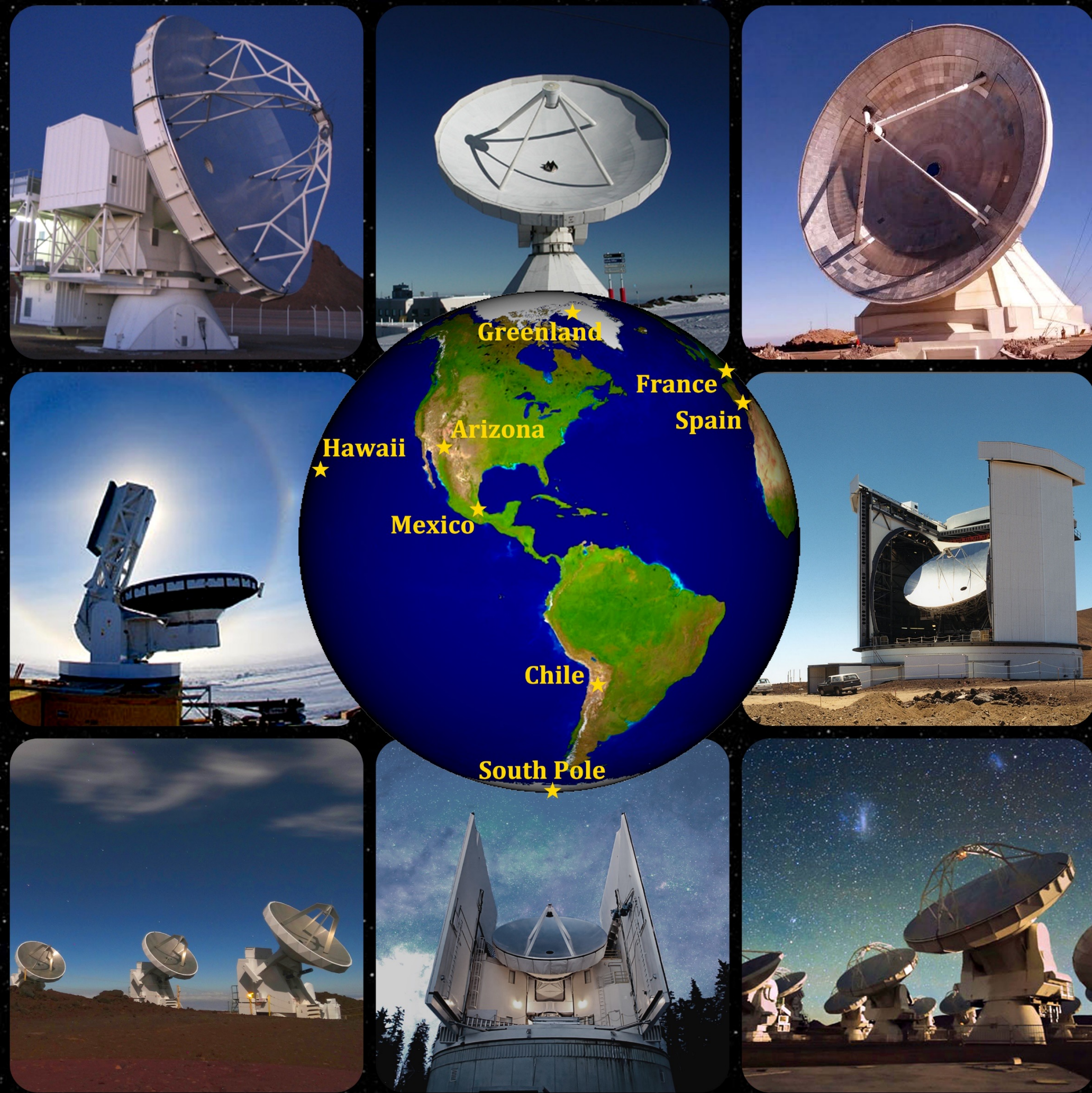




Credit: ESO

Data Science and Imaging the Black Hole Shadow

Shiro Ikeda
Inst. of Stat. Math.
EHT Collaboration



About Myself

- Mar.1996 Ph. D., Dept. of Engineering, Univ. of Tokyo
- Apr.1996 Brain Science Institute, RIKEN
- Apr.2001 Kyushu Institute of Technology
- Feb.2003~ The Institute of Statistical Mathematics
- Visiting Positions: NAOJ, IPMU Kavli Institute



shiro@ism.ac.jp

- Information Geometry
- Signal Processing
- Information Theory
- Brain Data Analysis
- Fisheries Resource
- Astronomical Data Analysis



Institute of Statistical Mathematics (ISM)

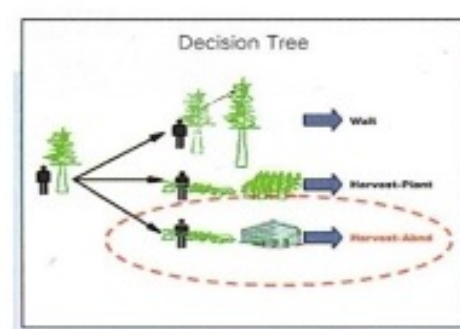
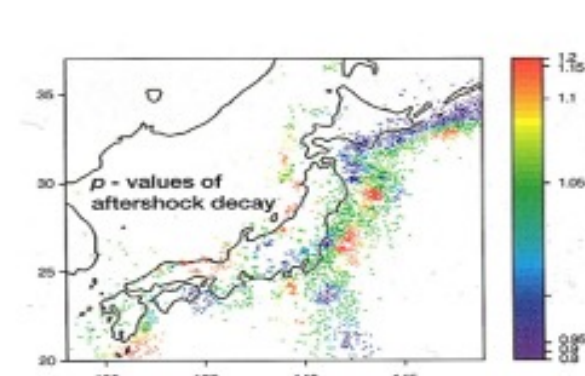
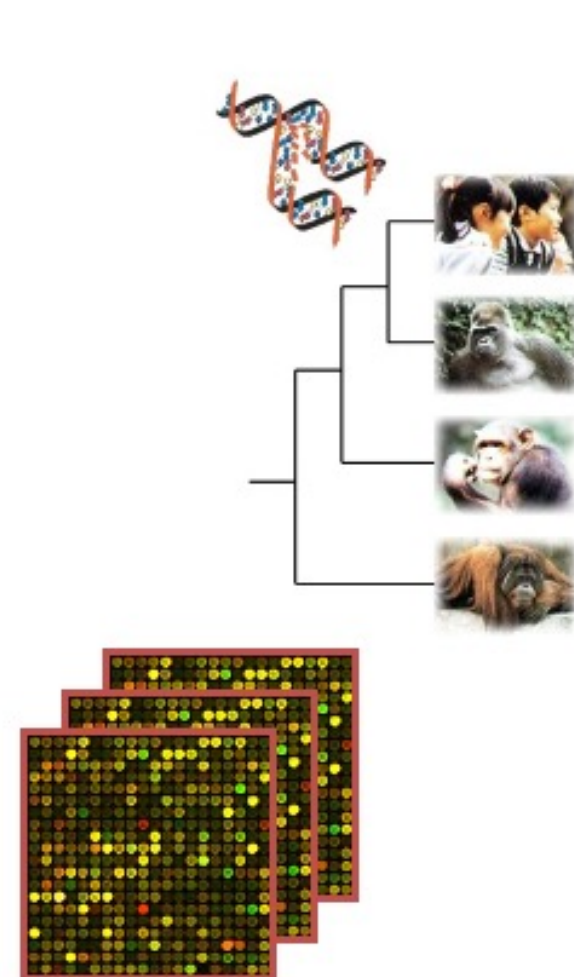
Unique institute focused on Statistical Science

- Founded in 1944
- Located in Tachikawa, Tokyo
- On of the 22 Inter-University Research Institutes
- 49 faculty, 80 visitors, 70 part-time, 29 grad. Students.

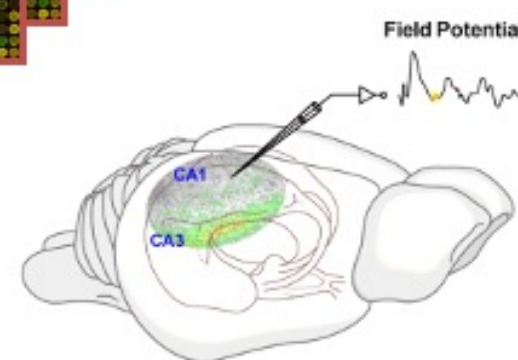
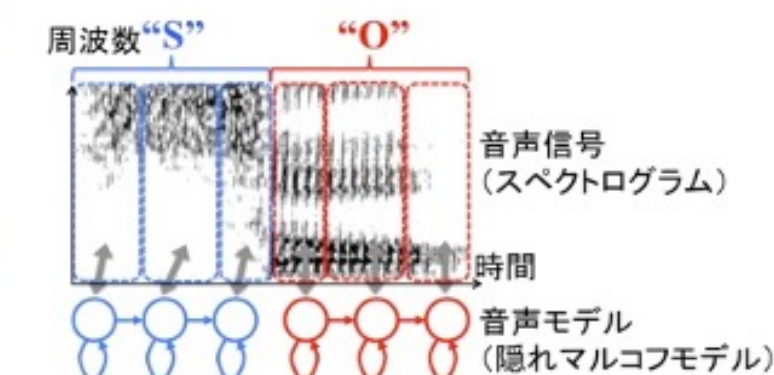
Theory and Methodology

- Information Criterion
- Time series analysis
- Survey methodology
- Quantification theory
- Multivariate analysis

- Bayesian modeling
- MCMC, particle filter
- Ensemble machine
- Sparse modeling
- Kernel method
- Meta-analysis
- Data assimilation method

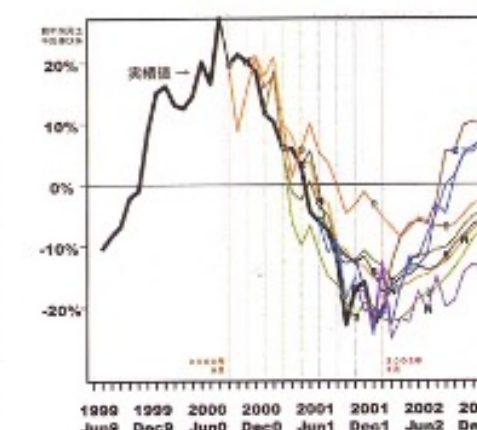
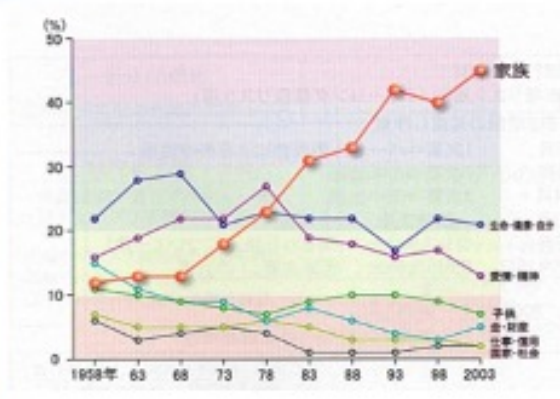
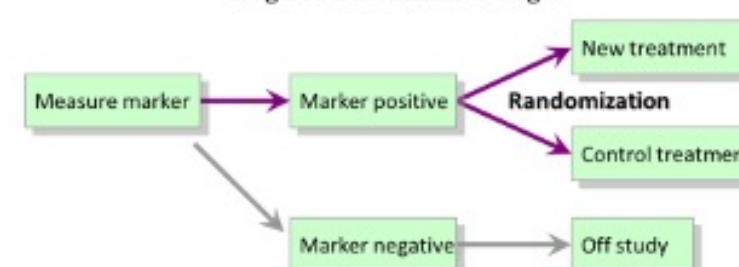


Promote the development of human resources capable of decision making based on data



ランダム化臨床試験のデザインの一例

Targeted Enrichment Design



① Introduction

② Supermassive Blackhole and Photon Ring

③ Event Horizon Telescope Collaboration

④ Radio Interferometry

⑤ M87* imaging

⑥ SgrA* imaging

⑦ Conclusion

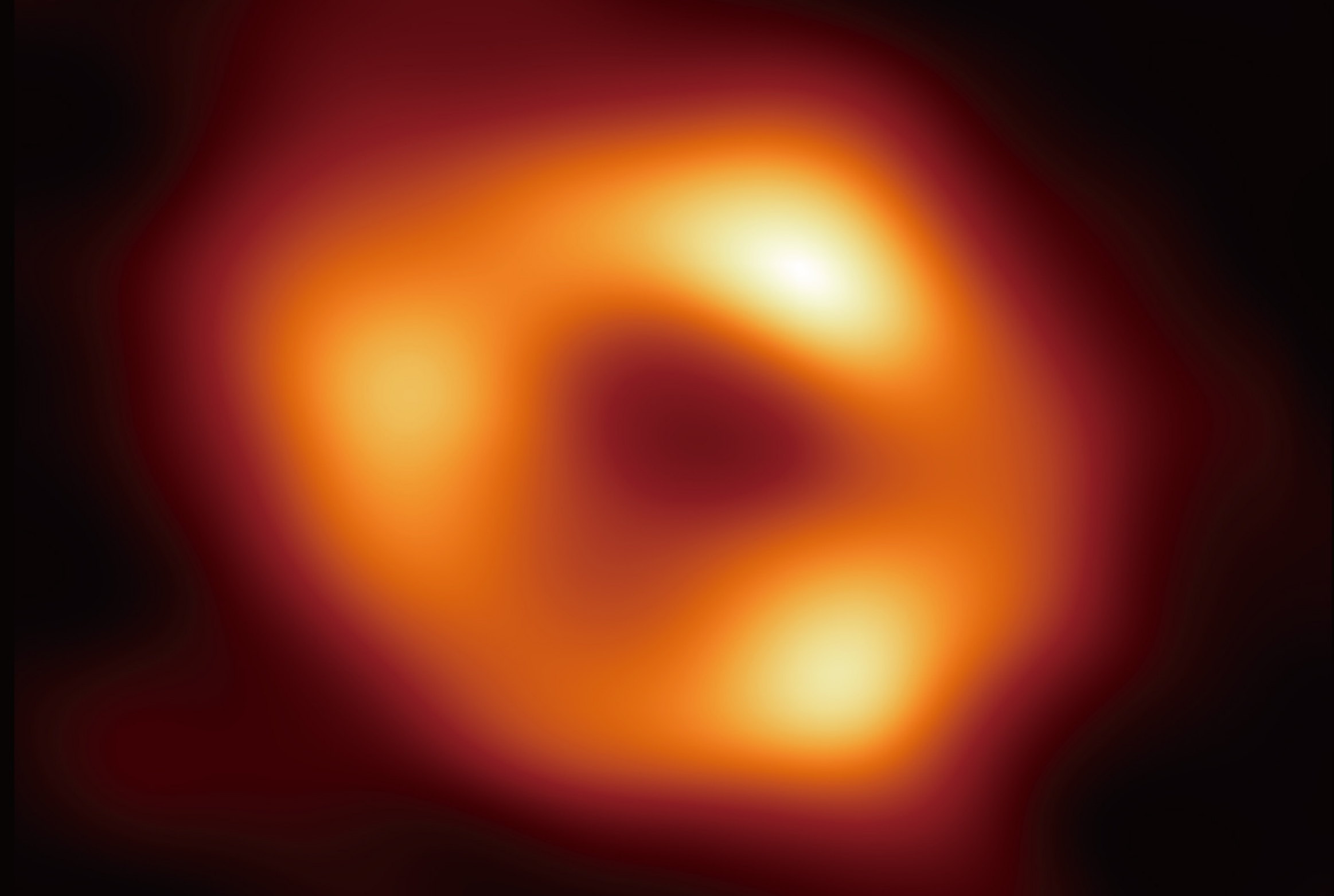
EHT observation April 2017

April 2019



M87*

May 2022



SgrA*



M87*



Credit:ESO/L.Calçada, Digitized Sky Survey 2, ESA/Hubble, RadioAstron, De Gasperin et al., Kim et al., EHT Collaboration

M87 Supermassive Blackhole



Center of M87 Galaxy

Mass : 6.5×10^9 Solar Mass

Distance : 55×10^6 Light year

Strong emission with different wavelength



Credit: H.Falcke/^{Credi: ESO, NAOJ}Radboud University/L.Krüger, EHT Collaboration
Event Horizon Telescope

13 September 2022, IAU-IAA

SgrA*



Credit: ESO/L. Calçada, N. Risinger, DSS, VISTA, VVV Survey/D. Minniti DSS, Nogueras-Lara et al., Schoedel, NACO, GRAVITY Collaboration, EHT Collaboration

Sgr A⁺ Supermassive Blackhole

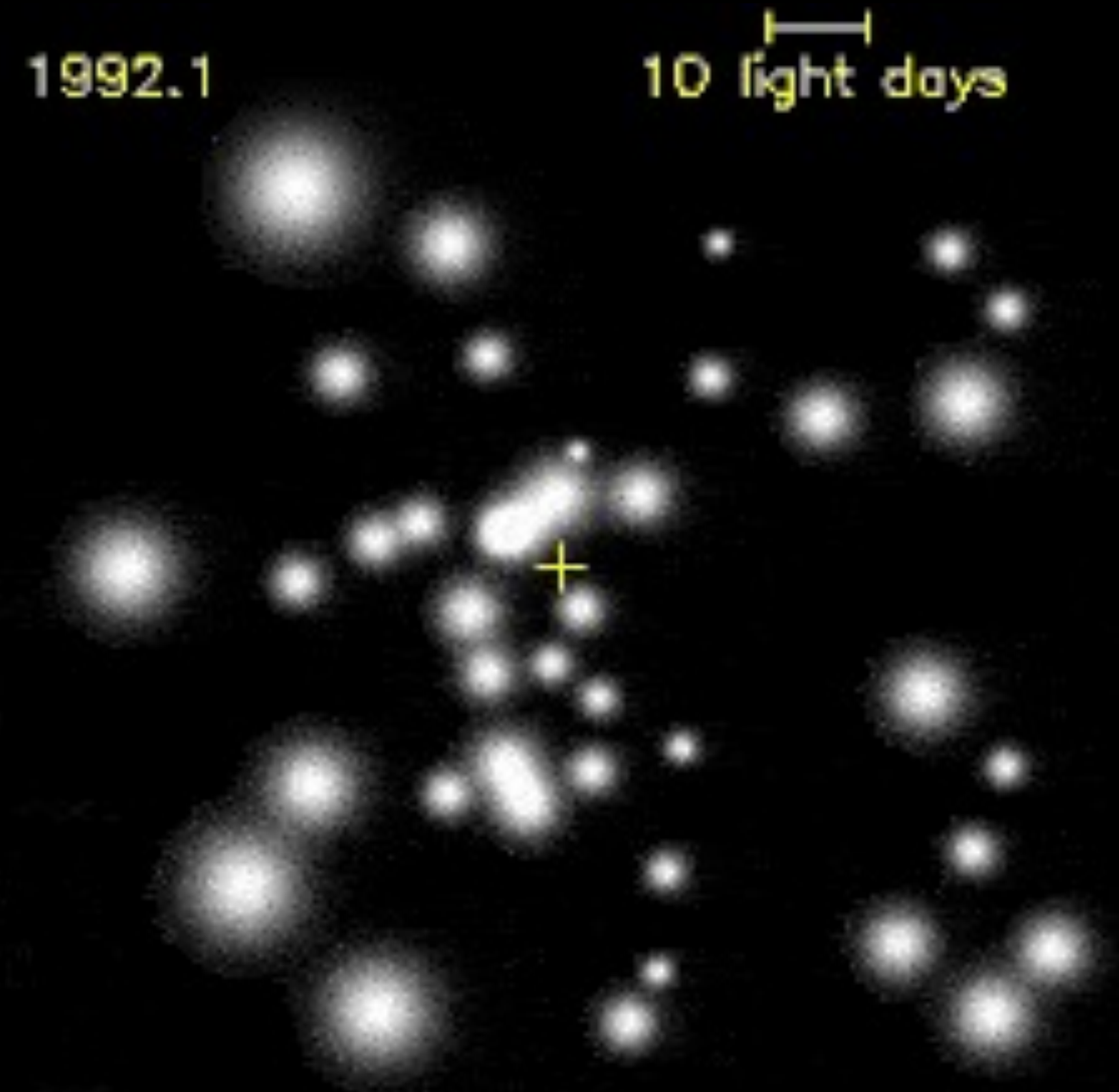
Center of Milkyway Galaxy

Mass : 4×10^6 Solar Mass

Distance : 26×10^3 light year

2020 Nobel Prize

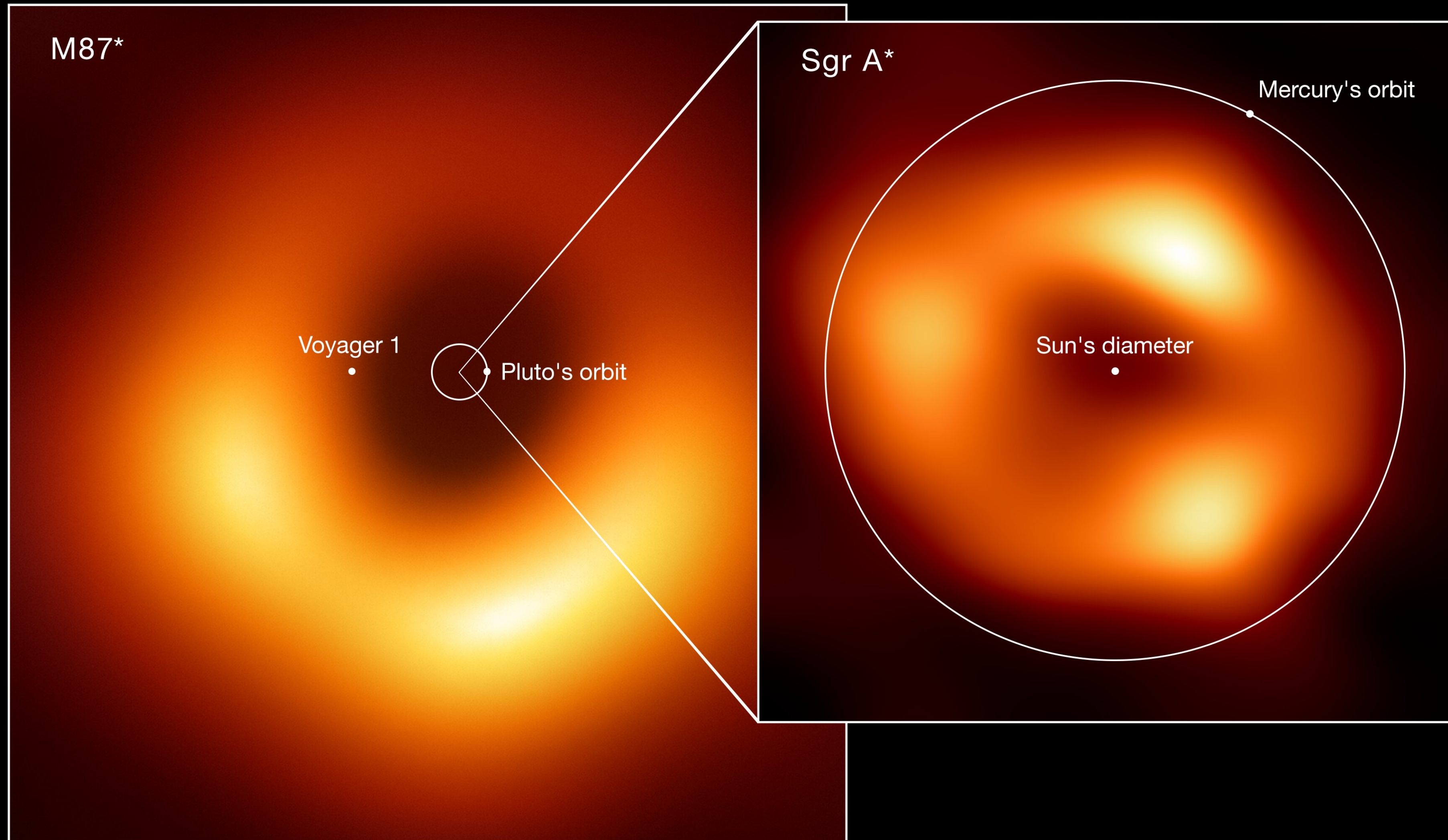
Supermassive compact object



Credit: A. Eckart (U. Koeln) & R. Genzel (MPE-Garching),
SHARP I, NTT, La Silla Obs., ESO
<https://www.universetoday.com/133511/>



M87* and Sgr A*



① Introduction

② Supermassive Blackhole and Photon Ring

③ Event Horizon Telescope Collaboration

④ Radio Interferometry

⑤ M87* imaging

⑥ SgrA* imaging

⑦ Conclusion

Supermassive Blackholes



Every Galaxy center

Supermassive BH

(Active Galactic Nuclei)



Supermassive Blackholes

Every Galaxy center
Supermassive BH

Singularity

At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".

Relativistic jets

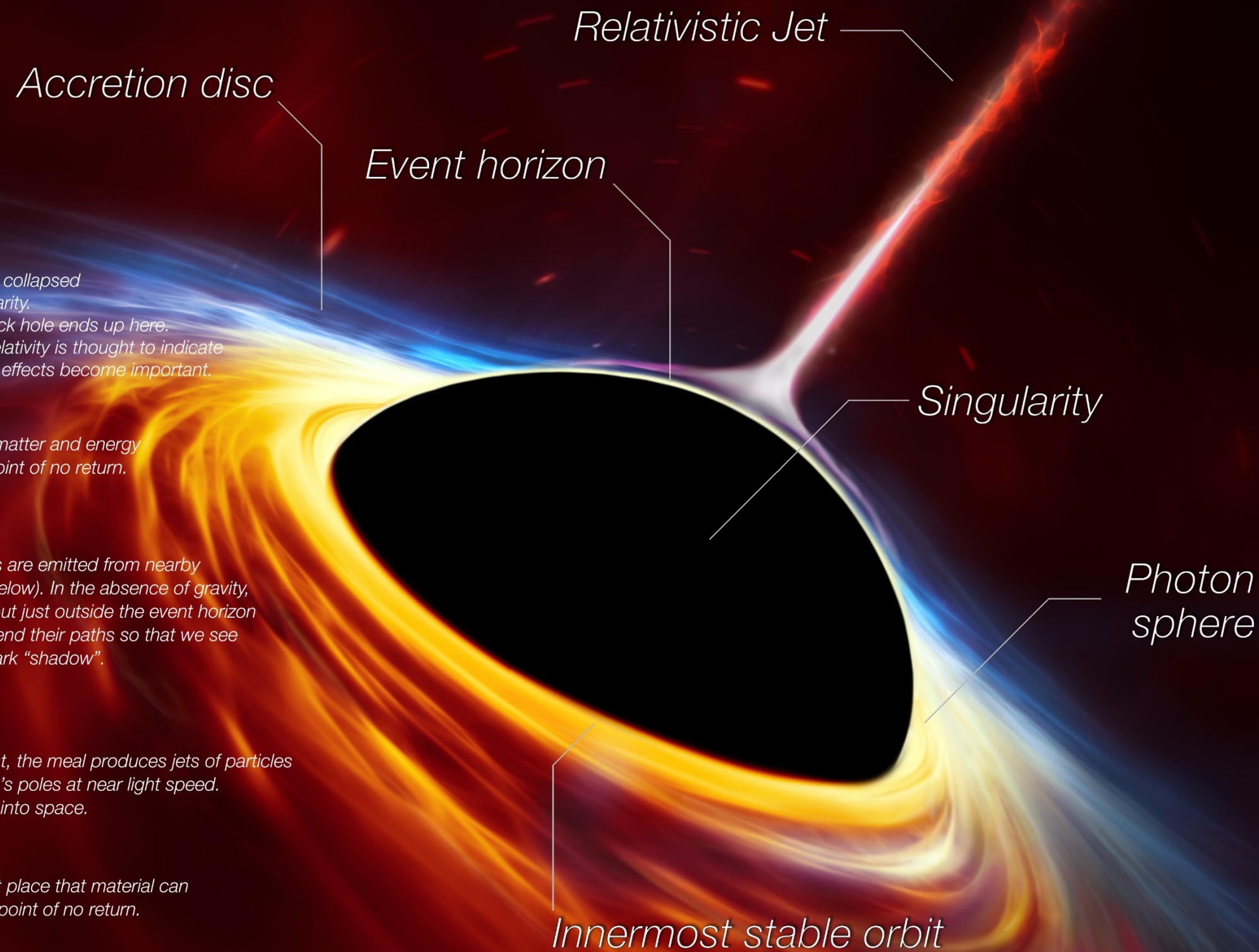
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space.

Innermost stable orbit

The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc

A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.



Credit: ESO, ESA/Hubble, M. Kornmesser



Event Horizon Telescope

13 September 2022, IAU-IAA

Supermassive Blackholes



Credit: Jordy Davelaar et al./Radboud University/BlackHoleCam

Every Galaxy center

Supermassive BH

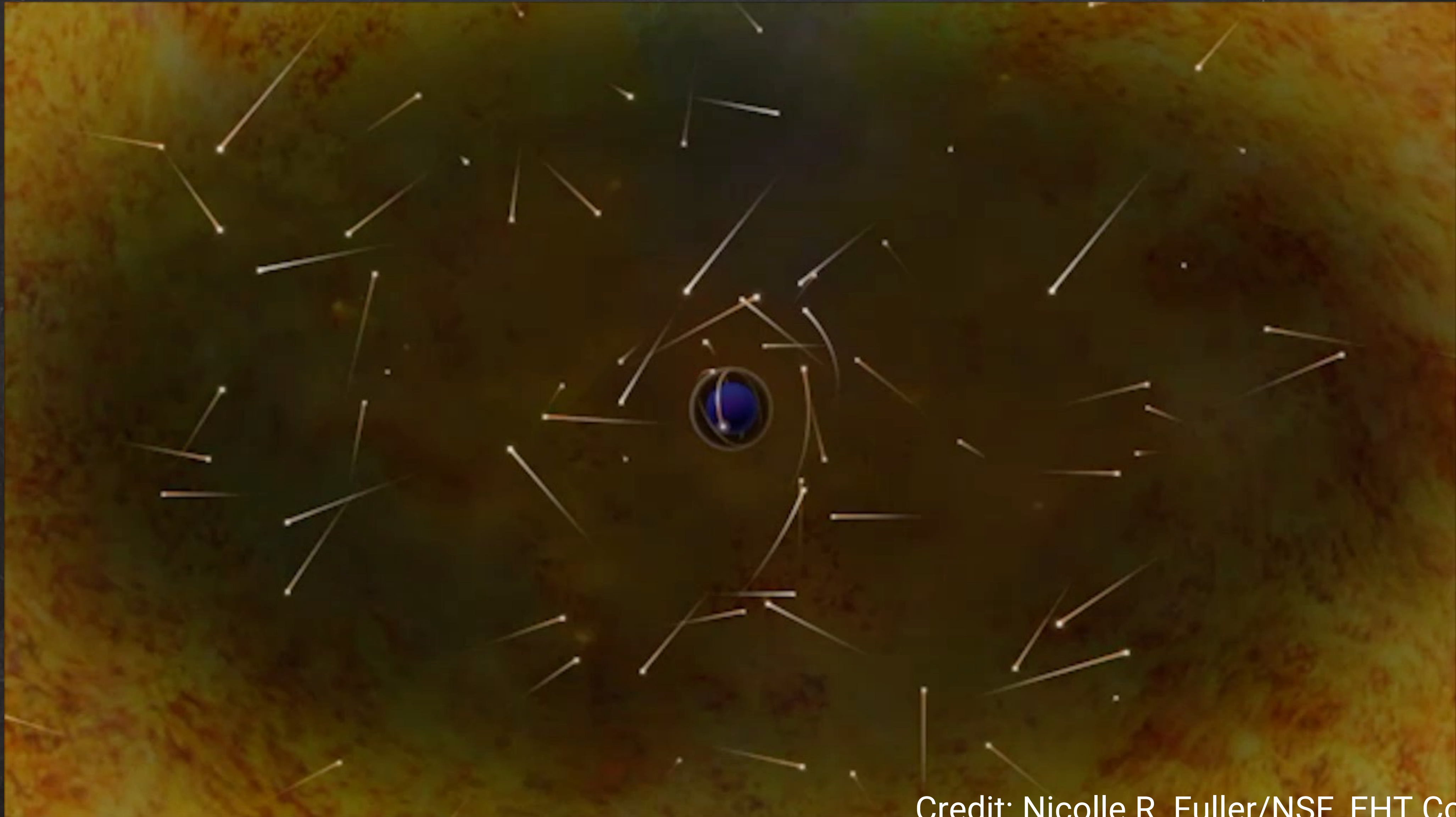
How Jet is coming out?

Simulations predict

⇒ Observations to check



Blackhole Shadow : How it looks like .



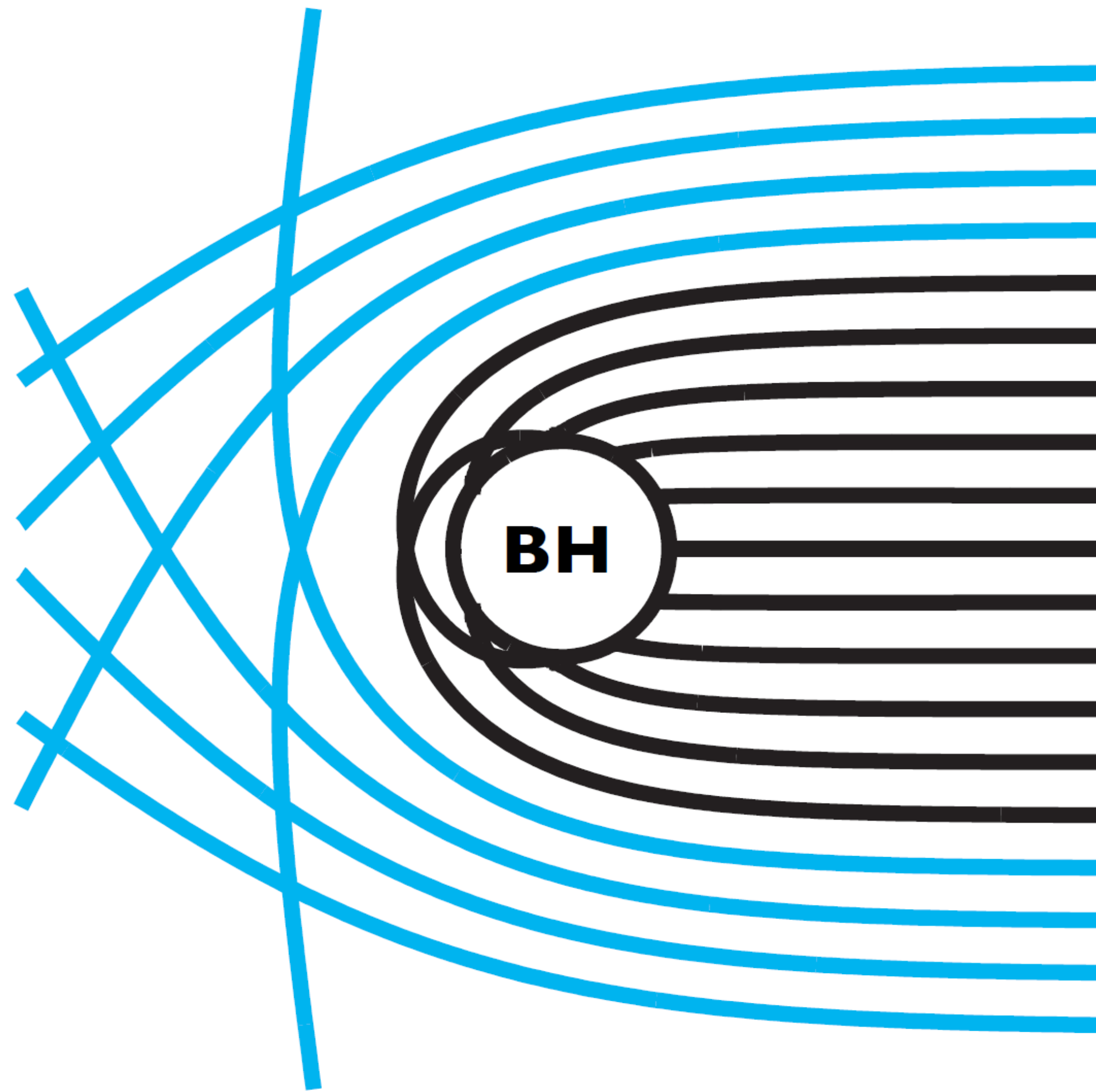
Credit: Nicolle R. Fuller/NSF, EHT Collaboration,



Event Horizon Telescope

13 September 2022, IAU-IAA

Blackhole Shadow : How it looks like .



Ring $\sim 2.6 \times \text{BH size}$

$\sim 5.2 R_s$

$$R_s = 2GM_{\text{BH}}/c^2$$

(Hilbert 1916)

Credit: Hung-Yi Pu



- ① Introduction
- ② Supermassive Blackhole and Photon Ring
- ③ Event Horizon Telescope Collaboration
- ④ Radio Interferometry
- ⑤ M87* imaging
- ⑥ SgrA* imaging
- ⑦ Conclusion

Taking a Picture of Supermassive BH

① Visual Proof of Blackhole

② Test of General Relativity

Ring Shape, Magnetic field around BH

③ Unsolved Problem

How strong Jet is produced.



Supermassive BHs are small from our sight



Credit: ESO/M. Kornmesser/L. Calçada

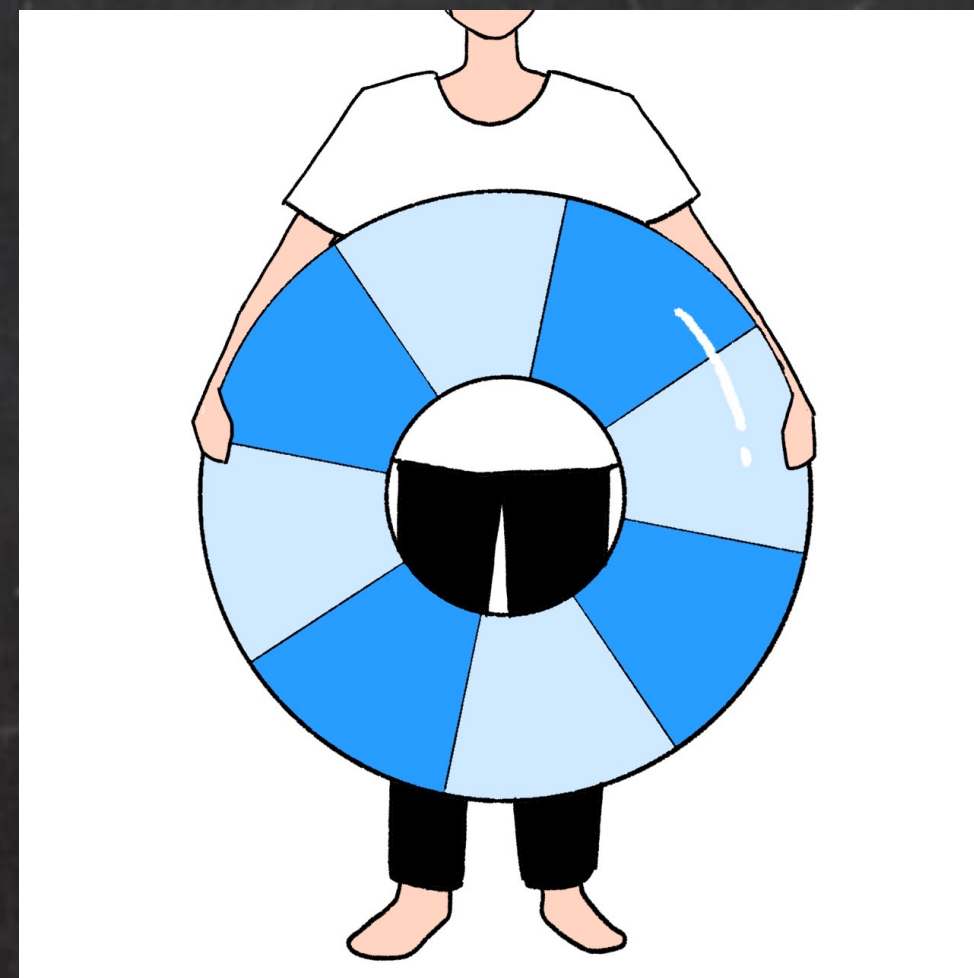
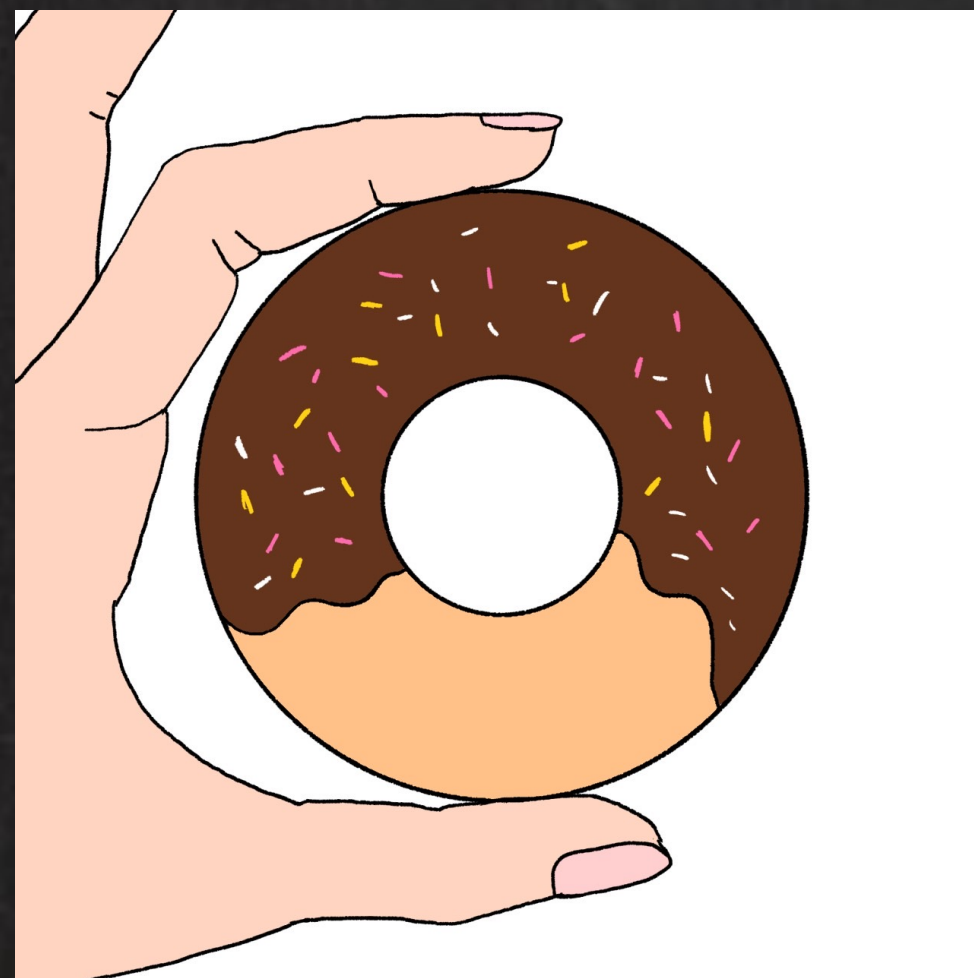


Event Horizon Telescope

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Supermassive BHs are small from our sight

Source	BH Mass (M_{solar})	Distance (Mpc)	1 R_s (μas)
Sgr A*	4×10^6	0.008	10
M87	6.5×10^9	16.8	7.6
M104	1×10^9	10	2
Cen A	5×10^7	4	0.25



Supermassive BHs are small from our sight

Angular resolution $\propto \frac{\text{wavelength}}{\text{diameter}}$

① Optical telescope

wavelength $< 1\mu\text{m}$

diameter $\approx 10\text{m}$



Credit: NAOJ,

② EHT (radio interferometer)

wavelength $= 1.3\text{mm}$

diameter $> 10 \times 10^6 \text{m}$



Event Horizon Telescope

13 September 2022, IAU-IAA

Event Horizon Telescope



Observation

April, 2017

6 locations

8 telescopes



International Collaboration



EHT Collaboration Meeting 2016@Boston

more than 300 members
80 institutes from
21 countries (2022)



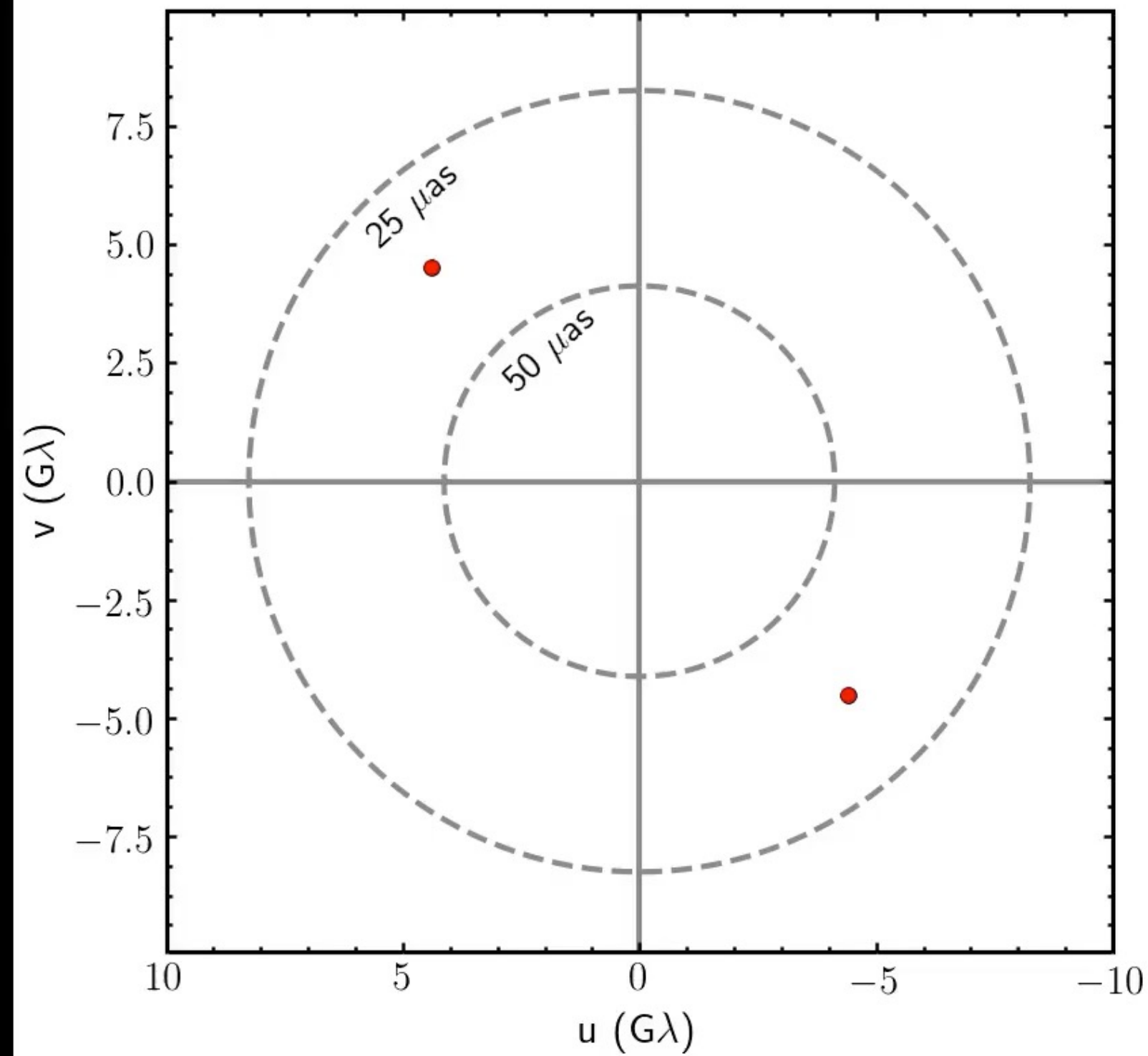
13 Stakeholder Institutions

EHT Collaboration Meeting 2019@Hilo, Hawaii

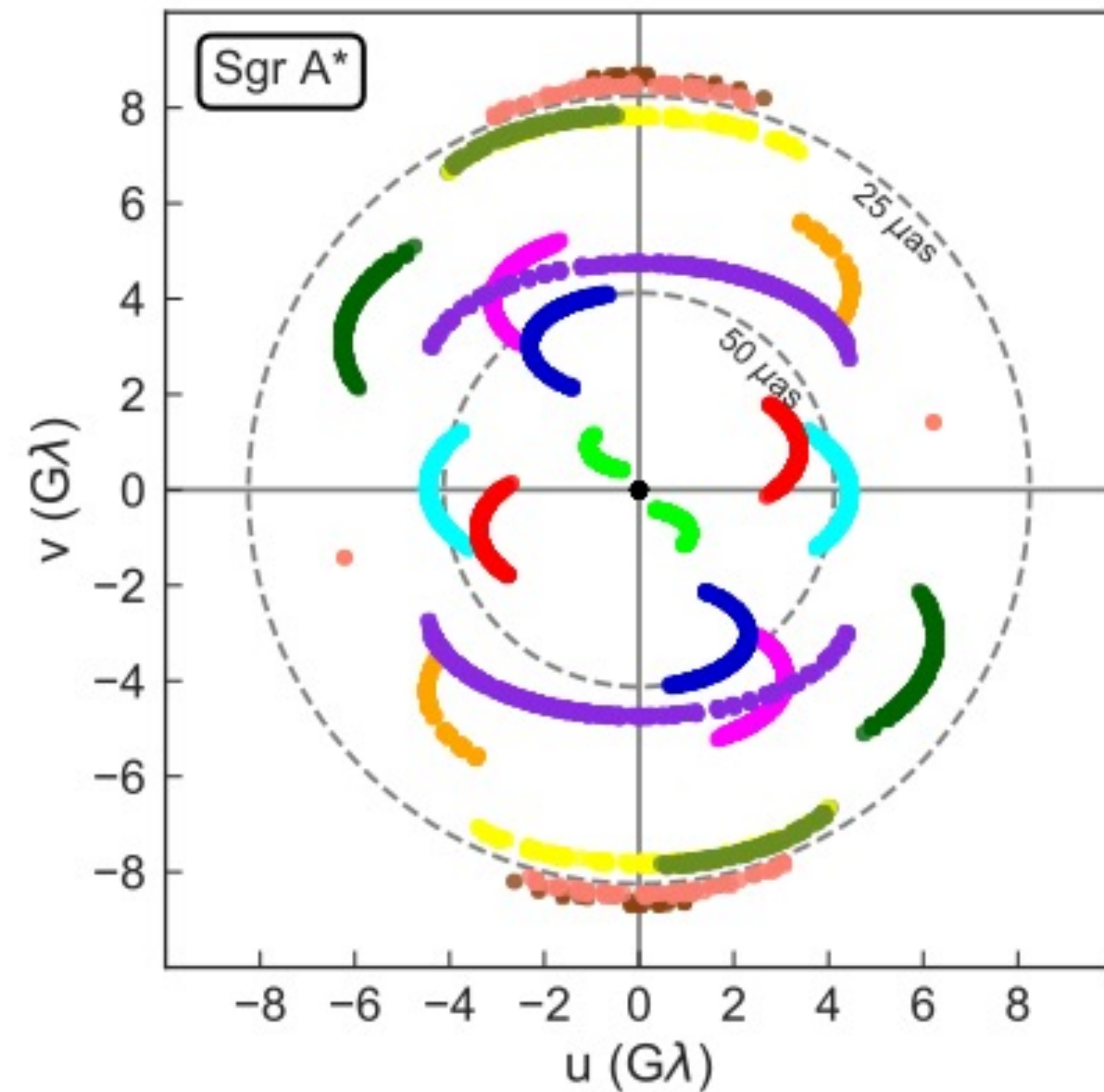
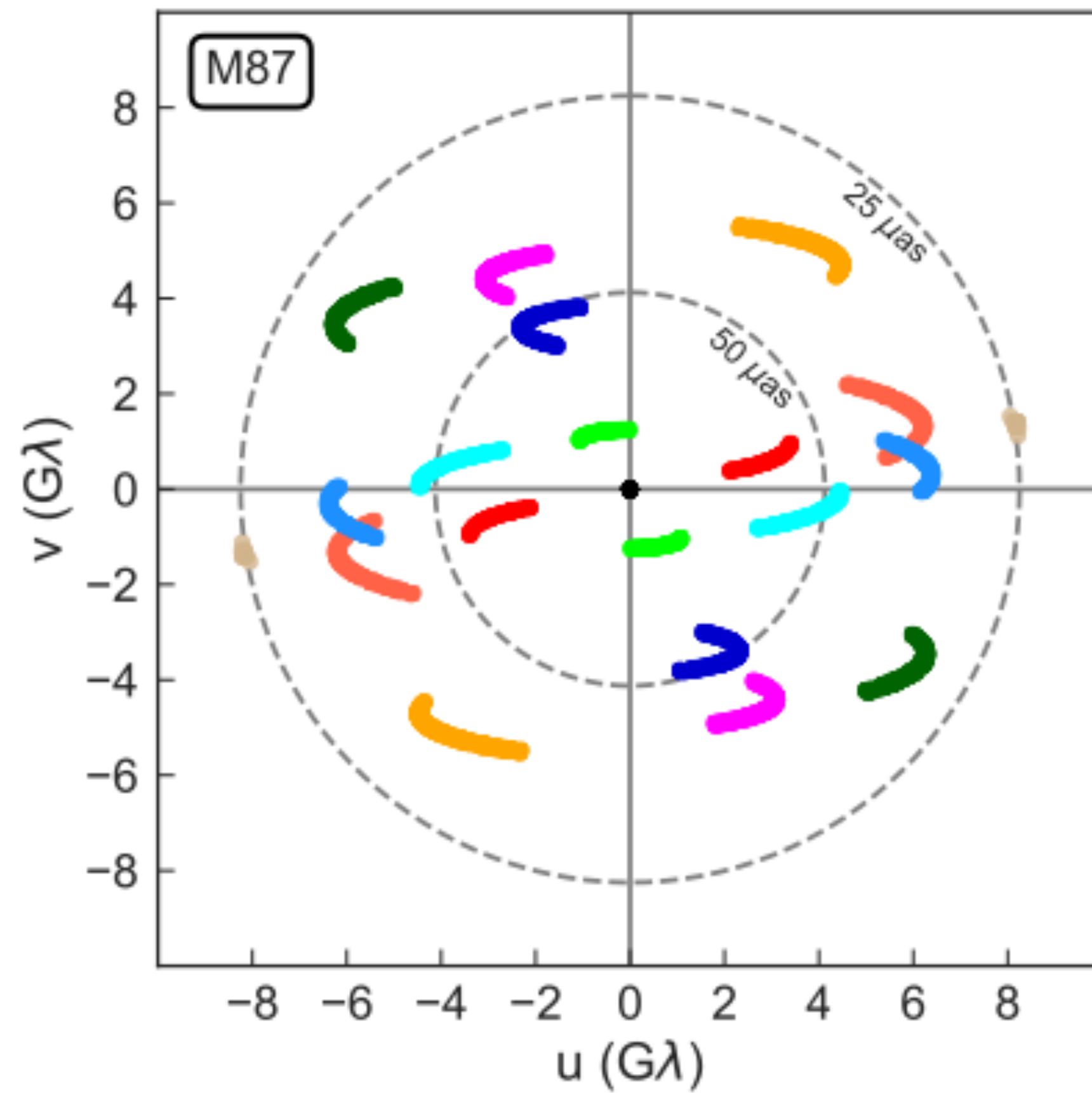


- ① Introduction
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- ④ Radio Interferometry
- ⑤ M87* imaging
- ⑥ SgrA* imaging
- ⑦ Conclusion

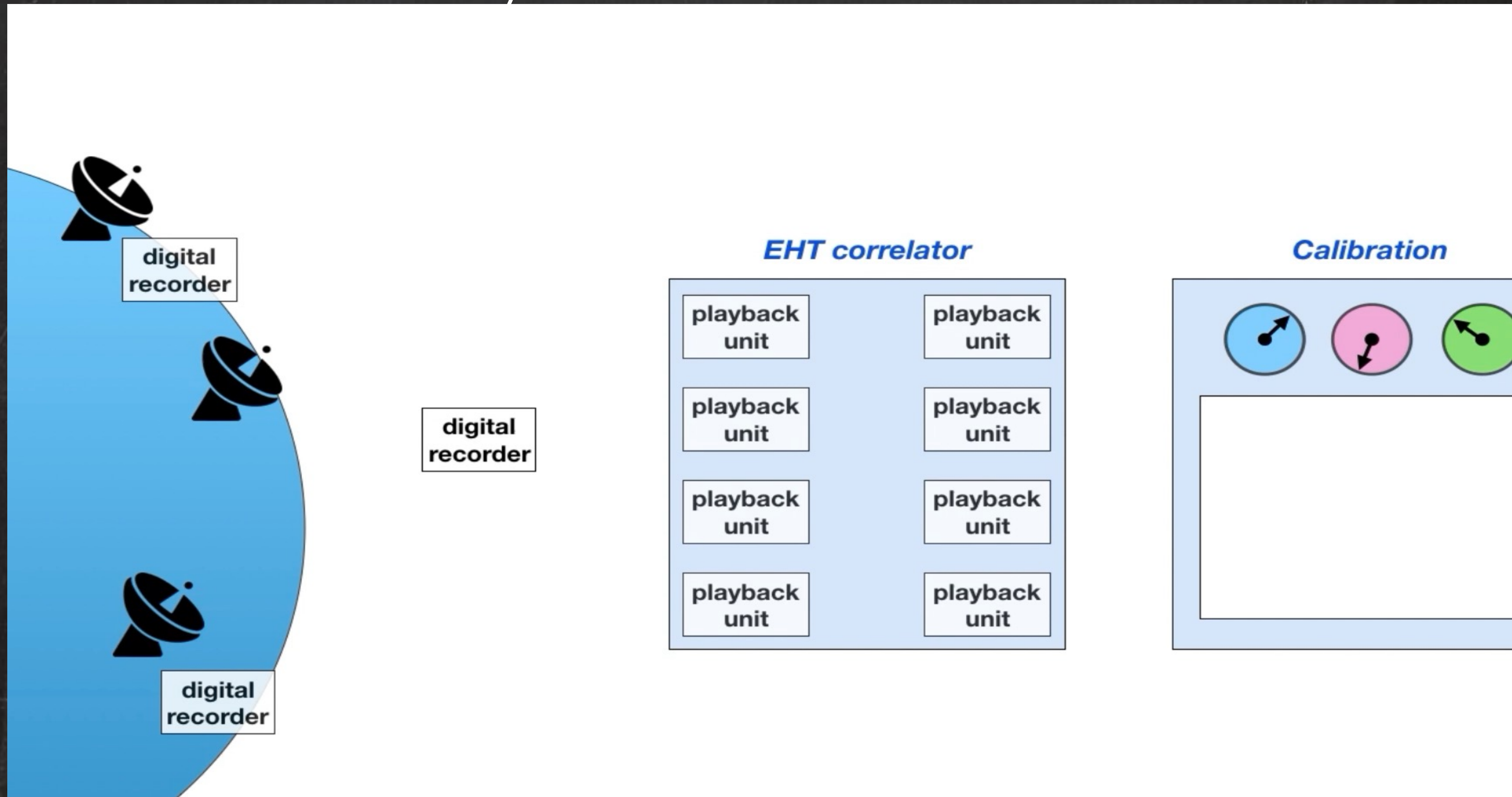
Radio Interferometry : How it works



Radio Interferometry : Sampling Points for M87 & Sgr A*



Radio Interferometry : How it worked



Credit:Lindy Blackburn



Fraunhofer Diffraction

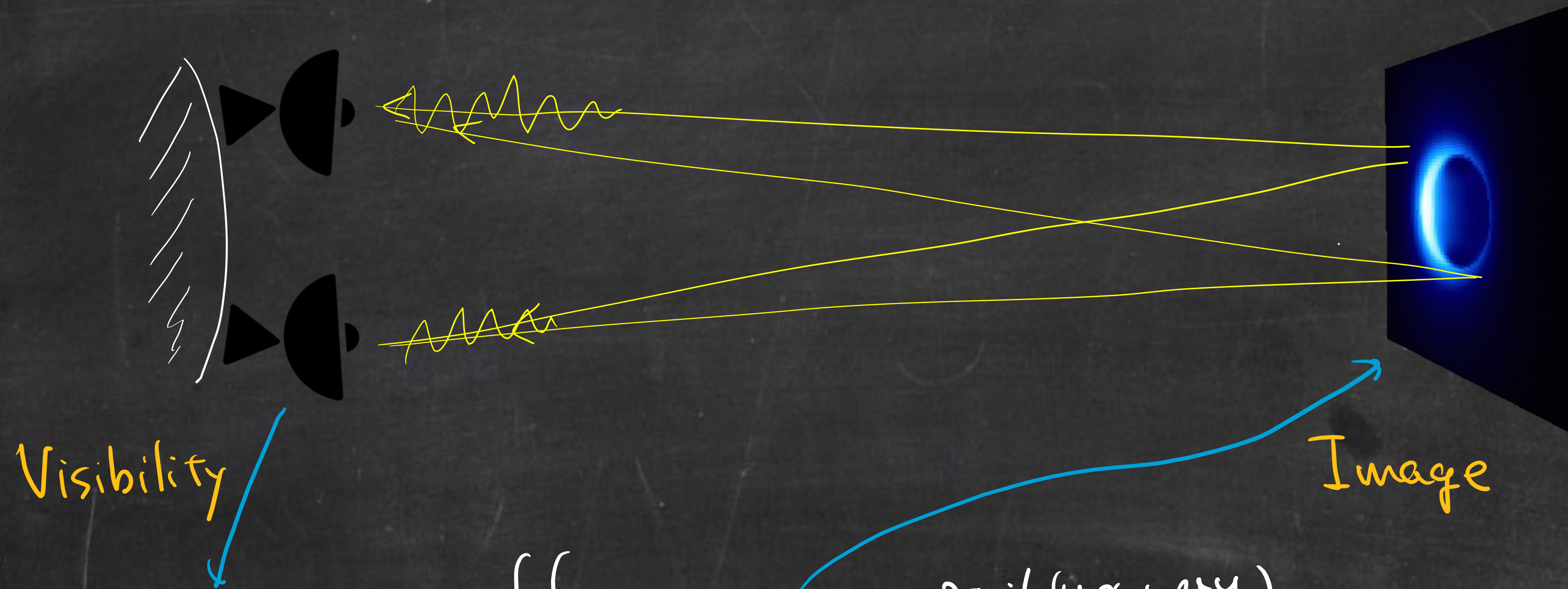


$$V(u, v) = \iint I(x, y) e^{\frac{2\pi i (ux + vy)}{\lambda L}} dx dy$$

Fourier transform appears



Fraunhofer Diffraction and Radio Interferometry

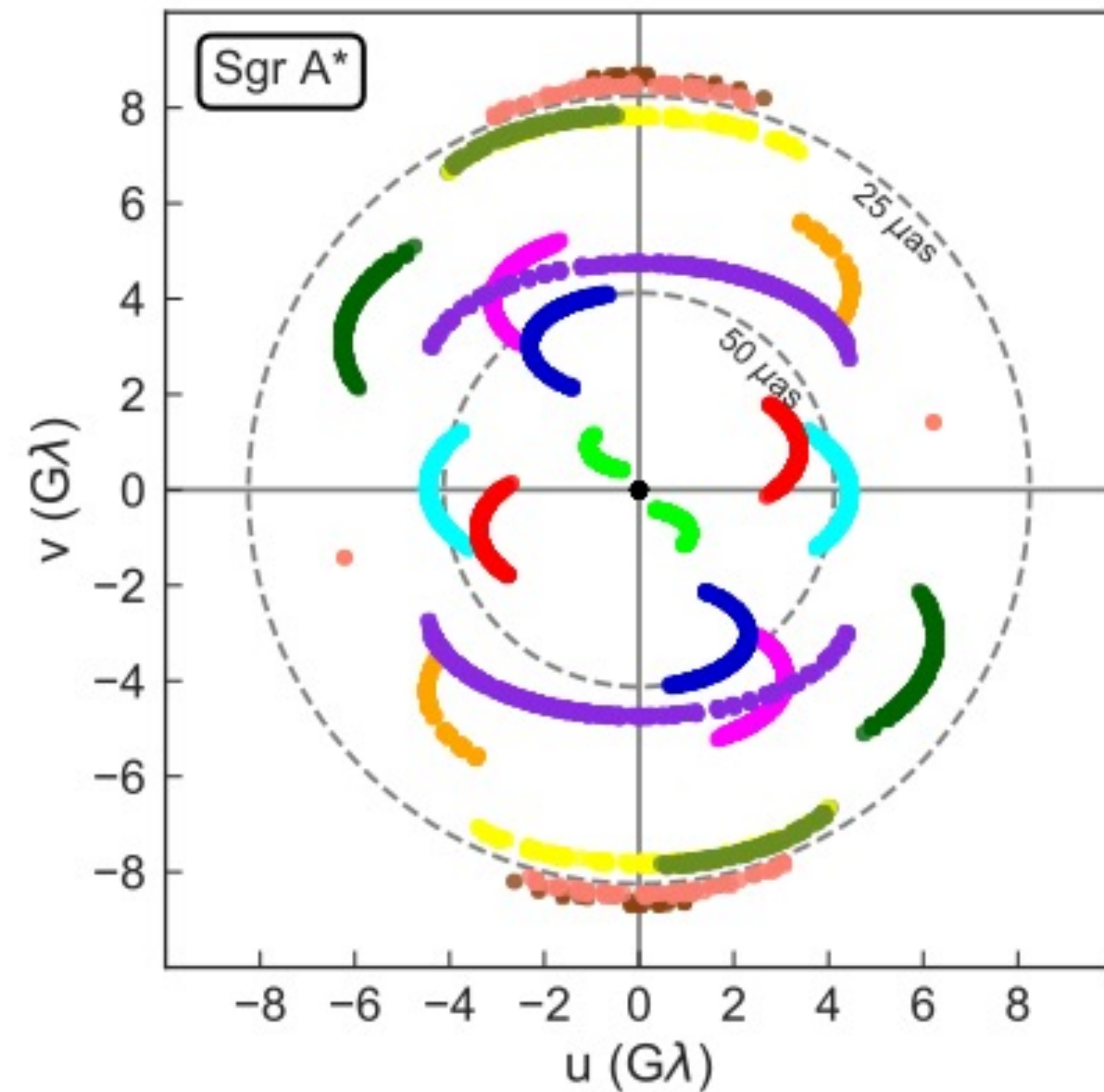
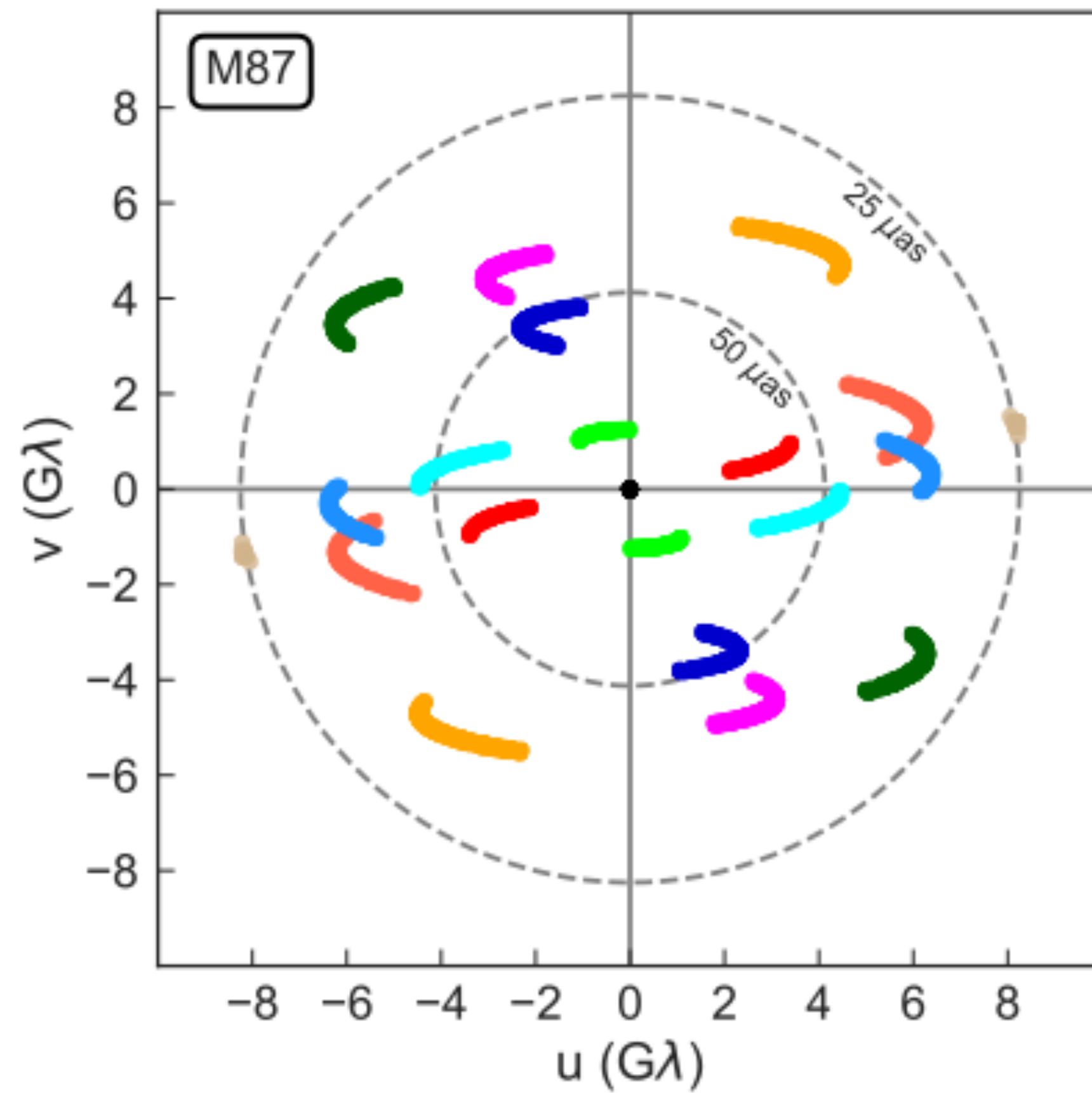


$$V(u, v) = \iint I(x, y) e^{2\pi i k (ux + vy)} dx dy$$

Observe Fourier components and reconstruct images.



Radio Interferometry : Sampling Points for M87* & Sgr A*



Radio Interferometry : Imaging

Fourier points are not sufficient

Additional information required

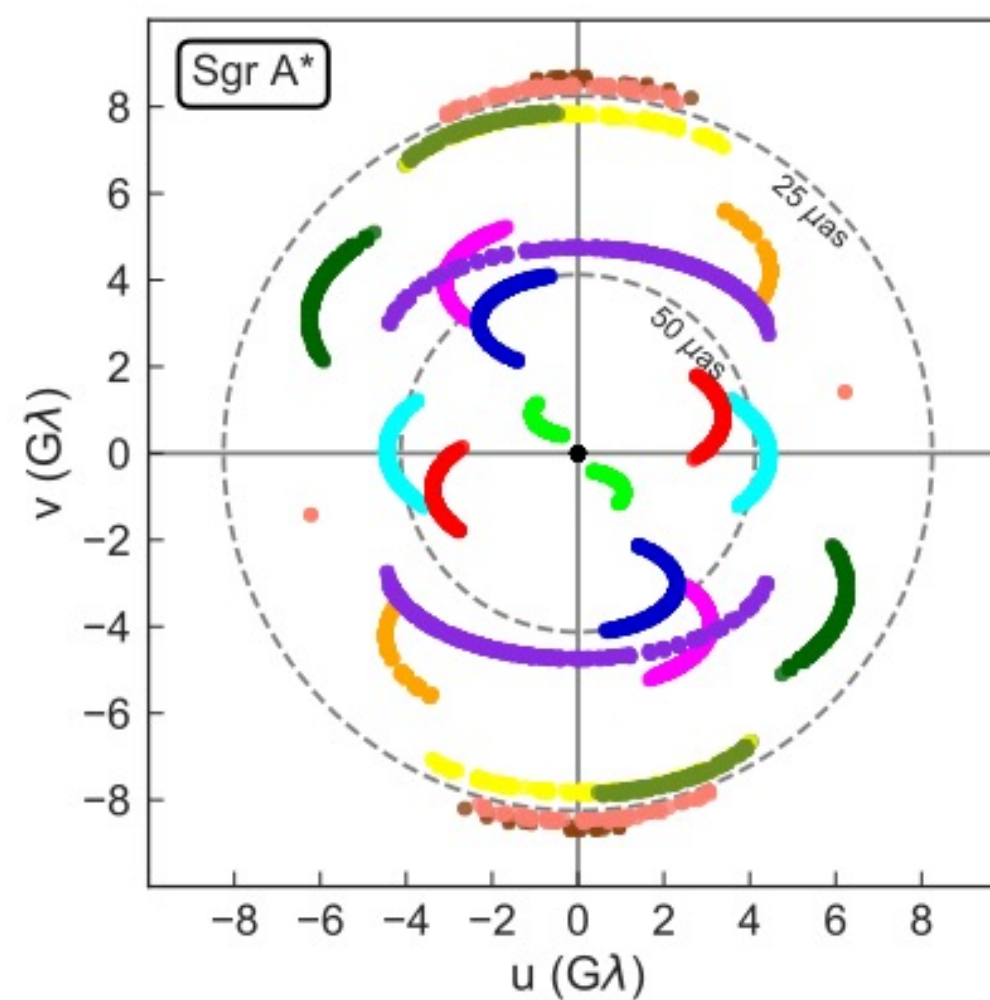
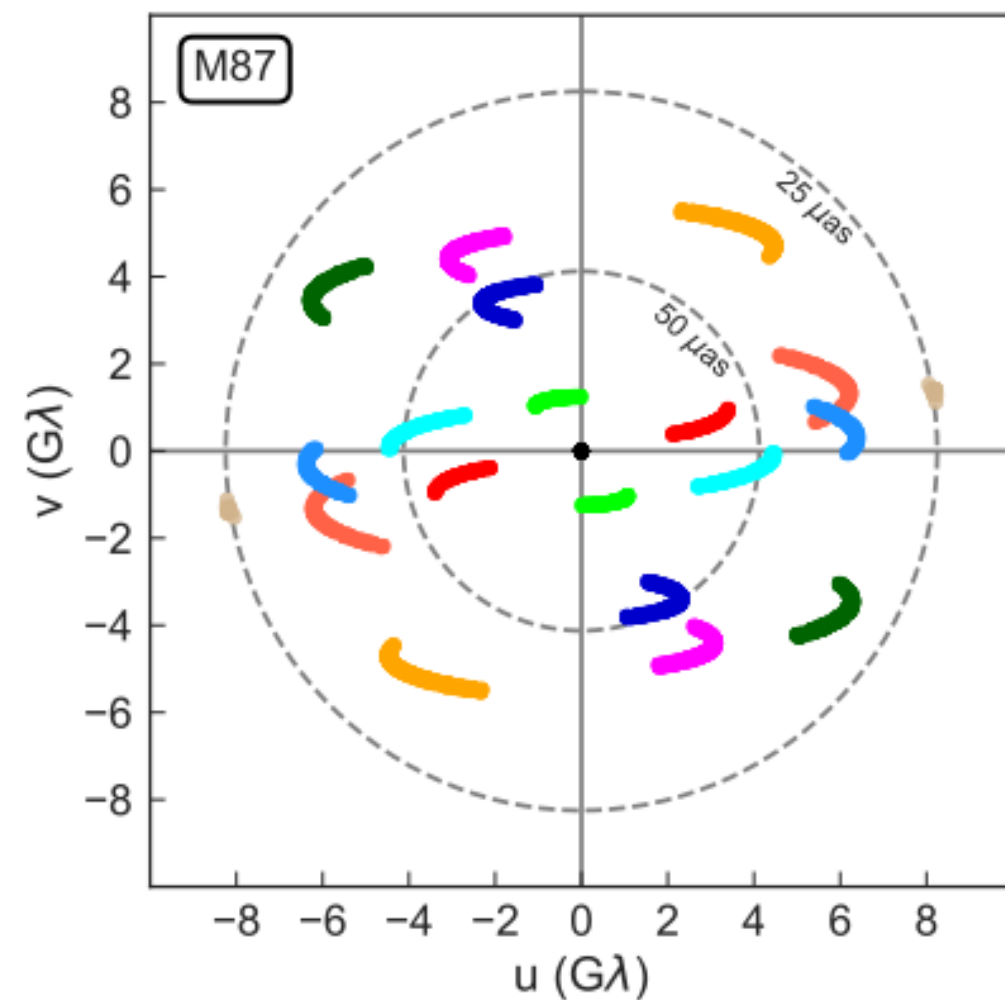
• Imaging

Image assumptions

Smooth, sparse, etc.

Algorithm to solve it.

EHT developed 3 new imaging methods



- ① Introduction
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- ④ Radio Interferometry
- ⑤ M87* imaging
- ⑥ SgrA* imaging
- ⑦ Conclusion

Image methods used for M87* imaging

Traditional Method

CLEAN

DIFMAP (Shepherd+97, 98, 03)

Model

General Pixelated Images
Residual Calibration Gains

Hyper Parameters

Image Assumptions

Sparse reconstruction

New Imaging Methods

Regularized Maximum Likelihood (RML)

eht-imaging (Chael+16, 18)

Model

General Pixelated Images

Hyper Parameters

Image Assumptions

Sparse
Smooth
Maximum Entropy
TotalFlux

SMILI (Akiyama+17a, b)

Model

General Pixelated Images
Residual Calibration Gains

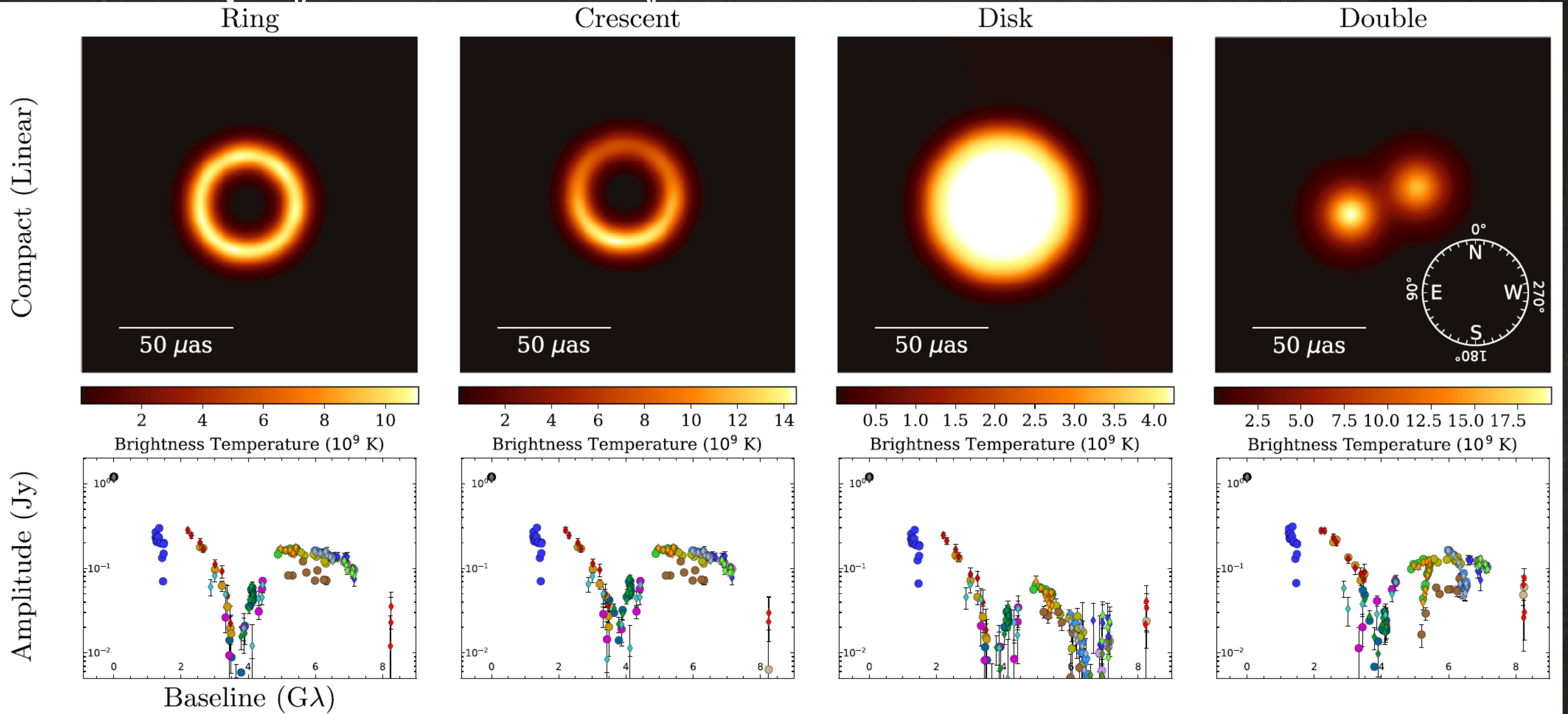
Hyper Parameters

Image Assumptions

Sparse
Smooth
Total flux



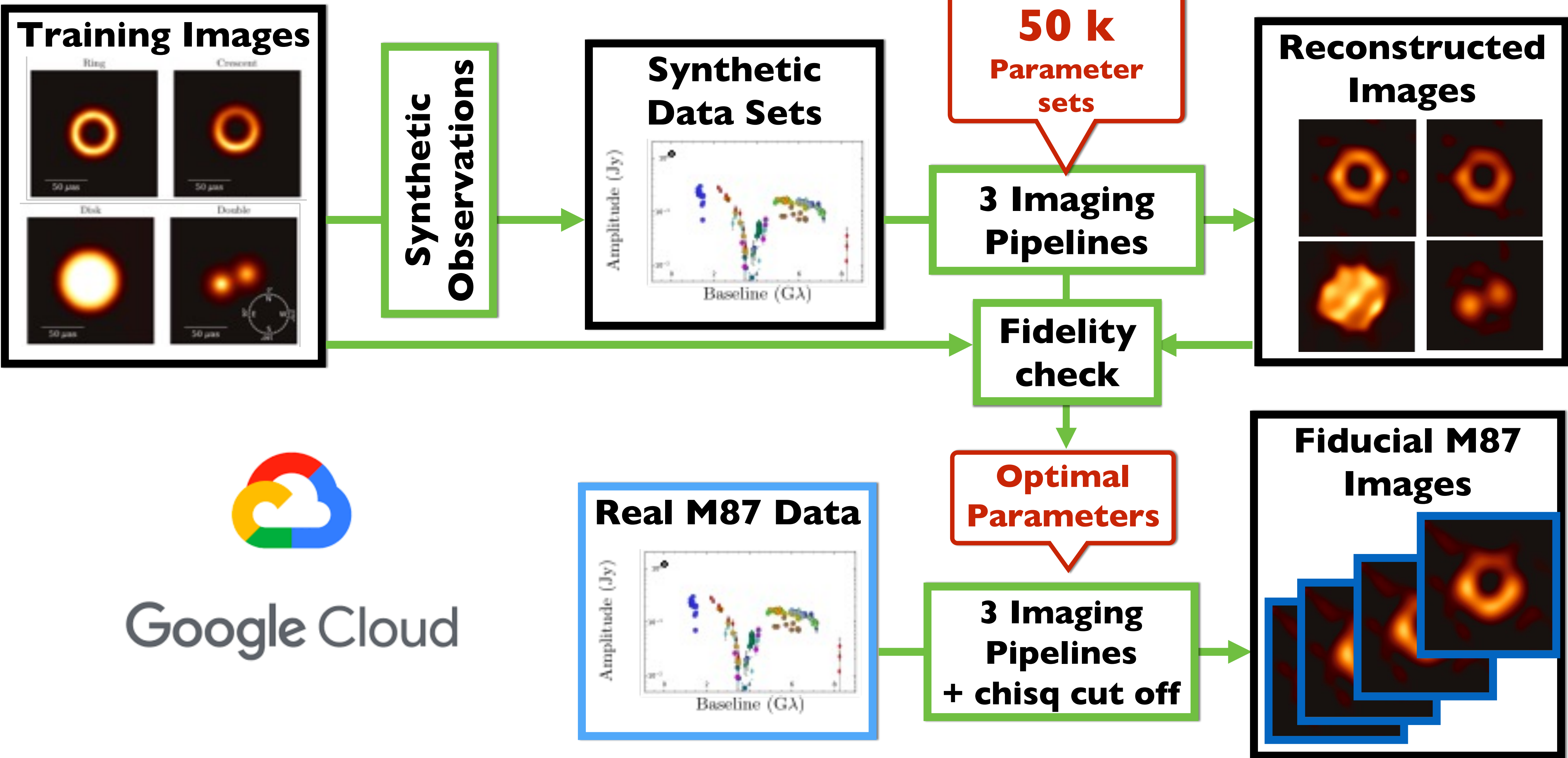
Can imaging methods distinguish these?



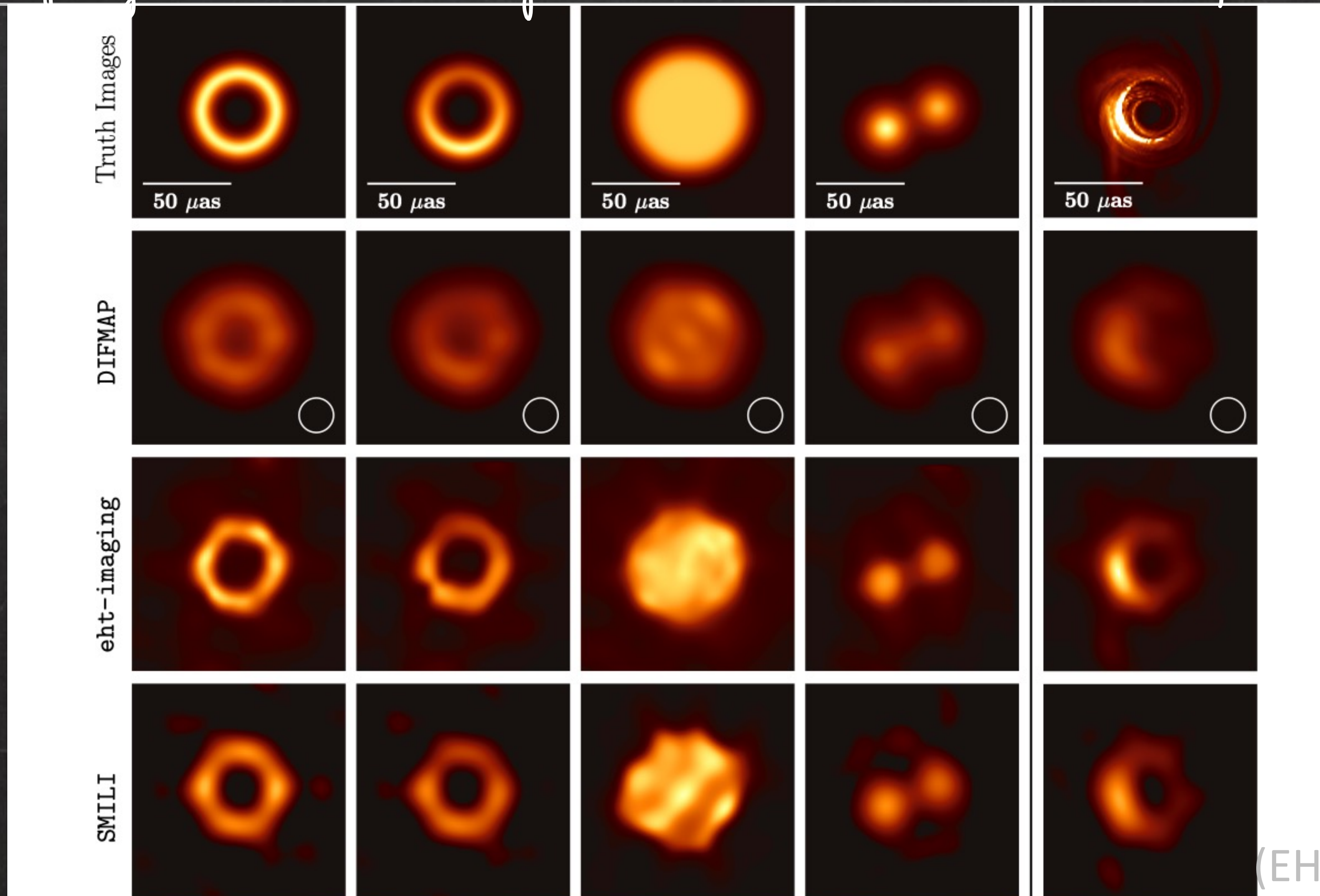
(EHT M87 Paper IV)



Imaging Process



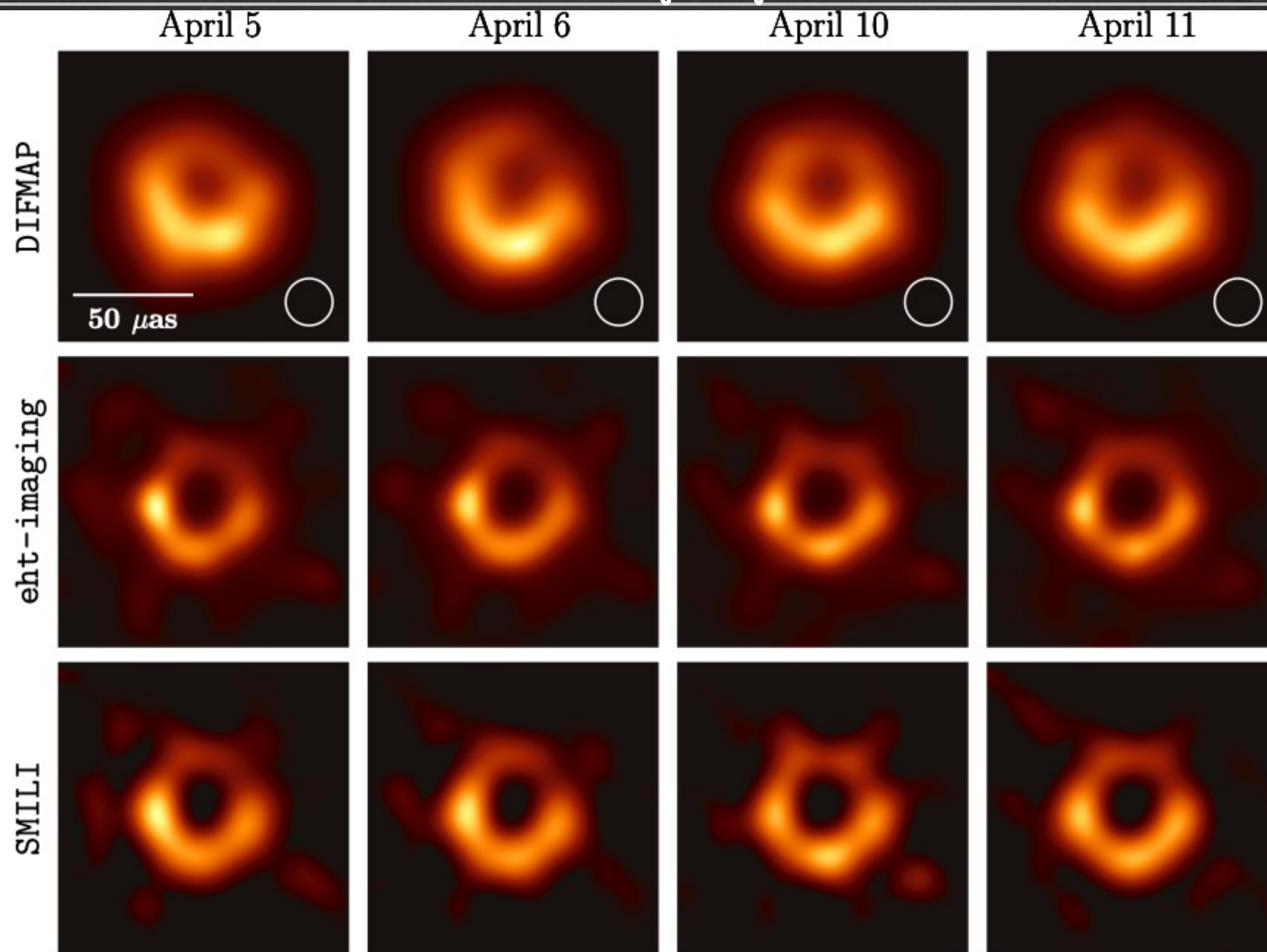
Can imaging methods distinguish these? Yes they can!



(EHT M87 Paper IV)



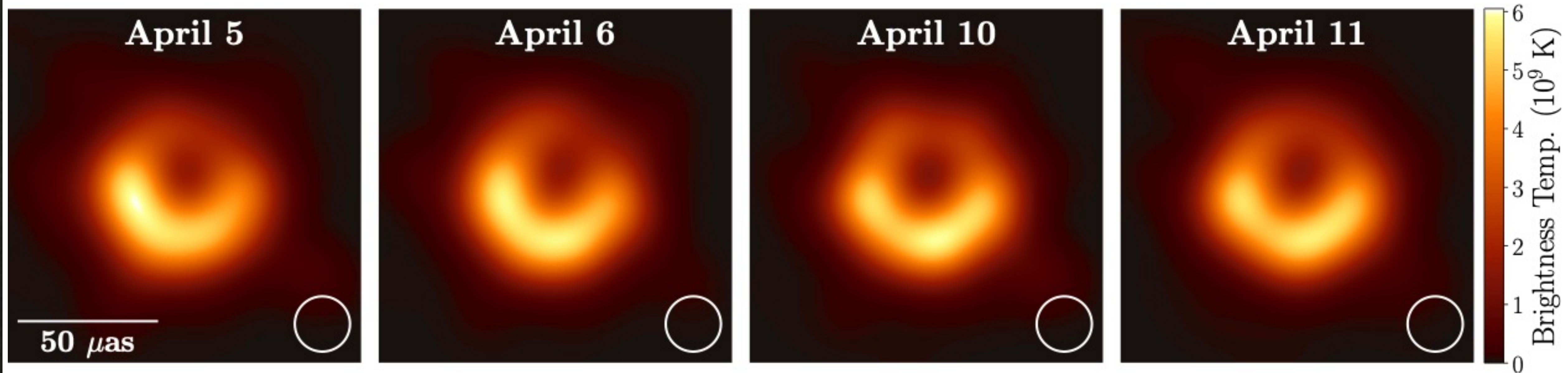
M87^{*} results with 3 imaging methods



(EHT M87 Paper IV)



Averaged Images



(EHT M87 Paper IV)



Event Horizon Telescope

13 September 2022, IAU-IAA

Release M87* image



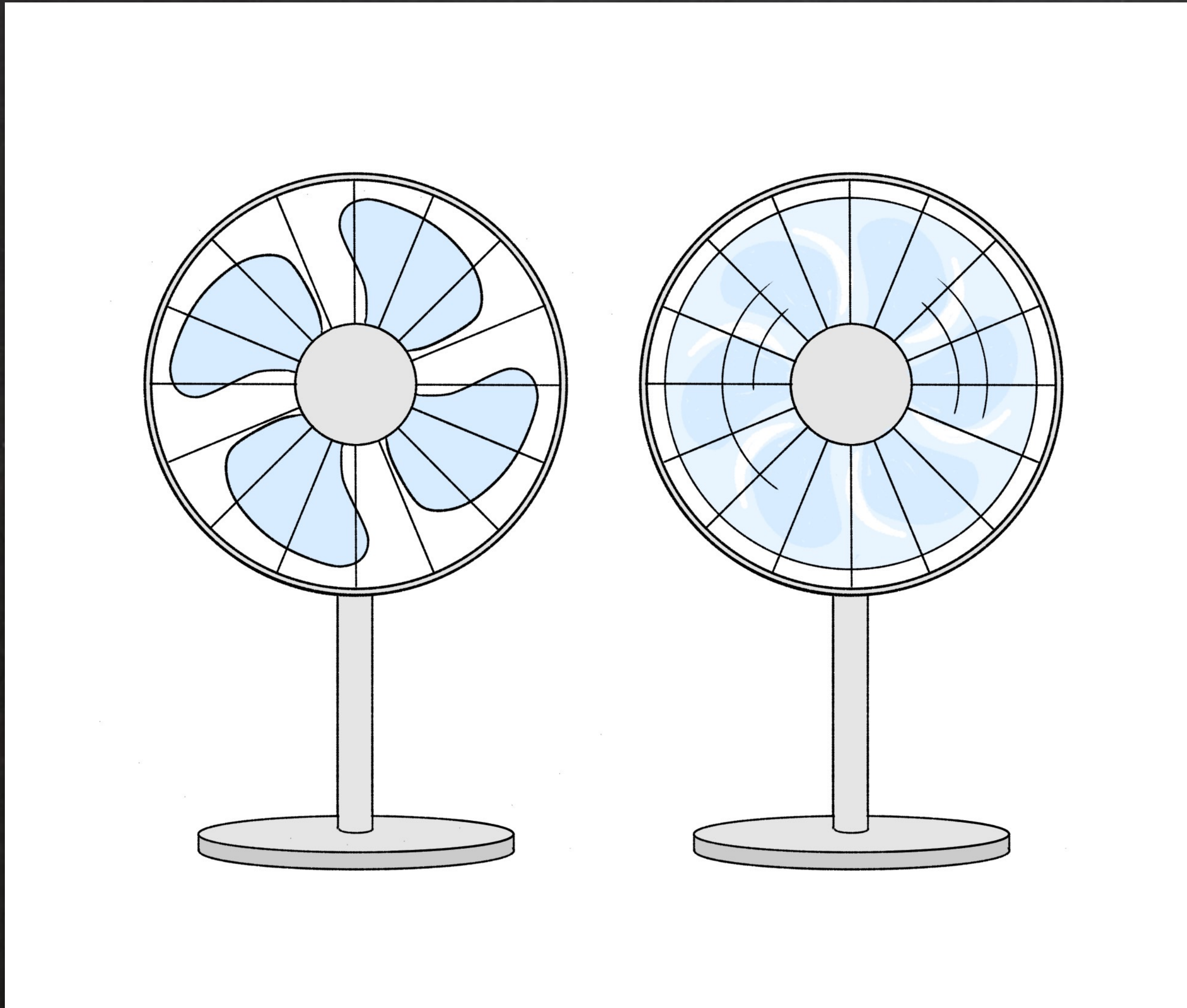
Event Horizon Telescope

EHT Collaboration

13 September 2022, IAU-IAA

- ① Introduction
- ② Supermassive Blackhole and Photon Ring
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- ④ Radio Interferometry
- ⑤ M87* imaging
- ⑥ SgrA* imaging
- ⑦ Conclusion

Imaging of Sgr A* is more difficult : Time variability



Sgr A* is time varying.

① Rotation, Shape change

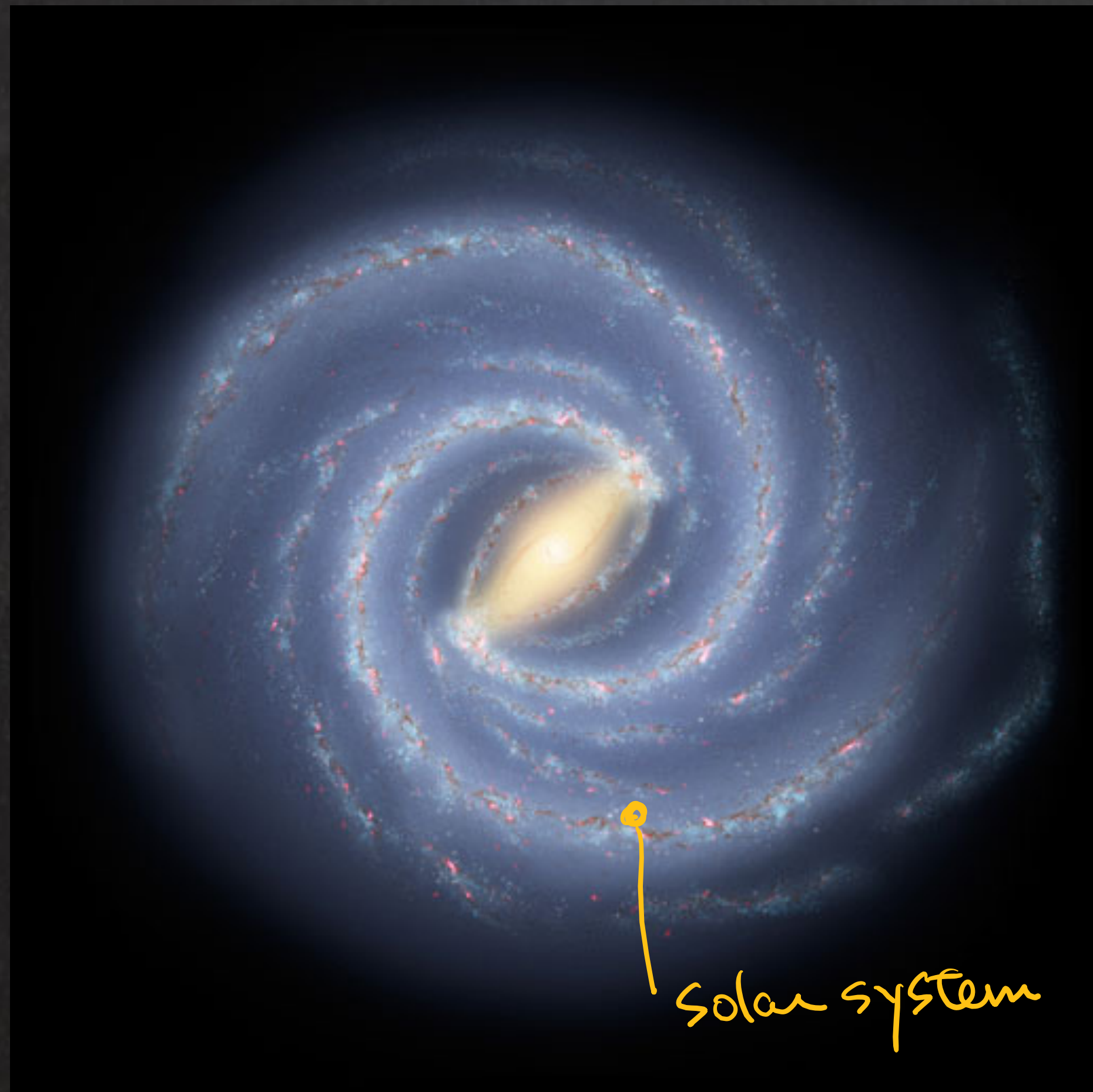
Theoretically : few ~ 30 min.

EHT observation

10 hours / night



Imaging of Sgr A* is more difficult : Scattering



Credit: NASA/JPL-Caltech

Seeing through Milkyway Galaxy

Interstellar medium $\Rightarrow$ Scattering



Credit: ESO/S. Brunier

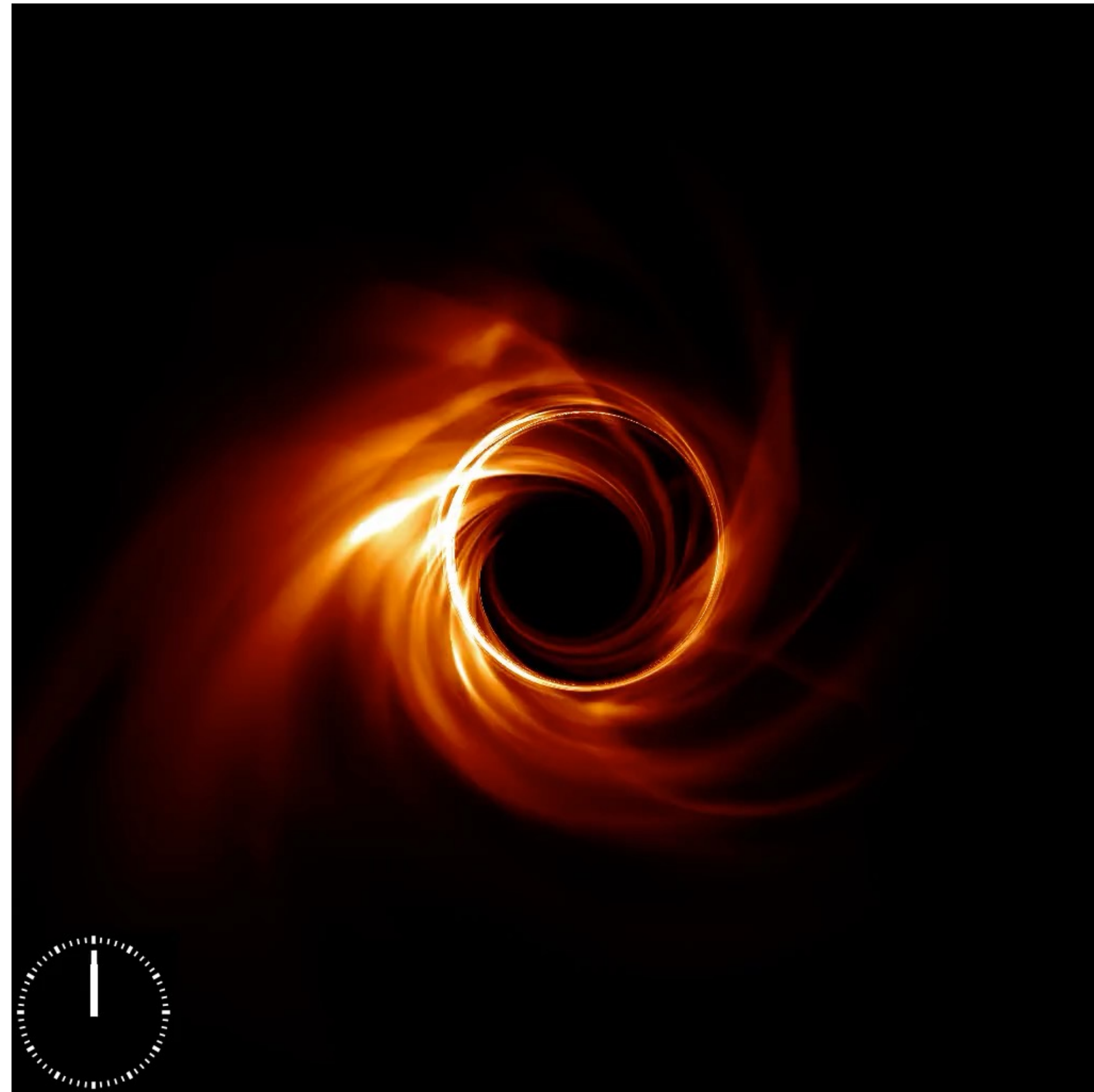


Event Horizon Telescope

13 September 2022, IAU-IAA

How they influence the images?

Time variability



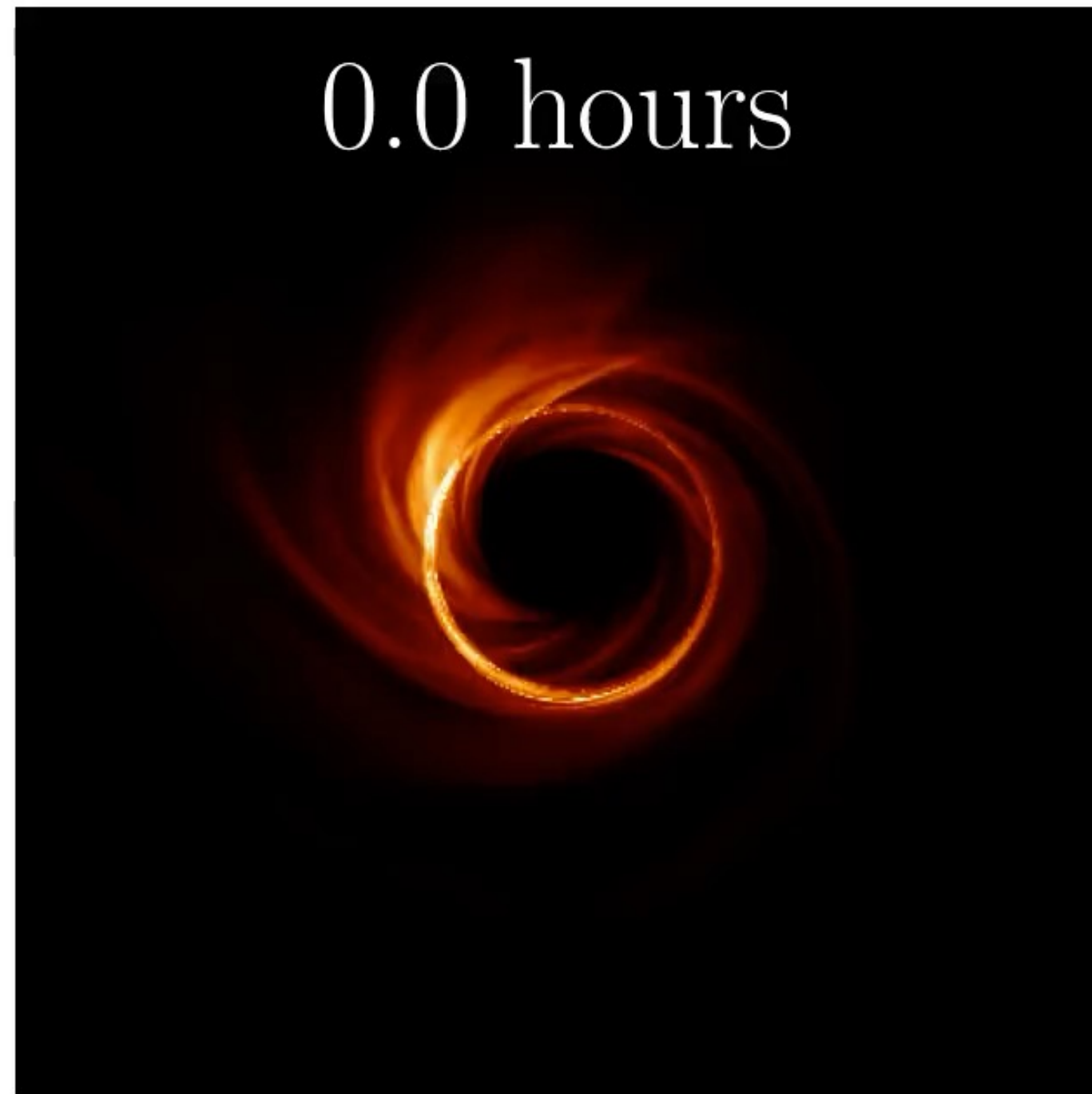
Simulation: EHT Collaboration et al. 2022, Sgr A* Paper V
Credit: Abhishek Joshi, University of Illinois at Urbana-Champaign

Slide by Kazu Akiyama@MIT



Dealing with Time Variability : Time Variability Mitigation

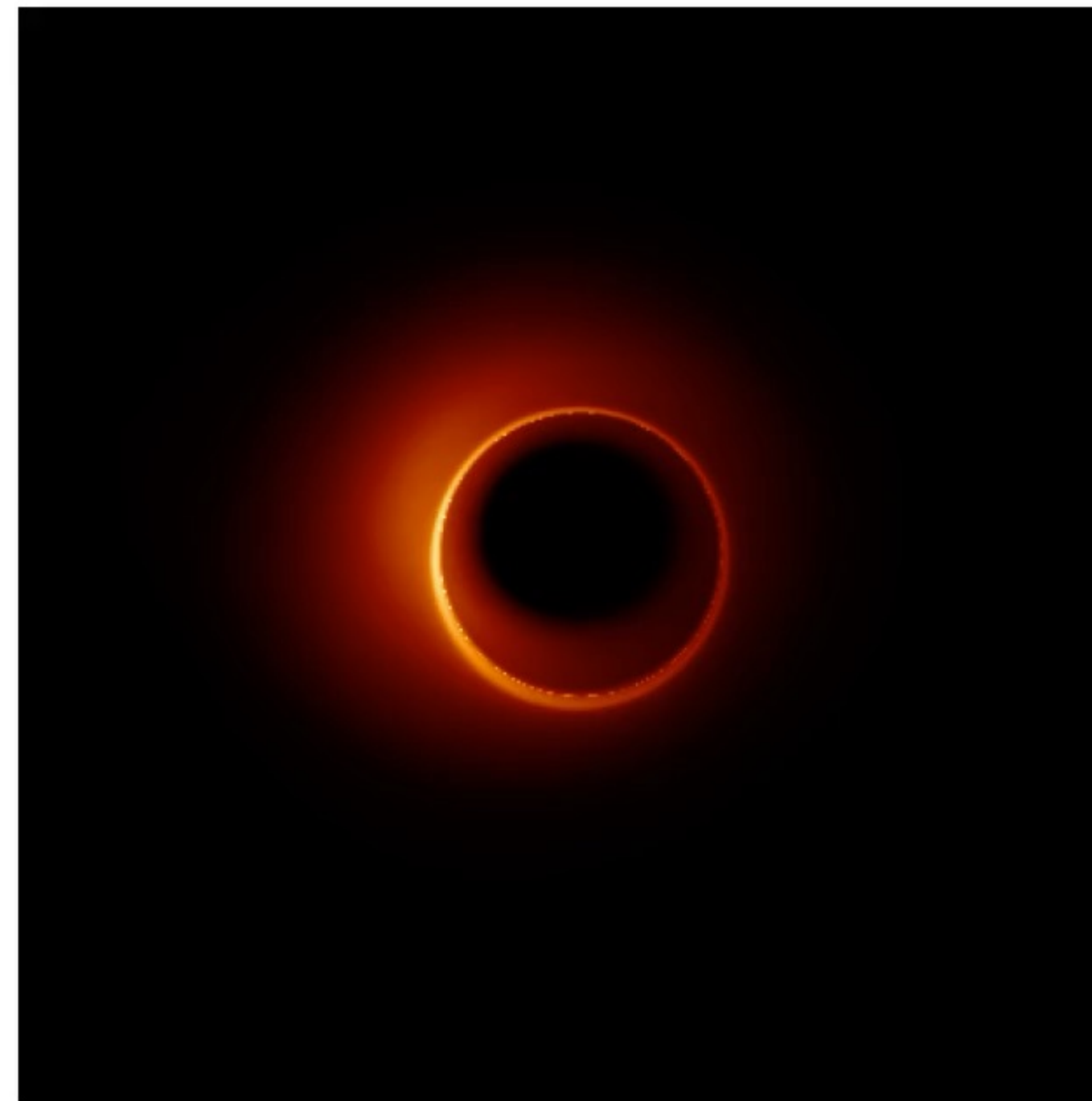
Snapshot Image



=

Mean Image

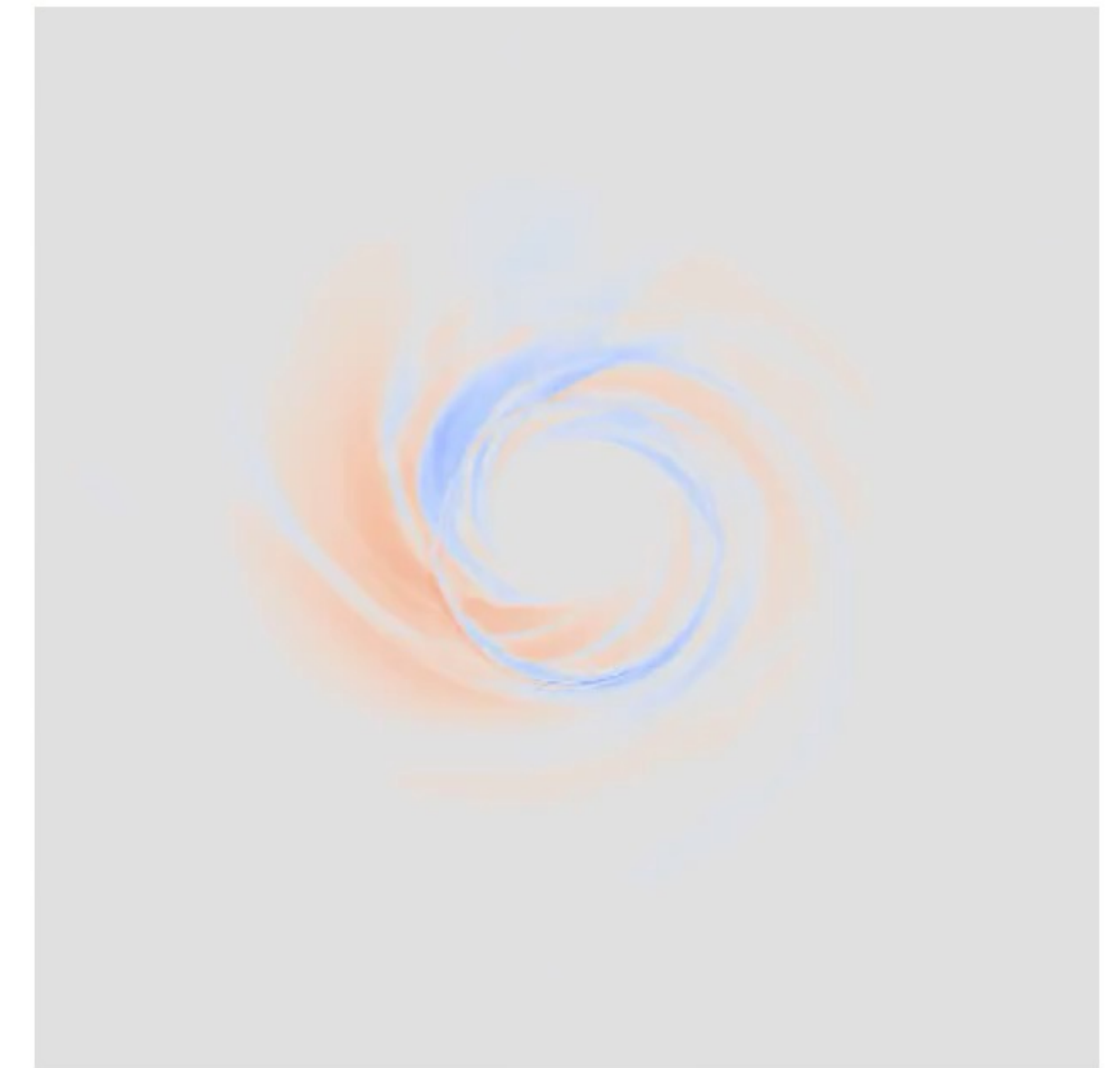
=



+

Residual Image

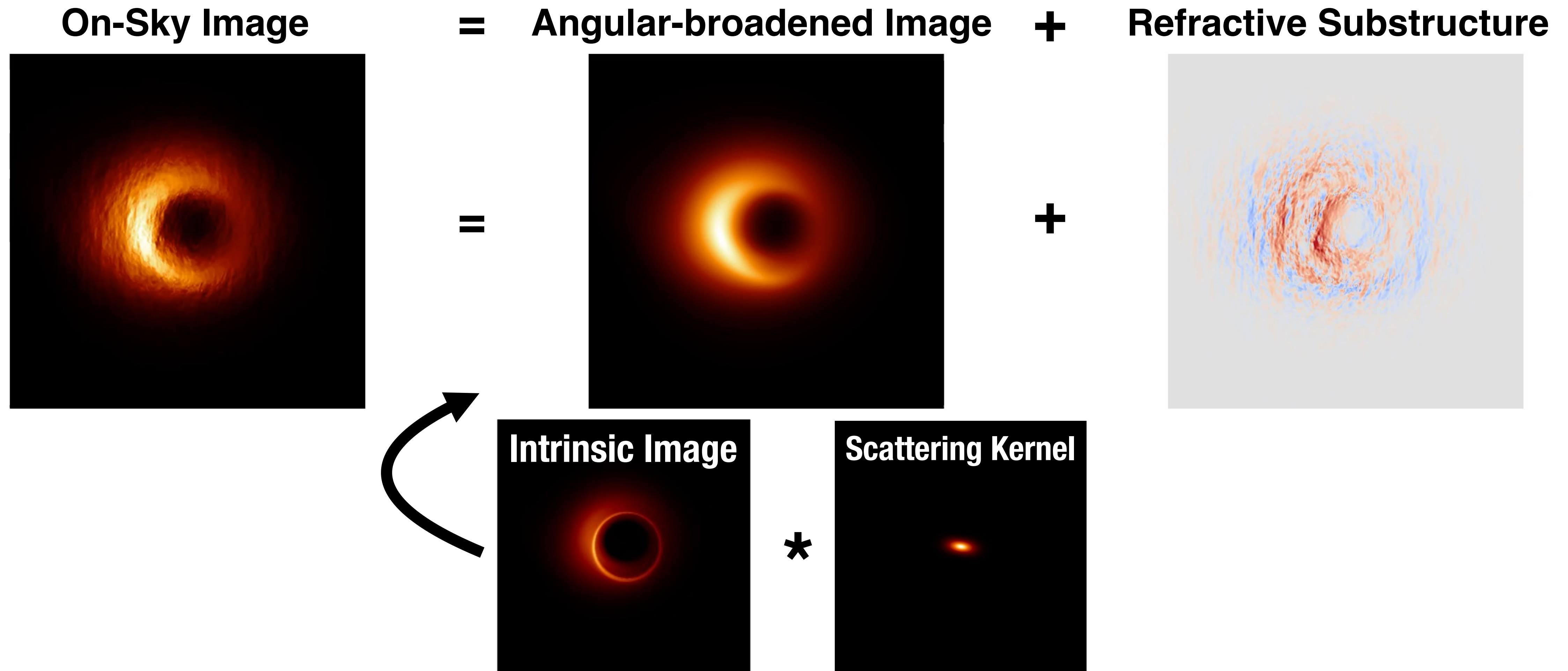
+



We treated the residuals as noises in the Fourier domain

Georgiev et al. 2022, Broderick et al. 2022, EHT Collaboration et al. 2022 Paper III, IV
Simulation: EHT Collaboration et al. 2022 Paper V
Slide by Kazu Akiyama@MIT

Dealing with Scattering : Scattering Mitigation



Refractive substructures appear as Gaussian noises in the Fourier domain

Johnson & Gwinn 2014, Johnson & Narayan 2016, Johnson et al. 2018, Psaltis et al. 2018

Image methods used for $Sgr A^*$ imaging

Traditional Method

CLEAN

DIFMAP (Shepherd+97, 98, 03)

Model

General Pixelated Images
Residual Calibration Gains

Hyper Parameters

Image Assumptions

Scattering Parameters

Variability Parameters

New Imaging Methods

Regularized Maximum Likelihood (RML)

eht-imaging (Chael+16, 18)

Model

General Pixelated Images

Hyper Parameters

Image Assumptions

Scattering Parameters

Variability Parameters

SMILI (Akiyama+17a, b)

Model

General Pixelated Images
Residual Calibration Gains

Hyper Parameters

Image Assumptions

Scattering Parameters

Variability Parameters

Bayesian Imaging

THEMIS (Broderick+20a, b)

More Restrictive Model

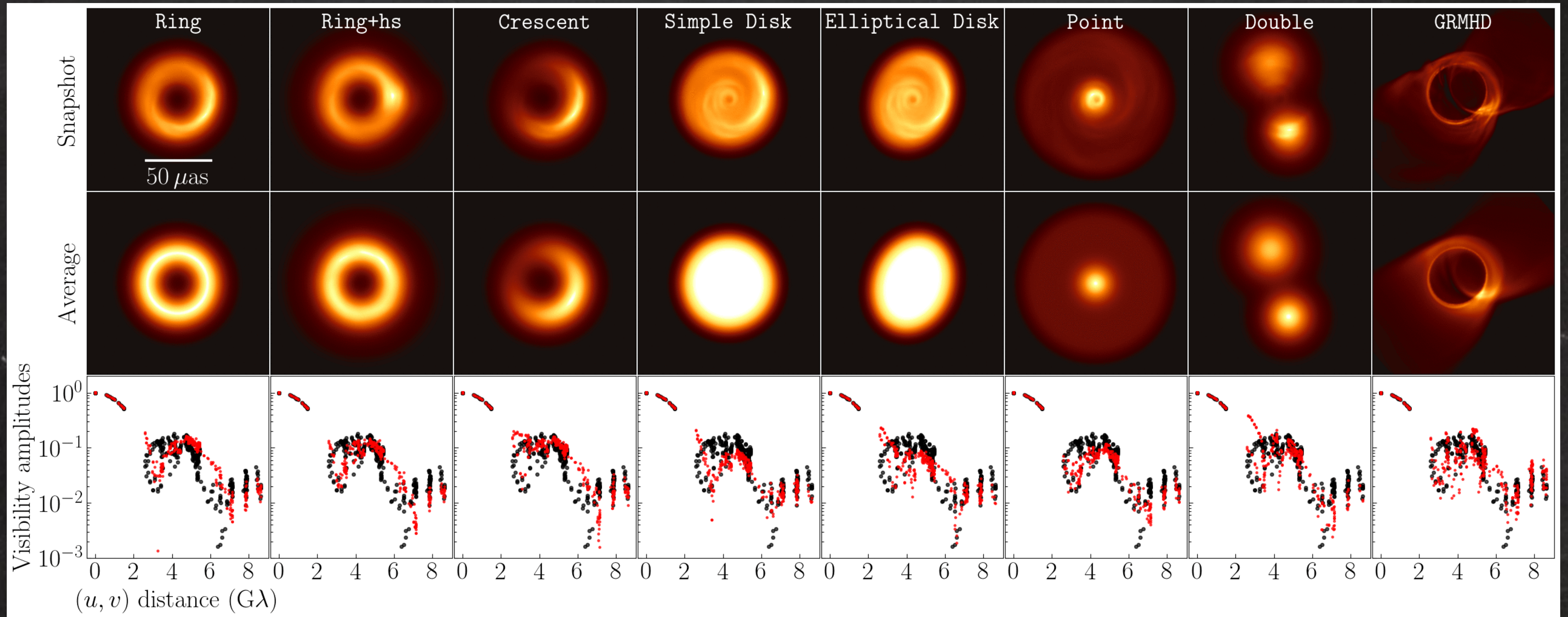
Low-resolution Pixel Images
Residual Calibration Gains
Scattering Parameters
Variability Parameters
Field of View / Grid
Orientations

Hyper parameters

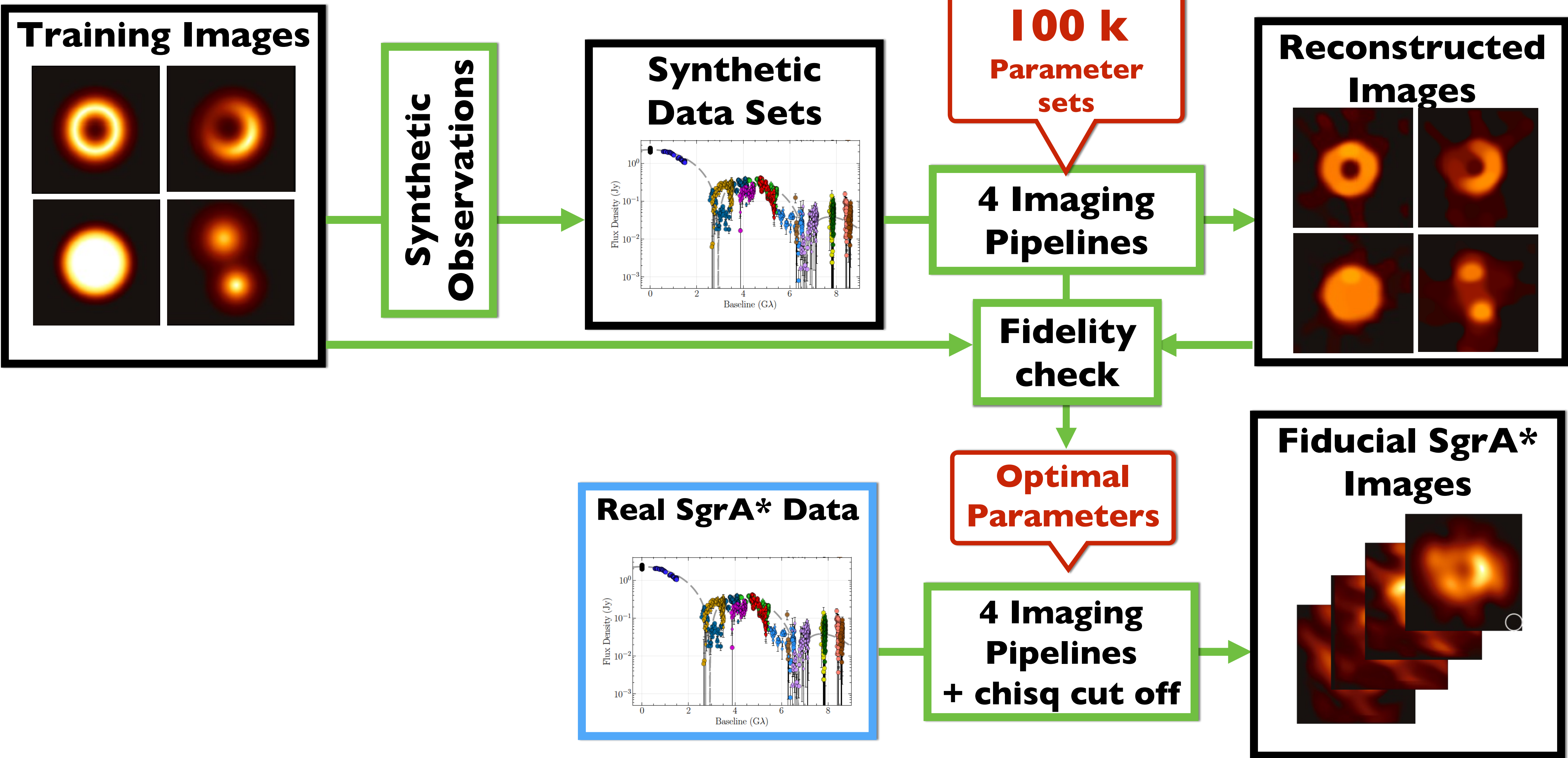
Number of Image Pixels



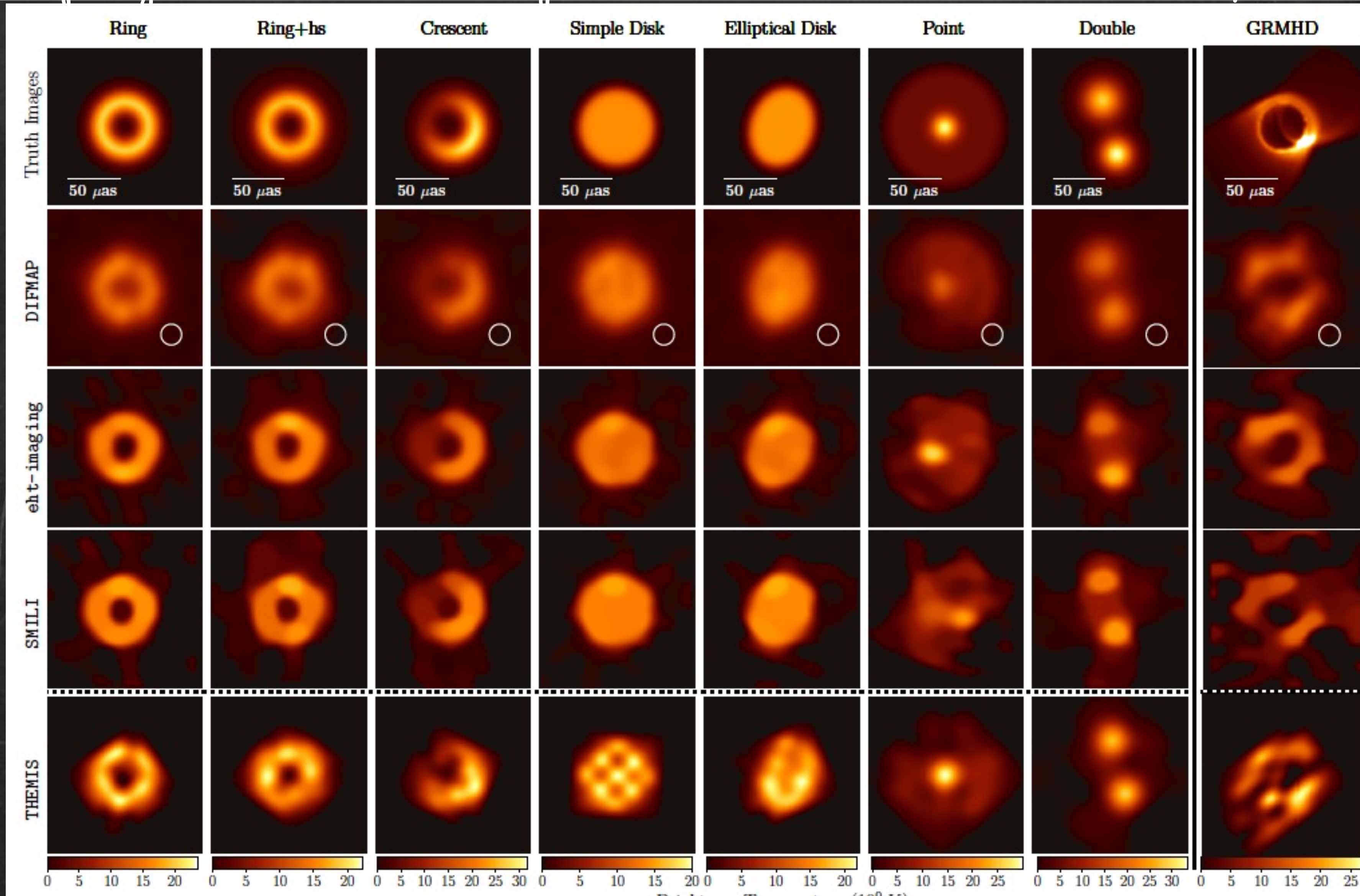
Can imaging methods distinguish these?

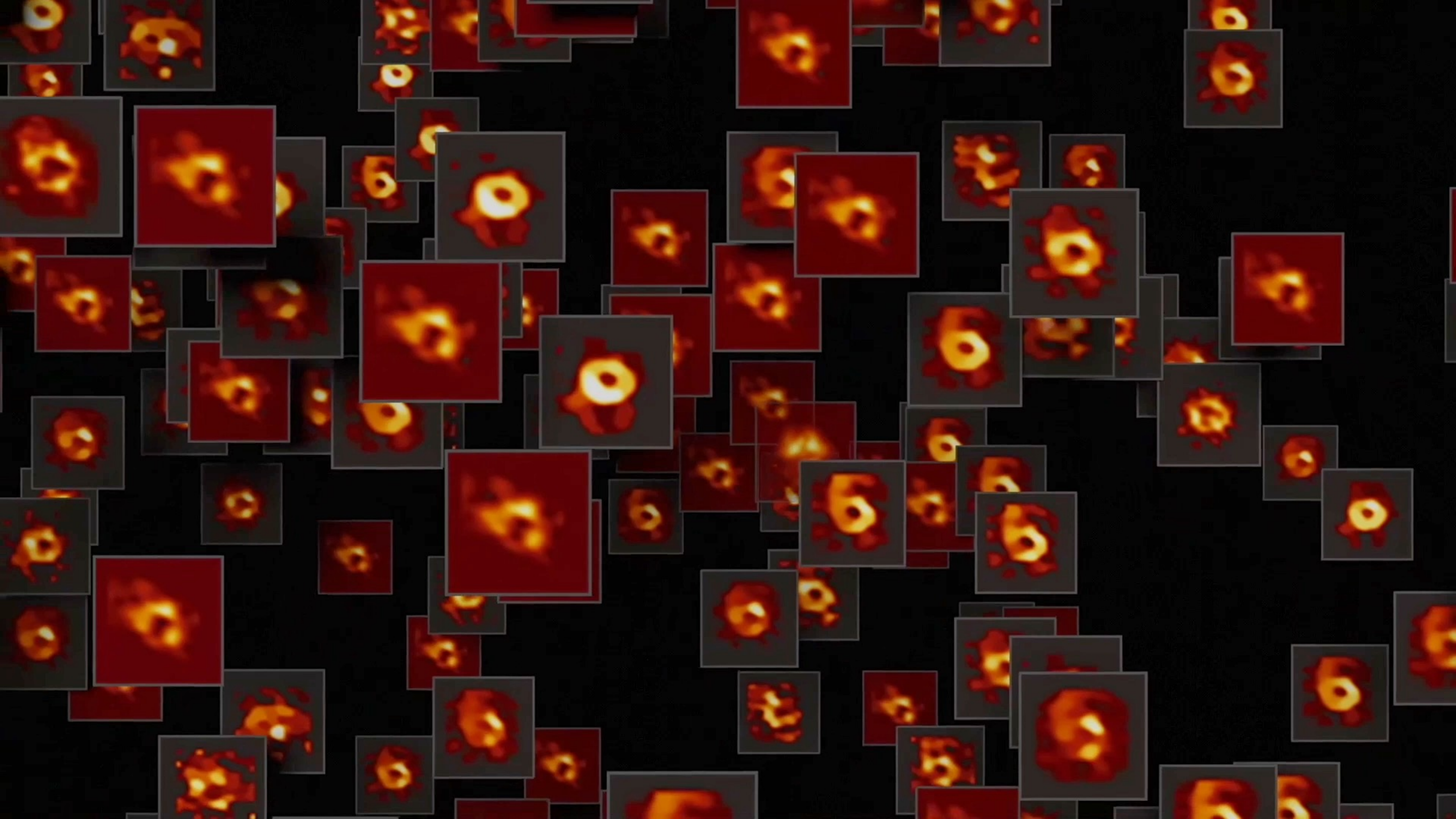


Imaging Process

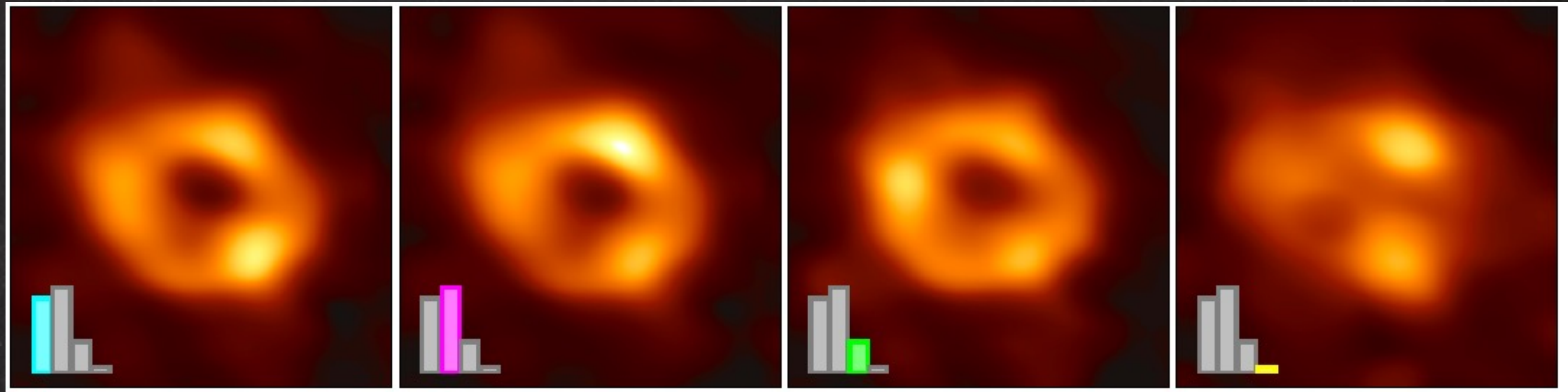


Can imaging methods distinguish these? Yes they can!





Ring or Non-ring?



Among 10,000 reconstructions, 3% are non-ring.

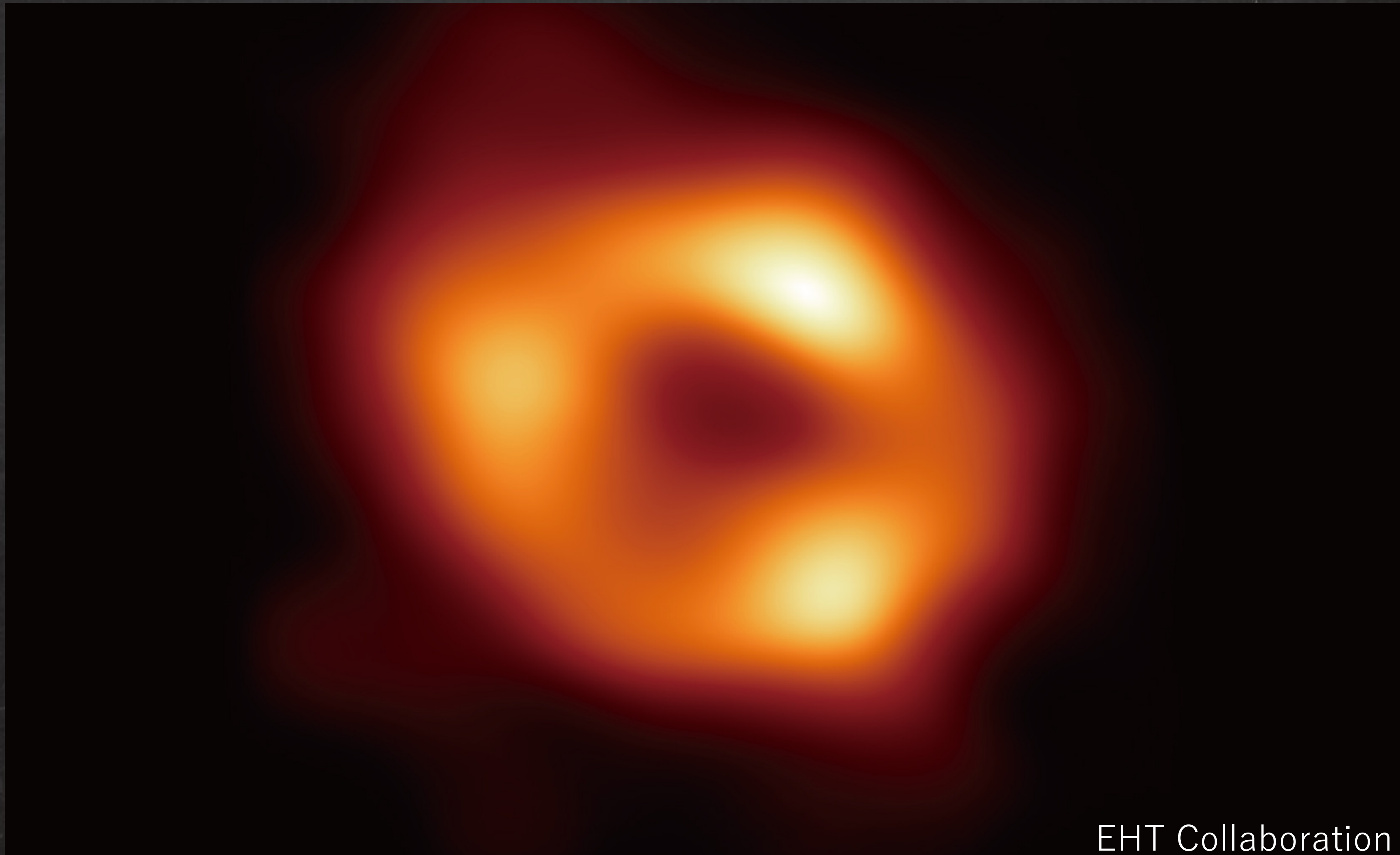
SgrA* is non-ring? - - - Not likely - GRMHD simulations

Scattering made it non-ring? - Not likely - WO scattering mitigation
most of images are ring

Time variability made it no-ring - Very Likely - GRMHD



Released Sgr A* image



- ① Introduction
- ② Supermassive Blackhole and Photon Ring
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- ④ Radio Interferometry
- ⑤ M87* imaging
- ⑥ SgrA* imaging
- ⑦ Conclusion

Conclusion

Big and difficult project

2 years for M87 image 2+3 years for Sgr A* image

Big question and direct answer

Visual clue for general relativity prediction



Conclusion

As a data scientist

Developing new imaging method.

Discussing how to build a scientific claim from data

Huge collaboration

Very Exciting.



Event Horizon Telescope



Observation

April, 2018

7 locations

9 telescopes

Credit: NRAO, AUI, NSF



Event Horizon Telescope

13 September 2022, IAU-IAA

Event Horizon Telescope



Observation

April, 2021, 2022

9 locations

11 telescopes



Event Horizon Telescope

Credit: Thalia Traianou

13 September 2022, IAU-IAA

Conclusion

Data Science

=

Building a claim from data

ML methods, Statistics

Designing Experiments

Big Data



Fun Part.

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Black Holes | The Edge of All We Know

2021 | | 1h 39m | US Movies

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