Lecture 20

Taking a picture of a black hole:
computational imaging taken to an extreme

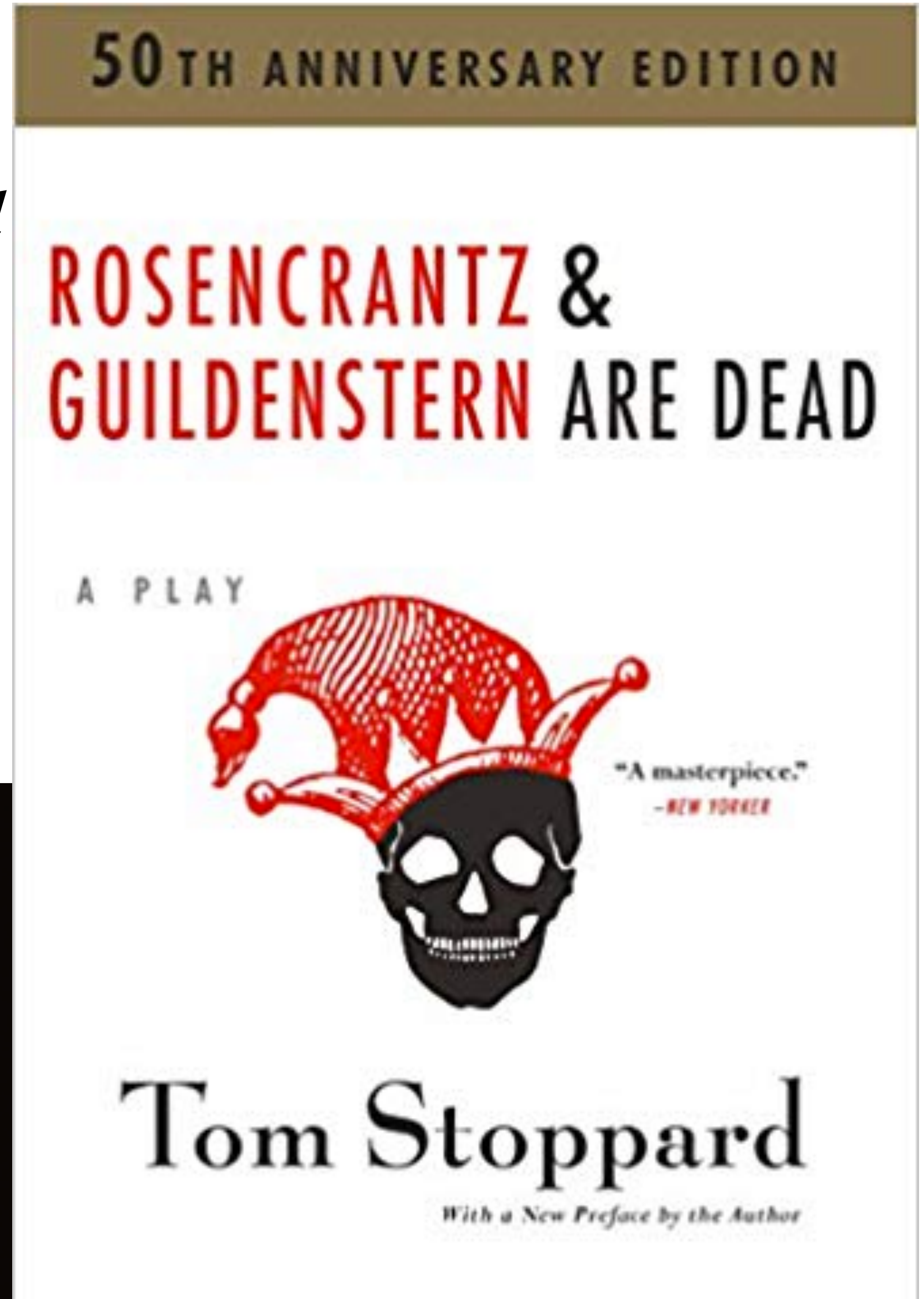
6.8300/6.8301 Advances in Computer Vision

spring 2023
Bill Freeman, Vincent Sitzmann, Mina Kolokovic Lukovic

April 25, 2023

The black hole story, told in the style of *Rosencrantz and Guildenstern are Dead*

Many slides courtesy of Event Horizon Telescope Imaging Working Group, and Katie Bouman



Hamlet

POLONIUS: My Lord! I have news to tell you.

HAMLET (releasing ROS and mimicking): My lord, I have news to tell you... When Rocius was an actor in Rome...

(ROS comes down to re-join GUIL.)

POLONIUS (as he follows HAMLET out): The actors are come hither my lord.

HAMLET: Buzz, buzz.

(Exeunt HAMLET and POLONIUS.)

Rosencrantz and Guildenstern are Dead

(ROS and GUIL ponder. Each reluctant to speak first.)

GUIL: Hm?

ROS: Yes?

GUIL: What?

ROS: I thought you...

GUIL: No.

ROS: Ah.

(Pause.)

GUIL: I think we can say we made some headway.

ROS: You think so?

GUIL: I think we can say that.

ROS: I think we can say he made us look ridiculous.

GUIL: We played it close to the chest of course.

ROS (derisively): "Question and answer. Old ways are the best ways"! He was scoring off us all down the line.

GUIL: He caught us on the wrong foot once or twice, perhaps, but I thought we gained some ground.

ROS (simply): He murdered us.

GUIL: He might have had the edge.

ROS (roused): Twenty-seven - three, and you think he might have had the edge?! He murdered us.

Shep Doleman

MIT’s Haystack Observatory, Westborough, MA


WARNING
RADIATION AREA
GET TRANSMITTER KEY
BEFORE CLIMBING
CAUTION
HARD HAT
AREA
HARD HAT
AREA
DANGER

Shep Doeleman <dole@haystack.mit.edu> Mon, Sep 23, 2013, 7:37 PM
to Bill, Katie, Daniel, Rusen, Victor, Vincent

Dear Bill, Dan and Katie,

It was great to talk with you all and to hear about Dan and Katie's interesting work - I don't think I'll look at leaves or fabric in the same way again.

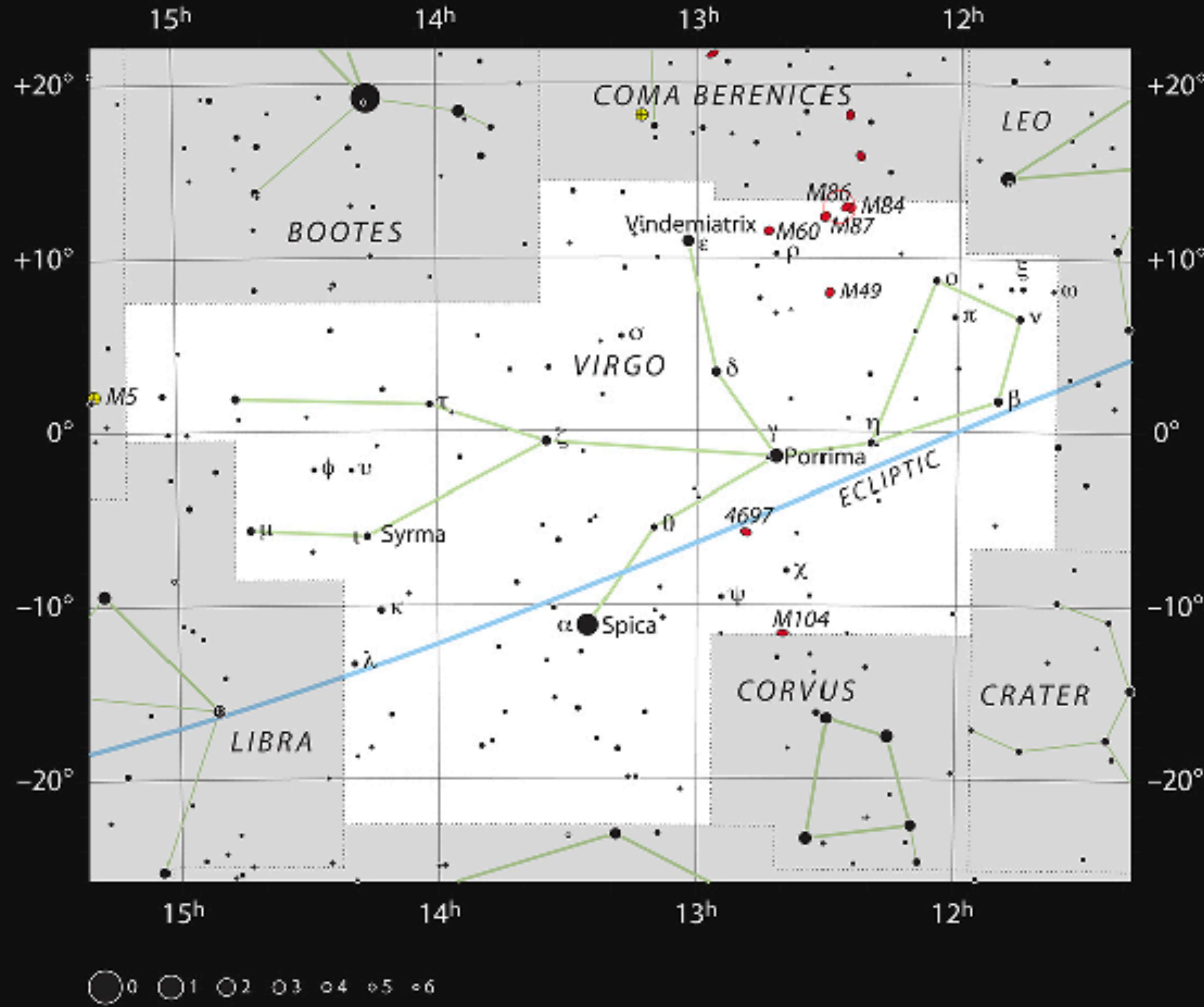
Your ideas and gameplan sound reasonable, and is along the lines I was hoping for - a fresh look at this problem with unjaded astronomer eyes. There will undoubtedly be course corrections along the way, but this is a good start. We can generate fourier plane baseline tracks for you, or we can supply routines that will do that for you (functions of telescope location on the Earth, Greenwich mean time, and the sky position of the source).

I wonder to what extent the textured approach will contain the imprint of the types of images we expect to see (a 'gentle' prior), but let's see what happens. I really like the idea of generating a family of images that all obey the observations, but differ where we have no fourier data.

All the Best, Shep

https://www.almaobservatory.org/en/press-releases/astronomers-capture-first-image-of-a-black-hole/

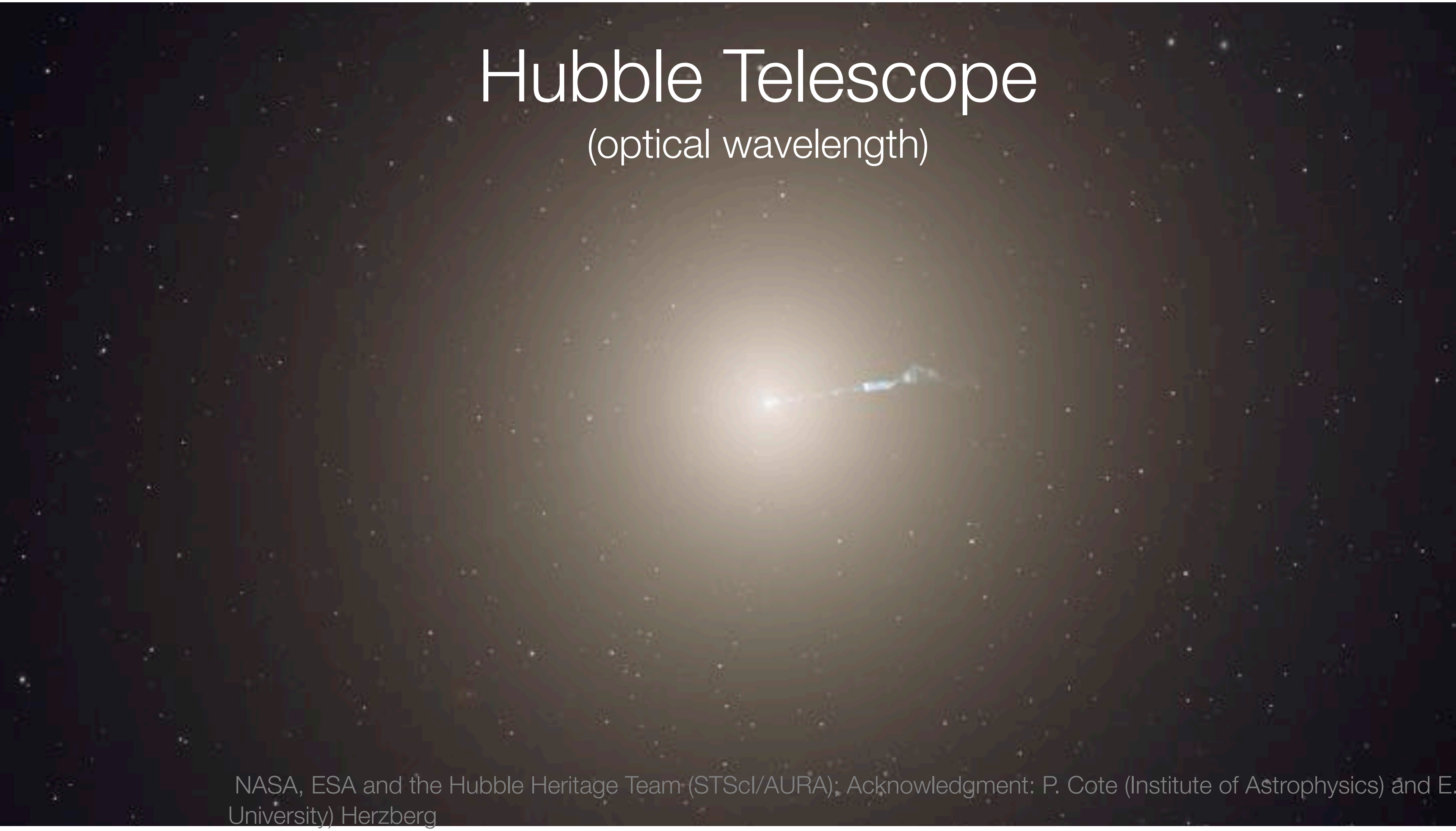
In the shadow of a black hole
1:13 - 3:50 or 5:05.



https://www.almaobservatory.org/wp-content/uploads/2019/04/iywysyua.jpg

Hubble Telescope

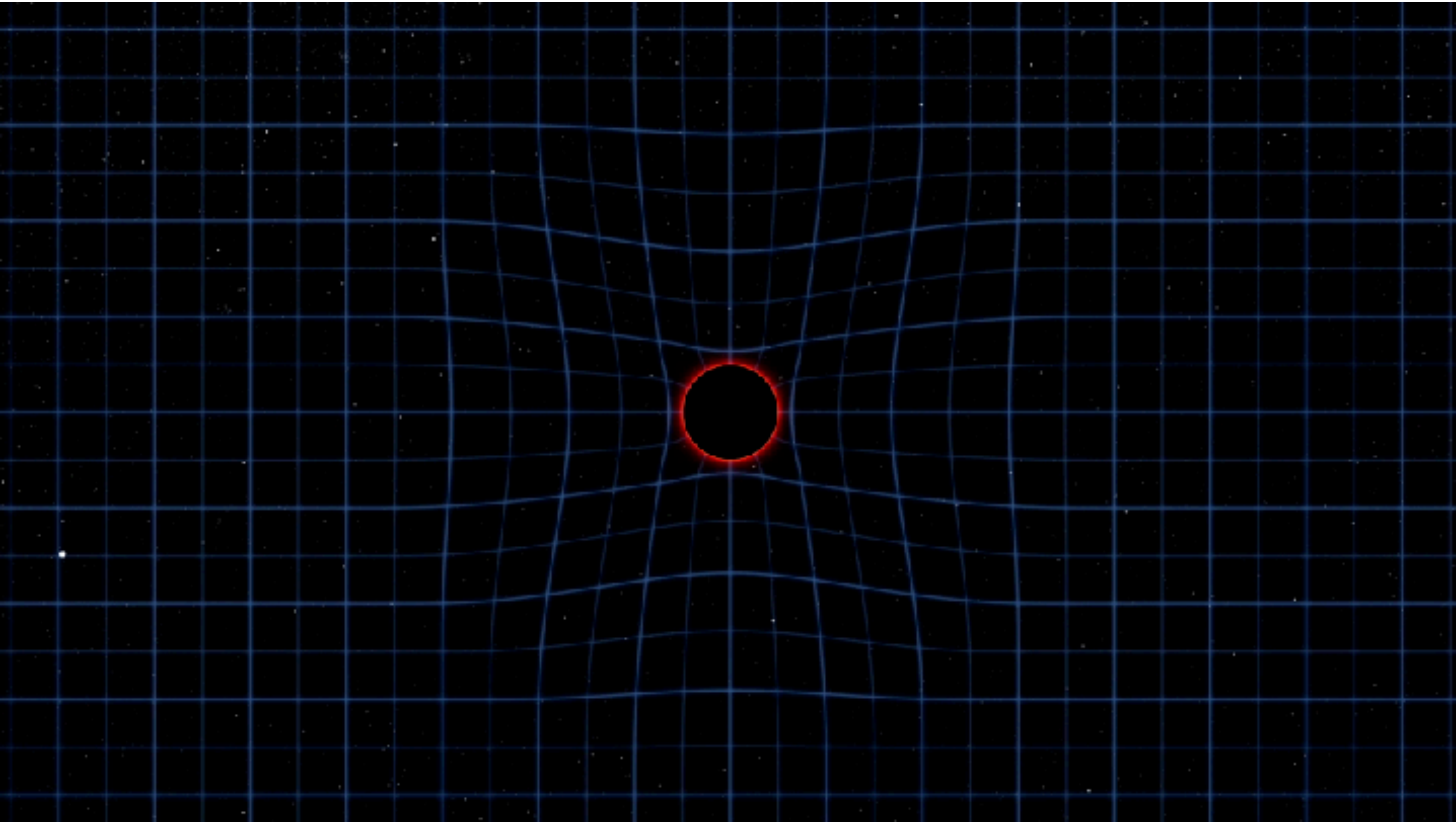
(optical wavelength)



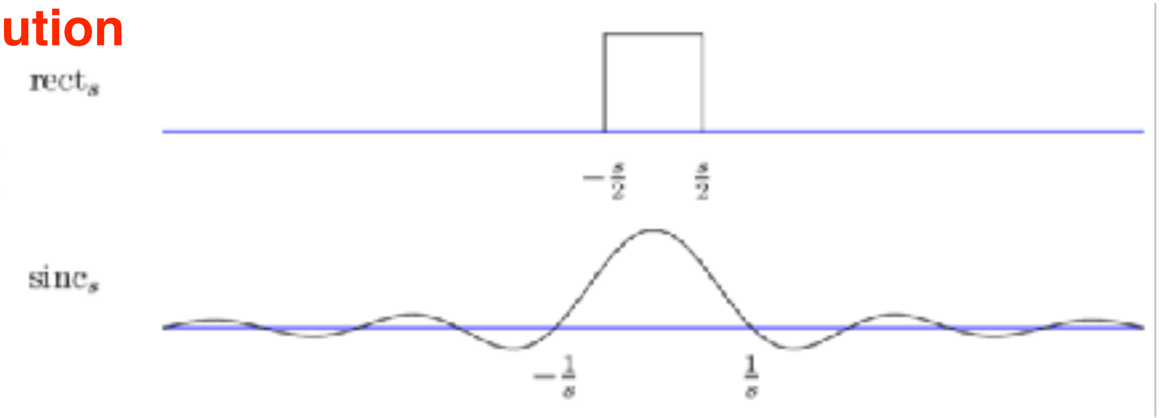
NASA, ESA and the Hubble Heritage Team (STScI/AURA); Acknowledgment: P. Cote (Institute of Astrophysics) and E.
University) Herzberg

This artist's impression depicts the black hole at the heart of the enormous elliptical galaxy Messier 87 (M87). This black hole was chosen as the object of paradigm-shifting observations by the Event Horizon Telescope. The superheated material surrounding the black hole is shown, as is the relativistic jet launched by M87's black hole. Credit: ESO/M. Kornmesser

Black Hole Simulation



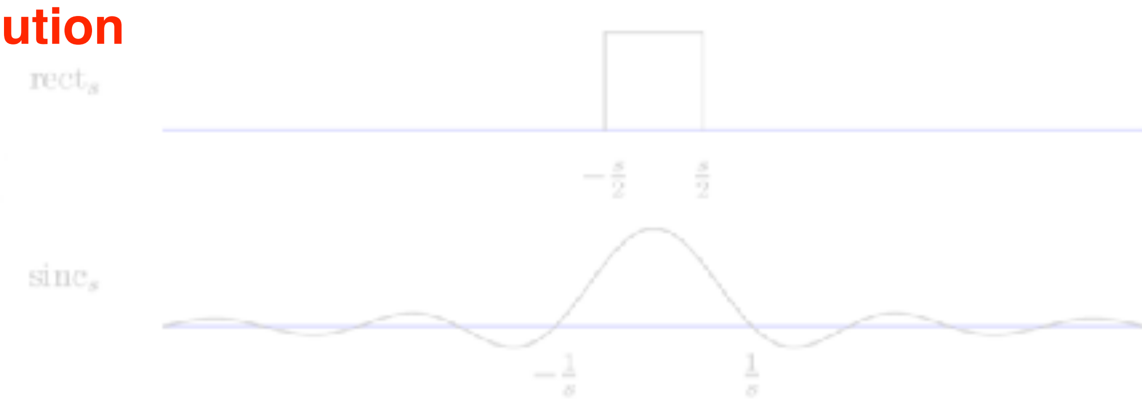
Telescope size and resolution



$$\theta = 1.22\frac{\lambda}{D}$$

The Fourier Transform relationship between the light amplitudes entering the aperture of the telescope and those focussed at the sensor impose a resolution limit on the image from an optical system.

Telescope size and resolution



$$\theta = 1.22\frac{\lambda}{D}$$

The Fourier Transform relationship between the light amplitudes entering the aperture of the telescope and those focussed at the sensor impose a resolution limit on the image from an optical system.

measured wavelength

$$1.22\frac{1.3mm}{12.7 \times 10^6 m} = 25.7\mu\text{arc seconds}$$

diameter of Earth

black hole photon capture radius:

$$R_c = \frac{\sqrt{27}GM}{c^2}$$

Predicted black hole mass: 3-6 Billion solar masses, 55M light years away implying shadow size: between 42 and 20 micro arc seconds

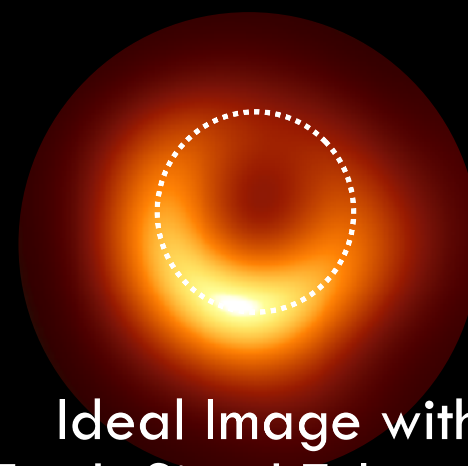
https://www.researchgate.net/figure/A-picture-of-a-Comb-s-rect-s-sinc-s-Gaussian-m-s_fig1_307862015

How Big Must Our Telescope Be?

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

$$13 \text{ million meters} = \frac{1.3 \text{ mm}}{20\ \mu as}$$

Simulation of M87



Ideal Image with Earth-Sized Telescope

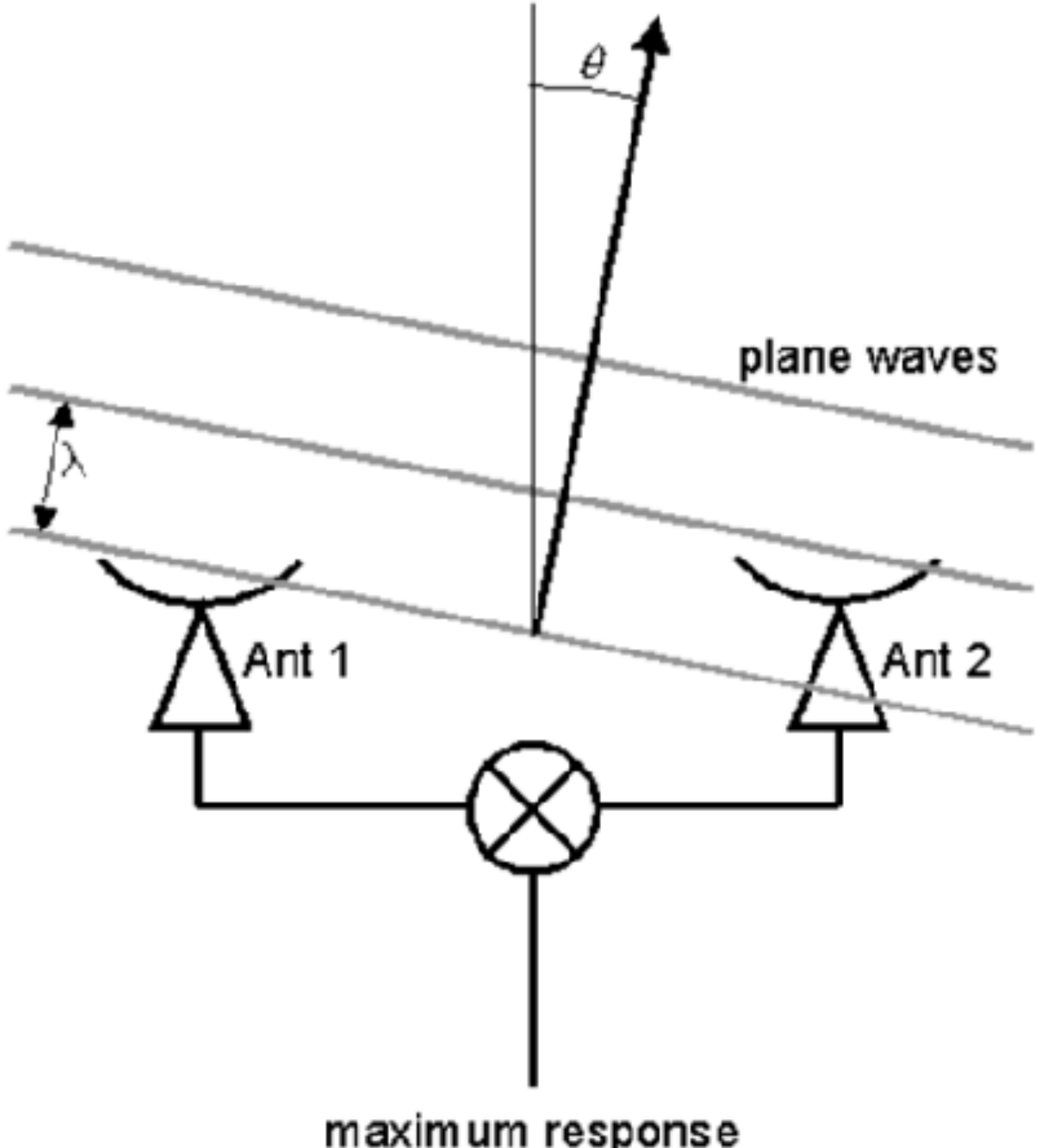
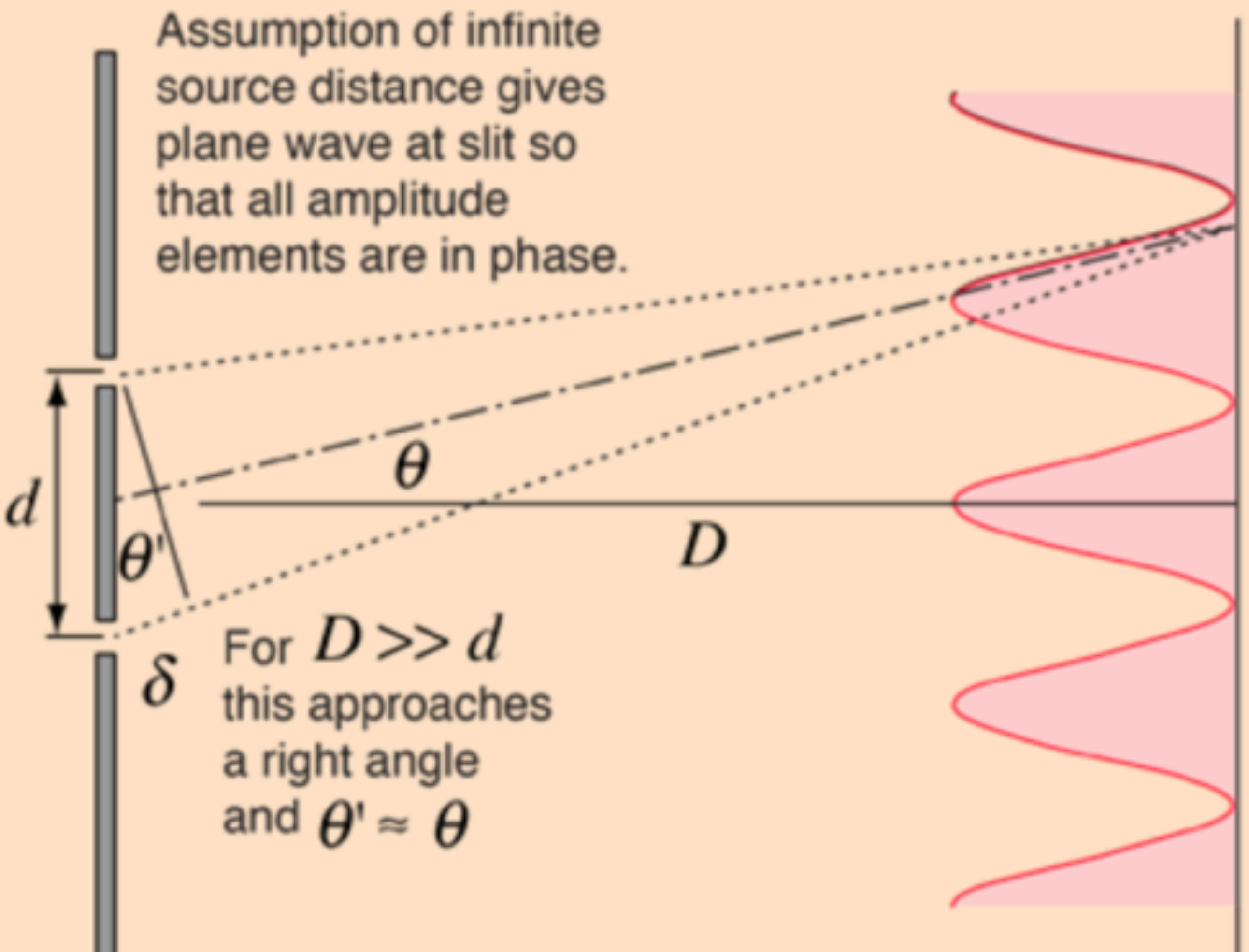


Figure 2: The same baseline as in Figure 1, but for waves incident from an angle θ from the vertical. The waves arrive at the antennas again exactly in phase, because the angle is such that the difference in path length is λ.

“We run a double-slit interference experiment in reverse” —Shep Doleman

Double Slit Interference



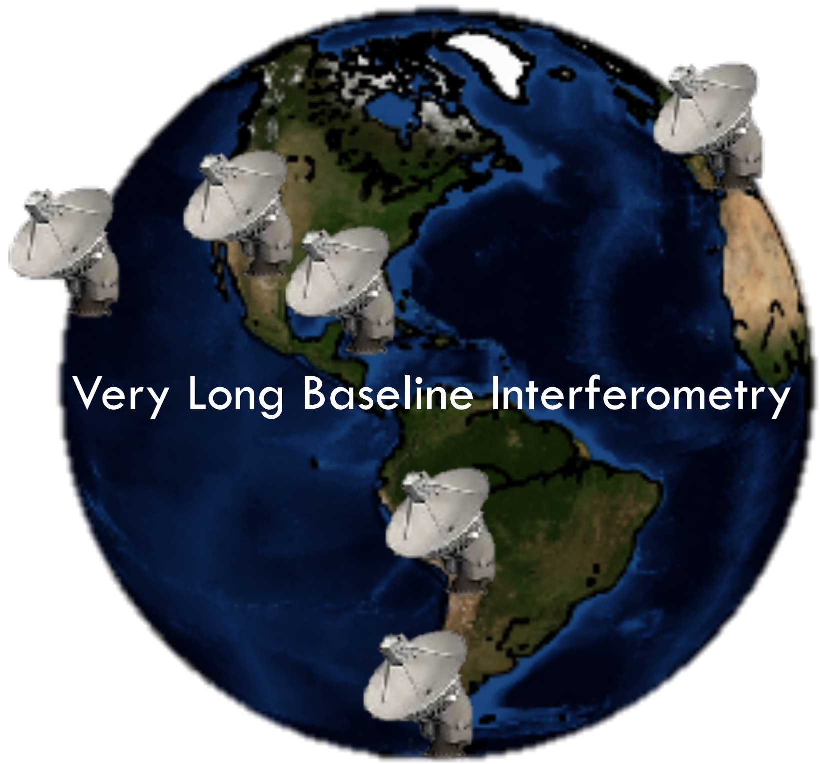
VAN CITTERT-ZERNIKE THEOREM

The theorem states that, for ideal sensors, the time-averaged correlation of the measured signals from two telescopes, i and j, for a single wavelength, λ, can be approximated as:

$$\Gamma_{i,j}(u,v) \approx \int_{\ell}\int_{m} e^{-i2\pi(u\ell+vm)} I_{\lambda}(\ell,m) dl dm \quad (1)$$

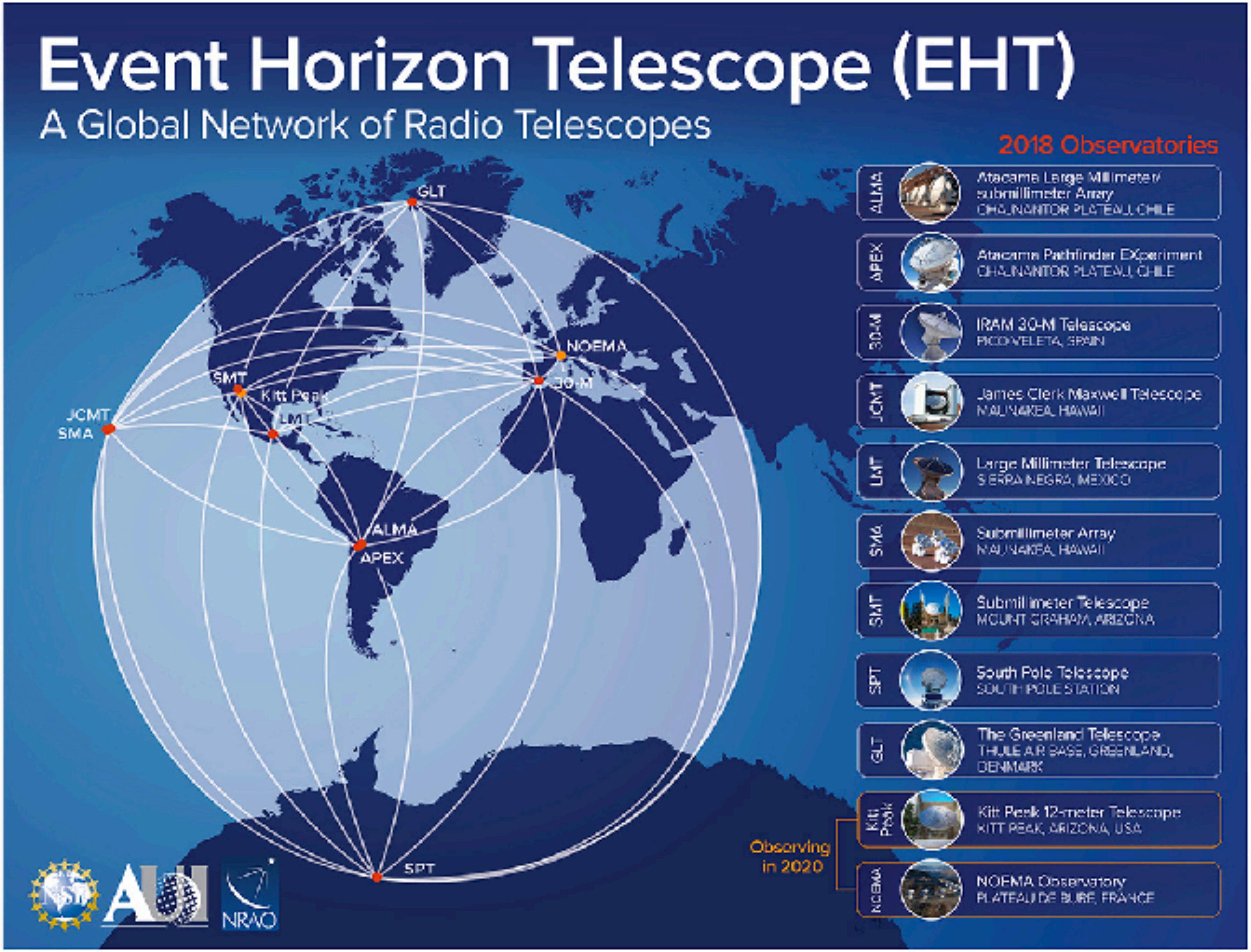
where $I_{\lambda}(\ell,m)$ is the emission of wavelength λ traveling from the direction $\hat{s} = (\ell, m, \sqrt{1-\ell^2-m^2})$. The dimensionless coordinates (u,v) (measured in wavelengths) are the projected baseline, B, orthogonal to the line of sight.[1]

The Event Horizon Telescope (EHT)



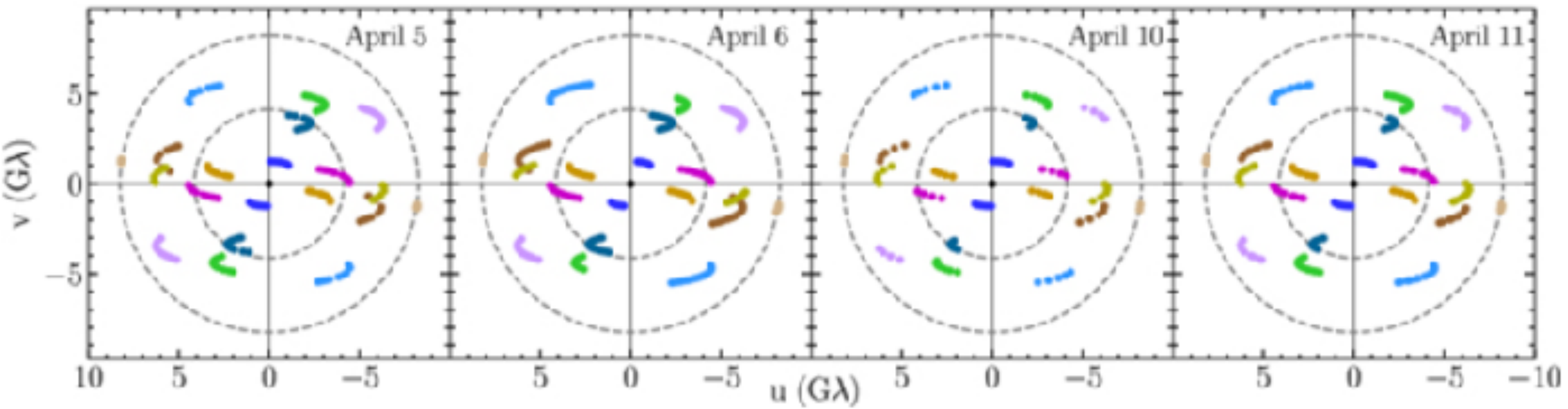
Imaging a Black Hole with the Event Horizon Telescope

EHT Collaboration



https://www.almaobservatory.org/wp-content/uploads/2019/04/20190410n-en.jpg

FOURIER DOMAIN COVERAGE OF THE 4 NIGHTS OF OBSERVATIONS



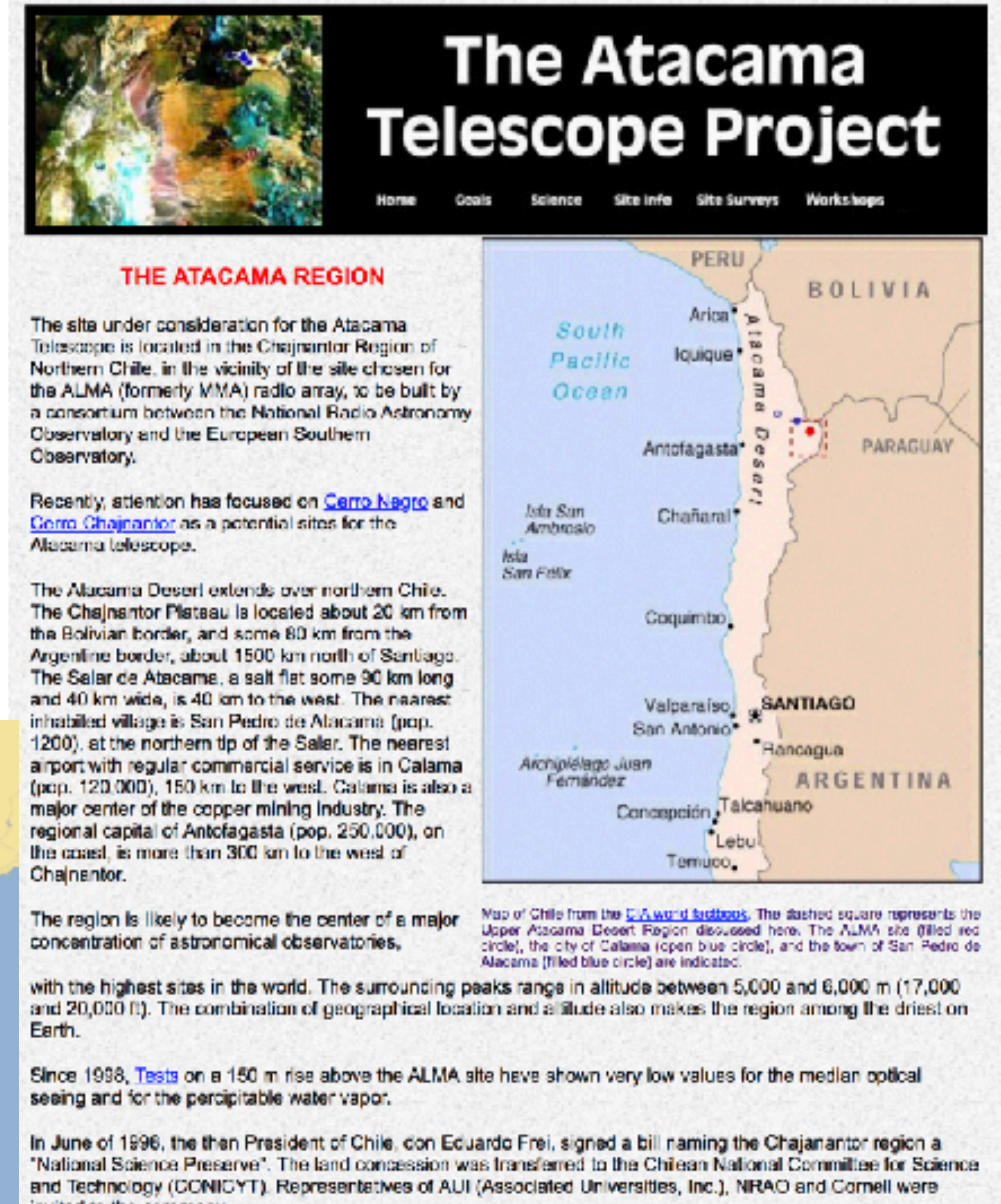
Fourier domain

Because the image is real valued, the Fourier transform is Hermitian.
K telescopes gives K chose 2 baselines, or observed Fourier frequencies.
As the Earth rotates over a night, the projected baselines sweep out elliptical paths in Fourier space.

https://www.almaobservatory.org/en/press-releases/astronomers-capture-first-image-of-a-black-hole/

ICCV 2015 was in Santiago, Chile

Shep said we should go see the Alma radio telescopes in Atacama, and I arranged for a trip there, with Bernhard Scholkopf, Yoav Schechner, and Katie Bouman.



The Atacama Telescope Project

Home Goals Science Site Info Site Surveys Workshops

THE ATACAMA REGION

The site under consideration for the Atacama Telescope is located in the Chajnantor Region of Northern Chile, in the vicinity of the site chosen for the ALMA (formerly MMA) radio array, to be built by a consortium between the National Radio Astronomy Observatory and the European Southern Observatory.

Recently, attention has focused on Cerro Negro and Cerro Chajnantor as a potential sites for the Atacama telescope.

The Atacama Desert extends over northern Chile. The Chajnantor Plateau is located about 20 km from the Bolivian border, and some 80 km from the Argentine border, about 1500 km north of Santiago. The Salar de Atacama, a salt flat some 90 km long and 40 km wide, is 40 km to the west. The nearest inhabited village is San Pedro de Atacama (pop. 1200), at the northern tip of the Salar. The nearest airport with regular commercial service is in Calama (pop. 120,000), 150 km to the west. Calama is also a major center of the copper mining industry. The regional capital of Antofagasta (pop. 250,000), on the coast, is more than 300 km to the west of Chajnantor.

Map of Chile from the CIA world factbook. The dashed square represents the Upper Atacama Desert Region discussed here. The ALMA site (filled red circle), the city of Calama (open blue circle), and the town of San Pedro de Atacama (filled blue circle) are indicated.

The region is likely to become the center of a major concentration of astronomical observatories, with the highest sites in the world. The surrounding peaks range in altitude between 5,000 and 6,000 m (17,000 and 20,000 ft). The combination of geographical location and altitude also makes the region among the driest on Earth.

Since 1998, Tests on a 150 m rise above the ALMA site have shown very low values for the median optical seeing and for the percipitable water vapor.

In June of 1998, the then President of Chile, don Eduardo Frei, signed a bill naming the Chajanantor region a "National Science Preserve". The land concession was transferred to the Chilean National Committee for Science and Technology (CONICYT). Representatives of AUI (Associated Universities, Inc.), NRAO and Cornell were invited to the ceremony.

Timelapse videos from Bernhard,
from Atacama, 2015

atacama milkyway

225 views • 3 years ago

https://youtu.be/O86mycdxtYM?t=12

atacama tree

111 views • 3 years ago

https://youtu.be/8YOqdAooO9A

The Atacama Large Millimeter/submillimeter Array (ALMA) by night, u...

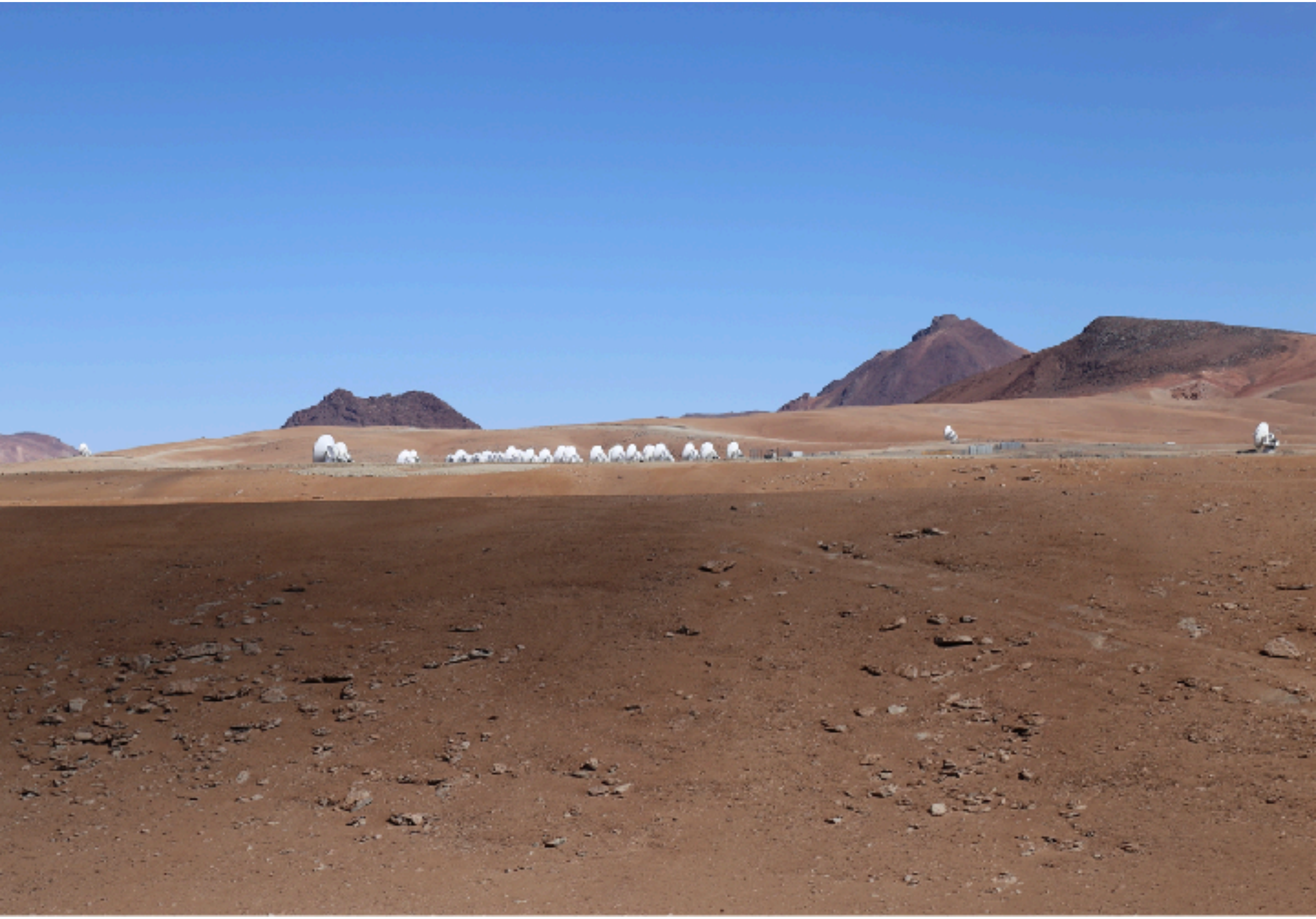
Eso Observatory

MAR 2013

Dec. 12, 2015
Below ALMA
telescope array,
Atacama, Chile
9,000 feet

Yoav in pressurized car,
going to 15,000 feet

ALMA telescope array, 15,000 feet.   Atacama, Chile, 2015

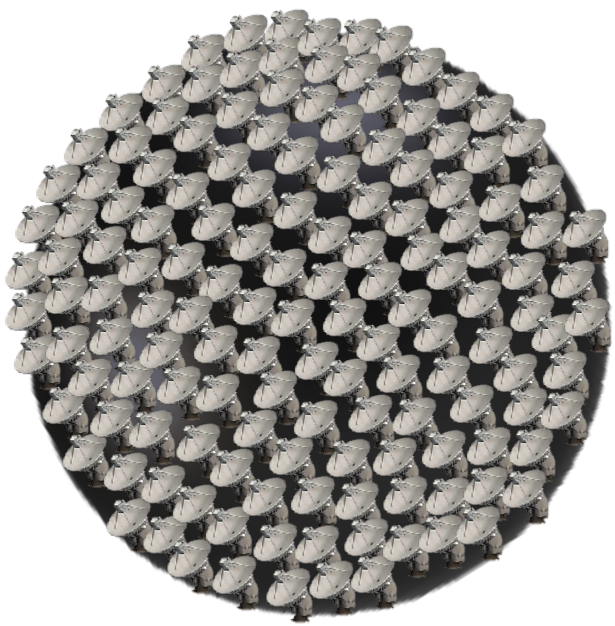


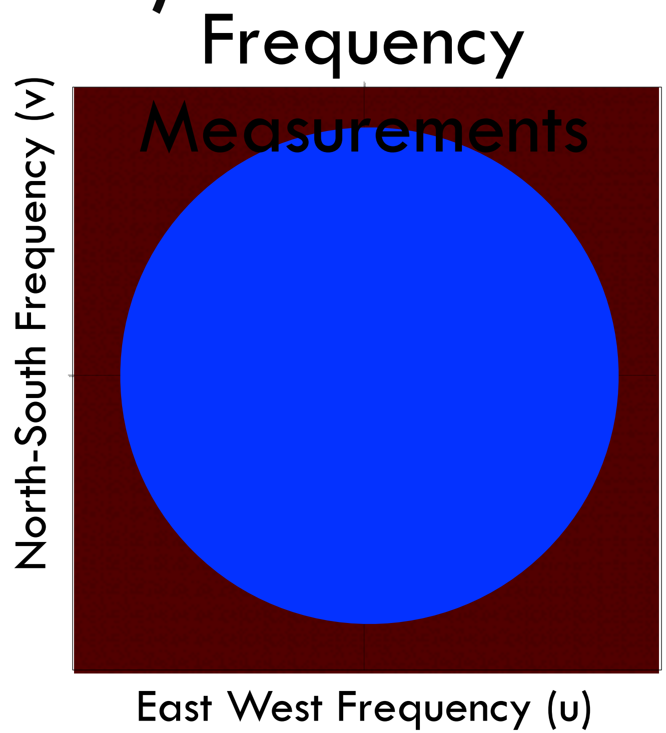
ALMA telescope array, 15,000 feet. Atacama, Chile, 2015

ALMA telescope array, 15,000 feet.   Atacama, Chile, 2015

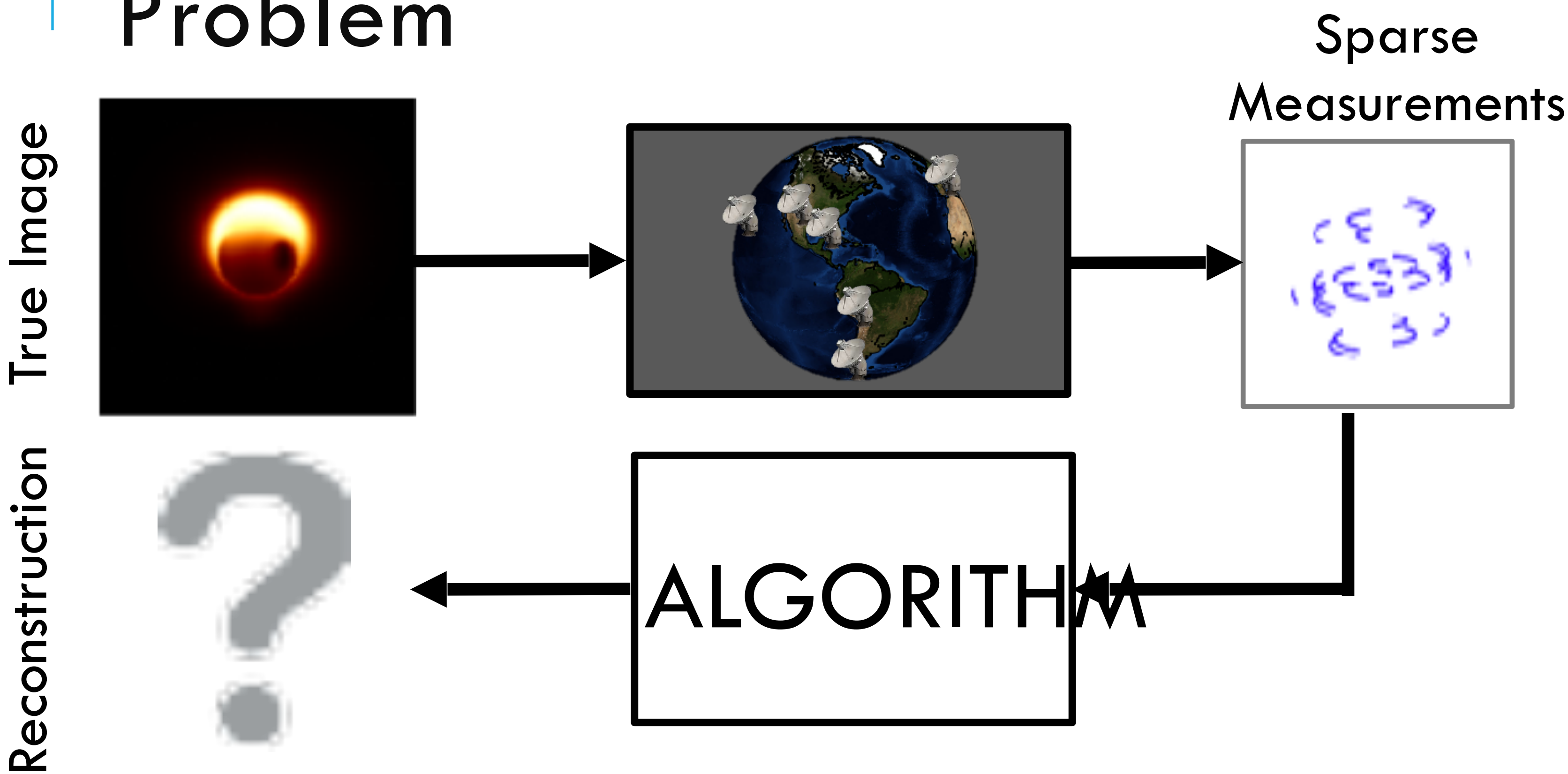

Astronomical Radio Imaging – Centaurus A Galaxy
Radio
Radio
Wavelengths

Very Long Baseline Interferometry (VLBI)

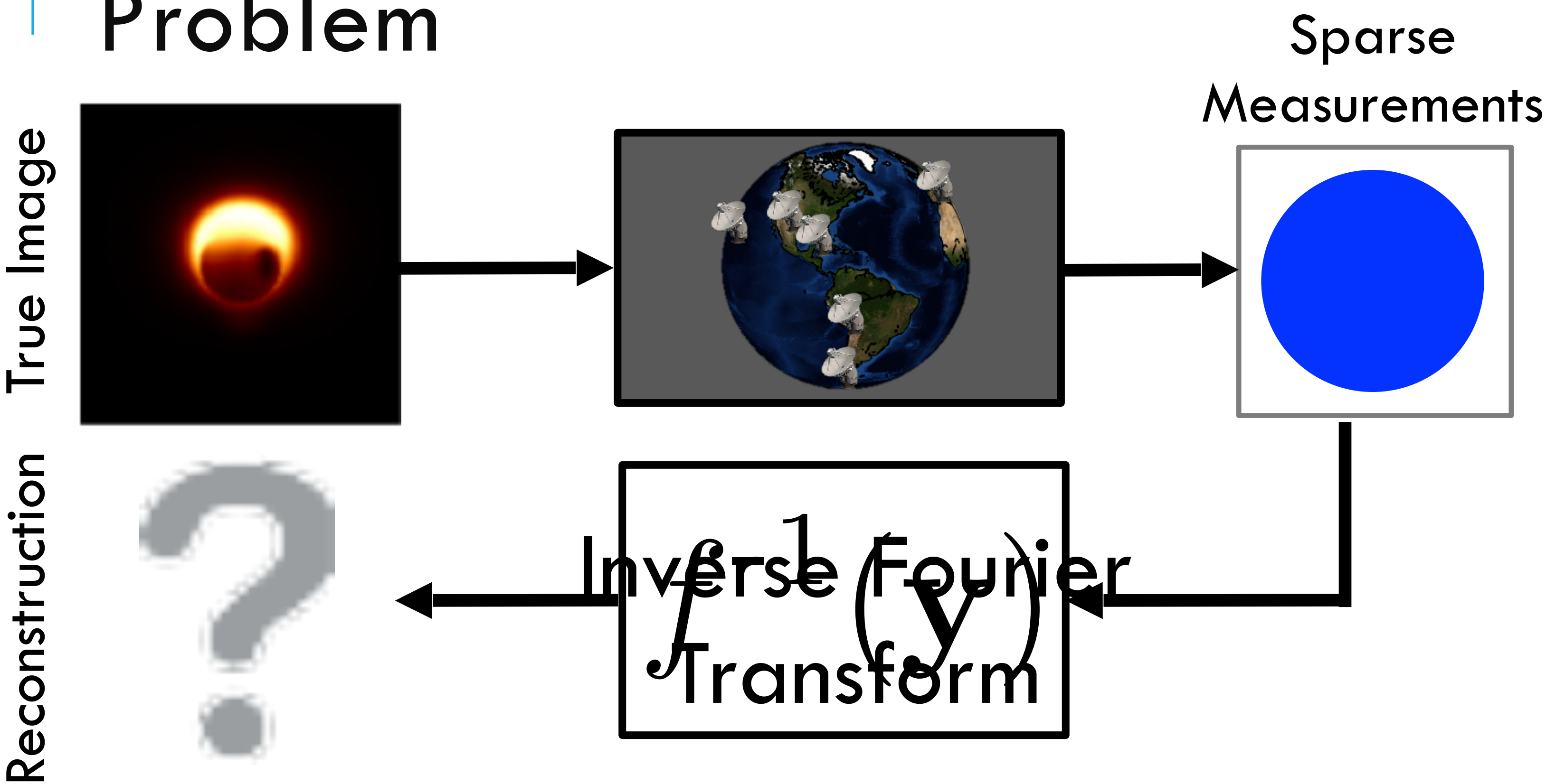




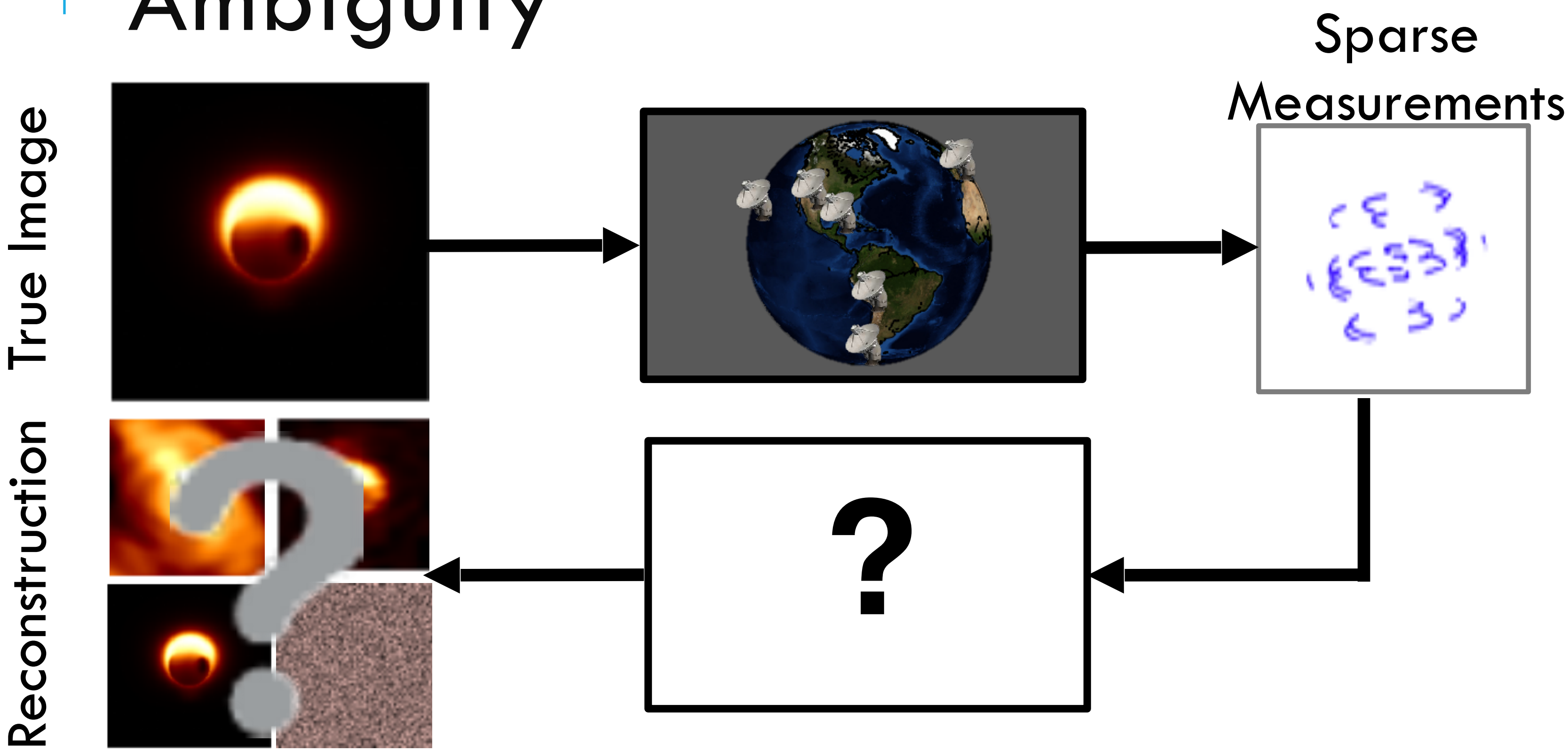
The Computational Imaging Problem



The Computational Imaging Problem



Inverting the Imaging System: Ambiguity



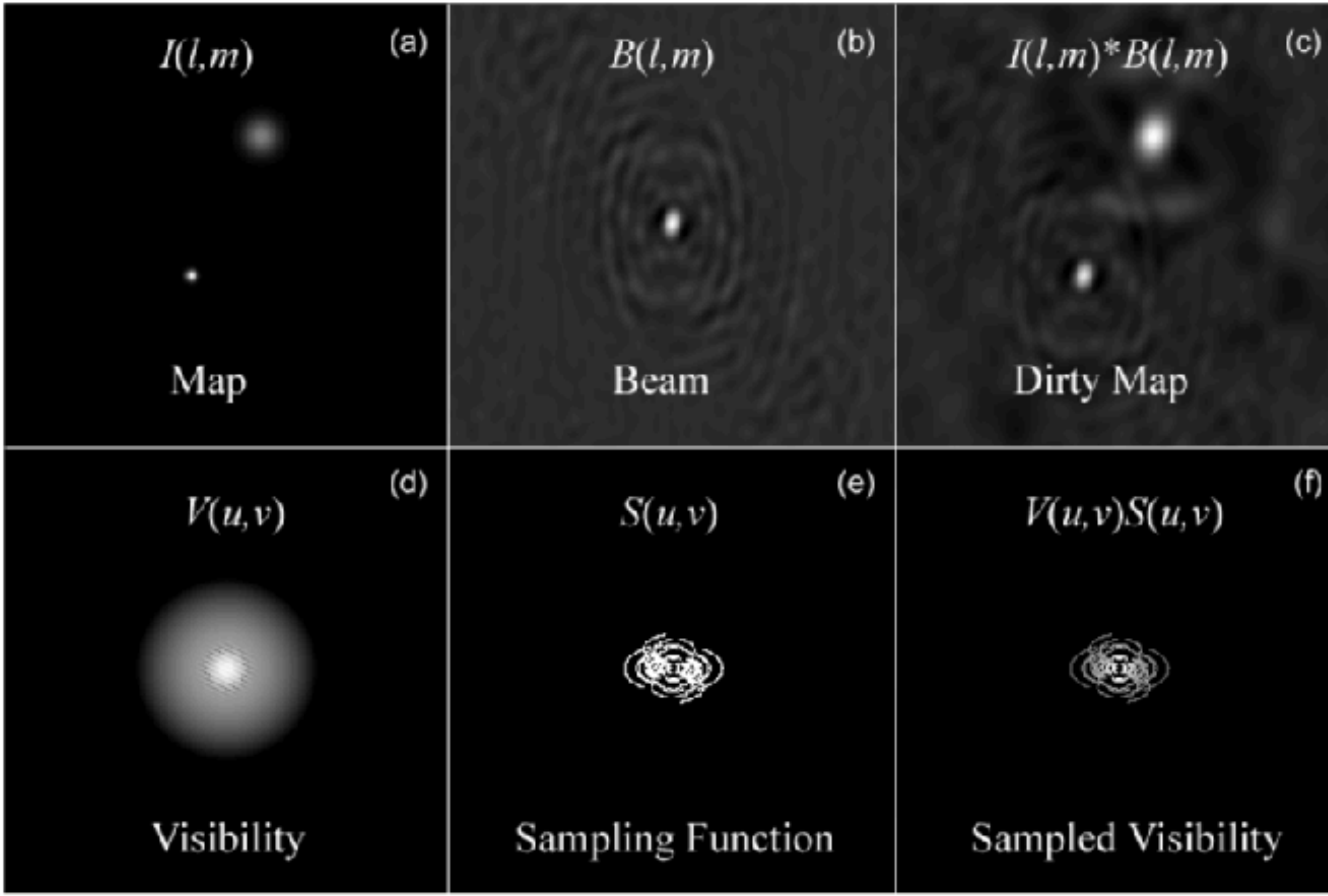
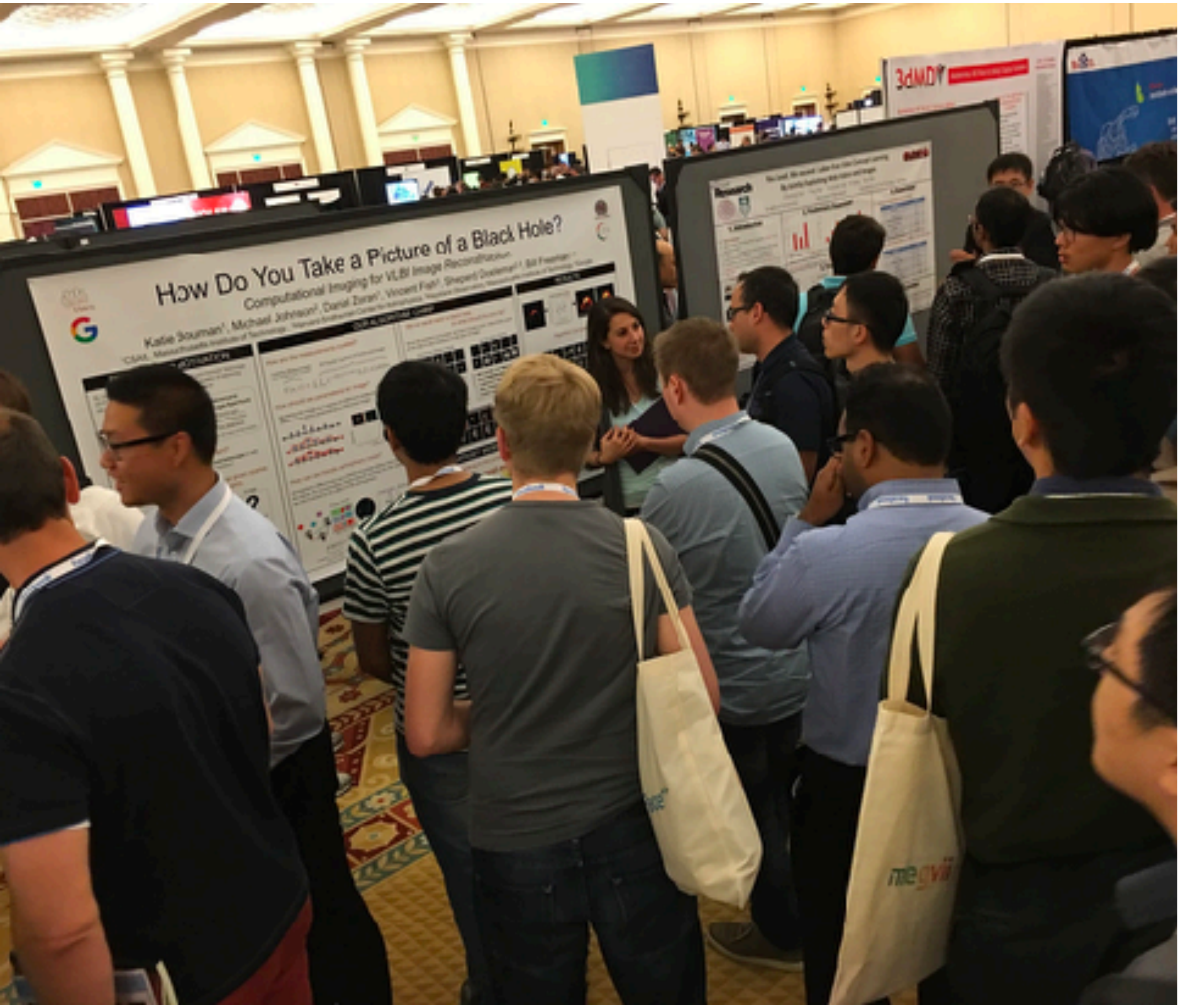
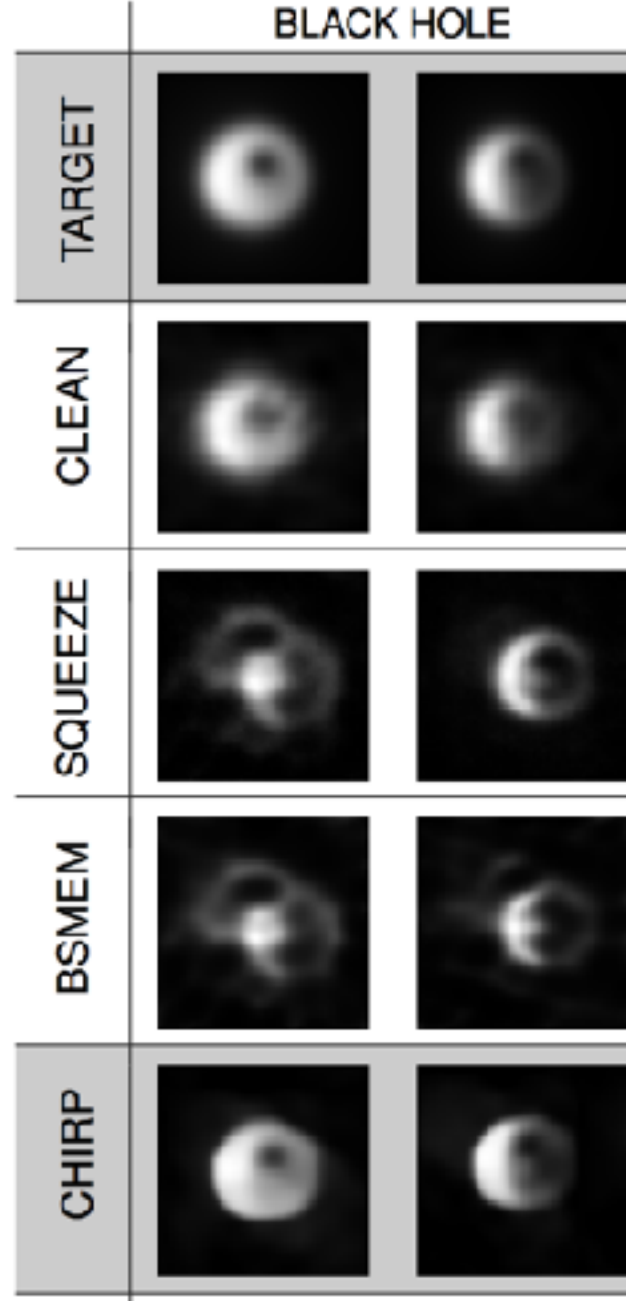


Figure 10: *a*) An example (model) sky map. *d*) The corresponding visibilities (Fourier Transform of the map). *c*) The synthesized beam, or point-spread-function, of a model antenna array. *e*) The sampling function of the array, whose Fourier Transform gives the beam in (*b*). *f*) The product of panels (*d*) and (*e*), representing the sampled visibilities. These are the actual measurements from the array. *c*) The dirty map that results from the Fourier Transform of the sampled visibilities. This is the same as the convolution of the map in (*a*) and the synthesized beam in (*b*).



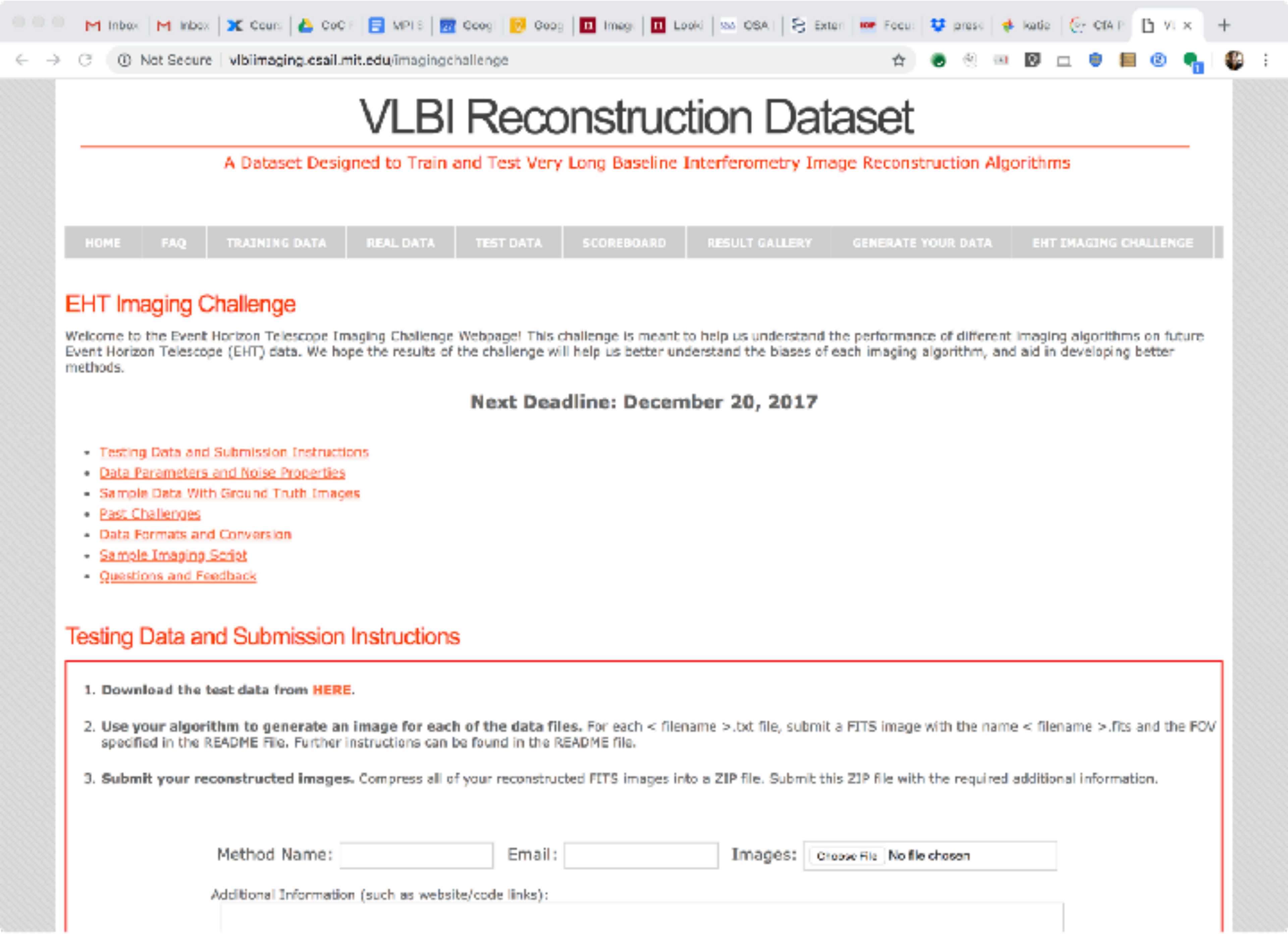
Katie presenting EHT poster at CVPR 2016



Some of the image priors explored for Event Horizon Telescope black hole image reconstructions one has ever seen

(what assumptions do you make about an image of something that no one has ever seen before?)

- Positivity: the light intensity must be positive.
- Compactness: The source has a finite size
- Image entropy (maximize entropy, consistent with the observations)
- Image smoothness
- Image sparsity in the pixel, or gradient, domains



Not Secure | vlbiimaging.csail.mit.edu/imagingchallenge
VLBI Reconstruction Dataset
A Dataset Designed to Train and Test Very Long Baseline Interferometry Image Reconstruction Algorithms
HOME
FAQ
TRAINING DATA
REAL DATA
TEST DATA
SCOREBOARD
RESULT GALLERY
GENERATE YOUR DATA
EHT IMAGING CHALLENGE
EHT Imaging Challenge
Welcome to the Event Horizon Telescope Imaging Challenge Webpage! This challenge is meant to help us understand the performance of different imaging algorithms on future Event Horizon Telescope (EHT) data. We hope the results of the challenge will help us better understand the biases of each imaging algorithm, and aid in developing better methods.
Next Deadline: December 20, 2017
Testing Data and Submission Instructions
Data Parameters and Noise Properties
Sample Data With Ground Truth Images
Past Challenges
Data Formats and Conversion
Sample Imaging Script
Questions and Feedback
Testing Data and Submission Instructions
1. Download the test data from HERE.
2. Use your algorithm to generate an image for each of the data files. For each < filename >.txt file, submit a FITS image with the name < filename >.fits and the FOV specified in the README File. Further instructions can be found in the README file.
3. Submit your reconstructed images. Compress all of your reconstructed FITS images into a ZIP file. Submit this ZIP file with the required additional information.
Method Name:
Email:
Images:
Choose File
No file chosen
Additional Information (such as website/code links):

Sample Data With Ground Truth Images

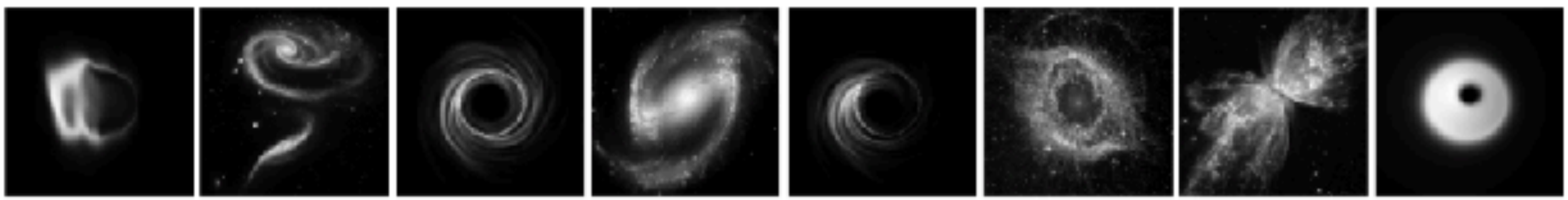
We provide a set of sample data, along with their ground truth images, to help in getting your imaging algorithms working on the blind, test data.

Static Emission

You can download the sample data from here. This sample data was generated with the same telescope parameters as the blind, test data. We have included data without any systematic errors or atmospheric errors, data with just atmospheric errors, and data with both systematic and atmospheric errors. Their naming is as follows:

Filename	Property
challenge_x_wNoPhaseError	Only thermal noise included in visibility measurements
challenge_x	Thermal and phase (atmospheric) errors included in visibility measurements
challenge_x_wSystematics	Thermal, amplitude (systematic) and phase (atmospheric) errors included in visibility measurements

Sample Ground Truth Images



Sample Number	Source Location	Telescopes	Total Flux (Janskys)	Field of View (arcseconds)
1	SgrA*	ALMA, SMT, LMT, SMA, SPT, CARMA, PV, PdBI, KP, Haystack	2	0.00016
2	SgrA*	ALMA, SMT, LMT, SMA, SPT, CARMA, PV, PdBI, KP, Haystack	2	0.00025
3	SgrA*	ALMA, SMT, LMT, SMA, PV, SPT, KP, PdBI	2	0.00016
4	SgrA*	ALMA, SMT, LMT, SMA, PV, SPT	2	0.00016
5	M87	ALMA, SMT, LMT, SMA, SPT, CARMA, PV, PdBI, KP, Haystack	2	0.00010
6	M87	ALMA, SMT, LMT, SMA, SPT, CARMA, PV, PdBI, KP, Haystack	2	0.00010
7	M87	ALMA, SMT, LMT, SMA, PV, SPT, KP, PdBI	2	0.00025
8	M87	ALMA, SMT, LMT, SMA, PV	2	0.00010

Extreme Imaging via Physical Model Inversion: Seeing Around Corners and Imaging Black Holes

by

Katherine L. Bouman

B.S.E., Electrical Engineering, University of Michigan, 2011
S.M., Electrical Engineering and Computer Science, M.I.T., 2013

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in Electrical Engineering and Computer Science
at the Massachusetts Institute of Technology

September 2017

Signature of Author: ______________________________

Department of Electrical Engineering and Computer Science
August 31, 2017

Certified by: ______________________________

Professor William T. Freeman
Thomas and Gerd Perkins Professor of Electrical Engineering and Computer Science
Thesis Supervisor

Katie and EHT team members at radio telescope in Mexico, April 2, 2017

Observations April 5-11, 2017

All sites were technically ready and with good weather on the first night of the observing window. Observations were triggered on 2017 April 5, 6, 7, 10, and 11. Table 1 shows the median zenith sky opacities for each of the triggered days. April 8 was not triggered due to thunderstorms at the LMT, SMT shutdown due to strong winds, and the need to run technical tests at ALMA. April 9 was not triggered due to a chance of the SMT remaining closed due to strong winds and LMT snow forecast. Weather was good to excellent for all other stations throughout the observing window.

…

Observations from the EHT's 2017 April campaign are the first ever to have the necessary sensitivity, coverage, and resolution for horizon-scale imaging of black hole candidates M87 and SgrA*.

The Astrophysical Journal Letters, 875:L3 (32pp), 2019 April 10 The EHT Collaboration et al.

2nd way the EHT got lucky

For M87, the expected shadow diameter is 19–38μas.

….

We present the first Event Horizon Telescope (EHT) images of M87, using observations from April 2017 at 1.3 mm wavelength. These images show a prominent ring with a diameter of ~40 μas,

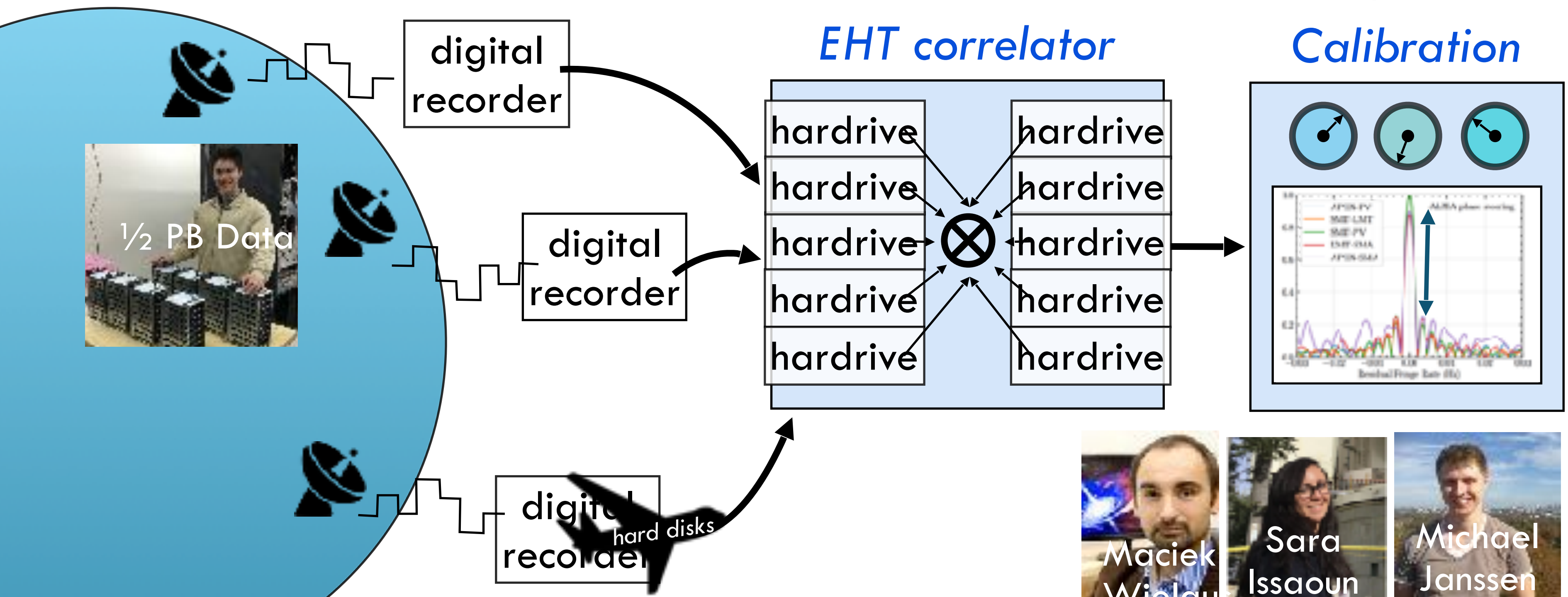
The Astrophysical Journal Letters, 875:L4 , 2019 April 10 The EHT Collaboration et al.

Katie with some of the data

350 Tbytes / day of data…

Correlating all the data, processing checking, writing, took 2 years!

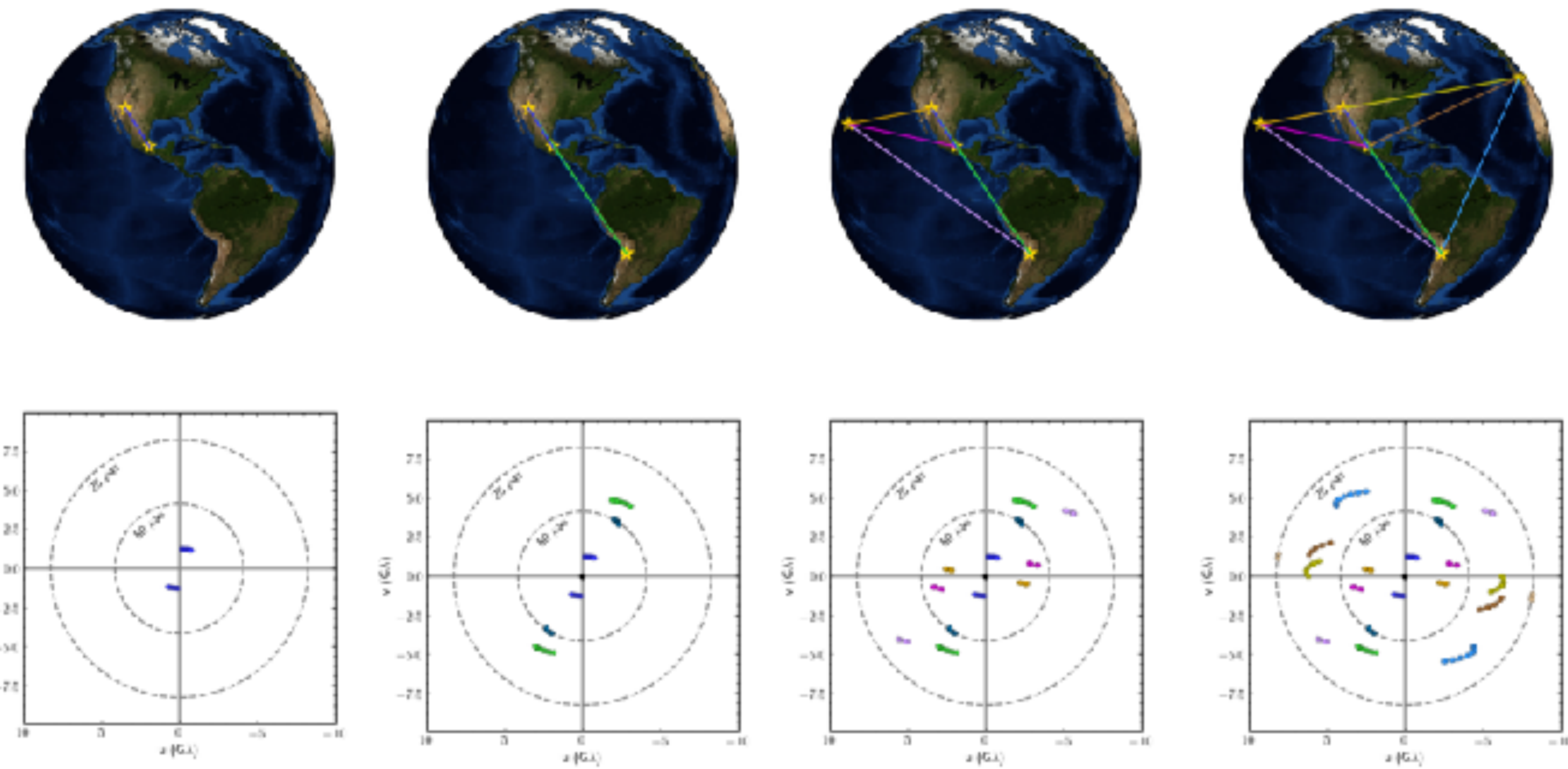
Extracting the Black Hole’s Weak Signal

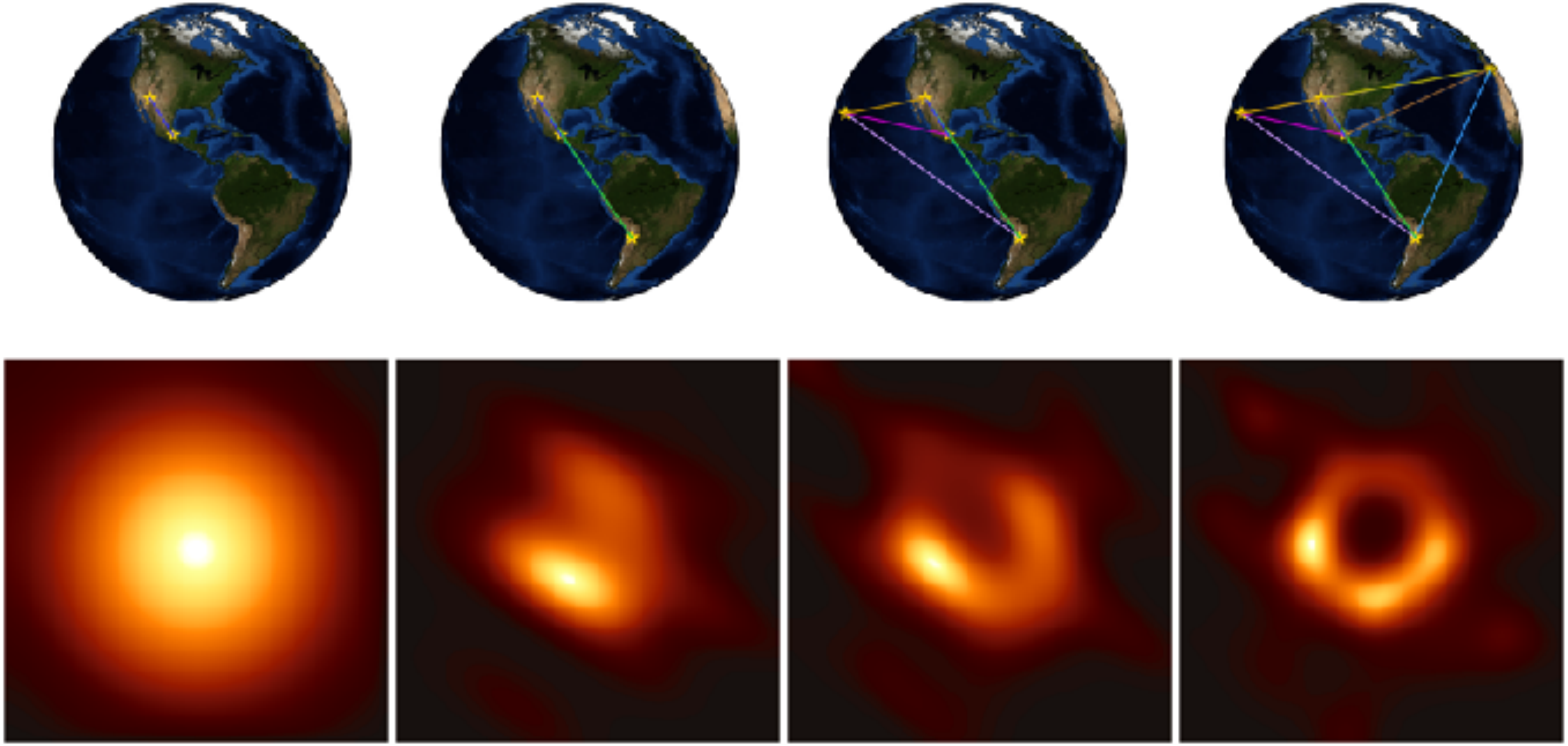


The black hole’s light arrives at the telescopes and is digitized as two-bit data streams. Petabytes of raw data are saved onto hundreds of hard disks.

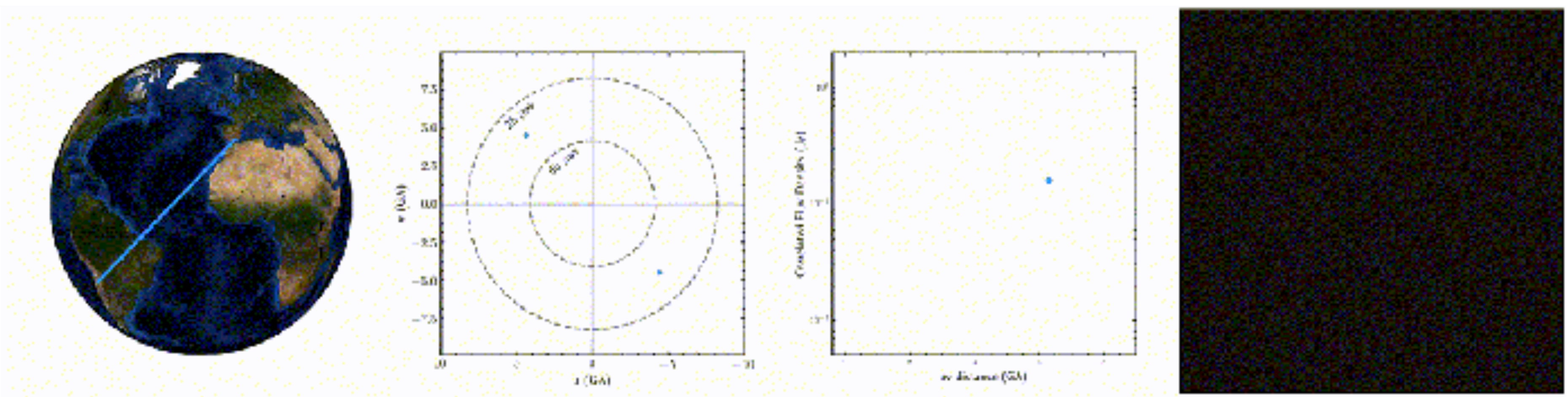
The correlator is a special-purpose supercomputer that combines data from the telescopes, to recover measurements that would be seen from an Earth-size telescope.

Calibration algorithms find the weak signals hiding in the correlator output, and more prescisely tune the data to extract a stronger signal.

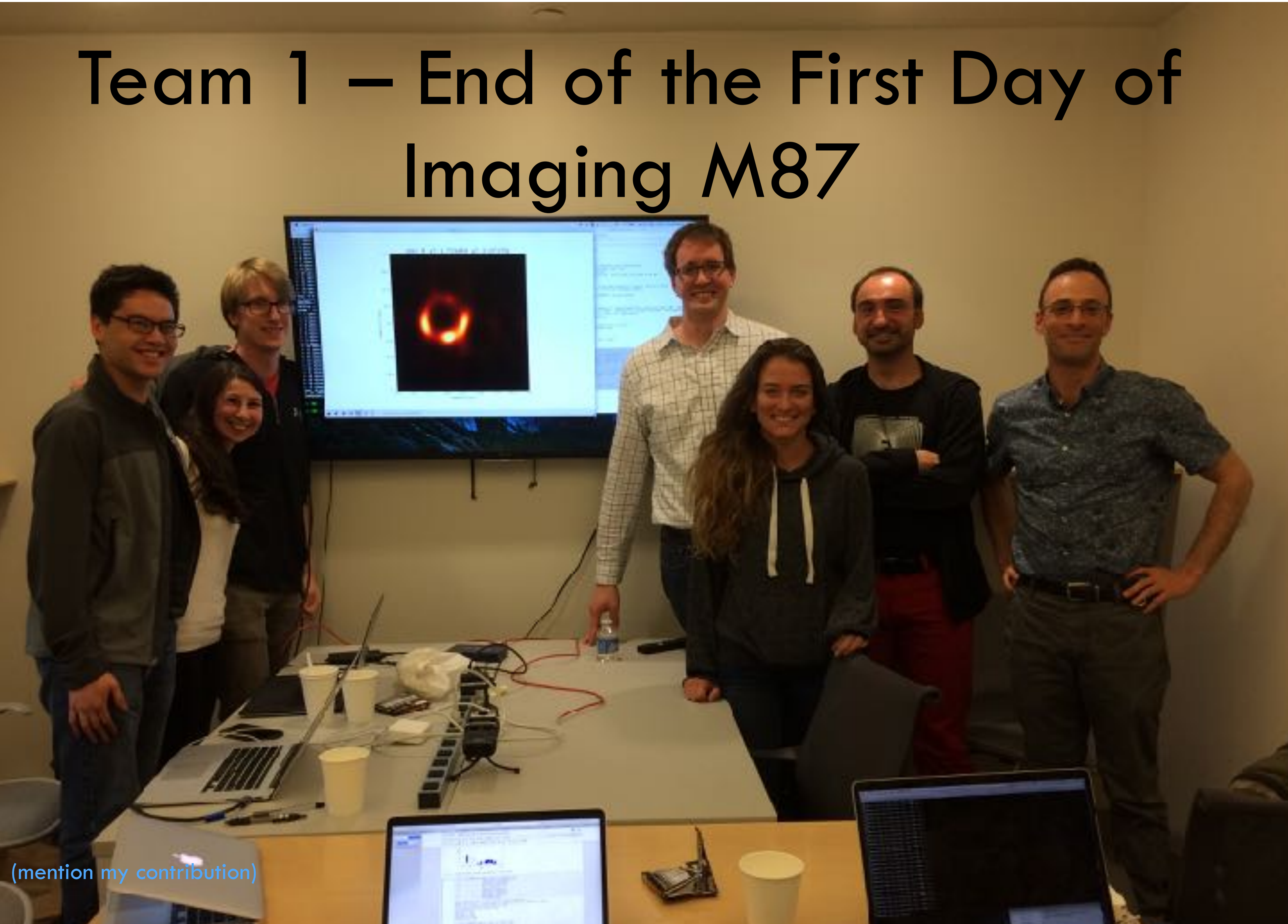




Lo-band eht-imaging on April 11: slowly building up data



Team 1 – End of the First Day of Imaging M87



(mention my contribution)

EHT Imaging Working Group

The dangers of false confidence and collective confirmation bias are magnified for the EHT because the array has fewer sites than typical VLBI arrays, there are no previous VLBI images of any source at 1.3 mm wavelength, and there are no comparable black hole images on event-horizon scales at any wavelength.

We subdivided our first M87 imaging efforts into four separate imaging teams. The teams were blind to each others' work, prohibited from discussing their imaging results and even from discussing aspects of the data that might influence imaging (e.g., which stations or data might be of poor quality).

Imaging Stage 1/2: Blind Imaging Comparisons

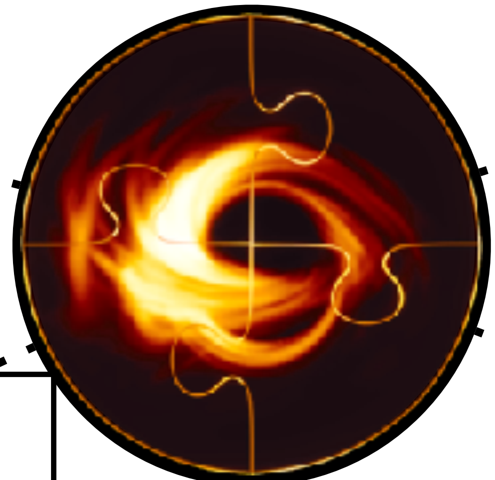
The Imaging WG was divided into four independent teams

Team 1

Region:
The Americas
(SAO, UoA, U.Concepcion)

Team 4

Region:
East Asia (ASIAA, KASI, NAOJ)



Team 2

Region:
Global
(MIT Haystack, Radboud U, NAOJ)

Team 3

Region:
Cross-Atlantic
(MPIfR, Boston U, IAA, Aalto)

Each team blindly reconstructed images

Goal: Assess human bias

The First EHT Images of M87

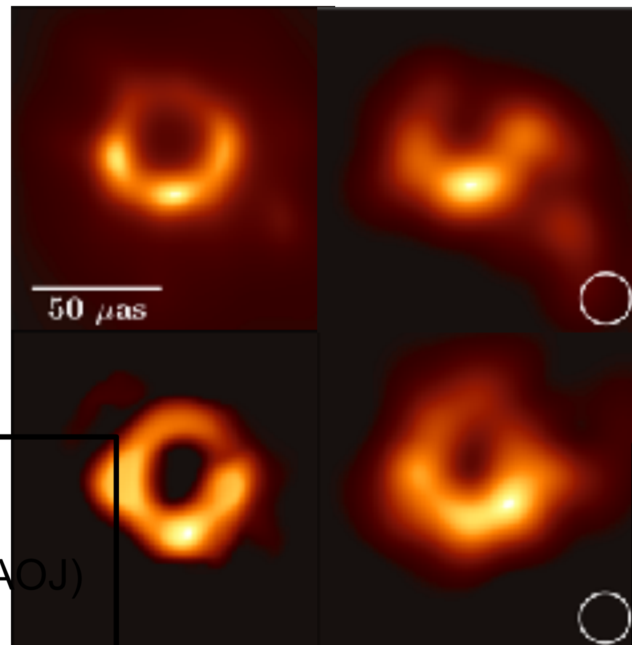
July 24, 2018

Team 1

Region:
The Americas
(SAO, UoA, U.Concepcion)

Team 4

Region:
East Asia (ASIAA, KASI, NAOJ)



Team 2

Region:
Global
(MIT Haystack, Radboud U, NAOJ)

Team 3

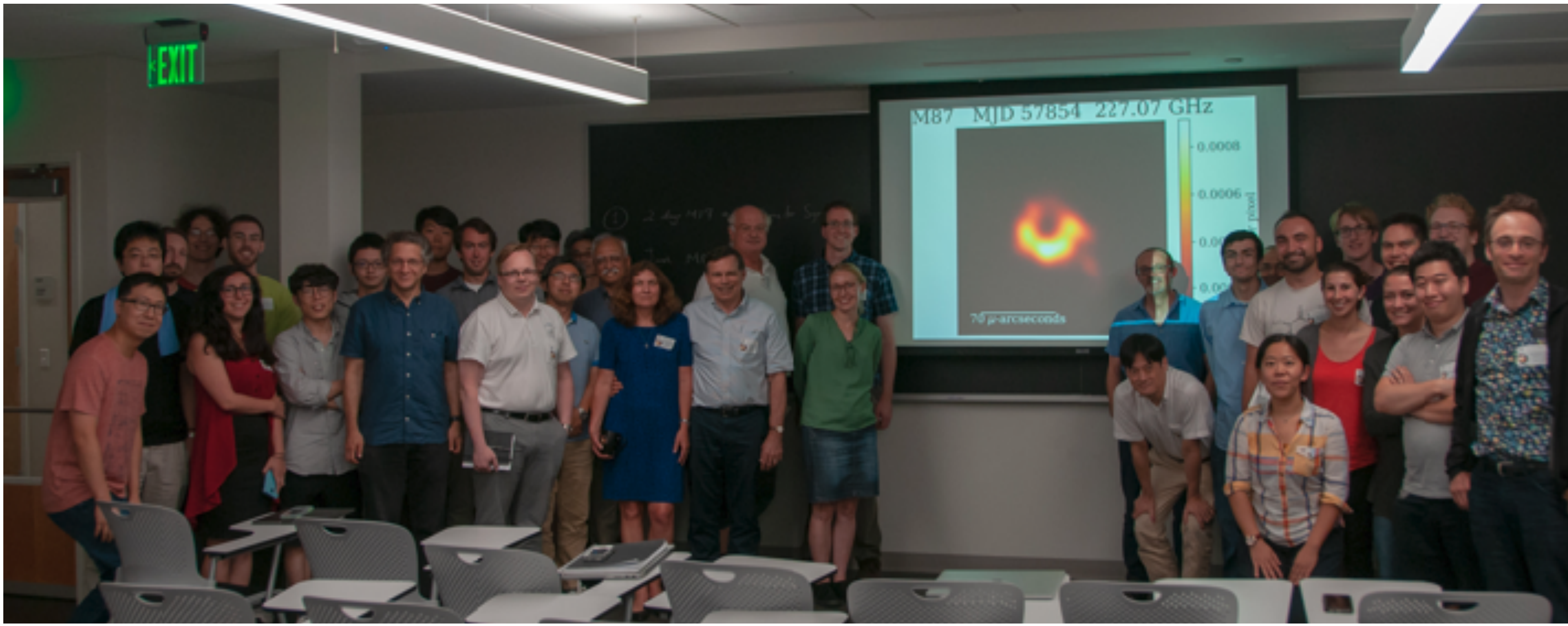
Region:
Cross-Atlantic
(MPIfR, Boston U, IAA, Aalto)

Each team blindly reconstructed images

Goal: Assess human bias

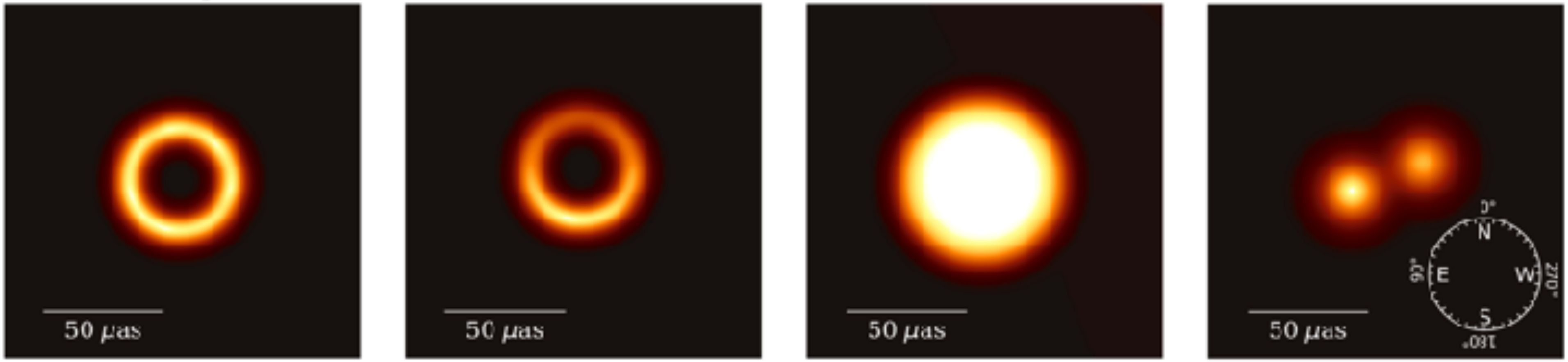
The First EHT Images of M87

July 24, 2018



2nd EHT Imaging Workshop

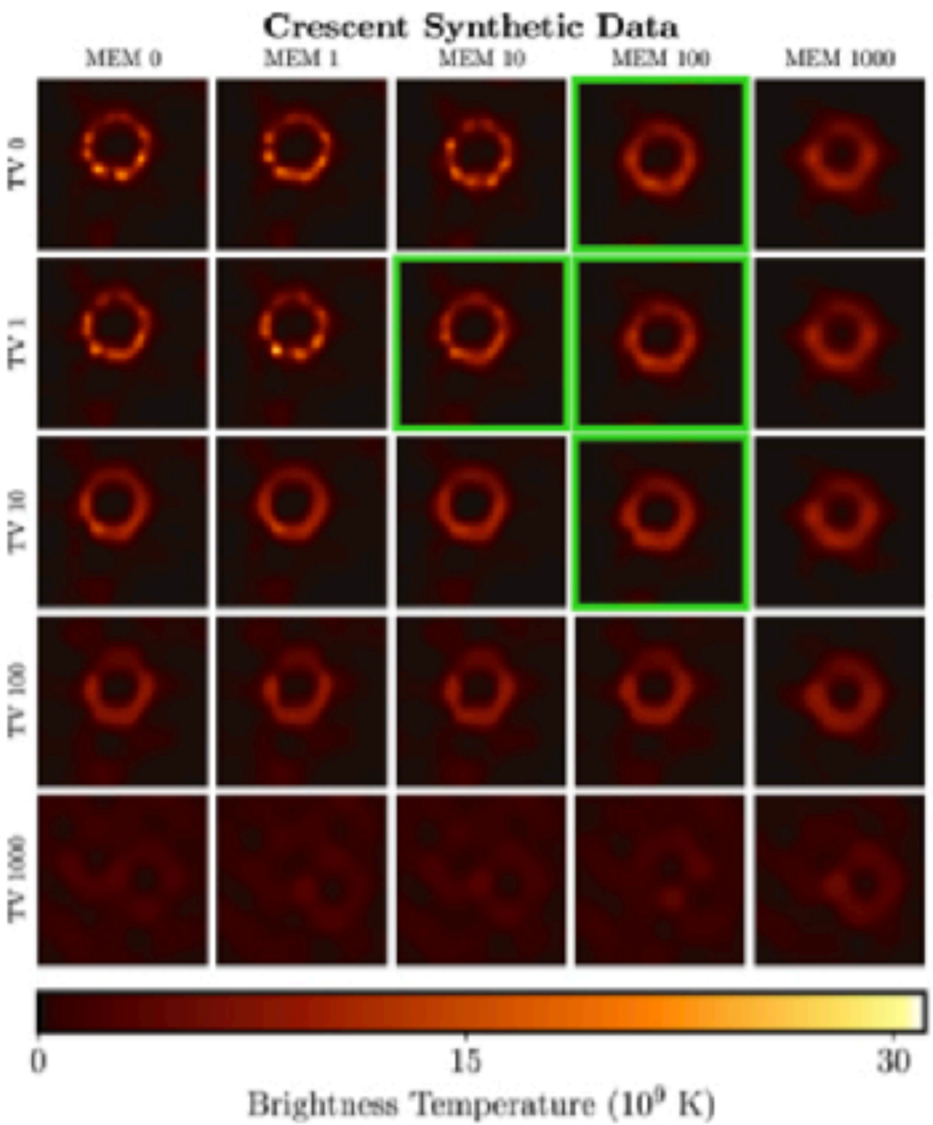
Imaging Stage 2/2: Imaging Parameter Survey



Imaging algorithms were tested on a suite of synthetic datasets

Goal: Optimize imaging algorithms with objective performance assessment

Imaging Stage 2/2: Imaging Parameter Survey



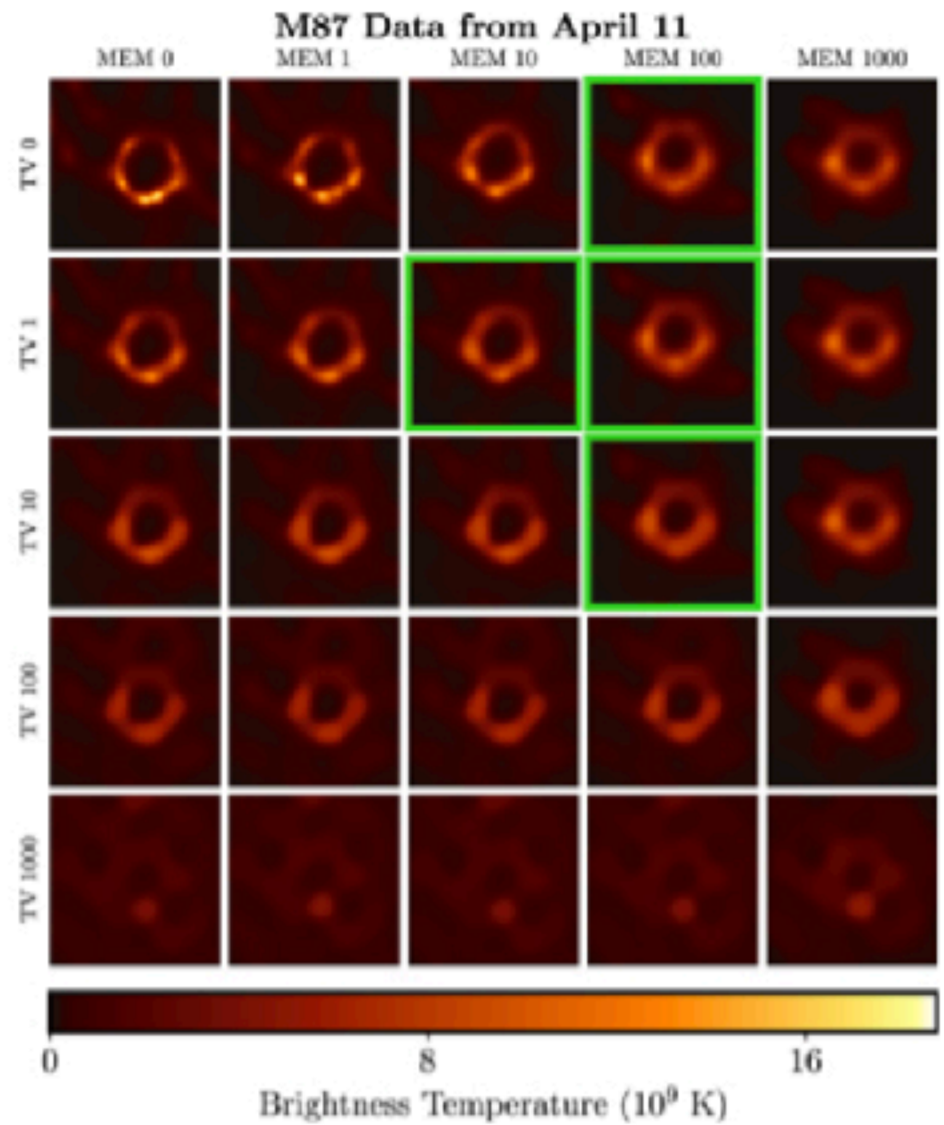
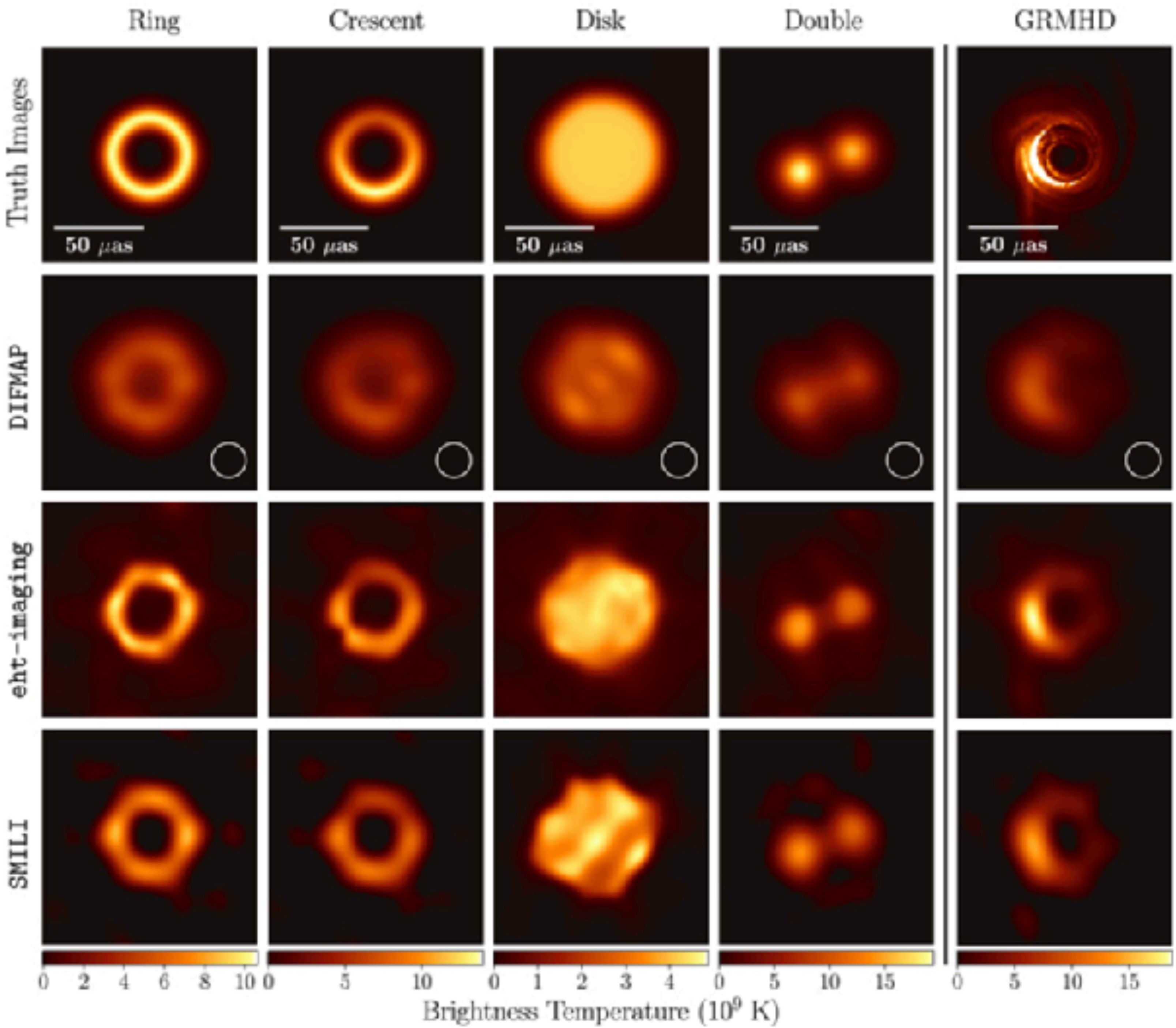


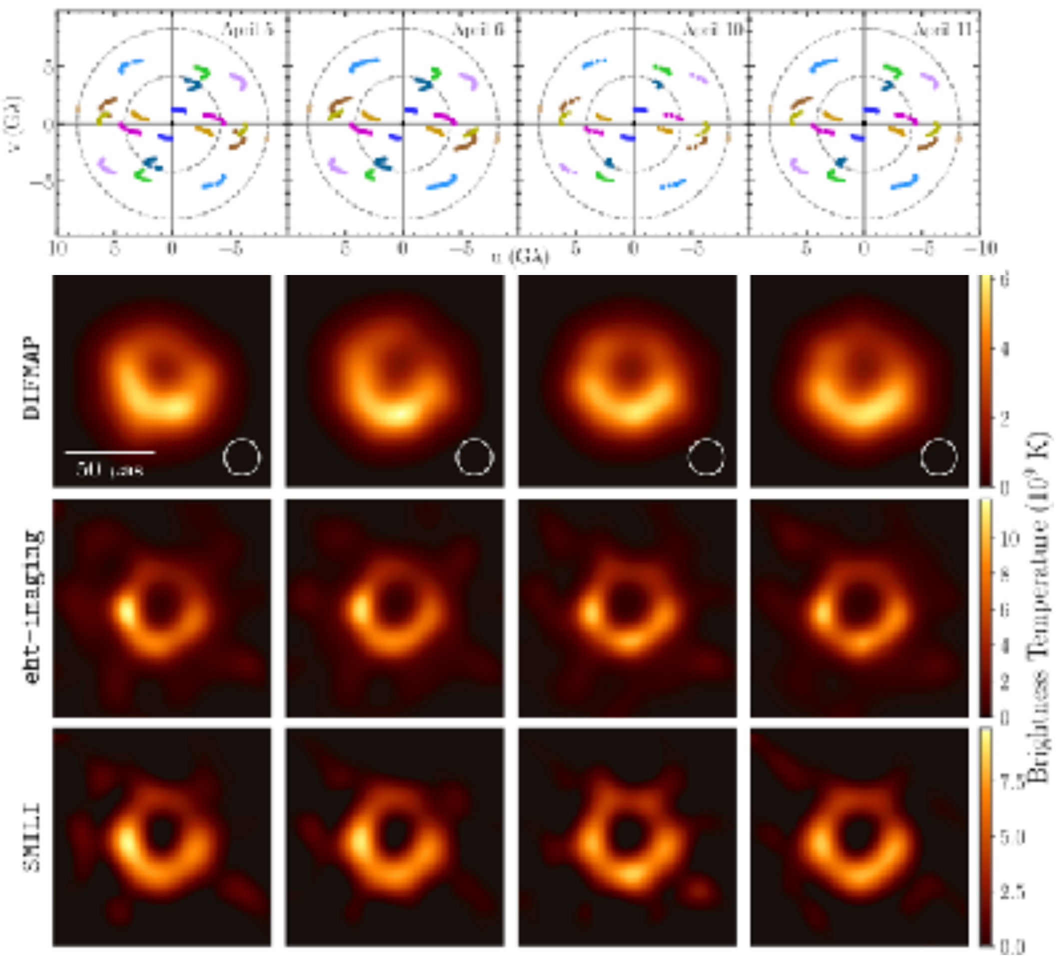
Figure 7. Selection of the `eht-imaging` (RML) parameter survey results on real and synthetic data with April 11 EHT baseline coverage. A 2D slice of the 7D parameter space is displayed, corresponding to different weights on the MEM and TV regularizers. All other parameters are kept constant (Compact Flux = 0.6 Jy, Initial/MEM FWHM = 40 μas, Systematic Error = 1%, TSV = 0, and $\ell_1 = 0$). The left panel shows results of the parameter search on the Crescent synthetic data, while the right panel shows reconstructions for the same parameters on M87 data. Images that meet the threshold for the Top Set are outlined in green. Note that the upper-left reconstruction has *no* regularization; it is produced by enforcing only image positivity and a constrained FOV.


Ring
Crescent
Disk
Double
GRMHD
Truth Images
DIFMAP
eht-imaging
SMILI
50 μas
0 2 4 6 8 10
0 5 10
0 1 2 3 4
0 5 10 15
0 5 10 15
Brightness Temperature (10^9 K)

scope

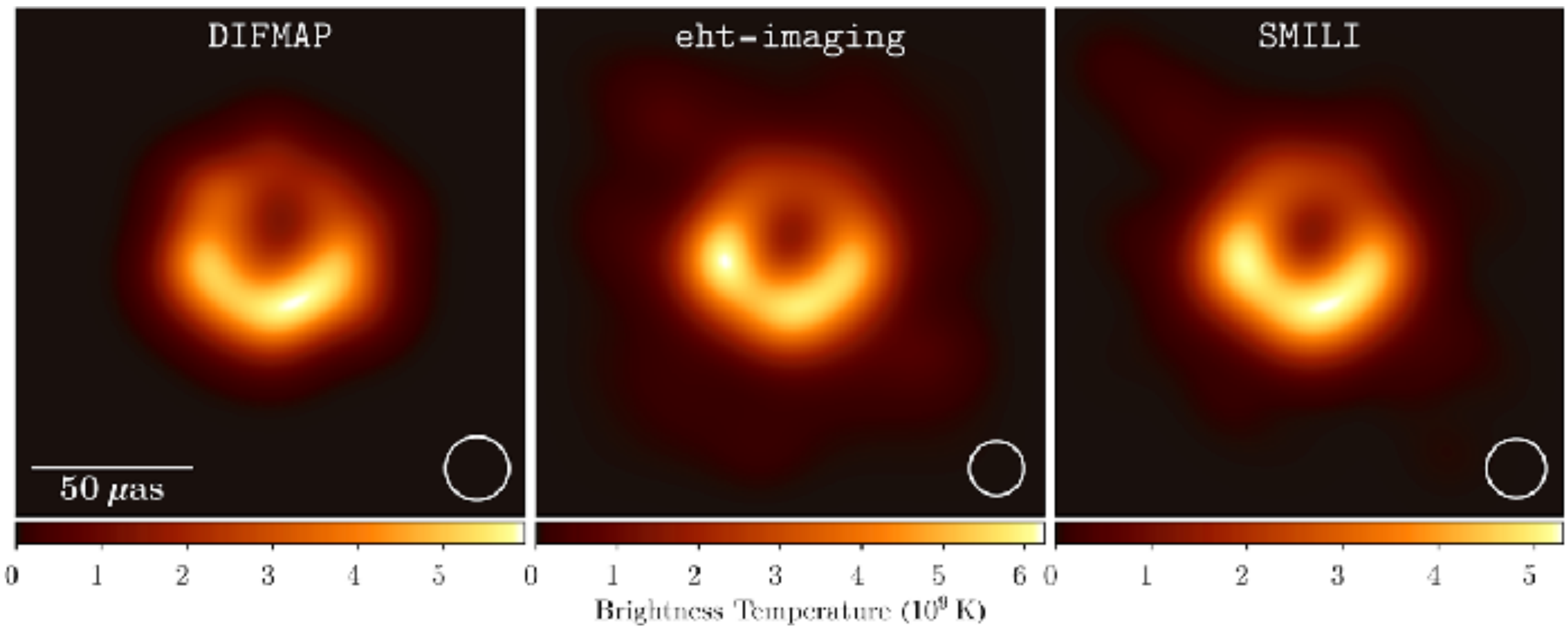
Figure 10. Cross-validation of the imaging parameter selection procedure. In each of the left four columns, we show reconstructed images for the simple geometric source models. These reconstructions do not use the fiducial imaging parameters identified by the full training set; instead, we selected the imaging parameters for each geometric source model after excluding that particular model from the parameter selection process. For example, in the disk reconstructions, the parameters were selected by assessing reconstructions of only the ring, crescent, and double source models. Thus, the selected parameters vary among these four columns, but we can verify that the training sets do not overly constrain the outcomes. In the fifth column, we show reconstructions of a GRMHD snapshot (Paper V) using the fiducial M87 parameters selected from all four geometric models. That is, the script and parameters used to produce these GRMHD image reconstructions are identical to those used to produce our fiducial M87 images (shown in Figure 11). Because the GRMHD snapshot has a substantially higher peak brightness than the reconstructions, its column has been scaled to the peak brightness of the `eht-imaging` reconstruction.

Fiducial images for all four days and three scripts

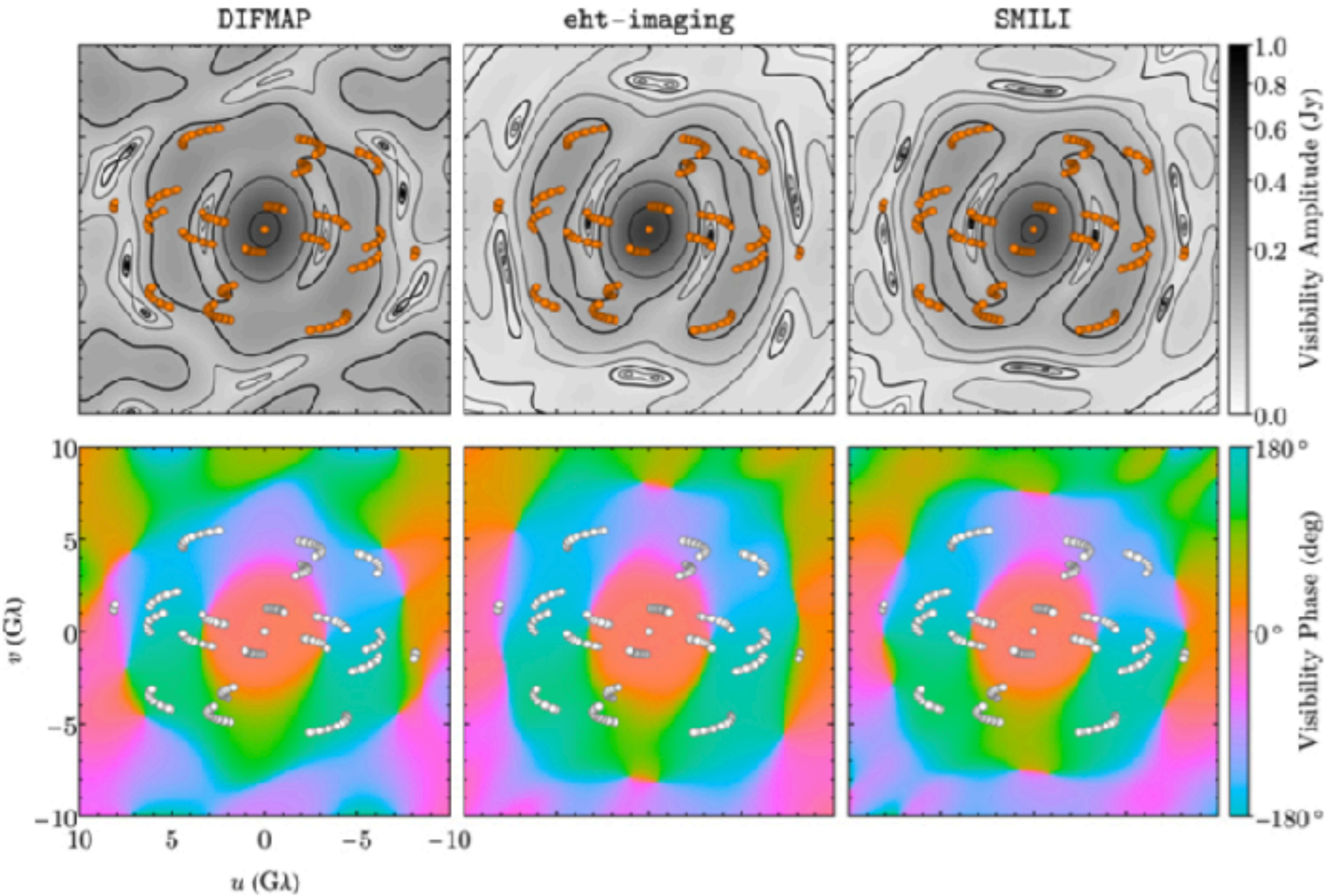


- Best images out of 1008, 37500, and 10800 images surveyed by the Difmap, eht-library, and SMILI scripts, respectively
- All images from the four different observing days show the asymmetric ring structure corresponding to the black hole shadow

Fiducial images of M87 for April 11 restored to an equivalent resolution show remarkably similar structure



Comparison of reconstructions, in the Fourier domain



THE ASTROPHYSICAL JOURNAL LETTERS

Focus on the First Event Horizon Telescope Results

Shep Doeleman (EHT Director) on behalf of the EHT Collaboration

April 2019

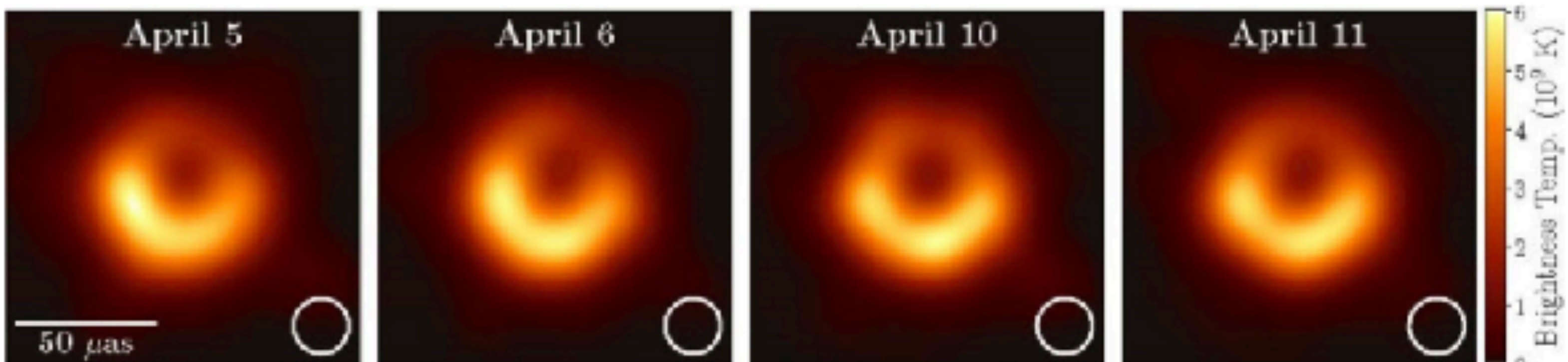


Figure 1. EHT images of M87 on four different observing nights. In each panel, the white circle shows the resolution of the EHT. All four images are dominated by a bright ring with enhanced emission in the south. From Paper IV (Figure 15).

We report the first image of a black hole.

This Focus Issue shows ultra-high angular resolution images of radio emission from the supermassive black hole believed to lie at the heart of galaxy M87 (Figure 1). A defining feature of the images is an irregular but clear bright ring, whose size and shape agree closely with the expected lensed photon orbit of a 6.5 billion solar mass black hole. Soon after Einstein introduced general relativity, theorists derived the full analytic form of the photon orbit, and first simulated its lensed appearance in the 1970s. By the 2000s, it was possible to sketch the "shadow" formed in the image when synchrotron emission from an optically thin accretion flow is lensed in the black hole's gravity. During this time, observational evidence began to build for the existence of black holes at the centers of active galaxies, and in our own Milky Way. In particular, a steady progression in radio astronomy enabled very long baseline interferometry (VLBI) observations at ever-shorter wavelengths, targeting supermassive black holes with the largest apparent event horizons: M87, and Sgr A* in the Galactic Center. The compact sizes of these two sources were confirmed by studies at 1.3mm, first exploiting baselines that ran from Hawai'i to the mainland US, then with increased resolution on baselines to Spain and Chile.

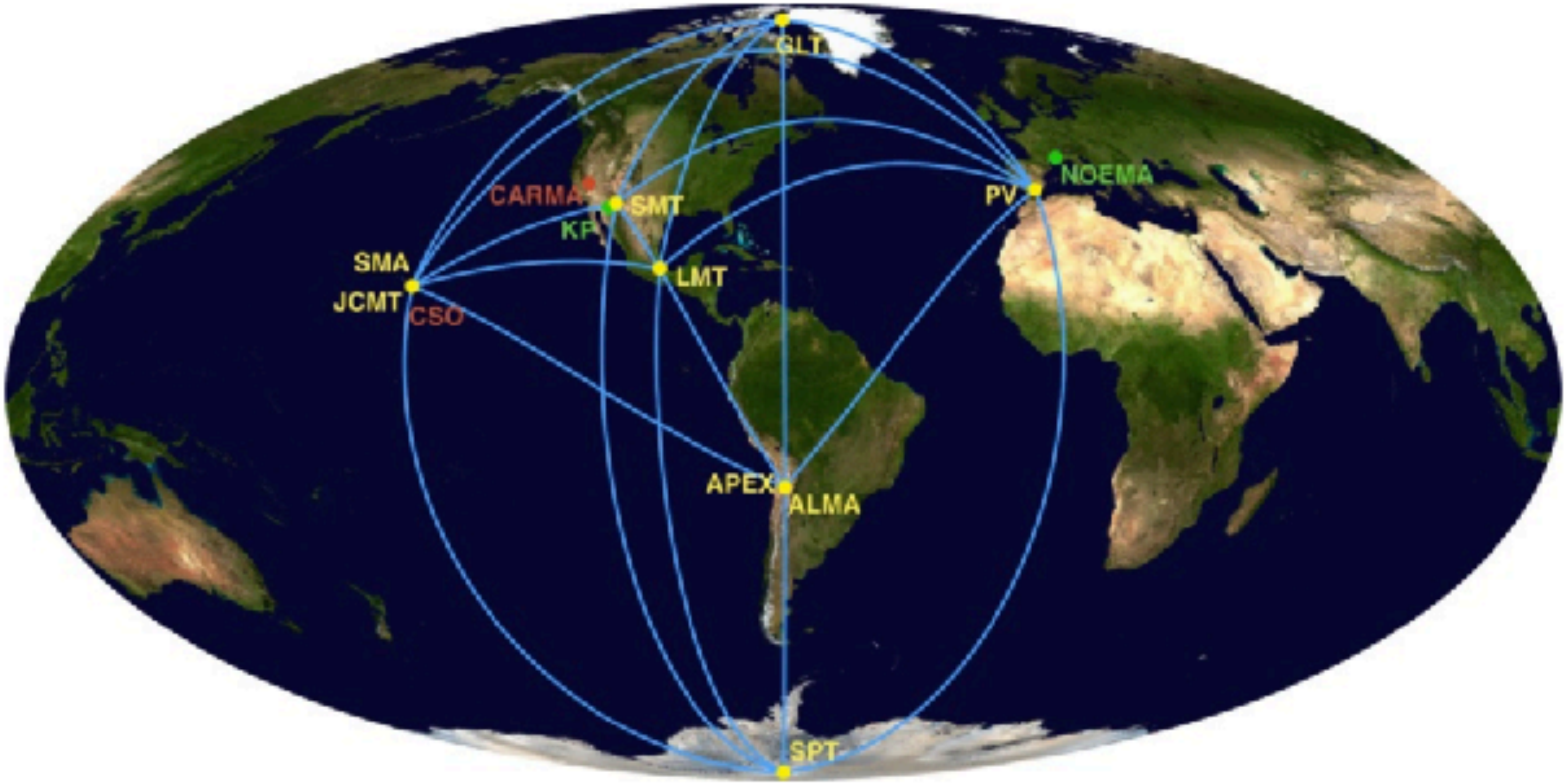


Figure 2. A map of the EHT. Stations active in 2017 and 2018 are shown with connecting lines and labeled in yellow, sites in commission are labeled in green, and legacy sites are labeled in red. From Paper II (Figure 1).

The sequence of Letters in this issue provides the full scope of the project and the conclusions drawn to date. Paper II opens with a description of the EHT array, the technical developments that enabled precursor detections, and the full range of observations reported here. Through the deployment of novel instrumentation at existing facilities, the collaboration created a new telescope with unique capabilities for black hole imaging. Paper III details the observations, data processing, calibration algorithms, and rigorous validation protocols for the final data products used for analysis. Paper IV gives the full process and approach to image reconstruction. The final images emerged after a rigorous evaluation of traditional imaging algorithms and new techniques tailored to the EHT instrument–alongside many months of testing the imaging algorithms through the analysis of synthetic data sets. Paper V uses newly assembled libraries of general relativistic magnetohydrodynamic (GRMHD) simulations and advanced ray-tracing to analyze the images and data in the context of black hole accretion and jet-launching. Paper VI employs model fits, comparison of simulations to data, and feature extraction from images to derive formal estimates of the lensed emission ring size and shape, black hole mass, and constraints on the nature of the black hole and the space-time surrounding it. Paper I is a concise summary.

Our image of the shadow confines the mass of M87 to within its photon orbit, providing the strongest case for the existence of supermassive black holes. These observations are consistent with Doppler brightening of relativistically moving plasma close to the black hole lensed around the photon orbit. They strengthen the fundamental connection between active galactic nuclei and central engines powered by accreting black holes through an entirely new approach. In the coming years, the EHT Collaboration will extend efforts to include full polarimetry, mapping of magnetic fields on horizon scales, investigations of time variability, and increased resolution through shorter wavelength observations.

In short, this work signals the development of a new field of research in astronomy and physics as we zero in on precision images of black holes on horizon scales. The prospects for sharpening our focus even further are excellent.

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L1

First M87 Event Horizon Telescope Results. II. Array and Instrumentation

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L2

First M87 Event Horizon Telescope Results. III. Data Processing and Calibration

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L3

First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L4

First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L5

First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L6

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration, Kazunori Akiyama[1,2,3,4], Antxon Alberdi[5], Walter Alef[6], Keiichi Asada[7], Rebecca Azulay[8,9,6], Anne-Kathrin Baczko[6], David Ball[10], Mislav Baloković[4,11], John Barrett[2], Dan Bintley[12], Lindy Blackburn[4,11], Wilfred Boland[13], Katherine L. Bouman[4,11,14], Geoffrey C. Bower[15], Michael Bremer[16], Christiaan D. Brinkerink[17], Roger Brissenden[4,11], Silke Britzen[6], Avery E. Broderick[18,19,20], Dominique Broguiere[16], Thomas Bronzwaer[17], Do-Young Byun[21,22], John E. Carlstrom[23,24,25,26], Andrew Chael[4,11], Chi-kwan Chan[10,27], Shami Chatterjee[28], Koushik Chatterjee[29], Ming-Tang Chen[15], Yongjun Chen (陈永军)[30,31], Ilje Cho[21,22], Pierre Christian[10,11], John E. Conway[32], James M. Cordes[28], Geoffrey B. Crew[2], Yuzhu Cui[33,34], Jordy Davelaar[17], Mariafelicia De Laurentis[35,36,37], Roger Deane[38,39], Jessica Dempsey[12], Gregory Desvignes[6], Jason Dexter[40], Sheperd S. Doeleman[4,11], Ralph P. 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Nowak[131], George Nystrom[15], Hideo Ogawa[132], Peter Oshiro[15], Tomoaki Oyama[133], Harriet Parsons[12], Scott N. Paine[11], Juan Peñalver[84], Neil M. Phillips[121,126], Michael Poirier[2], Nicolas Pradel[7], Rurik A. Primiani[134], Philippe A. Raffin[15], Alexandra S. Rahlin[23,135], George Reiland[10], Christopher Risacher[16], Ignacio Ruiz[84], Alejandro F. Sáez-Madaín[102,126], Remi Sassella[16], Pim Schellart[17,136], Paul Shaw[7], Kevin M. Silva[12], Hotaka Shiokawa[11], David R. Smith[137,138], William Snow[15], Kamal Souccar[76], Don Sousa[2], T. K. Sridharan[11], Ranjani Srinivasan[15], William Stahm[12], Anthony A. Stark[11], Kyle Story[139], Sjoerd T. Timmer[17], Laura Vertatschitsch[11,134], Craig Walther[12], Ta-Shun Wei[7], Nathan Whitehorn[140], Alan R. Whitney[2], David P. Woody[141], Jan G. A. Wouterloot[12], Melvin Wright[142], Paul Yamaguchi[11], Chen-Yu Yu[7], Milegros Zeballos[105,143], Shuo Zhang[104], and Lucy Ziurys[10] — Hide full author list

Published 2019 April 10 •

The Astrophysical Journal Letters, Volume 875, Number 1

Focus on the First Event Horizon Telescope Results

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My friend, Carl

“No, it won’t be on the front page of every newspaper because the image is just too blurry”

The Boston Globe

THURSDAY, APRIL 11, 2019

dren's
pital
prince
3.5m

royal promised
t of child's care

iz Kowalczyk
LOBE STAFF

Hospital has sued a member
mily for $3.5 million, alleging
ise to pay for the care of a very
ne country.

One less mystery in our vast universe

Earthbound teams record first image of black hole

By Brian MacQuarrie
GLOBE STAFF

Katherine Bouman had devoted years to the astonishing quest — to help capture the first image of a massive black hole in a distant galaxy, a void so dense no light can escape.

But when the mind-bending breakthrough finally came almost a year ago, the discovery had to stay a secret.

So, after the stunning image was revealed to the world Wednesday, Bouman's excitement spilled out at what seemed the speed of light.

"We've been busting at the seams about what we've seen, but we had to keep our mouths shut," said Bouman, 29, a doctoral graduate of MIT who continued her studies at the Harvard-Smithsonian Center for Astrophysics.

What she and a large team of scientists from MIT, Harvard, and other universities had seen was the first-ever image of a cosmic black hole 53 million light-years away, a time-warping and light-twisting mystery of the universe whose existence Albert Einstein had hinted at a century ago.

BLACK HOLE, Page A12

EVENT HORIZON TELESCOPE COLLABORATION

The image of a black hole spawned celebrations.

Bernie Sanders
$18.2 million

Warren

Middle of the pack total cases concerns about forgoing big donors

The Black Hole Shadow in M 87

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May defies critics with vow to stay on and see Brexit deal through
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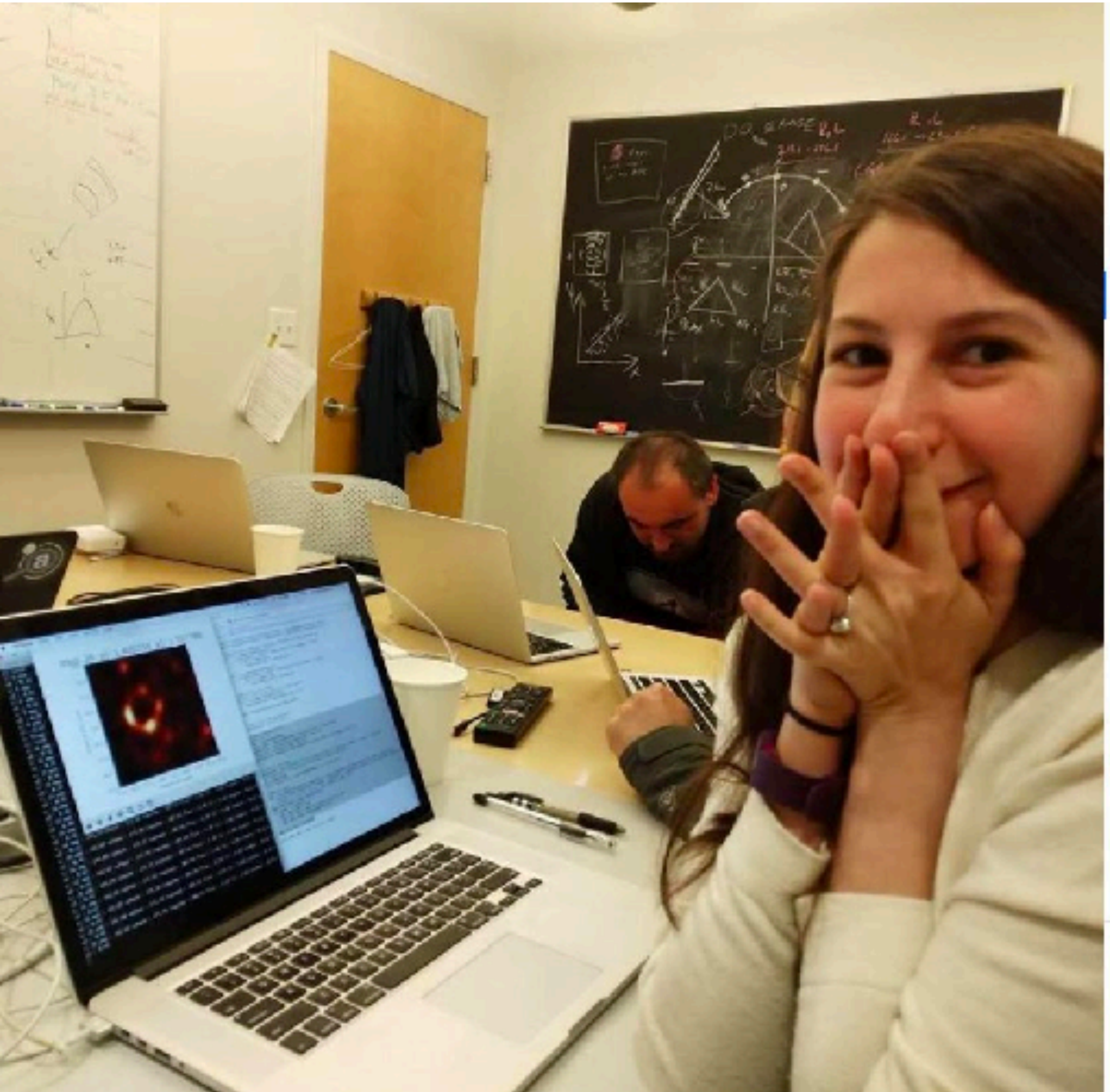

Katie Bouman

1 hr

Watching in disbelief as the first image I ever made of a black hole was in the process of being reconstructed.

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Kayhan Batmanghelich This is amazing Katie! Congratulations

1h

Wardah Inam That is so cool!

1h

Shaun Puraglove You are so cute!

1h

Vikas Ramachandra very cool Katie!

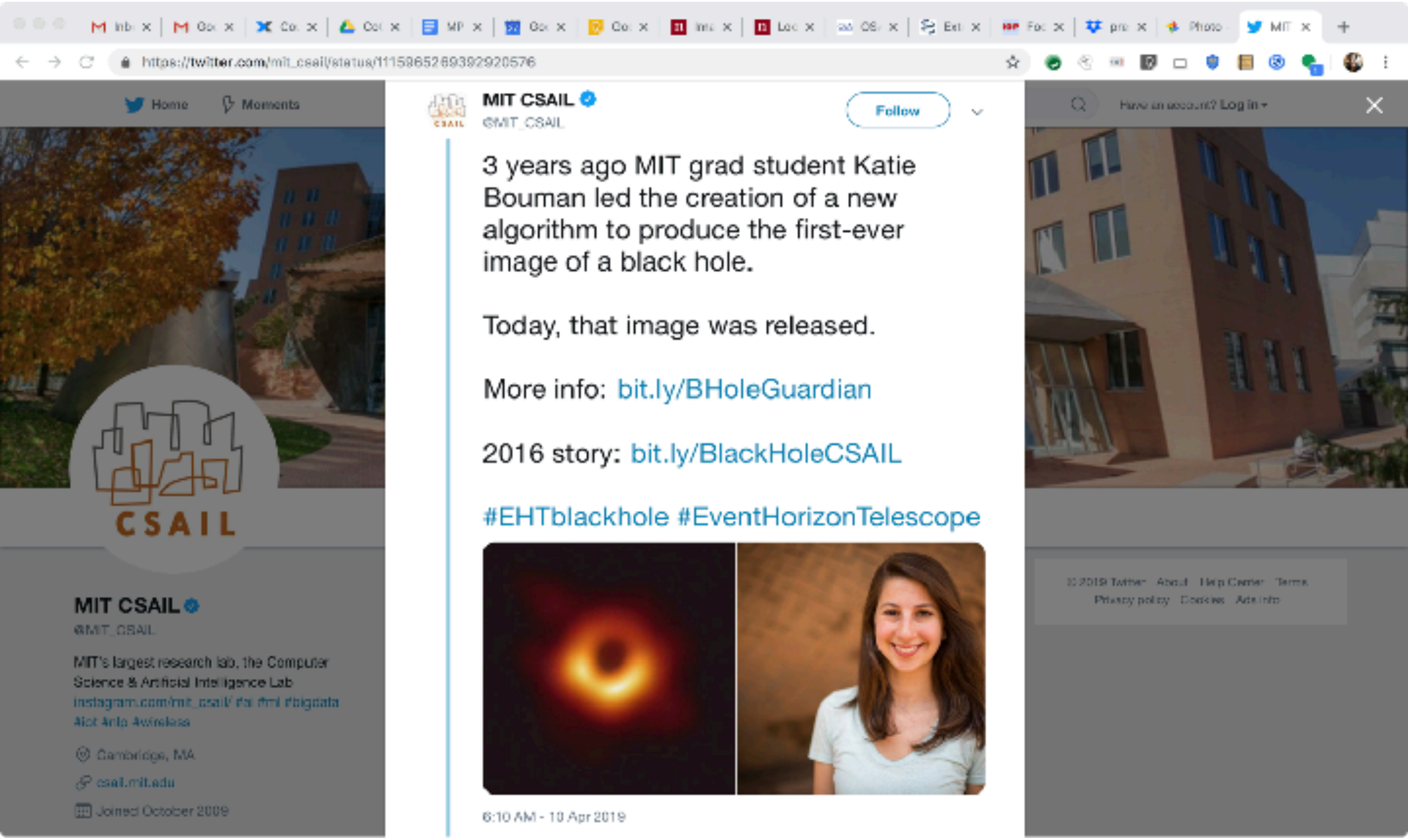
47m

Adrian Dalca Congrats 😃

36m

Miki Rubinstein Congratulations!!

17m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3 years ago MIT grad student Katie Bouman led the creation of a new algorithm to produce the first-ever image of a black hole.
Today, that image was released.
More info: bit.ly/BHoleGuardian
2016 story: bit.ly/BlackHoleCSAIL
#EHTblackhole #EventHorizonTelescope
6:10 AM - 10 Apr 2019
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MIT's largest research lab, the Computer Science & Artificial Intelligence Lab
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Here's the moment when the first black hole image was processed, from the eyes of researcher Katie Bouman. #EHTBlackHole #BlackHoleDay #BlackHole (v/@dfbarajas)
9:51 AM - 10 Apr 2019
17,550 Retweets 58,160 Likes
579
18K
58K
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Take your rightful seat in history, Dr. Bouman! 🔭
Congratulations and thank you for your enormous contribution to the advancements of science and mankind.
Here's to #WomenInSTEM! 👩‍🔬👩‍💻👷‍♀️👩‍🏫
Tamy Emma Pepin @TamyEmmaPepin
Congratulations to Katie Bouman to whom we owe the first photograph of a black hole ever. Not seeing her name circulate nearly enough in the press....
1:41 PM - 10 Apr 2019
23,584 Retweets 101,843 Likes
1.0K 24K 102K
Rafael @pentateu · Apr 10
Replying to @AOC
Alexandria Ocasio-Cortez
@AOC
Congresswoman for NY-14 (Bronx + Queens). In a modern, moral, + wealthy society, no American should be too poor to live. 💯% People-Funded, no corporate PAC $.
Bronx + Queens, NYC
Ocasio2018.com
Joined April 2010
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Nancy Pelosi
@SpeakerPelosi

Congratulations to Dr. Katie Bouman, who developed the algorithm which captured the first ever image of a black hole! You are an inspiration to all Americans and especially to young women and girls with STEAM dreams! cnn.com/2019/04/10/us/…

♡ 40.3K 6:46 PM - Apr 11, 2019

That image of a black hole you saw everywh…
The effort wouldn't have succeeded without Katie Bouman, who developed a crucial algorithm and
cnn.com

Barbie
@Barbie

Congratulations Katie Bouman on this remarkable accomplishment! Thank you for leading by example and encouraging girls to push the boundaries of science. 👩‍🔬
#YouCanBeAnything #MoreRoleModels

> **AJ+** @ajplus
> Replying to @ajplus
> This is Dr. Katie Bouman. She's the computer scientist behind the first-ever image of a black hole.
>
> She developed the algorithm that turned telescopic data into the historic photo we see today.

♡ 550 6:46 PM - Apr 10, 2019

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We at @MIT_CSAIL are so proud of the role our alum Dr. Katie Bouman played in the development of the first-ever picture of a black hole. She's been psyched about all the #blackhole interest & just wanted to clarify a few things. (1/7)
11:49 AM - 12 Apr 2019
128 Retweets 434 Likes
26 128 434
MIT CSAIL @MIT_CSAIL · Apr 12
In our first tweet about this, we linked to a 2016 story about an algorithm she led the development of while at CSAIL. That algorithm was intended to take a picture of a black hole, but didn't create the final image. (cont.)(2/7)
4 11 81
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It inspired image validation procedures in the final paper, and the EHT team together developed new methods that were used in reconstructing the black hole image.(3/7)
2 9 79
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New York Times

7:34

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How Katie Bouman Accidentally Became the Face of the Black Hole Project

By Sarah Mervosh

April 11, 2019

Leer en español

As the first-ever picture of a black hole was unveiled this week, another image began making its way around the internet: a photo of a young scientist, clasping her hands over her face and reacting with glee to an image of an orange ring of light, circling a deep, dark abyss.

It was a photo too good not to share. The scientist, Katie Bouman, a postdoctoral fellow who contributed to the project, became an instant hero for women and girls in STEM, a welcome symbol in a world hungry for representation.

Public figures from Washington to Hollywood learned her name. And some advocates, familiar with how history can

The Atlantic

5:40

Katie Bouman and the Black Hole That M...
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SCIENCE

The Dark Saga of Katie Bouman

How a young scientist got sucked into the black hole of the internet

MARINA KOREN 1:16 PM ET

DESIGN / GETTY / EHT / NATIONAL SCIENCE FOUNDATION VIA REUTERS / THE ATLANTIC

Two photos—one long anticipated, the other a

People also view

Katie Bouman: Black hole colleagues dismiss attacks over hero scientists's role in creating famous image

Katie Bouman is with **Sara Issaoun** and 6 others.
April 10 at 7:47 PM ·

I'm so excited that we finally get to share what we have been working on for the past year! The image shown today is the combination of images produced by multiple methods. No one algorithm or person made this image, it required the amazing talent of a team of scientists from around the globe and years of hard work to develop the instrument, data processing, imaging methods, and analysis techniques that were necessary to pull off this seemingly impossible feat. It has been truly an honor, and I am so lucky to have had the opportunity to work with you all.

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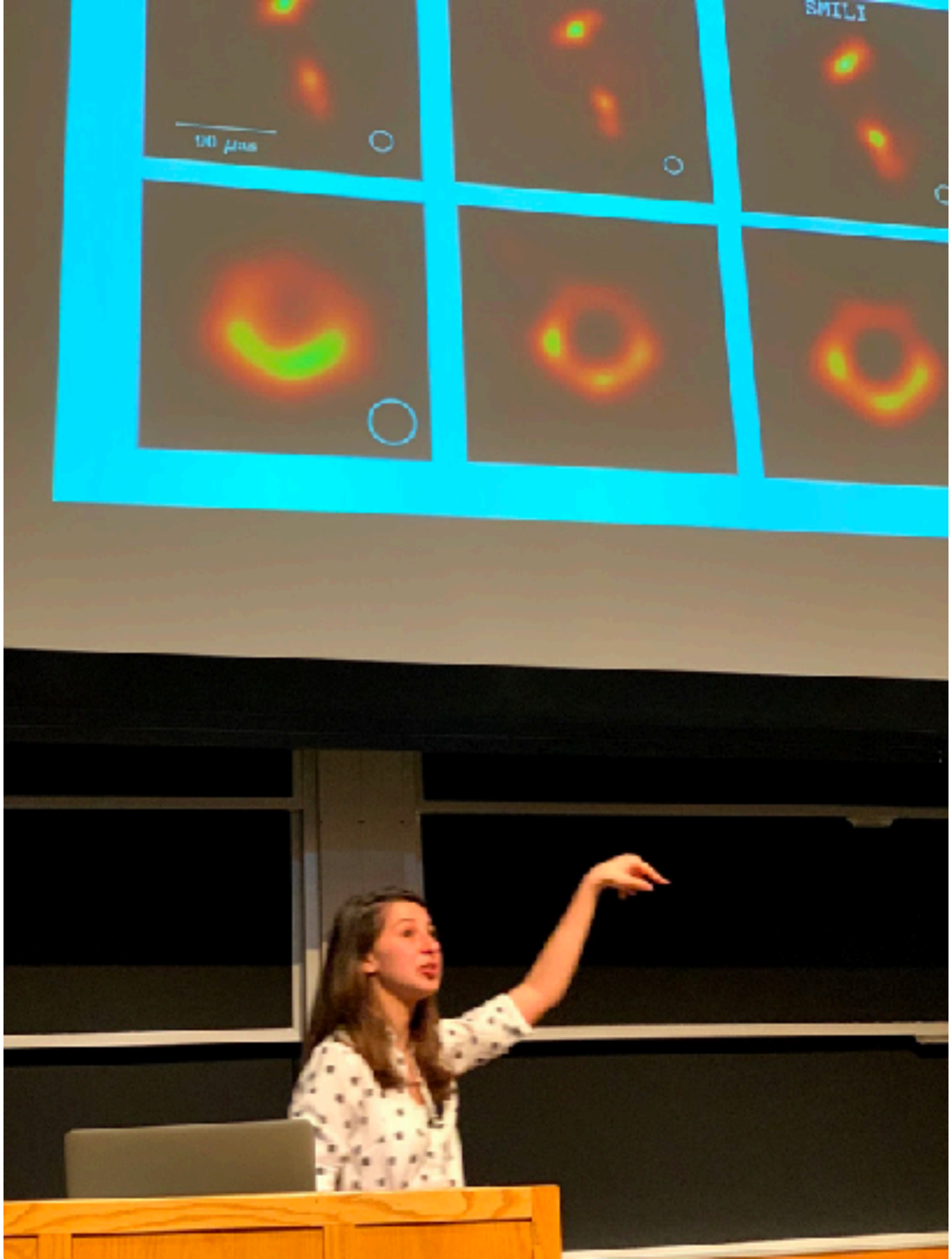
Katie speaking at MIT



Katie speaking
at MIT

CSAIL 32-123

Katie speaking
at Stanford

Katie's audience
at Stanford

Katie speaking at CSAIL's annual gala at ICA, April 27, 2019

Franny, Bill, Katie, Joe at ICA

next: SgrA*

- The EHT team is processing the data from the black hole at the center of our galaxy
- Much less massive (4M vs 6.5B solar masses), and therefore faster dynamics than M87*

SgrA*

The Astrophysical Journal Letters, 930:L12 (21pp), 2022 May 10 https://doi.org/10.3847/2041-8213/ac6674

First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
Received 2022 March 25; revised 2022 April 4; accepted 2022 April 8; published 2022 May 12

Abstract

We present the first Event Horizon Telescope (EHT) observations of Sagittarius A* (Sgr A*), the Galactic center source associated with a supermassive black hole. These observations were conducted in 2017 using a global interferometric array of eight telescopes operating at a wavelength of $\lambda = 1.3$ mm. The EHT data resolve a compact emission region with intrahour variability. A variety of imaging and modeling analyses all support an image that is dominated by a bright, thick ring with a diameter of 51.8 ± 2.3 μas (68% credible interval). The ring has modest azimuthal brightness asymmetry and a comparatively dim interior. Using a large suite of numerical simulations, we demonstrate that the EHT images of Sgr A* are consistent with the expected appearance of a Kerr black hole with mass $\sim 4 \times 10^6 M_\odot$, which is inferred to exist at this location based on previous infrared observations of individual stellar orbits, as well as maser proper-motion studies. Our model comparisons disfavor scenarios where the black hole is viewed at high inclination ($i > 50°$), as well as nonspinning black holes and those with retrograde accretion disks. Our results provide direct evidence for the presence of a supermassive black hole at the center of the Milky Way, and for the first time we connect the predictions from dynamical measurements of stellar orbits on scales of 10^3–10^5 gravitational radii to event-horizon-scale images and variability. Furthermore, a comparison with the EHT results for the supermassive black hole M87* shows consistency with the predictions of general relativity spanning over three orders of magnitude in central mass.

SgrA*

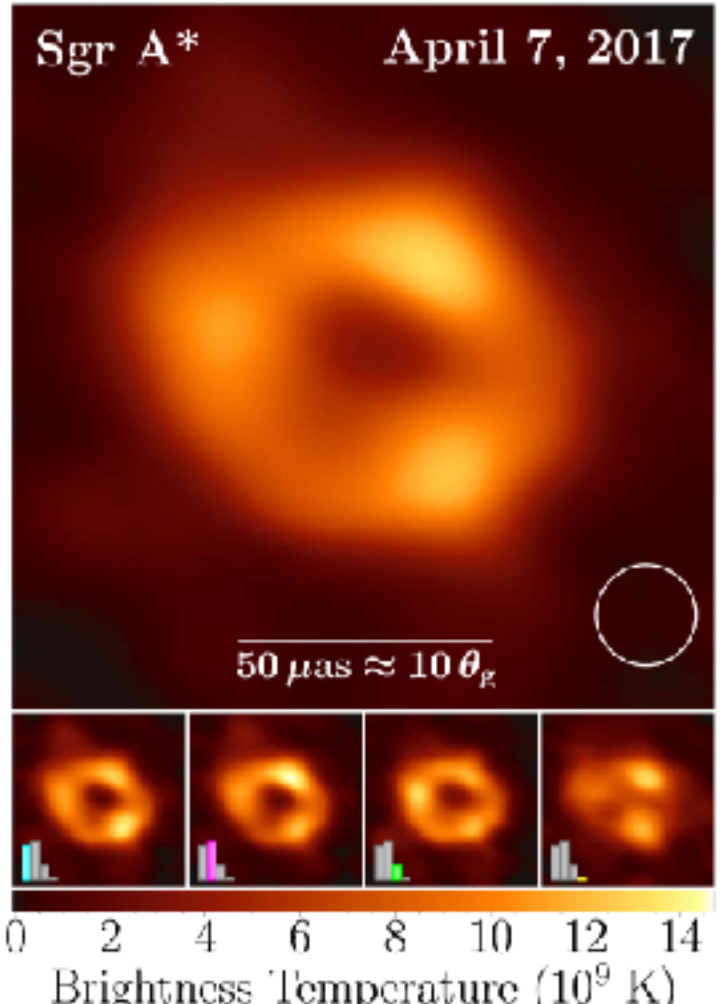


Figure 3. Representative EHT image of Sgr A* from observations on 2017 April 7. This image is an average over different reconstruction methodologies (CLEAN, RML, and Bayesian) and reconstructed morphologies. Color denotes the specific intensity, shown in units of brightness temperature. The inset circle shows the restoring beam used for CLEAN image reconstructions (20 μas FWHM). The bottom panels show average images within subsets with similar morphologies, with their prevalence indicated by the inset bars. The multiplicity of image modes reflects uncertainty due to the sparse baseline coverage; it does not correspond to different snapshots of the variable source. Nearly all reconstructed images show a prominent ring morphology. While the diameter and thickness of the ring are generally consistent across the reconstructions, the azimuthal structure of the ring is poorly constrained.