Photographing a Black Hole with the Event Horizon Telescope

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Princeton University

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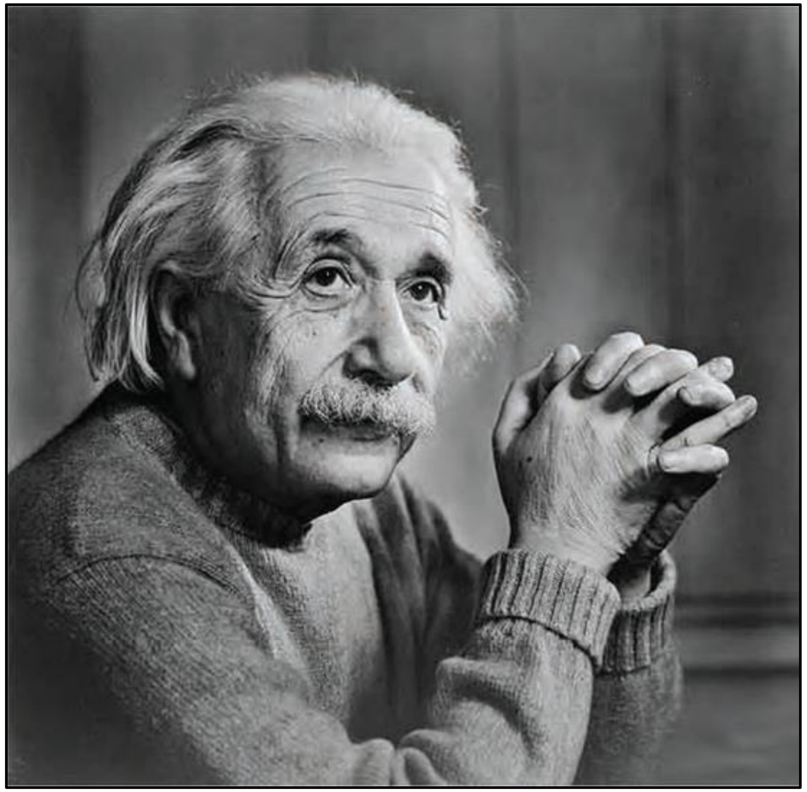
PRINCETON UNIVERSITY

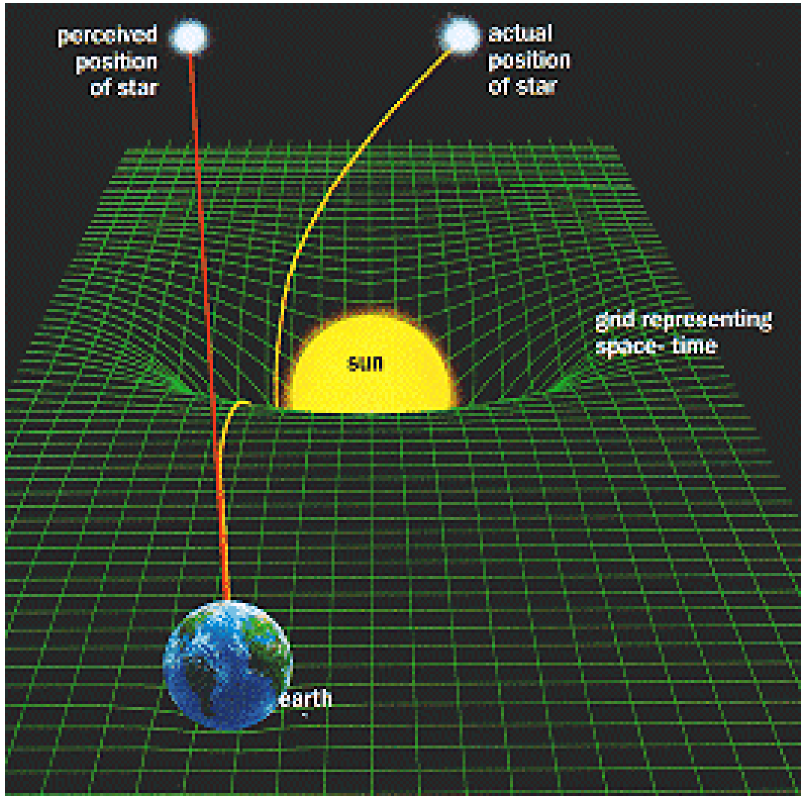
Event Horizon Telescope

The EHT Collaboration

What does a black hole look like?

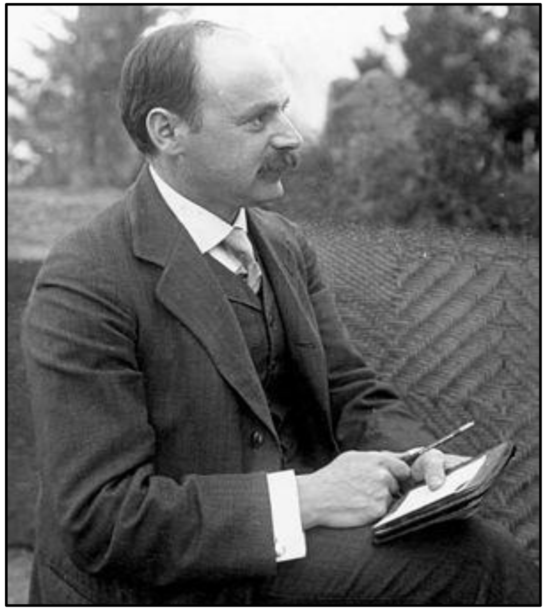
Black Holes





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

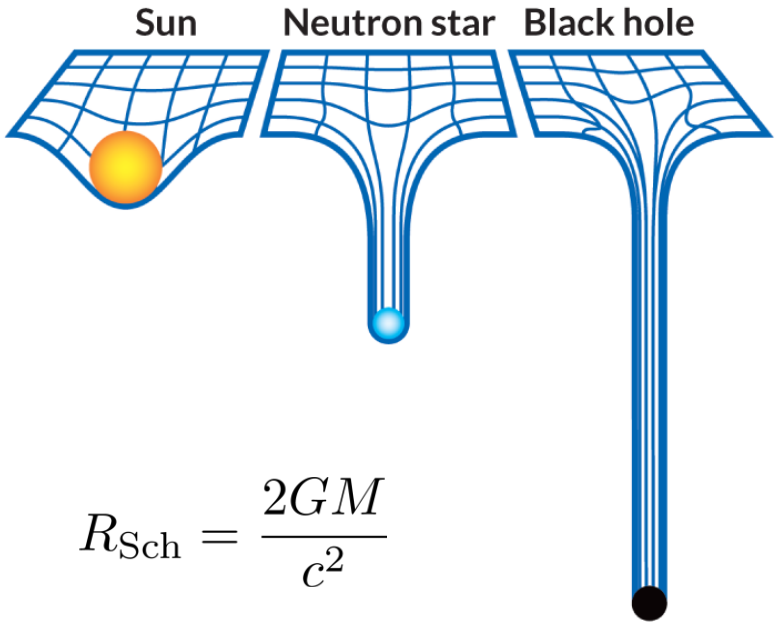
Black Holes



1916

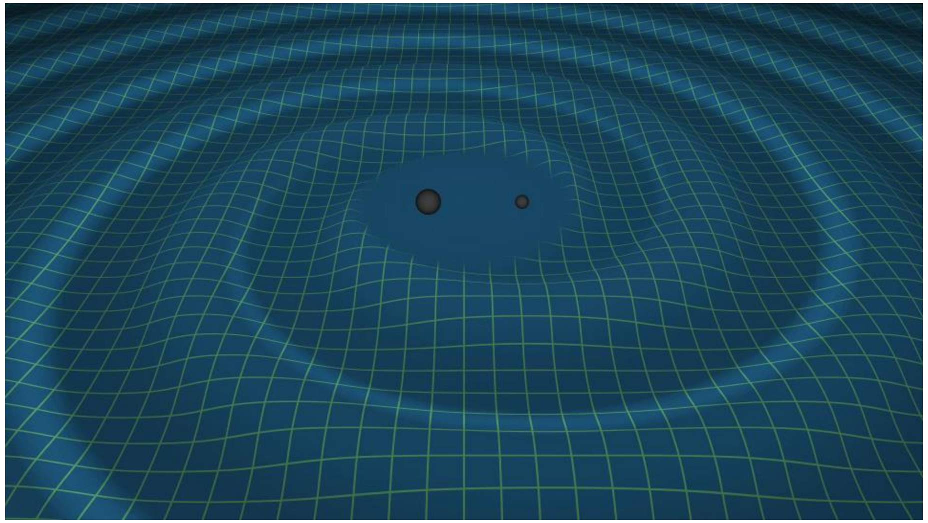
Karl Schwarzschild discovers the first exact solution in General Relativity

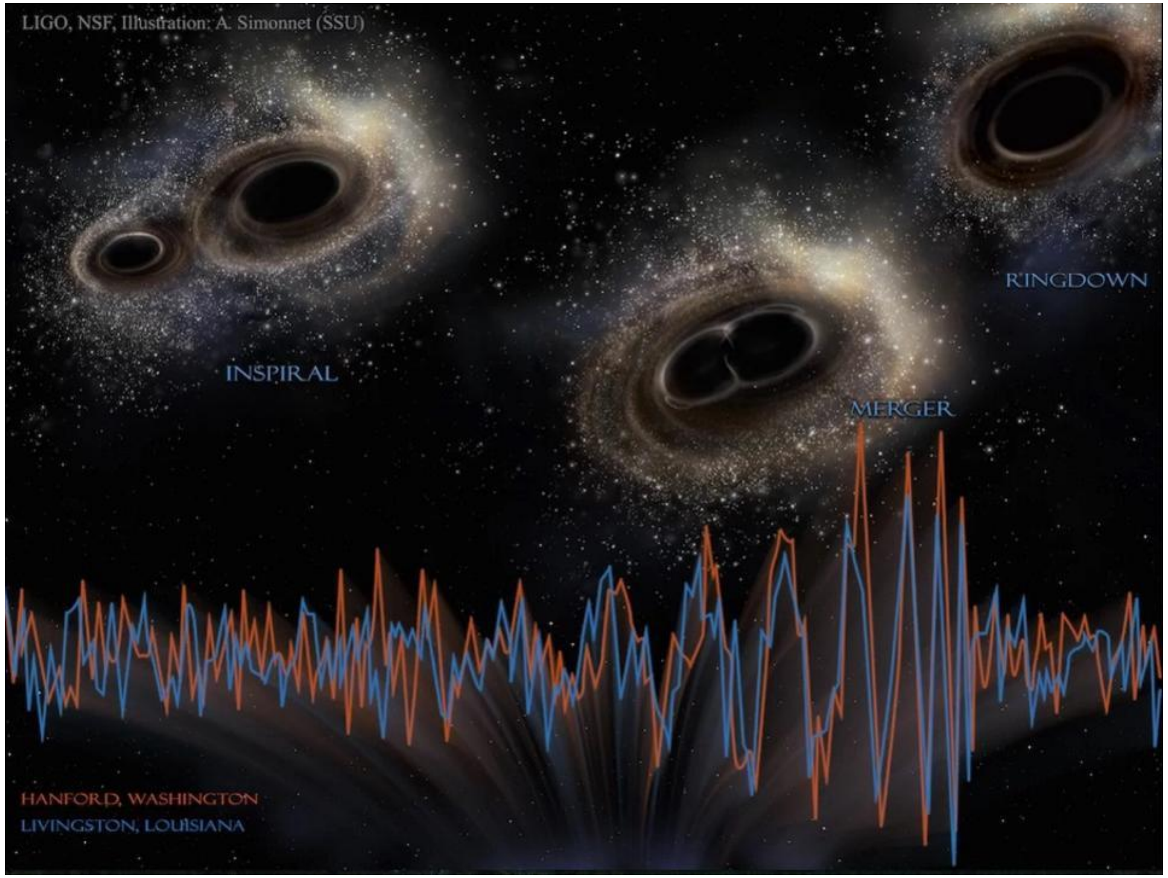
His solution predicts that even light cannot escape from the inside the “Schwarzschild radius”, which marks the black hole’s event horizon (Finkelstein, 1958)



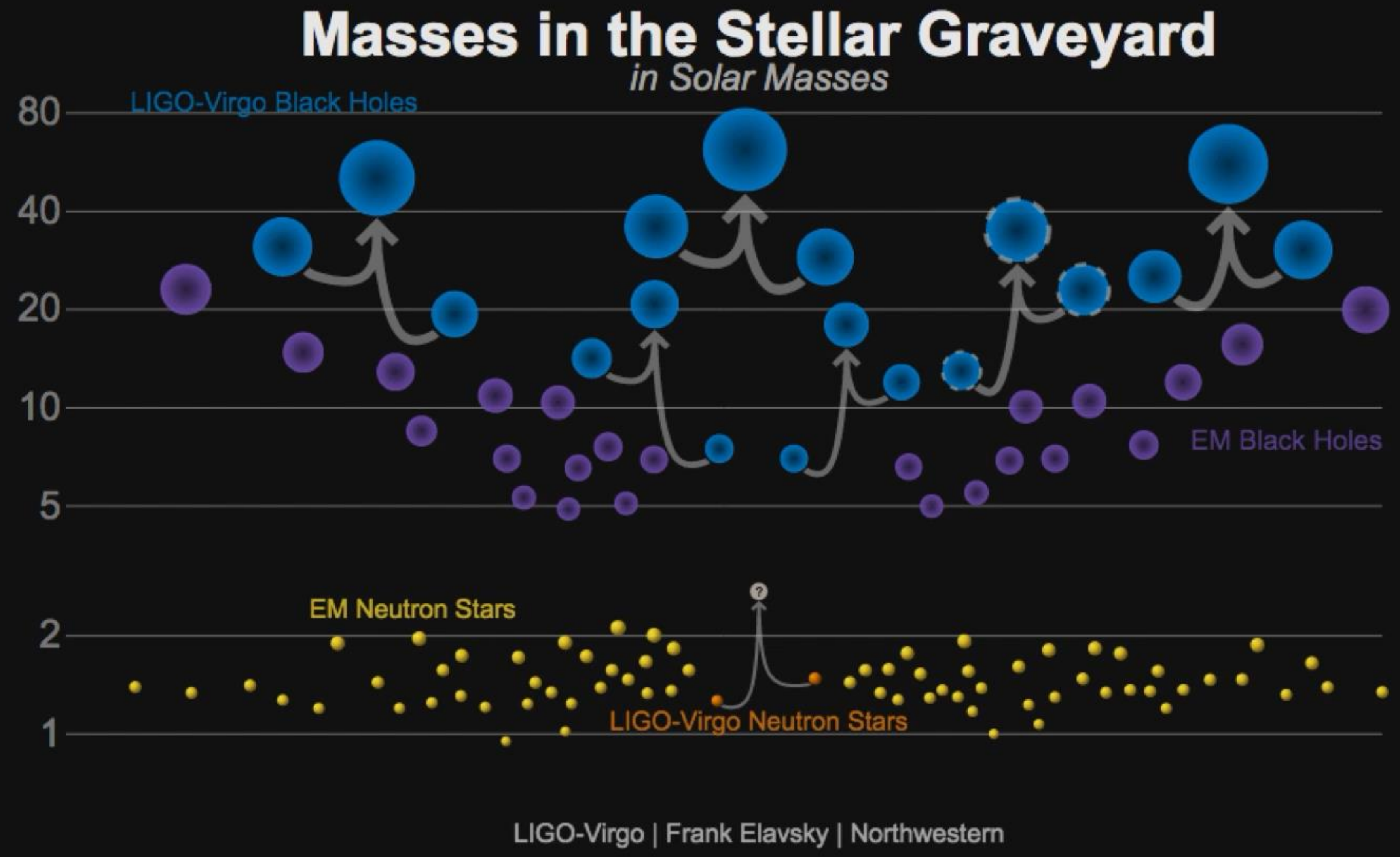
$$R_{\rm Sch} = \frac{2GM}{c^2}$$

Gravitational Waves – “Hearing” Black Holes



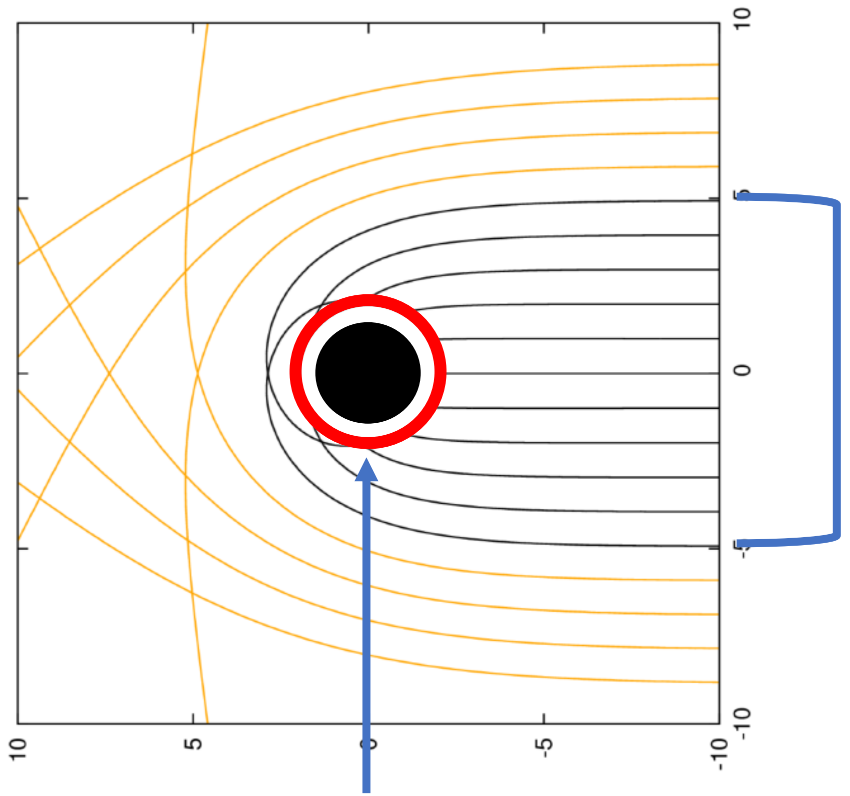


LIGO/NSF



Credit: L. Blackburn

The Black Hole Shadow



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

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

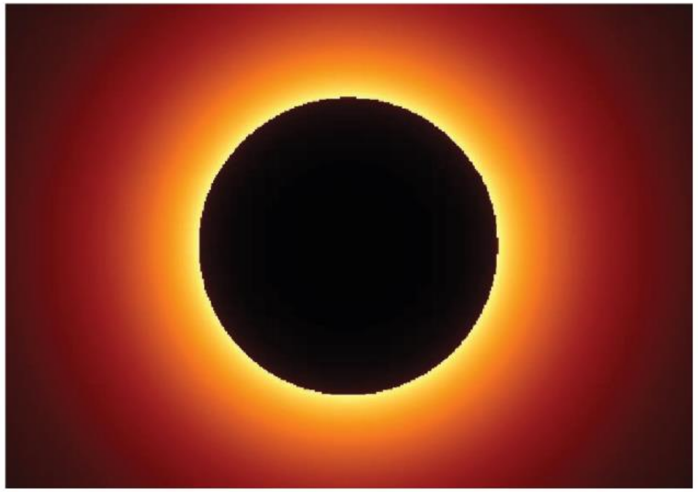


Image credit: Keiichi Asada

What “lights up” a black hole?

Accretion Energy:
black holes can shine brightly

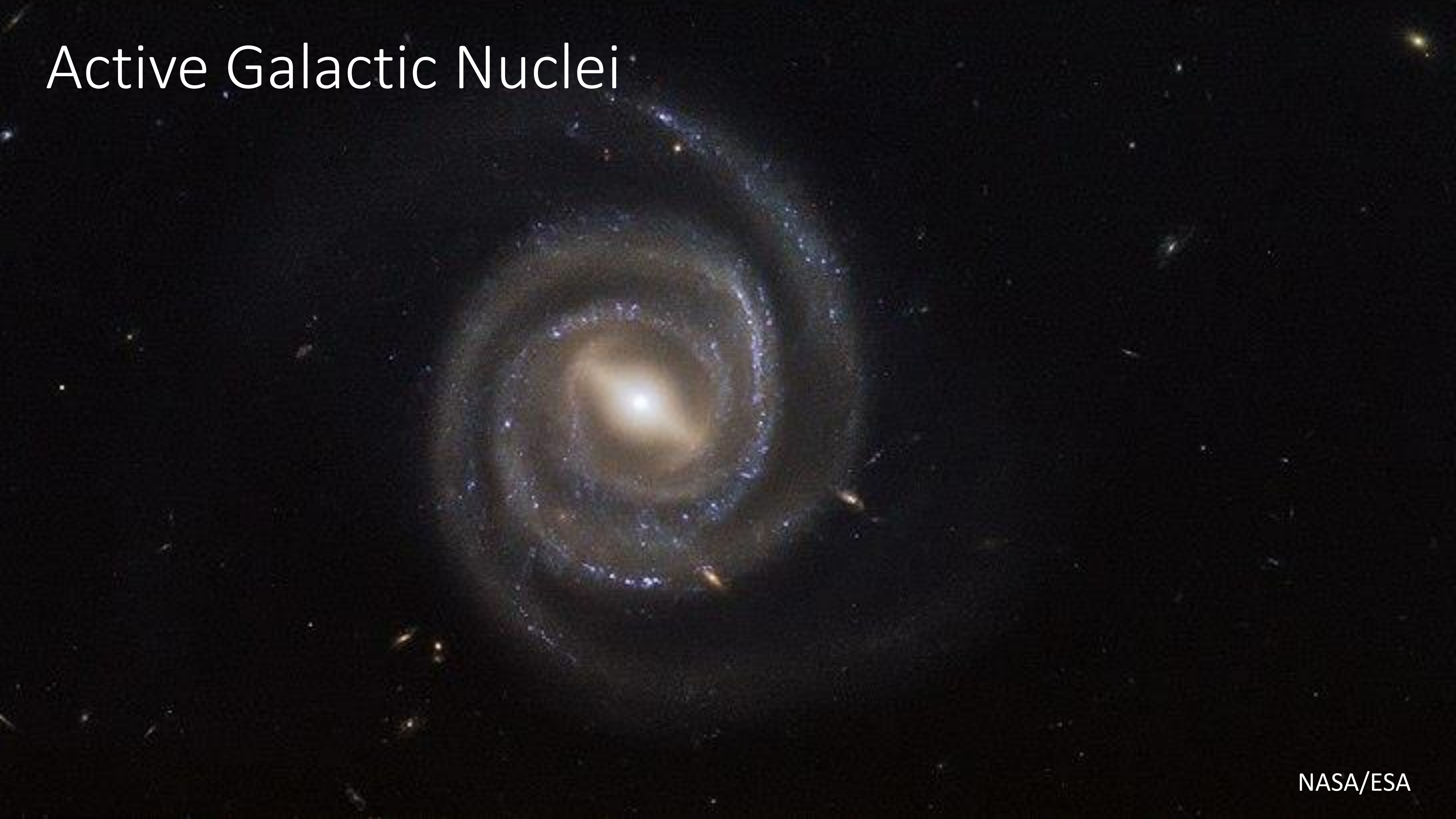
Accretion power per unit mass:

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

For nuclear fusion:

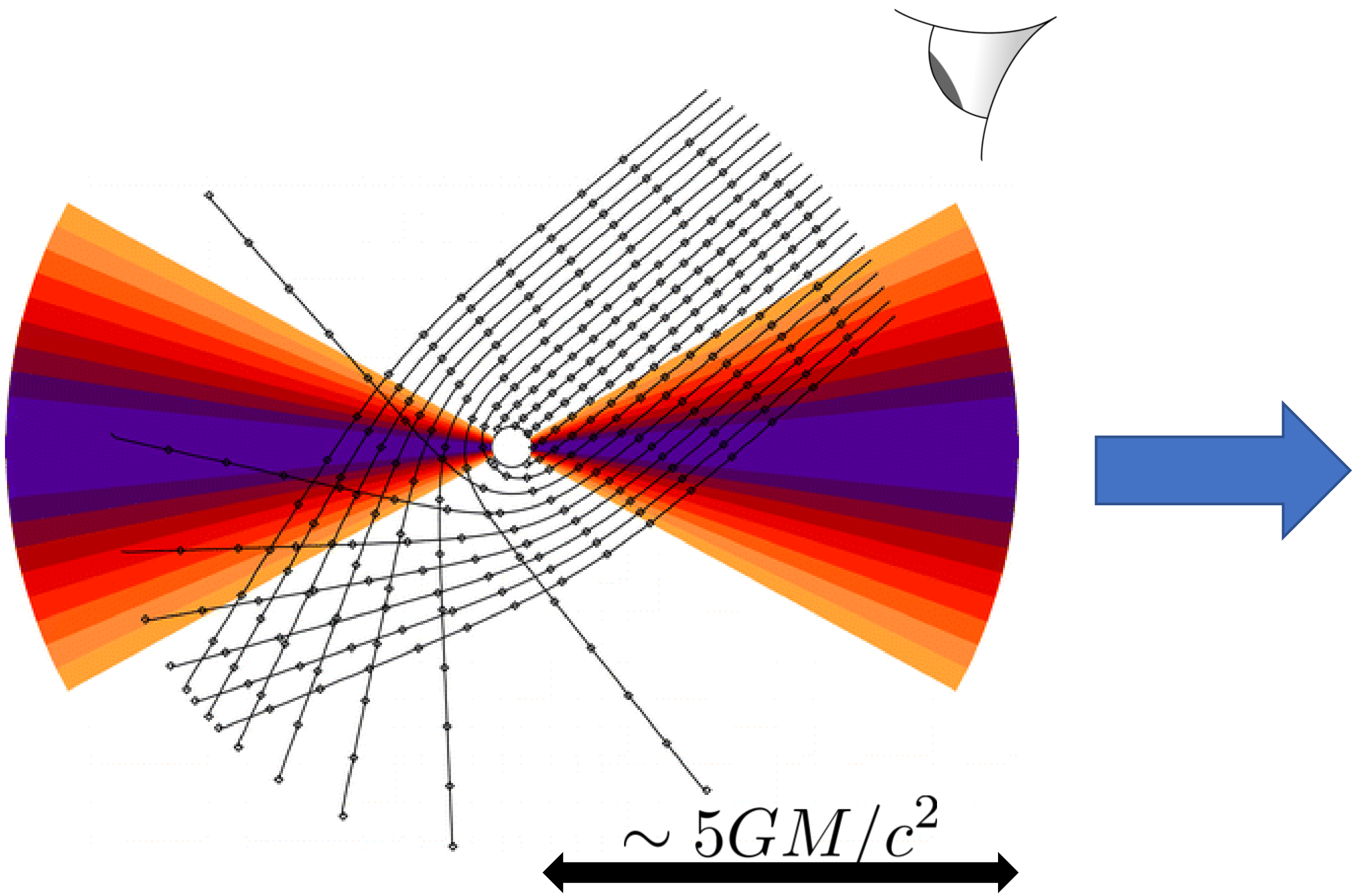
$$\Delta E/mc^2 = 0.007$$

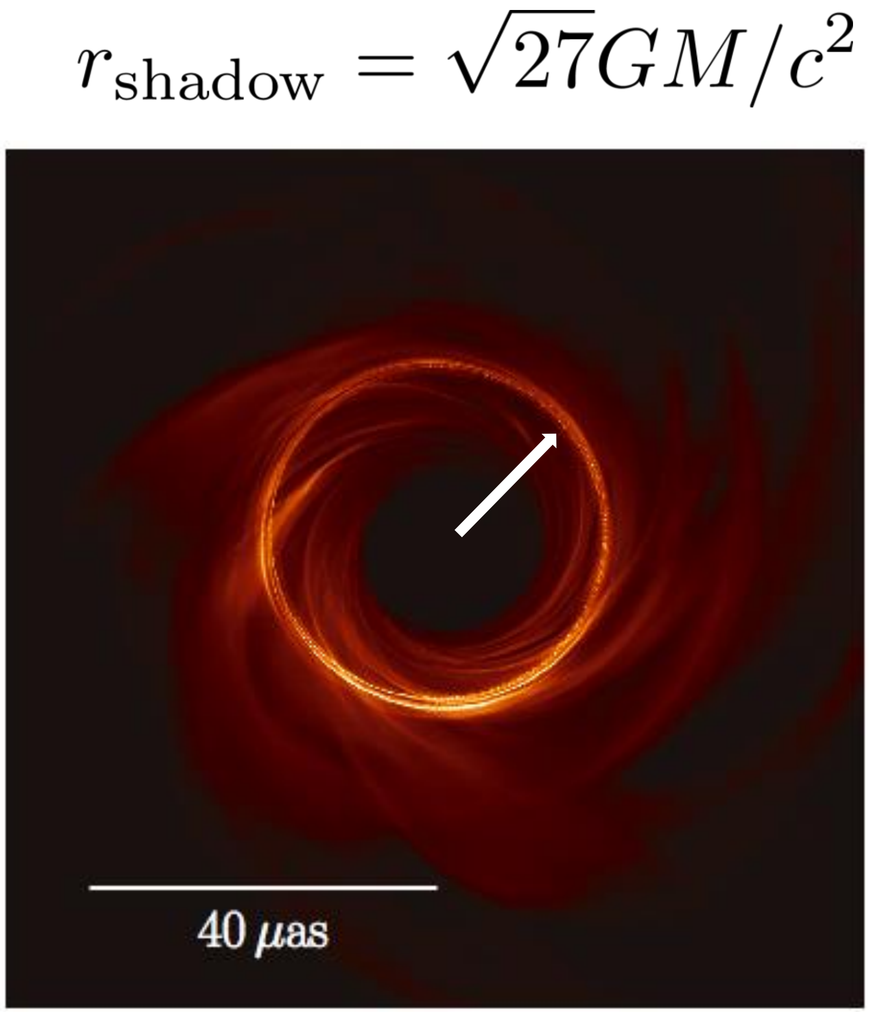
Active Galactic Nuclei



NASA/ESA

The Black Hole Shadow: Modern Simulations





Schnittman+ (2006)

EHTC+ 2019

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

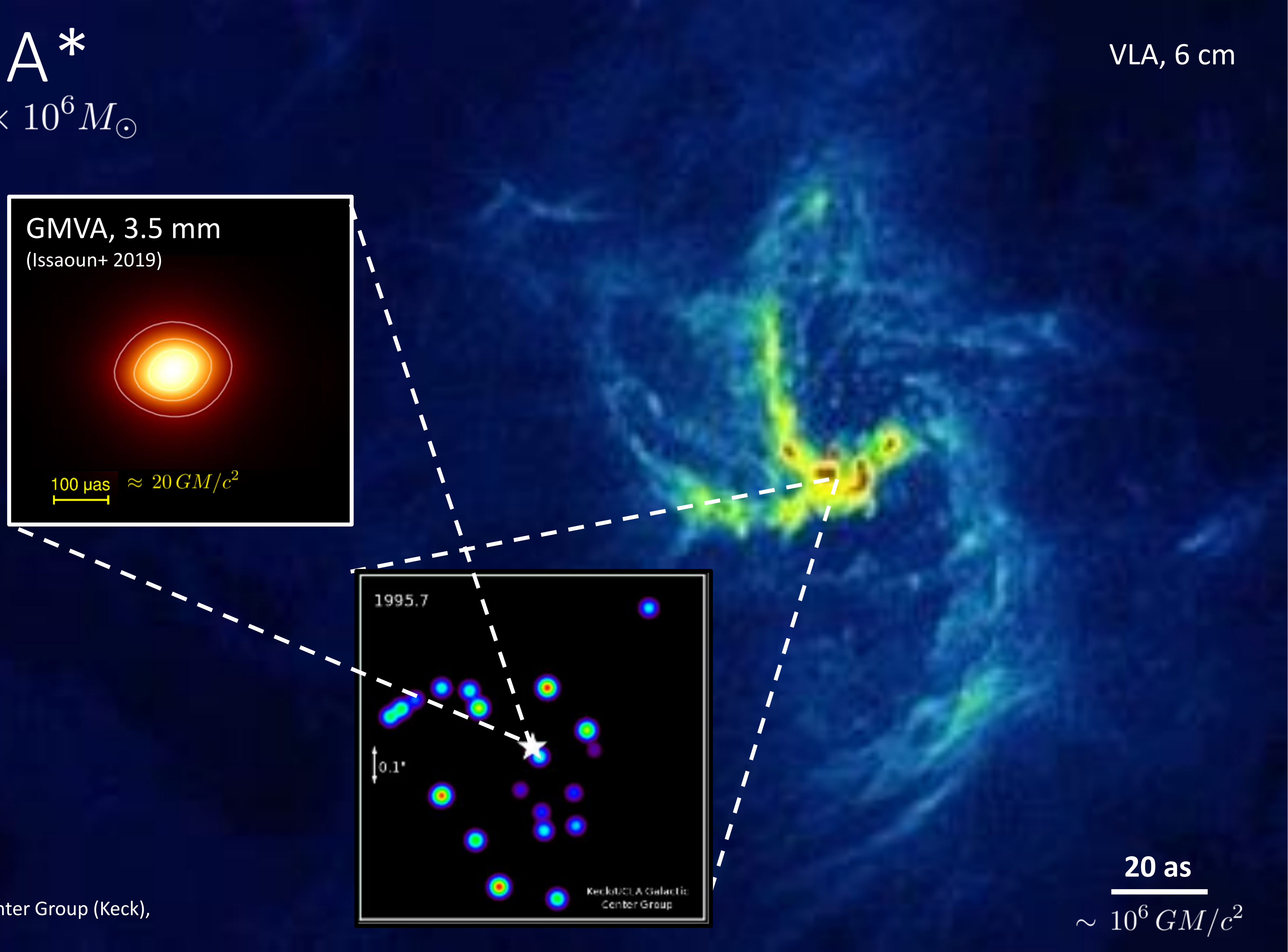


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

M87

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

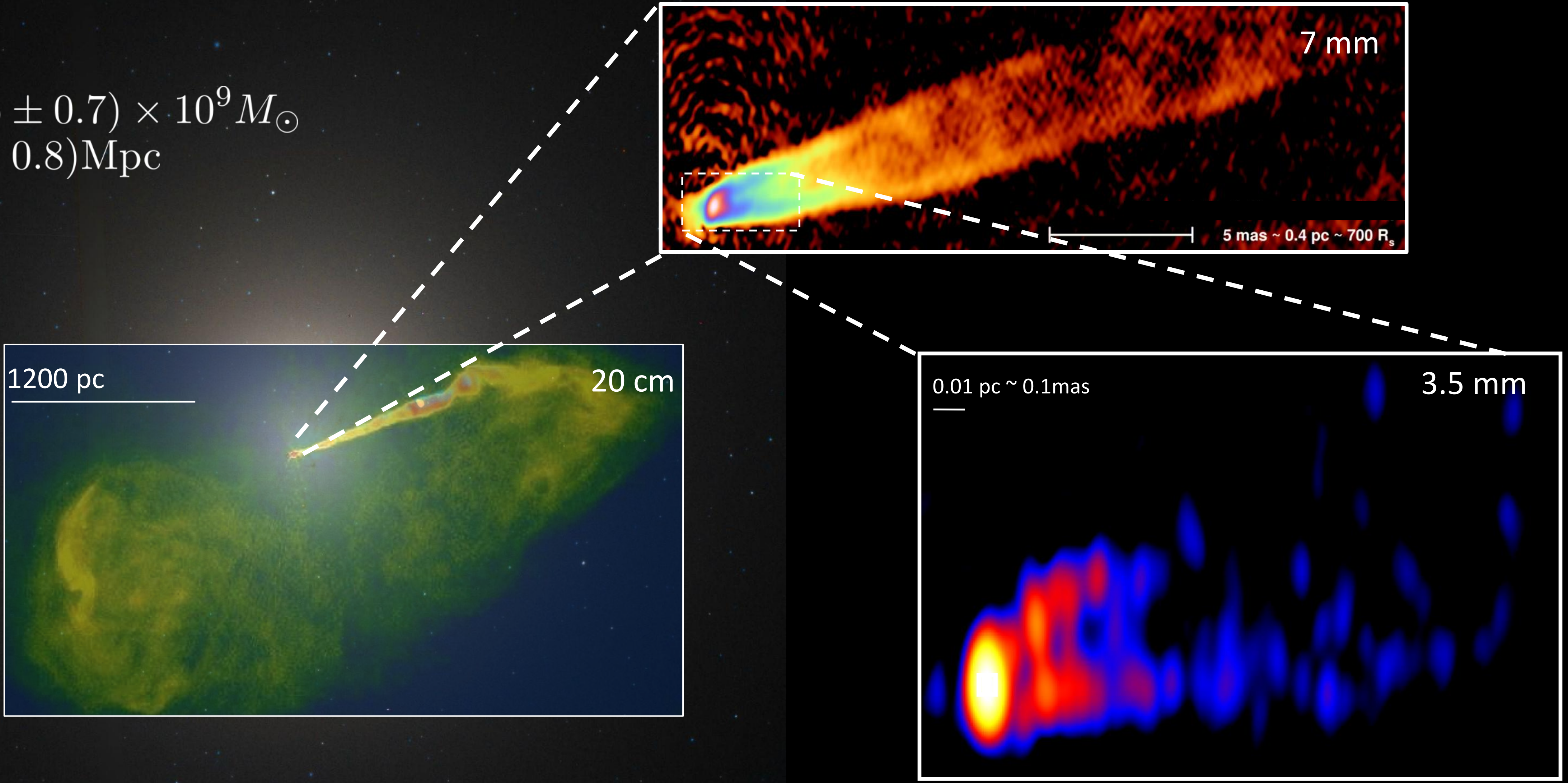
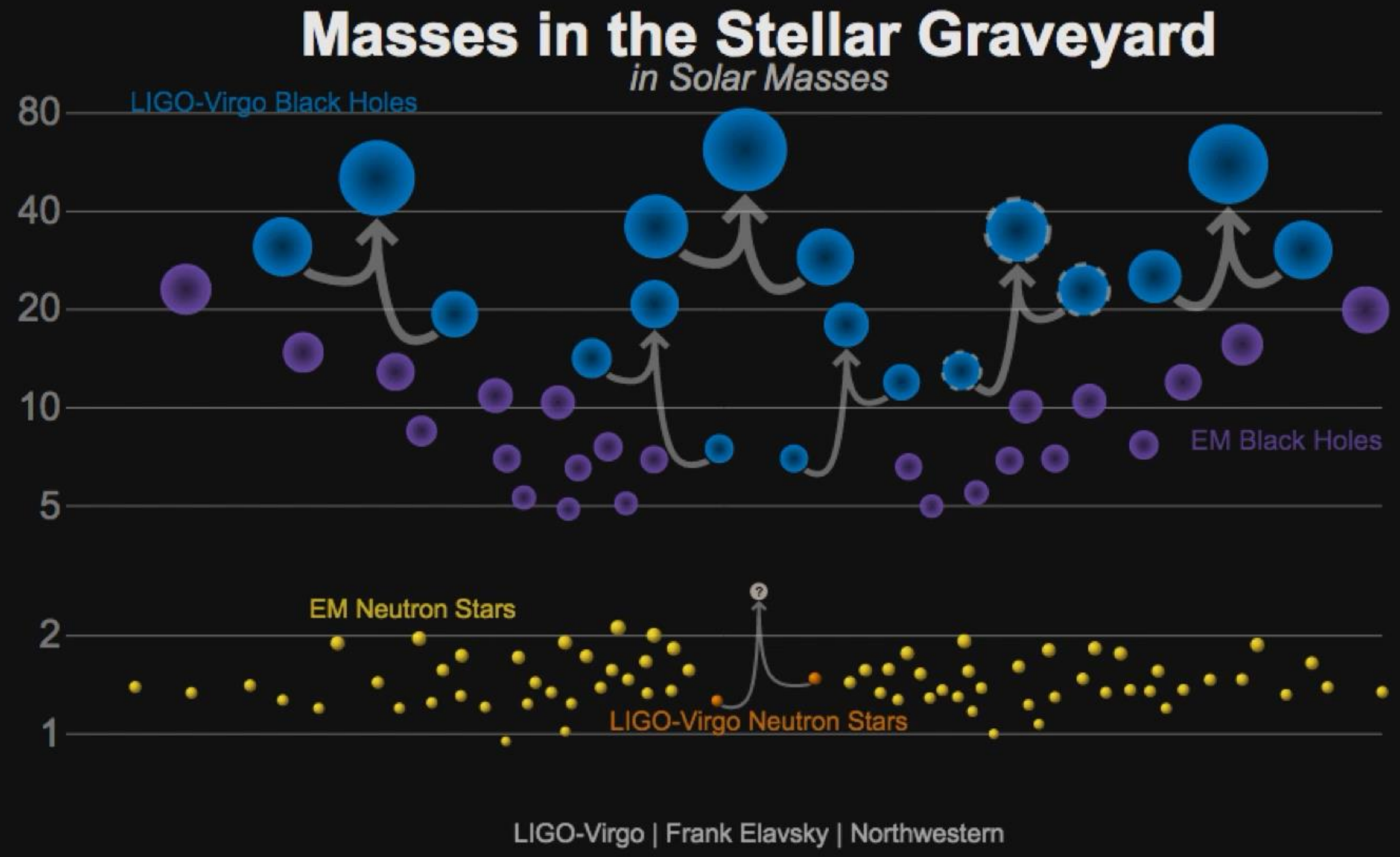


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)



Credit: L. Blackburn

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…..

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

How big is the shadow?

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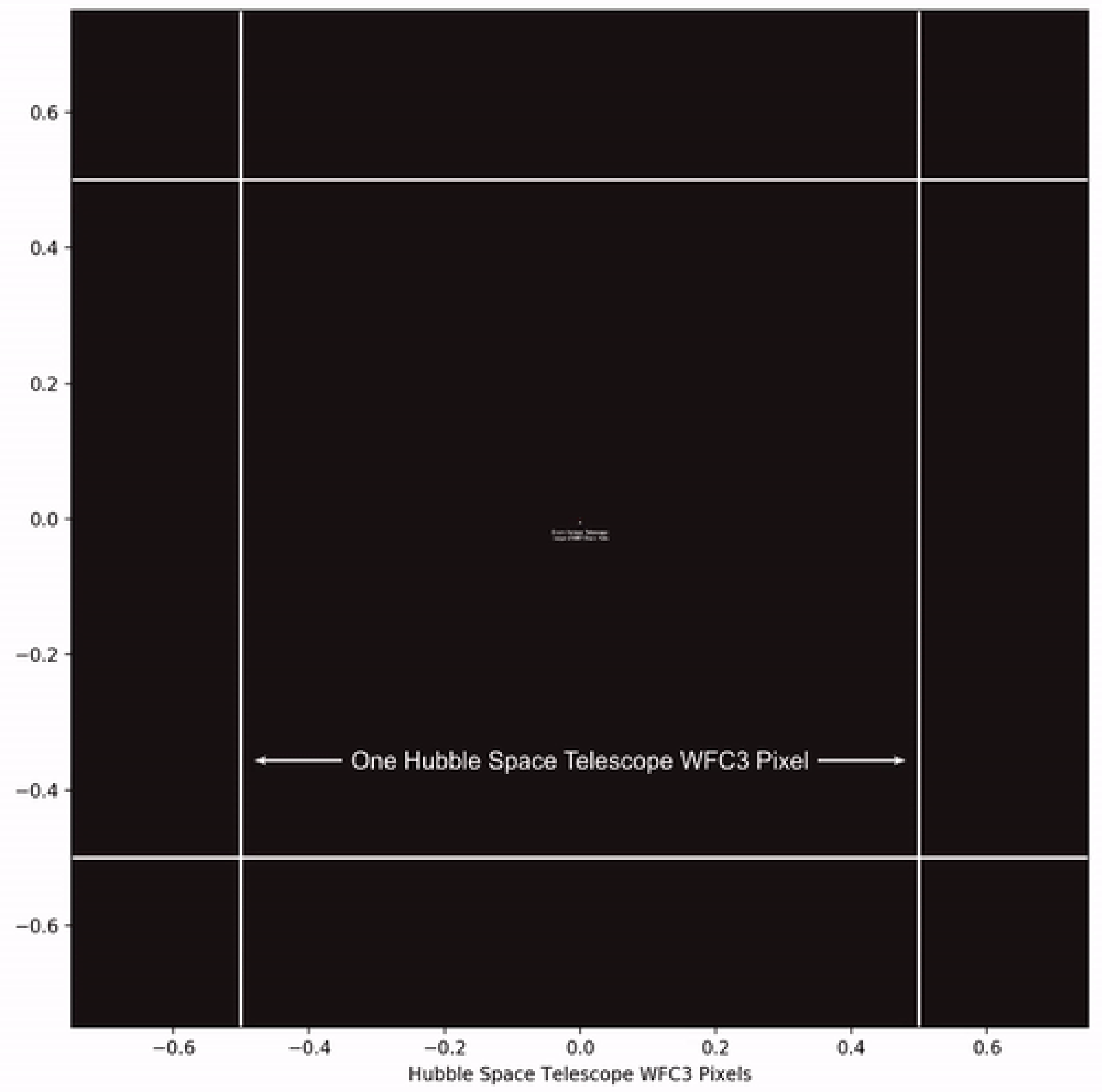
Unfortunately, M87 is really far away…..

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

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?

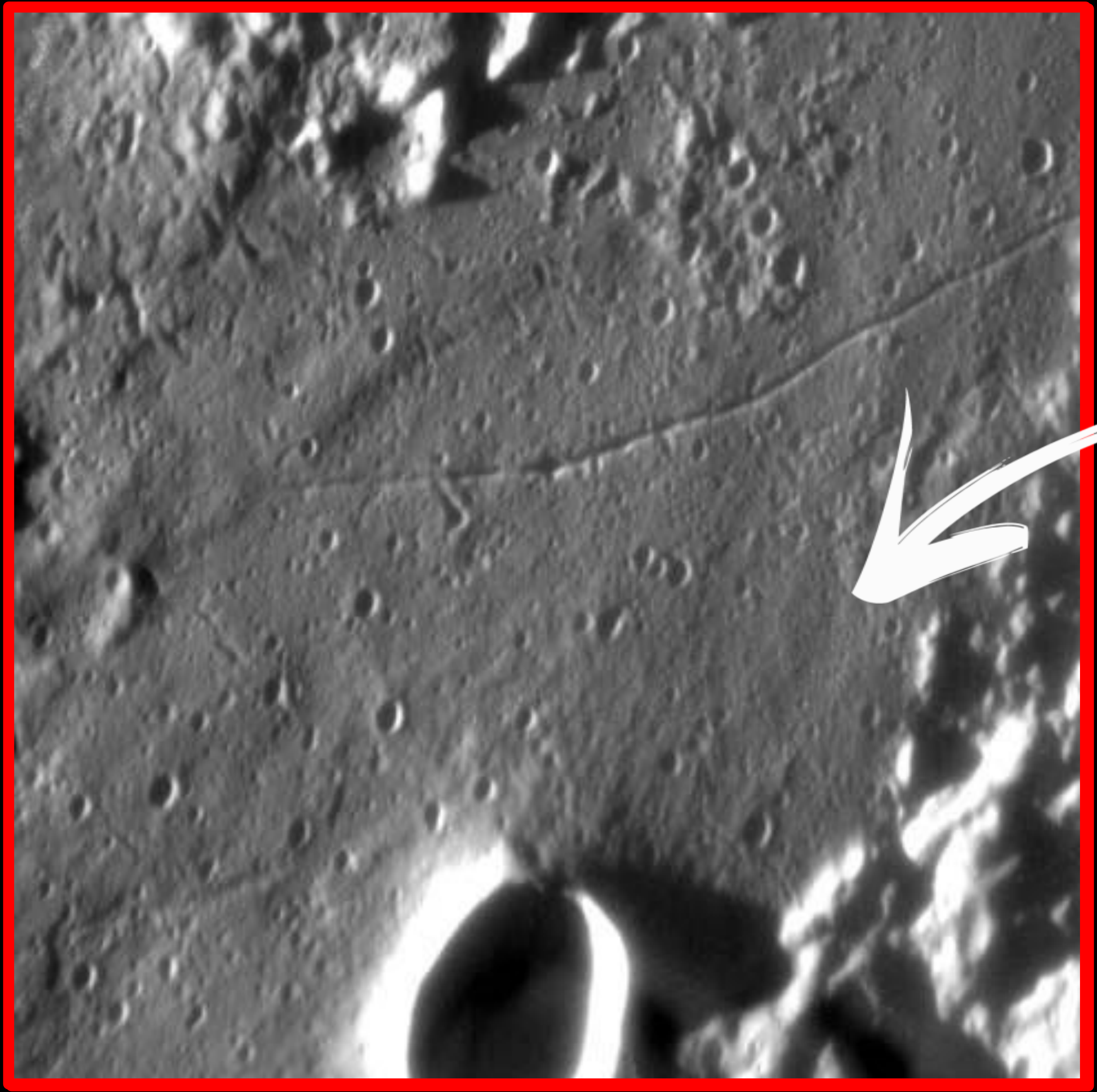


Animation credit: Alex Parker

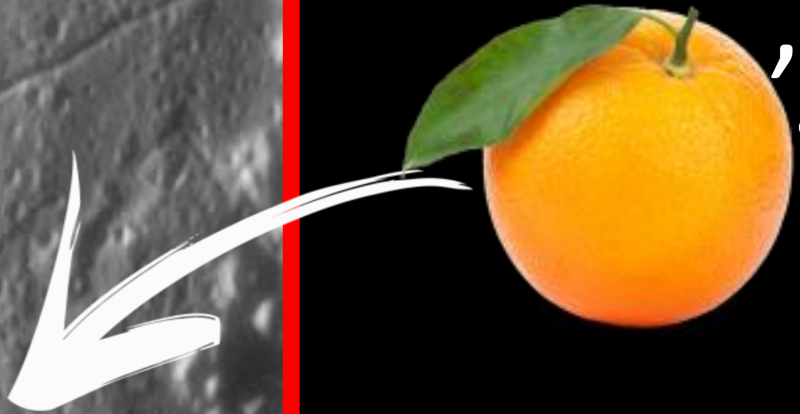
Orange on the Moon

Black Hole Shadow

Video courtesy of Hotaka Shiokawa



Each Pixel is 1.5 Million



’s

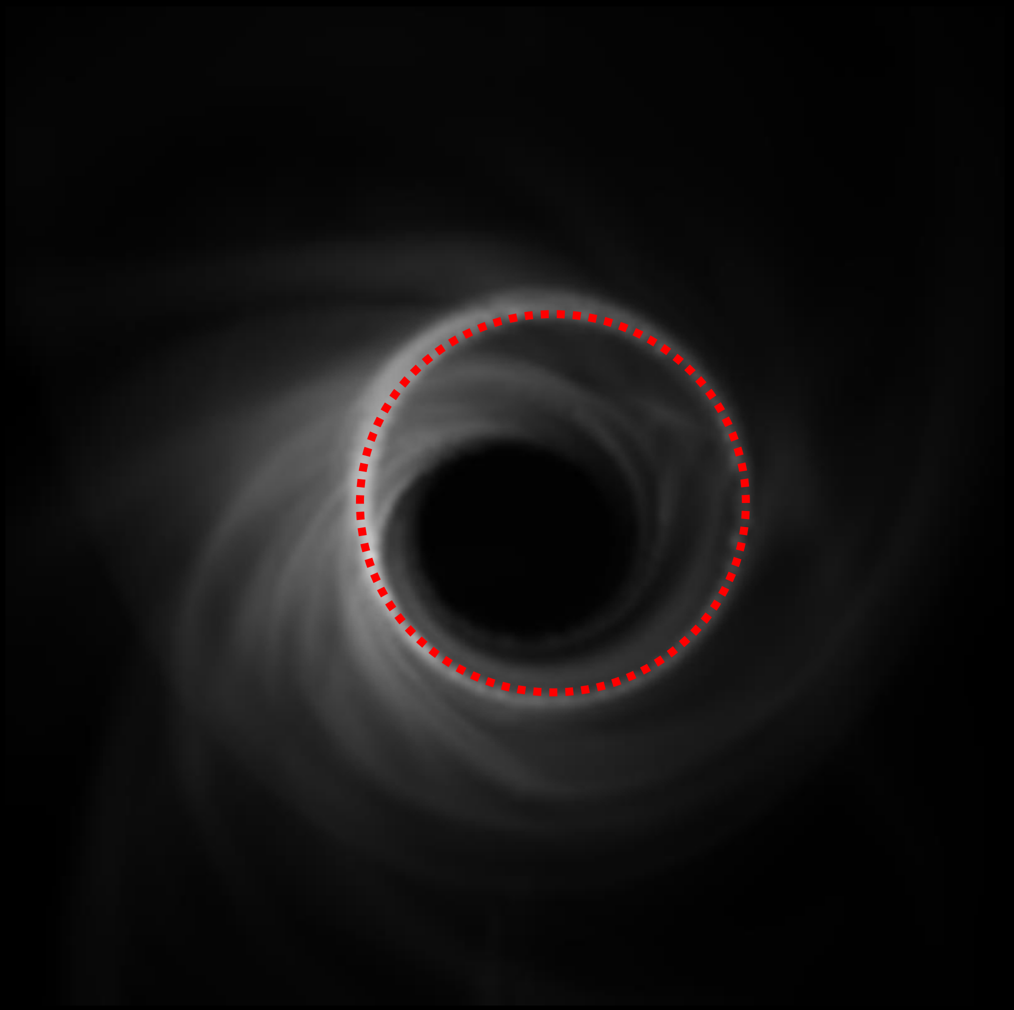
Yepun telescope, Paranal Observatory in Chile / George Tarsoudis

Diffraction Limit

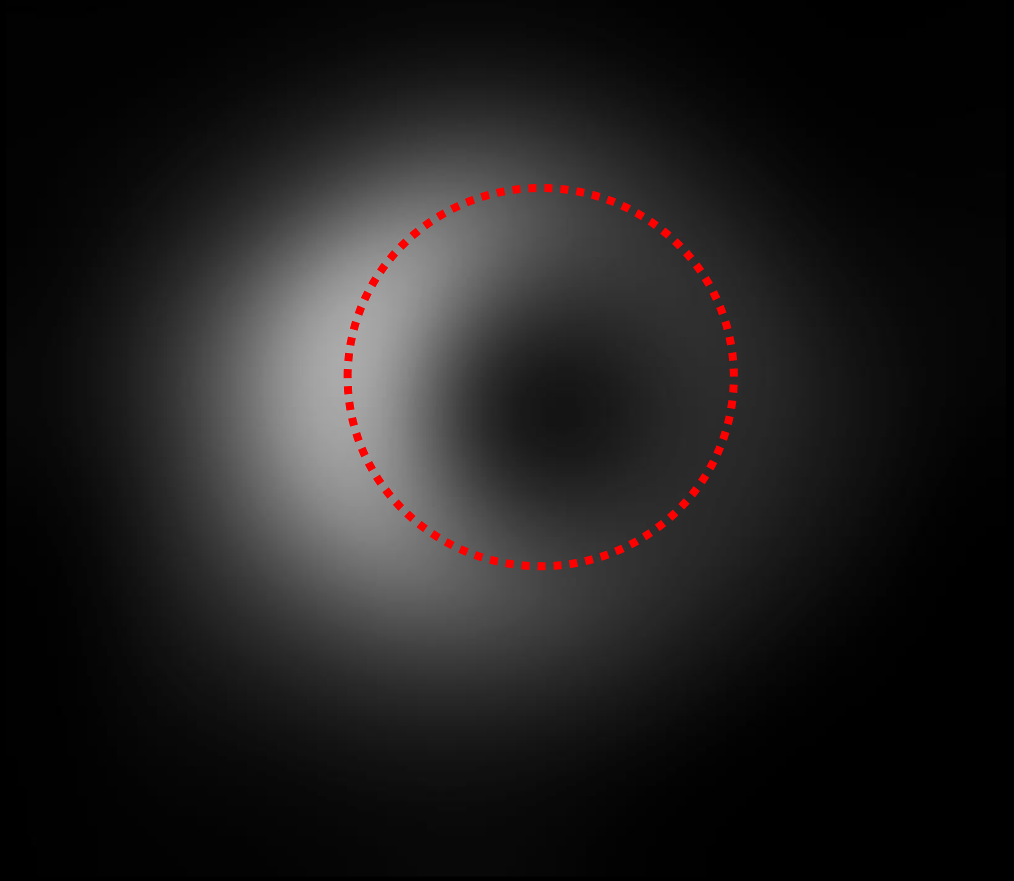
$$\text{Angular Resolution} \propto \frac{\text{Wavelength}}{\text{Telescope Size}}$$

We Need an Earth-Sized Telescope!

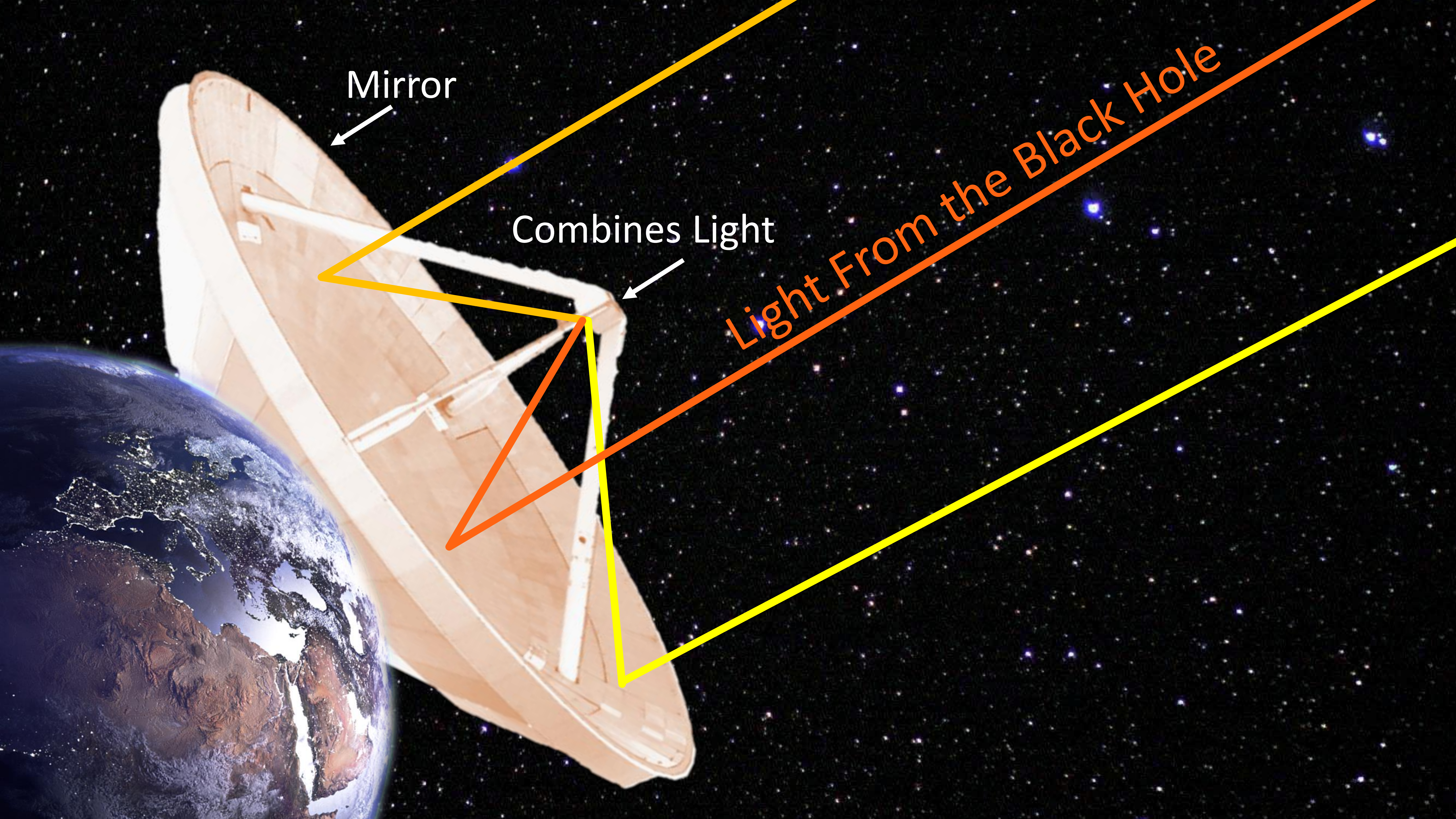
Best-Guess Simulation

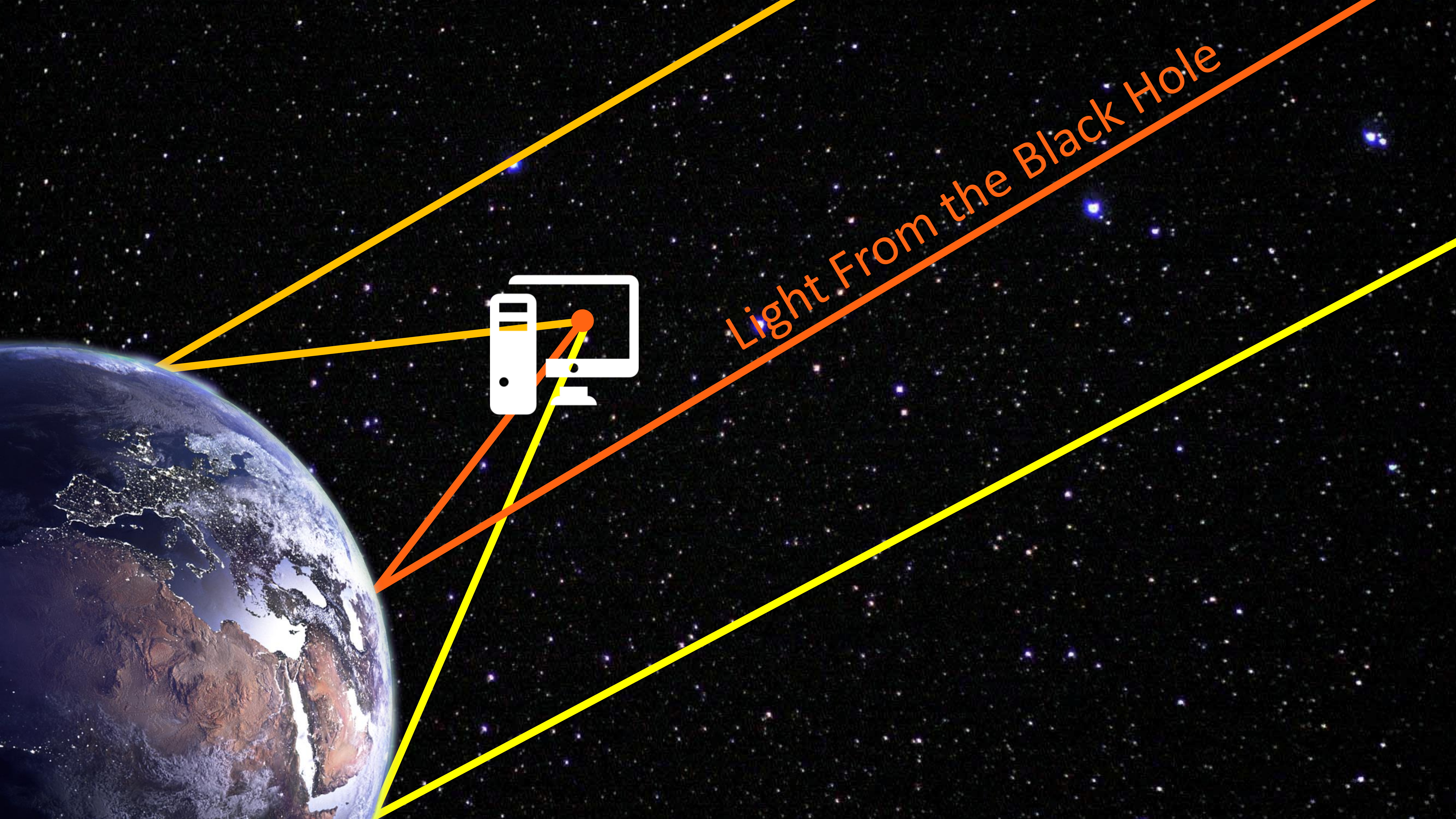


Picture with an Earth-Sized Telescope

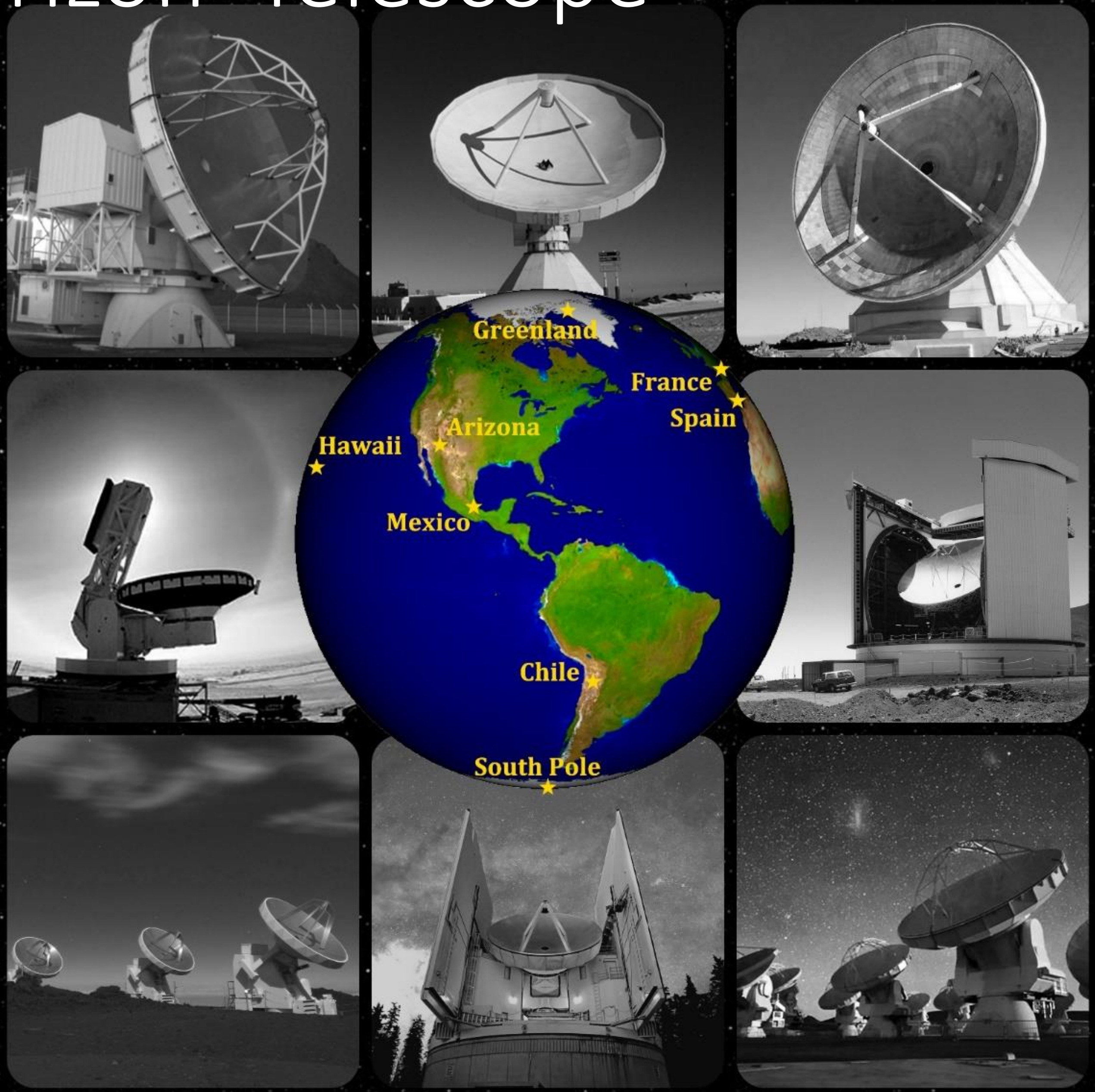


Original Image courtesy of Jason Dexter, Monika Moscibrodzka, Hotaka Shiokawa


Mirror
Combines Light
Light From the Black Hole

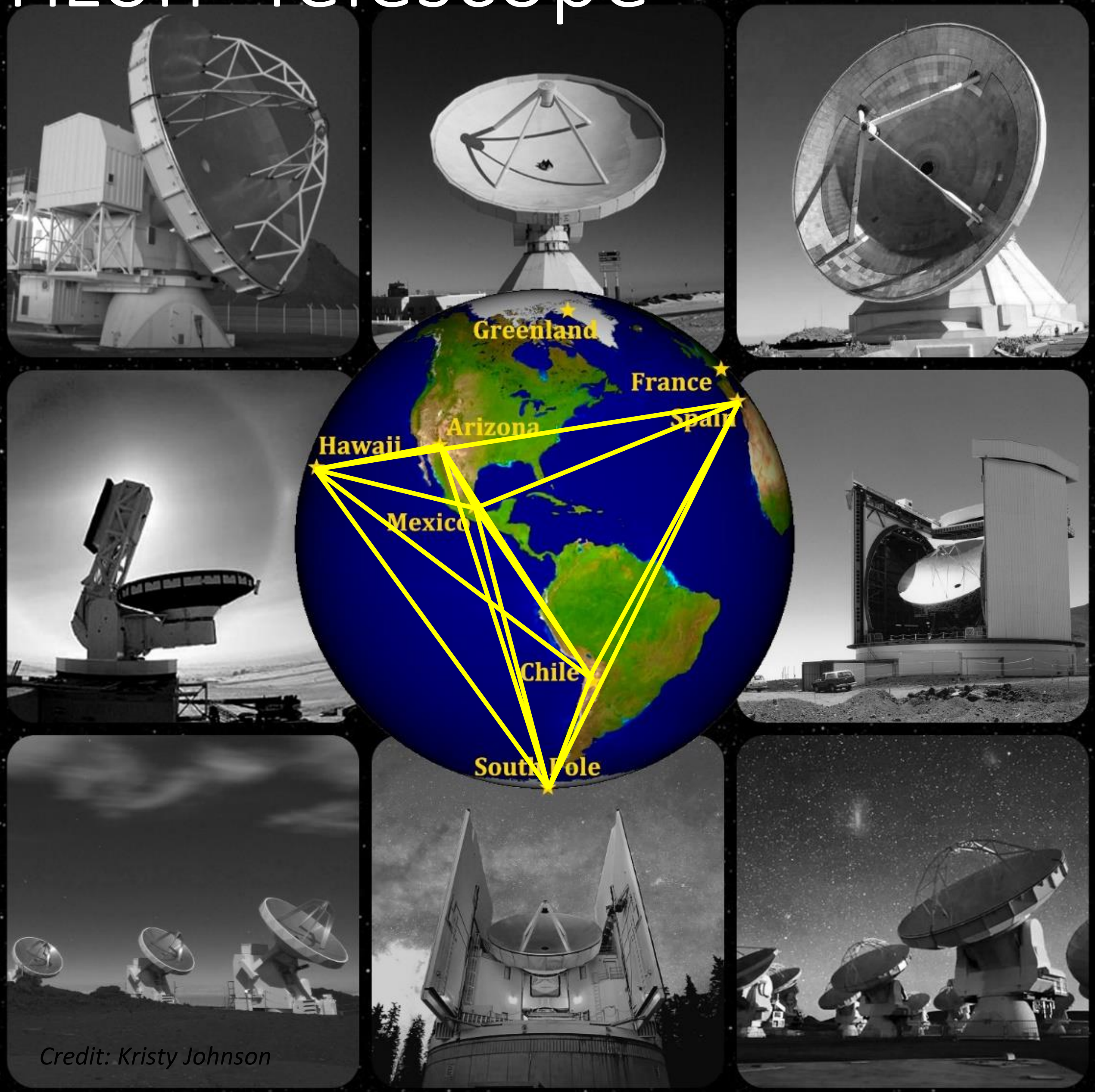

Light From the Black Hole

The Event Horizon Telescope



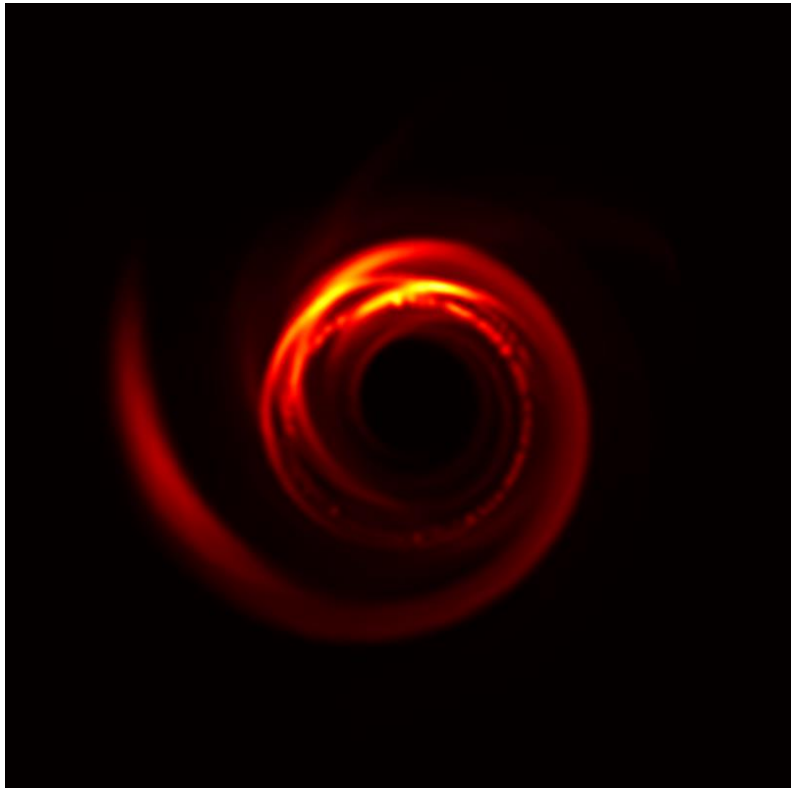
Credit: Kristy Johnson

The Event Horizon Telescope



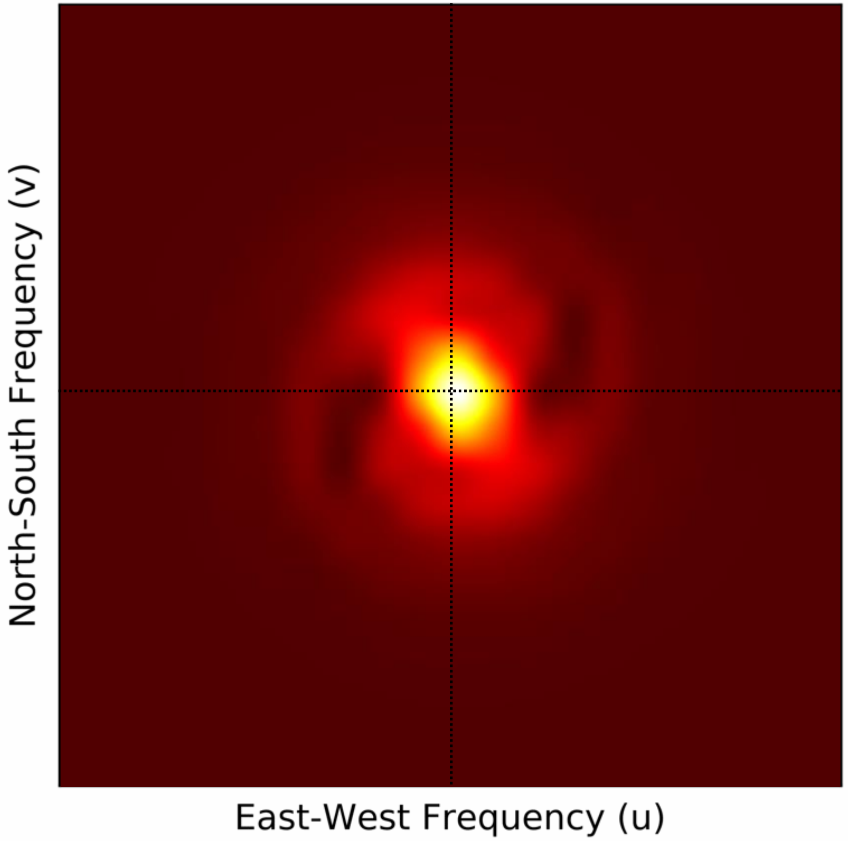
Very Long Baseline Interferometry (VLBI)

Black Hole Image

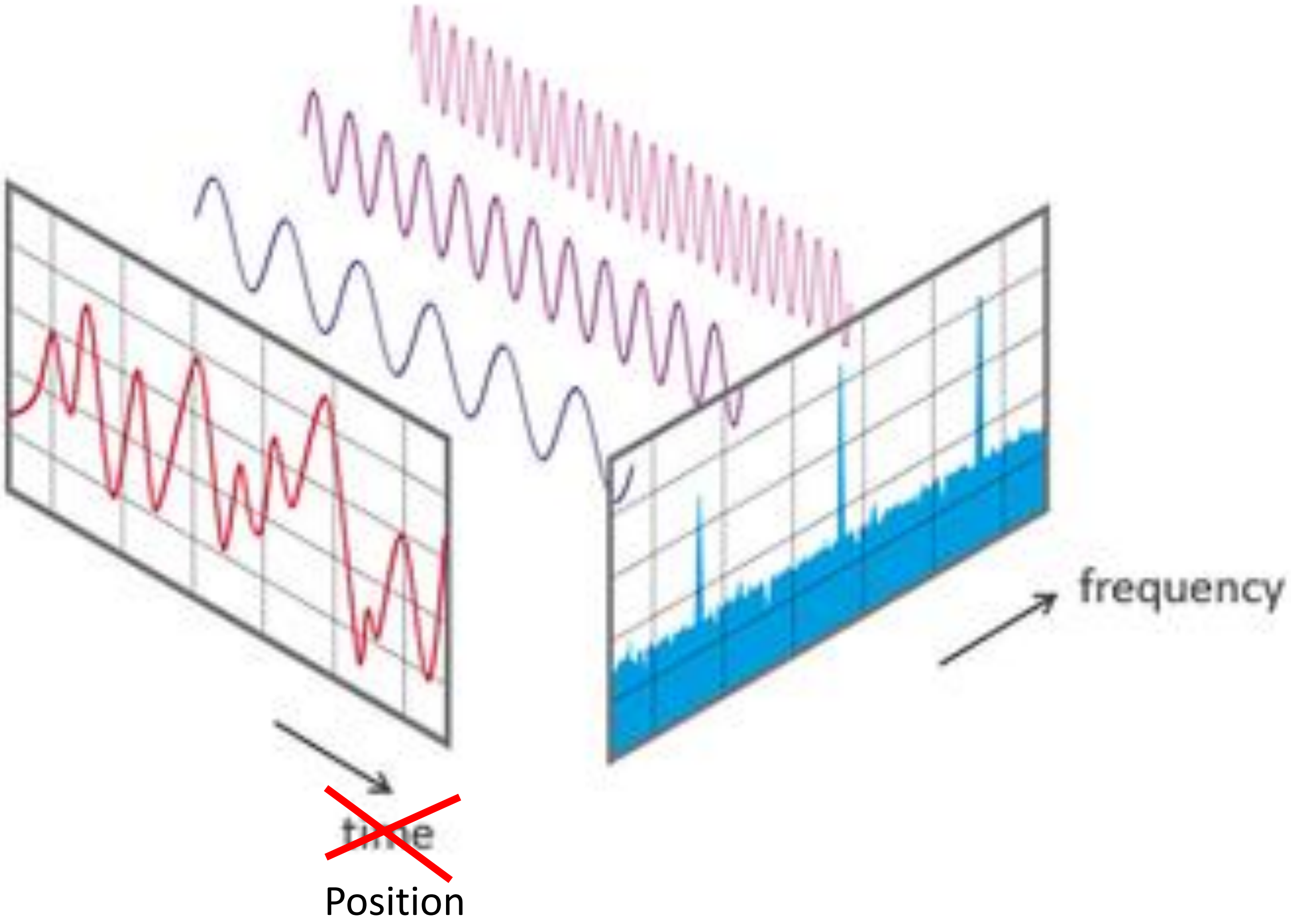


Fourier Transform

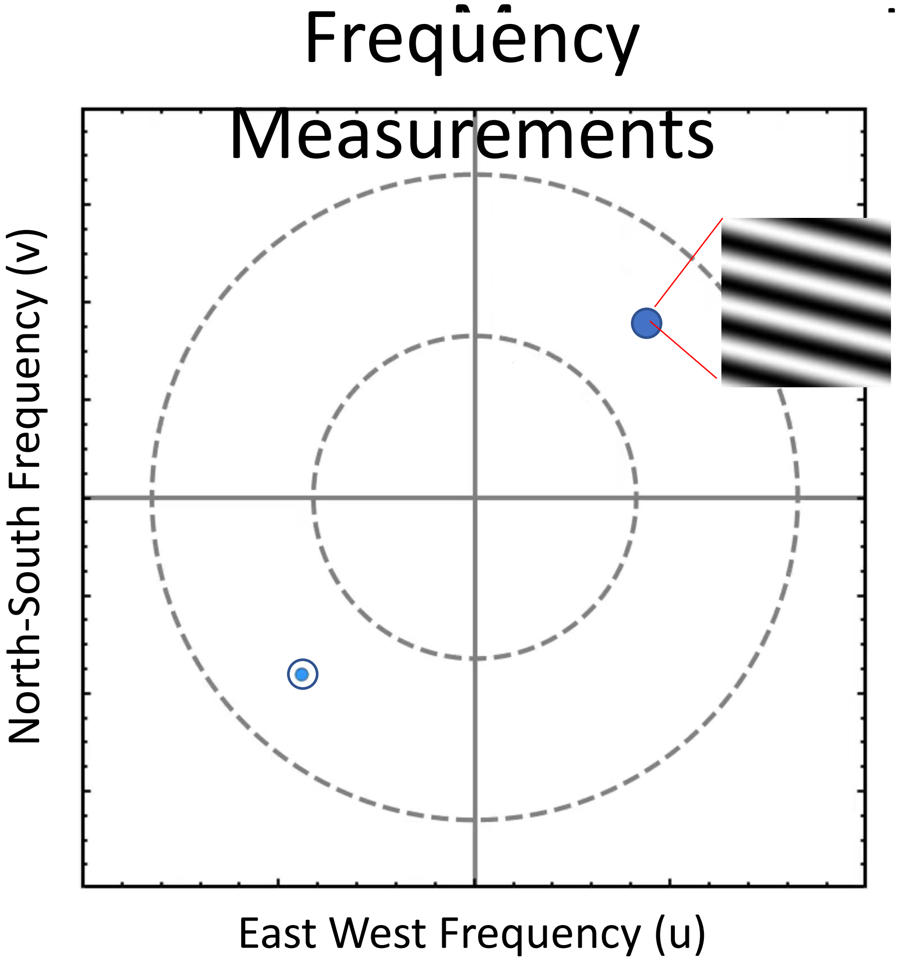
Spatial Frequencies



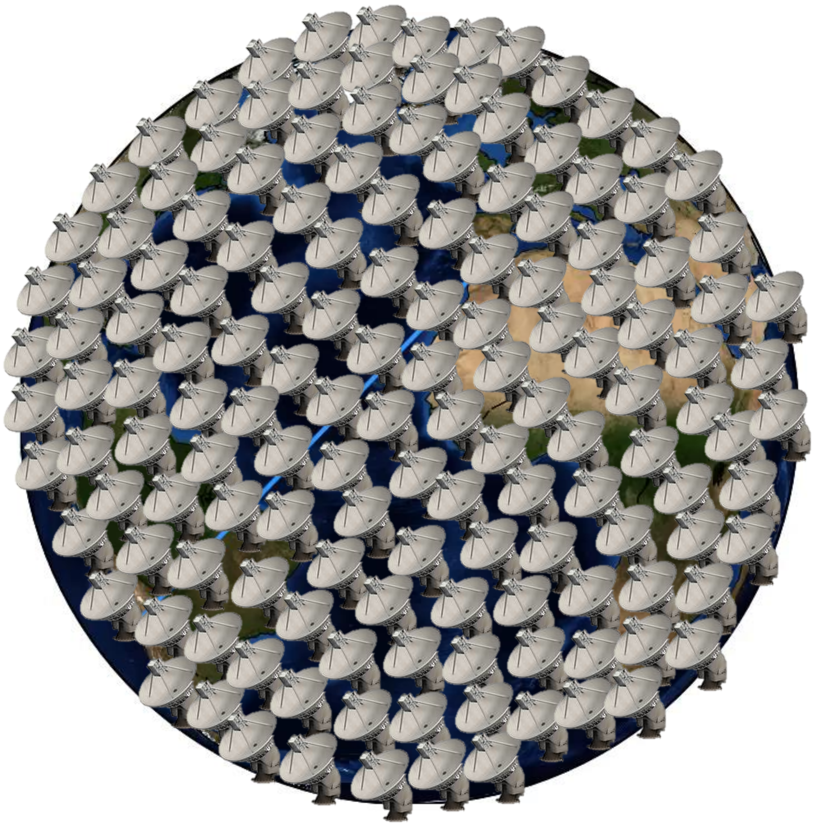
Fourier Transform 101

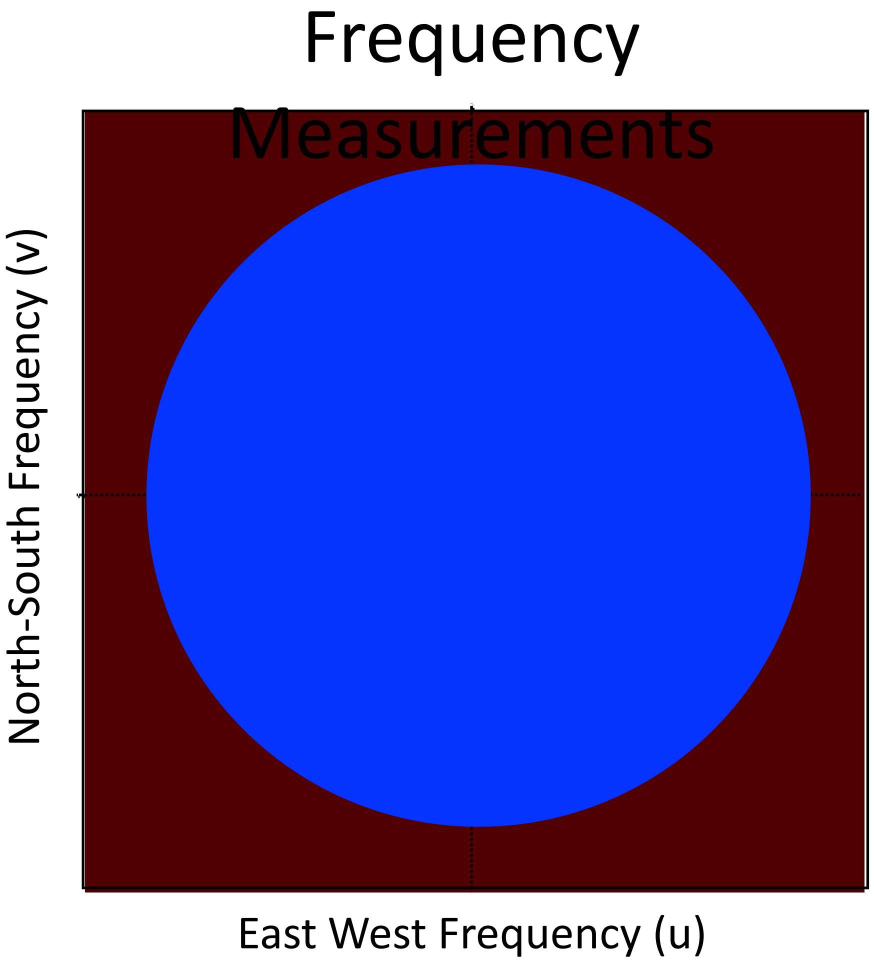


Very Long Baseline Interferometry (VLBI)

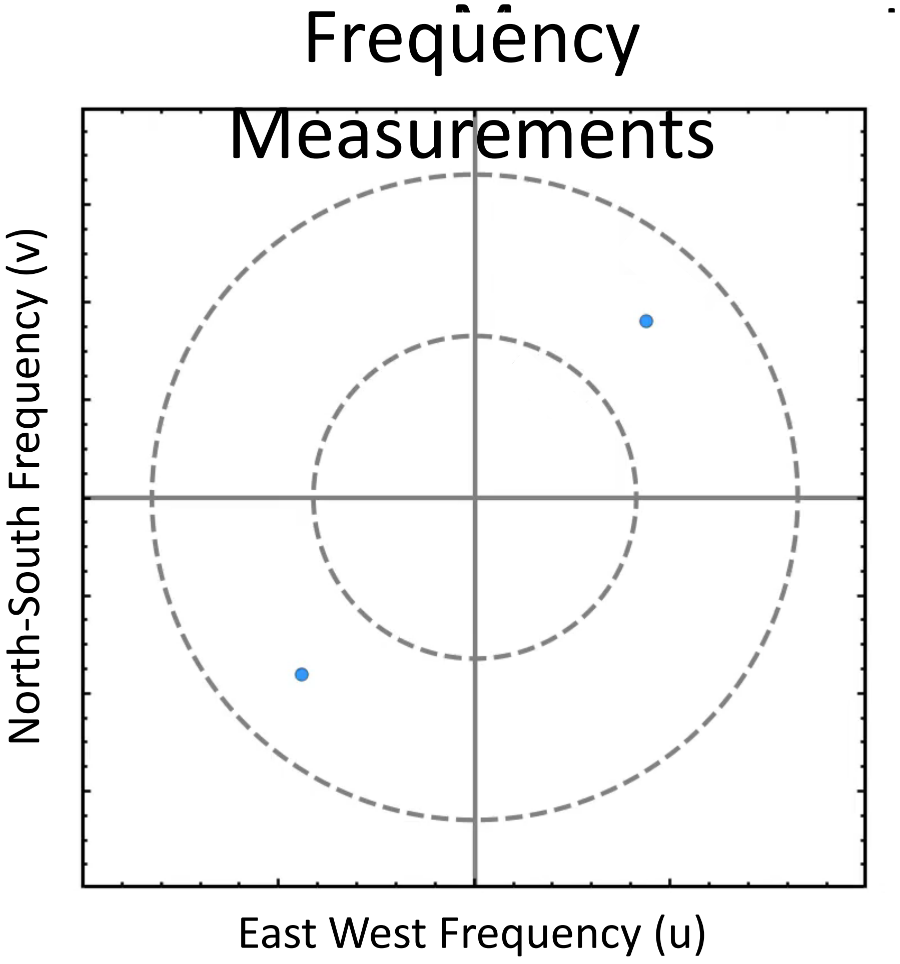


Very Long Baseline Interferometry (VLBI)



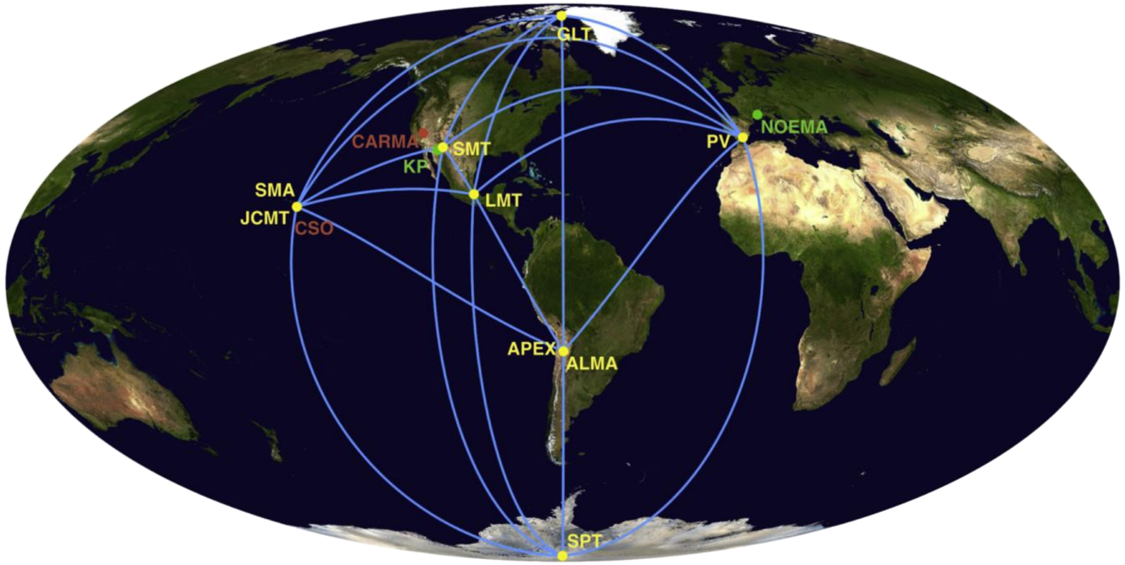


Earth’s Rotation gives us more measurements



The EHT and the VLA

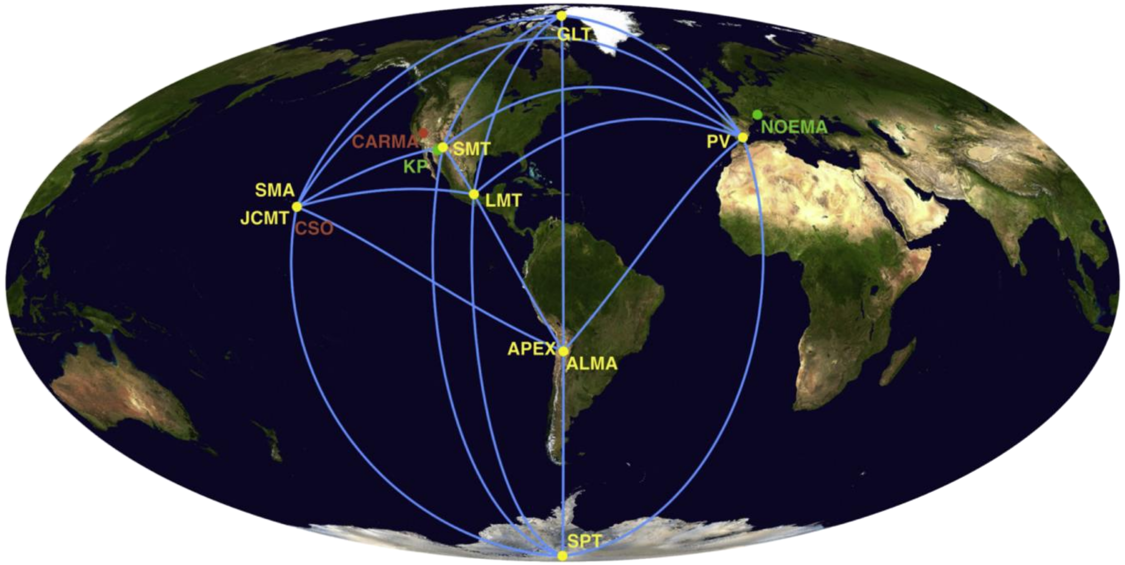
- Same basic principles are behind the EHT and other interferometric arrays like the VLA!



The EHT and the VLA

- Same are basic principles behind the EHT and other interferometric arrays like the VLA!

- EHT data are considerably harder to work with, since:
    - we have many fewer dishes
    - they are separated by much larger distances,
    - and we work at high frequencies where the atmosphere is a problem



EHT 2017

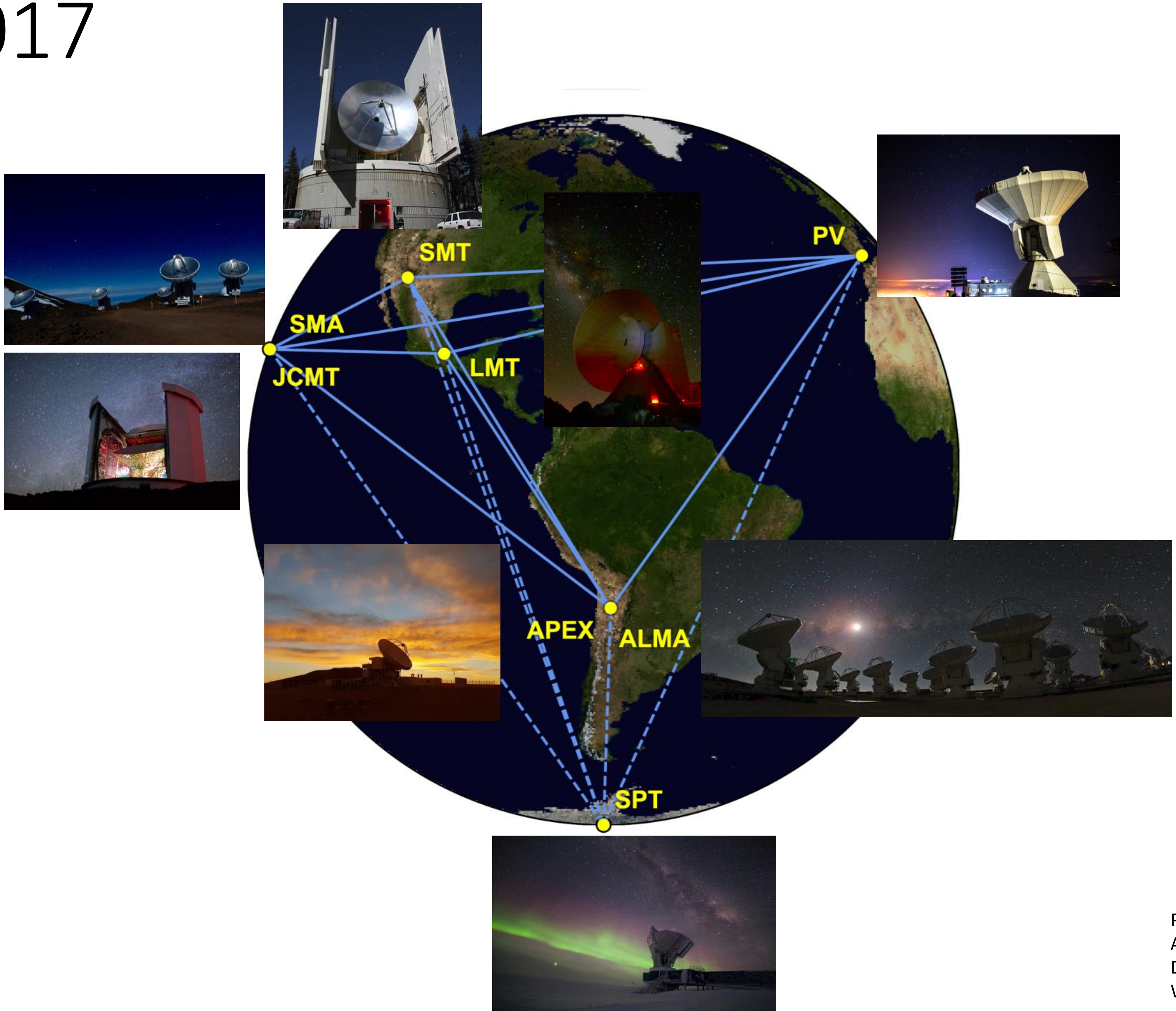
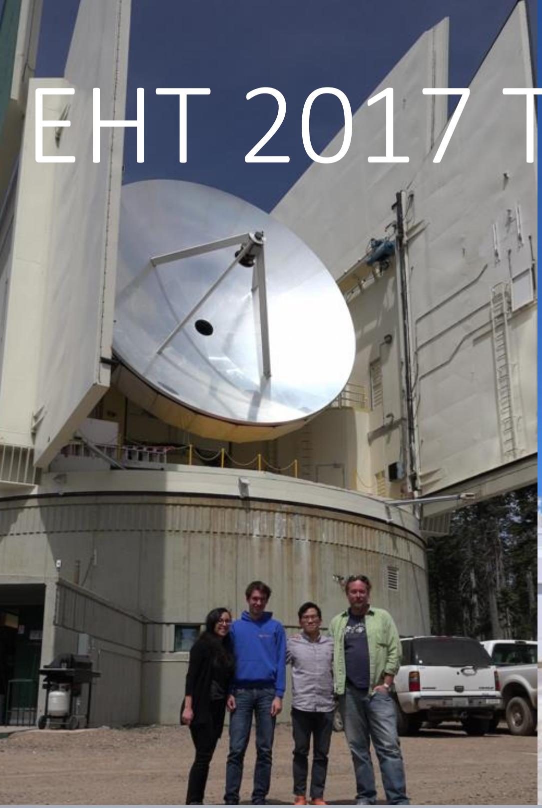
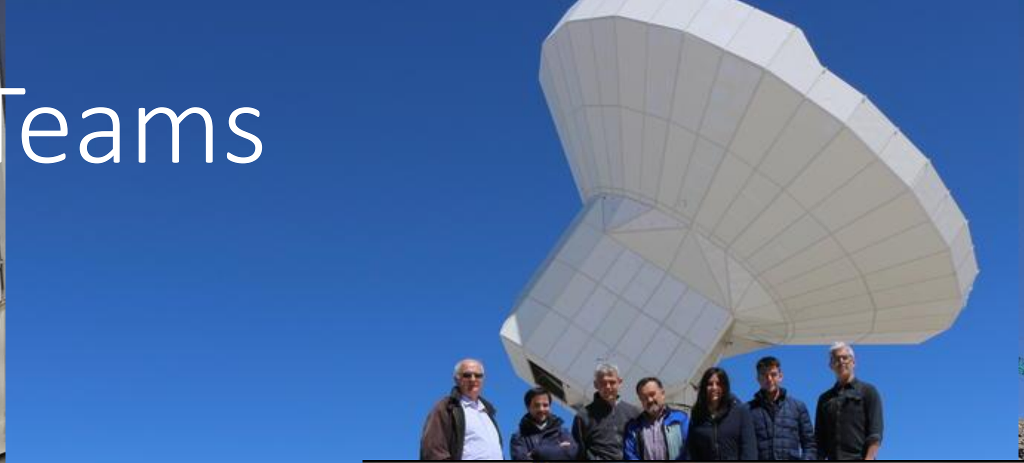


Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

EHT 2017 Teams





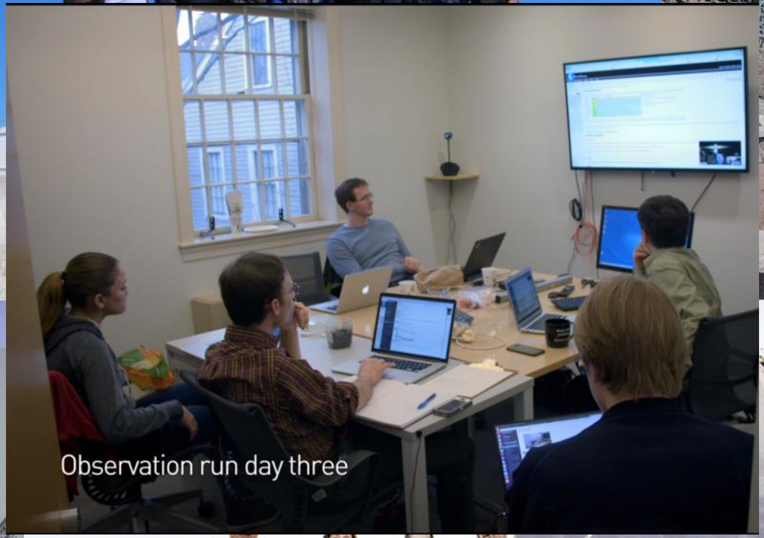
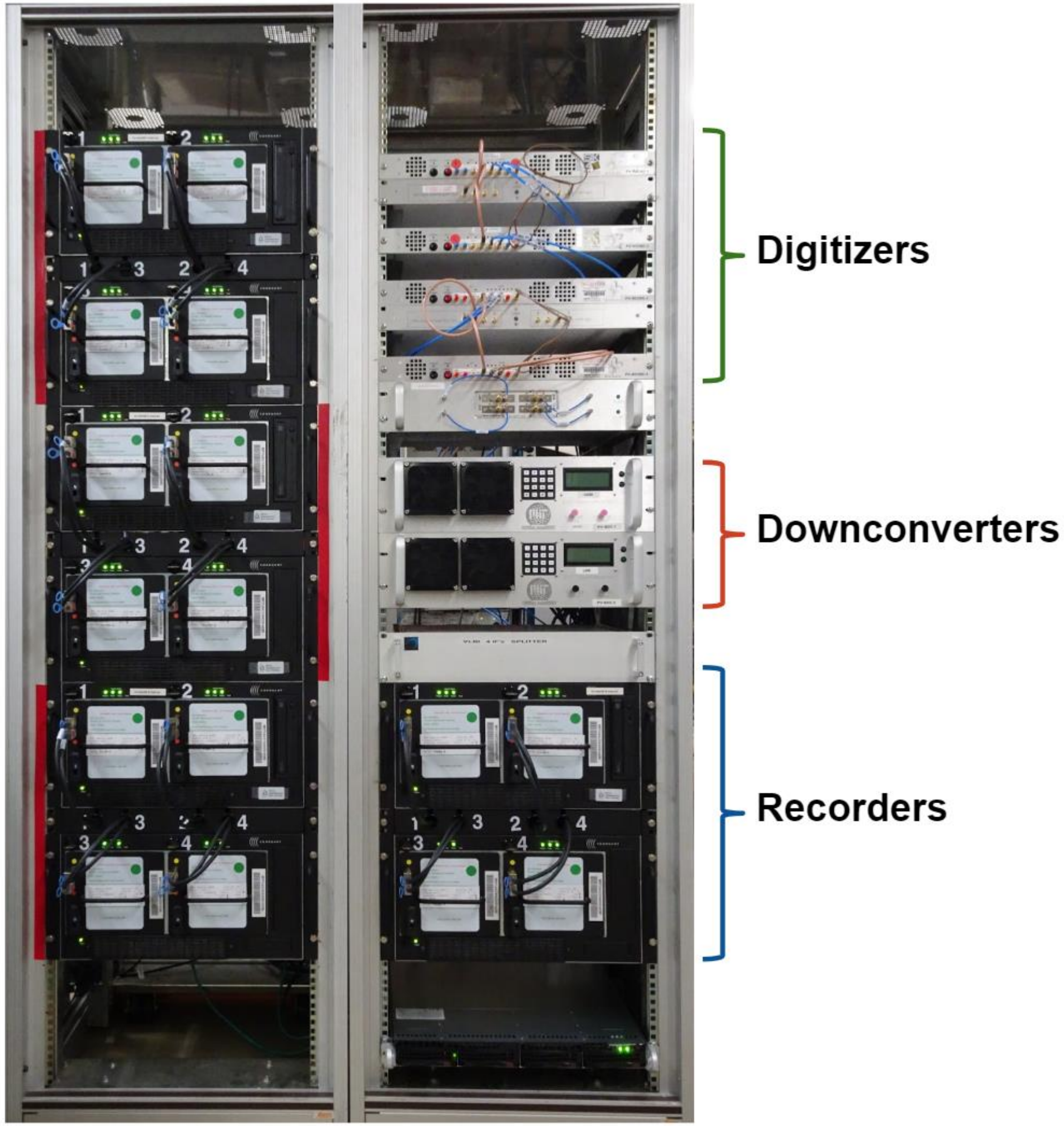
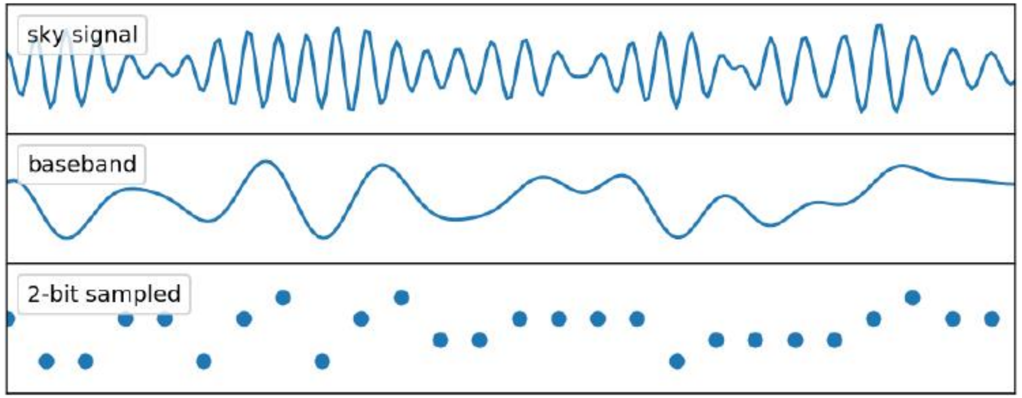
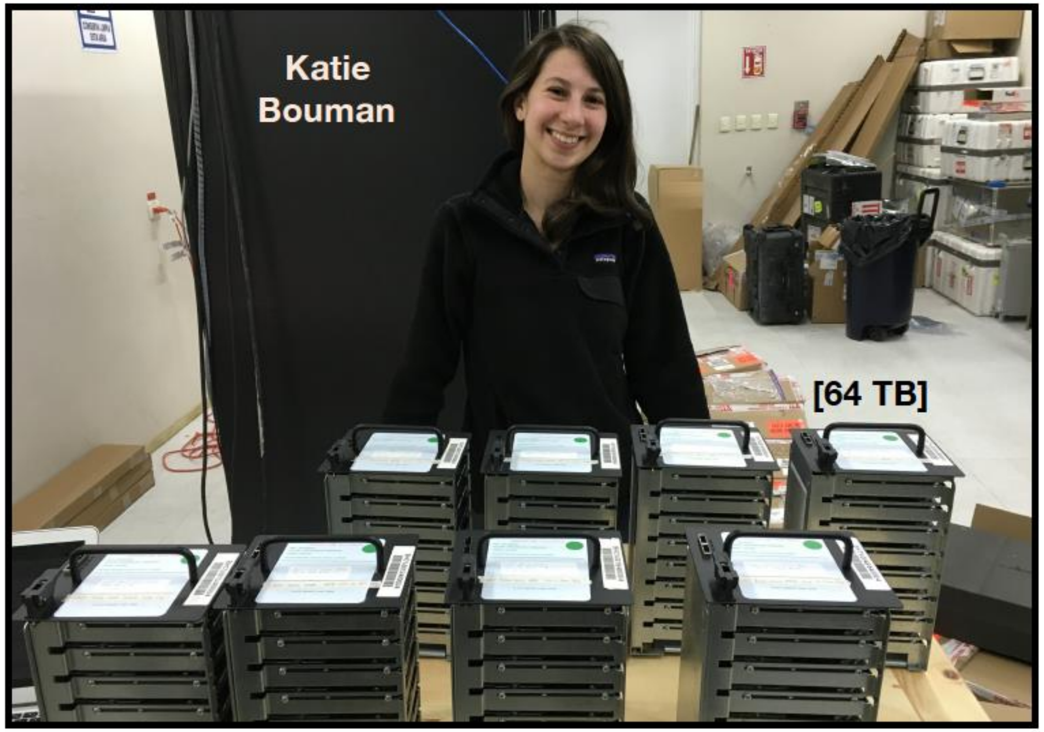


Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

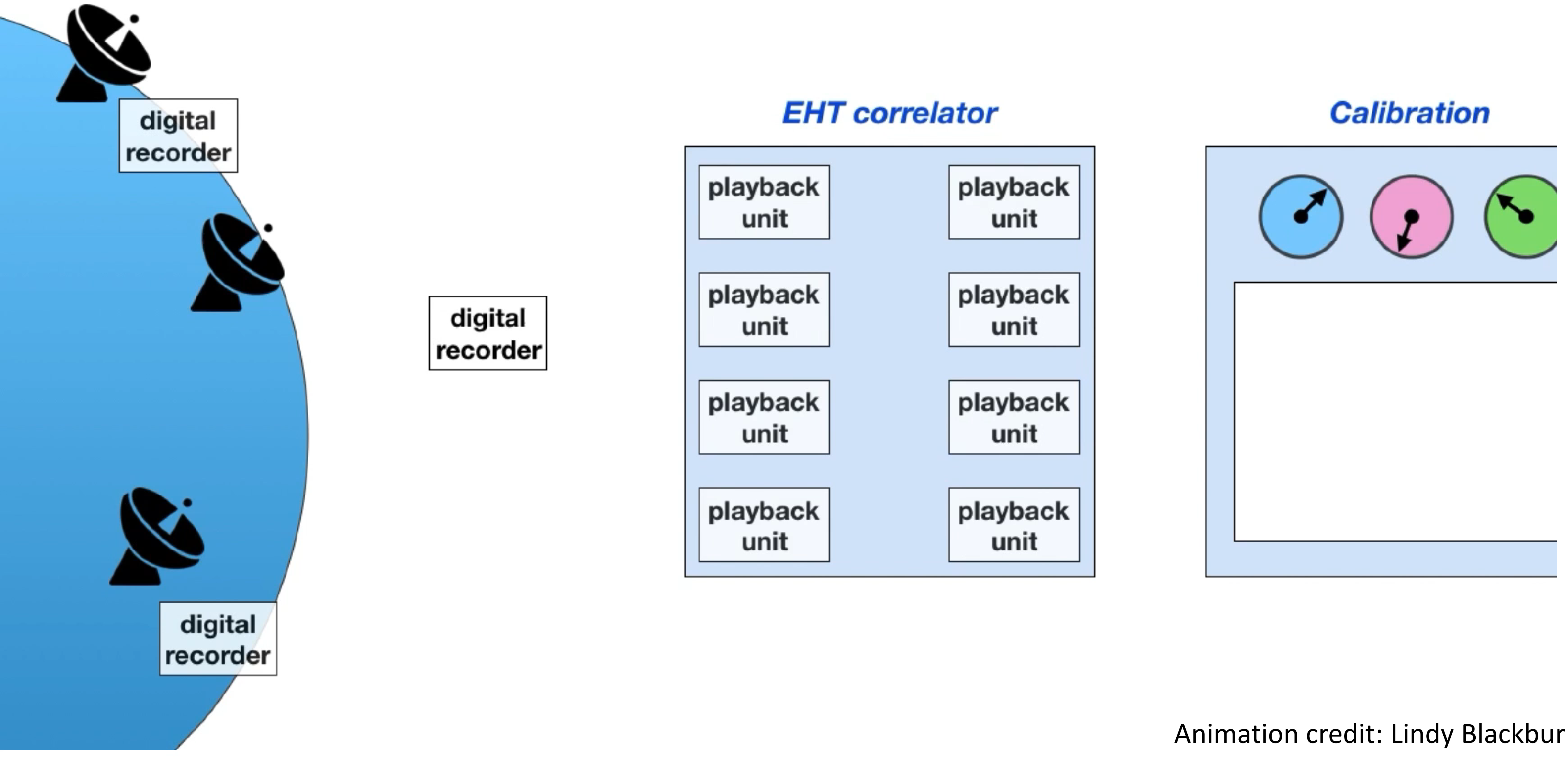
EHT Instrumentation – records data at 8 Gb/sec





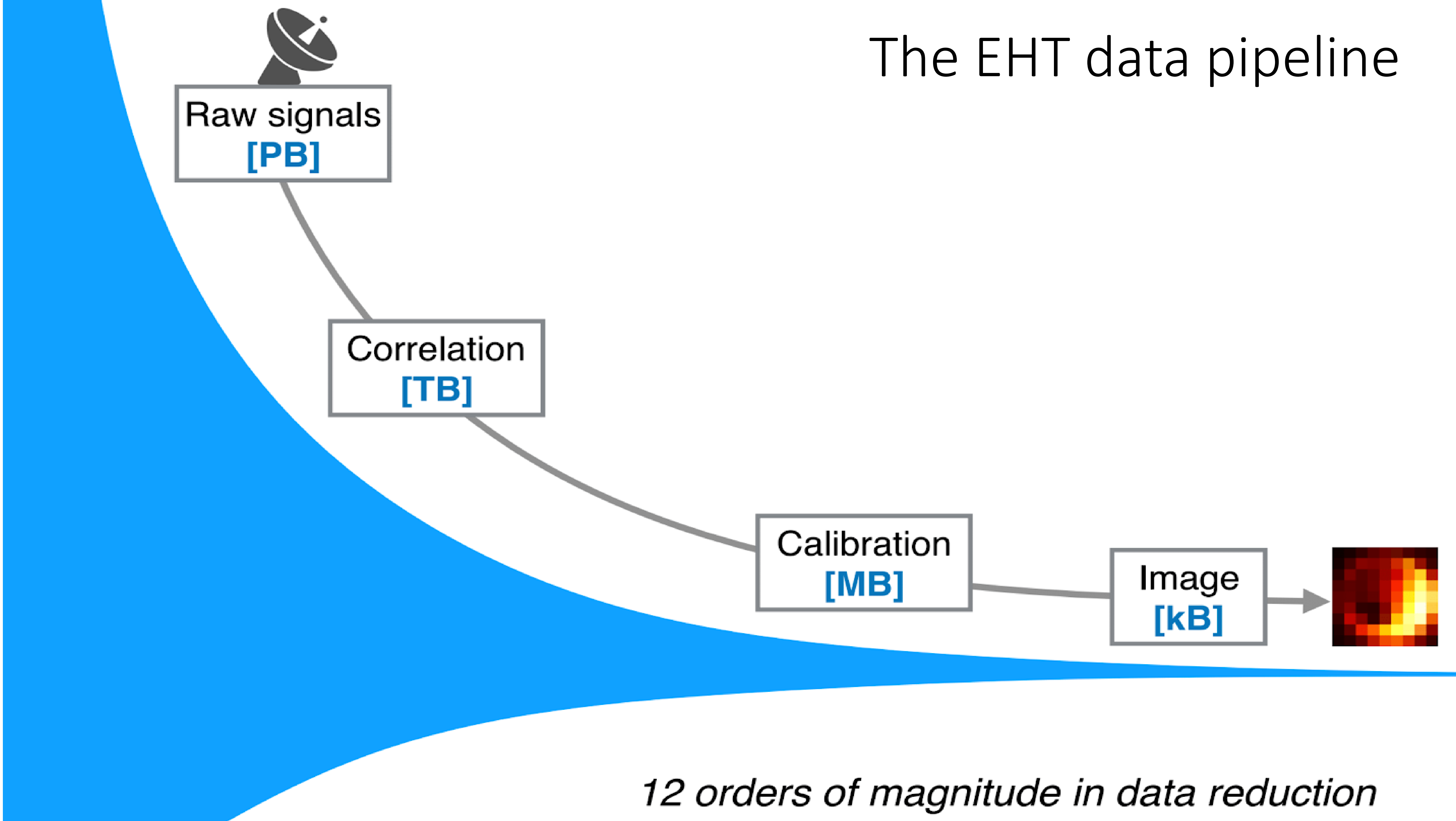


The EHT data pipeline

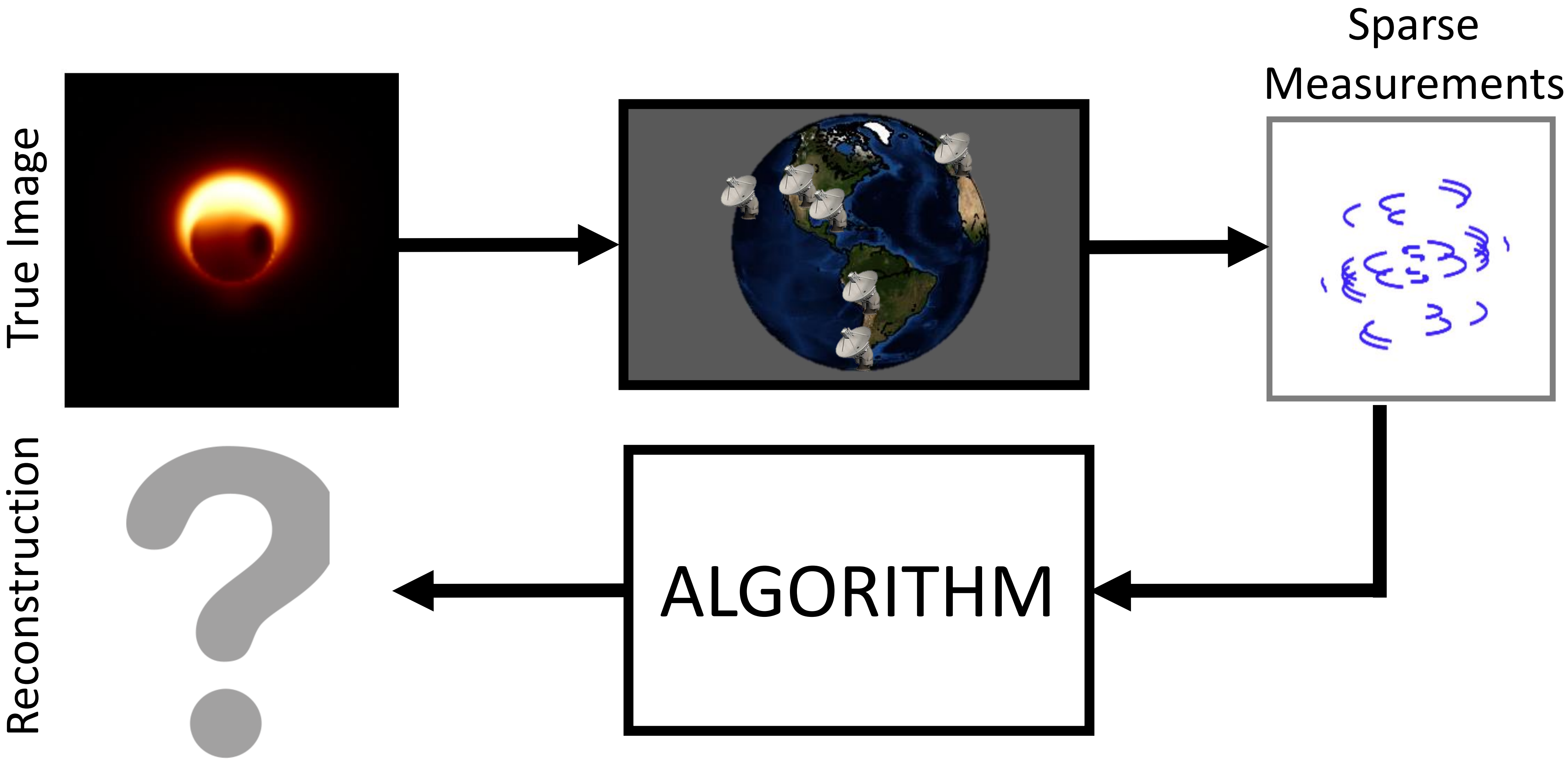


Animation credit: Lindy Blackburn

The EHT data pipeline



Solving for the Image



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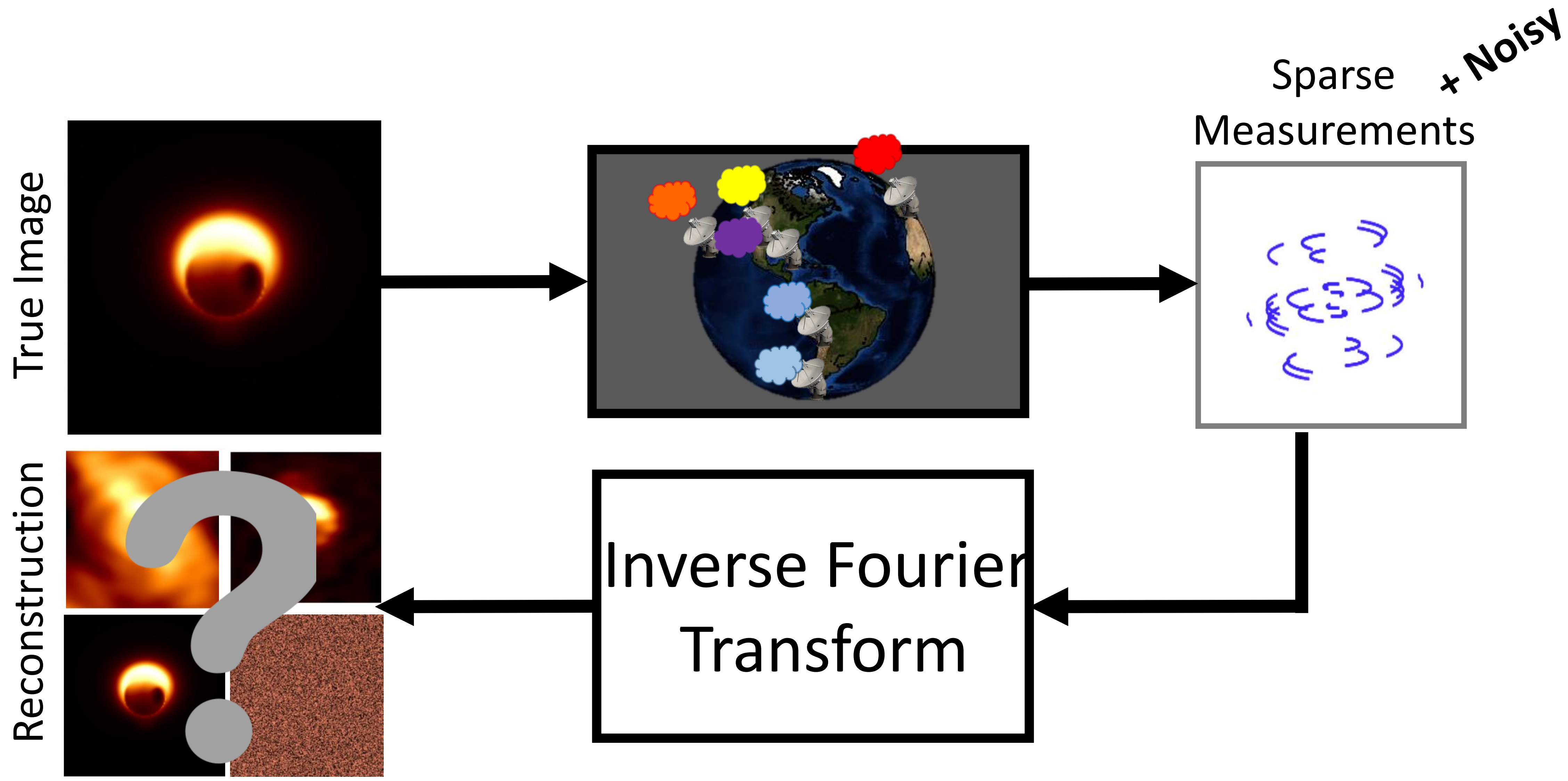
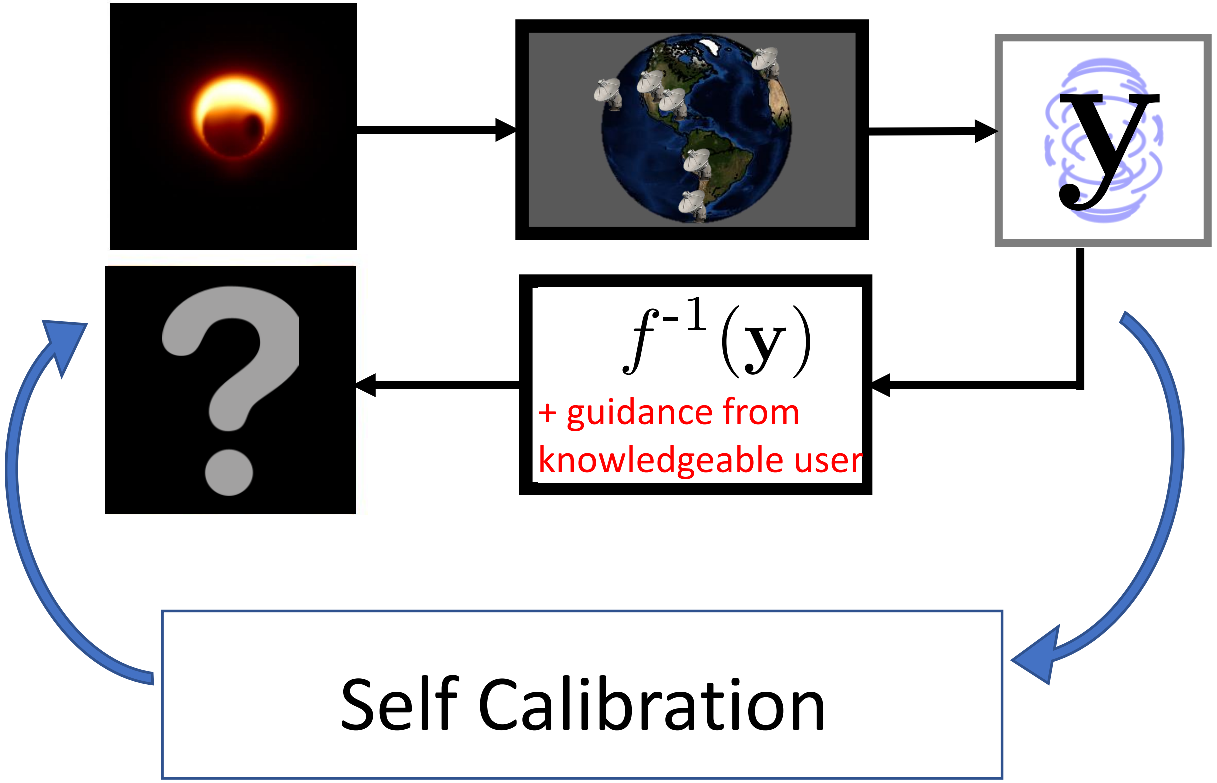
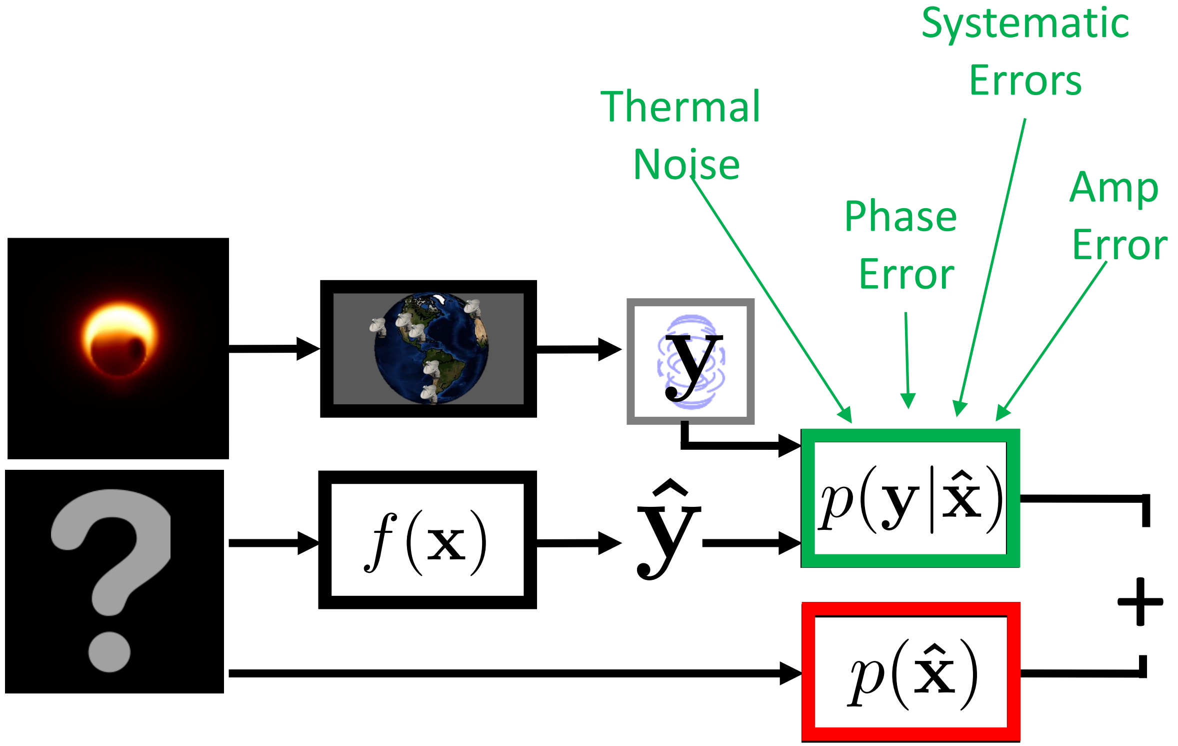


Two Classes of Imaging Algorithms



Standard Inverse Modeling
(CLEAN + Self-Calibration)



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

Forward Modeling
(Regularized Maximum Likelihood)

How do we verify what we are reconstructing is real?

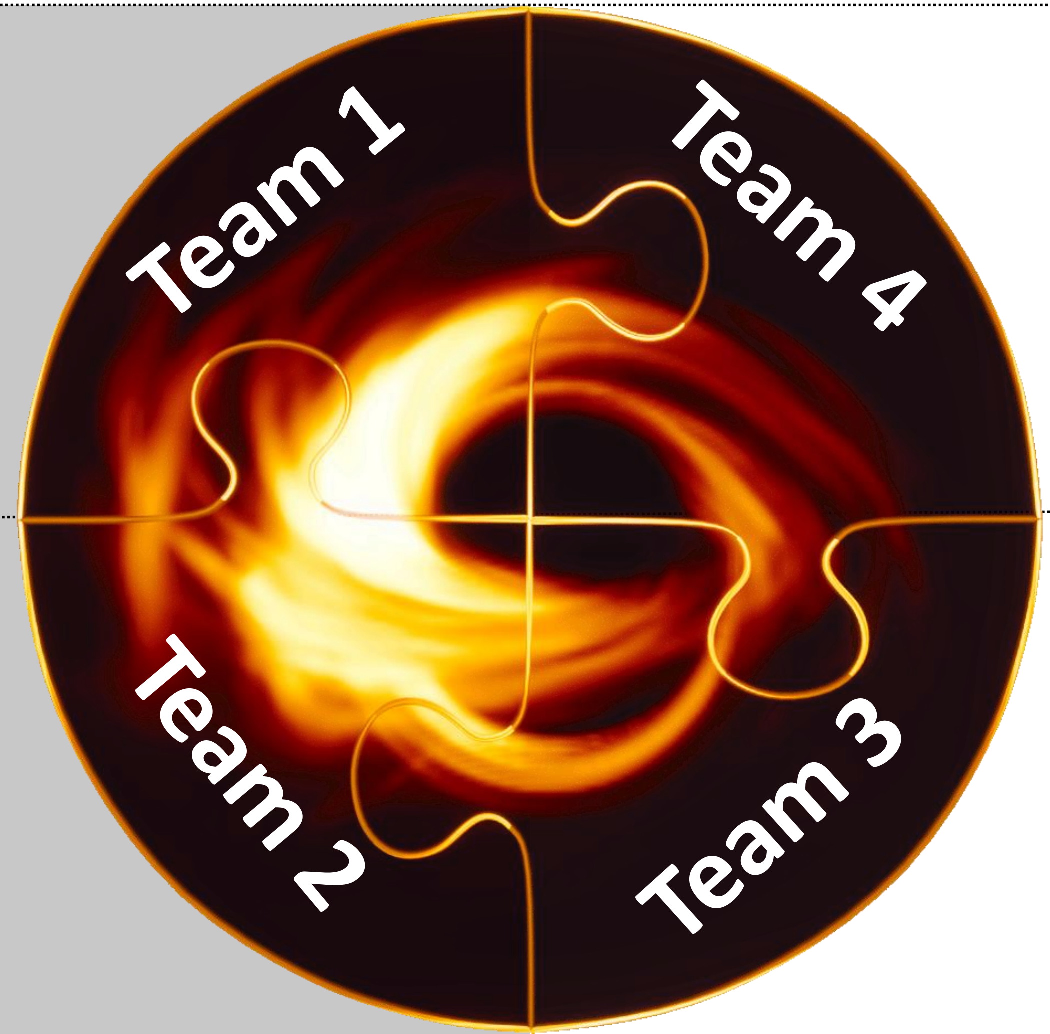
Step 1: Blind Imaging

The Americas

Harvard-Smithsonian
University of Arizona
U. Concepcion

Global

MIT Haystack
Radboud University
NAOJ



ASIAA
KASI
NAOJ

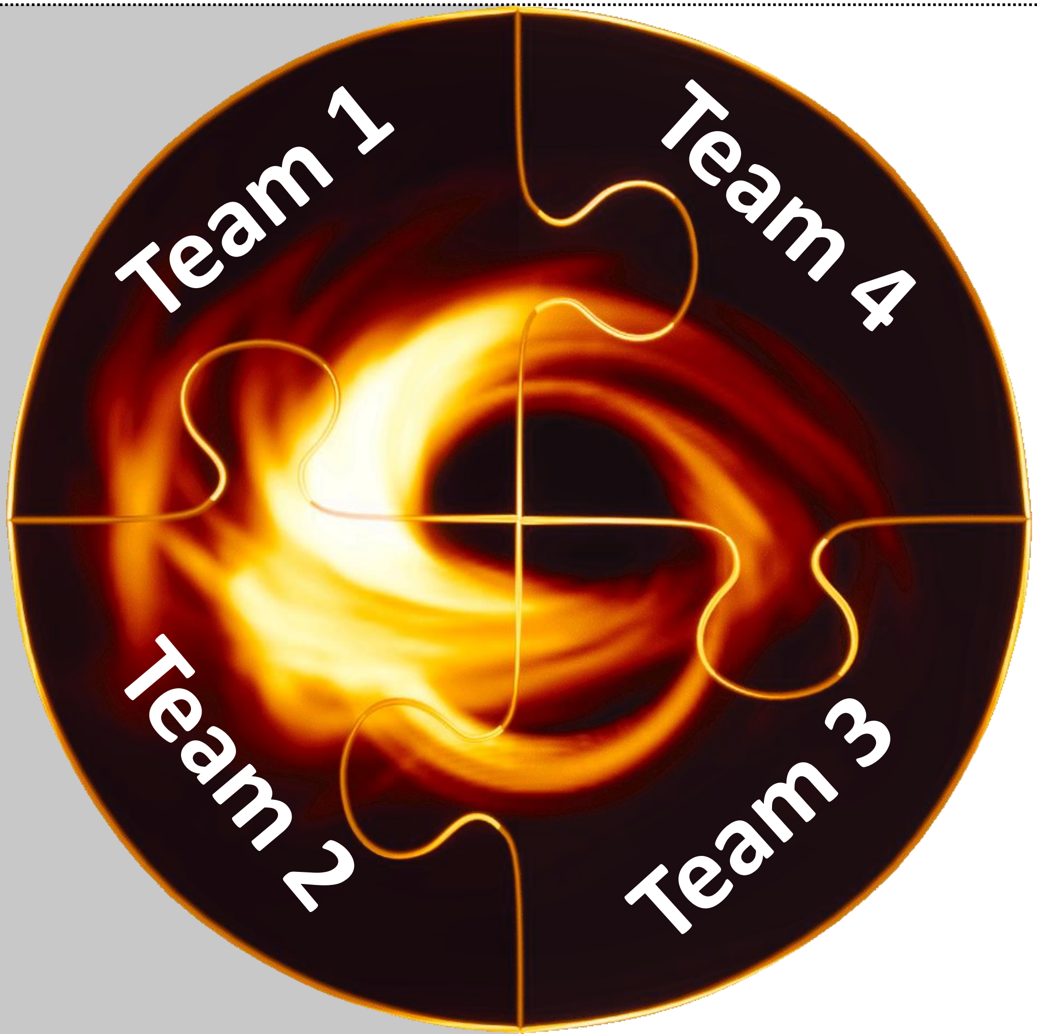
East Asia

MPIfR
Boston University
IAA
Aalto

Cross-Atlantic

Step 1: Blind Imaging

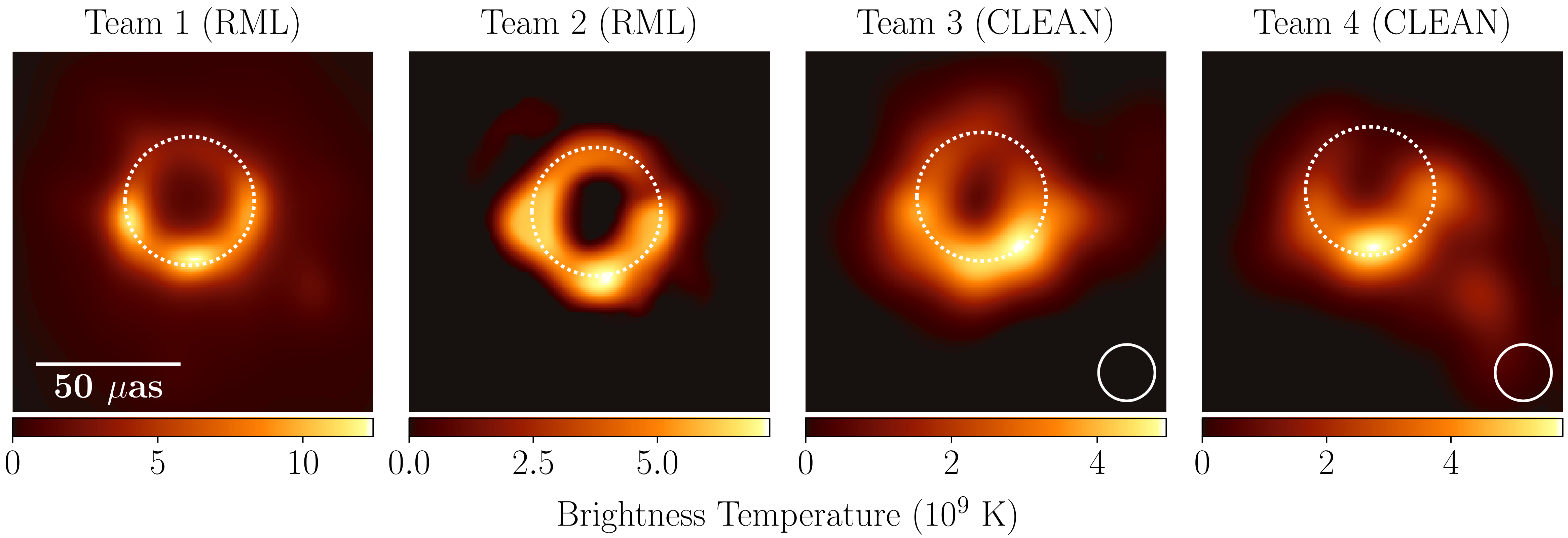
Regularized Maximum Likelihood

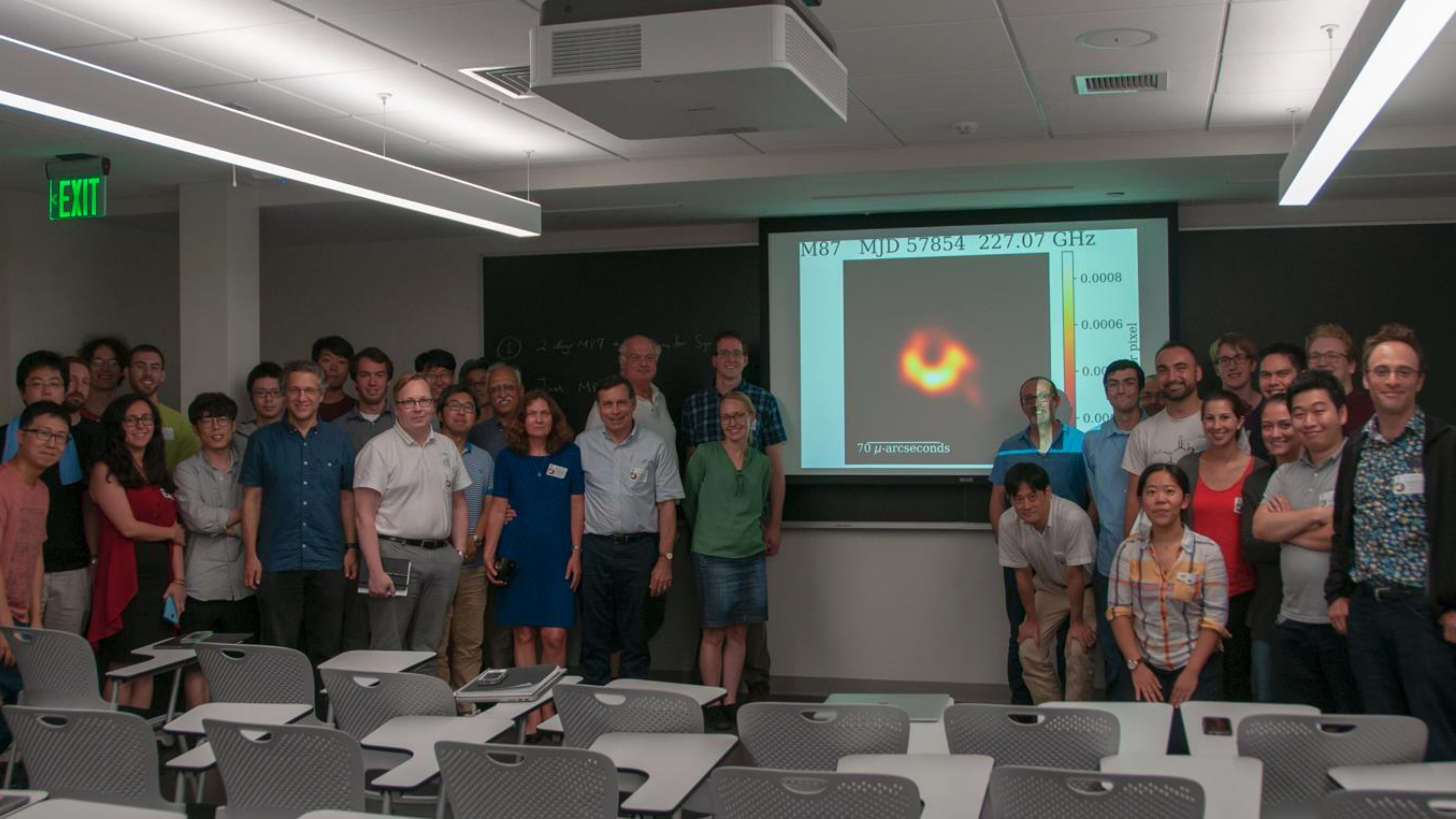


CLEAN + Self Calibration

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

My software ☺

DIFMAP
(CLEAN + Self Calibration)

Compact Flux
Stop Condition
Weighting on ALMA
Mask Size
Data Weights

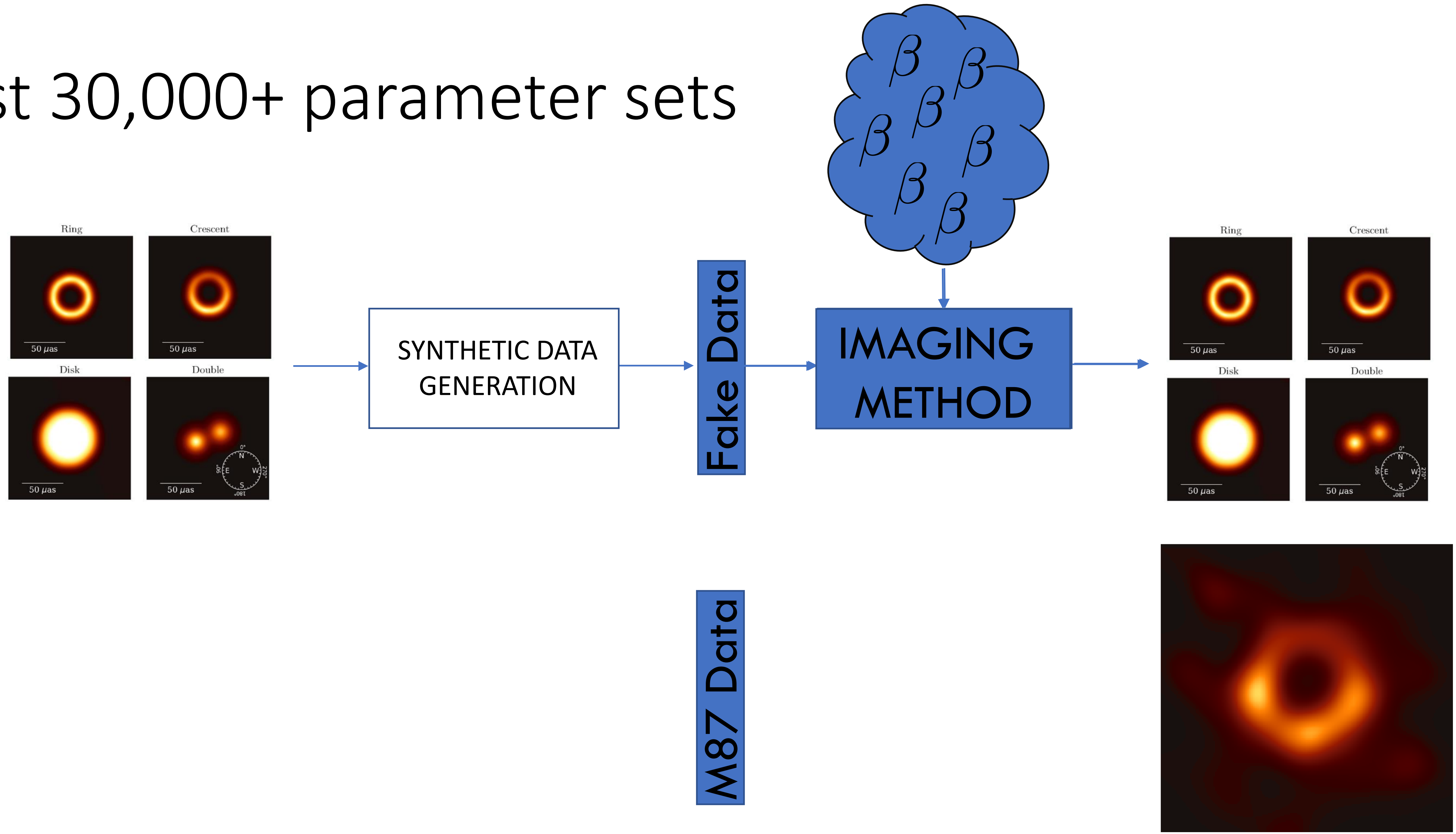
eht-imaging
(Regularized Max Likelihood)

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

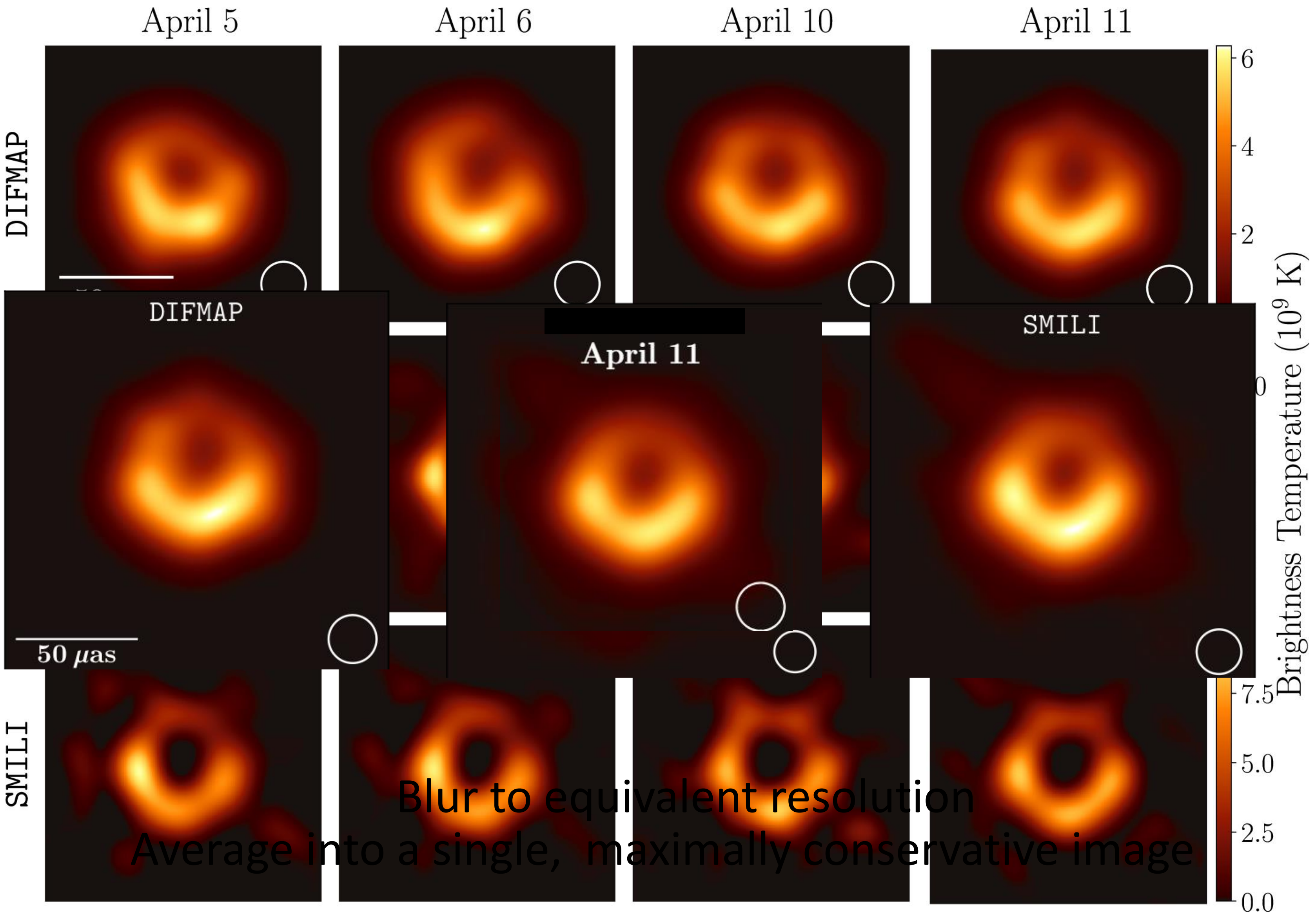
SMILI
(Regularized Max Likelihood)

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

Test 30,000+ parameter sets



Three pipelines, four days

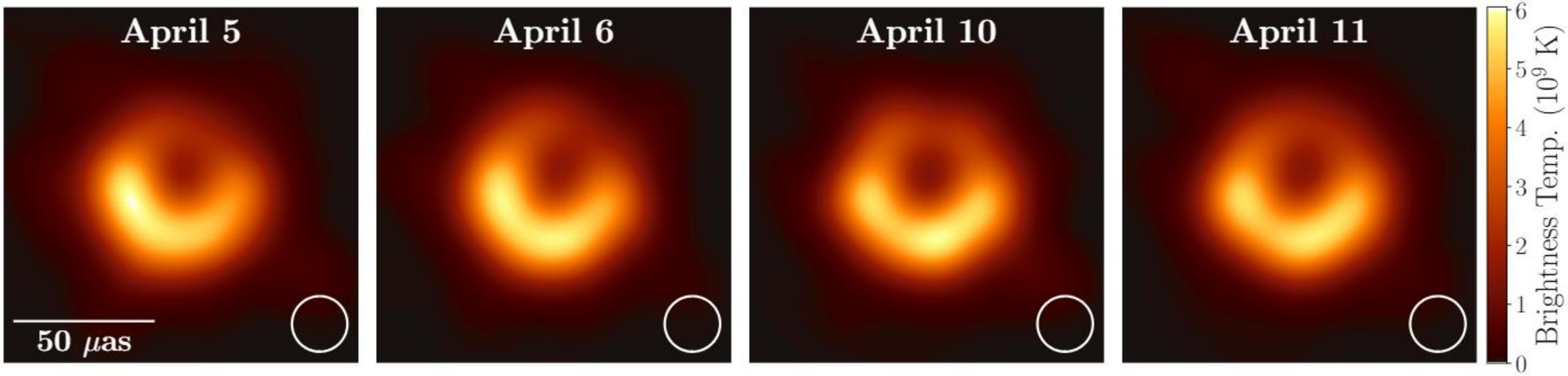


Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

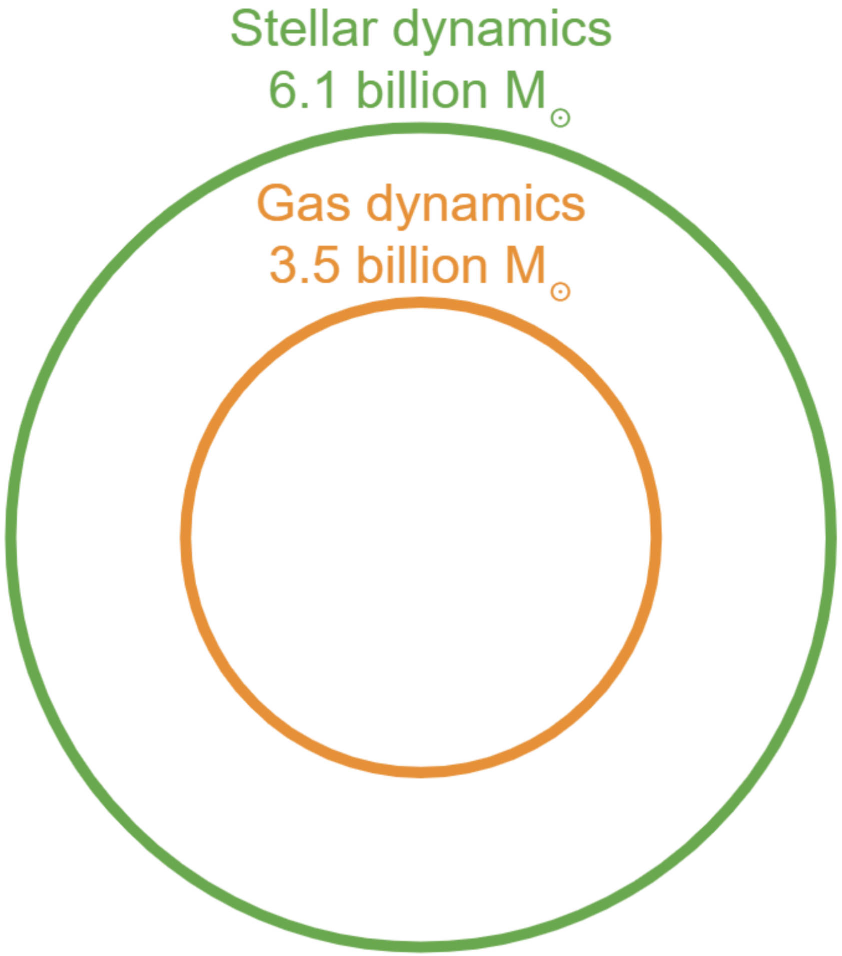
The Averaged Image From Each Day



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

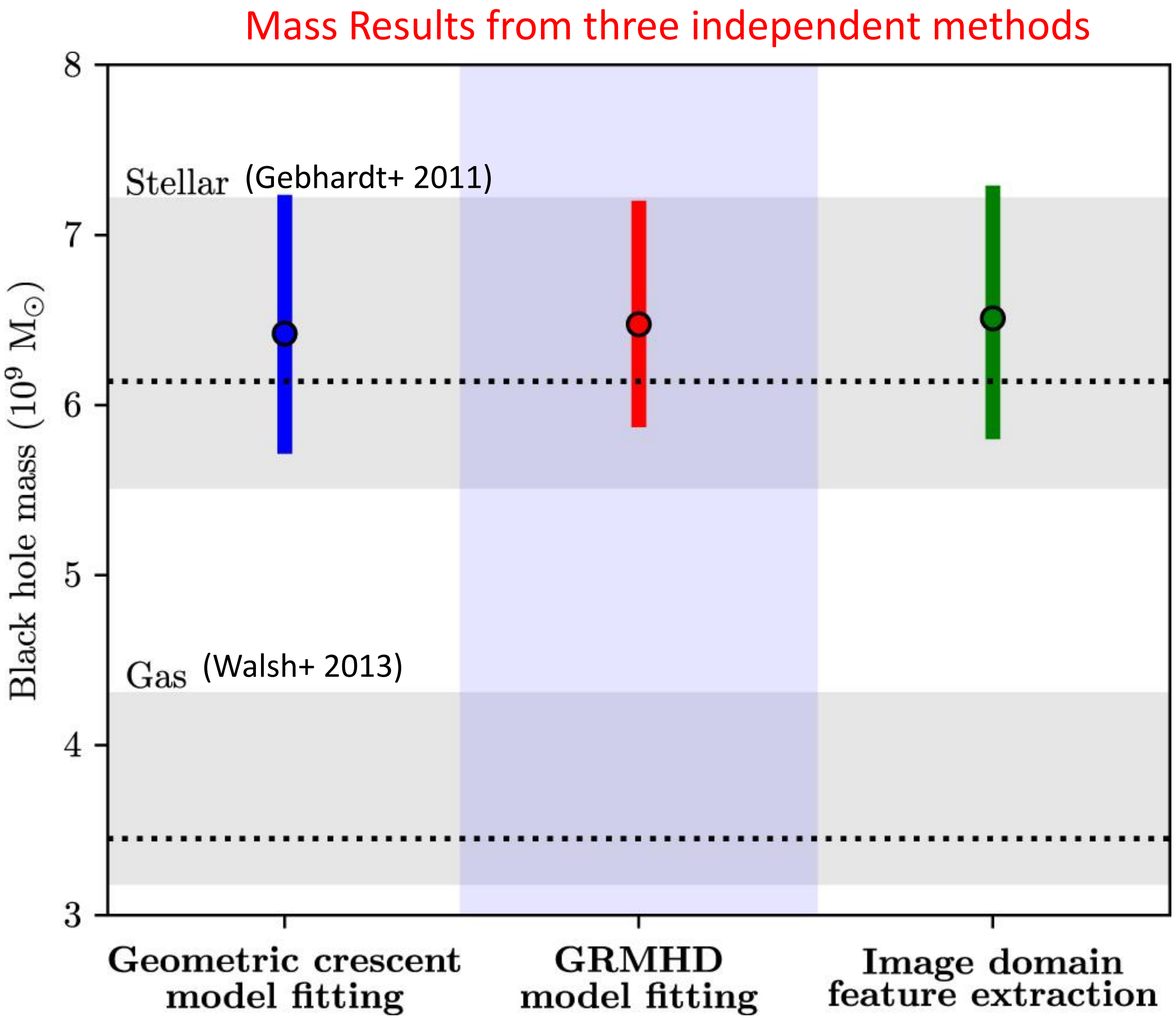
What does this image tell us?

Previous measurements of the M87 black hole mass disagreed!



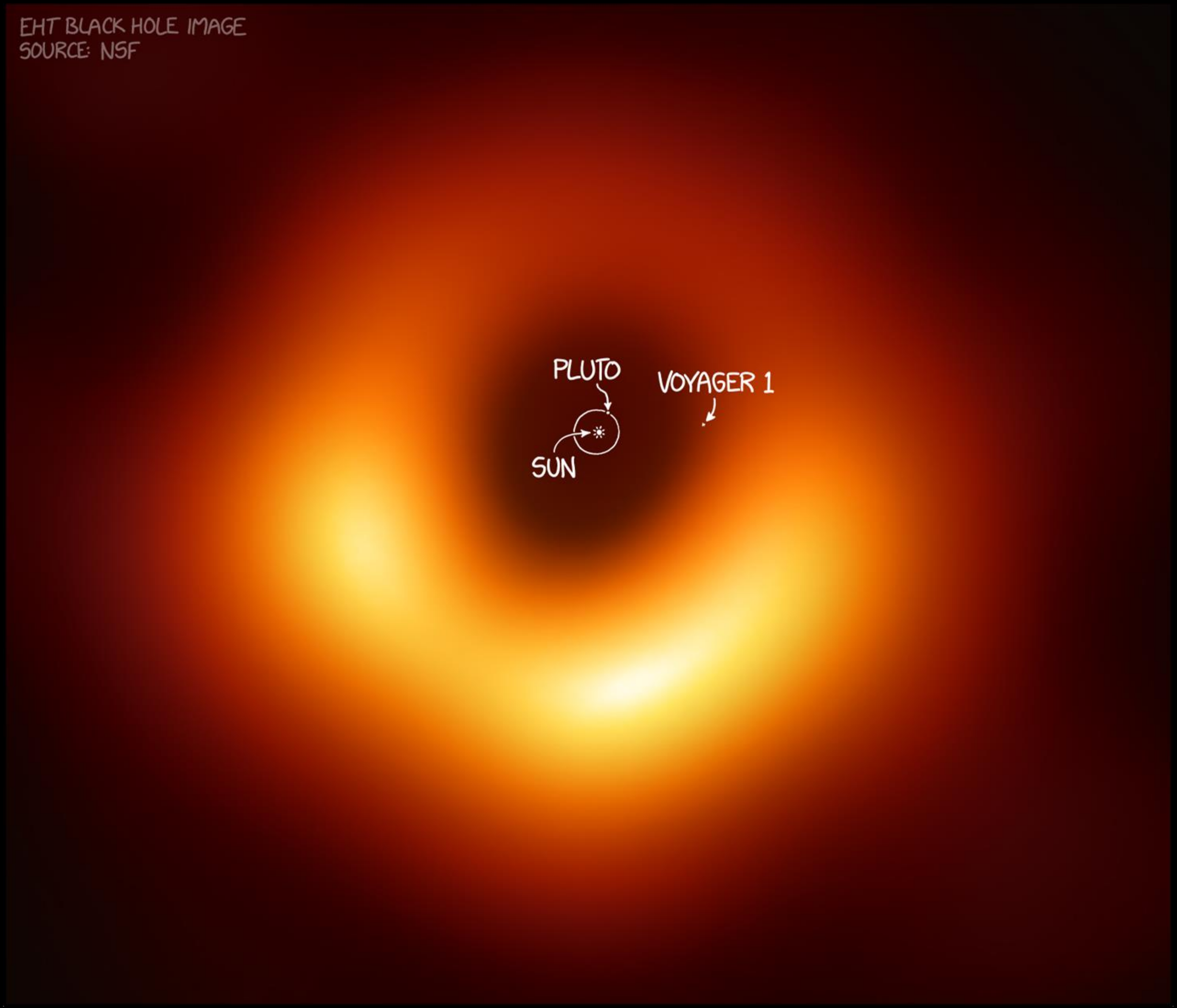
Gebhardt et al. (2011); Walsh et al. (2013)

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



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

Image Credit:
EHT Collaboration 2019 (Paper VI)



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

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

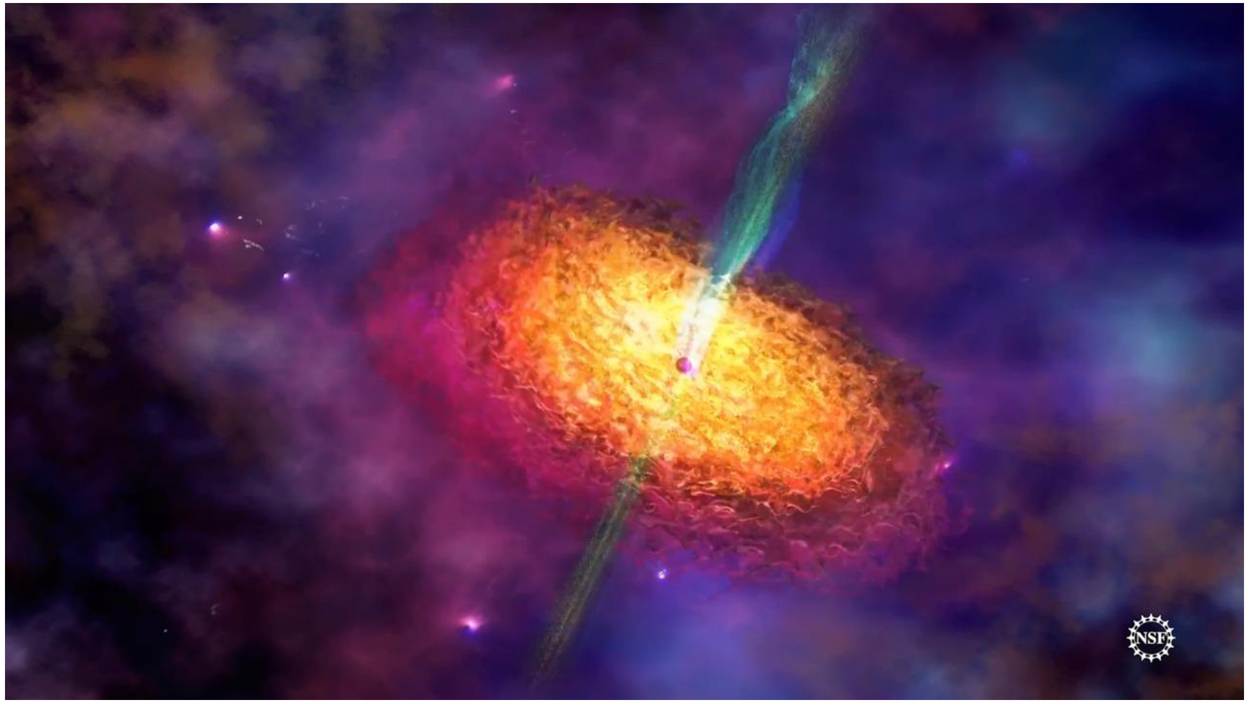
Credit: R. Munroe

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

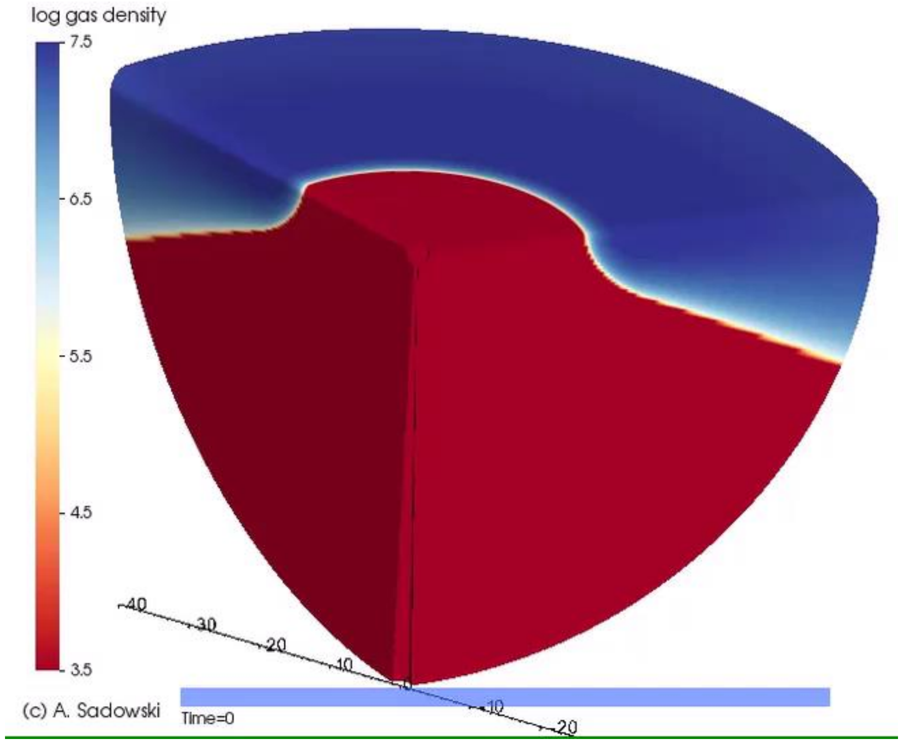
- Thick accretion disk of hot plasma (tens of billions of degrees K)
    - produces the strongest emission in sub-mm where the EHT observes!

- Strong and turbulent magnetic fields

- Launches a powerful relativistic jet

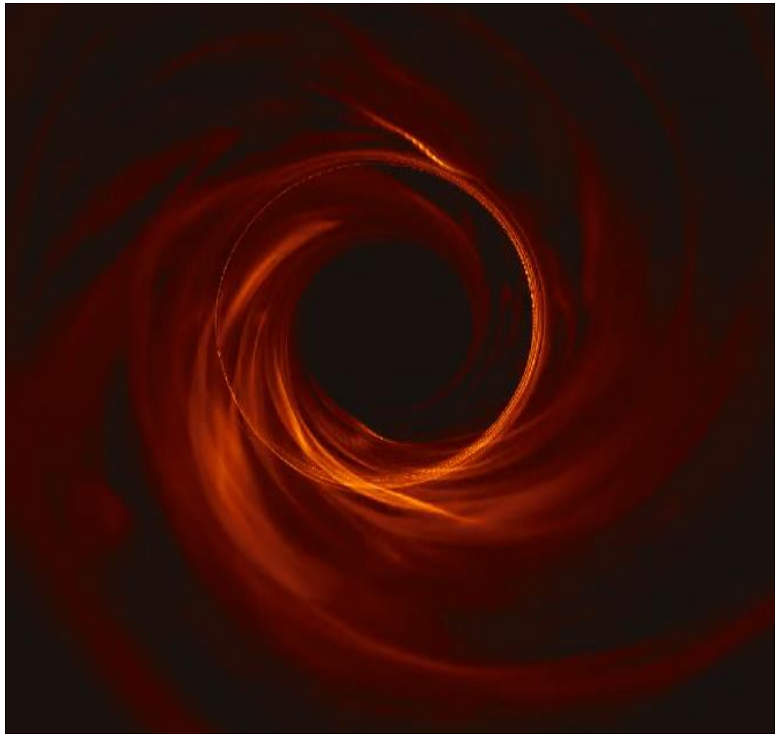


General **R**elativistic **M**agneto**H**ydro**D**ynamics



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

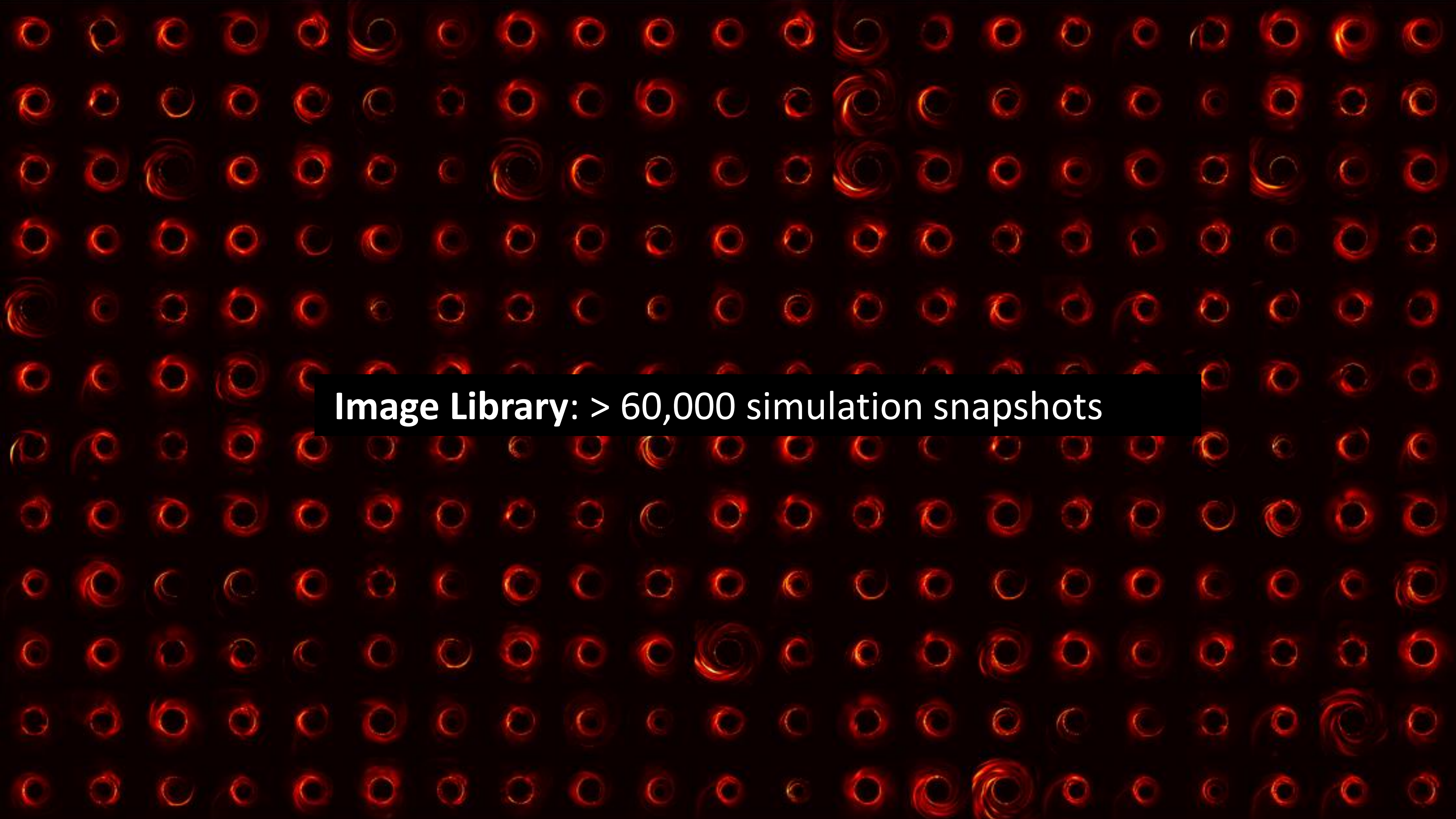
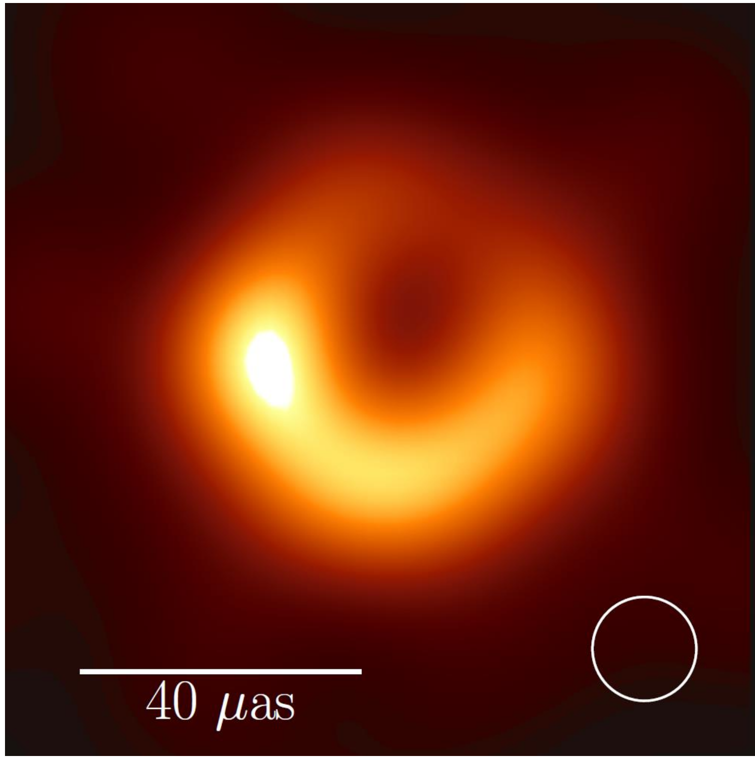


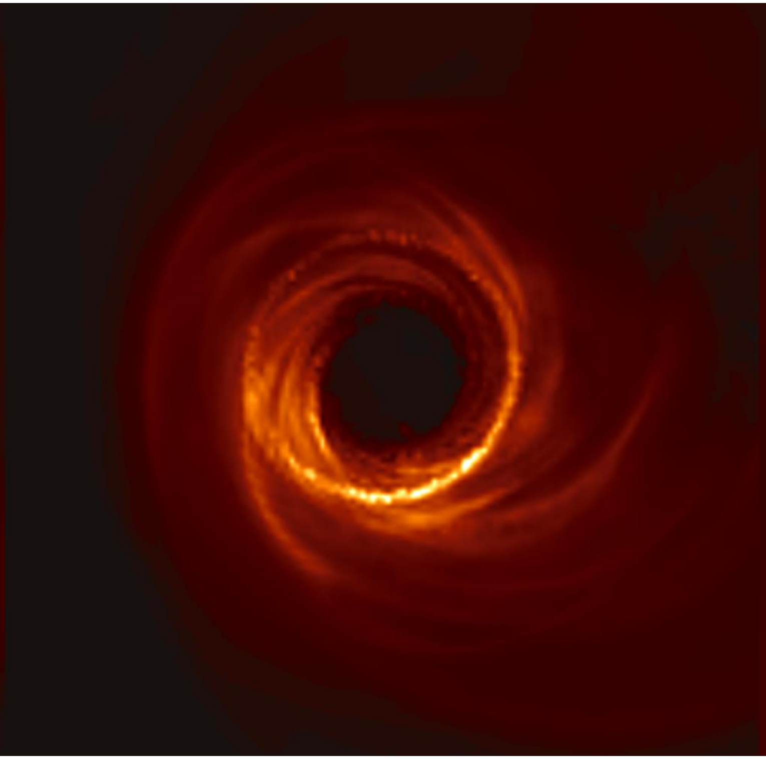
Image Library: > 60,000 simulation snapshots

Matching Simulations and Images

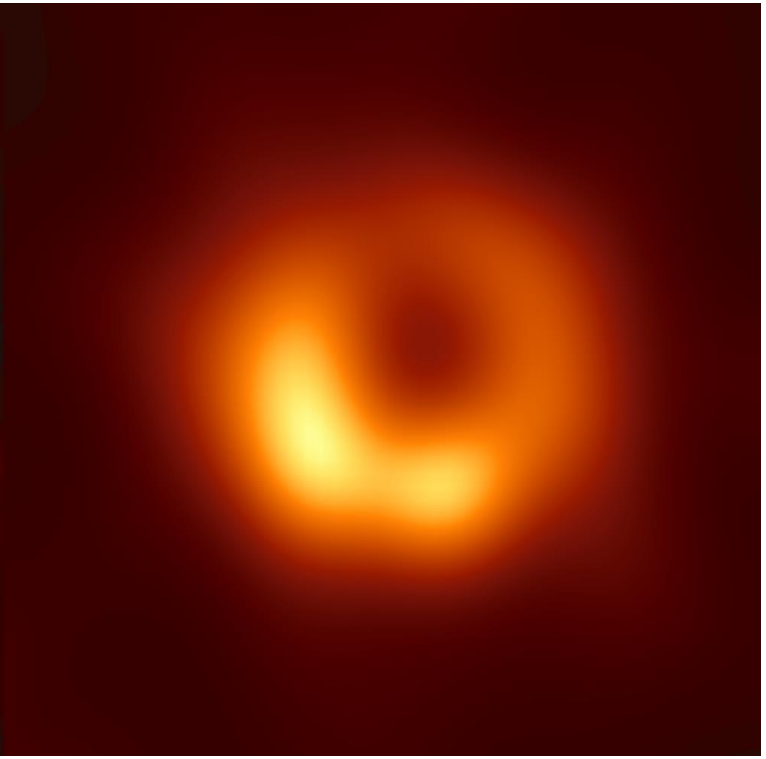
EHT 2017 image



Simulated image
from (my) GRMHD model



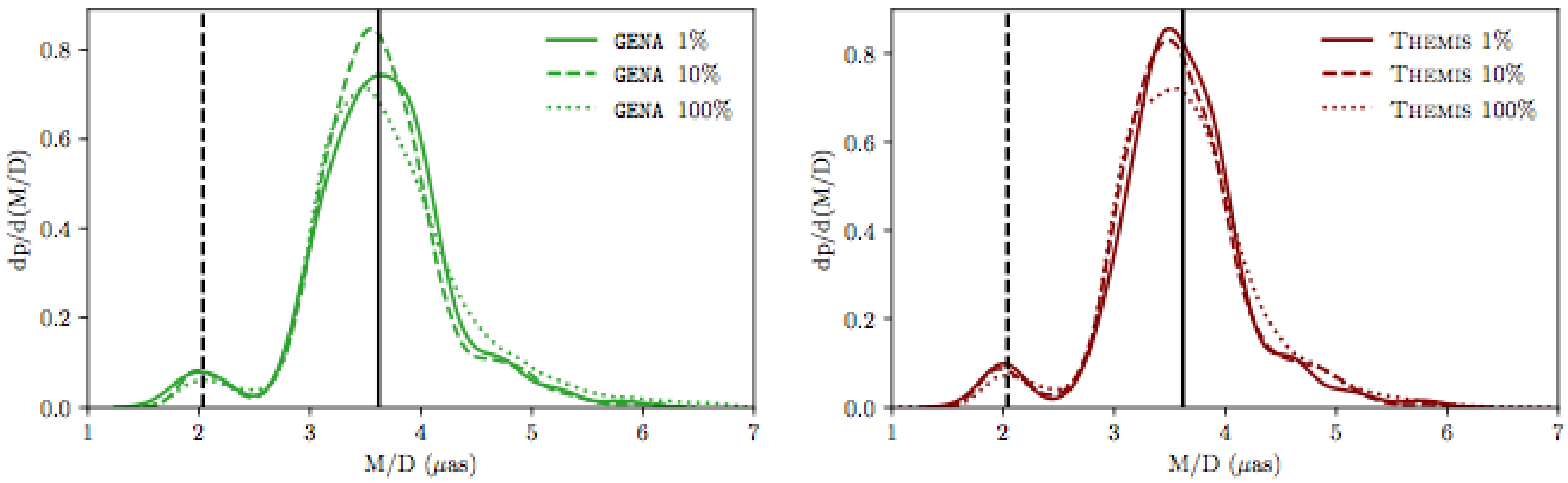
Simulated image reconstructed
with EHT pipeline



Simulation fitting results

- We 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

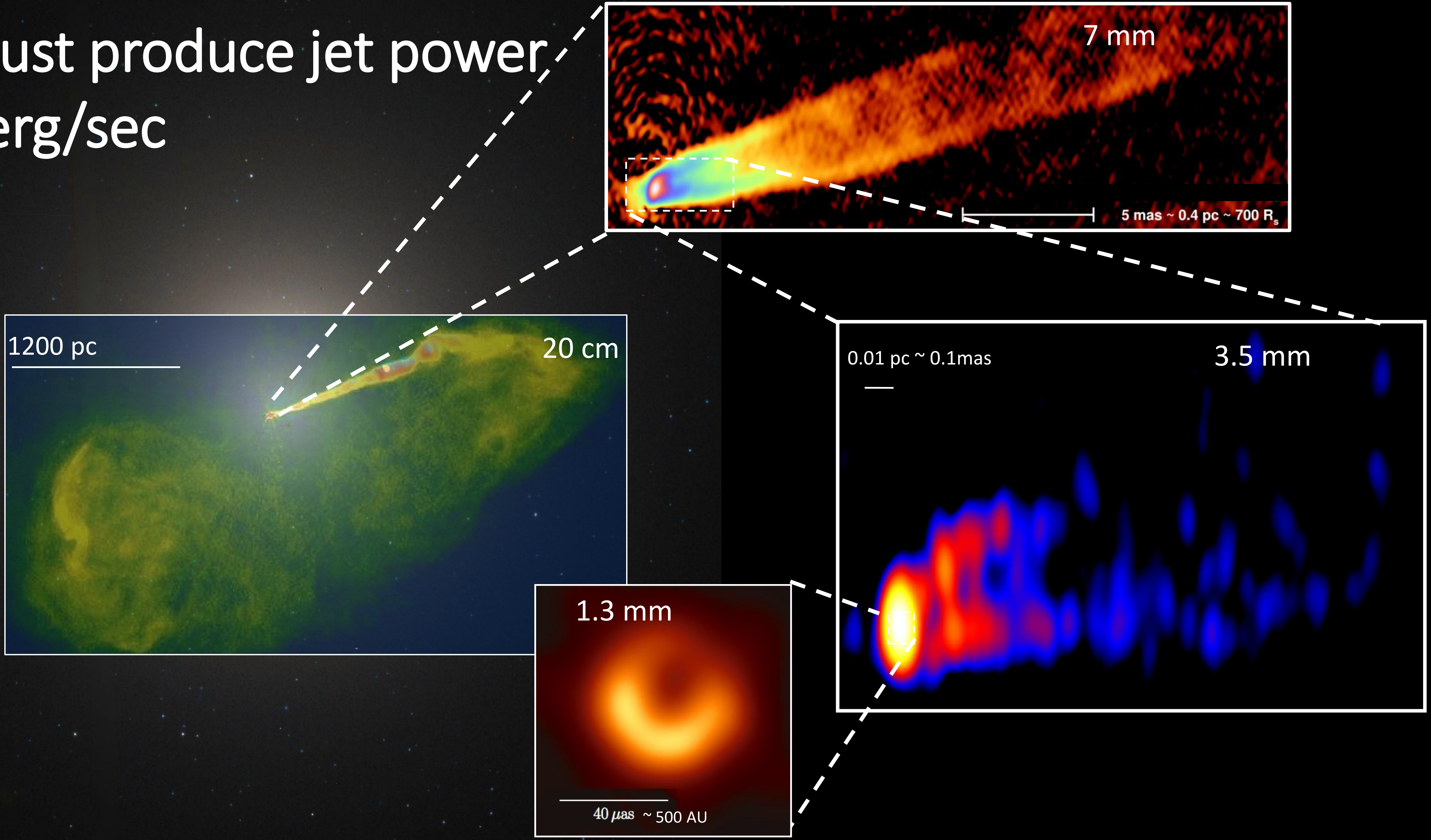


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

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):

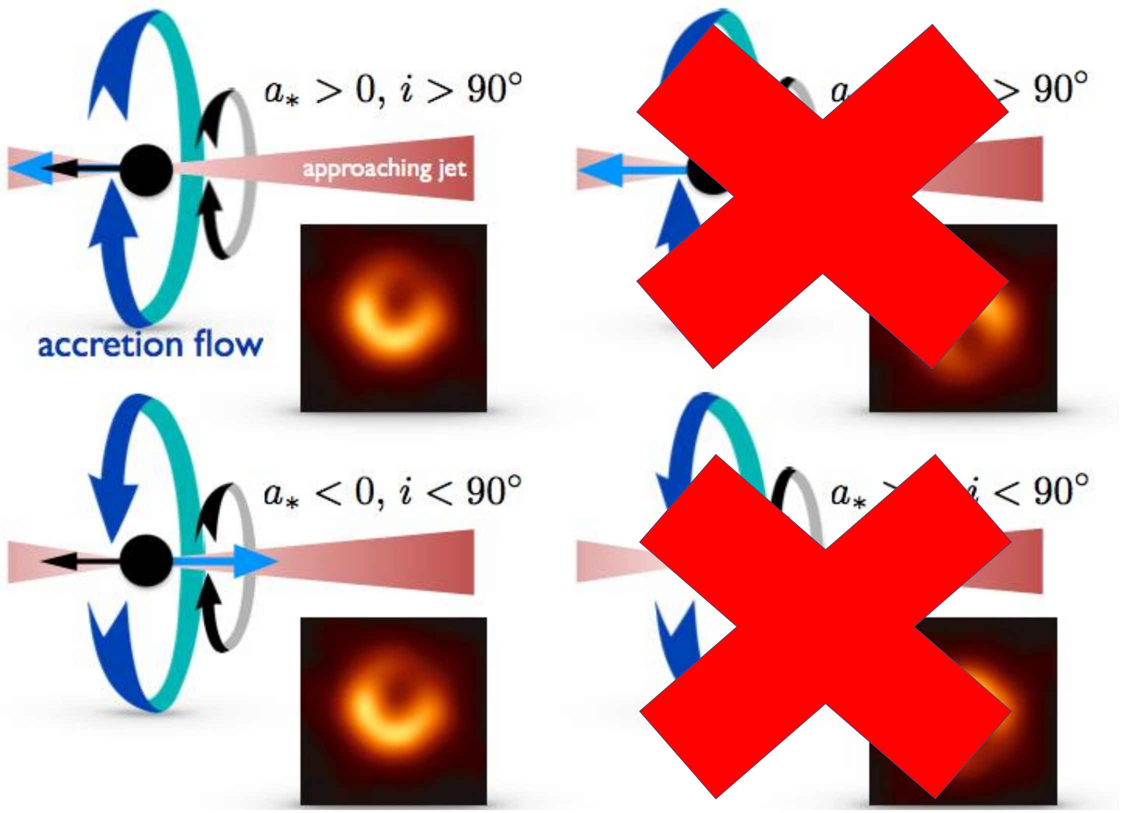
$$P_{\rm jet} \propto \Phi_{\rm mag}^2 \Omega_{\rm H}^2 / c$$

Magnetic flux

Angular velocity of the horizon

Ring Asymmetry and Black Hole Spin

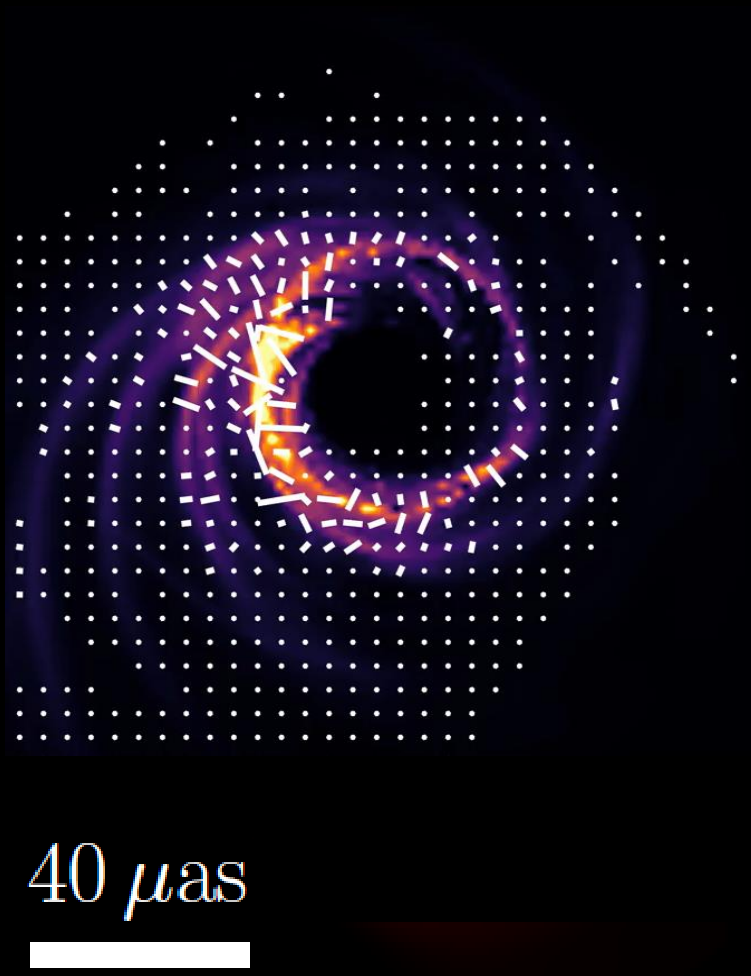
BH angular momentum determines the image orientation

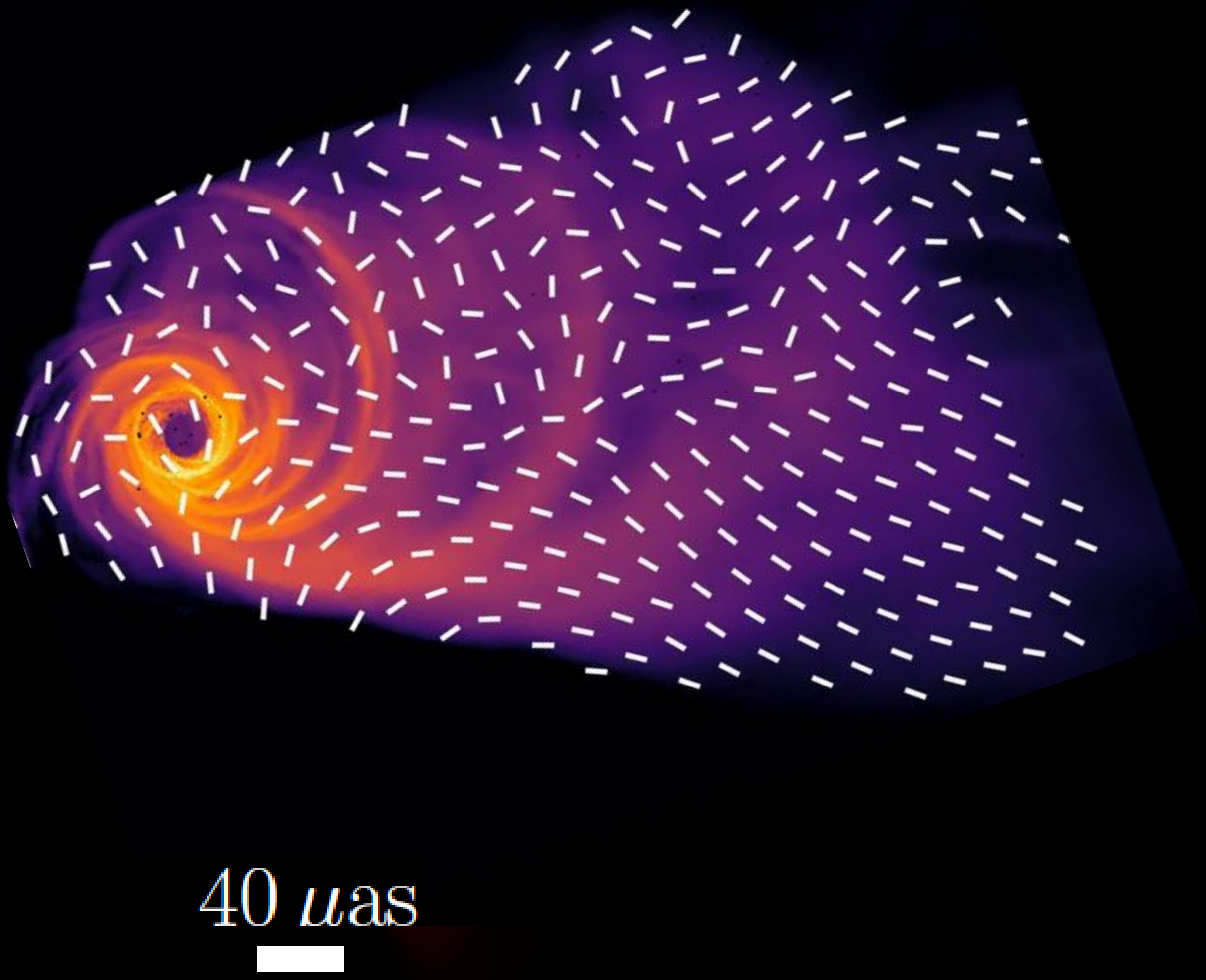


BH spin-away (clockwise rotation) models are strongly favored

Next Steps

Next Steps: Polarization!





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

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

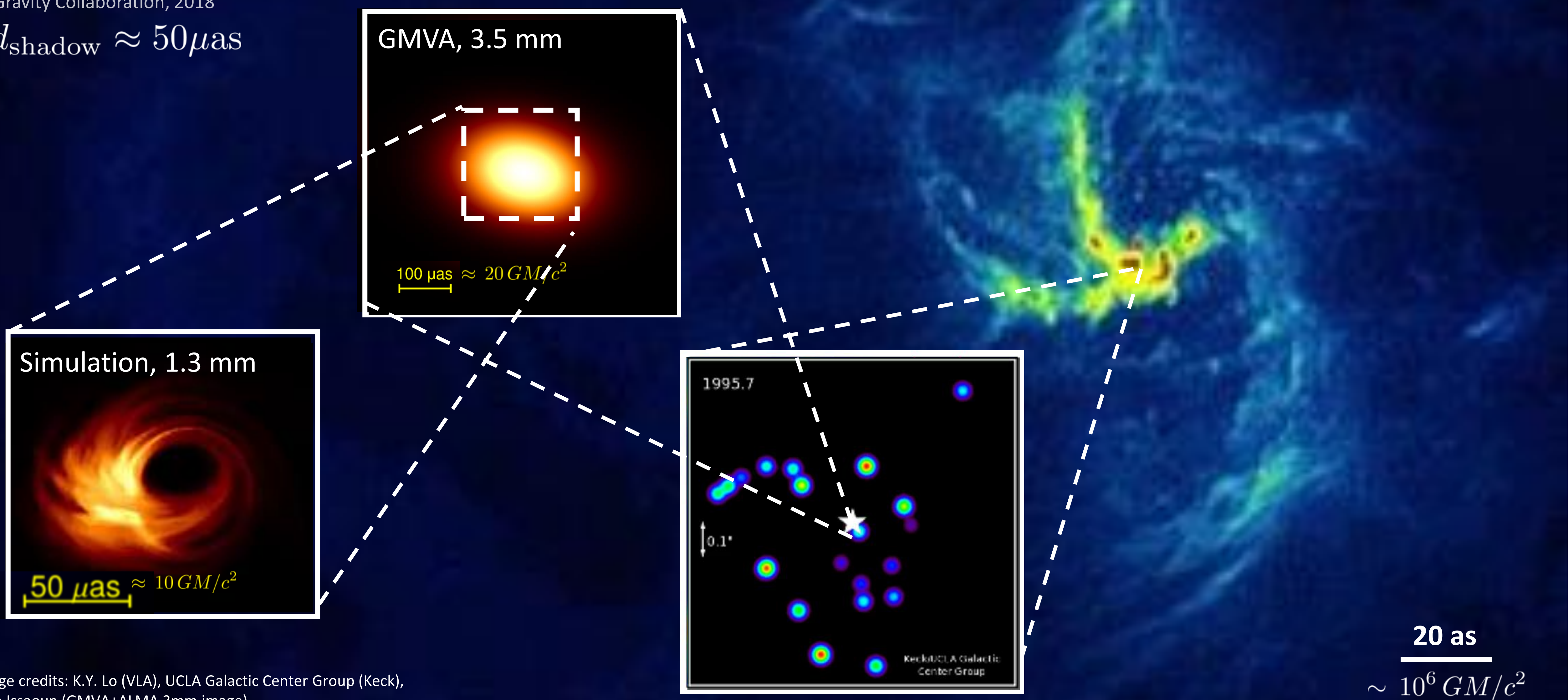
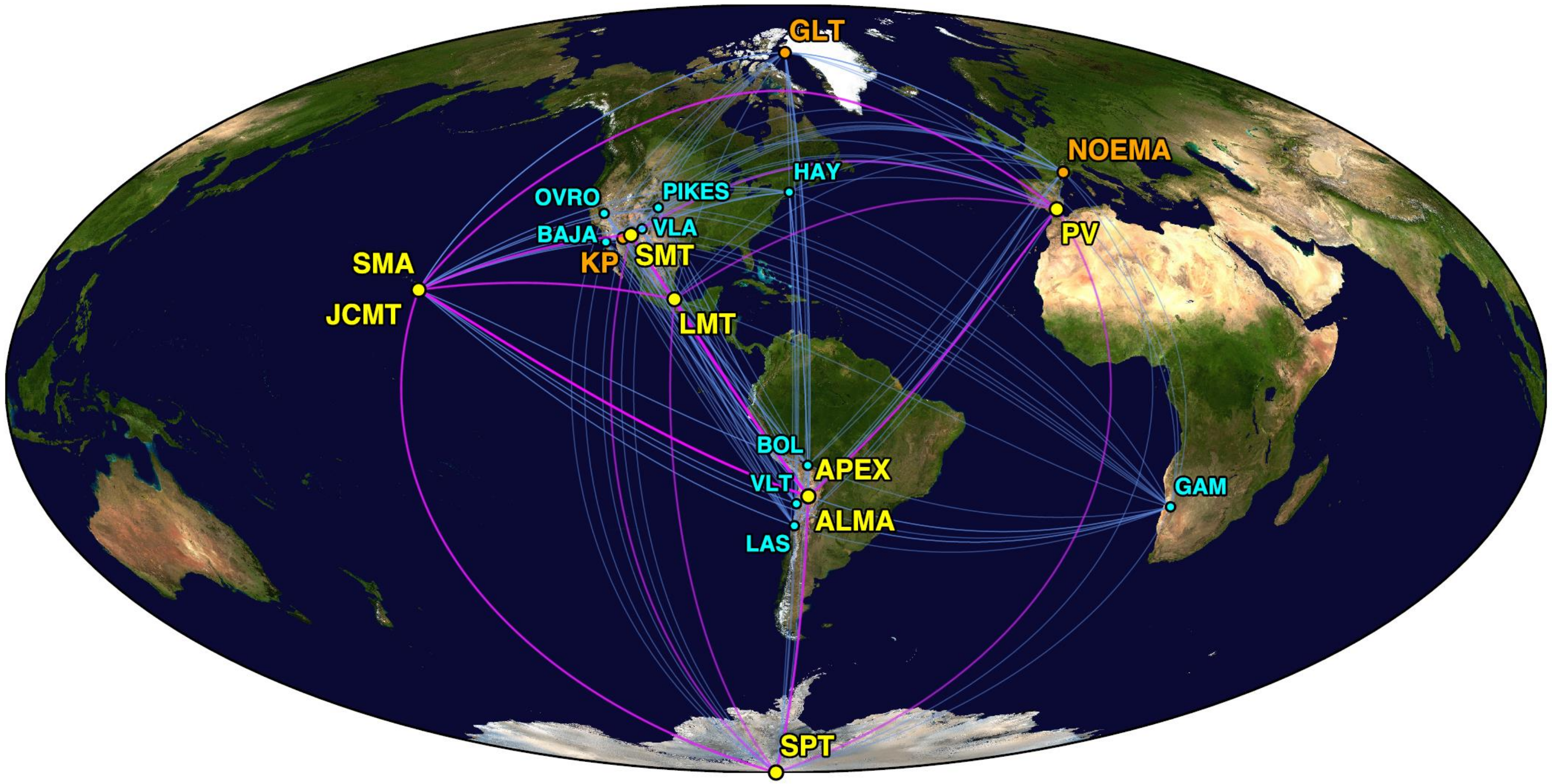
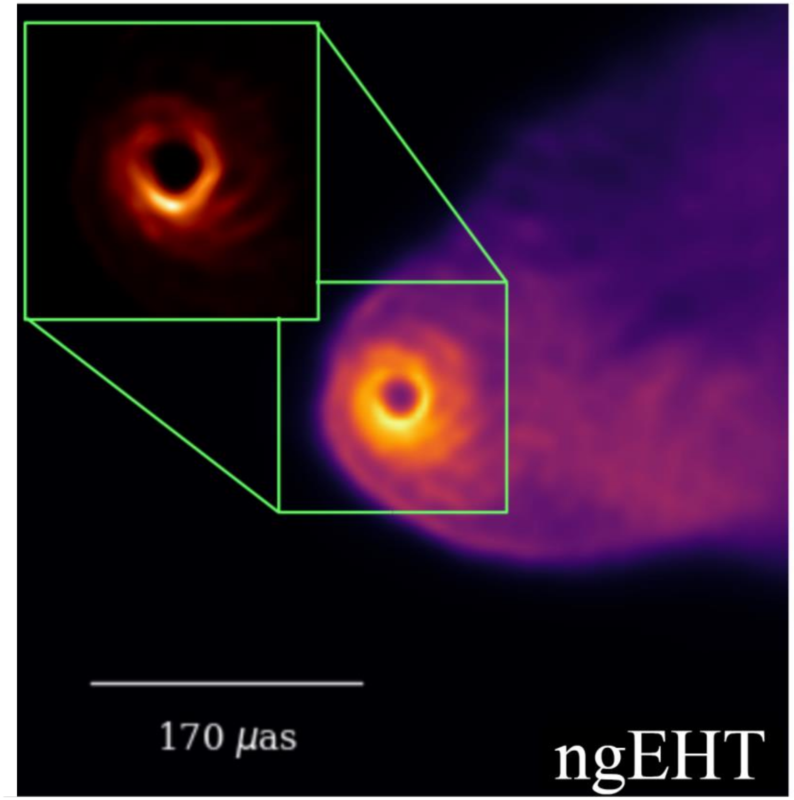


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

ngEHT will illuminate the BH-jet connection





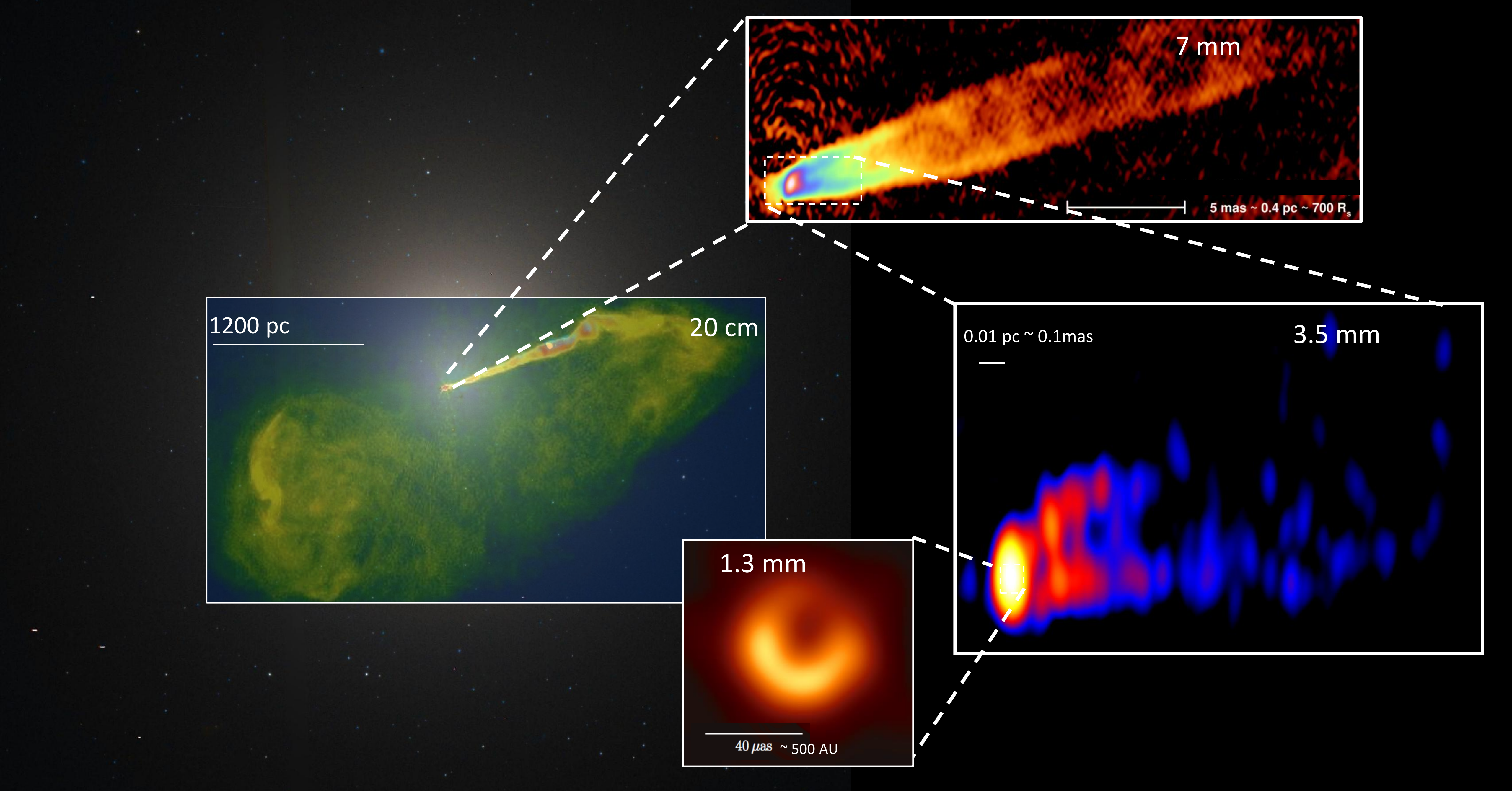
The current EHT lacks short baselines, which are necessary to detect extended structure.

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 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
- 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



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