

Seeing the Unseen

Cover Pages Around The World

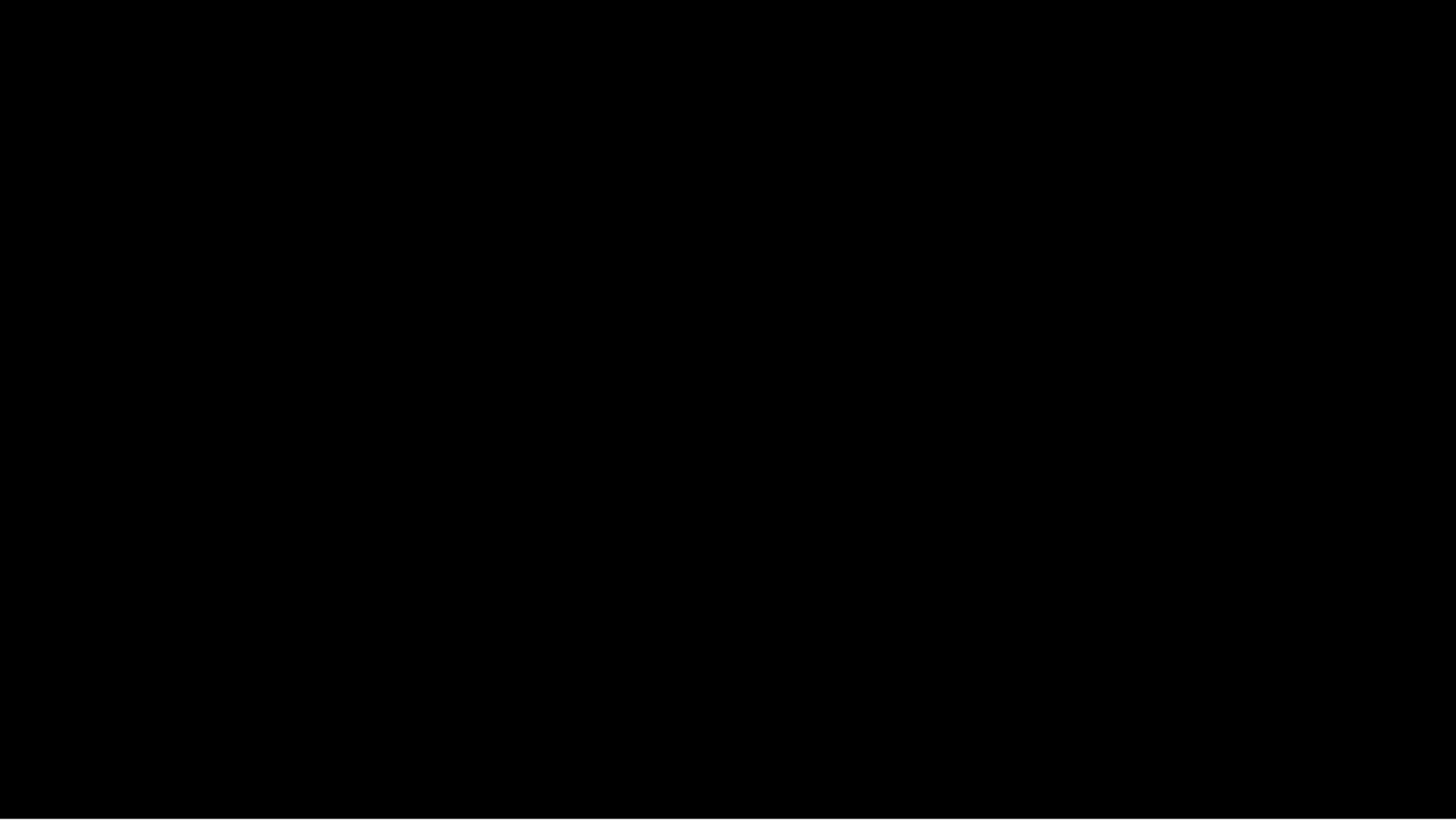
April 11, 2019



The Event Horizon Telescope Collaboration



200+ scientists from 59 institutes in 18 countries in
Europe, Asia, Africa, North and South America





Black Hole Simulation



Grain of Sand
in New York

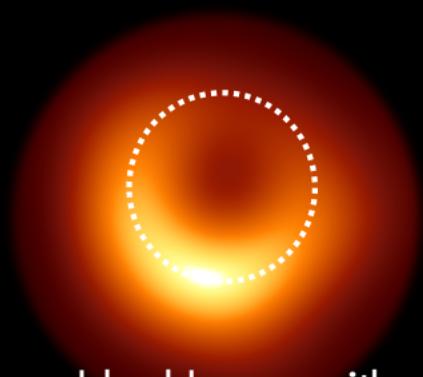
How Big Must Our Telescope Be?

$$13 \text{ million meters} \propto \frac{\text{Wavelength}}{\text{Angular Resolution}}$$

Telescope Size \propto Wavelength
 Angular Resolution



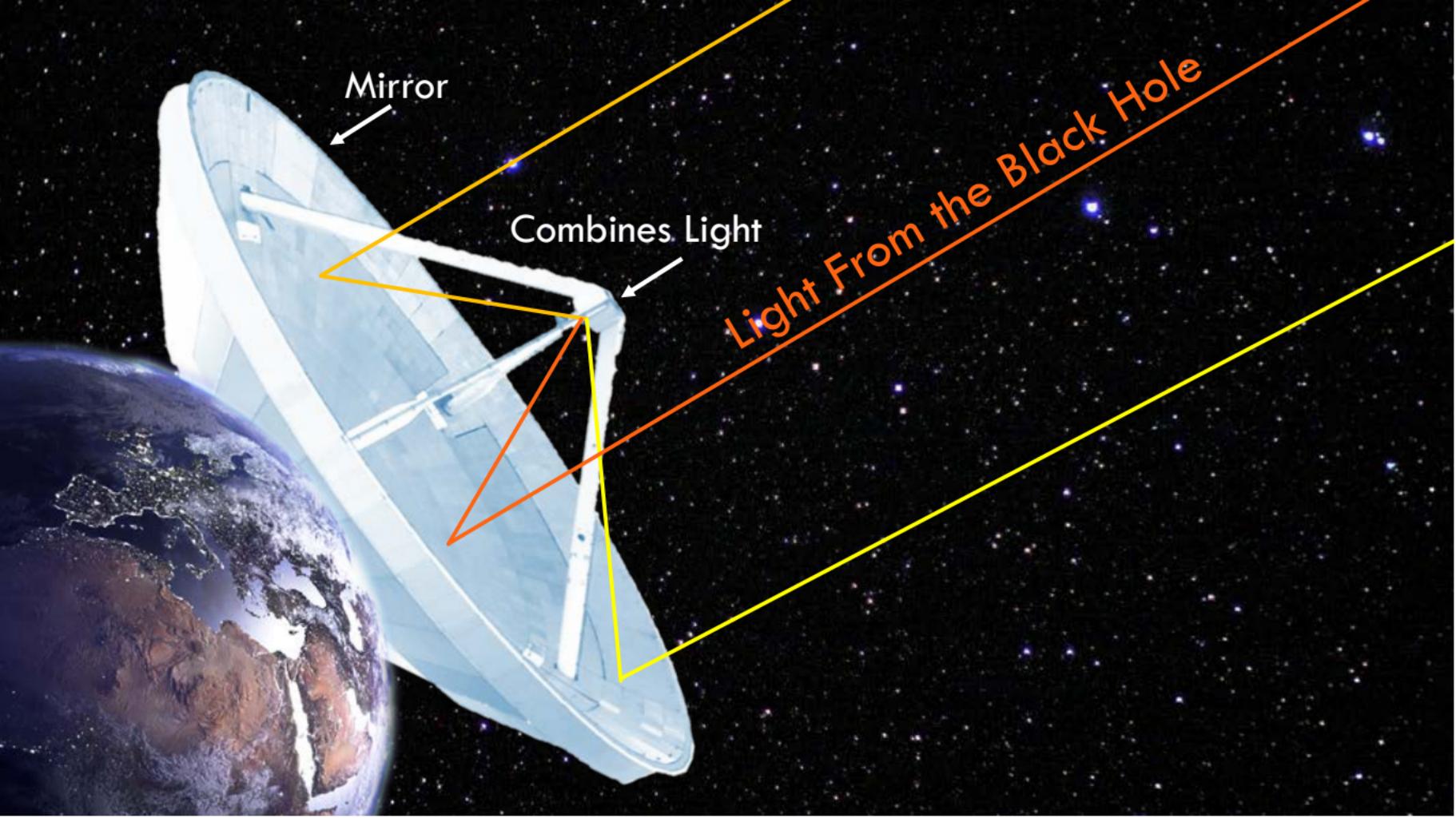
Simulation of M87*



Ideal Image with
Earth-Sized Telescope

The Event Horizon Telescope (EHT)

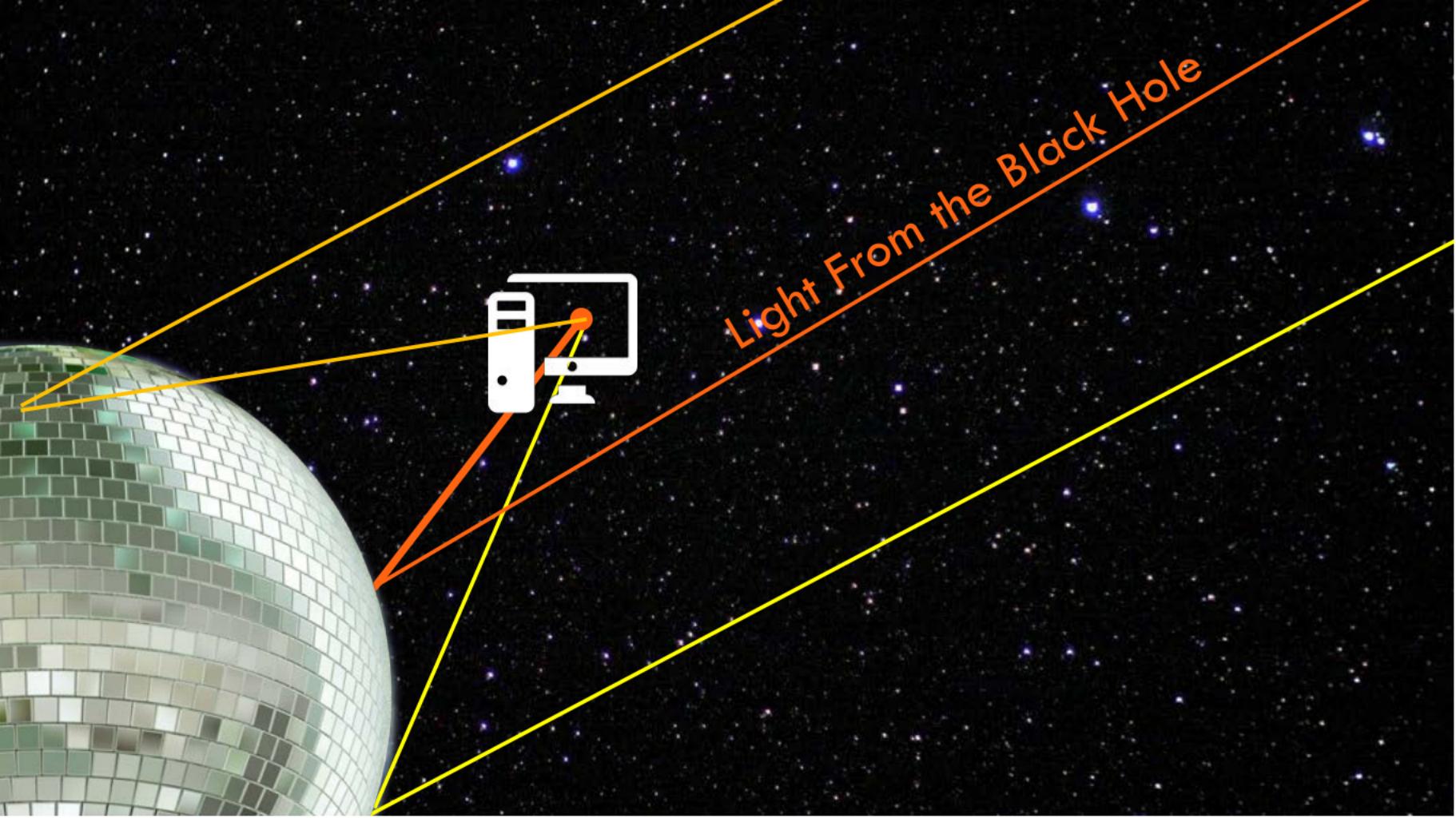




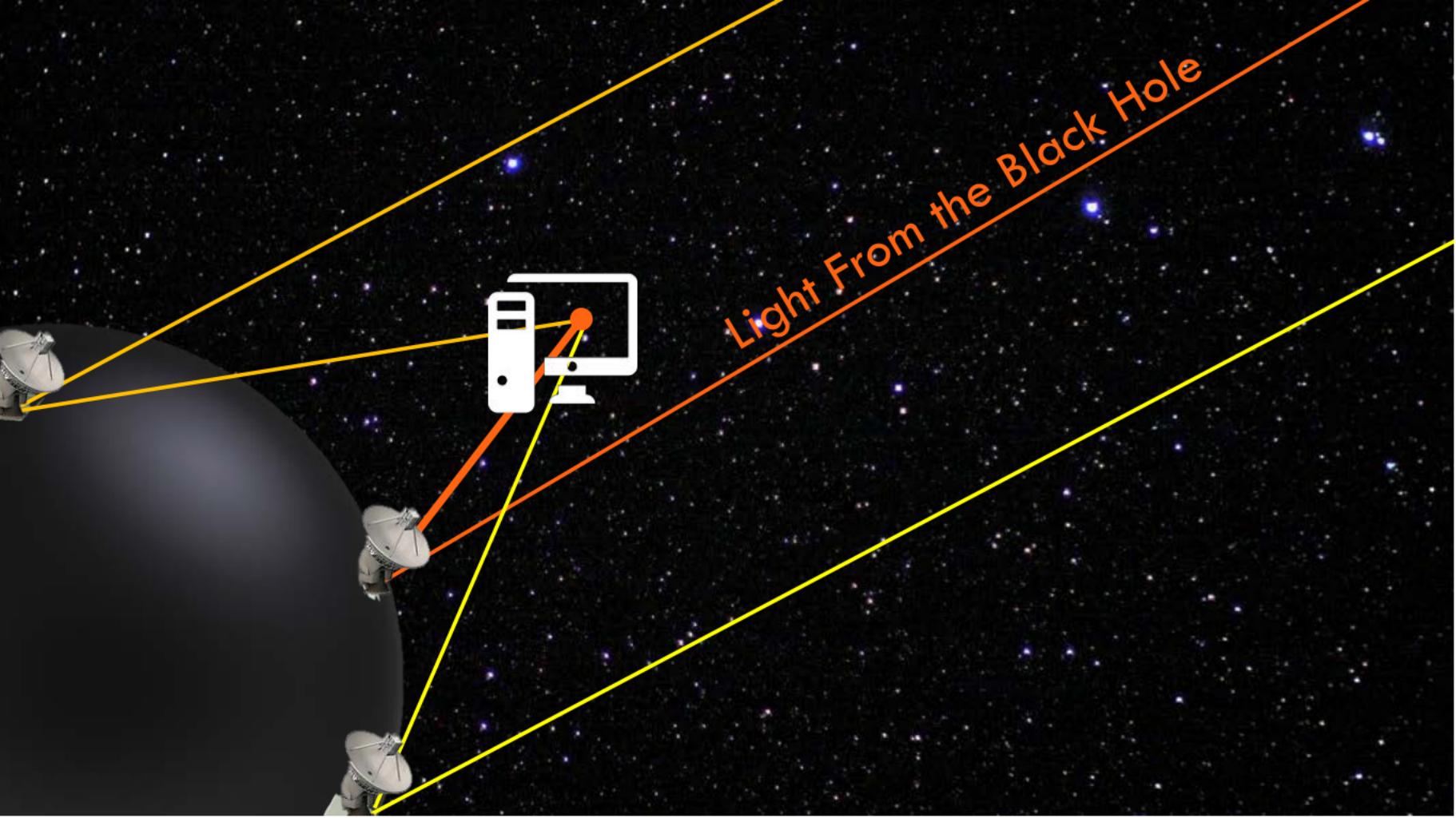
Mirror

Combines Light

Light From the Black Hole



Light From the Black Hole



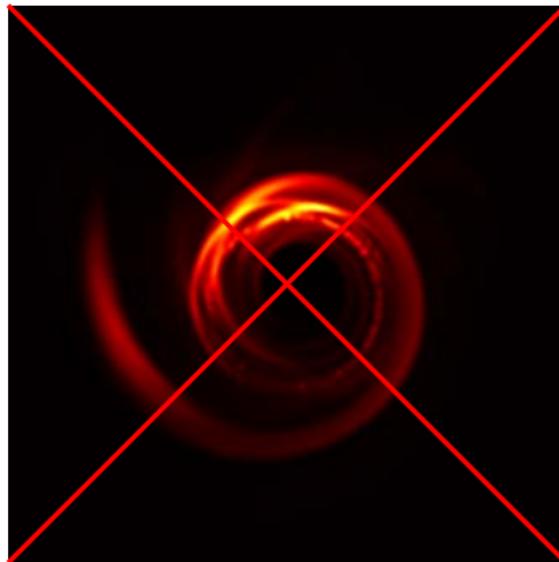
A diagram illustrating the observation of a black hole. A large gray sphere represents Earth, with three white satellite dish antennas mounted on its surface. Three yellow lines extend from the top left, middle, and bottom right of the sphere to a central point. From this central point, three orange lines radiate outwards towards the upper right. The text "Light From the Black Hole" is written in orange along the uppermost orange line. In the center of the diagram, there is a white icon depicting a computer monitor and a keyboard.

Light From the Black Hole

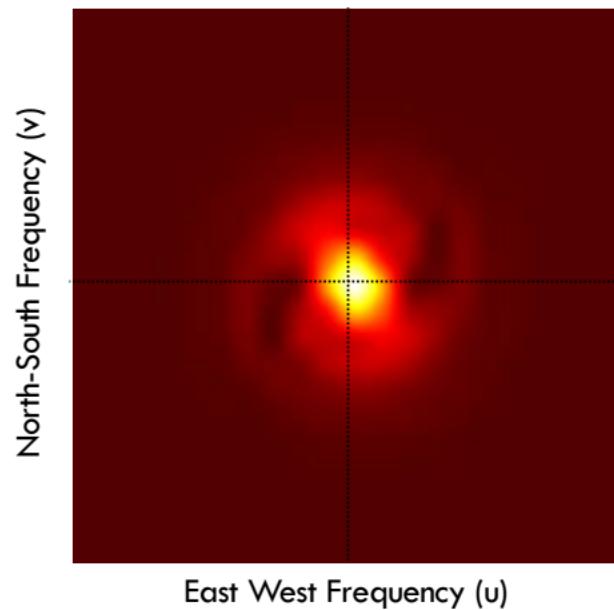


The Event Horizon Telescope (EHT)

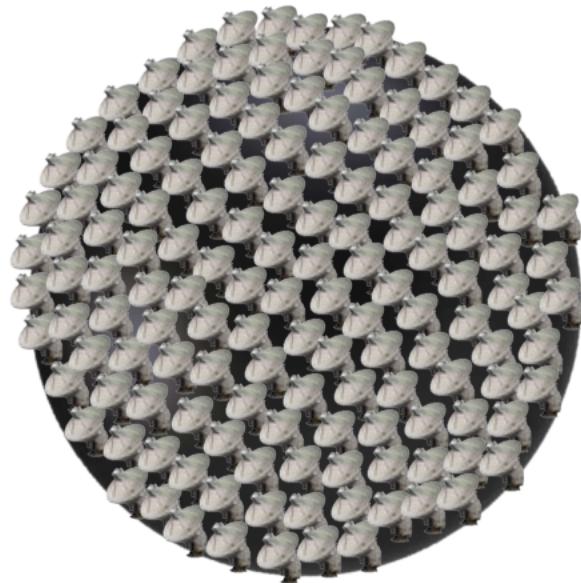
Black Hole Image



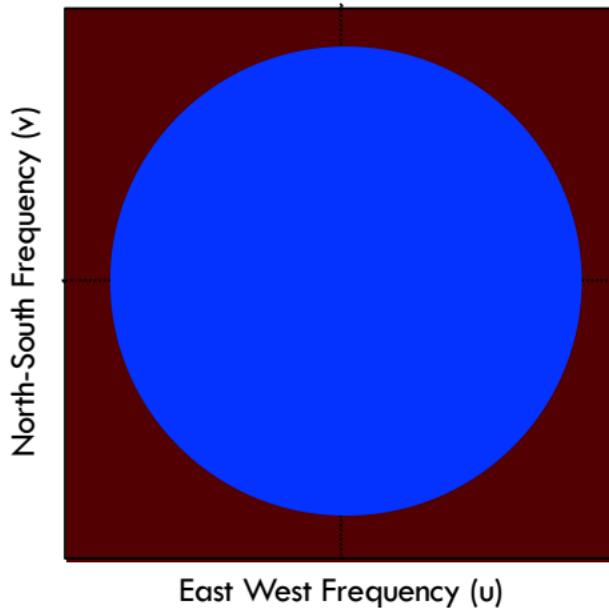
Frequency Measurements



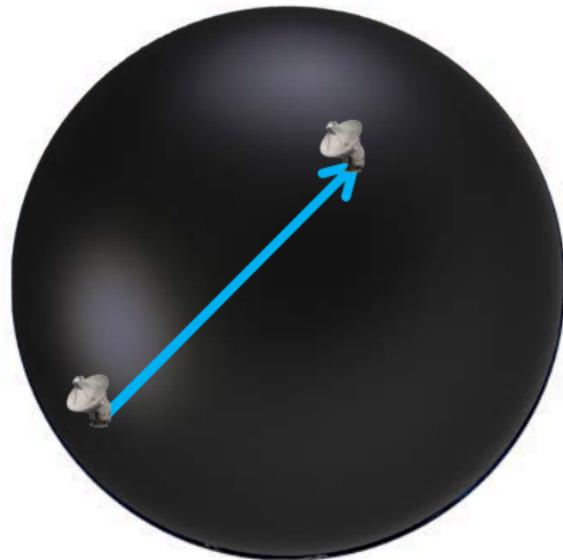
The Event Horizon Telescope (EHT)



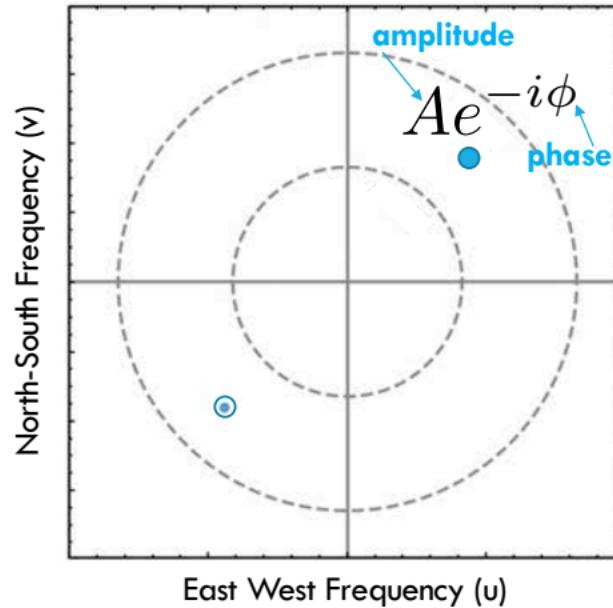
Frequency Measurements



The Event Horizon Telescope (EHT)



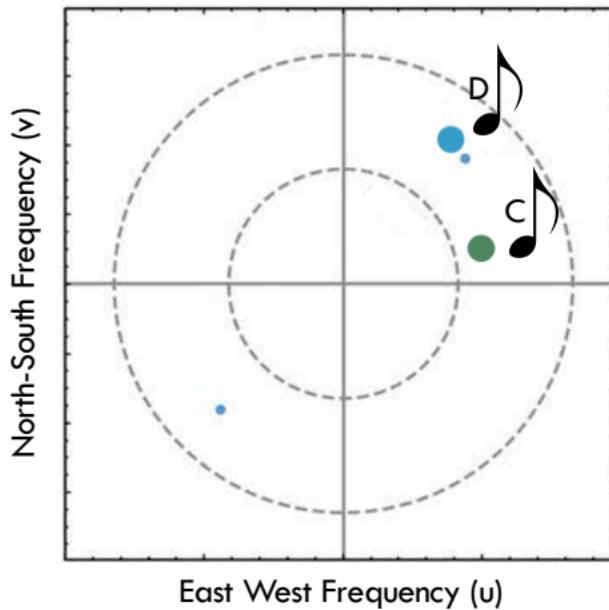
Frequency Measurements



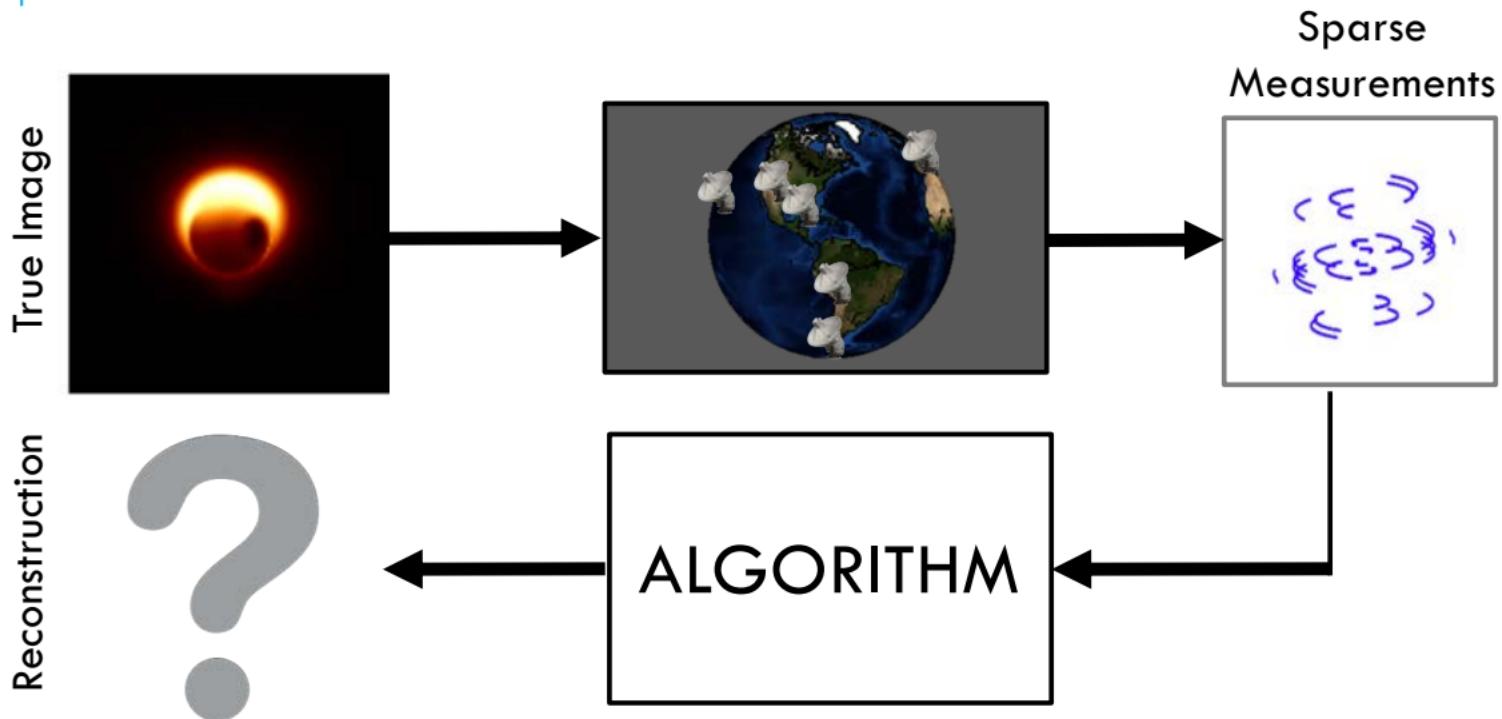
The Event Horizon Telescope (EHT)



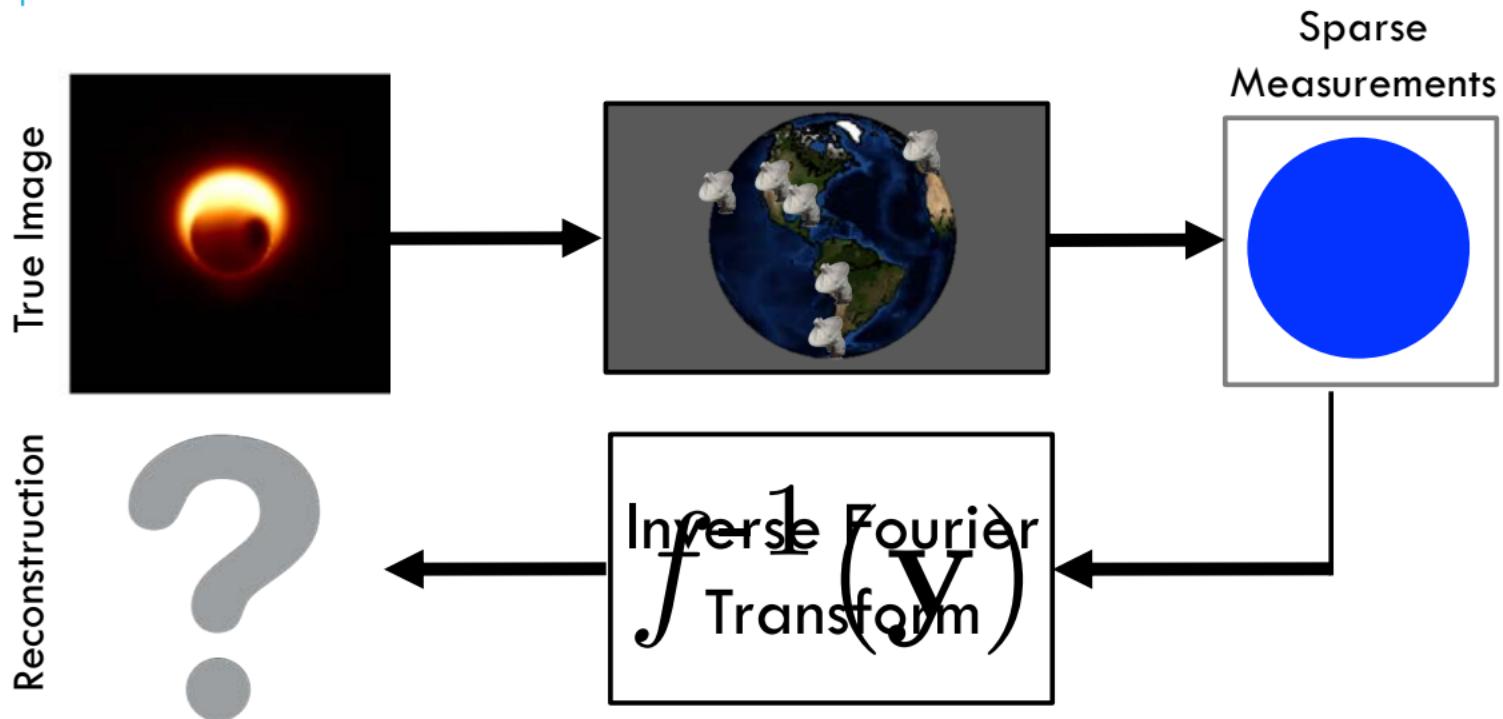
Frequency Measurements



Solving for the Image

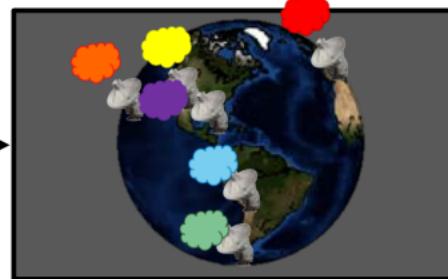
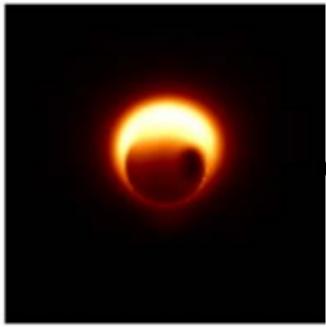


Solving for the Image



Solving for the Image

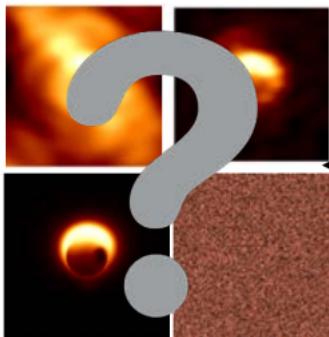
True Image



Sparse + Noisy
Measurements

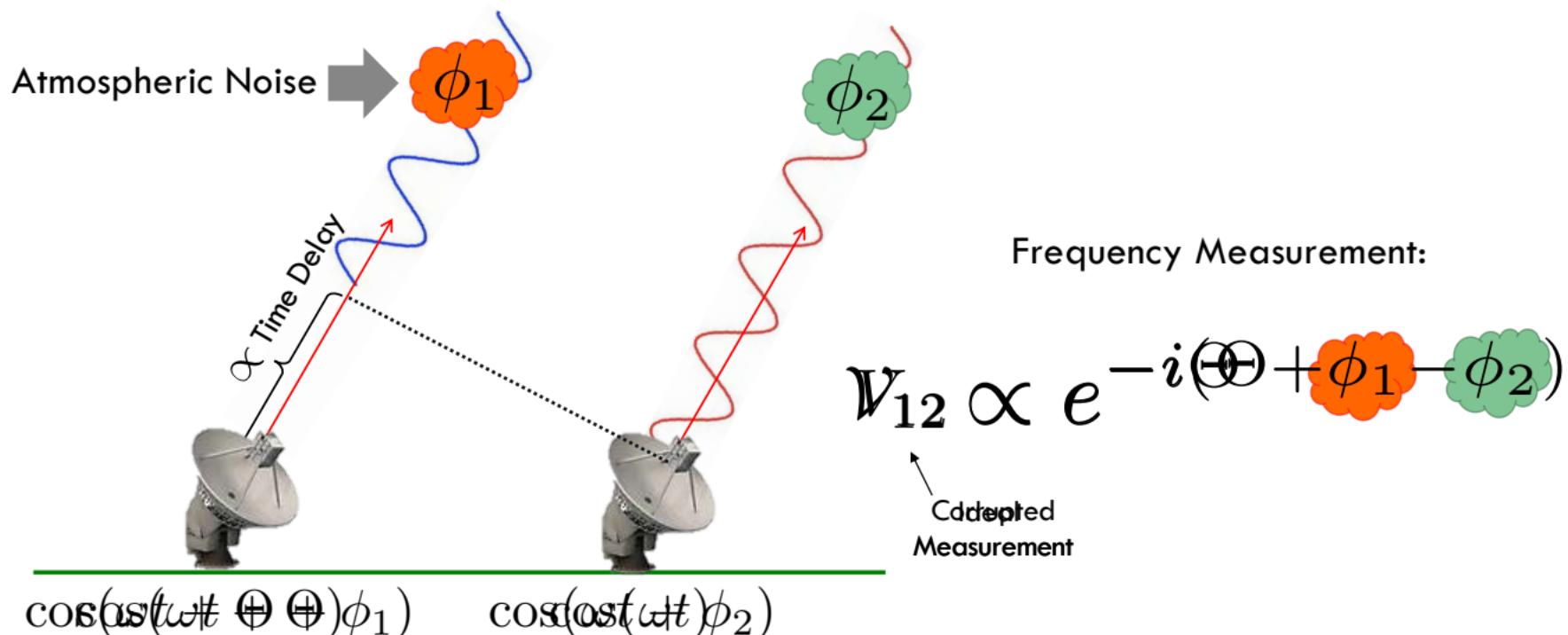
$\langle \dots \rangle$
 $\langle \dots \rangle$
 $\langle \dots \rangle$
 $\langle \dots \rangle$

Reconstruction

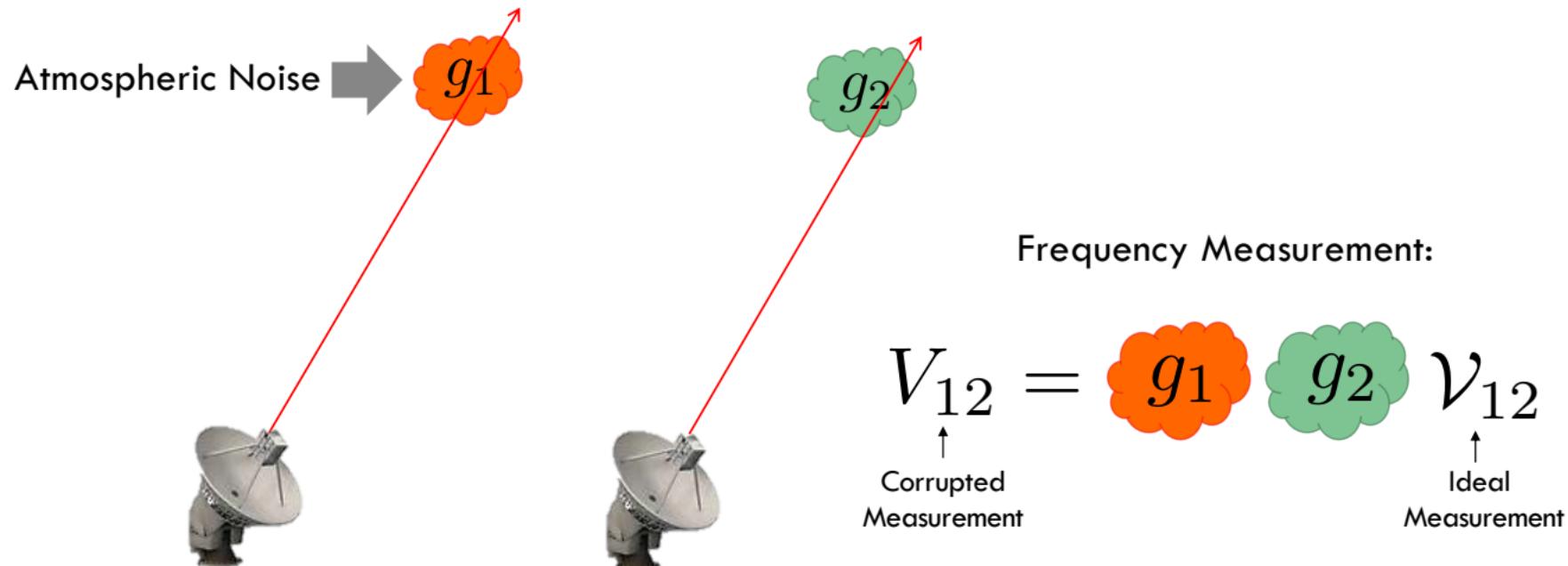


Inverse Fourier
Transform

Atmospheric Error: Unknown Phase



Atmospheric Error: Amplitude Attenuation



Phase & Amplitude Error

$$\text{Measured} \downarrow V_{12} = g_1 \ g_2 \ e^{-i(\phi_1 - \phi_2)} \mathcal{V}_{12} \text{ Ideal} \downarrow$$

Amplitude Errors Phase Error

Phase & Amplitude Error

$$\text{Measured} \downarrow V_{\frac{12}{3}} = g_{\frac{1}{3}} g_2 e^{-i(\phi_{\frac{1}{3}} - \phi_2)} \mathcal{V}_{\frac{12}{3}}$$

Amplitude Errors Phase Error

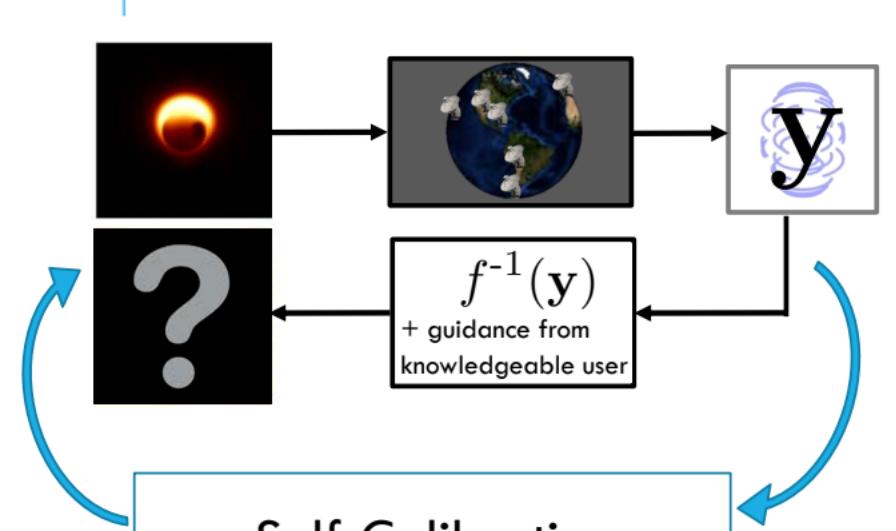
The diagram illustrates the decomposition of a measured signal into amplitude and phase errors. On the left, a blue arrow labeled "Measured" points down to the term $V_{\frac{12}{3}}$. On the right, a blue arrow labeled "Ideal" points down to the term $\mathcal{V}_{\frac{12}{3}}$. The expression $V_{\frac{12}{3}} = g_{\frac{1}{3}} g_2 e^{-i(\phi_{\frac{1}{3}} - \phi_2)} \mathcal{V}_{\frac{12}{3}}$ is shown. The terms $g_{\frac{1}{3}}$ and g_2 are grouped by a blue bracket labeled "Amplitude Errors". The term $e^{-i(\phi_{\frac{1}{3}} - \phi_2)}$ is grouped by a blue bracket labeled "Phase Error". The terms $g_{\frac{1}{3}}$, g_2 , and $e^{-i(\phi_{\frac{1}{3}} - \phi_2)}$ are all enclosed in blue circles.

Two Classes of Imaging Algorithms

Inverse Modeling
(CLEAN + Self-Calibration)

Forward Modeling
(Regularized Maximum Likelihood)

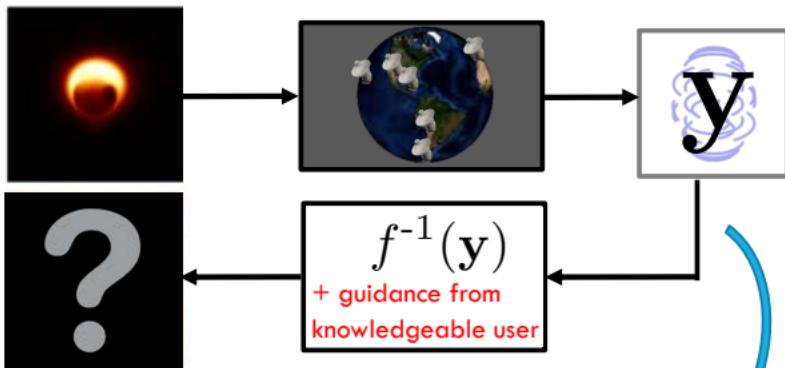
Two Classes of Imaging Algorithms



Standard
(CLEAN + Self-Calibration)

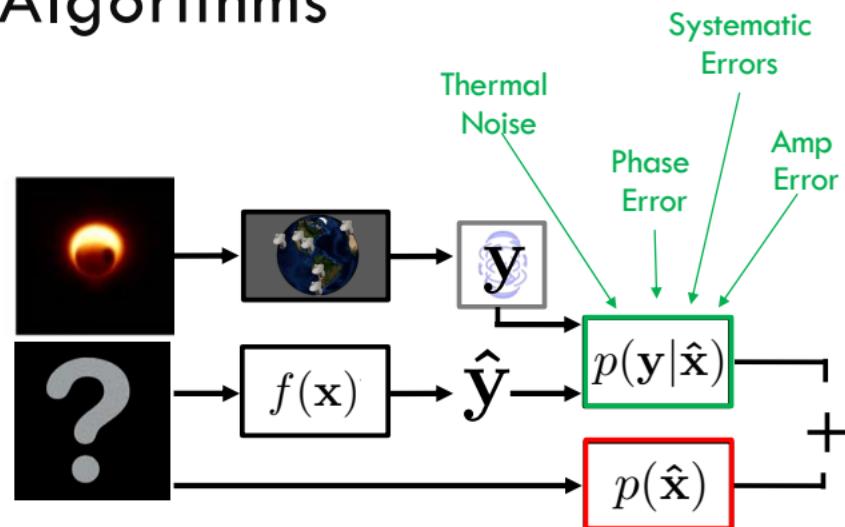
Forward Modeling
(Regularized Maximum Likelihood)

Two Classes of Imaging Algorithms



Self Calibration

Standard Inverse Modeling
(CLEAN + Self-Calibration)



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

Forward Modeling
(Regularized Maximum Likelihood)

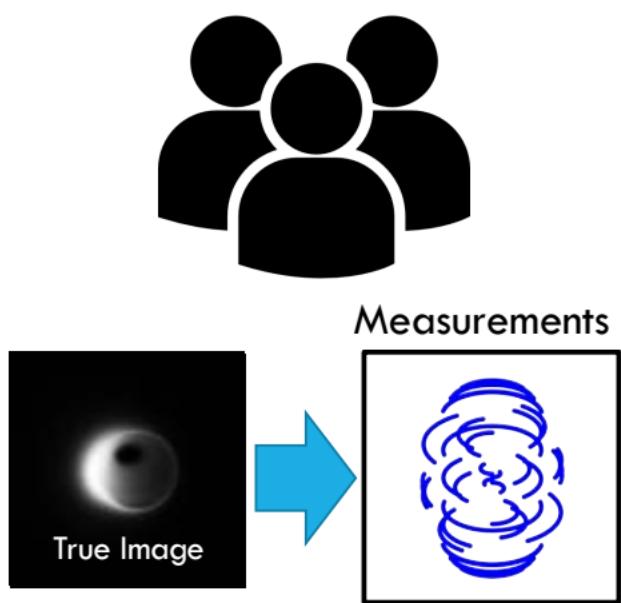
How do we verify what we are
reconstructing is real?

The 4-Step Process to Making a Picture of a Black Hole

1. Synthetic Data Tests
2. Blind Imaging of M87 Data
3. Objectively Choosing Imaging Parameters
4. Validation of Images

Step 1: Synthetic Data Tests

Event Horizon Telescope Imaging Challenges

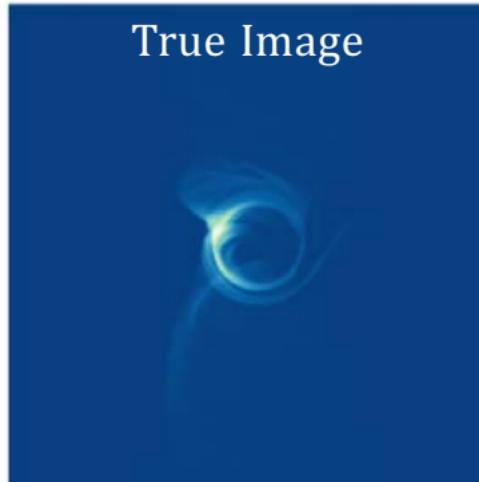


1) Generate Measurements

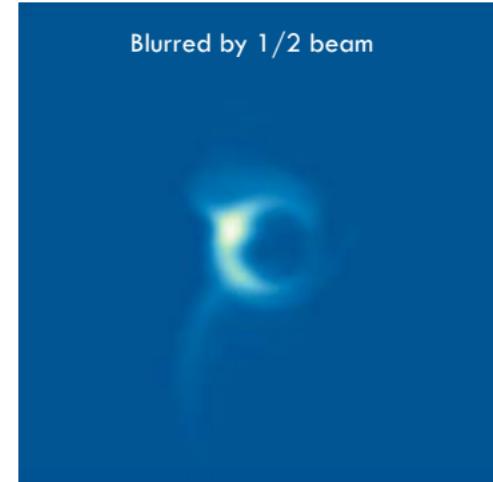
2) Make Images

3) Evaluate Quality

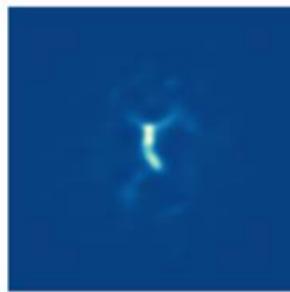
True Image



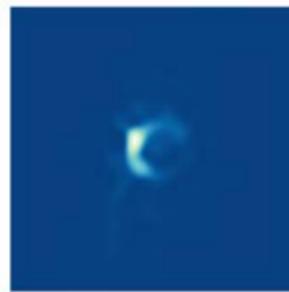
Blurred by 1/2 beam



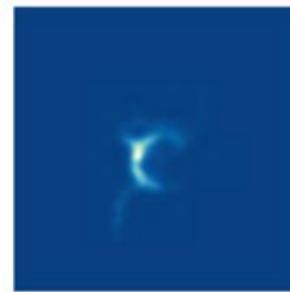
Method 1



Method 2



Method 3



Method 4



Method 5

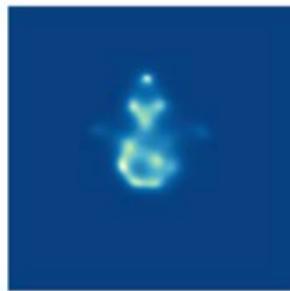
True Image



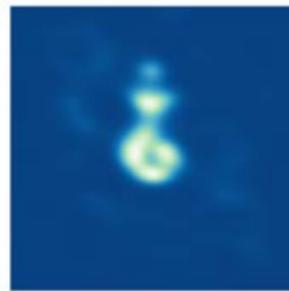
Blurred by 1/2 beam



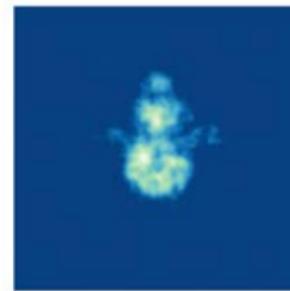
Method 1



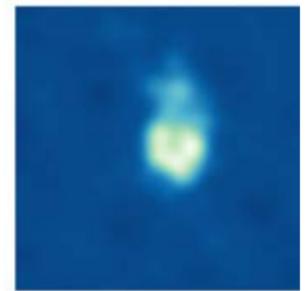
Method 2



Method 3



Method 4



Method 5

Step 2: Blind Imaging of M87 Data

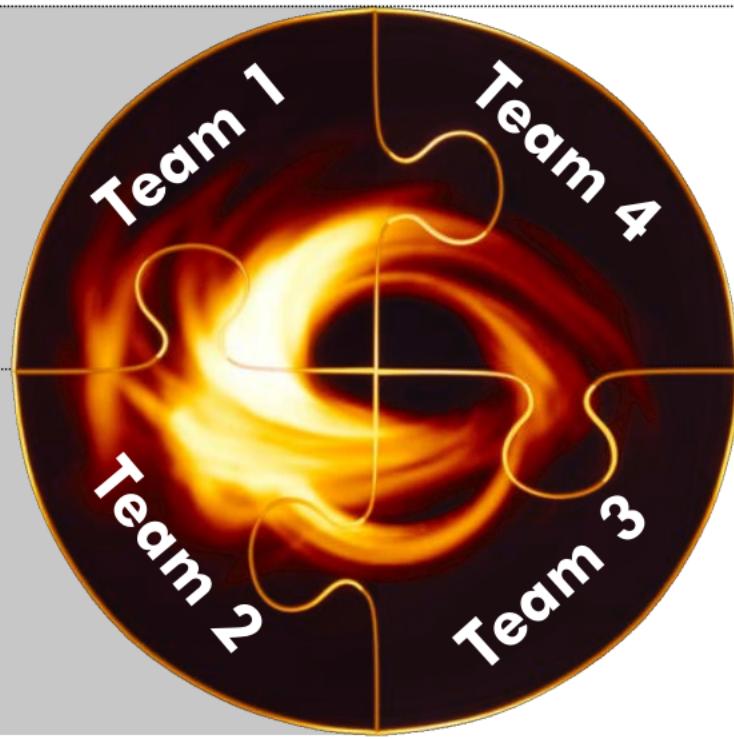
Step 2: Blind Imaging

The Americas

Harvard-Smithsonian
University of Arizona
U. Concepcion

Global

MIT Haystack
Radboud University
NAOJ



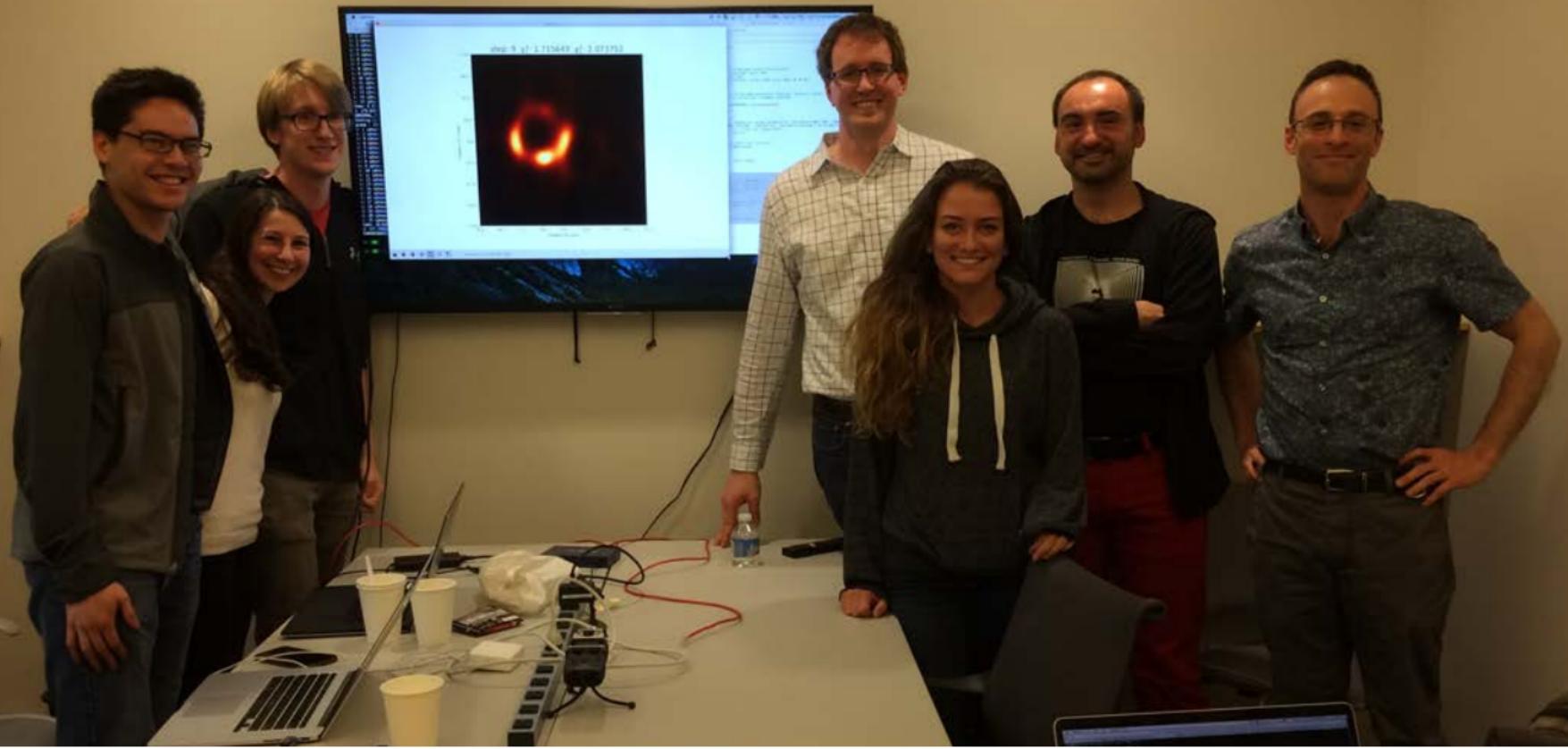
ASIAA
KASI
NAOJ

East Asia

MPIfR
Boston University
IAA
Aalto

Cross-Atlantic

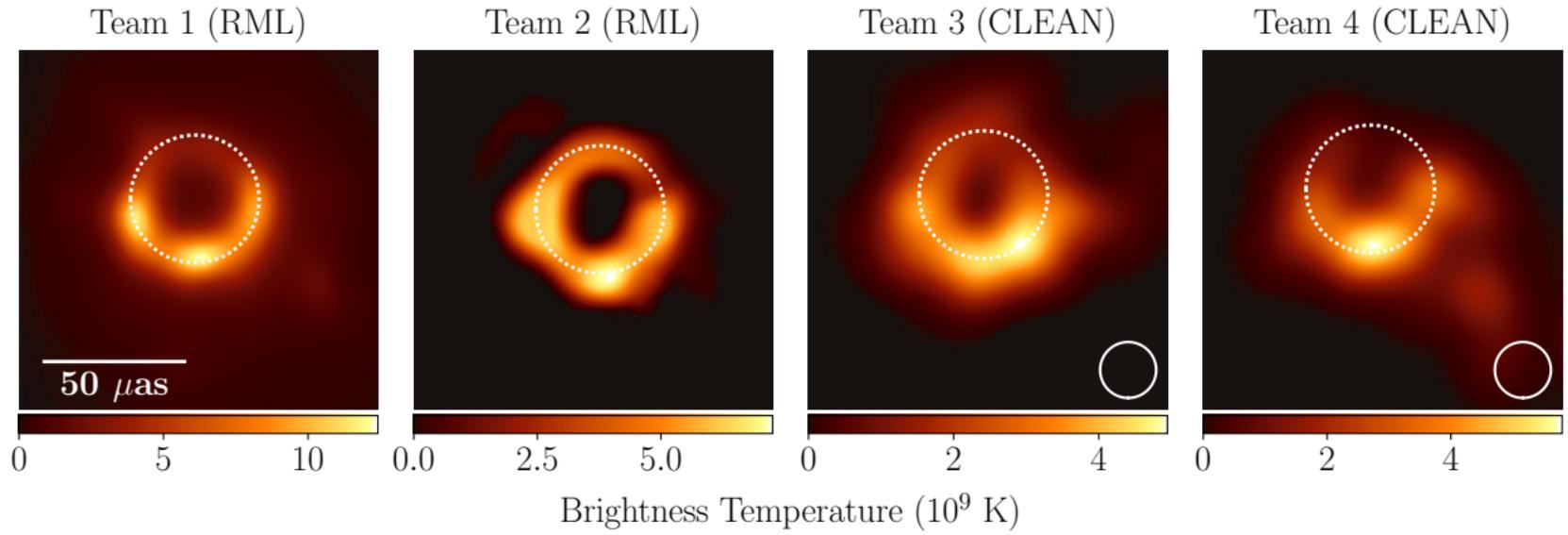
Team 1 – End of the First Day of Imaging M87

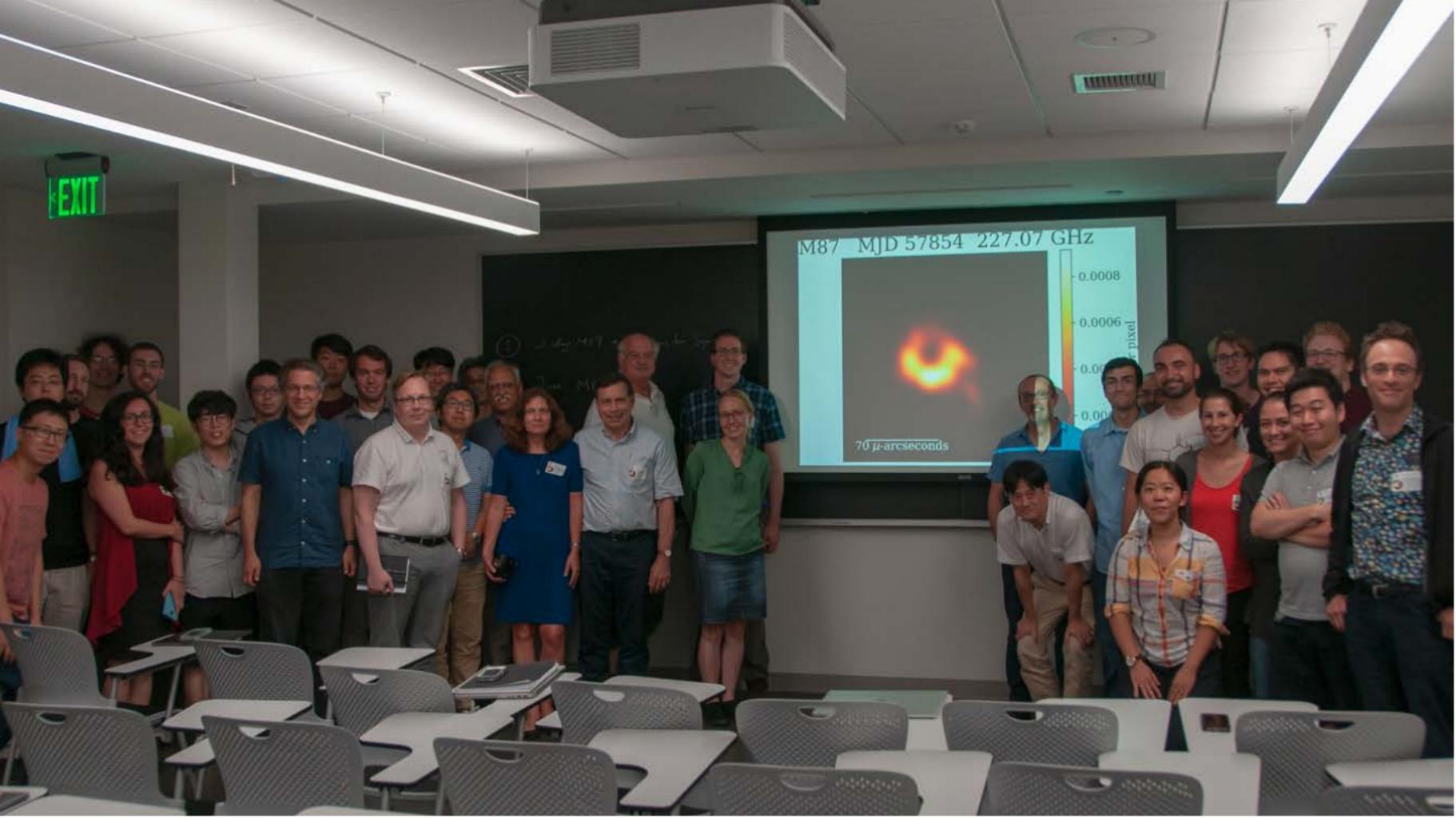


7 weeks later...



Step 2: Blind Imaging





M87 MJD 57854 227.07 GHz

70 μ -arcseconds

0.0008
0.0006
0.0004
0.0002
0.0000
pixel

Step 3: Objectively Choosing Parameters

Step 3: Imaging Pipelines

DIFMAP

(CLEAN + Self Calibration)

- Compact Flux
- Stop Condition
- Weighting on ALMA
- Mask Size
- Data Weights

eht-imaging

(Regularized Max Likelihood)

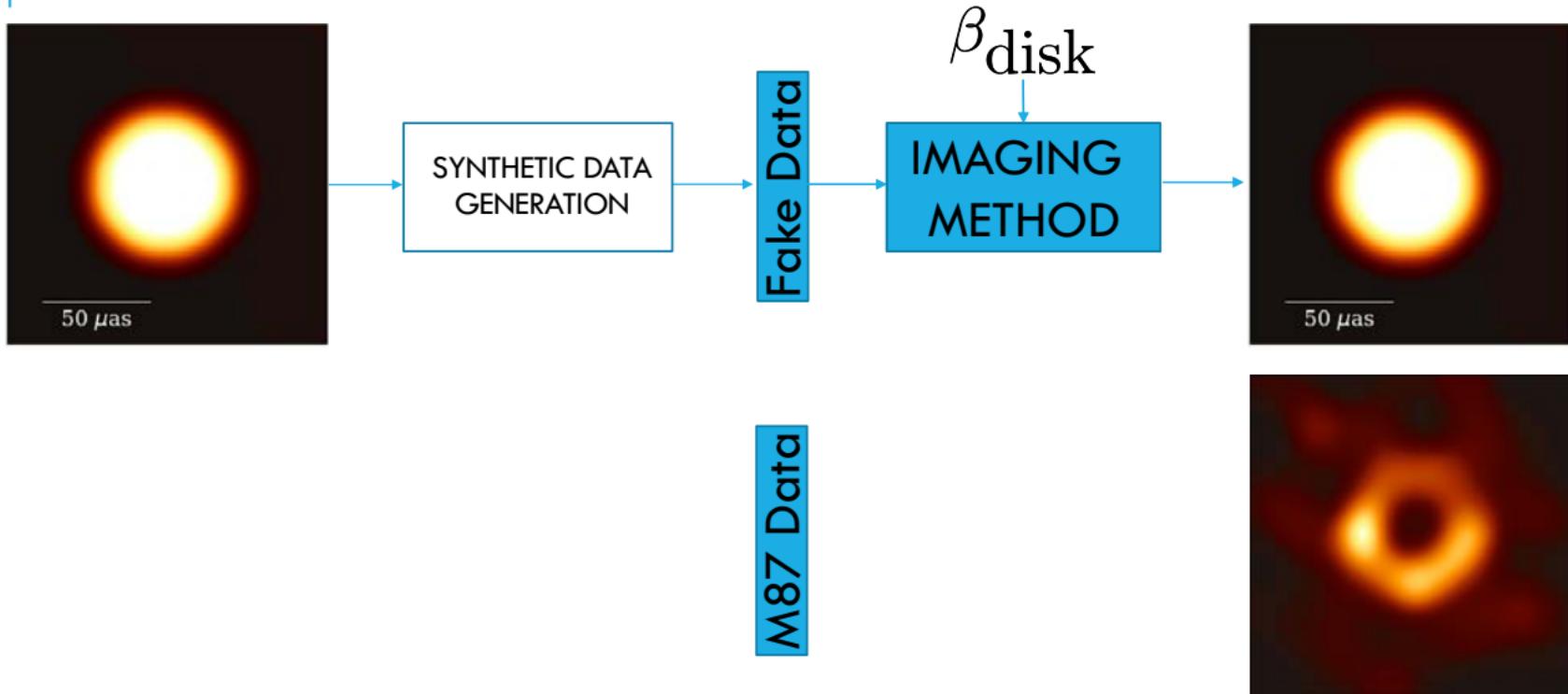
- Compact Flux
- Initial Gaussian Size
- Systematic Error
- Regularizes
 - MEM
 - TV
 - TSV
 - L1

SMILI

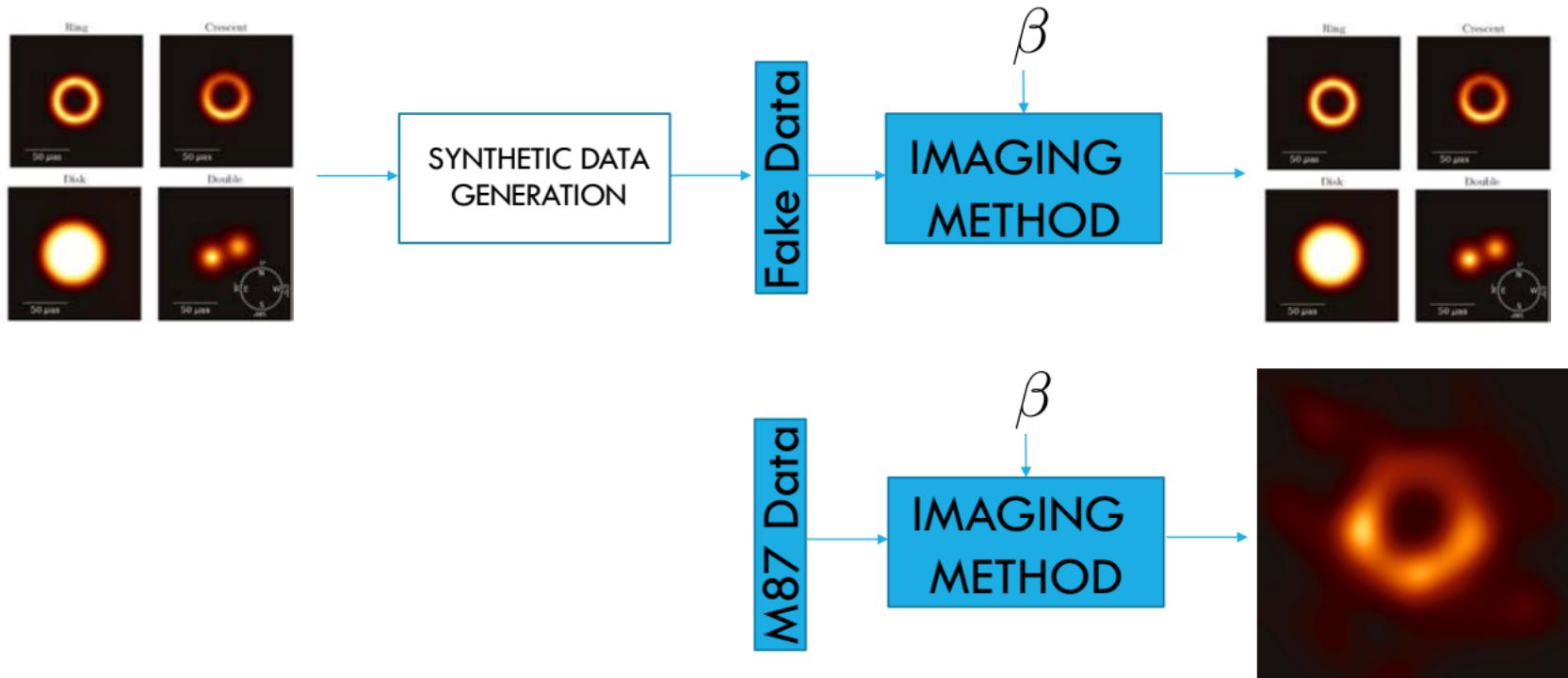
(Regularized Max Likelihood)

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

Step 3: Training on a Disk



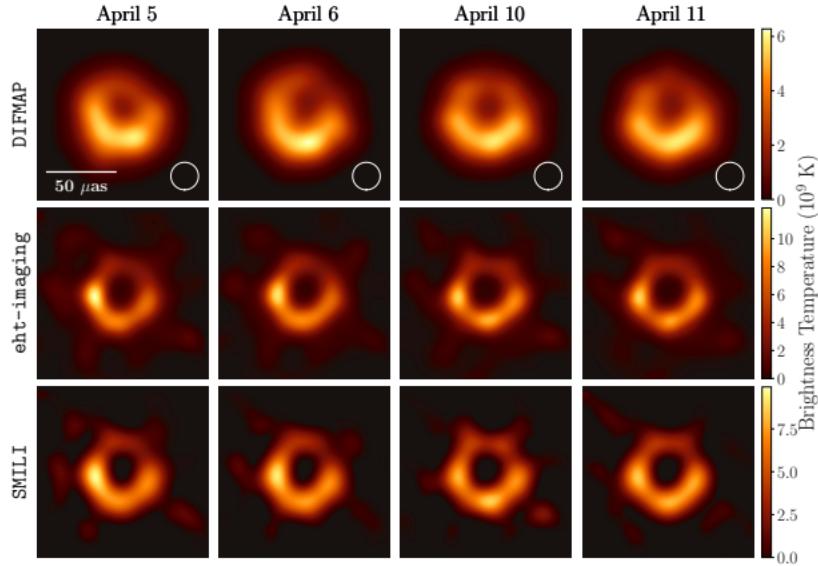
Step 3: Training on Full Set



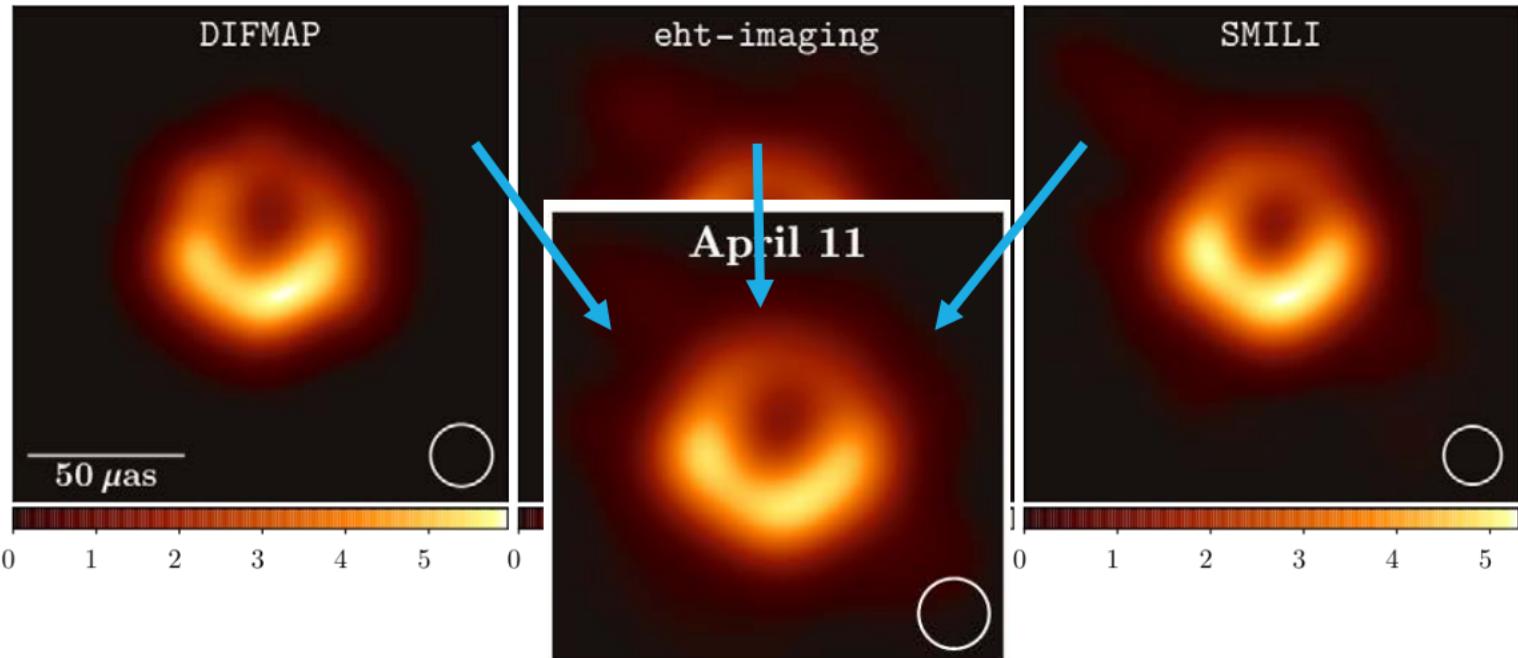
Step 3: Different Days and Imaging Pipelines

Imaging Pipeline

Observing Day

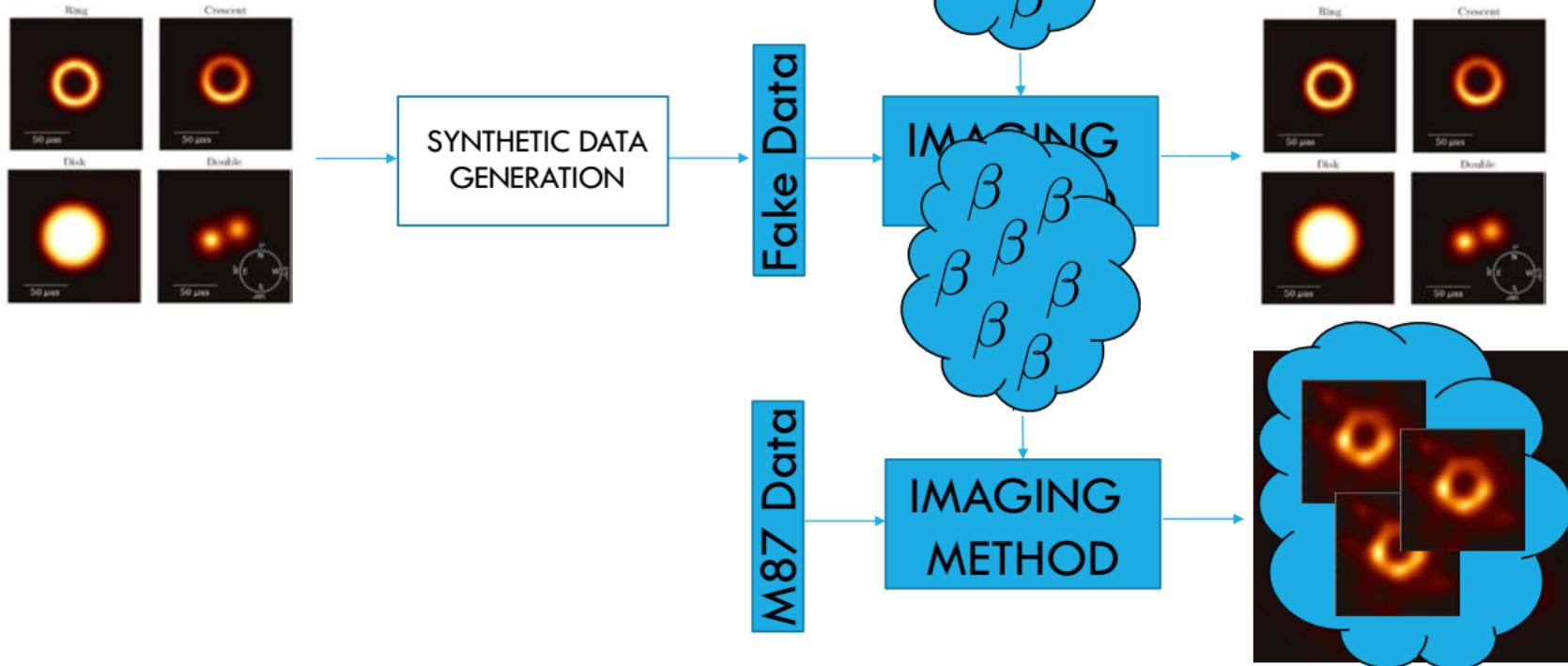


Step 3: Blurred to Equivalent Resolution

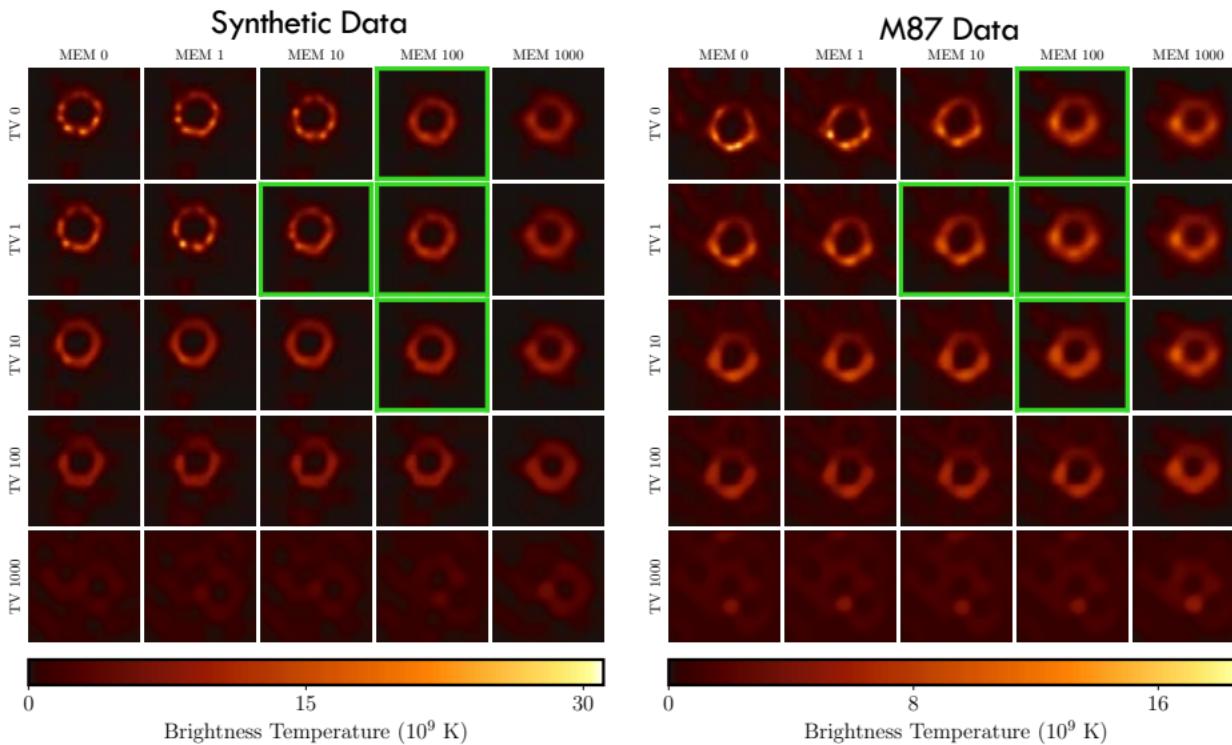


Step 4: Validation

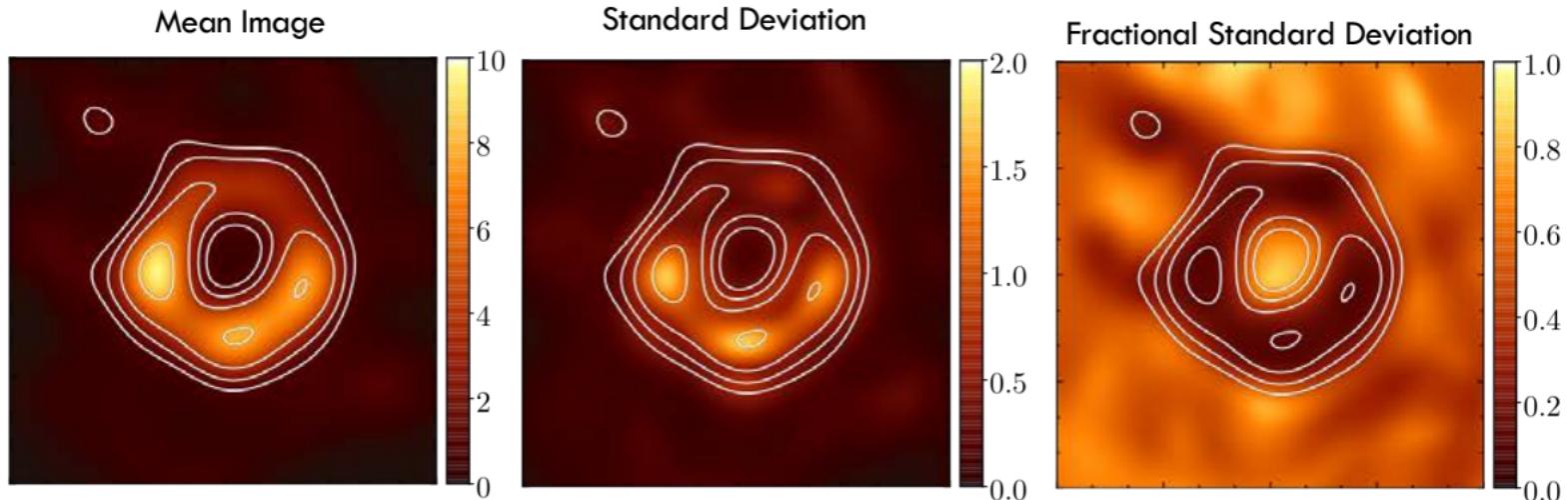
Step 4: Finding “Top Set” Parameters



Step 4: eht-imaging Parameter Slice

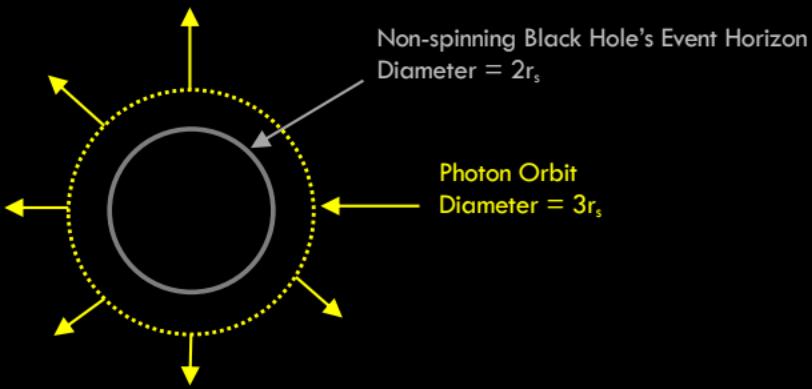


Step 4: Variance Over the Top Set

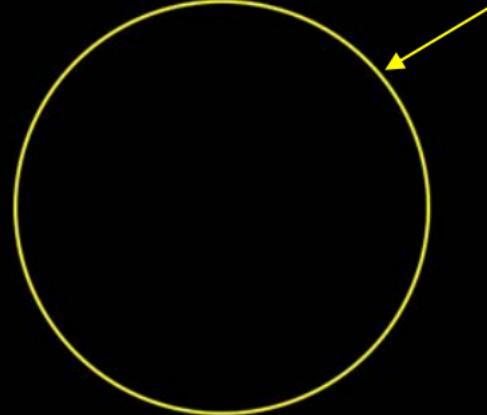


Did We Prove Einstein Was Right?

Short answer: No, but we didn't prove he was wrong

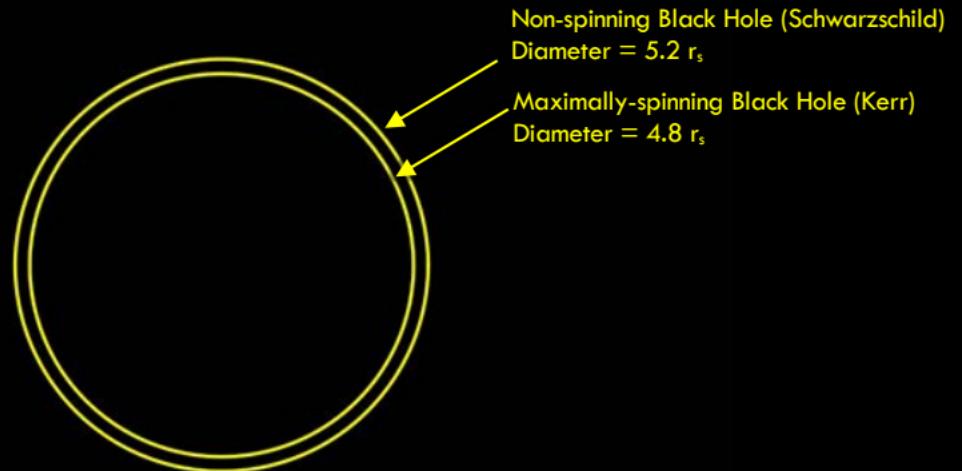


$$\text{Schwarzschild Radius: } r_s = \frac{2GM}{c^2}$$

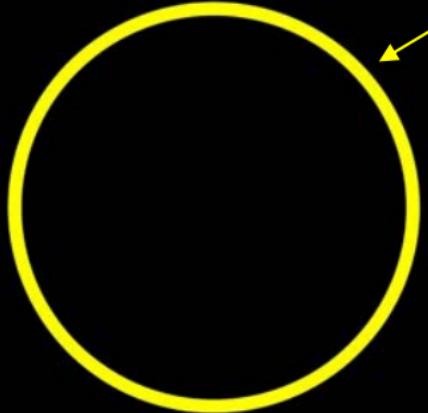


Non-spinning Black Hole (Schwarzschild)
Diameter = $5.2 r_s$

$$r_s = \frac{2GM}{c^2}$$



$$r_s = \frac{2GM}{c^2}$$



Spinning Black Hole (Kerr)
Diameter = (4.8 – 5.2) r_s

$$r_s = \frac{2GM}{c^2}$$

M87 Mass from Gas Dynamics

$$M_{\text{BH}} = 3.5 \times 10^9 M_{\odot}$$

[Walsh et al 2013]

M87 Mass from Stellar Dynamics

$$M_{\text{BH}} = 6.6 \times 10^9 M_{\odot}$$

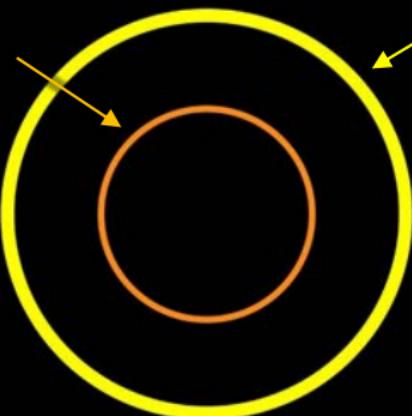
[Gebhardt et al 2011]

Spinning Black Hole (Kerr)

$$\text{Diameter} = (4.8 - 5.2) r_s$$

Spinning Black Hole (Kerr)

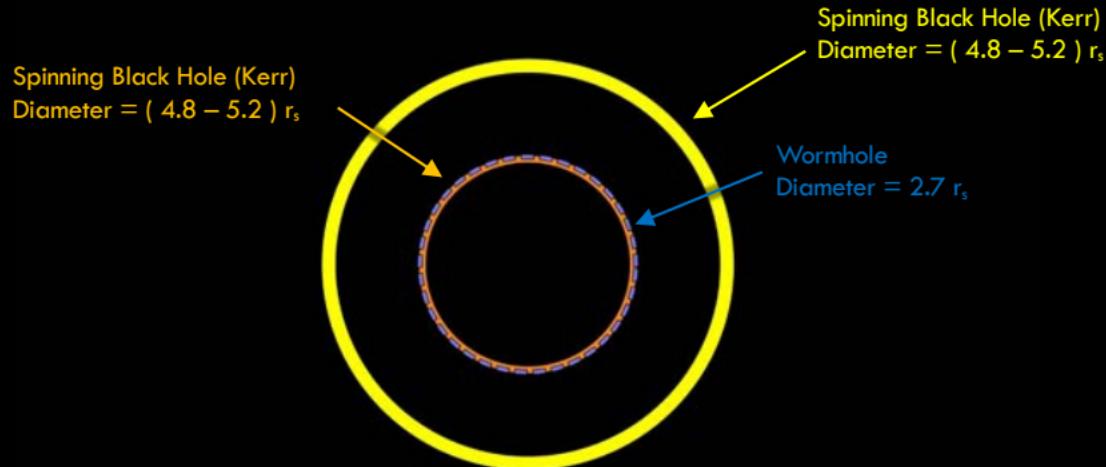
$$\text{Diameter} = (4.8 - 5.2) r_s$$



$$r_s = \frac{2GM}{c^2}$$

M87 Mass from Gas Dynamics
 $M_{\text{BH}} = 3.5 \times 10^9 M_{\odot}$

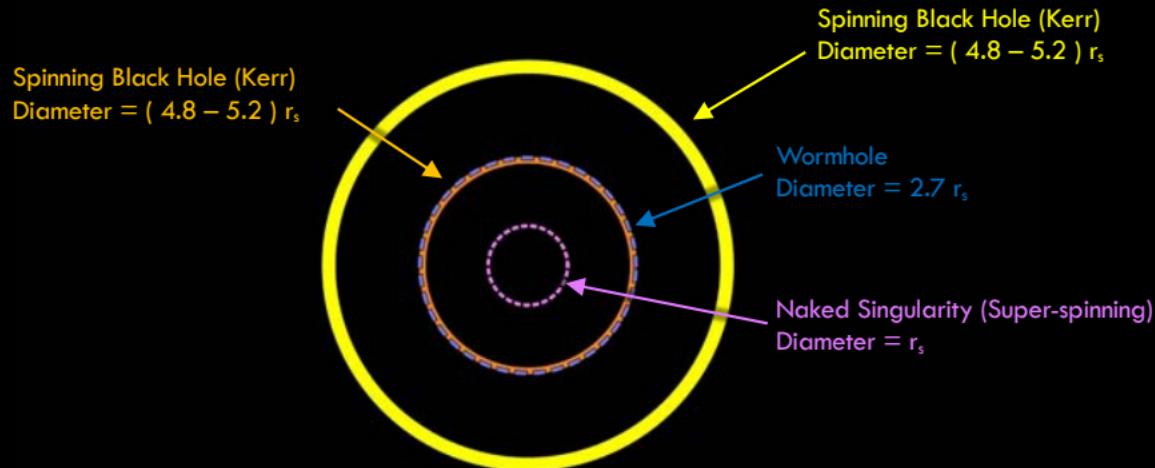
M87 Mass from Stellar Dynamics
 $M_{\text{BH}} = 6.6 \times 10^9 M_{\odot}$



$$r_s = \frac{2GM}{c^2}$$

M87 Mass from Gas Dynamics
 $M_{\text{BH}} = 3.5 \times 10^9 M_{\odot}$

M87 Mass from Stellar Dynamics
 $M_{\text{BH}} = 6.6 \times 10^9 M_{\odot}$



$$r_s = \frac{2GM}{c^2}$$



M87 Mass from Gas Dynamics
 $M_{\text{BH}} = 3.5 \times 10^9 M_{\odot}$

M87 Mass from Stellar Dynamics
 $M_{\text{BH}} = 6.6 \times 10^9 M_{\odot}$



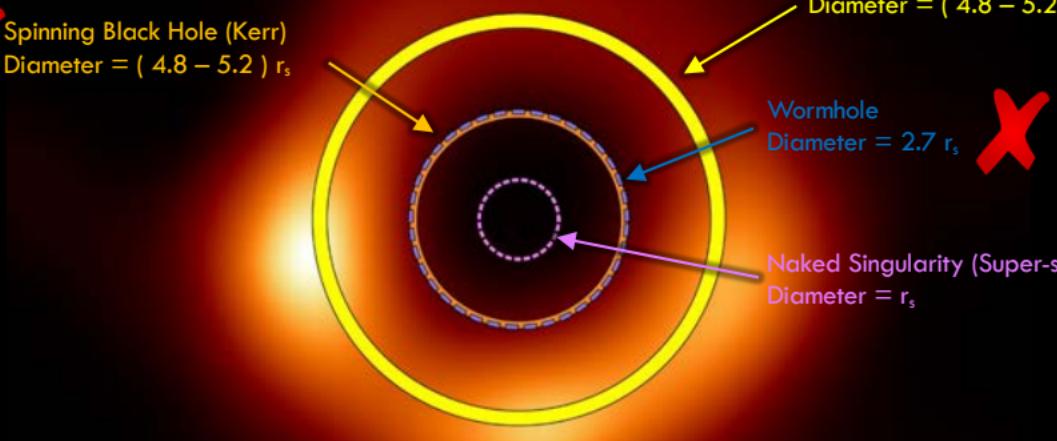
Spinning Black Hole (Kerr)
Diameter = $(4.8 - 5.2) r_s$

Spinning Black Hole (Kerr)
Diameter = $(4.8 - 5.2) r_s$

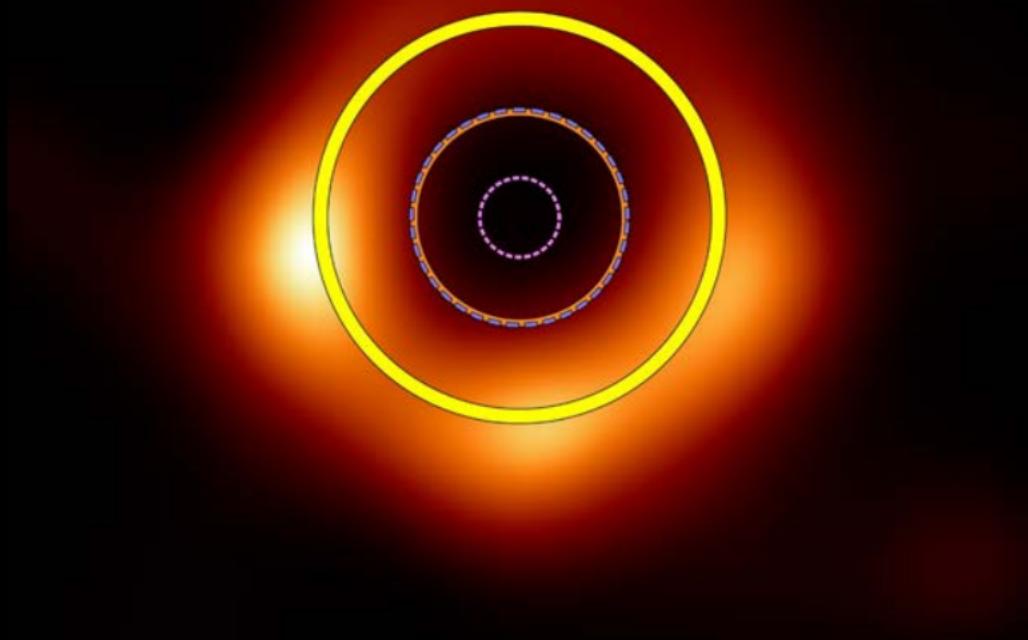


Wormhole
Diameter = $2.7 r_s$

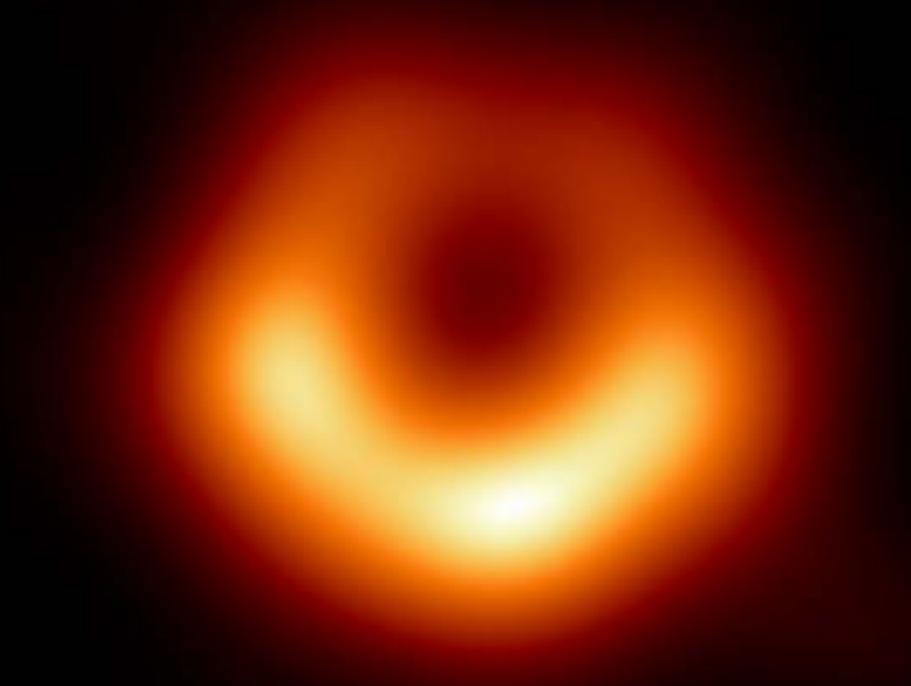
Naked Singularity (Super-spinning)
Diameter = r_s



$$r_s = \frac{2GM}{c^2}$$



April 11

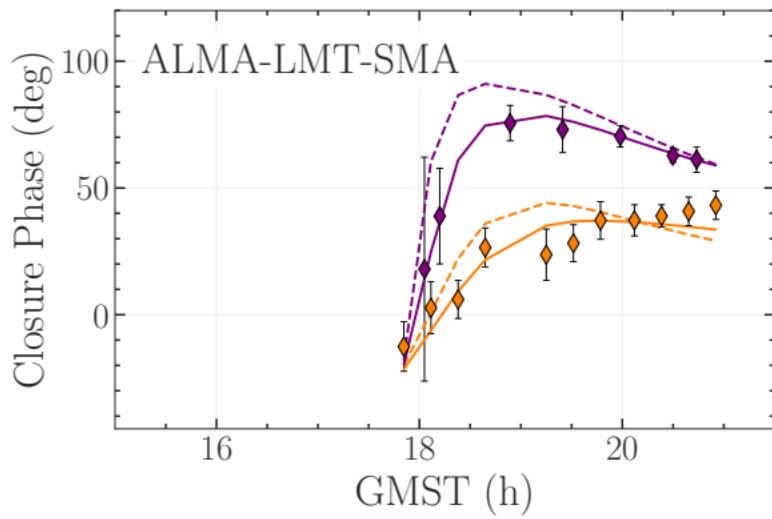
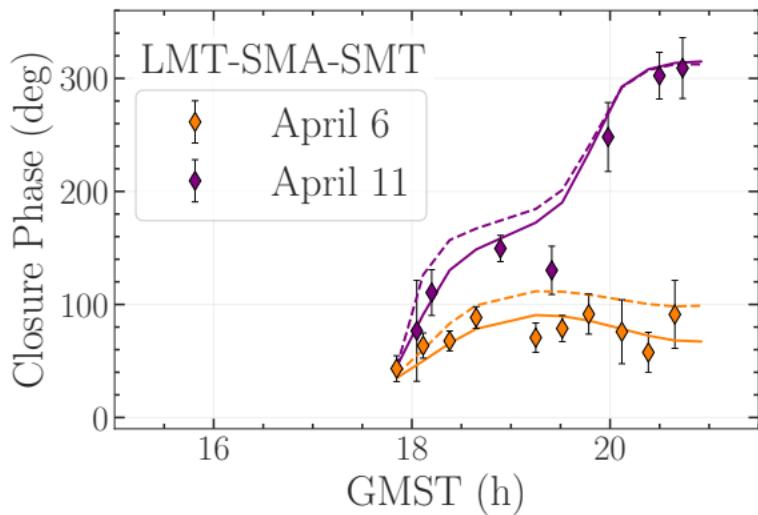


April 11



Time Variability in M87

Clear Signature of Evolution over the 5 day span



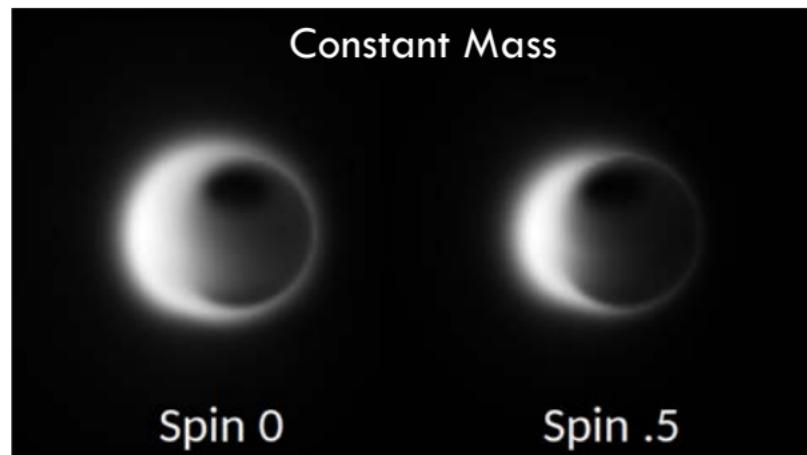
The “No Hair” Theorem

The spacetime surrounding a black hole can be fully characterized by three numbers:

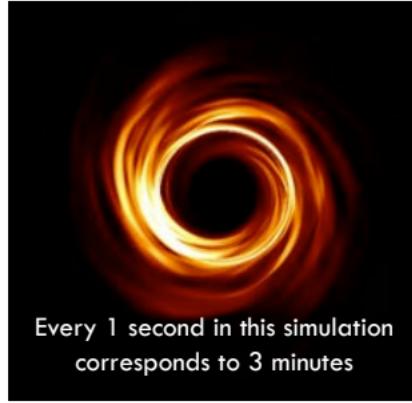
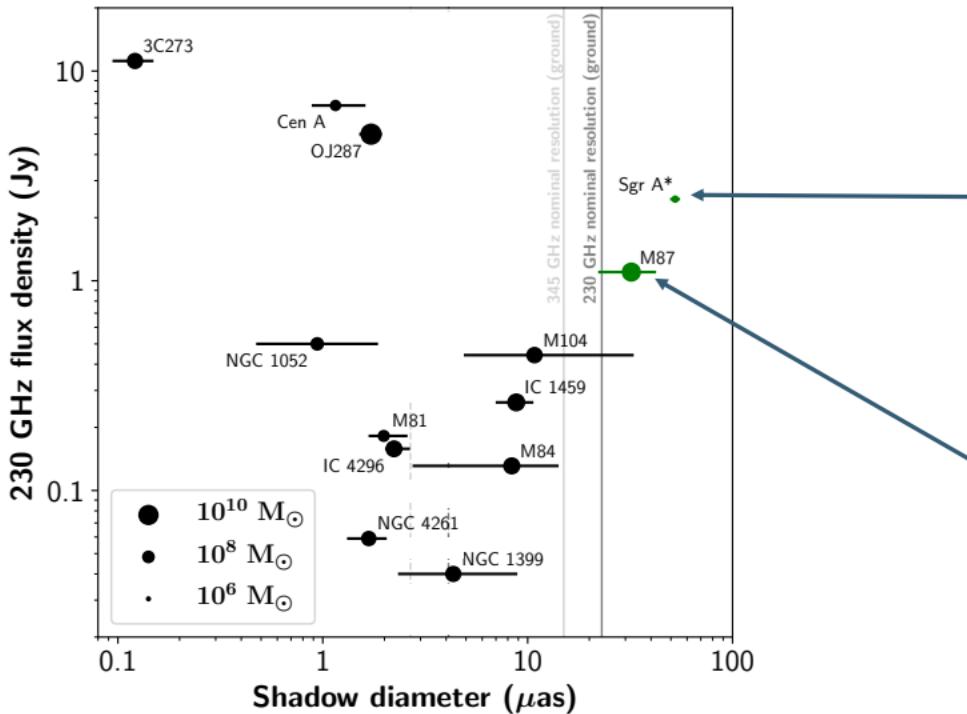
Mass

Angular Momentum (spin)

~~Charge~~



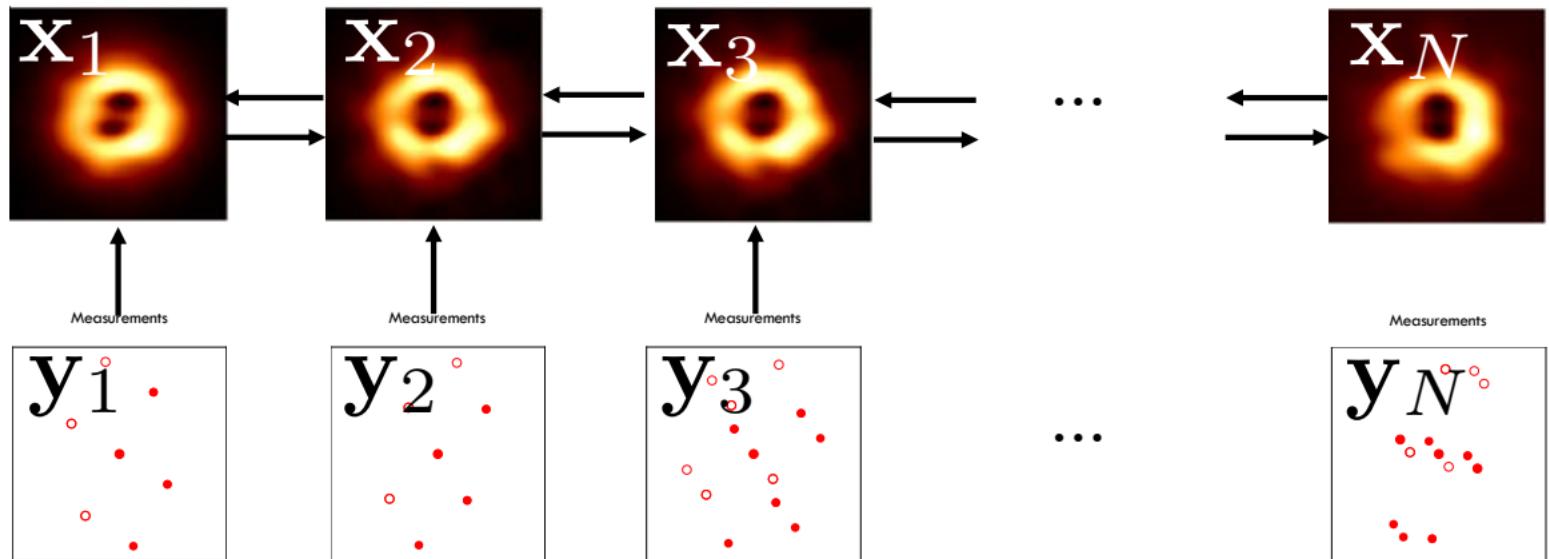
The EHT's Black Hole Targets



Sagittarius A* (Sgr A*)
4 Million Solar Masses
Orbital Period: 4 – 30 minutes

M87
6.5 Billion Solar Masses
Orbital Period: 4 – 30 days

Reconstructing a Video Over a Night



Video Reconstruction Simulation of Sagittarius A*

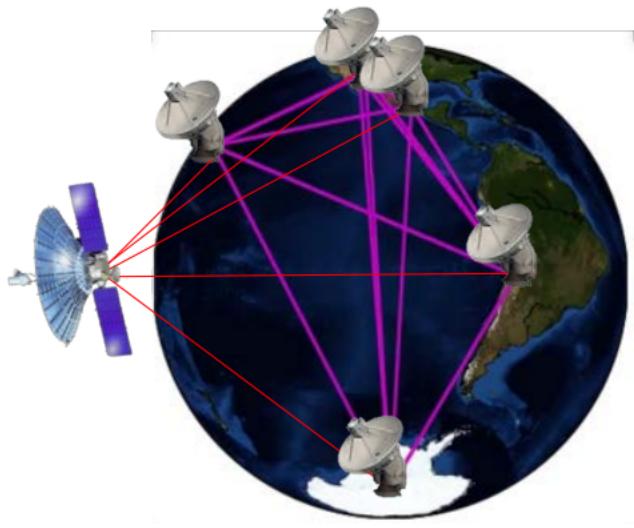
Truth Video



EHT Ground Sites



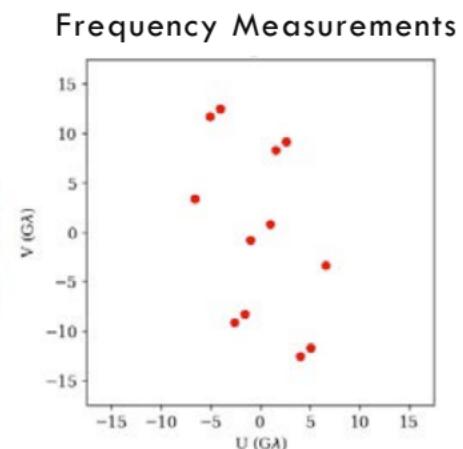
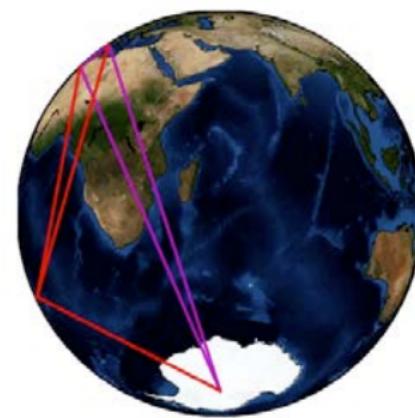
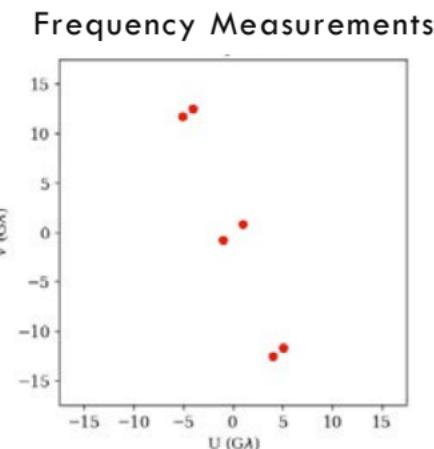
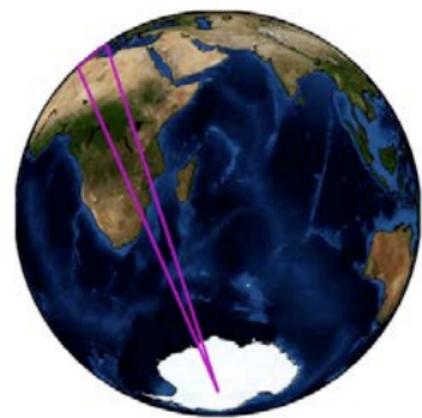
Adding Face-On Low Earth Orbiters



"Metrics and Motivations for Earth-Space VLBI: Time-Resolving Sgr A* with the Event Horizon Telescope"

Daniel Palumbo, Michael Johnson, Katie Bouman, Andrew Chael, Shep Doeleman

Low Earth Orbiters: 90 minute period

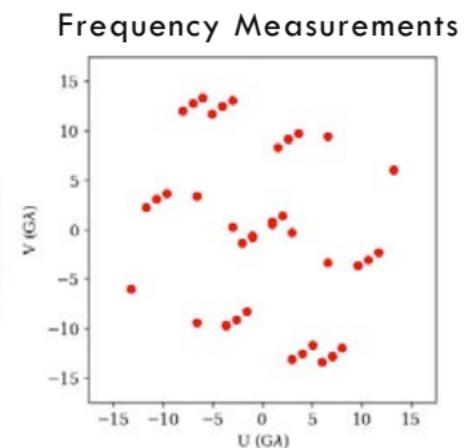
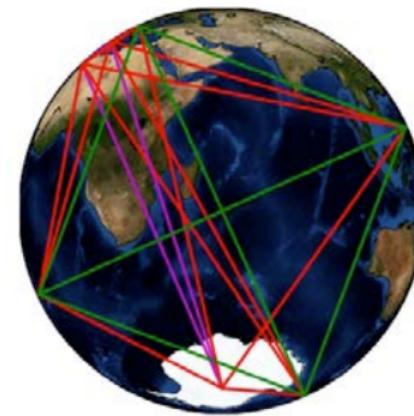
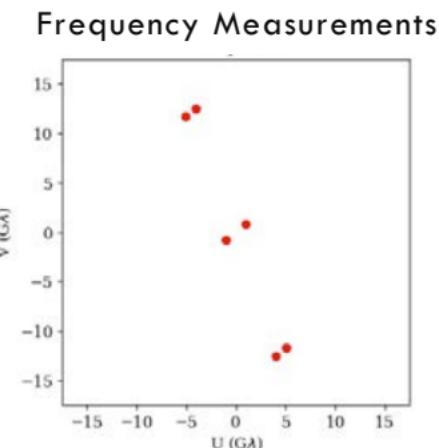
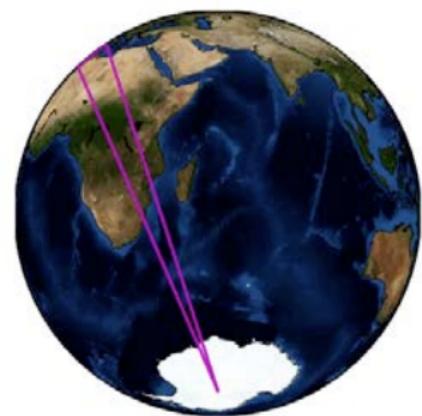


EHT's Current Ground Based Sites

EHT's Current Ground Based Sites
+ 1 Low-Earth Orbiter

simulation credit: Daniel Palumbo

Low Earth Orbiters: 90 minute period



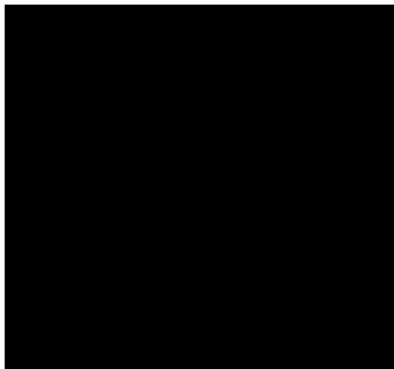
EHT's Current Ground Based Sites

EHT's Current Ground Based Sites
+ 4 Low-Earth Orbiter

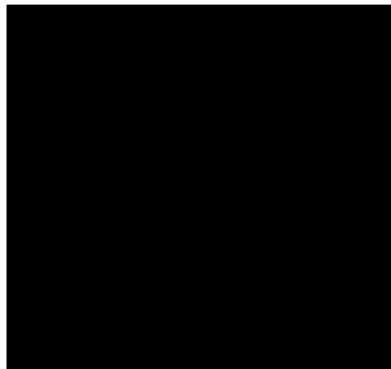
simulation credit: Daniel Palumbo

Video Reconstruction Simulations of Sagittarius A*

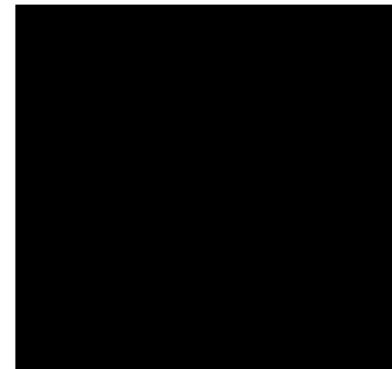
Truth Video



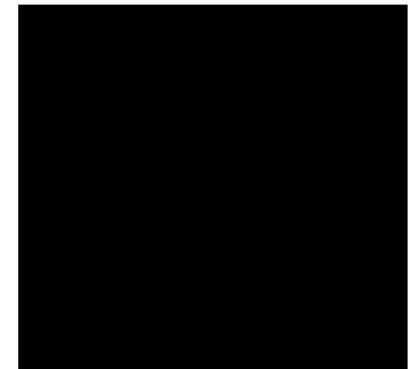
EHT Ground Sites

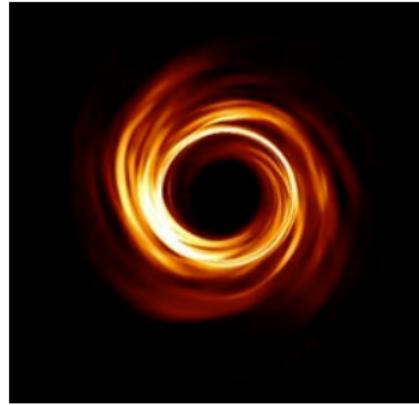


+ 1 Orbiter



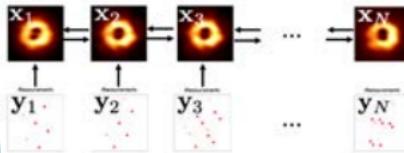
+ 4 Orbiters



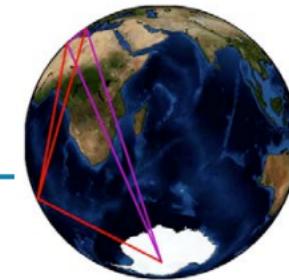


**Theoretical Simulation
& Computer Graphics**

$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$



**Reconstruction &
Inference
Algorithms**



**Instrumentation &
Observing Strategies**

