INAF
Istituto di Radioastronomia

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

MAGIC and MWL monitoring of the blazar TXS 0506+056 in the 2017/2019 season

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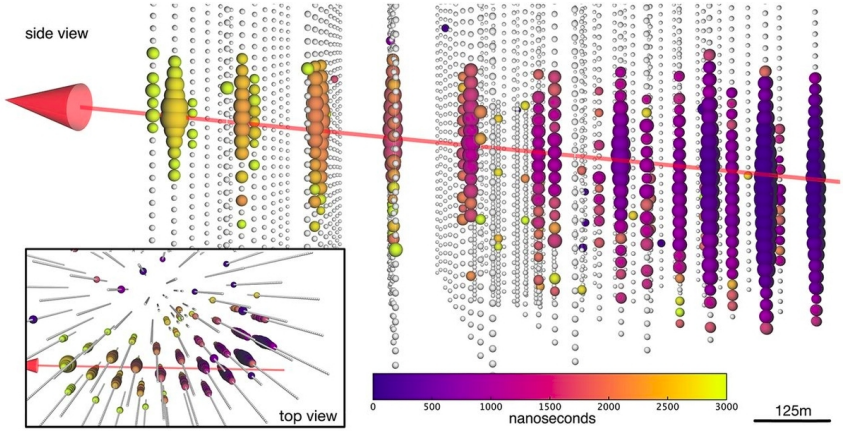
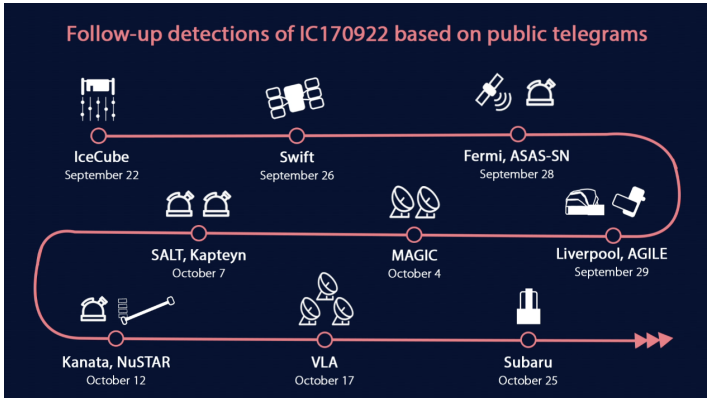
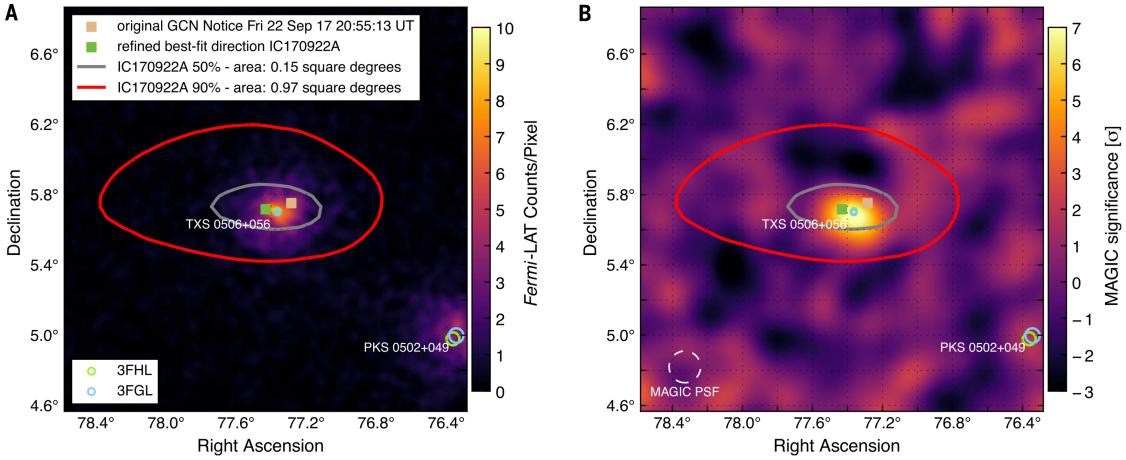
for the MAGIC Collaboration

IceCube-170922A / TXS 0506+056

Most significant association (3-σ) of a high-energy (290 TeV) neutrino with an astrophysical source

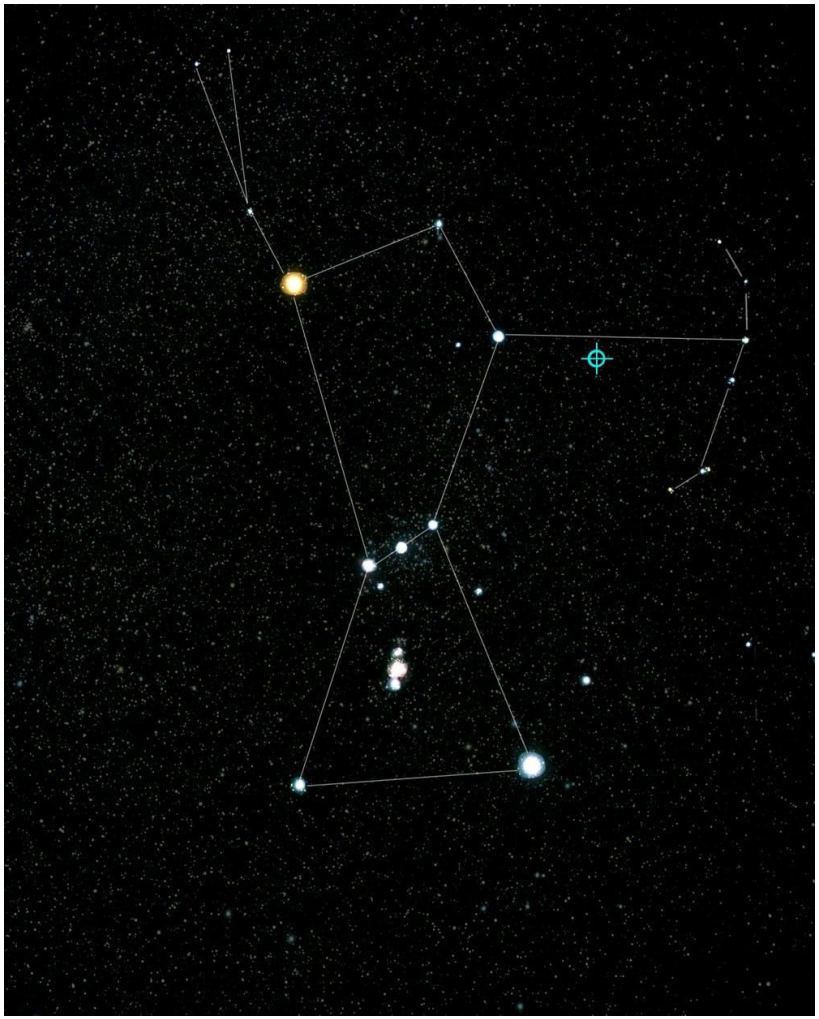






IceCube, Fermi, MAGIC et al. 2018, Science, 361, eaat 1378

TXS 0506+056

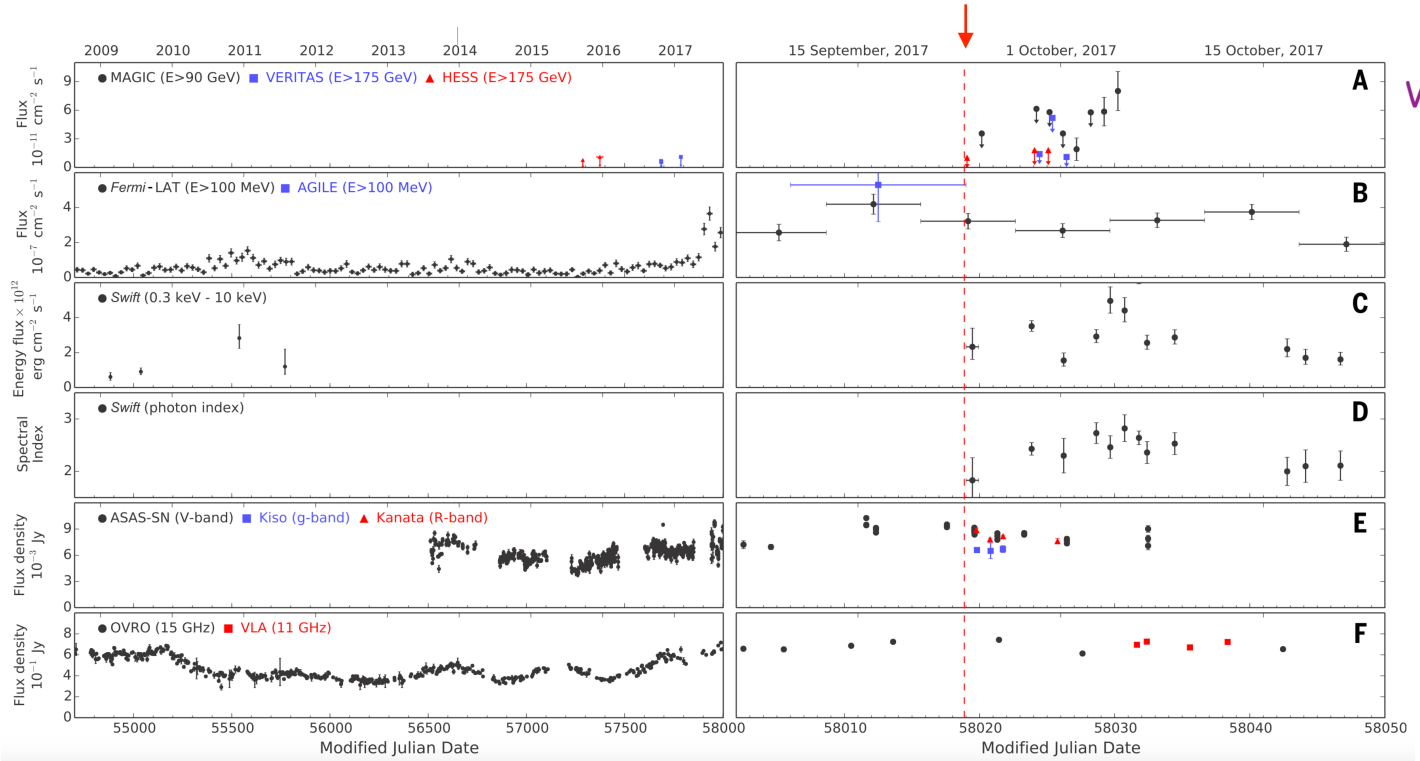


Credits: Silvia Bravo Gallart/Project WIPAC Communications

- Texas survey of radio sources, discovered in 1983
- Classified as a BL Lac object, but suggested also as a "hidden FSRQ" by Padovani et al. (2019)
- Among the brightest 5% of blazars detected in HE γ-rays (4FGL J0509.4+0542, 3FHL J0509.4+0542)
- Redshift z = 0.3365, ~4 billion light years (Paiano et al. 2018)

IceCube-170922A / TXS 0506+056

IC-170922A



VHE γ-rays: MAGIC discovery day-scale variability

HE γ-rays: flare 0.5 yr

X-ray: day-scale variability

X-ray: spectral variability

Optical: enhanced emission

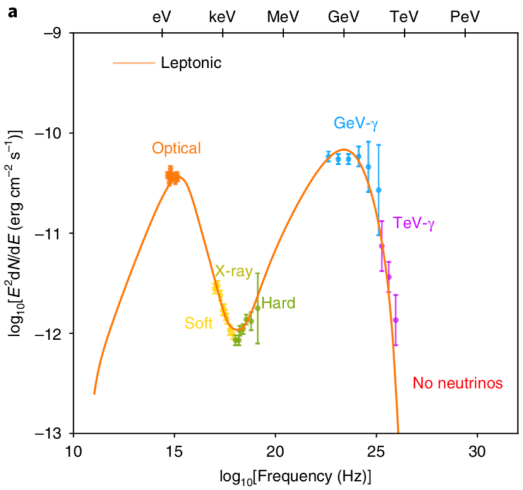
Radio: enhanced emission

IceCube, Fermi, MAGIC et al. 2018

IceCube-170922A / TXS 0506+056

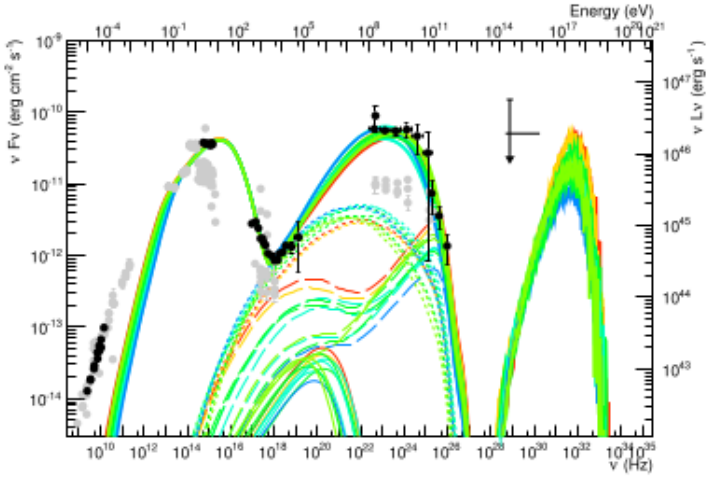
Several independent modeling efforts

Pure Leptonic



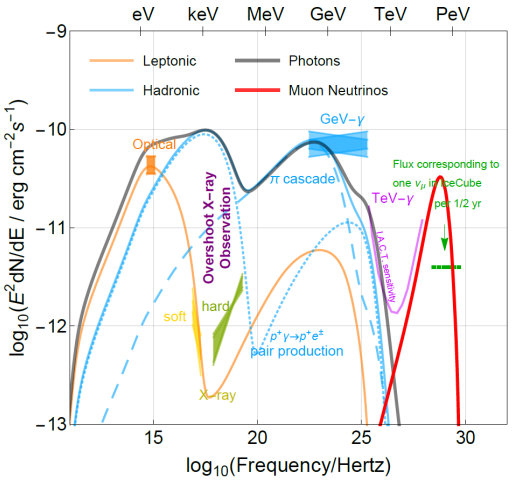
Gao et al. 2019

Lepto-hadronic



Cerruti et al. 2019

Pure Hadronic (π cascade)

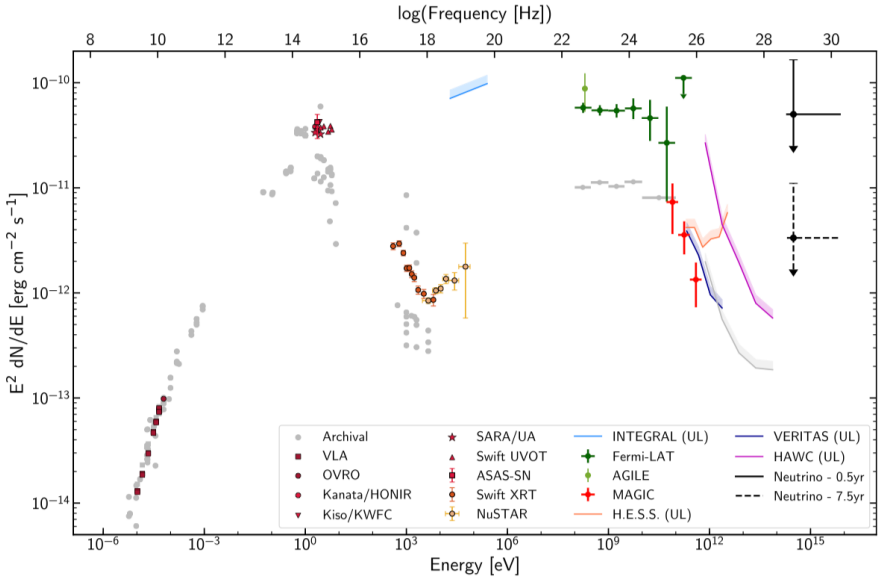


Gao et al. 2019

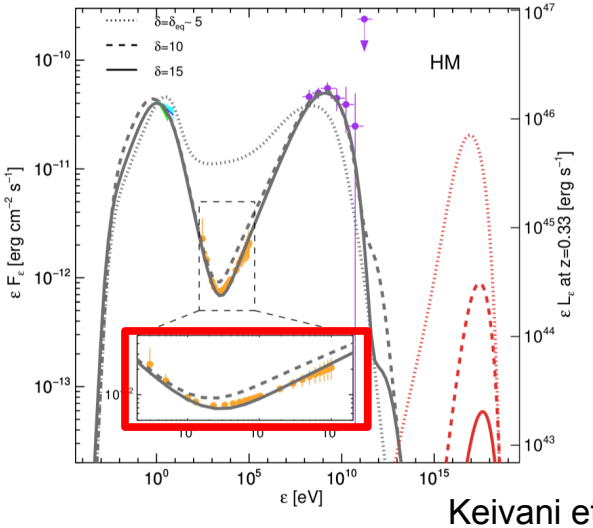
- pure hadronic models are disfavored
- leptonic-dominated SED with subdominant hadronic component can work
- if proton-photons on external field, it can work even better (also OK for energetics)

IceCube-170922A / TXS 0506+056

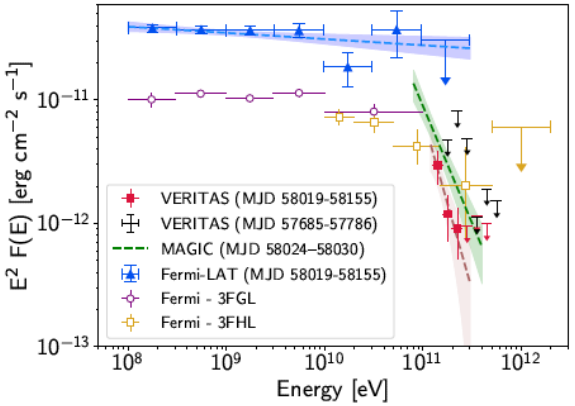
X-rays / VHE γ-rays proved to be extremely important to constrain the emission models



IceCube, Fermi, MAGIC et al. 2018



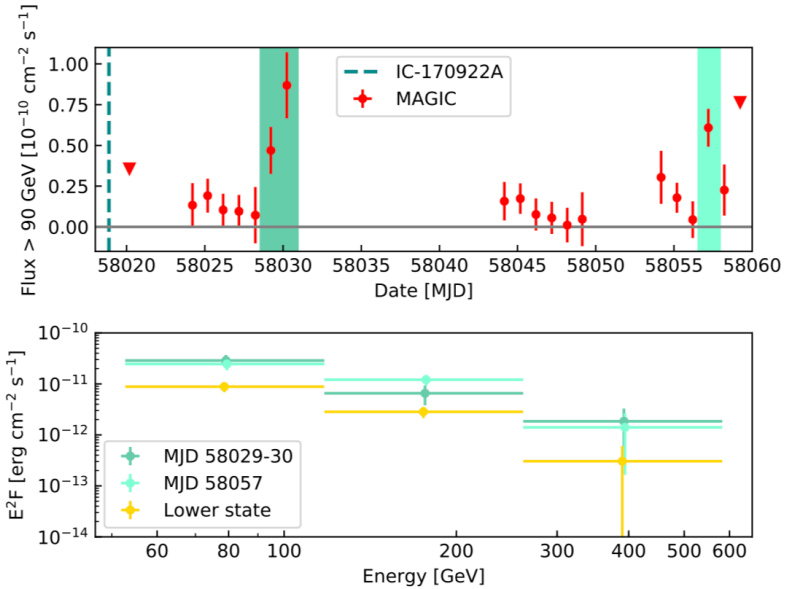
Keivani et al. 2018

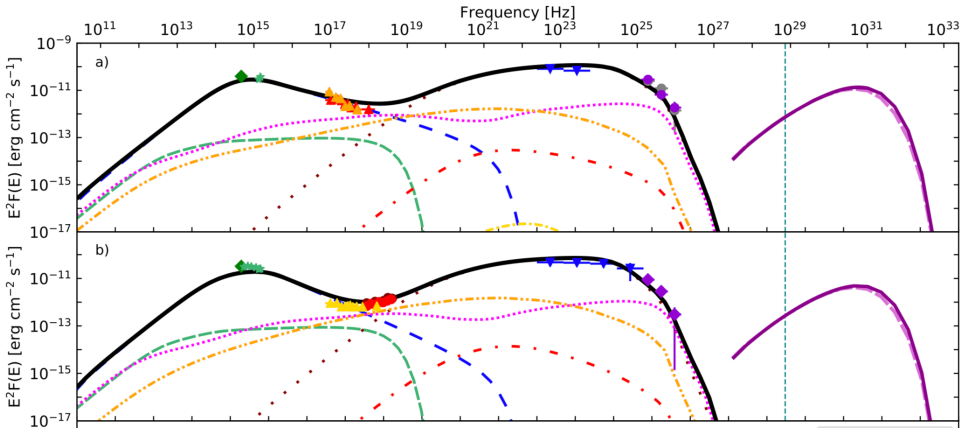


VERITAS Collaboration 2019

IceCube-170922A / TXS 0506+056

The MAGIC Collaboration reported a more extensive characterization of the VHE emission, and SED modeling

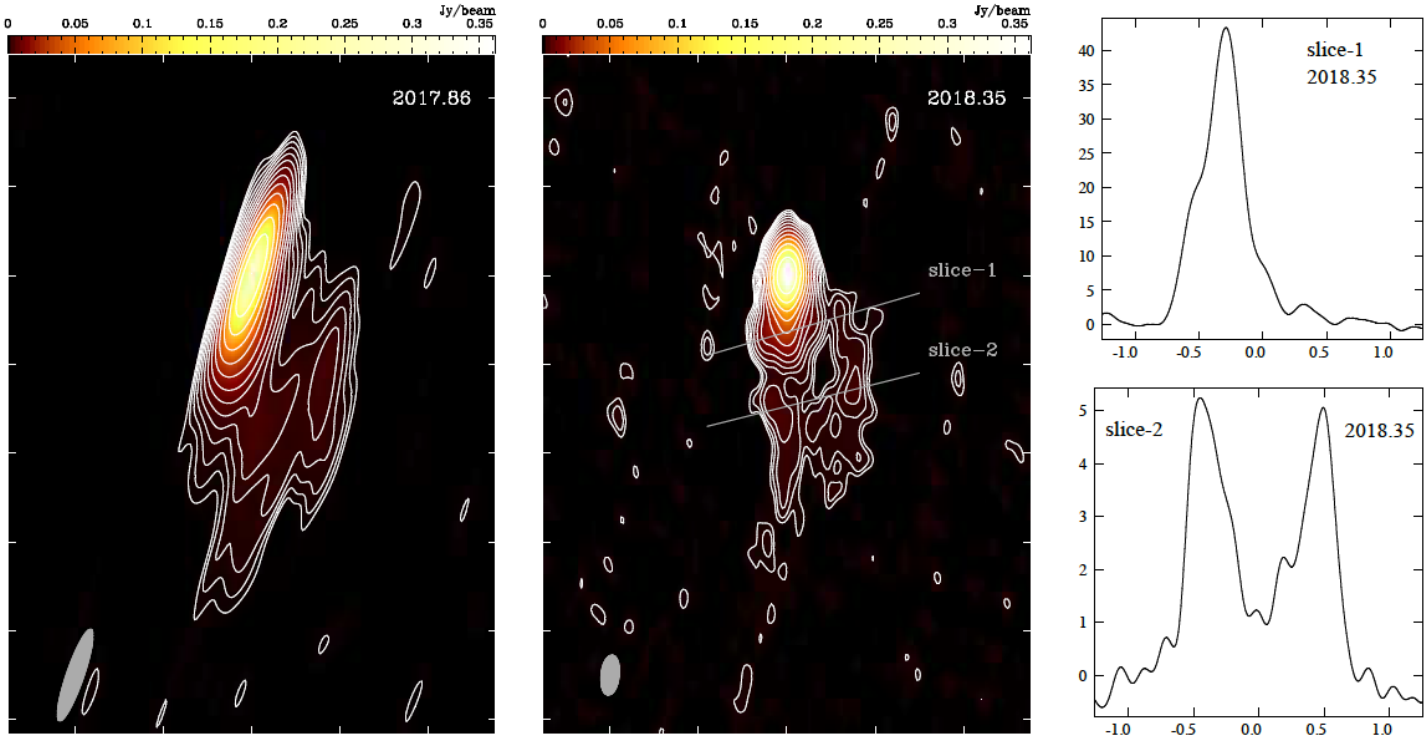




MAGIC Collaboration et al. 2018

- Favoured scenario: leptonic + subdominant hadronic component → **pure hadronic** solutions are **excluded**!
- Clear spectral curvature in VHE γ-rays, apart from EBL effect: **internal absorption**, primary particle spectral break, production inefficiency…
- Scan of $E_{p,max}$: 10^{14}-10^{18} eV (co-moving frame) → **TXS 0506+056 able to accelerate CR to UHE!**

Radio observations of TXS 0506+056

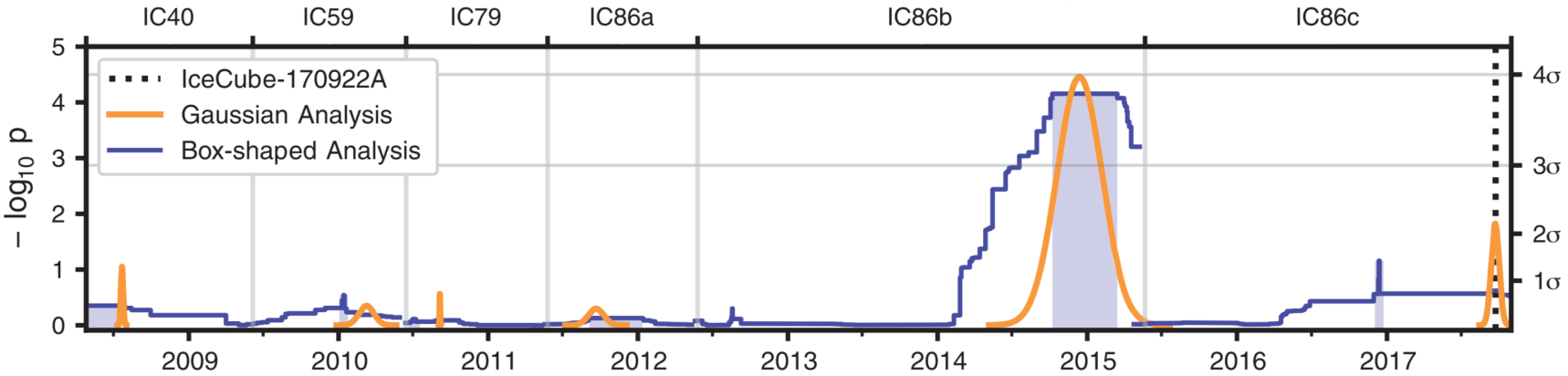


Ros et al. 2020

- The flux density of the core changes, almost doubling its value within 6 months
- A **spine-layer structure** within 1 mas from the mm-VLBI core (and an apparent limb brightening) has been detected at 43 GHz, in agreement with the production of neutrino and γ-rays due to interactions of electrons and protons in the spine with external photons originating from the layer

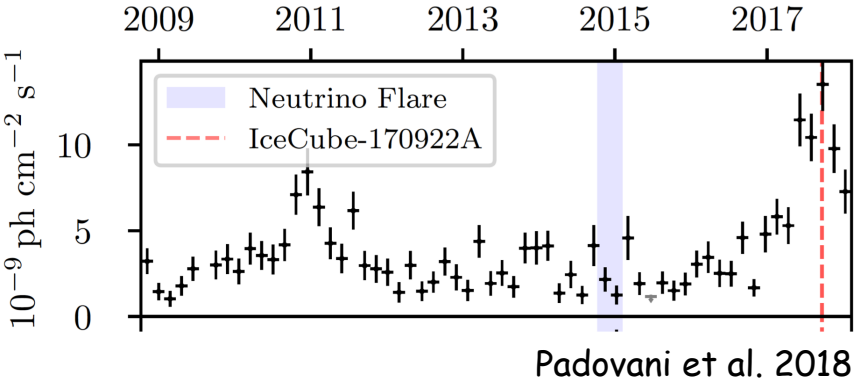
Past IceCube data of TXS 0506+056

Looking into IceCube past data: 3.5-σ evidence for neutrino emission between 2014 September and 2015 March from TXS 0506+056, independent from the 2017 event



IceCube et al. 2018b

Detection of a neutrino flare (at TeV energies) in 2014-2015 (without a γ-ray counterpart)



Padovani et al. 2018

Only a sparse multi-wavelength coverage of TXS 0506+056 in 2014-2015

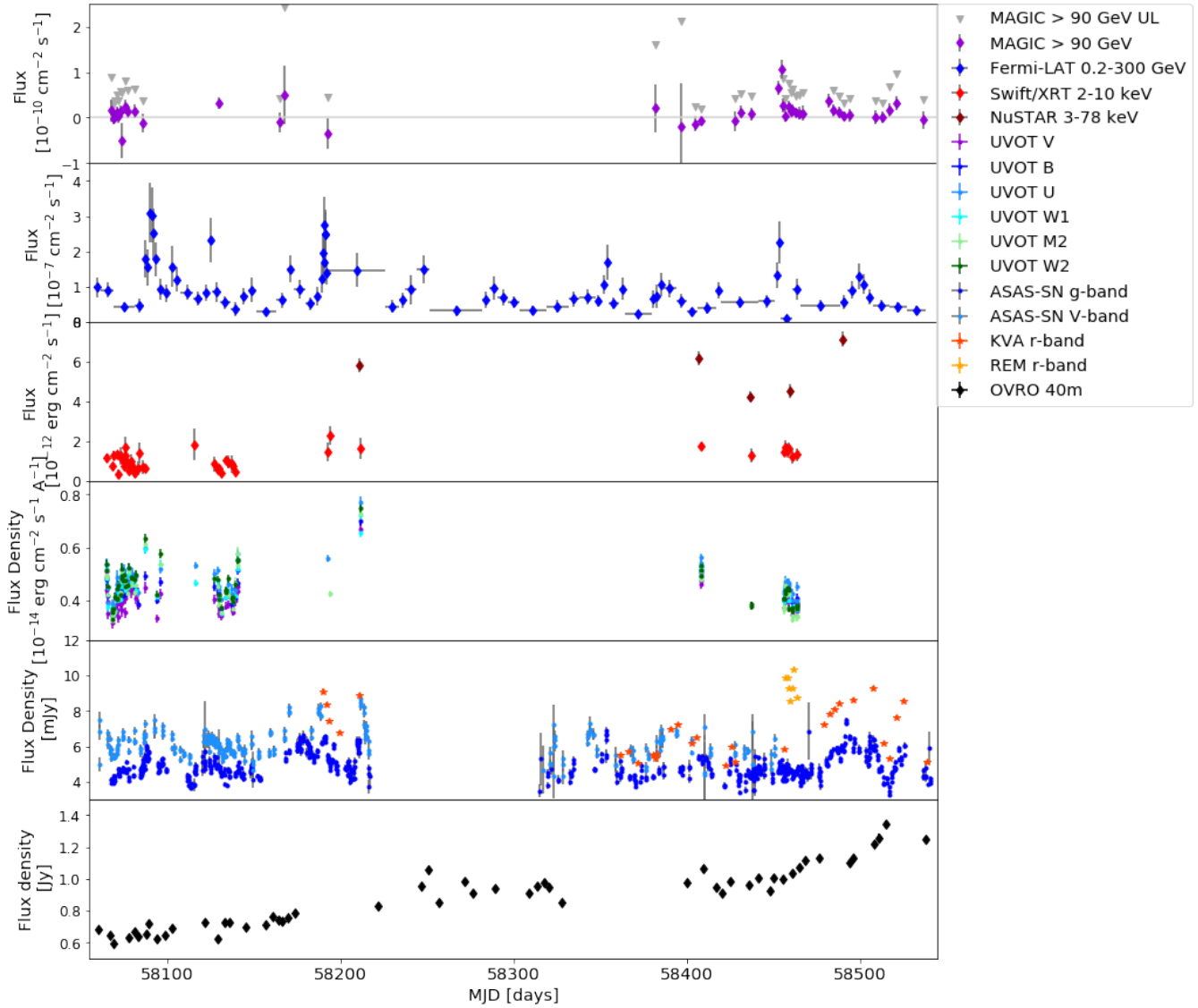
TXS 0506+056

Why a new MWL campaign?

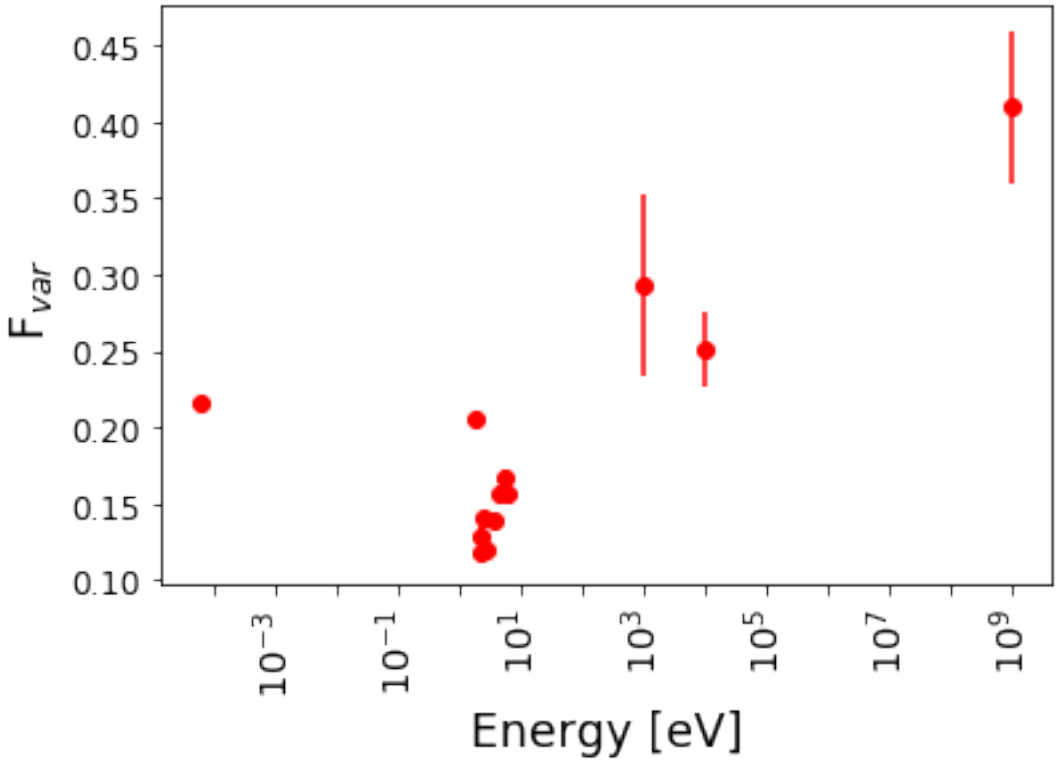
The 2017 MWL campaign following the neutrino event was the first and only detailed MWL study on the source

- **Dedicated MWL monitoring program:** collect a long-term data sample of TXS 0506+056
- From 2017 November to 2019 February: **MAGIC collected 79 hr of data**
- **2018 December 1 and 3**: enhanced VHE emission observed (ATel #12260), comparable to the 2017 flare; neutrino flux UL available
- Detailed SED modeling in frame of a lepto-hadronic model

MWL light curves during 2017-2019

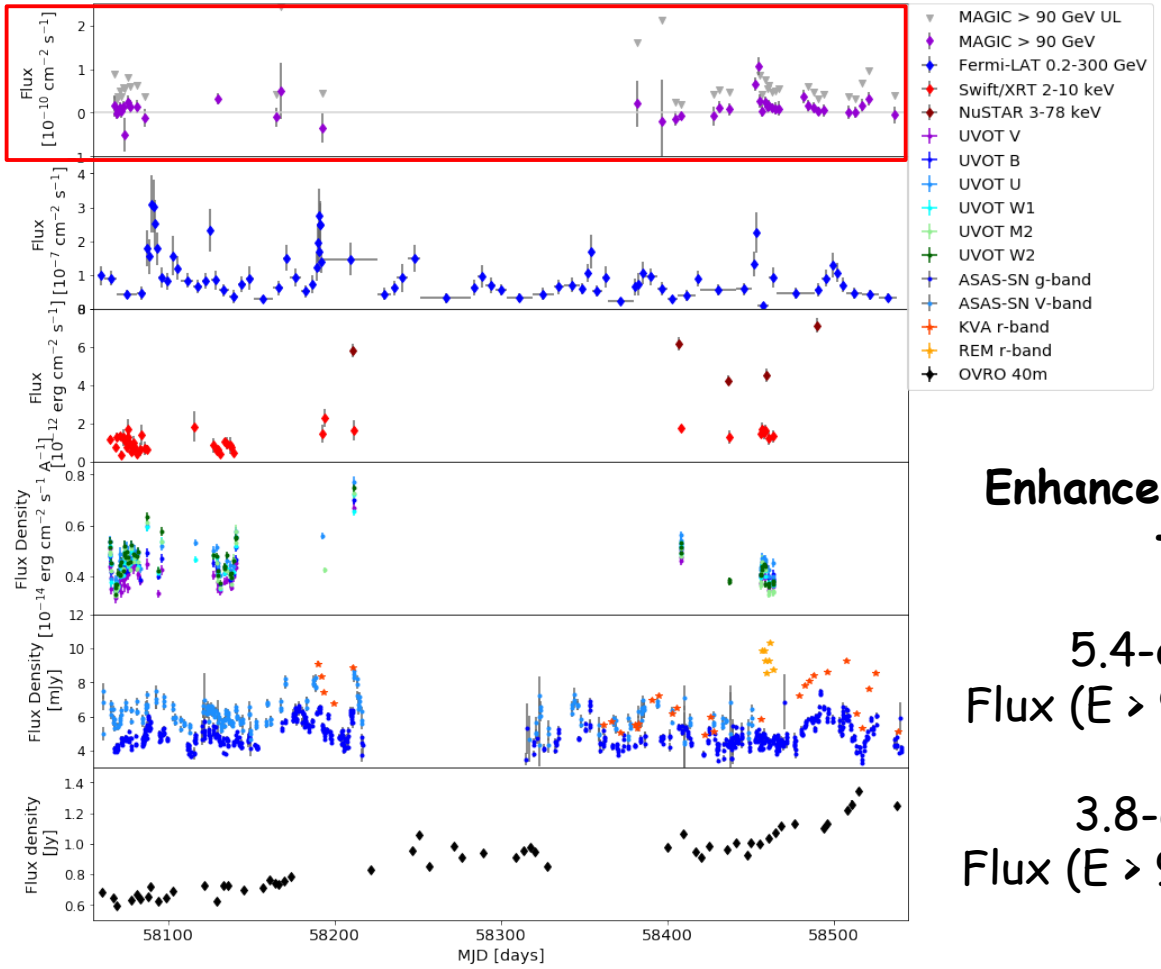


Fractional Variability



- The most pronounced variability is observed in the X-ray and γ-ray bands, in particular at HE γ-rays
- The radio and optical bands display a moderate variability

MWL light curves during 2017-2019



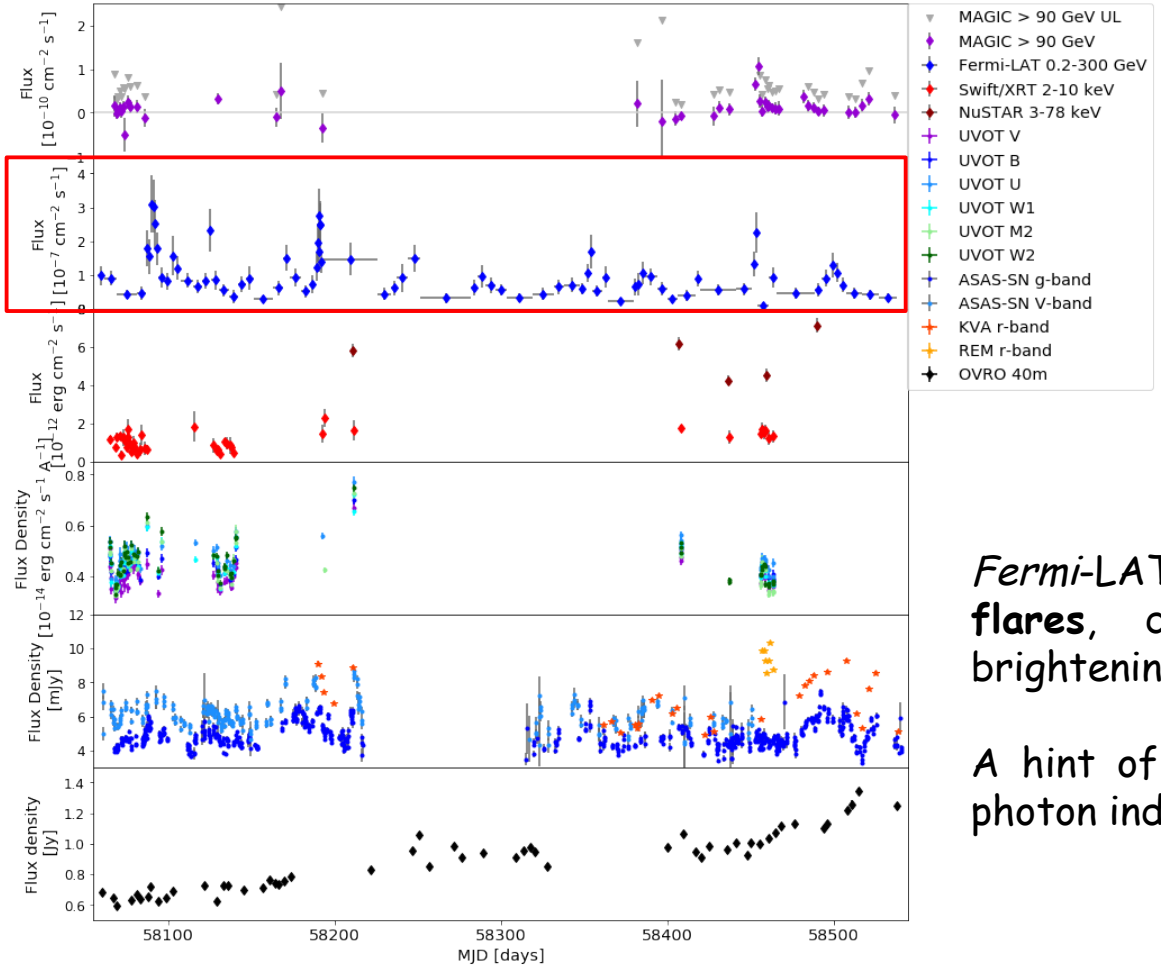
Enhanced activity observed at VHE in two nights by MAGIC:

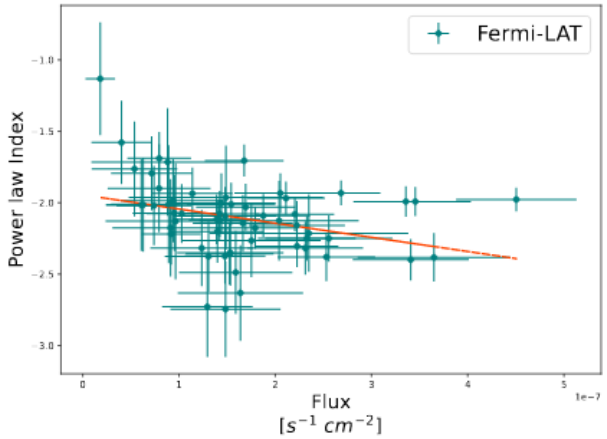
5.4-σ detection on 2018 Dec 3,
Flux (E > 90 GeV) = $(6.5\pm1.5)\times10^{-11}$ cm^{-2} s^{-1}

3.8-σ detection on 2018 Dec 1,
Flux (E > 90 GeV) = $(10.6\pm2.1)\times10^{-11}$ cm^{-2} s^{-1}

Low state detection at 4-σ, Flux (E > 90 GeV) = $(1.0\pm0.5)\times10^{-11}$ cm^{-2} s^{-1}

MWL light curves during 2017-2019

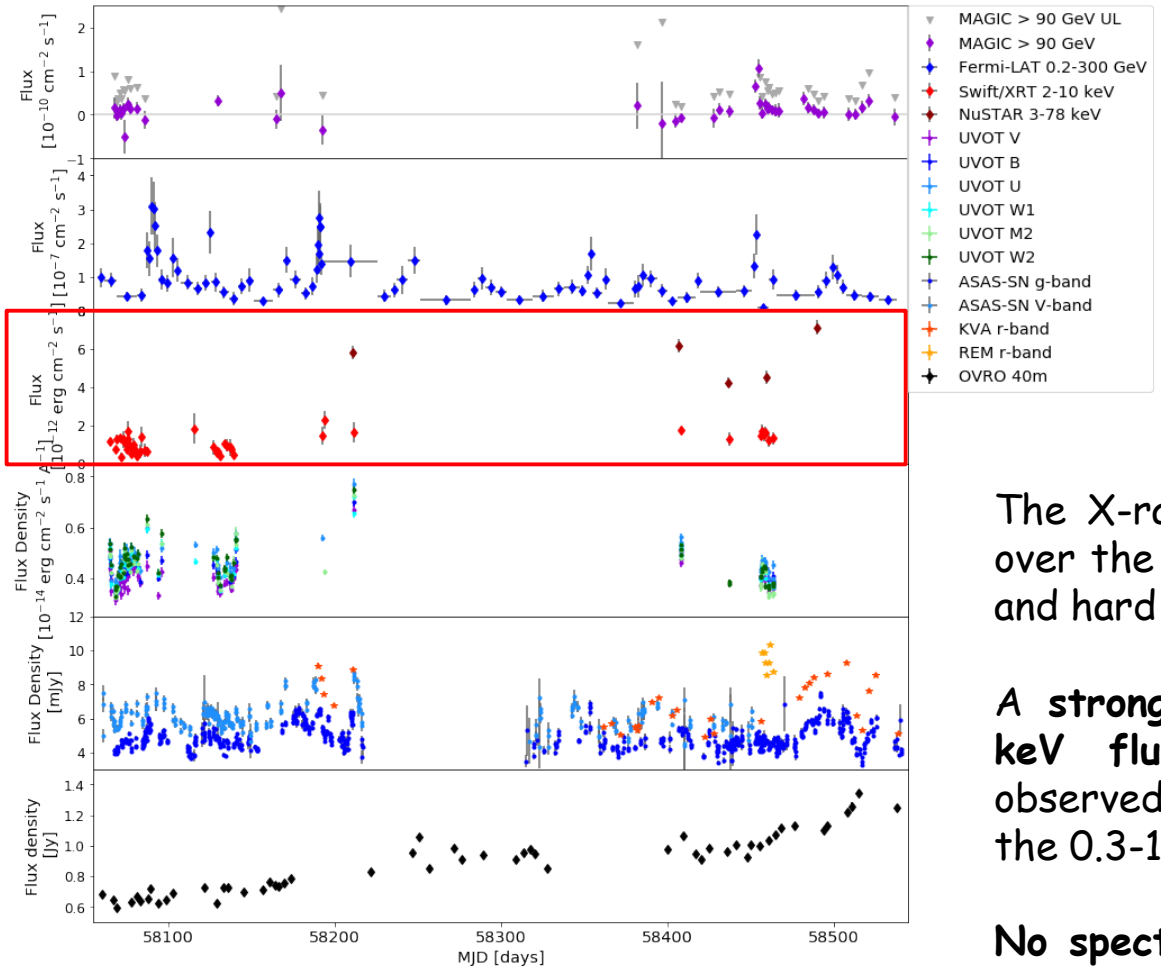


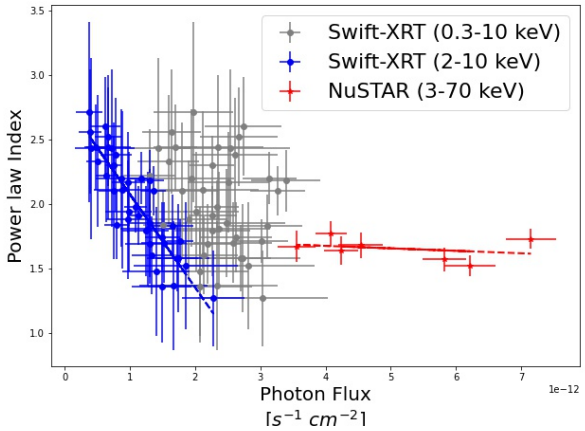


Fermi-LAT observations show **several short flares**, differently from the long-term brightening observed in 2017.

A hint of anti-correlation between flux and photon index has been observed at HE γ-rays.

MWL light curves during 2017-2019



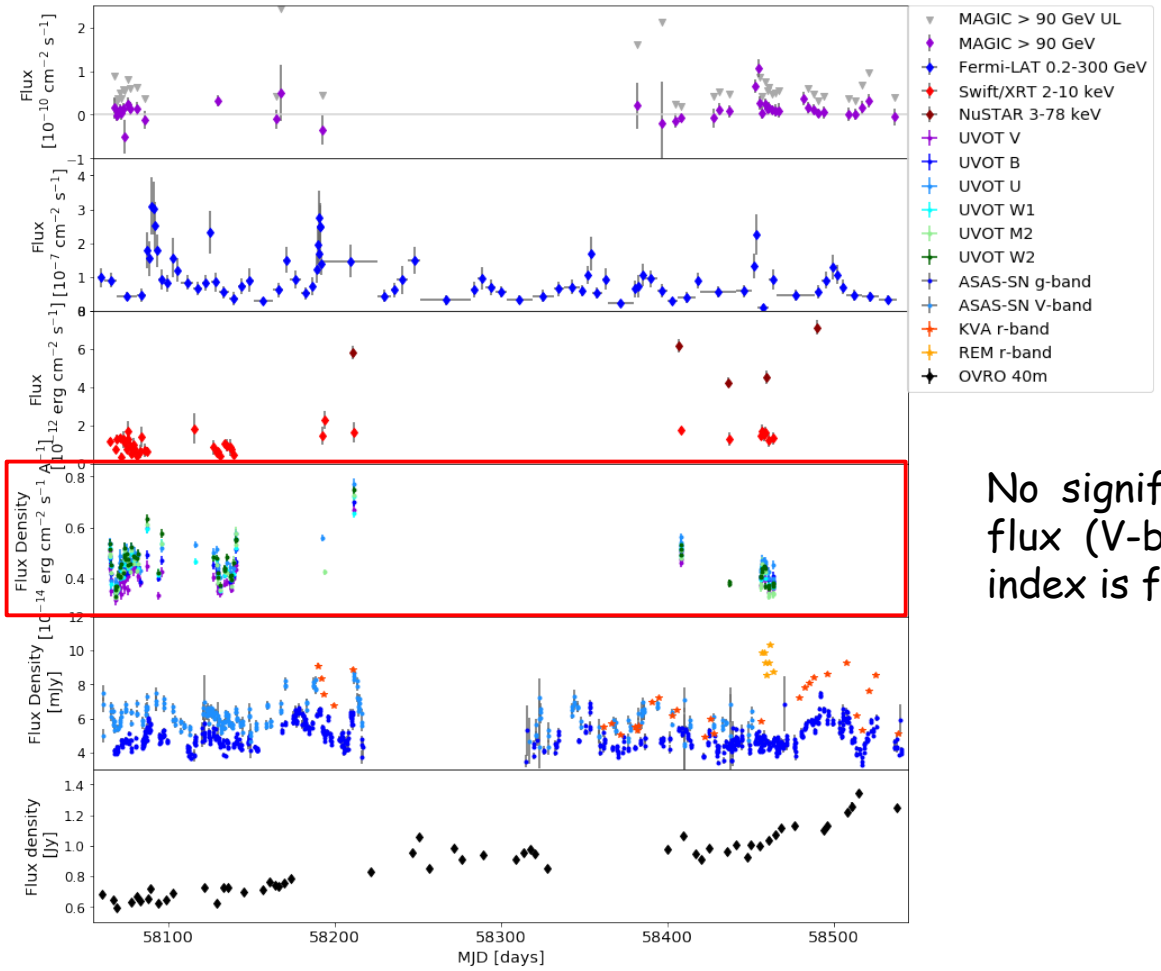


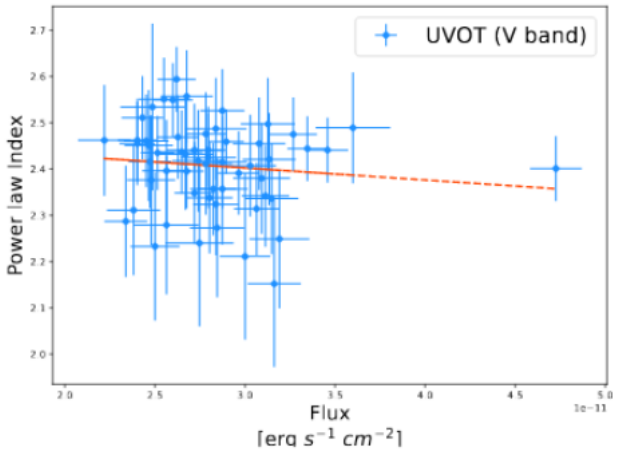
The X-ray flux changed by a factor of 2 over the monitoring period in both the soft and hard X-ray energy ranges.

A **strong anti-correlation between 2-10 keV flux** and photon index has been observed by ***Swift*-XRT**, not confirmed if the 0.3-10 keV flux is taken into account.

No spectral variability is observed in hard X-rays with ***NuSTAR*** data.

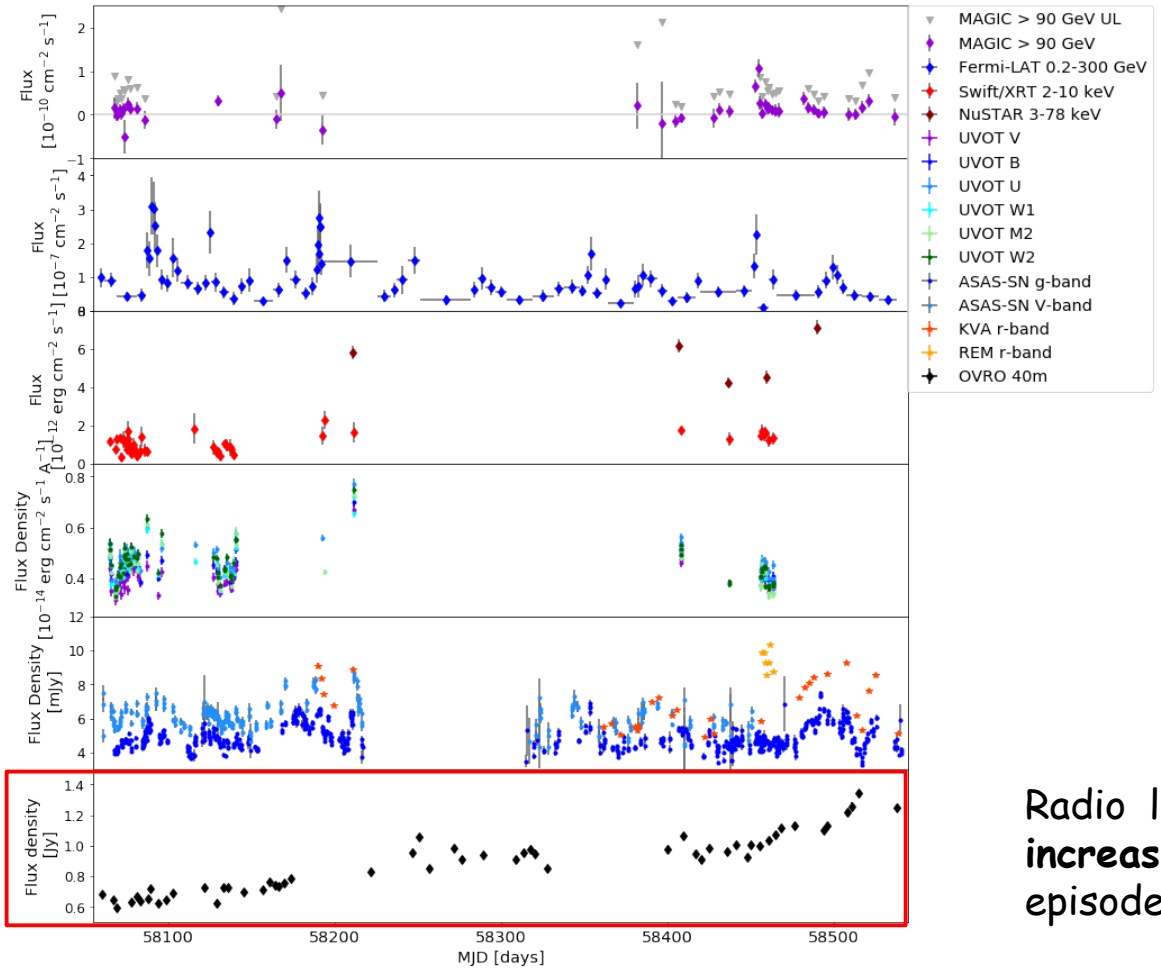
MWL light curves during 2017-2019





No significant correlation between optical flux (V-band) and the optical-UV spectral index is found using *Swift*-UVOT data

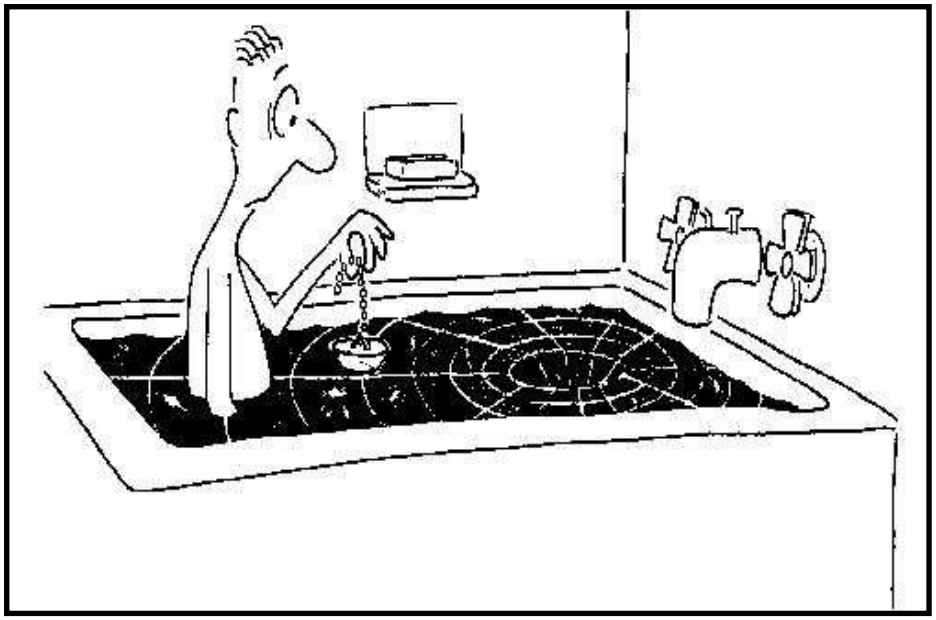
MWL light curves during 2017-2019



Radio light curve at 15 GHz shows an **increasing trend** with super-imposed episodes of relatively rapid variability.

Summary

- TXS 0506+056 was a poorly studied object before its association with the emission of a high-energy neutrino observed by IceCube in 2017
- The MAGIC Collaboration organized a multi-wavelength campaign lasting 16 months (from 2017 November to 2019 February), covering the radio-band (OVRO), the optical/UV (ASAS-SN, KVA, REM, *Swift*/UVOT), the X-rays (*Swift*/XRT, *NuSTAR*), the high-energy γ-rays (*Fermi*-LAT) and the very-high-energy γ-rays (MAGIC)
- New VHE flares detected by MAGIC on 2018 December 1 and 3, and a 4-σ detection in the low-state
- *Fermi*-LAT observations show several short flares, differently from the long-term brightening observed in 2017
- No significant flares are detected in optical, UV, and X-rays. The radio light curve at 15 GHz shows an increasing flux trend over the period with episodes of rapid variability
- Detailed SED modelling is ongoing
- *The MWL campaign still continues and we have data up to 2021 February*



Thanks for your attention!