Title: Imaging Supermassive Black Holes and mapping spacetime

Speakers:

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

Date: May 08, 2023 - 10:15 AM

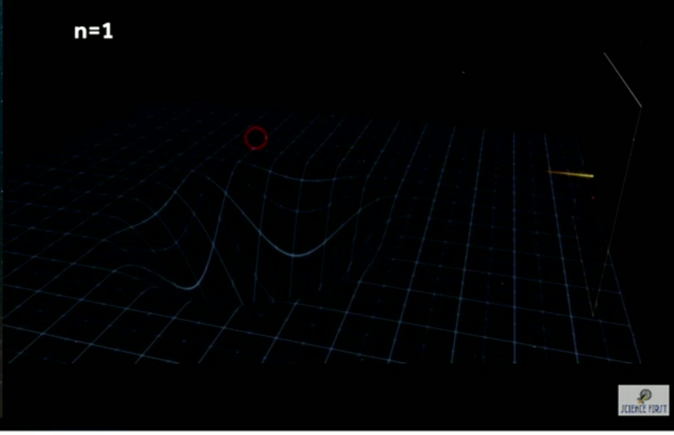
URL: https://pirsa.org/23050106

Abstract: I will give an overview of how the Event Horizon Telescope achieves its horizon scale science and what's to come. I will also review selected recent results from the Event Horizon Telescope both on Sgr A* and refined analysis of M87*. A focus will be on analysis aspects that are relevant for any theory / model building along with a few examples. The presentation aims to provide key conceptual aspects relevant to gravity experts who are new to VLBI.

Zoom Link: https://pitp.zoom.us/j/94575380034?pwd=Y21DMTRqeFFGNnd5dnVBc1dac2tUQT09

Quantum Spacetime in the Cosmos: From Conception to Reality

Perimeter Institute, May 8th



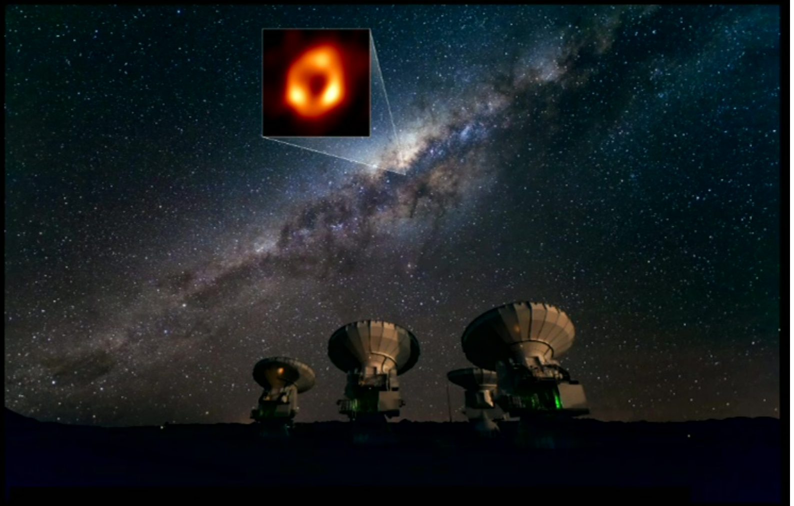
Imaging Supermassive Black Holes, mapping spacetime

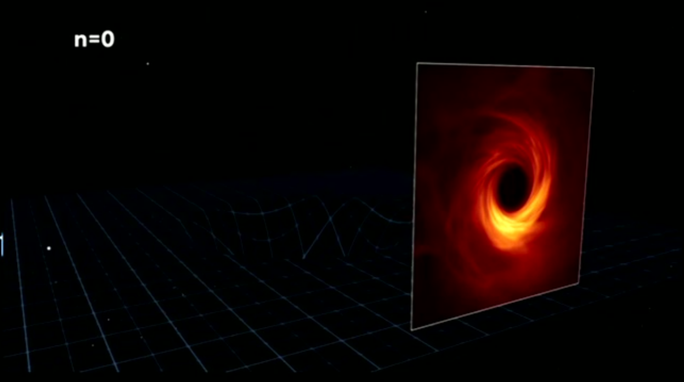
Roman Gold

UNIVERSITY OF SOUTHERN DENMARK

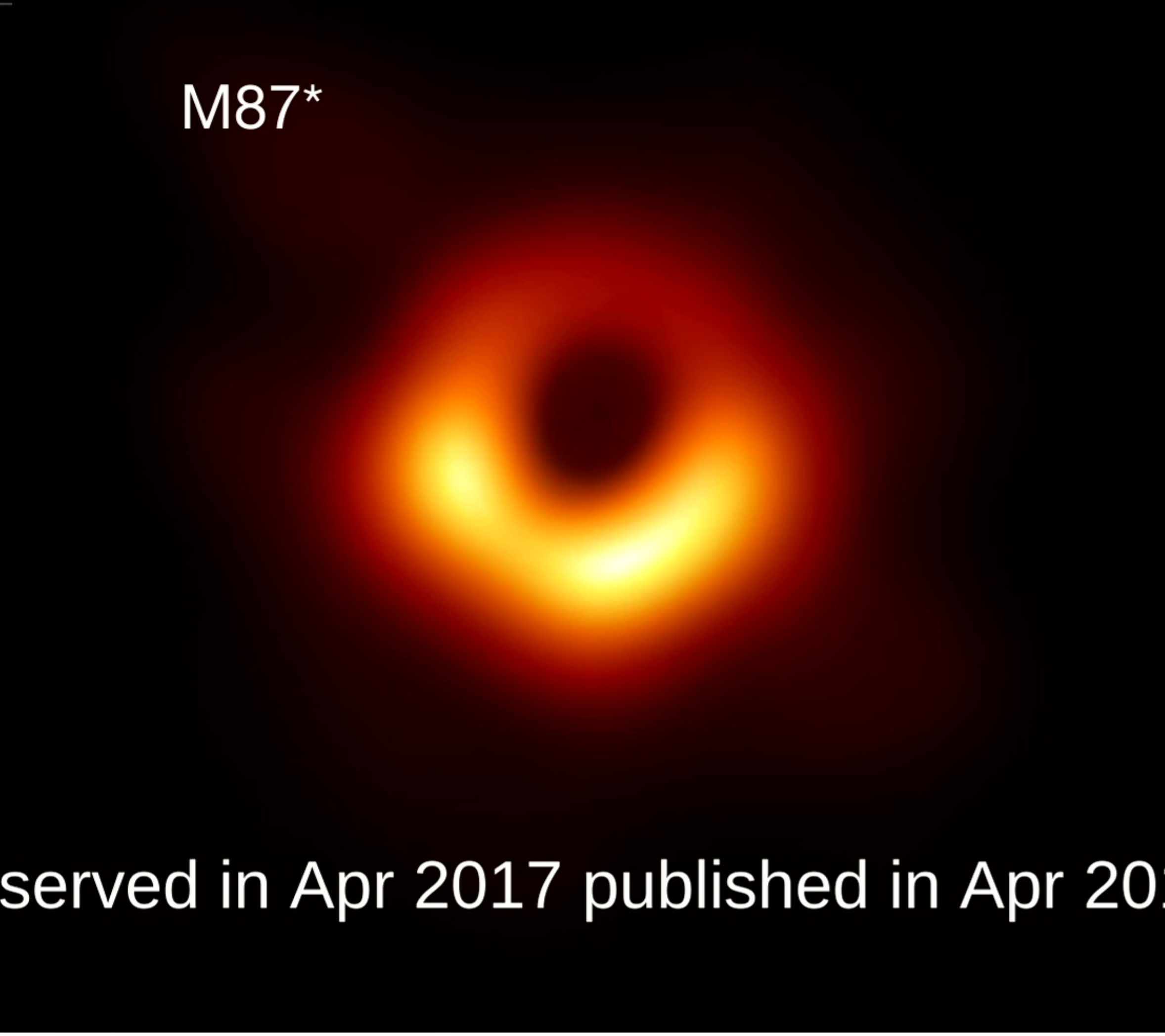
Outline

- How to take images of black holes?
  - Very-Long-Baseline Interferometry
  - Making the highest resolution image of astronomy
  - Event Horizon Telescope: Past, Present, Future
- The image isn't everything!
  - Image only one model representing the data
  - Ideally want model predictions in Fourier domain
- Why do we think that it is a black hole
  - What are we actually looking at?
  - Einstein's General Relativity
- What it all means for you:
  - Theory vs Observations -> theory ~ observations
  - Study black holes and the surrounding astrophysics in their natural habitat: ignore astrophysics and it will bi
  - Probing gravity





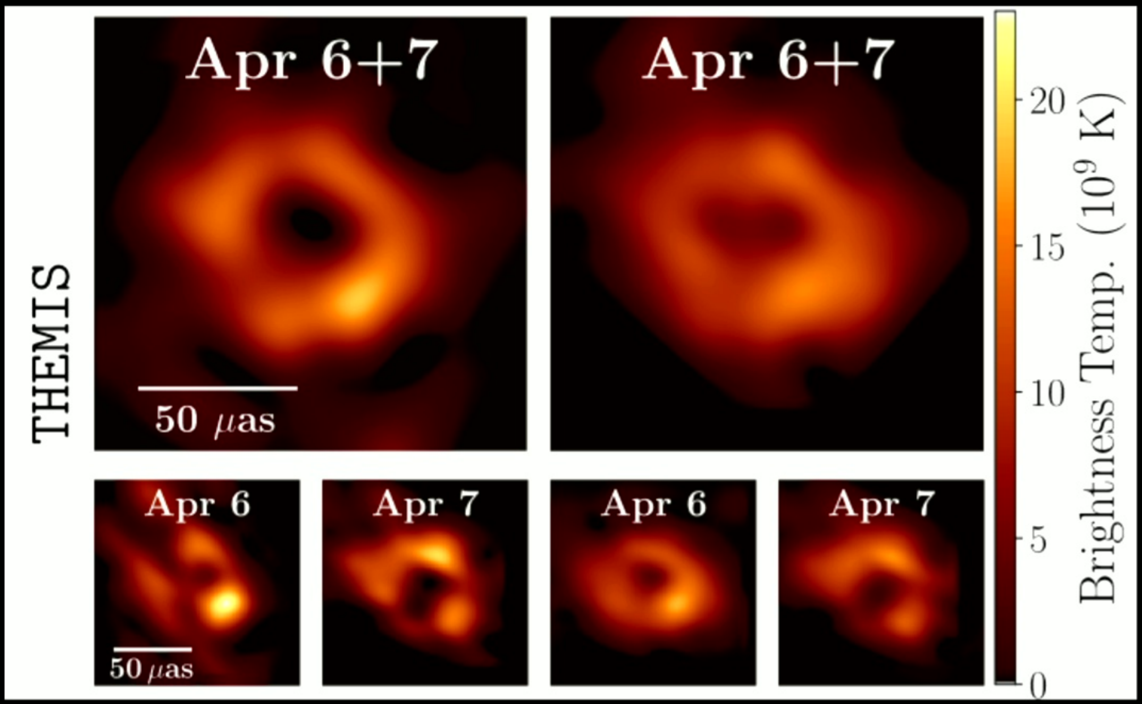
An easier case than the milky way black hole:

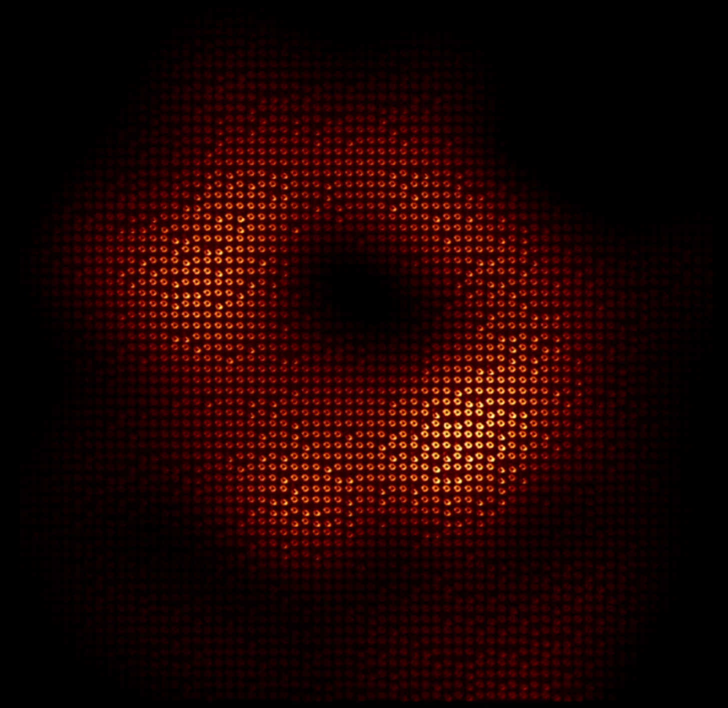


observed in Apr 2017 published in Apr 2019

New Bayesian Imaging: Imaging with an error bar!

Full image posteriors, no reliance on training sets, quantify image uncertainty





New Bayesian Imaging: Imaging with an error bar!

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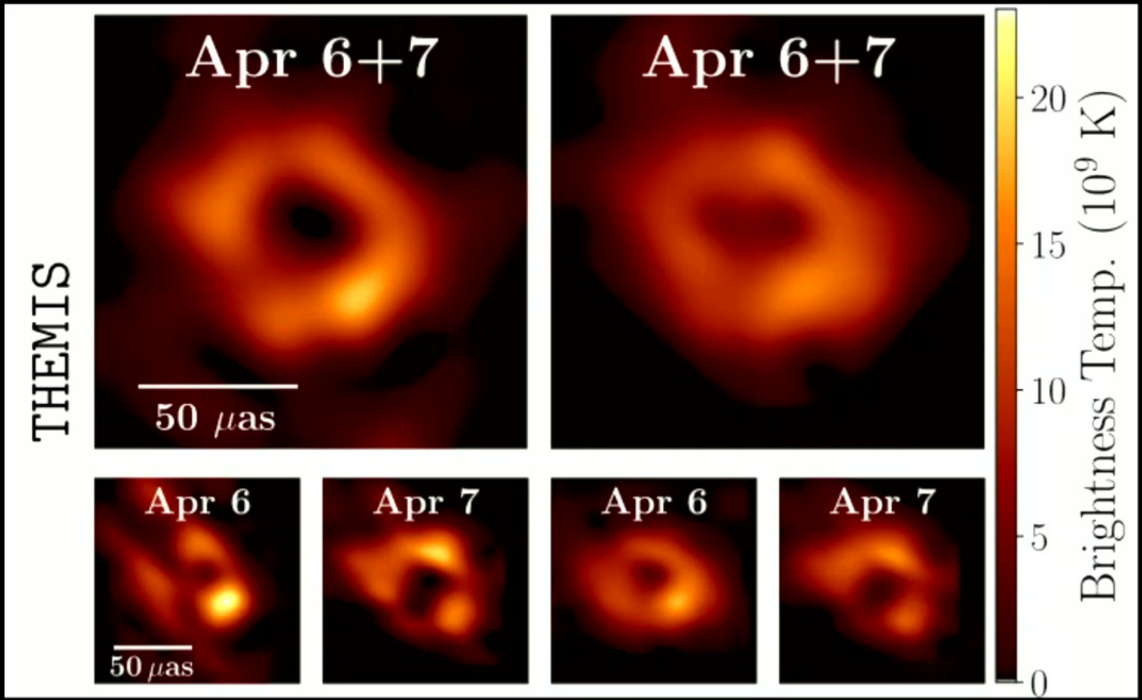
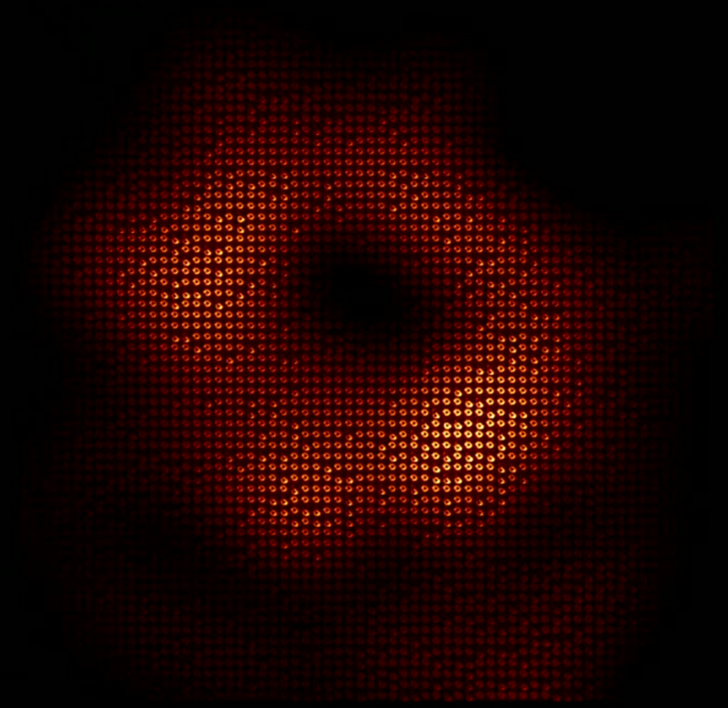
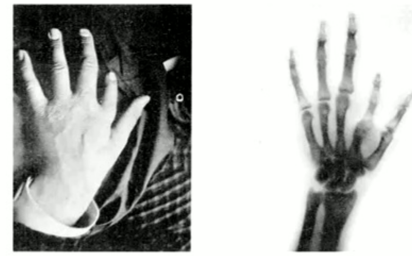
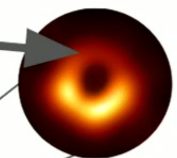




What does it take to make that image?



- **<u>Unobstructed view</u>**: Use light with a **<u>wavelength</u>** that reveals the black hole
- ~40 microarcsond **<u>resolution</u>**
  - ~ separating 2 golf balls on the moon
  - ~ read a newspaper in LA from New York

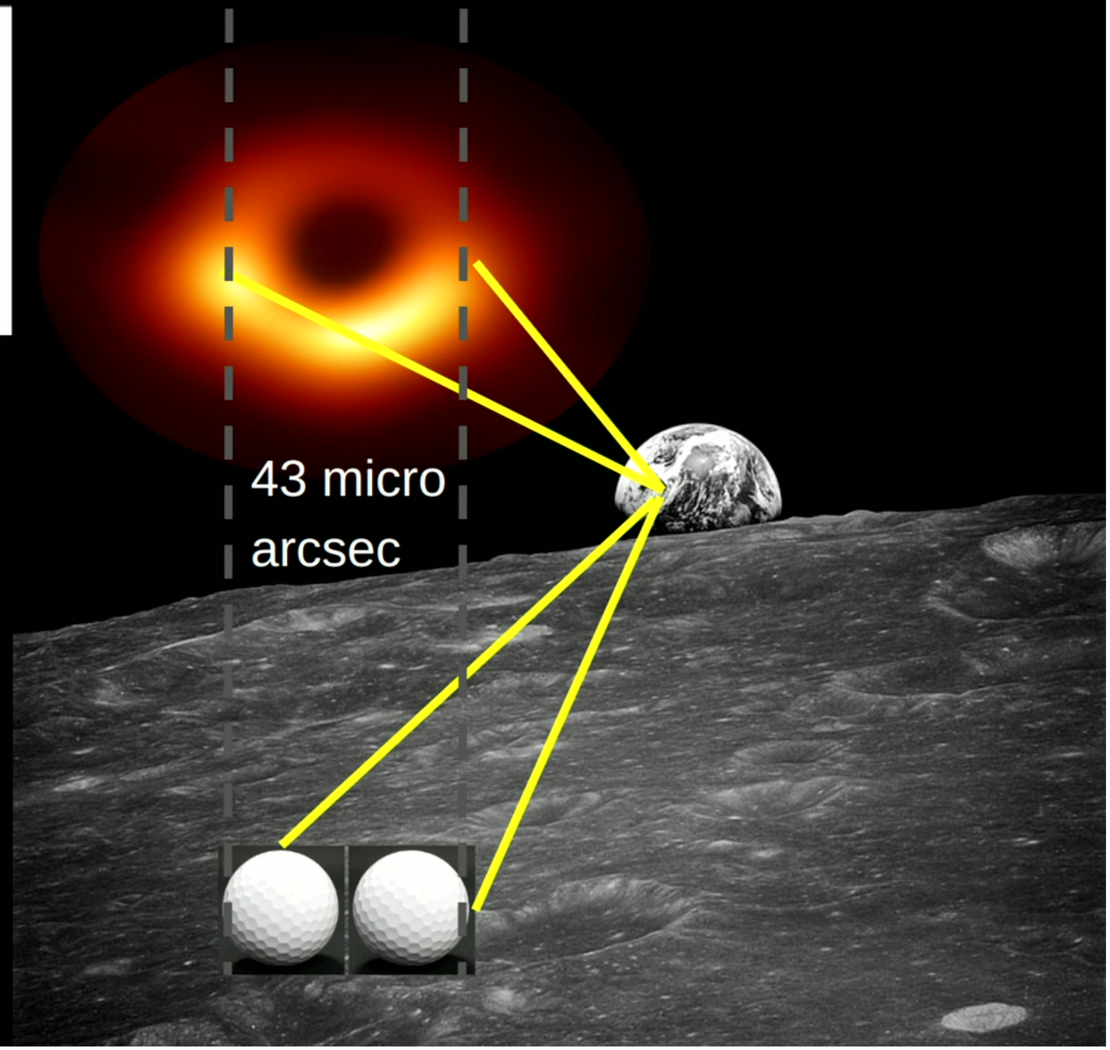


- -> **<u>Telescope needs as big as Earth</u>**…
  $\boldsymbol{\Delta\theta} \sim 1.22\boldsymbol{\lambda}/D$ -> for $\boldsymbol{\lambda} \sim 1.3$mm D ~ Size of Earth
  Cannot build Radio telescopes this big …
  But: We can **<u>combine distant telescopes to form an interferometer</u>**

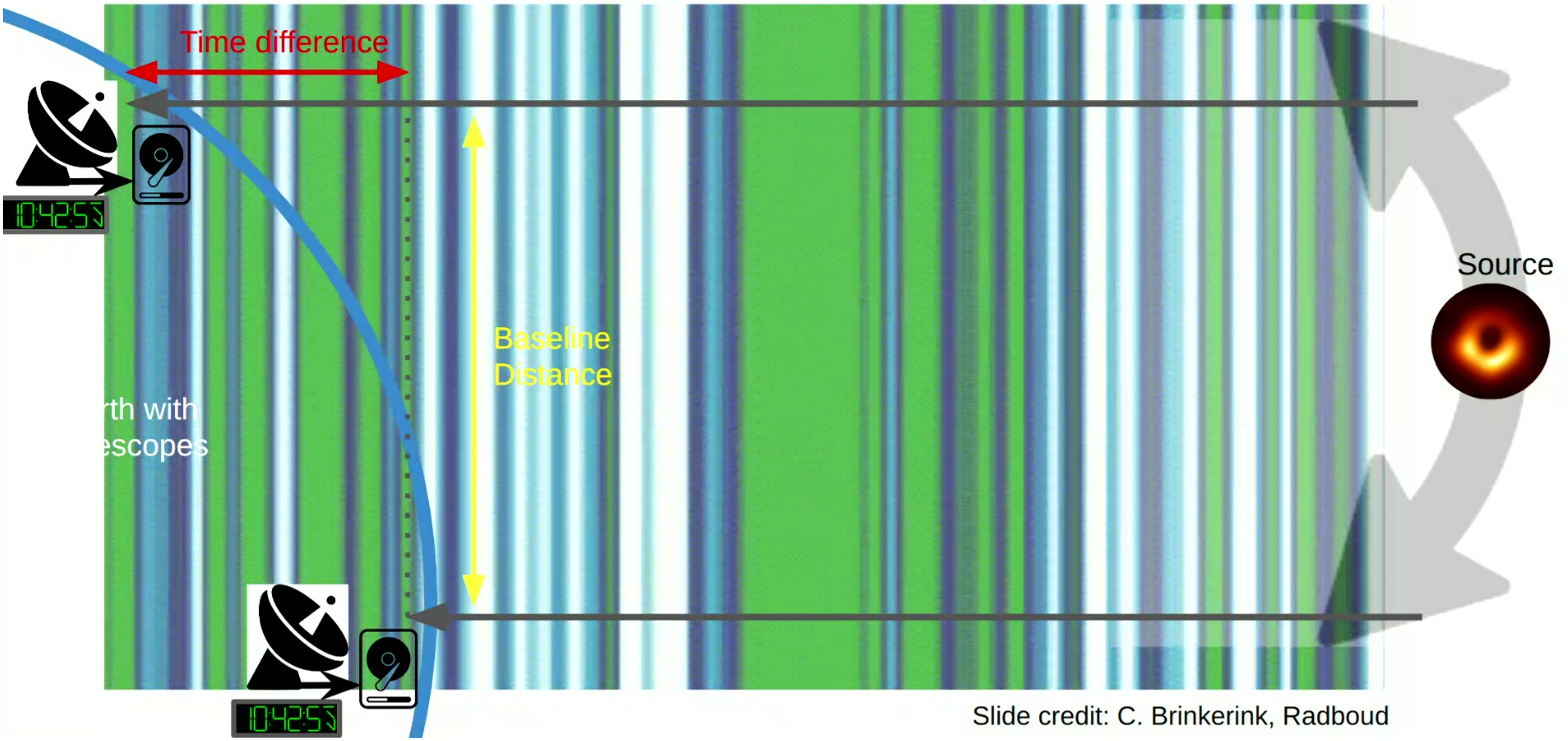
- **<u>Sensitivity and telescope coverage</u>**
- **<u>Algorithms</u>**

The highest resolution image ever made

43 micro arcsec
= 0.000000000208 rad
“Like resolving two golf balls on
the moon from Earth”

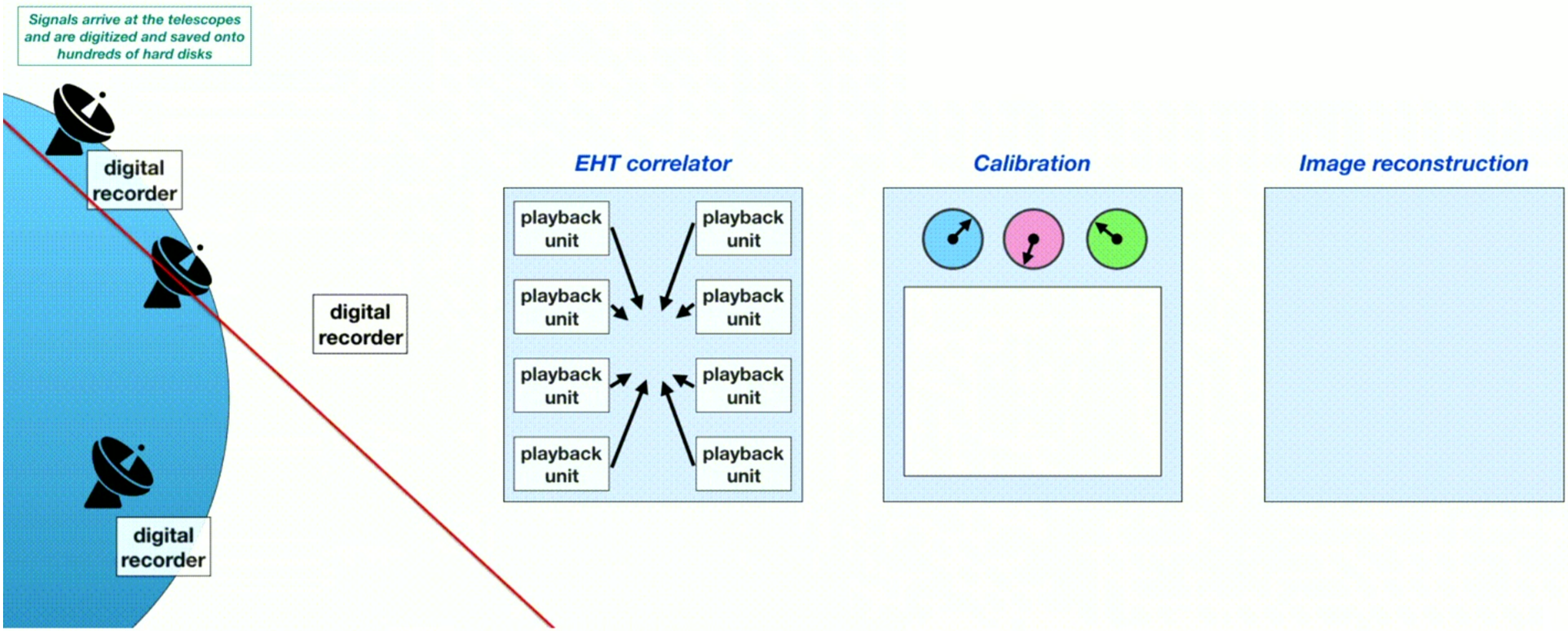


A Telescope as big as Earth: Very Long Baseline Interferometry



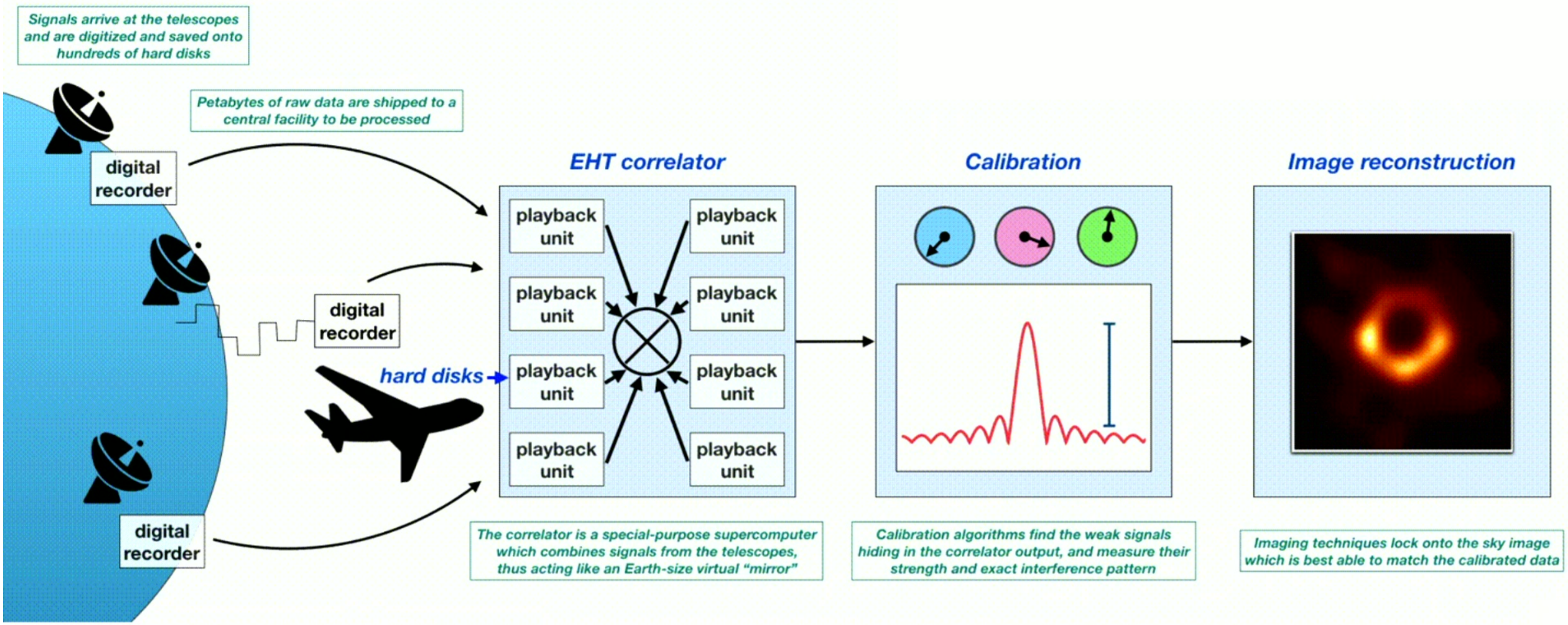
Slide credit: C. Brinkerink, Radboud

The data path from observation to image



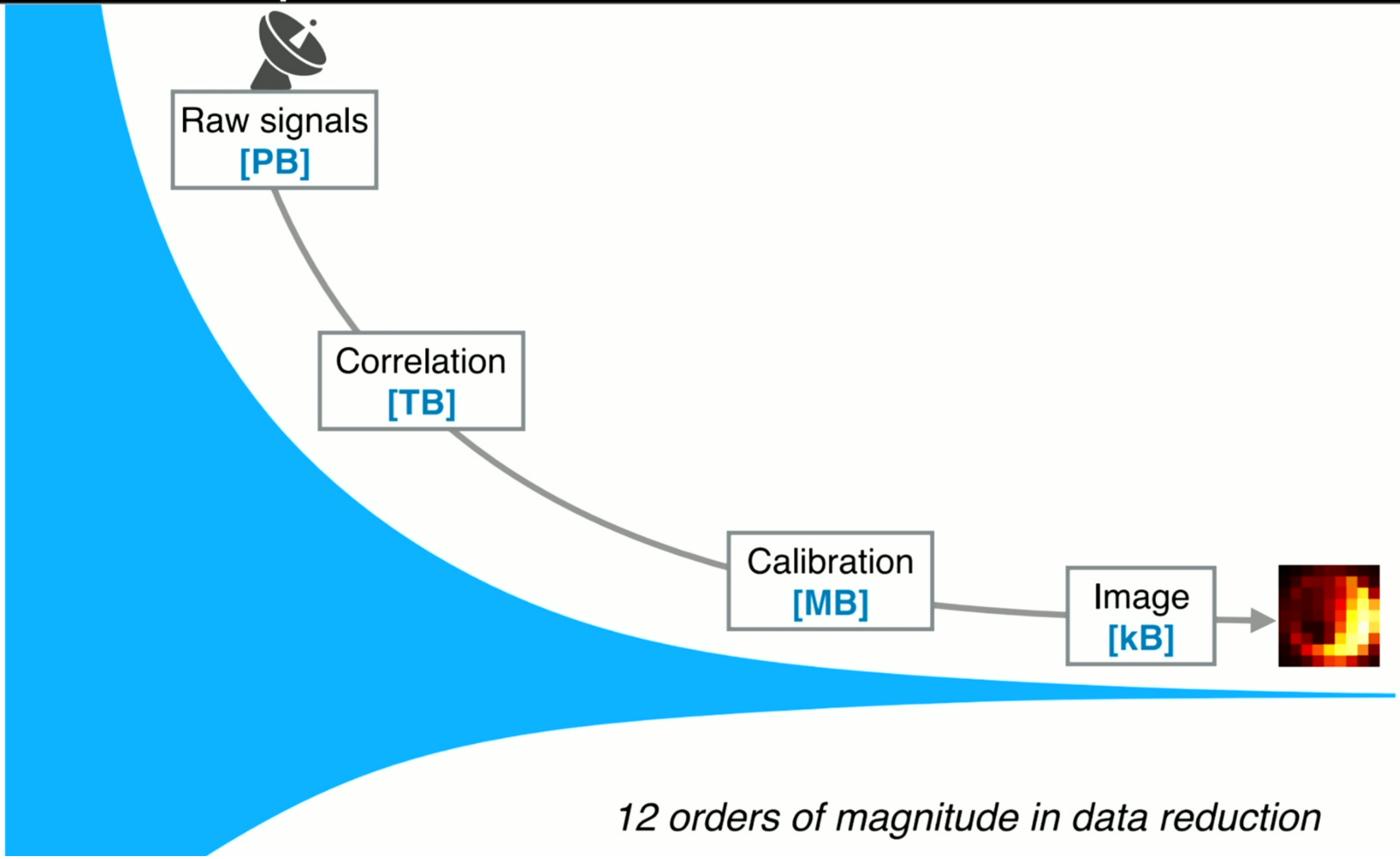
PBs -> GB -> MB -> KB

The data path from observation to image



PBs -> GB -> MB -> KB

The data path



Interferometry

Interferometry is a powerful tool in astronomy that links together one or more pairs of radio antennas, even those thousands of kilometers apart, to create a new and vastly more powerful "virtual" telescope called an interferometer.

Interferometers harness the space between the antennas: the **larger the spacings, the higher the resolving power,** allowing it to see finer and finer details, like the zoom lens of a camera.

How Is This Done?

Astronomers reconstruct images of an object in space using interferometers, telescopes that observe the Fourier transform of an object's brightness pattern on the sky.

Inteference Pattern

Wave patterns from an interferometer are similar to the wave patterns created when light passes through a pair of slits. In radio astronomy, the antenna pair takes the place of the two slits, but the resulting patterns are similar.

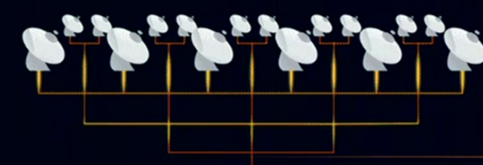
Fourier Transform

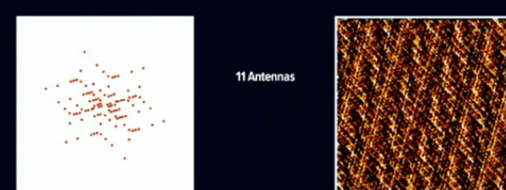
The Fourier transform is a mathematical tool that deconstructs any signal into a sum of sine waves.

A sine wave in 2 dimentions looks like a set of stripes

More Antennas = Clearer Picture

Turning this pattern into an image takes many hours of observations. Like a time-lapse exposure, this slowly builds up an image of even a very dim source. It also allows Earth's rotation to, in effect, fill in the empty spaces in the array to produce a more complete picture.





The signals received at each antenna must be matched wave for wave, even for antennas that are half a world away. Atomic clocks at each site allow for their observations to be mathematically combined using a specialized supercomputer called a **correlator.**

Measurements in Fourier space reconstructed image

Perfect world
(Earth entirely covered by Radio telescopes)

Only widely separated telescopes:

Only nearby telescopes

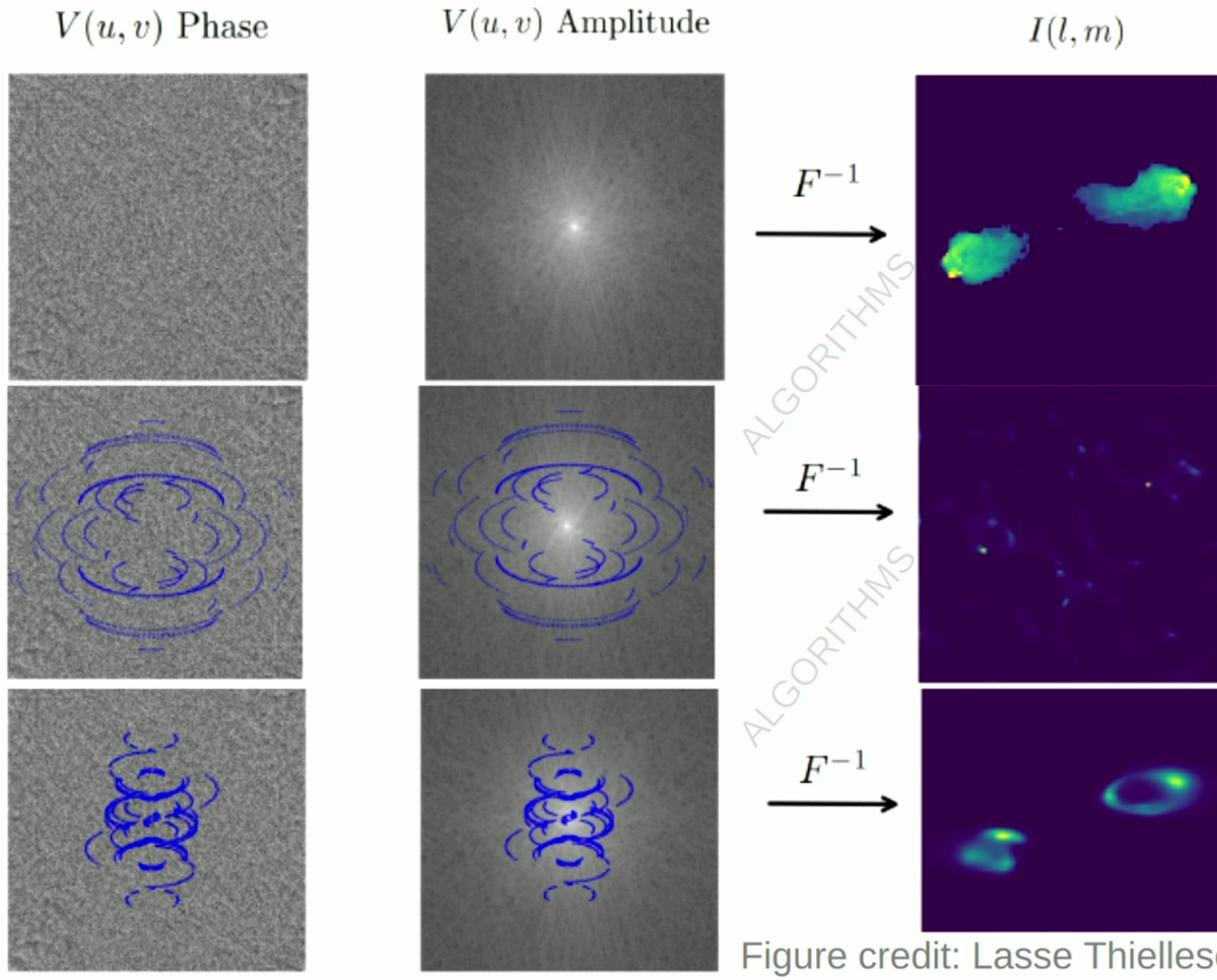
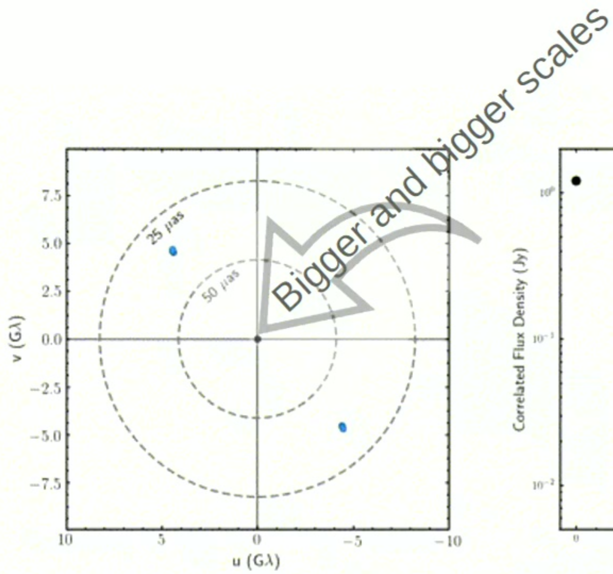


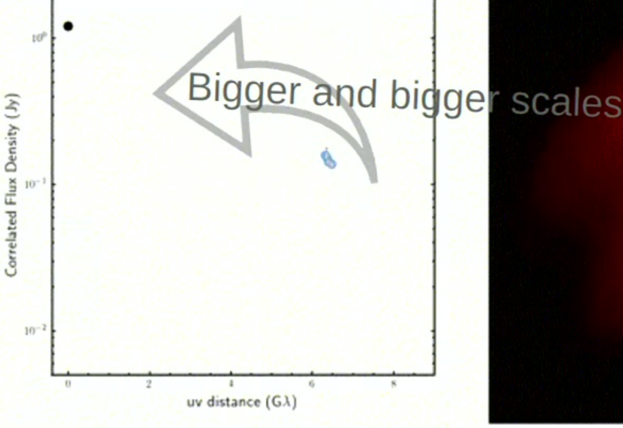
Figure credit: Lasse Thiellesen

One observing night: Earth rotation helps!

Lines between telescopes rotate with Earth thereby probing different image structures



When 2 telescopes both see the source we probe its structure (in the Fourier domain)



Each data point probes different size scales in the image

imaging ***algorithms*** reconstruct an image from the sparse data

Simulation Credit: D. Palumbo, M. Wielgus

Meet the Telescopes

Photos: ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann, David Sanchez, Daniel Michalik, Jonathan Weintroub, William Montgomerie

Meet the Telescopes

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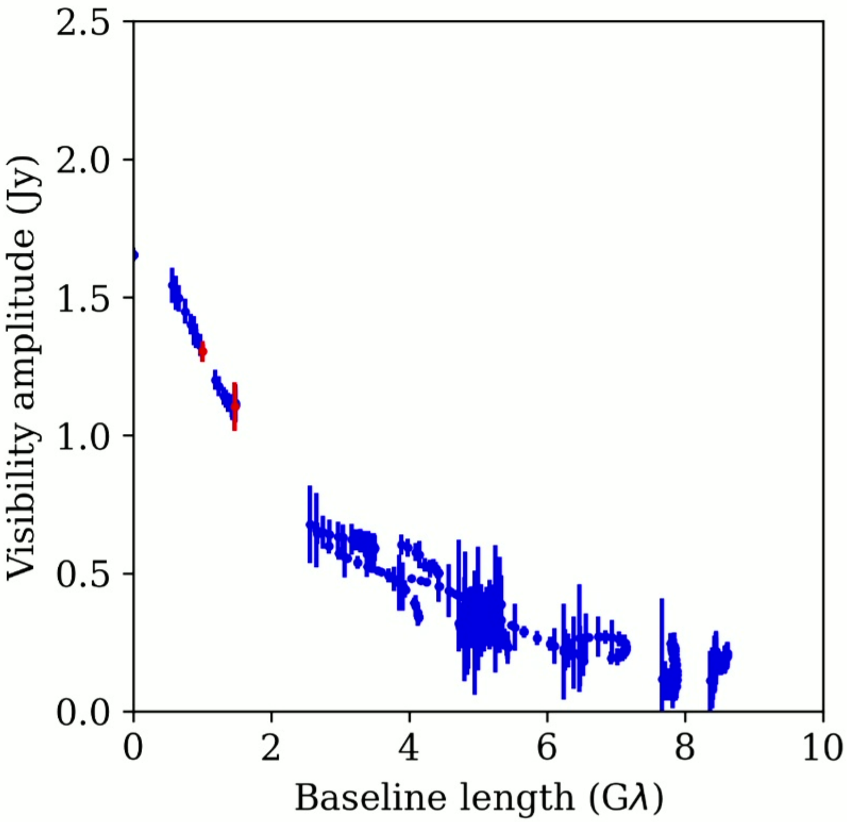
Future: EHT, ngEHT, …

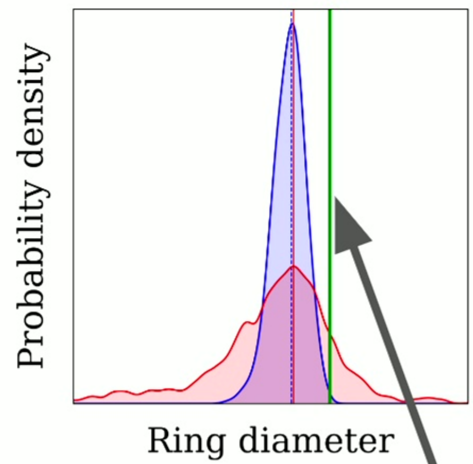
- More stations being added (3 more in 2021 compare to 2017)
  - ~10 new stations for ngEHT by ~2032
- Other improvements:
  - 230GHz -> 230+345GHz
  - Maybe even 690GHz further down the road
  - Sensitivity enhancements, eg. by multifrequency phase-transfer [Rioja et al 2023]
  - Improved pointing, dish surface smoothness, improved calibration, …
  - GLT move to Greenland summit by 2027/2028?
- Space-VLBI?
- Bottom line:
  - ~50% improvement in direct angular resolution
  - Improvements in Signal-to-noise (leading to more effective super resolution capabilities)
  - Overall better data quality (improved systematics)
  - More telescope coverage (faster images: Sgr A*)
  - Monitoring

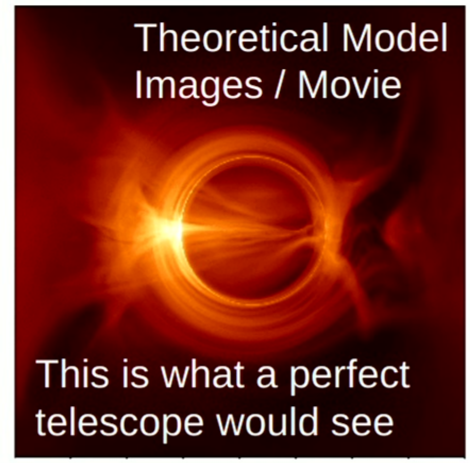
Why is Imaging the black hole in our galaxy harder?

- Mass sets gravitational time scale: **Sgr A* changes faster than M87***
  - Appearance of the black hole in M87* changes after ~7 hours (slightly)
  - This means that the image basically remains the same while we make a picture
    It takes us a whole night to make one still image
  - Appearance of the black hole in Sgr A* (our galaxy) changes after 20secs !!!
  - If we make an image over one entire night, the image will have changed many times!
- Refractive scattering: More intervening gas disturbs signal, needs correction

Why is variability mitigation necessary?







key issue:
unmitigated variability impacts scientific measurements

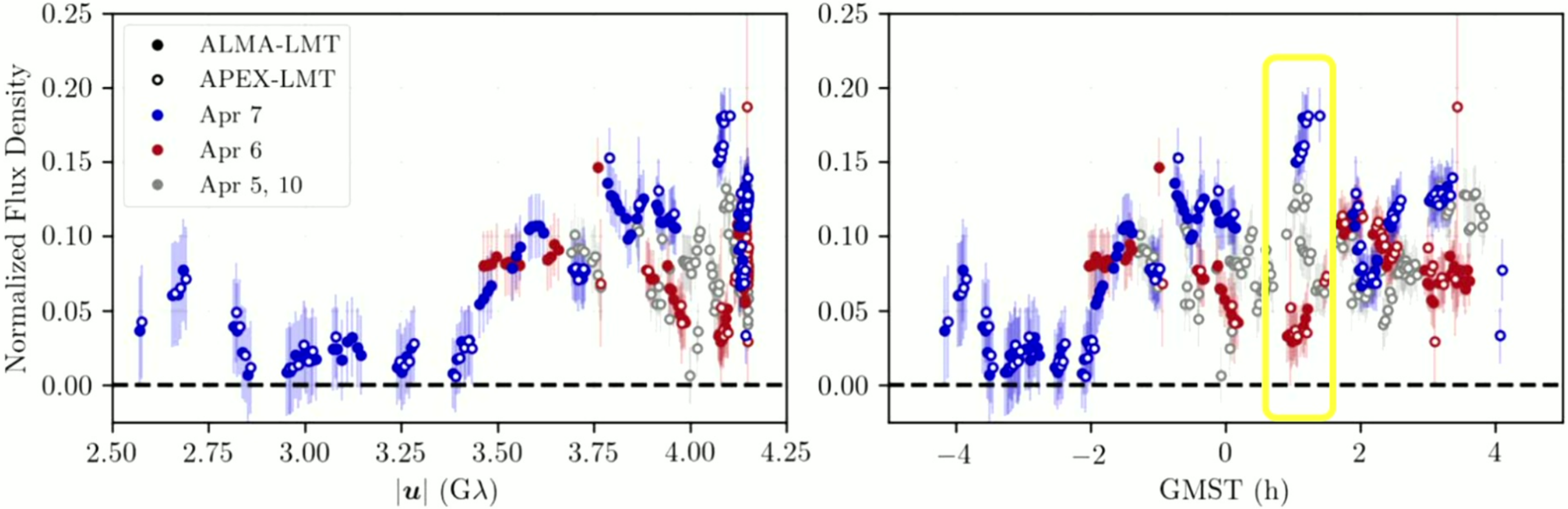
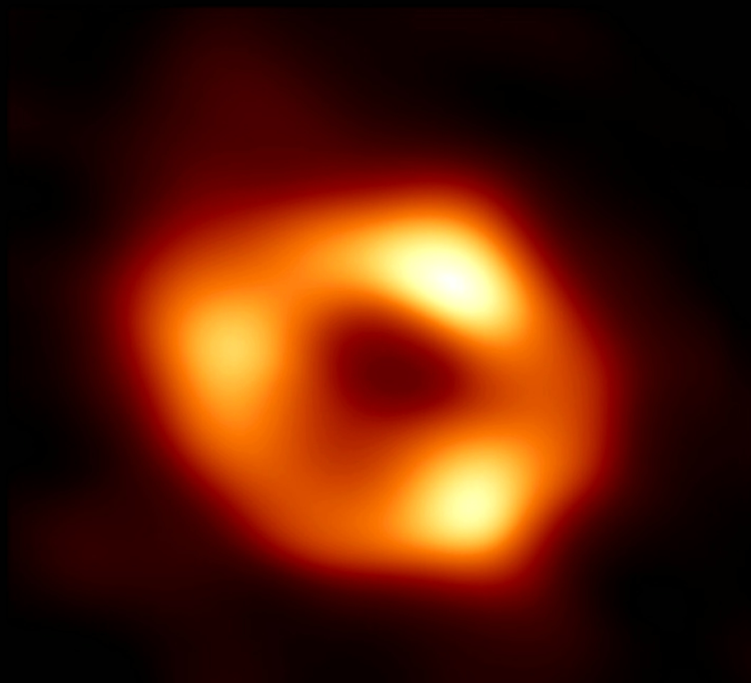


Figure 24. Visibility amplitudes from the HOPS low-band Sgr A* data set, averaged coherently over 120 s segments, on Apr 6 (red), April 7 (blue), and April 5 and 10 (gray) on the Chile-LMT baselines as functions of baseline length (left) and observing time (right). Error bars indicate the error implied by the mean noise model and are intended to account for fluctuations due to variability in addition to statistical and known systematic error components.

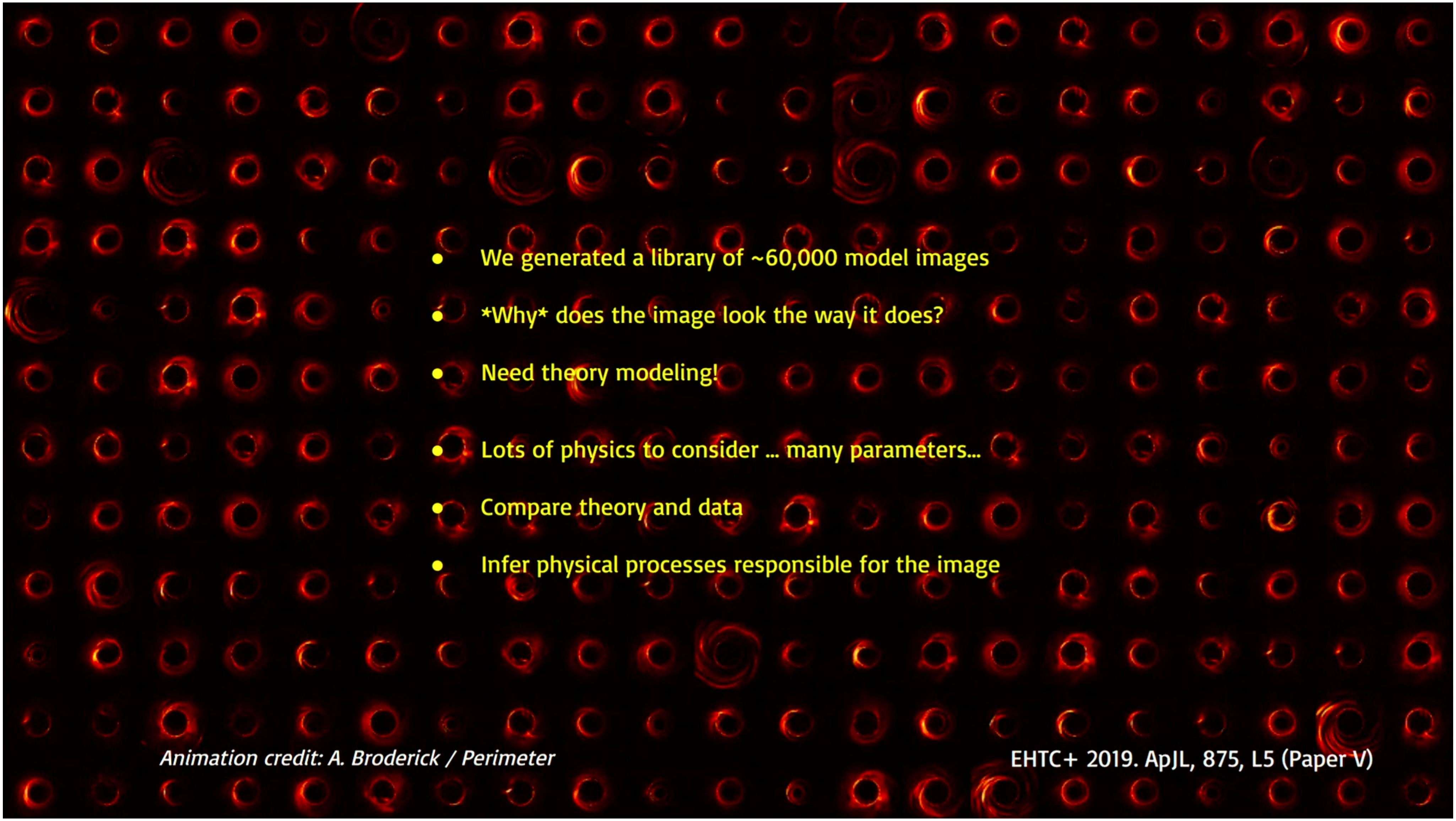
Why do we think it is a black hole?



Independent observations and lots of theoretical work! And more work is needed!

Black holes are *consistent with all we see* and the *most conservative interpretation*

Not the final word: Black holes have issues too (singularities) … Quantum gravity …


• We generated a library of ~60,000 model images
• *Why* does the image look the way it does?
• Need theory modeling!
• Lots of physics to consider … many parameters…
• Compare theory and data
• Infer physical processes responsible for the image
Animation credit: A. Broderick / Perimeter
EHTC+ 2019. ApJL, 875, L5 (Paper V)

First Sgr A* Event Horizon Telescope Results. IV. Variability, morphology, and black hole mass

Variability

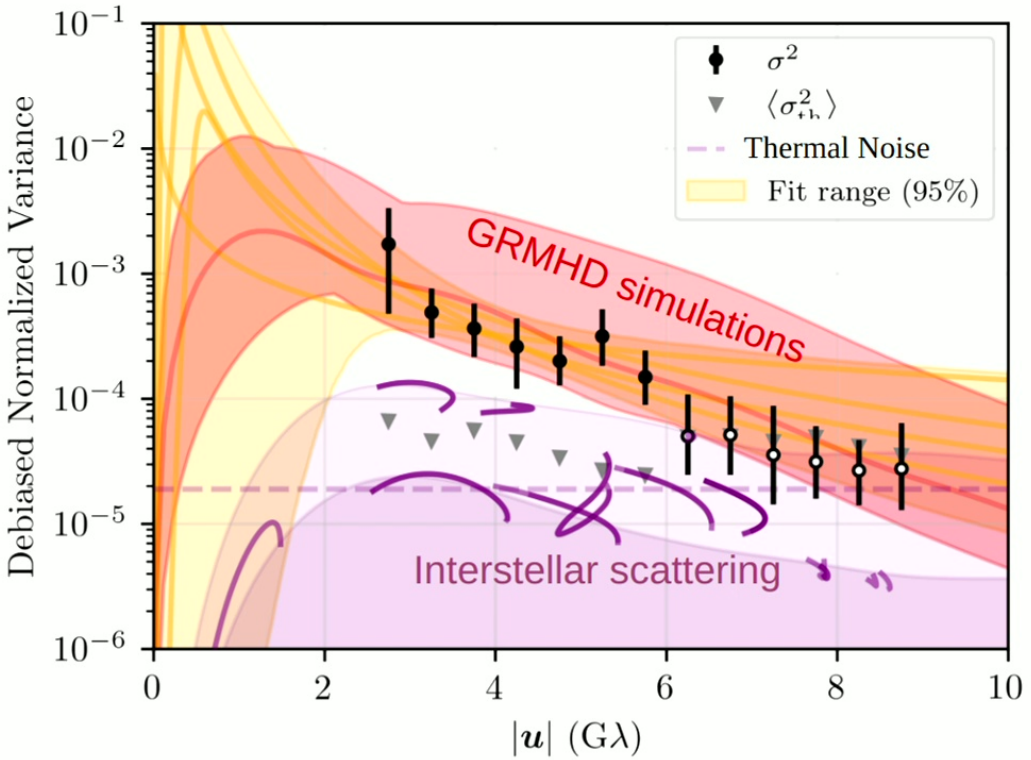
Intrinsic structural variability is the primary challenge for imaging and modelling Sgr A*

Lightcurve-normalized visibility amplitudes exhibit a variance that exceeds measurement uncertainty or scattering effects

- The excess variance follows an approximately power-law decline with increasing baseline length
- The magnitude and power-law index of this variability agree with that expected from GRMHD simulations

Two strategies to mitigate the impact of variability during imaging and modeling:

1. "Snapshot" approach fits to short segments of data over which the source is static, and then averages these independent fits
2. "Full-track" approach fits the average source structure alongside a parameterized model for the variability about that average source structure



The detected variability is most statistically significant on baselines between ~2.5 and 6 Gλ.

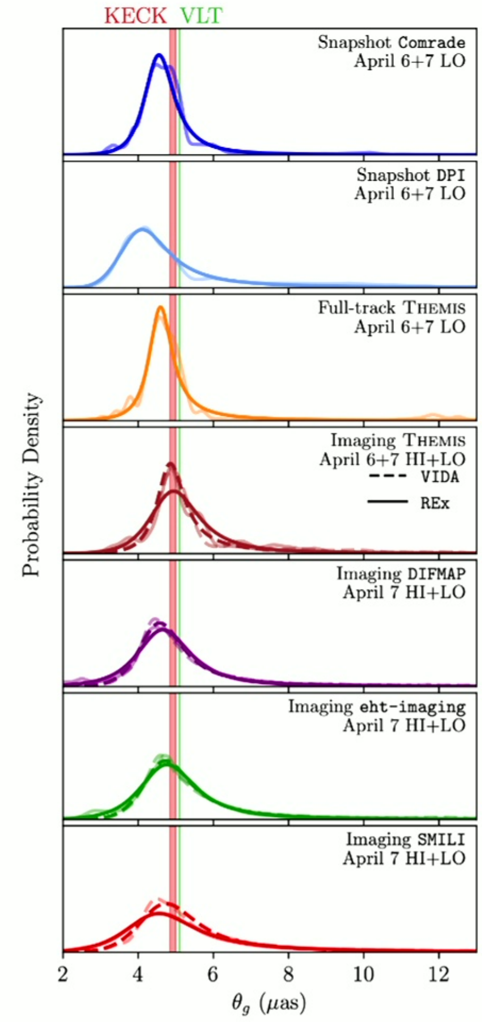
Gravitational radius and black hole mass

To bring the Sgr A* diameter measurements from the various methods to a common physical scale, we calibrate them using synthetic data generated from GRMHD simulations

- The resulting constraint on the angular size of the gravitational radius of Sgr A* is **$\theta_g = GM/(c^2 D) =$ 4.8 (+1.4,-0.7) μas**
- The large uncertainty arises from both the model flexibility needed to capture structural variability in the source, as well as the broad morphological diversity of the GRMHD calibration suite (reflecting the unknown inclination of Sgr A*)

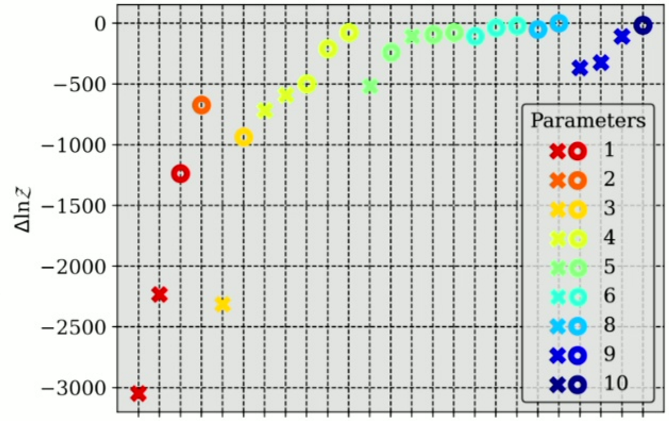
Combining the gravitational radius constraint with an independent distance measurement from maser parallaxes (Reid et al. 2019), we determine the mass of Sgr A* to be **$M = 4.0\ (+1.1,-0.6) \times 10^6\ M_\odot$**

Both the gravitational radius and mass measurements are consistent with the more precise constraints obtained from stellar orbits (Do et al. 2019, Gravity Collaboration et al. 2019, 2020)



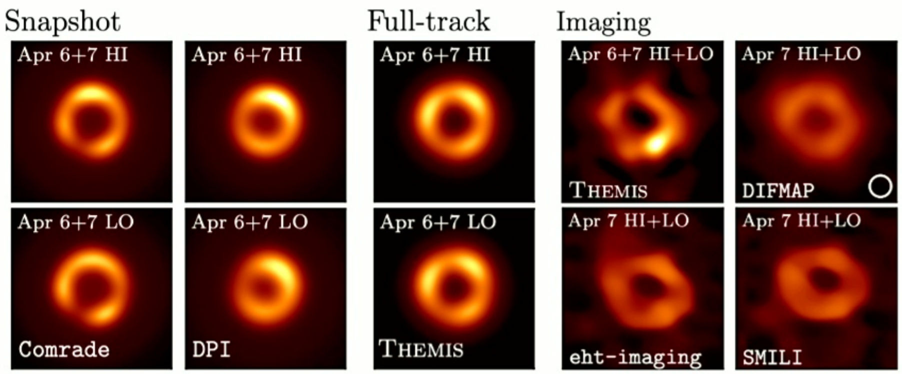
Morphology

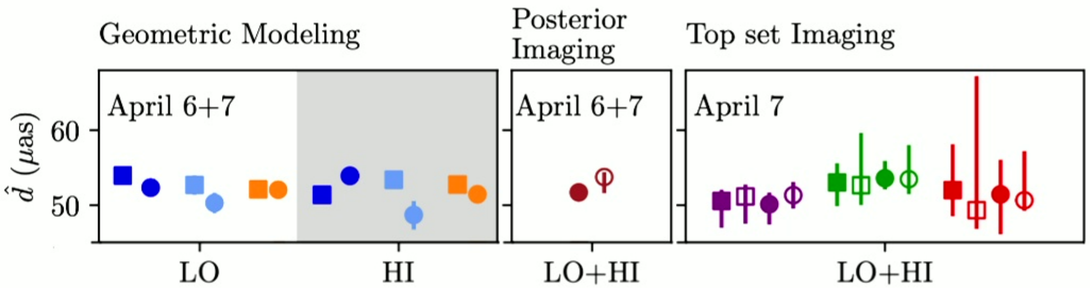
An exploration of simple geometric source models demonstrates that ring-like morphologies provide better fits to the Sgr A* data than do other morphologies with comparable complexity



ring-like model

non-ring-like model





We quantify various morphological parameters using both geometric modeling and image-domain feature extraction techniques

- we recover a ring diameter of 51.8 ± 2.3 μas
- the ring thickness is constrained to have a FWHM between ~30-50% of the ring diameter
- other morphological quantities – magnitude and orientation of the asymmetry, depth of the central brightness depression – are poorly constrained and depend on the measurement method

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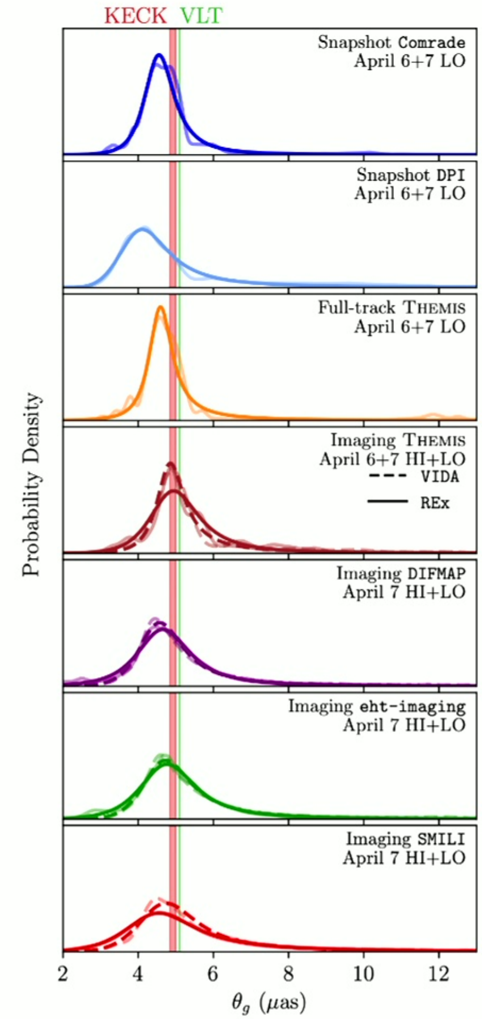


https://iopscience.iop.org/article/10.3847/1538-4357/ab9c1f
https://iopscience.iop.org/article/10.3847/1538-4357/ac4970
https://iopscience.iop.org/article/10.3847/1538-4357/ac7c1d

The Astrophysical Journal, 898:9 (15pp), 2020 July 20
https://doi.org/10.3847/1538-4357/ab9c1f

CrossMark

Hybrid Very Long Baseline Interferometry Imaging and Modeling with THEMIS

The Astrophysical Journal, 927:6 (12pp), 2022 March 1
https://doi.org/10.3847/1538-4357/ac4970

CrossMark

Measuring Spin from Relative Photon-ring Sizes

The Astrophysical Journal, 935:61 (19pp), 2022 August 10
https://doi.org/10.3847/1538-4357/ac7c1d

CrossMark

The Photon Ring in M87*

Avery E. Broderick[1,2,3], Dominic W. Pesce[4,5], Roman Gold[6], Paul Tiede[1,2,3,4,5], Hung-Yi Pu[7,8,9],
Richard Anantua[4,5,10], Silke Britzen[11], Chiara Ceccobello[12], Koushik Chatterjee[4,5], Yongjun Chen (陈永军)[13,14],
Nicholas S. Conroy[4,15], Geoffrey B. Crew[16], Alejandro Cruz-Osorio[17], Yuzhu Cui (崔玉竹)[18,19,20],

Two distinct studies:

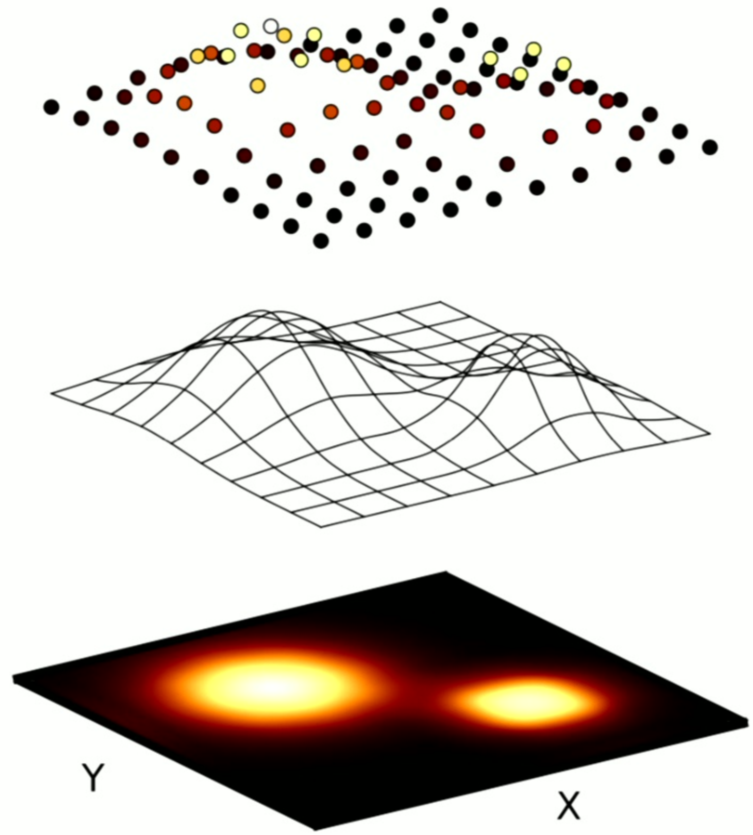
1. Application of Themaging to M87 -- Extracting ring
    a. Ring + Imaging
    b. Ring + jet
    c. Posteriors on ring sizes across the 2017 campaign
    d. Possible variability of surrounding emission
    e. Ring-size biases: n=1 vs n=∞

2. Measuring **mass** and **spin** from n=0, 1, 2 ring sizes
    a. Measurement concept and breaking degeneracies
    b. Simulated applications
    c. Initial systematic explorations
    d. Implications of GR “tests” in M87

Themaging Redux

Broderick et al., 2020, ApJ, 898, 9

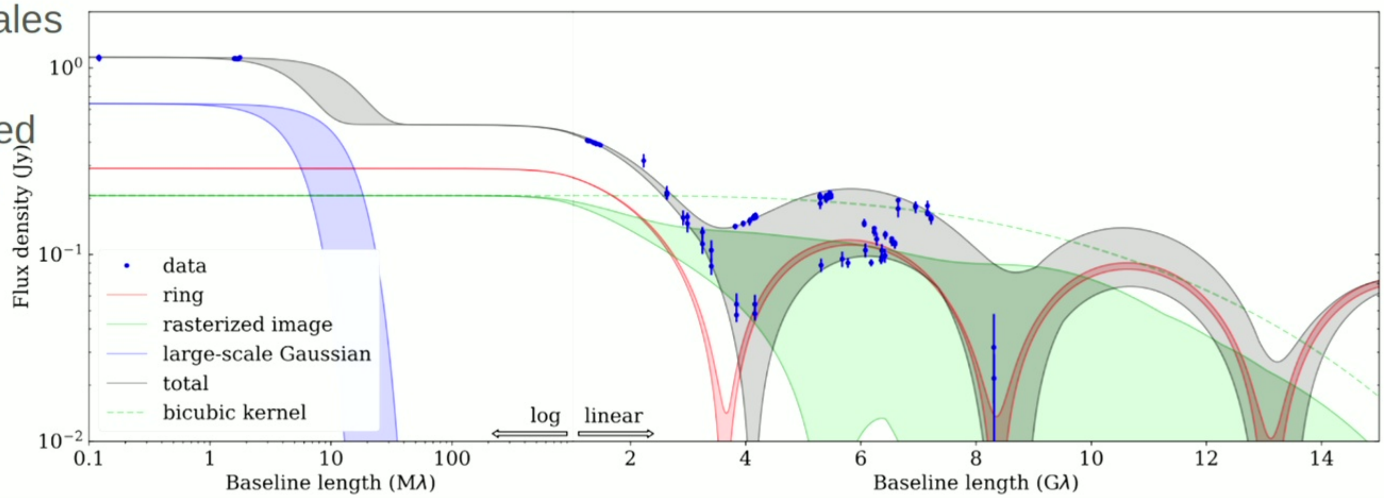
- Raster model of image via:
  - Control points (set by image resolution)
  - Cubic "spline" interpolation in log(I)
- Surprisingly flexible (Gaussians exact!)
- "Non-parametric" ← → "Imaging"
- Variable Field of view & raster orientation
- Gain reconstructions in normal way
- Can fit any Themis-implemented data type(s)
  - Complex visibilities
  - Amplitudes
  - Closure phases
  - Parallel+crosshand visibilities
- Produces **posteriors** on the image



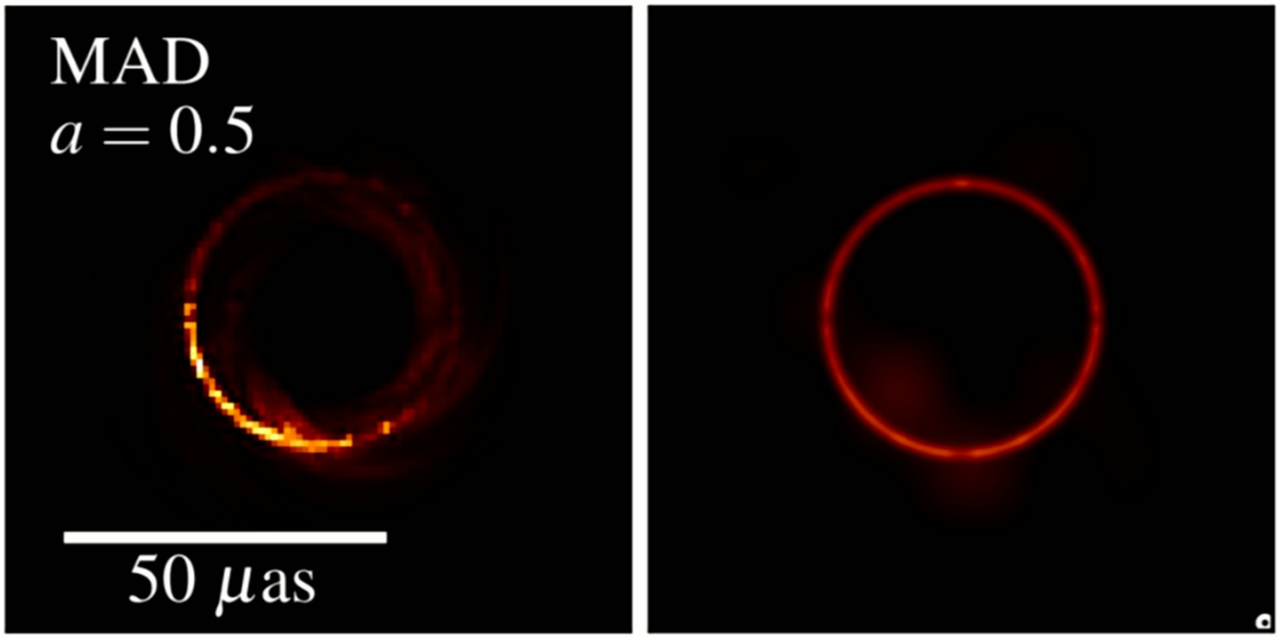
Modeling and Imaging

- Hybrid Themaging
  - Model what you can → natural physical interpretation
  - Image the rest → addresses stochasticity/uncertainty (e.g., turbulence)
  - Bayesian imaging enables this simultaneously!

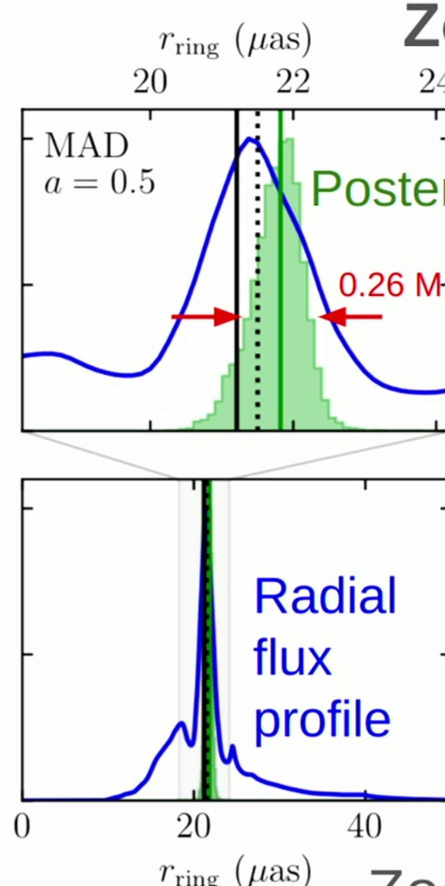
- What does the data imply if we impose our GR expectations of a narrow ring?
  - Separation of scales
  - Ring diameter faithfully recovered in GRMHD tests
  - Flux in ring component biased upward



Extracting Rings -- Imaging + Ring fitting (M87)

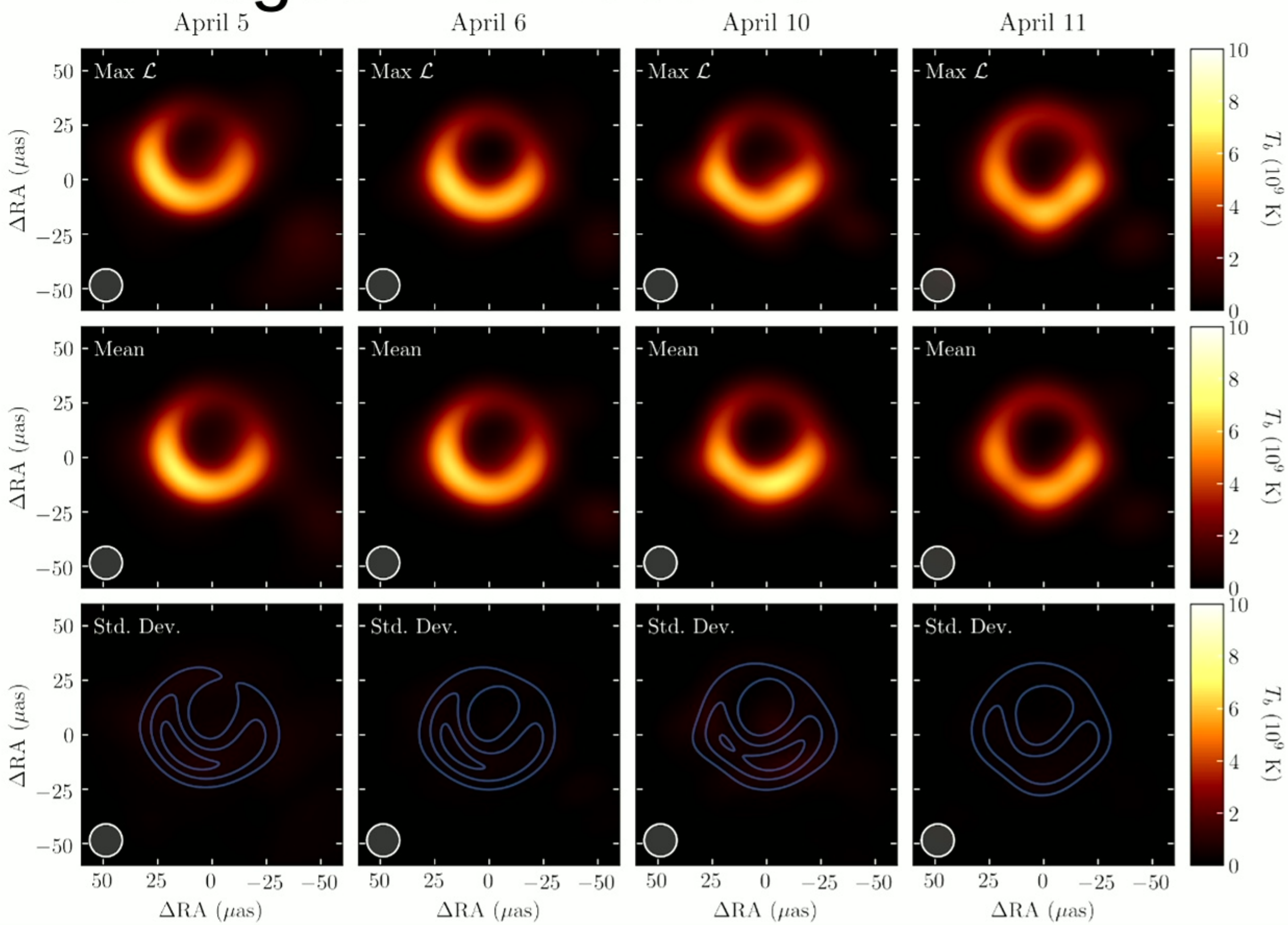


Zoom in!

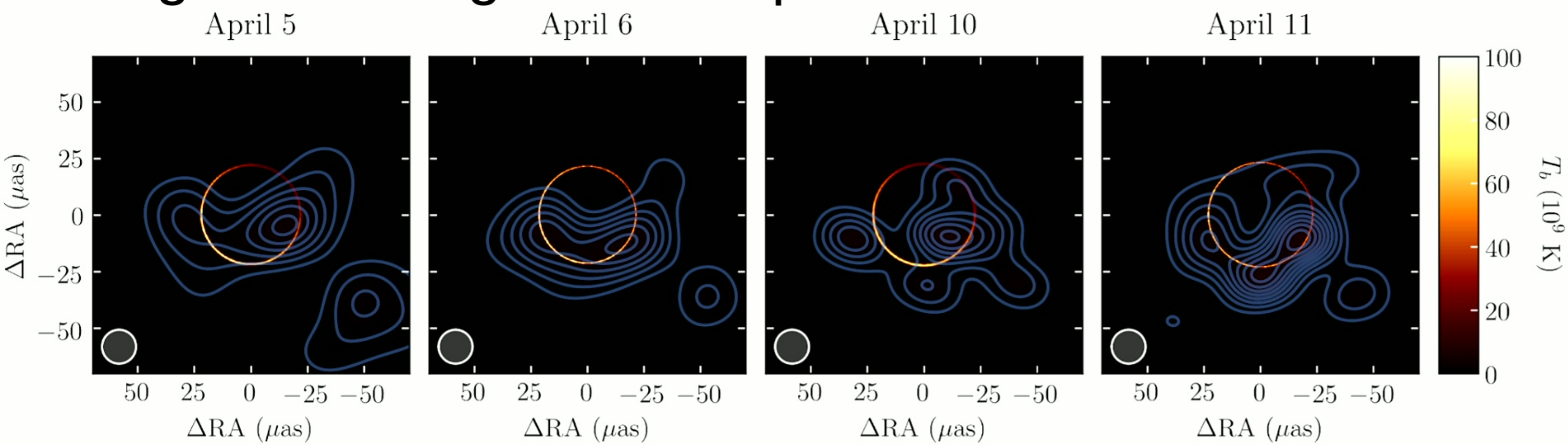


Zoom out

Ringed Themages -- Smoothed

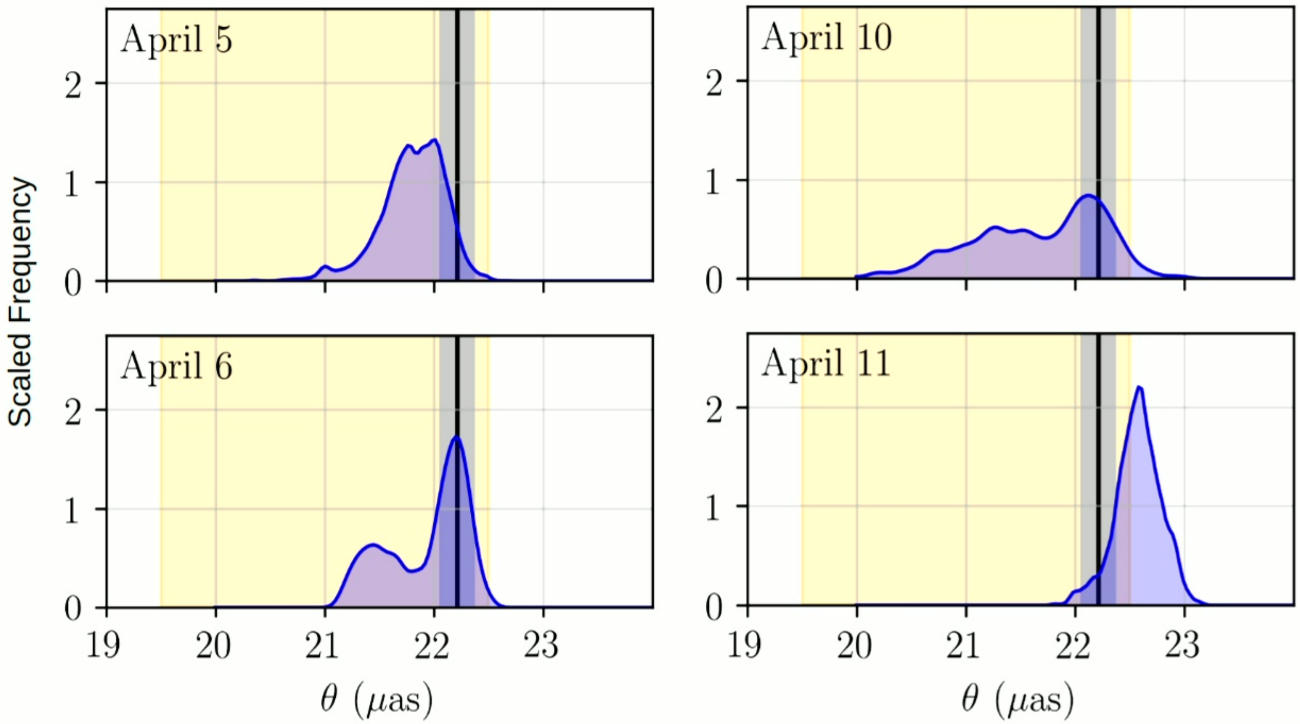


Ringed Themages -- Components



- Ring emission shown in colormap
- Themage shown in contours, 4×10^8 K - 2.4×10^9 K in steps of 4×10^8 K
- Ring position and size are free to change!
- Hints of evolution

Photon Ring Radii



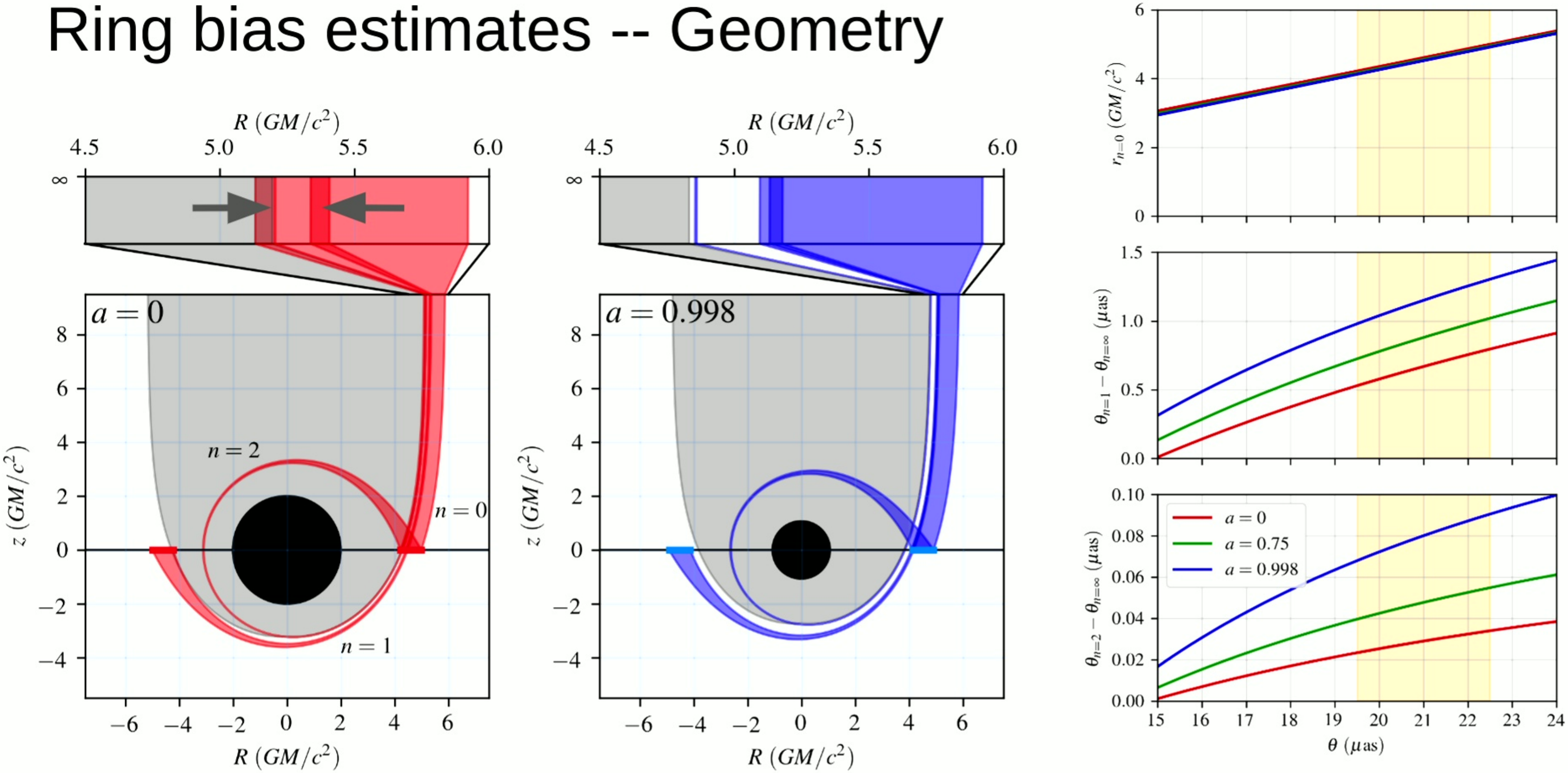
Combined ring radius:

θ ~ 22.14+-0.15 uas

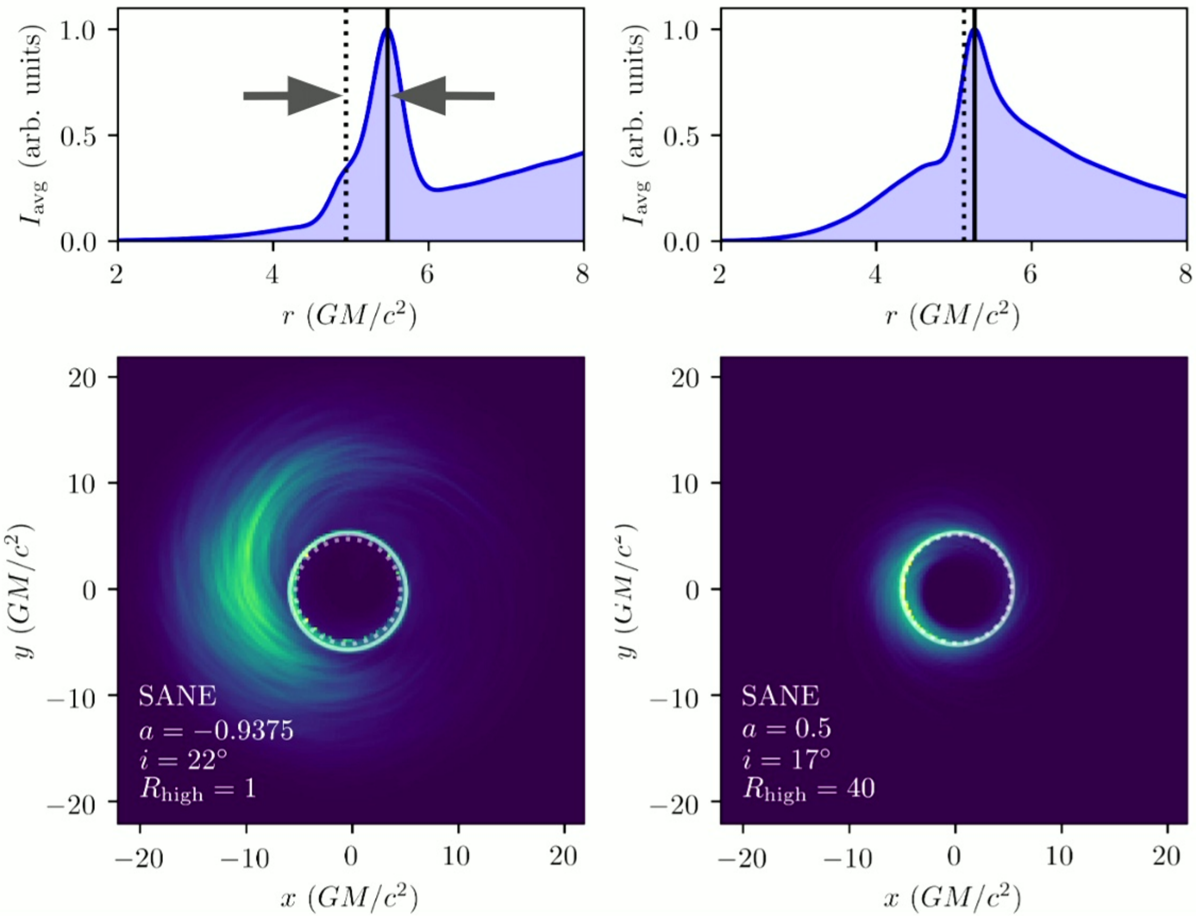
How to convert to M/D?

- Dominated by n=1 photon ring
- Biased from n=∞ photon ring
- Depends on spin modestly
- Depends on inclination weakly
- Estimate ...

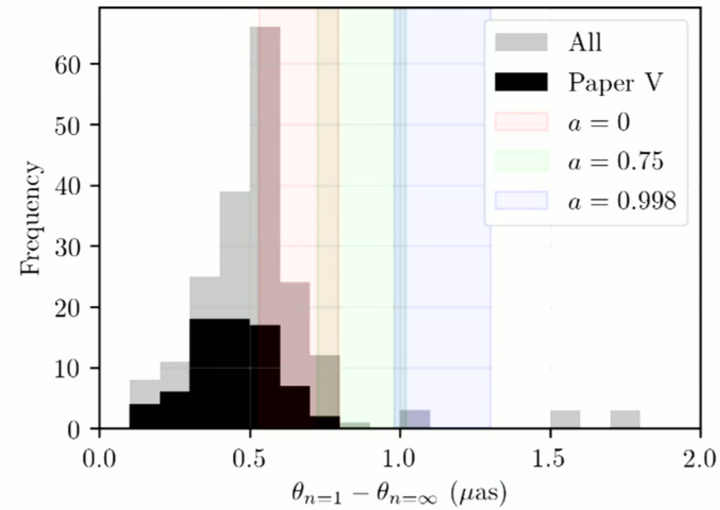
Ring bias estimates -- Geometry



Ring bias -- GRMHD simulations



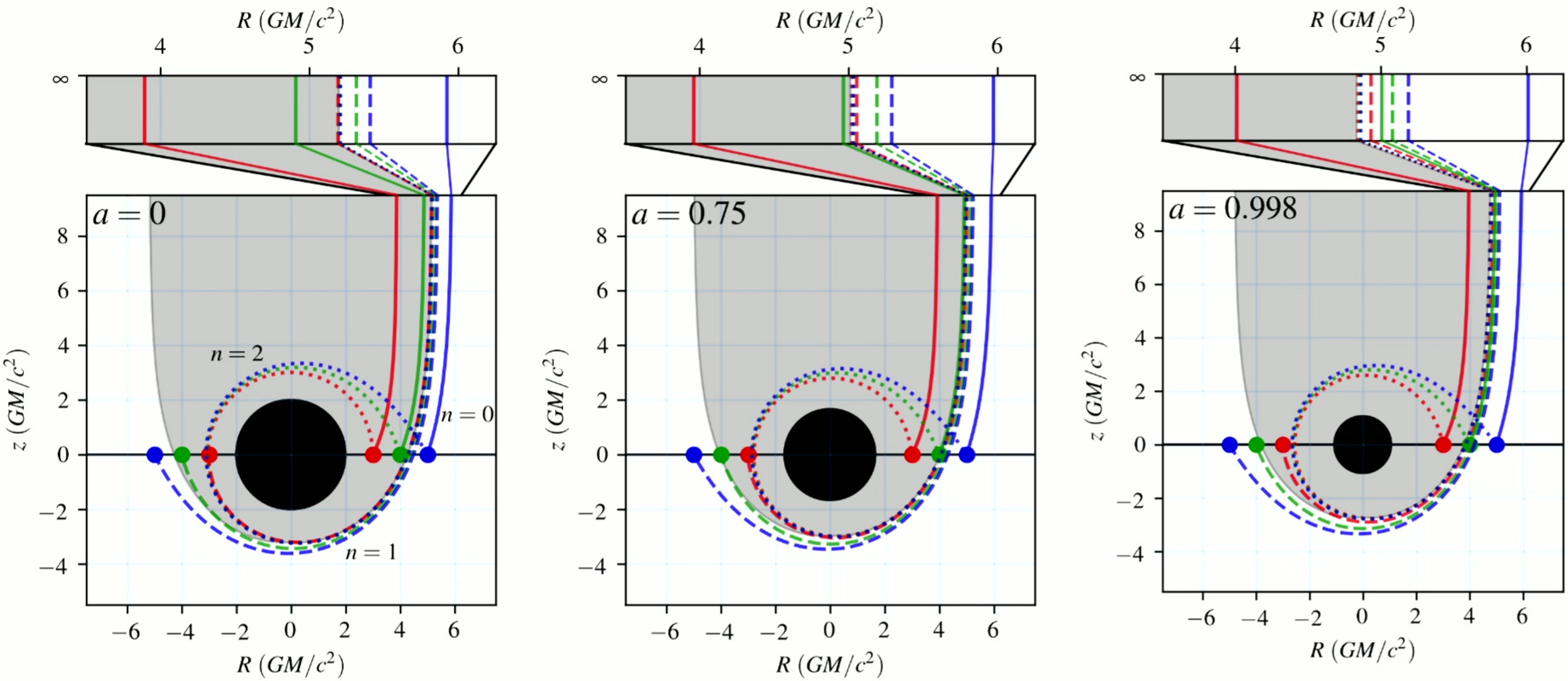
Even after variety of accretion flow, outward bias of **0.56+-0.32 uas**



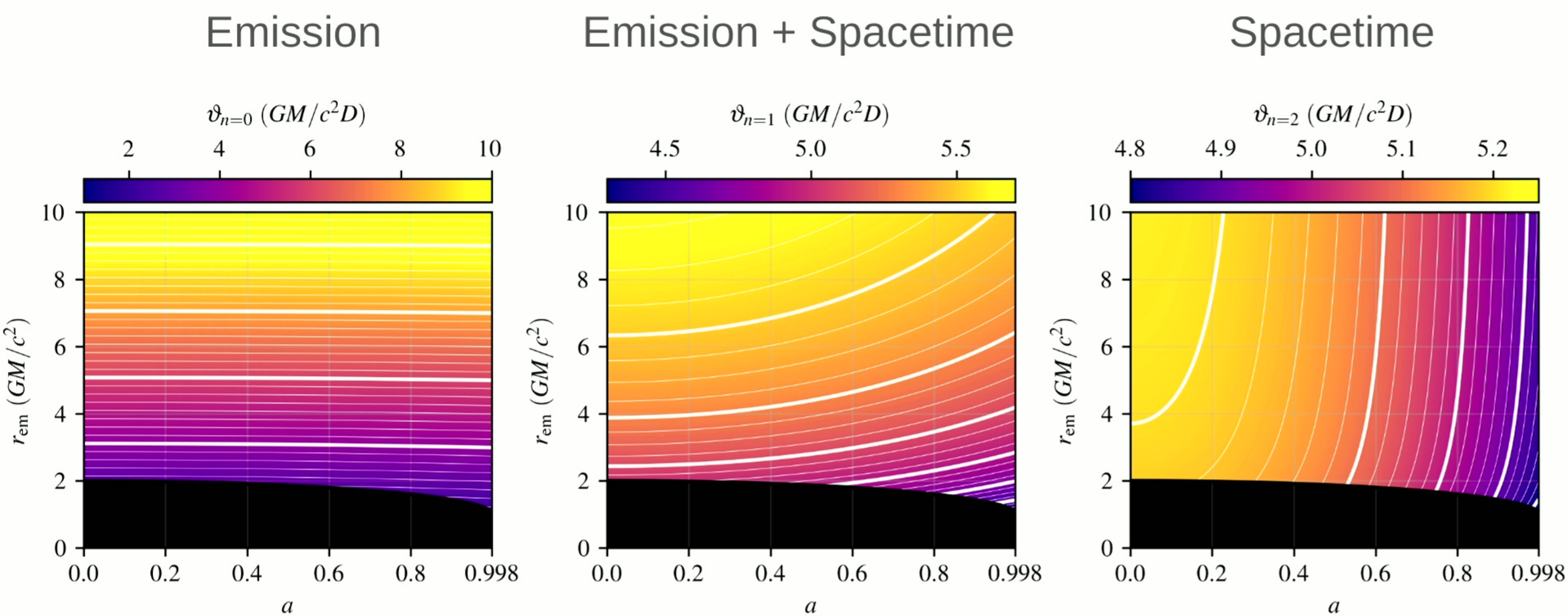
$$\theta_M = 4.28 \pm 0.03 \pm 0.06|_{\Delta\theta} \pm 0.13|_a \ \ \mu\text{as},$$

$$M_9 = 7.27 \pm 0.05 \pm 0.11|_{\Delta\theta} \pm 0.22|_a \pm 0.35|_D \,,$$

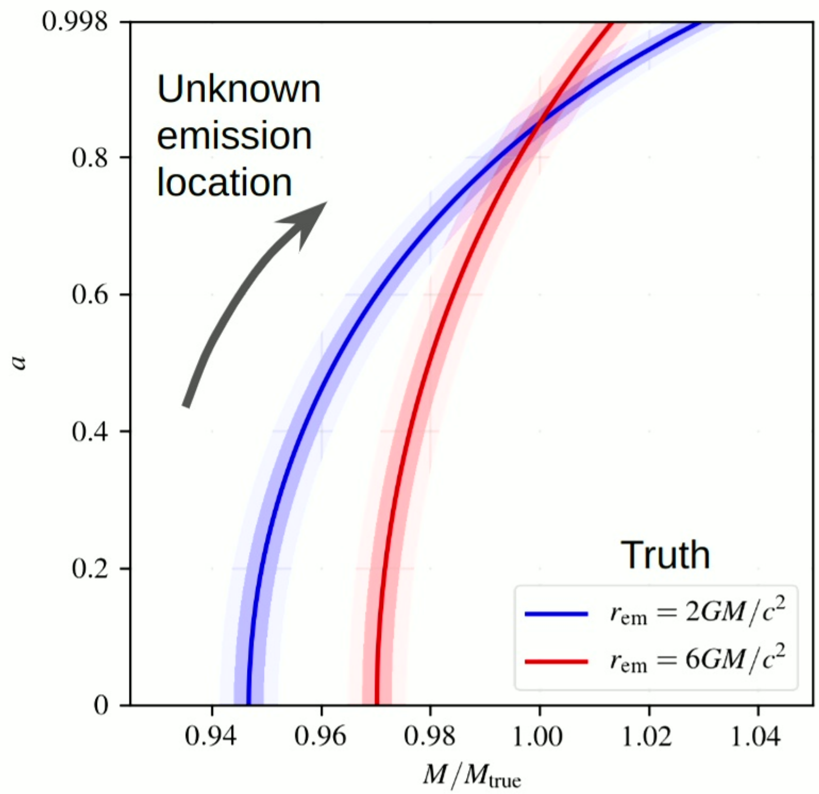
Photon Rings Revisited



Mapping Observation vs Spacetime vs Emission



Implications for Mass and Spin



Each measurement of $\theta_{n=0}$ and $\theta_{n=1}$ gives a *degenerate* mass and spin constraint.

This degenerate constraint is **different** for for different emission radii.

→ Variations in the emission region would allow a measurement of M and a, limited only by the precision of the EHT!

Depends on angular ratios, and thus spin is independent of distance!

Illustration of a possible GR test

THE ASTROPHYSICAL JOURNAL, 927:6 (12pp), 2022 March 1 Broderick et al.

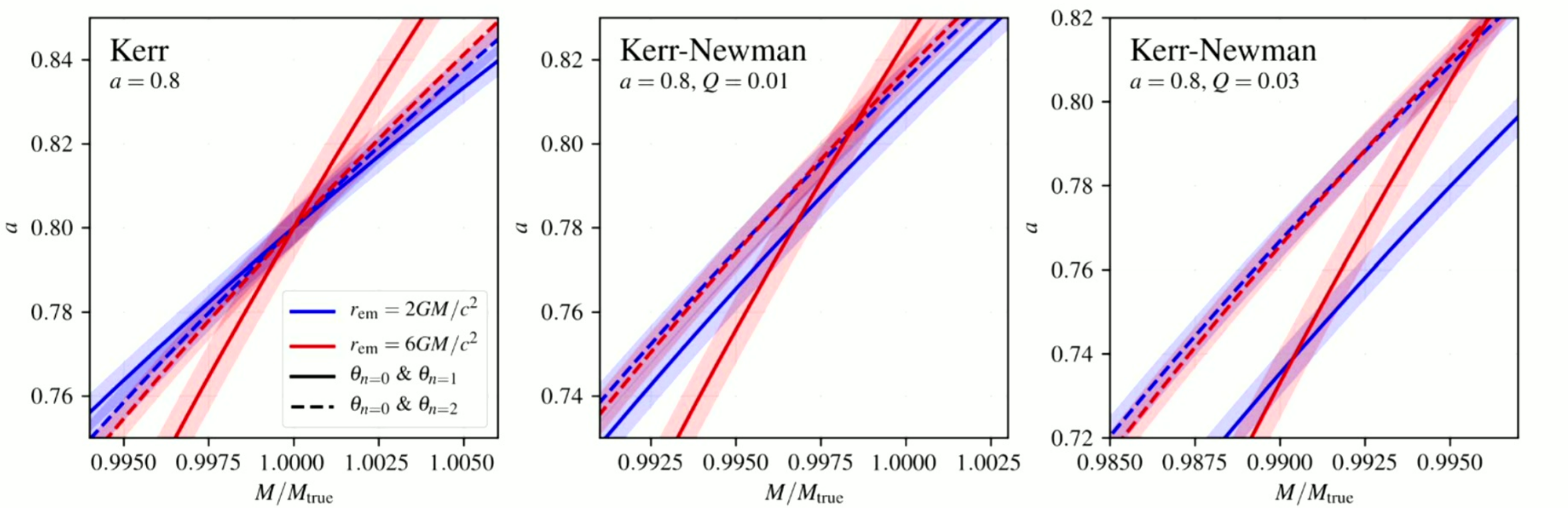


Figure 12. Comparison of mass–spin contours from observations of $\theta_{n=0}$, $\theta_{n=1}$, and $\theta_{n=2}$ made assuming Kerr (left) and Kerr–Newman (right) spacetimes over two epochs with differing r_{em}. Solid and dashed contours show the $\theta_{n=0}$–$\theta_{n=1}$ and $\theta_{n=0}$–$\theta_{n=2}$ constraints, respectively. The bands indicate a 0.05% uncertainty on the measurements of $\theta_{n=1}$ and $\theta_{n=2}$. Truth values for the spin (both) and charge (Kerr–Newman) are listed in the panels.

Summary of rings analysis for M87*

- M87 is variable
  - One epoch: 2017 data: Weak demonstration on weeks time scale
  - Two epochs: M87 with 2017 + 2018 data: First opportunity at a spin measurement
  - Three epochs: 2017+2018+2021 data: GR test!
- Strong justification for semi-analytical modeling (of which this is a subset)
- Promising applicability for improved arrays on the ground and in space