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M87's Multi-Wavelength Behavior during the 2018 EHT Campaign including a Very High Energy Gamma-Ray Flaring Episode

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EHT-MWL

2017 Campaign

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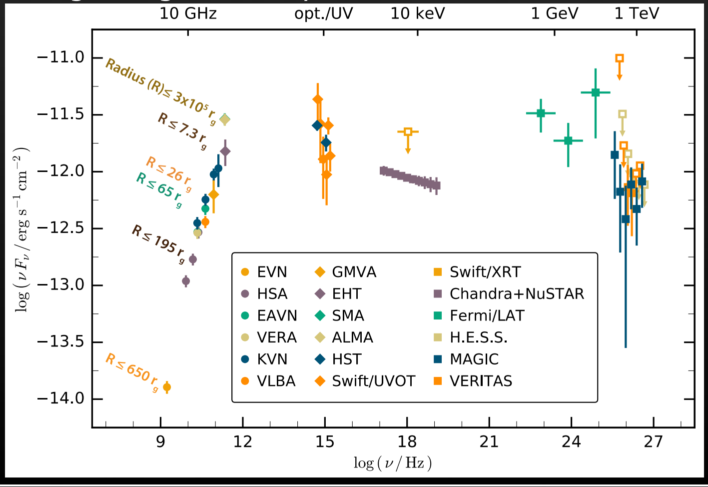
- Resolved structures from radio to X-rays
- Straight, highly collimated jet
- Limb brightening, parabolic collimation profile
- VLBA and GMVA: inner jet significantly offset from large scale jet (long-term periodic oscillations, Walker et al. 2018a)
- No component ejection detected
- M87* in relatively low state in all wavebands HST-1 knot subdominant
- SED cannot be modelled by single zone
- Origin of gamma rays still unclear



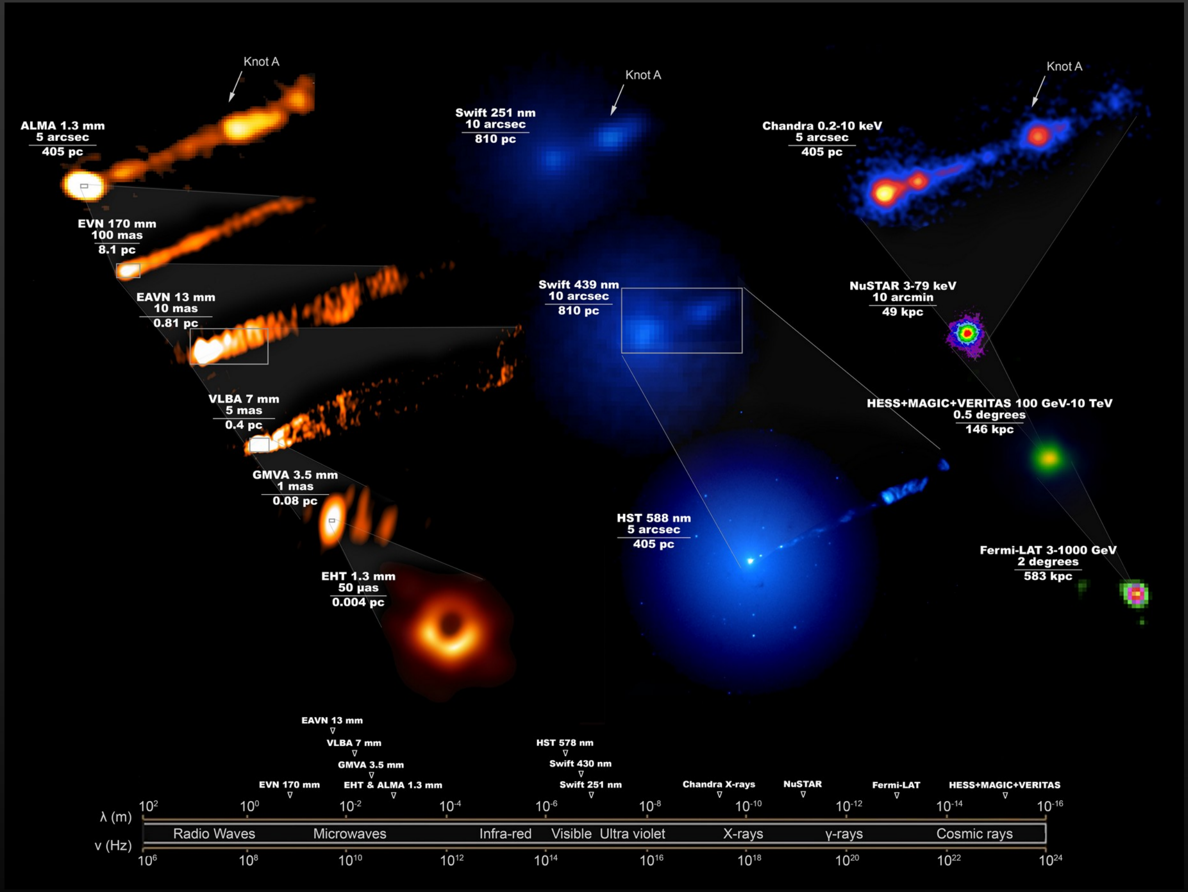
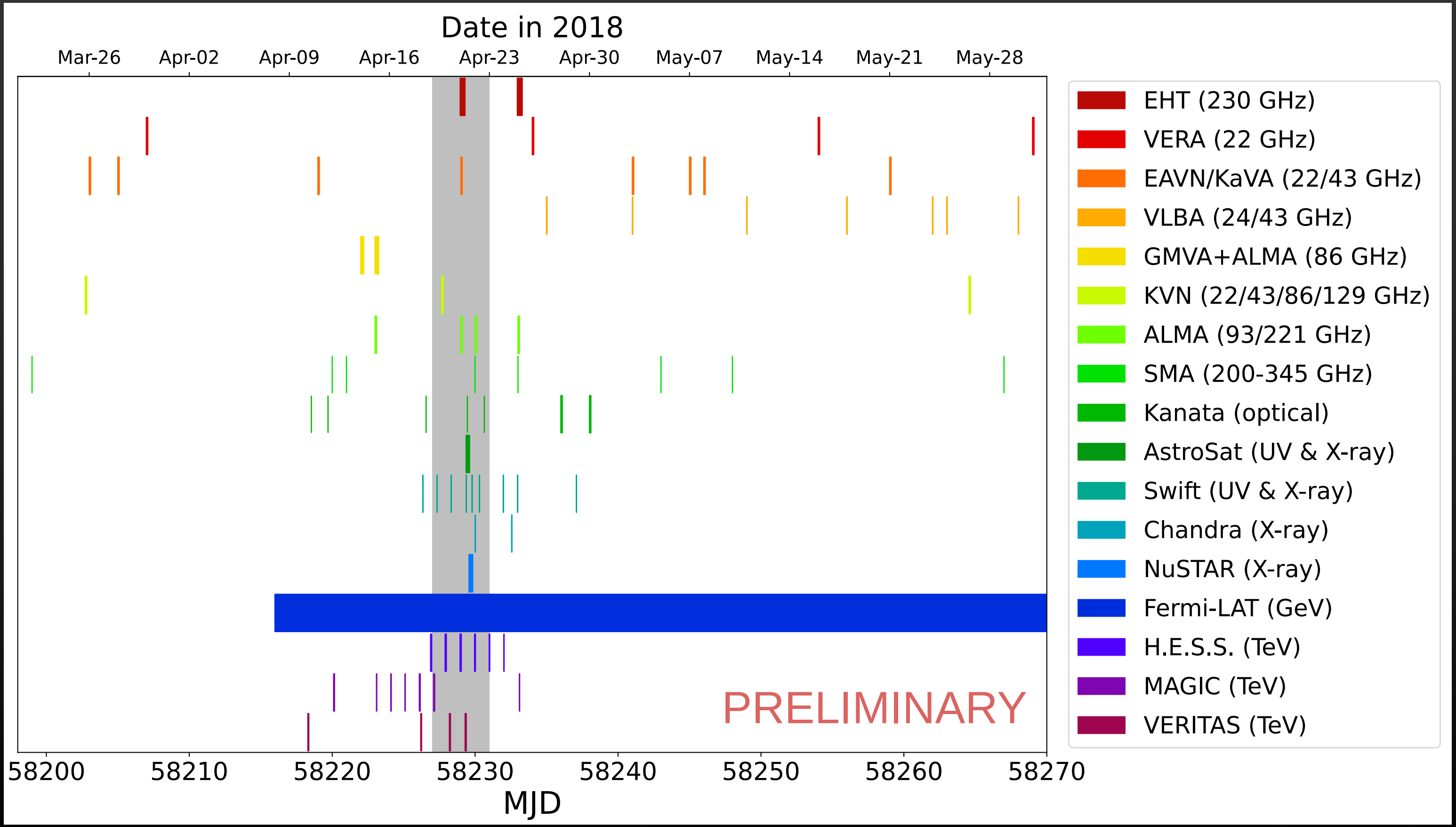


Image Credit: The EHT Multi-Wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope, the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array;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

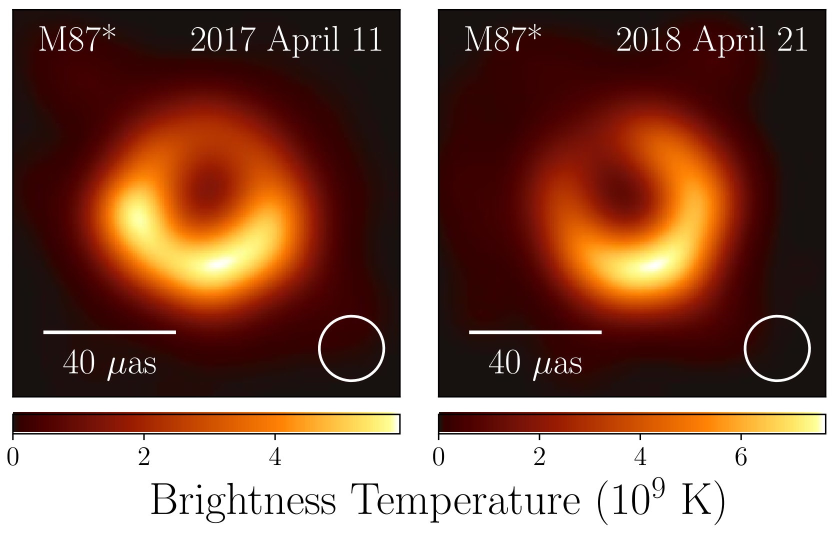
EHT-MWL
2018 Observations

- Dense coordinated MWL campaign in 2018

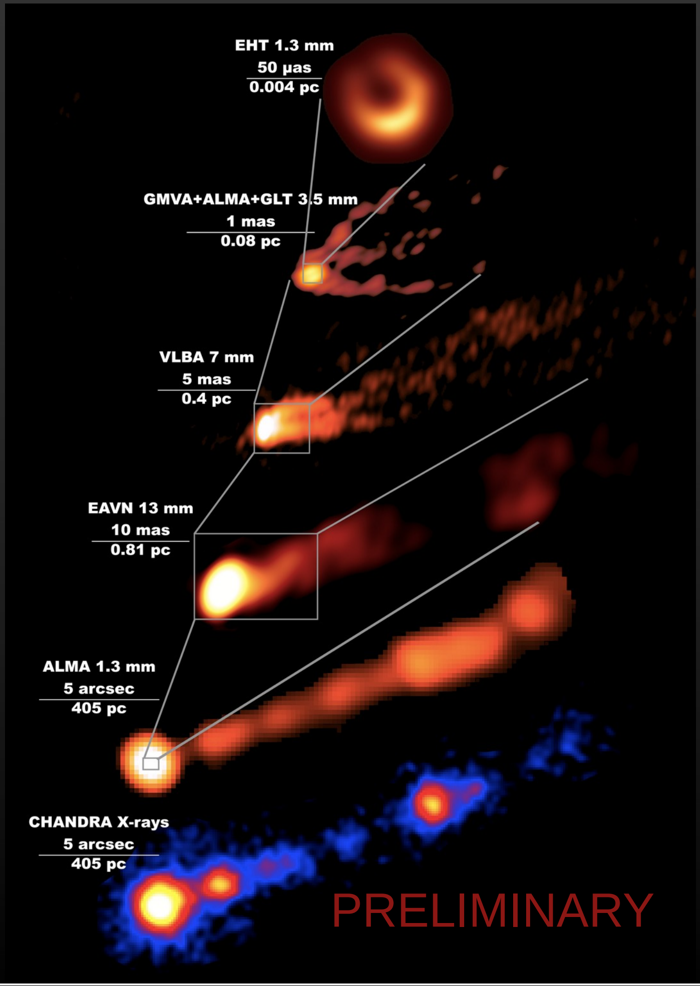


EHT-MWL
2018 images

- EHT: persistent size and shape of the black hole shadow, change of position angle of brightness asymmetry (EHT coll. et al. 2024)
- M87 jet imaged from ~ 1kpc down to few r_S



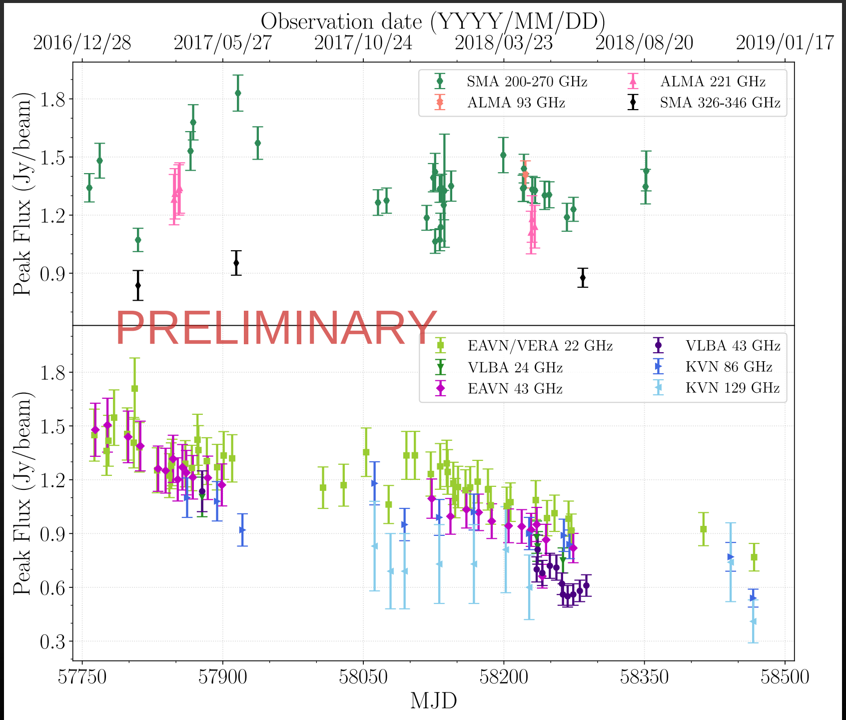
EHT coll. et al 2024

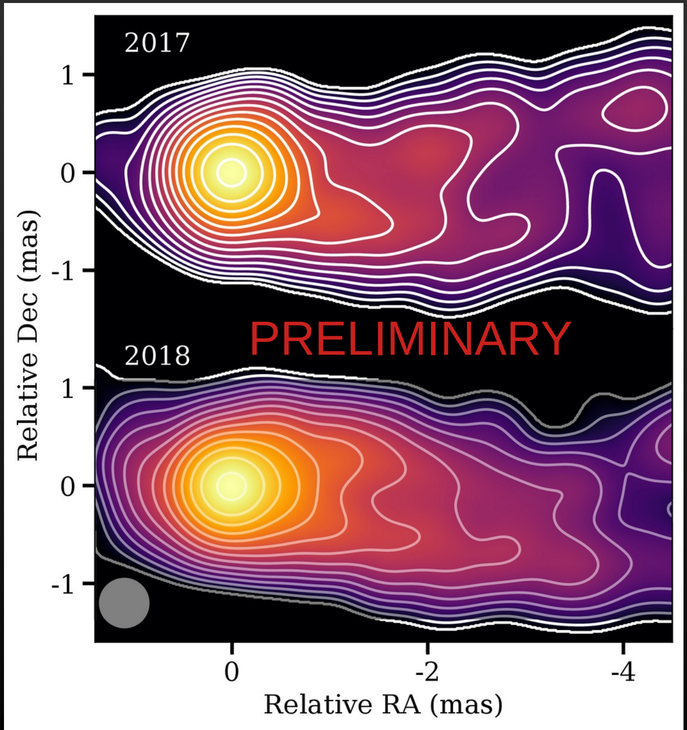


EHT-MWL

2018 radio

- cm and mm radio emission was comparable or even lower than 2017
- EHT change of position angle of brightness asymmetry
  Similarly: Observed change in jet position angle by VLBA
  Indicating year-scale structural evolution traverse to jet (Cui et al. 2023)

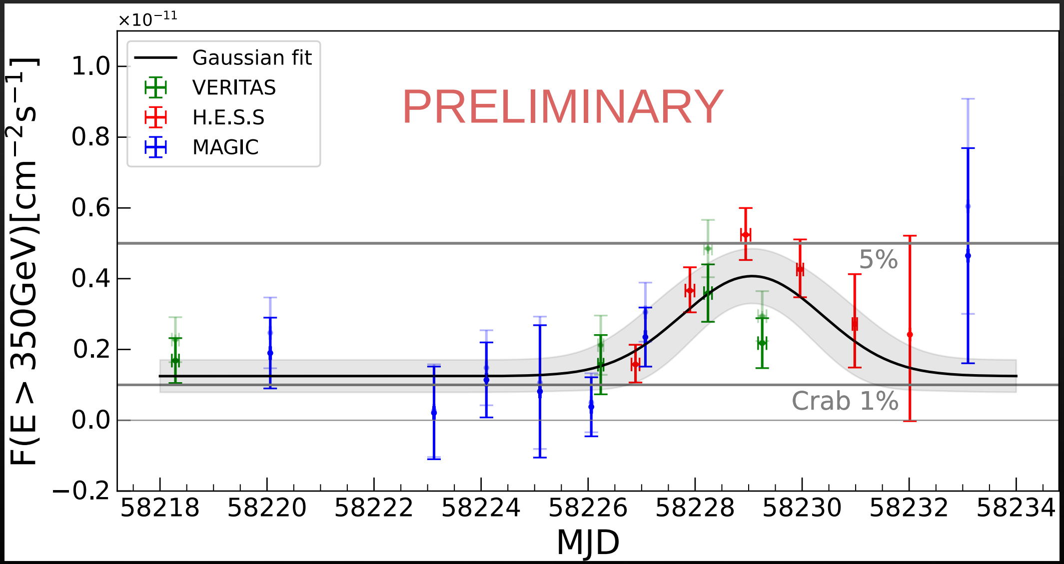


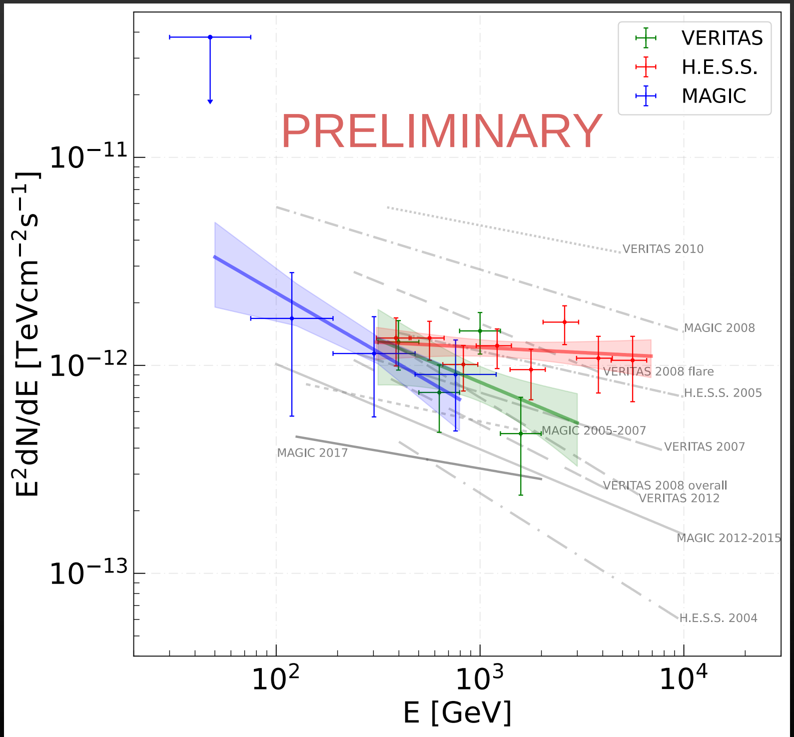


EHT-MWL

2018 VHE gamma rays

- During the 2018 MWL campaign H.E.S.S., MAGIC and VERITAS detected a short VHE (>100 GeV) gamma-ray flare
- First observed flare since 2010
- Hint for spectral hardening during flux increase

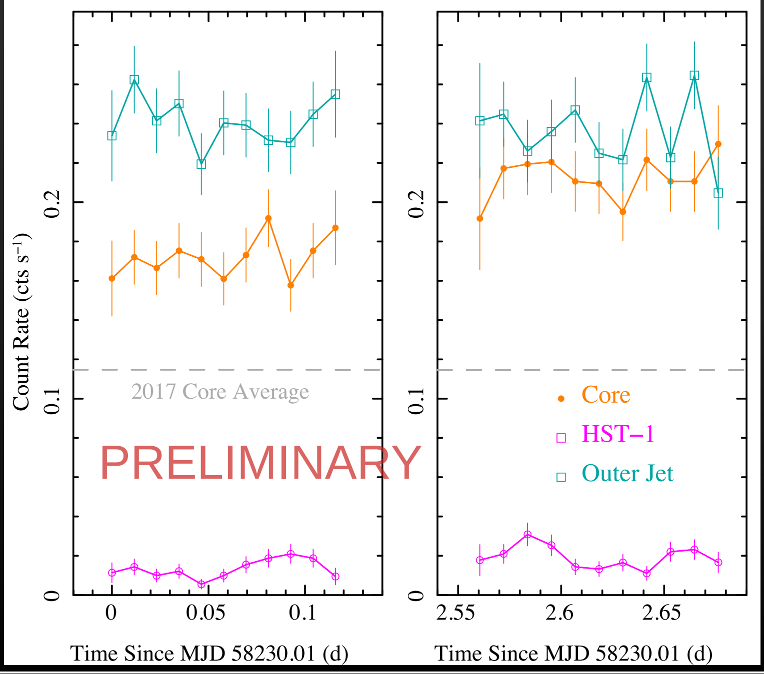


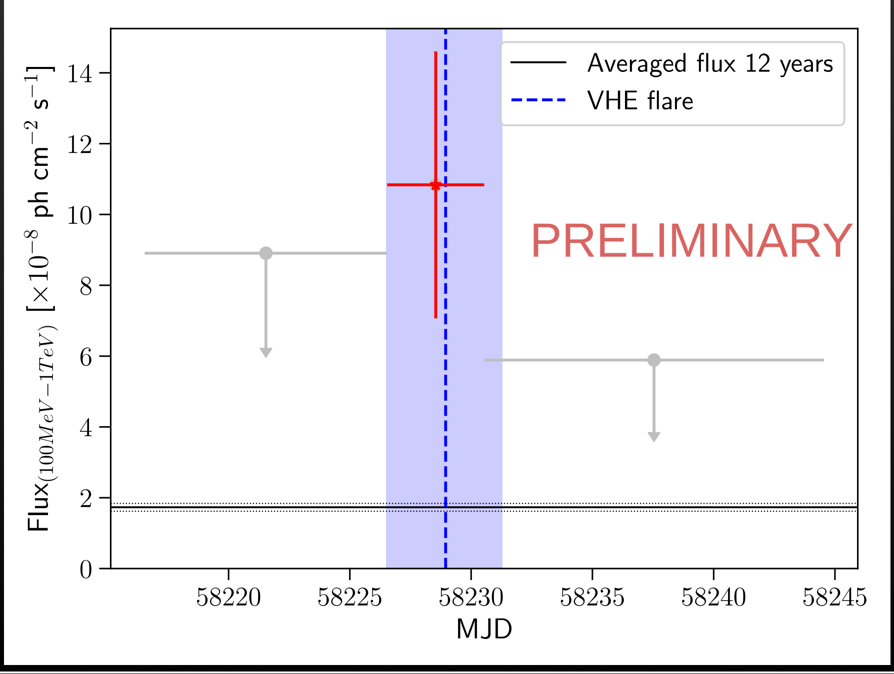


EHT-MWL

2018 X-rays and HE gamma rays

- X-ray (*Chandra* + *NuSTAR*)
  - Flux increase by factor 2 w.r.t. to 2017
  - HST1 subdominant
  - Core and outer jet similar emission
  - Not strictly simultaneous
    ⇒ Connection to VHE flare unclear
- HE gamma ray (*Fermi*-LAT > 100 MeV)
  - Flux increase by factor ~8 w.r.t. to average flux during VHE flare

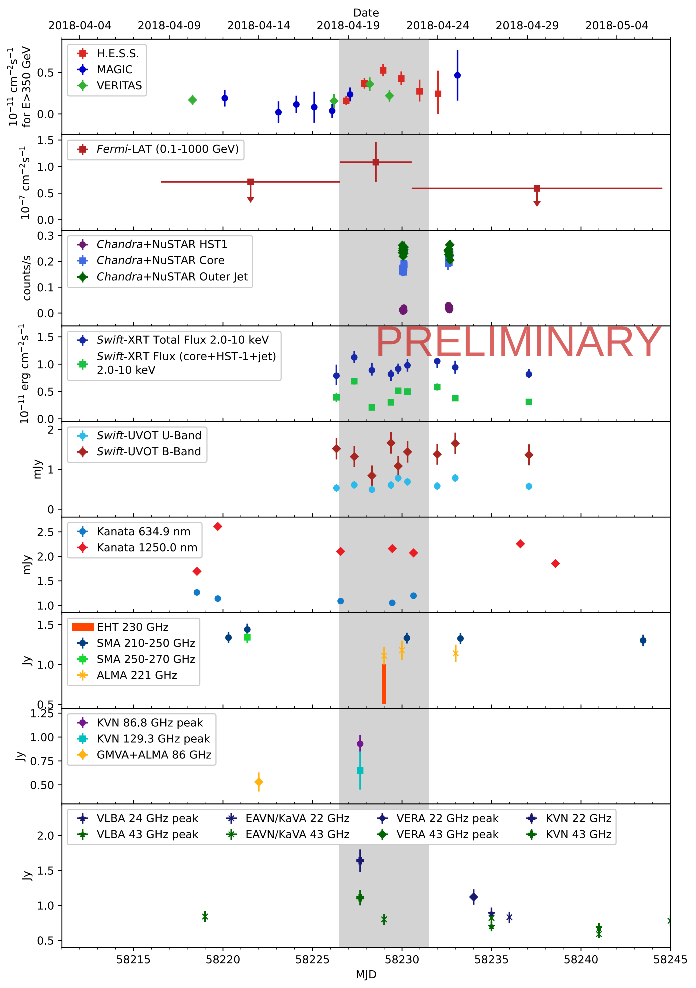




EHT-MWL
2018 light curves

- Short time scales: from observed variability time scale $R_{\text{VHE, flare}} \sim 2\, R_{\text{EHT}}$, for Doppler factor = 1

$$R_{\text{HE}} \lesssim 8 r_g \delta \left(\frac{\Delta t}{3\ \text{days}} \right)$$



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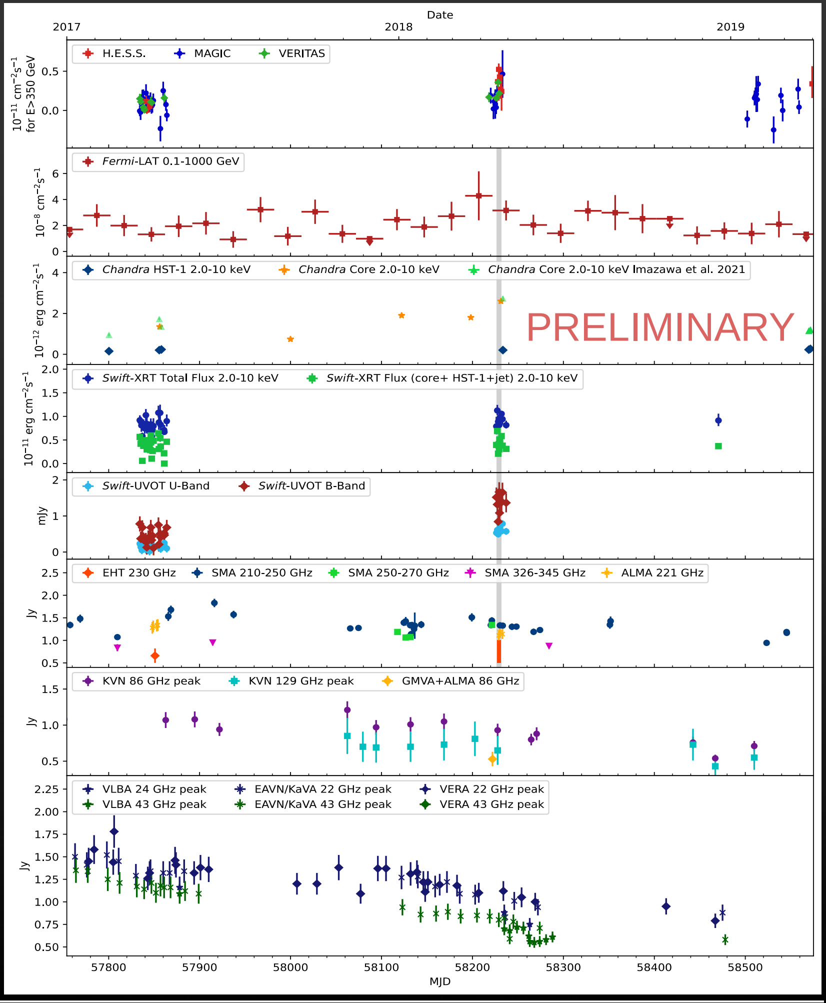
EHT-MWL

2017—2019 light curves

- Short time scales: from observed variability time scale $R_{VHE,\,flare} \sim 2\,R_{EHT}$, for Doppler factor = 1

$$R_{\mathrm{HE}} \lesssim 8 r_g \delta \left(\frac{\Delta t}{3 \text{ days}} \right)$$

- Mid time scales



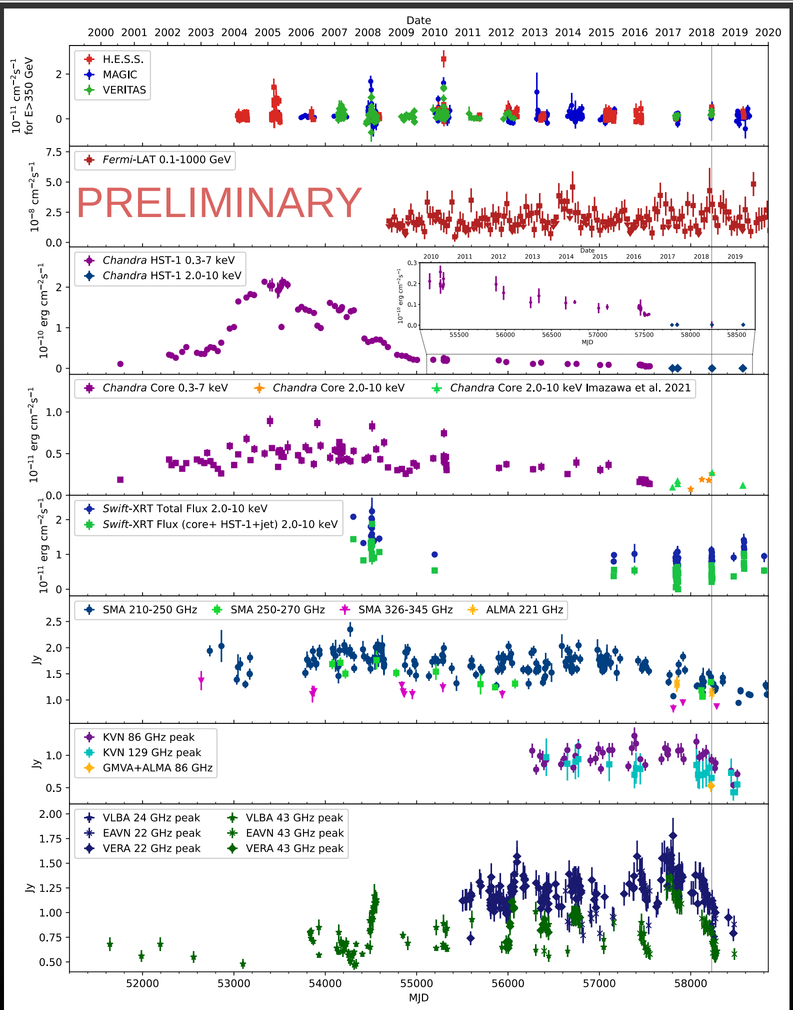
EHT-MWL

2000—2022 light curves

- Short time scales: from observed variability time scale $R_{VHE,\ flare} \sim 2\ R_{EHT}$, for Doppler factor = 1

$$R_{\mathrm{HE}} \lesssim 8 r_g \delta \left(\frac{\Delta t}{3\ \mathrm{days}} \right)$$

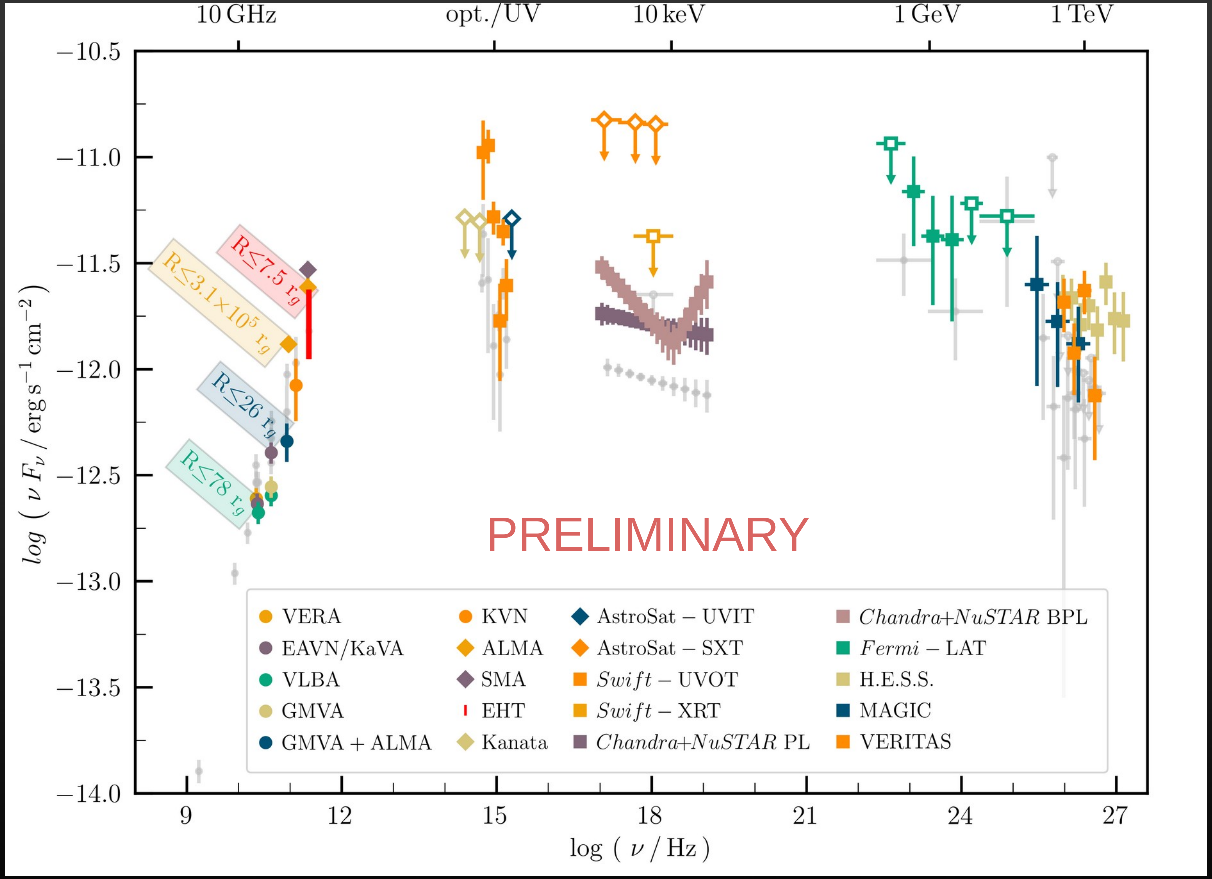
- Mid time scales
- Long time scales



EHT-MWL

2018 MWL SED

- 2017 MWL SED in grey
- *Chandra* + *NuSTAR* BPL derived with stacked analysis of 14 *NuSTAR* observations (Sheridan et al., in prep)

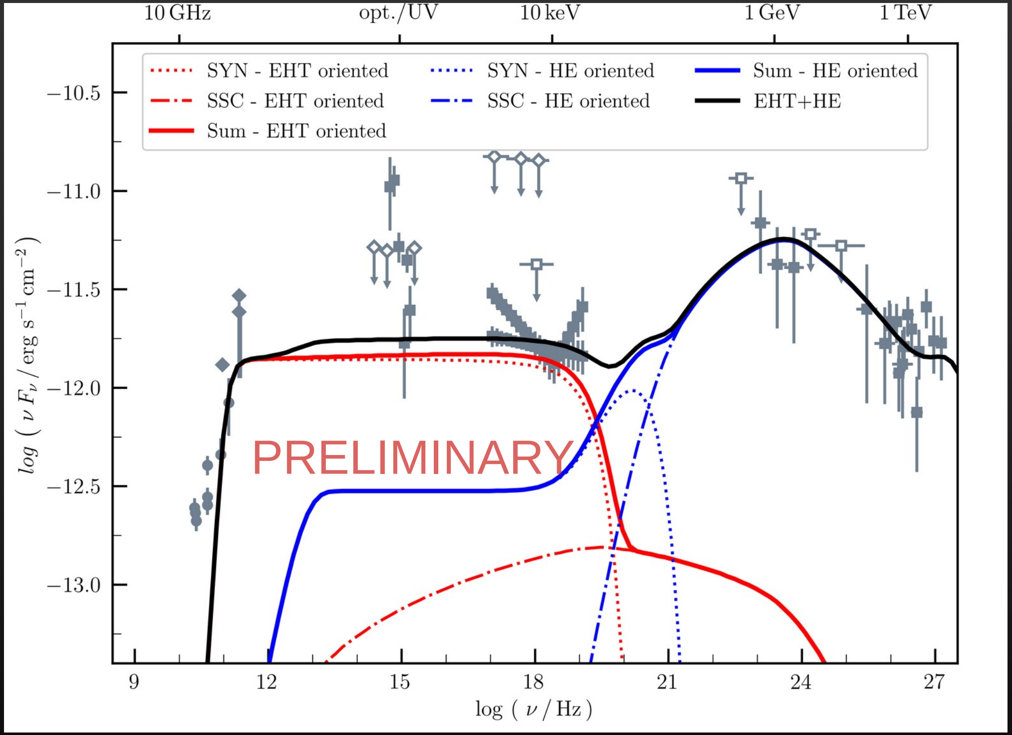


EHT-MWL

2018 SED Models

- Two component models (c.f. 2017 MWL models)
- EHT oriented, no differences between 2017 and 2018
- Model A: $p_1 > p_2$
- Hard electron spectrum approximates effect of inefficient cooling in Klein-Nishina regime

Model	A (EHT) [5]	A (HE)
δ	1	1.82
$R\ [r_g]$ [1 2]	5.0	10.0
$n'_e\ [\mathrm{cm}^{-3}]$ [3]	2.0×10^6	1.7×10^1
B' [G]	5.3	2.3×10^{-2}
$\gamma_{\min}$	1	5×10^3
γ_{br}	–	7×10^6
$\gamma_{\max}/10^6$	1.0	50
p_1	3.0	3.0
p_2	–	2.0
U_e/U_B [4]	2.9	6.7×10^3
L_e [erg s^{-1}]	2.0×10^{42}	2.1×10^{42}
L_{poy} [erg s^{-1}]	7.0×10^{41}	3.2×10^{38}

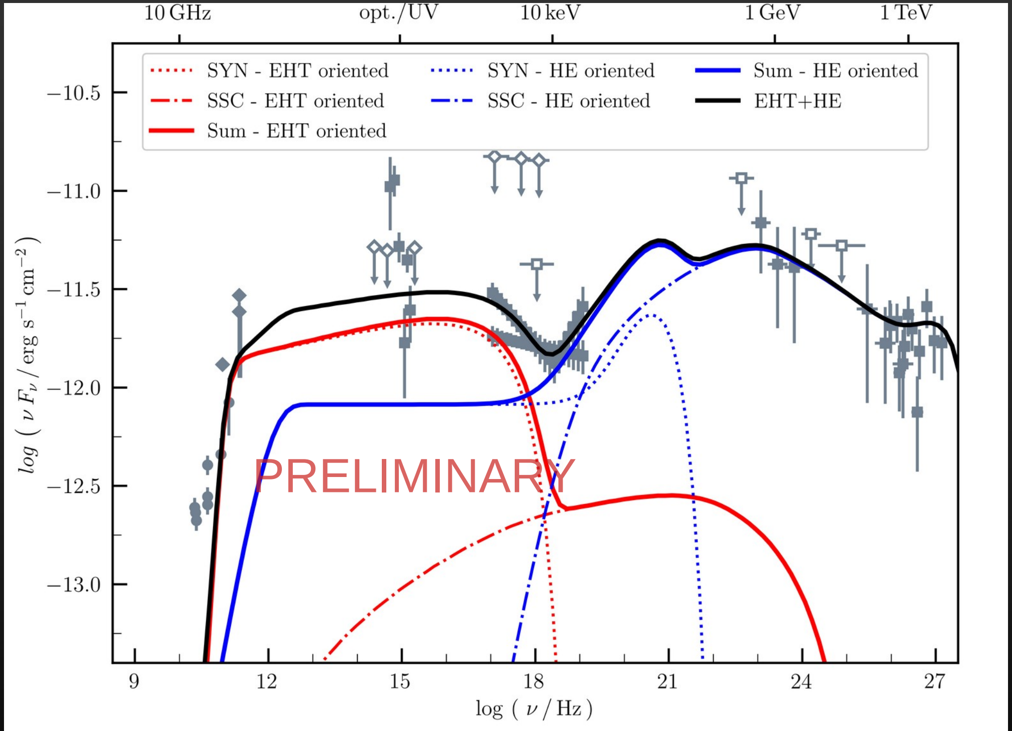


EHT-MWL

2018 SED Models

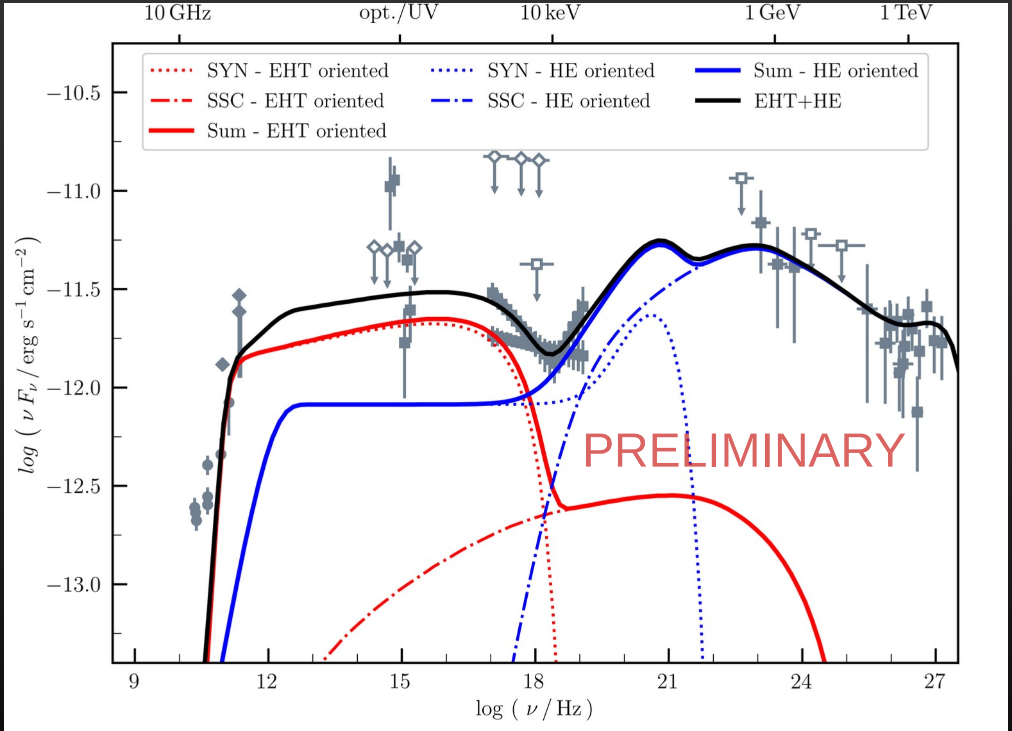
- Two component models (c.f. 2017 MWL models)
- EHT oriented, no differences between 2017 and 2018
- Model A: $p_1 > p_2$
- Hard electron spectrum approximates effect of inefficient cooling in Klein-Nishina regime
- Broken power-law to explain observed hardening at VHE

Model	A (EHT/BPL)	A (HE/BPL)
δ	1	1.82
R $[r_g]$ [1 2]	5.0	10.0
n'_e $[\mathrm{cm}^{-3}]$ [3]	1.8×10^{6}	6.6×10^{1}
B' [G]	4.6	8.0×10^{-2}
$\gamma_{\min}$	1	1.2×10^{3}
γ_{br}	–	7×10^{6}
$\gamma_{\max}/10^{6}$	0.19	45
p_1	2.9	3.0
p_2	–	2.0
U_e/U_B [4]	3.6	5.2×10^{2}
L_e $[\mathrm{erg\ s^{-1}}]$	1.9×10^{42}	2.0×10^{42}
L_{poy} $[\mathrm{erg\ s^{-1}}]$	5.2×10^{41}	3.8×10^{39}



EHT-MWL
2018 SED Models

- Two component models (c.f. 2017 MWL models)
- EHT oriented, no differences between 2017 and 2018
- Model A: $p_1 > p_2$
- Hard electron spectrum approximates effect of inefficient cooling in Klein-Nishina regime
- Broken power-law to explain observed hardening at VHE
- Physical origin is not obvious

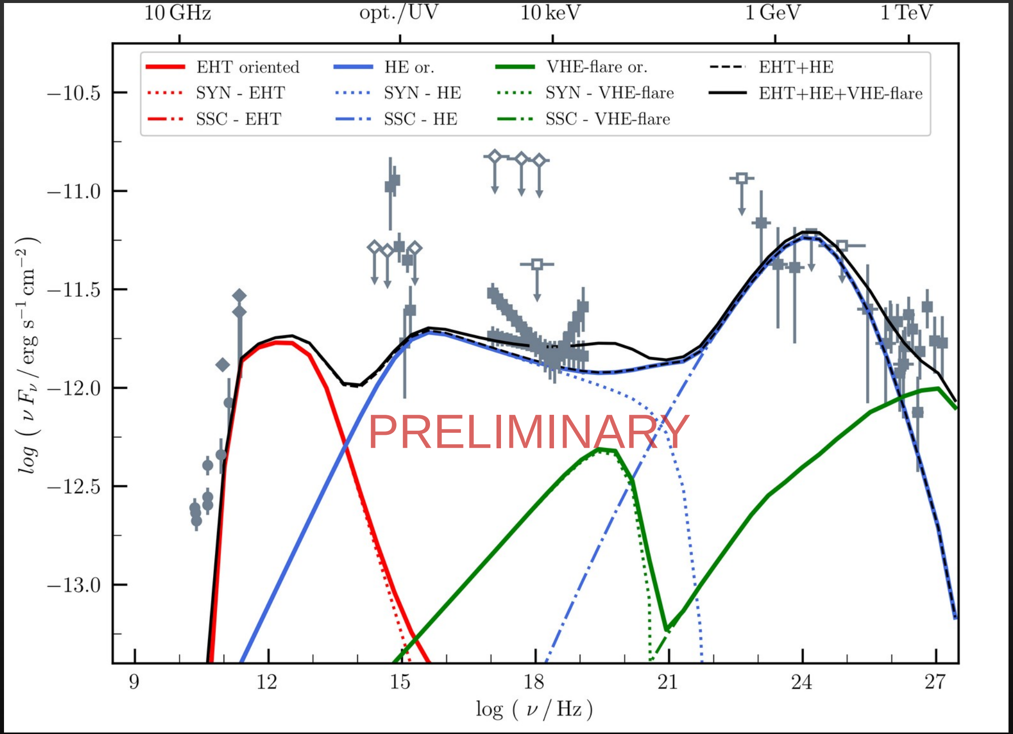


EHT-MWL

2018 SED Models

- Model B: $p_1 < p_2$
  - Klein-Nishina effect ⇒ decrease of VHE
  - Fast moving blob as an additional component to account for VHE hardening
  - Very weak B in VHE-flare zone
  - Very matter dominated

Model	B (EHT)	B (HE)	B (VHE-flare)
δ	1	1.82	2.55
$R\ [r_g]$ [1, 2]	5.0	10.0	20.0
$n'_e\ [\mathrm{cm}^{-3}]$ [3]	4.0×10^5	1.6×10^3	1.5×10^1
B' [G]	10	2.5×10^{-2}	4.0×10^{-3}
$\gamma_{\min}$	1	30	10^3
γ_{br}	4×10^2	3×10^5	–
$\gamma_{\max}/10^6$	10	100	60
p_1	2.8	2.1	2.5
p_2	4.5	3.15	–
U_e/U_B [4]	0.18	7.6×10^3	5.8×10^4
L_e [erg s^{-1}]	1.6×10^{42}	2.5×10^{42}	3.7×10^{42}
L_{poy} [erg s^{-1}]	9.0×10^{42}	3.4×10^{38}	6.4×10^{37}



EHT-MWL
2018 Summary

- Results:
  - Detected first M87 VHE gamma-ray flare since 2010
  - Hint for spectral hardening at VHE gamma-rays
  - Likely longer-term core flux enhancement in X-rays
  - Radio cm and mm core fluxes compatible with 2017
    But clear change of jet-position angle, similar to change of micro-arcsec scale position angle of ring brightness asymmetry
  - Detection of flare allowed to constrain size of VHE emission region
    But location is still uncertain
  - Demonstrated the importance of continued MWL monitoring in parallel to precision imaging

- Outlook:
  - Gamma-ray flare is challenging simpler modelling approaches
    More detailed, structured jet models necessary
  - All data will be public
  - Preprint: 10.48550/arXiv.2404.17623


Thank you for your attention

Backup

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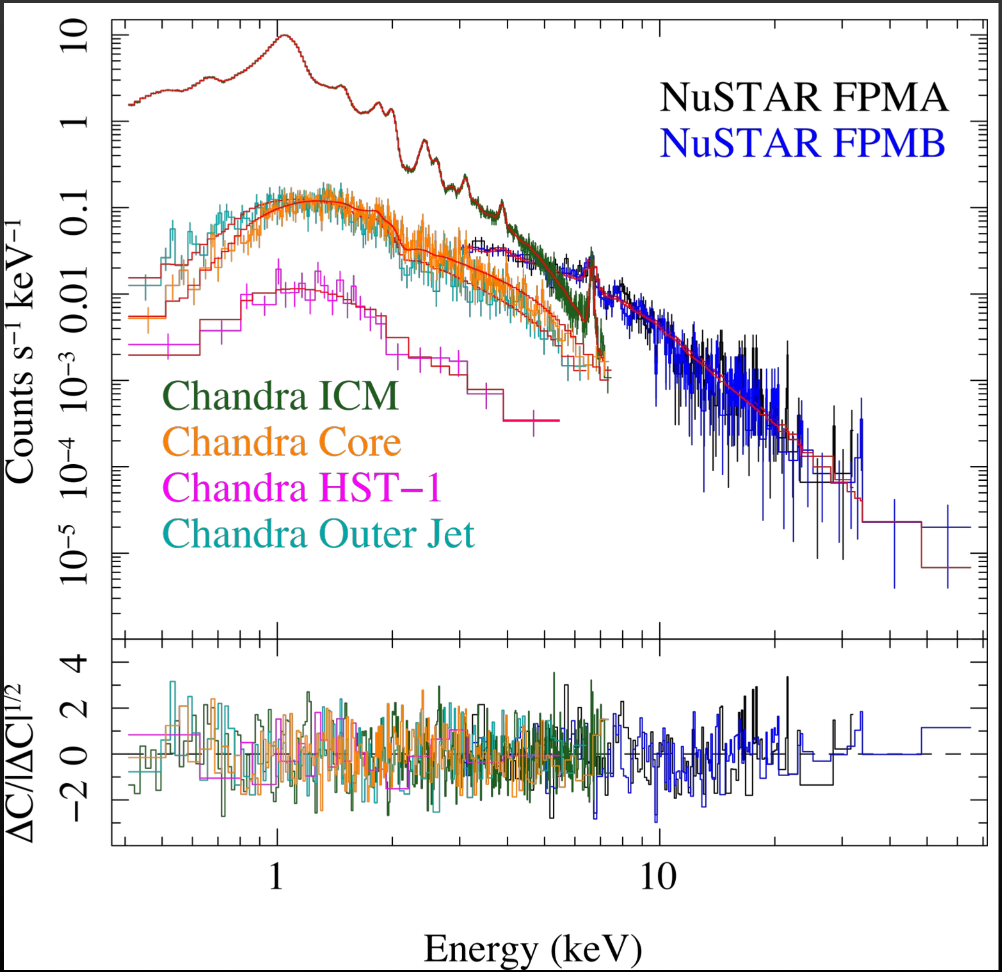
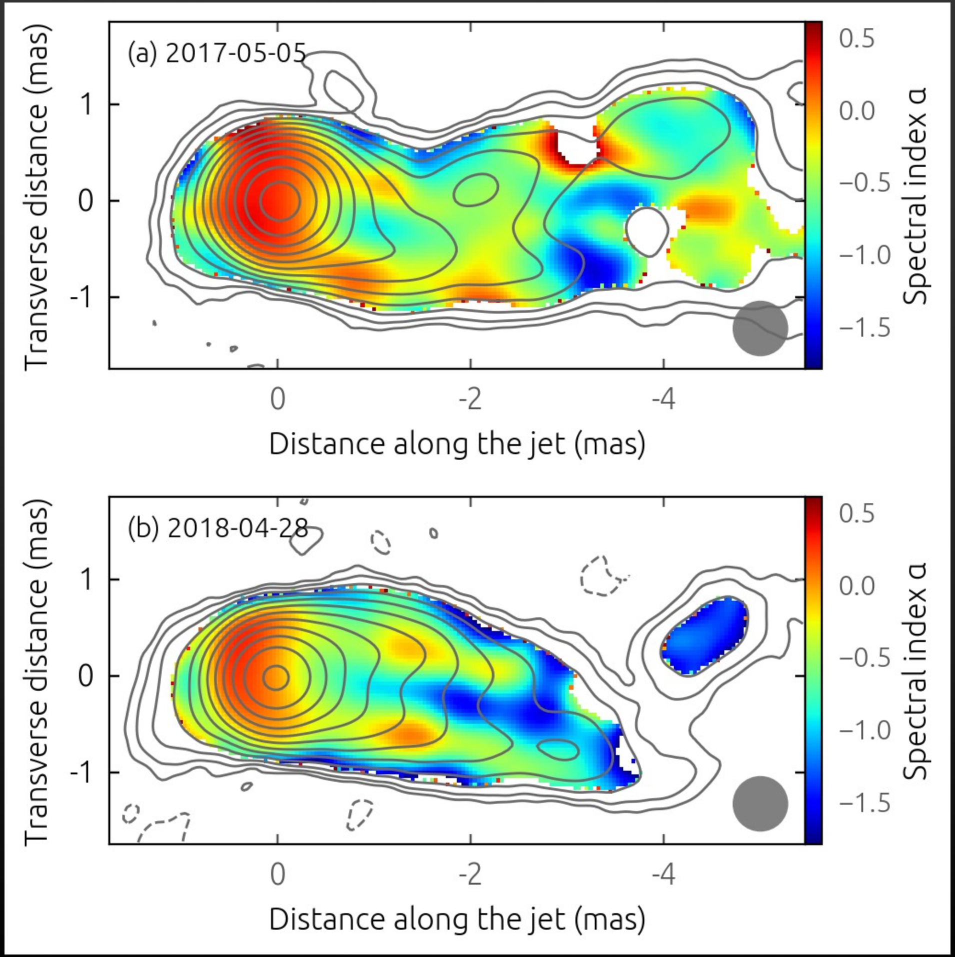
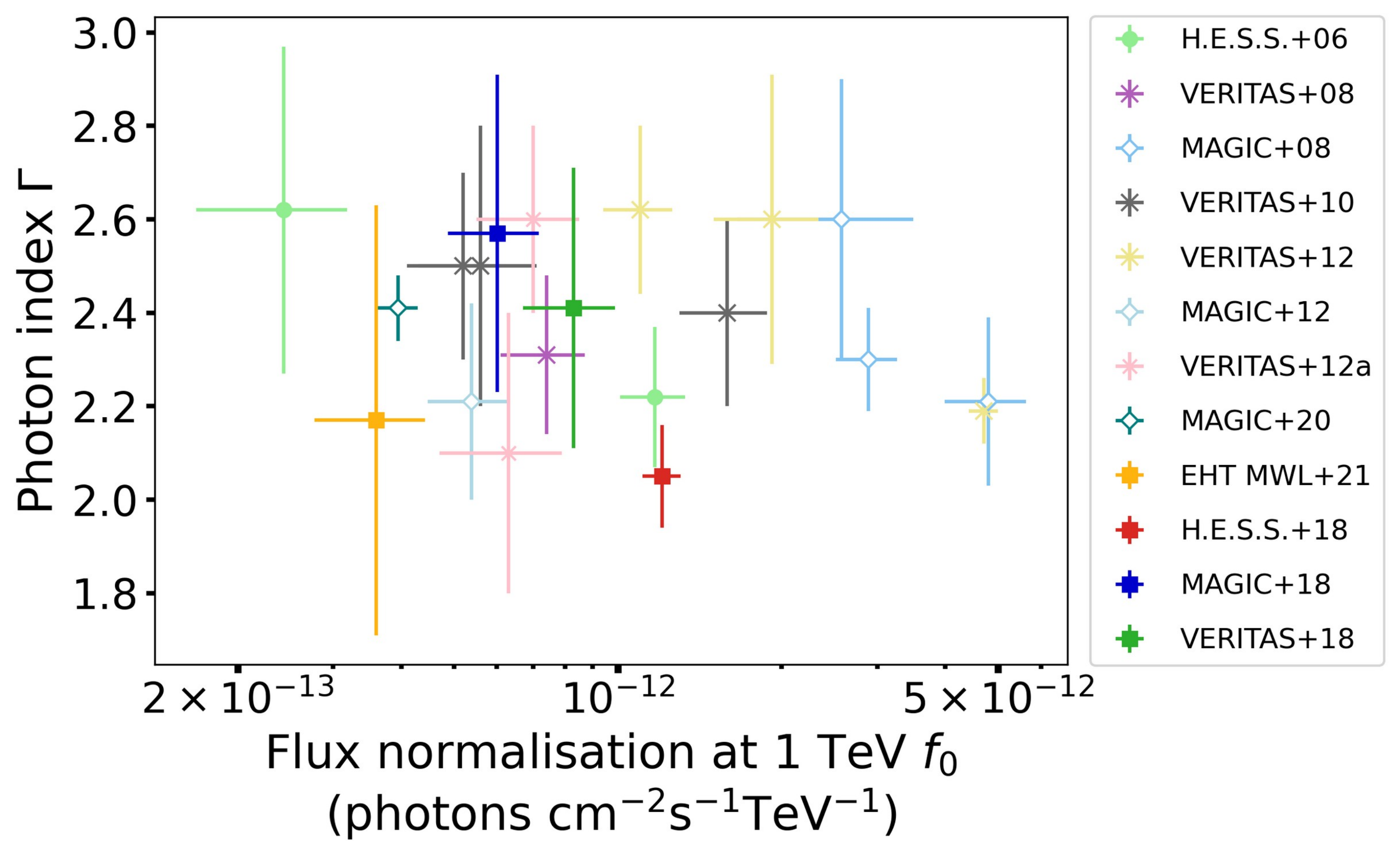



(a) 2017-05-05
Transverse distance (mas)
1
0
-1
0
-2
-4
Distance along the jet (mas)
0.5
0.0
−0.5
−1.0
−1.5
Spectral index α
(b) 2018-04-28
Transverse distance (mas)
1
0
-1
0
-2
-4
Distance along the jet (mas)
0.5
0.0
−0.5
−1.0
−1.5
Spectral index α



Photon index Γ
3.0
2.8
2.6
2.4
2.2
2.0
1.8
2 × 10−13
10−12
5 × 10−12
Flux normalisation at 1 TeV f0
(photons cm−2s−1TeV−1)
H.E.S.S.+06
VERITAS+08
MAGIC+08
VERITAS+10
VERITAS+12
MAGIC+12
VERITAS+12a
MAGIC+20
EHT MWL+21
H.E.S.S.+18
MAGIC+18
VERITAS+18