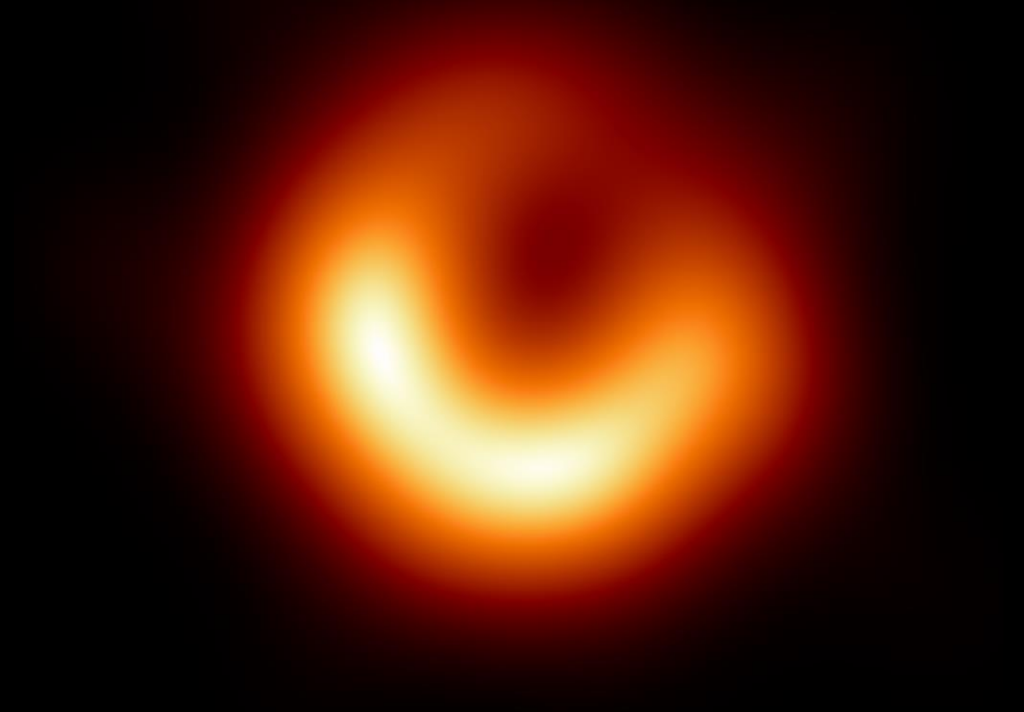
Photographing a Black Hole with the Event Horizon Telescope

Andrew Chael '13

May 14, 2019



HARVARD UNIVERSITY
Department of Physics

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Event Horizon Telescope

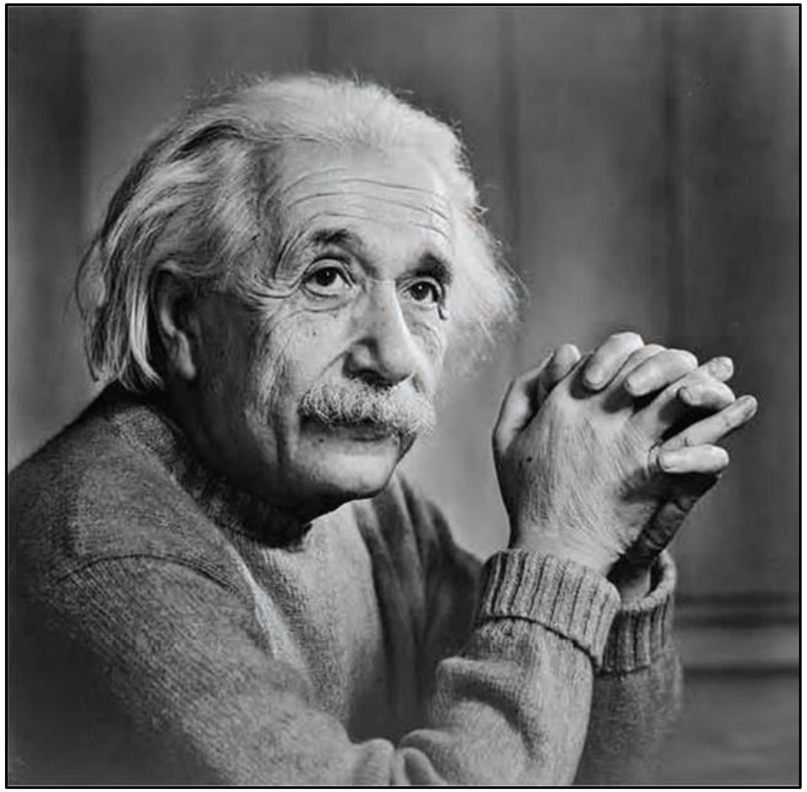

CSIRO

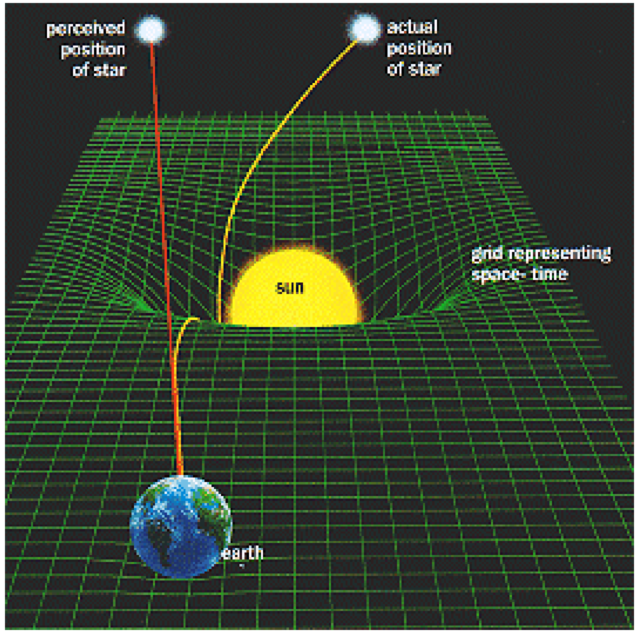
The EHT Collaboration

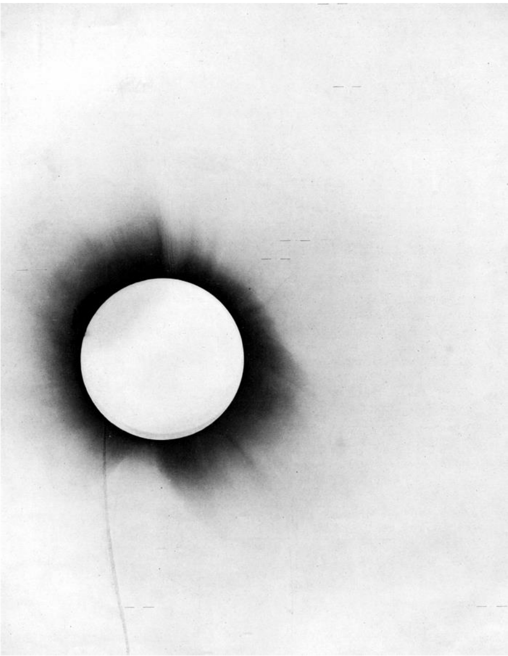
What does a black hole look like?

Black Holes

$$G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$$

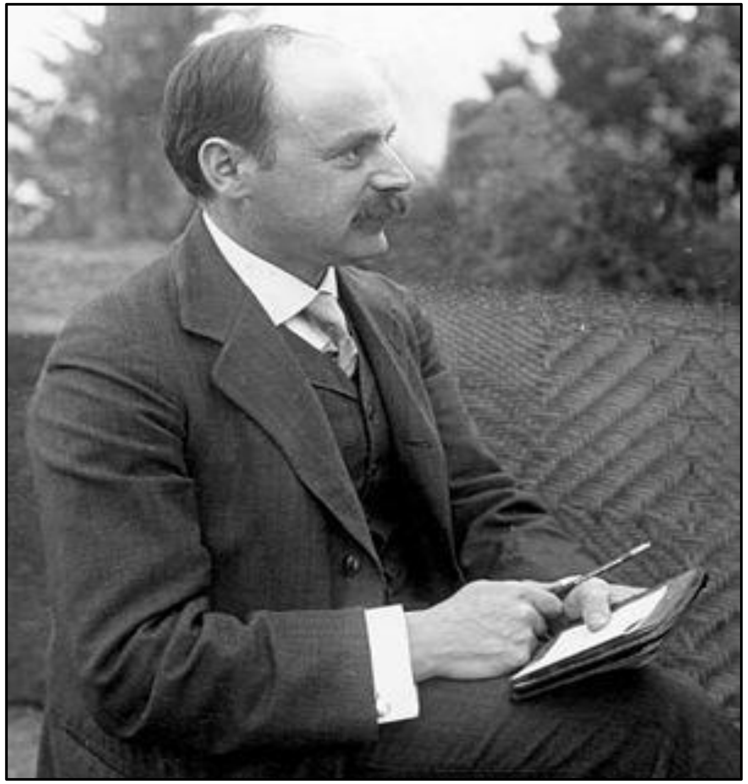






1915 Albert Einstein’s general theory of relativity.
Predicts that light is bent by gravity

Black Holes



1916
Karl Schwarzschild discovers the first non-trivial exact solution in General Relativity

His solution predicts that even light cannot escape from the inside the “Schwarzschild radius”, which marks the black hole’s event horizon (Finkelstein 1958)

$$R_{\mathrm{Sch}} = \frac{2GM}{c^2}$$

$$c^2\,d\tau^2 = \left(1-\frac{r_{\mathrm{s}}}{r}\right)c^2\,dt^2 - \left(1-\frac{r_{\mathrm{s}}}{r}\right)^{-1}dr^2 - r^2\left(d\theta^2+\sin^2\theta\,d\varphi^2\right)$$

Accretion Energy:
black holes can shine brightly

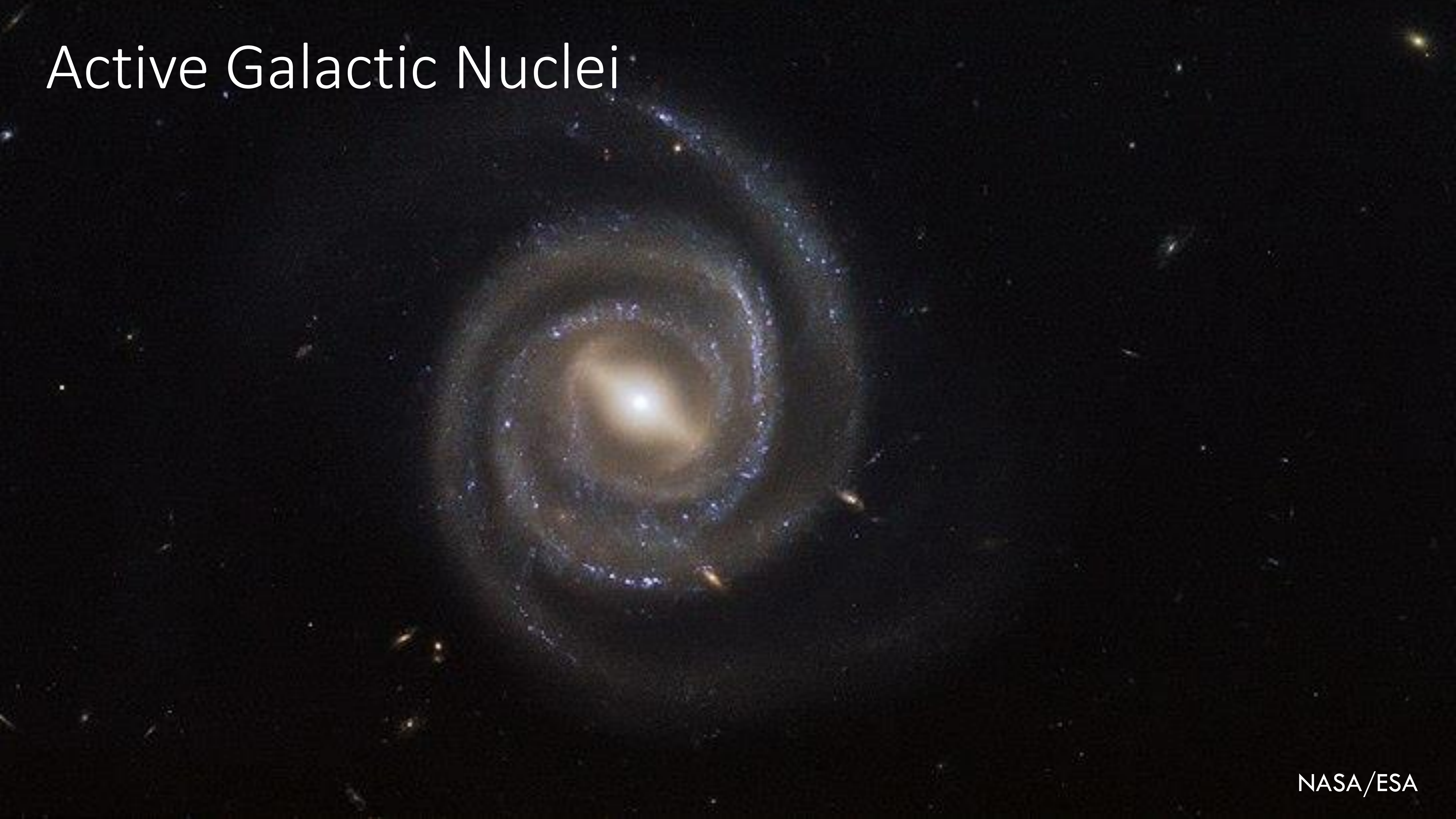
Accretion power per unit mass:

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

For nuclear fusion:

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

Active Galactic Nuclei



NASA/ESA

Sagittarius A*

$$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$$
$$D = (8.12 \pm 0.03)\mathrm{kpc}$$

Gravity Collaboration, 2018

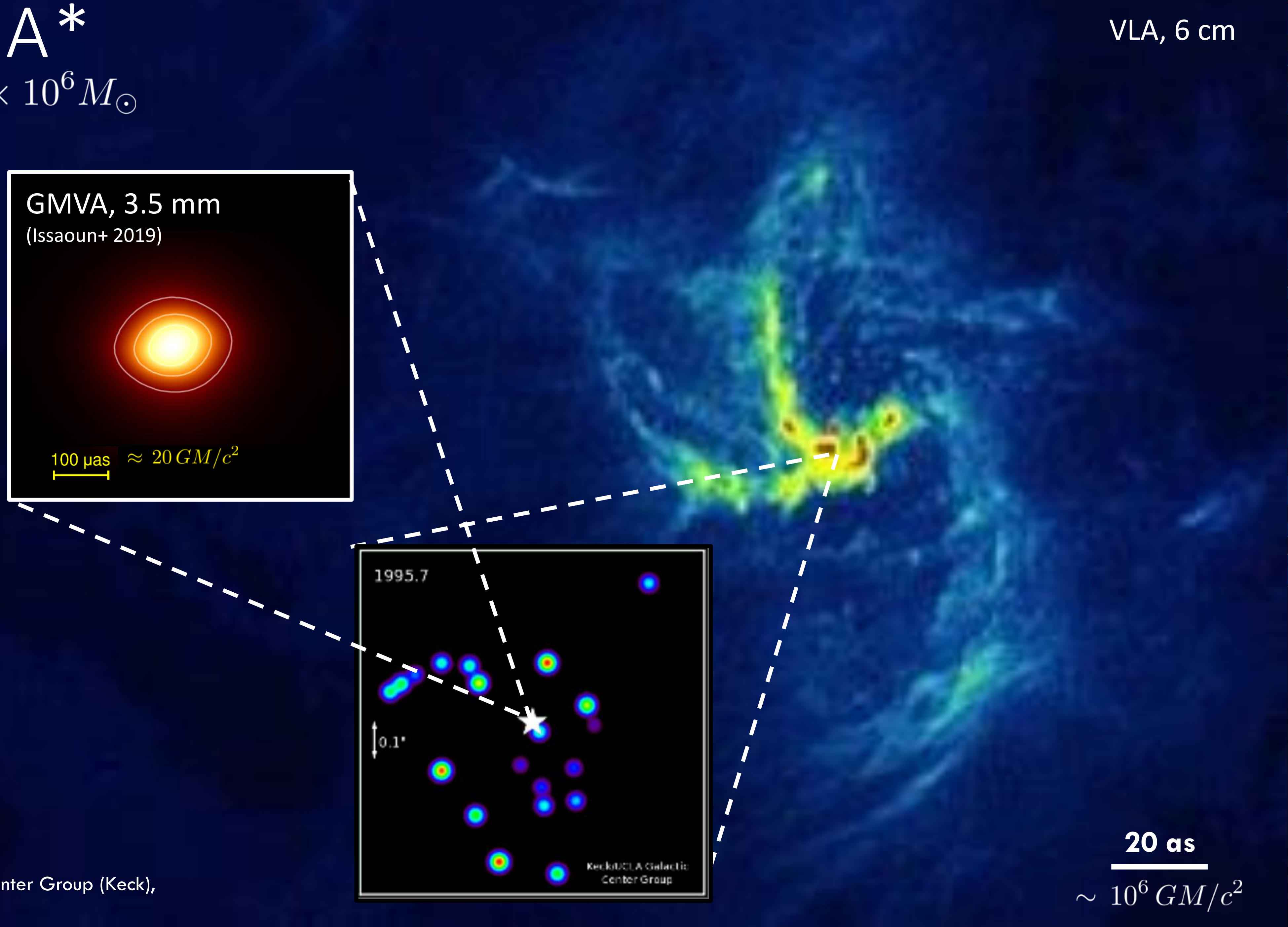


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

M87

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$

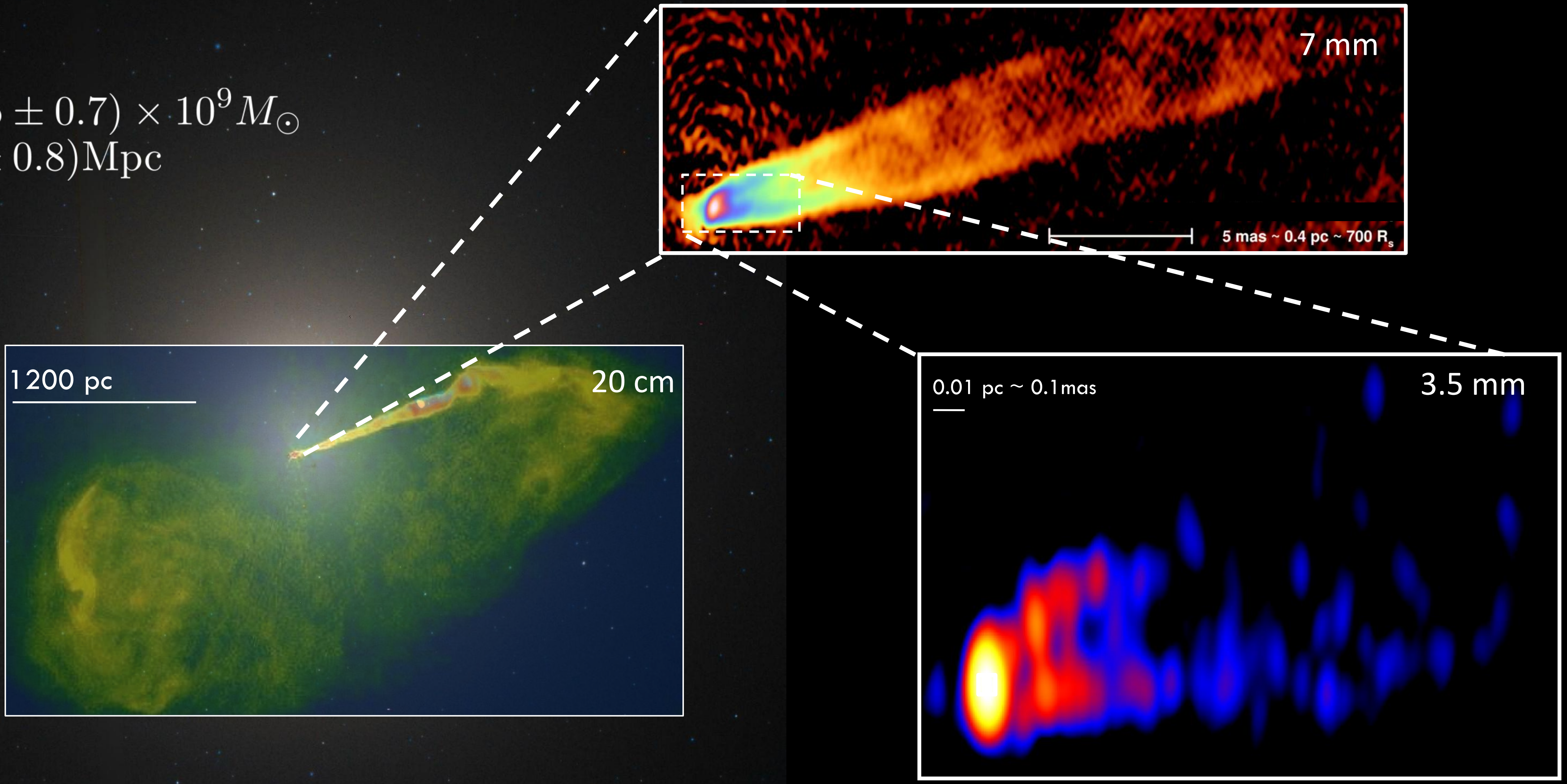
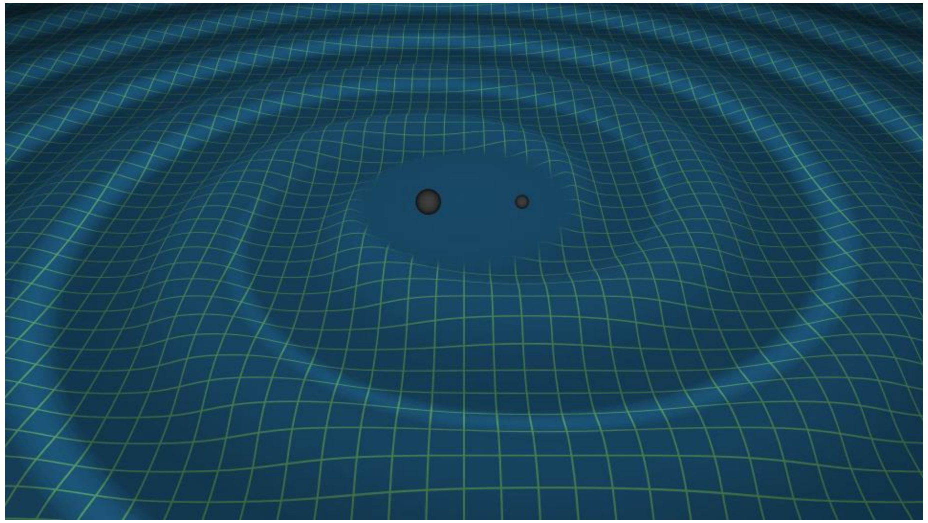
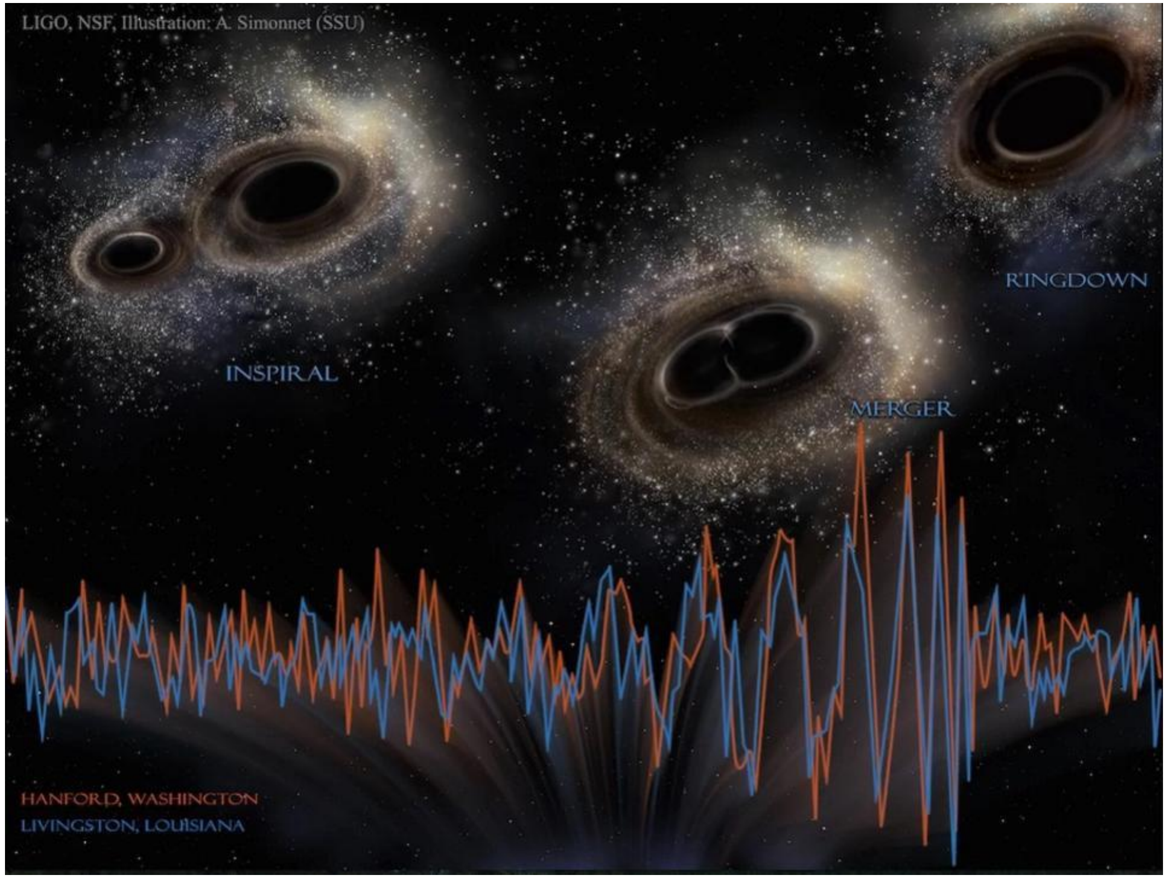


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

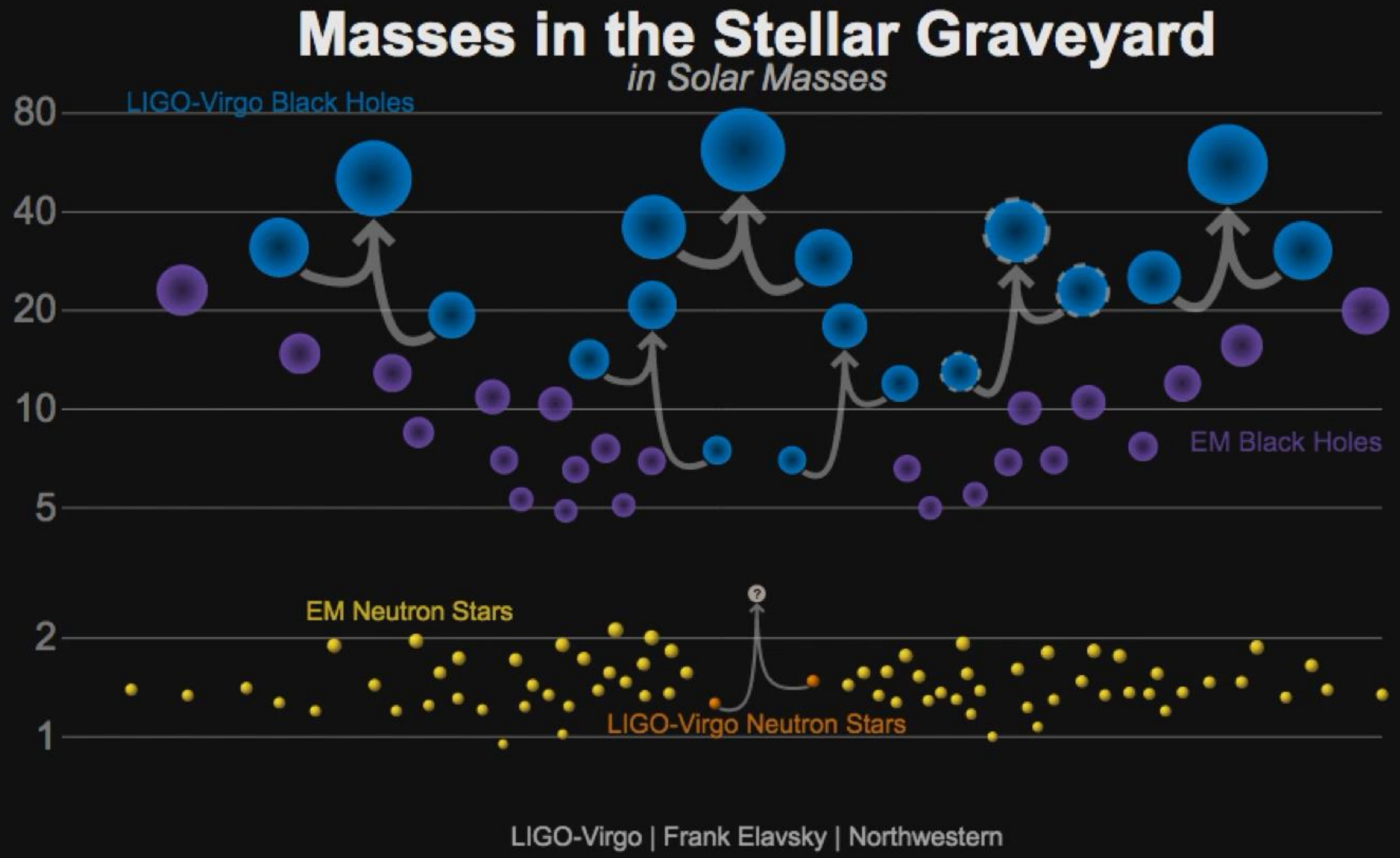
Gravitational Waves – 2015





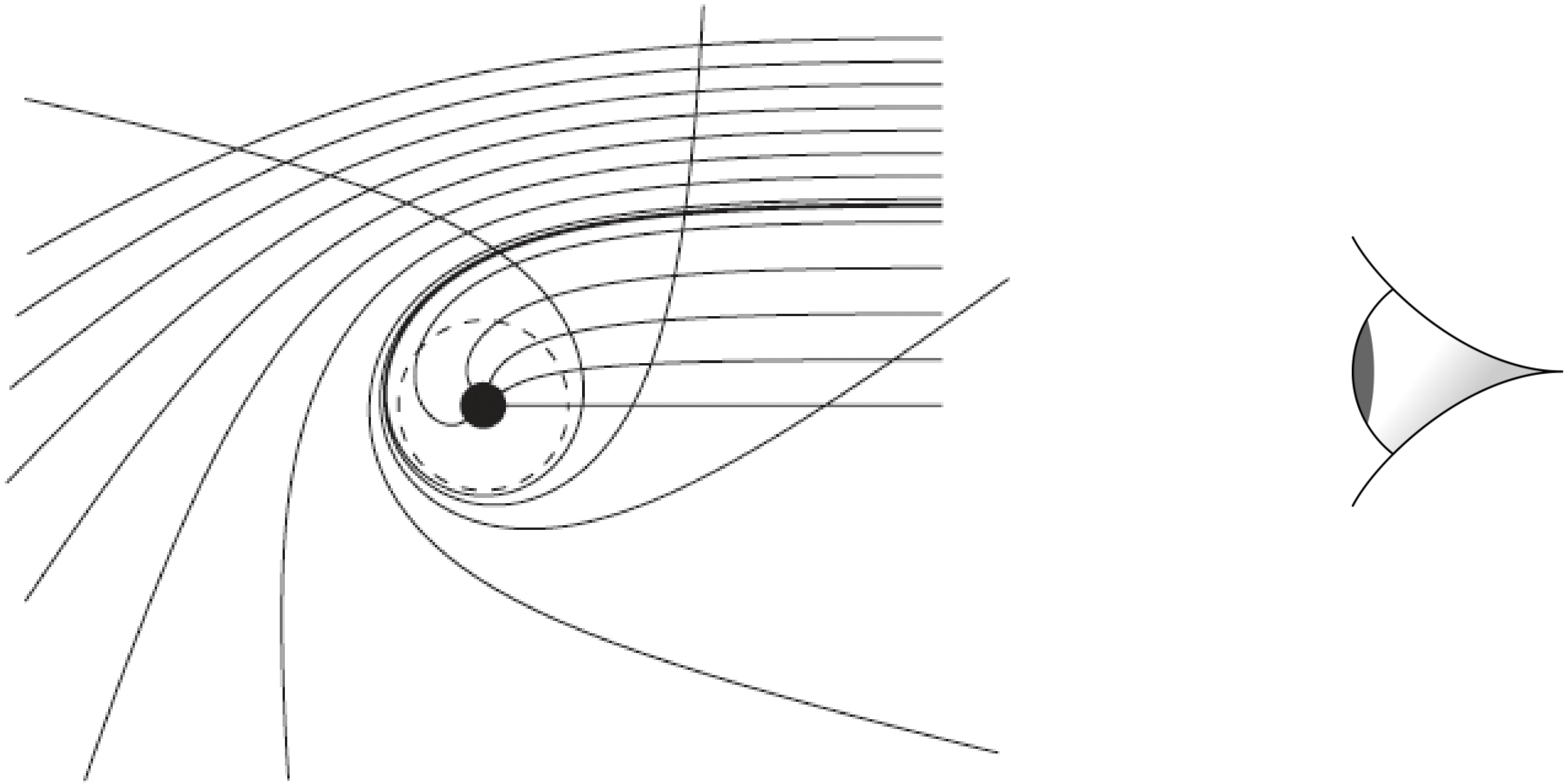
LIGO, NSF, Illustration: A. Simonnet (SSU)

LIGO/NSF

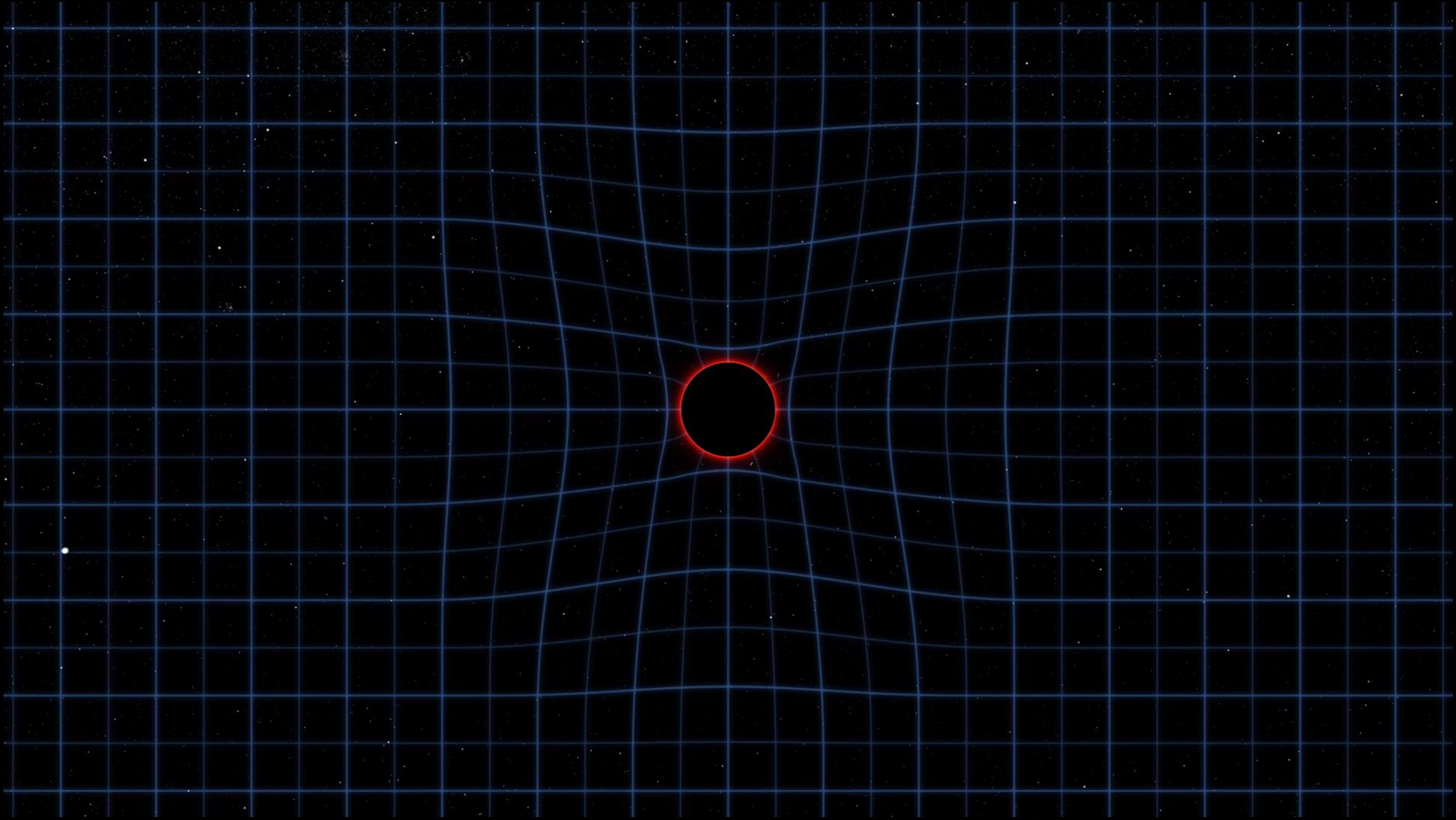


Credit: L. Blackburn

What would a black hole look like?



Thomas Muller



What would a black hole look like?

$$d_{\rm shadow} = \sqrt{27}R_{\rm Sch}$$

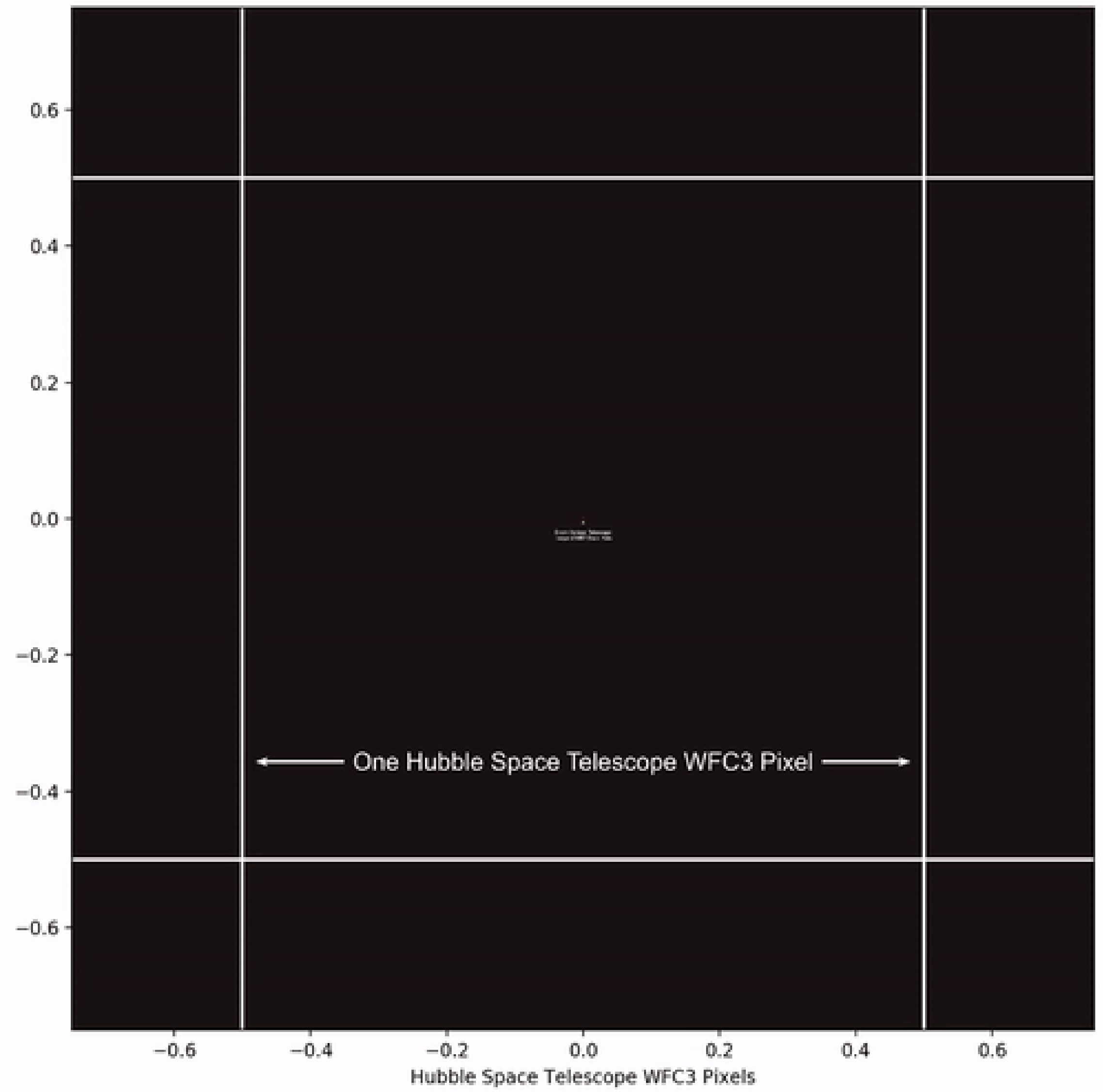
For M87:

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

> "It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole... Unfortunately, there seems to be no hope of observing this effect." (Bardeen 1973,1974)

Luminet, 1979

How small is 40 microarcseconds?

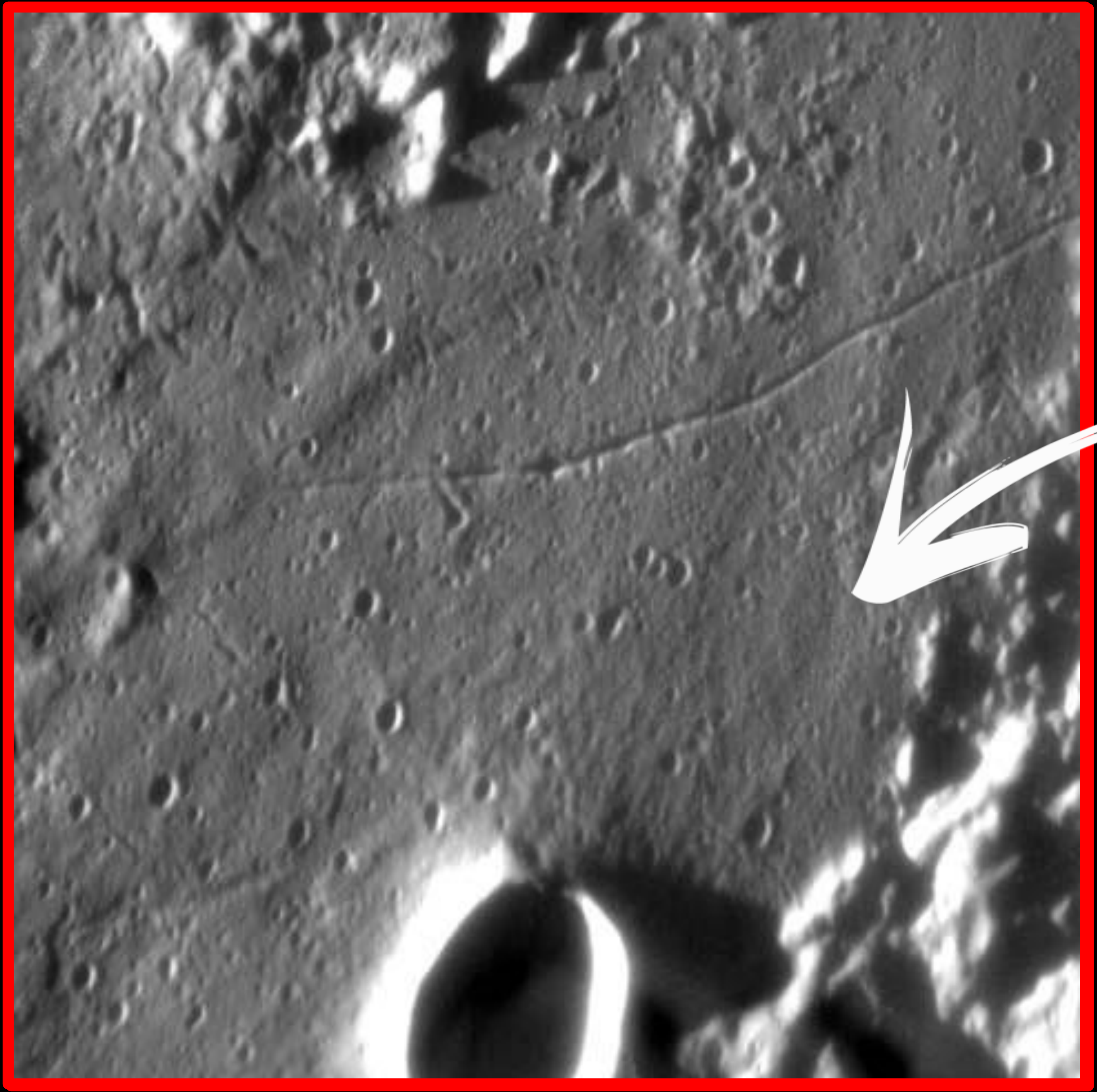


Animation credit: Alex Parker

Orange on the Moon

Black Hole
Shadow

Video courtesy of Hotaka Shiokawa



Each Pixel is

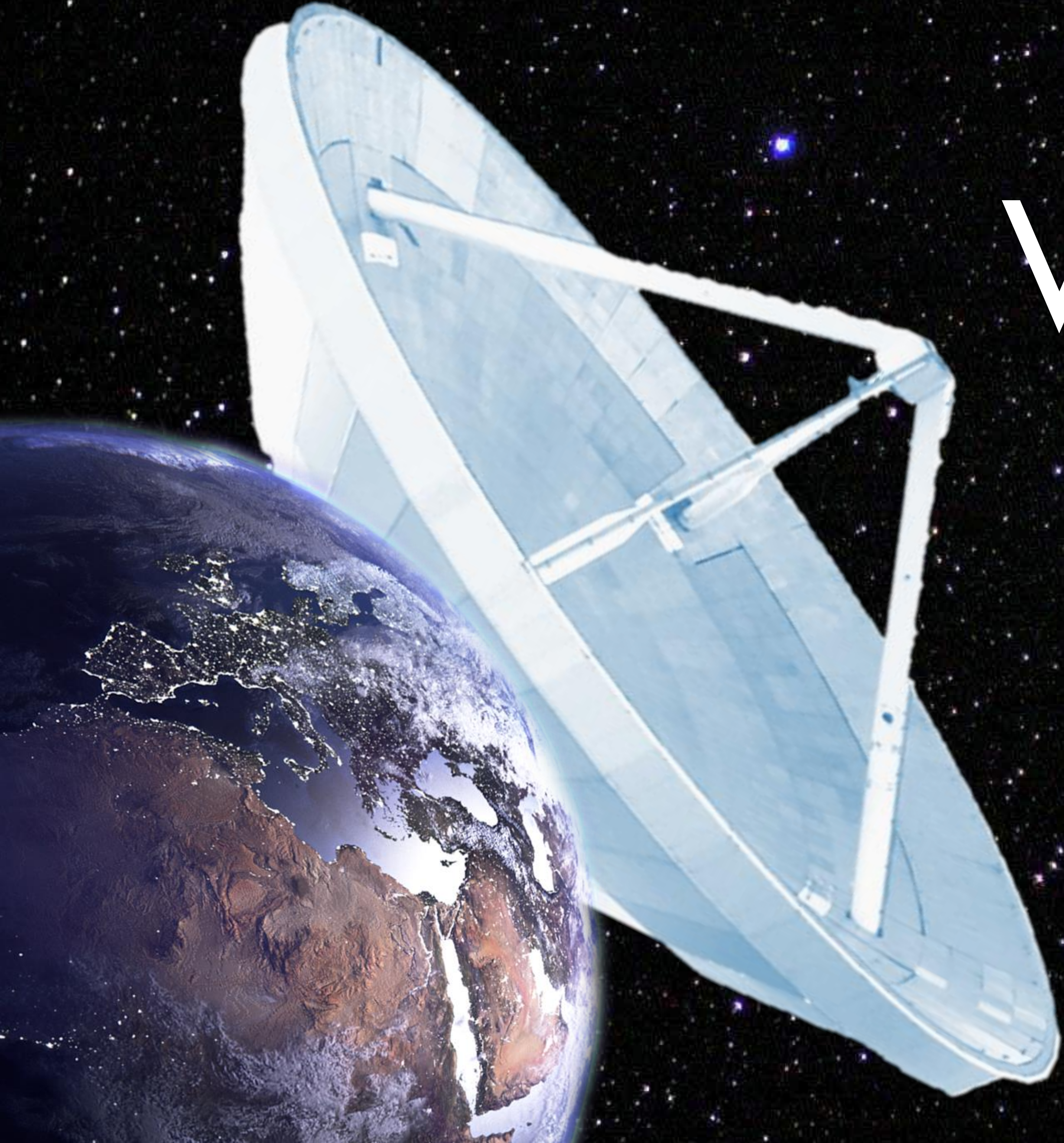
1.5 Million

’s

Yepun telescope, Paranal Observatory in Chile / George Tarsoudis

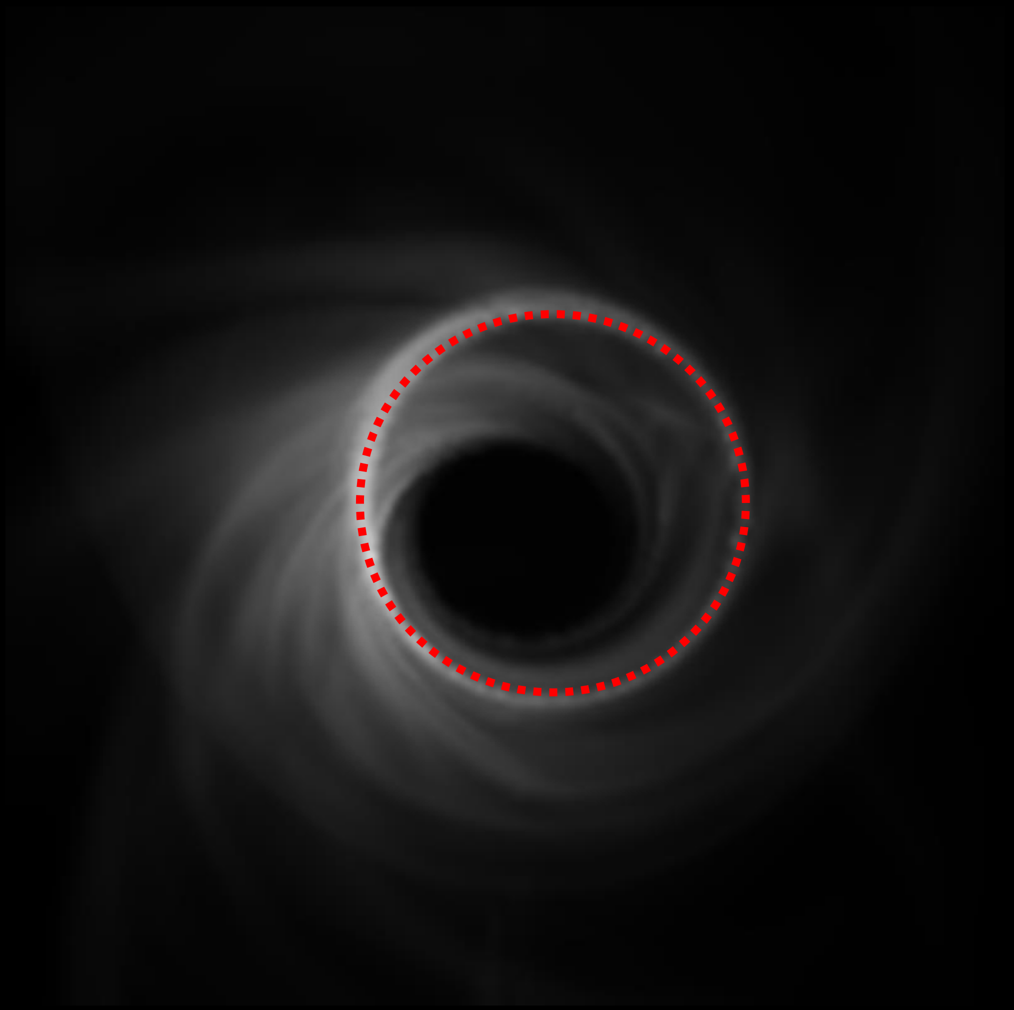
Diffraction Limit

$$\text{Angular Resolution} \propto \frac{\text{Wavelength}}{\text{Telescope Size}}$$

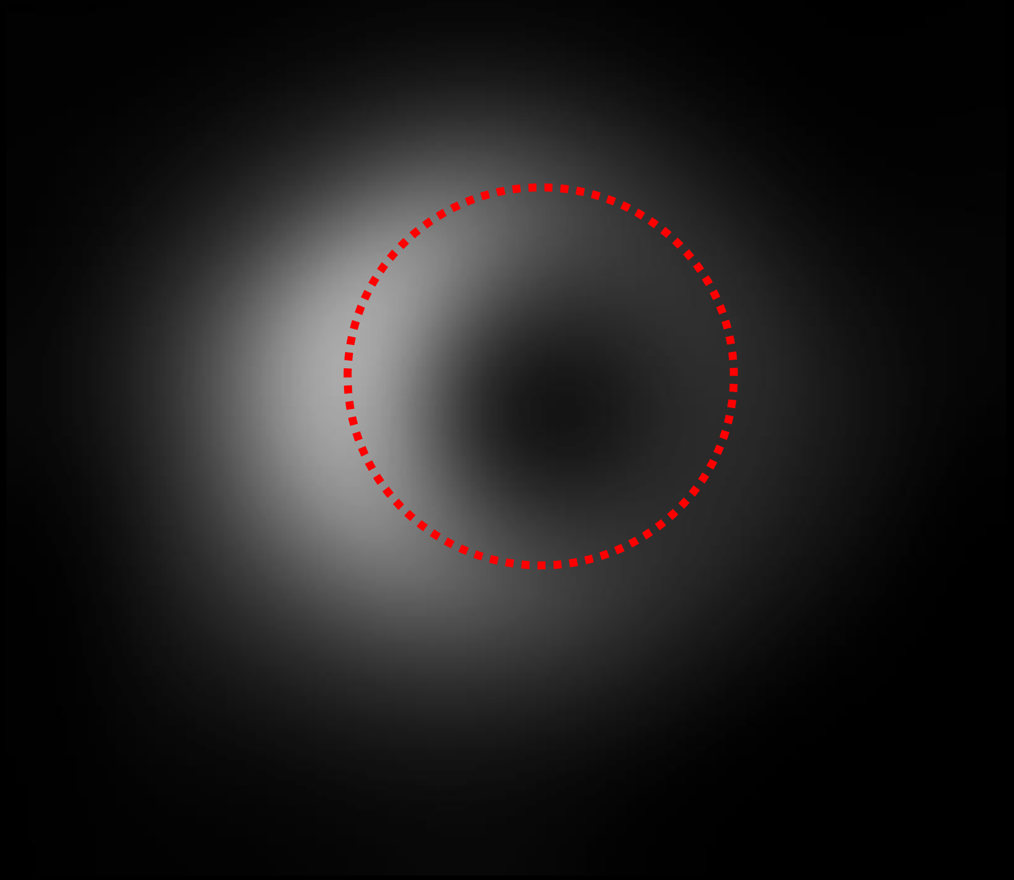


We Need an Earth-Sized Telescope!

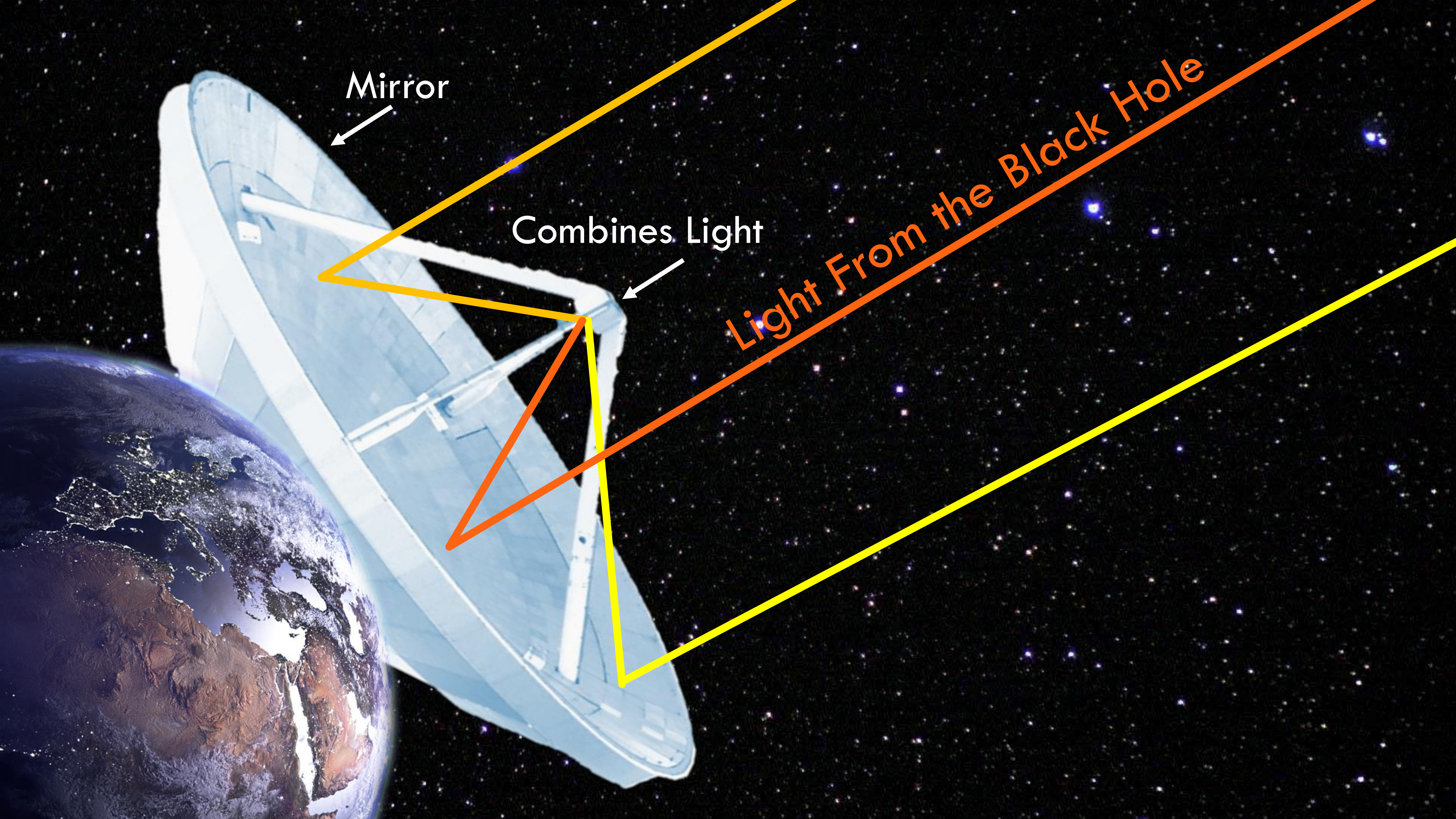
Best-Guess Simulation

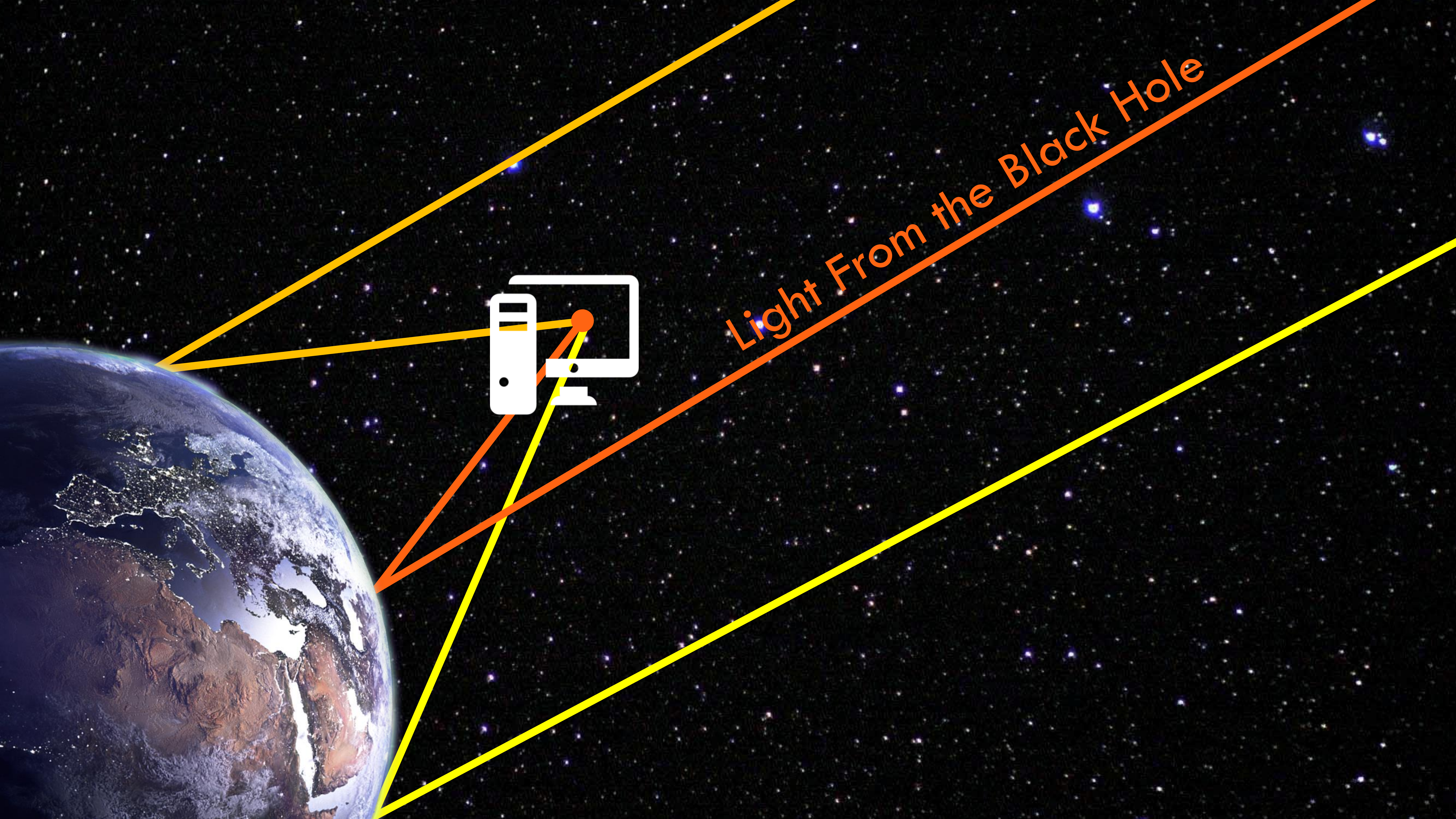


Picture with an Earth-Sized Telescope

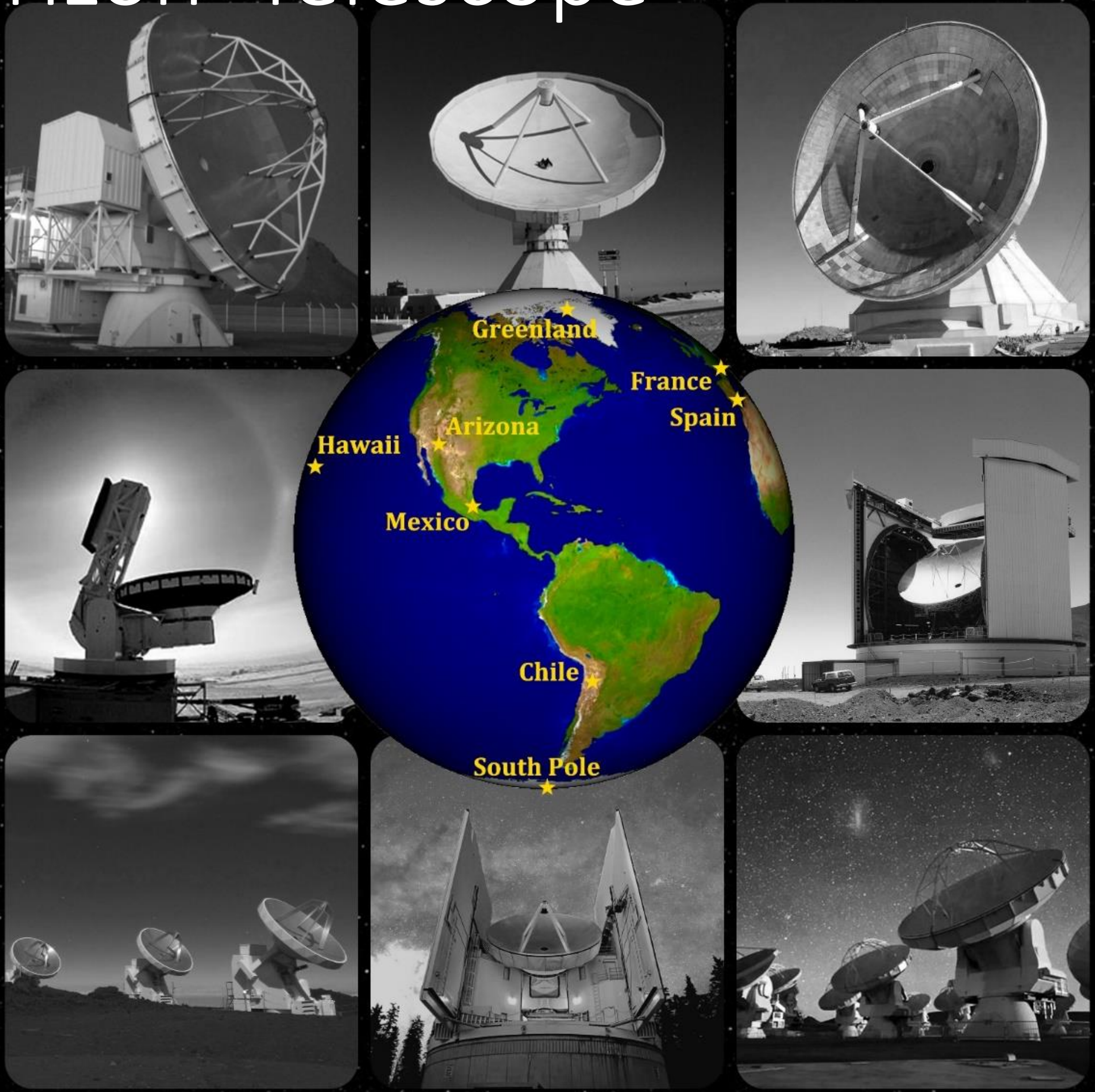


Original Image courtesy of Jason Dexter, Monika Moscibrodzka, Hotaka Shiokawa


Mirror
Combines Light
Light From the Black Hole

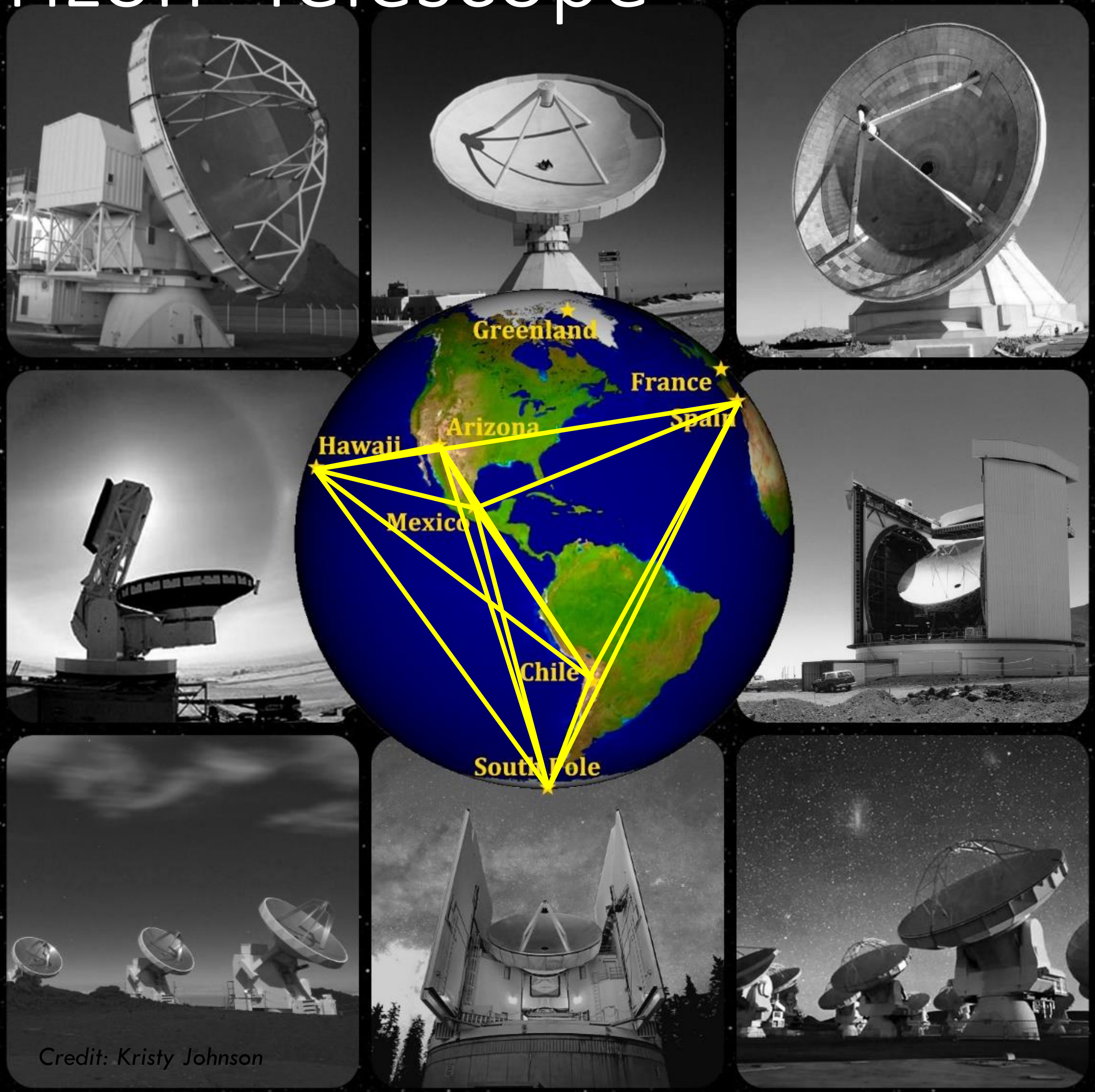

Light From the Black Hole

The Event Horizon Telescope



Credit: Kristy Johnson

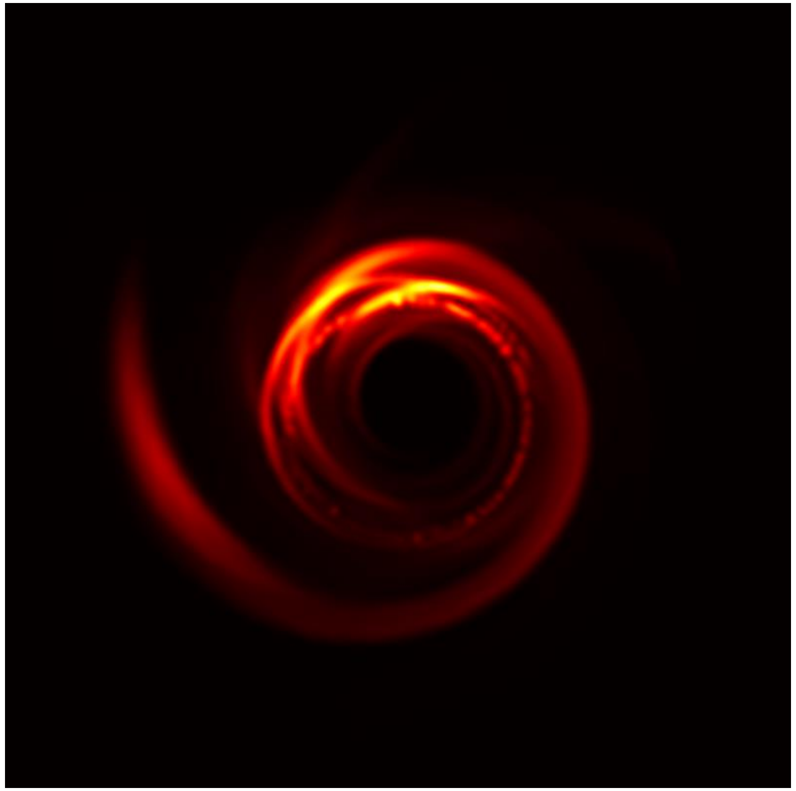
The Event Horizon Telescope



Credit: Kristy Johnson

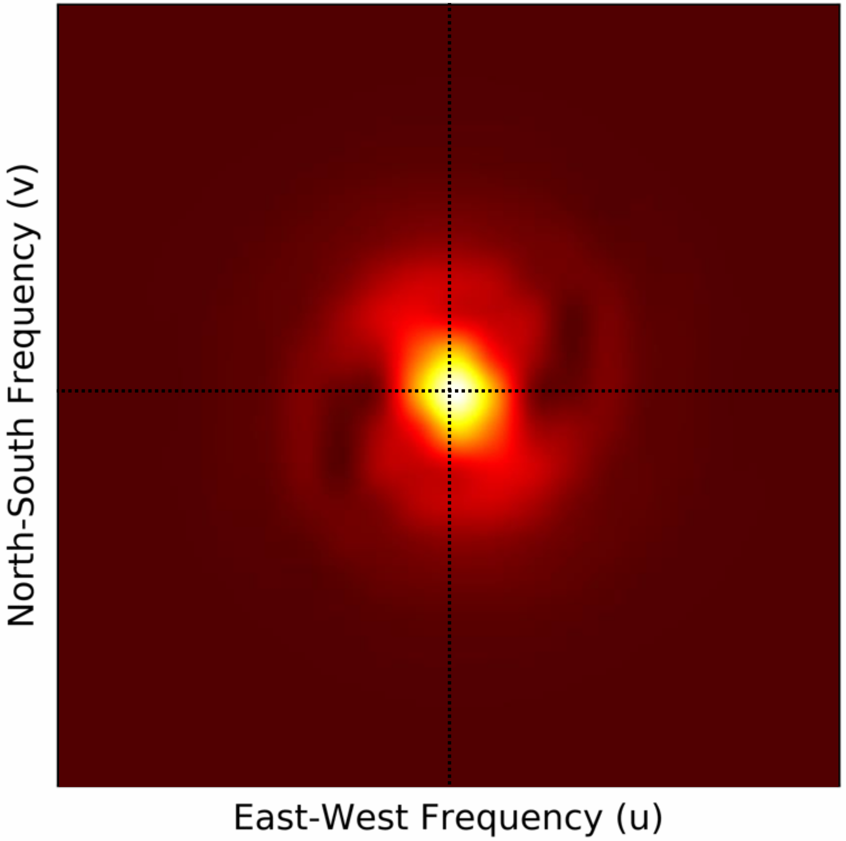
Very Long Baseline Interferometry (VLBI)

Black Hole Image

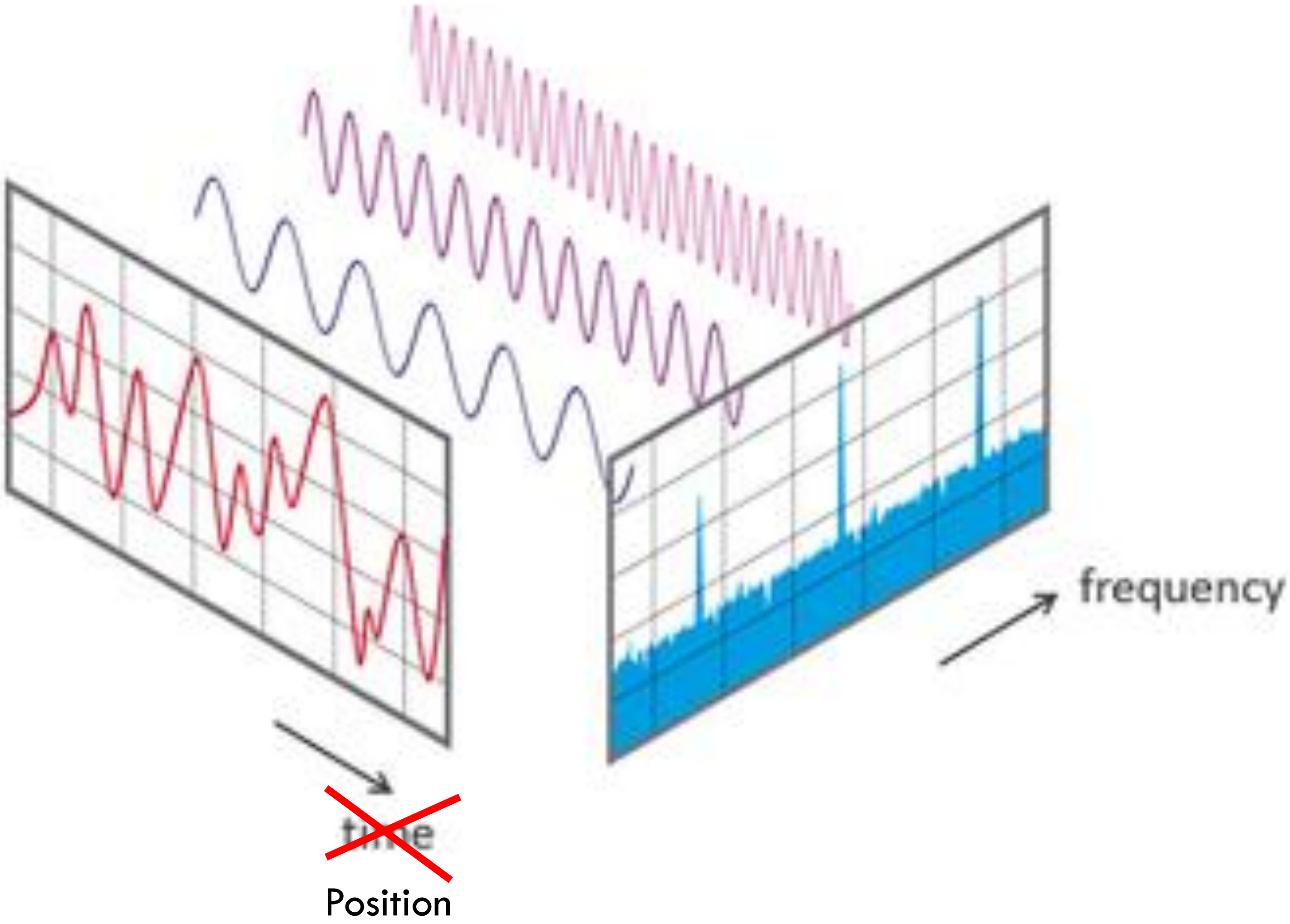


Fourier Transform

Frequency Measurements

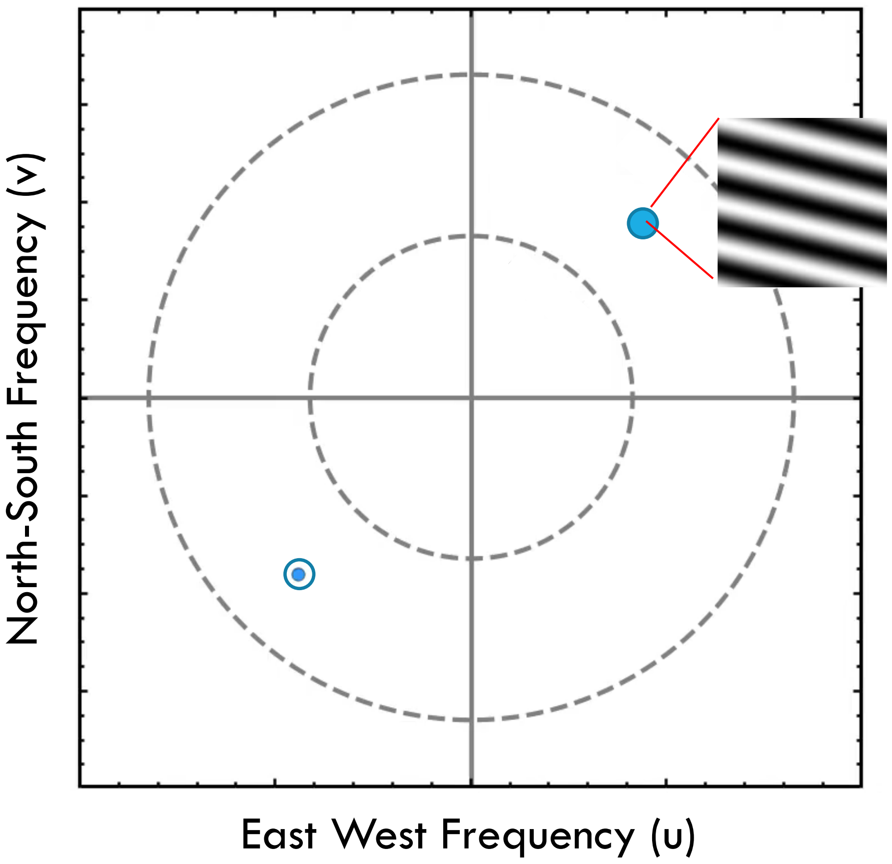


Fourier Transform

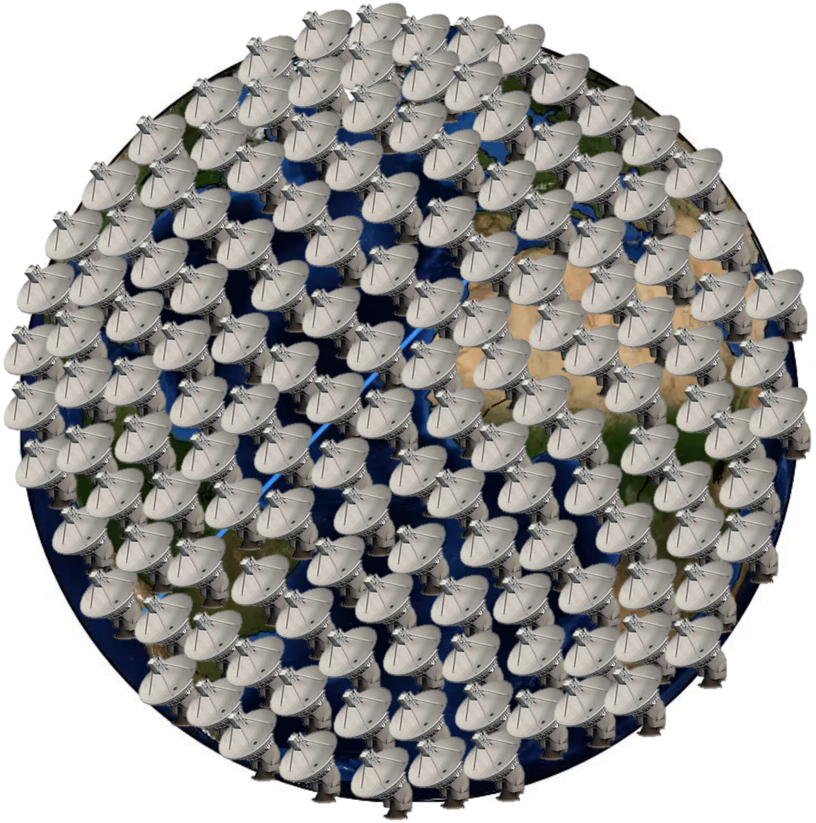


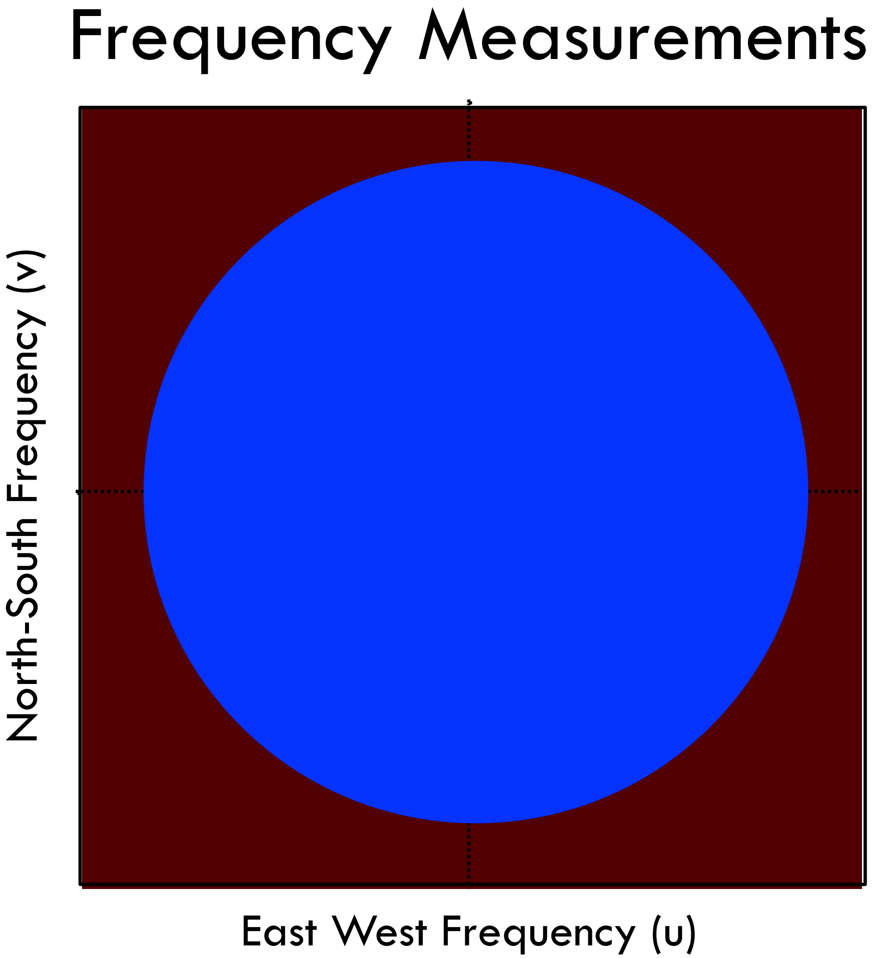
Very Long Baseline Interferometry (VLBI)

Frequency Measurements

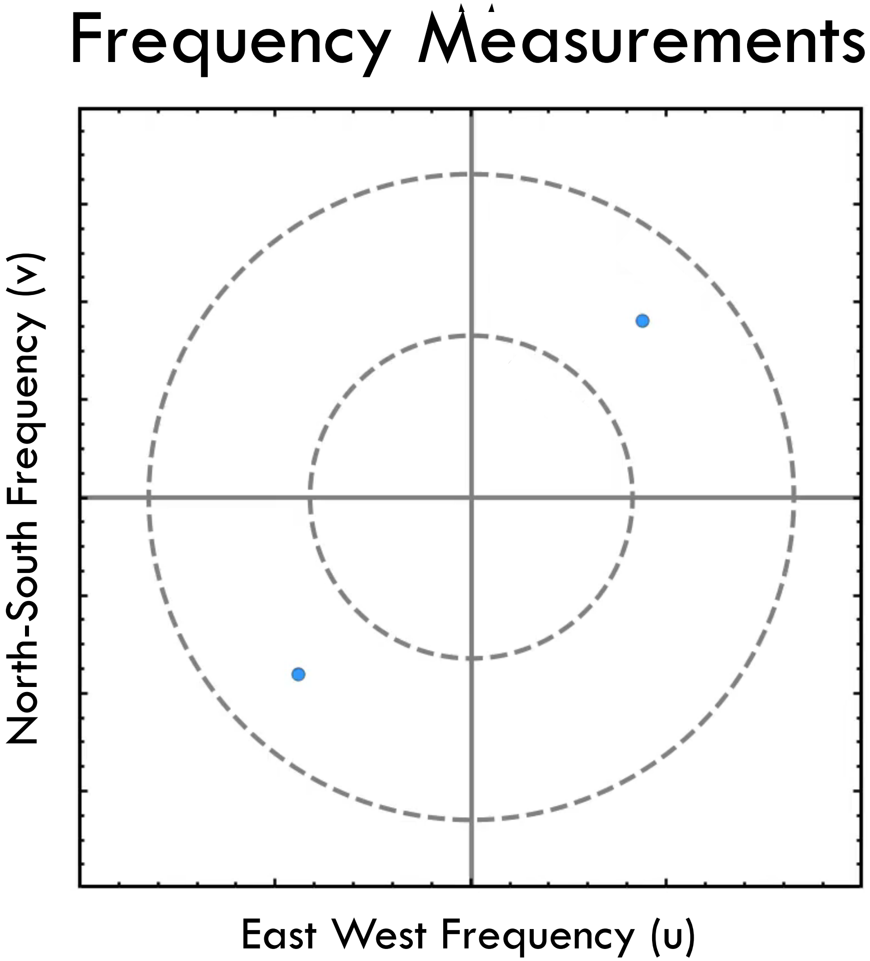


Very Long Baseline Interferometry (VLBI)





Earth’s Rotation gives us more measurements



EHT 2017

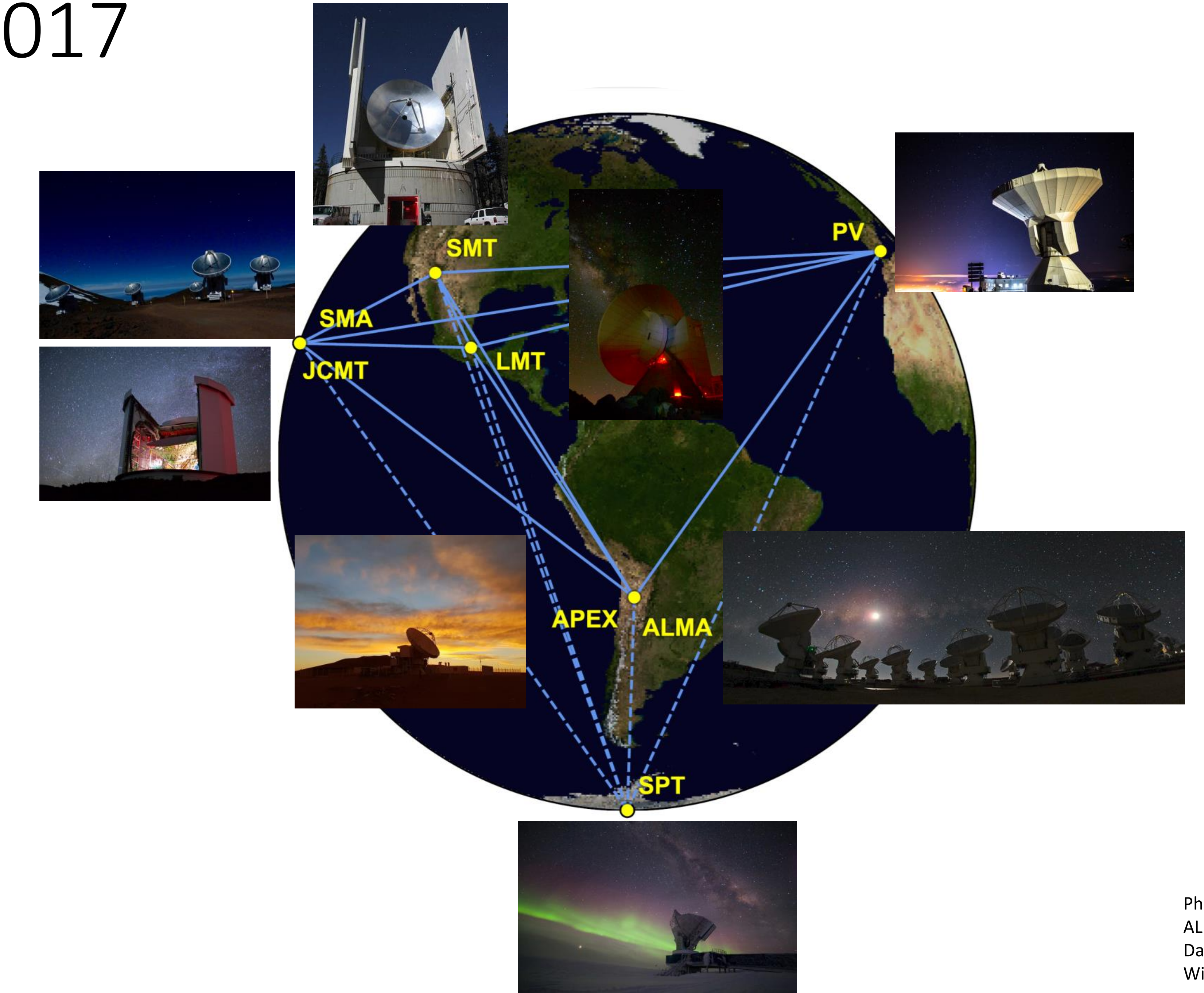
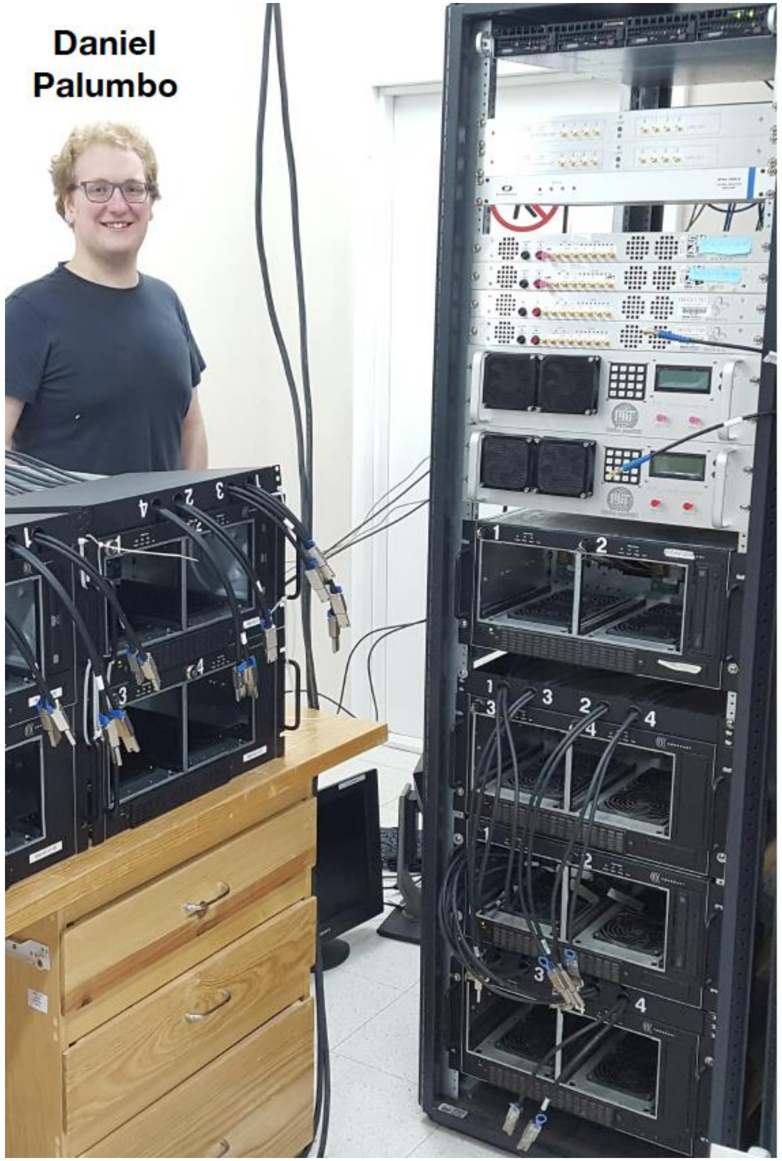
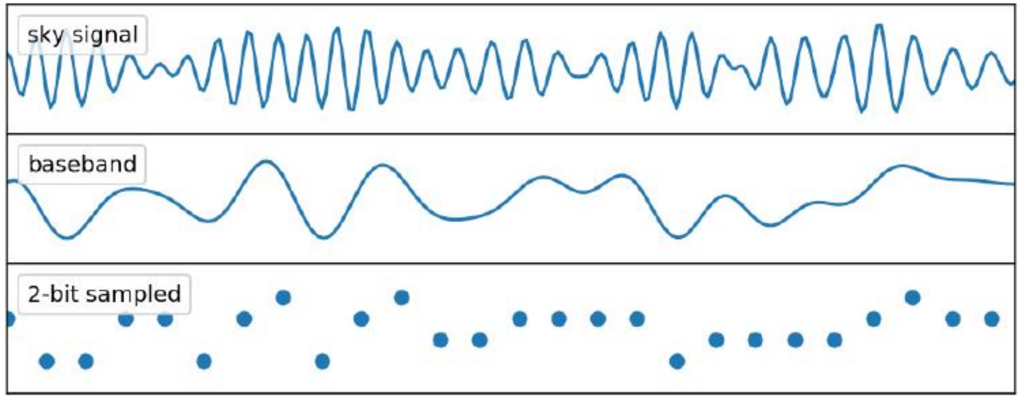
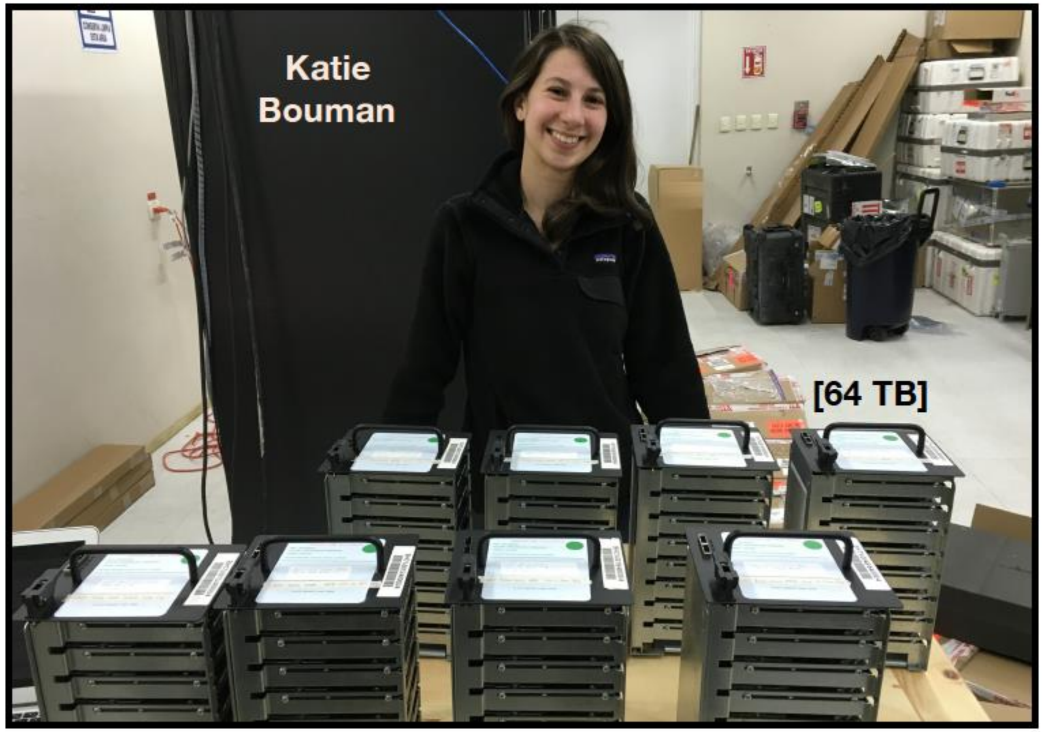


Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

EHT Instrumentation – records data at 8 Gb/sec





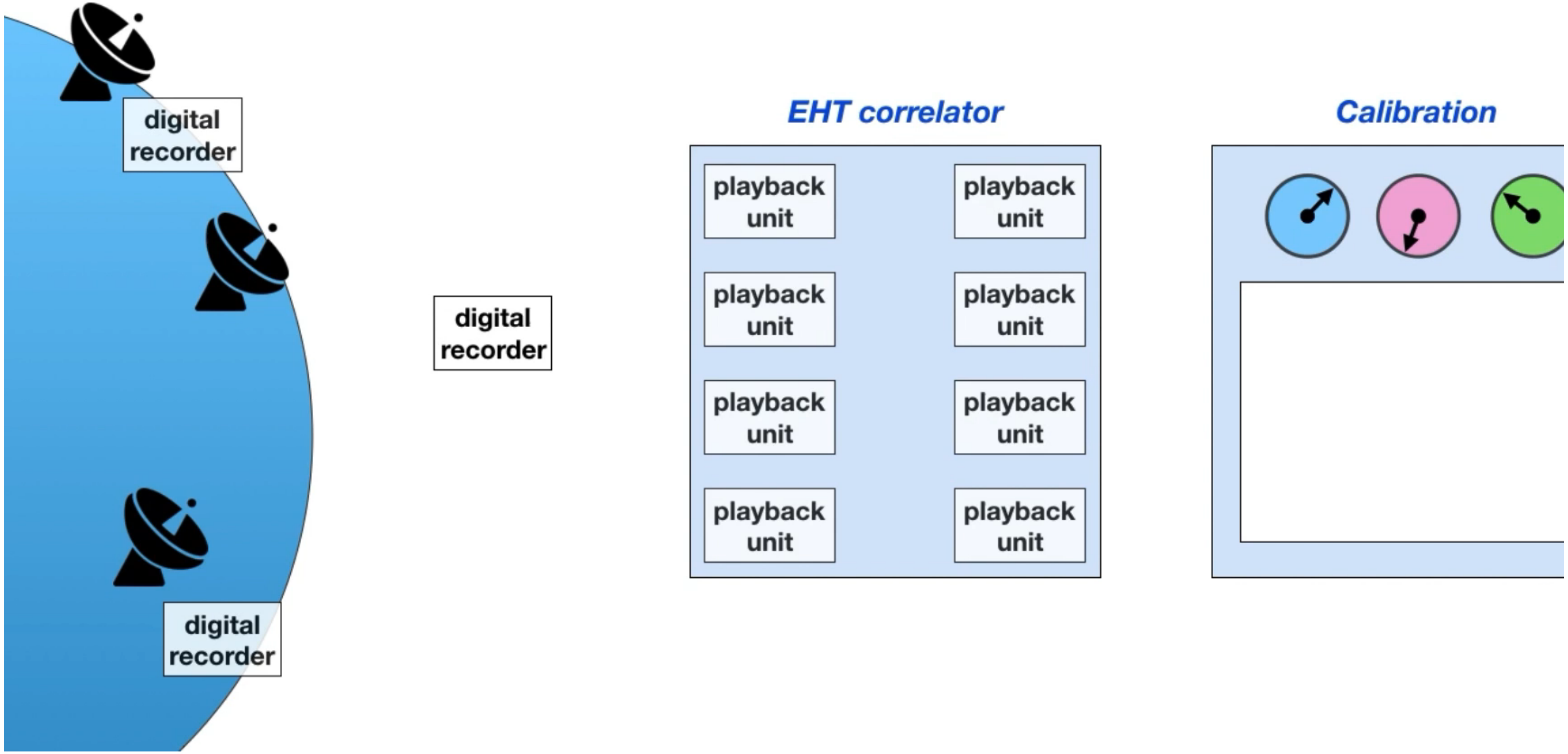


EHT 2017 Teams

Observation run day three

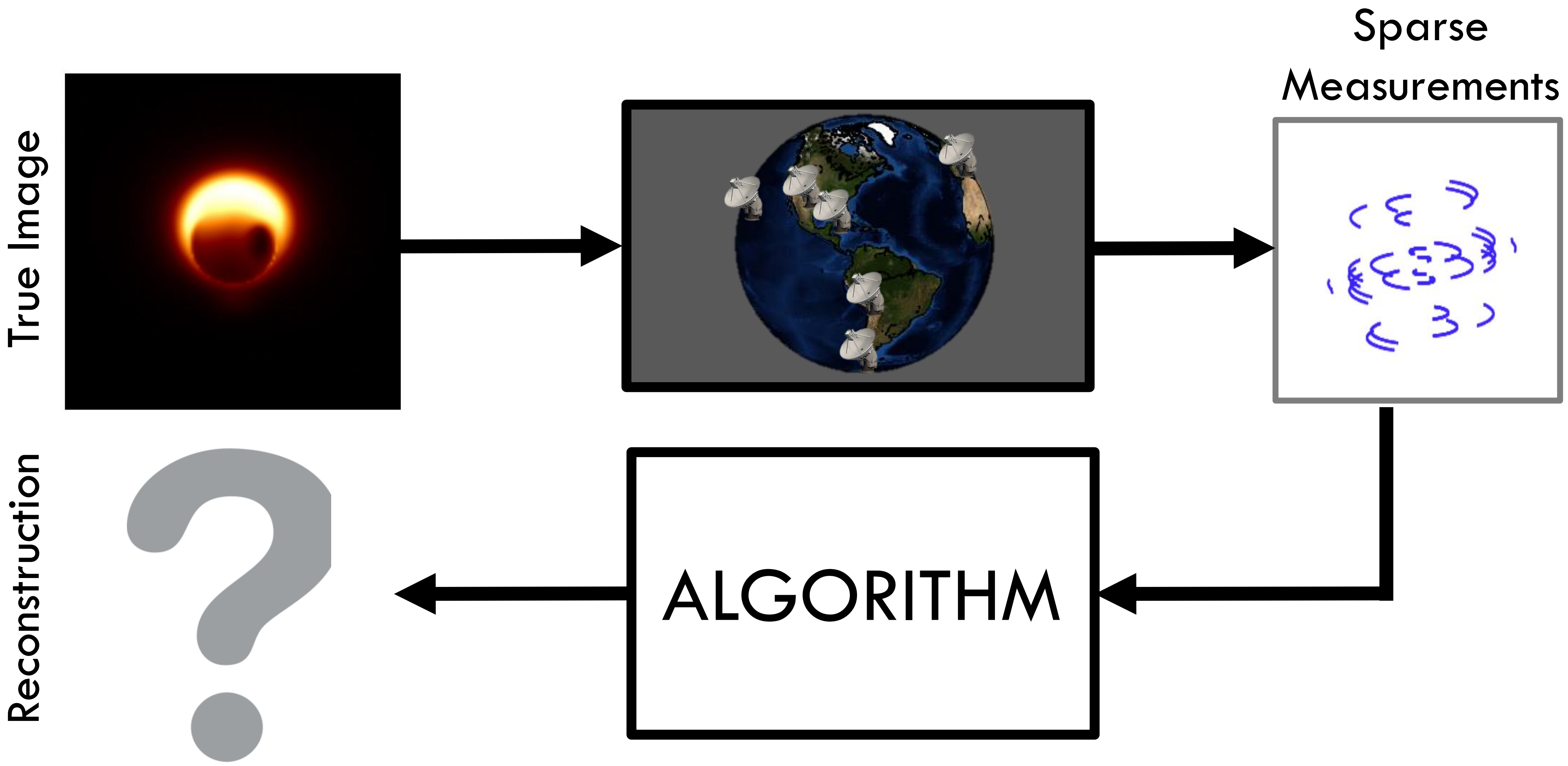
Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

The EHT data pipeline



Animation credit: Lindy Blackburn

Solving for the Image



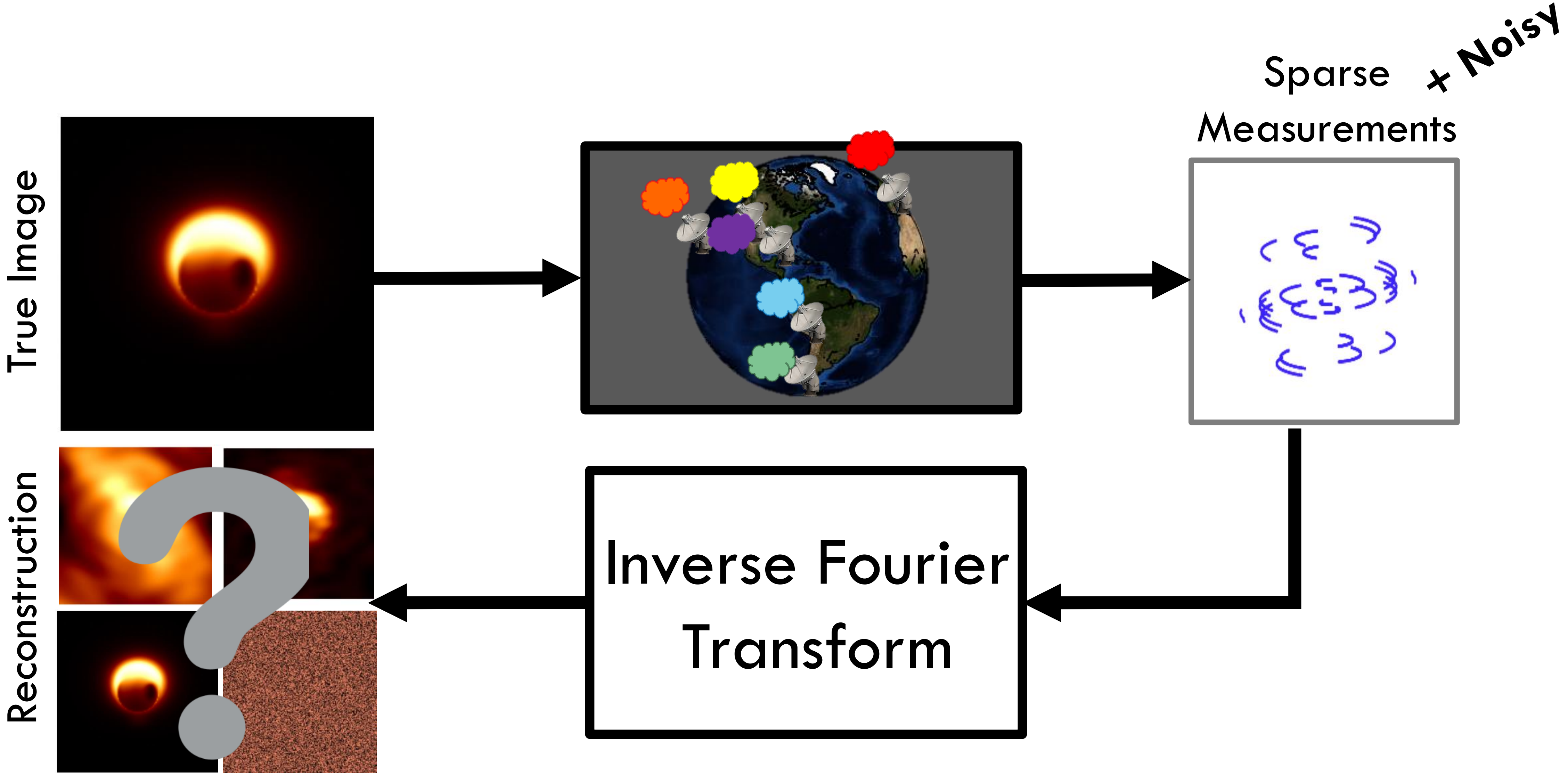
True Image

Sparse Measurements

ALGORITHM

Reconstruction

Solving for the Image



True Image

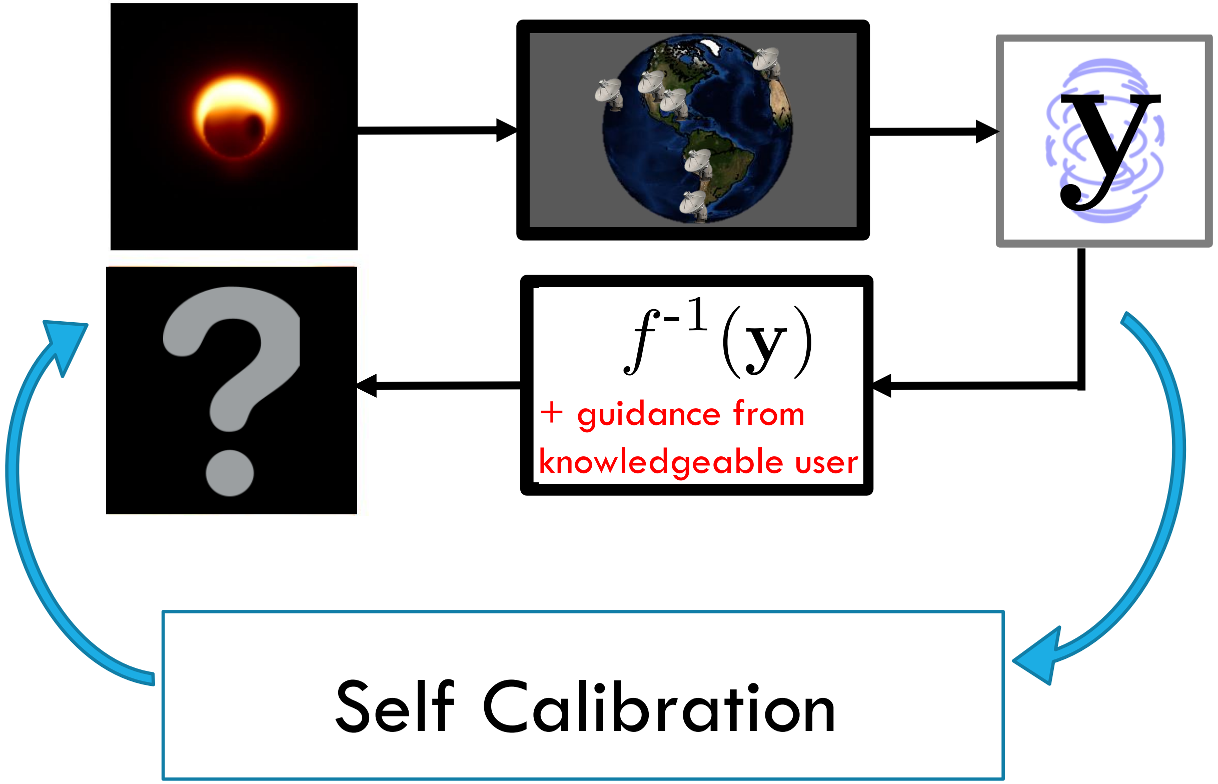
Sparse Measurements

+ Noisy

Inverse Fourier Transform

Reconstruction

Two Classes of Imaging Algorithms



$\mathbf{y}$

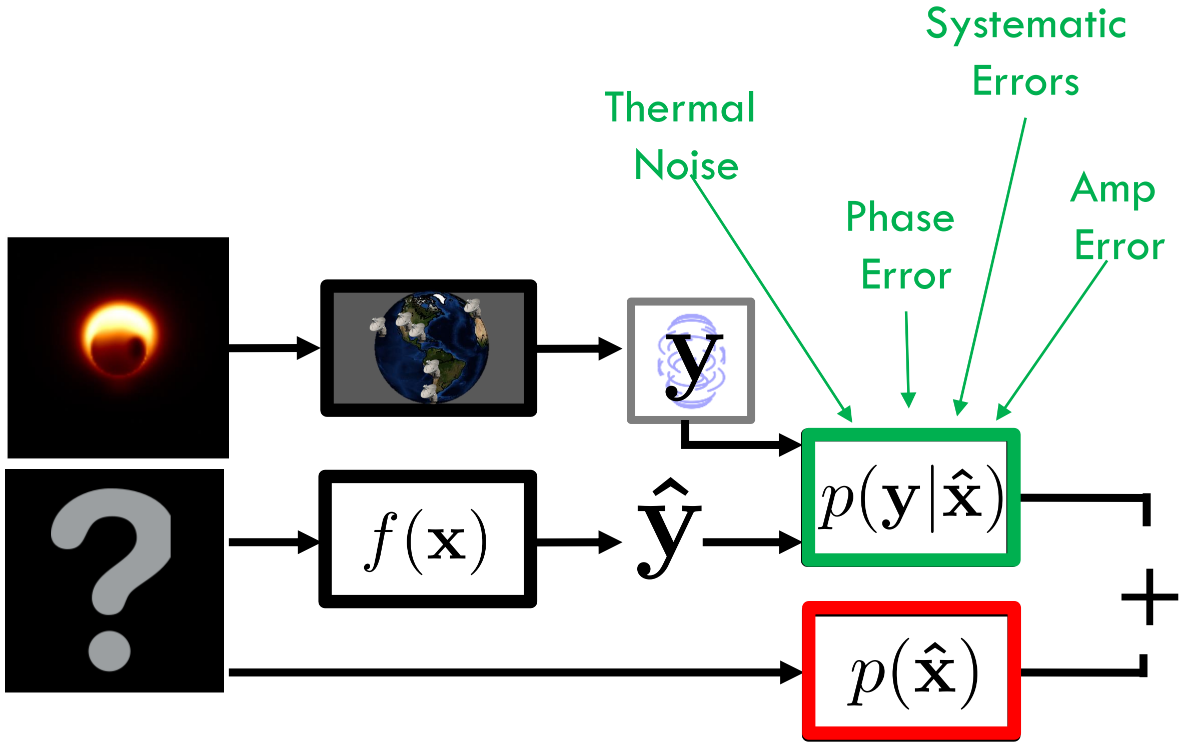
$f^{-1}(\mathbf{y})$

+ guidance from knowledgeable user

Self Calibration

Standard Inverse Modeling

(CLEAN + Self-Calibration)



Systematic Errors

Thermal Noise

Phase Error

Amp Error

$\mathbf{y}$

$p(\mathbf{y}|\hat{\mathbf{x}})$

$f(\mathbf{x})$

$\hat{\mathbf{y}}$

$+$

$p(\hat{\mathbf{x}})$

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

Forward Modeling

(Regularized Maximum Likelihood)

How do we verify what we are reconstructing is real?

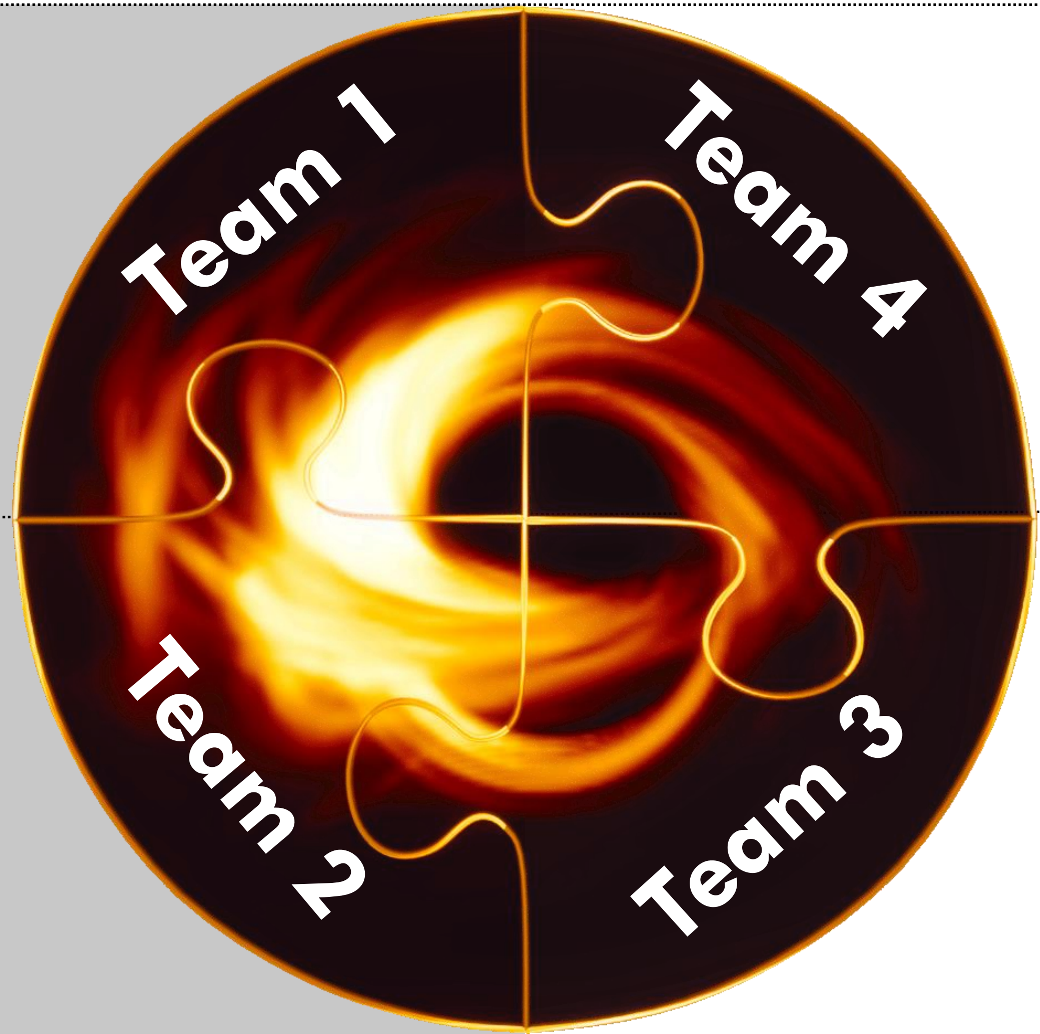
Step 1: Blind Imaging

The Americas

Harvard-Smithsonian
University of Arizona
U. Concepcion

Global

MIT Haystack
Radboud University
NAOJ



East Asia

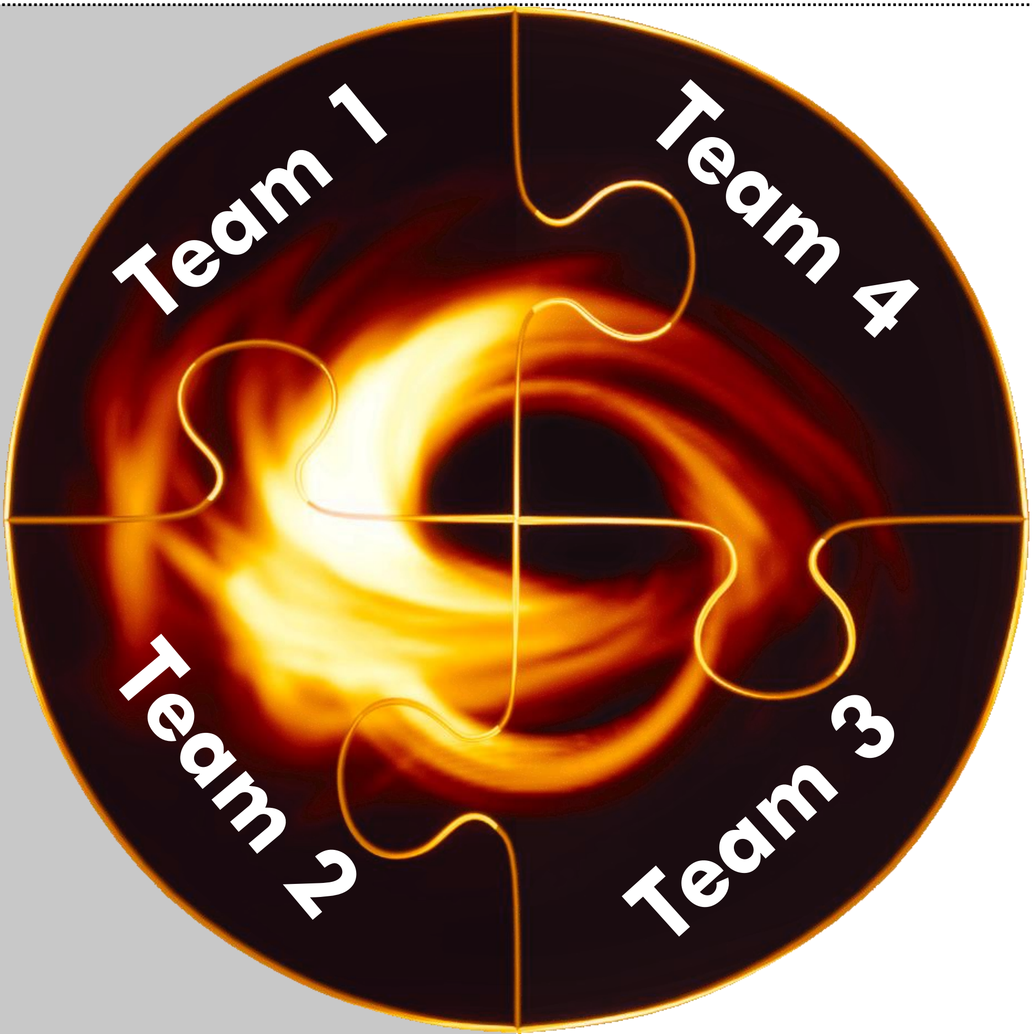
ASIAA
KASI
NAOJ

Cross-Atlantic

MPIfR
Boston University
IAA
Aalto

Step 1: Blind Imaging

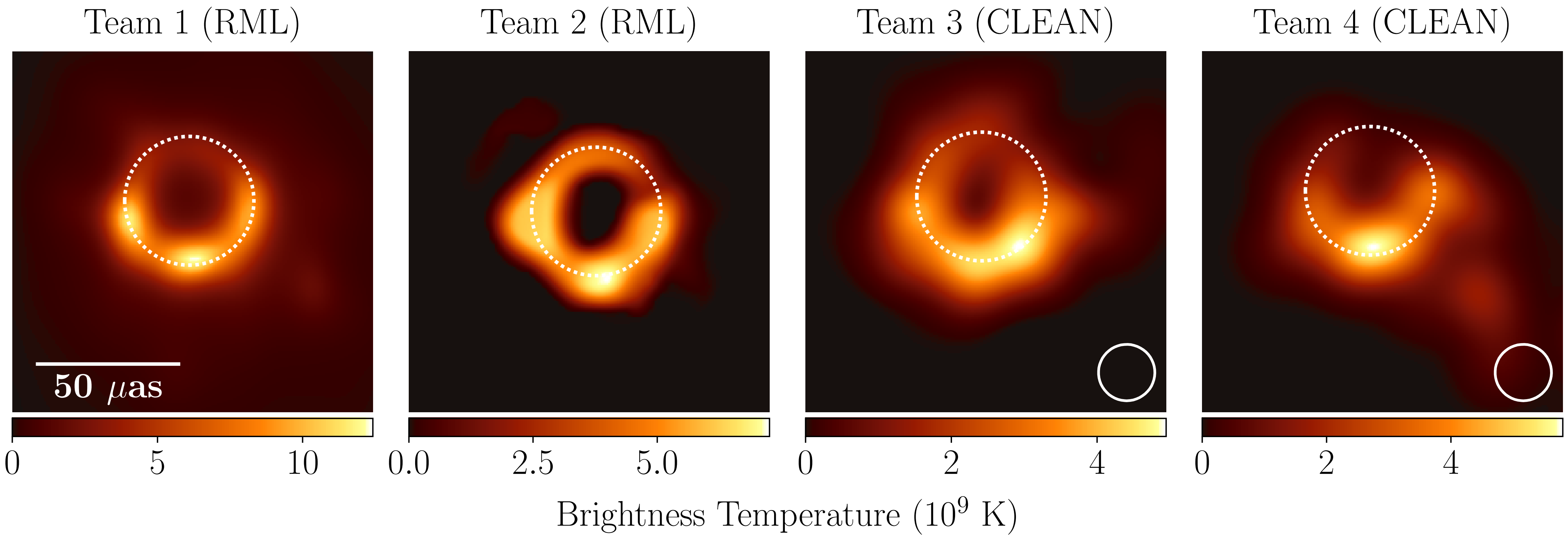
Regularized
Maximum
Likelihood

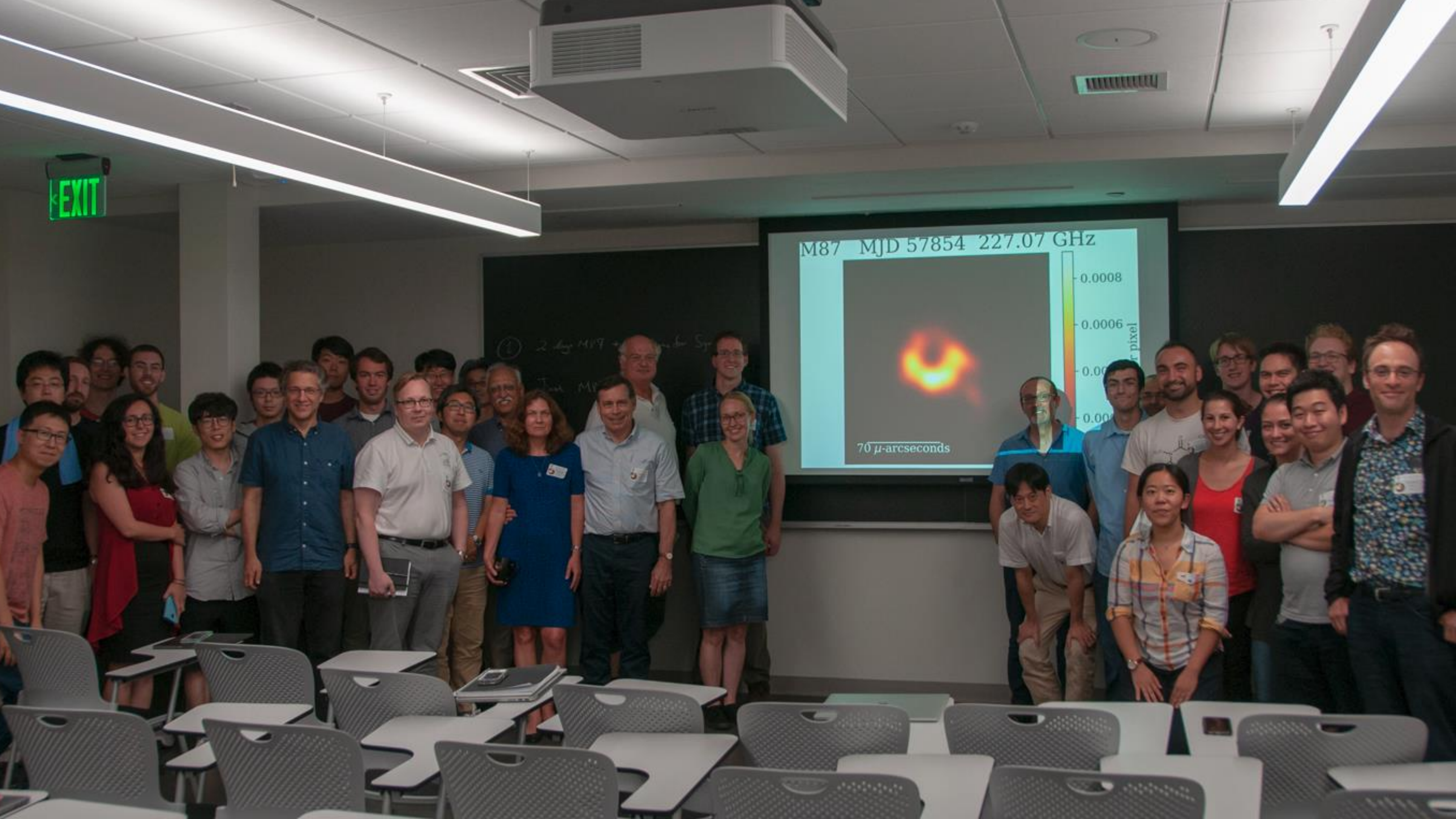


CLEAN
+
Self Calibration

7 weeks later…

Step 1: Blind Imaging




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

Step 2: Objectively Choosing Parameters

A big part of my thesis ☺

DIFMAP
(CLEAN + Self Calibration)

Compact Flux
Stop Condition
Weighting on ALMA
Mask Size
Data Weights

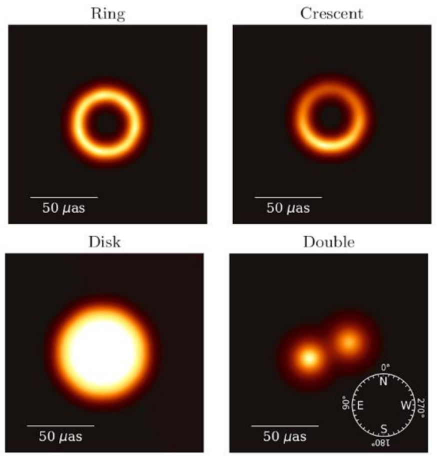
eht-imaging
(Regularized Max Likelihood)

Compact Flux
Initial Gaussian Size
Systematic Error
Regularizes
- MEM
- TV
- TSV
- L1

SMILI
(Regularized Max Likelihood)

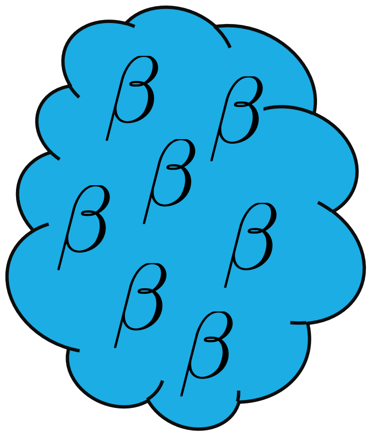
Compact Flux
L1 Soft Mask Size
Systematic Error
Regularizes
- TV
- TSV
- L1

Test 30,000+ parameter sets

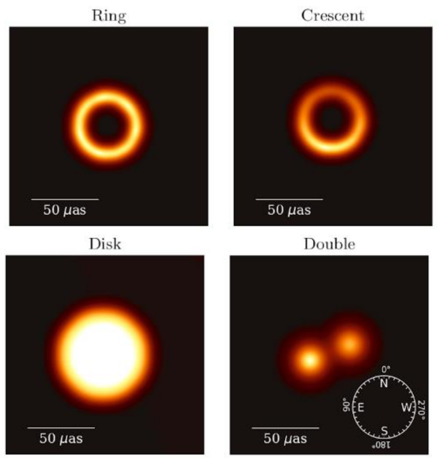


SYNTHETIC DATA GENERATION

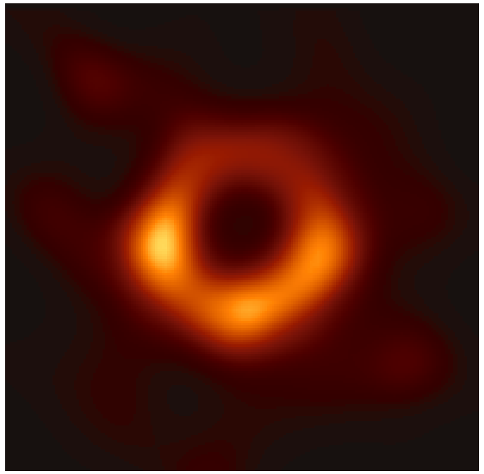
Fake Data



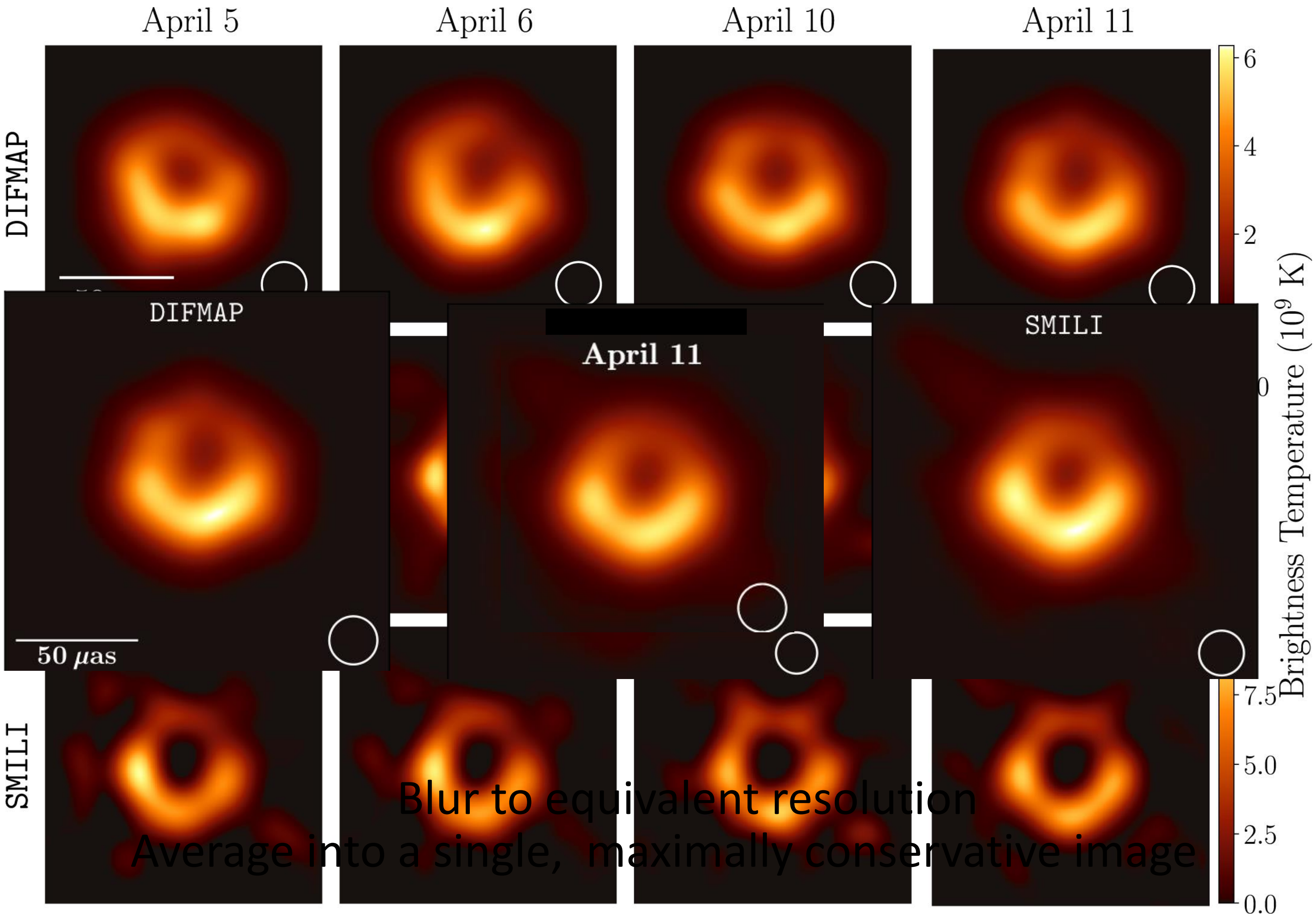
IMAGING METHOD



M87 Data



Three pipelines, four days

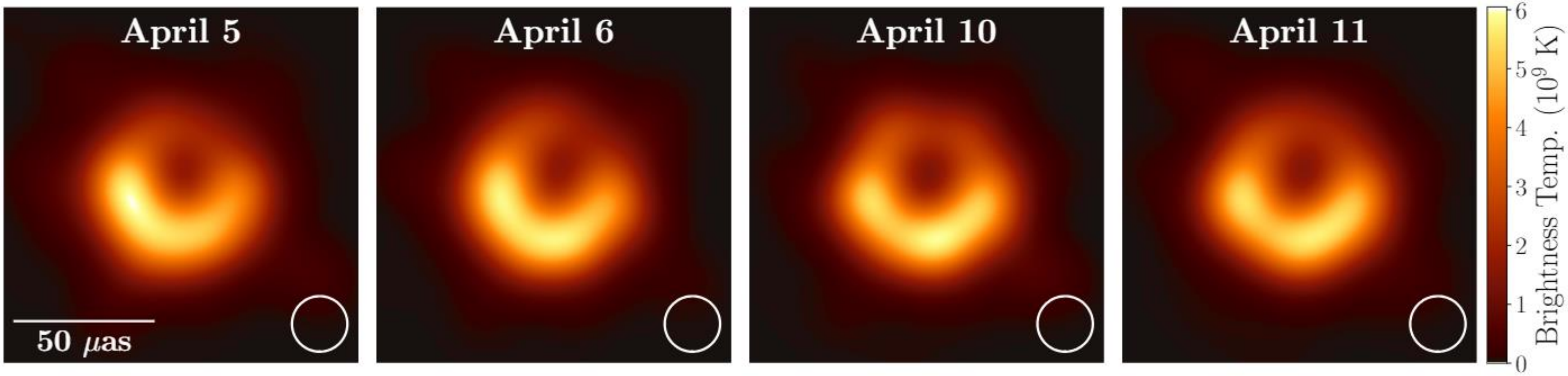


Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

The Averaged Image From Each Day

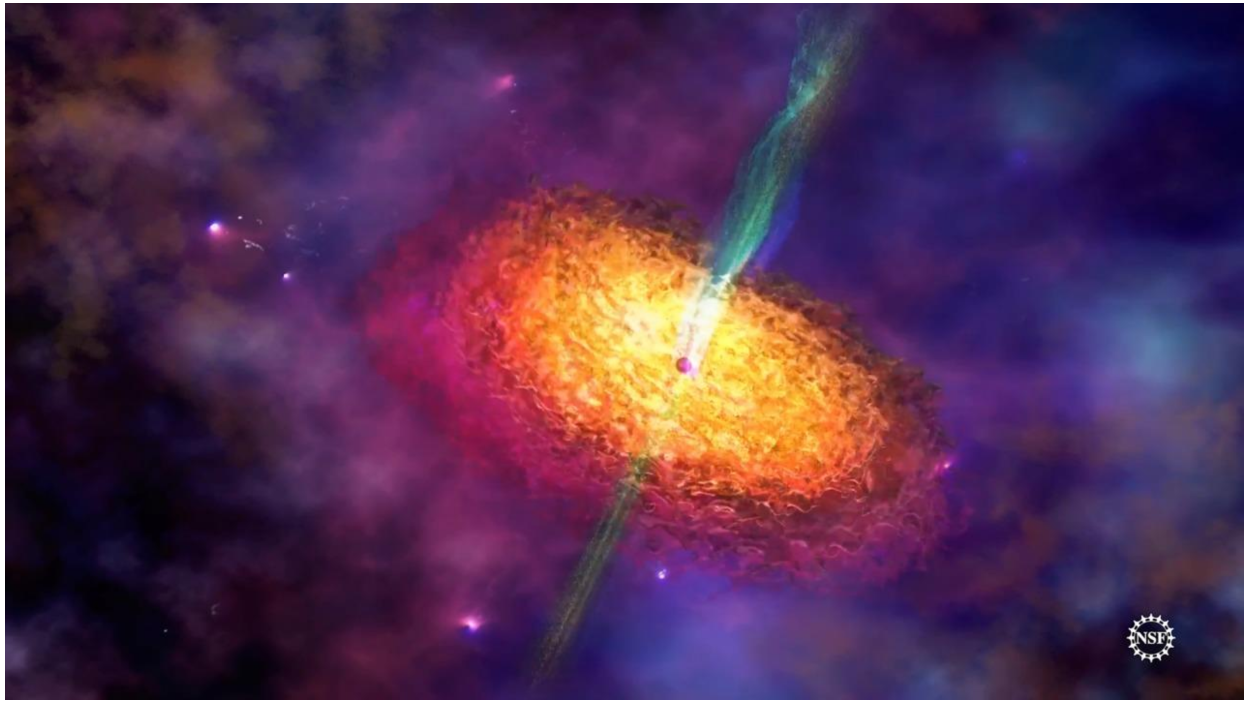


Consistent structure from night-to-night, but hints of evolution?

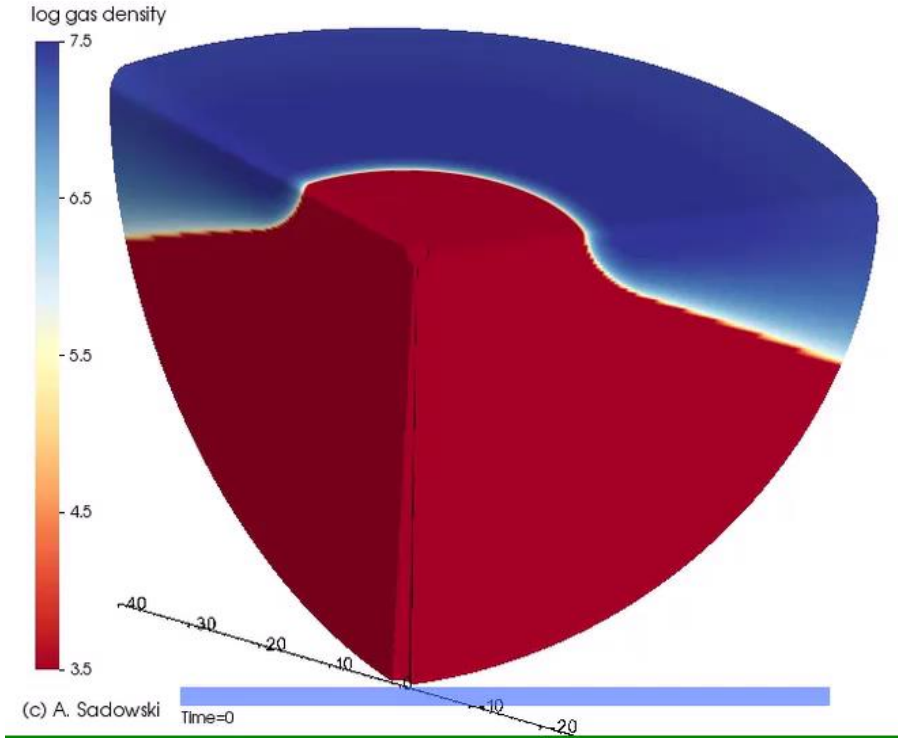
What does this image tell us?

M87’s physical environment – what can we learn?

- 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

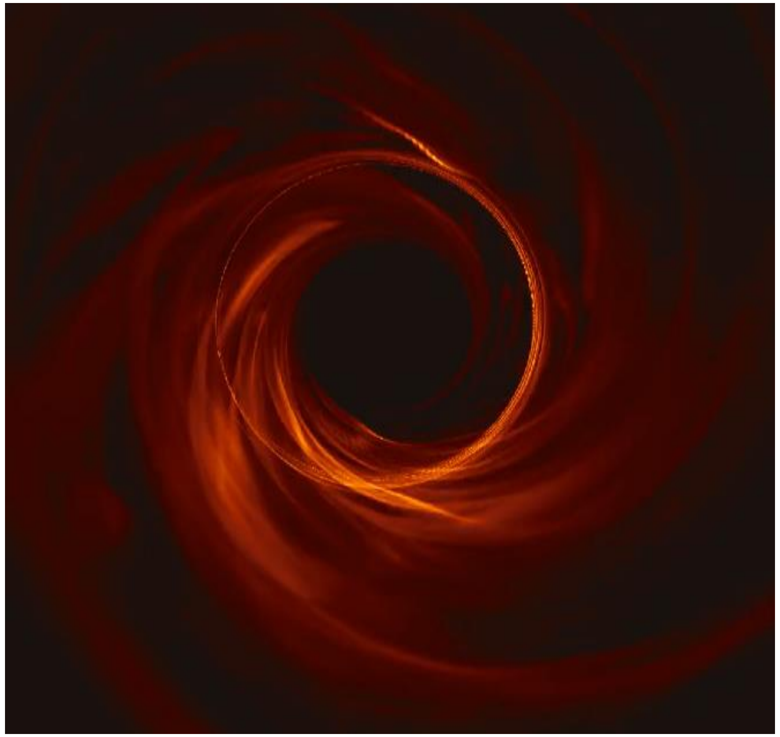


Solves coupled equations of fluid dynamics and magnetic field in a black hole spacetime

Another big part of my thesis ☺

T_e?

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



Tracks light rays and solves for the emitted radiation

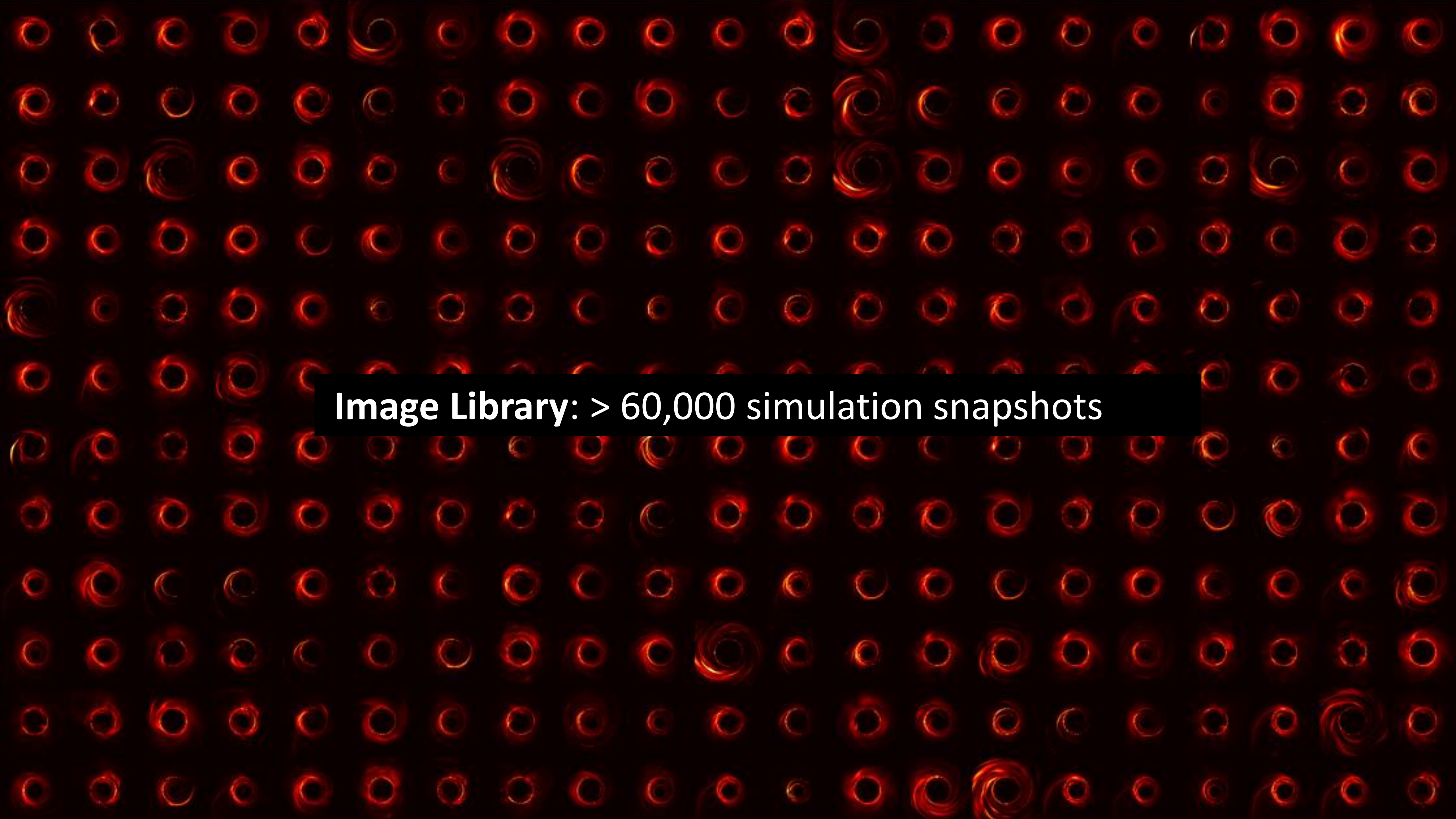
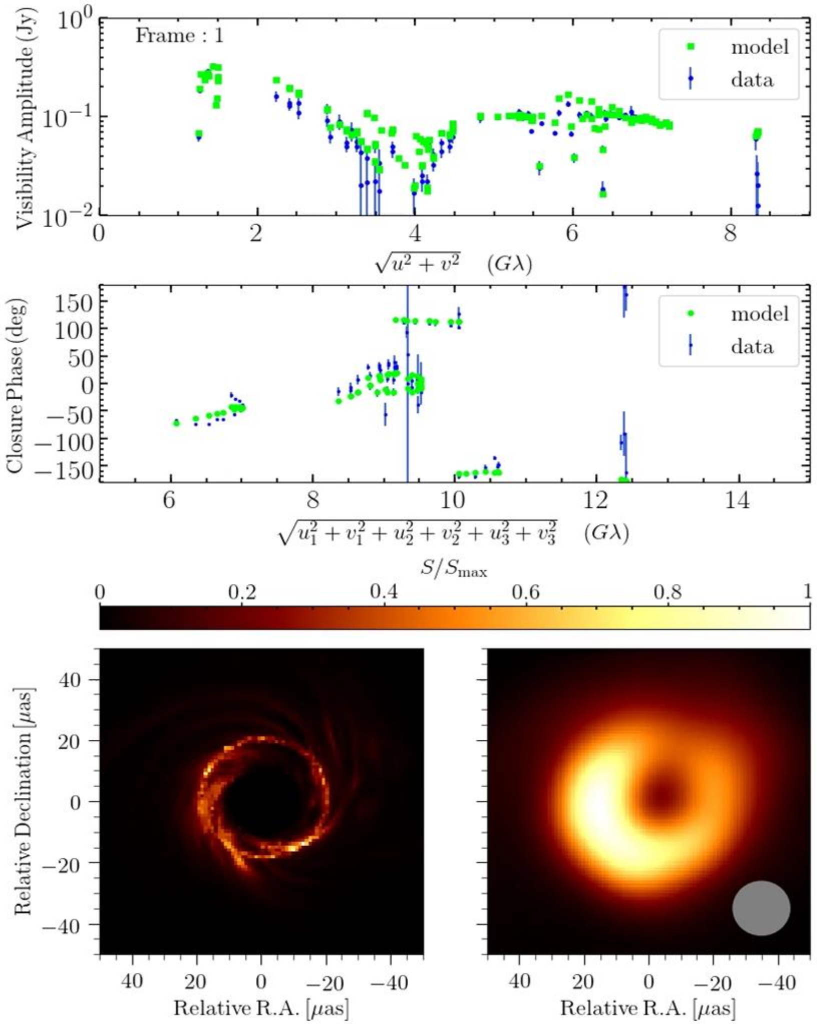


Image Library: > 60,000 simulation snapshots

Fitting Simulations to EHT observations

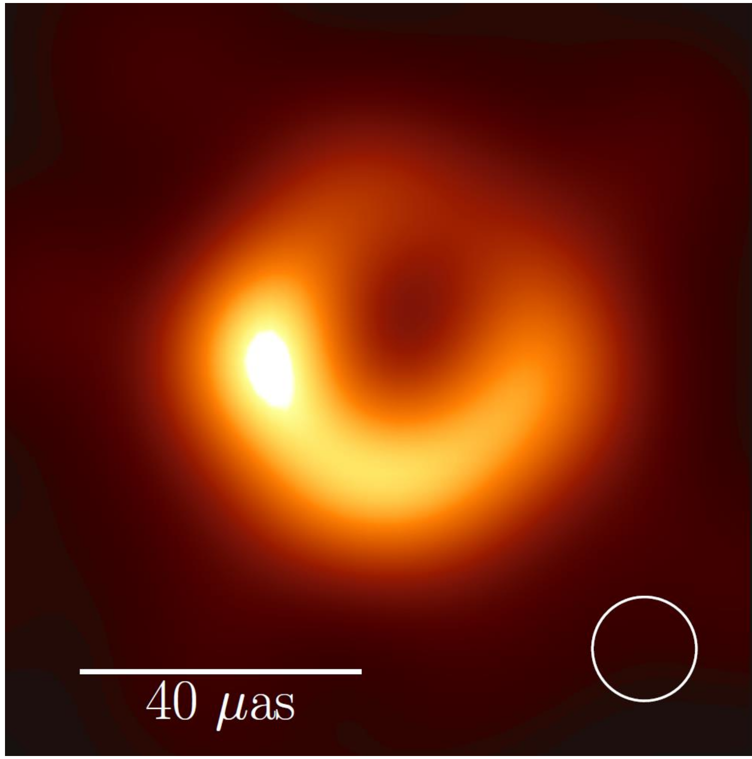


- Since each simulation runs for only a limited time, no single frame is likely to exactly match the observations

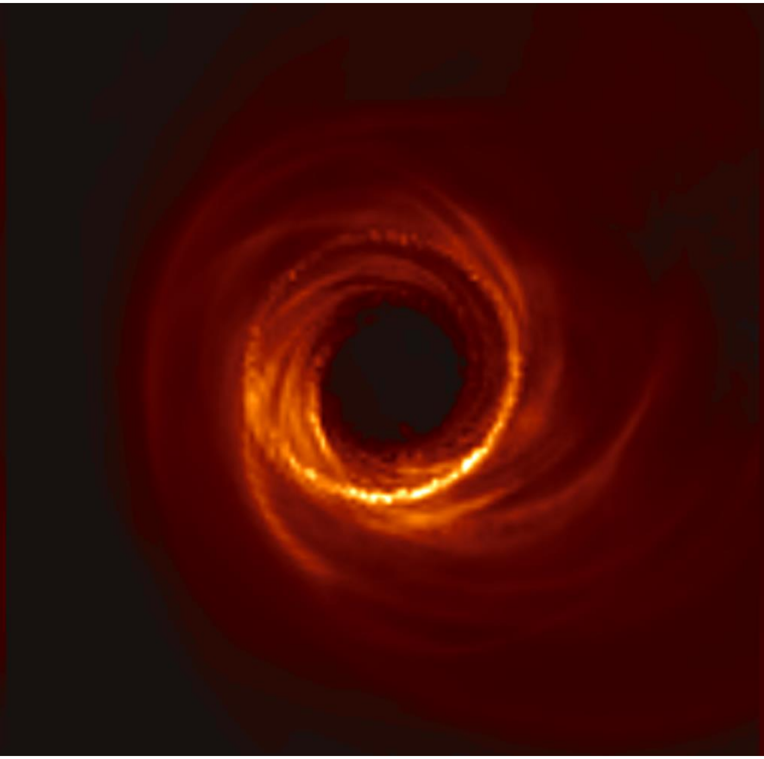
- **Average Image Scoring:** how likely is it that the data might come from the underlying simulation if it ran forever?

Matching Simulations and Images

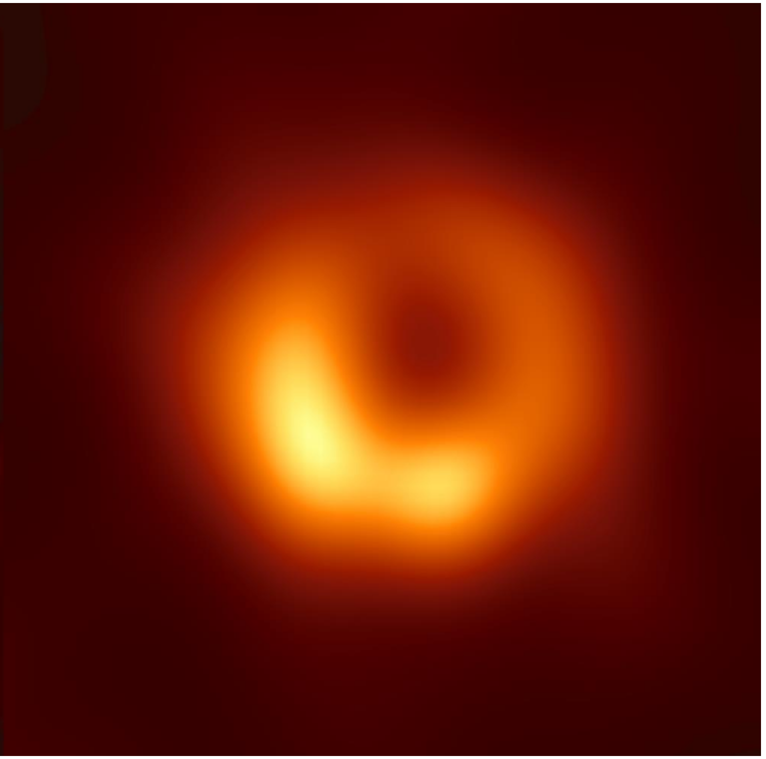
EHT 2017 image



Simulated image
from (my) GRMHD model



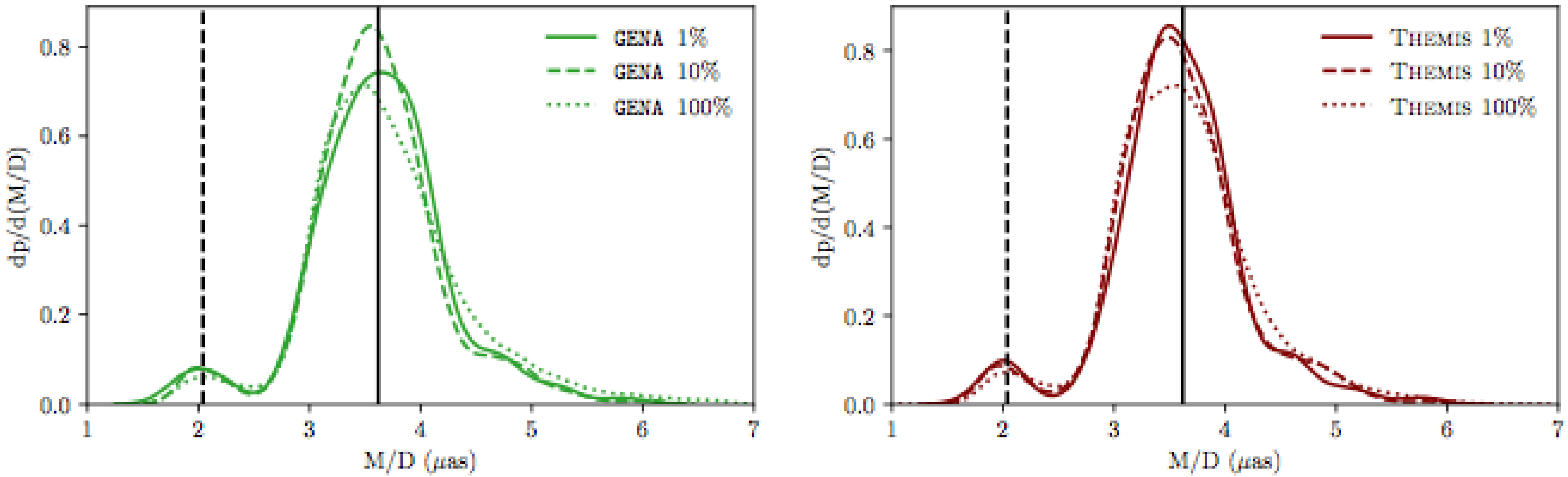
Simulated image reconstructed
with EHT pipeline



Simulation fitting results

- AIS rejects only a few simulations! The EHT image is dominated by the shadow.

→The underlying spacetime determines the image, not the astrophysical details



Distribution of M/D (mass-to-distance-ratio) from fitting all simulations to 2017 April 6th EHT data

M87 Must produce jet power $\geq 10^{42}$ erg/sec

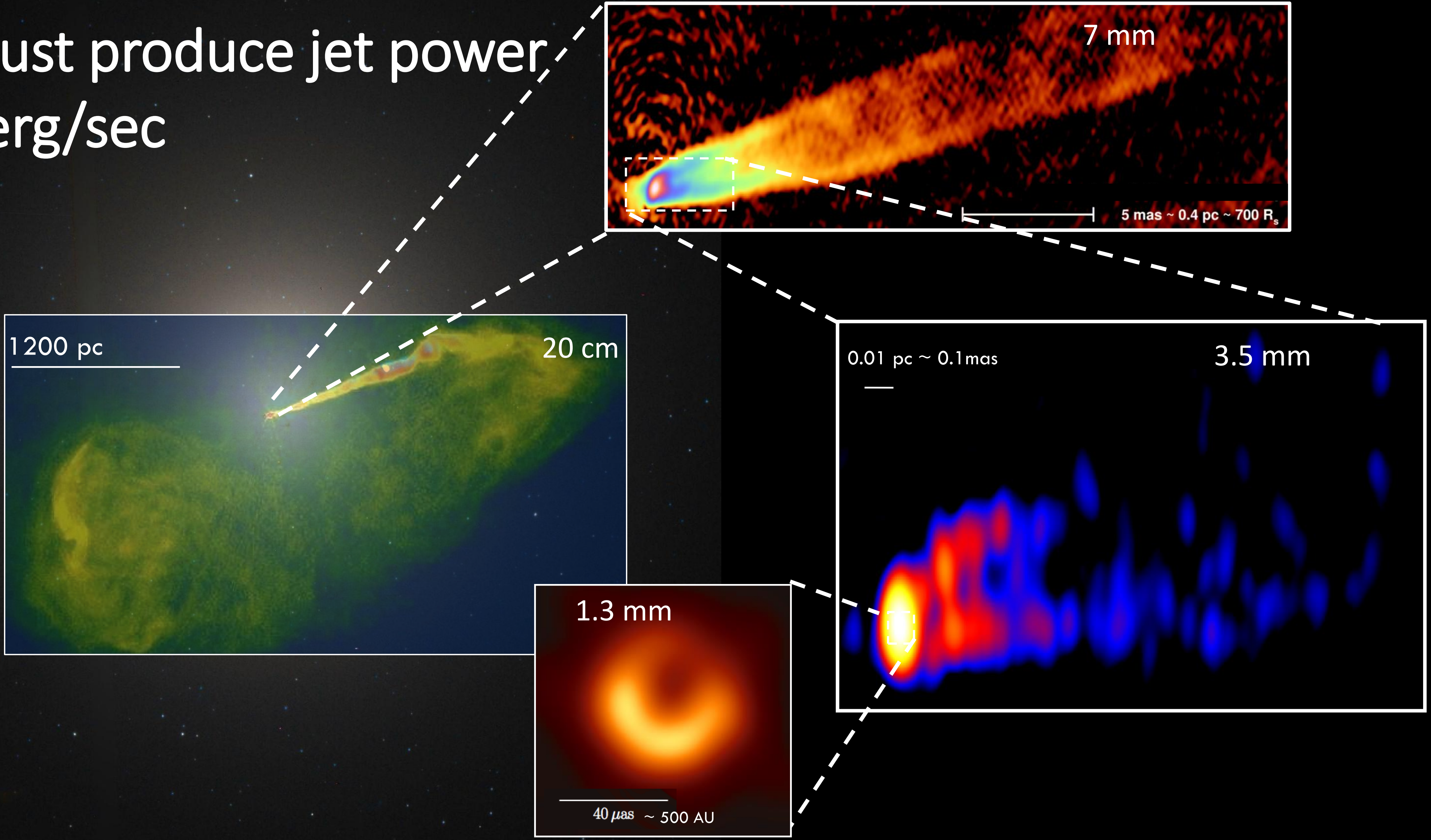


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

The Jet power constraint rejects **all** spin 0 models

- Low spin, low magnetic field models are rejected.
- Most high spin, high *B*-field models are acceptable.
- In all successful models, the jet is
  driven by extraction of the black hole spin energy

Blandford-Znajek (1977):

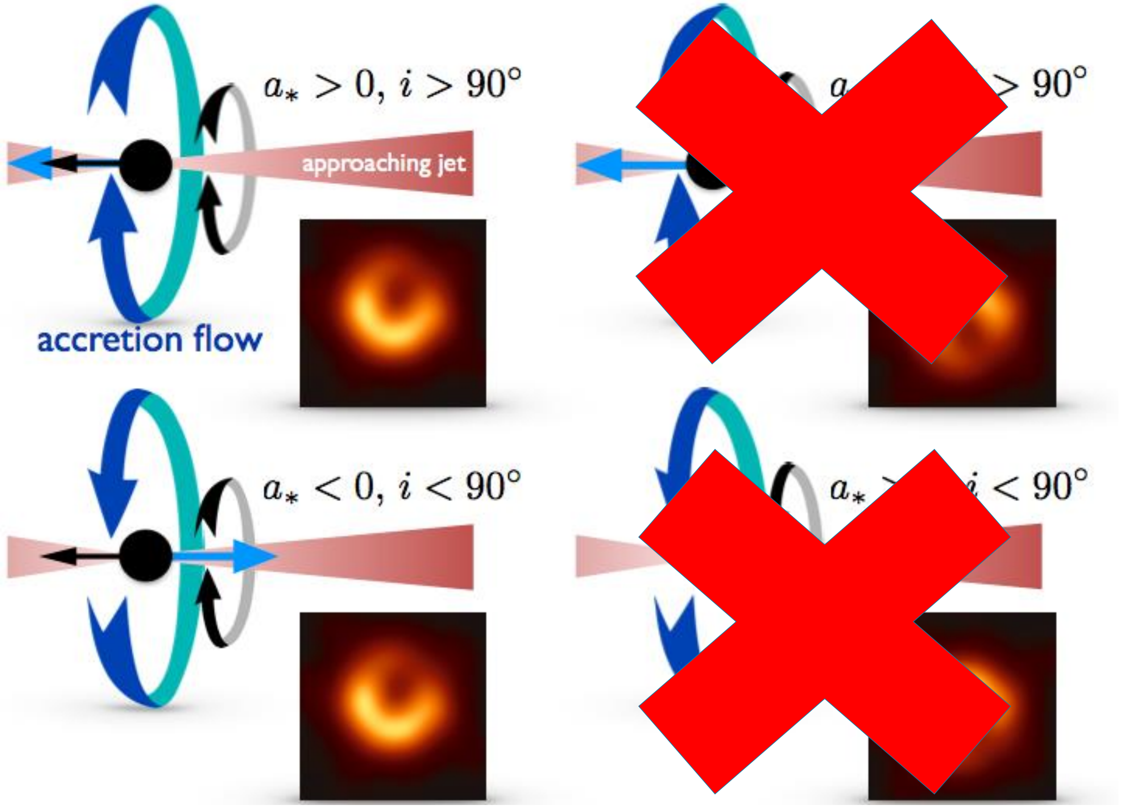
$$P_{\text{jet}} \propto \underset{\nearrow}{\Phi^2_{\text{mag}}}\,\underset{\uparrow}{\Omega^2_{\text{H}}}/c$$

Magnetic flux

Angular velocity
of the horizon

Ring Asymmetry and Black Hole Spin

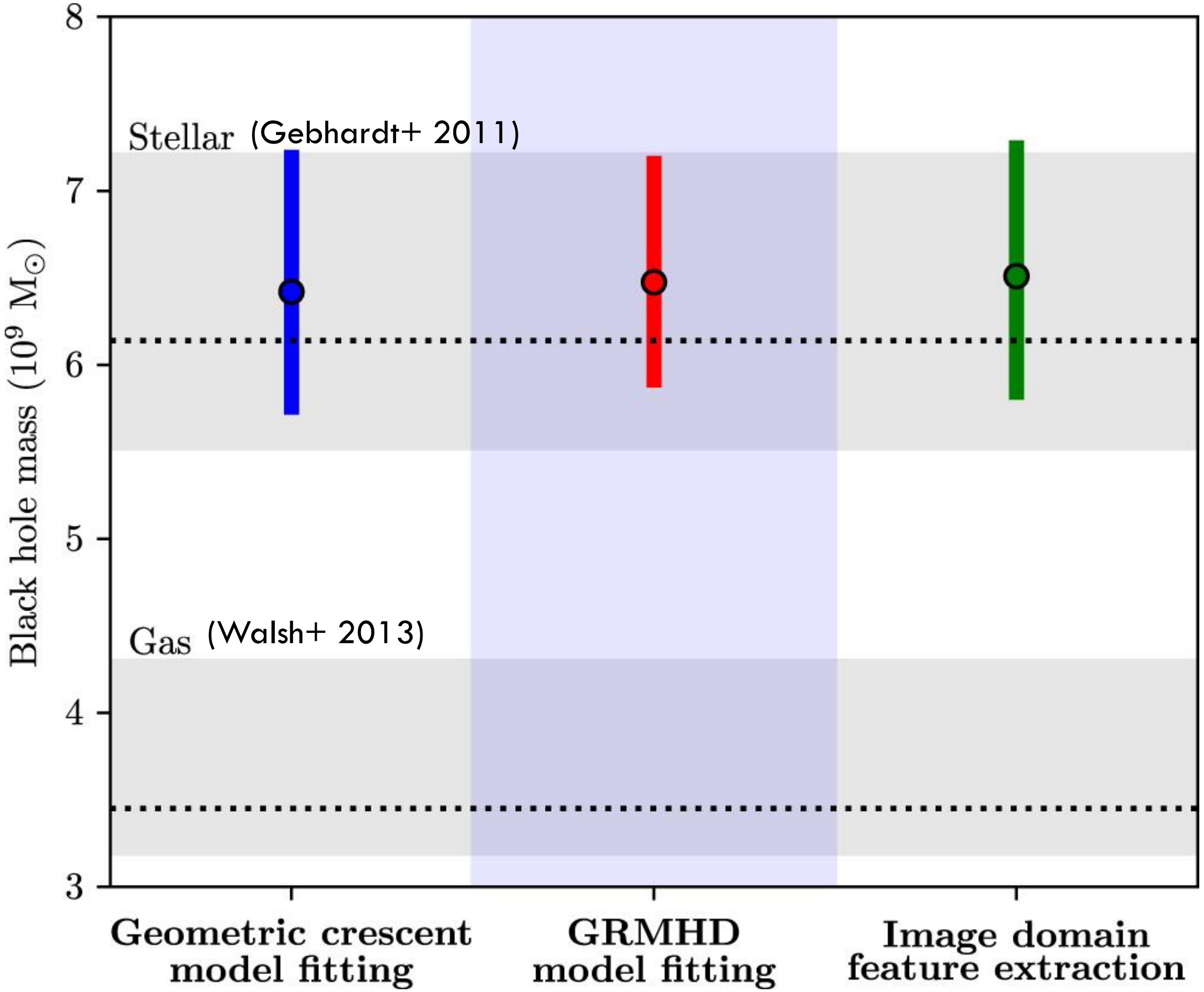
BH angular momentum determines the image orientation



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

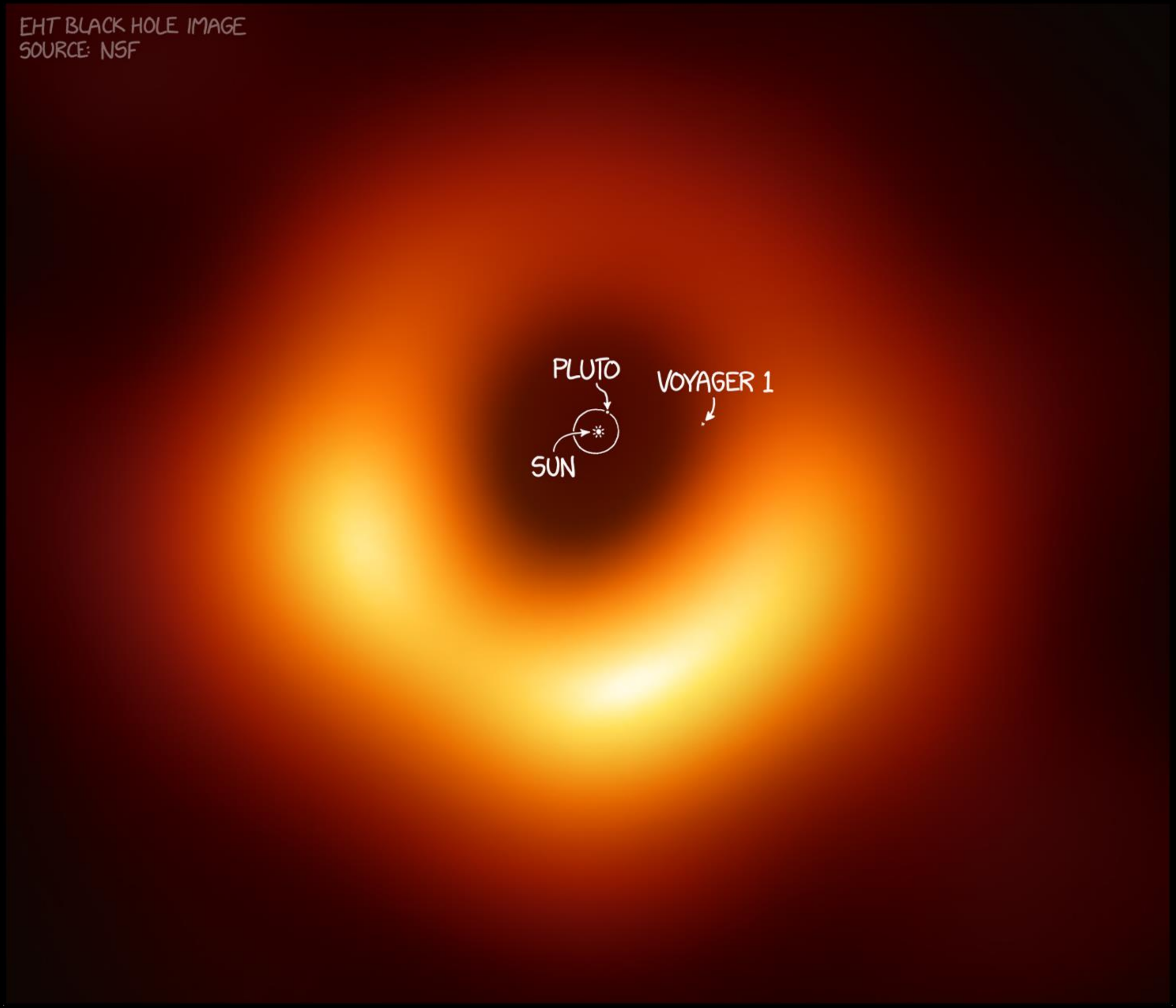
Directly weighing a black hole with $r_{\text{shadow}} = \sqrt{27}GM/c^2$

Mass Results from three independent methods



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

Image Credit:
EHT Collaboration 2019 (Paper VI)



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

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

Credit: R. Munroe

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 through 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 to reduce bias
- Simulations suggest that the M87 black hole is spinning counterclockwise 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

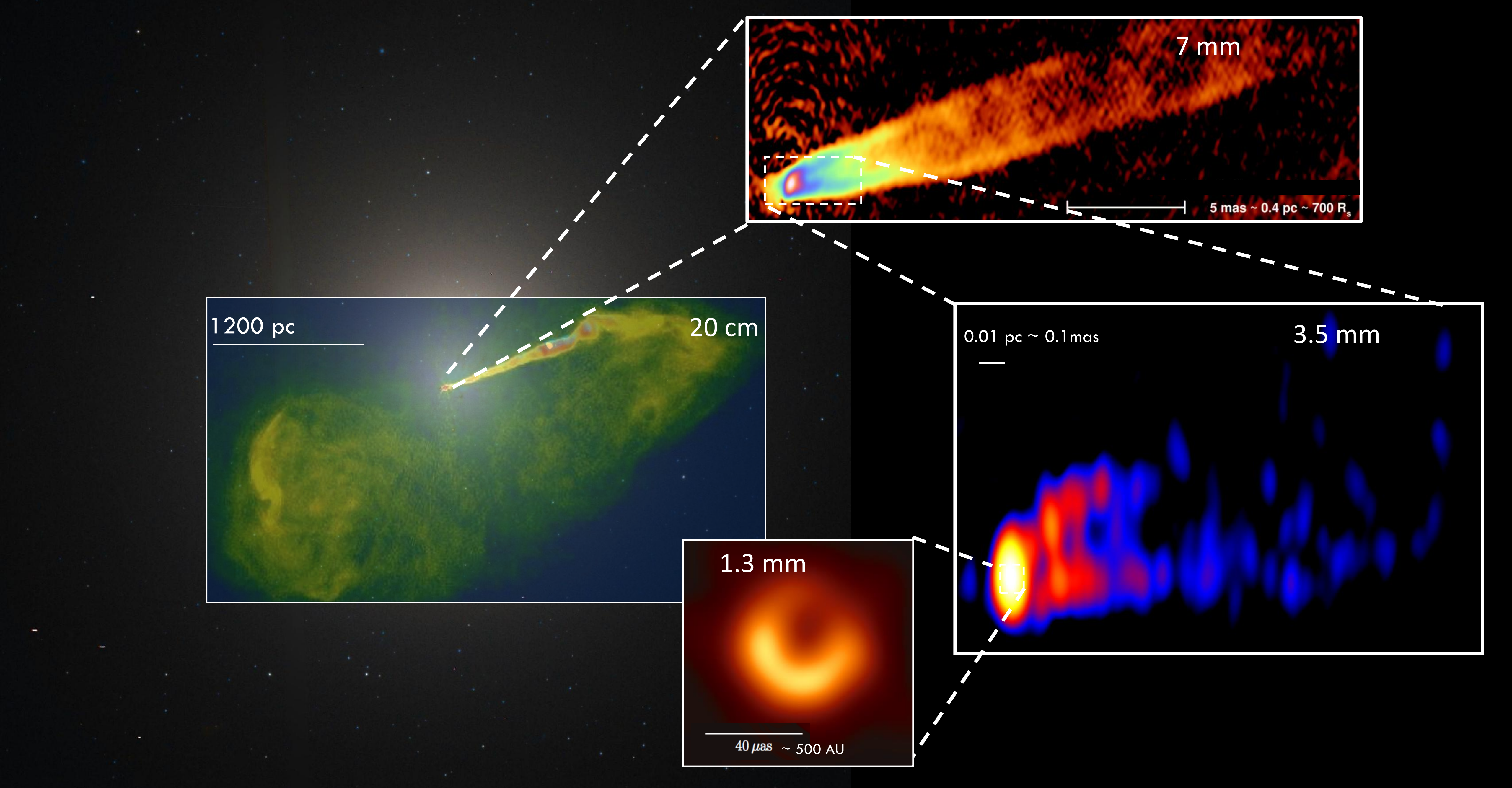
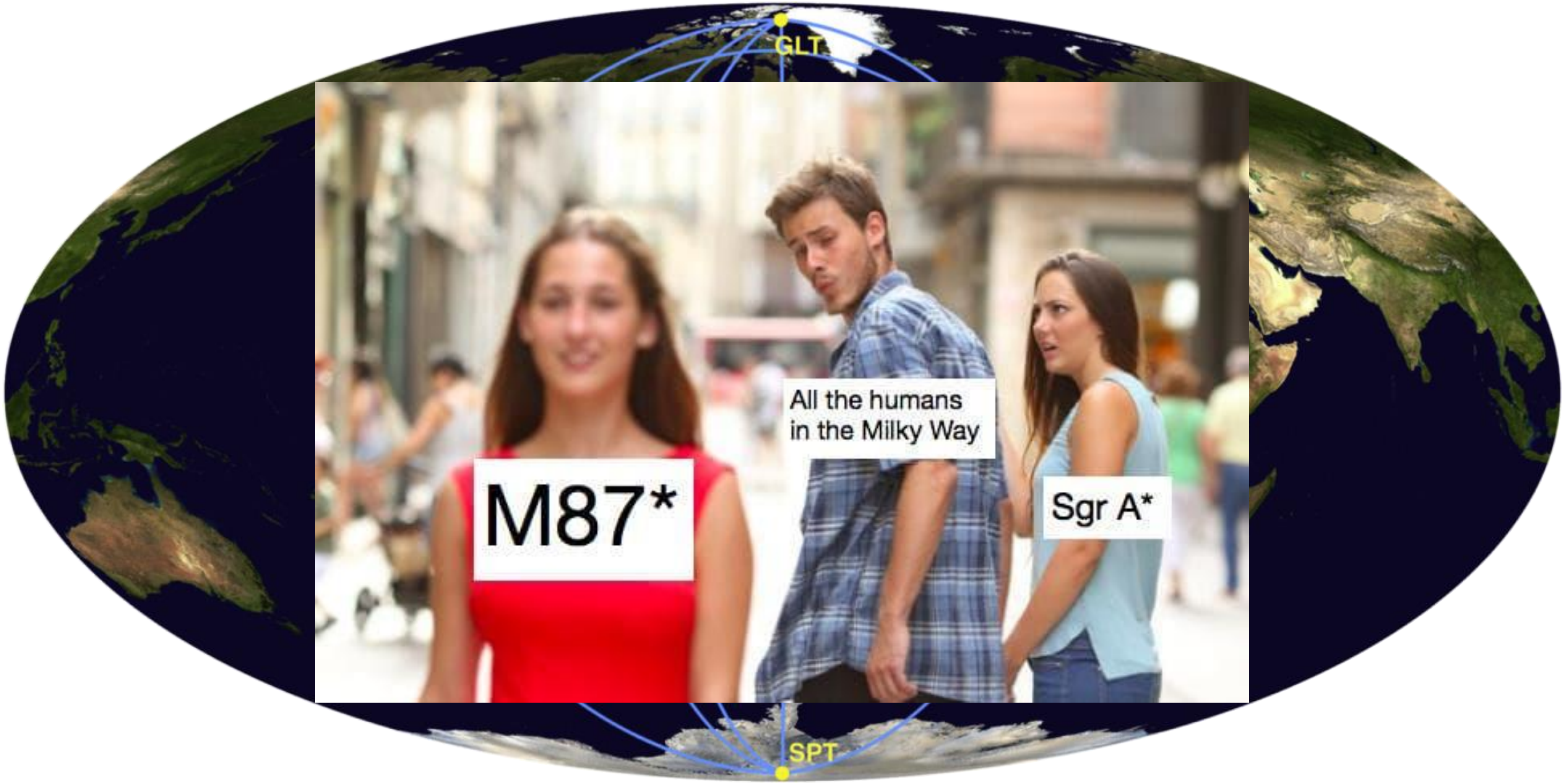


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

The Event Horizon Telescope



$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

Image Credit:
EHT Collaboration 2019 (Paper II)