Simulating and Imaging Supermassive Black Hole Accretion Flows

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May 7, 2019

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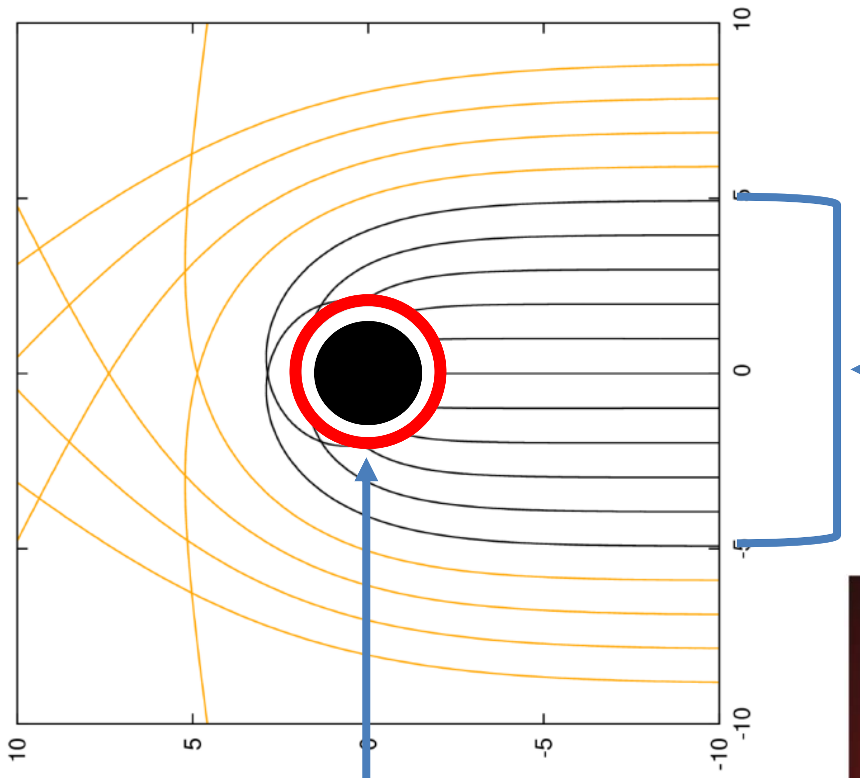
Event Horizon Telescope

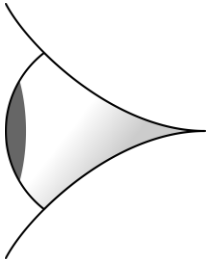
What does a black hole look like?

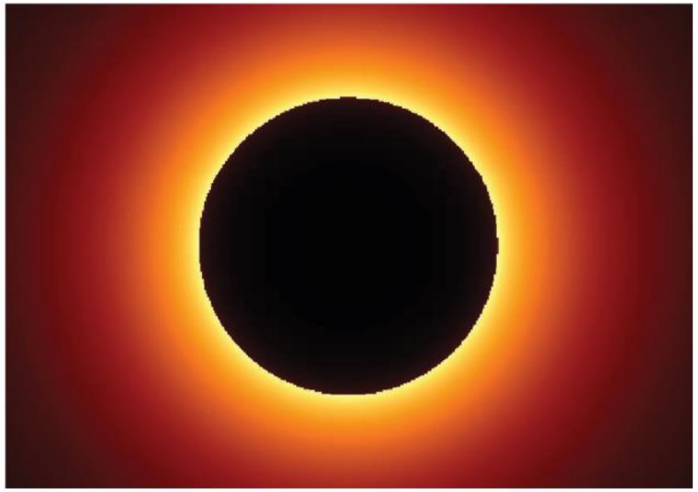
The Black Hole Shadow



$d_{\text{shadow}} = 2\sqrt{27}GM/c^2$

photon orbit $r_\gamma = 3GM/c^2$

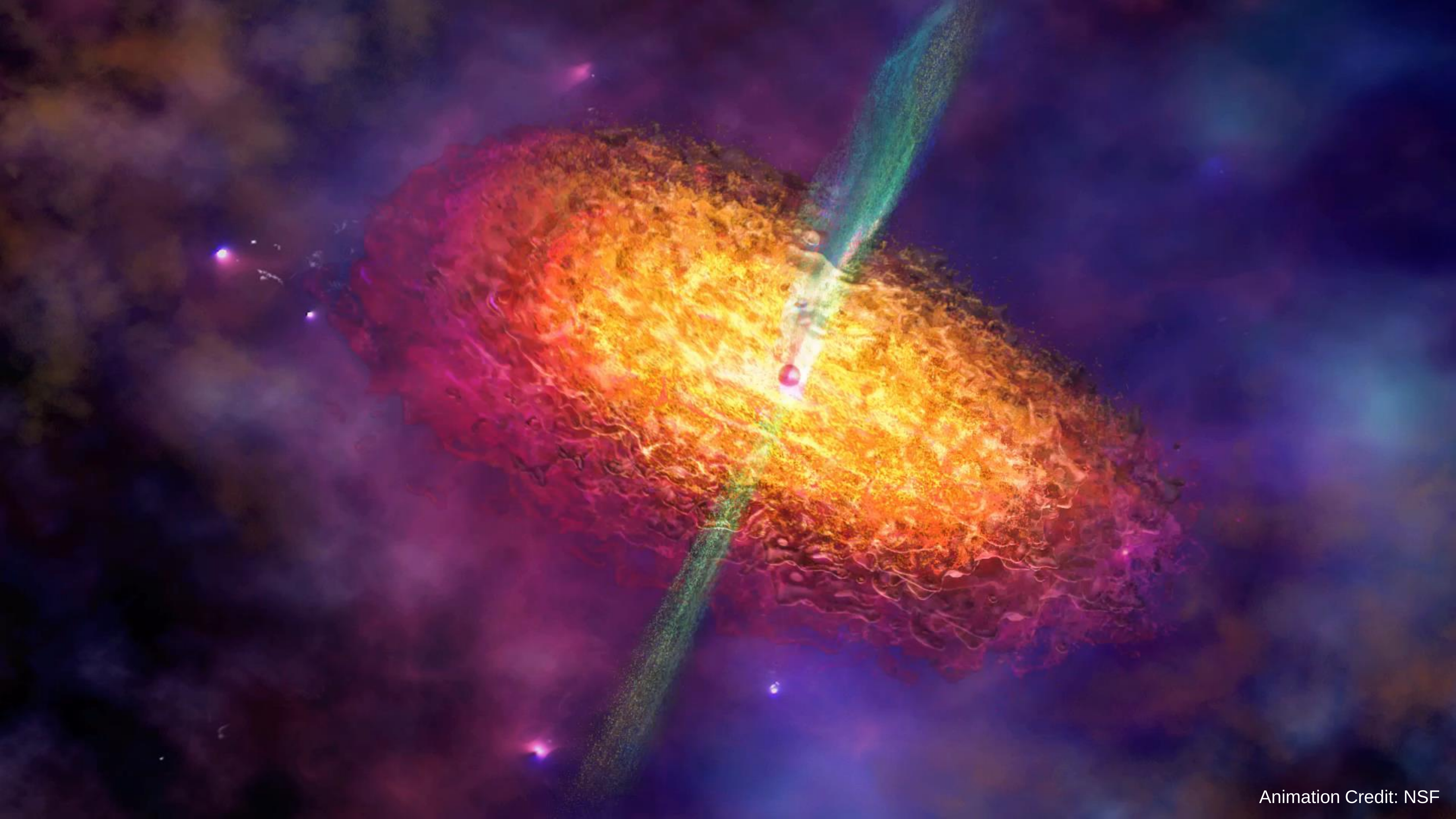




Sgr A*: d ≈ 50 µas

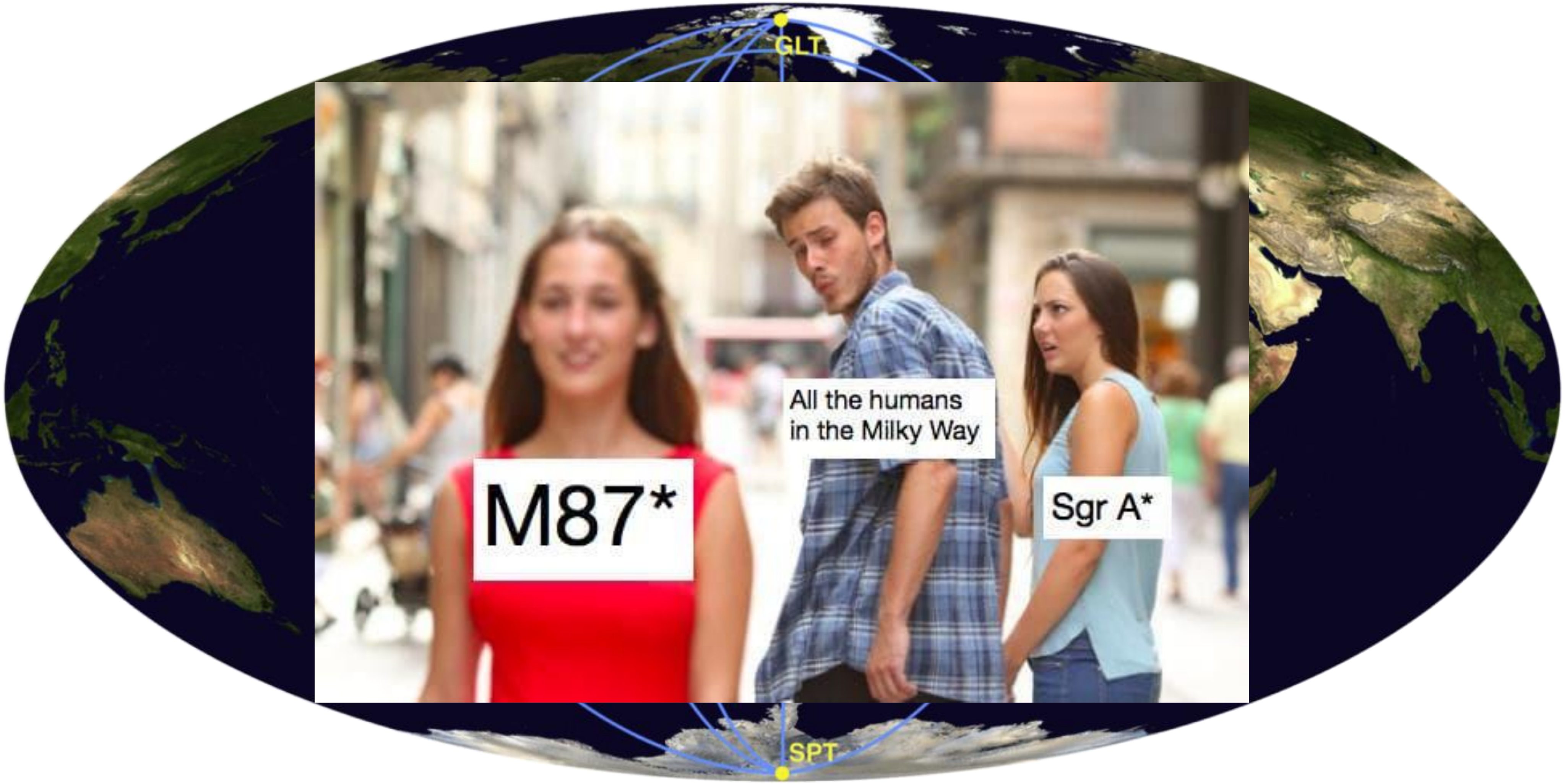
M87: d ≈ 40 µas

Image credit: Keiichi Asada



Animation Credit: NSF

The Event Horizon Telescope



$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3\times10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

Image Credit:
EHT Collaboration 2019 (Paper II)

M87

$$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$$
$$D = (16.8 \pm 0.8)\mathrm{Mpc}$$
$$d_{\mathrm{shadow}} \approx 40\mu as$$

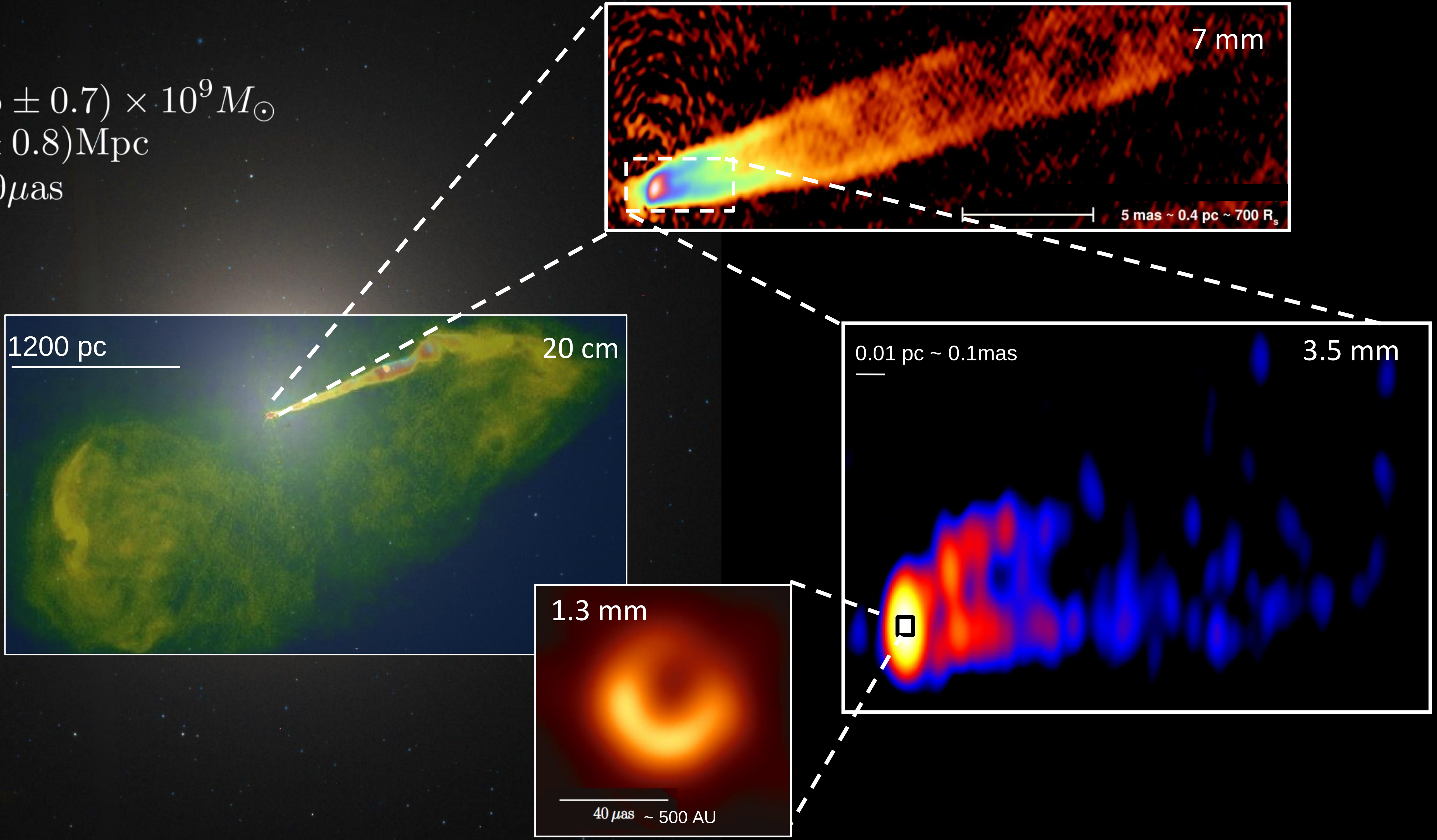
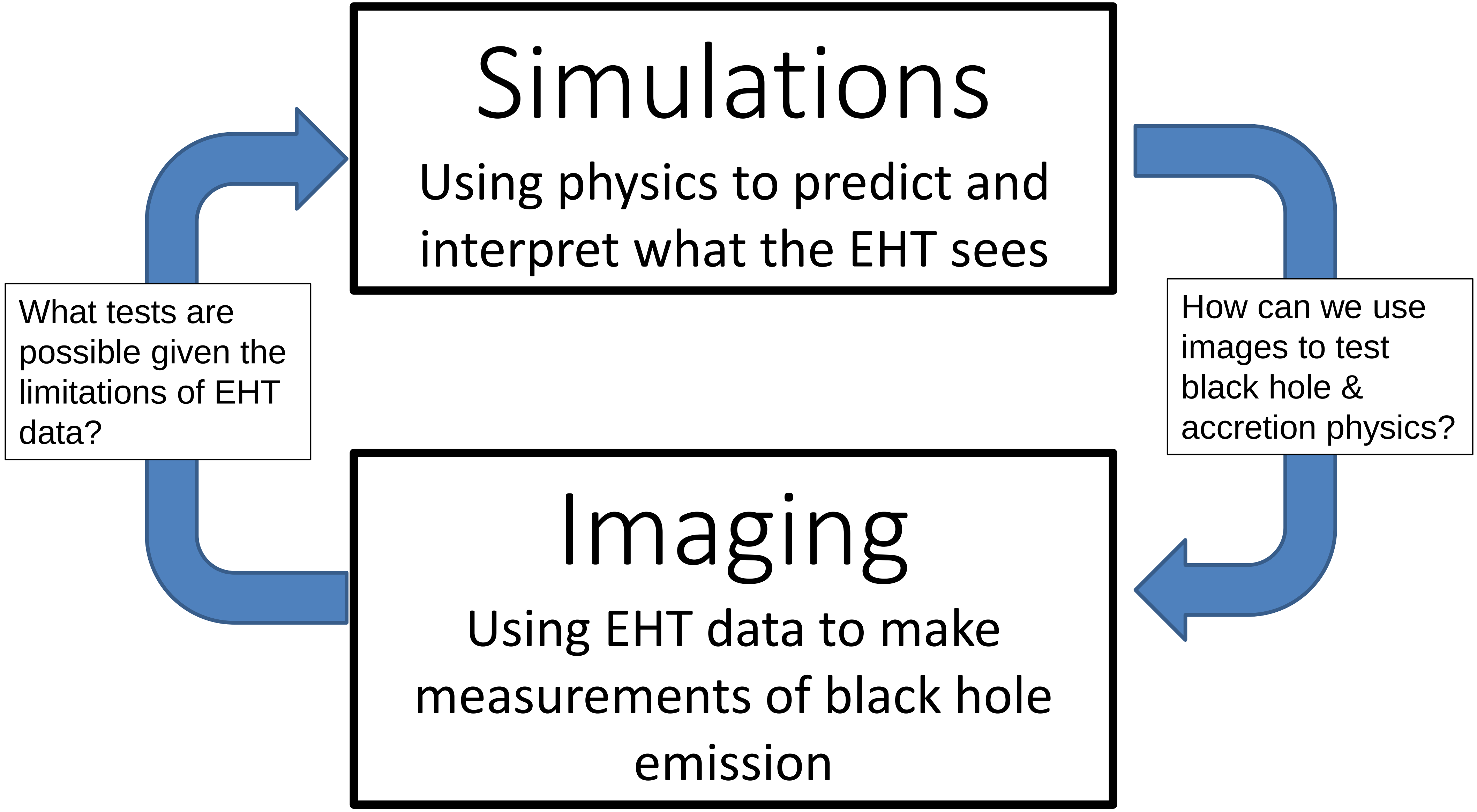


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)


Simulations
Using physics to predict and interpret what the EHT sees
How can we use images to test black hole & accretion physics?
Imaging
Using EHT data to make measurements of black hole emission
What tests are possible given the limitations of EHT data?

Outline

✓ **Introduction**

I. Simulations

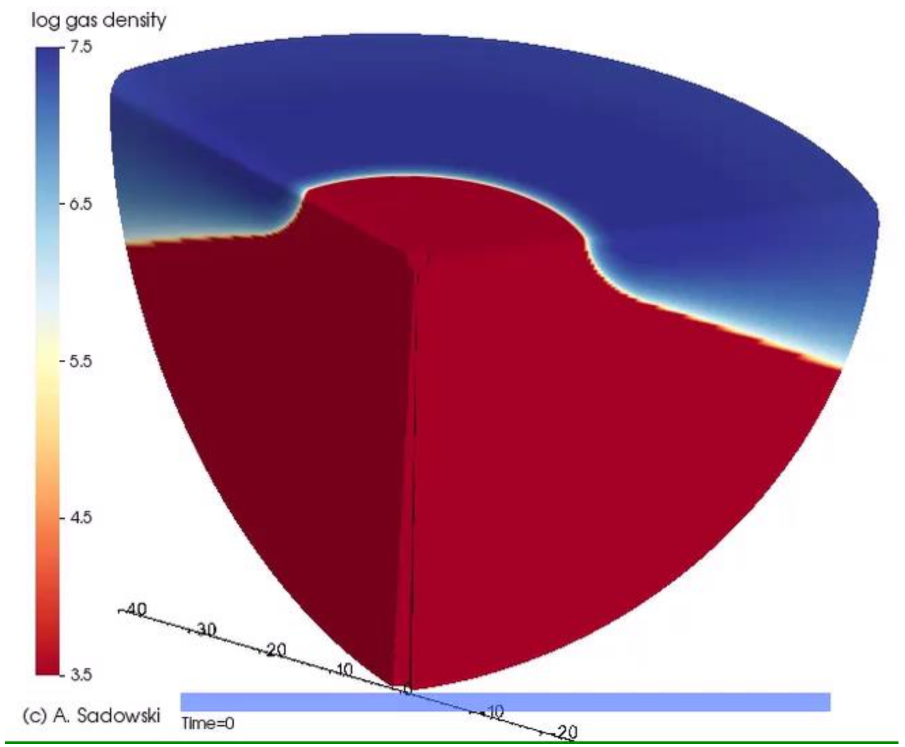
- Two-temperature simulations in `KORAL`
- MAD Simulations of M87

II. Imaging

- Regularized Maximum Likelihood
- EHT Images of M87

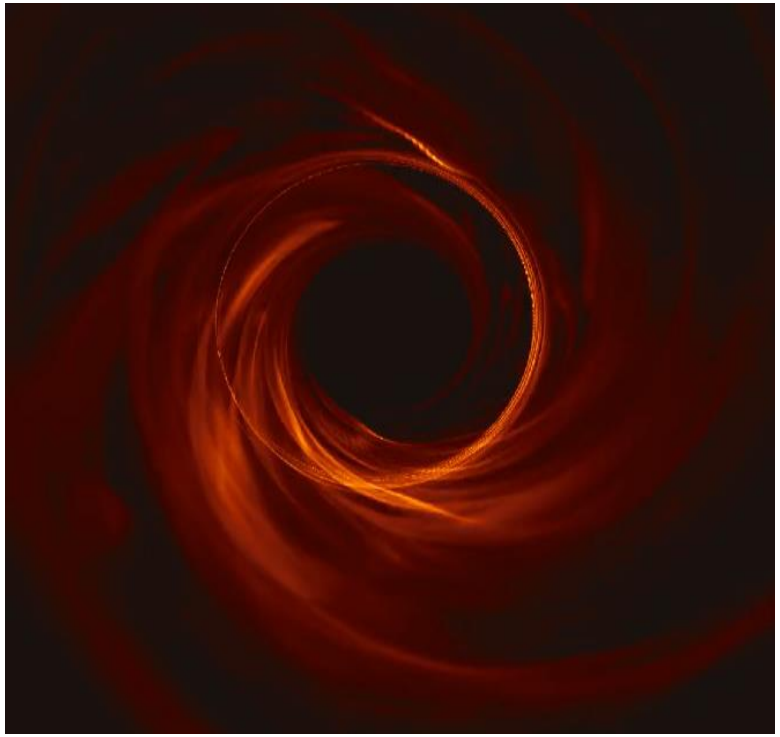
Part I:
Simulating Accretion Flows with Electron Physics

General Relativistic MagnetoHydroDynamics



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

General Relativistic Ray Tracing



Tracks light rays and solves for the emitted radiation

Movie Credits: Aleksander Sądowski, EHT Collaboration 2019 (Paper V)

Simulations: What does the EHT see?

1. Spacetime geometry
   -The gravity and shadow of the black hole.

2. Fluid dynamics
   -How is stuff moving? Jet/disk/outflow?

3. Electron (non)thermodynamics.
   -Where are the emitting electrons?
   -What is their distribution function?

M87 and Sgr A* are **Two-Temperature** Flows

- Inefficient Coulomb coupling between ions and electrons.

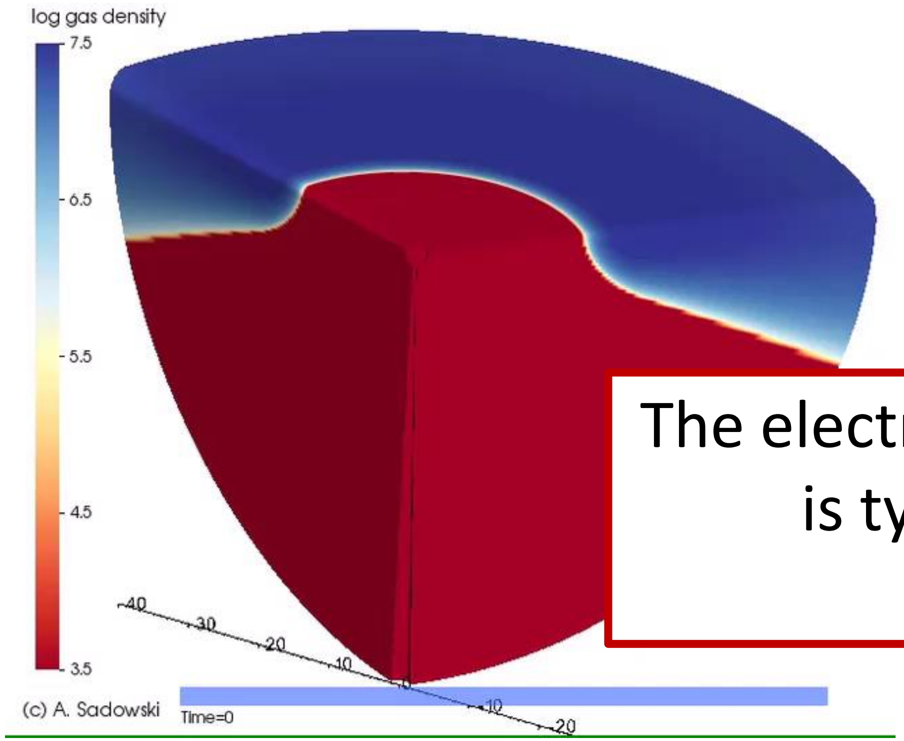
$$T_{\rm e} \neq T_{\rm i} \neq T_{\rm gas}$$

- Generally expect electrons to be **cooler** than ions.

- But if electrons are **heated** much more, they can remain hotter.

Mahadevan+ 97,98, Sądowski+ 17, Ressler+ 15,17, Ryan+ 18

From simulations to observables



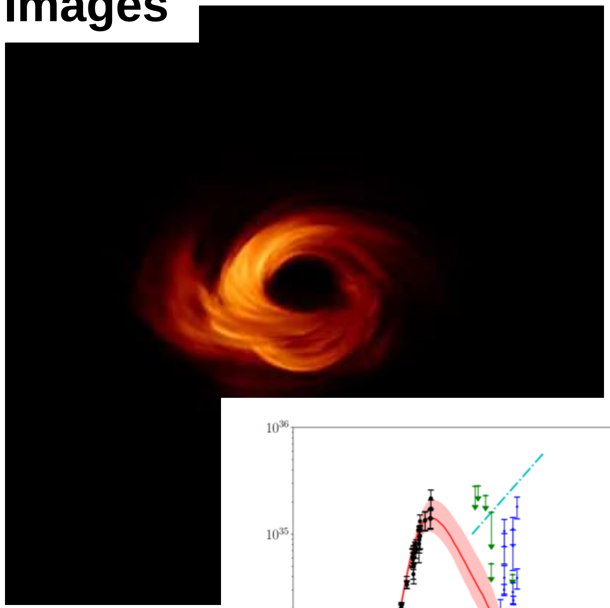
$T_e?$

The electron-to-ion temperature ratio is typically set **manually** in **post-processing**

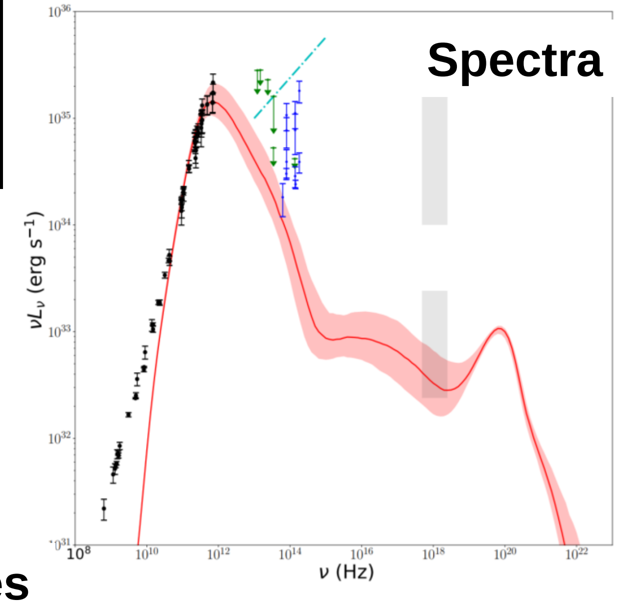
GRMHD Simulations

Usually evolve a **single** fluid and magnetic field

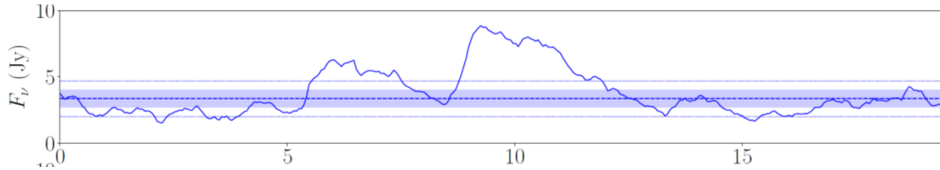
Images



Spectra



Light Curves



Movie & Image Credits: Aleksander Sądowski, Chael+ 2018b

Two-Temperature GRRMHD Simulations

- Using the code KORAL: (Sądowski+ 2013, 2015, 2017)

- Electron and ion energy densities are evolved via the covariant 1st law of thermodynamics:

$$\mathrm{d}U = -P\mathrm{d}V + T\mathrm{d}S$$

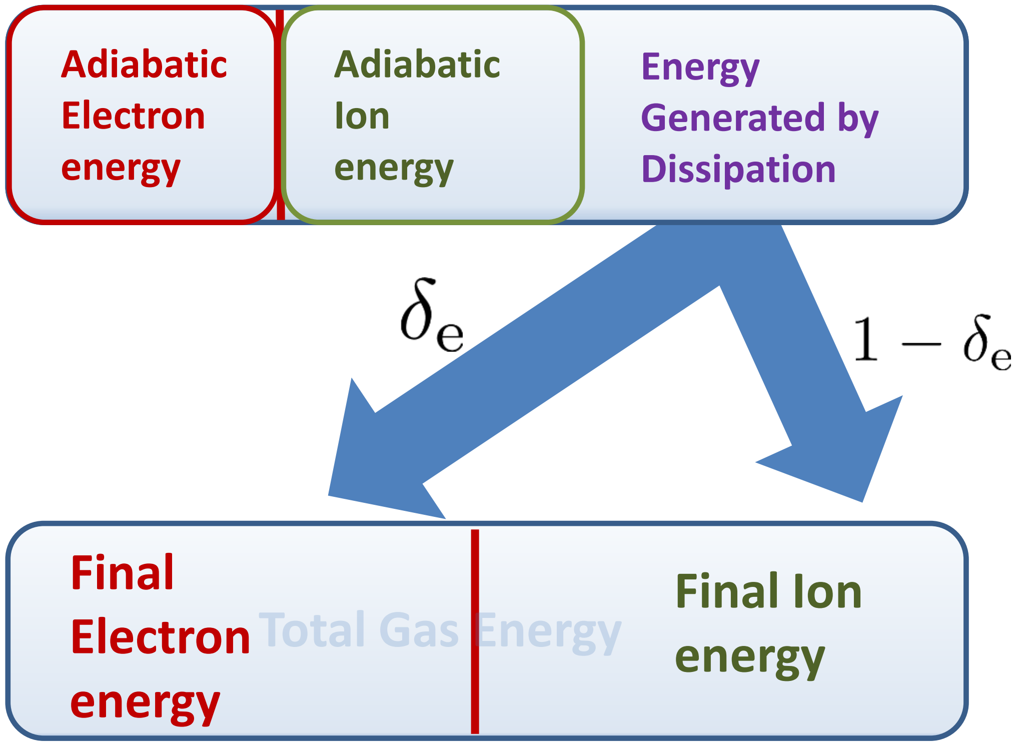
Adiabatic Compression and Expansion

Entropy Generated Through Dissipation (at the end of a turbulent cascade)

Electron & Ion Heating

- The **total** dissipative heating in the simulation is internal energy of the total gas minus the energy of the components **evolved adiabatically.**

- **Sub-grid physics** must be used to determine what fraction of the dissipation goes into the electrons.

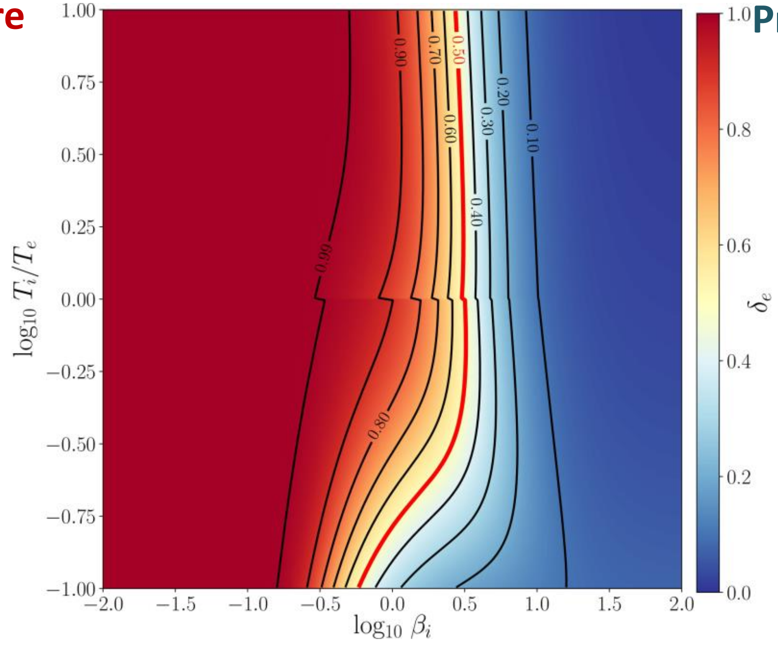


Sub-grid Heating Prescriptions

Turbulent Dissipation (Howes 2010)

- Non-relativistic physics (Landau Damping)
- Predominantly heats electrons when magnetic pressure is high, and vice versa

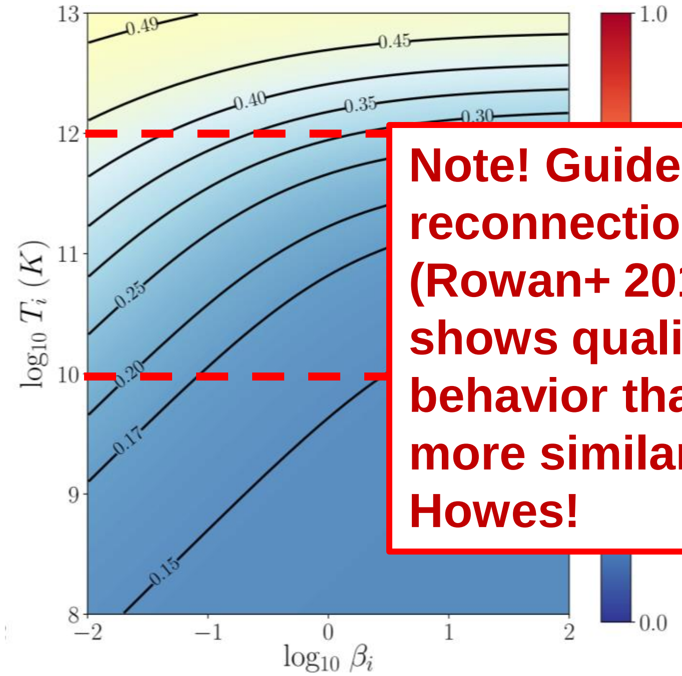
High Magnetic Pressure ⟷ **Low Magnetic Pressure**



Almost all energy to electrons ⟷ Almost all energy to ions

Magnetic Reconnection (Rowan+ 2017)

- Based on PIC simulations of trans-relativistic reconnection.
- **Always** puts more heat into ions
- Constant nonzero δ_e at low magnetization.



Note! Guide-field reconnection (Rowan+ 2019) shows qualitative behavior that is more similar to Howes!

ively flat δ_e large range of erature, beta.

Image Credit: Chael+ 2018b
see also: Kawazura+ 2018 (turbulent damping). Werner+ 2018 (reconnection)

Sgr A* Simulations

arXiv:1804.06416

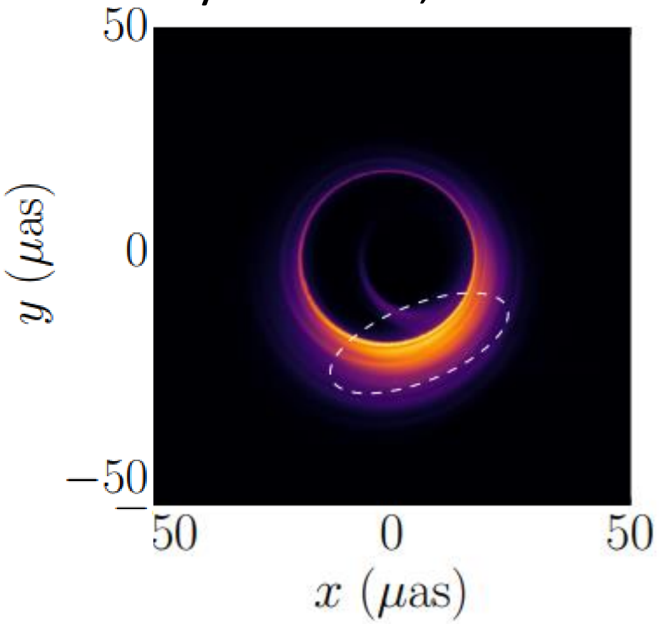
M87 Simulations

Previous work:

Mościbrodzka+ 2016, Ryan+ 2018

- Simulations with **weak magnetic flux.**
- Ryan 2018+ **used a two-temperature method** with the turbulent cascade prescription.
- Jet powers **relatively weak**, jet opening angle is **narrow.**

Ryan+ 2018, 230 GHz



Mościbrodzka + 2016, 43 GHz

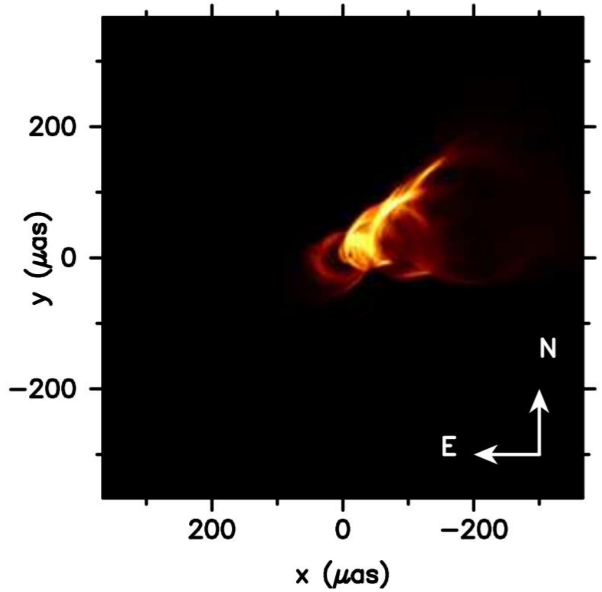
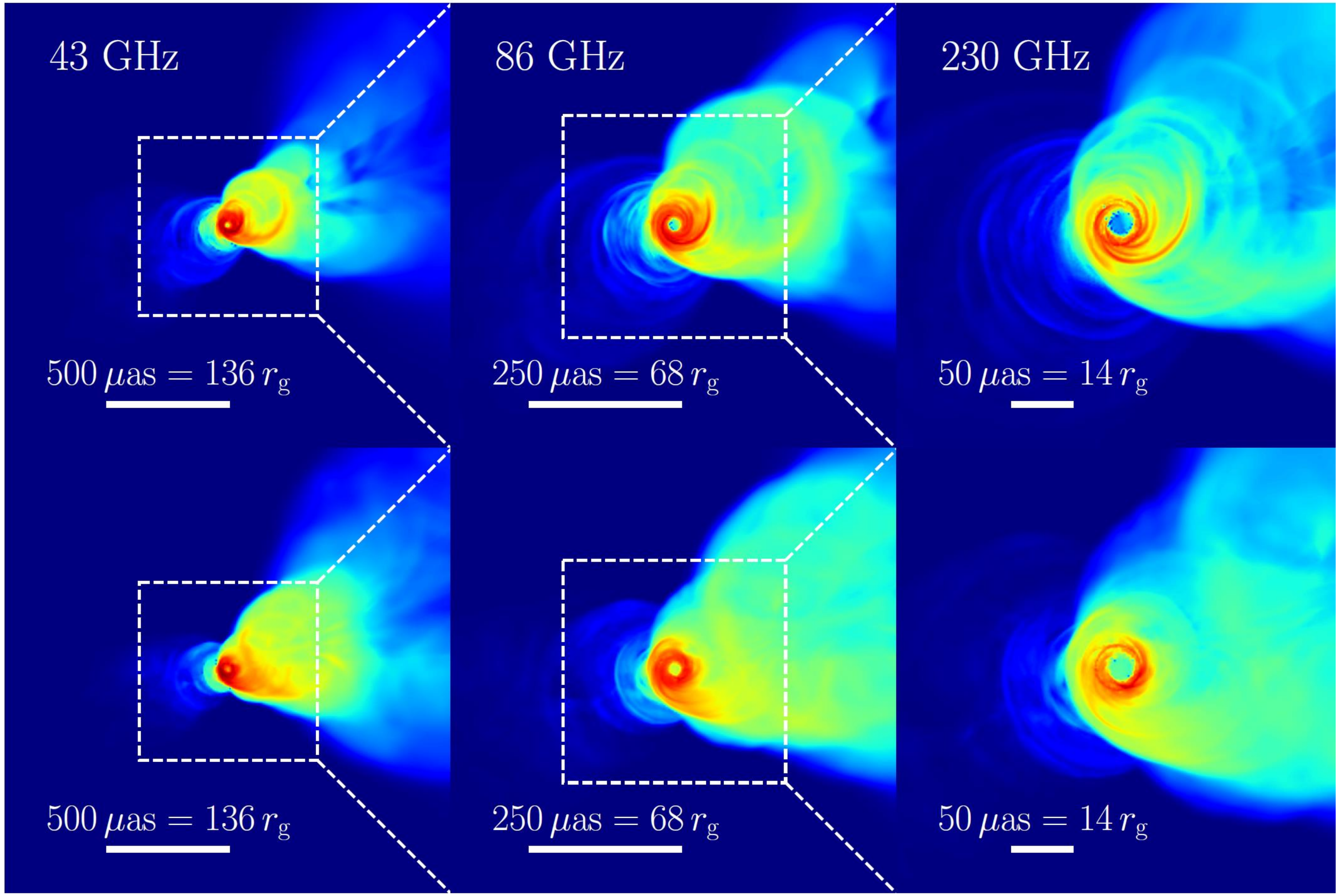


Image Credit: Ryan+ 2018, Moscibrodzka+ 2016
Also: Dexter+ 2012,, 2017

M87 Jets at millimeter wavelengths

Turbulent Heating

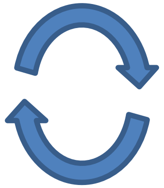
Reconnection Heating



Inclination angle (down from pole)

17°

Disk/Jet rotation sense



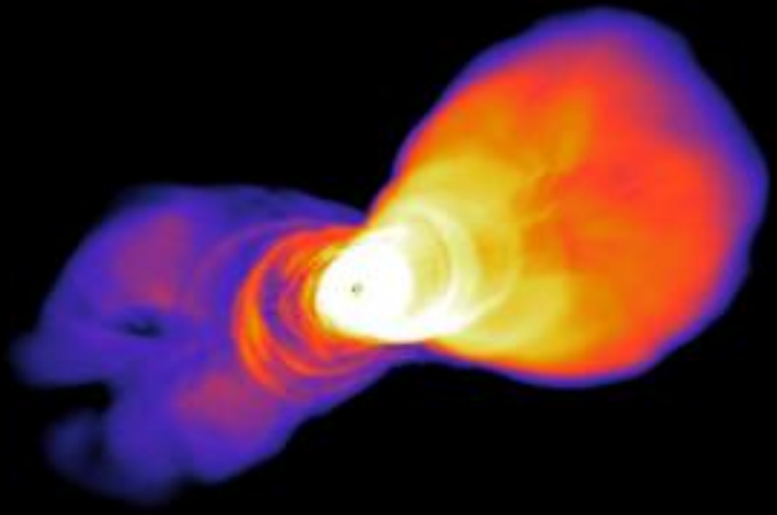
Wide apparent opening angles get **larger** with increasing frequency

Image Credit: Chael+ 2019

Two M87 simulations

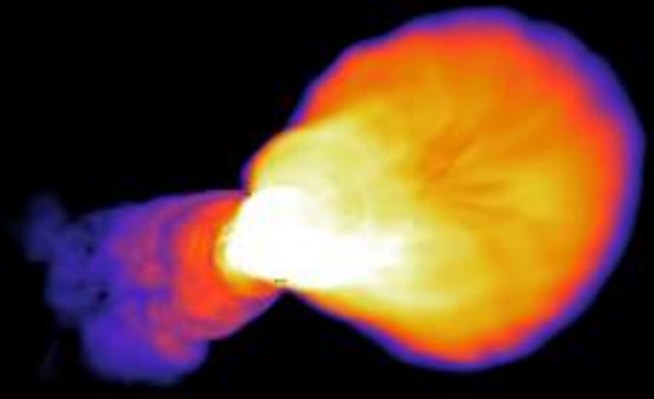
43 GHz jets

Turbulent Heating



P_{jet} is too small!

Reconnection Heating

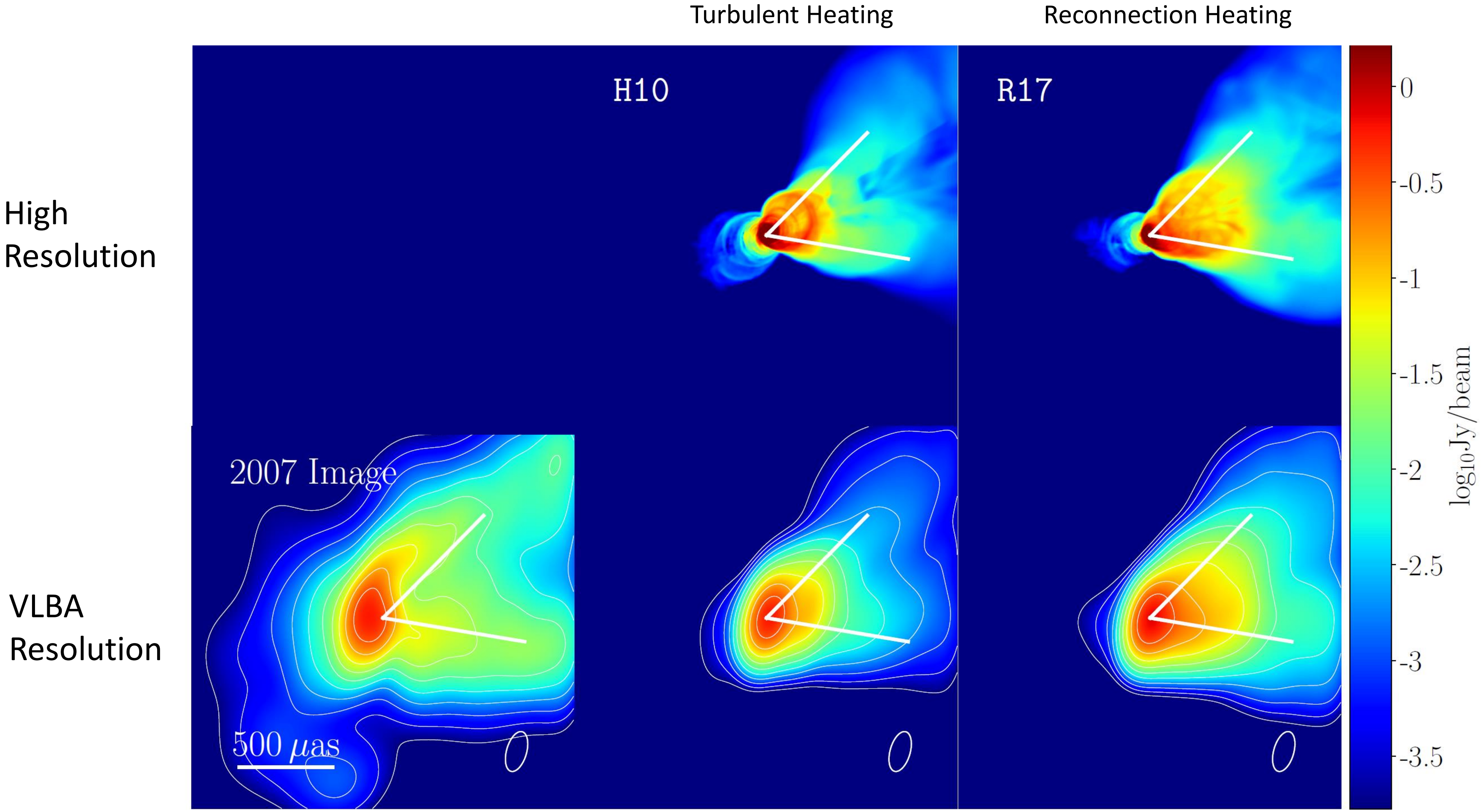


P_{jet} in the measured range!

Movie Credit: Chael+ 2019

43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

$55°$

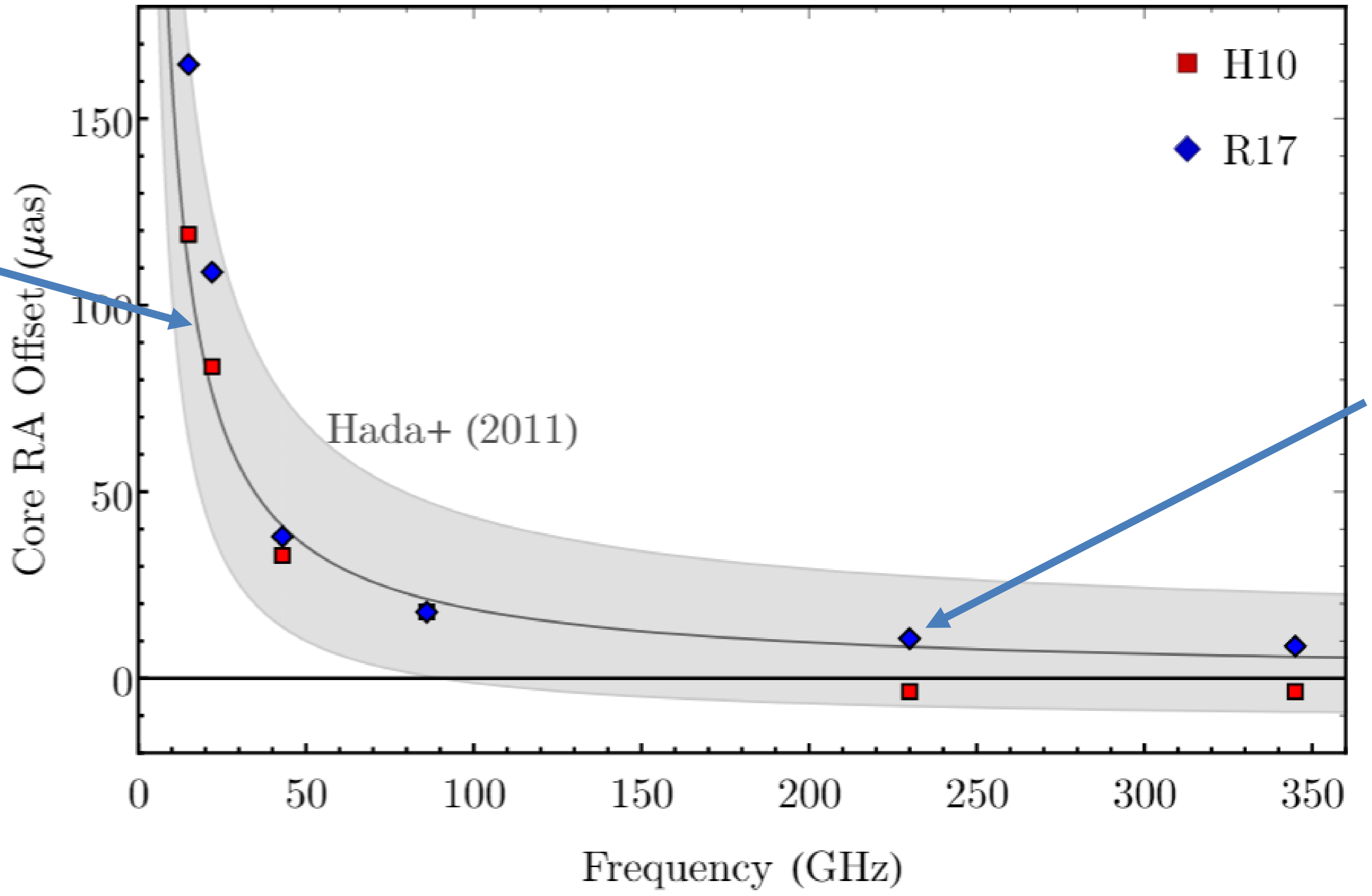
(Walker+ 2018)

The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s!

Image Credit: Chael+ 2019
VLBA Image Credit: Chael+ 2018a
Original VLBA data: Walker+ 2018

M87 Core-Shift

At lower frequencies, the optically thick synchrotron core moves up the jet



At 230 GHz and higher, the core is coincident with the black hole

Agreement with measured core shift up to cm wavelengths.

Hada+ 2011

Image Credit: Chael+ 2019

230 GHz Images

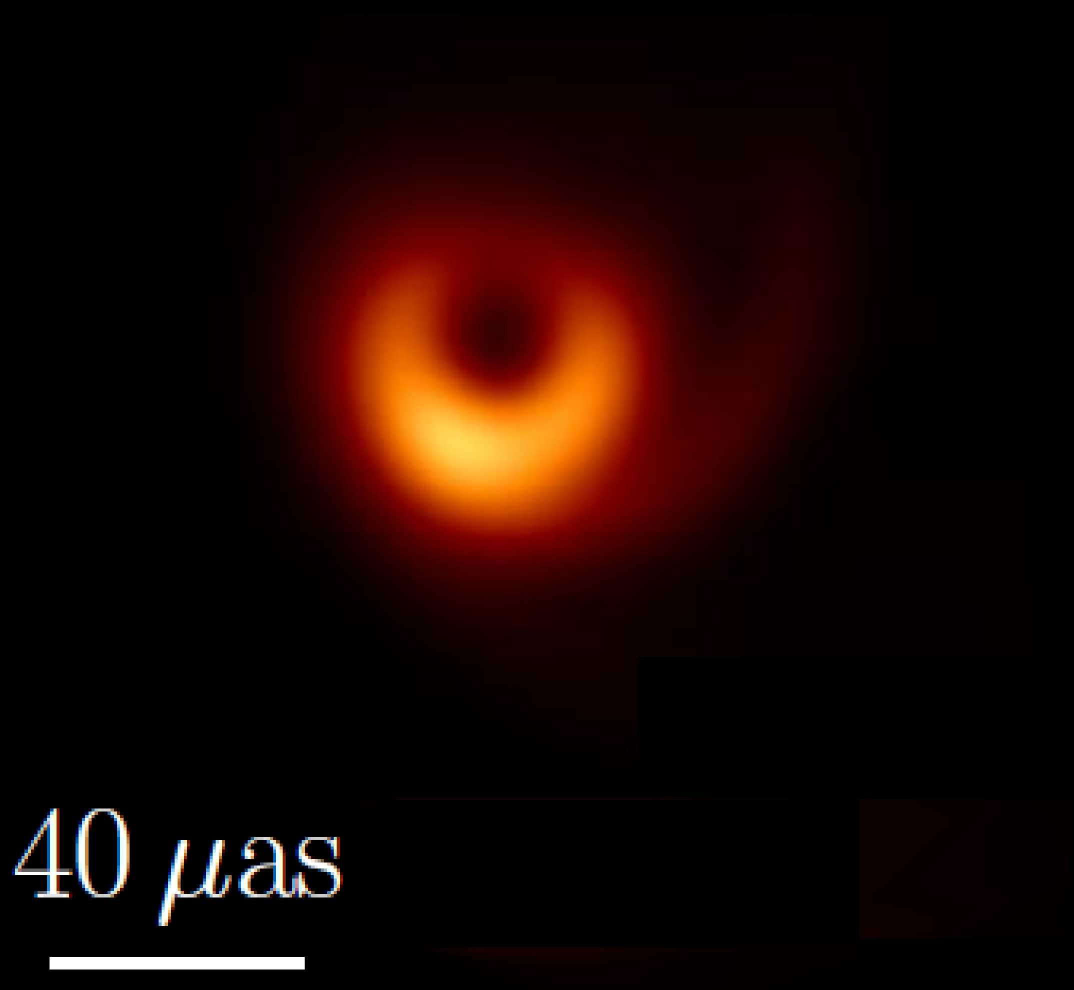
Turbulent Heating

Reconnection Heating

40 μas

230 GHz Images

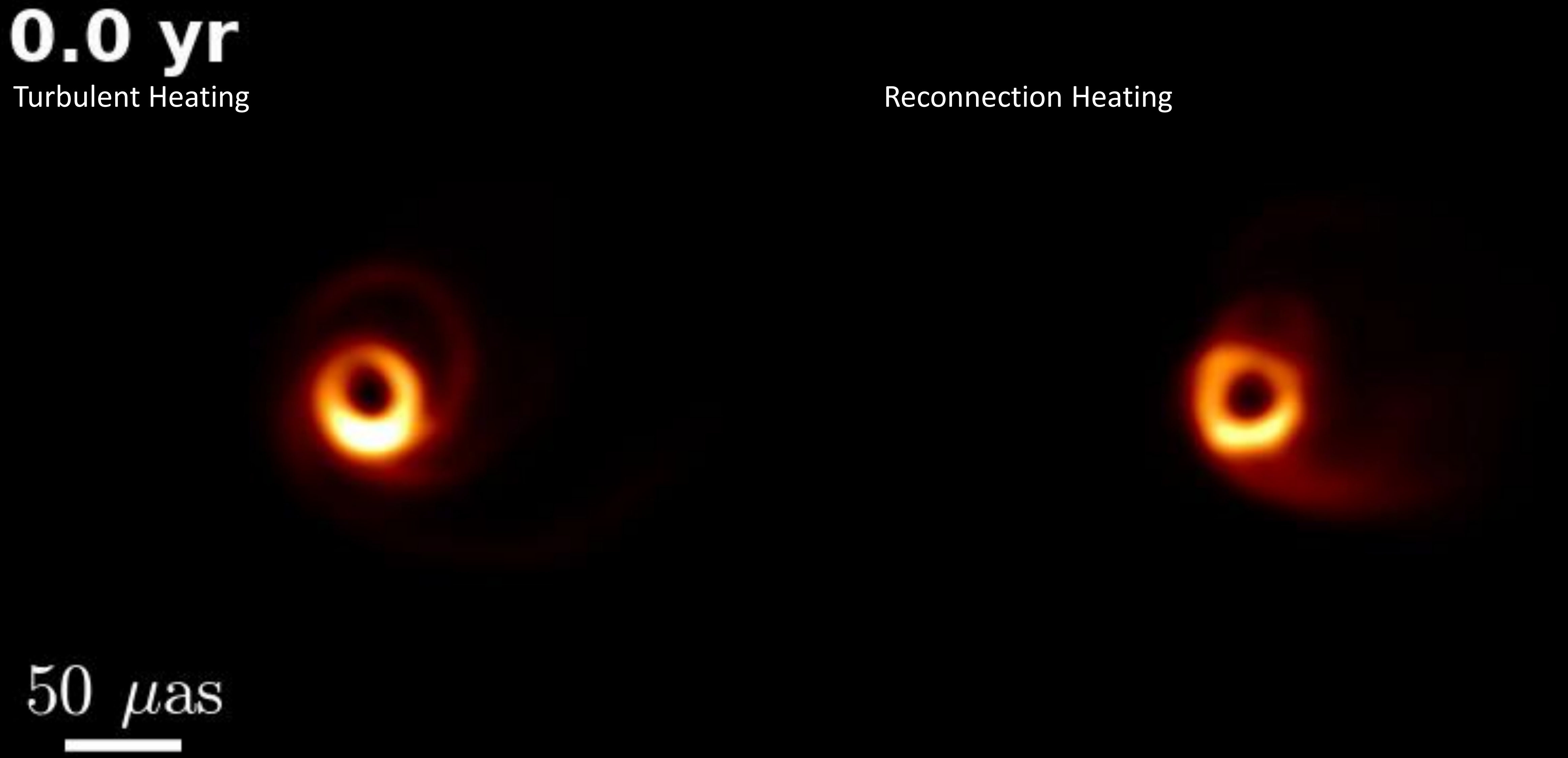
Turbulent Heating



Reconnection Heating

Image Credit: Chael+ 2019

230 GHz Images



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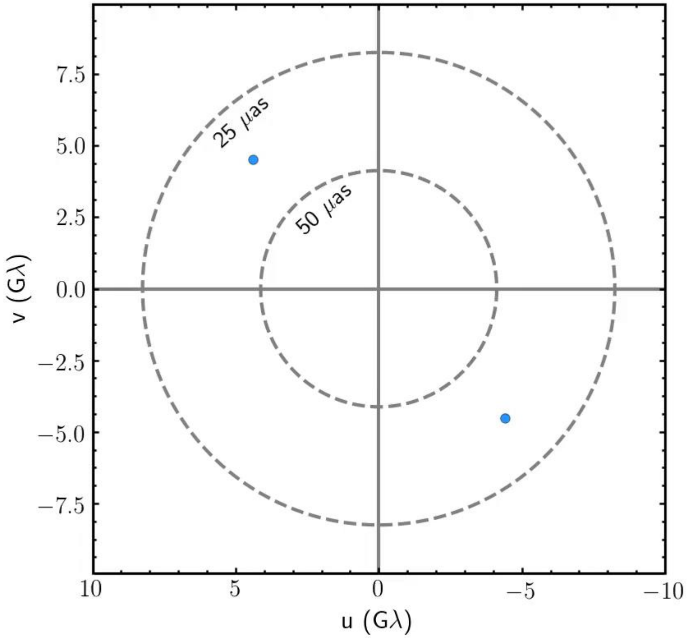
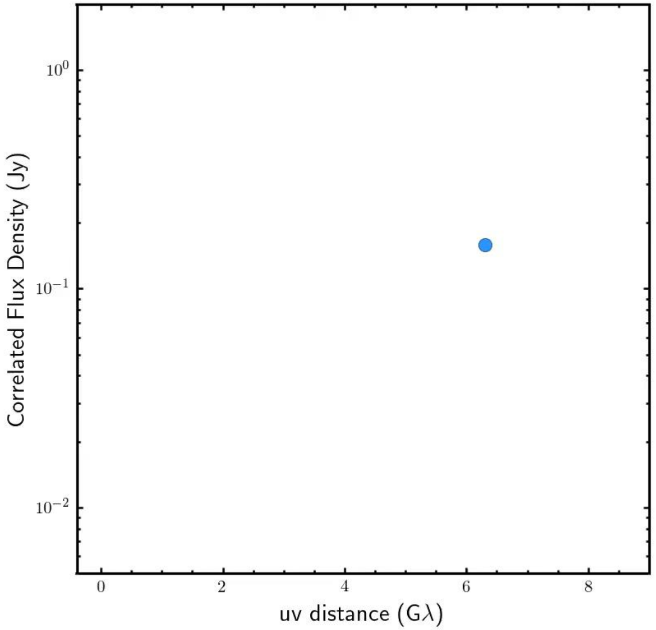
Part II:
Imaging a Supermassive
Black Hole

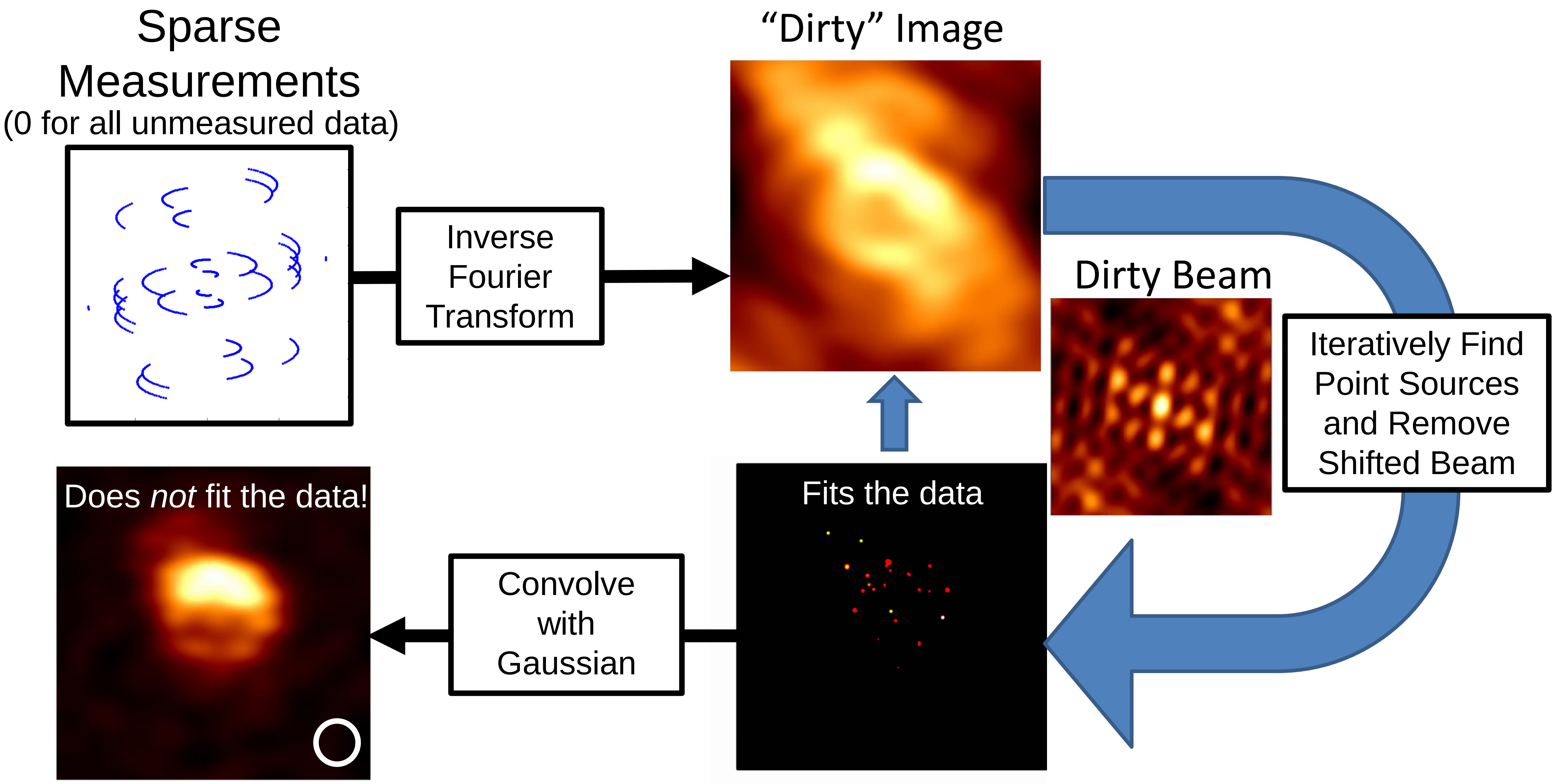
Earth Rotation Aperture Synthesis





Movie Credit: Daniel Palumbo

Traditional Approach: CLEAN



Simulation Credit: Avery Broderick

"Bayesian" Model Inversion

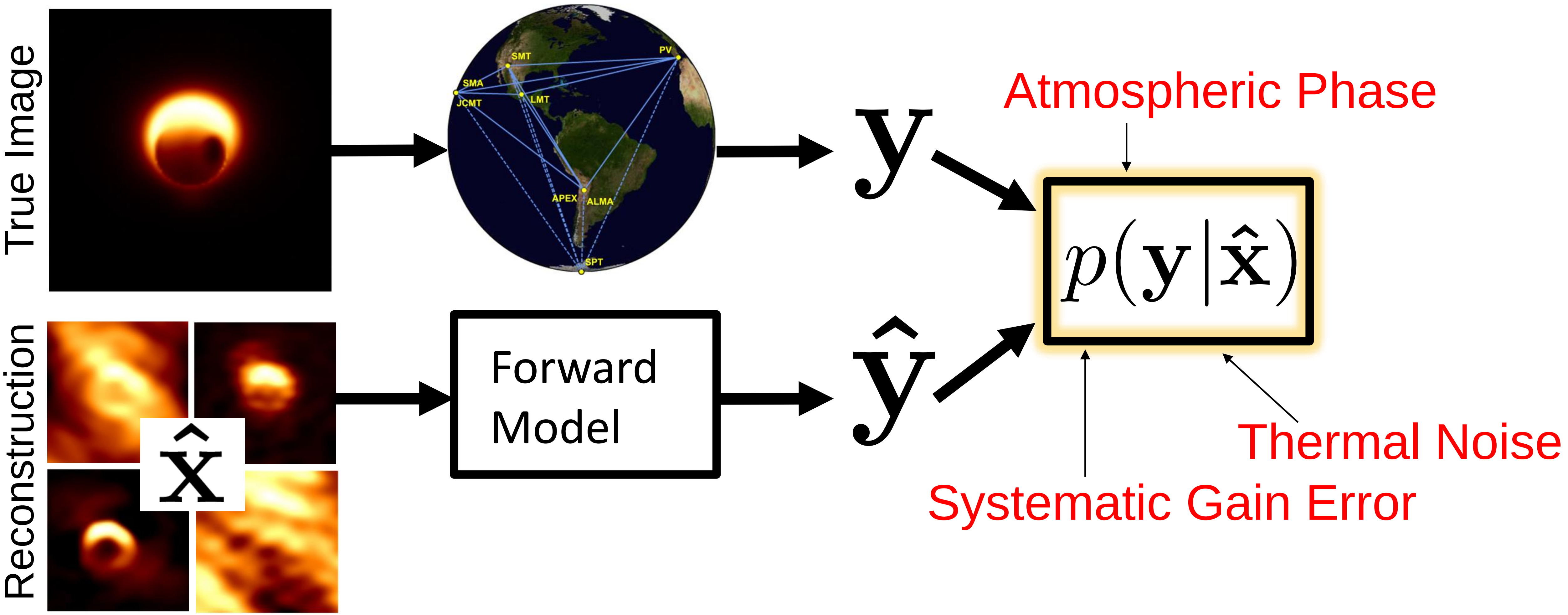


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

“Bayesian” Model Inversion

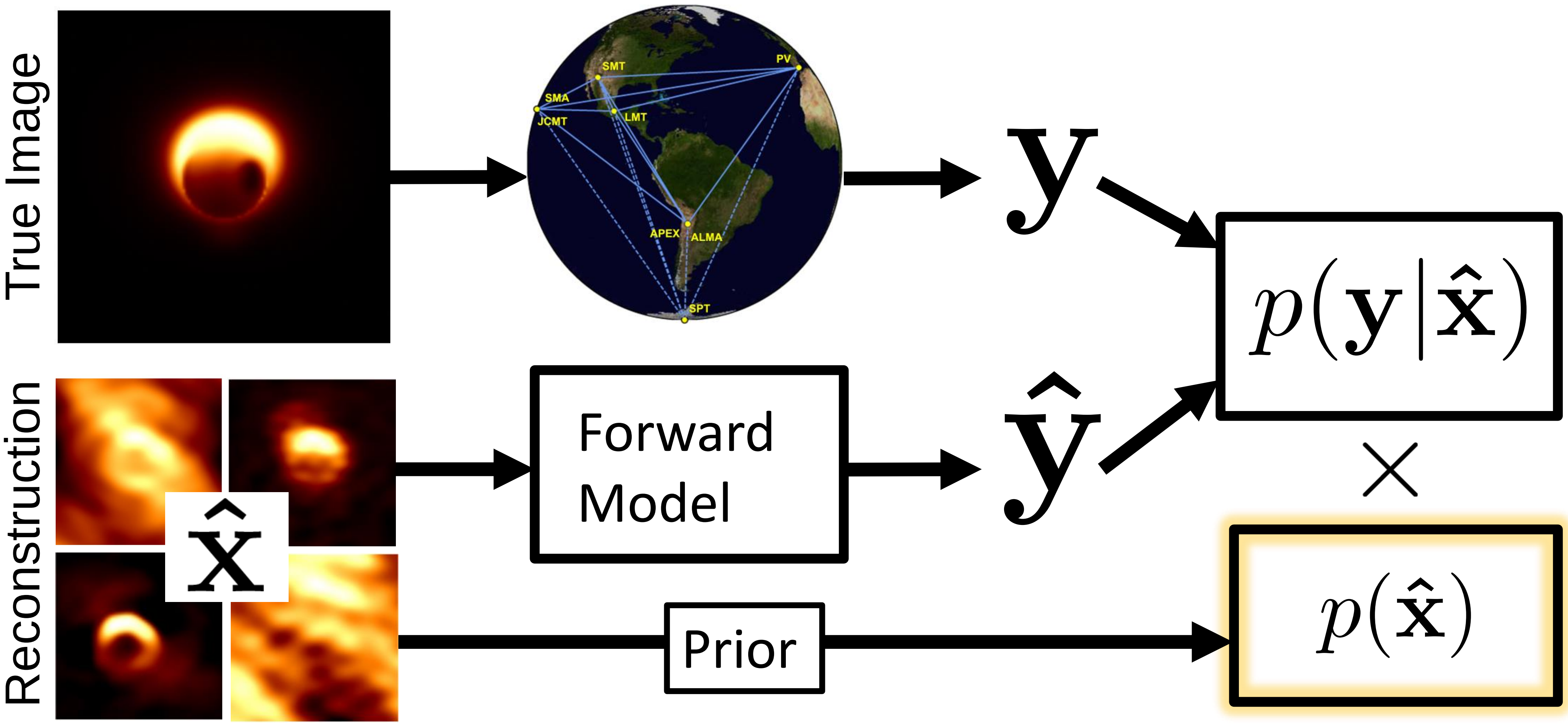


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

Regularized Maximum Likelihood

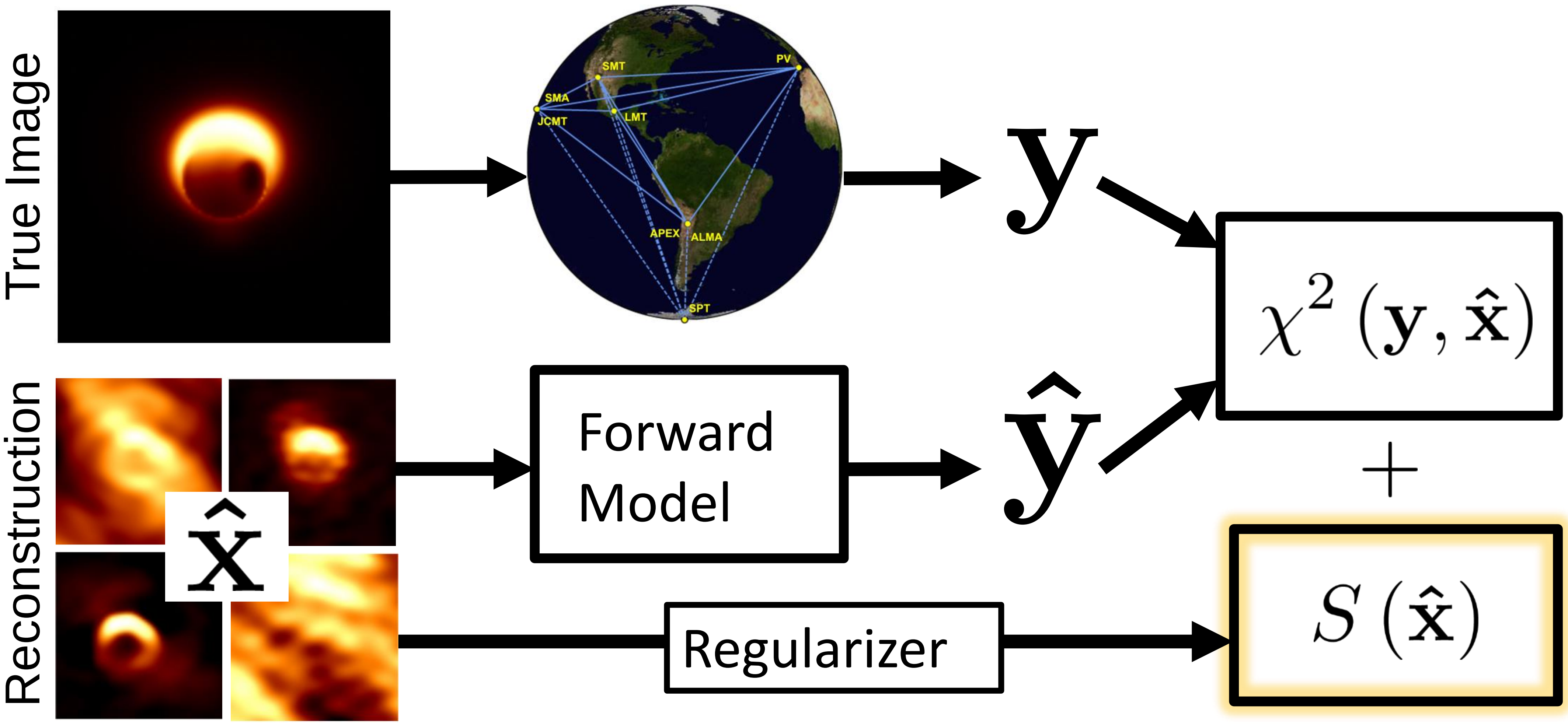


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

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

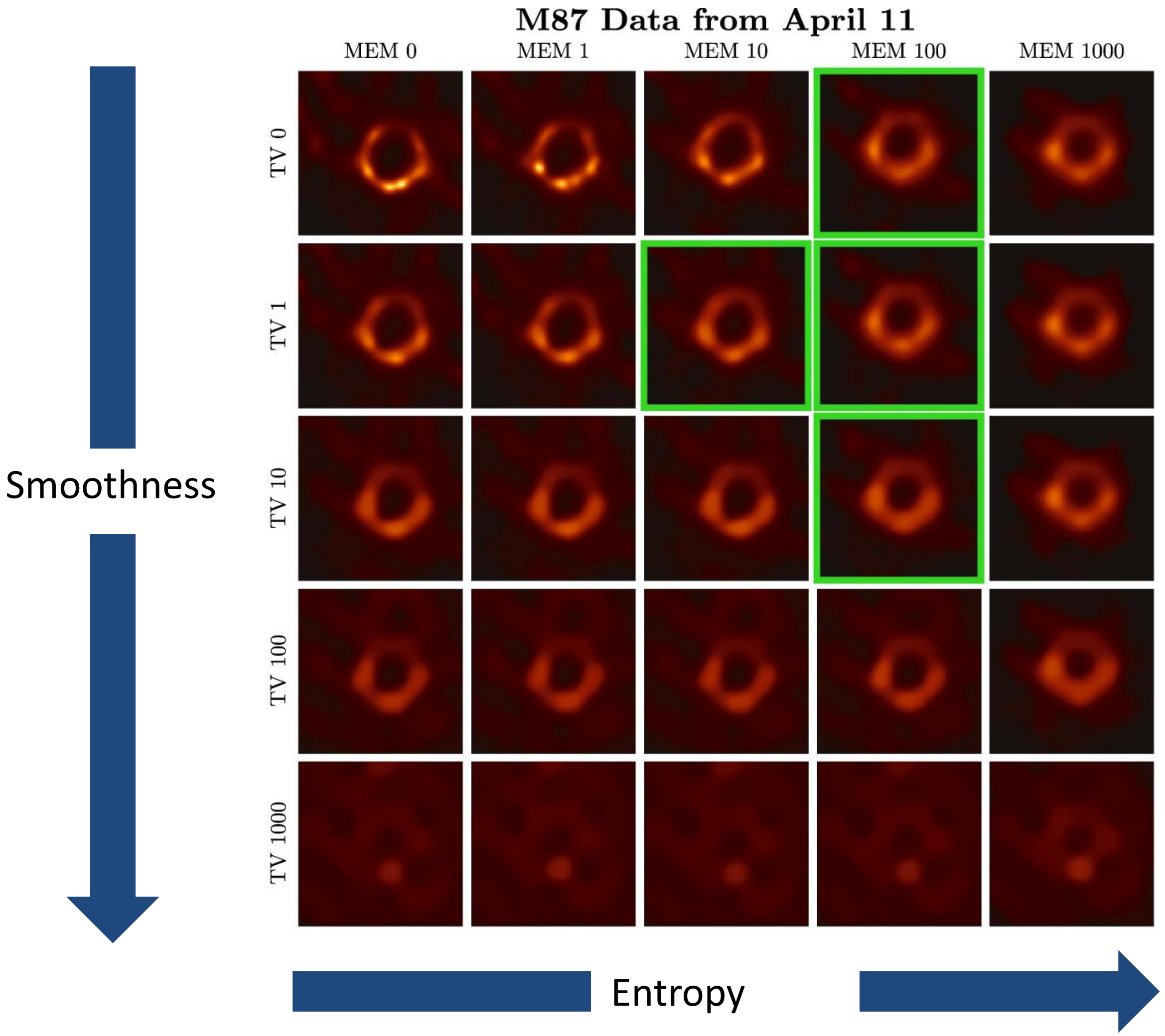
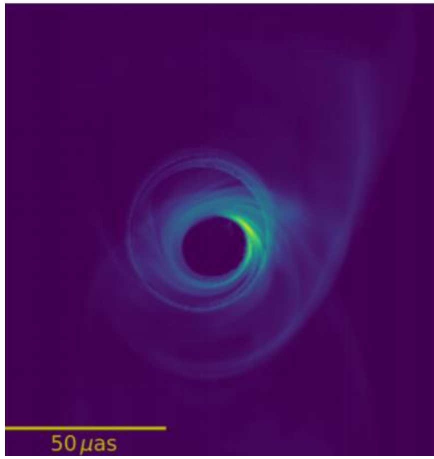


Image Credit: EHT Collaboration 2019 (Paper IV)

Closure-only imaging



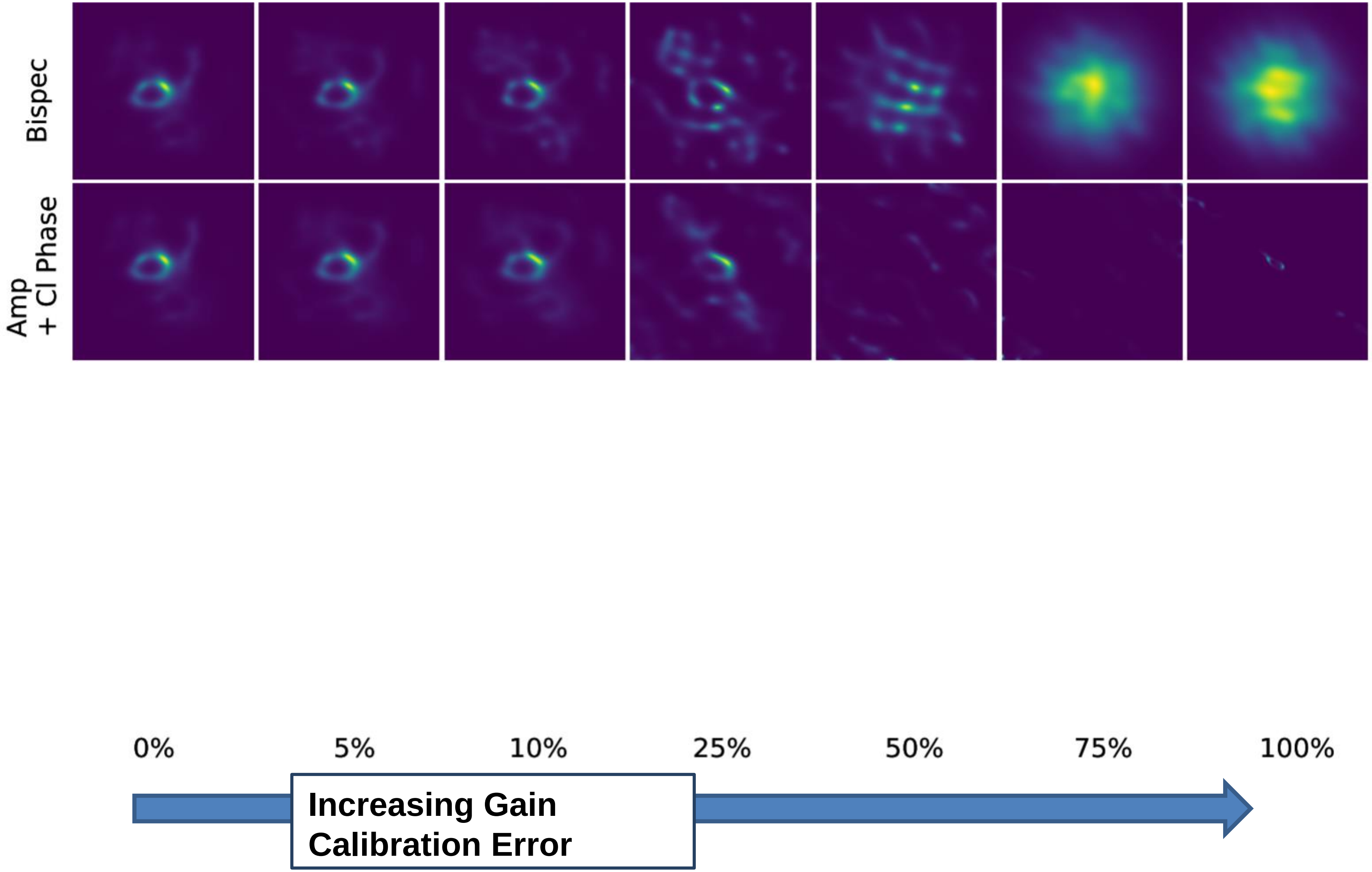


Image Credit: Chael+ 2018a
Simulation Credit: Roman Gold

Closure-Only & RML Imaging have wide applicability!

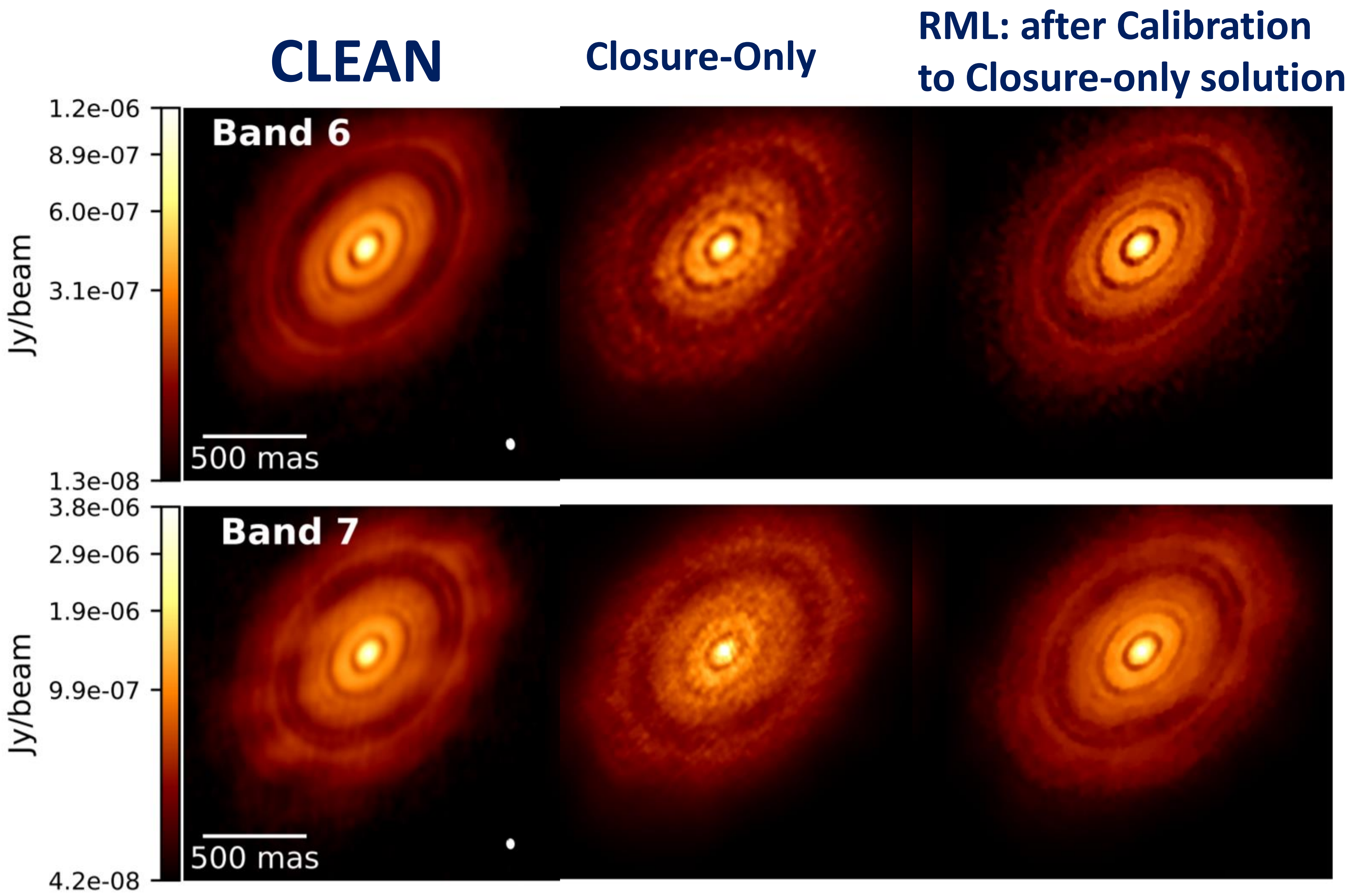
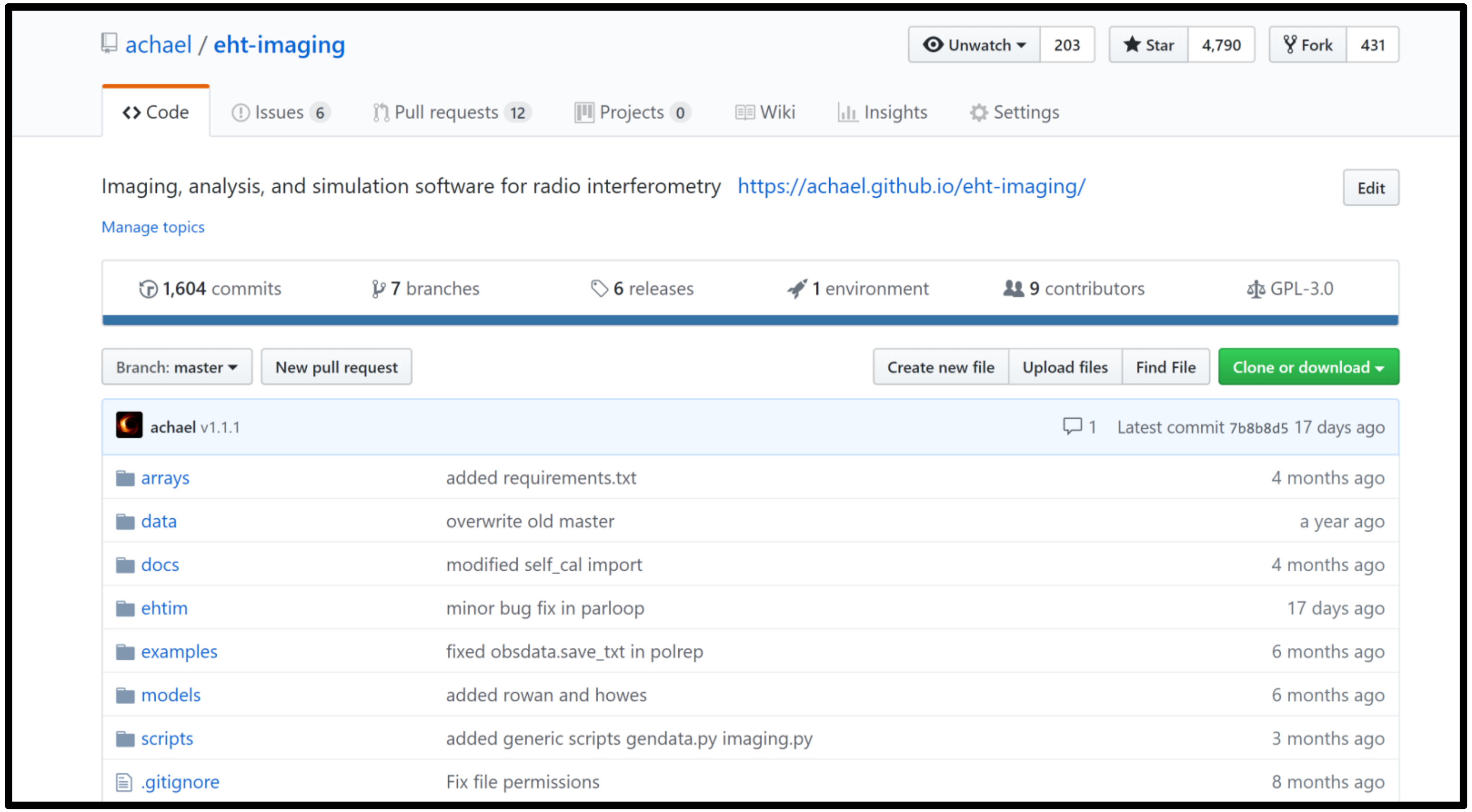


Image Credit: Chael+ 2018a

The eht-imaging software library



- Python software to image, analyze, and simulate interferometric data
- Flexible framework for developing new tools – e.g. polarimetric imaging, dynamical imaging.
- Used in 18 published papers (including all 5/6 EHT result papers)

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

Imaging M87 with the EHT

BHI, July 2018

EHT 2017

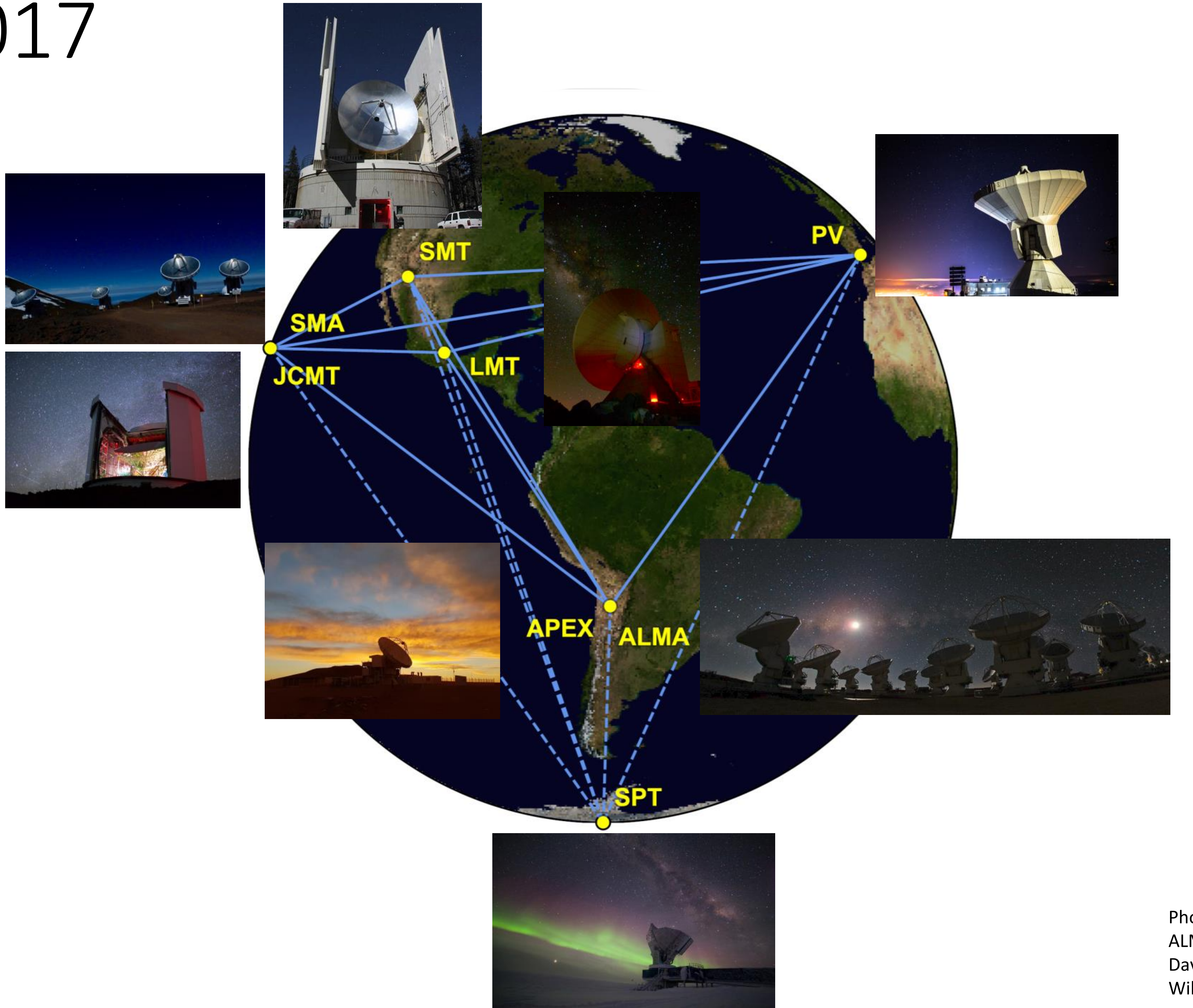
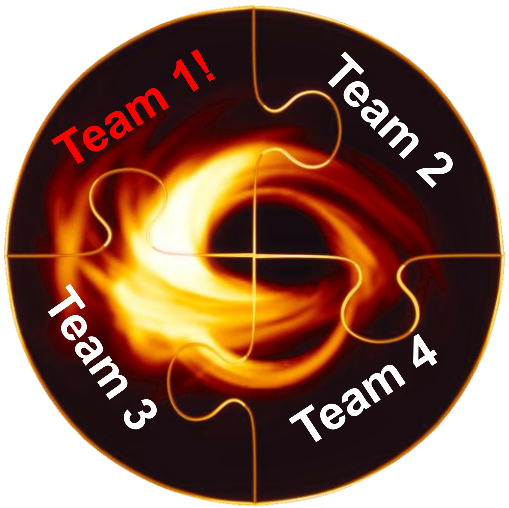
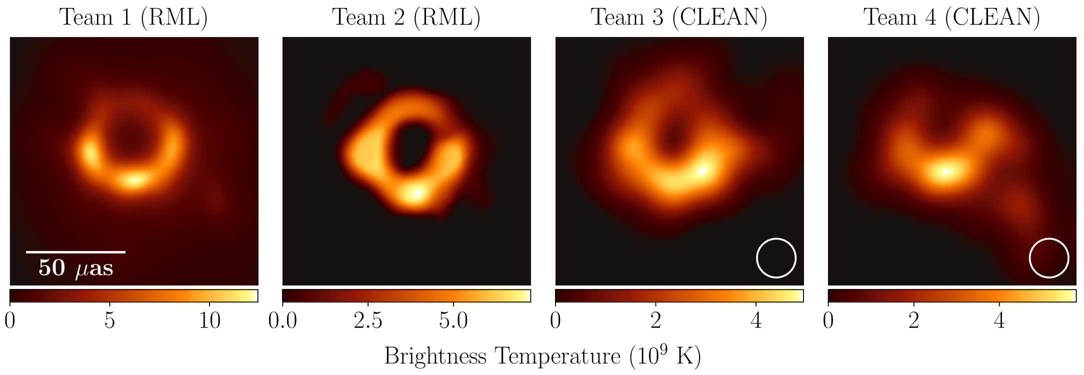


Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

Two stages of imaging M87

Stage 1: **Blind Imaging**





Stage 2: **Parameter Surveys & Synthetic data tests**

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

Compact Flux (Jy)	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
	12%	19%	24%	23%	22%
Init./MEM FWHM (μas)	**40**	**50**	**60**		
	58%	42%	0%		
Systematic Error	**0%**	**1%**	**2%**	**5%**	
	26%	27%	26%	20%	
Regularizer:	**0**	**1**	**10**	$\mathbf{10^2}$	$\mathbf{10^3}$
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%

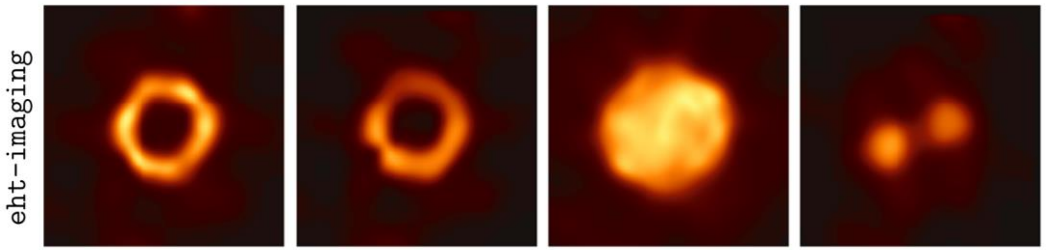
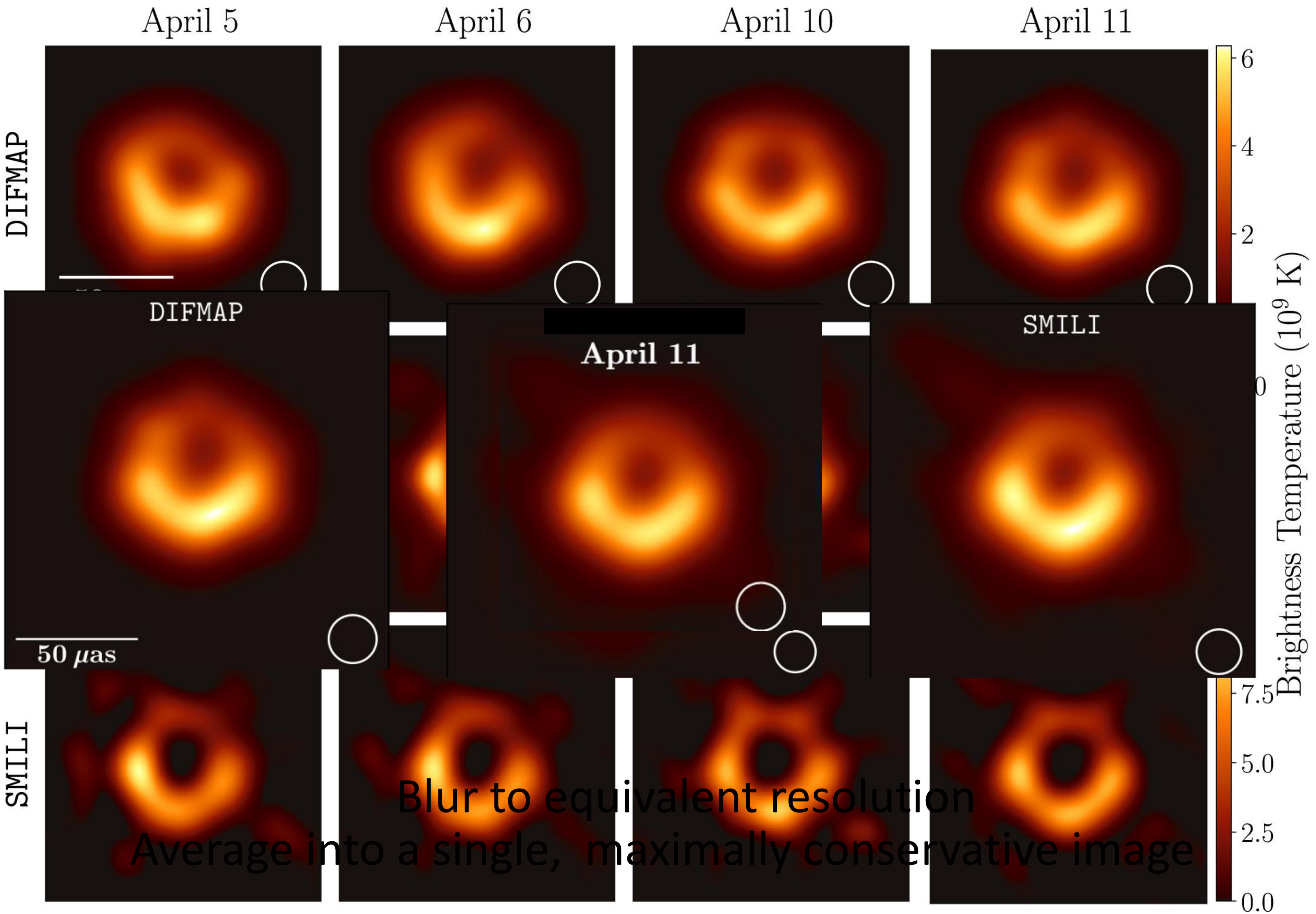


Image Credit: EHT Collaboration 2019 (Paper IV)

Three pipelines, four days

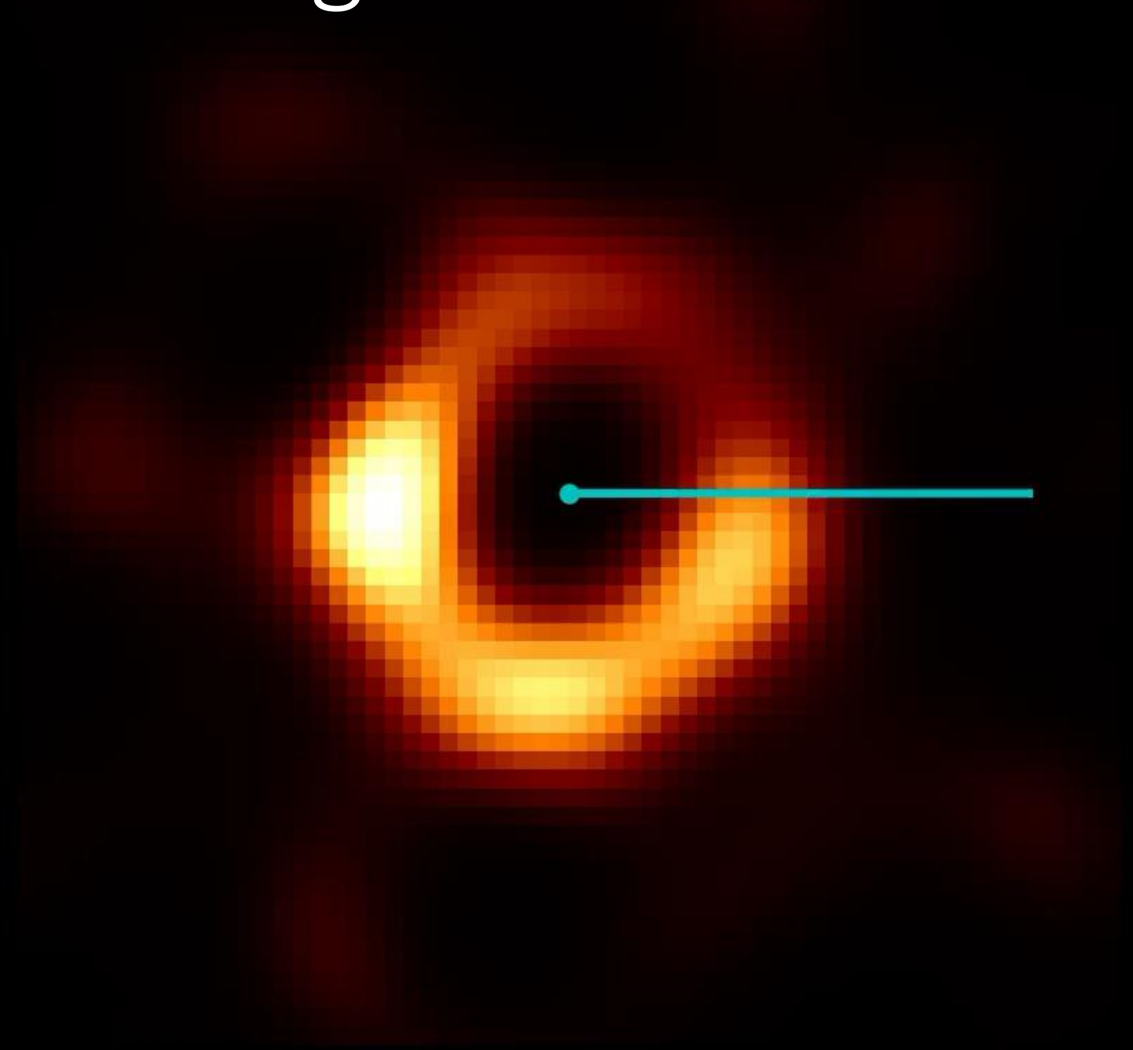


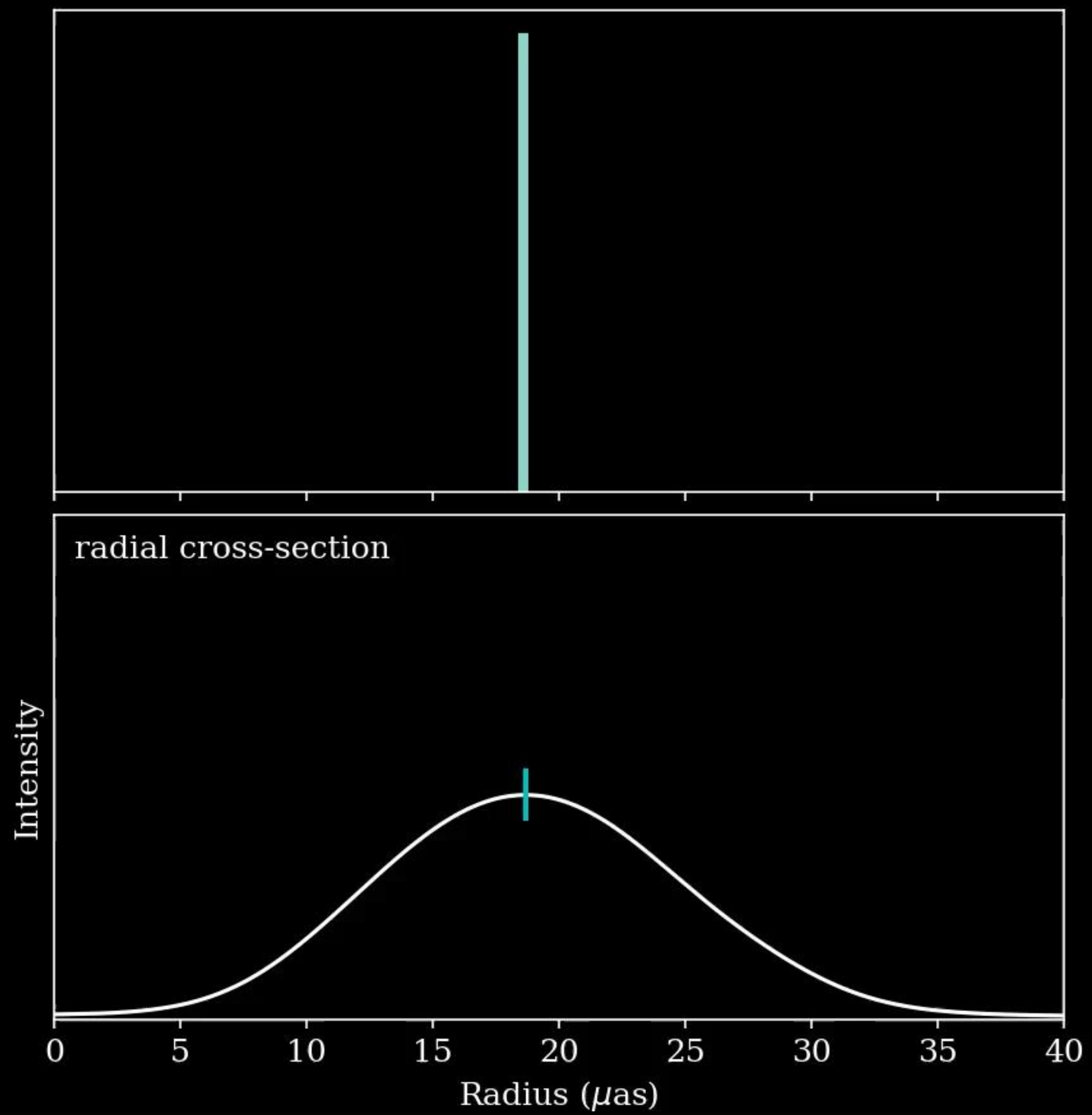
Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

ReX: Ring Extractor

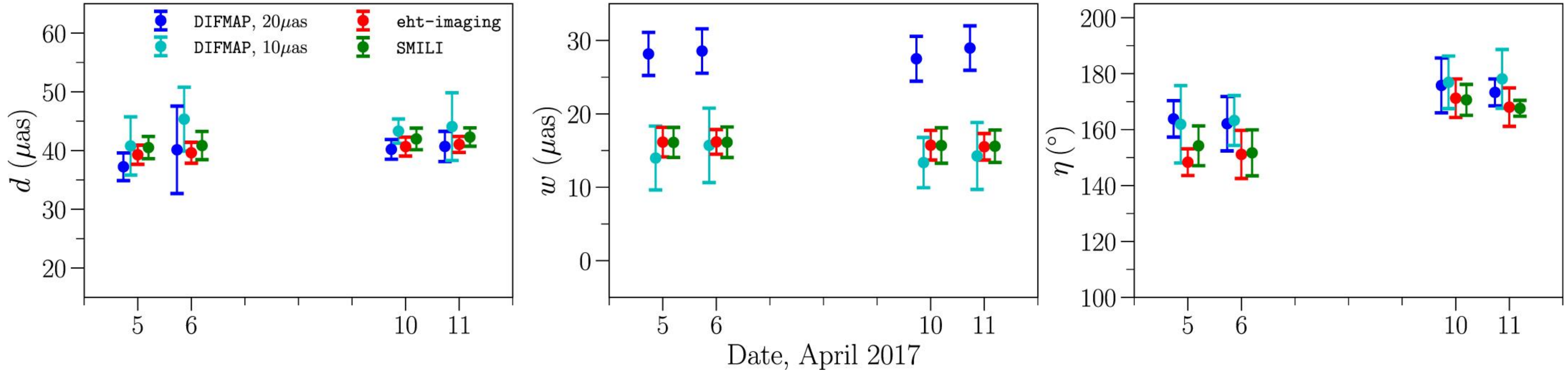




Animation Credit: Dom Pesce

M87 Ring Properties

Diameter Width Angle

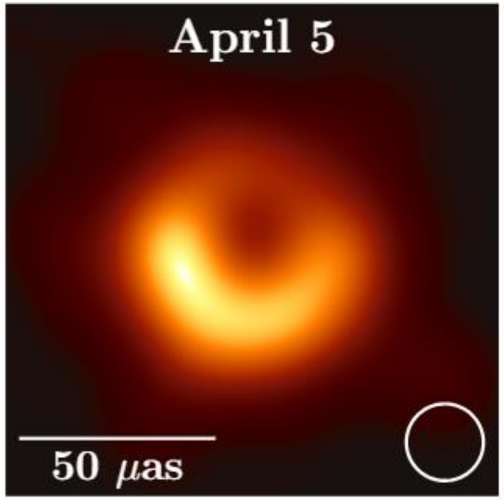


- Diameter $d \approx 41\ \mu\mathrm{as}$ is consistent across time and method
- Ring width is resolution dependent, and is at best an upper limit.
- Orientation angle shows tentative $\approx 20^\circ$ CCW shift from April 5 - 11

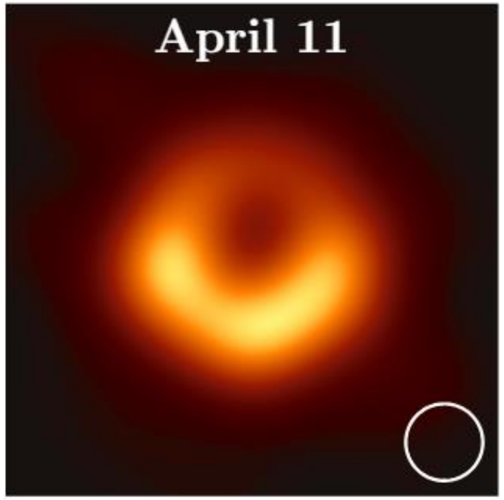
Image Credit:
EHT Collaboration 2019 (Paper V)

Time Variability?

M87



$$6\,\mathrm{day} = 16\,t_{\mathrm{g}}$$



Simulation

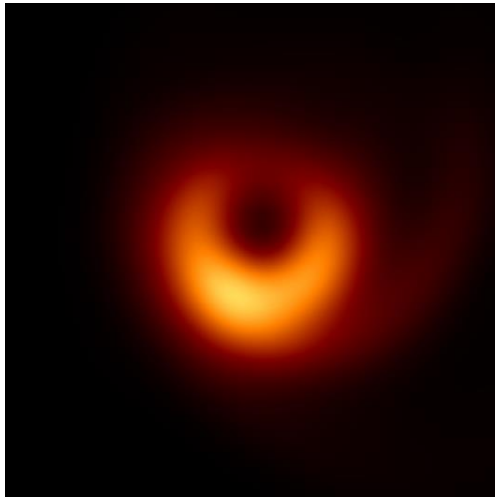
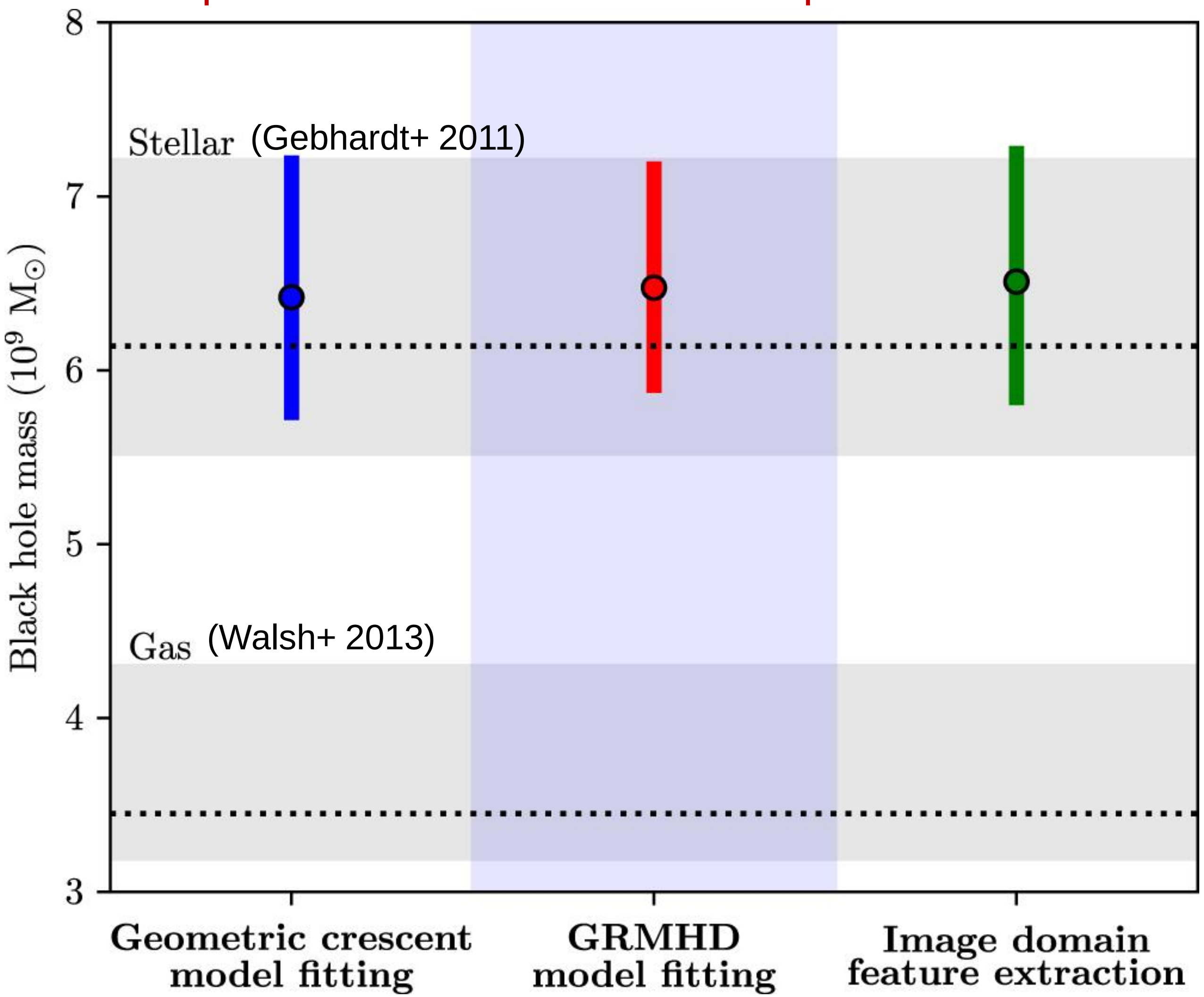


Image Credit: EHT Collaboration 2019 (Paper IV), Chael+ 2019

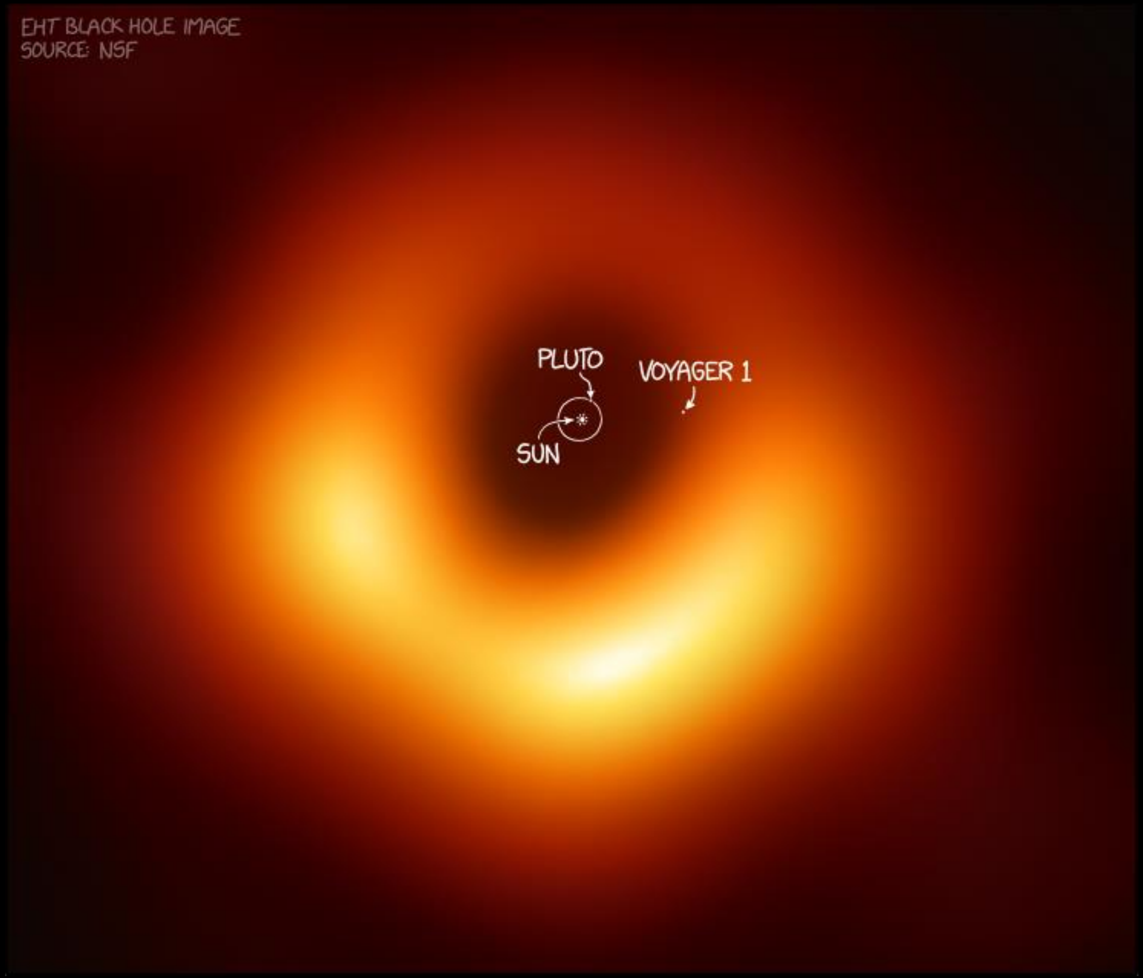
Weighing a black hole

Paper VI Results from three independent methods



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

Image Credit:
EHT Collaboration 2019 (Paper VI)



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

$$R_{\rm Sch} = 128 \, {\rm AU}$$

Image Credit: Randall Munroe, https://xkcd.com/2135/

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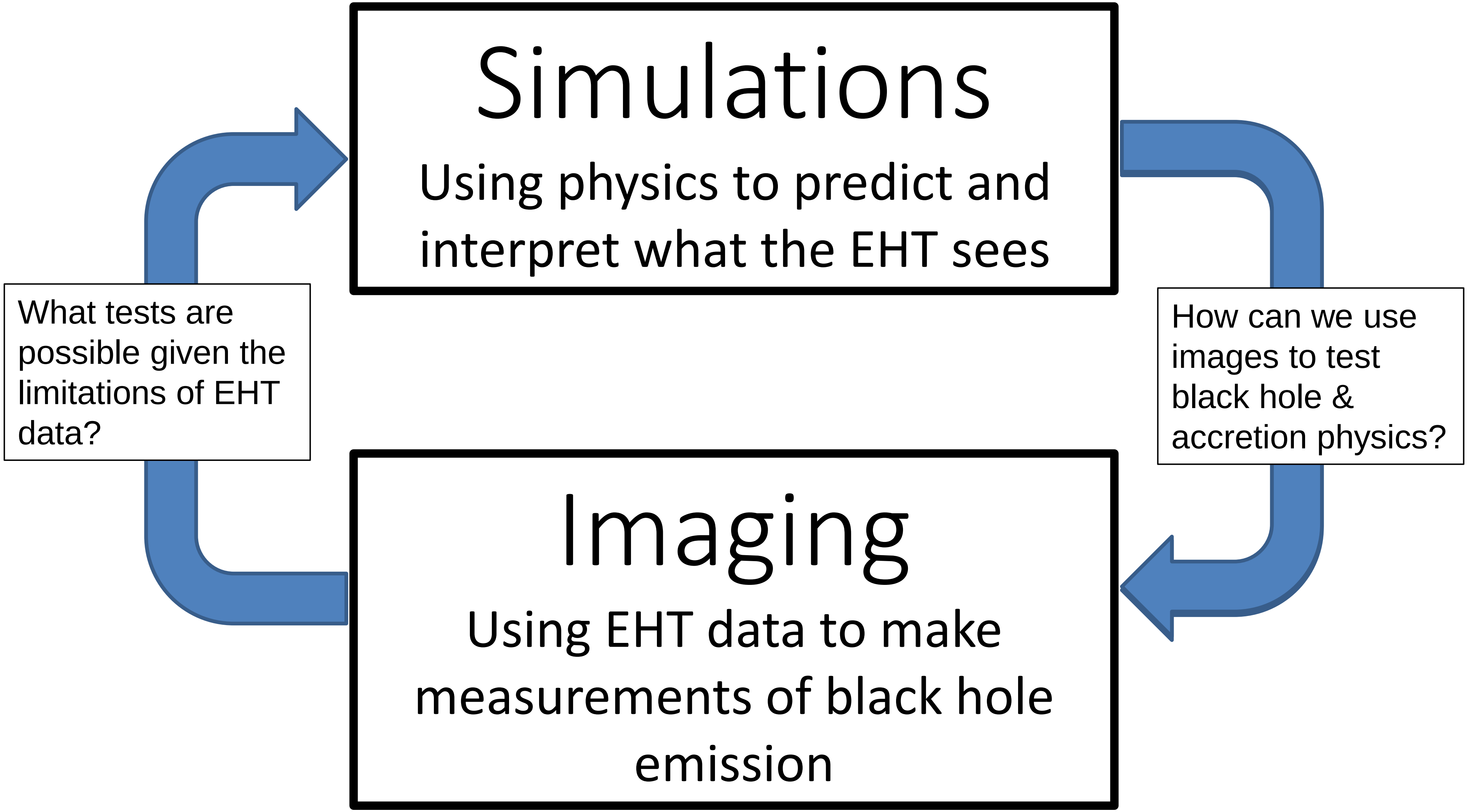
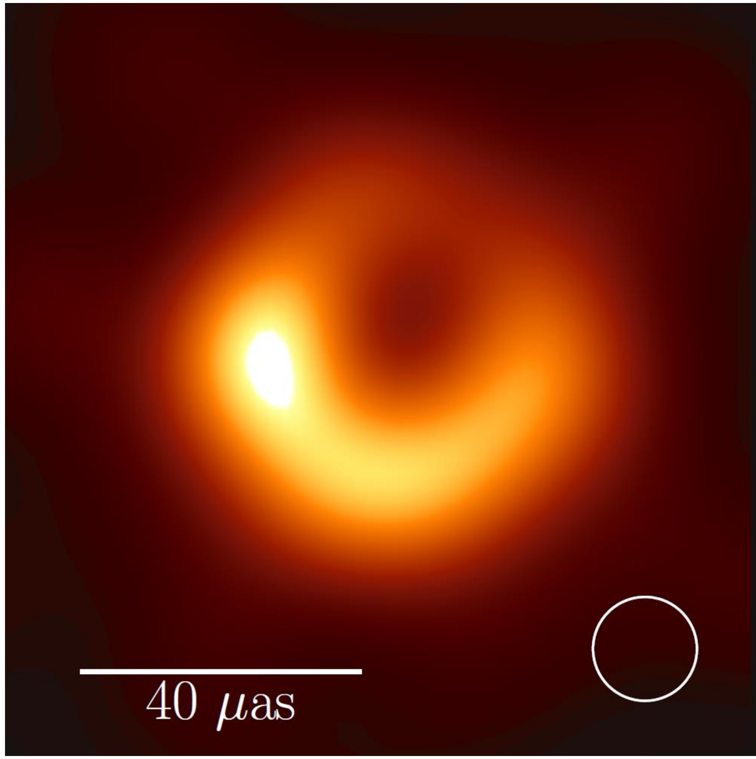
- Regularized Maximum Likelihood
- EHT Images of M87

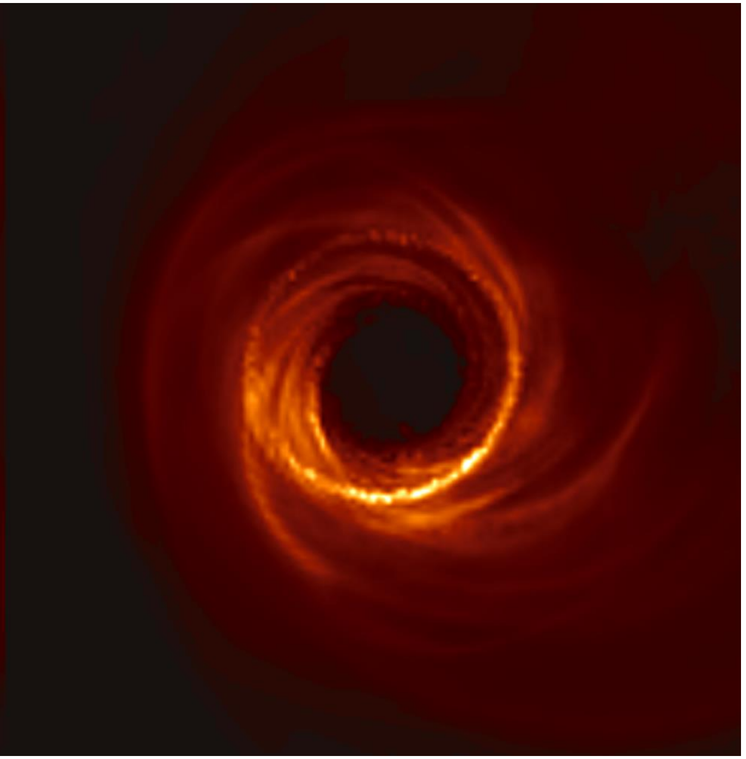

Simulations
Using physics to predict and interpret what the EHT sees
How can we use images to test black hole & accretion physics?
Imaging
Using EHT data to make measurements of black hole emission
What tests are possible given the limitations of EHT data?

The Black Hole in M87: Simulations and Images

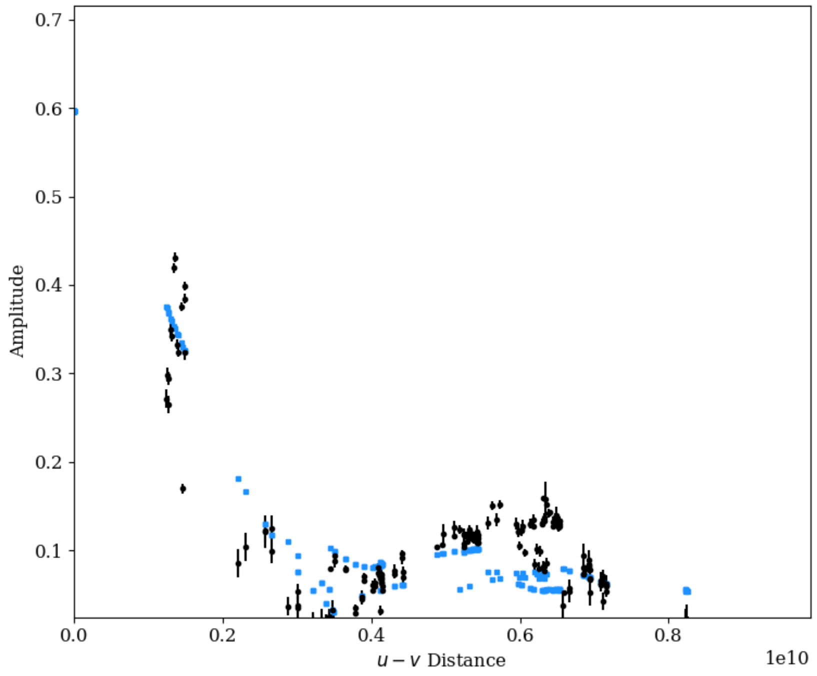
EHT 2017 image



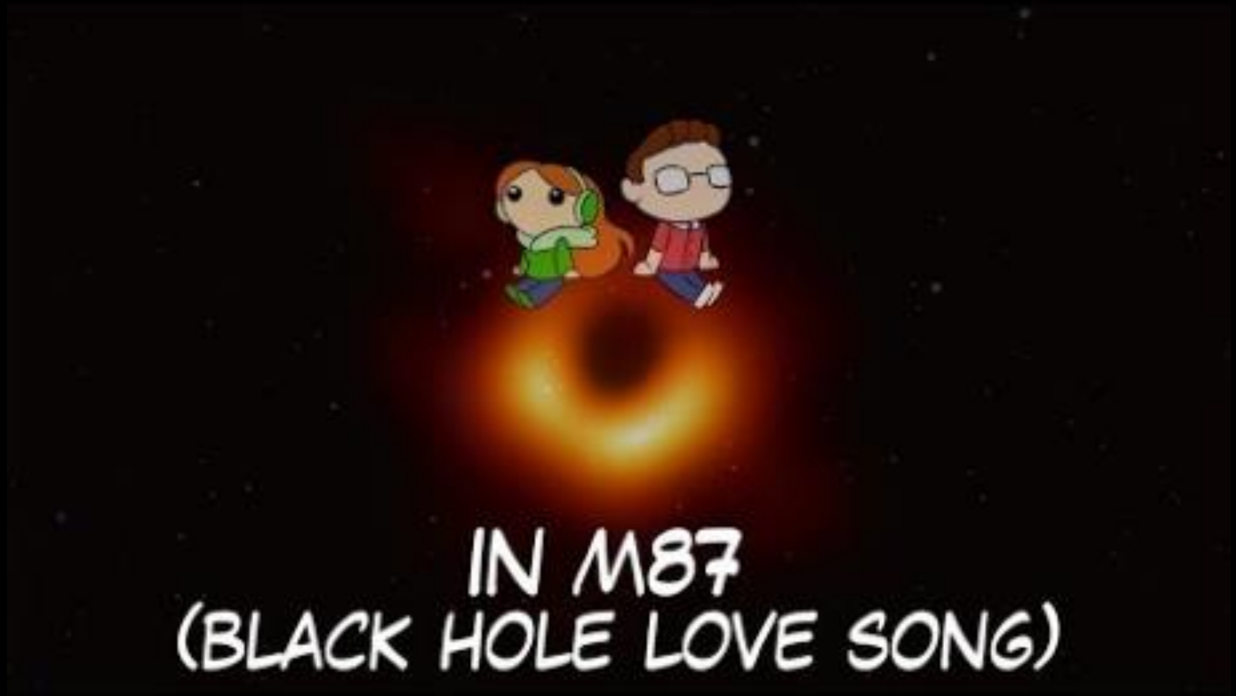
Simulated image from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes




Thank You!
FRIENDSHIP



Video Credit: Chi-Chi
https://www.youtube.com/watch?v=RNZgl4L7I-k