ngEHT insights from radiative simulations: extended jets and lensed horizons

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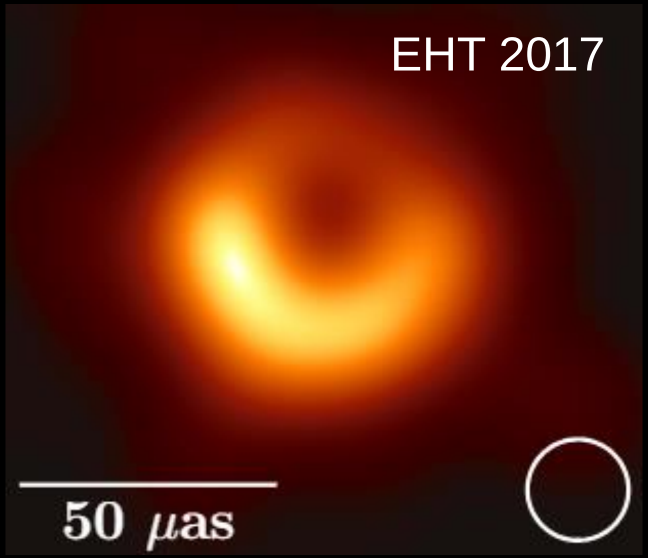
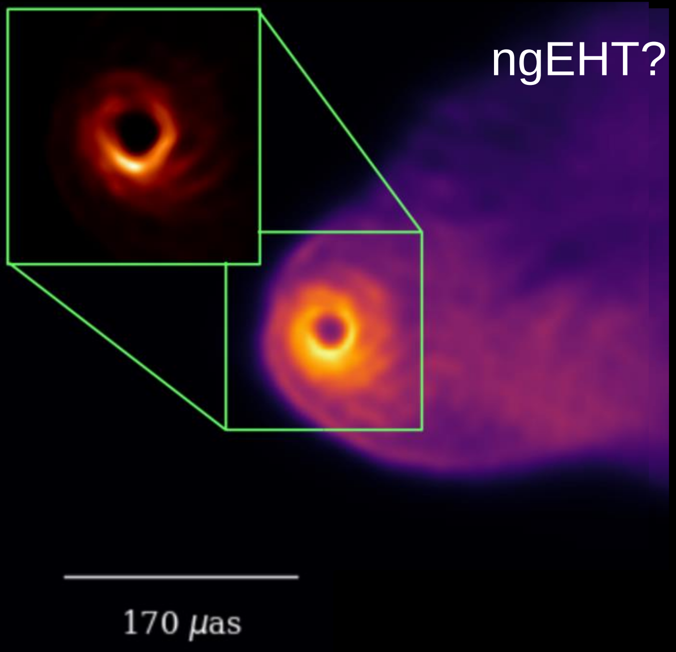
ngEHT Science Meeting
February 25, 2021





What can simulations tell us about the what the ngEHT might see in M87?

In particular, what might the ngEHT learn about the extended jet, the near-horizon region, and their interconnection?

M87

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

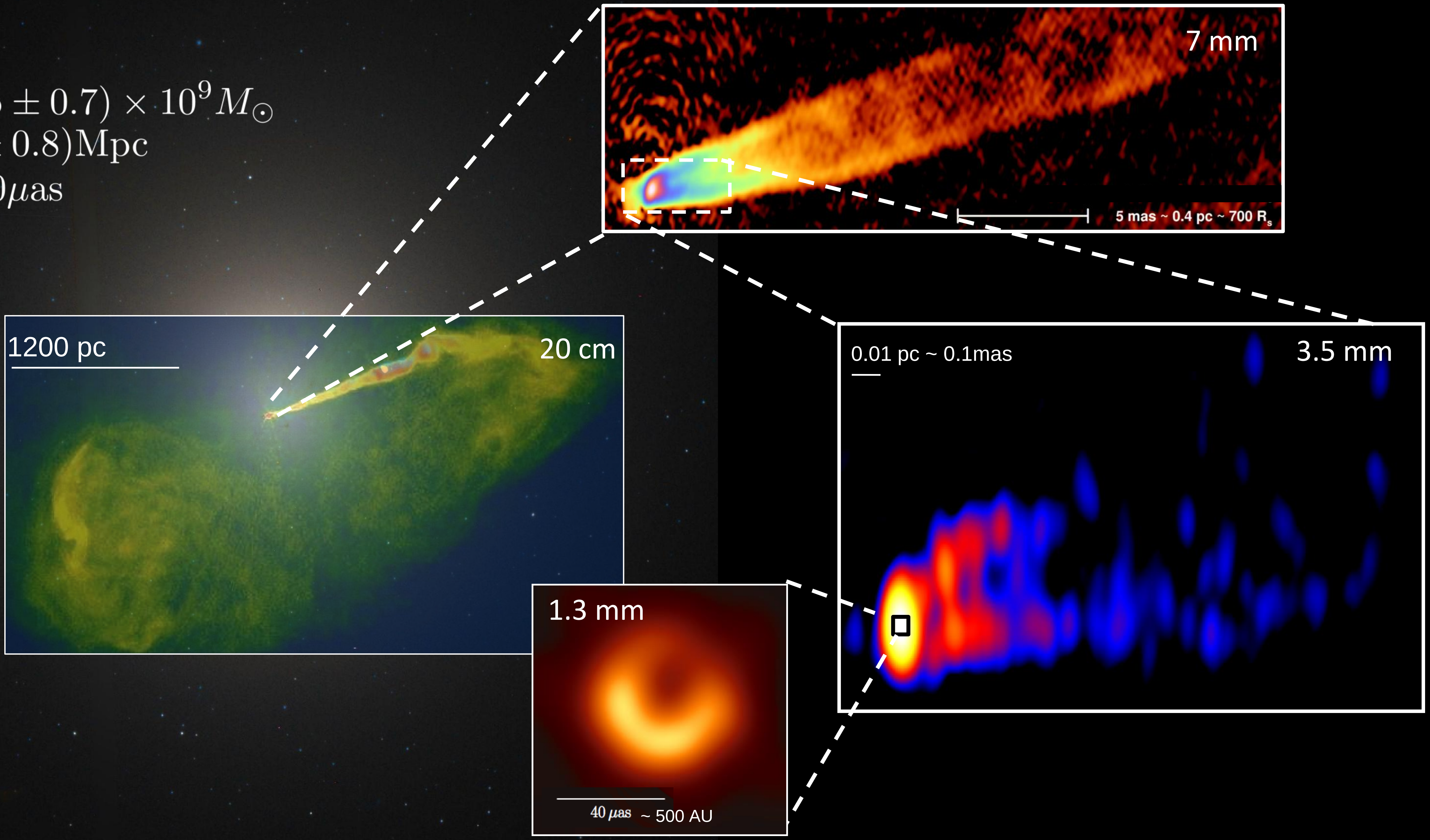
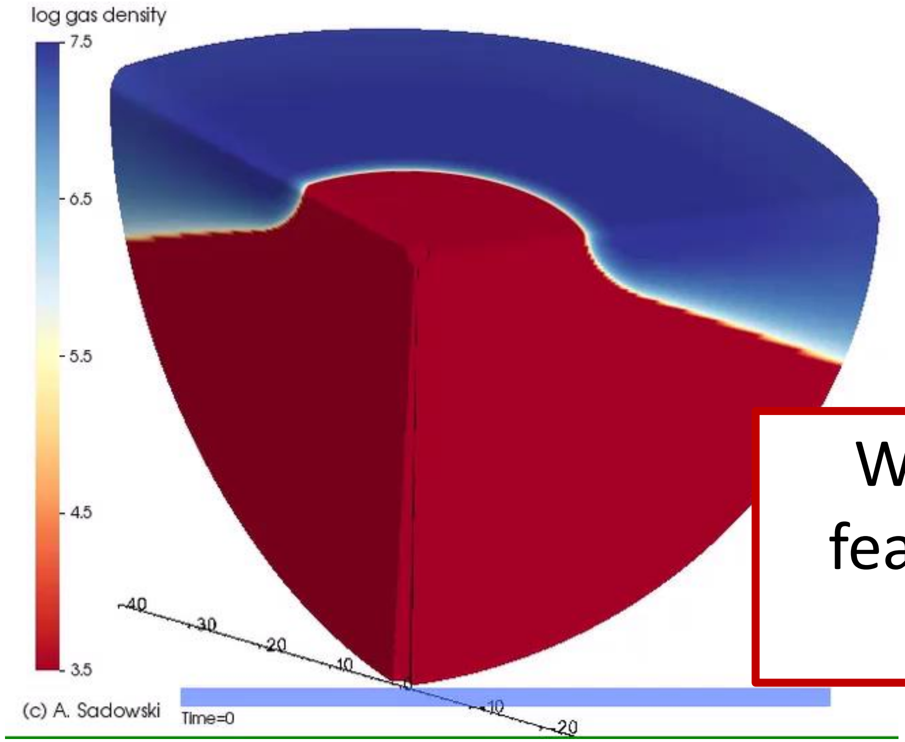


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

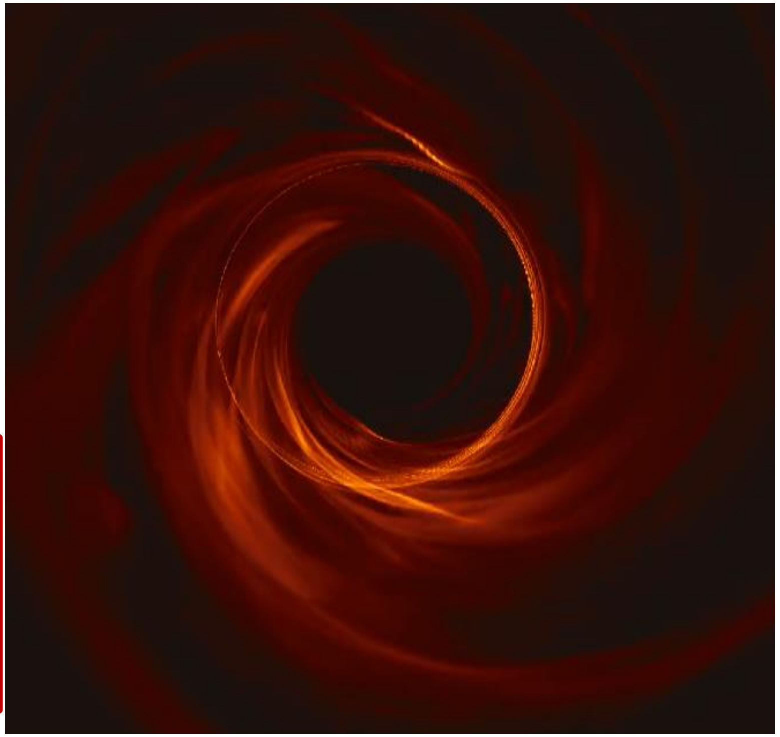
1. Simulations with Radiation and Heating

What determines the images we see in simulations, and can we do better?

General Relativistic MagnetoHydroDynamics (GRMHD)



General Relativistic Ray Tracing



What determines the features of the (ng)EHT image?

Solves coupled equations of fluid dynamics and magnetic field in a black hole spacetime

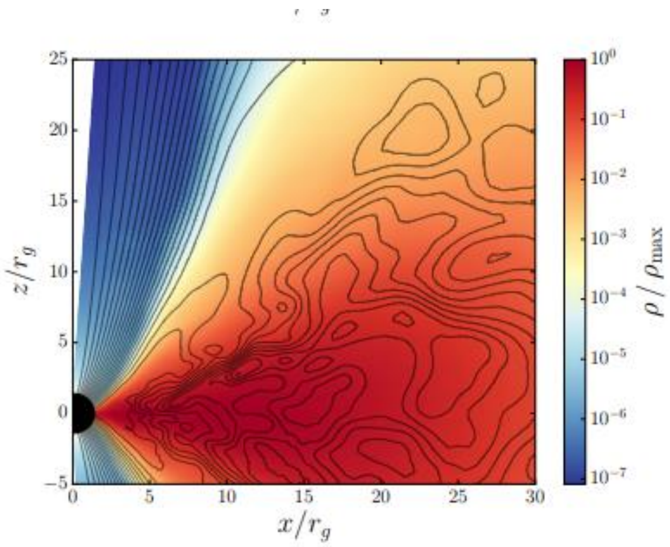
Tracks light rays and solves for the emitted radiation

Movie Credits: Aleksander Sądowski, EHT Collaboration 2019 (Paper V)

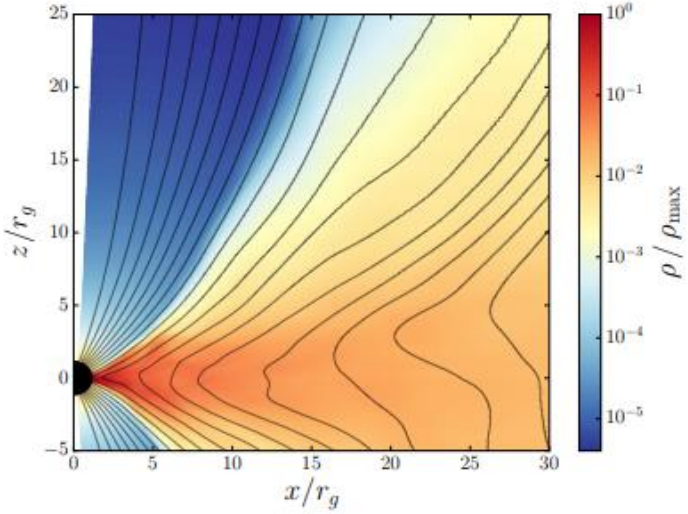
What is the magnetic field structure?

- Two accretion states that depend on the accumulated magnetic flux on horizon:

Magnetic fields are turbulent



"Standard" Turbulent field evolution



MAD: Magnetically Arrested Disk

Coherent magnetic fields build up on the horizon

$$\Phi_B/\sqrt{\dot{M}} \approx 50$$

- Blandford-Znajek (1977): Jet is powered by the black hole's angular momentum:

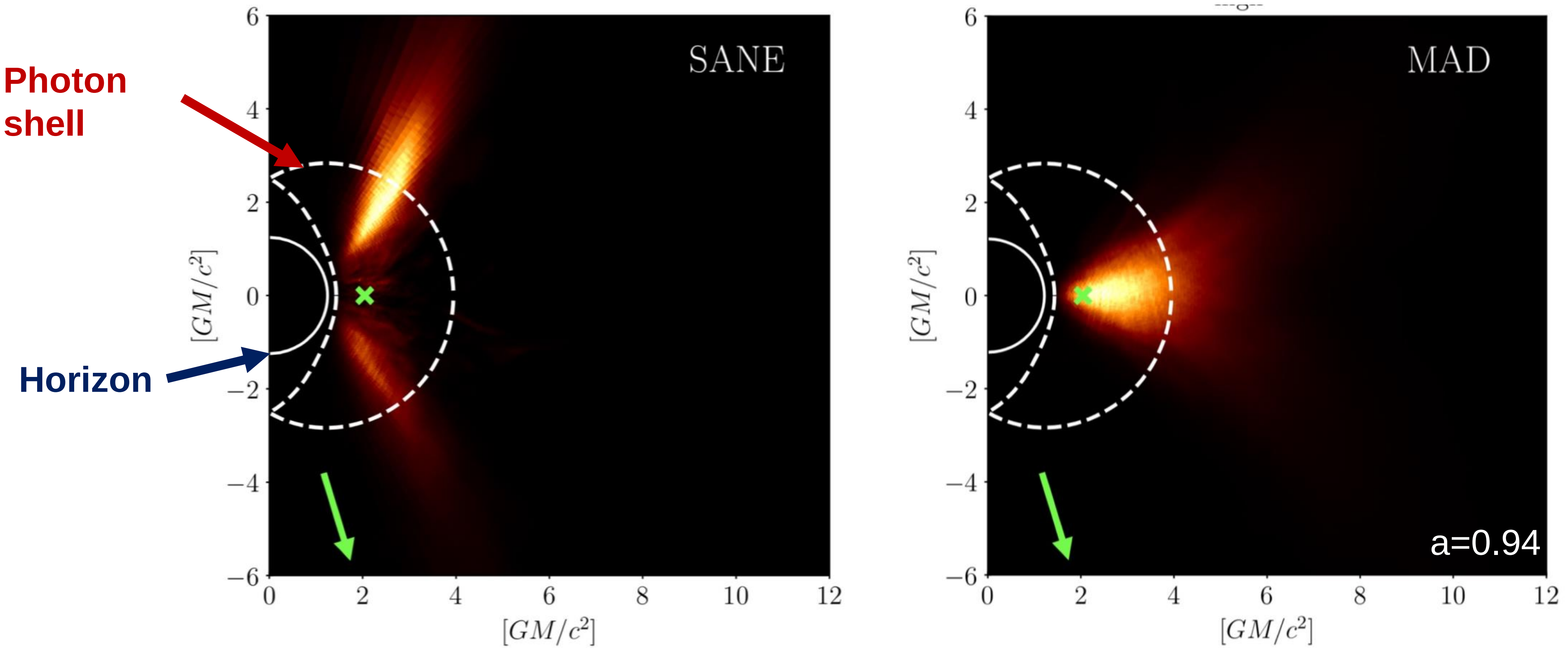
$$P_{\rm jet} \propto \Phi_B^2 a^2$$

- … so MAD systems may naturally produce powerful jets

Image credit: Riordan+ 2017

Where does the emission come from?

In EHT Paper V models, the emission region is within ~5 gravitational radii of the black hole:



In EHT Paper V models, the emission region is within ~5 gravitational radii of the black hole

Typical plasma parameters: $T_e \sim 10^{12}\,\mathrm{K}\,,\ B \sim 5\,\mathrm{G}\,,\ n_e \sim 10^4\,\mathrm{cm}^{-3}$

EHTC+ 2019, Paper V

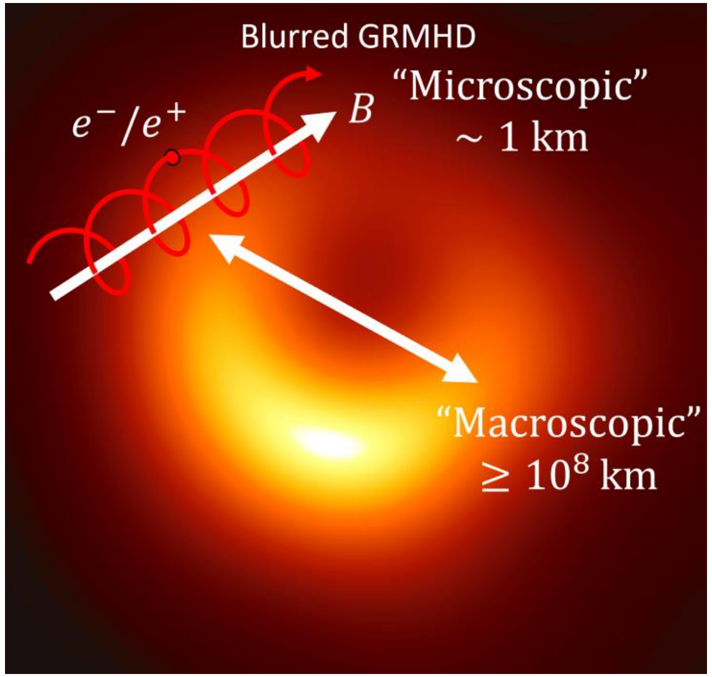
What is the distribution of the emitting electrons?

- Coulomb coupling between ions and electrons is **inefficient**:

$$T_\mathrm{e} \neq T_\mathrm{i}$$

- The electron temperature is sensitive to **radiative cooling** and microscale **plasma heating** processes.

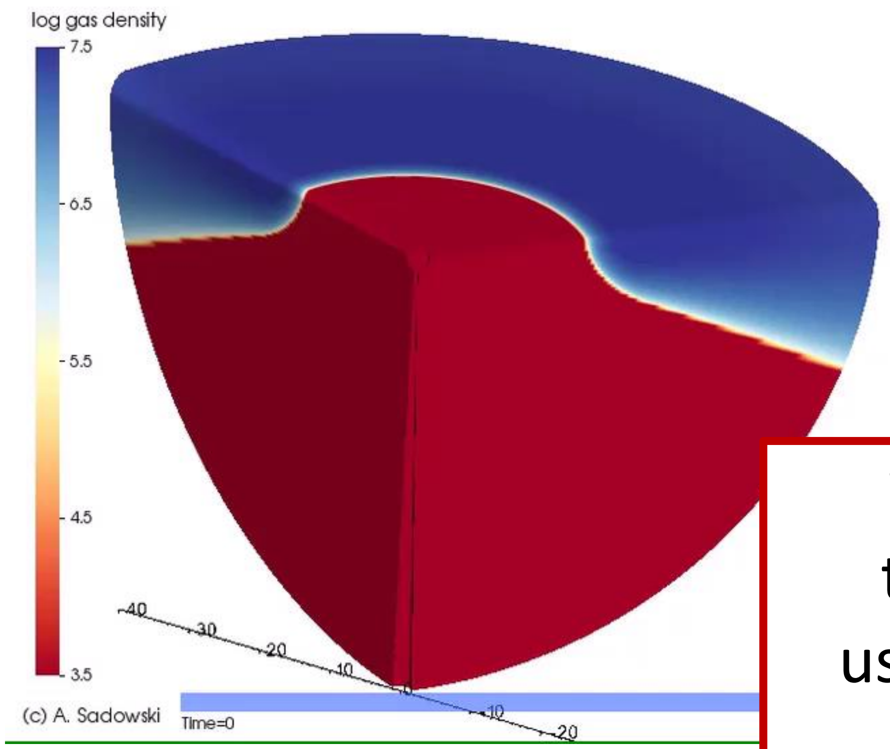
- Electrons near the BH may or may not be thermal!

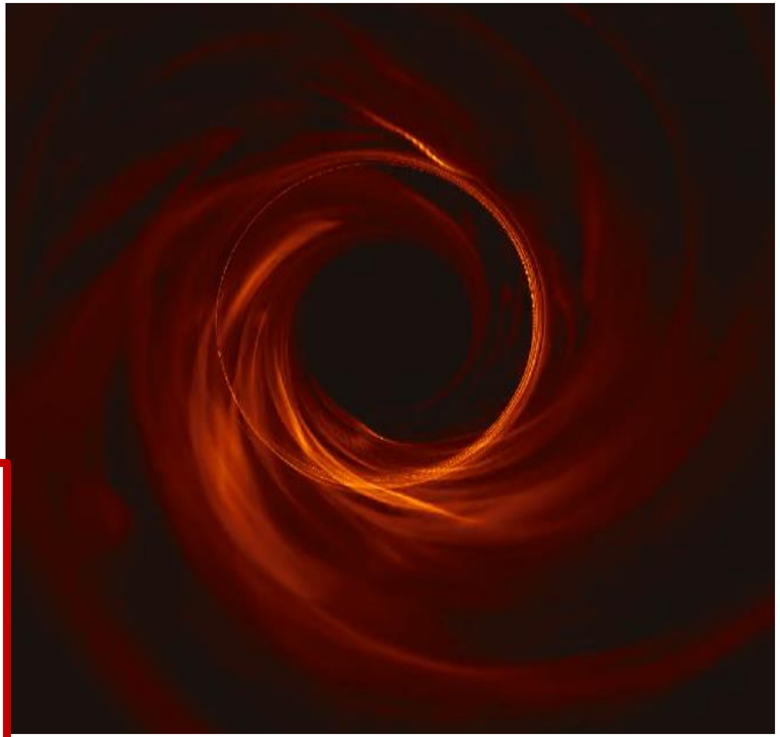


Huge scale separation in hot accretion flows

Image credit: Bart Ripperda

From simulations to images



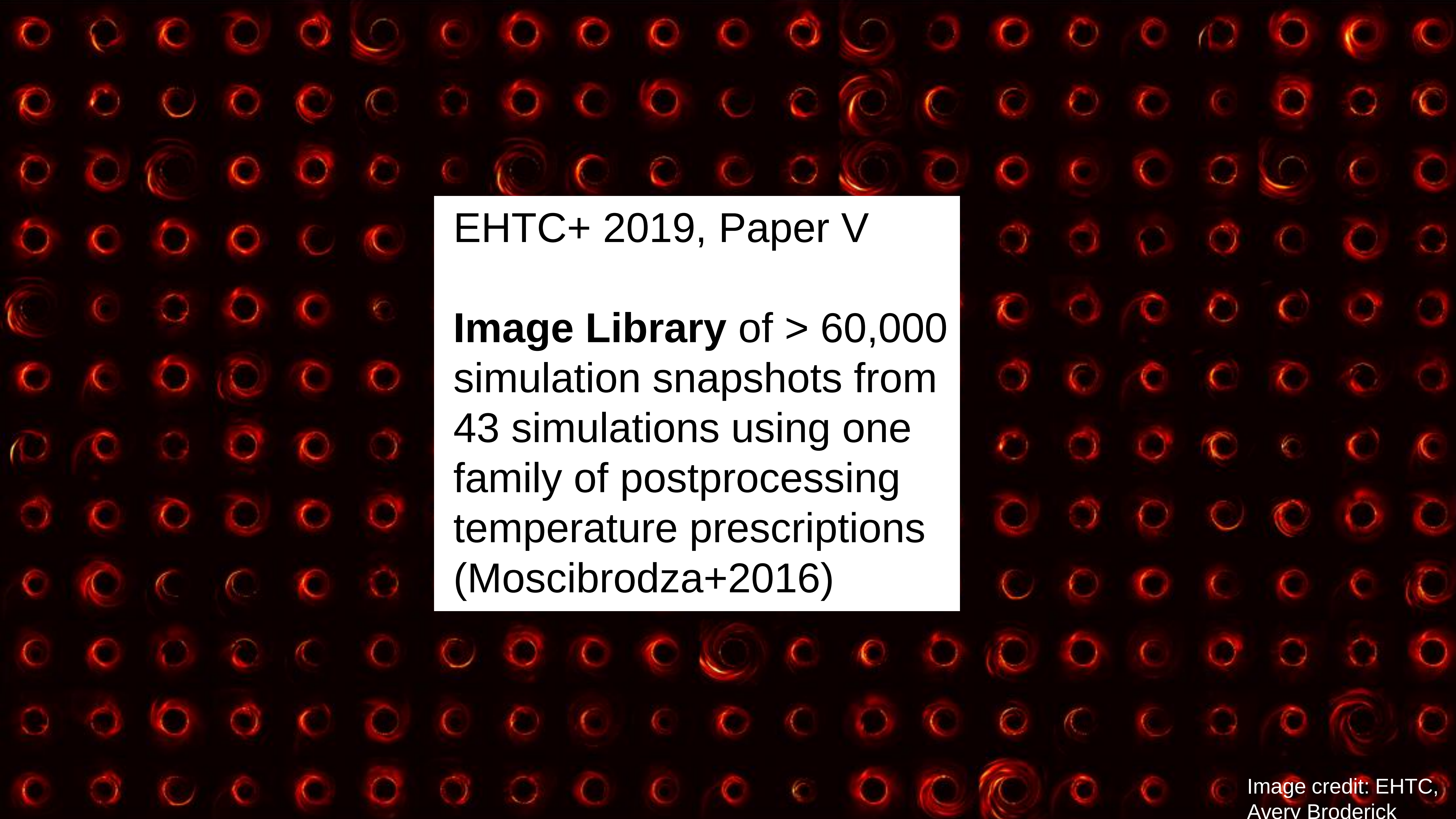


The ion-to-electron temperature ratio is usually set **manually** in **post-processing**

GRMHD: does not evolve a separate electron temperature

GRRT: requires the temperature (or distribution function) of electrons

Movie Credits: Aleksander Sądowski, EHT Collaboration 2019 (Paper V)



EHTC+ 2019, Paper V

Image Library of > 60,000 simulation snapshots from 43 simulations using one family of postprocessing temperature prescriptions (Moscibrodza+2016)

Image credit: EHTC, Avery Broderick

Radiative GRMHD

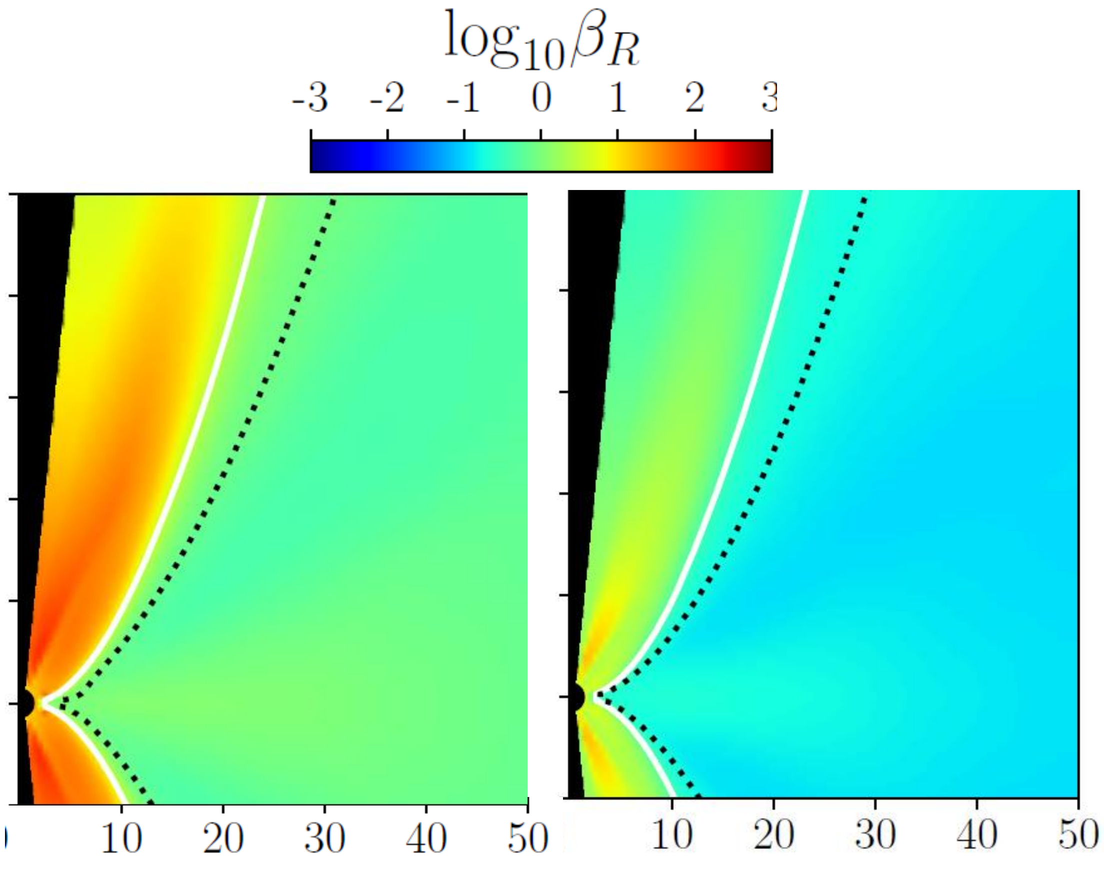
M87's accretion rate is high enough that radiative feedback may be important:

- **M87's radiative efficiency ~1%**
  (e.g. Ryan+ 2018, EHTC+ 2019 Paper V)

Radiative GRMHD simulations include **radiative cooling and feedback** on gas energy-momentum.

- Several codes & methods now available: e.g. M1 closure (Sadowski+ 2013), Monte-Carlo (Ryan+ 2015), Method of Characteristics (Ryan+ 2019), full frequency & angle dependent transport (Davis&Gammie 2019)

Radiative GRMHD makes it natural to include subgrid models for electron heating.



Example: radiation pressure / gas pressure in two radiative M87 simulations

Image credit: Chael+2019

Two-Temperature GRMHD

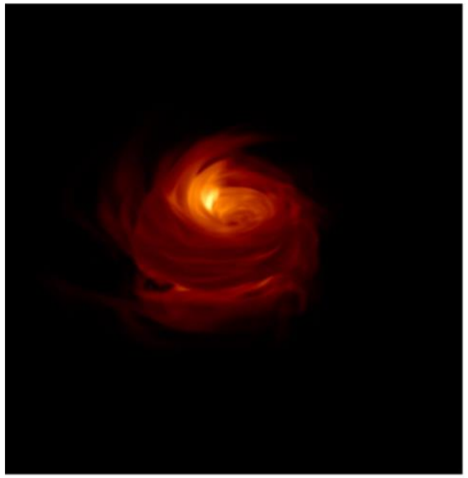
- Radiative simulations allow us to incorporate different models for the electron heating mechanism at small scales self-consistently during the simulation evolution.

- Some options: magnetic reconnection (e.g. Rowan 2017), Landau damping (e.g. Howes+ 2010), Fermi-type acceleration (e.g. Zhdankin+ 2019)

- Major limitation: the space of heating models is currently unconstrained

Example: 43 GHz Sgr A* simulation images

Heating from sub-grid Landau damping produces hot electrons in the jet

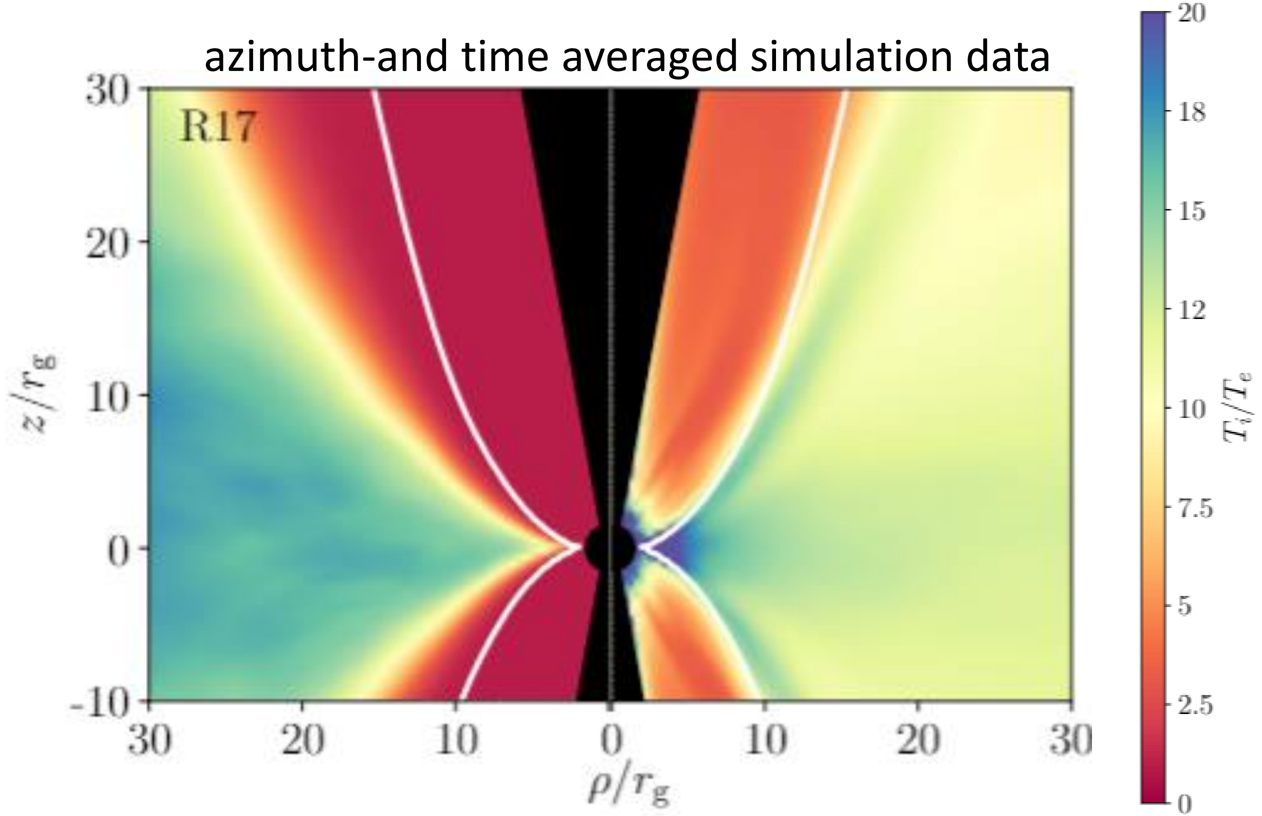


Heating from sub-grid reconnection produces hot electrons in the disk

Chael+ 2018, 2019
also Sadowski+2016, Ressler+ 2017, Ryan+ 2018, 2019, Davis+ 2019, Dexter+ 2020

Radiative, two-temperature GRMHD produce electron temperature distributions **outside** the space of EHT postprocessing models

Postprocessing model from Mosicbrodzka+16, EHTC+19 V



Simulation evolved temperature ratio

In prep: a library of radiative, two-temperature simulations for M87 across spin and accretion rate

Fundamental issues: no freedom to adjust accretion rate, space of heating models unconstrained

2. Jets from MAD simulations

How similar are jets from these simulations to M87? What features could we observe with ngEHT?

Radiative, Two-temperature, MAD simulations of M87

Turbulent Heating

Reconnection Heating

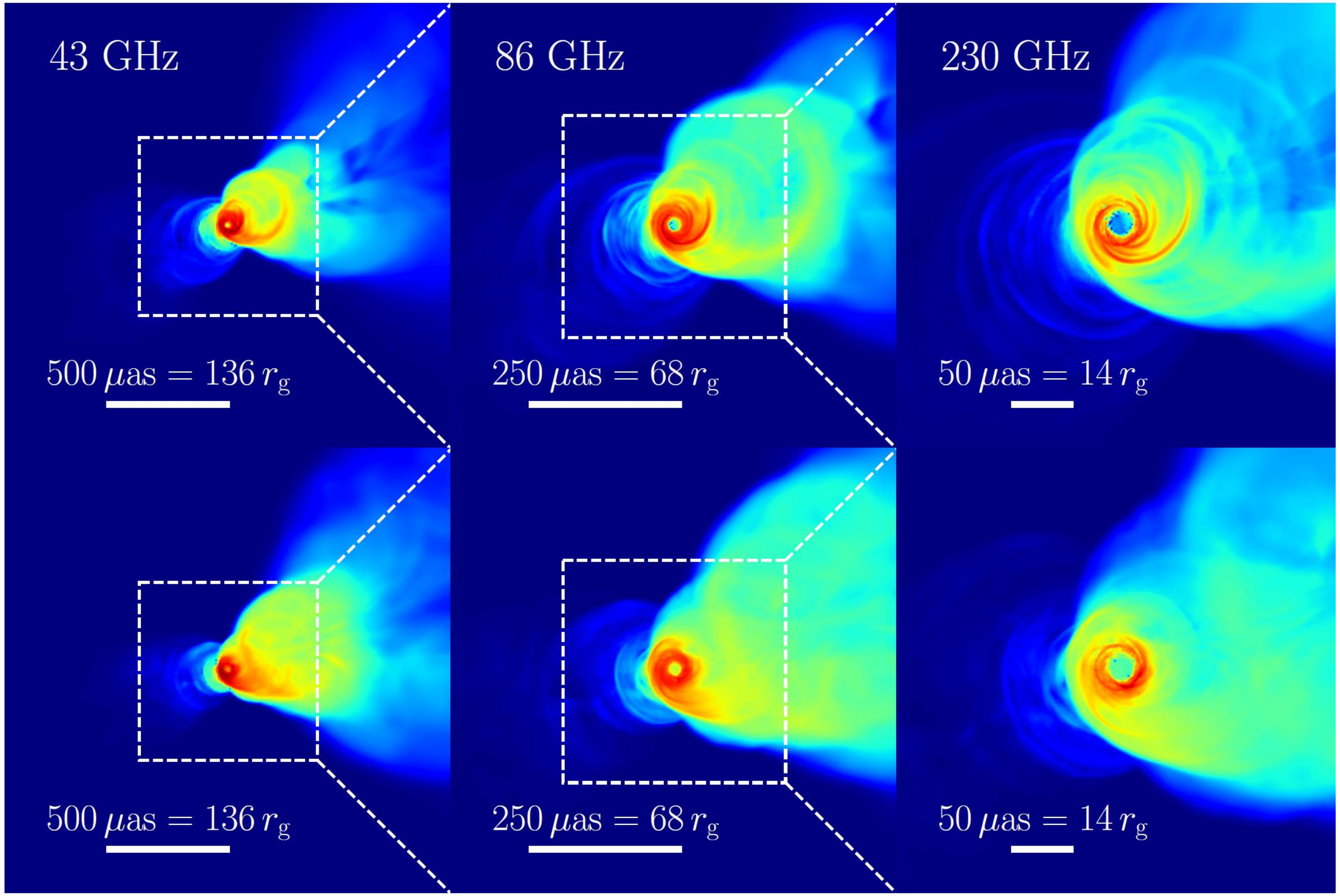
40 μas

Simulations in this talk are from Chael+ 2019
Using KORAL code (Sadowski+ 2013,16)

M87 Jets at millimeter wavelengths

Turbulent Heating

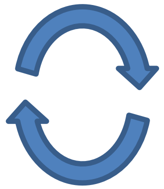
Reconnection Heating



Inclination angle (down from pole)

$17°$

Disk/Jet rotation sense

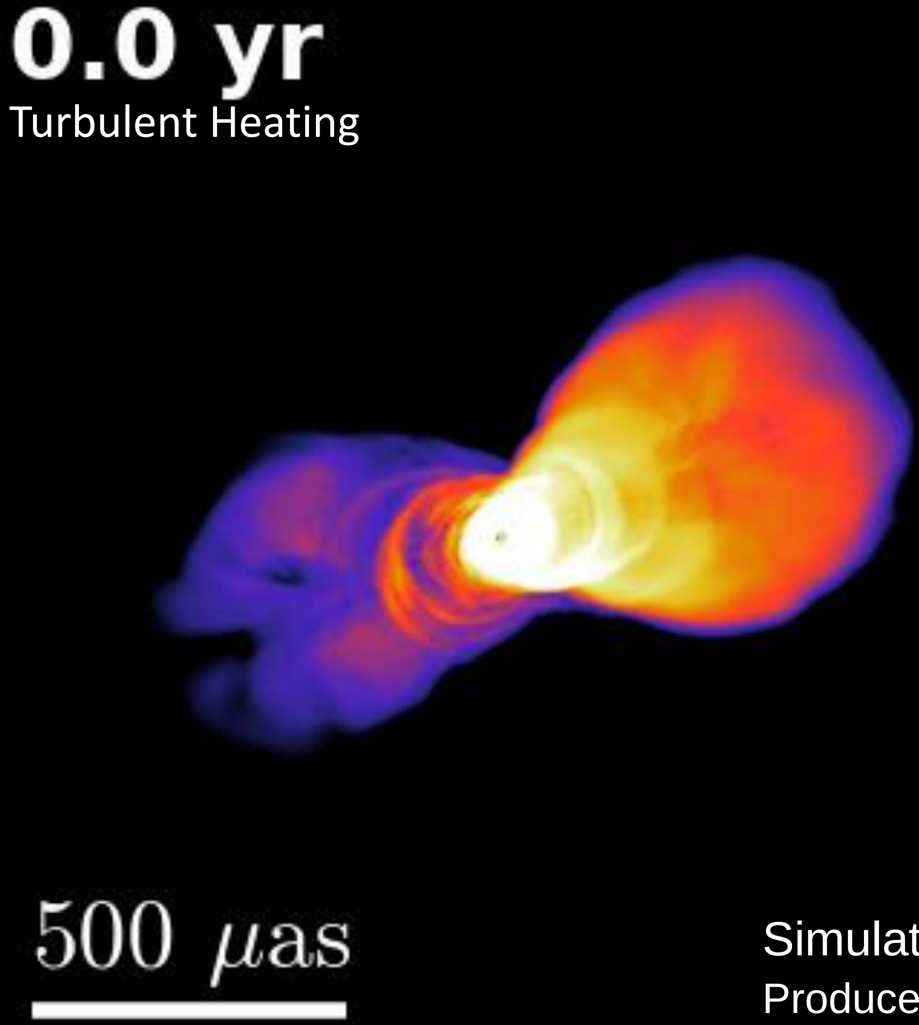


Wide apparent opening angles get **larger** with increasing frequency

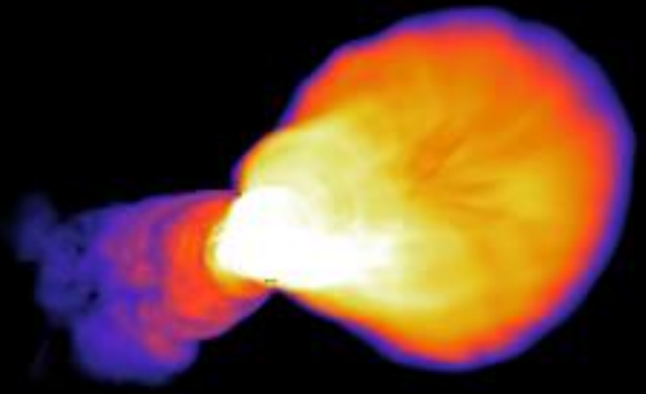
Image Credit: Chael+ 2019

43 GHz jets from MAD simulations

Turbulent Heating



Reconnection Heating

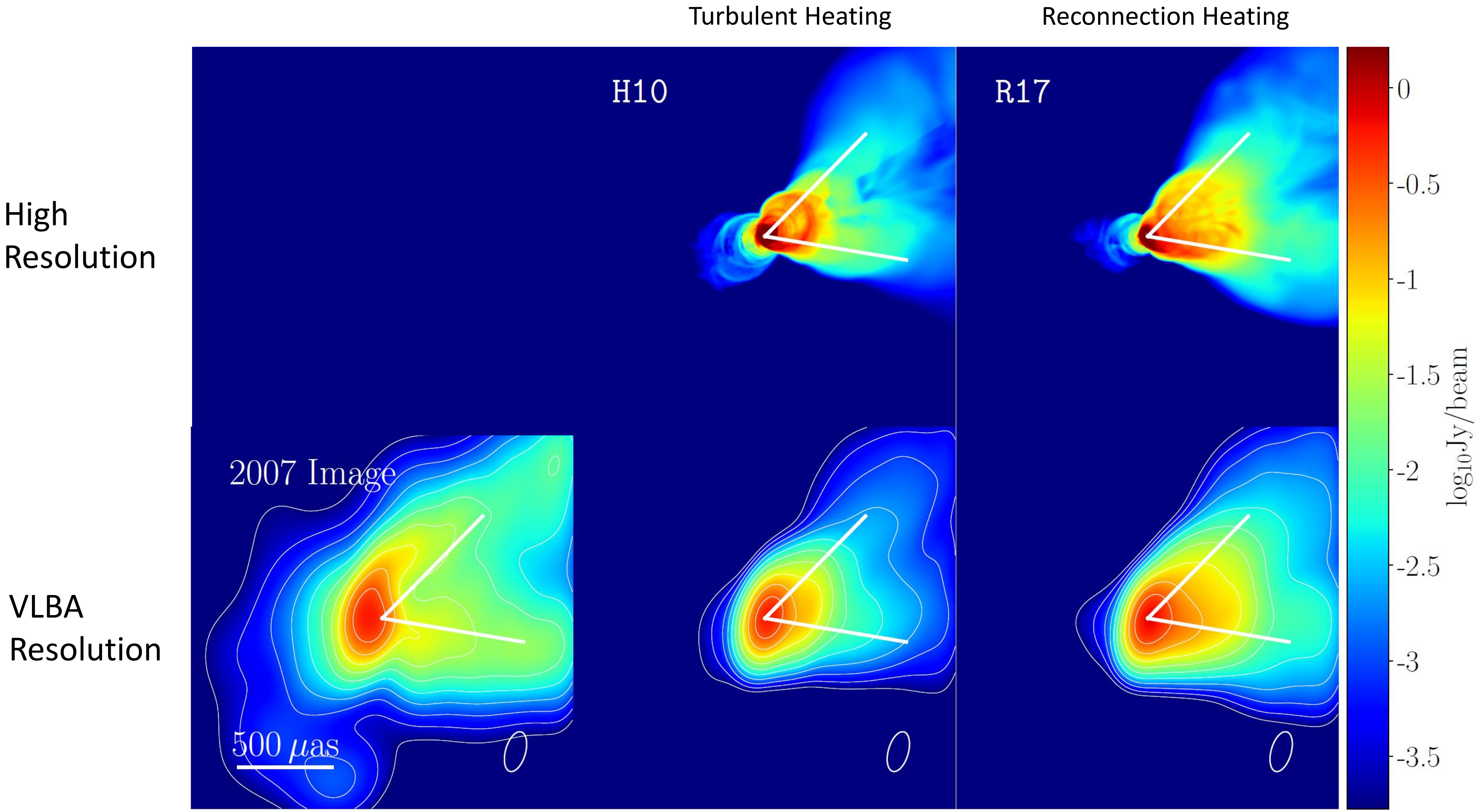


Simulations evolved for 16K t_g,
Produce jets out to ~1pc (~1 mas projected).
Reasonable SED down to ~1cm

Movie Credit: Chael+ 2019

43 GHz jets – comparison with VLBI

Walker+ 2018



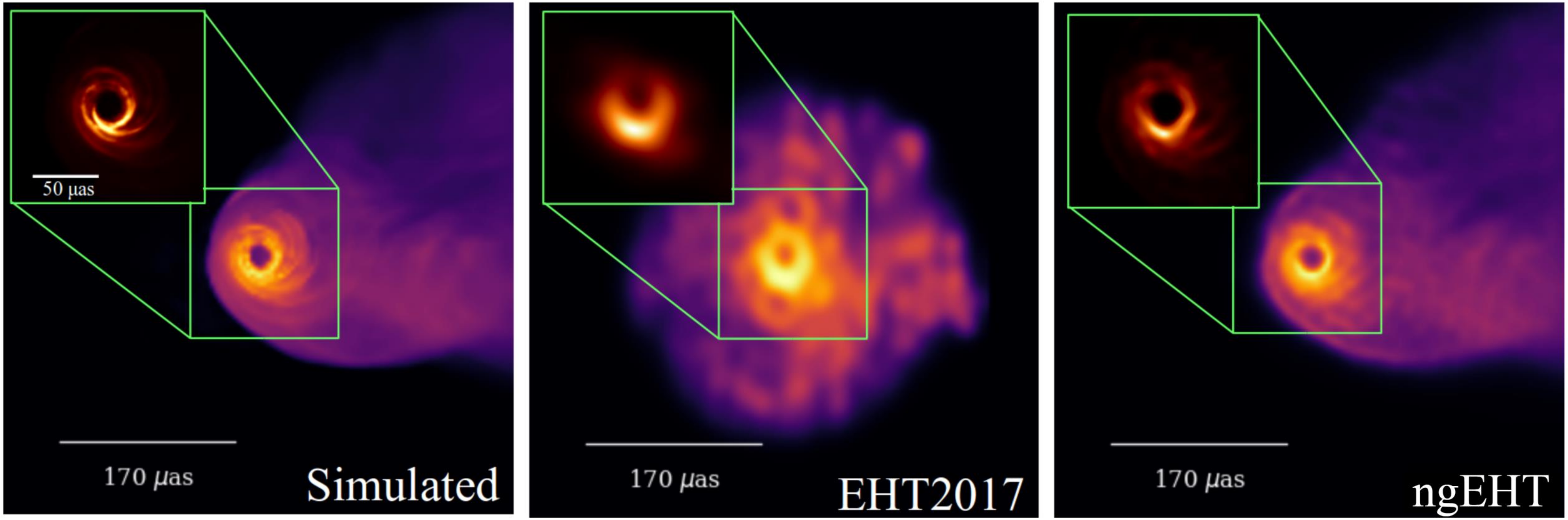
Large apparent jet opening angle at 43 GHz: $55°$ (Walker+ 2018)

The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s, but H10 is too weak

Neither jet is as limb-brightened as in VLBI images

Image Credit: Chael+ 2019
VLBA Image Credit: Chael+ 2018a
Original VLBA data: Walker+ 2018

ngEHT will illuminate the BH-jet connection



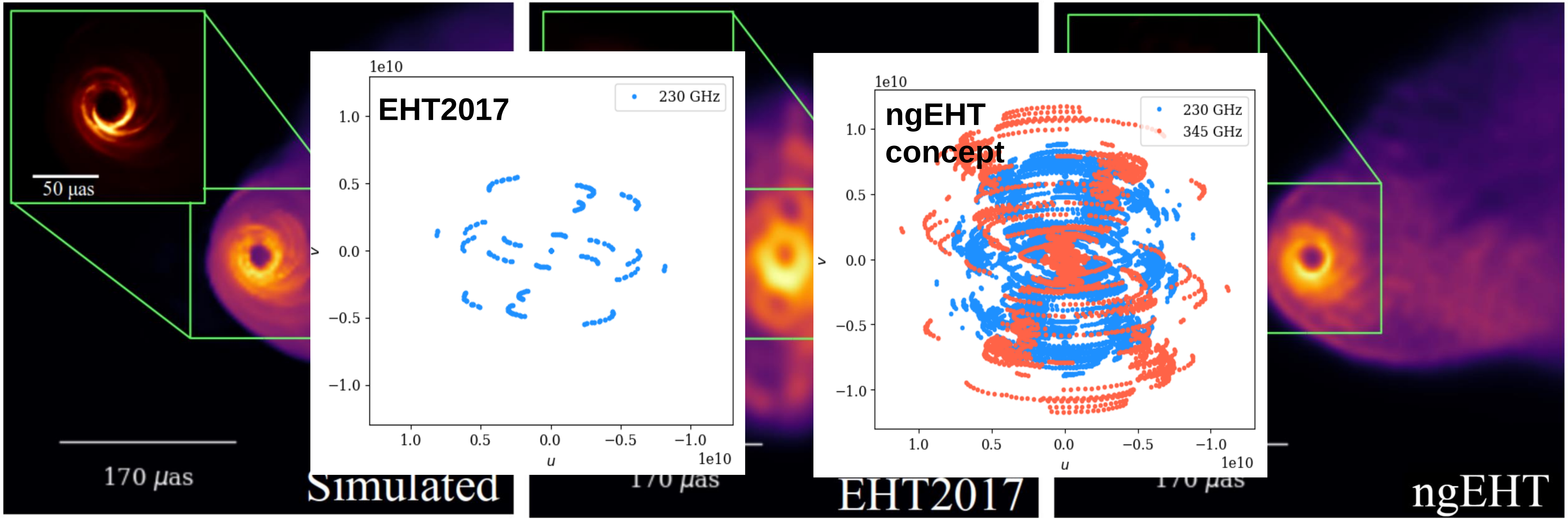
The current EHT lacks many <u>short</u> baselines, which are necessary to detect extended structure.

Going to 345 GHz will increase **resolution**

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

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

ngEHT will illuminate the BH-jet connection



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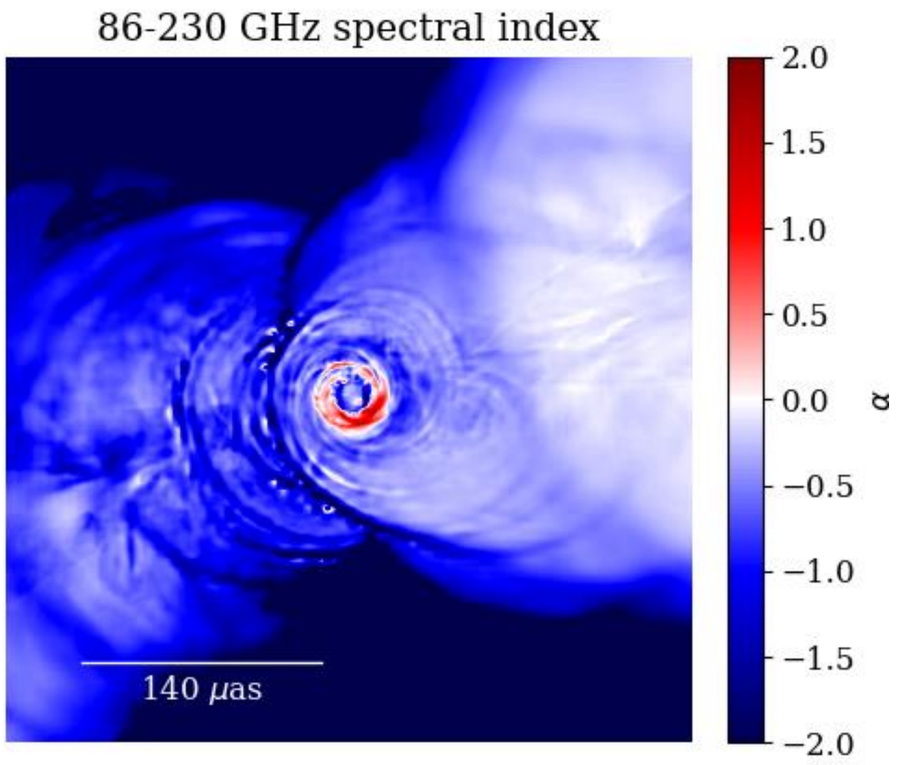
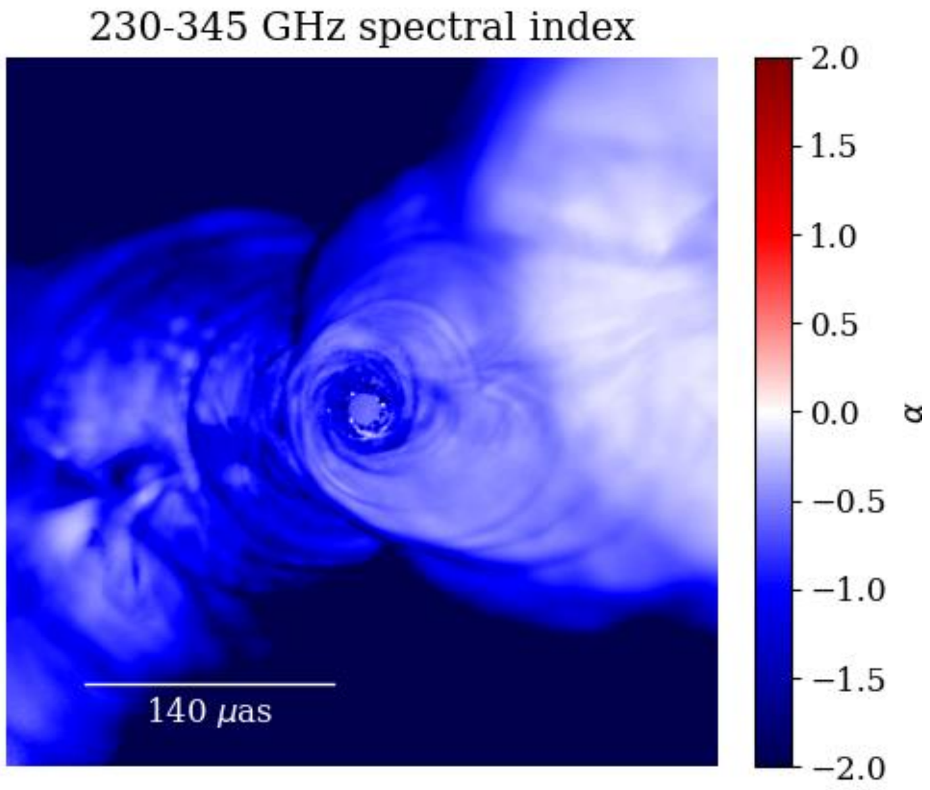
Multiwavelength jet science with ngEHT

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



Between 86 and 230 GHz, near-horizon emission becomes optically thin



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

Multifrequency ngEHT imaging can constrain plasma properties with spectral information

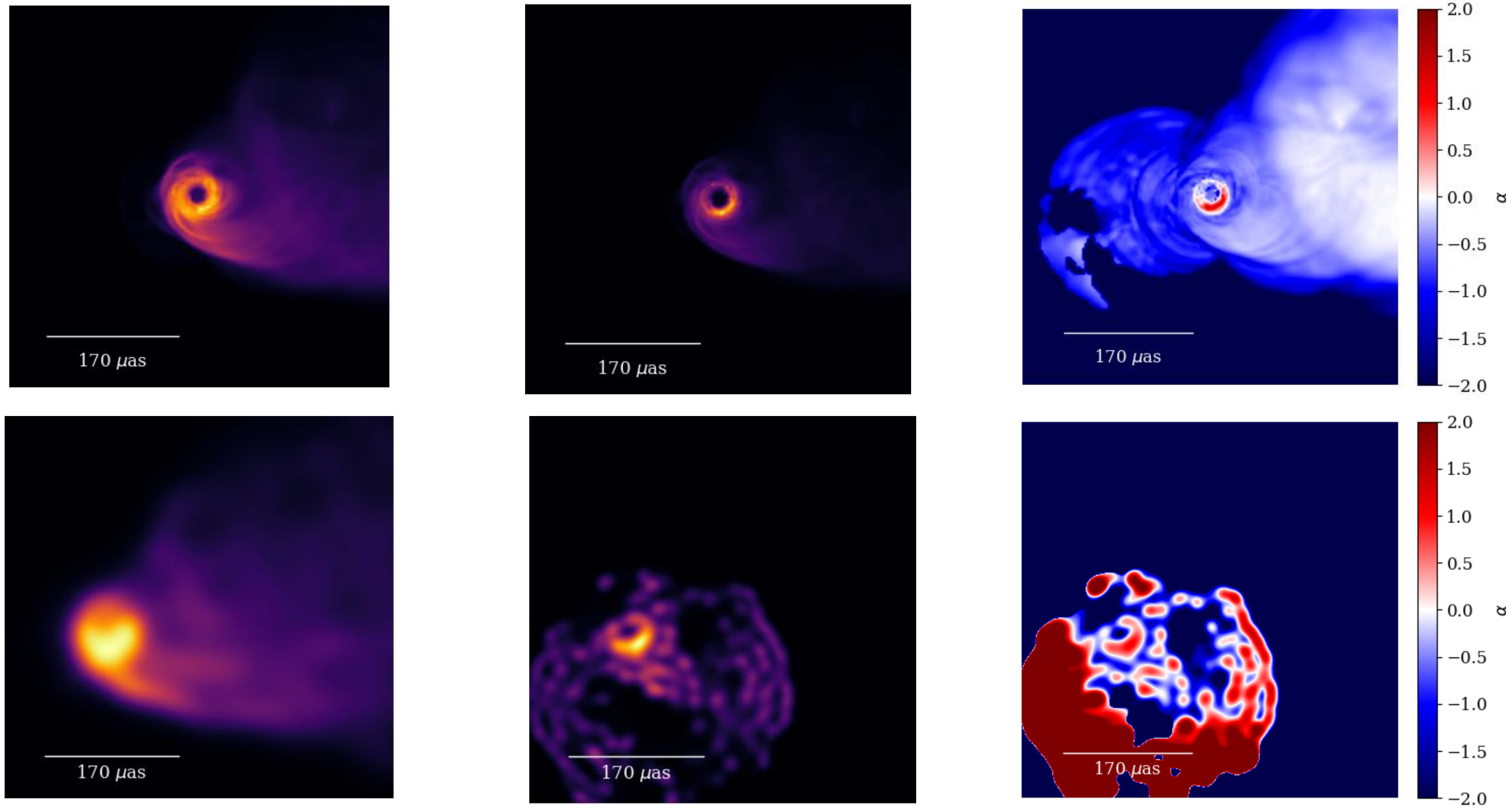
Chael+ in prep.

Multifrequency imaging with ngEHT+GMVA

86 GHz | 230 GHz | spectral index

Simulation

EHT2021 + GMVA, imaged **separately**



Chael+ in prep.
Using eht-imaging, Chael+ 2016,18

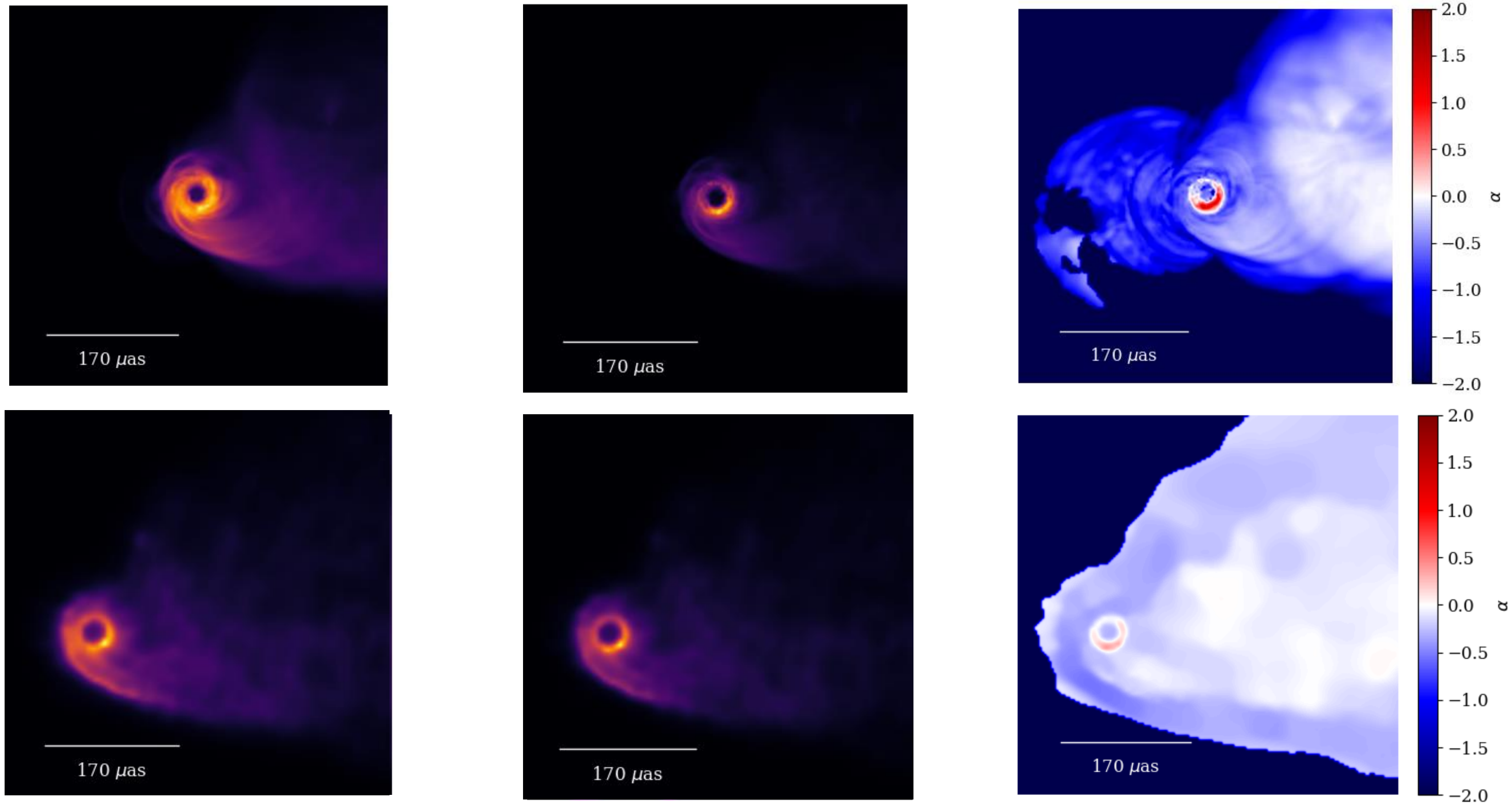
Multifrequency imaging with ngEHT+GMVA

Very preliminary!

86 GHz | 230 GHz | spectral index

Simulation

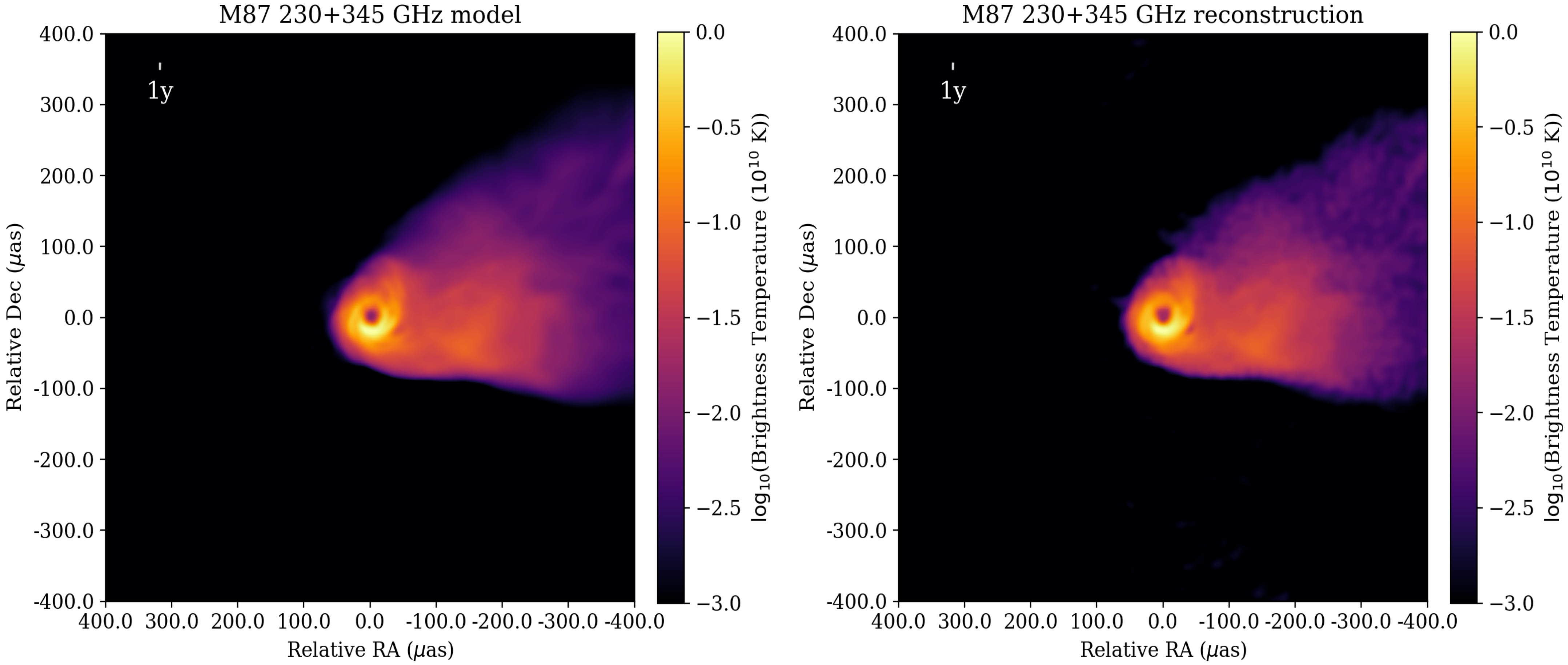
ngEHT +GMVA, imaged **jointly**



Multifrequency synthesis can combine ngEHT and GMVA coverage.
Imaging **jointly** allows us to share structural information across frequencies

Chael+ in prep.
Using eht-imaging, Chael+ 2016,18

ngEHT can trace jet-BH dynamics



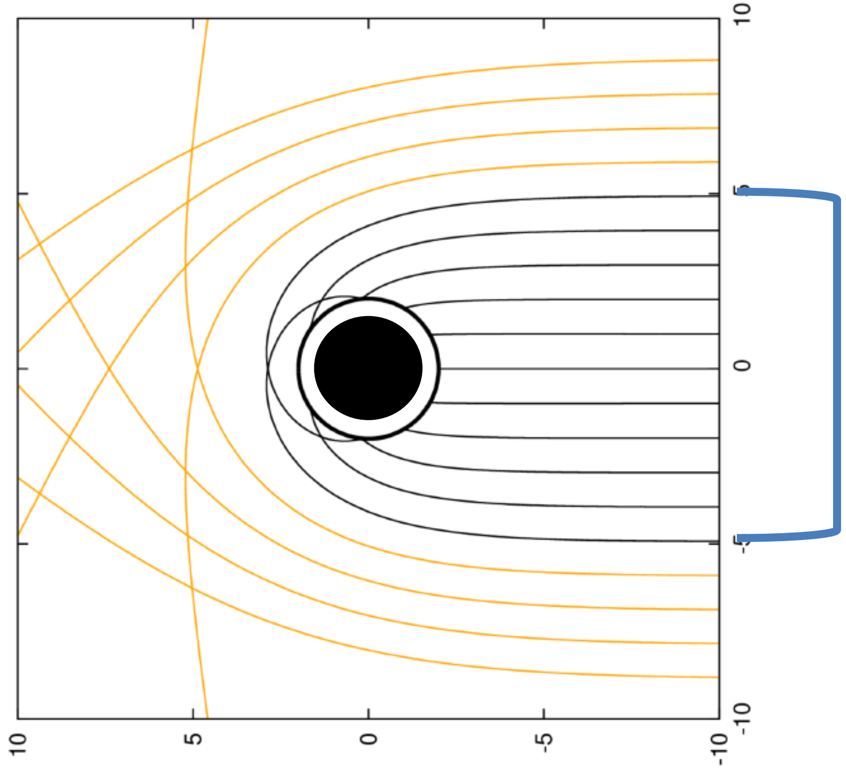
Multifrequency imaging using ngEHT
230+345 GHz coverage over five years

Movie/reconstruction
credit: Lindy Blackburn

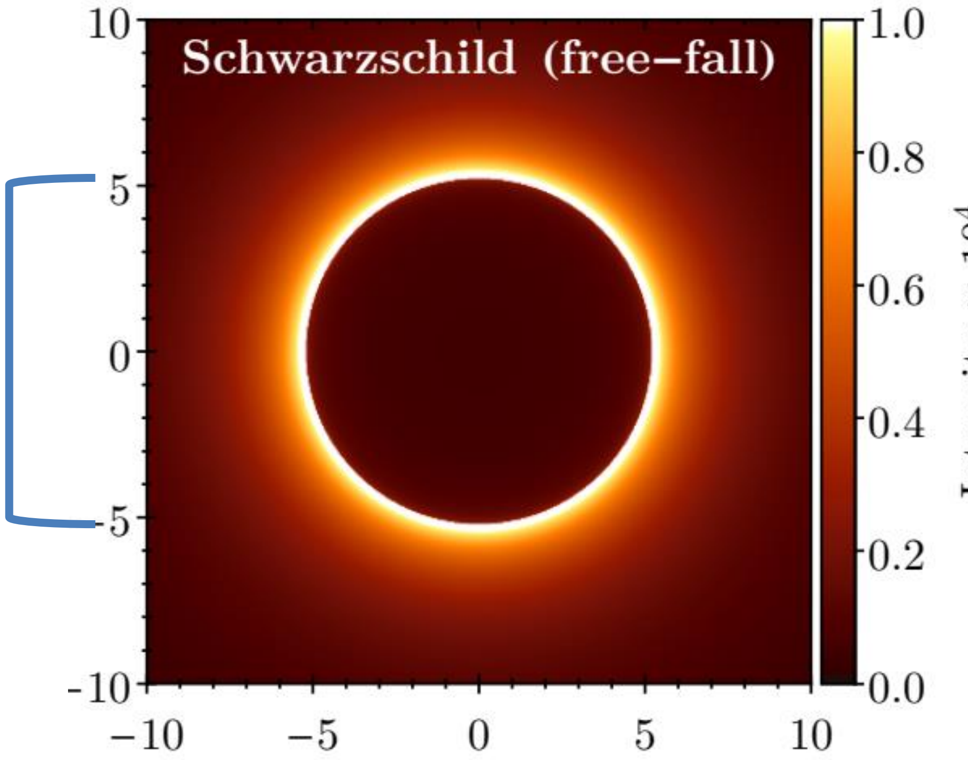
3. Horizon Images

What do these simulations reveal about what ngEHT might see on horizon scales?

The Black Hole Shadow



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

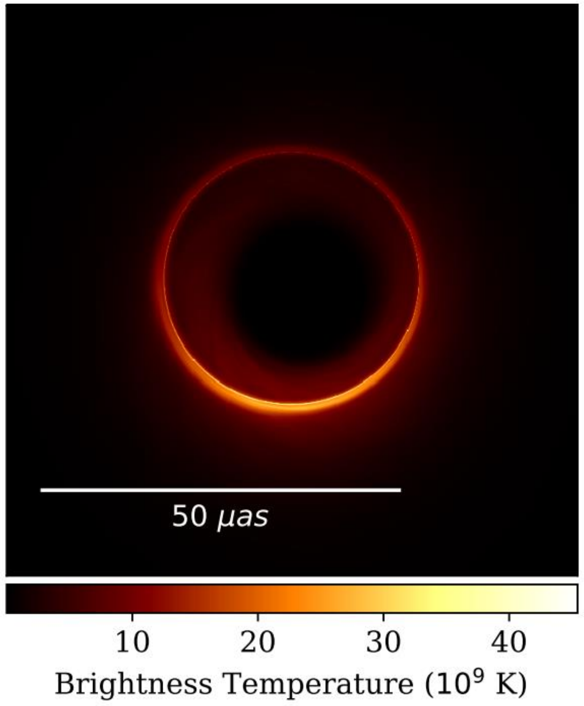


- The black hole ‘shadow’ is the set of rays from the observer that end in the event horizon
- The boundary of the shadow is the ‘critical curve’
- It is a universal feature in simulated images from optically thin, **spherically symmetric** accretion

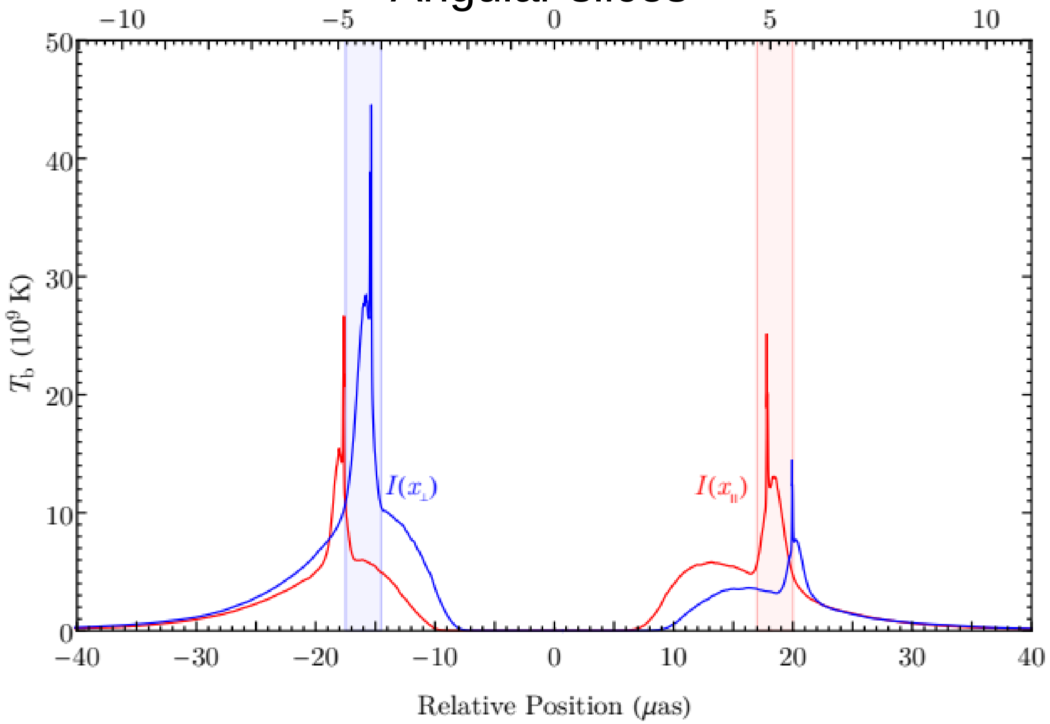
Image credit: Keiichi Asada
Narayan+ 2019 (also Falcke+ 2000, many others)

Photon Rings

Time-averaged GRMHD



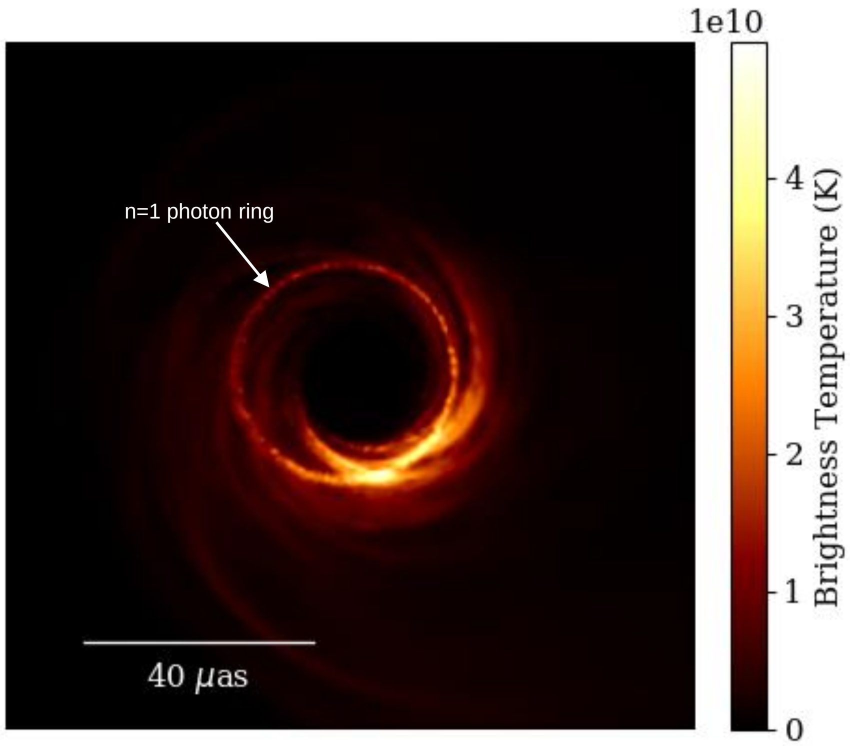
Angular slices

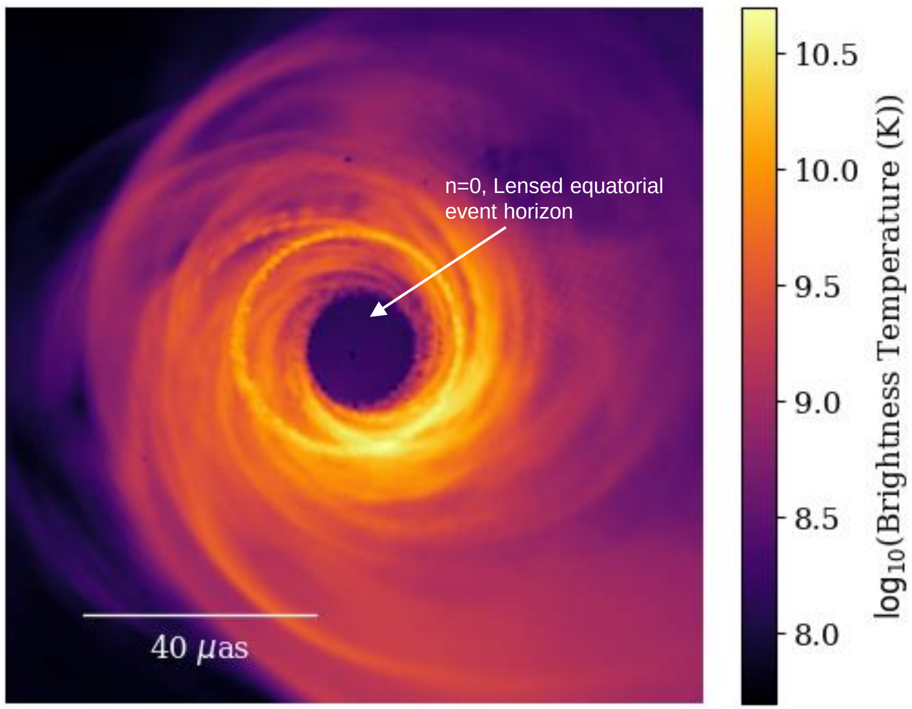


- As geodesics wrap around the black hole multiple times, they form a **series of images** lensed into **increasingly narrow rings**
- Subrings approach the critical curve.
- Resolving the subrings requires a **spatially limited emission region**

Image credit: Johnson+ 2019
Simulation Credit: George Wong

Central brightness depression in GRMHD images



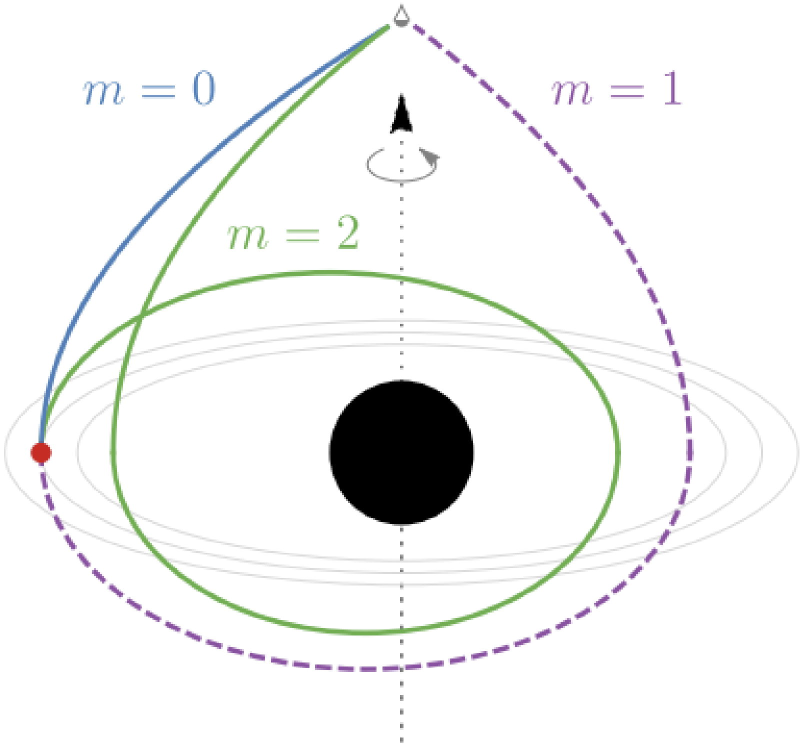


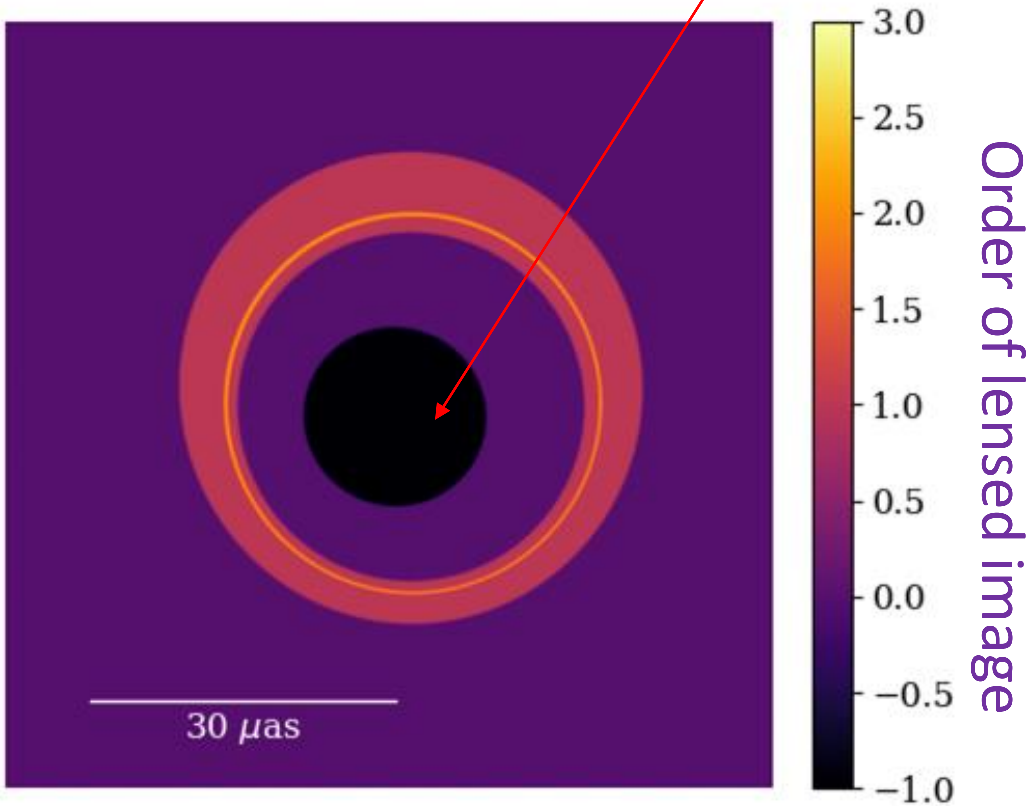
- This high dynamic range feature is the outline of the equatorial event horizon
- While not ‘universal’ like the shadow/photon ring, it may be visible with the ngEHT

Lensed images of the equatorial plane

Curve: n=0 image of the equatorial event horizon

Interior: Silhouette of the horizon northern hemisphere





a=0.94, i=163 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: Gralla & Lupsasca 2019 (left)
Chael+ in prep (right)

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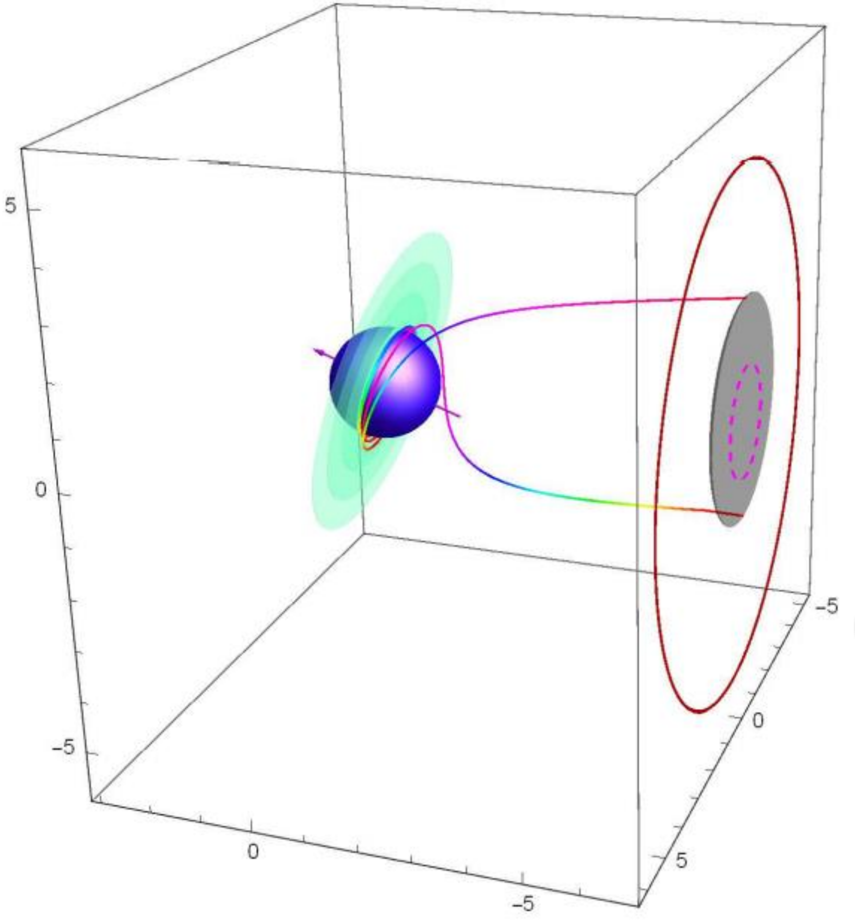

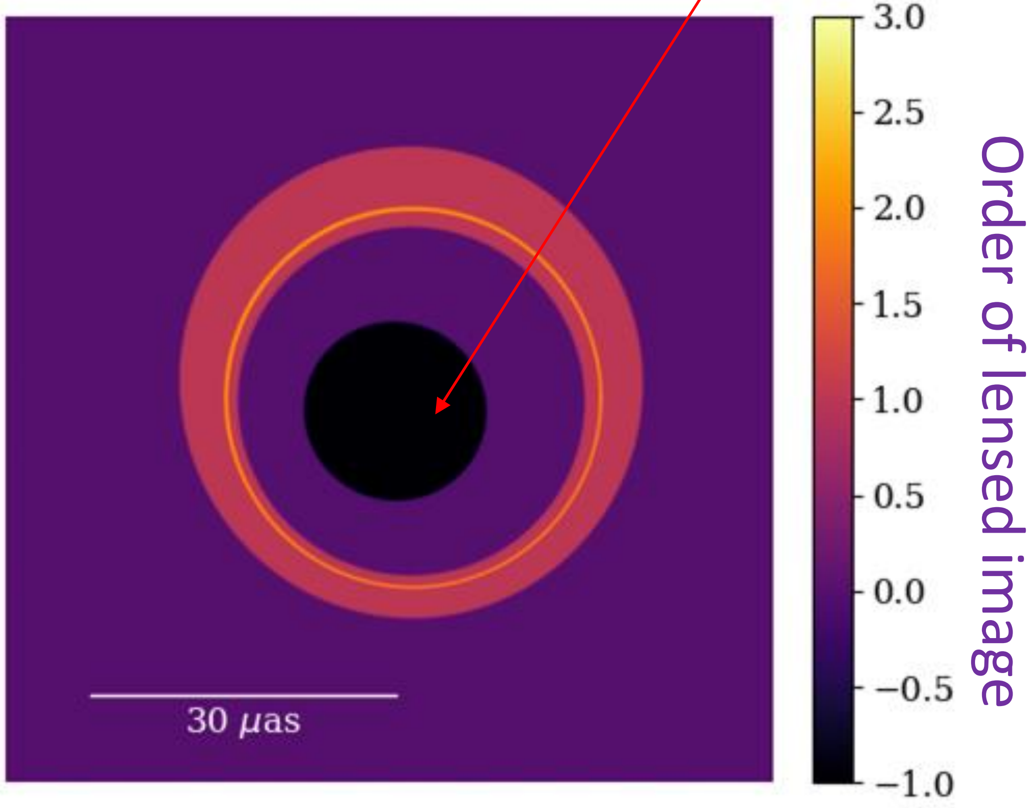

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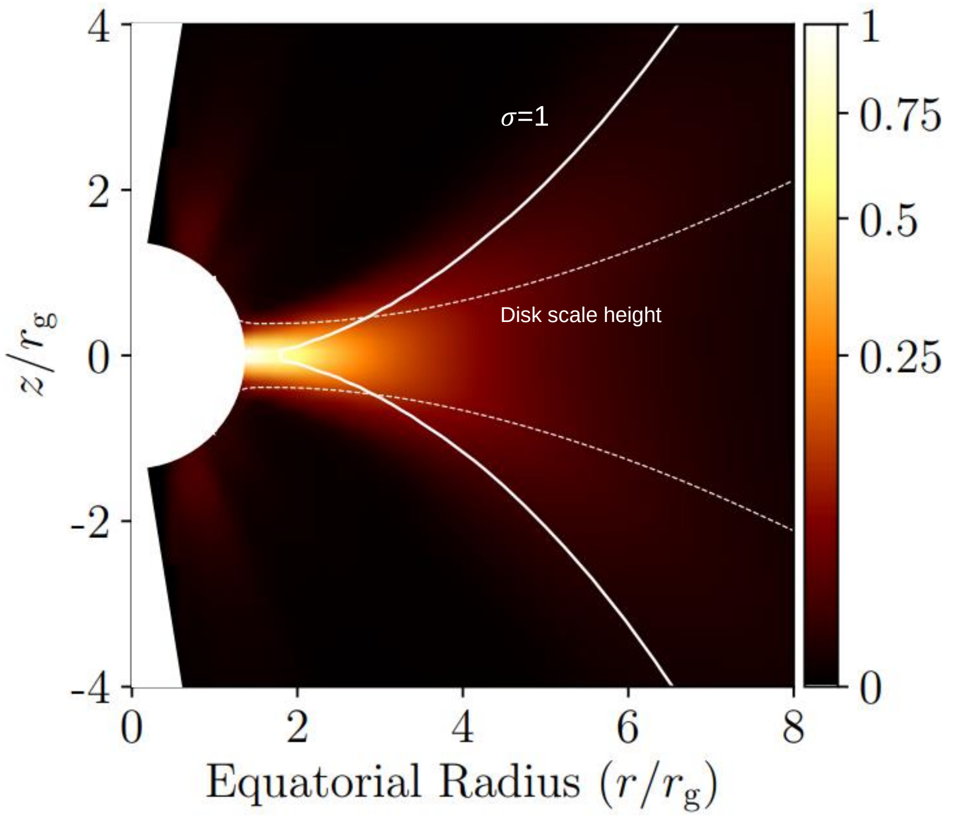
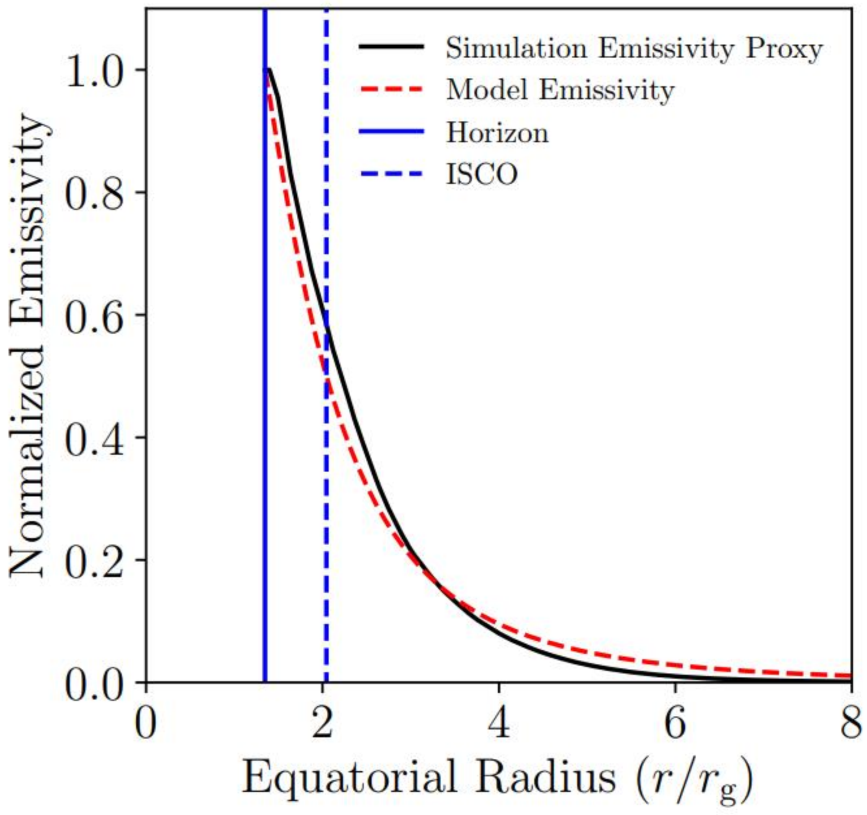
Image credit: Dokuchaev 2019 (left)
Chael+ in prep (right)

Why is the horizon visible in these simulations?

Emissivity proxy

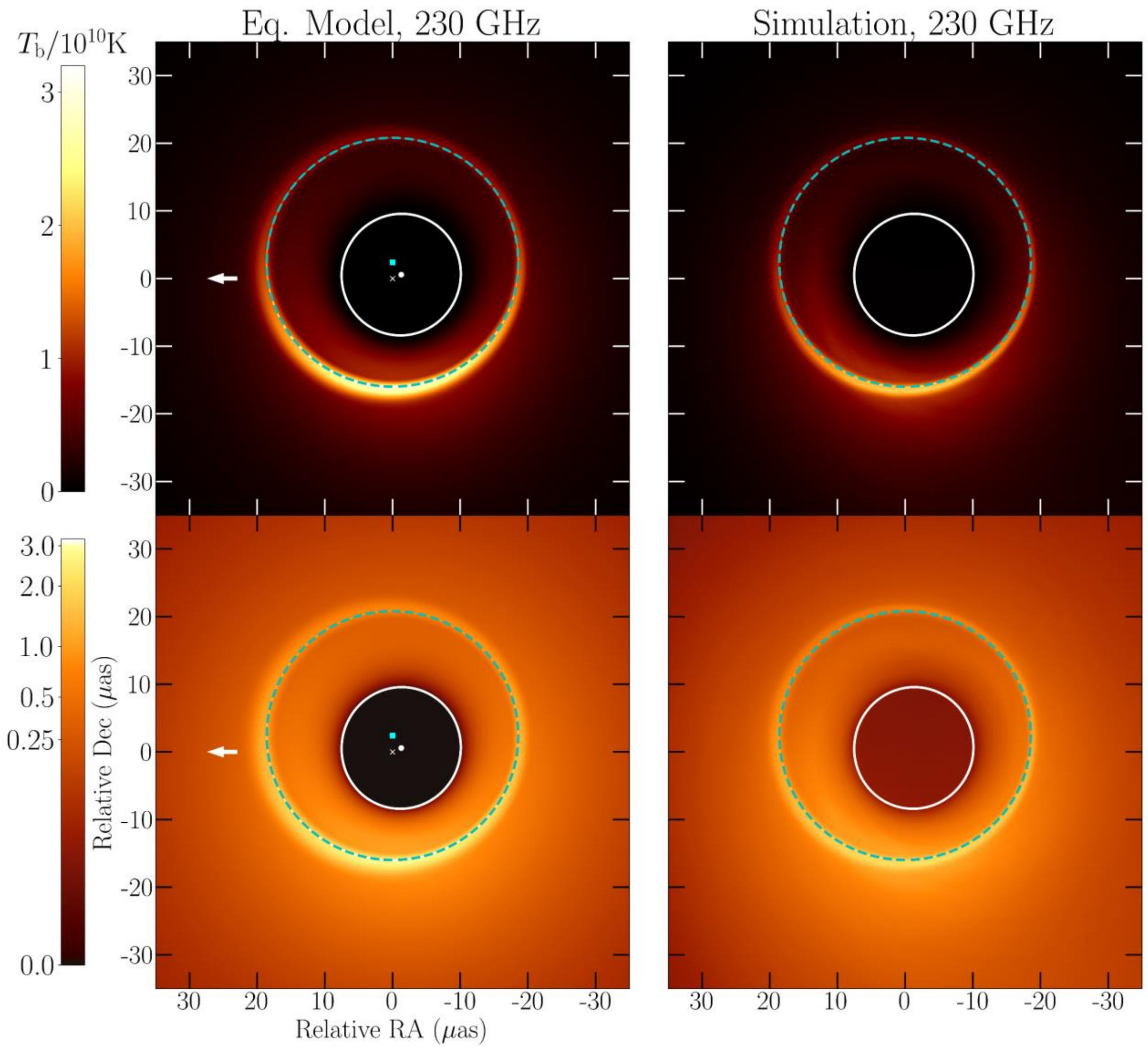




Equatorial slice

- 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 redshift

Time-averaged simulation images at high dynamic range



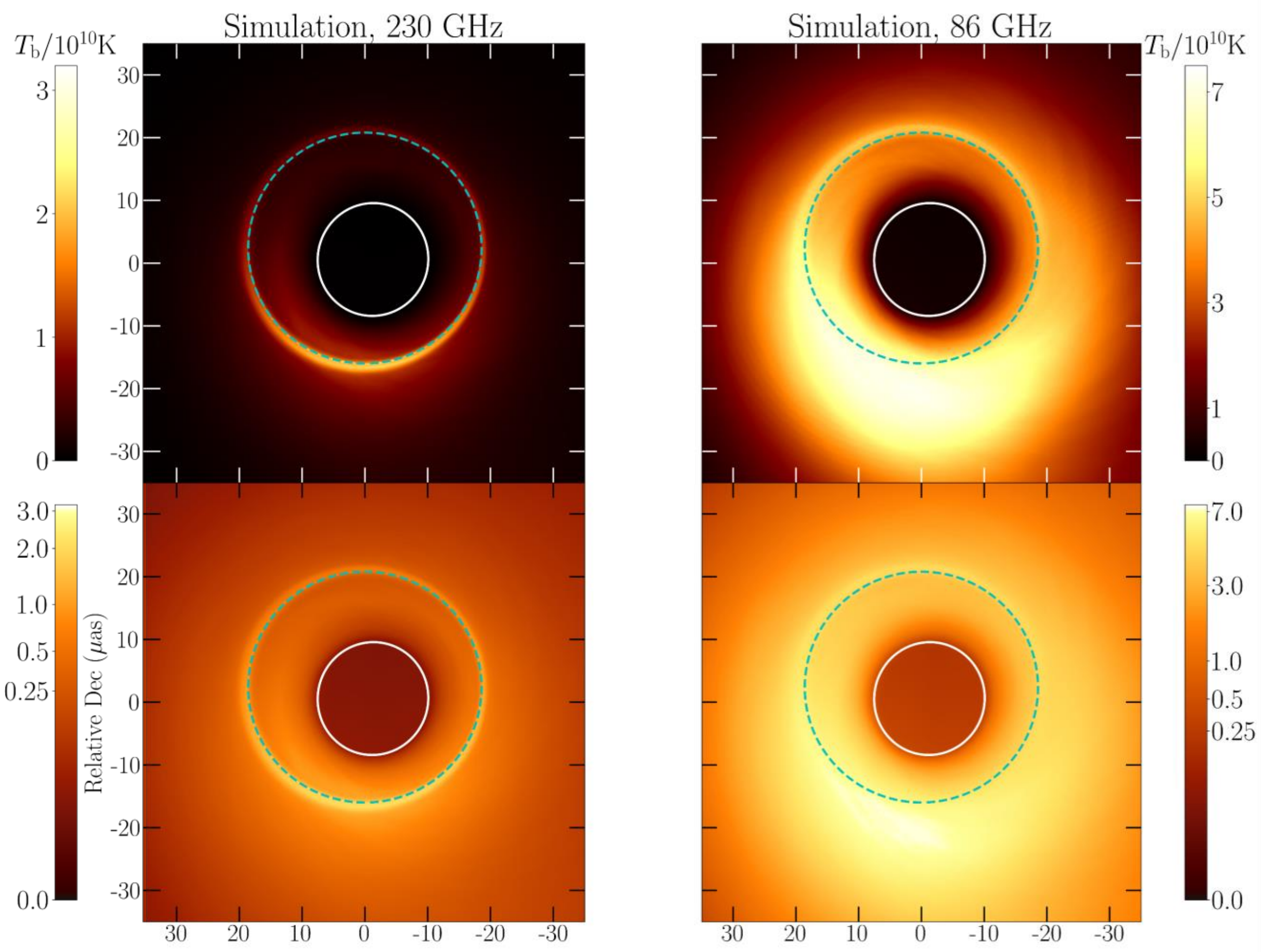
- The averaged simulation image shares the primary features of an analytic equatorial emission model (Gralla,Lupsasca,Marrone+ 2020)

- Some forward jet emission in the simulation gives the horizon image a finite “floor”

230 vs 86 GHz Simulation images

Linear scale

Gamma scale

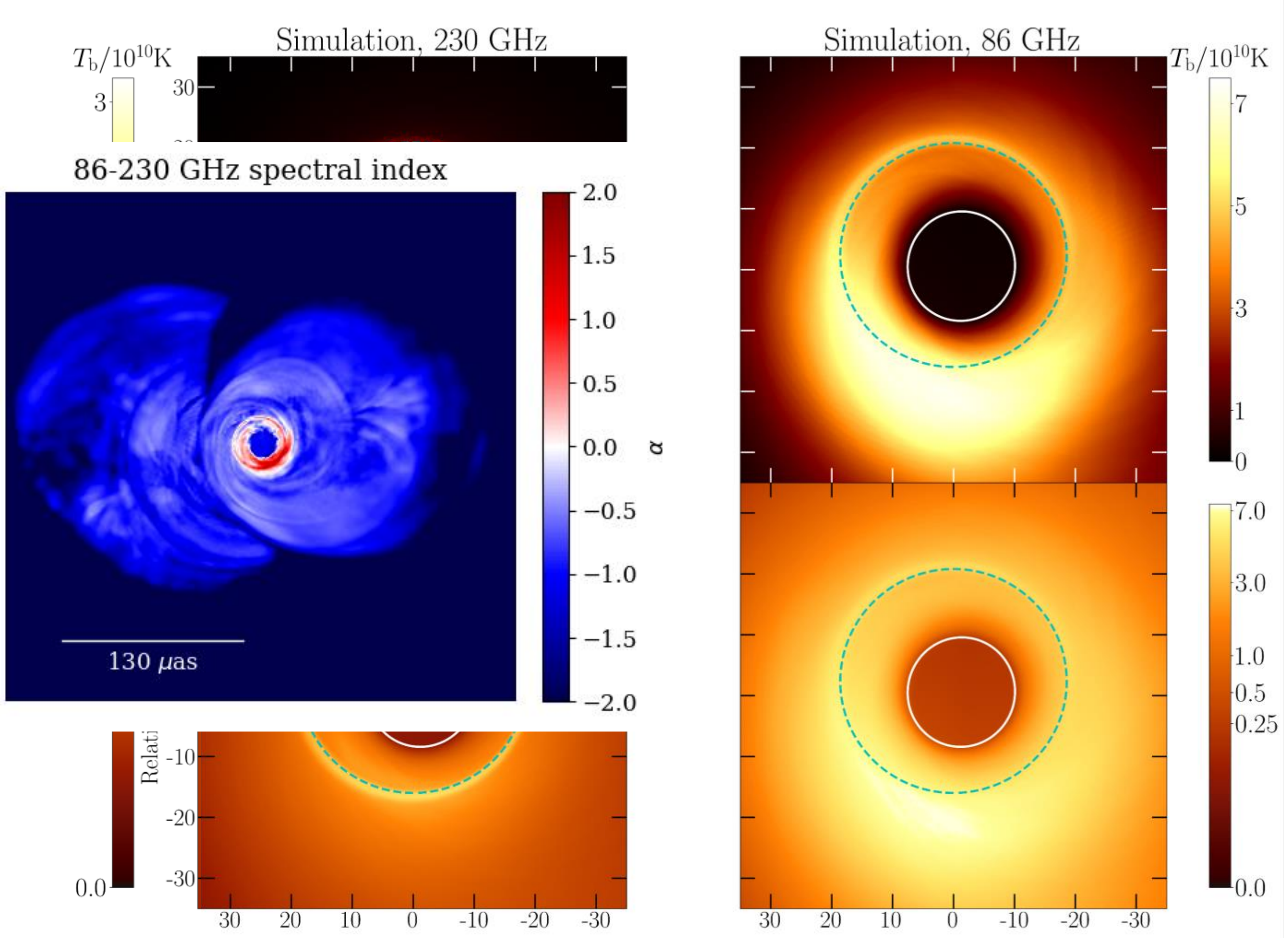


- The n=1 photon ring is supressed by optical depth at 86 GHz,
- but the n=0 lensed horizon image is not
- Optical depth doesn't matter, if the emission is primarily equatorial and not obscured by the forward jet

230 vs 86 GHz Simulation images

Linear scale

Gamma sca



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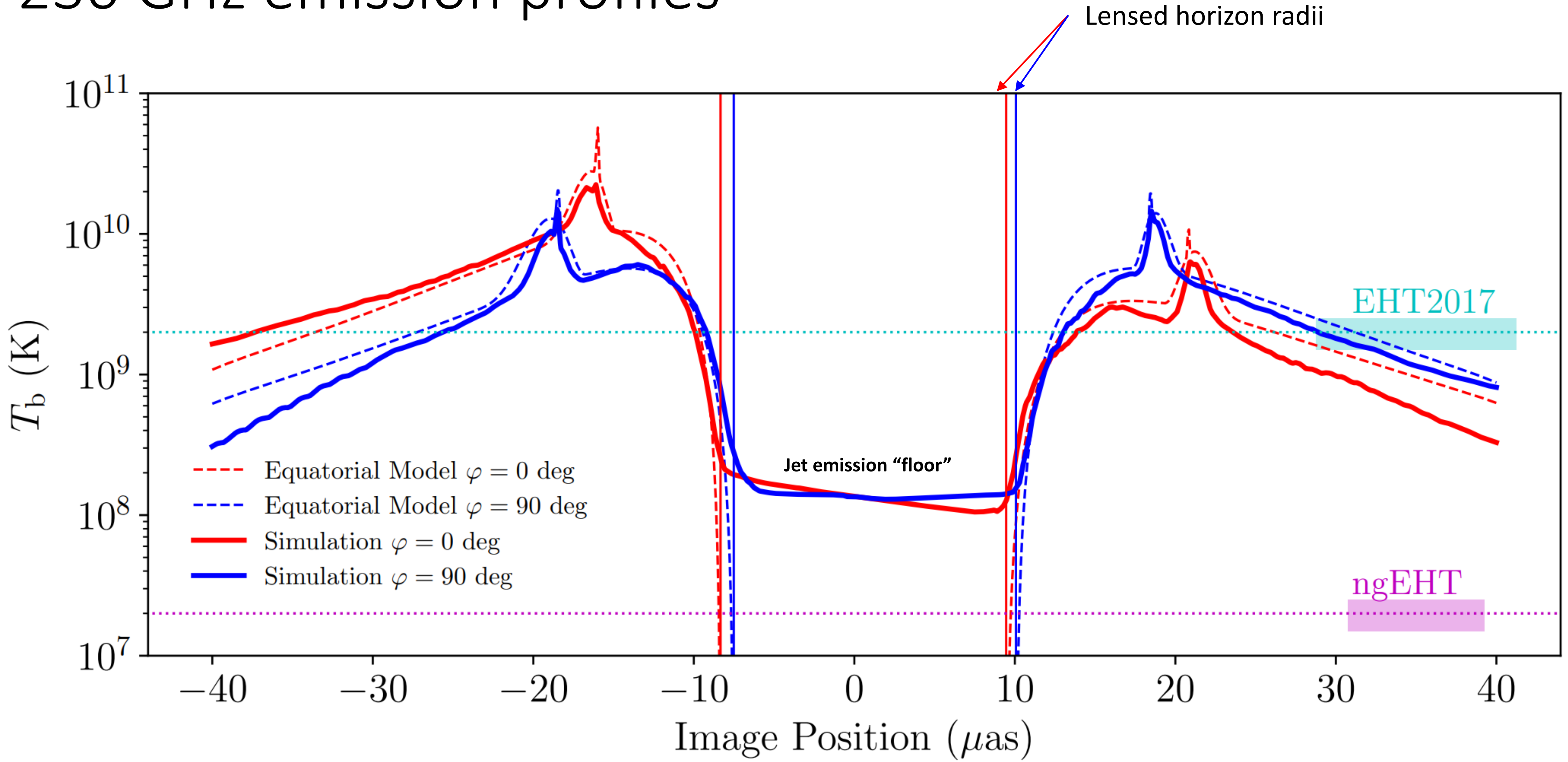
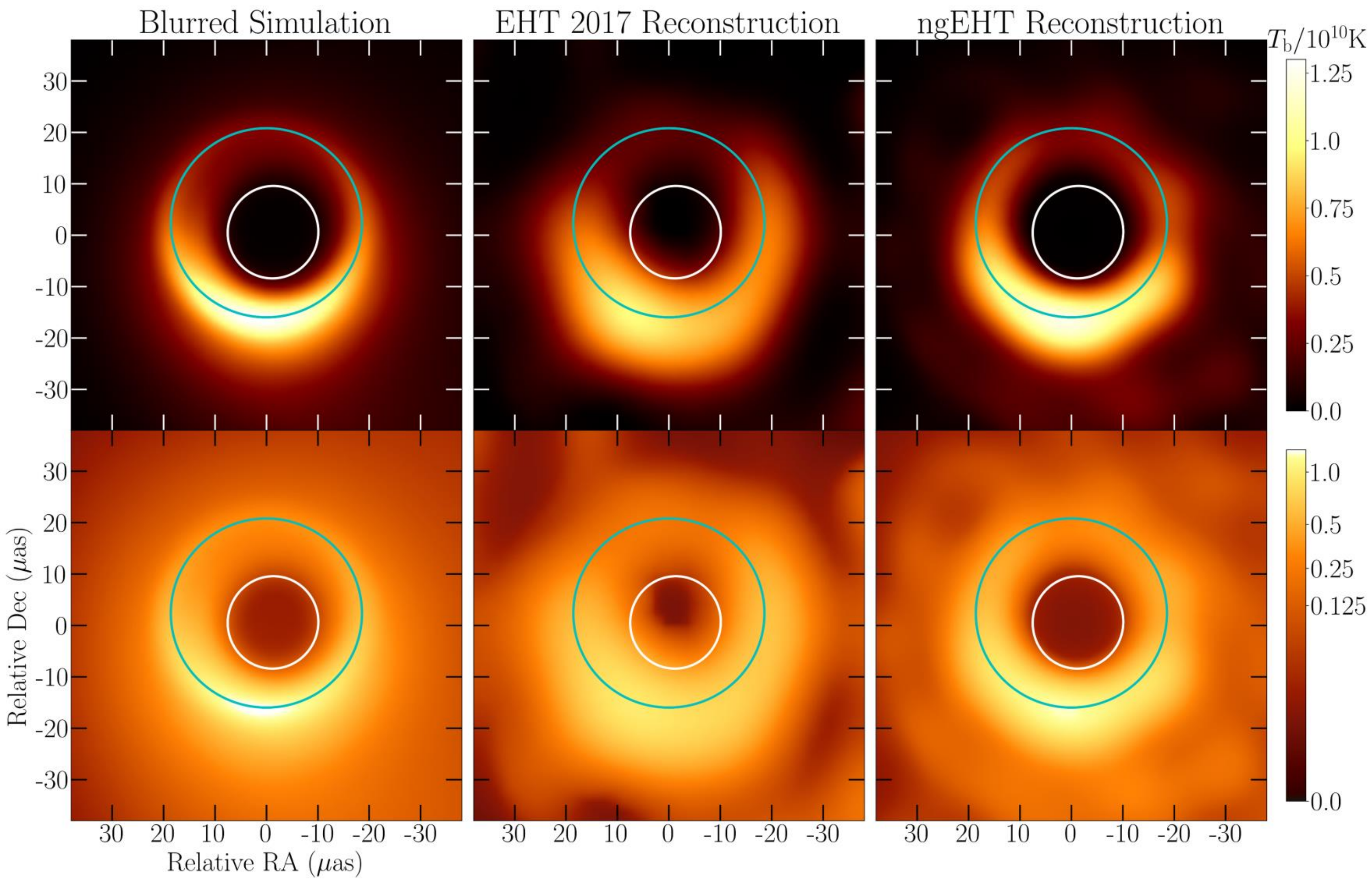
230 GHz emission profiles



The ngEHT should have the dynamic range to observe the lensed horizon feature, if present

EHT 2017 and ngEHT image reconstructions

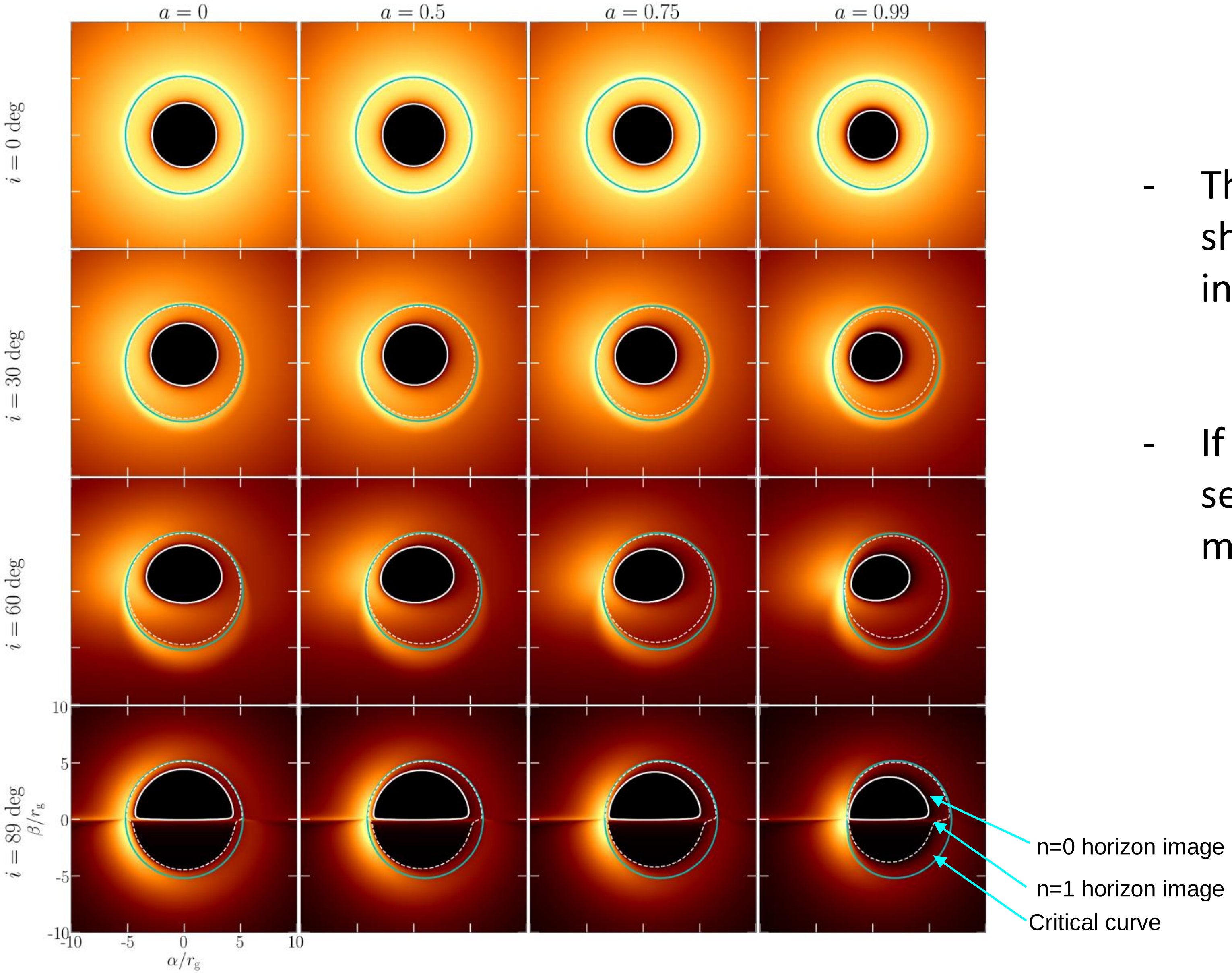


'Realistic' eht-imaging scripts using closure phases and amplitudes

But the data is from a time-averaged simulation, not a snapshot

Imaging algorithms can detect this feature in ngEHT data – analytic modeling may constrain its shape more precisely

Lensed horizon images provide another probe of spacetime



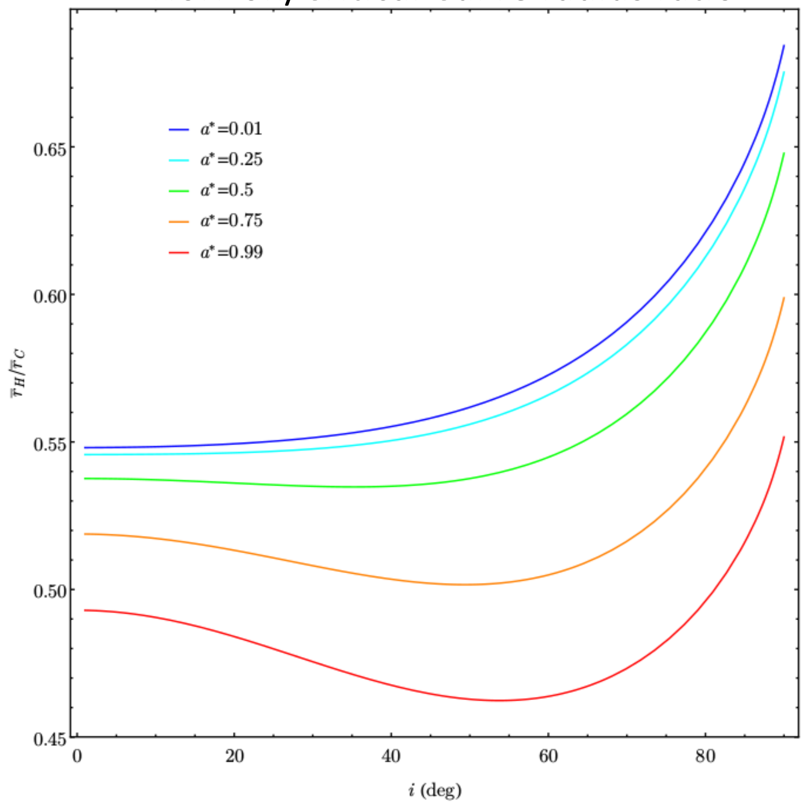
- The horizon image changes in shape and size with spin and inclination
- If observable, it would provide a second set of constraints on the metric from the n=1 photon ring

Relative centroid and relative radius

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

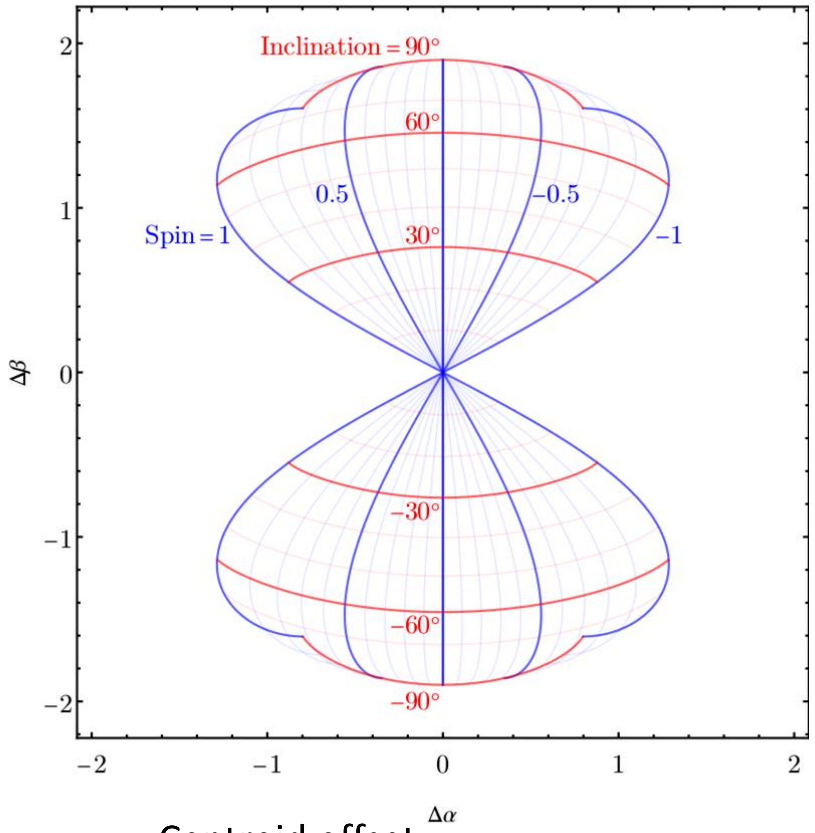
→ removes effect of uncertain mass

Horizon/Critical Curve radius ratio



At low inclination, horizon-to-shadow size Is **spin-dependent** and decreases from 55% to 49% from a=0 to a=1

Horizon-Critical Curve centroid offset

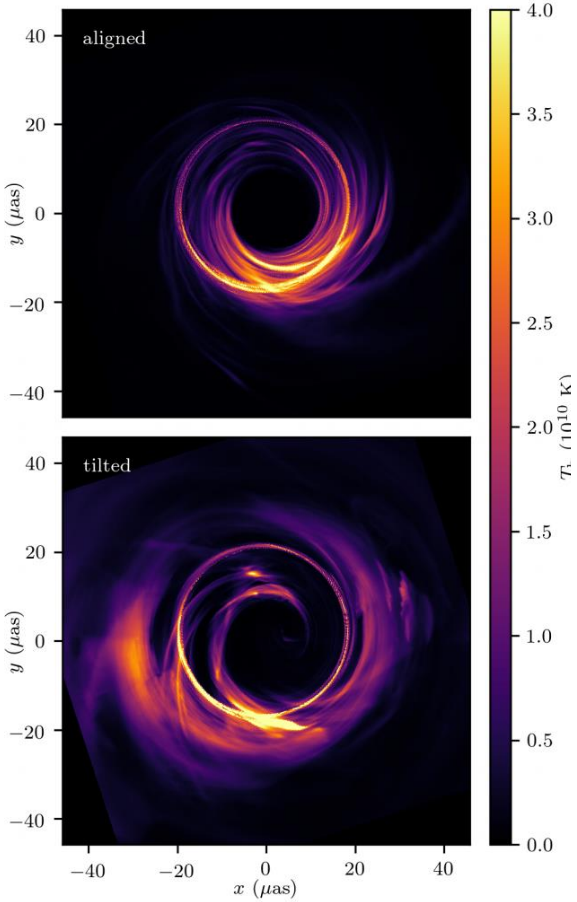


Centroid offset:
angle depends on spin,
magnitude on inclination

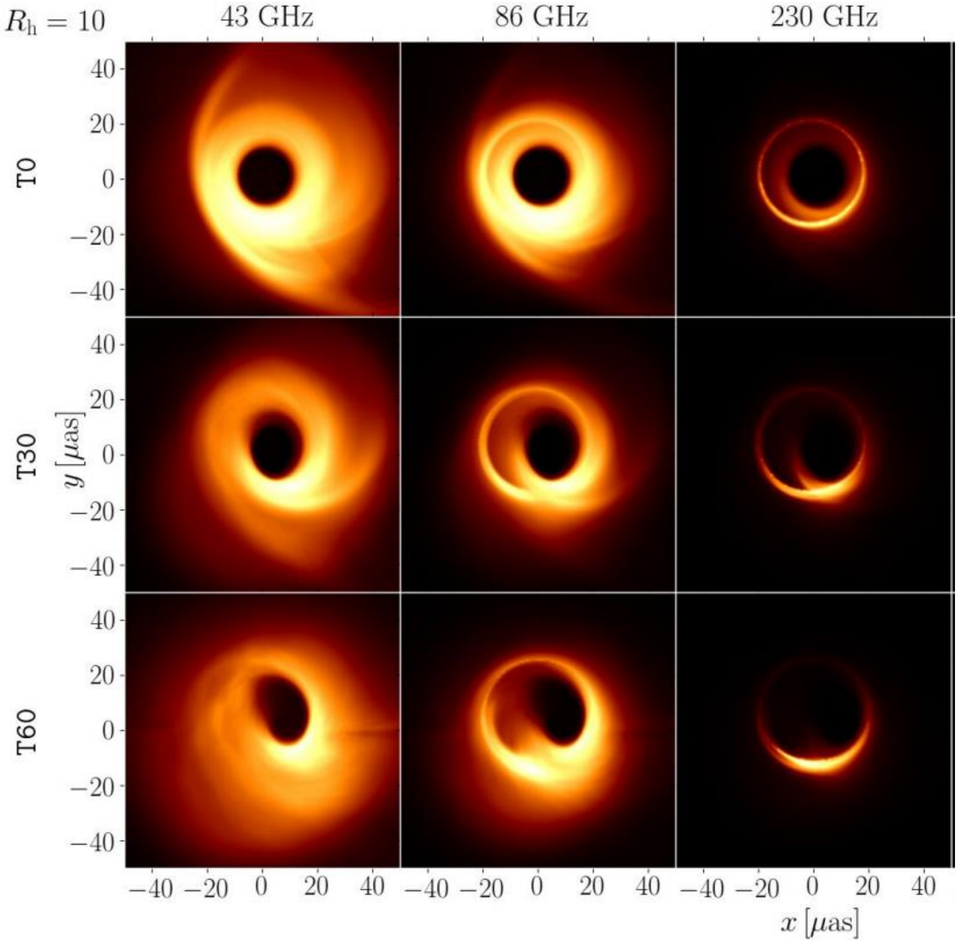
$$a \approx -1.64 \arctan\left(\pm_o 0.61 \Delta\alpha / \Delta\beta\right)$$
$$\theta_o \approx \pm_{\Delta\beta} 0.42 \sqrt{\Delta\alpha^2 + (\Delta\beta/0.61)^2}.$$

A caveat: disk tilt?

White+ 20
(230 GHz)



Chatterjee+20



Disk tilt could change the signature by moving emission outside of equatorial plane

Takeaways

1. Simulations with Radiation and Heating
   Radiative simulations with subgrid plasma physics can be powerful ways to go beyond limitations of standard GRMHD, but they come with their own issues.

2. Jets from MAD Simulations
   MADs from radiative simulations produce powerful jets that share many features with M87's. The ngEHT should be able to image the jet launching region in high dynamic range, across frequency and time.

3. Horizon Images
   These MAD simulations show a central dark depression corresponding to the lensed equatorial event horizon at multiple frequencies. If it exists in M87, this feature should be detectable by the ngEHT.

Thank you!