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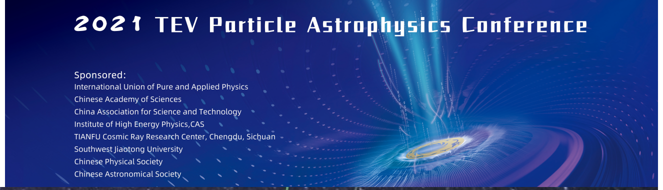

Unveiling the complex correlation patterns and emission mechanisms in Mrk 421

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David Paneque, Lea Heckmann
for the MAGIC, FACT and *Fermi*-LAT Collaborations and multiwavelength collaborators

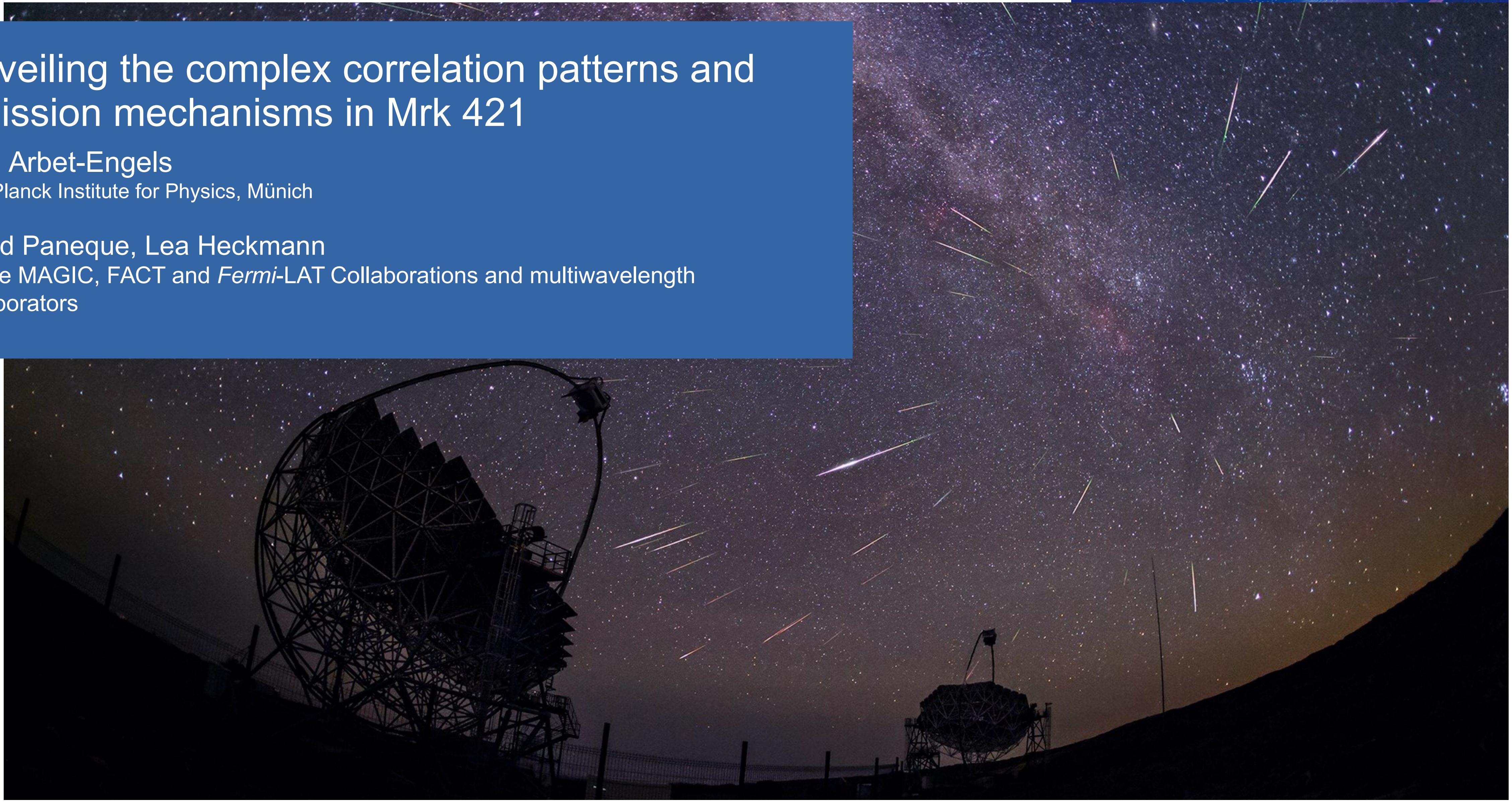
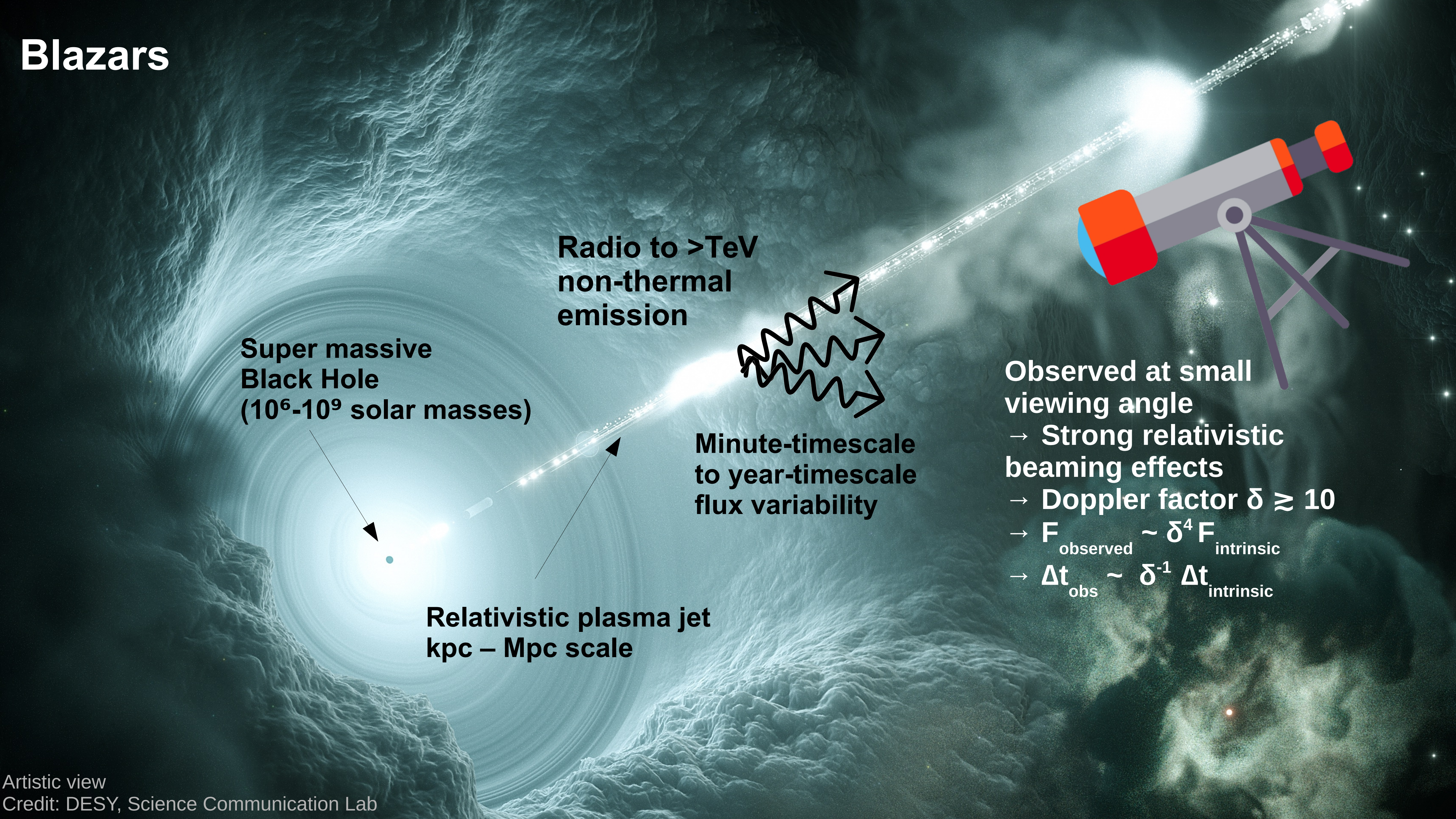


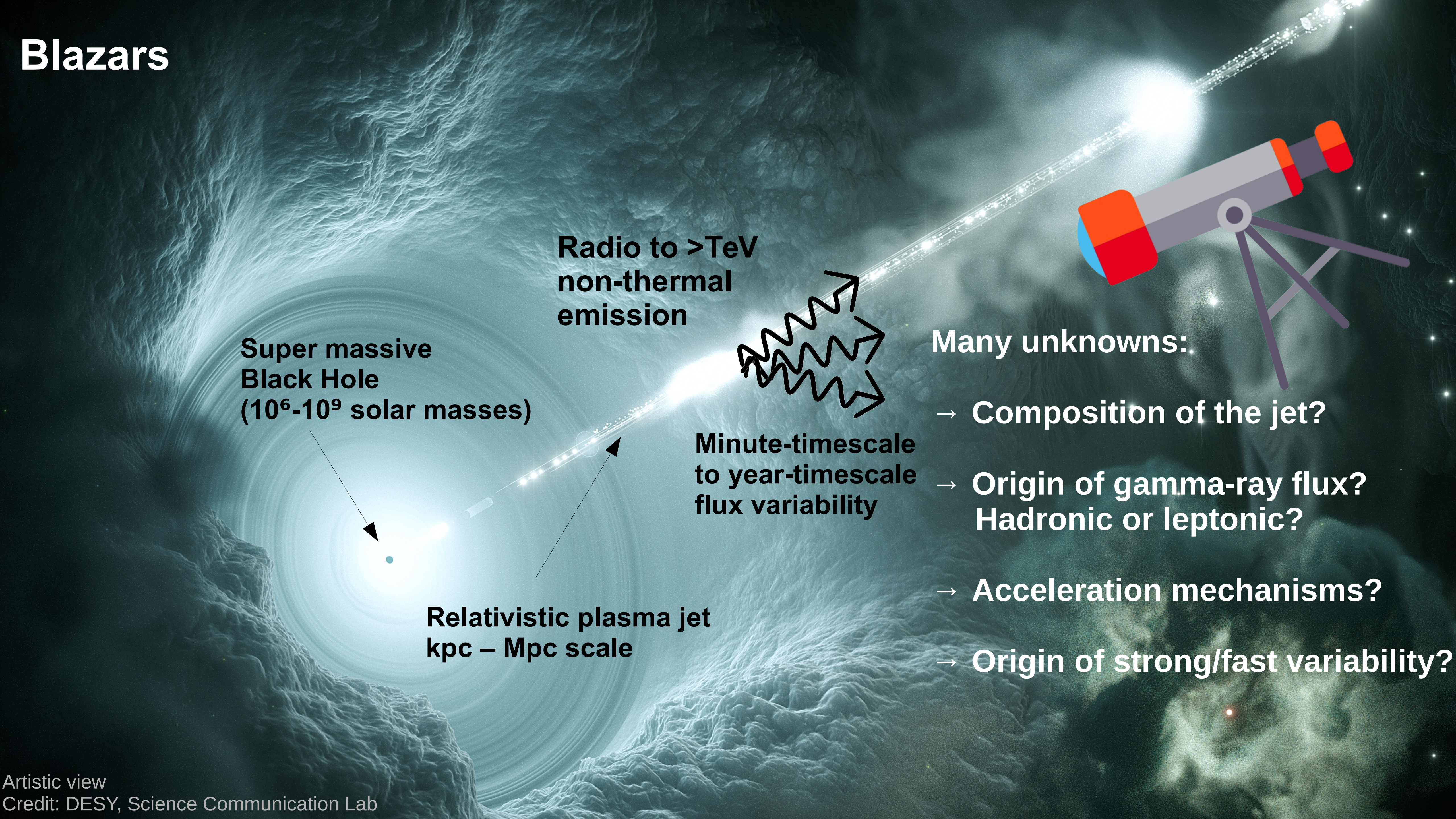
Image credits: Daniel Lopez

Blazars



Artistic view
Credit: DESY, Science Communication Lab

Blazars



Many unknowns:

→ Composition of the jet?

→ Origin of gamma-ray flux?
Hadronic or leptonic?

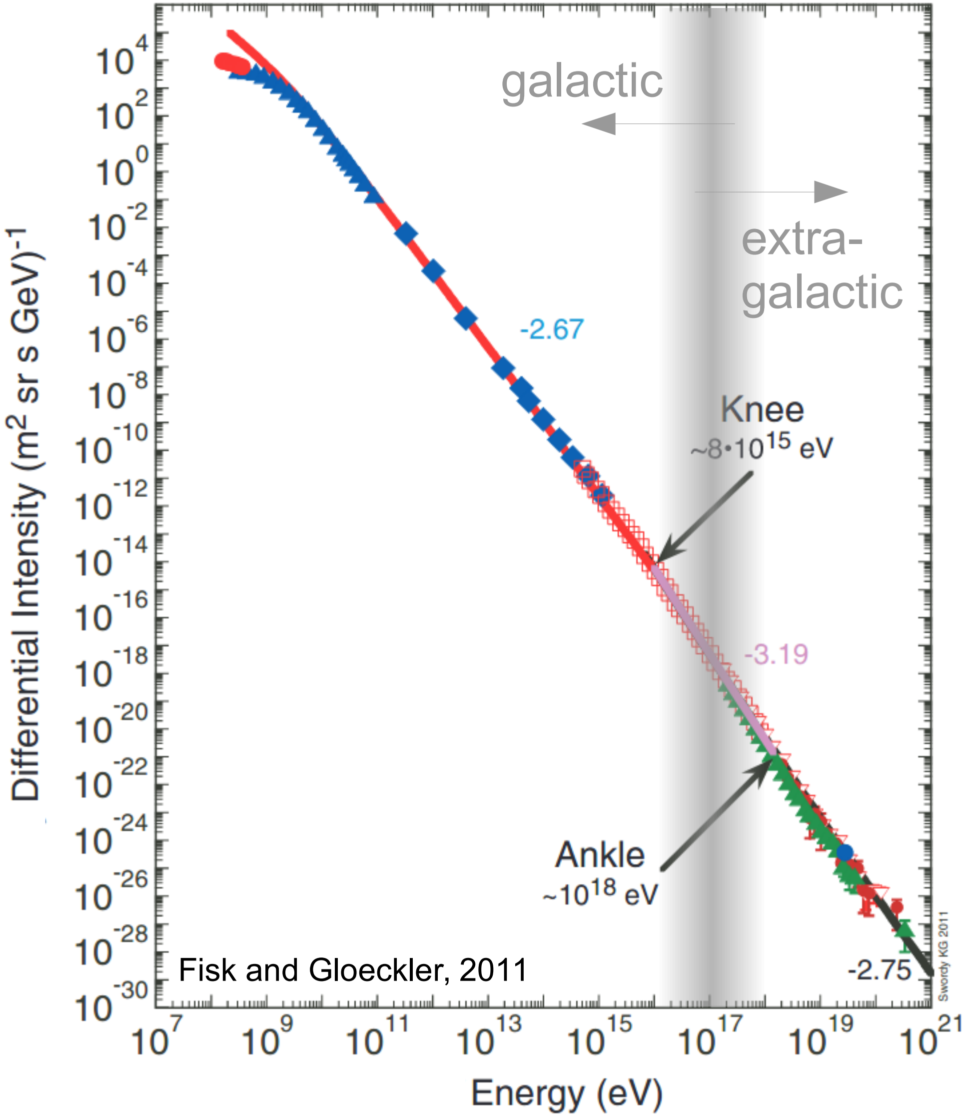
→ Acceleration mechanisms?

→ Origin of strong/fast variability?

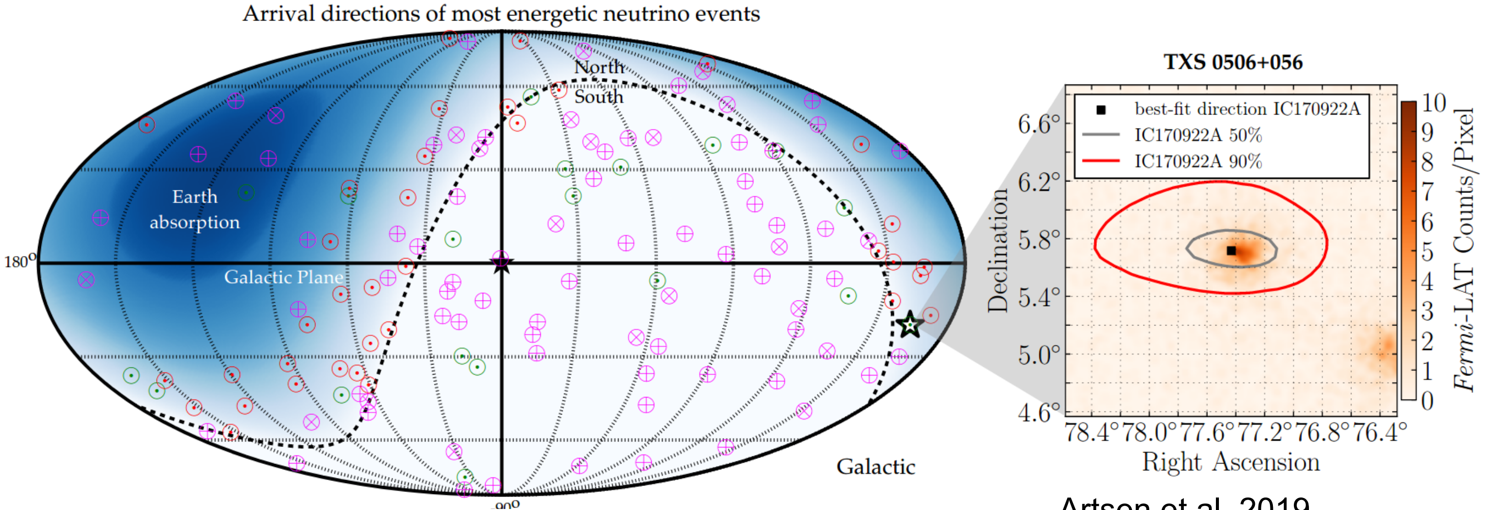
Artistic view
Credit: DESY, Science Communication Lab

Blazars

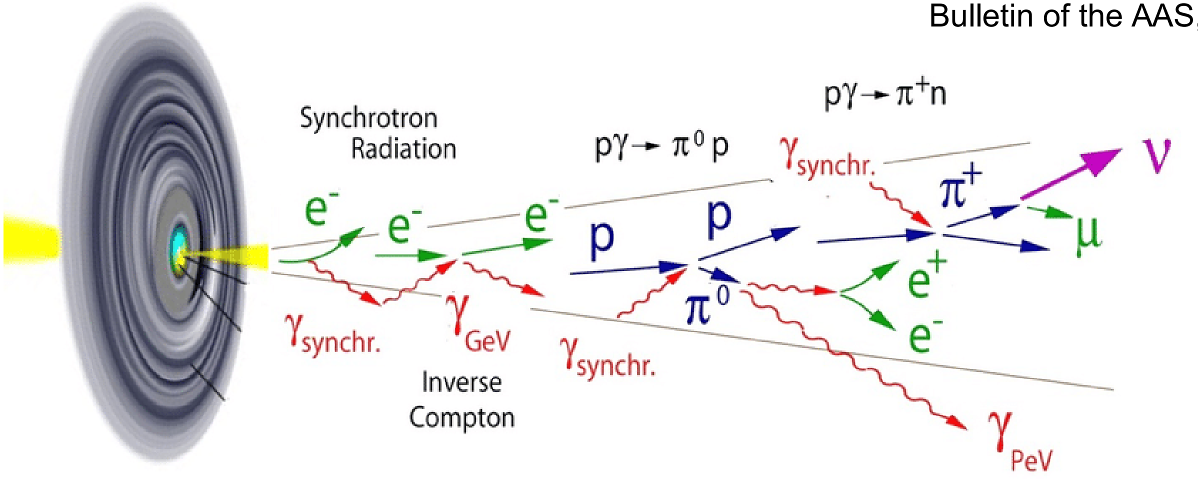
Sources of >10^{18} eV cosmic rays?



Sources of PeV neutrinos ?



Artsen et al. 2019,
Bulletin of the AAS, 51(7)

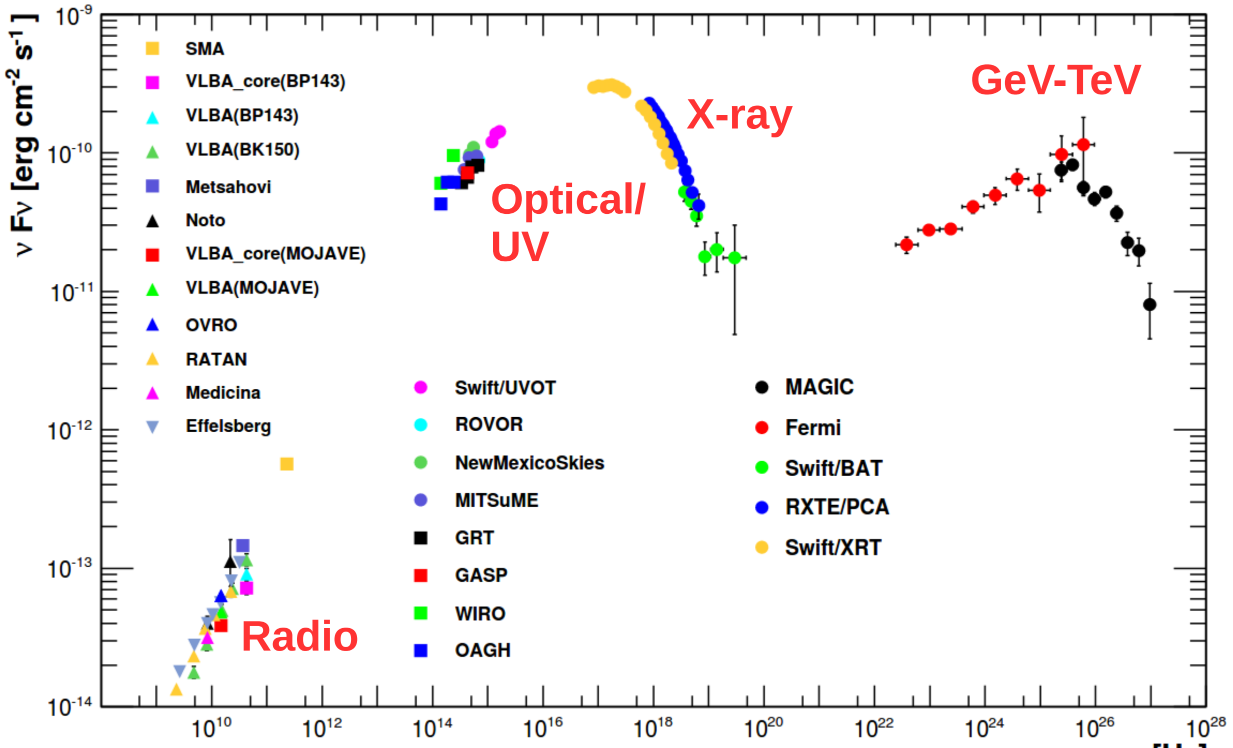


Credits:M. Spurio'14

The blazar Markarian 421 (Mrk 421)

- **Bright** and **nearby** blazar (redshift 0.031)

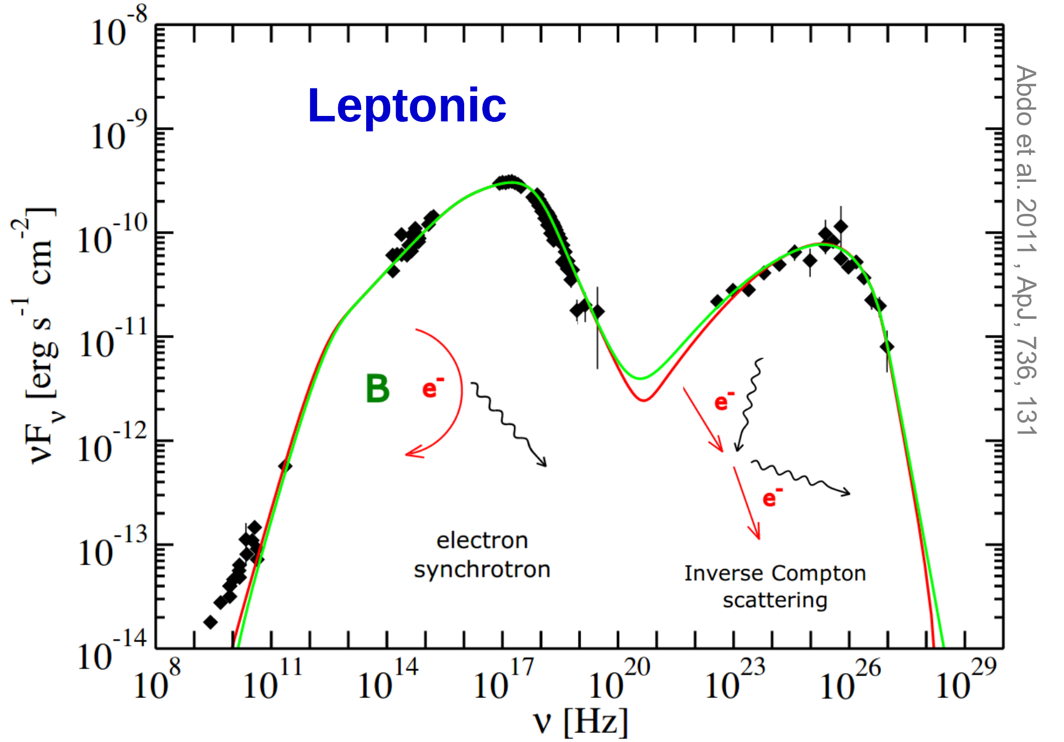
- Easily detectable during low & high states
  → **Ideal to probe acceleration & emission processes in blazar jets**

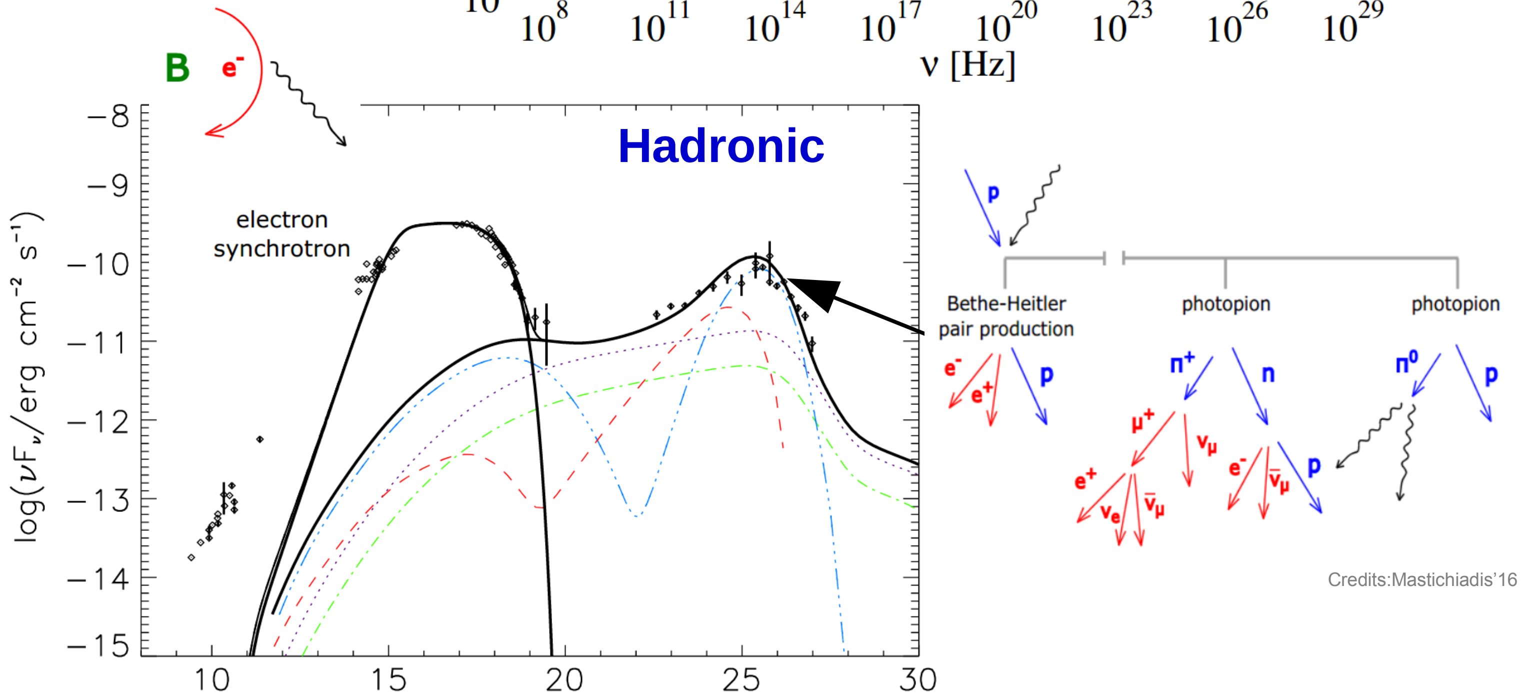


Abdo et al. 2011 , ApJ, 736, 131

The blazar Mrk 421

- **Bright** and **nearby** blazar (redshift 0.031)
- Easily detectable during low & high states
  → **Ideal to probe acceleration & emission processes in blazar jets**
- Measured broadband SED can be produced by **leptonic** & **hadronic** scenarios
- Constraining models only possible via **dense & simultaneous MWL observations** that exploit the temporal evolution of the broadband emission





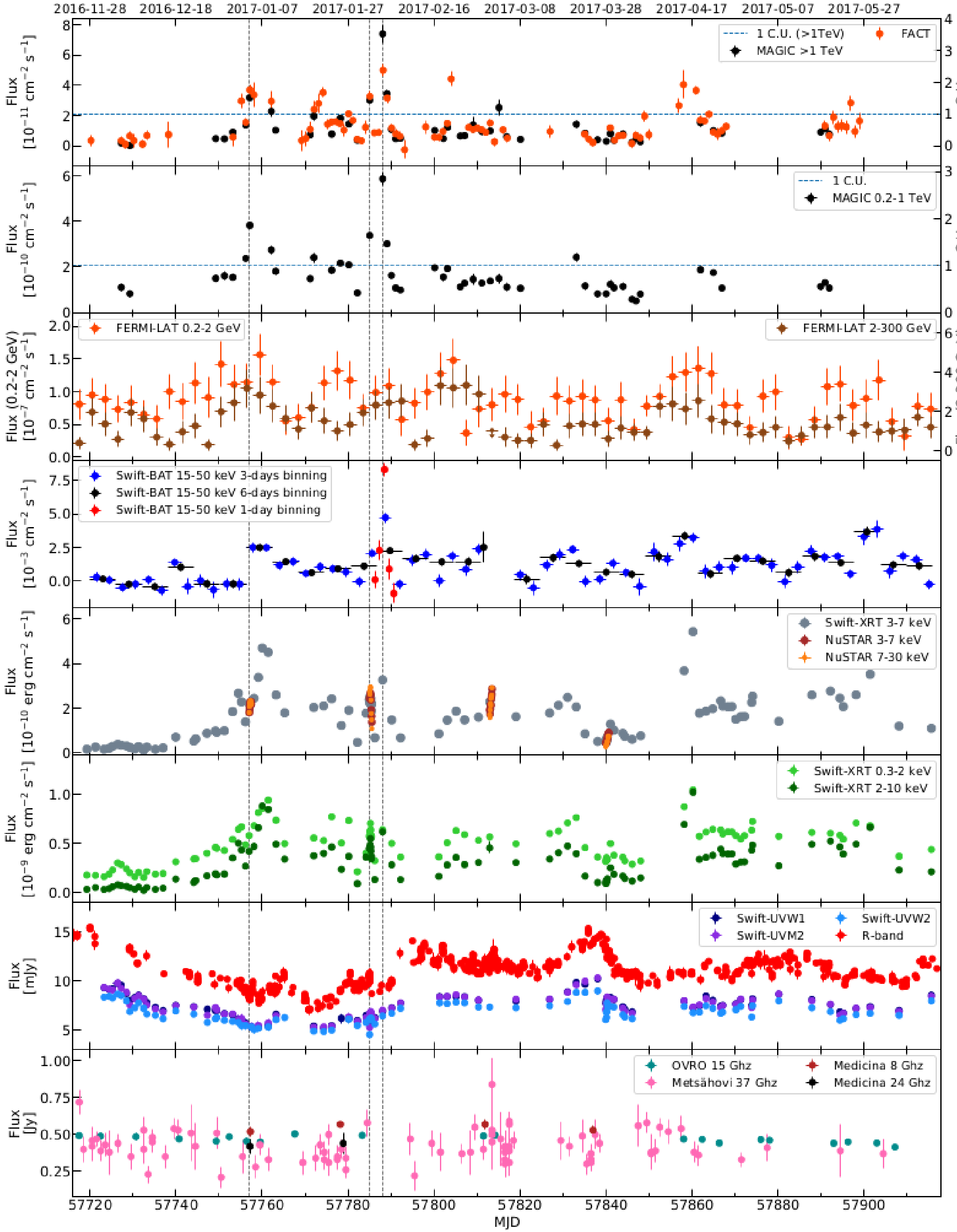
Abdo et al. 2011 , ApJ, 736, 131

Multi-wavelength observations in 2017

- ~7-month multi-wavelength campaign
- Dense temporal coverage
- Radio to VHE (E>100GeV) observations
- 4 long *NuSTAR* observations simultaneous to MAGIC

→ **Excellent dataset to probe intra-band correlations and spectral evolutions**

MAGIC Collaboration et al., 2021, arXiv:2106.05516



MAGIC
>1TeV
FACT
>0.95TeV
(1-day bin)

MAGIC
0.2-1TeV
(1-day bin)

Fermi-LAT
0.3-2GeV
2-300GeV
(3-day bin)

X-ray
15-50keV
(1,3,6-day bin)

X-ray
3-7keV
7-30keV
(1-day bin and 1.5hr-bin)

X-ray
0.3-2keV
2-10keV
(1-day bin)

Optical/UV
(1-day bin)

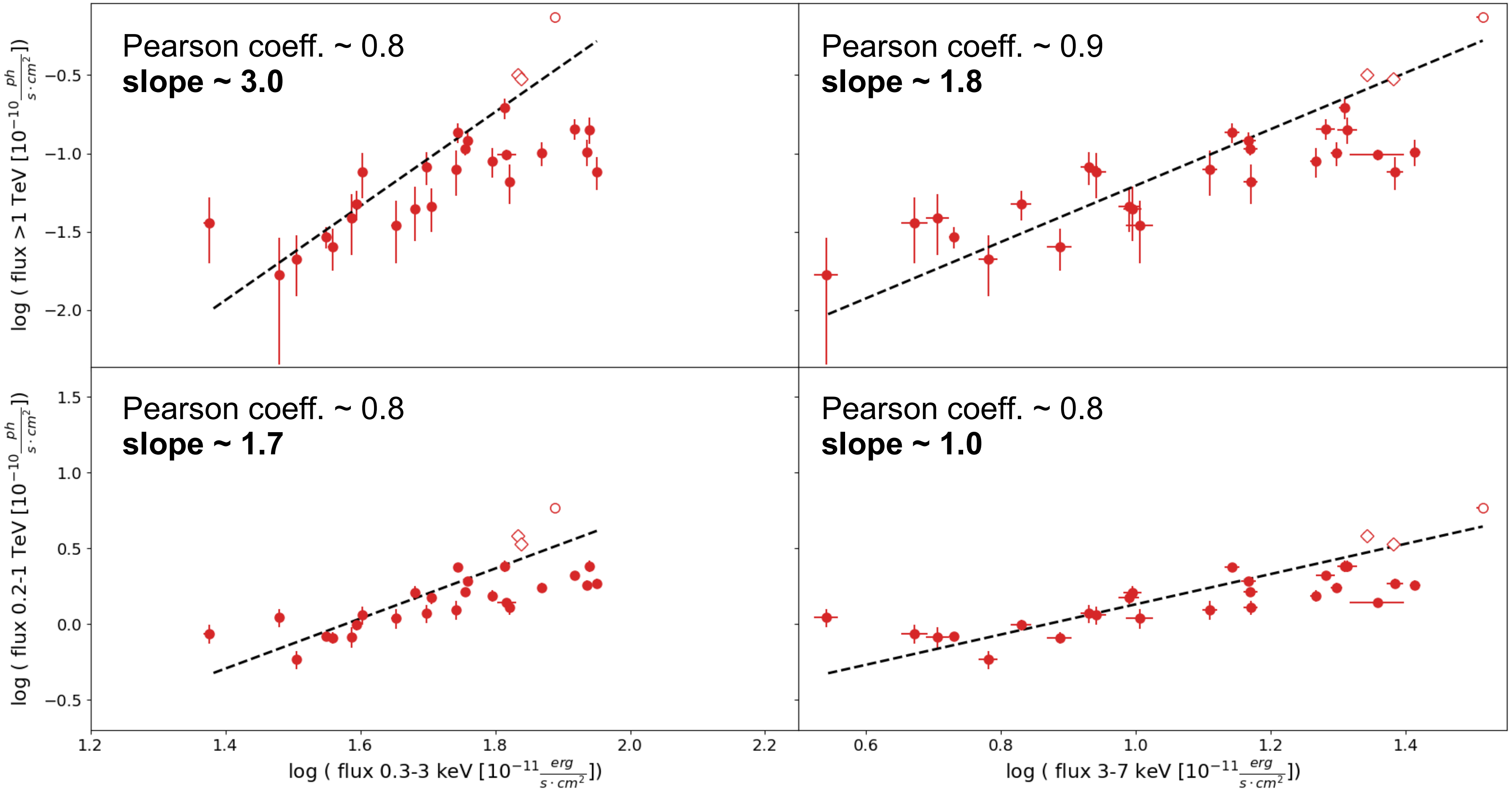
Radio
(1-day bin)

VHE gamma-ray versus X-ray correlation – full campaign

VHE

>1 TeV

0.2-1 TeV



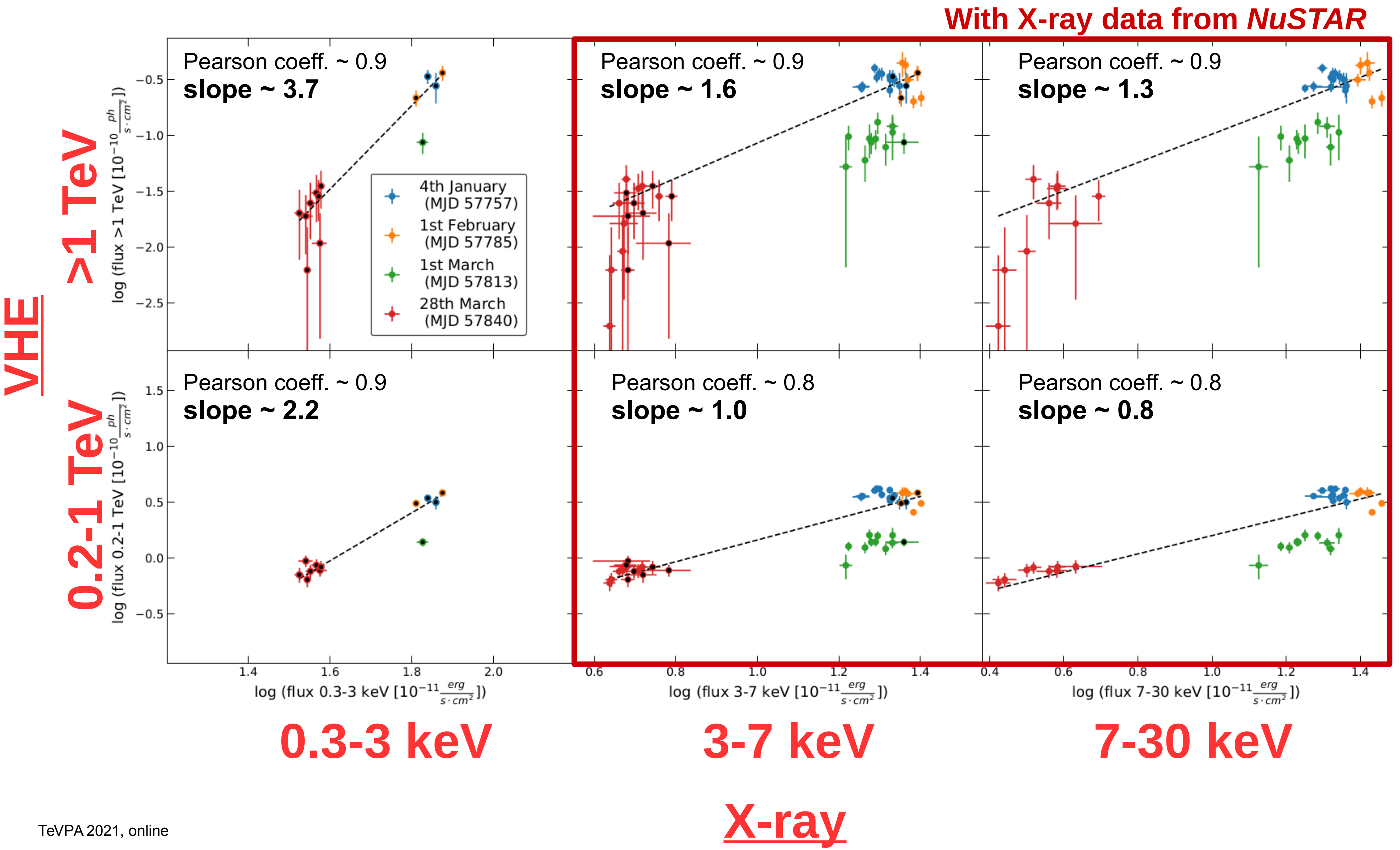
0.3-3 keV

3-7 keV

X-ray

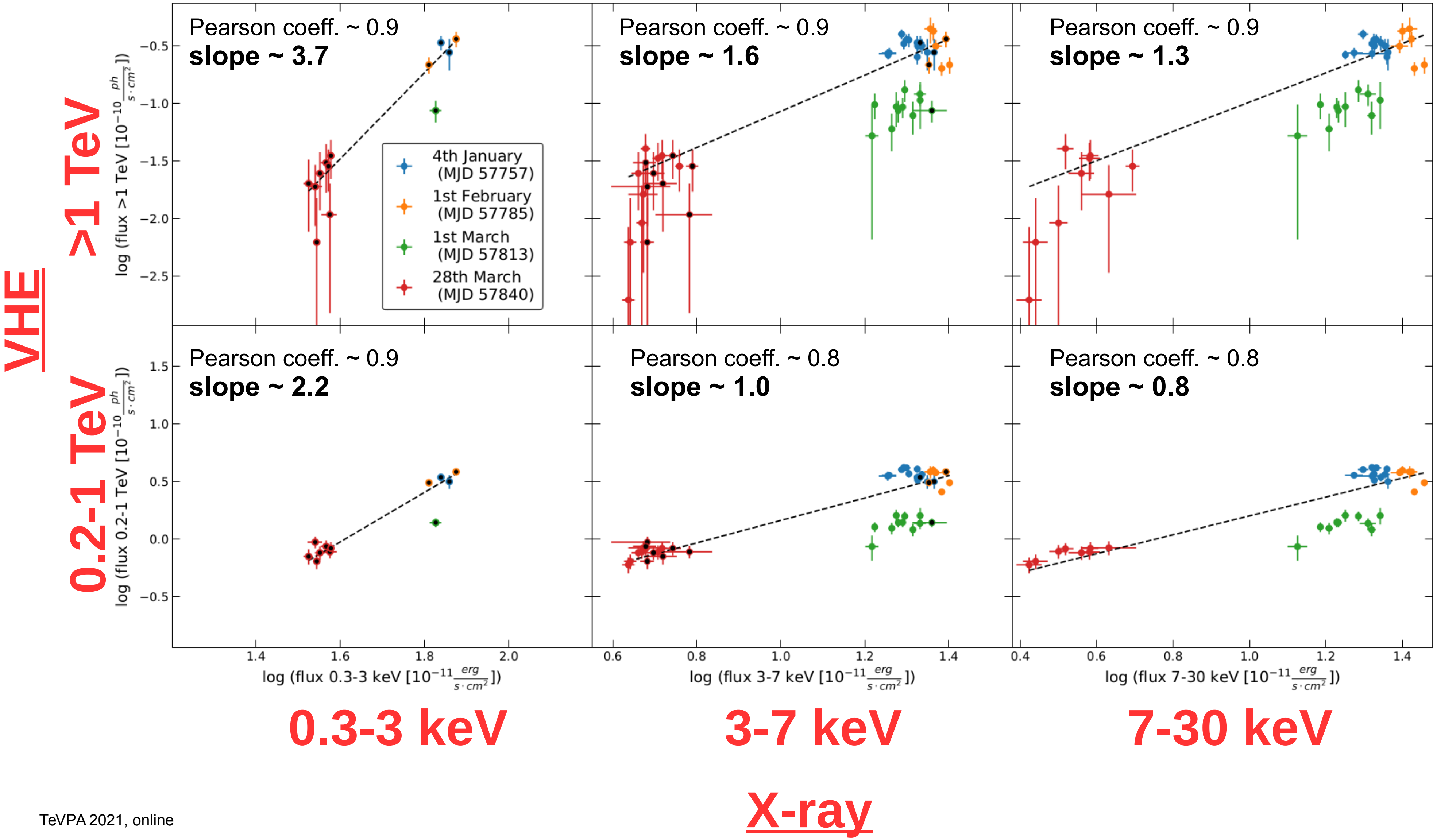
- Strong correlation
  → **Agrees with leptonic models**
- Slope varies significantly
  → **Complex behaviour**
- Clear energy dependence
  → **No Single X-ray/VHE correlation type**

VHE gamma-ray versus X-ray correlation – MAGIC/*NuSTAR* observations



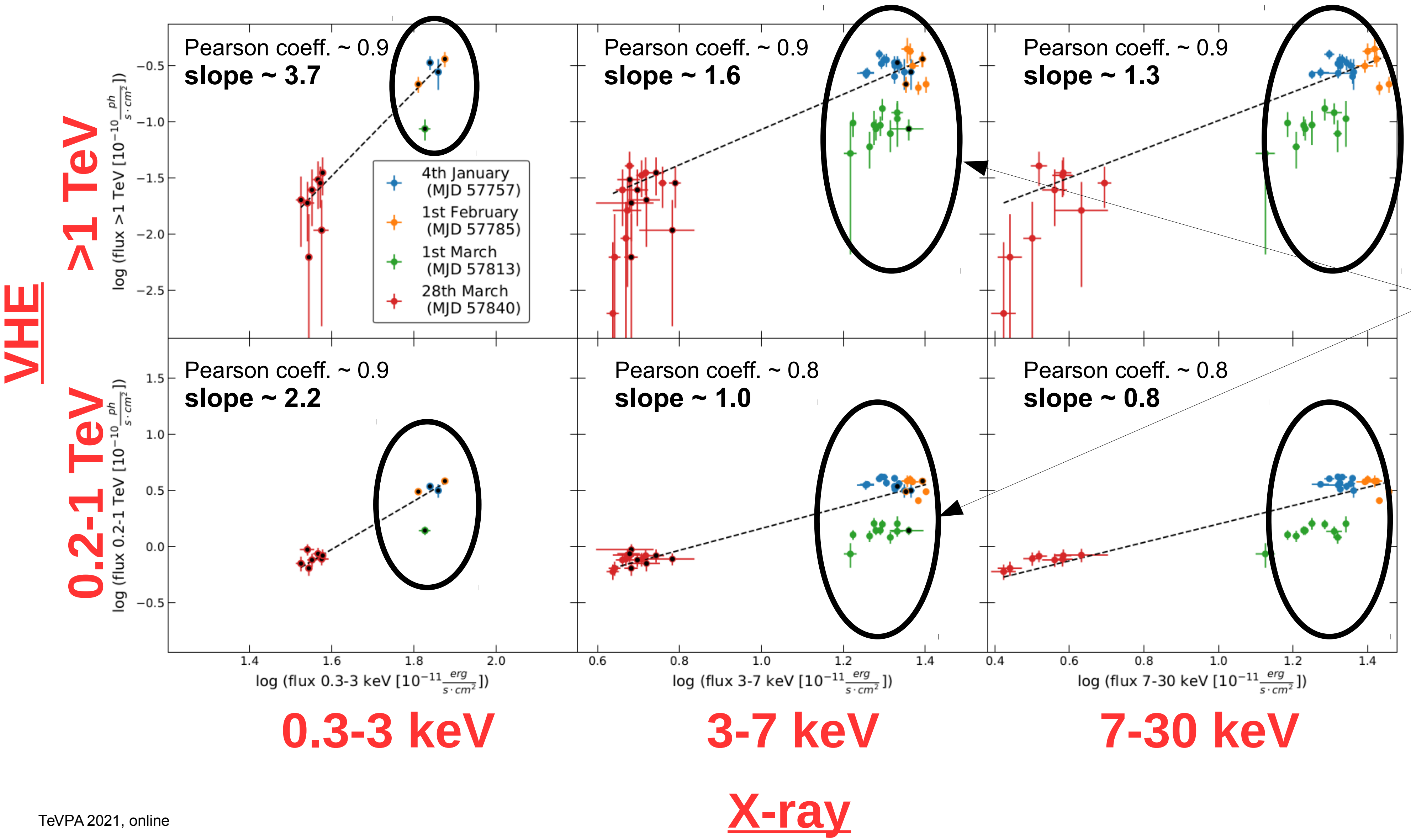
- VHE/X-ray correlations in various sub-energy bands **up to hard X-rays (i.e., > 10keV)**

VHE gamma-ray versus X-ray correlation – MAGIC/*NuSTAR* observations



- VHE/X-ray correlations in various sub-energy bands **up to hard X-rays (i.e., > 10keV)**
- **Sub-linear to more-than-cubic relations**
- >1TeV flux shows stronger scaling with the X-rays than the 0.2-1TeV flux

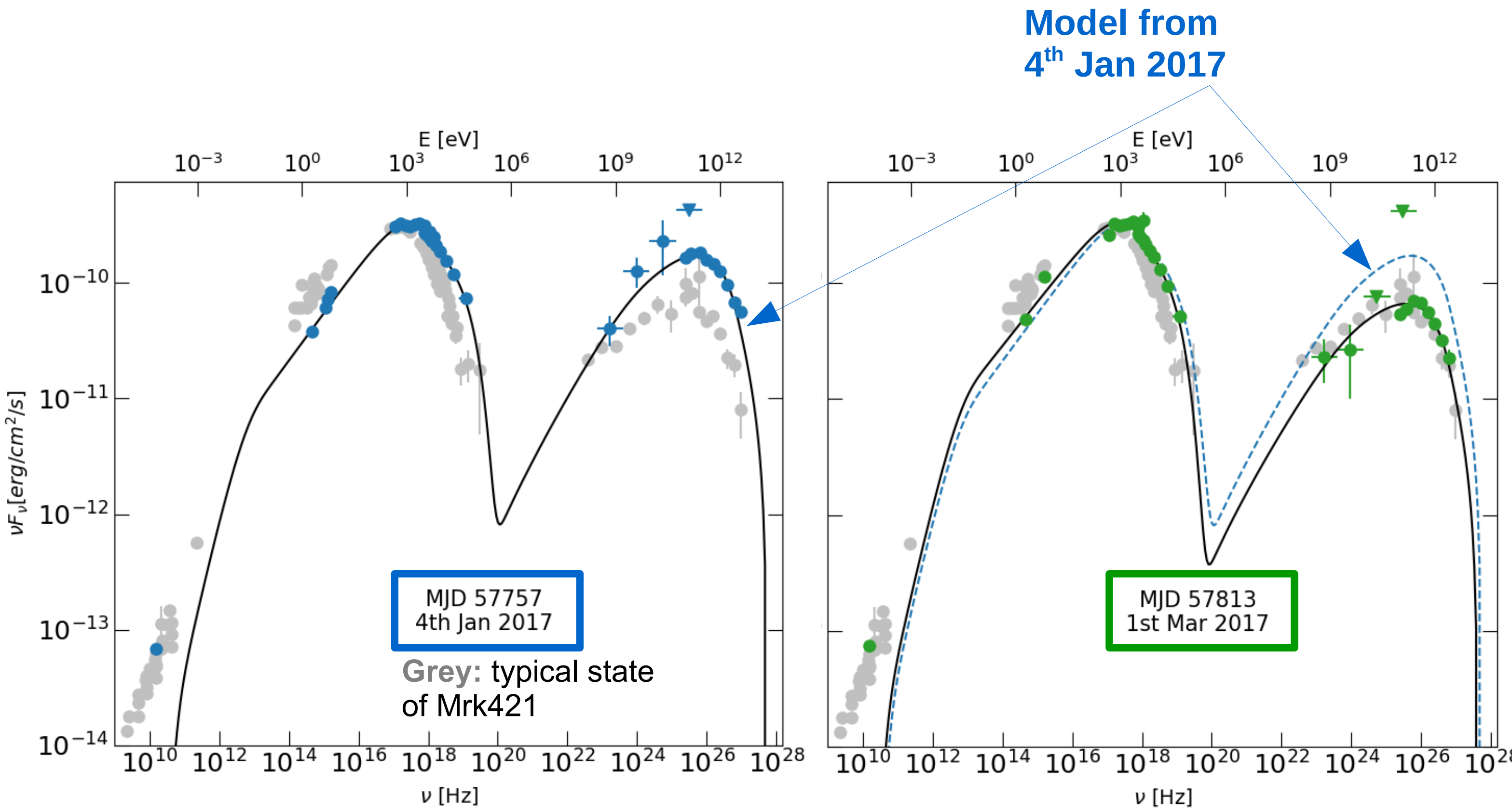
VHE gamma-ray versus X-ray correlation – MAGIC/*NuSTAR* observations



VHE flux change without X-ray counterpart?

VHE gamma-ray versus X-ray correlation

- **Gamma-ray emission changed by factor ~3, no change in the X-rays**
- Interpreted within a **one-zone leptonic model**
- **Adiabatic expansion of emitting zone** over time (but no significant loss of electrons)



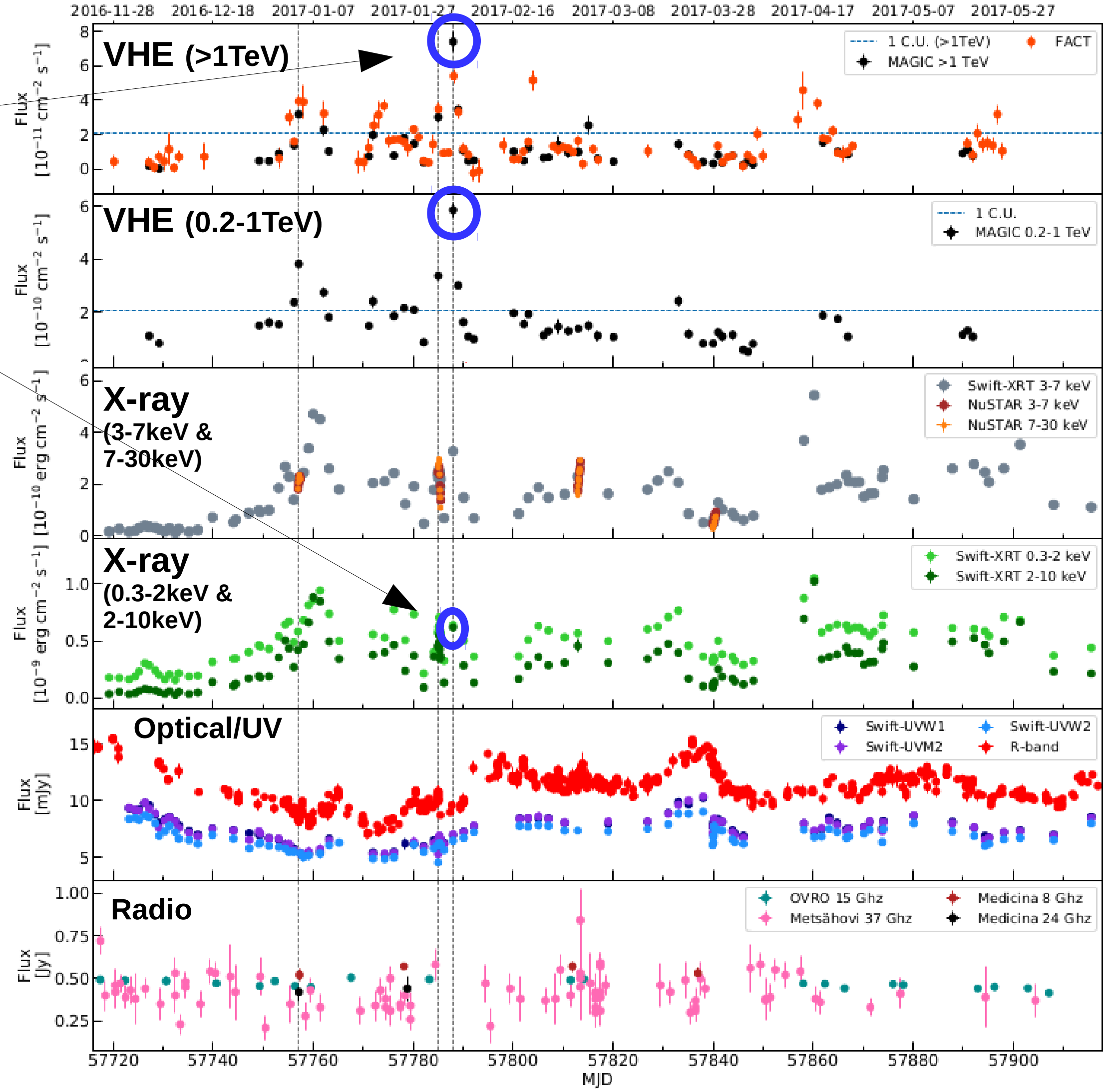
$R' \approx 1.3 \times 10^{16}$ cm
$R' \approx 1.4 \times 10^{-2}$ light year

$R' \approx 2.2 \times 10^{16}$ cm
$R' \approx 2.3 \times 10^{-2}$ light year

Intriguing VHE flare on 2017 February 4th

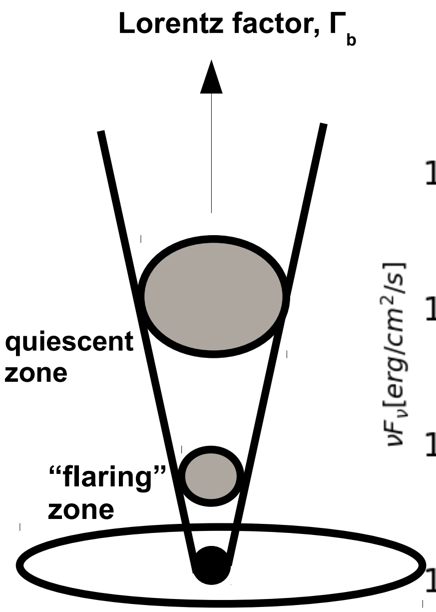
- **Strong VHE flux but small X-ray counterpart**
- Intepreted within a **two-zone leptonic scenario**

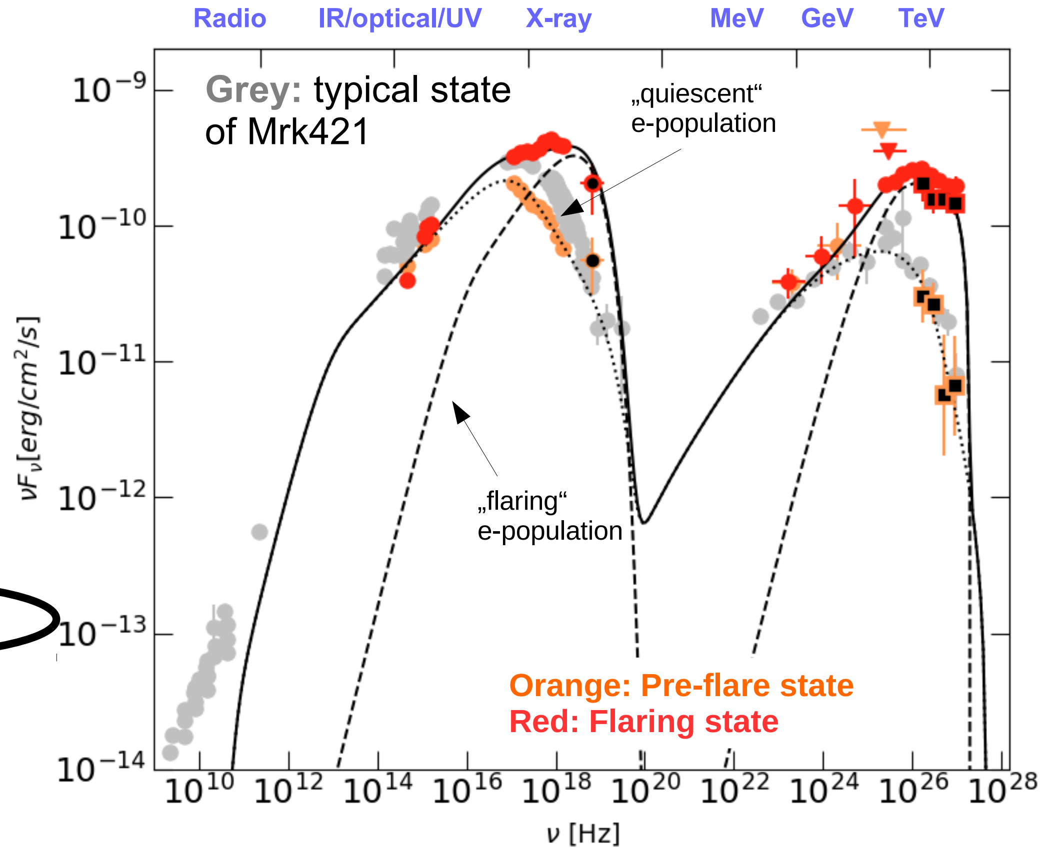
Daily bin light curves



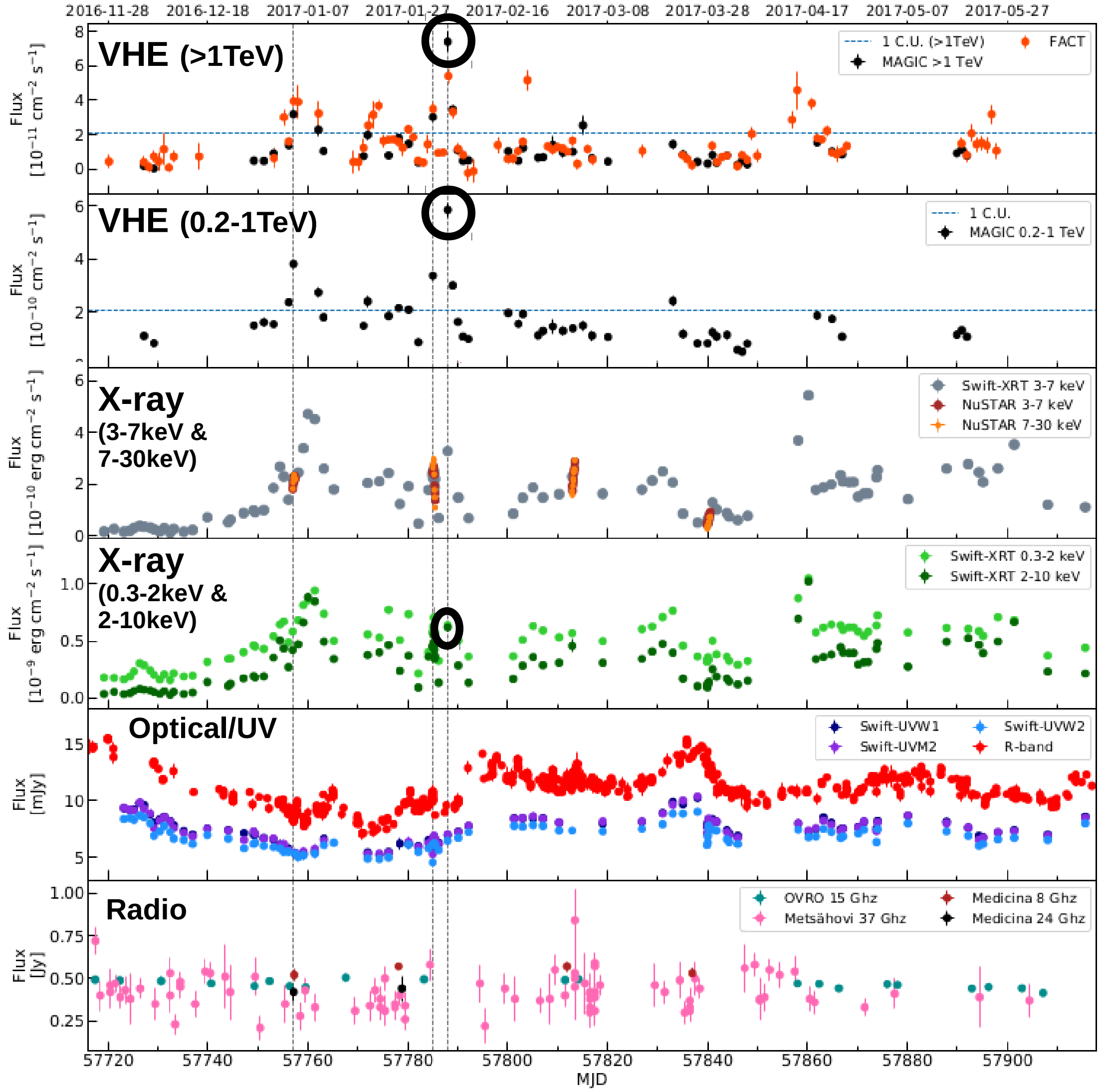
Intriguing VHE flare on 2017 February 4th

- **Strong VHE flux but small X-ray counterpart**
- Intepreted within a **two-zone leptonic scenario**
  → appearance of **narrow & energetic electron distribution**



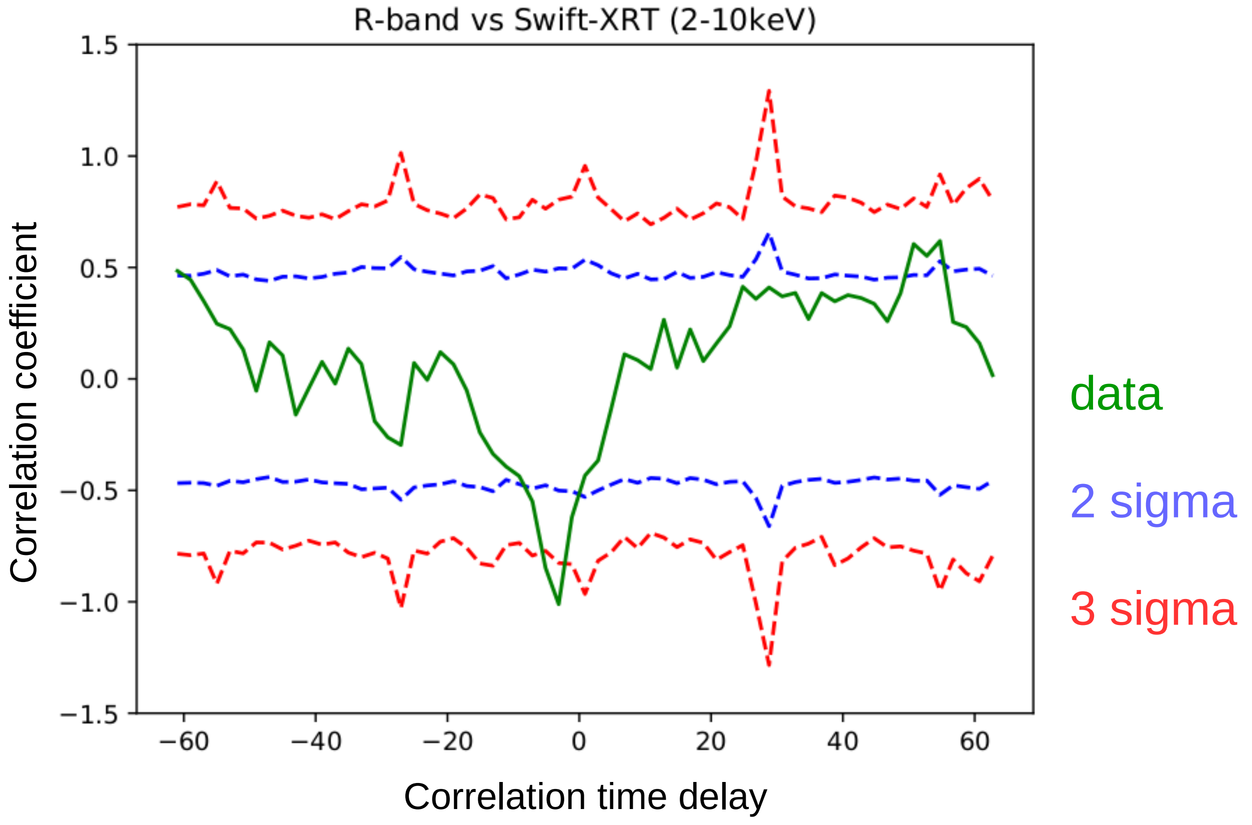


Daily bin light curves



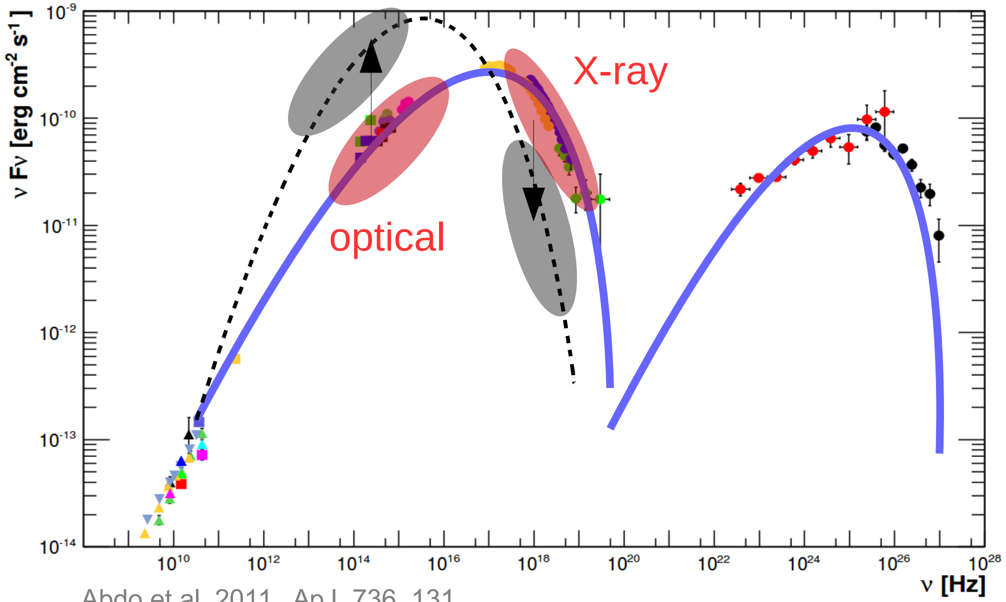
Optical versus X-ray *anti*-correlation

- Anti-correlation at >3 sigma C.L. between **X-ray** and **optical** emission
- **Reported only once** so far, at low significance (Aleksic et al. 2015, A&A, 576, A126)



Optical versus X-ray *anti*-correlation

- Anti-correlation at >3 sigma C.L. between **X-ray** and **optical** emission
- **Reported only once** so far, at low significance (Aleksic et al. 2015, A&A, 576, A126)
- Suggests shift of low-energy SED component due to **changes in electron cooling and acceleration efficiencies**



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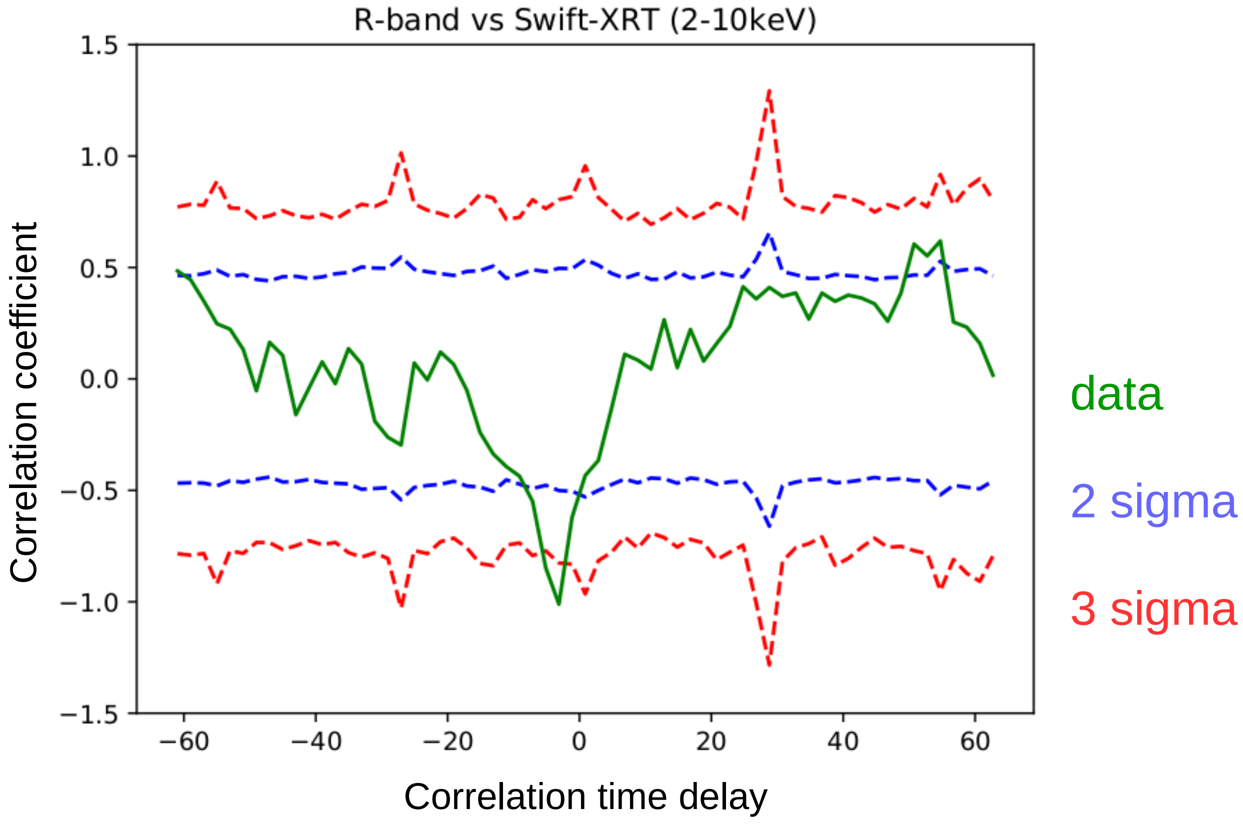


Conclusions

- Blazars still poorly understood

  → Simultaneous & dense MWL monitoring key to disentangle/constrain models

- Characterised intra-band correlations from extensive MWL campaign
  - X-ray/VHE tightly correlated, but complex & strong energy dependence
  - >3 sigma optical/X-ray *anti*-correlation; change of cooling/acceleration efficiencies ?
- Some intriguing results
  - „orphan“ gamma-ray activity; sign of adiabatic expansion of emitting zone?
  - Strong VHE flare with faint X-ray counterpart; suggest appearance of narrow & energetic electron distribution

Backup

Table 5: Parameters of the SSC models obtained for each MAGIC/*NuSTAR*/*Swift* simultaneous observing epoch.

Parameters	MJD 57757 4th January 2017	MJD 57785 1st February 2017	MJD 57813 1st March 2017	MJD 57840 28th March 2017
Γ_b	25	25	25	25
B' [10^{-2} G]	6.1	7.0	6.1	10.0
R' [10^{16} cm]	1	1	1.65	1.33
U'_e [10^{-2} erg cm^{-3}]	1.1	1.0	0.24	0.22
α_1	2.2	2.2	2.2	2.0
α_2	3.8	3.1	3.9	4.0
γ'_{min} [10^3]	1.0	1.0	1.0	1.0
γ'_{br} [10^5]	2.1	1.4	2.1	0.8
γ'_{max} [10^6]	1.5	0.9	1.5	0.6
U'_B/U'_e	1.4×10^{-2}	2×10^{-2}	6.1×10^{-2}	1.8×10^{-1}

Notes. See text in Sect. 6 for the description of each parameter.

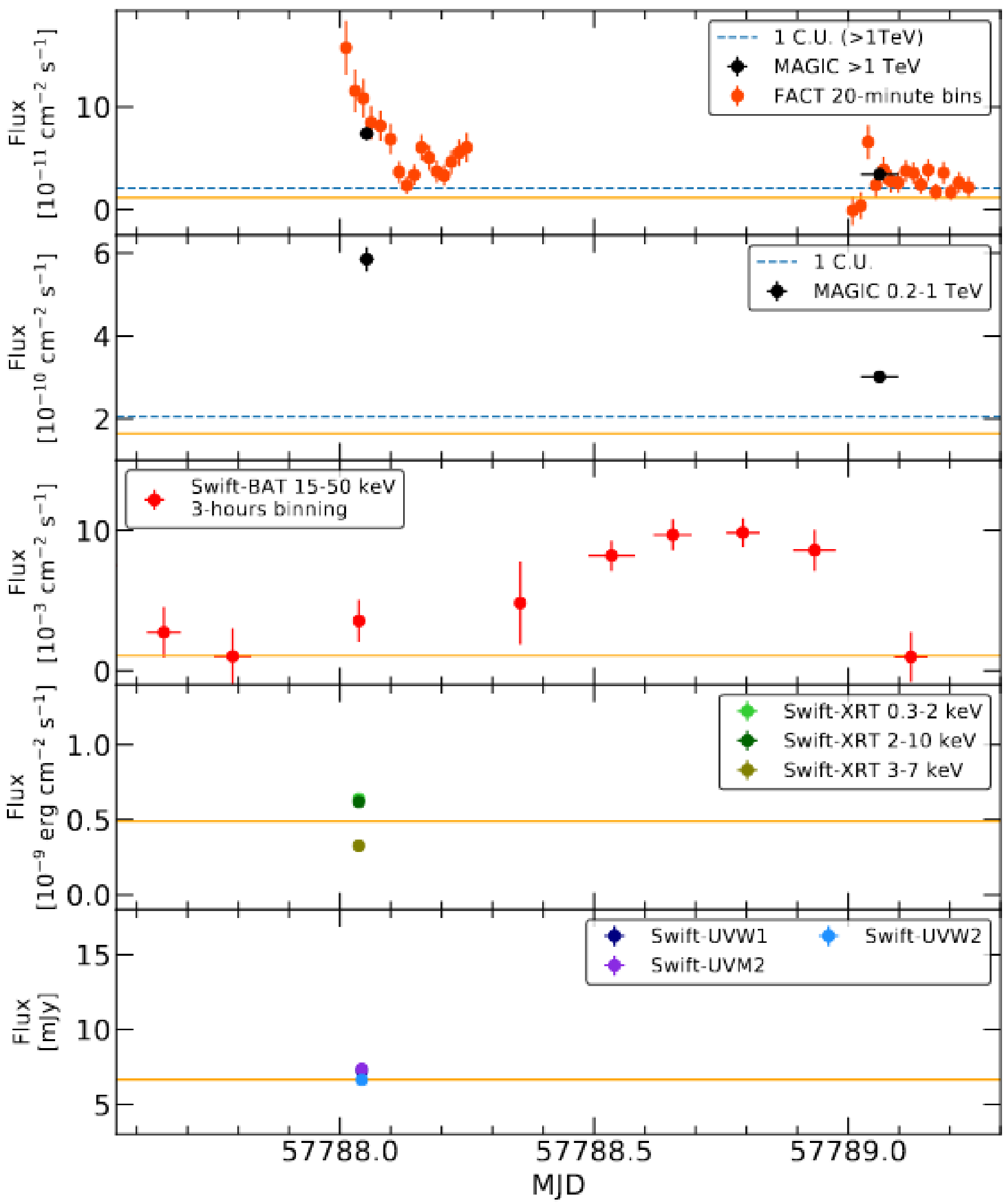
Backup

Table 6: Parameters of the 2-zone SSC model shown in Fig. 16 during the flare of MJD 57788.

Parameters	quiescent zone	flaring zone
Γ_b	25	25
B' [10^{-2} G]	6.1	16.5
R' [10^{16} cm]	1.6	0.1
U'_e [erg cm^{-3}]	3.4×10^{-3}	3.4×10^{-1}
α_1	2.3	2.0
α_2	4.0	–
γ'_{min} [10^3]	1.0	20
γ'_{br} [10^5]	1.3	–
γ'_{max} [10^6]	1.5	0.6
U'_B/U'_e	4×10^{-2}	3×10^{-3}

Notes. See text for the description of each parameter. The EED of the quiescent zone follows a broken power-law (BPL) with indices α_1 and α_2 before and after the break Lorentz factor γ'_{br}. In the case of the flaring zone, a simple power-law function (with index α_1) is adopted.

Backup



1 C.U. (>1TeV)
MAGIC >1 TeV
FACT 20-minute bins
1 C.U.
MAGIC 0.2-1 TeV
Swift-BAT 15-50 keV
3-hours binning
Swift-XRT 0.3-2 keV
Swift-XRT 2-10 keV
Swift-XRT 3-7 keV
Swift-UVW1
Swift-UVW2
Swift-UVM2
Flux [10^-11 cm^-2 s^-1]
Flux [10^-10 cm^-2 s^-1]
Flux [10^-3 cm^-2 s^-1]
Flux [10^-9 erg cm^-2 s^-1]
Flux [mJy]
57788.0
57788.5
57789.0
MJD