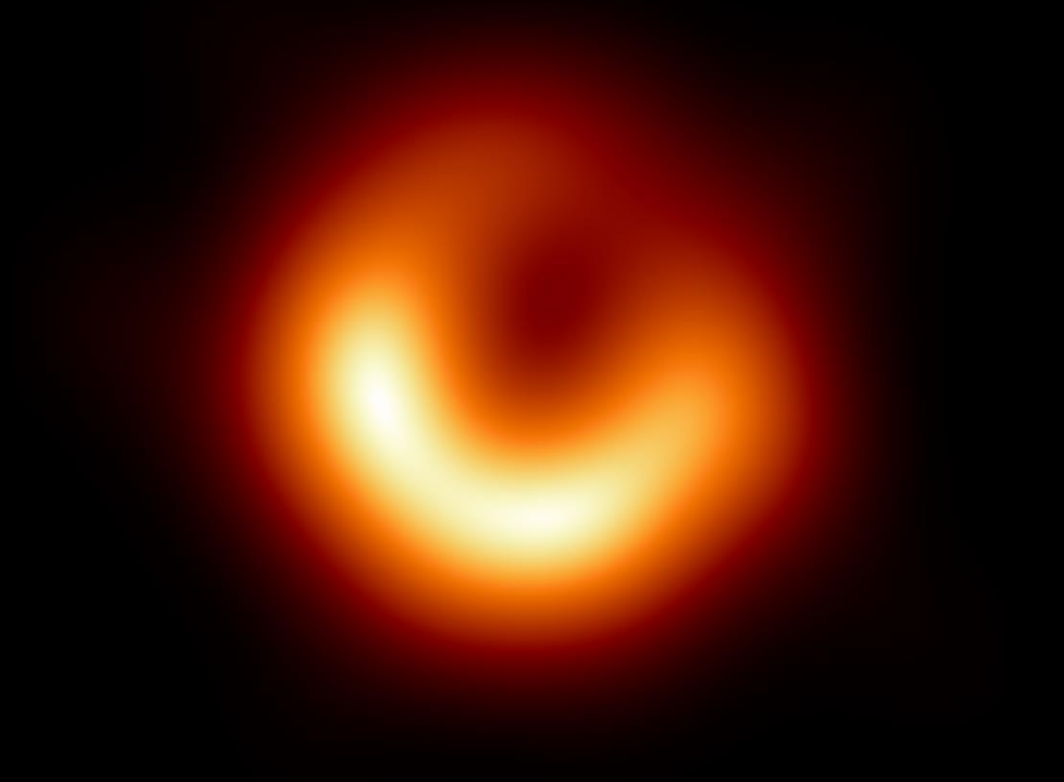
Reconstructing an Image of M87 from EHT data

Andrew Chael

May 21, 2019



Event Horizon Telescope

M87

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

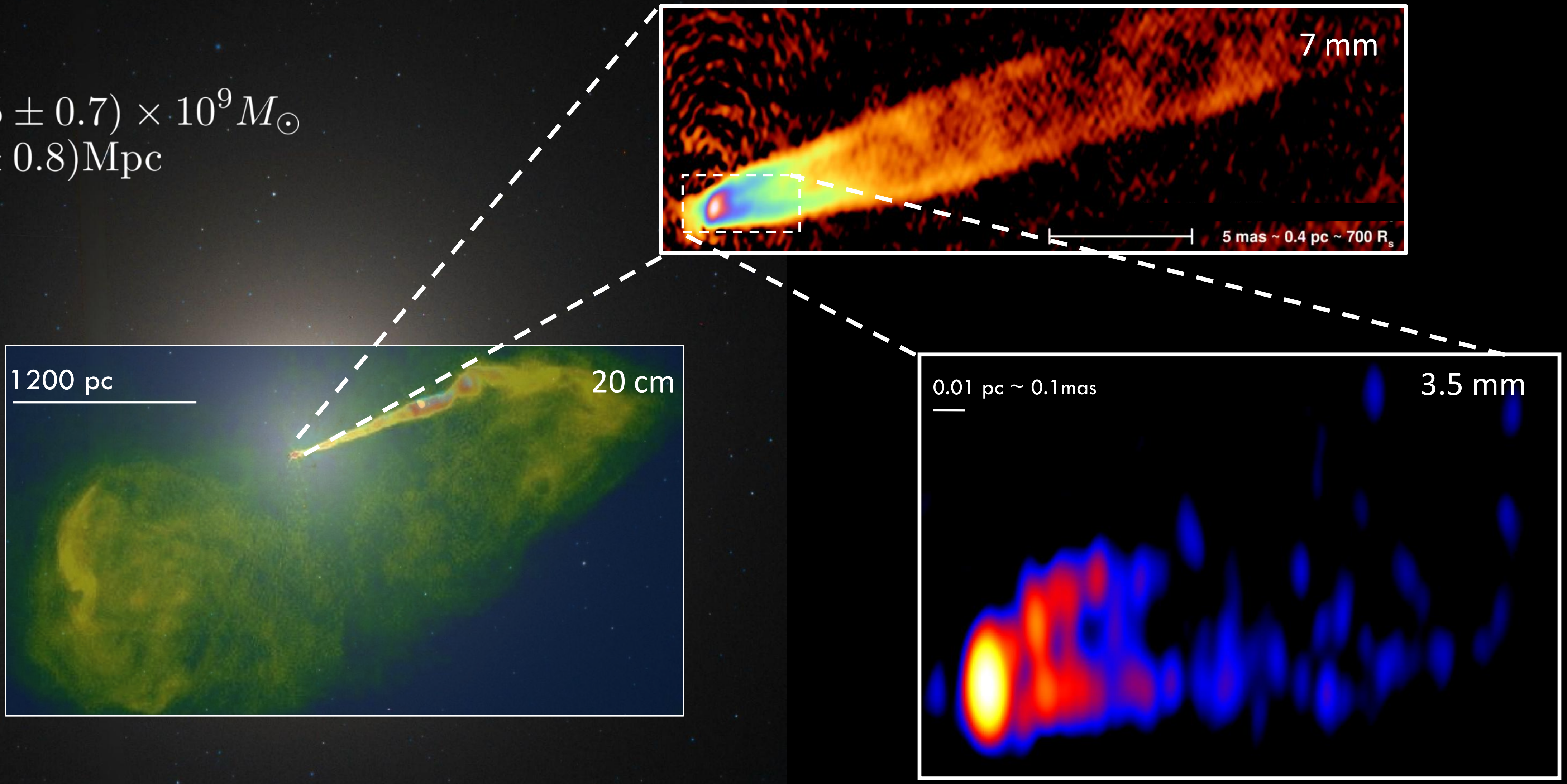


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)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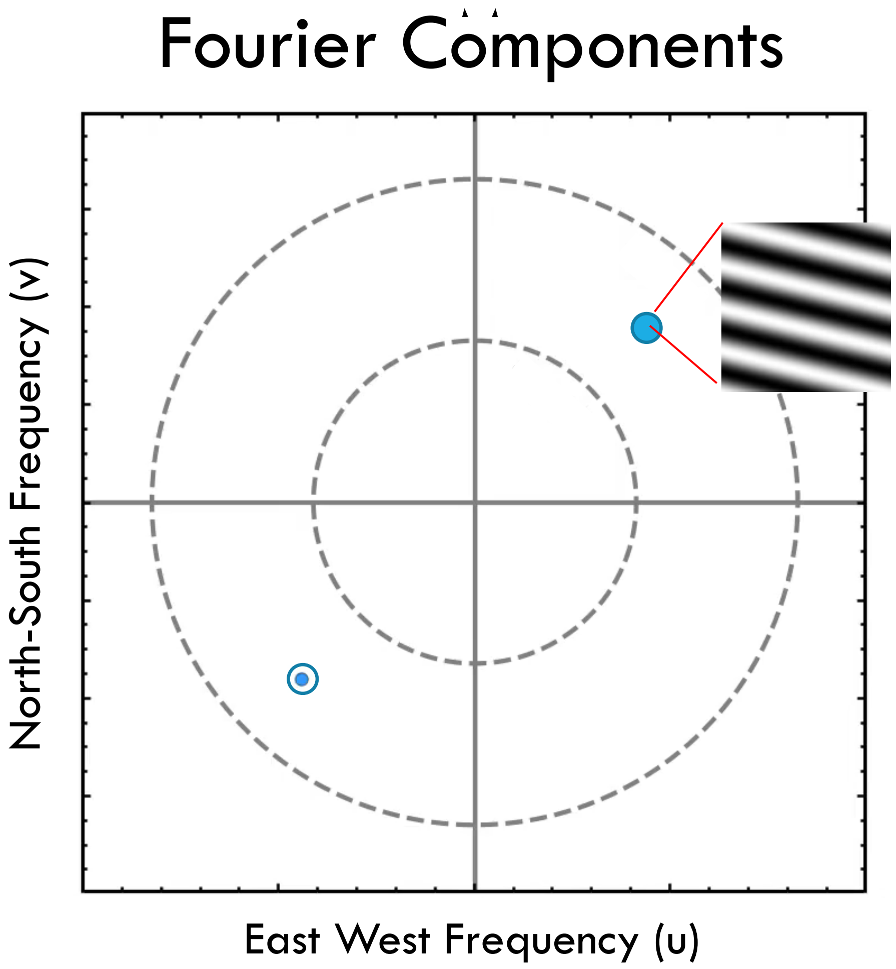
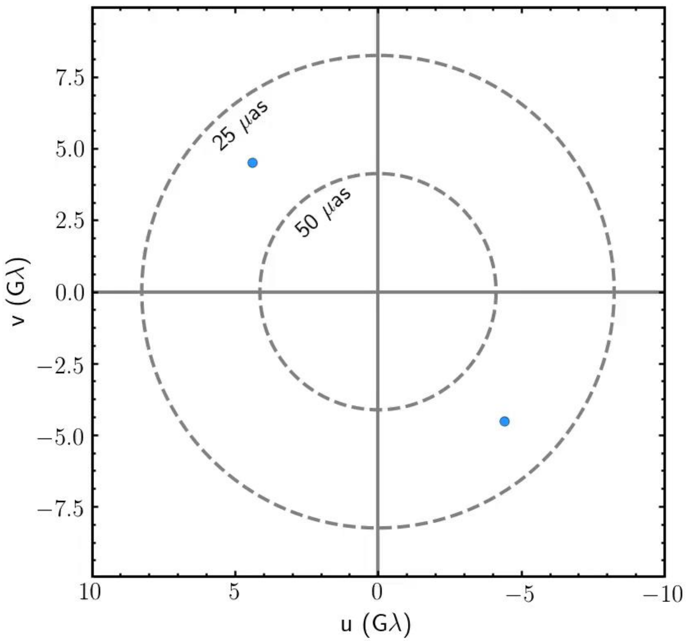
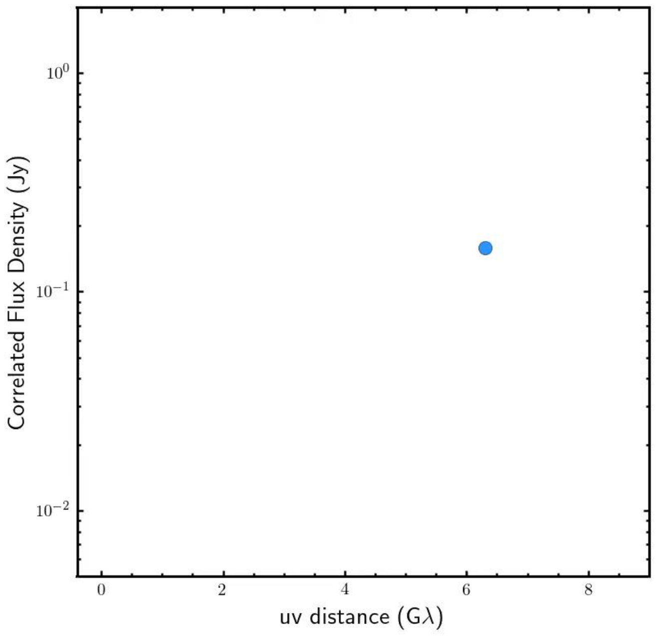
Yosuke Mizuno
Tuomas Savolainen
Jae-Young Kim
Alan Marscher
Svetlana Jorstad
(photo taker)
Jose Luis Gomez

Very Long Baseline Interferometry (VLBI)



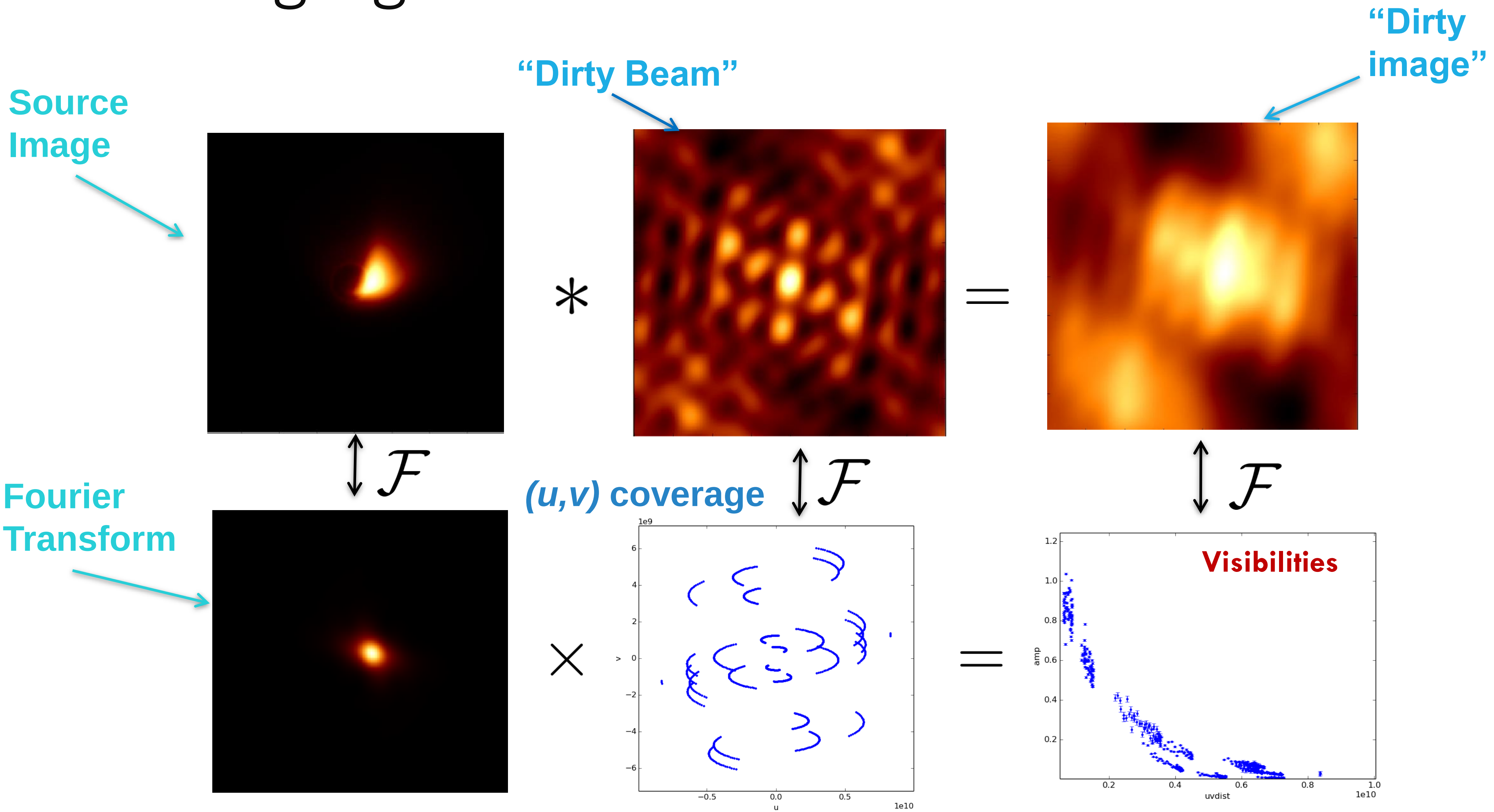
Earth’s Rotation gives us more measurements





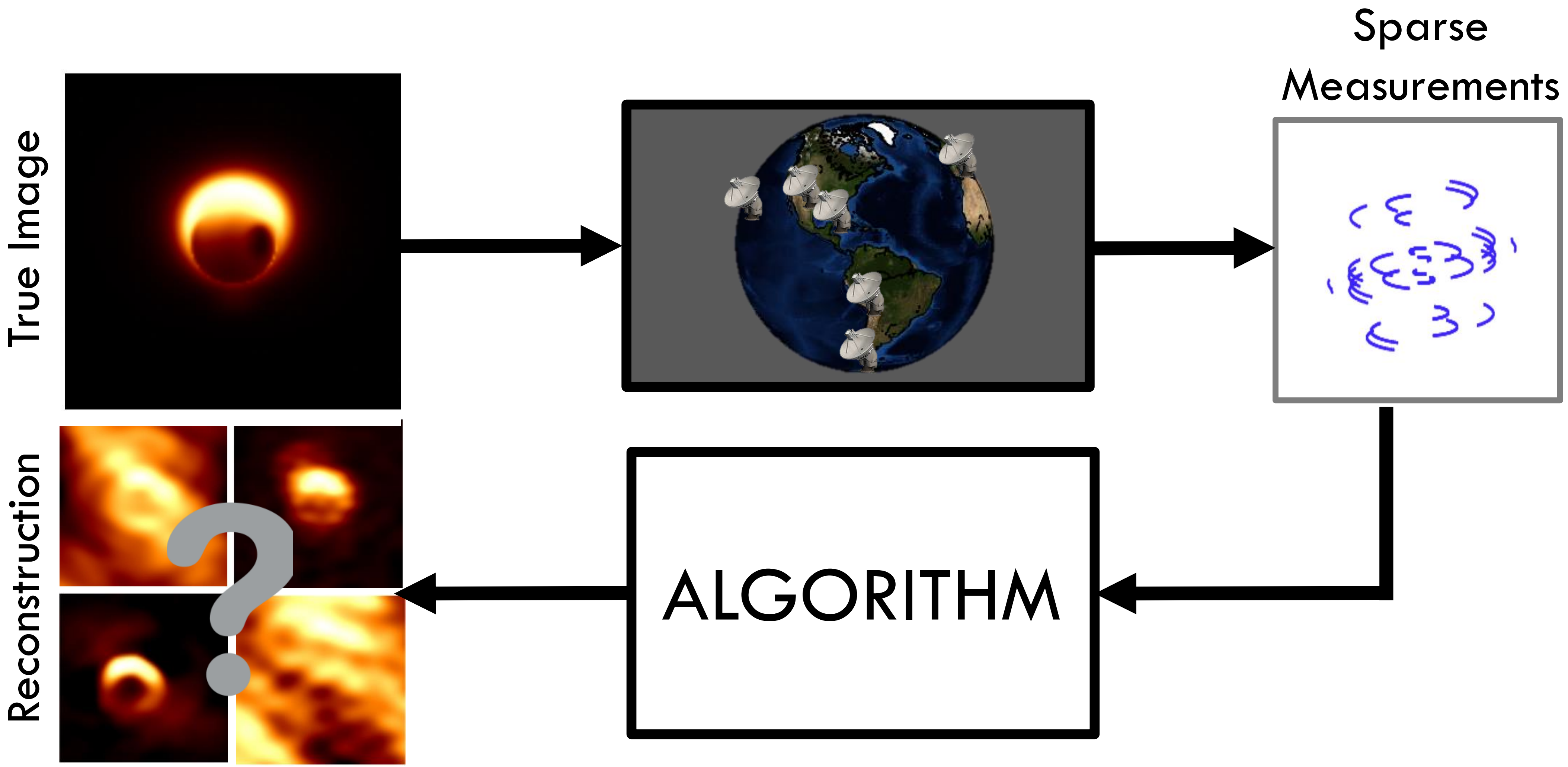
Animation credit: Daniel Palumbo

The Imaging Problem



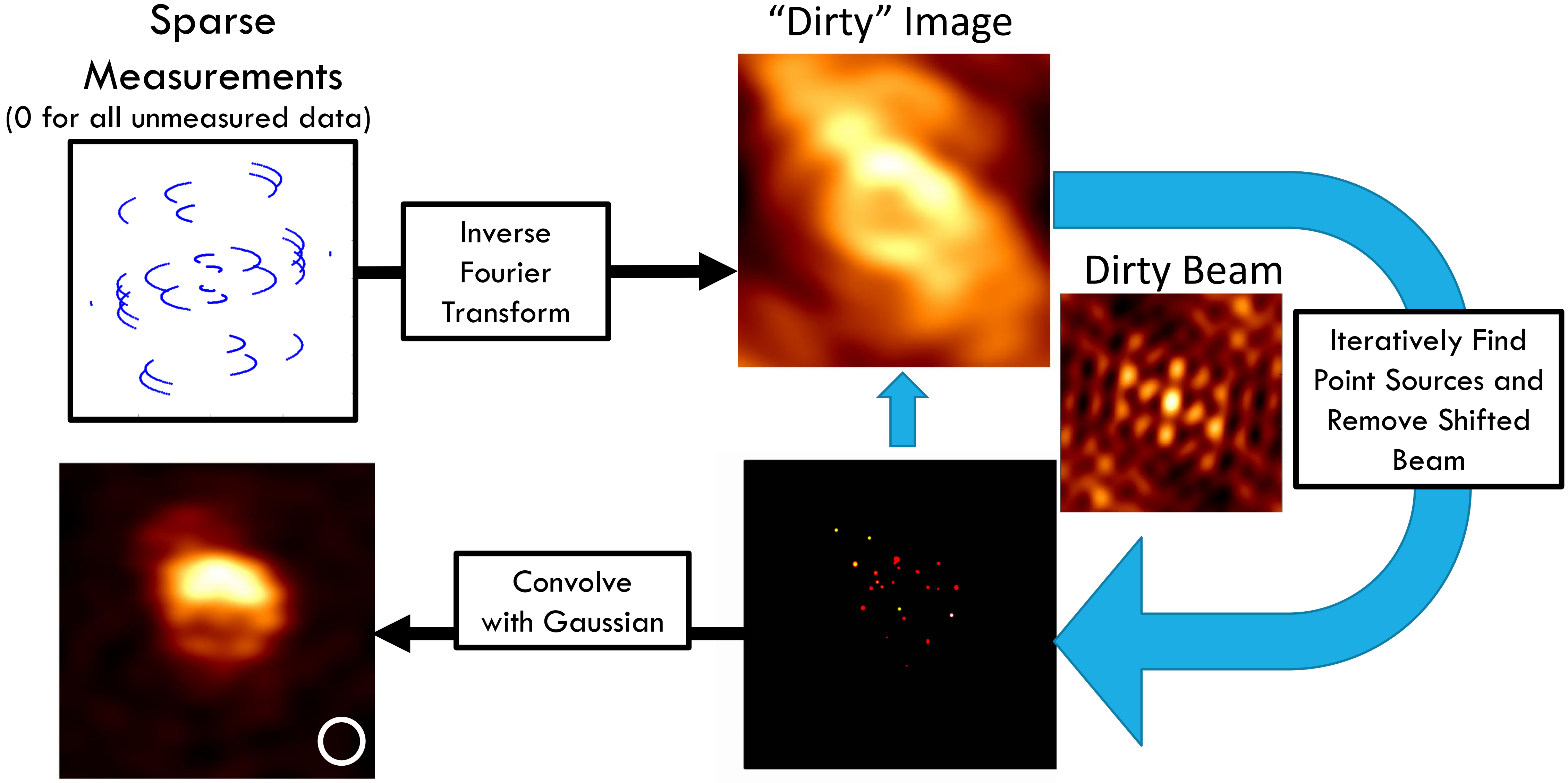
Simulation Credit: Avery Broderick

Solving for the Image



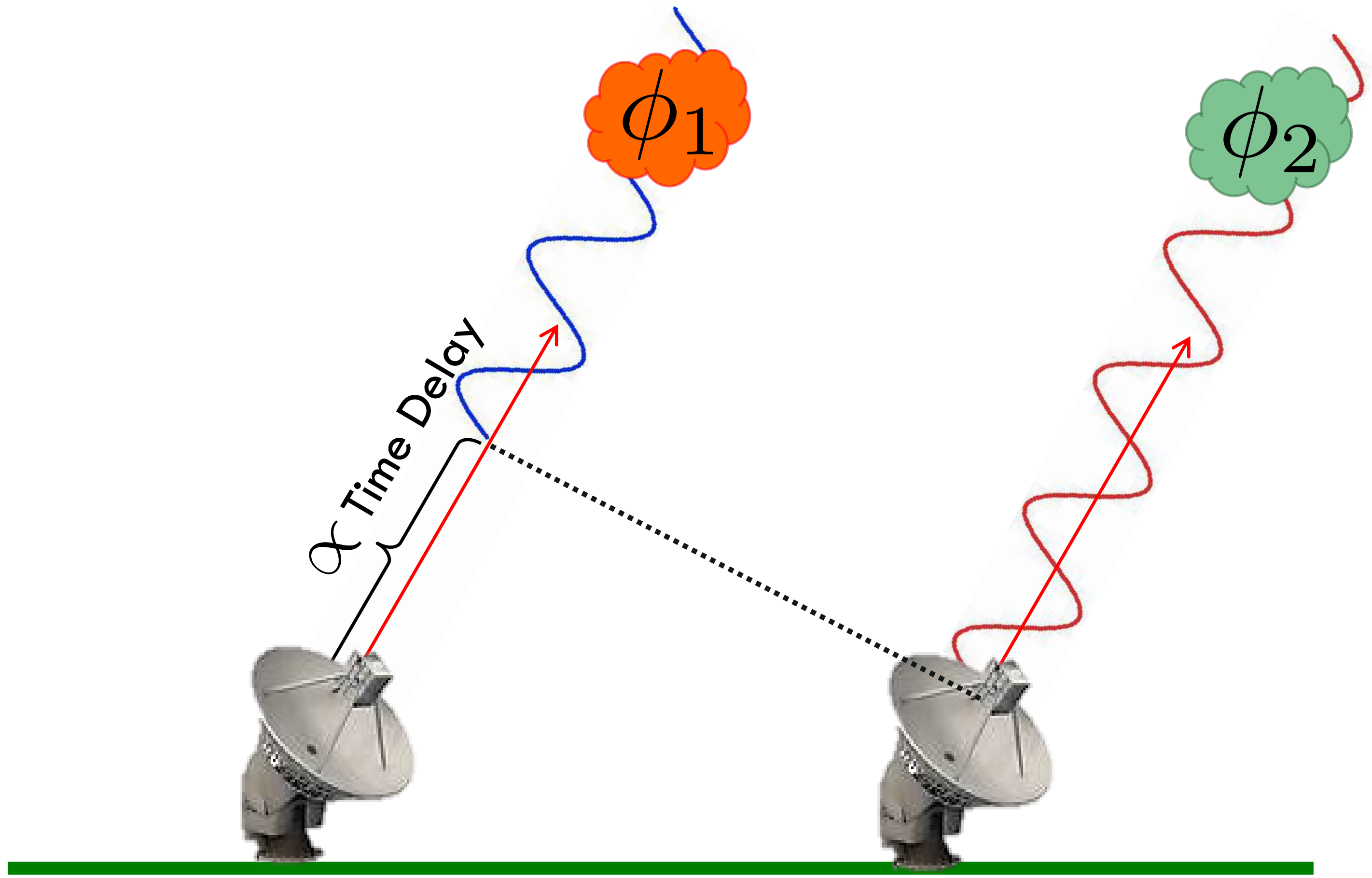
VLBI Imaging Methods and EHT data challenges

CLEAN Algorithm



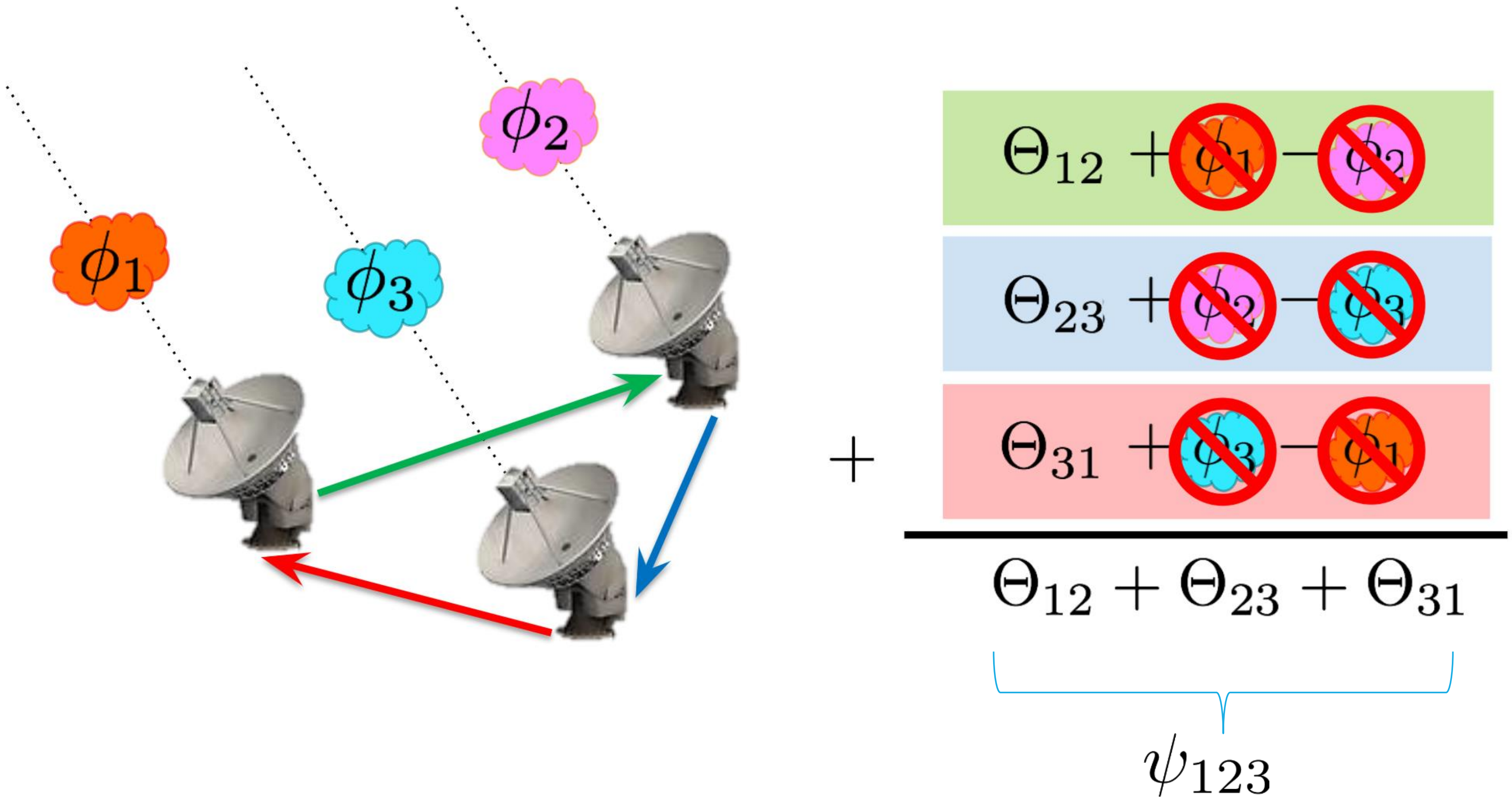
Simulation Credit: Avery Broderick

Phase Error from the atmosphere

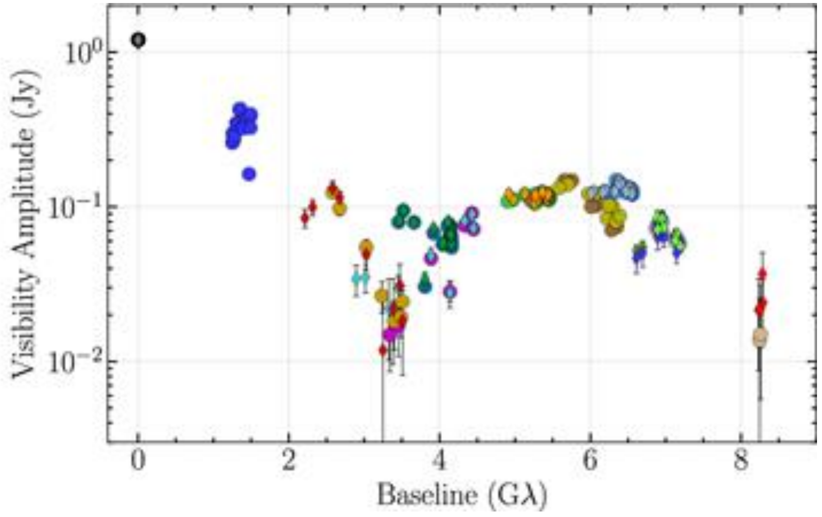


$\cos(\omega t + \Theta + \phi_1)$ $\cos(\omega t + \phi_2)$

Closure Phase is a robust observable

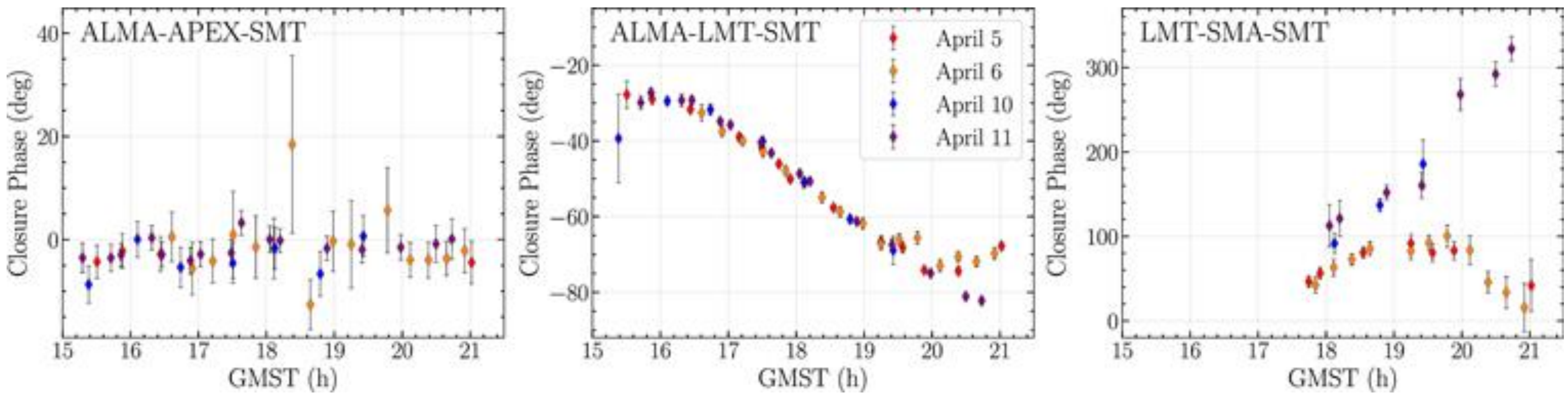


Closure phases carry lots of structural information



In M87, visibility amplitudes are mostly constant from day-to-day

Closure phases show the **source is evolving** over the week of observations

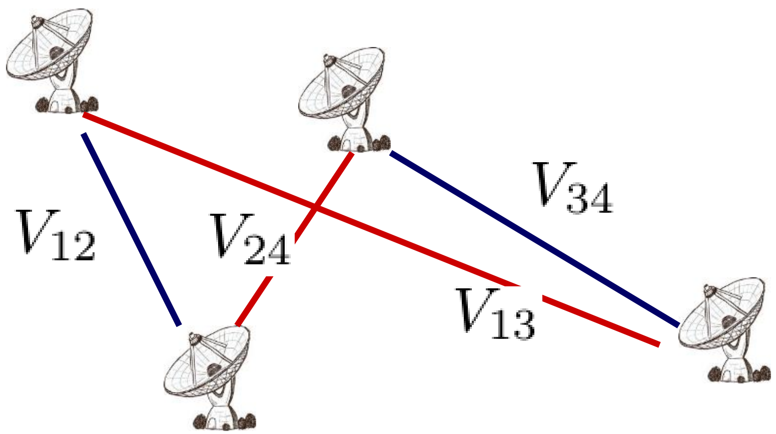


Amplitude gain terms & Closure Amplitude

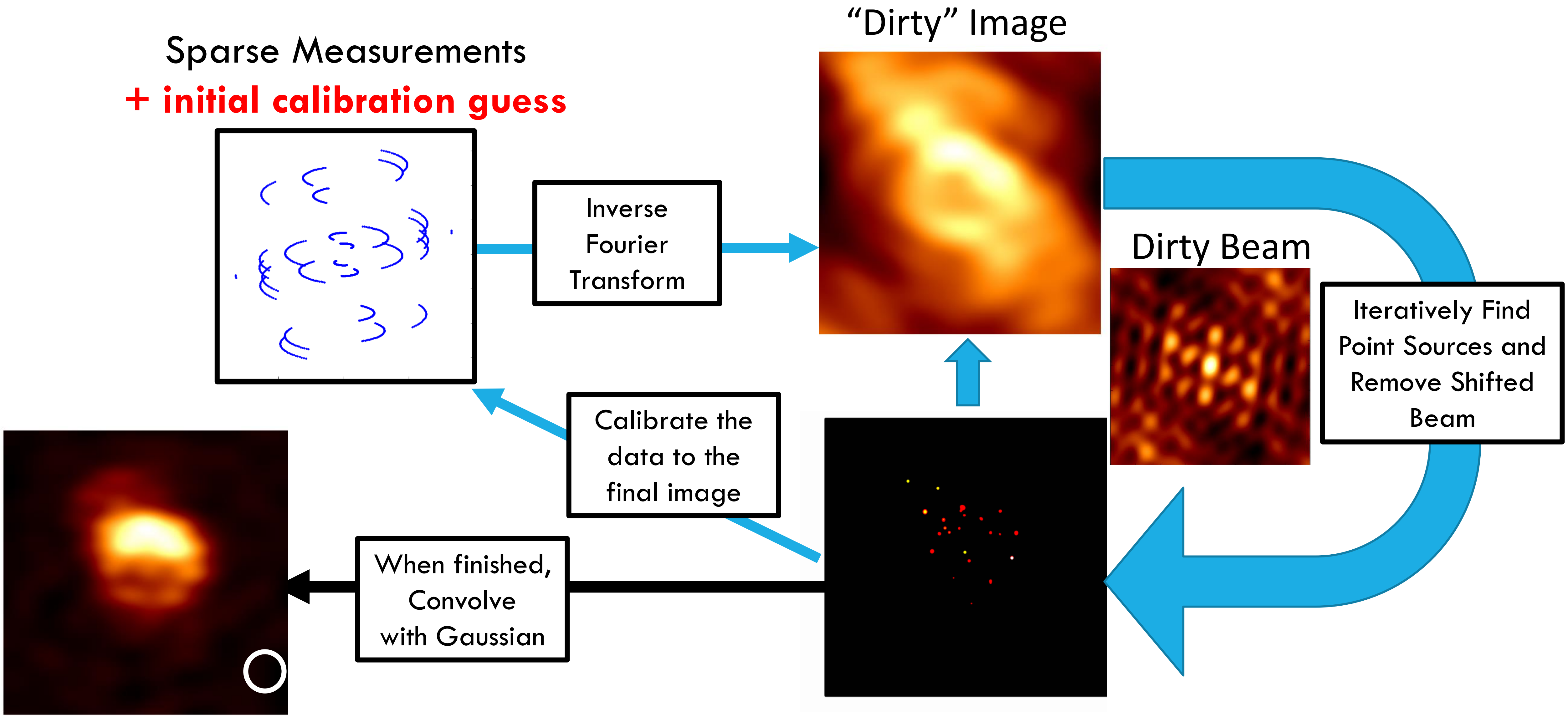
- In addition to the loss of phase from the atmosphere, individual telescopes can also have imperfect amplitude calibration

$$V_{measured} = G_1 G_2 V_{true}$$

- **Closure amplitudes** are invariant to these gain errors



CLEAN + Self Calibration



Simulation Credit: Avery Broderick

Bayesian Model Inversion

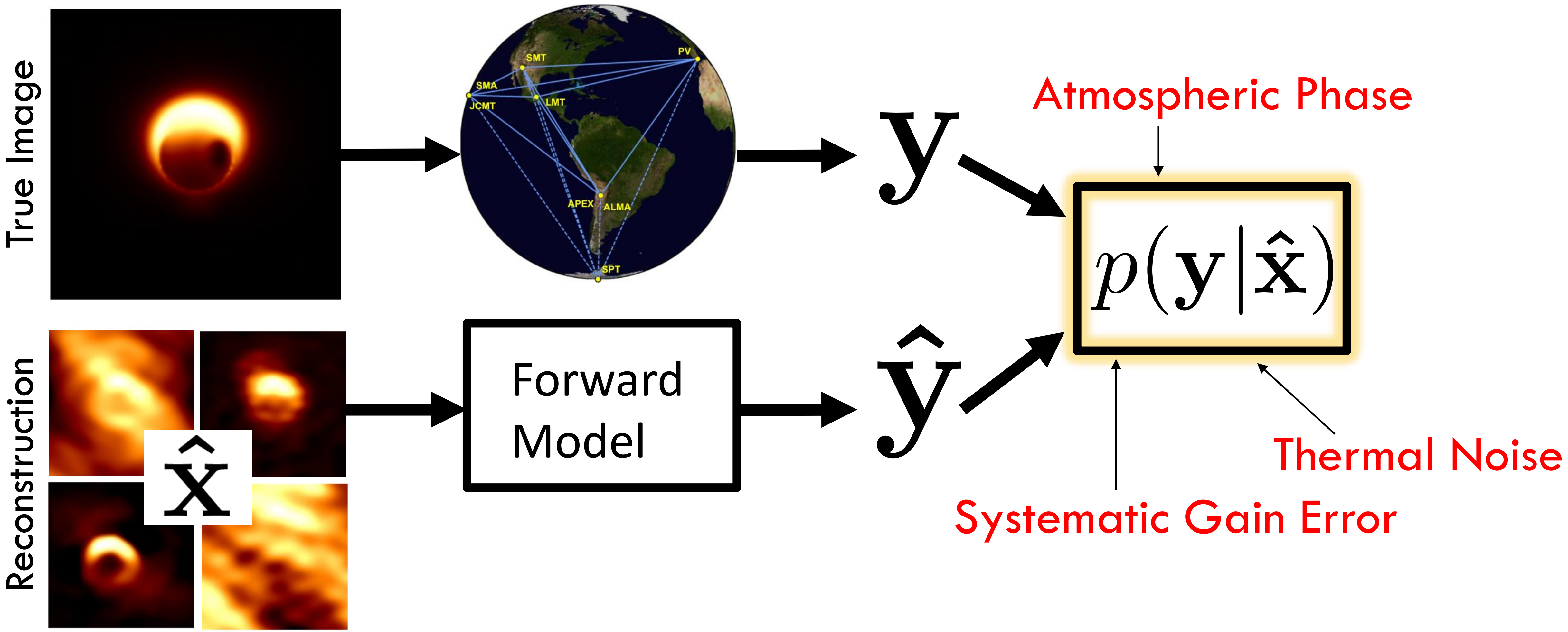


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

Bayesian Model Inversion

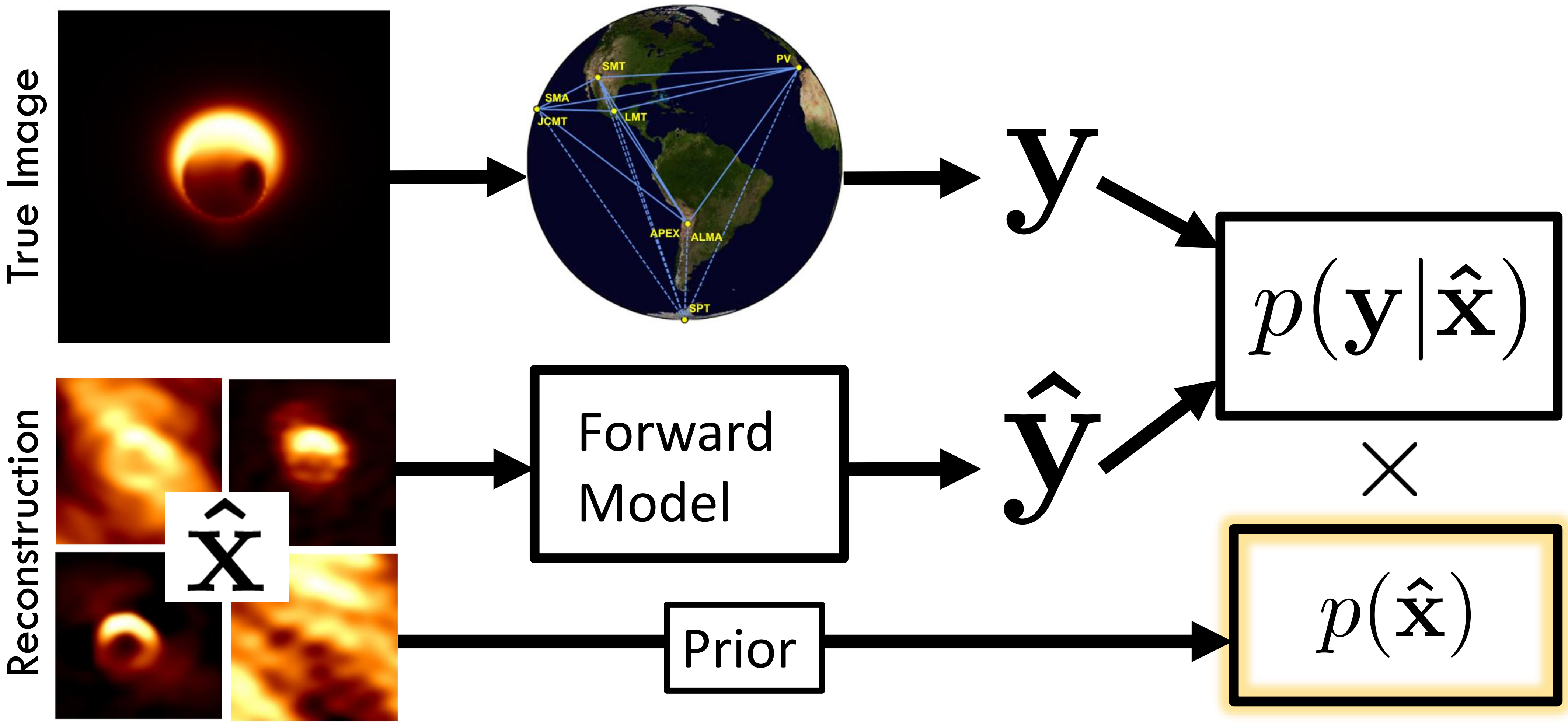


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

Regularized Maximum Likelihood

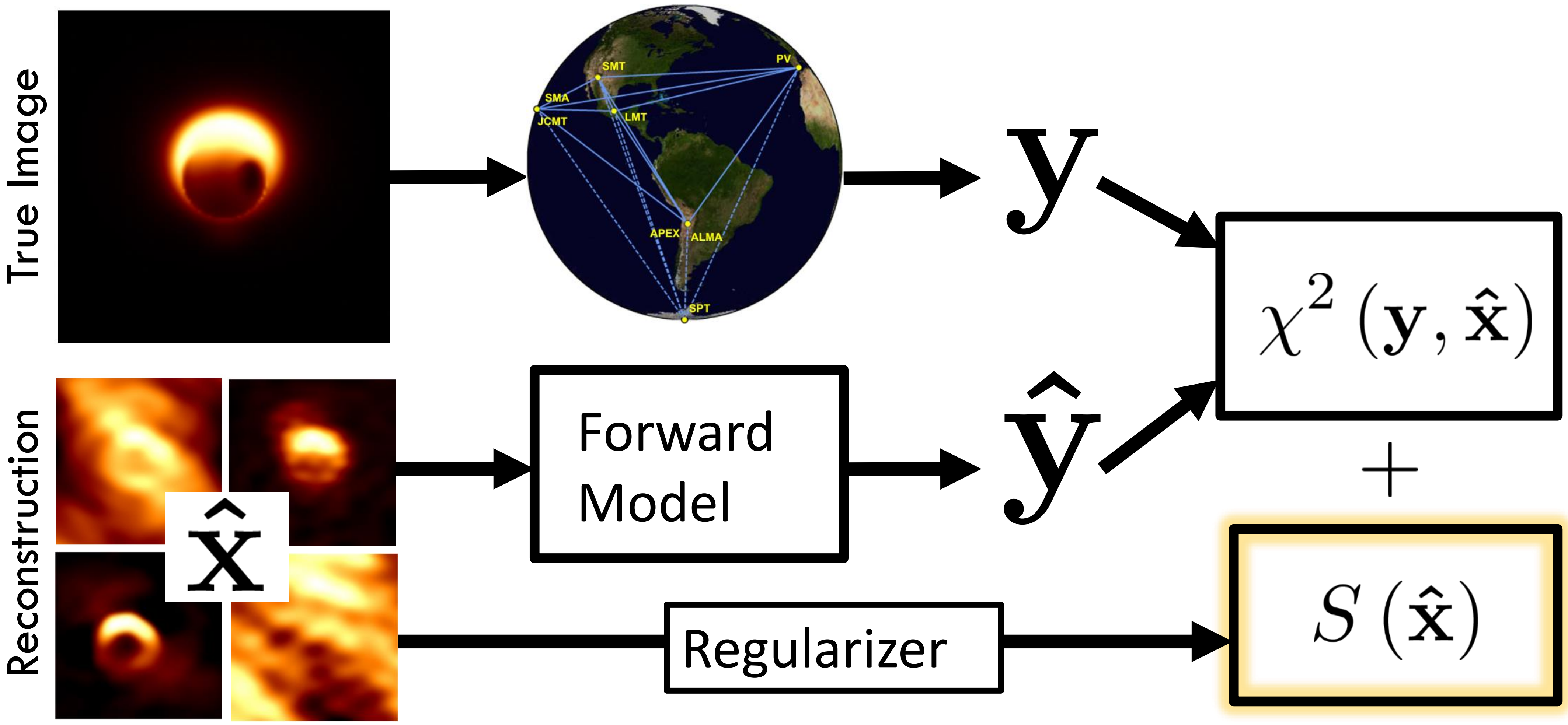


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

Imaging with Regularized Maximum Likelihood

"hyperparameters"

Minimize: $$J(\mathbf{I}) = \sum_{\text{data terms}} \alpha_D \chi^2_D(\mathbf{I}, \mathbf{d}) - \sum_{\text{regularizers}} \beta_R S_R(\mathbf{I}) \,.$$

Any **data product**
(with approx. Gaussian errors)

Regularizers

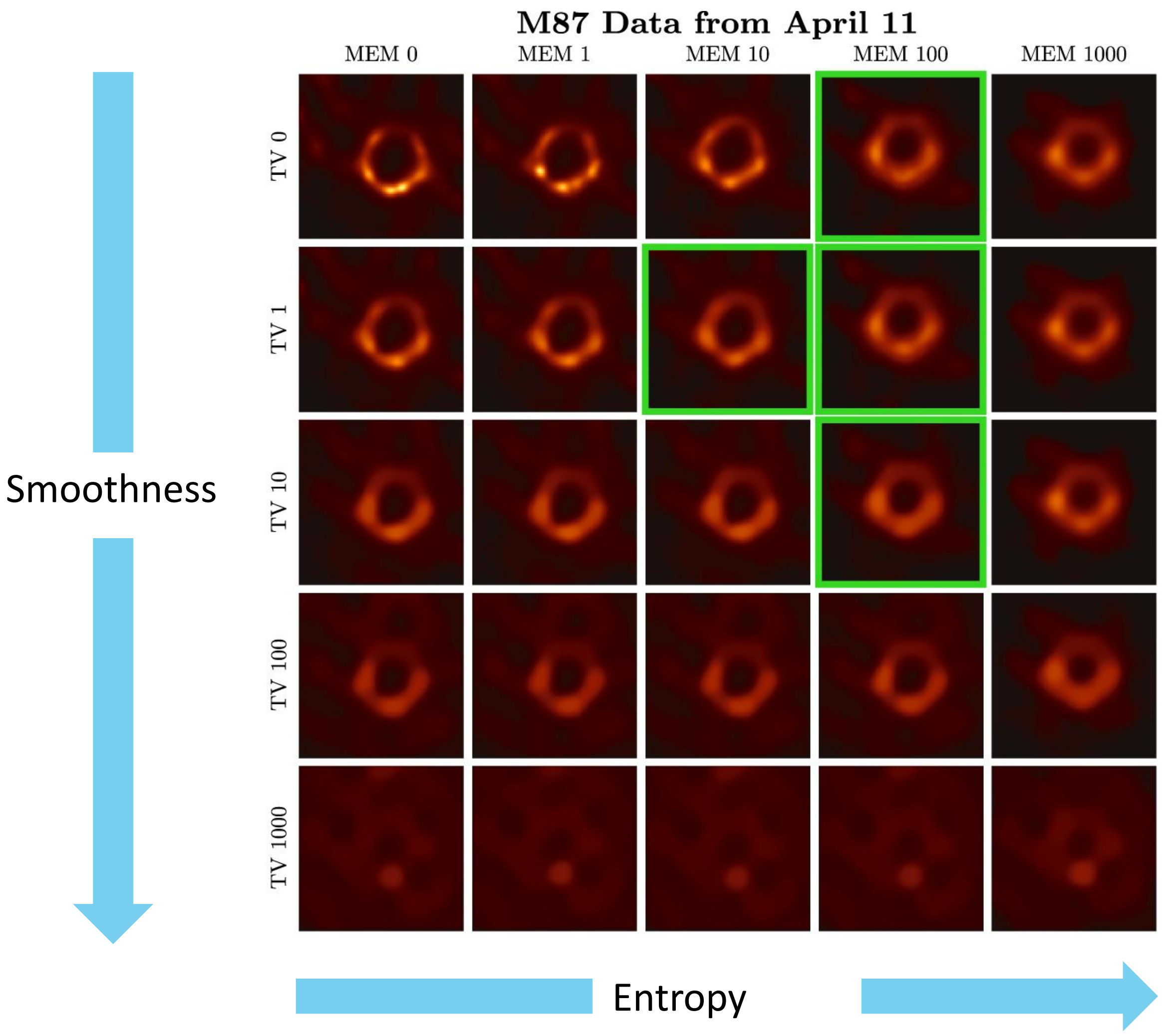
- Flexible framework enables development of new data and regularizer terms
- Hyperparameters weight relative importance of the different terms.
- Implemented in eht-imaging (Chael+ 2016,18,19) and SMILI (Akiyama+ 2017a,b) software libraries.

Feature-driven Image Regularizers

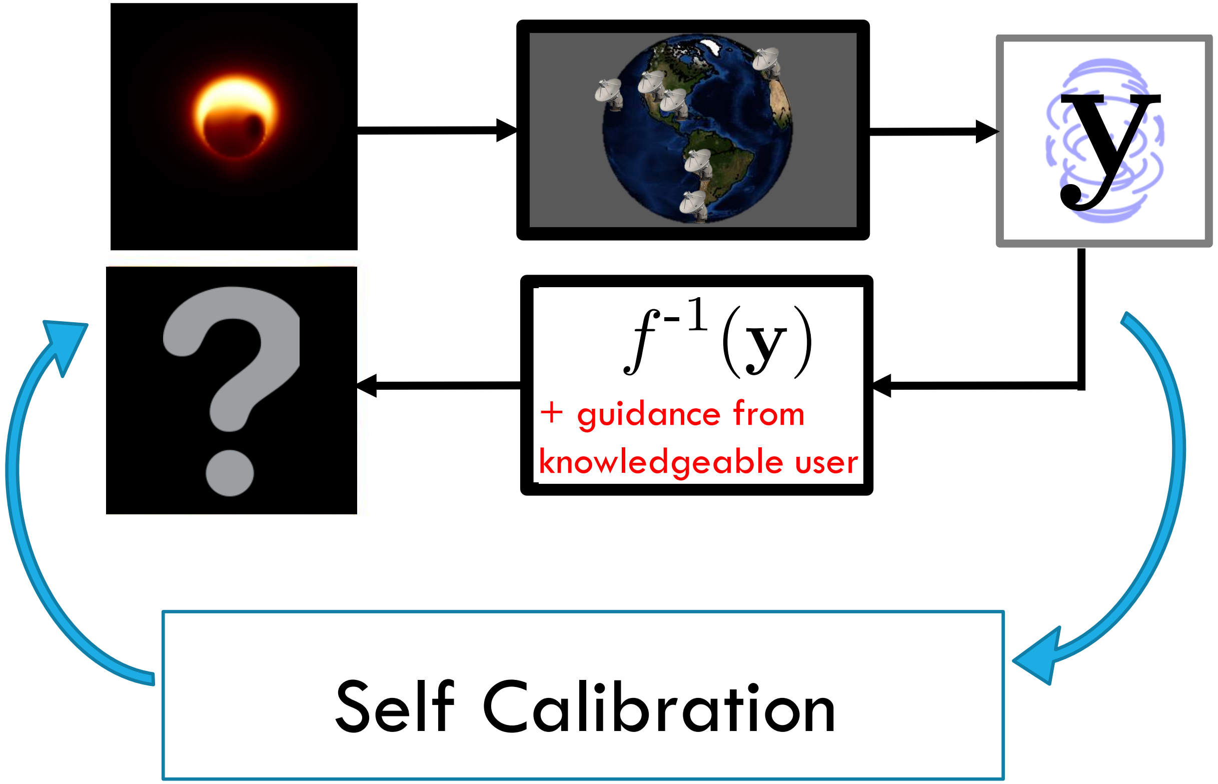
Sparsity:
Favors the image to be mostly empty space

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

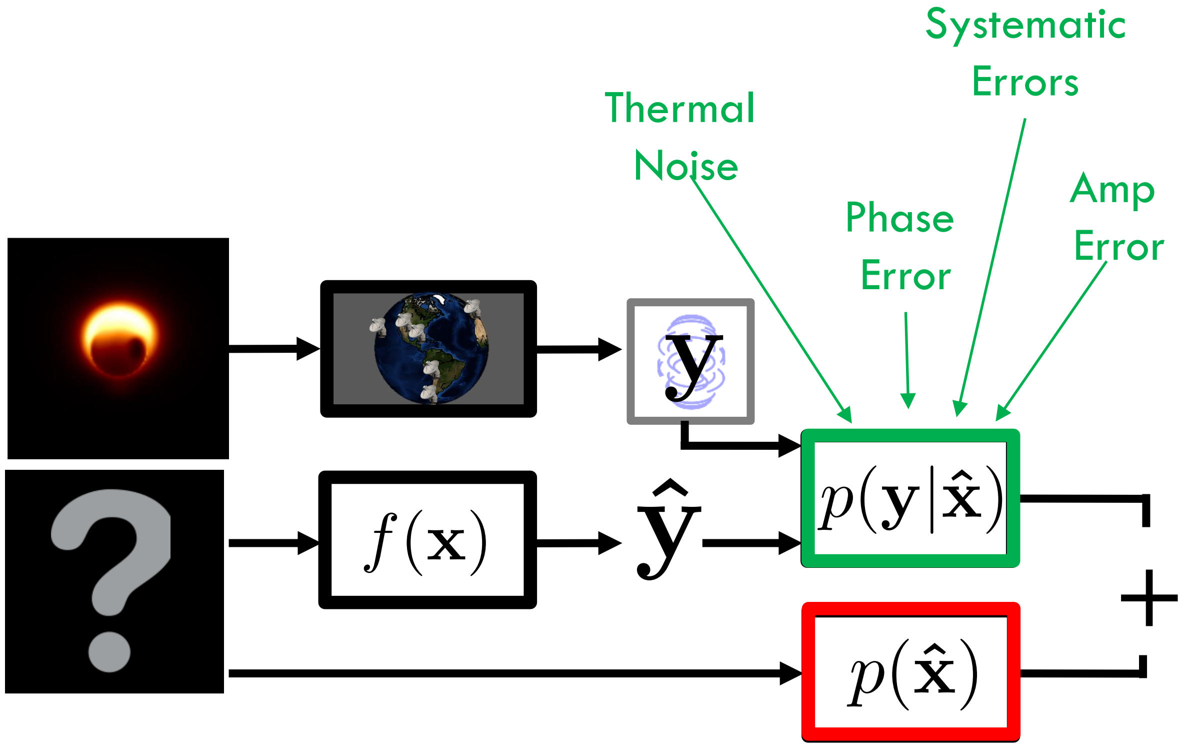
Maximum Entropy:
Favors compatibility with a specified “prior” image (which can be flat)



Two Classes of Imaging Algorithms



Standard Inverse Modeling
(CLEAN + Self-Calibration)



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

Forward Modeling
(Regularized Maximum Likelihood)

Imaging M87:
How do we verify what we are reconstructing is real?

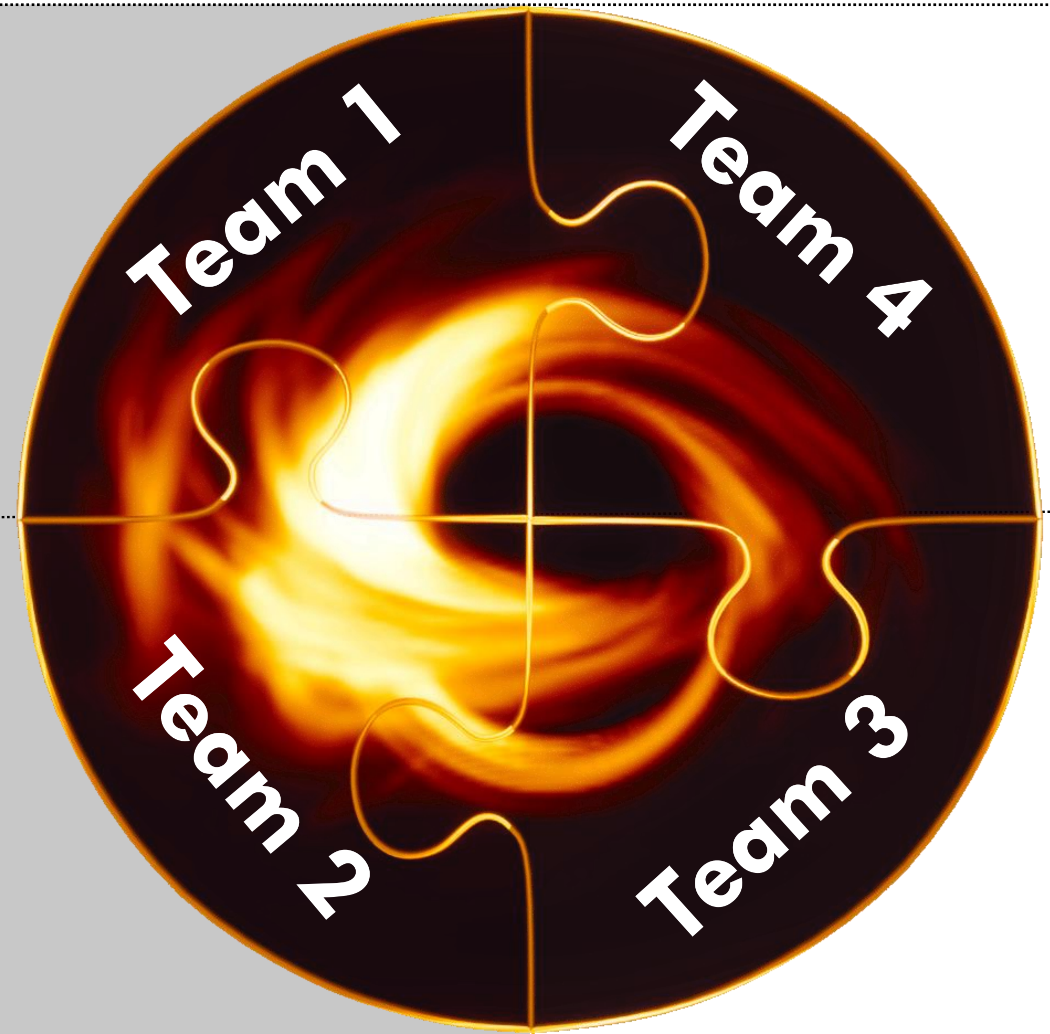
Step 1: Blind Imaging

The Americas

Harvard-Smithsonian
University of Arizona
U. Concepcion

Global

MIT Haystack
Radboud University
NAOJ



ASIAA
KASI
NAOJ

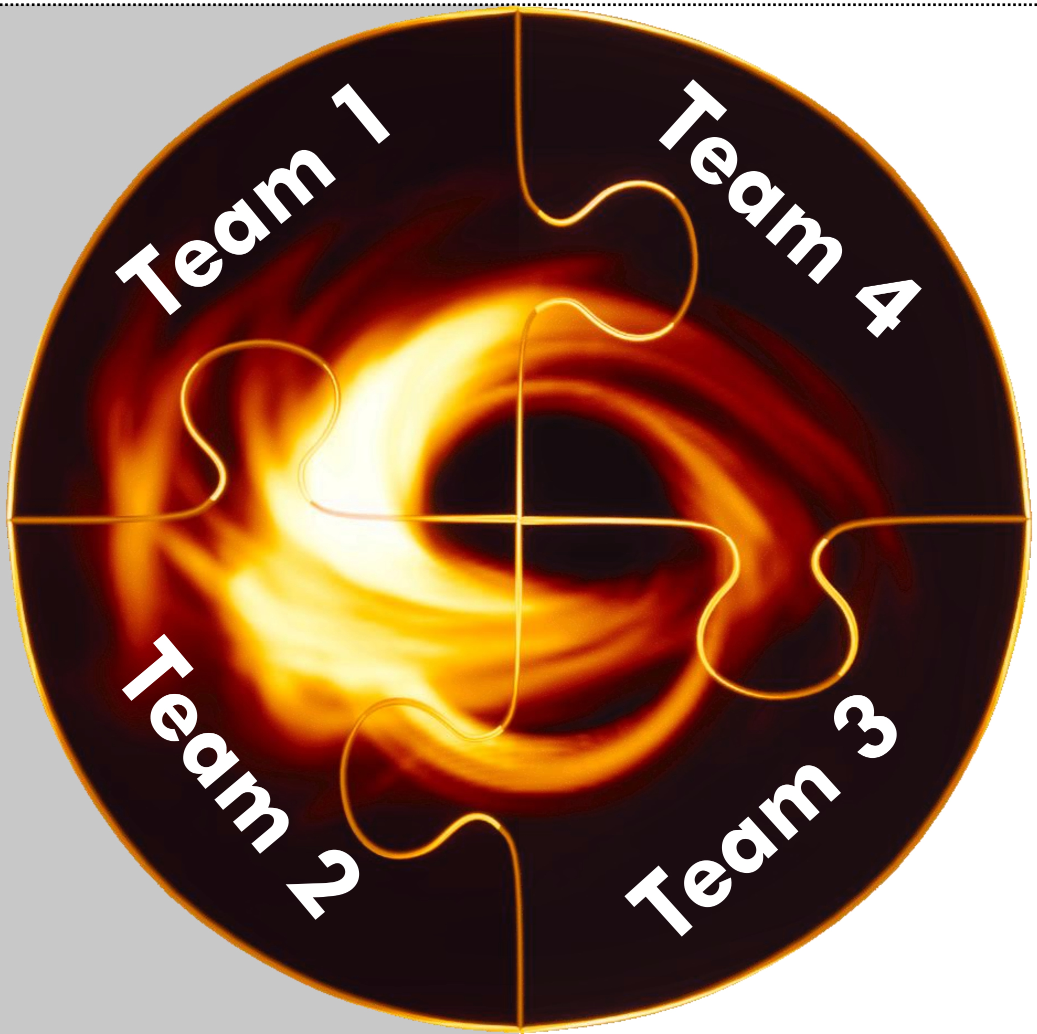
East Asia

MPIfR
Boston University
IAA
Aalto

Cross-Atlantic

Step 1: Blind Imaging

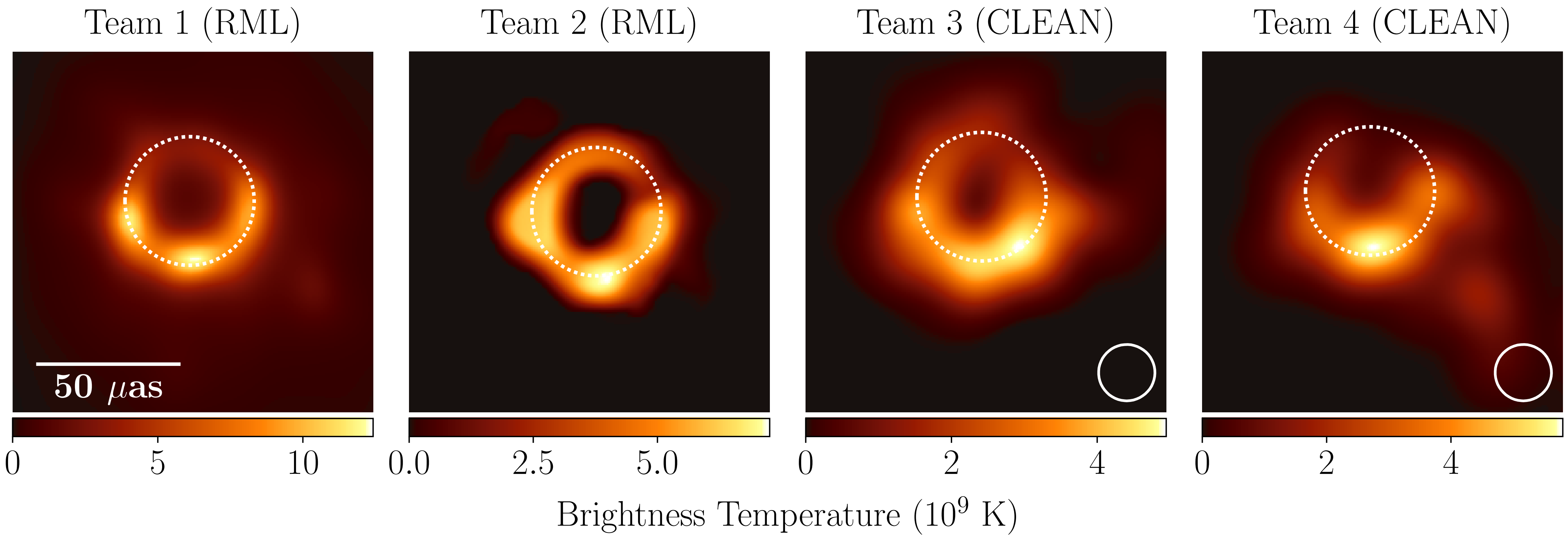
Regularized
Maximum
Likelihood

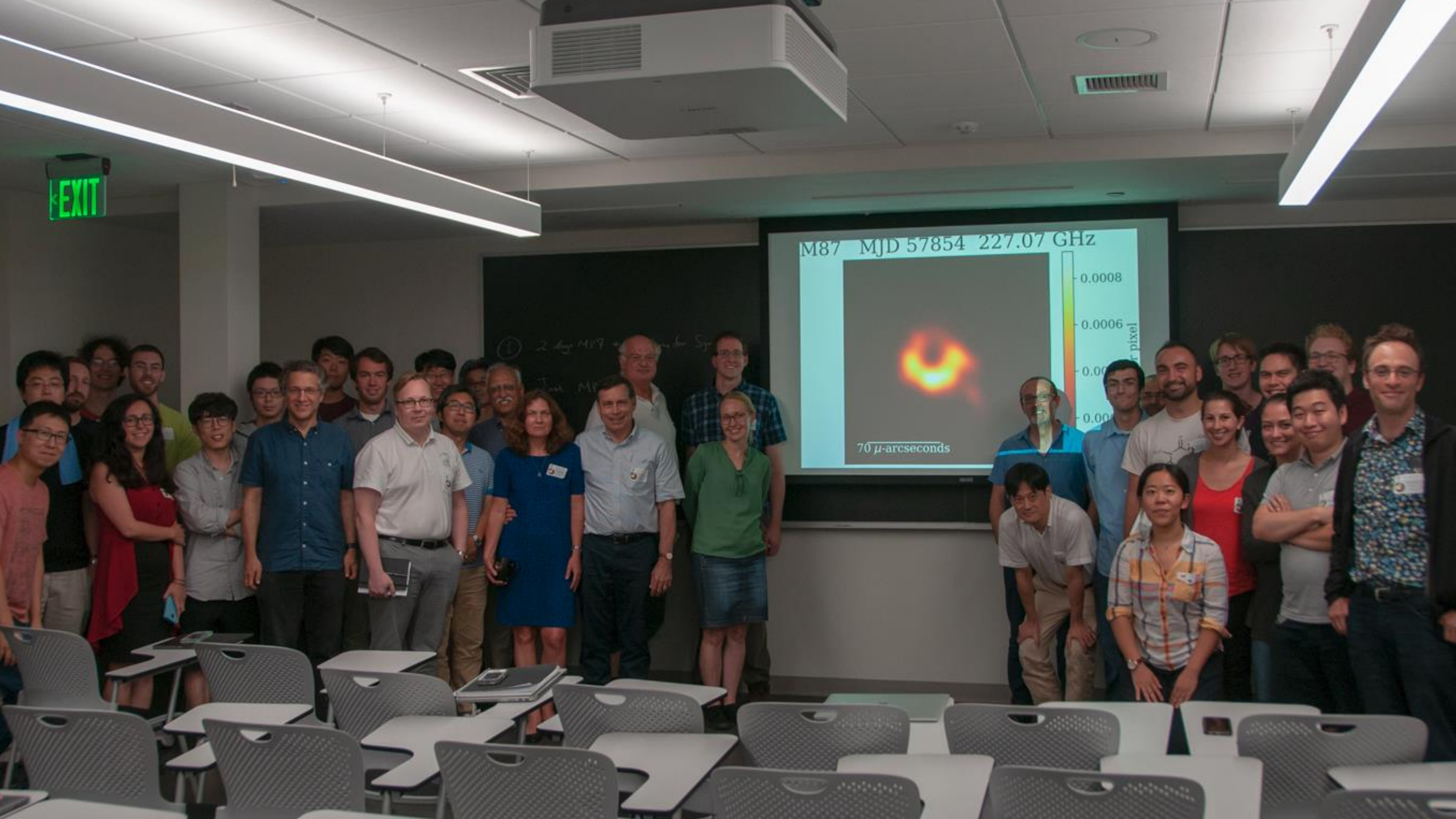


CLEAN
+
Self Calibration

7 weeks later…

Step 1: Blind Imaging




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

Step 2: Imaging Parameter Surveys

DIFMAP
(CLEAN + Self Calibration)

- Compact Flux
- Stop Condition
- Weighting on ALMA
- Mask Size
- Data Weights

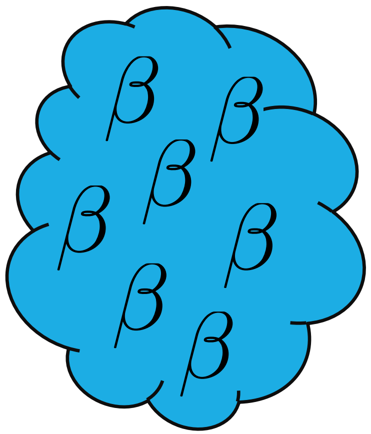
eht-imaging
(Regularized Max Likelihood)

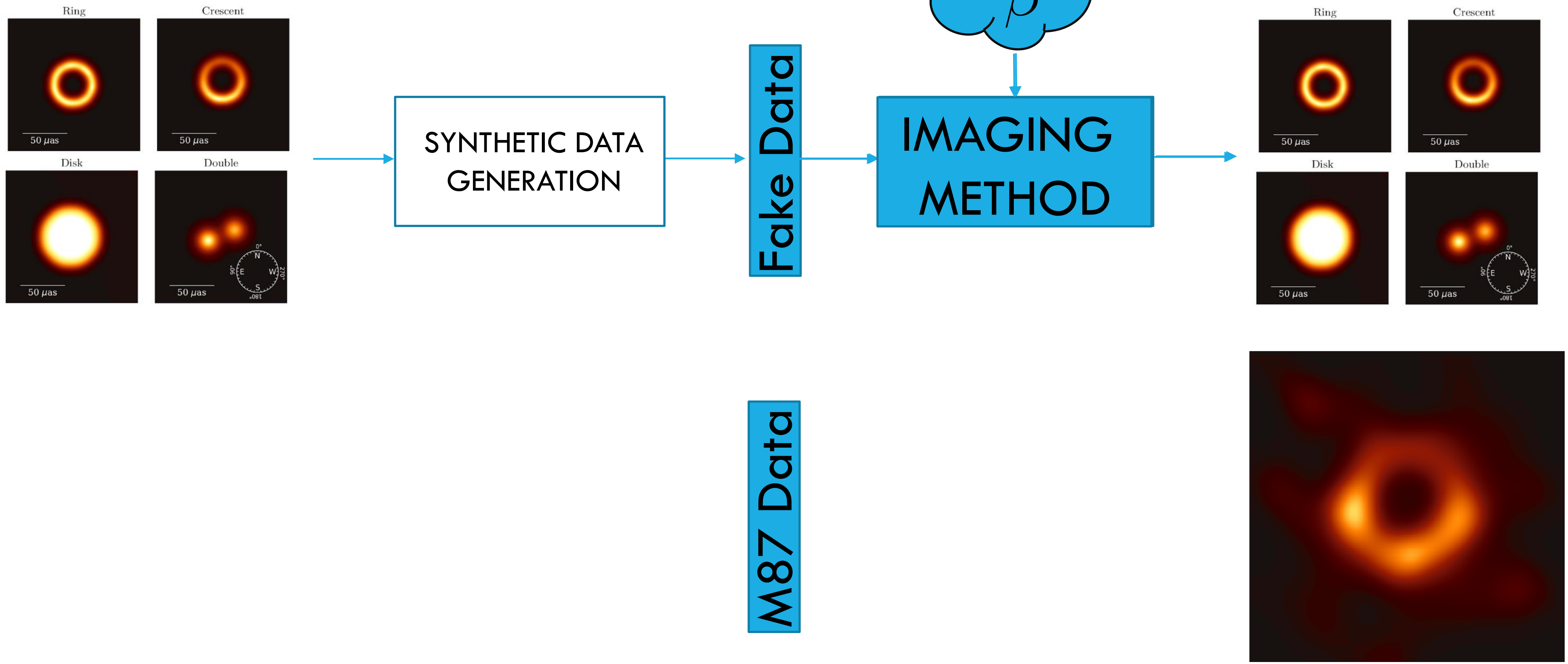
- Compact Flux
- Initial Gaussian Size
- Systematic Error
- Regularizes
  - MEM
  - TV
  - TSV
  - L1

SMILI
(Regularized Max Likelihood)

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

Testing thousands of parameter sets per method





Parameter survey results

- The parameter selection procedure identifies a "top set" of parameters that all distinguish well between the different model images
  → we can start to study uncertainties in our images and derived parameters from parameter choices.

- The best performing, fiducial parameters are not necessarily the best for producing the cleanest image of M87, but they produce accurate images of different sources without user intervention

DIFMAP (1008 Param. Combinations; 30 in Top Set)

Compact	0.5	0.6	0.7	0.8			
Flux (Jy)	**27%**	27%	30%	17%			
Stop	Flux Reached		ΔRMS $\leq 10^{-4}$				
Condition	**70%**		30%				
ALMA	0.01	0.1	0.3	0.5	0.7	1.0	
Weight Factor	17%	**60%**	20%	3%	0%	0%	
Mask	40	50	60	70	80	90	100
Diam. (μas)	0%	0%	**47%**	27%	23%	3%	0%
UV Weight	0	-1	-2				
Exponent κ	10%	**60%**	30%				

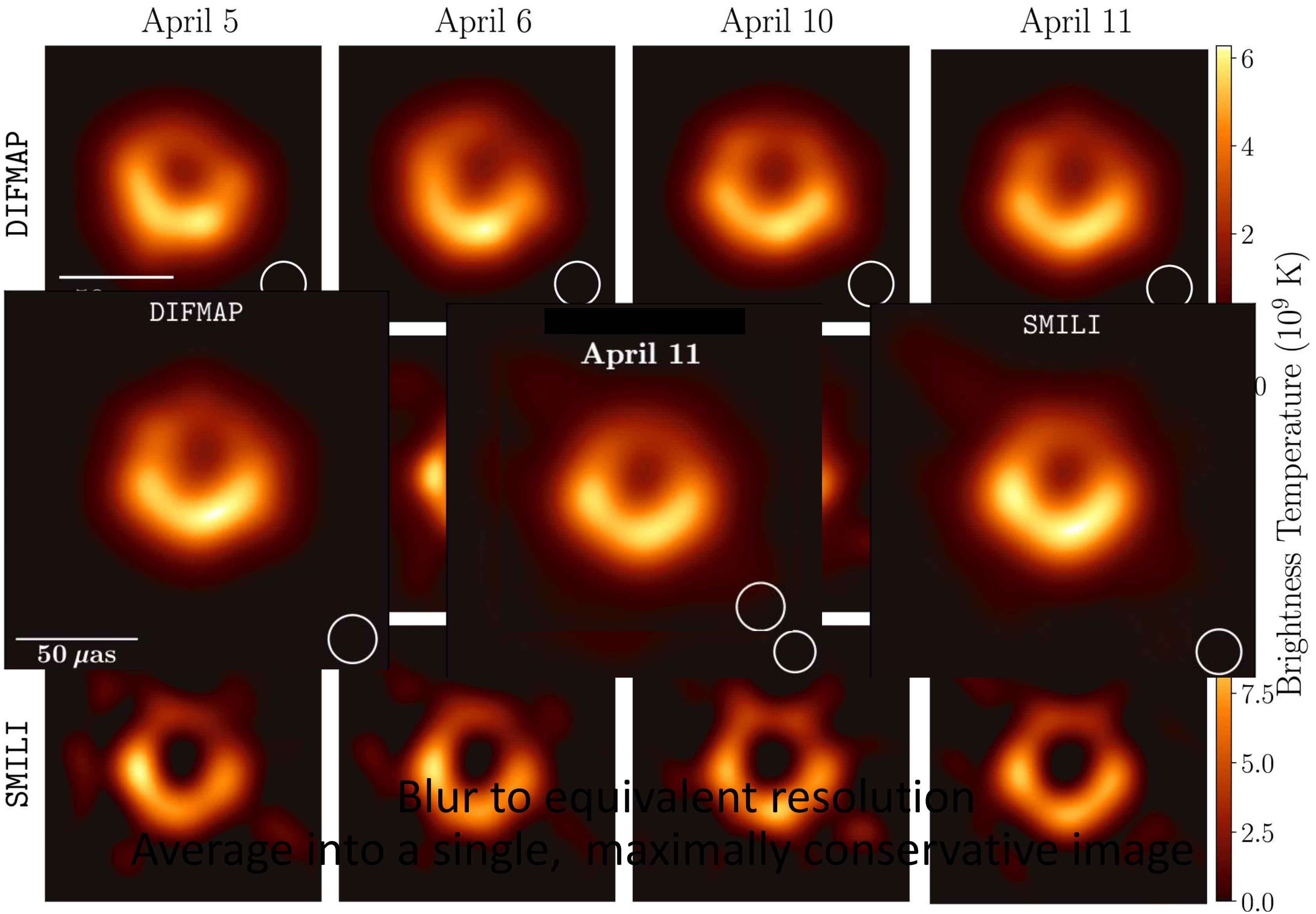
eht-imaging (37500 Param. Combinations; 1572 in Top Set)

Compact	0.4	0.5	0.6	0.7	0.8
Flux (Jy)	12%	19%	**24%**	23%	22%
Init./MEM	40	50	60		
FWHM (μas)	**58%**	42%	0%		
Systematic	0%	1%	2%	5%	
Error	26%	27%	**26%**	20%	
Regularizer:	0	1	10	10^2	10^3
MEM	0%	0%	8%	**92%**	0%
TV	31%	**35%**	33%	0%	0%
TSV	31%	**34%**	32%	3%	0%
ℓ_1	**23%**	24%	24%	22%	7%

SMILI (10800 Param. Combinations; 529 in Top Set)

Compact	0.4	0.5	0.6	0.7	0.8	
Flux (Jy)	22%	**31%**	25%	14%	8%	
ℓ_1^w Soft Mask	40	50	60	70	80	
FWHM. (μas)	**29%**	19%	21%	21%	15%	
Systematic	0%	1%				
Error	**50%**	50%				
Regularizer:	0	10	10^2	10^3	10^4	10^5
TV	9%	9%	11%	**38%**	32%	0%
TSV	13%	14%	13%	24%	**36%**	0%
	0	10^{-2}	10^{-1}	1	10	10^2
ℓ_1^w	0%	0%	9%	**47%**	44%	0%

Images from three pipelines over four days

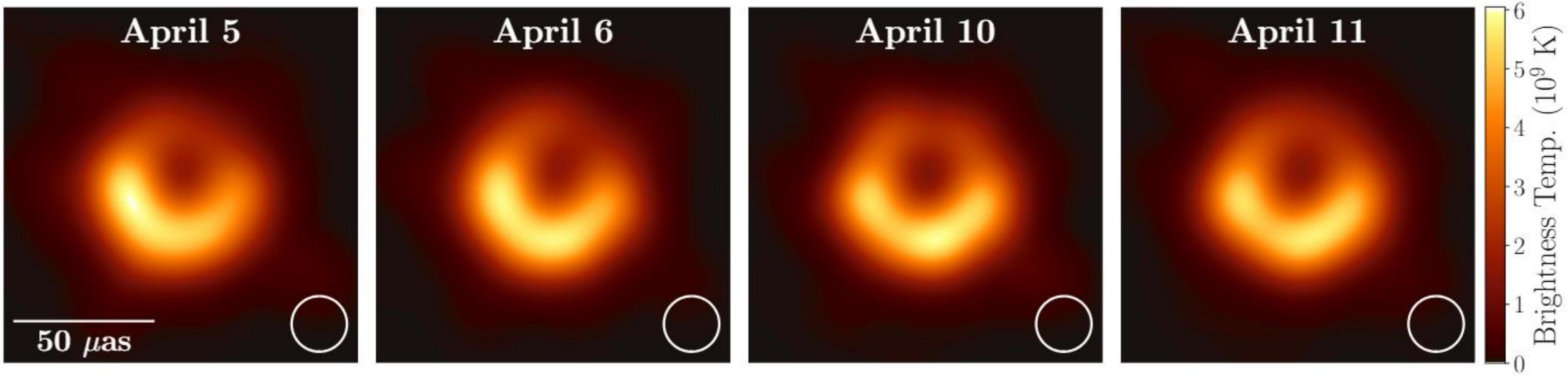


Blur to equivalent resolution

Average into a single, maximally conservative image

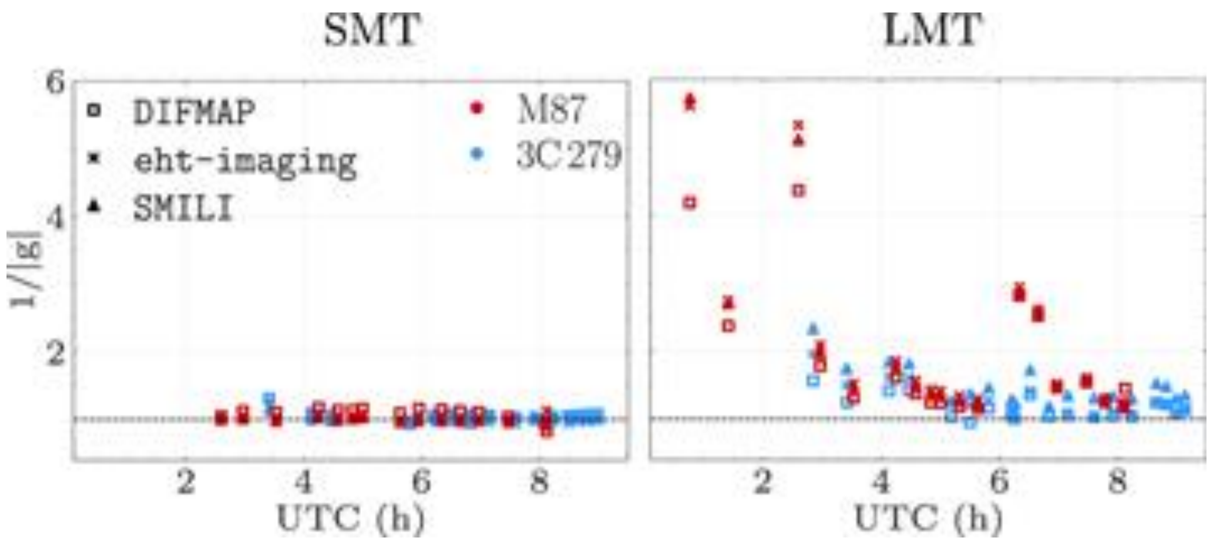
Image Credit: EHT Collaboration 2019 (Paper IV)

The Averaged Image From Each Day



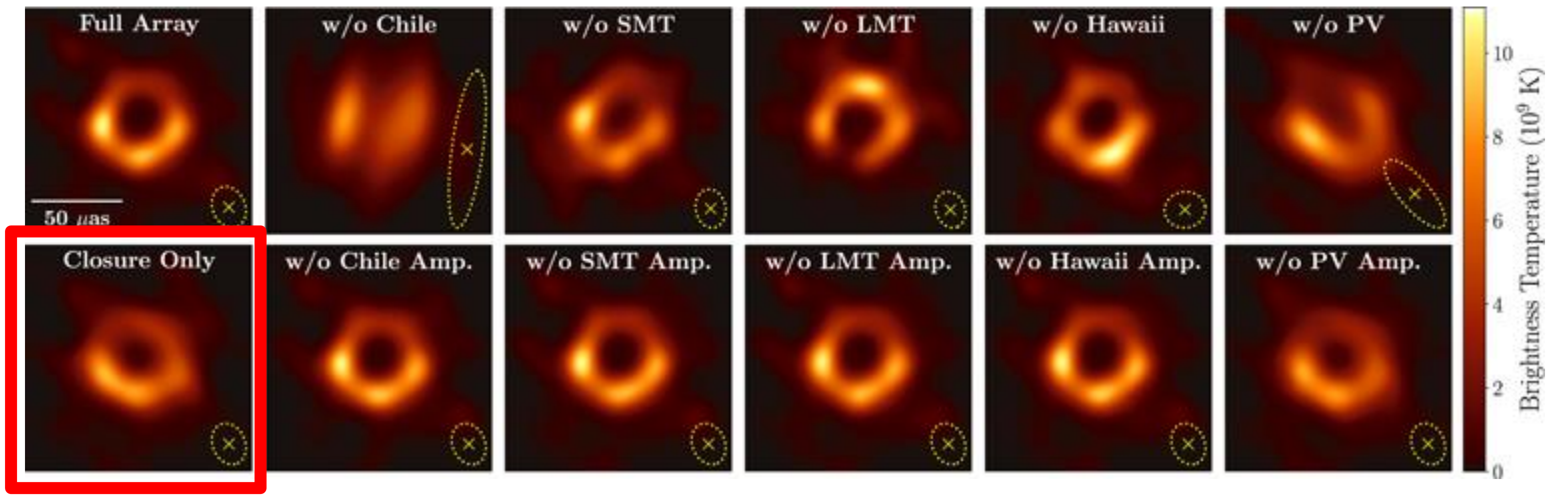
Consistent structure from night-to-night, **hints of time evolution?**

Validation: Calibrator Gains & Omitting stations



1.) The gain corrections derived for M87 observations should be consistent with the corrections for interleaved observations of 3C279, **imaged independently**

2.) Our images should not be too sensitive to the loss or miscalibration of any one telescope



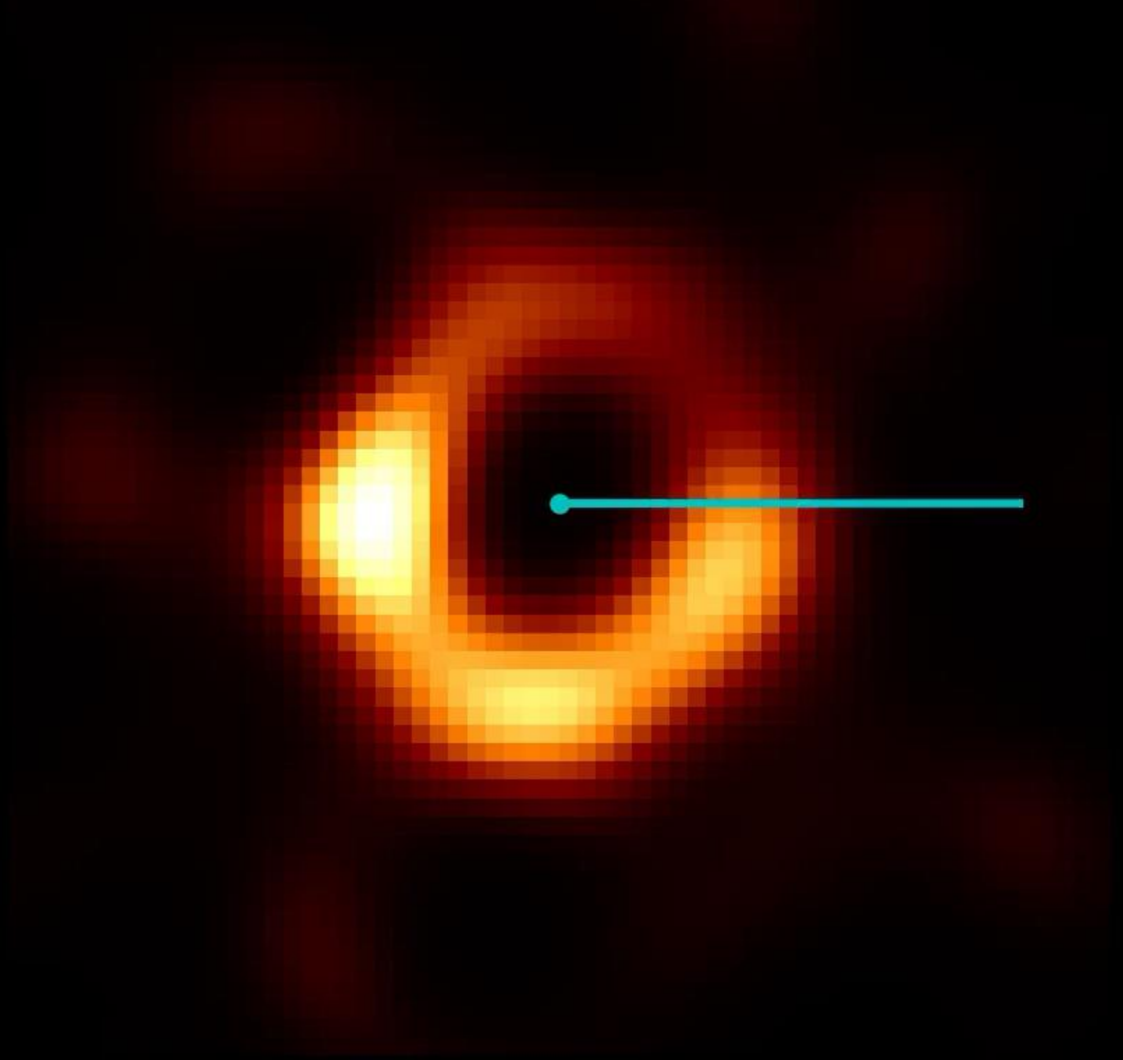
Measuring ring features

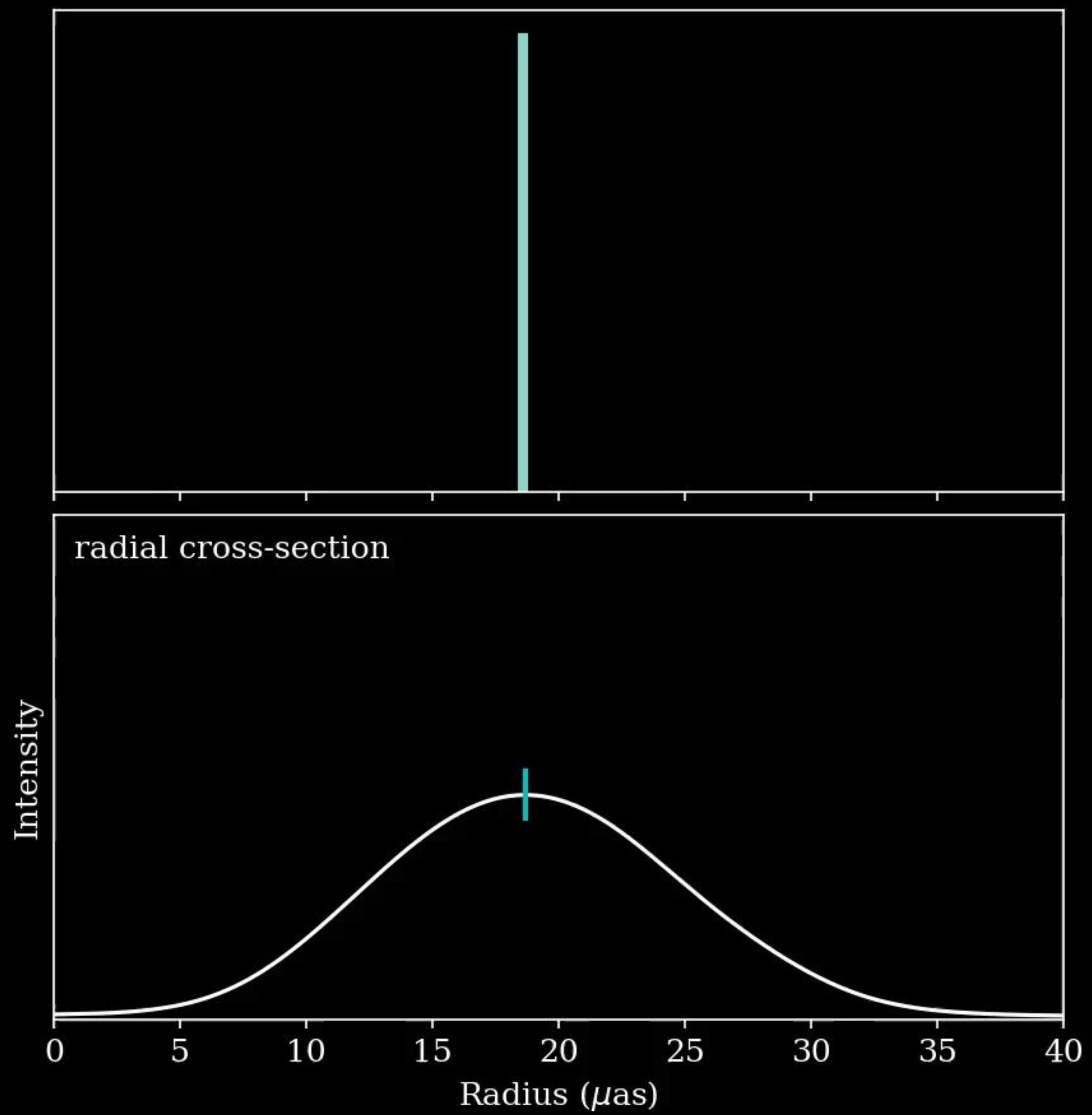
- Measuring characteristic features tells us how consistent the reconstructions are across methods and time
- **Five** characteristic features:
  - Diameter d
  - Width w
  - Orientation angle η
  - Asymmetry A
  - Central Contrast f_C
- The black hole **mass** is proportional to the ring **diameter**

$$M = \frac{c^2 D}{G} \frac{d}{\alpha}$$

Proportionality constant:
For perfect, zero spin: $\alpha = 2\sqrt{27}$
but **resolution bias**, spin, and **image structure** can shift α

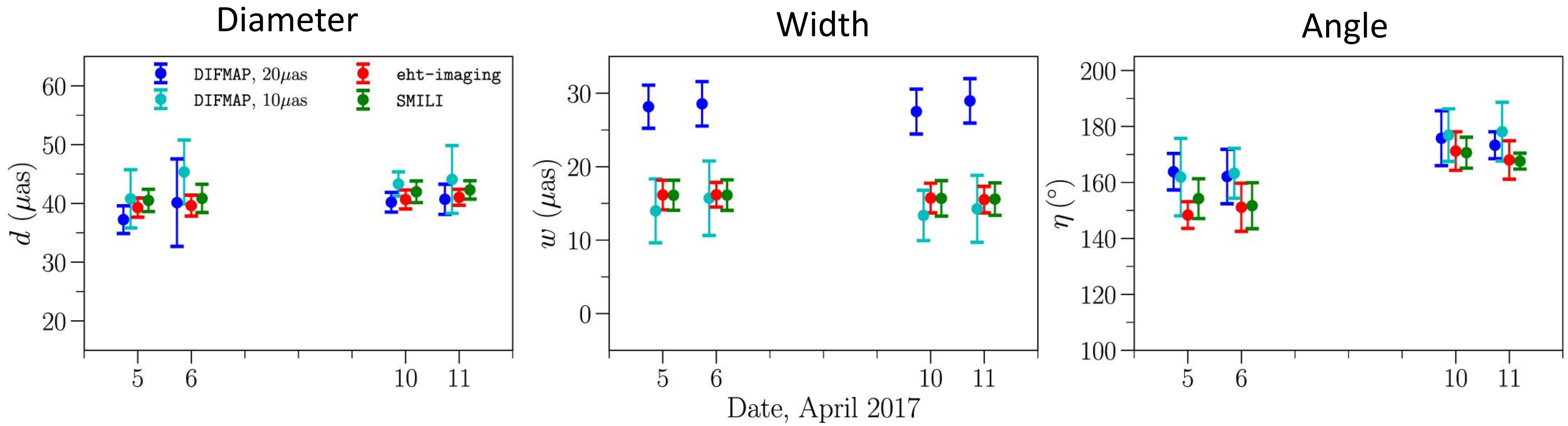
Extracting a Ring from an Image





Animation Credit: Dom Pesce

M87 ring features



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

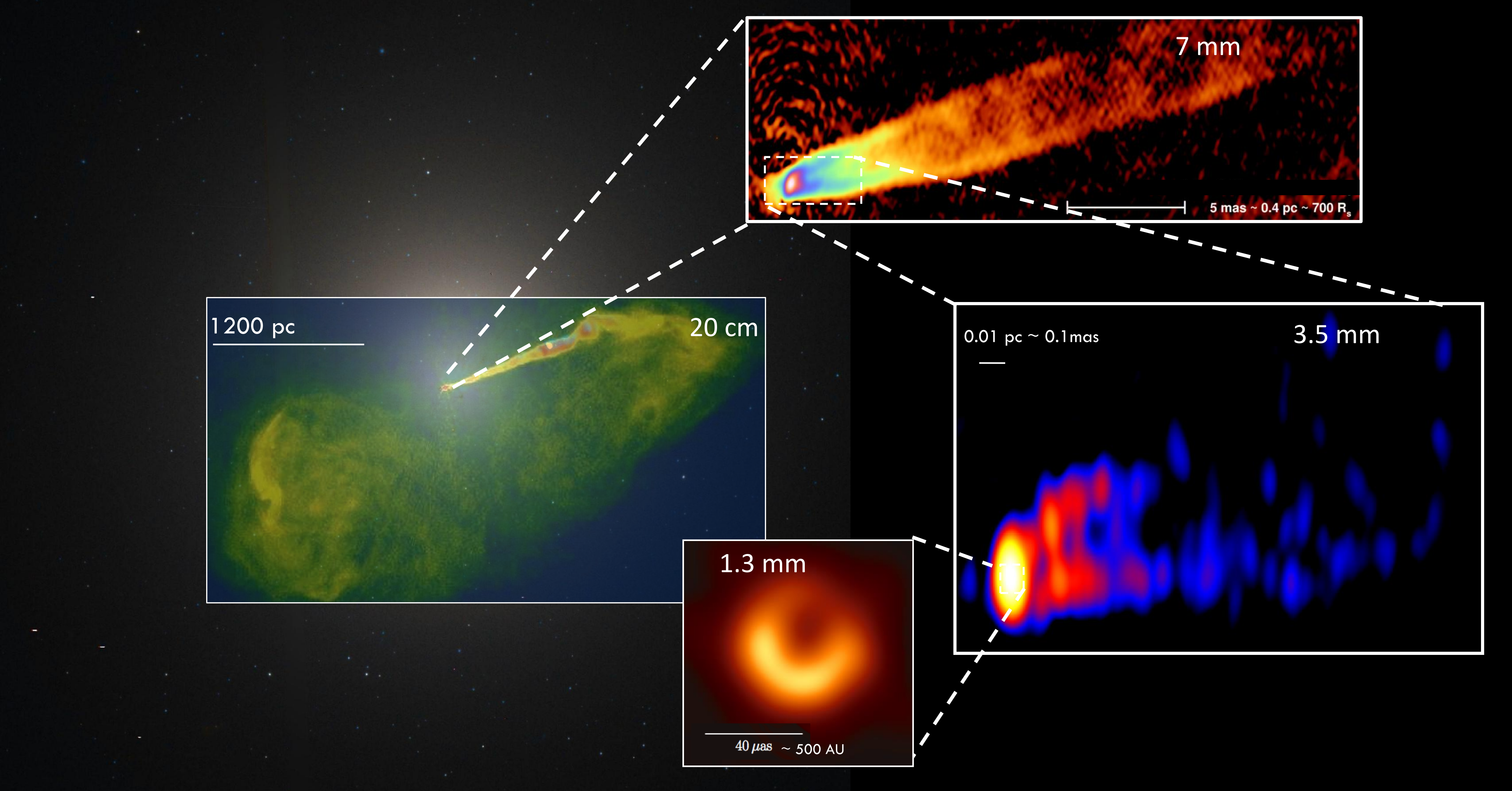


Image Credits: NRAO (VLA),
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