Event Horizon Telescope

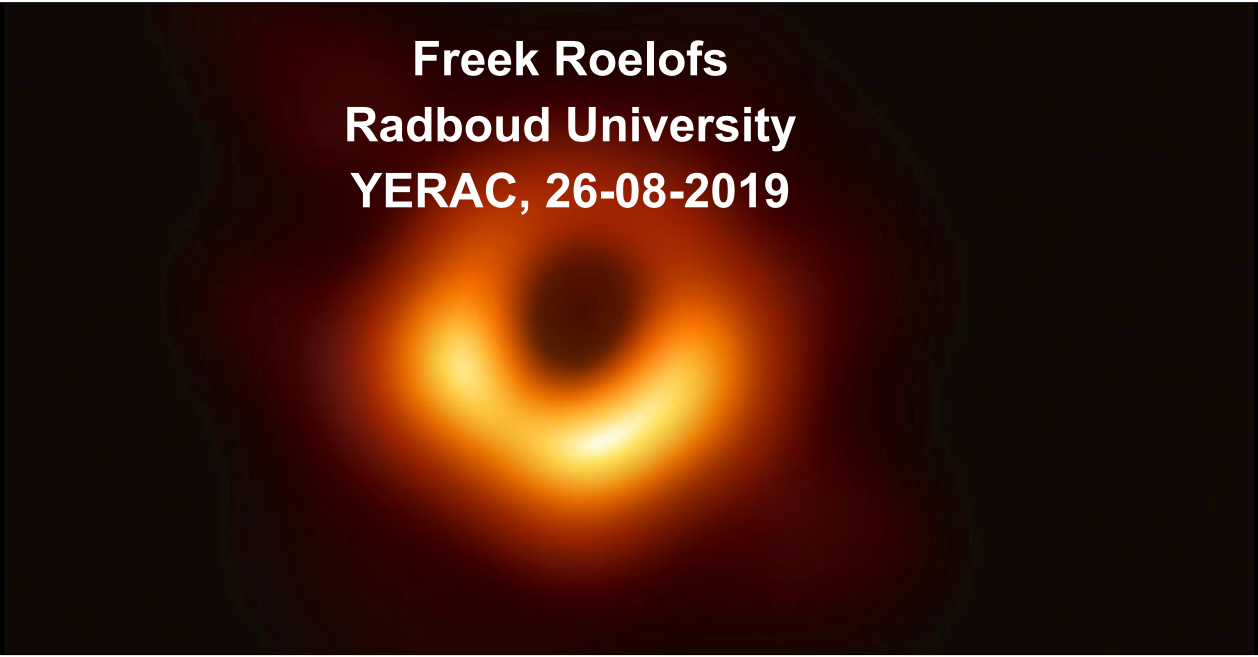
BLACK HOLE CAM

European Research Council
Established by the European Commission

RADBOUD RADIO LAB

Radboud University

Comparing the EHT 2017 data to physical models of M87*



Freek Roelofs
Radboud University

YERAC, 26-08-2019

Simulating the accreting plasma

GRMHD simulations

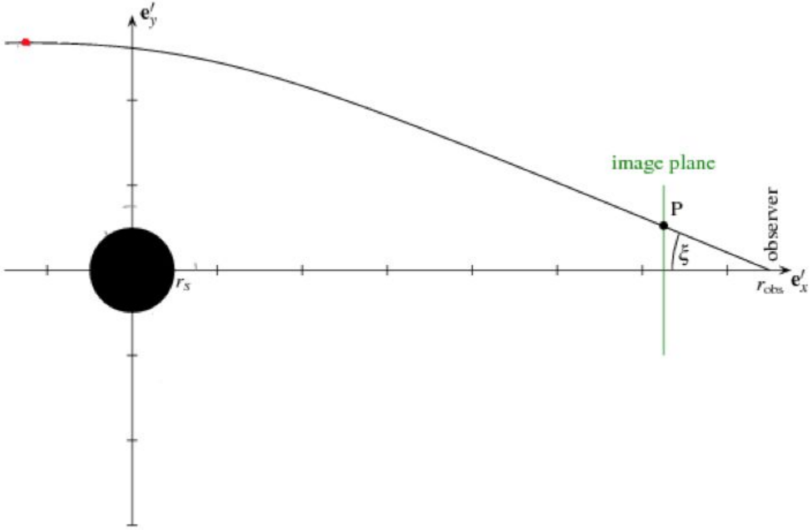
Credit: EHT collaboration

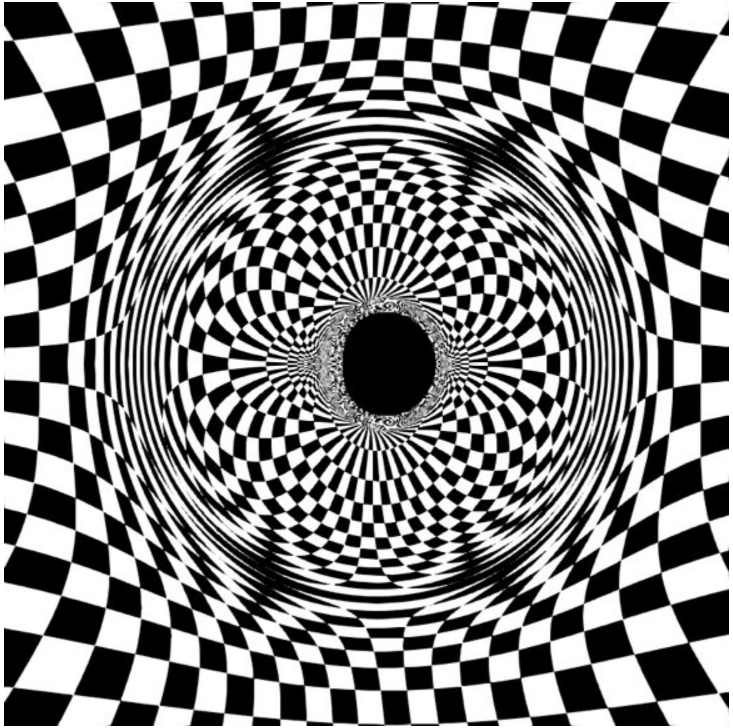
Use laws of general relativistic magnetohydrodynamics to simulate plasma behavior

Calculate emissivities and absorptivities from plasma properties such as density, magnetic field, temperature

Trace photons through curved spacetime to calculate the appearance of the source for a distant observer

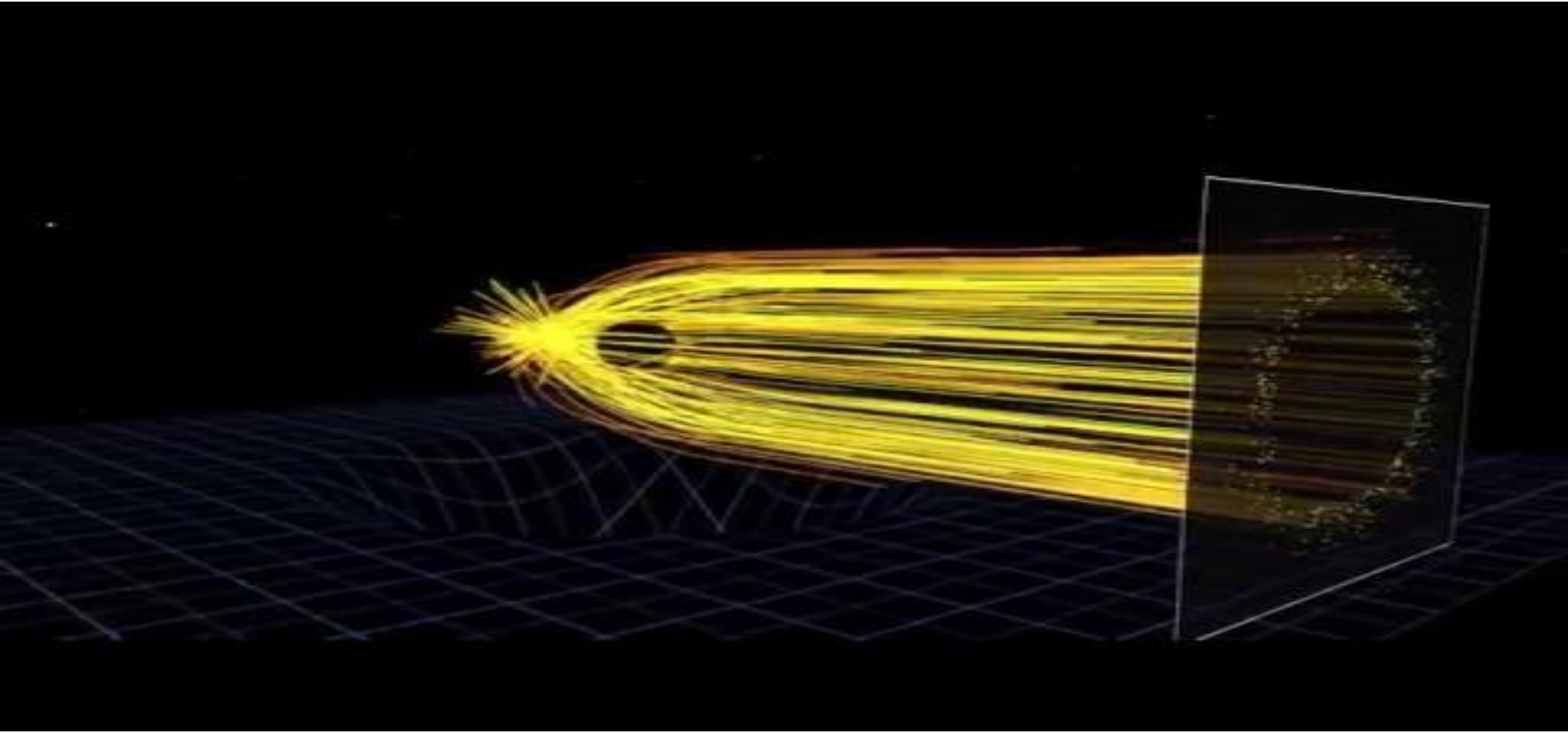
Ray tracing





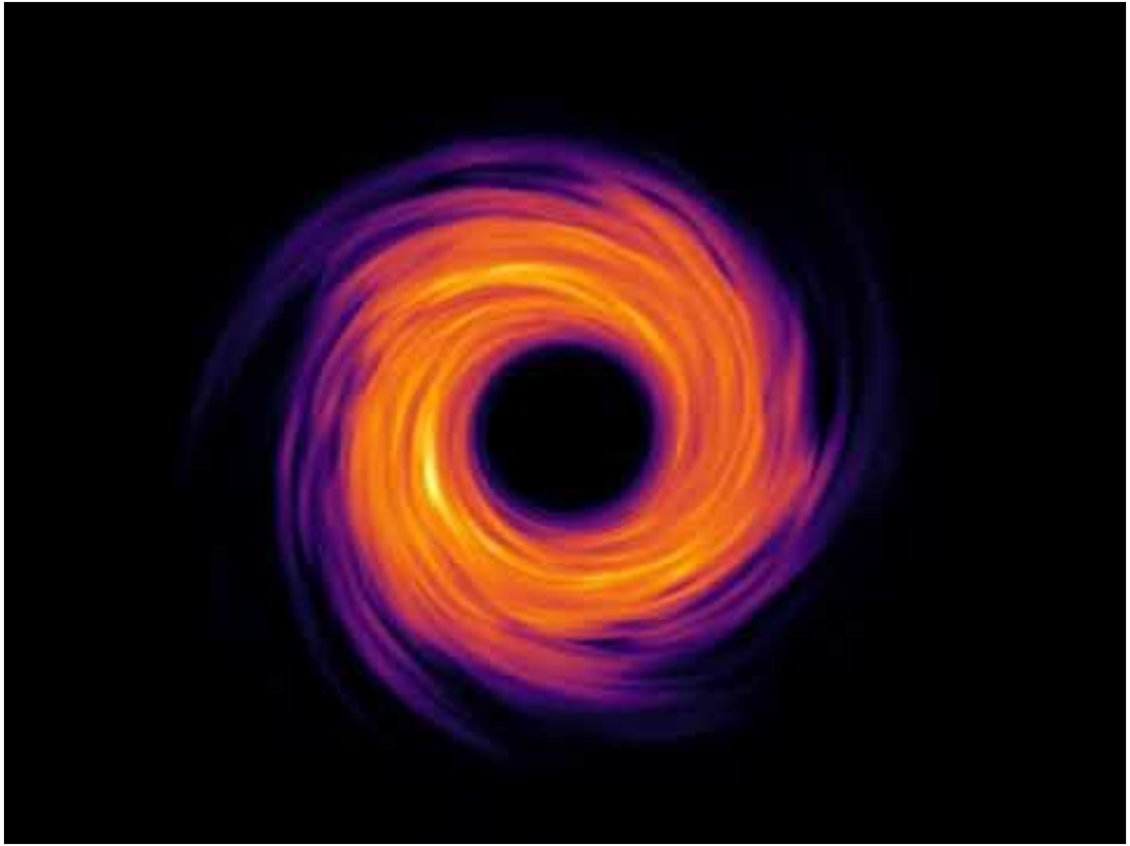
Credit: T. Bronzwaer

What is the black hole shadow?



Animation credit: CrazyBridge Studios

GRMHD + ray tracing



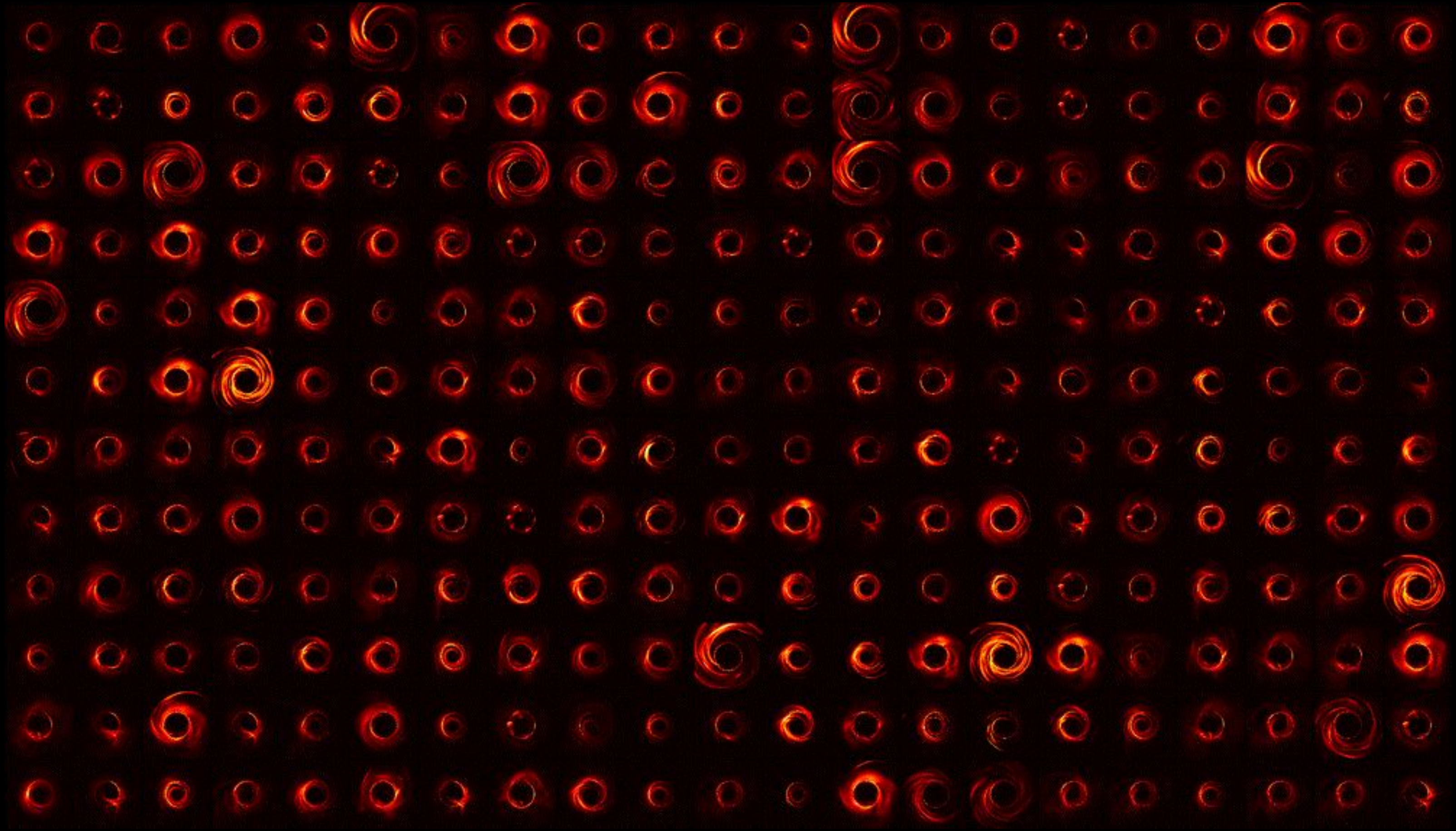
Credit: Z. Younsi, T. Bronzwaer & J. Davelaar

Black hole acts like lens -> black hole shadow

Image appearance depends on viewing angle with respect to black hole spin axis

Large inclination angle -> strong Doppler boosting

Simulation library



Animation credit: A. Broderick, Perimeter

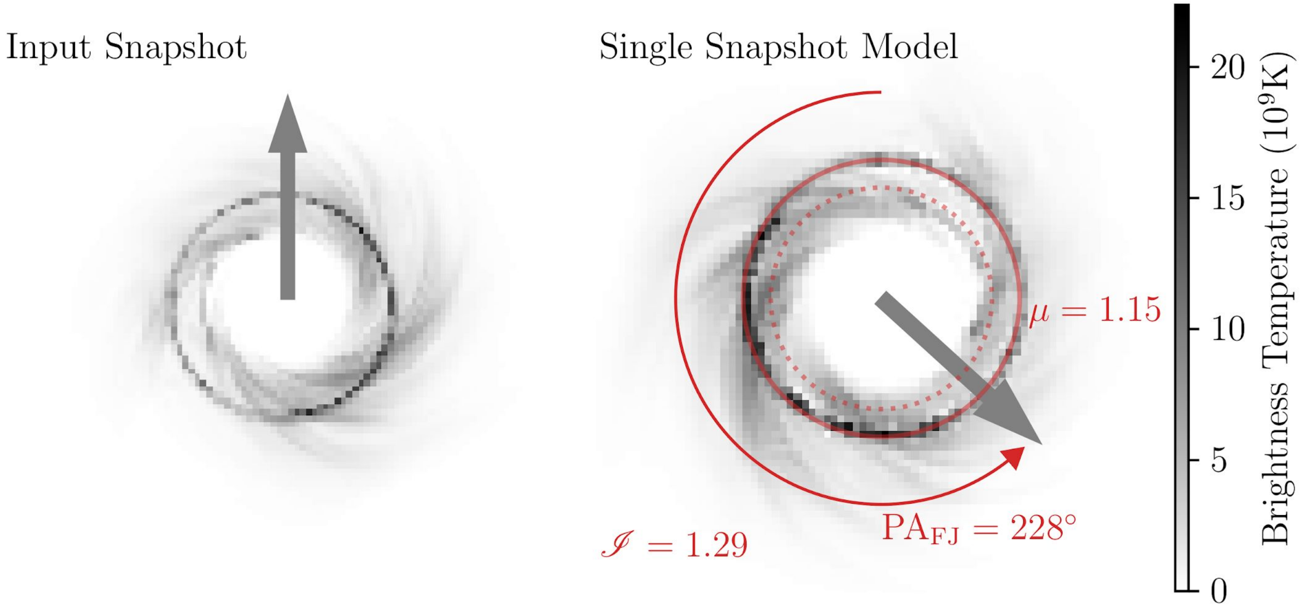
EHTC+ 2019. ApJL, 875, L5 (Paper V)

GRMHD scoring

GRMHD image library has models with different spin, magnetic flux (SANE/MAD), electron temperatures, inclination angles, each with multiple frames (time evolution)

For each frame, the best fit sky orientation, angular size, and total flux are found for the EHT 2017 data

Angular size determines $\theta_g = GM/Dc^2$, angular size of one gravitational radius



GRMHD scoring results

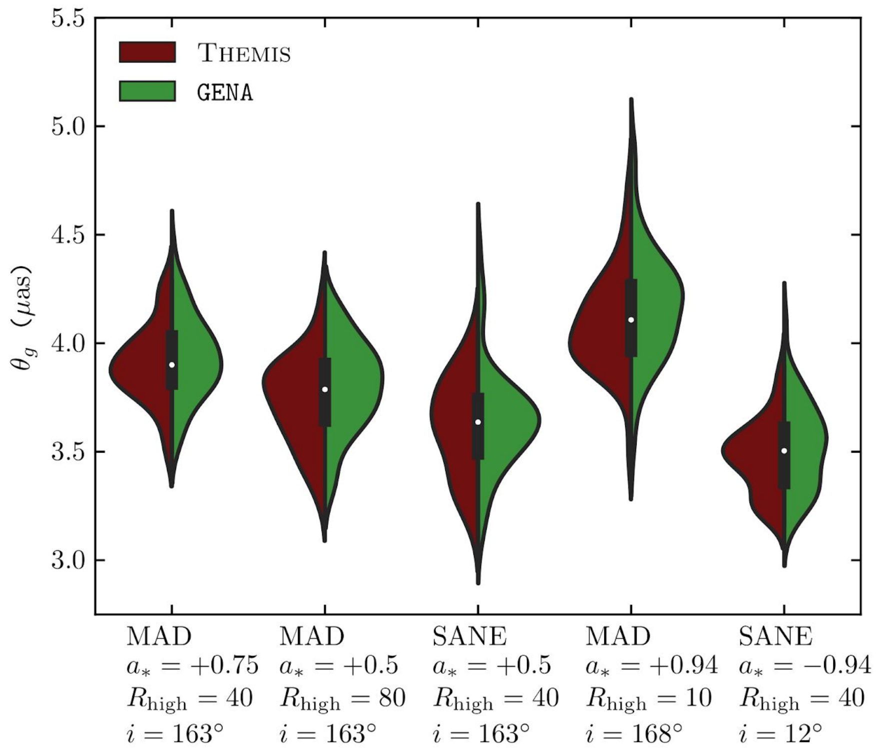
All models except MAD $a_* = -0.94$ (too variable) fit the EHT data

Some models rejected based on other constraints:

- all $a_* = 0$, SANE $a_* \leq 0.5$ (insufficient jet power)
- MAD $R_{high} = 1$ (cool too rapidly)
- SANE $R_{high} < 20$ (overproduce X-rays)

Comparing position angle fit to large-scale jet orientation: black hole spin vector is pointed away from us

All days, bands, simulations, and methods combined:
$\theta_g = GM/Dc^2 = 3.80\ (+0.39/-0.31)\ \mu as$



See Shan-Shan Zhao's talk for details on fitting methods

The mass of M87

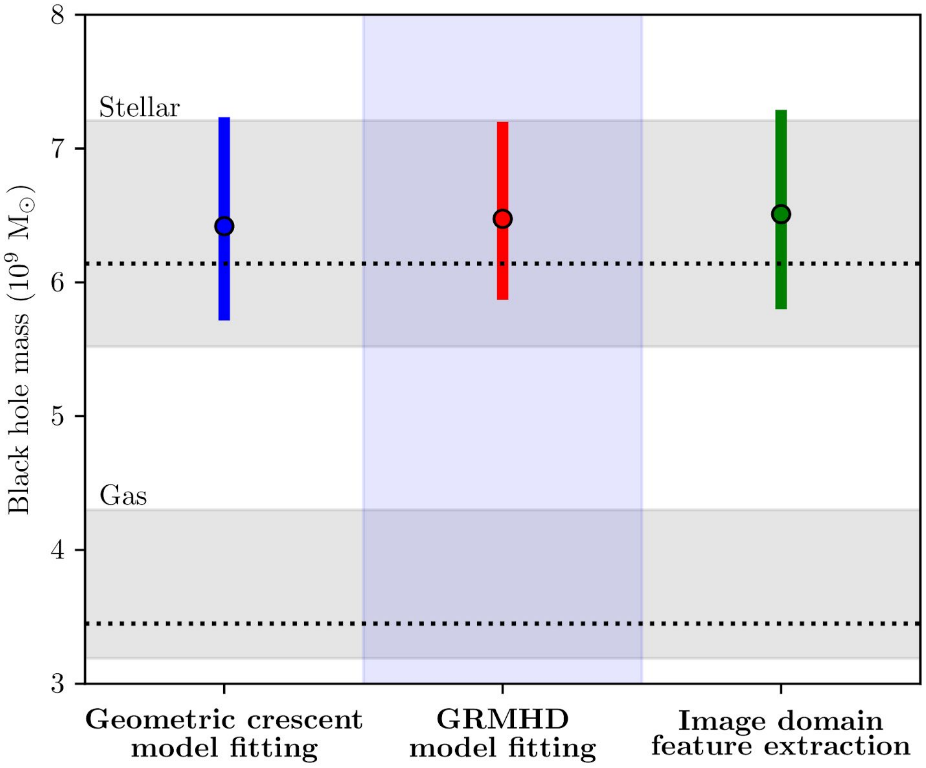
Angular size of one gravitational radius $\theta_g = GM/Dc^2$:

- GRMHD scoring: θ_g = 3.80 (+0.39/-0.31) μas
- Crescent model fit: θ_g = 3.77 (+0.45/-0.40) μas
- Image ring fit: θ_g = 3.83 (+0.42/-0.36) μas

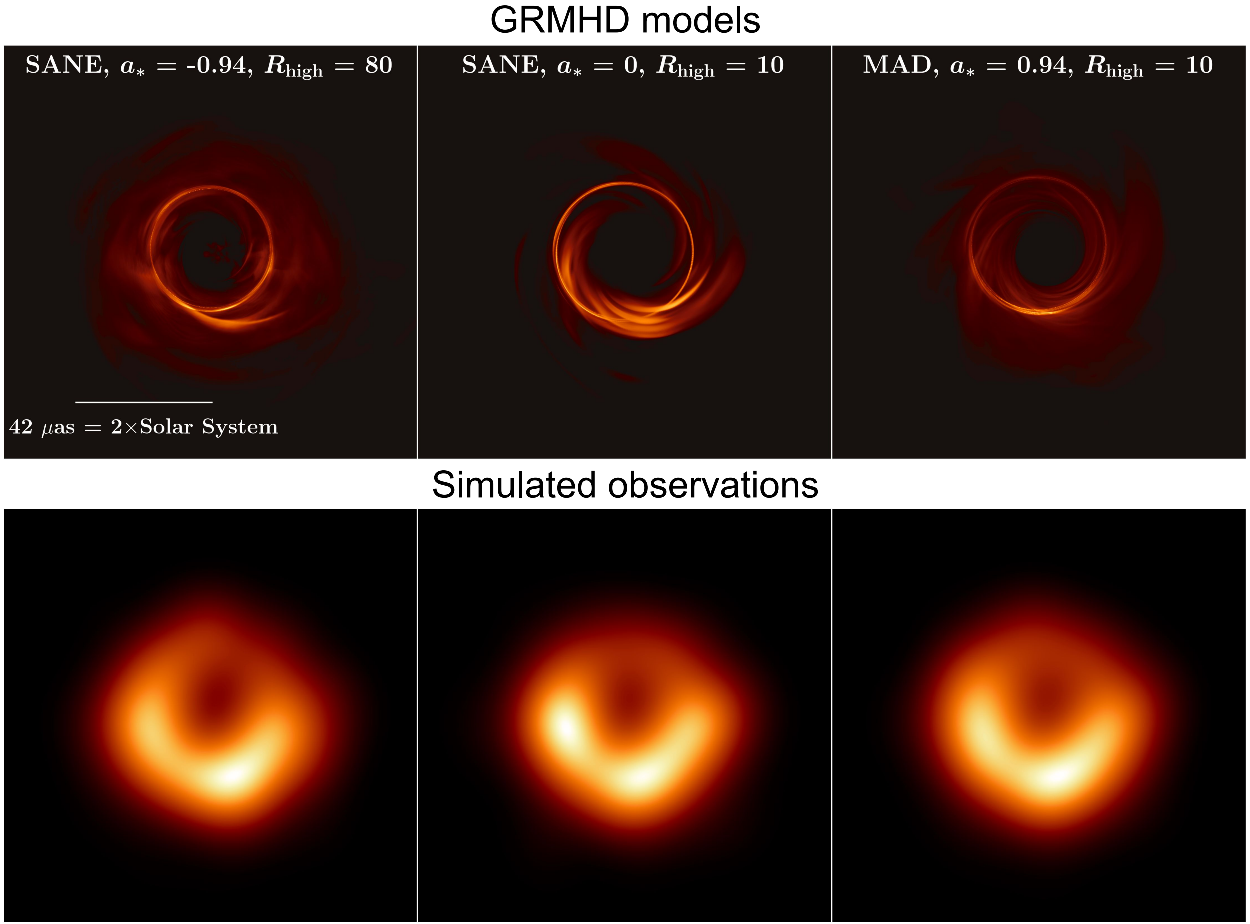
Distance to M87 = 16.8 (+0.8/-0.7) Mpc

Inferred black hole mass: M = (6.5 +/- 0.7) x 10^9 M_{sun}

Consistent with mass measurement from stellar dynamics (Gebhardt et al. 2011)



Simulated observations



Observations simulated with SYMBA (Roelofs, Janssen et al. 2019, in prep.)

Simulated observations include realistic corruption effects:

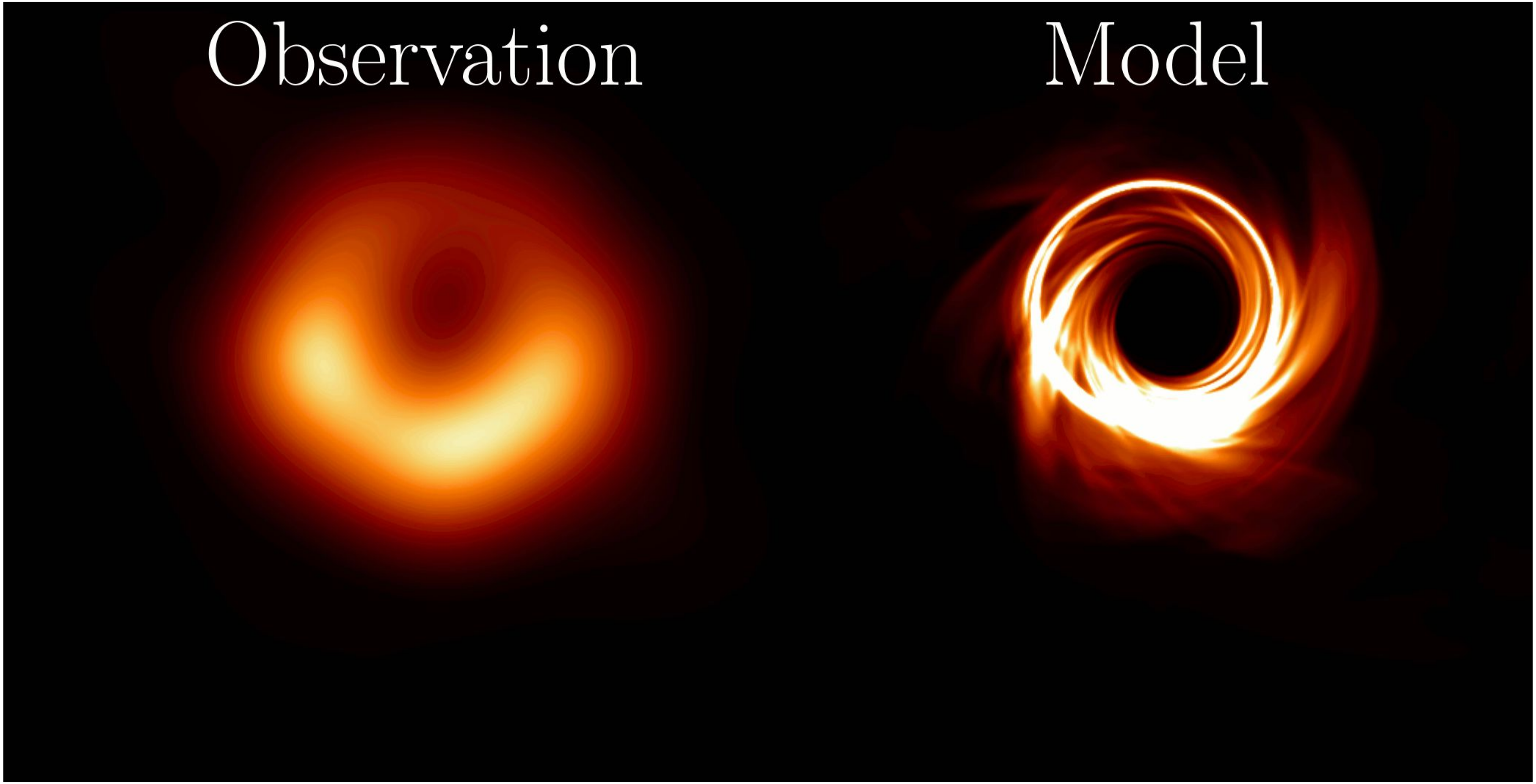
- Receiver noise
- Antenna pointing offsets
- Atmospheric attenuation, emission, and turbulence

Corruptions based on station and weather parameters measured during the EHT 2017 campaign

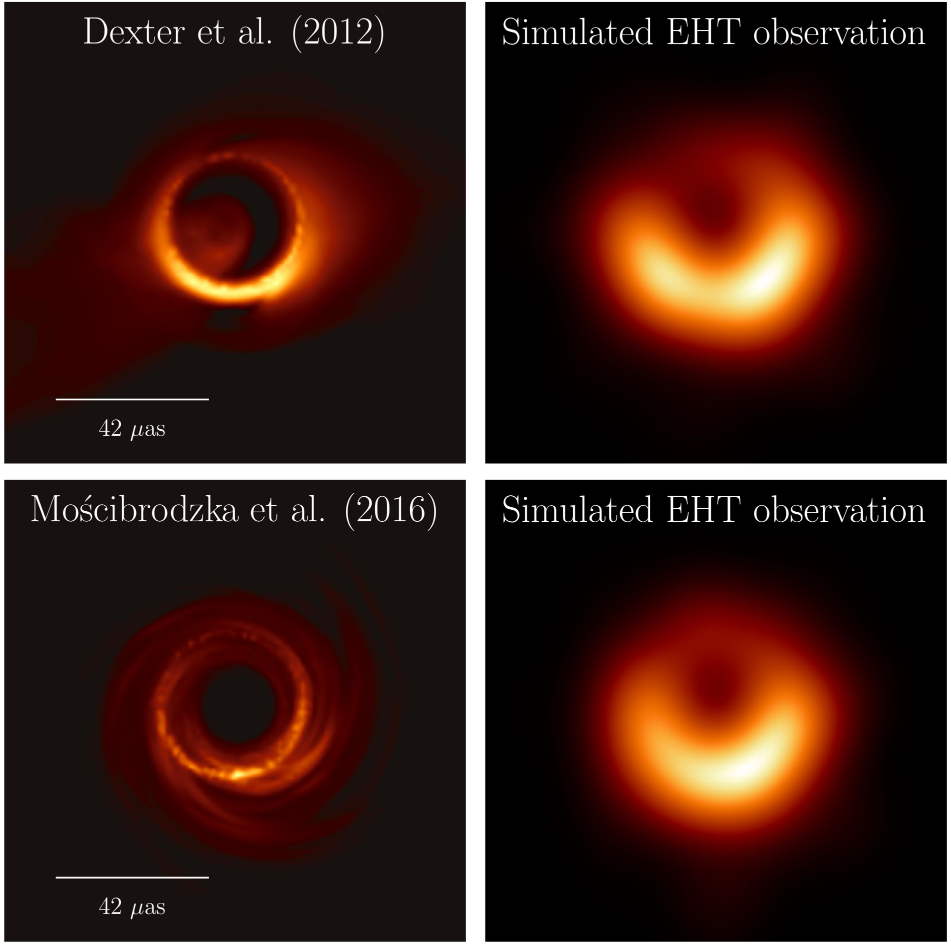
Simulated data is processed through EHT calibration pipeline rPICARD (Janssen et al. 2019) and then imaged exactly as EHT data

Simulated observations

Theory WG, Model comparison WG



Earlier models

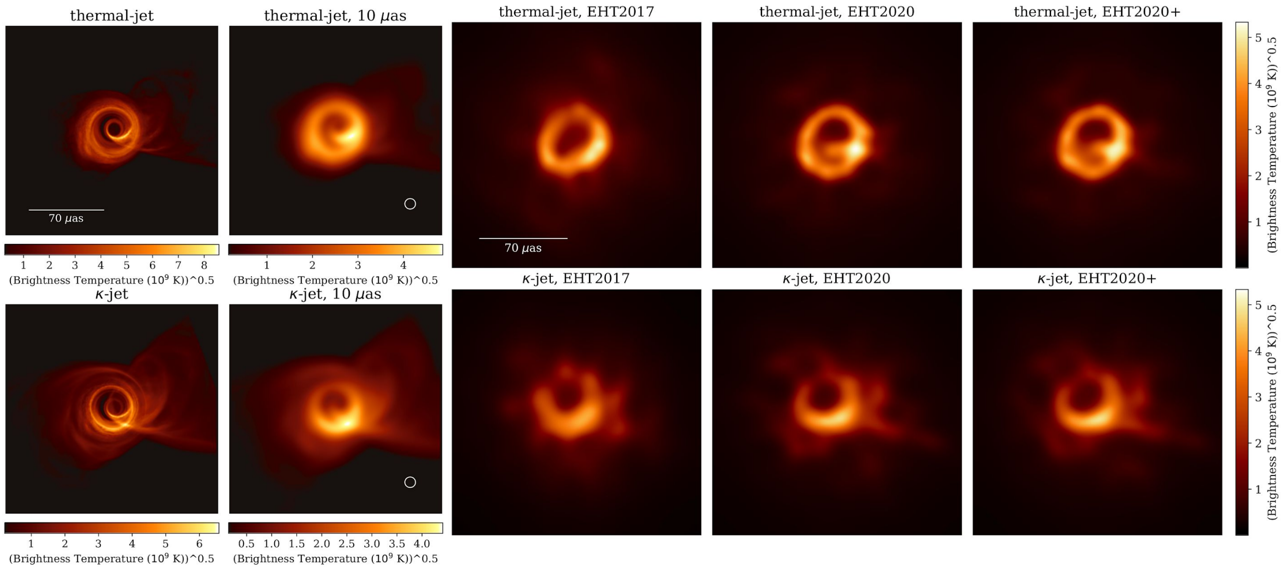


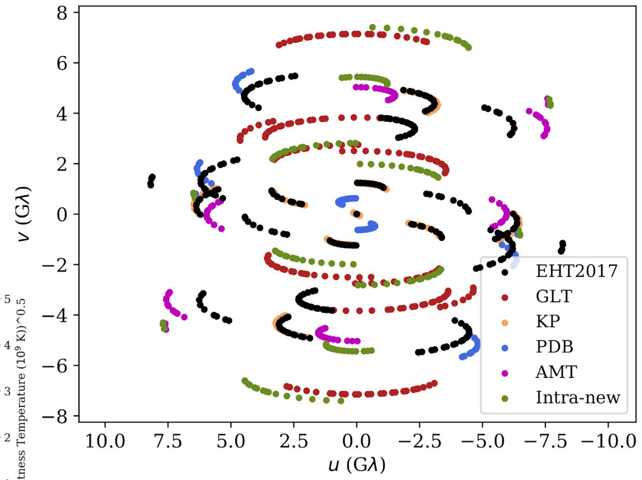
When rotated and scaled to fit the data, earlier models also produce reconstructed images with remarkable similarity to the observed image

The future: new EHT stations

New stations:

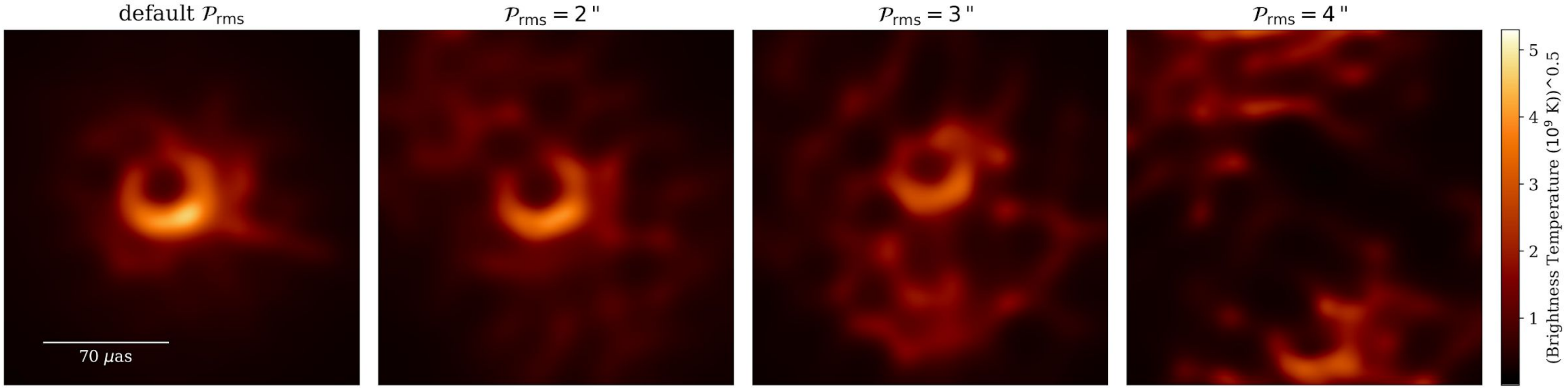
- Greenland Telescope (GLT) (2018)
- Kitt Peak observatory (KP) in Arizona (2020)
- IRAM NOEMA interferometer (PDB) in France (2020)
- Africa Millimetre Telescope in Namibia (2020+)





Davelaar et al (2019); Roelofs, Janssen et al. (2019, in prep.)

Varying observing conditions



The (not so?) far future: Space VLBI

Idea developed in collaboration with ESTEC (M. Martin-Neira, V. Kudriashov)

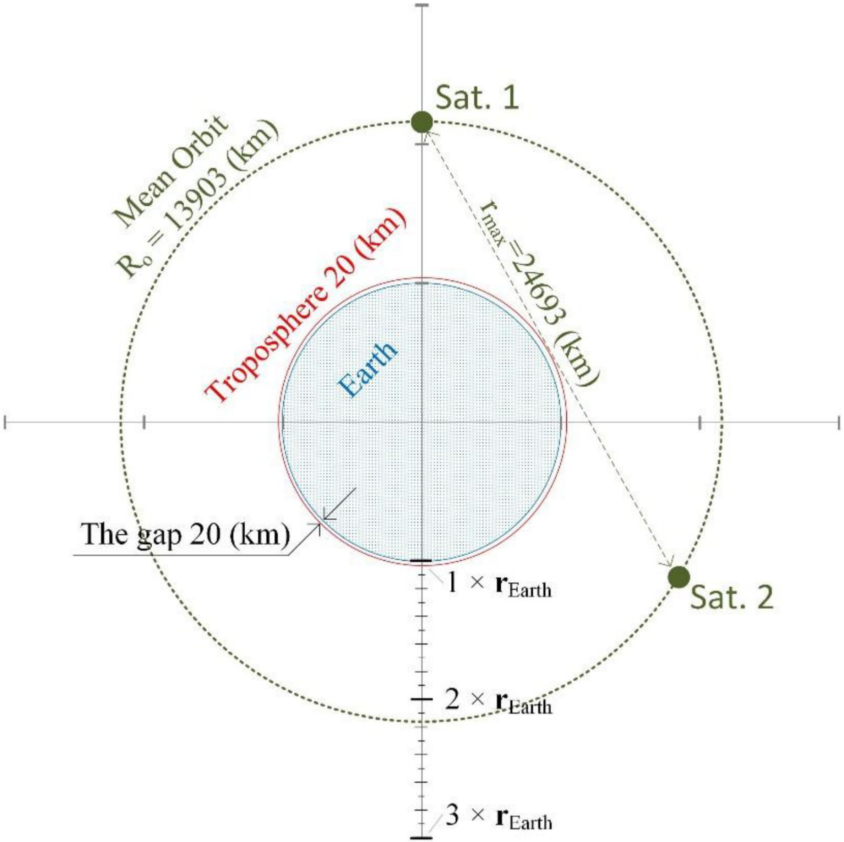
Two satellites at slightly different orbital radii, observing at high frequencies up to ~690 GHz

Satellites send data and correlate on the fly

Positions determined by GNSS satellites, fringe fitting in post-processing on ground

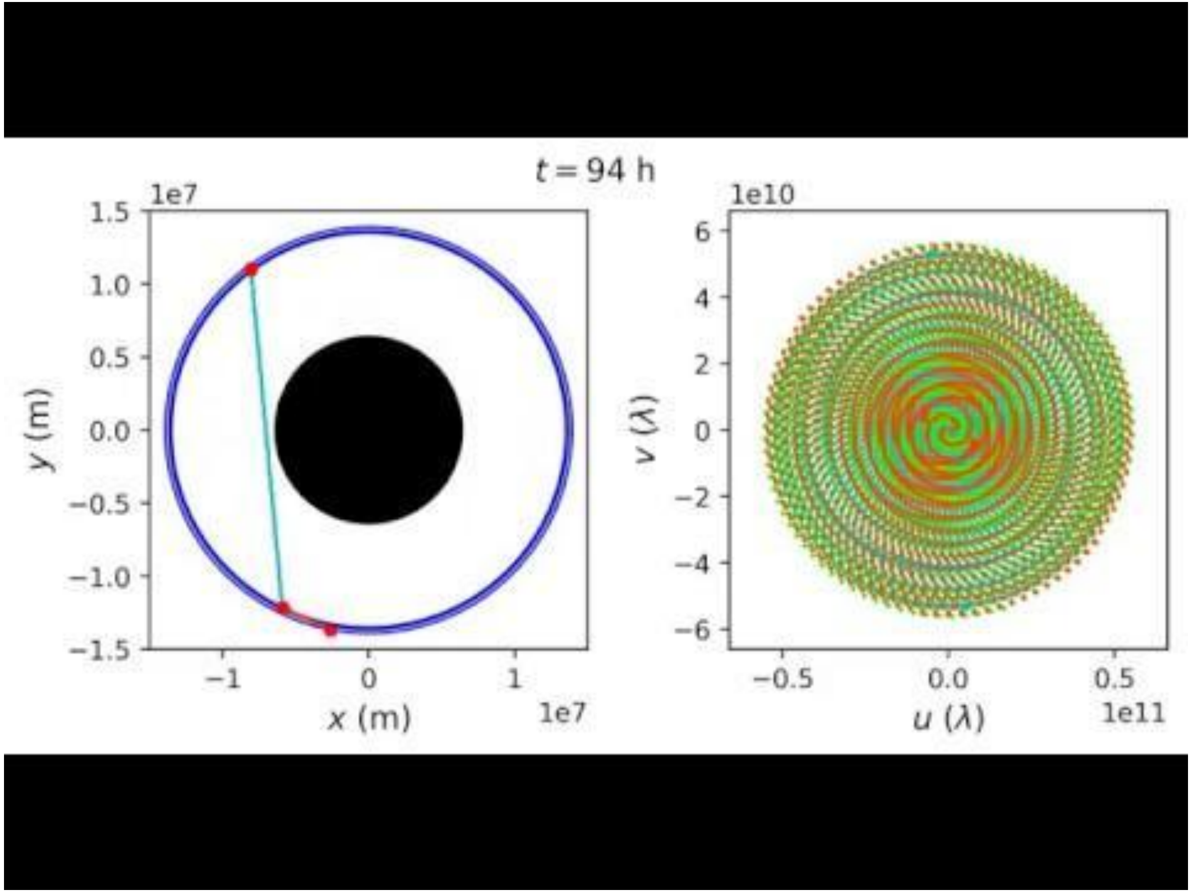
May be suitable for Medium-class ESA mission

Collaboration with ESA to assess engineering challenges



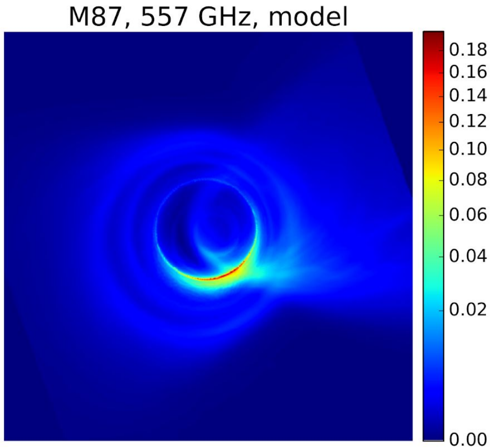
Marin-Neira et al. (2017), Kudriashov et al. (2019, subm.)

Dense and isotropic uv-coverage

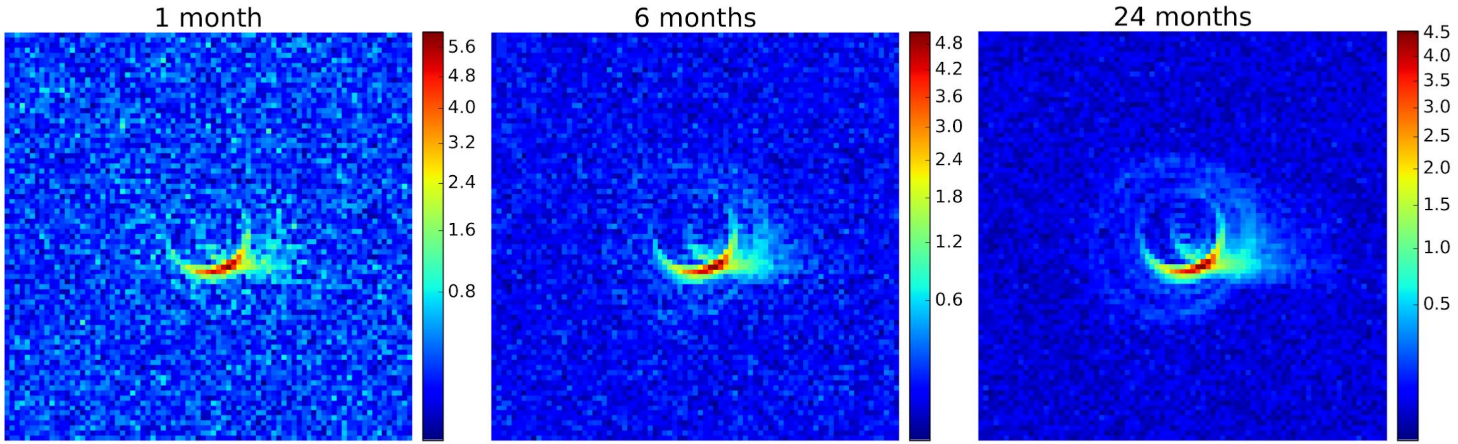


Roelofs et al. (2019), Kudriashov et al. (2019, subm.)

Simulated images

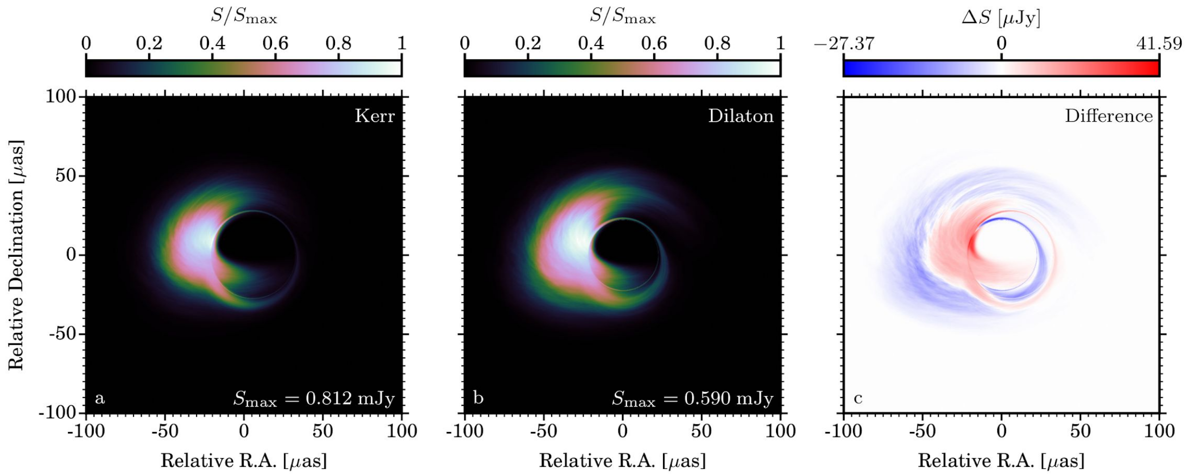


Davelaar et al. (2019)

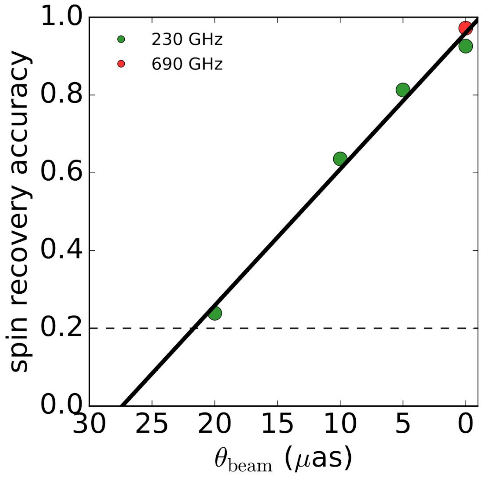


Roelofs et al. (2019), Kudriashov et al. (2019, subm.)

Test GR, measure spin



Mizuno et al. (2018)



Van der Gucht et al.
(2019, in prep.)

Summary

Radboud Radio Lab Radboud University

The EHT has imaged M87 at 230 GHz as an asymmetric ring structure

Consistent with prediction of Einstein's theory of General Relativity

The observed structure is consistent with GRMHD simulations of an accretion flow around a Kerr black hole

The inferred black hole mass is
$M = (6.5 +/- 0.7) \times 10^9 M_{sun}$

The image may be improved with an upgraded EHT array and later a space VLBI array