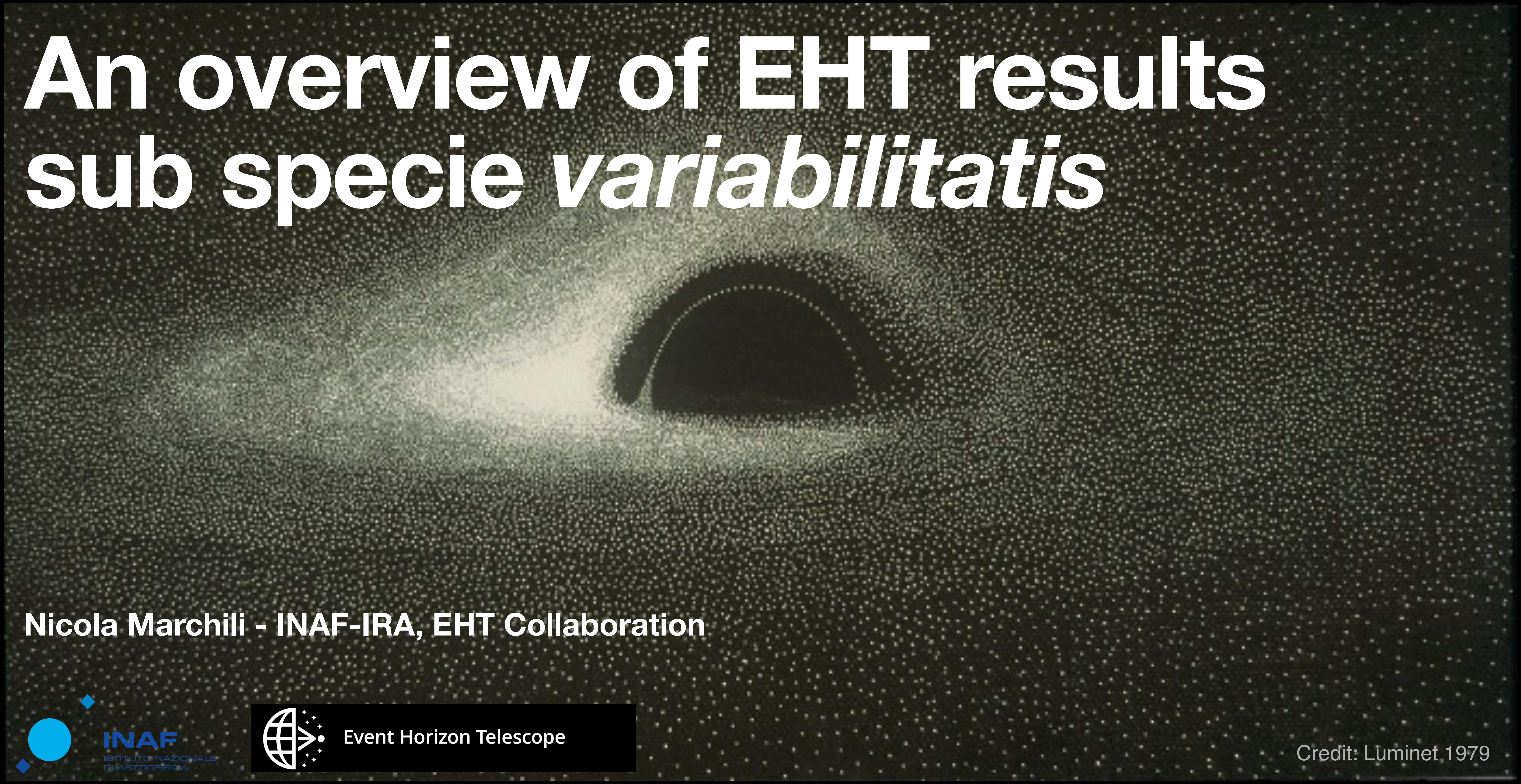
An overview of EHT results sub specie *variabilitatis*

Nicola Marchili - INAF-IRA, EHT Collaboration



Credit: Luminet 1979

INAF ISTITUTO NAZIONALE DI ASTROFISICA

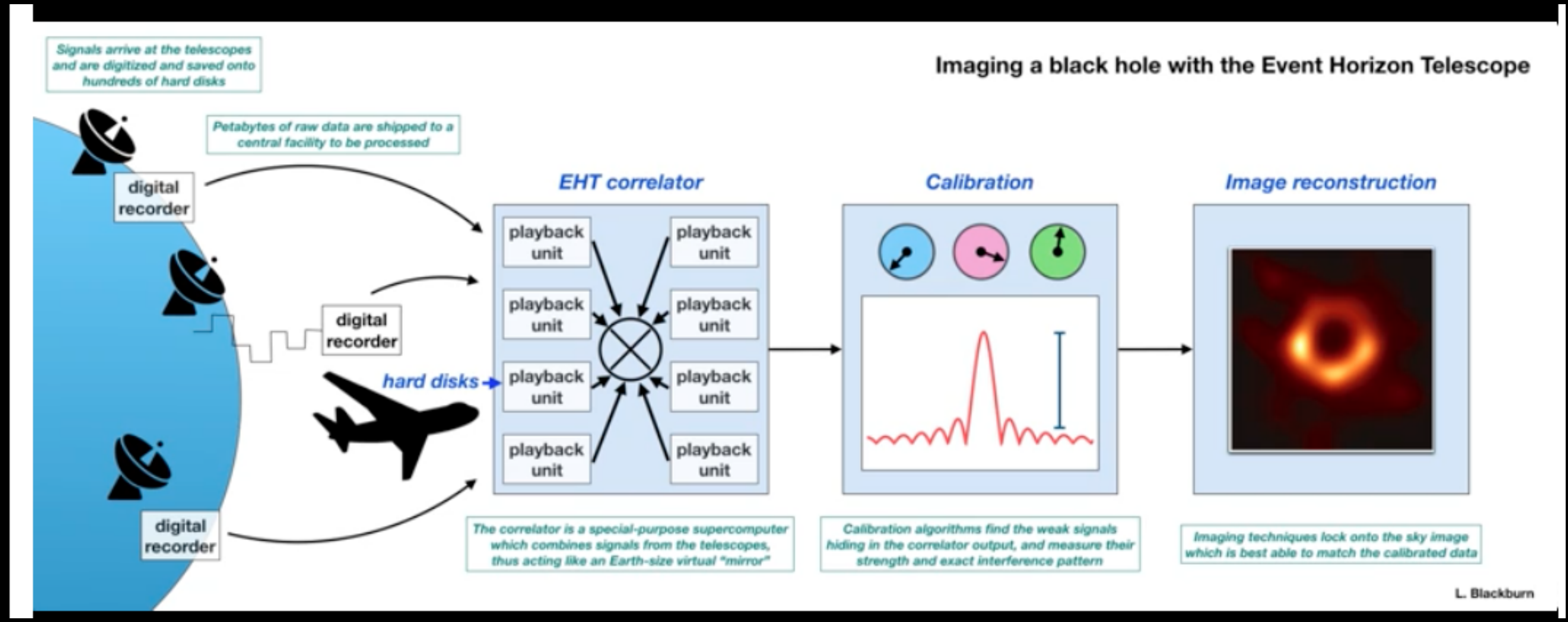
Event Horizon Telescope

Different flavors of EHT science

Different flavors of EHT science

Black Holes
Science

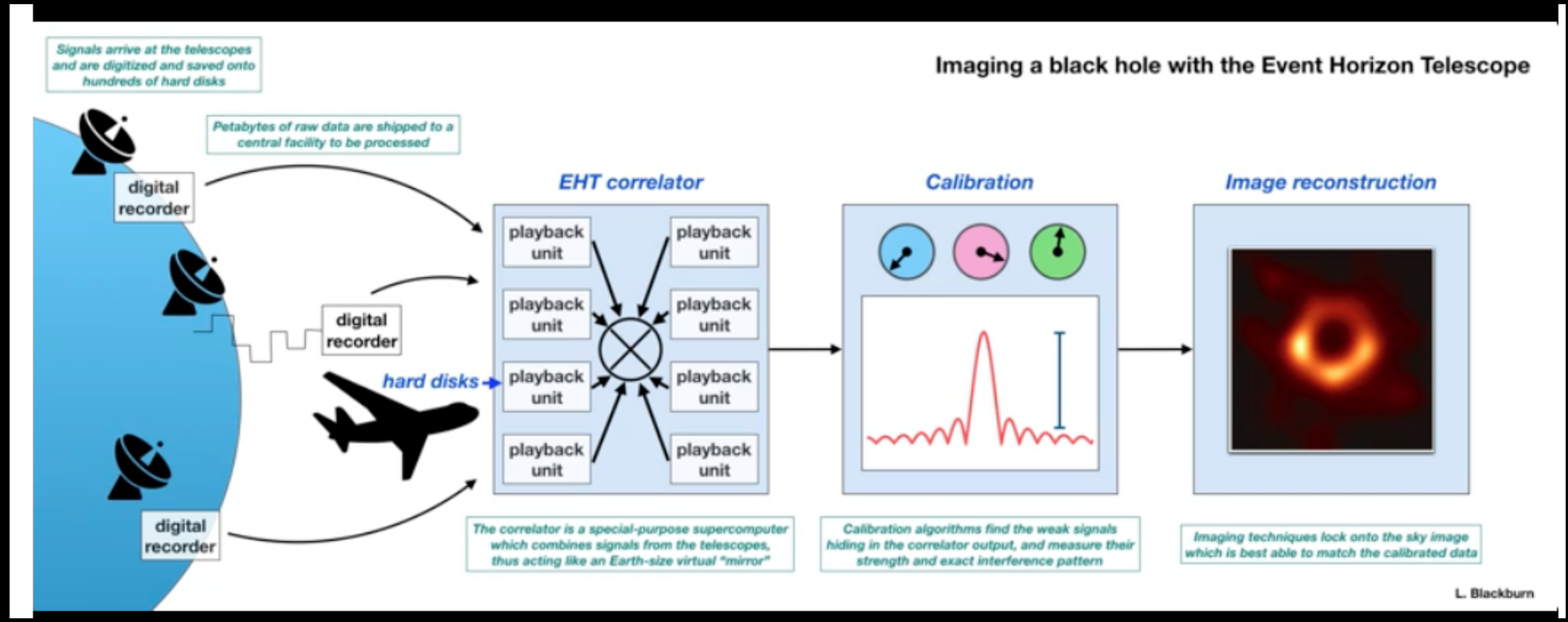
Different flavors of EHT science



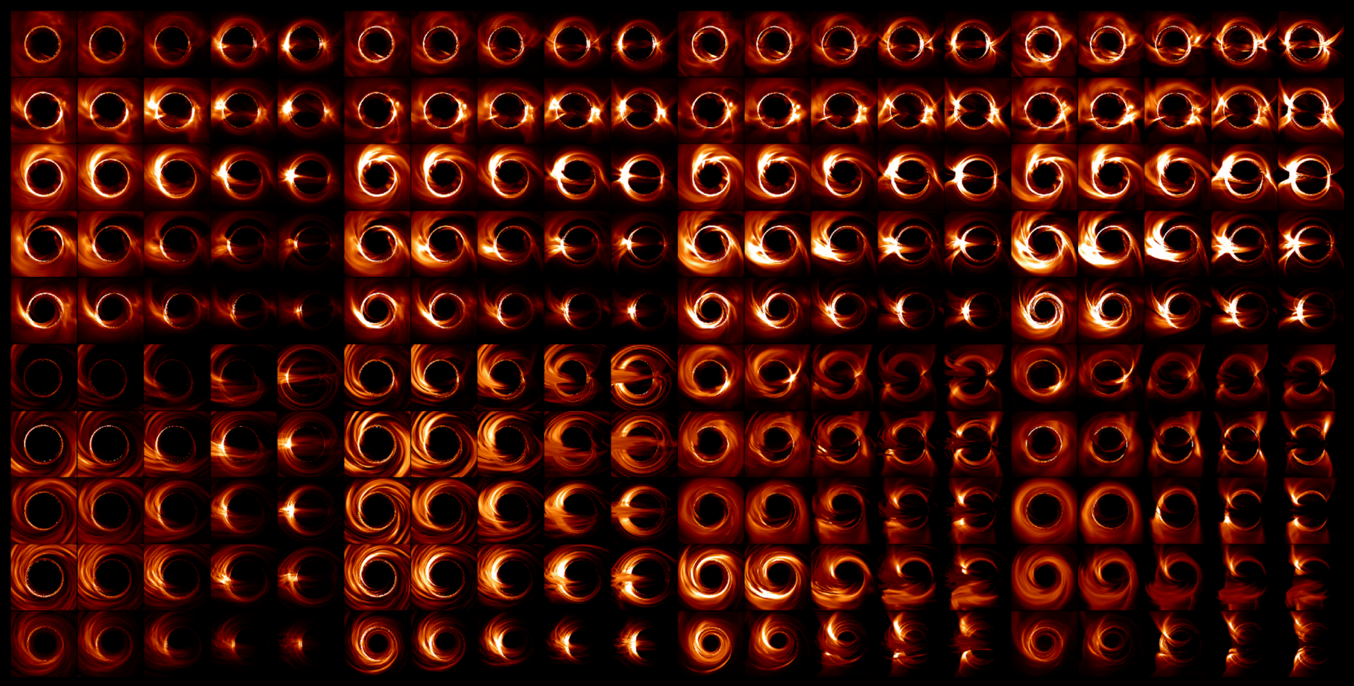
Technology

Black Holes Science

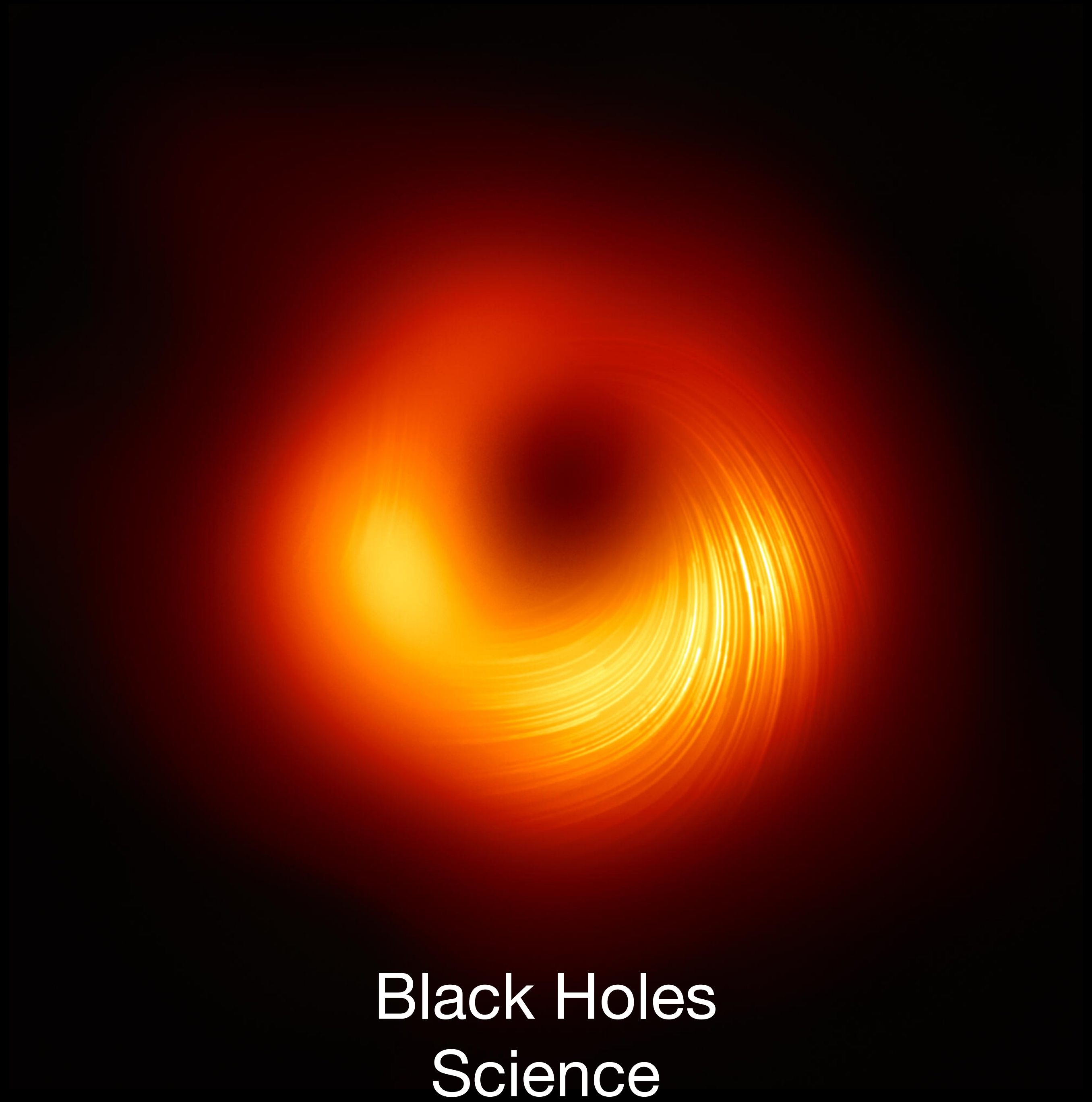
Different flavors of EHT science



Technology

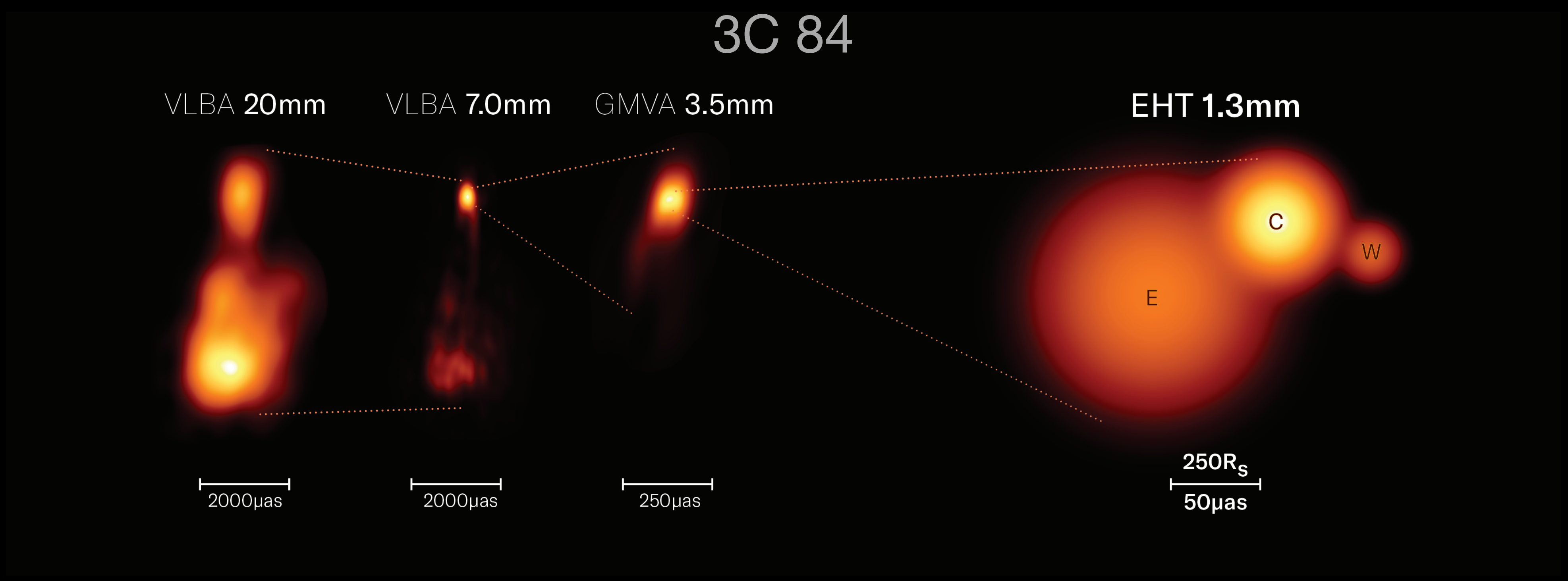


GRMHD modelling

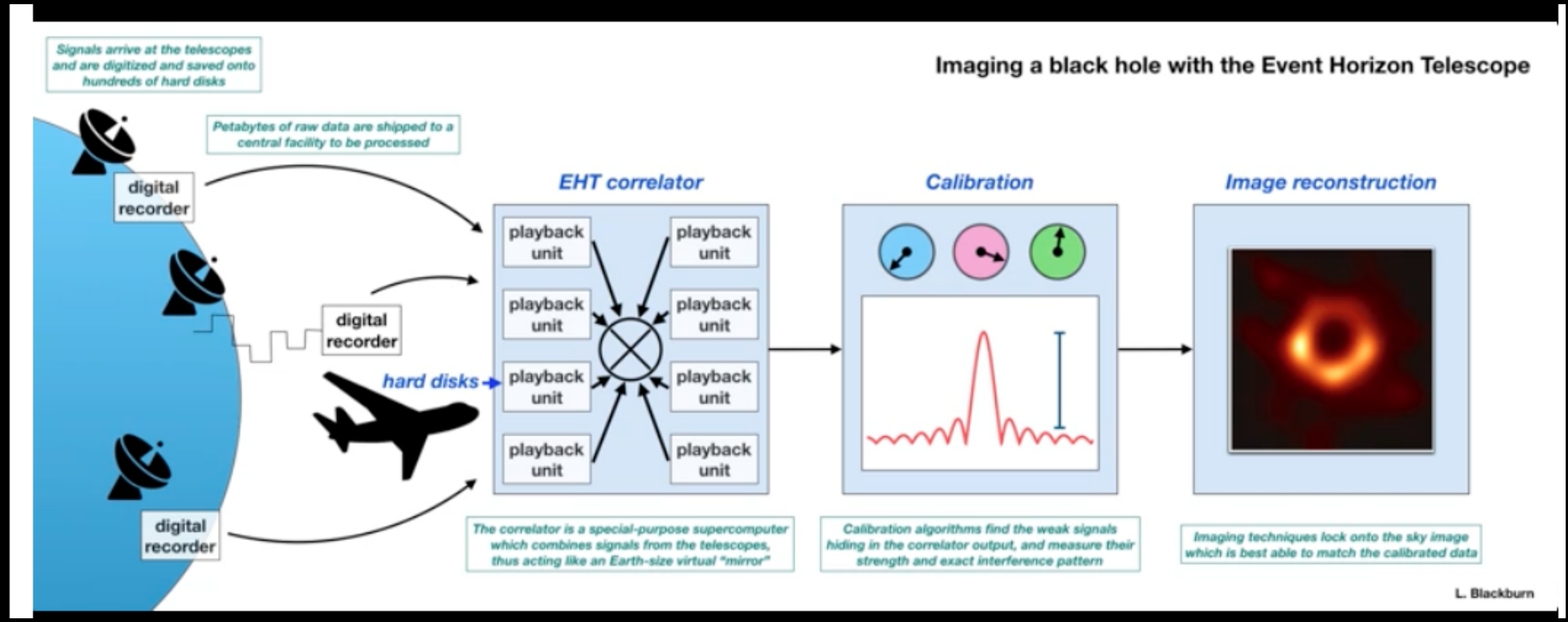


Black Holes Science

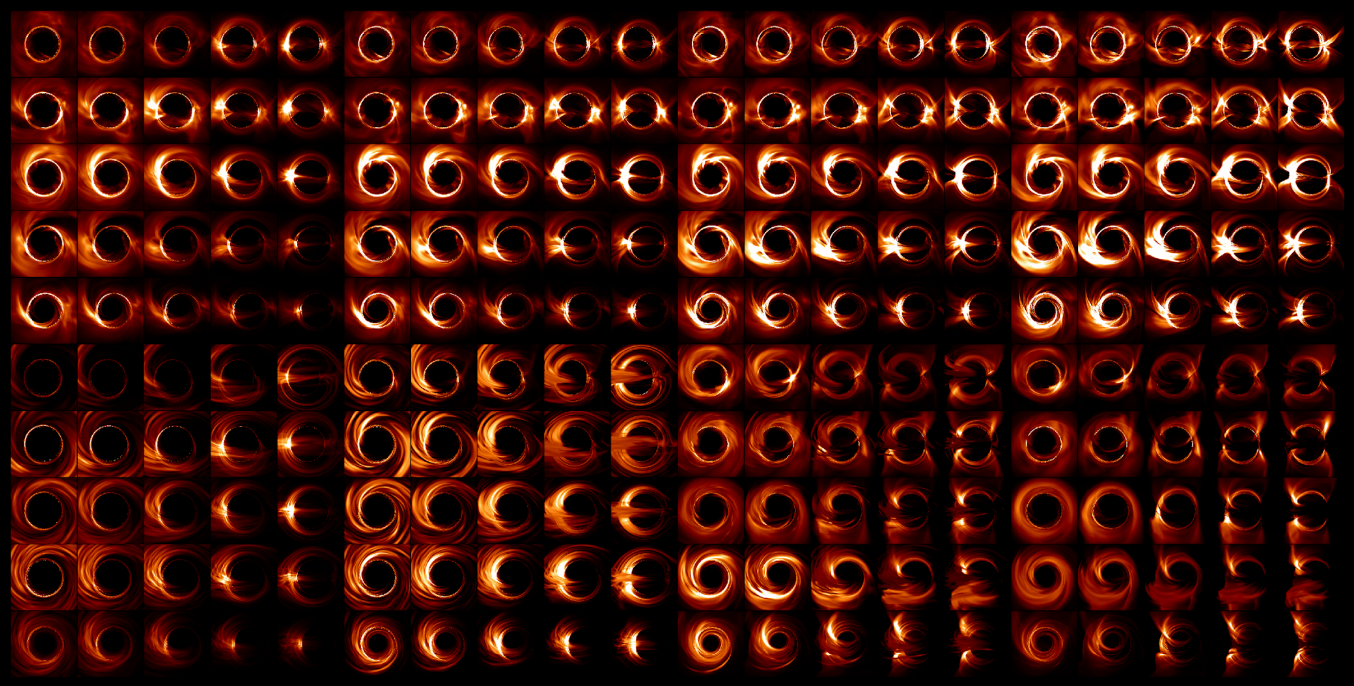
Different flavors of EHT science



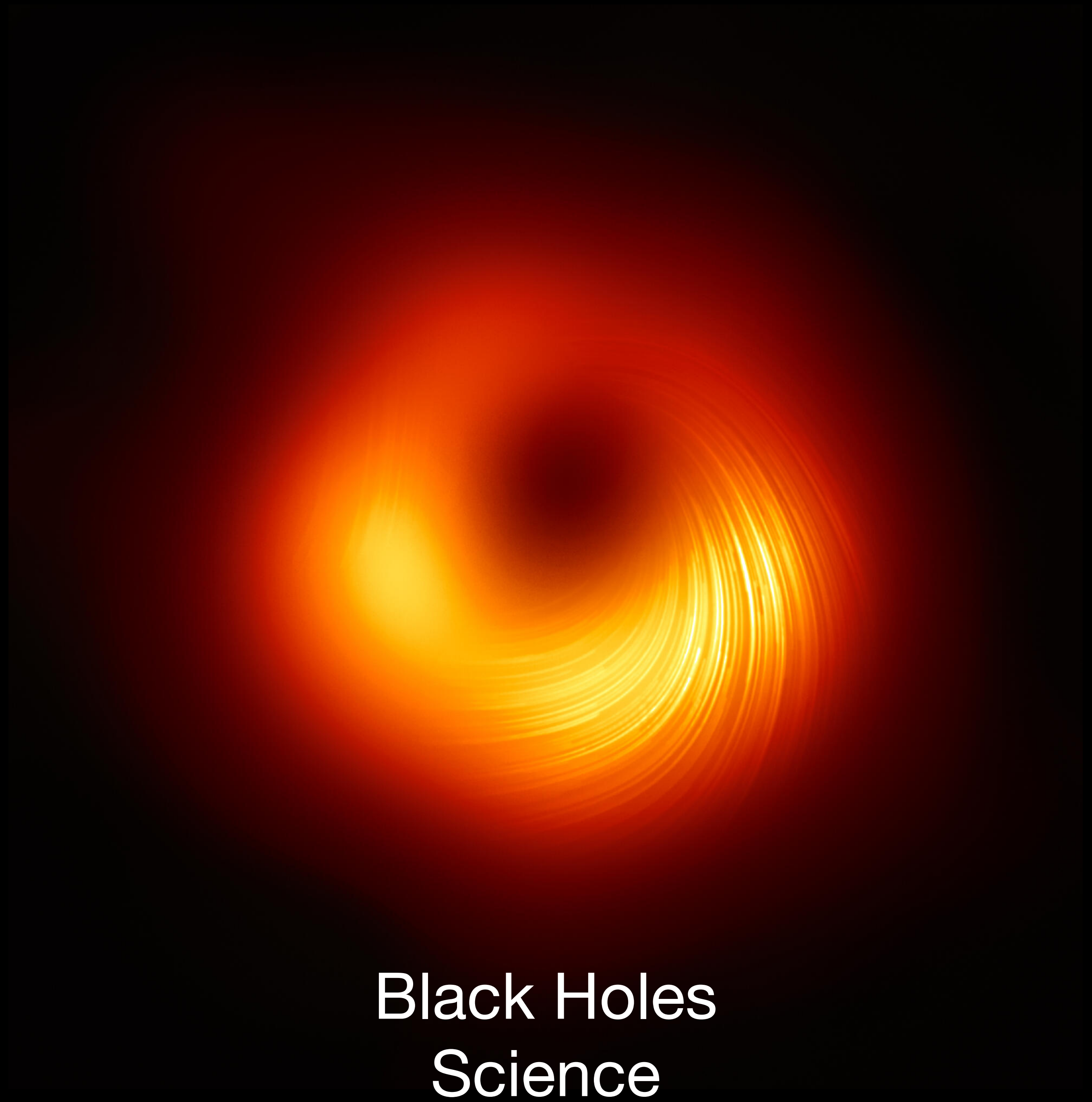
AGN physics



Technology



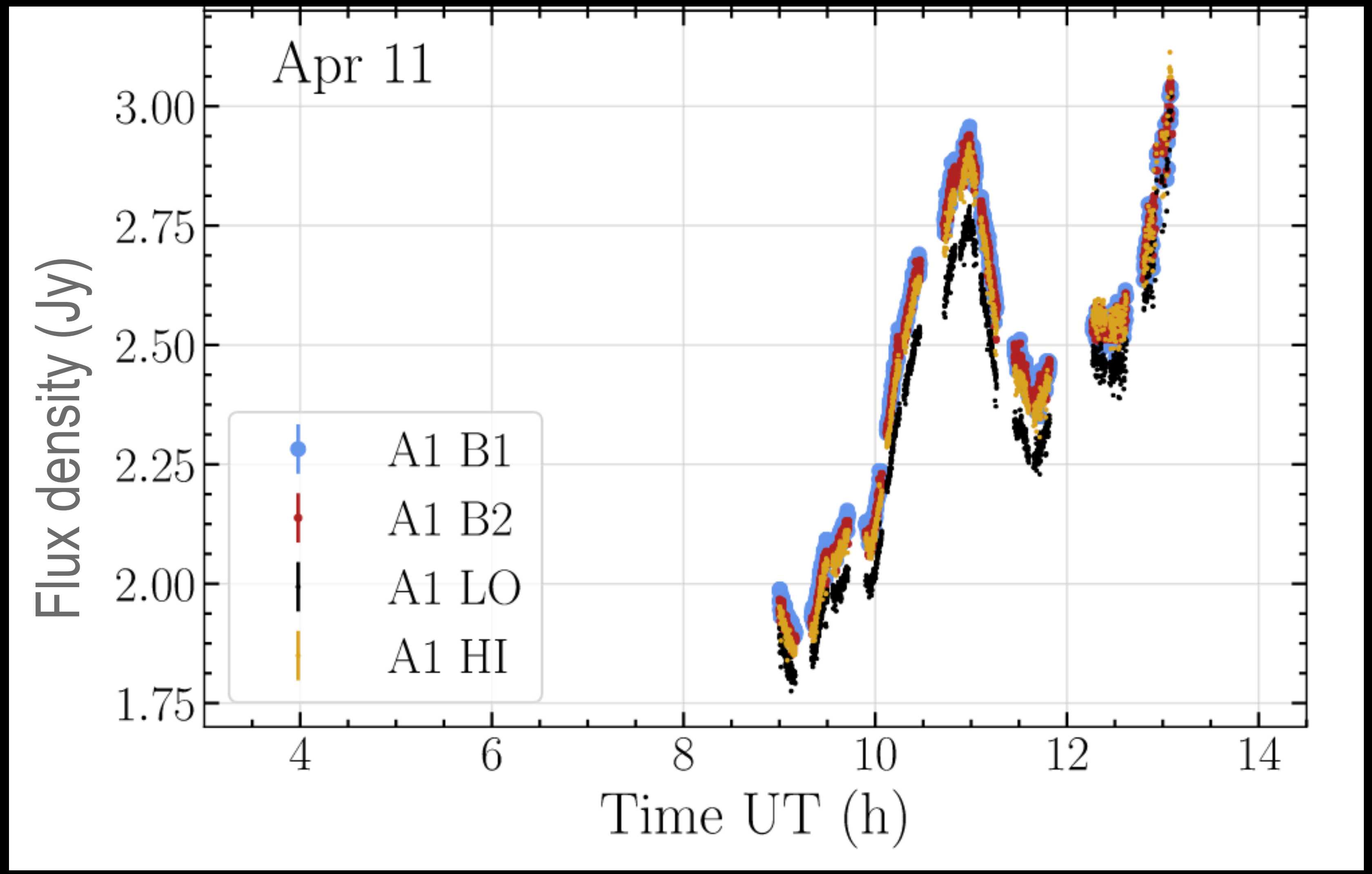
GRMHD modelling



Black Holes Science

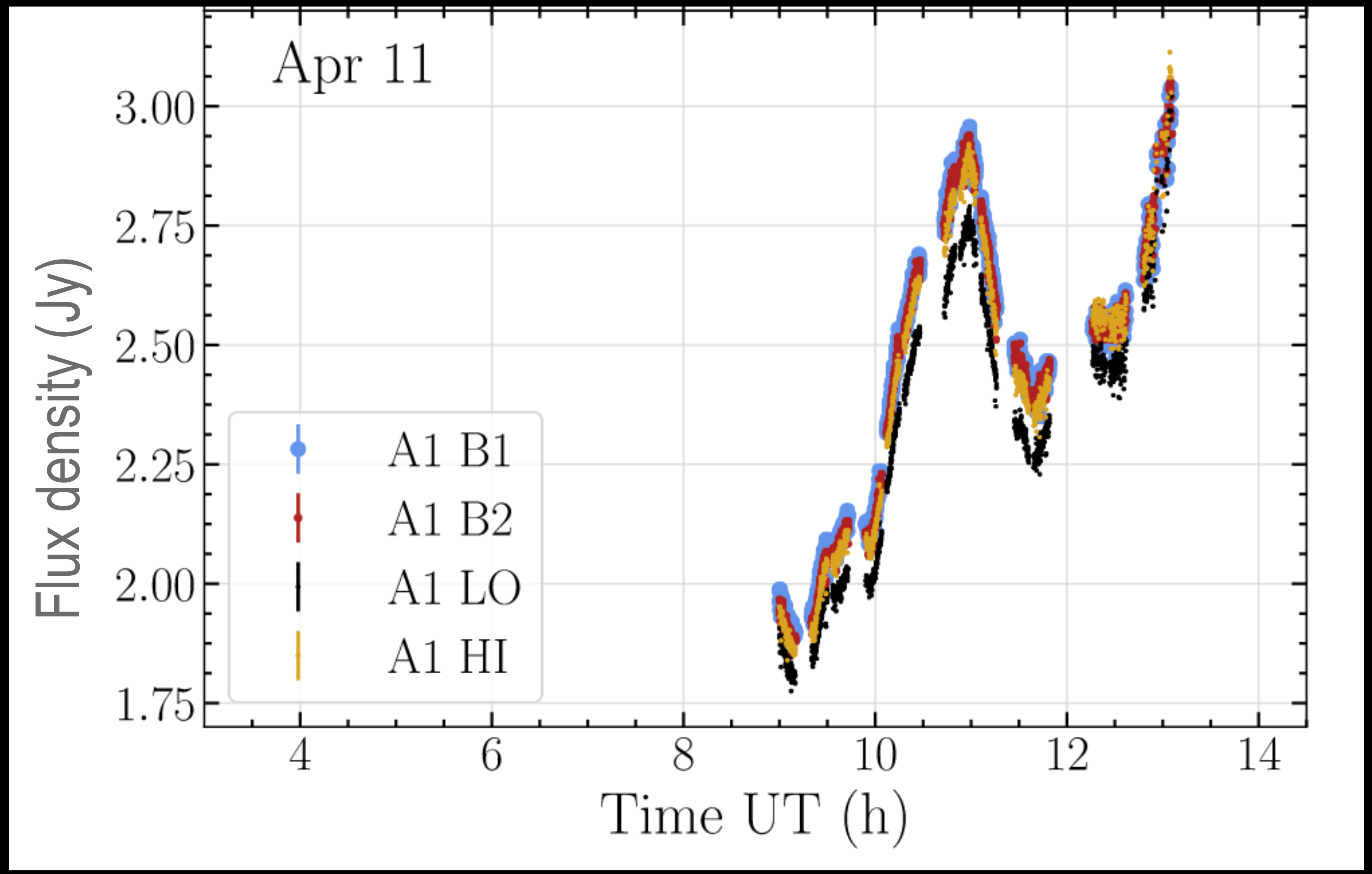
Why Variability

Why Variability

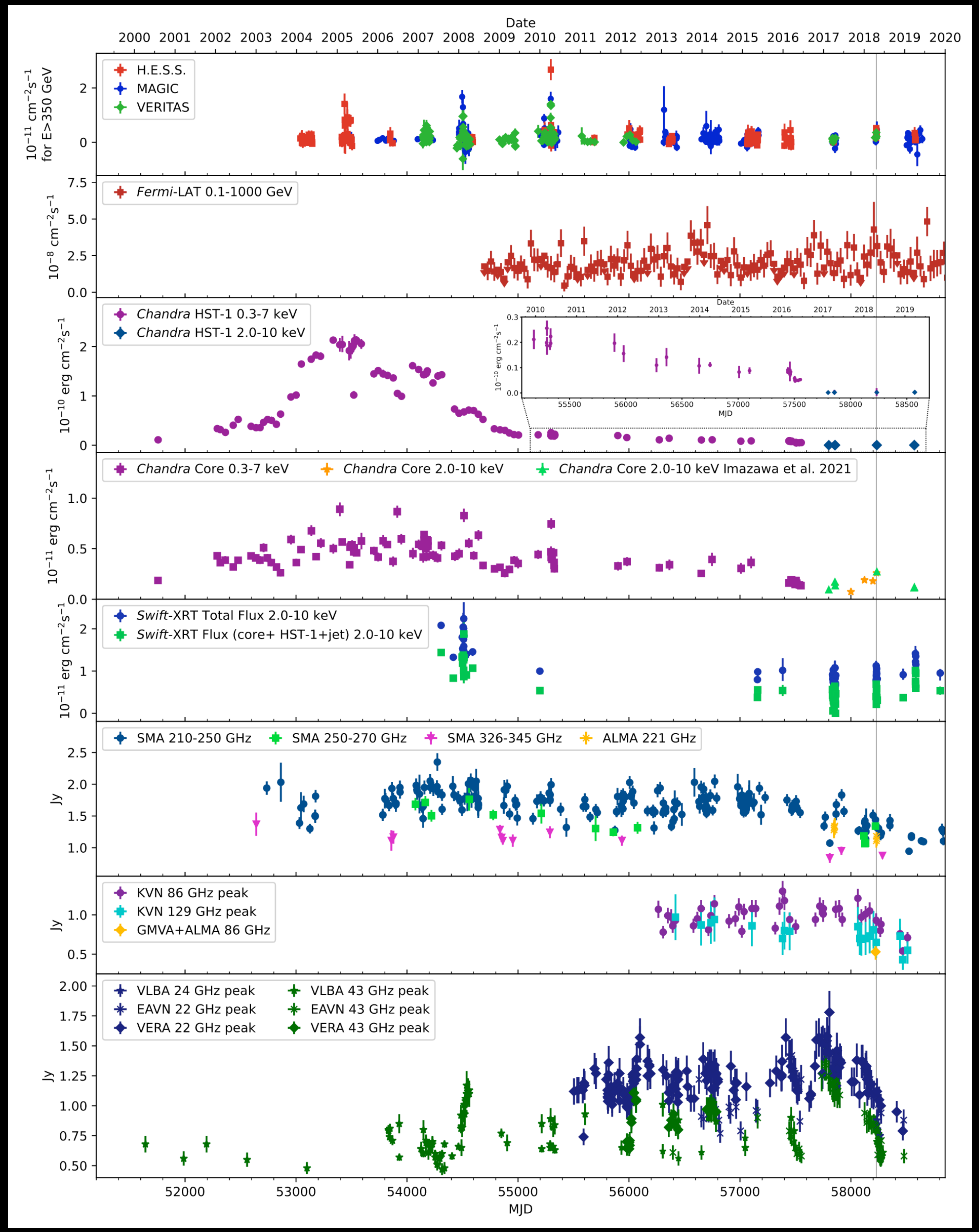


Sgr A*, 2017, Wielgus et al. (2022a)

Why Variability

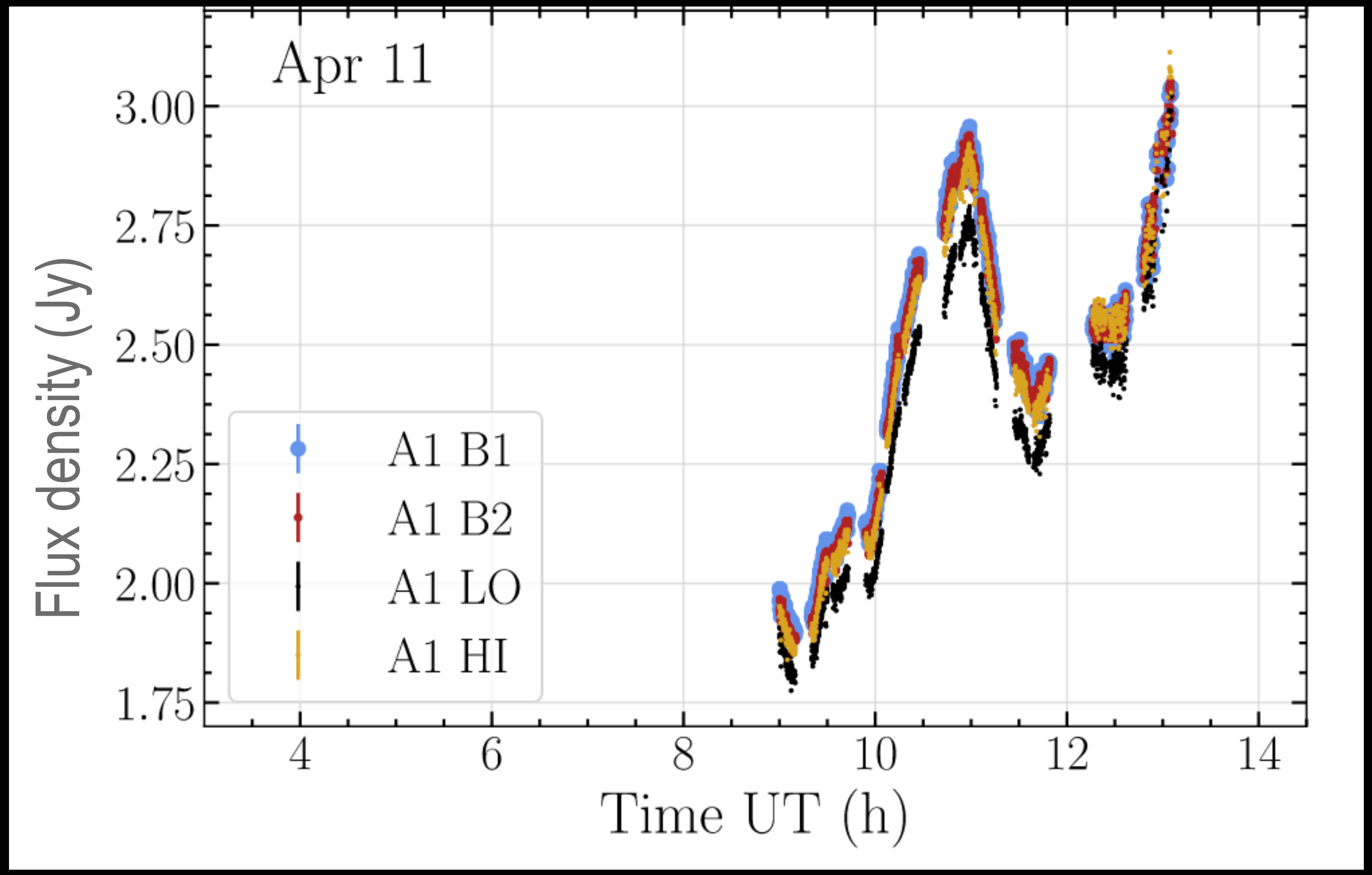


Sgr A*, 2017, Wielgus et al. (2022a)



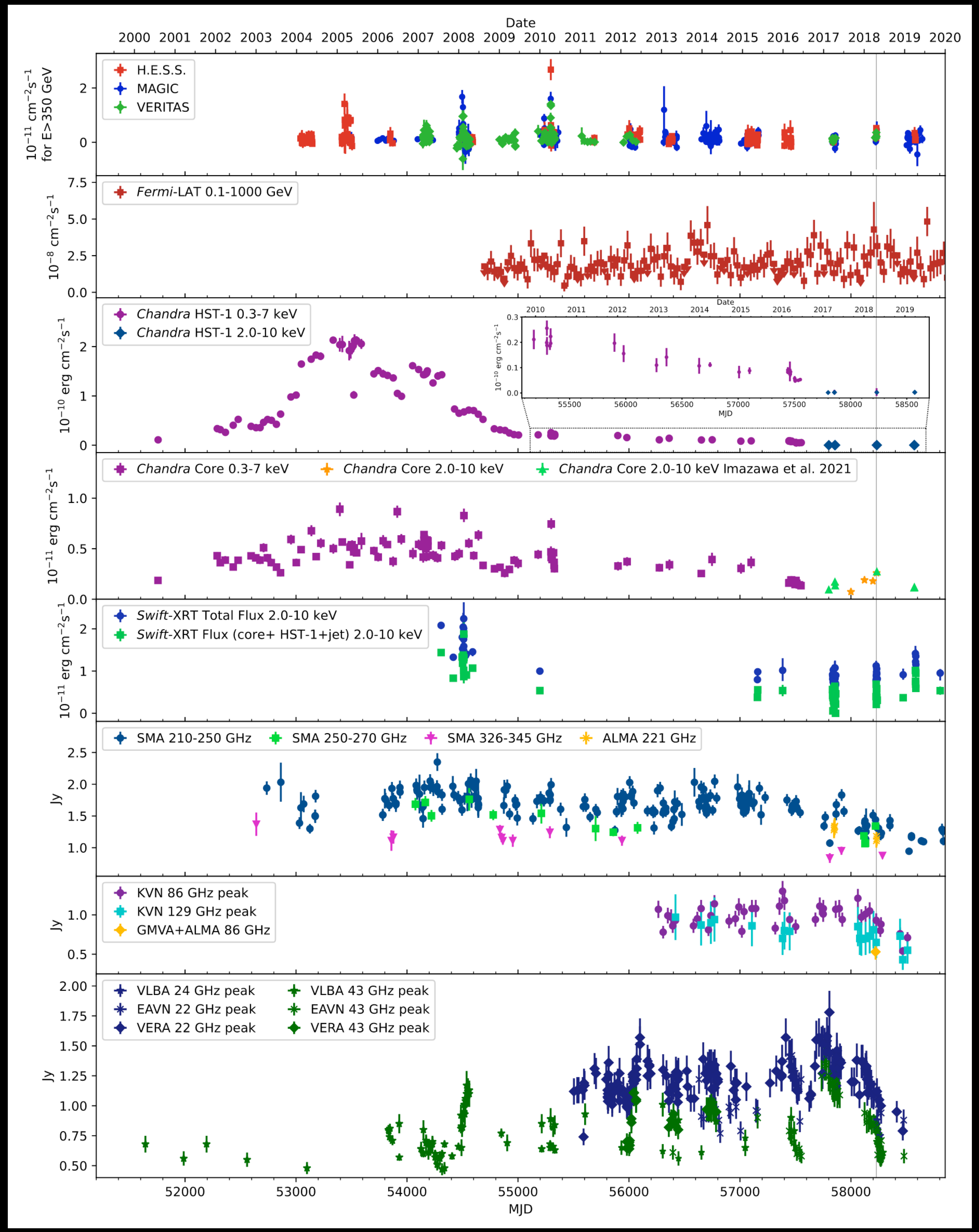
M87, 2018, Algaba et al. (2024)

Why Variability



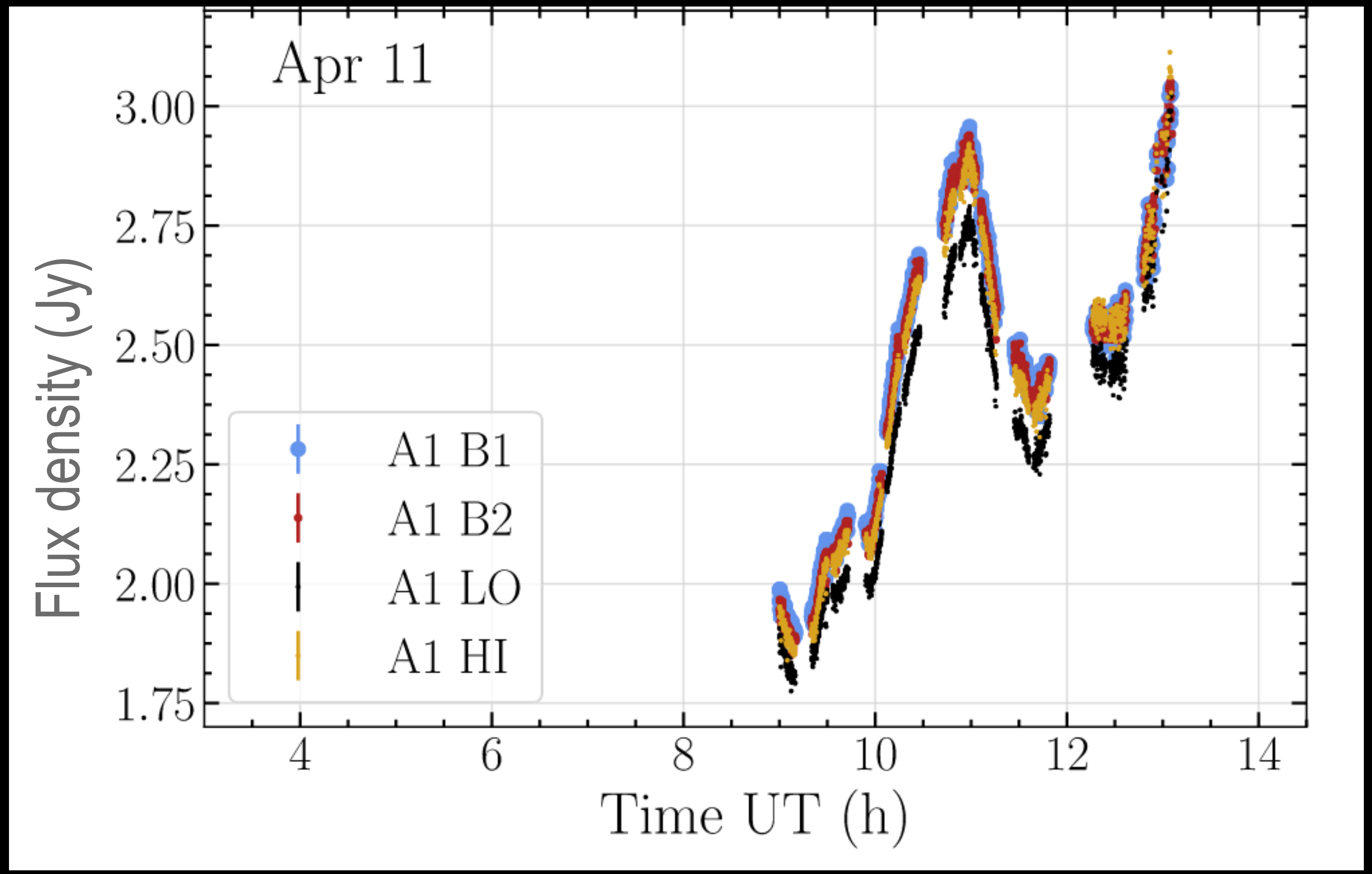
Sgr A*, 2017, Wielgus et al. (2022a)

www.lomography.it/homes/flanflipflop



M87, 2018, Algaba et al. (2024)

Why Variability



Sgr A*, 2017, Wielgus et al. (2022a)

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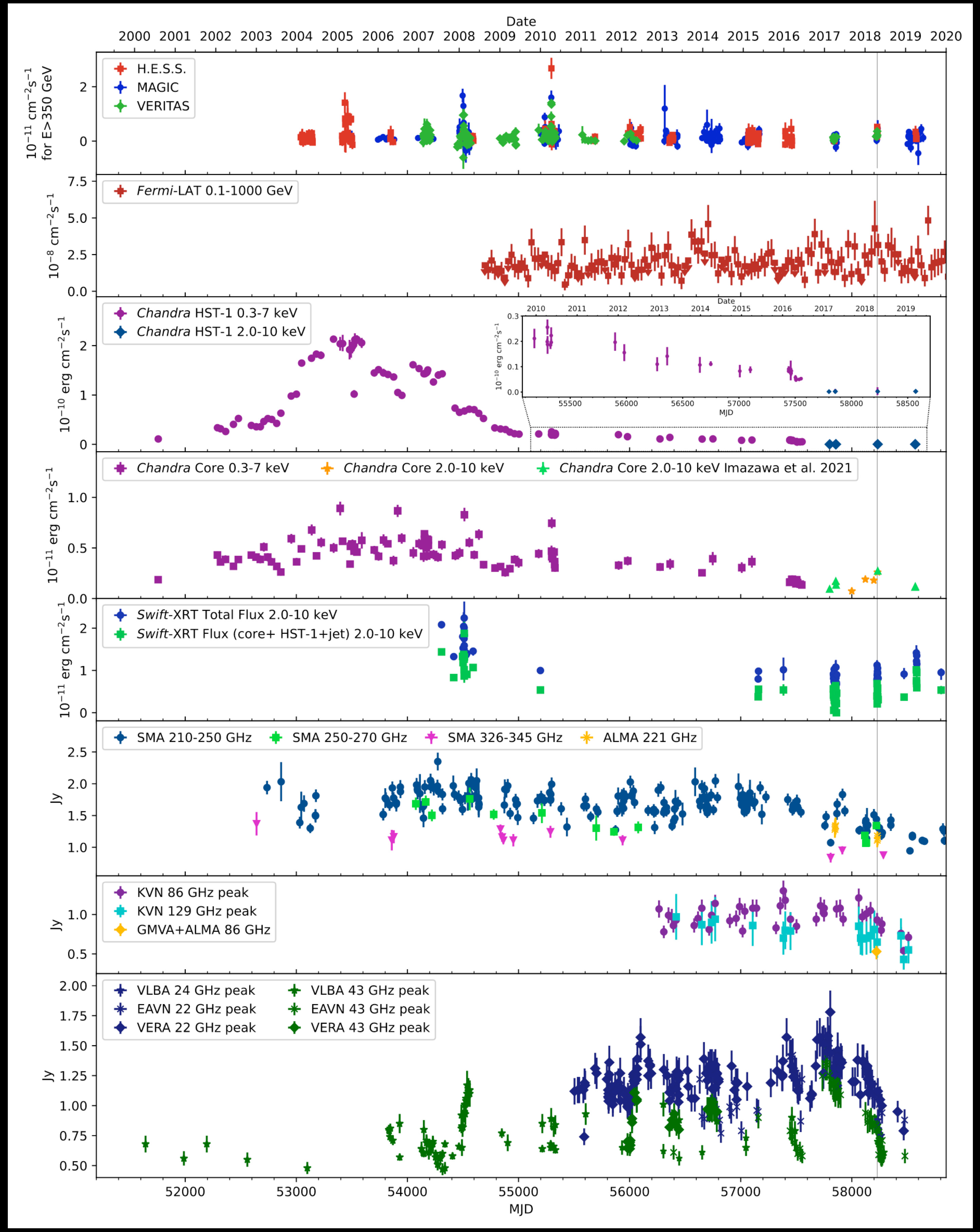
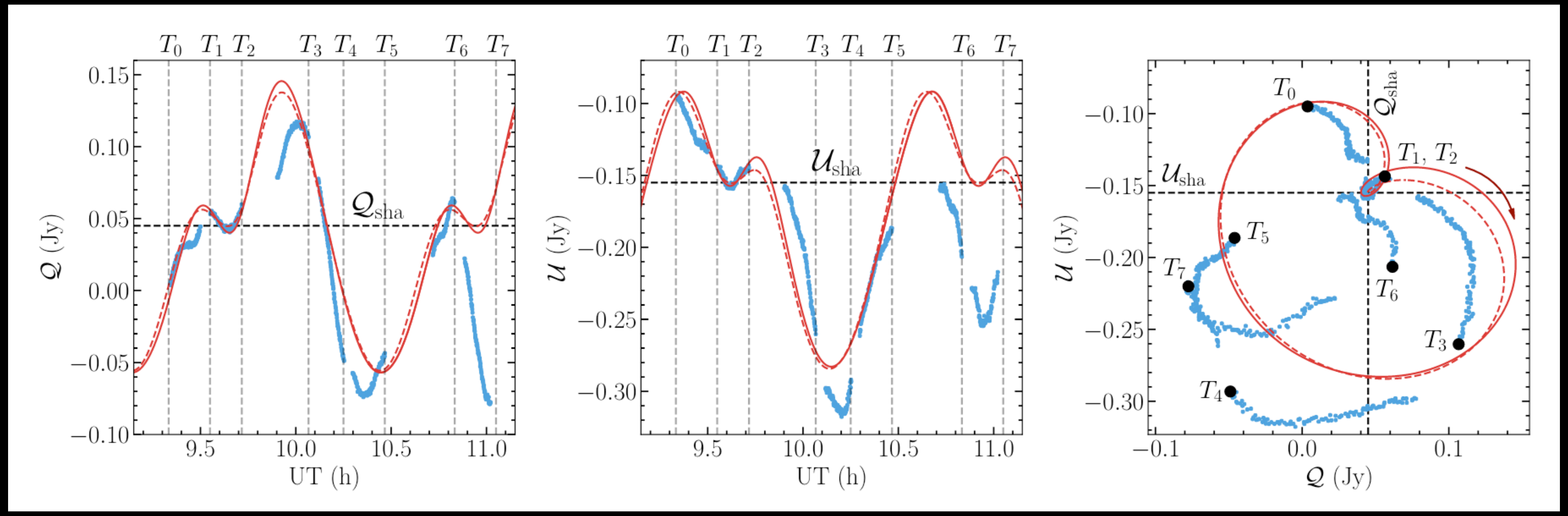


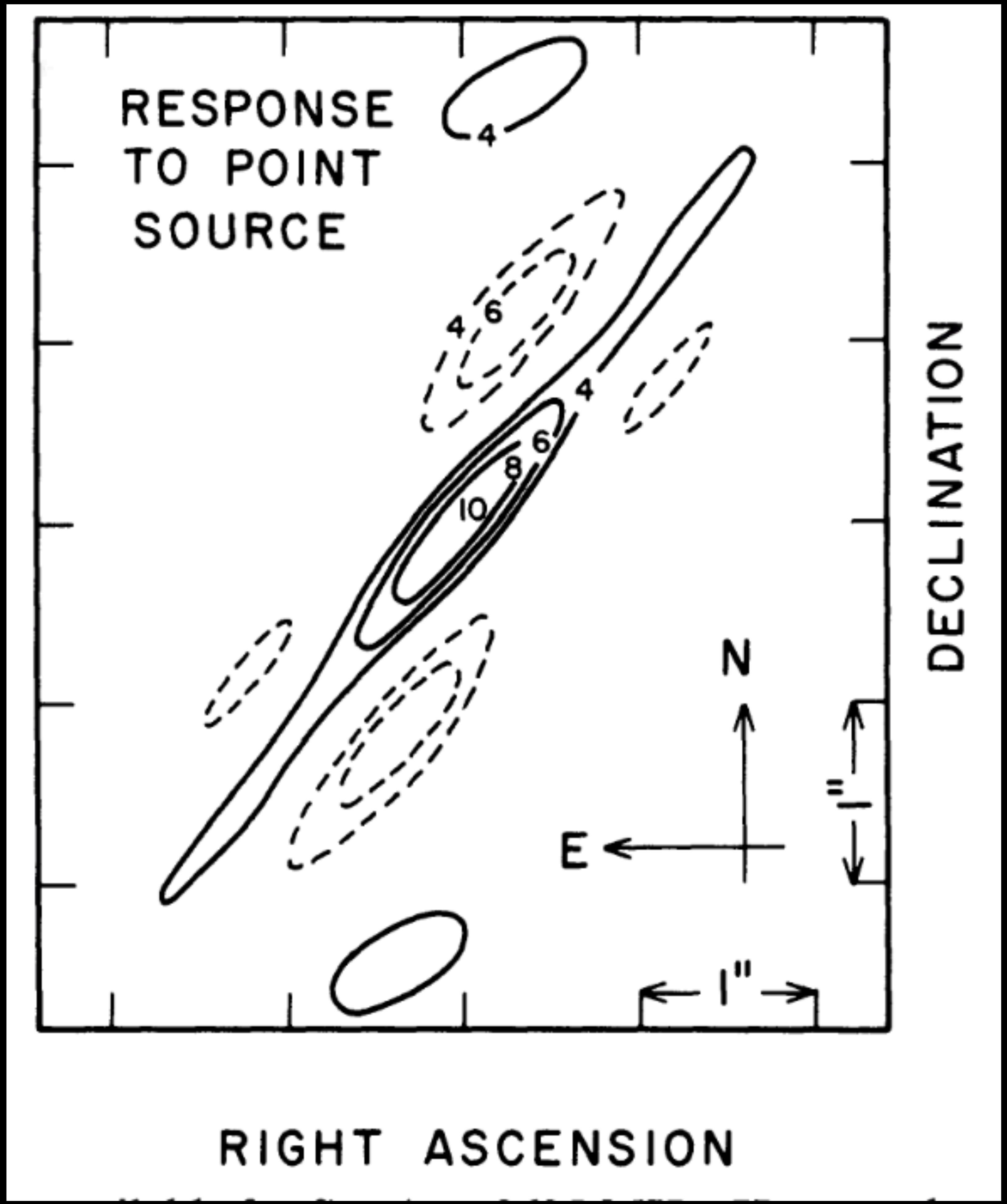
M87, 2018, Algaba et al. (2024)



Sgr A*, 2017, Wielgus et al. (2022b)

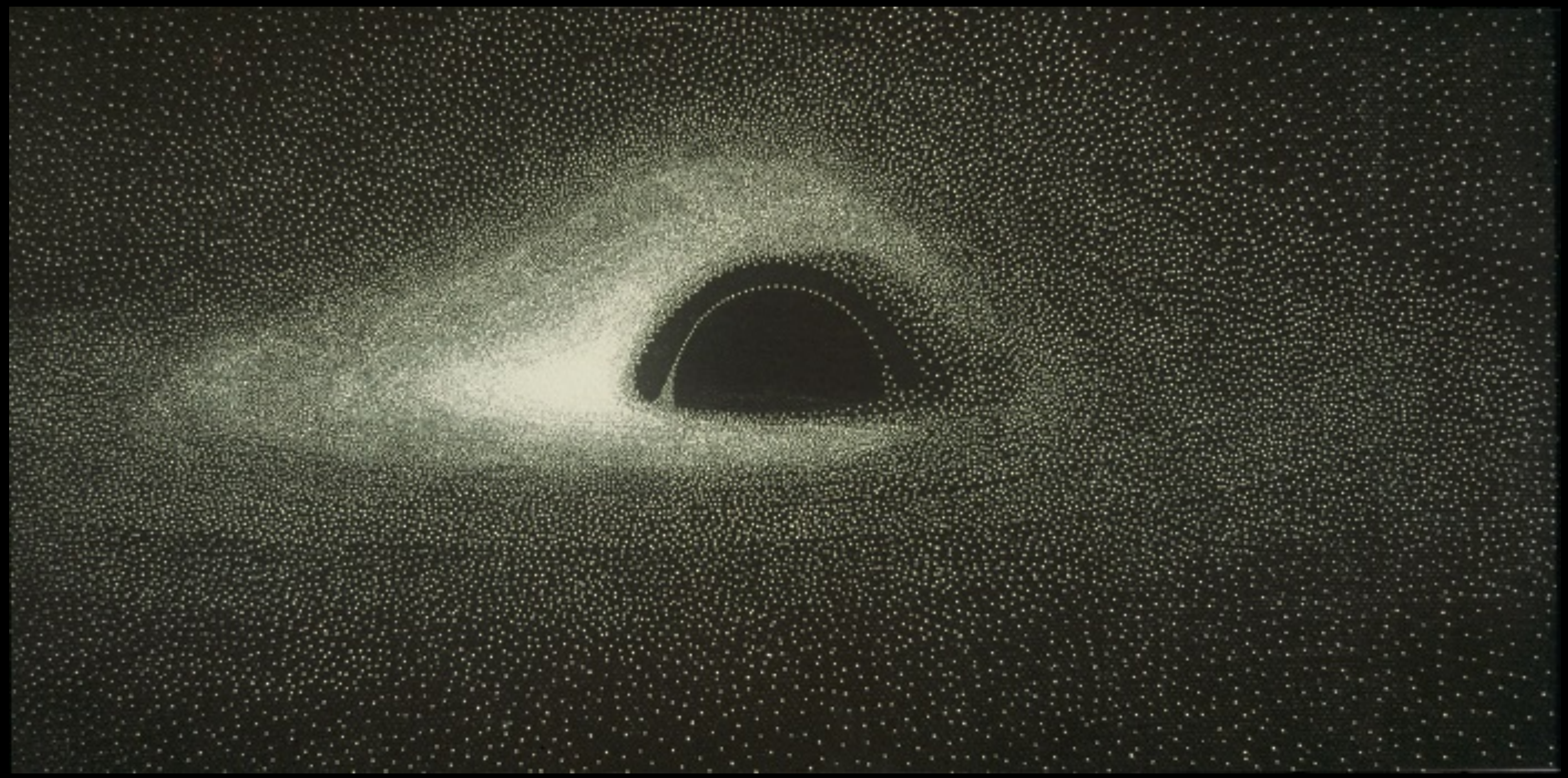
A bit of history: Sgr A*

Discovery of a compact radio source towards the centre of our Galaxy (NRAO interferometer, λ 3.7cm, 4 antennas)



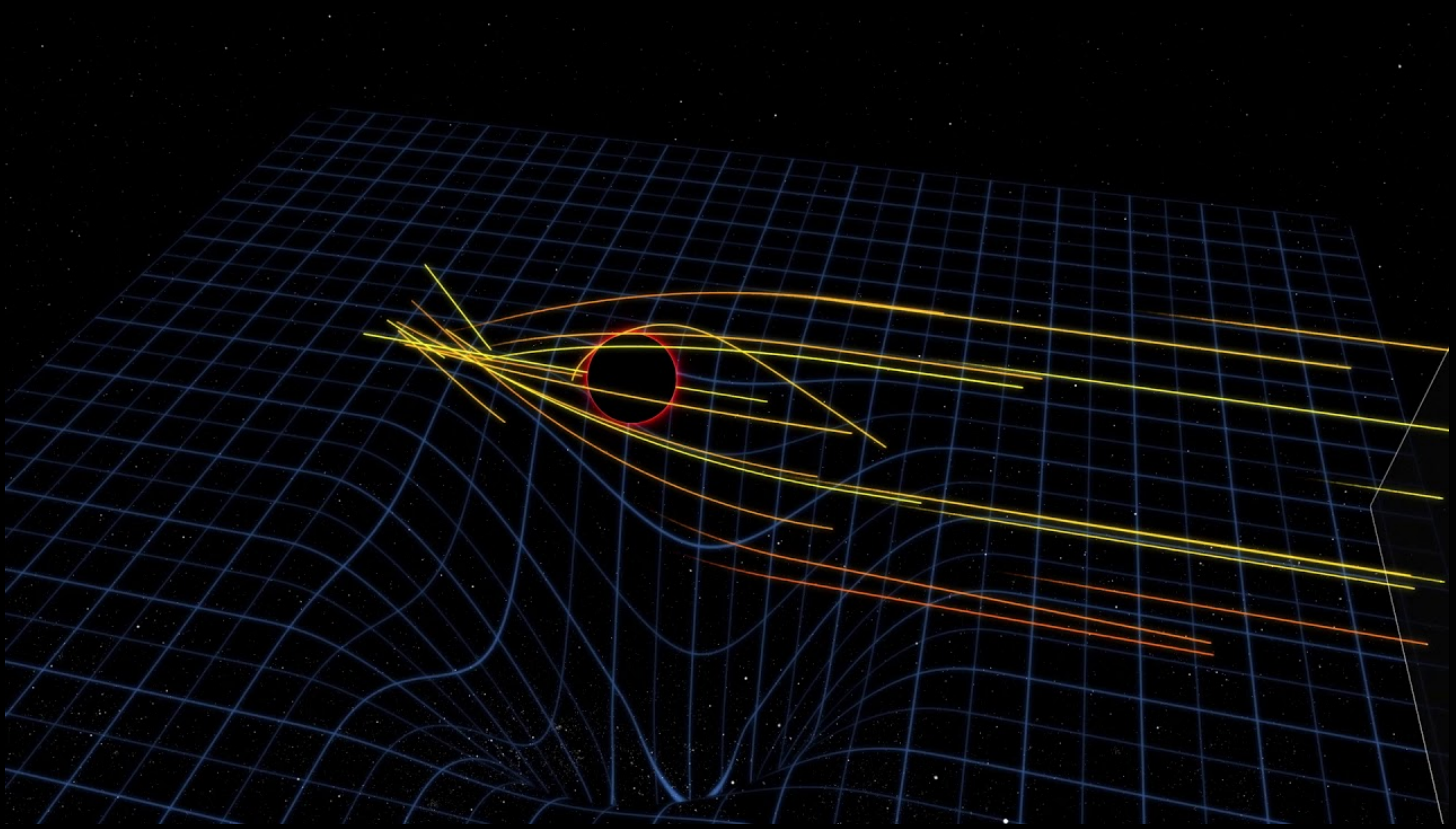
Balick and Brown 1974

A bit of history:
what may be lying at the centre of the Milky Way…

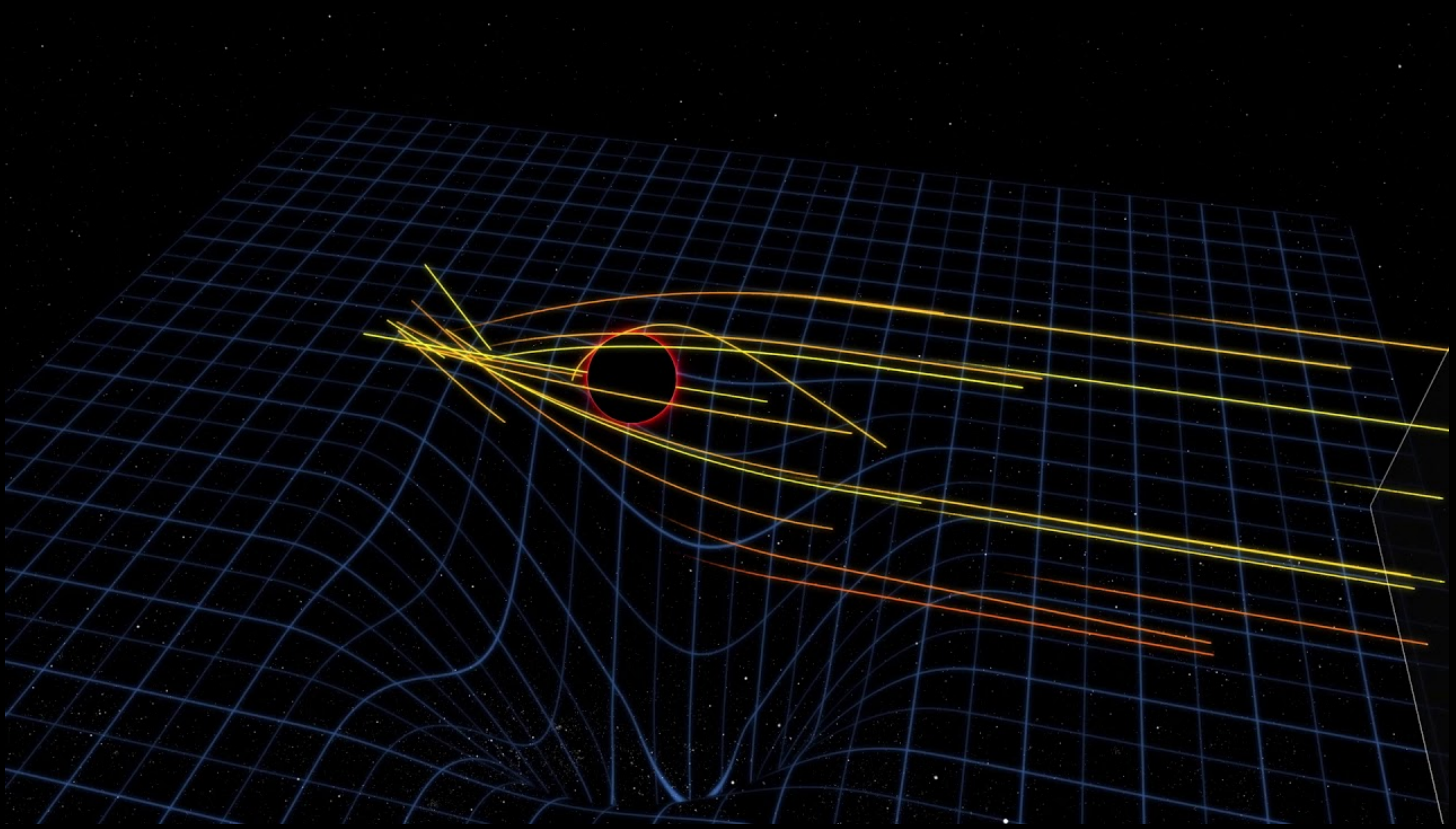


Luminet 1979

First simulation of a black hole shadow

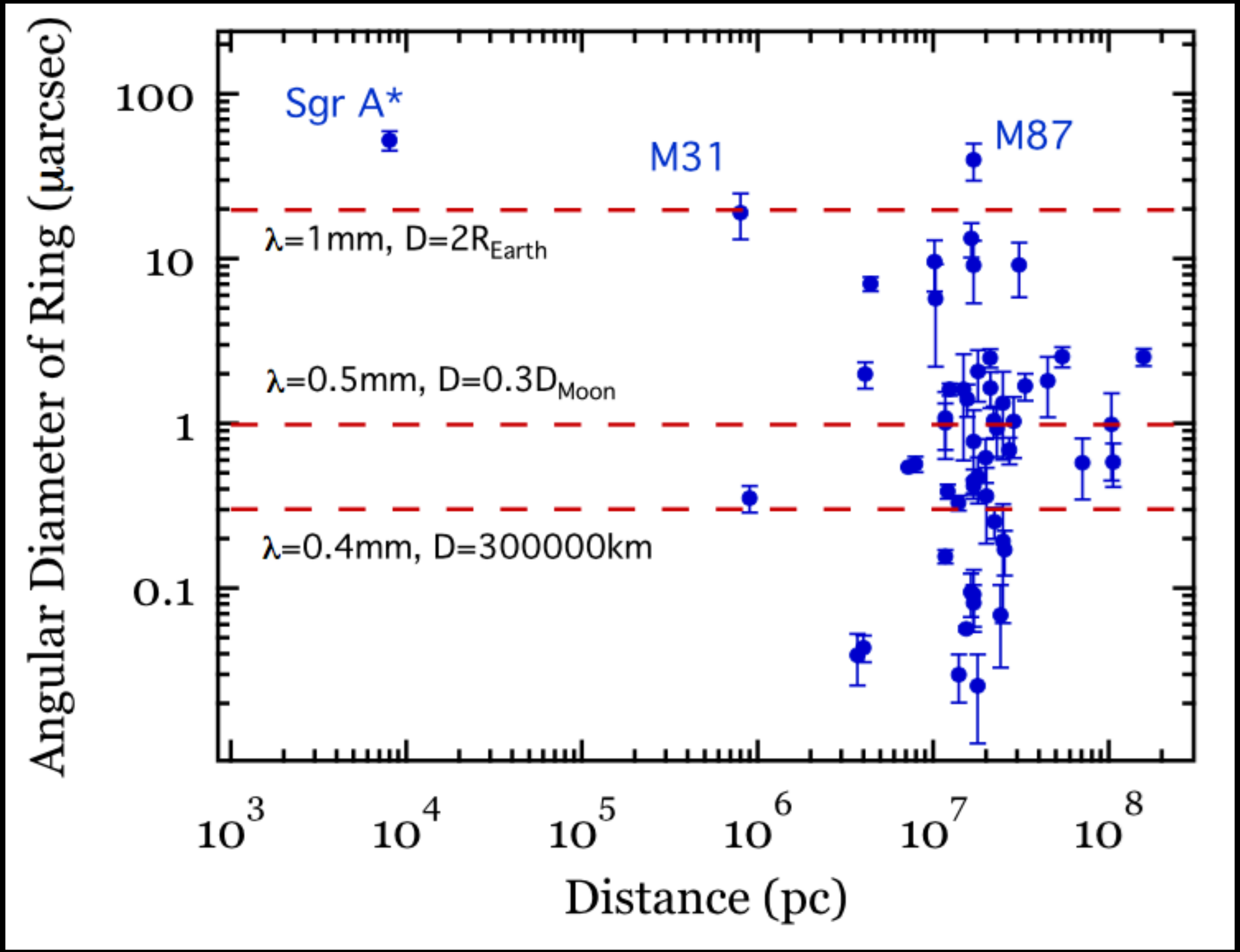


Credits: Crazybridge Studios, Center for Astrophysics | Harvard & Smithsonian, US National Science Foundation



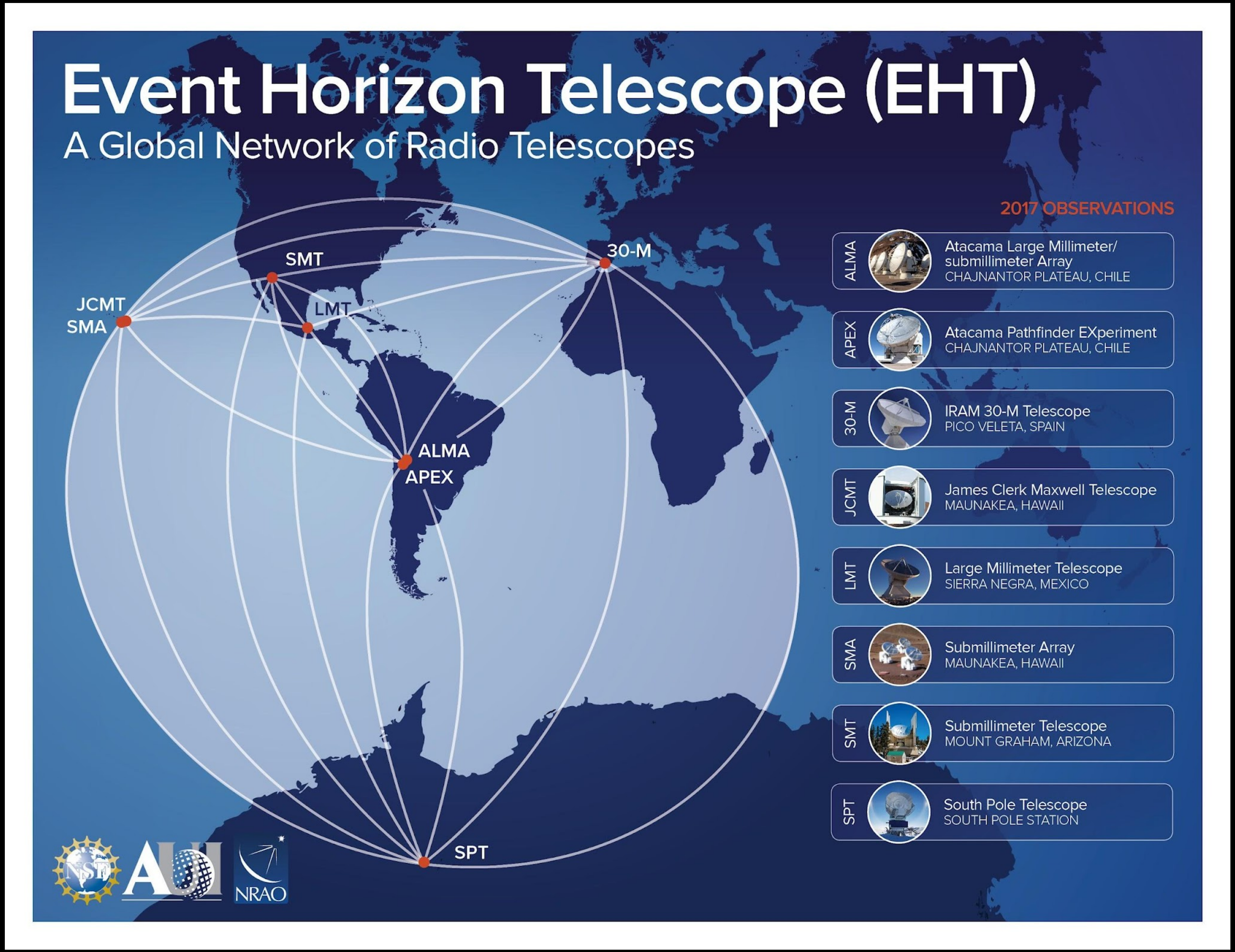
Credits: Crazybridge Studios, Center for Astrophysics | Harvard & Smithsonian, US National Science Foundation

A bit of history:
Which sources are observable?



Johannsen et al. 2012

A bit of history: The Event Horizon telescope



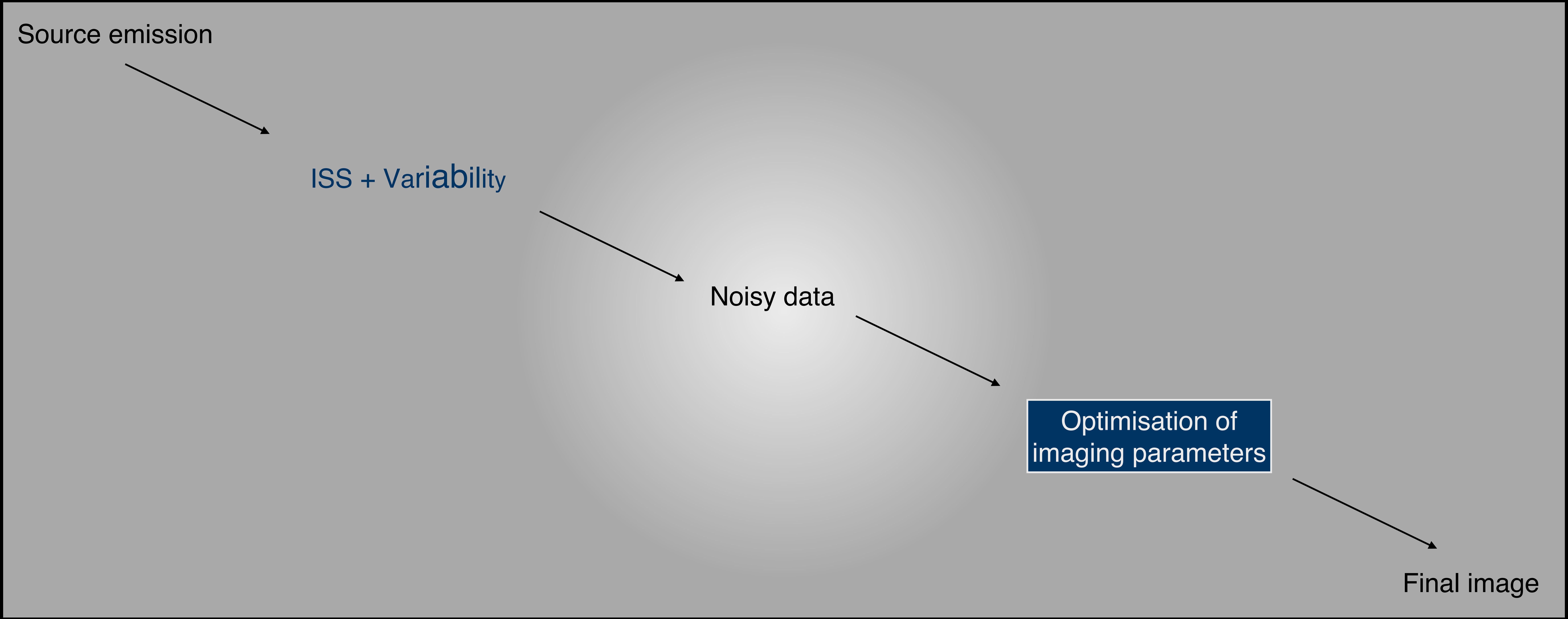
A bit of history: The EHT Collaboration

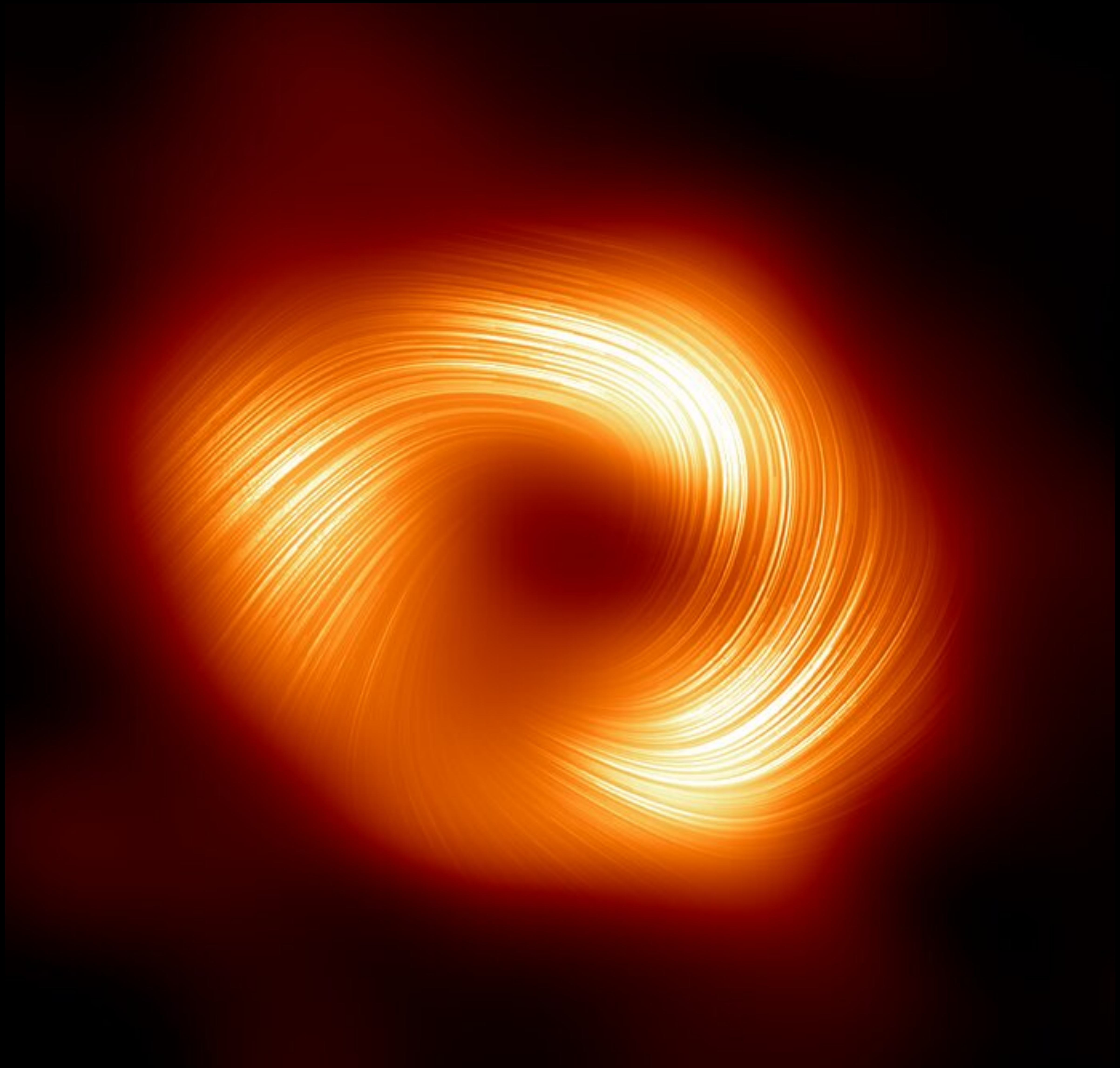
M87*

The EHT Collaboration (2019a, b, c, d, e, f; 2021a, b)


Adobe Firefly

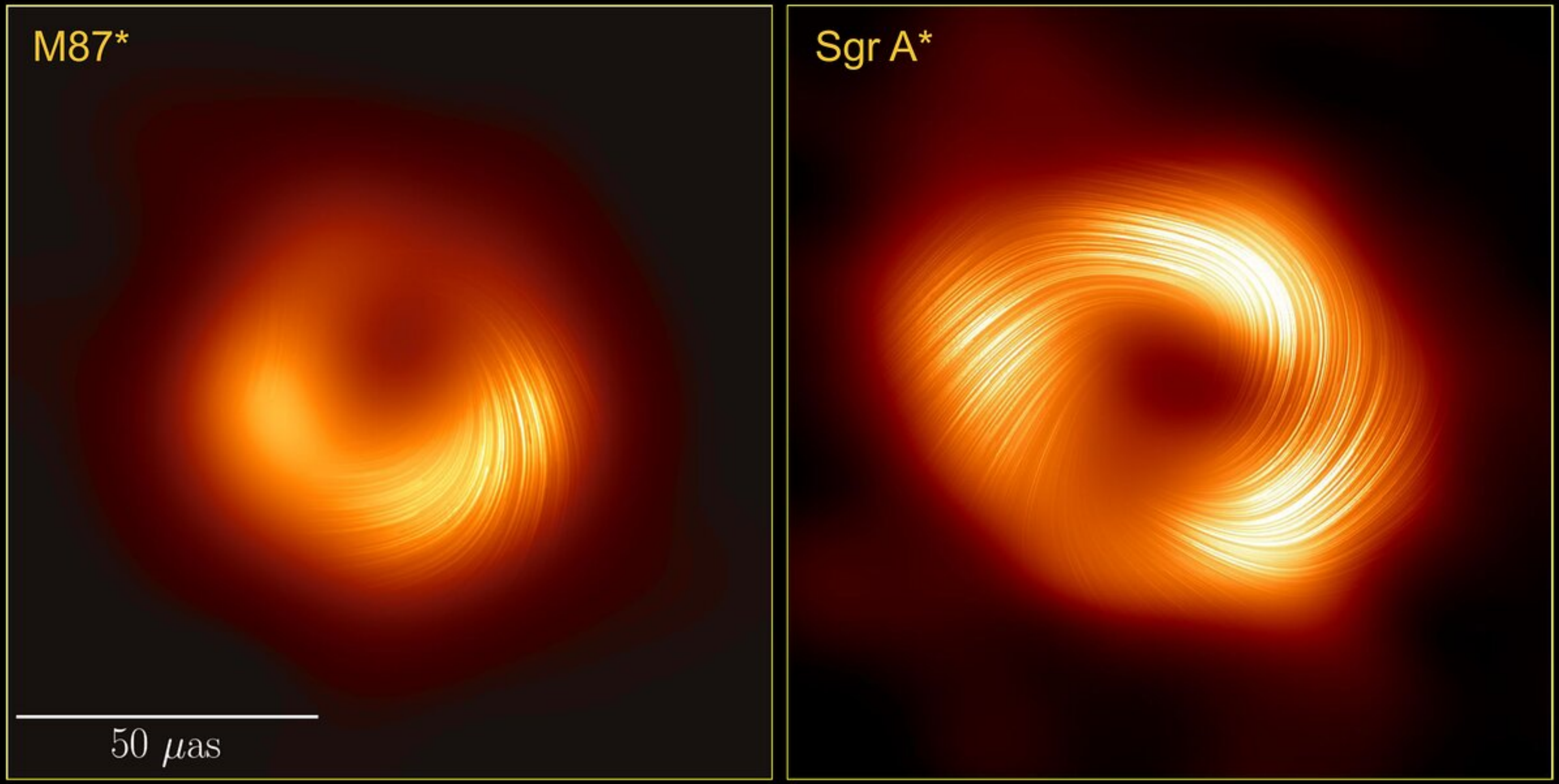
How do we deal with variability?





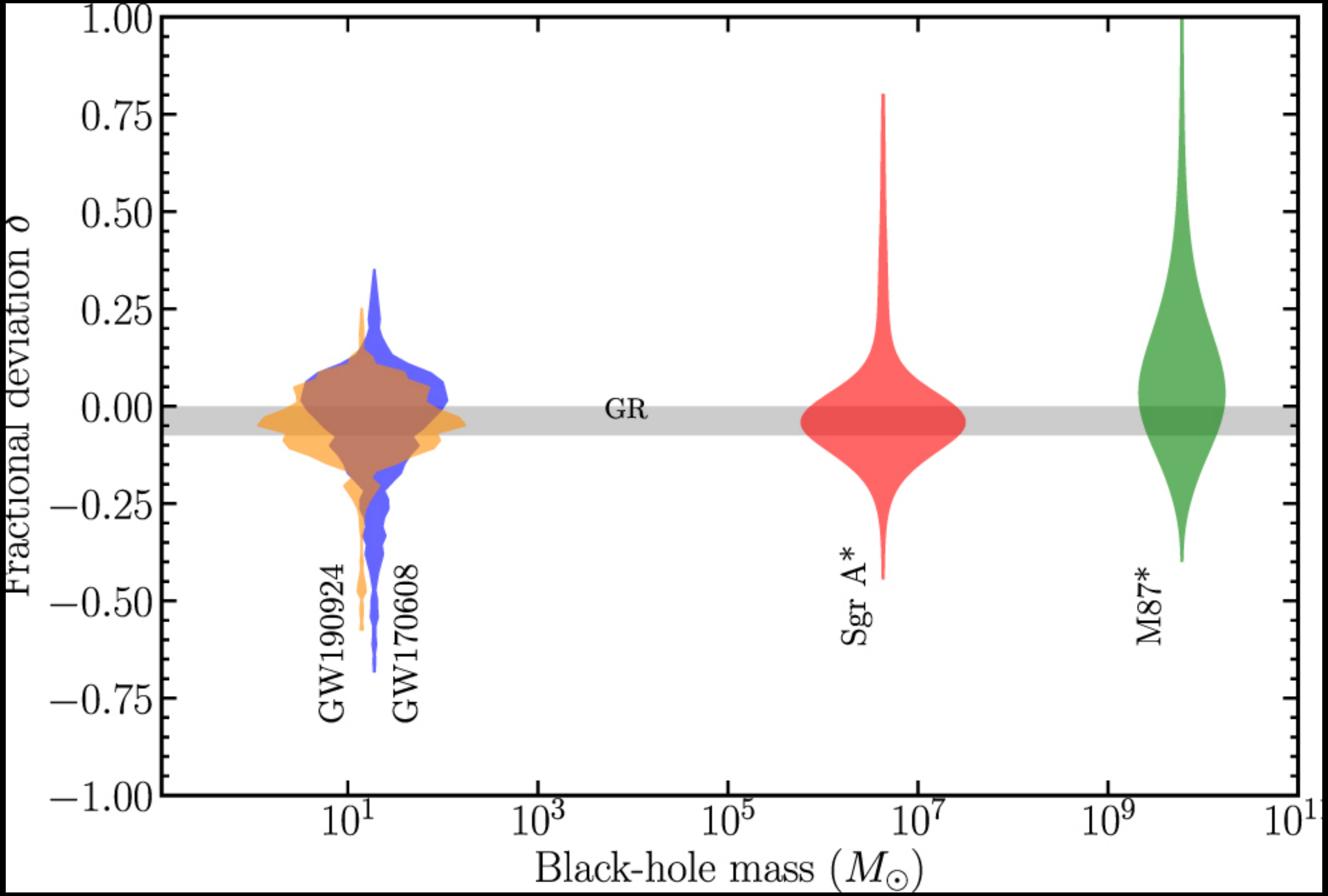
Sgr A*
The EHT Collaboration (2022a, b, c, d, e, f, 2024b, c)

Comparison between the two shadows



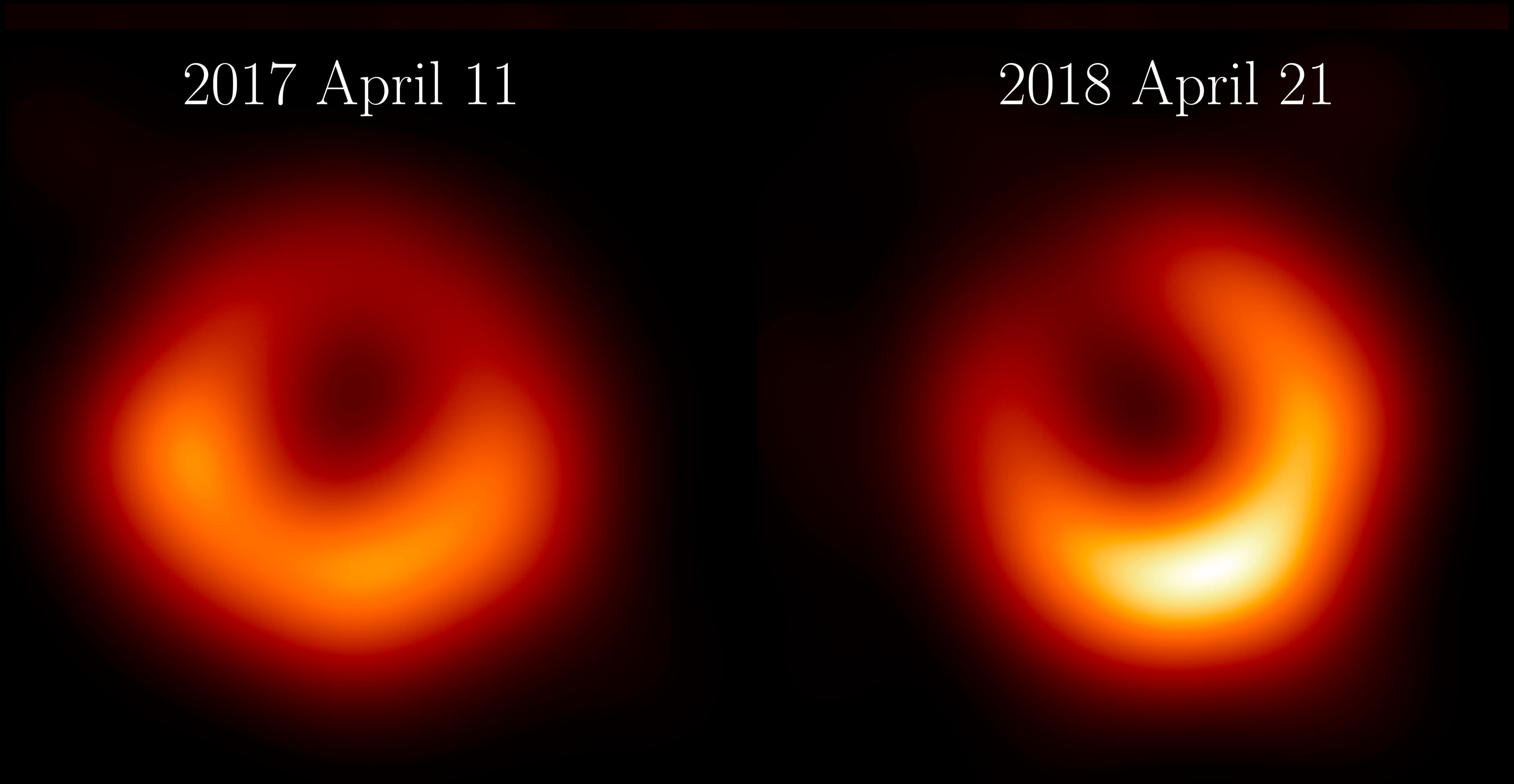
Credits: The EHT Collaboration

EHT results beyond the shadows: Relativity



The EHT Collaboration (2022f)

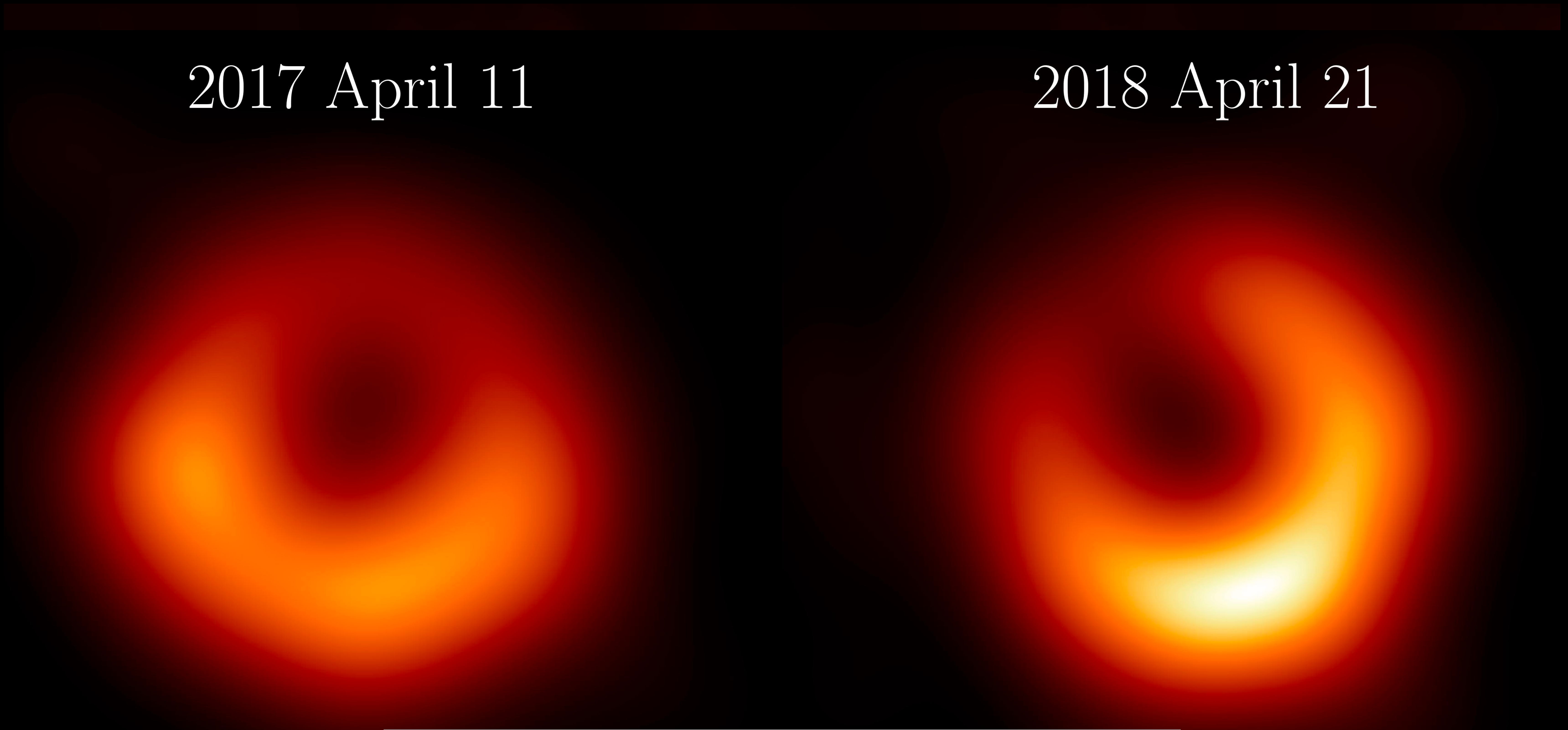
M87: Comparison between M87 shadows



The EHT Collaboration (2019a, b, c, d, e, f)

The EHT Collaboration (2024a)

M87: Comparison between M87 shadows



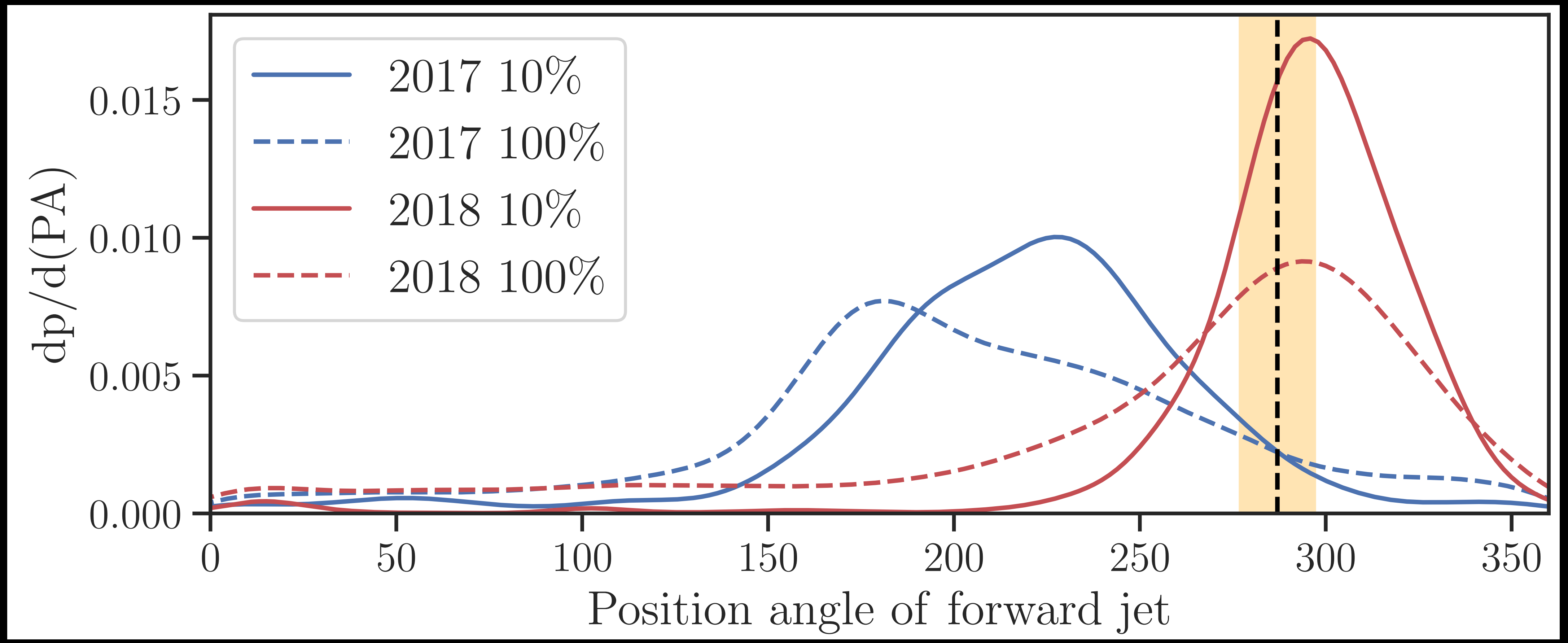
The position angle of the brightness asymmetry
goes from 180 to 210 deg

The EHT Collaboration (2019a, b, c, d, e, f)

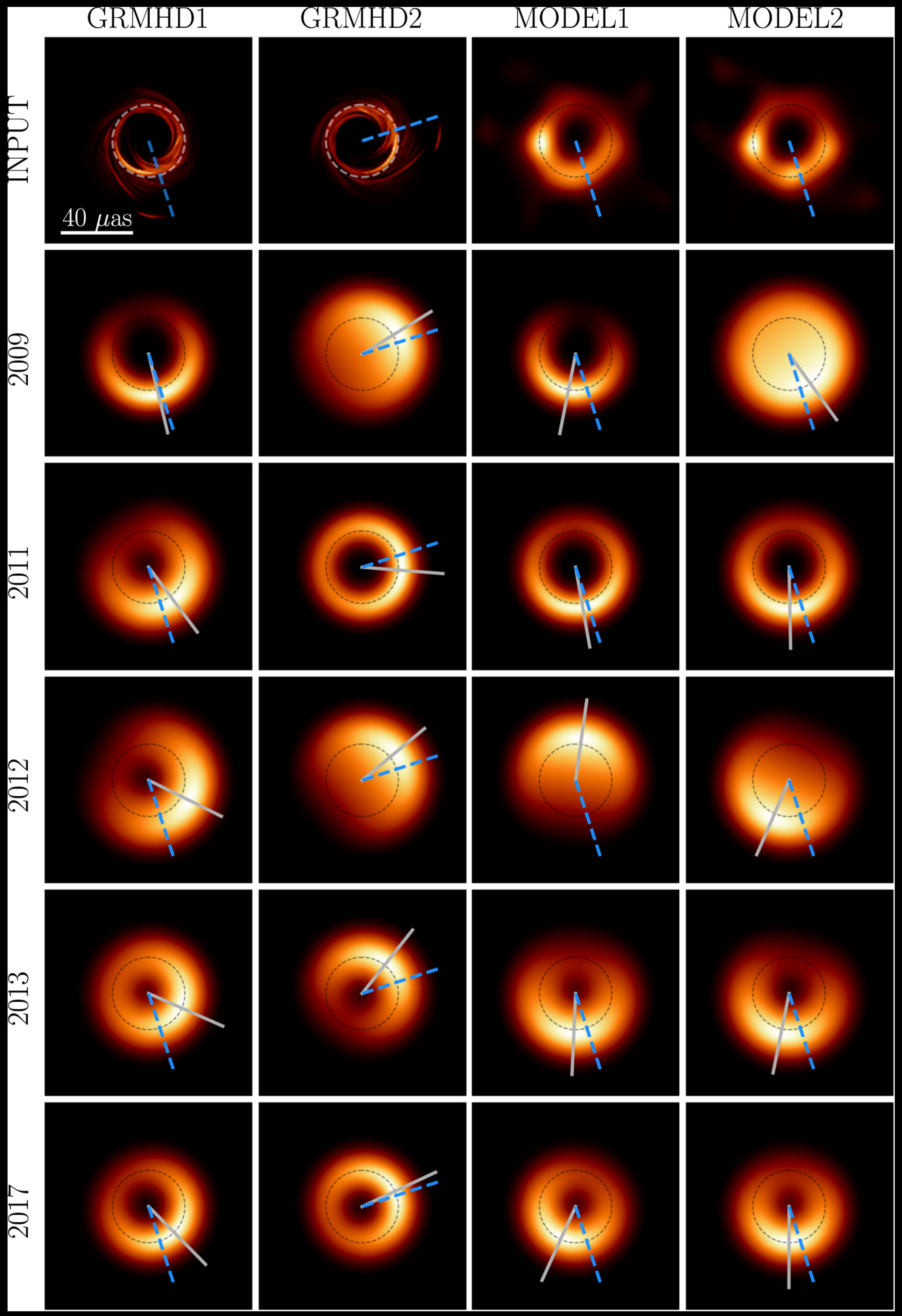
The EHT Collaboration (2024a)

M87: Are the structural changes real?

- Supported by the findings of Wielgus et al. (2020)
- Consistent with the variability expected from GRMHD simulations, due to the turbulent, magnetized accretion environment
- The brightness asymmetry can be converted into a black hole spin direction: the 2018 image would be consistent with the orientation of the large-scale jet: the 2018 observations could be a snapshot of the most common orientation of the accretion flow.



The EHT Collaboration (2024a)

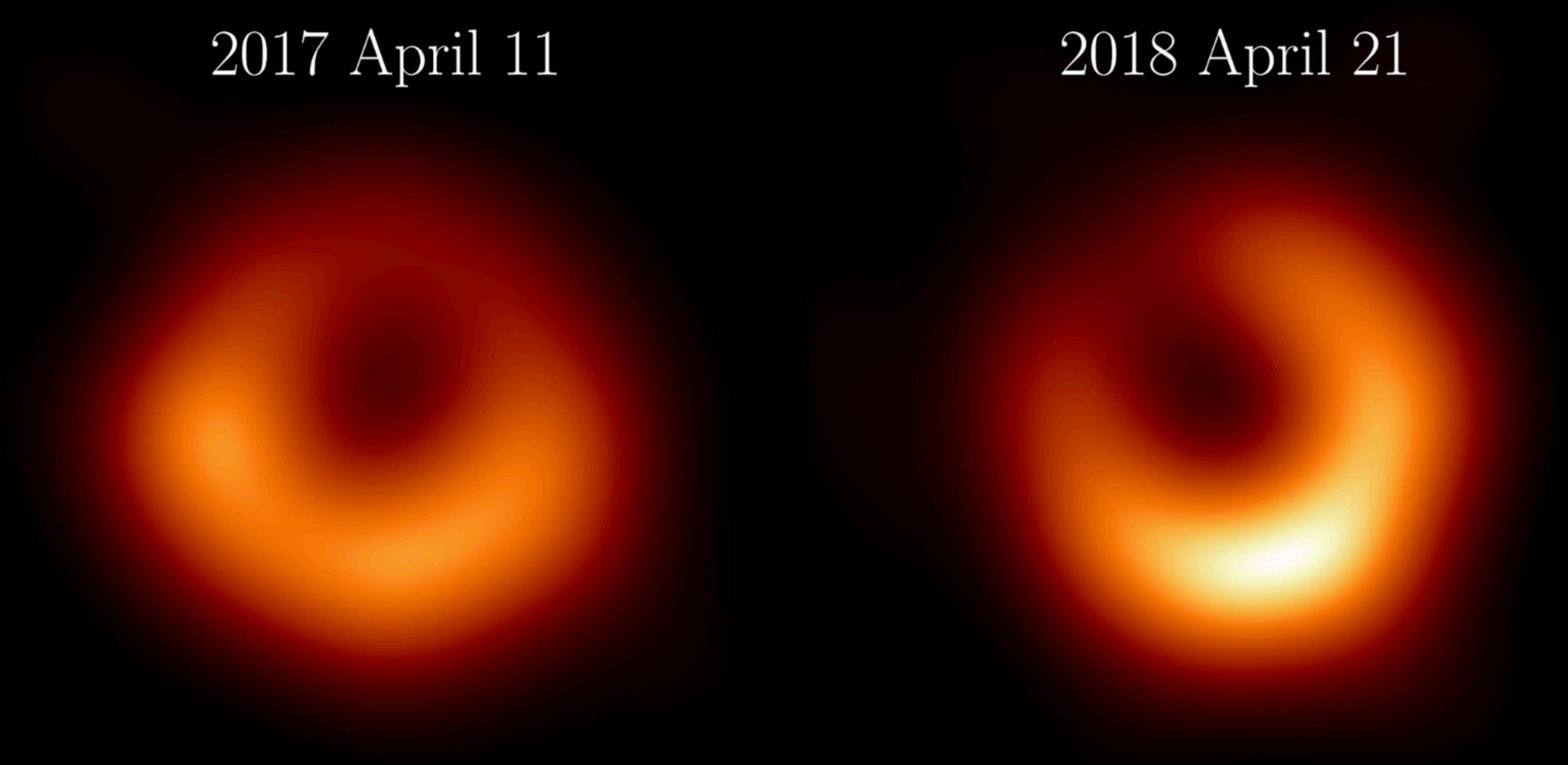


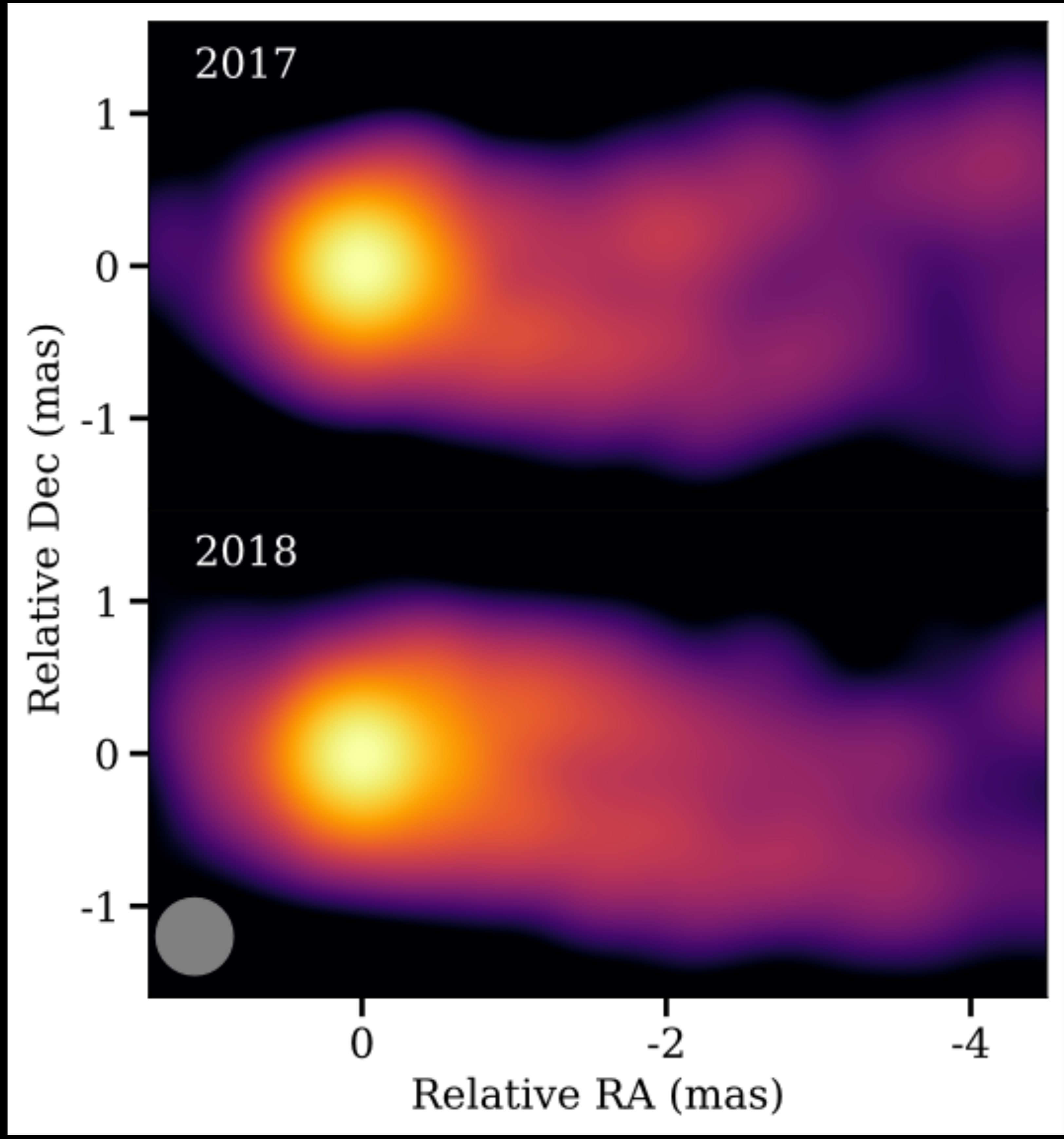
Wielgus et al. (2020)

M87-2018: change in the jet position angle

Courtesy of Giacomo Principe

Similarly to the change in the micro-arcsec scale of the ring asimmetry position, we observed a change in jet position angle (VLBA) indicating the presence of year-scale structural evolution transverse to the jet (see Cui et al., 2023)



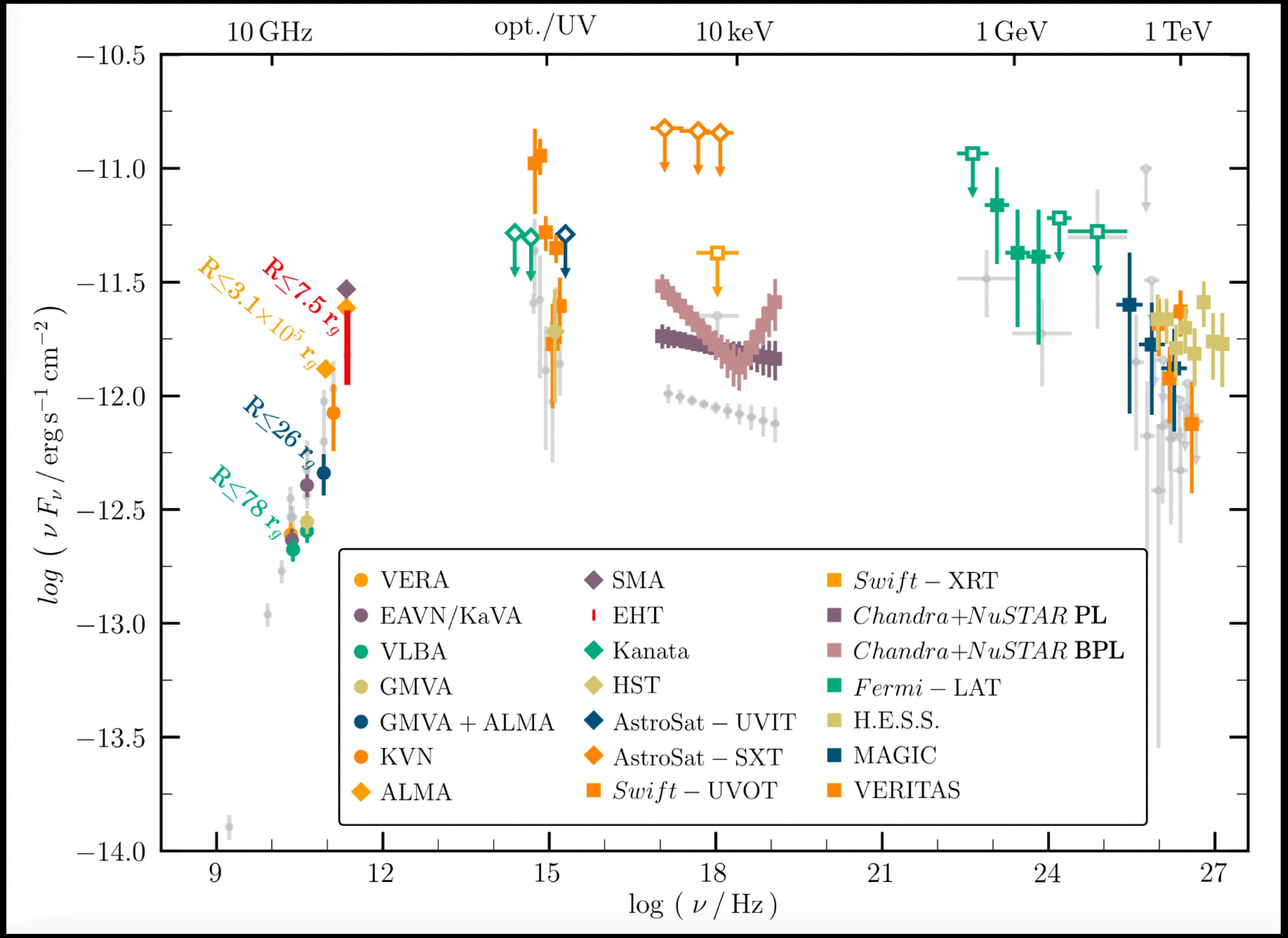


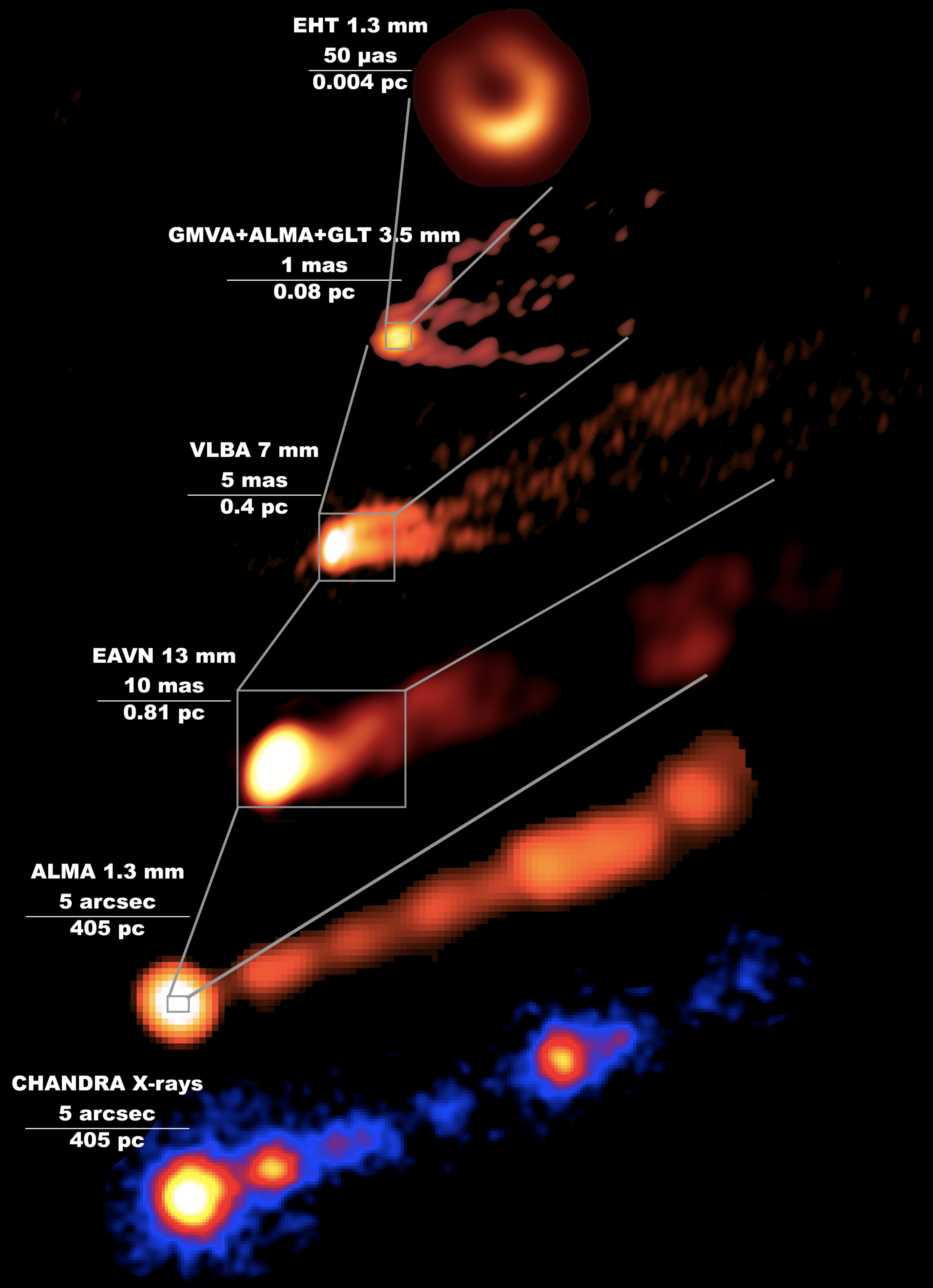
Algaba et al. (2024)

M87-2018 MWL results

Courtesy of Giacomo Principe

During 2018 EHT-MWL observational campaign the M87 jet is imaged at all scales from ~1 kpc down to a few Schwarzschild radii.





Algaba et al. (2024)

M87-2018: VHE gamma-ray flaring episode

Courtesy of Giacomo Principe

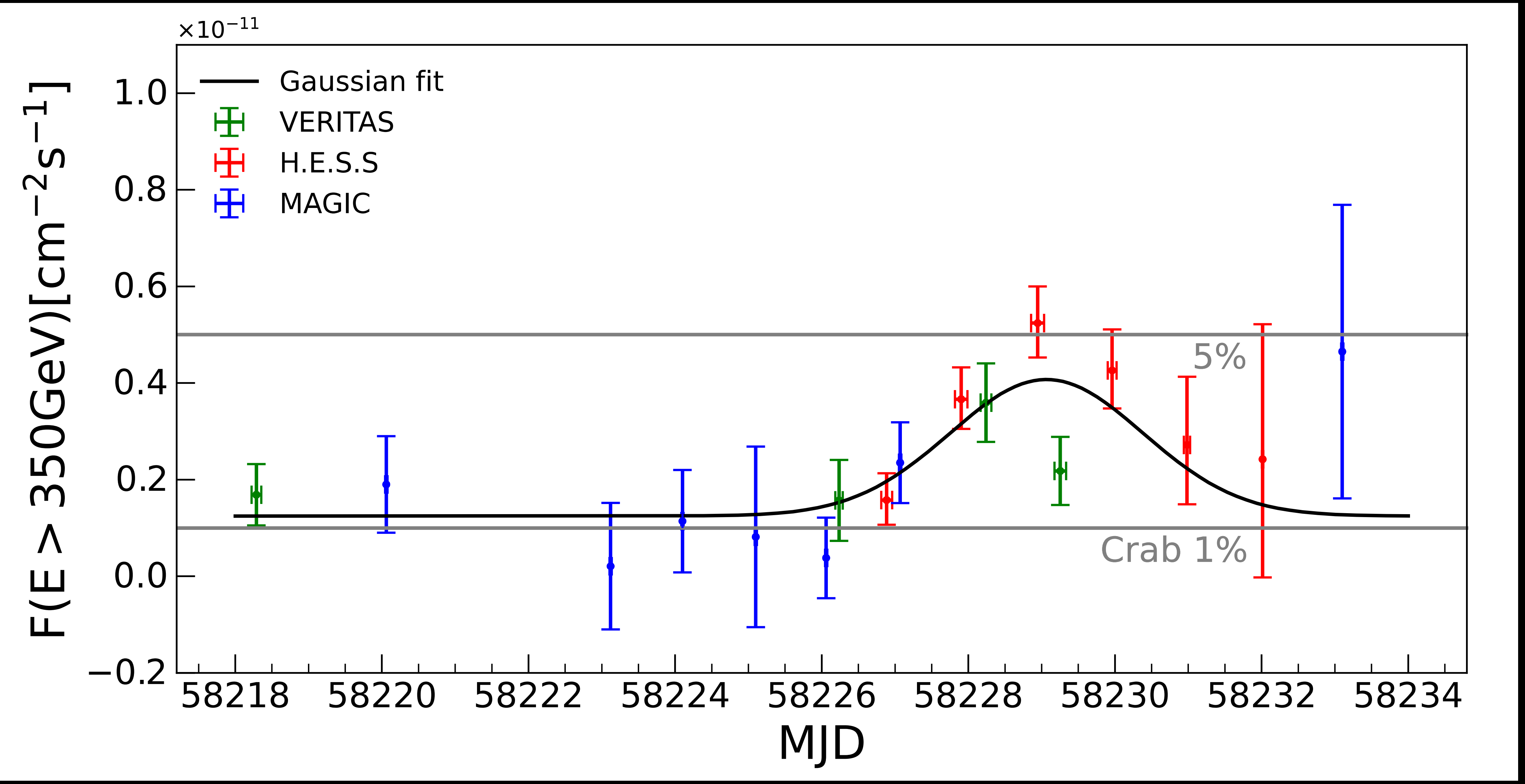
We detected the first VHE γ-ray flare from M87 since 2010 and identify a hint for a spectral hardening during the flare.

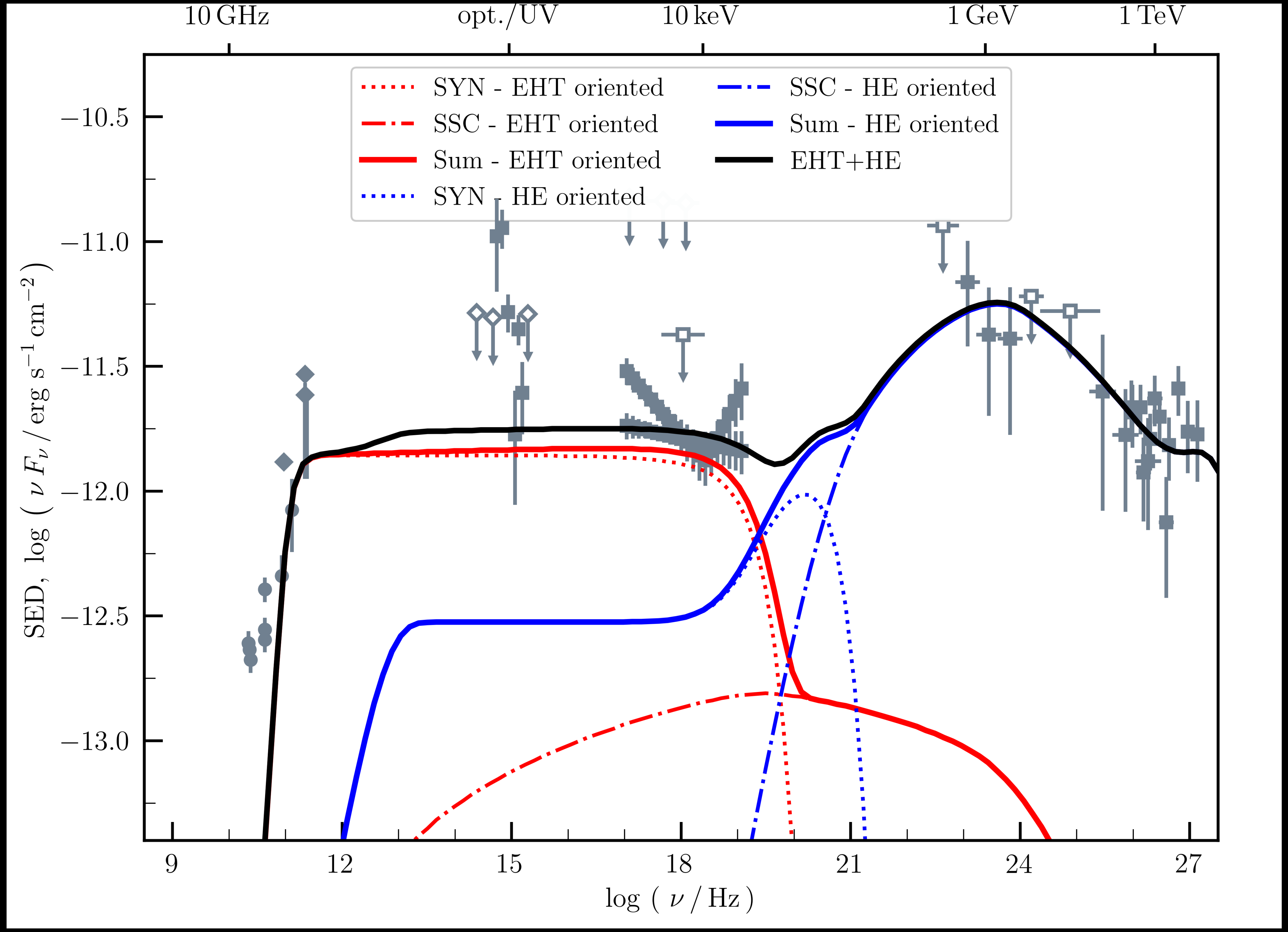
- A likely longer-term core flux enhancement was observed in the X-ray band by Chandra
- The radio and mm core fluxes are compatible with the emission seen in April 2017
- Although the presence of the flaring episodes allowed us to constrain the size of the VHE γ-ray emitting region in the SED modelling, its location is still uncertain.

Algaba et al. (2024)

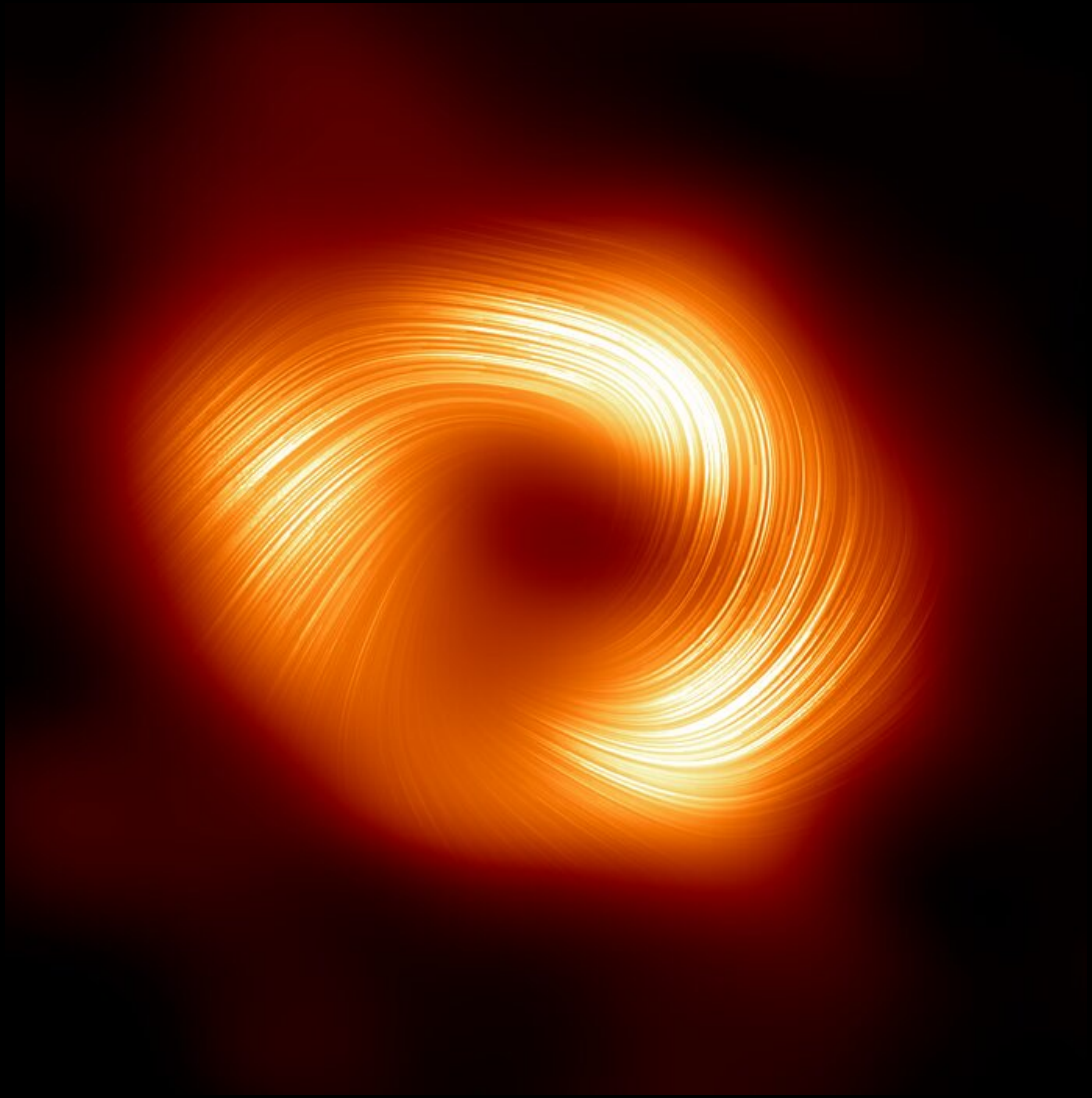
$R_{HE} \lesssim 8\ r_g\delta\ (\Delta t/3\ \text{days})$

($\mathbf{R_{VHE} \sim 2\ R_{EHT}}$, for a Doppler factor $\delta = 1$)

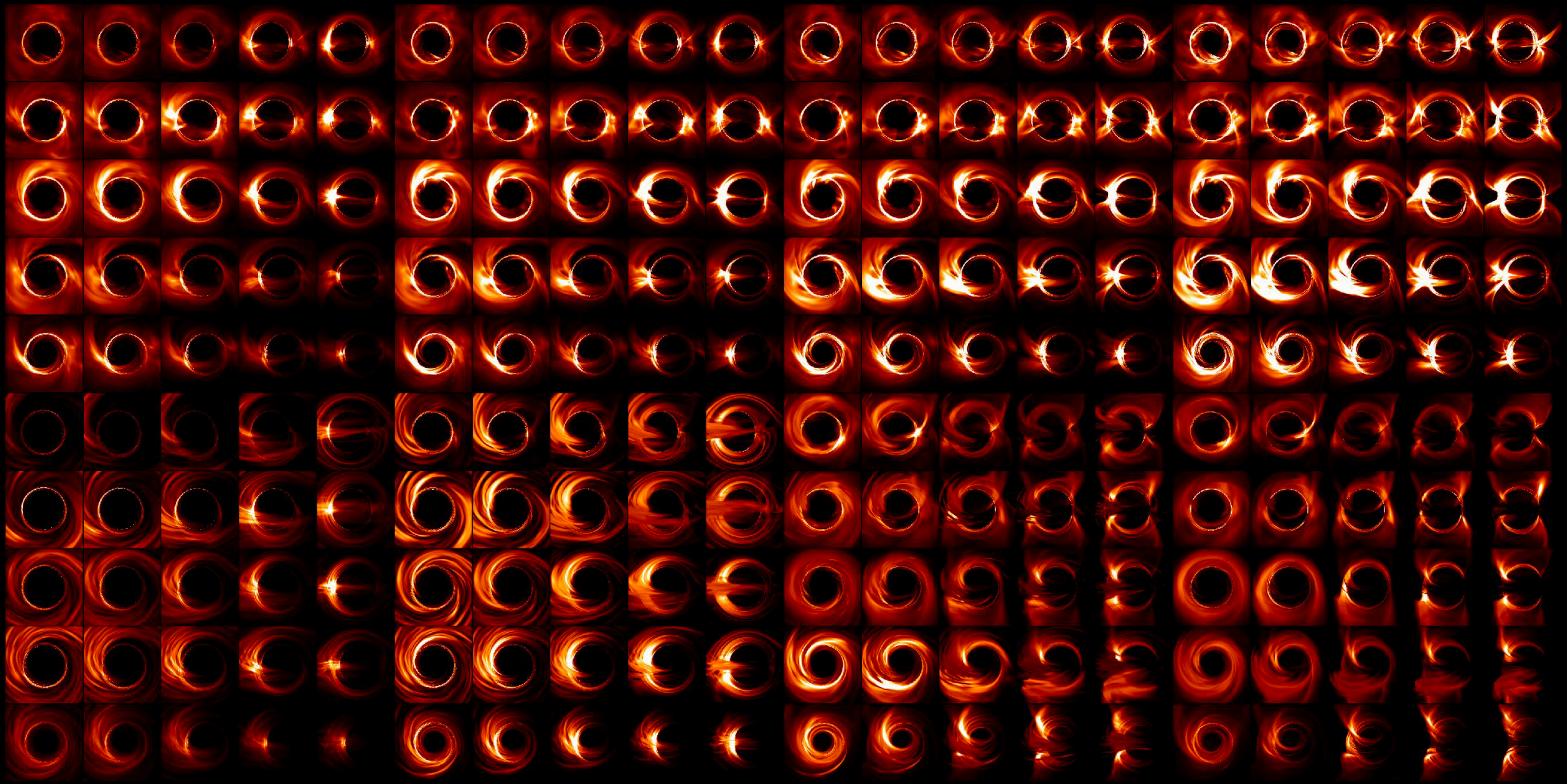




Sgr A*



Constraining Sgr A*'s parameters through GRMHD models



Sgr A*: constraints on GRMHD models

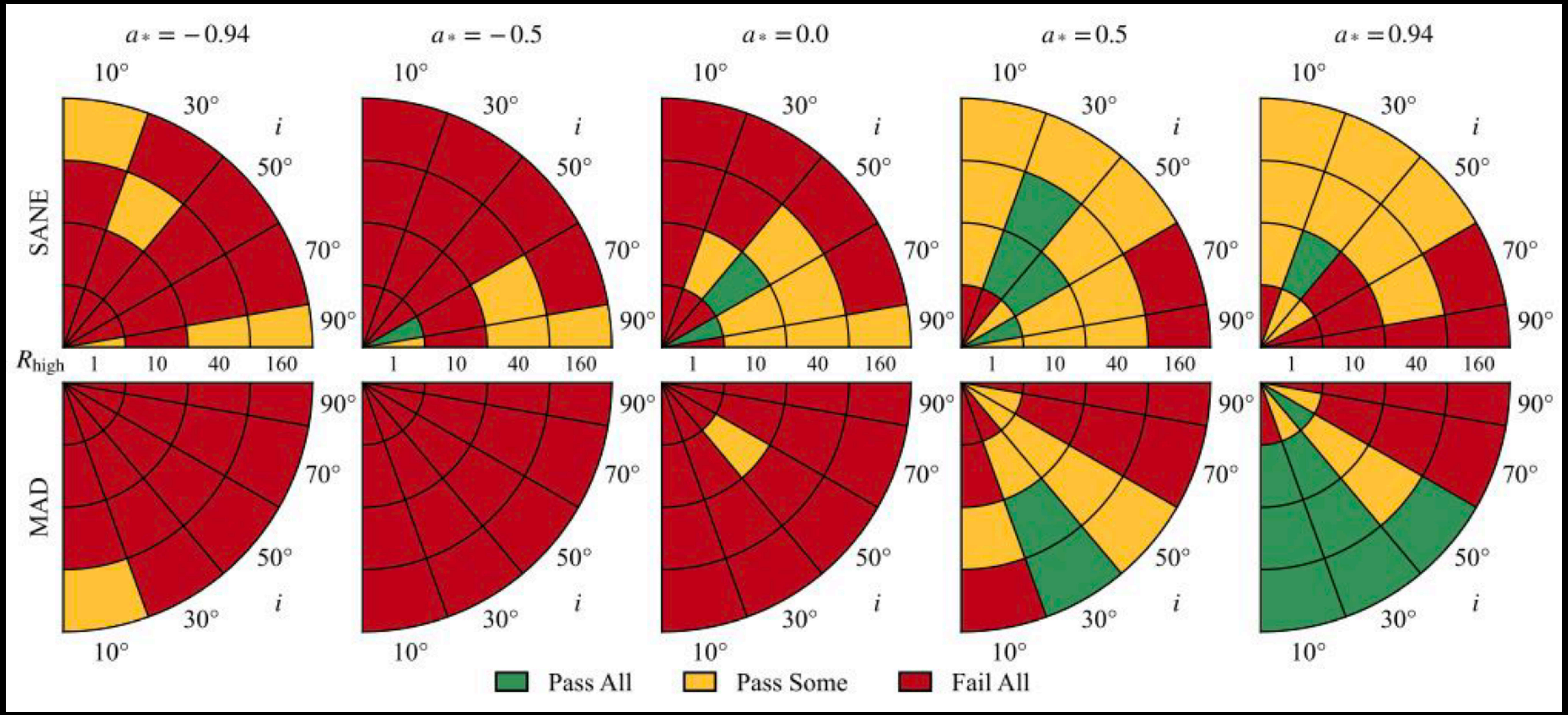
EXPLORED PARAMETERS

- Accretion disk: Magnetically Arrested Disk Vs Standard And Normal Evolution
- Dimensionless spin, $-1 < a_* < 1$, with the angular momentum of the accretion flow and black hole going from antiparallel (retrograde) to parallel (prograde)
- Inclination i (the angle between the line of sight and the spin axis)
- R_{high} (proton-to-electron temperature ratio)

CONSTRAINTS

- EHT interferometric constraints
- Emission at other wavelengths
- Variability

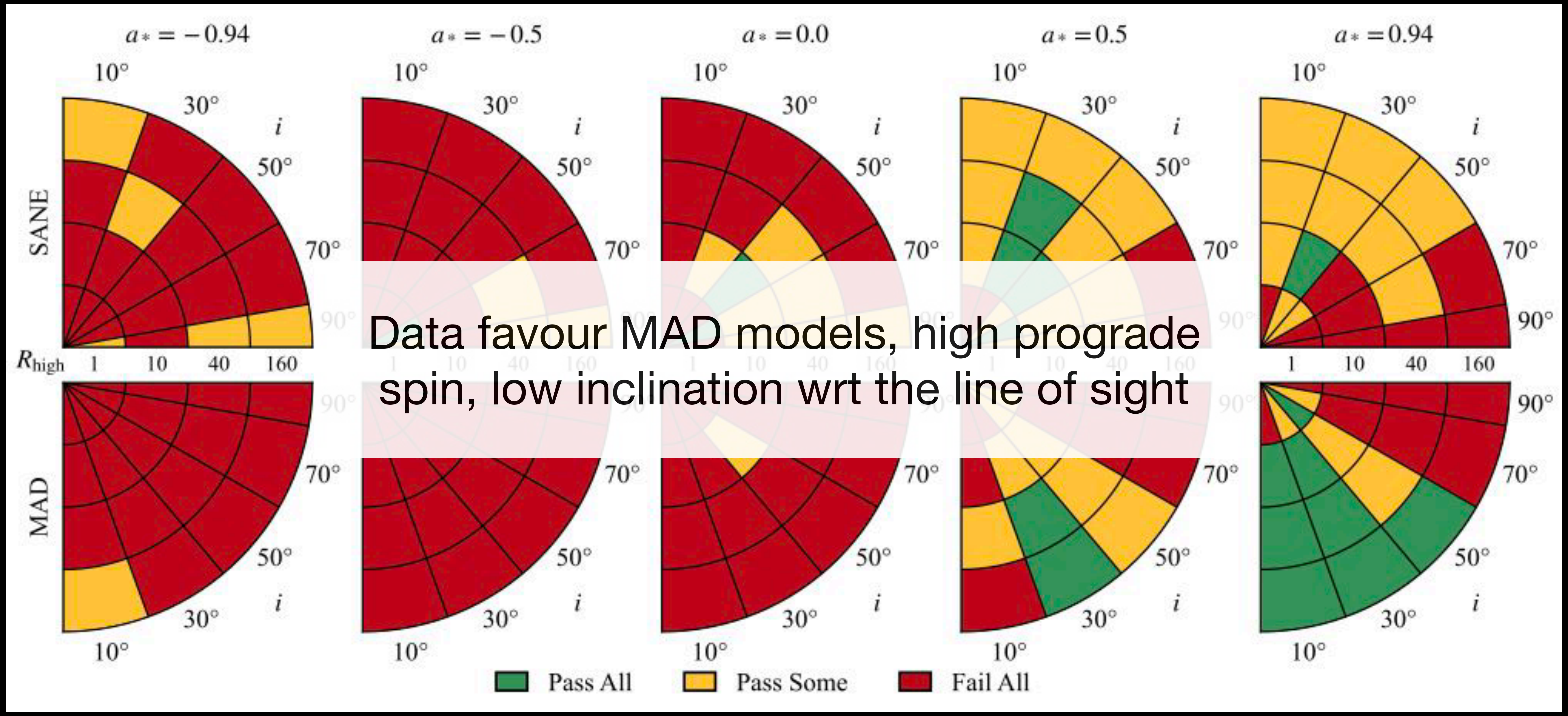
Sgr A*: constraints on GRMHD models



Sgr A*

The EHT Collaboration (2022a, e)

Sgr A*: constraints on GRMHD models

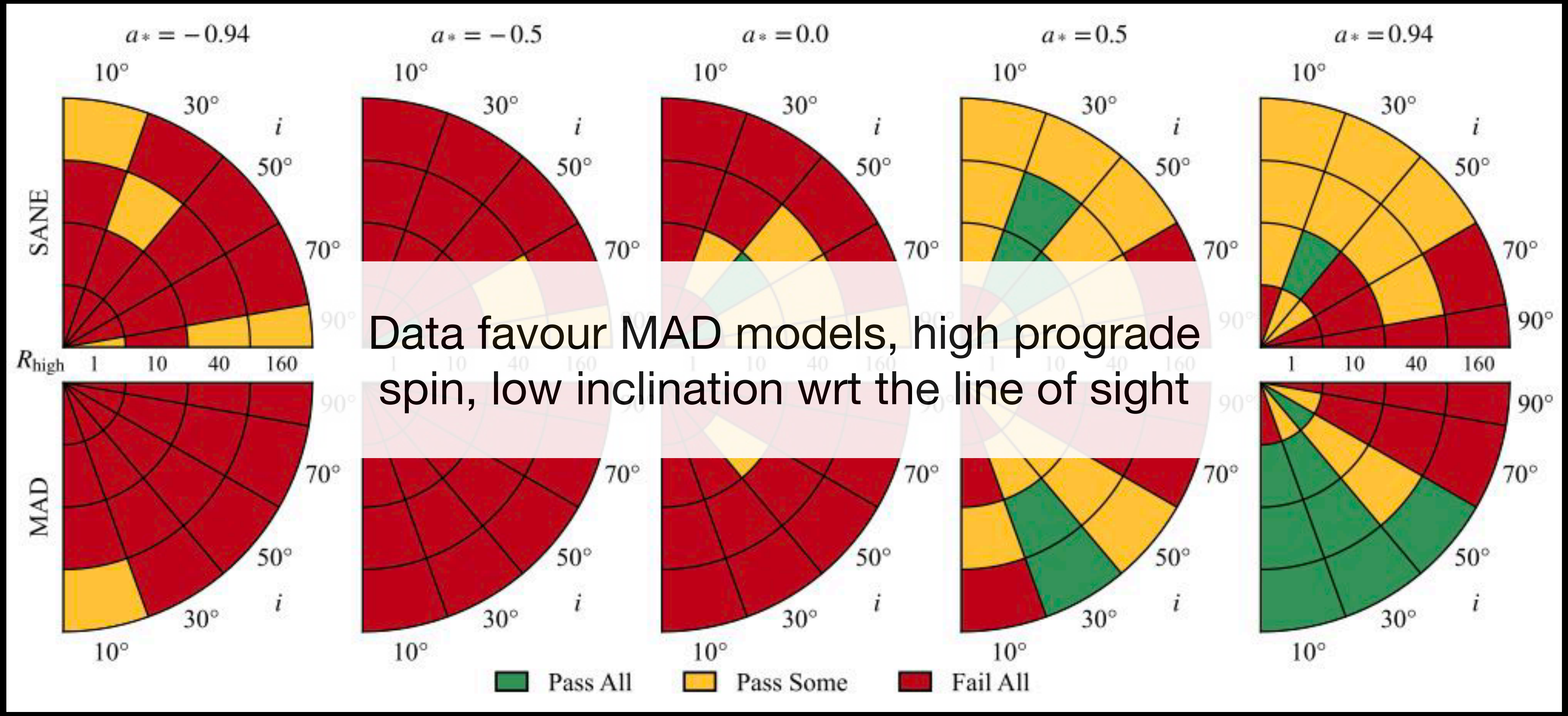


Data favour MAD models, high prograde spin, low inclination wrt the line of sight

Sgr A*
The EHT Collaboration (2022a, e)

Sgr A*: constraints on GRMHD models

The strongest constrains come from variability!

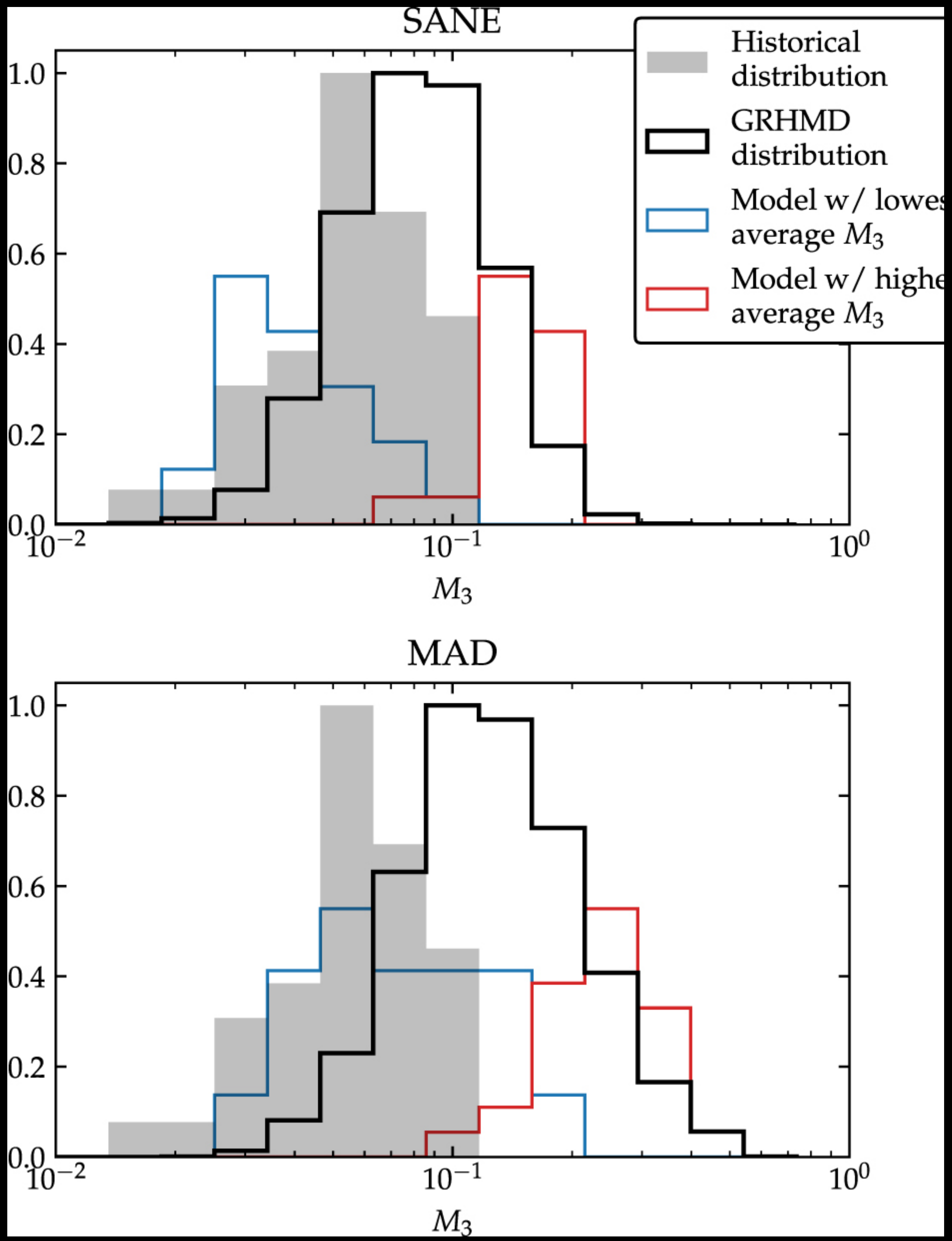


Data favour MAD models, high prograde spin, low inclination wrt the line of sight

Sgr A*
The EHT Collaboration (2022a, e)

Sgr A*: a source way less variable than expected…

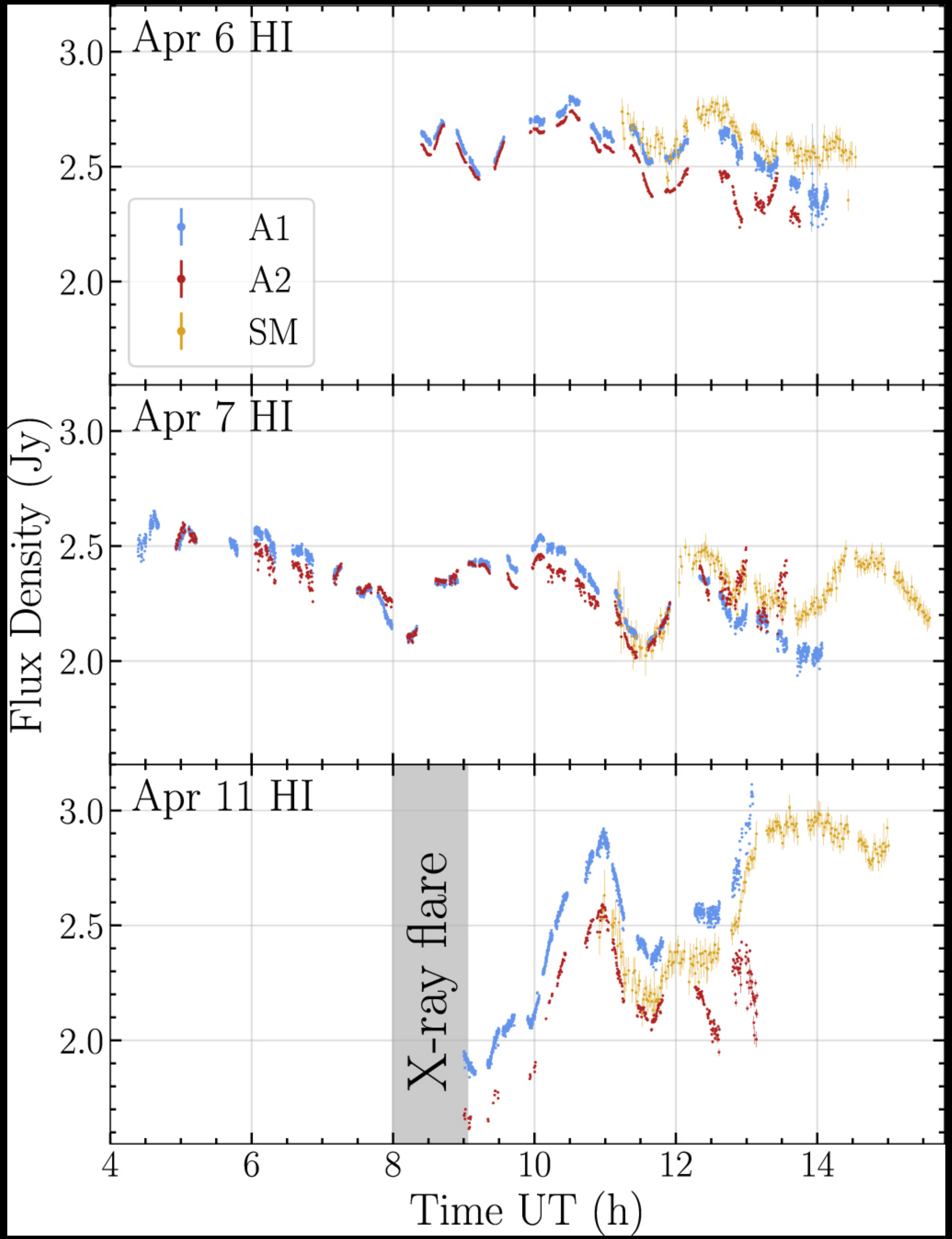
- $(\sigma/\mu)_{3h} = 3\text{-}10\%$, while most of the GRMHD models expect >10% (Magnetically Arrested Disk models worse than Standard and Normal Evolution models)



The EHT Collaboration (2022e)

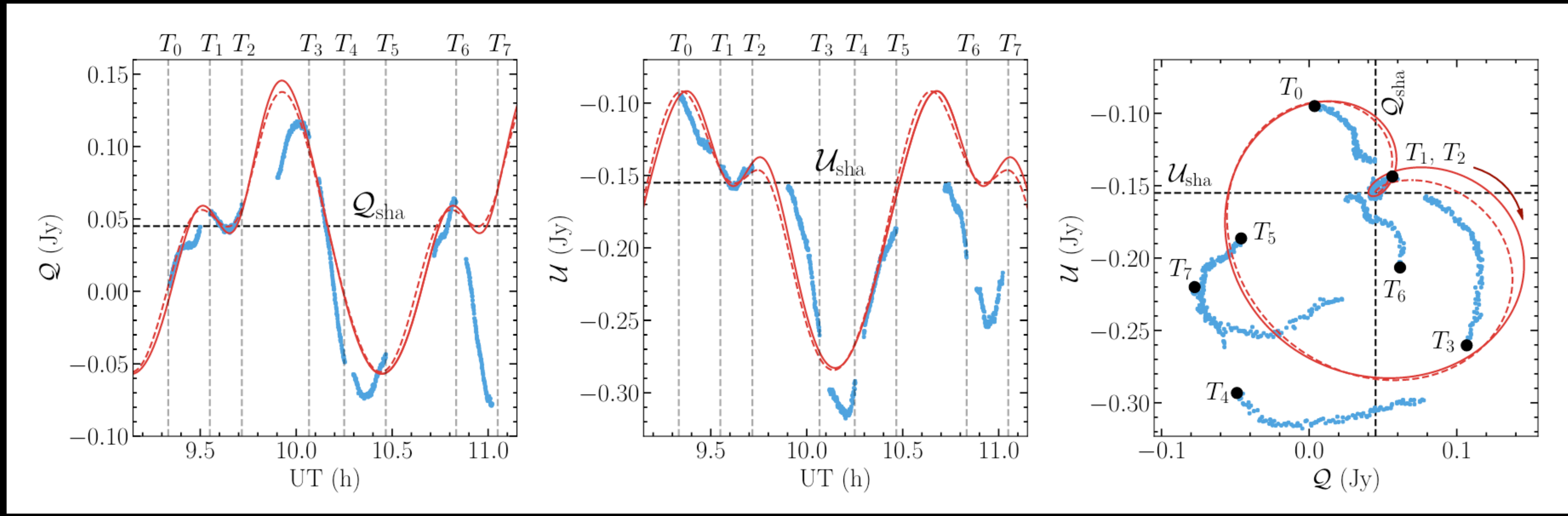
Sgr A*: a source way less variable than expected…

- $(\sigma/\mu)_{3h} = 3\text{-}10\%$, while most of the GRMHD models expect >10% (Magnetically Arrested Disk models worse than Standard and Normal Evolution models)
- Model limitations? Collisionless effects, radiative cooling, improved electron heating models could reduce variability
- Only exception, April 11, just after X-ray flare: substantial difference in all the variability parameters (e.g. PSD, spectral index)

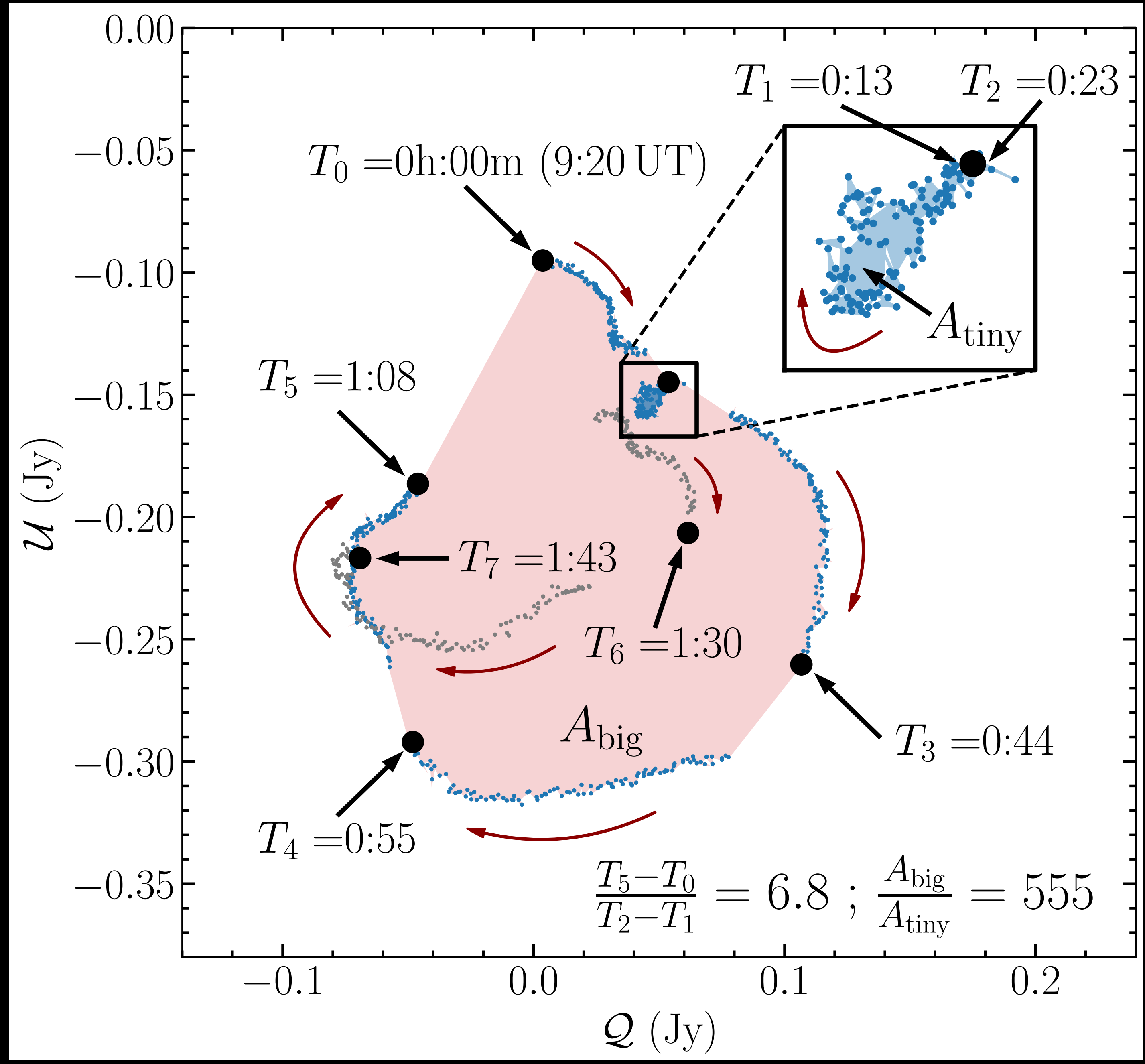


Wielgus et al. (2022a)

Sgr A*: Orbital motion of a hot spot detected through polarized light curves



Wielgus et al. (2022b)



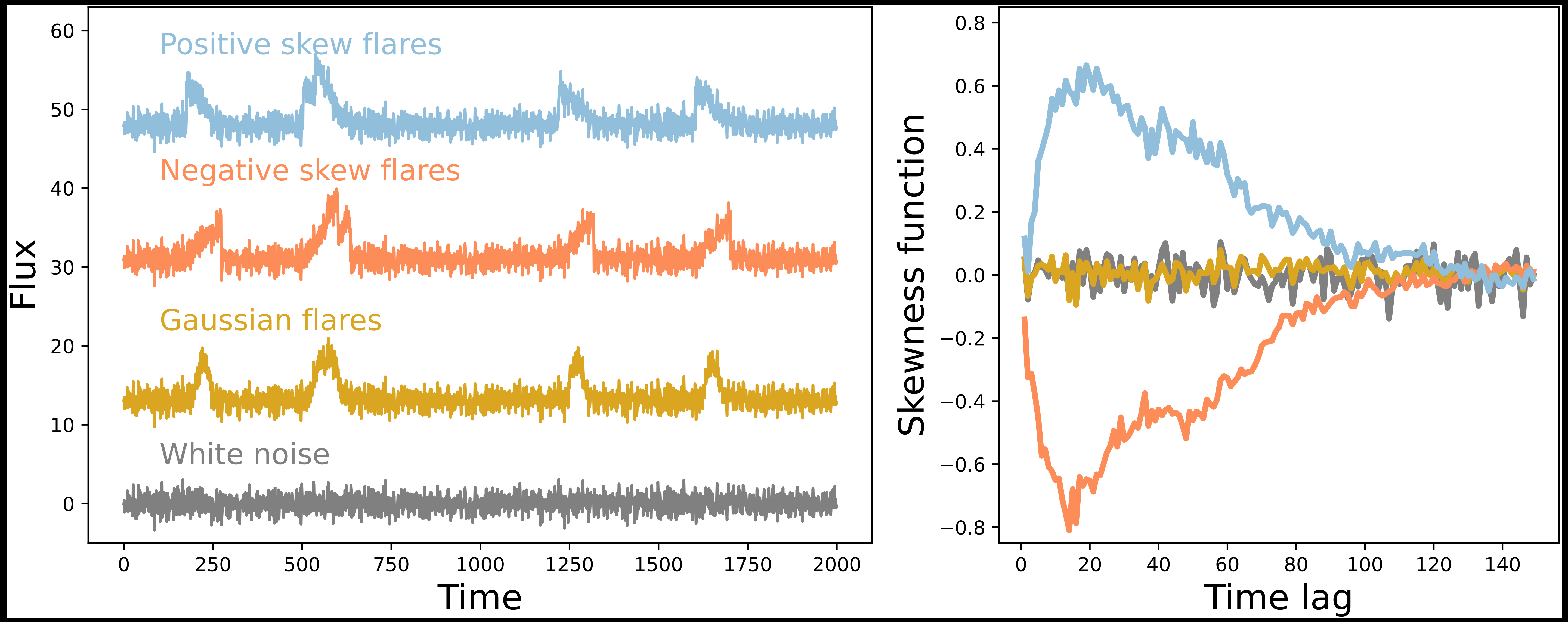
- Prograde orbital motion wrt the black hole rotation
- Orbital radius ~ 5 Schwarzschild radii
- Favours MAD models; disk rotating clockwise (prograde motion); low inclination wrt the line of sight
- Conclusions are consistent with the ones reached by the GRAVITY Collaboration (2018, 2020a,b)

A short detour into new analysis methods: third-moment structure function

$$SF_{\mu_3}(\tau_i) \propto \frac{SF'_{\mu_3}(\tau_i)}{(SF'_{\mu_2}(\tau_i))^{3/2}}$$

$$SF'_{\mu_3}(\tau_i) = \frac{1}{N}\sum_{t_j,t_k}\left[F(t_i) - F(t_k)\right]^3$$

$$SF'_{\mu_2}(\tau_i) = \frac{1}{N}\sum_{t_j,t_k}\left[F(t_i) - F(t_k)\right]^2$$



von Fellenberg et al. (2024)

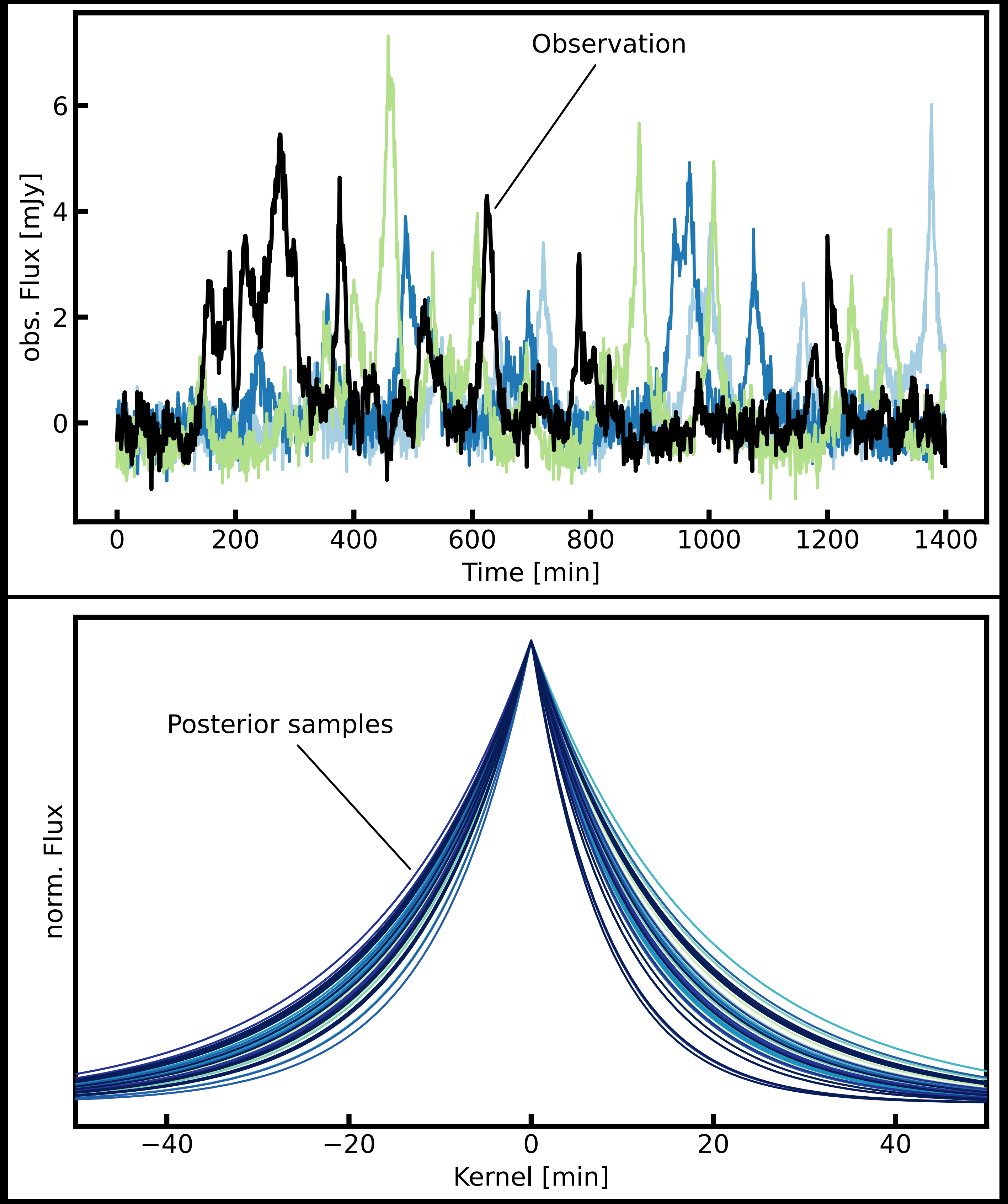
A short detour into new analysis methods: third-moment structure function

Sgr A*'s observed light curve in the NIR can be successfully modeled with an almost symmetric kernel, with an average rise and decay time of $\tau \approx 15$ minutes

Since $SF_{\mu 3}$ shows no significant deviation from zero, high-inclination viewing angles are ruled out

The absence of significant asymmetry is surprising because the radiative processes thought relevant for Sgr A* are typically asymmetric

An orbiting hot spot can plausibly explain the symmetry in Sgr A*'s flares



von Fellenberg et al. (2024)

Conclusions

- Variability is a fundamental aspect in the study of EHT sources. It is both a complication and a resource
- It provides strong constraints to GRMHD models, and helps us to derive essential properties of the sources
- The indications from (very) different aspects of variability studies are quite consistent among each other, making us confident in the reliability of the results, and in the importance of the retrieved information