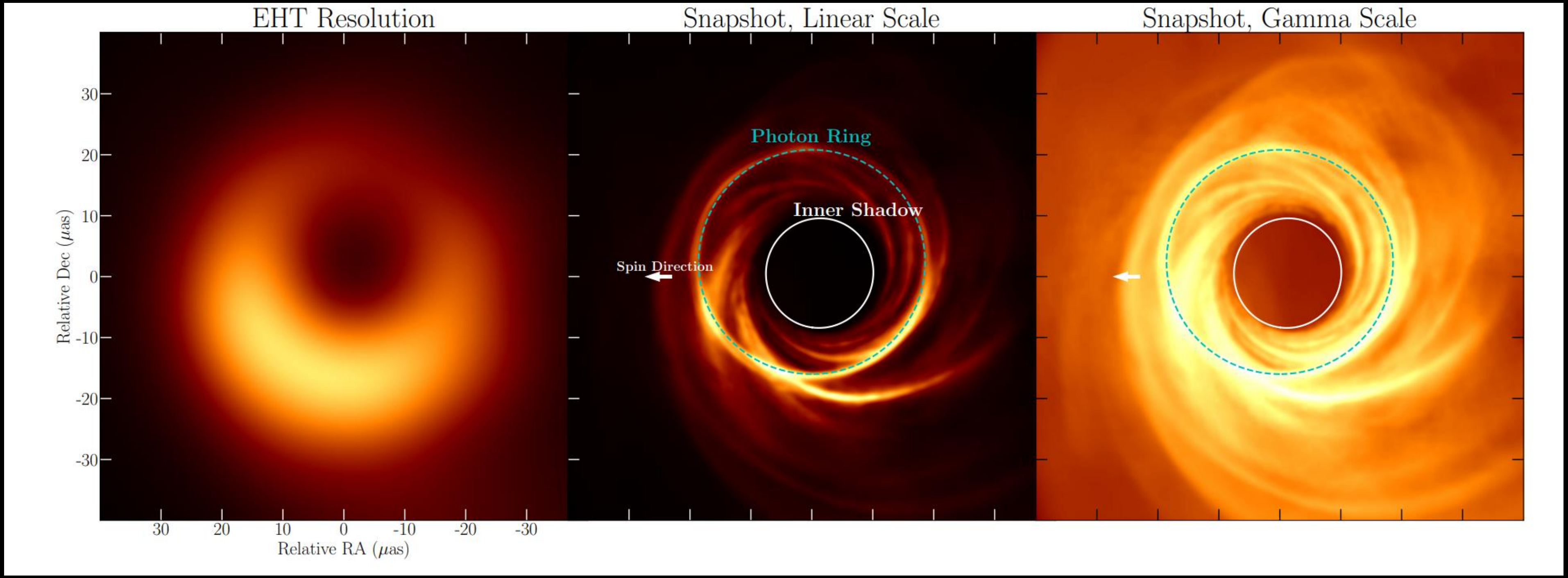
The inner shadow of a black hole:
A direct view of the event horizon

arXiv: 2106.00683



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(he/him)

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7/13/2021

NHFP
NASA Hubble Fellowship Program

PRINCETON UNIVERSITY

Event Horizon Telescope

M87 & M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
$d_{\mathrm{shadow}} \approx 40\mu\mathrm{as}$

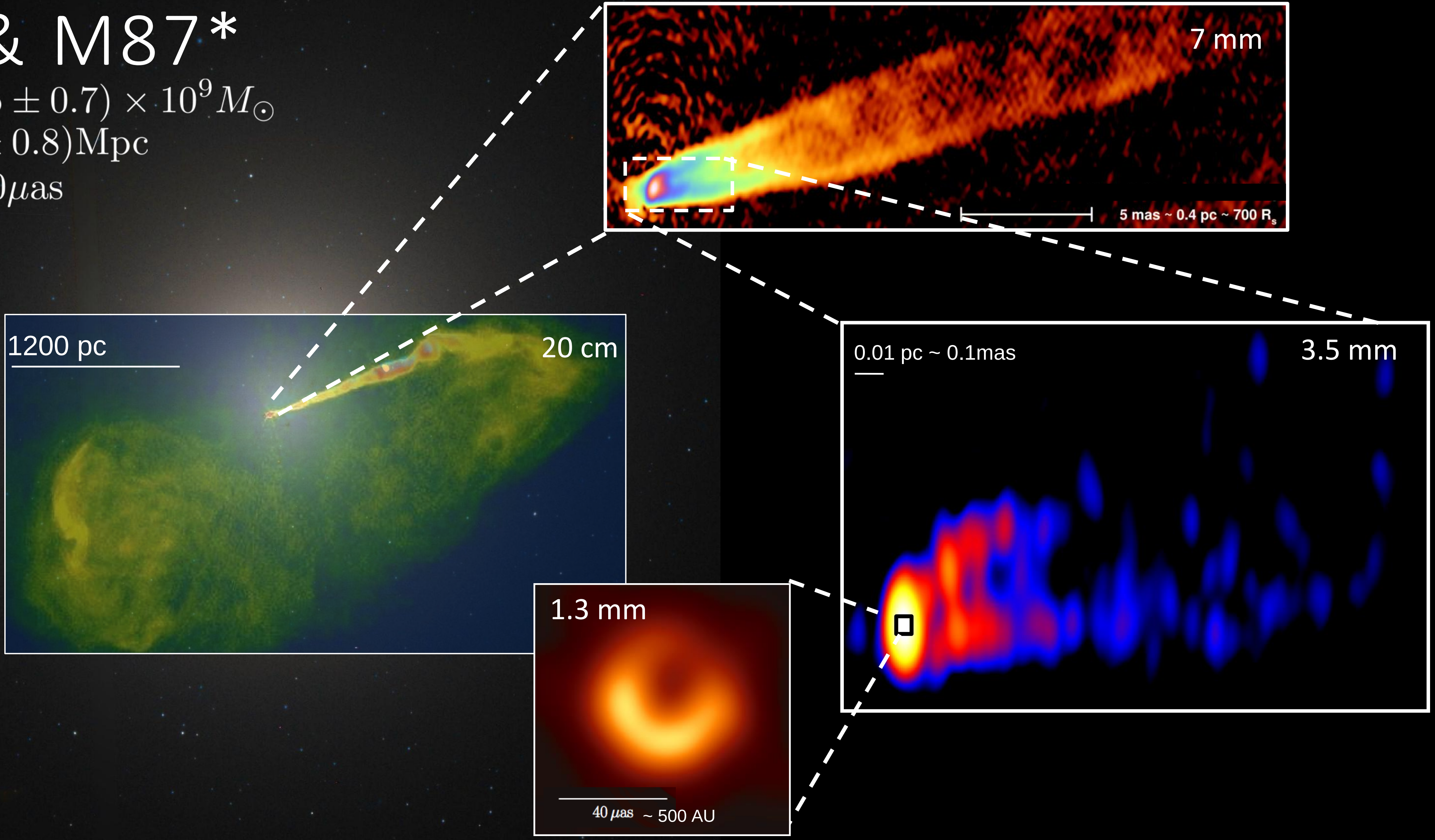
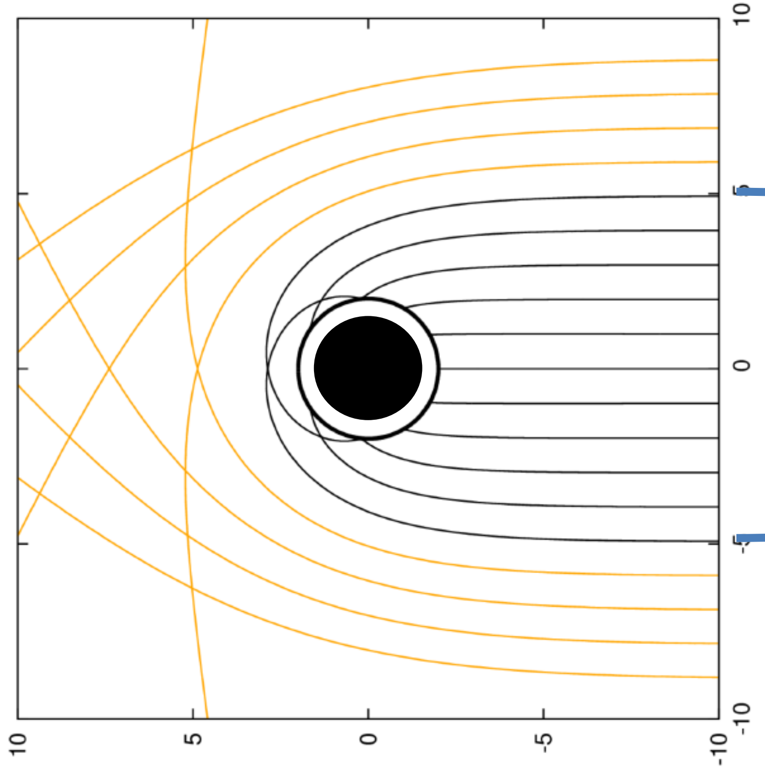
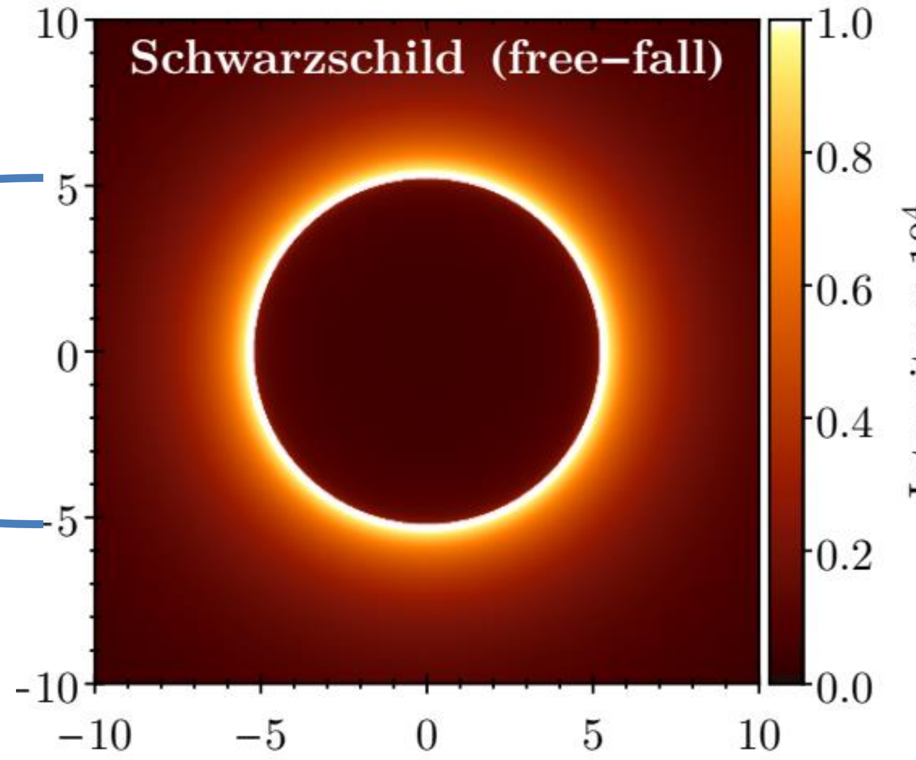


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

The Black Hole Shadow



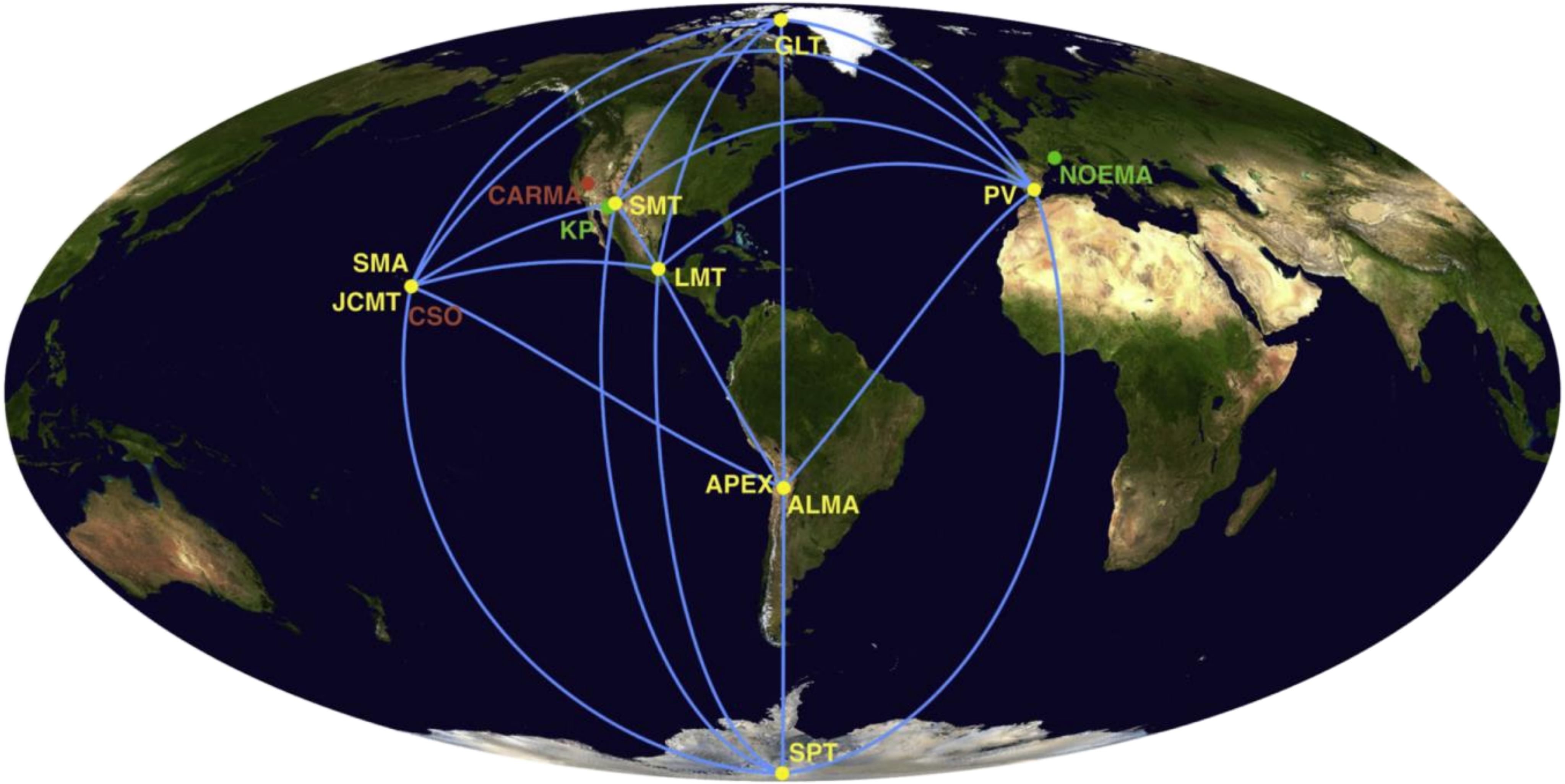
$$d_{\text{shadow}} = 2\sqrt{27}GM/c^2$$



- 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’, where all rays end on the horizon

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

The Event Horizon Telescope



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

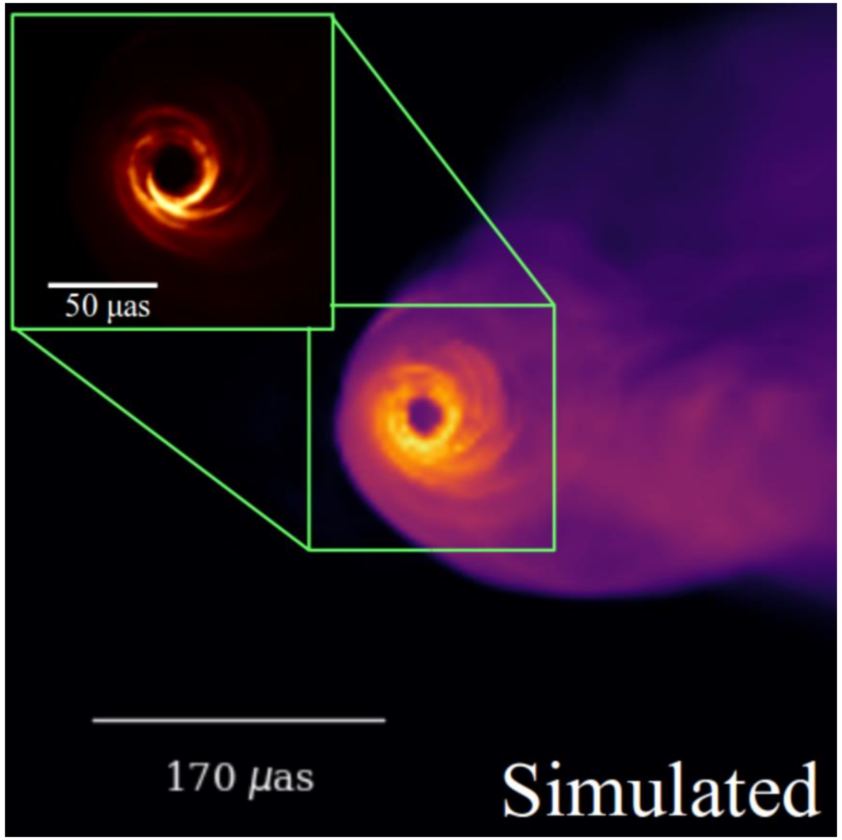
Image Credit:
EHT Collaboration 2019 (Paper II)

What do the EHT results tell us about the environment around M87's supermassive black hole?

At the heart of M87…

What we know:

- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Synchrotron Emission from very hot ($T \gtrsim 10^{10}\,\mathrm{K}$) plasma close to the event horizon
- Launches a powerful relativistic jet ($P_{\mathrm{jet}} \geq 10^{42}\ \mathrm{erg\ s^{-1}}$) outside of the galaxy

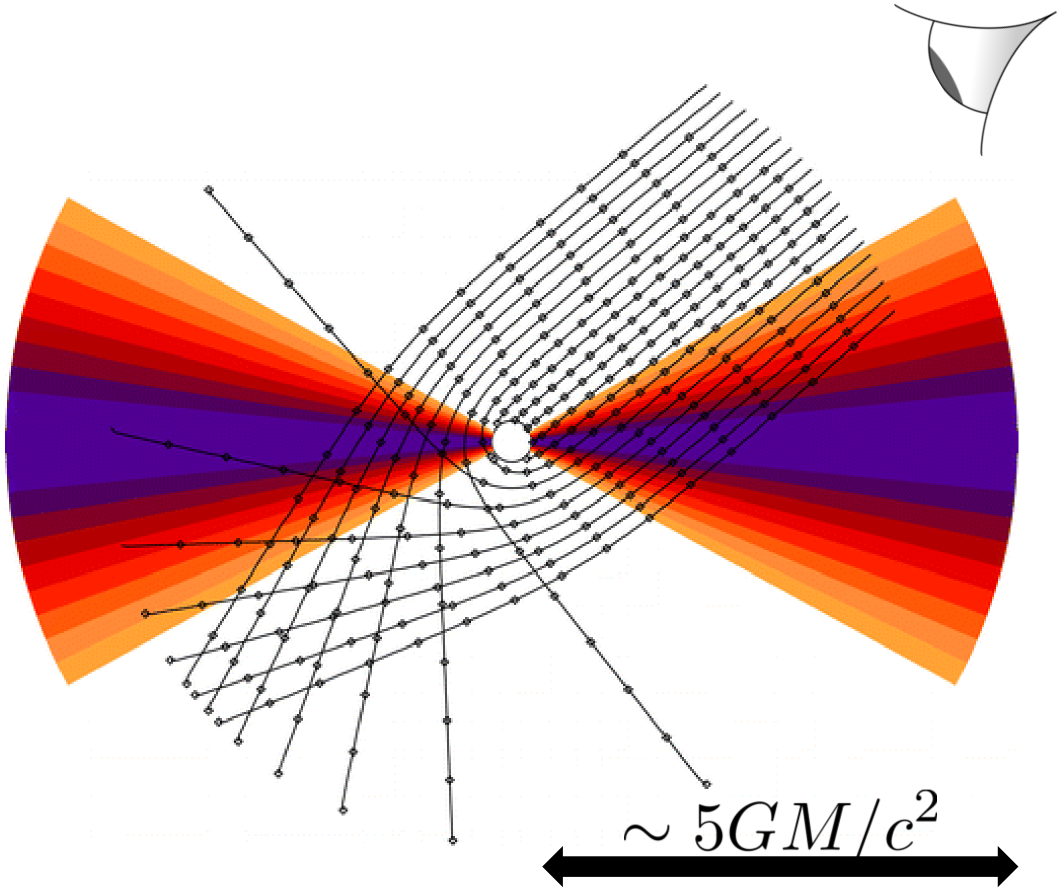


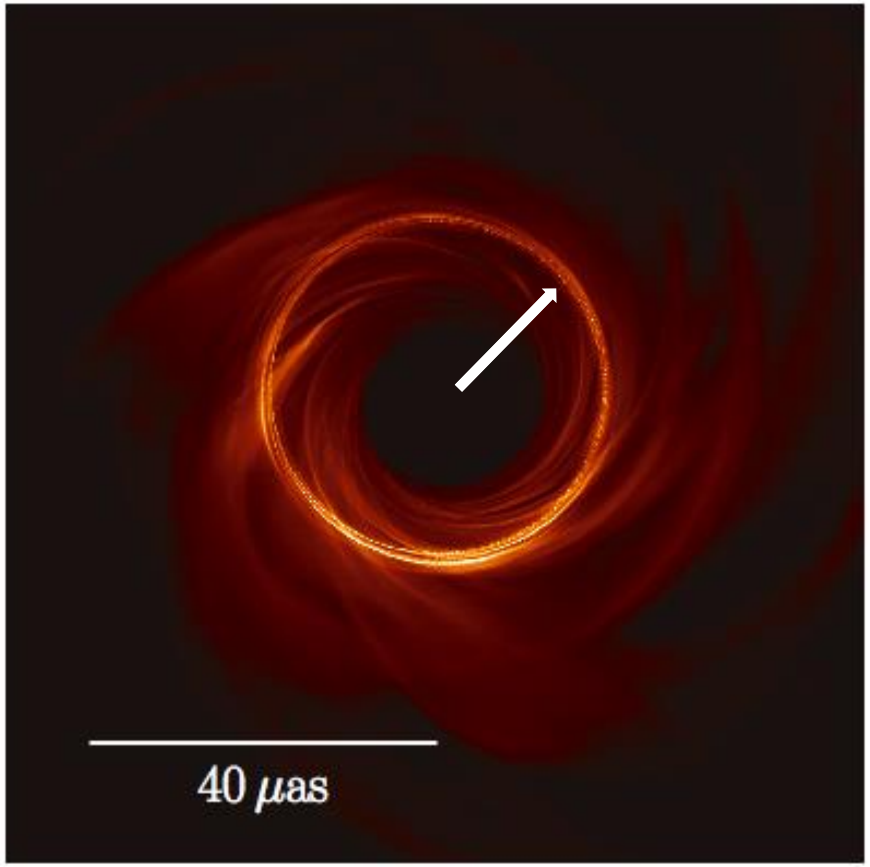
Open Questions:

- Where exactly does the emission come from?
- What is the temperature and distribution of the emitting particles?
- What is the strength and configuration of the magnetic field?

Image credit: Andrew Chael, Lindy Blackburn

Images of a Black Hole

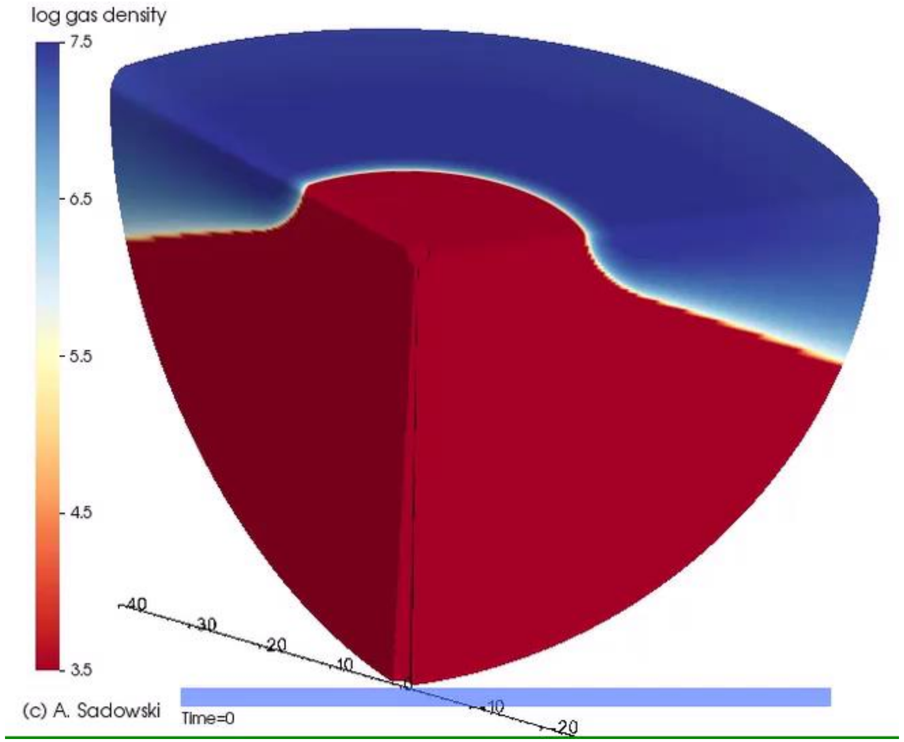




Schnittman+ (2006)

EHTC+ 2019

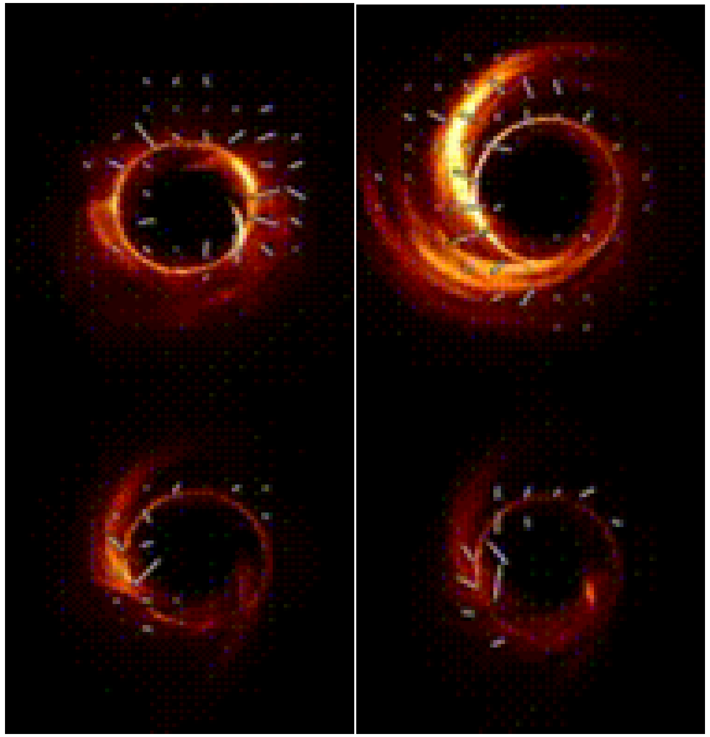
General Relativistic MagnetoHydroDynamic (GRMHD) simulations



Solves coupled equations of fluid dynamics and magnetic field in Kerr spacetime

$T_e?$

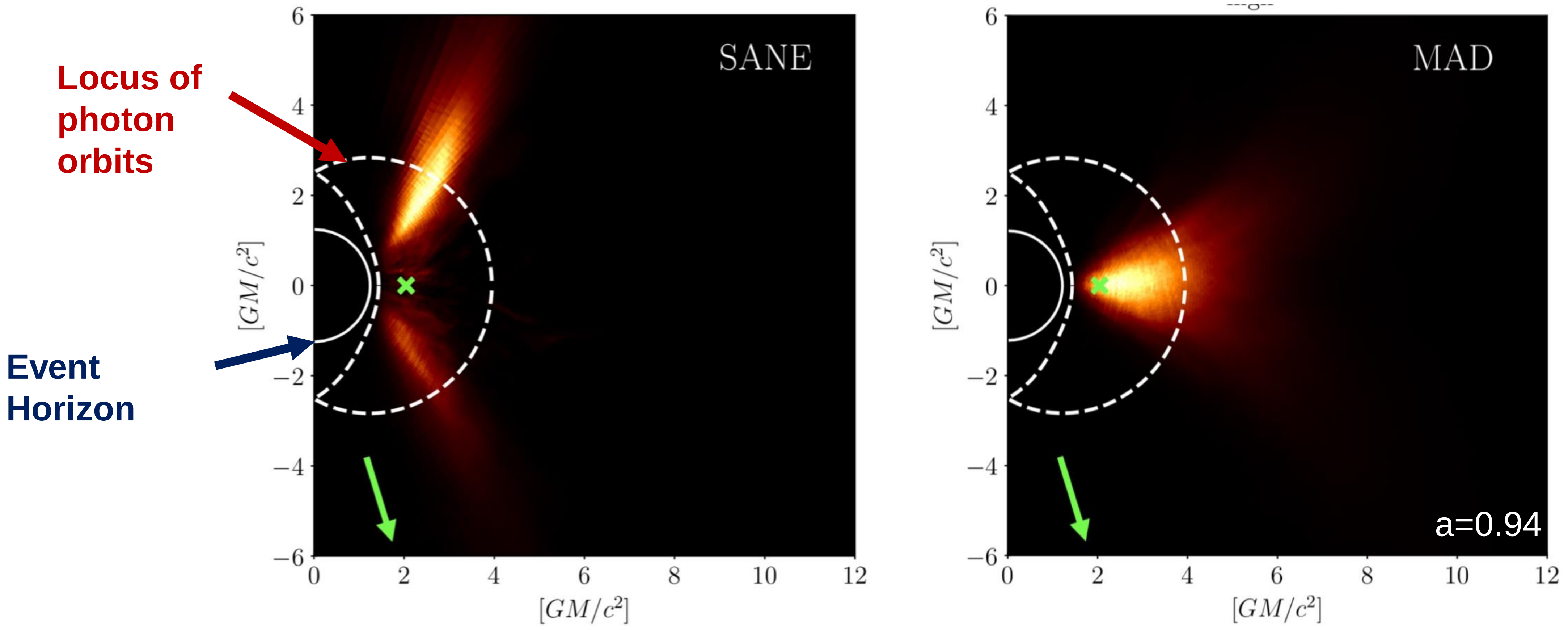
General Relativistic Ray Tracing (GRRT)



Tracks light rays and solves for the polarized radiation (including light bending and Faraday Rotation)

Movie Credits: Aleksander Sądowski (left) George Wong/Ben Prather

Where does the emission come from?

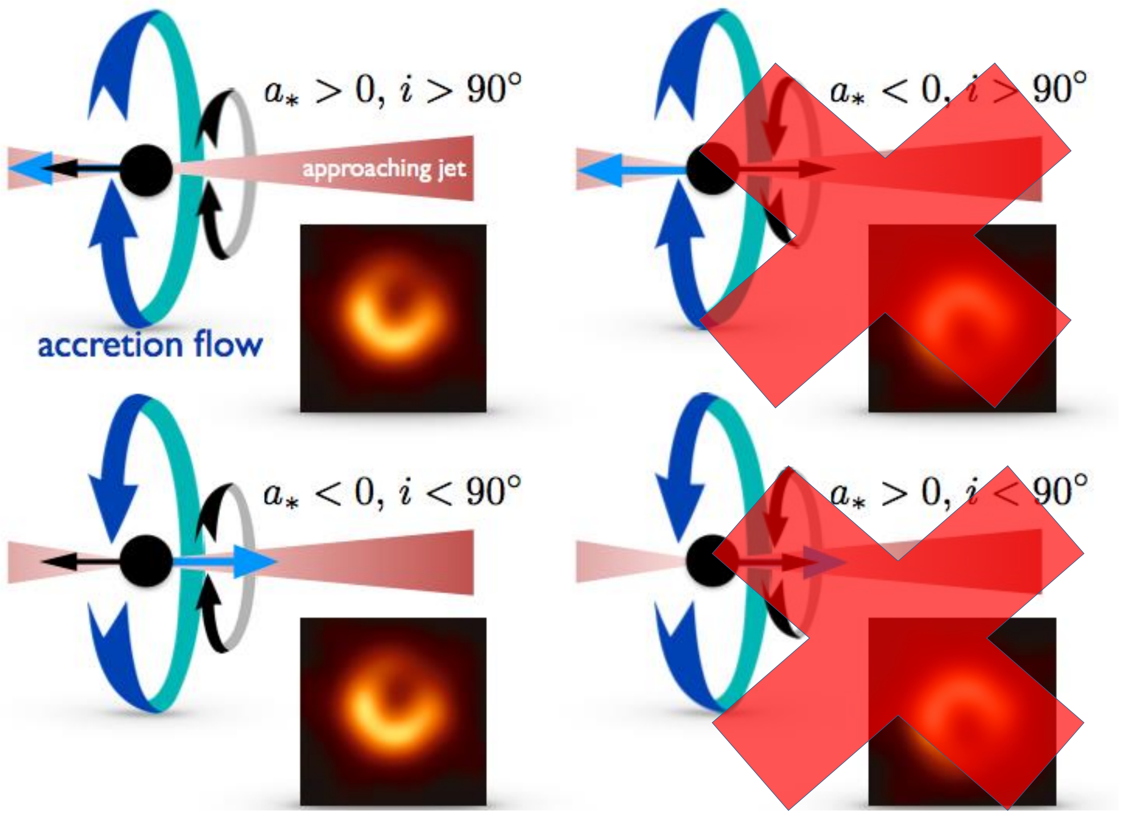


All simulations show emission region is within a few Schwarzschild radii of the black hole, but in different spatial regions

EHTC+ 2019, Paper V
Wong+ 2021

Ring Asymmetry and Black Hole Spin

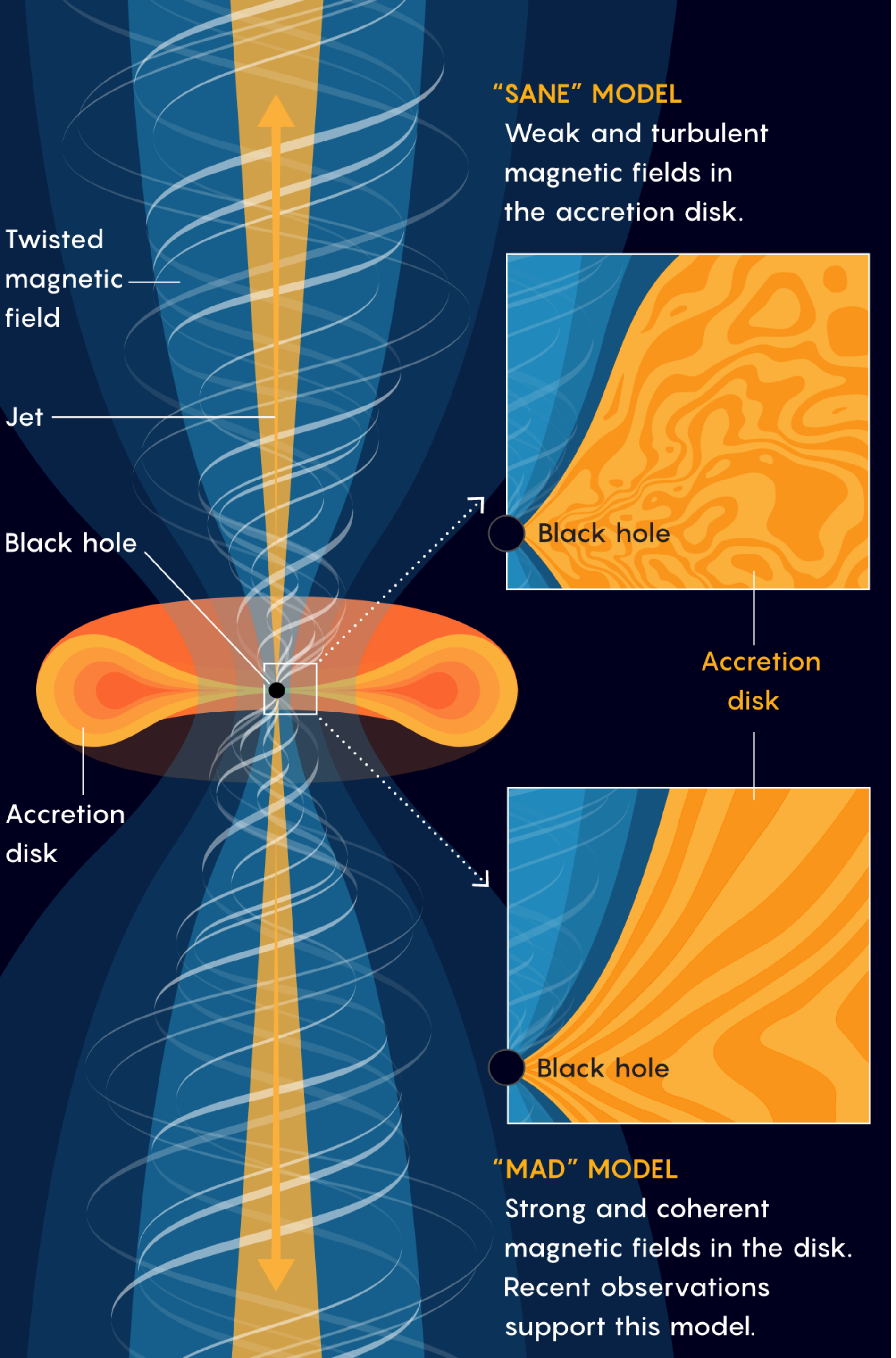
Because the emission originates close to the black hole, it is the **BH angular momentum**, (not the disk angular momentum) that determines the image orientation



BH spin-away -- **clockwise rotation -- models are strongly favored**

EHTC+ 2019, Paper V

What is the magnetic field structure?



Simulations show two accretion states that depend on the accumulated magnetic flux on horizon

Magnetic fields are weak and turbulent

"SANE" – Standard and "Normal" Evolution

Strong, coherent magnetic fields build up on the horizon

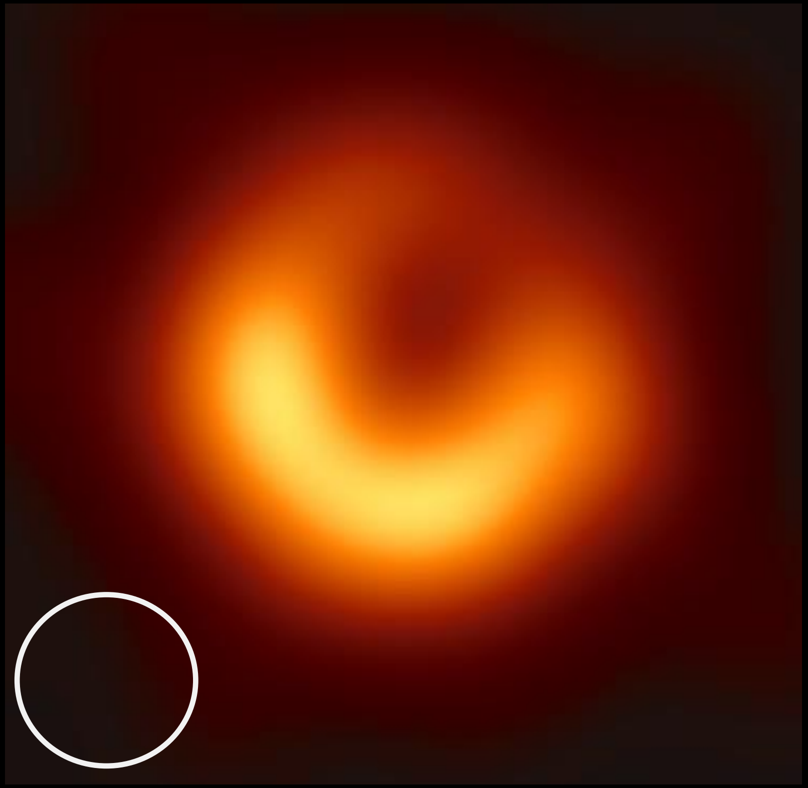
"MAD" - Magnetically Arrested Disk

Note: 'strong' fields mean **dynamically important ones**
→ ~10-50 G at the horizon for M87*

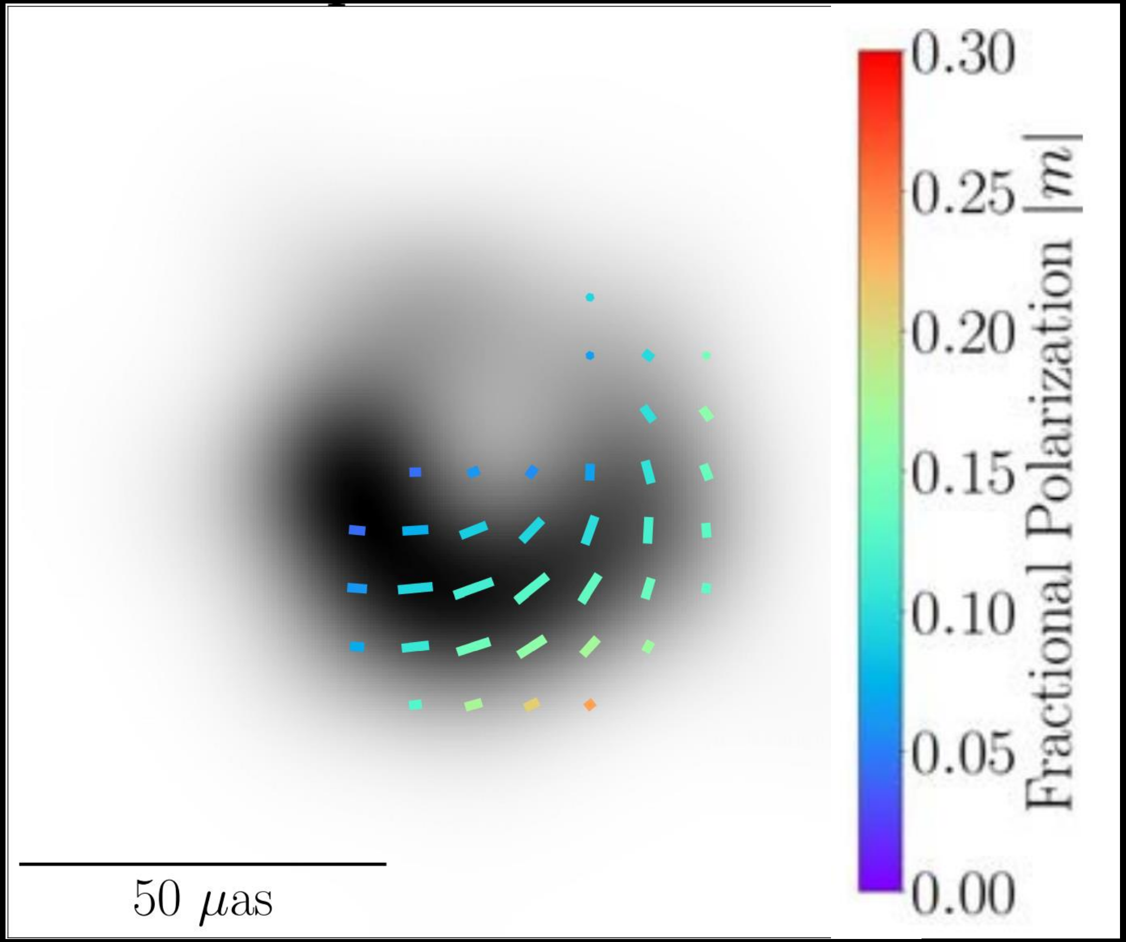
Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012
Image credit: O'Riordan+ 2017, Quanta Magazine

M87* in Linear Polarization

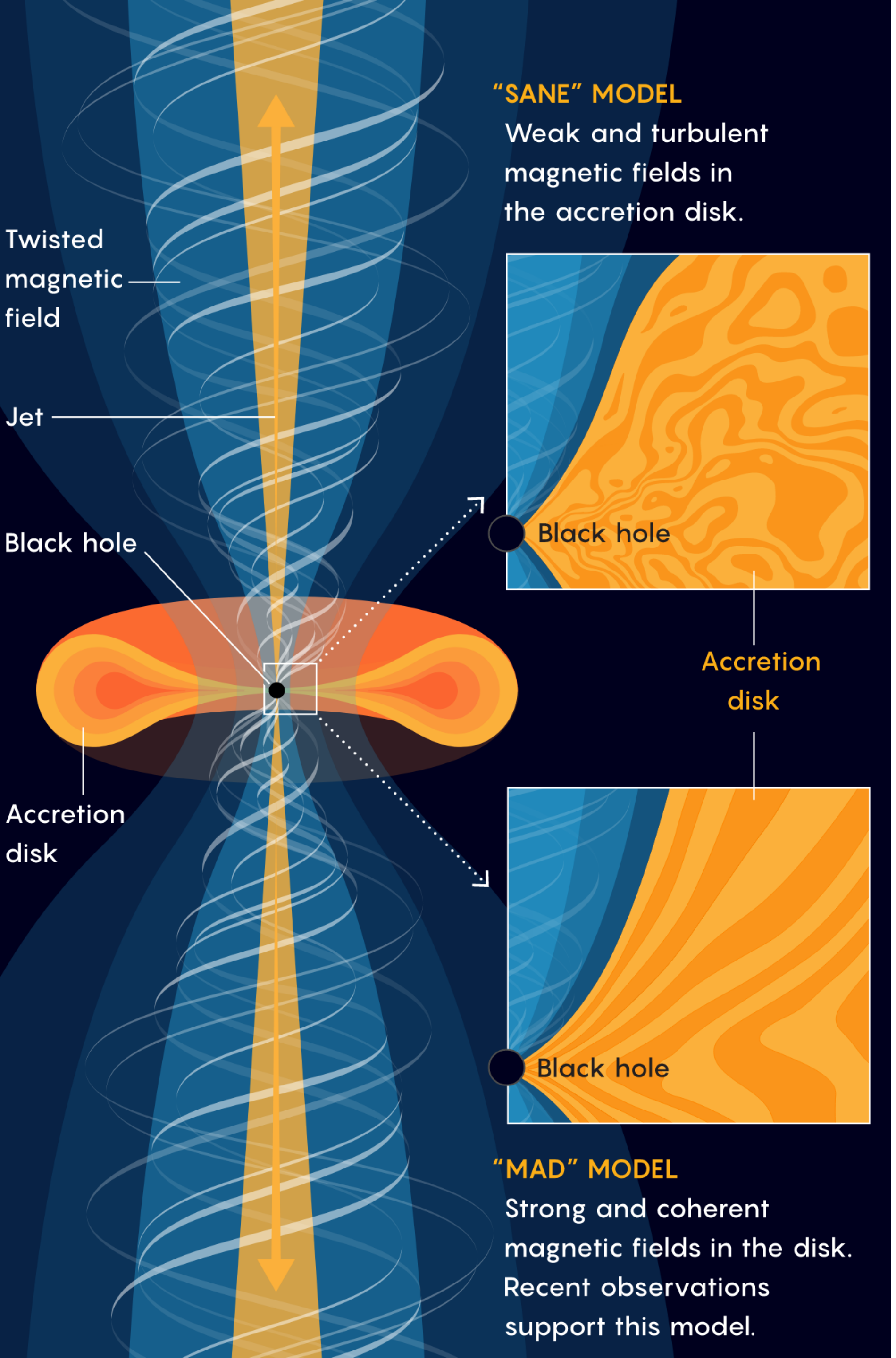
Total intensity



Linear Polarization



EHTC 2021, Papers VII, VIII



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MAD Strongly favored by polarization results!

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012,EHTC+2021 Paper VIII

Image credit: O'Riordan+ 2017, Quanta Magazine

What happens when we look at GRMHD simulation images at high dynamic range?

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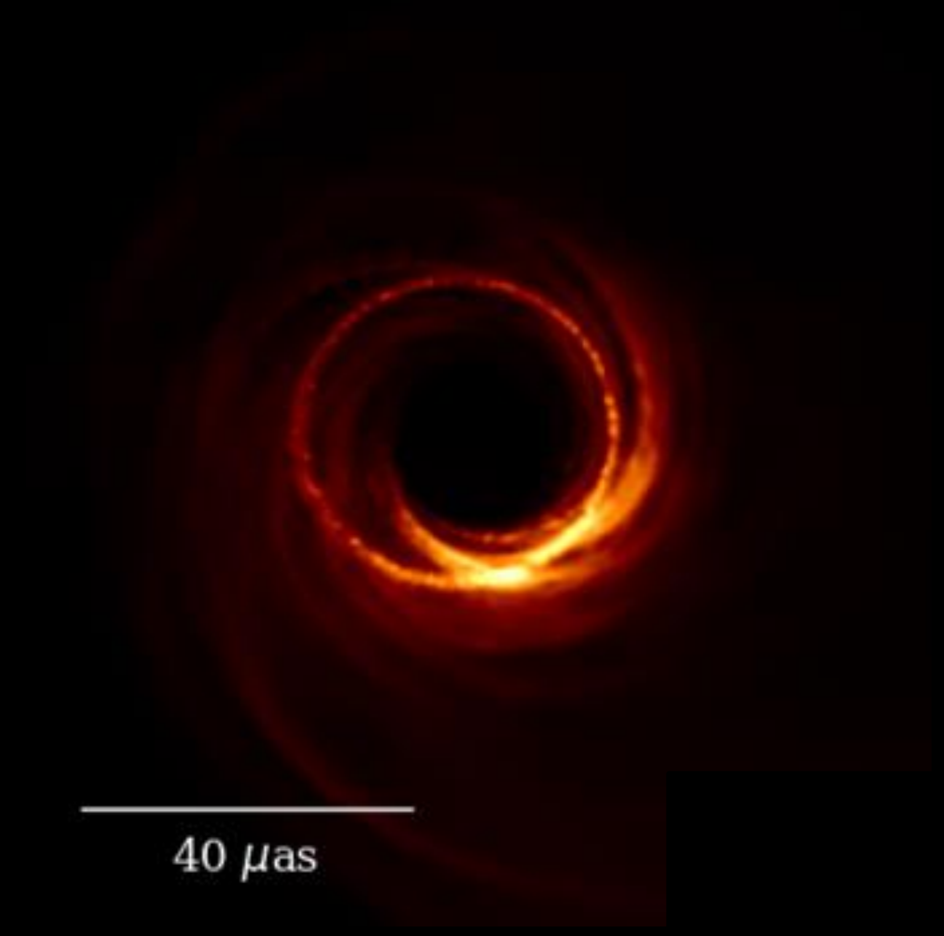
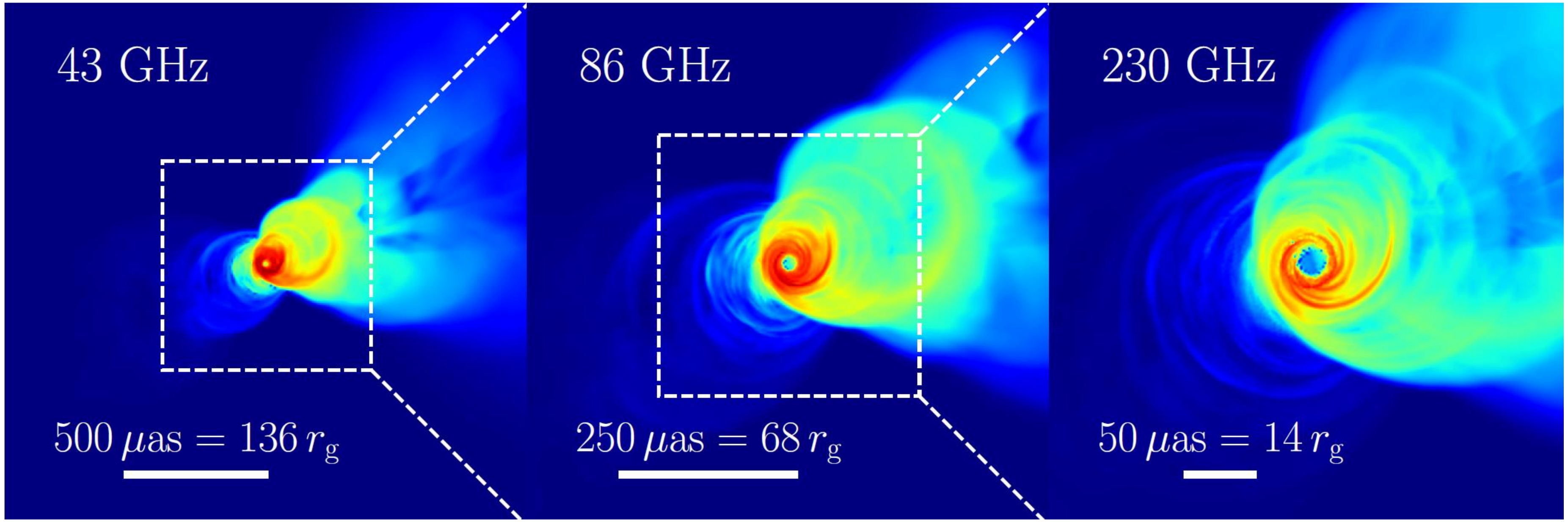


Simulations in this talk are of **magnetically arrested disks (MADs)**

From Chael+ 2019 using KORAL code (Sadowski+ 2013,16)

What happens when we look at GRMHD simulation images at high dynamic range?



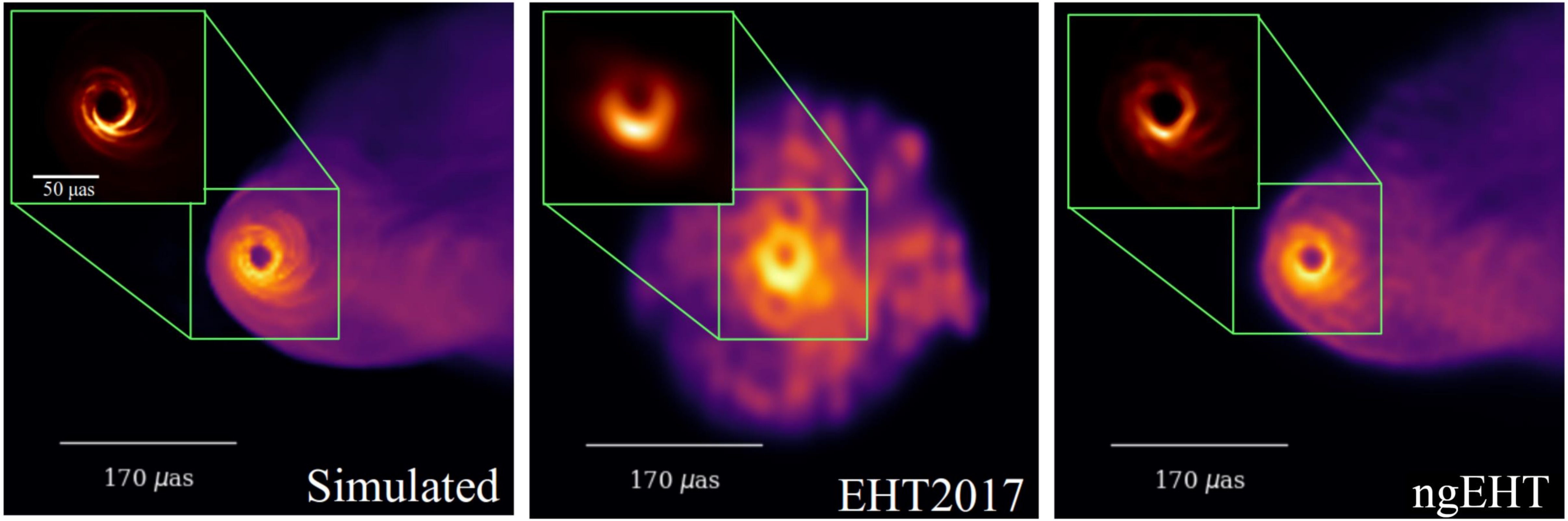
- If the simulation is run long enough and with the right prescription for electron heating, we see a visible jet like in M87
- Future EHT observations should be able to see this dim extended jet emission around the black hole image

Simulations in this talk are of **magnetically arrested disks (MADs)**

From Chael+ 2019 using KORAL code (Sadowski+ 2013,16)

Image Credit: Chael+ 2019

Aside: ngEHT will illuminate the BH-jet connection



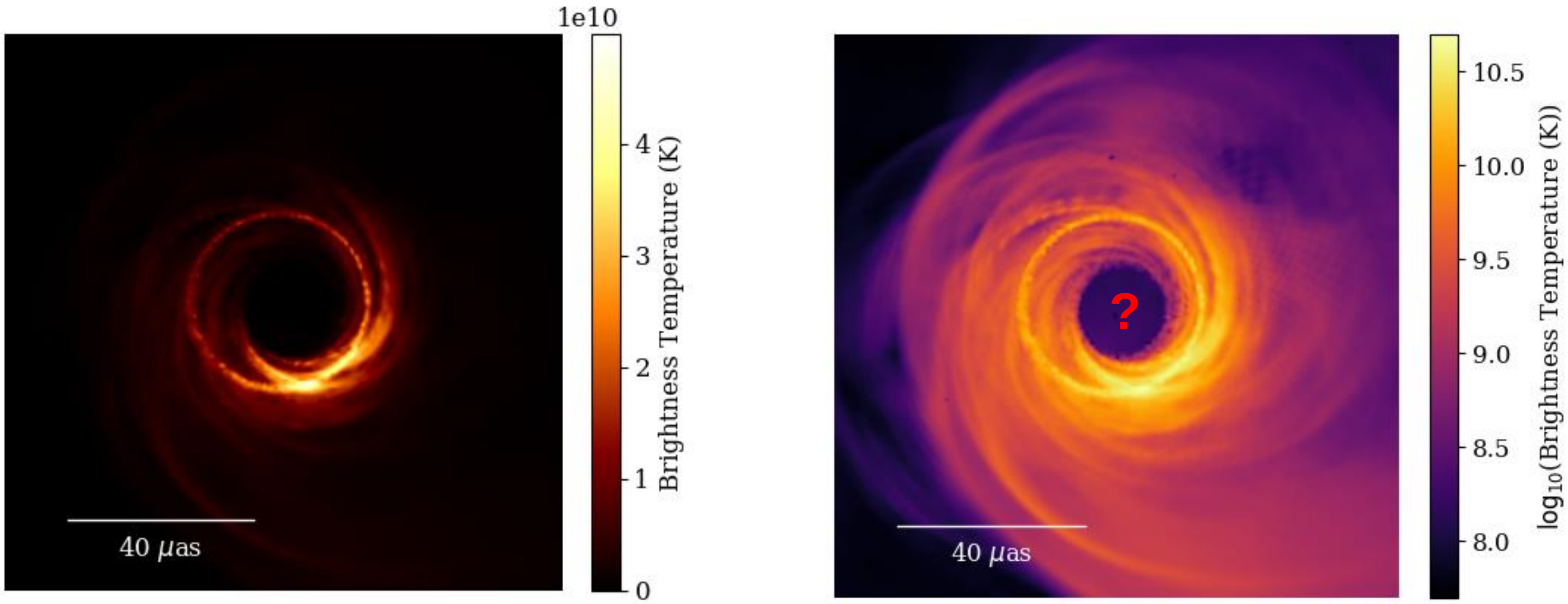
The current EHT lacks many <u>short</u> baselines, which are necessary to detect extended structure.

Increased u,v filling from new sites in ngEHT will enhance **dynamic range**

Going to 345 GHz will increase **resolution**

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

A sharp central brightness depression in high dynamic range images



Is this a consequence raytracing choices? An artifact of polar coordinates?

Sharp central brightness depression in GRMHD images

- This is **the inner shadow**: the lensed (n=0) image of the equatorial event horizon.

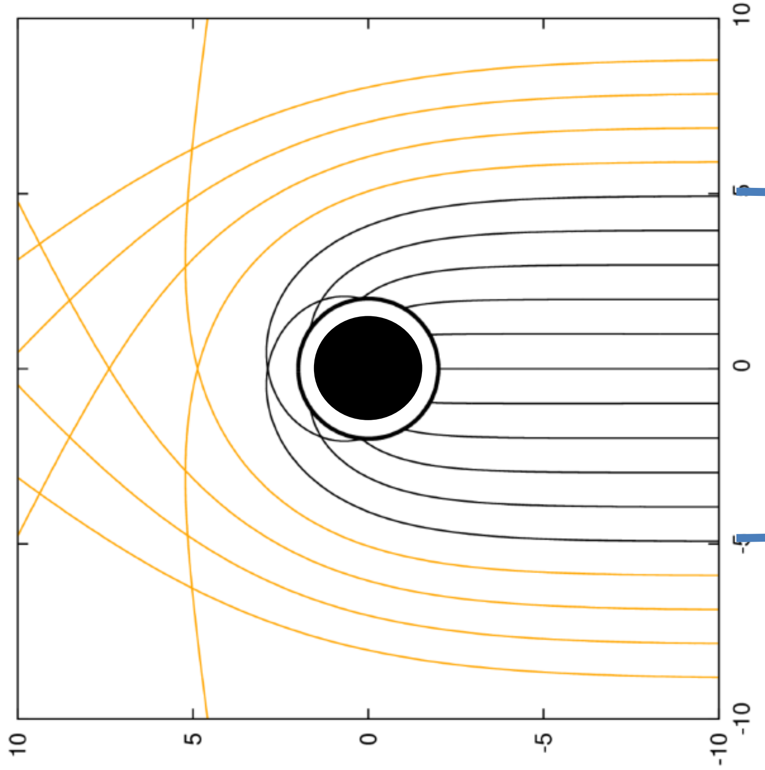
- While not ‘universal’ like the photon ring, **many GRMHD simulations have the conditions necessary to make this feature observable**

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

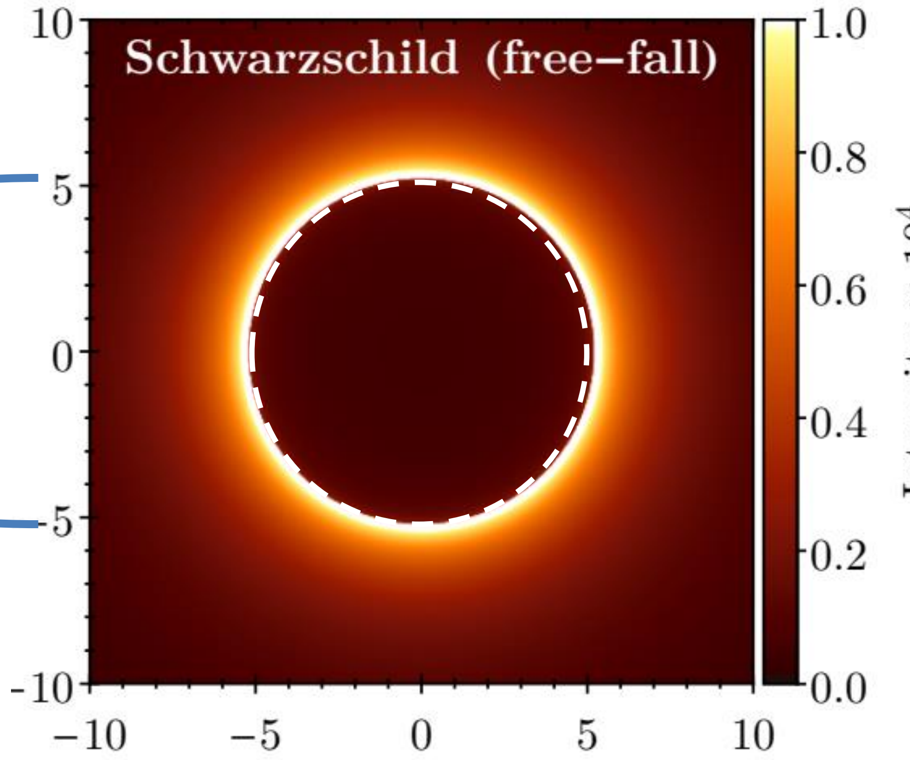
- The **ngEHT will have the dynamic range and resolution necessary** to observe this feature

What is the “inner shadow” and why is it visible in these simulation images?

The Critical Curve or "Black Hole Shadow"



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



- 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', where all rays end on the horizon
- The shadow is particularly prominent as an image feature when the emission is optically thin and **spherically symmetric**

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

Lensed images of the **equatorial plane**

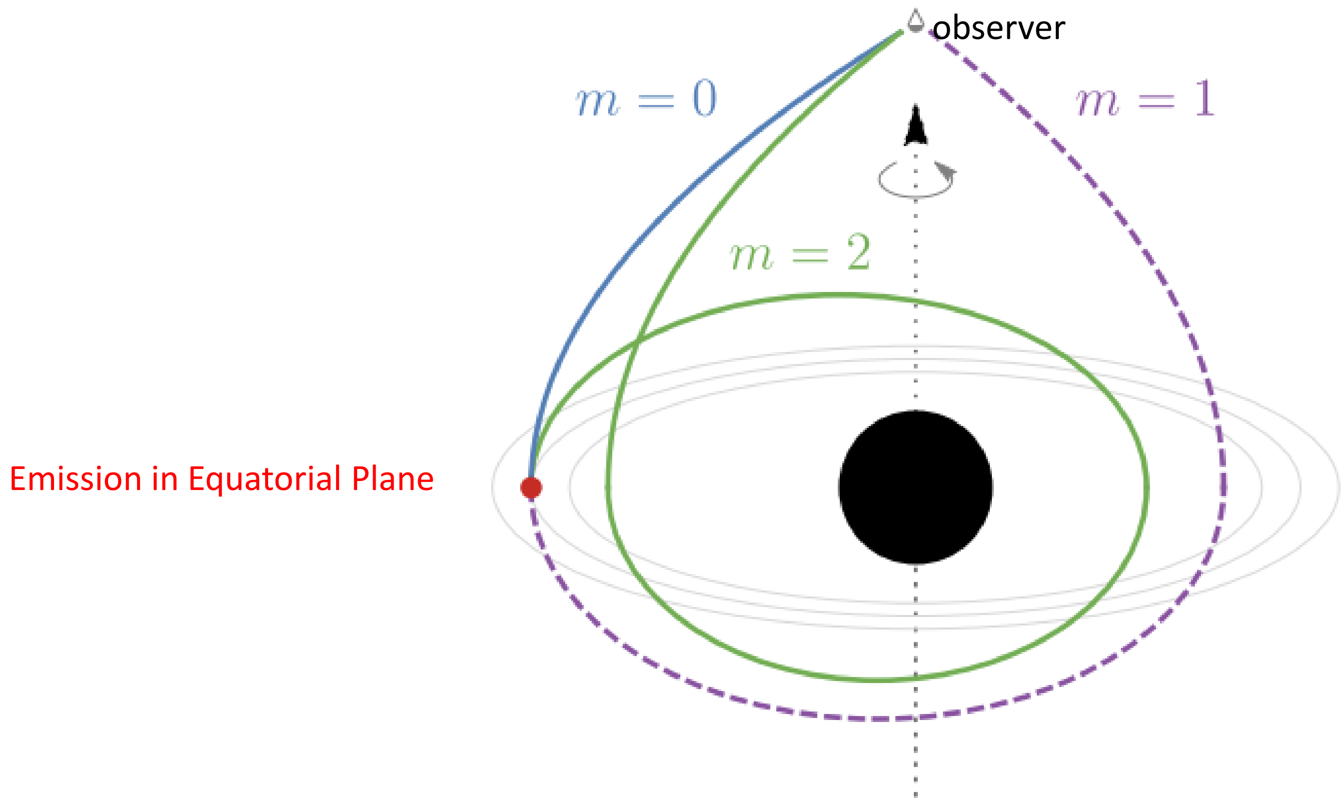
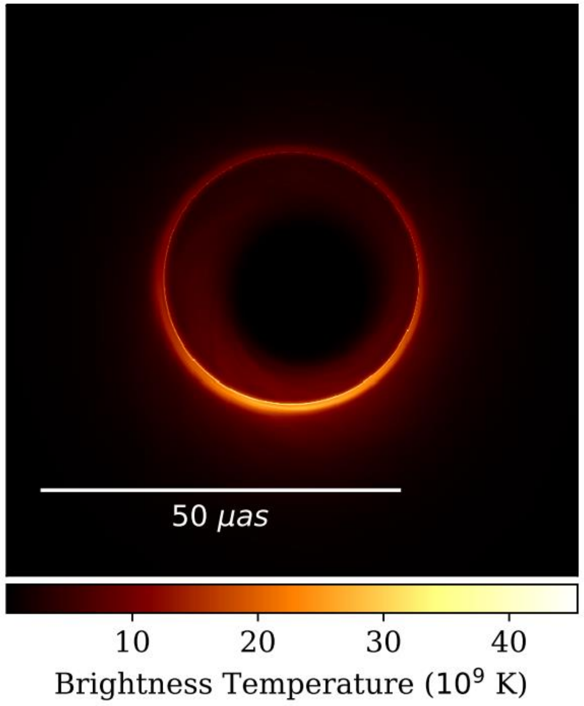


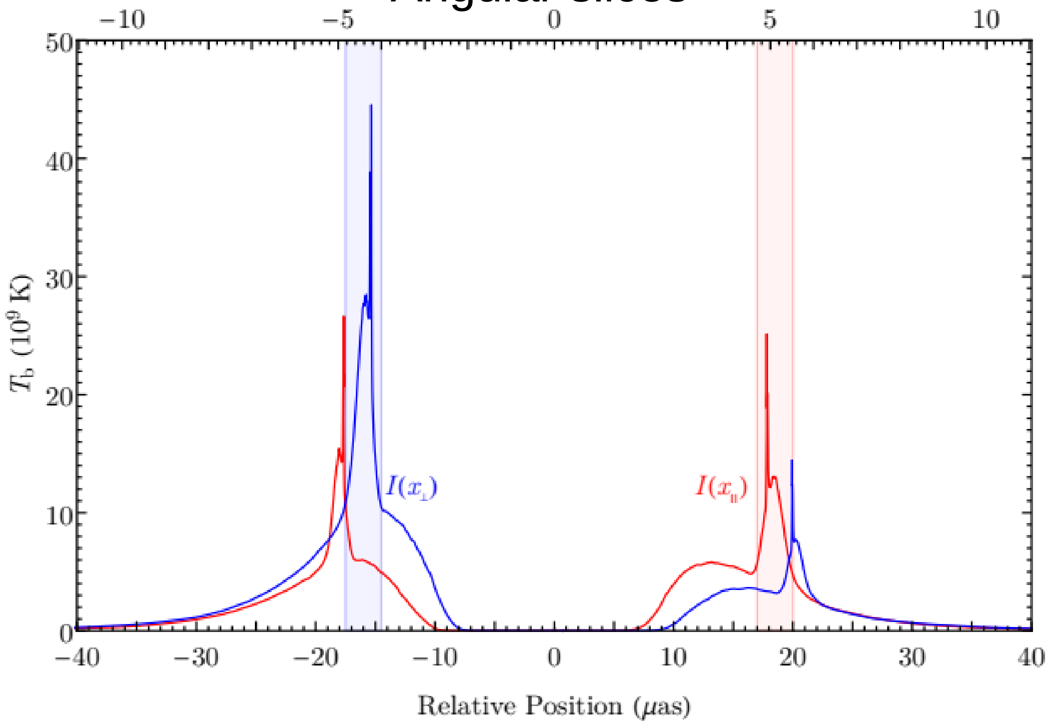
Image credit: Gralla & Lupsasca 2019

Photon Rings

Time-averaged GRMHD



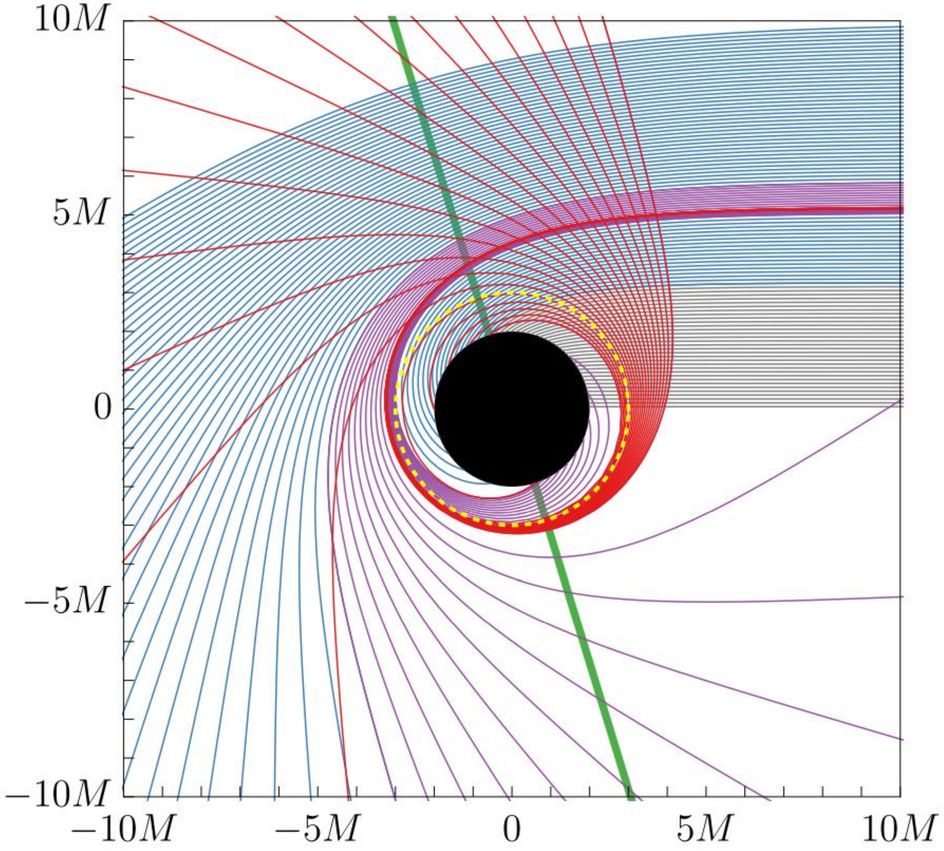
Angular slices

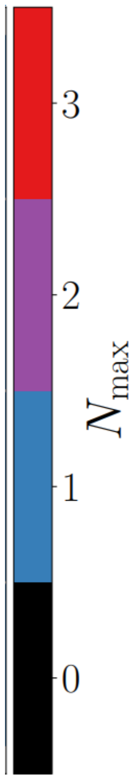


- As geodesics wrap around the black hole multiple times, they form a **series of images** lensed into **increasingly narrow rings**
- These subrings approach the critical curve exponentially.
- Resolving the subrings requires a **spatially limited emission region** (e.g. emission confined to the equatorial plane)

Image credit: Johnson+ 2019
Simulation Credit: George Wong

Lensed images of the equatorial plane





This feature has been discussed many times in analytic models in e.g.:

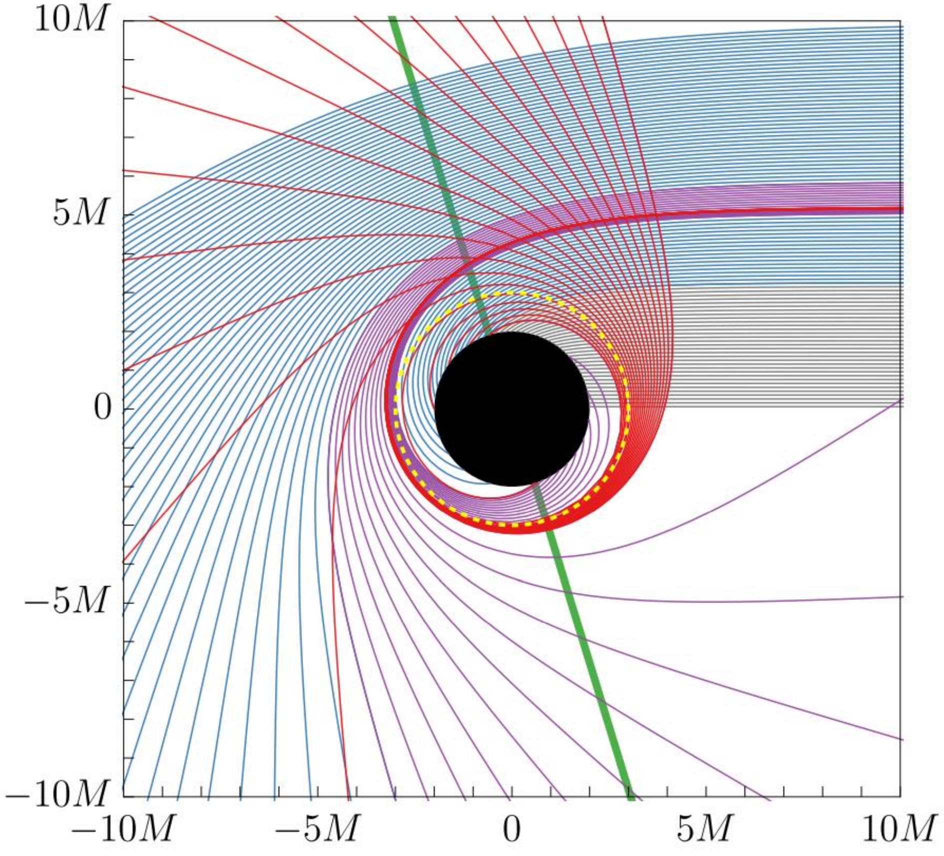
- Luminet 1979, Figure 2
- Takahashi 2004, Figure 1
- Gralla, Holz, Ward 2019, Figure 1
- Dokuchaev 2019

Image credit Chael+ 2021

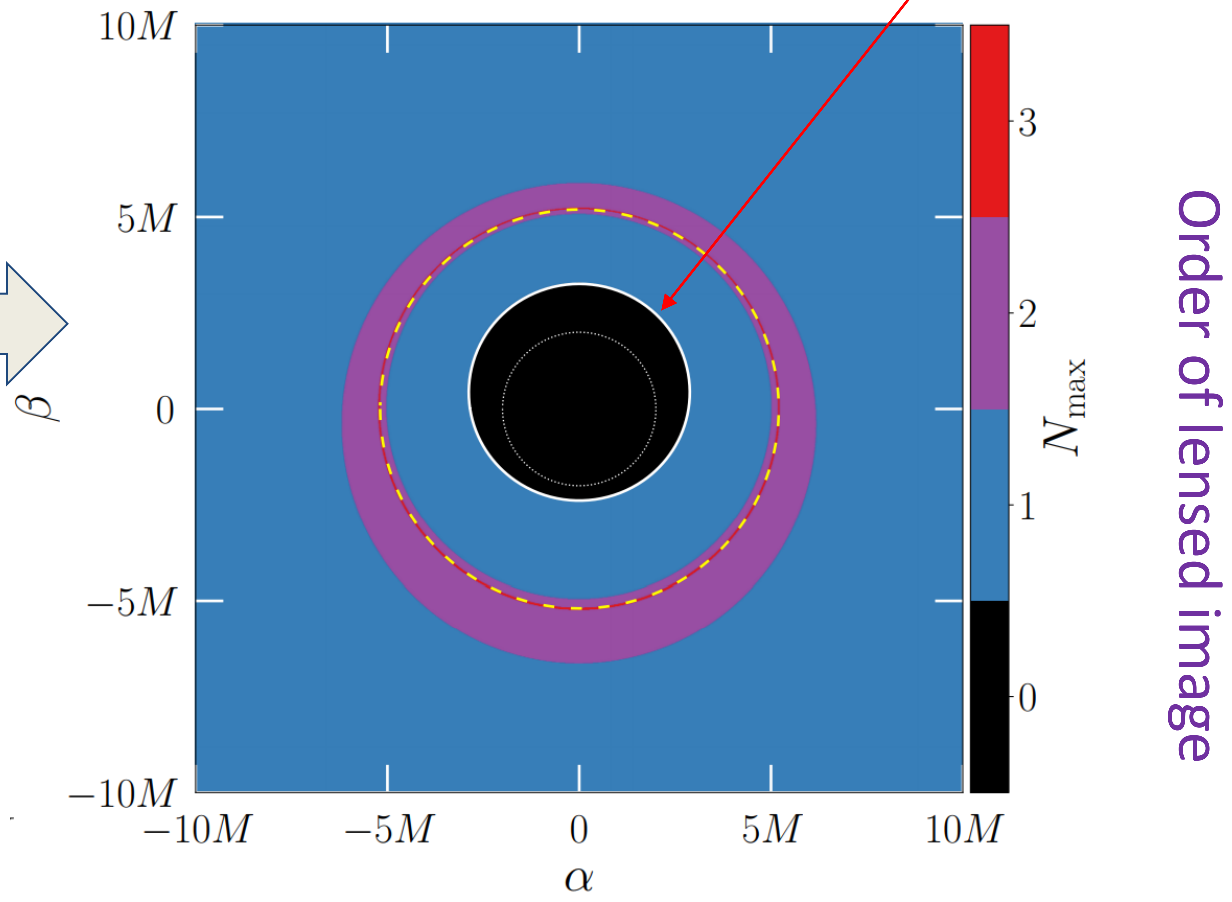
Lensed images of the equatorial plane

Curve: n=0 image of the equatorial event horizon

Interior: Silhouette of the horizon northern hemisphere



Multiply-lensed images of the equatorial plane



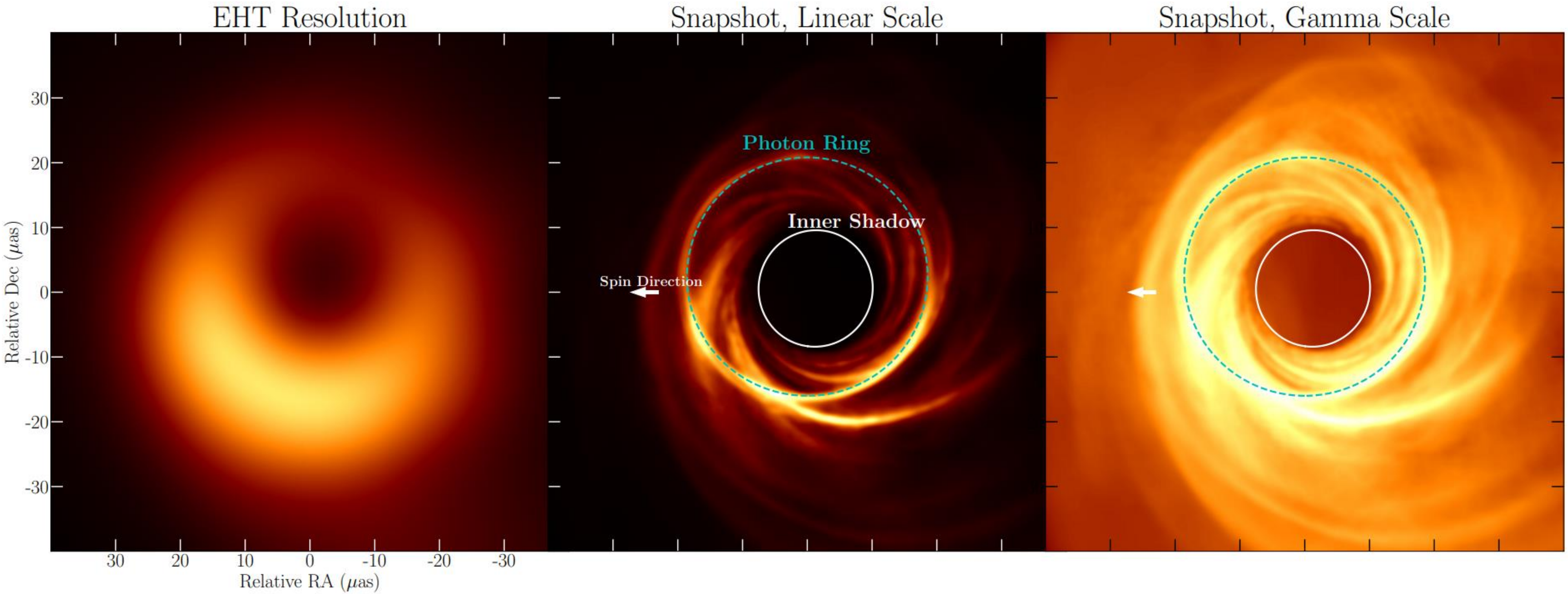
(a=0, i=17 deg)

This feature has been discussed many times in analytic models in e.g.:

- Luminet 1979, Figure 2
- Takahashi 2004, Figure 1
- Gralla, Holz, Ward 2019, Figure 1
- Dokuchaev 2019

Image credit Chael+ 2021

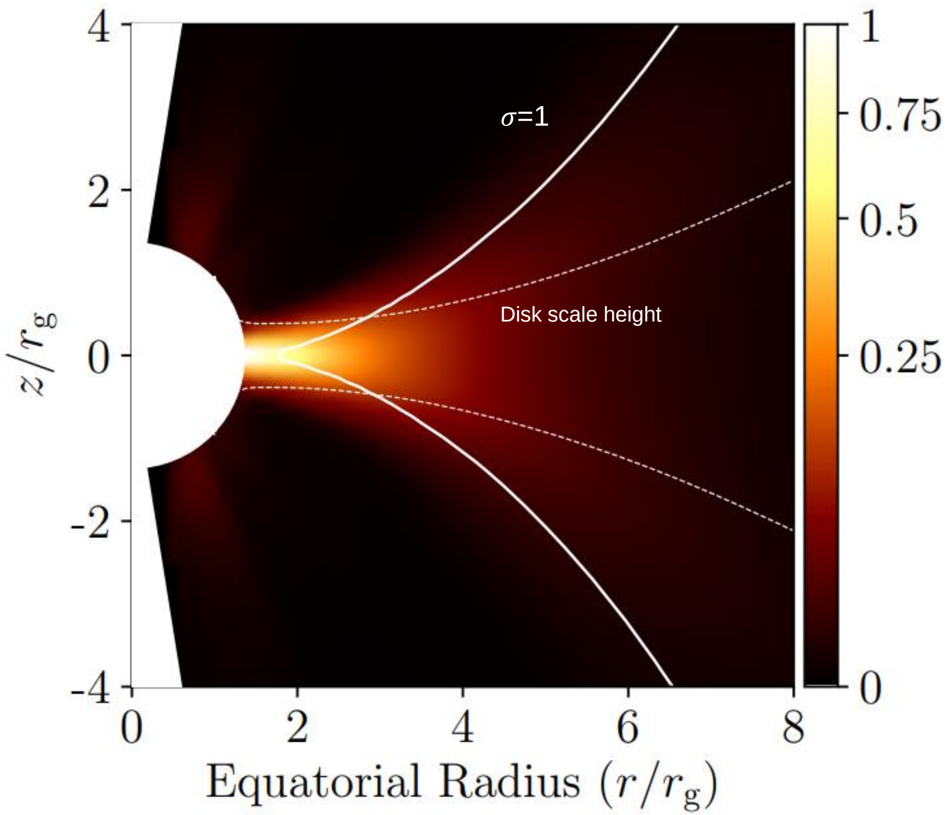
Inner shadow in GRMHD images

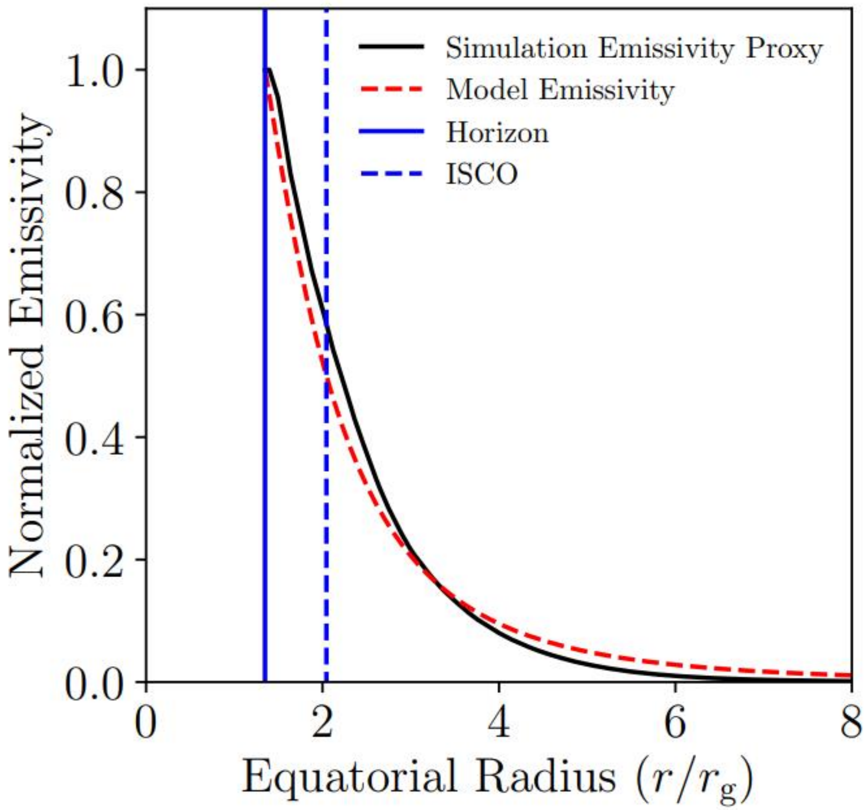


- This high dynamic range feature is the **outline of the equatorial event horizon**
- While not 'universal' like the shadow/photon ring, it may be visible with the ngEHT

Why is the horizon visible in these simulations?

Emissivity proxy (same as in Porth+ 2019)

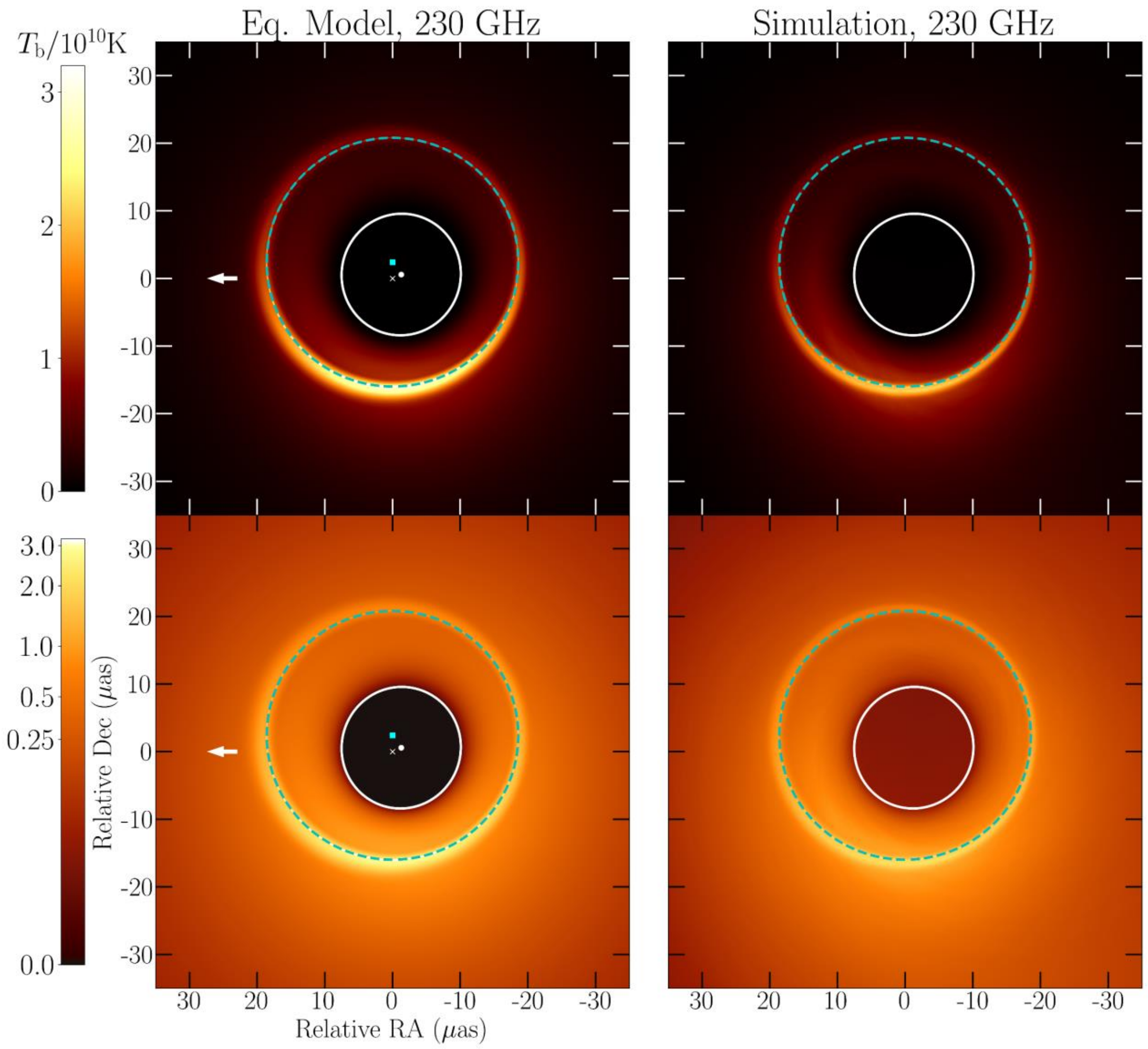




Equatorial slice

- The 230 GHz emissivity is predominantly **equatorial** in this simulation
- It does not truncate at the ISCO, but **extends to the horizon**
- Fluid velocities are **subkeplerian** – reducing the overall redshift

Time-averaged simulation images at high dynamic range

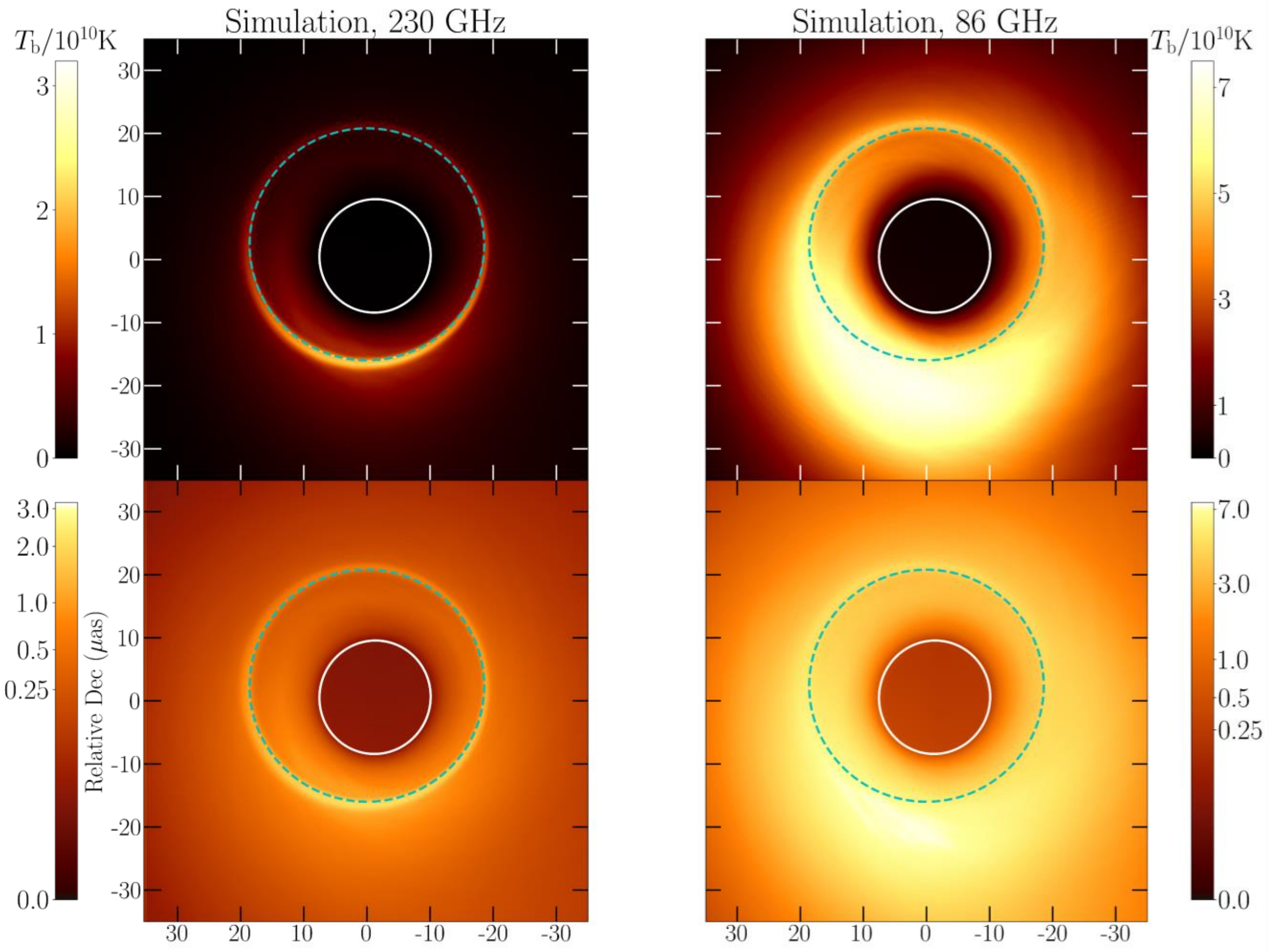


- The averaged simulation image shares the **primary features of an image from a purely equatorial disk model** (Gralla,Lupsasca,Marrone+ 2020)
- **Forward jet emission** in the simulation gives the horizon image a finite "floor"

230 vs 86 GHz Simulation images

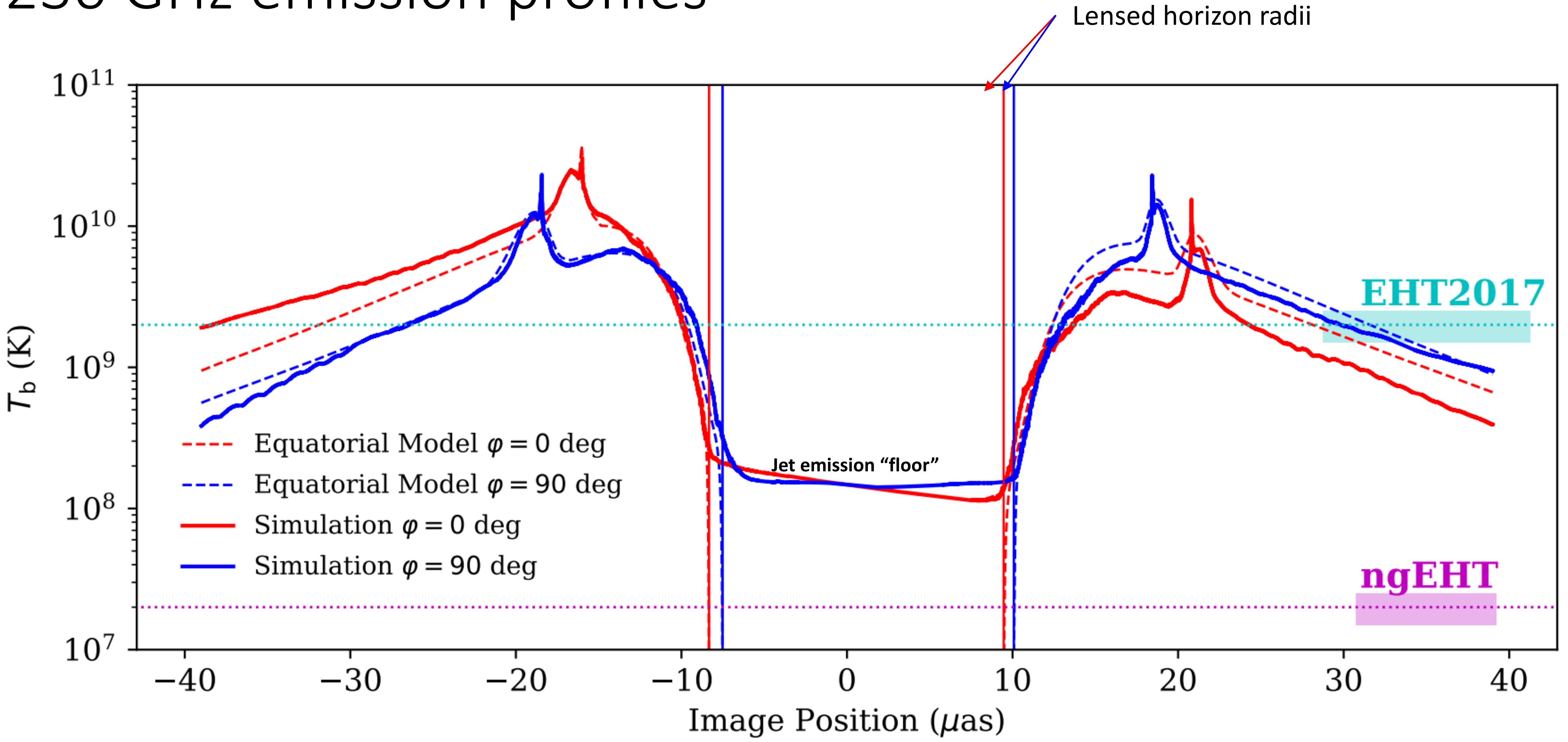
Linear scale

Gamma scale



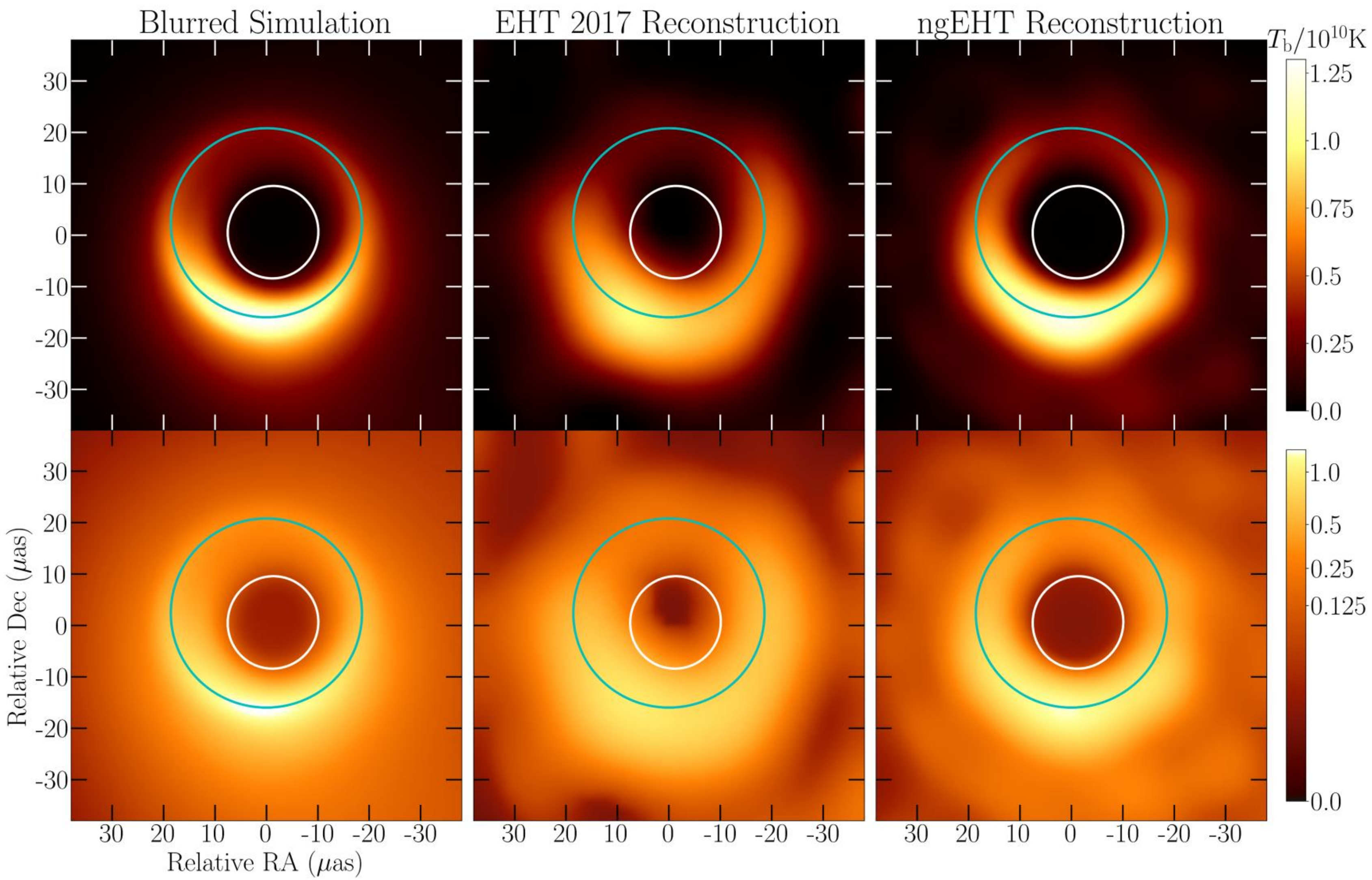
- The *n*=1 photon ring is supressed by optical depth at 86 GHz, but the *n*=0 lensed horizon image is not
- Optical depth doesn't matter if the emission is primarily equatorial and not obscured by the forward jet

230 GHz emission profiles



The ngEHT should have the dynamic range to observe the inner shadow feature, if present

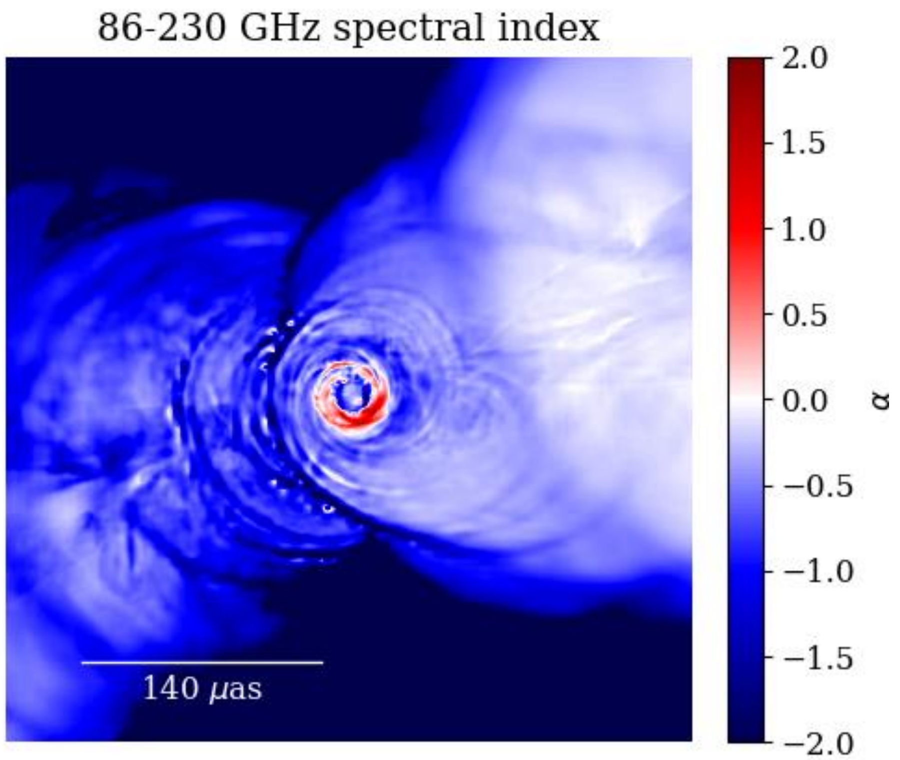
EHT 2017 and ngEHT image reconstructions



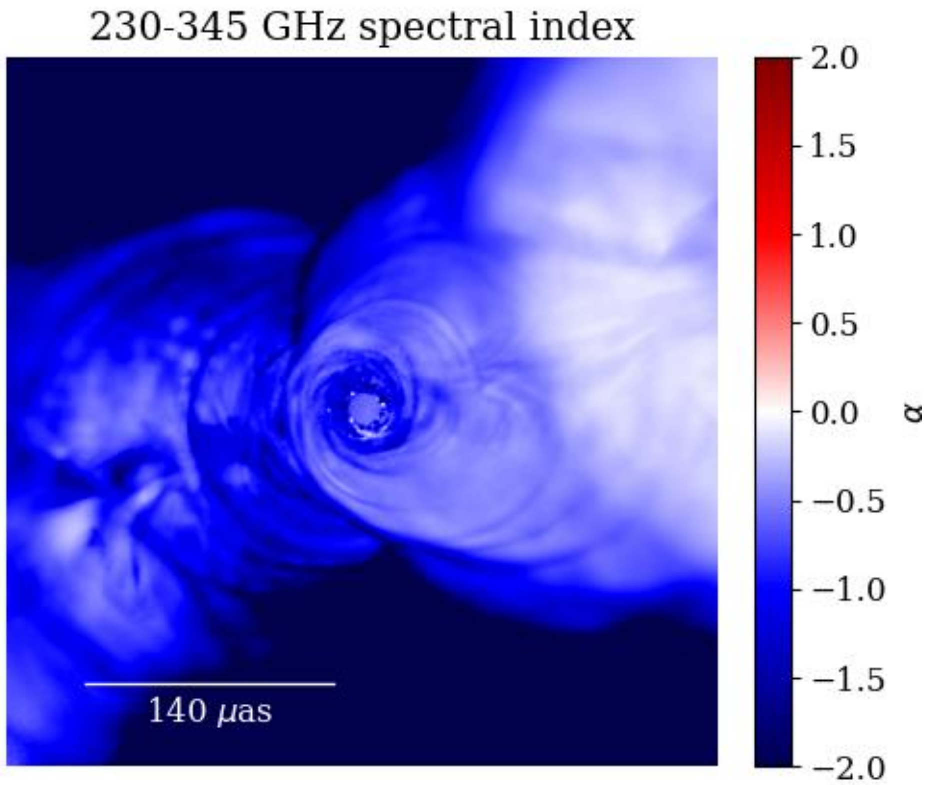
- ‘Realistic’ EHT imaging scripts using closure phases and amplitudes, but on the time-averaged image
- **Imaging algorithms can detect the inner shadow in ngEHT data** – analytic modeling may constrain its shape more precisely

Spectral Index Maps

$$I_\nu \propto \nu^\alpha$$



Between 86 and 230 GHz, near-horizon emission in the midplane goes from optically thin to thick – lensed horizon is always optically thin



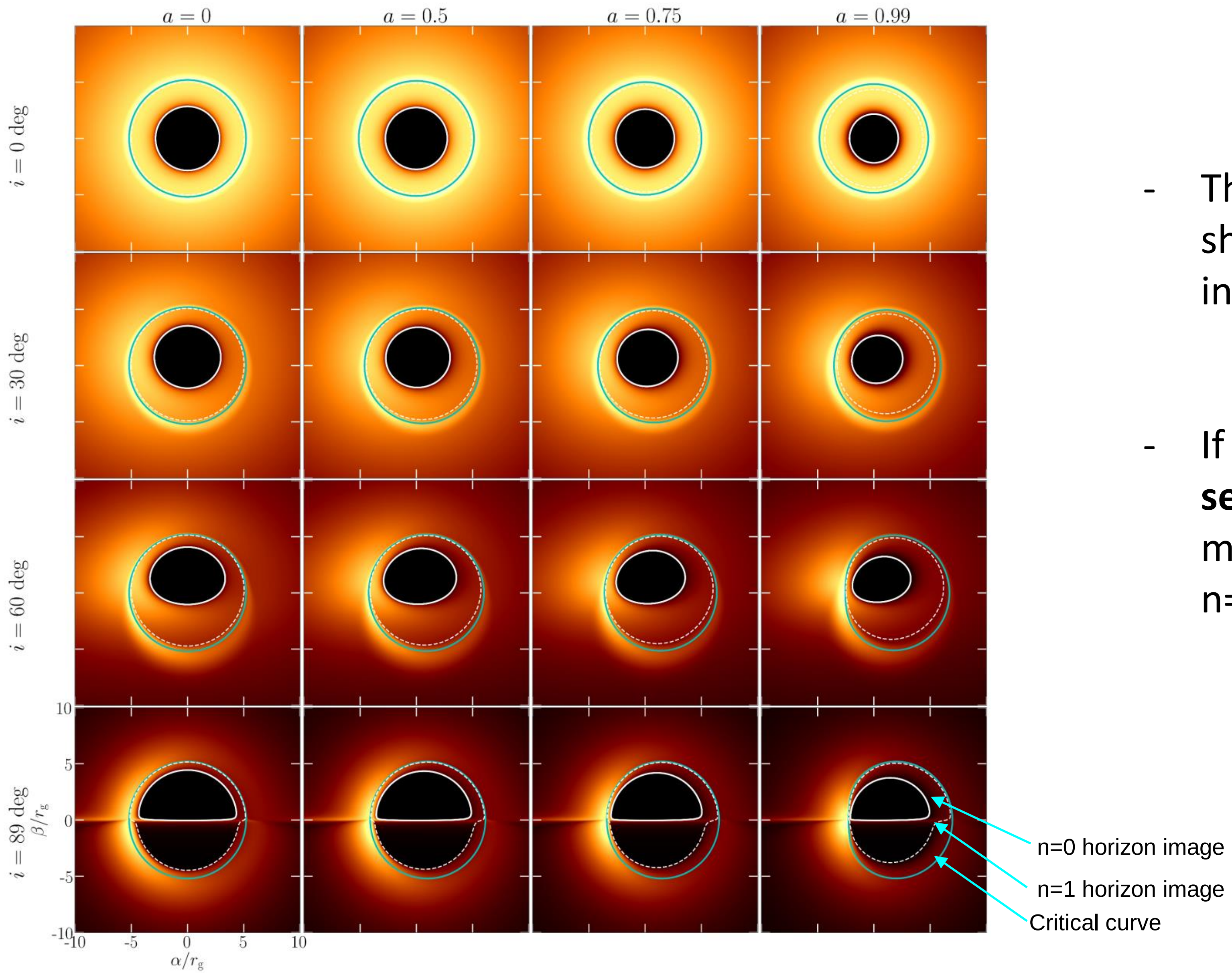
Between 230 and 345 GHz, all emission is optically thin with ~constant spectral index

Multifrequency ngEHT imaging can better constrain the position of the lensed horizon feature

Chael+ in prep.

What could we learn by observing the inner shadow?

Inner shadow images provide another probe of spacetime



- The horizon image changes in shape and size with spin and inclination

- If observable, it would provide a **second set of constraints** on the metric from observations of the n=1 photon ring

Properties of the lensed horizon image

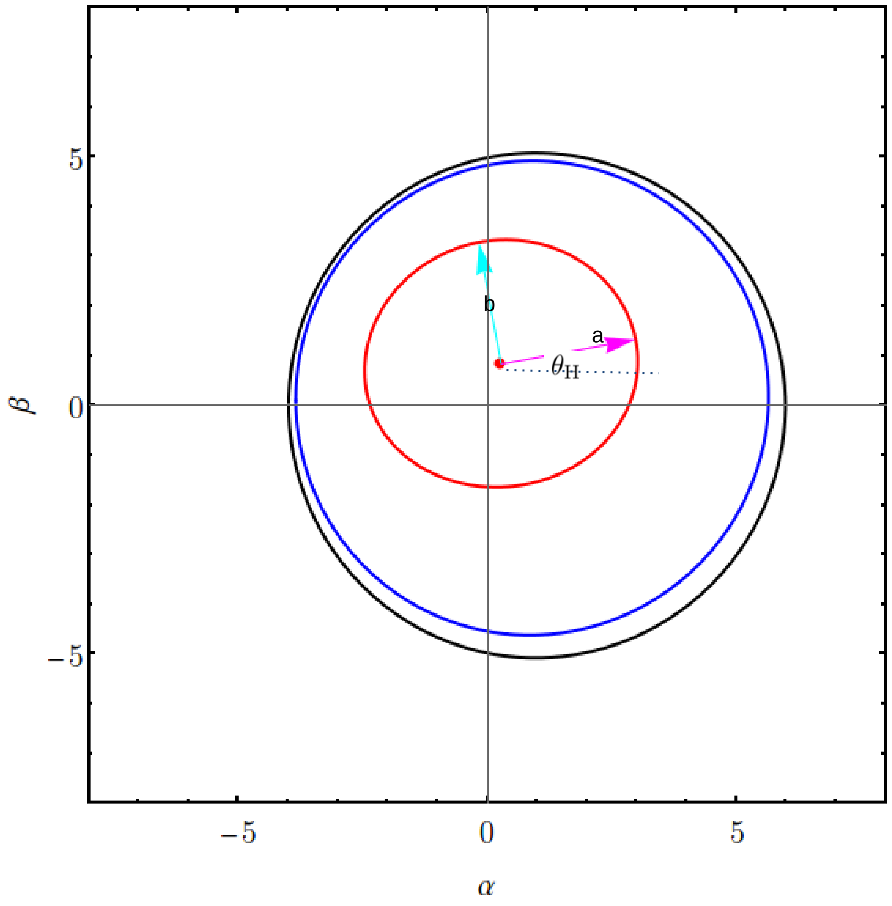
We characterize the lensed horizon shape with image moments:

- 0th moment: Area
- 1st moment: Centroid
- 2nd moment: Principal axes & orientation

From the 2nd moment we get the mean radius ($\bar{r}_{\rm H}$) , orientation angle ($\theta_{\rm H}$), and eccentricity ($e_{\rm H}$)

$a = 0.77, i = 37°$

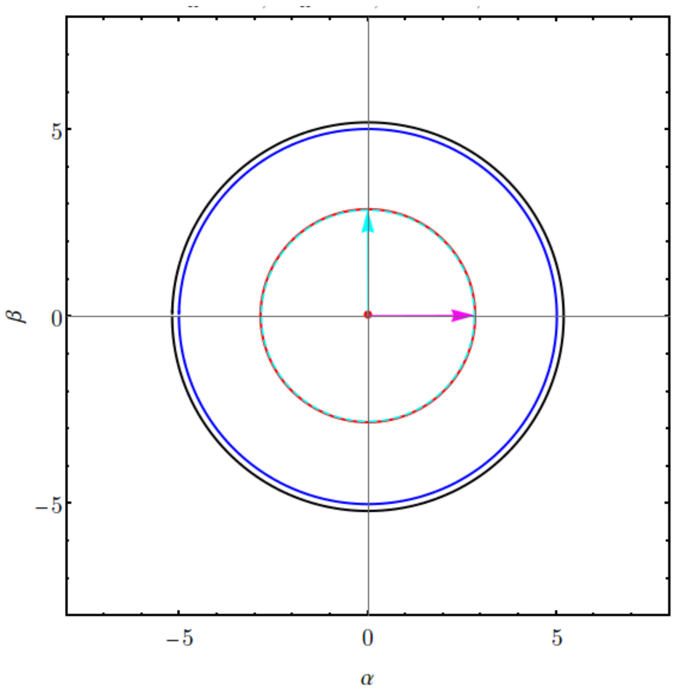
A_H=21.4, $\overline{r_H}$=2.62, θ=10.40°, e=0.43



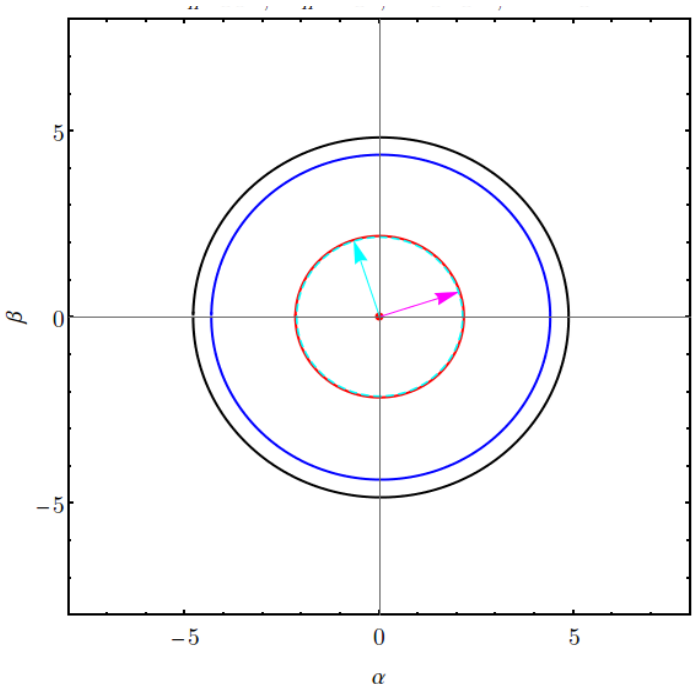
$$\bar{r}_{\rm H} = \sqrt{\frac{a^2 + b^2}{2}} \qquad e_{\rm H} = \sqrt{1 - \frac{b^2}{a^2}}$$

Inner shadow size and shape

At face on inclination: $\rho(a) \approx 2\sqrt{r_+(a)}$

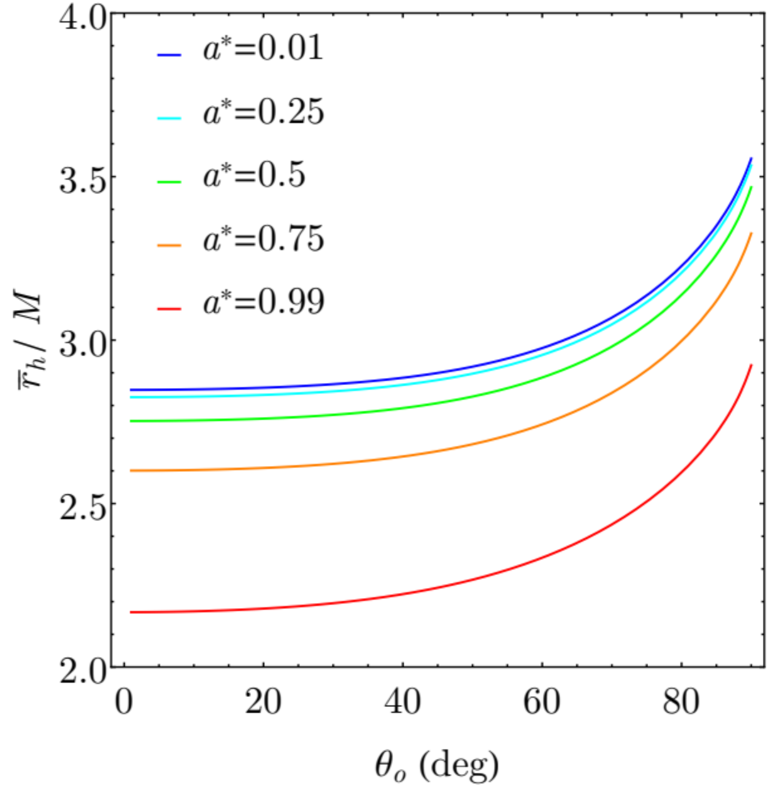


$a = 0, \rho \approx 2\sqrt{2}$

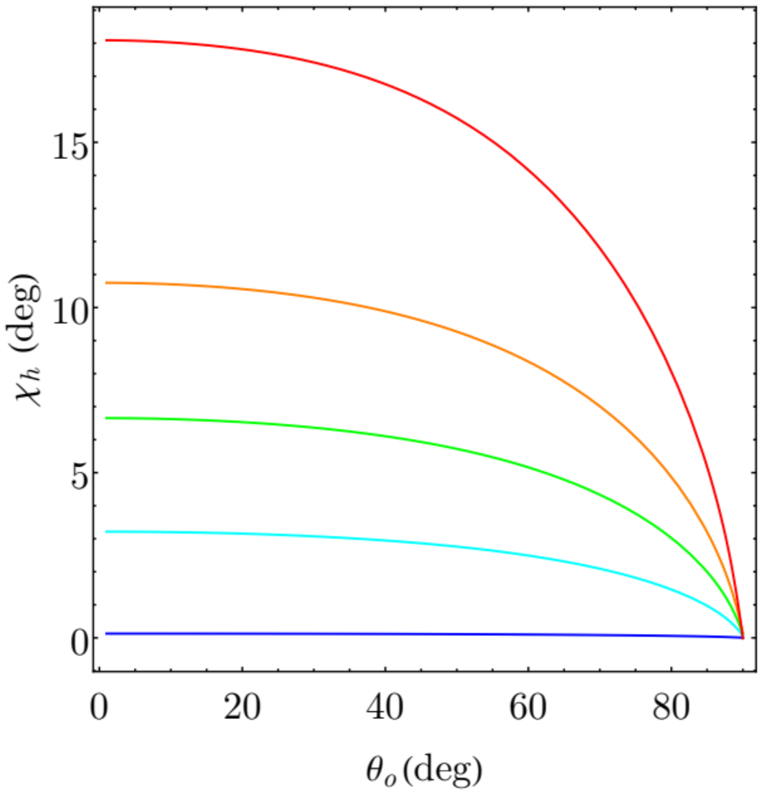


$a = 0.99, \rho \approx 2$

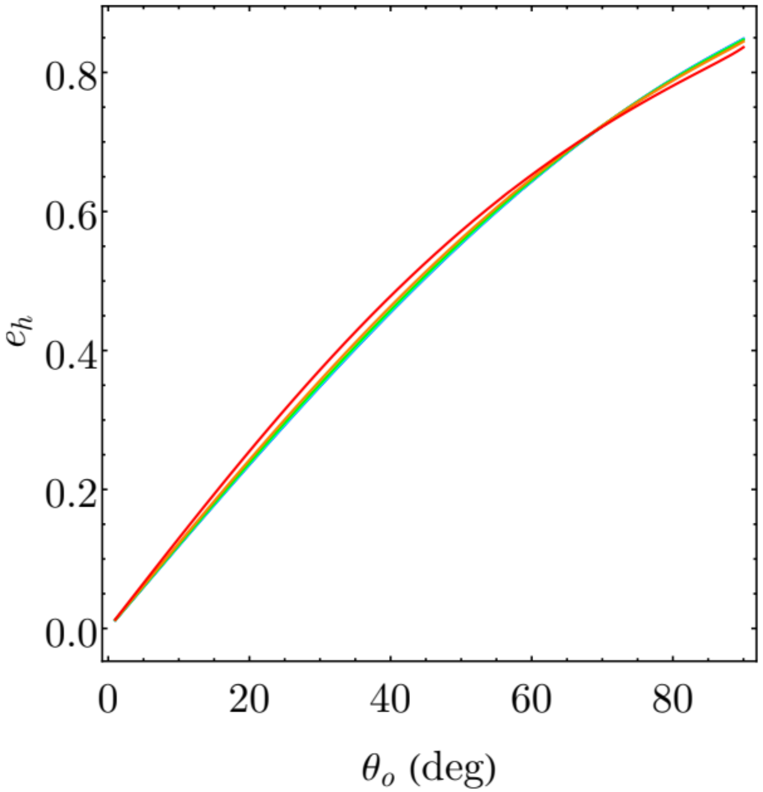
Properties of the lensed horizon image



Radius depends mostly on spin at low inclination



Orientation depends only on spin at low inclinations



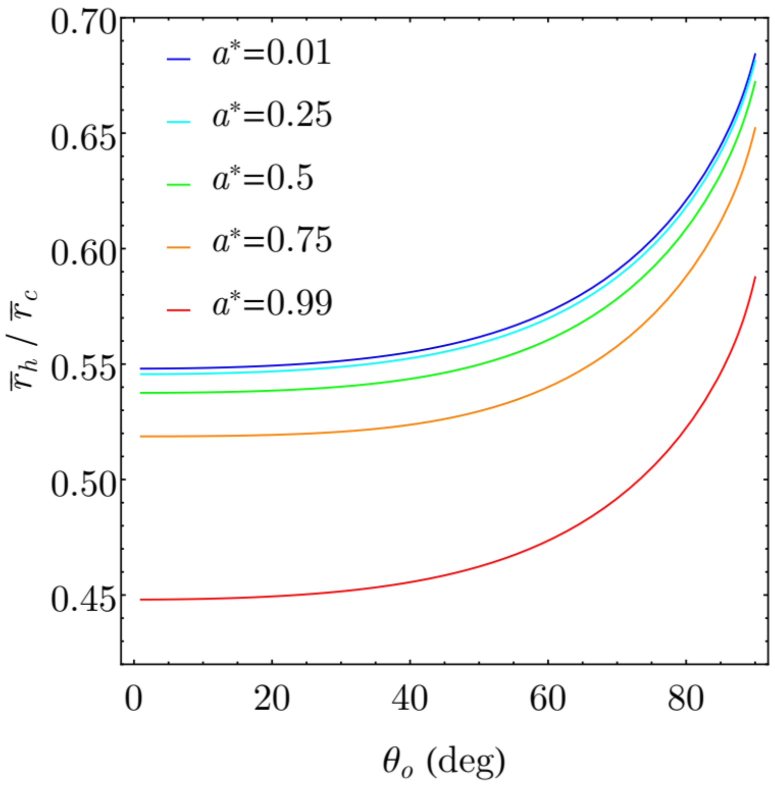
Eccentricity depends ~only on the inclination at all spins

The face-on inner shadow size changes by **~40% from spin 0 to spin 1**, while the shadow/photon ring size changes by only 4% (Johannsen+Psaltis 2010)

Relative centroid and relative radius

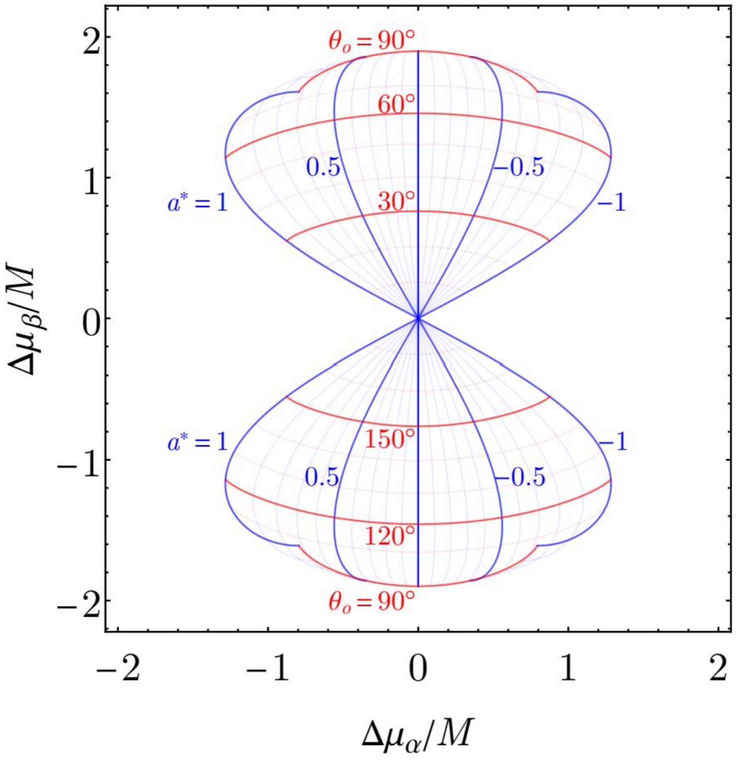
With **two** curves in the image (horizon and photon ring/shadow),
we can measure **relative** offsets and sizes and remove the effect of uncertain mass

Horizon/Critical Curve radius ratio



At low inclination, horizon-to-shadow size
Is **spin-dependent** and decreases from
55% to 45% from a=0 to a=1

Horizon-Critical Curve centroid offset



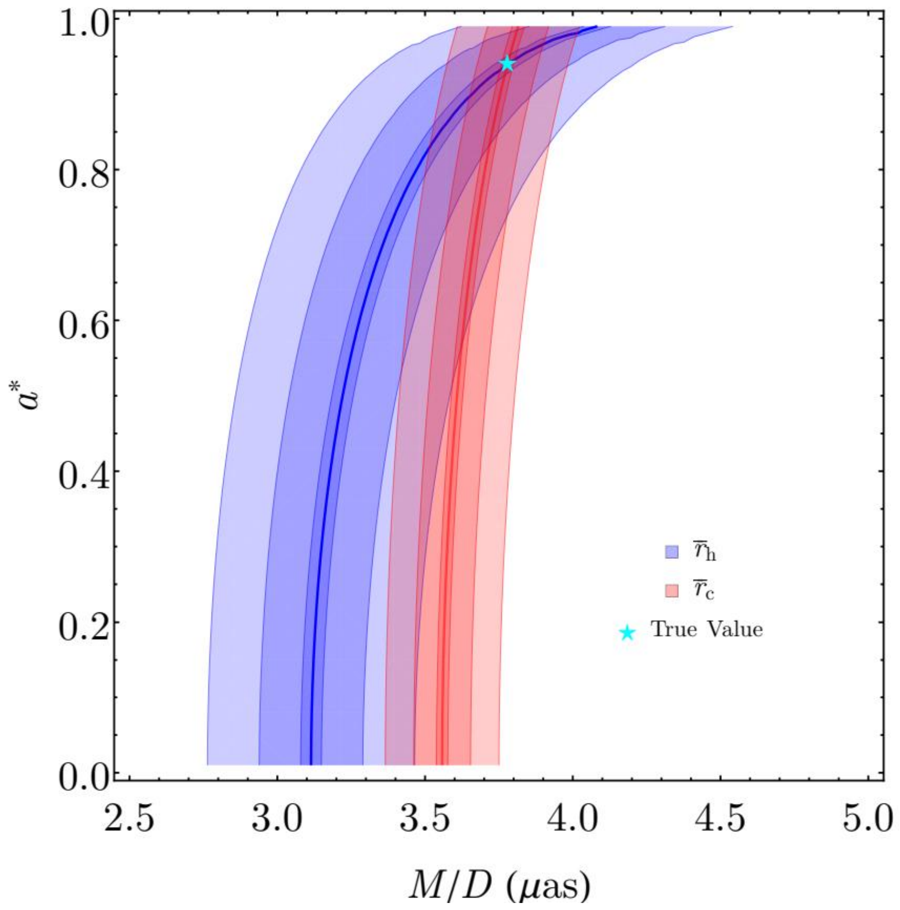
Centroid offset:
angle depends on spin,
magnitude on inclination

$$a \approx -1.64 \arctan\left(\pm_o 0.61 \Delta\alpha/\Delta\beta\right)$$

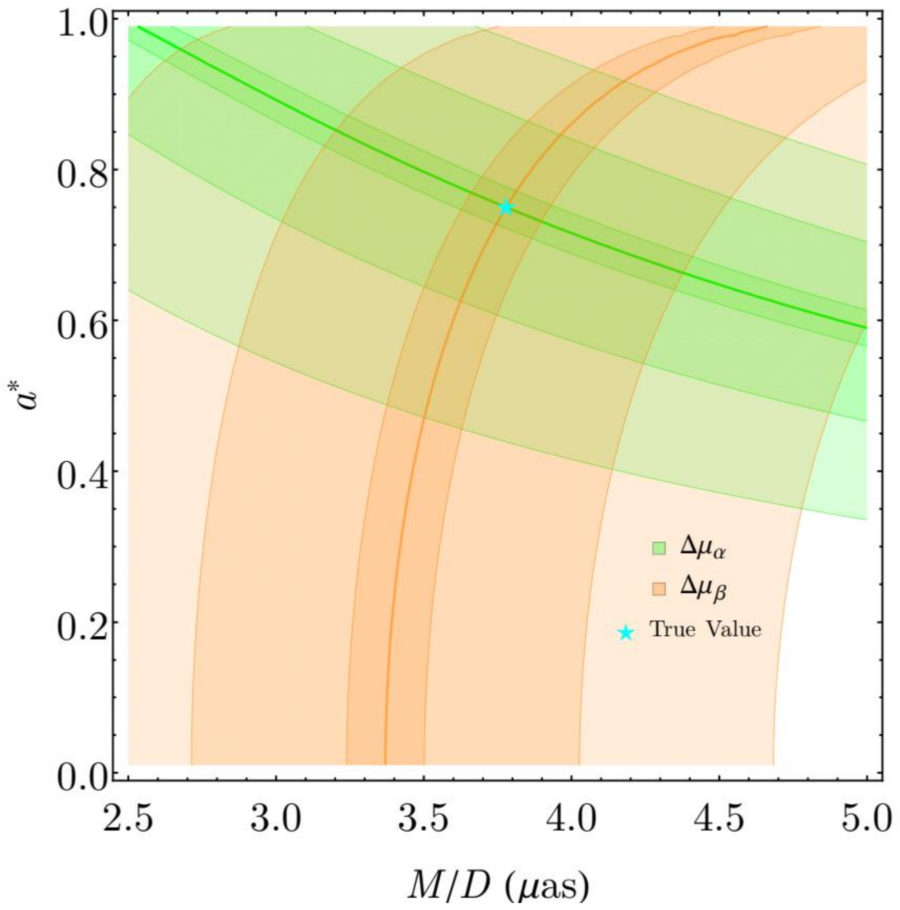
$$\theta_o \approx \pm_{\Delta\beta} 0.42\sqrt{\Delta\alpha^2 + (\Delta\beta/0.61)^2}.$$

Relative centroid and relative radius: toy example

Measurements of both the inner shadow and photon ring at fixed M87* inclination
Error bands for uncertainties of 0.1, 0.5, 1 uas



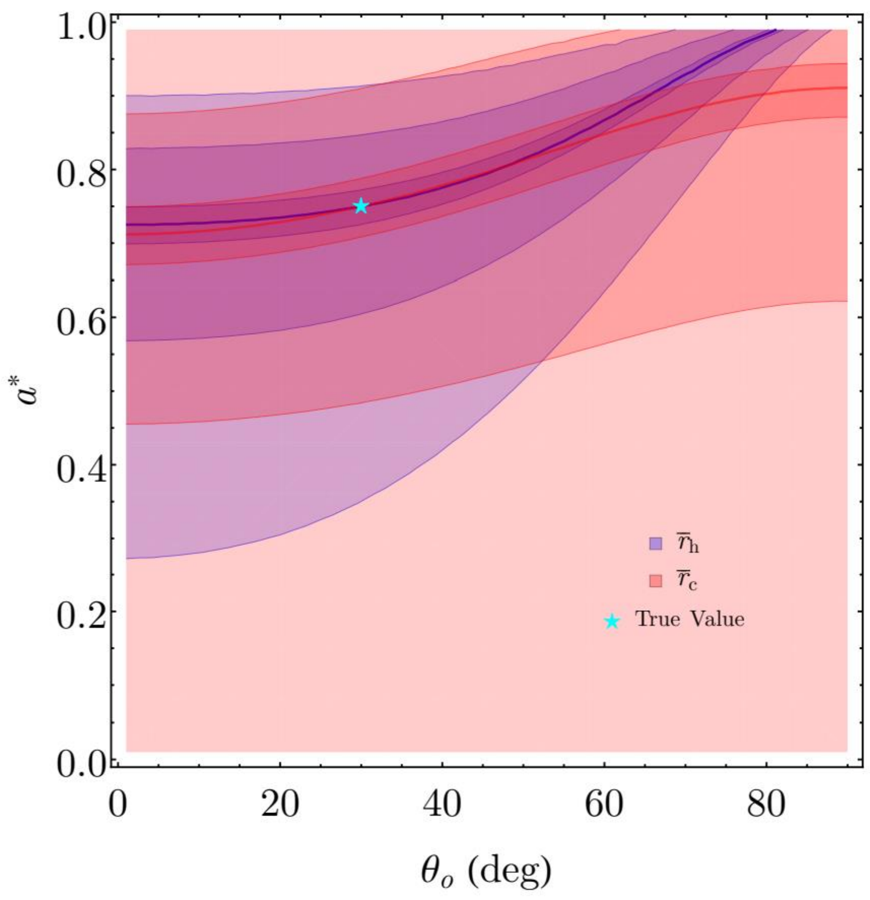
Inner shadow & photon ring sizes



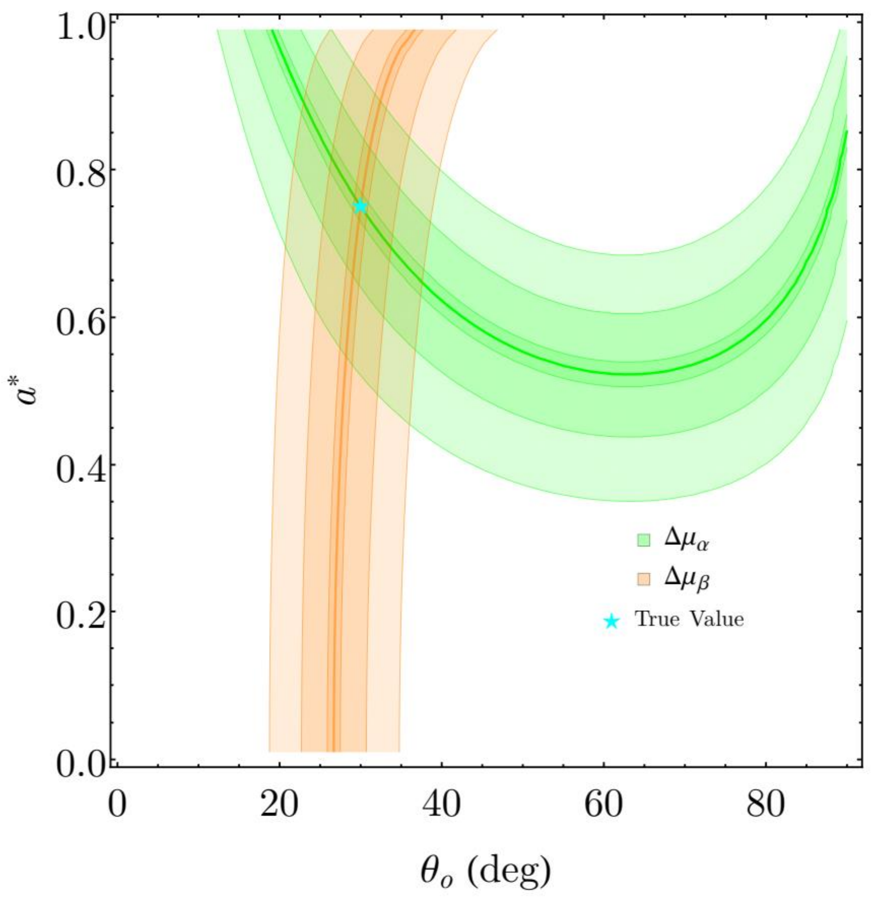
Centroid offset

Relative centroid and relative radius: toy example 2

Measurements of both the inner shadow and photon ring at fixed Sgr A* mass
Error bands for uncertainties of 0.1, 0.5, 1 uas

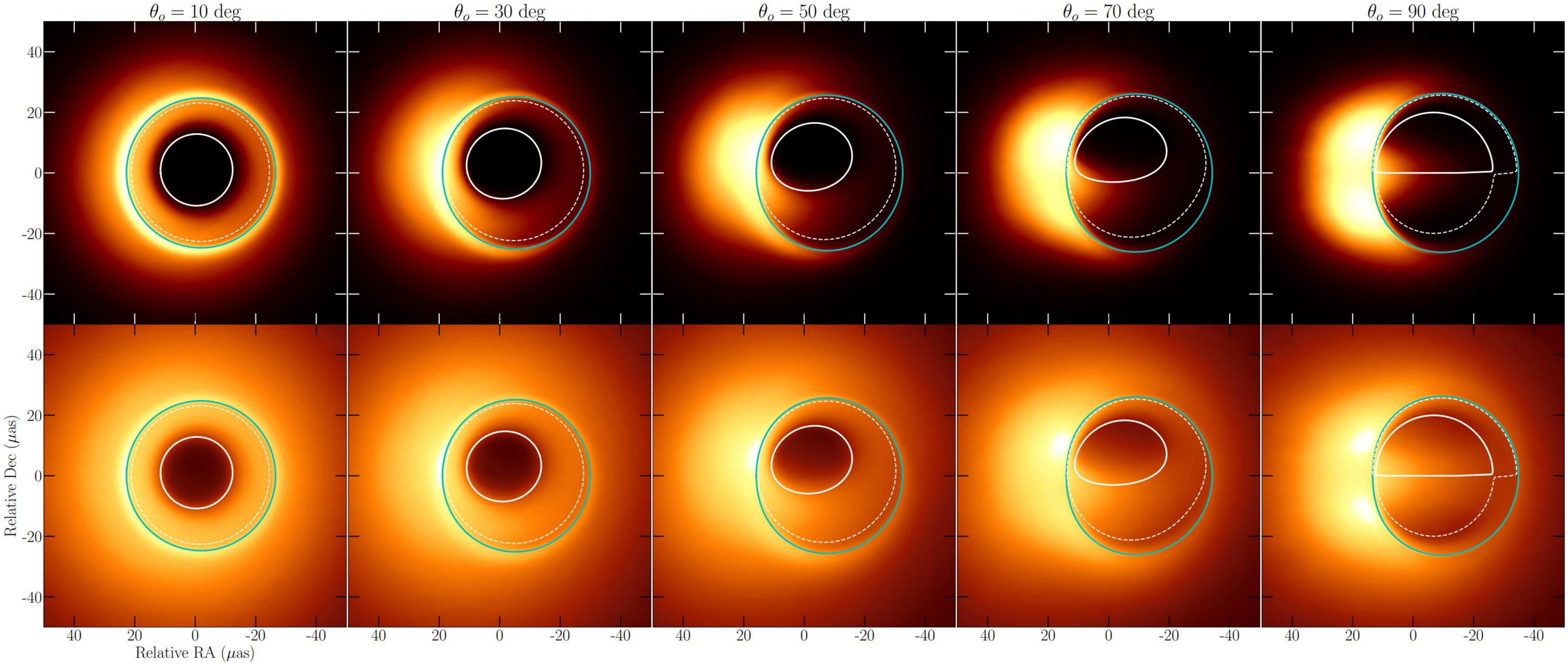


Inner shadow & photon ring sizes



Centroid offset

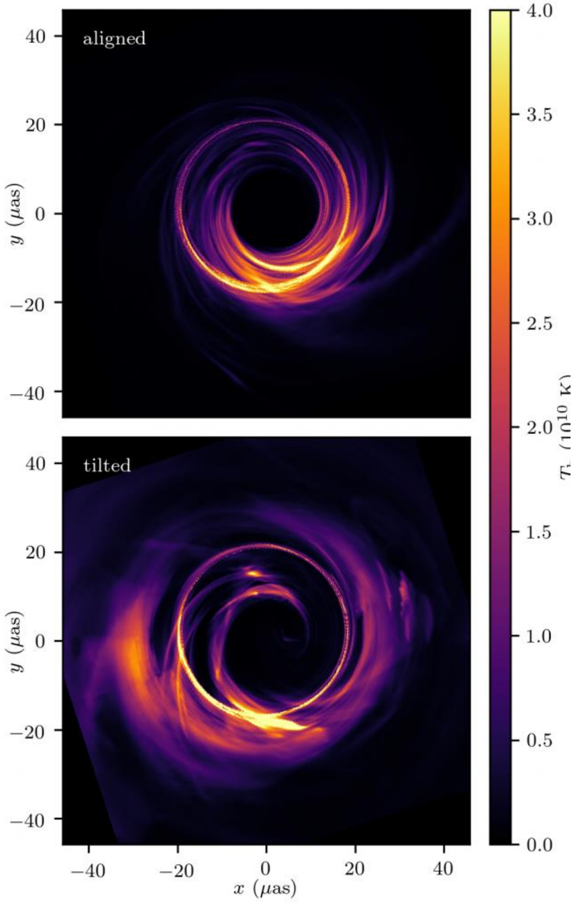
What about disk thickness?
Inner shadow in SANE simulations



Still apparent at low inclination, obscured by thick disk when edge-on

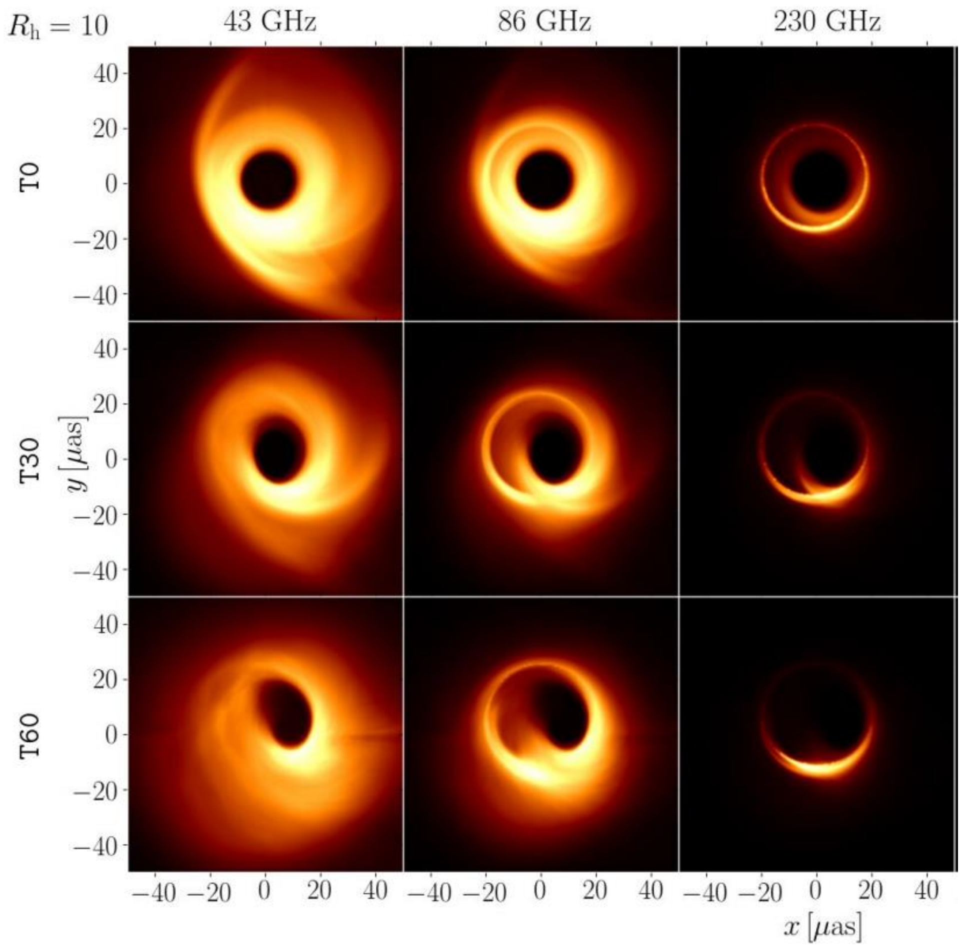
What about disk tilt?

White+ 20 (230 GHz)



Disk tilt can introduce new direct emission features from standing shocks

Chatterjee+20



In these simulations, there is an inner shadow feature with a different size/shape that may originate from the horizon image in the tilted disk plane

Summary

- The lensed (n=0) image of the equatorial event horizon is present in GRMHD simulations and should be observable
- While not ‘universal’ like the photon ring, many GRMHD simulations have the conditions necessary to make this feature observable
- Features of this image (radius, eccentricity, offset from the photon ring) can be used to measure spin and inclination
- The ngEHT will have the dynamic range and resolution necessary to observe this feature, and it could be observable at 86 GHz
- Next steps:
    - Paper on feature properties and appearance in M87 MAD simulations in progress
    - More investigations needed on dependence on simulation parameters!