

Pegasus Users Group

MEETING



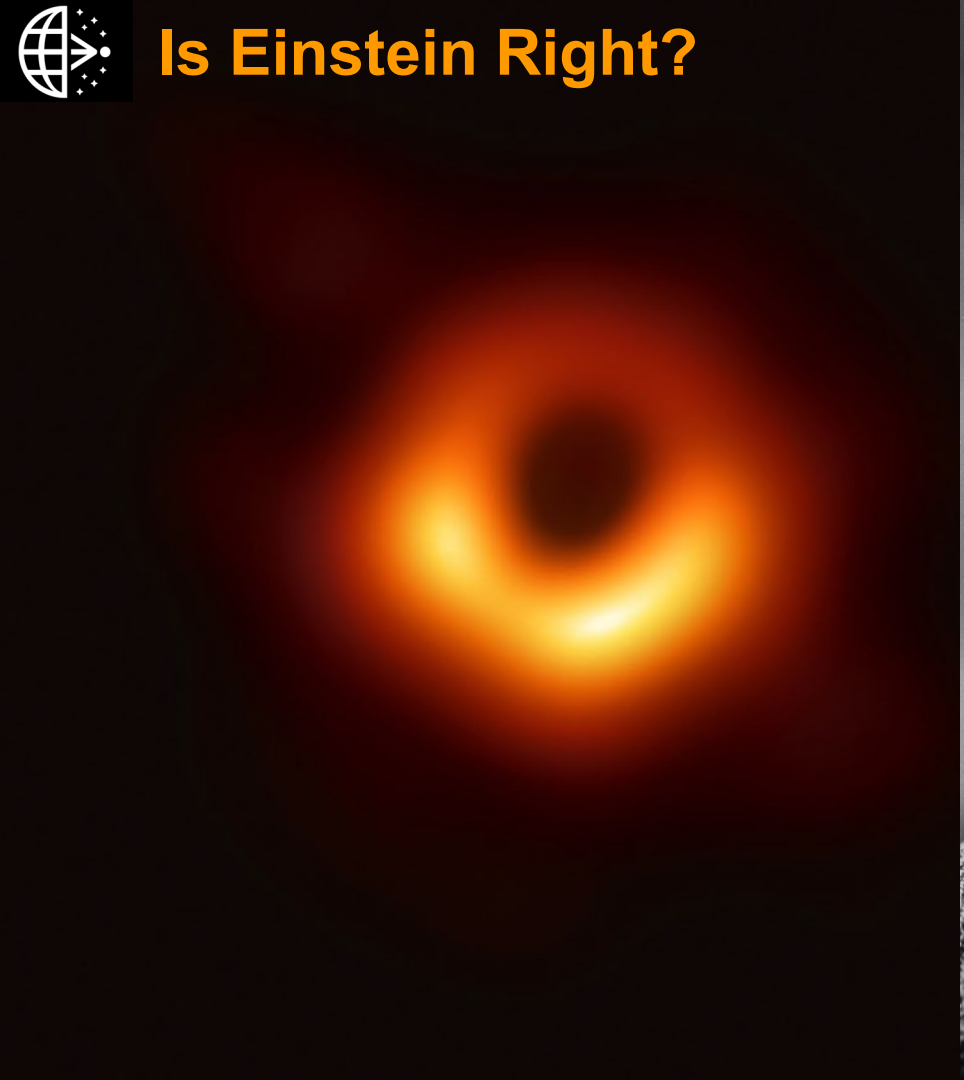
Connecting Observation and Theory: Black Hole Modeling with Large Scale Synthetic Data Generation

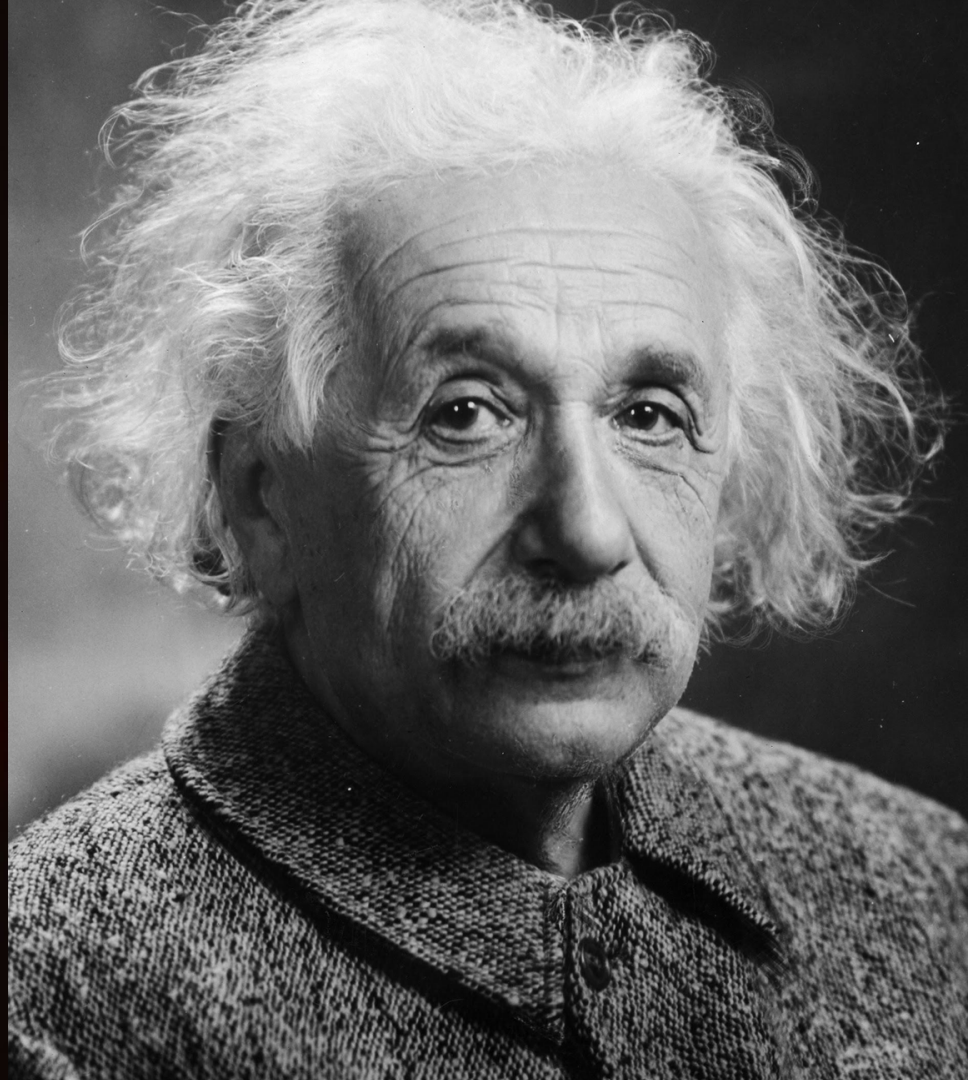
Chi-kwan Chan, Michael Janssen, et al.

Assistant Astronomer, University of Arizona
Event Horizon Telescope Collaboration

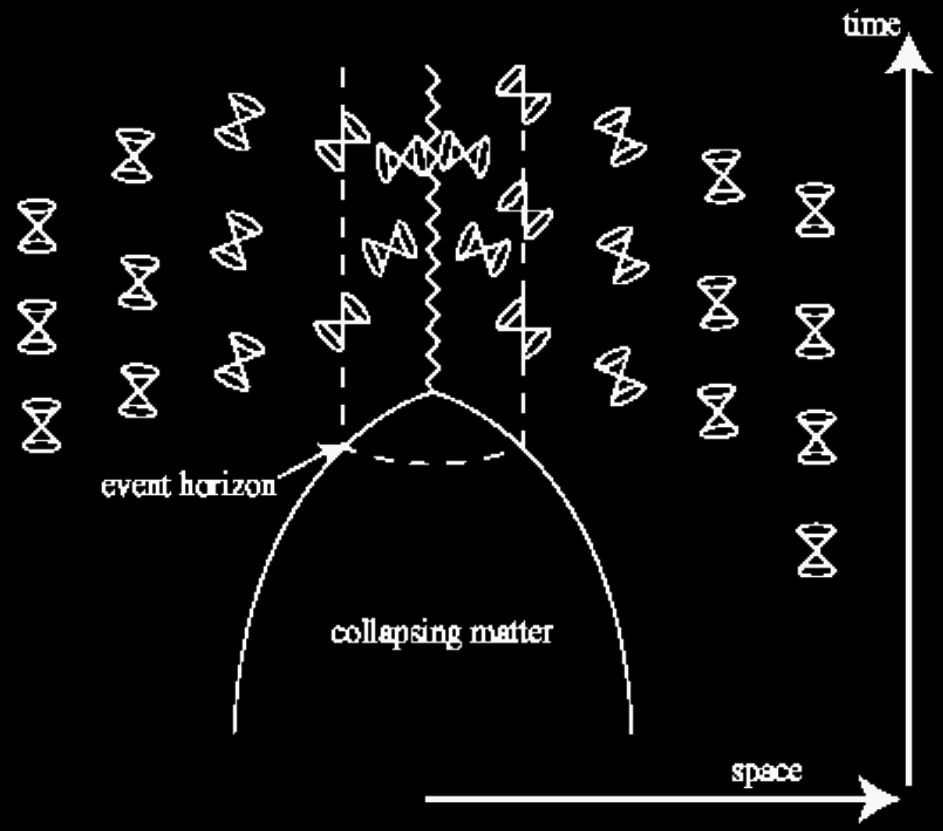
February 23rd, 2021

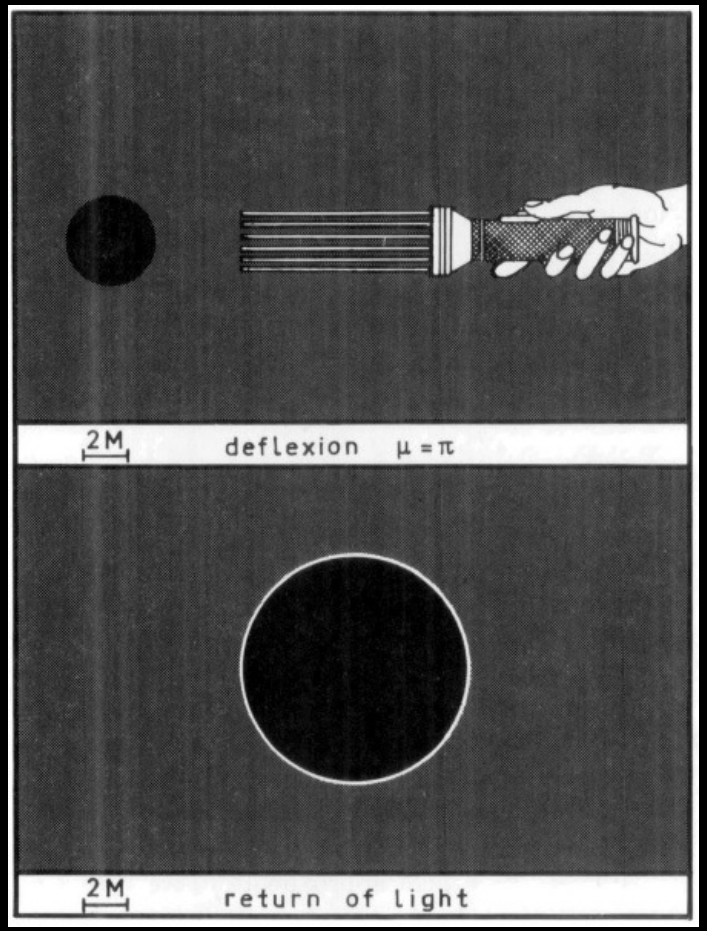
Is Einstein Right?





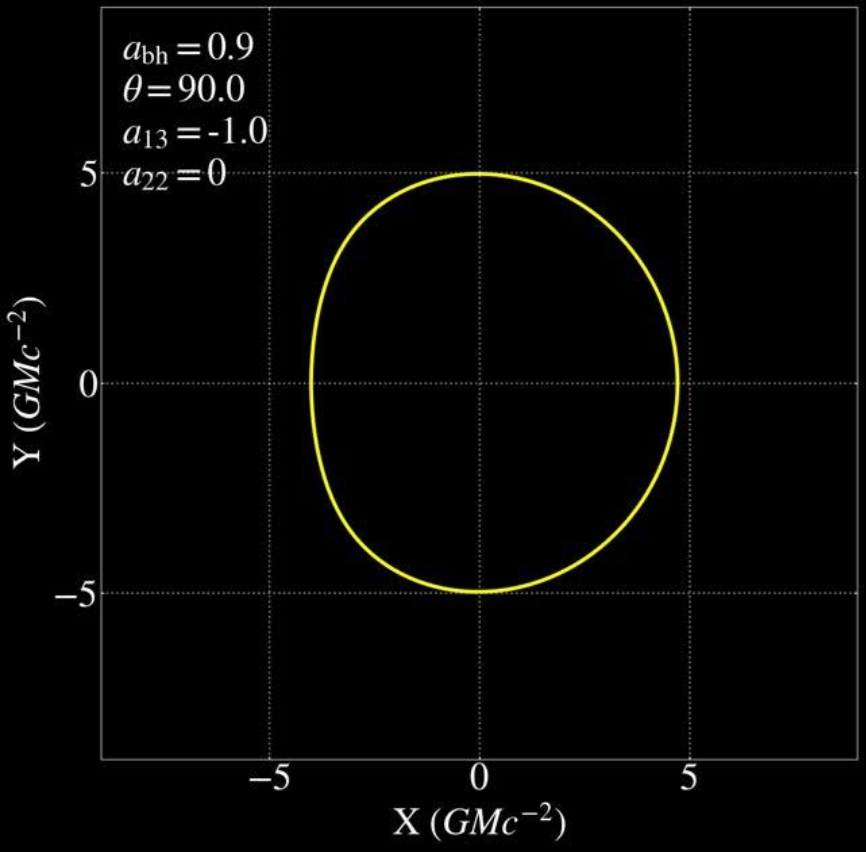
Black Hole Shadow

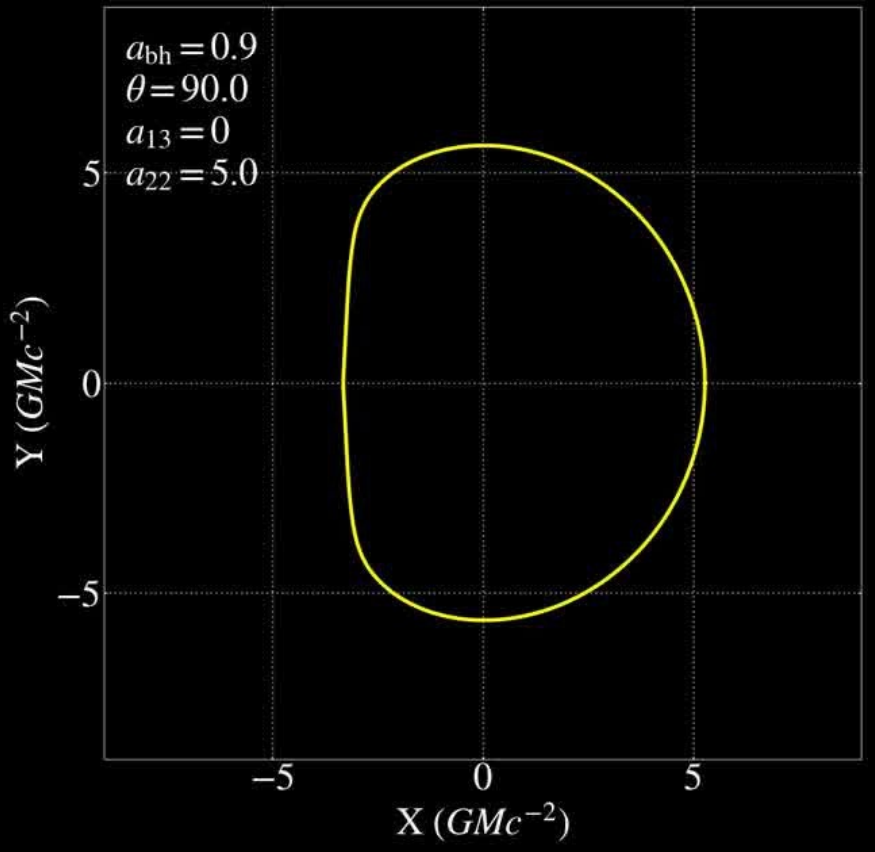




Bardeen 1973, Luminet 1979

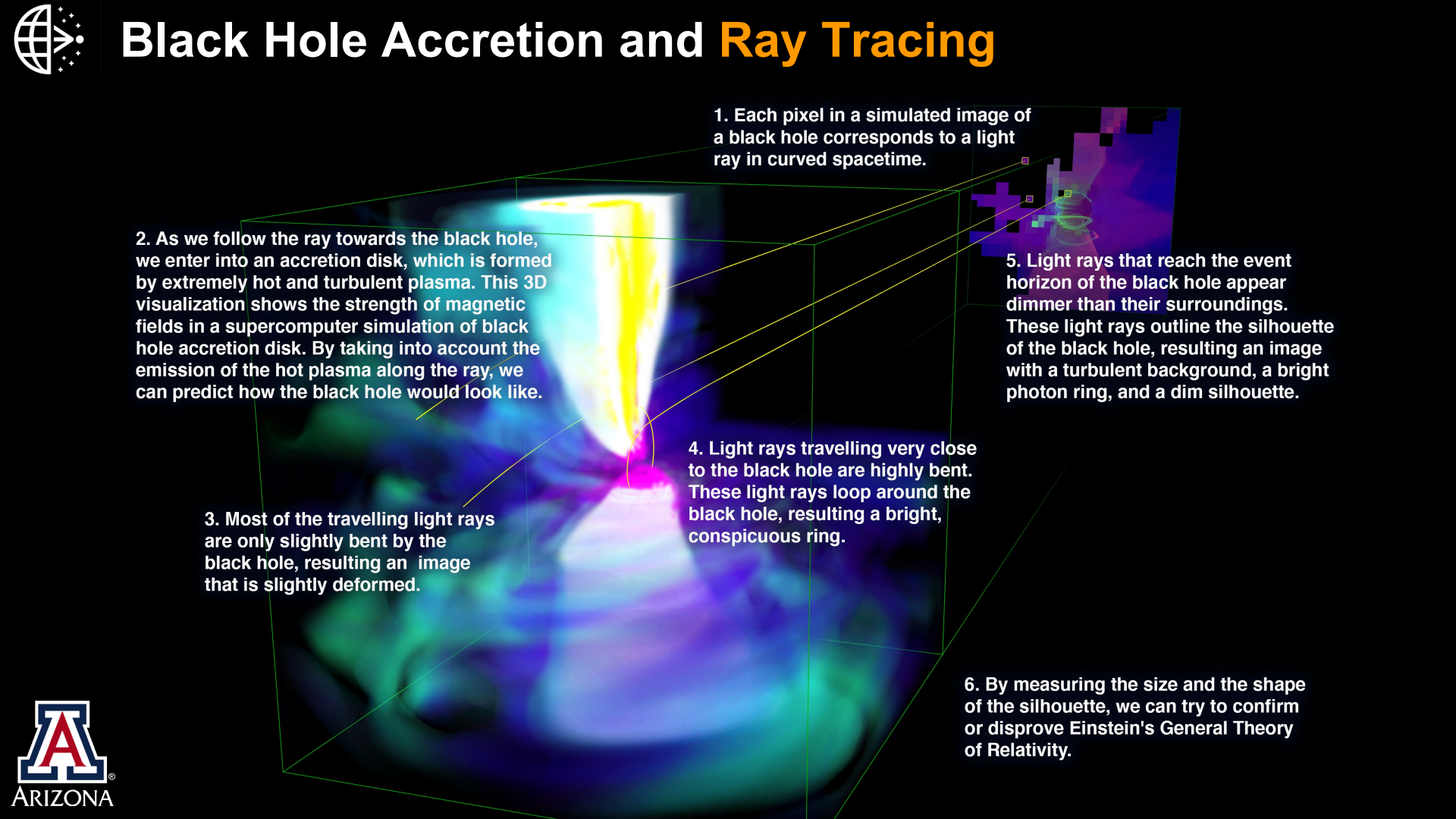
Derivation from Circular Shadows in Other Gravity





Johannsen & Psaltis 2010
Medeiros, Psaltis, & Ozel 2019

Black Hole Accretion and Ray Tracing



1. Each pixel in a simulated image of a black hole corresponds to a light ray in curved spacetime.

2. As we follow the ray towards the black hole, we enter into an accretion disk, which is formed by extremely hot and turbulent plasma. This 3D visualization shows the strength of magnetic fields in a supercomputer simulation of black hole accretion disk. By taking into account the emission of the hot plasma along the ray, we can predict how the black hole would look like.

3. Most of the travelling light rays are only slightly bent by the black hole, resulting an image that is slightly deformed.

4. Light rays travelling very close to the black hole are highly bent. These light rays loop around the black hole, resulting a bright, conspicuous ring.

5. Light rays that reach the event horizon of the black hole appear dimmer than their surroundings. These light rays outline the silhouette of the black hole, resulting an image with a turbulent background, a bright photon ring, and a dim silhouette.

6. By measuring the size and the shape of the silhouette, we can try to confirm or disprove Einstein's General Theory of Relativity.

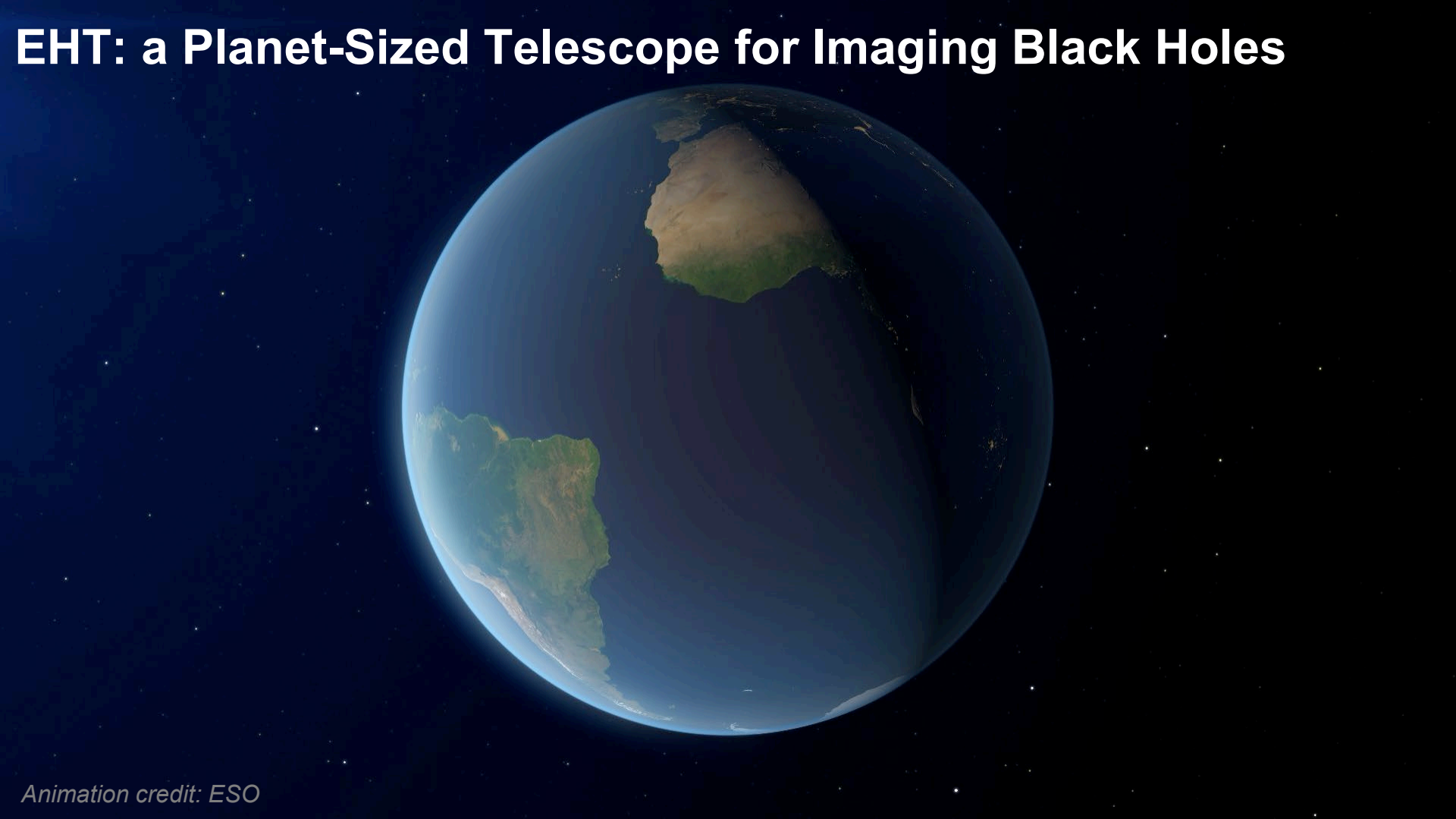
ARIZONA

The Event Horizon Telescope Collaboration



207 members, 59 institutes, 18 countries in Europe, Asia, Africa, North and South America.

EHT: a Planet-Sized Telescope for Imaging Black Holes

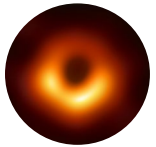


Animation credit: ESO

VLBI Introduction

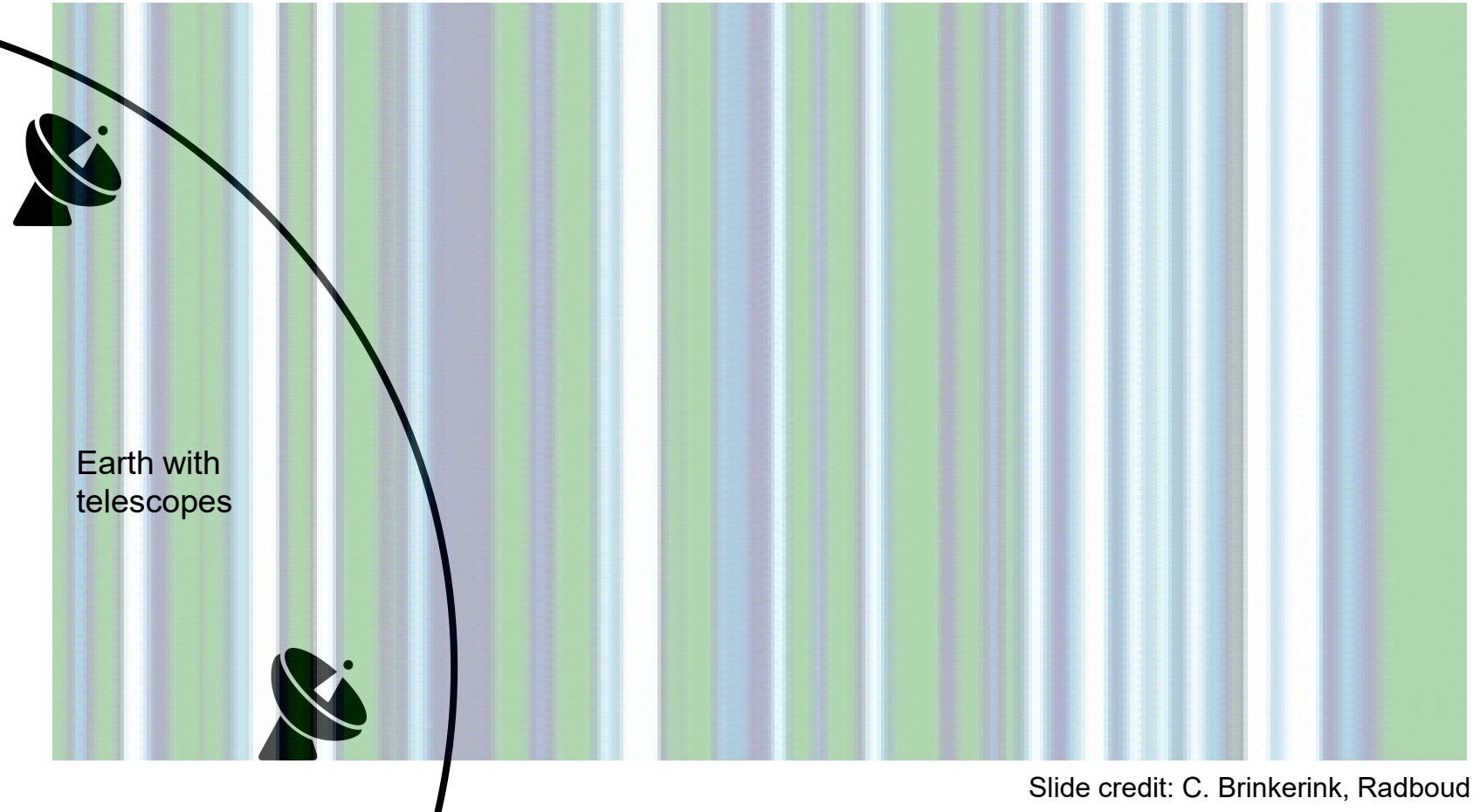
Earth with telescopes

Source

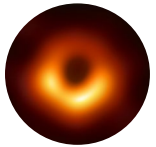


Slide credit: C. Brinkerink, Radboud

VLBI Introduction

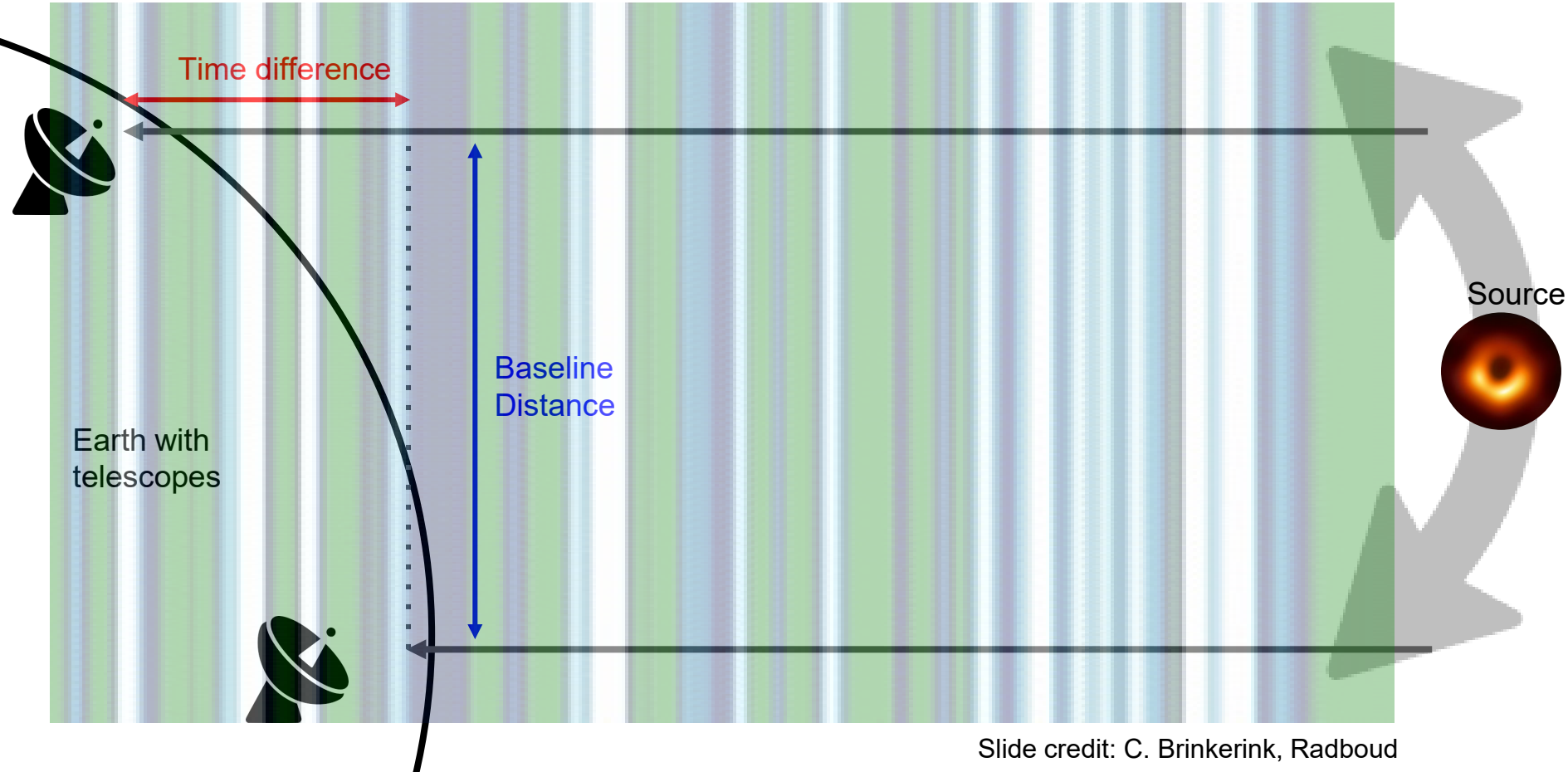


Source



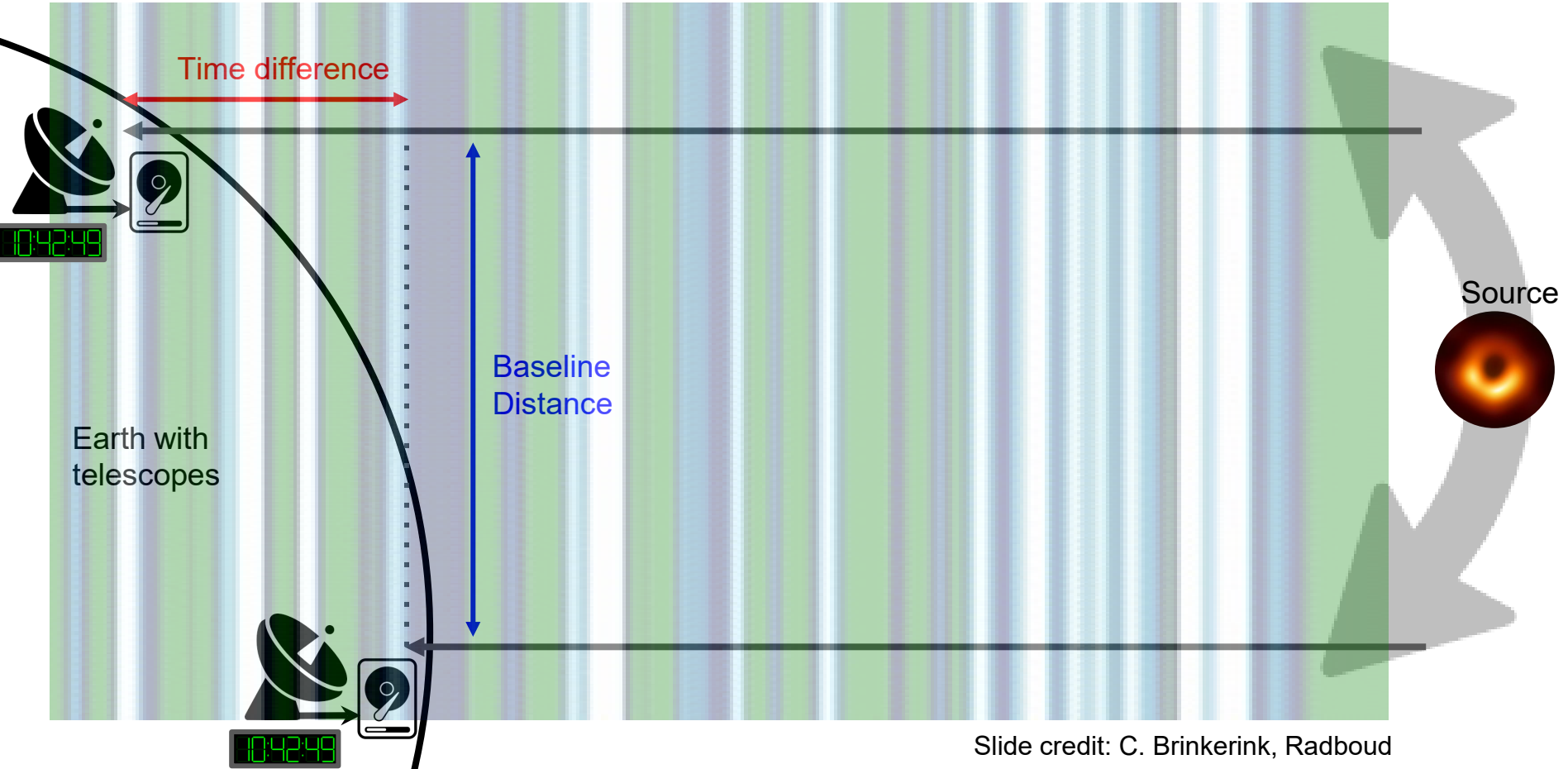
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VLBI Introduction



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VLBI Introduction

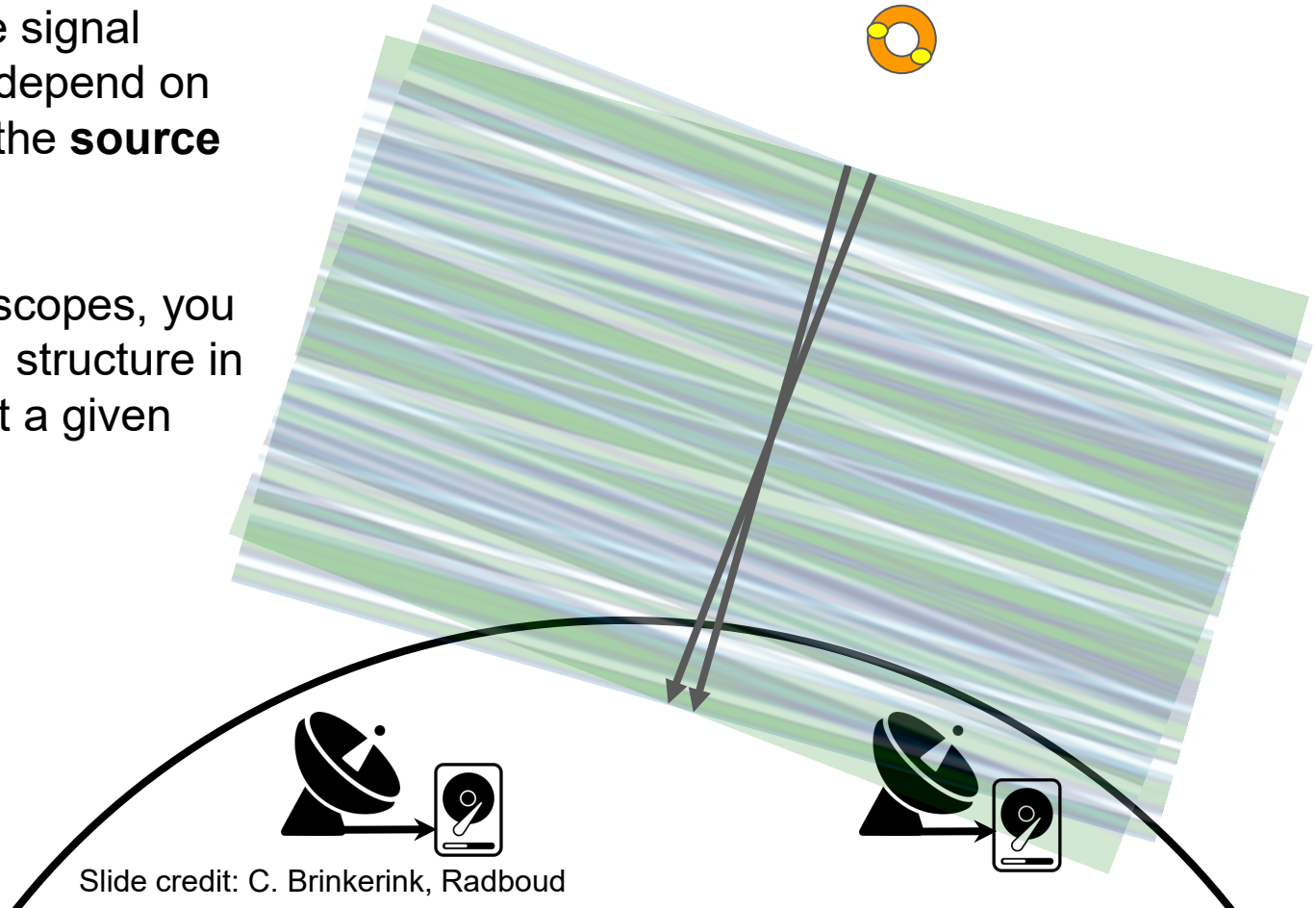


Slide credit: C. Brinkerink, Radboud

VLBI Introduction

The similarities of the signal between telescopes depend on their **distance** - and the **source structure**!

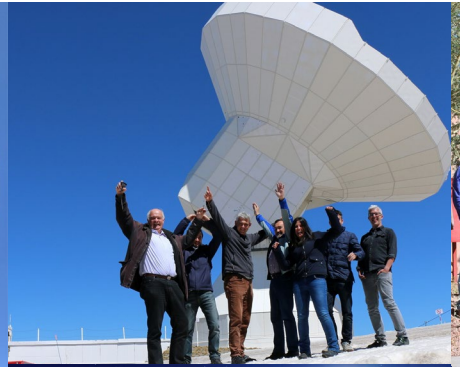
Note: per pair of telescopes, you obtain information on structure in one given direction at a given time.



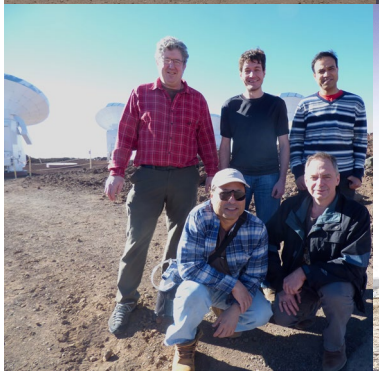
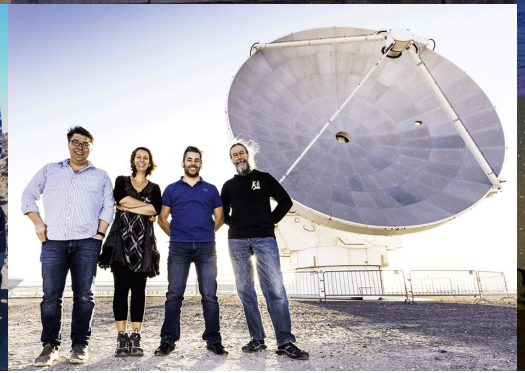
Slide credit: C. Brinkerink, Radboud

The 2017 observations

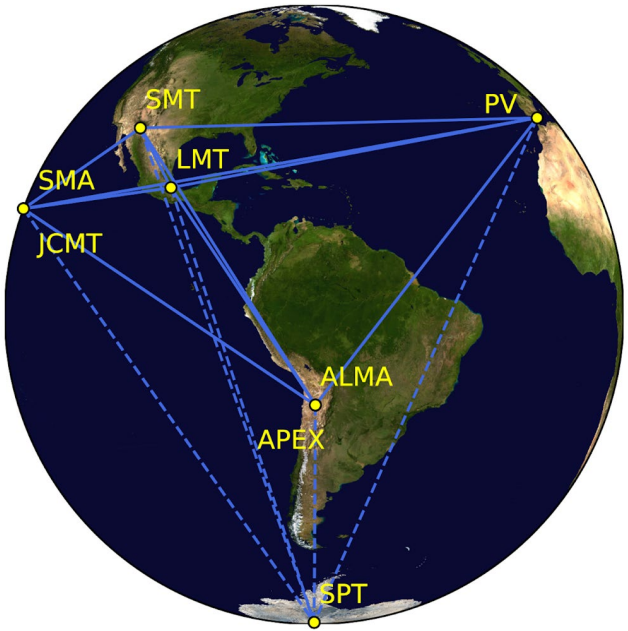




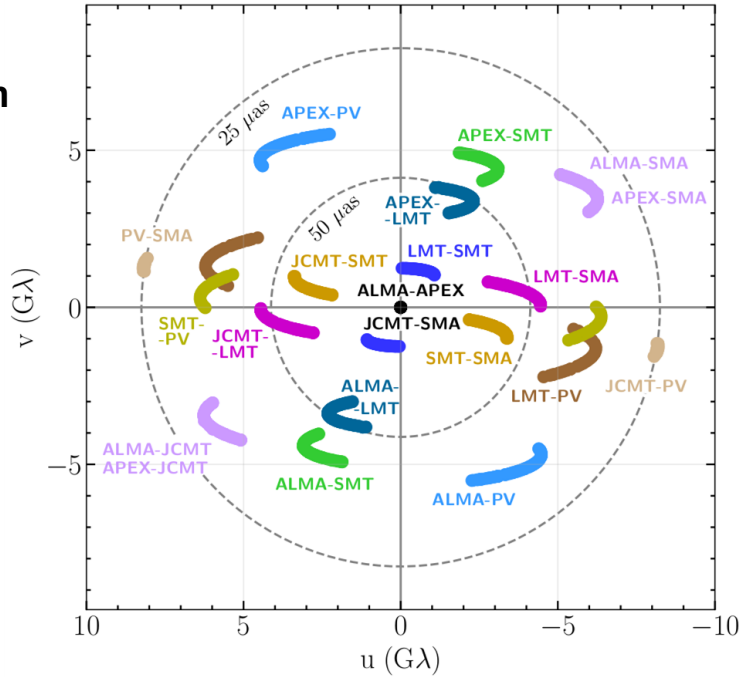



Calibration Process

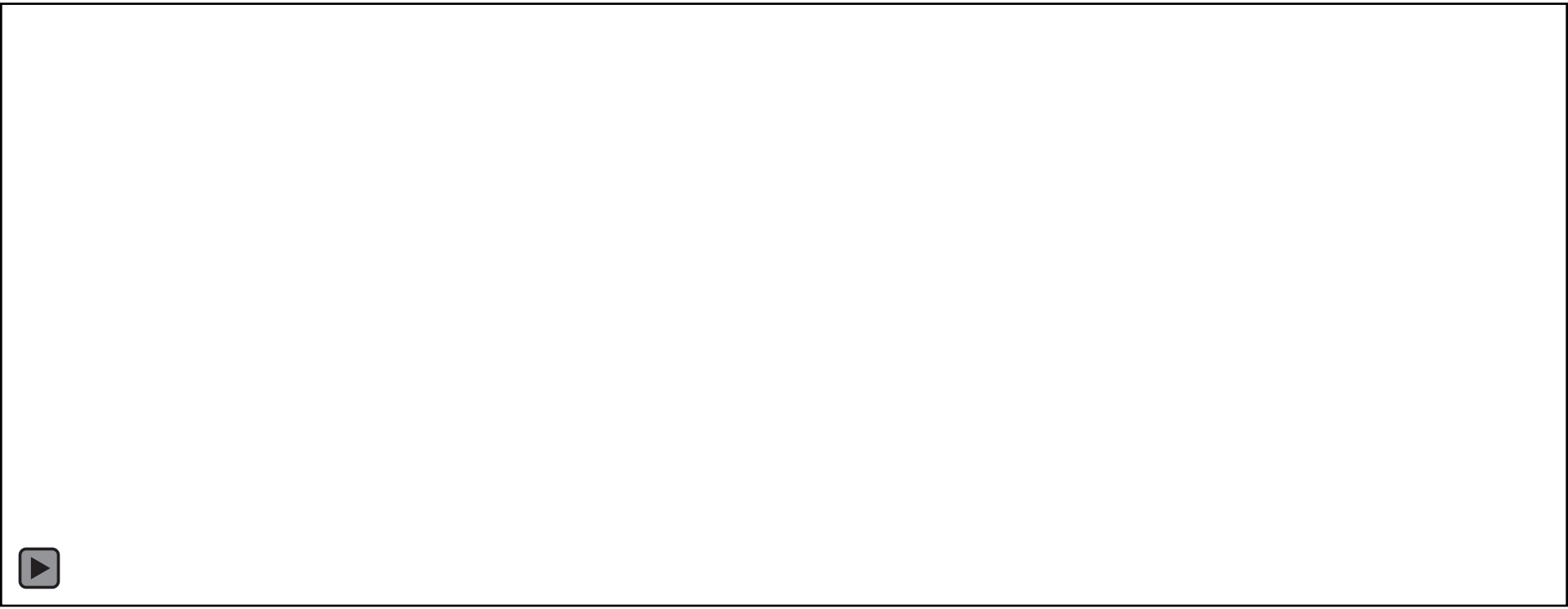


How do we get from correlated data to imageable data?



EHTC+ 2019, ApJL, 875, L3 (Paper III)

The Data Path



The Data Path

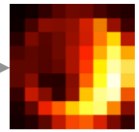


Raw signals
[PB]

Correlation
[TB]

Calibration
[MB]

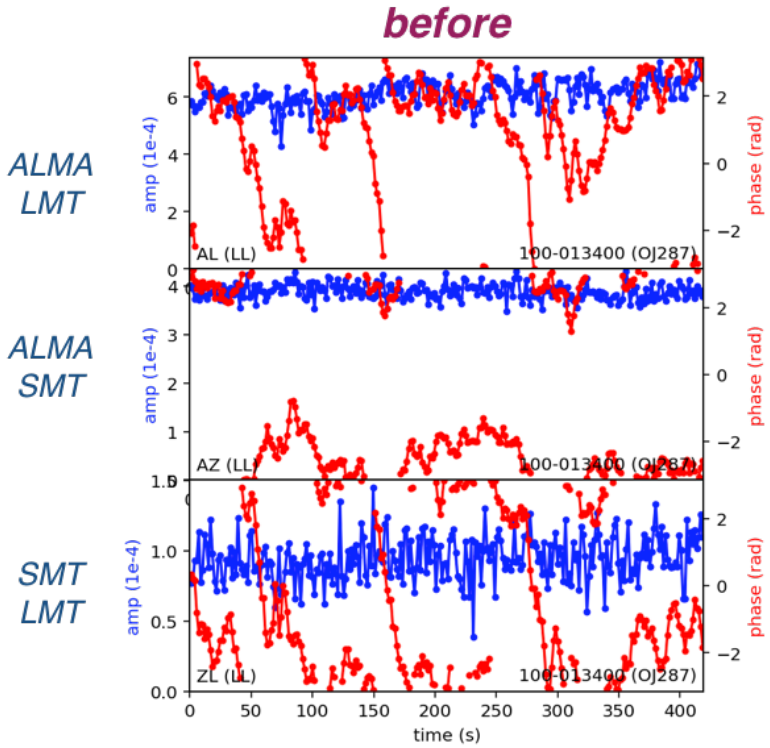
Image
[kB]



12 orders of magnitude in data reduction!

Phase Calibration

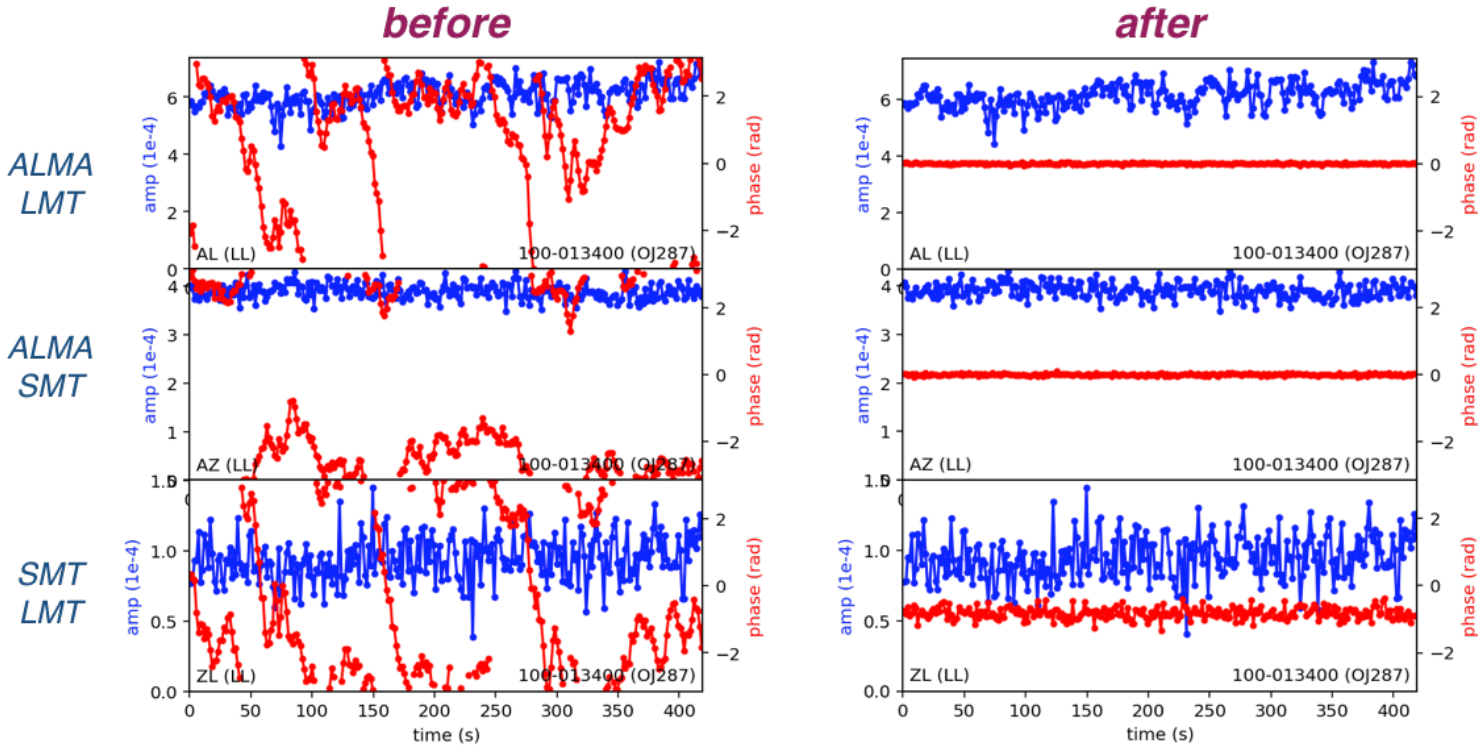
Refined corrections of imperfect correlation and removal of the effects of the atmosphere result in **more stable, stronger detections**



source structure phase varies on ~hour
but can only average for ~few seconds due to atmosphere

Phase Calibration

Refined corrections of imperfect correlation and removal of the effects of the atmosphere result in **more stable, stronger detections**

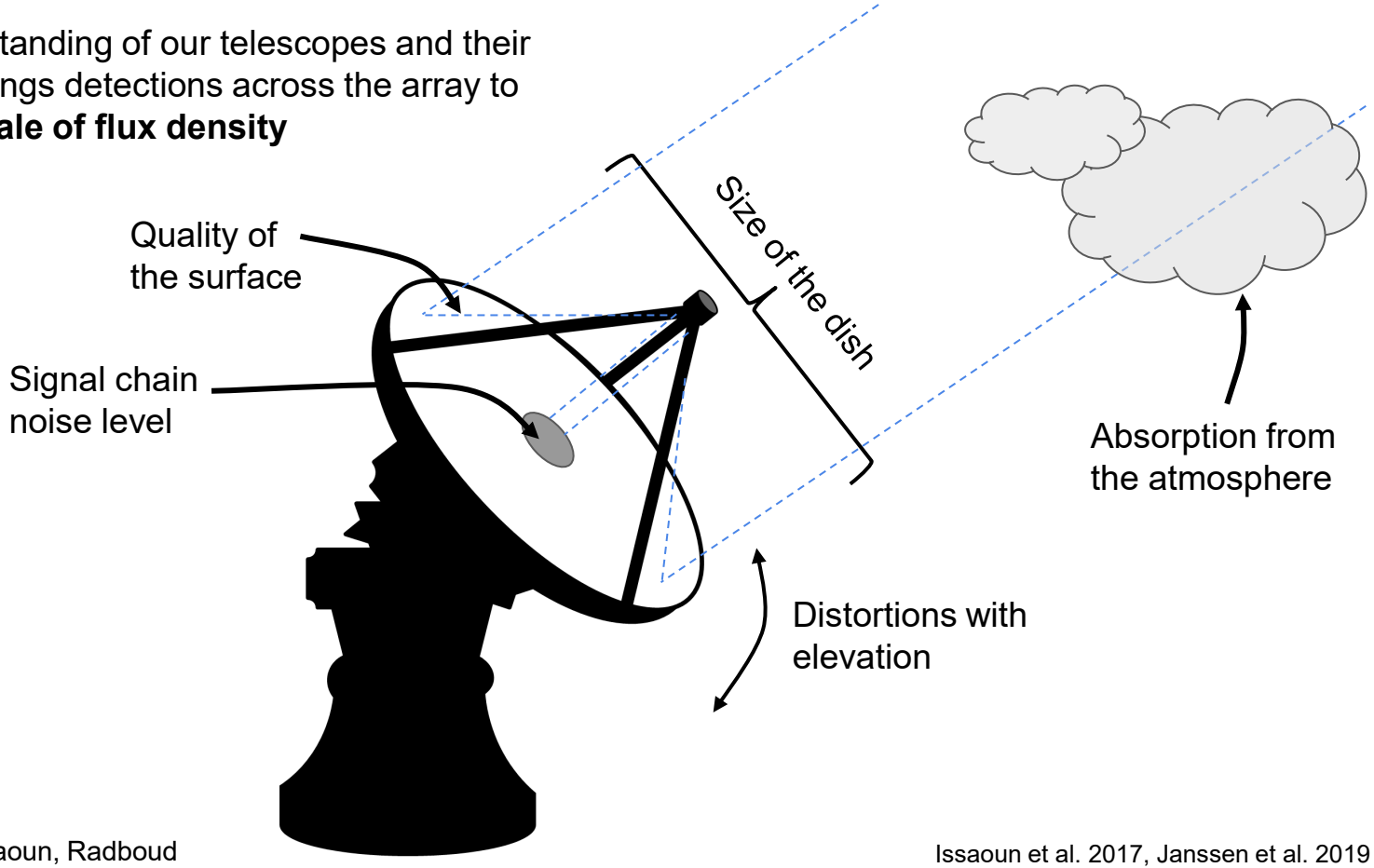


source structure phase varies on ~hour
but can only average for ~few seconds due to atmosphere

can average for entire scan

A-Priori Calibration

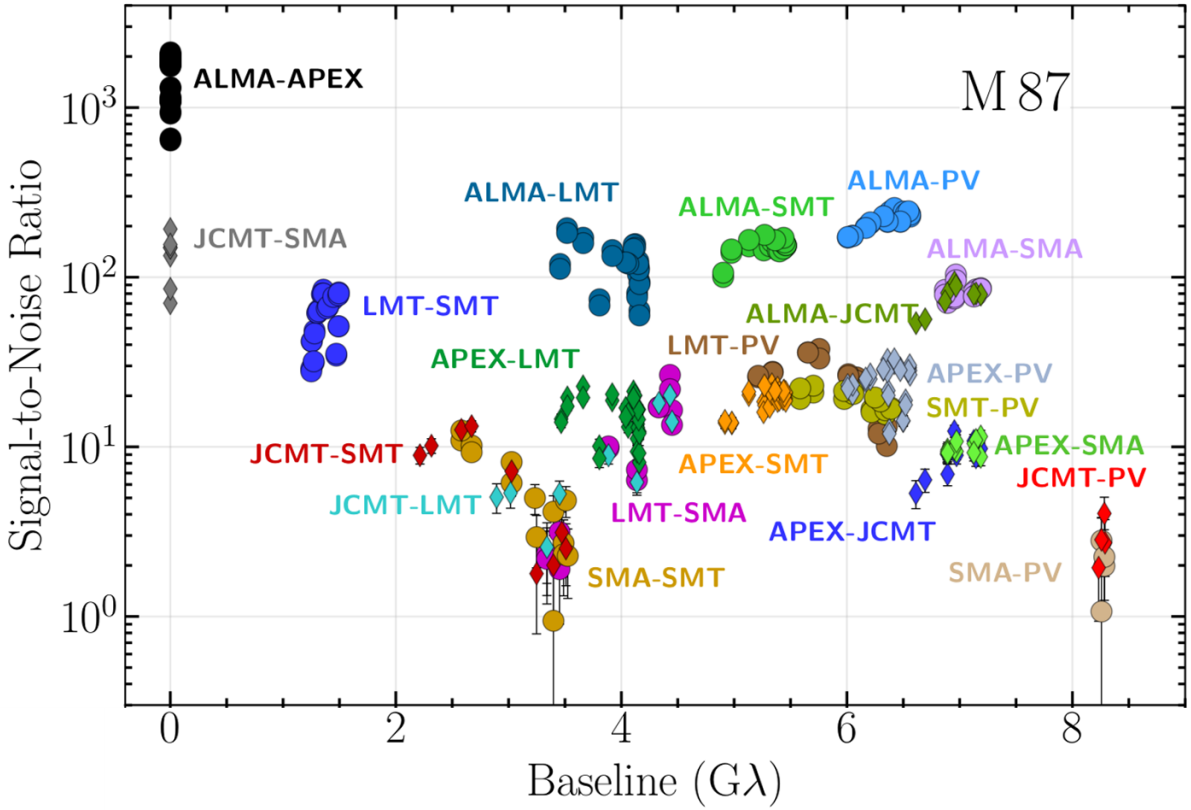
A good understanding of our telescopes and their sensitivities brings detections across the array to **a common scale of flux density**



Slide credit: S. Issaoun, Radboud

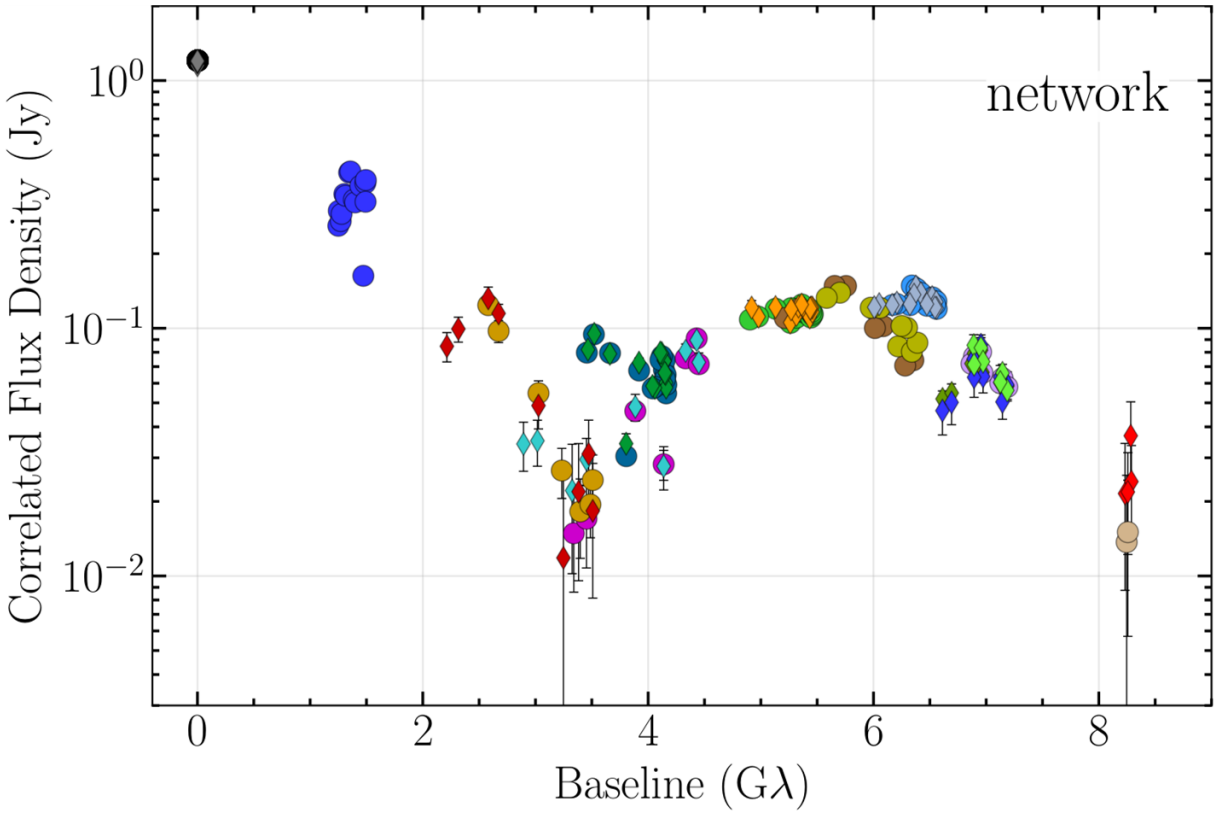
Issaoun et al. 2017, Janssen et al. 2019

M87: After Flux Calibration



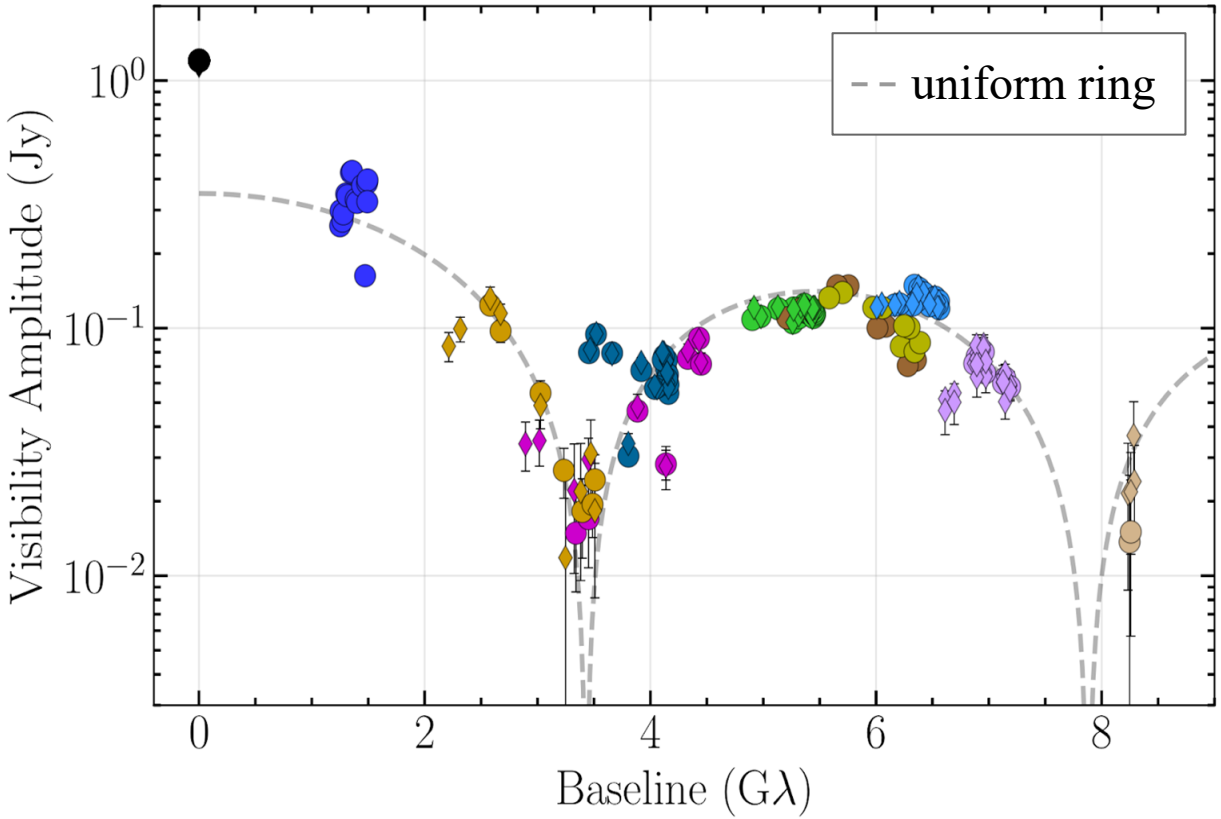
EHTC+ 2019, ApJL, 875, L3 (Paper III)

M87: After Flux Calibration



EHTC+ 2019, ApJL, 875, L3 (Paper III)

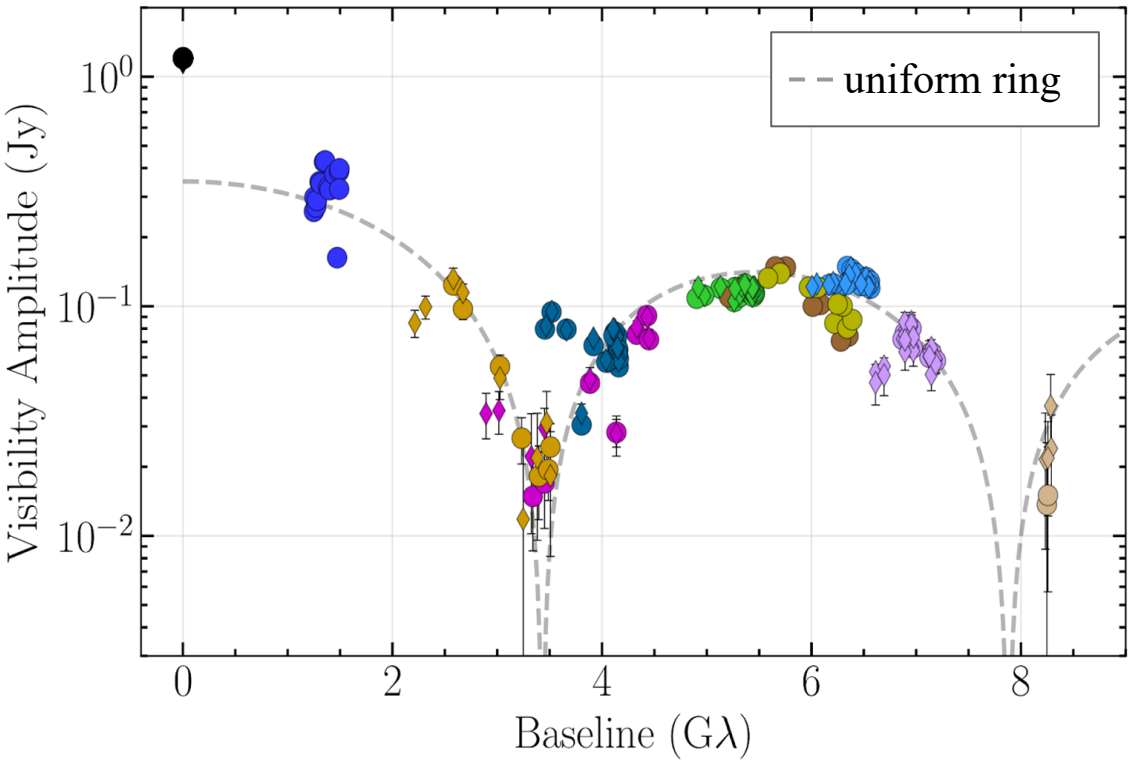
M87: After Flux Calibration



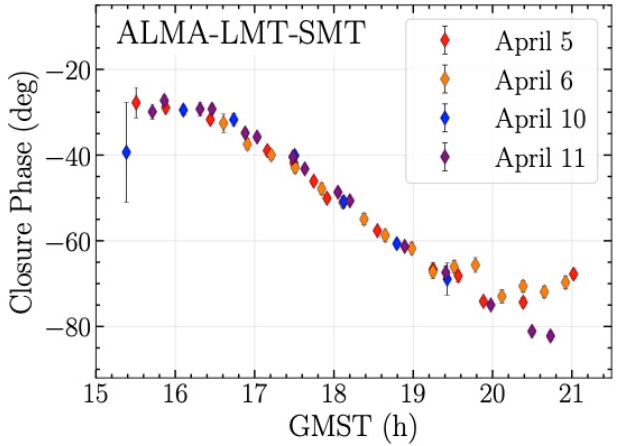
EHTC+ 2019, ApJL, 875, L3 (Paper III)

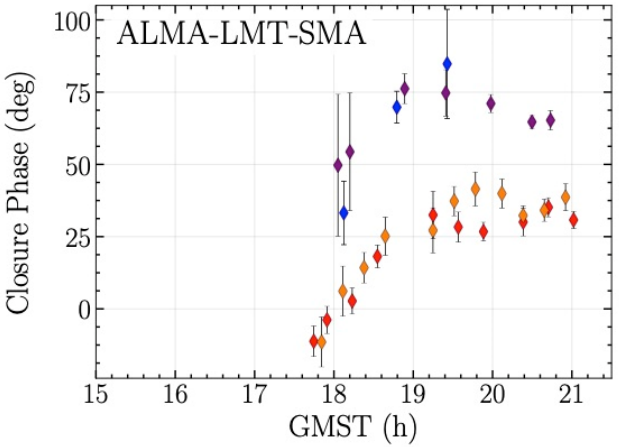
M87: Data Ready for Imaging

amplitudes



+phases

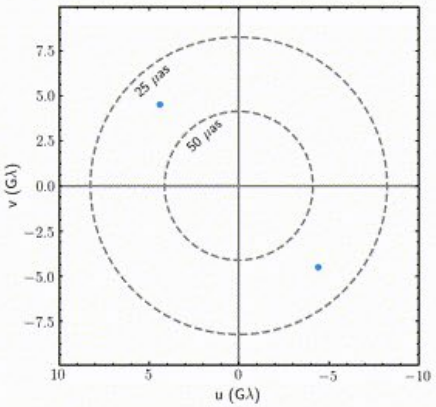




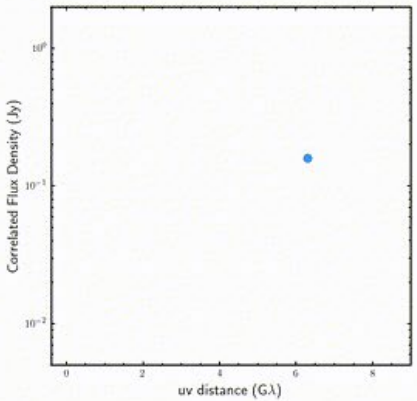
VLBI Imaging



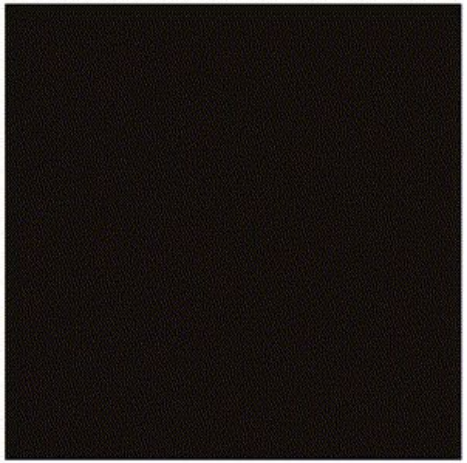
M87 becomes visible to new stations as Earth rotates



Our coverage, or “virtual mirror” fills up



We get new data that samples different size scales in the image



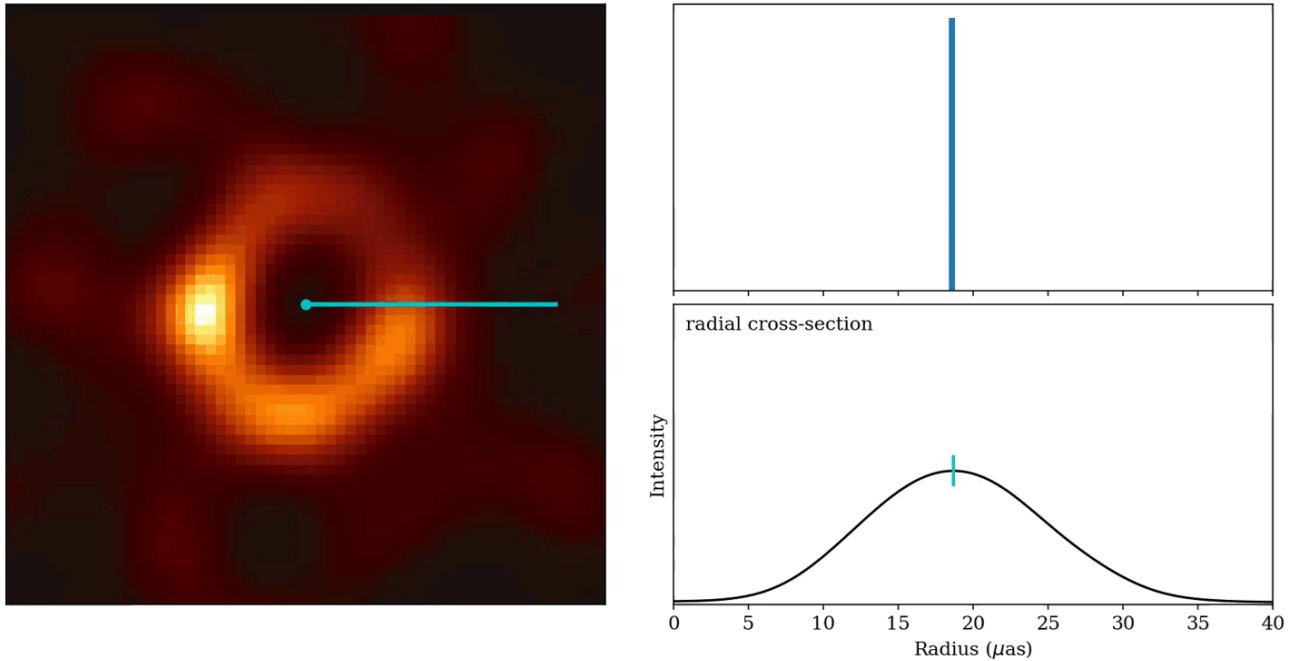
We use imaging algorithms to reconstruct an image from the sparse data

Simulation Credit: D. Palumbo, M. Wielgus

Measuring the Size of the Black Hole

We use **three** different techniques to measure the size of the black hole

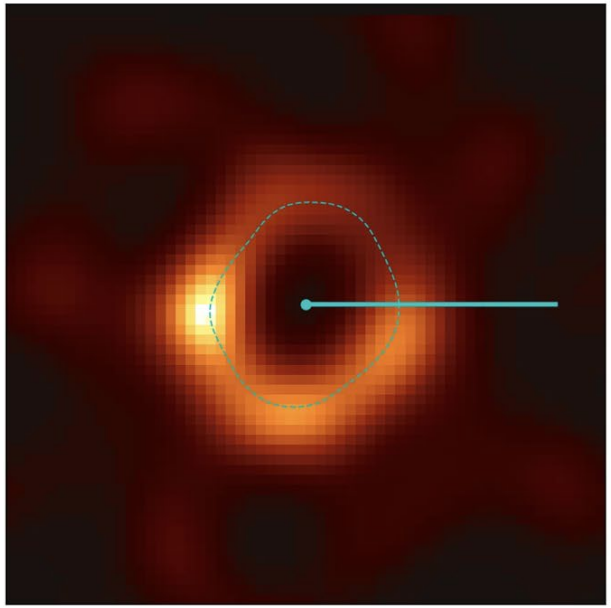
1. Measure the diameter directly from the image



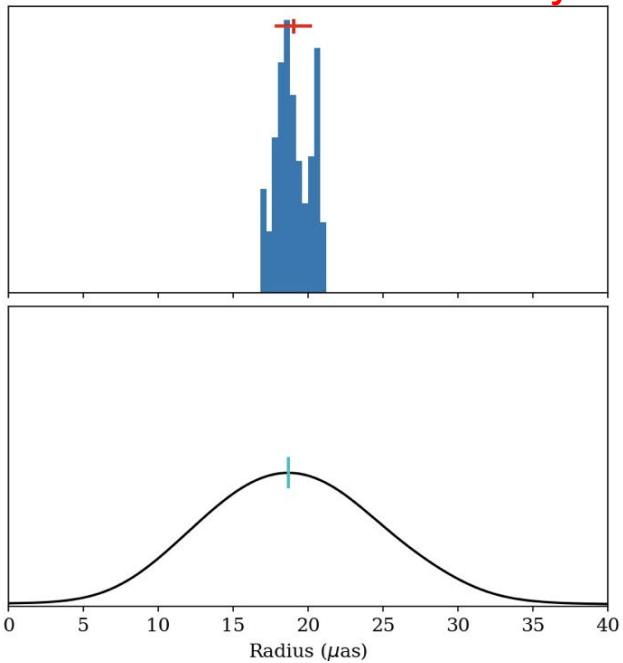
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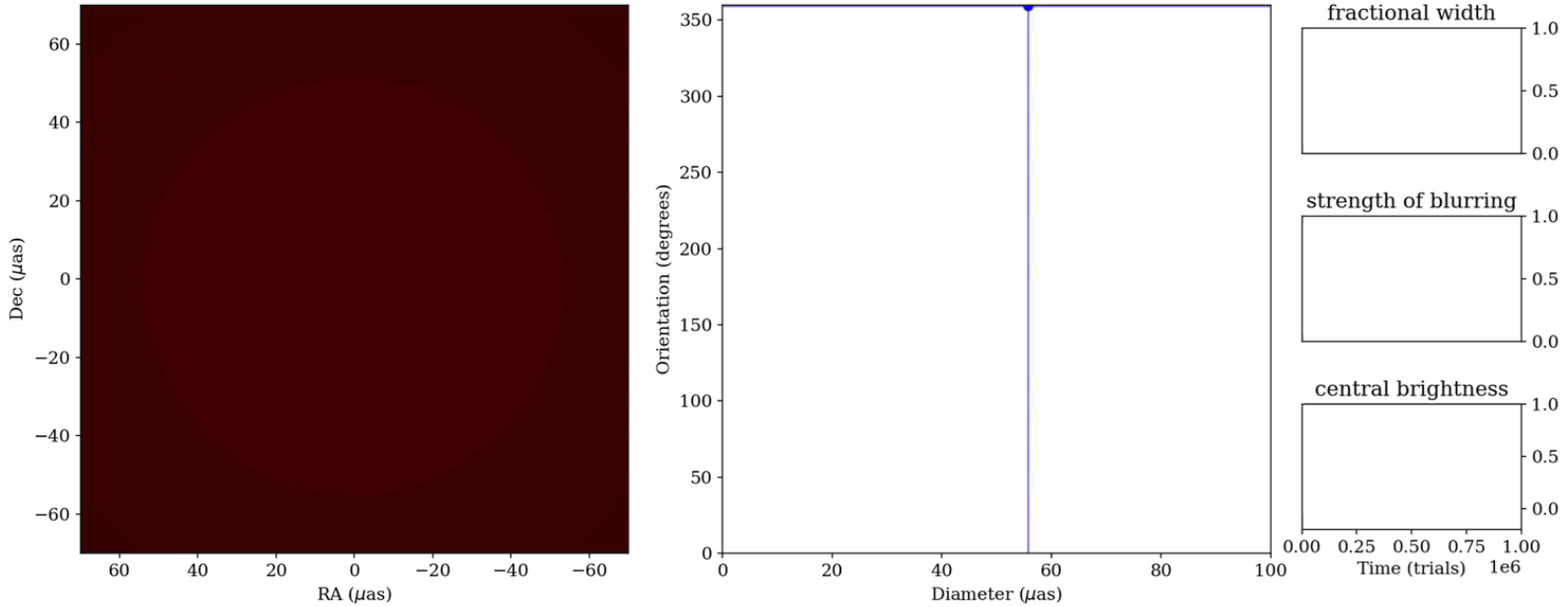
diameter and uncertainty



Measuring the Size of the Black Hole

We use **three** different techniques to measure the size of the black hole

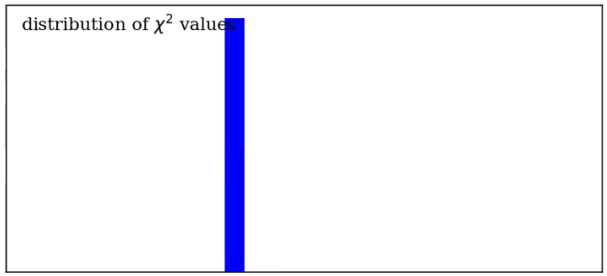
1. Measure the diameter directly from the image
2. Model the data using simple shapes

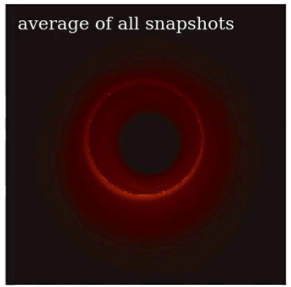


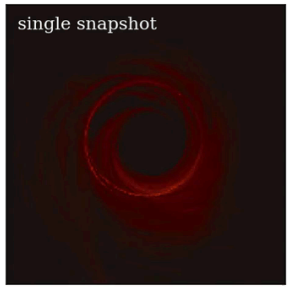
Measuring the Size of the Black Hole

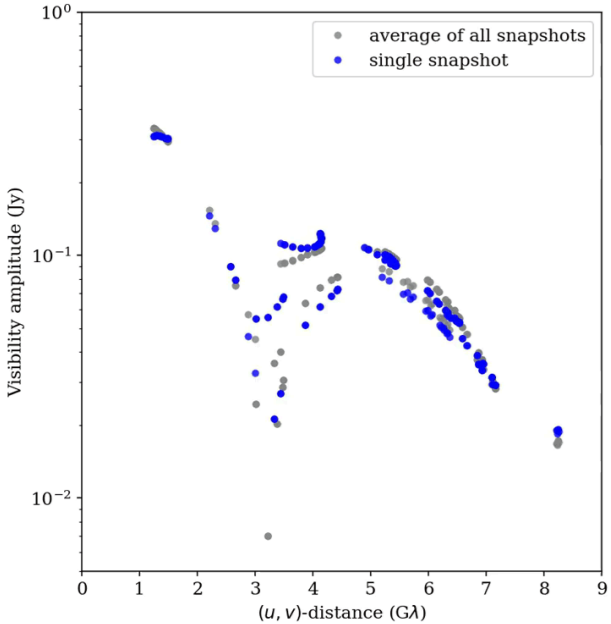
We use **three** different techniques to measure the size of the black hole

1. Measure the diameter directly from the image
2. Model the data using simple shapes
3. Fit individual frames from GRMHD simulations

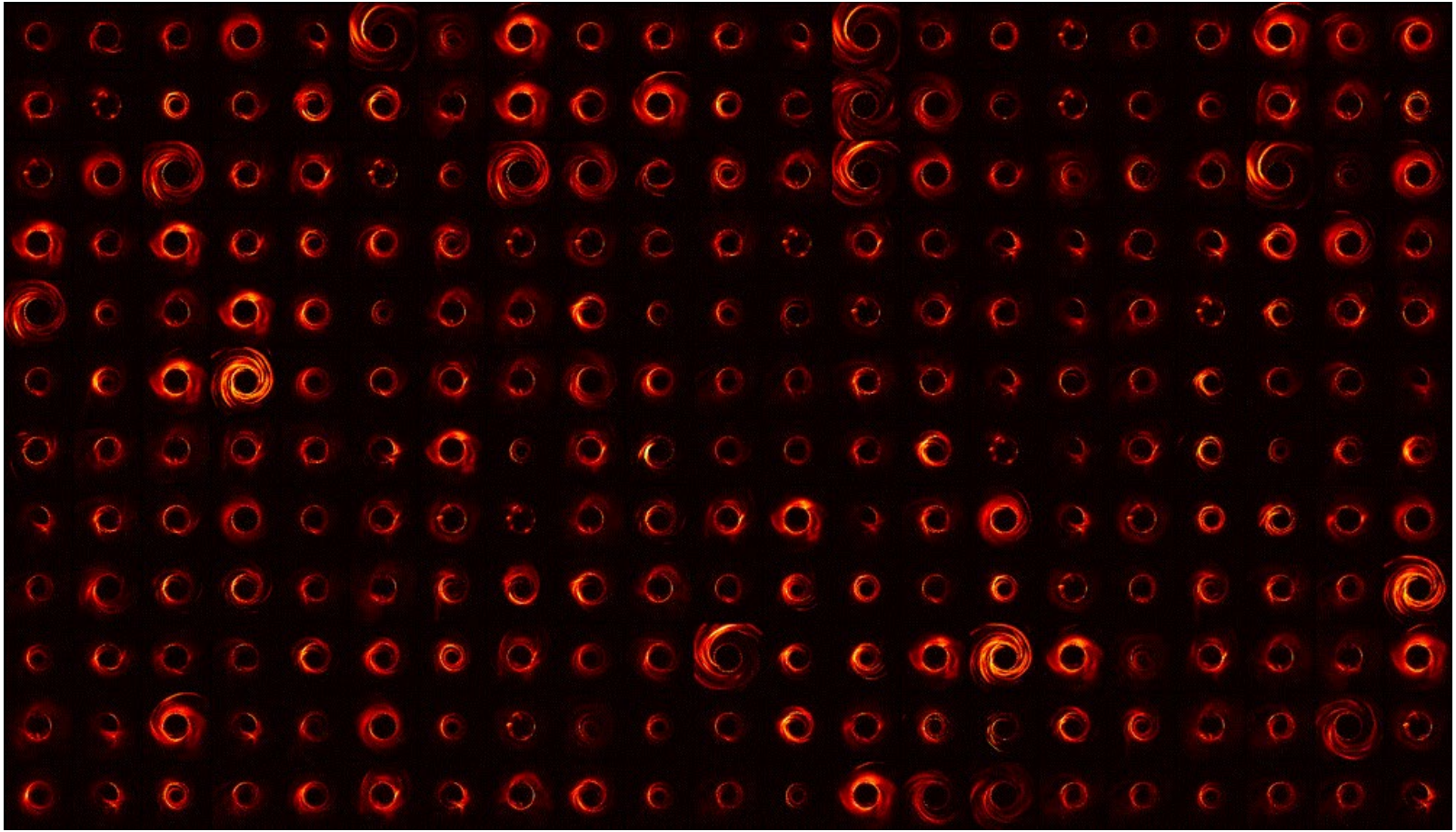








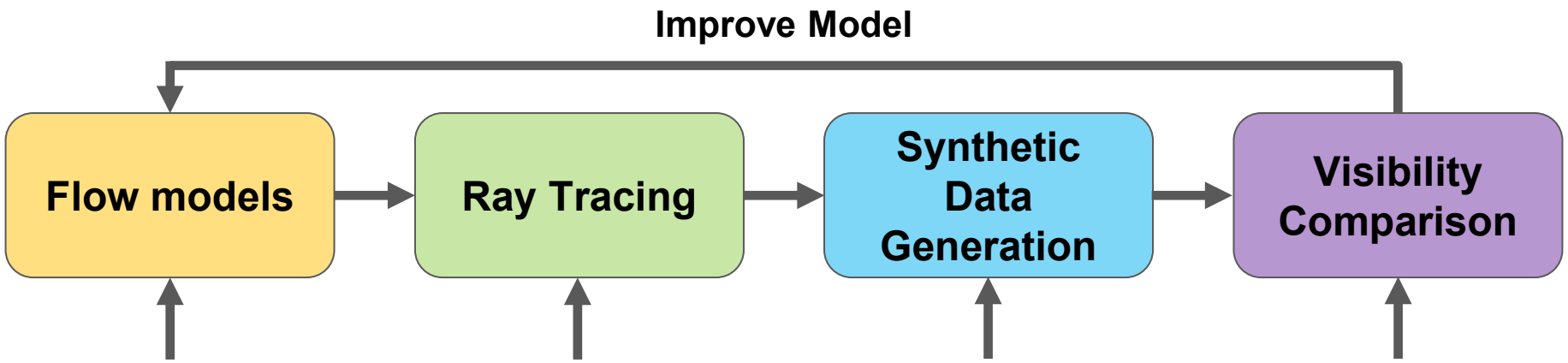
GRMHD Simulation Image Library



Animation credit: A. Broderick, Perimeter

EHTC+ 2019. ApJL, 875, L5 (Paper V)

Full Forward Modeling



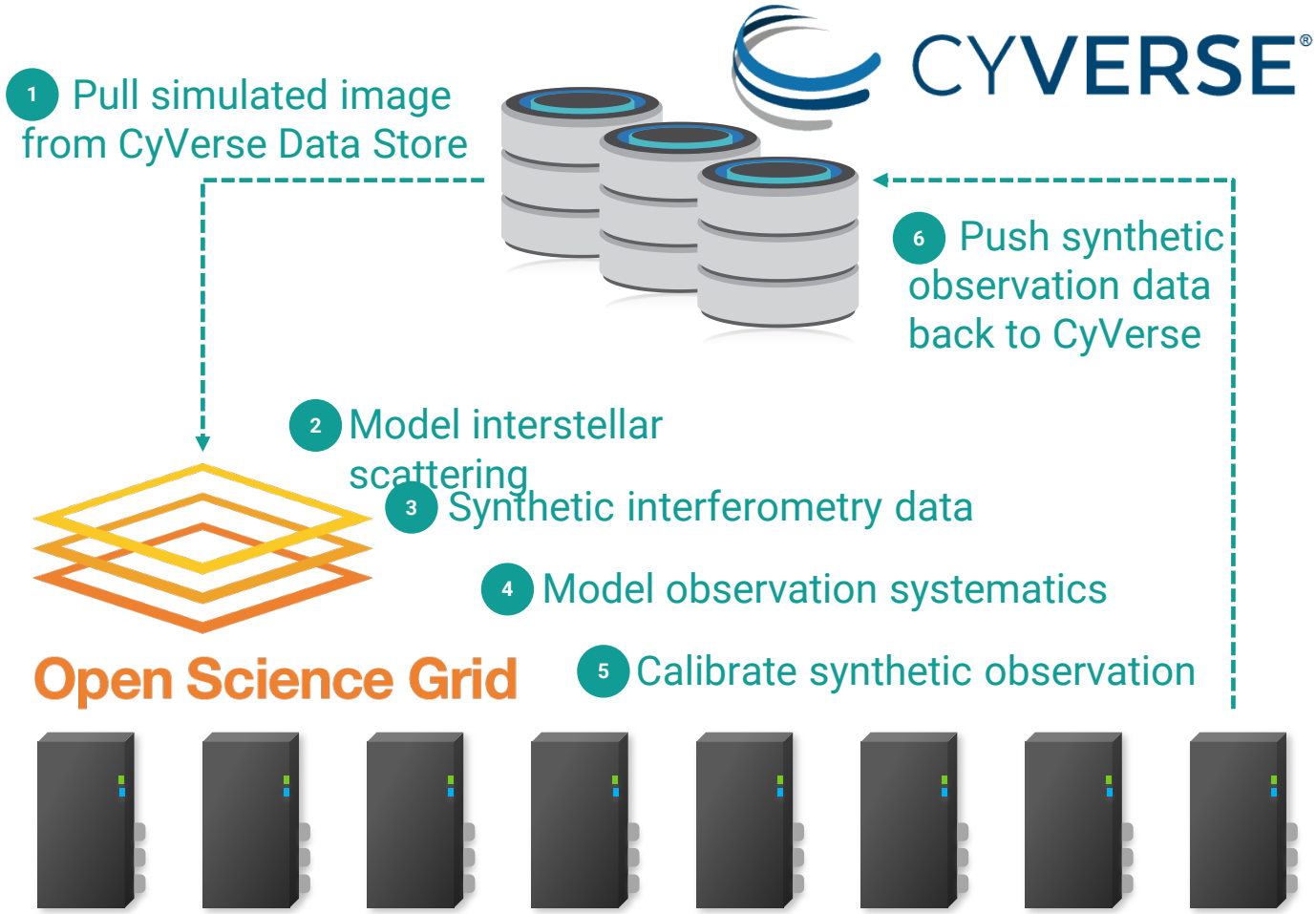
10 models, 1000 frames, 10,000 total

20 possibilities, 5 frequencies, 1,000,000 total

100 configs, 10 realizations, 1,000,000 obs

Comparing 1,000,000 of models

Pegasus-SYMBA Pipeline



Current Progress

- Fully automated Pegasus-SYMBA pipeline for synthetic data generation
- Customized codes to work with CyVerse Data Store
- Fault-tolerance and self-healing
- 500,000 jobs; 2,000,000 core hours so far on OSG
  - #15 in all OSG projects in last 6 months
  - #2 in all OSG astronomy projects in the last 6 months
- Two more workflows in development:
  - Monte Carlo radiative transfer for spectral modeling
  - Feature extraction from simulations and synthetic data
- Major results upcoming, stay tuned

Our Pegasus Feedback



- Thanks for developing such a great tool!

- iRODS integration
- Per-workflow limit on concurrent file transfer
- Allow multiple containers to interact with each other in a single node



Thank You!