Re-analyses of EHT data on M87

Nithyanandan Thyagarajan (CSIRO)

[1] Carilli & Thyagarajan (2021)
https://ui.adsabs.harvard.edu/abs/2021arXiv211111626C/abstract

[2] Arras et al. (2020)
https://ui.adsabs.harvard.edu/abs/2020arXiv200205218A/abstract (time permitting)

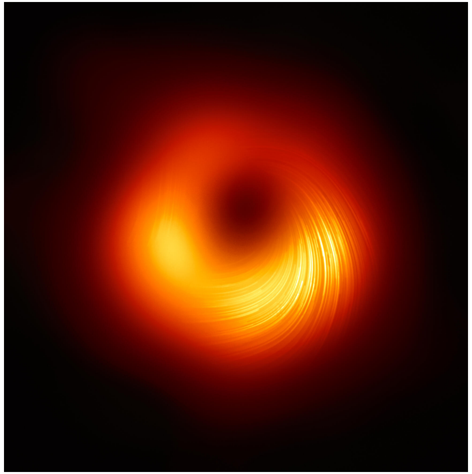


Image credit: EHT collaboration

I/CSIRO acknowledge the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture and we pay our respects to their Elders past and present.

Recap: M87 Results from EHT

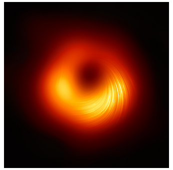
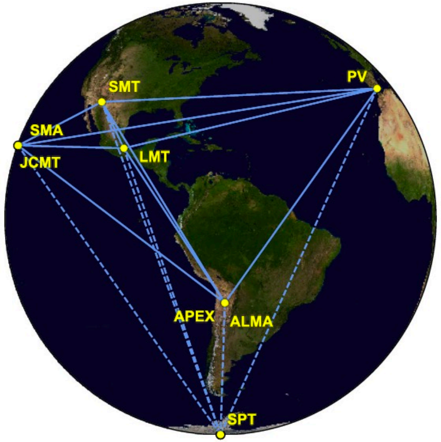
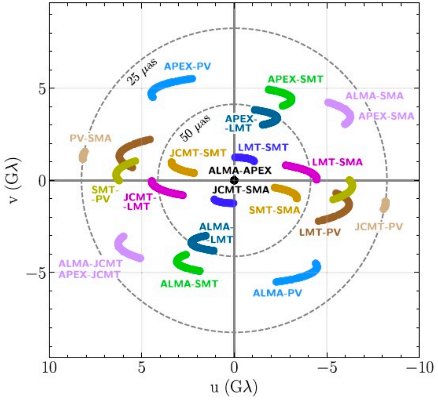
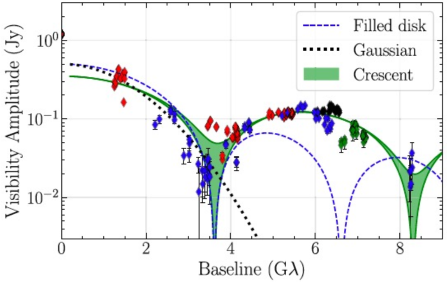


Image credit: EHT collaboration



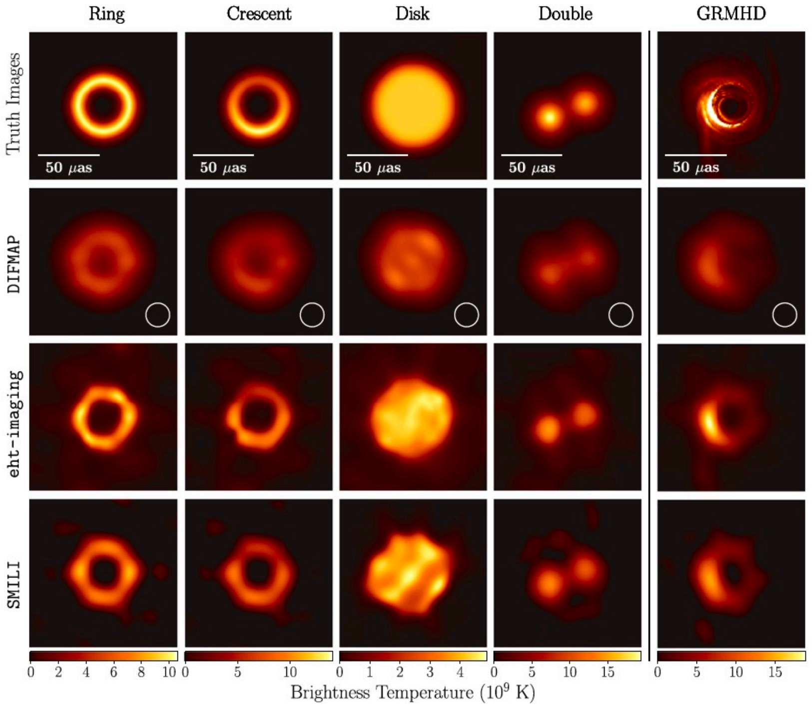
228 GHz

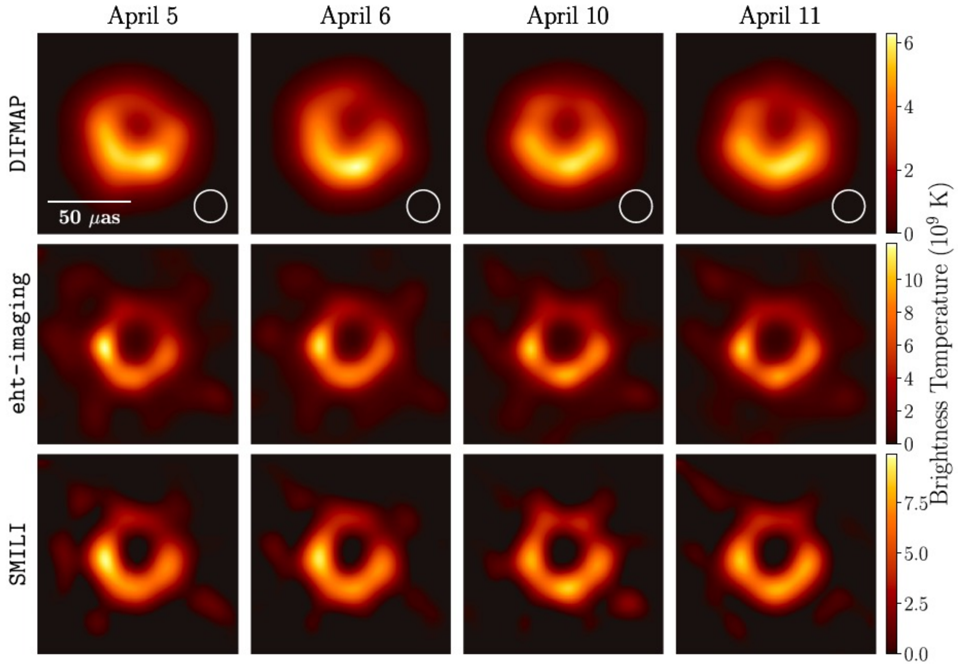




EHT collaboration papers (I-VI)

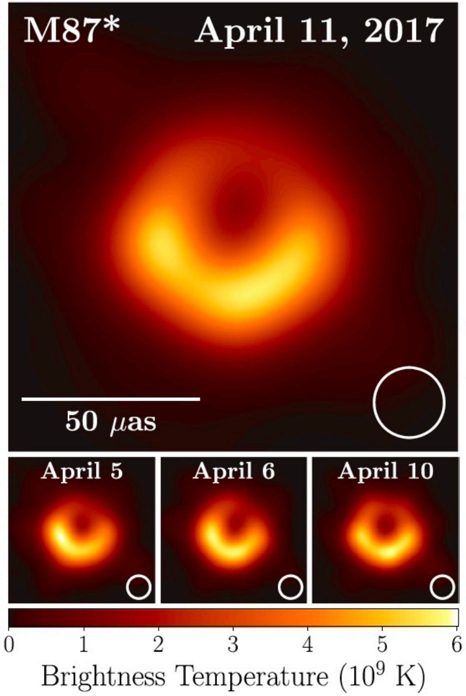
Cross-validation of imaging parameter selection





EHT images of M87

- Forward-modeling: search image-plane parameter space that best matches visibility amplitudes and closure phases (station phases are not well-calibrated)
- Inverse-modeling: Hybrid mapping (iterative self-calibration and imaging, with an a priori model)



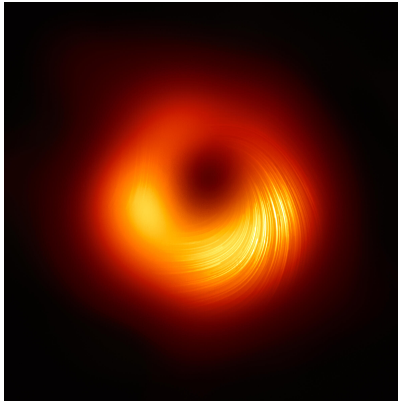


Image credit: EHT collaboration

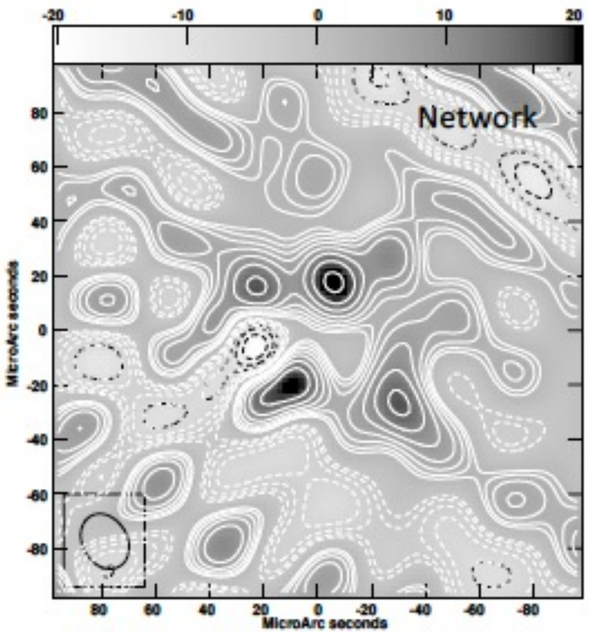
Table 1
Parameters of M87*

Parameter	Estimate
Ring diameter [a] d	42 ± 3 μas
Ring width [a]	<20 μas
Crescent contrast [b]	$>10{:}1$
Axial ratio [a]	$<4{:}3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	3.8 ± 0.4 μas
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M [c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$
Parameter	**Prior Estimate**
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9\ M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

Public EHT data on M87

https://eventhorizontelescope.org/for-astronomers/data

- Network-calibrated data (amplitude cal, basic delay cal, redundant cal)
- Amplitudes ~10% precision, phase stable to ~10s for averaging
- But insufficient for phase-coherent imaging (errors in clock, tropospheric model, pol leakage, etc.) => need iterative self-calibration in post-processing



Carilli & Thyagarajan (2021)

Are results robust to starting models?

- For extended or complex source morphologies, and sparse uv-coverage (insufficient constraints), self-calibration can turn the data into the model
- How do starting models in self-calibration affect final image outcome?
- Details in https://arxiv.org/abs/2111.11626

Summary of results

Hybrid mapping of the Black Hole Shadow in M87

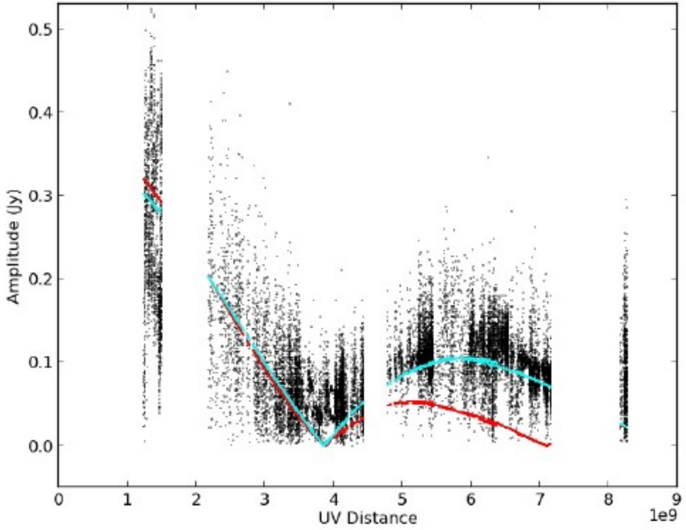
Chris L. Carilli[1] and Nithyanandan Thyagarajan[1,2]

ABSTRACT

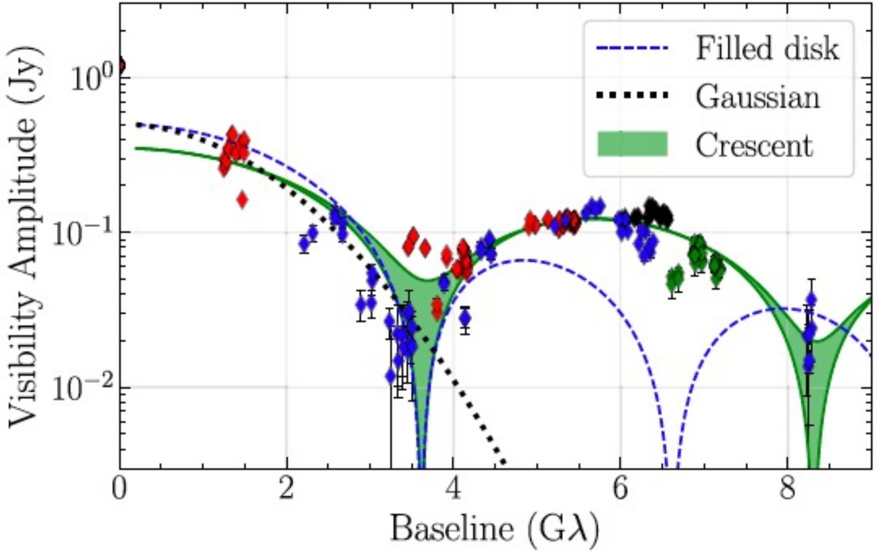
We present a reanalysis of the EHT 228 GHz observations of M87. We apply traditional hybrid mapping techniques to the publicly available 'network-calibrated' data. We explore the impact on the final image of different starting models, including: a point source, a disk, an annulus, a Gaussian, and an asymmetric double Gaussian. The images converge to an extended source with a size $\sim 44\ \mu$as. Starting with the annulus and disk models leads to images with the lowest noise, smallest off-source artifacts, and better closure residuals. The source appears as a ring, or edge-brightened disk, with higher surface brightness in the southern half, consistent with previous results. Starting with the other models leads to a surface brightness distribution with a similar size, and an internal depression, but not as clearly ring-like. A consideration of visibility amplitudes vs. UV-distance argues for a roughly circularly symmetric structure of $\sim 50\ \mu$as scale, with a sharp-edge, based on a prominent minimum in the UV-distribution, and the amplitude of the secondary peak in the UV-plot is more consistent with an annular model than a flat disk model. With further processing, we find a possible modest extension from the ring toward the southwest, in a direction consistent with the southern limb of the jet seen on 3mm VLBI images on a factor of few larger scales. However, this extension appears along the direction of one of the principle sidelobes of the synthesized beam, and hence requires testing with better UV-coverage.

https://arxiv.org/abs/2111.11626

Visibility amplitude information



Carilli & Thyagarajan (2021)



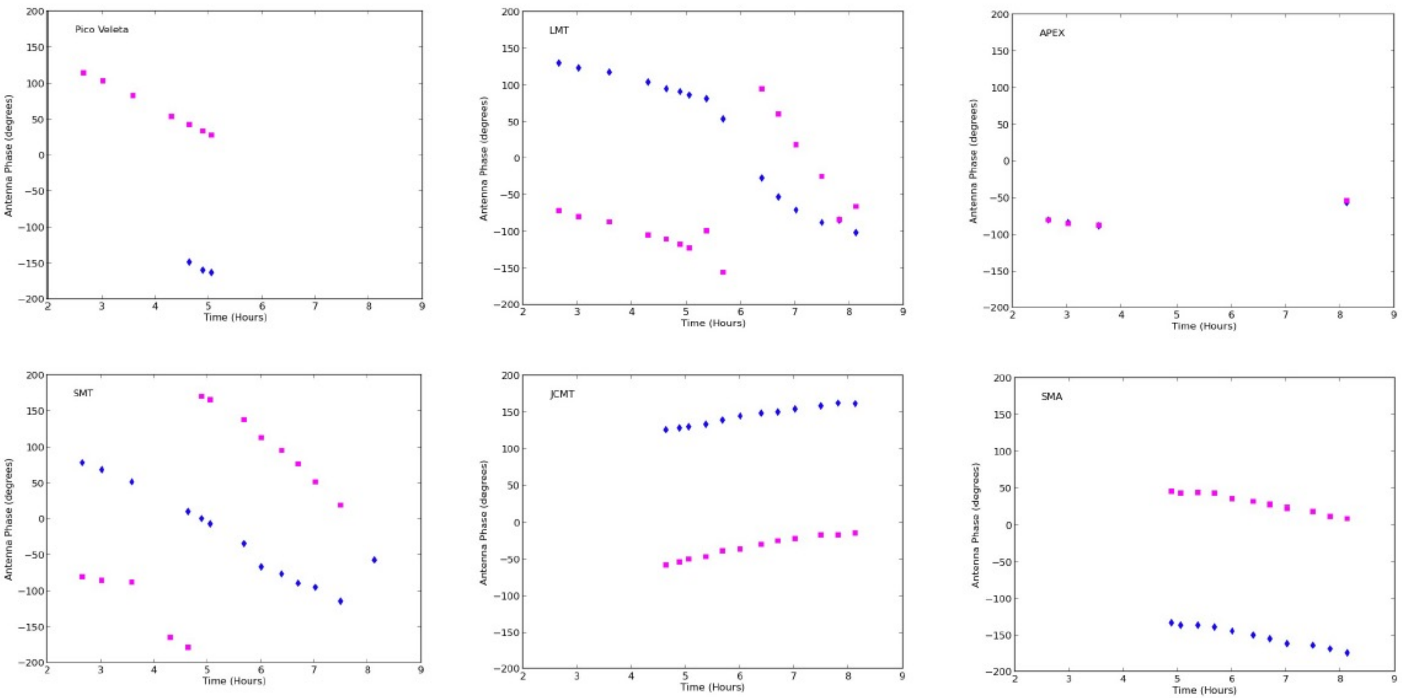
EHT papers I, IV, VI

Challenges to self-calibration

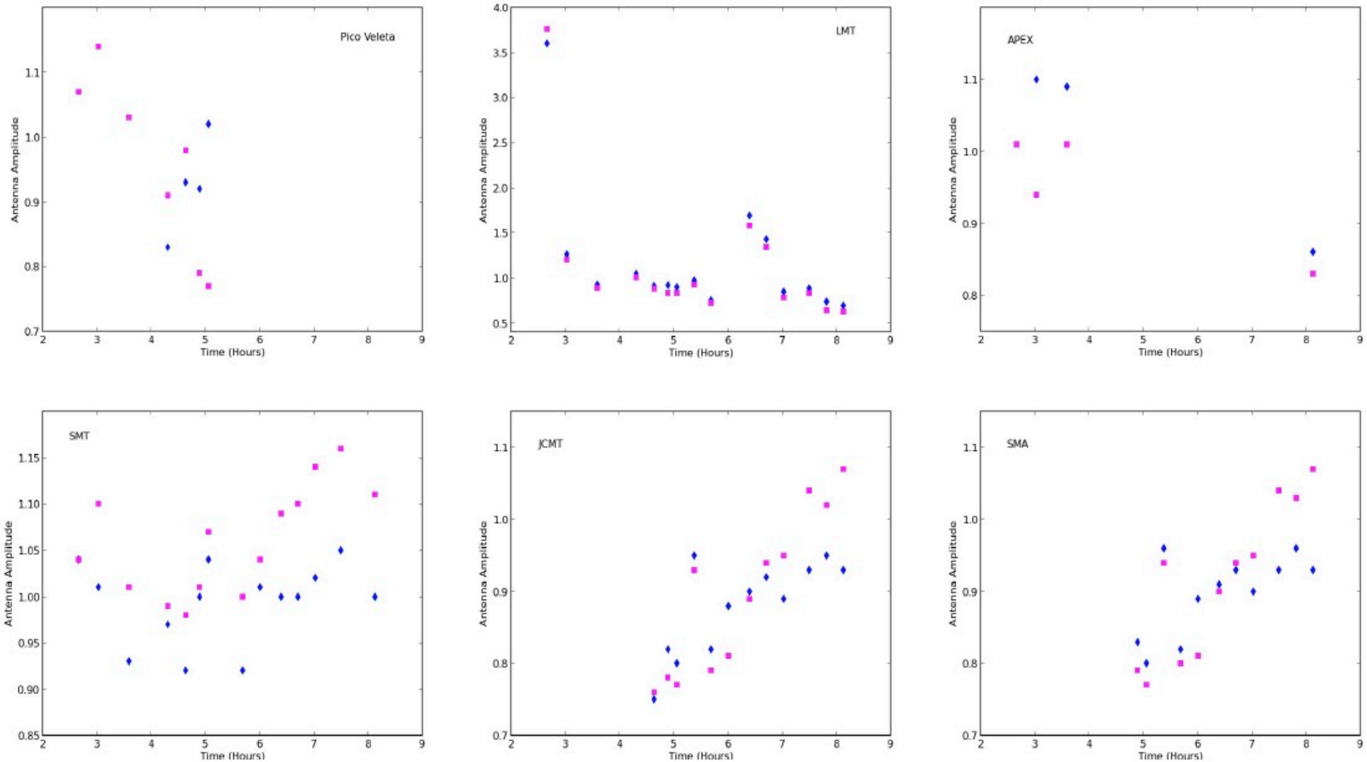
- Sparse uv-coverage
- Significant source structure
- Network-calibrated data has no coherent structure => not usable as starting model
- ALMA >60 times sensitive as any other station => undue weighting in calibration

- Reweight visibility data to lower dominance of ALMA
- Simple starting models
  - Point source
  - Gaussian FWHM = 40 μas
  - Disk of diameter 55 μas
  - Annulus of inner/outer dia 25/55 μas
  - Asymmetric 2:1 double
- Self-cal: 2 x P-only + 2 x A&P

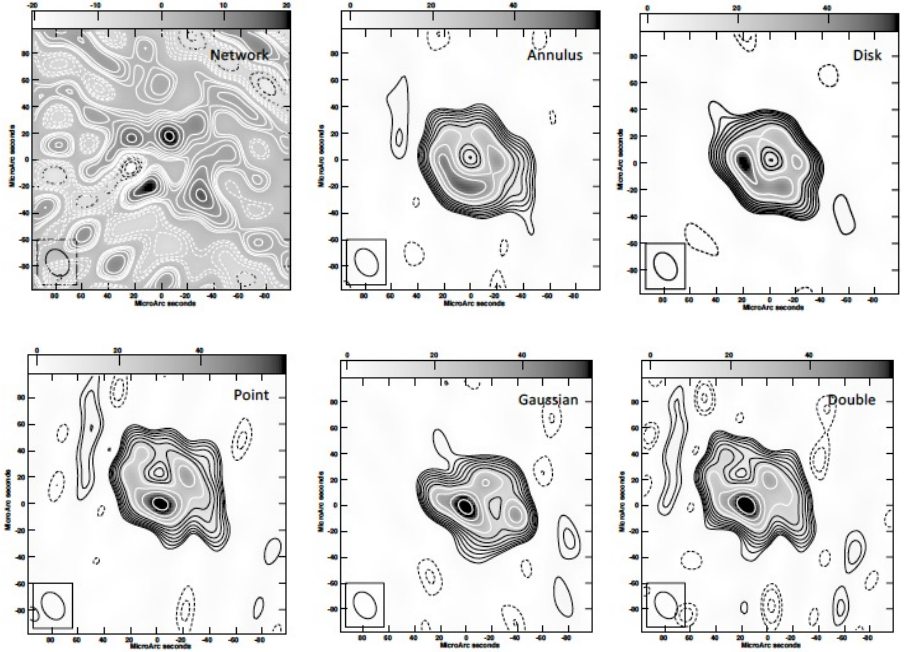
Phase calibration solutions



Amplitude calibration solutions



Images



Closure Phase Agreement

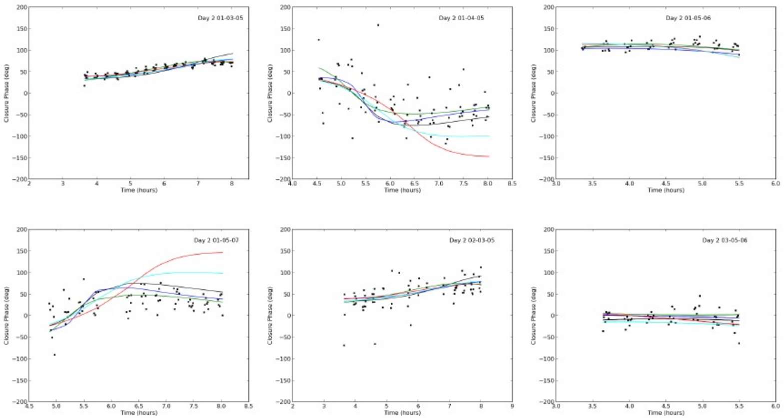
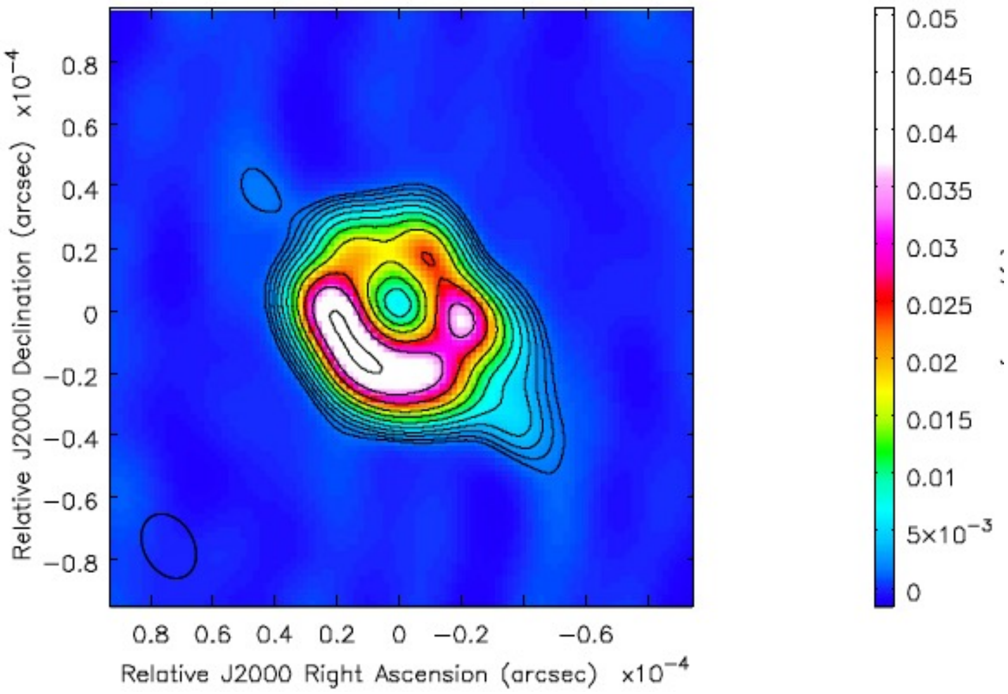


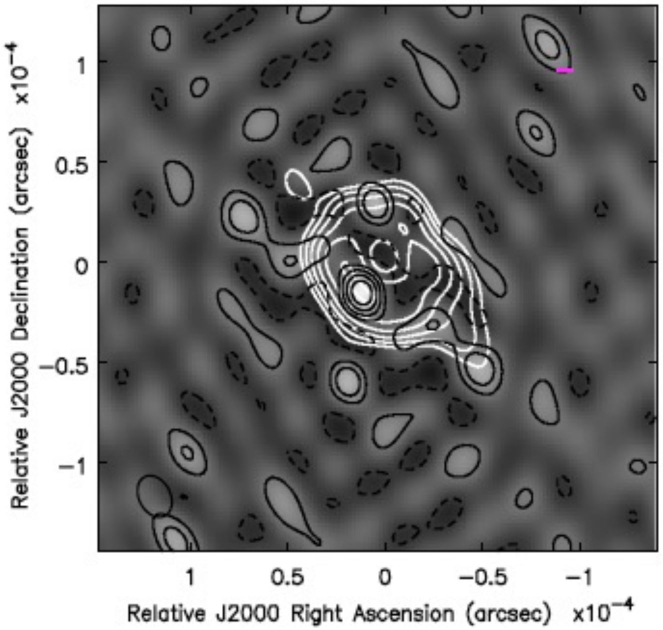
Table 1. Imaging results at 229.1 GHz

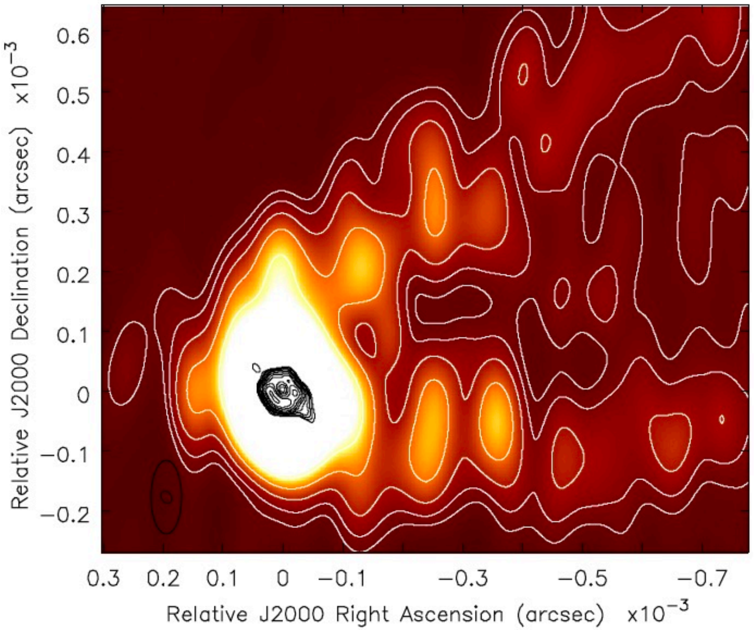
Starting model	Max $(\frac{\text{mJy}}{\text{beam}})$	Min $(\frac{\text{mJy}}{\text{beam}})$	RMS $(\frac{\text{mJy}}{\text{beam}})$	Total (mJy)	Closure Phase $\langle\chi^2\rangle^{\frac{1}{2}}$ (normalized)
Annulus	55.4	−3.4	0.66	262	0.98
Point	73.3	−3.4	0.89	266	1.25
Disk	59.0	−3.4	0.66	245	0.99
Gaussian	76.0	−3.2	0.83	241	0.97
Asym. Double	83.1	−4.2	1.1	277	1.42

Image with annulus starting model + wider CLEAN box



Possible jet structure?



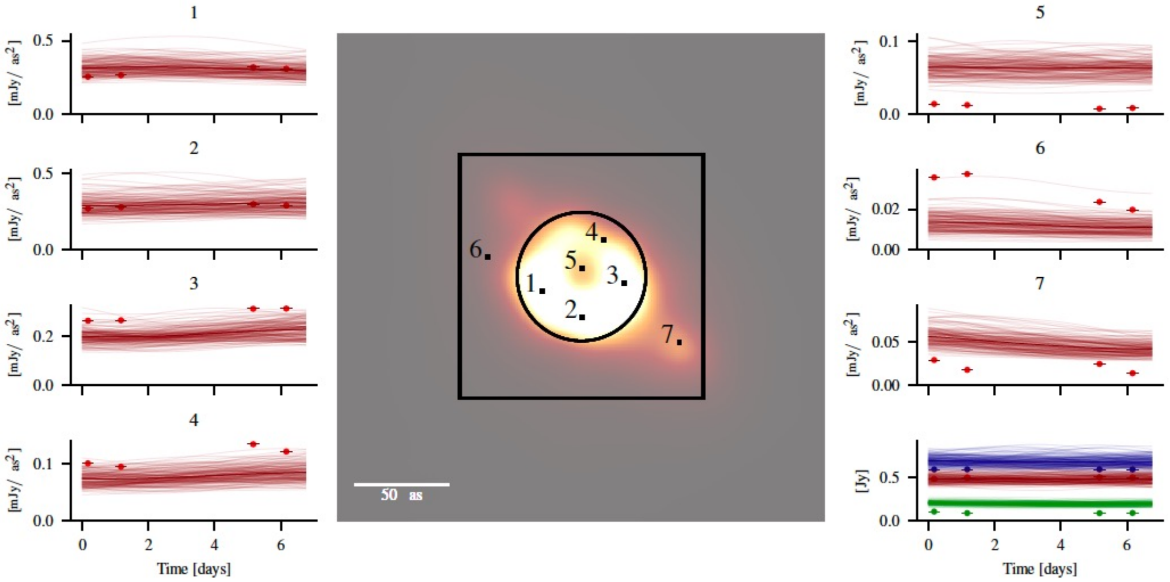


Overlay on 3 mm images from Kim+(2018)

A forward-modeled Bayesian approach

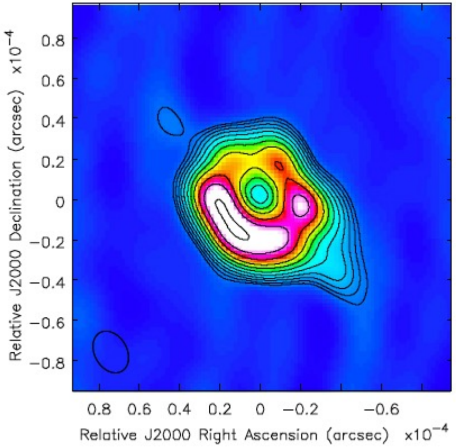
Arras et al. (2020): arXiv: 2002.05218

- Priors for correlations in 4D: 2 (space) + 1 (time) + 1 (spectrum)
- Find temporal variations
- Find significant features outside the ring

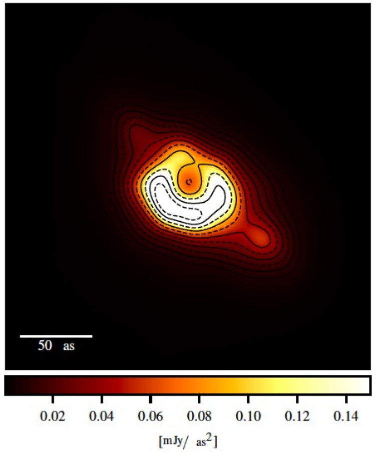


Summary of re-analyses results

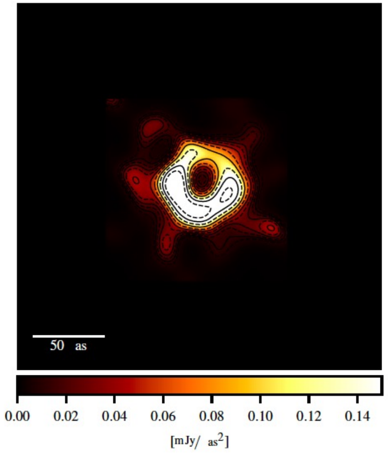
- The asymmetric ring feature appears to be robust
- New features not identified previously may be present



Carilli & Thyagarajan (2021)



Arras+(2020)



EHT collaboration (2019)

Need more data!!!