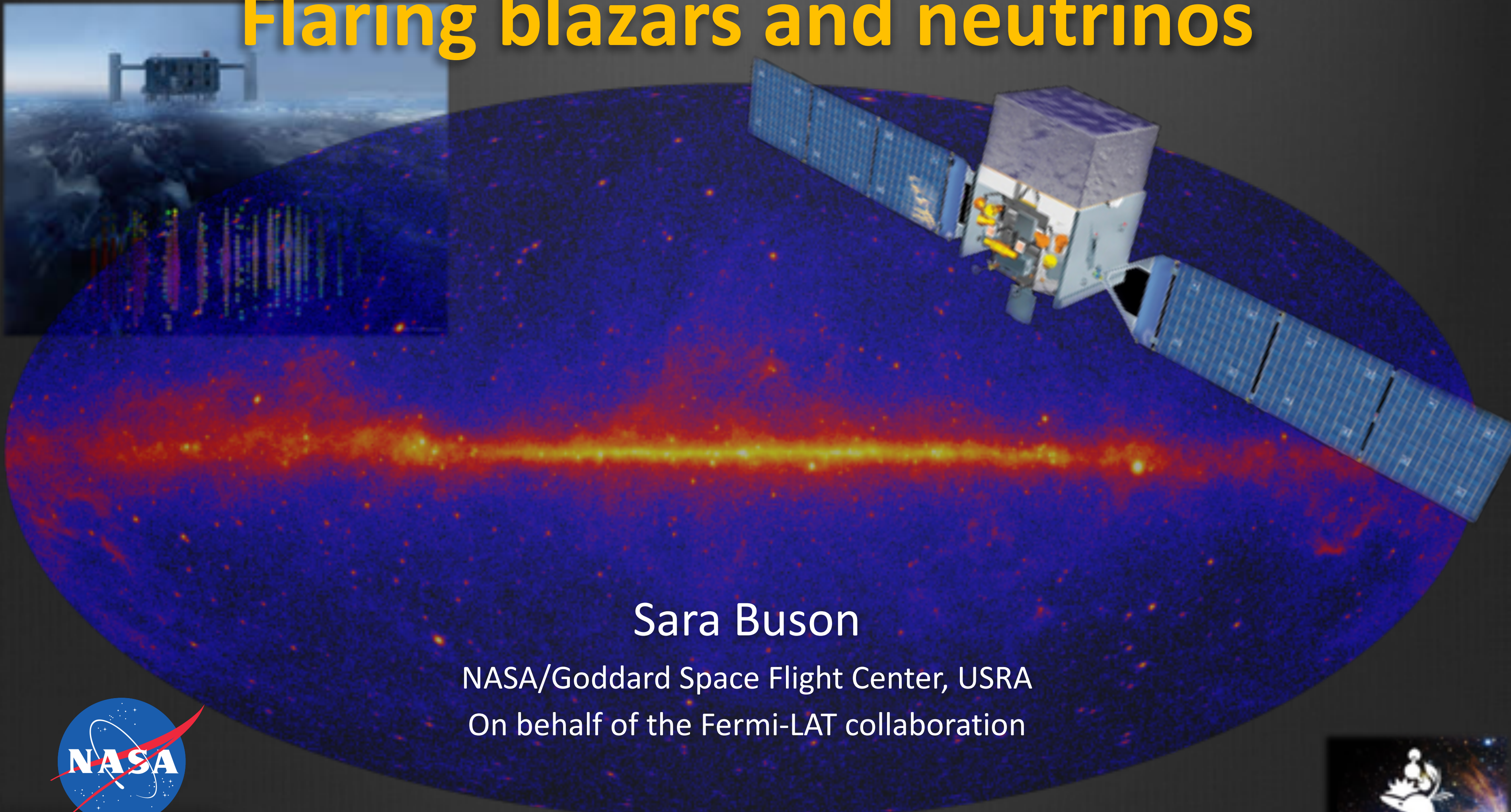
Multi-messenger astrophysics: Flaring blazars and neutrinos



Sara Buson

NASA/Goddard Space Flight Center, USRA

On behalf of the Fermi-LAT collaboration

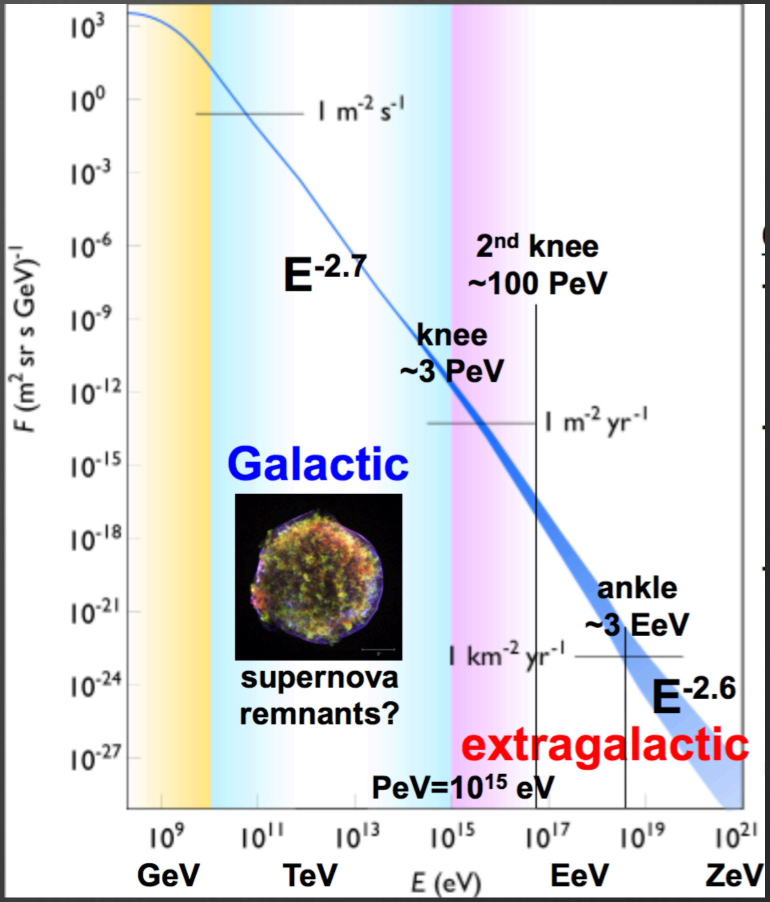
Vulcano Workshop, May 2018

A Century Old Puzzle: Cosmic Rays

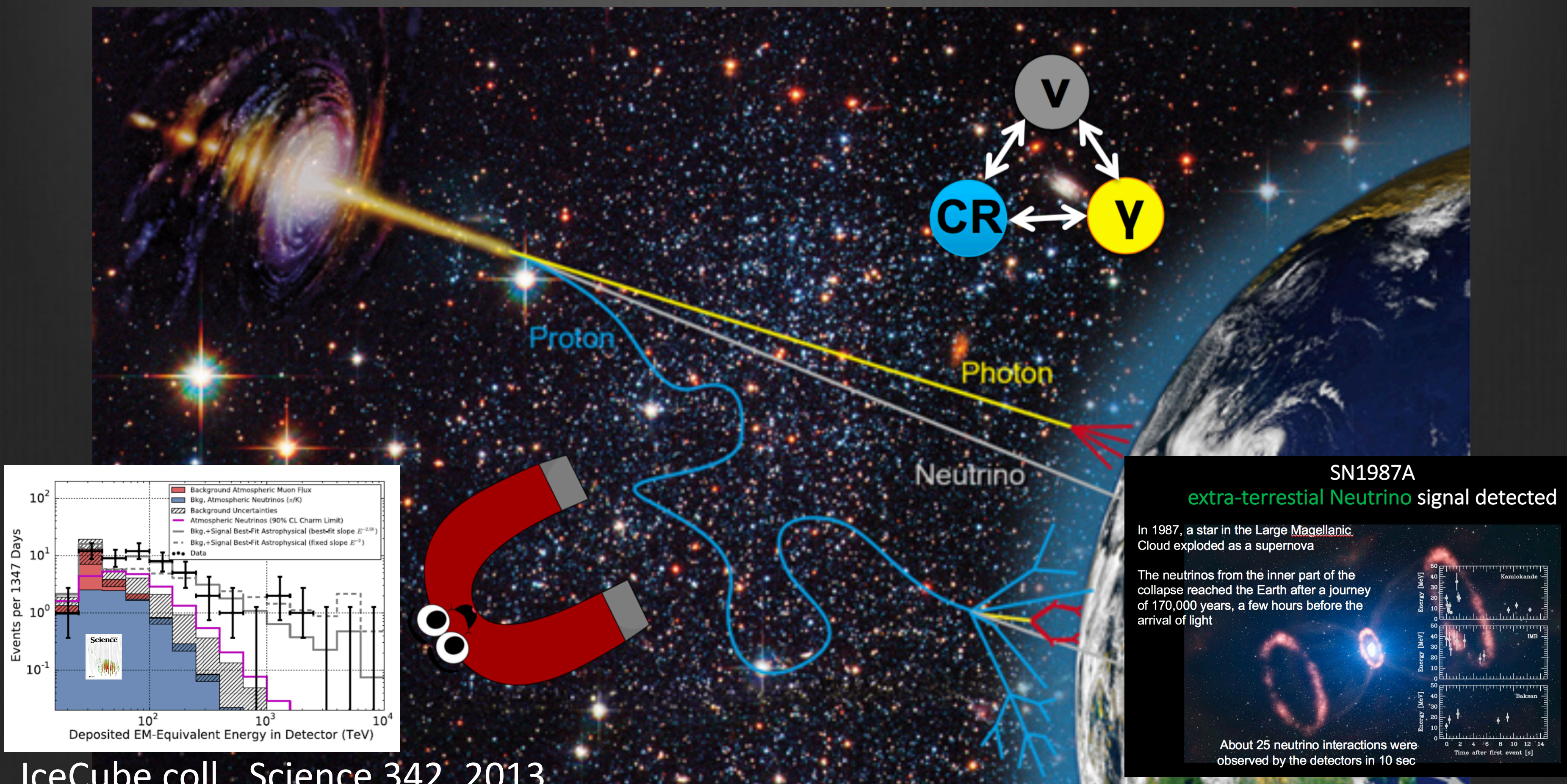
How is the spectrum composed?

How are CRs accelerated?

How do CRs propagate?



Neutrinos
- an exciting step forward -



IceCube coll., Science 342, 2013

Production of astrophysical High-Energy Neutrinos

- Variety of models:
  - "CR accelerator models"
    - neutrinos are produced within the CR source
    - mesons are typically produced by interactions of CRs with radiation
  - "CR reservoir models"
    - neutrinos are produced while they are confined within the environment surrounding the CR source
    - produced by inelastic hadronuclear collisions

Murase & Waxman
Phys. Rev. D **94**, 103006

Cosmic Rays/Neutrinos: Extreme Universe

Astrophysical source candidates:

- The heaviest black holes (M_{BH}~ $10^{8\text{-}9}$ M_{sun})
  - AGNs
- The strongest magnetic fields (B ~ 10^{15} G)
  - Magnetars
- The brightest explosions (L ~ 10^{52} erg/s)
  - GRBs
- The biggest gravitationally bounded objects
  - Galaxy clusters/groups

Astrophysical Extragalactic Scenarios

Cosmic-ray Accelerators

- **Gamma-ray bursts**
  (e.g. Waxman & Bahcall 97, KM et al. 06 // (Cholis & Hooper 13, Liu & Wang 13, Murase & Ioka 13, Winter 13, Senno, Murase & Meszaros 16)

- **Active Galactic Nuclei**
  (e.g. Stecker et al. 91, Mannheim 95 // Reimer 2012, Kalashev, Kusenko & Essey 13, Stecker 13, Murase, Inoue & Dermer 14, Dermer, KM & Inoue 14, Tavecchio et al. 14, Kimura, Murase & Toma 15, Padovani et al. 15, Wang & Li 1, Lamastra 2017)

Cosmic-ray Reservoirs

- **Starburst galaxies**
  (Loeb & Waxman 06, Thompson+ 07; Murase, Ahlers & Lacki 13, Katz et al. 13, Liu+ 14, Tamborra, Ando & Murase 14, Anchordoqui+ 14, Senno+ 15

- **Galaxy groups/clusters**
  (Berezinsky+ 97, KM et al. 08, Kotera+ 09 // Murase, Ahlers & Lacki 13, Fang & Olinto 16)

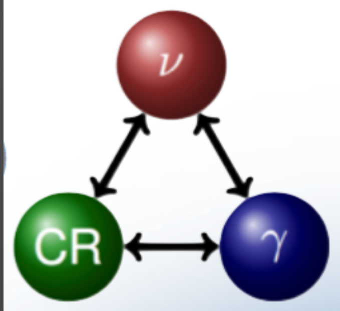
Constraints from neutrinos

- No single source detection & no significant clustering
- Neutrino data sample is isotropically distributed
- Equal contents of ν_e, ν_μ and ν_τ and their anti-particles

→ hint to a cosmological origin of the observed neutrino flux
→ suggests a (dominant) extragalactic origins

Neutrinos are becoming a mature means to explore our Universe

HE NEUTRINO PRODUCTION PROCESSES



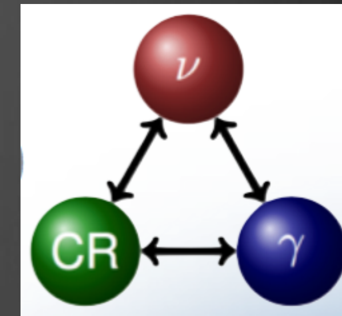
- **Hadronuclear**

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

- **Photohadronic**

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

HE NEUTRINO PRODUCTION PROCESSES



- **Hadronuclear**

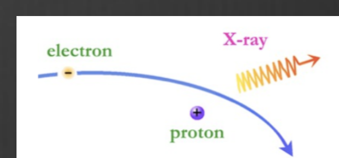
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e\, \nu_\mu\, \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e\, \bar{\nu}_\mu\, \nu_\mu \end{cases}$$

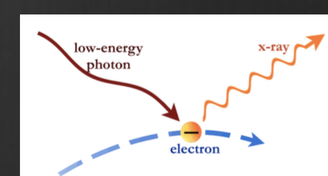
- **Photohadronic**

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\, \pi^0 \rightarrow p\, \gamma\, \gamma \\ n\, \pi^+ \rightarrow n\, \mu^+ \nu_\mu \rightarrow n\, e^+ \nu_e\, \bar{\nu}_\mu\, \nu_\mu \end{cases}$$

(Caveats: multi-messenger relationship may be more complicated)

- **Gamma-rays are not exclusively produced in hadronic processes**





γ - ν connection: strategies

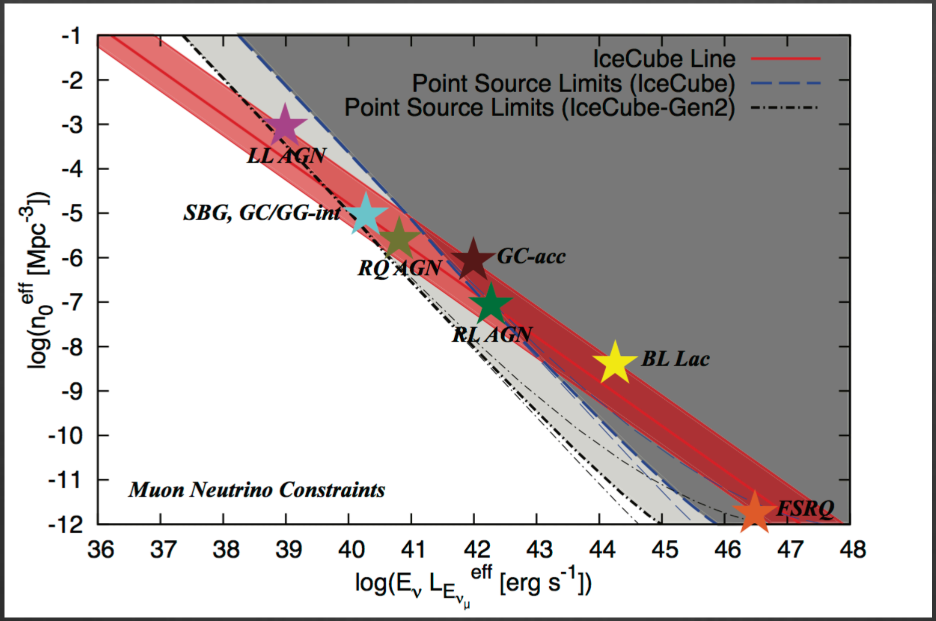
Correlation with known catalogs

- 3LAC (>100MeV, 4years); 2FHL (>50 GeV, 6years); 2WHSP (most complete list of HSP)
- None of the three blazar catalogs tested showed any significant evidence for a neutrino signal above background expectations.
- All the outcomes from the three catalog stacking analyses are fully compatible with background fluctuations.

IC - PoS(ICRC2017)994

γ - ν connection: strategies

- Limits on source density inferred by non-observation of neutrino multiplets



steady sources

Kowalski, 2014; Ahlers, Halzen, 2014; Murase, Waxman, 2016

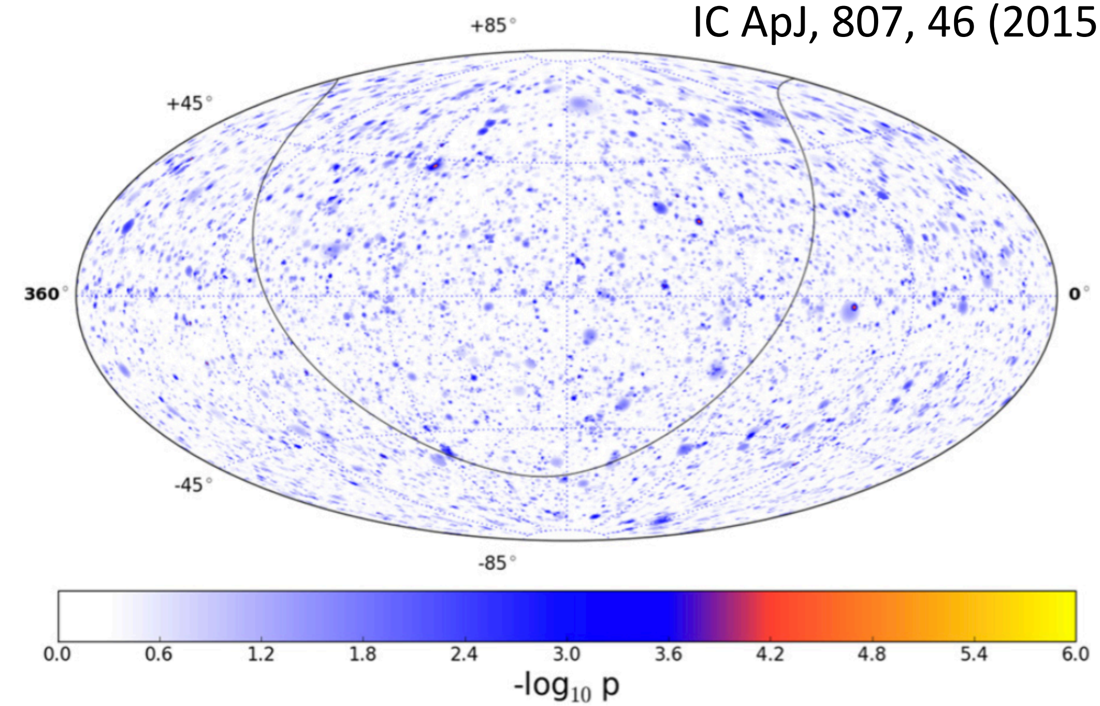
Another key ingredient

TIME DOMAIN:

SEARCHES FOR TIME-DEPENDENT NEUTRINO SOURCES

Searches for Neutrino Flares

IC ApJ, 807, 46 (2015)



- untriggered search: performed only using the neutrino data themselves

IC-86I skymap in equatorial coordinates showing the pre-trial p value for the best-fit flare hypothesis tested in each direction of the sky

Most significant point (smallest pre-trial p value) found in the IceCube data sample :

Data Set	R.A.	Decl.	$\hat{n}_s$	$\hat{\gamma}$	$\hat{T}_0$ (MJD)	$\hat{\sigma}_T$ (days)	p value Pre-trial	p value Post-trial
IC-59	21°.35	−0°.25	14.5	3.9	55,259	5.5	2.04×10^{-7}	1.4%
IC-79	343°.45	−31°.65	7.2	3.95	55,466	1.8	1.07×10^{-5}	66.0%
IC-86I	235°.95	42°.95	13.1	2.0	55,882	7.57	1.06×10^{-5}	63.0%

The Power of

MULTI-MESSENGER

+

TIME DOMAIN

Search for neutrino emission correlated with g-ray flares

- Search for neutrino emission temporally consistent with g-ray blazars:
- Enhanced states pointed out by Fermi-LAT monitoring (IC ApJ, 807, 46 2015)
- TeV "orphaned" flares (IC ApJ, 744, 1 2012; ApJ, 807, 46 2015)

  - No significant neutrino excess pointed out

A previous suspect

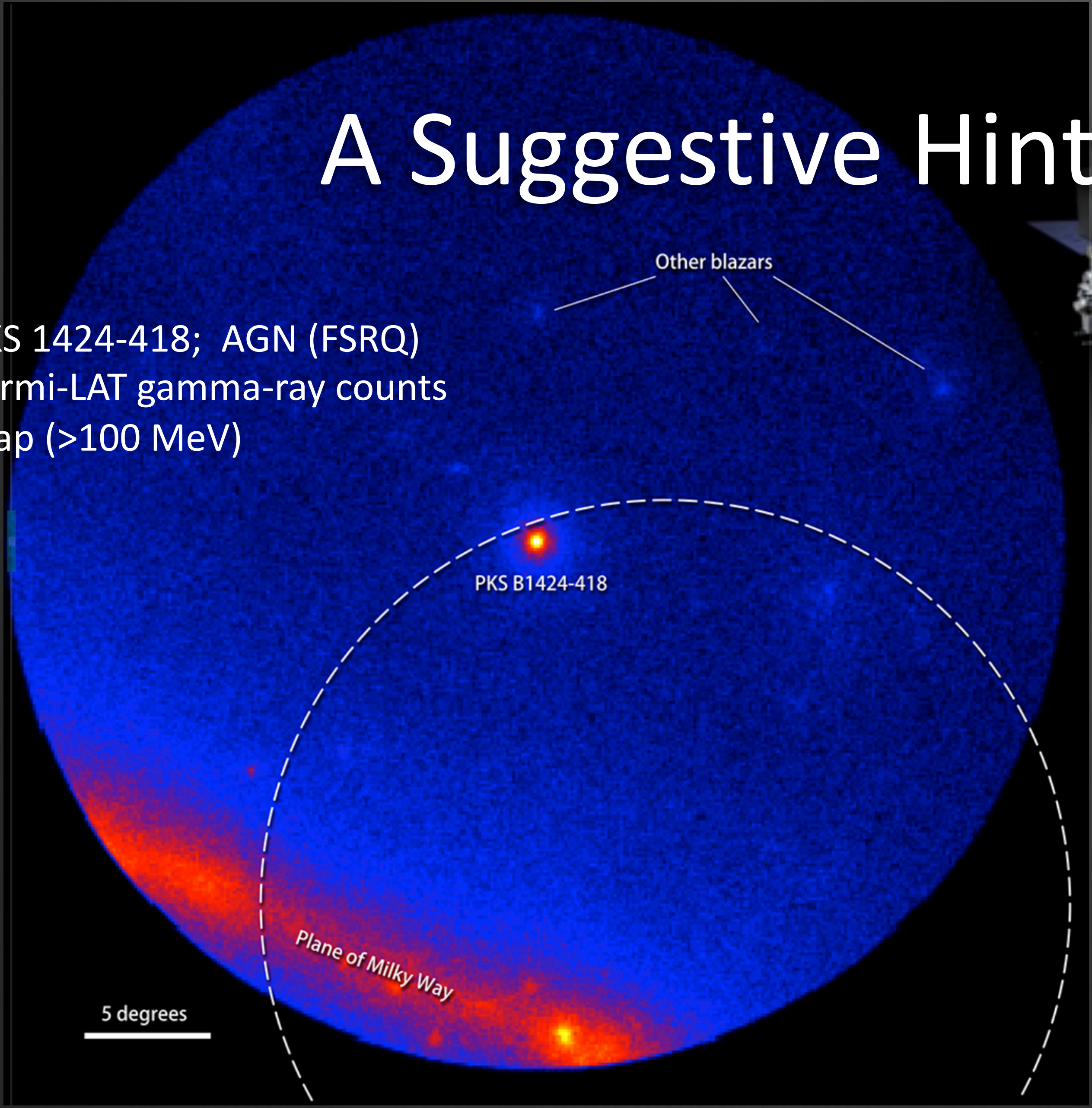
The high-peaked BL Lac object **1ES 1959+650**:

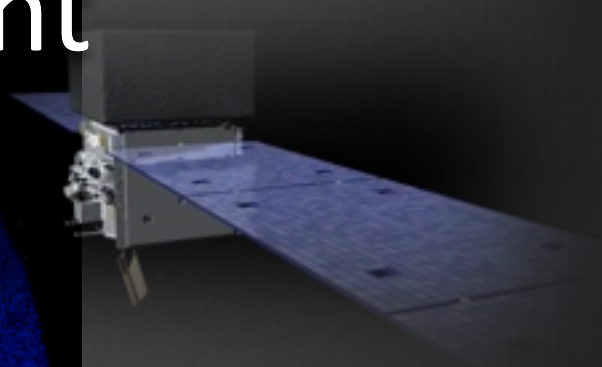
- "Orphan" VHE flaring episode on June 4th, 2002 (WHIPPLE)
- Three neutrino events were found to arrive during the flaring episode (AMANDA); one within a few hours of the gamma ray observations
- Exhibited major flares in VHE gamma rays in the spring of 2016 (Buson+ Atel #9010, Fermi-LAT, FACT, MAGIC and VERITAS coll.)
- Test for time-clustering of neutrinos with IceCube
  - No significant emission neither by integrating over the whole flaring episode, nor by testing for clusters on shorter time scales

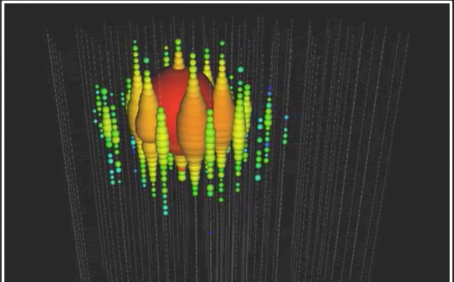
IC – PoS(ICRC2017)969

A Suggestive Hint

PKS 1424-418; AGN (FSRQ)
Fermi-LAT gamma-ray counts map (>100 MeV)

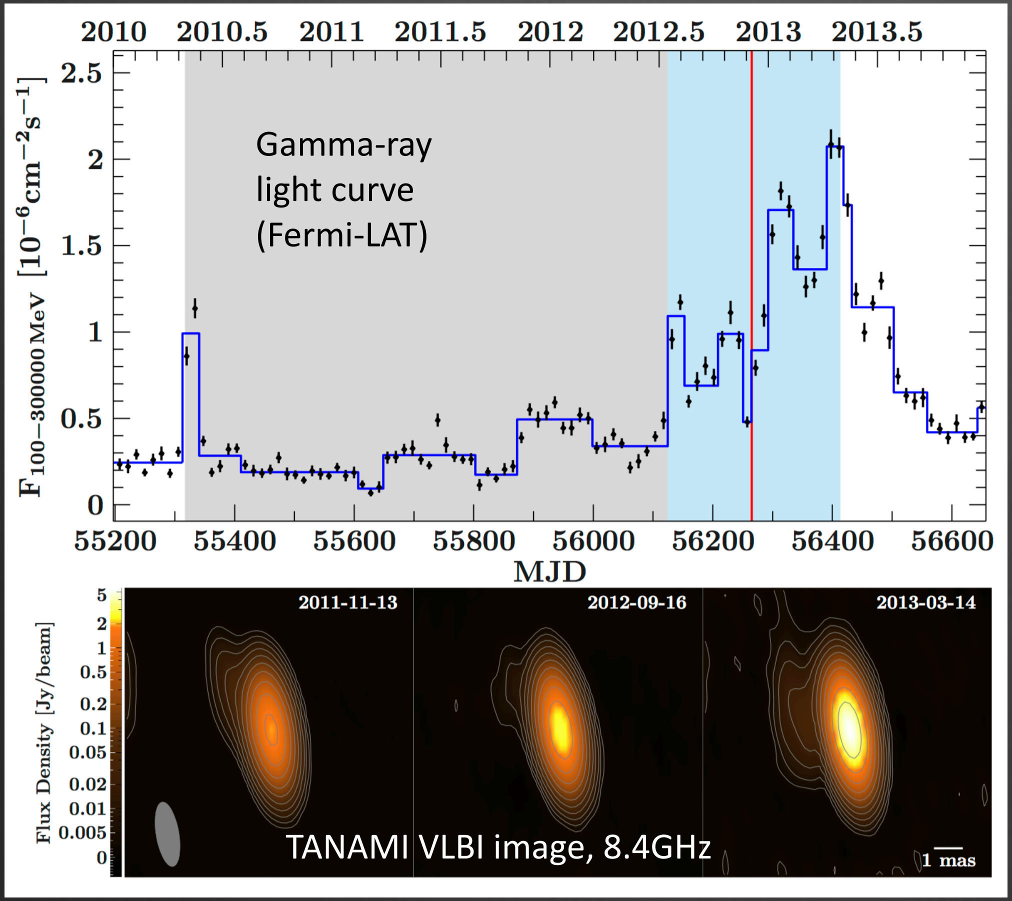






Big Bird – 2 PeV
December 4, 2012

A Suggestive Hint



chance coincidence prob of about 5% (a-posteriori)

Kadler+ 2016
Nature Physics 12, 807
(Gao+ ApJ, 2017)

integrated emission of the blazar population has a sufficiently high electromagnetic flux to explain the observed IceCube events

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

- Most of the results in the literature are based on archival IceCube neutrino dataset
- about 80 HE neutrinos

Real-Time Alerts

- Since April 2016, the IceCube collaboration began releasing real-time alerts of detections of high-energy (>100 TeV) neutrinos
  - 8 HESE + 6 EHE events

IceCube Alert – IC170922A

```
//////////////////////////////////////////////////////////////////////
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]
```

IC170922A – Updated Info

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon that traverses the detector volume, and have a high light level (a proxy for energy).

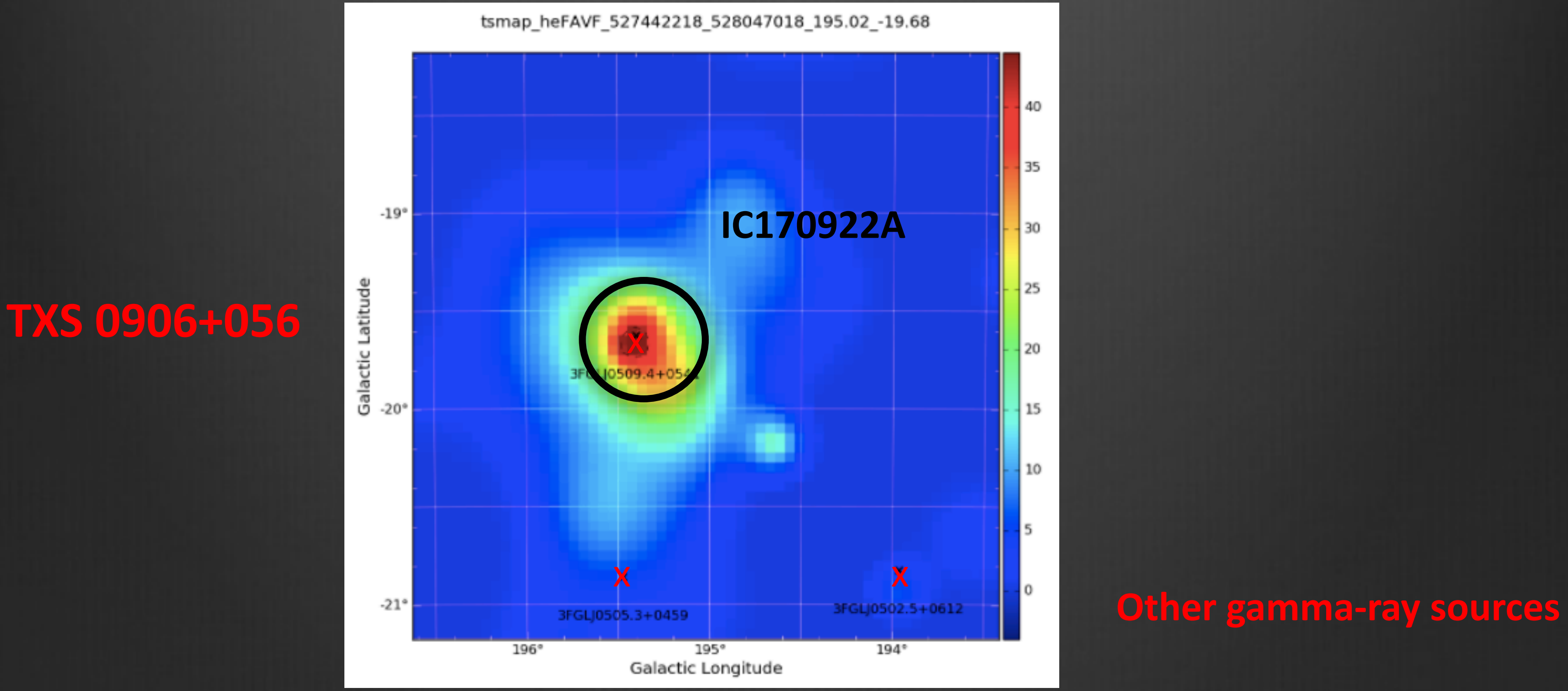
After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

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



The Astronomer's Telegram

- **First detection of gamma-ray excess positionally and temporally consistent with an IC EHE neutrino!**

H.E.S.S. follow-up of IceCube-170922A

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

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

Further Swift-XRT observations of IceCube 170922A

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

VERITAS follow-up observations of IceCube neutrino event 170922A

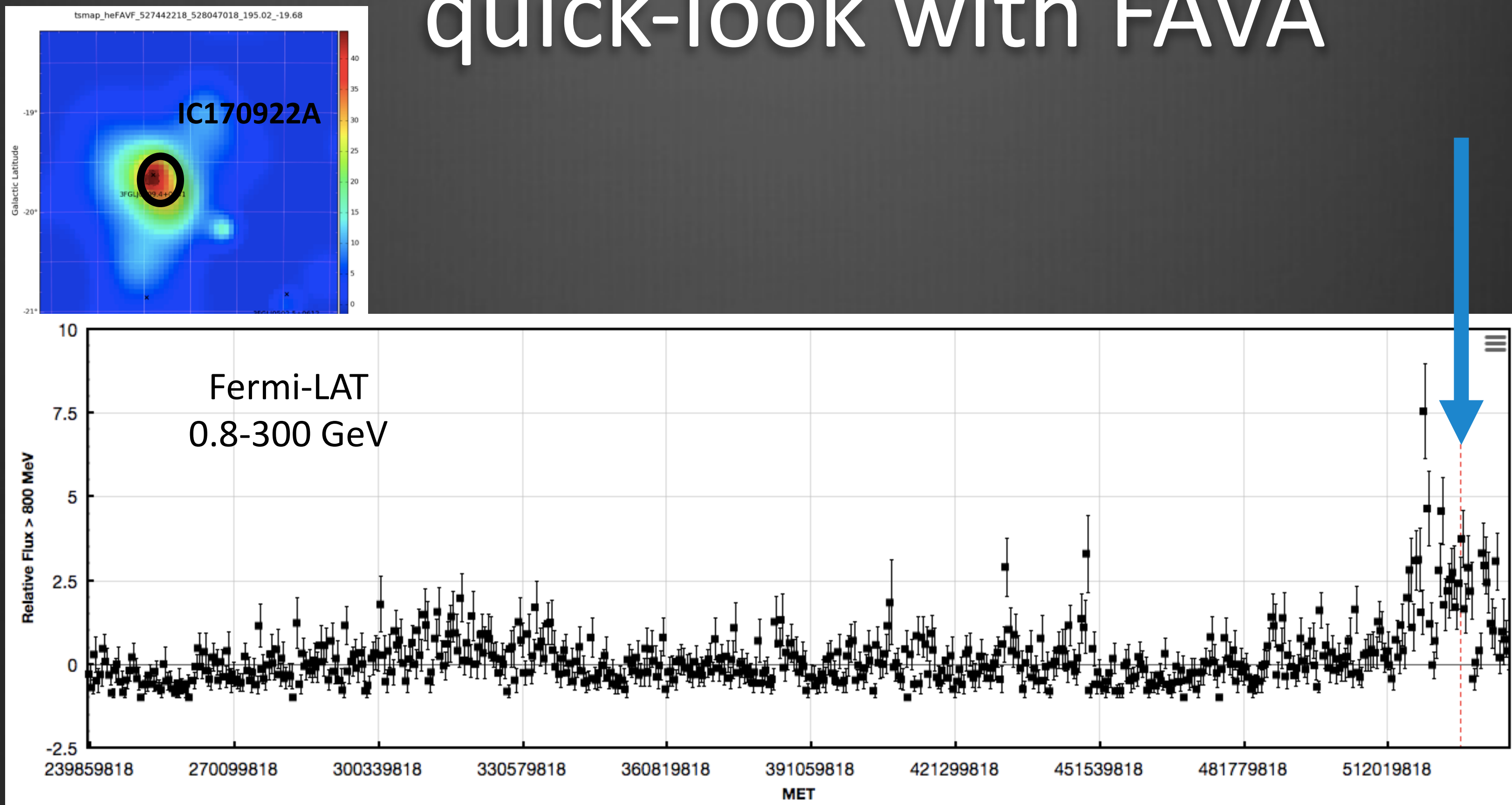
Related

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-170922A
10801	AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799	Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794	ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792	Further Swift-XRT observations of IceCube 170922A
10791	Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787	H.E.S.S. follow-up of IceCube-170922A
10773	Search for counterpart to IceCube-170922A with ANTARES

Radio, optical, X-rays, g-rays, Antares follow up

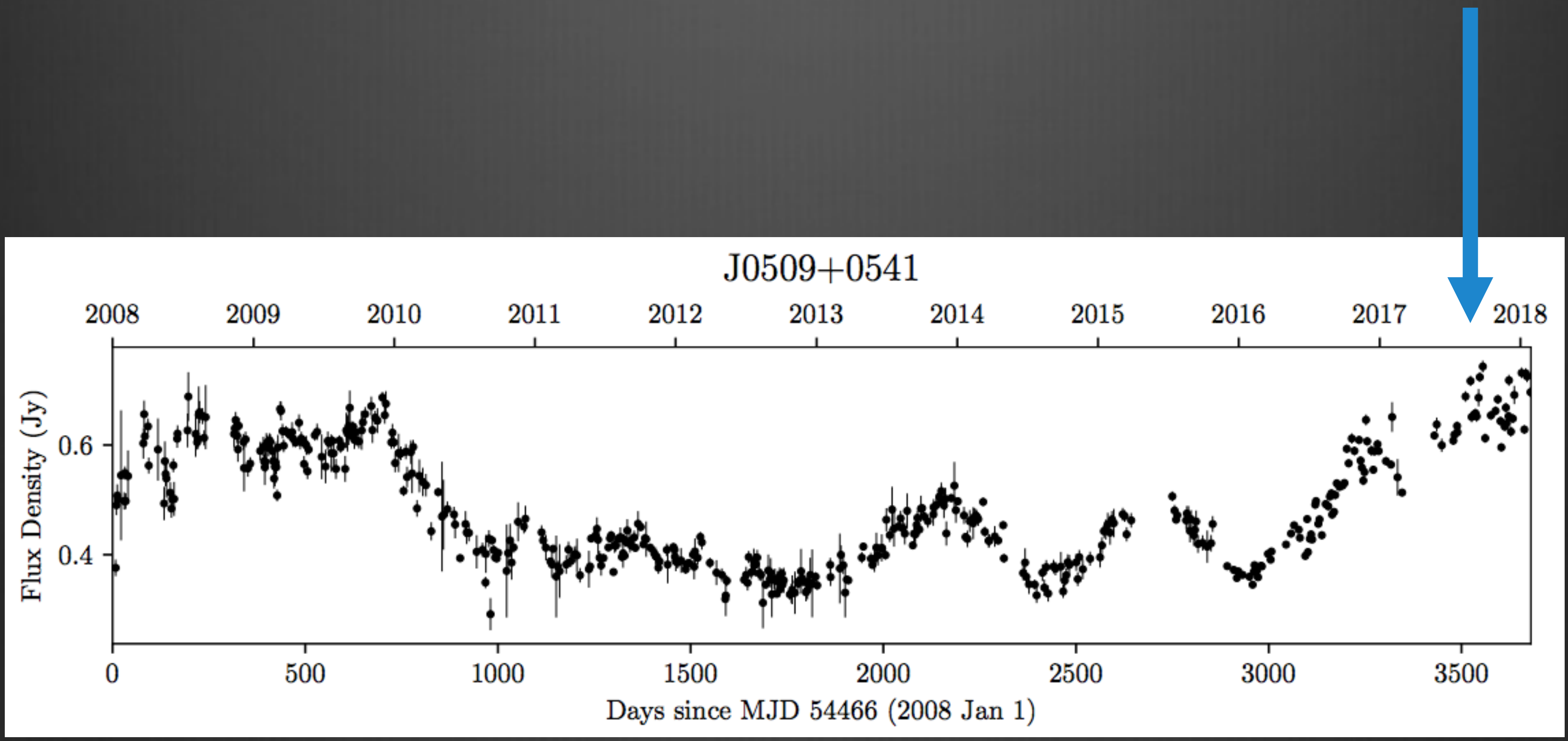
- 17/09/23 09:31:27 GMT (GCN 21917), INTEGRAL, upper limit
- 17/09/24 19:34:55 GMT (GCN 21923), ANTARES, upper limit (+/-1h, +/-1d)
- 17/09/25 01:55:22 GMT (GCN 21924), HAWC, upper limit
- **17/09/26 14:34:30 GMT (GCN 21930), Swift (3.25h after the neutrino trigger, 800s per field, 19-point tiling), 9 sources identified**
- 17/09/27 14:33 GMT (ATel 10787), HESS, observation 4h after neutrino trigger (for ~1h) and consecutive night (1h), no detection
- **17/09/28 10:10 GMT (ATel 10791), Fermi-LAT, known gamma-ray source TXS 0506+056 (3FGL J0509.4+0541) in error circle, in flaring state, redshift unknown**
- 17/09/28 11:58:48 GMT (GCN 21941), further Swift observations, additional 5ks of TXS position, possible spectral evolution
- 17/09/28 18:00 GMT (ATel 10794): ASAS-SN finds enhanced optical flux of TXS 0506+056
- 17/09/29 13:00 GMT (ATel 10799): Liverpool telescope takes optical spectrum, no redshift measurement possible
- 17/09/29 15:41 GMT (ATel 10801): AGILE confirms gamma-ray flare
- 17/09/30 02:10 GMT (ATel 10802): HAWC, no detection in 12day window

Fermi Large Area Telescope (LAT) quick-look with FAVA



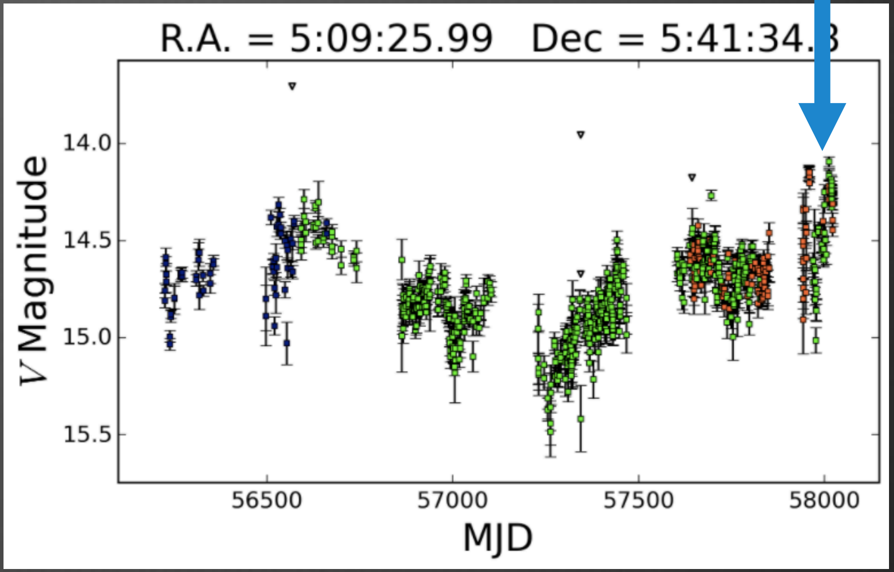
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27

Radio Light Curve

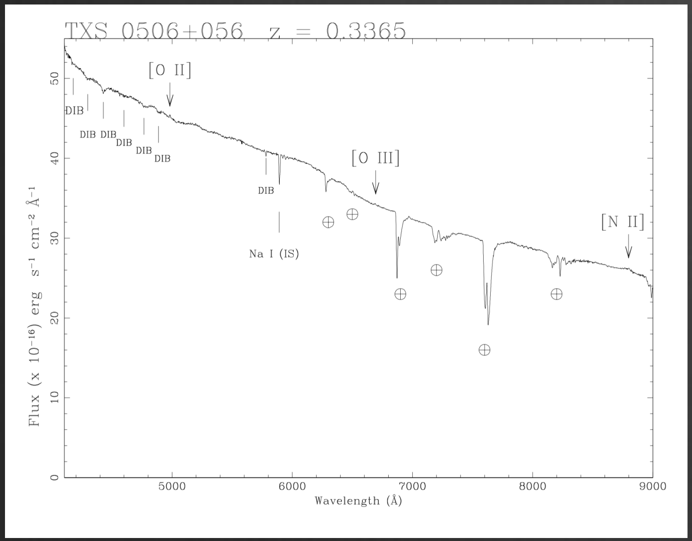


OVRO 40m Telescope (15 GHz)

ASAS-SN Optical Light Curve



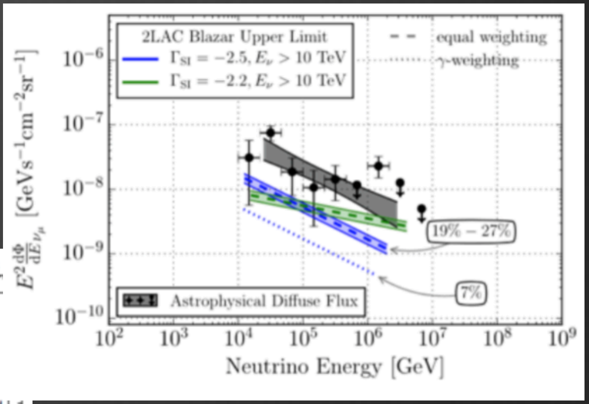
TXS 0506+056 redshift



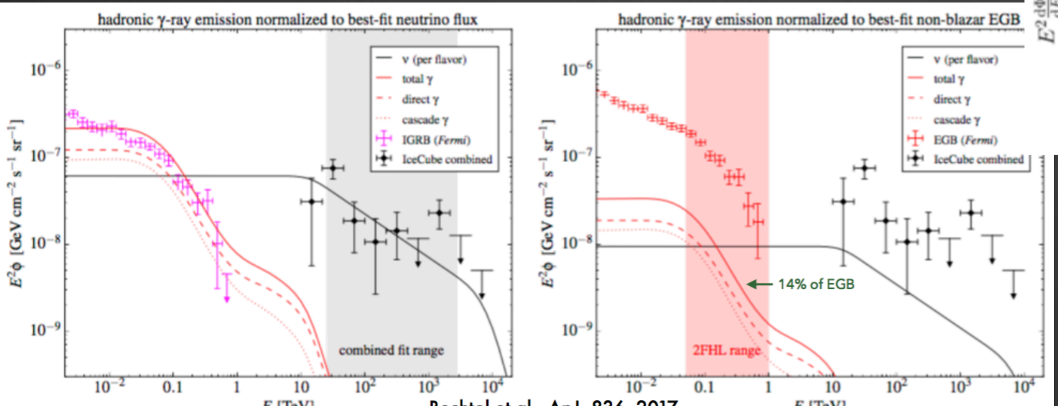
- z = 0.3365±0.0010 (Paiano+ 2018 ApJ, 854, 32)

Lessons learned

- **Decomposing the diffuse gamma-ray / neutrino bkg.**
  - Latest results on the IGBR by Fermi and IC provide strong constraints on source populations
  - IceCube flux:
    - Blazars <10-20%
    - Star Forming Galaxies <30%
  - Less room for pp scenarios



IceCube coll 2017

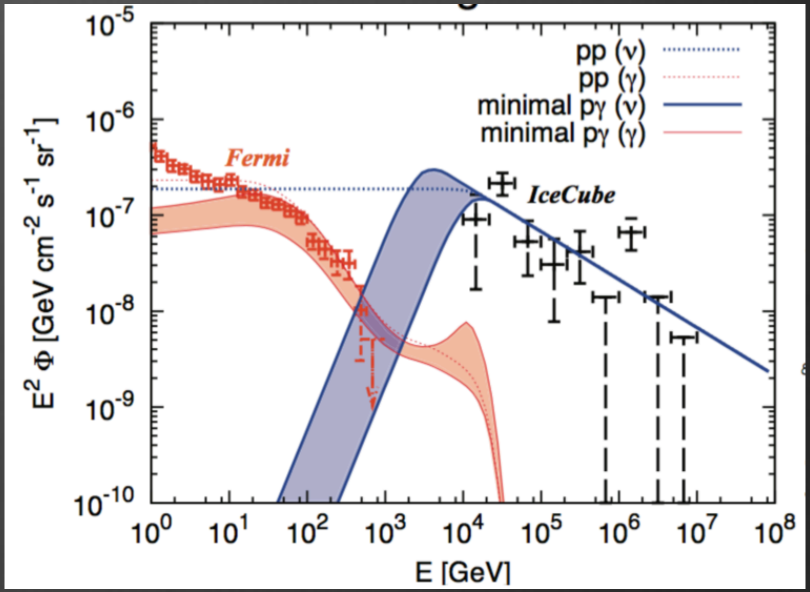


Bechtol et al., ApJ, 836, 2017

(see also subthreshold sources studies, Fermi coll. 16, Lisanti+ 16)

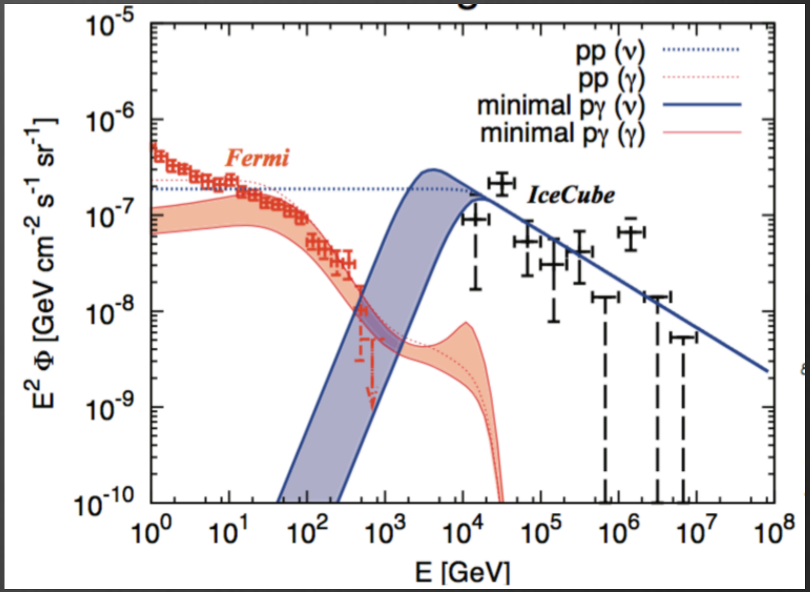
Lessons learned

- Best fit spectral indices tend to be as soft as 2.5
- At 10-100 TeV, high flux
  (~1e^{-7} GeV cm^{-2} s^{-1} sr^{-1})
- If $\boldsymbol{\gamma}$-ray transparent → strong tensions w. diffuse $\boldsymbol{\gamma}$-ray bkg. for both pp & p$\boldsymbol{\gamma}$



Lessons learned

- Best fit spectral indices tend to be as soft as 2.5
- At 10-100 TeV, high flux
  (~1e^{-7} GeV cm^{-2} s^{-1} sr^{-1})
- If γ-ray transparent → strong tensions w. diffuse γ-ray bkg. for both pp & pγ
- **γ -ray dark cosmic-ray accelerators**
  $\gamma\gamma$→e+e- inevitable in pγ sources (e.g. GRBs, AGN)
- **The same target photons prevent γ-ray escape**



Sources originating the astrophysical neutrinos detected by IceCube may be opaque to 1–100 GeV gamma-rays if the neutrino flux originates from photo-hadronic processes (Stecker 1991; Murase+ 2015, 2016)

Summary

- Multi-messenger + time-domain is a promising path to reveal the origin of neutrinos (and cosmic rays)
- Neutrino fans are eager users of gamma-ray data
- Warning:
  - the different messengers may not come from the same objects
  - and/or production regions within the same object
- Remarkable wealth of available data
  - Need improvements in theoretical models in order to interpret the current multi-messengers