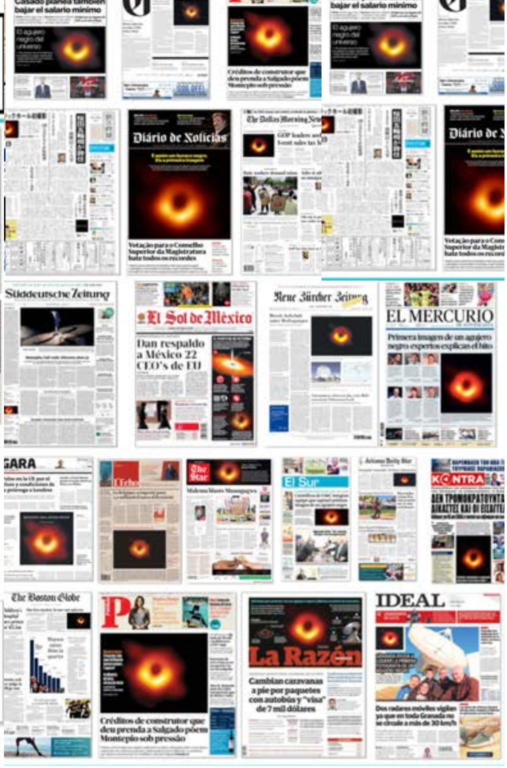
Seeing the Unseen

Cover Pages Around The World
April 11, 2019



The Event Horizon Telescope Collaboration

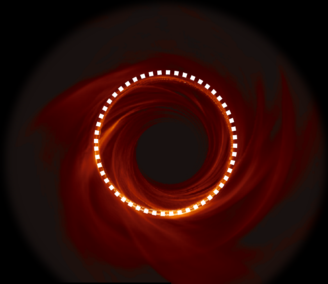
200+ scientists from 59 institutes in 18 countries in
Europe, Asia, Africa, North and South America

Black Hole Simulation

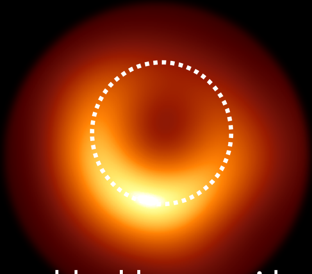
How Big Must Our Telescope Be?

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

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

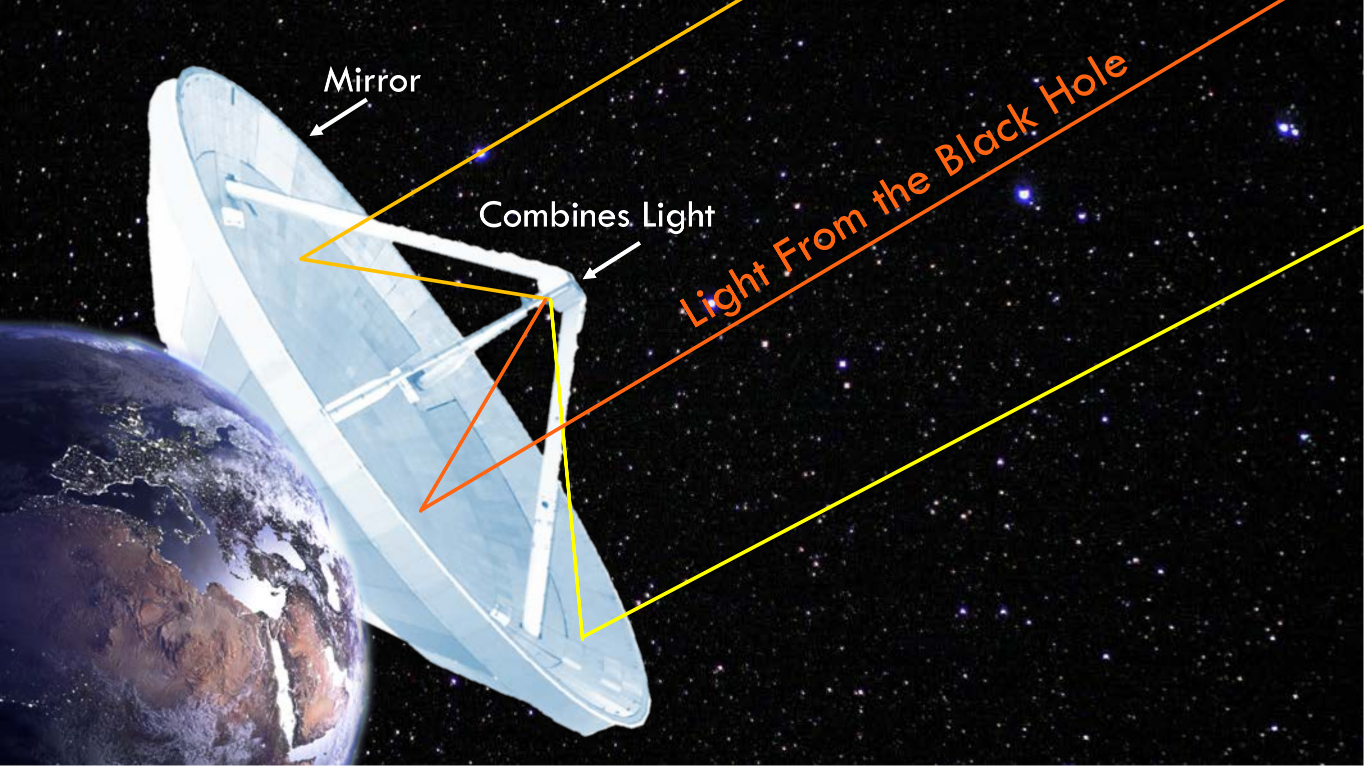


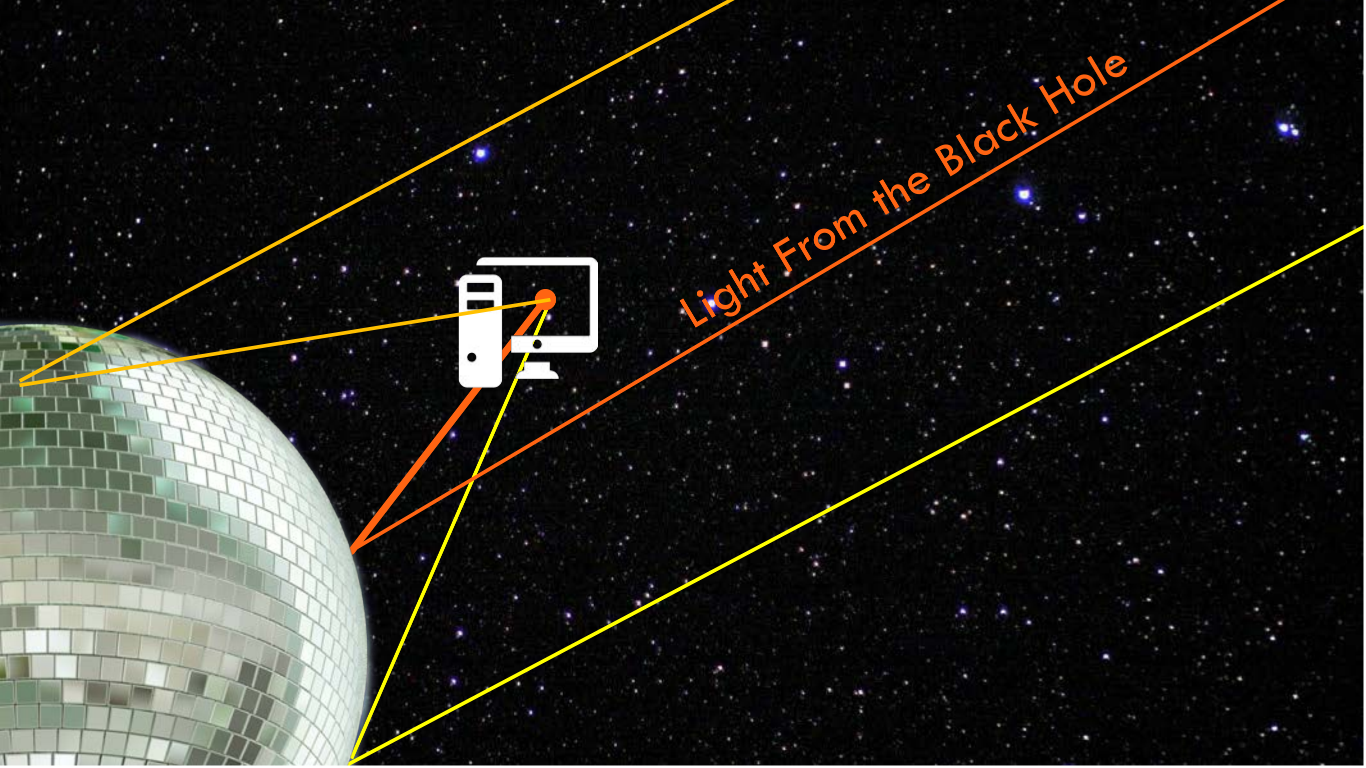
Simulation of M87

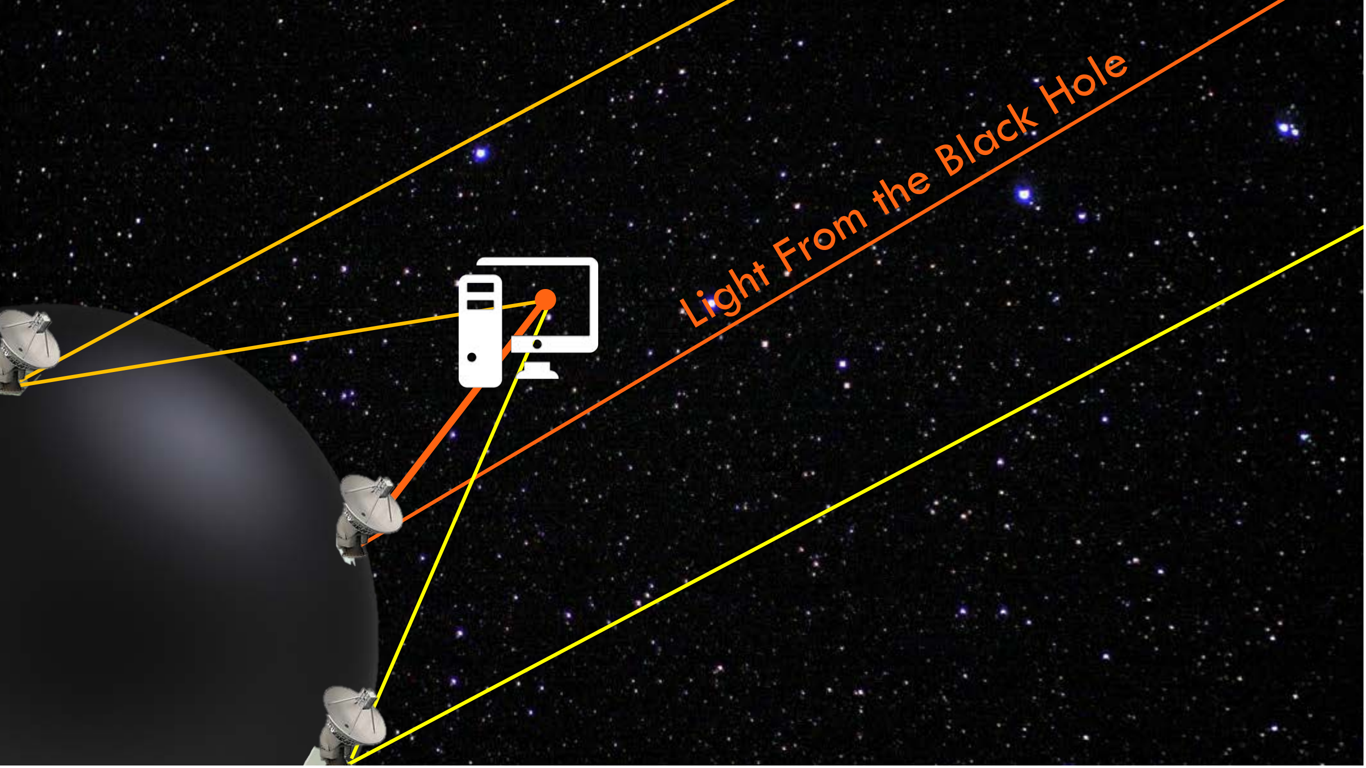


Ideal Image with
Earth-Sized Telescope

The Event Horizon Telescope (EHT)

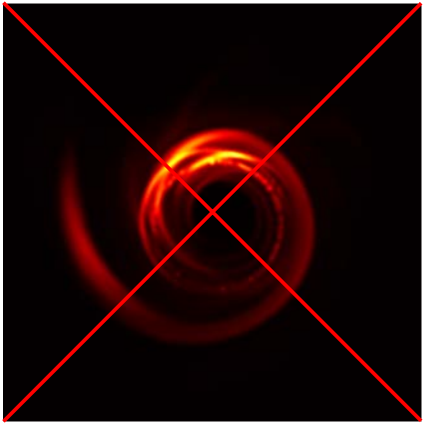

Mirror
Combines Light
Light From the Black Hole


Light From the Black Hole

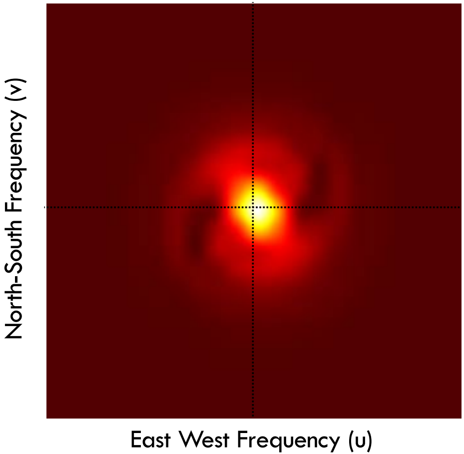

Light From the Black Hole

The Event Horizon Telescope (EHT)

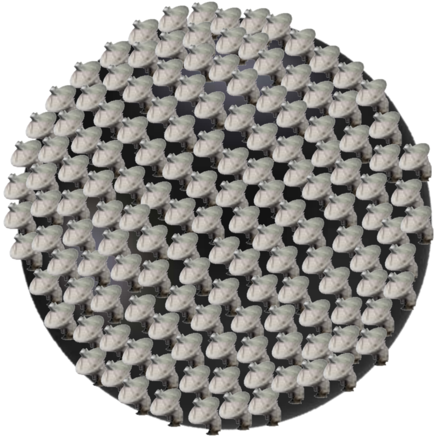
Black Hole Image

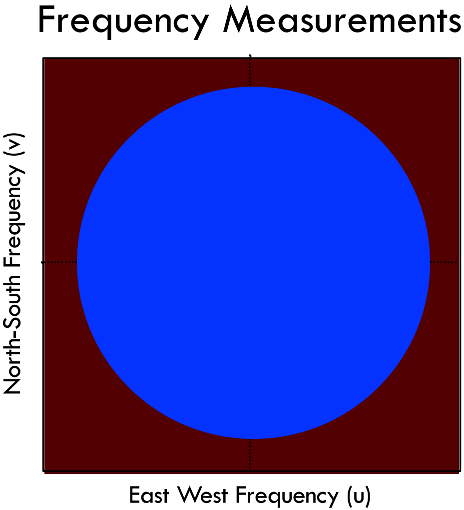


Frequency Measurements

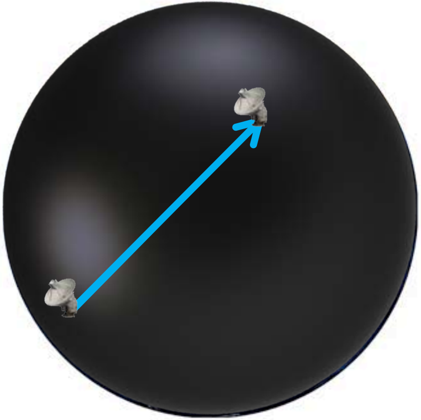


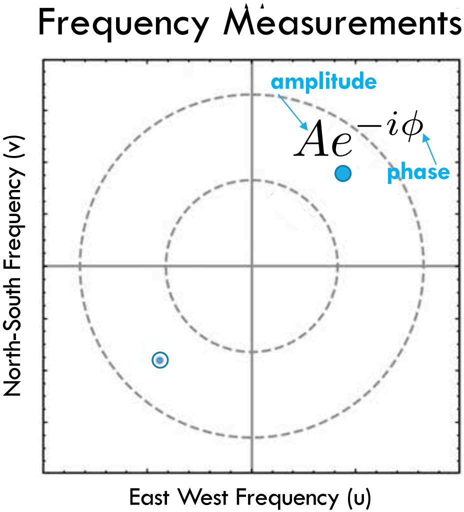
The Event Horizon Telescope (EHT)



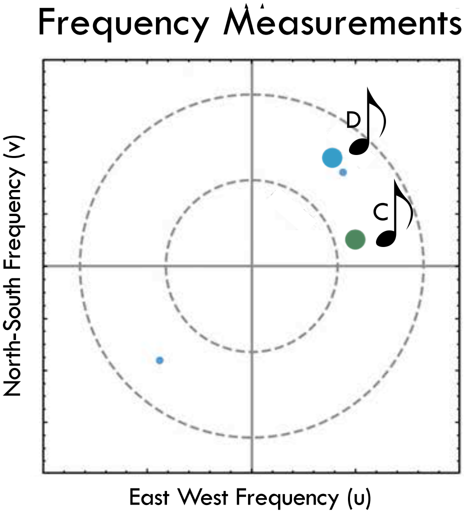


The Event Horizon Telescope (EHT)

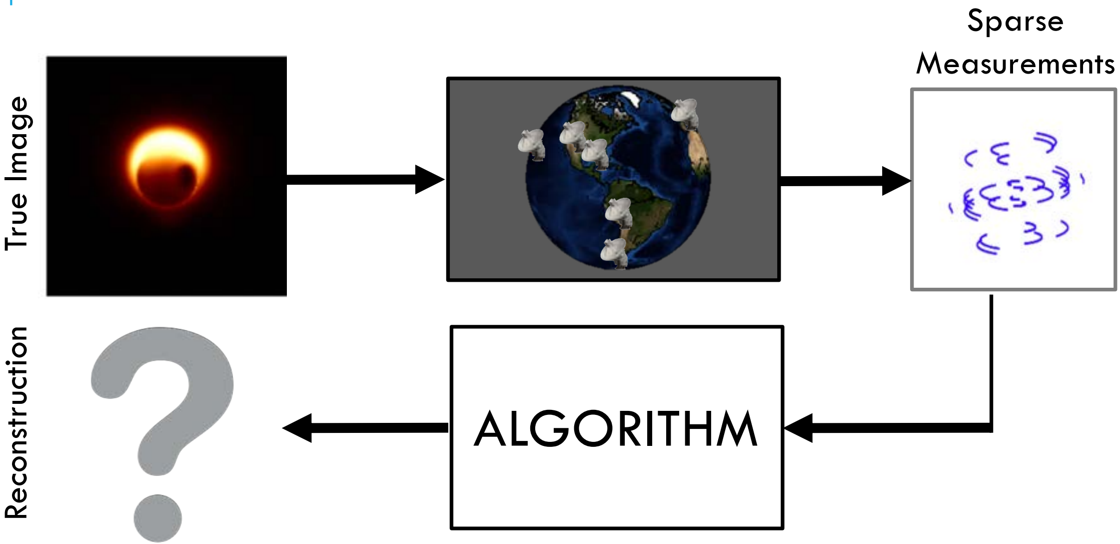




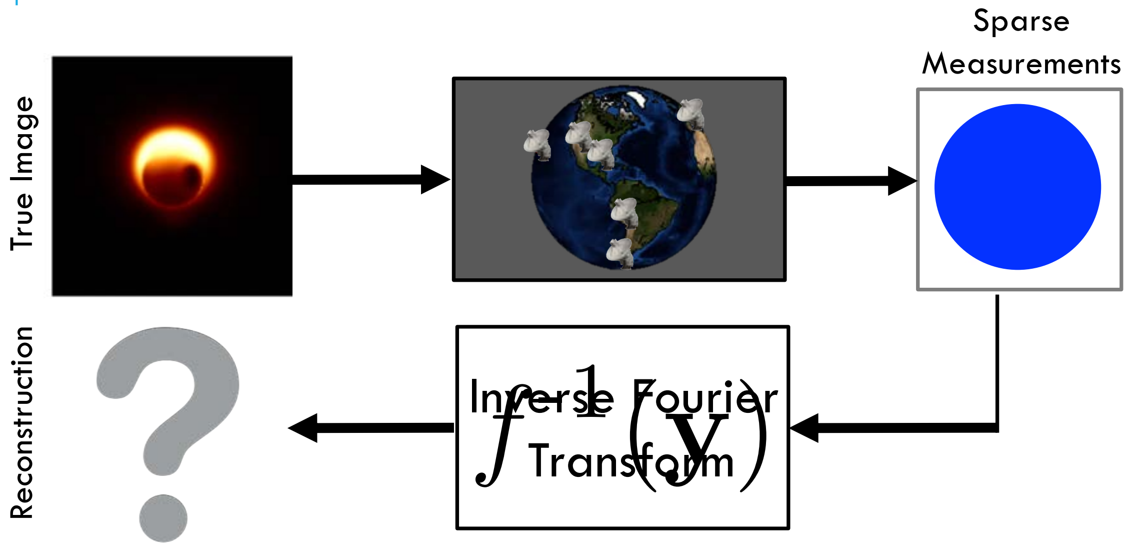
The Event Horizon Telescope (EHT)



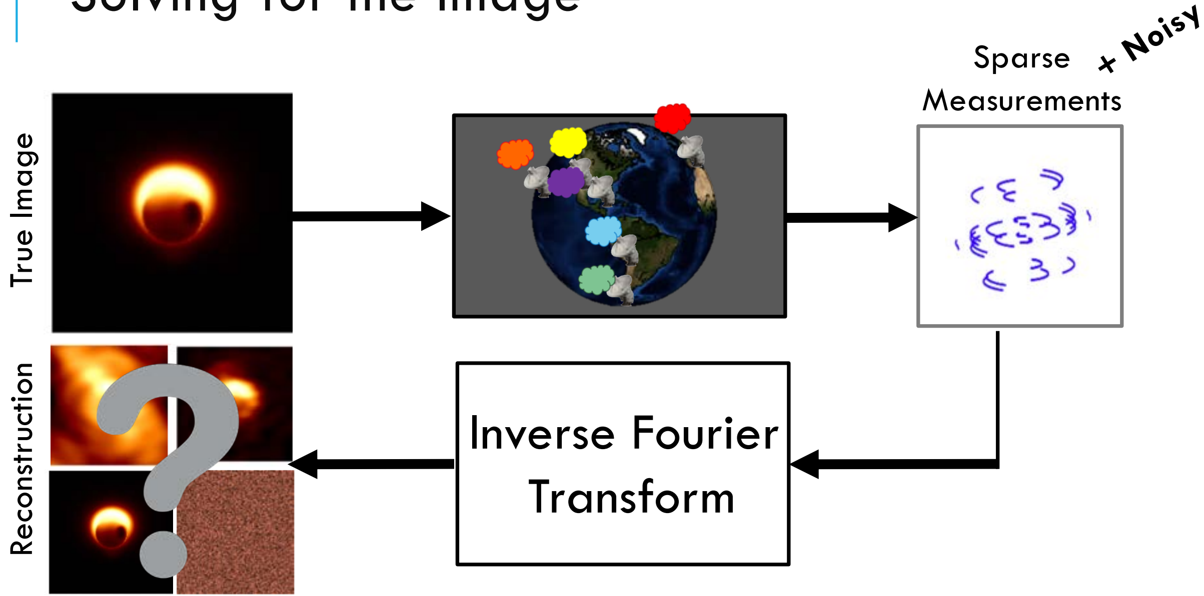
Solving for the Image



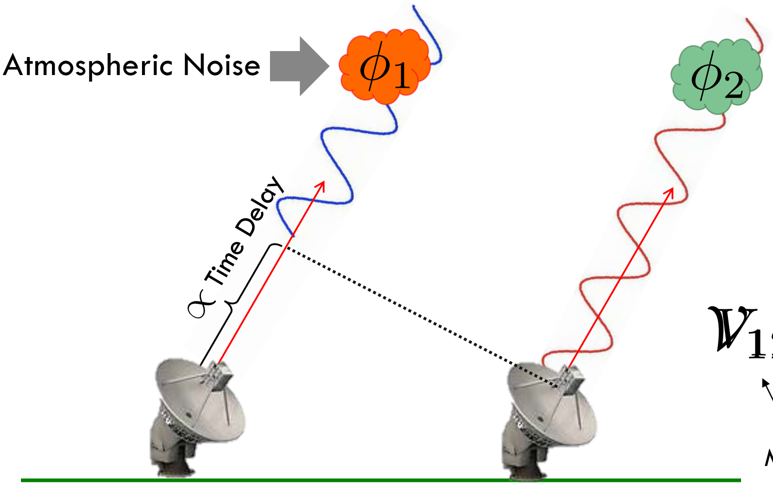
Solving for the Image



Solving for the Image



Atmospheric Error: Unknown Phase



$\cos(\omega t + \Theta + \phi_1)$ $\cos(\omega t + \phi_2)$

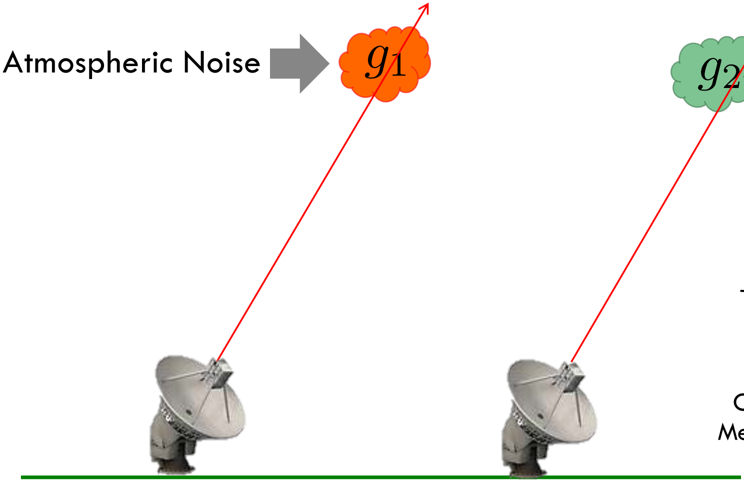
Frequency Measurement:

$$V_{12} \propto e^{-i(\Theta + \phi_1 - \phi_2)}$$

Corrupted Calibrated

Measurement

Atmospheric Error: Amplitude Attenuation



Frequency Measurement:

$$V_{12} = g_1 \, g_2 \, \mathcal{V}_{12}$$

Corrupted Measurement

Ideal Measurement

Phase & Amplitude Error

$$\overset{\text{Measured}}{V_{12}} = \underbrace{g_1 \; g_2}_{\text{Amplitude Errors}} \; e^{-i\underbrace{(\phi_1 - \phi_2)}_{\text{Phase Error}}} \overset{\text{Ideal}}{\mathcal{V}_{12}}$$

Phase & Amplitude Error

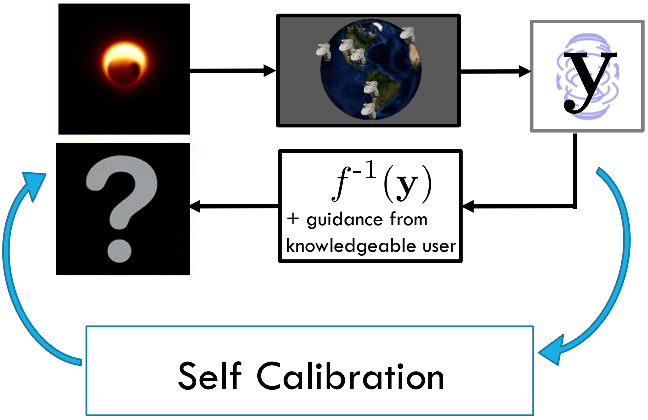
$$\overset{\text{Measured}}{\overset{\downarrow}{V_{\underset{3}{\cancel{1}}2}}} = \underbrace{g_{\underset{3}{\cancel{1}}}\, g_2}_{\text{Amplitude Errors}}\; e^{-i\underbrace{(\phi_{\underset{3}{\cancel{1}}} - \phi_2)}_{\text{Phase Error}}}\; \overset{\text{Ideal}}{\overset{\downarrow}{\mathcal{V}_{\underset{3}{\cancel{1}}2}}}$$

Two Classes of Imaging Algorithms

Inverse Modeling
(CLEAN + Self-Calibration)

Forward Modeling
(Regularized Maximum Likelihood)

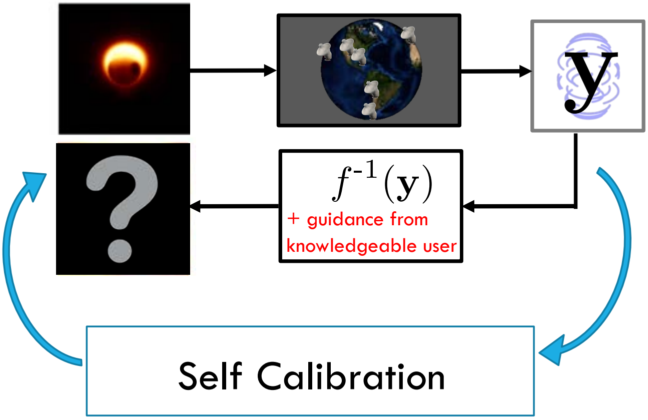
Two Classes of Imaging Algorithms



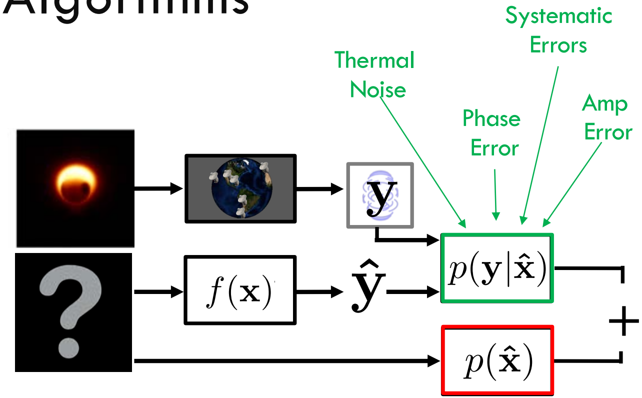
Standard Inverse Modeling
(CLEAN + Self-Calibration)

Forward Modeling
(Regularized Maximum Likelihood)

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)

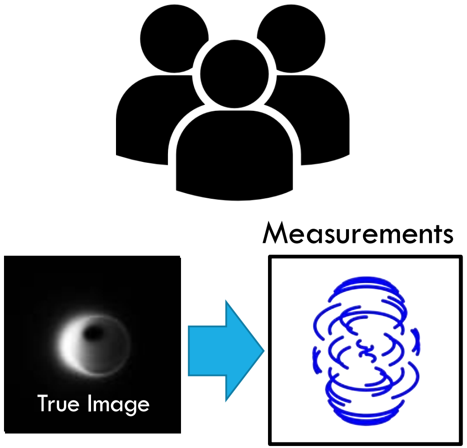
How do we verify what we are reconstructing is real?

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

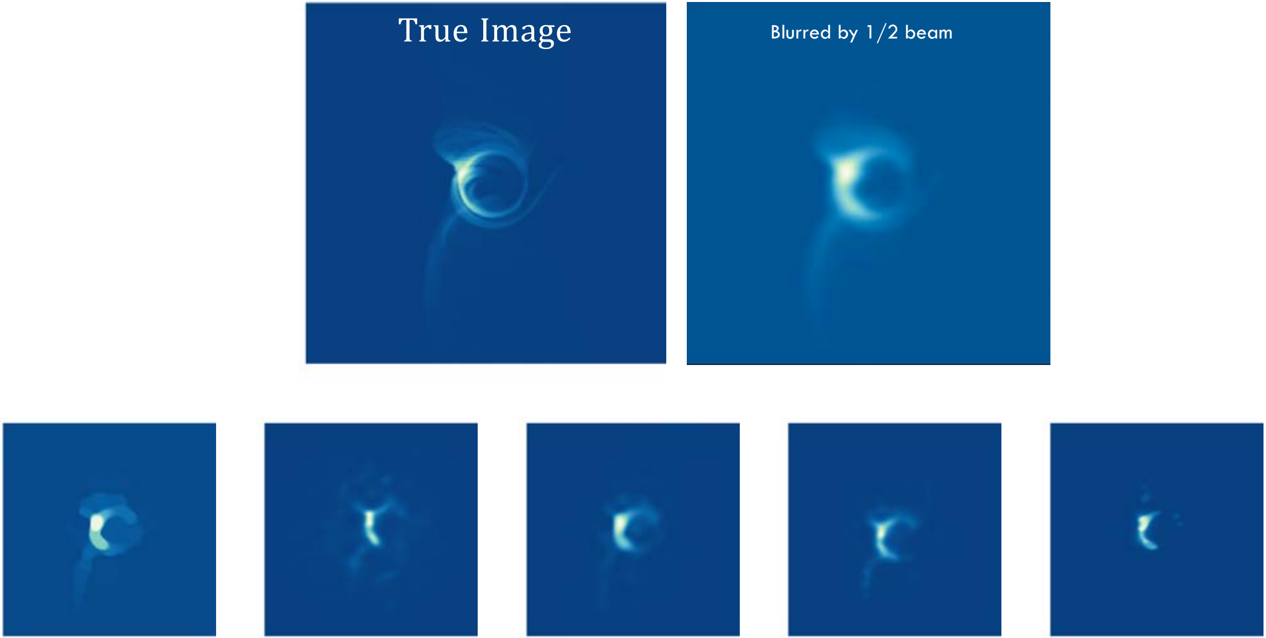
Event Horizon Telescope Imaging Challenges



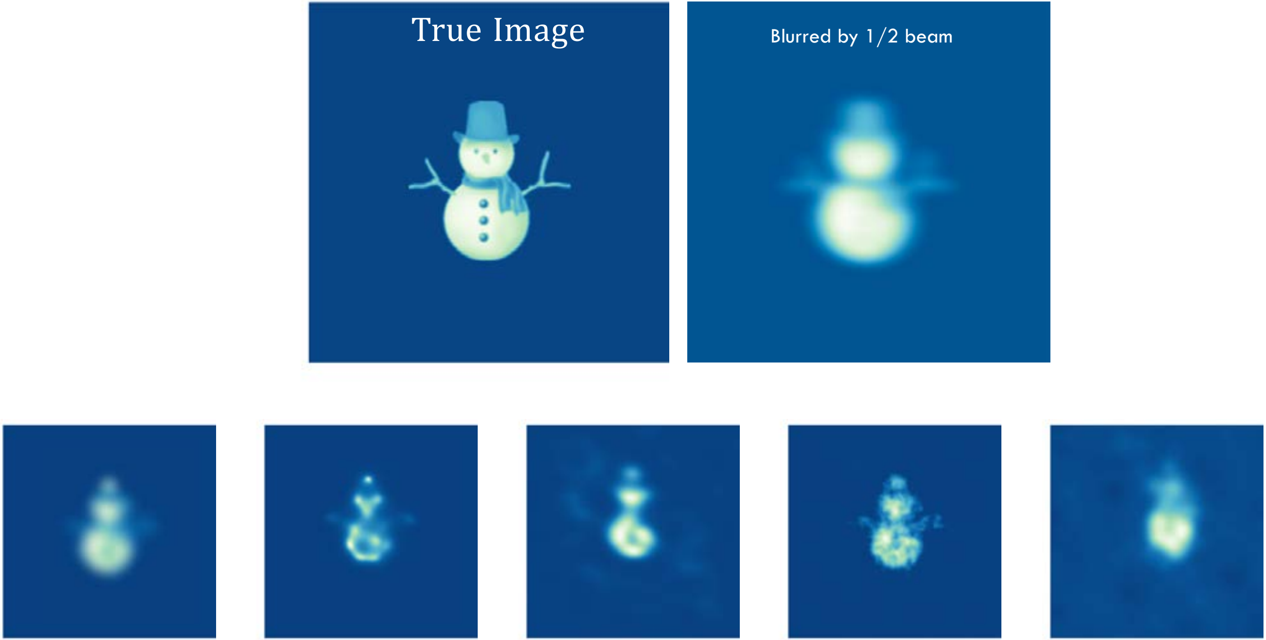
1) Generate Measurements

2) Make Images

3) Evaluate Quality



Method 1 Method 2 Method 3 Method 4 Method 5



Method 1 | Method 2 | Method 3 | Method 4 | Method 5

Step 2: Blind Imaging of M87 Data

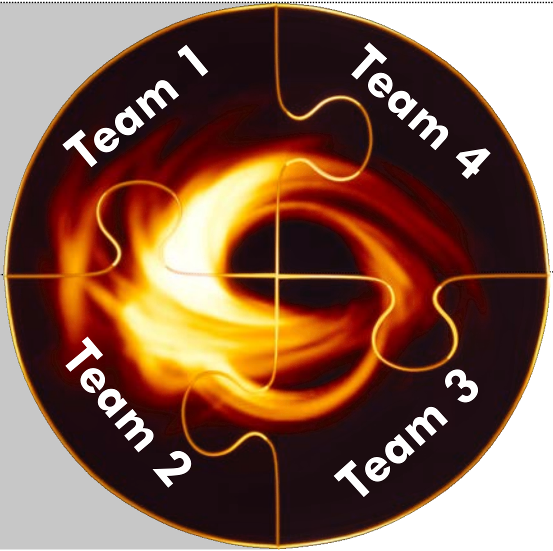
Step 2: Blind Imaging

The Americas

Harvard-Smithsonian
University of Arizona
U. Concepcion

Global

MIT Haystack
Radboud University
NAOJ



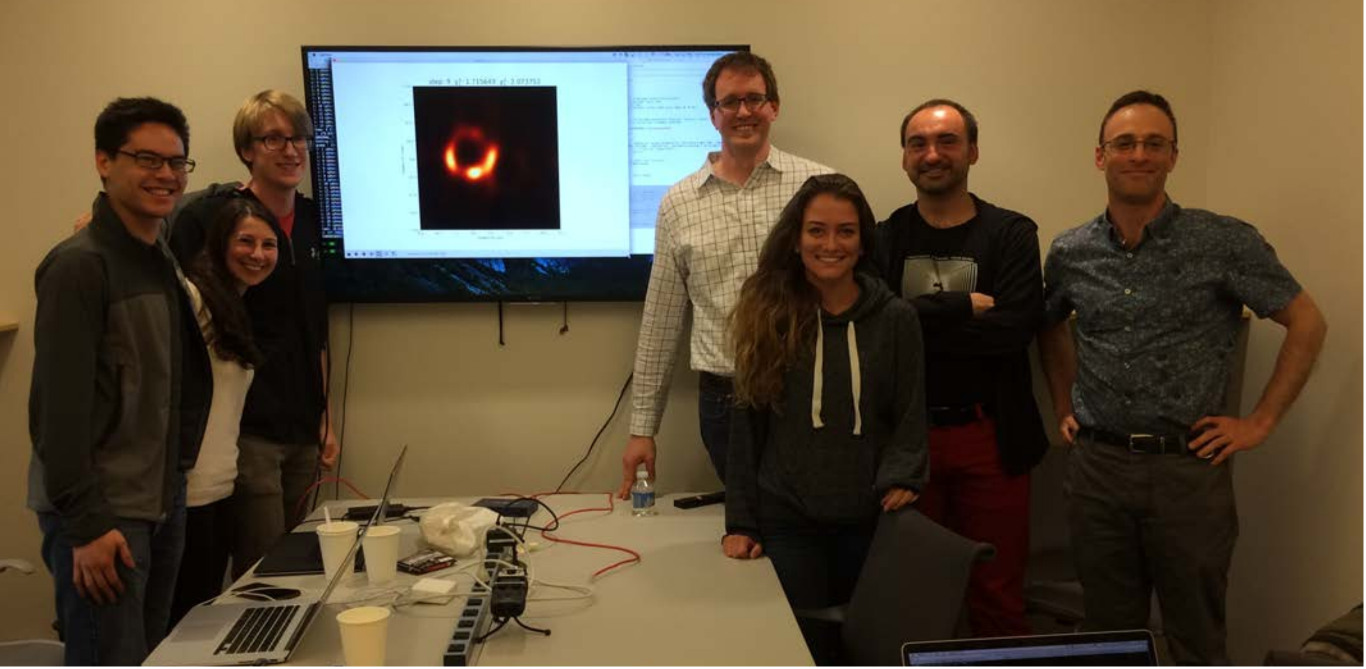
ASIAA
KASI
NAOJ

East Asia

MPIfR
Boston University
IAA
Aalto

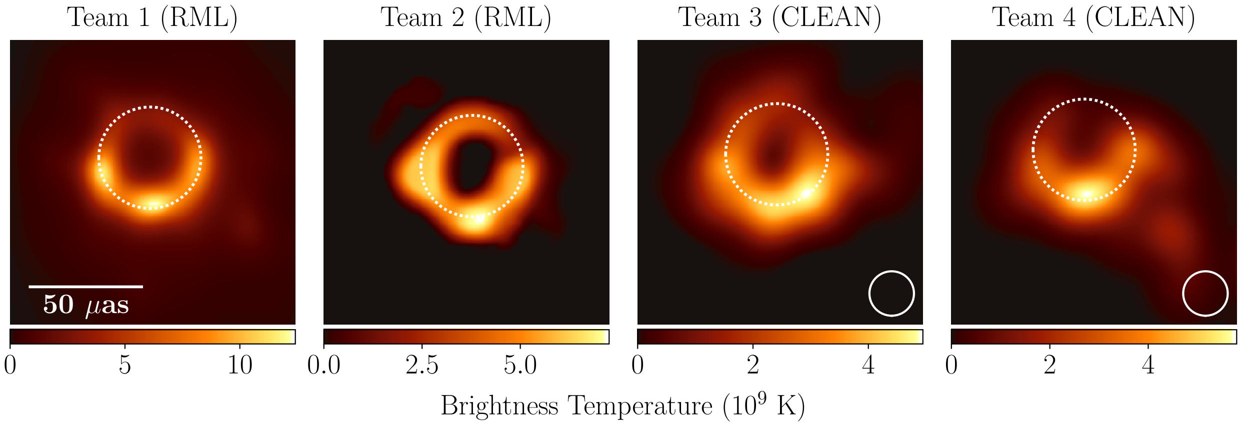
Cross-Atlantic

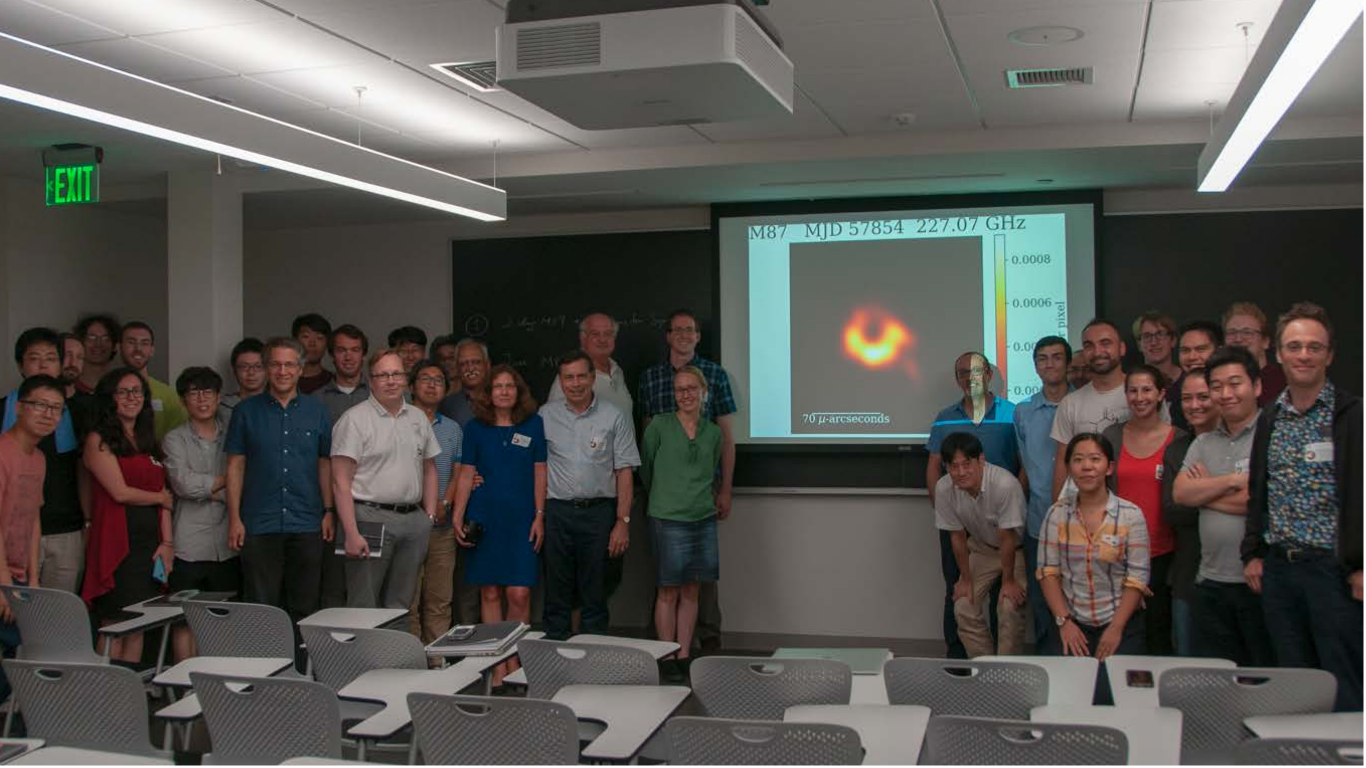
Team 1 – End of the First Day of Imaging M87




7 weeks later…

Step 2: Blind Imaging




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

Step 3: Objectively Choosing Parameters

Step 3: Imaging Pipelines

DIFMAP
(CLEAN + Self Calibration)

Compact Flux
Stop Condition
Weighting on ALMA
Mask Size
Data Weights

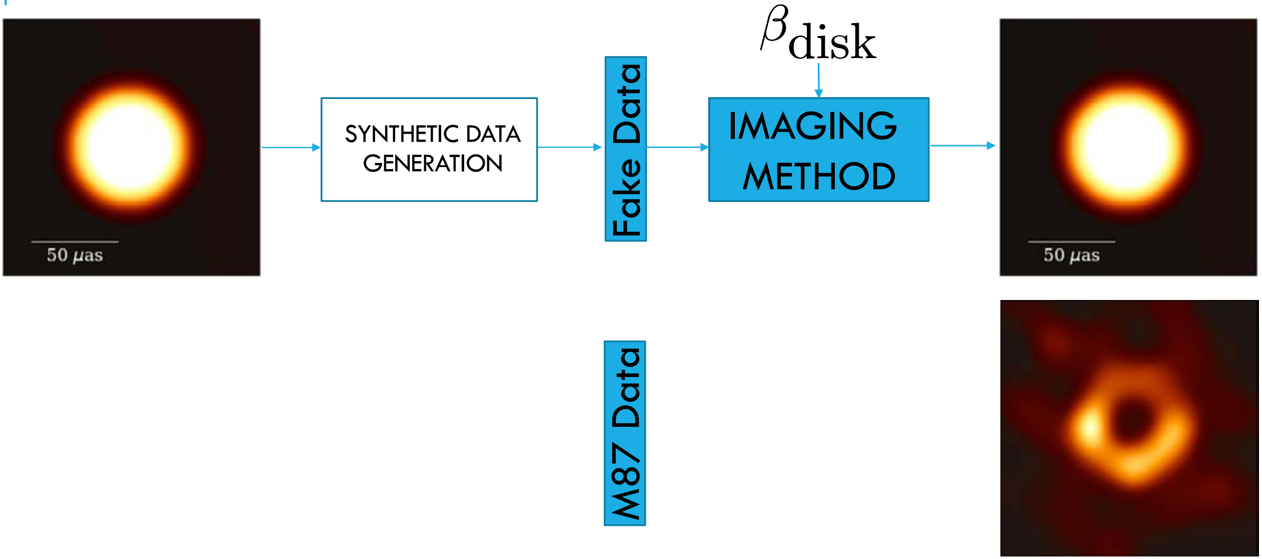
eht-imaging
(Regularized Max Likelihood)

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

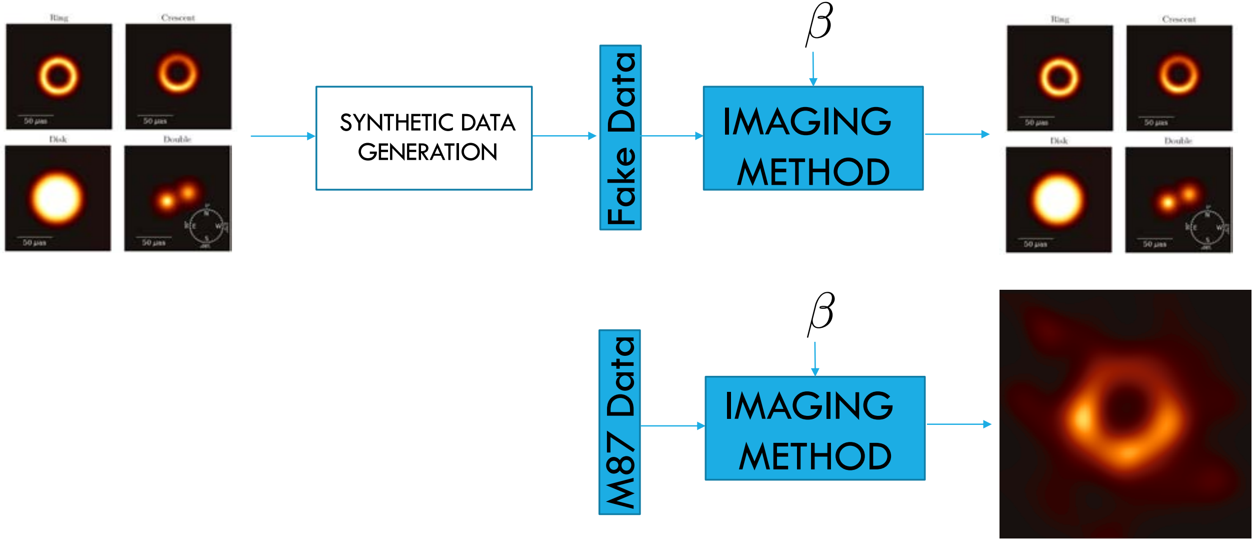
SMILI
(Regularized Max Likelihood)

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

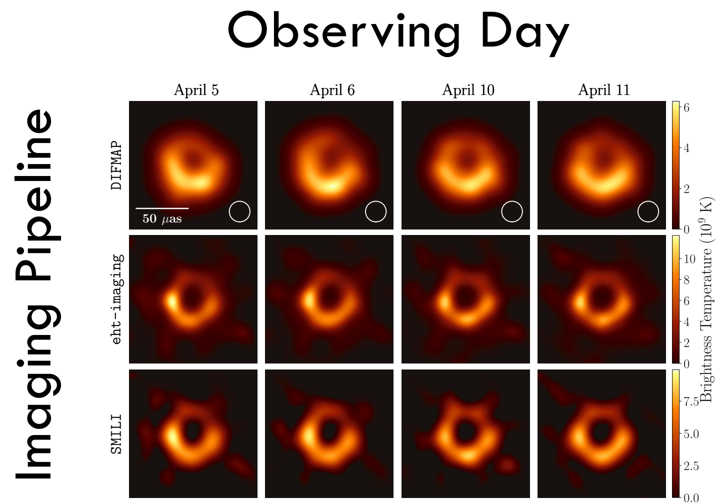
Step 3: Training on a Disk



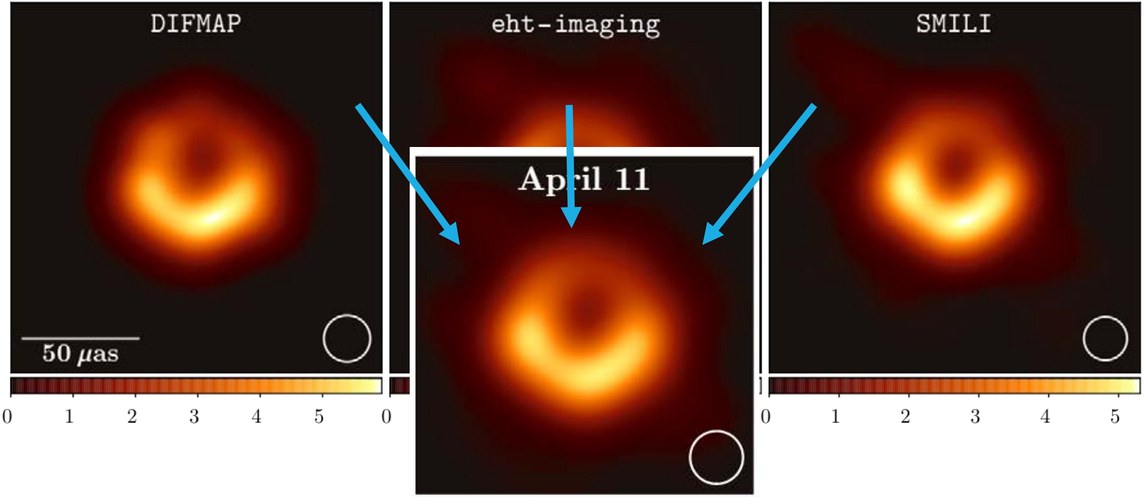
Step 3: Training on Full Set



Step 3: Different Days and Imaging Pipelines

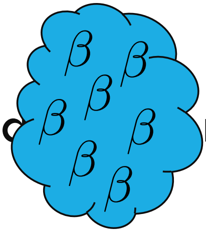


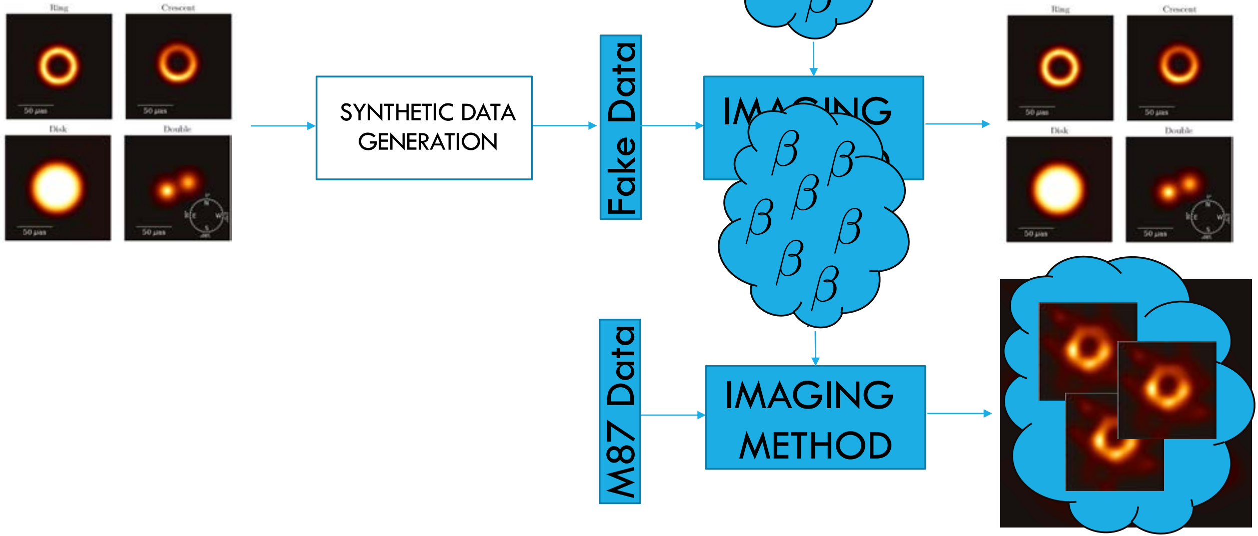
Step 3: Blurred to Equivalent Resolution



Step 4: Validation

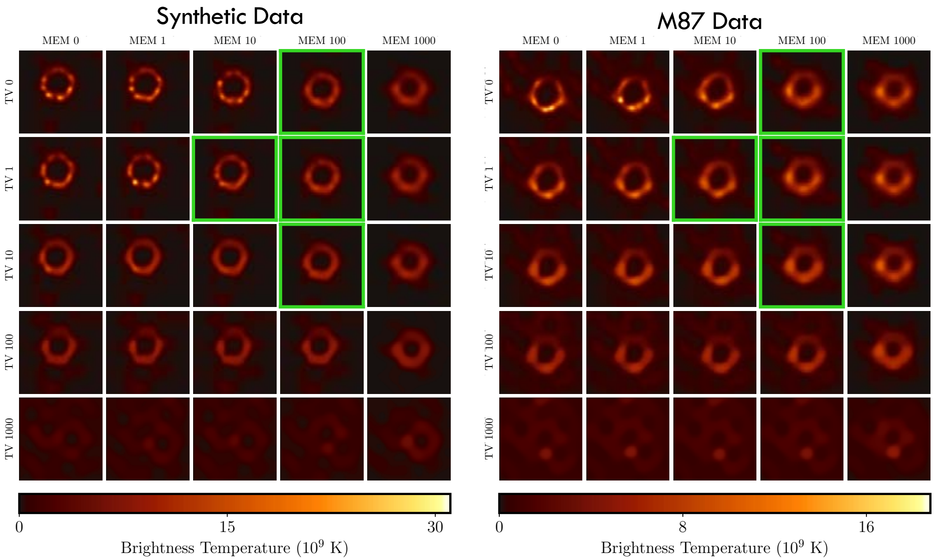
Step 4: Finding “Top Set” Po rs



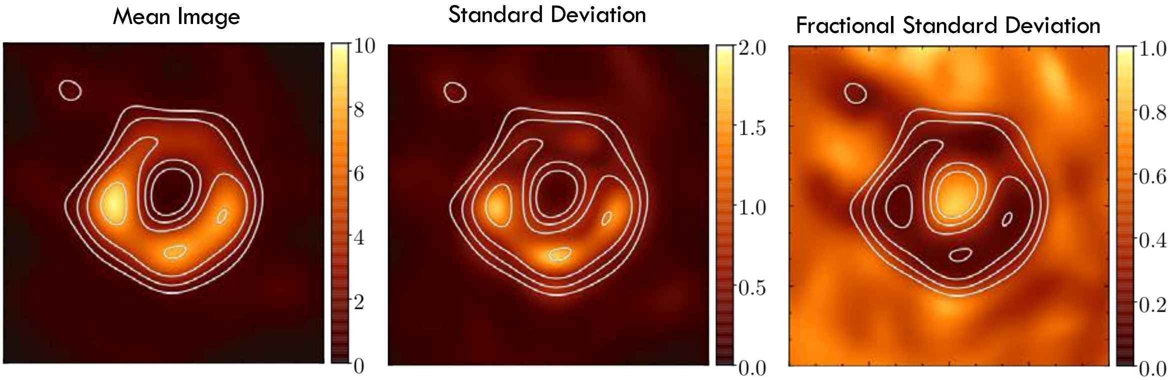


Step 4: eht-imaging Parameter Slice

Top Set Parameters

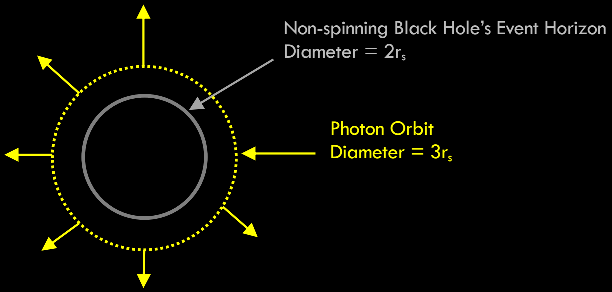


Step 4: Variance Over the Top Set

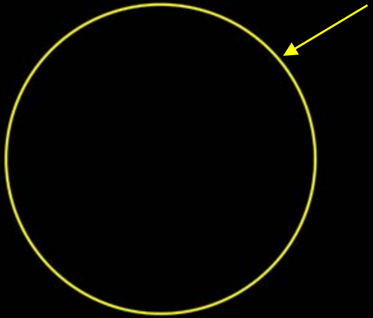


Did We Prove Einstein Was Right?

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

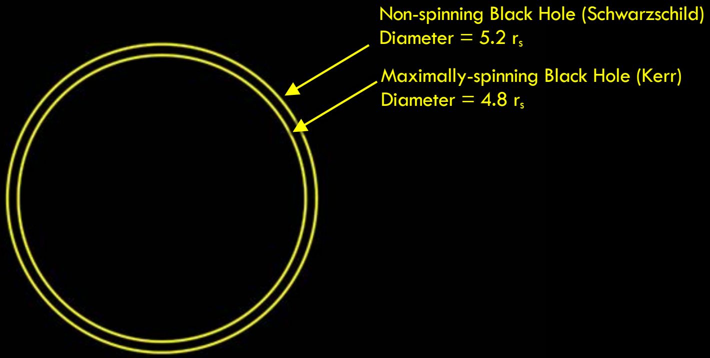


Schwarzschild Radius: $r_s = \frac{2GM}{c^2}$



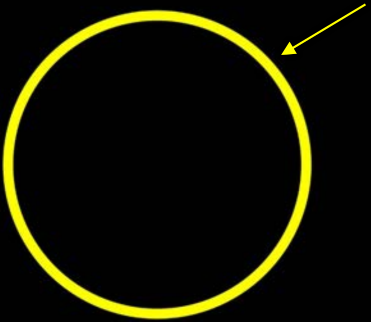
$$r_s = \frac{2GM}{c^2}$$

adapted from Michael Johnson



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

adapted from Michael Johnson



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

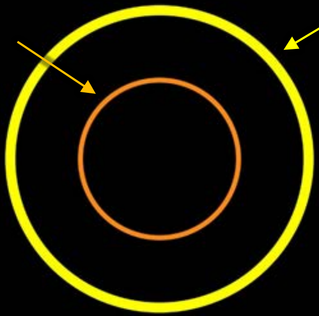
adapted from Michael Johnson

M87 Mass from Gas Dynamics
$M_{BH} = 3.5 \times 10^9 M_\odot$
[Walsh et al 2013]

M87 Mass from Stellar Dynamics
$M_{BH} = 6.6 \times 10^9 M_\odot$
[Gebhardt et all 2011]

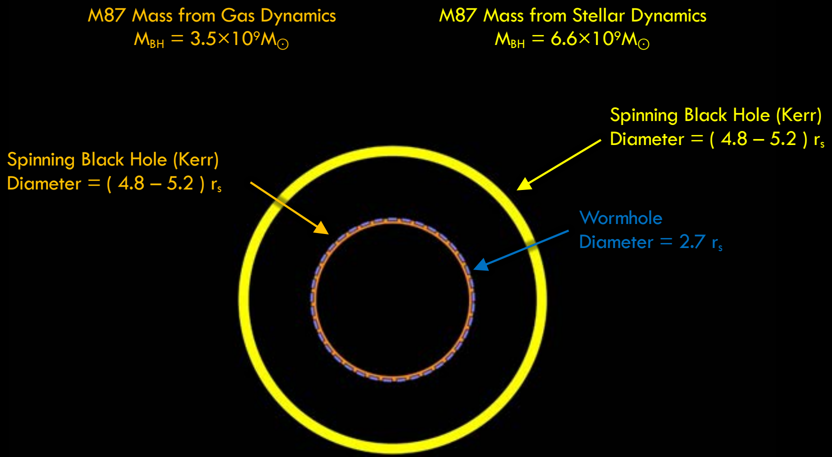
Spinning Black Hole (Kerr)
Diameter = (4.8 – 5.2) r_s

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



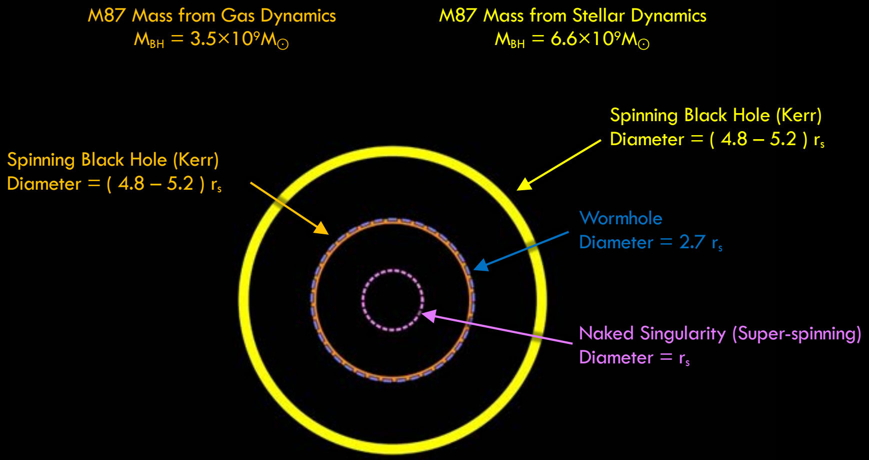
$$r_s = \frac{2GM}{c^2}$$

adapted from Michael Johnson



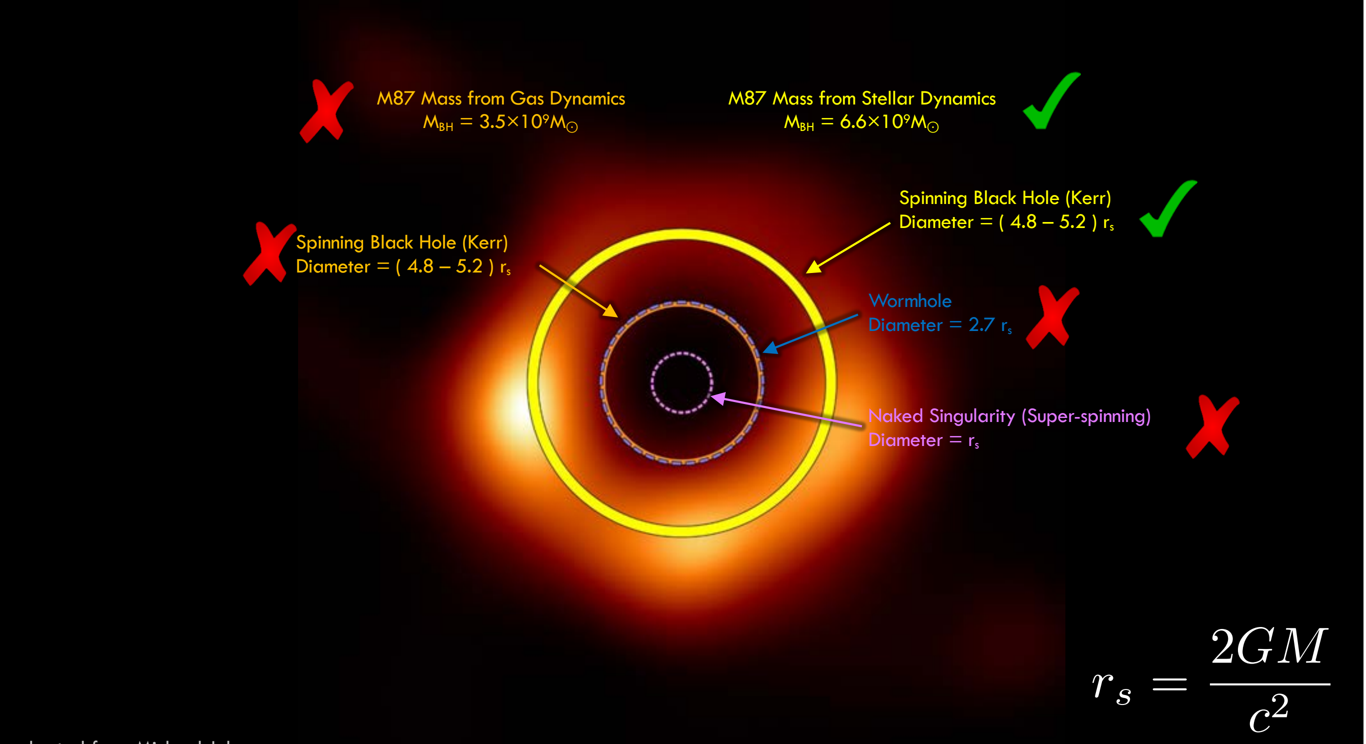
$$r_s = \frac{2GM}{c^2}$$

adapted from Michael Johnson



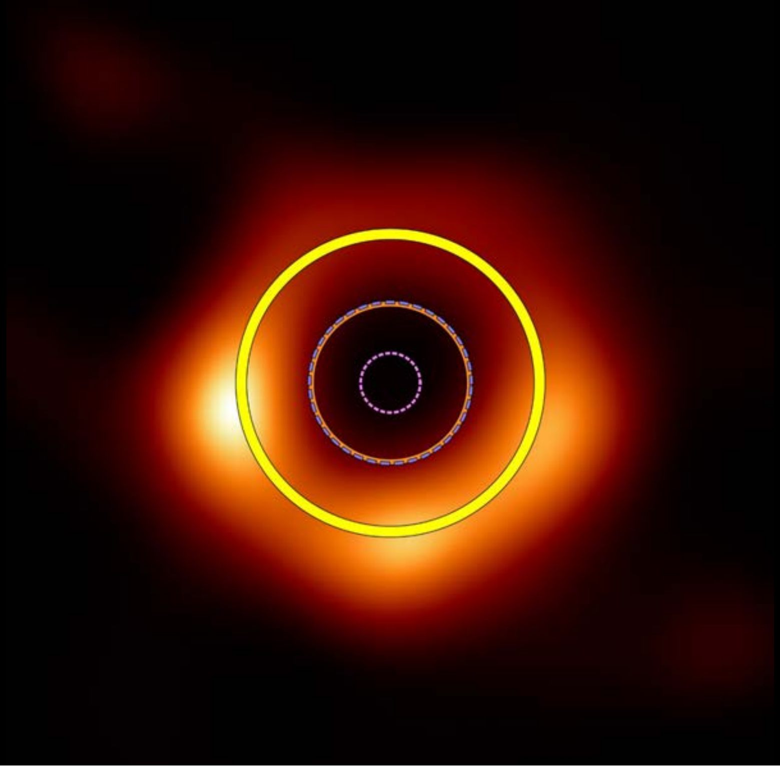
$$r_s = \frac{2GM}{c^2}$$

adapted from Michael Johnson

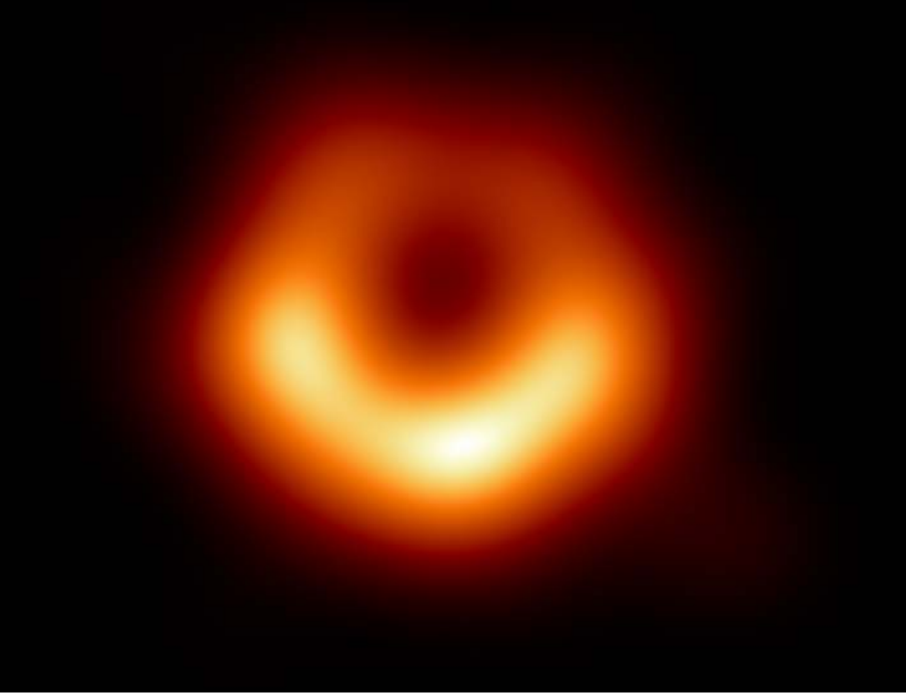


$$r_s = \frac{2GM}{c^2}$$

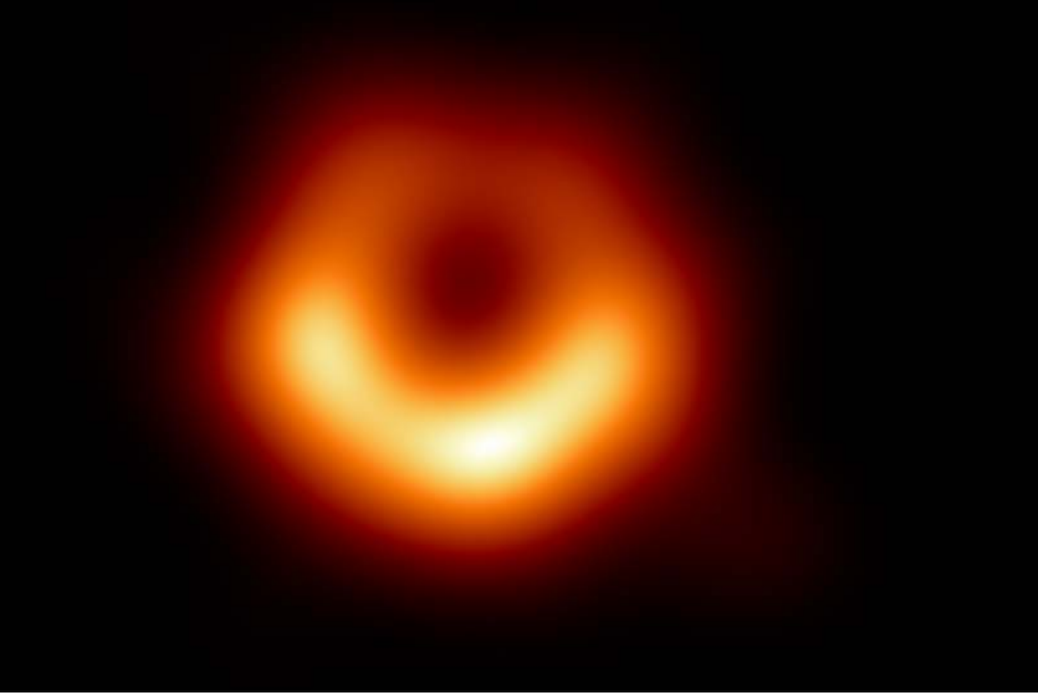
adapted from Michael Johnson



April 11

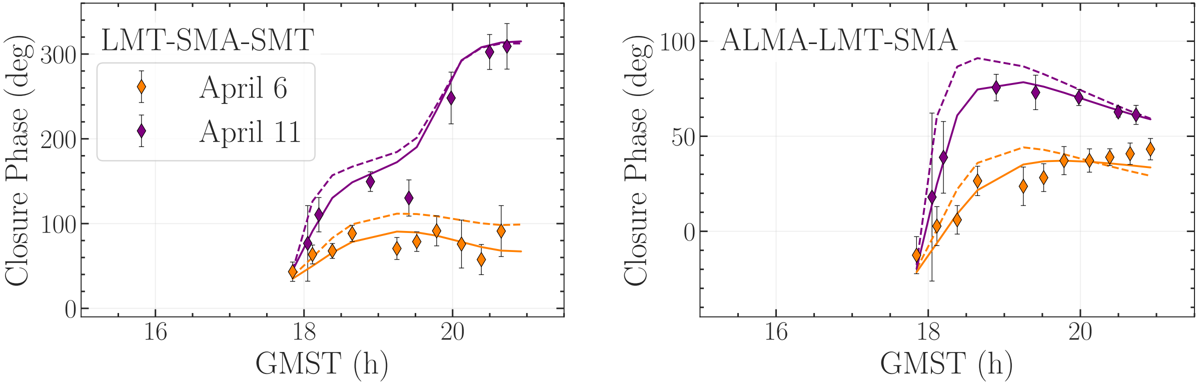


April 11



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~~

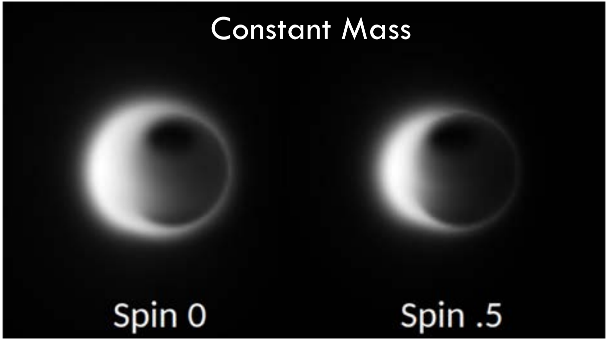
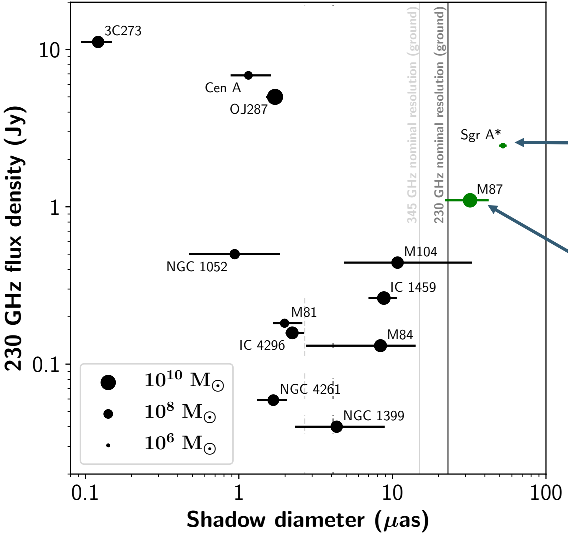
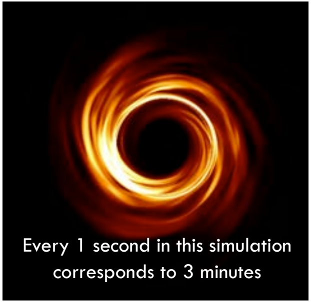


Image credit: Avery Broderic

The EHT's Black Hole Targets





<u>Sagittarius A* (Sgr A*)</u>

4 Million Solar Masses

Orbital Period: 4 – 30 <u>*minutes*</u>

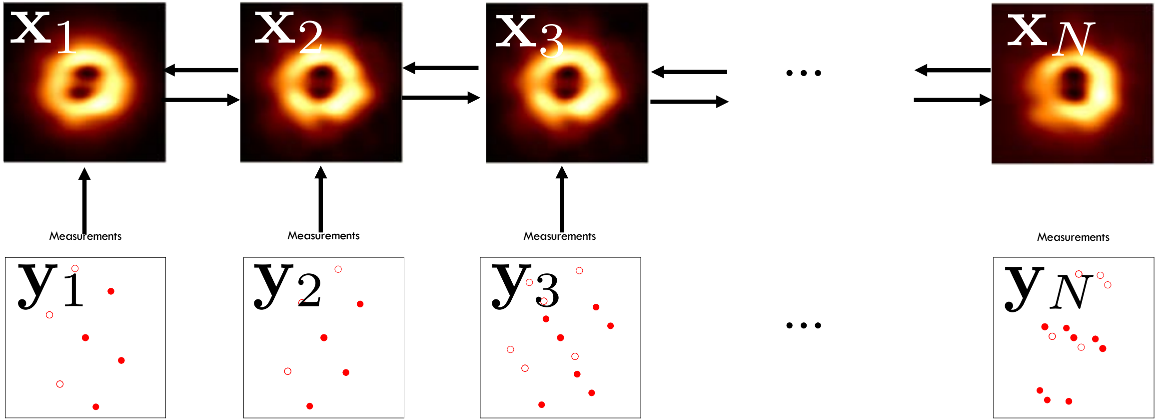
<u>M87</u>

6.5 Billion Solar Masses

Orbital Period: 4 – 30 <u>*days*</u>

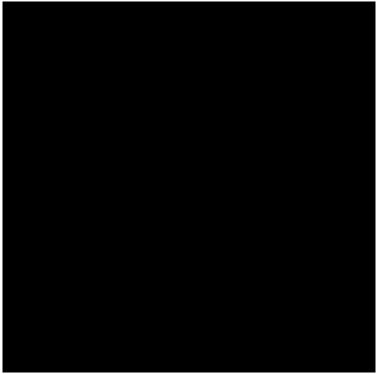
video credit: Hotoka Shiokawa, plot credit: Dom Pesce

Reconstructing a Video Over a Night

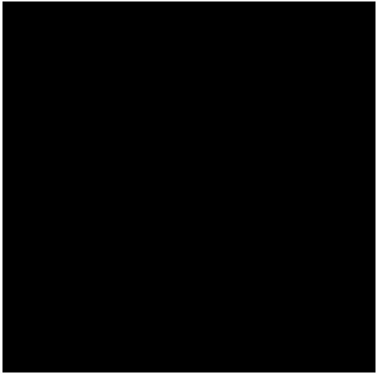


Video Reconstruction Simulation of Sagittarius A*

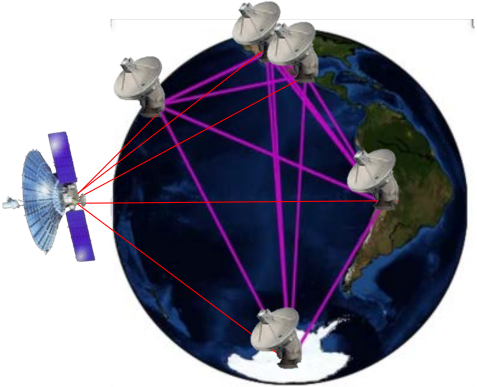
Truth Video



EHT Ground Sites



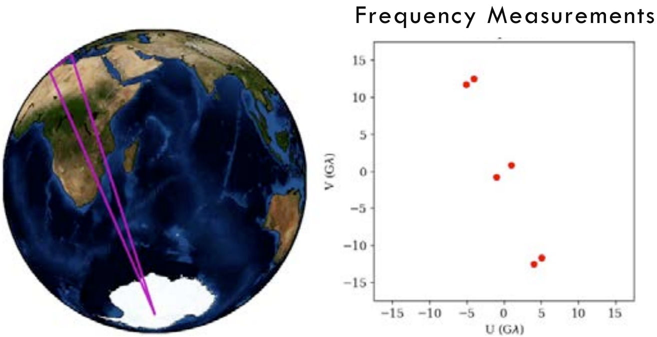
Adding Face-On Low Earth Orbiters



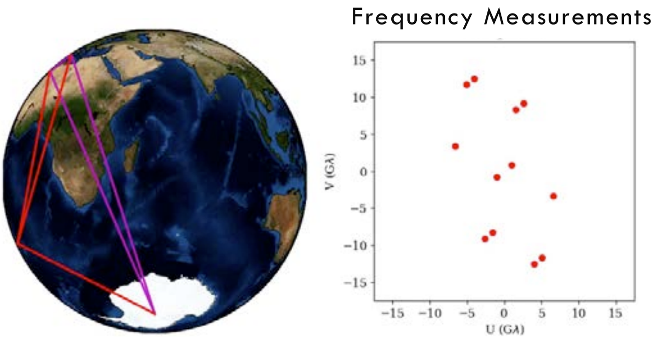
“Metrics and Motivations for Earth-Space VLBI: Time-Resolving Sgr A* with the Event Horizon Telescope”

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

Low Earth Orbiters: 90 minute period



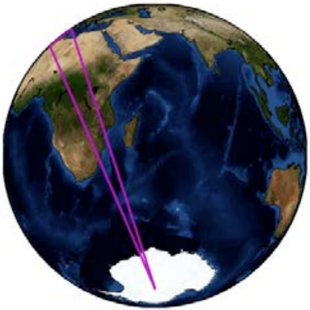
EHT’s Current Ground Based Sites

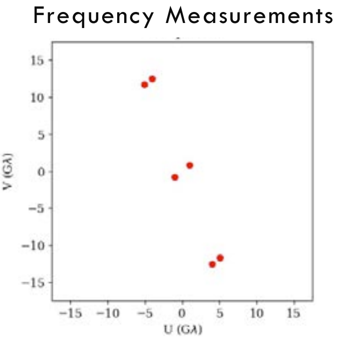


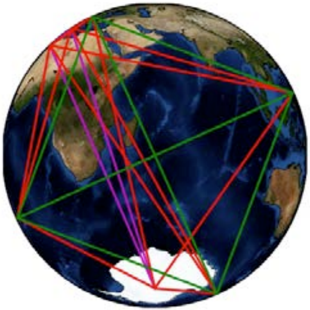
EHT’s Current Ground Based Sites
+ 1 Low-Earth Orbiter

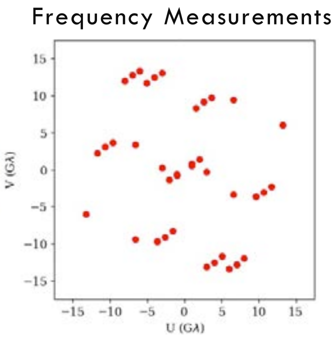
simulation credit: Daniel Palumbo

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

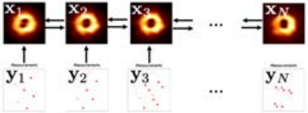
EHT Ground Sites

+ 1 Orbiter

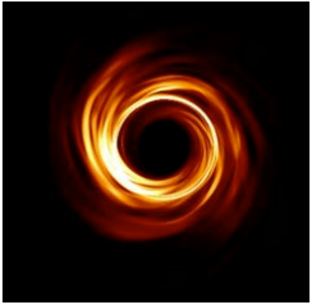
+ 4 Orbiters

simulation credit: Daniel Palumbo

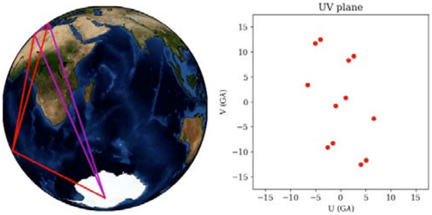
$$p(\mathbf{X},\mathbf{Y}) \propto \prod_{t=1}^{N} \varphi_{\mathbf{y}_t|\mathbf{x}_t} \prod_{t=1}^{N} \varphi_{\mathbf{x}_t} \prod_{t=2}^{N} \varphi_{\mathbf{x}_t|\mathbf{x}_{t-1}}$$



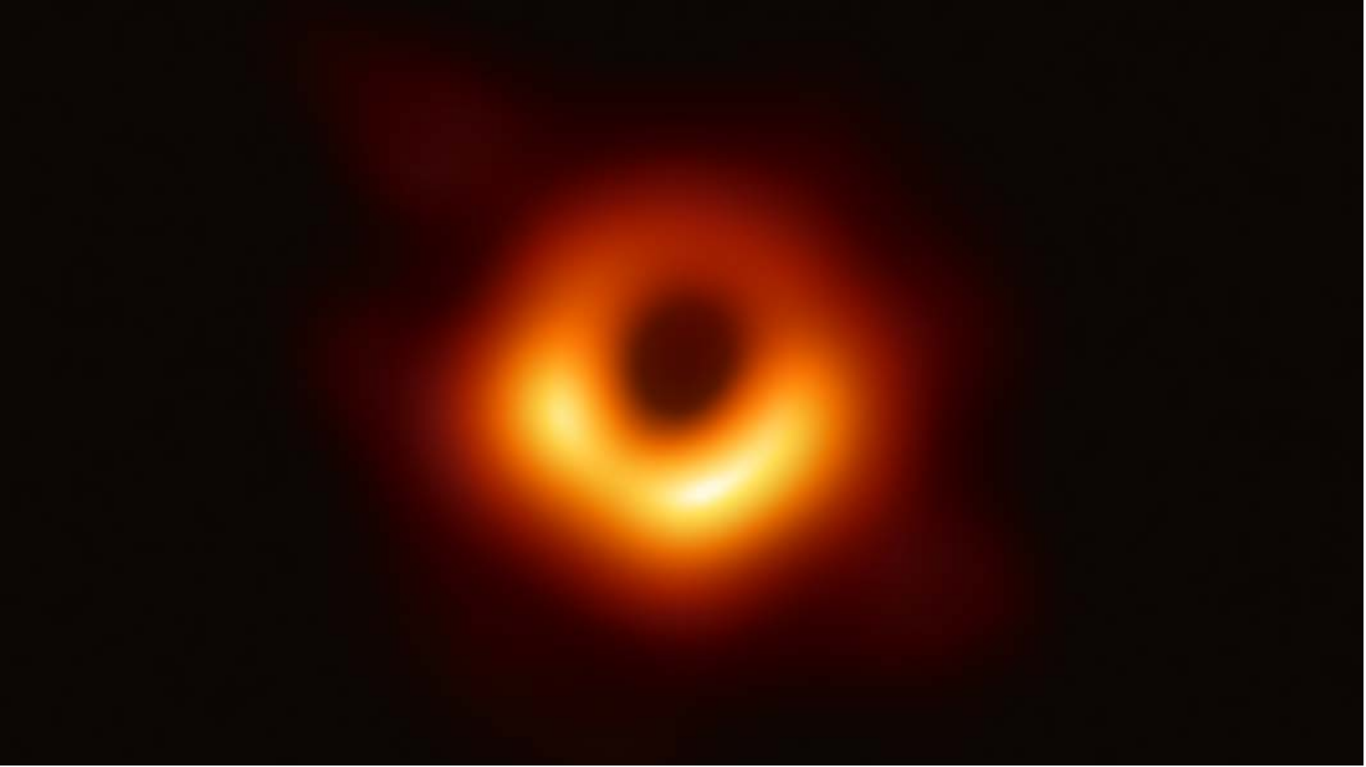
Reconstruction & Inference Algorithms



Theoretical Simulation & Computer Graphics



Instrumentation & Observing Strategies



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