New insights on the nature of blazars from a decade of multi-wavelength observations

Discovery of a very large shift of the synchrotron peak frequency, long-term optical-γ-ray flux correlations, and rising flux trend in the BL Lac 1ES 1215+303

Janeth Valverde

with the Fermi-LAT, VERITAS, Tuorla, VLBA, MOJAVE, OVRO and Metsähovi collaborations.

Supervisors: Deirdre Horan & Denis Bernard

ApJ 891 (2020) 170 (Valverde et al.) thesis.fr (24 Feb. 2020)

Parcours de Janeth

- *B.Sc. in Physics*, UNI, Peru. 2013.
- *Postgraduate Diploma Programme*, HEP, ICTP, Italy. 2014.
- *M.Sc. in Physics*, HEP, Ecole Polytechnique, France. 2016.
- *PhD in Astroparticles and Cosmology*, Ecole Polytechnique/IPP, France. 2020.

  - Data-quality-monitoring.

  - Sky-watch (flare advocate) shifts: ATels #11854, #11419, #11412, #10987, #10952, #10951, #10721 & X-ray ToOs.

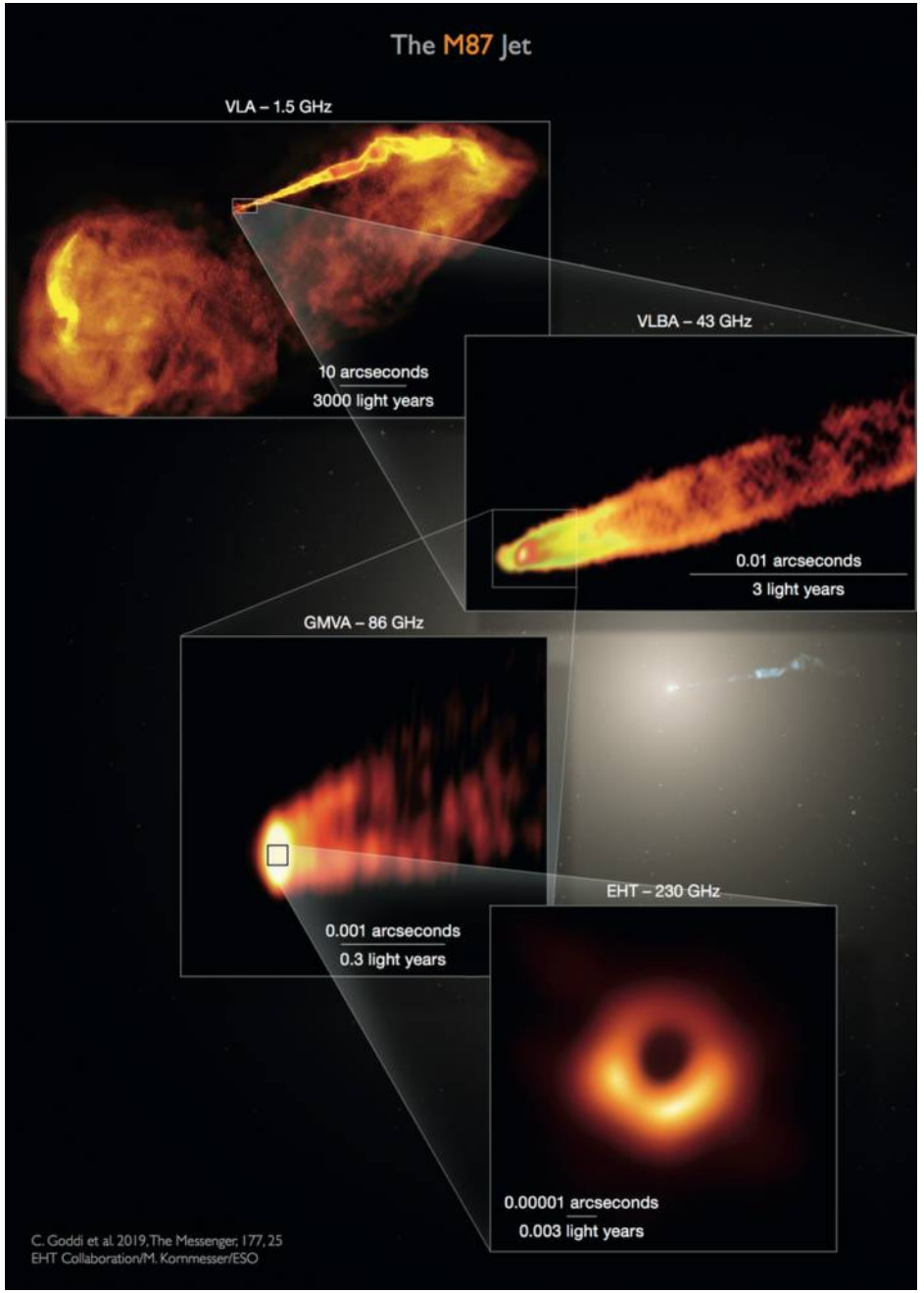
  - Internal referee for: BL Lacertae paper published in ApJ.
    Mrk 421 paper in progress.

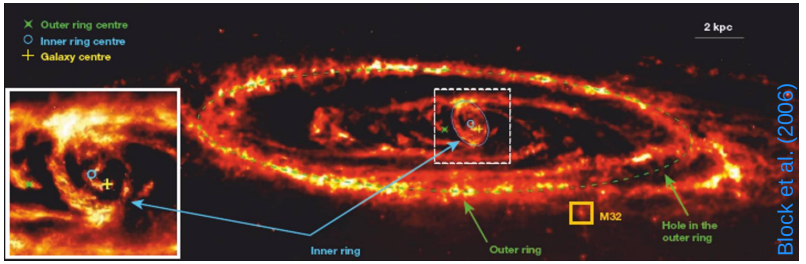
  - MWL long-term study of 1ES 1215+303.

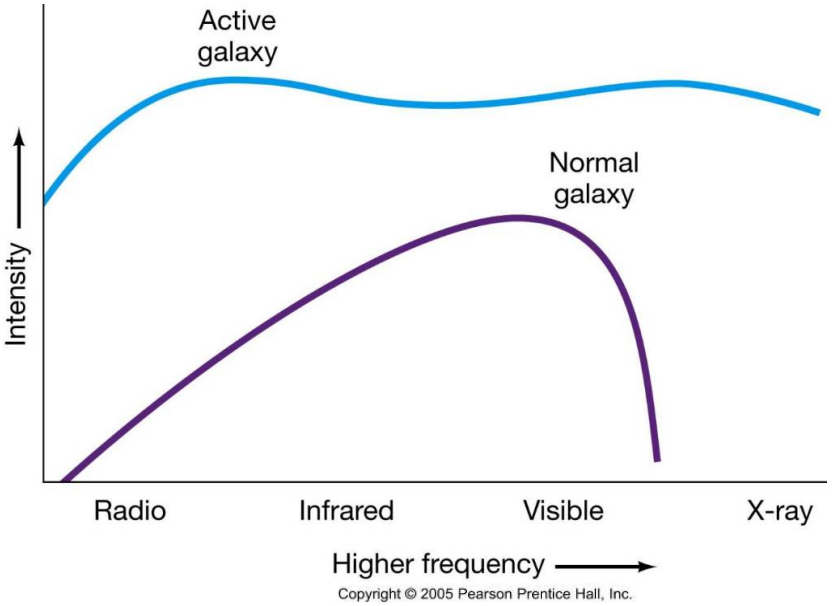
- *Now a Post-doctoral Researcher at* UMBC / NASA's Goddard Space Flight Center (GSFC).

Outline

Active galactic nuclei



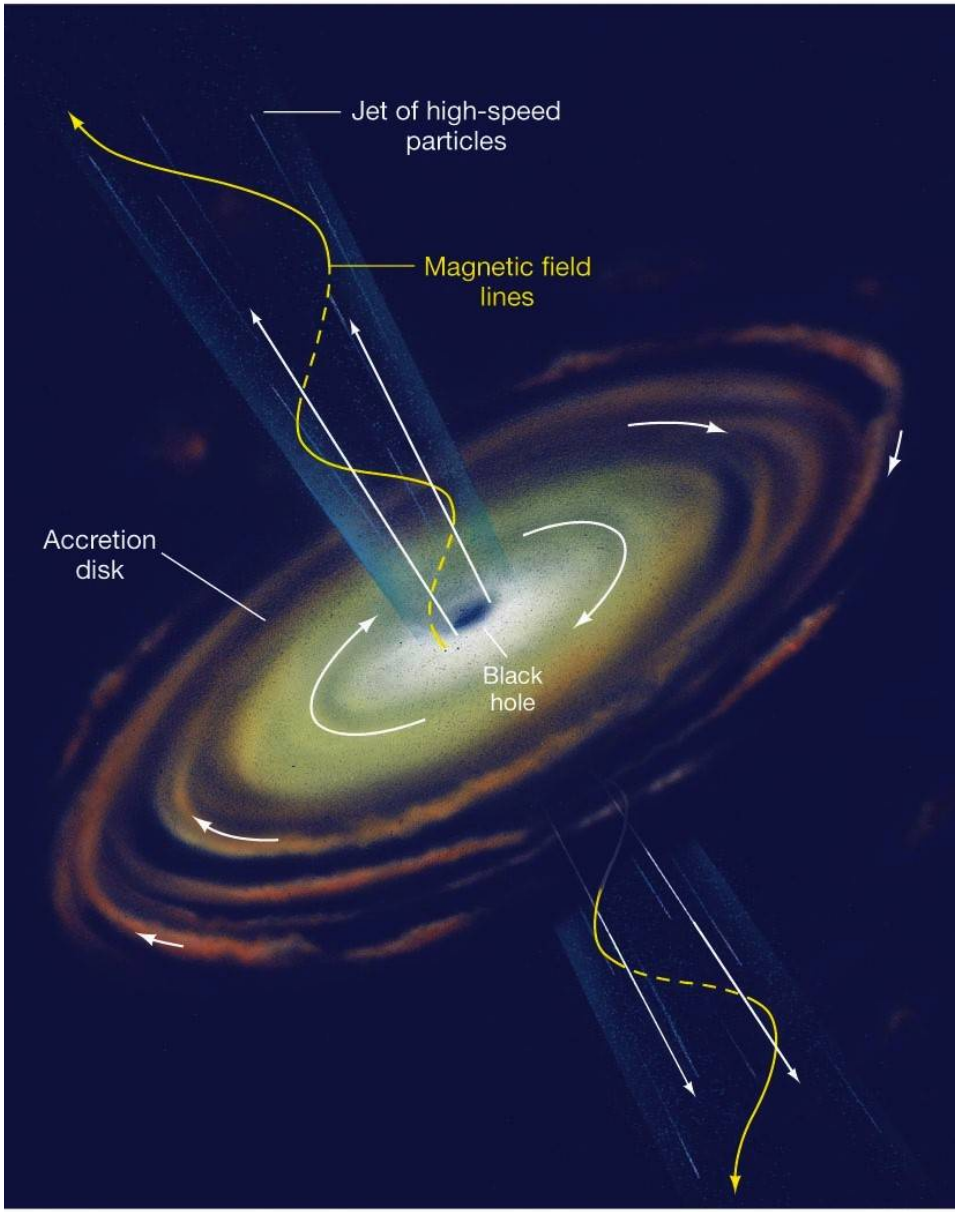




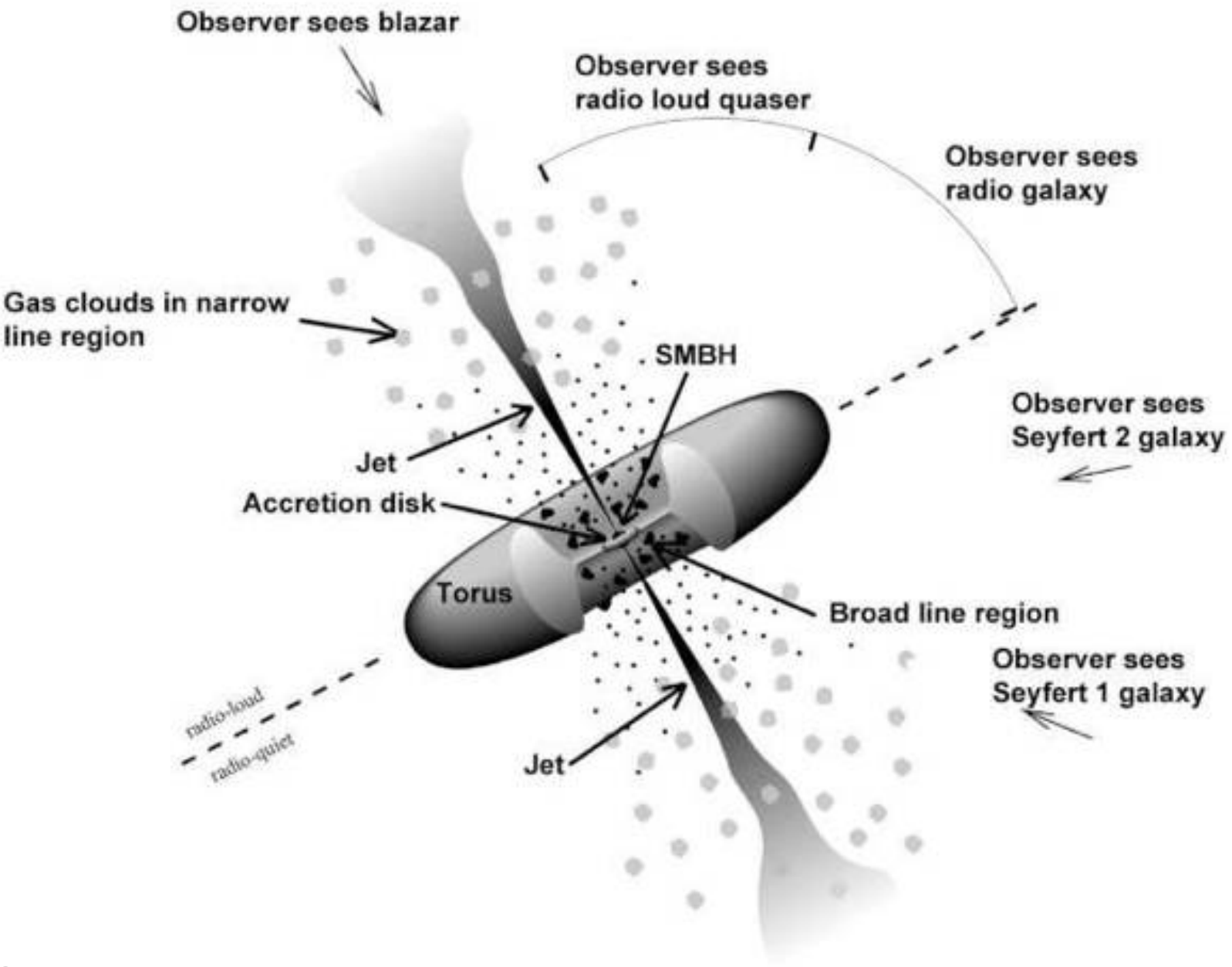
- Many show relativistic plasma jets, related to radio loudness.
- Extremely luminous compared to a normal galaxy.
- Emission from radio to GeV/TeV.
- Natural accelerators. Non thermal.

What is an Active Galactic Nucleus (AGN)?

- A few % of galaxies.
- Activity centered in the galactic nucleus.
- Rapid variations => extremely compact source.
- Central super massive black hole (SMBH) >≈ 10^9 solar masses, surrounded by accretion disk.
- Strong twisted magnetic fields (B) possibly confine particles in the jet (Blandford & Znajek 1977, Blandford & Payne 1982).
- Billions of light years away => possibly an early stage in galaxy development.



What we see depends on how we view it



Credits: NASA

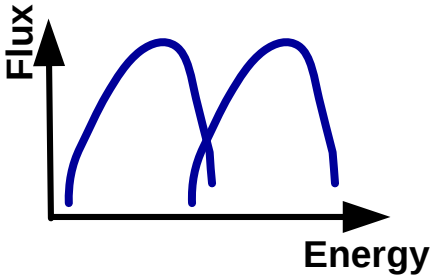
Outline

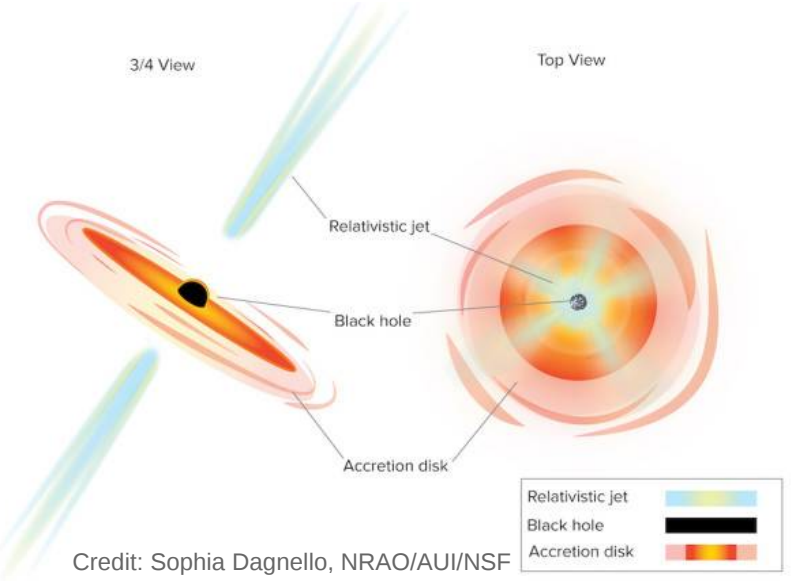
Blazars

- A few % of AGNs, radio loud.
- Jet points at us.
- Can be Flat Spectrum Radio Quasars (FSRQs, broad emission lines) or BL Lac objects with weak of no emission or absorption lines.
- Large amplitude variability.
- Relativistic beaming, Doppler factor:

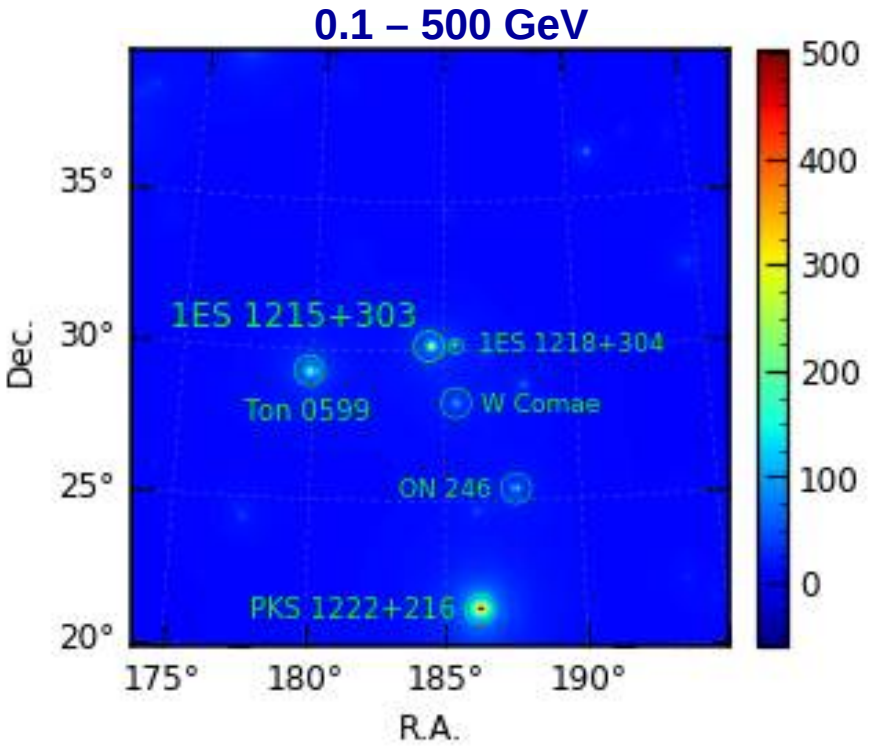
$$\delta = \frac{1}{\gamma(1 - \beta\ \cos(\theta))}, \qquad \gamma = (1 - \beta^2)^{-1/2}$$

- Characteristic spectral energy distribution (SED):

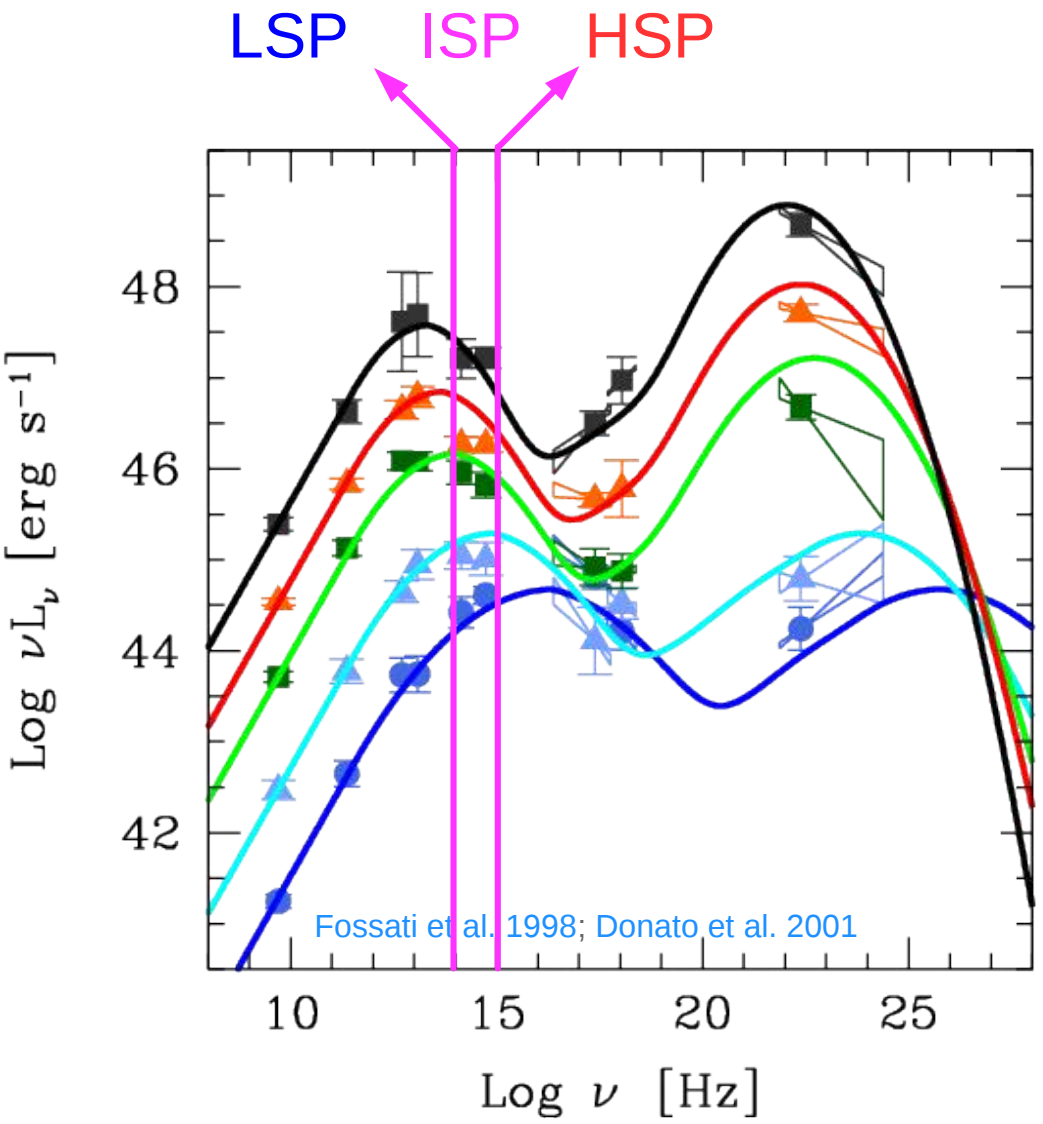




Credit: Sophia Dagnello, NRAO/AUI/NSF

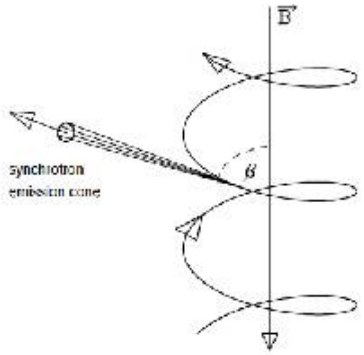


Blazar Spectral Energy Distribution

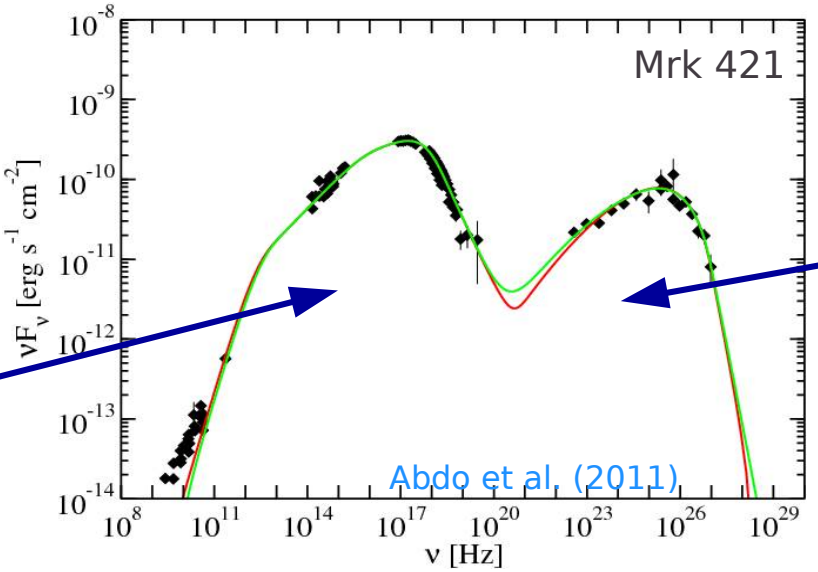


- BL Lacs subtypes: low-, intermediate- or high-synchrotron-peaked (LSP, ISP, HSP).
- Based in Padovani & Giommi (1995; ratio 5GHz/1 keV flux): low-, intermediate- or high-frequency peaked BL Lac (LBL, IBL, HBL).

Models of blazar emission



Synchrotron emission



Leptonic
(e+/e- plasma)
or
hadronic
(ionized matter)

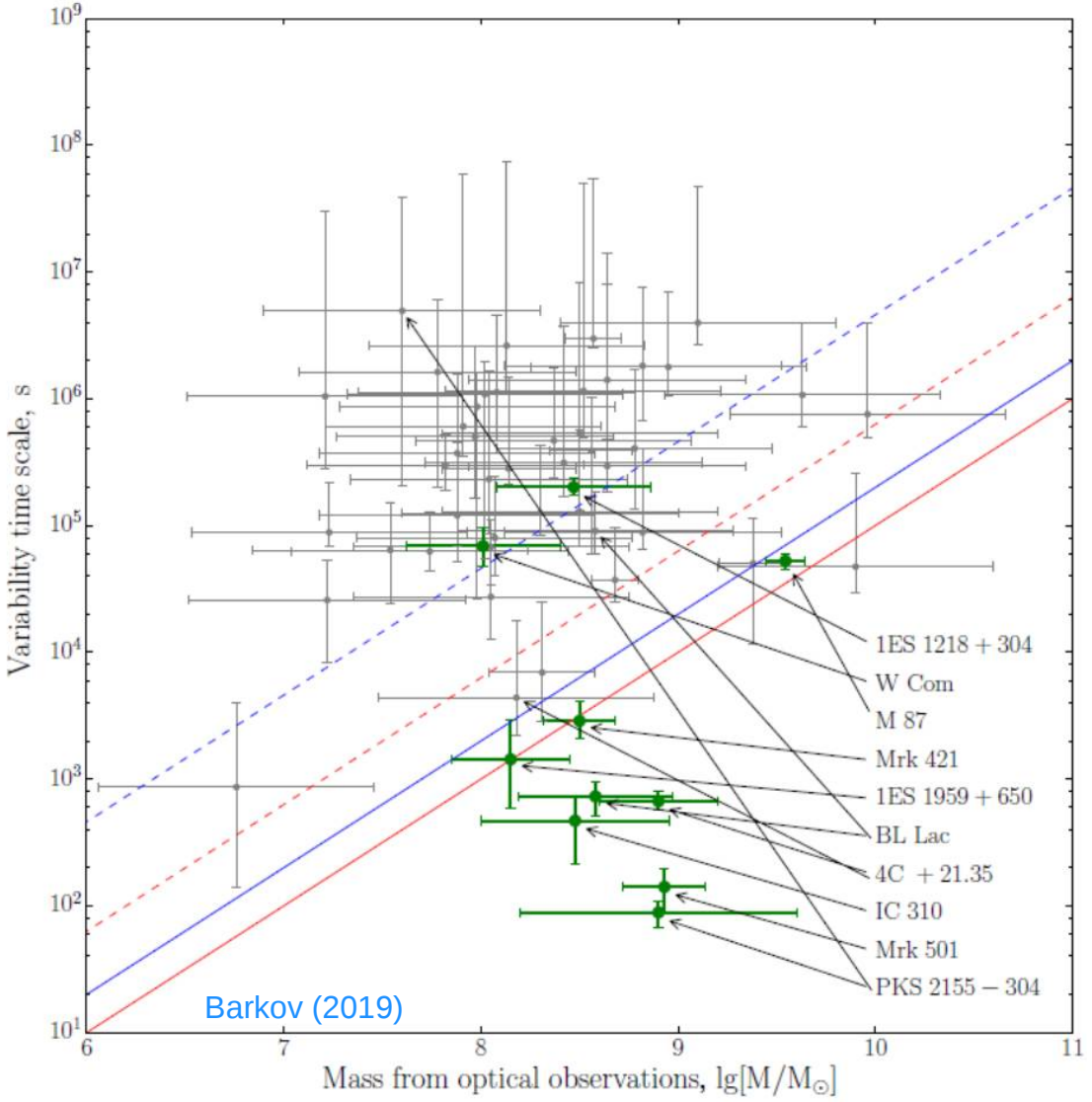
Leptonic

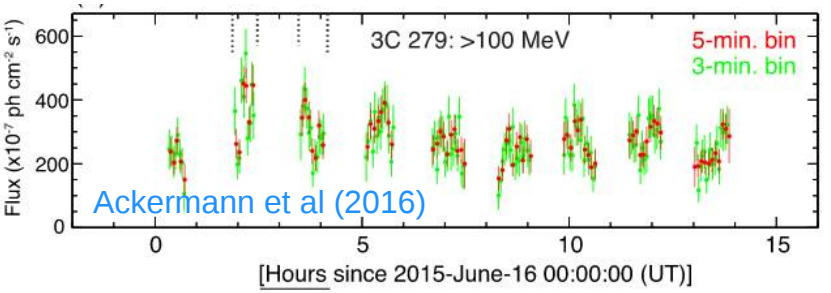
- HE emission likely from **inverse Compton** scattering by same **e-/e+** that emitted synch: **synchrotron self-Compton** (SSC).
- Upscatter of low-energy photons from broad-line region, disk or torus: **external inverse Compton** (EIC).
- Synch. and Compton variations **correlated**.

Hadronic

- HE emission from ultra-relativistic **e-/e+** & **protons**.
- γ-ray emission via e.g. proton synchrotron, or photo-pion prod.
- Synch & Compton emission from secondary products of $\pi^{\pm}$.
- Production or **neutrinos**.

Blazar variability





- Variability timescales from years to minutes.
- Rapid variability challenge theoretical models:

  - large δ

  - long cooling time in hadronic models

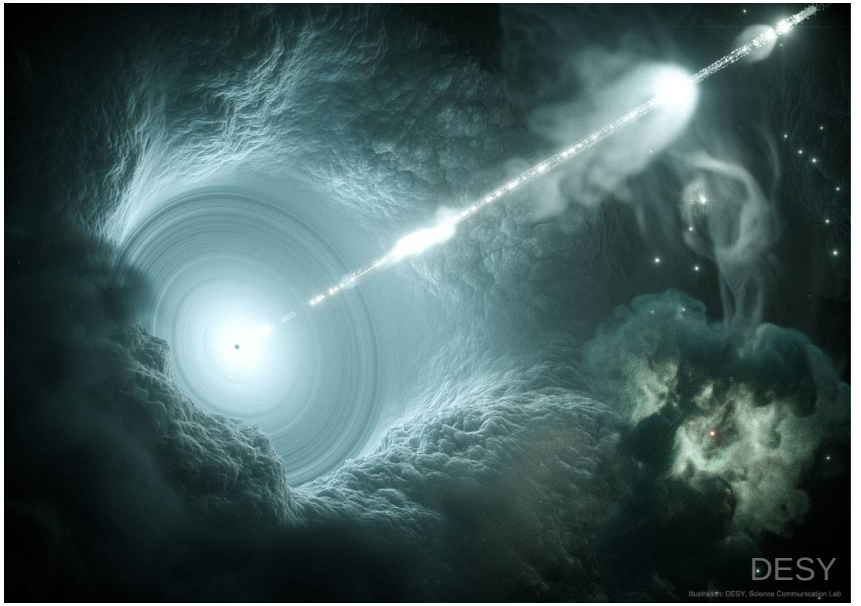
  - can be produced by proton synch with very high energy protons & extremely large B.

Outline

What are the big open questions?

- What is the nature of the particles in the jet: leptonic/hadronic, cosmic rays? Neutrinos could be a clue.
- What causes the acceleration of high-energy particles?
- How are jets formed and launched?
- What does classification mean?
- How do blazars evolve?

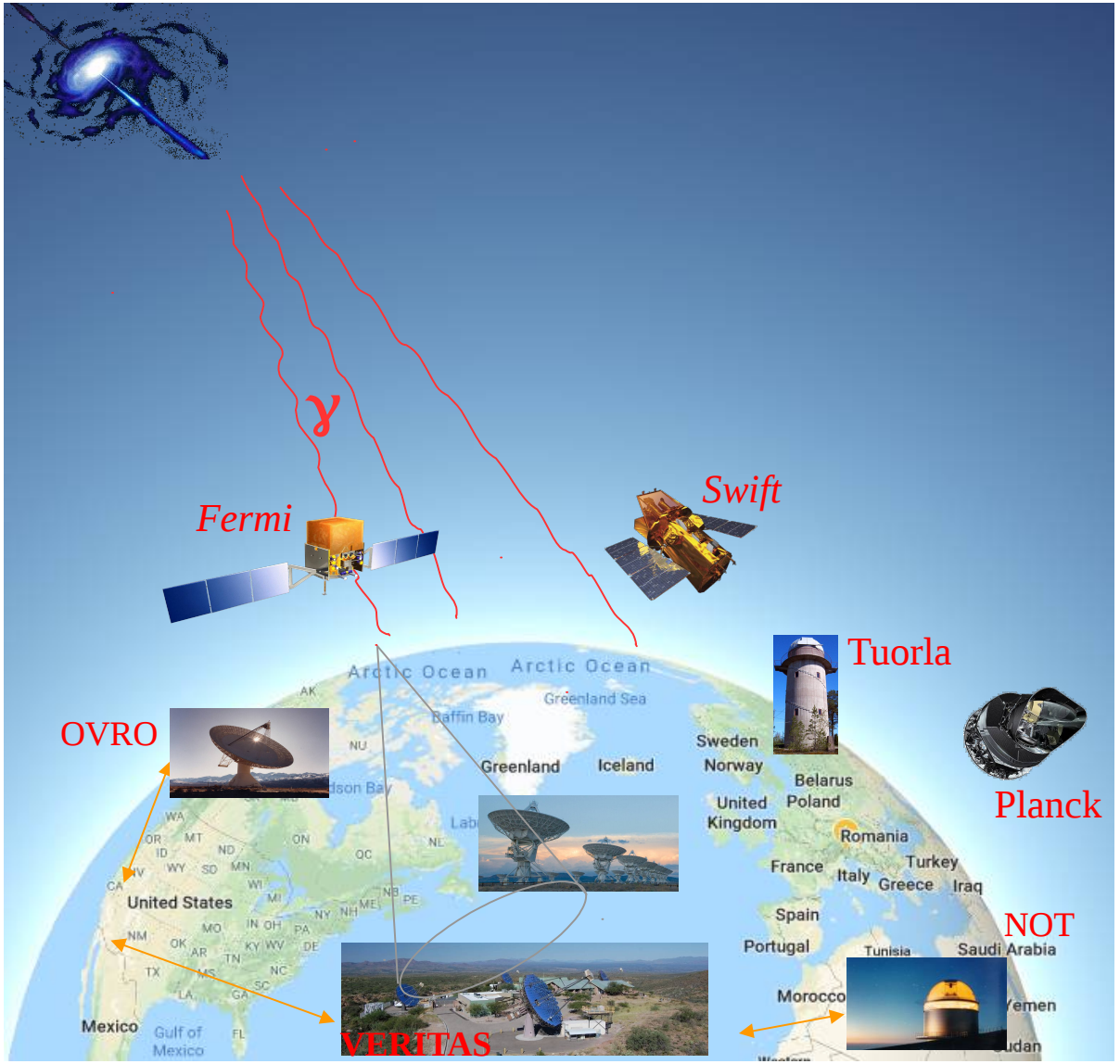
➡ Will use our data to contribute.



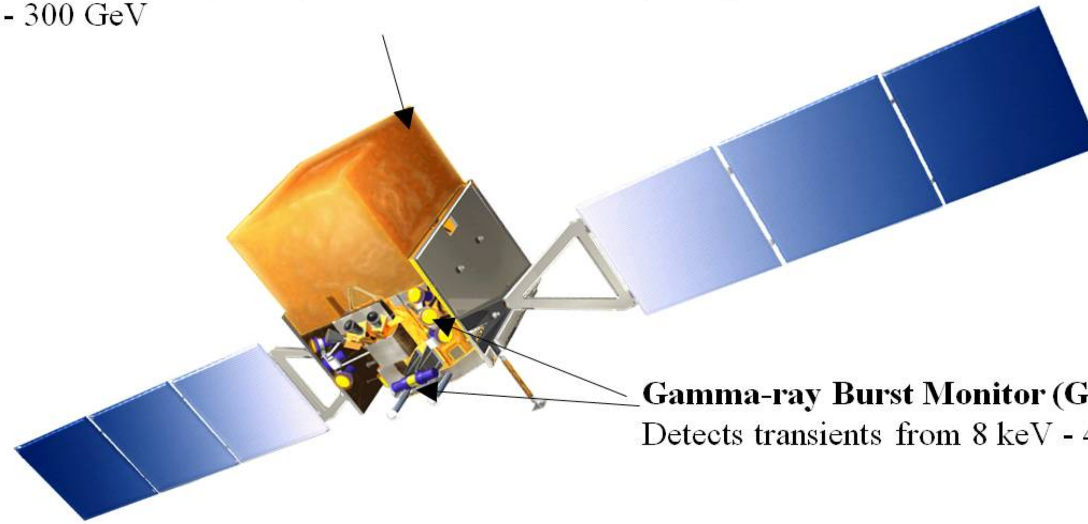
Outline

This work

- Variability:
  - Need long-term well-sampled light curves (LCs).
- Entire spectrum.
  - Need multi-wavelength (MWL) data.
- **Difficult to obtain observations over a long time & entire spectrum.**
- *Fermi*-LAT Collaboration member, contributed to MWL campaigns: Astronomer's Telegrams & X-ray obs. Requests.
- **Analysis highlights**: 10 yrs variability & MWL correlations, size of emission regions; flaring & quiescent states.



Fermi Large Area Space Telescope

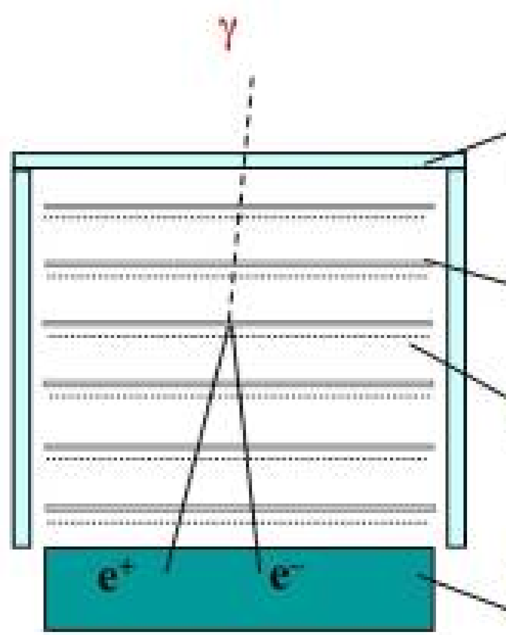


Launch: 11 June 2008 12:05 pm EDT

Fermi-LAT: $\gamma \rightarrow e^+ + e^-$

Energy range: 0.02 - >500 GeV

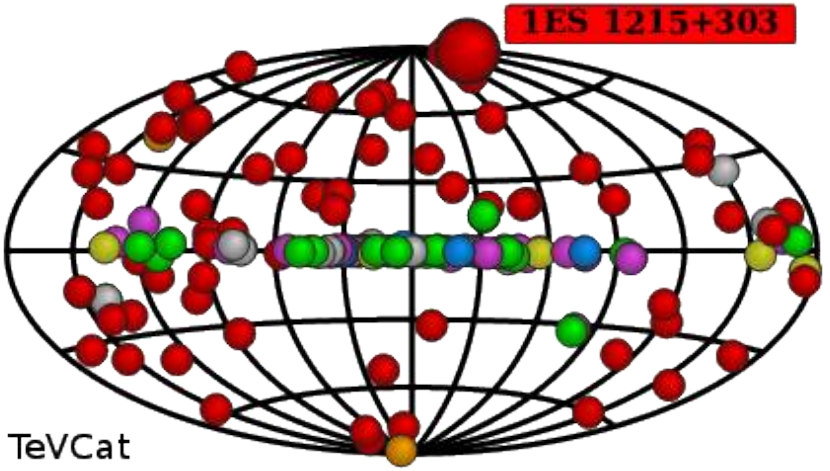
Fermi-LAT fourth catalog (4FGL-DR2):
> 5000 sources detected since launch.



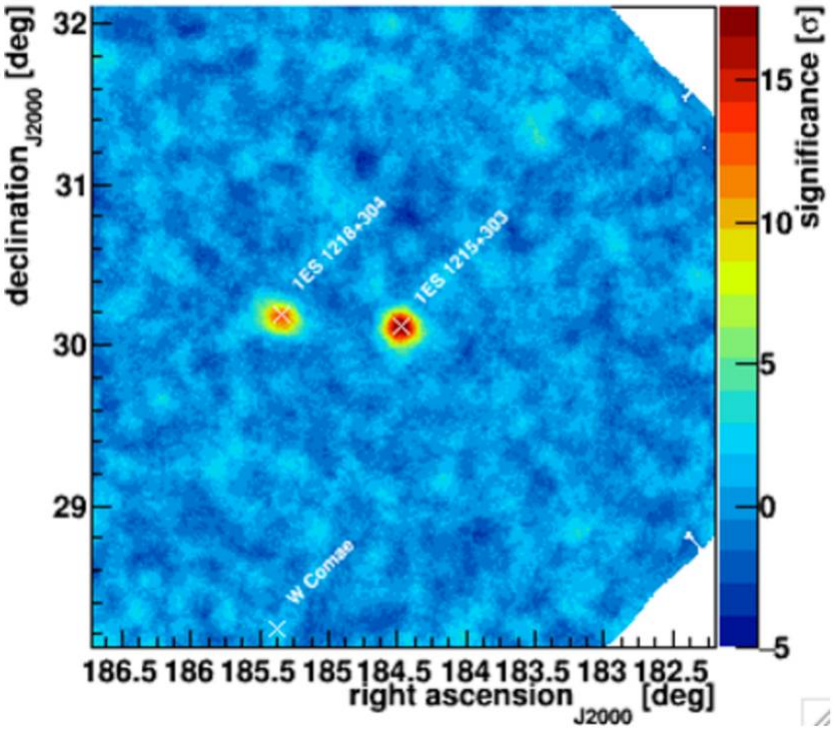
www-glast.stanford.edu

1ES 1215+303

- First detected in 1970 at 408 MHz.
- First detected at VHE by MAGIC in 2011
- z = 0.13 (Paiano et al. 2017).
- HBL in publications before 2019. ISP in fourth catalog of LAT AGNs (4LAC).
- MWL radio – γ-ray.
- At a distance of 0.76° from 1ES 1218+304 (z=0.183).



VERITAS 2015



MWL light curves

TeV γ-rays

GeV γ-rays

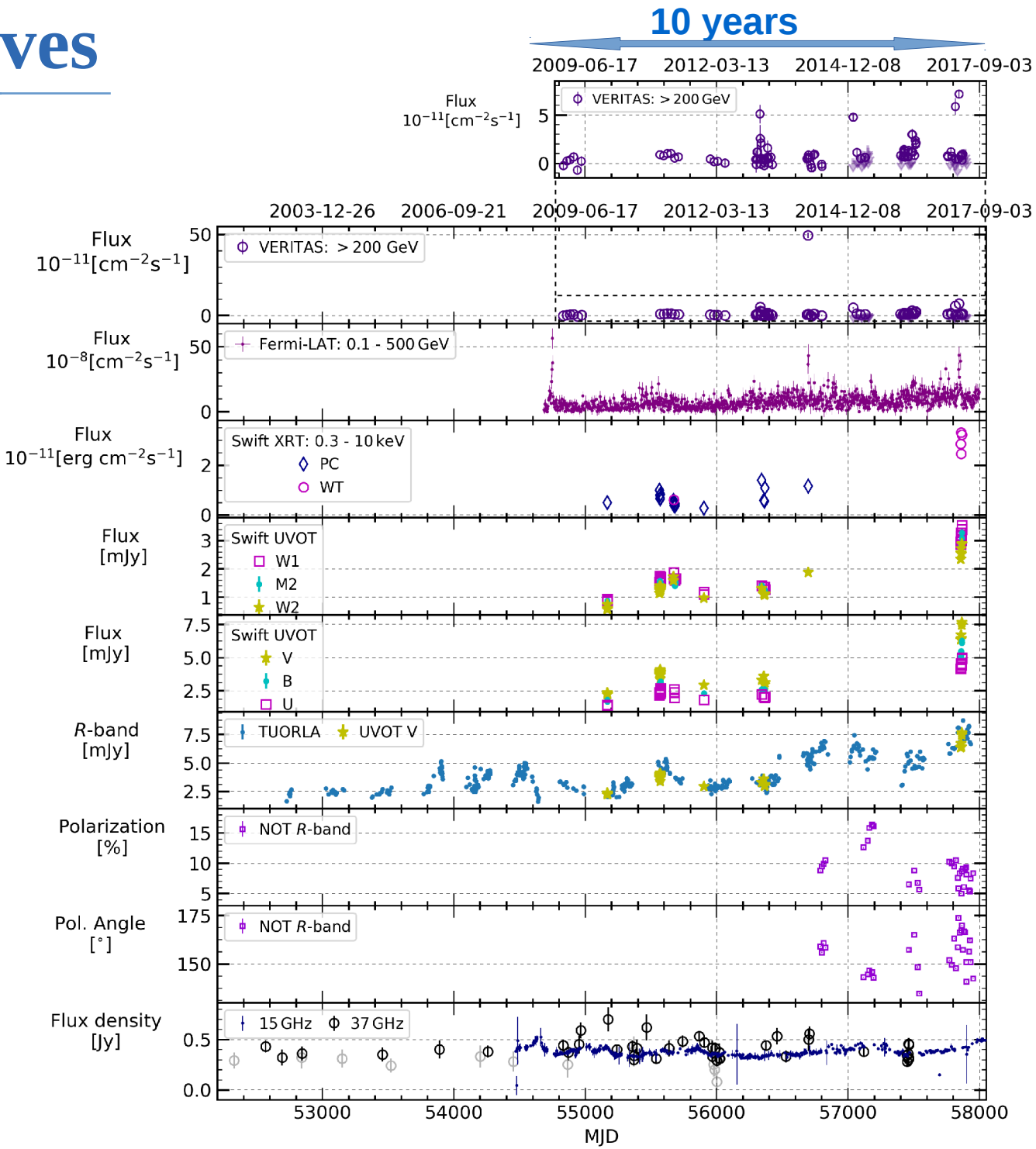
X-ray

UV-Optical

Optical

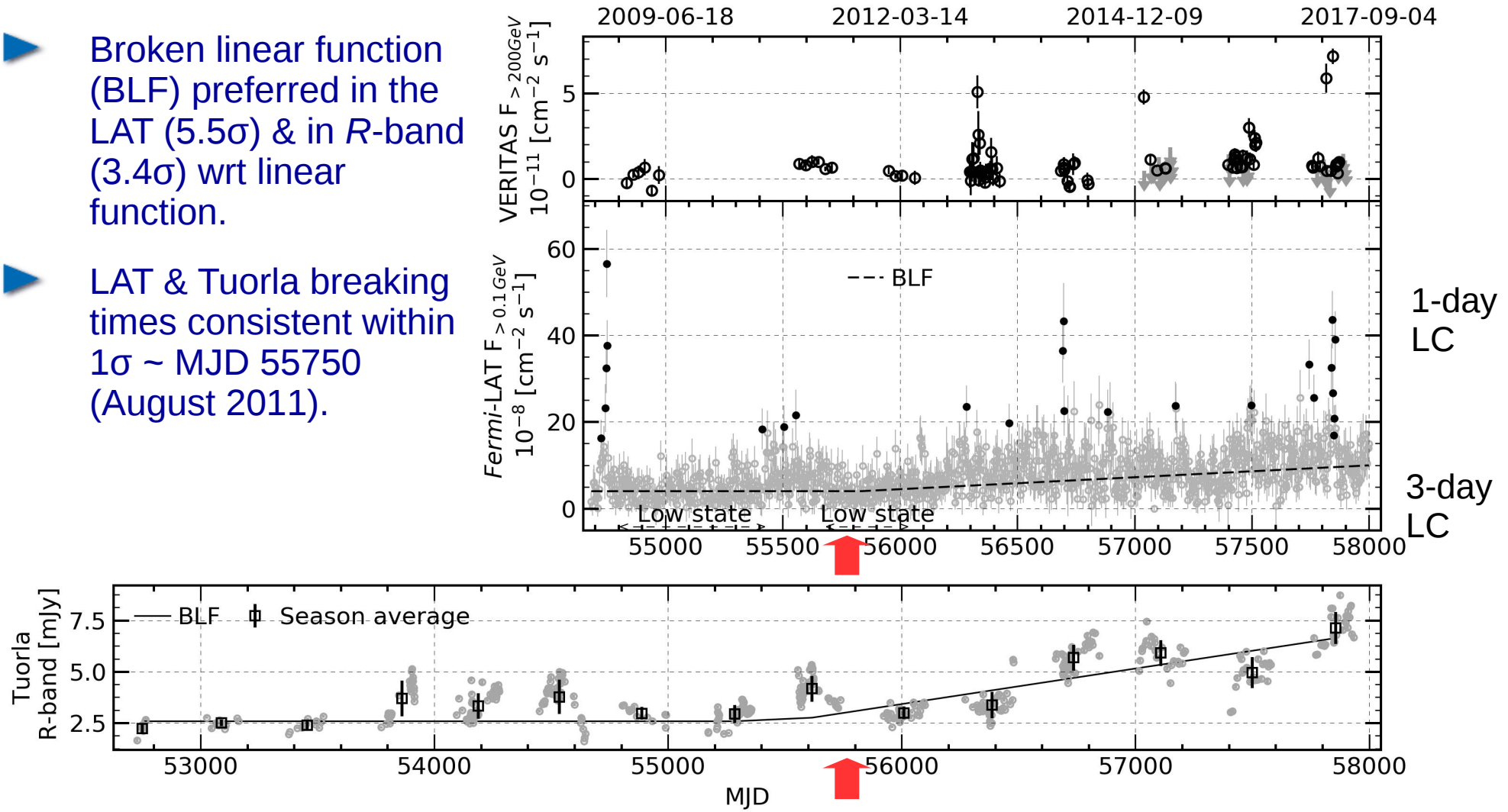
Optical polarization

Radio

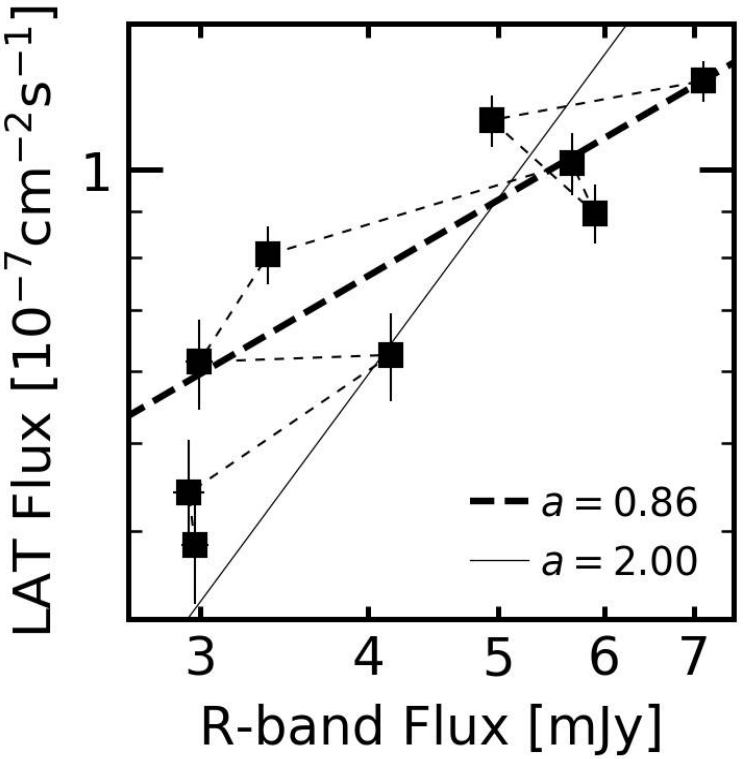


LAT & Tuorla: decade-long flux increasing trend

- Broken linear function (BLF) preferred in the LAT (5.5σ) & in *R*-band (3.4σ) wrt linear function.
- LAT & Tuorla breaking times consistent within 1σ ~ MJD 55750 (August 2011).



Strong long-term optical-GeV Correlation



a = Slope of the linear fit.

a = 1: In SSC, compatible with change of B & δ, does not favor a change of particle density.
In EIC: compatible with increase of B or particle density, does not favor change of δ.

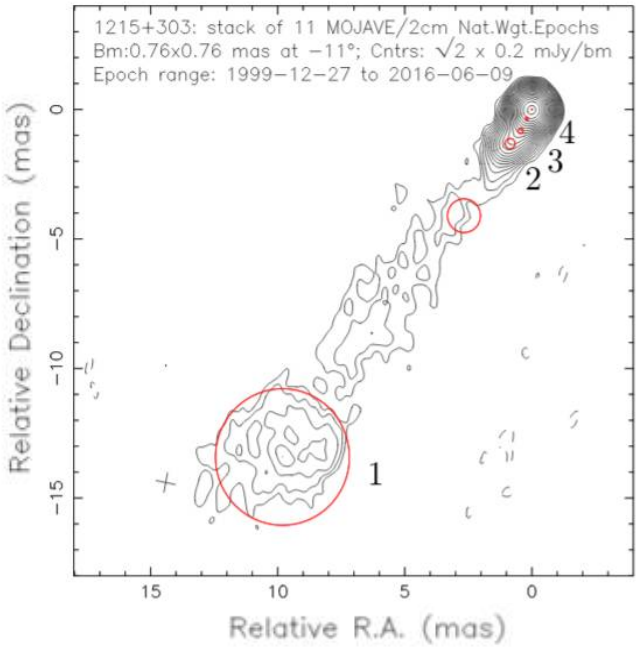
a = 2: In SSC: compatible with a change of particle density.
In EIC: compatible with a change of δ.

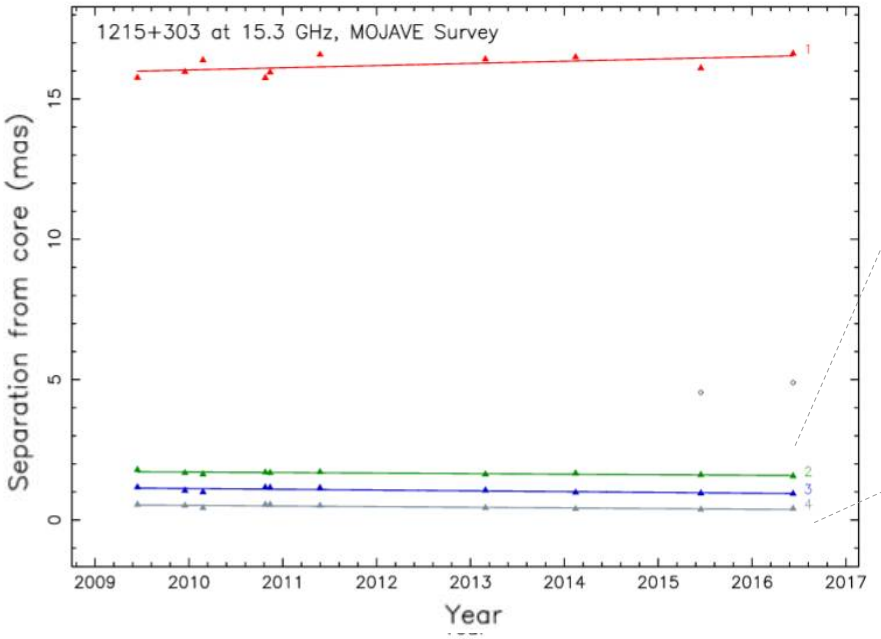
- a = 0.86 ± 0.21
- Excluded a ≈ 2 (> 3.6 σ)
- No evidence of correlation between other bands.

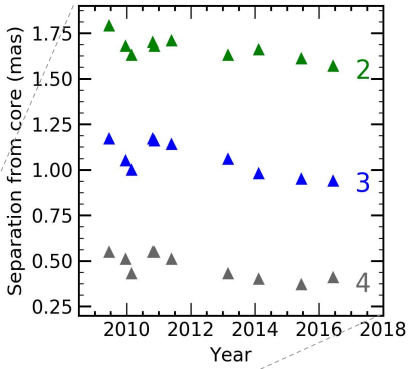
Does not favor particle density change in SSC scenario.

Does not favor Doppler factor change in EIC scenario.

Jet structure: MOJAVE 15 GHz







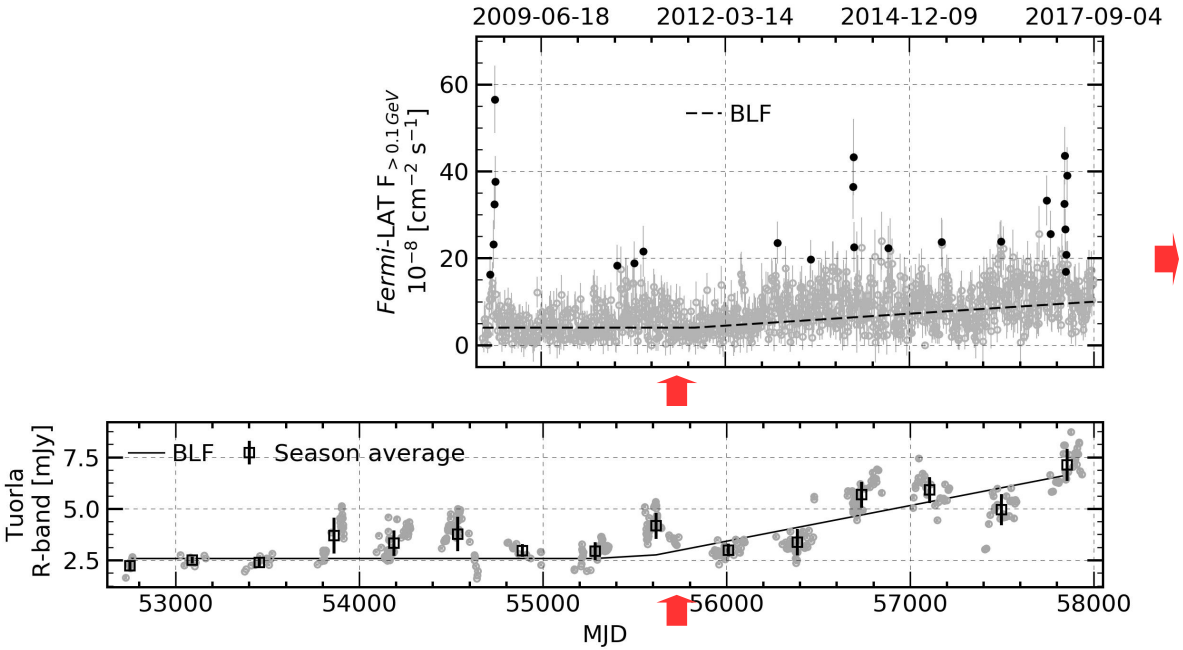
Knots 2,3,4 show similar inward motion ≃ 0.2c

(Lister et al. 2019)

Apparent inward motion possibly caused by long term power increase that would increase the distance (optically thin at larger distance) and size of radio core.

➡ **Fairly constant separation & stable jet.**

Long-term GeV-optical flux increase



LAT: linear increasing trend inconsistent with stochastic modeling @ ≈ 3.3σ (from simulated LCs).

Continuous increase since 2011

Jet precession: **X**

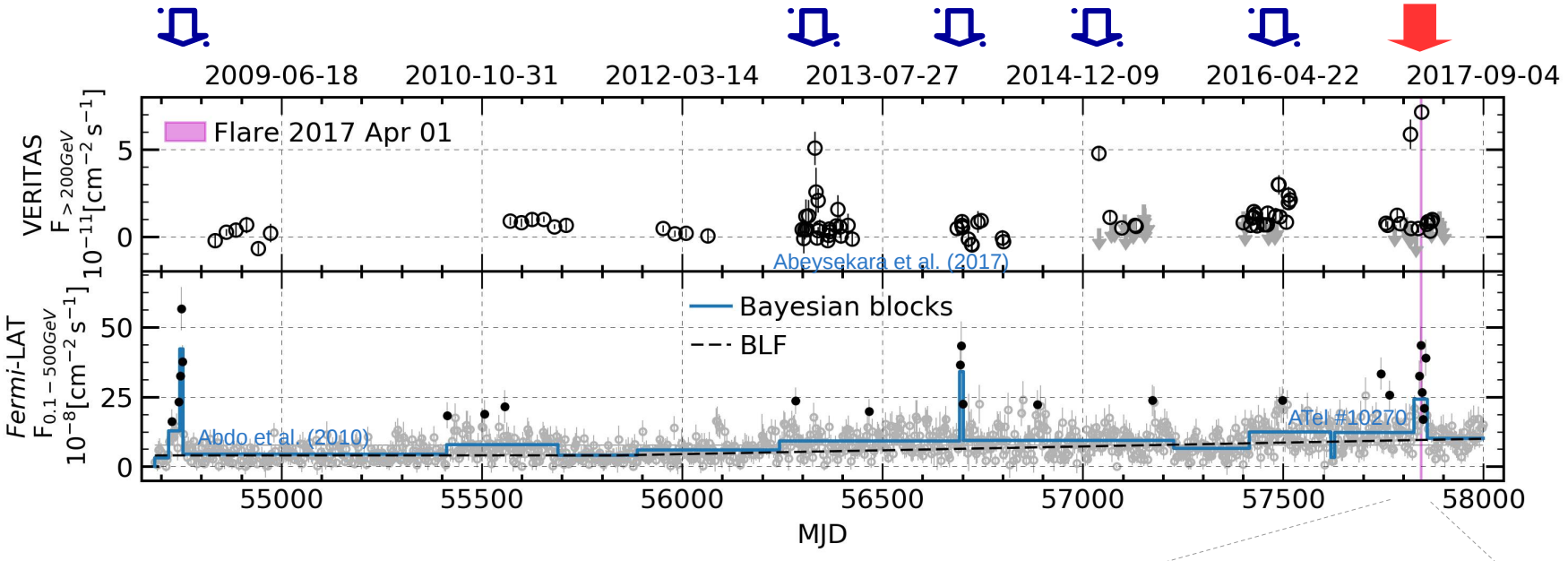
No strong radio-knot oscillation/ shift
No clear increase of radio luminosity
No jet broadening from stacked VLBI images

Accretion process: ~ **V**

Timescale consistent with the falling time considering the SMBH mass and an ADAF disk

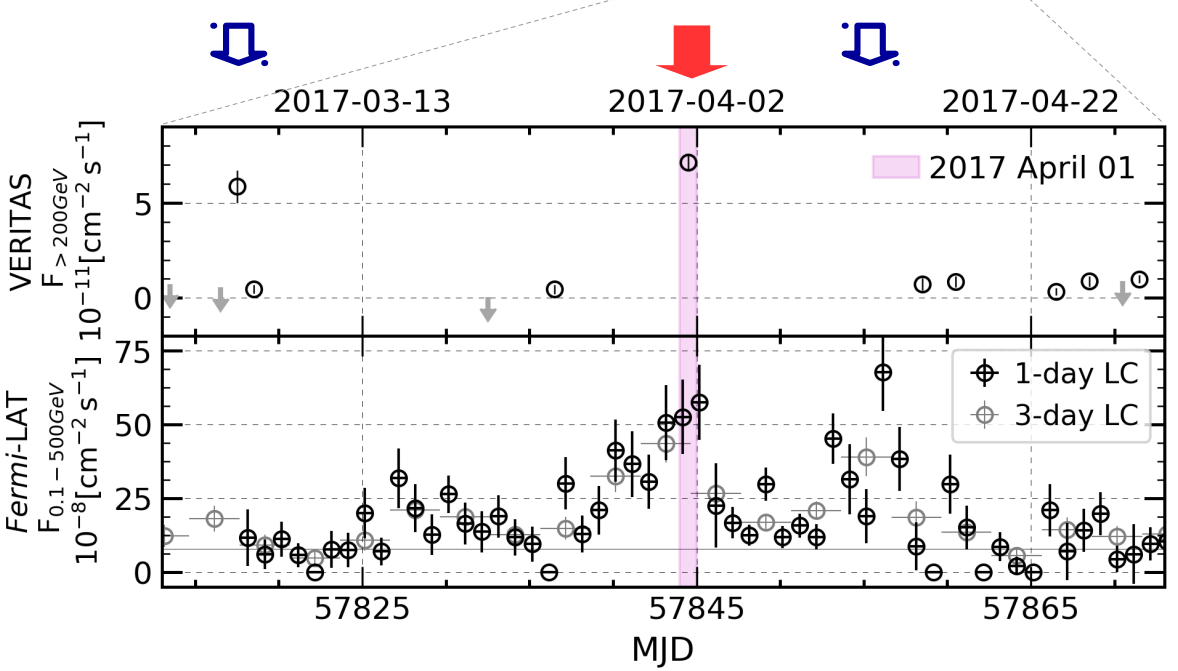
$$\tau_{ff} = 4.63\times10^{-5}\left(\frac{r}{1.0\times10^{3}r_g}\right)^{3/2}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\text{days} \simeq 8.7\ \text{years}$$

Constraints on size of emission region



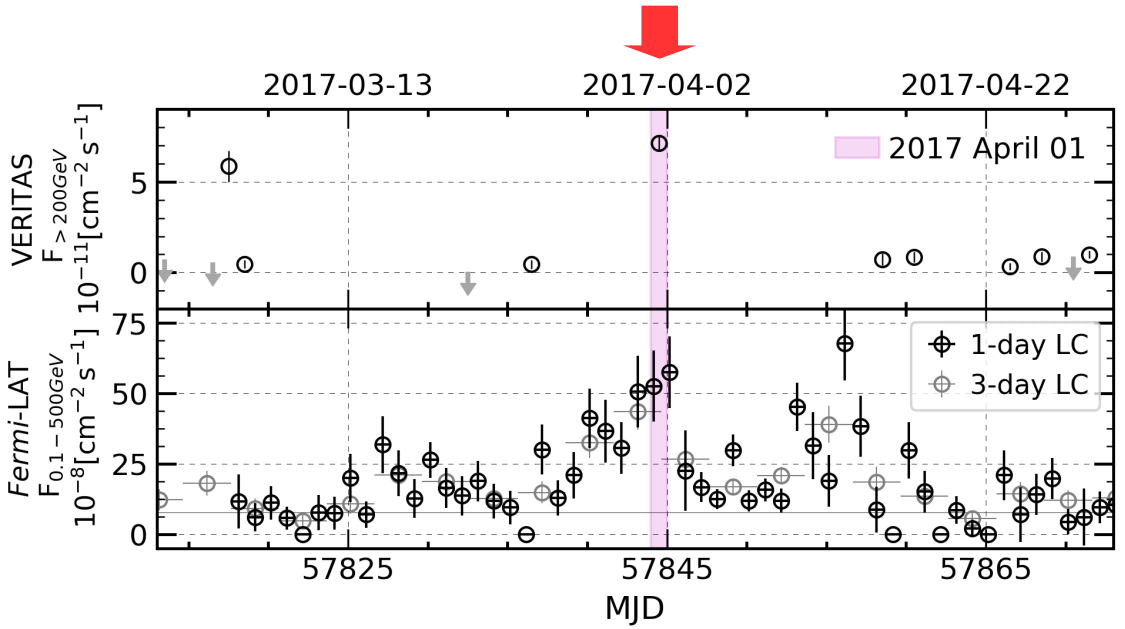
γ-ray flares

- Only 2 out of 8 flares had a detailed publication.
- Simultaneous coverage of flare 2017 Apr 01.



2017 April 01 flare

Strongest constraints on size of emission region



From unpublished data, strongest constraint given by flare 2017 Apr 01.

$$F(t) = F_0 + F_1 \times 2^{-(t-t_0)/t_{\rm var}}$$

$$R\delta^{-1} \leq t_{\rm var}/(1+z)$$

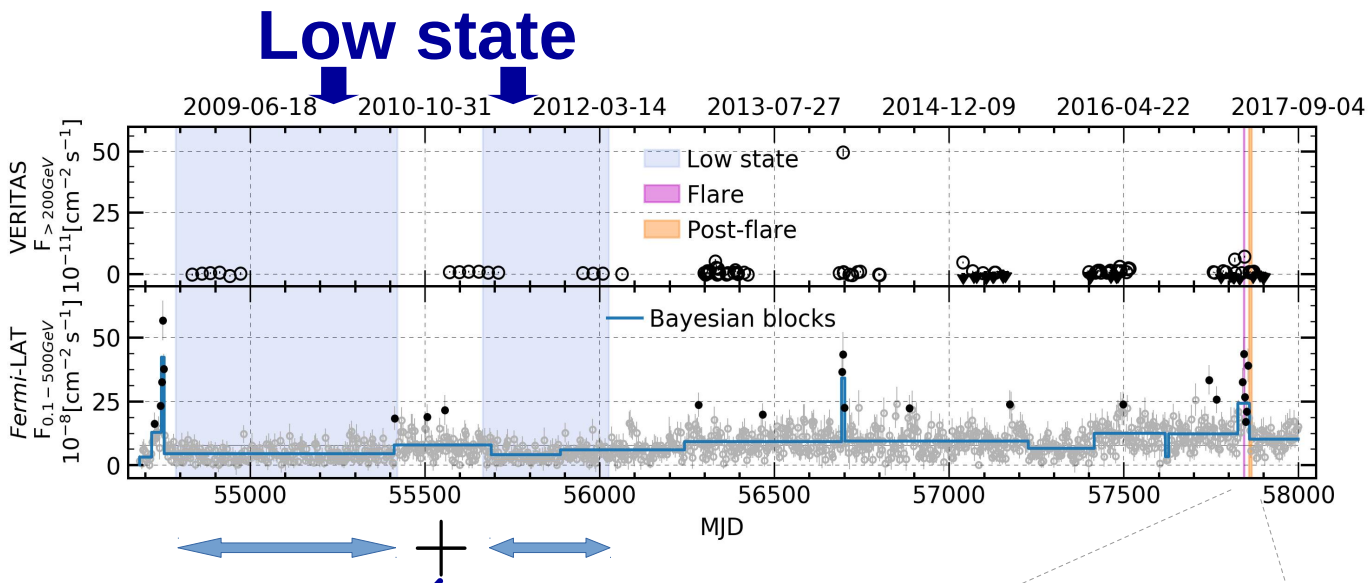
- GeV data, halving time: < 0.9 days.
- From SED modeling: $\delta \approx 25$.
- SMBH mass: $1.3\times10^8 M_\odot$ => $\sim 3.9\times10^{11}$ m.
  (Woo & Urry 2002)
- Size of emitting region: $R \leq 1350 R_{\rm S}.$

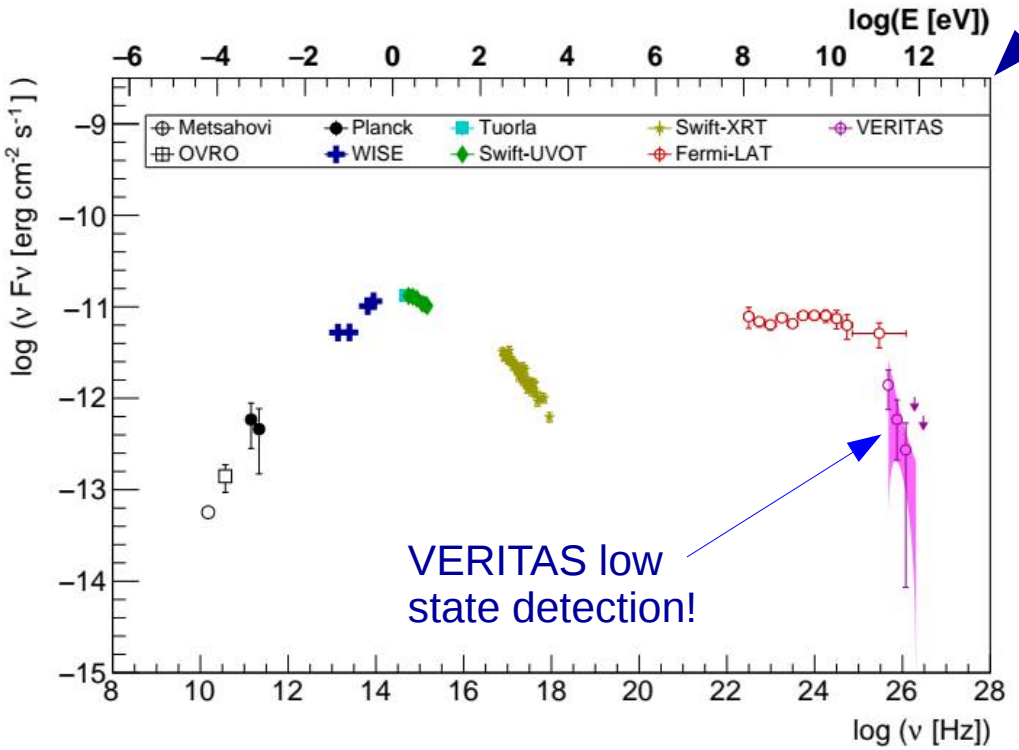
Outline

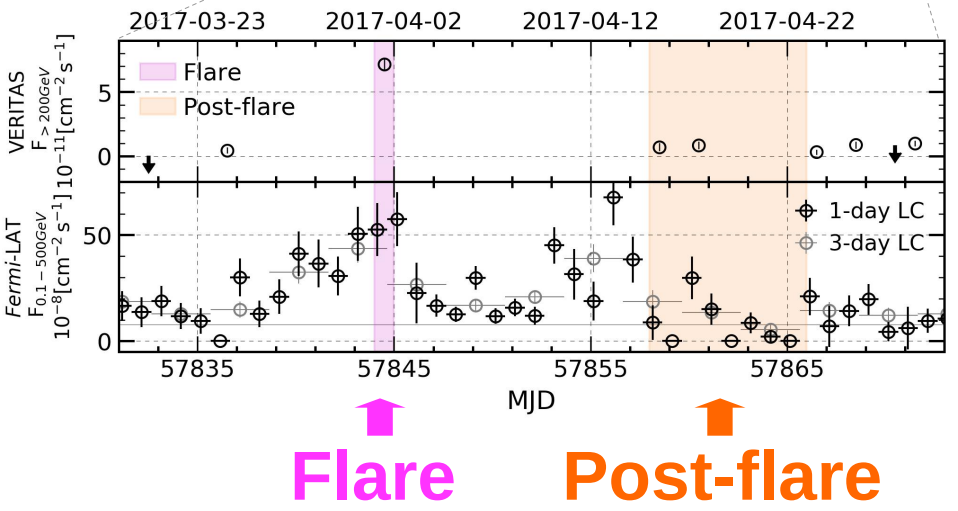
Modeling the spectra in different flux states

No flare detected at any wavelength during the *Fermi*-LAT low state.

Planck & WISE data taken during the low state periods.

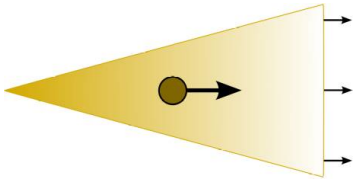




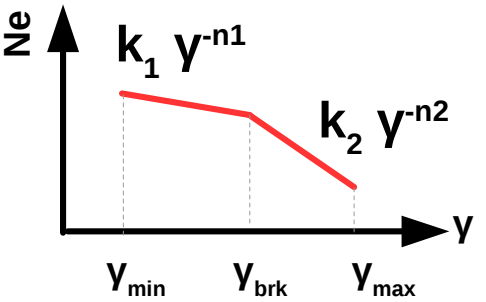


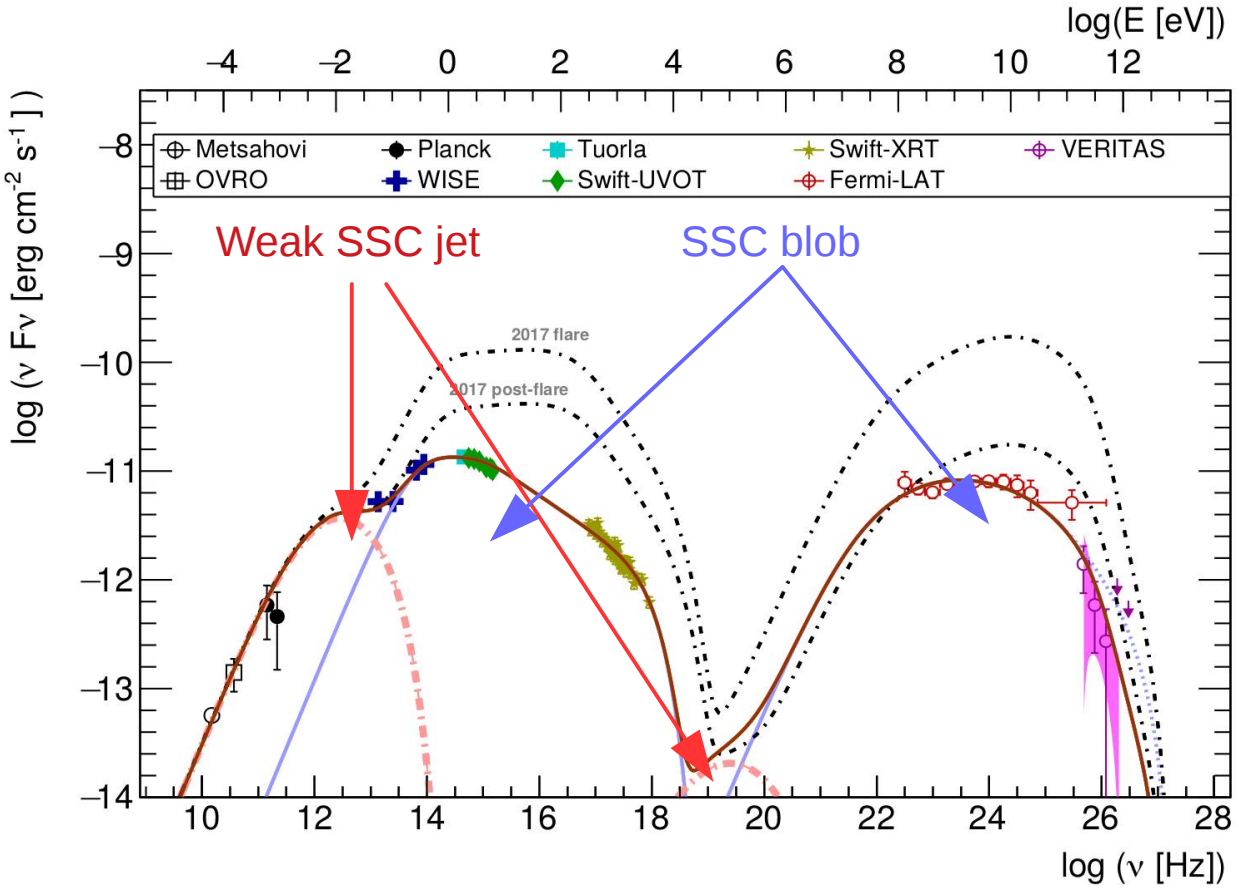
SED modeling: Low state

Blob-in-Jet model (Bjet)
(Hervet et al. 2015)



Particle energy distribution

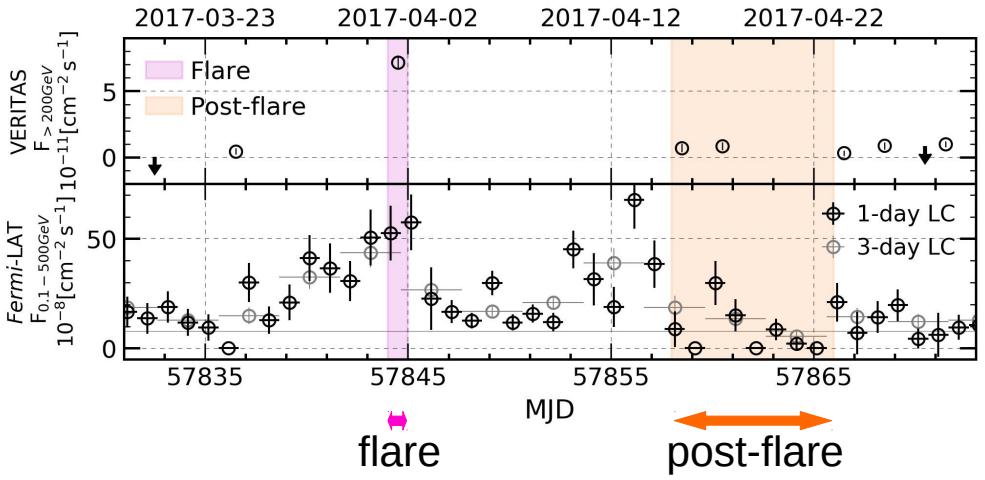


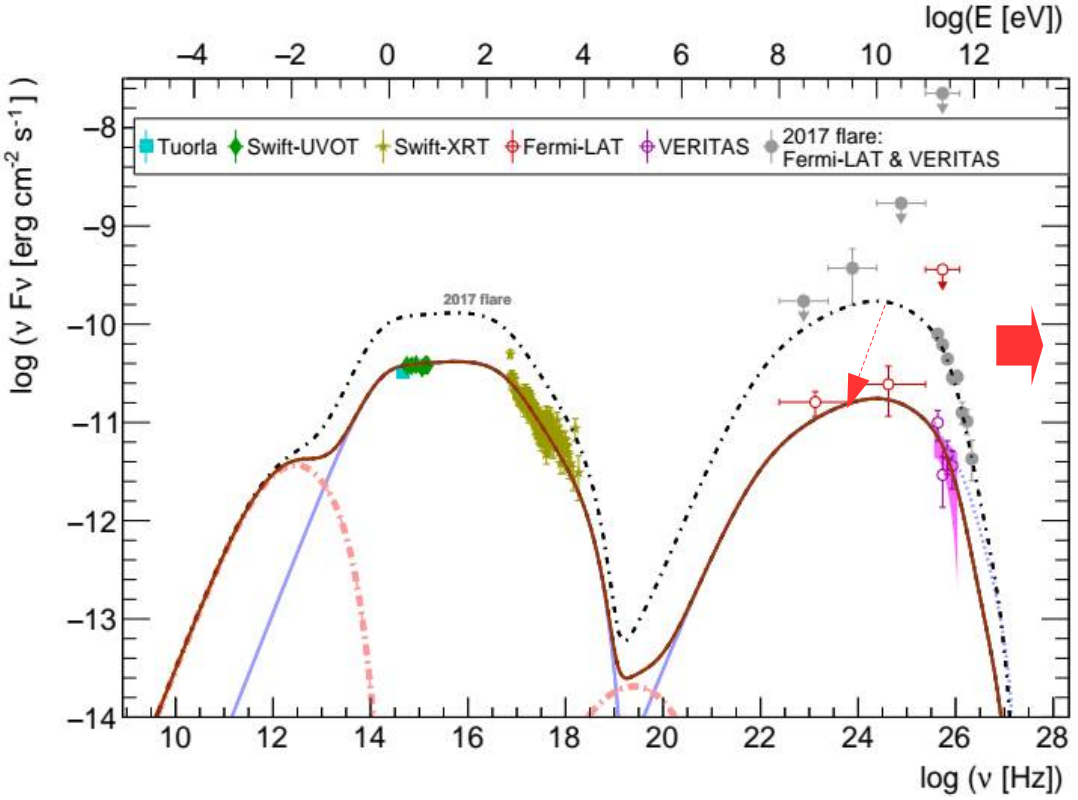


Parameter	Value	Unit
θ	2.0	(°)
Blob		
δ	25	–
K_1	1.5×10^6	cm^{-3}
n_1	2.82	–
n_2	3.7	–
γ_{min}	4.7×10^3	–
γ_{max}	6.5×10^5	–
γ_{brk}	2.0×10^4	–
B	2.0×10^{-2}	G
R	5.8×10^{16}	cm
Jet		
δ	15	–
K	51.3×10^4	cm^{-3}
n	2.82	–
γ_{min}	9.0×10^2	–
γ_{max}	3.5×10^3	–
B_1	3.5×10^{-2}	G
R_1	1.0×10^{17}	cm
L^*	1.0×10^2	pc
$\alpha/2^*$	2.4×10^{-1}	°

* *Host galaxy frame.*

SED modeling: 2017 Apr 1st Flare & post-flare

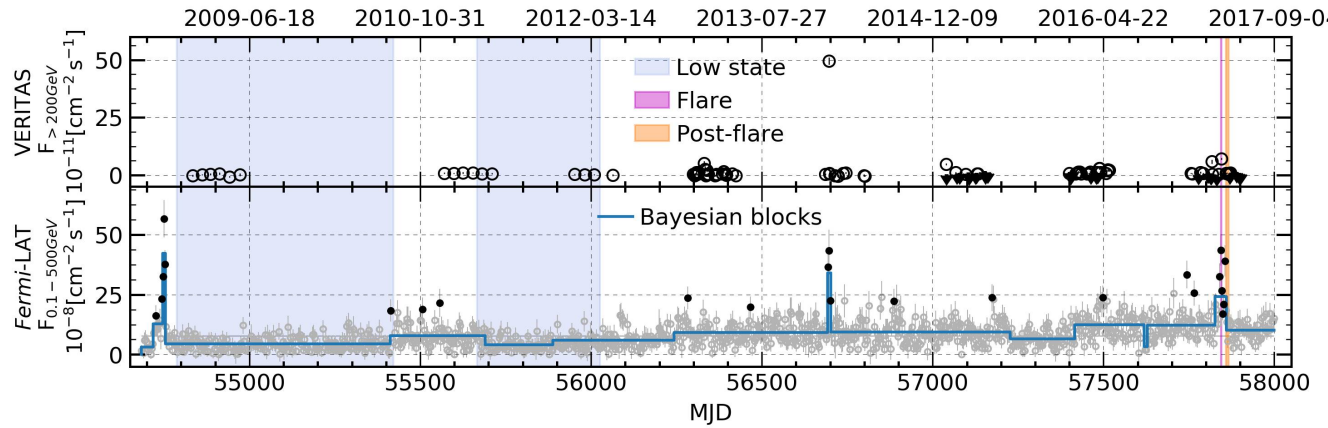


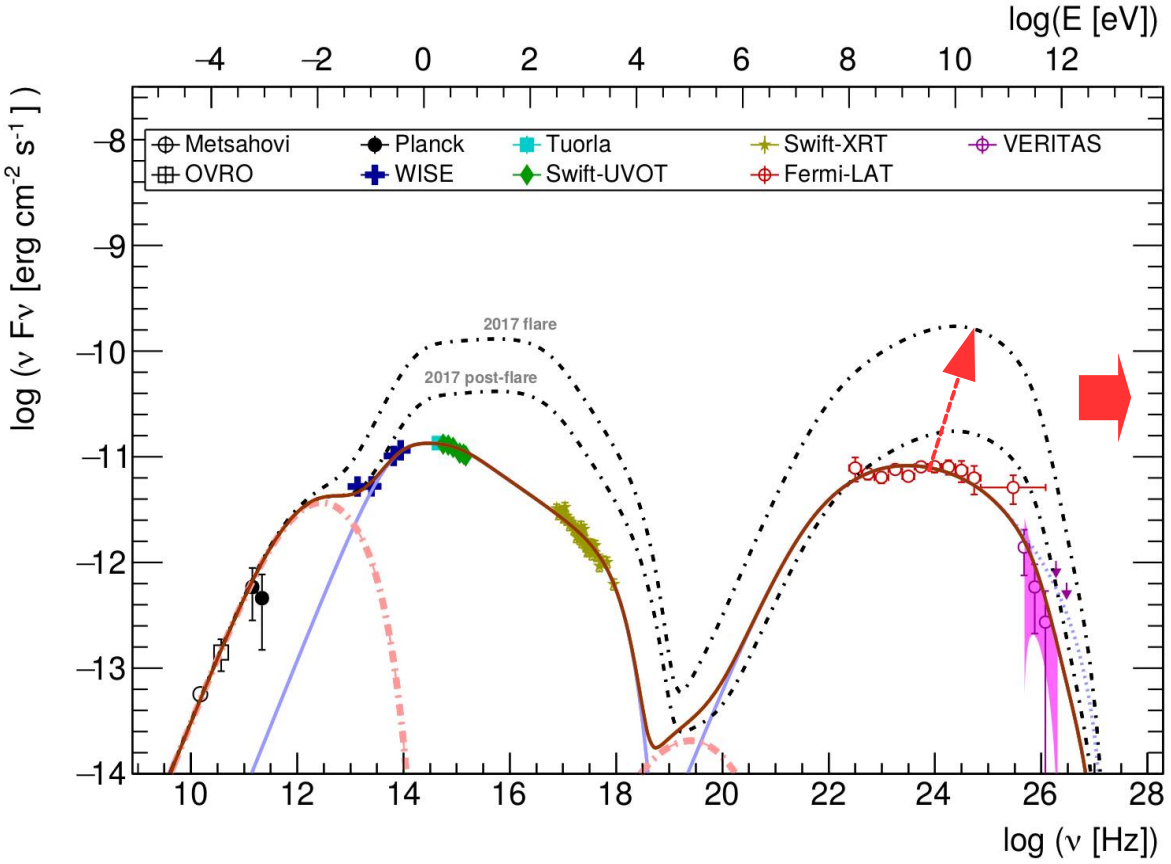


Particle density ÷ ≈ 3

Widely matter dominated blob

SED modeling: from low state to high state





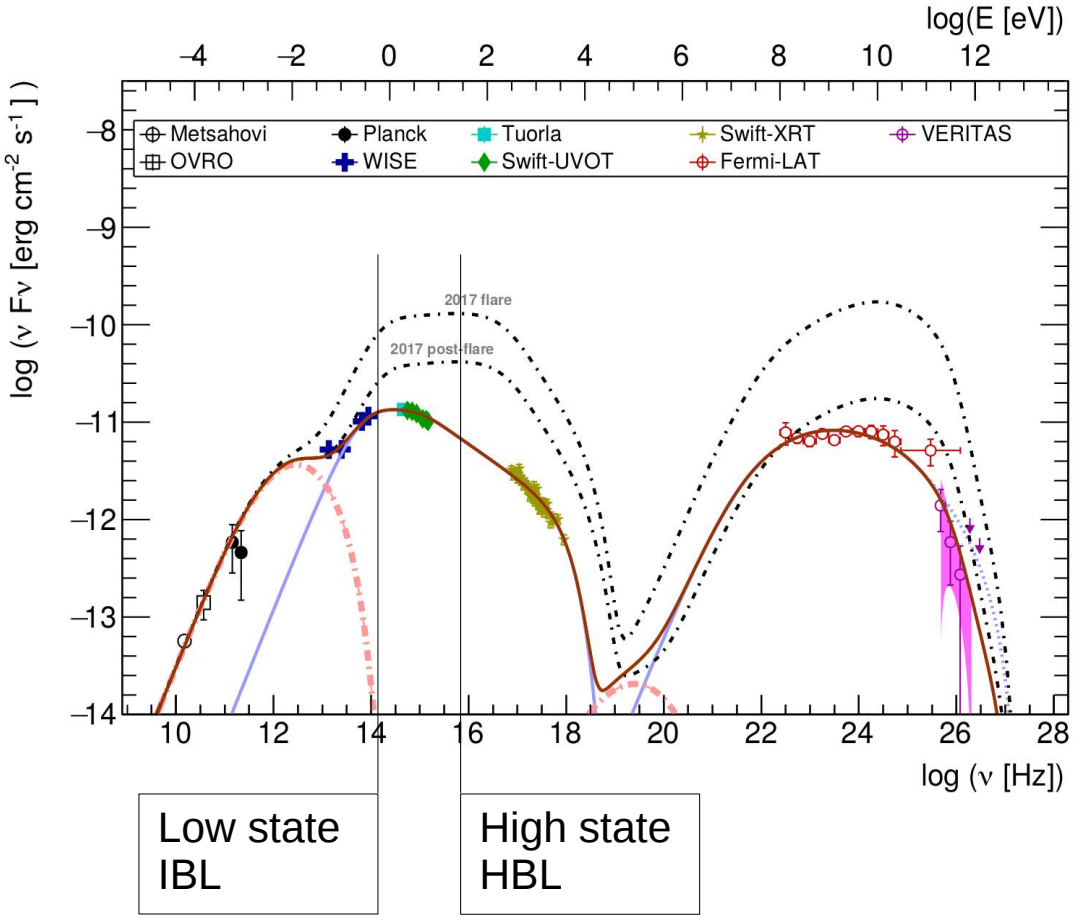
$K_1 \times 3$

$B \times 2.4$

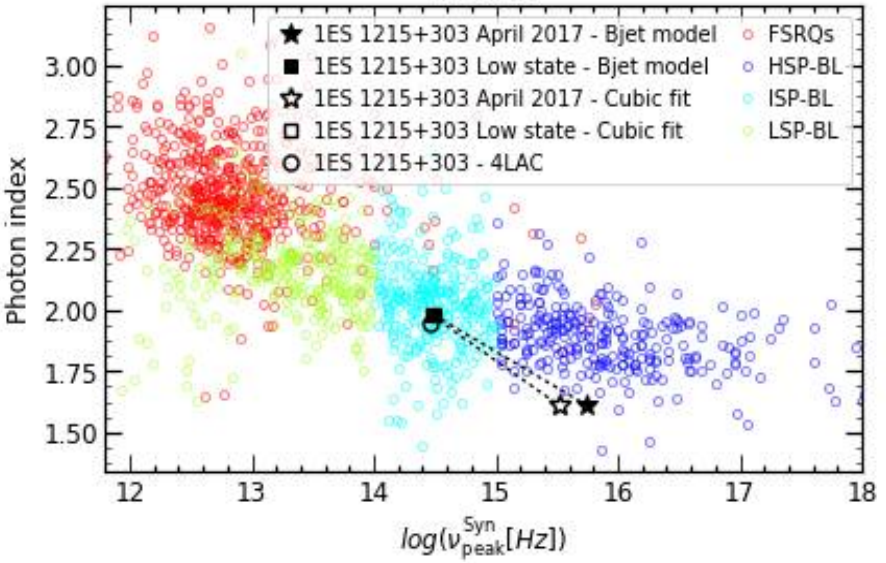
$\gamma_{brk} \times 4.5$

$n_2 \times 1.2$

Dramatic synchrotron peak shift



In 4LAC



Largest IR - X-ray frequency peak shift observed in a BL Lac.

Relatively more efficient adiabatic/advective cooling during flare state.

Main results

The HE and optical domains are strongly temporally correlated, consistent with a SSC emission process.

The HE and optical fluxes follow a log-normal distribution and continuously increase for years, consistent with accreting modulations.

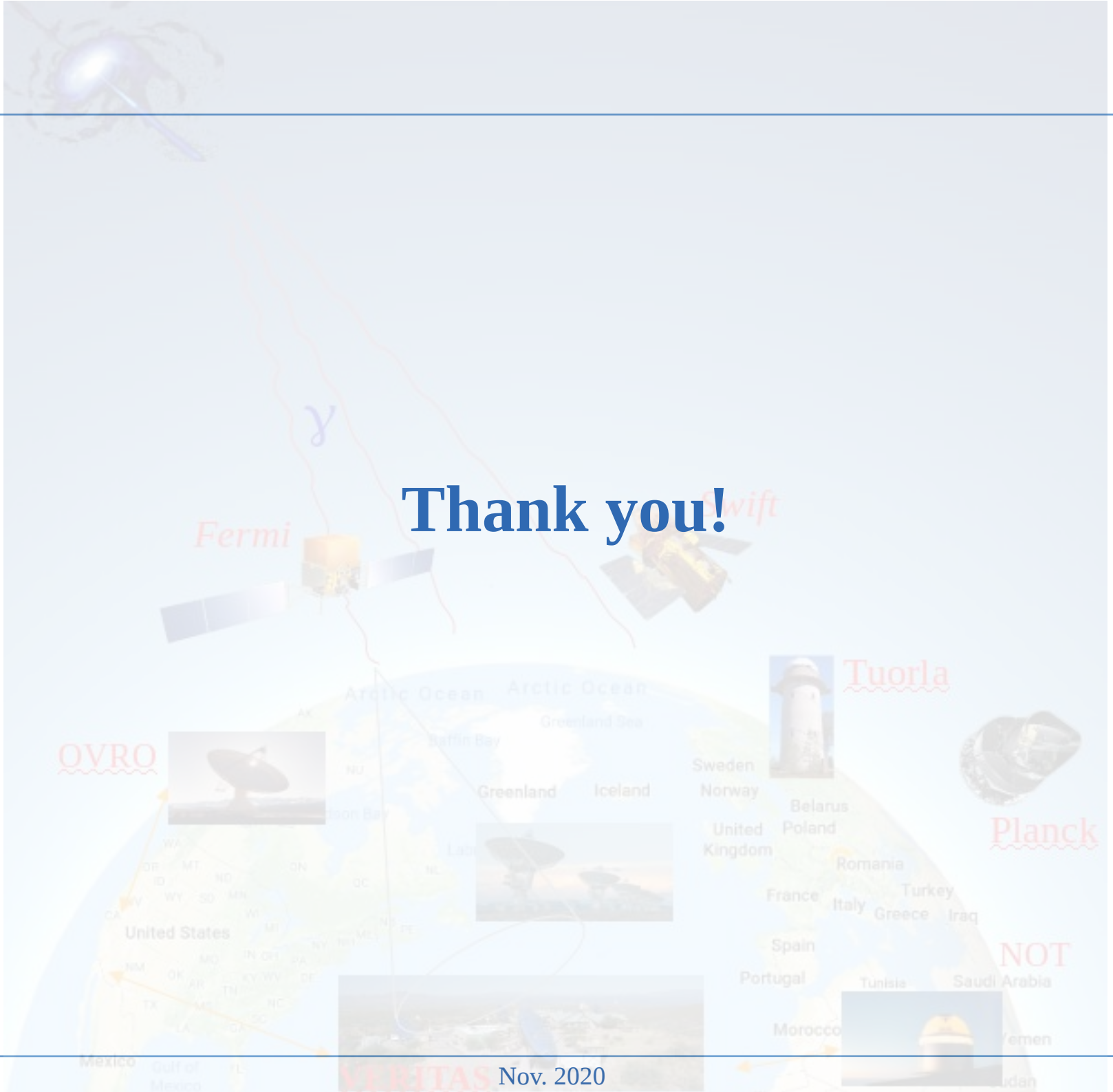
No evidence of QPOs in the Tuorla optical or Fermi-LAT light curve.

Time-resolved SEDs indicates that the individual flares have different characteristics and are likely to have different origins.

Radio structure, flux distributions, and polarizations are typical of TeV HBLs

Long term optical-gamma flux increase & synchrotron peak shift are very unusual.

Thank you!


γ
Fermi
Swift
Tuorla
OVRO
Planck
NOT
VERITAS
Arctic Ocean
Greenland Sea
Baffin Bay
Greenland
Iceland
Sweden
Norway
Belarus
Poland
United Kingdom
Romania
France
Italy
Turkey
Greece
Iraq
Spain
Portugal
Tunisia
Saudi Arabia
Morocco
Yemen
United States
Mexico
Gulf of Mexico