First Images of a Black Hole

Kazu Akiyama

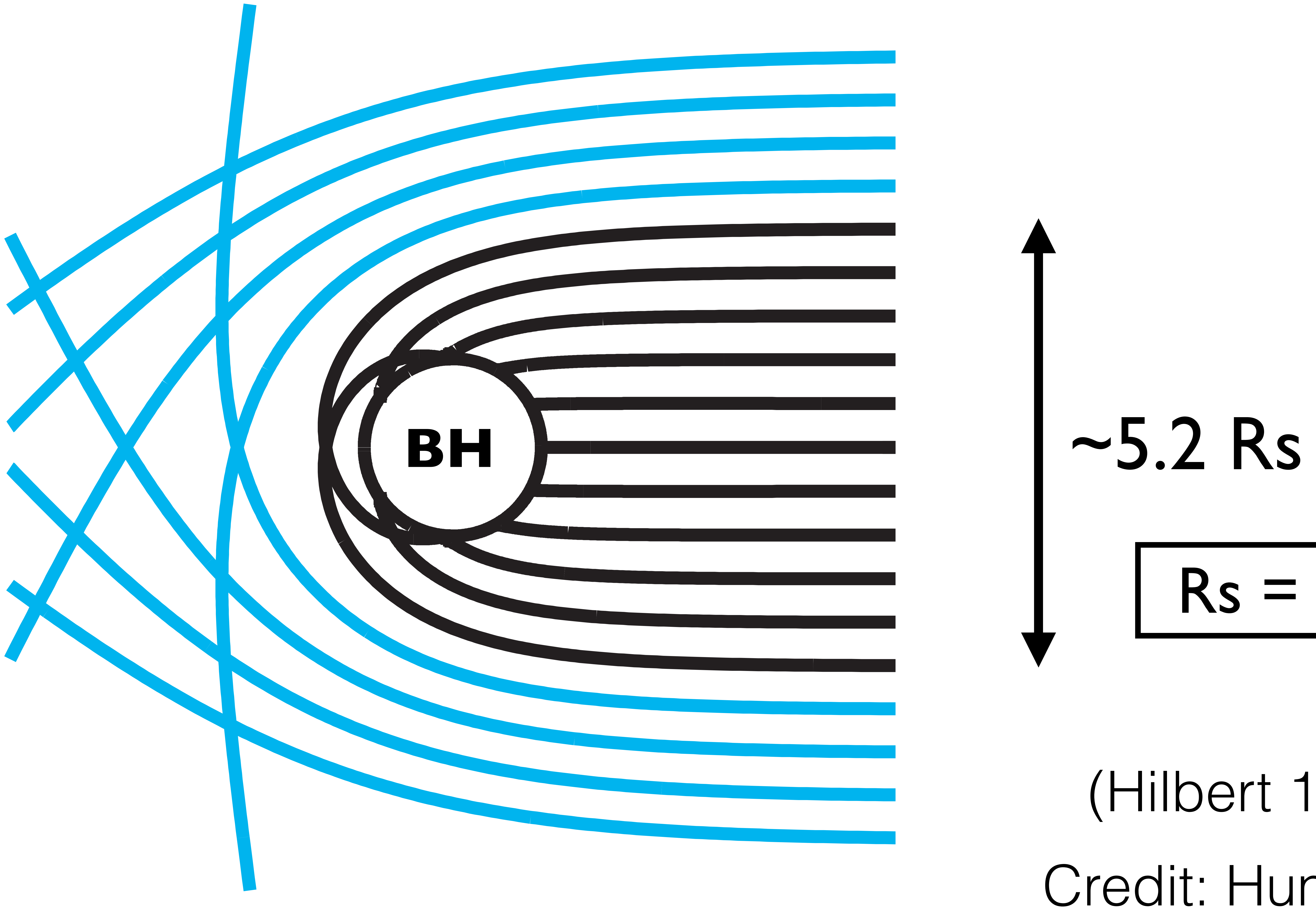
(Jansky Fellow / MIT Haystack Observatory)

Event Horizon Telescope

NRAO

HAYSTACK OBSERVATORY

The Shadow of a Black Hole



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

(Hilbert 1916)

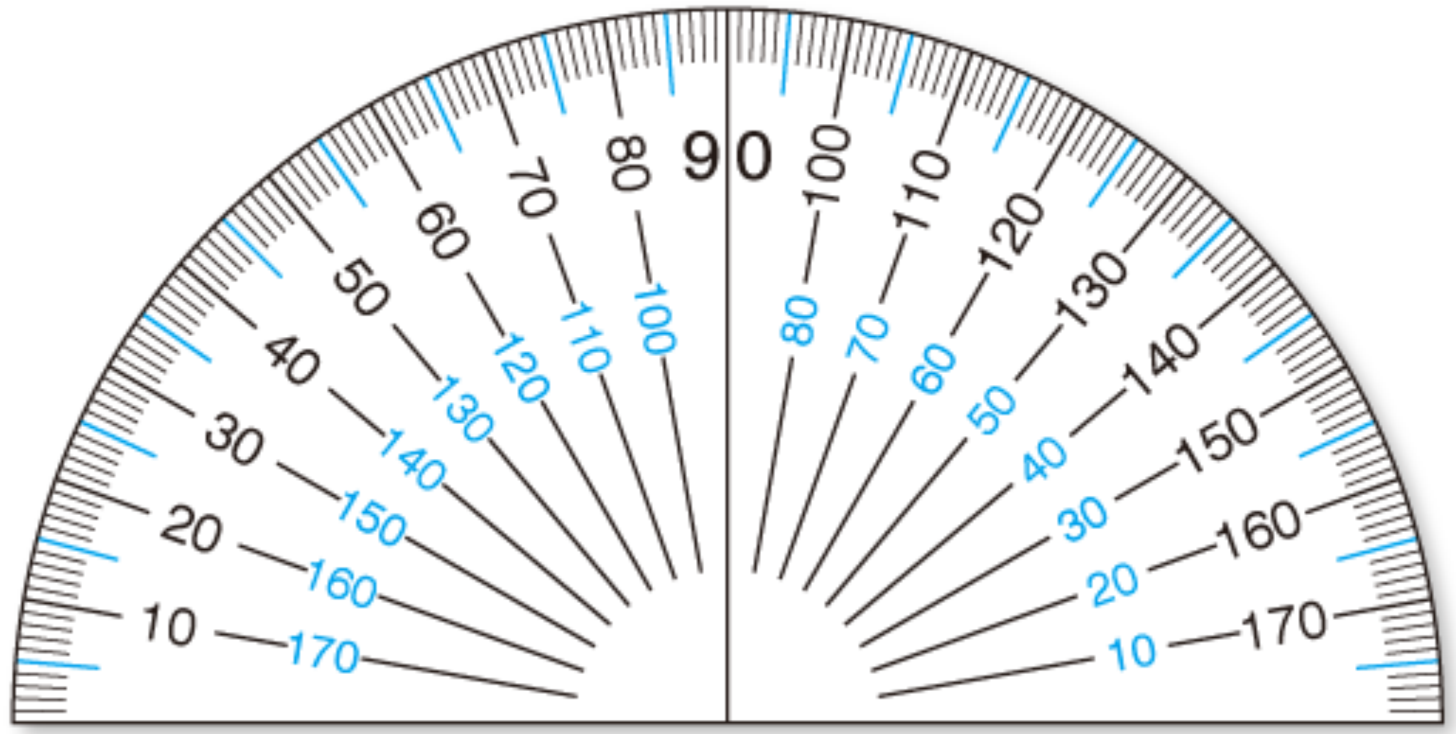
Credit: Hung-Yi Pu

Event Horizon Telescope

Black Holes with the Largest Angular Sizes

Source	BH Mass (M_{solar})	Distance (Mpc)	1 R_s (μas)
Sgr A*	4×10^6	0.008	10
M87	~~**$3.3 - 6.2 \times 10^9$**~~ **6.5×10^9**	**16.7**	~~**3.6 - 7.3**~~ **7.6**
M104	1×10^9	10	2
Cen A	5×10^7	4	0.25

Units of the Angular Size



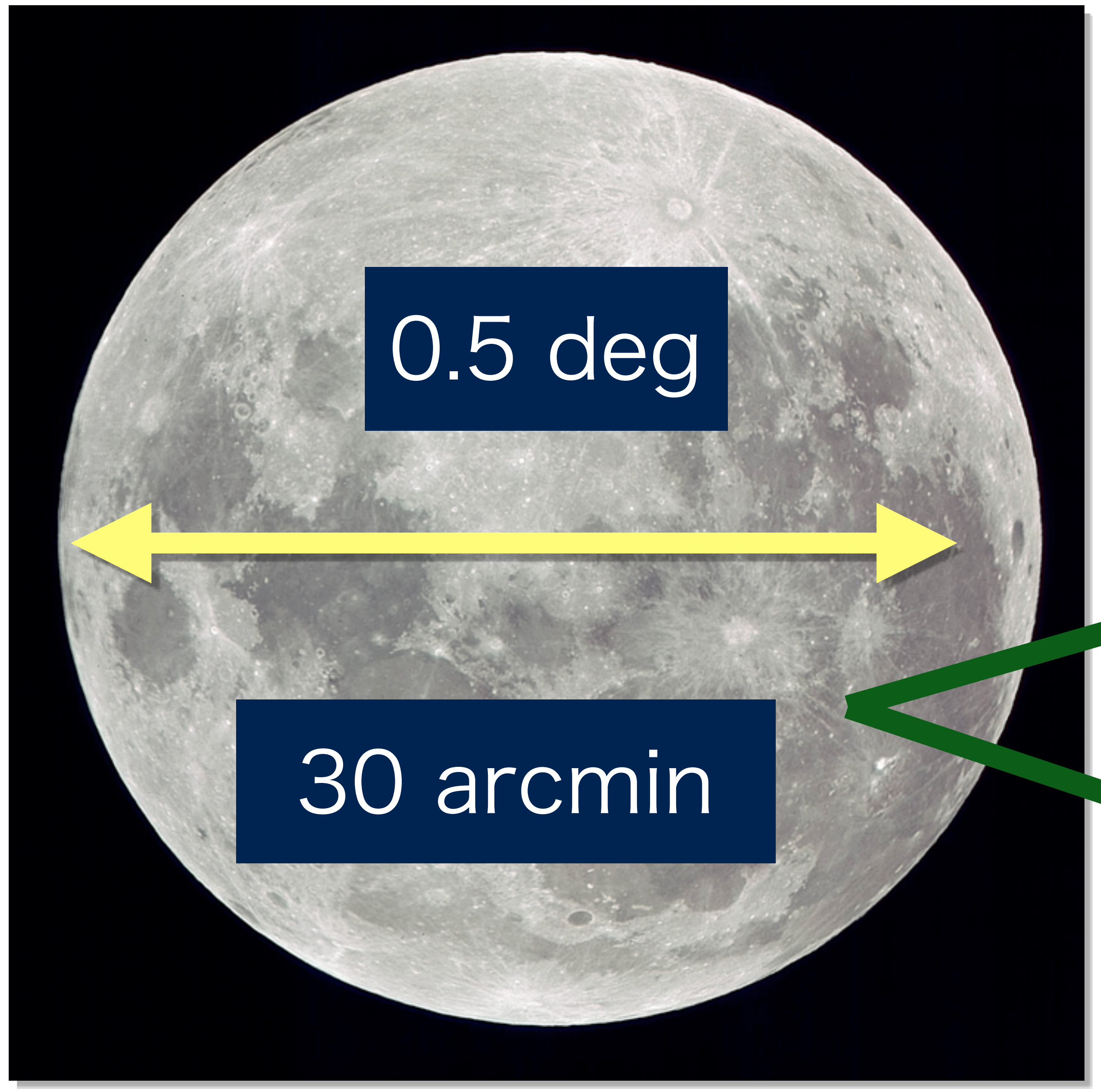
Protractor : 1 ticks = 1 degree

x 1/60 = 1 arcmin

x 1/60 = 1 arcsec

x 1/1000 = 1 mas

x 1/1000 = 1 μas



40 - 50 μas

Event Horizon Telescope

Event Horizon Telescope

Event Horizon Telescope Collaboration

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

Meet the Telescope

Photos: ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann, David Sanchez, Daniel Michalik, Jonathan Weintroub, William Montgomerie

Meet the Telescope

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From Observations to Images

Credit: Lindy Blackburn

From Observations to Images

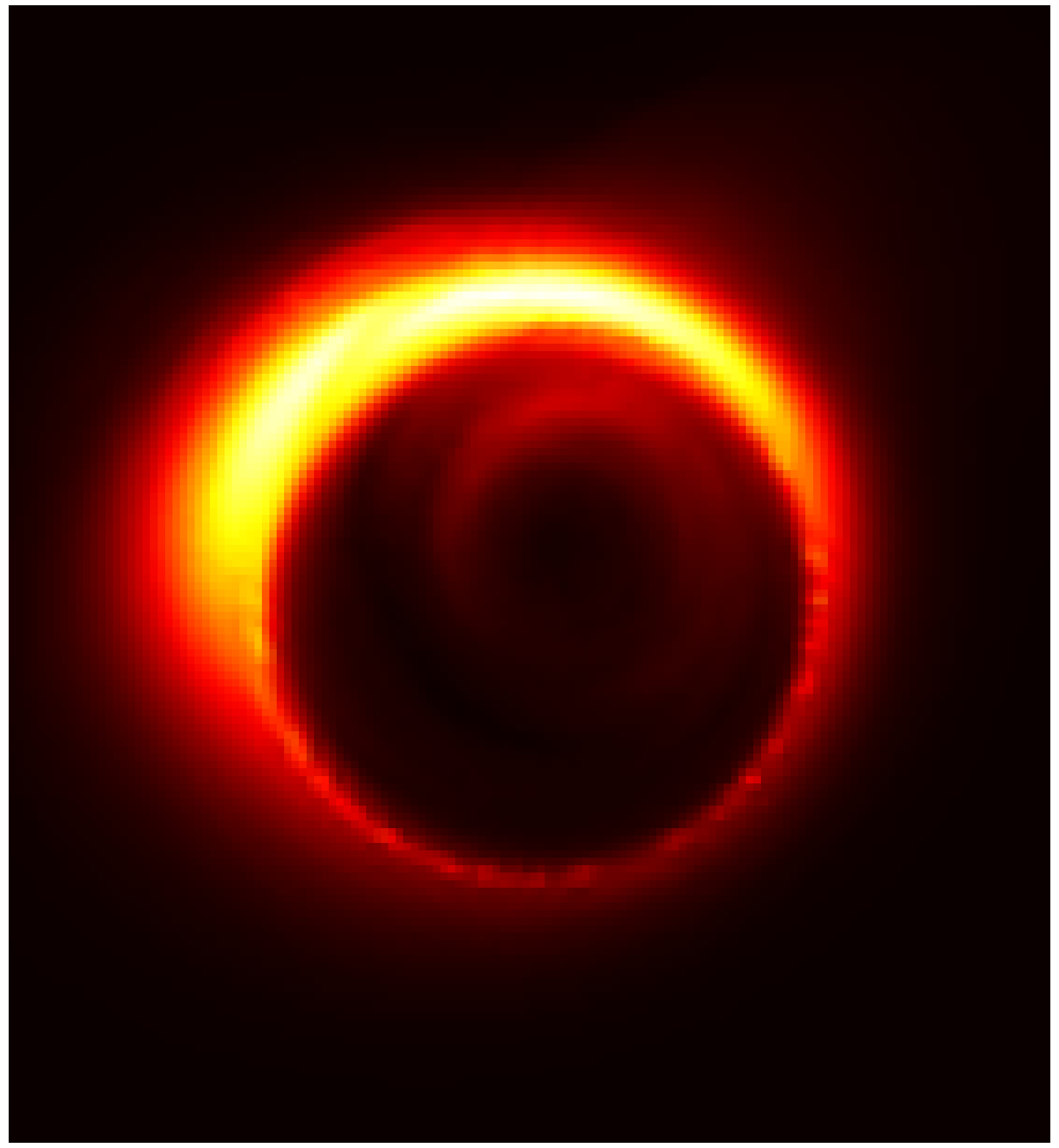
Credit: Bryce Vickmark

12 orders of magnitude in data reduction!

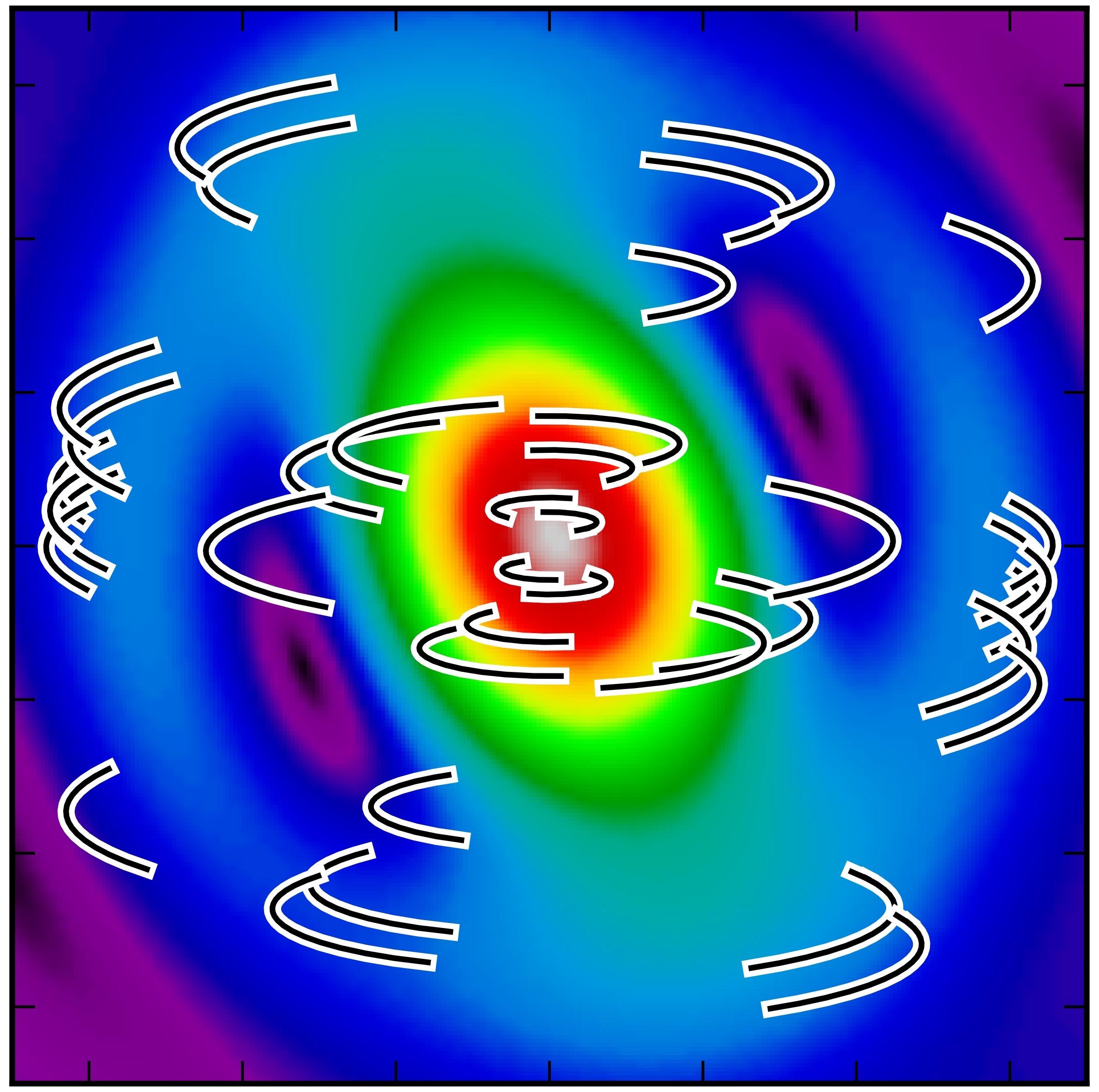
Credit: Lindy Blackburn

How the EHT works?

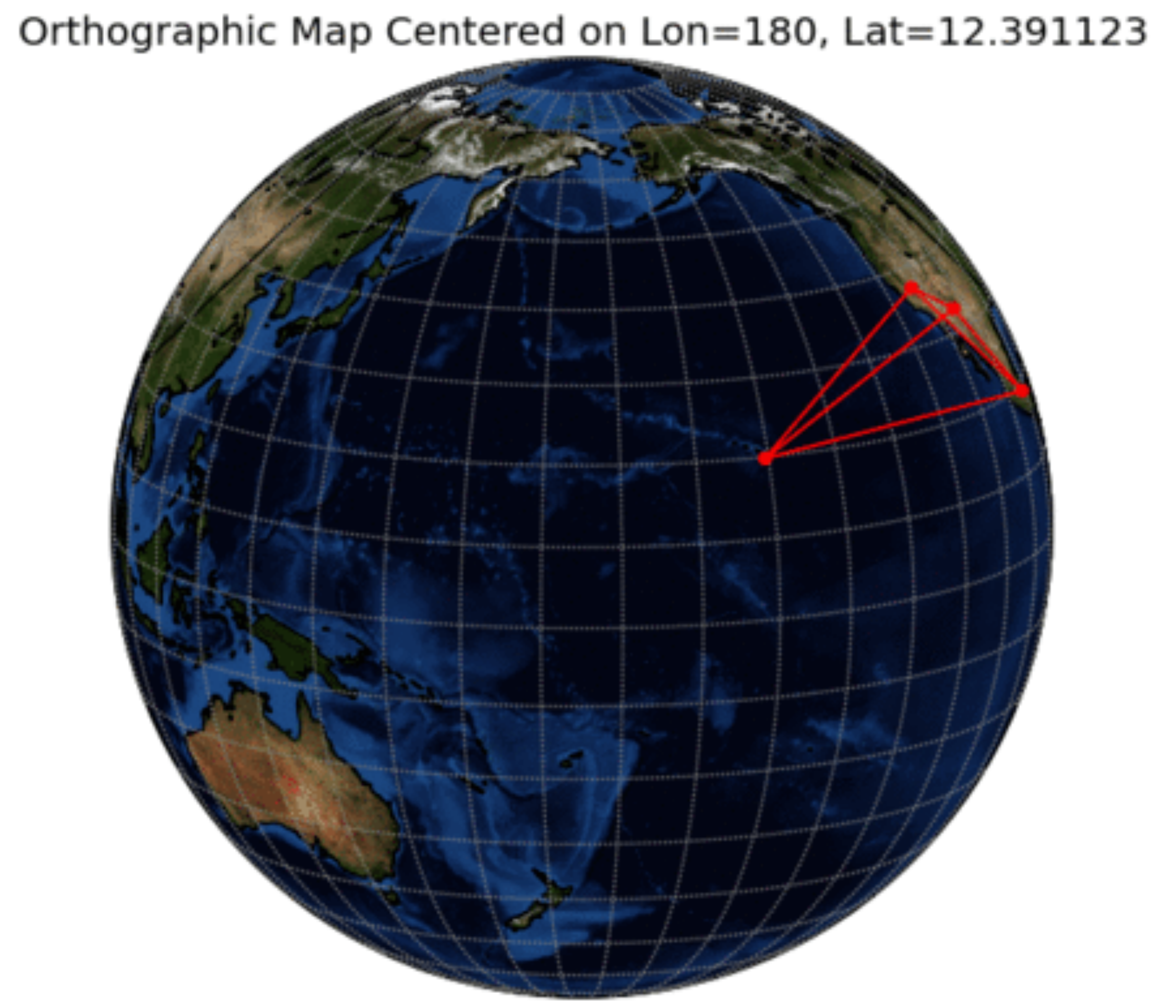
Image



Fourier Domain
(Visibility)

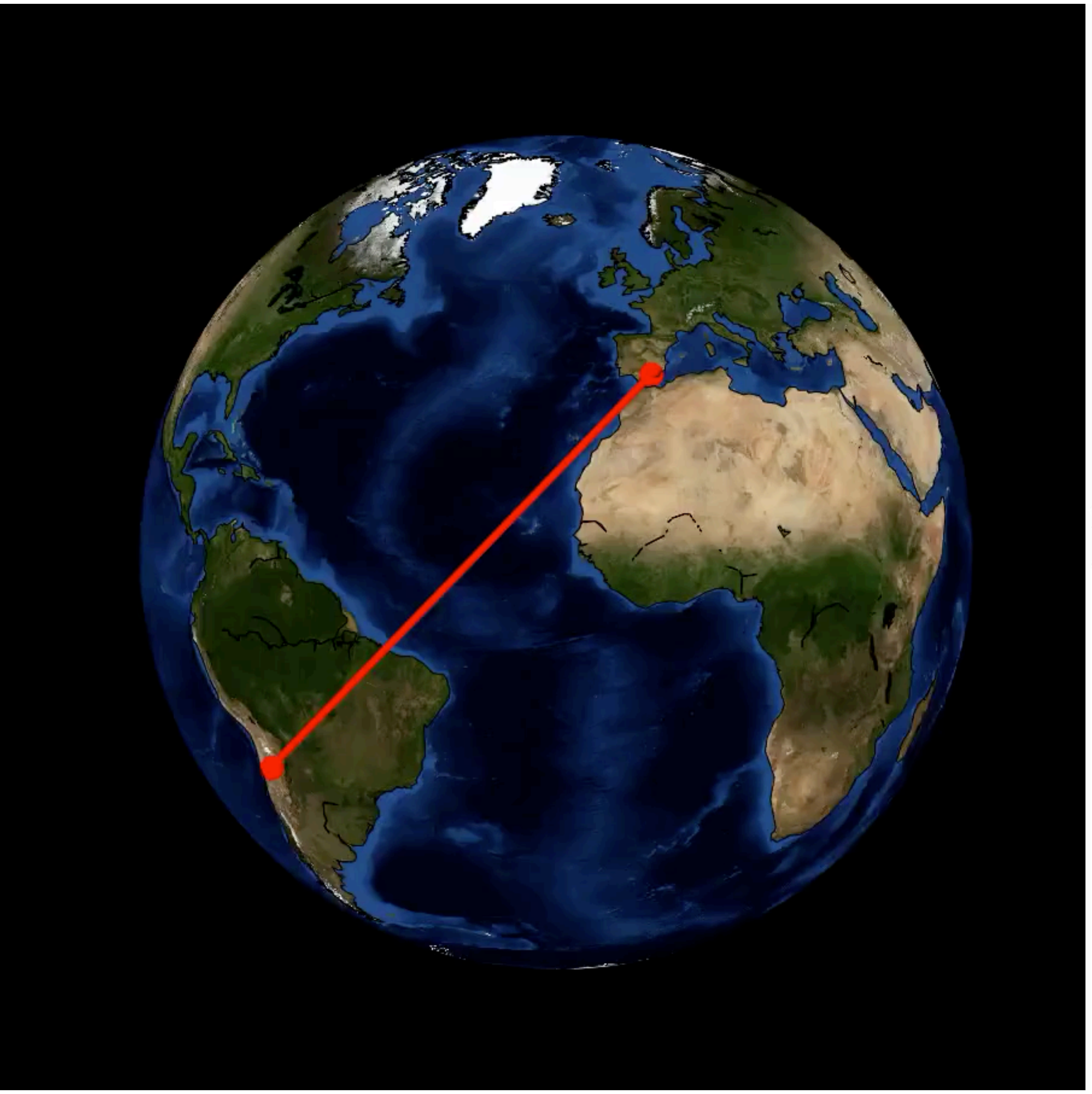


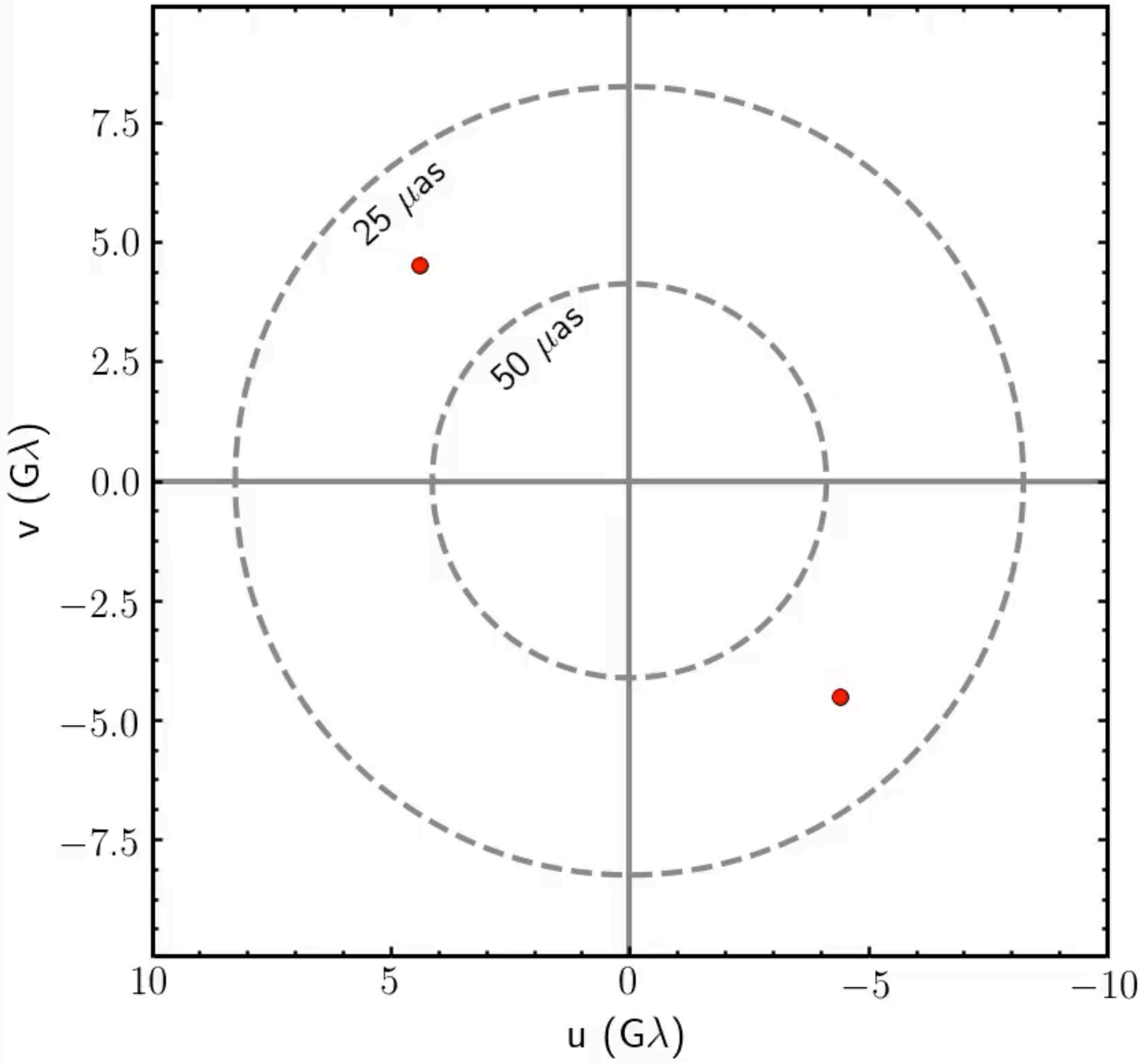
Sampling Process
(Projected Baseline = Spatial Frequency)

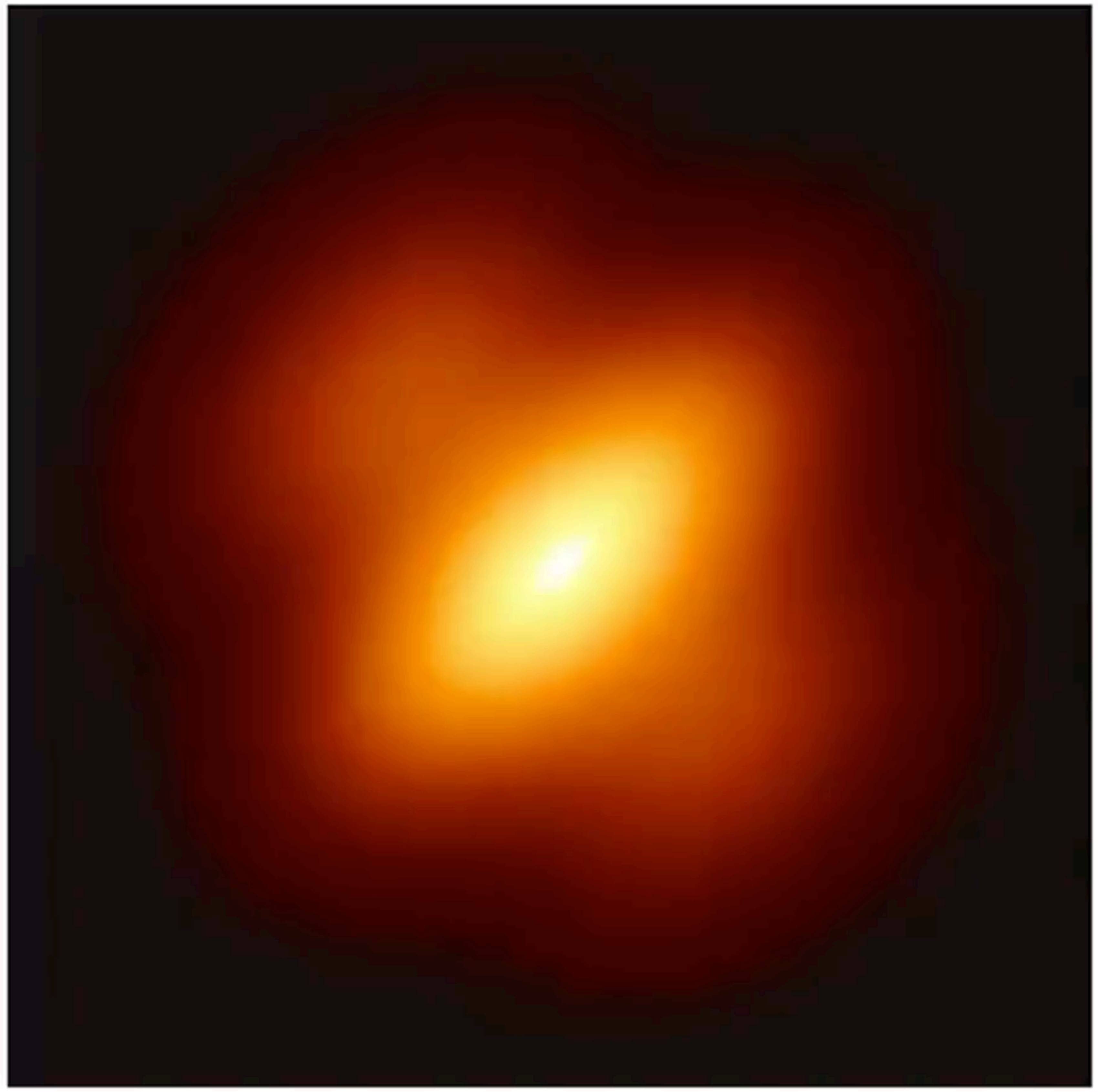


(Images: adapted from Akiyama et al. 2015, ApJ ; Movie: Laura Vertatschitsch)

Earth Rotation Synthesis







Credit: Daniel Palumbo

Event Horizon Telescope

Interferometric Imaging — Ideal Case —

$$\underset{\text{(Data)}}{V} = \underset{\text{(Fourier Matrix)}}{F}\ \underset{\text{(Image)}}{I} + \underset{\text{(Thermal Noise)}}{\varepsilon}$$

$$\begin{pmatrix} V_1(u_1) \\ V_2(u_2) \\ V_3(u_3) \\ \vdots \\ V_M(u_M) \end{pmatrix} = \begin{pmatrix} \exp(i2\pi u_1 x_1) & \exp(i2\pi u_1 x_2) & \dots & \exp(i2\pi u_1 x_N) \\ \exp(i2\pi u_2 x_1) & \exp(i2\pi u_2 x_2) & \dots & \exp(i2\pi u_2 x_N) \\ \exp(i2\pi u_3 x_1) & \exp(i2\pi u_3 x_2) & \dots & \exp(i2\pi u_3 x_N) \\ \vdots & \vdots & & \vdots \\ \exp(i2\pi u_M x_1) & \exp(i2\pi u_M x_2) & \dots & \exp(i2\pi u_M x_N) \end{pmatrix} \begin{pmatrix} I_1(x_1) \\ I_2(x_2) \\ I_3(x_3) \\ \vdots \\ I_N(x_N) \end{pmatrix}$$

- Sampling is NOT perfect
  Number of data M < Number of image pixels N
- Equation is *ill-posed*: infinite numbers of solutions
- Interferometric Imaging:
  Picking a reasonable solution based on a prior assumption

Remained Phase & Amplitude Errors after Calibrations

Measured → V_{12}; Ideal+Thermal Noise → $\mathcal{V}_{12}$

$$V_{12} = g_1 \; g_2 \; e^{-i(\phi_1 - \phi_2)} \, \mathcal{V}_{12}$$

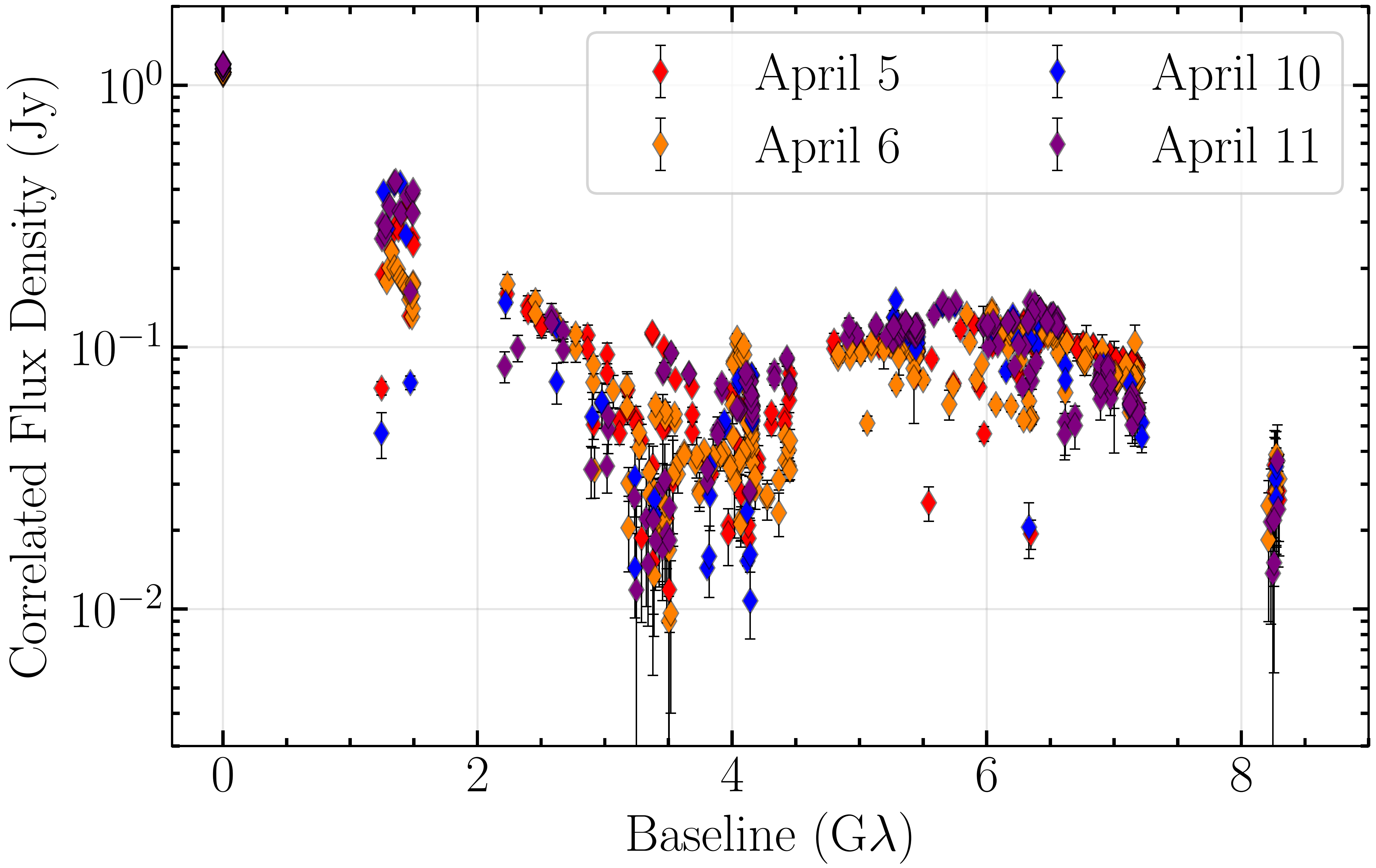
Amplitude Errors ($g_1 \; g_2$)

Typically: few~10%
LMT: > 50%

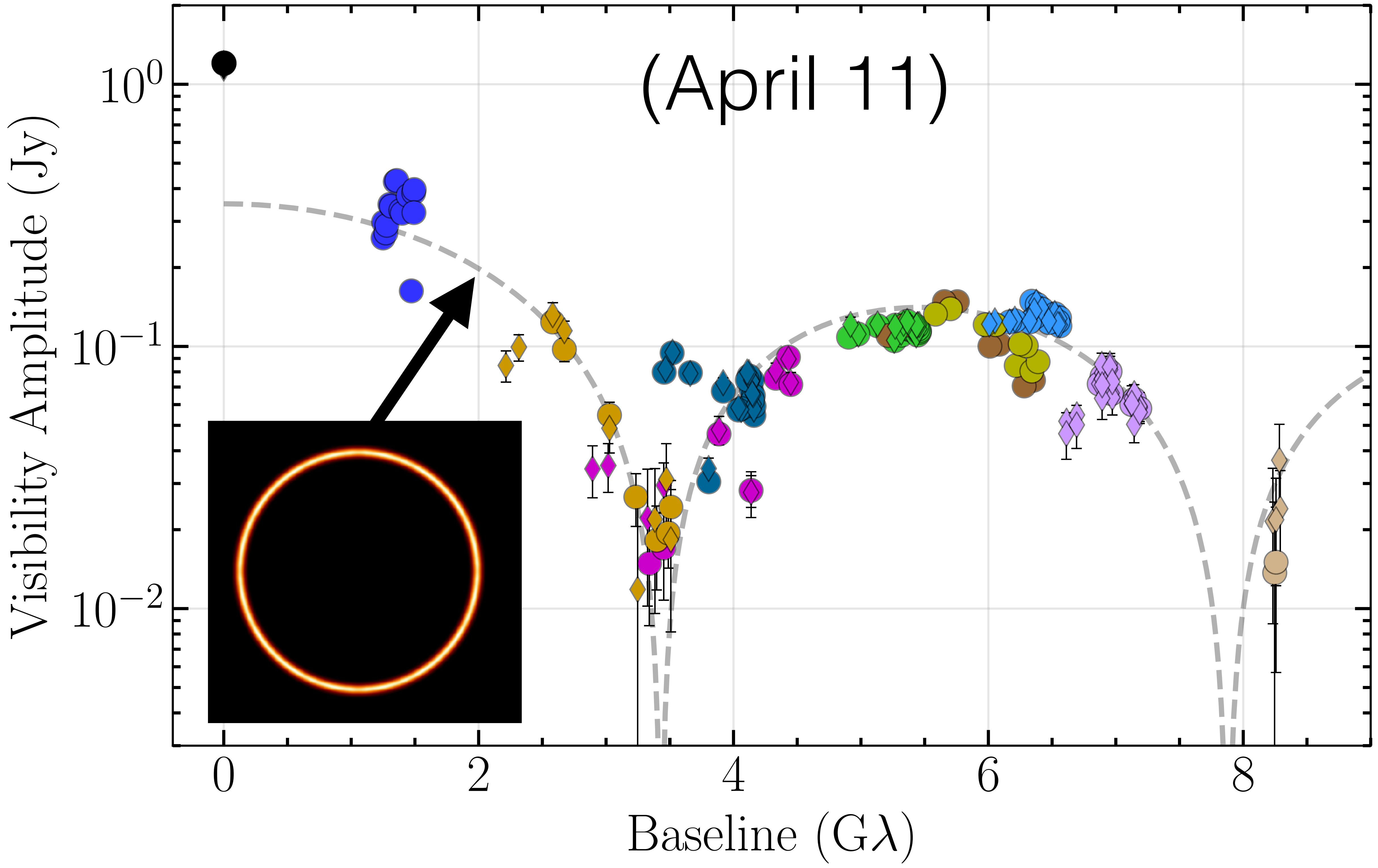
Phase Error ($e^{-i(\phi_1 - \phi_2)}$)

Only fast (~sec to min) fluctuations are corrected

Calibrated data sets (before imaging)

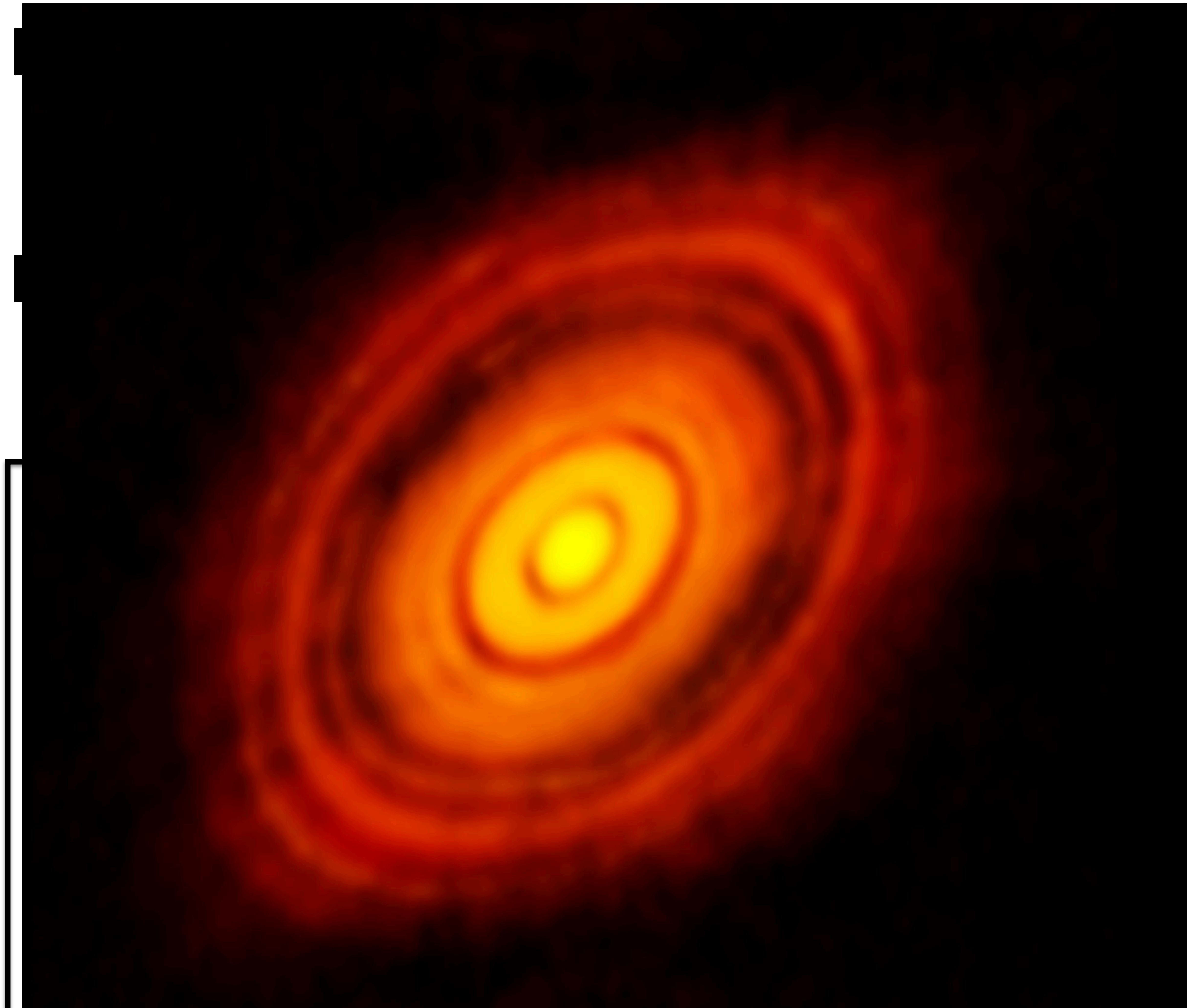


EHT Collaboration 2019c, ApJL, 875, L3

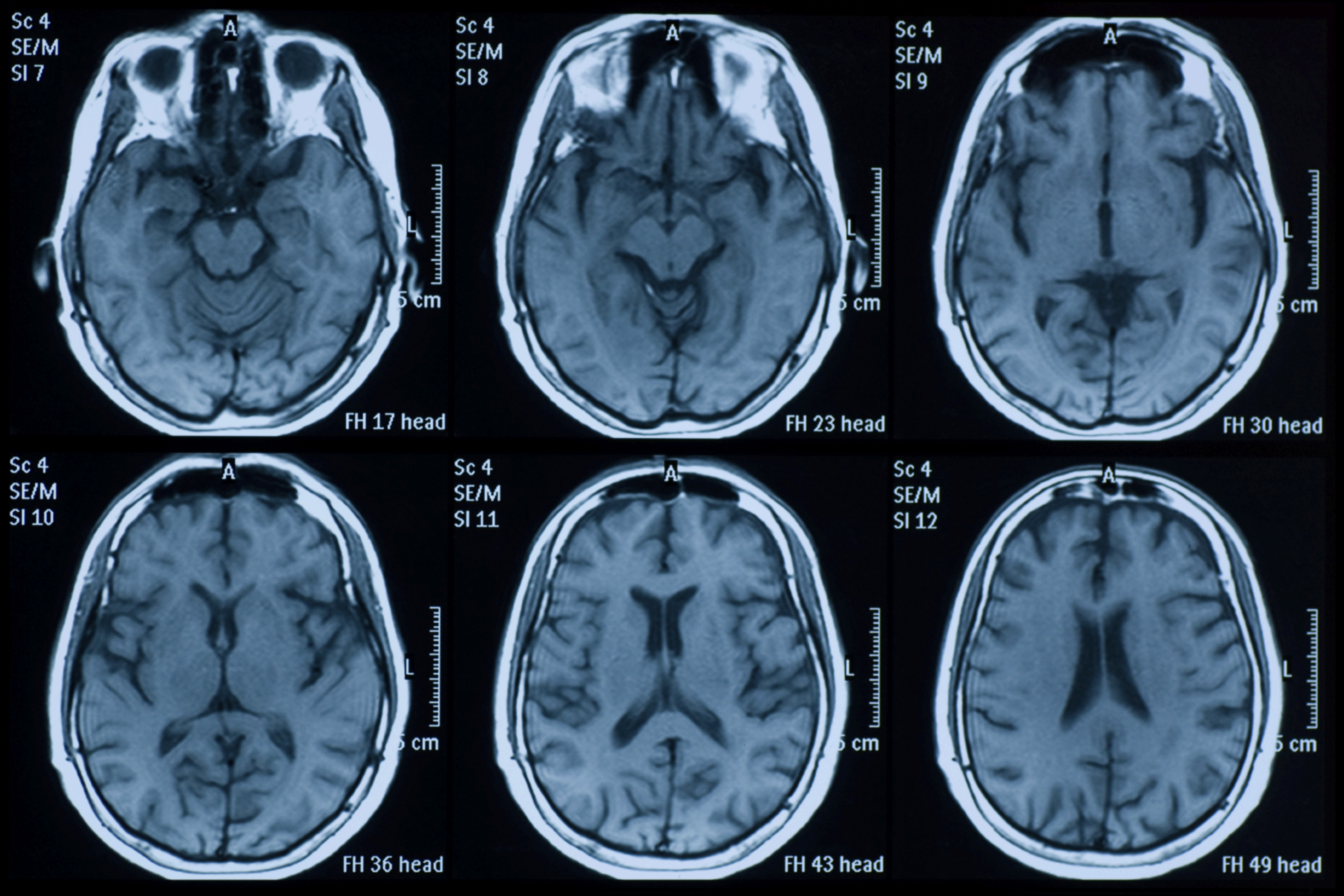


EHT Collaboration 2019a, ApJL, 875, L1

Challenges and Philosophy of EHT Imaging

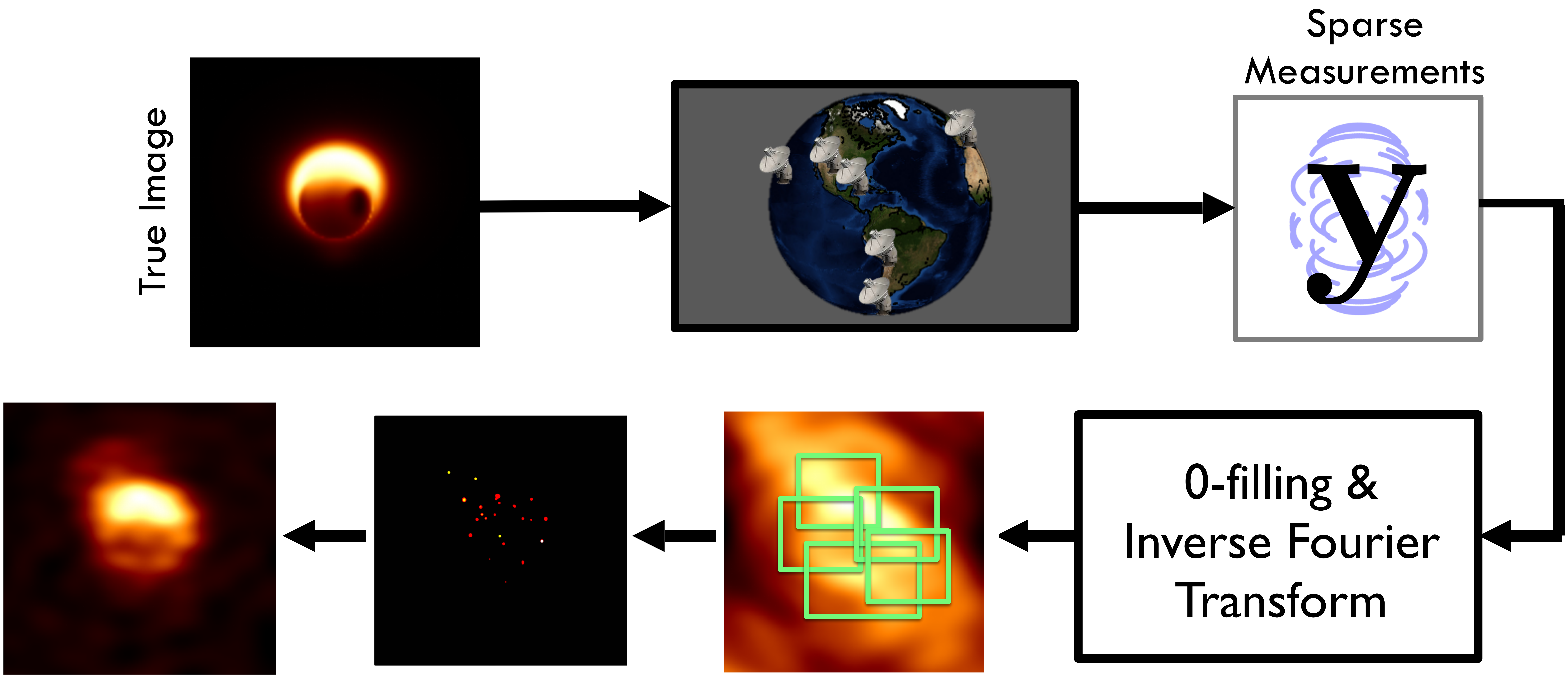


ALMA Partnership et al. 2015



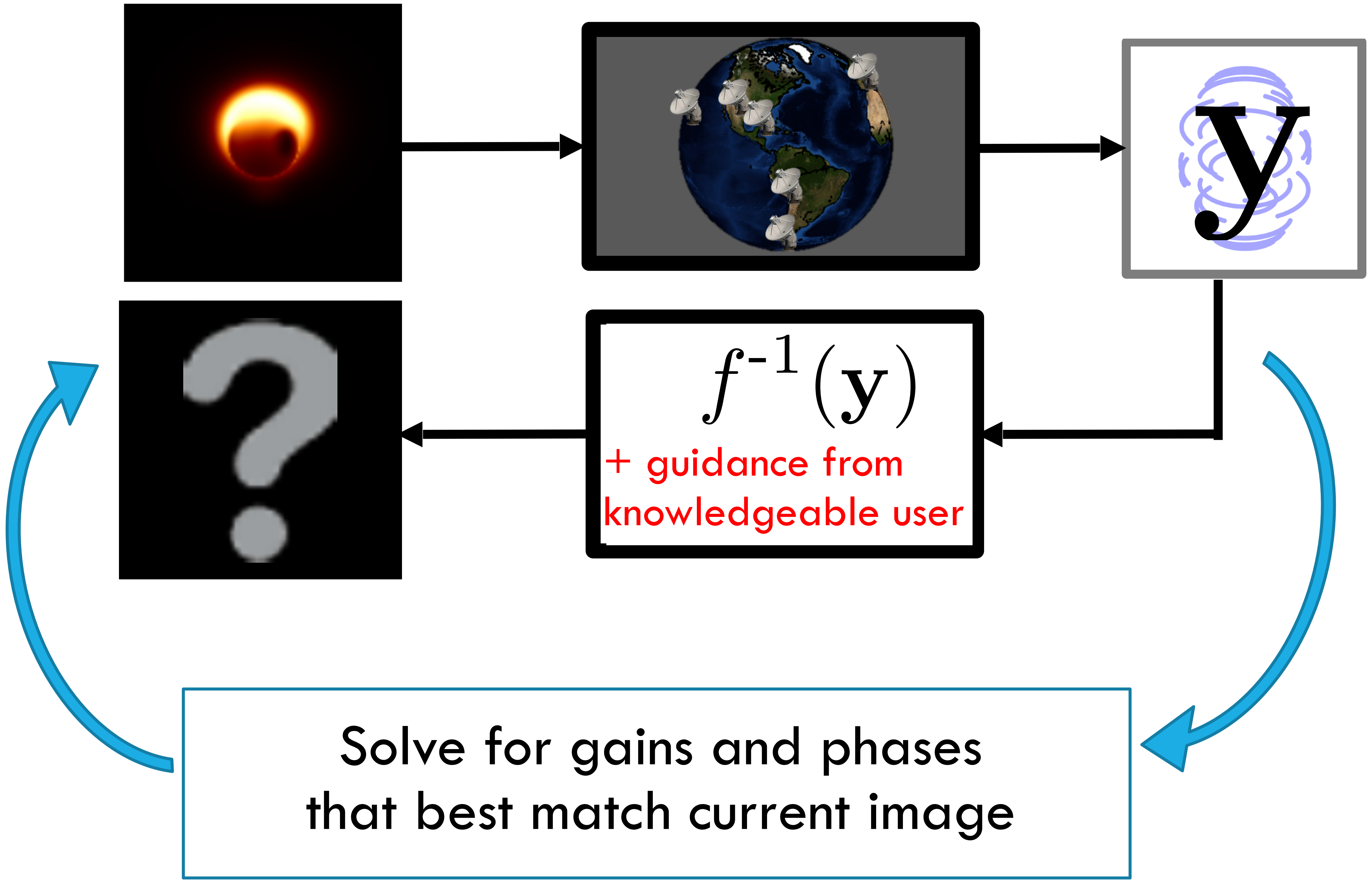
Credit: Times

CLEAN (Hobgom 1974) = Matching Pursuit (Mallet & Zhang 1993)



Two Classes of Imaging Algorithms

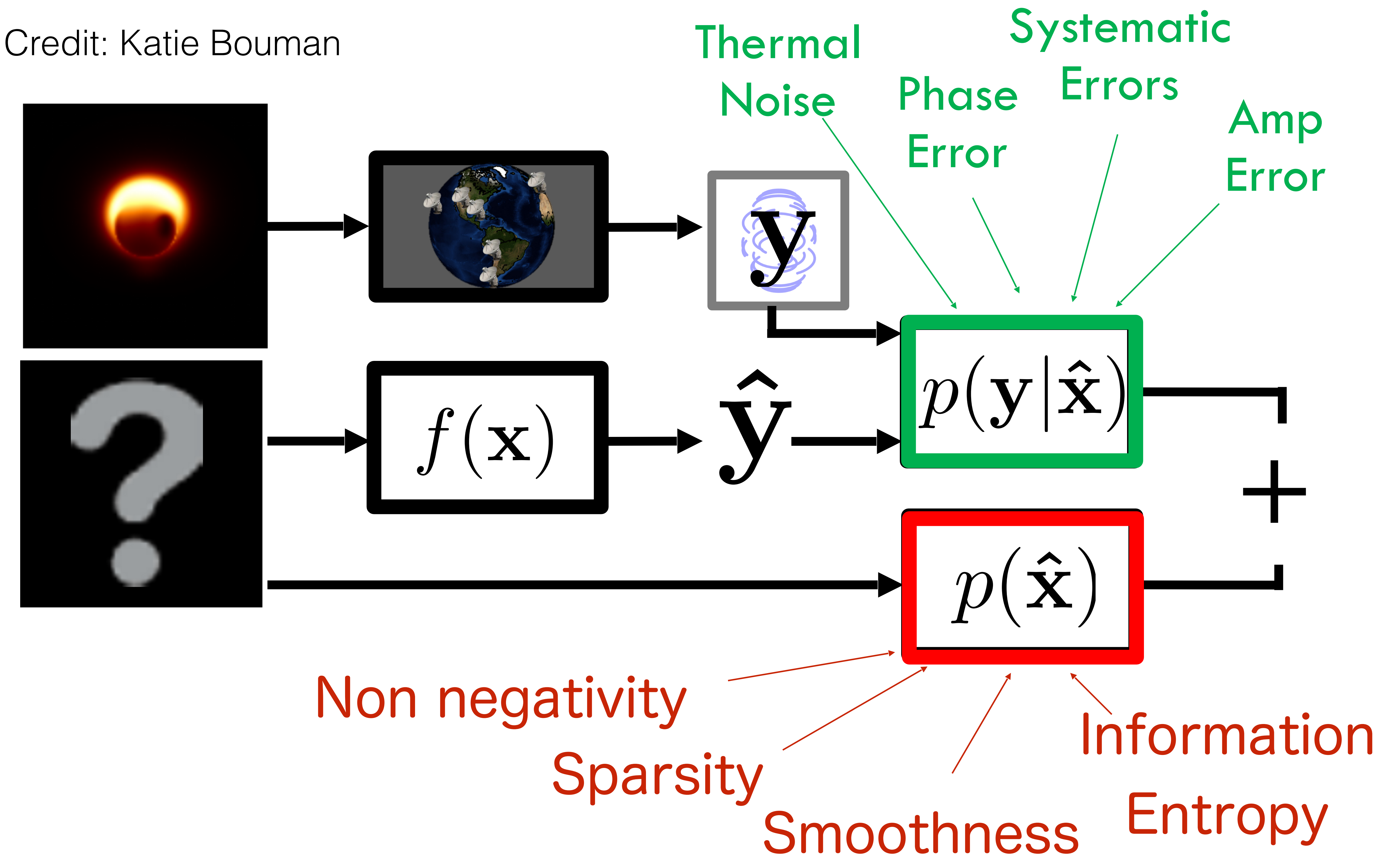
Credit: Katie Bouman



Traditional

Inverse Modeling
(CLEAN + Self-Calibration)

Credit: Katie Bouman

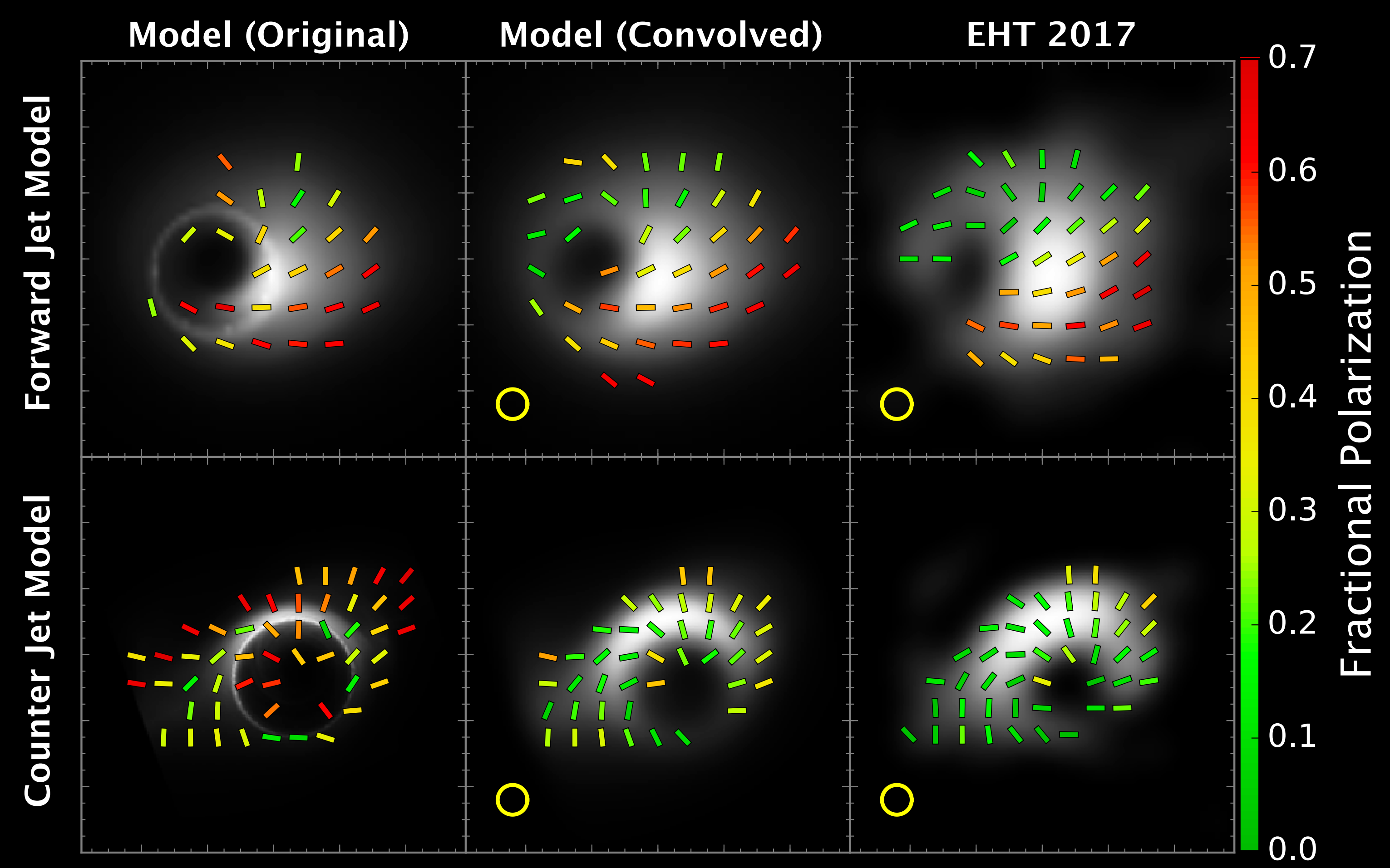


$$\hat{\mathbf{x}}_{\mathrm{MAP}} = \mathrm{argmax}_{\mathbf{x}} \left[\log p(\mathbf{y}|\mathbf{x}) + \log p(\mathbf{x})\right]$$

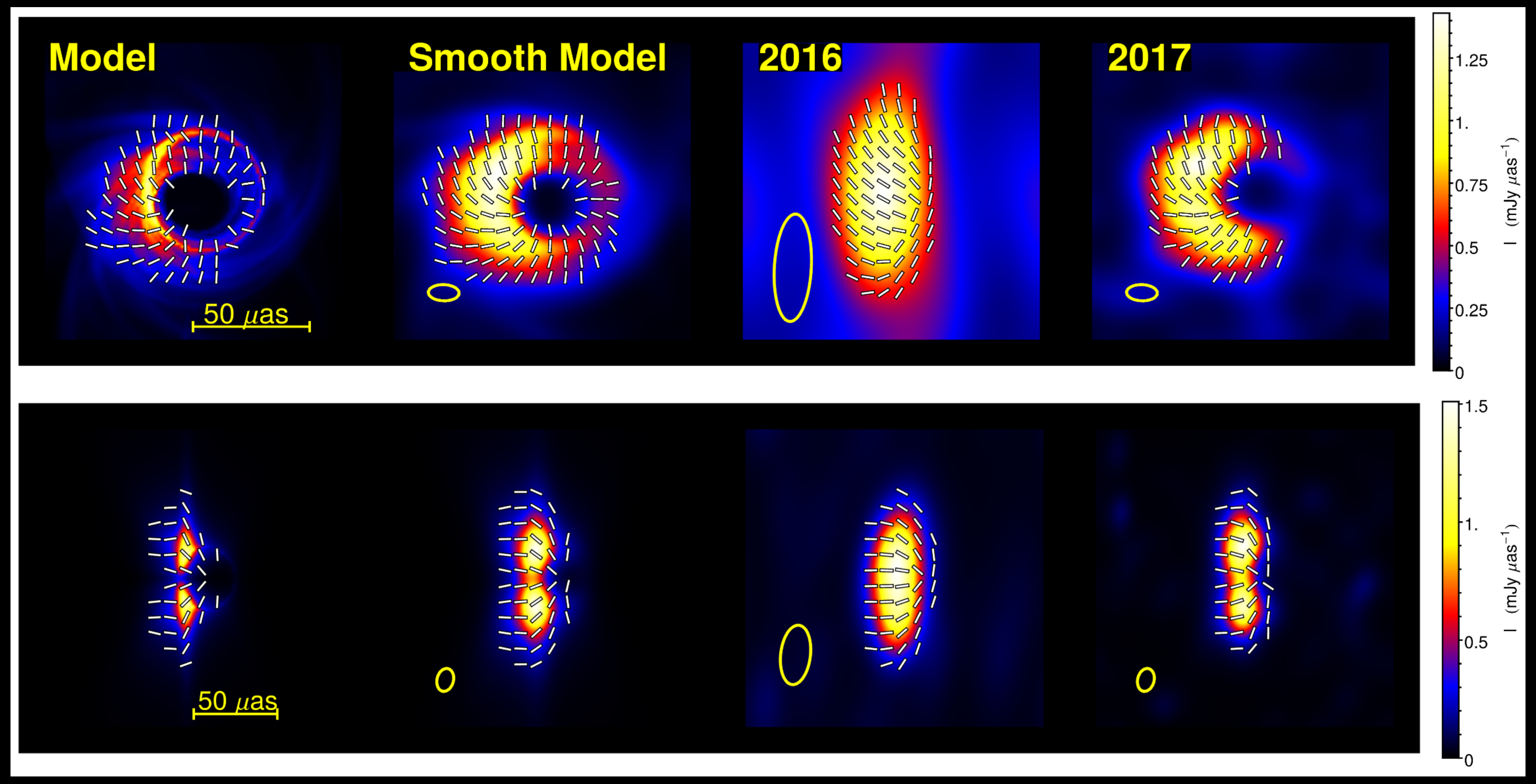
Forward Modeling
(Bayesian Inspired Optimization)

New Imaging Methods

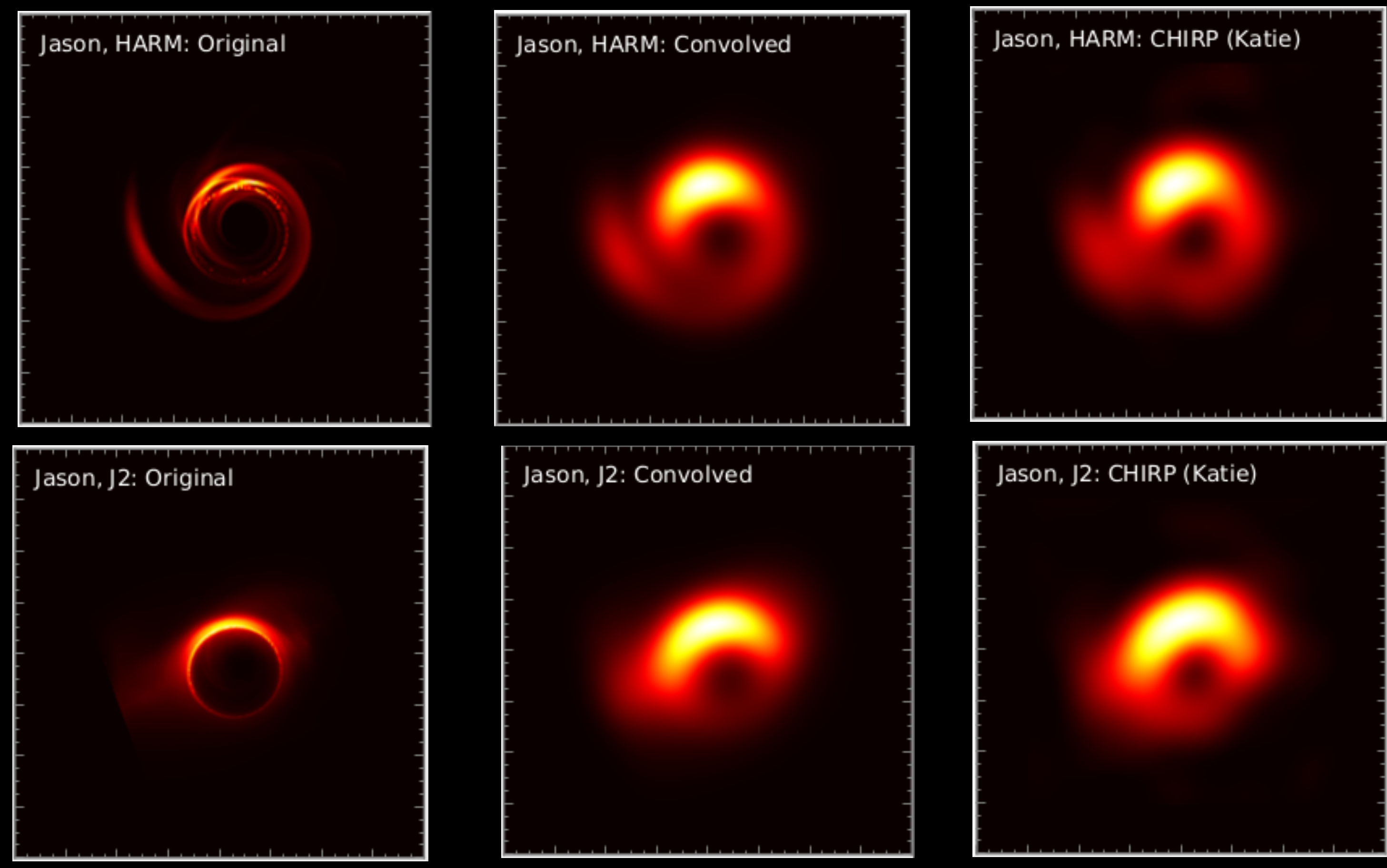
Sparse Modeling
Akiyama et al. 2017a, 2017b
Ikeda et al. 2016, Honma et al. 2014



Maximum Entropy Method (MEM)
Chael et al. 2016, Fish et al. 2014,
Lu et al. 2014, 2016



CHIRP (Machine-learning)
Bouman et al. 2016

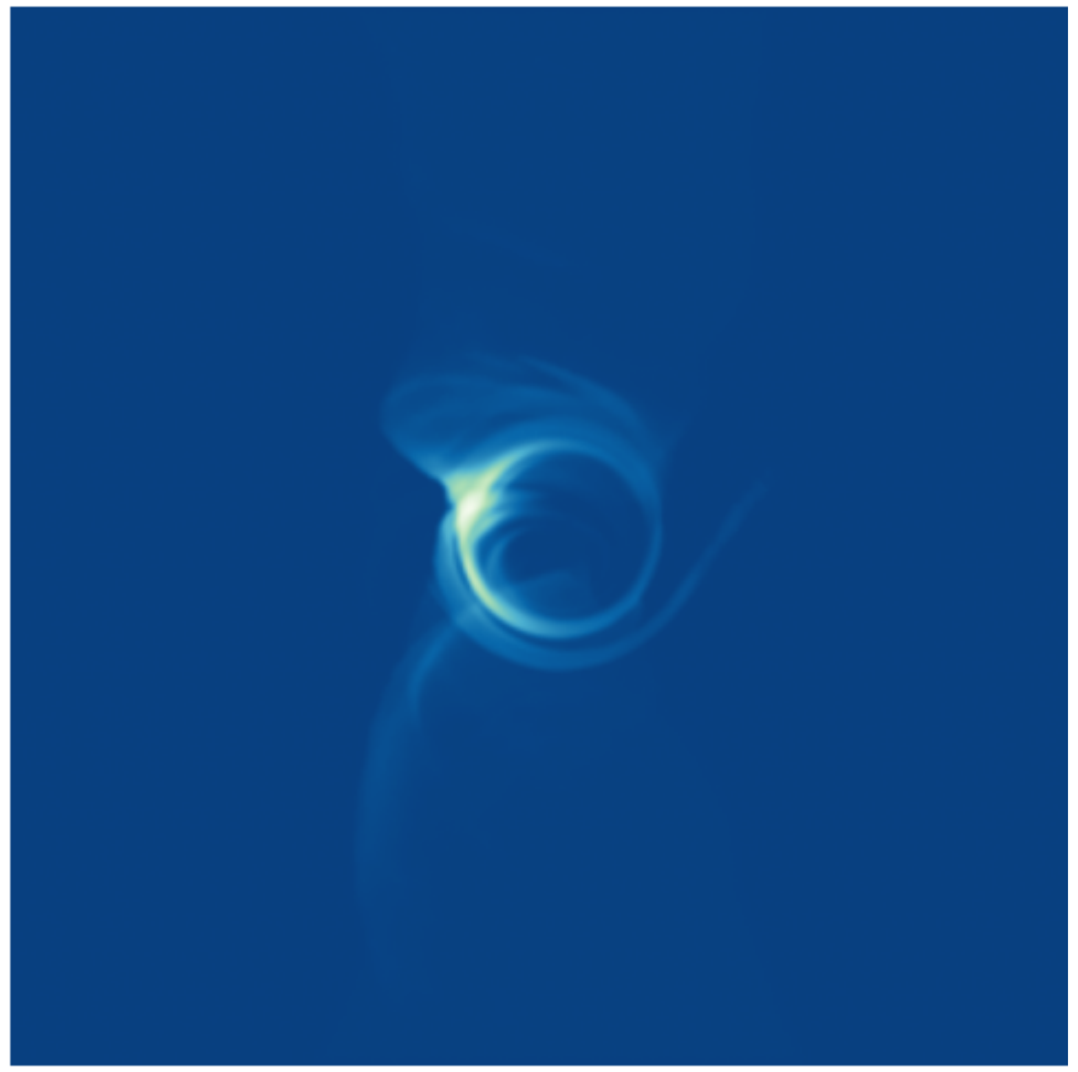


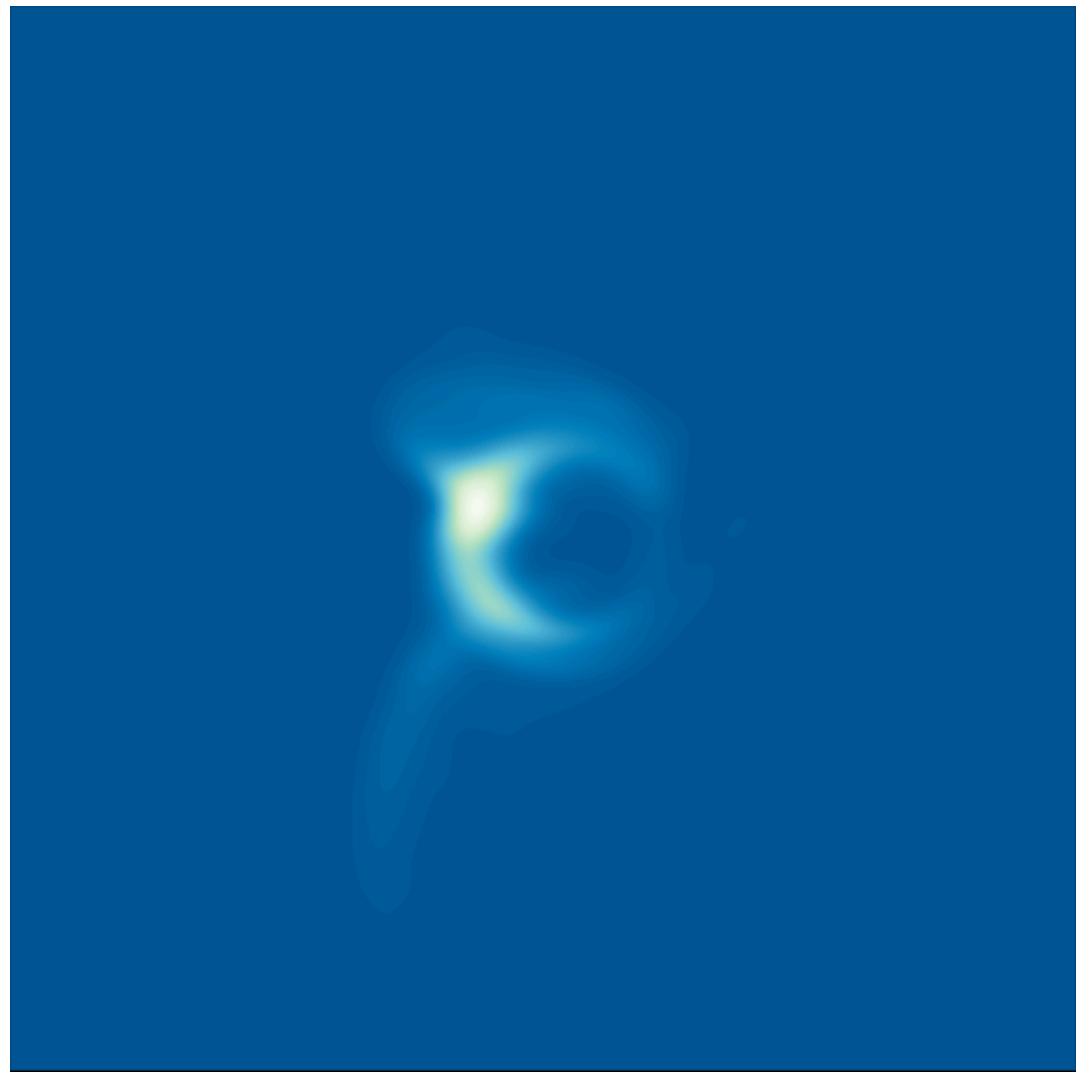
Two Imaging Libraries

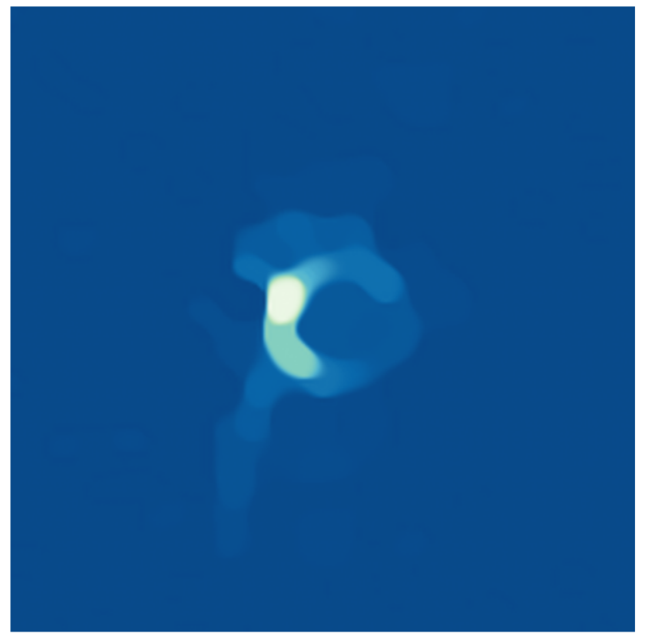
eht-imaging (Chael+2016,2018) : https://github.com/achael/eht-imaging

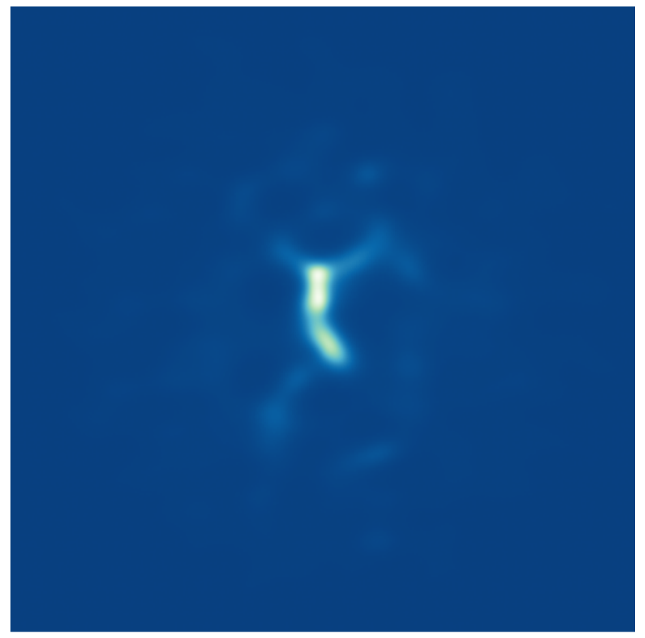
SMILI (Akiyama+2017a,b) : https://github.com/astrosmili/smili

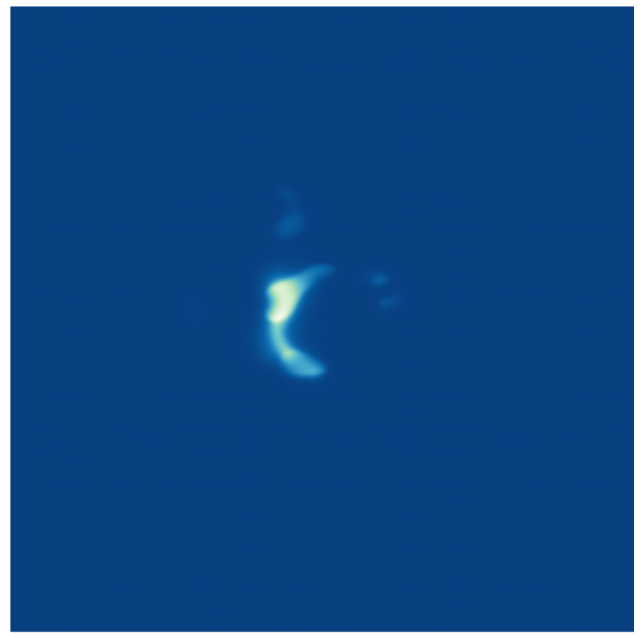
EHT Blind Imaging Challenges (2016 -)











Method 1 Method 2 Method 3 Method 4 Method 5

(Katie Bouman 2016, PhD thesis; the EHT Imaging WG)

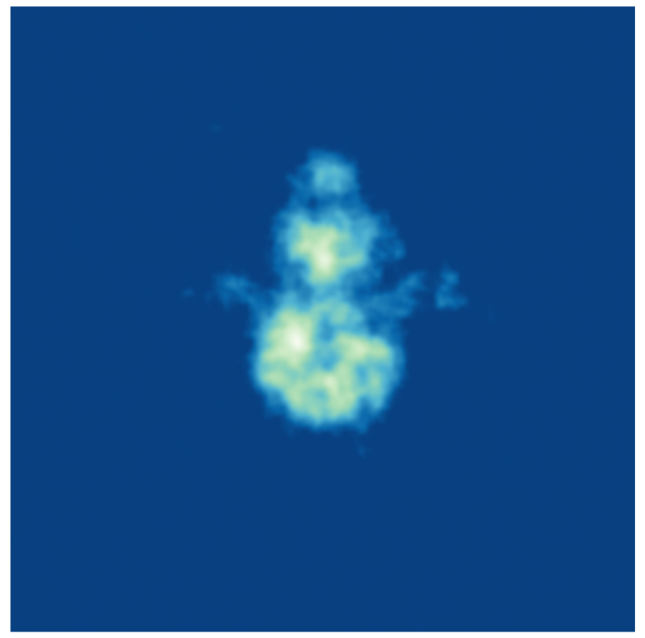
Event Horizon Telescope

EHT Blind Imaging Challenges (2016 -)

Method 1

Method 2

Method 3



Method 4

Method 5

(Katie Bouman 2016, PhD thesis; the EHT Imaging WG)

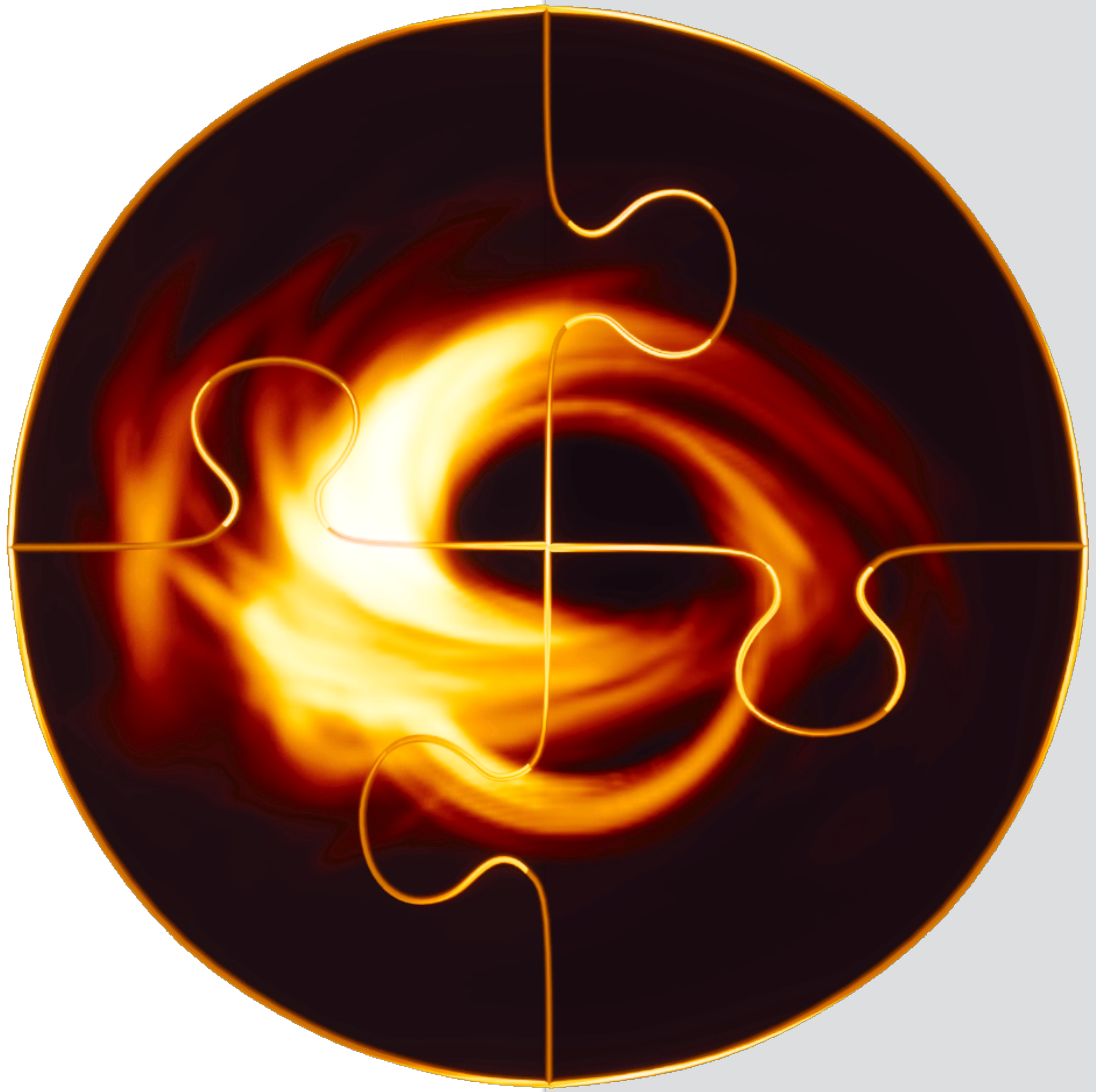
Four Imaging Teams

Team 1 **New techniques**

Traditional Techniques **Team 4**

Americas
US & Chile
(SAO, U. Arizona, U. Conception)
Leader: K. Bouman & A. Chael

East Asians
Korea, Japan & Taiwan
(ASIAA, KASI, NAOJ)
Leader: S. Koyama



Team 2

Global
US, Japan, Netherlands
(MIT, NAOJ, Hiroshima U., Radboud U.)
Leader: K. Akiyama & S. Issaoun

Team 3

Cross Atlantic
US, Spain, Germany, Finland
(Boston U, MPIfR, IAA, Aalto)
Leader: T. Krichbaum & A. Marscher

7 weeks later…..


Image
Team
Individual Image Statistics

Four Imaging Teams

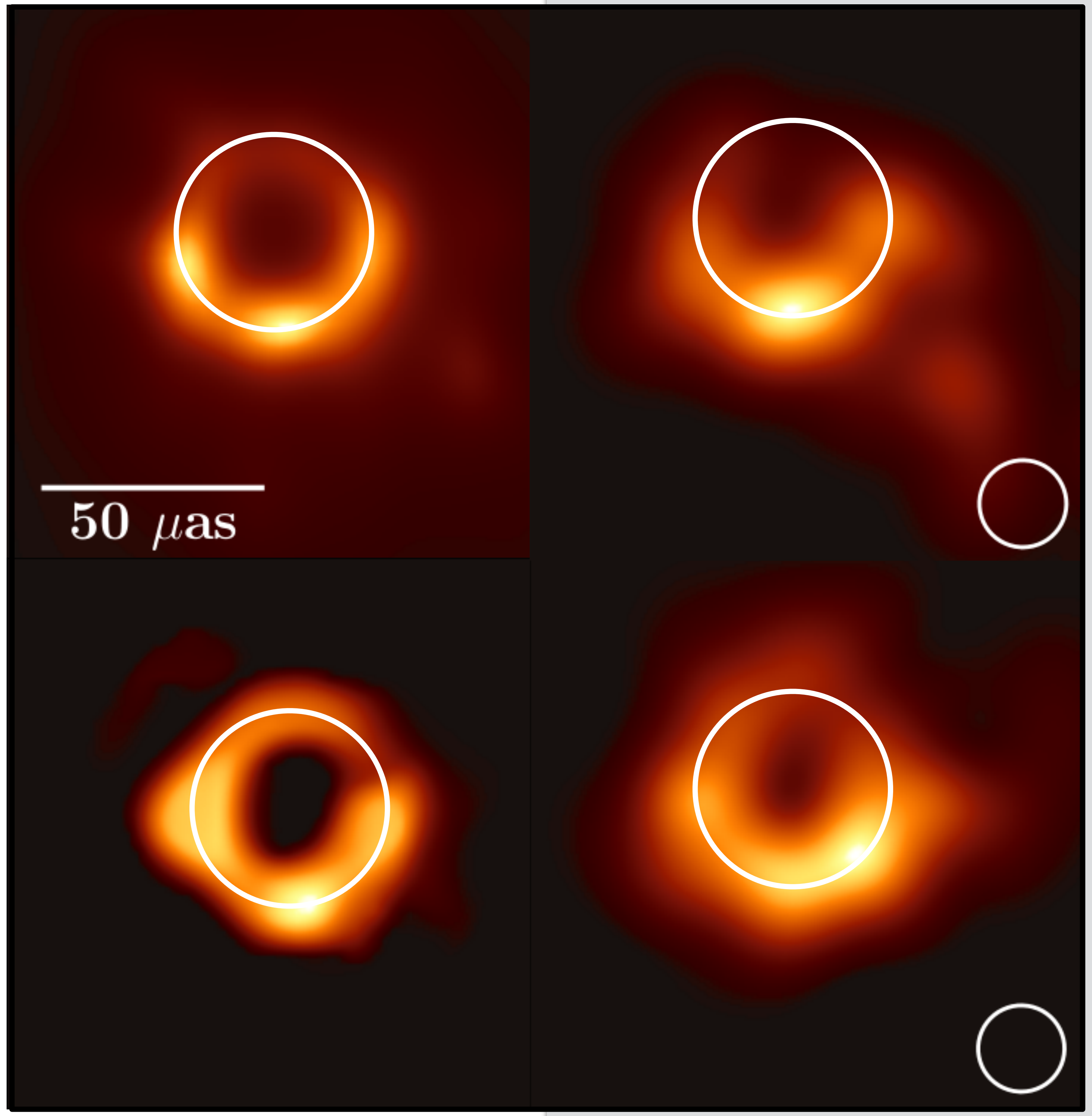
Team 1 **New techniques**

Traditional Techniques **Team 4**

Americas

US & Chile
(SAO, U. Arizona, U. Conception)
Leader: K. Bouman & A. Chael

April 11



East Asians

Korea, Japan & Taiwan
(ASIAA, KASI, NAOJ)
Leader: S. Koyama

Team 2

Global

US, Japan, Netherland
(MIT, NAOJ, Hiroshima U., Radboud U.)
Leader: K. Akiyama & S. Issaoun

Team 3

Cross Atlantic

US, Spain, Germany, Finland
(Boston U, MPIfR, IAA, Aalto)
Leader: T. Krichibaum & A. Marscher

The First EHT Images of M87 (July 24, 2018)

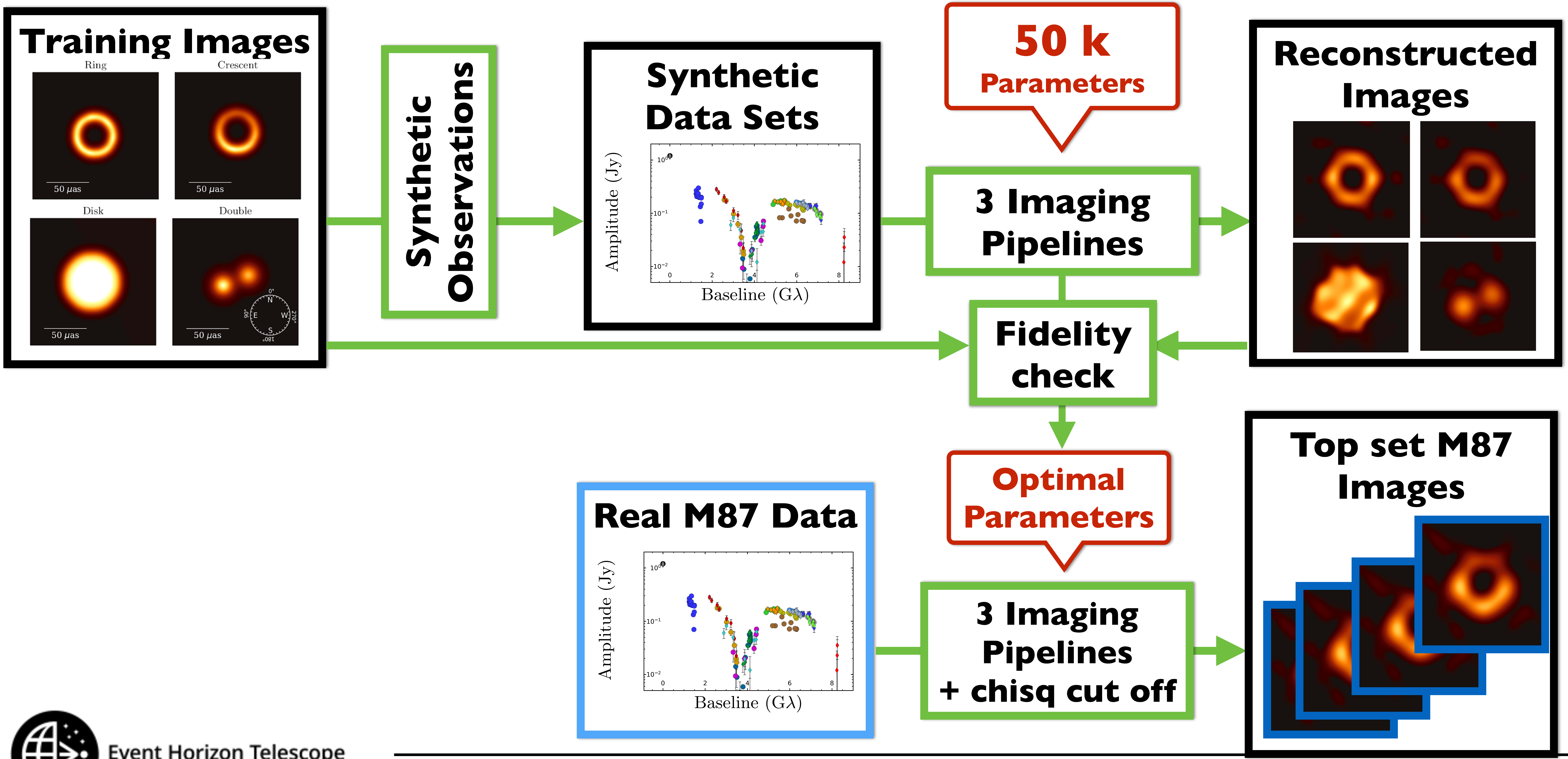
2nd EHT Imaging Workshop

Imaging Pipelines: Human Choices

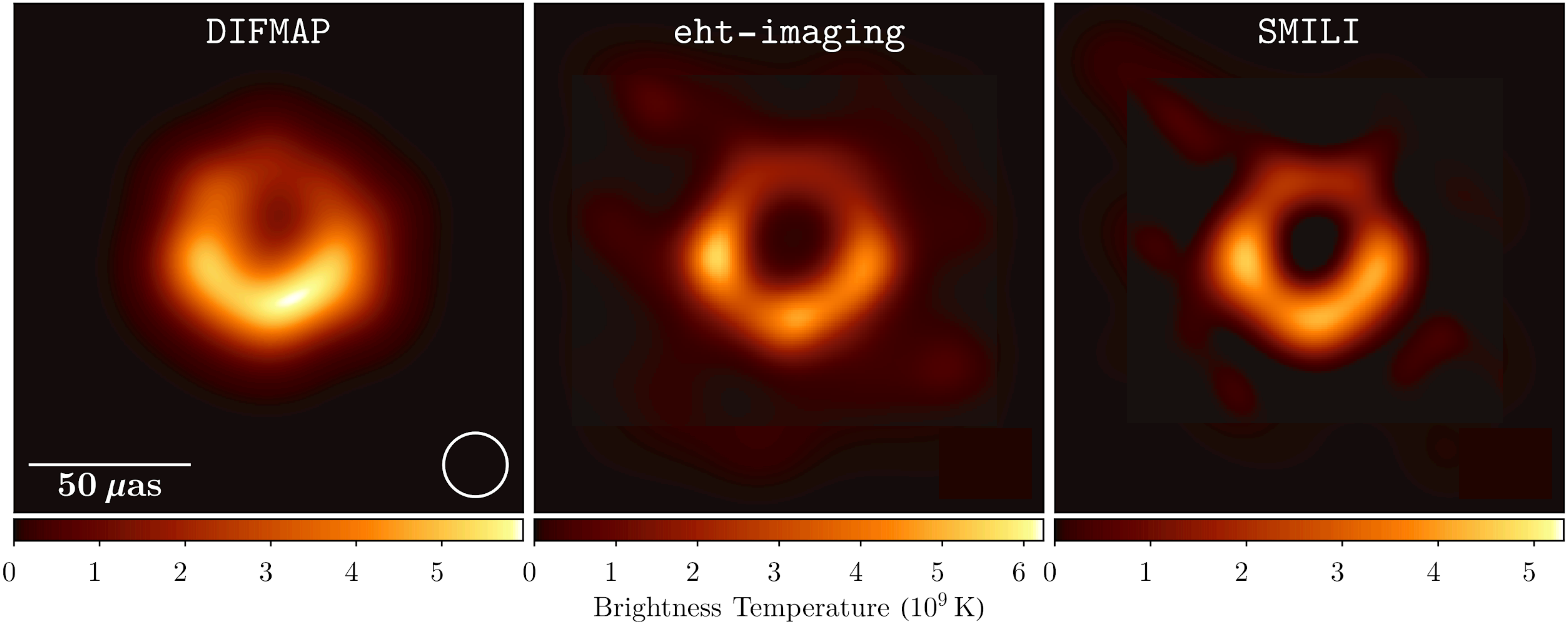
DIFMAP (CLEAN + Self Calibration)	eht-imaging (Regularized Max Likelihood)	SMILI (Regularized Max Likelihood)
Compact Flux Stop Condition Weighting on ALMA Mask Size Data Weights	Compact Flux Initial Gaussian Size Systematic Error Regularizes MEM TV TSV L1	Compact Flux L1 Soft Mask Size Systematic Error Regularizes TV TSV L1
(Shepherd et al. 1997,1998)	(Chael et al. 2016, 2018)	(Akiyama et al. 2017a,b)

Credit: Katie Bouman

Objective Imaging Process



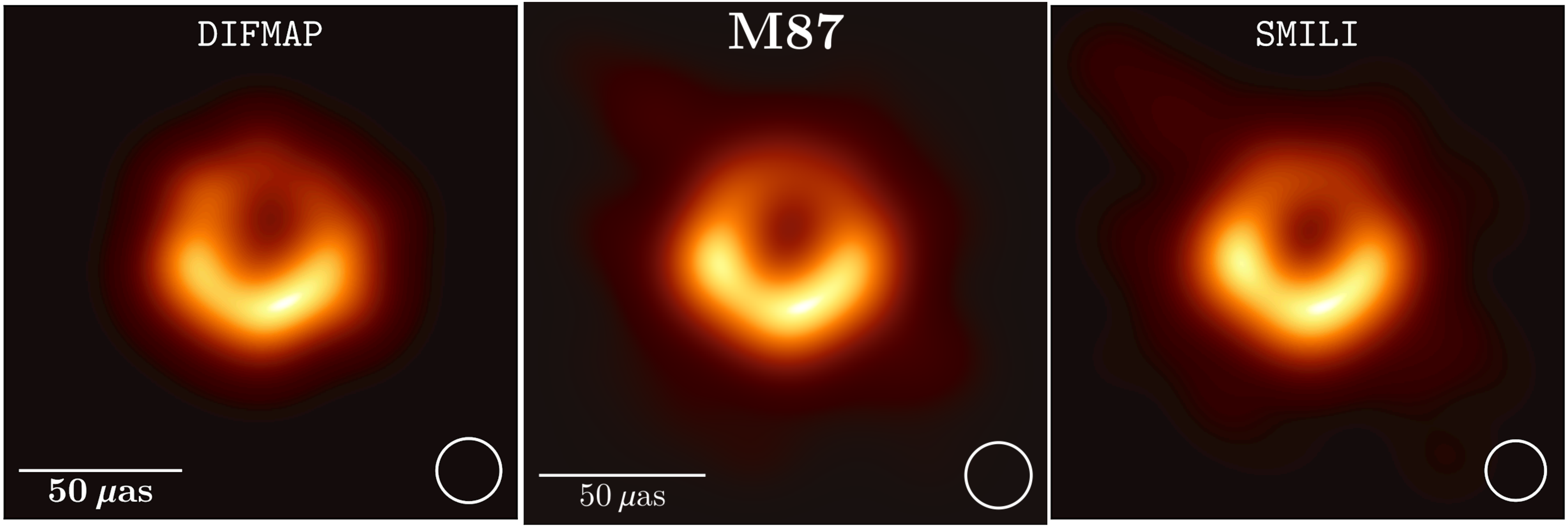
Fiducial Images on Apr 11



Event Horizon Telescope

EHT Collaboration 2019d, ApJL, 875, L4

Fiducial Images on Apr 11



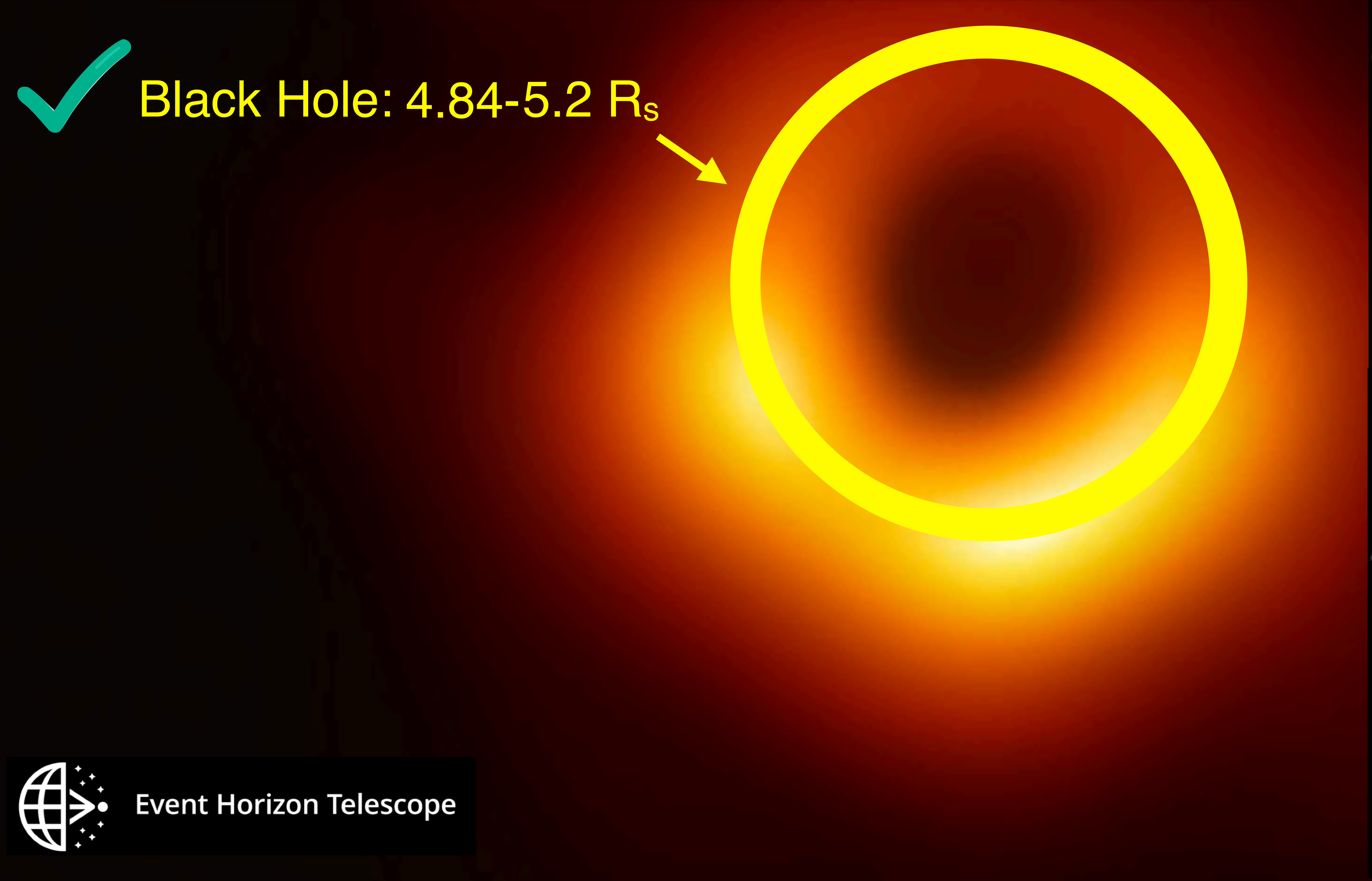
EHT Collaboration 2019d, ApJL, 875, L4

Event Horizon Telescope

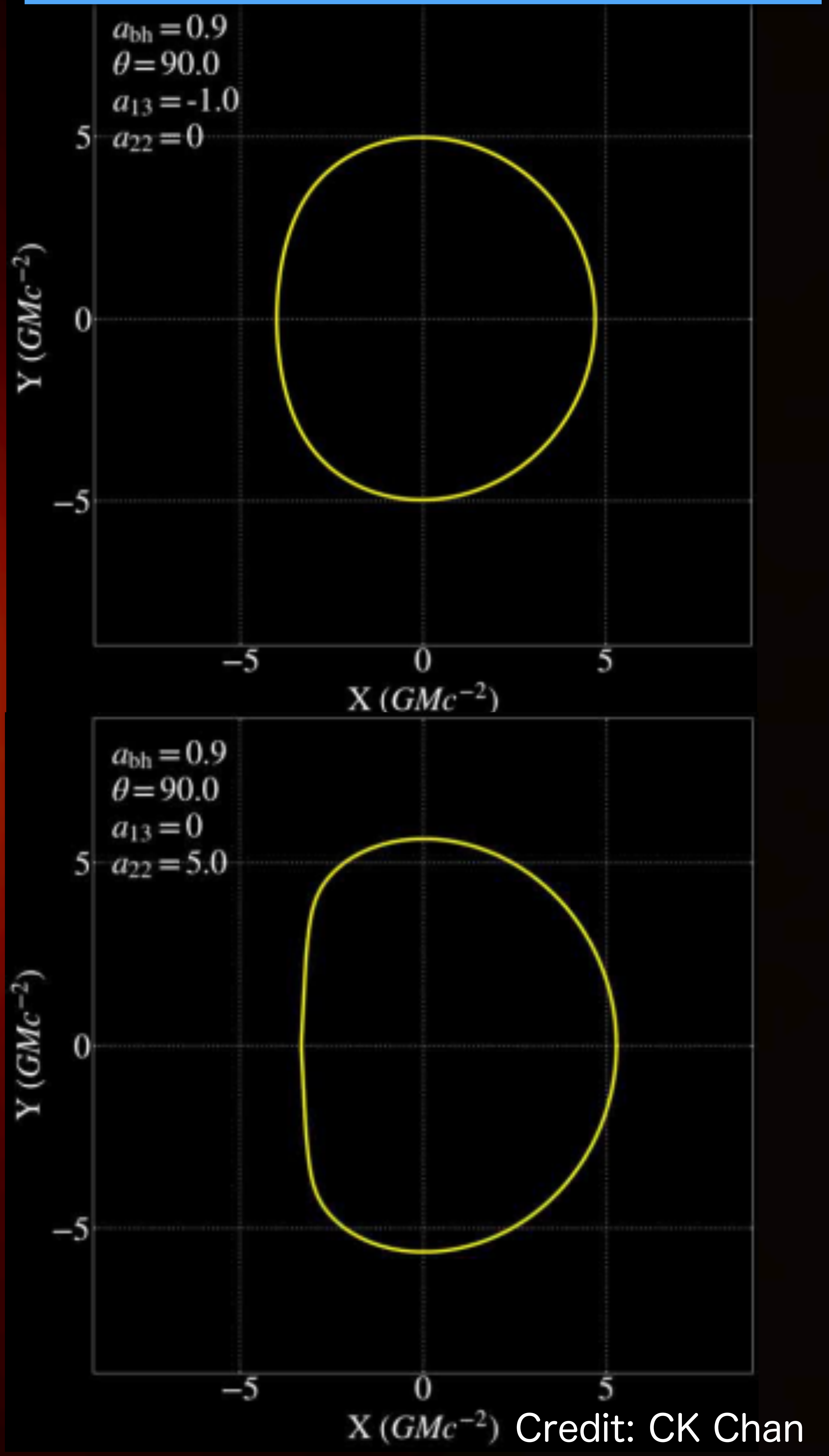
Stellar Mass: $6.2 \times 10^9\ M_{sun}$
(Gebhardt et al. 2011)
Gas Mass: $3.5 \times 10^9\ M_{sun}$
(Walsh et al. 2013)
Black Hole: 4.84-5.2 R_s
Black Hole: 4.84-5.2 R_s
A worm Hole: ~2.7 R_s
Naked Singularity: 1 Rs
(extremely spinning)
6.5 Billion Solar Mass Black Hole
Event Horizon Telescope

Deviation from the circle < within 10%

No significant deviations from GR



Non GR Shadow



Credit: CK Chan

Event Horizon Telescope

https://xkcd.com/2135/


Statistics
Astronomy
Mathematics
Physics


Event Horizon Telescope
Collaboration Meeting
Welcome to Nijmegen
Radboud University
Event Horizon Telescope
Collaboration Meeting
Welcome to Nijmegen!