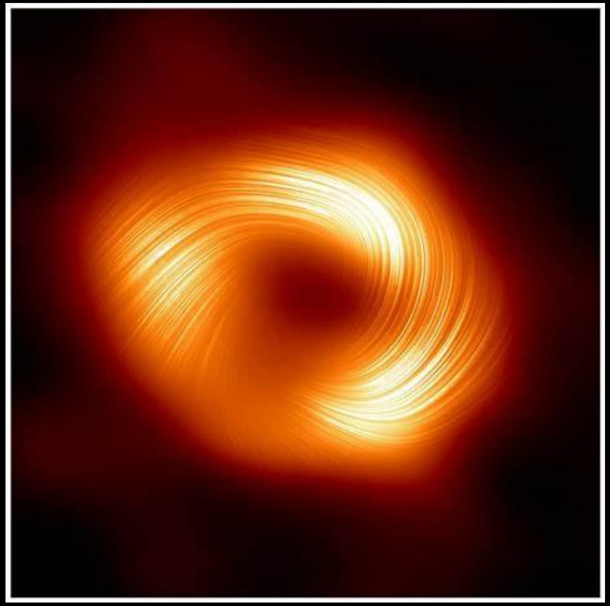
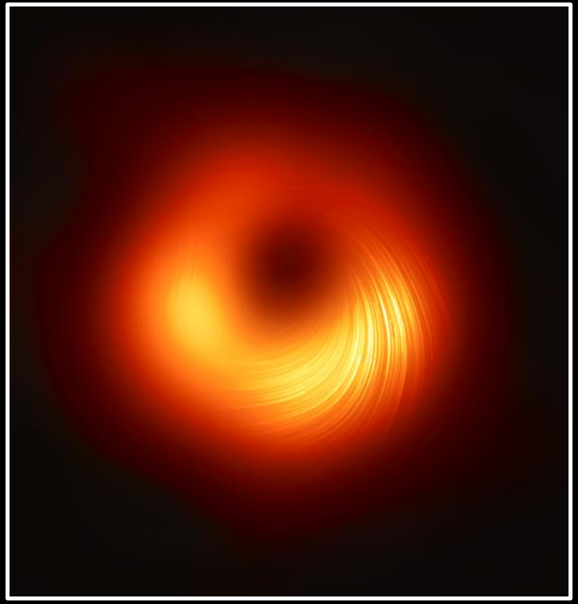
Imaging Black Holes with the Event Horizon Telescope

Andrew Chael
Princeton University

July 16, 2025





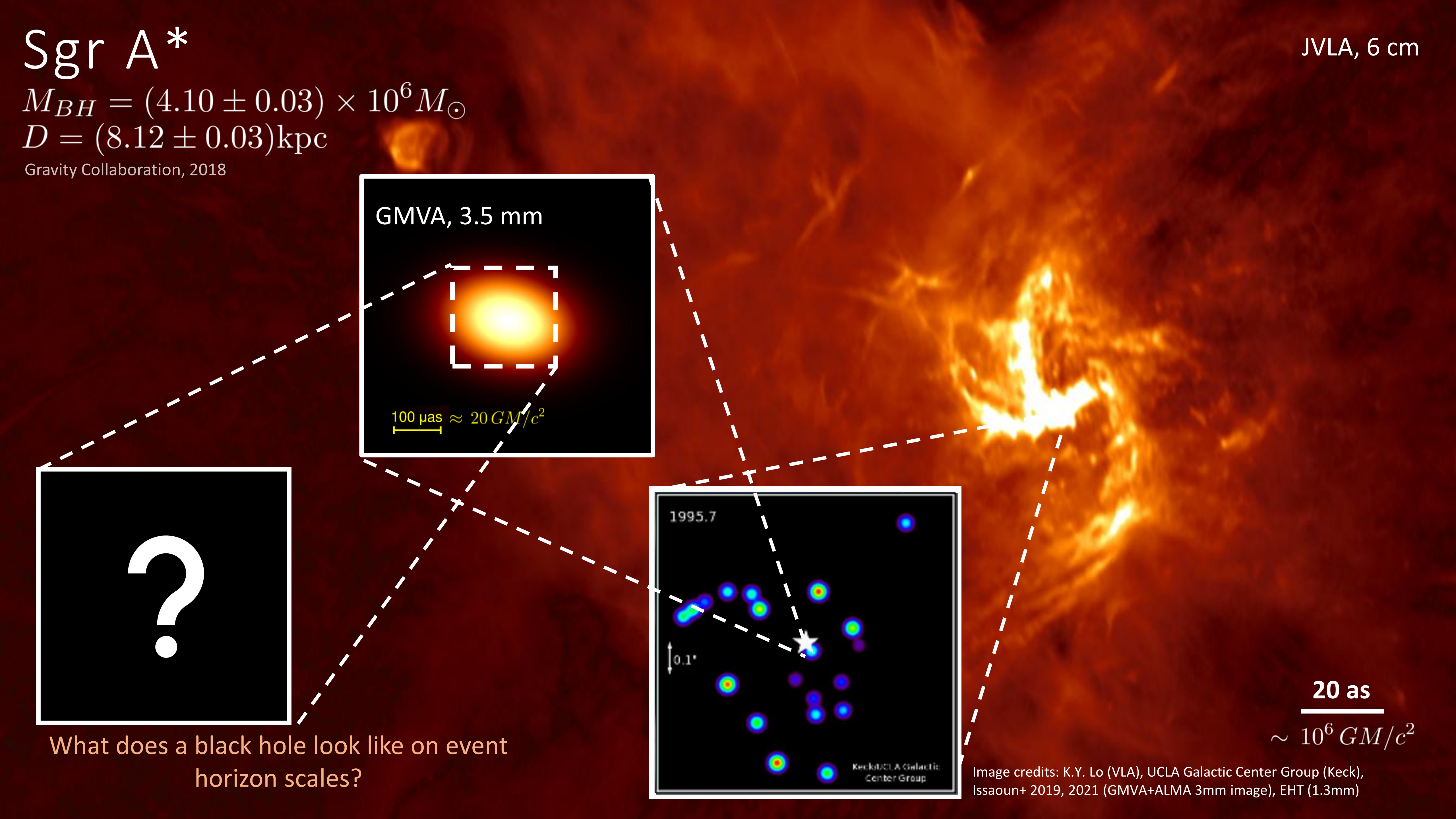
PRINCETON UNIVERSITY

Event Horizon Telescope

Sgr A*

$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$
$D = (8.12 \pm 0.03)\text{kpc}$

Gravity Collaboration, 2018

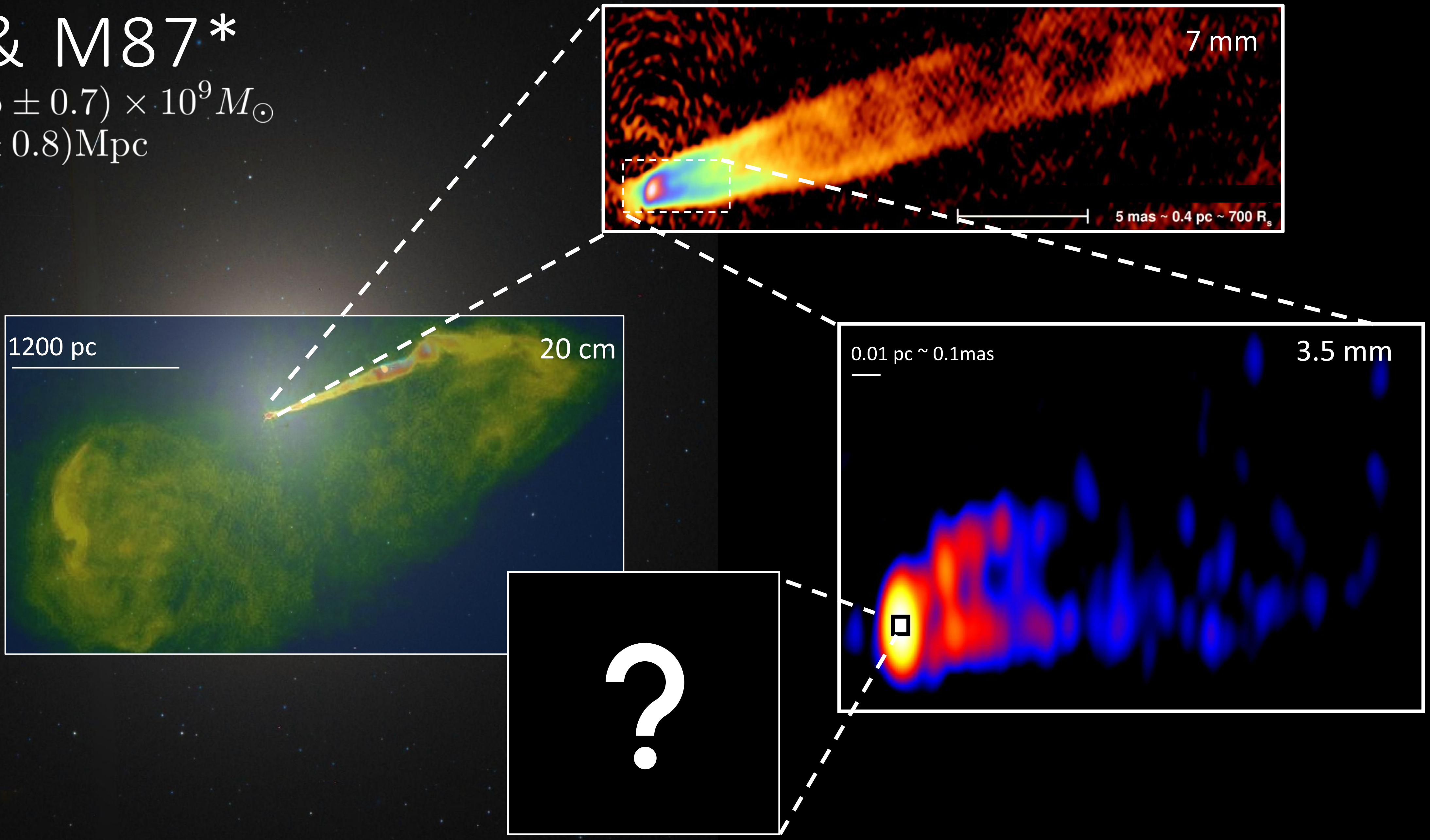


What does a black hole look like on event horizon scales?

Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHT (1.3mm)

M87 & M87*

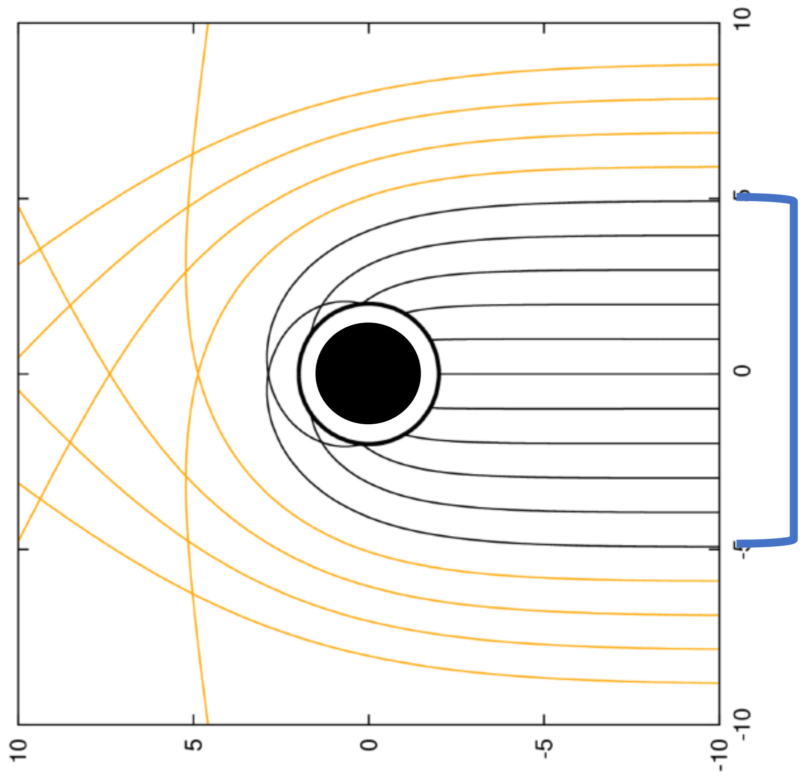
$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$



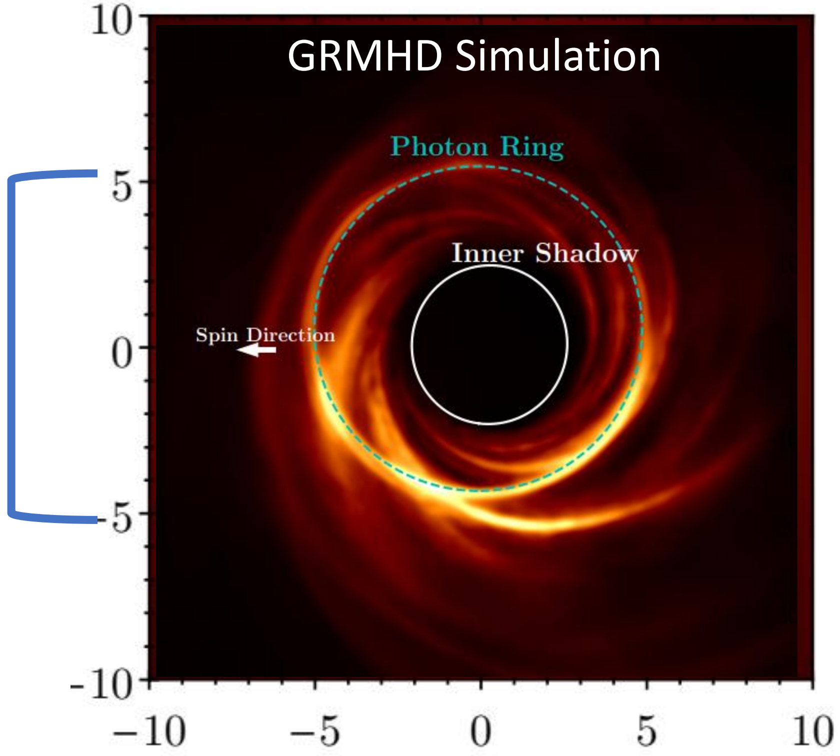
What does a *jet launching* black hole look like on event horizon scales?

Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)

The Black Hole Shadow



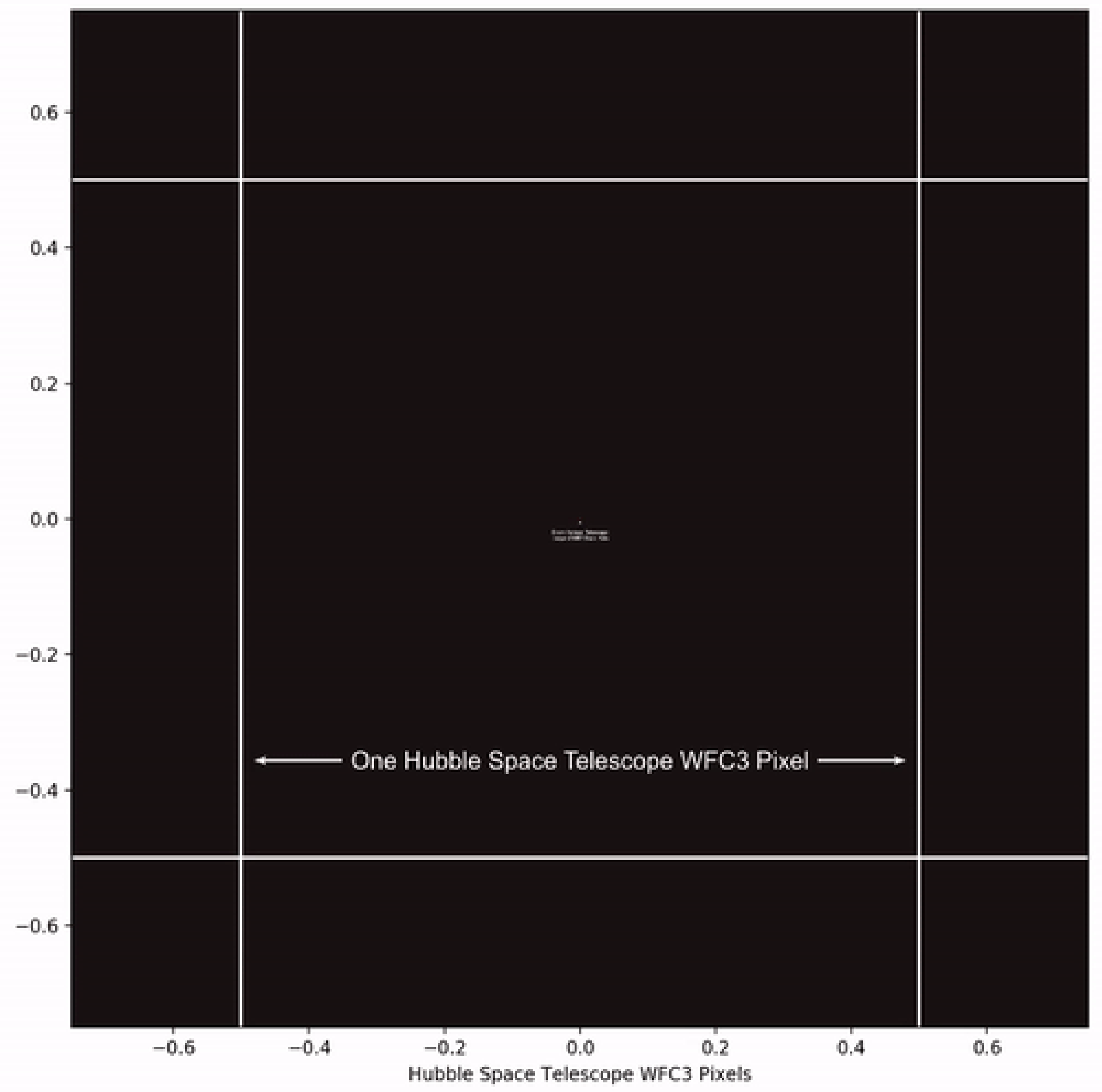
$$d_{\text{shadow}} \approx 5R_S/D$$
$$\approx 40\,\mu\text{as for M87}^*$$



The largest black hole shadow sizes:
Sgr A*: 50 μas → 1.4 x 10^{-8} degrees
M87*: 40 μas → 1.1 x 10^{-8} degrees

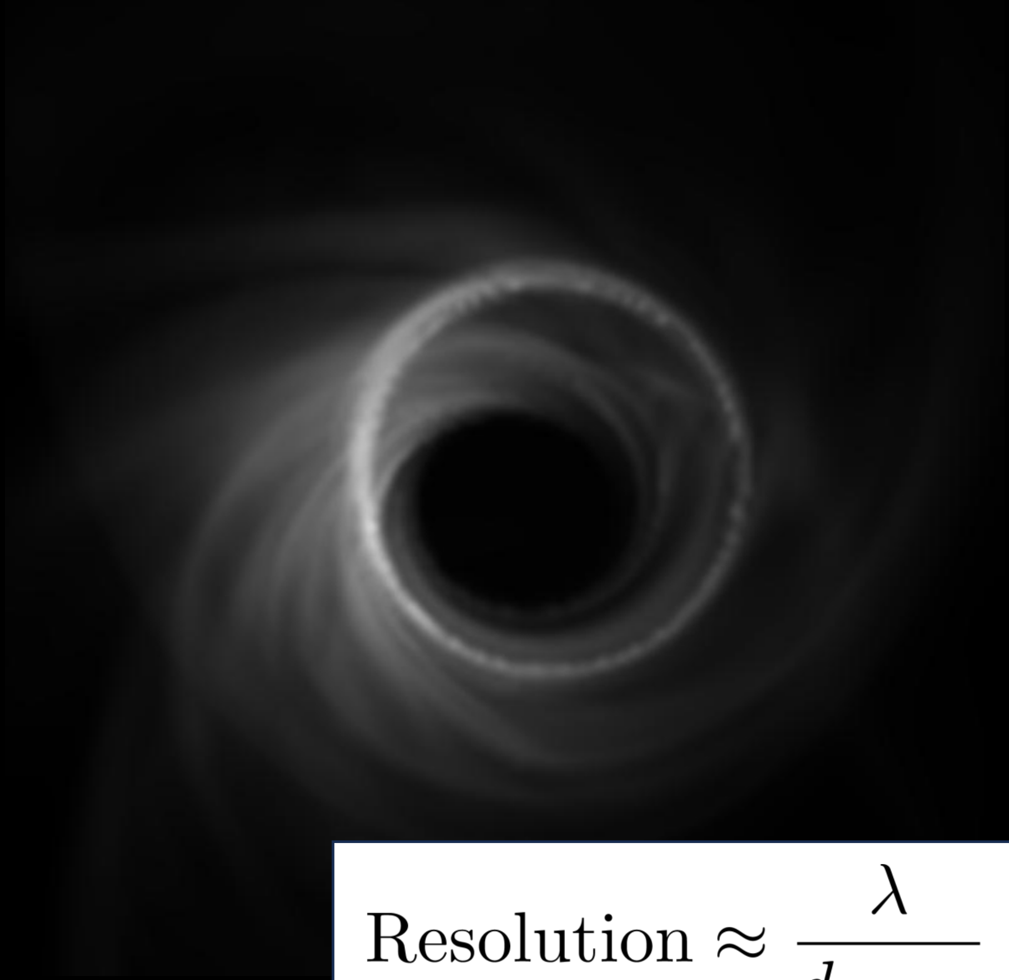
Image credit: Keiichi Asada (left), Narayan+ 2019, **Chael+** 2021

How small is 40 microarcseconds?



Animation credit: Alex Parker

Black Hole Simulation

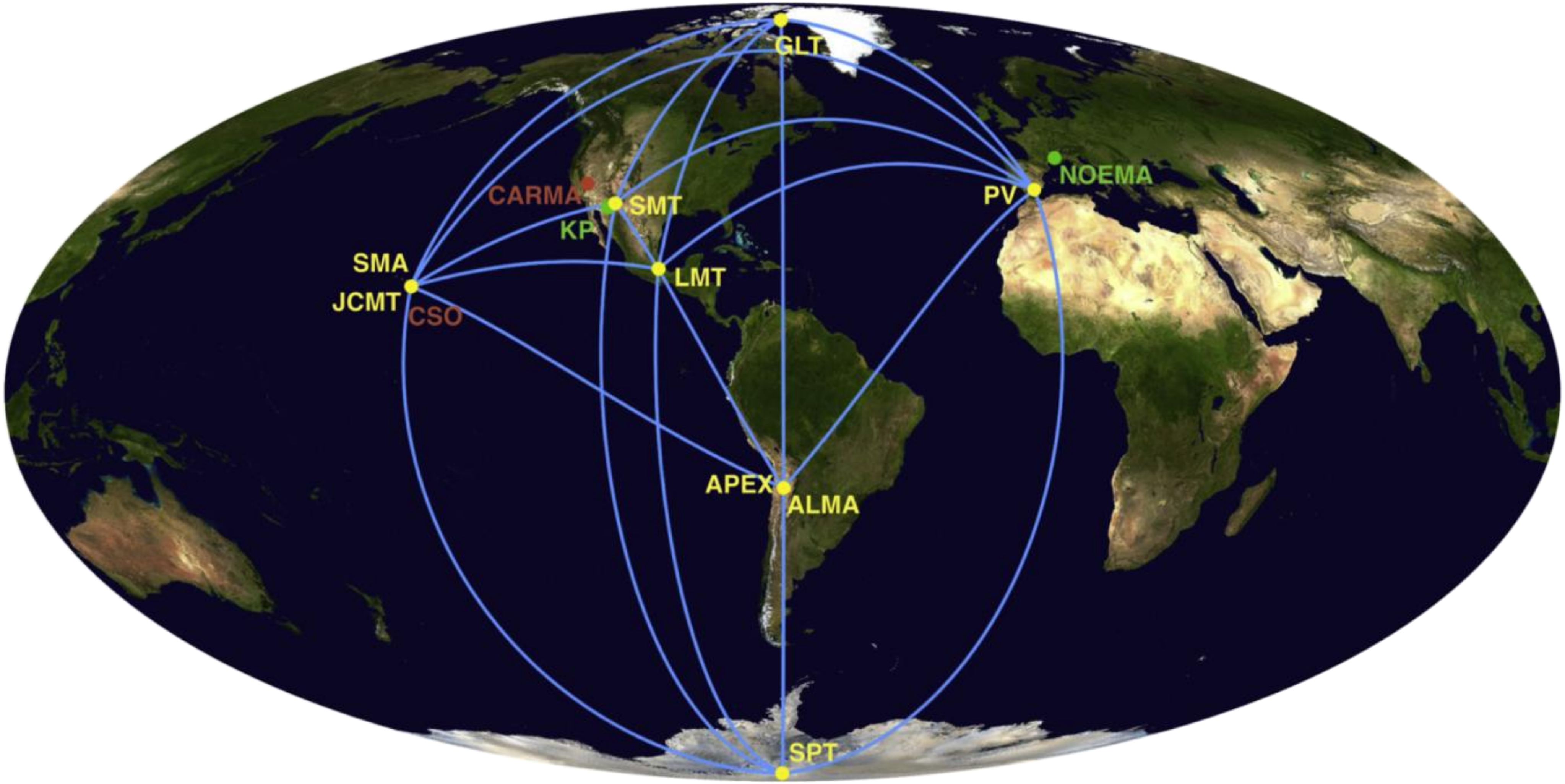


Simulation viewed through an Earth-Sized Telescope

$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

Slide Credit: Katie Bouman
Image Creidt: Jason Dexter, Monika Moscibrodzka, Hotaka Shiokawa

The Event Horizon Telescope



$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

EHTC+ II, 2019

M87 & M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$

$D = (16.8 \pm 0.8)\mathrm{Mpc}$

$R_s = 2GM/c^2 \approx 64\,\mathrm{AU}$

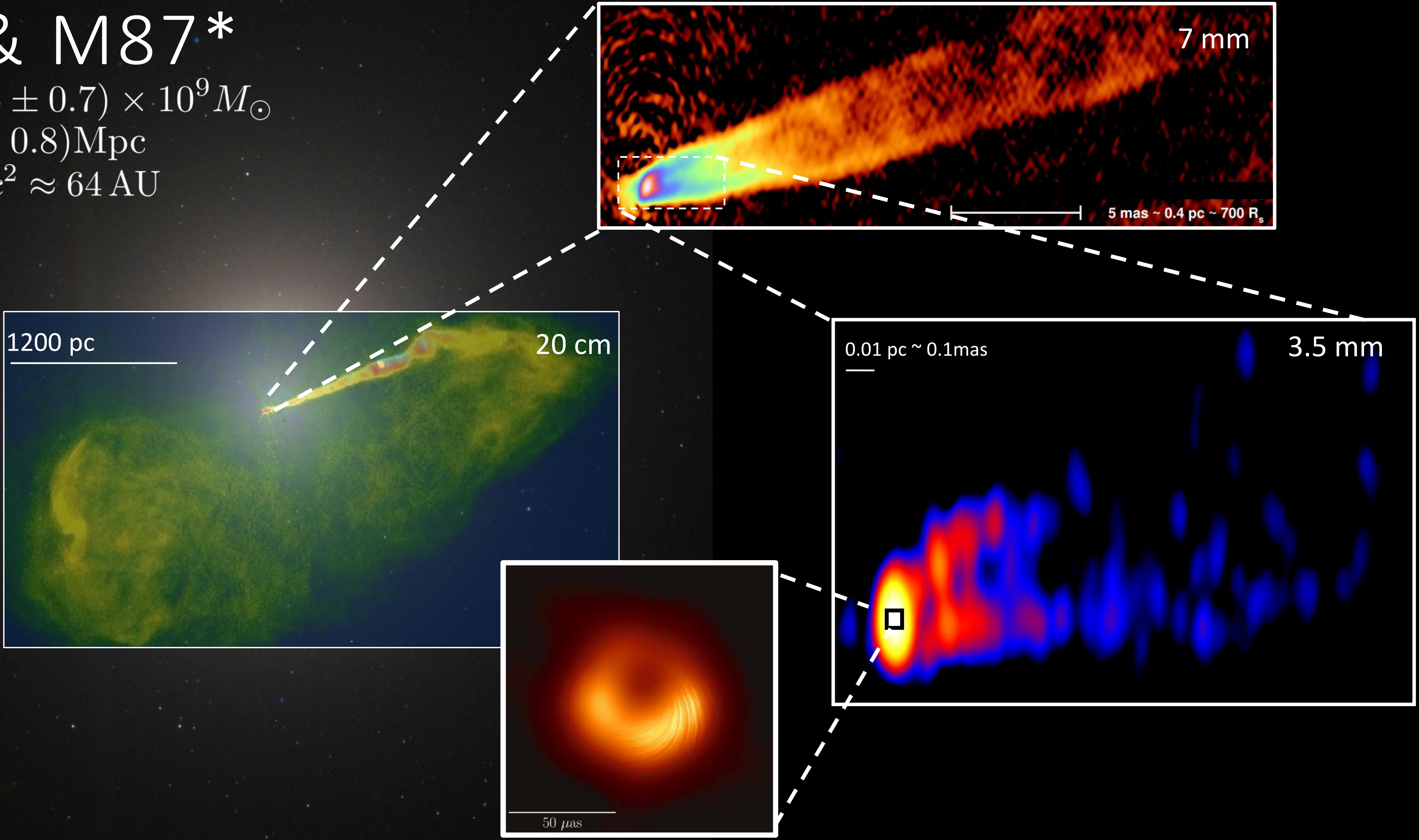
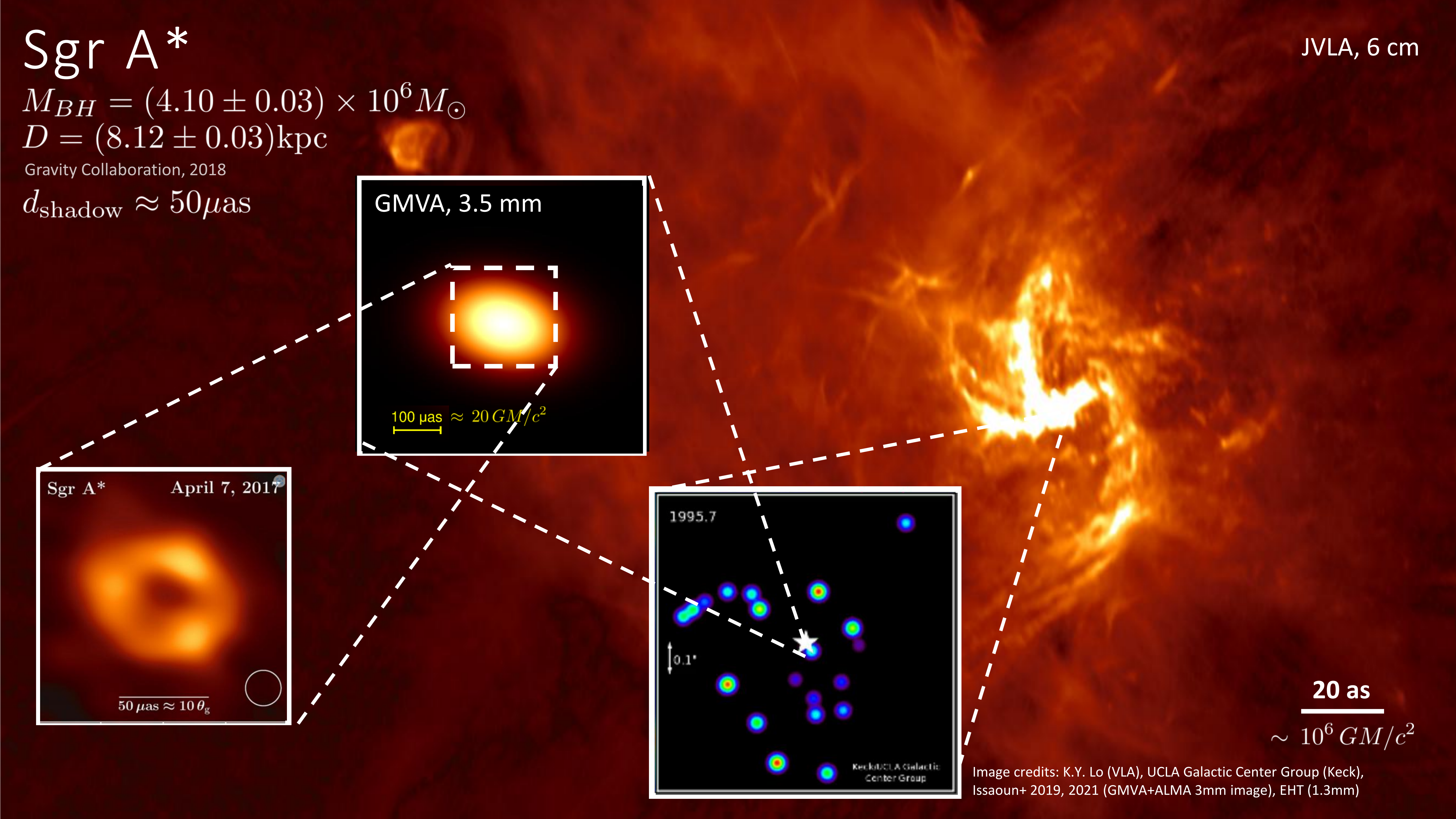


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm), EHT (1.3 mm)


Sgr A*
$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$
$D = (8.12 \pm 0.03)\text{kpc}$
Gravity Collaboration, 2018
$d_{\text{shadow}} \approx 50\mu\text{as}$
JVLA, 6 cm
GMVA, 3.5 mm
100 µas $\approx 20\,GM/c^2$
Sgr A*
April 7, 2017
$50\,\mu\text{as} \approx 10\,\theta_g$
1995.7
0.1"
Keck/UCLA Galactic Center Group
20 as
$\sim 10^6\,GM/c^2$
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHT (1.3mm)

International Collaboration Drives the EHT

300+ members, **60+** institutes, **20+** countries, **5** continents

The EHT: Many antennas + lots of software + international teamwork = one **computational** telescope

Outline

1. How did the EHT make images of black holes?

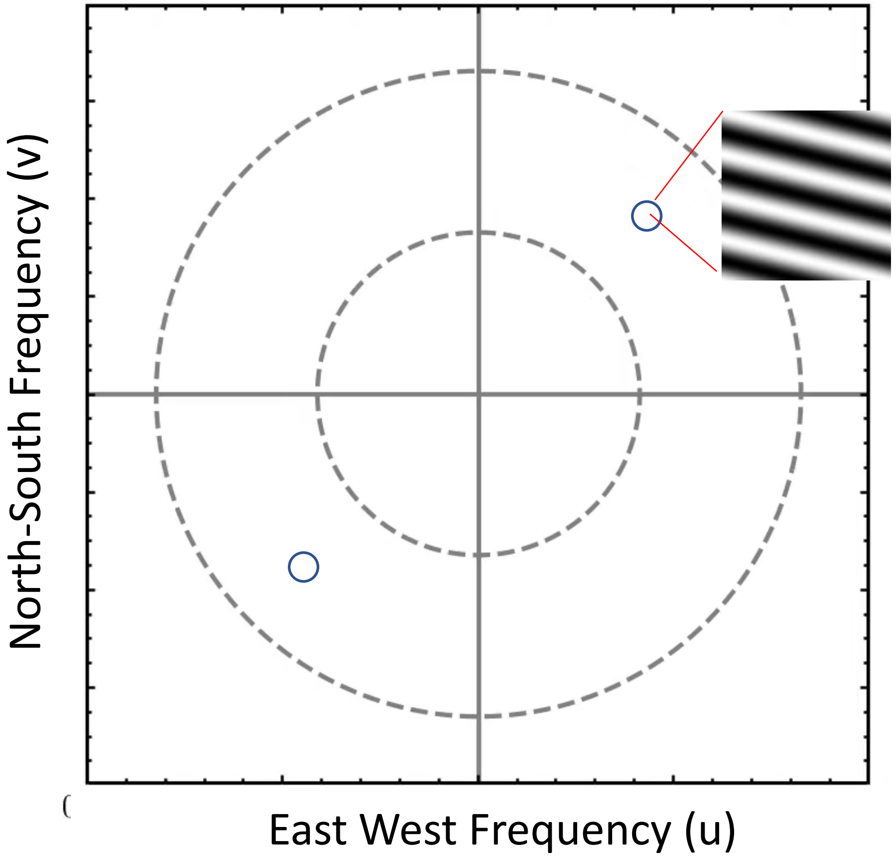
2. What have we learned from EHT images?

3. Next Steps in EHT capabilities and new imaging methods

How do we obtain black hole images with the EHT?

EHT M87 Papers I-VI, *ApJL* 2019
EHT M87 Papers VII-IX, *ApJL* 2021, 2024 (Polarization)
EHT Sgr A* Papers I-VIII, *ApJL* 2022, 2024

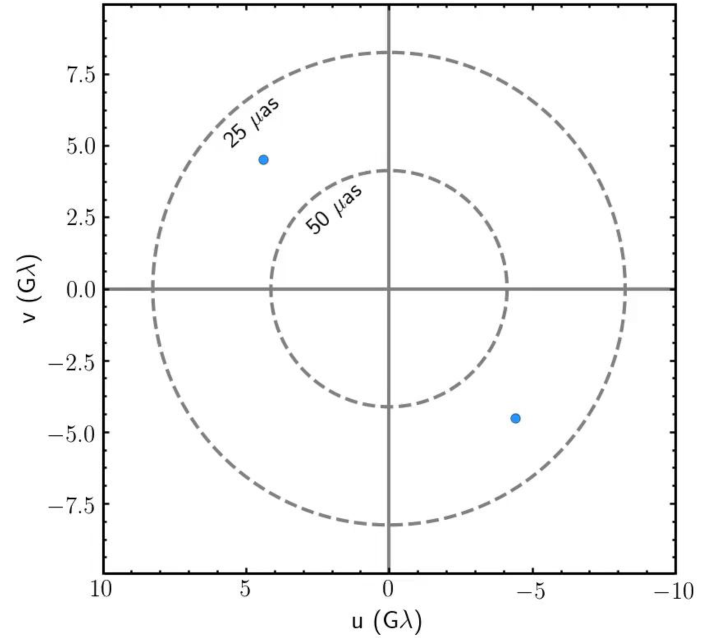
Very Long Baseline Interferometry (VLBI)

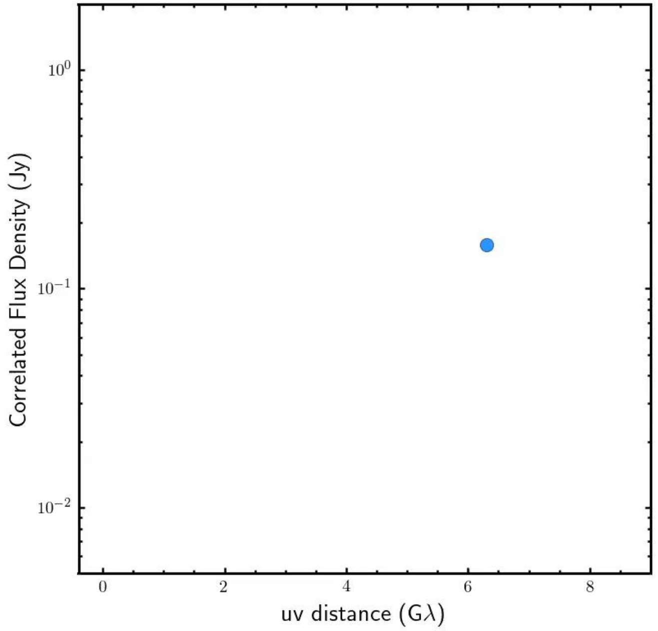


Every projected **baseline** between two telescopes provides **one Fourier component** of the image

movie credit: Katie Bouman

Very Long Baseline Interferometry (VLBI)





Every projected **baseline** between two telescopes provides **one Fourier component** of the image

Earth's rotation helps **fill in** the Fourier plane

movie credit: Daniel Palumbo

EHT: Array

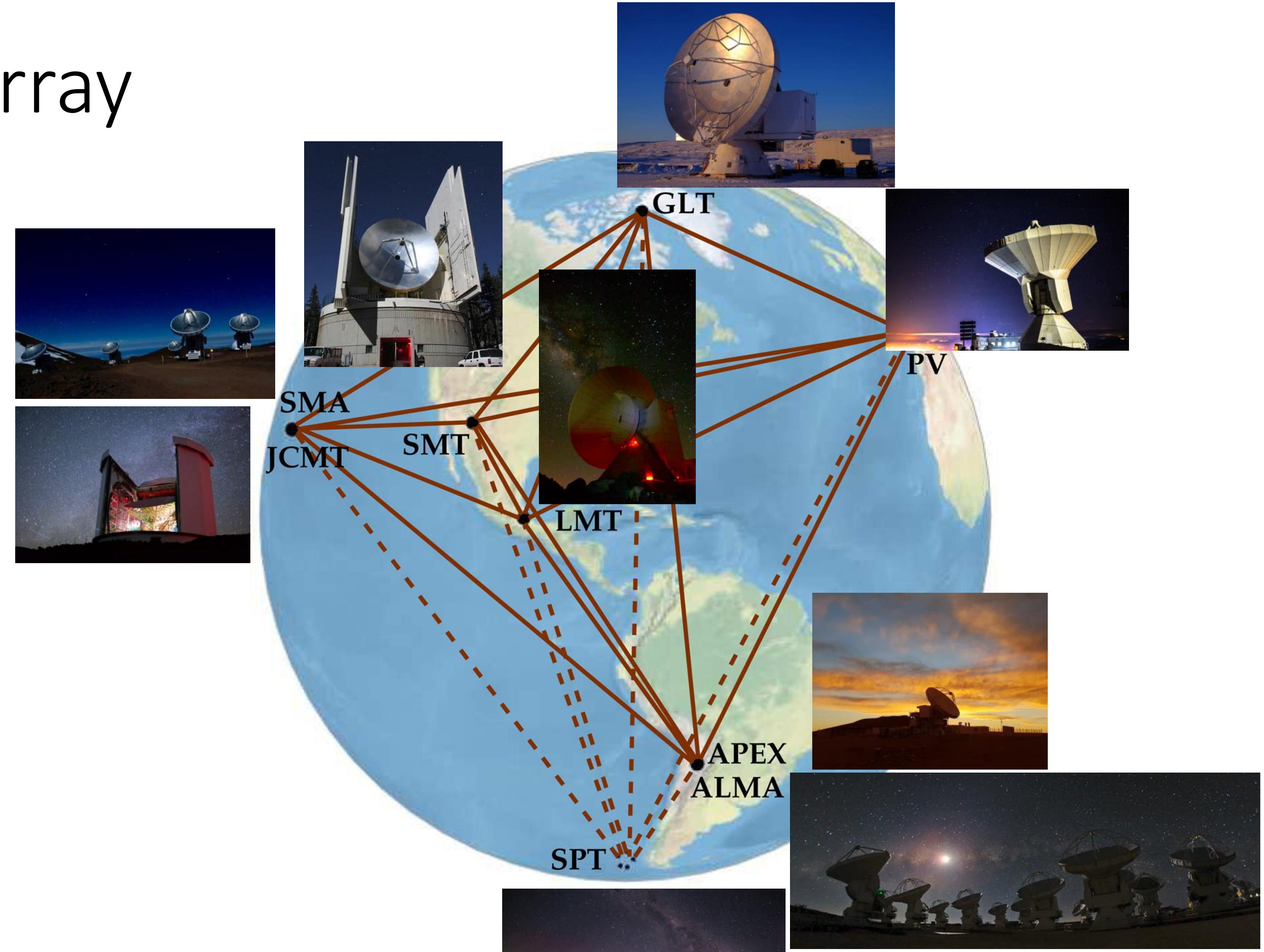
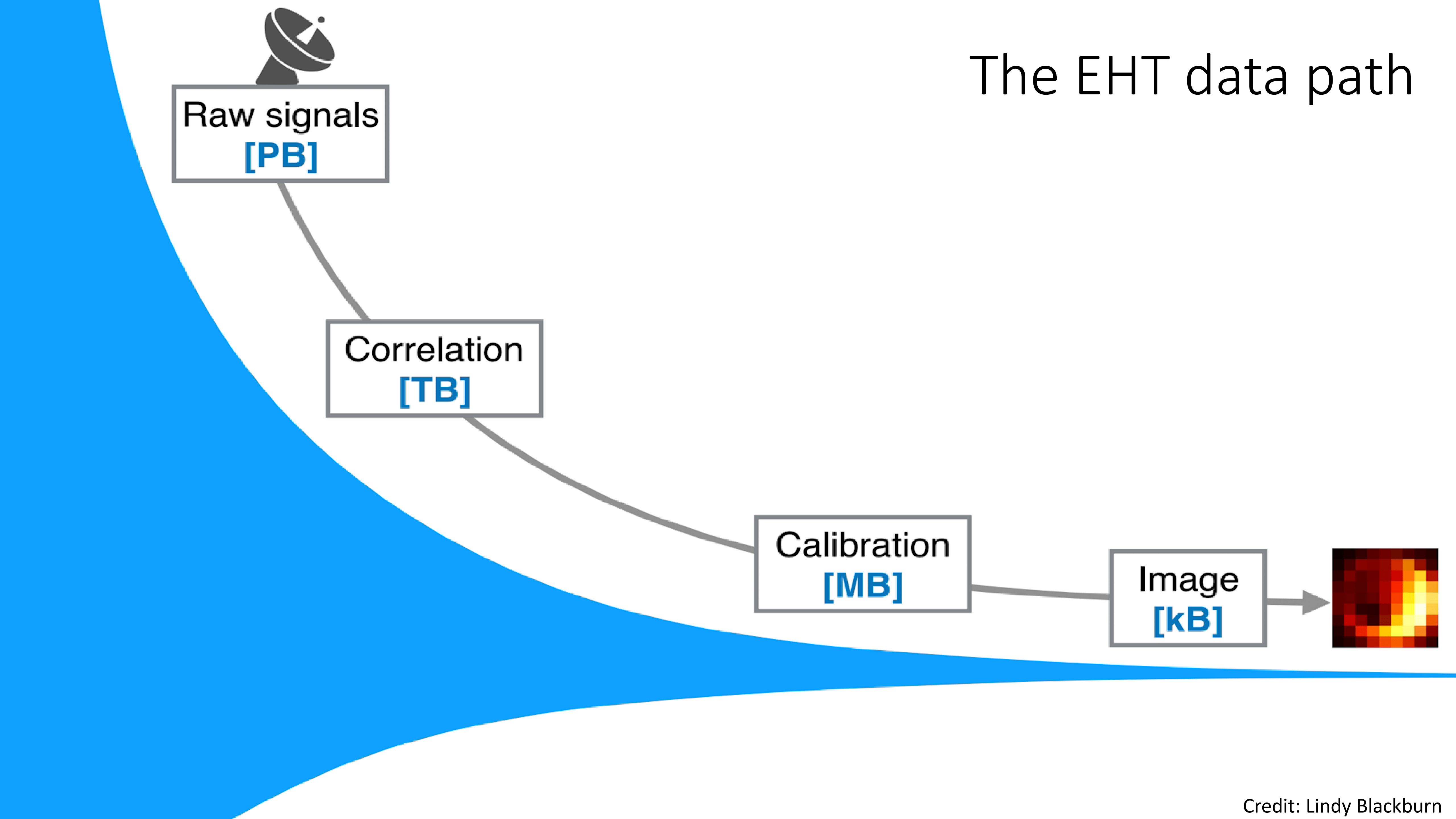


Photo Credits: EHTC 2024 I
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM, Nimesh Patel

EHT Observations

Photo credits:
David Michalik, Junhan Kim , Salvaor Sanchez, Helge Rottman
Jonathan Weintroub, Gopal Narayanan

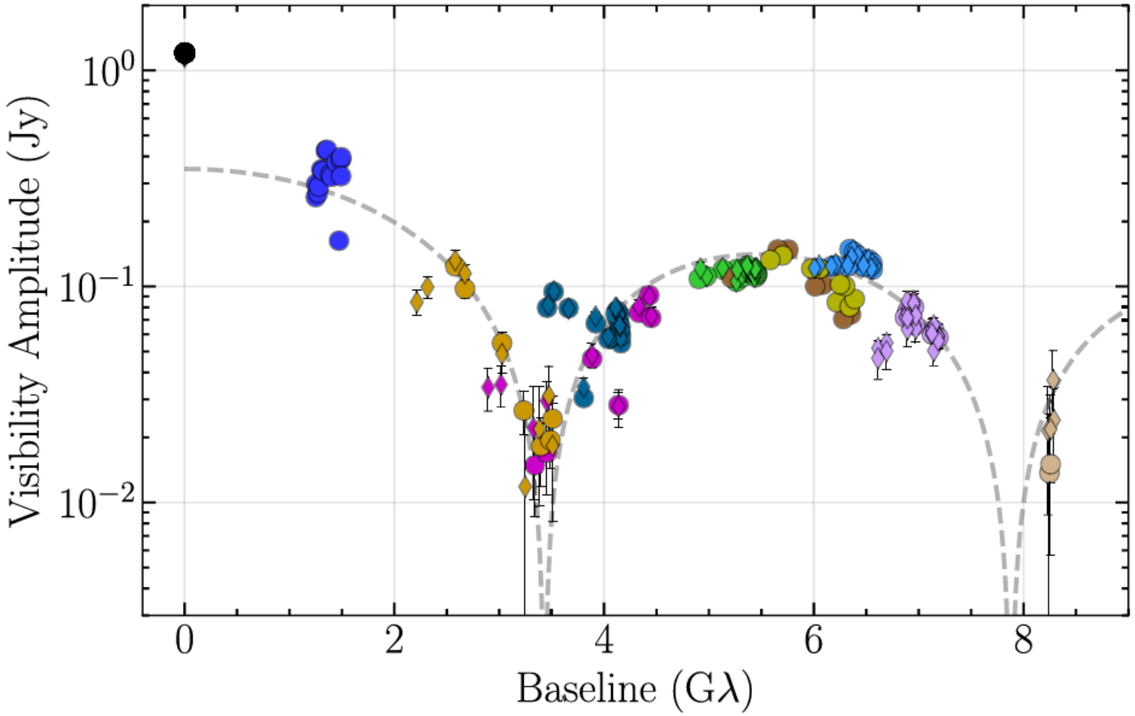
The EHT data path



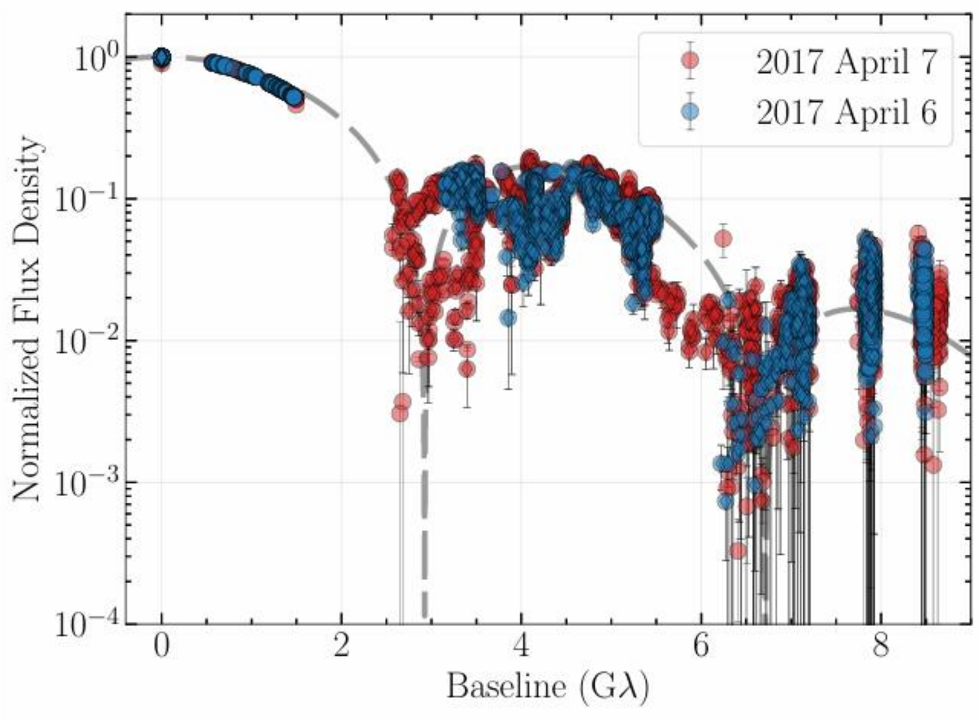
Credit: Lindy Blackburn

EHT Data Suggests Ring Structure

M87*

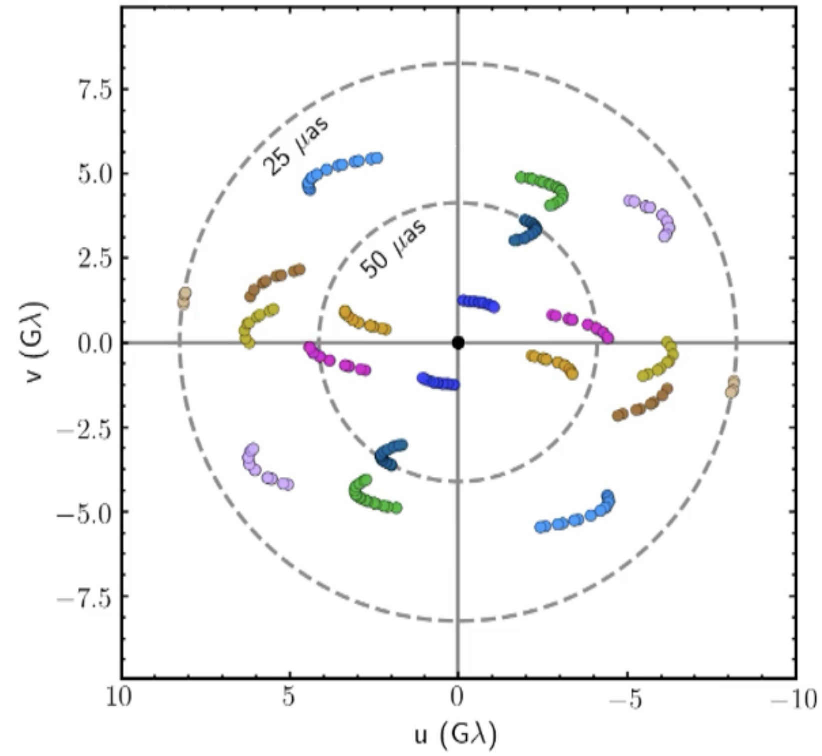


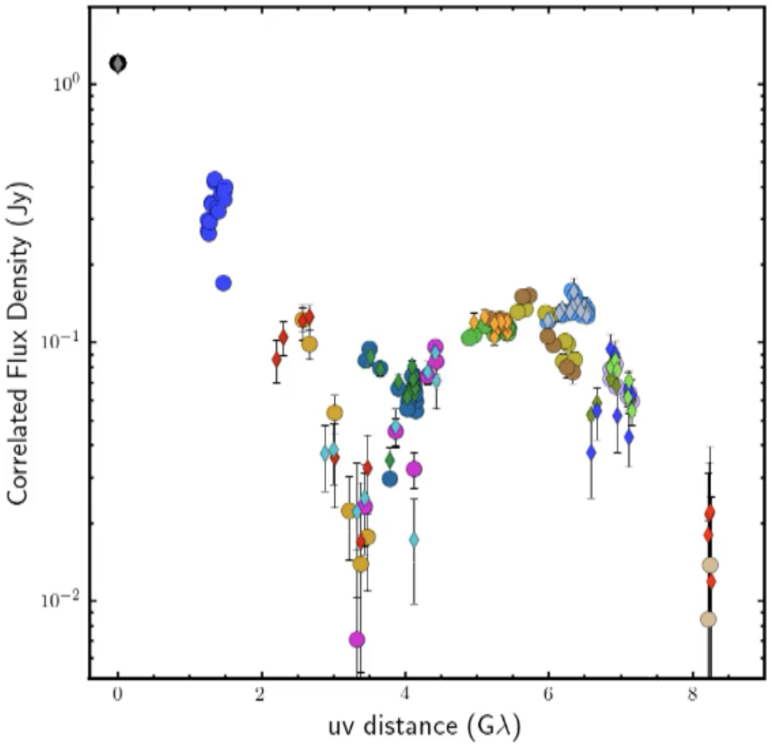
Sgr A*



EHTC I, 2019; EHTC II, 2022

Why imaging is hard: Our Data are *Sparse*

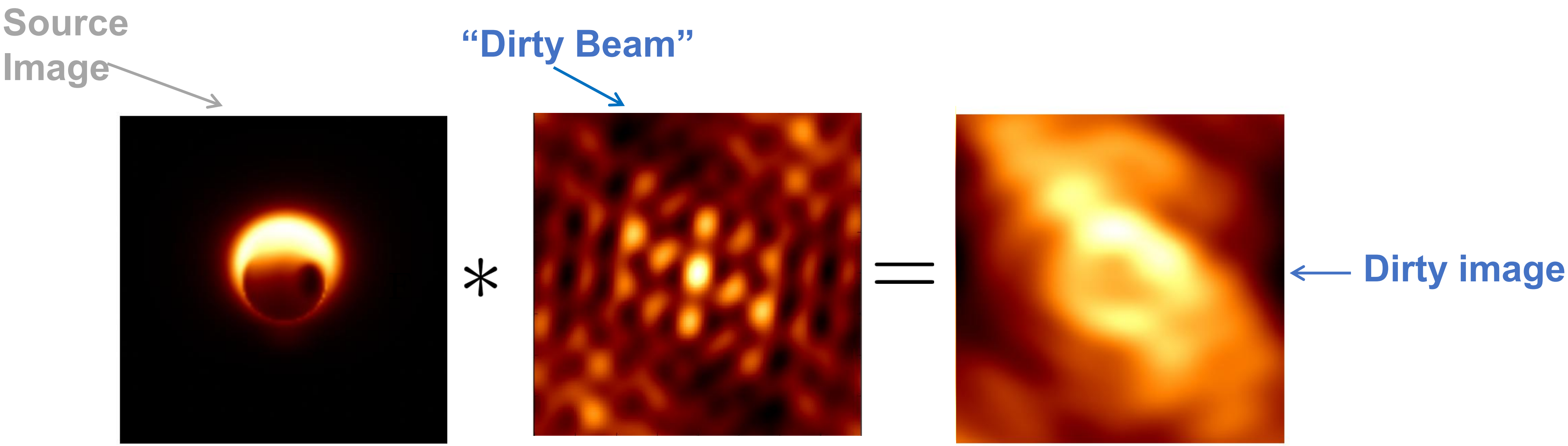




EHT coverage is **sparse**: inversion of image from the data is highly unconstrained

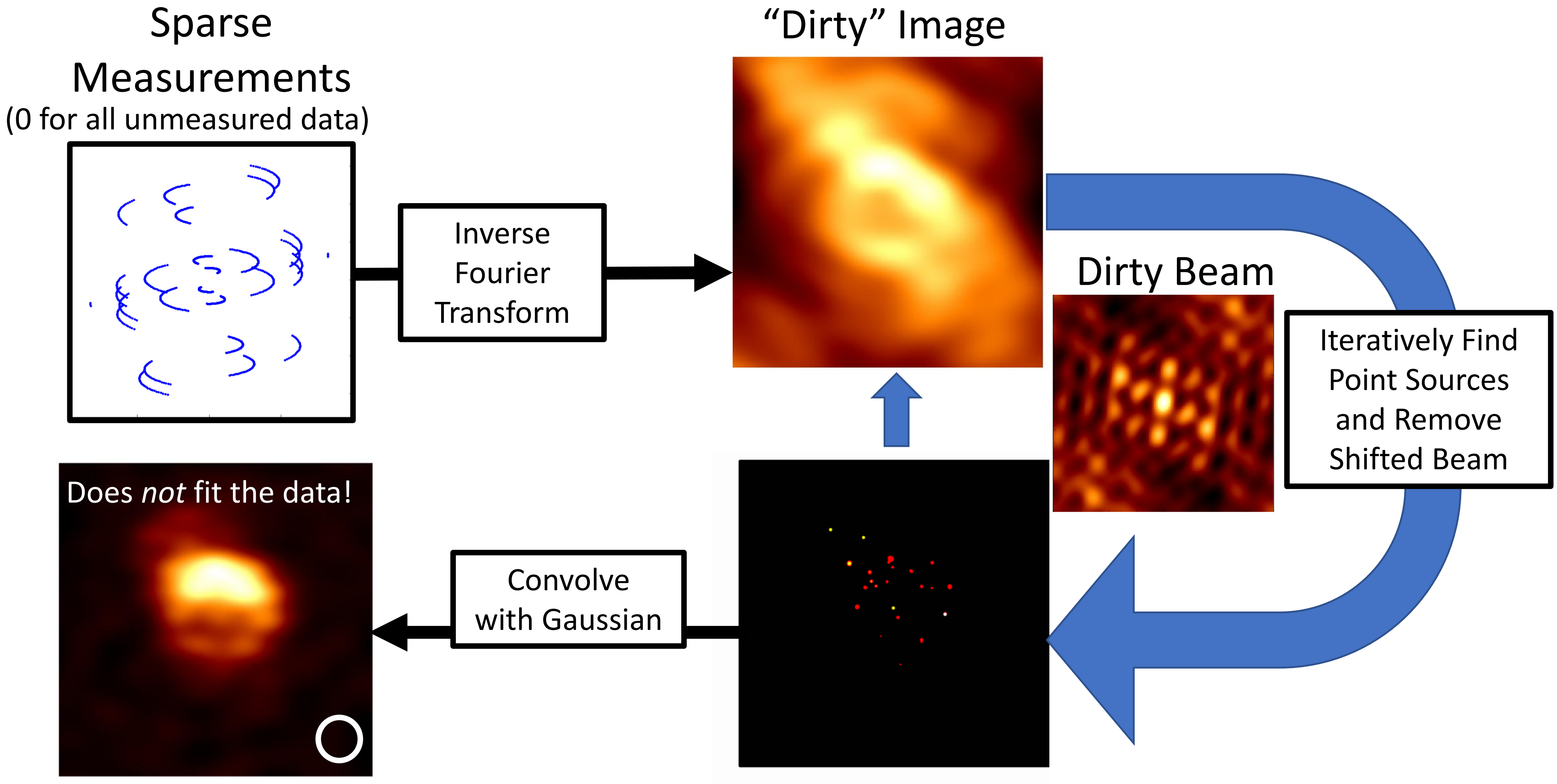
movie credit: Daniel Palumbo

Dealing with Sparsity: Deconvolution



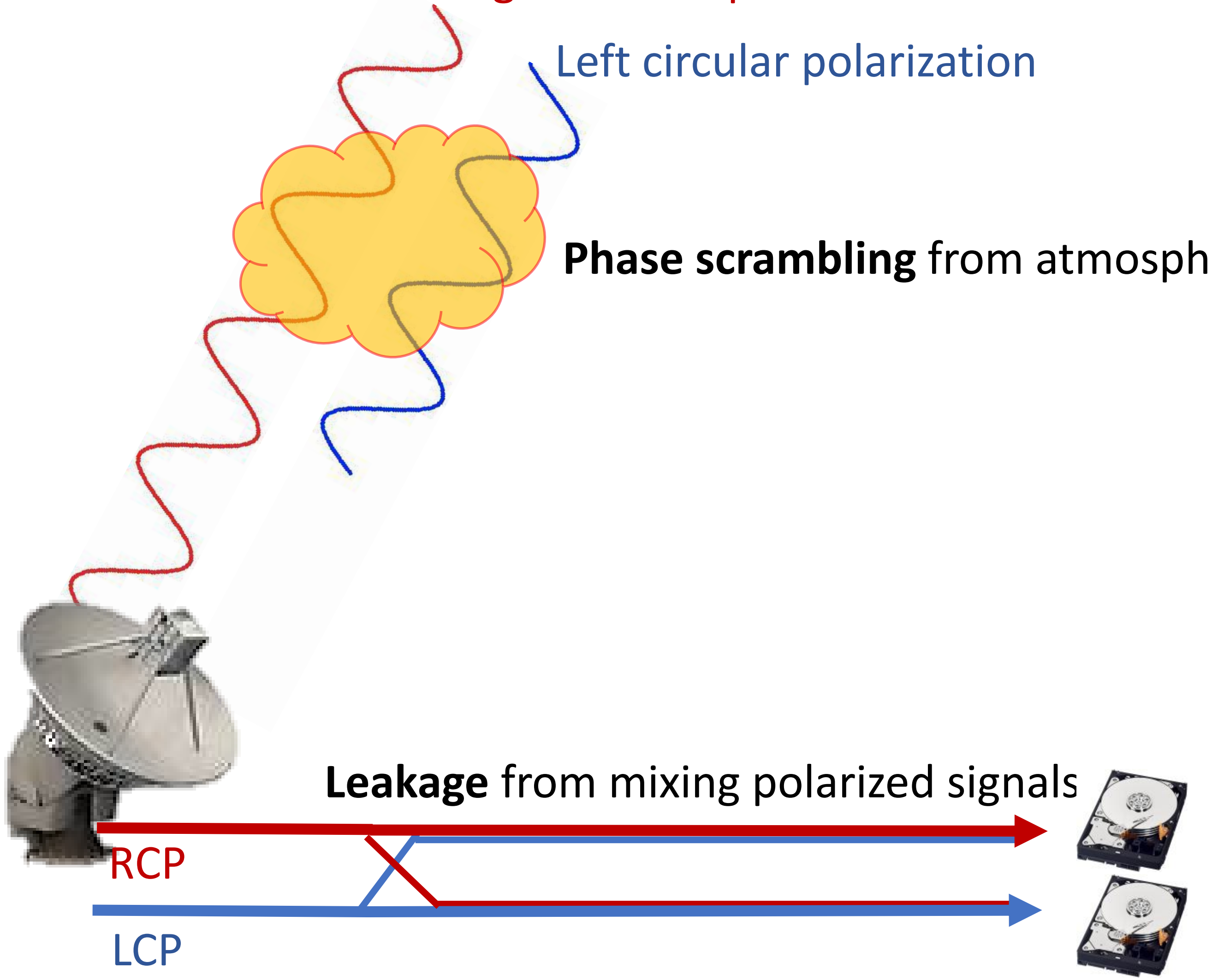
Simulation Credit: Avery Broderick

Traditional Approach: CLEAN



Simulation Credit: Avery Broderick

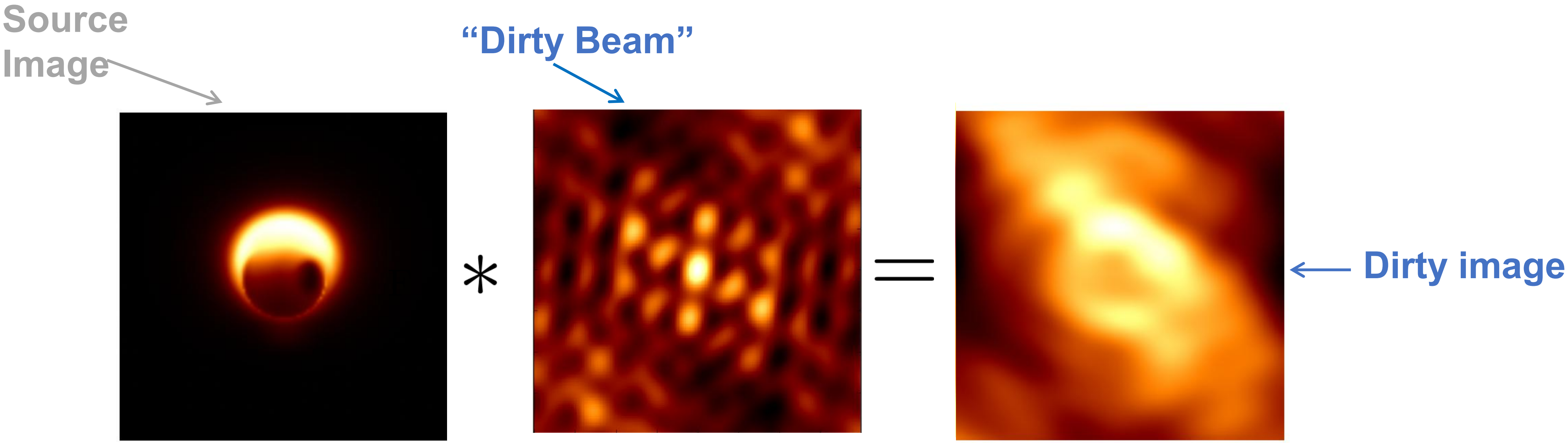
Why imaging is hard: Our Data are *Corrupted*



Data at each station are corrupted by unknown **gain and leakage** systematics

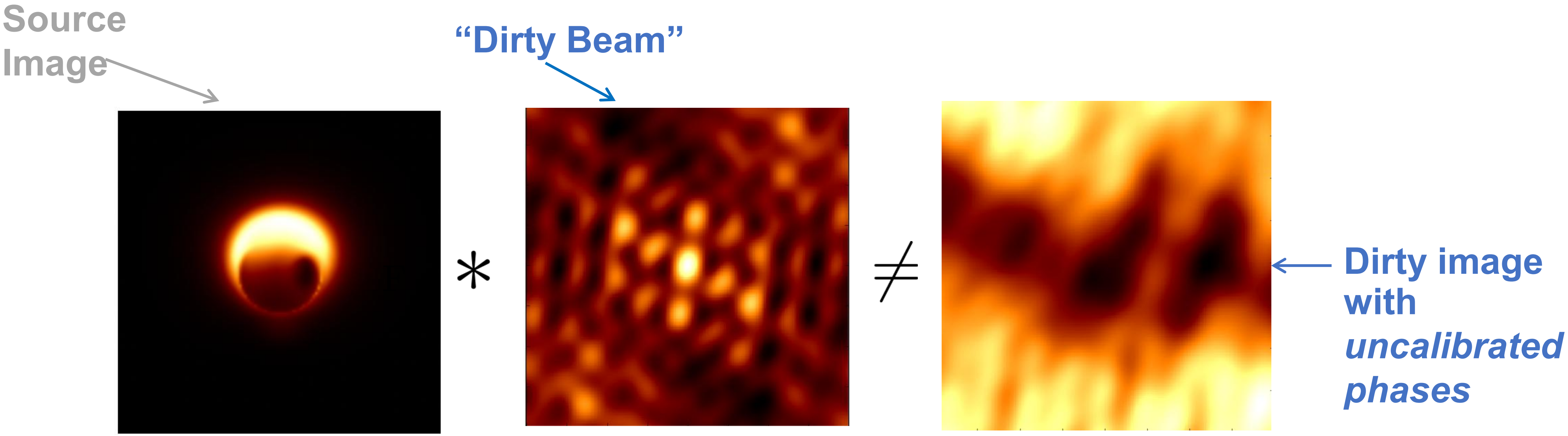
Animation credit: Andrew Chael

The importance of phase



Simulation Credit: Avery Broderick

The importance of phase



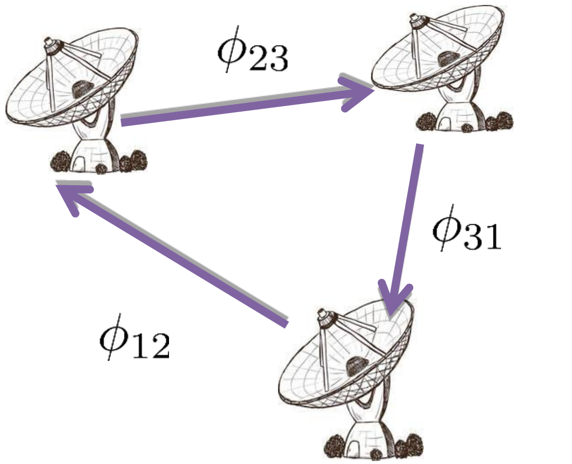
Simulation Credit: Avery Broderick

Closure Quantities

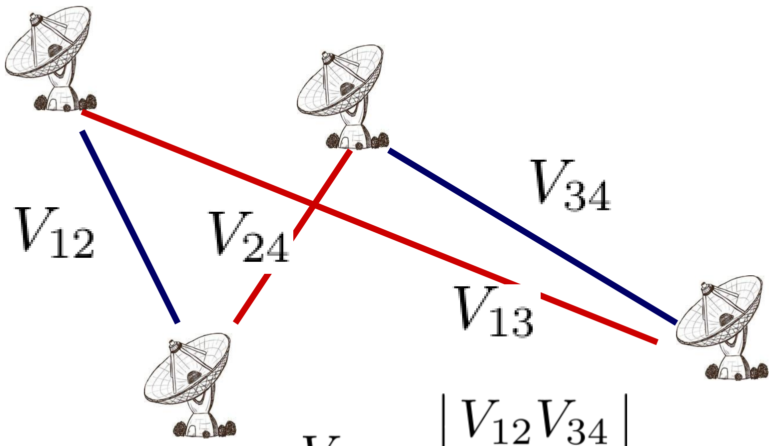
- Visibilities are corrupted by **station-based** gain errors

$$V_{\text{measured}} = G_1 e^{i\phi_1} G_2 e^{-i\phi_2}\, \mathcal{V}_{\text{true}}$$

- **Closure phases** are invariant to station-based phase errors and **Closure amplitudes** are invariant to amplitude gains

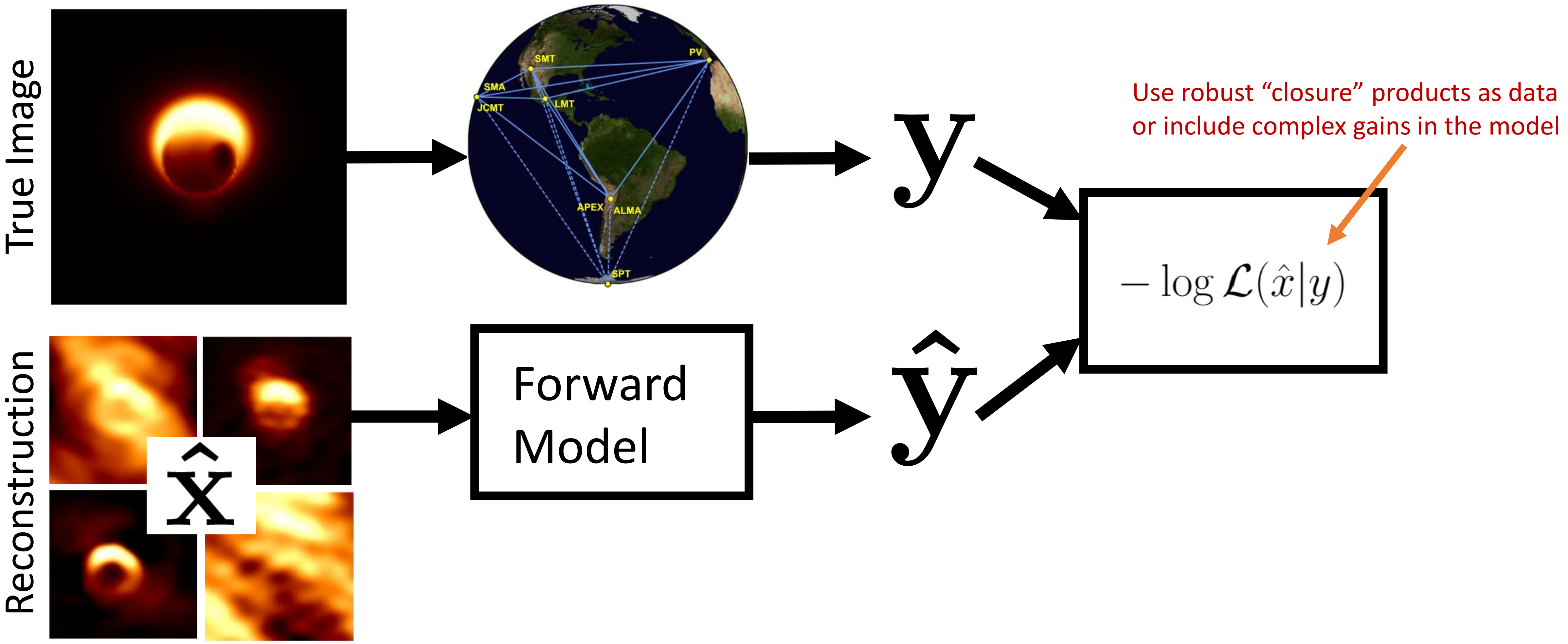


$$\psi_{\text{C}} = \phi_{12} + \phi_{23} + \phi_{31}$$

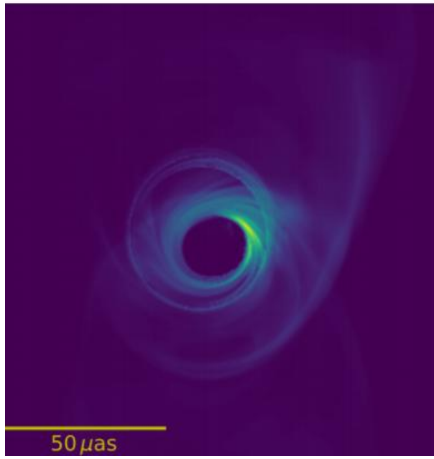


$$V_{\text{C}} = \left| \frac{V_{12} V_{34}}{V_{13} V_{24}} \right|$$

Forward Modeling for the Image



Imaging with robust closure observables



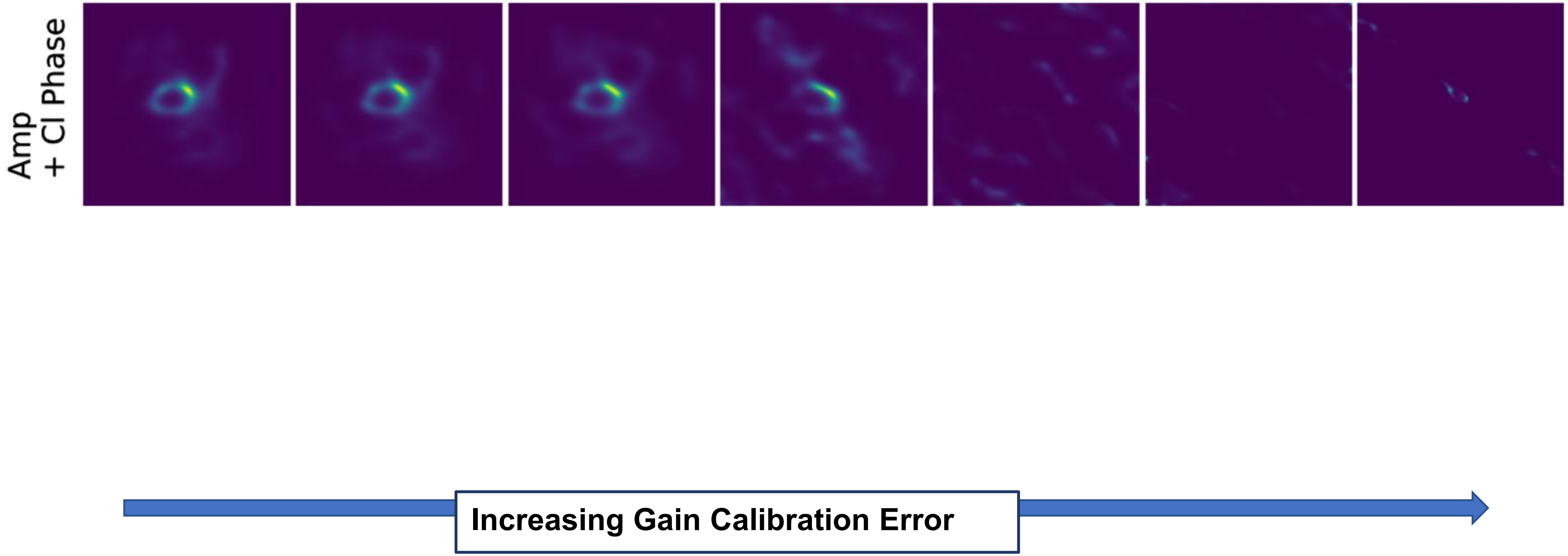
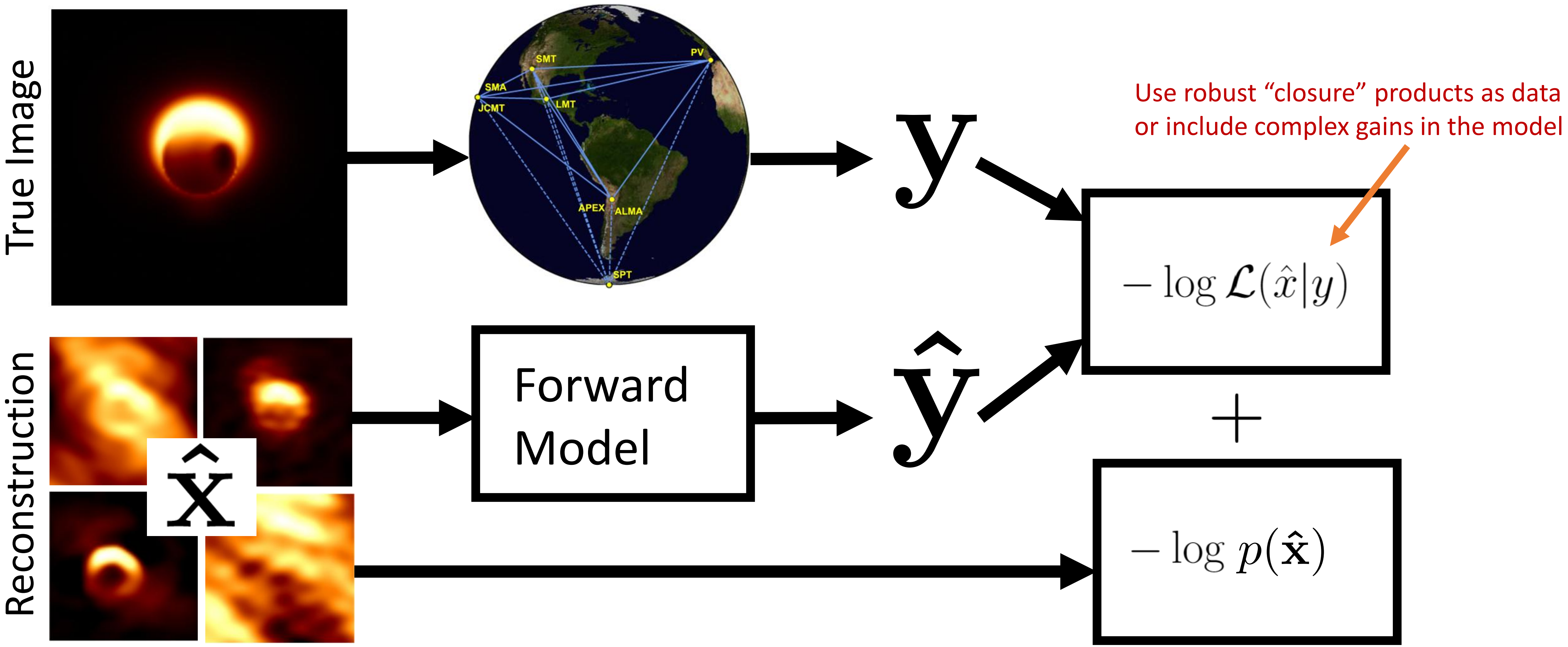
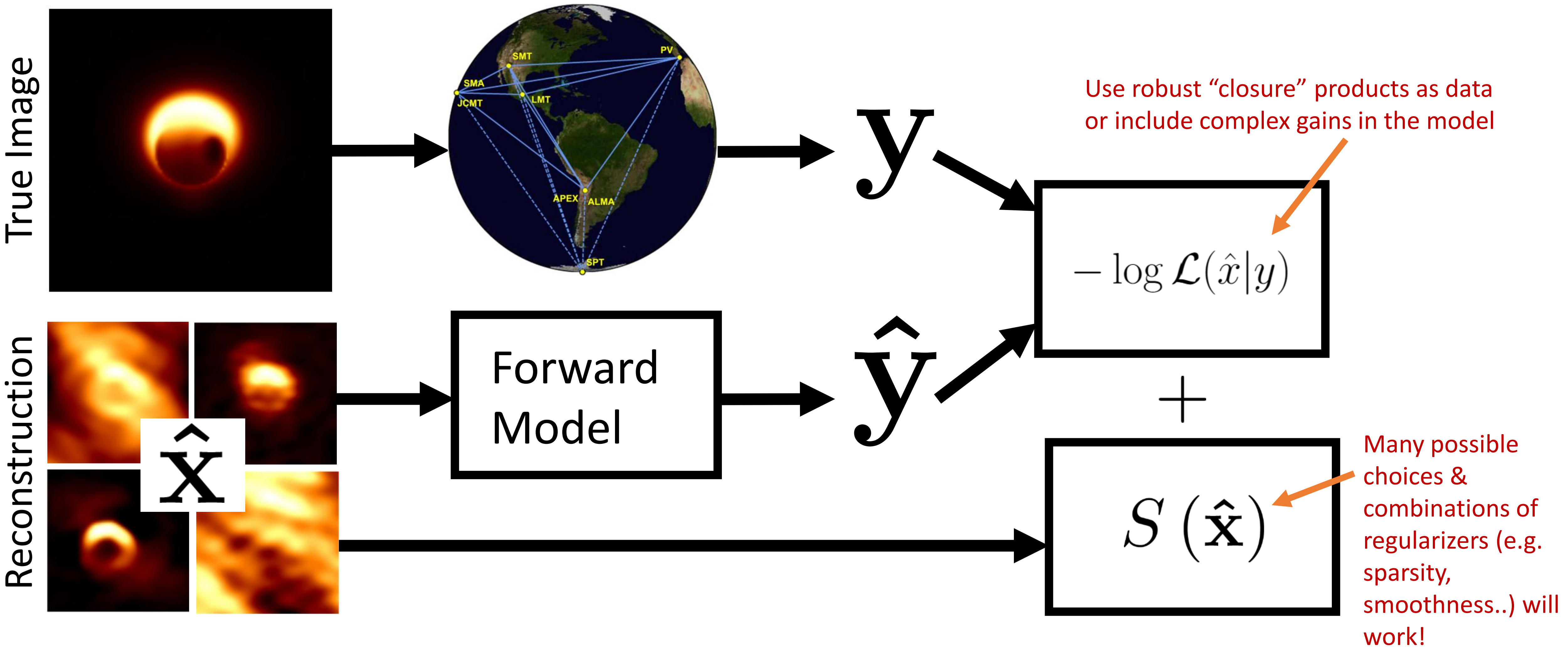


Image Credit: Chael+ 2018a
Simulation Credit: Roman Gold

``Bayesian'' Imaging



Regularized Maximum Likelihood (RML)

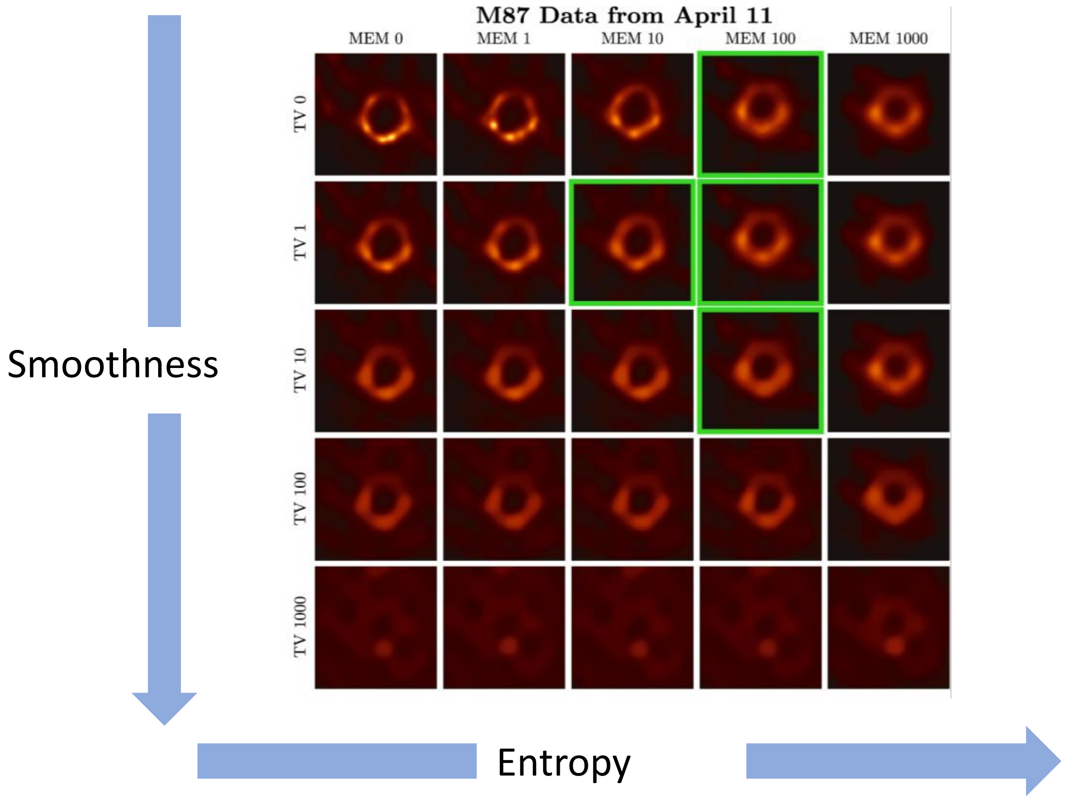


Regularizers and hyperparameter surveys

Sparsity (l1):
Favors the image to be mostly empty space

Smoothness (TV):
Favors an image that varies slowly over small spatial scales

Maximum Entropy (MEM):
Favors compatibility with flat brightness or a specified image



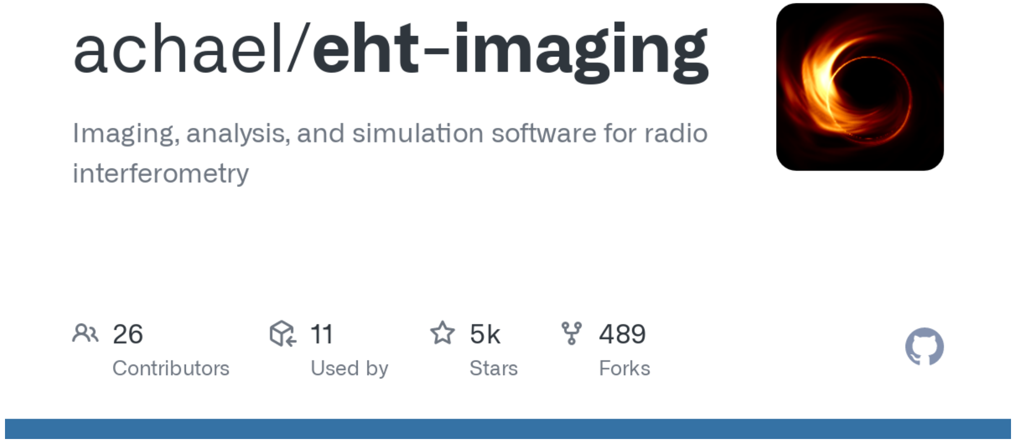
EHTC+ 2019 Paper IV (**Chael,** paper writing team)

The **eht-imaging** software library

- python toolkit for **analyzing, simulating,** and **imaging** interferometric data

- A flexible framework for developing new tools:
  - dynamical imaging (Johnson+ 2017)
  - **multi-frequency imaging (Chael+ 2023a)**
  - geometric modeling (Roelofs+ 2023)

- Uses:
  - All EHT results to date
  - Next-generation EHT design
  - Imaging & analysis from VLBA, GMVA, ALMA, RadioAstron…



https://github.com/achael/eht-imaging

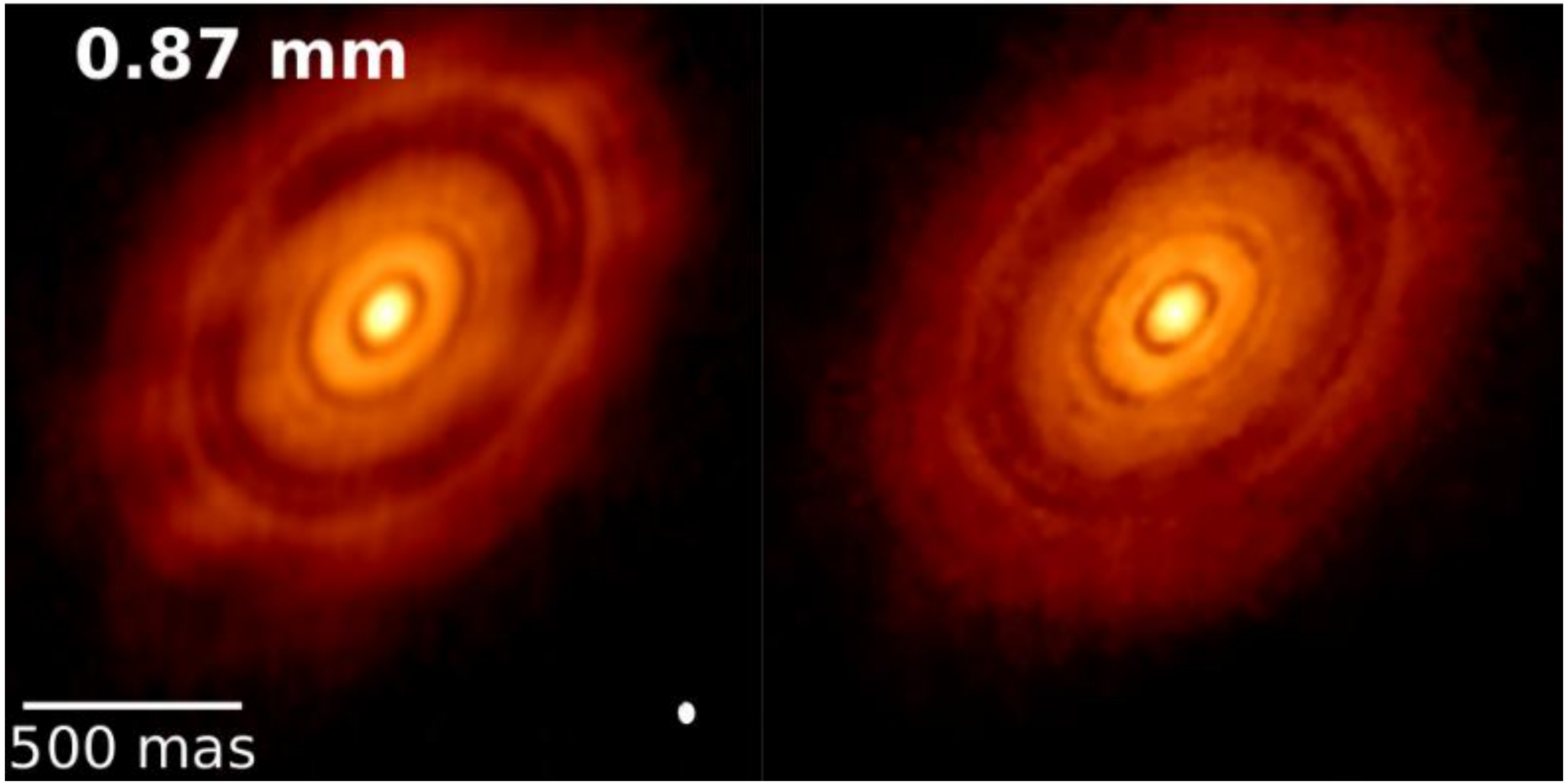
`pip install ehtim`

Chael+ 2016, 2018a, 2023a

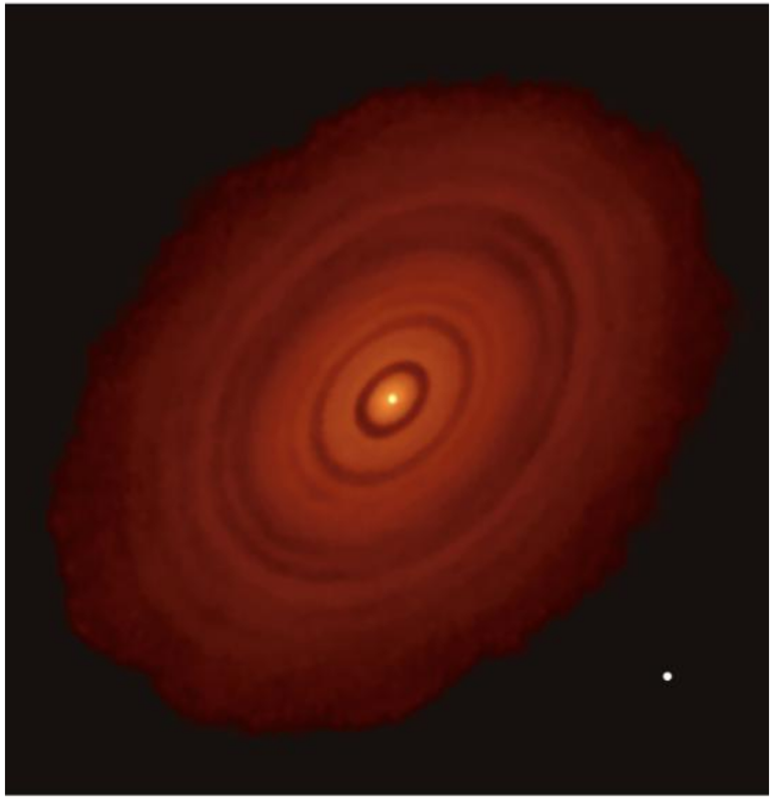
eht-imaging beyond the EHT

HL Tau with ALMA

Original CLEAN image | With eht-imaging



With eht-imaging (multifrequency)



Chael+2018, 2023

Data & CLEAN image: ALMA Partnership+ 2015

How do we verify what we are reconstructing is real?

Paper IV coordinators

Michael Johnson

Kazu Akiyama

First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

Received 2019 February 11; revised 2019 March 5; accepted 2019 March 6; published 2019 April 10

Abstract

We present the first Event Horizon Telescope (EHT) images of M87, using observations from April 2017 at 1.3 mm wavelength. These images show a prominent ring with a diameter of $\sim$40 μas, consistent with the size and shape of the lensed photon orbit encircling the "shadow" of a supermassive black hole. The ring is persistent across four observing nights and shows enhanced brightness in the south. To assess the reliability of these results, we implemented a two-stage imaging procedure. In the first stage, four teams, each blind to the others' work, produced images of M87 using both an established method (CLEAN) and a newer technique (regularized maximum likelihood). This stage allowed us to avoid shared human bias and to assess common features among independent reconstructions. In the second stage, we reconstructed synthetic data from a large survey of imaging parameters and then compared the results with the corresponding ground truth images. This stage allowed us to select parameters objectively to use when reconstructing images of M87. Across all tests in both stages, the ring diameter and asymmetry remained stable, insensitive to the choice of imaging technique. We describe the EHT imaging procedures, the primary image features in M87, and the dependence of these features on imaging assumptions.

Key words: black hole physics – galaxies: individual (M87) – galaxies: jets – techniques: high angular resolution – techniques: image processing – techniques: interferometric

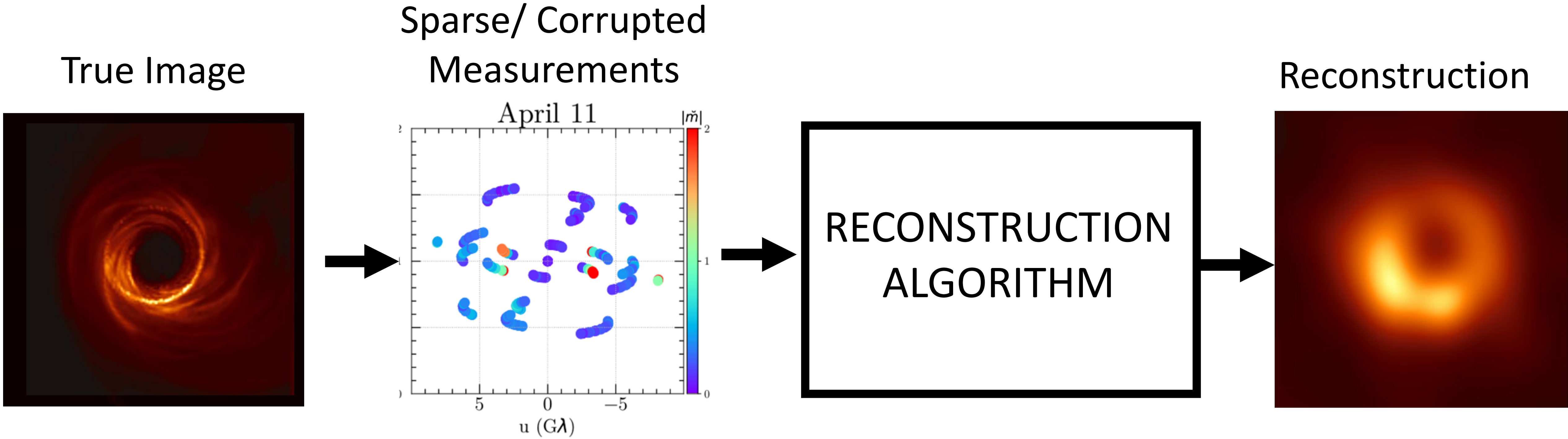
+ many, many contributions from across the EHT collaboration

José L. Gómez

Katie Bouman

Andrew Chael

We can’t rely on one reconstruction algorithm

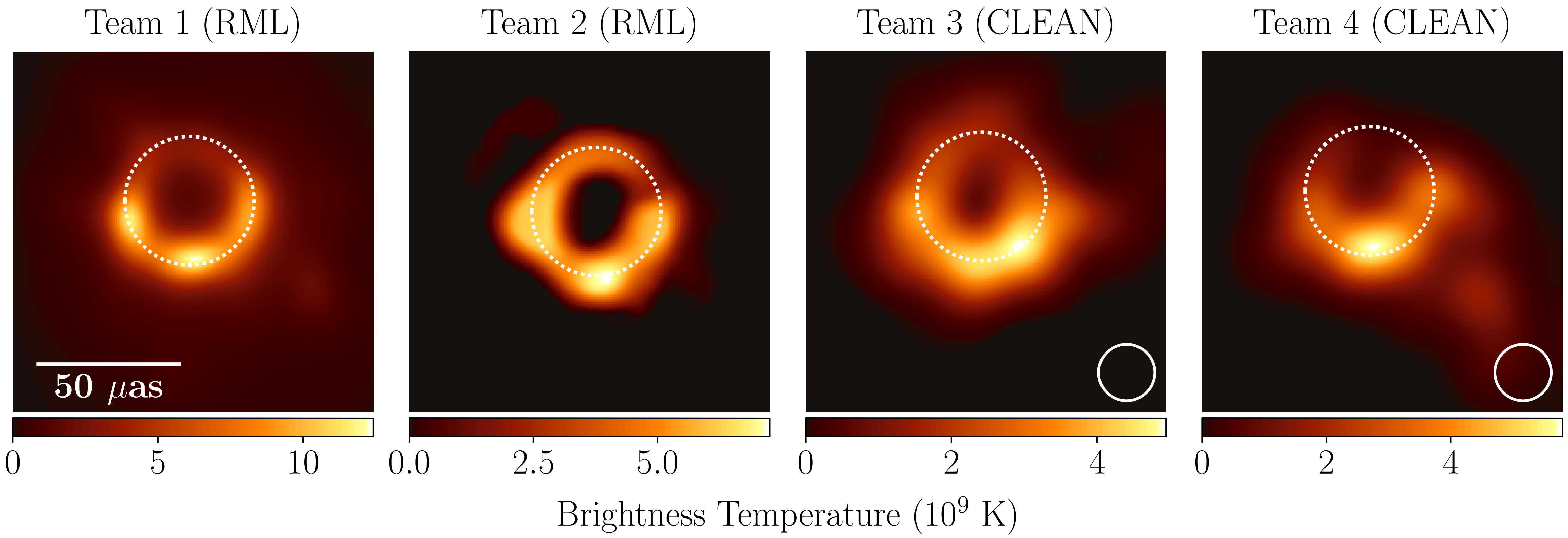


We **test and compare** many reconstruction methods to determine the most reliable image and image features:

- **CLEAN-based**: standard and efficient, but can have difficulties on very sparse data
    - Difmap (Shepherd 1997), LPCAL/GPCAL (Park+ 2021)
- **Regularized Maximum Likelihood / Gradient Descent**: fast and flexible, but lots of hyperparameters
    - eht-imaging (Chael+ 2016, 2018), SMILI (Akiyama+ 2017)
- **Bayesian MCMC posterior exploration:** fully characterizes uncertainty, but more expensive
    - Themis (Broderick+ 21), DMC (Pesce+ 21), Comrade (Tiede 2022)

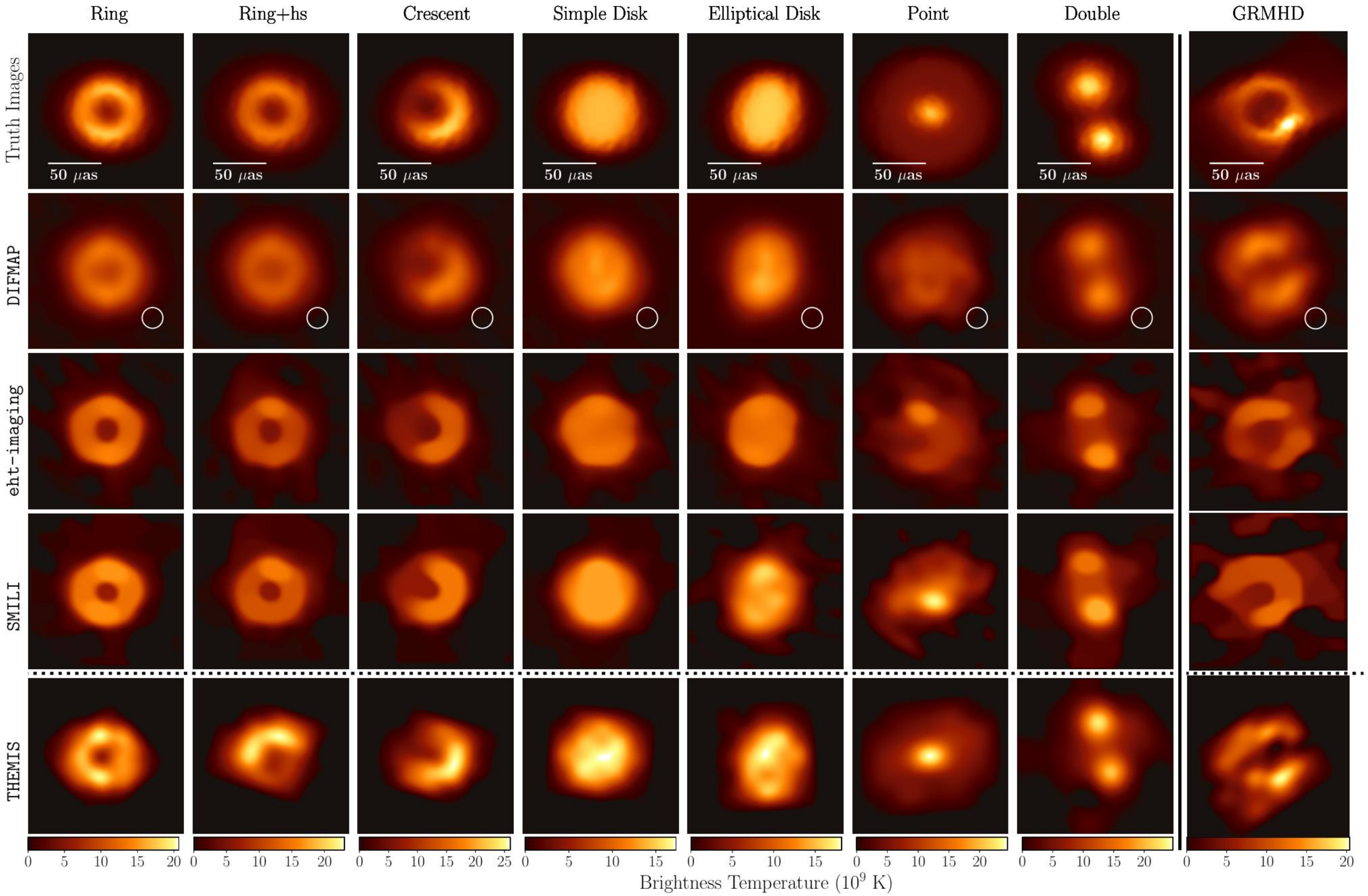
Slide credit: Katie Bouman, Andrew Chael, EHTC 2021, VII

Stage 1: Blind Imaging



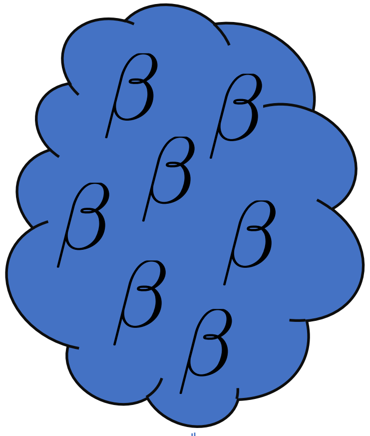
EHTC+ 2019 Paper IV (**Chael,** paper coordinator)

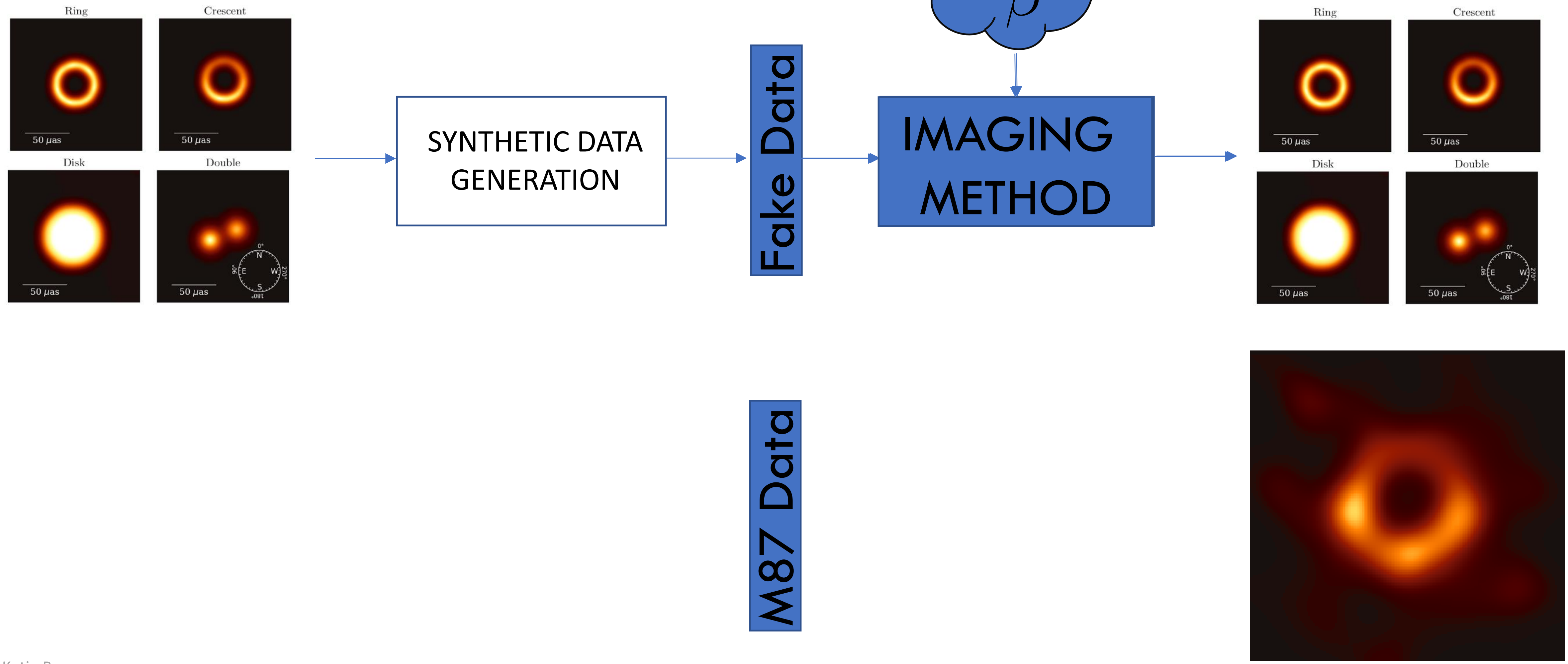
Stage 2: Testing our methods with synthetic data



EHTC+ 2019 Paper IV (**Chael,** paper coordinator)

Stage 3:
Test 30,000+ hyperparameter sets

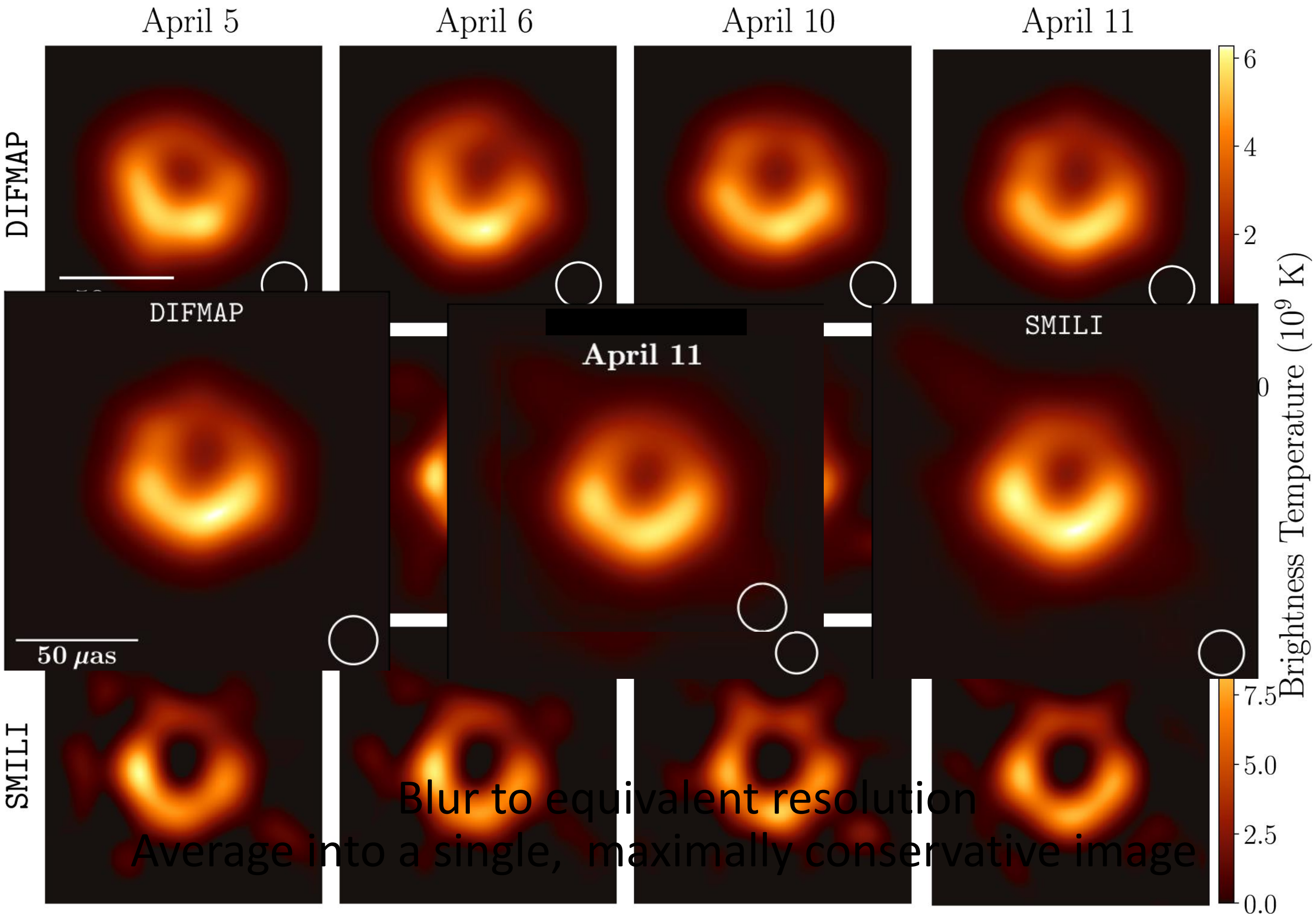




Slide credit: Katie Bouman

EHTC+ 2019 Paper IV (**Chael,** paper coordinator)

Stage 4: Look for consistent features from different methods



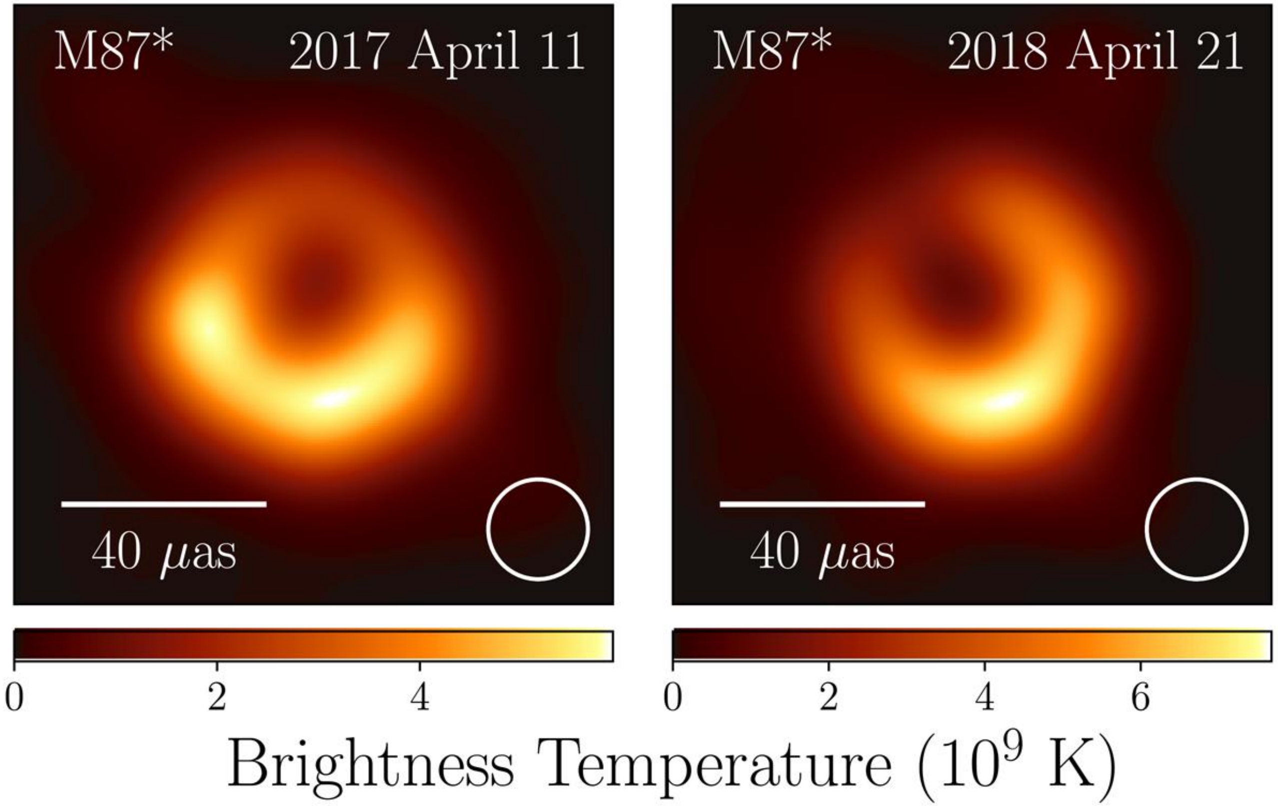
Blur to equivalent resolution

Average into a single, maximally conservative image

EHTC+ 2019 Paper IV (**Chael,** paper coordinator)

Image persistance across years

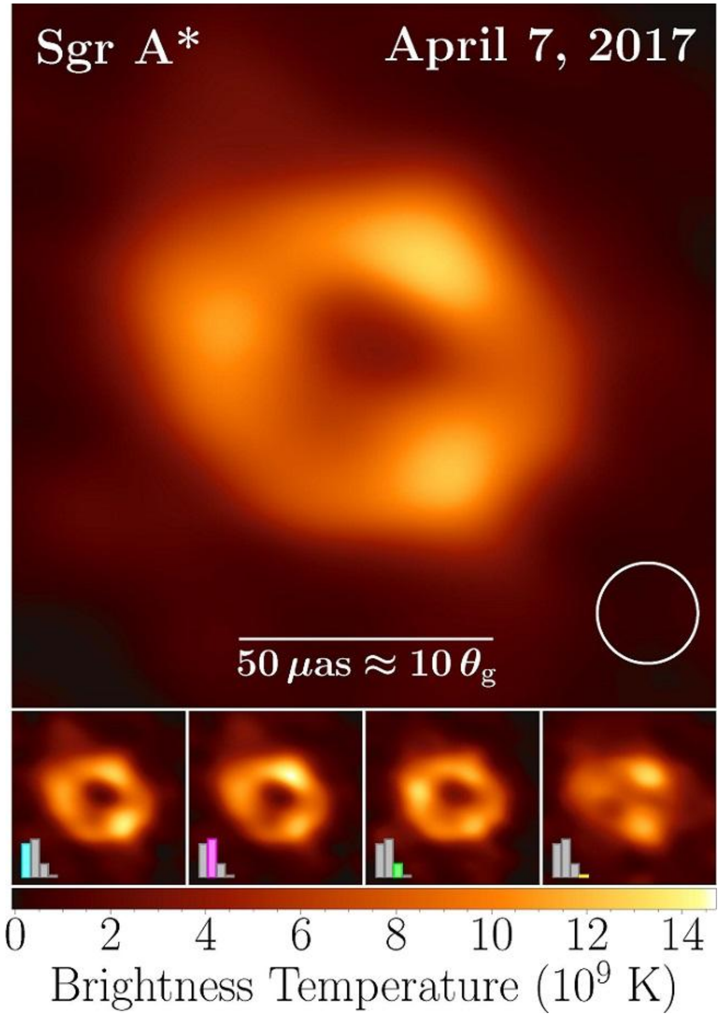
- 2018 observations show consistent horizon-scale structure in M87* **1000 gravitational timescales later.**
- Observations performed with a **more complete array** (including Greenland Telescope)
- Image **diameter is consistent** but brightness **position angle shifts**
- Stay tuned for more soon….



EHTC I, 2024

Our Galactic Center Black Hole: Sgr A*

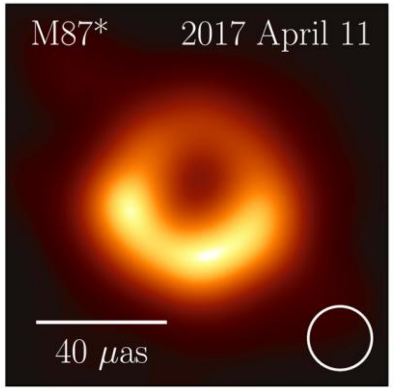
- Imaging Sgr A* is **much more challenging than M87** due to rapid sub-hour **variability** and **interstellar scattering**.
- Sgr A* images predominantly (but not uniquely) show a **≈50μas diameter ring.**
- Sgr A* images do not currently constrain the ring position angle
- Sgr A* is **more polarized** (≈30%) than M87*, and it shows a similar **helical linear polarization pattern**.



EHTC I, 2022; EHTC VII, 2024 **Chael**, paper writing team)

What do we learn from Black Hole Images?

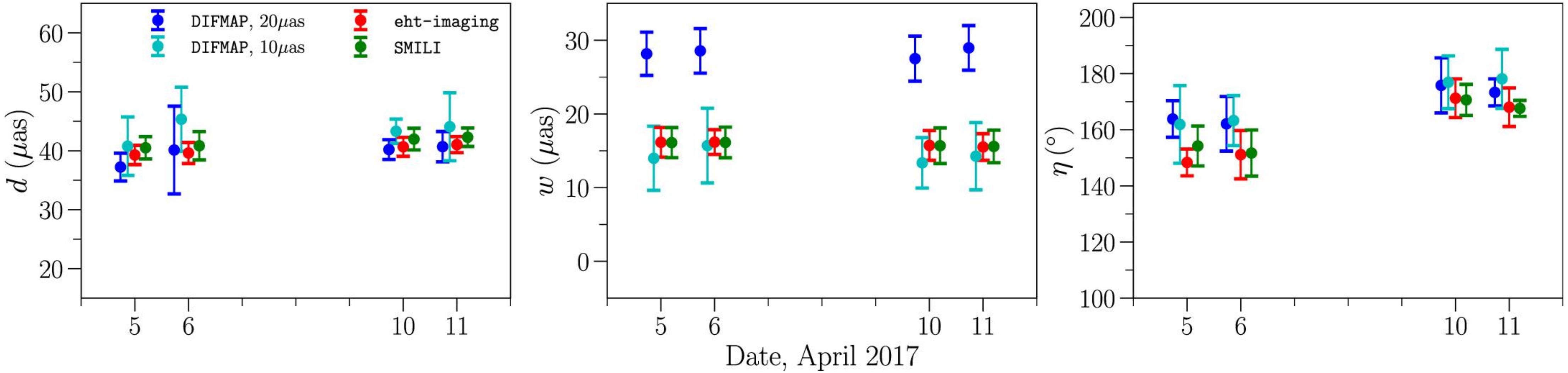
M87 Properties (2017)



Diameter

Width

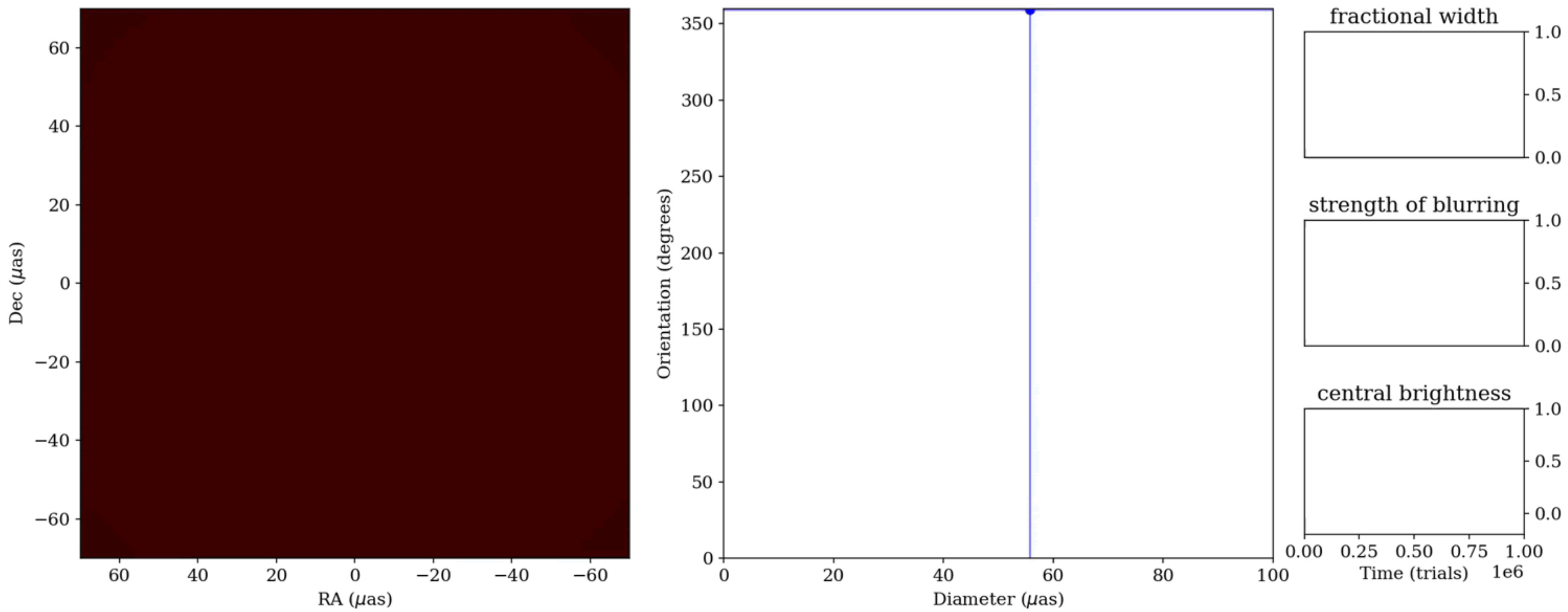
Angle



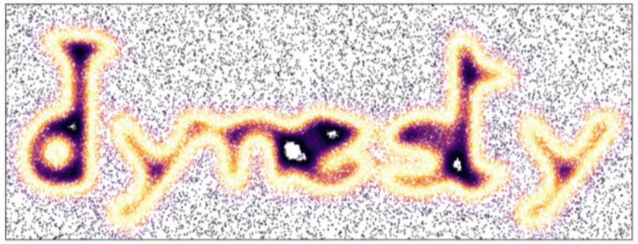
- Diameter $d \approx 41\ \mu\text{as}$ is consistent across time and imaging method
- The width is **resolution dependent**, and is at best an upper limit.
- Orientation angle shows tentative $\approx 20^{\circ}$CCW shift from April 5 – 11, 2017

EHTC IV, VI 2019 (**Chael**, paper writing team)

Weighing a black hole with Geometric Modeling



dynesty



A Dynamic Nested Sampling package for computing Bayesian posteriors and evidences. Pure Python. MIT license.

Dynesty: pure python nested sampling code
https://github.com/joshspeagle/dynesty

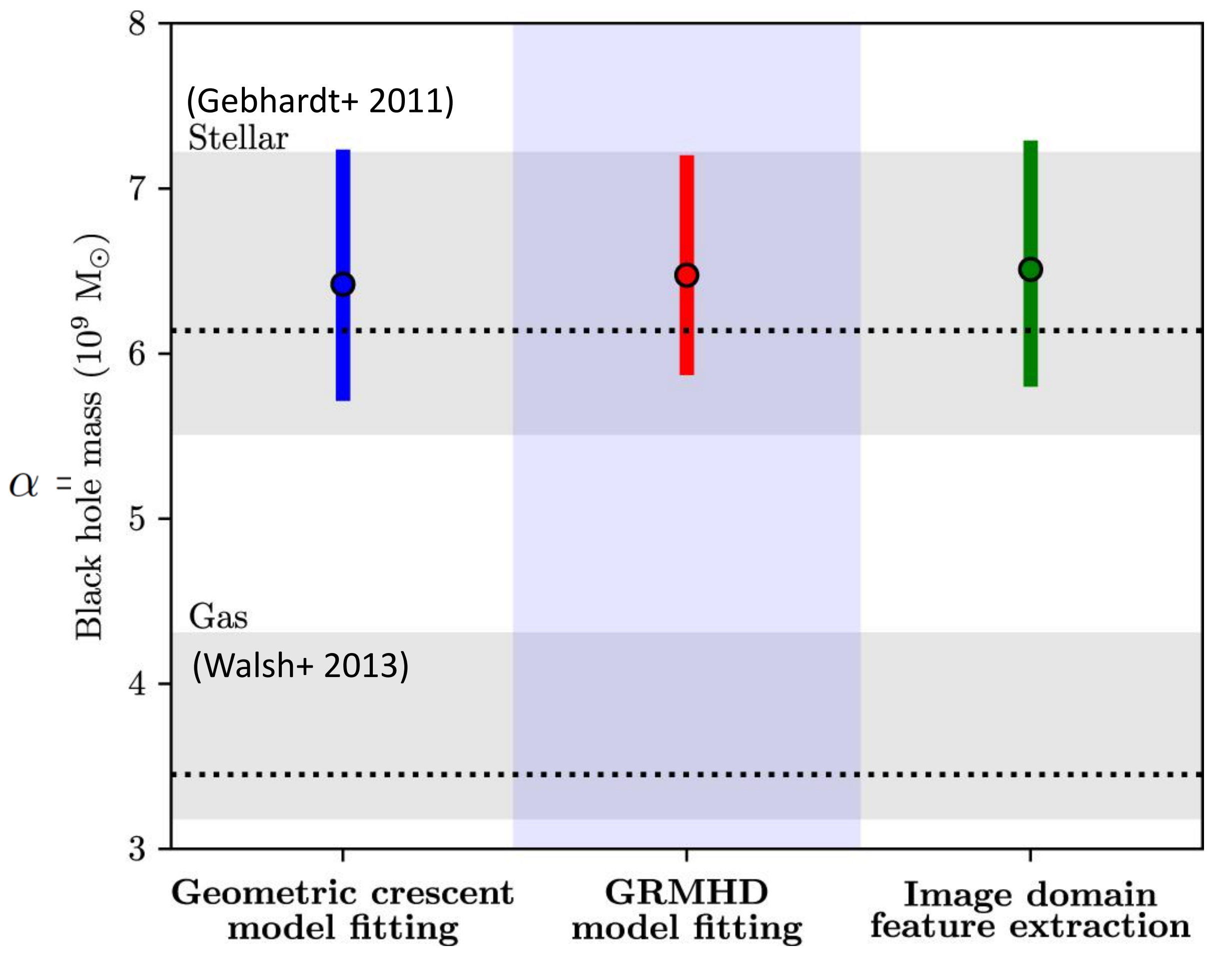
Also used several results from other MCMC codes and image reconstructions

EHT Paper VI, 2019
Animation Credit: Dom Pesce

Weighing a black hole

- Connecting EHT image ring diameter to predicted shadow size from GR requires **astrophysical** calibration
- M87* image size is consistent with previous measurements from stellar dynamics but not competing measurements from gas dynamics

Mass Results from three methods

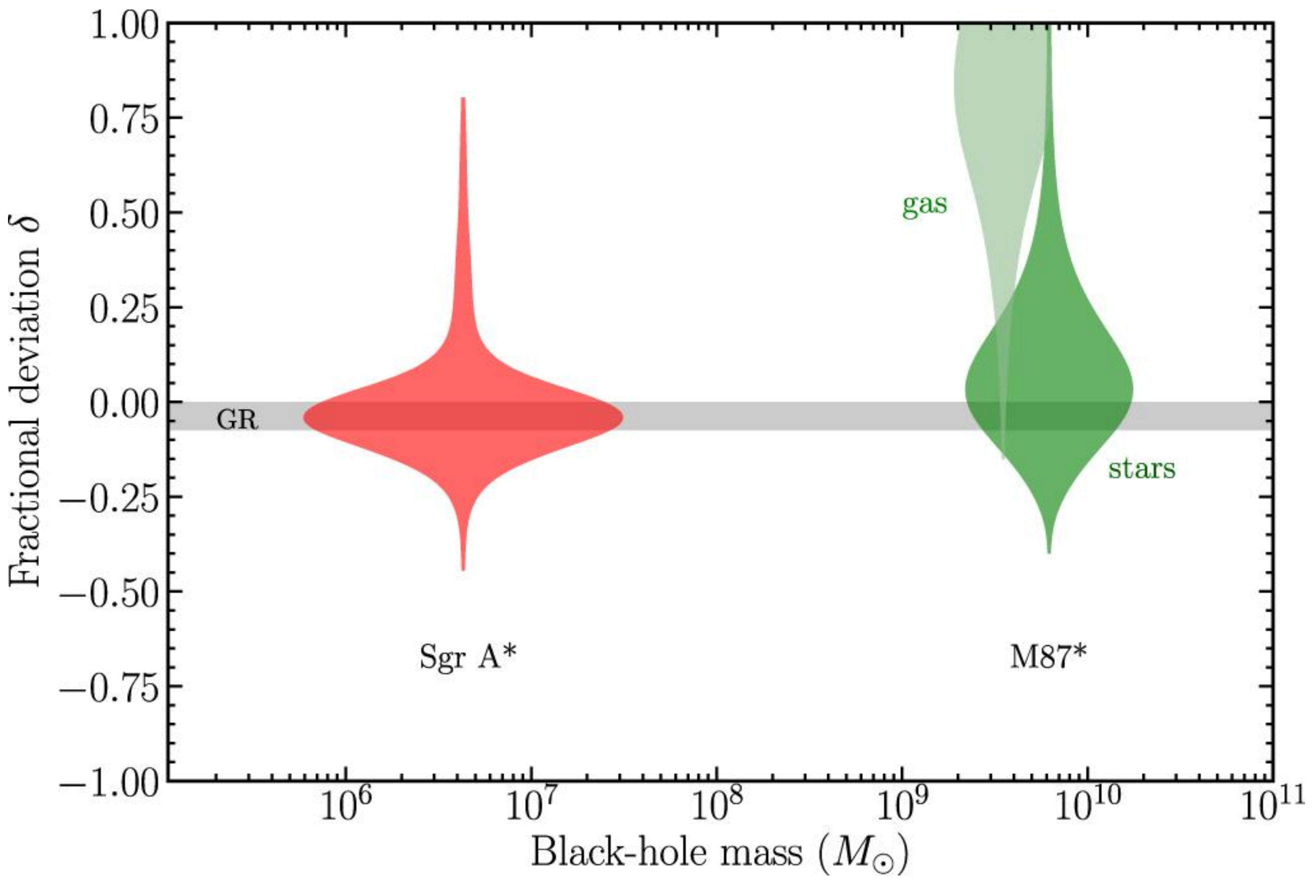


$$M = (6.5 \pm 0.7) \times 10^9 \, M_\odot$$

EHT Collaboration 2019 (Paper VI)

Weighing a black hole

- Connecting EHT image ring diameter to predicted shadow size from GR requires **astrophysical** calibration
- M87* image size is consistent with previous measurements from stellar dynamics but not competing measurements from gas dynamics
- After astrophysical calibration (and assuming a stellar mass prior) both M87* and Sgr A* have image sizes consistent with GR prediction.



EHT Collaboration 2022 (Paper I)

Astrophysics: what's going on near the event horizon?

- Thick accretion disk of hot plasma (tens of billions of degrees K)
- Strong and turbulent magnetic fields
- Launches a powerful relativistic jet

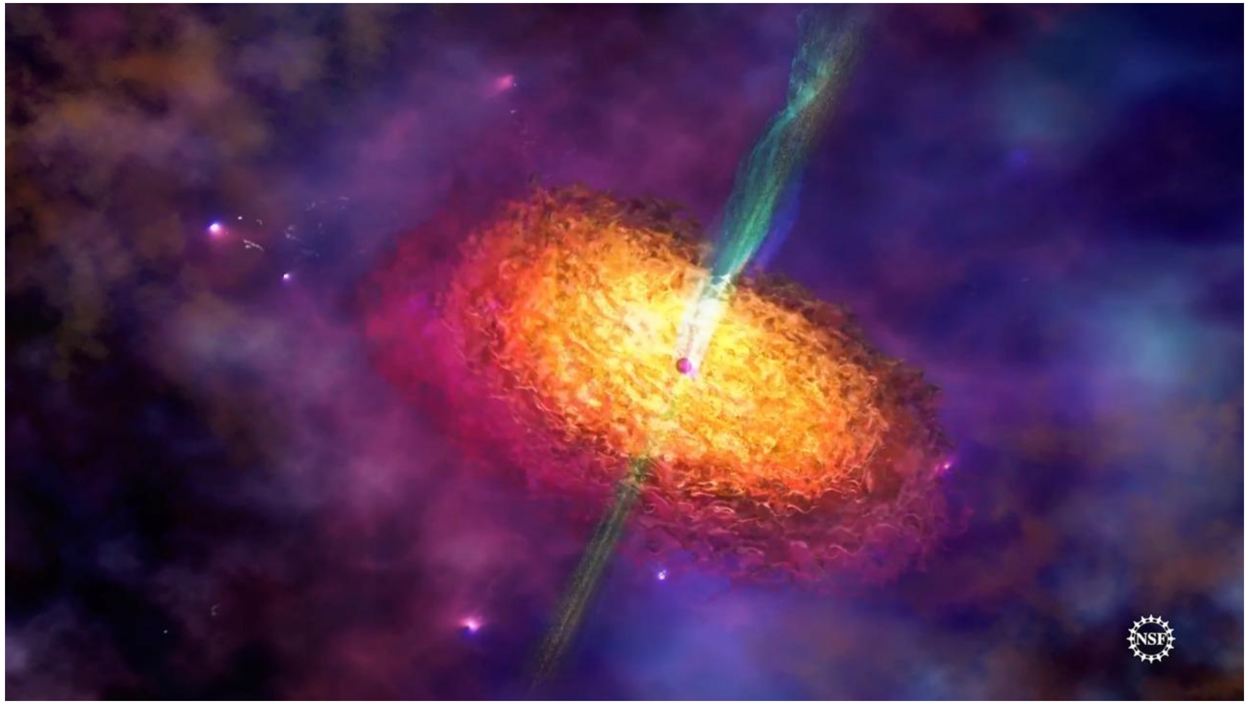
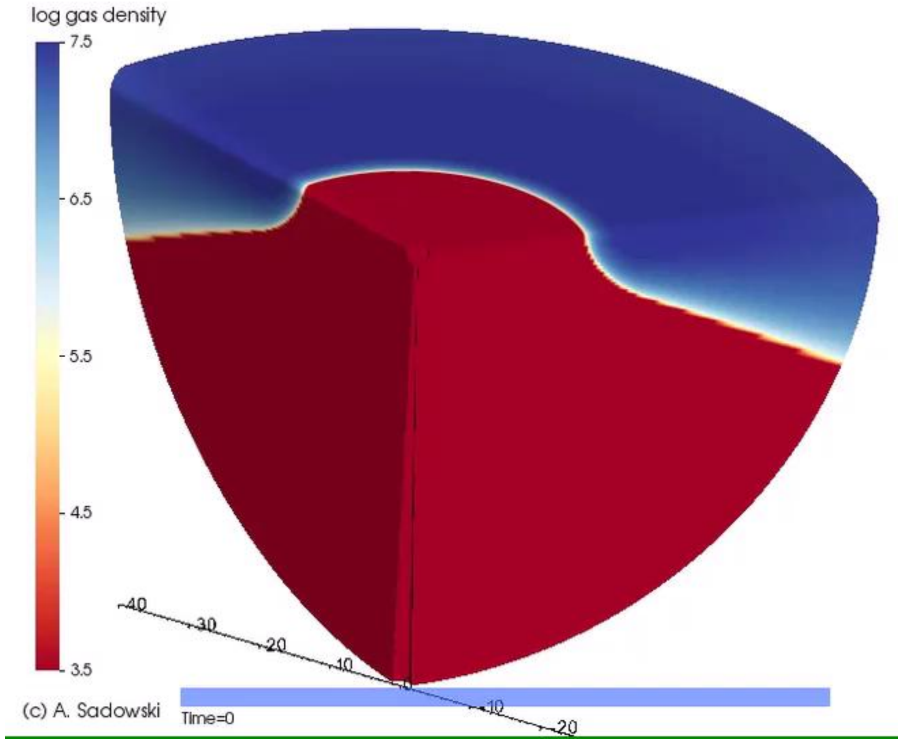


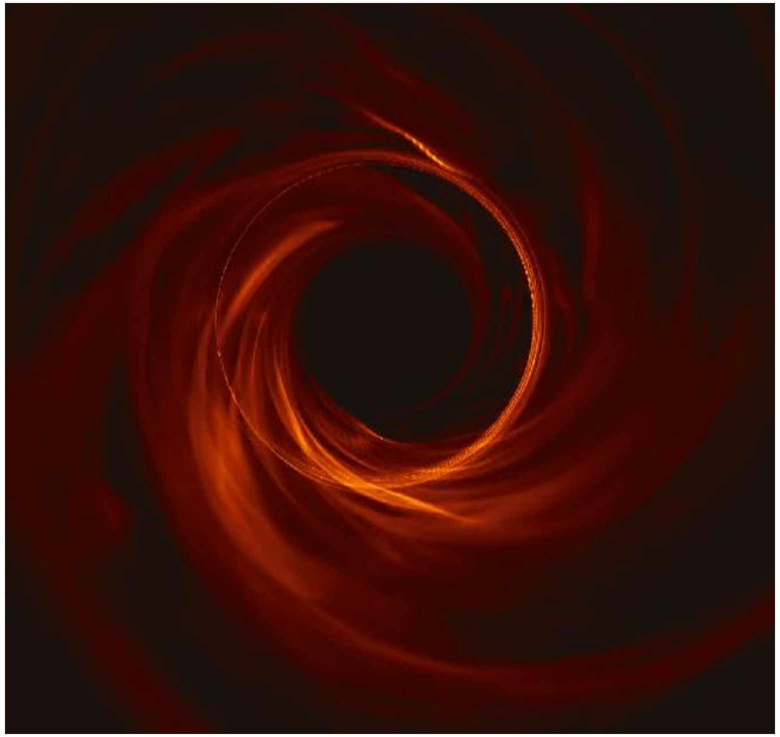
image credit: NSF

General **R**elativistic **M**agneto**H**ydro**D**ynamic Simulations

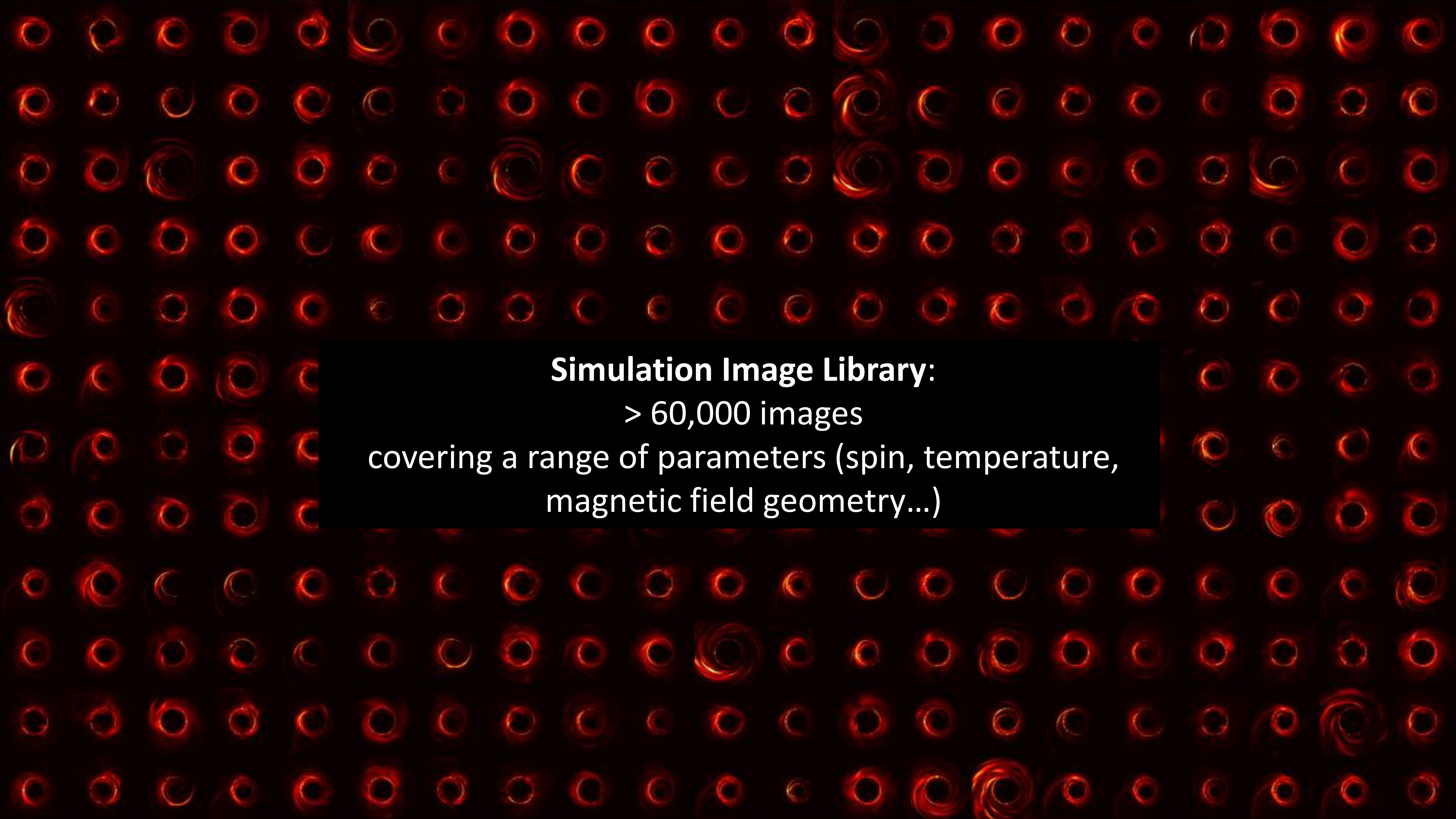


Solves coupled equations of fluid dynamics and magnetic field in a black hole spacetime

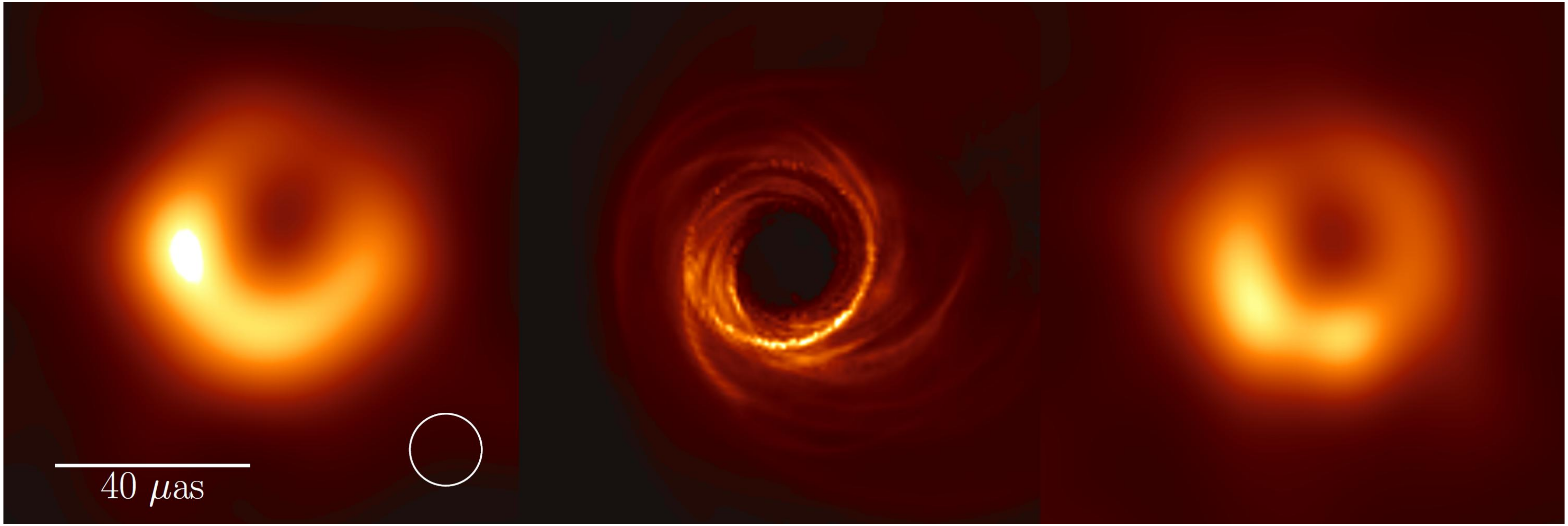
General **R**elativistic **R**ay Tracing



Tracks light rays and solves for the emitted radiation


Simulation Image Library:
> 60,000 images
covering a range of parameters (spin, temperature, magnetic field geometry…)

Simulations Match BH Images almost too Well!



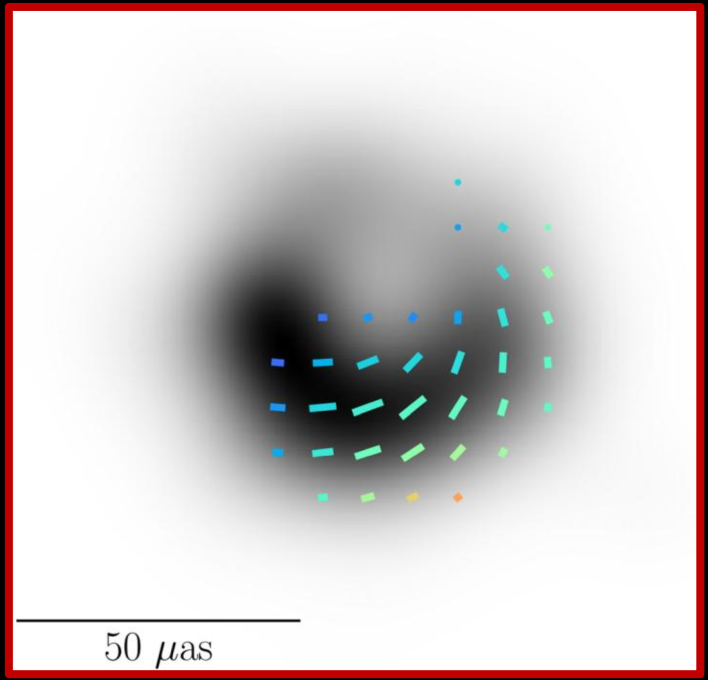
Initial EHT images were consistent with almost all of our simulations!

Chael+ 2019

M87* in **linear polarization**

Total intensity

Linear Polarization



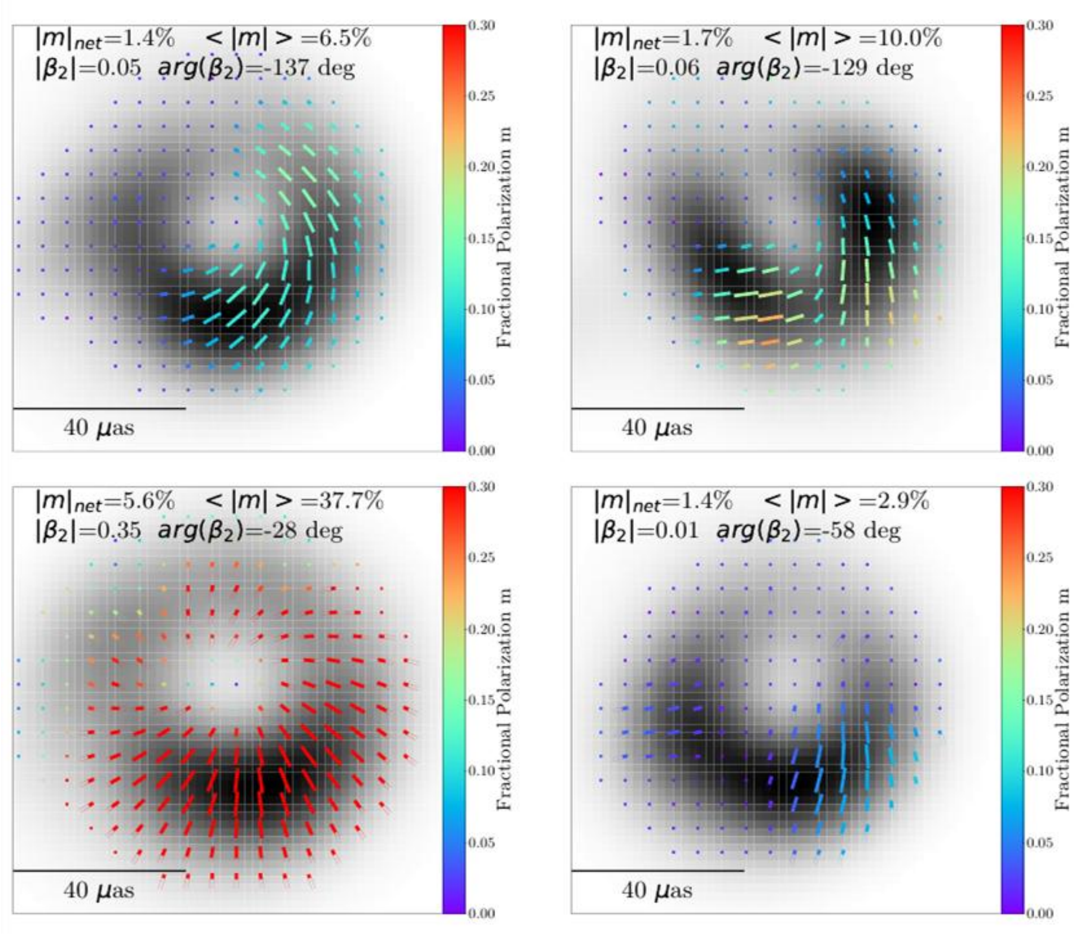
- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **somewhat weak**, ~15 %

EHTC+ 2021 VII (**Chael,** paper writing team)

Polarization is the key for learning more

- Synchrotron radiation is emitted with polarization **perpendicular** to magnetic field lines
- Polarization is sensitive to the **magnetic field, plasma, and spacetime.**
- Simulation polarization images show many different structures:
  - **strongly** or **weakly** polarized
  - patterns that are **radial** or **helical**

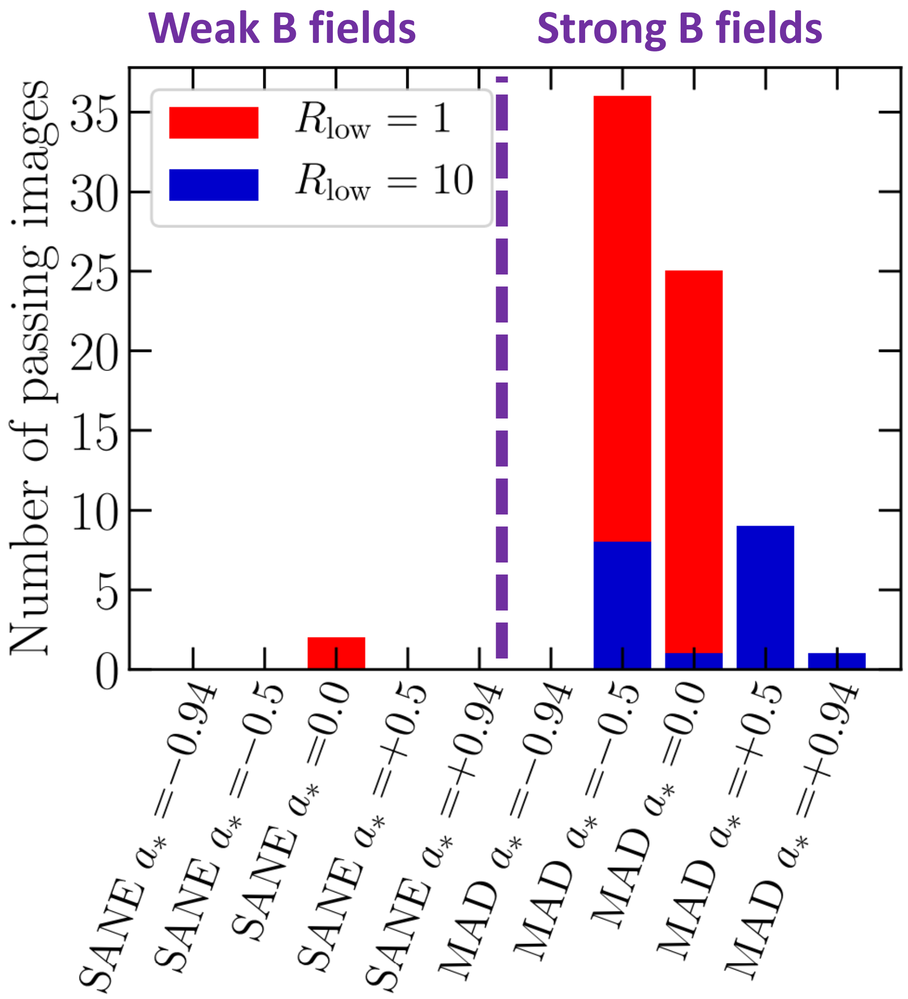
Simulation Polarization Images



EHTC+ VII, VIII 2021 (**Chael**, paper coordinator)

Polarization shows M87* has **strong magnetic fields**

- Scoring simulations with polarized images favors a **magnetically arrested accretion disk**
- Strong magnetic fields more easily launch jets by extracting black hole spin energy (Blandford & Znajek 1977)
- Can we use polarization to determine if magnetic fields extract energy from black holes?

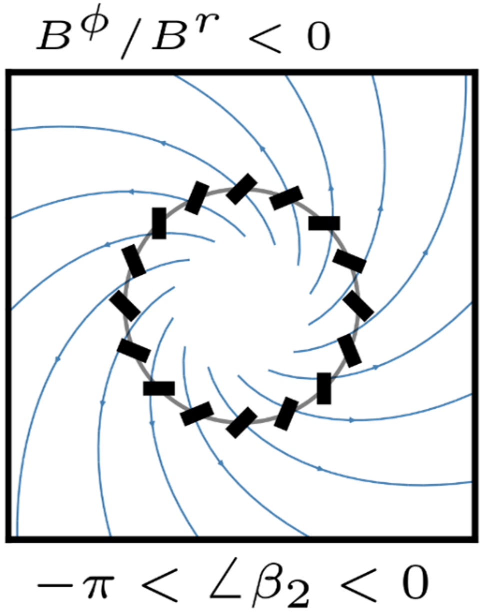


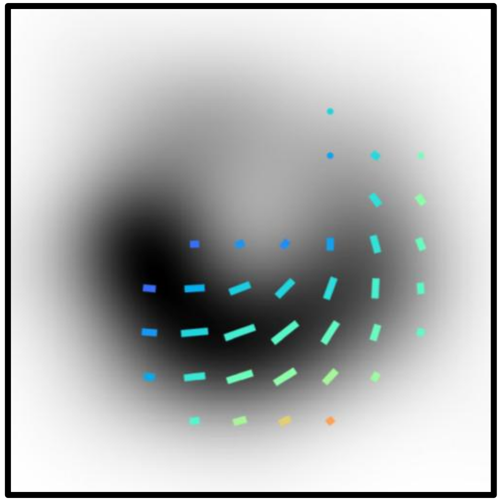
EHTC 2021 VIII, 2023 IX (**Chael**, paper coordinator)

Polarization tracks **electromagnetic energy flux**

- We found (Chael+ 2023b) that the sign of the polarization spiral is directly connected to the direction of energy flow, assuming we know the angular velocity.
- Ignoring Faraday effects, **the EHT's polarization image implies electromagnetic energy flows away from the black hole in M87***
- If we can **zoom in** and **zoom out** on near-horizon polarization, we can potentially track energy flow from the black hole into the extended jet and look for black hole energy extraction (Gelles+ 2025, Chael+ in prep)

Energy Outflow





Chael+ 2023b

What will we see next?

Future directions: dynamics

- Black holes are highly dynamic – Sgr A* varies on minute-to-minute timescales and flares more than once a day!
- Tracking motion around the event horizon will allow for new tests of plasma physics, accretion, and gravity.
- But recovering a movie with traditional VLBI techniques is hard: need a combination of more telescopes and innovative reconstruction methods.

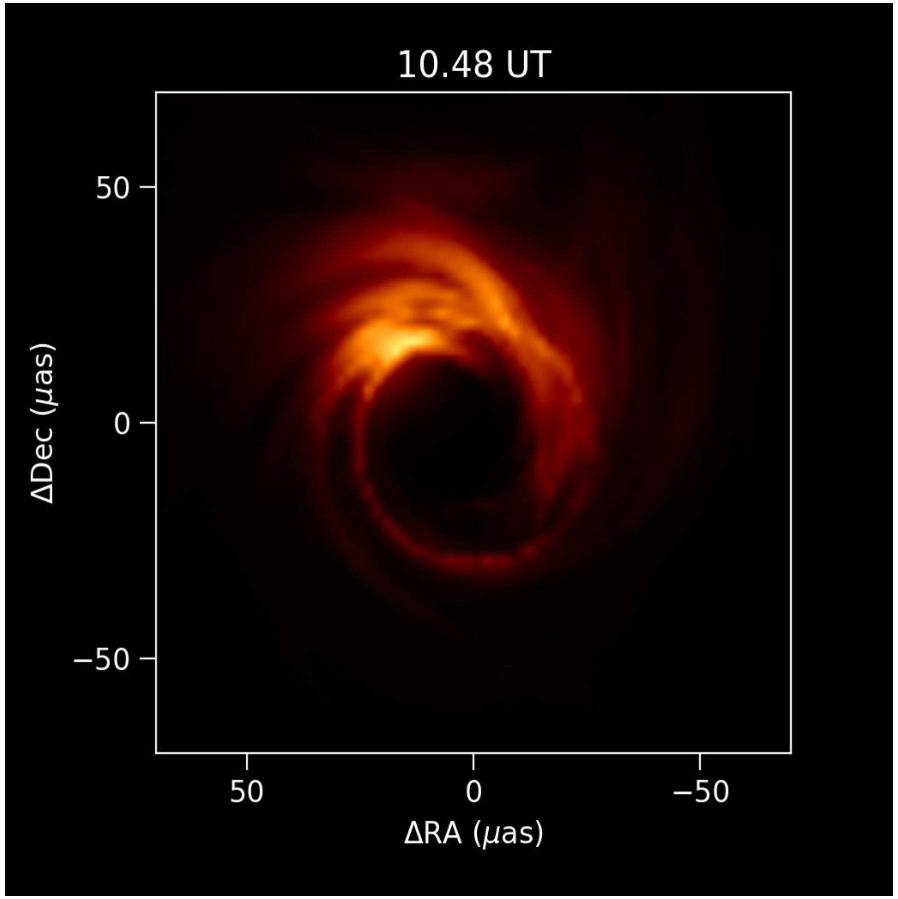
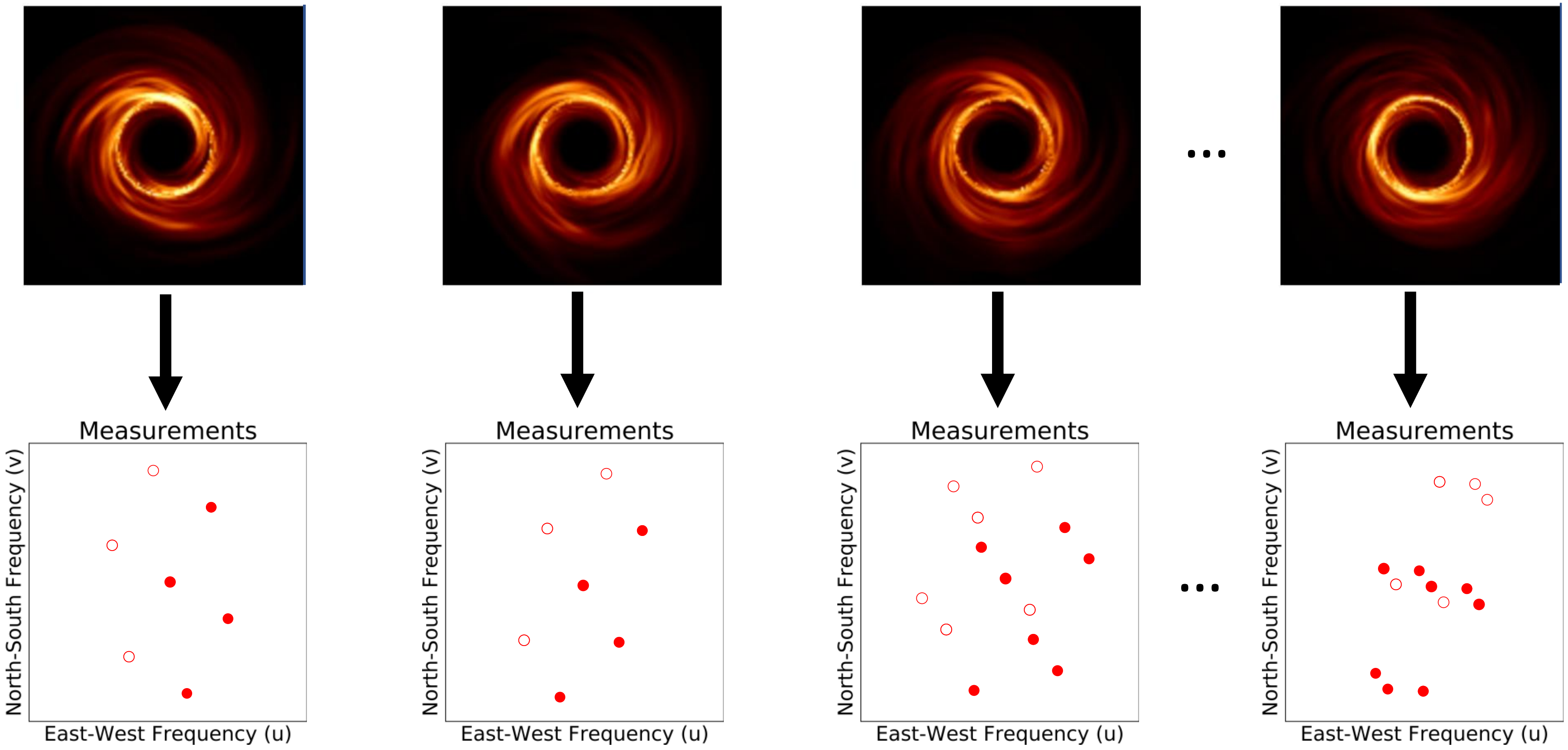


Image Credit: Antonio Fuentes, Foschi+ 2025

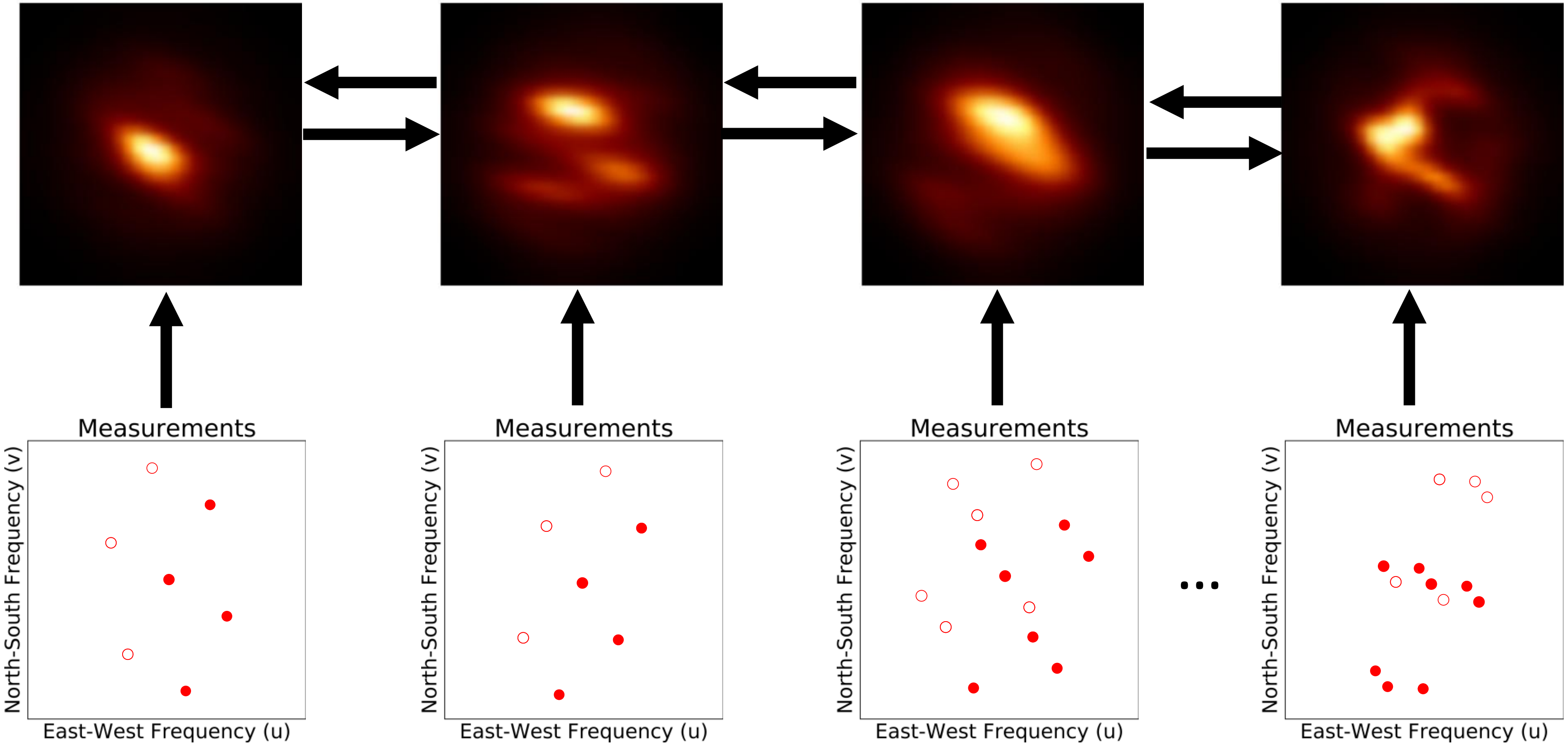
Future directions: dynamics



Each ``frame'' provides very little data

Image credit: Katie Bouman

Future directions: dynamics

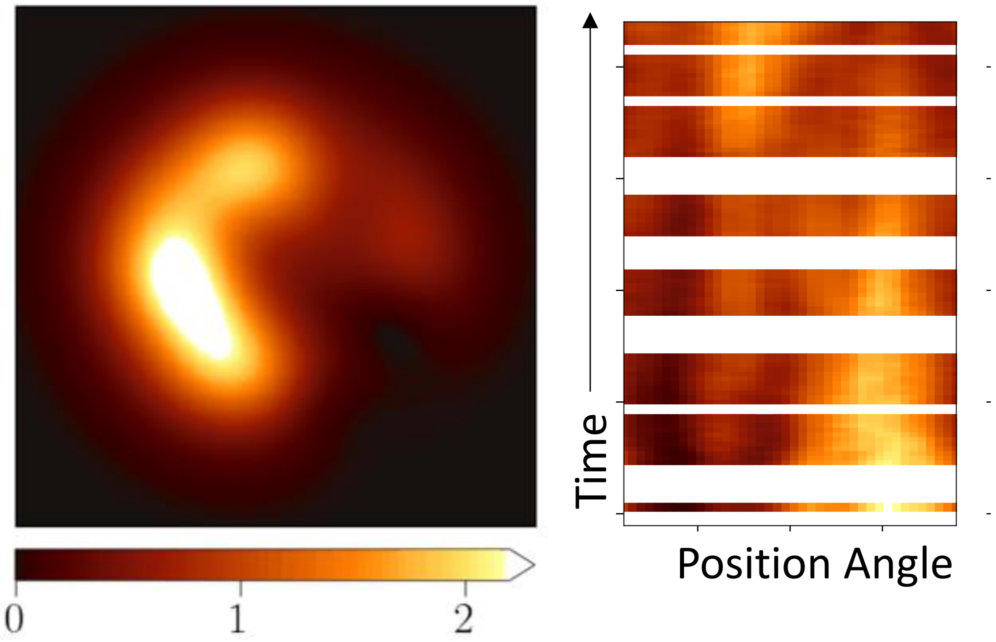


Each ``frame'' provides very little data
We need **temporal regularization**

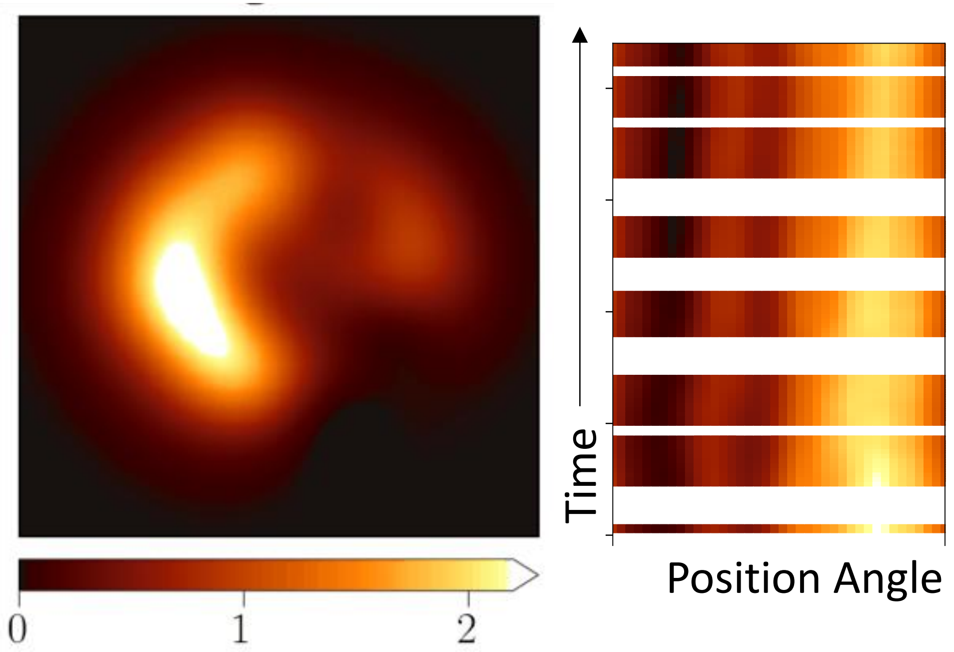
Image credit: Katie Bouman

Imaging Dynamics: Sgr A* with StarWarps

Lower Temporal Regularization



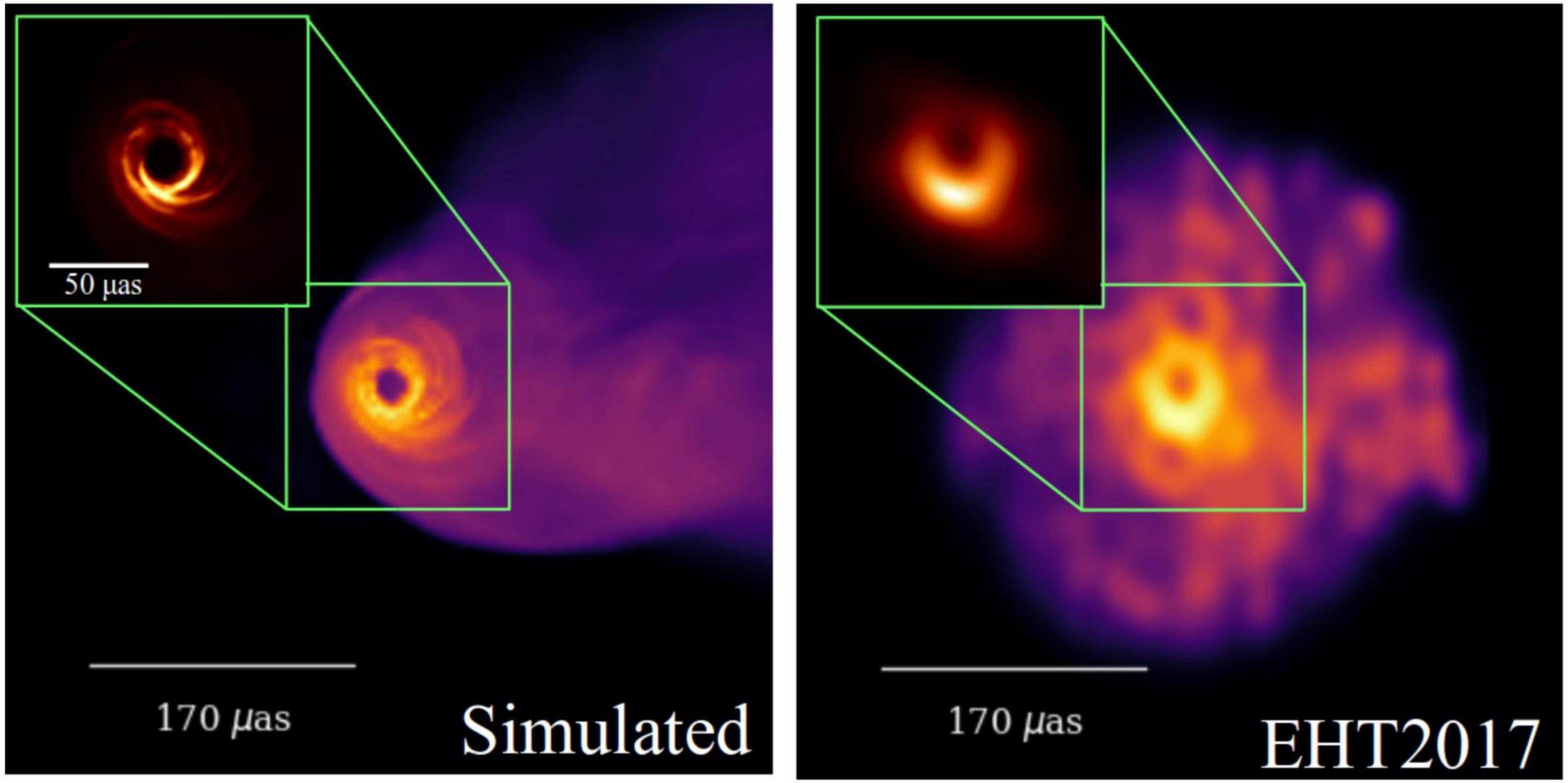
Higher Temporal Regularization



Temporal Regularization: Each video frame should look similar to its adjacent frames (**StarWarps**: Bouman+ 2018)

Which movie is more accurate? More data and testing are needed. Stay tuned!

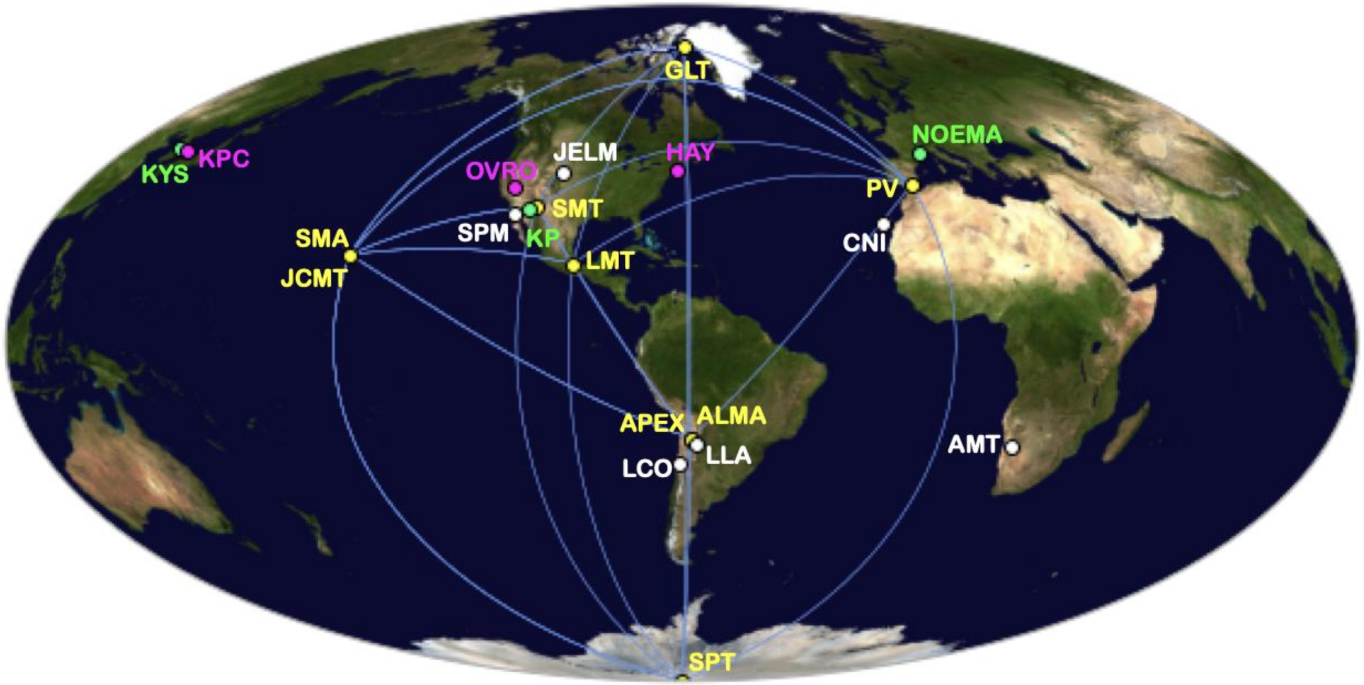
Future directions: high dynamic range

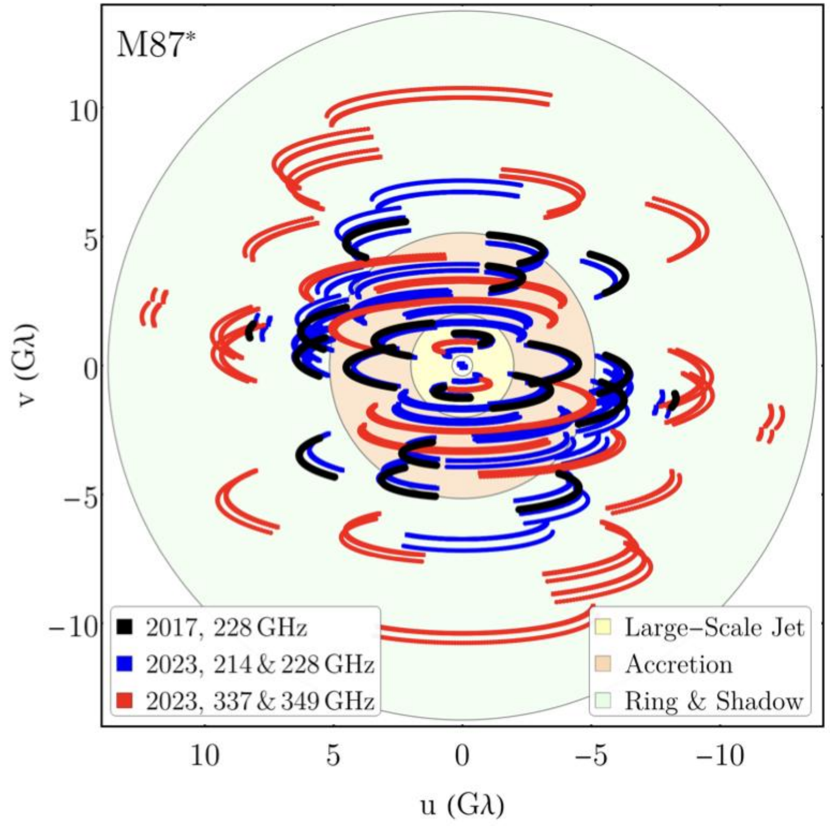


- Past EHT observations have suffered from **limited dynamic range** from **array sparsity**

Figure: Blackburn+ 2019
Simulation & Imaging: **Chael**+ 2019

EHT array expansion





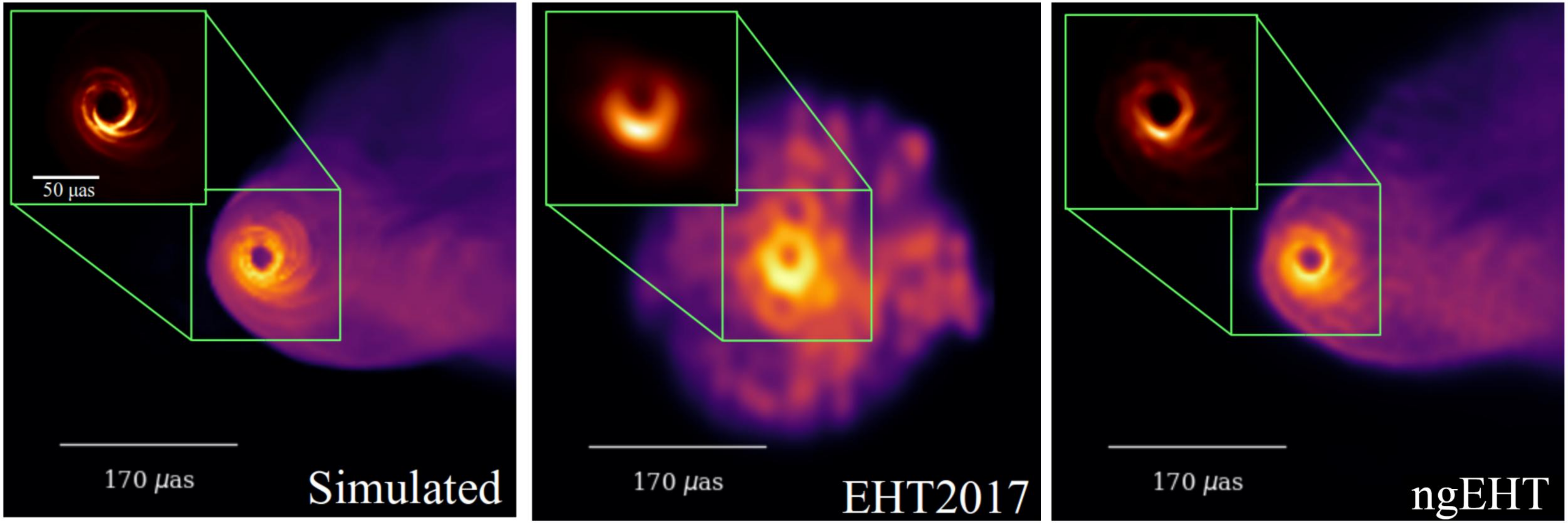
Increased coverage from new sites and observing frequencies in the EHT will enhance **dynamic range**

2017: Observations at 6 distinct sites
2018: Observations at 7 sites (+ GLT)
2021-22: Observations at 9 sites (+ Kitt Peak & NOEMA)
2024-25: 230+345 GHz observations
2025-2030s: observations at 15+ sites

$$N_{\rm obs} = \binom{N_{\rm sites}}{2} \propto N_{\rm sites}^2$$

EHTC+ 2025, Doeleman+ 2023

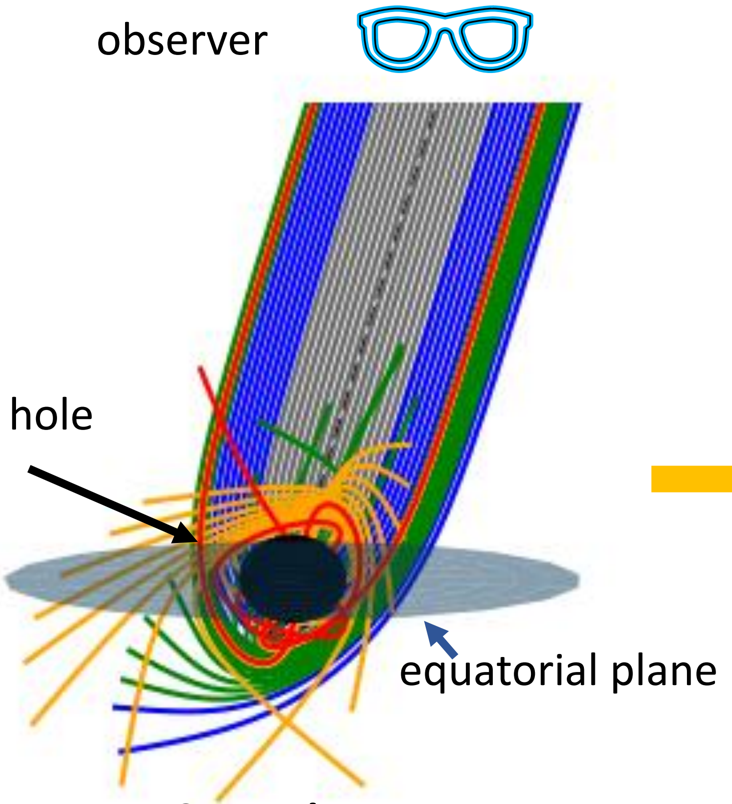
Future directions: high dynamic range



- Increased (*u,v*) filling from new telescope sites will enhance image **dynamic range**
  - High dynamic range images will illuminate the **BH-jet connection**
  - High dynamic range images may also reveal the **'inner shadow'**

Figure: Blackburn+ 2019
Simulation & Imaging: **Chael**+ 2019

Future directions: high resolution



Spacetime

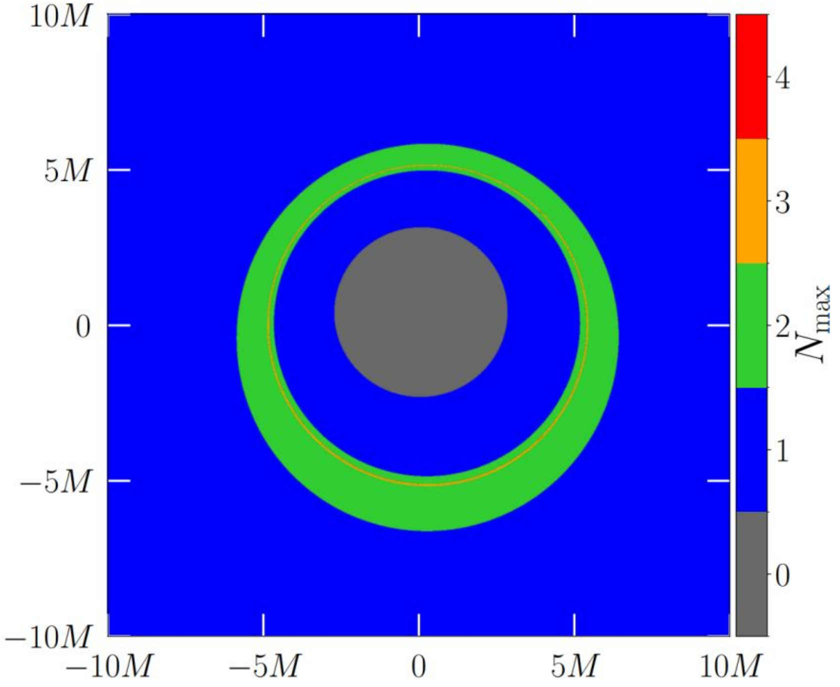


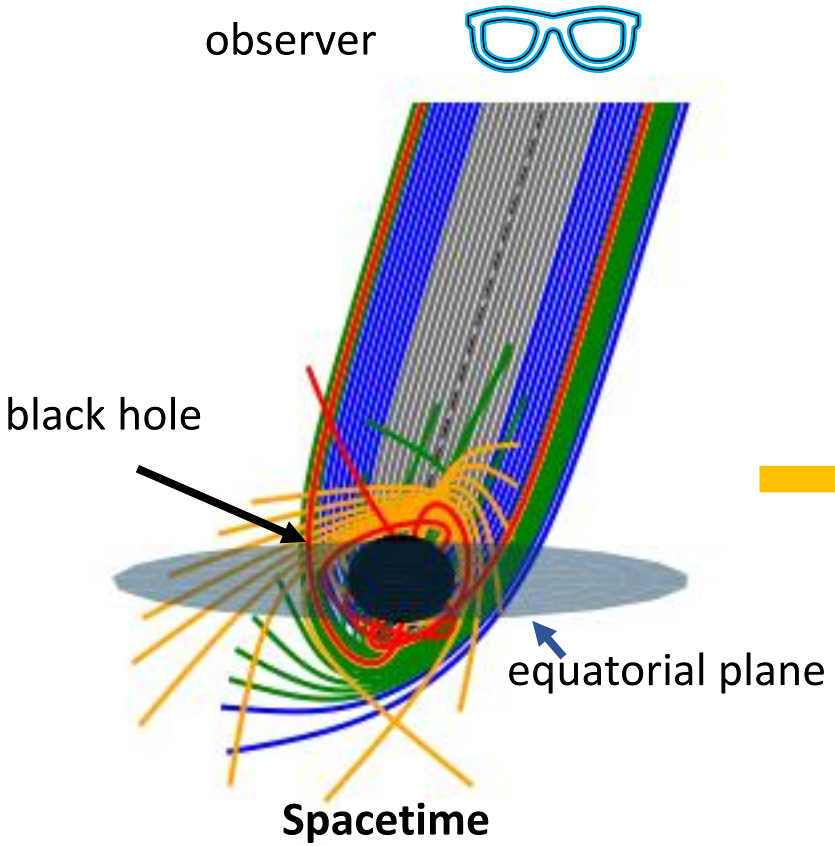
Image plane

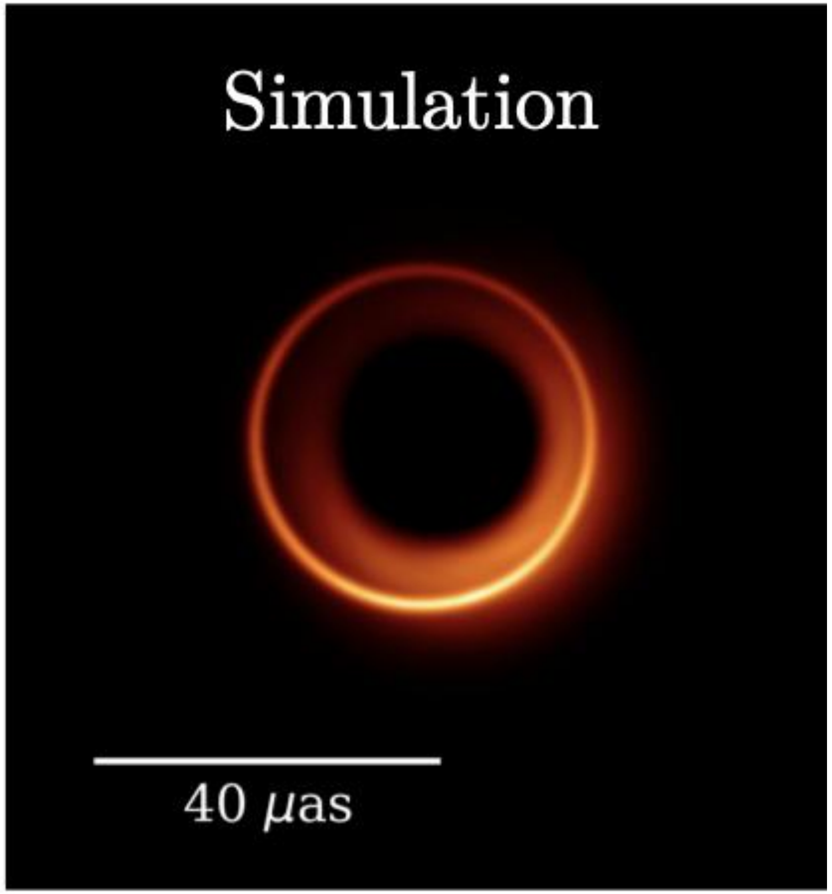
Strongly lensed light rays that wrap around the BH form **narrow photon rings on the image**

Chael+ 2021

Plots from my code **kgeo**: https://github.com/achael/kgeo

Future directions: high resolution

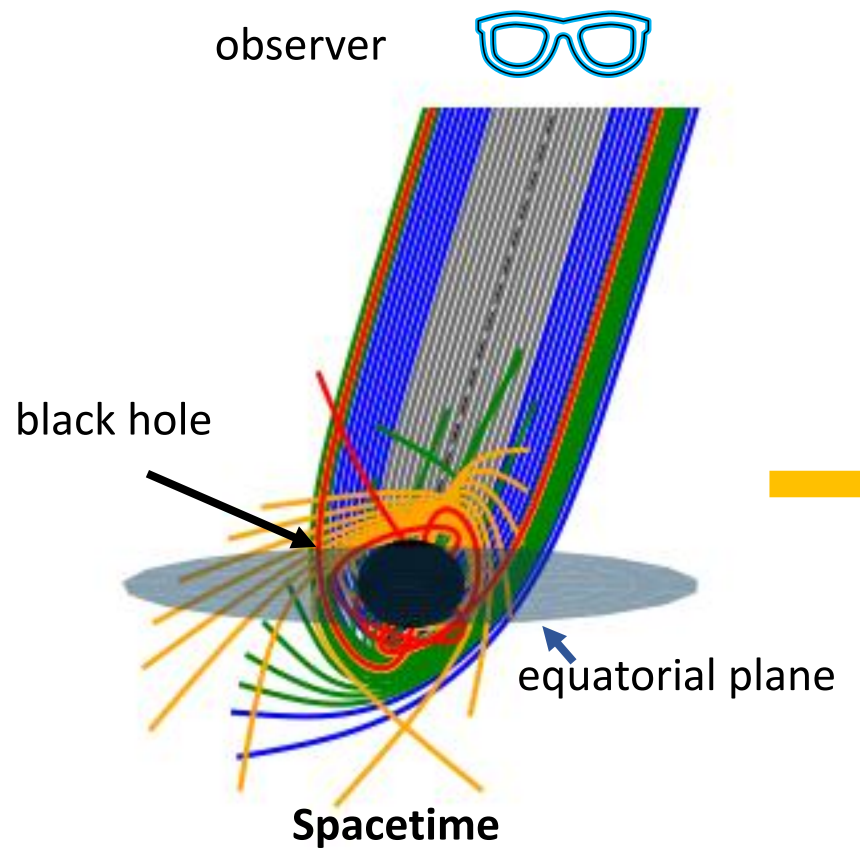


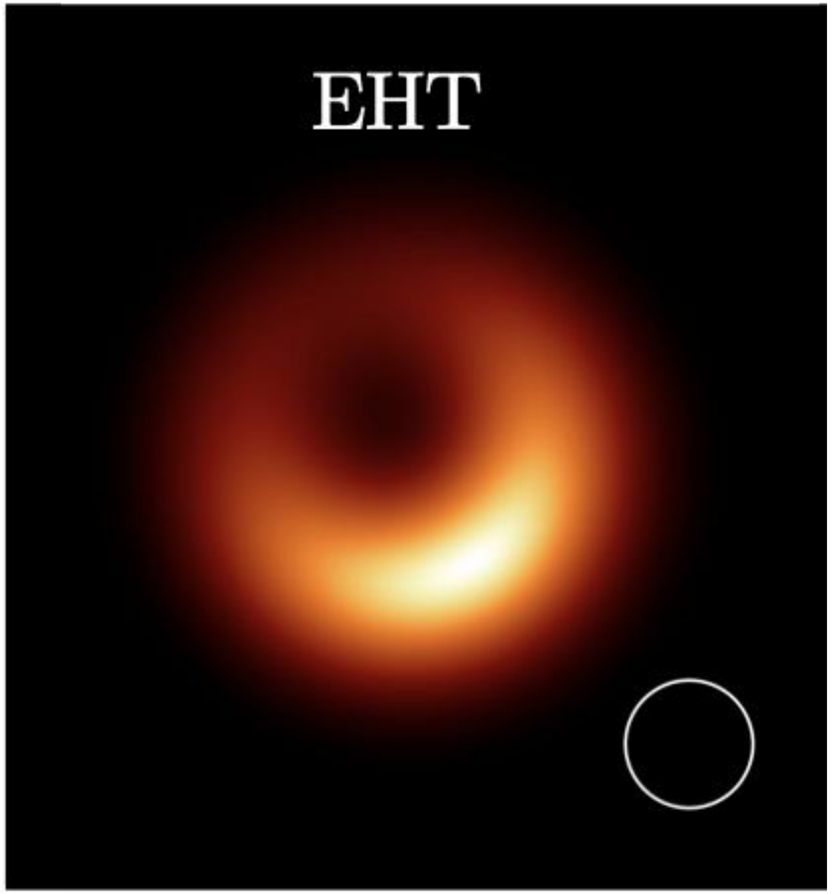


Strongly lensed light rays that wrap around the BH
form **narrow photon rings on the image**

Chael+ 2021, Johnson+ 2024
Plots from my code **kgeo**: https://github.com/achael/kgeo

Future directions: high resolution





Strongly lensed light rays that wrap around the BH form **narrow photon rings on the image**

Chael+ 2021, Johnson+ 2024

Plots from my code **kgeo**: https://github.com/achael/kgeo

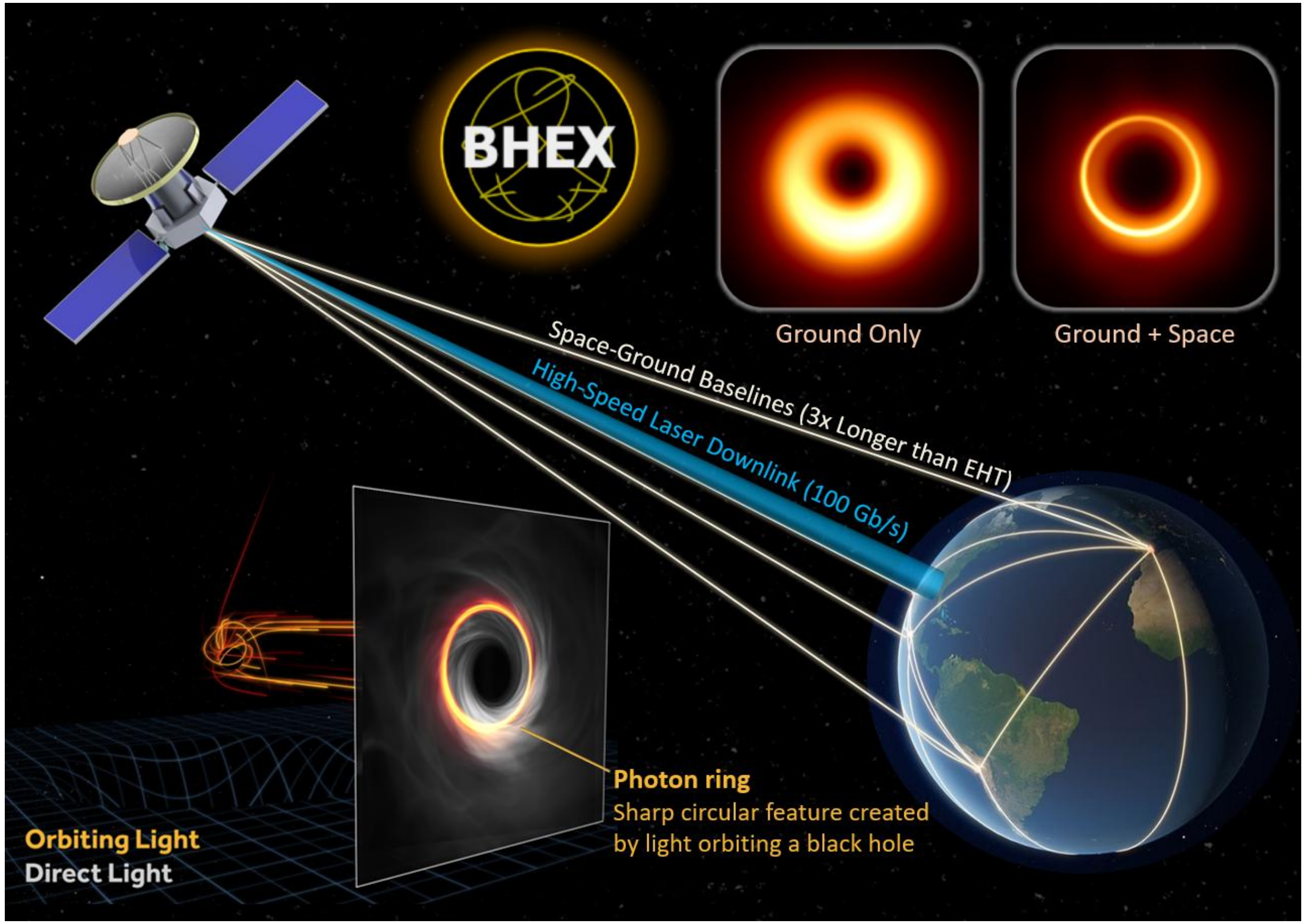
The Black Hole Explorer (BHEX)

Earth-Space VLBI at 1.3 mm

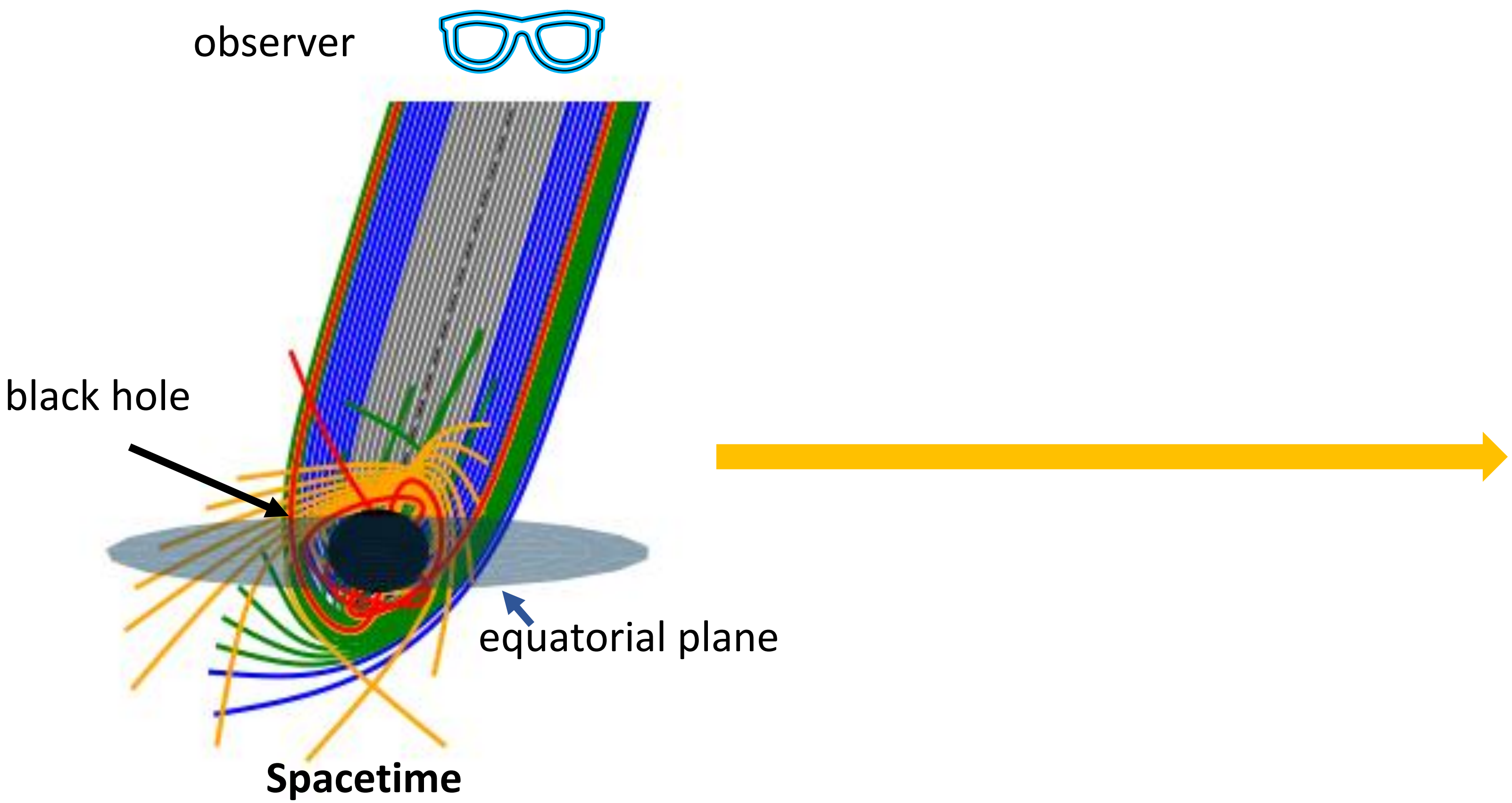
- 3.5 m dish in 20,000 km orbit
- Simultaneous dual-band observations (80 + 240 GHz)
- Leverages existing ground infrastructure & pioneers optical laser downlink
- Targeting a NASA SMEX proposal

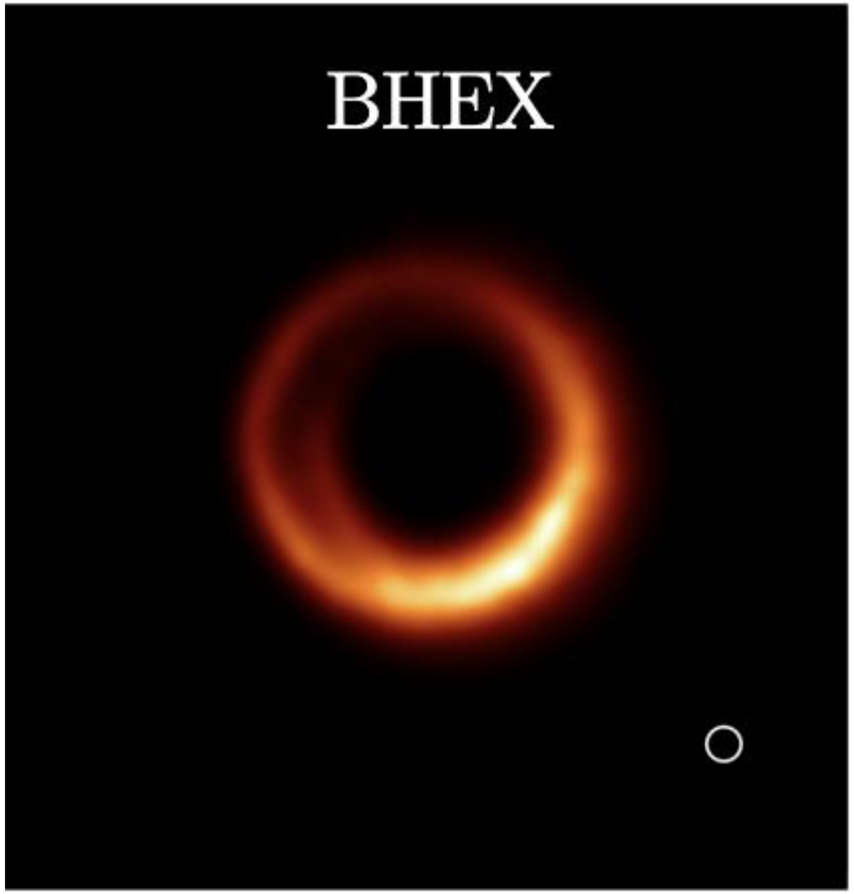
BHEX Science Goals

- Discover a black hole's photon ring
- Make direct measurements of a black hole's mass and spin
- Reveal the shadows of *dozens* of supermassive black holes



Future directions: high resolution

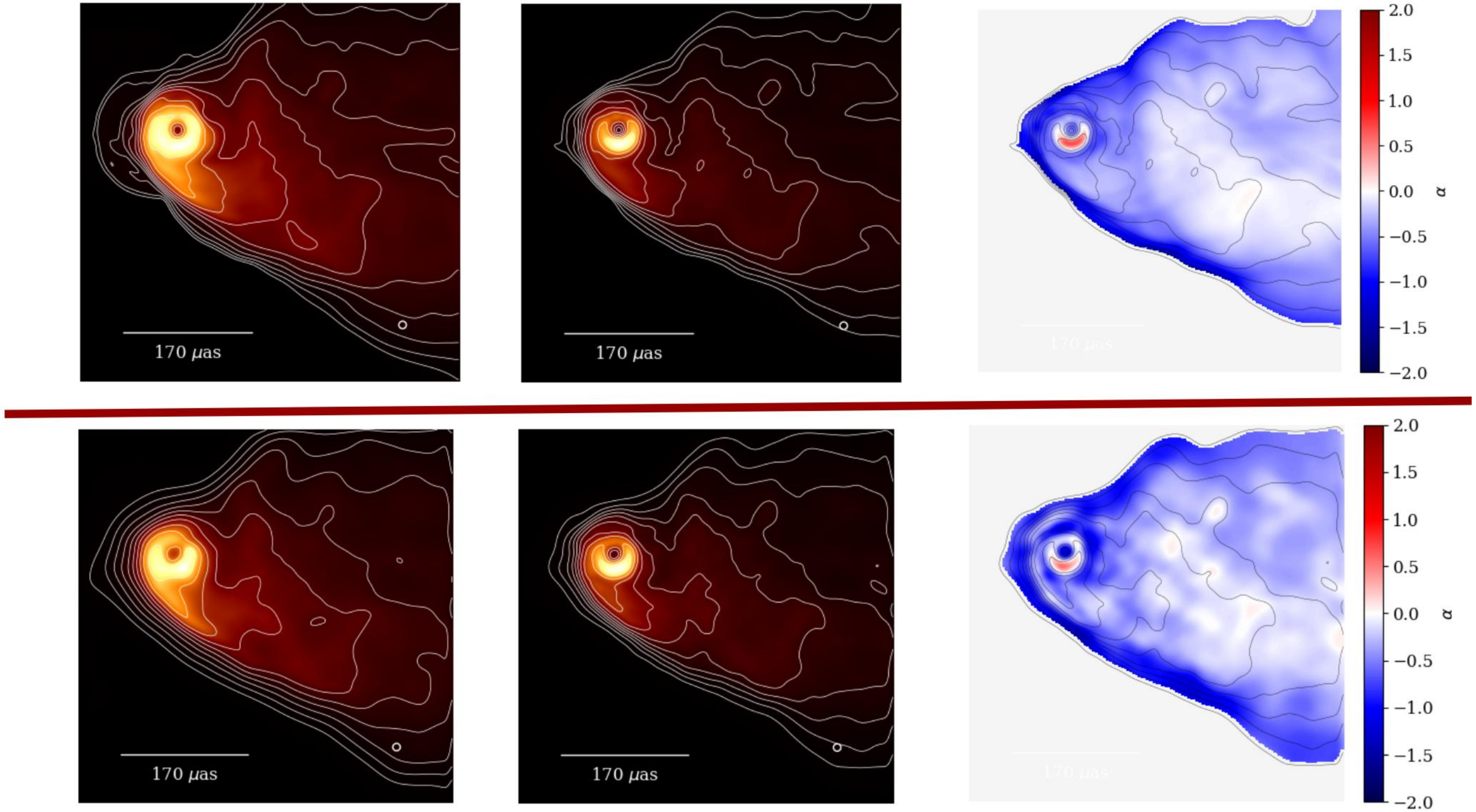




Chael+ 2021, Johnson+ 2024
Plots from my code **`kgeo`**: https://github.com/achael/kgeo
Reconstruction with Comrade: Tiede+ 2022

Pushing Black Hole Imaging Forward

Multifrequency Imaging in eht-imaging



86GHz 230GHz Spectral index

Simulation

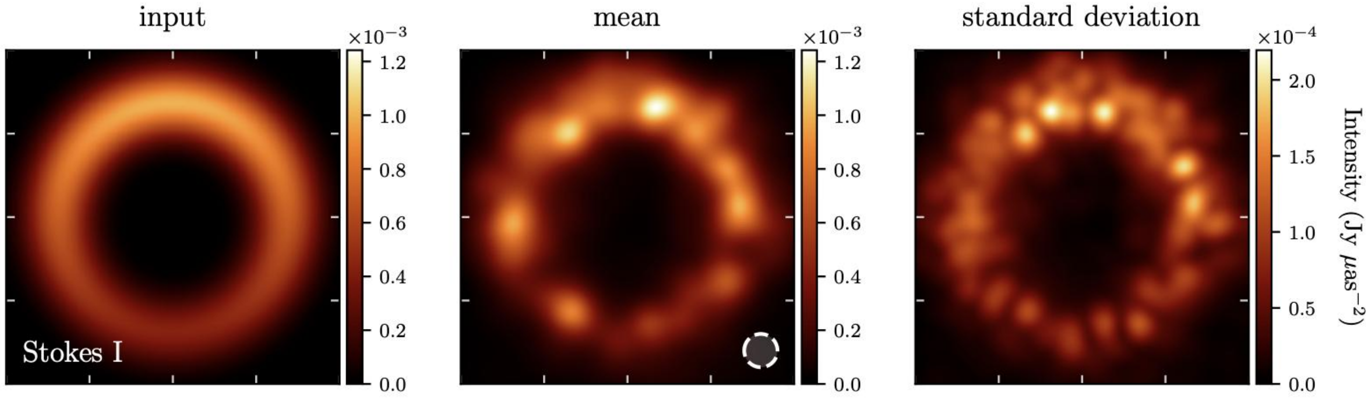
$$\log I_i\left(\vec{\theta}\right) = \log\left[I_0(\vec{\theta})\right] + \alpha(\vec{\theta})\log\left(\frac{\nu_i}{\nu_0}\right)$$

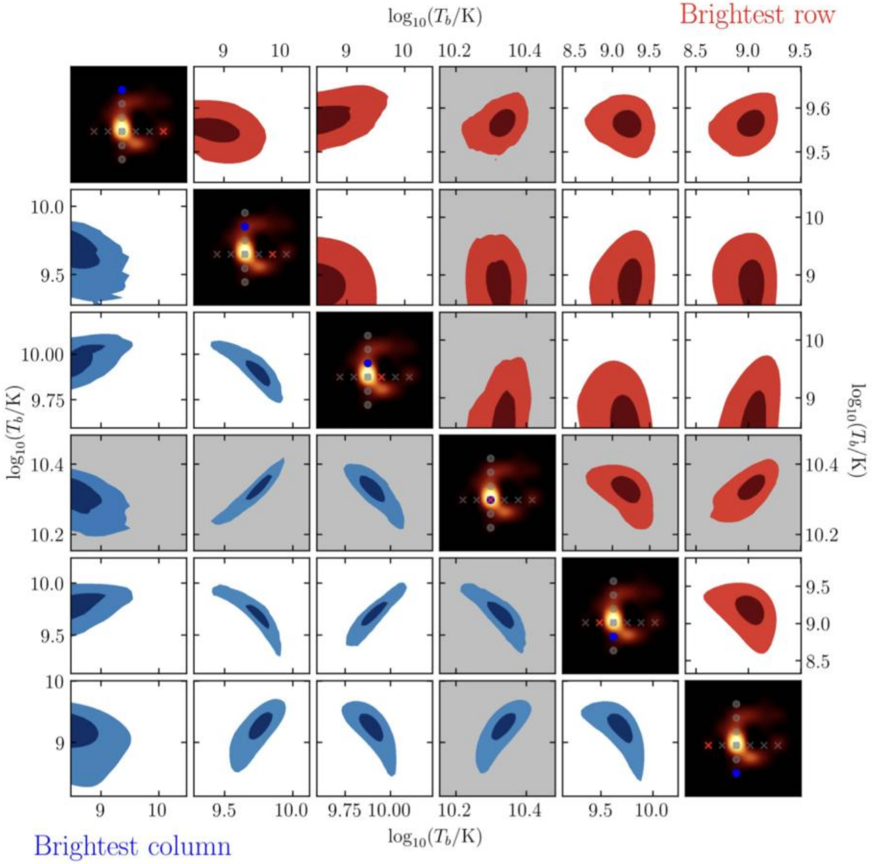
Simulated image using **multifrequency synthesis**

- Multifrequency imaging ties together data at frequencies to obtain a higher quality image
- Understanding the spectral behavior probes plasma properties

Chael+ 2023

True Bayesian Imaging: Themis, DMC, Comrade



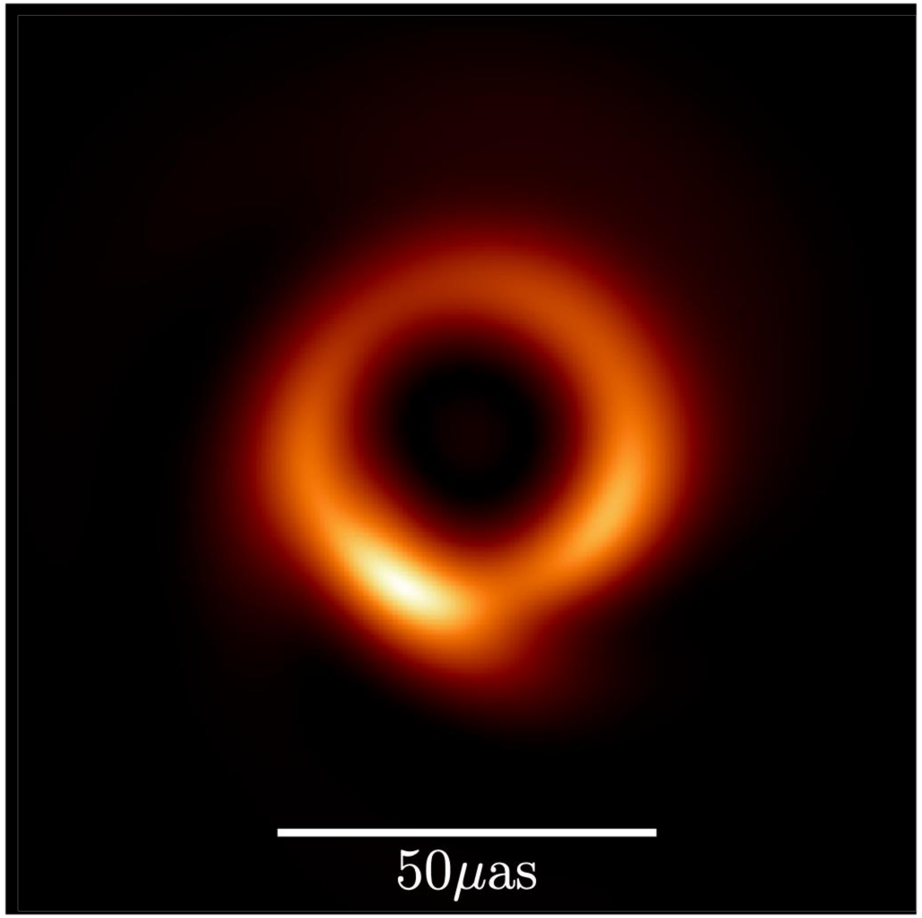


- New methods that use modern sampling techniques and GPU acceleration to measure posteriors for individual pixels in full polarization
- **The new standard** for understanding image parameter uncertainties
- Able to jointly solve for image, instrument gain terms, and prior hyperparameters

Broderick+ 2020, Pesce+ 2021, Tiede+ 2022

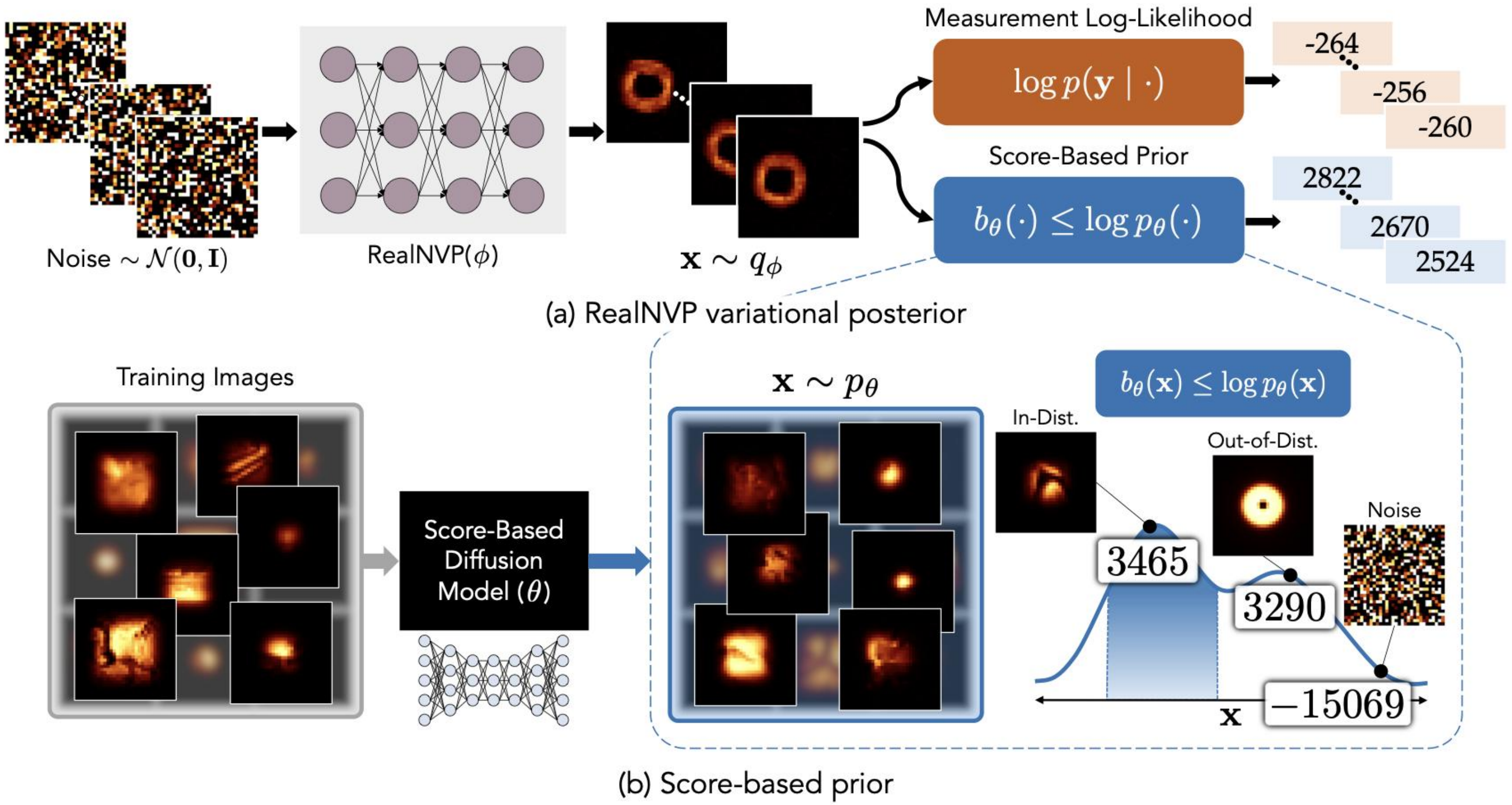
Black Hole Imaging with a PCA basis: PRIMO

- Uses PCA to learn an image basis from a large set of GRMHD simulations
- Fills in Fourier space in a physically motivated manner
- Does not produce ``knot'' image artifacts
- Can reconstruct images that are not contained in original simulation data set
- Allows for direct comparisons of results with simulations



EHT M87 Papers I & IV, 2019
Medeiros et al. 2023b

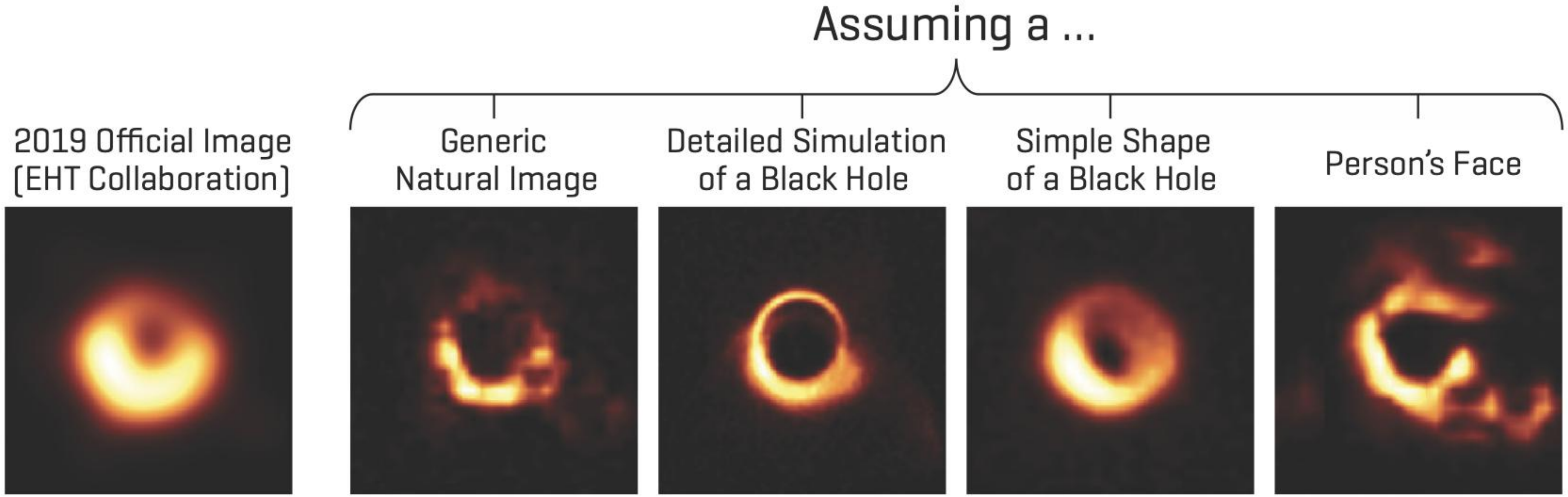
New Image Priors from Diffusion Models



New method to apply diffusion models trained on different image sets as image priors and estimate an EHT image posterior distribution with variational inference

Feng, Bouman, Freeman 2024

New Image Priors from Diffusion Models

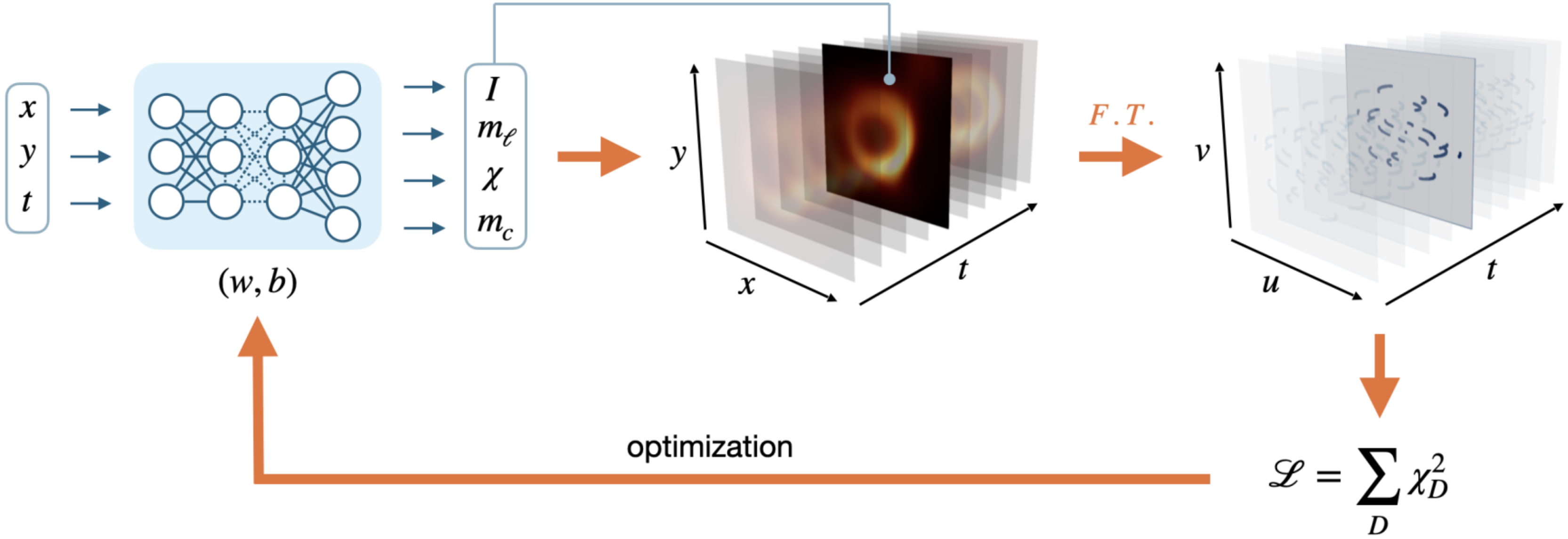


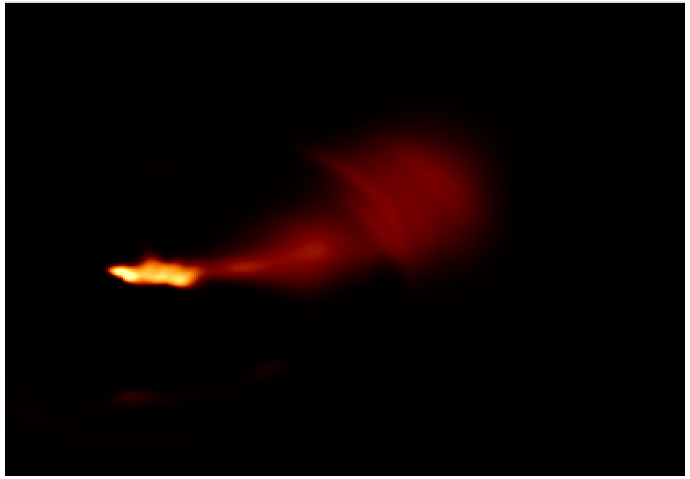
New method to apply diffusion models trained on different image sets as image priors and estimate an EHT image posterior distribution with variational inference

Feng, Bouman, Freeman 2024

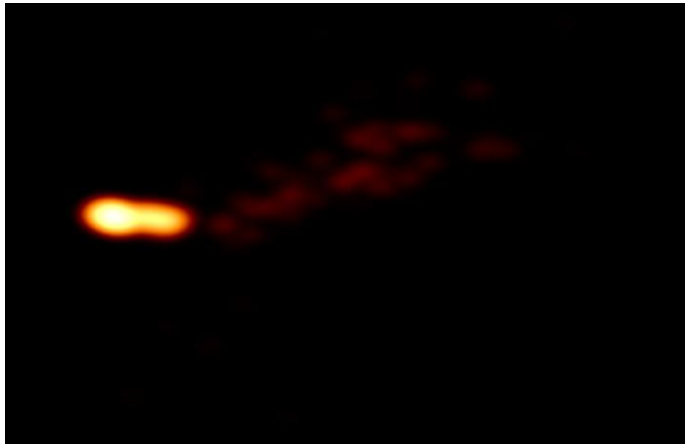
Imaging Dynamics: kine

- Models image intensity and polarization in time as a neural network.
- **No** explicit regularization.
- Shows improved performance over original temporal regularization methods in movie recovery.





VLBA 3C345 reconstruction with kine

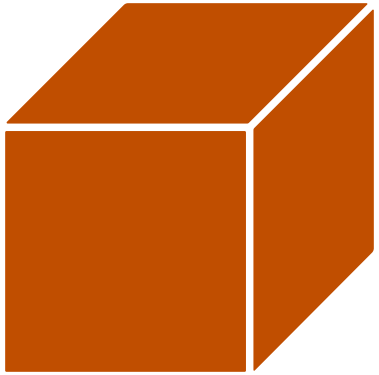


VLBA 3C345 reconstruction with CLEAN

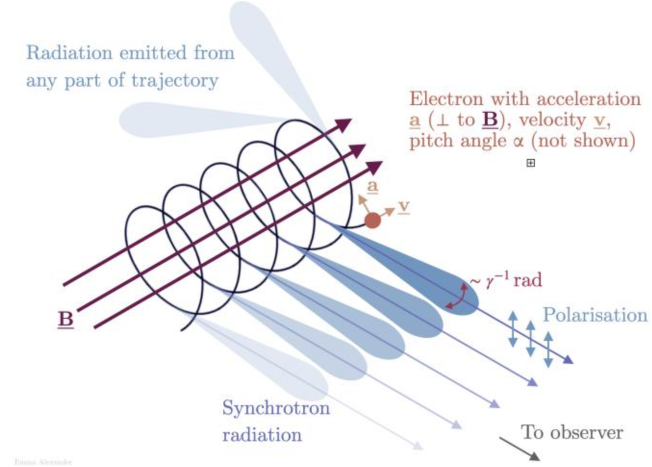
Foschi+ 2025

Imaging 3D structure: BH-NeRF

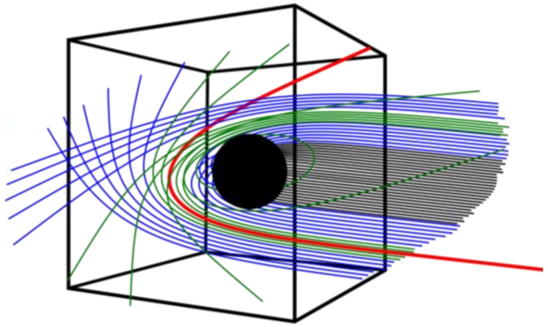
3D Structure



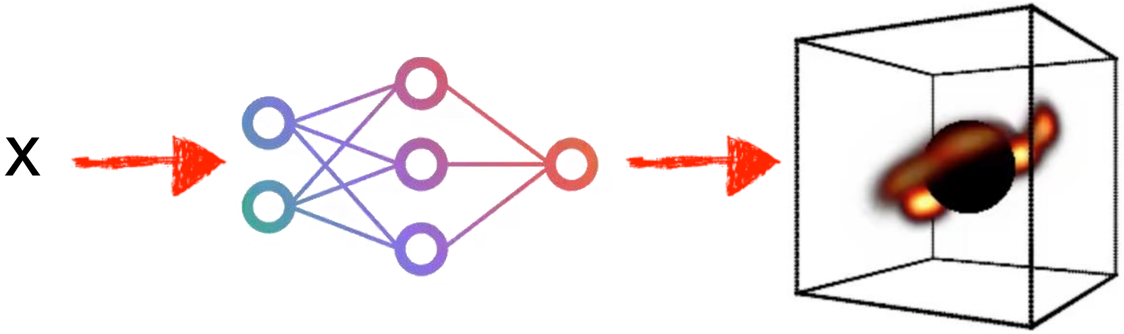
+



Physics



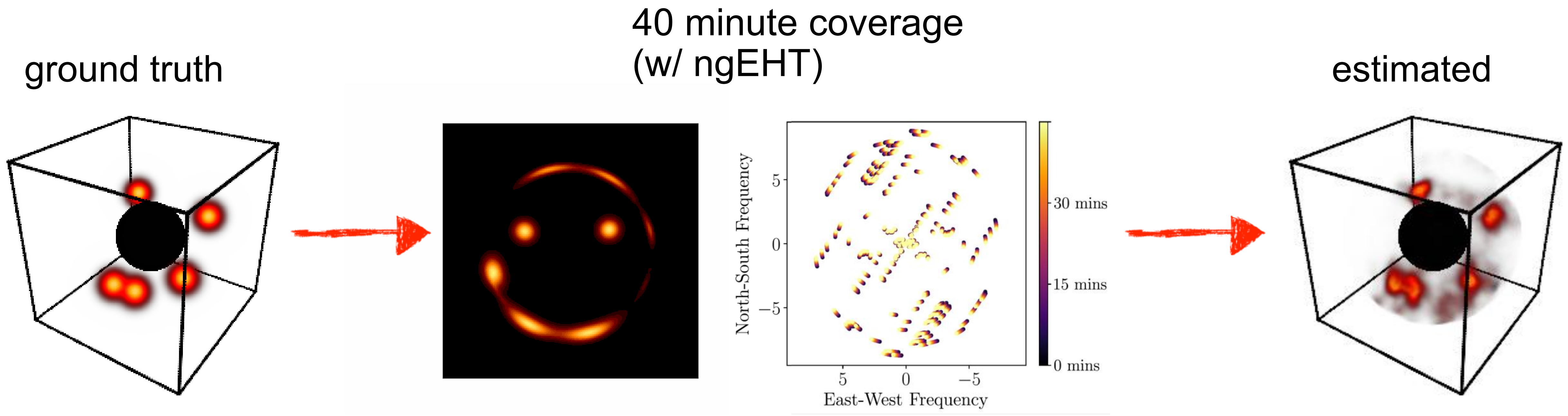
Implicit Regularization



- Method to **reconstruct 3D emitting region** from EHT observations
- Builds in physical in lensing & synchrotron physics
- Uses a neural network as a model of 3D space with implicit regularization

Levis*, et al, CVPR, 2022, Nature Astronomy 2024

Imaging 3D structure: BH-NeRF



- Method to **reconstruct 3D emitting region** from EHT observations
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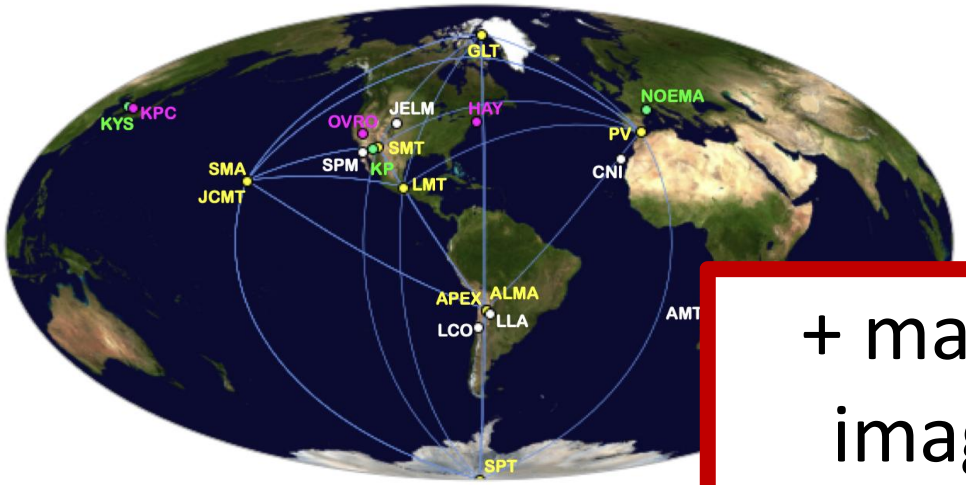
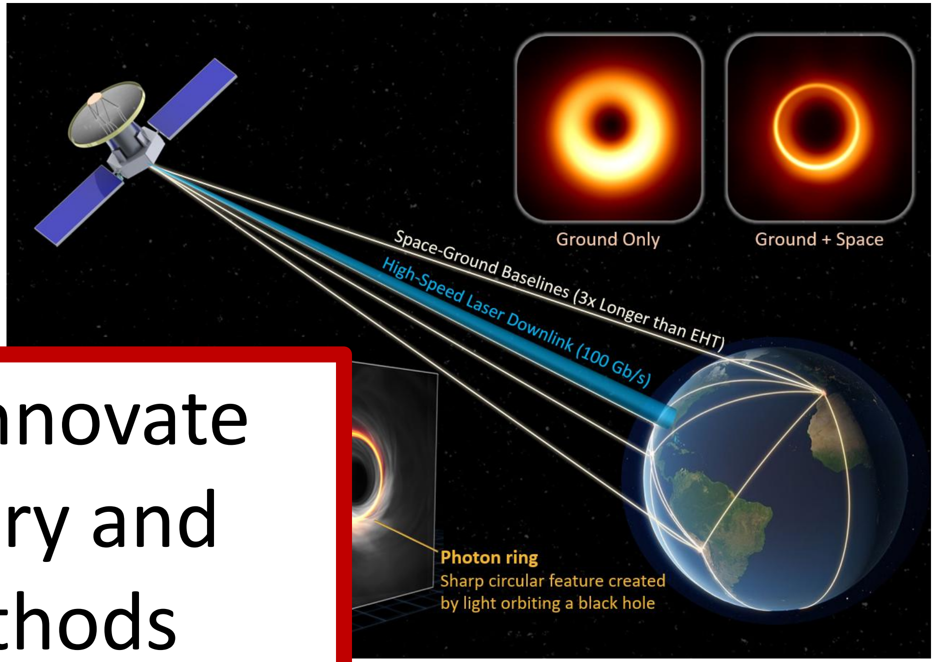
Levis*, et al, CVPR, 2022, Nature Astronomy 2024

The future of near-horizon black hole astrophysics

Expanded ground-based EHT array



Space VLBI / Black Hole Explorer (BHEX)



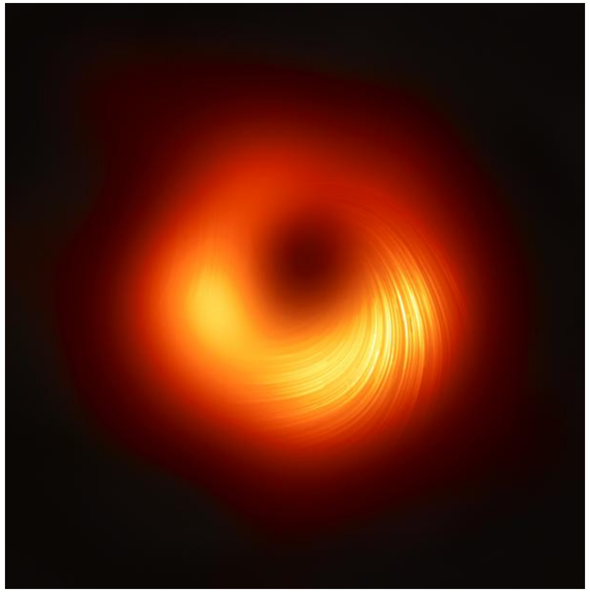
+ many new innovate image recovery and analysis methods

- Expand all EHT sites to multi-frequency observing and add 4-5 new stations (e.g. ngEHT concept, Doeleman+ 2023)
- Image black holes and AGN jets in **high dynamic range** at multiple frequencies
- Probe black hole jet launching from horizon to hundreds of Schwarzschild radii (e.g. Gelles+ 2024**:** 2410.00954)
- Make movies of Sgr A* and resolve black hole flares

- NASA SMEX proposal for a mmVLBI telescope in mid-earth orbit (Johnson+ 2024).
- Image black holes and other sources in **high resolution**
- Image extreme gravitational lensing and measure BH spin by resolving the **photon ring** (Lupsasca+ 2024).
- Expand number of horizon-scale sources from 2 to ~12 (Zhang+ 2024)

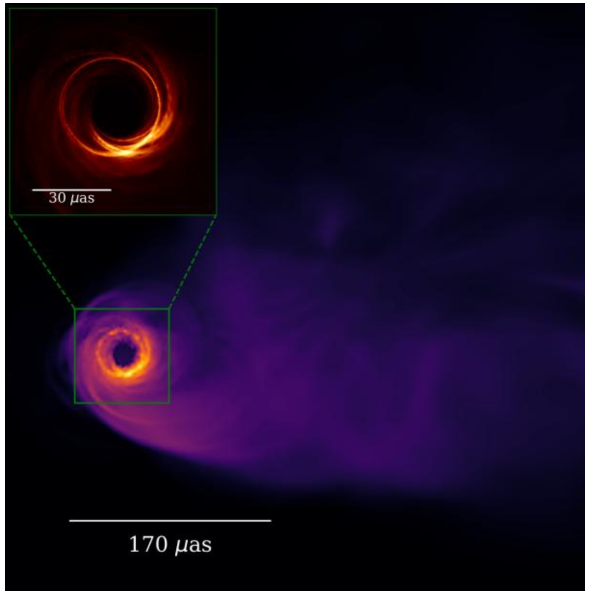
Takeaways…

1. **We can now regularly study black holes on the horizon scale** in exquisite detail by the Event Horizon Telescope
2. **The EHT has developed new imaging methods** to extract the most information we can from sparse, noisy images
3. **Rigorous validation and cross-comparison** between methods is essential for obtaining reliable images
4. **Polarization** is the key for constraining near-horizon astrophysics
5. **We are just getting started** in what we can learn from black hole images



…and more questions

- Can we measure black hole energy extraction in M87*?
- What plasma physics sets the temperature/distribution of the electrons?
- What powers flares in Sgr A* and M87*?
- What can EHT/BHEX observation tell us about the near-horizon environments of supermassive black holes beyond Sgr A* and M87*?



EHT VII, 2021; **Chael** 2025