The “Inner Shadow” of a Supermassive Black Hole

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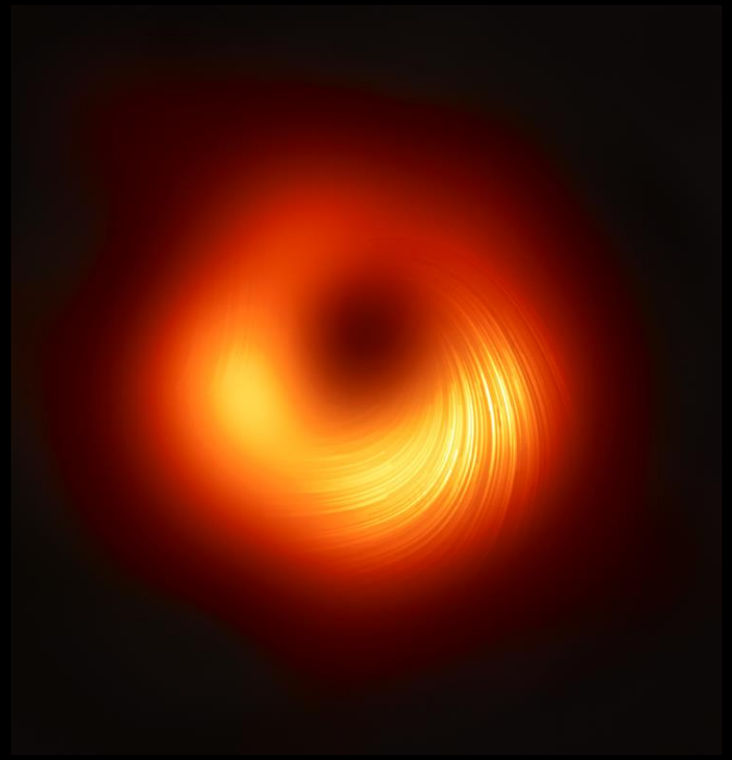

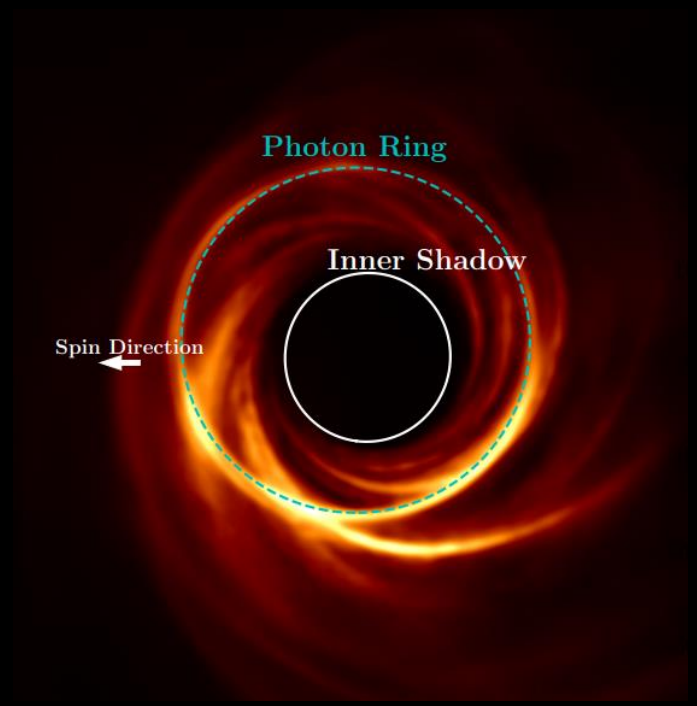

NHFP NASA Hubble Fellowship Program

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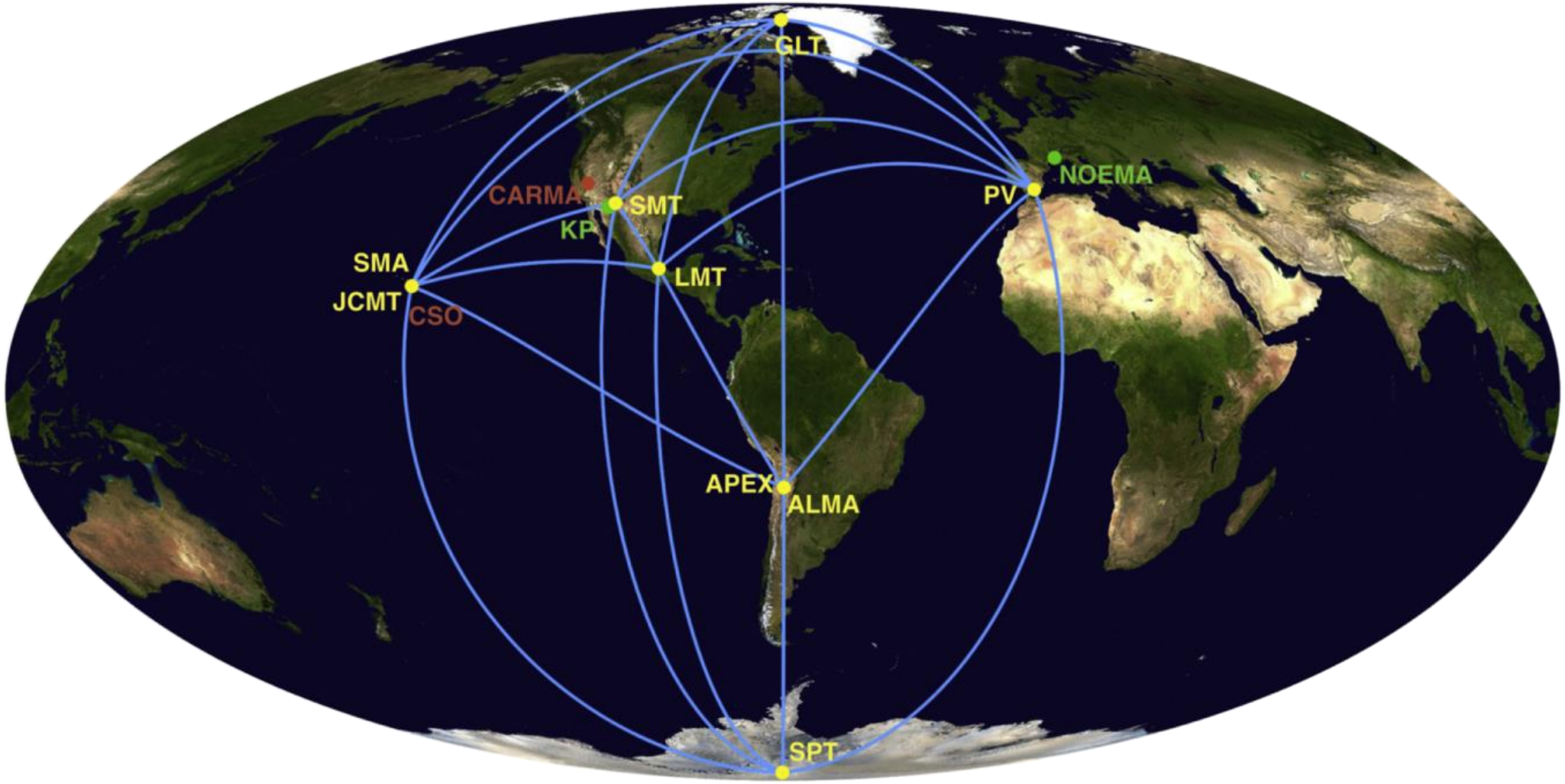
Event Horizon Telescope

The Event Horizon Telescope



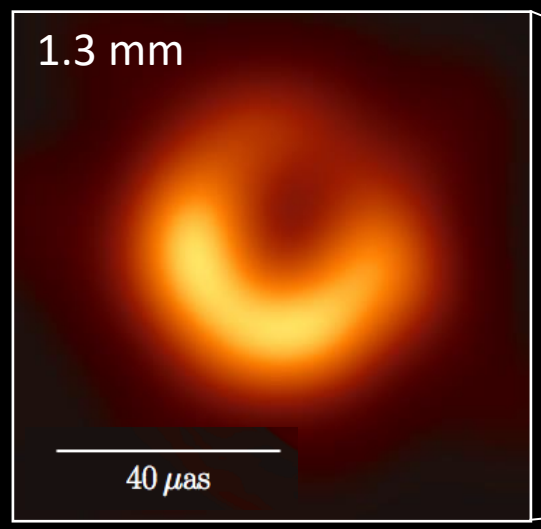
$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

EHTC+ 2019 (Paper II)

M87* with the EHT

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$

$D = (16.8 \pm 0.8)\mathrm{Mpc}$



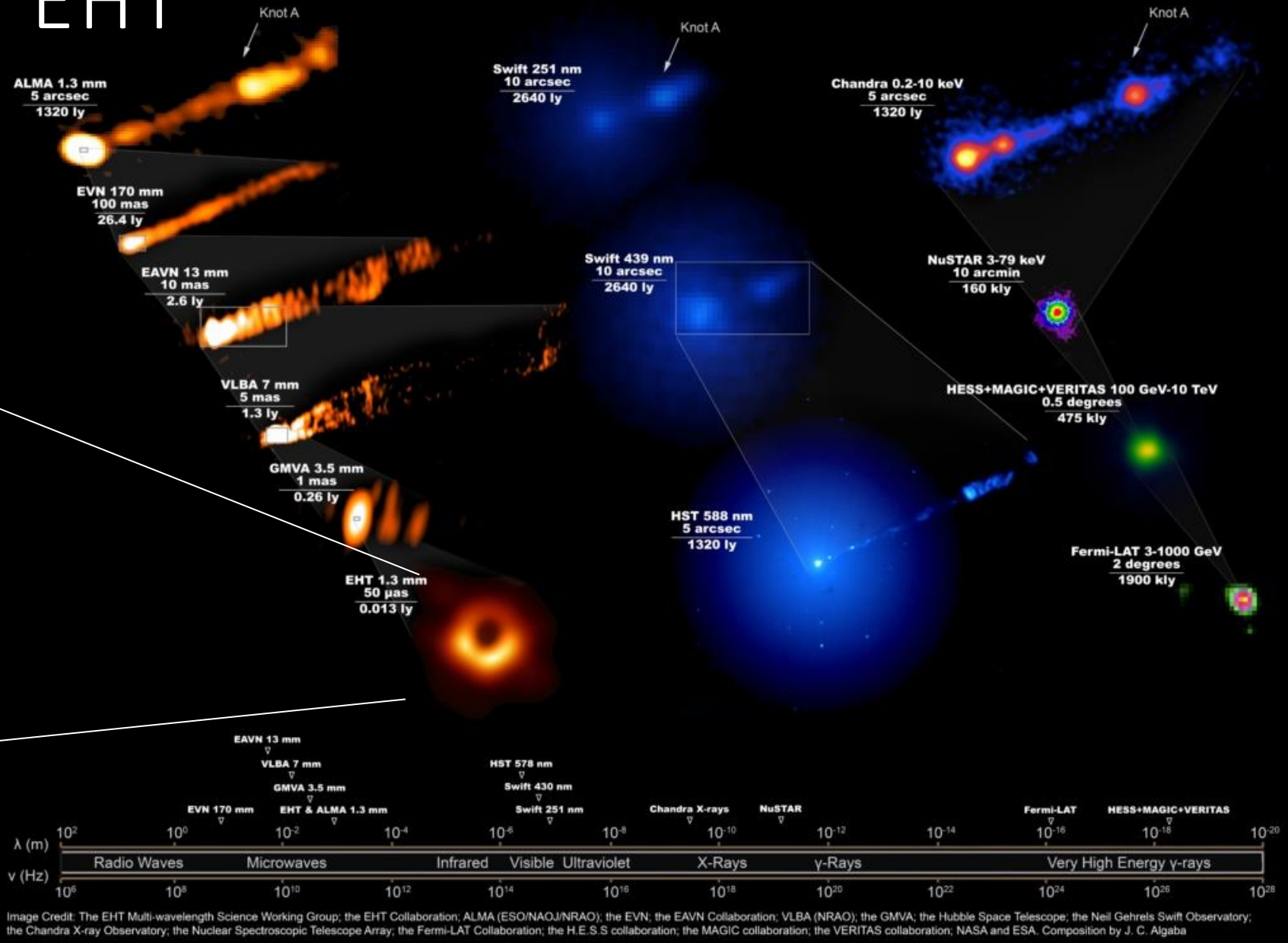
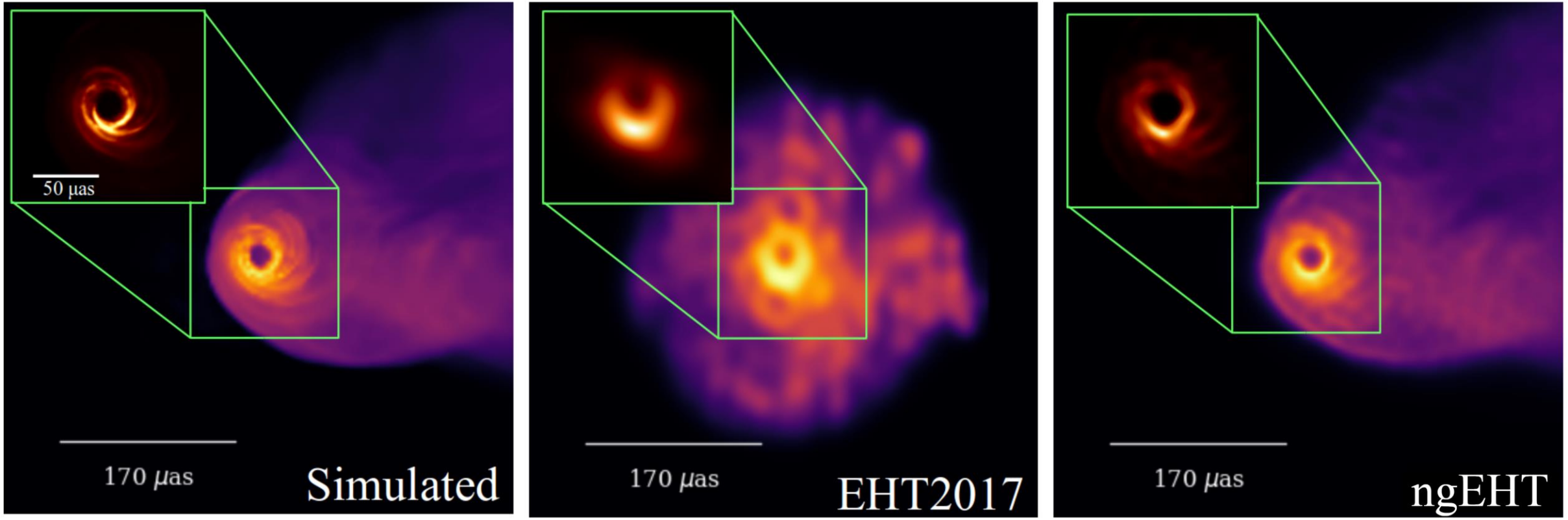


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array;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

Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

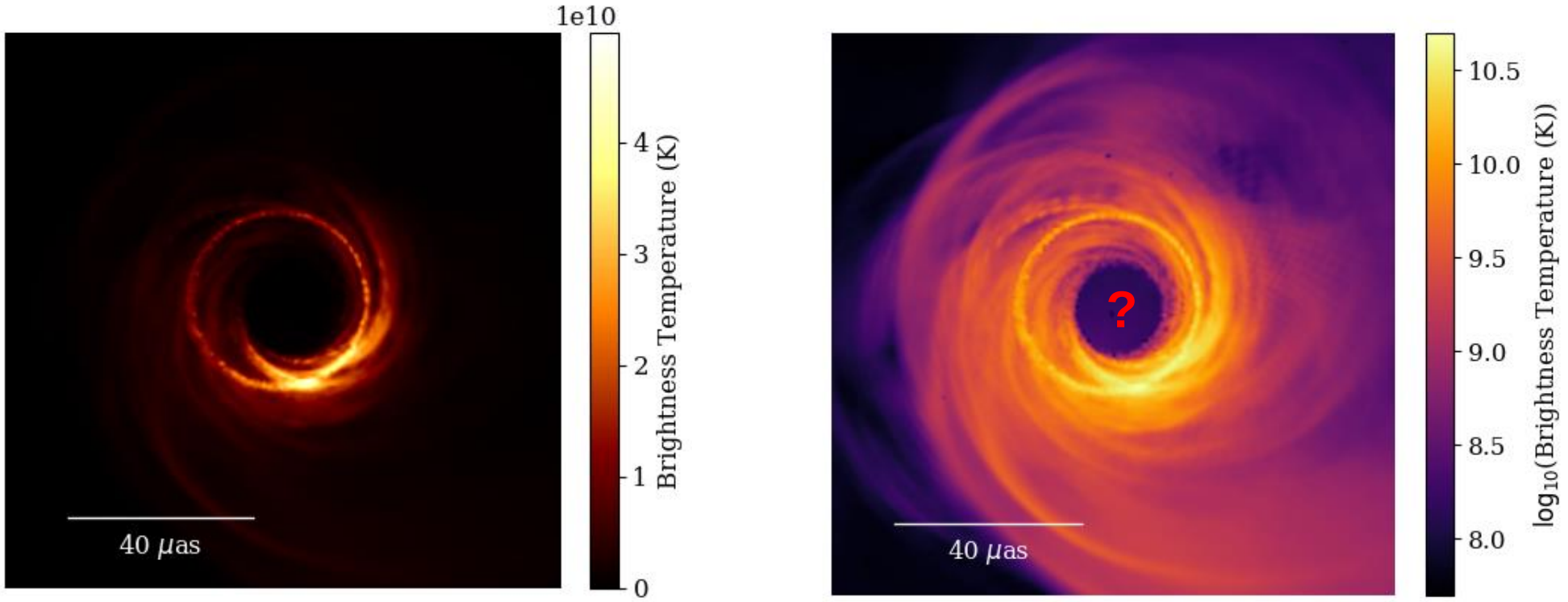
ngEHT: a high dynamic range black hole imager



- Increased (u,v) filling from new telescope sites in ngEHT will enhance image **dynamic range** from ~10 (EHT2017) to > 1000.
- High dynamic range images will illuminate the **BH-jet connection**
- High dynamic range images may also **reveal the 'inner shadow' feature**

See EHT Ground Astro2020 APC White Paper (Blackburn, Doeleman+; arXiv:1909.01411)
Simulation credit: Chael+ 2019

What is the sharp central brightness depression in high dynamic range images?



Is this the jet base? An artifact of the simulation grid?

Image Credit: Chael+ 2019

Sharp brightness depression in simulated images

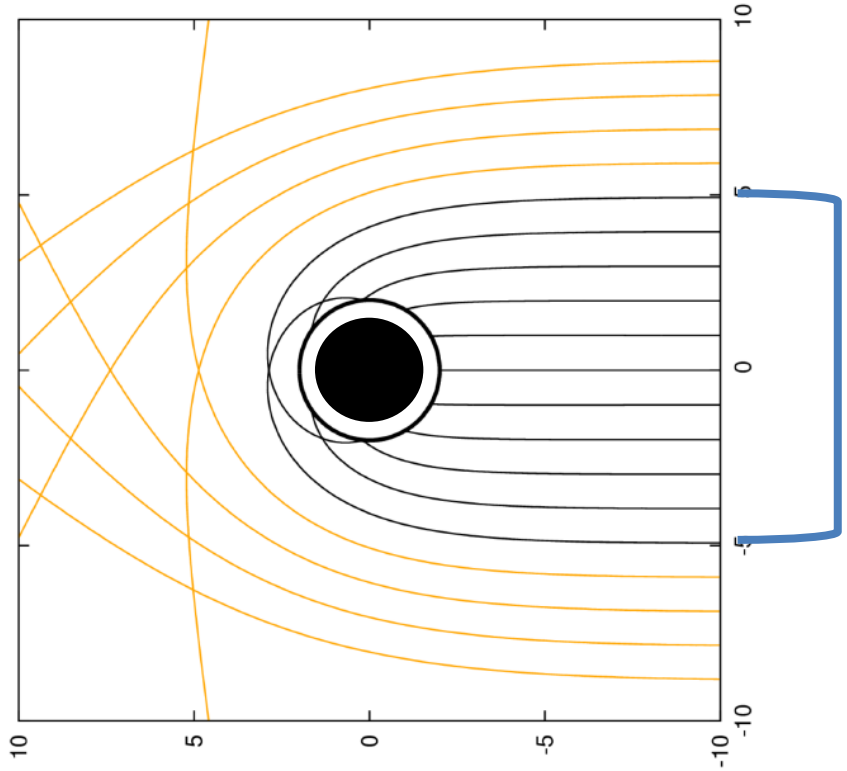
- This is the **inner shadow**: the lensed image of the equatorial event horizon.

- While not ‘universal’, **many simulations of EHT sources have the right conditions** necessary to make the inner shadow observable

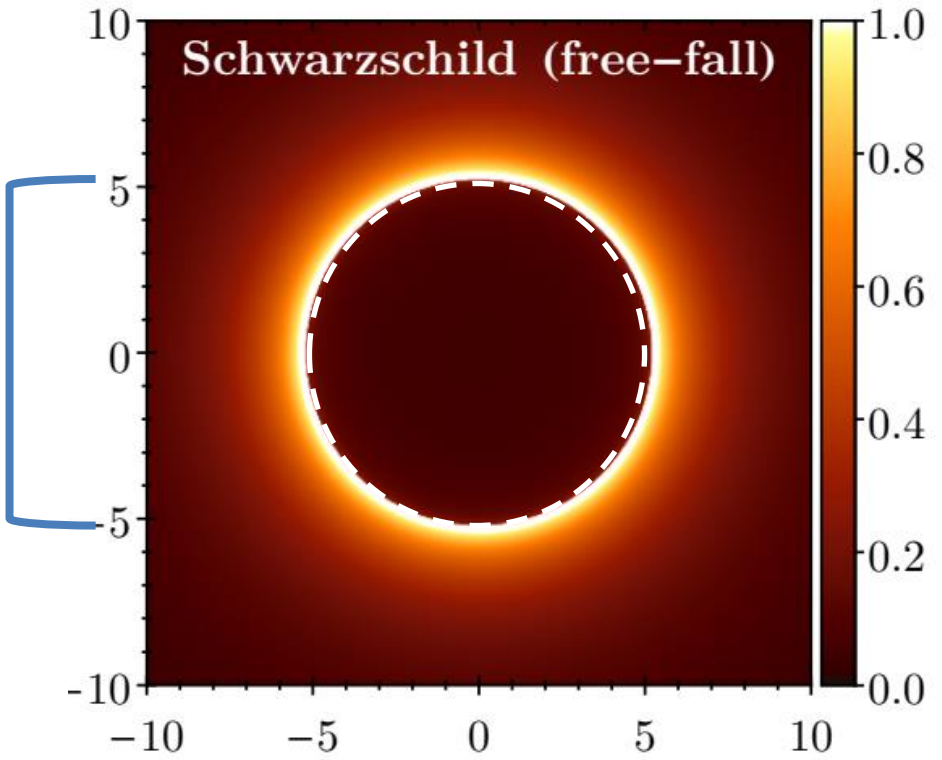
- Features of this image (radius, eccentricity, offset from the photon ring) can be used to **measure a black hole’s spin, mass, and inclination**

- The **ngEHT will have the dynamic range and resolution necessary** to observe the inner shadow and **use it to constrain BH spin, mass, and inclination**

The (Outer) Black Hole Shadow



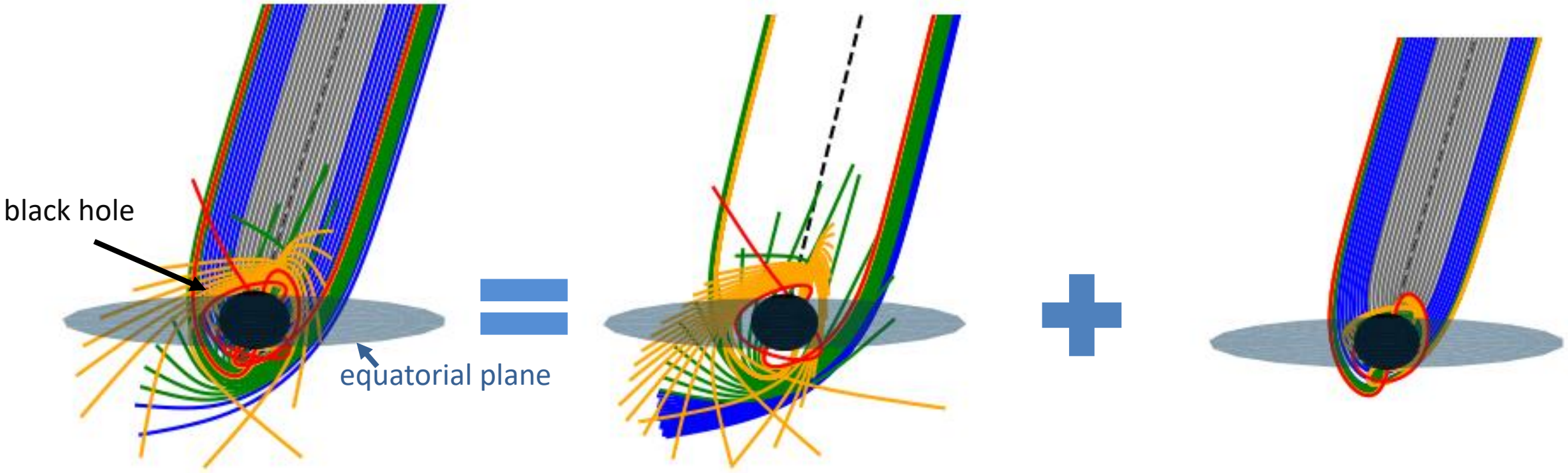
$$d_{\rm shadow} = 2\sqrt{27}GM/c^2$$



- The 'critical curve' on the image **separates of rays that end on the event horizon with those that escape to infinity**
- The interior of the critical curve is the 'black hole shadow' -- **all rays inside end on the horizon**
- The shadow is most prominent when the emission region is **spherically symmetric and optically thin**

Image credit: Keiichi Asada
Narayan+ 2019 (also Falcke+ 2000, many others)

observer



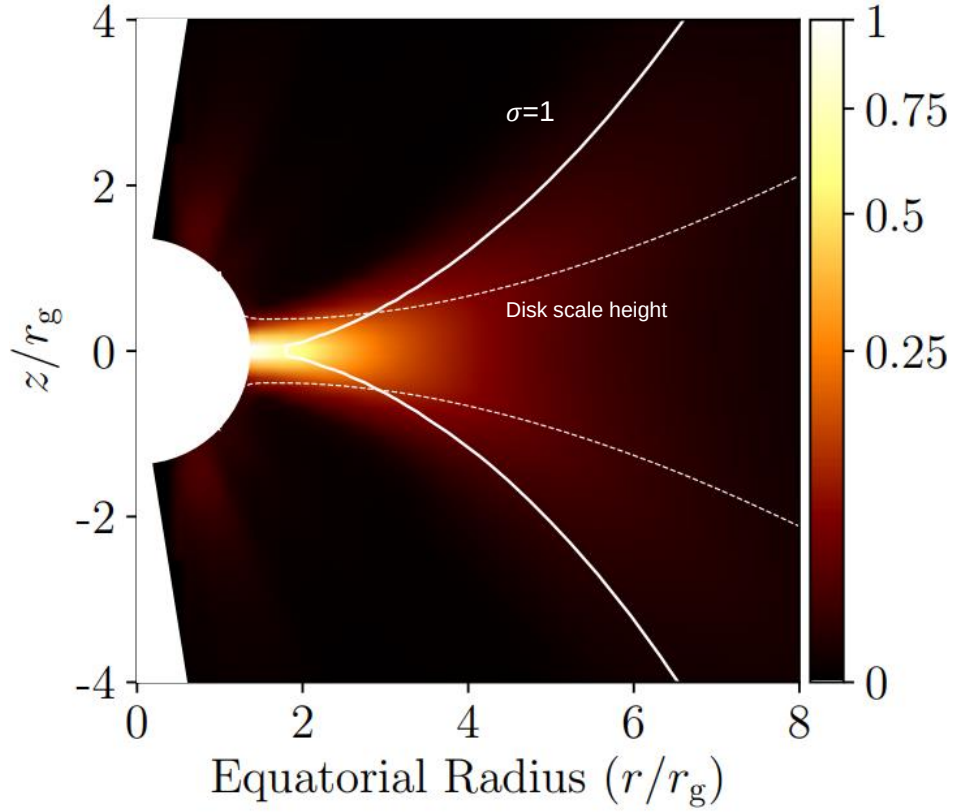
all rays

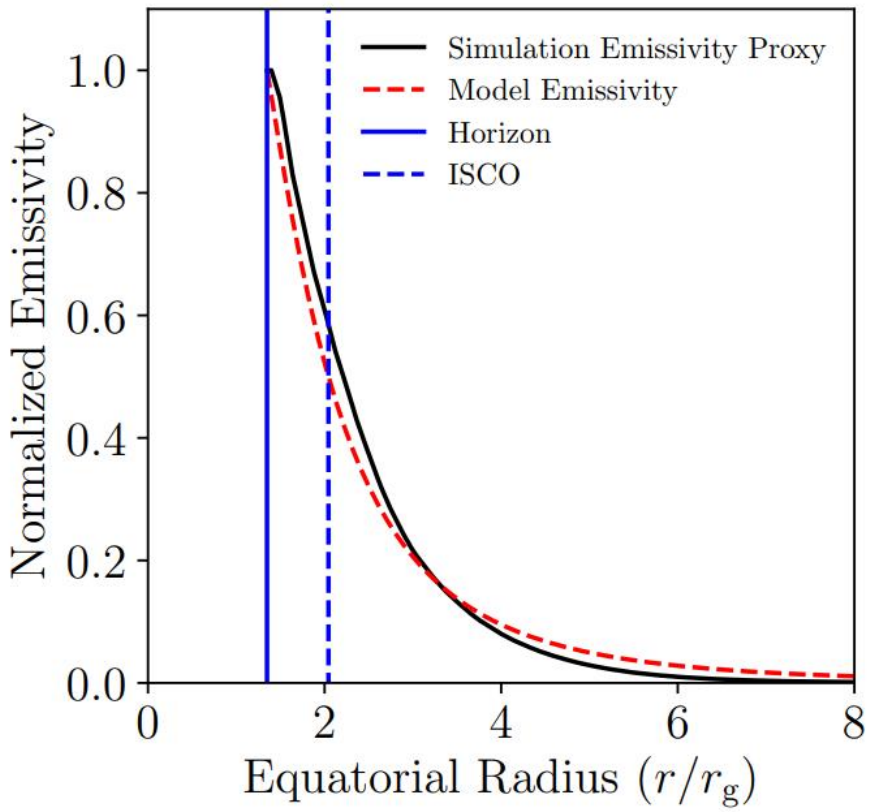
Rays that
escape to infinity

Rays that
end up on the black hole (the shadow)

Emission origin in (magnetically arrested) simulations

Rest-frame emissivity proxy





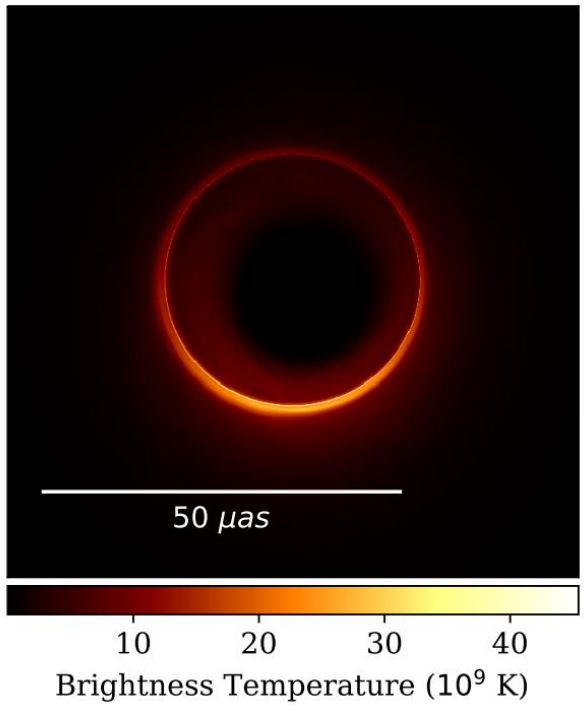
Rest-frame emissivity: Equatorial slice

- The 230 GHz emissivity is **predominantly equatorial** in many magnetically arrested simulations
  - The accretion flow is **not a think disk, but it looks somewhat like one** (at 230 GHz)
- Emission does not truncate at the ISCO, but **extends to the horizon**

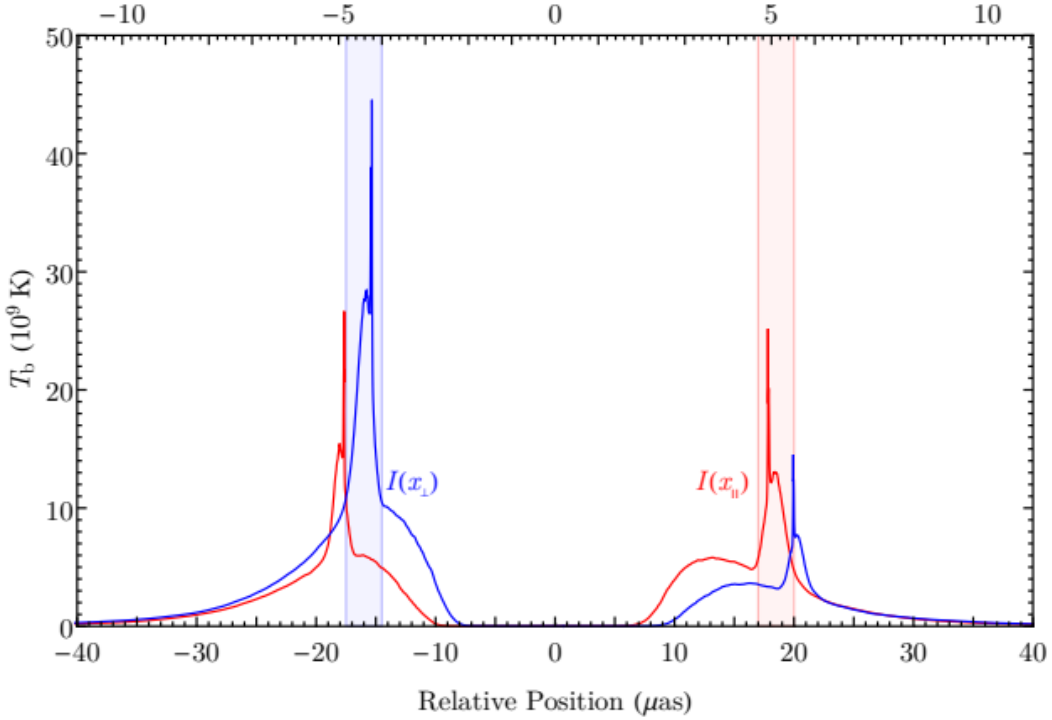
Chael+ 2021

Photon Rings

Time-averaged simulation



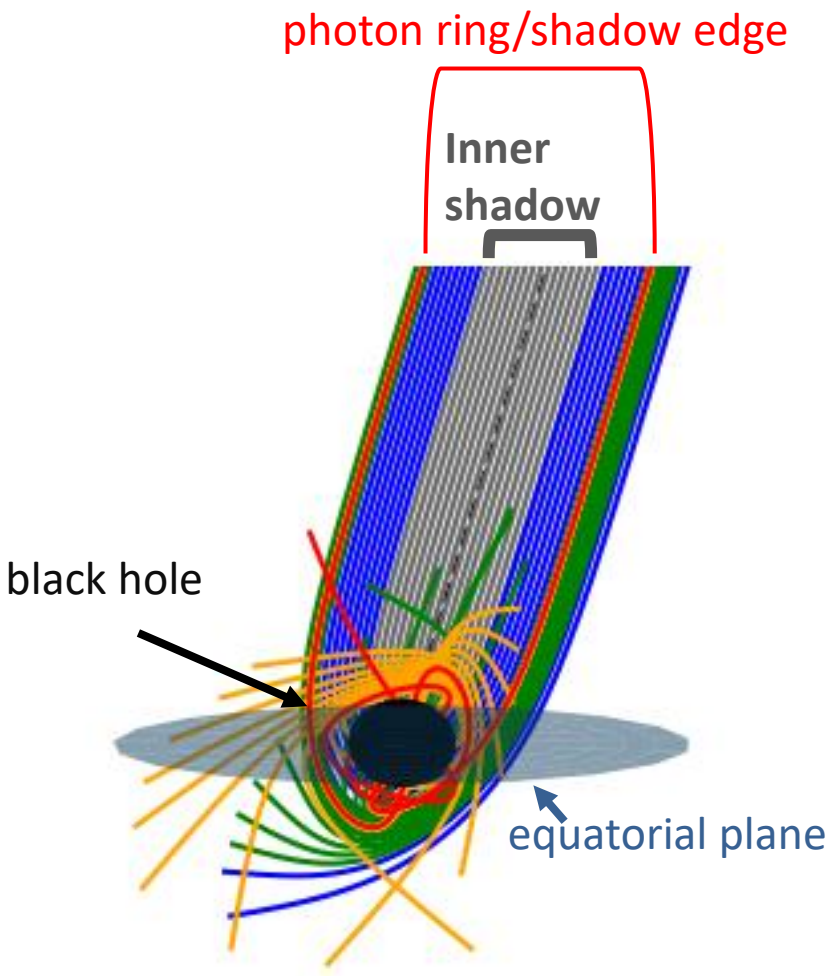
Angular slices (image)



- Direct emission (n=0) comes from geodesics that cross the equatorial plane only once
- Photon rings (n=1,2,3…) come from images that geodesics that cross the equatorial plane multiple times
  - These form a **series of stacked images** lensed into **narrow rings**
  - These subrings **approach the black hole shadow edge exponentially**.

Johnson+ 2019

Photon Rings and the Inner shadow



Gray rays – never cross the equatorial plane
- these form the **'inner shadow'**

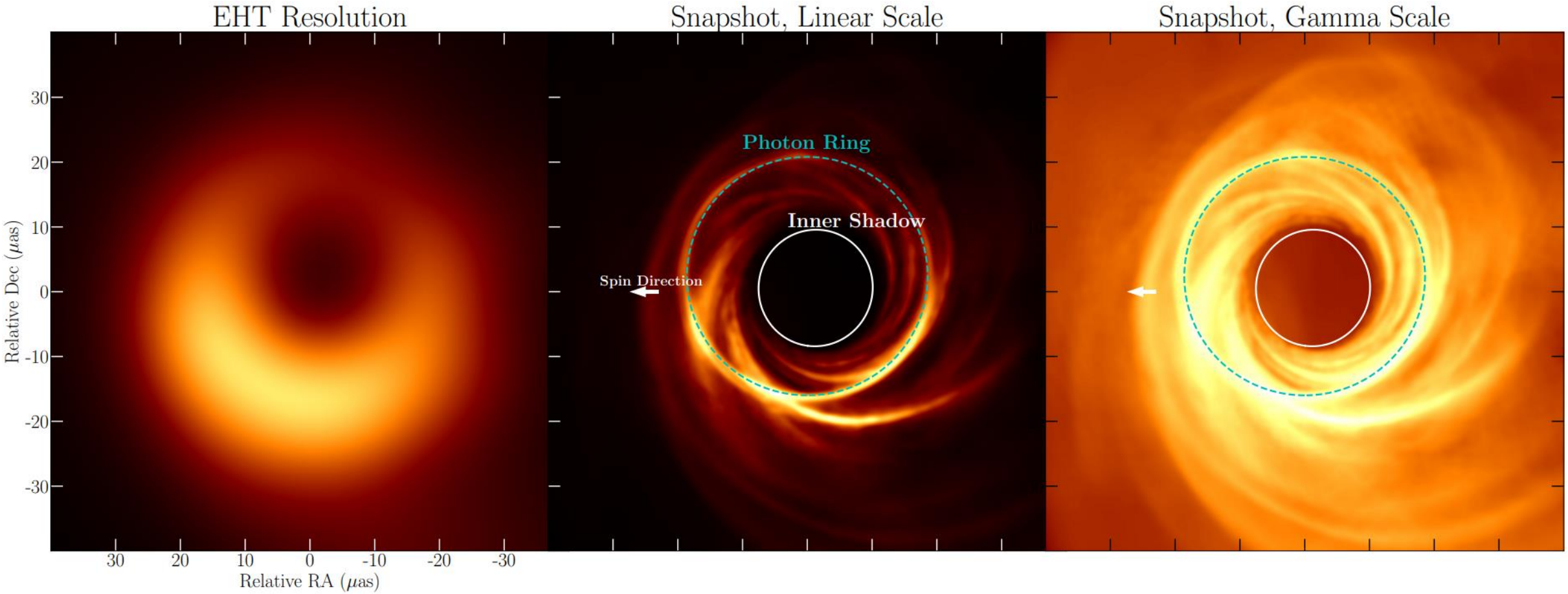
Blue rays – cross once (the direct image)

Green rays – cross twice (the first photon ring)

Orange rays – cross 3x (the second photon ring)

Red rays – cross 4x (the third photon ring)

Inner shadow in (magnetically arrested) simulations



- The **inner shadow is visible in simulations**; its edge **approaches** the **lensed position of the event horizon**
- Redshift increases near the horizon → the inner shadow is **most visible at high dynamic range**

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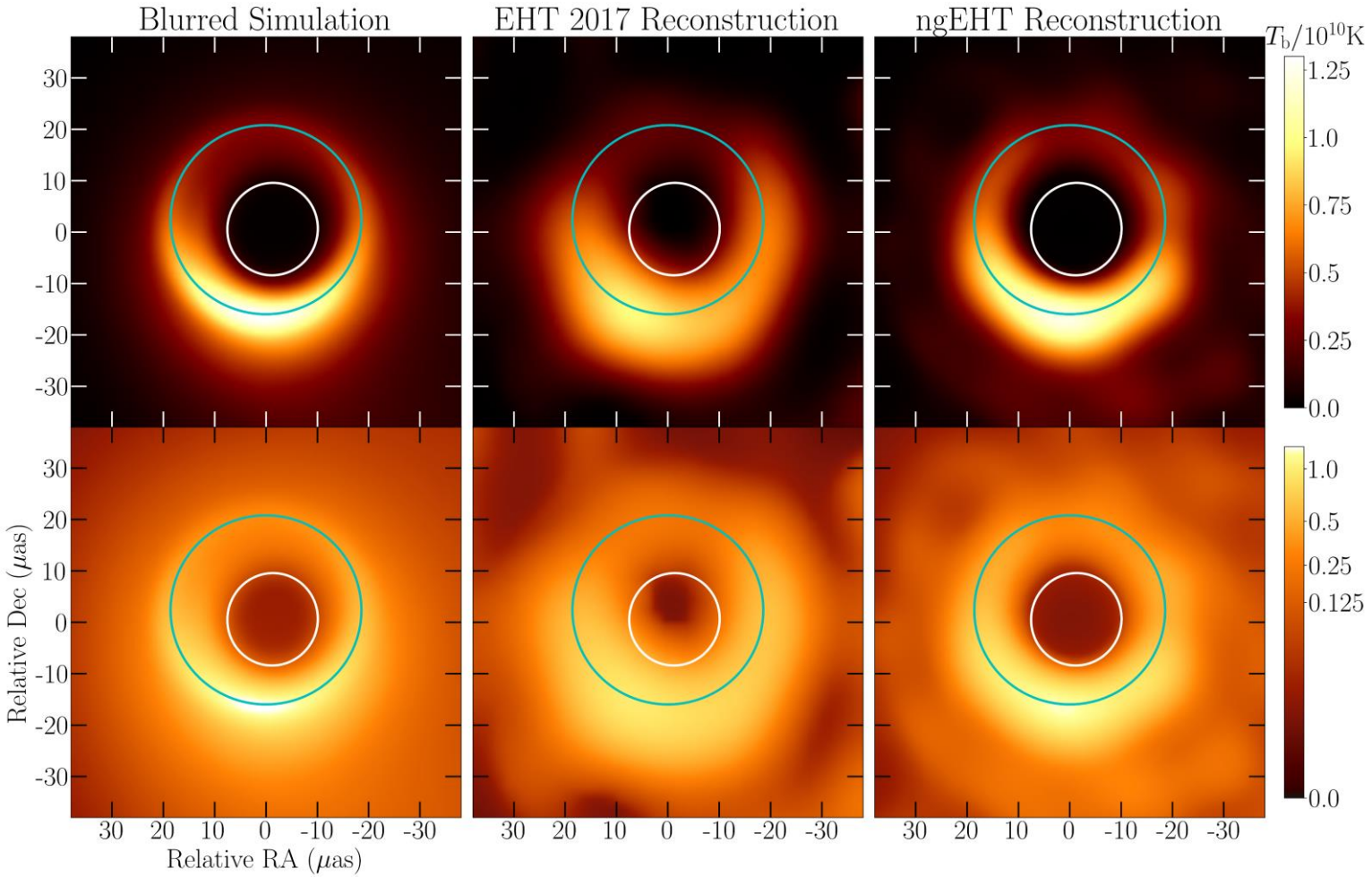
EHT 2017 and ngEHT image reconstructions



- Reconstructions use realistic EHT imaging scripts (using closure phases and amplitudes)
- **Imaging algorithms can detect the inner shadow in ngEHT data**
- Analytic modeling may constrain its shape more precisely

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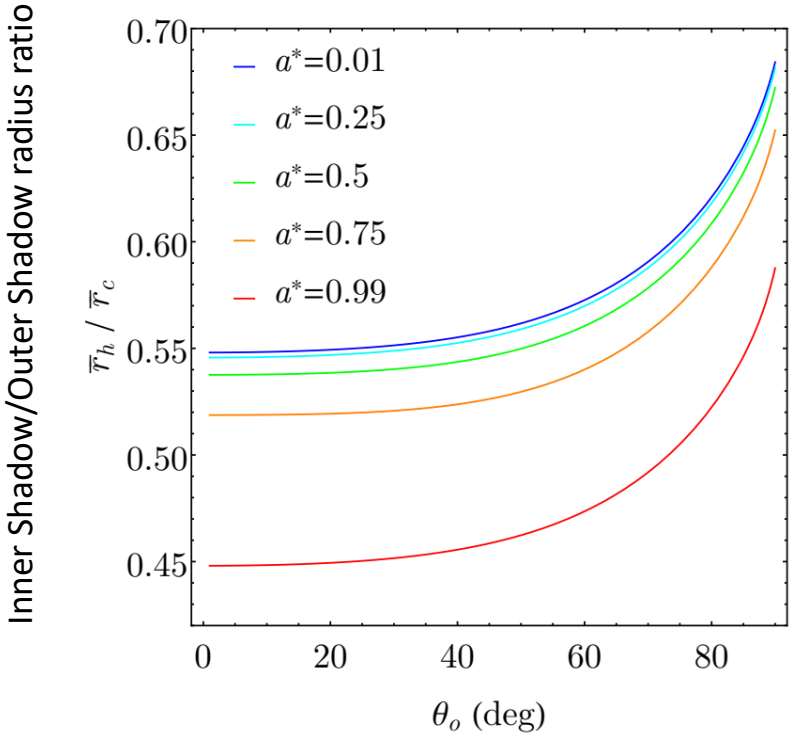
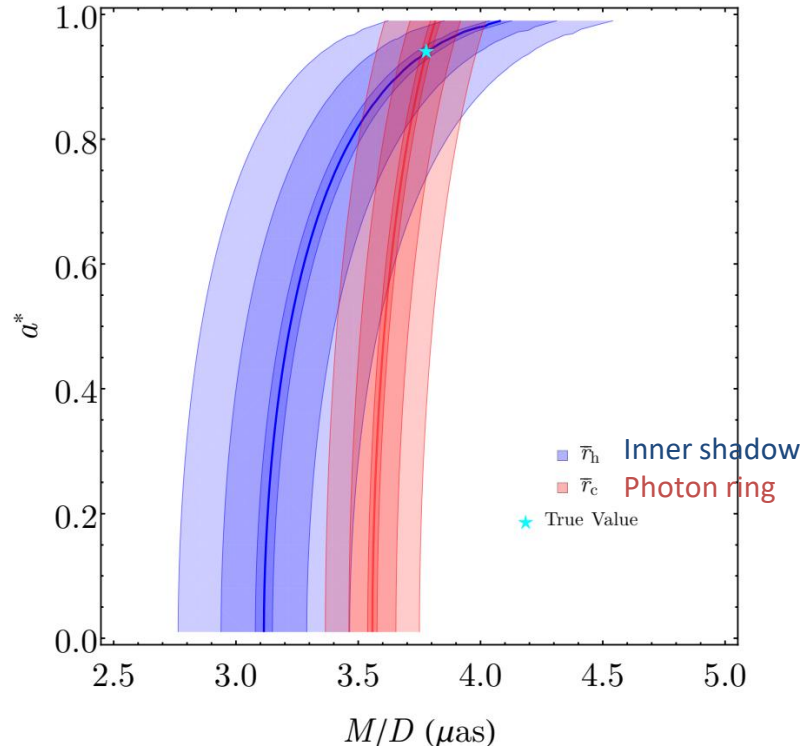
Inner shadow images provide another probe of spacetime

With **two** curves in the image (inner shadow and photon ring/'outer' shadow)
we can measure **relative sizes and positions**
removing degenercies in estimating mass, spin, and inclination



At low inclination, inner/outer shadow size ratio is **spin-dependent**
decreases from 55% to 45% from a=0 to a=1



Toy example of jointly estimating mass and spin
with inner shadow (blue) and photon ring (red) radii **at M87* inclination**
(Bands represent measurement uncertainties of 0.1, 0.5, 1 uas)

Chael+ 2021

Summary

- The **inner shadow** is the lensed image of the equatorial event horizon
- **The inner shadow is present in simulations of EHT sources** because the 230 GHz emission is predominantly equatorial
- Measuring features of both the inner and ‘outer’ shadow shapes **can remove degeneracies in mass, spin, and inclination measurements**
- The **ngEHT will have the dynamic range and resolution** necessary to observe this feature

Chael, Johnson, Lupsasca 2021
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