Observing Supermassive Black Holes and Relativistic Jets with the Event Horizon Telescope

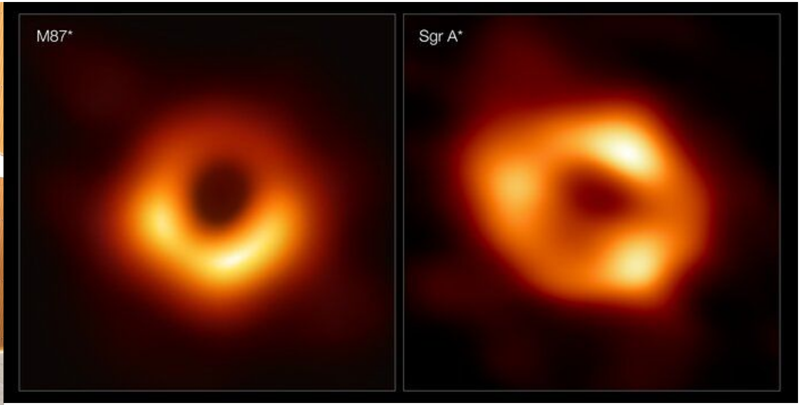
Zhao Guang-Yao (IAA-CSIC) on behalf of
the Event Horizon Telescope Collaboration

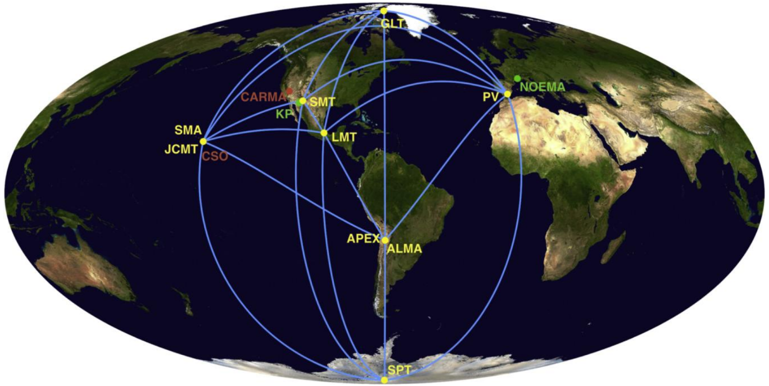
Event Horizon Telescope

INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

EXCELENCIA SEVERO OCHOA

The EHT Collaboration and the Black Hole "Shadow" Images

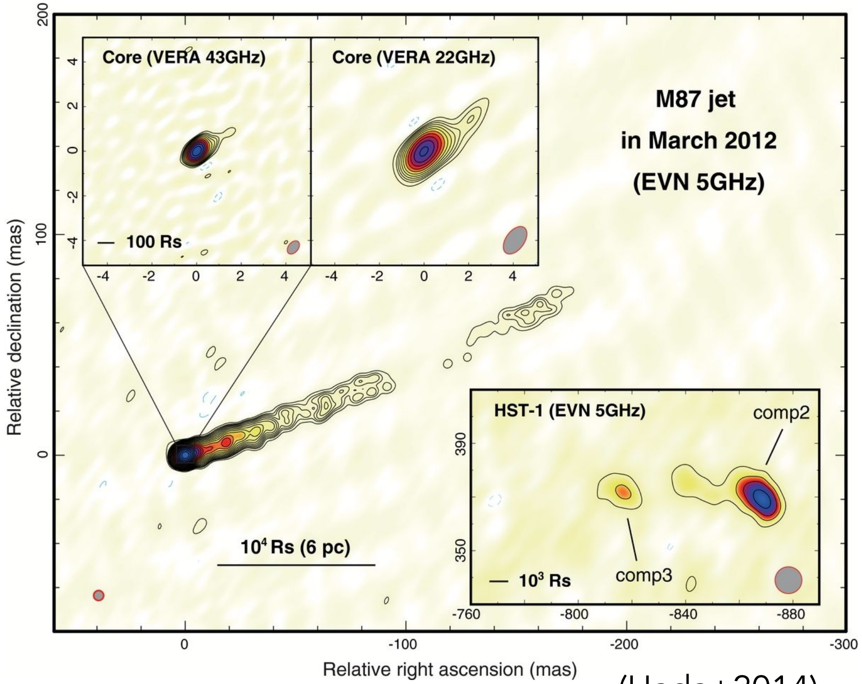




Event Horizon Telescope

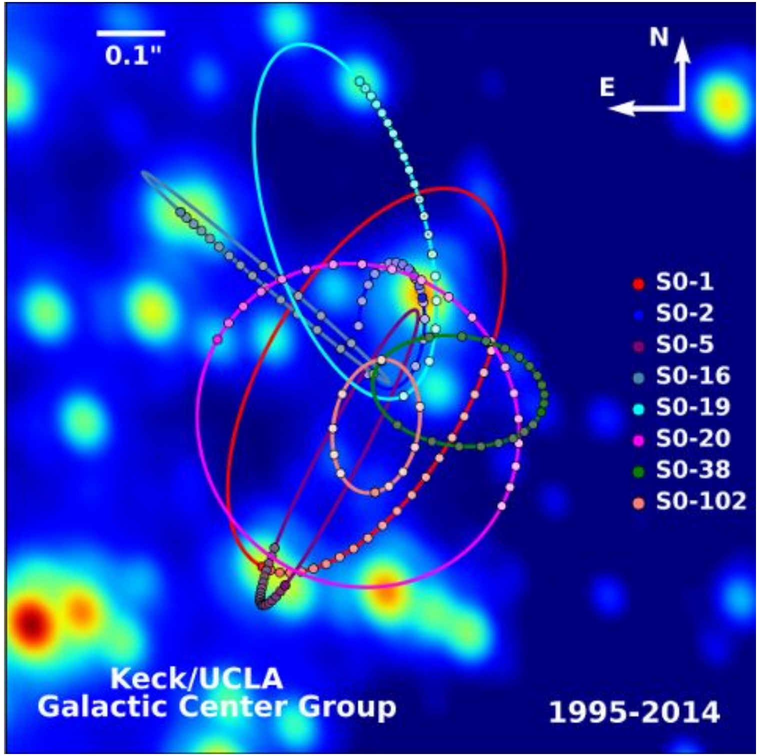
Observational Phenomenon Associated with SMBHs

Powerful relativistic jets from AGNs

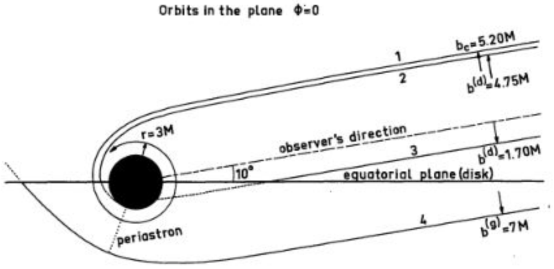


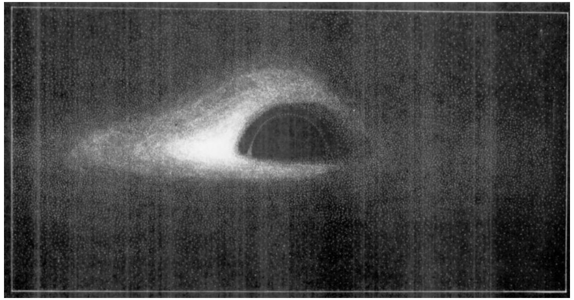
(Hada+2014)

Stellar orbits of S-stars



Theoretical Predictions of “Shadows”

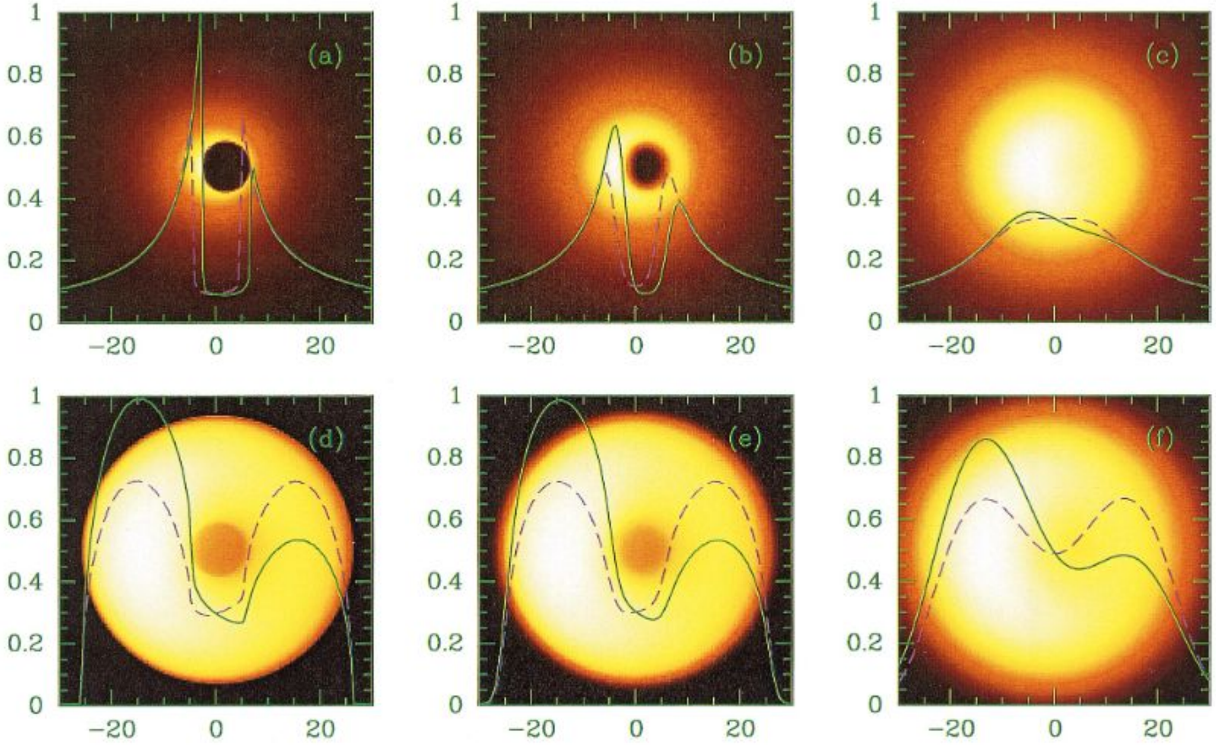




(Luminet 1979)

θ_{shadow} ~ 5.2 R_s

~40 μas (M87*)
~50 μas (Sgr A*)



(Falcke+ 2000)

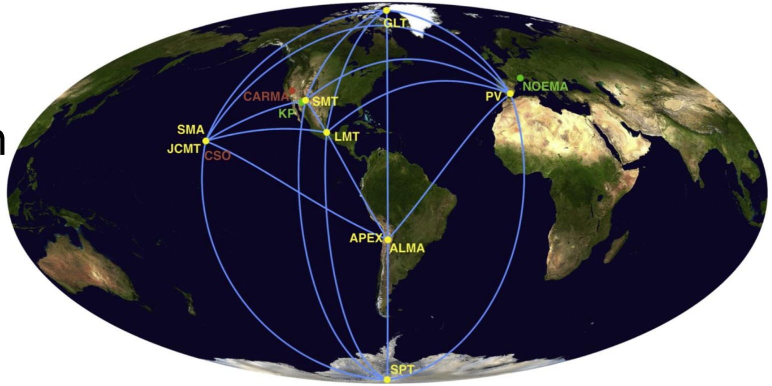
Event Horizon Telescope

To Image the Shadows of the largest BHs

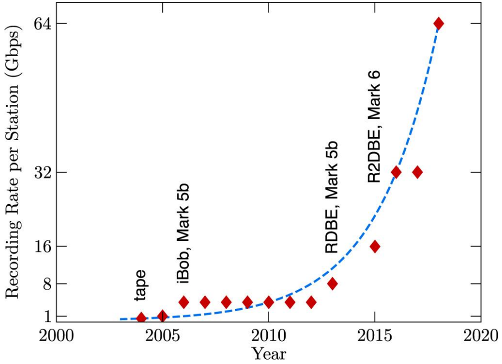
Ultra-high angular resolution required
To resolve **a doughnut on the moon**
VLBI to the extreme:

- ➢ Planet-size baselines
- ➢ Highest frequencies
- ➢ High sensitivity
  - ➢ Large apertures
  - ➢ Wide bandwidth

- ➢ New imaging methods desired
- ➢ Theory and simulation tools

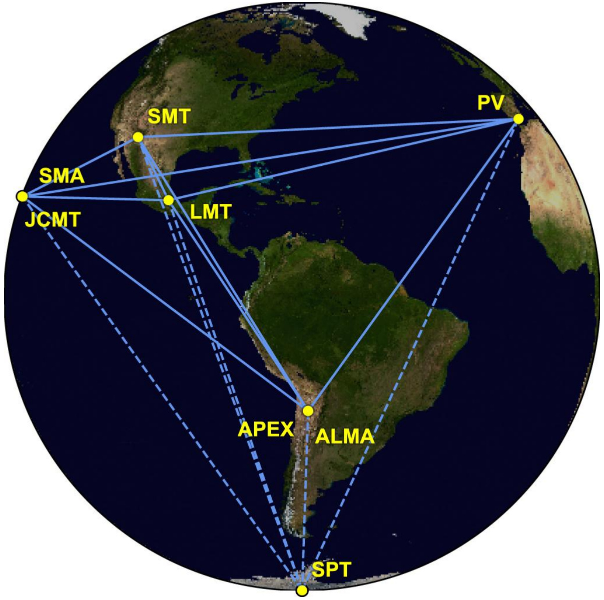


(EHTC+ 2019, Paper II)

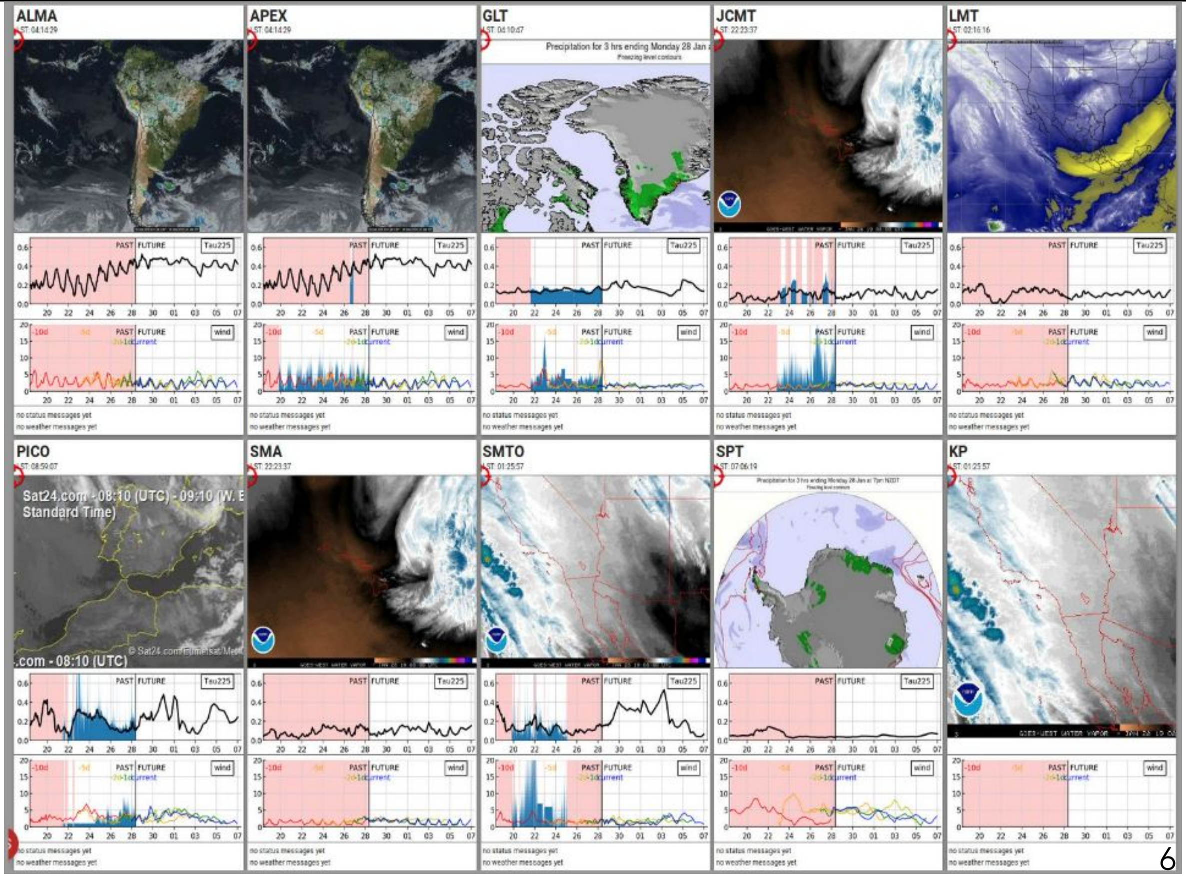


(EHTC+ 2019 Paper II)

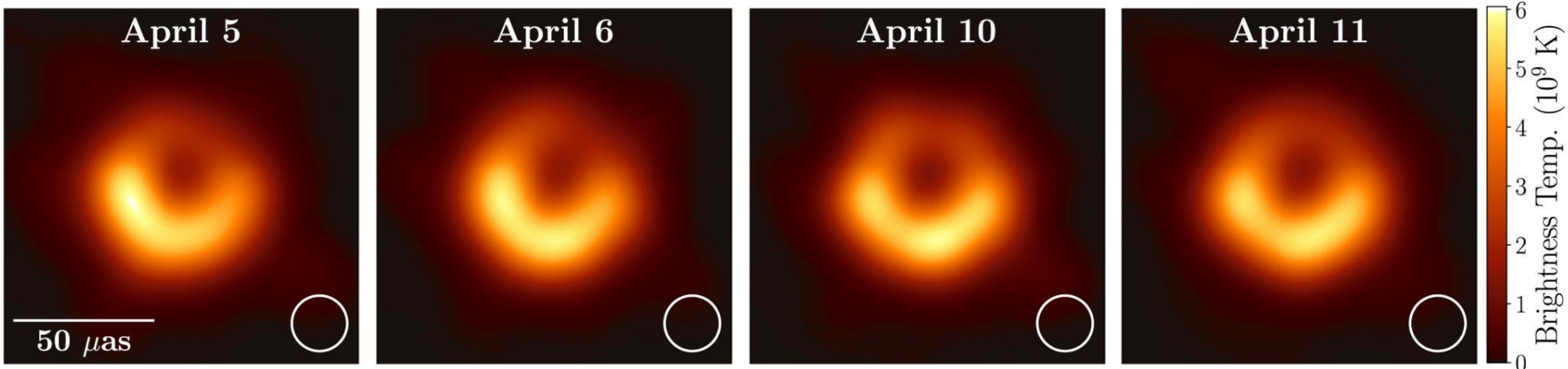
EHT 2017 Observations



(EHTC+ 2019, Paper I)



Images of M87*



(EHTC+ 2019, Paper I, IV)

- First image of the “Shadow” of a Black Hole
- Ring diameter ~42 μas ⟺ $M_{BH} = 6.5 \pm 0.7 \times 10^9 M_\odot$
- No significant changes during the 6-day span of EHT 2017 Campaign

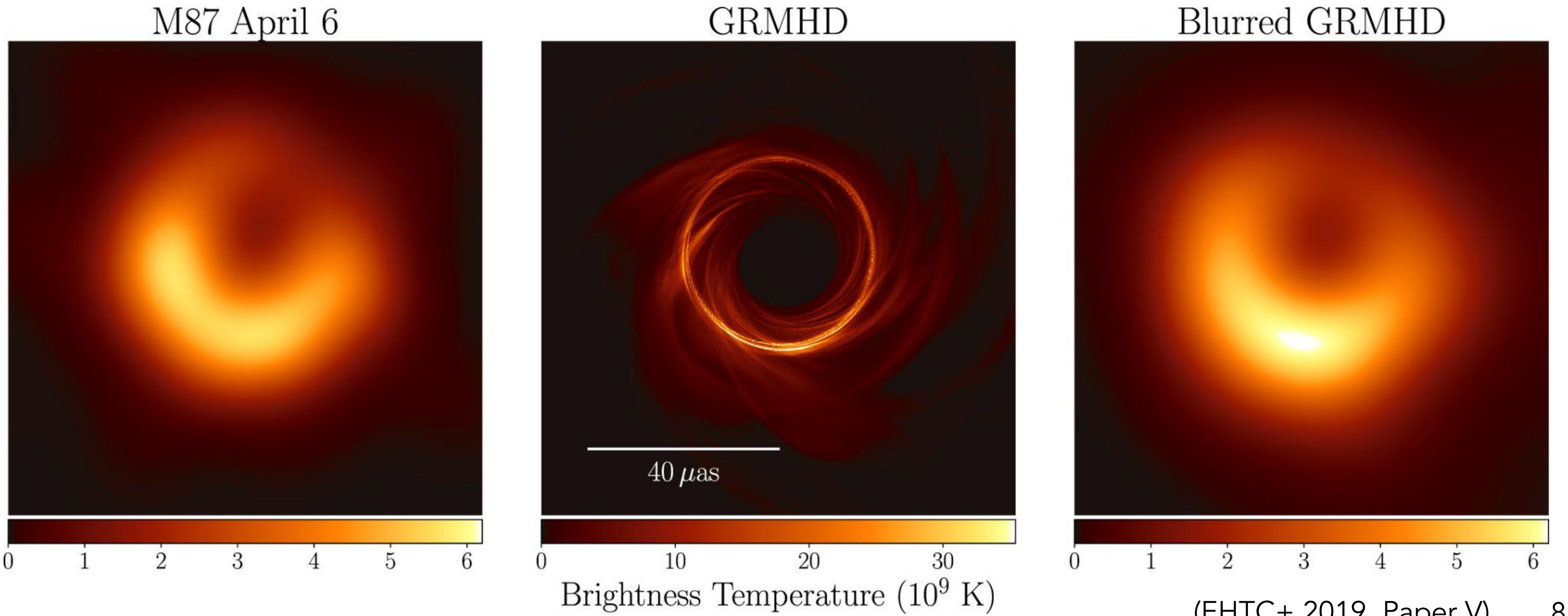
Event Horizon Telescope

Representative GRMHD model for M87*

EHT 2017 image

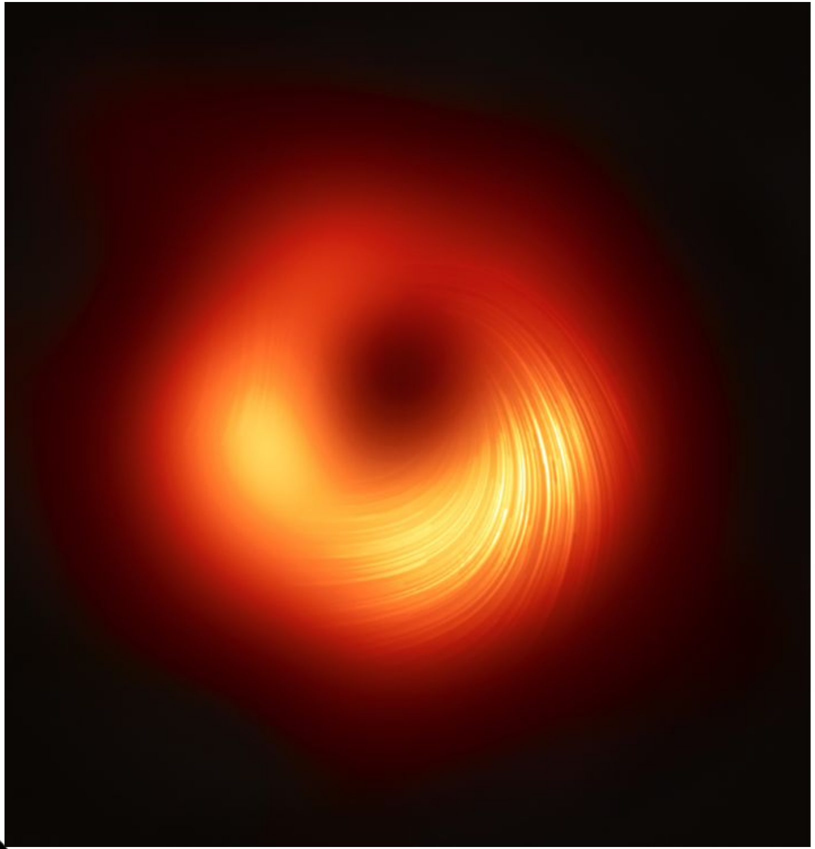
Simulated image from GRMHD model

Simulated image convolved with 20 uas beam



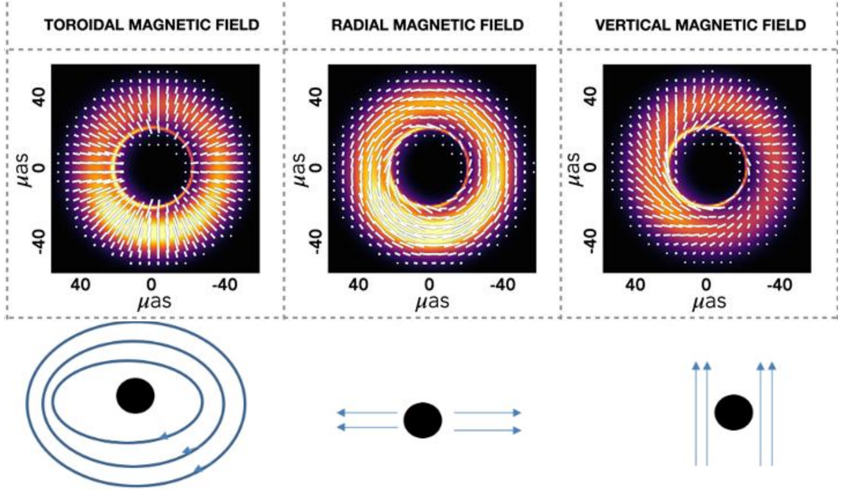
(EHTC+ 2019, Paper V)

Polarization of the Ring



(EHTC+ 2021, Paper VII)

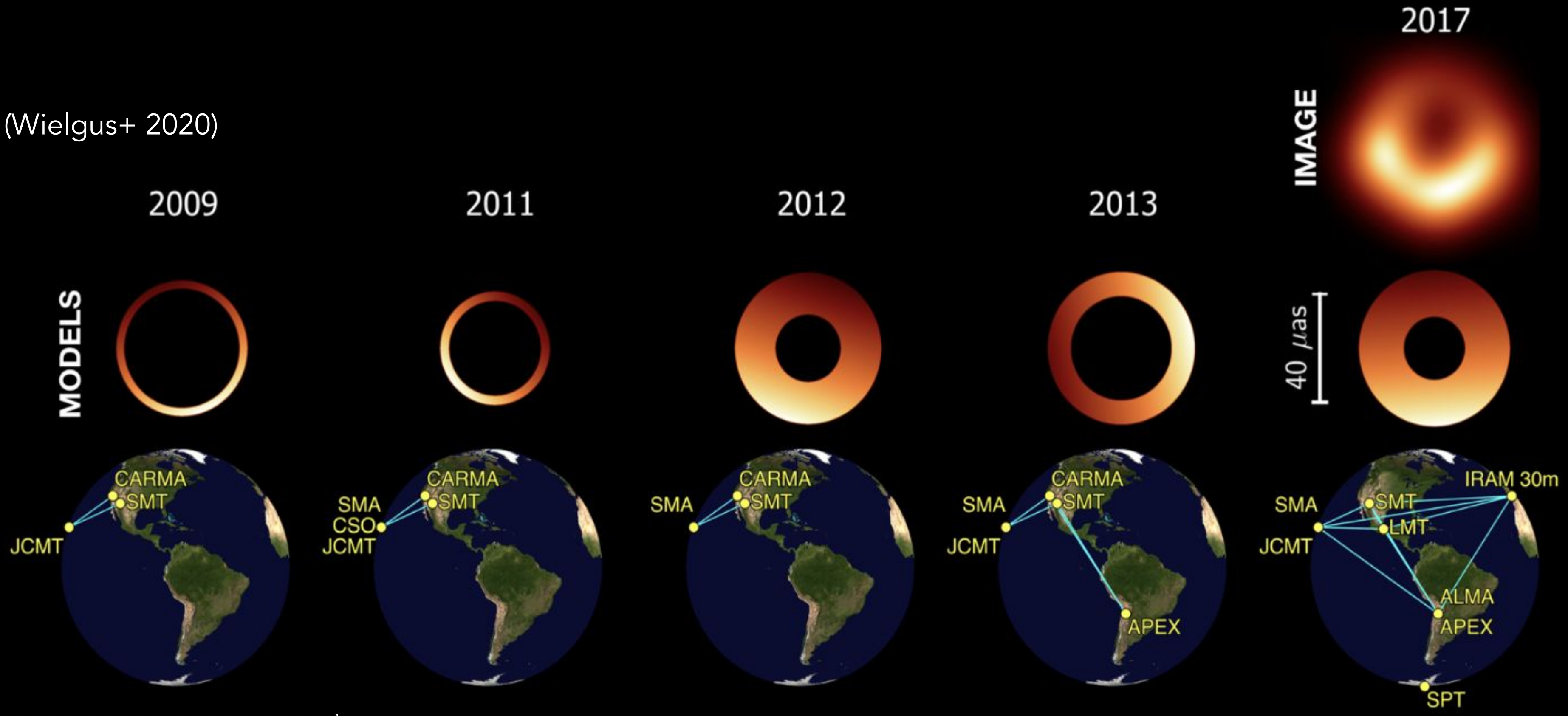
The BH Magnetosphere



(EHTC+ 2021, Paper VIII)

Ring Morphology over Years

(Wielgus+ 2020)



The 2017 Multi-λ View of M87 jet

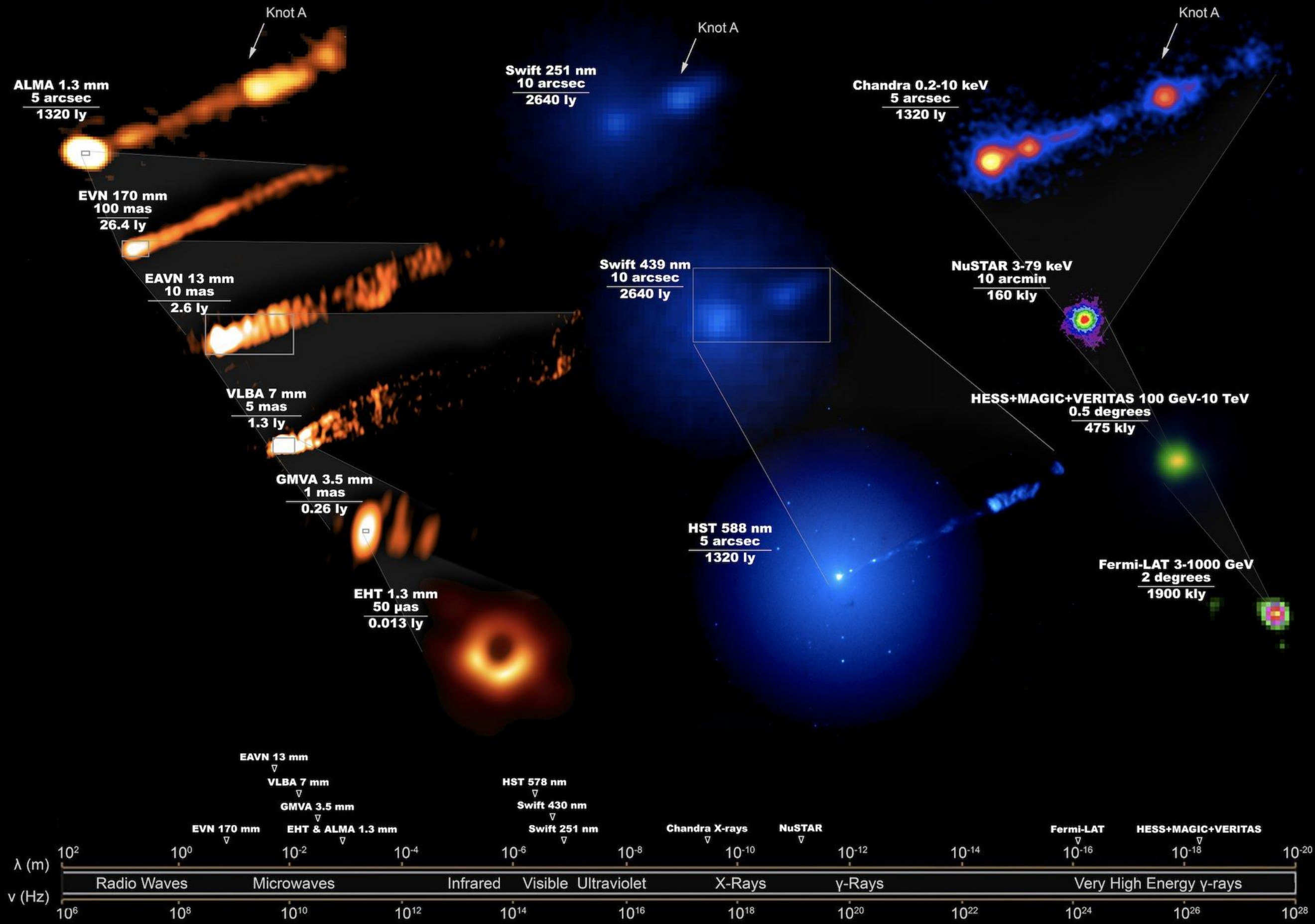
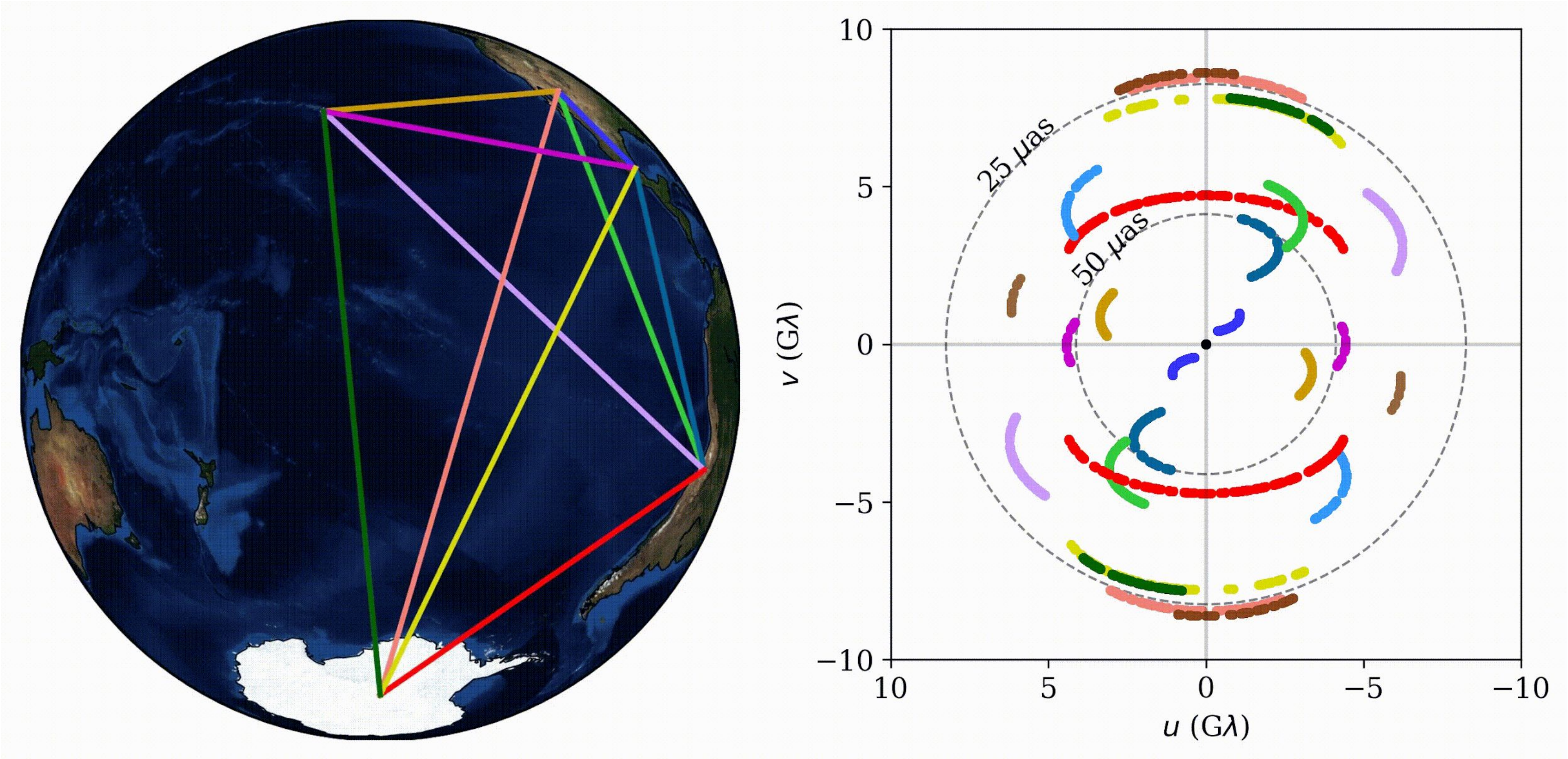


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array;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

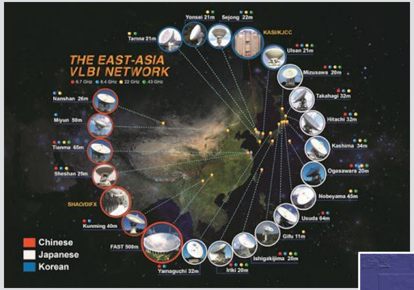
Event Horizon Telescope

The EHT 2017 Observations of Sgr A*



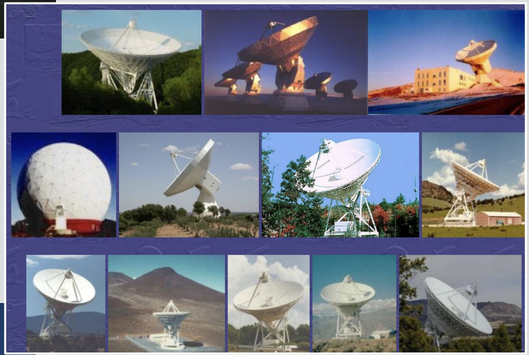
Movie credit: **Daniel Palumbo**

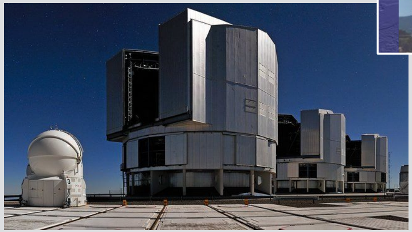
Multi-wavelength Coordination



East Asian VLBI Network (EAVN)

Global mm VLBI Array (GMVA)

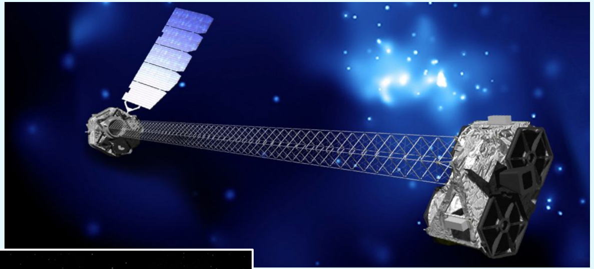


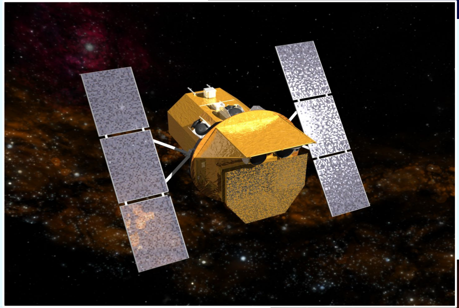


Very Large Telescope (VLT/NACO)

Ground | Space

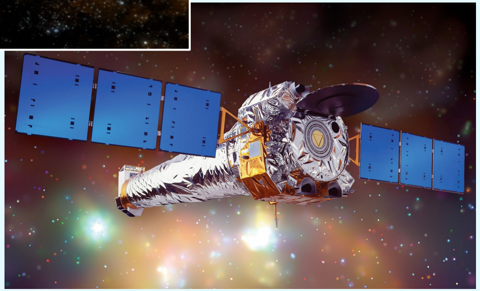
Nuclear Spectroscopic Telescope Array (NuSTAR)



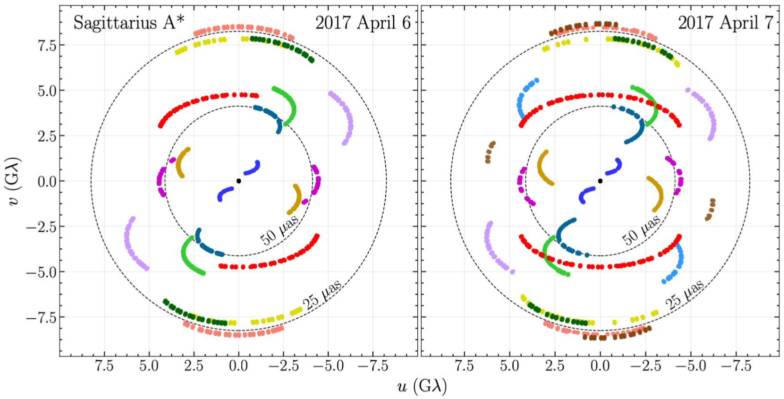


Neil Gehrels SWIFT Observatory

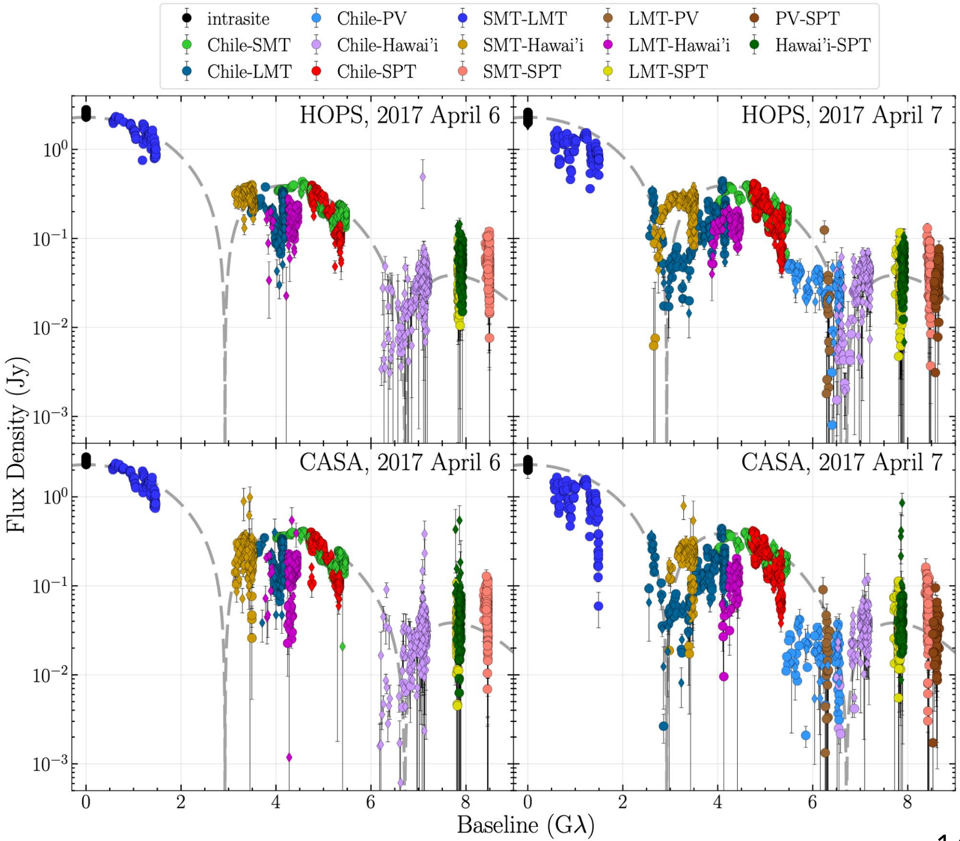
Chandra X-ray Observatory



EHT Final Data Products



(EHTC+2022, Paper II)

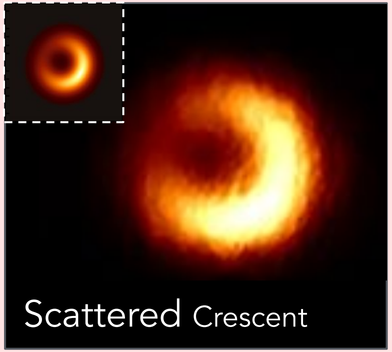


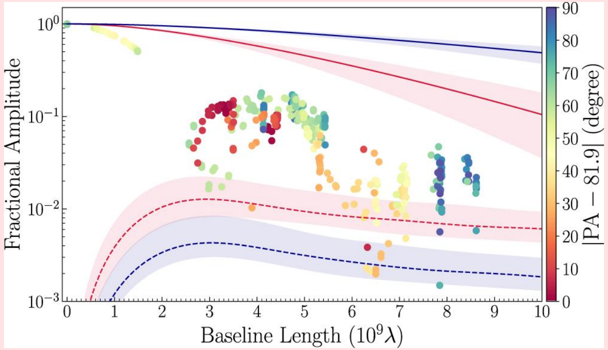
- Amplitudes well described by a ~50 μas ring model
- Good (u, v) coverage on April 6 vs April 7
- Consistency between calibration pipelines

Unique Challenges for Sgr A* Analyses

Interstellar scattering:
- Diffractive scattering: angular broadening
- Refractive scattering: substructure

Mitigation strategy:
(1) Add noise budget to compensate the refractive scattering.
(2) Deblur to invert the diffractive scattering

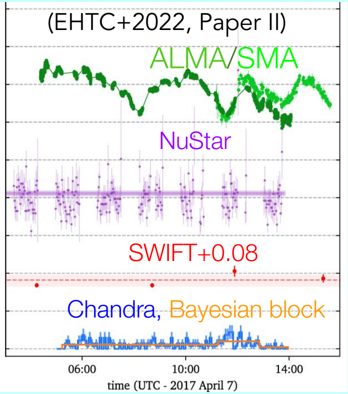


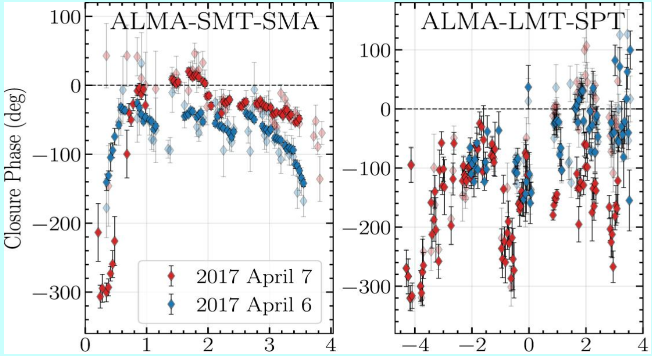


(EHTC+2022, Paper III)

Temporal variation:
- Flux variation: ALMA+Vis amp
- Structural variation: closure phases

Mitigation process:
(1) Intrasite normalization
(2) Variability modeling





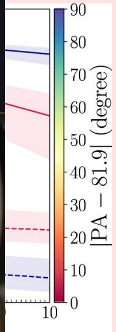
(EHTC+2022, Paper III)

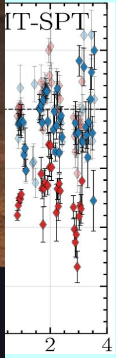
Unique Challenges for Sgr A* Analyses

Inte
▪Dif
▪Re
Mit
(1) A
refra
(2) D

Te
▪Flu
▪St
Mi
(1) I
(2) Y

Image Credit: https://www.youtube.com/watch?v=EpHbwGRhf4A, Pinterest



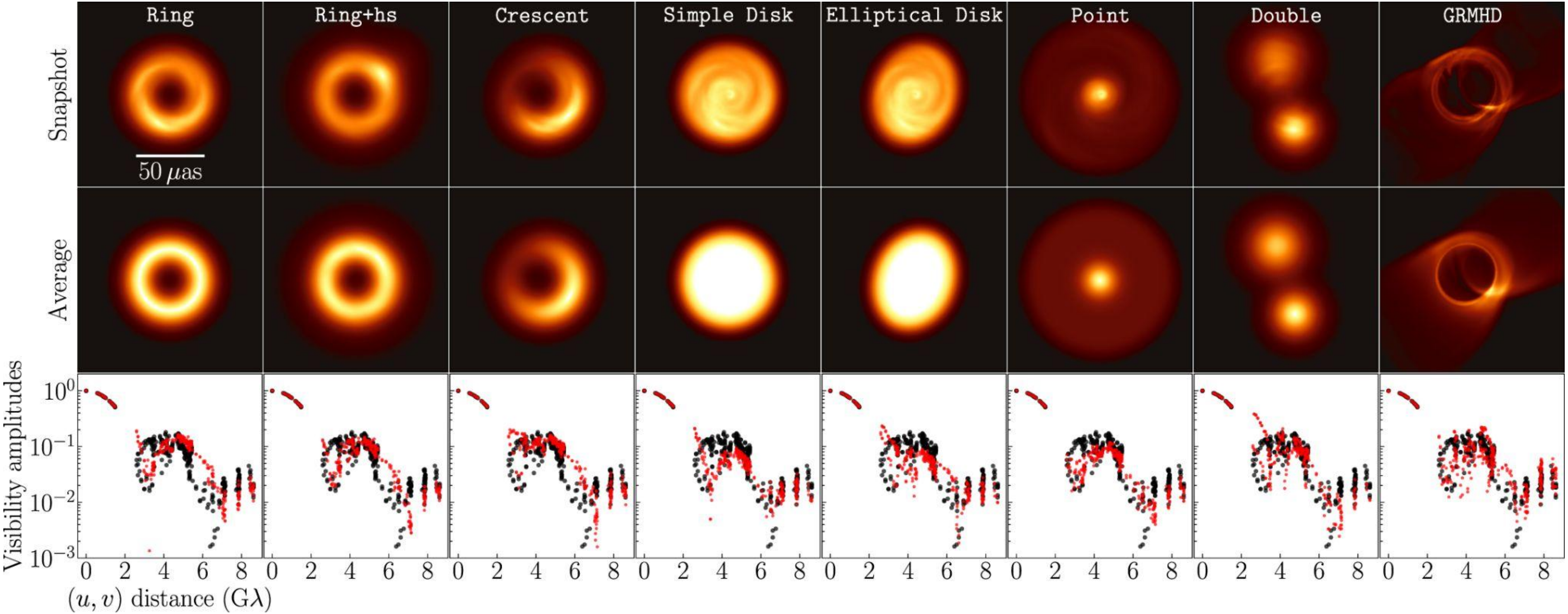


Four Imaging methods

Inverse Imaging Method	Forward Imaging Method		
CLEAN	Regularized Maximum Likelihood (RML)		Bayesian Imaging
DIFMAP (Shepherd+97, 98, 03)	eht-imaging (Chael+16, 18)	SMILI (Akiyama+17a, b)	THEMIS (Broderick+20a, b)
Model General Pixelated Images Residual Calibration Gains	**Model** General Pixelated Images	**Model** General Pixelated Images Residual Calibration Gains	**Model** Low-resolution Pixel Images Residual Calibration Gains Scattering Parameters Variability Parameters Field of View / Grid Orientations
Hyper Parameters Image Assumptions Scattering Parameters Variability Parameters	**Hyper Parameters** Image Assumptions Scattering Parameters Variability Parameters	**Hyper Parameters** Image Assumptions Scattering Parameters Variability Parameters	**Hyper parameters** Number of Image Pixels

Event Horizon Telescope

Imaging Tests with Synthetic Data



(EHTC+2022, Paper III)

Imaging Tests with Synthetic Data

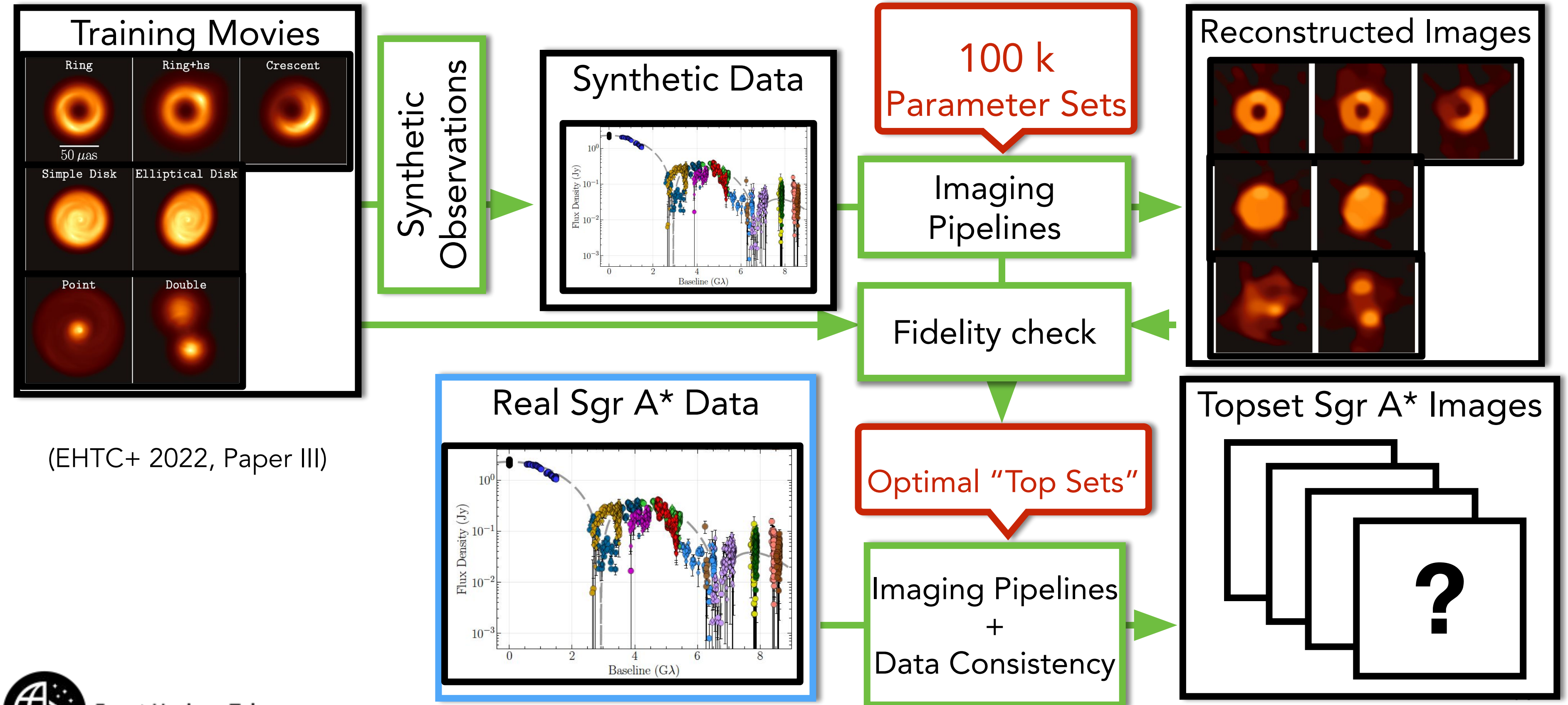
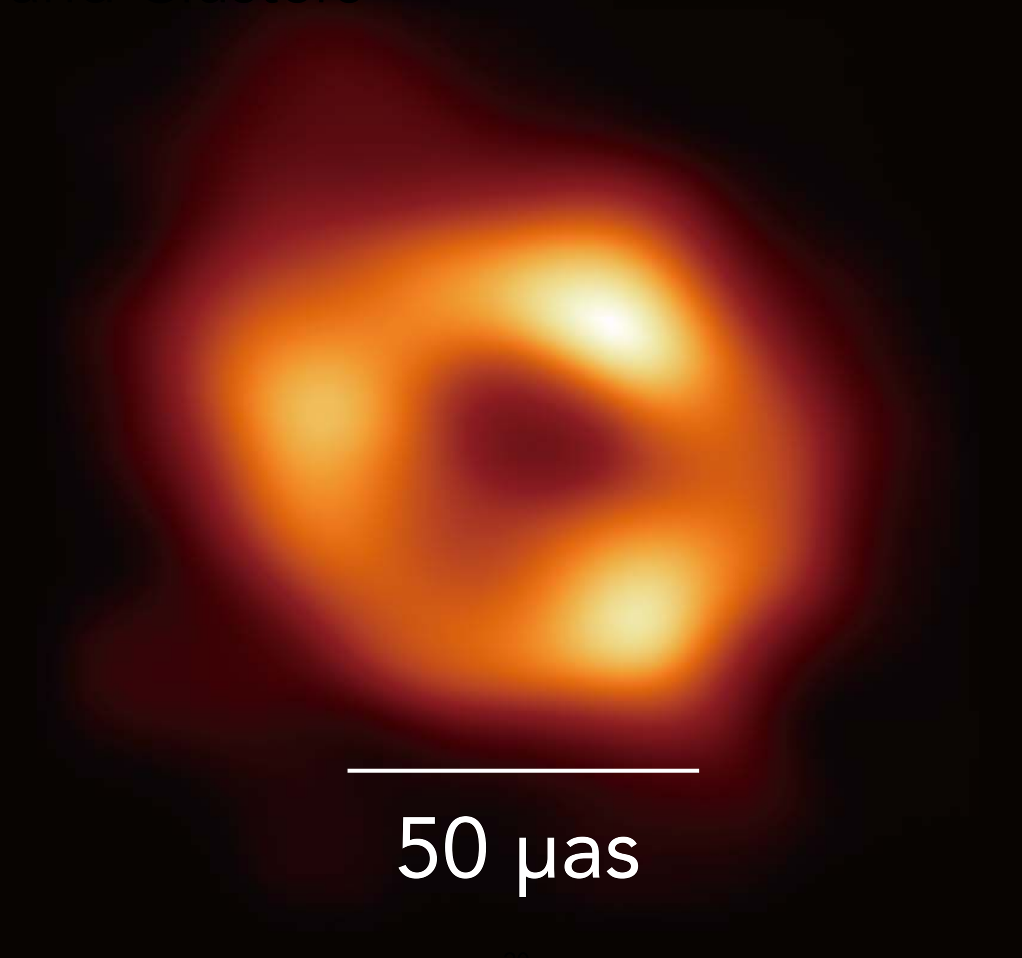


Image Gallery and Clusters

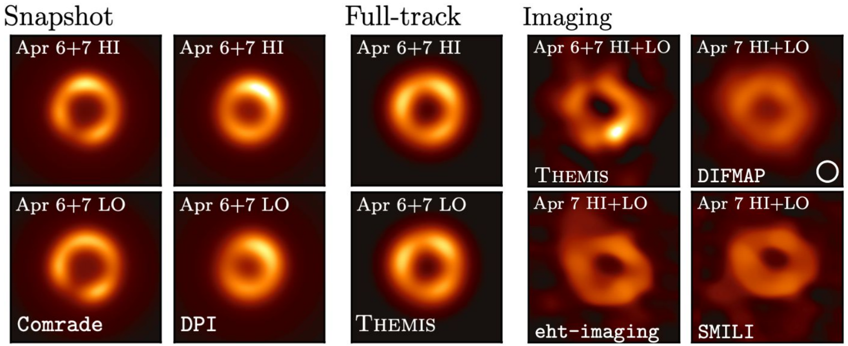


20

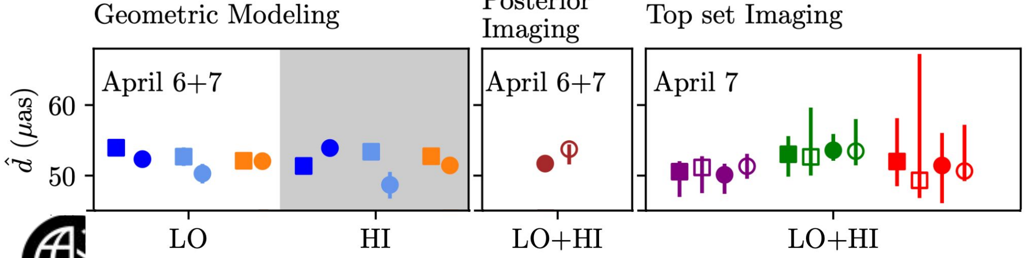
Geometric Modeling and Feature Extraction

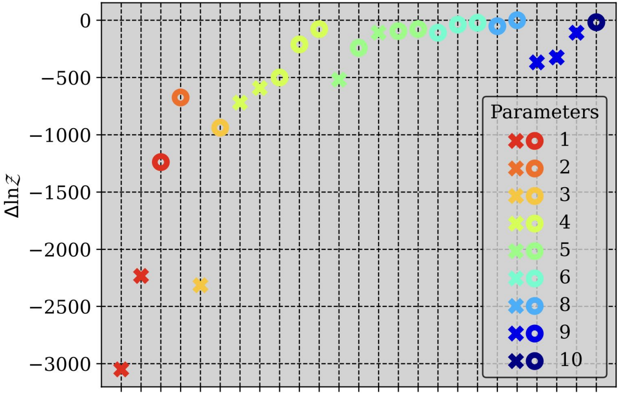
Geometric modeling

Ring-like morphologies provide better fits than other morphologies with comparable complexity



(EHTC+2022,Paper IV)





ring-like model

non-ring-like model

(EHTC+2022, Paper IV)

Morphological parameters from geometric modeling and image-domain feature extraction

- Ring diameter of 51.8 ± 2.3 μas
- Ring thickness: FWHM ~30-50% of the ring diameter
- Other morphological quantities: less constrained and depend on the measurement method

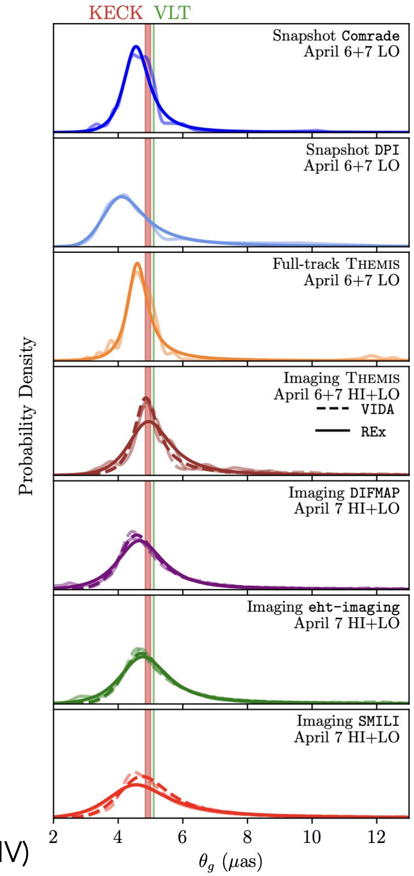
Gravitational radius and black hole mass

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 $\boldsymbol{\theta}_g$ = 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)



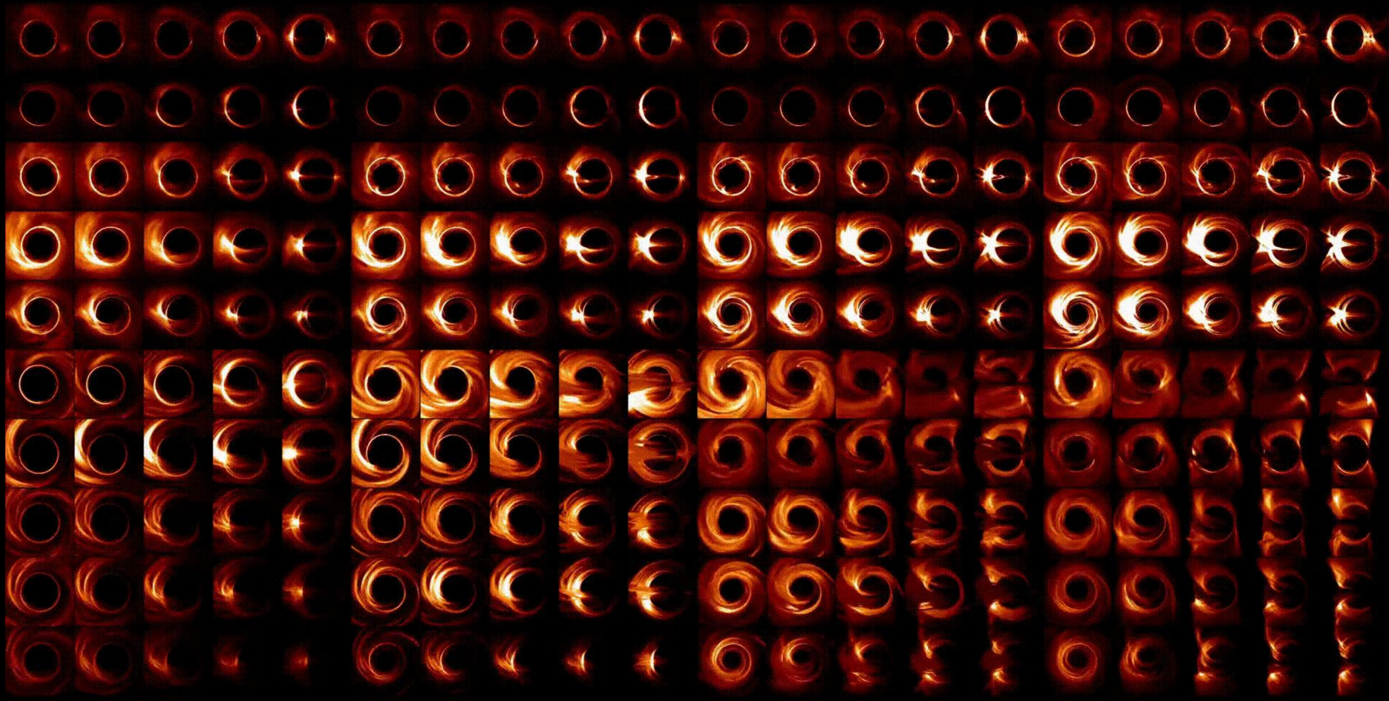
(EHTC+2022, Paper IV)

Event Horizon Telescope

Constraints on GRMHD models

11 constraints in total

- EHT 230 GHz data:
  - 230 GHz size
  - visibility morphology
  - m-ring diameter
  - m-ring width
  - m-ring asymmetry
- MWL data:
  - 86 GHz size
  - 86 GHz flux
  - 2μm flux
  - X-ray flux
- Variability:
  - lightcurve
  - structural variabilities

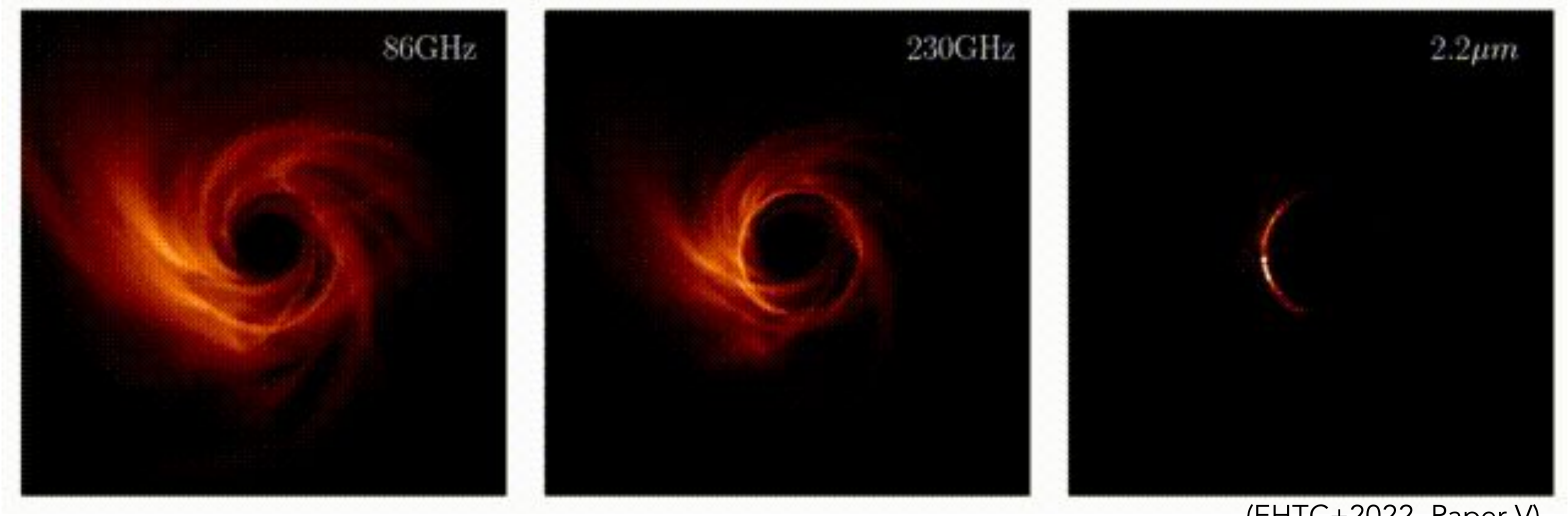


(EHTC+2022, Paper V)

Event Horizon Telescope

Constraints on GRMHD models: Results

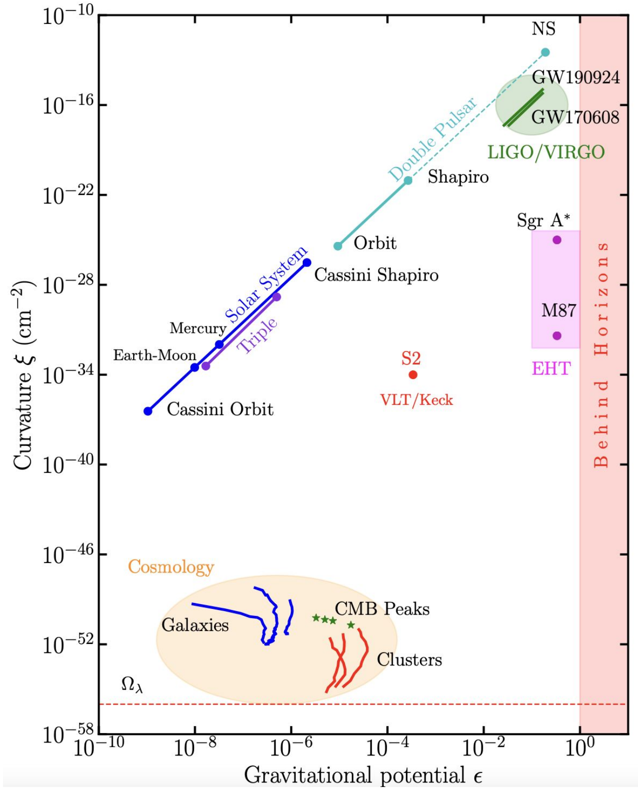
- EHT image is a key constraint; none of the models pass all constraints!
- Most models are too variable. A small reduction in variability would make many models pass

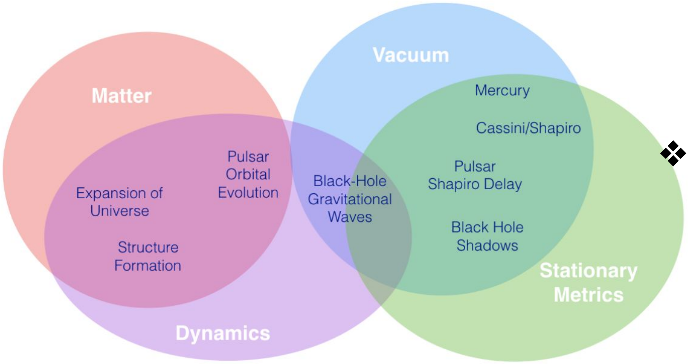


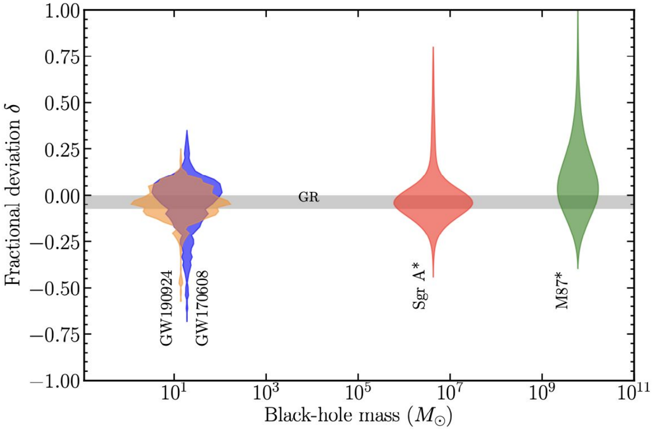
(EHTC+2022, Paper V)

- Setting aside variability, a region of best-bet models that satisfy all remaining constraints: MAD, prograde ($a^* > 0$), low inclination ($i < 70$ deg) and cool electrons ($R_{high} = 160$)
- Strongly disfavored: single-temperature ($R_{high} = 1$); edge-on; retrograde

Testing the Black Hole Metric



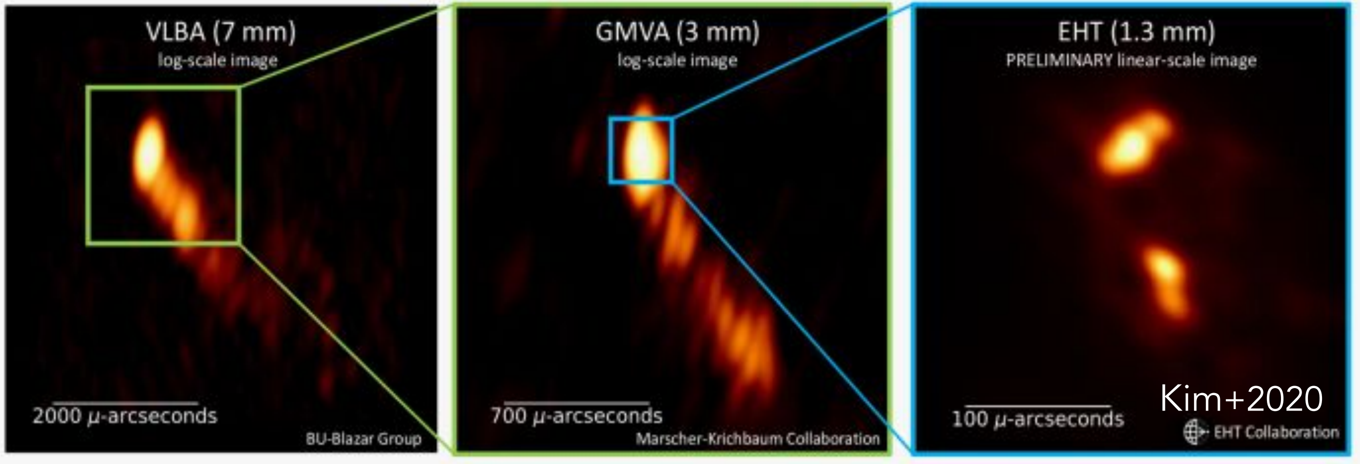


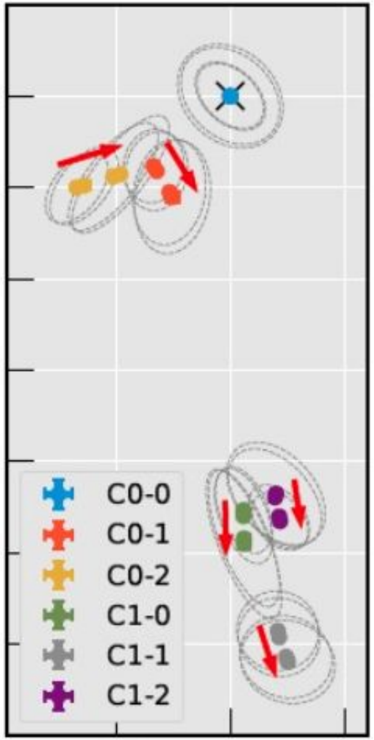


- ❖ Tests with gravitational waves and black-hole images span black- hole masses that are different by 8 orders of magnitude.
- ❖ All consistent with the GR predictions that all black holes are described by the same metric, independent of their mass.

(EHTC+2022, Paper VI)

EHT Observations of AGNs: 3C 279





(Kim+2020)

3C 279: an archetypal blazar

- One of the first AGN jets with superluminal motions (e.g., Whitney+71)

EHT 2017 Observations

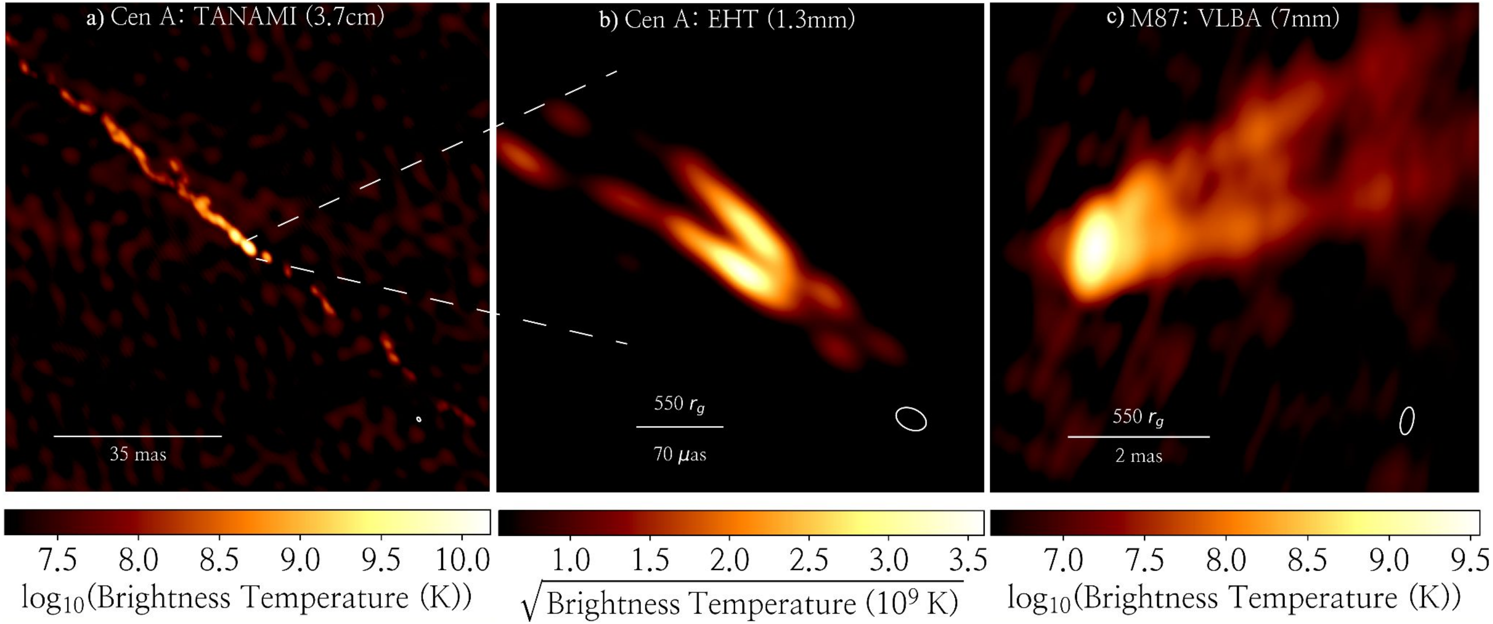
- Fringe-detection up to 8.9 Gλ → ~20 μas resolution
- Peculiar "core" elongation, perpendicular to the jet axis
- Fast inter-day motion of the jet components (10-20c)

Event Horizon Telescope

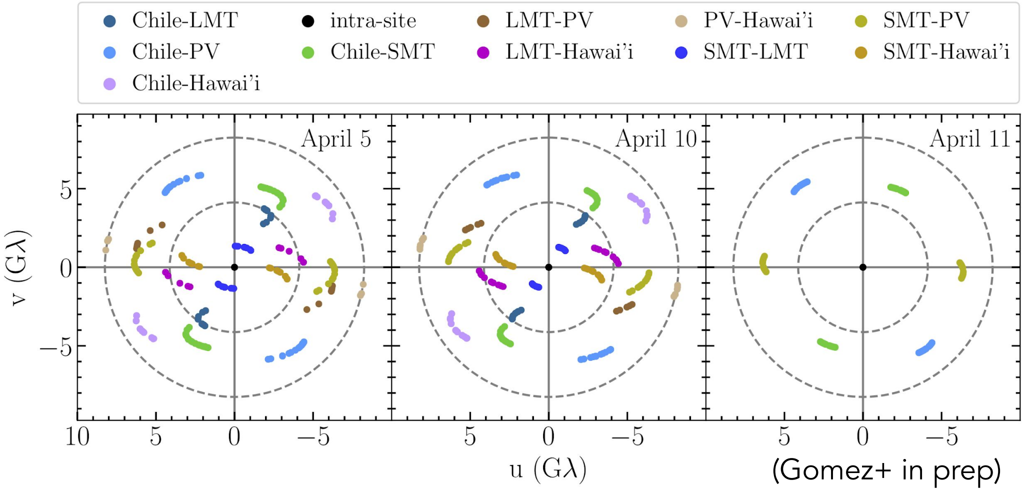
EHT Observations of AGNs: Cen A

Cen A: the nearest radio galaxy
EHT image: 10x frequency & 16x resolution (< 1 lightday) compared to the TANAMI image
An double-sided jet with edge-brightening (ratio > 5)

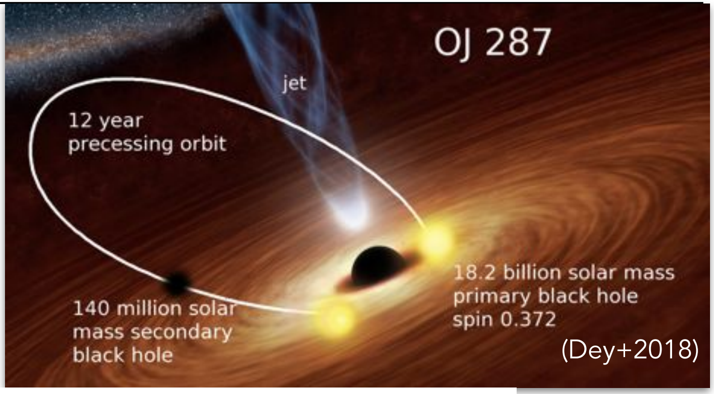
(Janssen+2021)



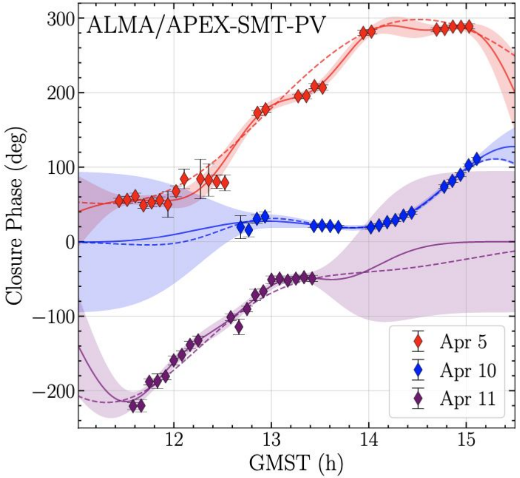
EHT Observations of AGNs: OJ 287



(Gomez+ in prep)



(Dey+2018)



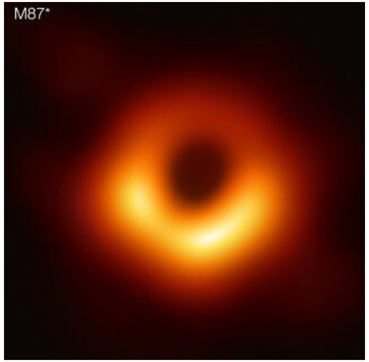
(Gomez+ in prep)

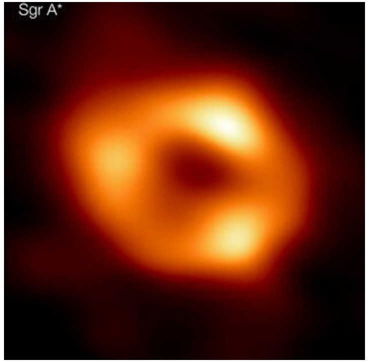
- OJ 287: A bright blazar, promising candidates for hosting a binary SMBH system
- EHT 2017 observations: good uv-coverages, high SNR
- Two good days for imaging, separated by 5 days
- Clear day-to-day variability in closure phases indicative of structural changes

Event Horizon Telescope

Summary

- EHT provides sharpest views of SMBHs and AGNs at mm/sub-mm wavelengths
- Ring-like image reconstructions: defining feature of the “shadow” of black holes
- Tight constraints on GRMHD models of accretion disks and relativistic jets
- GR tests of BHs spanning 3 orders of magnitude
- Multi-band VLBI observations: connect horizon-scale physics to larger scale jet physics





Follow updates online:

https://eventhorizontelescope.org

https://twitter.com/ehtelescope

https://www.facebook.com/ehtelescope