Detection of M 87 with LHAASO

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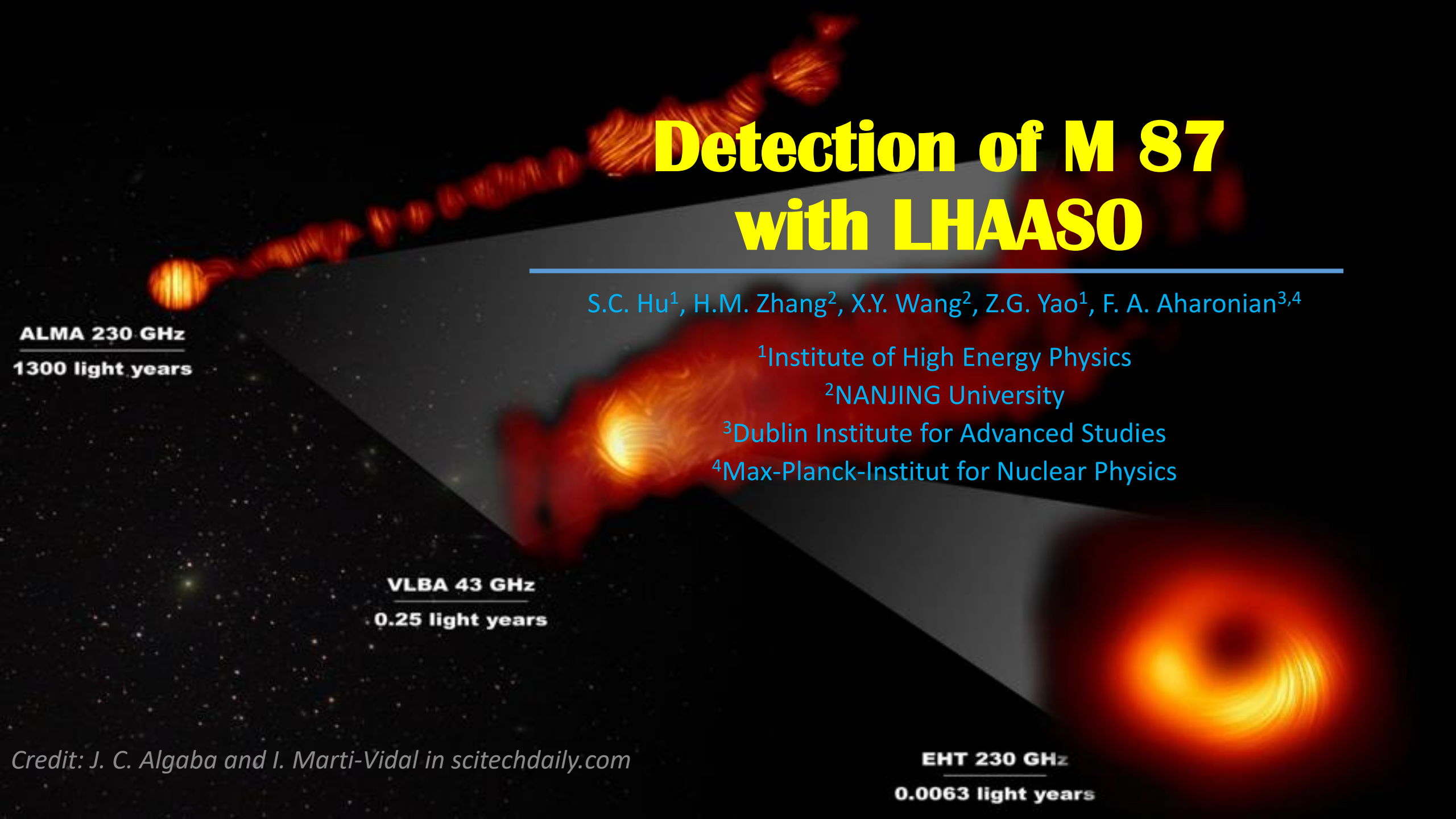


Credit: J. C. Algaba and I. Marti-Vidal in scitechdaily.com

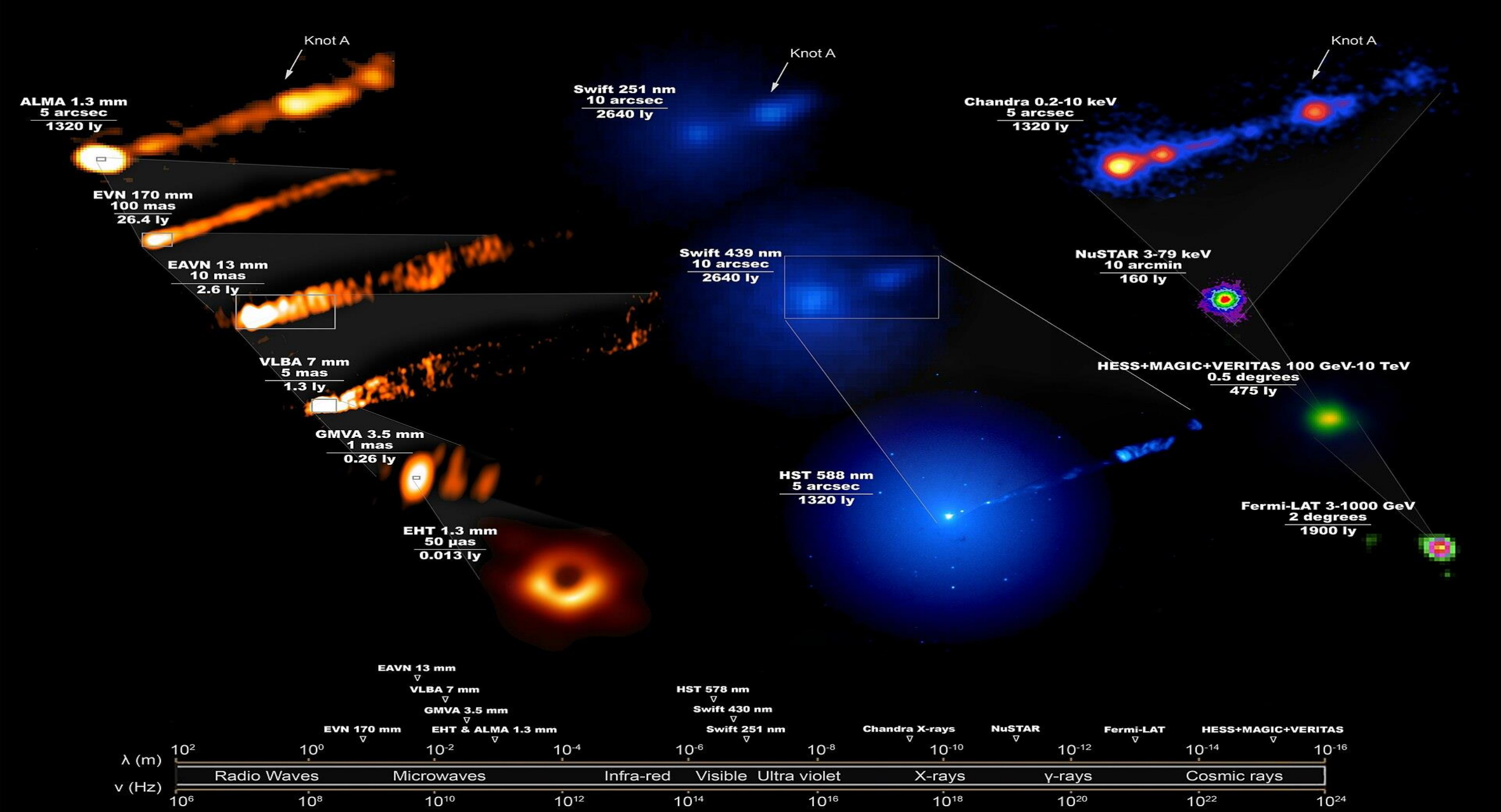
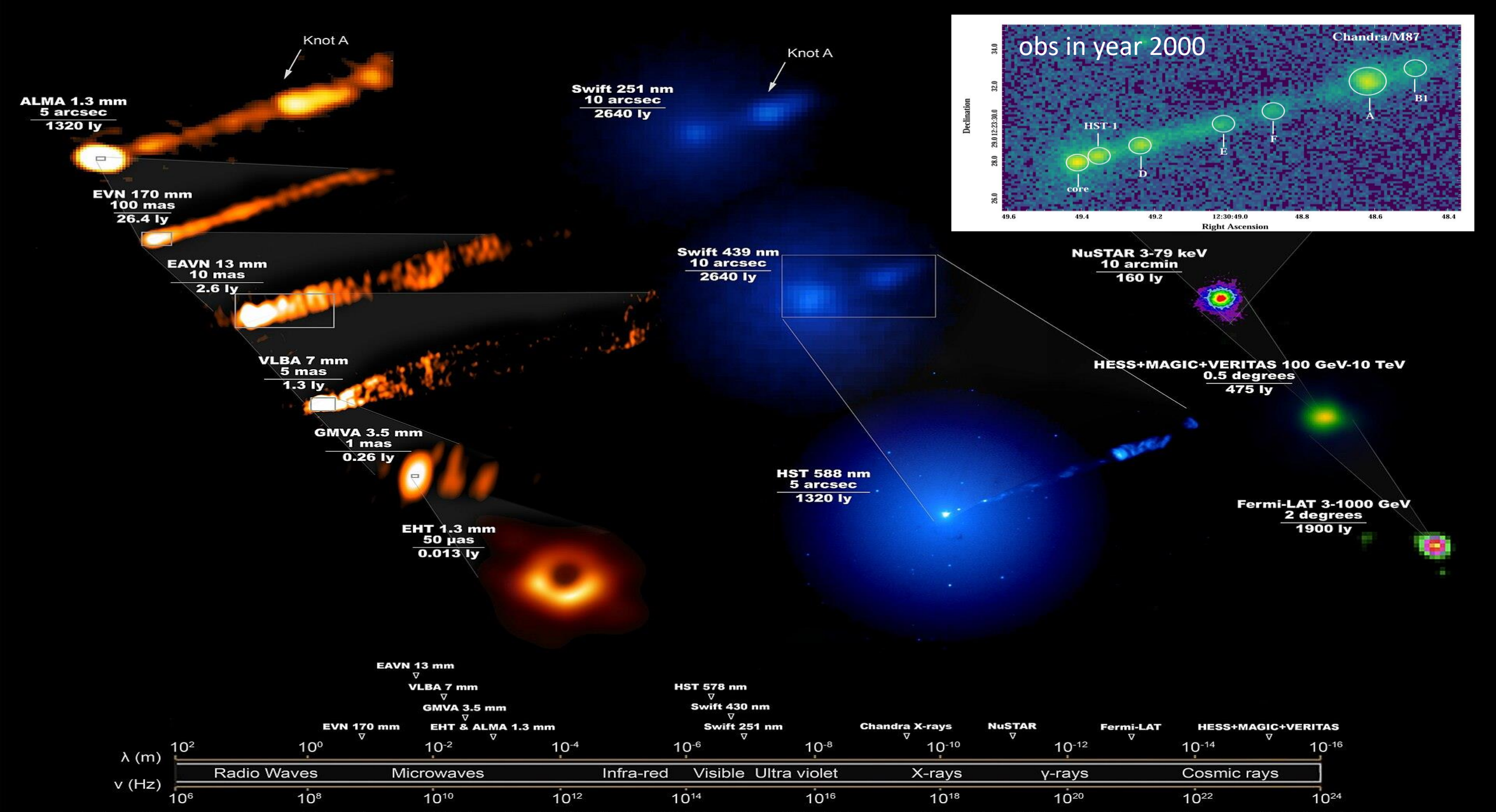


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba



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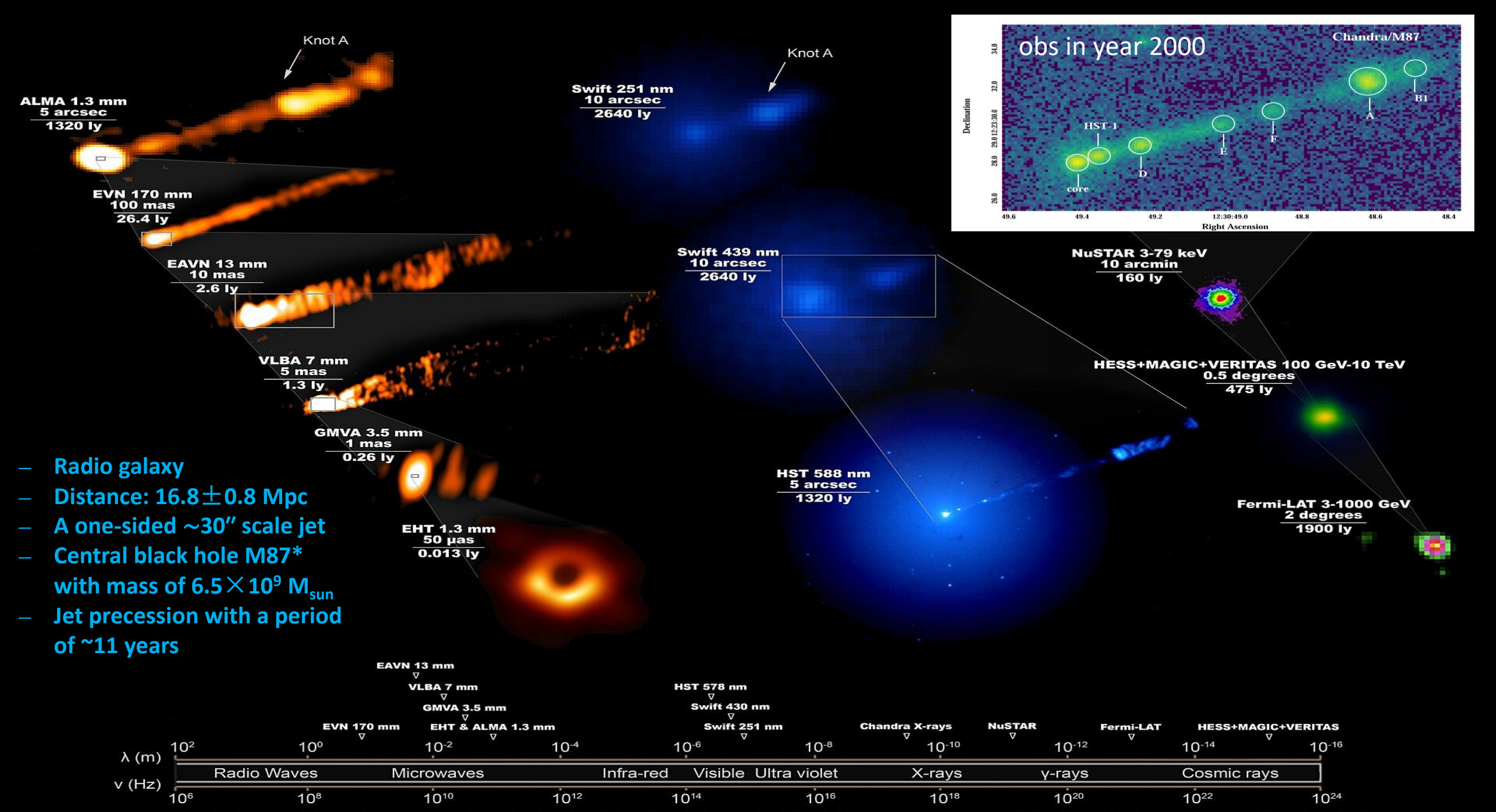
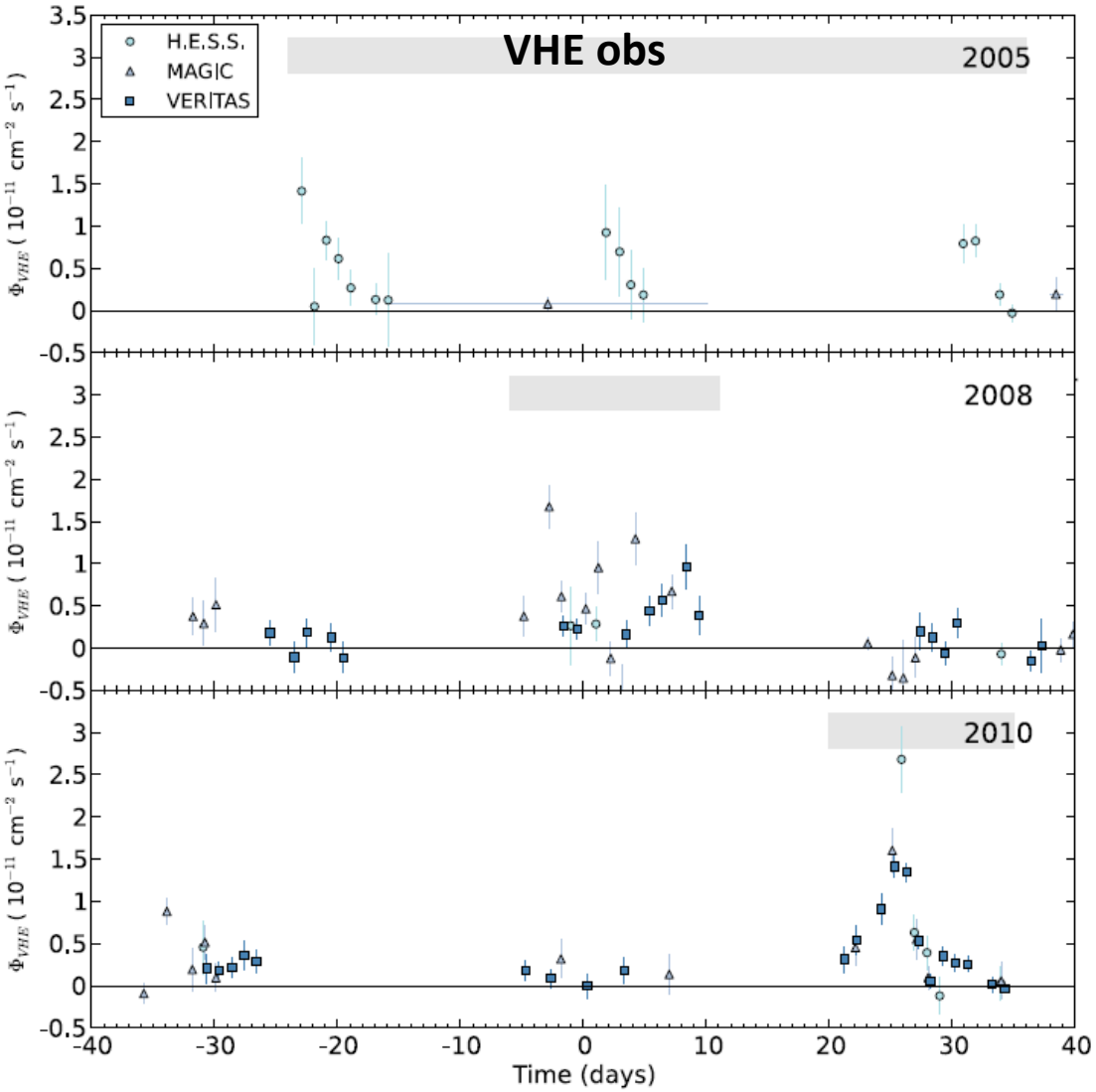


- Radio galaxy
- Distance: 16.8±0.8 Mpc
- A one-sided ~30″ scale jet
- Central black hole M87* with mass of 6.5×10^9 M_{sun}
- Jet precession with a period of ~11 years

Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

VHE observations of M 87



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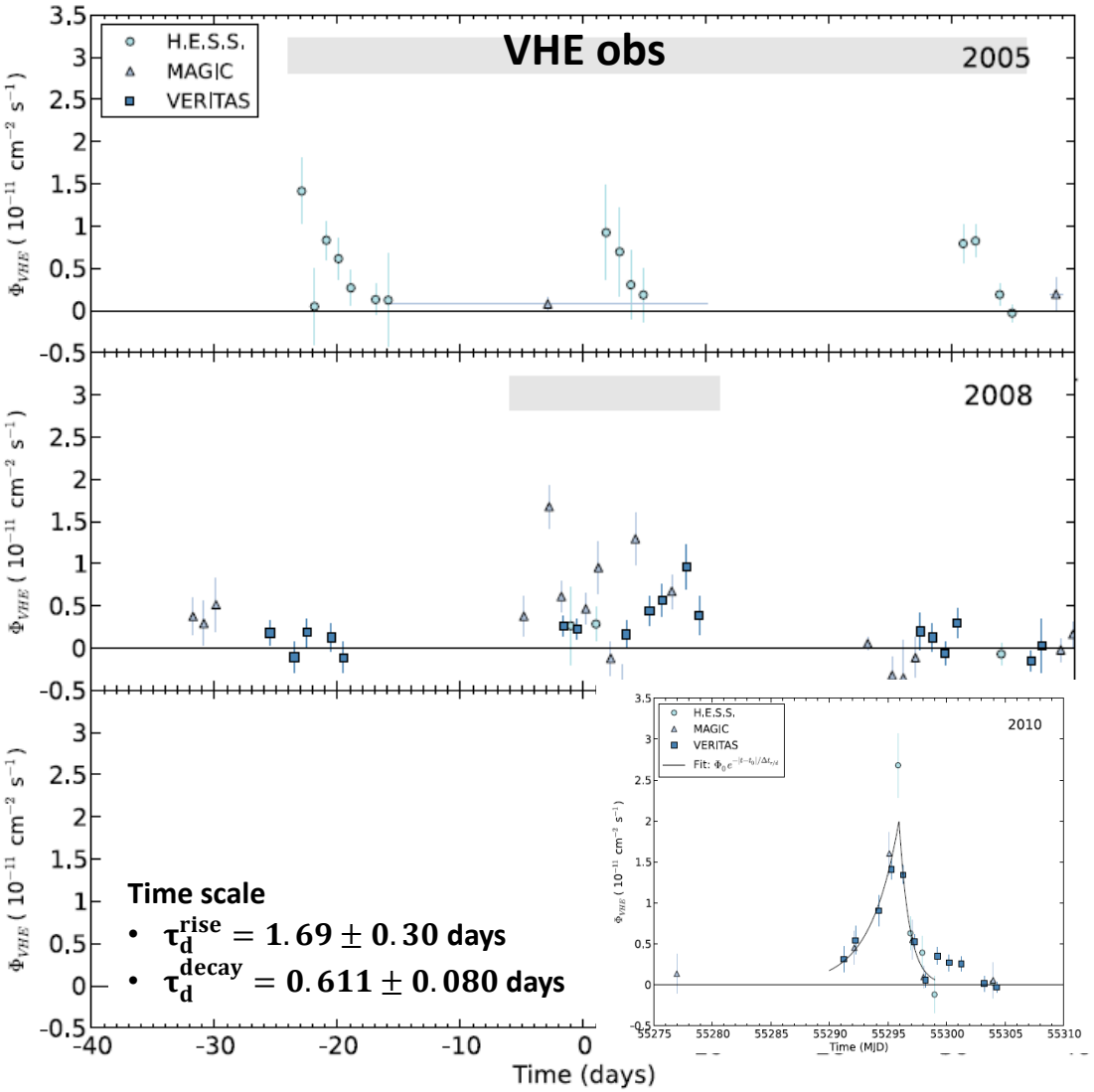

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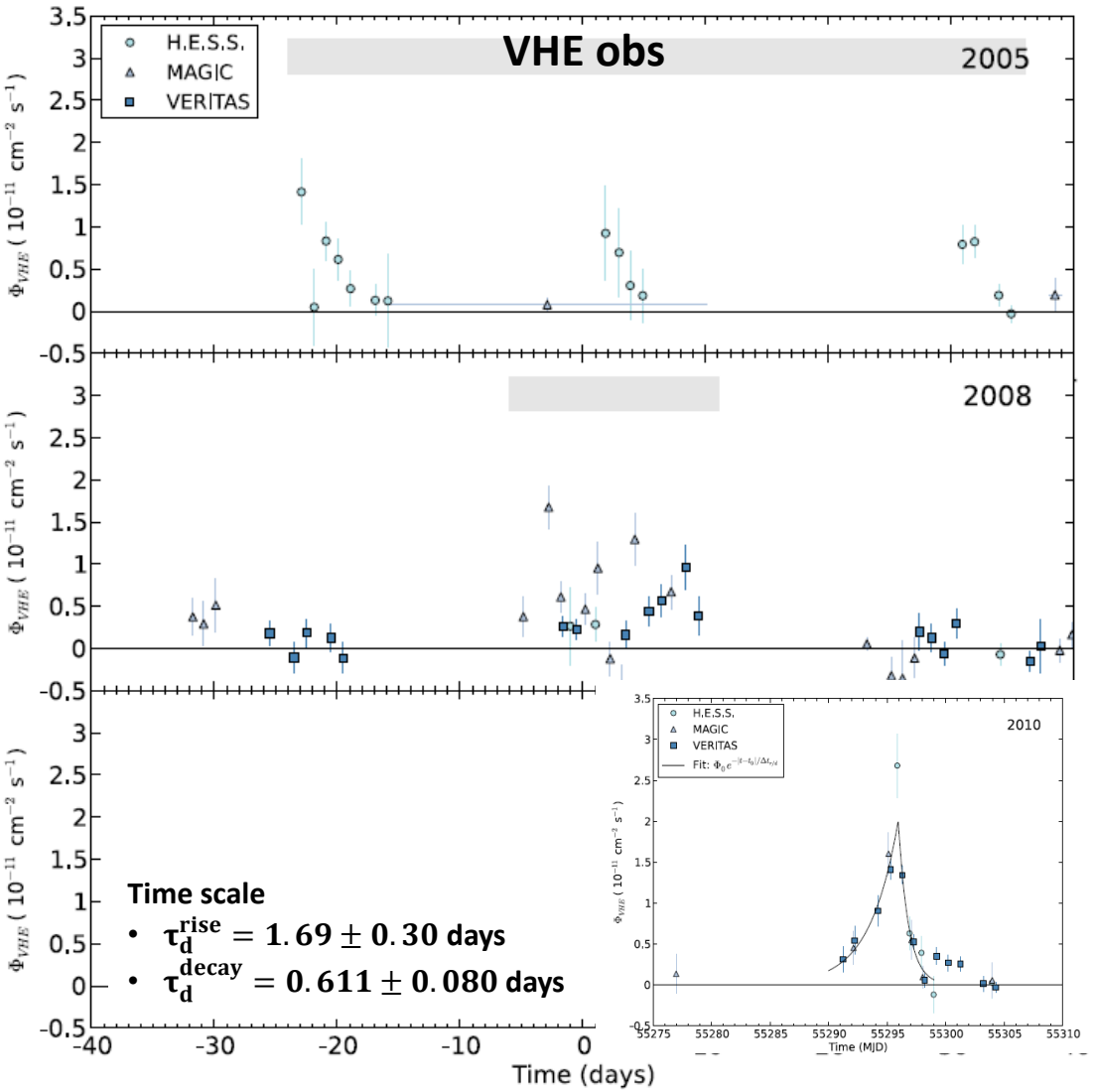

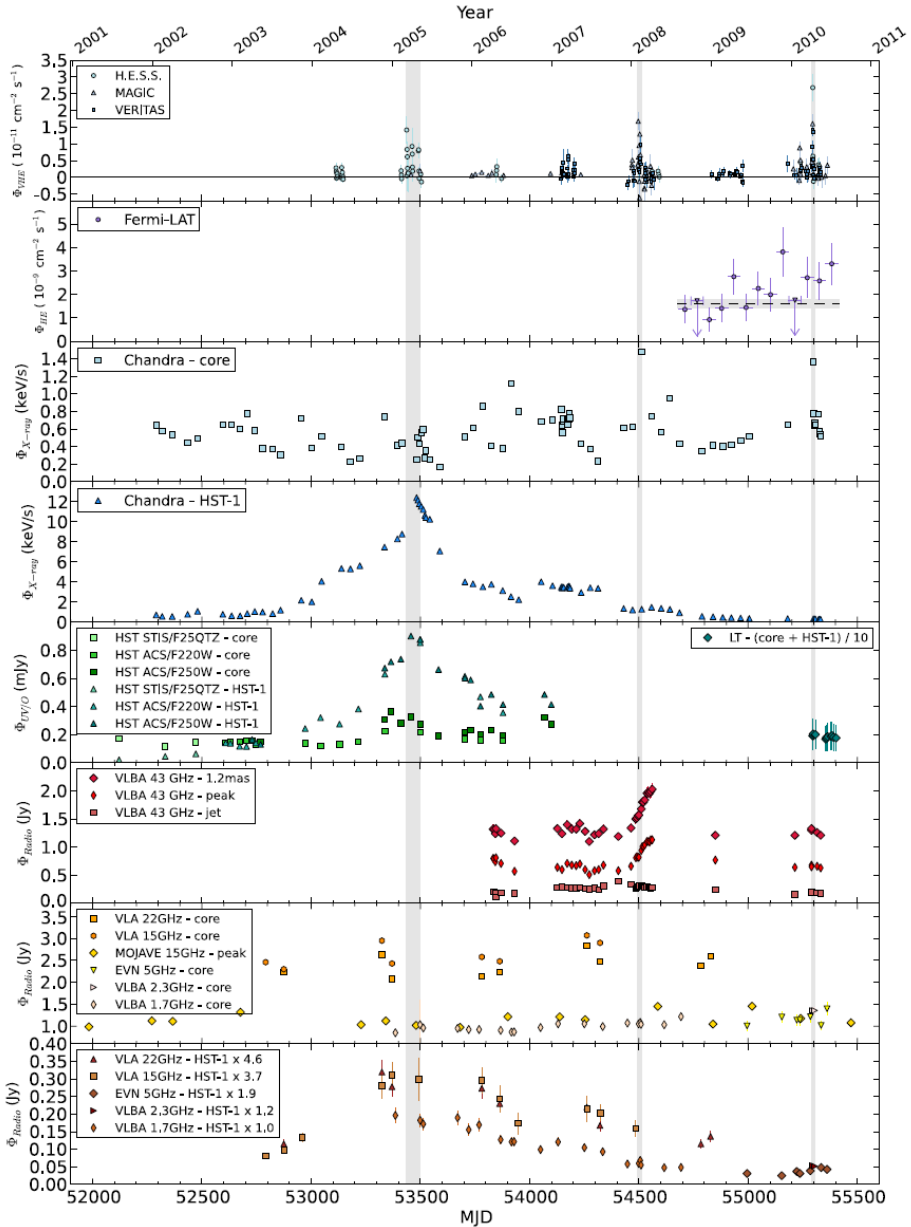

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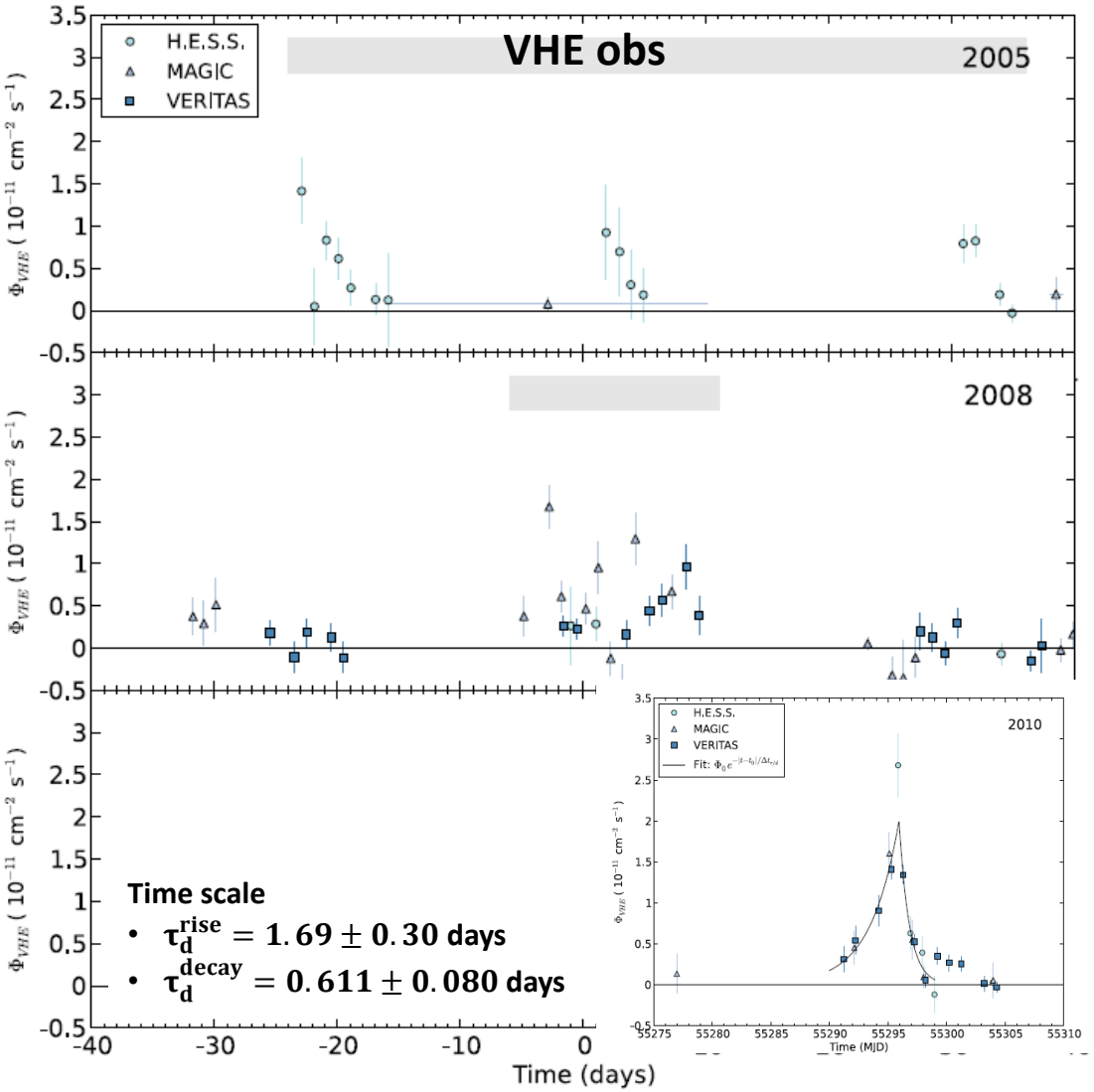
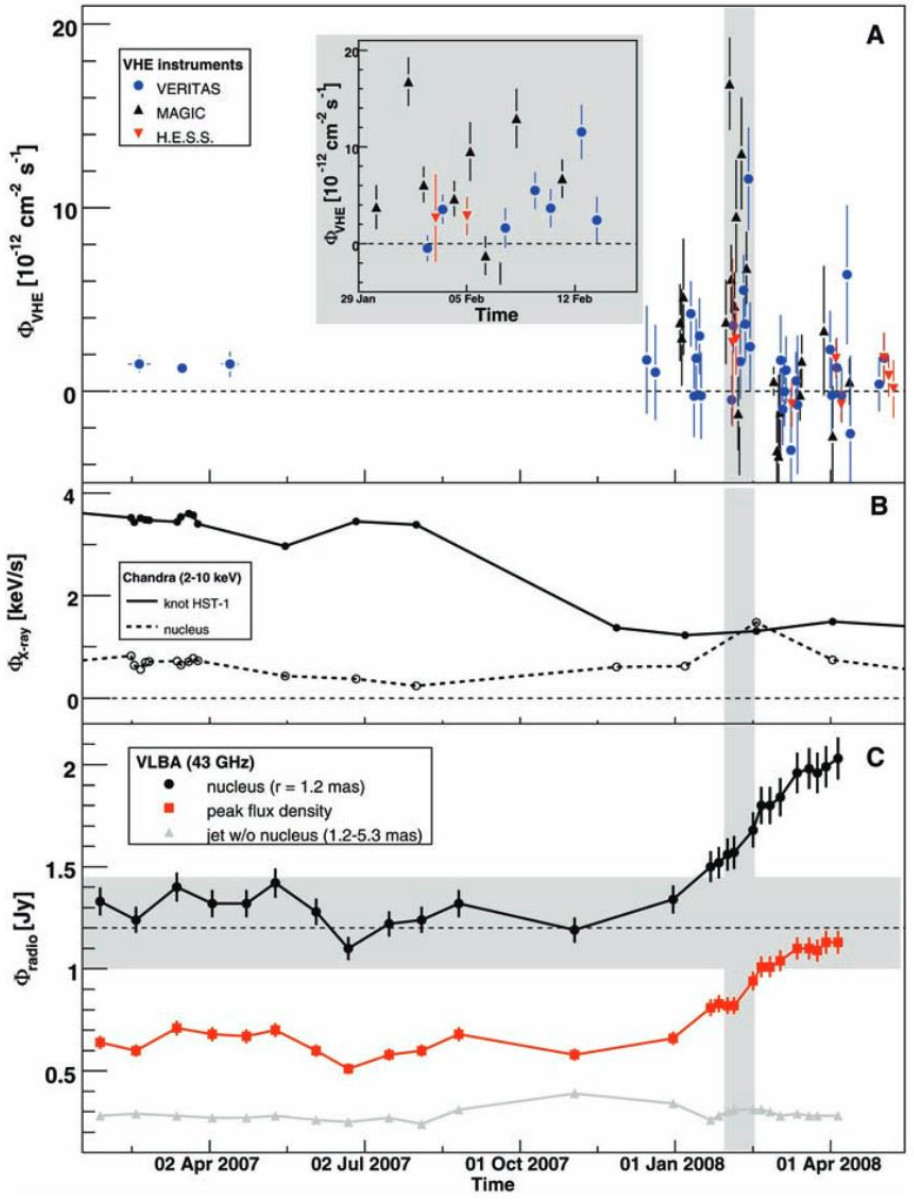
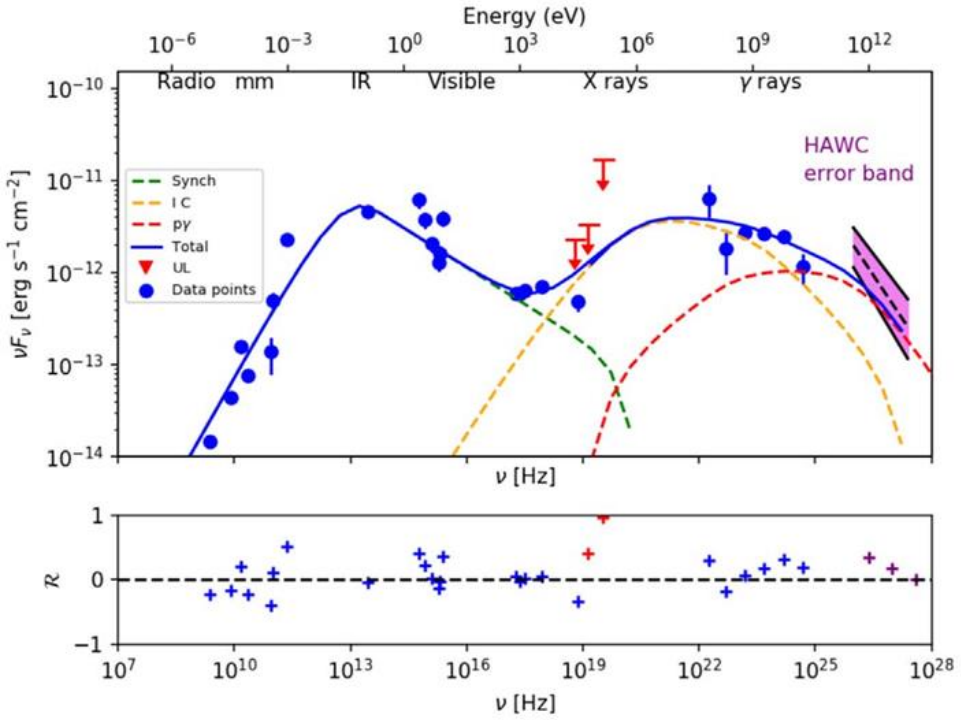


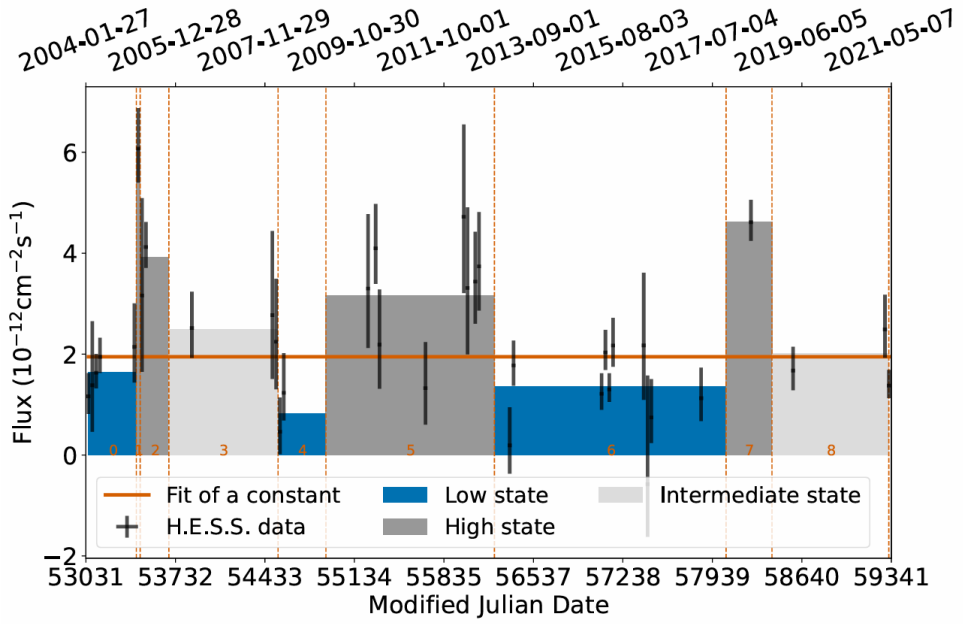


HAWC, 2022



- Significance: ~4 σ
- EBL model: Domínguez et al. (2011)
- Intrinsic $\Gamma = 2.63 \pm 0.22_{\mathrm{sta}} \pm 0.10_{\mathrm{syst}}$

H.E.S.S., 2023-2024



Low state

- Observed $\Gamma = 2.63 \pm 0.09$

High state

- Spectrum: log-parabola
- EBL model: Finke 2022
- Intrinsic $\Gamma = 1.80 \pm 0.08, \beta = 0.27 \pm 0.08$

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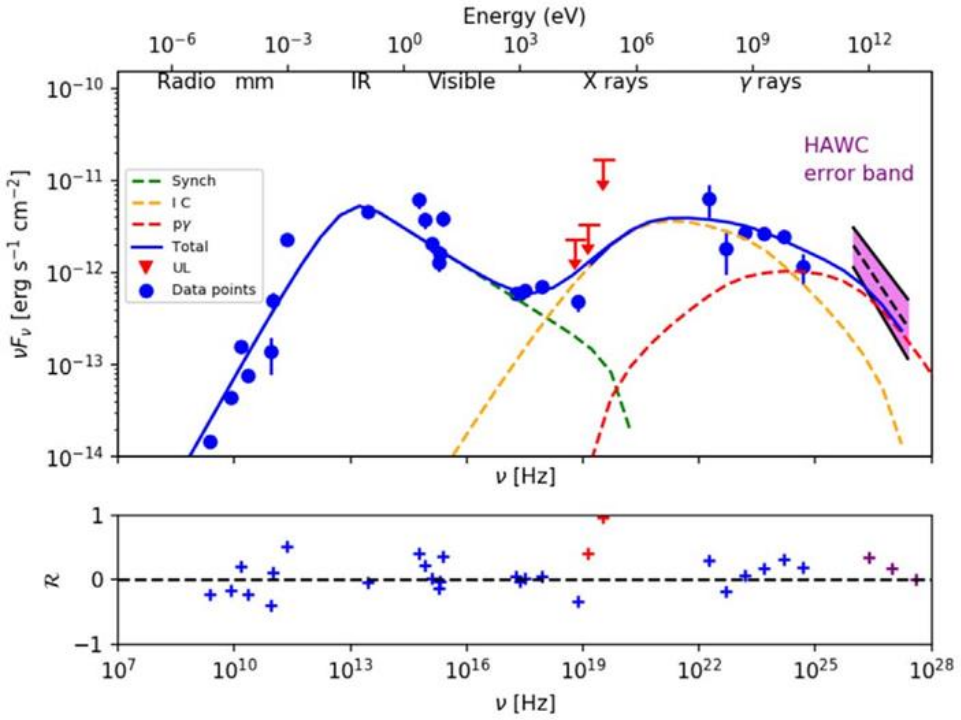

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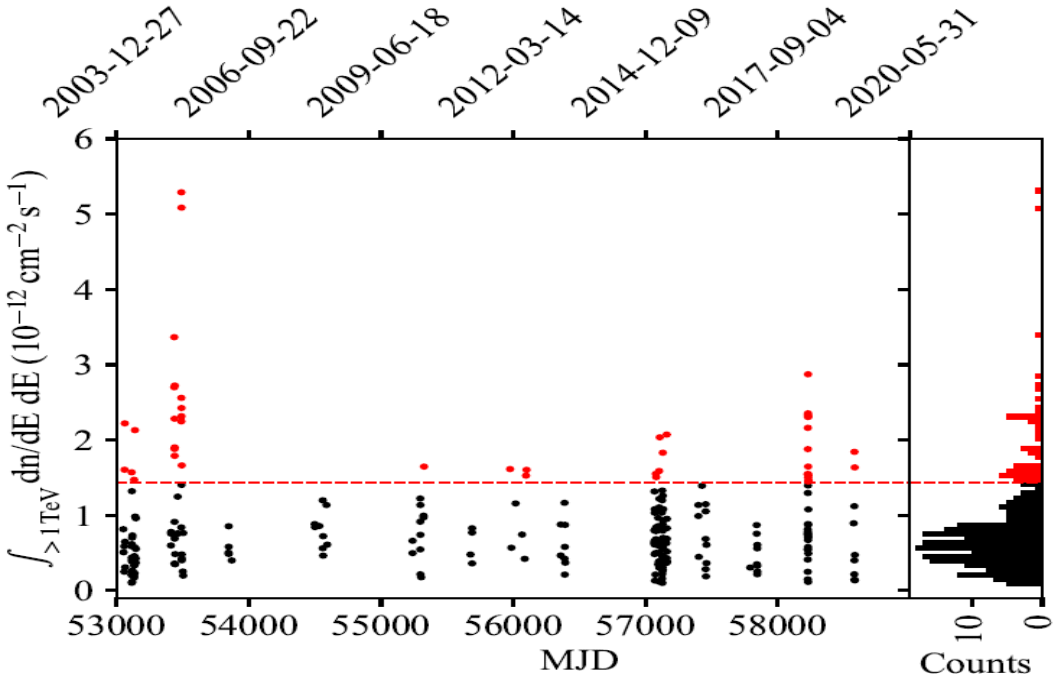

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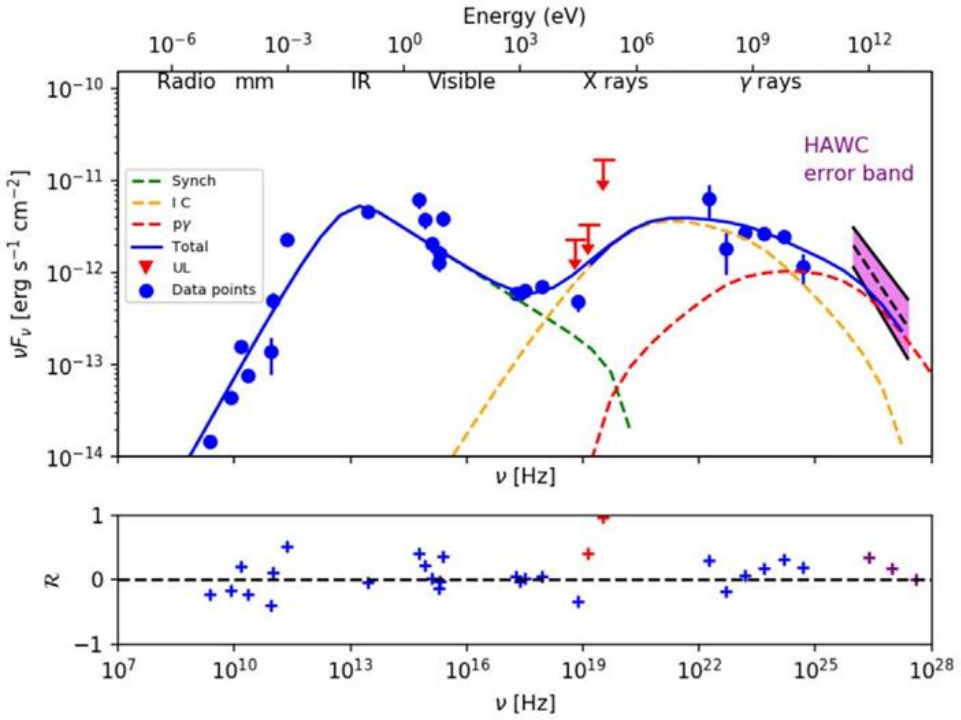

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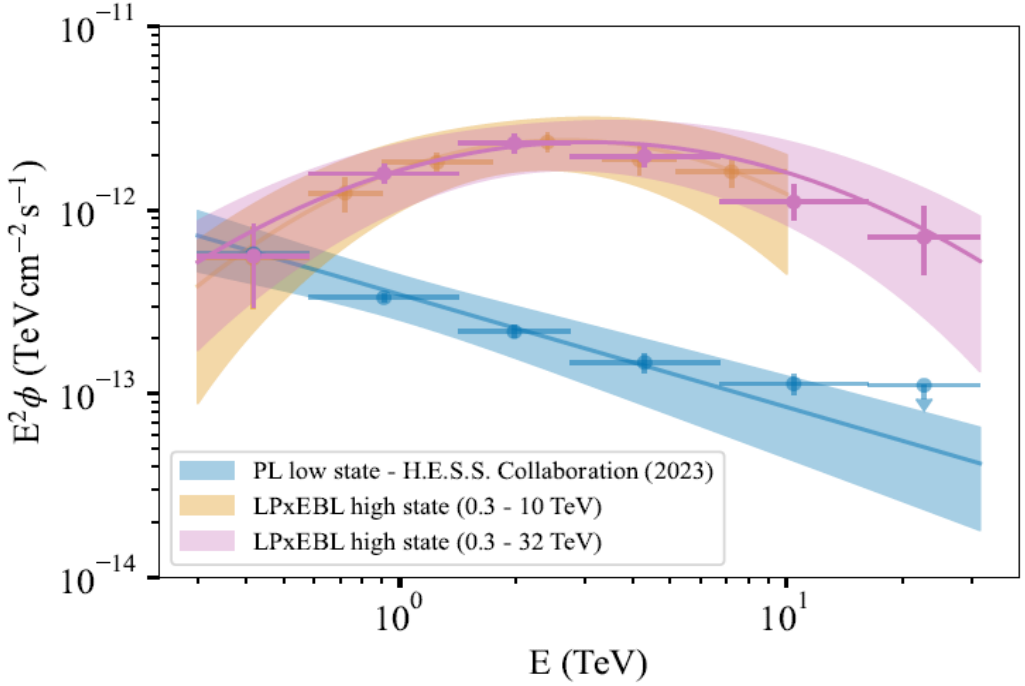

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LHAASO observations

Data

- WCDA 1026 days + KM2A 884 days

Method

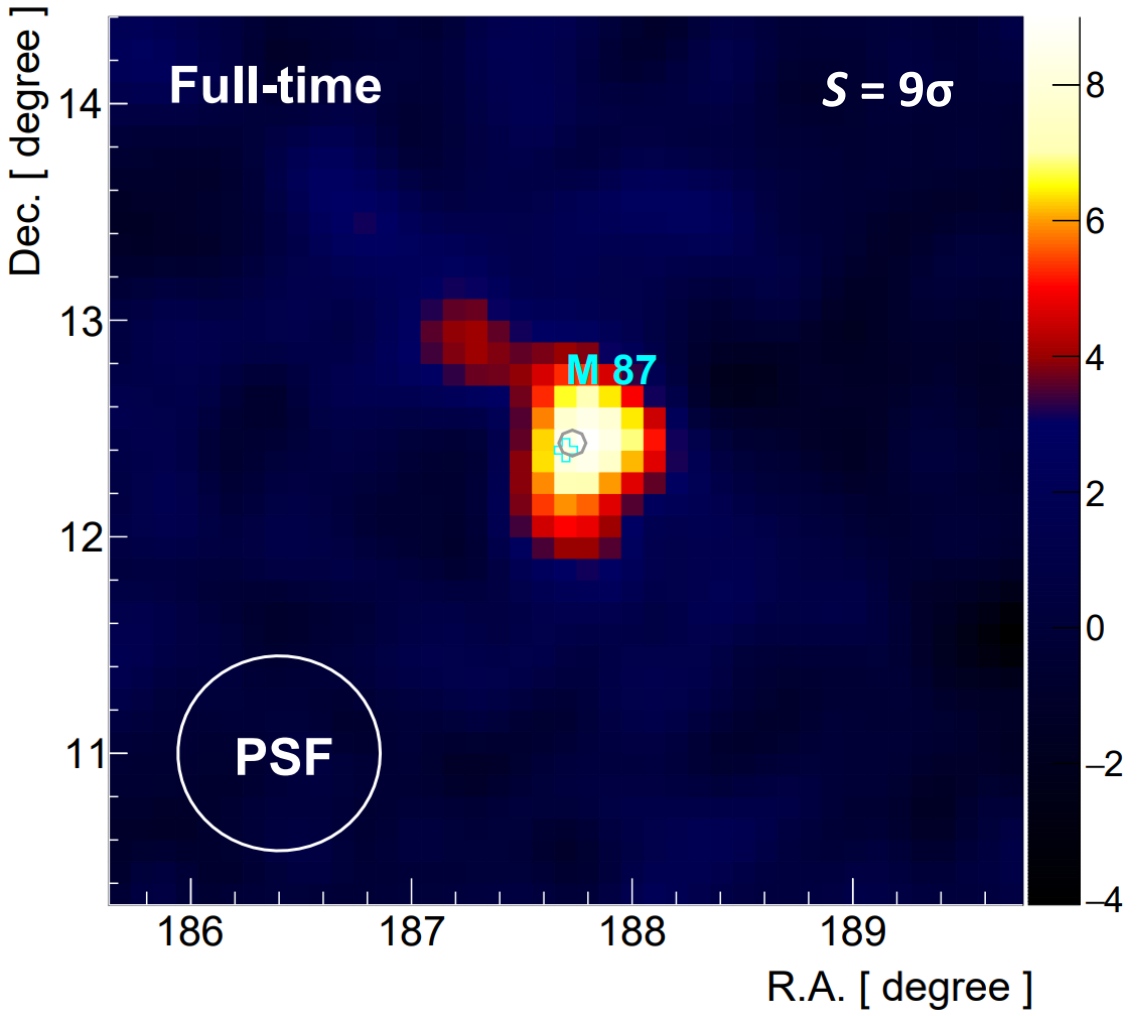
- Background estimation
  - Direct integral method
- Binned maximum likelihood fitting

➢ Best-fit position 0.03°away from the radio position of core

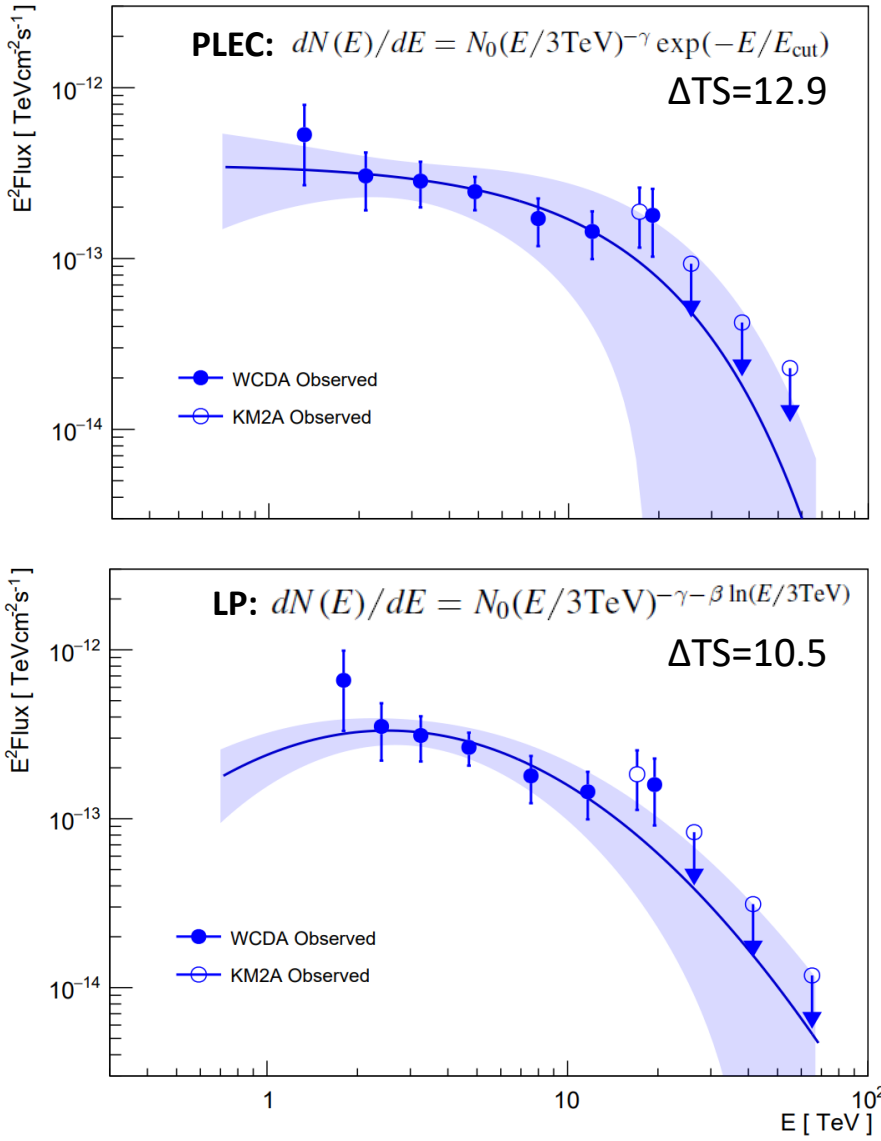
➔ **spatially associated with M 87**

➢ TS between point-like model and extended gaussian model is smaller than 0.1

➔ **no extended emission detected.**



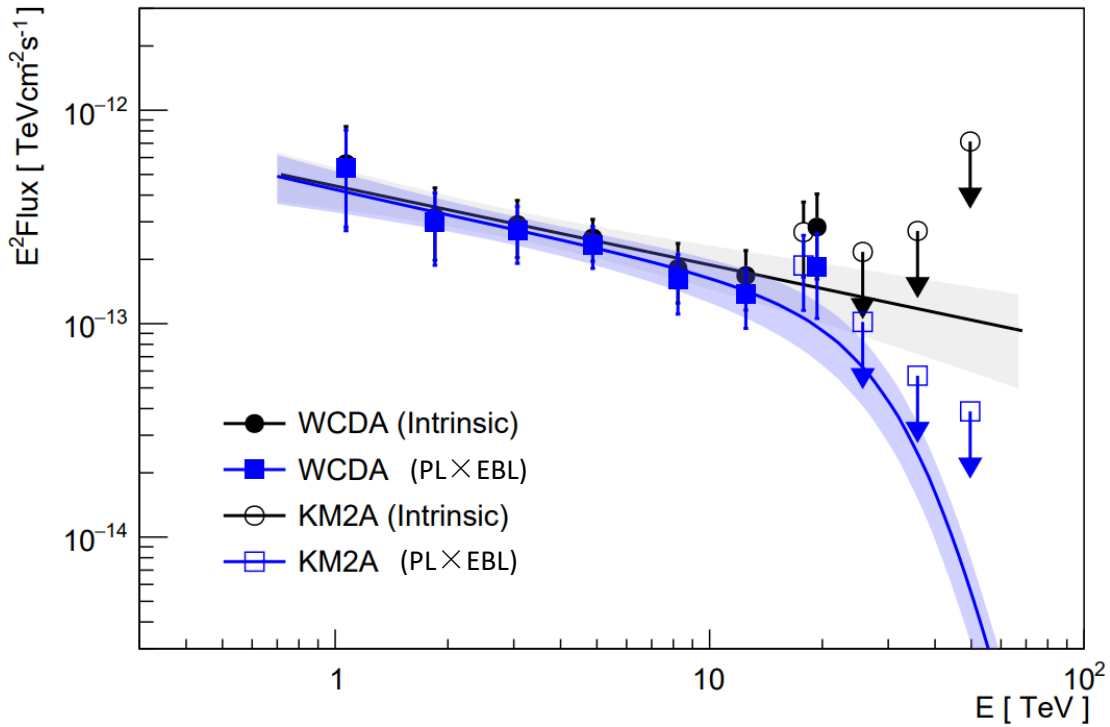
➢ **Observed full-time VHE spectra of M87**



? origin of cutoff shape: absorption of EBL or curved intrinsic SED

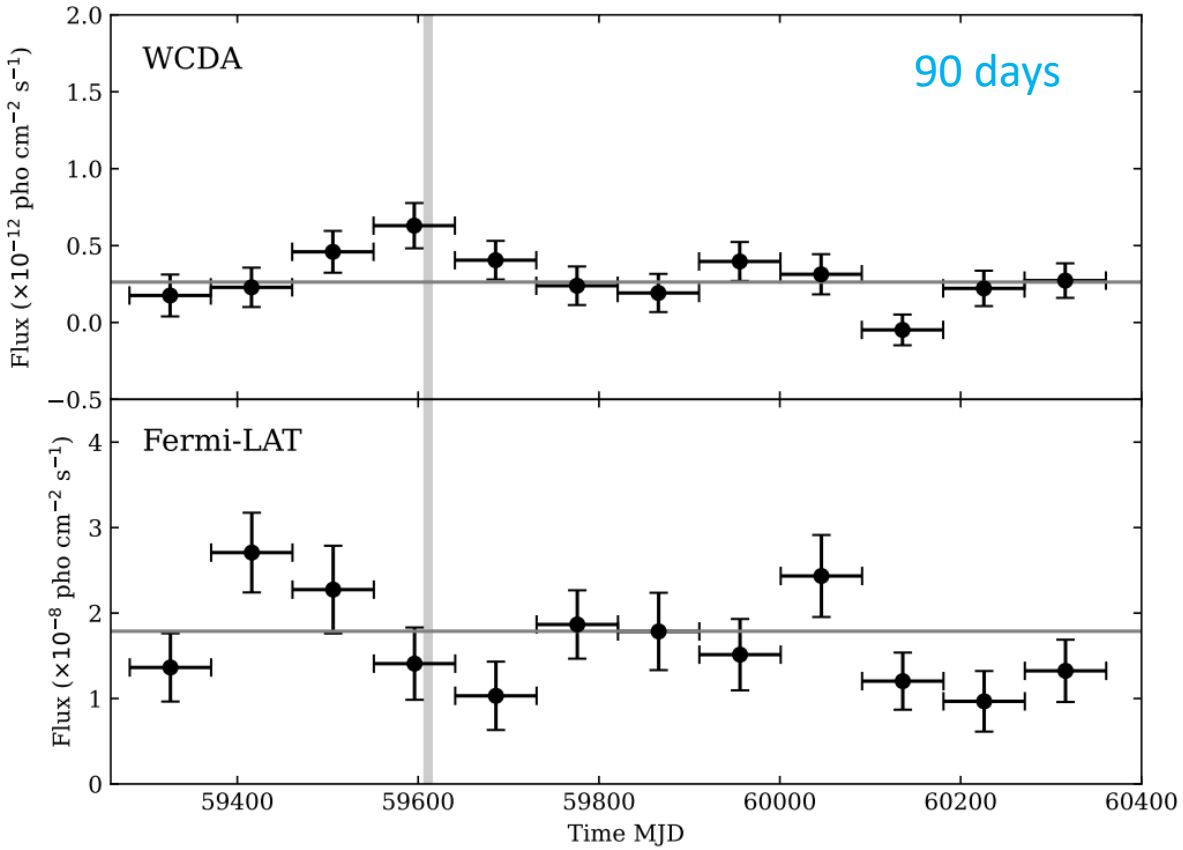
➢ **Intrinsic full-time VHE spectra of M87**

SED model	N_0@3 TeV (10^{-13} TeV^{-1} cm^{-2} s^{-1})	γ	β (E_{cut}/TeV)	$E_{\gamma,\mathrm{max}}$ (TeV)	ΔTS
PL	0.327 ± 0.050	2.37 ± 0.14	···	19.4	0
LP	0.327 ± 0.056	2.37 ± 0.17	$\beta = 0.00 \pm 0.78$	19.4	−0.12
PLEC	0.337 ± 0.058	2.30 ± 0.18	$E_{\mathrm{cut}} = 117 \pm 309$	19.1	0.07



➔ **cutoff shape in the observed SED could be fully caused by EBL**

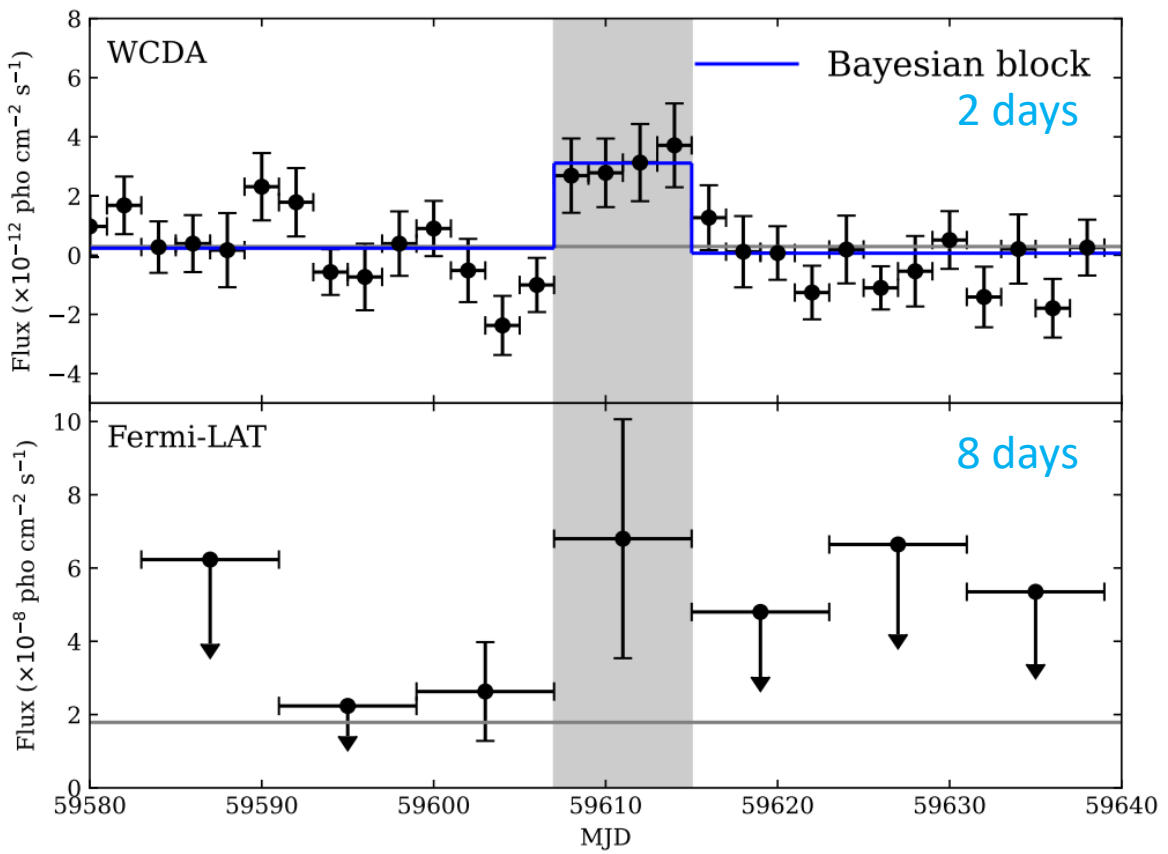
➢ WCDA and Fermi-LAT light curve



- TS of each time interval larger than 4

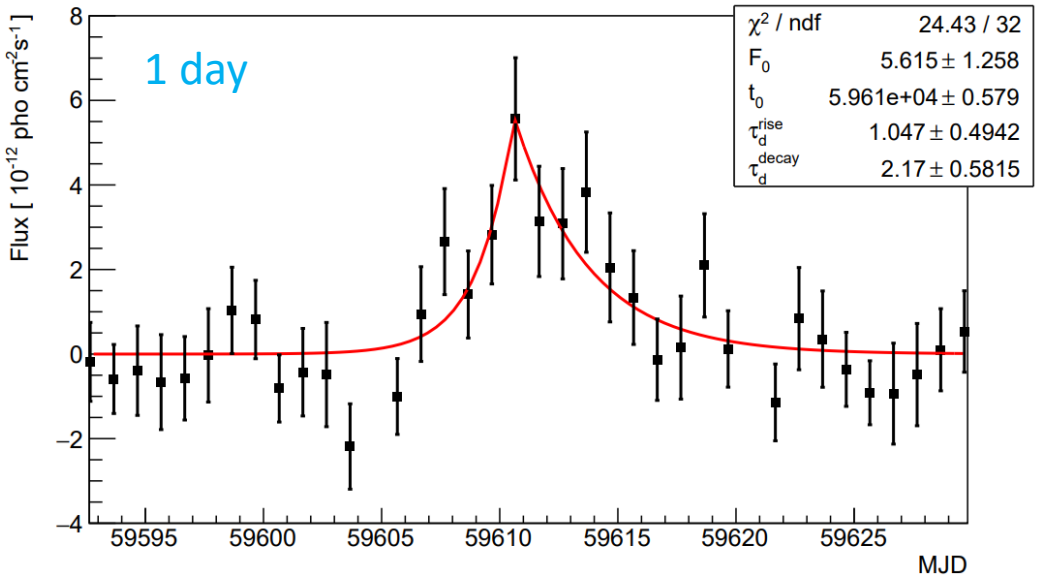
➔ **detection of long-term steady emission**

MJD: 59607-59615



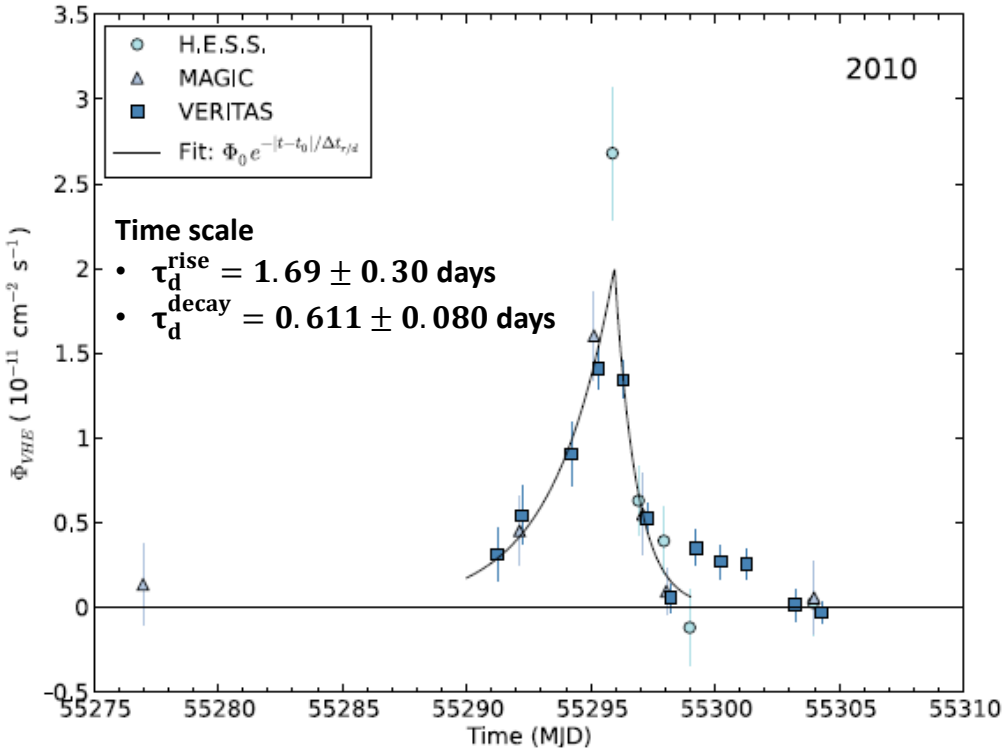
- For 2-days WCDA light curve, likelihood variability test of a constant flux -> p-value of 4×10^{-3}
- Post-trial significance of M 87 within the block is 4.4σ

➢ Temporal analysis: time scale of the flare



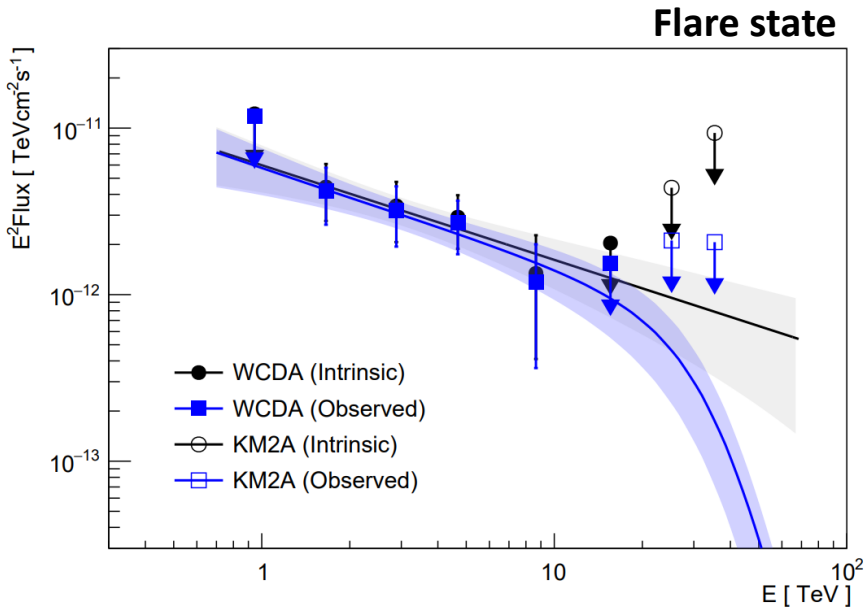
$$\Phi = \Phi_0 \times e^{-|t-t_0|/\Delta\tau} \text{ with } \begin{cases} \Delta\tau = \Delta\tau^{\text{rise}} \text{ for } t < t_0 \\ \Delta\tau = \Delta\tau^{\text{decay}} \text{ for } t \geqslant t_0 \end{cases}$$

Parameter	Value	Unit
Fit range	59593–59629	MJD
F_0	$(5.43 \pm 1.22) \times 10^{-13}$	$\text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$
t_0	59610 ± 0.58	MJD
τ_d^{rise}	1.05 ± 0.49	day
τ_d^{decay}	2.17 ± 0.58	day



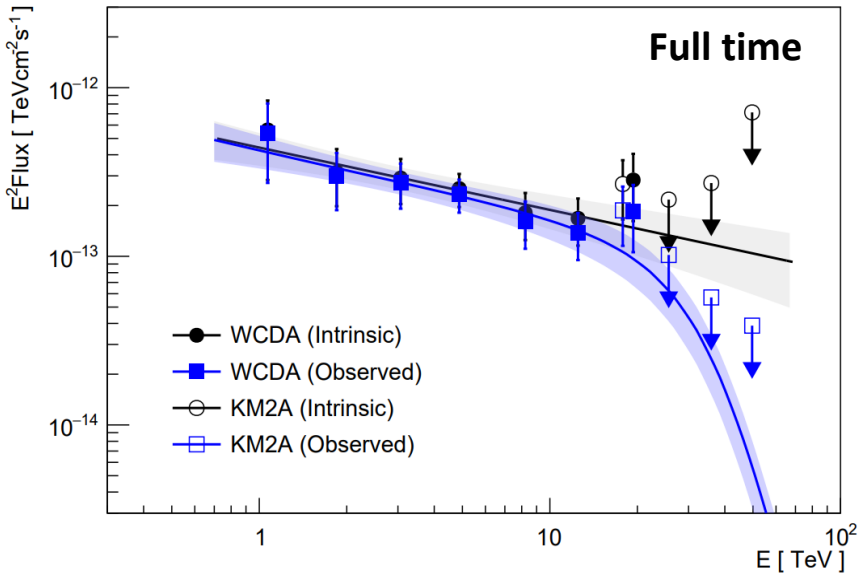
➔ **The variability time scale is ~1 day, similar to that of the 2010 flare**

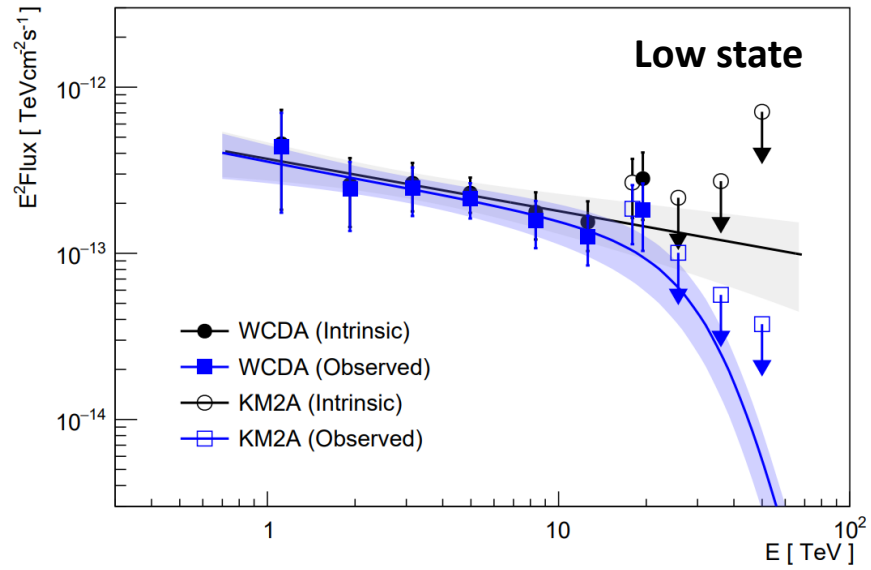
➢ Temporal analysis: SED



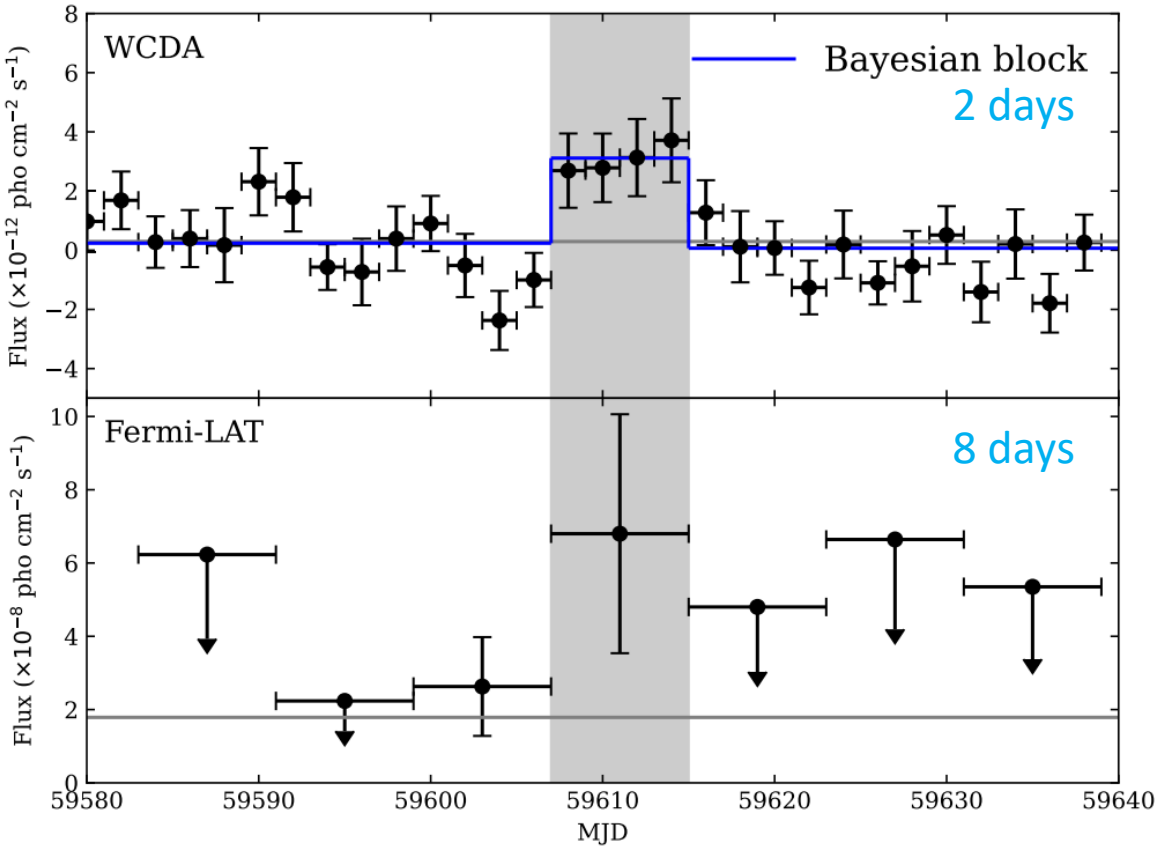
State	TS	N_0@3 TeV ($TeV^{-1}\ cm^{-2}\ s^{-1}$)	γ
Full time	87.4	$(3.27 \pm 0.50) \times 10^{-14}$	2.37 ± 0.14
Flare	40.1	$(3.56 \pm 0.67) \times 10^{-13}$	2.57 ± 0.23
Low	76.0	$(2.91 \pm 0.53) \times 10^{-14}$	2.31 ± 0.17

- The spectral index of the flare is slightly softer than that of the full-time data.
- The integral flux of flare state is 13 times higher than that of low state.

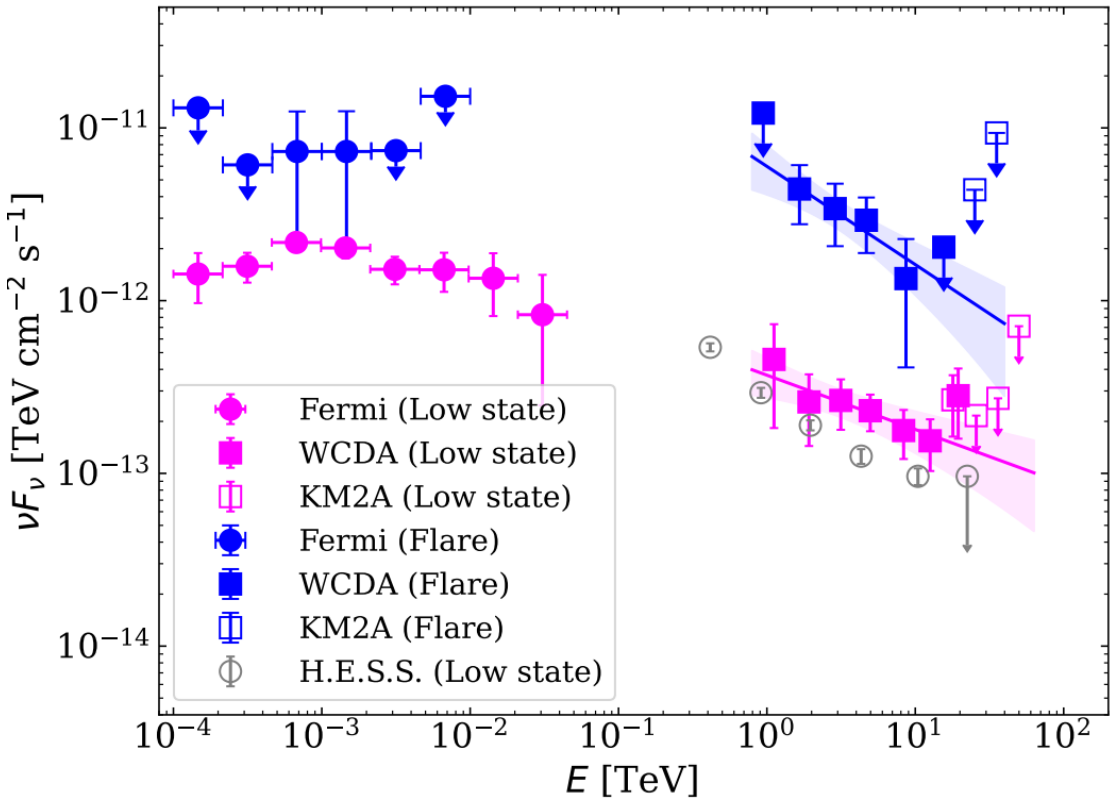




➢ Simultaneous Fermi-LAT observations

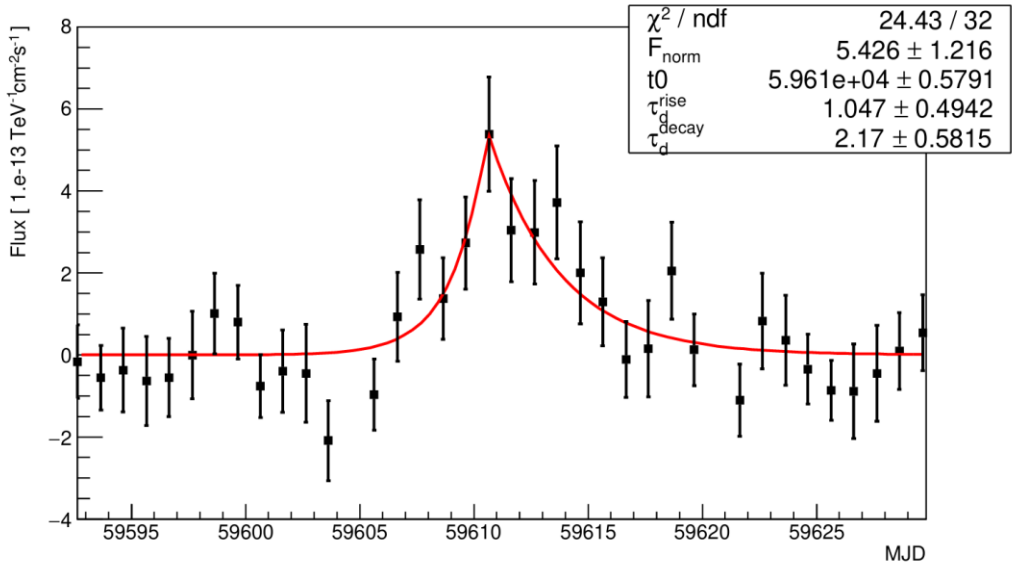


Time Interval (MJD)	TS	N_0 (photons cm^{-2} s^{-1})	Γ_{LAT}
54682.65–60385	2434.31	$(1.67 \pm 0.05) \times 10^{-12}$	2.05 ± 0.03
59281–60385	505.29	$(1.78 \pm 0.13) \times 10^{-12}$	2.06 ± 0.05
59607–59615	9.50	$(2.75 \pm 1.48) \times 10^{-12}$	2.40 ± 0.35



- For the low-state SED, the VHE emission is consistent with the extrapolation of the GeV spectrum

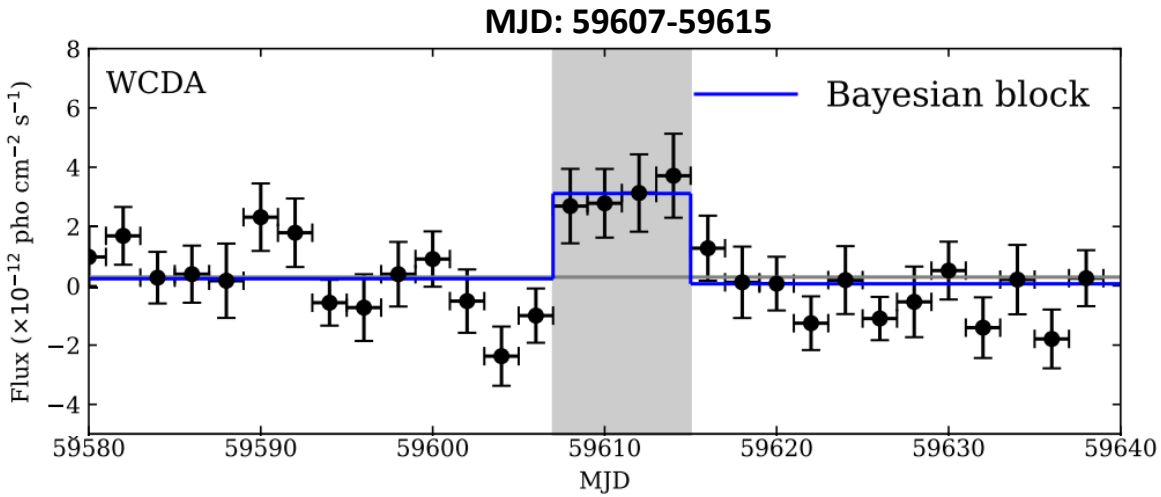
➢ The VHE flare



Parameter	Value	Unit
Fit range	59593–59629	MJD
F_0	$(5.43 \pm 1.22) \times 10^{-13}$	$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$
t_0	59610 ± 0.58	MJD
τ_d^{rise}	1.05 ± 0.49	day
τ_d^{decay}	2.17 ± 0.58	day

the time scale is 1.05 days

➔ The size of the emission region **$< 2.7 \times 10^{15} \delta$ cm**, only a few Schwarzschild radii of the SMBH ($\sim 2 \times 10^{15}$cm)



the duration of the flare is ~8 days

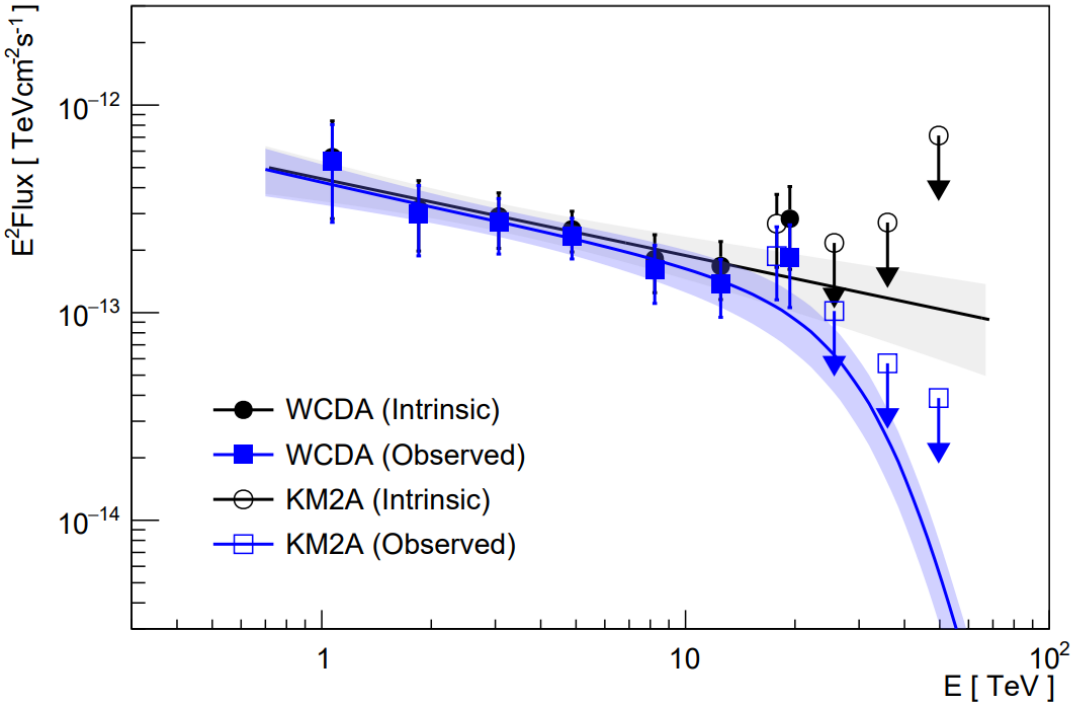
➔ **duty cycle** is 8days/3years **~1%** for energy flux reaching 1.38×10^{-11} erg/cm2/s in 1-20 TeV

duty cycle reported by IACT are ~14%, 7% and 4% for flux of 0.5×10^{-11}/cm2/s, 0.8×10^{-11}/cm2/s and 10^{-11}/cm2/s

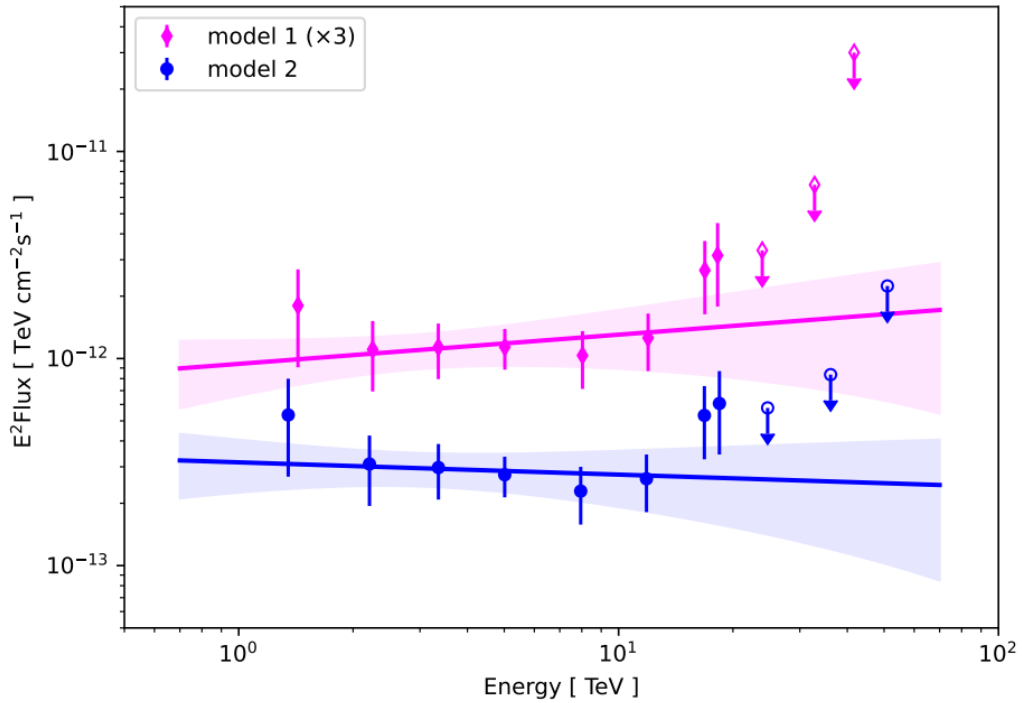
(A. Abramowski et al. 2012)

➢ Influence of the possible internal absorption on the spectrum

Index = 2.37 ± 0.14



Index = 1.86 ± 0.21 Index = 2.06 ± 0.20



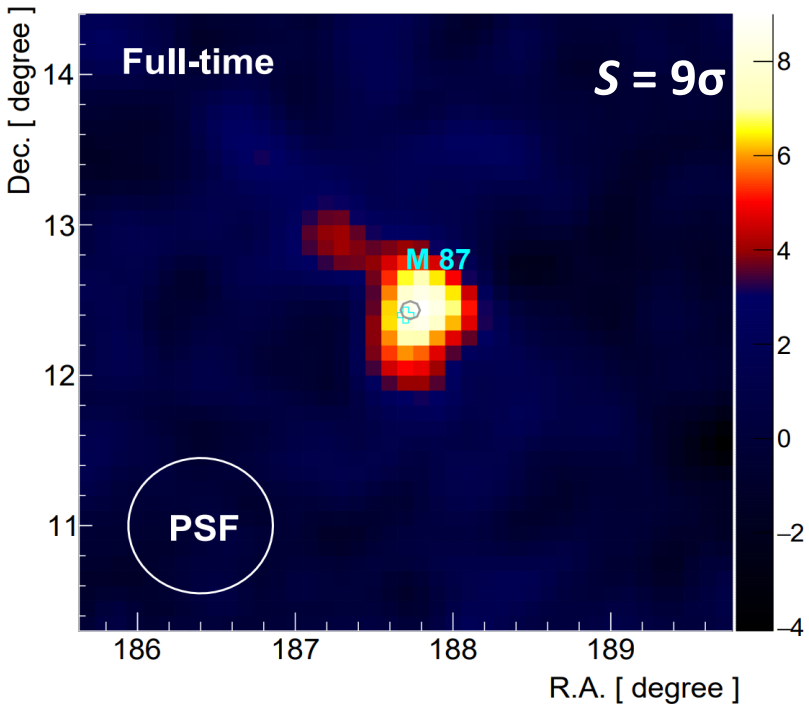
- assumed that the emitting region of the VHE emission during the low state is close the AGN core
- adopt two internal absorption models: A. Neronov&F. A. Aharonian (2007) and K. A. Brodatzki et al. (2011) and found that spectra become harder and the excess at 20 TeV becomes more pronounced

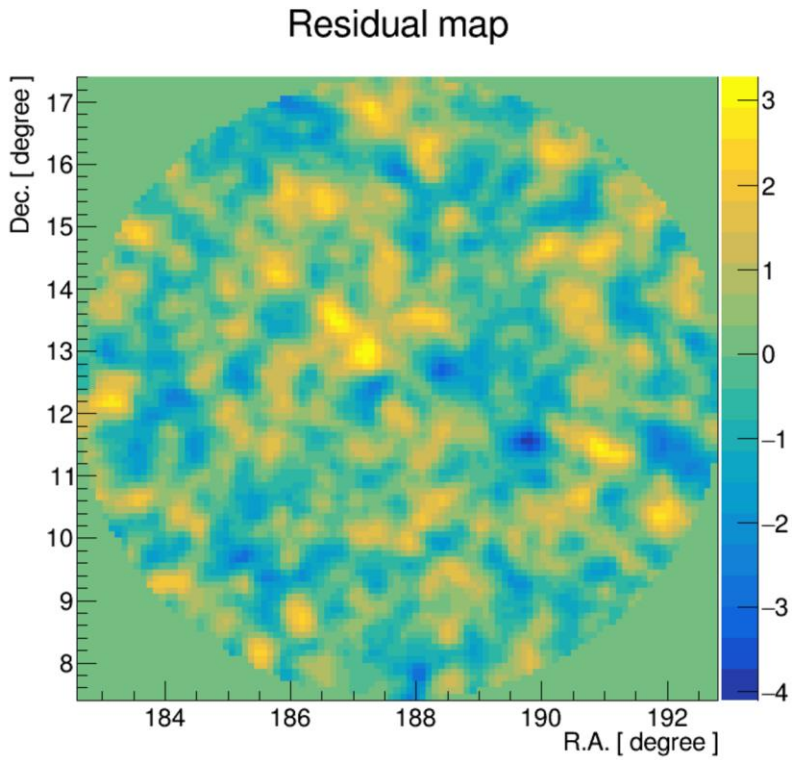
Summary

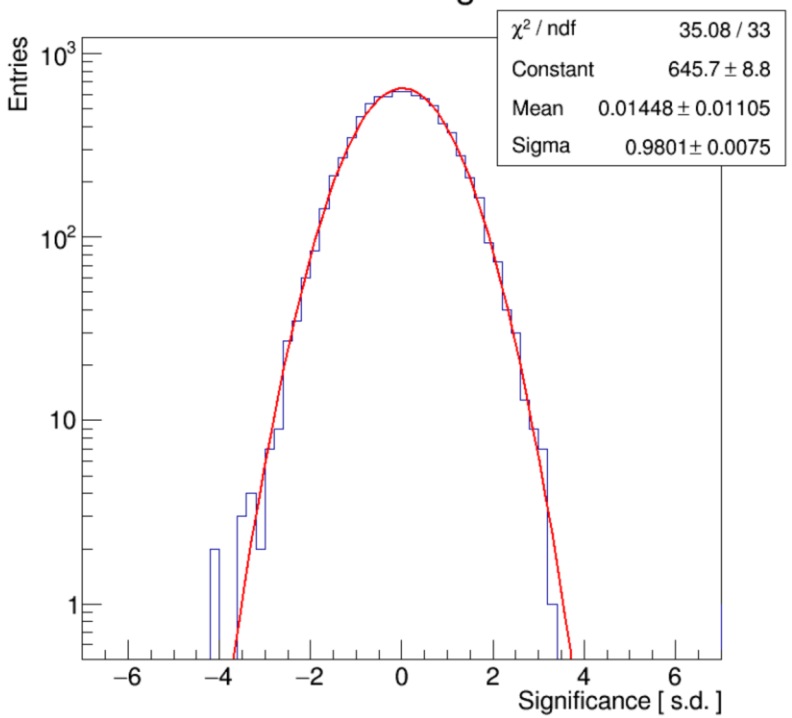
- With three years of LHAASO-WCDA data, M87 is detected with significance of 9 σ. Full-time spectrum index is $\Gamma = 2.37 \pm 0.14$ and extends to ~>20TeV.
- For the first time, 90-days light curve presents an steady flux, $F_0@3\mathrm{TeV} = (0.327 \pm 0.050) \times 10^{-13}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

- A flare with duration of a few days is detected with pre-trail significance of 6 σ. Fitting with a two-sided exponential function gives time scale of ~1 day, which is consistent with IACTs' observations of the 2010 flare.
- Spectrum of flaring period is softer than that of full-time period and is roughly consistent with H.E.S.S. high state spectrum.

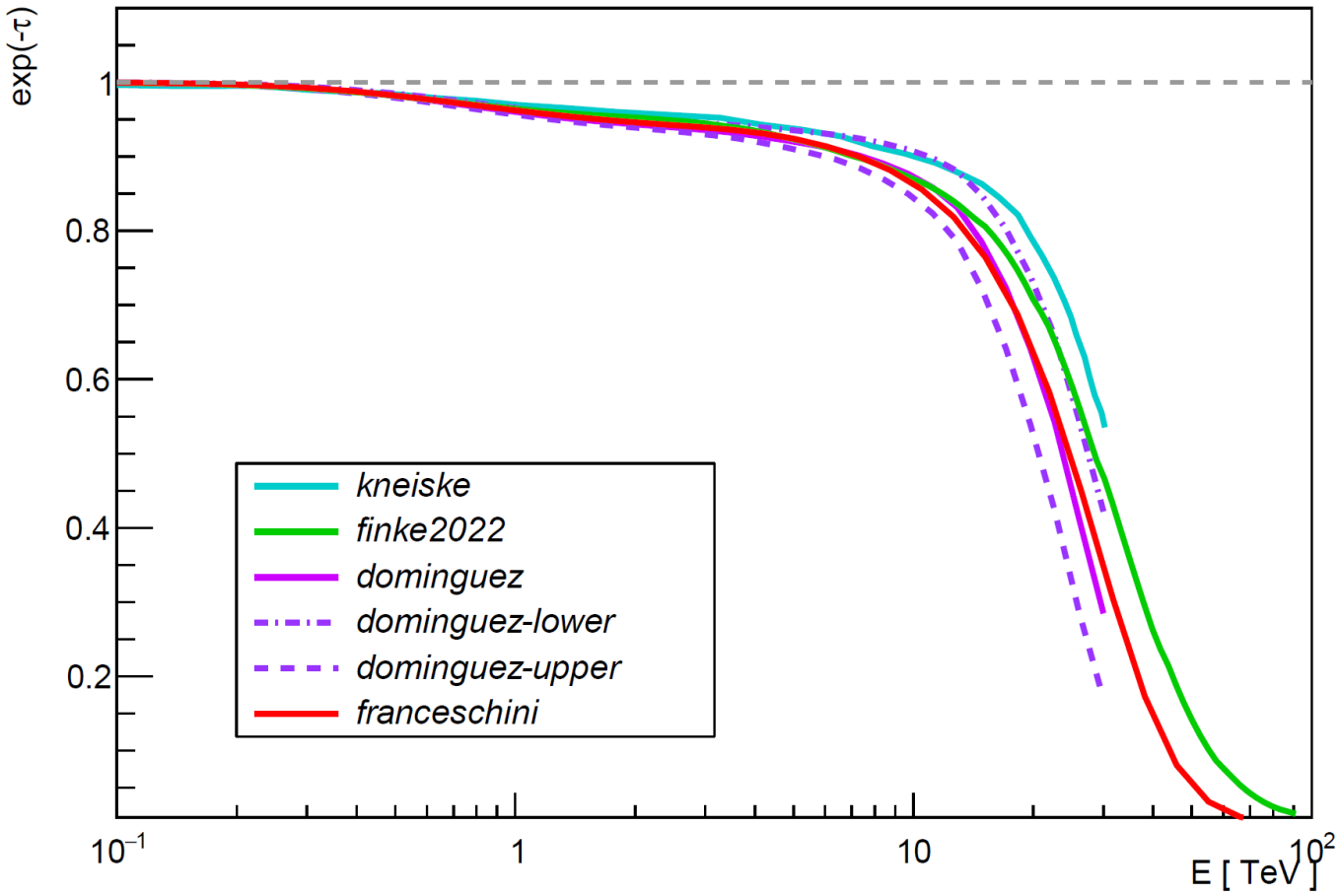
➢ Residual map







Optical depth (z=0.0042)



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dominguez-upper	0.323 ± 0.055	2.25 ± 0.18	18.4	87.5	3.47/4
franceschini	0.327 ± 0.050	2.37 ± 0.14	19.4	87.4	3.00/4
kneiske	0.330 ± 0.044	2.56 ± 0.12	20.6	84.4	3.97/4