UPPSALA UNIVERSITET

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

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3rd December 2020

SEARCH FOR NEUTRINO SIGNATURES IN HIGH-ENERGY ACTIVITY OF BLAZARS

HEF Department Seminar

Credits: https://multimessenger.desy.de

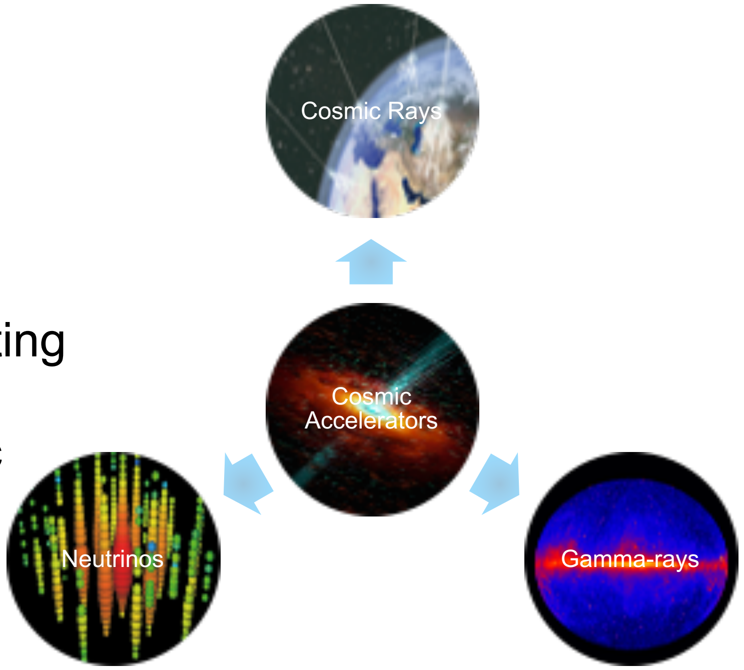
OUTLINE

- **Introduction**
- **Past Research**
- **Current Focus**

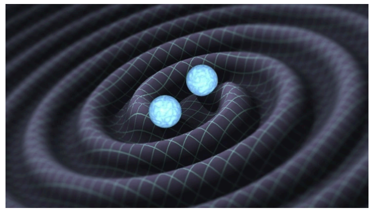
MULTI-MESSENGER ASTRONOMY

Observation of the so called ultra-high energy cosmic rays (UHECRs) proves the existence of very powerful cosmic particle accelerators

PeV neutrinos observed by IceCube, suggesting acceleration of protons in cosmic sources



γ-ray photons observed with E ~ 100 TeV. Fermi collaboration has identified > 3000 point-like γ-sources and measured a diffuse galactic flux of γ-rays



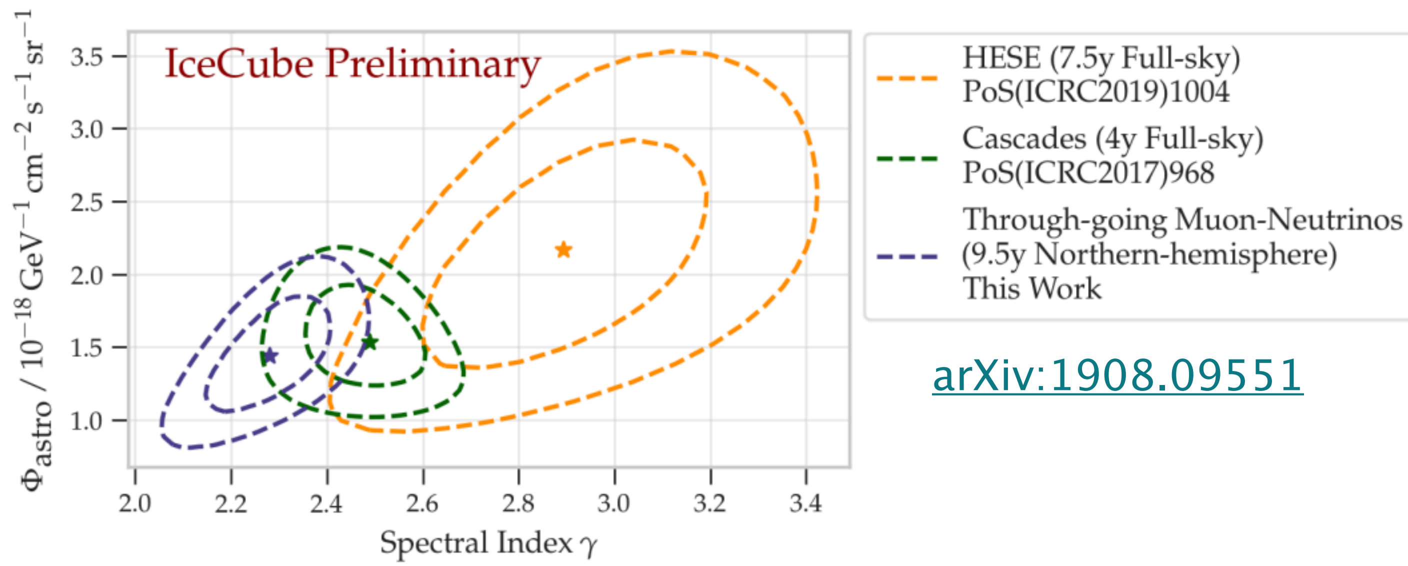
Gravitational waves also joining the fore!

Interactions of very high-energy (VHE) cosmic ray particles inside the sources also produce high energy neutrinos and γ-rays

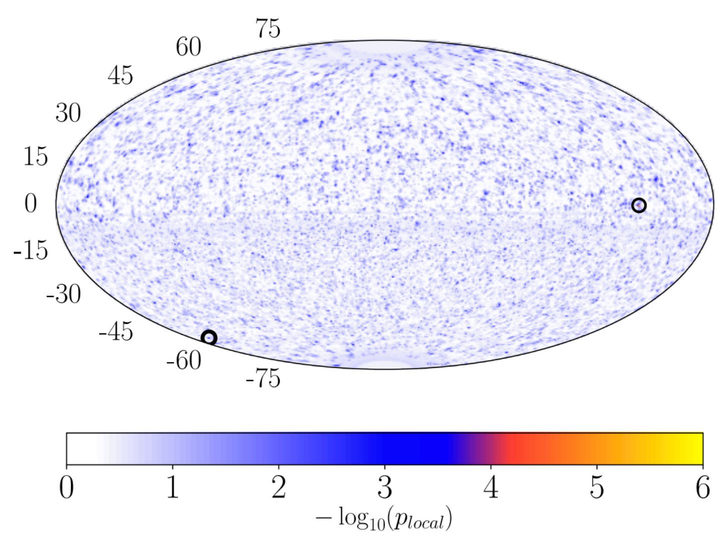
Deflection of charged cosmic rays under galactic and extra-galactic magnetic fields (EGMF), and the absorption of high-energy γ-rays and cosmic rays by CMB and other background radiation (Extra-galactic Background Light - EBL) poses a problem in probing the Universe at the highest energies beyond a few hundred Mpc!!

Neutrinos are charge neutral and weakly interacting – an ideal messenger for revealing the interior mechanisms of extreme sources!

- Diffuse astrophysical neutrino signal detected by IceCube with **6.7σ**
- Spectral index in the Northern hemisphere measured with ν_μ (~ 2.3) is harder than the fully-sky index measured with starting track events (~ 2.9)

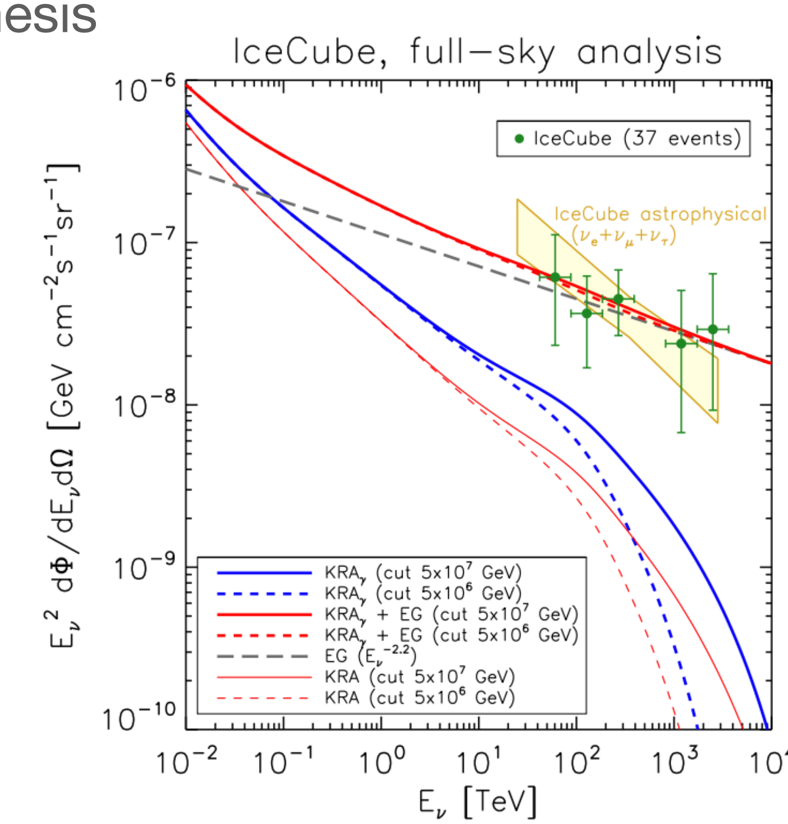


arXiv:1908.09551



arXiv:1910.08488

- Time-integrated searches reveal no significant clustering in data
- Brightest hotspot (~ 2.9σ, NGC 1068) consistent with background only hypothesis



Diffuse galactic contribution to the astrophysical ν-flux < 10 %

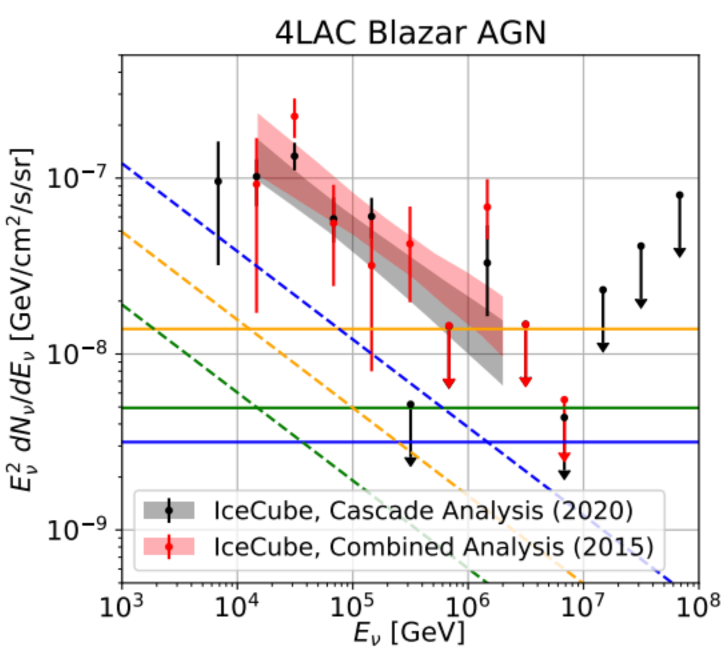
~ 90% of diffuse ν-flux is extra-galactic!

Gaggero et al. 2015, Aartsen et al. ApJ 2017

EXTRA-GALACTIC NU-SOURCES

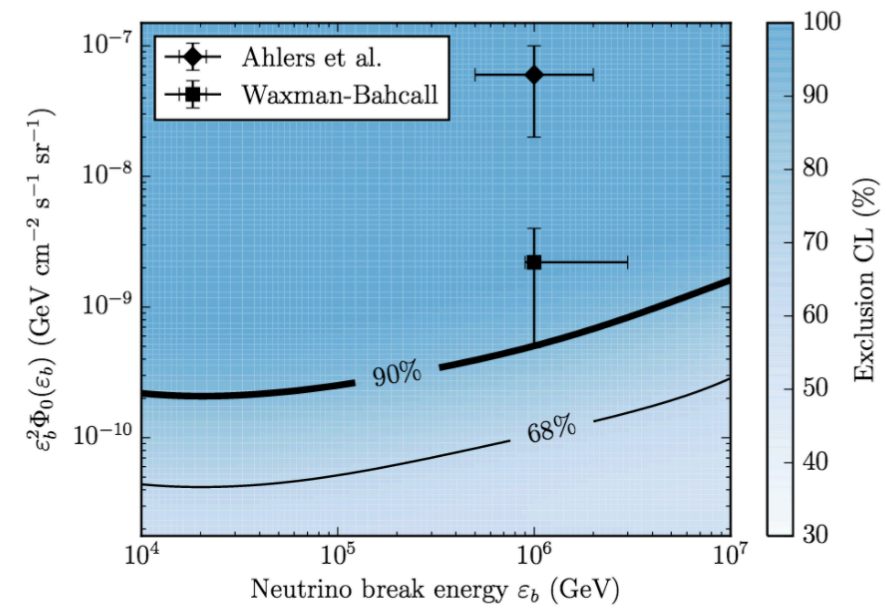
Contribution from most of the source classes suspected of producing the extra-galactic ν-flux is constrained:

AGN [> 15%]



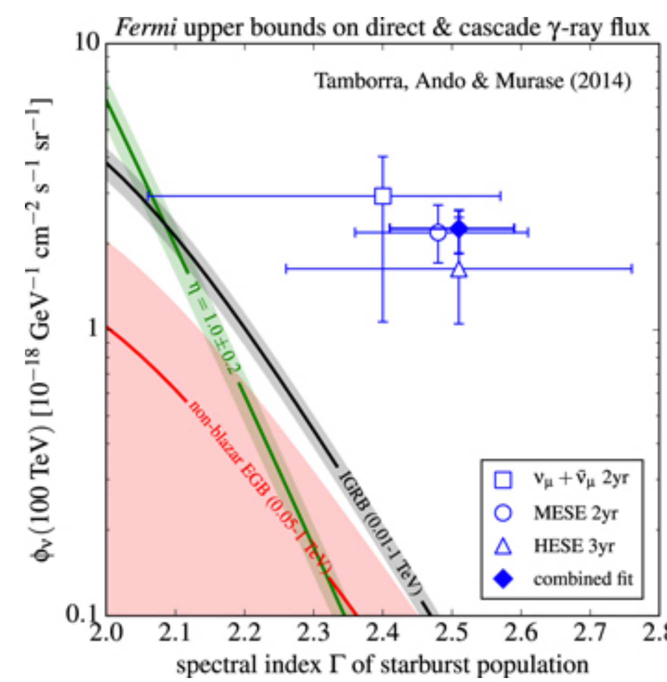
arXiv:2007.12706

Star-forming galaxies (SFGs) [10 - 30%]



Aartsen et al ApJ 2016

GRBs (transients) [< 1%]



Bechtol et al. ApJ 2017

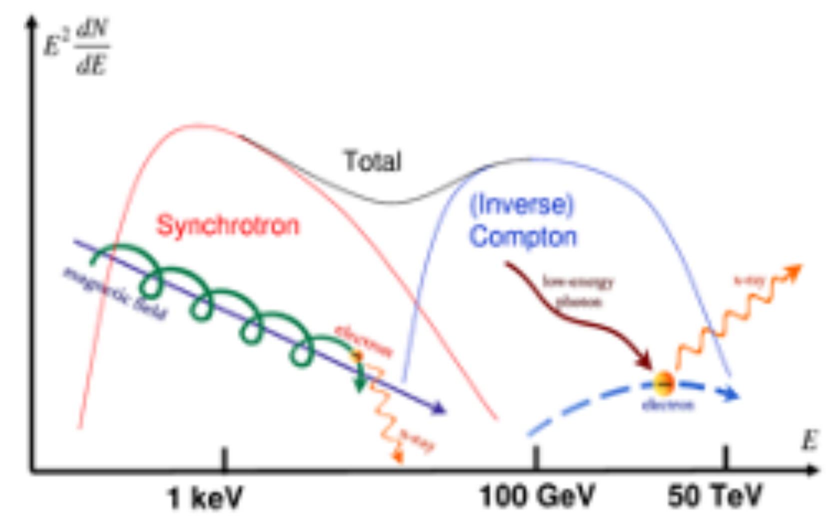
Depending on the model, AGNs can explain the entirety of IceCube astrophysical ν-flux

Blazars are AGN with their jets pointed towards the Earth

Spectral Energy Distribution (SED):

Non-thermal emission over a broad range of the EM spectrum defined by Synch. Self Compton (SSC) model. Two major humps:

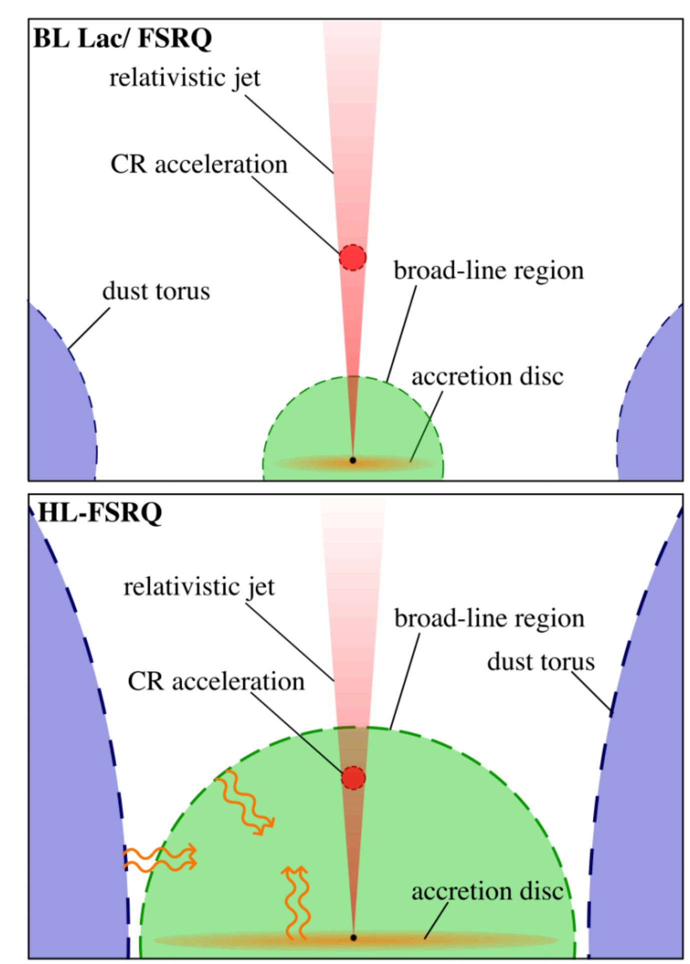
1. **Electron Synchrotron**: Emission from relativistic e- gyrating under high magnetic fields inside jets
2. **Inverse Compton**: Compton up-scattering of the synchrotron photons



BL Lacs -- High optical polarisation
weak emission lines

FSRQs -- More luminous
strong optical emission lines
prominent Compton hump in SED

Difference between the two sub-classes possibly based on jet-power and mass of central engine



Rodrigues et al. ApJ 2018

HADRONIC EMISSION

Accelerated CRs in astrophysical jets can produce neutrinos via 2 main mechanisms:

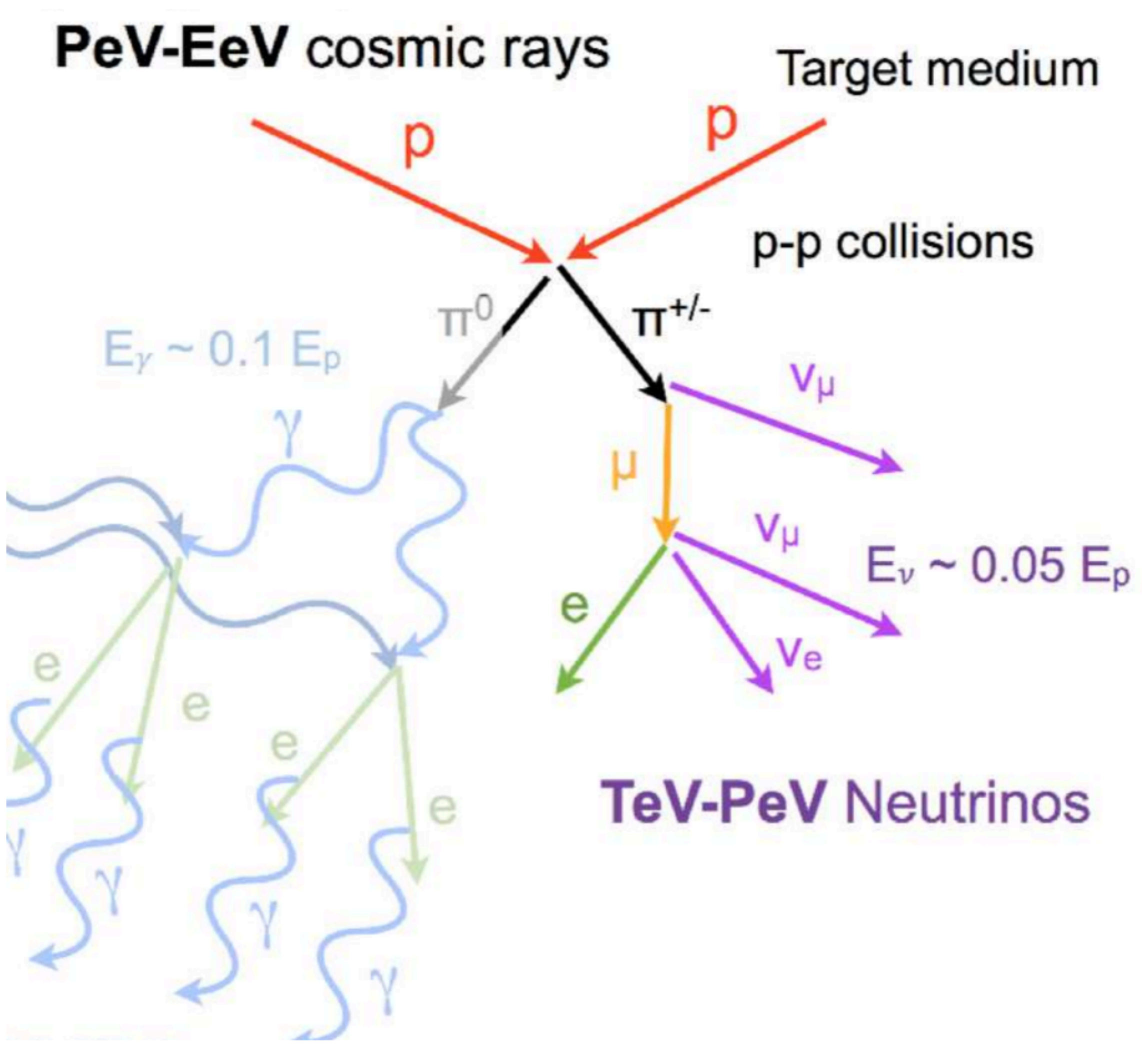
- Astrophysical beam dump (*pp* collisions)

DENSE GAS

Protons interact with surrounding gas to produced π

π0 decay emits 2 γ-rays, while charged-pions decay to produce neutrinos and e± pairs

Each ν carries away 5% of parent proton's energy



Credit: Ke Fang

HADRONIC EMISSION

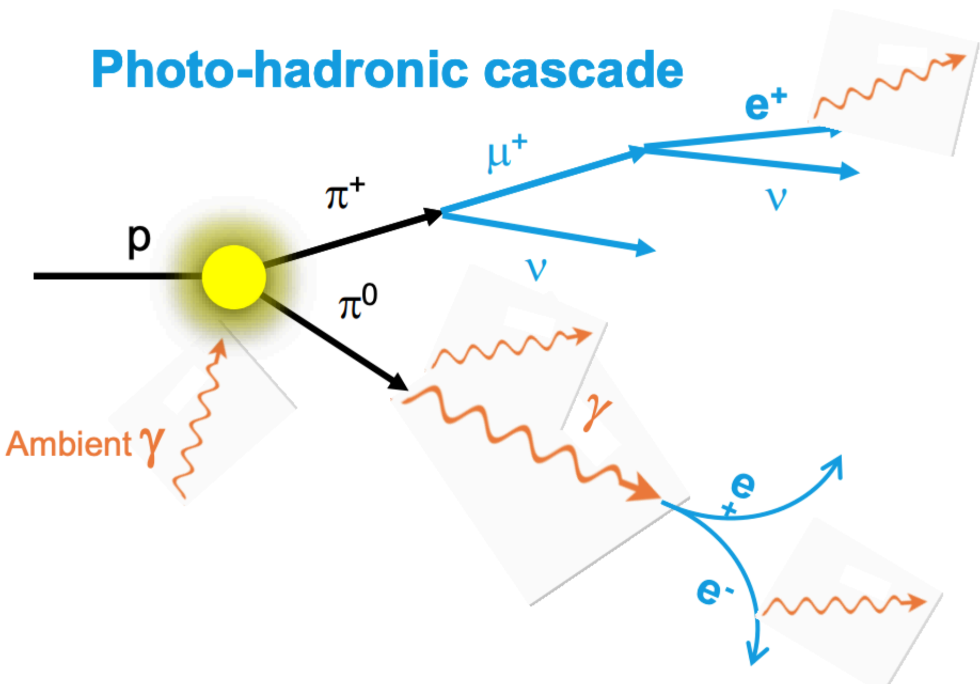
Accelerated CRs in astrophysical jets can produce neutrinos via 2 main mechanisms:

- Astrophysical beam dump (*pp* collisions) **DENSE GAS**

- Photohadronic/photopion interactions (*pγ*) **DENSE PHOTON FIELDS**

Credit: A. Fedynich

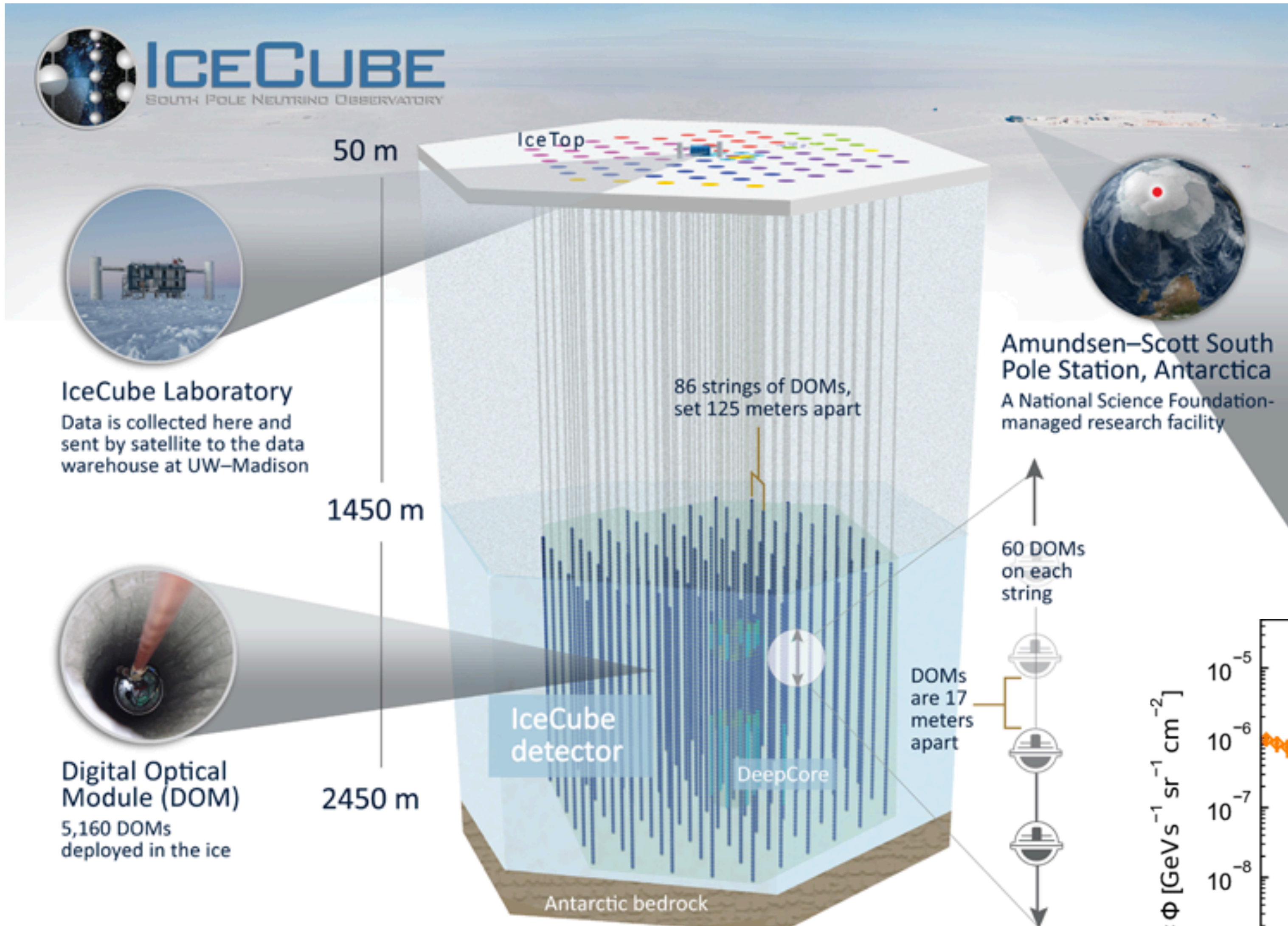
$$p + \gamma \rightarrow p/n + \pi^{\pm}, \pi^{0} \rightarrow 2\gamma + 2\nu_{\mu} + \nu_{e}$$

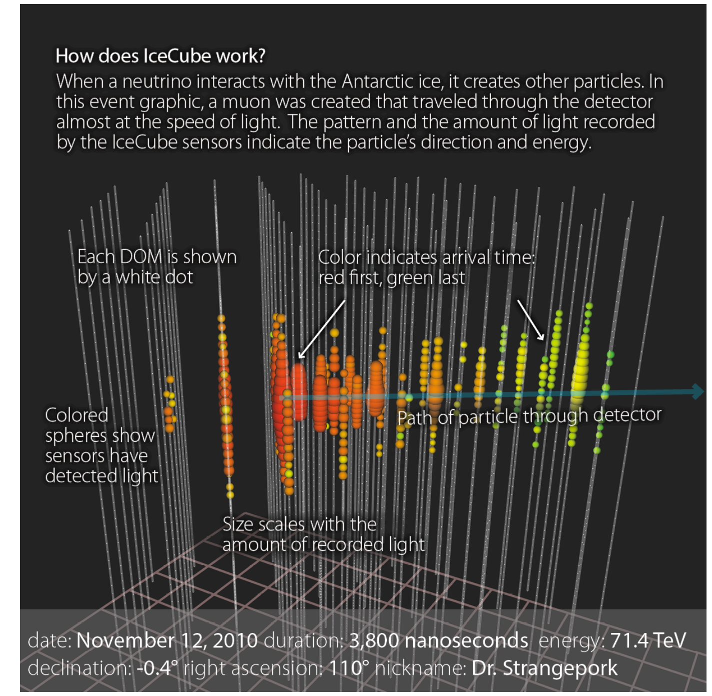


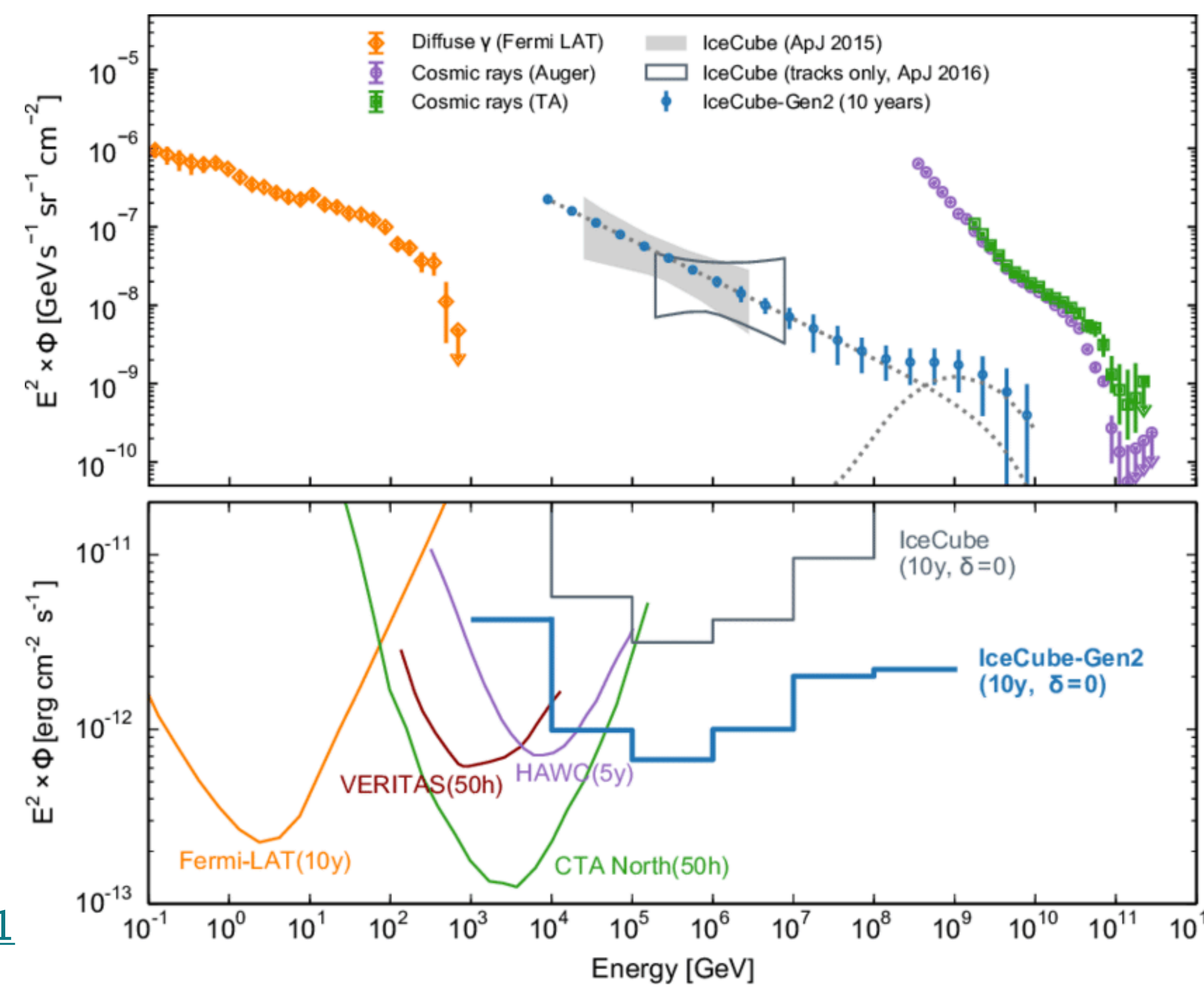
100 TEV NEUTRINO —> 2 PEV PROTON

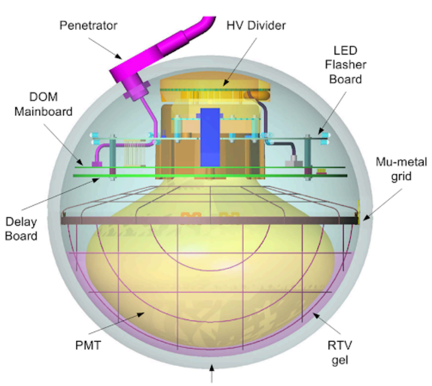
If a source can accelerate protons to sufficiently high energies, it can emit VHE neutrinos & high-energy γ-rays!

ICECUBE OBSERVATORY









DOM schematic

Proposed IceCube Gen-2 promises to increase sensitivity by a factor of 10, and potentially combine optical and radio detections to extend our reach to UHE ν sky

arXiv:1911.02561

AMON REALTIME ALERT SYSTEM

AMON - Astrophysical Multi-messenger Observatory Network

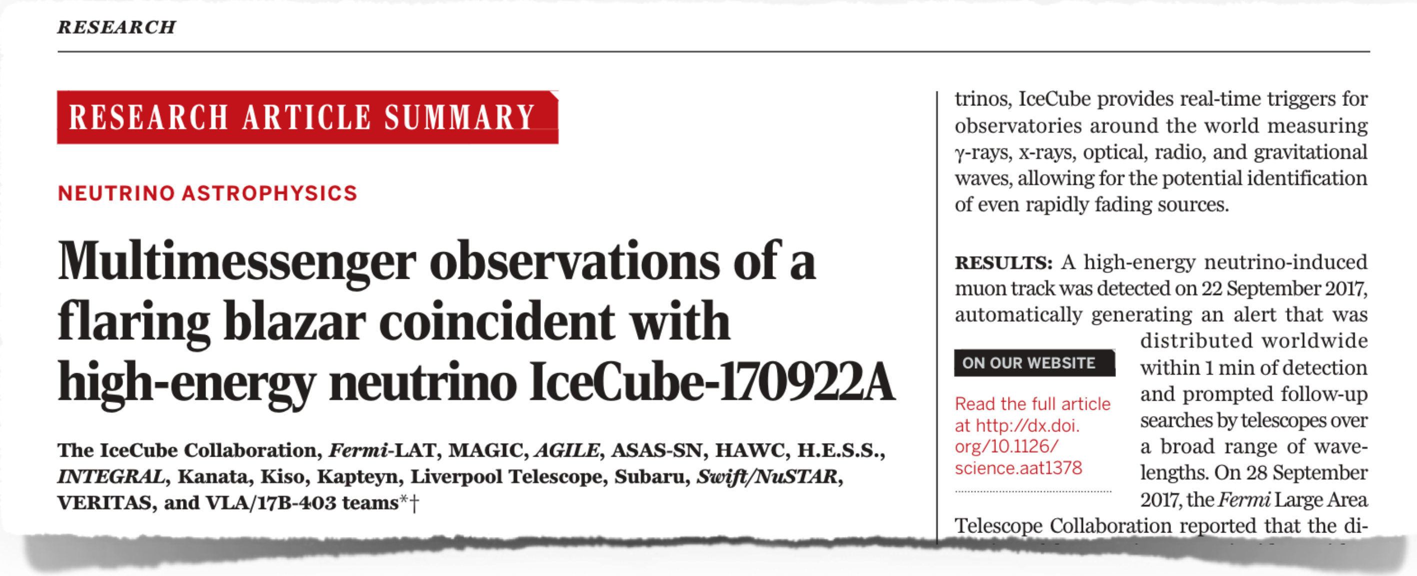
- IceCube releases public alerts in real time (~ min) for ν-events of probable astrophysical origin through the GCN network
- Followed-up by observatories like Fermi, MAGIC, HAWC for coincident γ-ray activity
- Since 2016; ~ 10 alerts per year
- First positive follow-up: TXS 0506+056 ; observed in a flaring state

AMON ICECUBE_GOLD and _BRONZE EVENTS

EVENT				OBSERVATION								
RunNum_EventNum	Rev	Date	Time UT	NoticeType	RA [deg]	Dec [deg]	Error90 [arcmin]	Error50 [arcmin]	Energy	Signalness	FAR [#/yr]	Comments
134751_31476488	1	20/11/30	20:21:46.47	GOLD	30.5399	-12.0999	70.79	41.39	2.0347e+02	1.4696e-01	1.3222	IceCube Gold event. The position error is statistical only, there is no systematic added.
134751_31476488	0	20/11/30	20:21:46.47	GOLD	30.4950	-11.6137	42.65	16.61	2.0347e+02	1.4696e-01	1.3222	IceCube Gold event. The position error is statistical only, there is no systematic added.
134715_65785778	1	20/11/20	09:44:40.55	BRONZE	307.5299	+40.7700	280.79	158.40	1.5396e+02	5.0338e-01	0.2947	IceCube Bronze event. The position error is statistical only, there is no systematic added.
134715_65785778	0	20/11/20	09:44:40.55	BRONZE	307.8471	+40.1903	30.80	12.00	1.5396e+02	5.0338e-01	0.2947	IceCube Bronze event. The position error is statistical only, there is no systematic added.

The AMON network enables multi-messenger discoveries ($\nu + \gamma$ and also GW $+\gamma$) by bringing together Gamma-ray, Neutrino and GW observatories and vastly improving the significance of observations by any single experiment/instrument

TXS 0506+056



RESEARCH

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

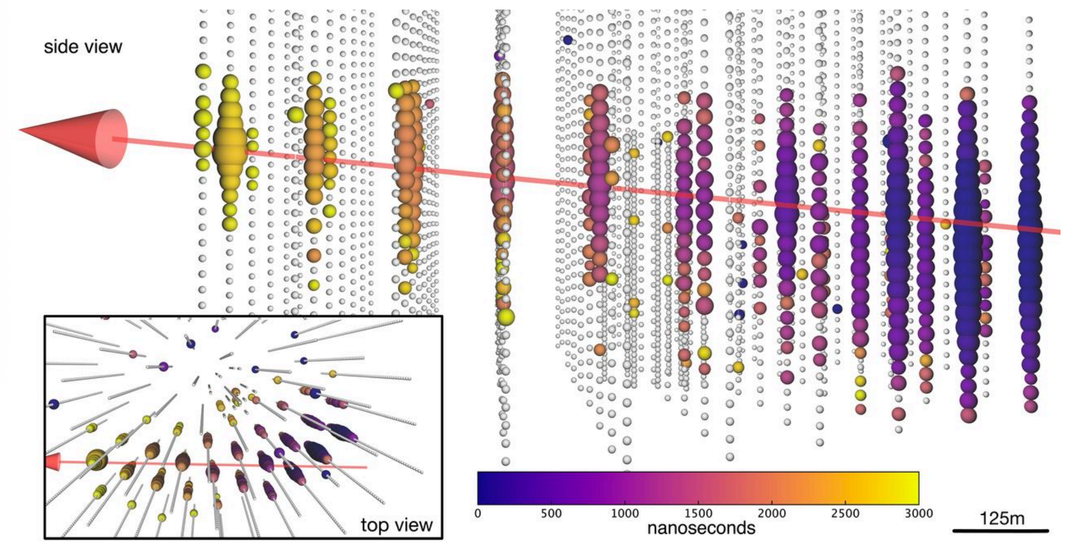
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†

trinos, IceCube provides real-time triggers for observatories around the world measuring γ-rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the di-

ON OUR WEBSITE

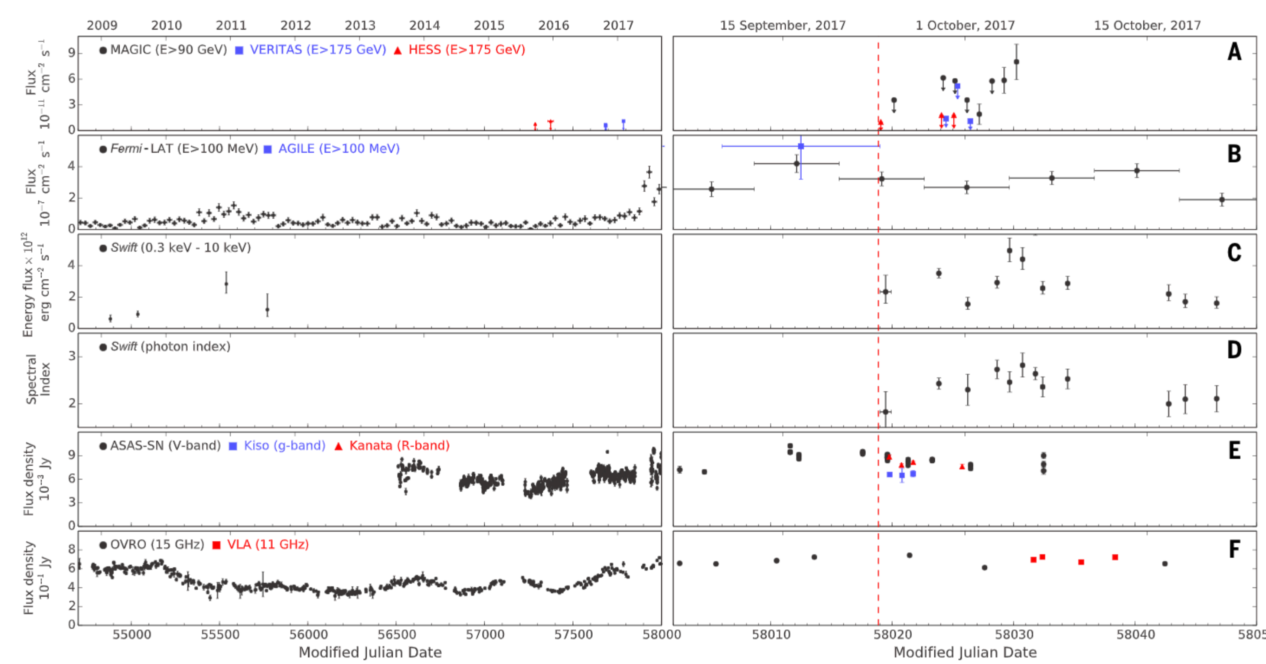
Read the full article at http://dx.doi.org/10.1126/science.aat1378



FIRST (POTENTIAL?) HE-NEUTRINO SOURCE

Aartsen et al. Science, 2018

- In Sept. 2017, IceCube observed a ~290 TeV neutrino from the direction of a blazar seen by Fermi in a flaring state
- MAGIC also observed increased activity between 80 - 400 GeV from the source in the following days
- Analysis of archival IceCube data confirmed an 3.5σ excess from the source direction in 2014



OUTLINE

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- **Past Research**
- Current Focus

OBJECTIVES

Motivation: Search for signatures of very high-energy neutrinos in the EM emission of blazars spatially correlated with IC astrophysical ν candidates

Objectives:

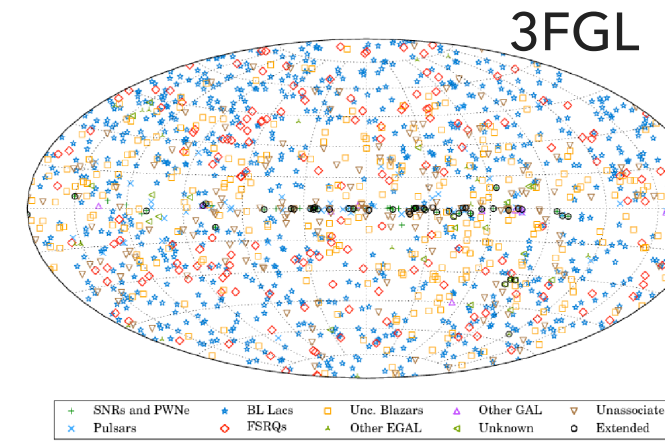
1. Build a sample of blazars spatially/temporally correlated with IceCube (muonic) neutrinos of astrophysical origin

2. Analyse their long-term γ-ray light curves:

- identify prominent flares
- calculate gamma-ray duty cycles
- spectral index variation and broadband SEDs

3. Derive the expected neutrino emission from the sources by applying lepto-hadronic models

4. Obtain "neutrino light curves" to investigate observability of these sources with km3 neutrino telescopes



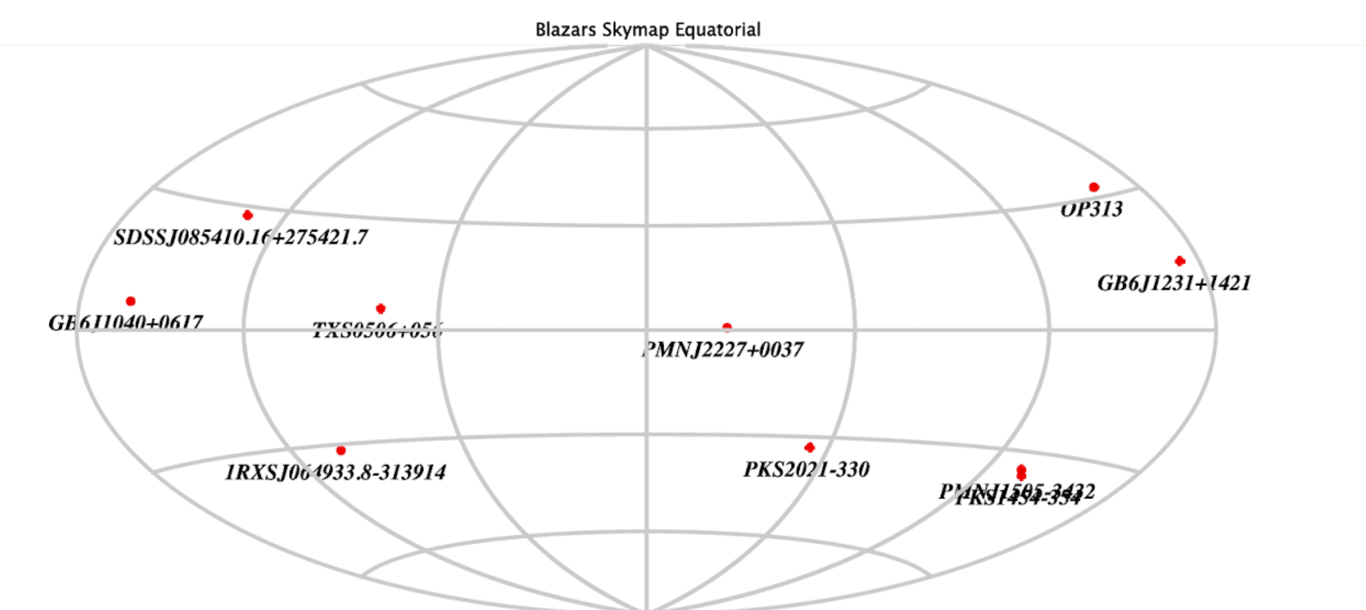
- ✓ **Source Catalogs** : Fermi-LAT 3FGL & 3FHL (Acero et al. 2015)
- ✓ **ν-event catalogs**: IceCube AMON alerts (Smith et al. 2013)

Muon neutrinos above 200 TeV (Aartsen et al. 2016)

IceCube HESE sample (Aartsen et al. PRL 2014; IceCube Coll. ICRC 2015 (1081); IceCube Coll. ICRC 2017 (981))

- ✓ **Selection criteria**: Best fit source position from Fermi-LAT within 1.3^0 of the best-fit neutrino position from IceCube (only nu-events with 50% C.L. error < 1.5^0 considered)

$$(\text{Fermi-LAT}_{centroid} - \text{IceCube}_{centroid}) < 1.3^0$$



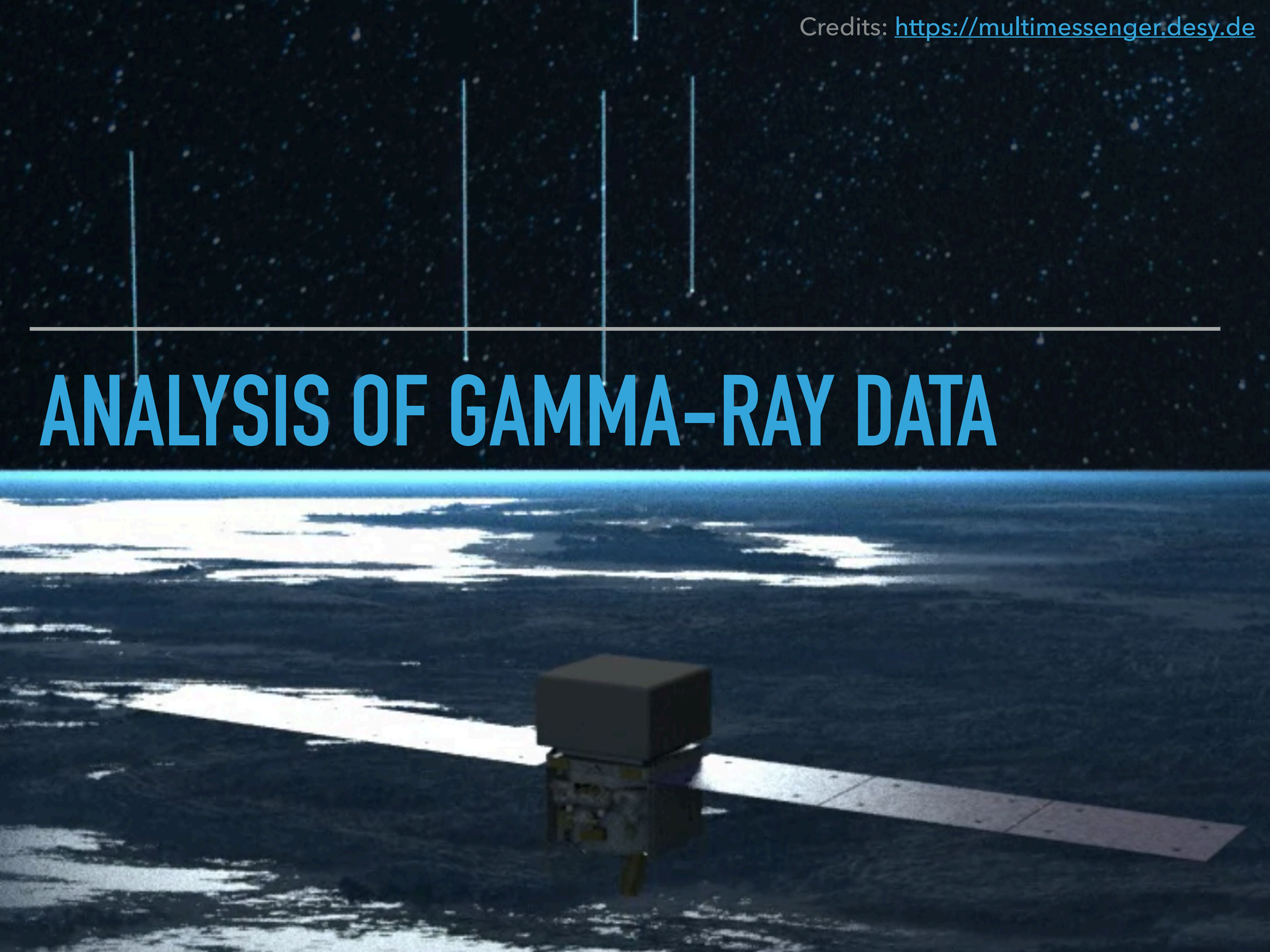
Skymap of blazar sample

7 FSRQs & 3 BL Lacs

S.no.	Source Name	RA (deg.)	Dec. (deg.)	Source Class	z
1	OP 313	197.649	32.351	fsrq	0.998
2	SDSS J085410.16+275421.7	133.532	27.883	bll	0.494
3	1RXS J064933.8-313914	102.386	-31.649	bll	≥ 0.563
4	GB6 J1040+0617	160.147	6.302	bll	0.735
5	GB6 J1231+1421	187.866	14.368	bll	0.256
6	PKS 1454-354	224.382	-35.648	fsrq	1.424
7	PMN J1505-3432	226.250	-34.547	bll	1.554
8	PMN J2227+0037	336.972	0.610	bll	-
9	PKS 2021-330	306.108	-32.905	fsrq	1.47
10	TXS 0506+056	77.364	5.706	bll	0.336

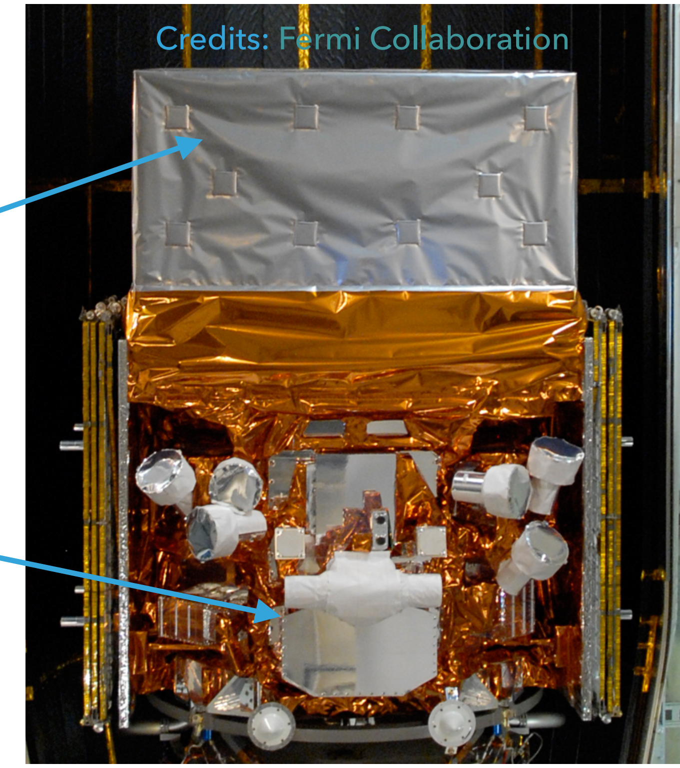
Credits: https://multimessenger.desy.de

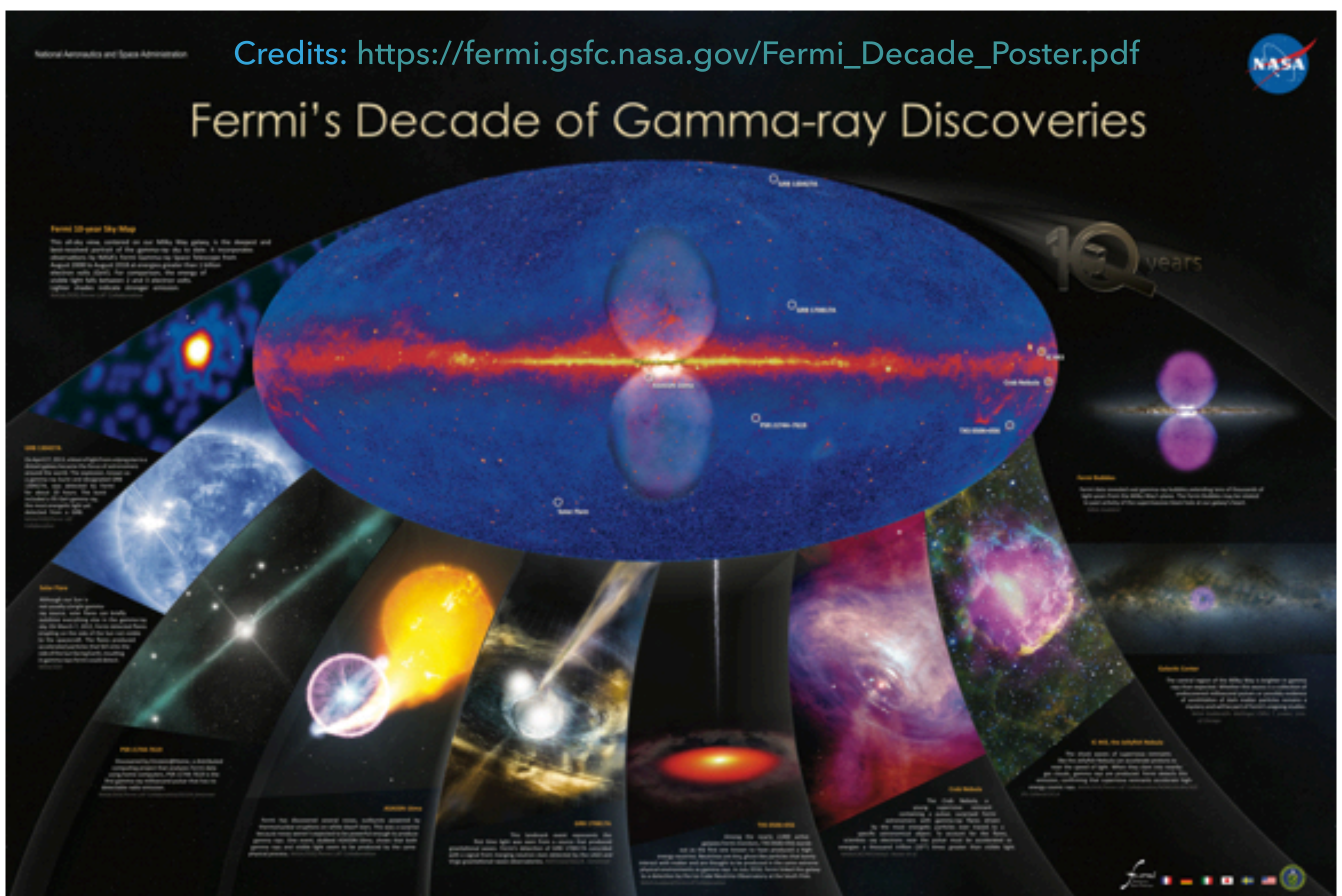
ANALYSIS OF GAMMA-RAY DATA



FERMI MISSION

- γ-ray observatory launched in 2008 (~ 30 MeV < E < ~ 500 GeV)
- Constant monitoring of the γ-ray sky with **Fermi-LAT** (Large Area Telescope)
  - Full sky survey every 3 hours, FoV ~ 2.4 str
- Transient monitoring with **Fermi-GBM** (Gamma-ray Burst Monitor)
  - ~ 1 GRB detected per day





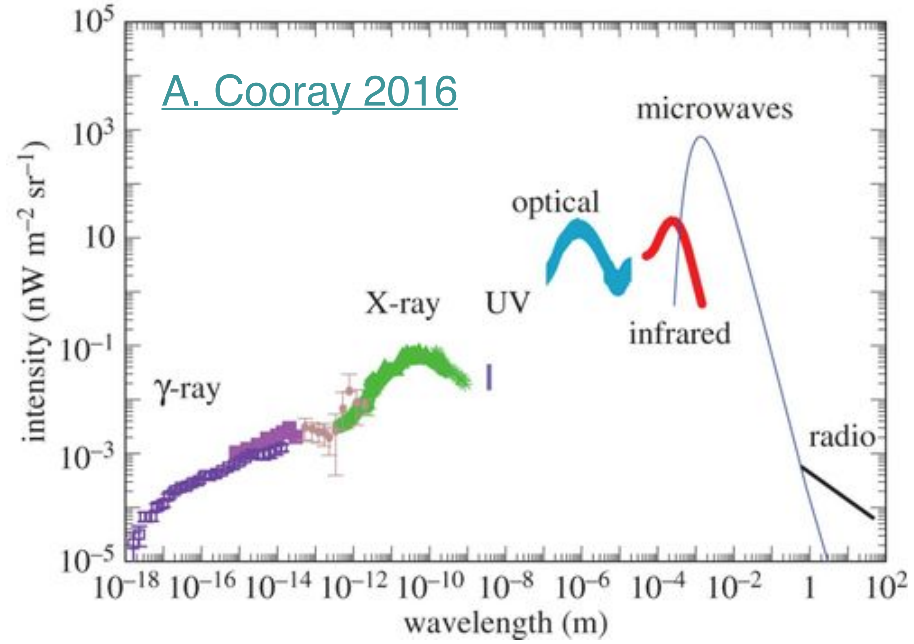
- Detailed maps of the γ-ray sky
- Fermi bubbles
- Energy invariance of speed of light
- GRB from binary neutron star merger detection with LIGO
- Gamma-ray flare of potential VHE neutrino blazar TXS 0506+056
- Most comprehensive AGN catalogs

EXTRA-GALACTIC BACKGROUND LIGHT

EBL is the integrated intensity of all EM radiation emitted throughout the history of the Universe

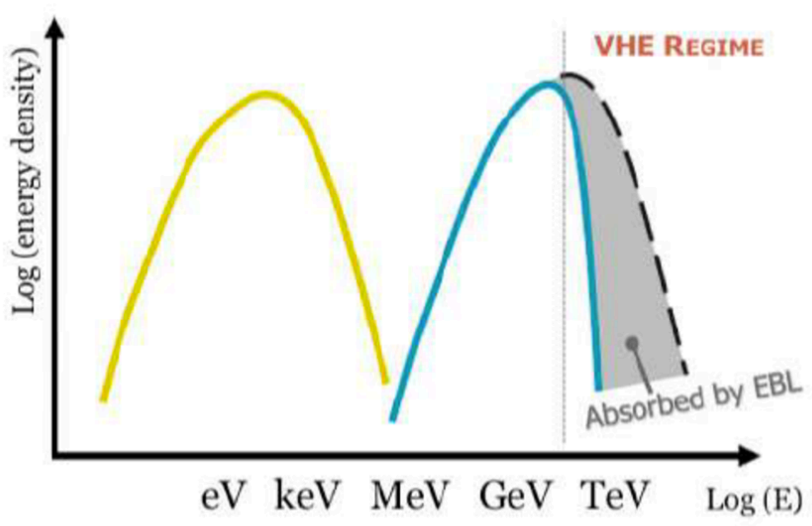
~ 20 decades of wavelengths

Different contributions at different wavelengths

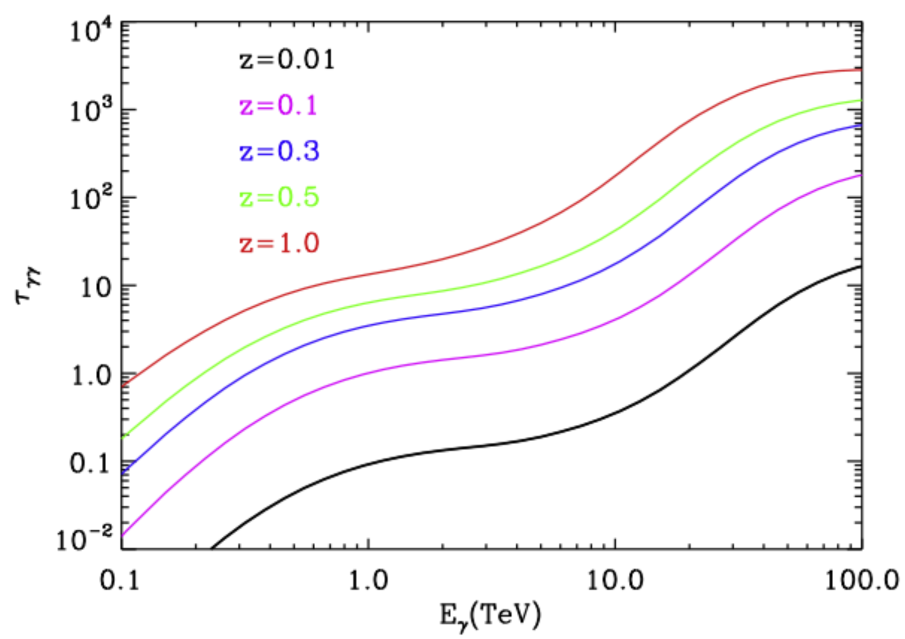


γ-rays propagating over large distances get attenuated due to absorption on EBL photons

- Process is redshift and energy dependent
- For z = 1, not possible to observe above ~ 300 GeV



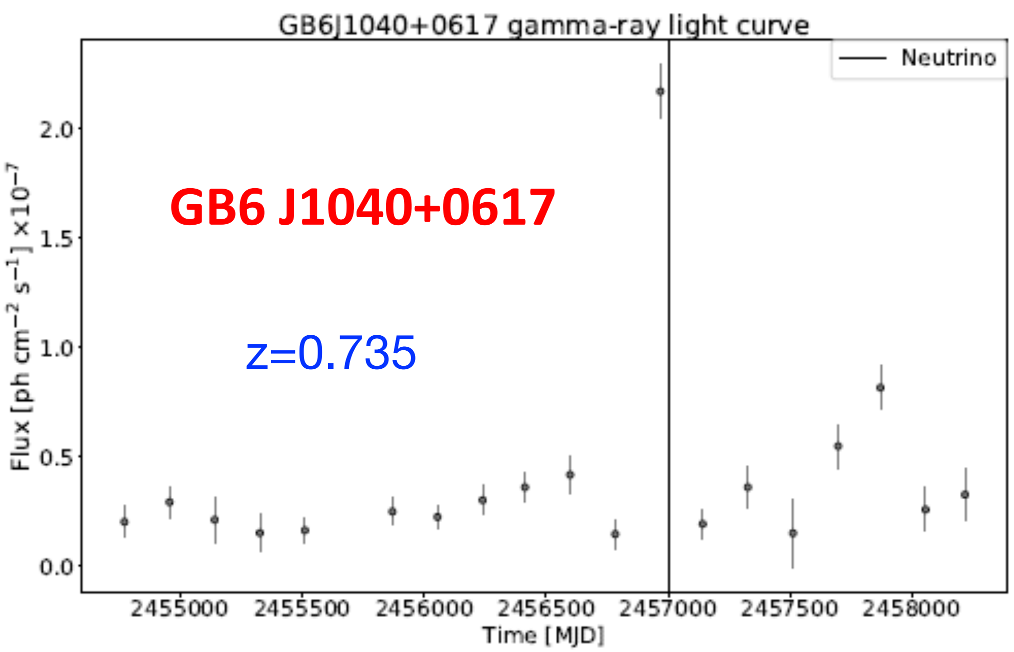
GAMMA-RAY HORIZON

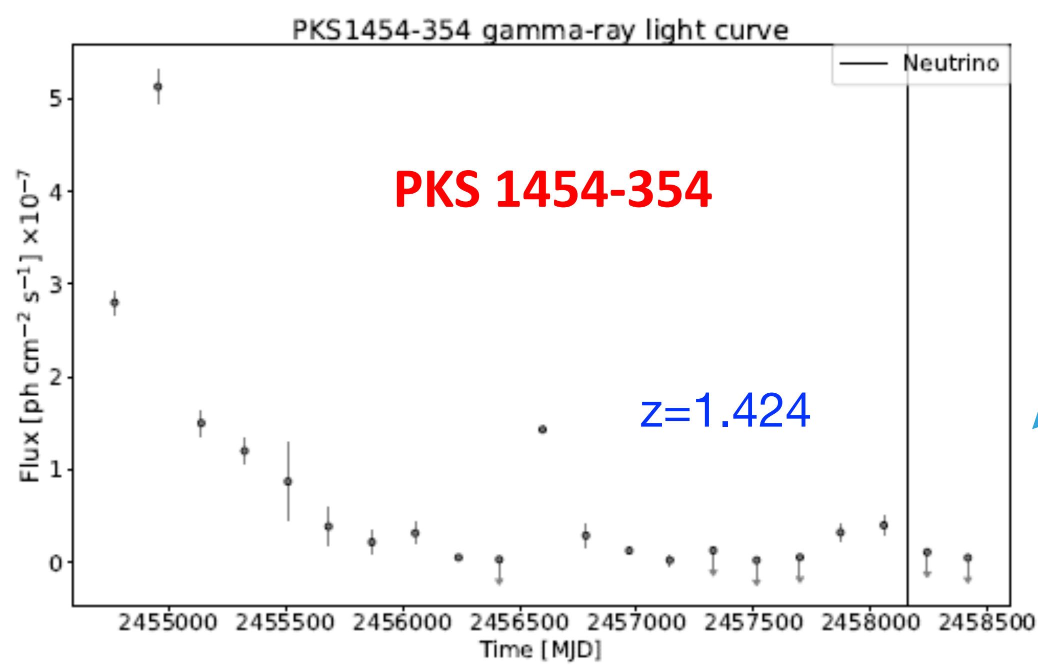


Dwek & Krennrich 2013

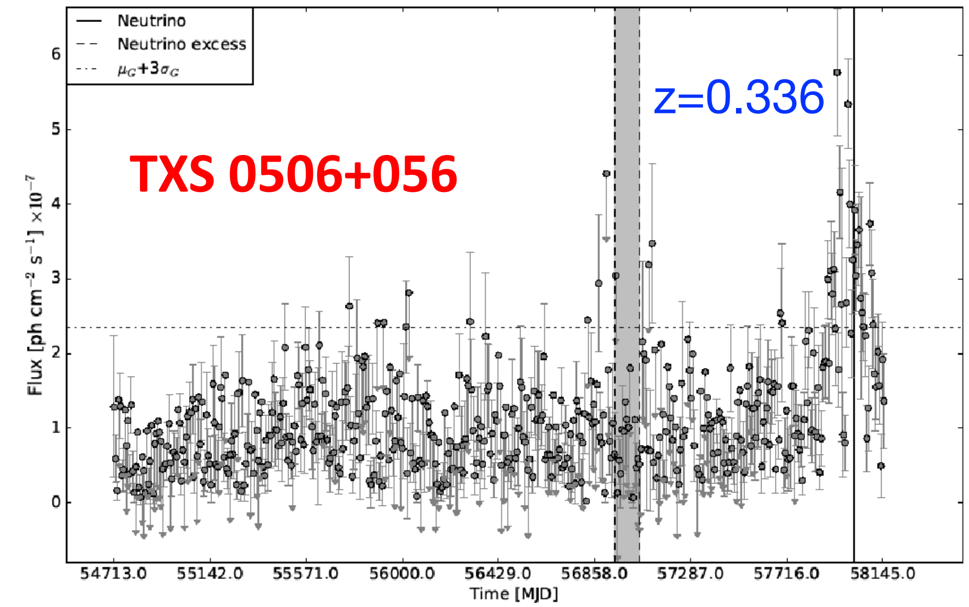
GAMMA-RAY LIGHT CURVES

- ~ 10 years of Fermi-LAT data
- Binned likelihood analysis
- $0.1 < E_{GeV} < 300$; 10^0 ROI; power law spectrum;
- EBL absorption with Franceschini et al. 2008

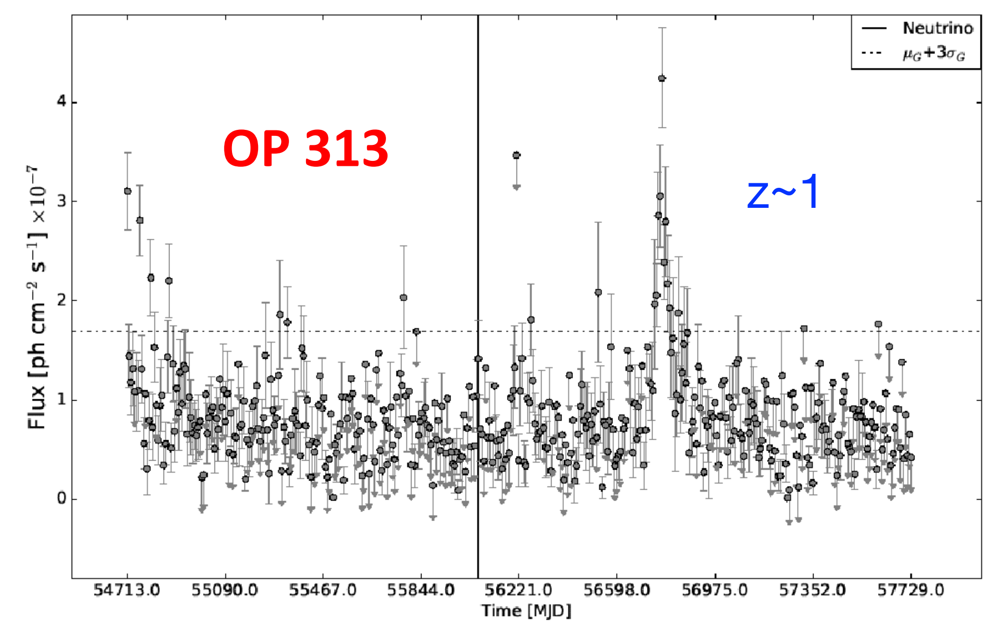




BL Lacs



FSRQs



Only TXS 0506+056 and GB6 J1040+0617 show a temporal correlation between spatially coincident neutrino and gamma-ray flare

GAMMA-RAY DUTY CYCLE

ESTIMATE OF HOW FREQUENTLY ACTIVE A SOURCE

Duty Cycle (DC) ➡ The fraction of time a source spends in an active state

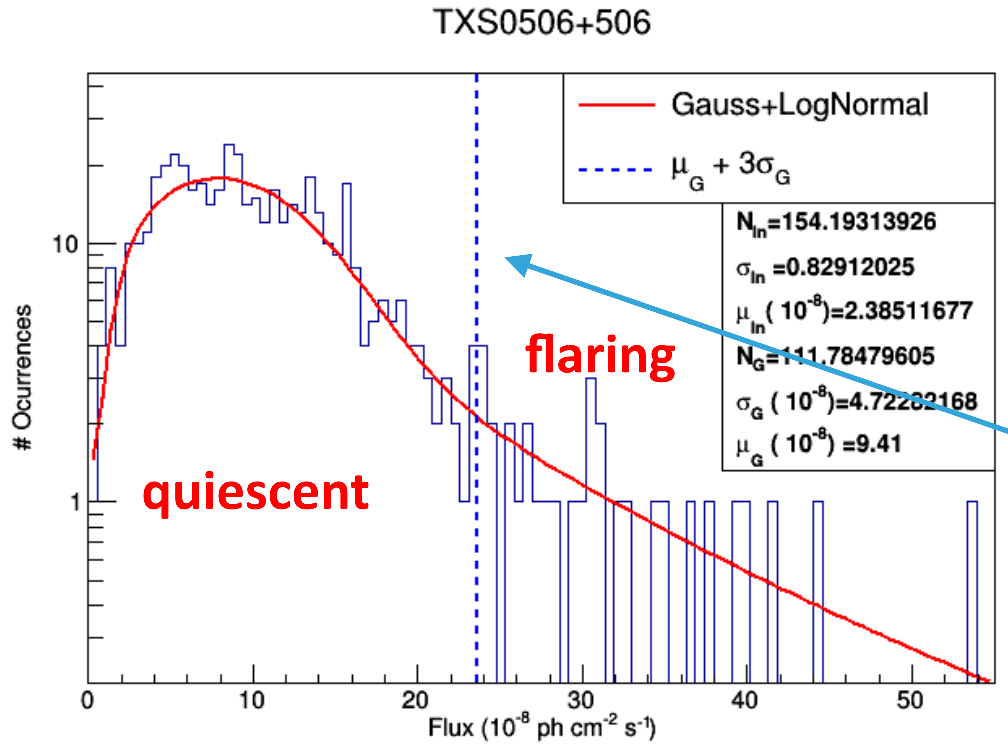
$$DC = \frac{T_{flaring}}{T_{flaring} + T_{quiescent}}$$

➡ **Blazars stay in a low-activity or "off" state for a large fraction of their time**

➡ **Important to factor in their DC while calculating long-term flux expectations**

DC I: TLUCZYKONT CRITERIA

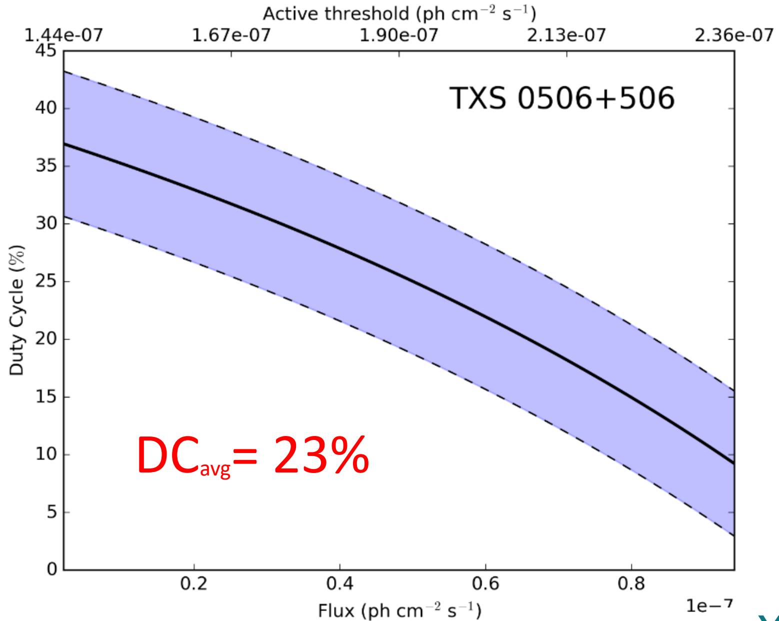
Method I: Fit a Gaus+LogNormal function to the flux distribution (Tluczykont et al. 2010)

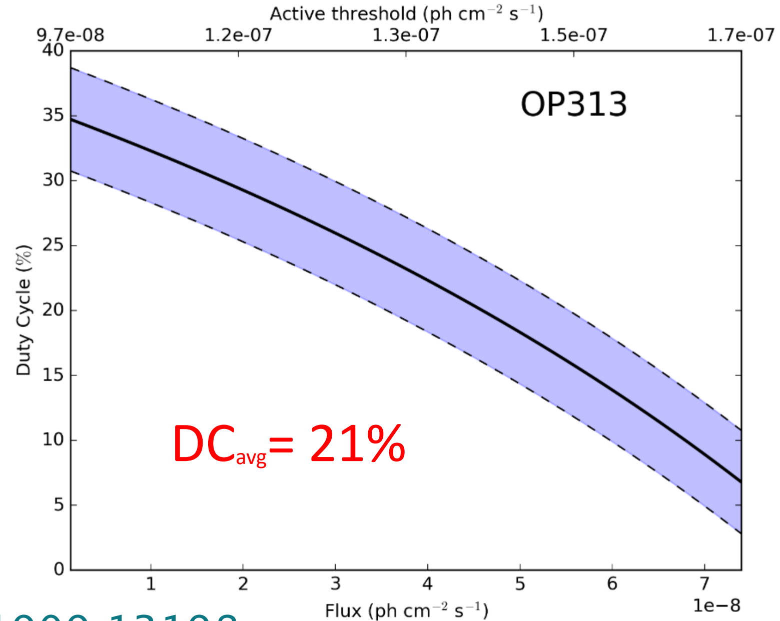


Gaussian represents the quiescent states while LogNormal is associated with the flaring states

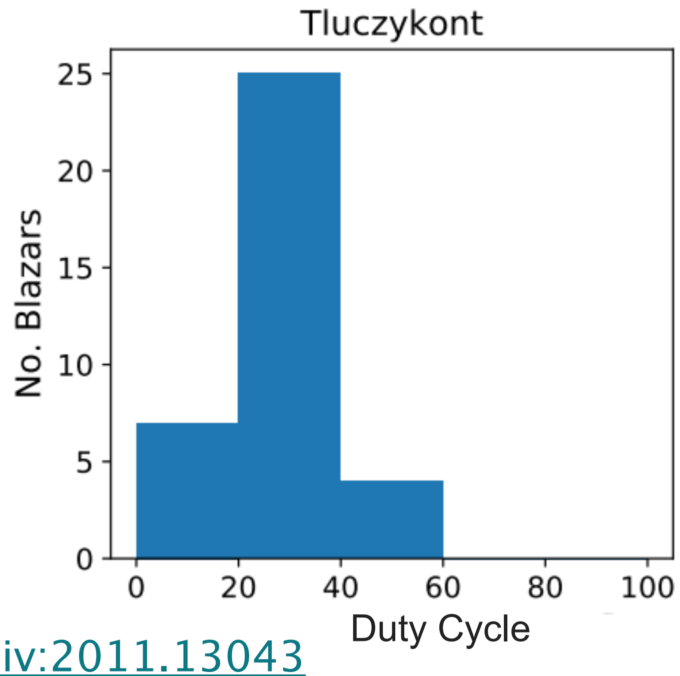
Vary the baseline to obtain a distribution in DC

Even the brightest blazars are active only 1/4th of the time





arXiv:1909.13198



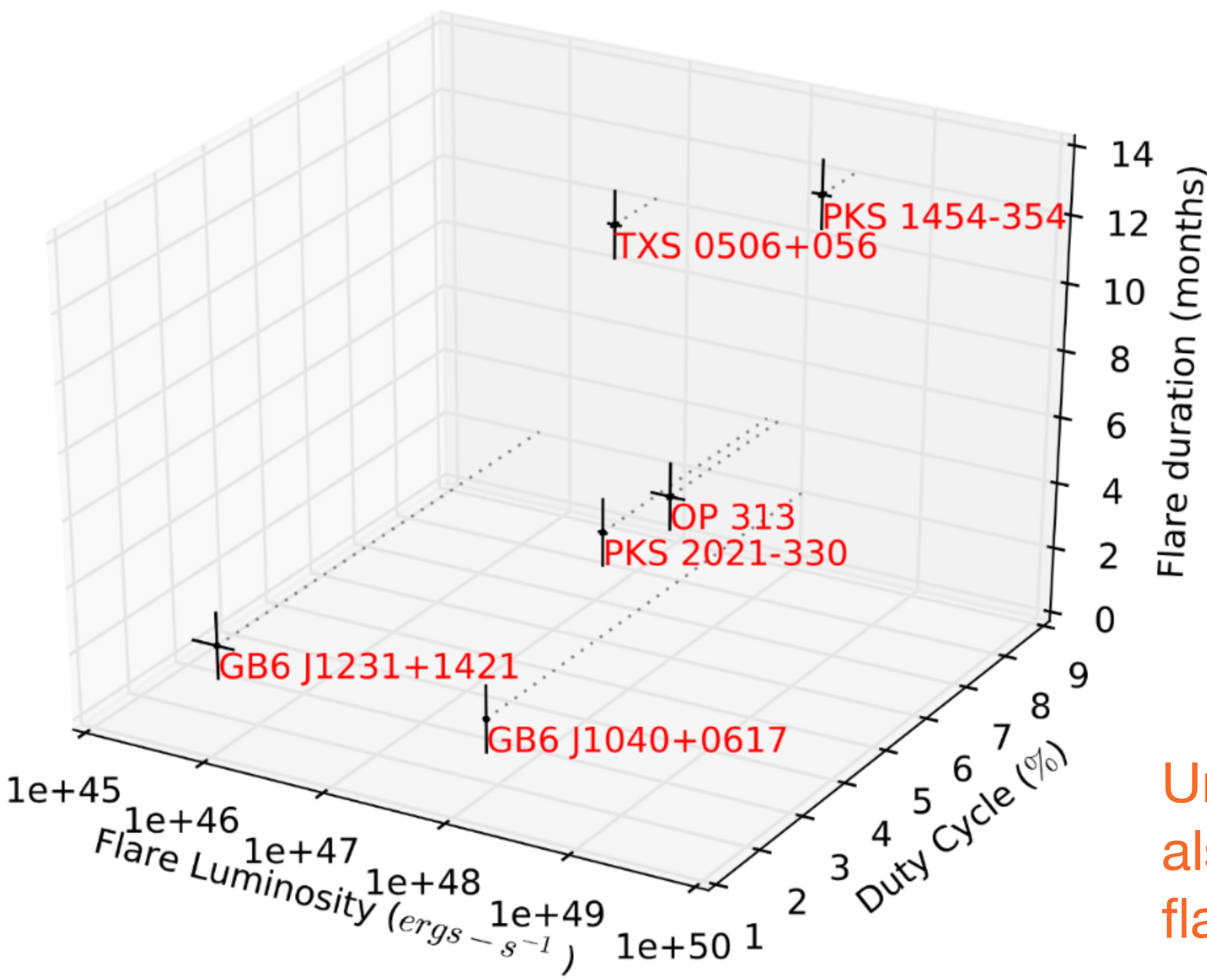
arXiv:2011.13043

DC II : VERCELLONE CRITERIA

Method I only feasible for sources that have discreet active states/discreet flares (flares with significant peak flux and duration in the time bins considered)

Method II: Threshold for active states defined as mean flux + 1 std. deviation. Only those bins considered as active states whose error bars lie completely above the threshold

This approach (based on Vercellone et al. 2004) allows for the DC calculation of fainter and far away sources



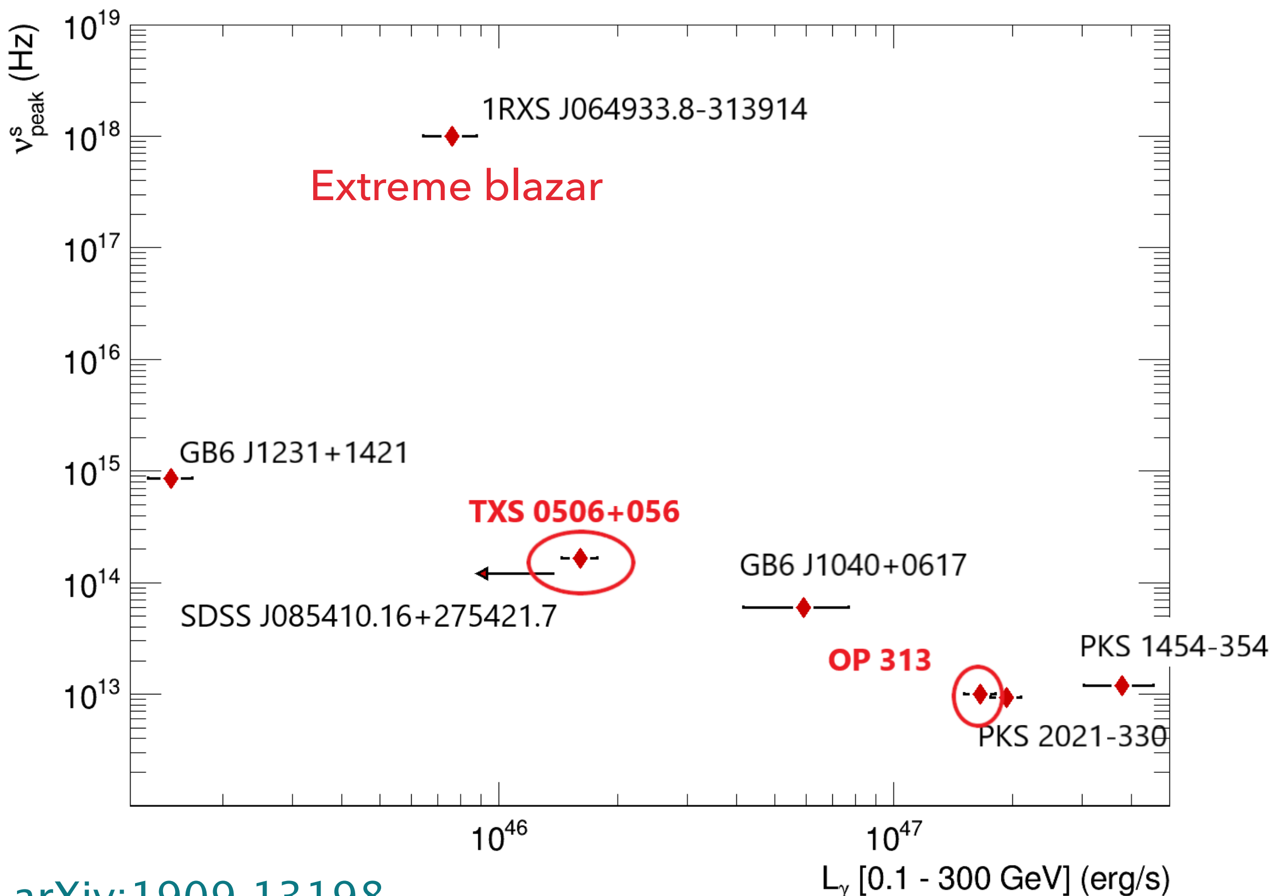
Assuming the presence of a hadronic component, sources with a longer flare duration and higher luminosity during the flare will be more likely to produce a neutrino fluence observable on Earth. Sources with high DC will have more such flares

Under the assumptions, one FSRQ, PKS 1454-354 also shows potential for neutrino emission during its flares

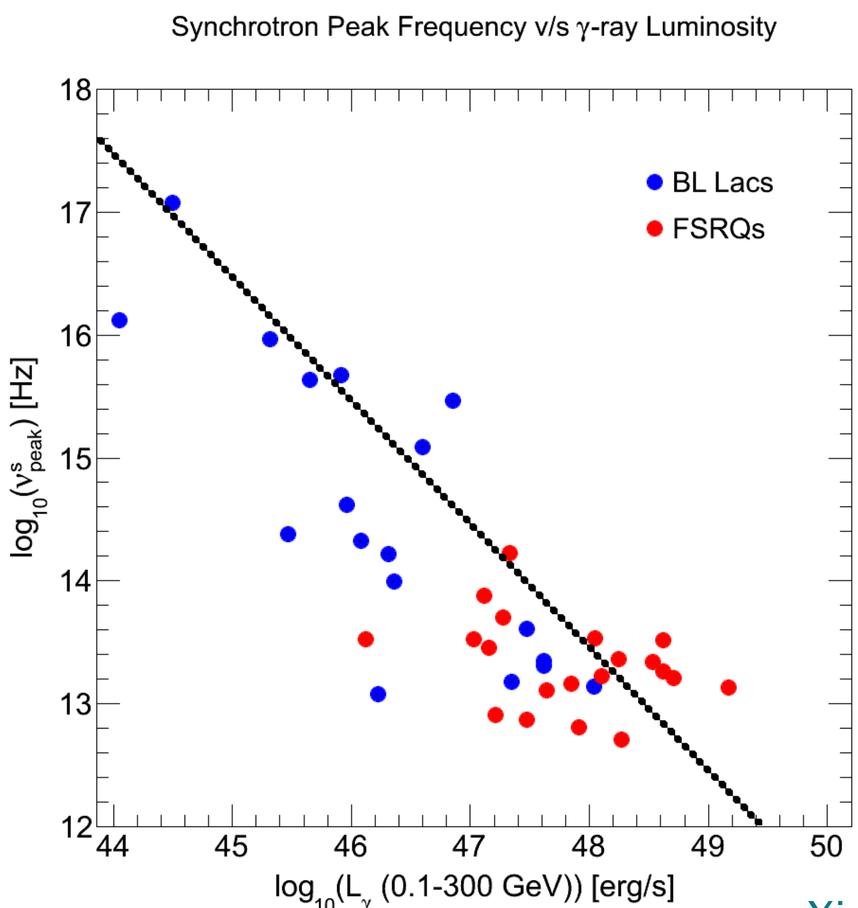
An observed anti-correlation trend between the bolometric luminosity and synchrotron peak frequency for blazars (Fossati et al. 98)

The sequence can also be tested with γ-ray luminosities since blazars emit most of their power in γ-rays

- Combined BL Lac + FSRQ anti-correlation trend in agreement with Ghisellini et al. 2017



arXiv:1909.13198



arXiv:2011.13043

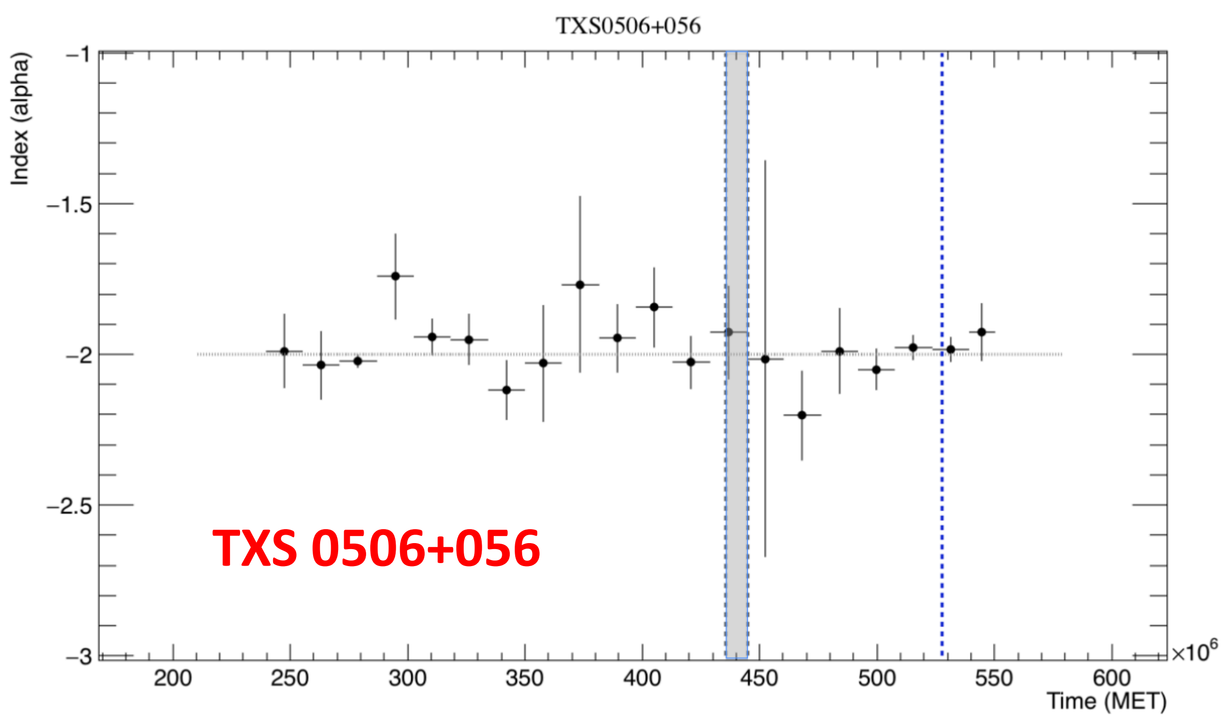
The anti-correlation trend suggests a leptonic SED for the sources, however hadronic activity cannot be ruled out during the flaring periods

✳ Synch. peak frequencies obtained from 3FHL catalog

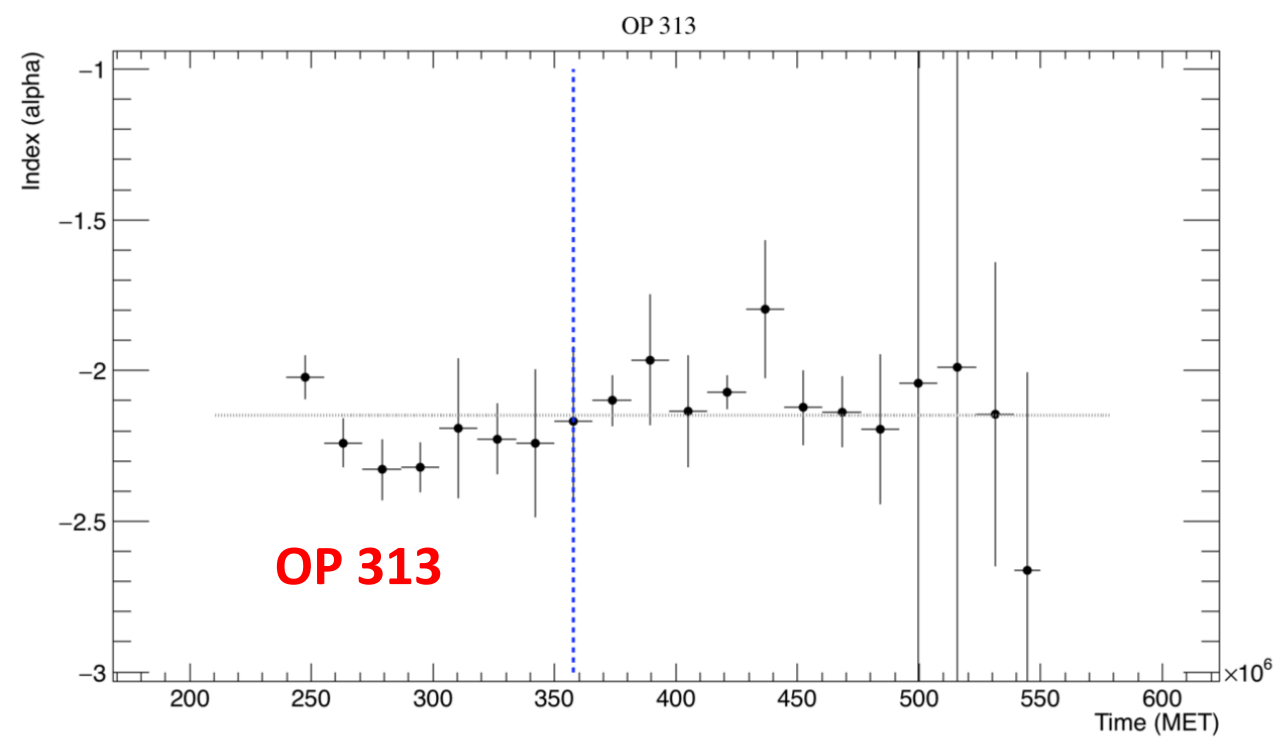
SPECTRAL INDEX VARIABILITY

- Variation in γ-ray index can be suggestive of increased γ-ray emission
- A "low/hard" (low flux but hard index) or a "high/soft" (high flux but no spectral hardening) state can be indicative of neutrino emission accompanying the γ-rays (Padovani et al. 2018)
- Far away sources can have γ-flares (and possible neutrino emission) w/o any major flux variations due to masking by EBL

$\alpha_{avg} = 1.97 \pm 0.04 \quad \sigma_{max} = 2.19$

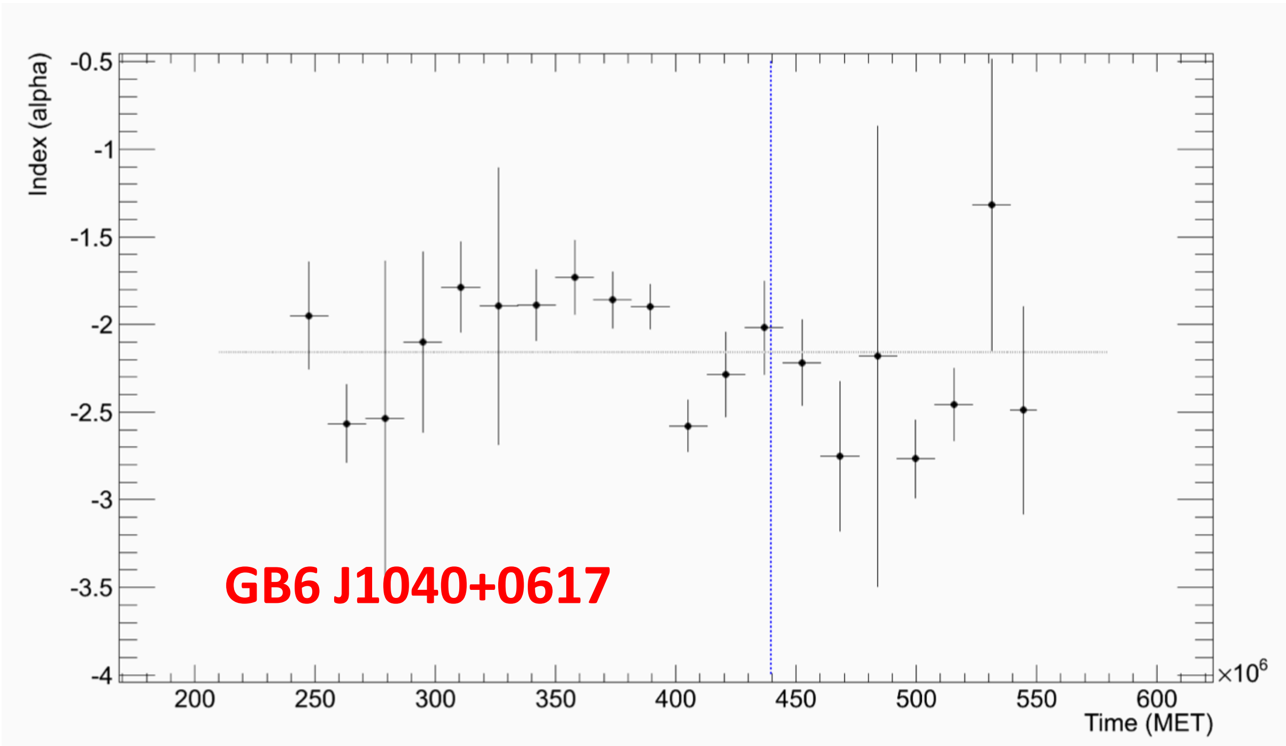


$\alpha_{avg} = 2.15 \pm 0.14 \quad \sigma_{max} = 2.92$

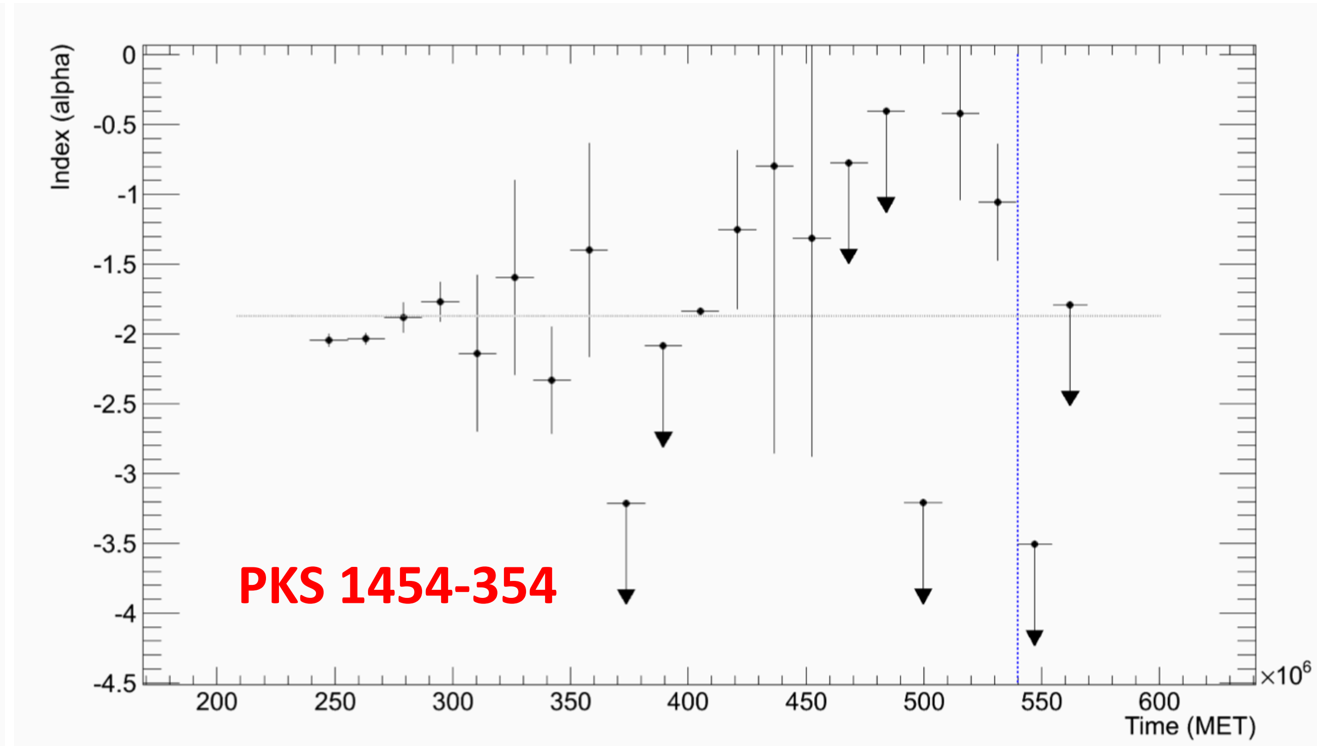


No significant hardening in 6-month bins….smaller bin size ??

SPECTRAL INDEX VARIABILITY



$$\alpha_{avg} = 2.16 \pm 0.05 \qquad \sigma_{max} = 1.74$$



$$\alpha_{avg} = 1.87 \pm 0.01 \qquad \sigma_{max} = 3.47$$

In a persistent hard state between 2011-13, with a slightly elevated flux level

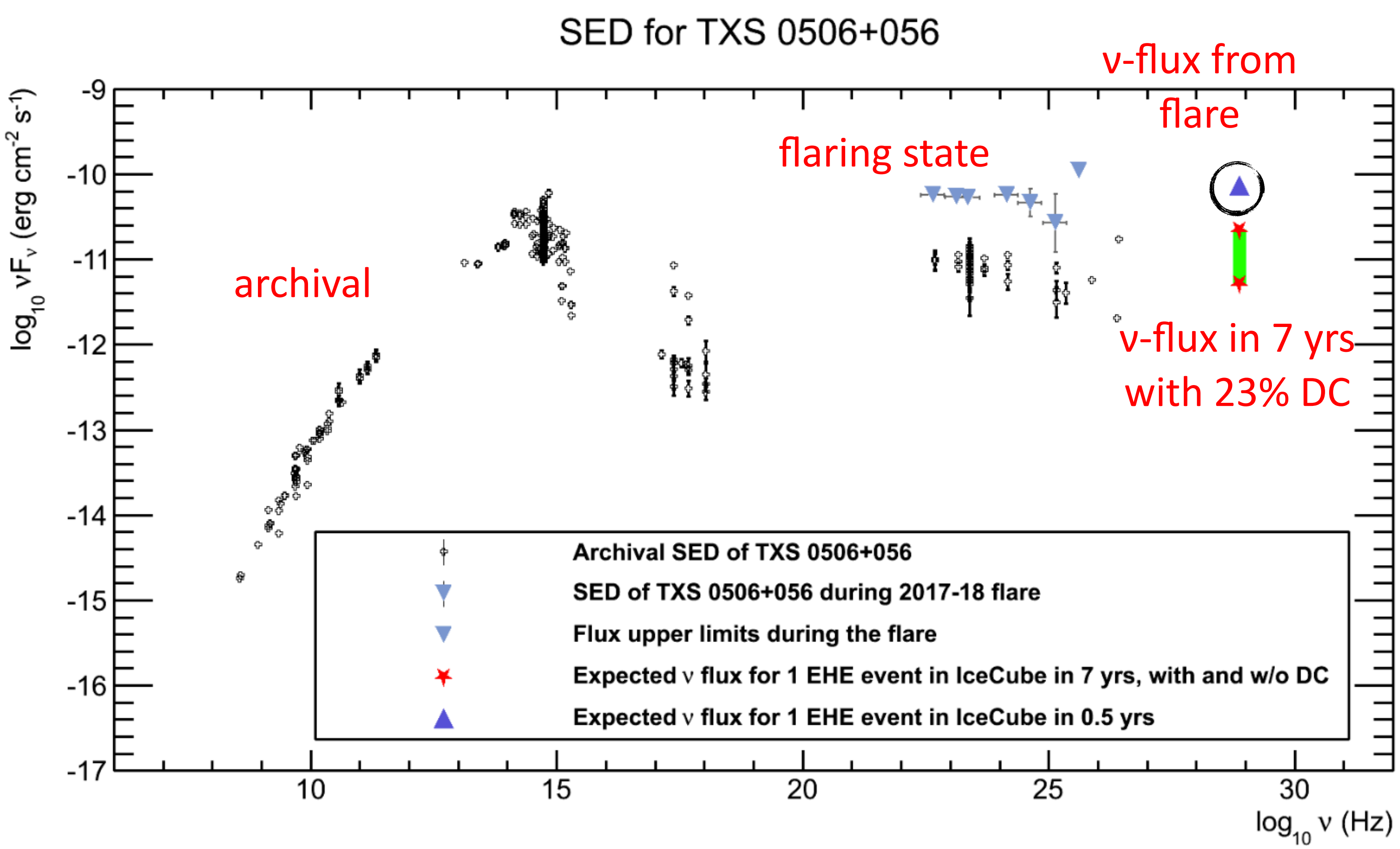
No significant hardening at the time of neutrino arrival in 2014

Source approaches a “high/soft” state during the gamma-ray flare of 2008-09

Hint of “low/hard” state at the time of neutrino arrival

BROADBAND SED

Application of DC can change the expected neutrino flux from a source over a long observation time



Archival SED from SED Builder Tool

Flaring state SED from Fermi-LAT data (most luminous flare)

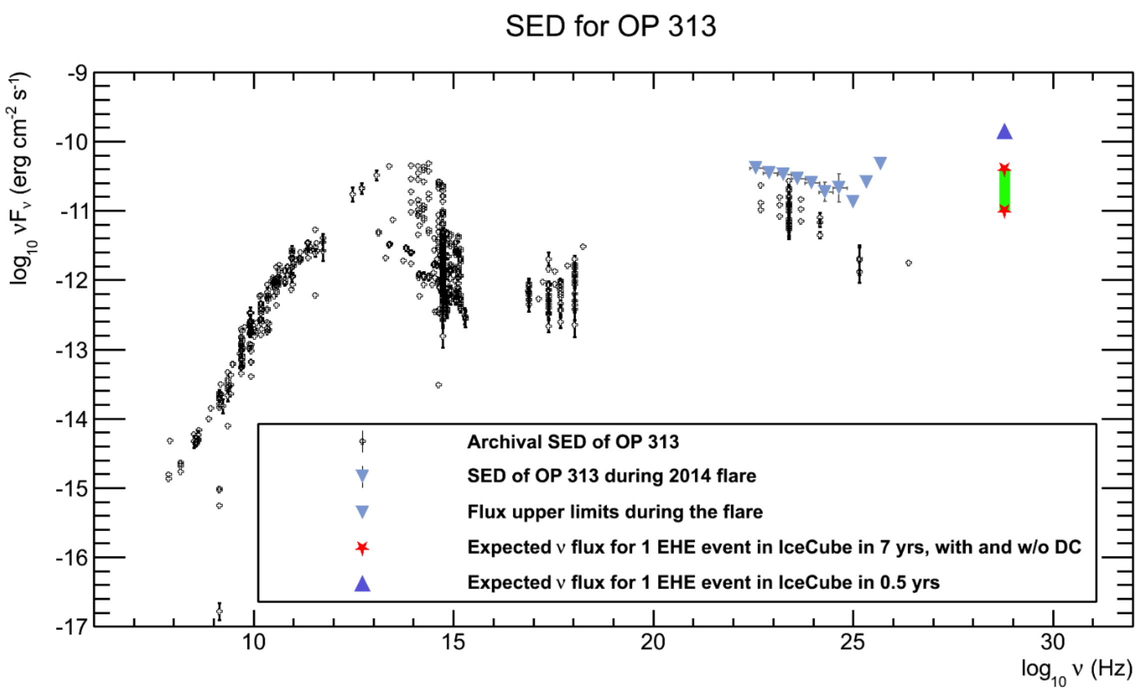
ν-flux estimated for 1 EHE event from the source in IceCube during its brightest flare, and in 7 years, also factoring an avg. DC

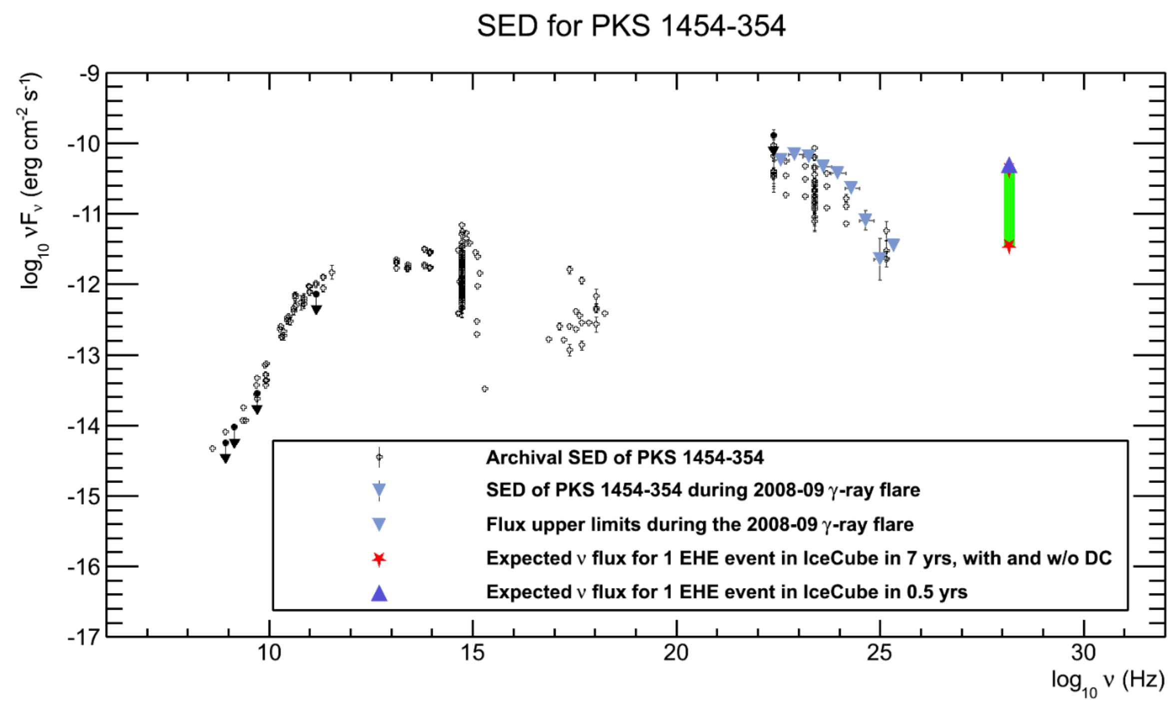
ν-flux estimation based on convolution of Eff. Area of detector at the decl. of source with the energy of the spatially coincident neutrino [no model required]

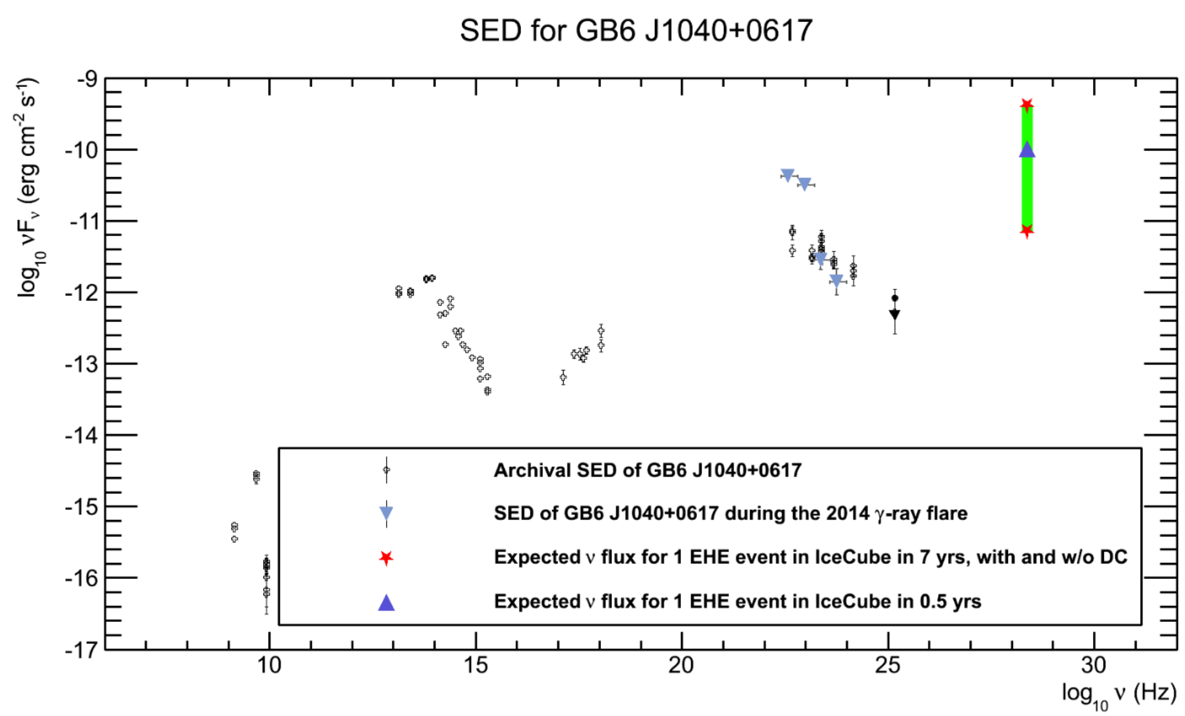
SED of TXS 0506+056 during the γ-ray flare is at a similar level as the expected ν-flux for 1 event during the flare

BROADBAND SED

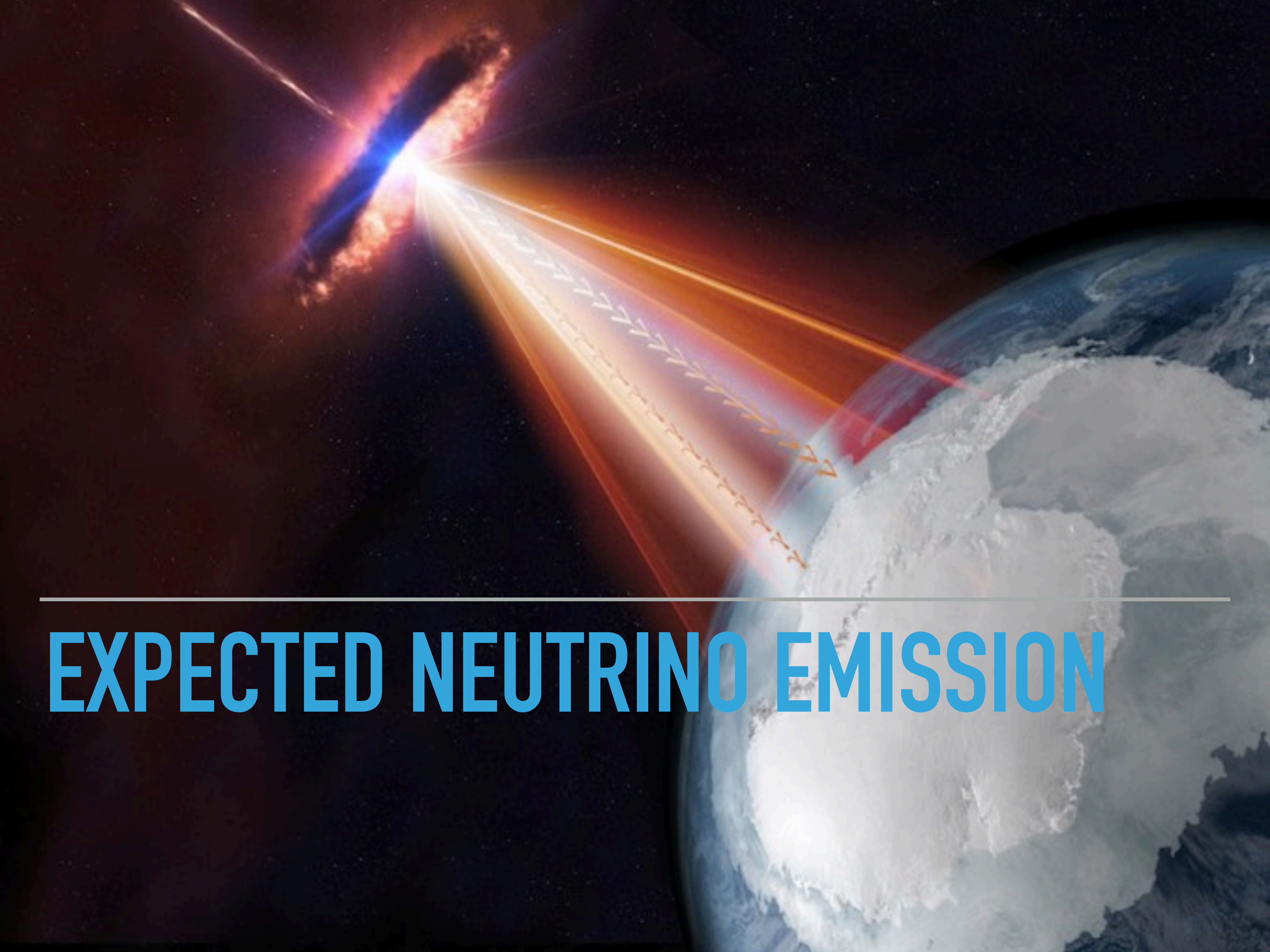
The ratio between peak γ-flux and ν-flux for all 4 sources lies within the upper limit of **$L_\nu < 3\ L_\gamma$** from Petropoulou et al. 2015, allowing for a possibility of neutrino emission at least during their brightest γ-ray flares







arXiv:1909.13198



EXPECTED NEUTRINO EMISSION

A LEPTO-HADRONIC MODEL

- Fermi-LAT γ-data correlated with IceCube ν-flux through a lepto-hadronic model; Petropoulou et al. MNRAS 2015
- 1-100 GeV γ-rays explained as the synchrotron emission of decay products of charged-π, produced in photo-pion interactions in the jets of blazars
- Low opacity ($\tau_{\gamma\gamma}$) assumed due to interact of BLR photons with GeV gamma-rays
- Relative intensities of muonic neutrino component and gamma component can be expressed as a fraction:

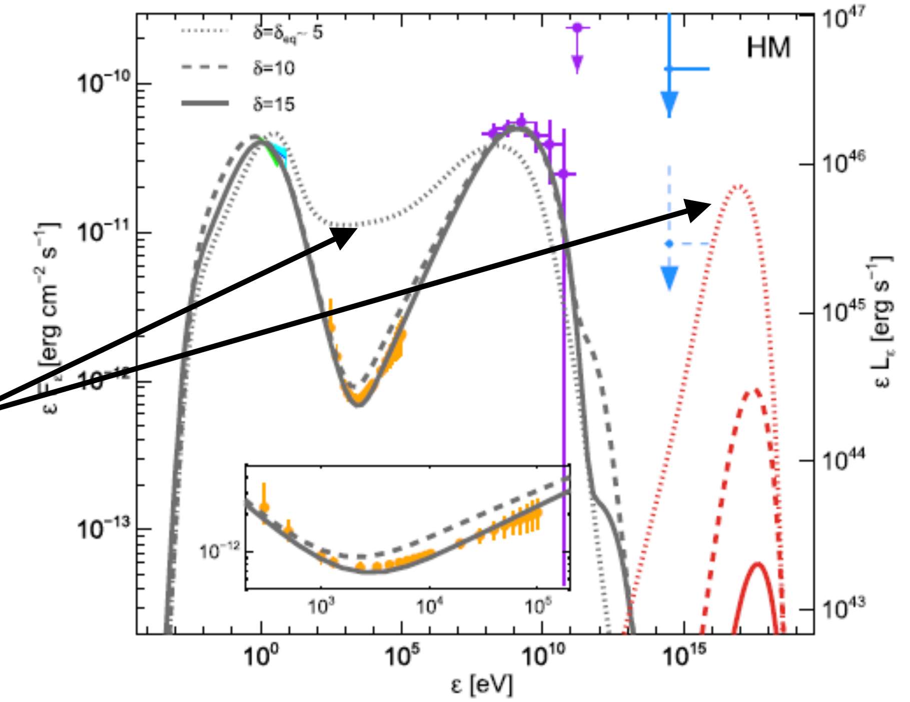
$$K_{\nu\gamma} = \frac{L_{\nu\,(10\,TeV-10\,PeV)}}{L_{\gamma\,(1\,GeV-100\,GeV)}}$$

$K_{\nu\gamma}$ has been constrained to < 0.15 by *Aartsen et al. 2018* for the model over a long observation period, however w/o considering duty cycle.

A high $K_{\nu\gamma}$ is still not ruled out during flaring activity

MODEL FOR TXS

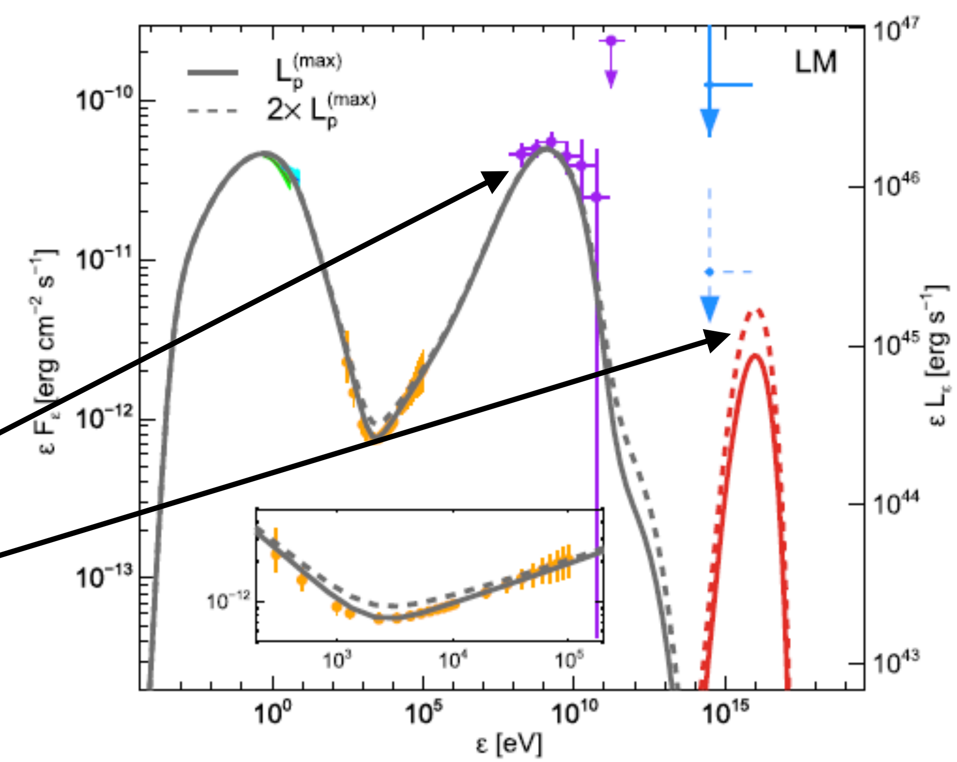
- Simultaneous observations in X-rays and γ-rays during the γ-ray flare allow us to test this approach for TXS 0506+056
- Modelling of the broadband SED for TXS 0506+056 suggests the predicted flux by this one-zone model overshoots the X-ray data



Keivani et al. 2018

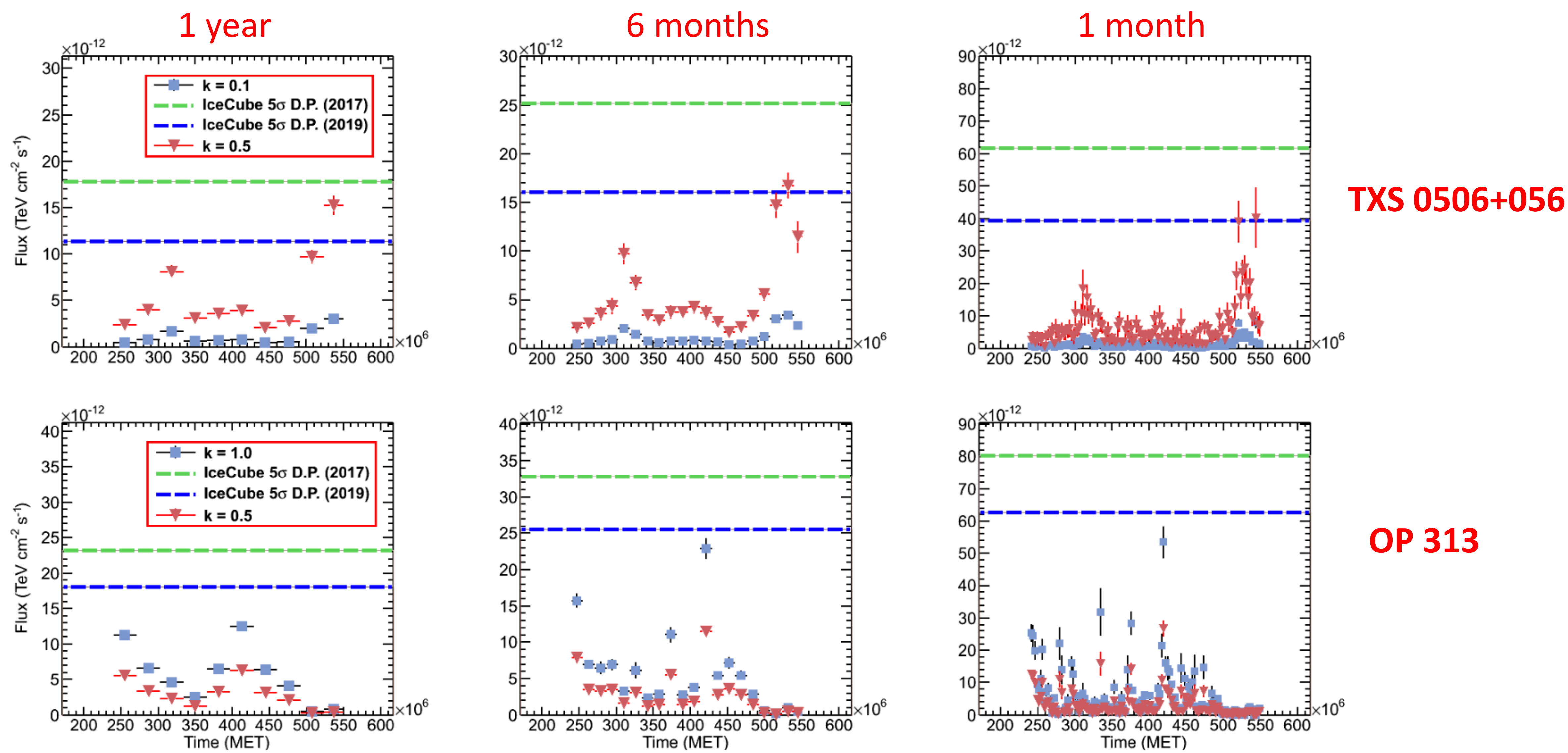
- To mitigate tension with the X-ray data, we adopt an approach for **TXS 0506+056** favoring leptonically dominated γ-rays: LMBB2b scenario from *Keivani et al. 2018*
- Inverse Compton up-scattering by synchrotron electrons considered as the dominant component in the high-energy hump of the EM SED

$K_{\nu\gamma} \sim 0.1$



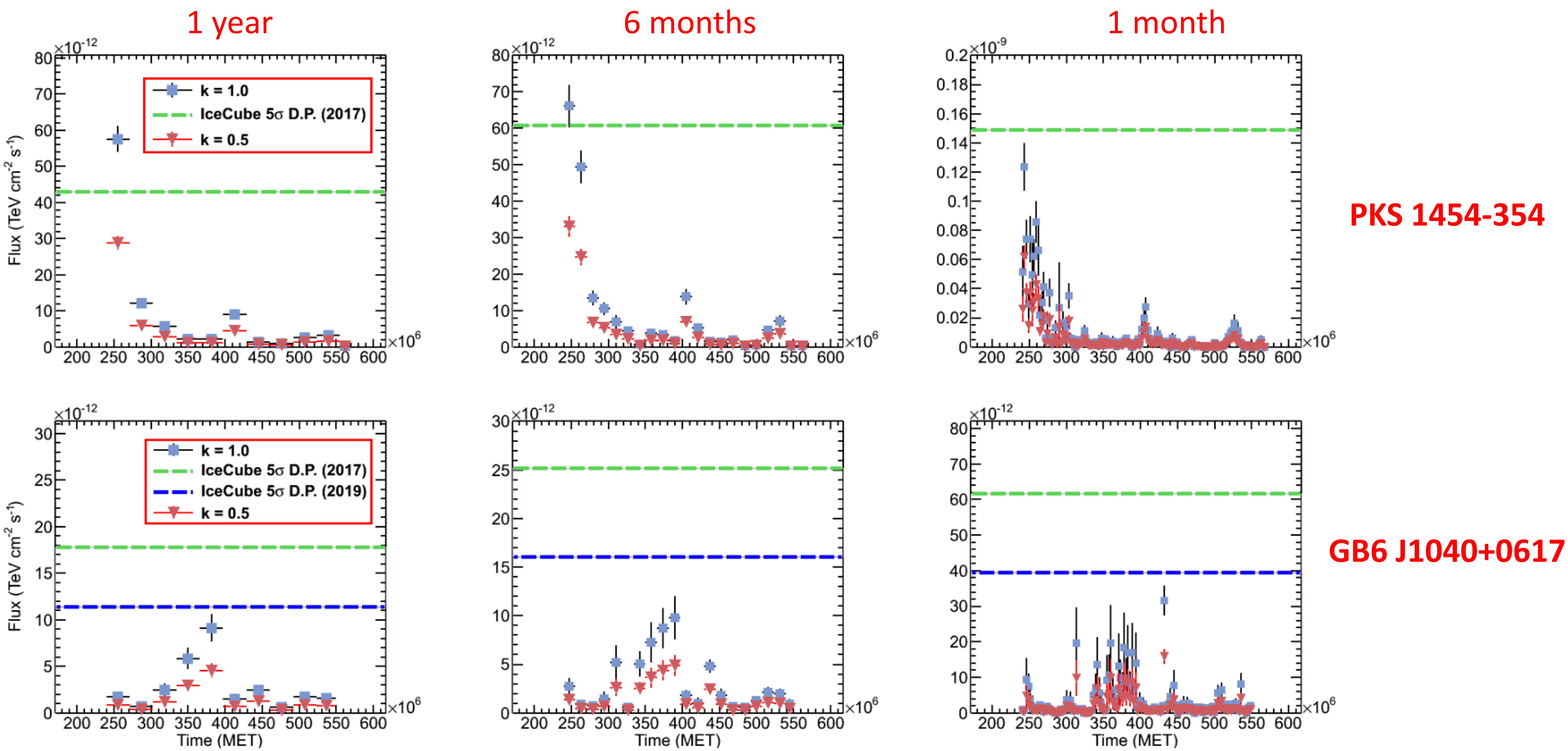
NEUTRINO LIGHT CURVES

- Neutrino light curves obtained by applying lepto-hadronic models to ~10 years of Fermi-LAT data between 1 < EGeV < 300 considering different time binning
- Comparison with IceCube discovery potential (Aartsen et al. 2016, Aartsen et al. 2019)
- Benchmark case: $K_{\nu\gamma}$ **= 1** ($K_{\nu\gamma}$ = 0.1 for TXS)
- Weighted Case: $K_{\nu\gamma}$ **= 0.5** (factoring all-sky upper limit of $K_{\nu\gamma}$ = 0.1 and DC of 20%)



NEUTRINO LIGHT CURVES

Flare duration of the order of a month or more required to observe a source in neutrinos



arXiv:1909.13198

OUTLINE

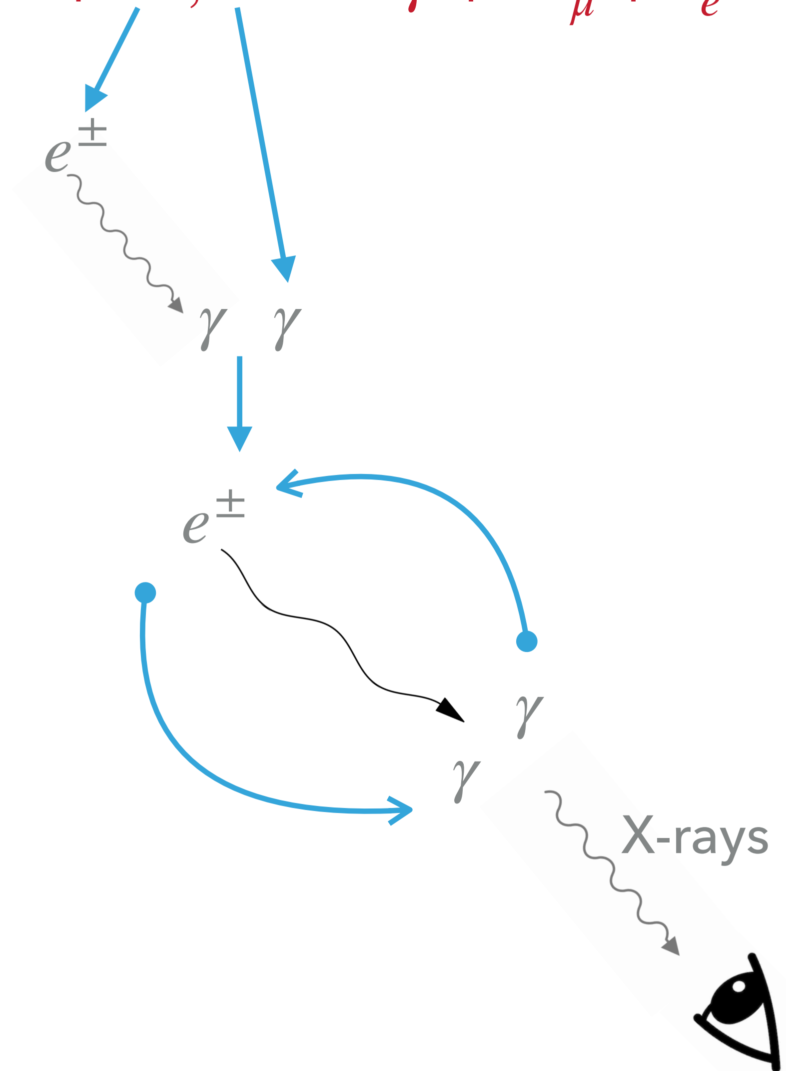
- Introduction
- Past Research
- **Current Focus**

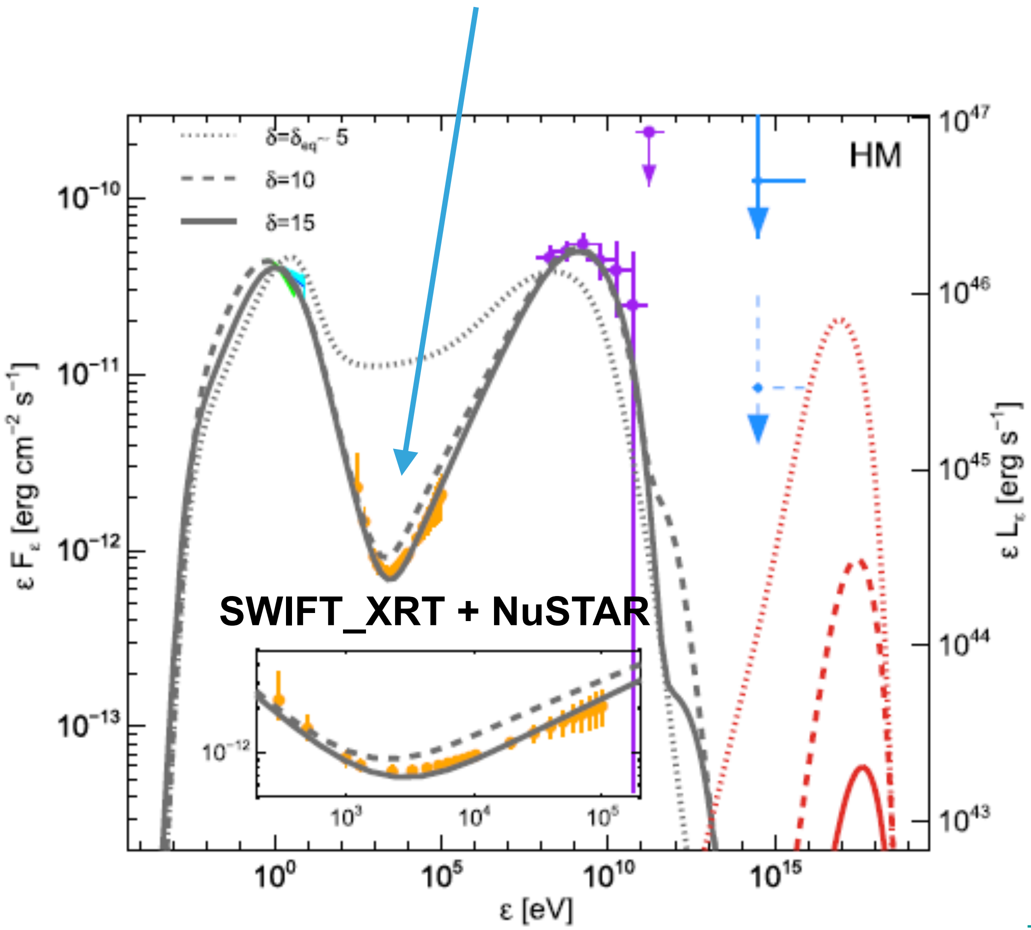
BLAZARS IN X-RAYS

Proton Induced Cascades (PIC) :

- Secondary $e^{\pm}$ pairs generated by pion decay produce high energy photons via Synch./Compton processes
- These photons combine to produce new pairs, which radiate a new generation of photons
- The *synchrotron-pair cascades* shift the extreme proton energies down to the X-ray band

$$p + \gamma \rightarrow p/n + \pi^{\pm}, \pi^{0} \rightarrow 2\gamma + 2\nu_{\mu} + \nu_{e}$$

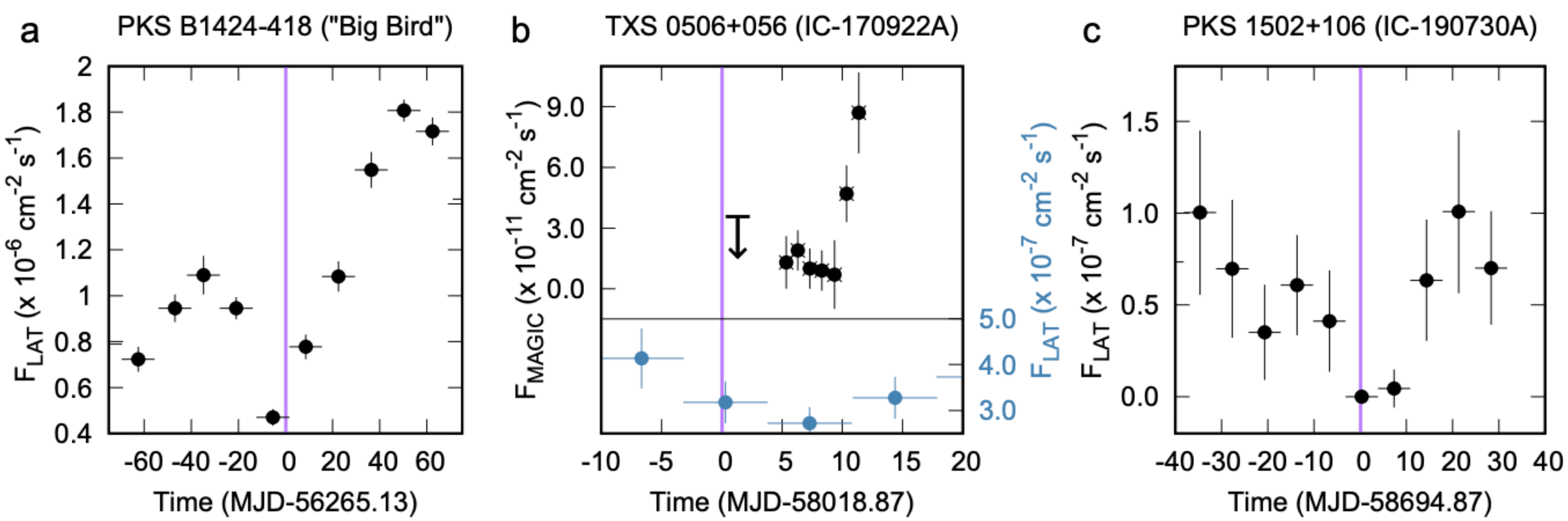




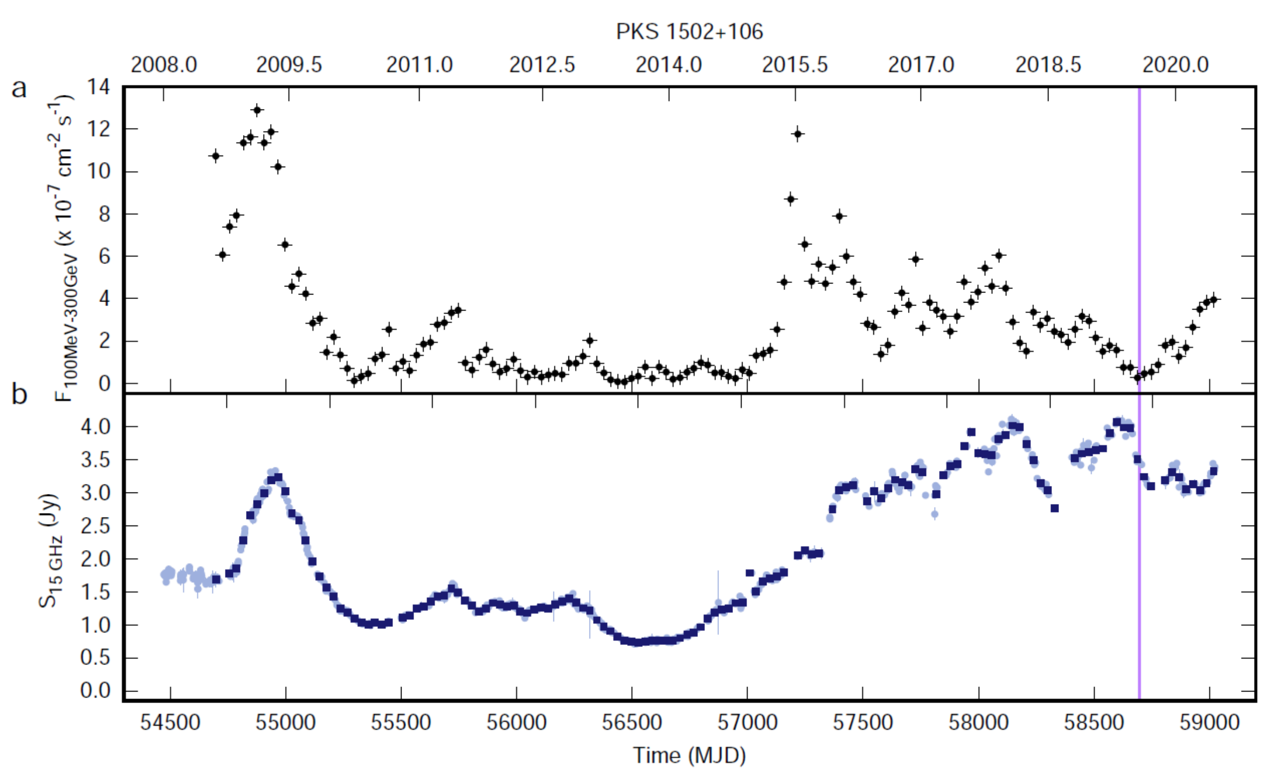
X-rays from PIC can be used to constrain the SED of sources, if a hadronic contribution is assumed

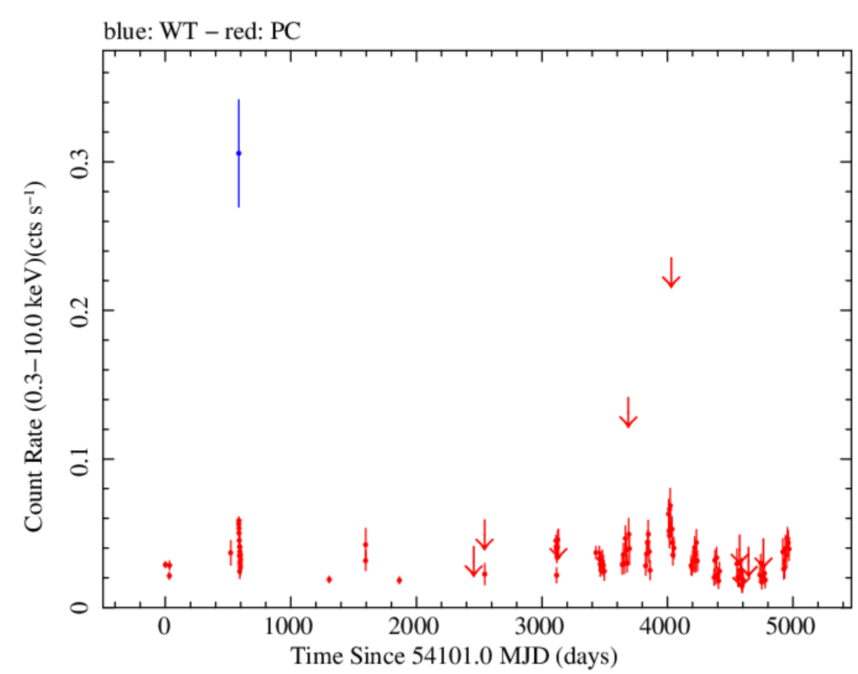
Keivani et al. 2018

Recent investigations find spatially coincident neutrinos from sources showing a minimum in their γ-ray flux……..



….but a high X-ray and radio flux state





arXiv:2009.09792

Objective: Search for correlation between X-ray selected blazars and **IceCube** neutrinos

We intend to perform two searches for neutrino emission from blazars -- selected from X-ray catalogs:

1. A **model independent** search: Perform a binomial test on the p-values obtained for each individual blazar from an unbinned likelihood maximisation (time-integrated)

2. A **model dependent** search: Test specific models for the promising sources by correlating X-ray and ν-fluxes and/or weighing the p-values

✤ **Additional possibilities**:

➡ Search for **'neutrino flares'** from each source

➡ Introduce a 'time-dependent weighting' based on X-ray signature

➡ Upper limits on blazar contribution to IceCube astrophysical flux using X-ray catalogs!

SOURCE SELECTION

2 multi-frequency + 2 X-ray catalogs:

1. **XRAYSELBLL** (2013*): 312 X-ray selected BL Lacs -- radio, optical and X-ray fluxes (0.1 - 2.4 keV) provided
2. **RomaBZCat 5** (2015*): Multi-frequency catalog of blazars, ~ 3500 blazars with data in radio, X-ray (0.1 - 2.4 keV) and gamma bands
3. **NuSTAR Master Catalog** (2020*): ~ 300 dedicated blazar observations (3-79 keV) band
4. **X-ray Master Catalog** (2020*): compiled using (almost) all X-ray catalogs by HEASARC (0.1 - 150 keV)

*** year indicates last update to the catalog**

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1. **XRAYSELBLL** (2013*): 312 X-ray selected BL Lacs -- radio, optical and X-ray fluxes (0.1 - 2.4 keV) provided

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4. **X-ray Master Catalog** (2020*): compiled using (almost) all X-ray catalogs by HEASARC (0.1 - 150 keV)

*** year indicates last update to the catalog**

SELECTION CRITERIA

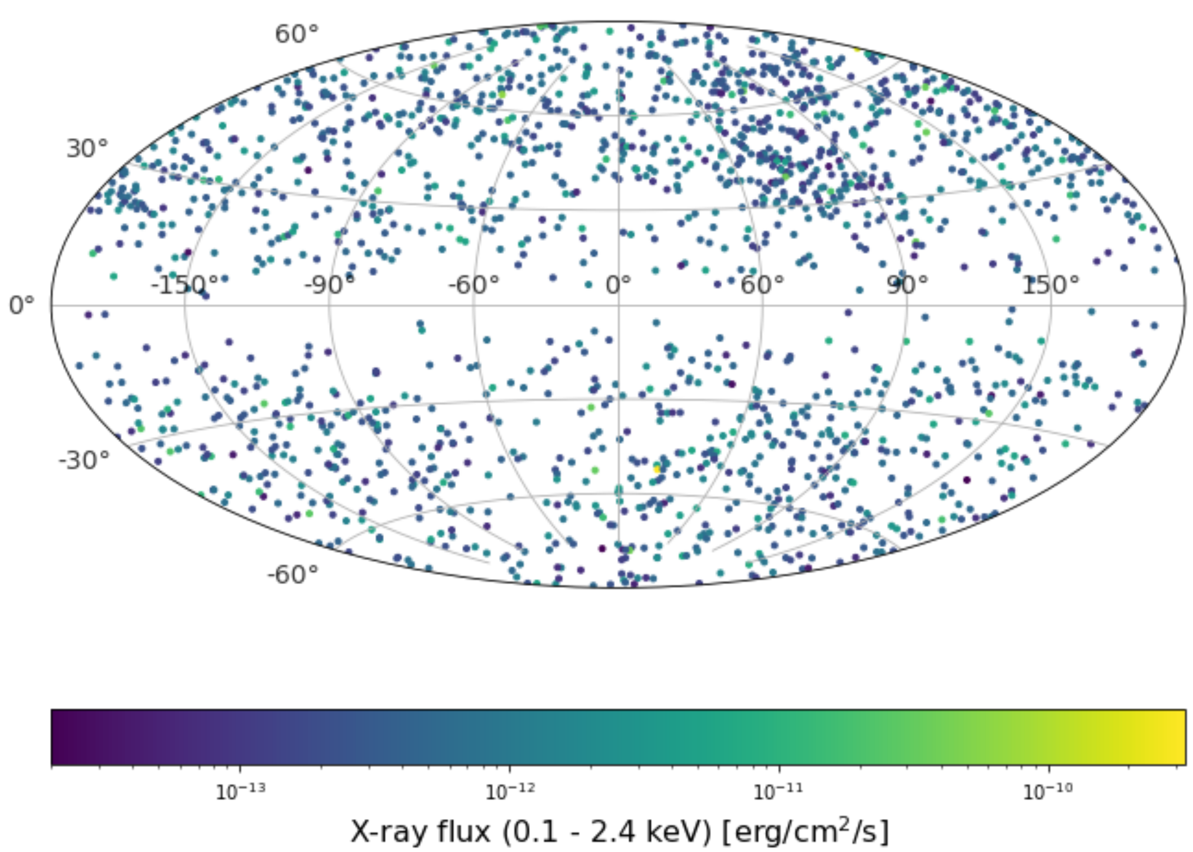
- **RomaBZCat** has a comprehensive coverage of the blazar sky
- Multi-wavelength data facilitates checks for correlations and applying weights
- **Caveat**: Covers a limited energy band in the soft X-rays (0.1 - 2.4 keV)

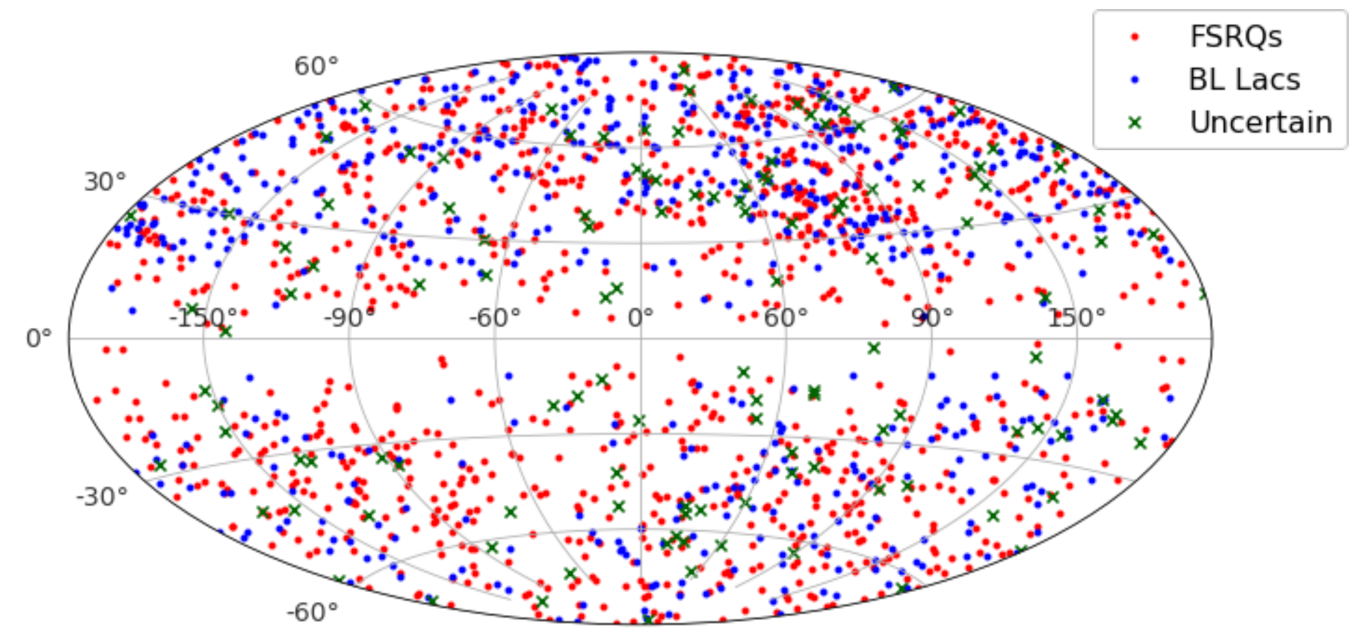
➡ Sources shortlisted from the catalog based on following criteria:

1. Non-zero **X-ray flux** (time-integrated)
2. Non-zero **Redshift** (limit is admissible)
3. Source **declination** between (-85, +85) degrees
4. No multiple entries for the same source not allowed (no **duplicates**)

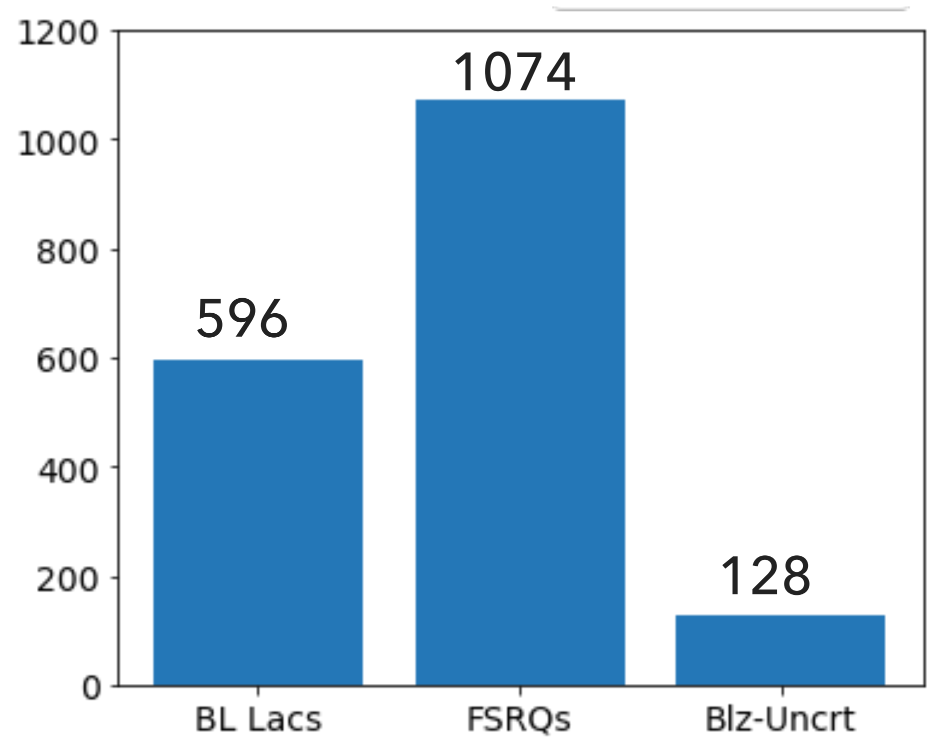
ROMABZCAT 5TH EDITION

- Multi-frequency blazar catalog with fluxes in **radio** (1.4 GHz), **microwave** (143 GHz), **X-ray** (0.1 - 2.4 keV) and **γ-ray** (1 - 100 GeV) frequencies
- **3561** blazar AGNs
- BL Lacs, BL Lac candidates, BL Lac galaxy dominated, FSRQs and blazars of uncertain type





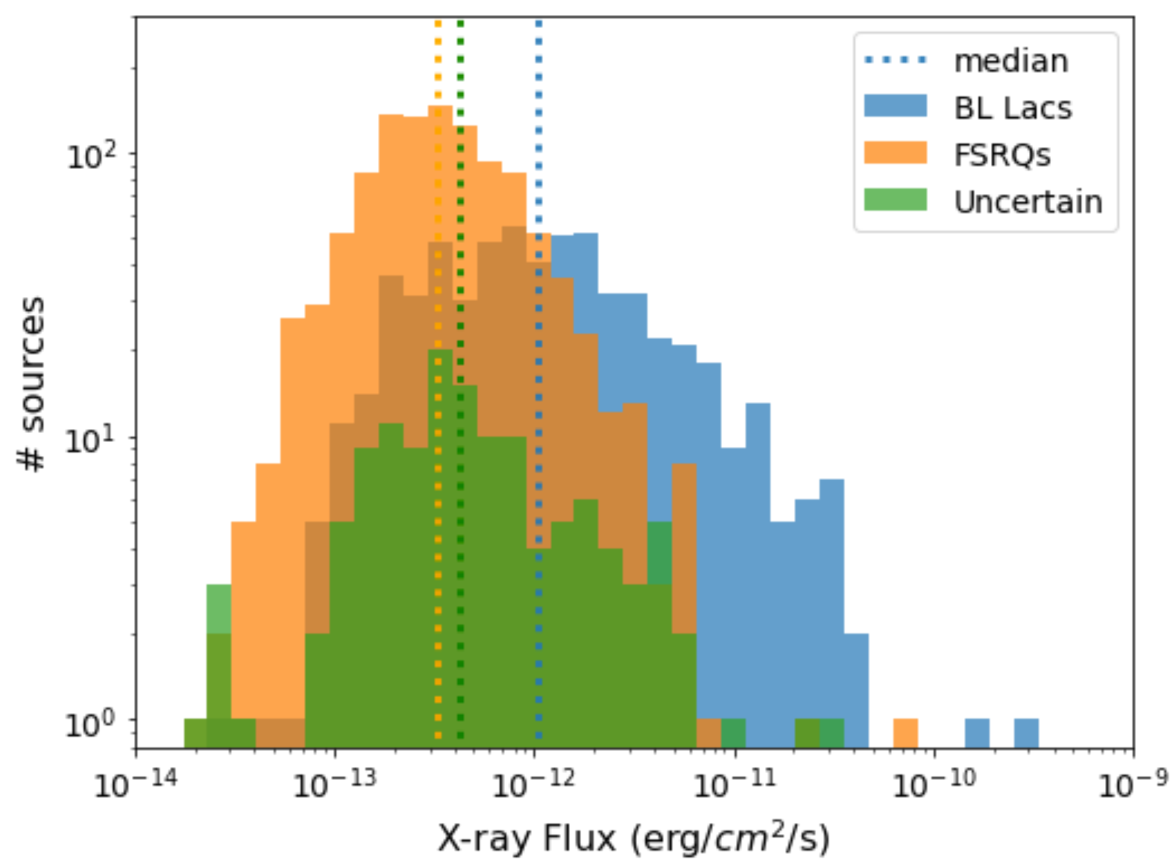
Skymap in Galactic coordinates

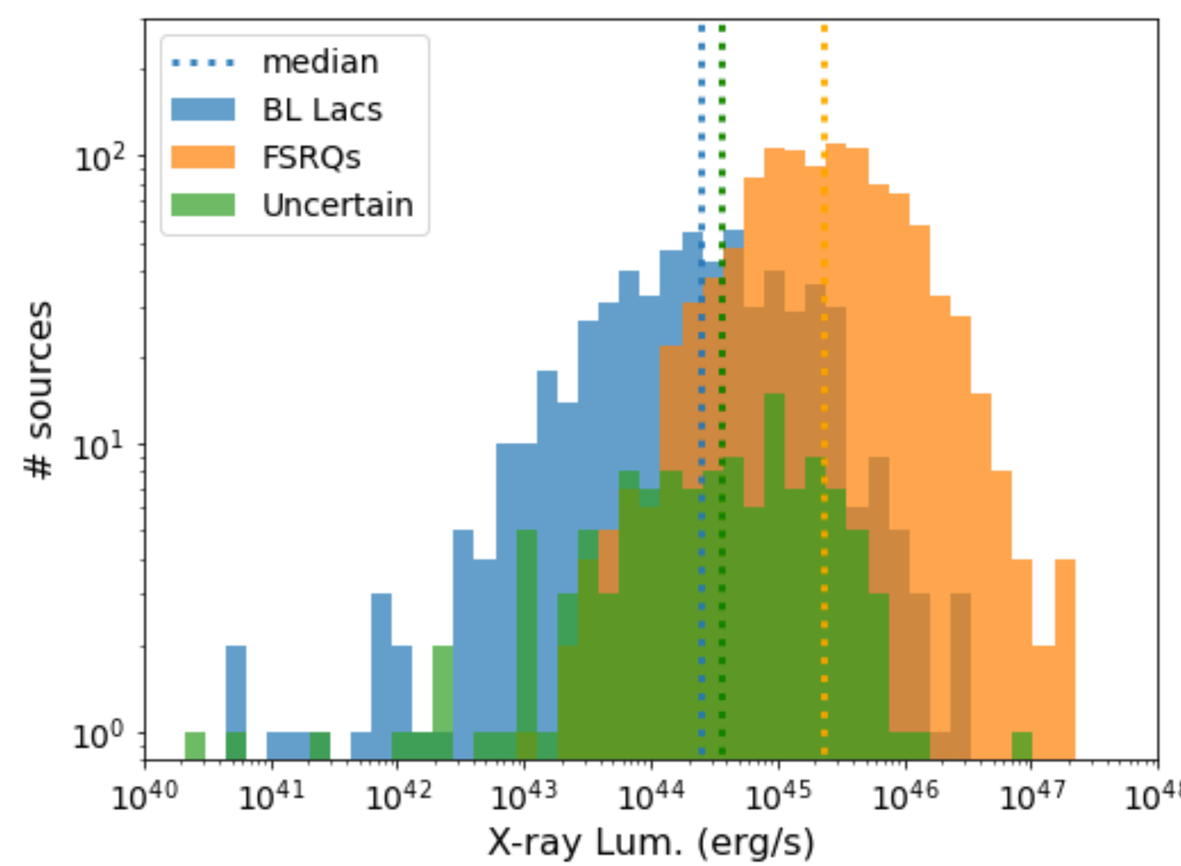


Trimmed down to **1798** sources

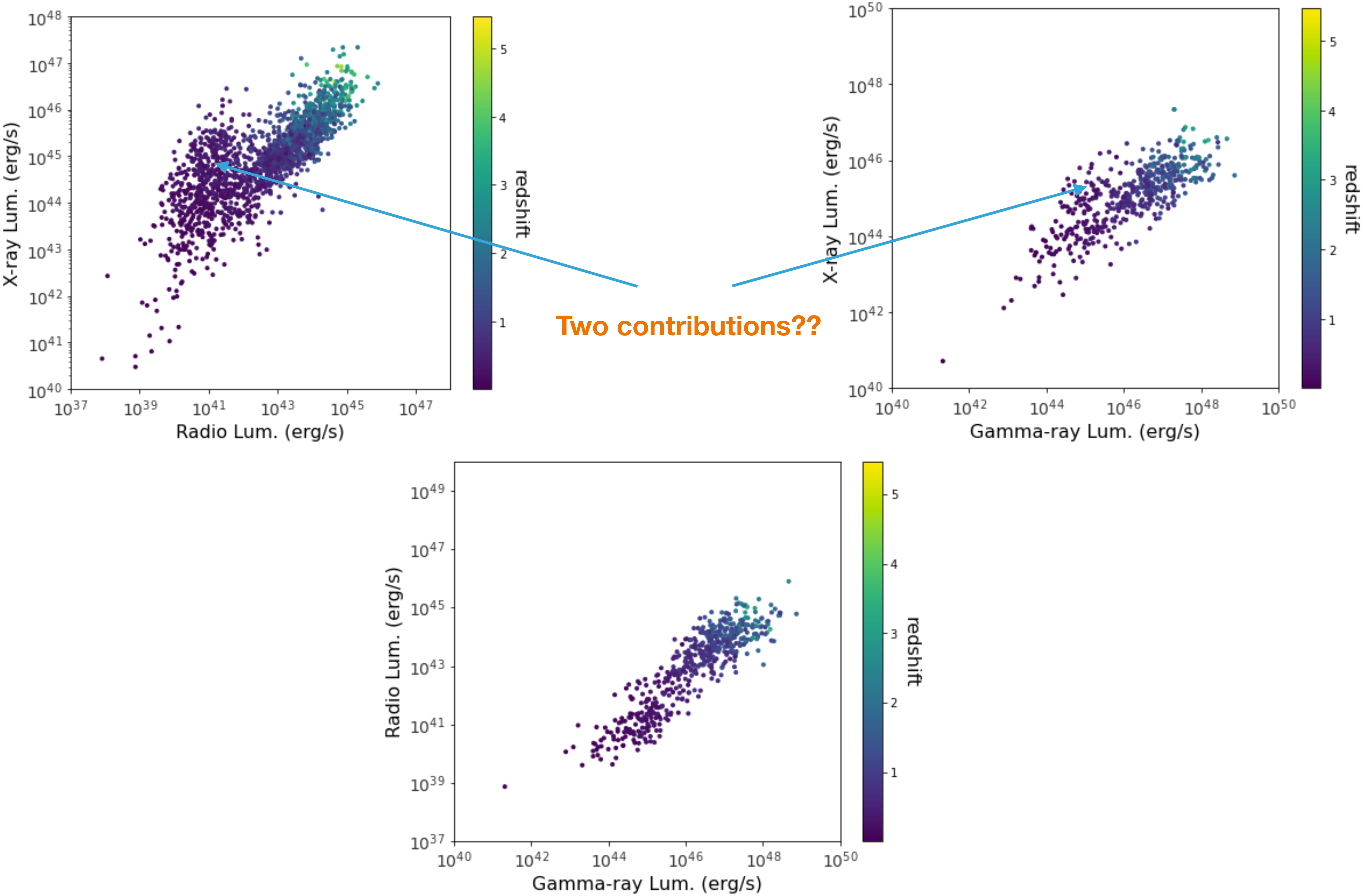
596 BL Lacs, 1074 FSRQs and 128 uncertain blazar candidates

X-ray fluxes taken from ROSAT

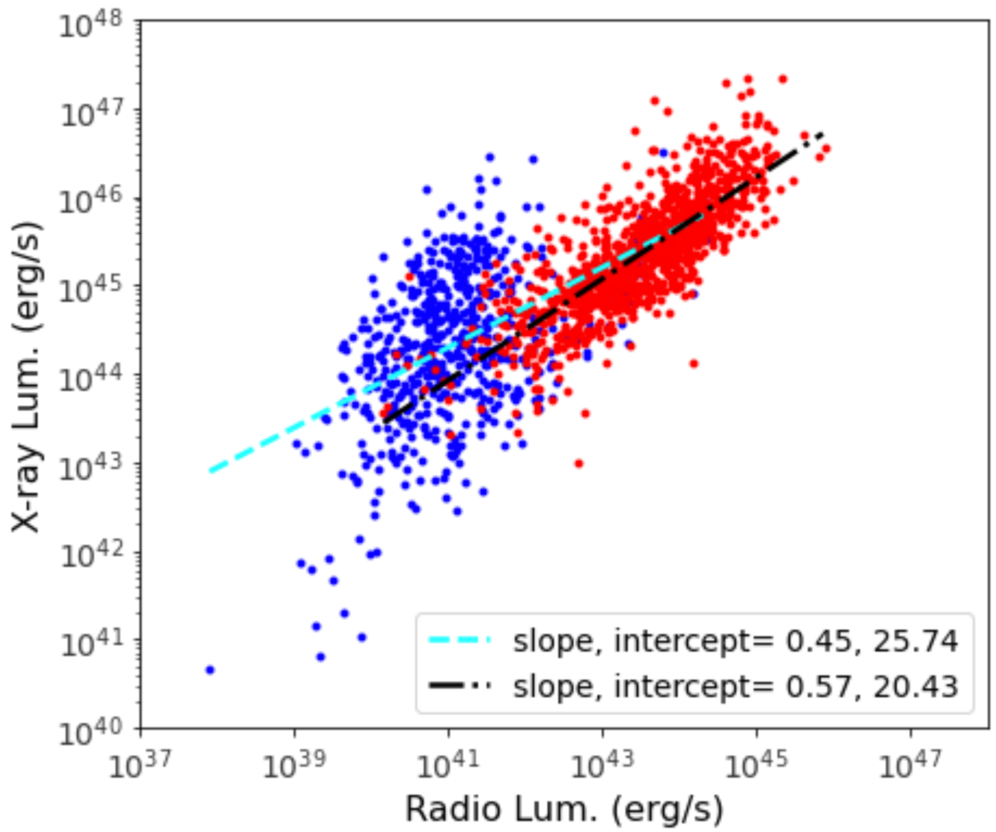


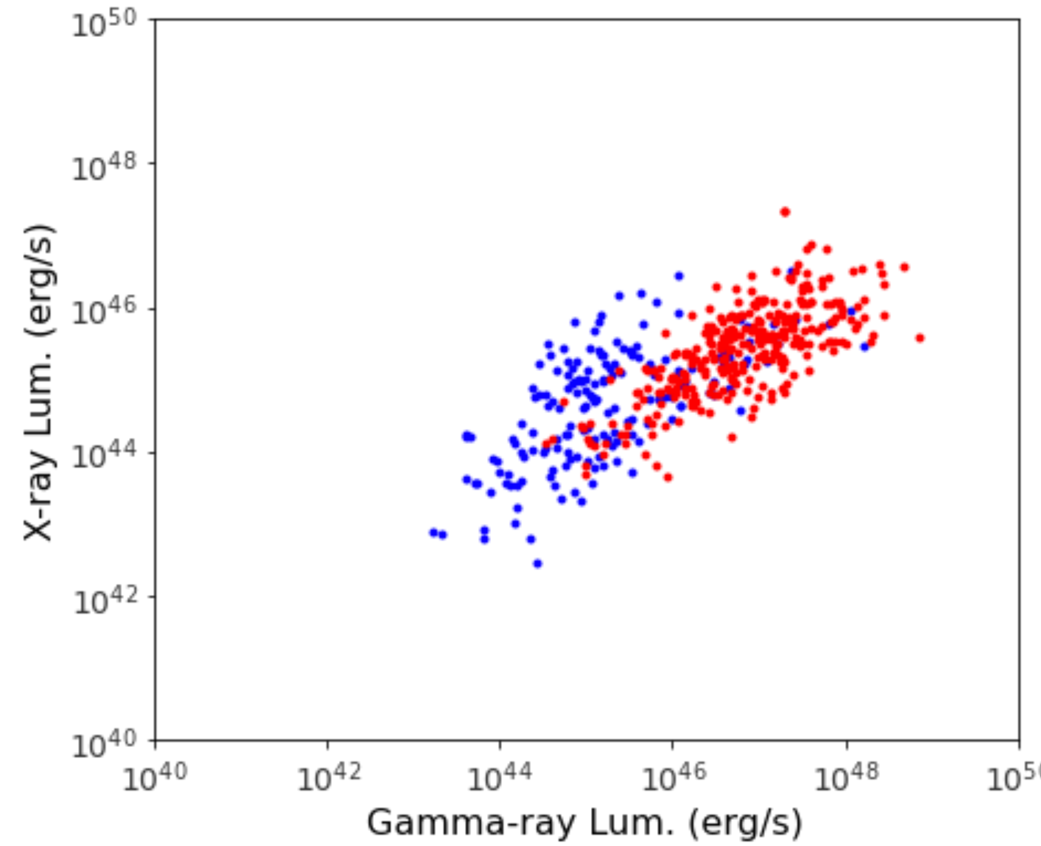


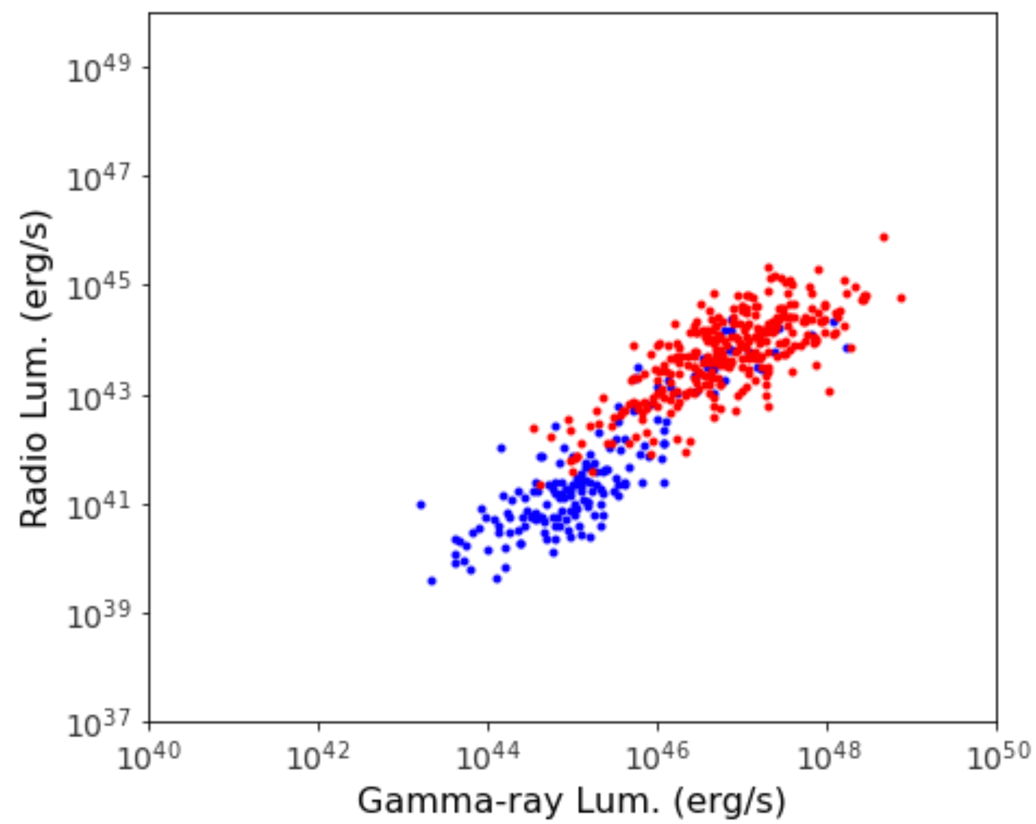
LUMINOSITY CORRELATIONS



TWO CONTRIBUTIONS?



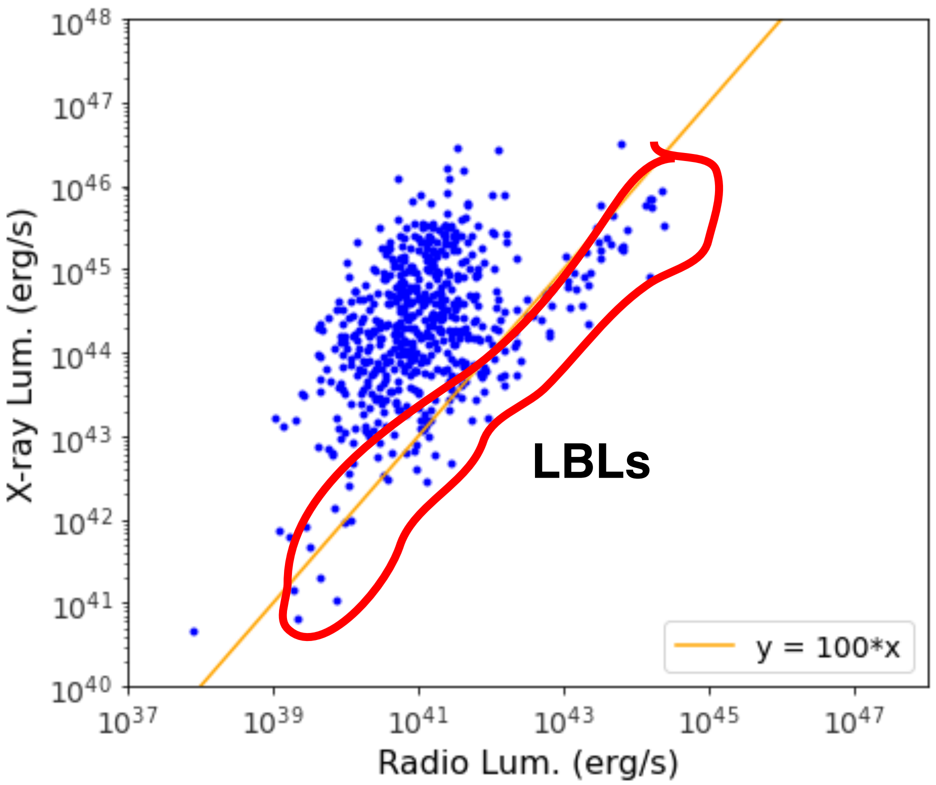


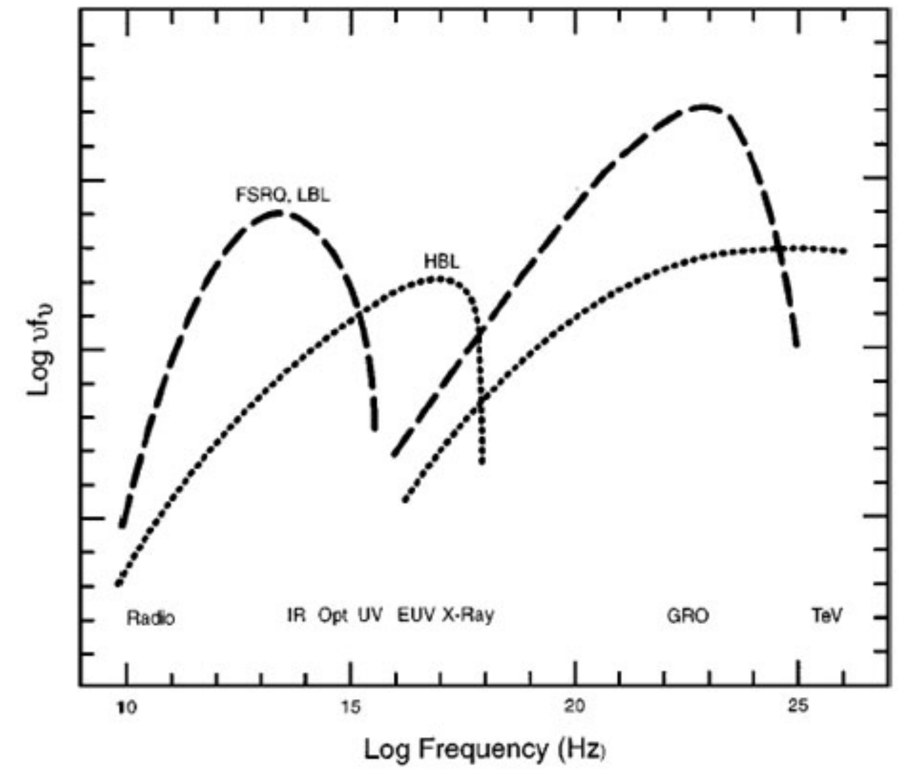


BL Lacs
FSRQs

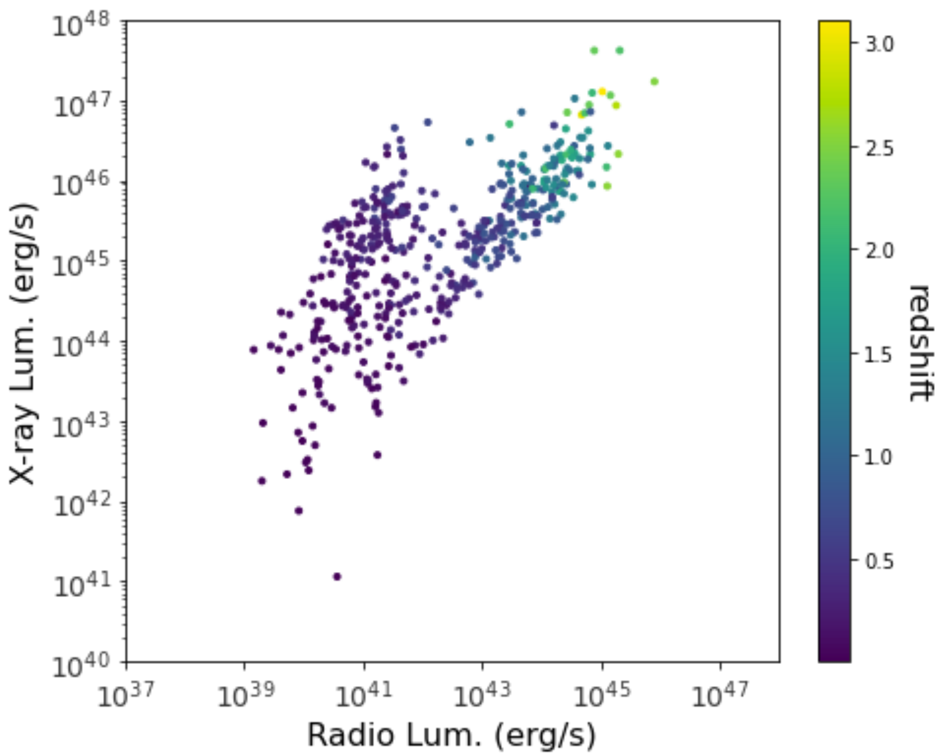
Contributions from BL Lacs and FSRQs can be disentangled

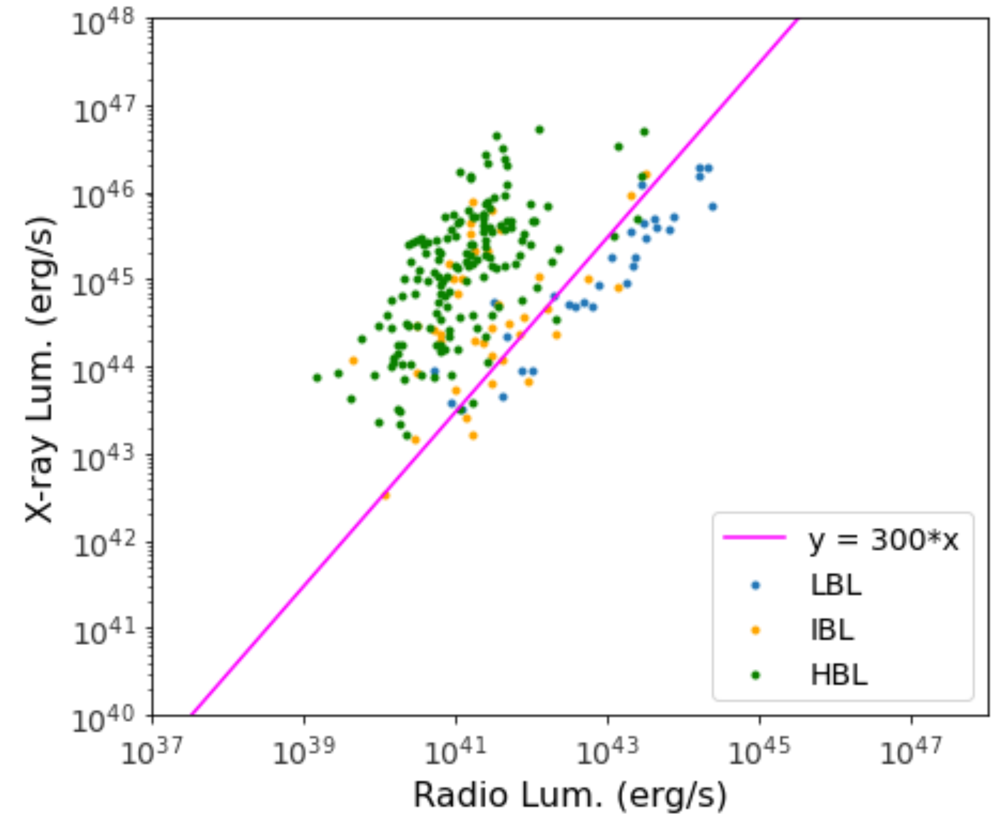
LOW-PEAKED VS. HIGH-PEAKED BL LACS





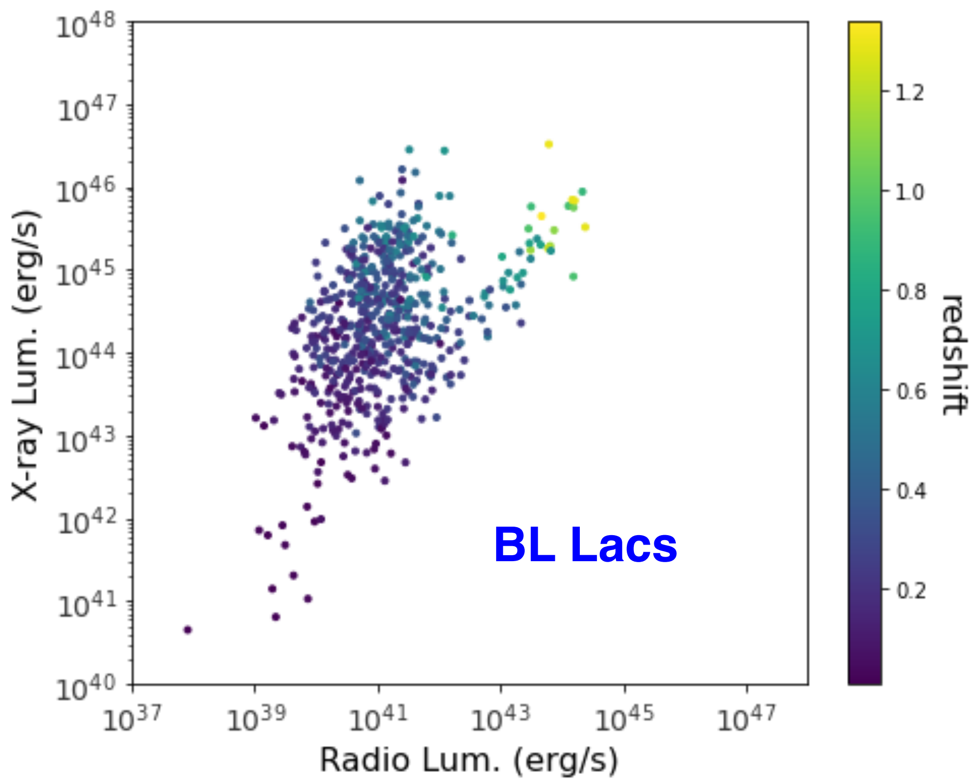
➔ **Synchrotron peak data not available in RomaBZCat to test further! Test using Fermi 3LAC catalog**

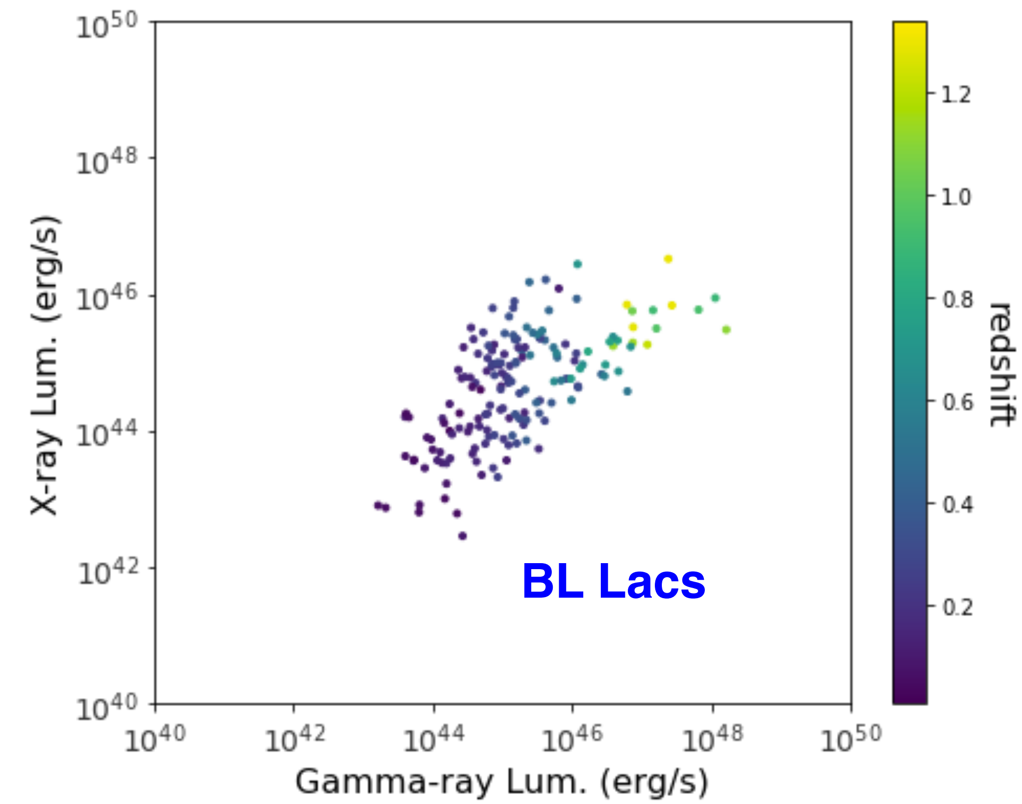




REDSHIFT EVOLUTION

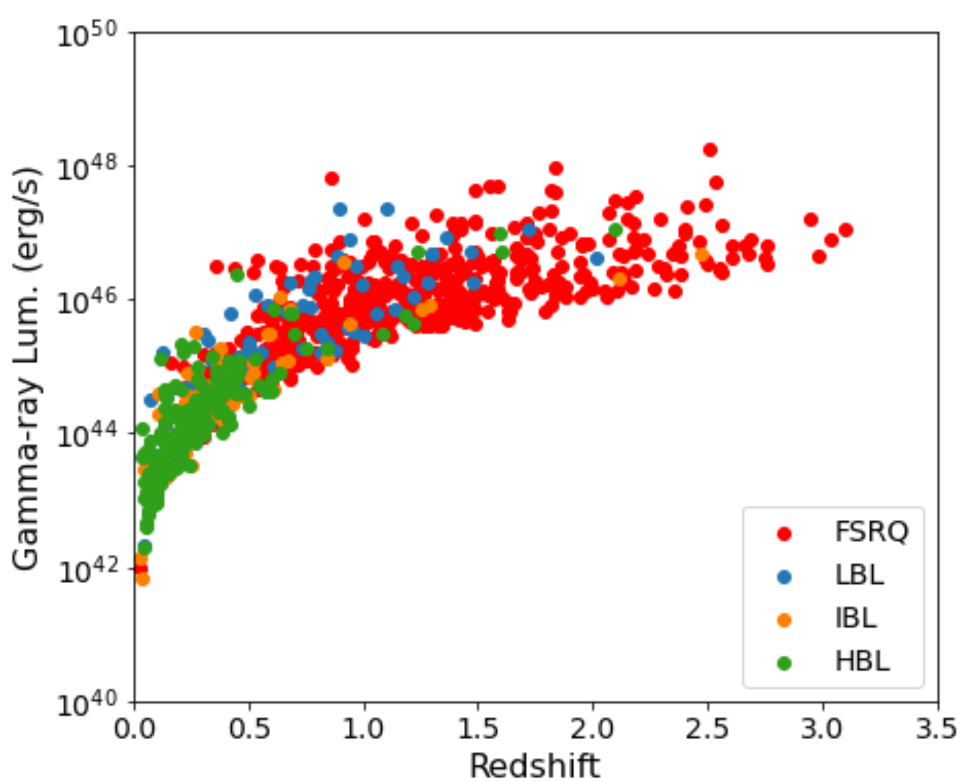
RomaBZCat



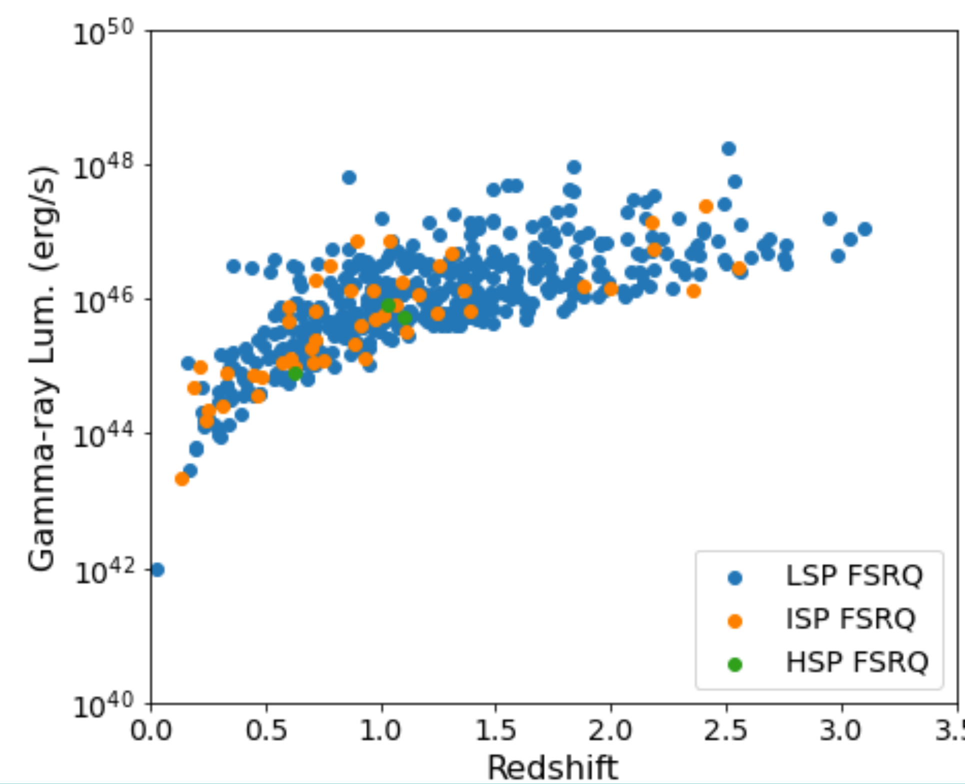


BL Lacs and FSRQs show a cosmological evolution favoring only LSP sources at high z

Observational bias?



Fermi 3LAC



- SOURCE CATALOG : ROMABZCAT 5

- SOFTWARE, DATASET

Next steps:
Explore weighting schemes for p-values
- X-ray luminosity
- Spectral index

Summary:

➡ Blazars are promising sources to explain a major part of the high-energy ν-spectrum

➡ The discovery of TXS 0506+056 and subsequent modelling of its SED provide a clear path forward in terms of multi-messenger inquiries using X-ray and γ-ray signatures of blazars

➡ The outlined analysis using X-ray selected blazars aims to tackle and possibly unravel the mystery surrounding the origin of VHE neutrinos and CRs

BACKUP SLIDES

GAMMA-RAY LUMINOSITY (AVERAGE)

The average gamma-ray luminosity calculated for the blazars of the sample

Source	Category	z	D_L (Mpc)	$\nu^s{}_{peak}$ (Hz)	L_{avg} (erg/s)	dL_{avg} (erg/s)
OP 313	fsrq	0.9975	6769.05	1e+13	1.65897e+47	1.5439e+46
SDSS J085410.16+275421.7	bll	0.494	2874.95	1.202e+14	1.38307e+46	4.97376e+45
1RXS J064933.8-313914	bll	0.563	3363.99	1e+18	7.61537e+45	1.17108e+45
GB6 J1040+0617	bll	0.7351	4651.82	5.956e+13	5.9124e+46	1.75879e+46
GB6 J1231+1421	bll	0.256	1334.65	8.511e+14	1.48302e+45	1.89055e+44
PKS 1454-354	fsrq	1.424	10501.9	1.188e+13	3.78476e+47	7.62444e+46
PMN J1505-3432	bll	1.554	11694.7	0	1.6239e+47	4.13623e+46
PMN J2227+0037	bll	0	0	2.558e+14	0	0
PKS 2021-330	fsrq	1.47	10921.4	9.33e+12	1.92659e+47	1.7053e+46
TXS 0506+056	bll	0.3365	1827.7	1.64e+14	1.60835e+46	1.66852e+45

The synchrotron peak frequency is obtained from the 3FHL catalogue

GAMMA-RAY LUMINOSITY (FLARING)

The gamma-ray luminosity calculated for the blazars during their most significant flare

Source	Category	z	DC (%)	dDC (%)	T_{flare} (months)	L_{flare} (erg/s)	dL_{flare} (erg/s)
OP 313	fsrq	0.9975	6.56	0.06	4	6.05542e+47	1.79493e+47
SDSS J085410.16+275421.7	bll	0.494	0	0	0	0	0
1RXS J064933.8-313914	bll	0.563	0	0	0	0	0
GB6 J1040+0617	bll	0.7351	1.72	0.02	2	1.03487e+48	4.58014e+46
GB6 J1231+1421	bll	0.256	1.89	0.02	2	5.24056e+45	1.94109e+45
PKS 1454-354	fsrq	1.424	8.33	0.07	12	2.4341e+48	3.89769e+47
PMN J1505-3432	bll	1.554	0	0	0	0	0
PMN J2227+0037	bll	0	1.67	0.01	2	0	0
PKS 2021-330	fsrq	1.47	5.26	0.04	4	4.8189e+47	3.12828e+46
TXS 0506+056	bll	0.3365	8.2	0.07	10	5.32805e+46	6.11817e+45

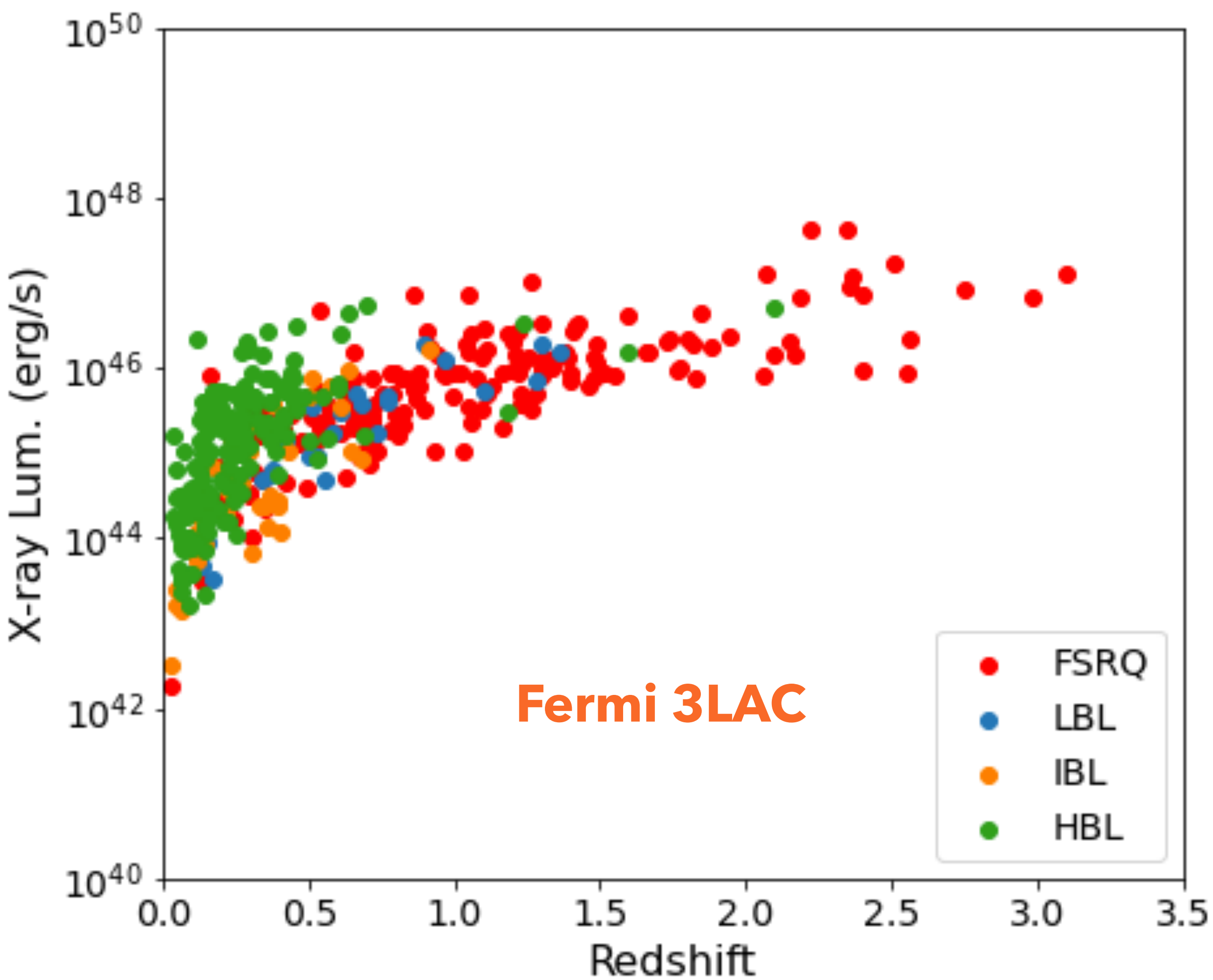
Duty Cycle is calculated here using the modified approach of Vercellone et al. 2004 as described previously (Method II)

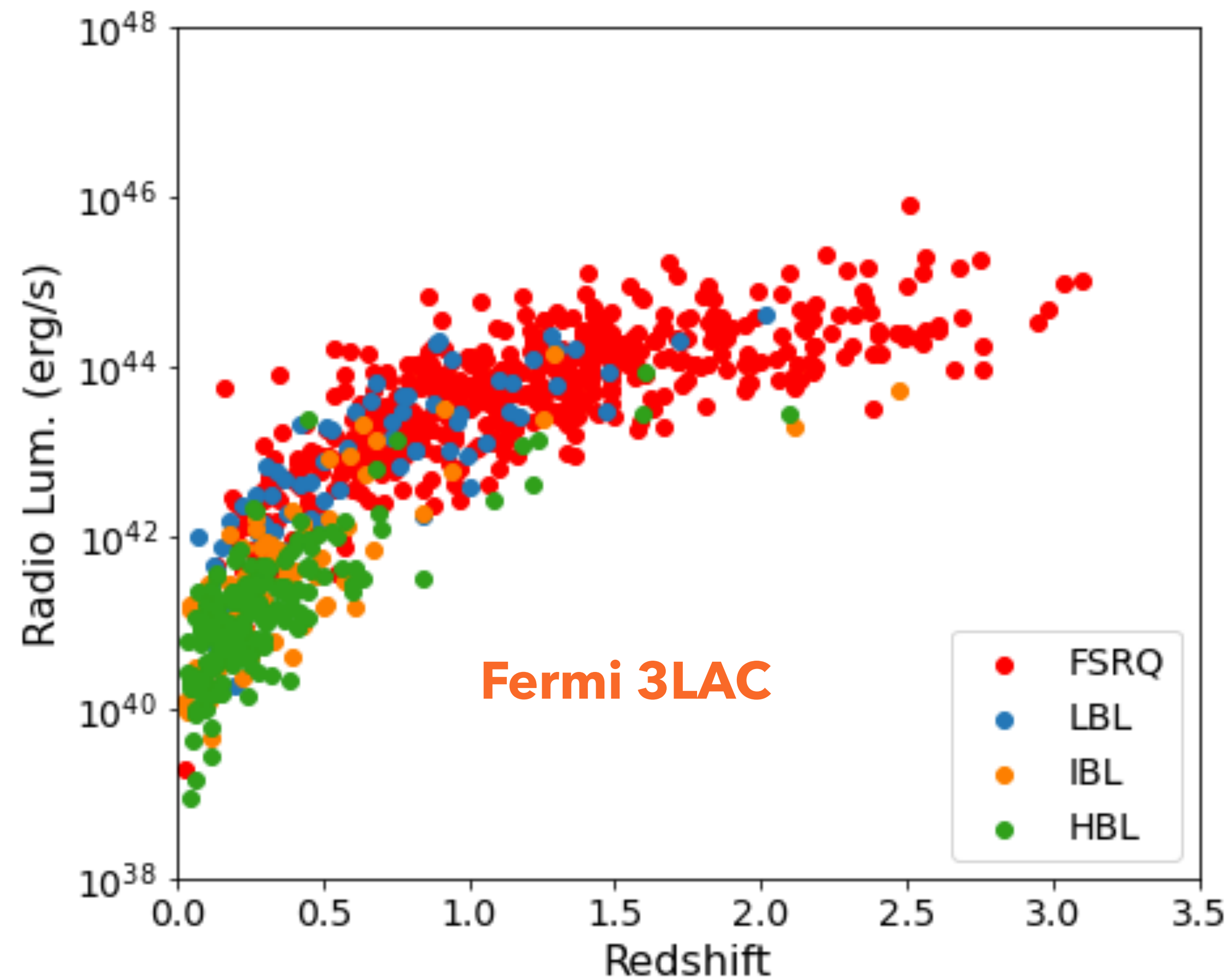
Source Name	z	Luminosity (erg/s)	DC (avg.)
Mkn 421	0.031	9.03 x 10^{44}	~ 29 %
TXS 0506+056	0.336	6.70 x 10^{46}	~ 23 %
OP 313	0.998	6.81 x 10^{47}	~ 21 %

DC is calculated here using the approach of Tluczykont et al. 2010

REDSHIFT EVOLUTION

Do AGNs in early Universe have more powerful central engines? Does this align with the cosmological evolution of supermassive black holes ??





- ➡ Radio luminosity distribution similar for FSRQs and LBLs!
- ➡ LBLs show a higher median (radio) luminosity than IBLs and HBLs