Photographing a Black Hole with the Event Horizon Telescope

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Princeton University

July 10, 2020

PRINCETON UNIVERSITY

Event Horizon Telescope

The EHT Collaboration

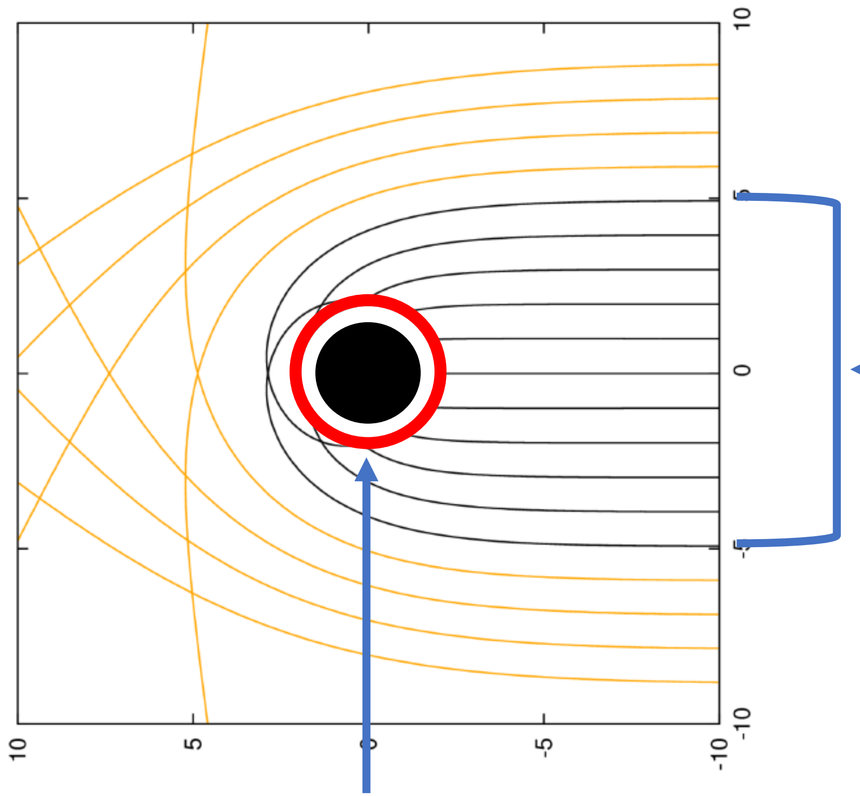
The EHT:
Many antennas, lots of software, one **computational** telescope

Result papers: EHTC+ 2019 papers 1-6: https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT

Story on software behind many steps of the EHT process: https://www.welcometothejungle.com/en/articles/btc-black-hole-imaging-software-telescope

What does a black hole look like?

The Black Hole Shadow



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

photon orbit $r_\gamma = 3GM/c^2$

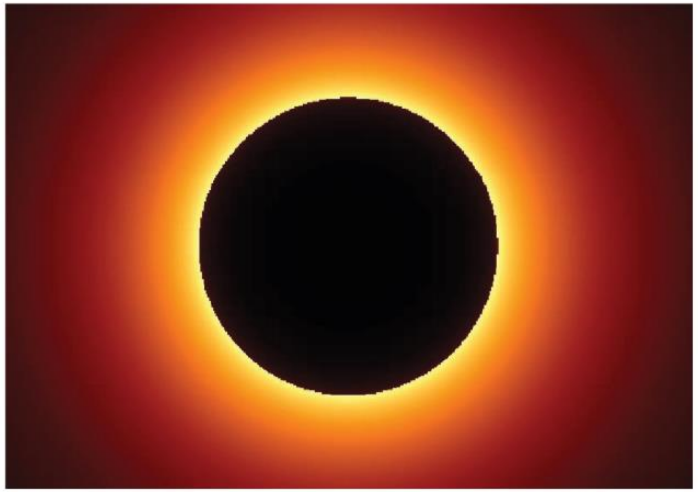


Image credit: Keiichi Asada

Accretion Energy:
black holes can shine brightly

Accretion power per unit mass:

$$\Delta E/mc^2 = GM/Rc^2$$
$$= 1/2 \;\text{ at }\; R = R_{\rm Sch}$$

For nuclear fusion:

$$\Delta E/mc^2 = 0.007$$

Active Galactic Nuclei

NASA/ESA

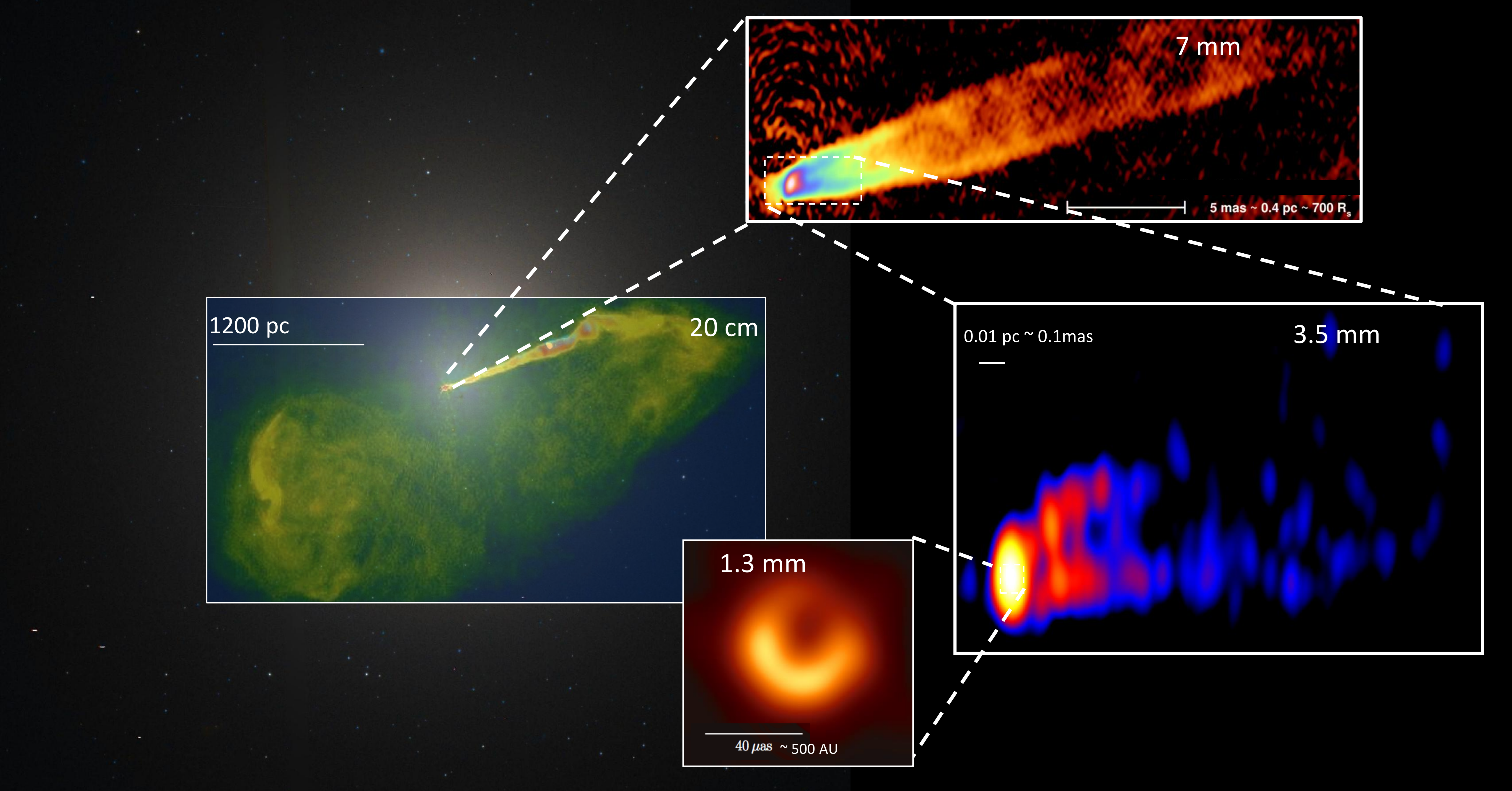
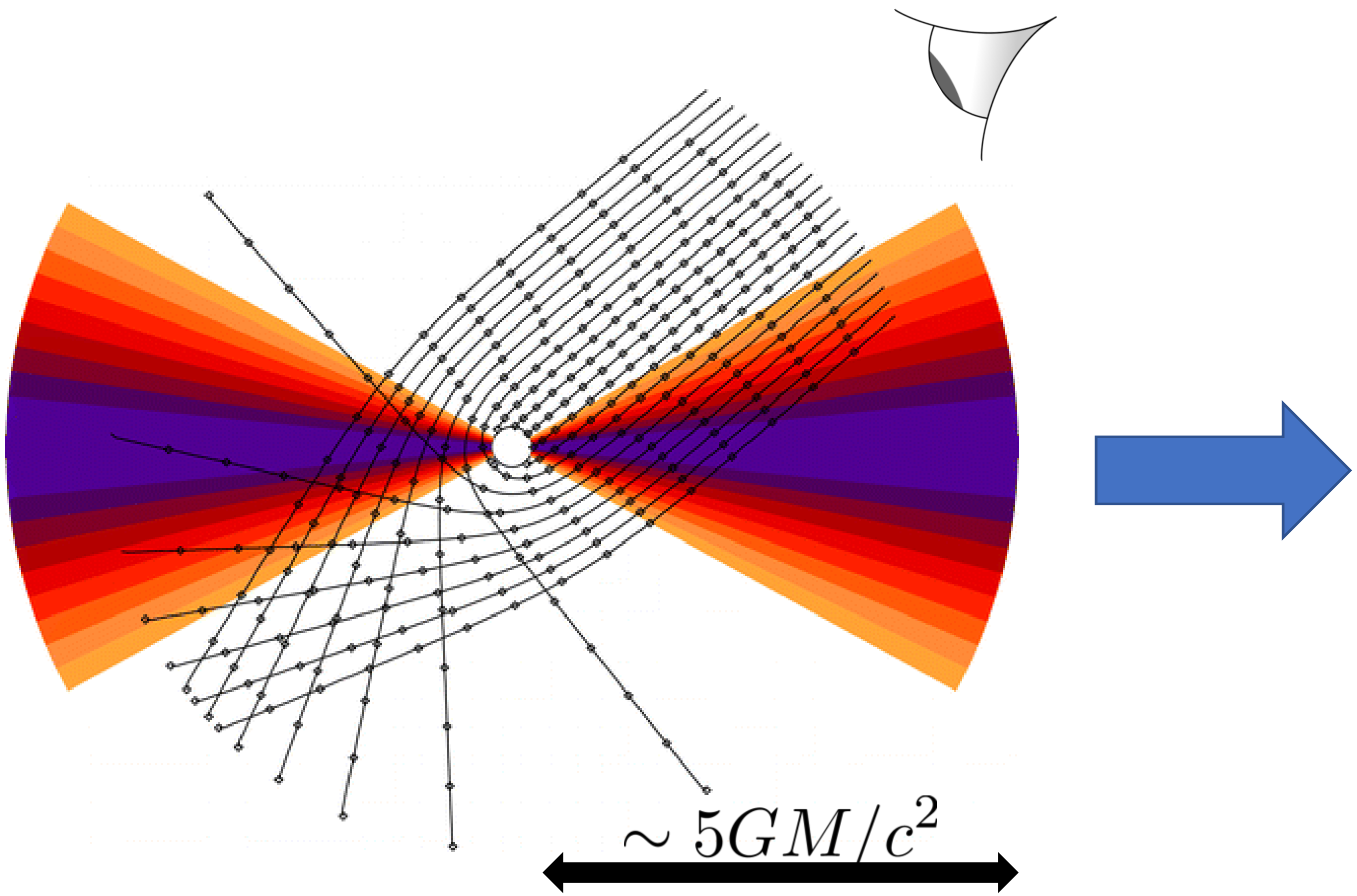
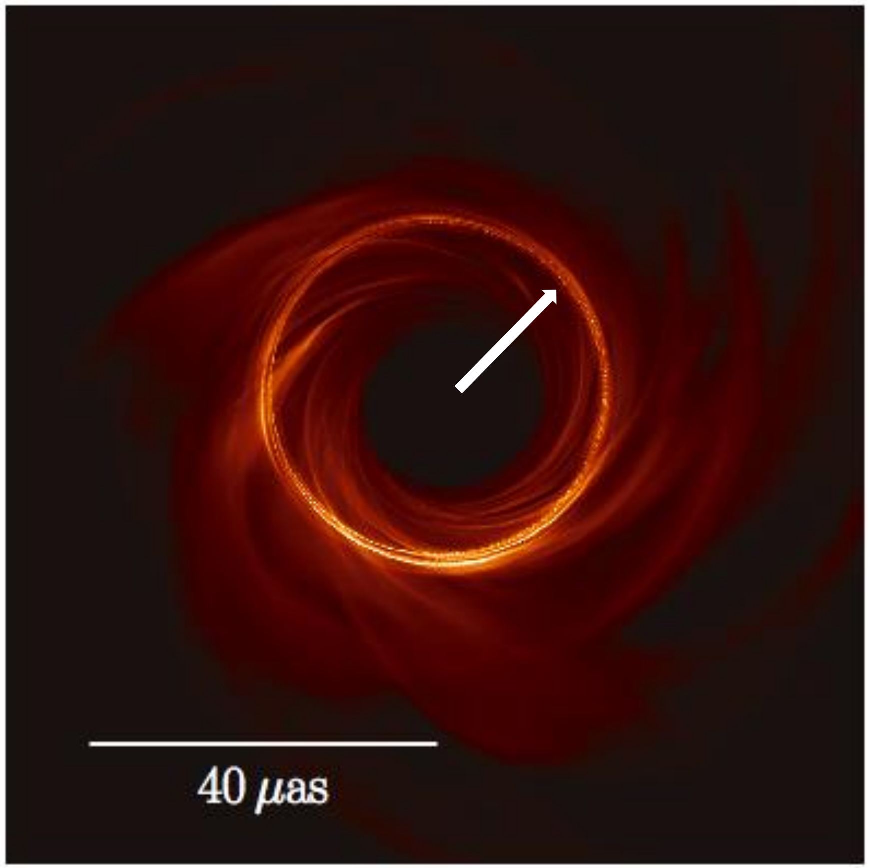


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

The Black Hole Shadow: Modern Simulations



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



Schnittman+ (2006)

EHTC+ 2019

How big is the shadow?

M87 is supermassive, so it’s shadow is big:

$$d_{\text{shadow}} \approx 650 \text{ AU}$$

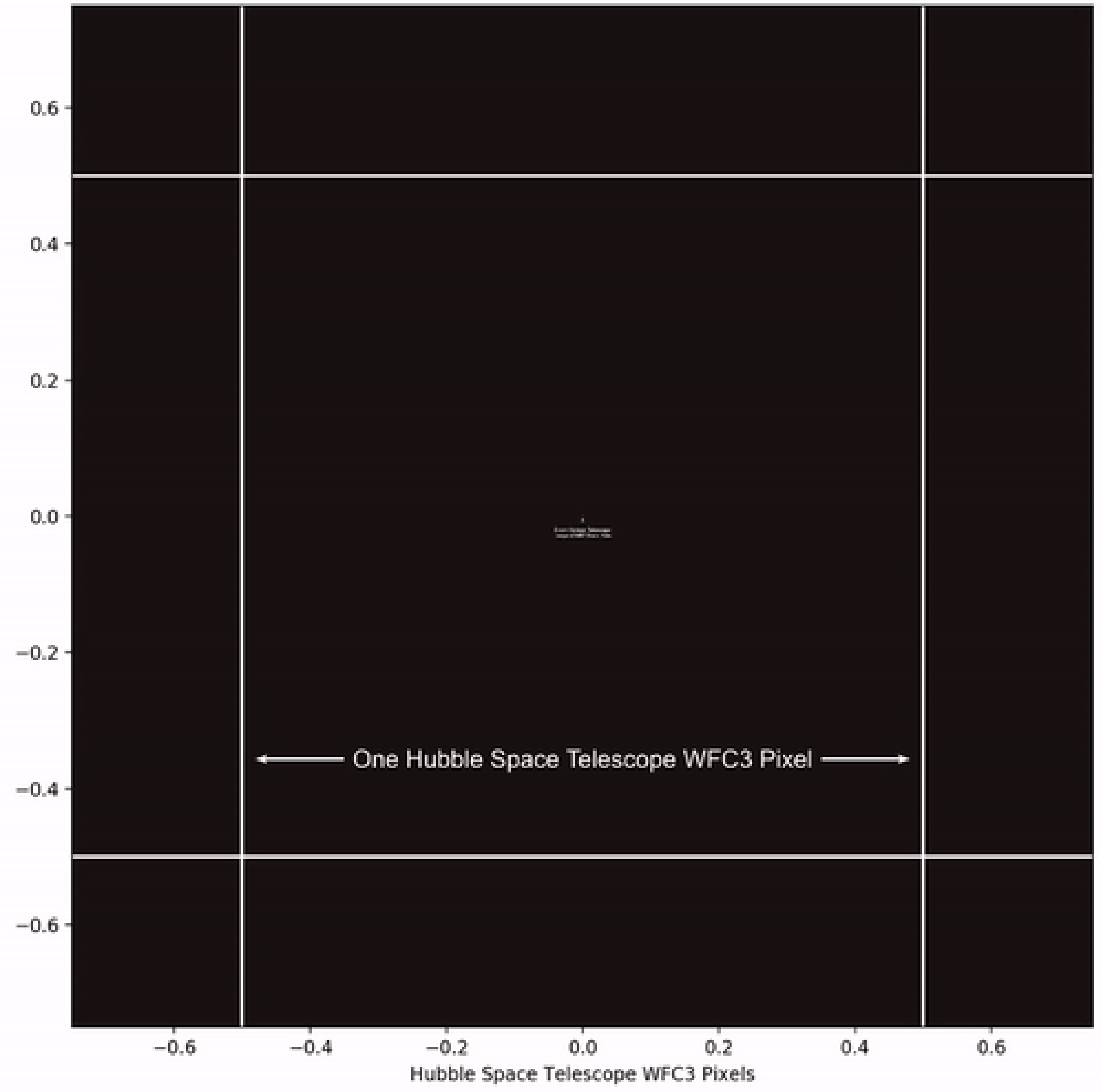
Unfortunately, M87 is really far away…..

$$D_{\text{M87}} \approx 50 \text{ million ly}$$

To us, M87’s shadow is really, really, really small

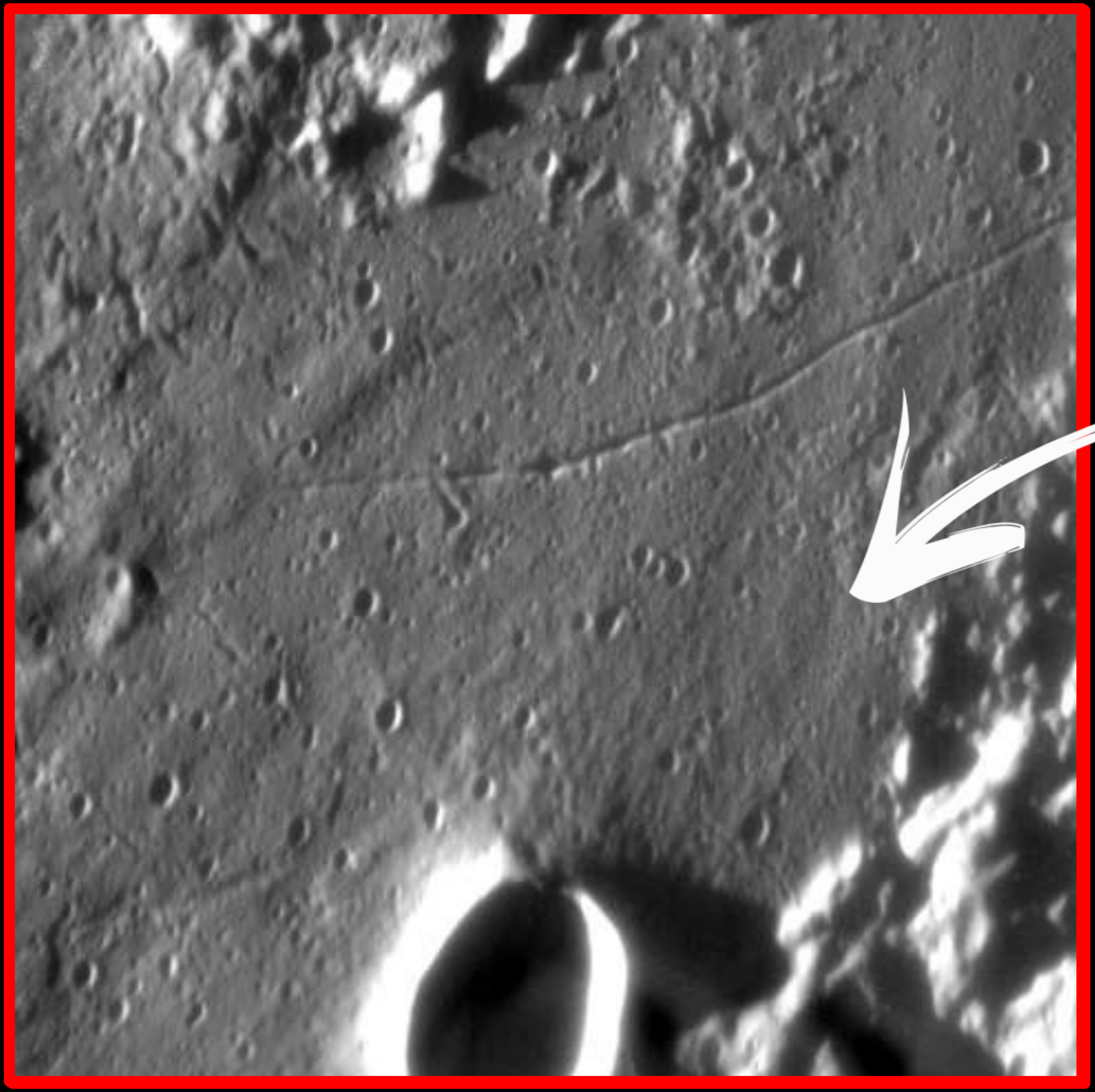
$$\frac{d_{\text{shadow}}}{D_{\text{M87}}} \approx 40\mu\text{as} \approx 10^{-8}\text{deg}$$

How small is 40 microarcseconds?



Animation credit: Alex Parker

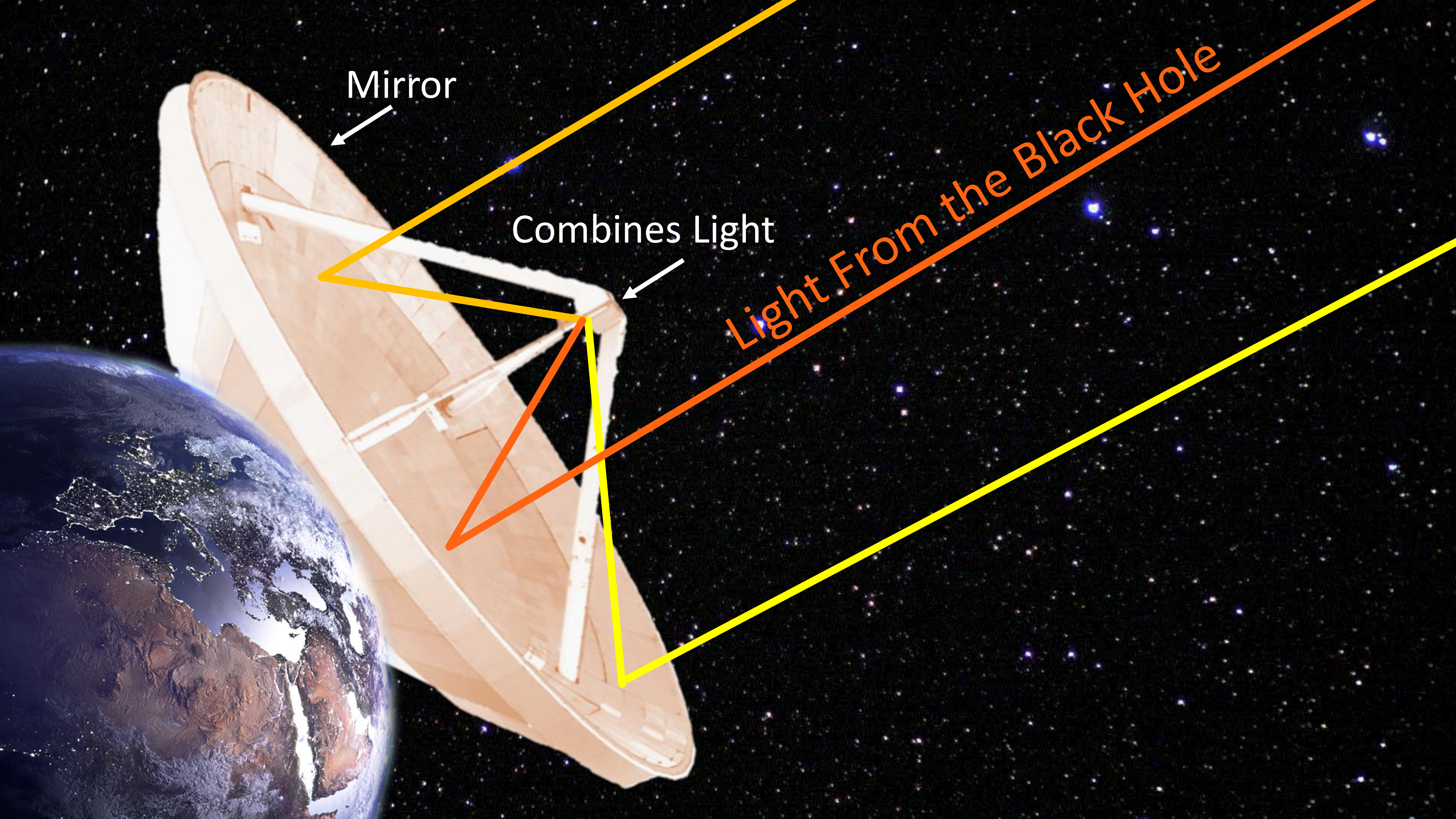
Slide credit: Katie Bouman
Video courtesy of Hotaka Shiokaw

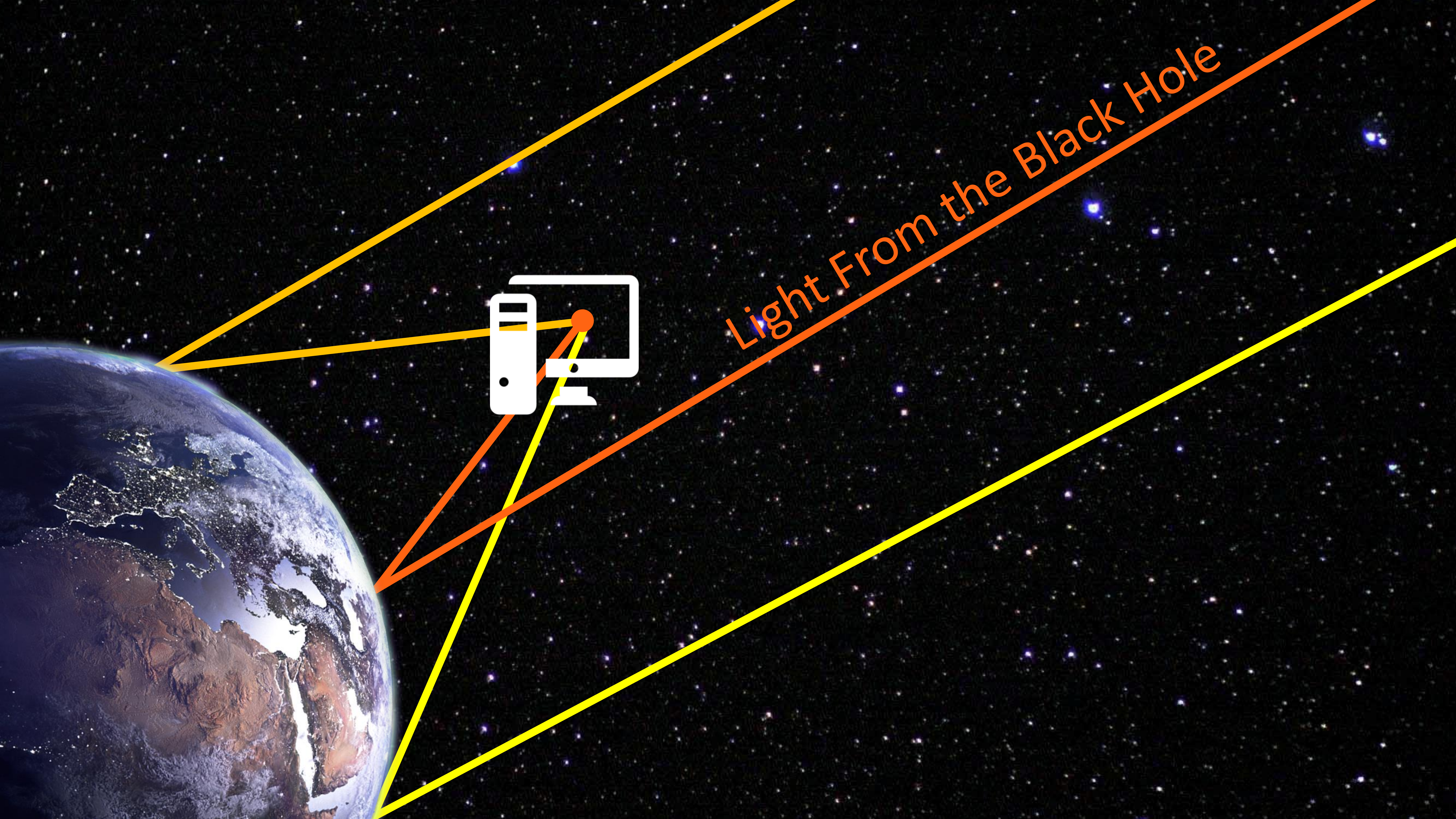


Each Pixel is 1.5 Million

’s

Slide credit: Katie Bouman
Yepun telescope, Paranal Observatory in Chile / George Tarsoudis


Mirror
Combines Light
Light From the Black Hole


Light From the Black Hole

The EHT:
Many antennas, one **computational** telescope

The Physical EHT

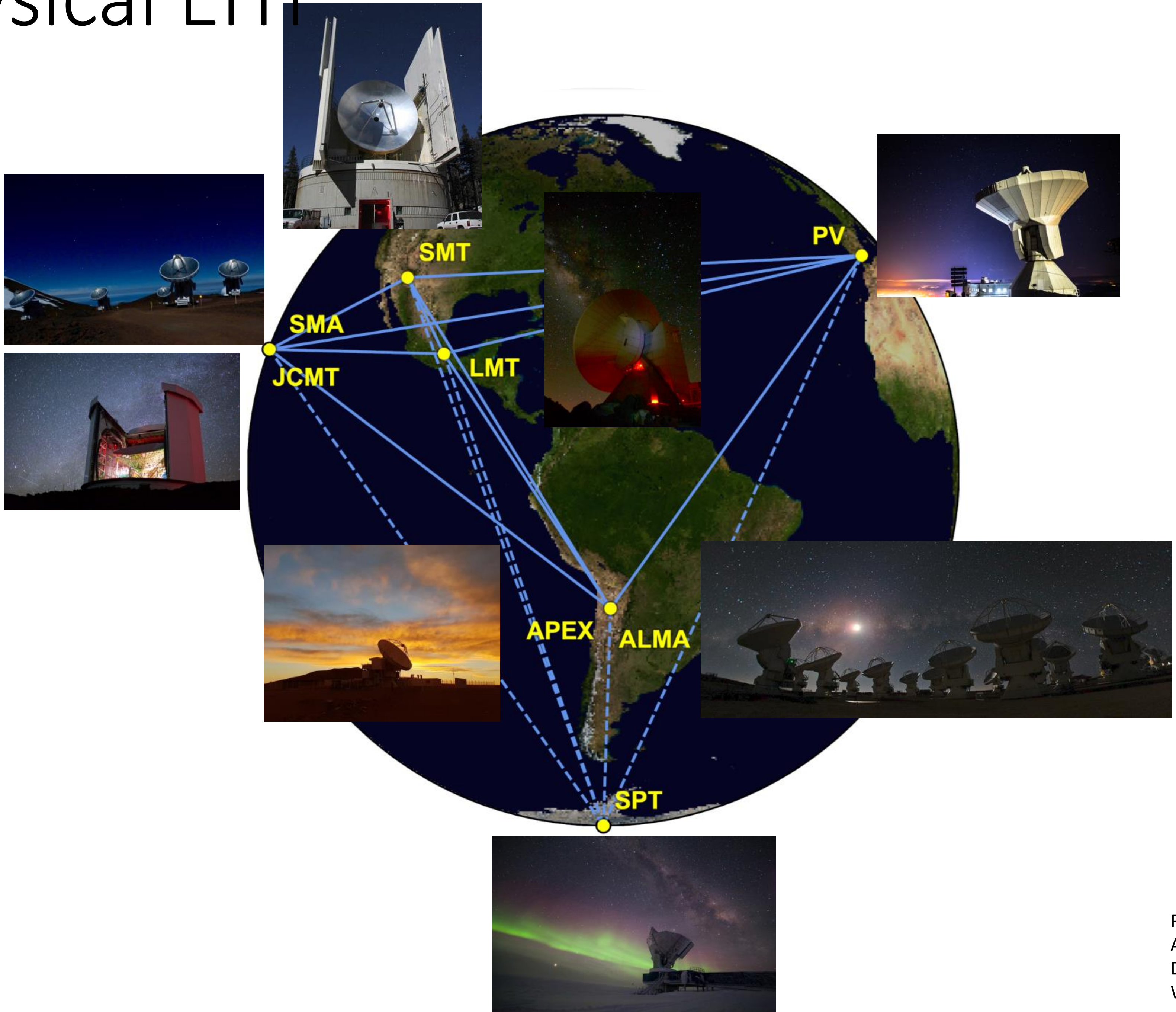


Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

The Computational EHT:

NumPy

scikit-image
image processing in python

GitHub

SciPy.org

h5py 2.10.0

seaborn 0.10.1

pandas

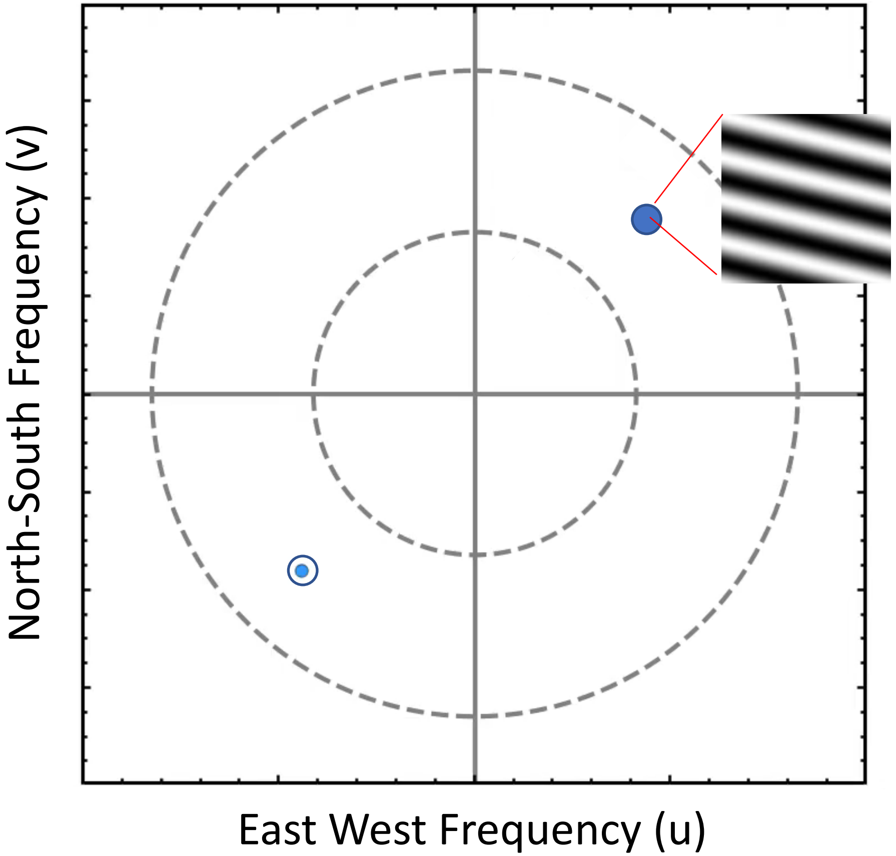
jupyter

matplotlib
Version 3.2.2

… and many, many more

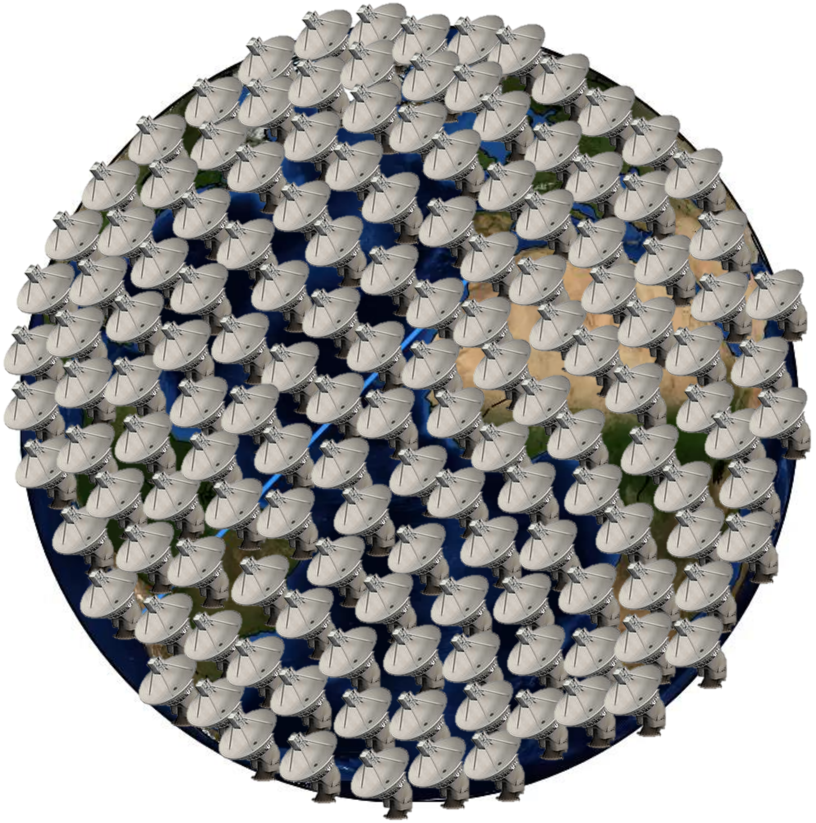
Very Long Baseline Interferometry (VLBI)

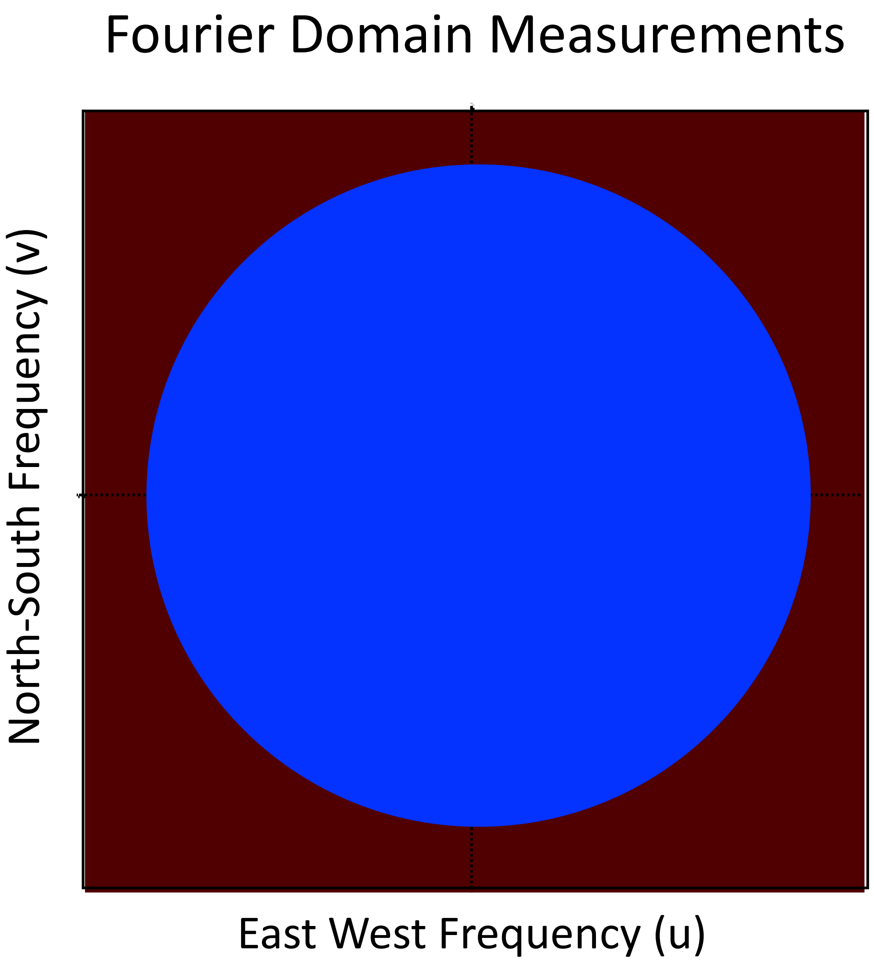
Fourier Domain Measurements



Slide Credit: Katie Bouman

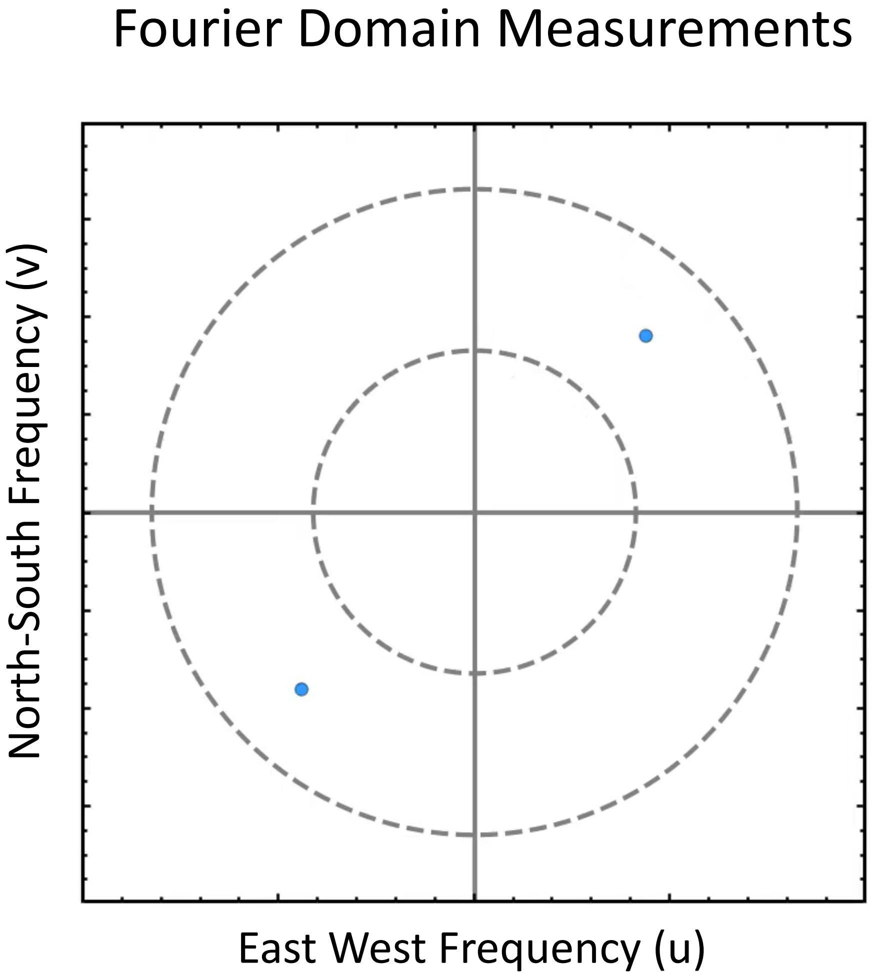
Very Long Baseline Interferometry (VLBI)





Slide Credit: Katie Bouman

Earth’s Rotation gives us more measurements

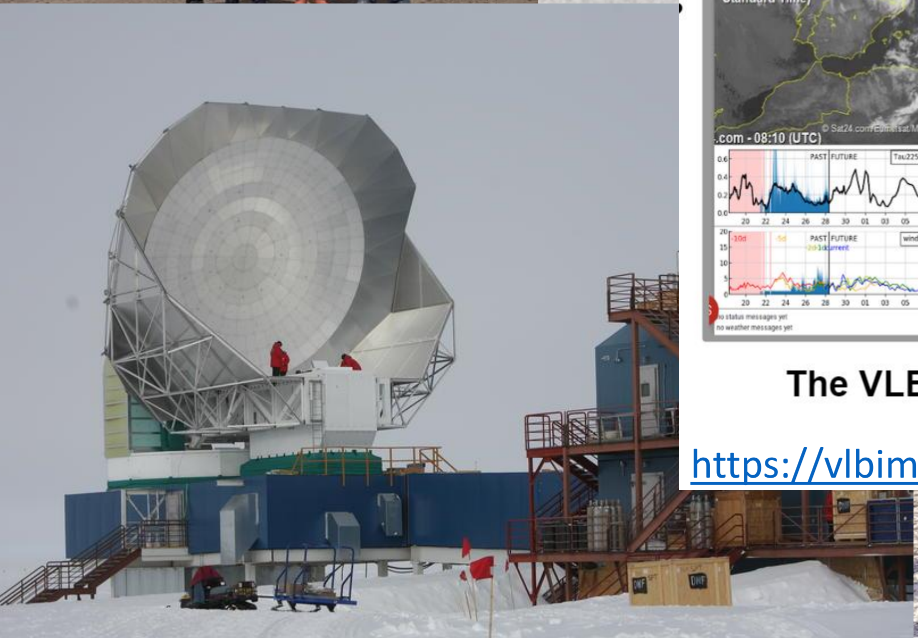


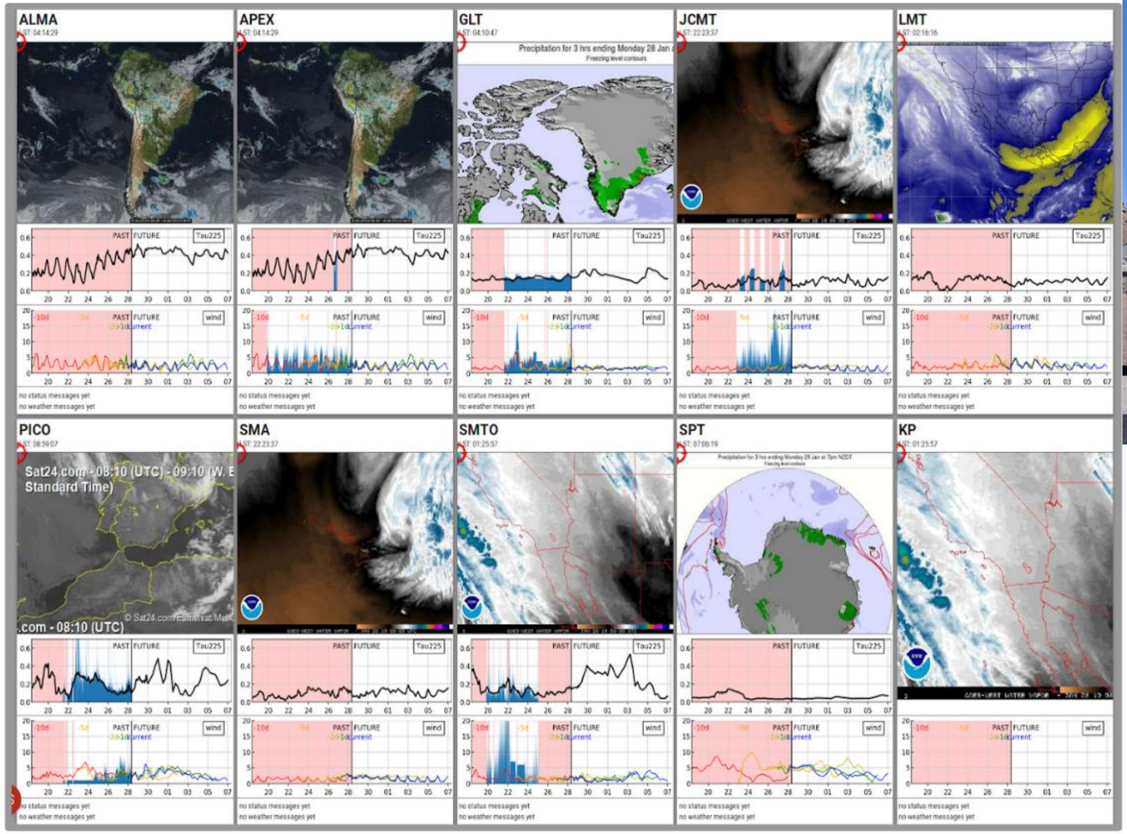
Slide Credit: Katie Bouman

EHT 2017 Observations

Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

EHT 2017 Observations



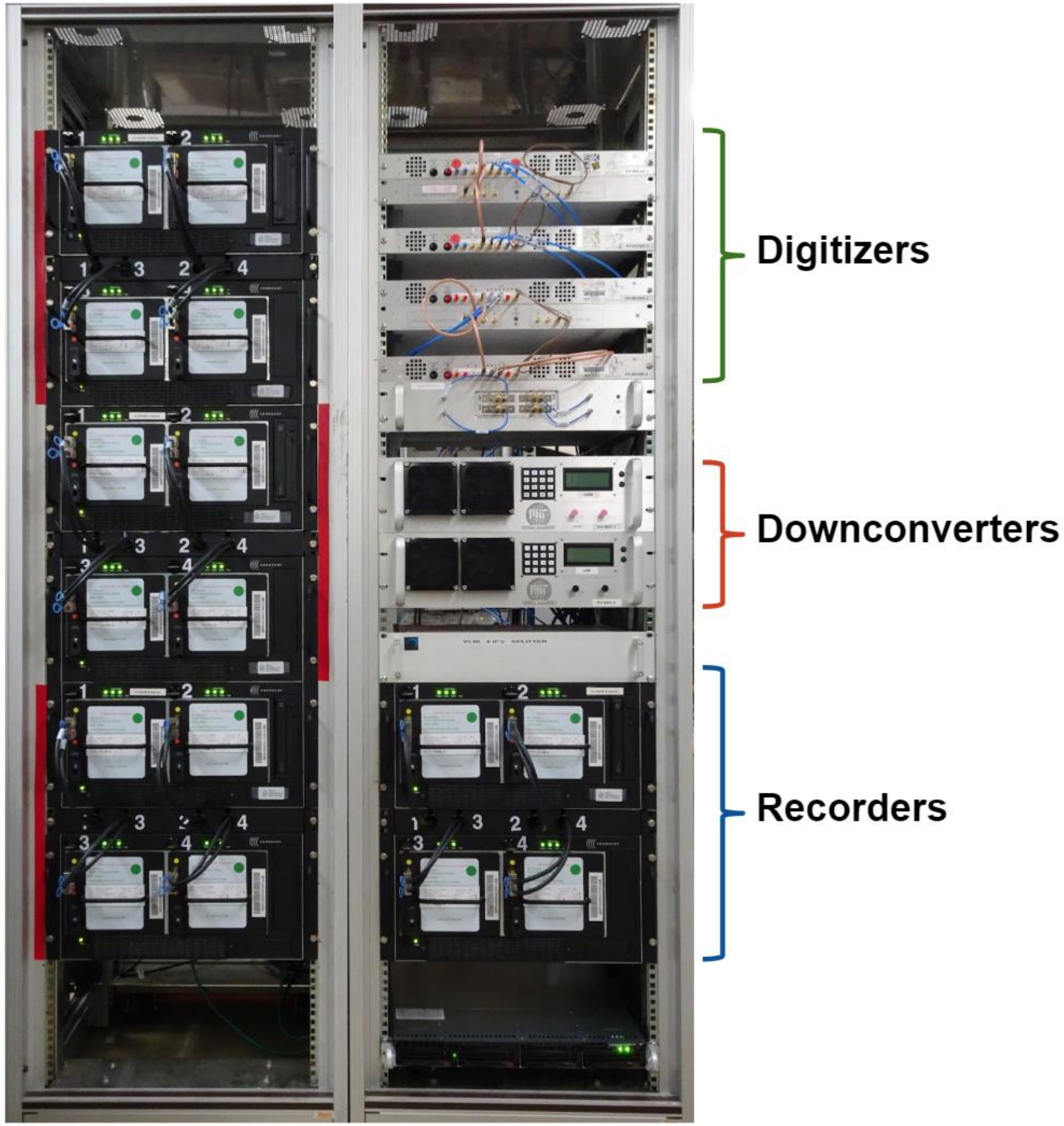


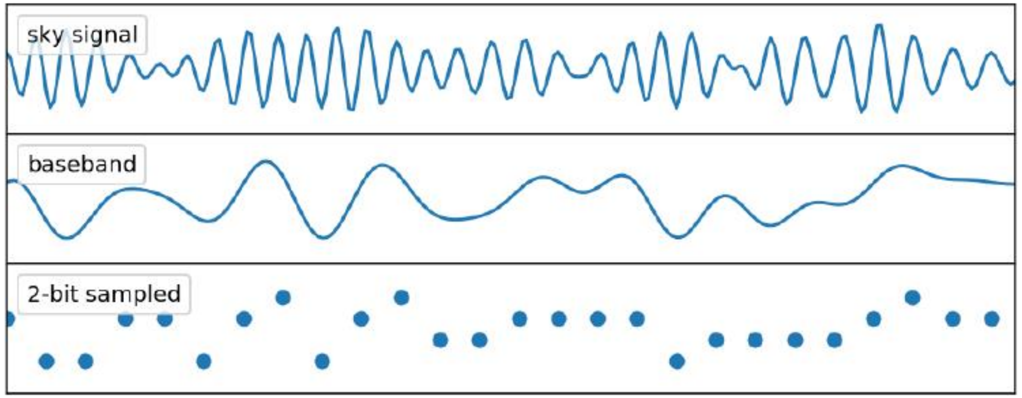
The VLBI monitor helps us track current and forecasted weather, and telescope operations

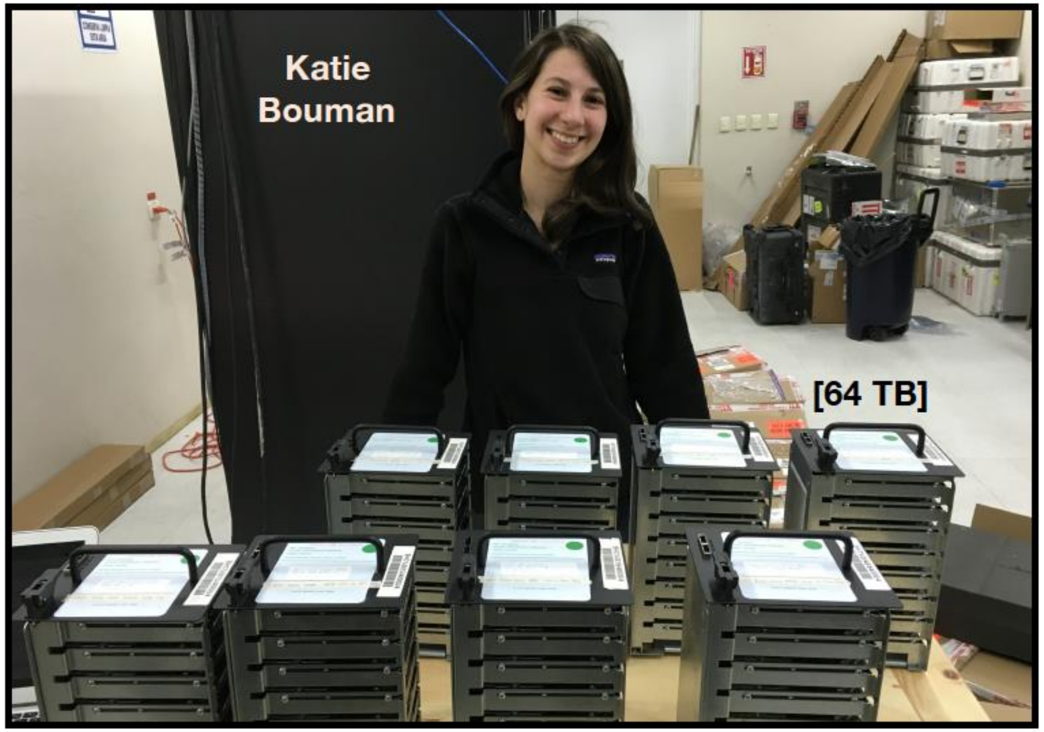
https://vlbimon1.science.ru.nl/login.html

Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

EHT Instrumentation – records data at 8 Gb/sec

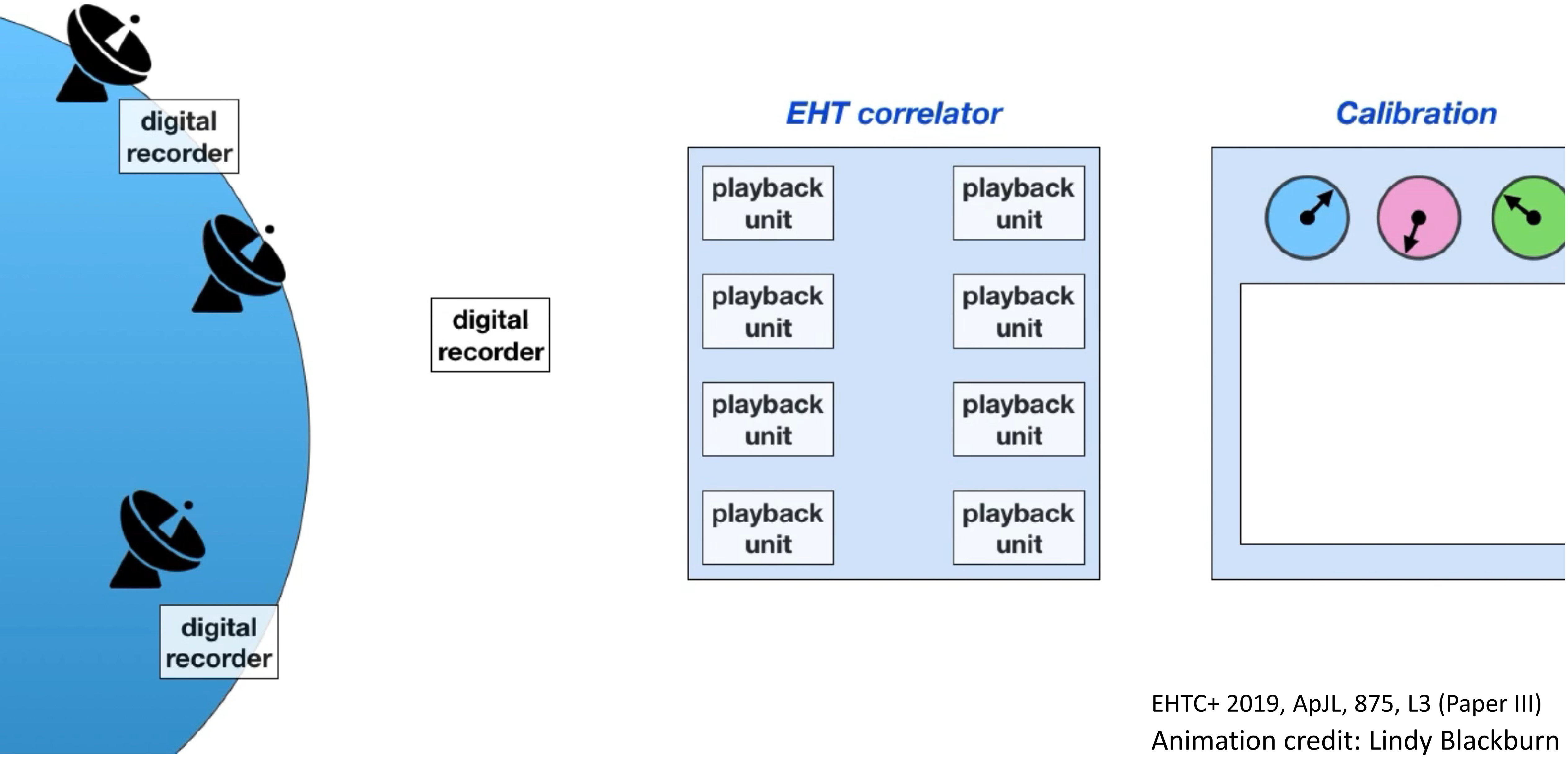






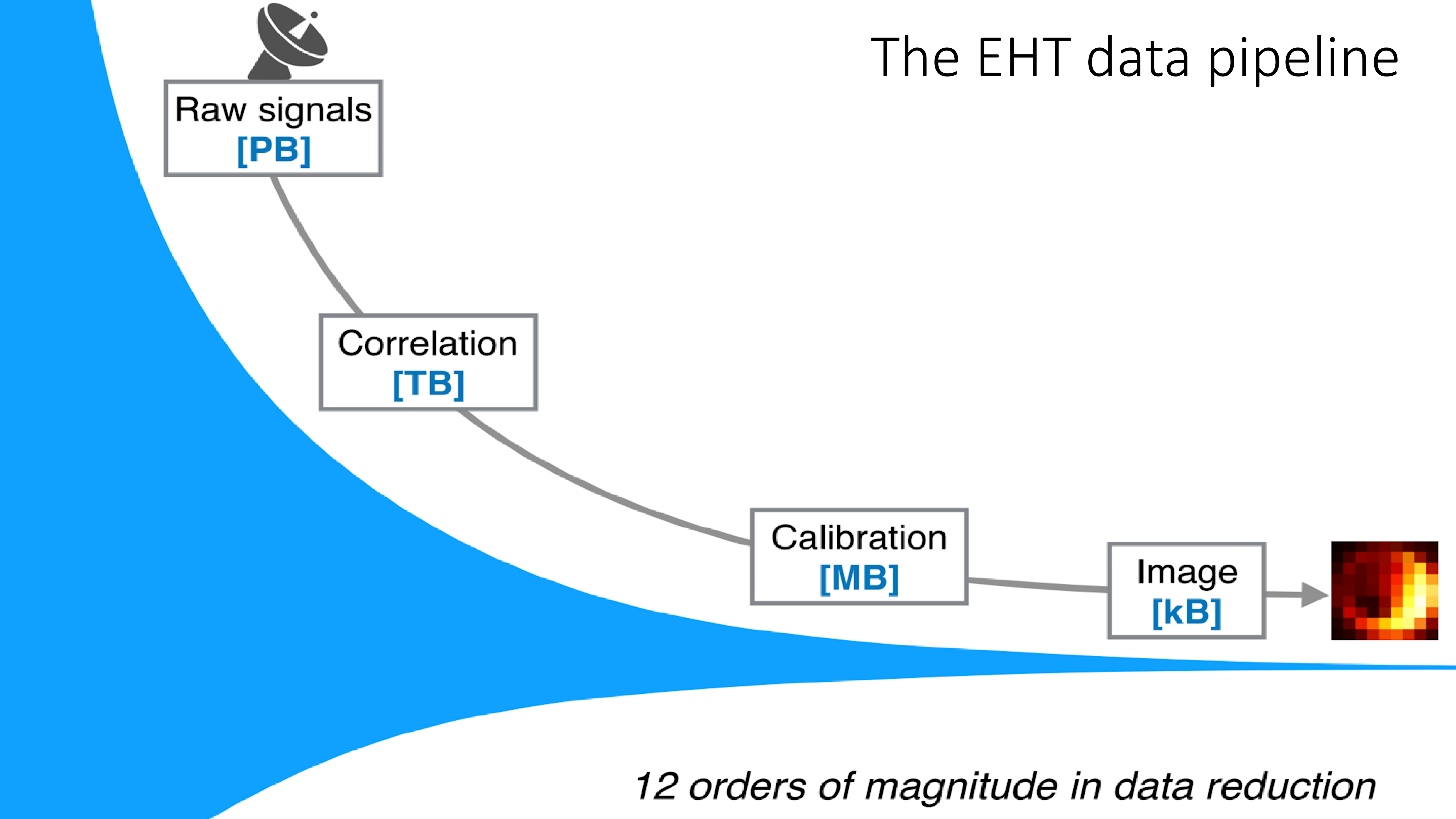
EHTC+ 2019, ApJL, 875, L2 (Paper II)

The EHT data pipeline



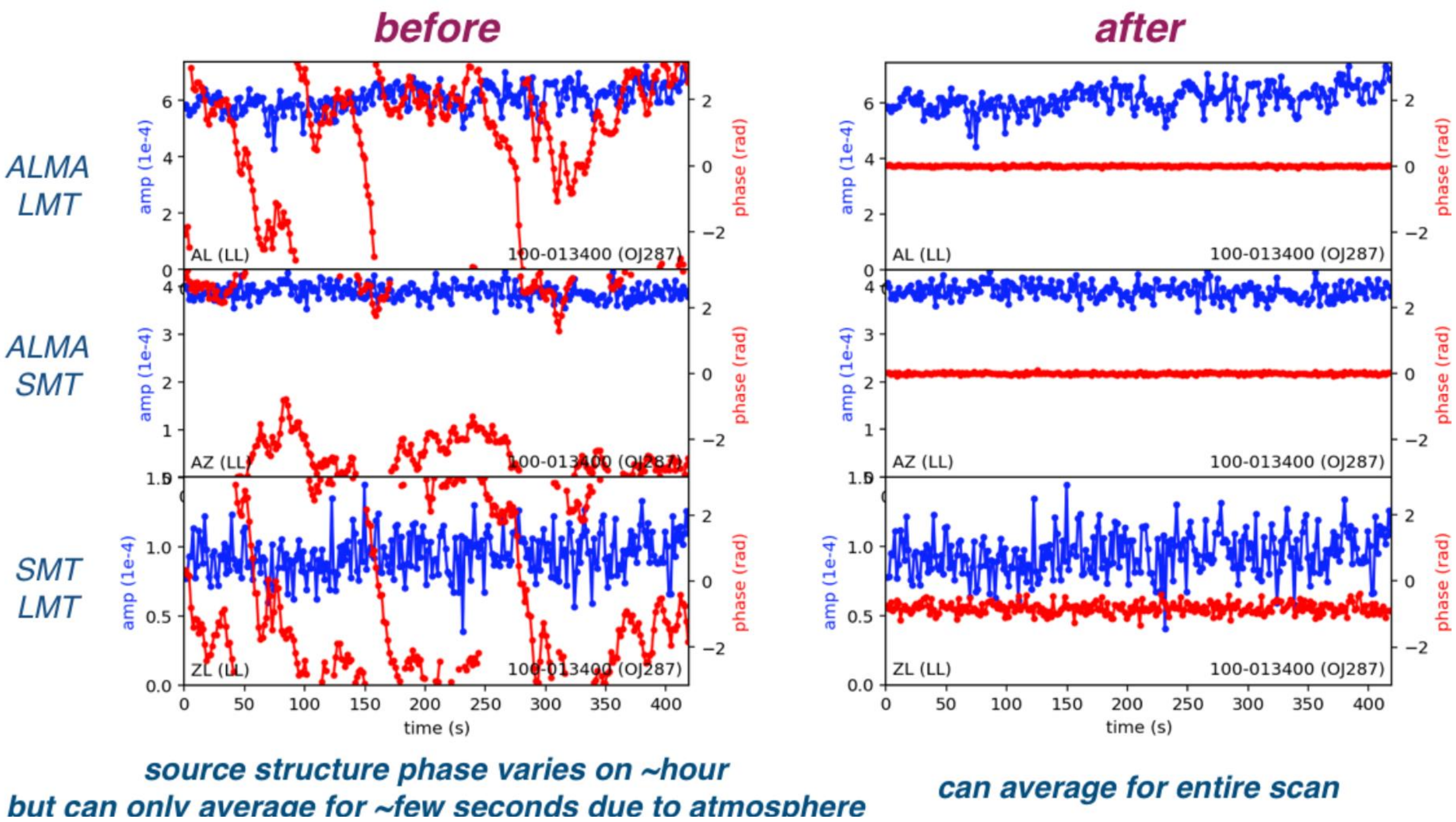
EHTC+ 2019, ApJL, 875, L3 (Paper III)
Animation credit: Lindy Blackburn

The EHT data pipeline



12 orders of magnitude in data reduction

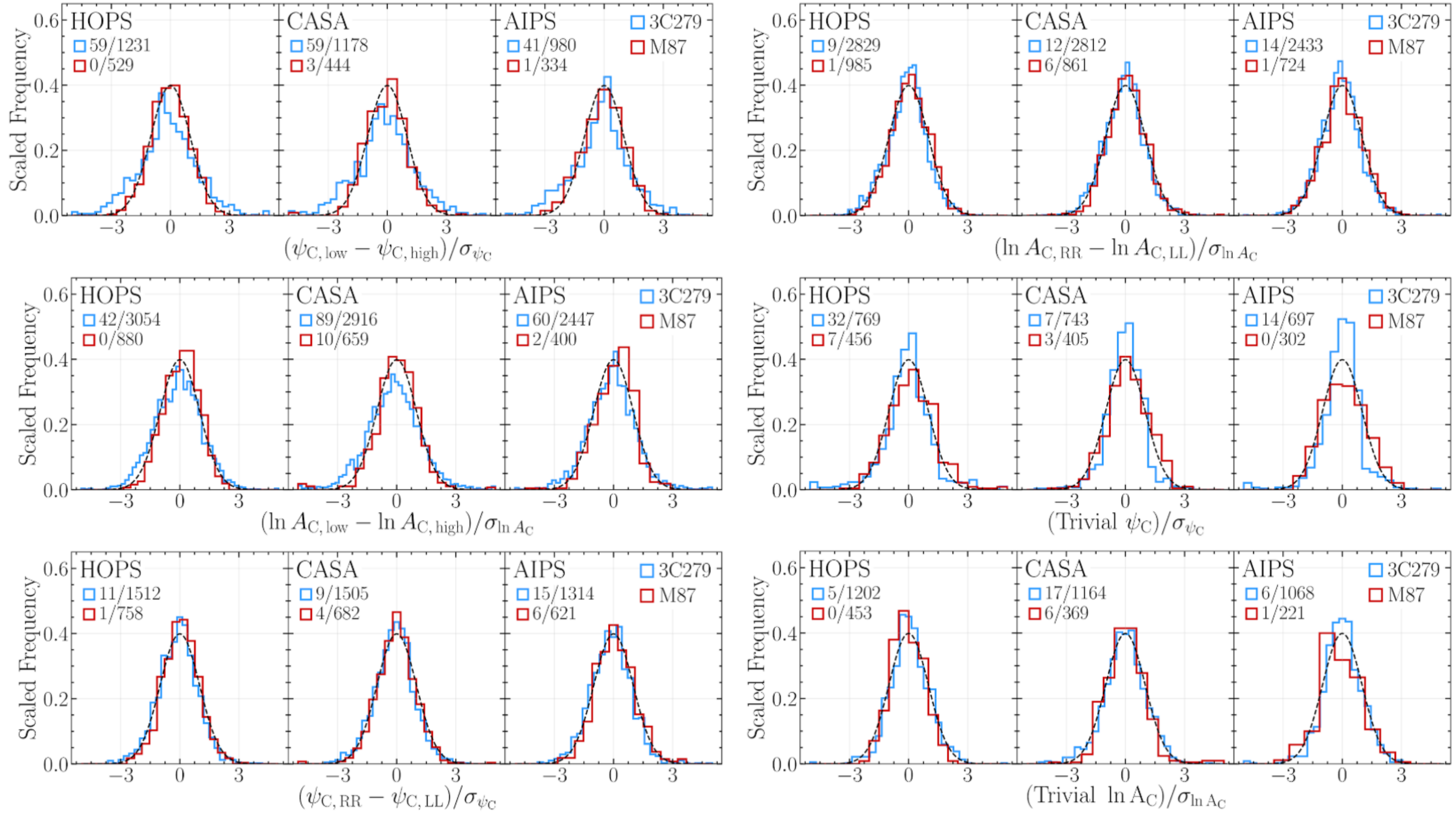
Data Calibration: correcting for atmospheric turbulence



Combination of specialized/old C code for VLBI:
with new python interfaces and plotting: https://github.com/sao-eht/eat

Image Credit:
Lindy Blackburn

Data Validation: statistical checks

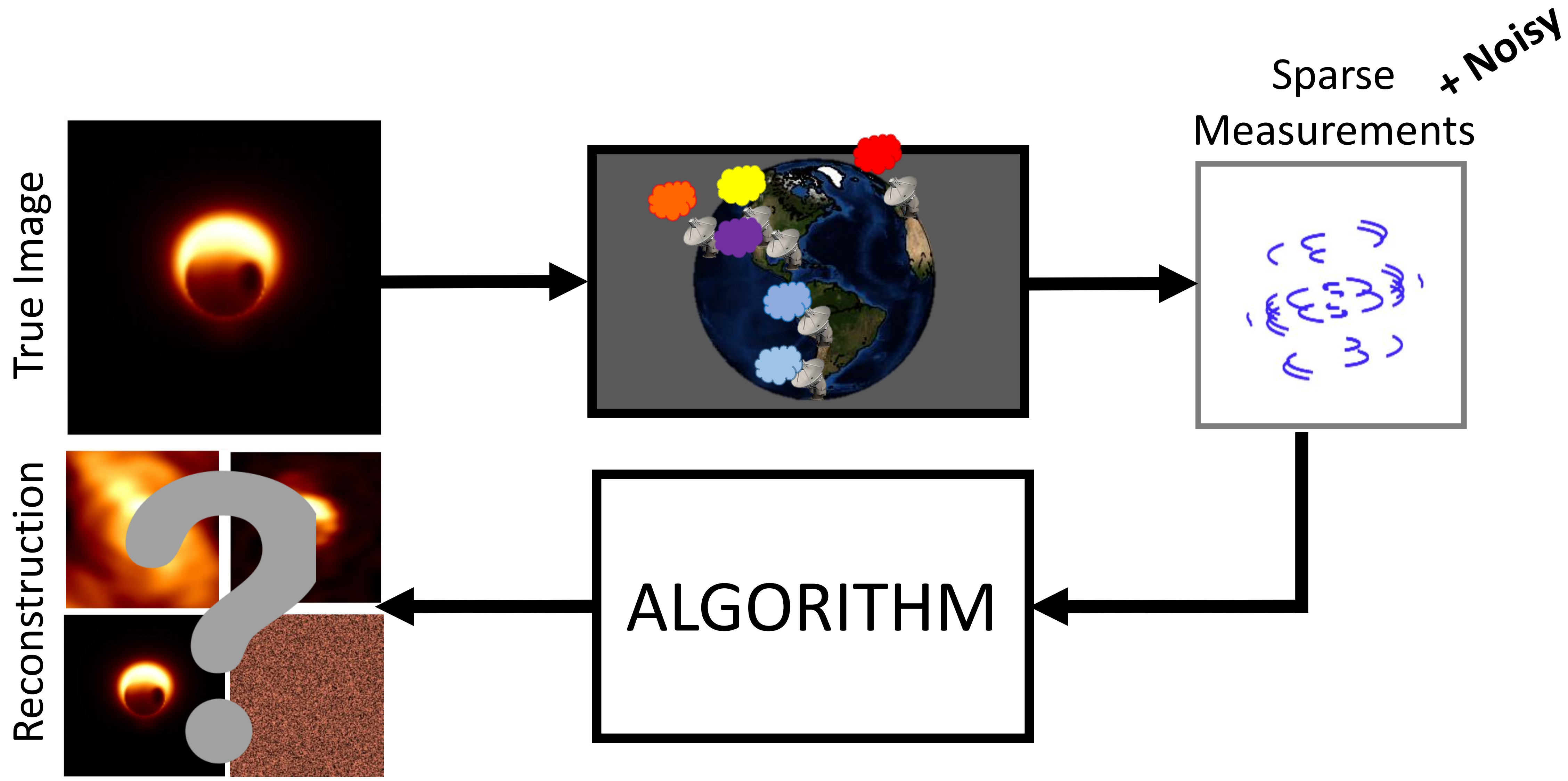


Verify calibration by pipeline cross-comparison across frequency bands, polarizations, and visibility quantities.

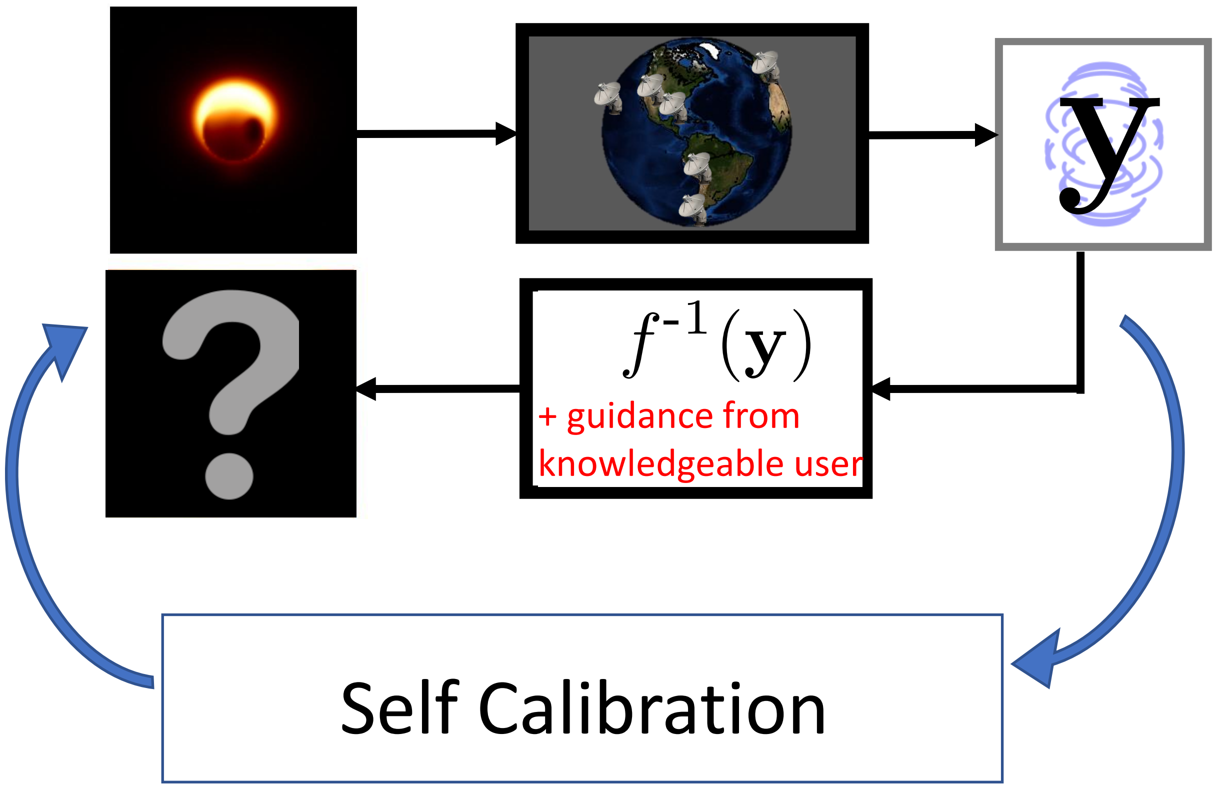
Pandas & Scipy critical for automating many validation tasks!

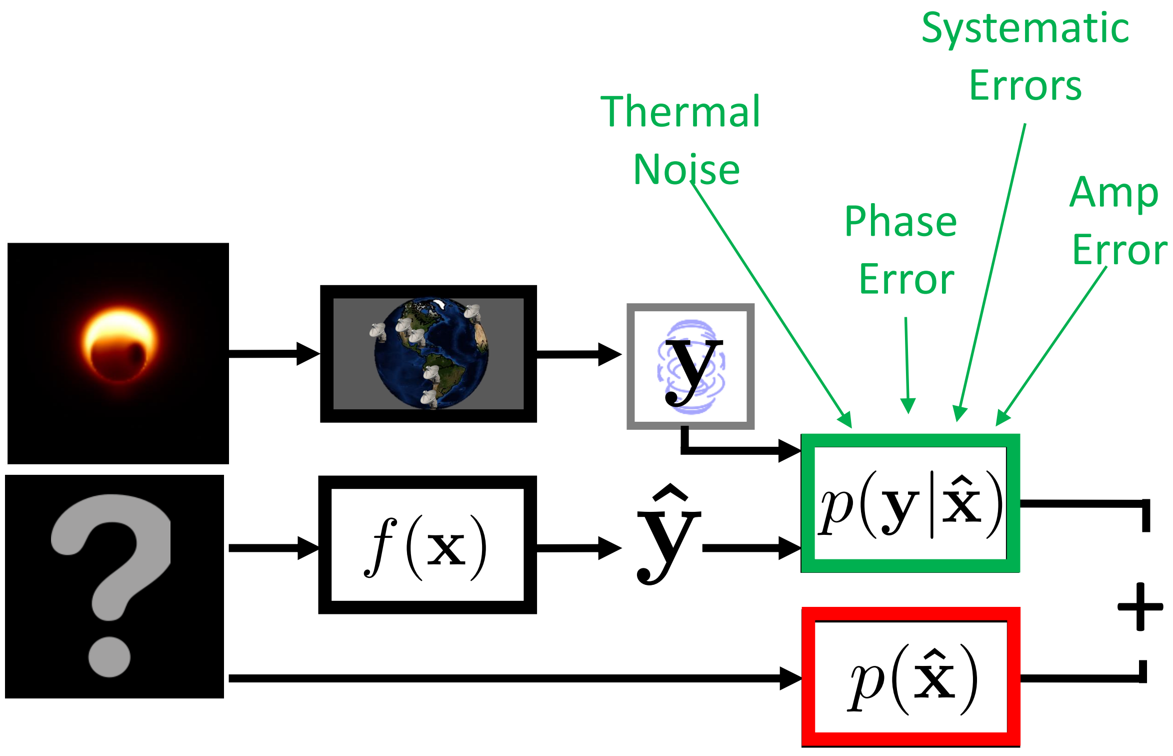
Image Credit: Maciek Wielgus

Solving for the Image



Two Classes of Imaging Algorithms





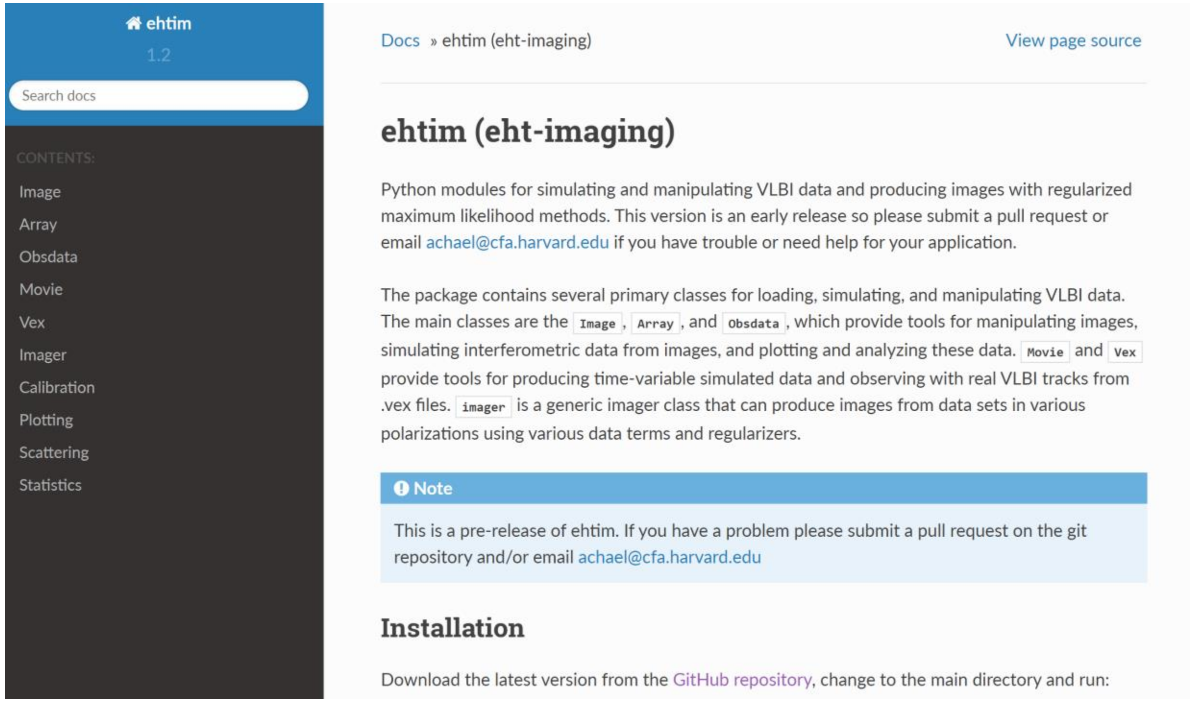
$$\hat{\mathbf{x}}_{\text{MAP}} = \text{argmax}_{\mathbf{x}} \left[\log p(\mathbf{y}|\mathbf{x}) + \log p(\mathbf{x})\right]$$

Standard Inverse Modeling
(CLEAN + Self-Calibration)

Forward Modeling
(Regularized Maximum Likelihood)

RML Imaging software developed for the EHT

eht-imaging: Chael+, Harvard/SAO


ehtim
1.2
Search docs
CONTENTS:
Image
Array
Obsdata
Movie
Vex
Imager
Calibration
Plotting
Scattering
Statistics

Docs » ehtim (eht-imaging) View page source

ehtim (eht-imaging)

Python modules for simulating and manipulating VLBI data and producing images with regularized maximum likelihood methods. This version is an early release so please submit a pull request or email achael@cfa.harvard.edu if you have trouble or need help for your application.

The package contains several primary classes for loading, simulating, and manipulating VLBI data. The main classes are the `Image`, `Array`, and `Obsdata`, which provide tools for manipulating images, simulating interferometric data from images, and plotting and analyzing these data. `Movie` and `Vex` provide tools for producing time-variable simulated data and observing with real VLBI tracks from .vex files. `imager` is a generic imager class that can produce images from data sets in various polarizations using various data terms and regularizers.

Note

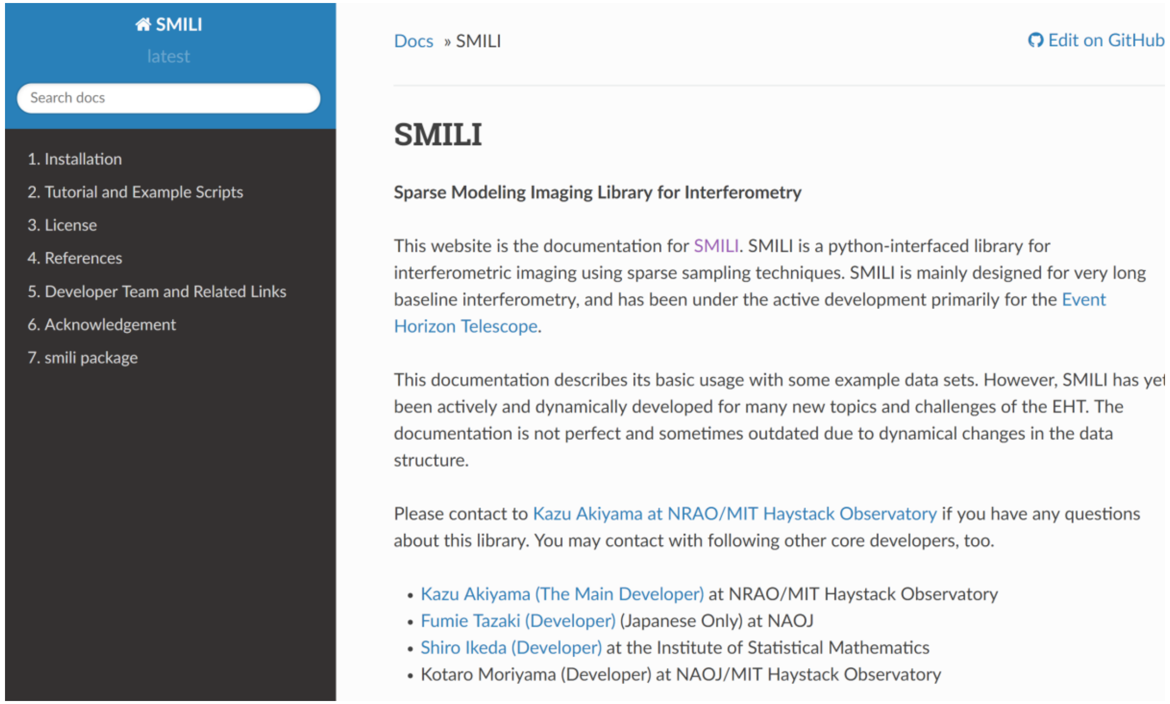
This is a pre-release of ehtim. If you have a problem please submit a pull request on the git repository and/or email achael@cfa.harvard.edu

Installation

Download the latest version from the GitHub repository, change to the main directory and run:

https://github.com/achael/eht-imaging

SMILI: Kazu Akiyama+, MIT Haystack / NAOJ


SMILI
latest
Search docs
1. Installation
2. Tutorial and Example Scripts
3. License
4. References
5. Developer Team and Related Links
6. Acknowledgement
7. smili package

Docs » SMILI Edit on GitHub

SMILI

Sparse Modeling Imaging Library for Interferometry

This website is the documentation for SMILI. SMILI is a python-interfaced library for interferometric imaging using sparse sampling techniques. SMILI is mainly designed for very long baseline interferometry, and has been under the active development primarily for the Event Horizon Telescope.

This documentation describes its basic usage with some example data sets. However, SMILI has yet been actively and dynamically developed for many new topics and challenges of the EHT. The documentation is not perfect and sometimes outdated due to dynamical changes in the data structure.

Please contact to Kazu Akiyama at NRAO/MIT Haystack Observatory if you have any questions about this library. You may contact with following other core developers, too.

- Kazu Akiyama (The Main Developer) at NRAO/MIT Haystack Observatory
- Fumie Tazaki (Developer) (Japanese Only) at NAOJ
- Shiro Ikeda (Developer) at the Institute of Statistical Mathematics
- Kotaro Moriyama (Developer) at NAOJ/MIT Haystack Observatory

https://github.com/astrosmili/smili

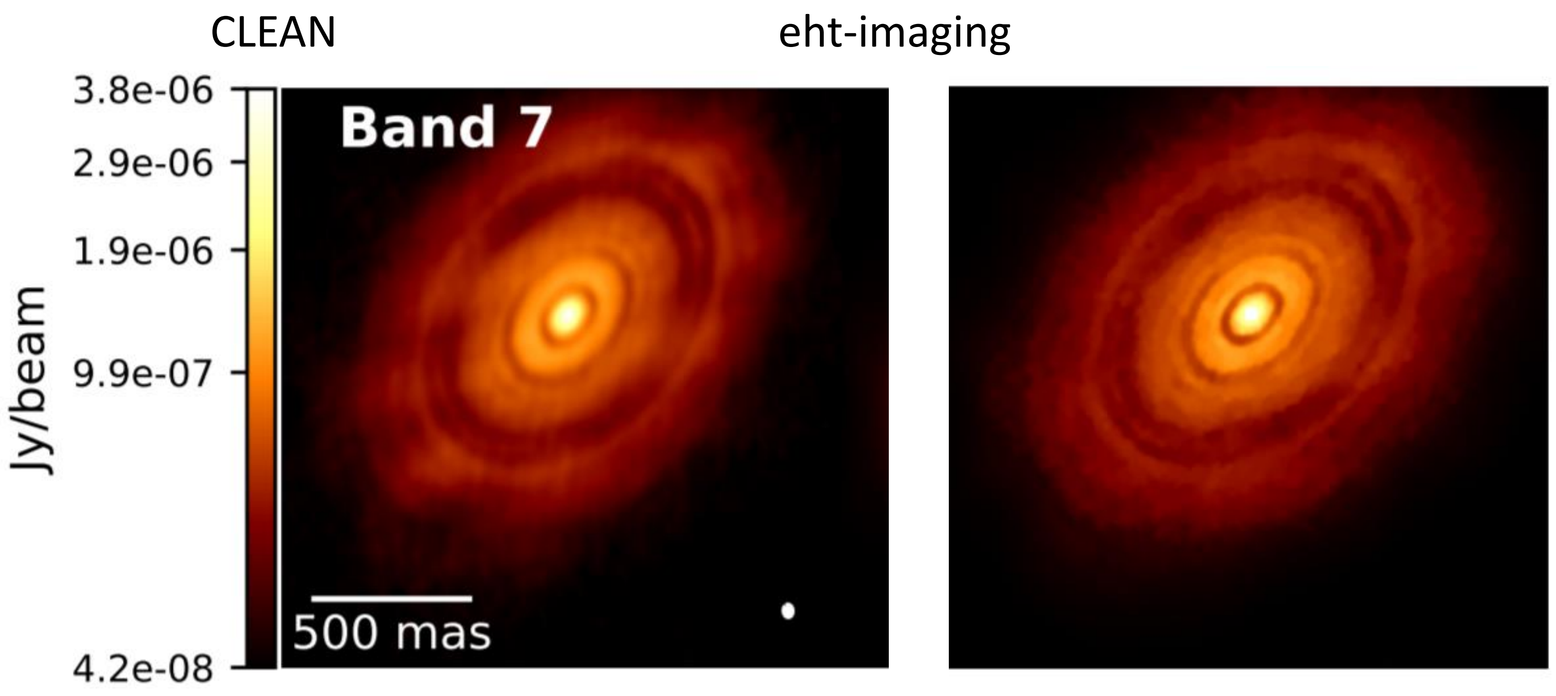
RML Imaging software developed for the EHT -- but with wide applicability

eht-im
Harvar

Search docs

CONTENTS:

- Image
- Array
- Obsdata
- Movie
- Vex
- Imager
- Calibration
- Plotting
- Scattering
- Statistics



ALMA Partnership+ 2015, Chael+ 2018

Edit on GitHub

on-interfaced library for
MILI is mainly designed for very long
opment primarily for the Event

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o dynamical changes in the data

servatory if you have any questions
developers, too.

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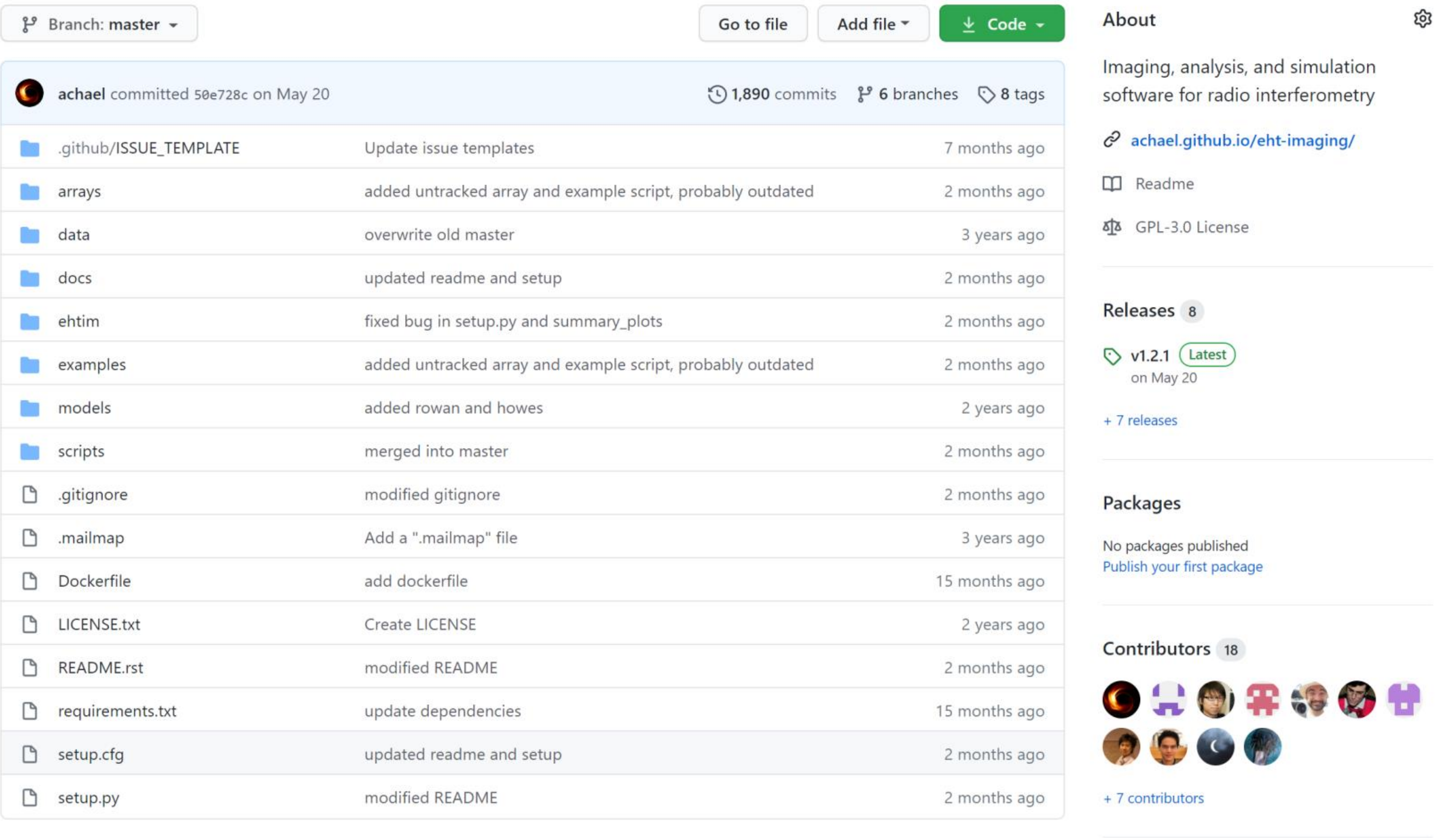
smili

The `eht-imaging` software library

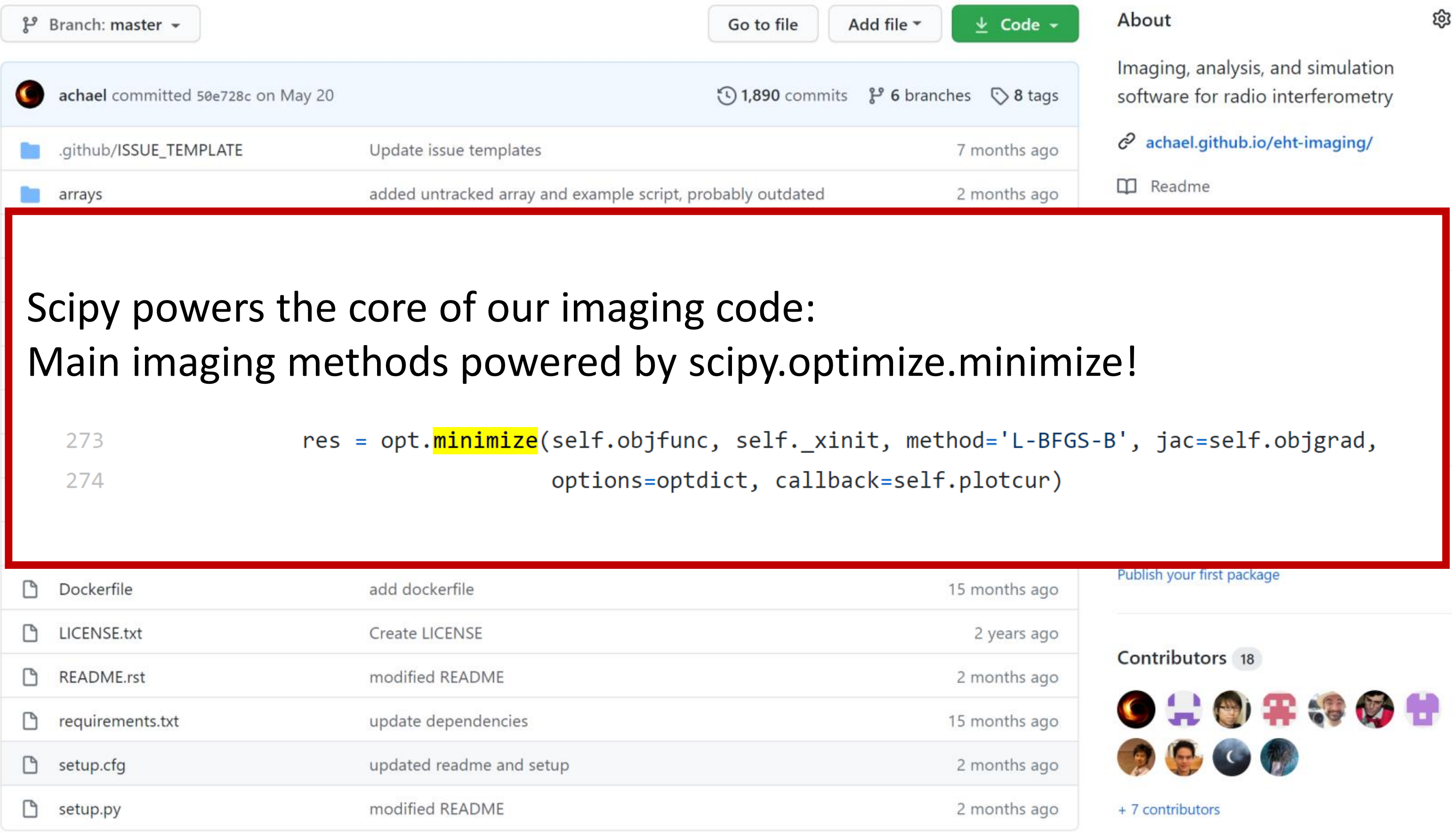


- Python software to image, analyze, manipulate, simulate interferometric data
- A lot of domain-specific code built up for data handling, but numpy+scipy power the main tasks!
- Flexible framework for developing new tools for imaging and model fitting

https://github.com/achael/eht-imaging

Chael+ 2016, 2018

The `eht-imaging` software library



Scipy powers the core of our imaging code:
Main imaging methods powered by scipy.optimize.minimize!

```
res = opt.minimize(self.objfunc, self._xinit, method='L-BFGS-B', jac=self.objgrad,
                   options=optdict, callback=self.plotcur)
```

- Python software to image, analyze, manipulate, simulate interferometric data
- A lot of domain-specific code built up for data handling, but numpy+scipy power the main tasks!
- Flexible framework for developing new tools for imaging and model fitting

https://github.com/achael/eht-imaging
Chael+ 2016, 2018

How do we verify what we are reconstructing is real?

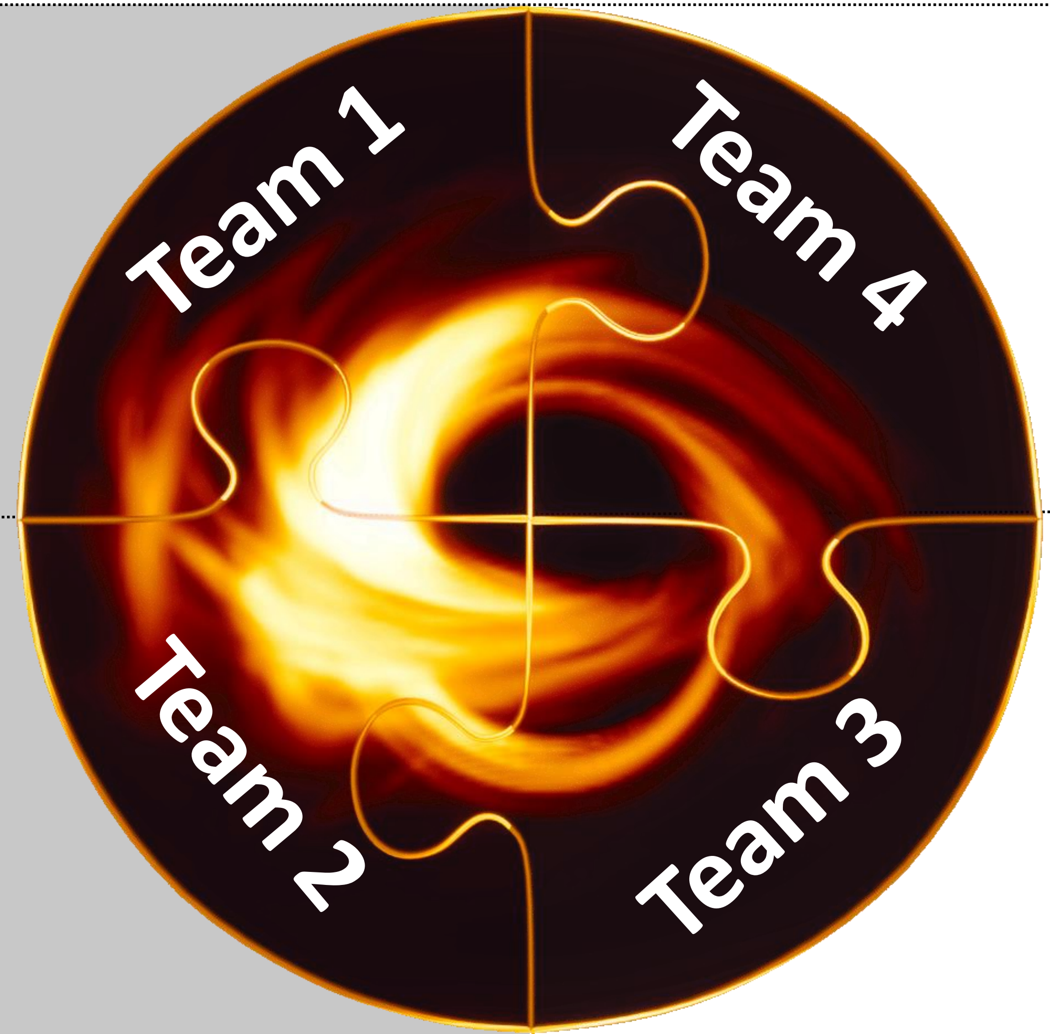
Step 1: Blind Imaging

The Americas

Harvard-Smithsonian
University of Arizona
U. Concepcion

Global

MIT Haystack
Radboud University
NAOJ



East Asia

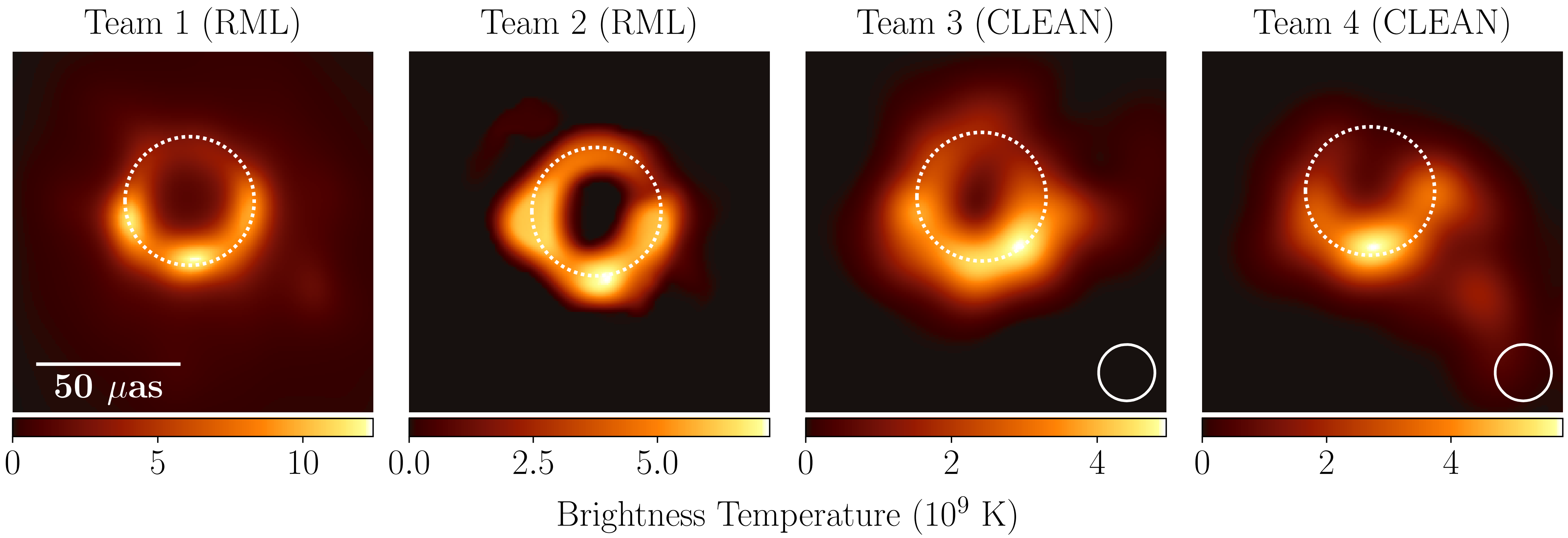
ASIAA
KASI
NAOJ

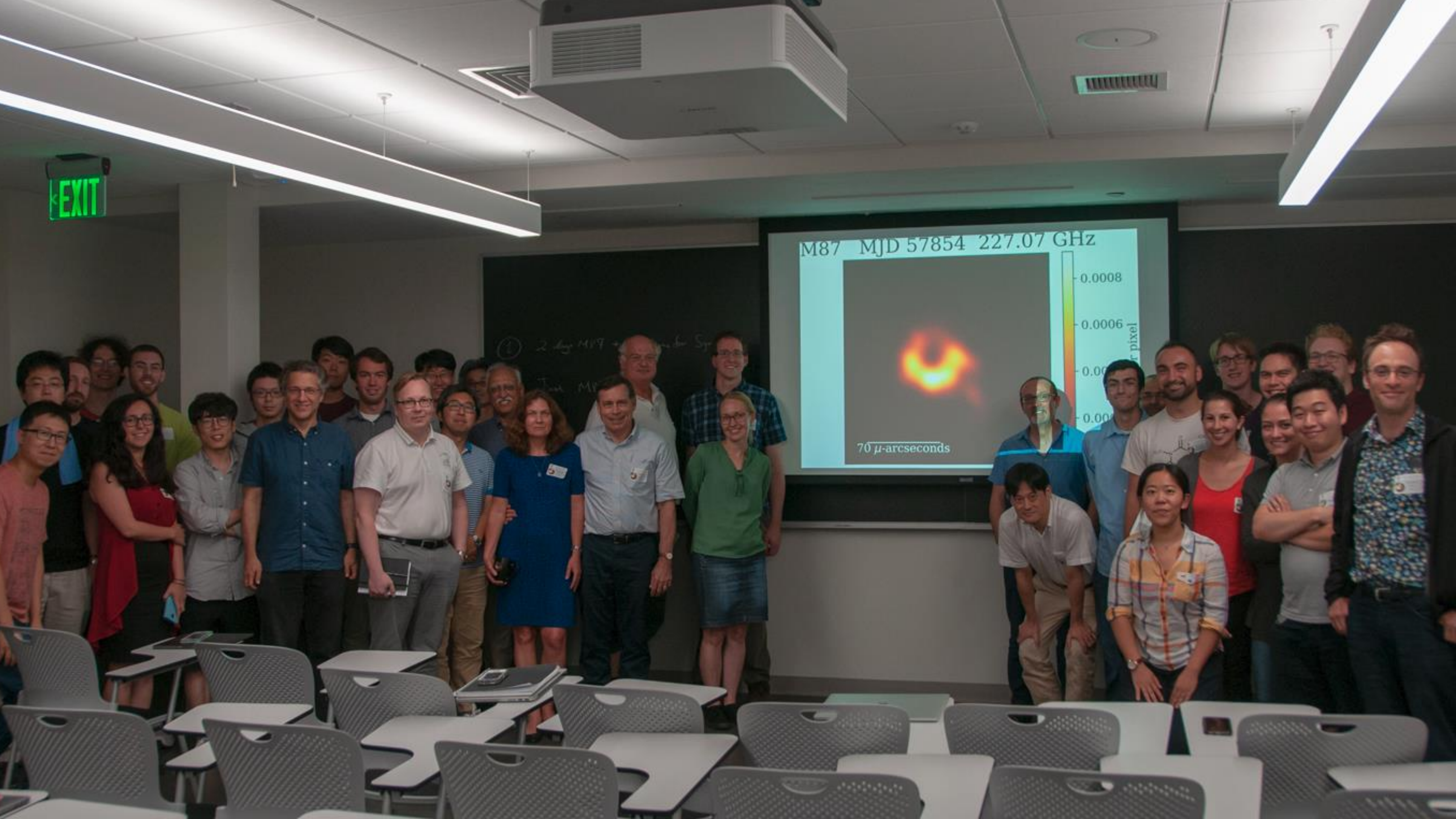
Cross-Atlantic

MPIfR
Boston University
IAA
Aalto

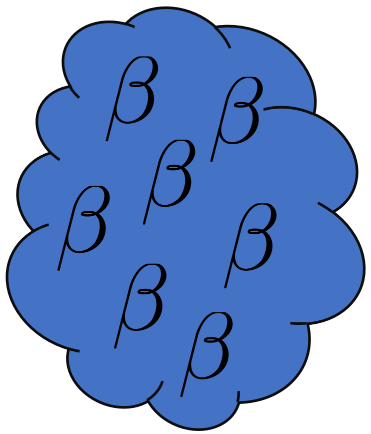
7 weeks later…

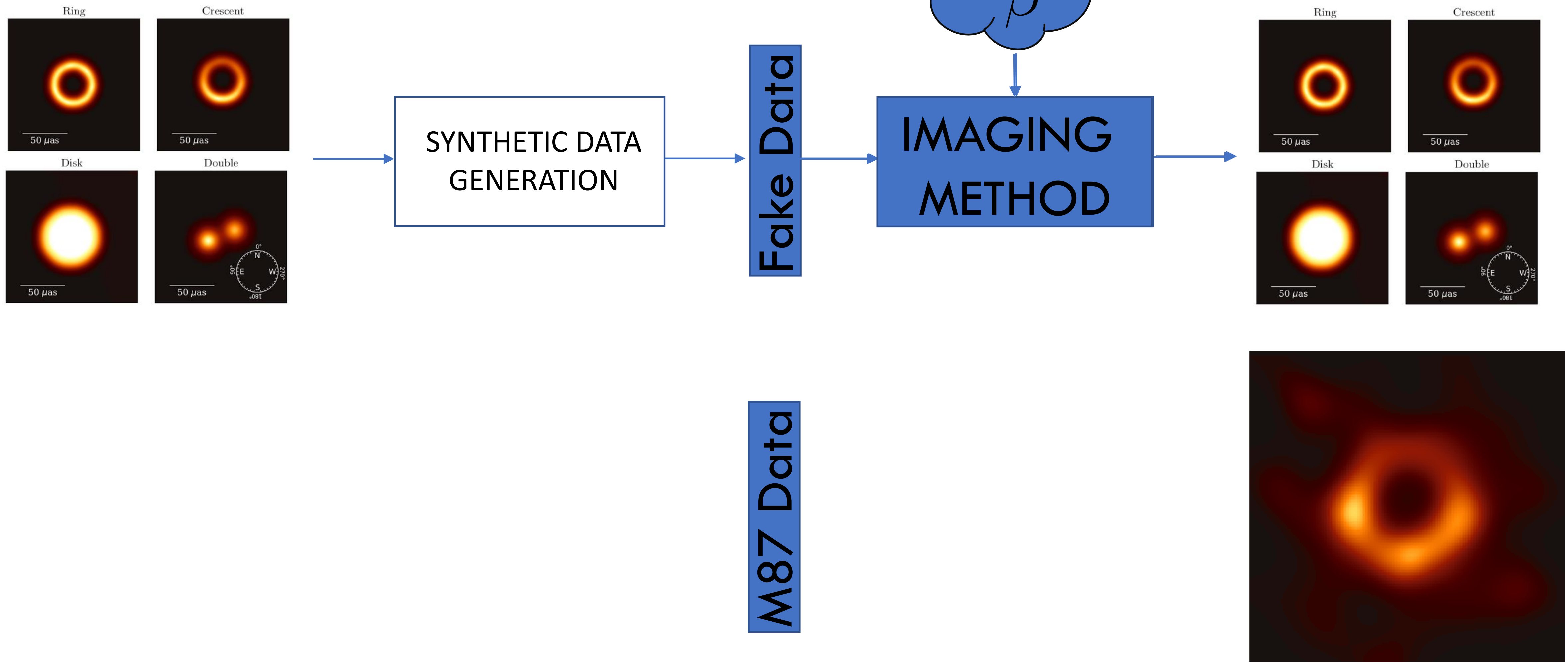
Step 1: Blind Imaging



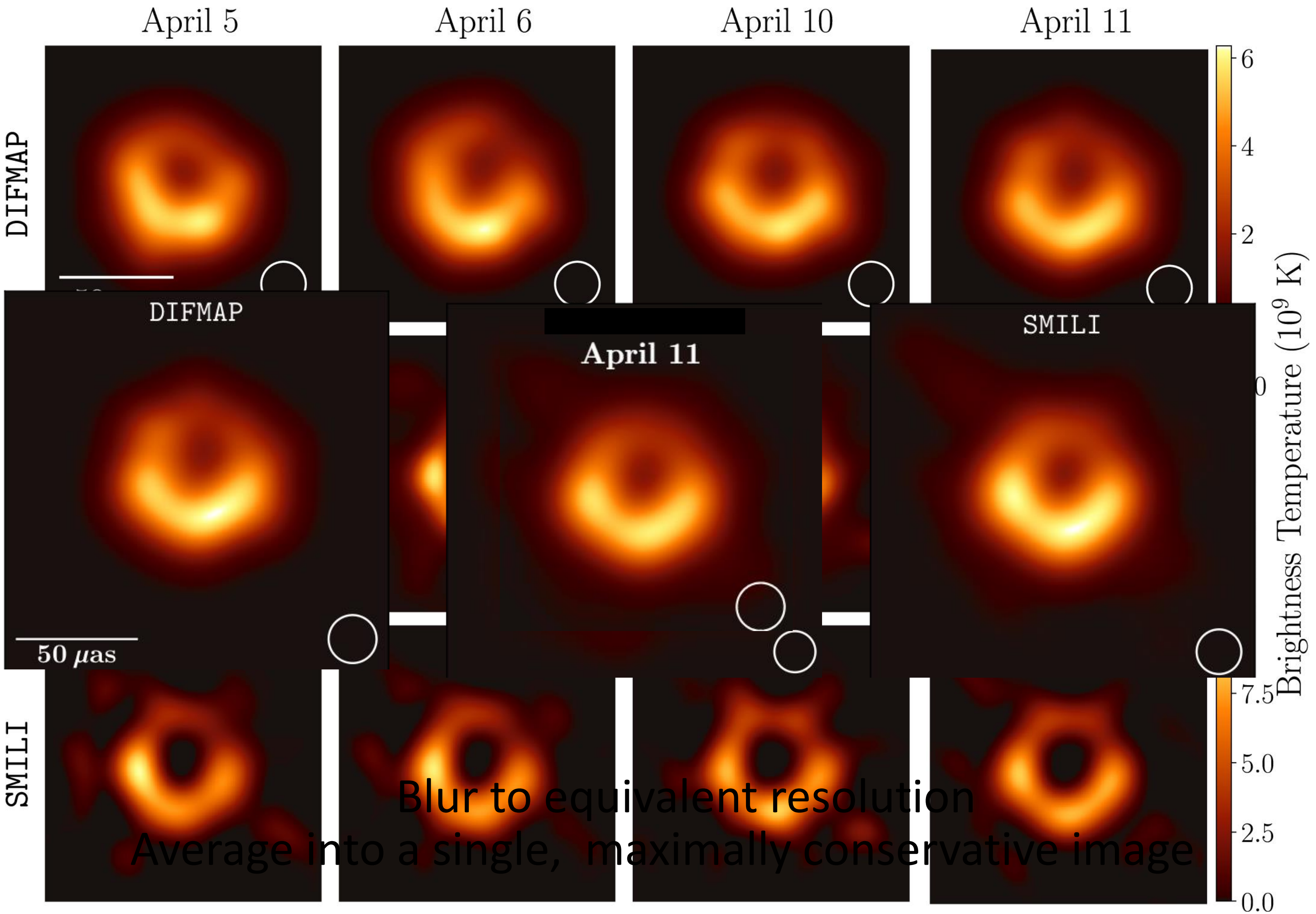

EXIT
M87 MJD 57854 227.07 GHz
0.0008
0.0006
70 μ-arcseconds

Step 2:
Test 30,000+ hyperparameter sets





Three pipelines, four days



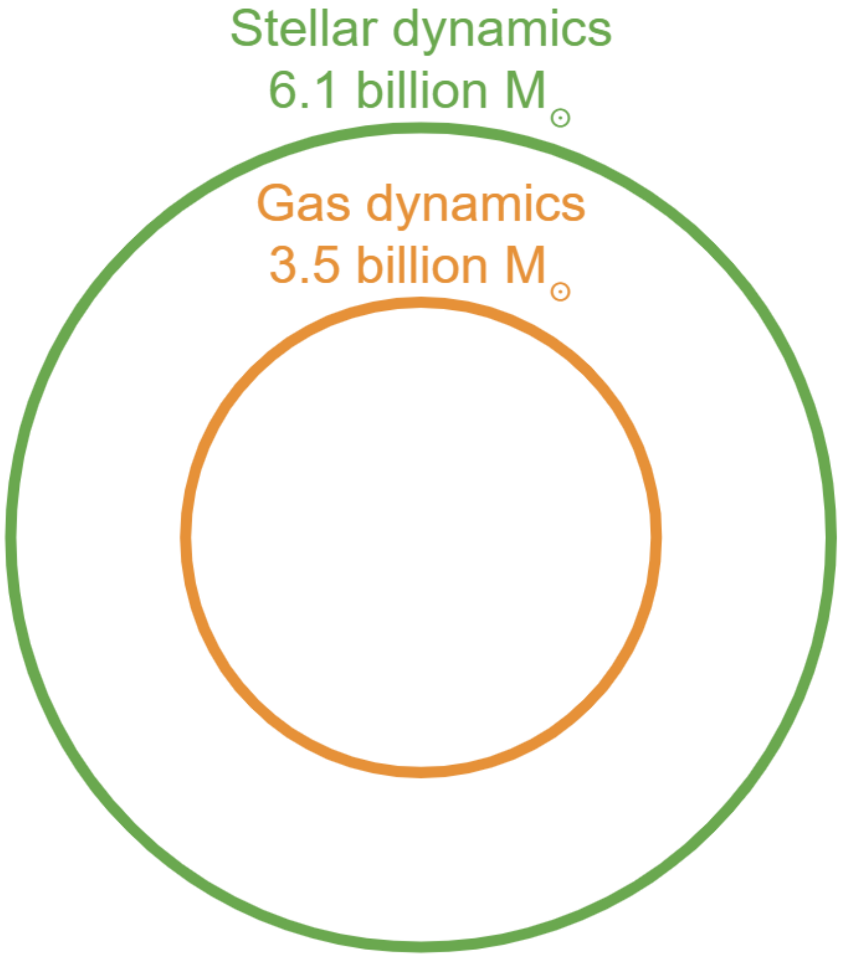
Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

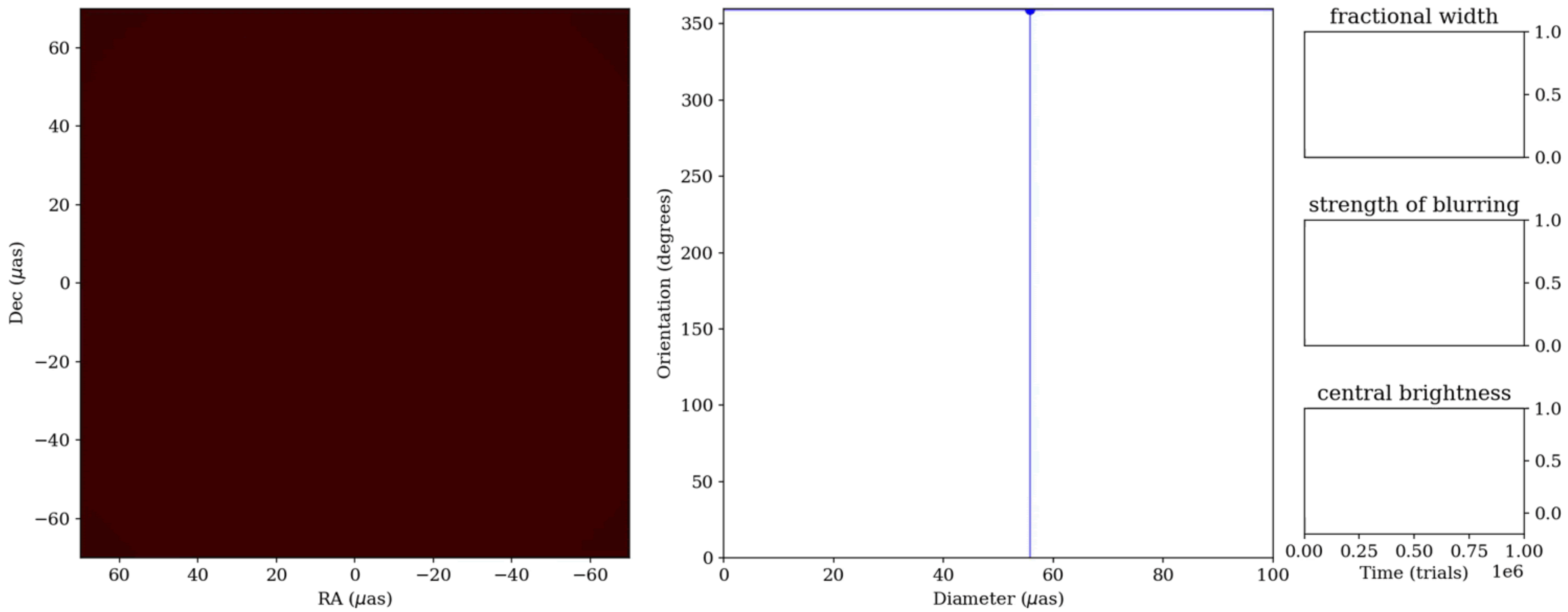
What does this image tell us?

Previous measurements of the M87 black hole mass disagreed!

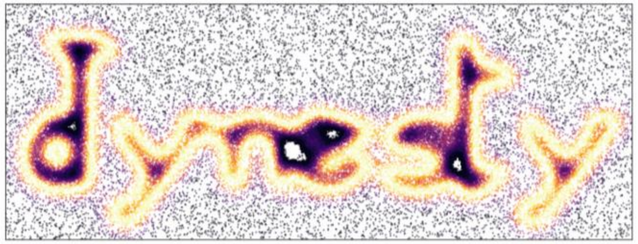


Gebhardt et al. (2011); Walsh et al. (2013)

Weighing a black hole with nested sampling



dynesty



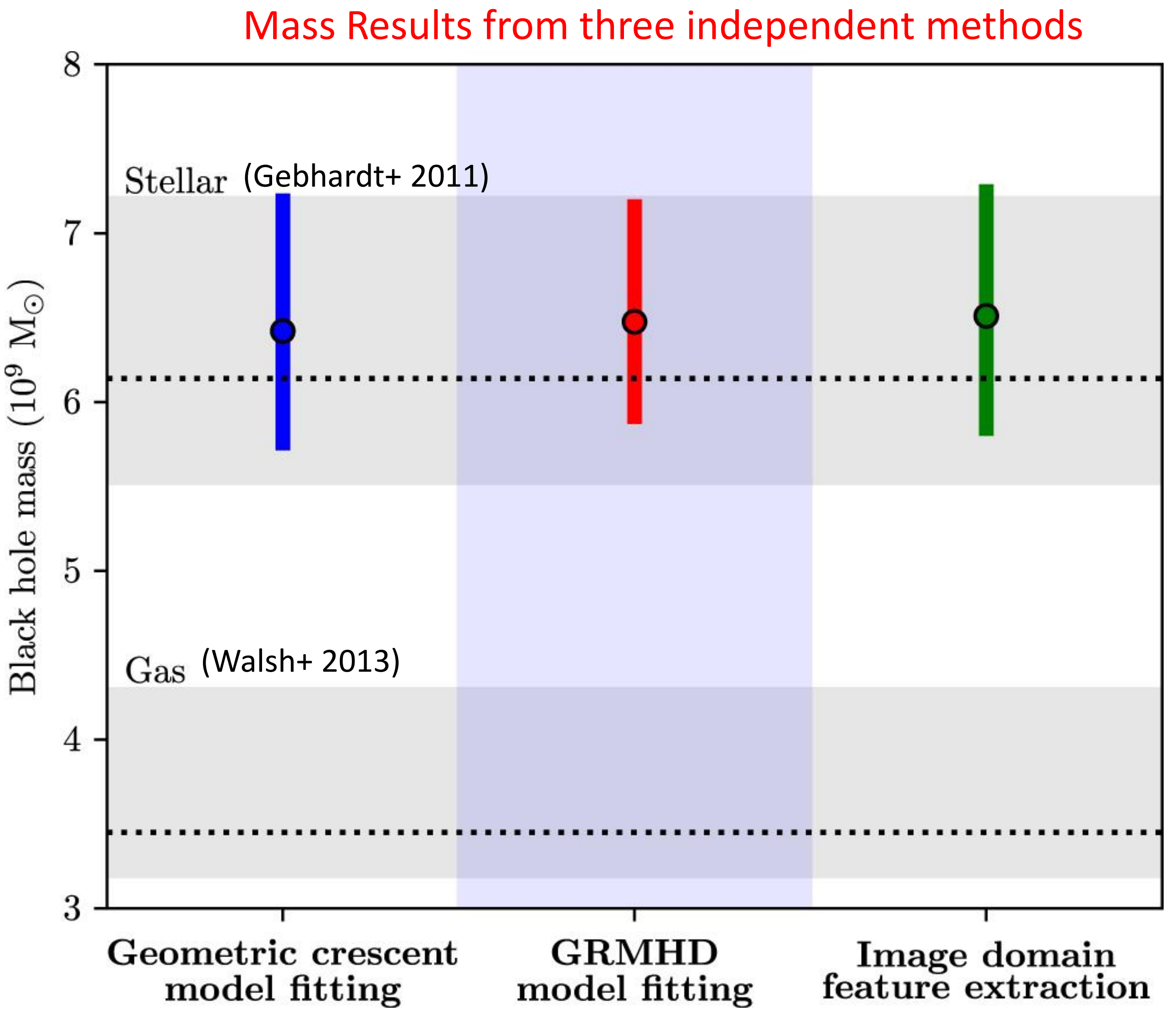
A Dynamic Nested Sampling package for computing Bayesian posteriors and evidences. Pure Python. MIT license.

Dynesty: pure python nested sampling code
https://github.com/joshspeagle/dynesty

Also used several results from other MCMC codes and image reconstructions

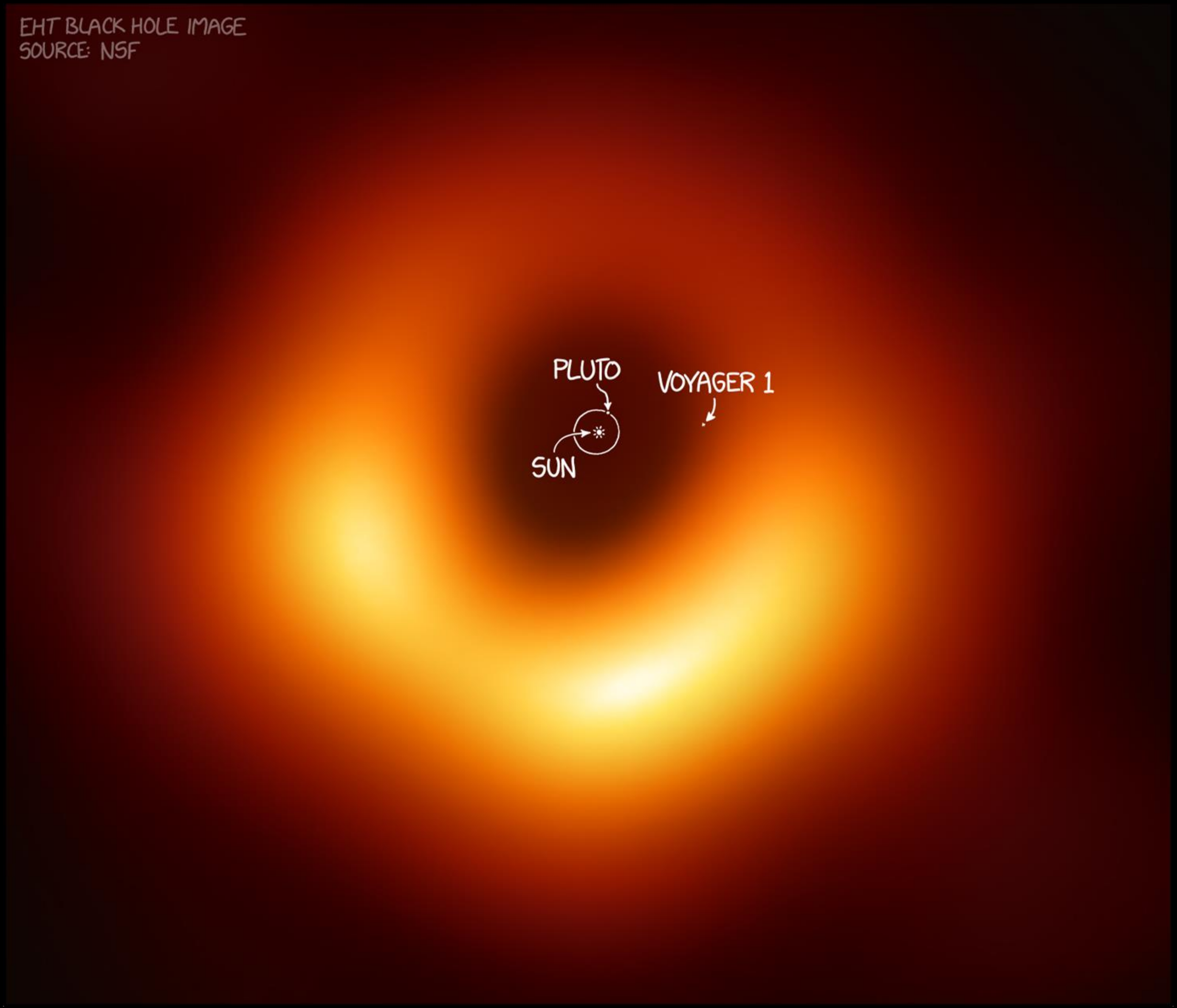
Animation Credit: Dom Pesce

Directly weighing a black hole with $r_{\rm shadow} = \sqrt{27}GM/c^2$



$$M = (6.5 \pm 0.7) \times 10^9\, M_\odot$$

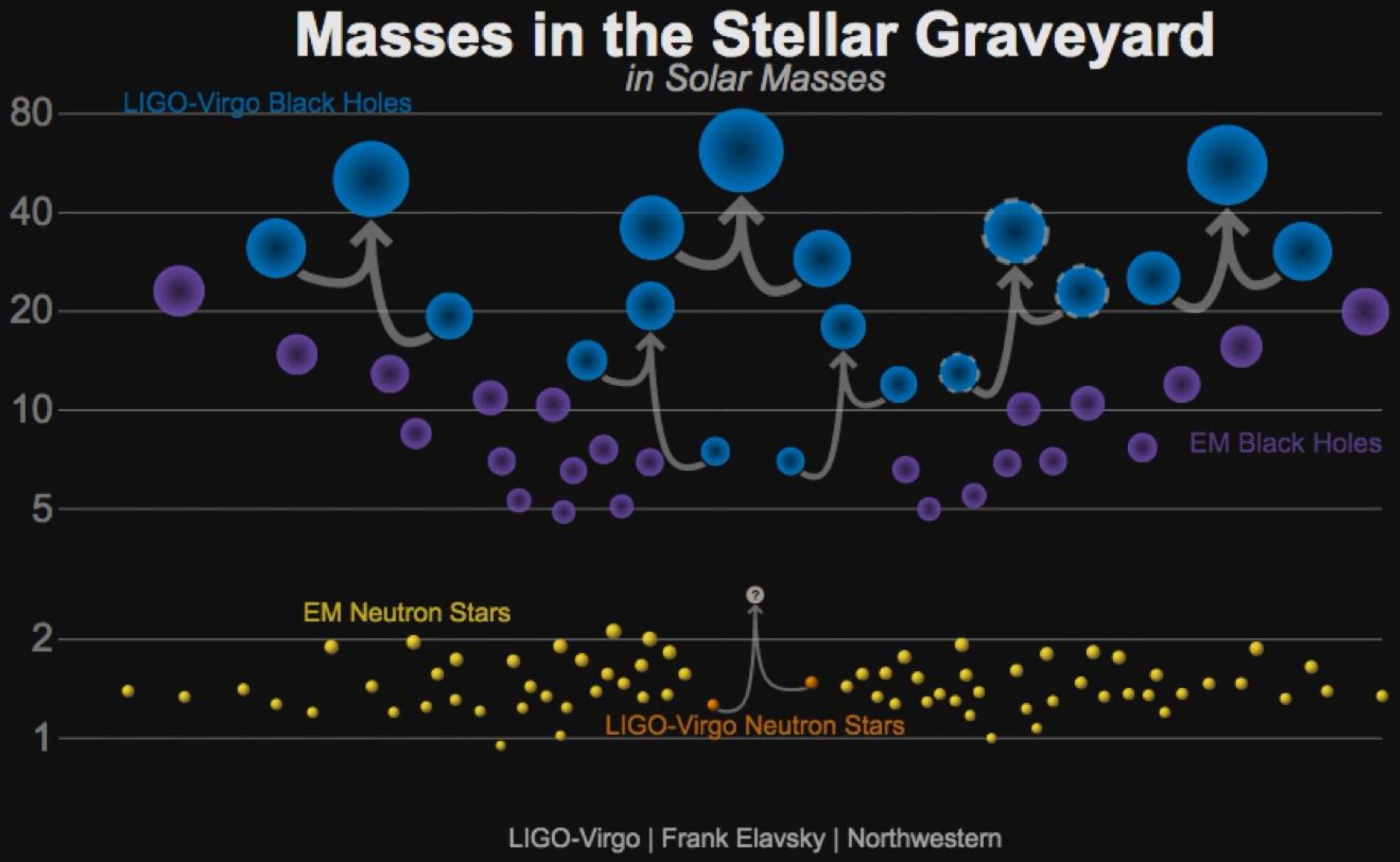
Image Credit:
EHT Collaboration 2019 (Paper VI)



$$M = (6.5 \pm 0.7) \times 10^9 \, M_\odot$$

$$R_{\rm Sch} = 128 \, \mathrm{AU}$$

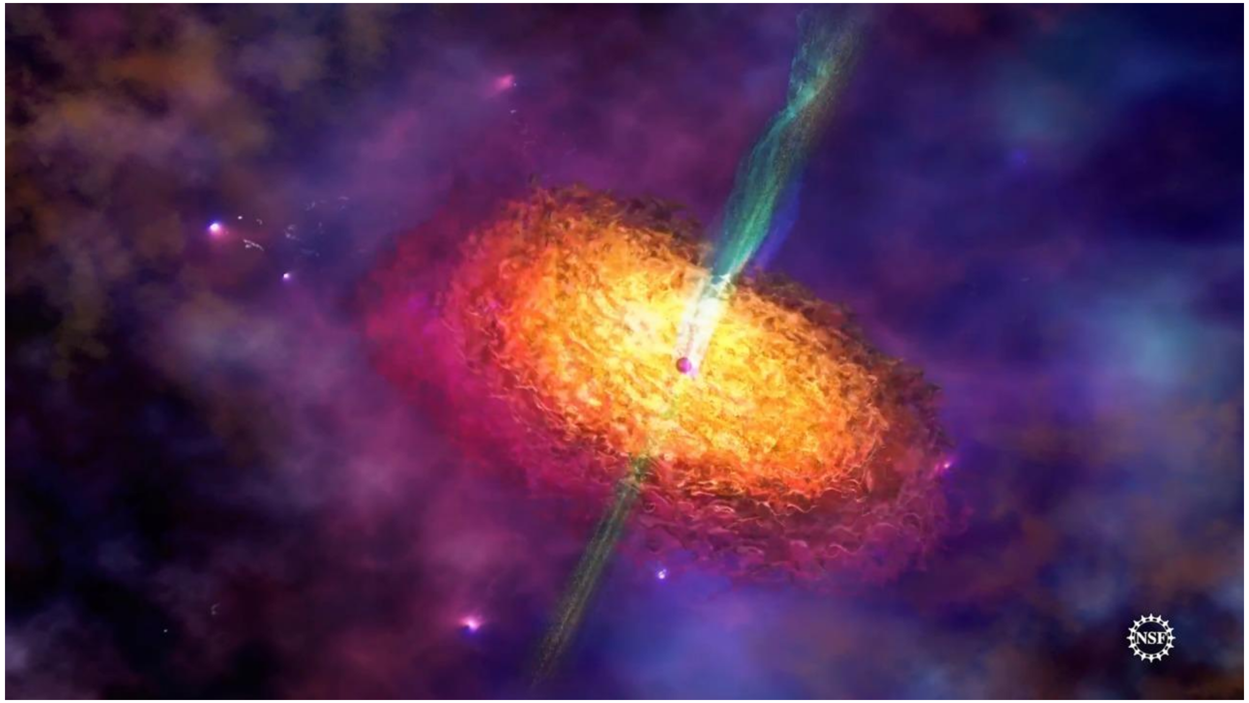
Credit: R. Munroe



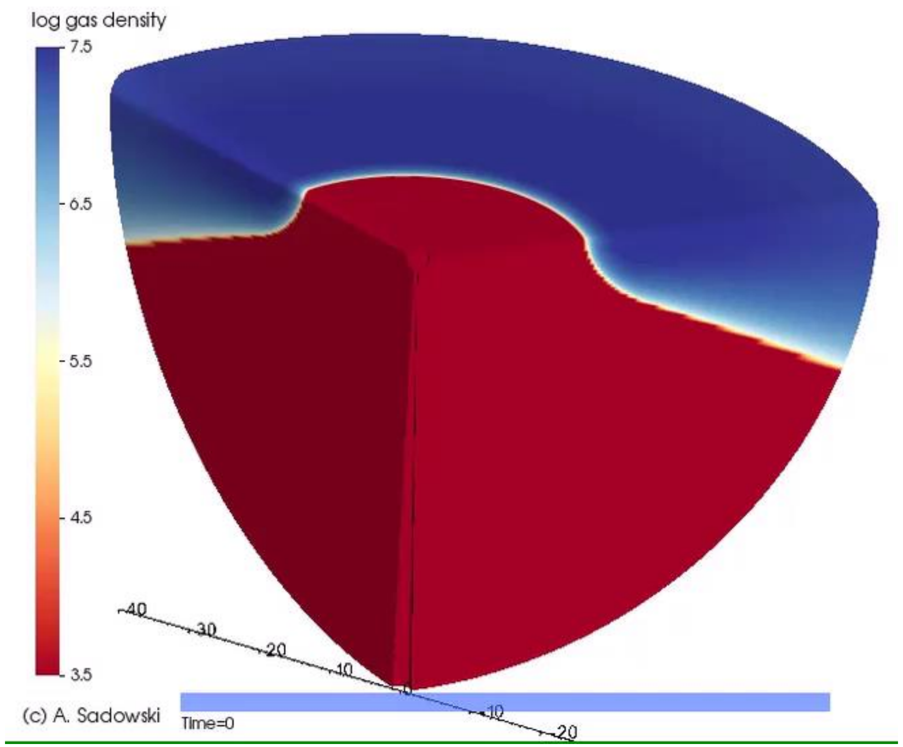
Credit: L. Blackburn

M87’s physical environment: what’s going on near the event horizon?

- Thick accretion disk of hot plasma (tens of billions of degrees K)
  - produces the strongest emission in sub-mm where the EHT observes!
- Strong and turbulent magnetic fields
- Launches a powerful relativistic jet

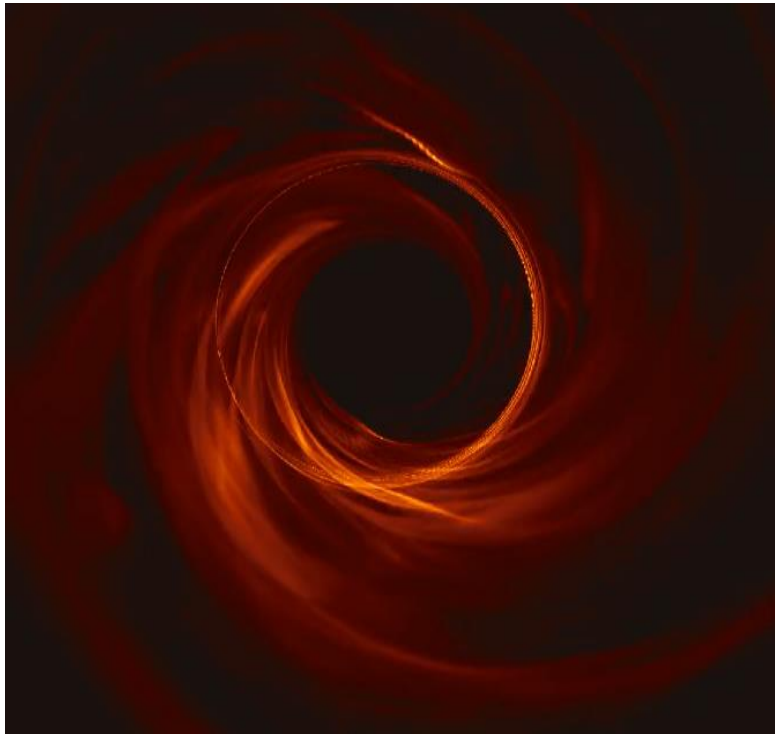


General **R**elativistic **M**agneto**H**ydro**D**ynamics



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

General **R**elativistic **R**ay **T**racing



Tracks light rays and solves for the emitted radiation

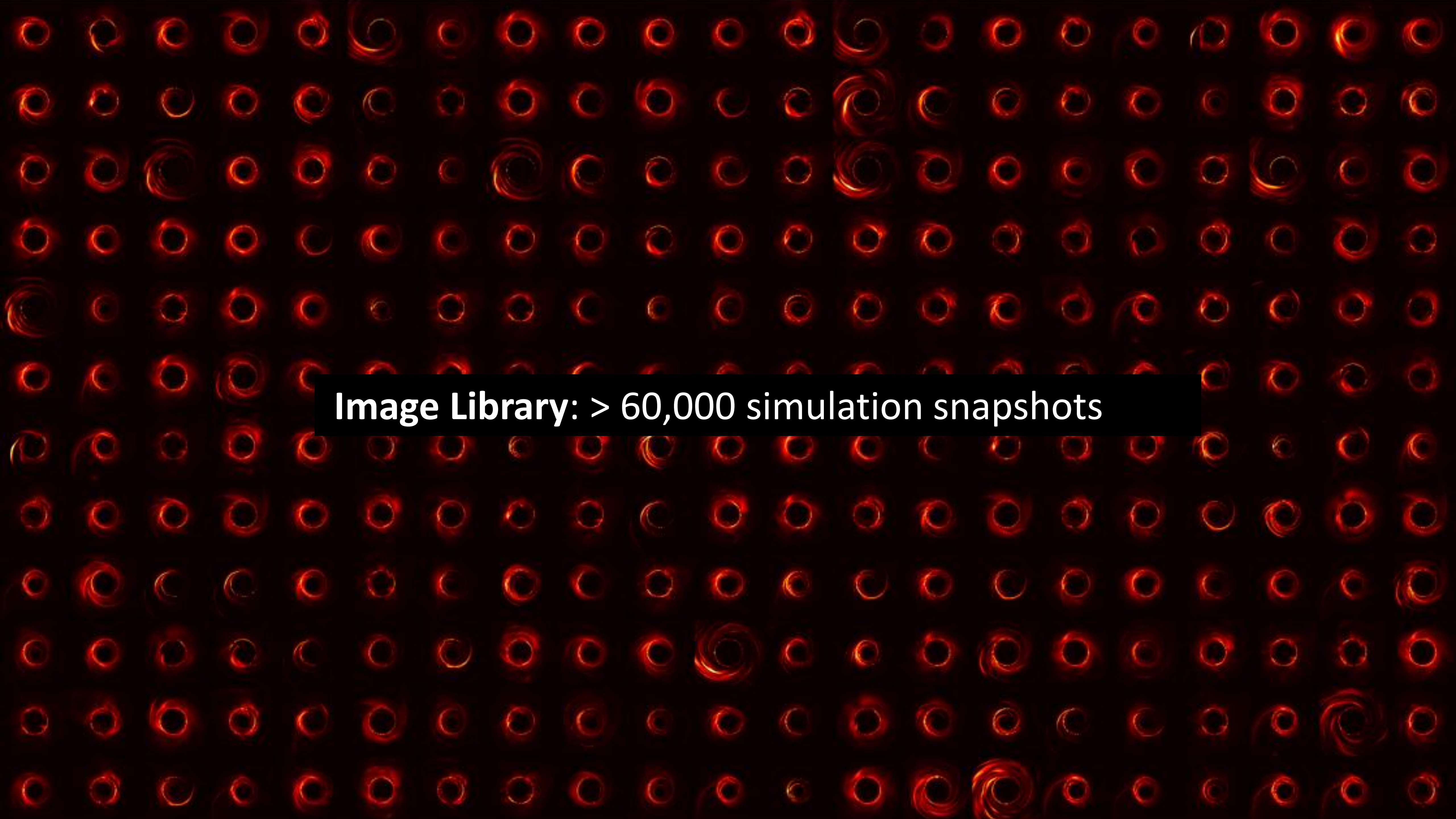
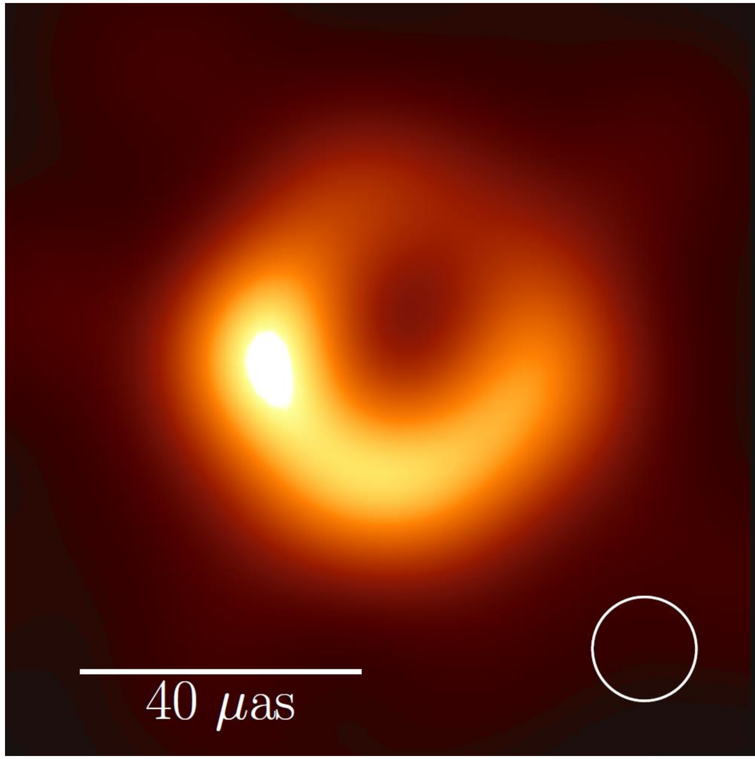


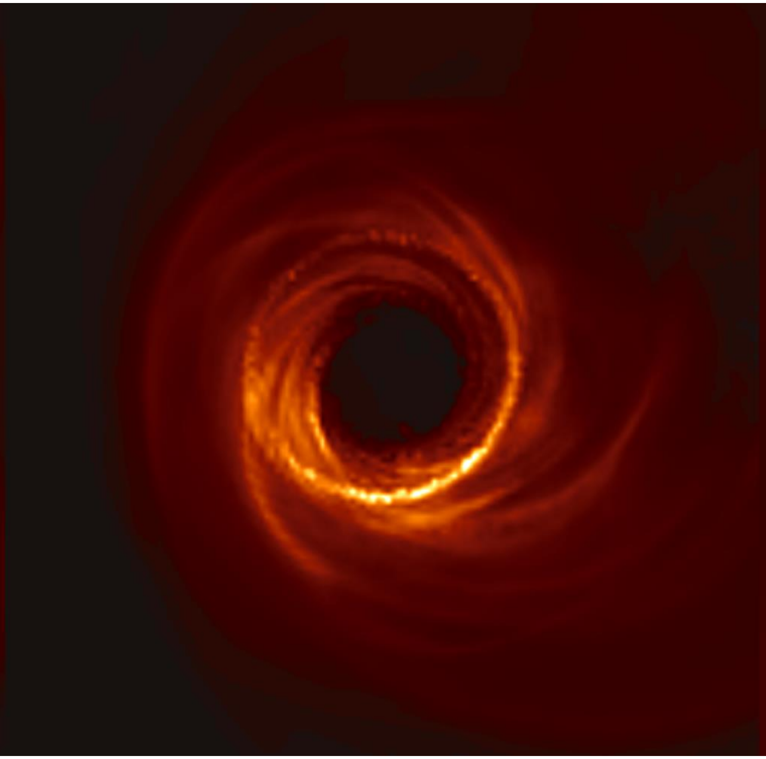
Image Library: > 60,000 simulation snapshots

Matching Simulations and Images

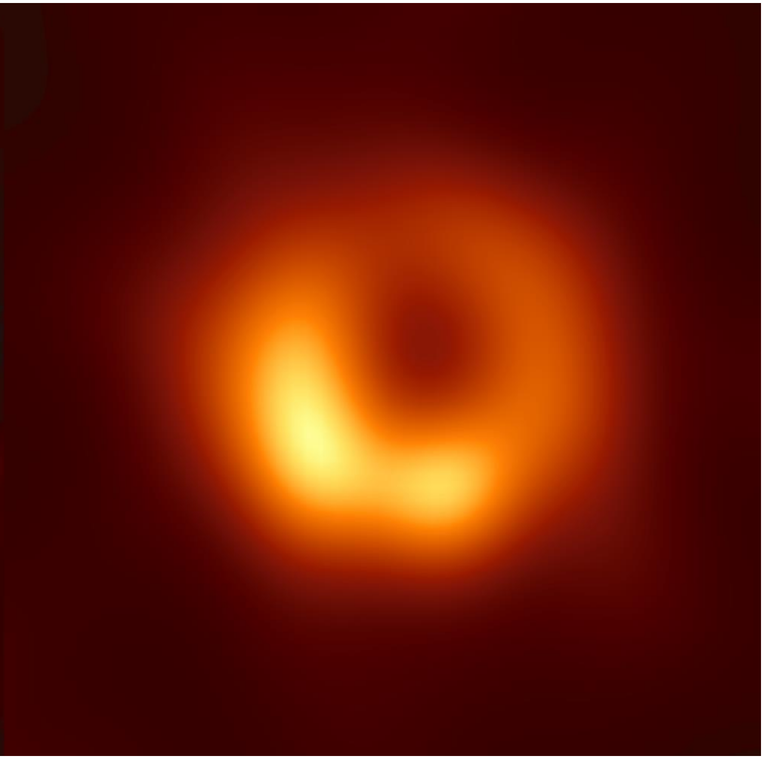
EHT 2017 image



Simulated image
from (my) GRMHD model

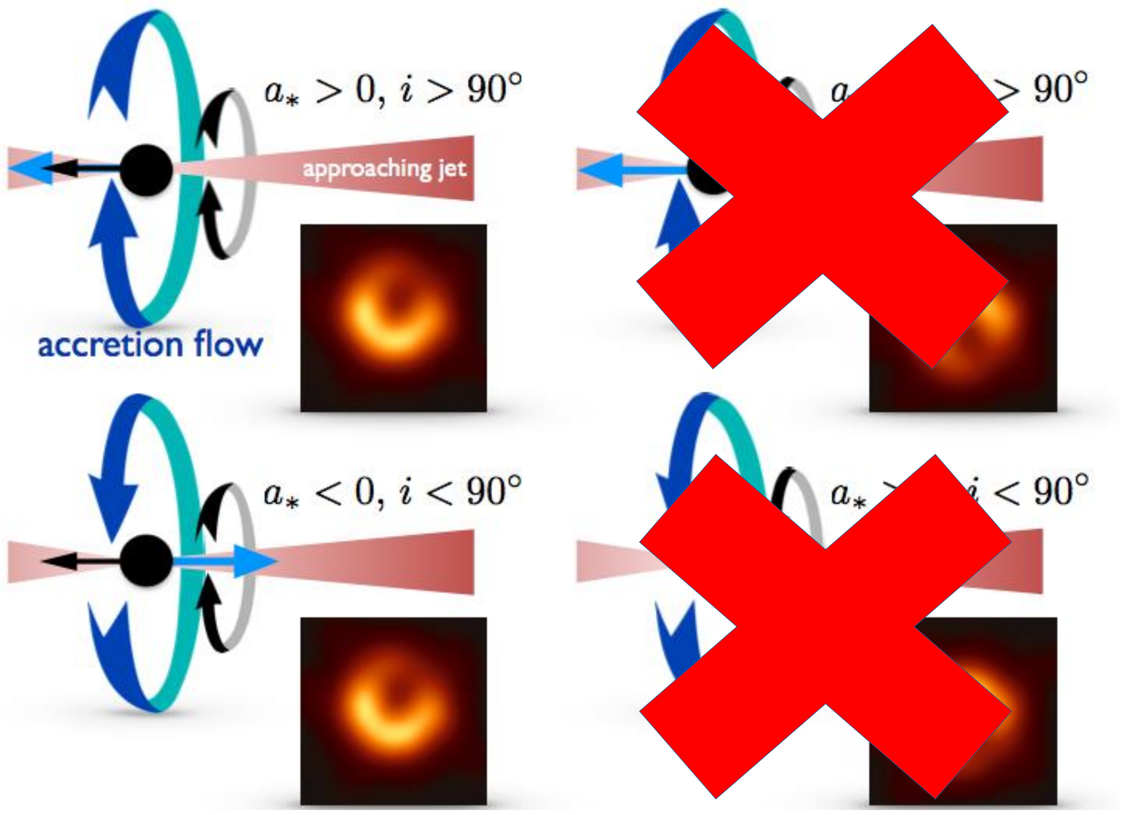


Simulated image reconstructed
with EHT pipeline



Ring Asymmetry and Black Hole Spin

BH angular momentum determines the image orientation

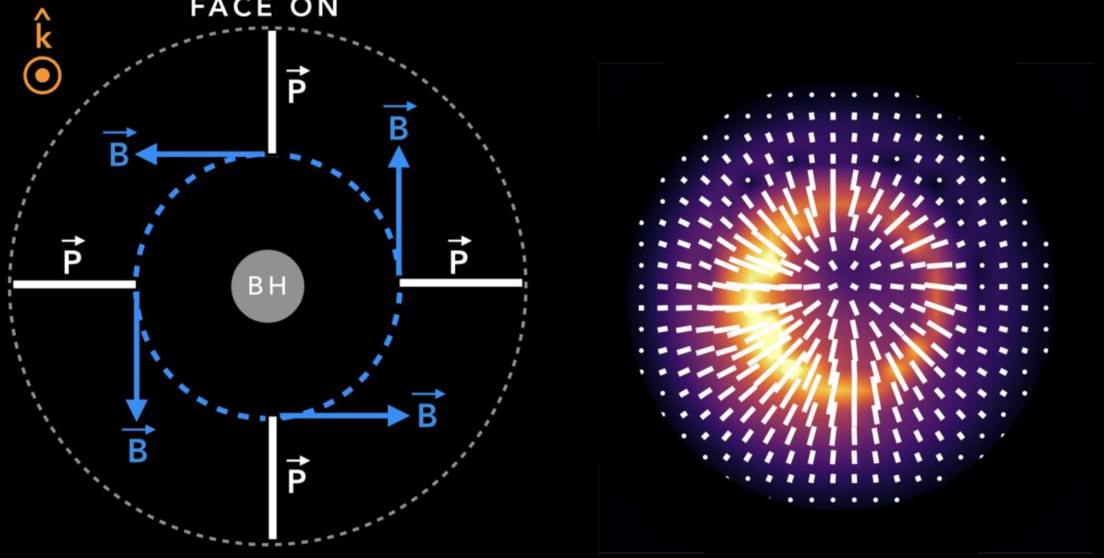


BH spin-away (clockwise rotation) models are strongly favored

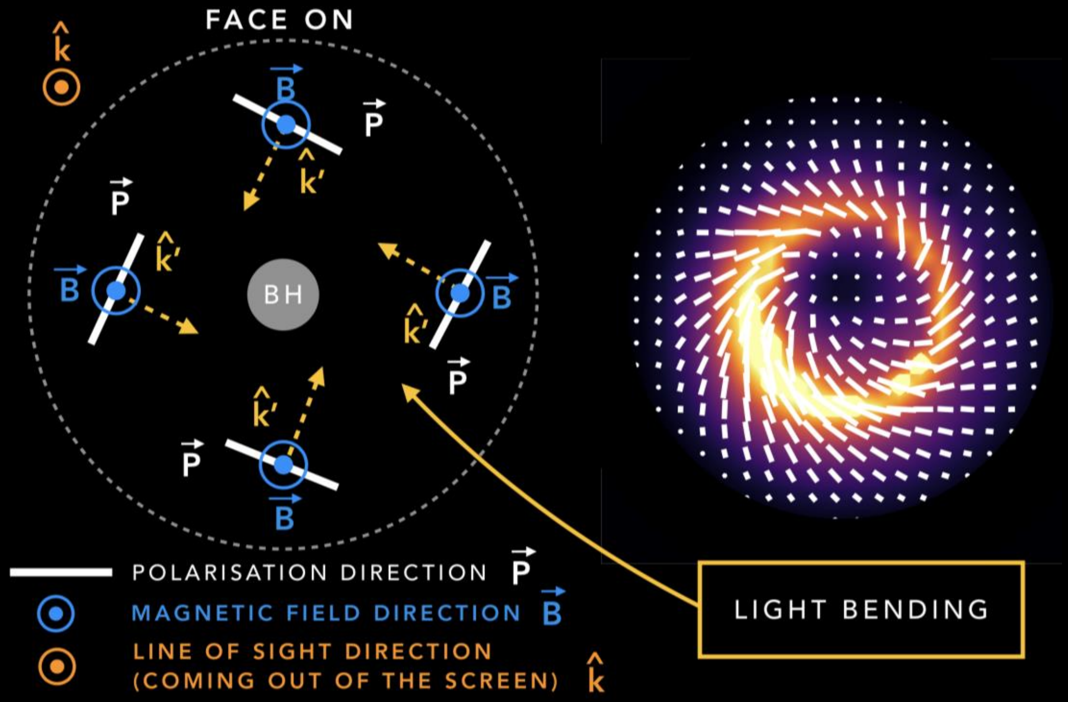
Next Steps

Polarization traces magnetic fields

Toroidal Field



Vertical field



Polarization Image Coming Soon!

Image credit: Alejandra Jiménez-Rosales

Sagittarius A*

$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$

$D = (8.12 \pm 0.03)\text{kpc}$

Gravity Collaboration, 2018

$d_{\text{shadow}} \approx 50\mu\text{as}$

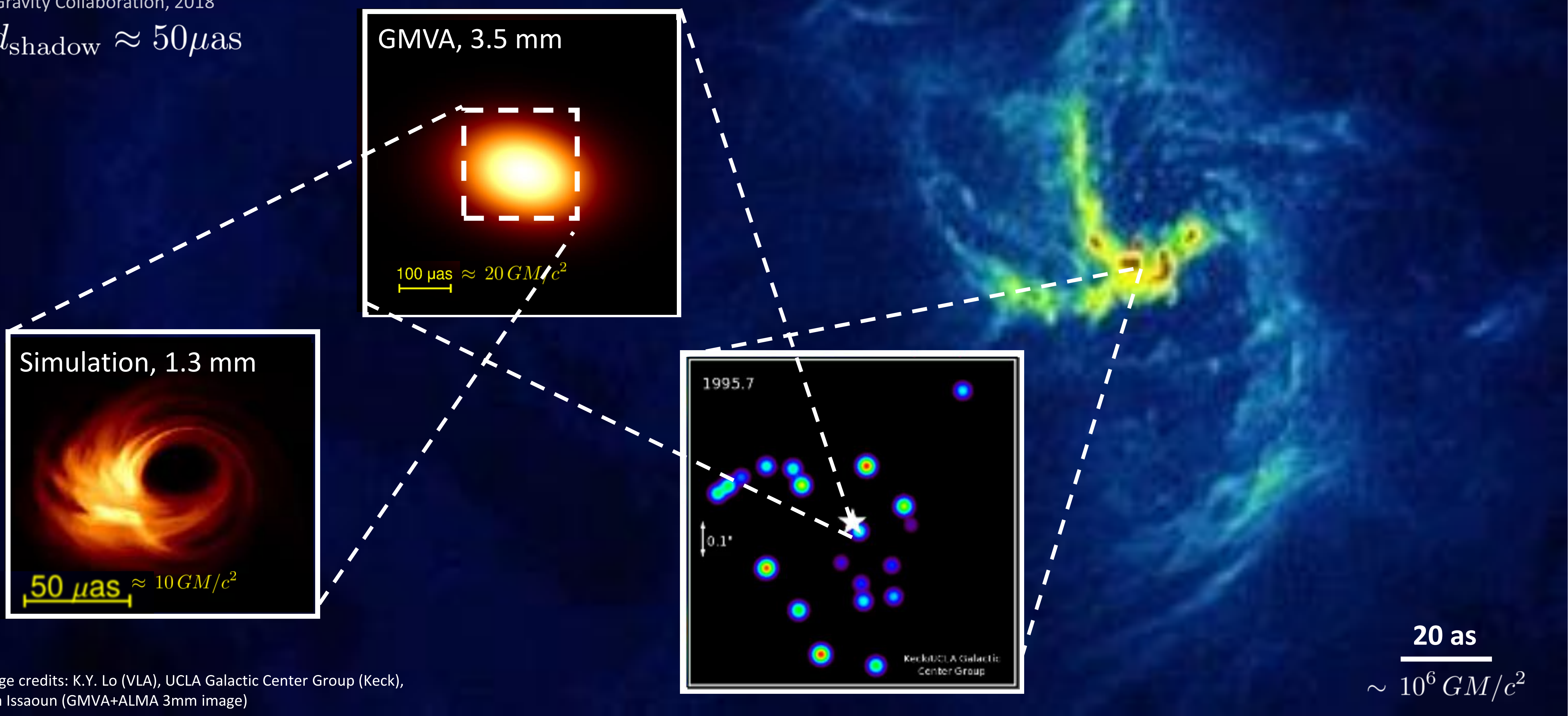
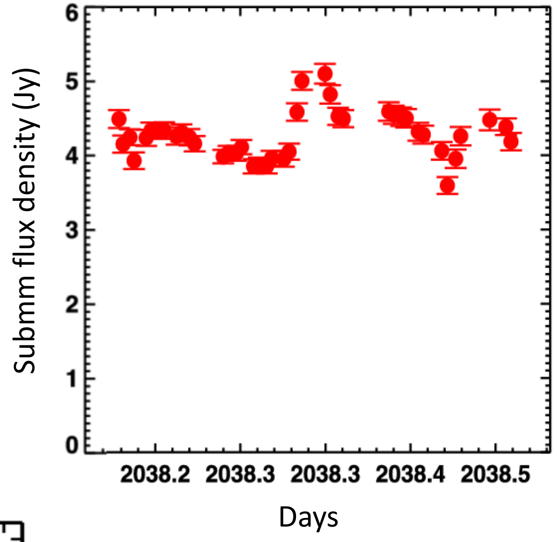
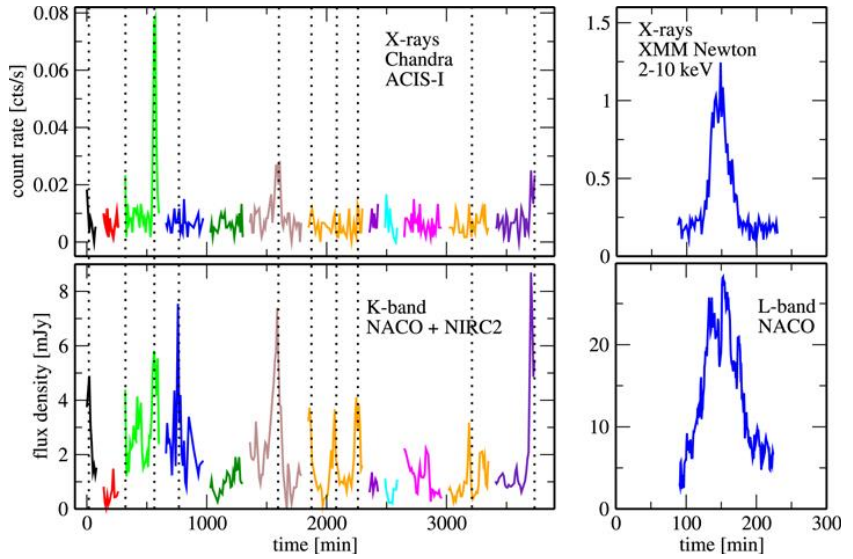


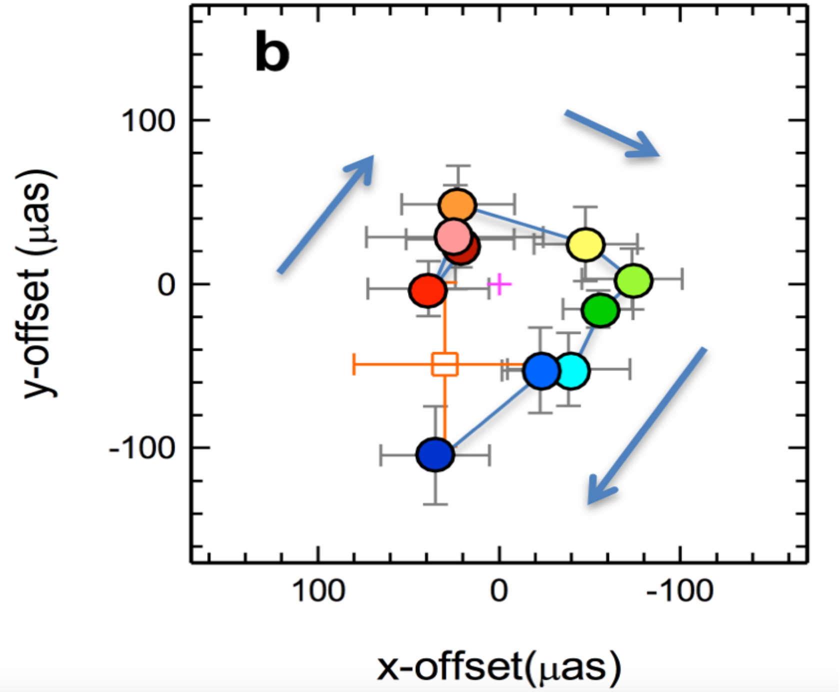
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

Time variability: Sgr A* Flares

- Intra-day 1.3 mm variability in Sgr A* on minute-hour timescales makes imaging very hard!



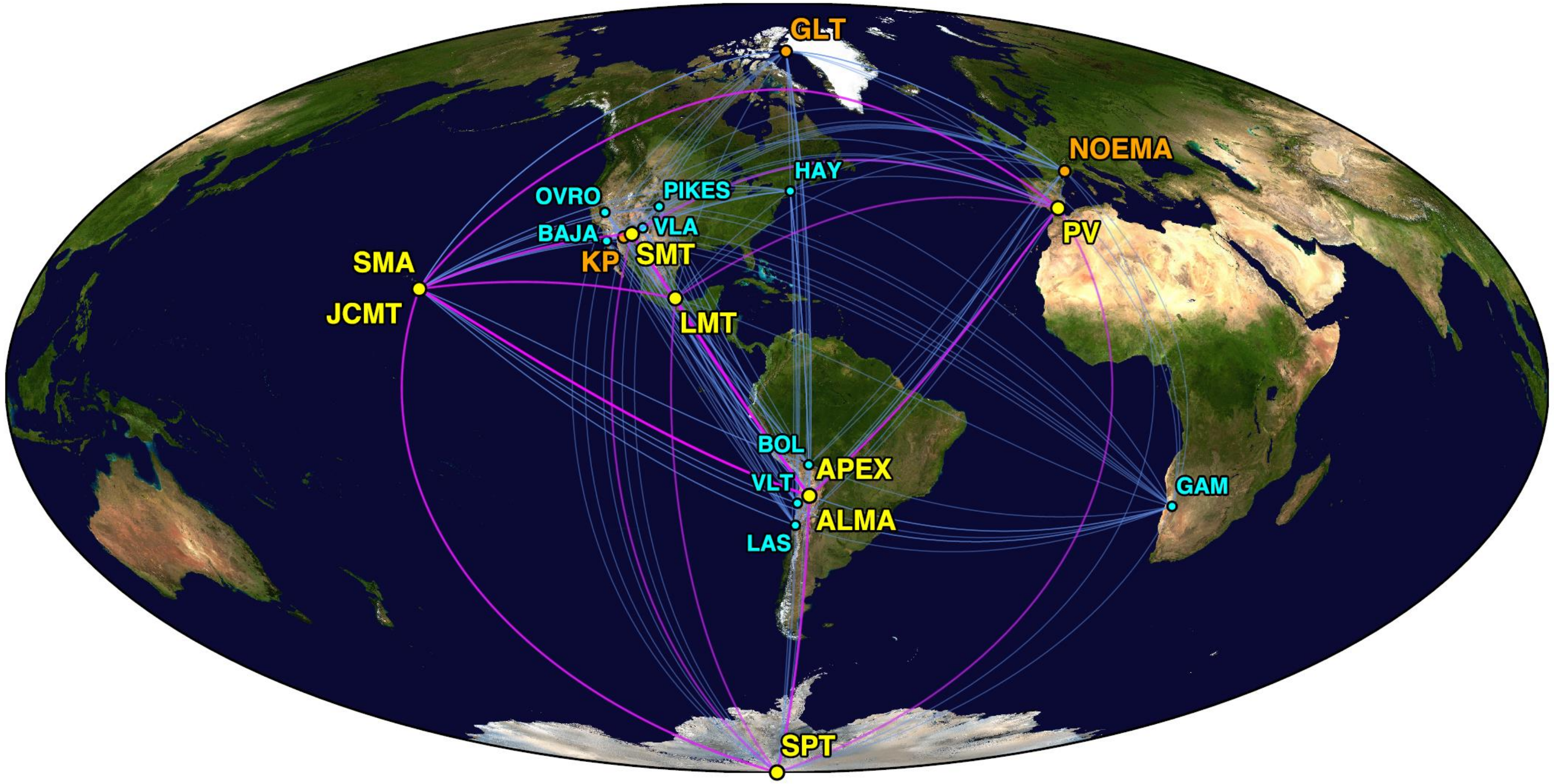


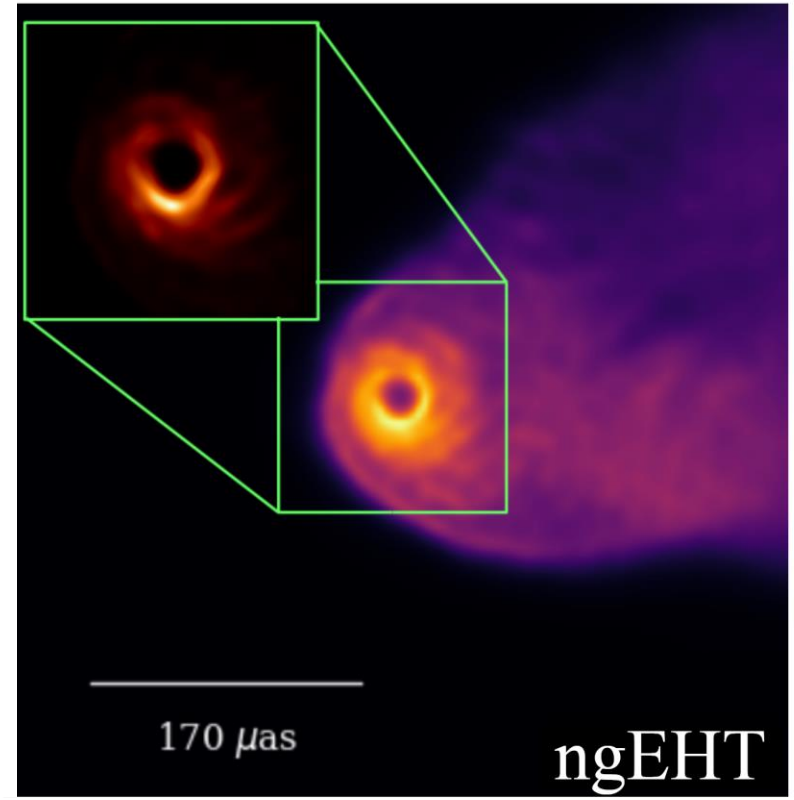


- GRAVITY NIR Interferometry: flares rotate near the horizon, $R \sim 3 - 5\, R_{\rm Sch}\,,\ v \sim 0.2 - 0.3c$

Marrone+2008, Dexter+2014, Fazio+ 2018, GRAVITY Collab+ 2018b

ngEHT will illuminate the BH-jet connection





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

Idea: add many more small, ~6m dishes to the array

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

Summary:

- **The EHT has captured the first image of a black hole shadow in M87.**
- The EHT is composed of diverse radio telescopes around the world combined into one instrument with years of collaboration and technical development
- EHT data is reduced from petabytes of recordings to kilobyte images; the data are uniquely challenging to calibrate because of the high observing frequency.
- EHT images were reconstructed from sparse data with multiple independent pipelines
- Simulations suggest that the M87 black hole is spinning and that the jet is formed by the extraction of the BH spin energy.
- The black hole mass in M87 can be measured from the shadow size; it is *really* heavy

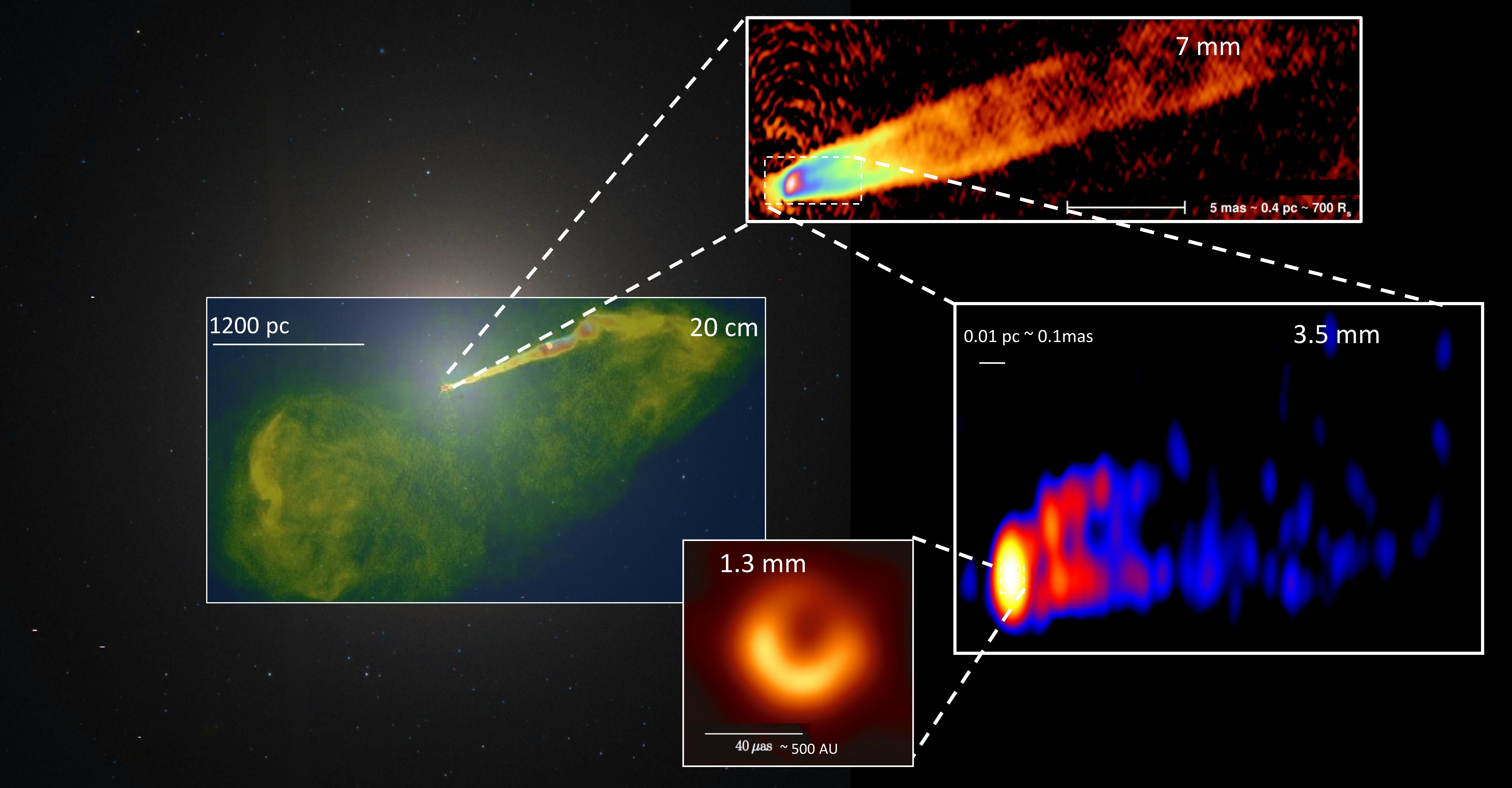


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)