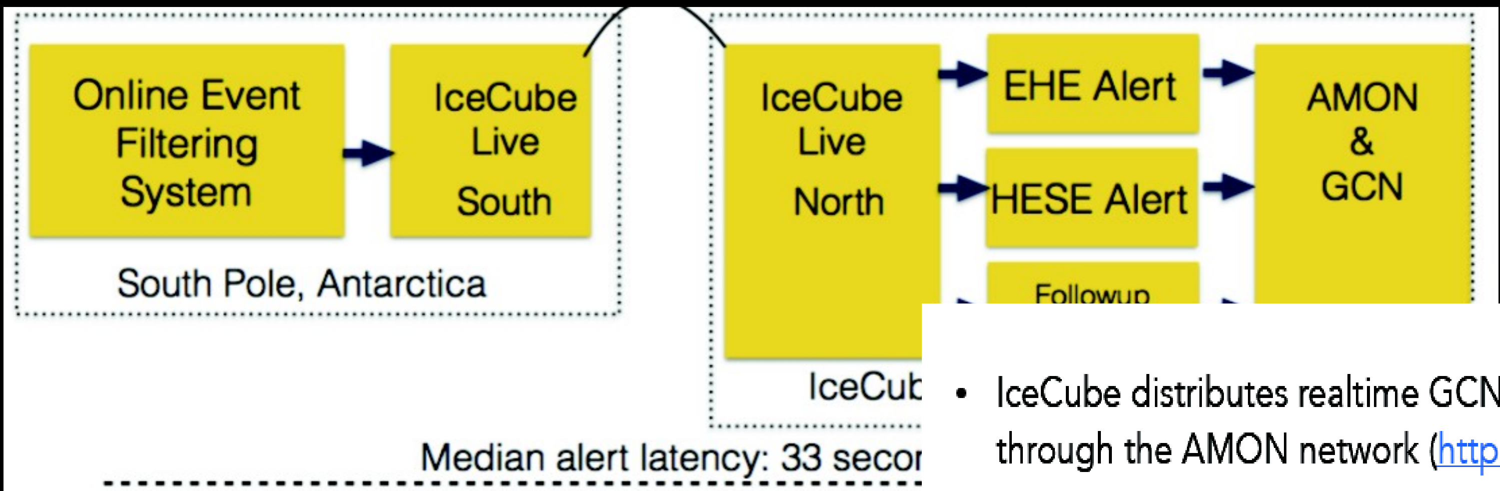
Multi-messenger Astrophysical Neutrino Signals

High Energy Starting Event (HESE) : Neutrinos interacting inside the detector, good energy measurement



Muon tracks : Good angular resolution, ideal for astronomy





- IceCube distributes realtime GCN alerts for muon neutrino events through the AMON network (http://amon.gravity.psu.edu/).
  - ~4 HESE events/year (~1 astrophysical)
  - ~4 EHE muon neutrino events (~2 astrophysical). 0.1° - 0.4°.