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Characterizing the High-Energy Activity of Blazars Possibly Correlated with Observed Astrophysical Neutrinos

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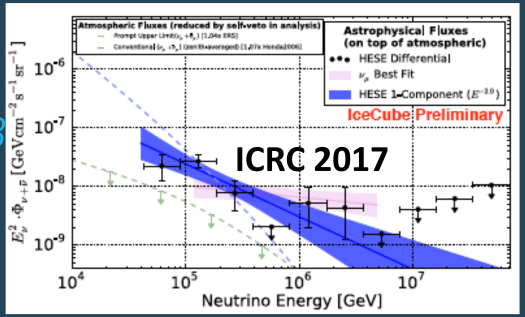
State of the Art & Motivation



- Evidence of astrophysical neutrino signal from IceCube

  M.G. Aartsen et al. Phys. Rev. Lett., 2015, M.G. Aartsen et al. Phys. Rev. Lett., 2013

- Diffuse galactic contribution < 10%   =>   90% extra-galactic

  M.G. Aartsen et al. ApJ, Nov 2017, Gaggero D. et al. ApJ Letters, Dec 2015

  A. Albert et al. Phys. Rev. D, 96(6):062001, Sept. 2017

- Extra-galactic source population??   → GRBs, Starbursts, AGN?? *K. Bechtol et al. ApJ, Feb '17*

  → Blazars??

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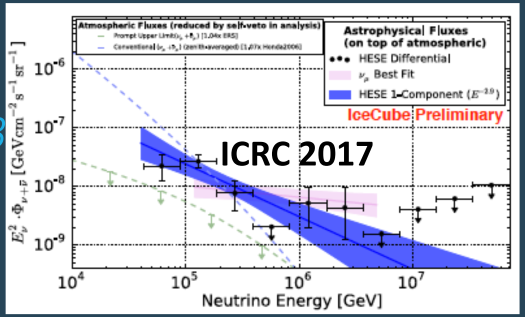

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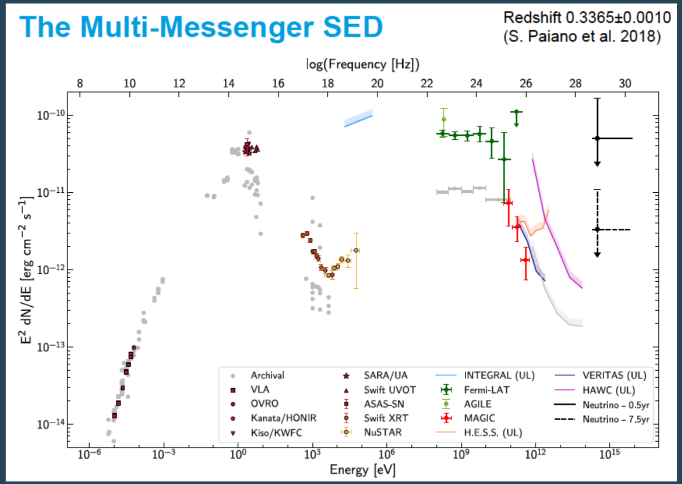
→ Blazars??



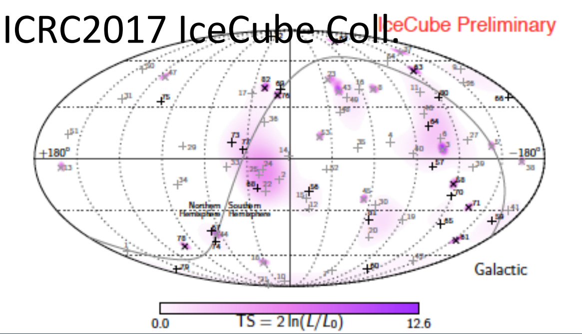
IC170922-A

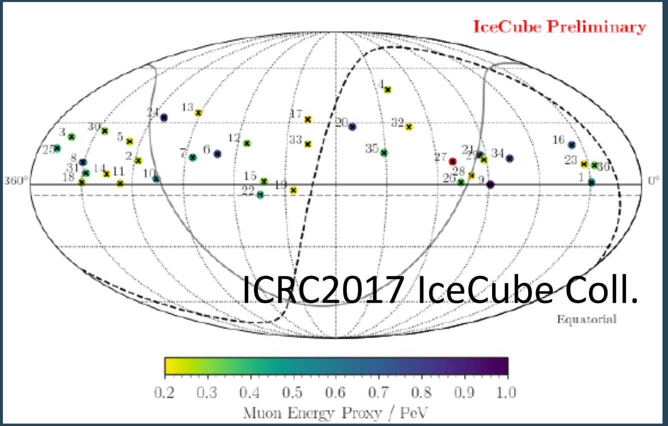
M.G. Aartsen et al. Science, 361(6398), 2018

Search for signatures in the EM emission of blazars spatially correlated with IC astrophysical ν candidates!!

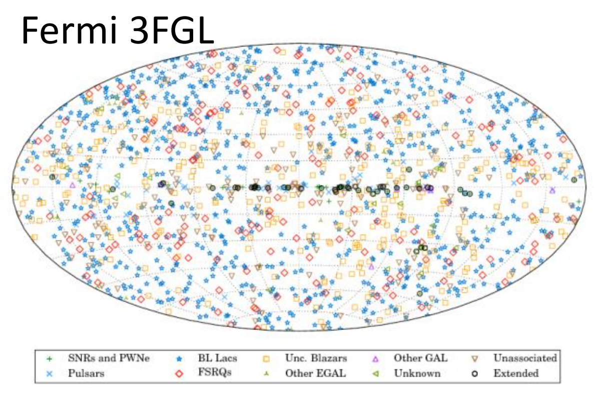
Sample of spatially correlated blazars

- Candidate ν_μ events (all track-like → need for good angular resolution):
  - ✓ 22 AMON alerts (HESE & EHE) *M.G. Aartsen et al. Astroparticle Phys., 92:30–41, June 2017*
  - ✓ 36 events above 200 TeV *M.G. Aartsen et al. ApJ, 833:3, Dec. 2016* and *IceCube Coll. PoS (ICRC2017) 1005, 2017*





80 candidate ν_μ events in total



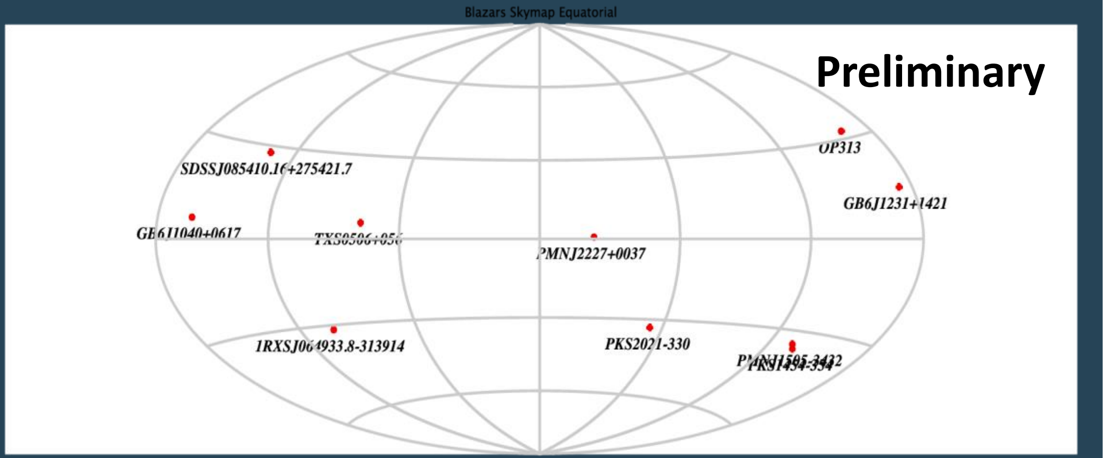
  - ✓ 22 events from HESE sample *PoS(ICRC2017)981 IceCube Coll.*

- Source Catalogs (Fermi-LAT):
  - ✓ 3FGL & 3FHL *F. Acero et al. ApJ Suppl. Series, 218:23, June 2015*

Sample of spatially correlated blazars

Selection criteria: Spatial coincidence with a candidate astrophysical neutrino event (events with 50% error < 1.5°)

$\text{Fermi-LAT}_{centr.} - \text{IceCube}_{centr.} < 1.3^{o}$



The sky map of blazars spatially connected with selected astrophysical ν_μ events

Table 1: Sample of blazars in spatial coincidence with selected IceCube ν_μ events

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	27.8826	bll	0.494
3	1RXS J064933.8-313914	102.386	-31.6491	bll	$\geq$ 0.563
4	GB6 J1040+0617	160.147	6.3023	bll	0.7351
5	GB6 J1231+1421	187.866	14.368	bll	0.256
6	PKS 1454-354	224.382	-35.6478	fsrq	1.424
7	PMN J1505-3432	226.25	-34.5472	bll	1.554
8	PMN J2227+0037	336.972	0.6101	bll	-
9	PKS 2021-330	306.108	-32.9047	fsrq	1.47
10	TXS 0506+056	77.3636	5.7066	bll	0.3365

Preliminary

Illustration Credit: DESY, Science Communication Lab

Gamma-Ray Observations

TXS 0506+056 (BL-Lac) vs OP 313 (FSRQ)

Gamma-Ray Light Curves

- γ-ray light curves with 9.5 years of Fermi data
- $0.1 < E_{GeV} < 300$; 10^0 ROI; power law spectrum; weekly bins
- EBL absorption with *Franchescini et al. A&A, 2008*

P. Padovani et al. MNRAS, Jan 2019

BL-Lac ??

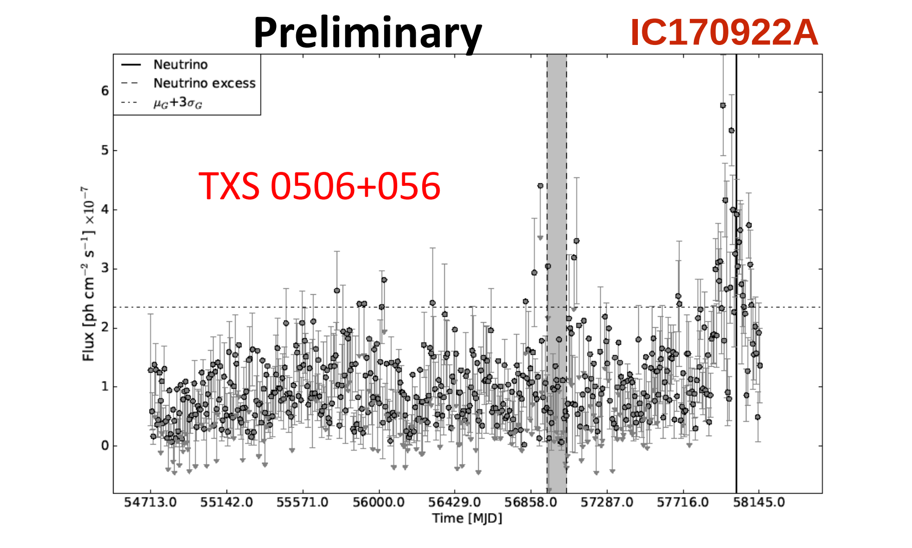
† TXS 0506+056 (z = 0.336):

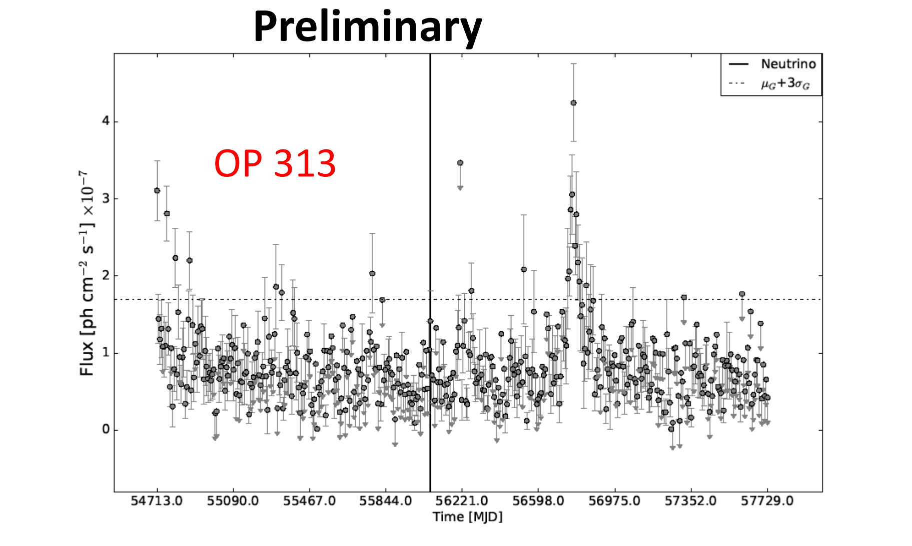
- Most likely counterpart of IC-170922A (E_ν = 290 TeV)
- Major gamma flare in 2017-18
- Neutrino excess from the direction in December 2014

FSRQ

† OP 313 (z = 0.998):

- Coincident with an EHE ν_μ from 15th May 2012 (E_ν > 200 TeV)
- Major gamma-ray flare in April 2014
- High avg. flux and a well defined flare in gamma, make it possible to study the high-energy activity





Looking for spectral variability

- Spectral index variation of TXS 0506+056 and OP 313 with 9.5 years of Fermi data
- Time bin of 6 months (good for neutrino observation)
- $0.1 < E_{GeV} < 300$; power law with cutoff

† TXS 0506+056:

† $\alpha_{avg} = -1.97 \pm 0.04$

† Max. dev. from mean = 2.19σ

† Deviation during ν-flare of 2014-15: 0.44σ

† Atleast 3 bins with higher deviation than during the 2014-15 excess

† OP 313:

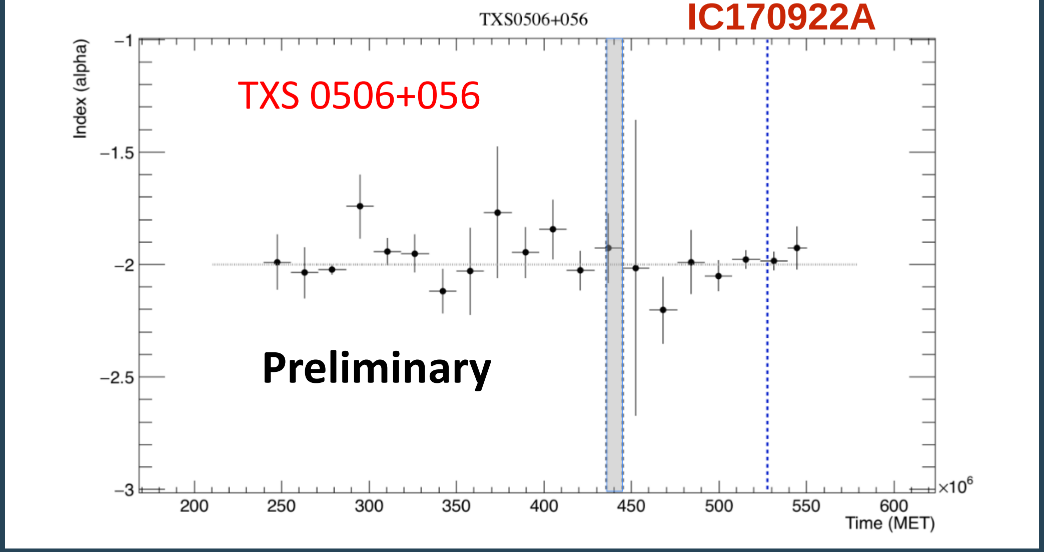
† $\alpha_{avg} = -2.15 \pm 0.14$

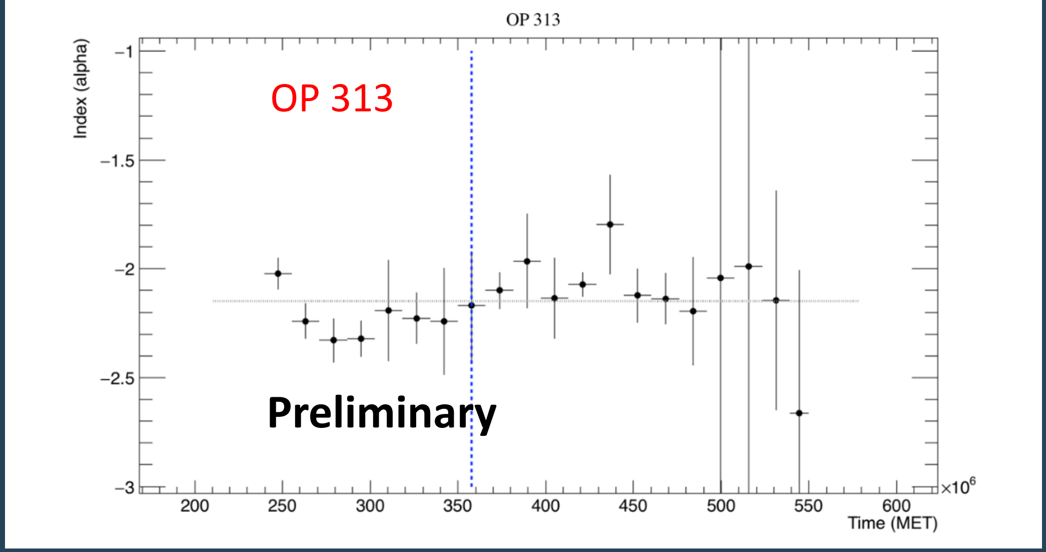
† Max. deviation from mean = 2.92σ

† No significant deviation from mean in the time bin of spatially coincident neutrino event

† Maybe smaller bin size needed to observe spectral variability (*P. Padovani et al. MNRAS, July 2018*)

† Not enough statistics for far away objects like OP 313 due to EBL absorption





Duty Cycles

- Duty Cycle (DC) → Fraction of time source spends in an active state

$$DC = \frac{T_{fl}}{T_{quies} + T_{fl}}$$

T_{fl} → time spent in flaring state;

T_{quies} → time spent in the quiescent state

- Estimate of how active a source is

† Blazars spend a significant part of their time in low-activity or “off” state

† Important to factor in while calculating neutrino flux expectations from blazars

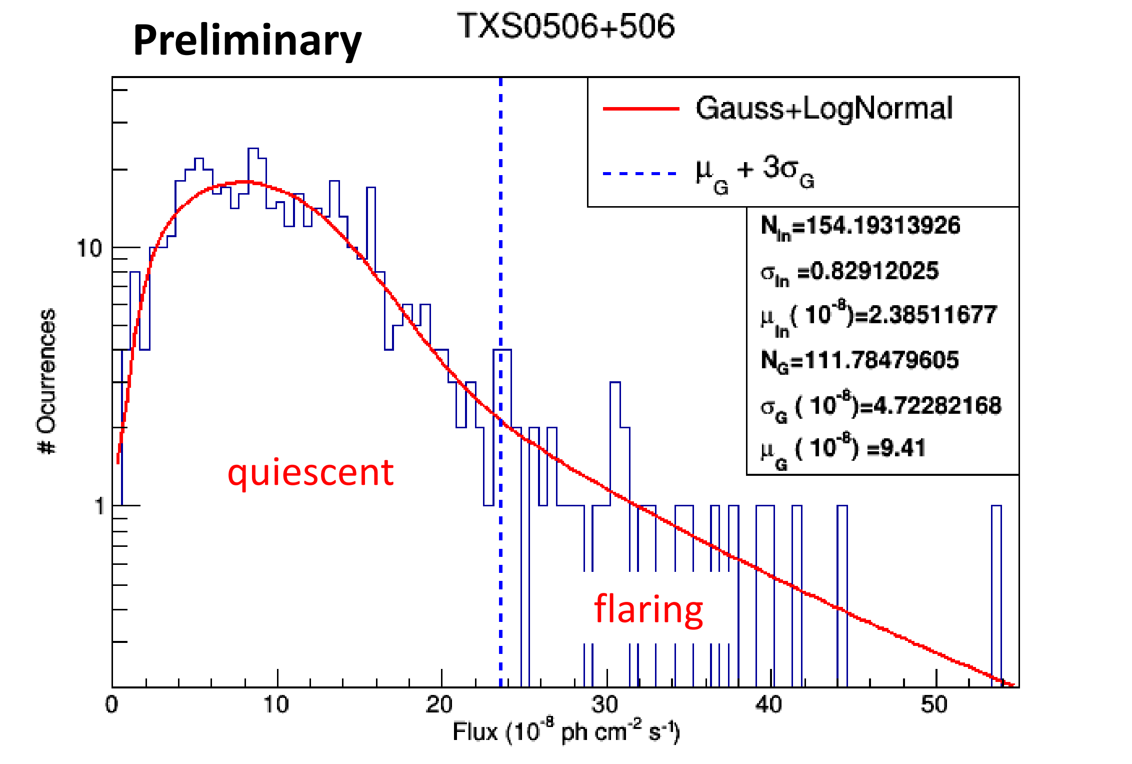
Duty Cycles

- Definition from *Tluczykont et al. 2010*
- Fit function: **Gaussian + LogNormal**
- Gaussian defines the quiescent states, LogN defines the active states
- Removing time dependence

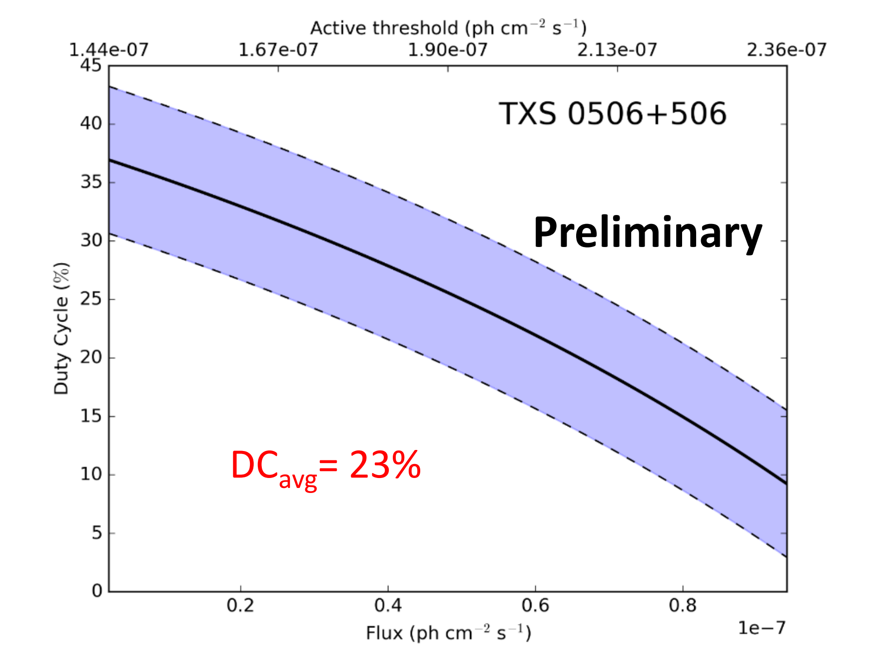
$$DC = \frac{F_{avg} - F_{bl}}{\langle F_{fl} \rangle - F_{bl}}$$

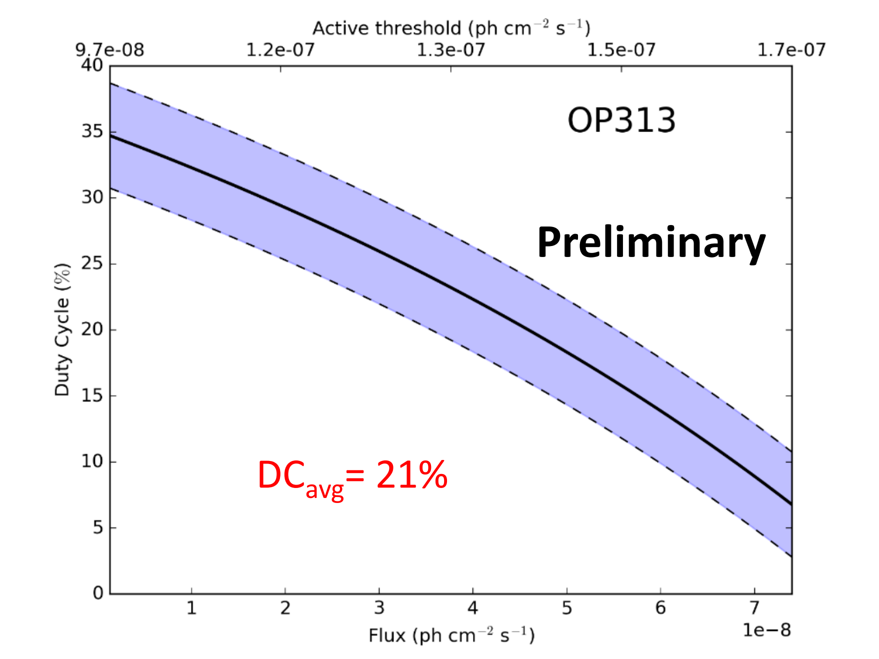
- $F_{bl} = \mu_{gaus} + 3\ \sigma_{gaus}$ (baseline flux)
- where F_{avg} -> avg. flux over all observations
- $\langle F_{fl} \rangle$ -> avg. flux during all flares
- Vary the baseline to calculate the DC distribution

† Gaus+LogNormal fit only gives good results for bright sources with well defined flares/active states



Duty Cycles: The cases of TXS 0506+056 & OP 313

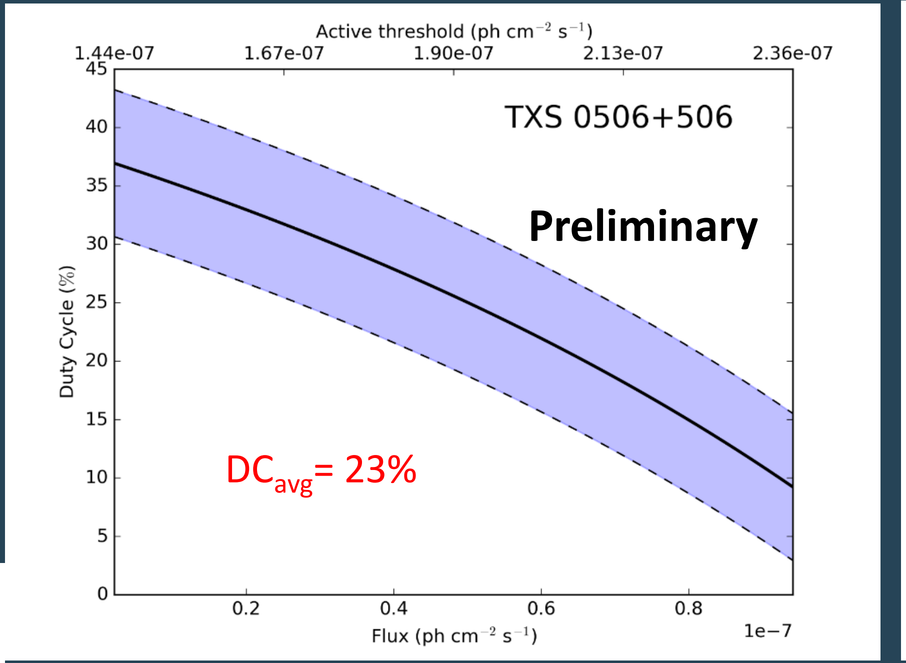


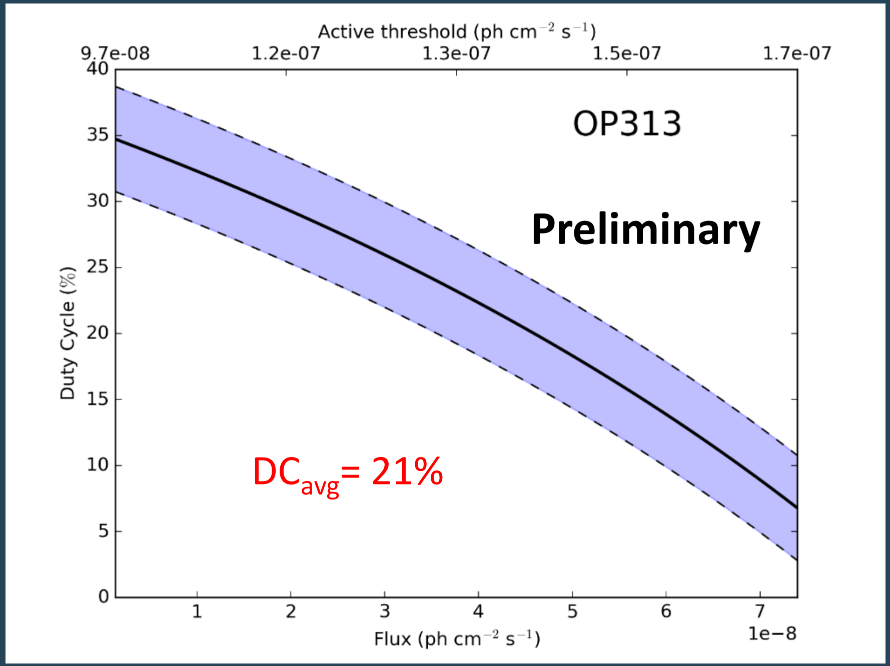


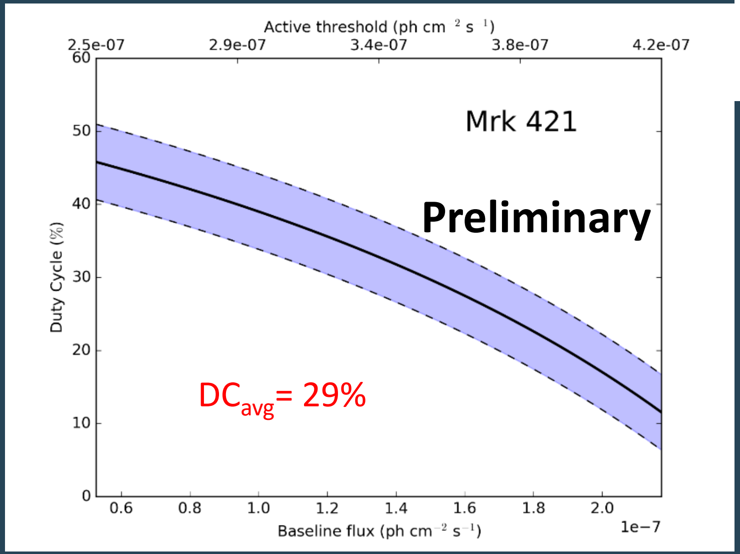
Only two sources from the sample for which DC could be calculated using the *Tluczykont et al.* Gaus+LogNormal fit, either due to low statistics or absence of a clear flare/active states

Duty Cycles

Even bright blazars like TXS 0506+056 and OP 313 are active only 1/4th of the total time







- Average duty cycles for TXS 0506+056 (23%) and OP 313 (21%) at a comparable level
- Not far from avg. DC of Mkn 421 (29%)

Flare Luminosity

- Isotropic γ-ray luminosities calculated for major flare of each source
- Flare duration from duty cycle calculation (active state: flux > 3 σ_{gaus})
- Standard cosmology from:

M. G. Aartsen et al. (IceCube Coll.) Science, 361(6398), 2018

- OP 313 ∼ 10X as bright as TXS 0506+056

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

A high gamma-ray luminosity does not necessarily imply a neutrino counterpart

The Blazar Sequence??!!

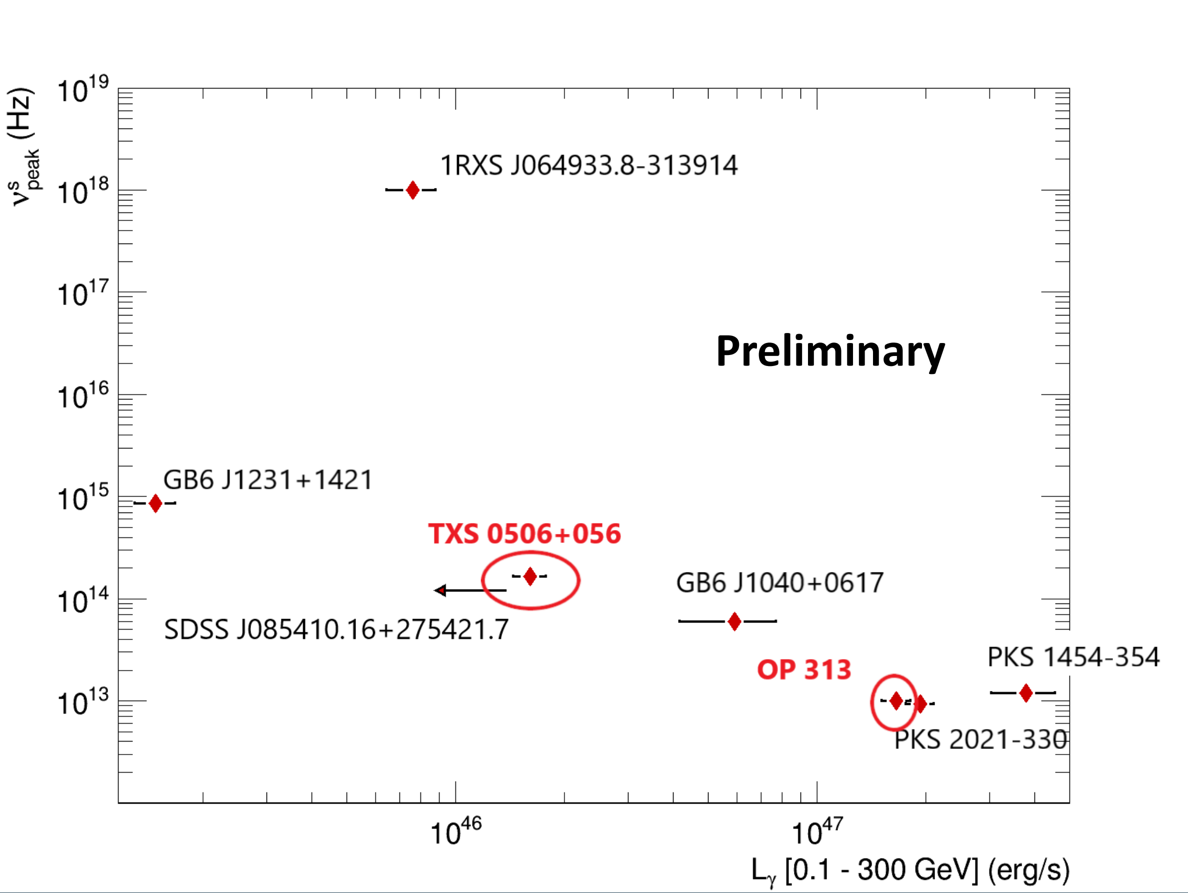
We also check if our candidate sources follow the blazar sequence.....

- L_γ with 9.5 years of Fermi data
- 0.1 GeV < E < 300 GeV
- ν^{syn}_{peak} from 3FHL catalog

† Anti-correlation between syn. peak and L_γ found for the sample

† The outlier (1RXS J064933.8-313914) is an extreme blazar (only 1 in sample)

† SDSS J085410.16+275421.7 shown as an upper limit due to low TS



Combined BL-Lac + FSRQ anti-correlation in agreement with *G. Ghisellini et al. MNRAS, Feb 2017*

Neutrino Observations

TXS 0506+056 and OP 313

The Model

- Fermi-LAT γ data correlated with IceCube ν-flux through a lepto-hadronic model;

  Petropoulou M. et al. MNRAS 2015

- 1-100 GeV γ-rays are explained by the synchrotron emission of decay products of charged-π, which are produced in photo-pion interactions in the jets of blazars

- We consider low opacity value ($\tau_{\gamma\gamma}$) due to interaction between BLR and γ-ray photons

- Relative intensities of the muonic neutrino component ($\nu_\mu + \bar{\nu}_u$) and γ component can be expressed as a fraction:

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

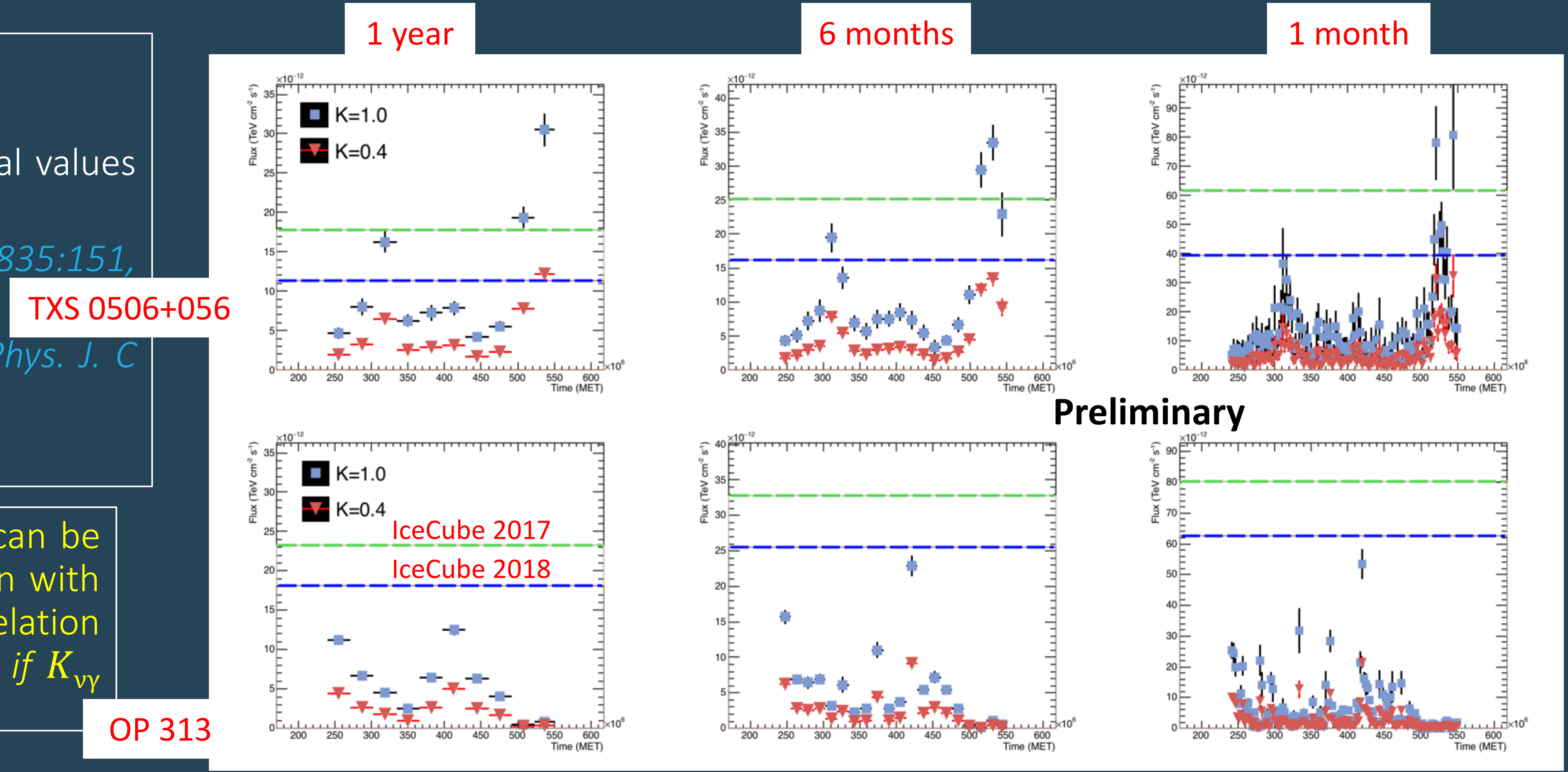
Neutrino Observability

Assuming all observed γ-rays to be produced through the sync. emission of pion cascade products we build a “neutrino light-curve” and look for possible Icecube observability during a flare

For TXS 0506+056, $(\nu_\mu + \bar{\nu}_u)$ flux will be detectable in 1 month or more for $K_{\nu\gamma}$ = 1 & in 1 yr for $K_{\nu\gamma}$ = 0.4, assuming the *Petropoulou et al.* correlation between γ *and* ν *flux*

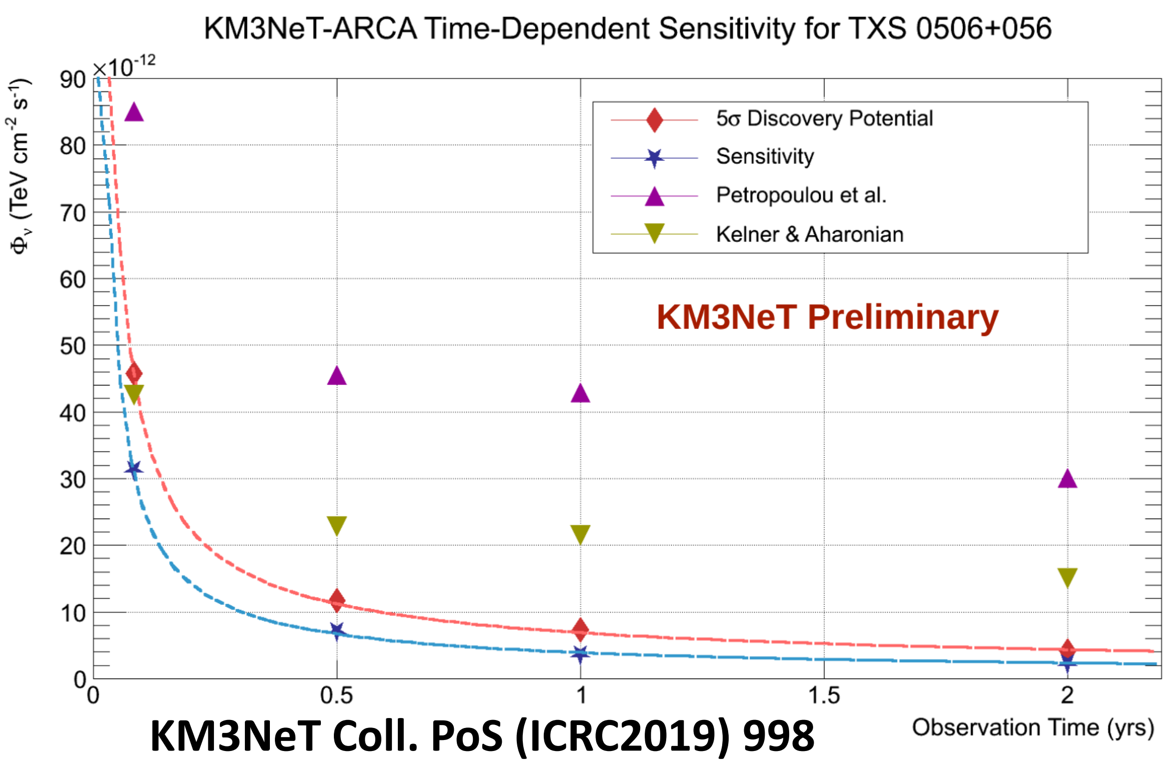
- 9.5 years of Fermi data
- $1 < E_{GeV} < 300$
- IceCube 5σ Disc. Potential values from:
  → *M.G. Aartsen et al. ApJ, 835:151, 2016*
  → *M.G. Aartsen et al. Eur. Phys. J. C (2019) 79: 234*
- $K_{\nu\gamma} = 1$ & $K_{\nu\gamma} = 0.4$

For OP 313, $(\nu_\mu + \bar{\nu}_u)$ flux can be detectable in a 6 month bin with the *Petropoulou et al.* correlation between γ *and* ν *flux, only if* $K_{\nu\gamma} > 1$



TXS 0506+056 – Observability with KM3NeT-ARCA

KM3NeT Collaboration has shown that with the assumptions of *Petropoulou et al.* for the flare of 2017-18 ($K_{\nu\gamma}$ = 1), TXS 0506+056 would be detected with significance > 5σ in one month or more of observation

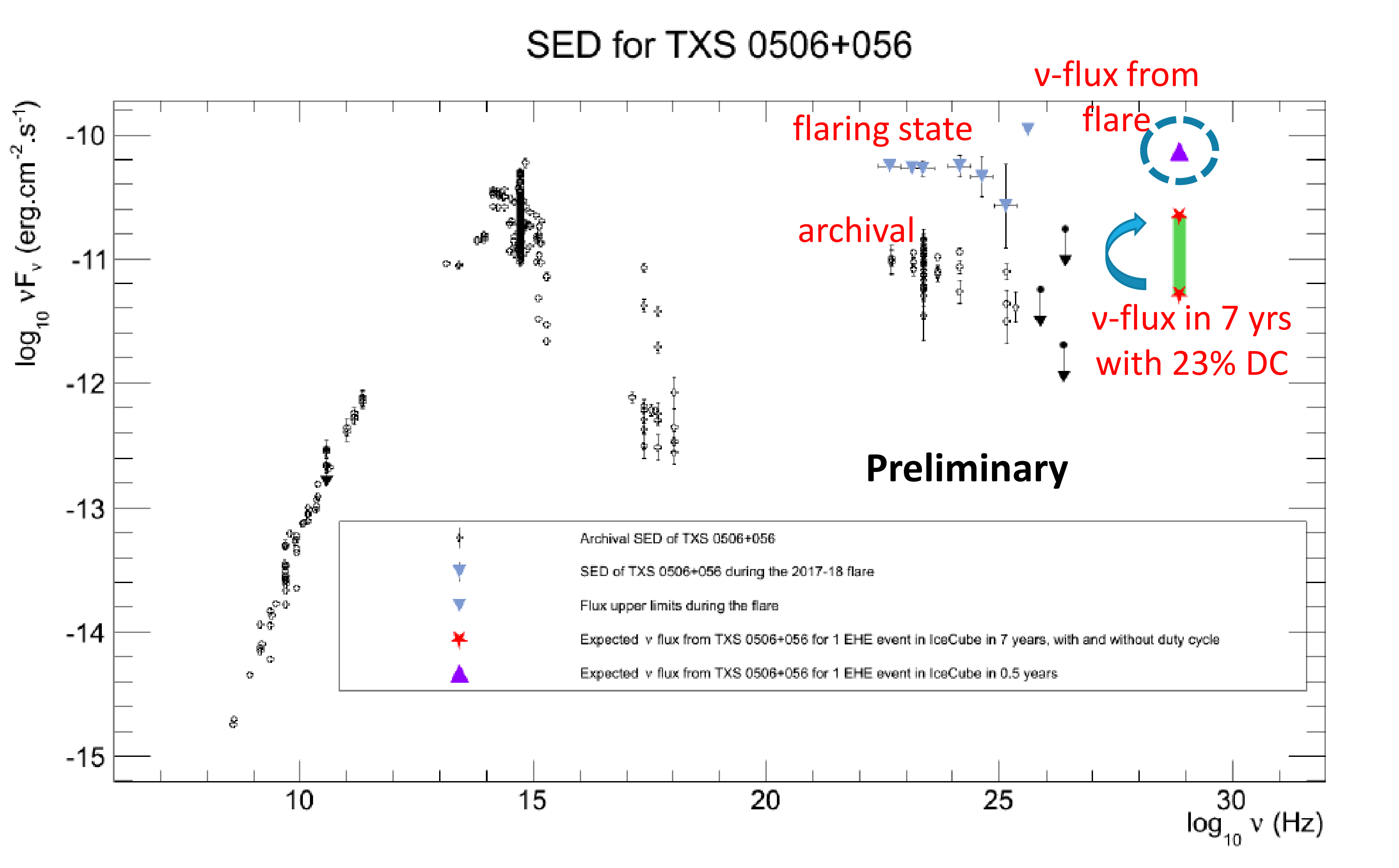


KM3NeT Coll. PoS (ICRC2019) 998

Comparing the 5σ discovery potential of KM3NeT-ARCA in the bins of 1 year, 6 month and 1 month, with our extrapolated fluxes of TXS 0506+056, but with $K_{\nu\gamma}$ = 0.4, we find that TXS 0506+056 should be detectable by KM3NeT-ARCA in atleast 6 months of observation time

Multi-Wavelength SED – TXS 0506+056

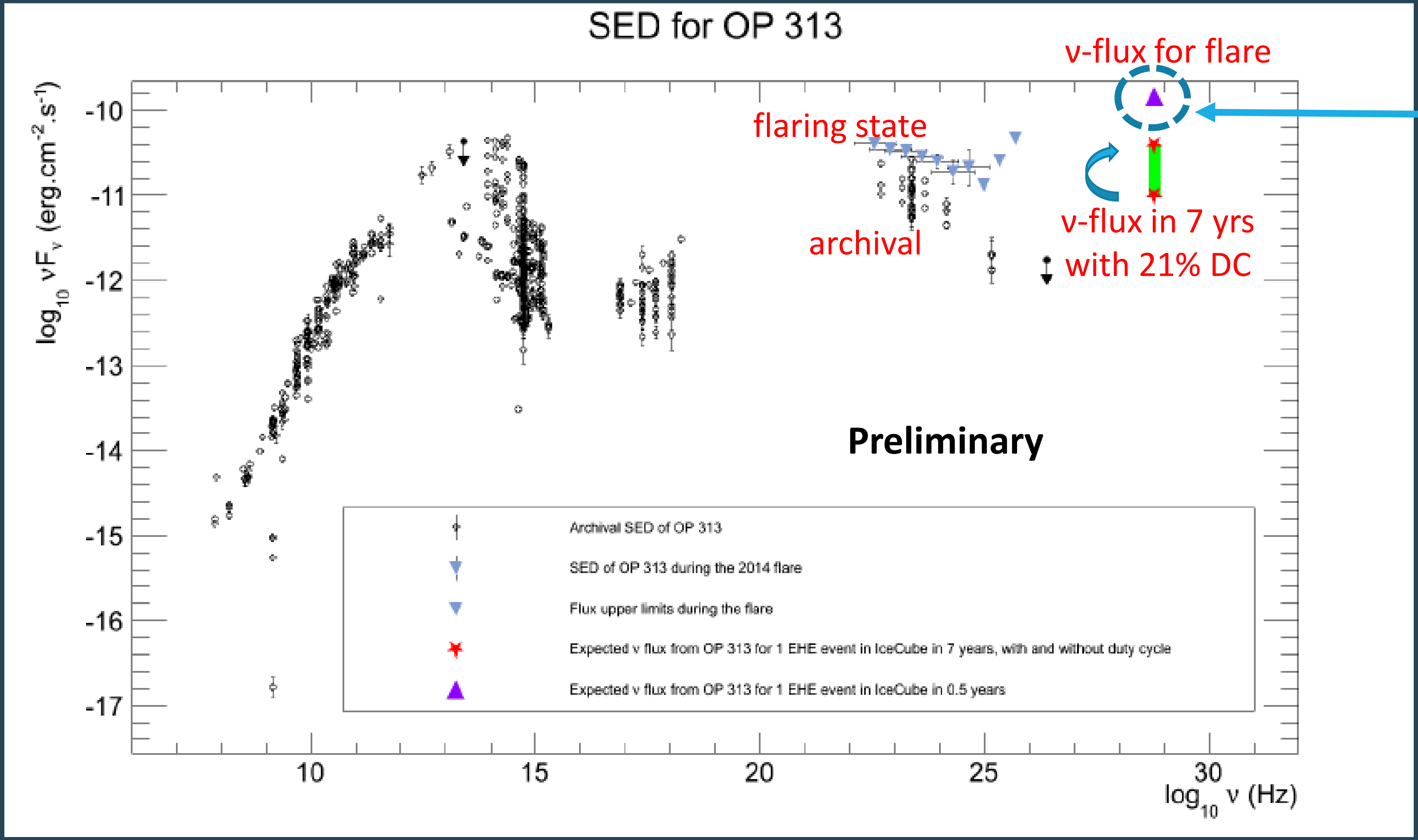
Application of DC can change the expected ν-flux from the source over a long observation time



- Archival SED
- Flaring state SED from Fermi data
- Expected ν-flux for 1 EHE event in IceCube during the 2017-18 flare of TXS 0506+056
- Expected ν-flux for 1 EHE event in IceCube in 7 years, also assuming an avg. DC

For TXS 0506+056, the DC correction can be applied to the ν-flux expected from the source for 1 EHE event in 7 years in IceCube

Multi-Wavelength SED – OP 313



For OP 313, (ν_{μ} + $\bar{\nu}_{u}$) flux calculated during the flare is virtual since it assumes the neutrino event to coincide with the flare duration

The level of ν-flux after the DC correction, and the level of γ-flux in the archival SED, still allow for the possibility of hadronic emission from OP 313

The level of ν-flux estimated during the flare is higher than the level of flaring state SED, possible reason for non-observation of neutrino during the flare

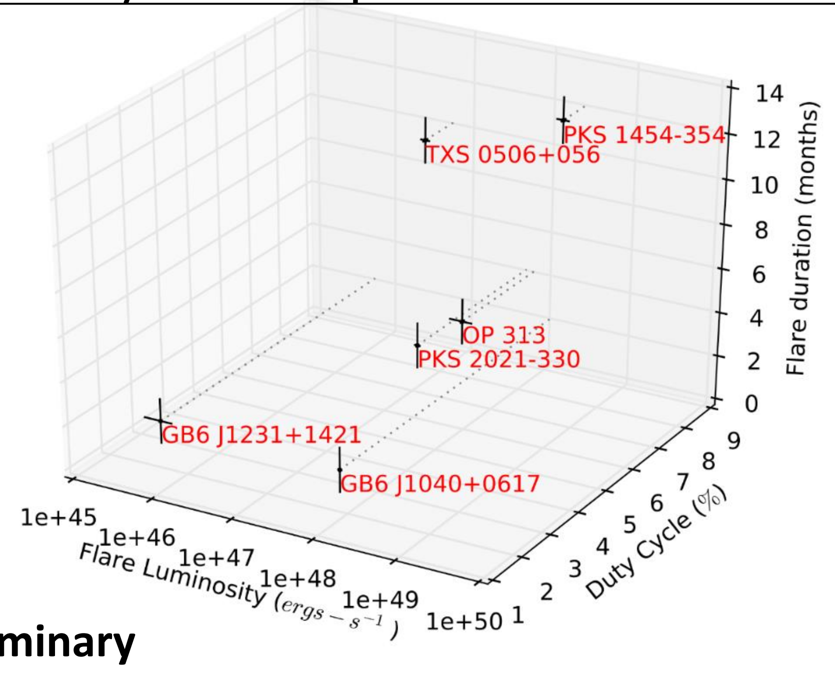
A Combined Picture

Assuming the *Petropoulou et al.* correlation between γ-rays and ν, more luminous γ-ray sources, with a longer duration of flare in high-energy γ-rays, can be more likely to emit VHE neutrinos

Following this criteria, the FSRQ PKS 1454-354 is a likely neutrino emitter candidate, but it flared in the initial years of IceCube, when the detector was not yet operating in full configuration

- For the sources in our sample, we plot the integrated luminosity during their brightest flare, along with the duty cycle and the duration of the flare itself
- DC for these sources calculated using the criteria of *S. Vercellone et al. MNRAS, 2004* but slightly modified for faint sources
- Mean flux calculated with upper limits, but for active states, only bins with errors bars completely above the threshold included. Threshold for activity defined as 1σ above the mean

But no evidence of the flaring γ-ray flux being dominated by hadronic production!!



Conclusions

- We construct a sample of 10 blazars in spatial coincidence with IceCube (EHE & HESE track-like) candidate astrophysical neutrinos; 7 BL-Lacs and 3 FSRQs
- Analyzing the γ-ray for the sources, TXS 0506+056 stands out with a high DC, flare duration and luminosity among the BL-Lacs, while PKS 1454-354 and OP 313 are the FSRQ candidates that show significant γ-ray activity and high flaring luminosity
- Some anti-correlation, akin to the blazar sequence seen among the sample sources

- Following the lepto-hadronic scenario from *Petropoulou et al. 2015*, we connect the 10 TeV – 10 PeV neutrinos to 1 – 100 GeV γ-rays from Fermi-LAT data
- Assuming this model, the minimum flare duration for a blazar to be observable to a km^3 Cherenkov telescope is of the order of months

- To achieve a 5σ detection with multi-messenger observations, like the case of IC170922A and the 2017-18 TXS 0506+056 γ-ray flare (1-100 GeV γ-rays and 10TeV-10PeV ν), the preferred way is to build a Global Neutrino Network with several km^3 Cherenkov detectors spread around the world