

Seeing the Unseen

Cover Pages Around The World

April 11, 2019



The Event Horizon Telescope Collaboration

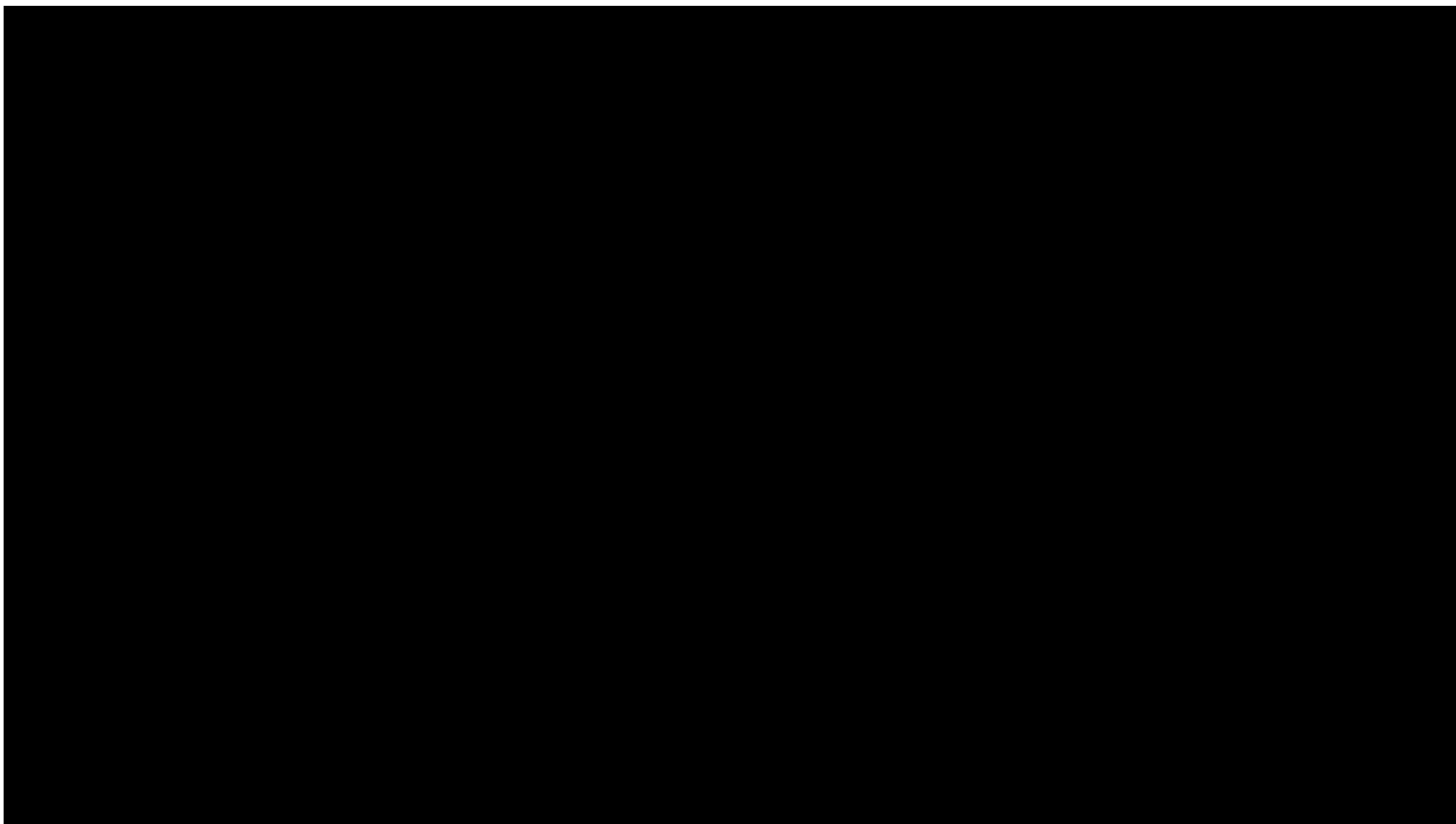


200+ scientists from 59 institutes in 18 countries in
Europe, Asia, Africa, North and South America

The Event Horizon Telescope's Extended Team



A Network of Open Source Contributors





Black Hole Simulation

EPFL

Grain of Sand
in Egypt



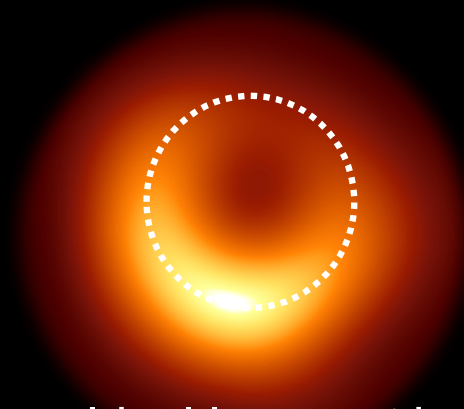
How Big Must Our Telescope Be?

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

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



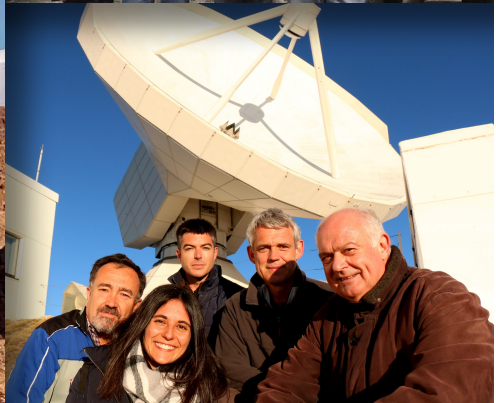
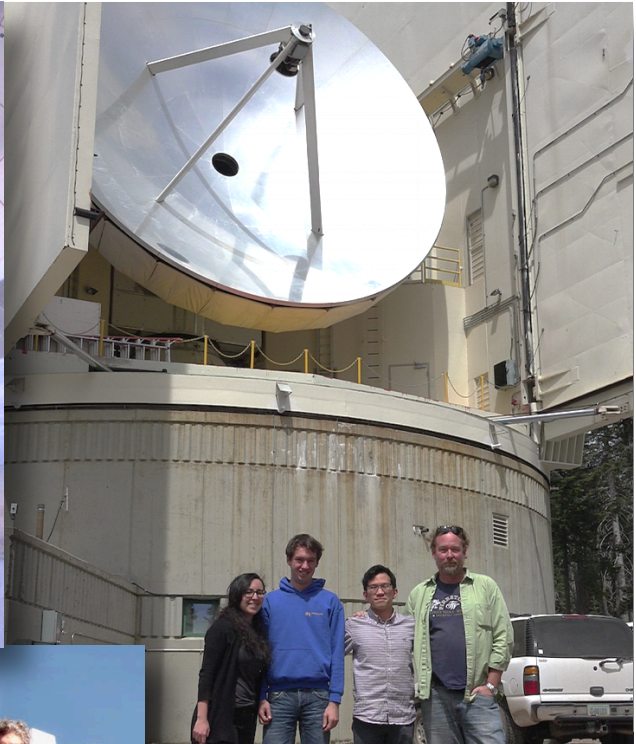
Simulation of M87



Ideal Image with
Earth-Sized Telescope

The Event Horizon Telescope (EHT)



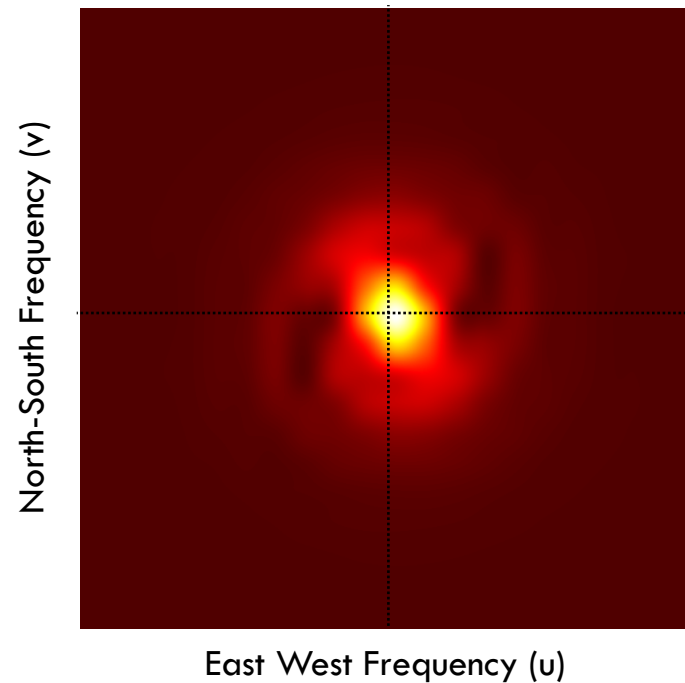


The Event Horizon Telescope (EHT)

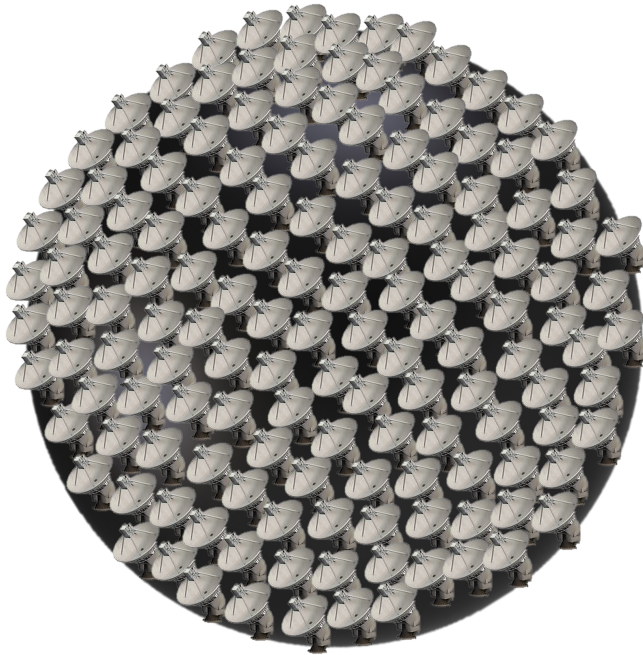
Black Hole Image



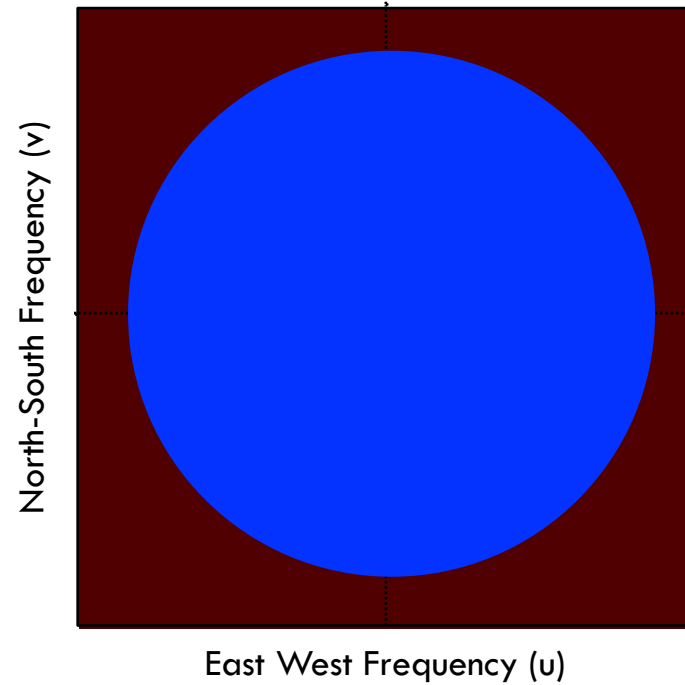
Frequency Measurements



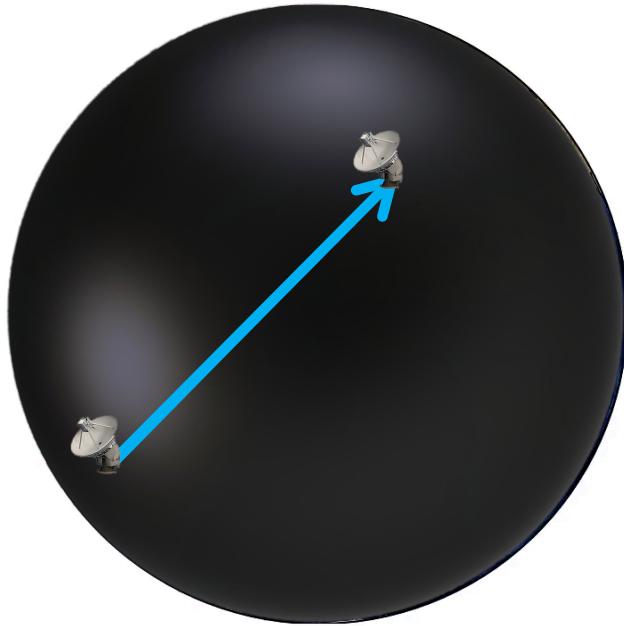
The Event Horizon Telescope (EHT)



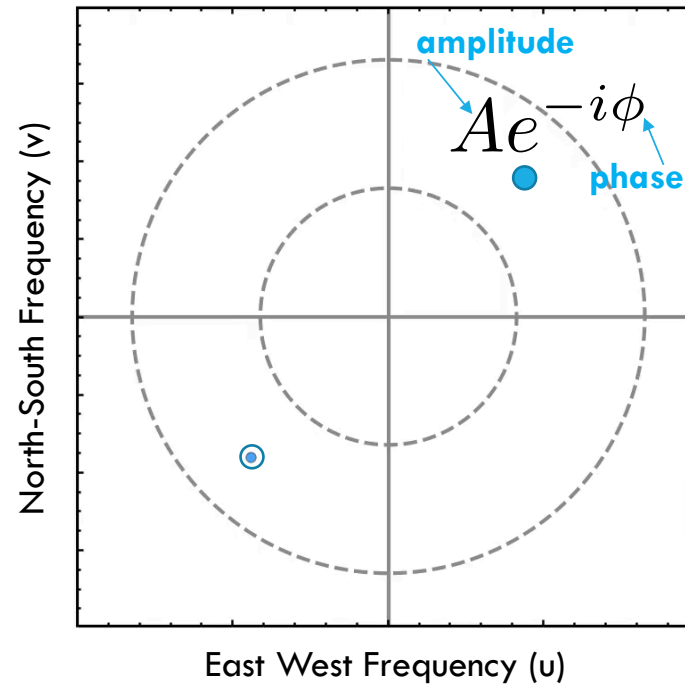
Frequency Measurements



The Event Horizon Telescope (EHT)



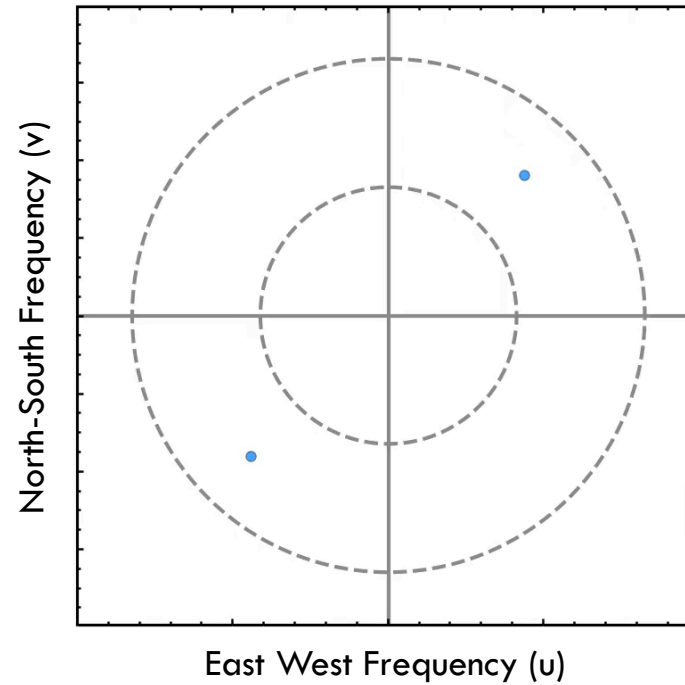
Frequency Measurements



The Event Horizon Telescope (EHT)



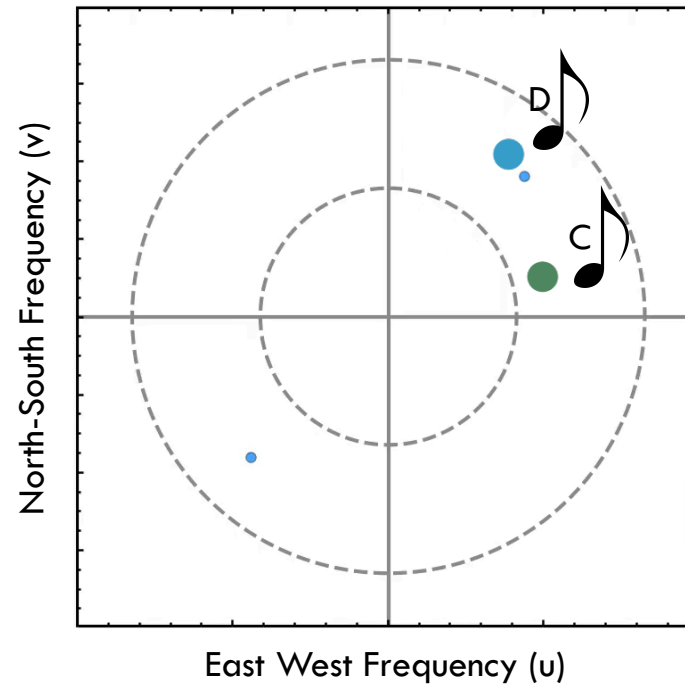
Frequency Measurements



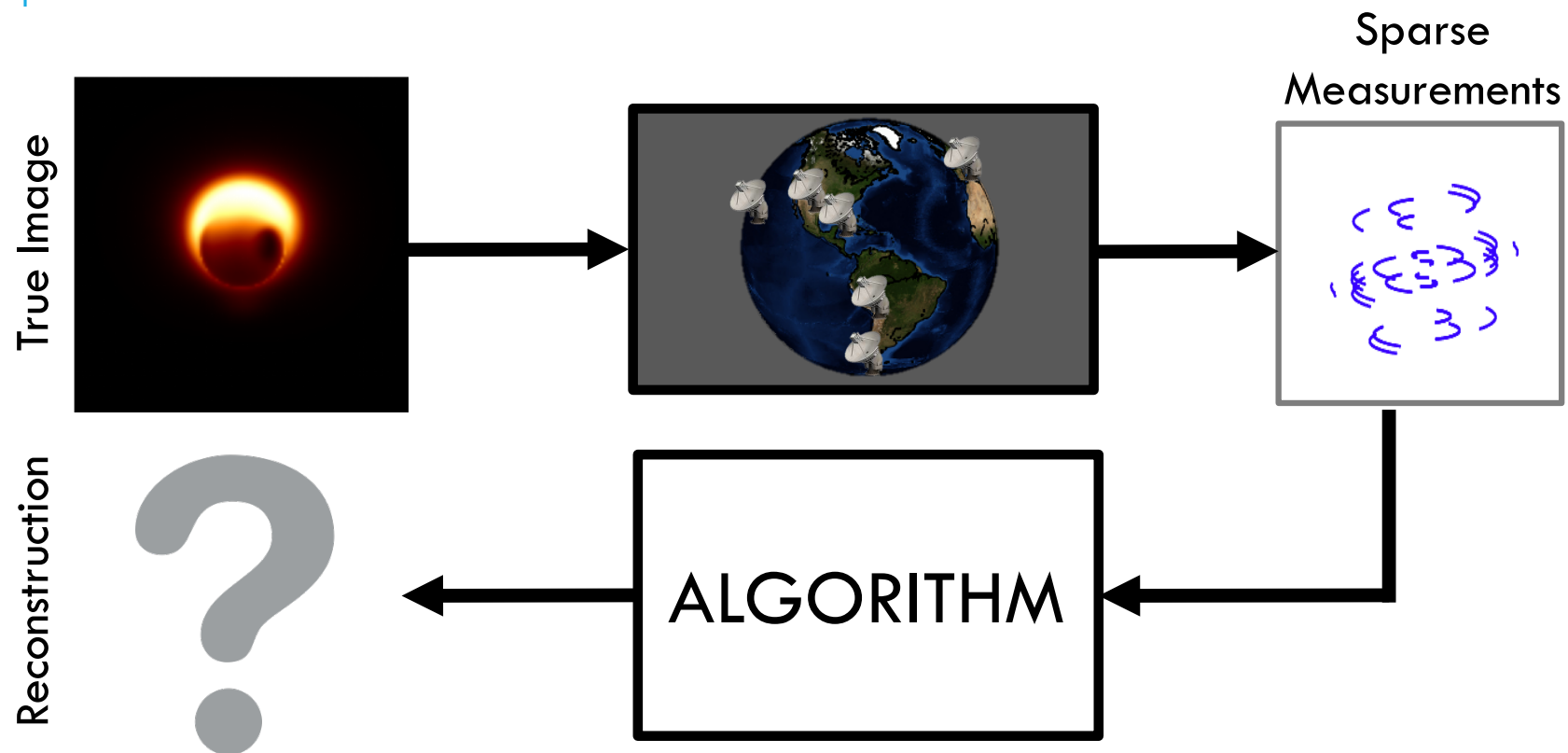
The Event Horizon Telescope (EHT)



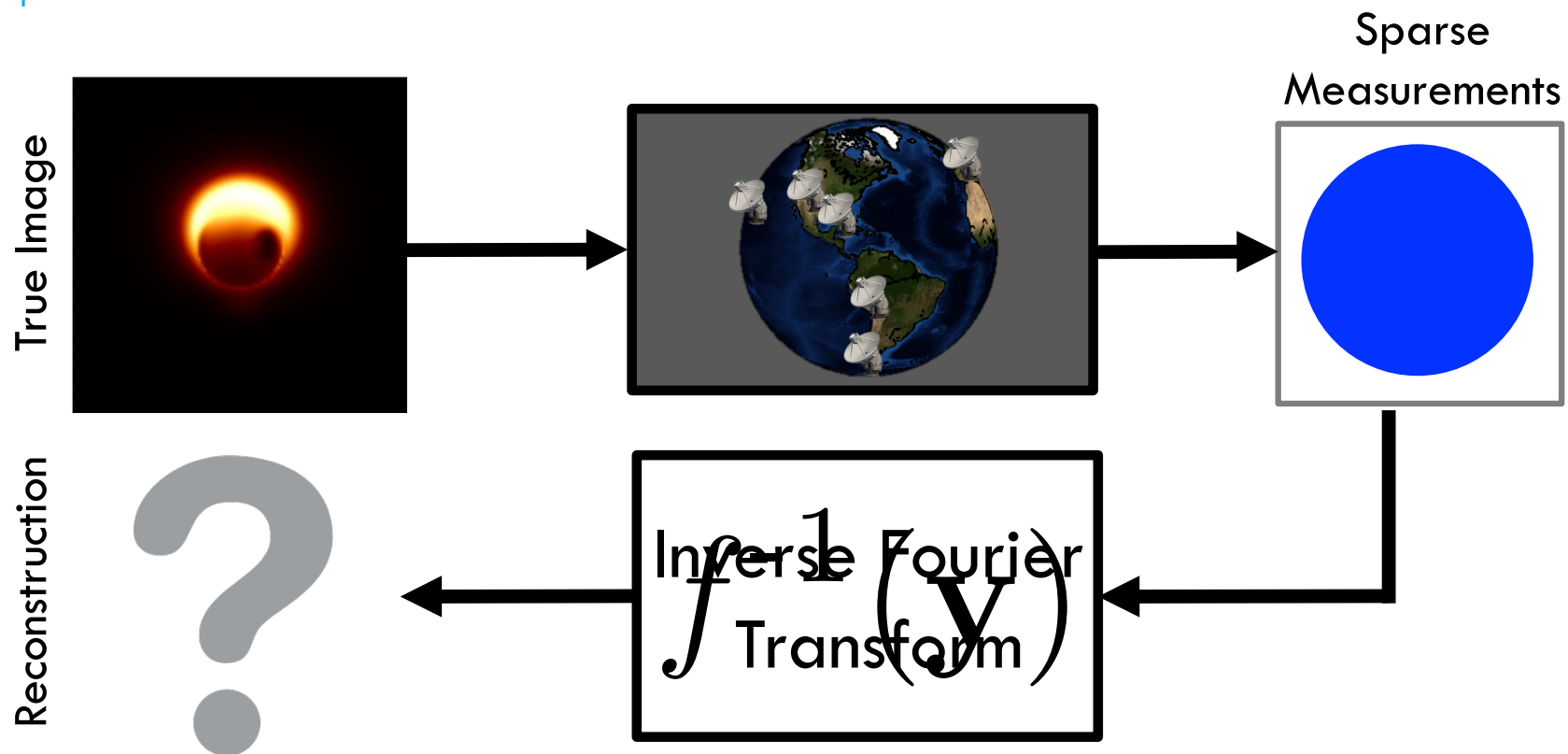
Frequency Measurements



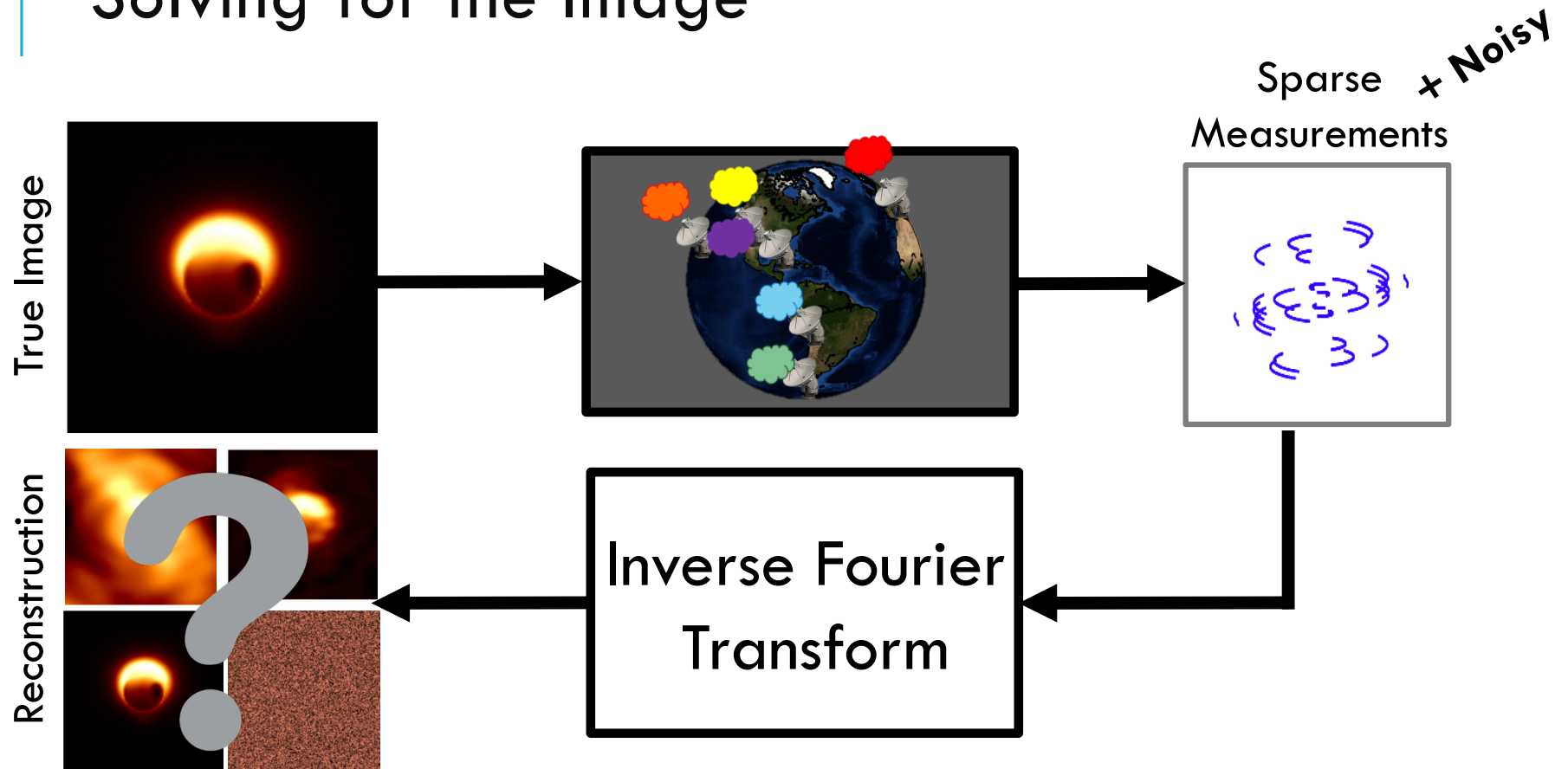
Solving for the Image



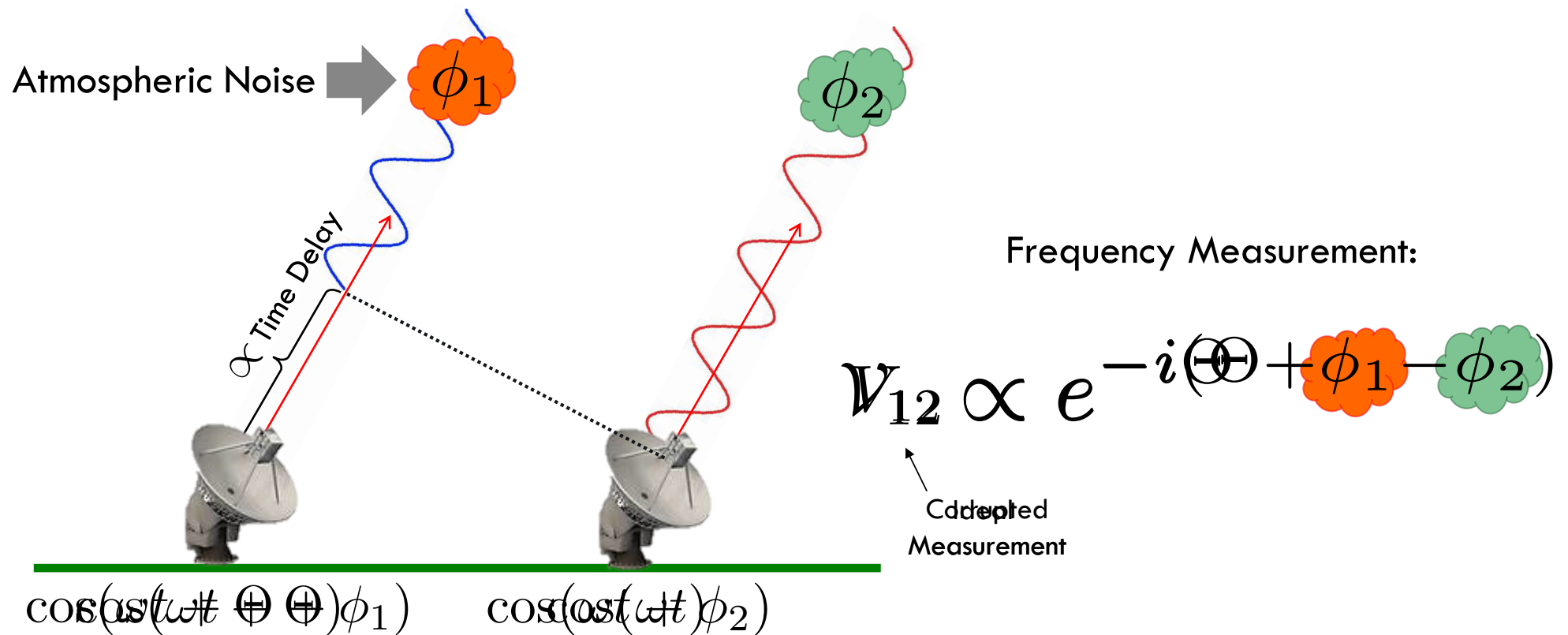
Solving for the Image



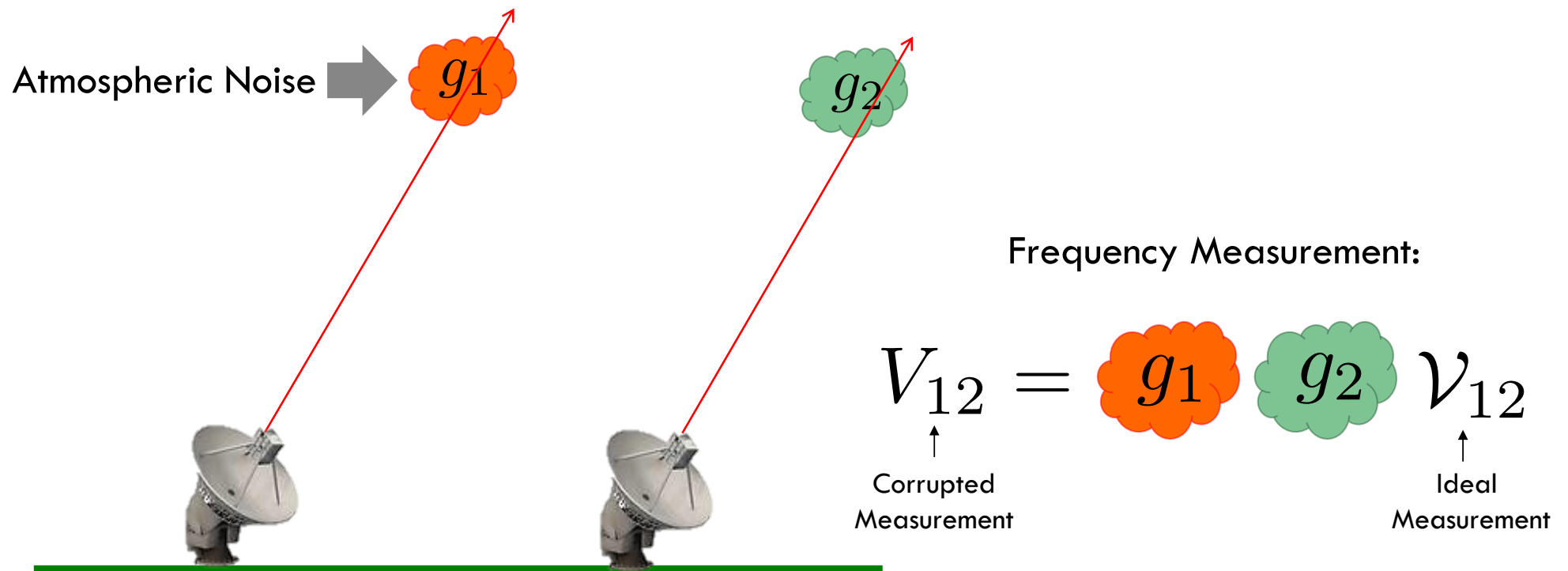
Solving for the Image



Atmospheric Error: Unknown Phase



Atmospheric Error: Amplitude Attenuation



Phase & Amplitude Error

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

Phase & Amplitude Error

Measured

$V_{\cancel{1}2}_3$

Ideal

$\mathcal{V}_{\cancel{1}2}_3$

$$V_{\cancel{1}2}_3 = \underbrace{g_{\cancel{1}3} g_2}_{\text{Amplitude Errors}} e^{-i(\underbrace{\phi_{\cancel{1}3} - \phi_2}_{\text{Phase Error}})}$$

Amplitude Errors

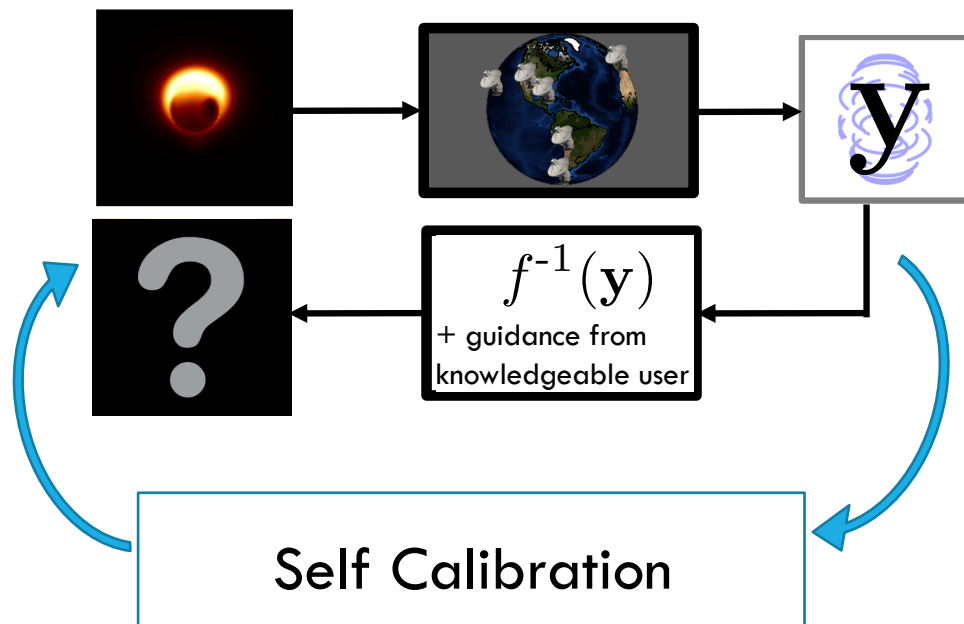
Phase Error

Two Classes of Imaging Algorithms

Inverse Modeling
(CLEAN + Self-Calibration)

Forward Modeling
(Regularized Maximum Likelihood)

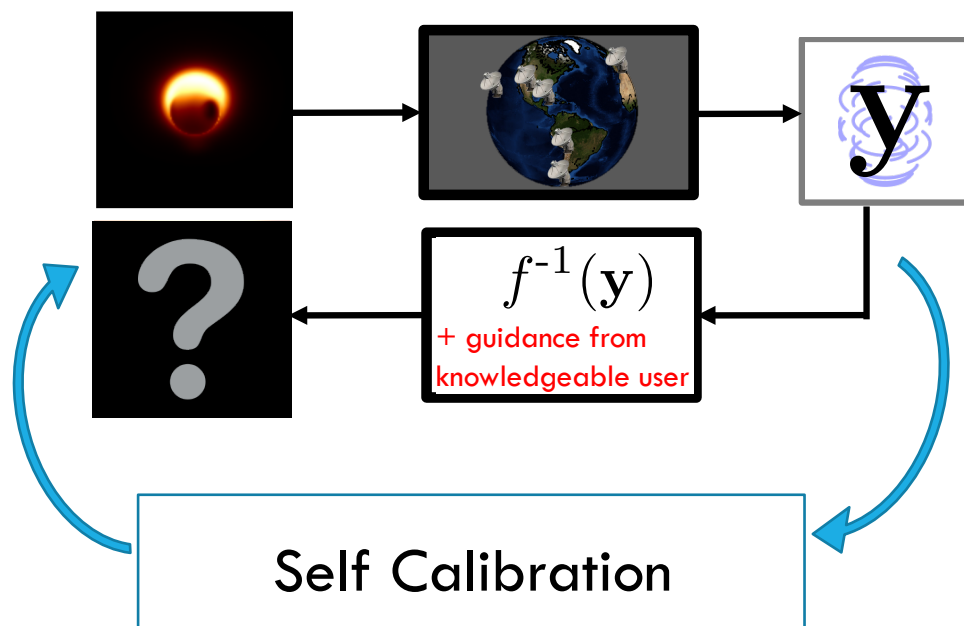
Two Classes of Imaging Algorithms



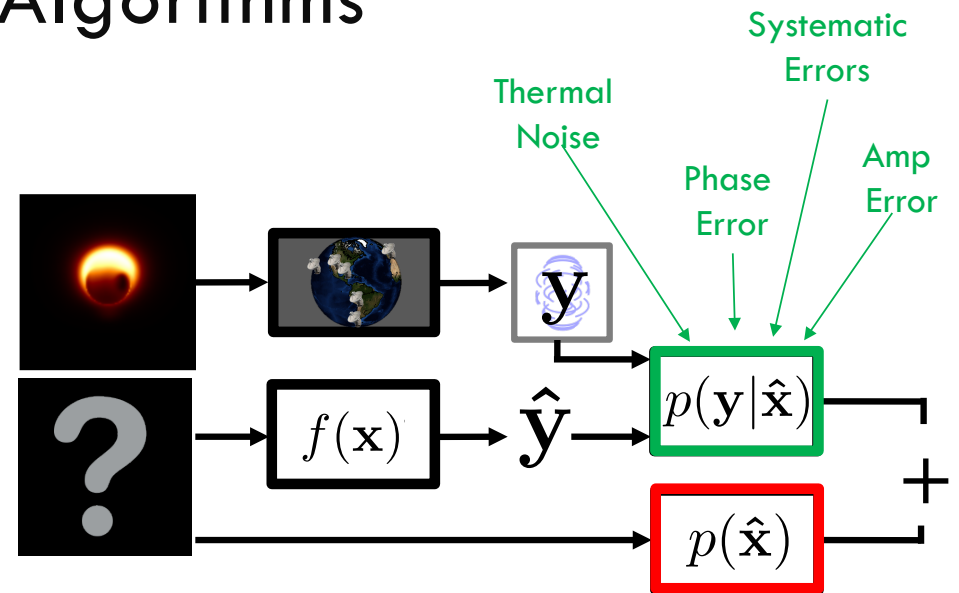
Standard Inverse Modeling
(CLEAN + Self-Calibration)

Forward Modeling
(Regularized Maximum Likelihood)

Two Classes of Imaging Algorithms



Standard Inverse Modeling
(CLEAN + Self-Calibration)



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

Forward Modeling
(Regularized Maximum Likelihood)

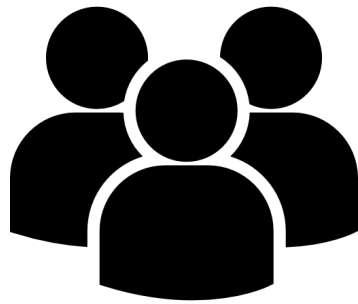
How do we verify what we are
reconstructing is real?

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

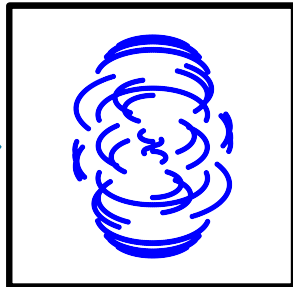
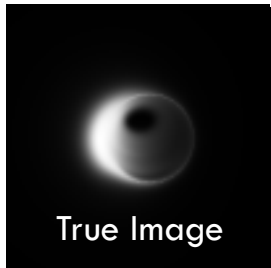
1. Synthetic Data Tests
2. Blind Imaging of M87 Data
3. Objectively Choosing Imaging Parameters
4. Validation of Images

Step 1: Synthetic Data Tests

Event Horizon Telescope Imaging Challenges



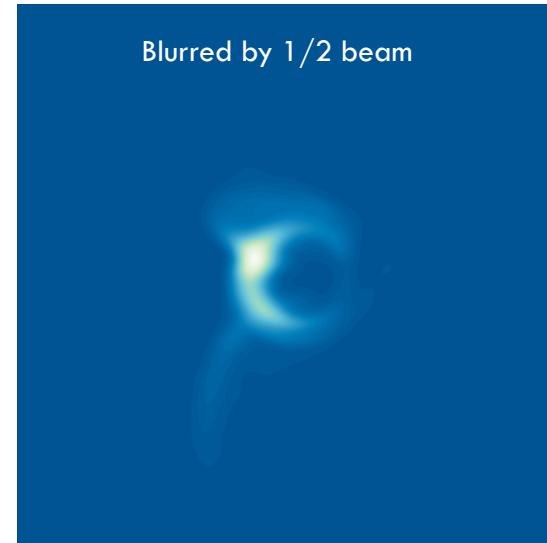
Measurements



1) Generate Measurements

2) Make Images

3) Evaluate Quality



Method 1



Method 2



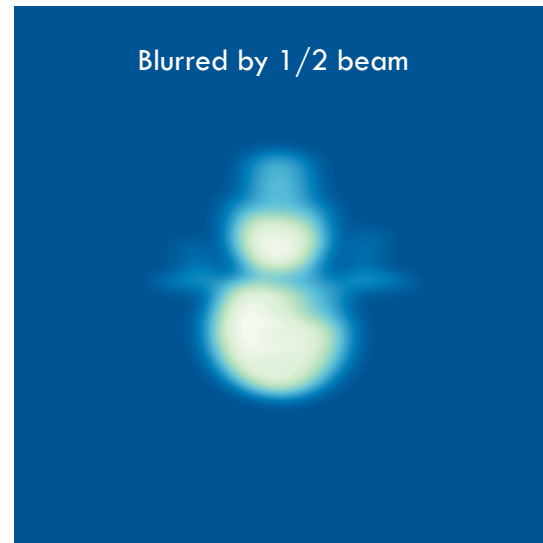
Method 3



Method 4



Method 5



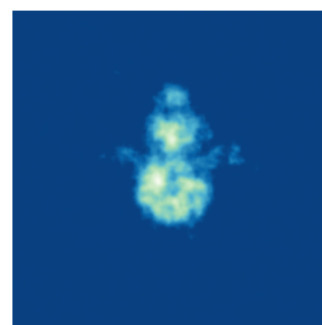
Method 1



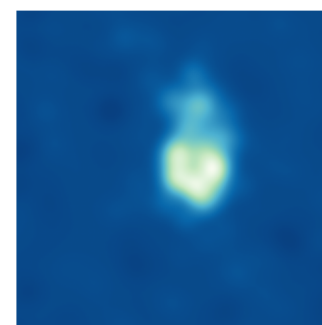
Method 2



Method 3



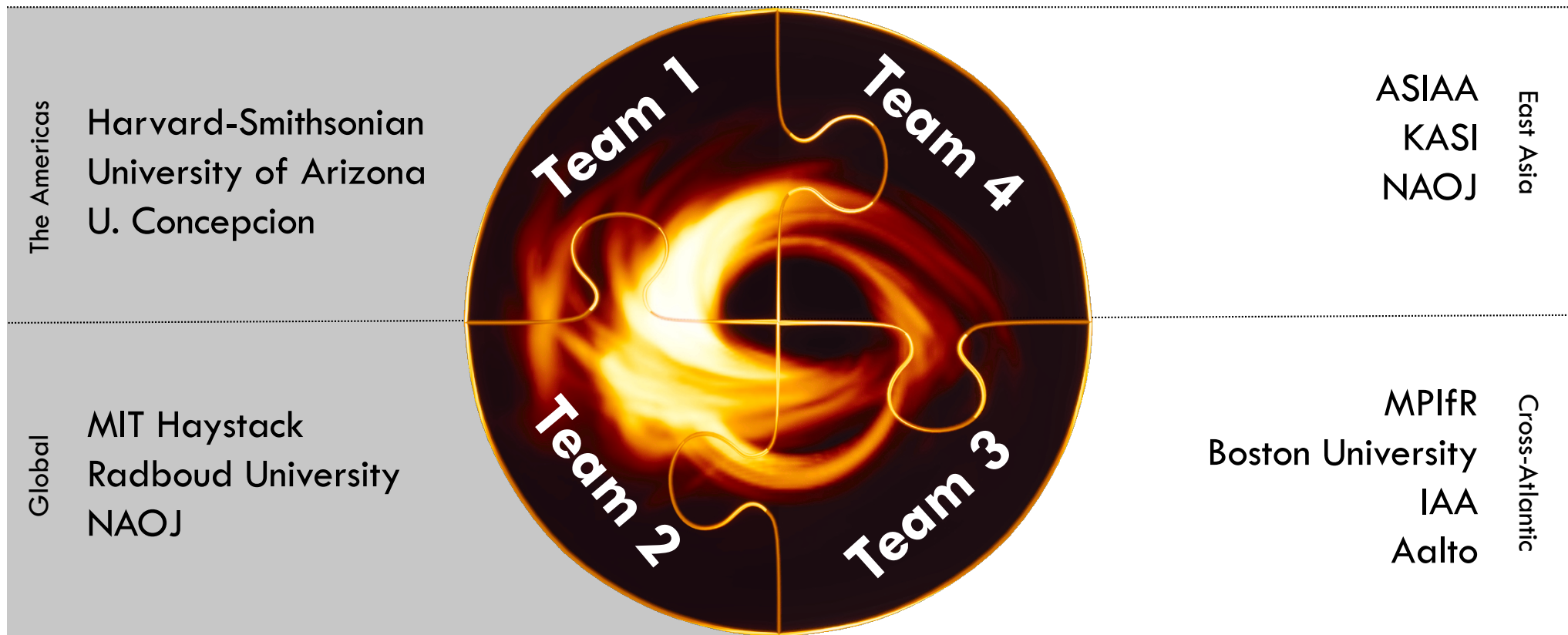
Method 4



Method 5

Step 2: Blind Imaging of M87 Data

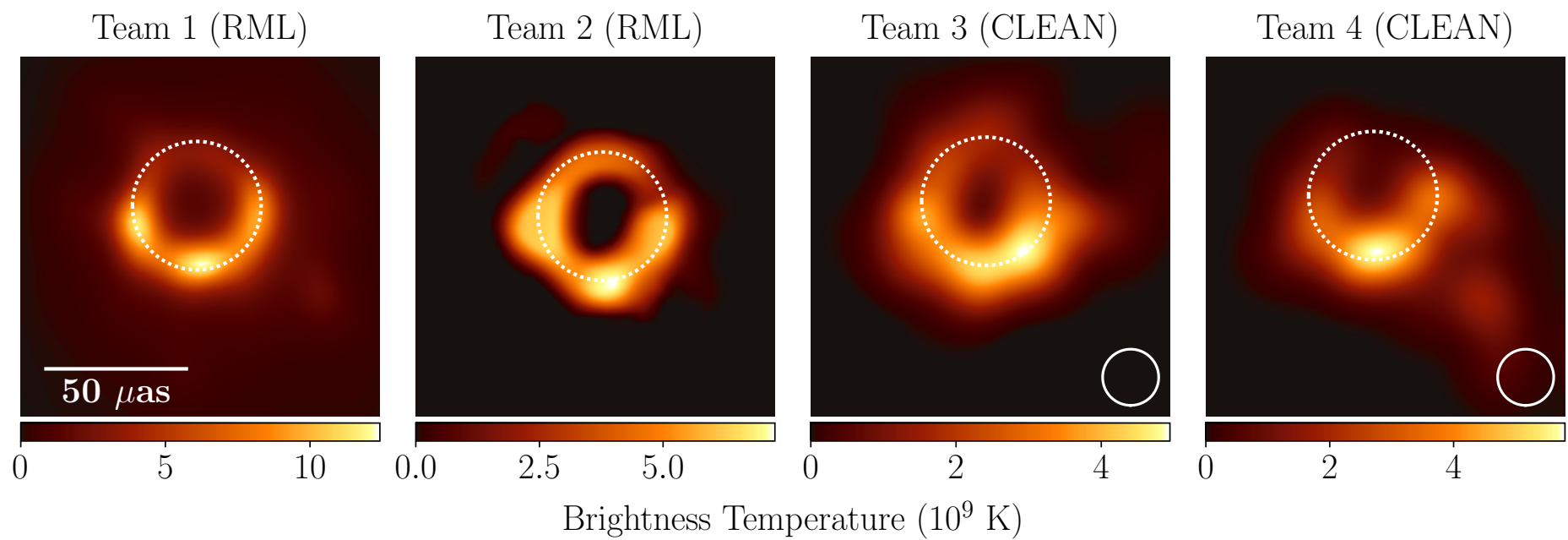
Step 2: Blind Imaging

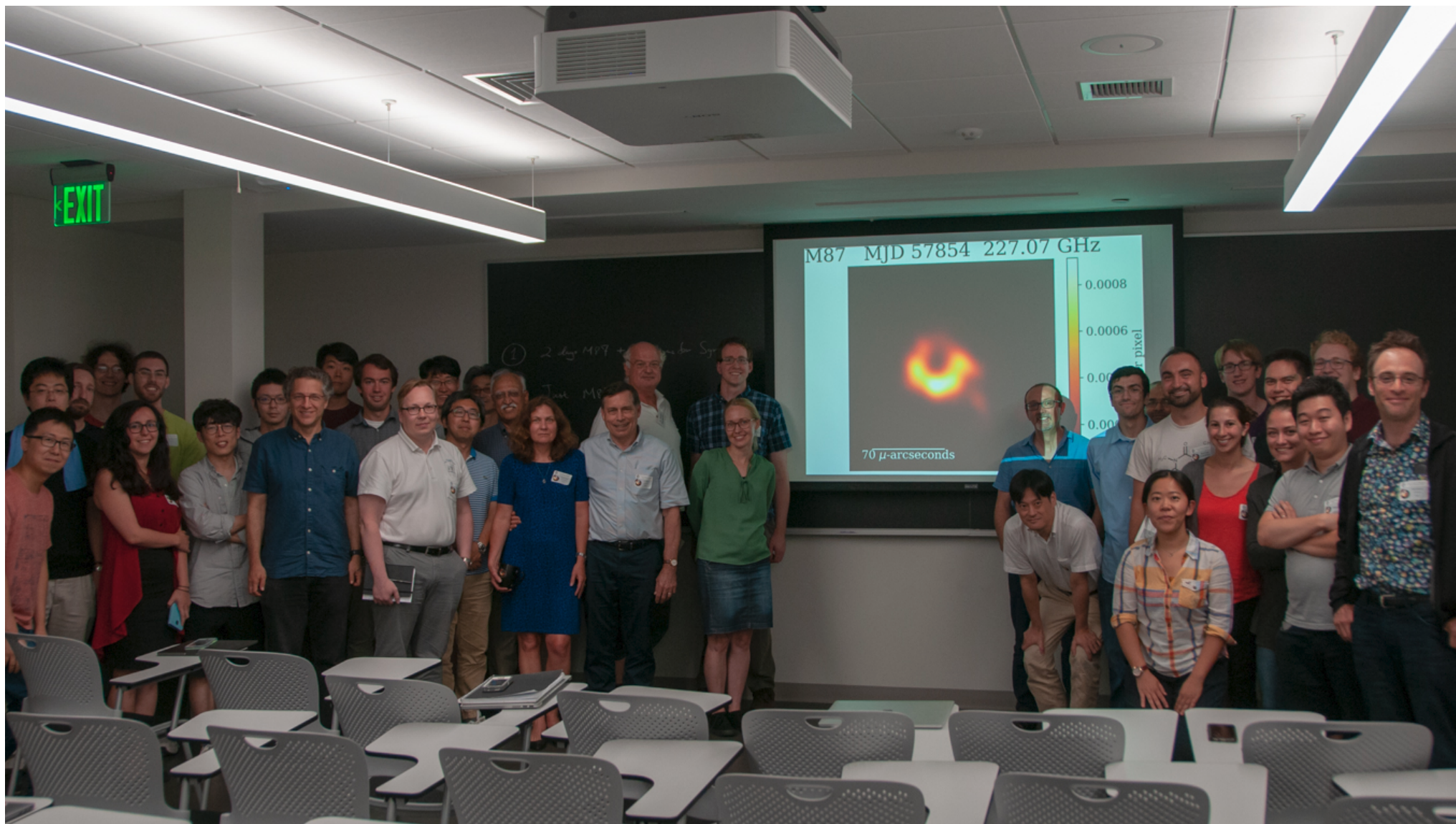


7 weeks later...



Step 2: Blind Imaging





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)

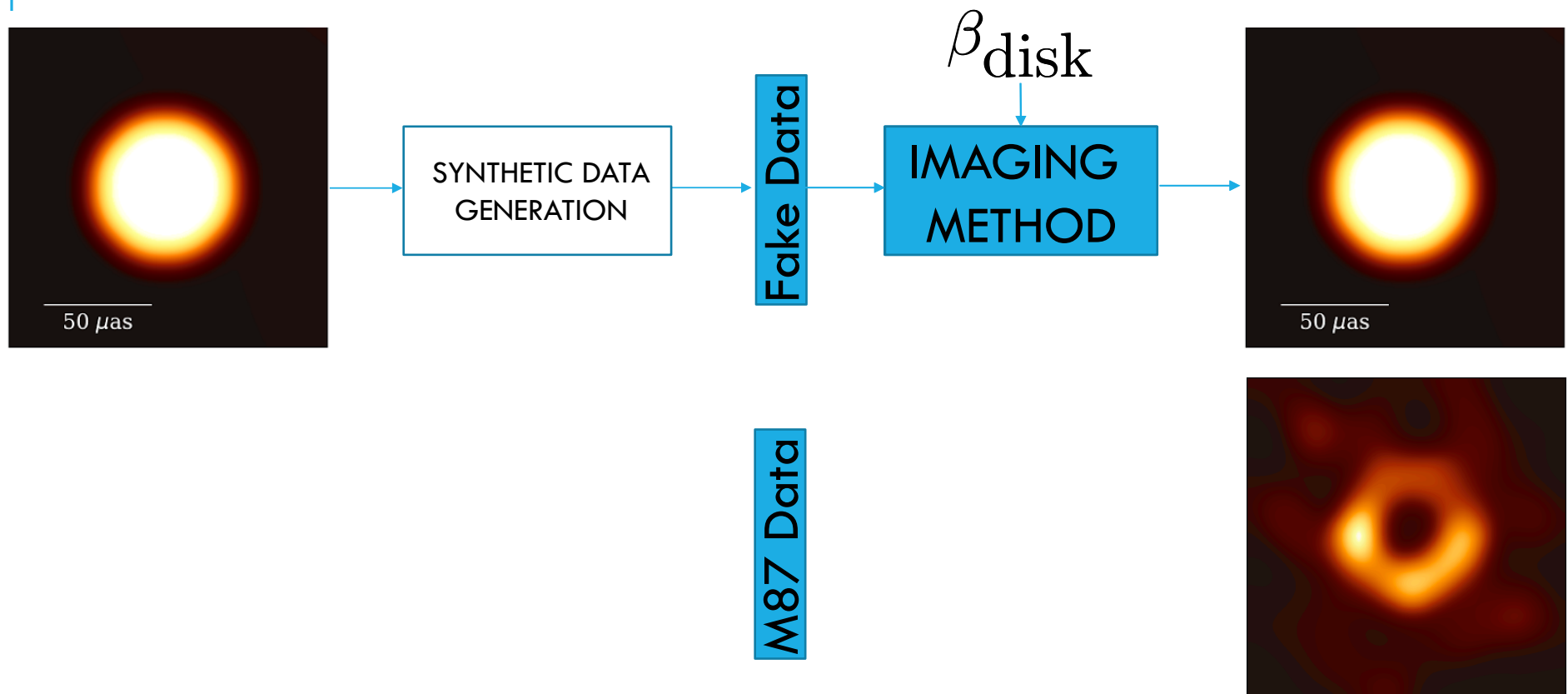
Compact Flux
Initial Gaussian Size
Systematic Error
Regularizes
MEM
TV
TSV
L1

SMILI

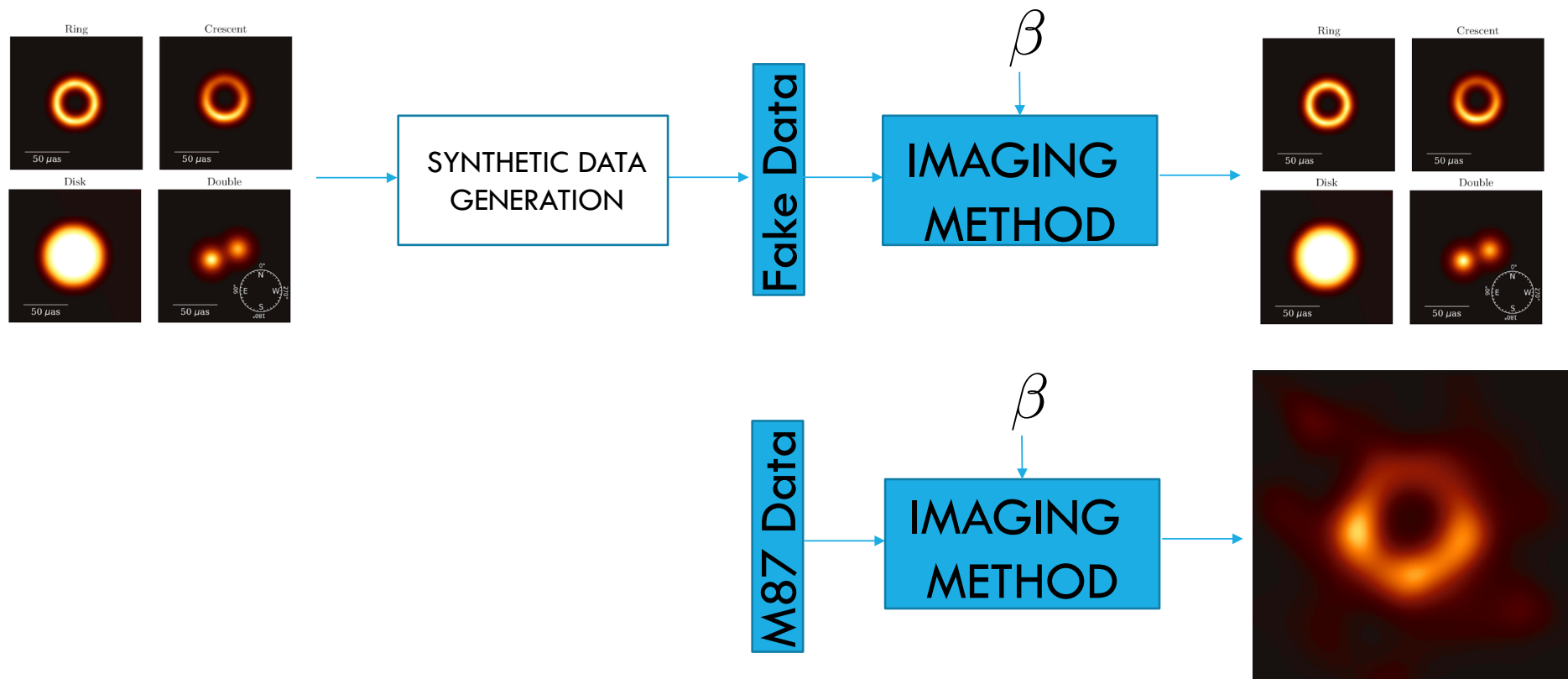
(Regularized Max Likelihood)

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

Step 3: Training on a Disk



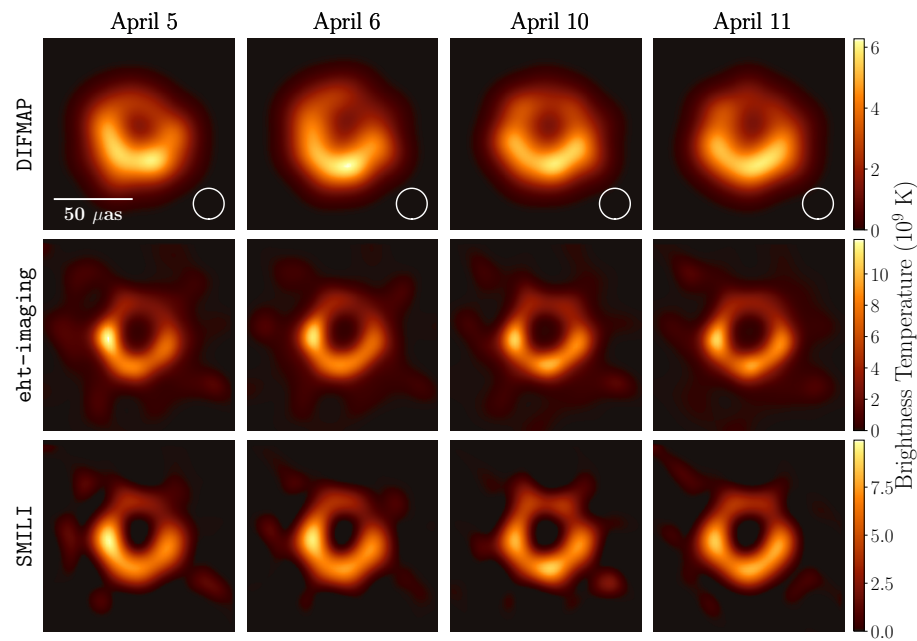
Step 3: Training on Full Set



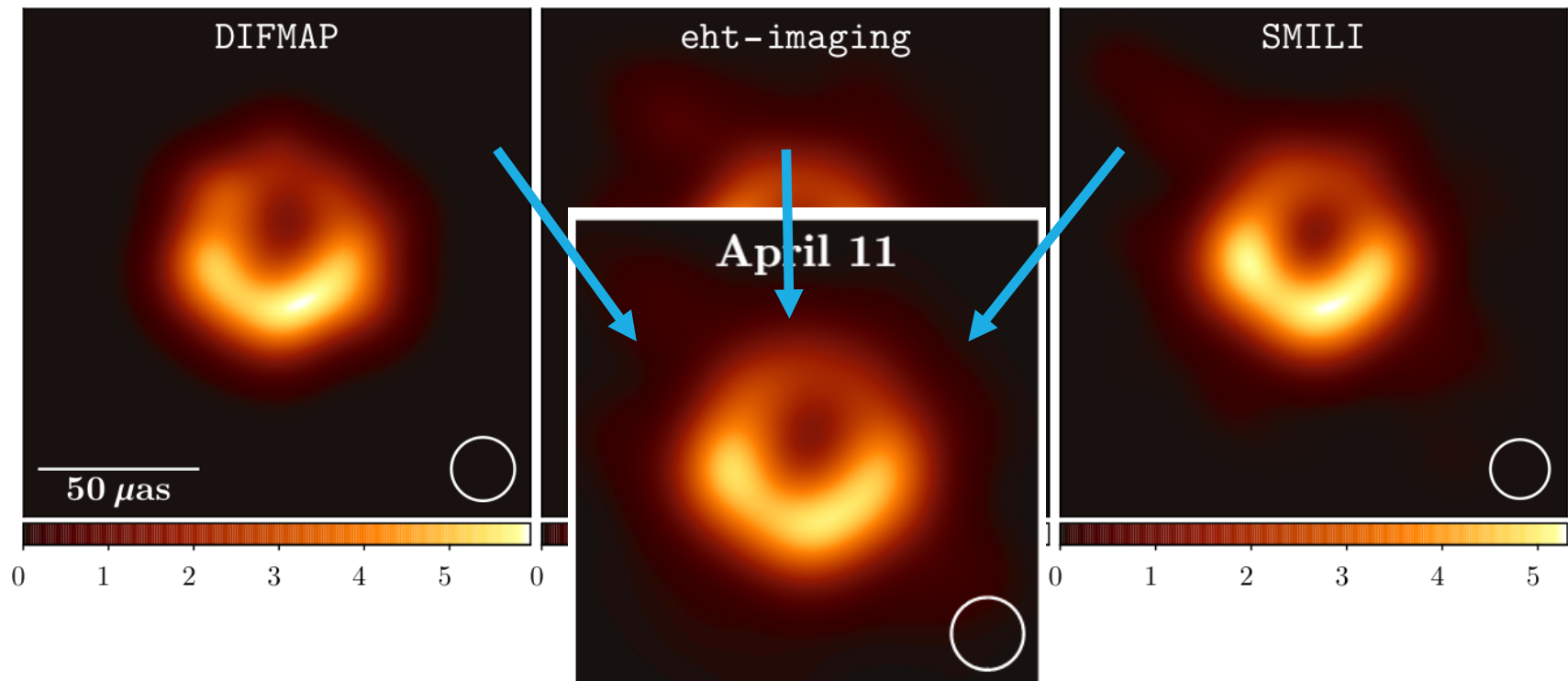
Step 3: Different Days and Imaging Pipelines

Observing Day

Imaging Pipeline



Step 3: Blurred to Equivalent Resolution



Publically Available Code and Datasets

<https://eventhorizontelescope.org/for-astronomers/data>



Event Horizon Telescope

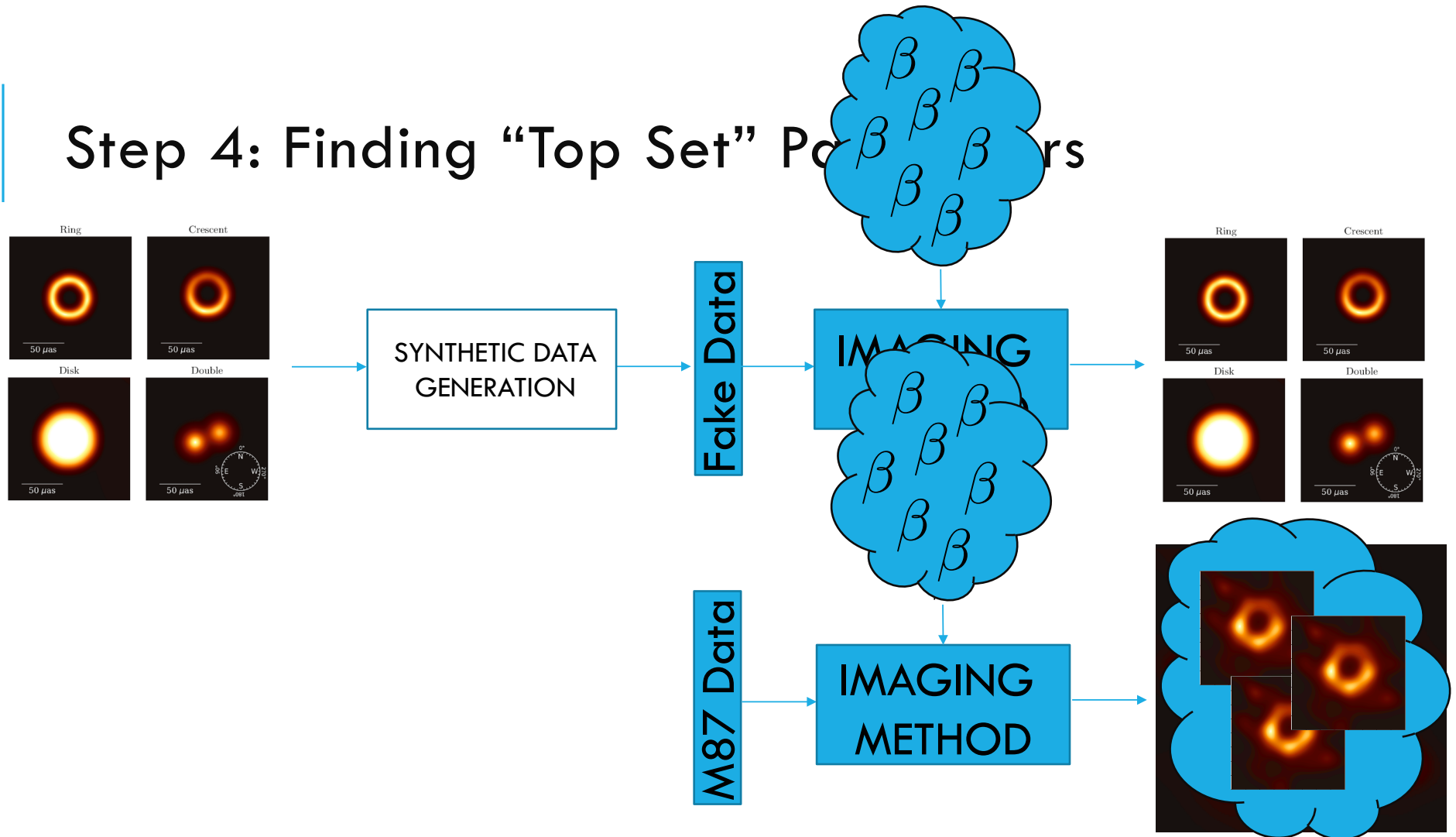
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EHT Data Products

EHT Data Product Code	Title	Author(s)	Last Updated	DOI	Reference
2019-D01-01	First M87 EHT Results: Calibrated Data	The EHT Collaboration et al.	10 Apr 2019	https://doi.org/10.25739/g85n-f134	EHT Collaboration et al. (2019c), M87 Paper III
2019-D01-02	First M87 EHT Results: Imaging Pipelines	The EHT Collaboration et al.	24 Apr 2019	https://github.com/eventhorizontelescope/2019-D01-02	EHT Collaboration et al. (2019d), M87 Paper IV

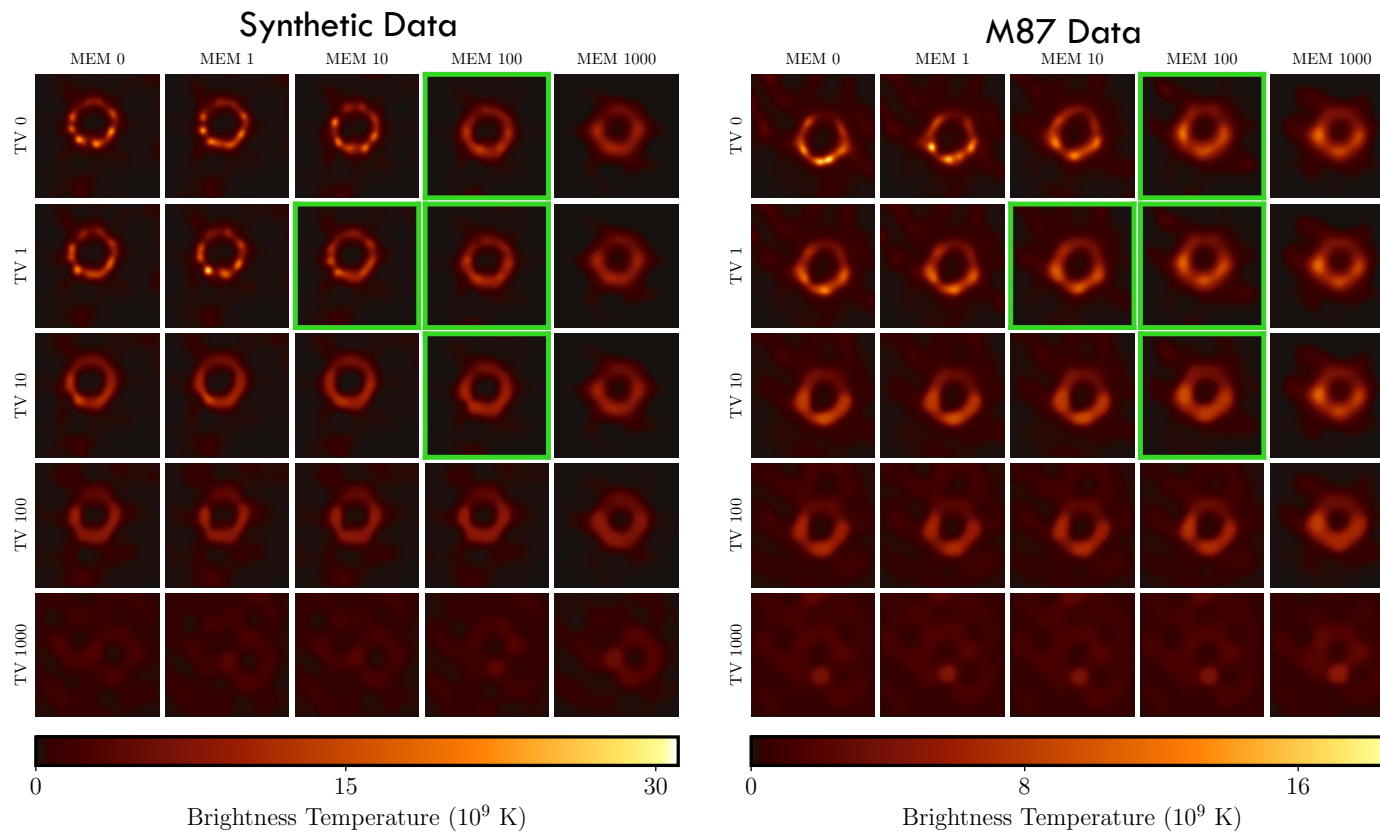
Step 4: Validation

Step 4: Finding “Top Set” Parameters

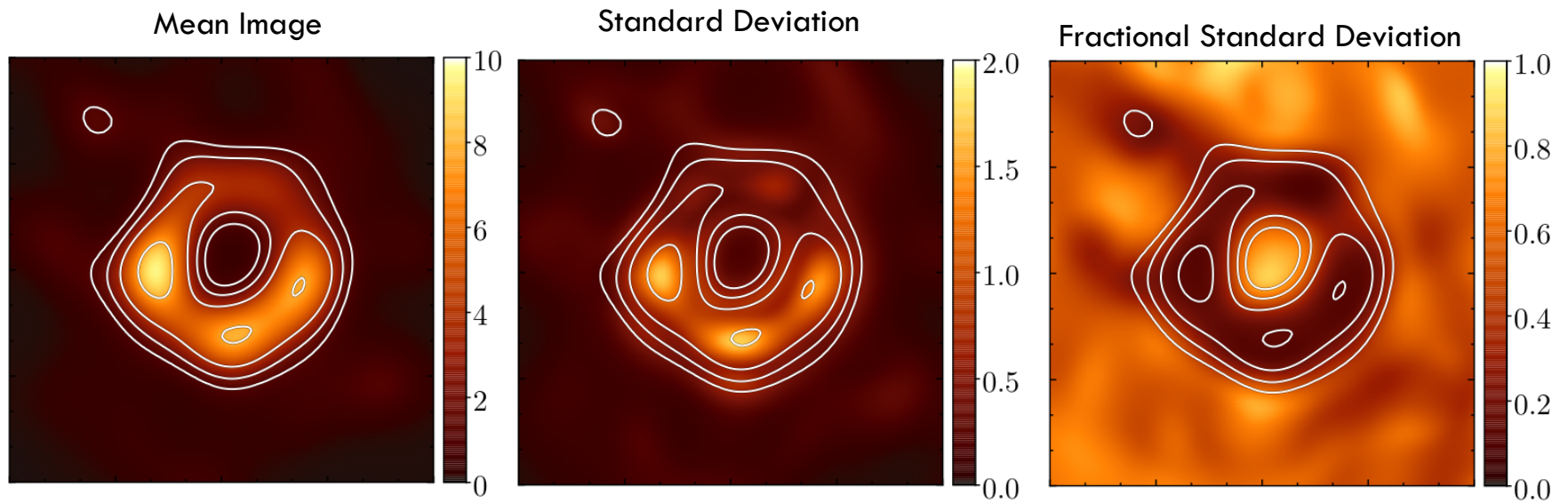


Step 4: eht-imaging Parameter Slice

Top Set
Parameters

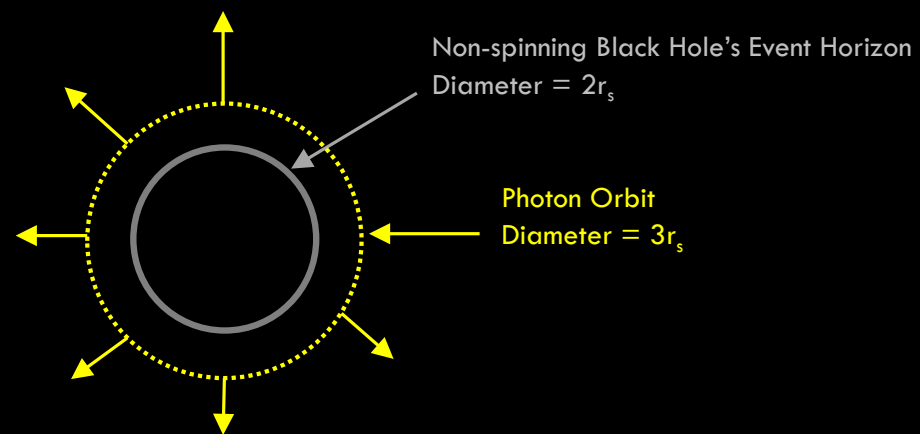


Step 4: Variance Over the Top Set

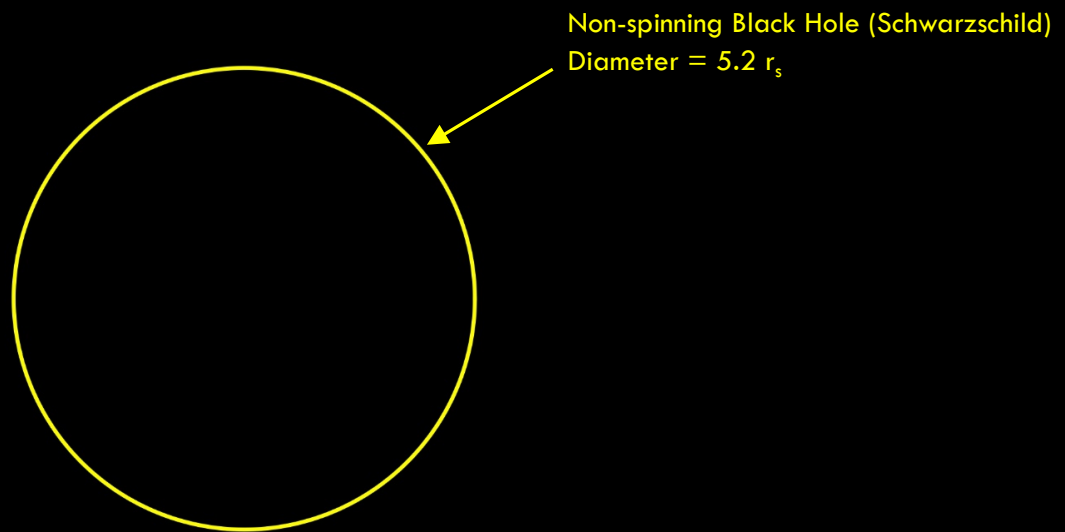


Did We Prove Einstein Was Right?

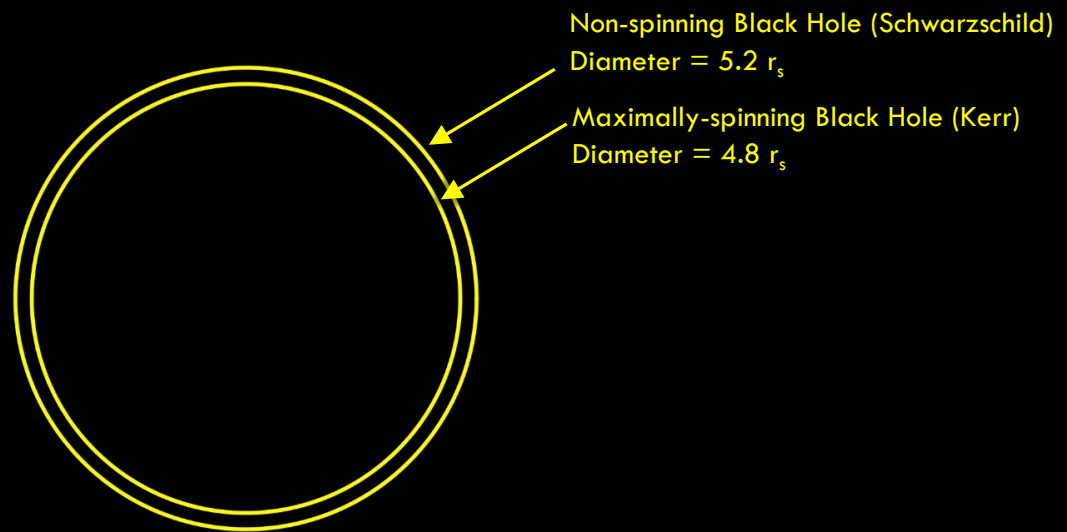
Short answer: No, but we didn't prove he was wrong



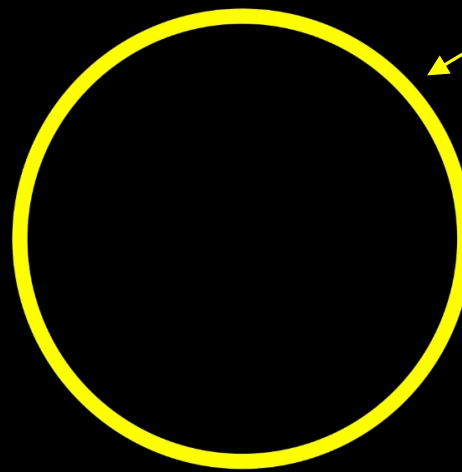
Schwarzschild Radius: $r_s = \frac{2GM}{c^2}$



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



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



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

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

M87 Mass from Gas Dynamics

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

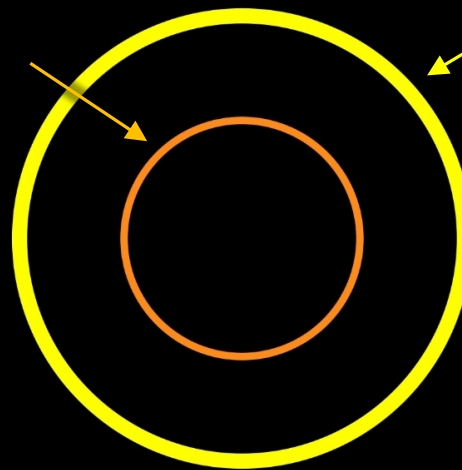
[Walsh et al 2013]

M87 Mass from Stellar Dynamics

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

[Gebhardt et al 2011]

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



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

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

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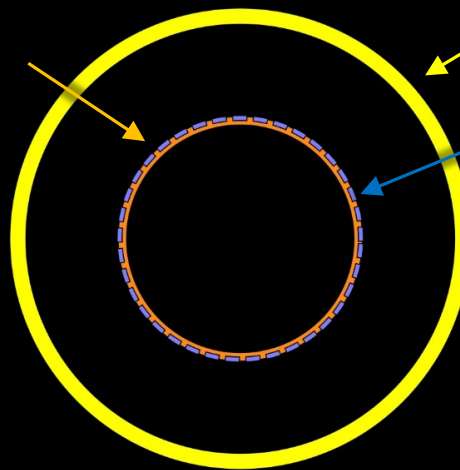
M87 Mass from Stellar Dynamics

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

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



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

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M87 Mass from Stellar Dynamics

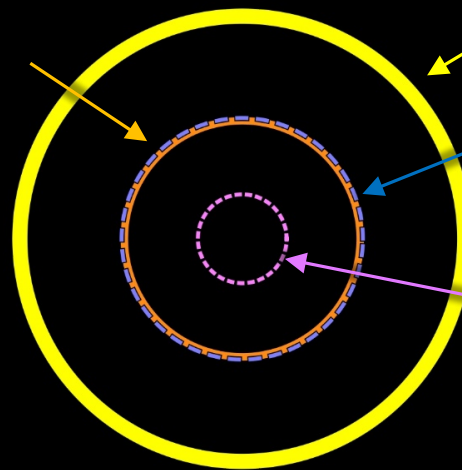
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Diameter = (4.8 – 5.2) r_s

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

Wormhole
Diameter = 2.7 r_s

Naked Singularity (Super-spinning)
Diameter = r_s



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



M87 Mass from Gas Dynamics

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

M87 Mass from Stellar Dynamics

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

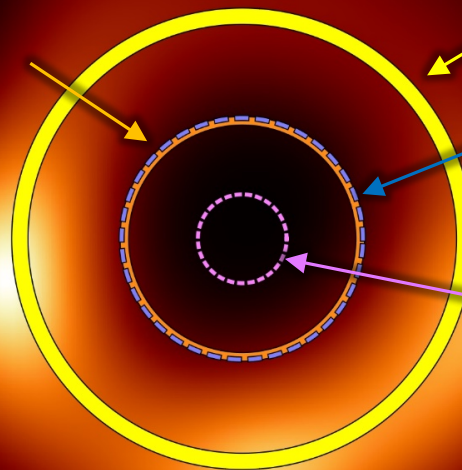


Spinning Black Hole (Kerr)

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

Spinning Black Hole (Kerr)

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



Wormhole

$$\text{Diameter} = 2.7 r_s$$



Naked Singularity (Super-spinning)

$$\text{Diameter} = r_s$$



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



Event Horizon Telescope





The Event Horizon Telescope Collaboration

Publically Available Code and Datasets

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Event Horizon Telescope

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Publically Available Code and Datasets

<https://eventhorizontelescope.org/for-astronomers/data>

eventhorizontelescope / 2019-D01-02

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1 branch

0 releases

0 contributors

Branch: master

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The Event Horizon Telescope Collaboration Bug fix: remove unspecified option

Latest commit 587c5d6 on Sep 14

difmap

2019-D01-02: First M87 EHT Results: Imaging Pipelines

6 months ago

eht-imaging

Bug fix: remove unspecified option

last month

smili

2019-D01-02: First M87 EHT Results: Imaging Pipelines

6 months ago

README.md

2019-D01-02: First M87 EHT Results: Imaging Pipelines

6 months ago

run.sh

2019-D01-02: First M87 EHT Results: Imaging Pipelines

6 months ago

README.md

First M87 EHT Results: Imaging Pipelines

Authors: The Event Horizon Telescope Collaboration et al.

achael/eht-imaging h5py/h5py PythonCharmers/python-future networkx/networkx **scipy** scikit-image/scikit-image jek/blinker
brandon-rhodes/pyepem kennethreitz/requests codecov/codecov-python urllib3/urllib3 micheles/decorator **pandas** pandas/pandas
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html5lib/html5lib-python pallets/click nedbat/coveragepy pallets/jinja mwaskom/seaborn pydot/pydot pytest-dev/pytest-mock

Analysis Courtesy of GitHub

22,953

Community Contributors

achael/eht-imaging h5py/h5py PythonCharmers/python-future networkx/networkx scipy/scipy scikit-image/scikit-image jek/blinker
brandon-rhodes/pyepem kennethreitz/requests codecov/codecov-python urllib3/urllib3 micheles/decorator pandas-dev/pandas
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adamchainz/flake8-comprehensions MobileDynasty/pytest-env brettcannon/importlib python-pillow/Pillow kjd/idna tornadoweb/tornado
python-babel/babel pallets/itsdangerous kataev/flake8-rst PyCQA/mccabe matthew-brett/texext joshspeagle/dynesty nose-devs/nose
mdsitton/configparser-3.2.0r3 lxml/lxml HypothesisWorks/hypothesis getsentry/raven-python calvinchengx/python-mock sphinx-gallery/sphinx-
gallery spyder-ide/qtpy gitpython-developers/GitPython nucleic/kiwi choldgraf/sphinx-copybutton rtd/sphinx_rtd_theme
html5lib/html5lib-python pallets/click nedbat/coveragepy pallets/jinja mwaskom/seaborn pydot/pydot pytest-dev/pytest-mock

Analysis Courtesy of GitHub



Publically Available Code and Datasets

<https://eventhorizontelescope.org/for-astronomers/data>

achael / eht-imaging

Unwatch 213 Star 5.1k Fork 452

<> Code 6 Issues Pull requests 3 Projects 0 Wiki Security Insights

Imaging, analysis, and simulation software for radio interferometry <https://achael.github.io/eht-imaging/>

1,625 commits 7 branches 6 releases 1 environment 14 contributors GPL-3.0

Branch: master New pull request Create new file Upload

achael Merge pull request #105 from gquarles/master

arrays	added requirements.txt	
data	overwrite old master	
docs	Fixes in documentation and readme	
ehtim	Remove redundant assignments	
examples	fixed obsdata.save_txt in polrep	last year
models	added rowan and howes	11 months ago
scripts	Merge pull request #91 from cclauss/patch-1	5 months ago
.gitignore	Fix file permissions	last year
.mailmap	Add a ".mailmap" file	2 years ago
Dockerfile	add dockerfile	6 months ago
LICENSE.txt	Create LICENSE	2 years ago

14 direct contributors

22,953 contributors in the [dependency graph](#)

+ 22,933