Neutrino/gamma-ray connections on blazars: IceCube-170922A and TXS 0506+056

16 August 2018

"Very High Energy Phenomena in the Universe 2018"

@Quy Nhon

Masaaki Hayashida (Konan Univ.)

for the Fermi-LAT collaboration++ (16 teams)

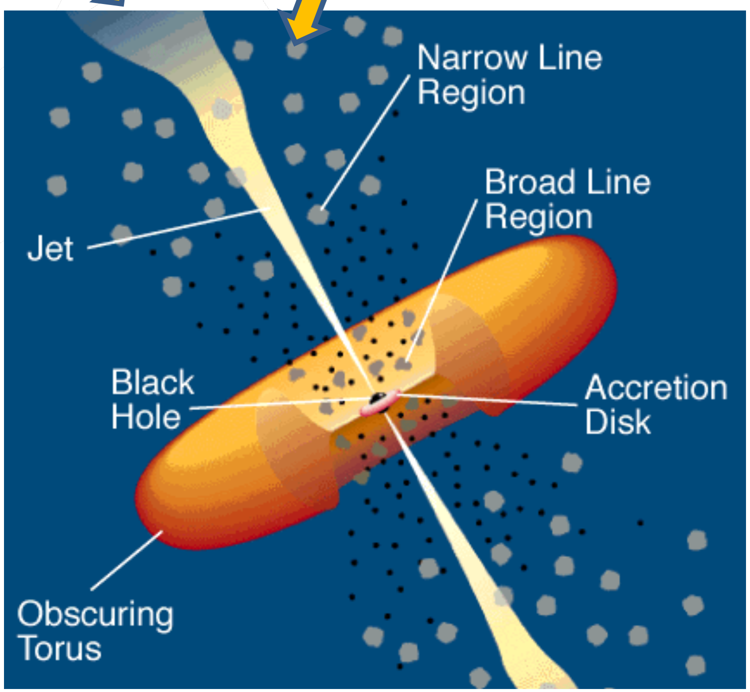
Outline

1. Introduction:
    1. Blazars as high-energy source
    2. Fermi transient search (ASP, FAVA)
2. IceCube-170922A/TXS0506+056
    1. Story to the discovery of the counterpart
    2. Multi-wavelength follow-up observations
    3. Chance coincidence calculation
    4. Gamma-ray band at the time of “neutrino flare” in the late 2014

Blazars: Active Galactic Nucleus Jets

Observer Observer

Blazar **Radio galaxy**



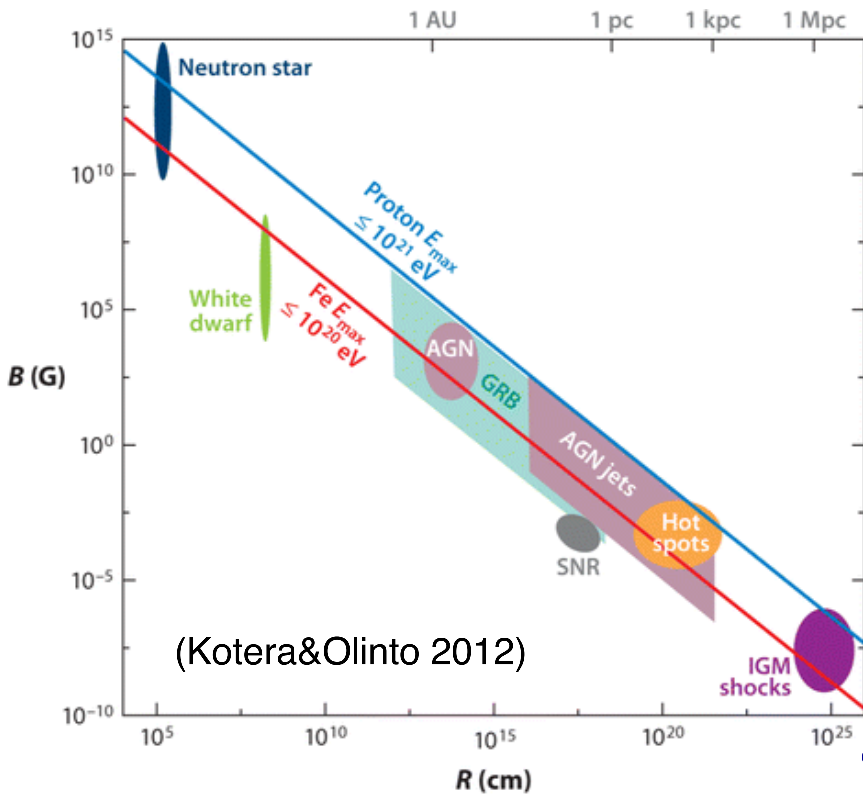
- polarized, variable emission
- flat radio spectrum

	Blazar	**Radio Galaxy**
• low power	BL Lac	FR I
• high power	FSRQ	FR II
	small viewing angle -> relativistic beaming (multiplied by $\delta^4 \rightarrow >10^4$)	mis-aligned blazar

- BL Lac type : weak disk (almost **no optical line**)
- Flat Spectrum Radio Quasar: luminous disk

High-energy astrophysical sources

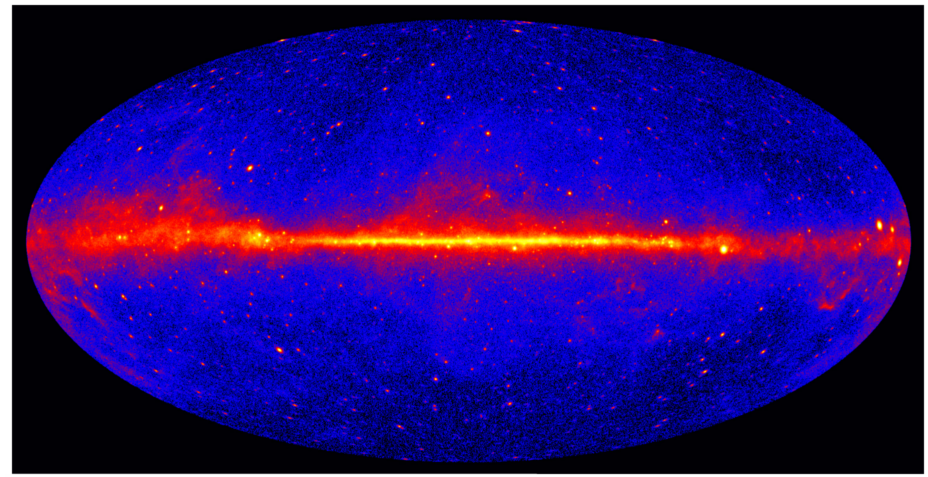
Hillas plot

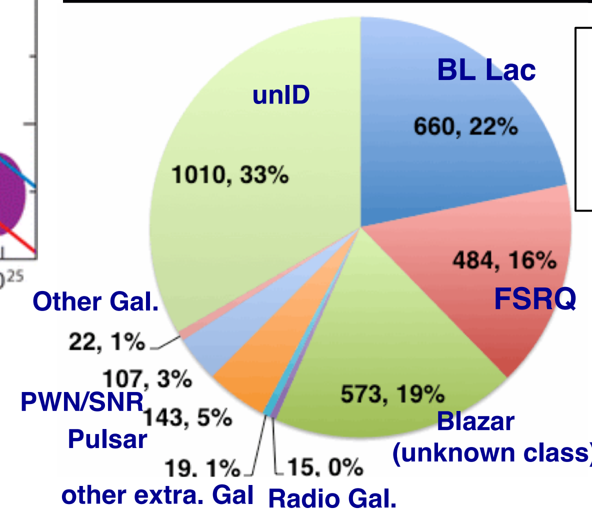


(Kotera&Olinto 2012)

AGN is a good candidate of the source of UHE cosmic rays

Gamma-ray sky (>100 MeV)





3rd LAT catalog (3FGL): 4-year data
3031 srcs

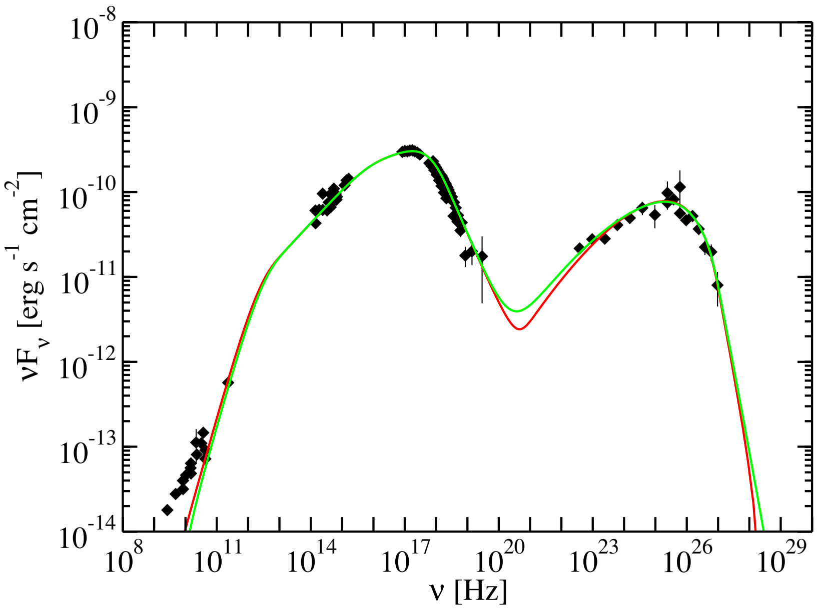
blazar is the most dominant HE γ-ray source

Origin of blazars emission

Leptonic models: synchrotron + inverse-Compton

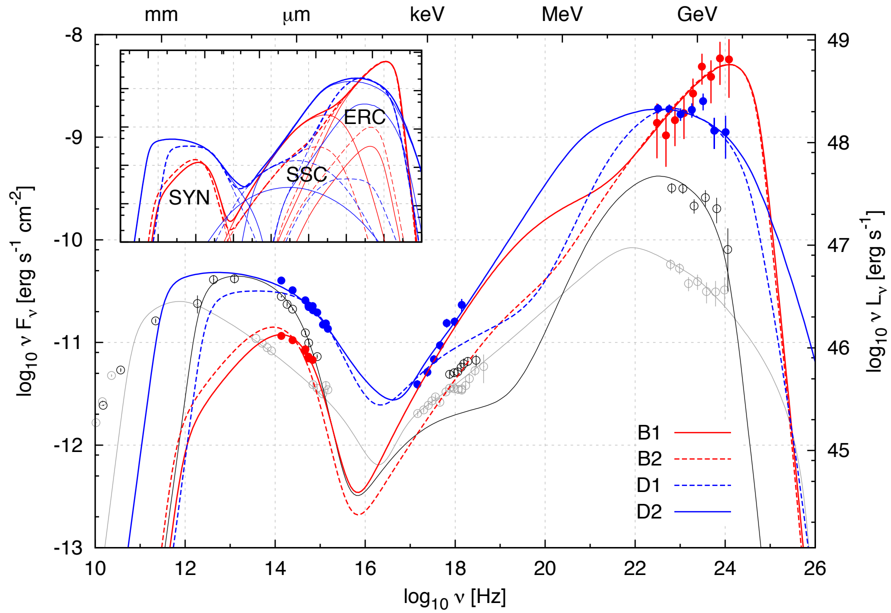
BL Lac (Mrk421) (Abdo+11)

synchrotron self-Compton (SSC)



FSRQ (3C 279) (Hayashida+15)

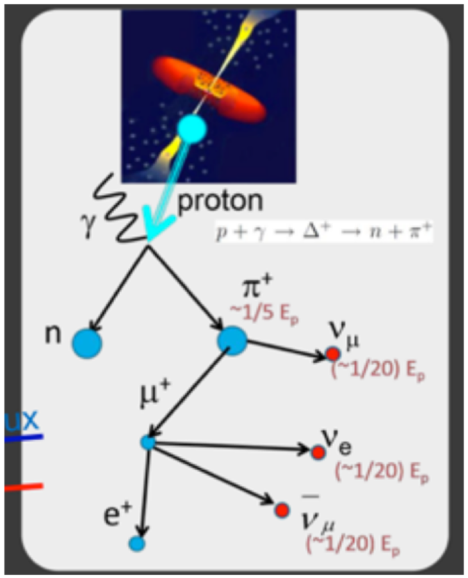
external Compton
(with dense disk photon fields)



the leptonic models successfully explain SED results
(mostly one-zone is fine, some for 2-zones, spine-sheath)

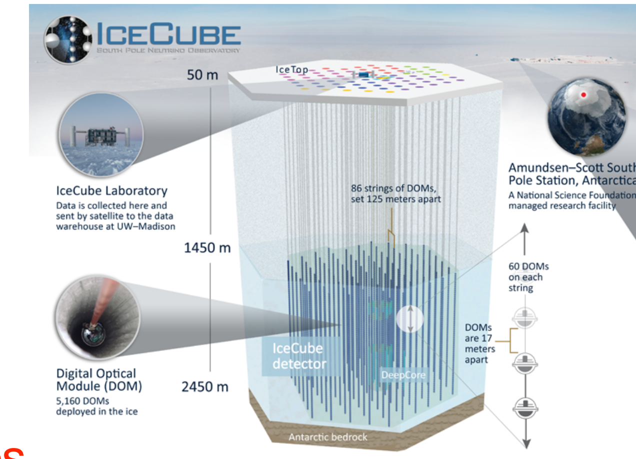
Searching for cosmic-ray origin

High-energy neutrinos are produced via interaction between cosmic rays and ambient photons (pγ) or protons (pp)



Neutrino source
＝Cosmic-ray source

Neutrino arrival direction indicates the direction of cosmic-ray sources



taken from IceCube webpage

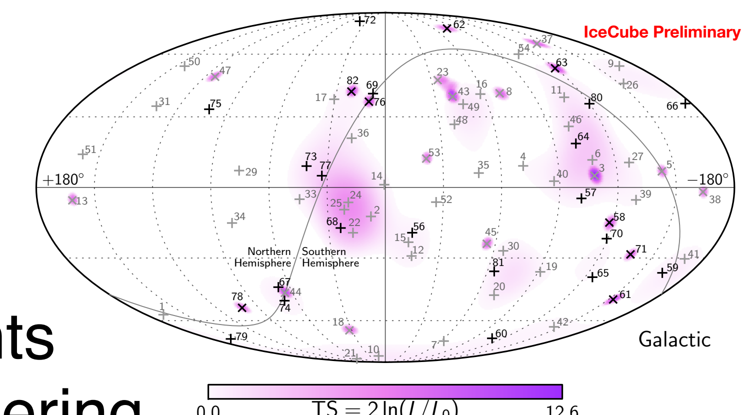
p (+ γ/N)

$\rightarrow \pi^0 \rightarrow 2\gamma$

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$

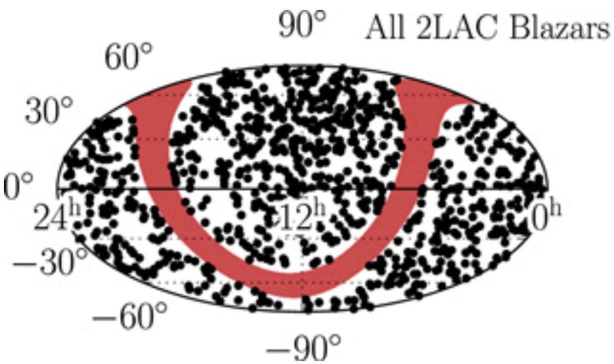
$\rightarrow e^\pm + \nu_\mu + \nu_e$

- tens of ν events
- no event clustering
  - extra-galactic origin?



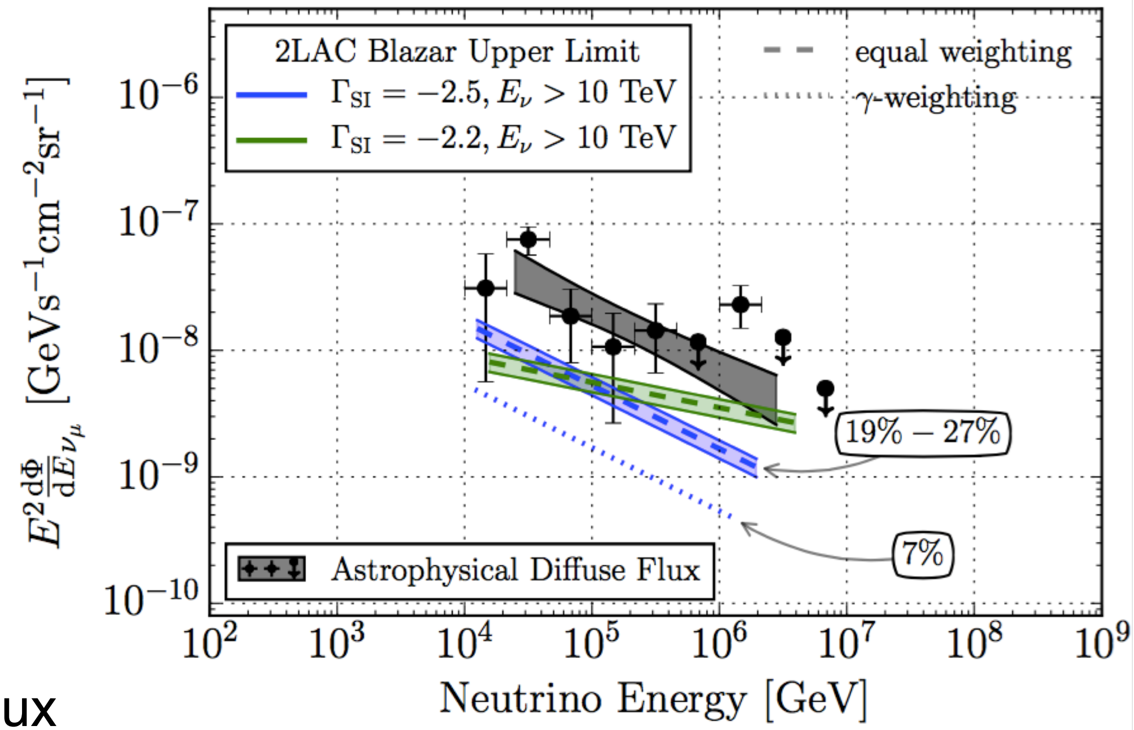
taken from ICRC 2017

LAT blazars and IceCube event correlations



(2LAC = 2nd LAT AGN catalog)
[862 srcs, |b| > 10 deg]

(IceCube Coll. 2017, ApJ)



no spatial correlation between 2LAC source and IC events

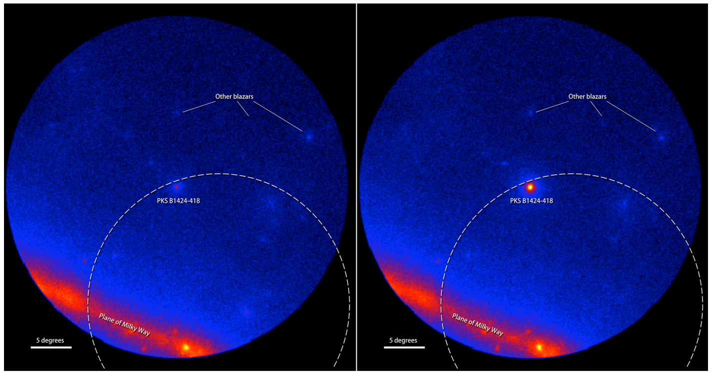
- < 27% of the IC neutrino flux

LAT blazars (steady emission) seem *not* to be dominant source for the neutrino origin

→ let's focus on transients (flares)

Possible association of PeV neutrino with high fluence GeV blazar PKS 1424-418 (z=1.522)

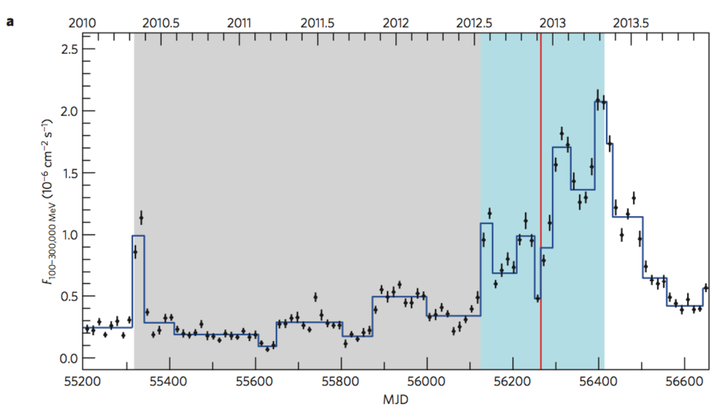
4 December 2011: 2 PeV



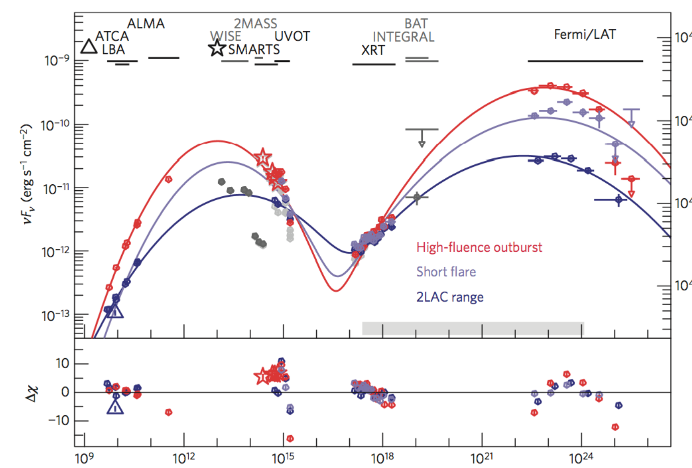
- Cascade event of error radius of ~10 deg (17 γ-ray blazars inside)
- ~5% chance probability

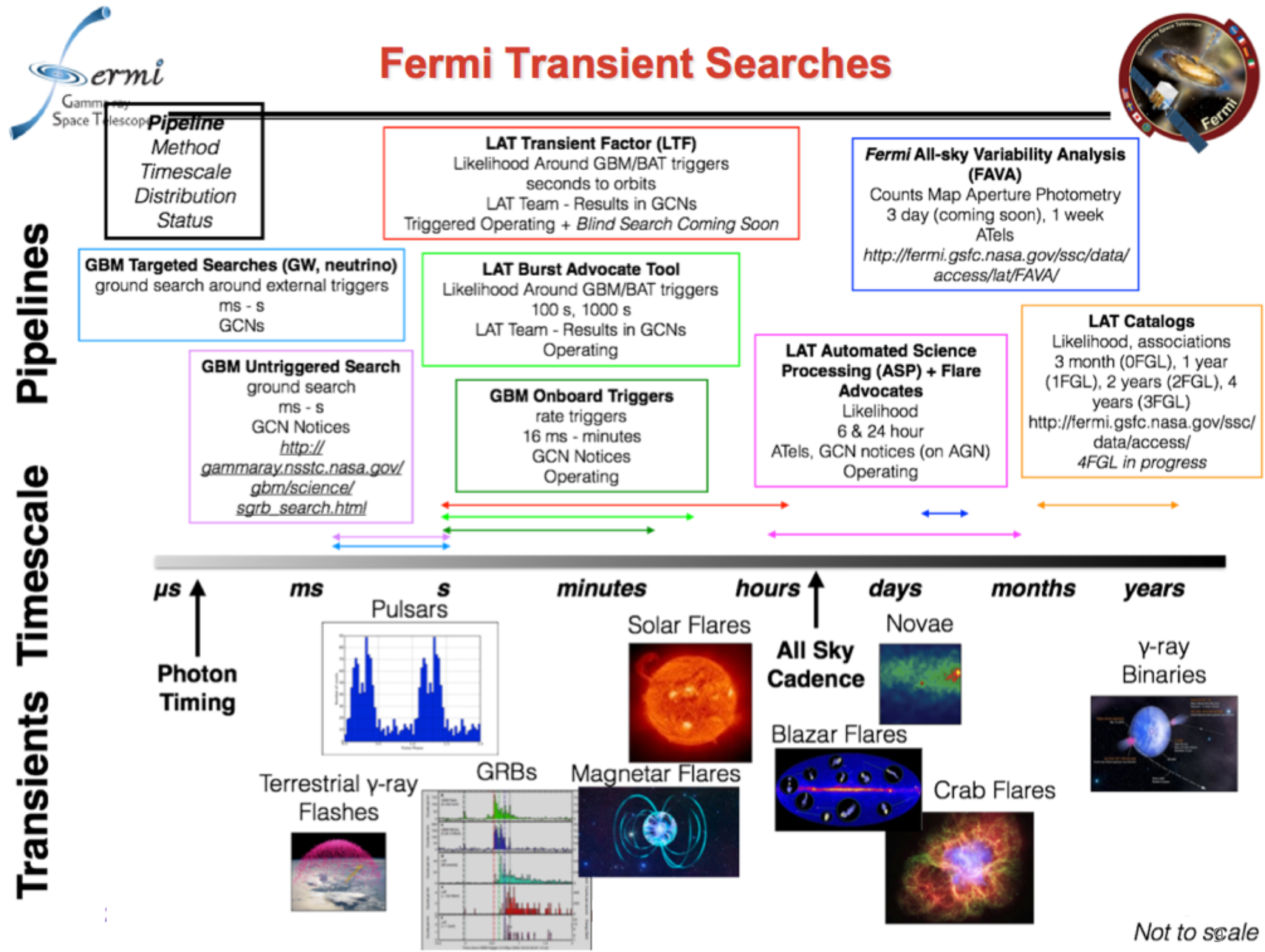
Table 1 | Maximum-possible number of petaelectronvolt-neutrino events in 36 months (988 days live-time) of IceCube data for the 17 2LAC γ-ray blazars in the field of the 2 PeV IceCube event based on 2LAC catalogue γ-ray spectra and contemporaneous X-ray data.

2FGL name	Common name	F_γ (erg cm^{-2} s^{-1})	$N^{max}_{\nu,PeV}$
2FGL J1230.2-5258	PMN J1229-5303	$(2.4^{+1.5}_{-1.5})\times10^{-11}$	0.14
2FGL J1234.0-5733	PMN J1234-5736	$(1.1^{+0.4}_{-0.4})\times10^{-11}$	0.06
2FGL J1303.5-4622	PMN J1303-4621	$(1.9^{+0.6}_{-0.6})\times10^{-11}$	0.11
2FGL J1303.8-5537	PMN J1303-5540	$(1.04^{+0.11}_{-0.11})\times10^{-10}$	0.38
2FGL J1304.3-4353	1RXS 130421.2-435308	$(2.11^{+0.25}_{-0.25})\times10^{-11}$	0.12
2FGL J1307.5-4300	1RXS 130737.8-425940	$(8.4^{+1.7}_{-1.7})\times10^{-12}$	0.05
2FGL J1307.6-6704	PKS B 1304-668	$(1.54^{+0.15}_{-0.15})\times10^{-10}$	0.89
2FGL J1314.5-5330	PMN J1315-5334	$(8.1^{+0.9}_{-0.9})\times10^{-11}$	0.47
2FGL J1326.7-5254	PMN J1326-5256	$(1.04^{+0.21}_{-0.18})\times10^{-10}$	0.59
2FGL J1329.2-5608	PMN J1329-5608	$(1.38^{+0.36}_{-0.29})\times10^{-10}$	0.93
2FGL J1330.1-7002	PKS B 1326-697	$(1.53^{+0.11}_{-0.11})\times10^{-10}$	0.89
2FGL J1352.6-4413	PKS B 1349-439	$(5.4^{+1.0}_{-1.0})\times10^{-11}$	0.32
2FGL J1400.6-5601	PMN J1400-5605	$(6.9^{+0.8}_{-0.8})\times10^{-11}$	0.40
2FGL J1407.5-4257	CGRaBS J1407-4302	$(1.6^{+0.5}_{-0.5})\times10^{-11}$	0.09
2FGL J1428.0-4206*	PKS B1424-418*	$(2.04^{+0.17}_{-0.16})\times10^{-10}$*	1.57*
2FGL J1508.5-4957	PMN J1508-4953	$(7.6^{+3.0}_{-2.3})\times10^{-11}$	0.55
2FGL J1514.6-4751	PMN J1514-4748	$(5.6^{+0.6}_{-0.6})\times10^{-11}$	0.32
Sum (2LAC)			7.9



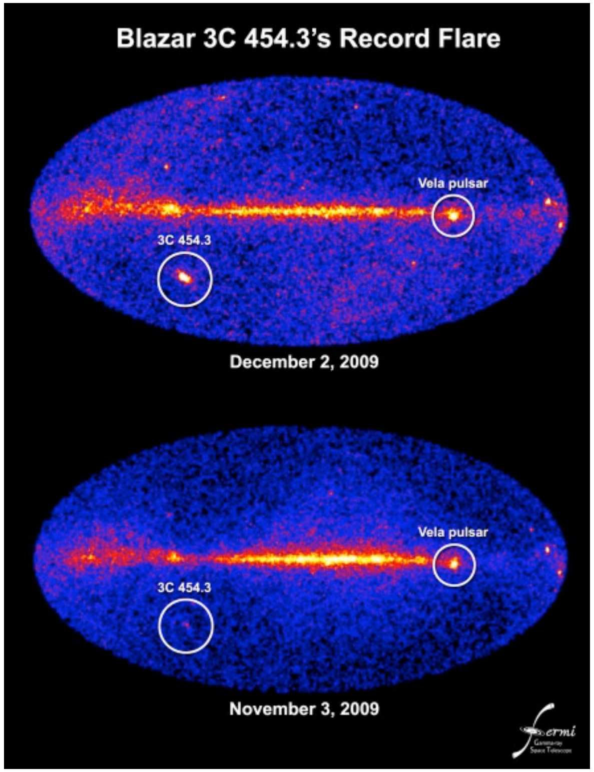
Kadler+16




Fermi Gamma-ray Space Telescope
Fermi Transient Searches
Fermi
Pipeline
Method
Timescale
Distribution
Status
LAT Transient Factor (LTF)
Likelihood Around GBM/BAT triggers
seconds to orbits
LAT Team - Results in GCNs
Triggered Operating + Blind Search Coming Soon
Fermi All-sky Variability Analysis (FAVA)
Counts Map Aperture Photometry
3 day (coming soon), 1 week
ATels
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/
GBM Targeted Searches (GW, neutrino)
ground search around external triggers
ms - s
GCNs
LAT Burst Advocate Tool
Likelihood Around GBM/BAT triggers
100 s, 1000 s
LAT Team - Results in GCNs
Operating
GBM Untriggered Search
ground search
ms - s
GCN Notices
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html
GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices
Operating
LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)
Operating
LAT Catalogs
Likelihood, associations
3 month (0FGL), 1 year (1FGL), 2 years (2FGL), 4 years (3FGL)
http://fermi.gsfc.nasa.gov/ssc/data/access/
4FGL in progress
Pipelines
Timescale
Transients
μs
ms
s
minutes
hours
days
months
years
Photon Timing
Pulsars
Solar Flares
All Sky Cadence
Novae
γ-ray Binaries
Blazar Flares
Terrestrial γ-ray Flashes
GRBs
Magnetar Flares
Crab Flares
Not to scale

LAT Automated Science Processing (ASP) +Flare advocate

LAT
1-day
data



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GLAST LAT detection of a possible new gamma-ray flaring blazar: PKS 1502+106

ATel #1650; *S. Ciprini (Univ./INFN Perugia) on behalf of the GLAST Large Area Telescope Collaboration*
on 8 Aug 2008; 00:02 UT
Credential Certification: Stefano Ciprini (stefano.ciprini@pg.infn.it)

Subjects: Gamma Ray, >GeV, AGN, Quasar

Referred to by ATel #: 1661, 1905

The Large Area Telescope (LAT), one of two instruments on the Gamma-ray Large Area Space Telescope (GLAST) (launched June 11, 2008), which is still in its post-launch commissioning and checkout phase, has been monitoring high flux from a source positionally consistent with the blazar PKS 1502+106 (R.A.:15h04m24.9797s; Dec.:+10d29m39.198s, also known as OR 103 and S3 1502+10) since August 6, 2008.

Preliminary analysis indicates that the source is in a high state with a gamma-ray flux (E>100MeV) well above pre-defined LAT flaring source reporting threshold of 2x10^-6 photons cm^-2 s^-1.

This is a well-known radio source classified as a Flat Spectrum Radio Quasar (FSRQ), observed by several X-ray instruments. This is the first time that it has been reported to have gamma-ray emission.

Please note that PKS 1502+106 has two possible redshifts listed in the literature: z=0.56 and 1.83; the former seems preferred (A.E. Wright et al. 1979 ApJ 229,73; B.J. Wilkes 1986, MNRAS, 218, 331).

Because GLAST has just started its scientific standard operations, regular gamma-ray monitoring of this source will be pursued. In consideration of the ongoing activity of this source we strongly encourage multiwavelength observations of PKS 1502+106.

The GLAST LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

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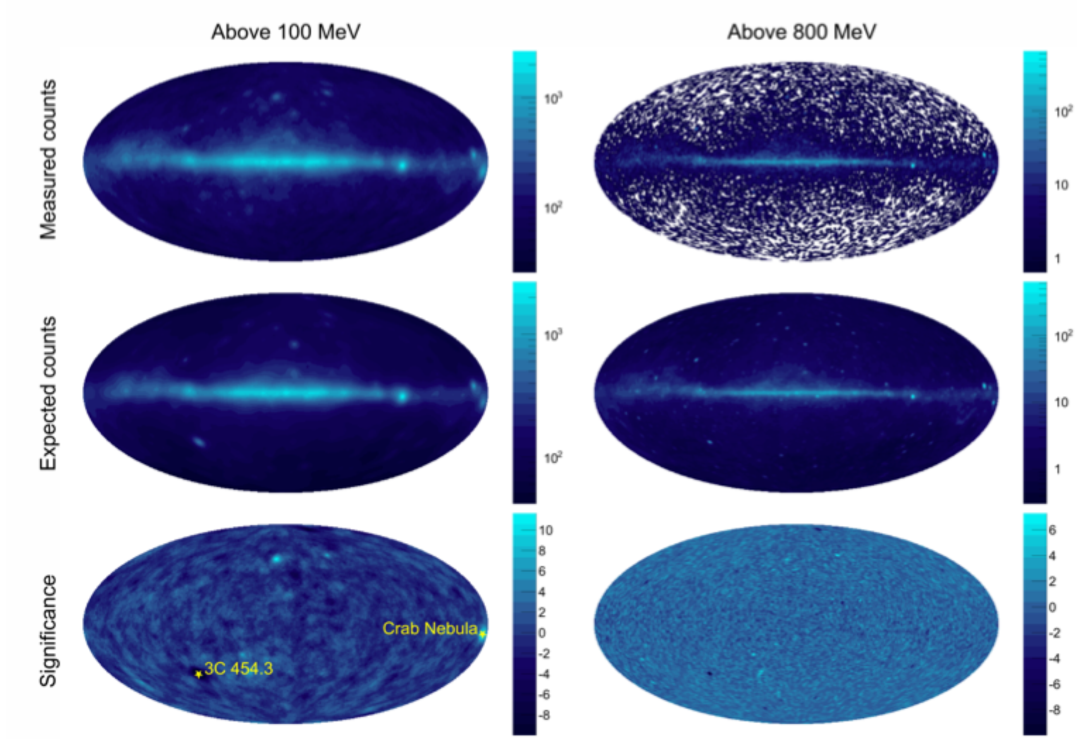
Related
- 1905 Fermi-LAT detection of renewed activity from the blazar PKS 1502+106
- 1661 Archival light curve for the flaring GLAST blazar PKS 1502+106
- 1650 GLAST LAT detection of a possible new gamma-ray flaring blazar: PKS 1502+106

- Flare Advocate run the daily (1-day and 6-hour data) analysis script and check the ASP result
- Once transient objects are found, Astronomers Telegram is issued (typically, flux >1.0×10^{-6} photons/cm^2/s for E>100 MeV)

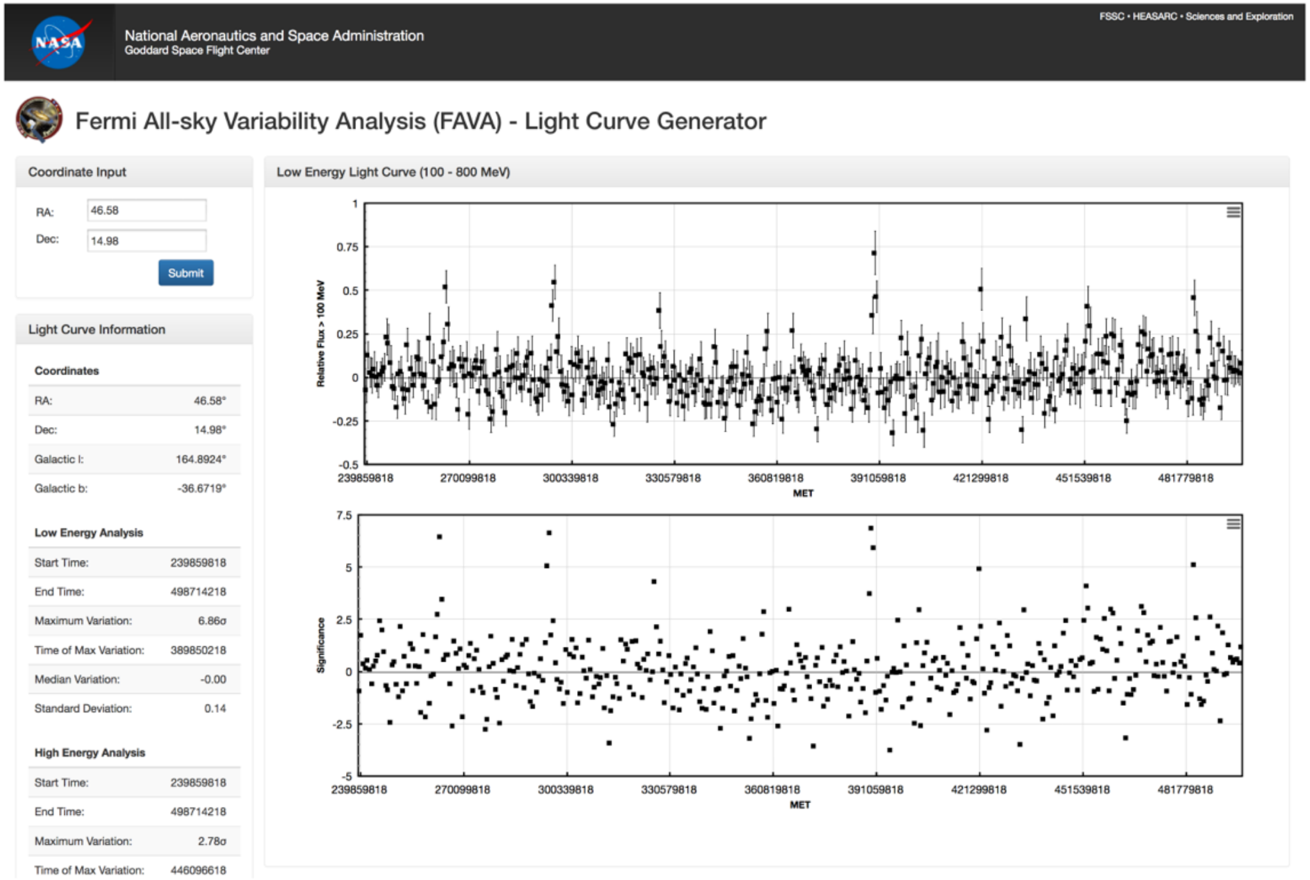
Fermi All sky Variability Analysis (FAVA)

- For Weekly-binned data
- Comparison of observed counts with average (expected) counts
- E>100 MeV, E>800 MeV
- aperture photometry (↔ max. likelihood fit for the standard analysis.)
- Crab nebula flare is first detected by this analysis



$$N^{exp}(\phi,\theta) = \sum_{E:j=1..12}\sum_{\alpha:i=1..4} N^{tot}_{i,j}(\phi,\theta) \times \frac{\epsilon^{week}_{i,j}(\phi,\theta)}{\epsilon^{tot}_{i,j}(\phi,\theta)},$$

FAVA webpage



- https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/LightCurve.php
- Automatic production of light curve at any locations (RA, Dec)

Real time Alert IceCube events (since April 2016)

9 HESE events: https://gcn.gsfc.nasa.gov/amon_hese_events.html

EventNum_RunNum	Date	Time UT	Type	RA(deg)	Dec(deg)	Err(min)	charge	Sig_Tr
71165249_130949	18/04/23	02:28:40.98	HESE	294.882	+71.953	534.0	13631.	0.34
34032434_130171	17/10/28	08:28:14.81	HESE	275.076	+34.501	534.0	6317.	0.30
56068624_130126	17/10/15	01:34:30.06	HESE	162.579	-15.861	73.79	13906.	0.51
32674593_129474	17/05/06	12:36:55.80	HESE	221.675	-26.036	73.79	8685.	0.35
65274589_129281	17/03/12	13:49:39.83	HESE	304.730	-26.238	73.79	8858.	0.78
38561326_128672	16/11/03	09:07:31.12	HESE	40.825	+12.559	66.00	7546.	0.30
58537957_128340	16/08/14	21:45:54.00	HESE	199.310	-32.016	89.39	10431.	0.12
6888376_128290	16/07/31	01:55:04.00	HESE	215.109	-0.458	73.79	15814.	0.91
67093193_127853	16/04/27	05:52:32.00	HESE	240.568	+9.342	35.99	18883.	0.92

6 EHE events: https://gcn.gsfc.nasa.gov/amon_ehe_events.html

EventNum_RunNum	Date	Time UT	Type	RA(deg)	Dec(deg)	Err(min)	Signalness
17569642_130214	17/11/06	18:39:39.21	EHE	340.250	+7.314	14.99	0.745
50579430_130033	**17/09/22**	**20:54:30.43**	**EHE**	**77.285**	**+5.752**	**14.99**	**0.565**
80305071_129307	17/03/21	07:32:20.69	EHE	98.327	-14.486	19.48	0.280
80127519_128906	16/12/10	20:06:40.31	EHE	45.855	+15.785	14.99	0.490
26552458_128311	16/08/06	12:21:33.00	EHE	122.798	-0.733	6.67	0.280
6888376_128290	16/07/31	01:55:04.00	EHE	214.544	-0.335	20.99	0.849

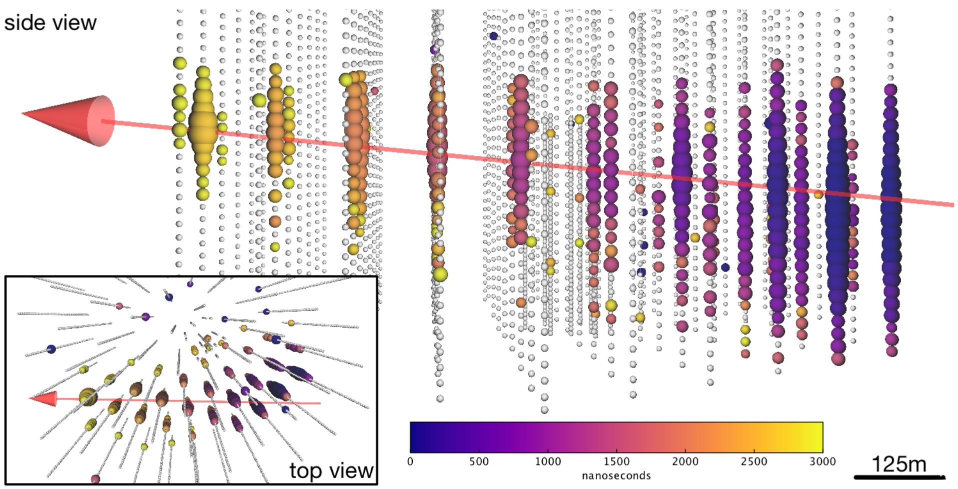
*No significant γ-ray counterpart was found by the Fermi-LAT team (e.g., ATel #9303, GCN #20269), **but expect for one***

IceCube-170922A

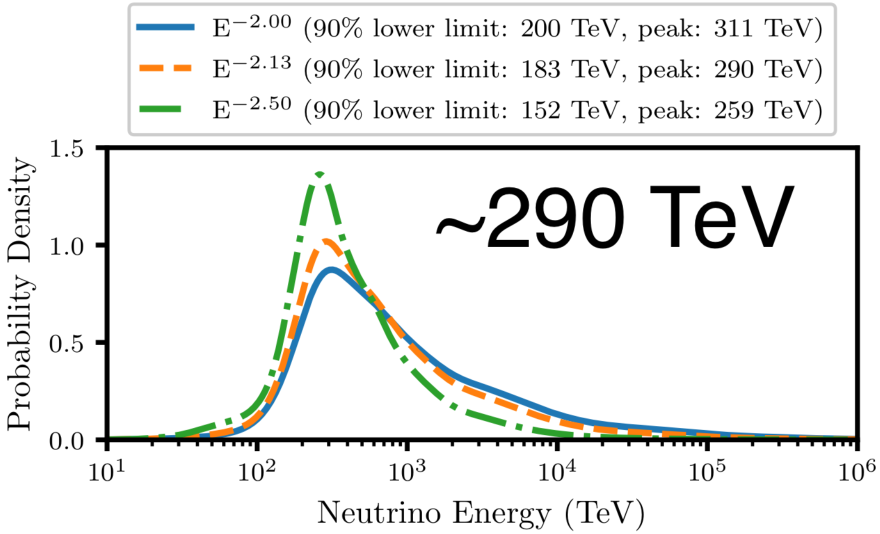
(IceCube, Fermi-LAT, MAGIC++Coll. 2018 Science, aat1378)

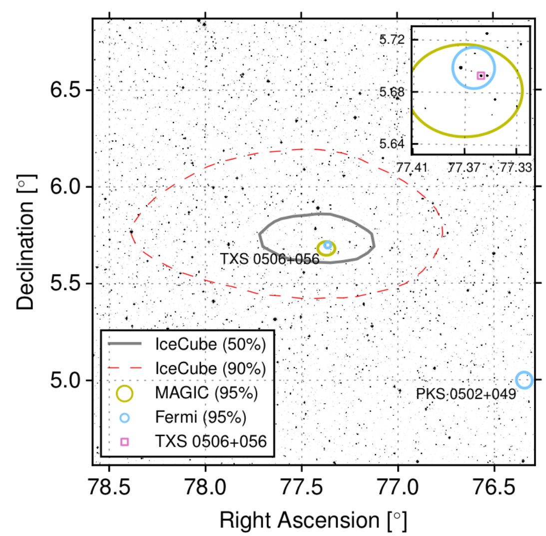
EHE alert: 2017/9/22 20:54:30 UTC

IceCube event
(ν_μ :muon track)



energy estimation



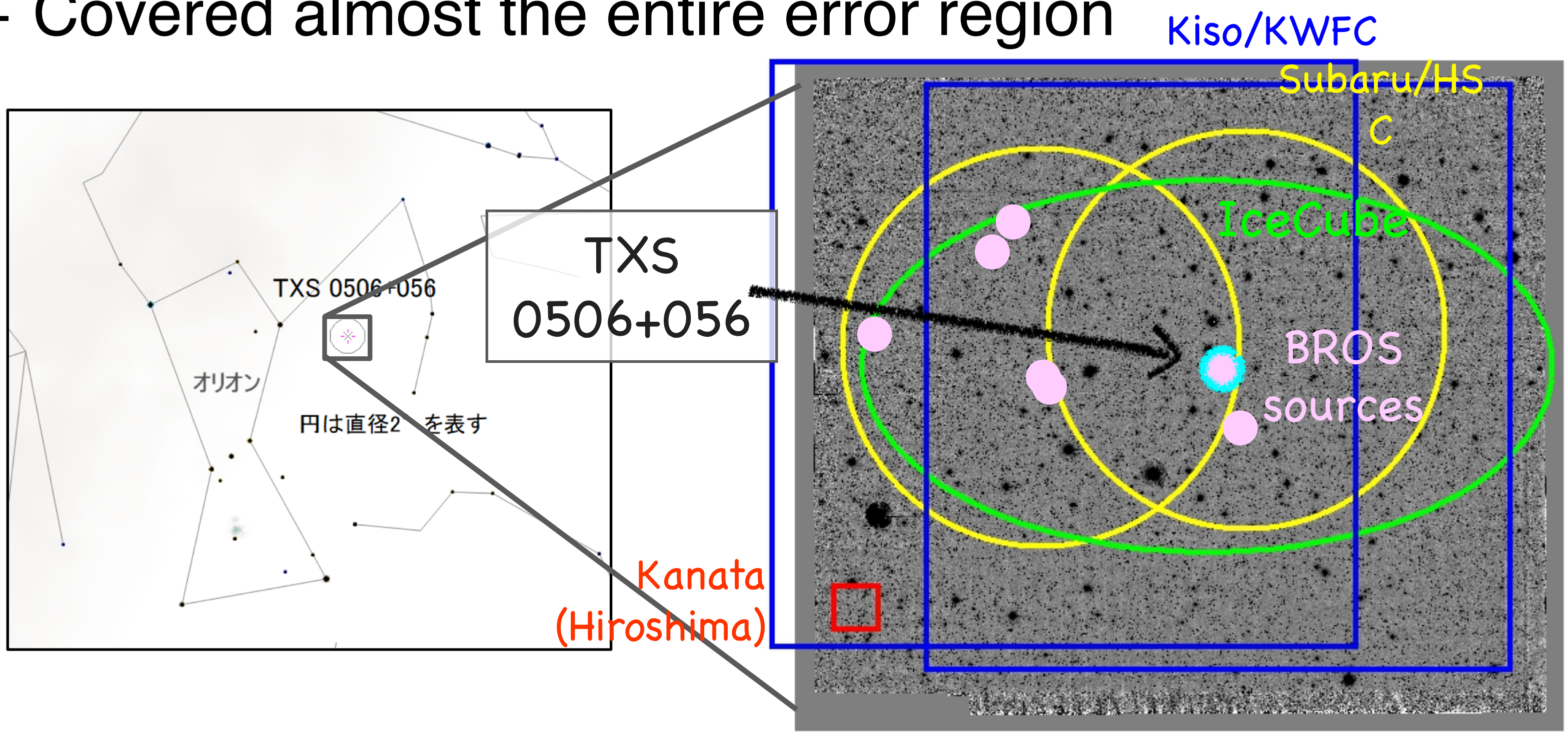


GCN CIRCULAR #21916

RA: 77.43 deg (-0.80/+1.30 deg)
Dec: 5.72 deg (-0.40/+0.70 deg)
(J2000: 90% error)

Story to the discovery of the counterpart - 1

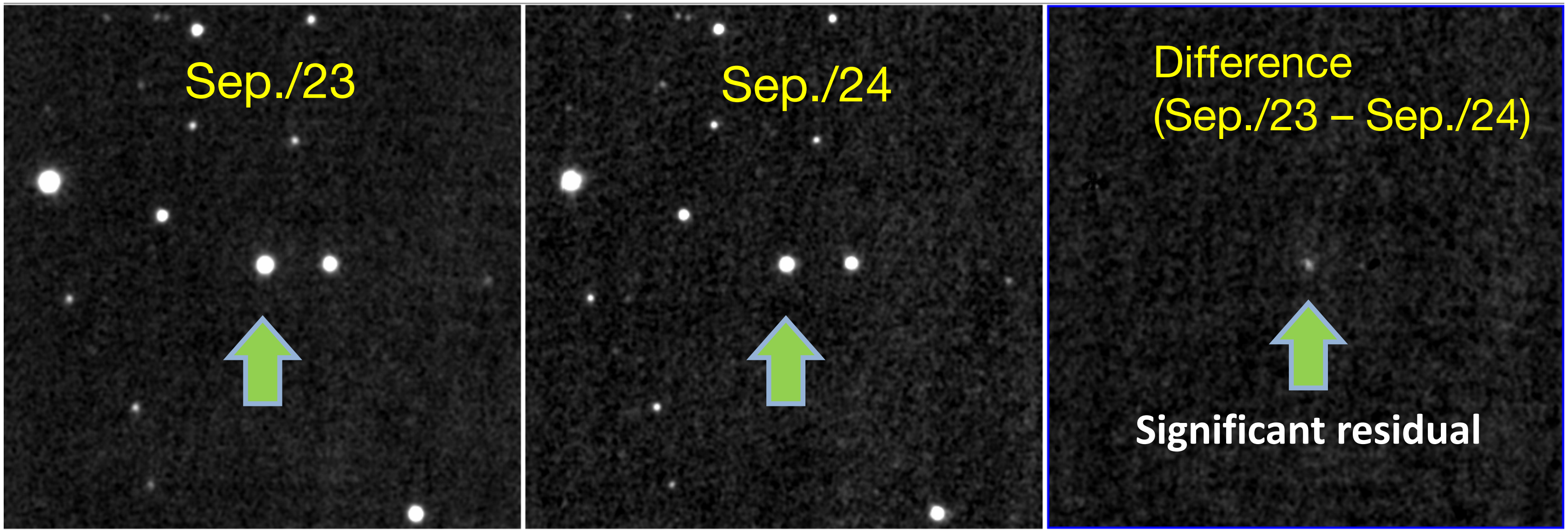
- The IceCube event error region includes 7 blazar candidates
  - Blazar Radio and Optical Survey (BROS: *Itoh+,in prep):* 56,315 srcs Dec >–40°
  - (a few 100 variable optical sources per 1deg^2)
- Observed all those blazars candidates with Subaru/HSC, Kiso/KWFC and Kanata **by optical teams in Japan**
  - Covered almost the entire error region



Story to the discovery of the the counterpart - 2

The quick optical follow-up by Kanata

PI: Y. Tanaka (Hiroshima Univ.)



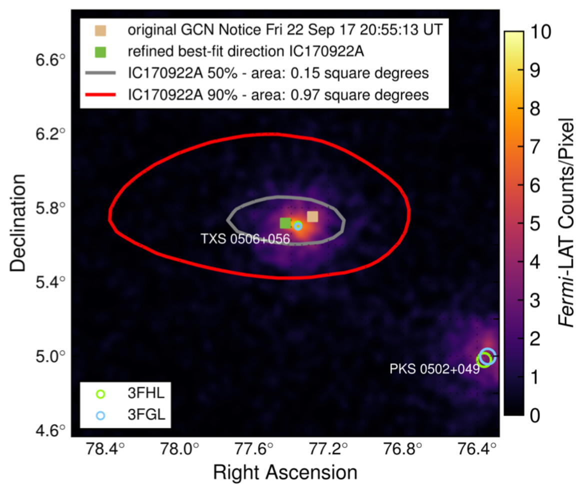
R-band Kanata/HONIR (Hiroshima Univ.)

- **One of the 7 blazars (=TXS 0506+056) showed significant variability (fading)**
- **Bright optical state among historical records**

→ *Let's check LAT data*

Story to the discovery of the the counterpart - 3

Fermi-LAT data for TXS 0506+056



Y.Tanaka+ (Fermi-LAT)
Atel #10791

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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, 10942

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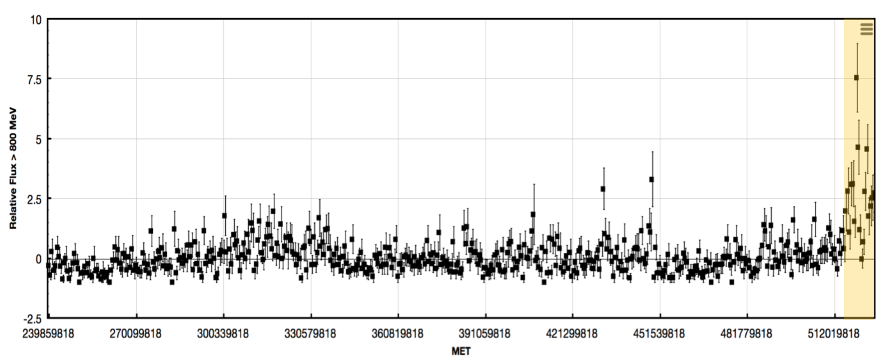
We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We 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 to NED, the R-band magnitude is reported as 15.1 (Healey et al. 2008, ApJS 175, 97). Radio observations show that this blazar has had increasing flux during the past year: http://www.astro.caltech.edu/ovroblazars/data.php?page=data_query, http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0506+056.shtml.

Because Fermi operates in an all-sky scanning mode, regular gamma-ray monitoring of this source region will continue. For this source the Fermi-LAT contact person is Yasuyuki T. Tanaka (ytanaka@astro.hiroshima-u.ac.jp). The Fermi-LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

Light curve (>800 MeV) from FAVA
(9+year: 2008 Aug.8 – 2017 Oct.)



TXS 0506+056 (z=0.3365) (Paiano+18)

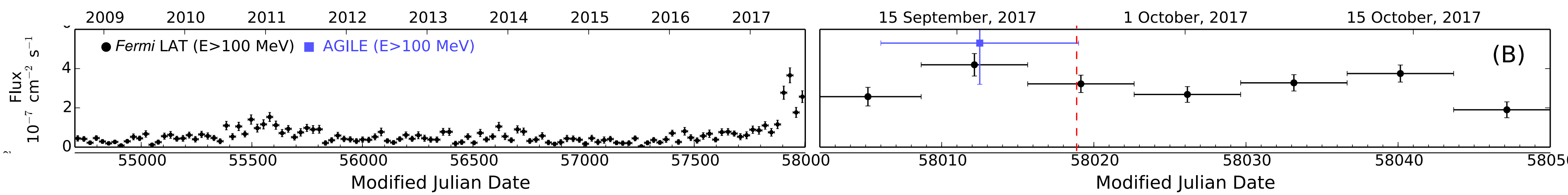
- (RA, Dec) = (05h09m25.964 +05°41'35".33)
- BL Lac, Intermediate Spectral Peaked (ISP) [log(ν_{sync}[Hz])~14.2]
- LAT source: 3FGL J0509.4+0541, 2FHL J0509.5+0541
- Bright radio source: a MOJAVE (15GHz VLBI) monitoring source

High-energy γ-ray light curve

9 years (28-day bins)

2 months (7-day bins)

IceCube-17922A



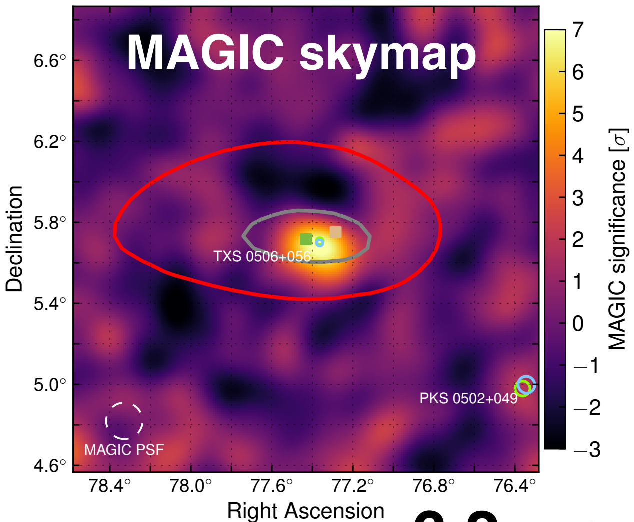
Flux(>0.1GeV): (7.6±0.2)e-8 [9.5-year average]
Maximum: (53 ± 6)e-8 [4 to 11 July 2017]
The ν event: (36 ± 5)e-8 [15 to 27 Sep. 2017]

→ ~ 5 times higher than the averaged flux

VHE γ-ray observations

IC170922A at <u>MJD 58018.87</u>

Detection of >90 GeV γ-ray by MAGIC



MAGIC observations: ~13 hrs

Date MJD	Effective time [hours]	Flux > 90 GeV $[10^{-11}\ \mathrm{cm^{-2}\ s^{-1}}]$	Significance σ
58020.16	1.07	<3.56	0
58024.21	1.25	<6.15	1.8
58025.18	2.9	<5.80	1.0
58026.17	3.0	<3.56	0.95
58027.18	2.9	1.91 ± 1.18	2.5
58028.23	0.8	< 5.78	1.7
58029.22	1.3	5.86 ± 1.50	4.3
58030.24	0.65	8.02 ± 2.05	5.4

6.2 σ excess (more detections from 41 hrs to 2017 Nov.: Ansoldi+18)

HESS observations: ~4hr (***non detection***)

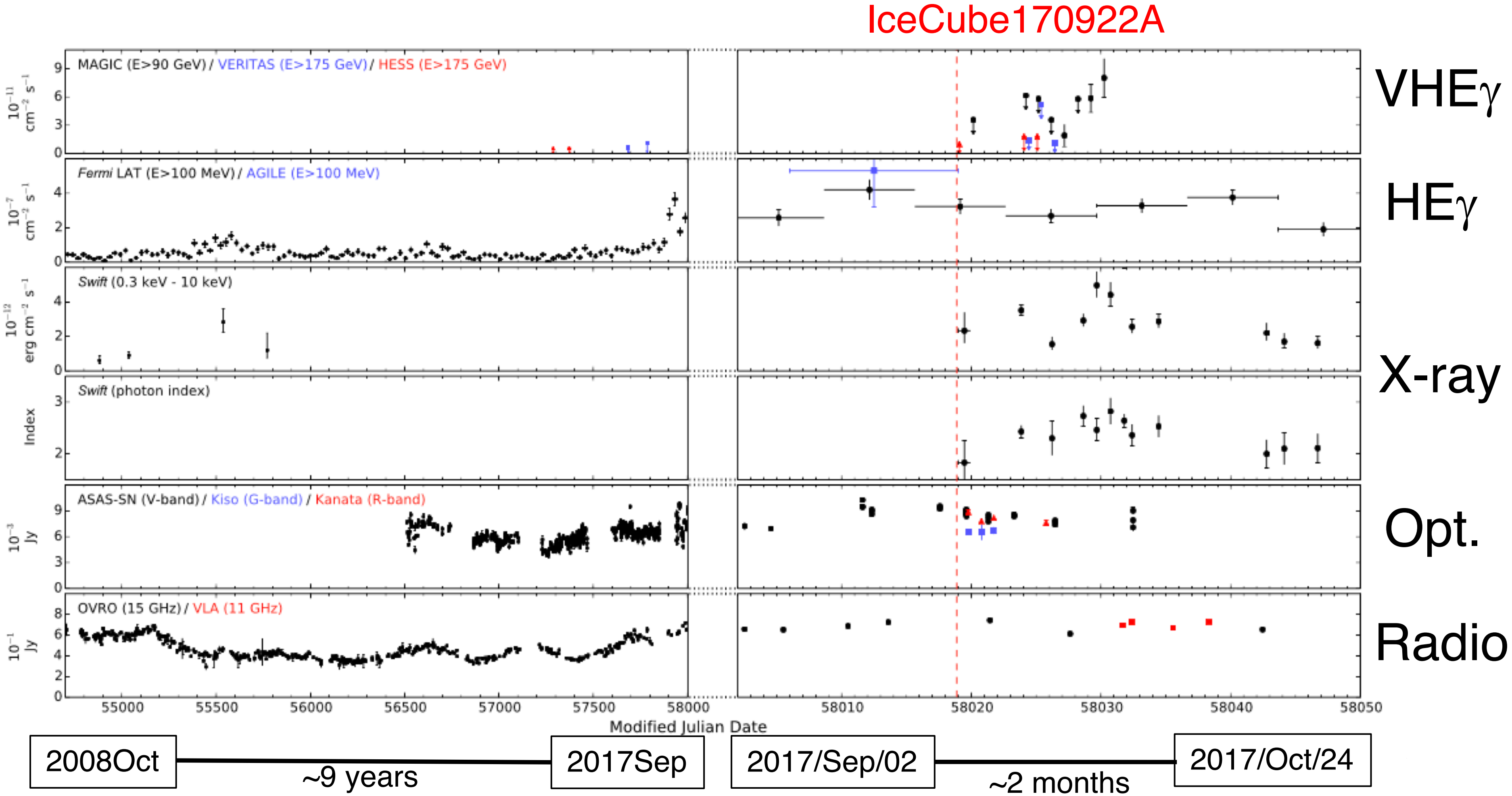
MJD [days]	Observation time [h]	E_{min} [TeV]	$dN_{95\%\,\mathrm{C.L.}}(E > E_{\mathrm{min}})$ $[\mathrm{ph\,/\,cm^{-2}\,s^{-1}}]$
57286 – 57287		0.175	$< 5.4 \times 10^{-12}$
57366 – 57382		0.175	$< 5.4 \times 10^{-12}$
58019.07	1.35	0.175	$< 1.0 \times 10^{-11}$
58024.08	0.48	0.175	$< 1.8 \times 10^{-11}$
58025.08	1.65	0.175	$< 1.8 \times 10^{-11}$

VERITAS observations: 5.5hrs (***non detection***)

MJD [days]	Time window (half width) [days]	$F(E > 175\ \mathrm{GeV})$ $[\mathrm{ph\ cm^{-2}\ s^{-1}}]$
57685.4392	±0.0104	$< 6.8 \times 10^{-12}$
57686.4500	±0.0200	$< 5.7 \times 10^{-12}$
57786.1544	±0.0142	$< 1.1 \times 10^{-11}$
58019.3971	±0.0124	$< 2.1 \times 10^{-10}$
58024.4380	±0.0653	$< 1.4 \times 10^{-11}$
58025.3932	±0.0219	$< 5.2 \times 10^{-11}$
58026.4399	±0.0211	$< 1.1 \times 10^{-11}$

(5.8σ from 35hr to 2018 Feb.: Abeysekara+18)

Multi-wavelength light curve



Flux enhancements can be seen in all waveband
(but no short time flare at the event)

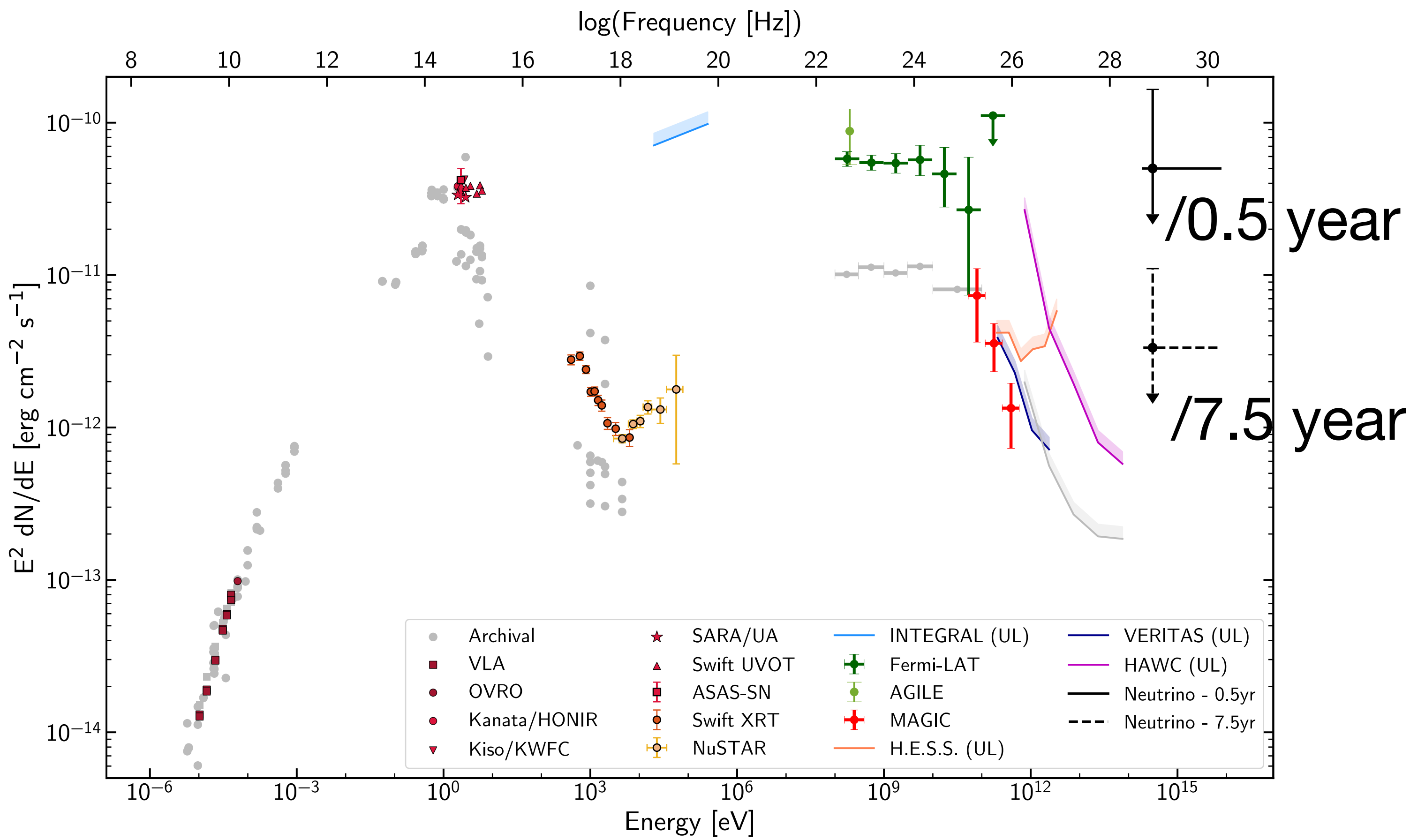
Summary of follow-up observations

Observations obtained within 14 days of IceCube-170922A

- Radio: **VLA** (Oct5: 2-12 GHz :Atel#10861), **OVRO** (15 GHz: monitoring)
- NIR/Optical/UV: **Kanata** (Sep23: *R*-band, Atel#10844), **Kiso** (Sep23: *g*-band), **SARA** (Sep29: *B,V,R*: Atel#10831), **ASAS-SN** (Sep23, *V*-band, Atel#10794), **Swift-UVOT** (Sep27, M2,W1,W2, U,V, B)
- X-ray: **Swift-XRT** (Sep27-30: 0.3-10 keV Atel#10792) Γ=2.78±0.30, **NuSTAR** (Sep29: 3-79 keV, Atel#10845) Γ =1.43±0.43, **INTEGRAL**(UL:20-250 keV) GCN#21917)
- HE gamma-ray: **Fermi-LAT** (Sep 9 – Oct 6, Atel#10791) Γ ~2, **AGILE** (Sep10-Sep23, Atel#10801) Γ ~2,
- VHE gamma-ray: **MAGIC** (Sep28 - Oct4: 80-400 GeV, Atel#10817) Γ =3.9±0.4, **VERITAS** (UL: >175 GeV, Atel#10833), **HESS**(UL: >175 GeV, Atel#10787), **HAWC**(UL:>1 TeV, Atel#10802)

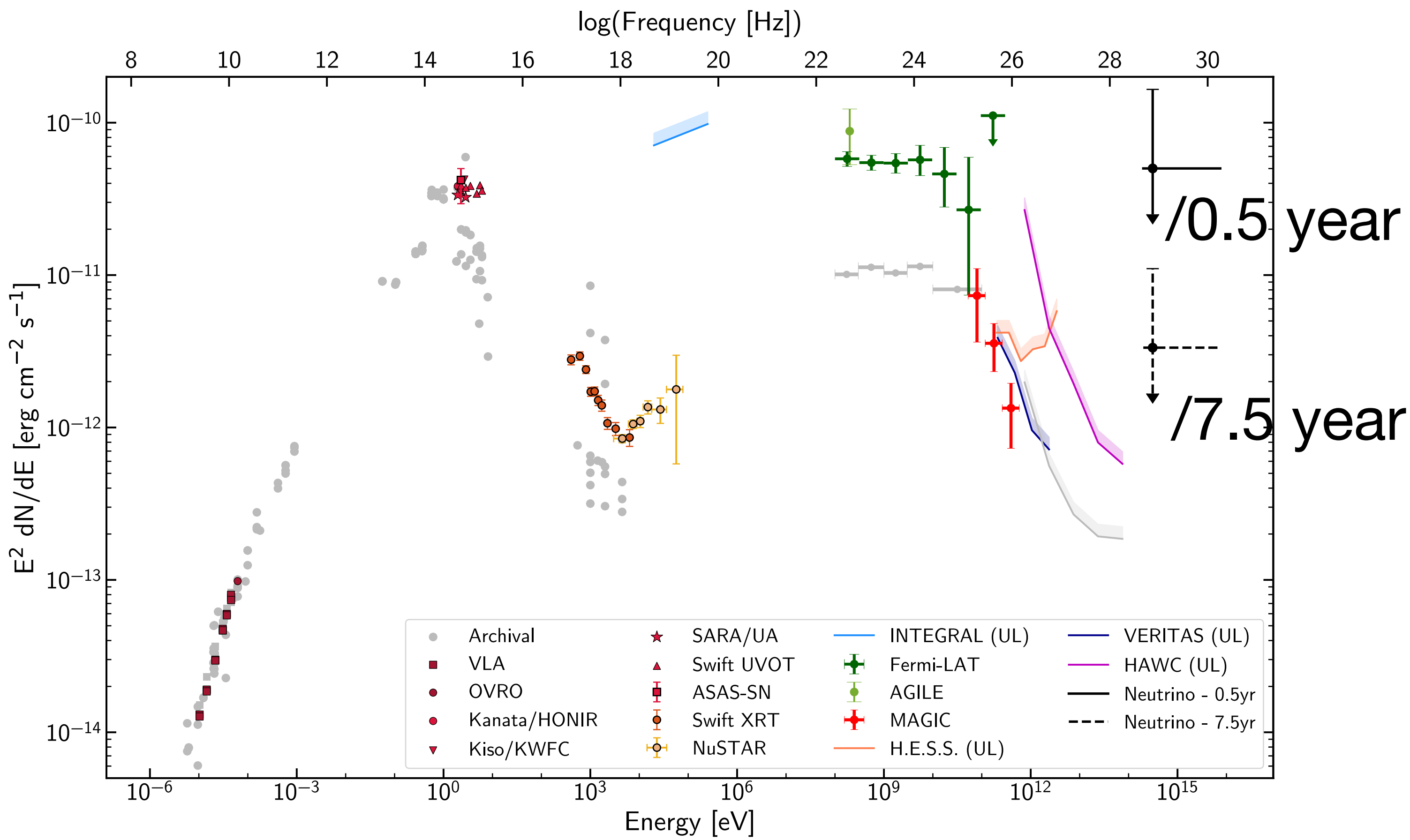
Broad Band SED

(color points: obtained within 14 days of the IC170922A event)



Broad Band SED

(color points: obtained within 14 days of the IC170922A event)



SED interpretations will be talked by Shan Gao (the next talk)
(Also by Susumu Inoue, yesterday)

Chance coincidence probability

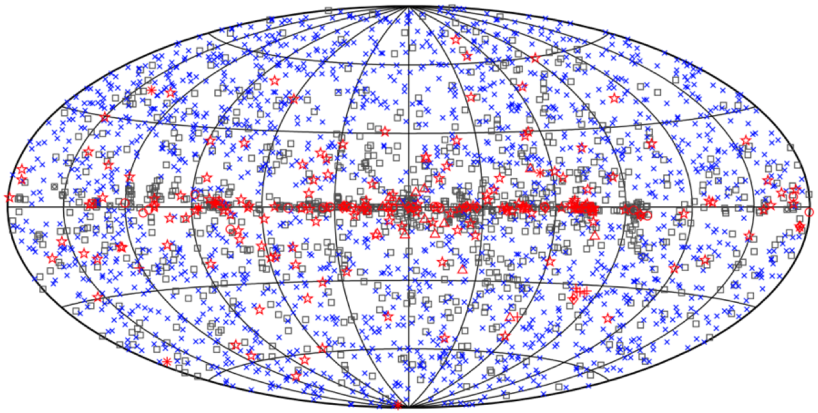
correlation

$$TS = 2\log\frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}.$$

no-correlation

$$\mathcal{L} \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}}$$

Fermi Gamma-ray sources (3FGL+3FHL)



There are more than 2000 extra-galactic gamma-ray sources in the sky. That ”coincidence” might be just by chance.

Check the hypothesis that
”there is a correlation between the neutrino event and the gamma-ray emission in space and time”
using a <u>likelihood ratio test</u>

Chance coincidence probability

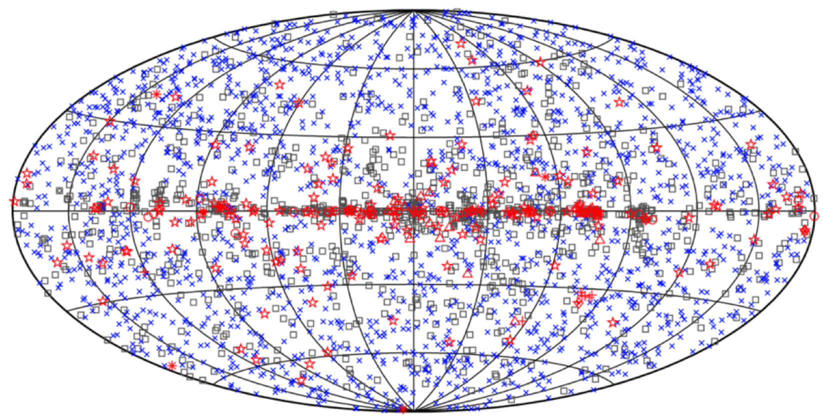
correlation

$$TS = 2\log\frac{\mathcal{L}(n_s=1)}{\mathcal{L}(n_s=0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}.$$

no-correlation

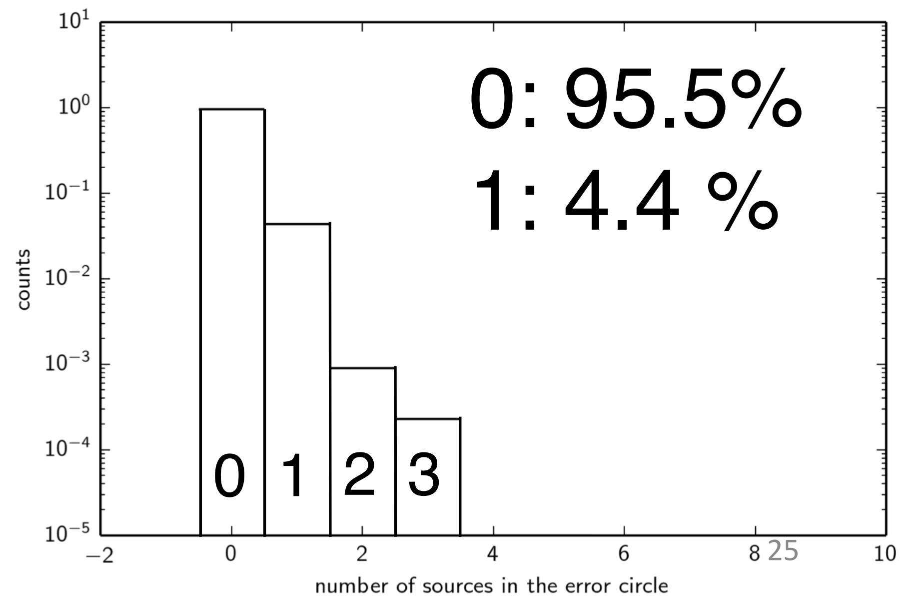
$$\mathcal{L} \propto \mathcal{L}_{\mathrm{spatial}} \cdot \mathcal{L}_{\mathrm{flux}}$$

Fermi Gamma-ray sources (3FGL+3FHL)



For example: γ-ray source density

<u>number of γ-ray sources **within 0.5deg radius** at a random position</u>



Likelihood function

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

Assuming N events observed

n_s=1 for the signal case

n_s=0 for the background case

- *S* and *B* are signal and background PDFs

$$\mathcal{S}(\vec{x}, t) = \mathit{Spacial}(\vec{x}) \times \mathrm{Energy}(\mathrm{E}_{\mathrm{reco}}, \sin\theta) \times \mathit{Temporal}(t)$$

PSF: 2D Gaussian

based on IceCube data

based on Fermi-LAT data

$$\mathcal{B}(\vec{x}) = \mathit{Spacial}(\sin\theta) \times \mathrm{Energy}(\mathrm{E}_{\mathrm{reco}}, \sin\theta)$$

Test Statistic

$$TS = 2\log\frac{\mathcal{L}(n_s = 1)}{\mathcal{L}(n_s = 0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}$$

pseudo-search trial using scrambled sample

Chance coincidence : temporal (flux)

$$\mathcal{L} \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}}$$

Flux (LAT γ-ray) data sample:

- All extragalactic and unID (|b|>5deg) sources from 3FGL and 3FHL sources → **2257 sources** (in total)
- Derived **9.2-year** light curves (2008/Aug – 2017/Oct) with **28-day** bin and **>1 GeV**

scales of the light curves:

1. energy flux

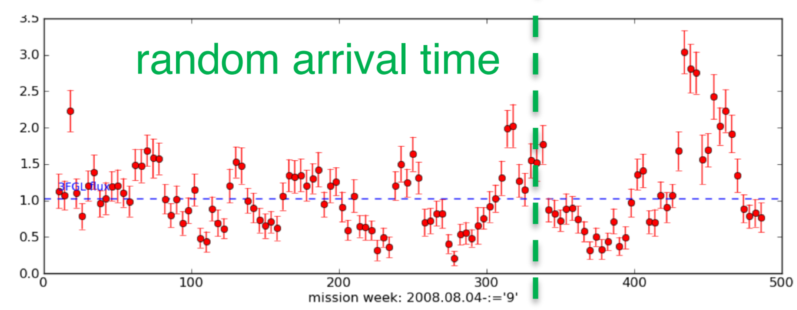
$$w_s(t) = \phi_E(t) = \int_{1\ \text{GeV}}^{100\ \text{GeV}} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

2. relative flux

$$w_s(t) = \phi_\gamma(t) / \langle \phi_\gamma \rangle$$

one example of LAT light curve

weighed by the flux level



119 bins/src

Chance coincidence probability

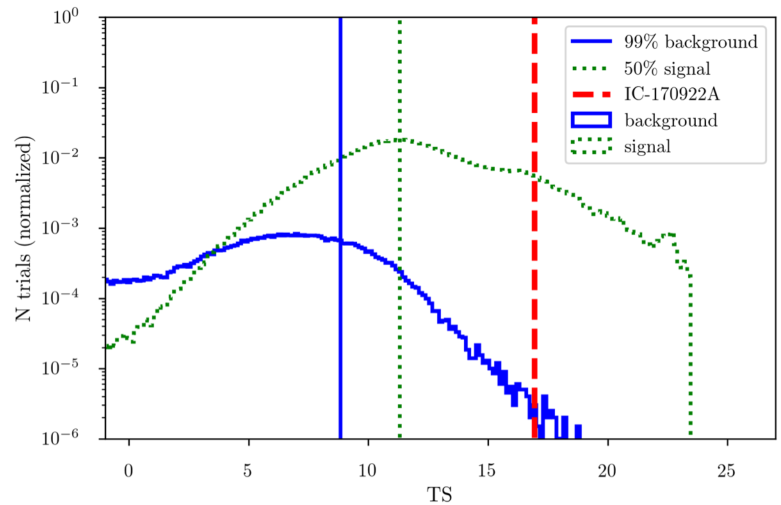
$$TS = 2\log\frac{\mathcal{L}(n_s=1)}{\mathcal{L}(n_s=0)} = 2\log\frac{\mathcal{S}}{\mathcal{B}}.$$

TS distribution:

Background trials (blue)

Signal trials (orange)

the TXS0506 event (red)



Probability: Pre-trial : **4.1σ** (~2.1×10^{-5})

Number of alerts:

10 alert events (since 2016/Apr)

41 archival events (since 2010 before the alert system started)

After the trial factor correction

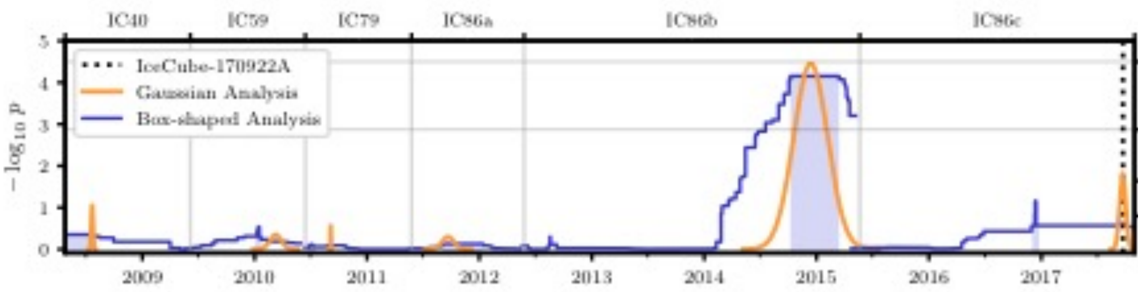
(including the 51 events)

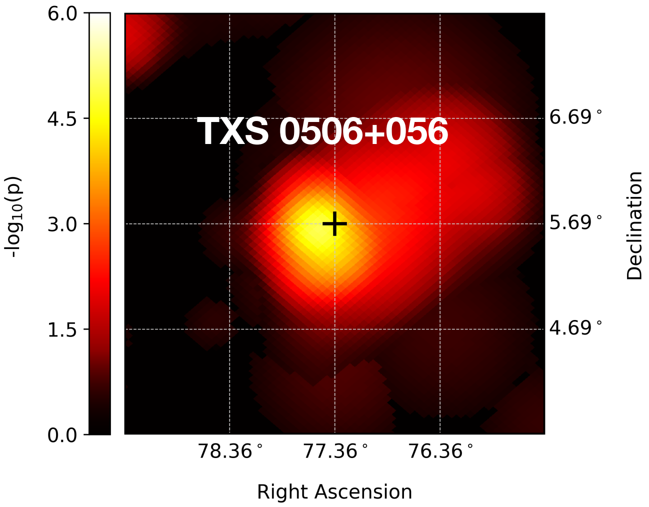
→ **3.0σ**

In the past IceCube data for TXS 0506+056

(IceCube Coll. 2018 Science aat2890)

April 2008 to October 2017





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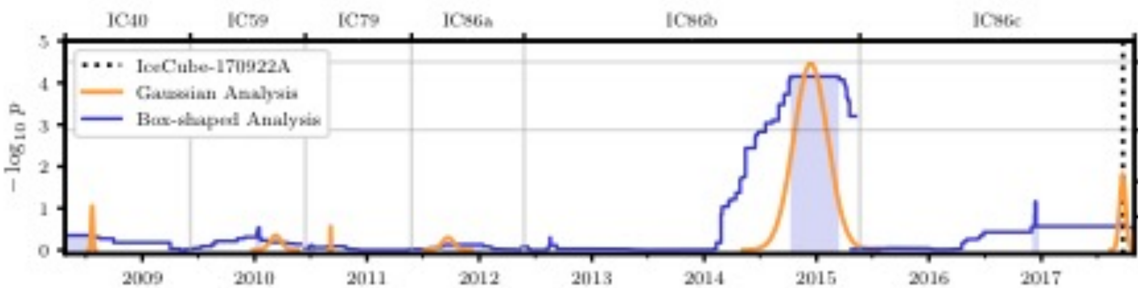
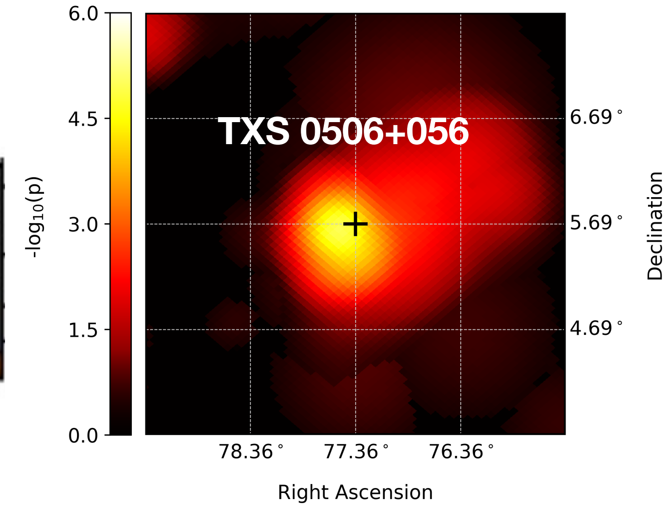
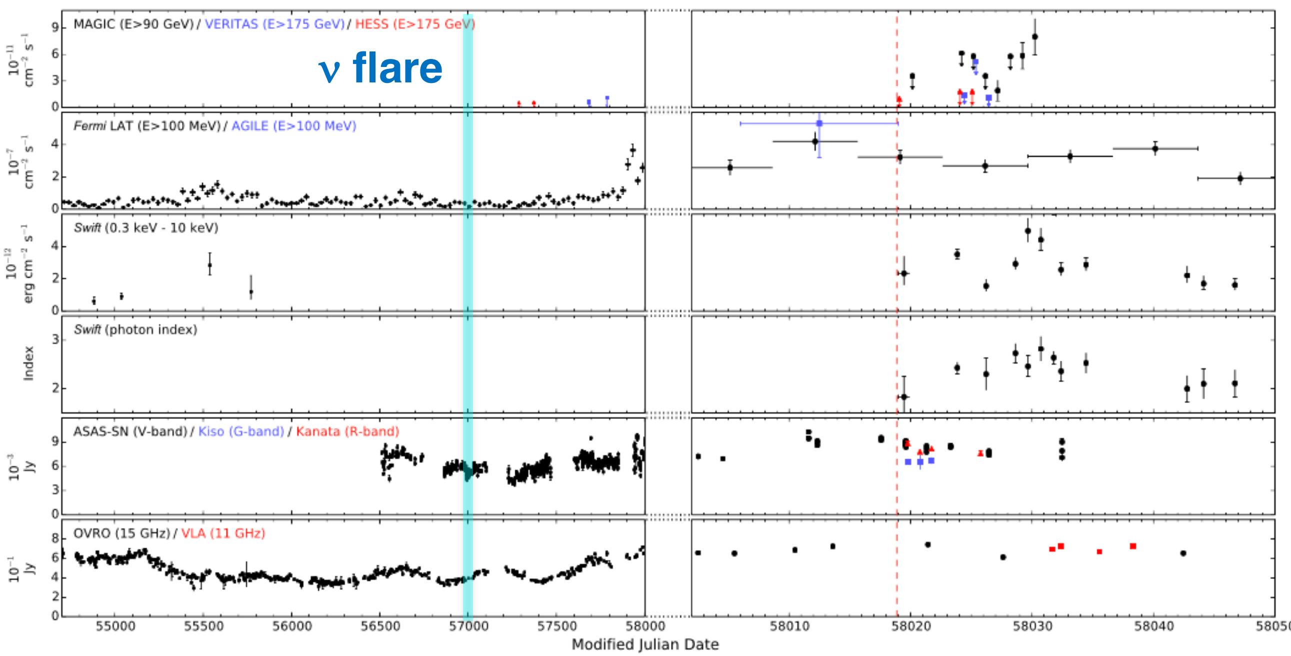




multi-band light curves



VHEγ

HEγ

X-ray

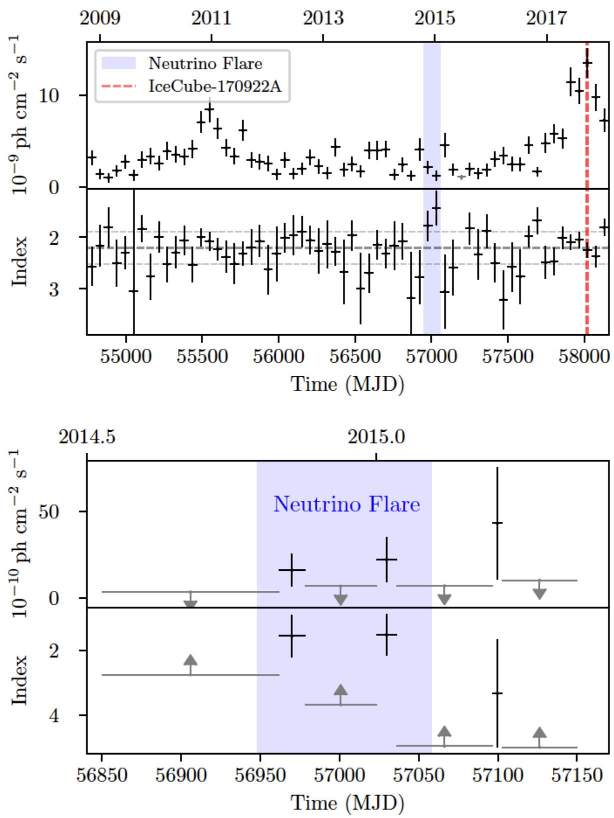
Opt.

Radio

Detailed look of the Gamma-ray band

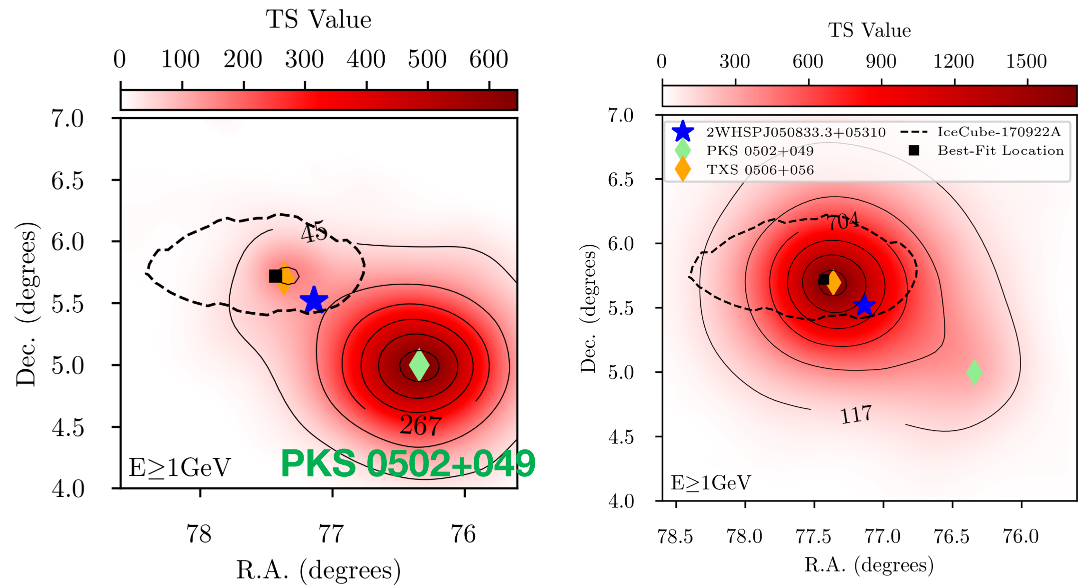
(Padovani+18 MNRAS, 480)

TXS 0506+056
Gamma-ray (> 2GeV)



Low flux, but hard state

Gamma-ray sky map (significance)



Oct. 2014 – Feb.2015 (neutrino flare)

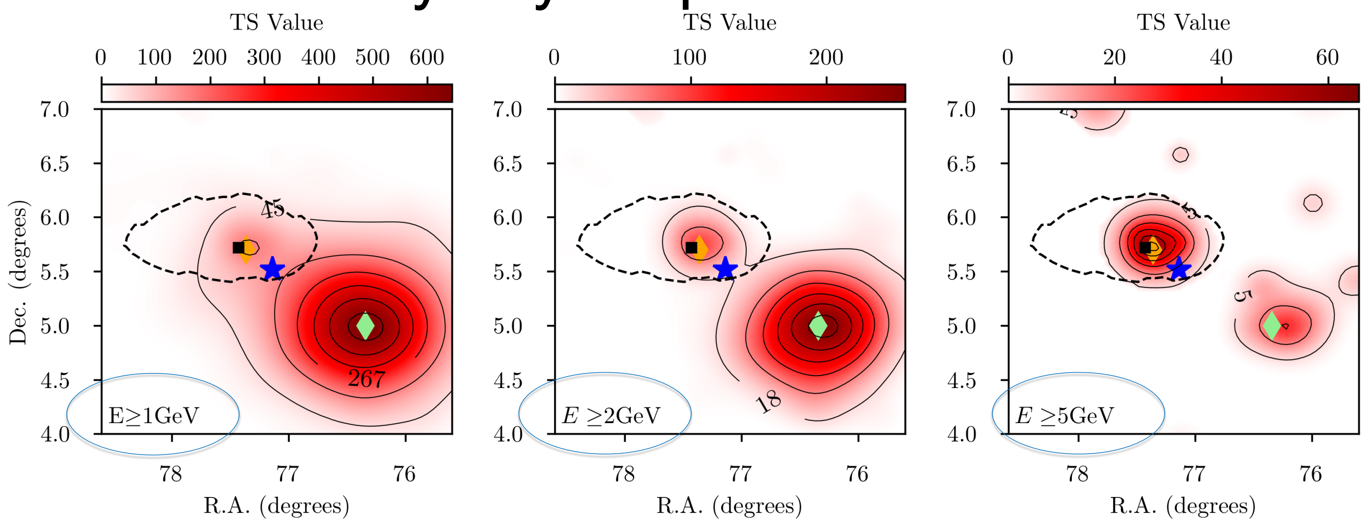
June-September 2017 (IC-170922A)

A nearby source PKS 0502+049 showed a flaring state at the time of neutrino flare

Detailed look of the Gamma-ray band

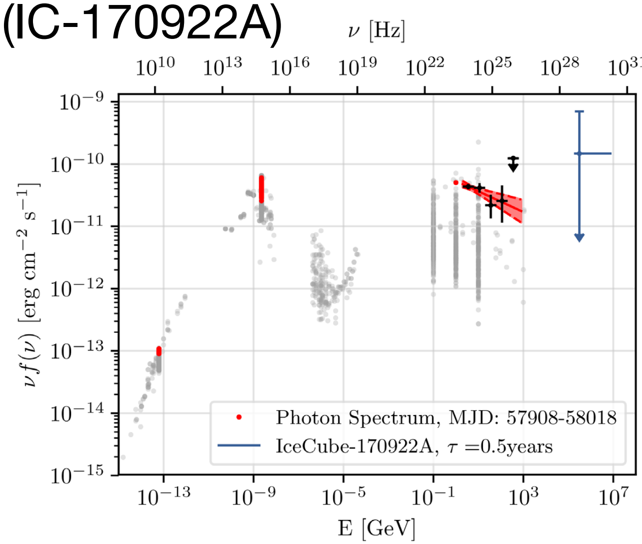
(Padovani+18 MNRAS, 480)

Gamma-ray sky map Oct. 2014 – Feb.2015

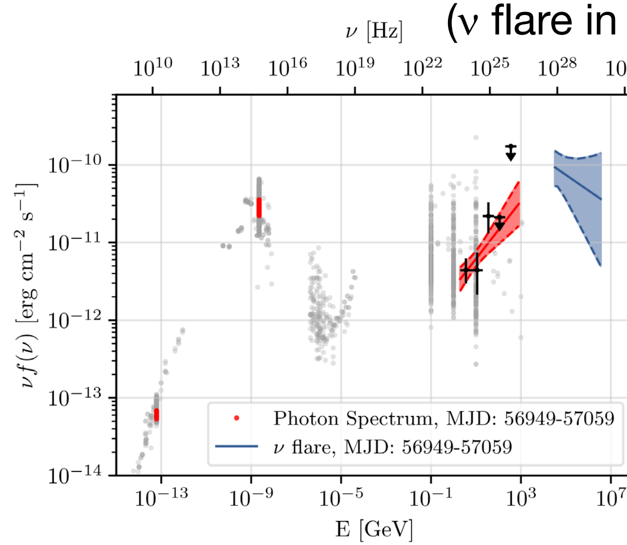


at > 5GeV,
TXS 0506+056
is brighter

(IC-170922A)



(ν flare in 2014-2015)



Summary

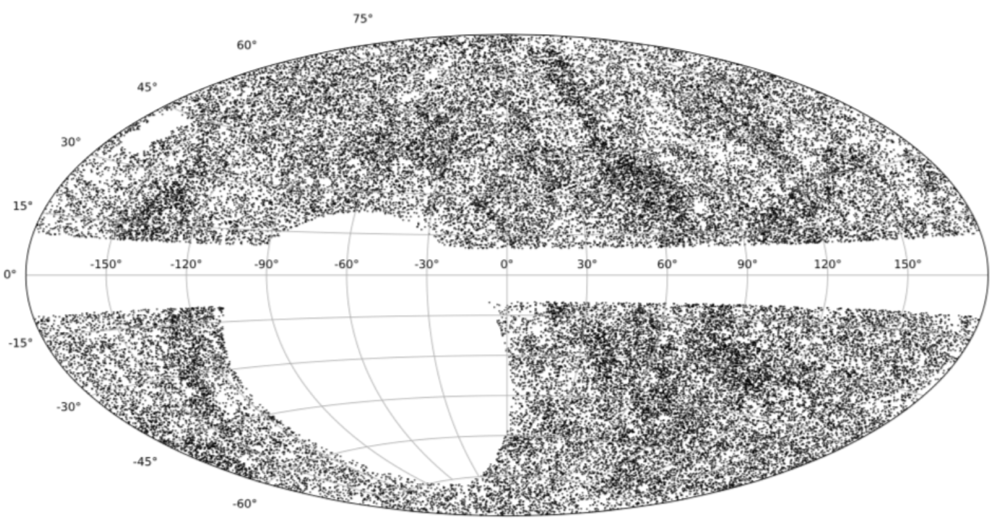
- Blazar is the most dominant high-energy γ-ray sources
- Emission origins can be explained by leptonic models
- No significant correlations were found between the IceCube ν events and the LAT γ-ray blazars (for steady emission)
  - Blazars seem not to be dominant source of the neutrino origin
- EM follow-up observations have been organized well for the IceCube Neutrino Alert
- IceCube-170922A: a flaring γ-ray blazar TXS 0506+056
  - ~290 TeV ν, 5 time higher >100 MeV γ, >100 GeV γ detection
  - Chance coincidence: 4 σ (pre-trial), 3 σ (post-trial: 51 events)
  - Also, a neutrino flare in late 2014
    - in the high-energy γ-ray band the low flux, but hard spectrum

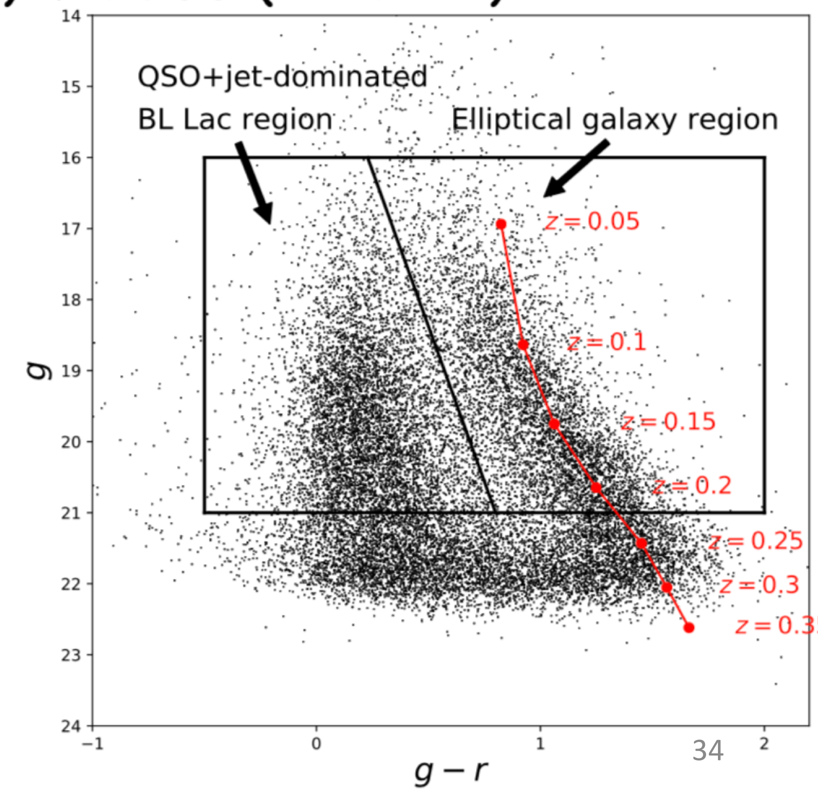
beginning of the neutrino multi-messenger Astronomy.

New Blazar Catalog (BROS)

(slide from Morokuma)

- Blazar Radio and Optical Survey (BROS; Itoh et al. in prep.)
- 56,315 sources at Dec.>-40 deg
  - ROMA-BZCAT: 3,516 sources
  - CRATES: ~11,000 sources
  - 3FGL (Fermi): ~1,500 sources
- flat-spectrum@radio: NVSS (1.4 GHz) + TGSS (151 MHz)
- Pan-STARSS(PS1)@optical
  - ~40% not detected in PS1 (r>23)



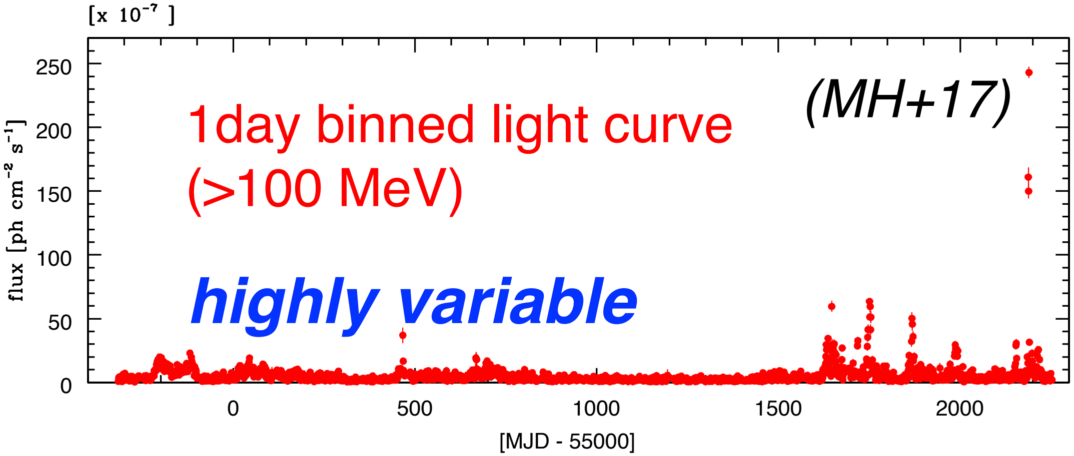


(slide from Morokuma)

objects in optical wavelengths

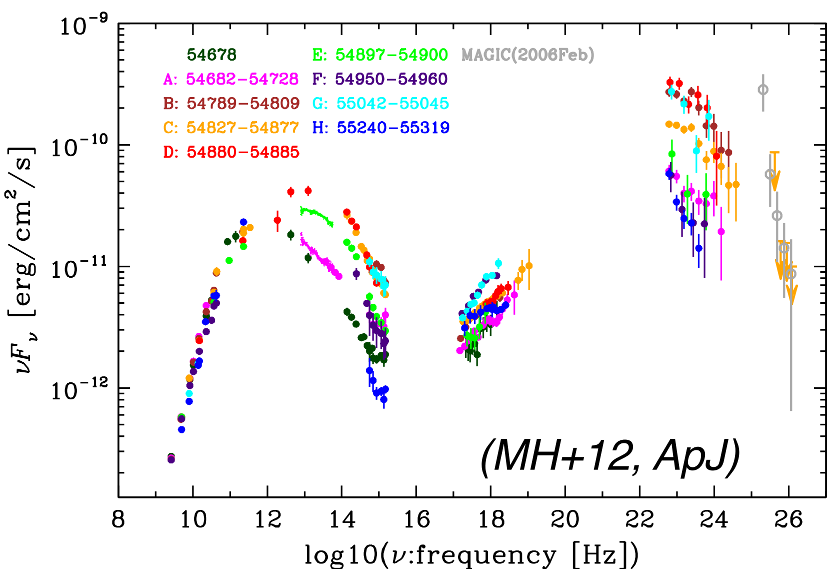
- non-transient: $O(10^{5-6})$ deg^{-2} (Furusawa+2008)
- transient: $O(10^{2})$ deg^{-2} (TM+2008)
  - variable star
  - [high proper motion star]
  - [asteroid]
  - supernova (SN)
  - active galactic nuclei (AGN)
  - gamma-ray burst (GRB)
  - fast radio burst (FRB): Parkes, ...
  - Gravitational Wave source (kilonova)
  - neutrino source

Emission from blazars



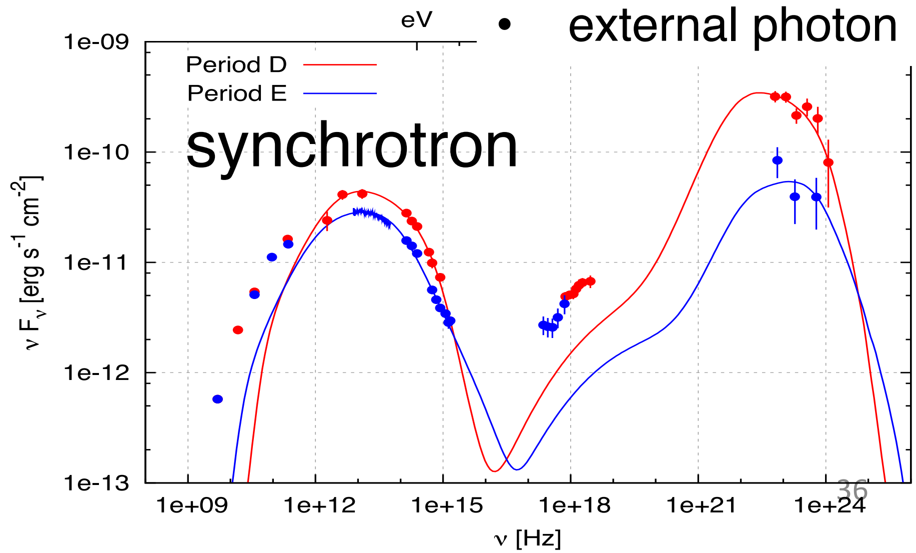
Leptonic origin models are successful for most cases
→ no exclusive evidence of hadronic origin emission

wide energy range: radio to VHE γ-ray



inverse-Compton

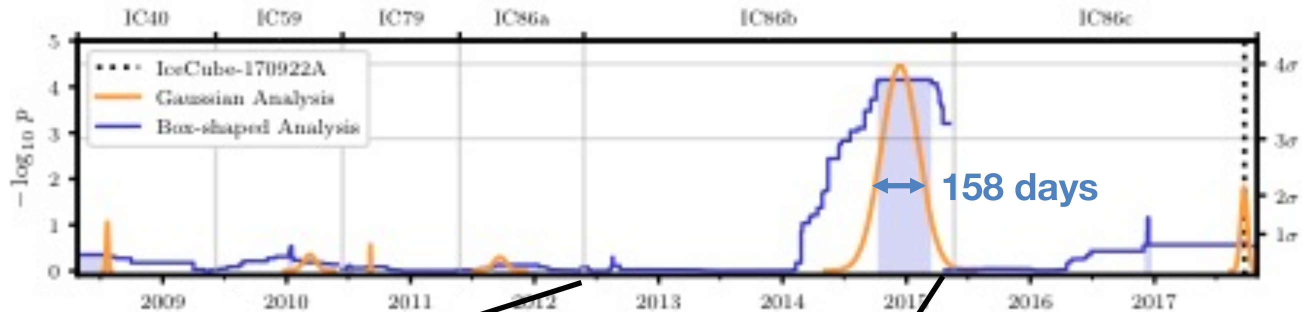
- SSC
- external photon

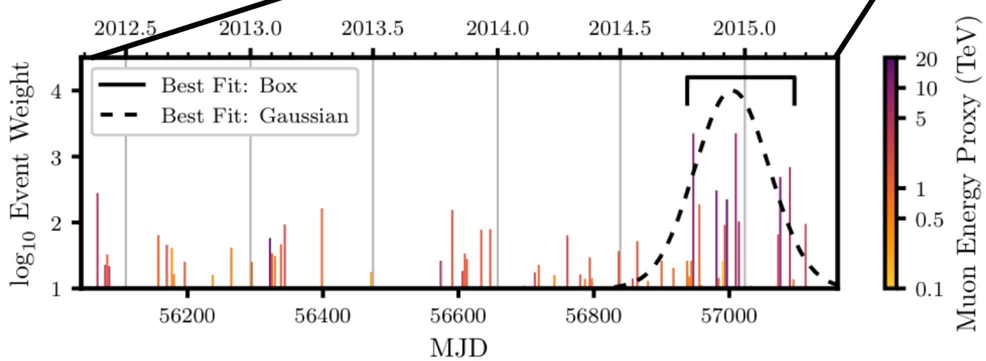


In the past IceCube data for TXS 0506+056

(IceCube Coll. 2018 Science aat2890)

April 2008 to October 2017



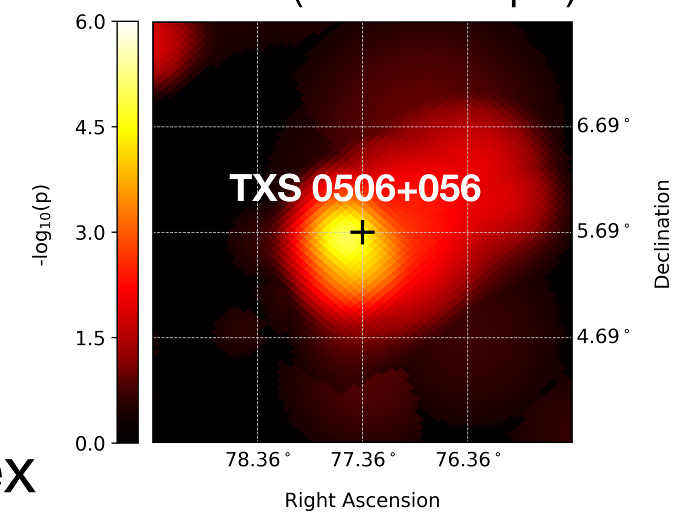


data samples

Sample	Start	End
IC40	2008 Apr 5	2009 May 20
IC59	2009 May 20	2010 May 31
IC79	2010 May 31	2011 May 13
IC86a	2011 May 13	2012 May 16
IC86b	2012 May 16	2015 May 18
IC86c	2015 May 18	2017 Oct 31

spatial map (p-value)

(IC86b sample)



excess:3.5σ

Gaussian fit:

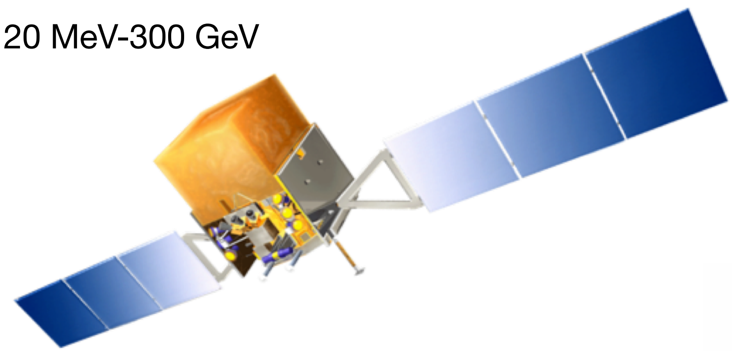
- **Center:** 13 Dec. 2014 (MJD 57004) (±21 days)
- **Width:** 110 $^{+35}_{-24}$ days

Spectral index = 2.1±0.2

Fermi Gamma-ray Space Telescope

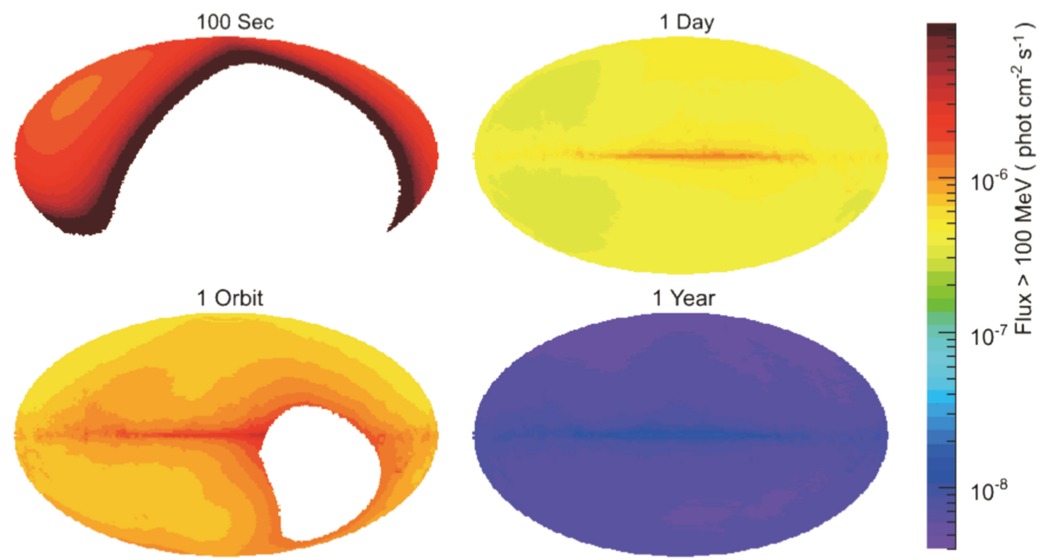
Large Area Telescope (LAT)

- 20 MeV-300 GeV



- Launched on 2008 June 11
- Continue to observe without any critical problems
- All sky survey mode

All-sky survey-mode observation



Thanks to the large FoV of 2.4 str, LAT scans all-sky every 3 hours (i.e., 2 orbits) and perform unbiased survey

→ good for monitoring variable sky every days