Simulating and Imaging Supermassive Black Hole Accretion Flows

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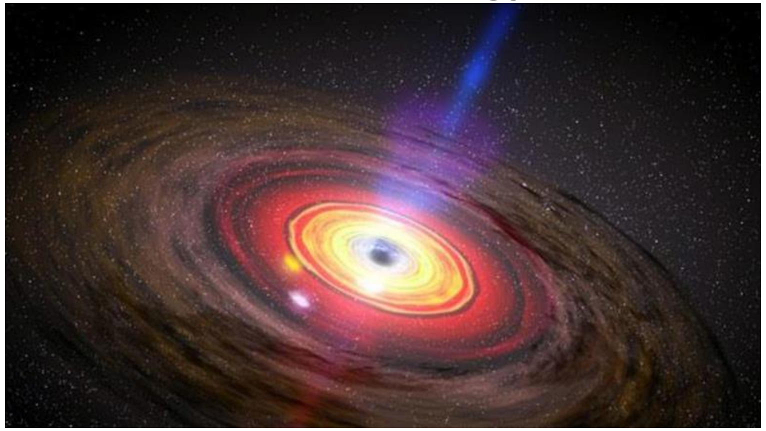
Event Horizon Telescope

What does a black hole look like?

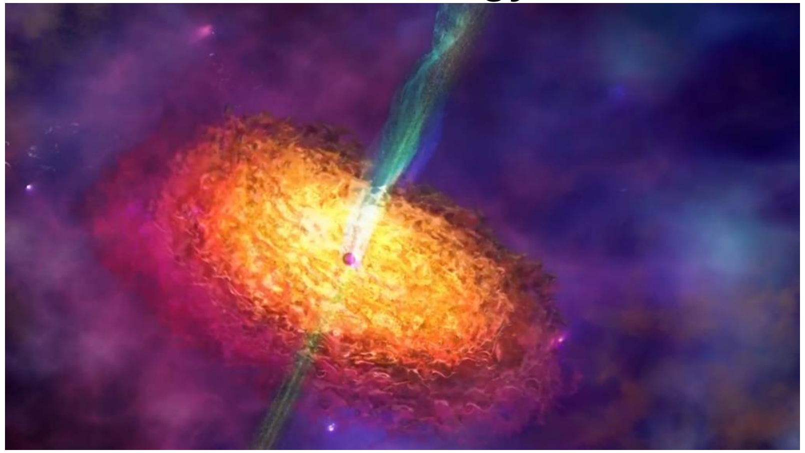
Modes of Black Hole Accretion

Quasars, AGN:
Most Liberated Energy is **Radiated**



- Geometrically Thin
- High Luminosity & Accretion Rate:
- Optically Thick

Low-Luminosity AGN:
Most Liberated Energy is **Advected**



- Geometrically Thick
- Low accretion rate/Luminosity
- Optically thin
- Hot: $T \gtrsim 10^{10}\,\mathrm{K}$

Image credits: NASA/NSF

Sagittarius A*

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

Gravity Collaboration, 2018

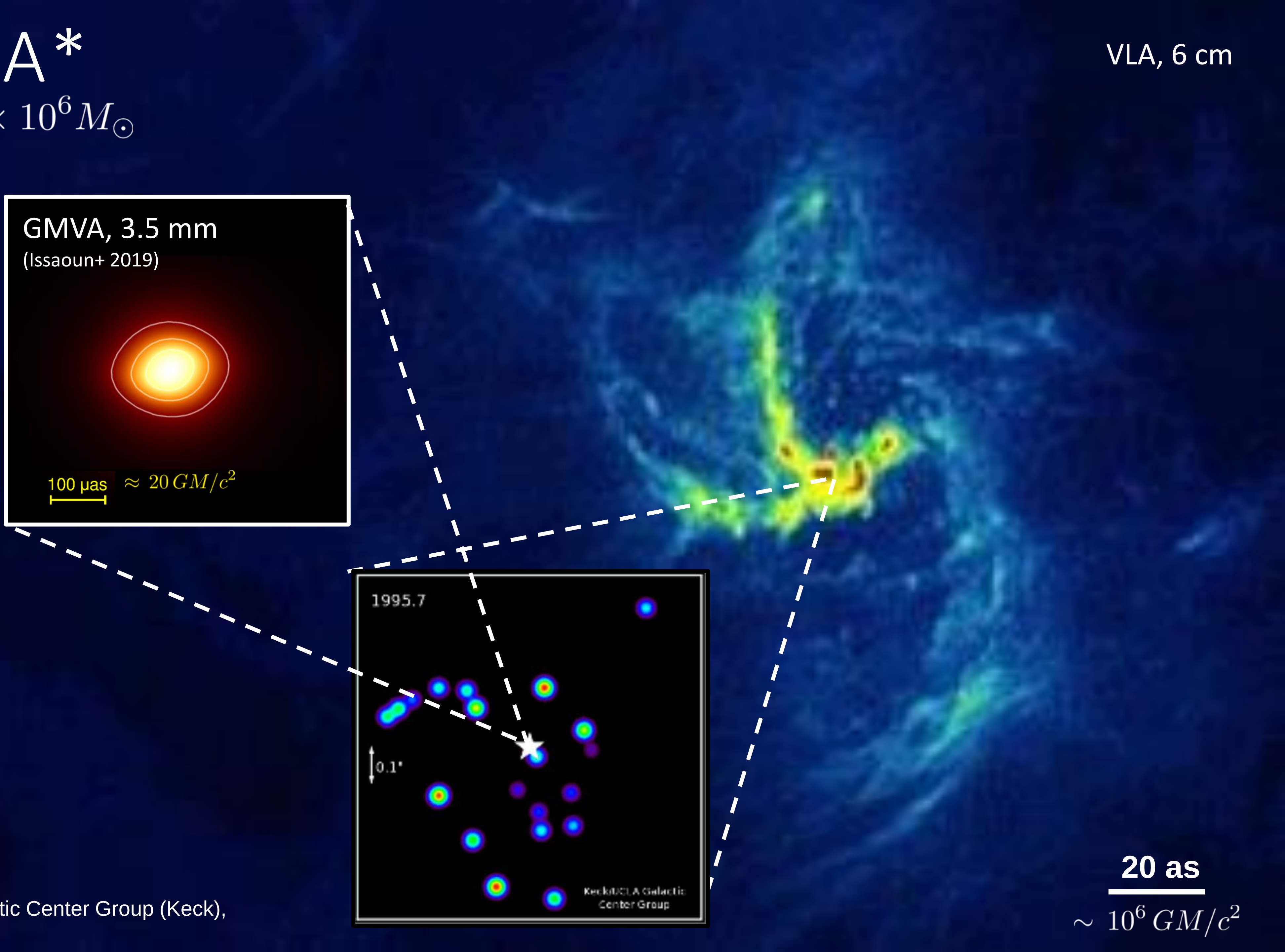
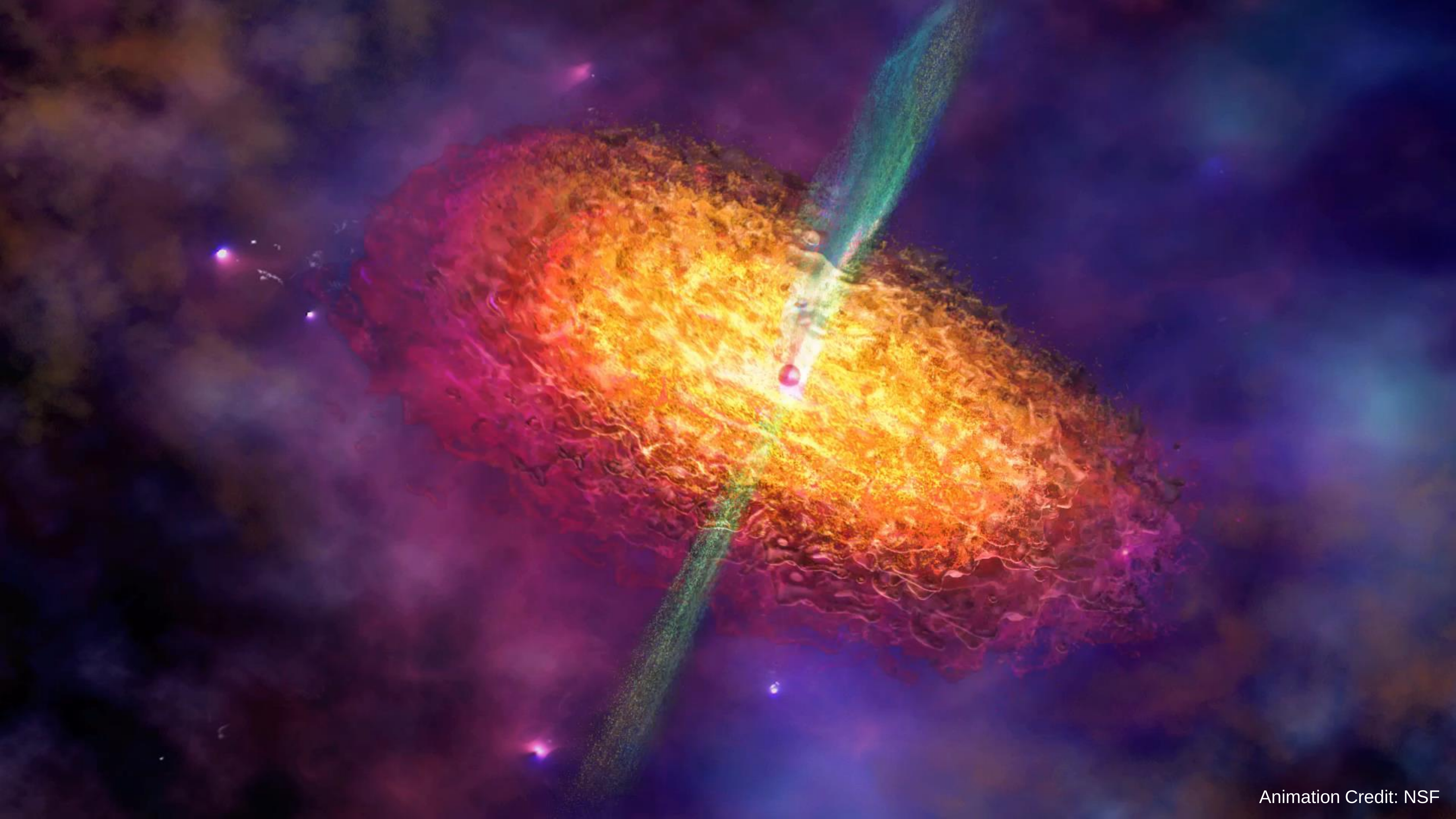
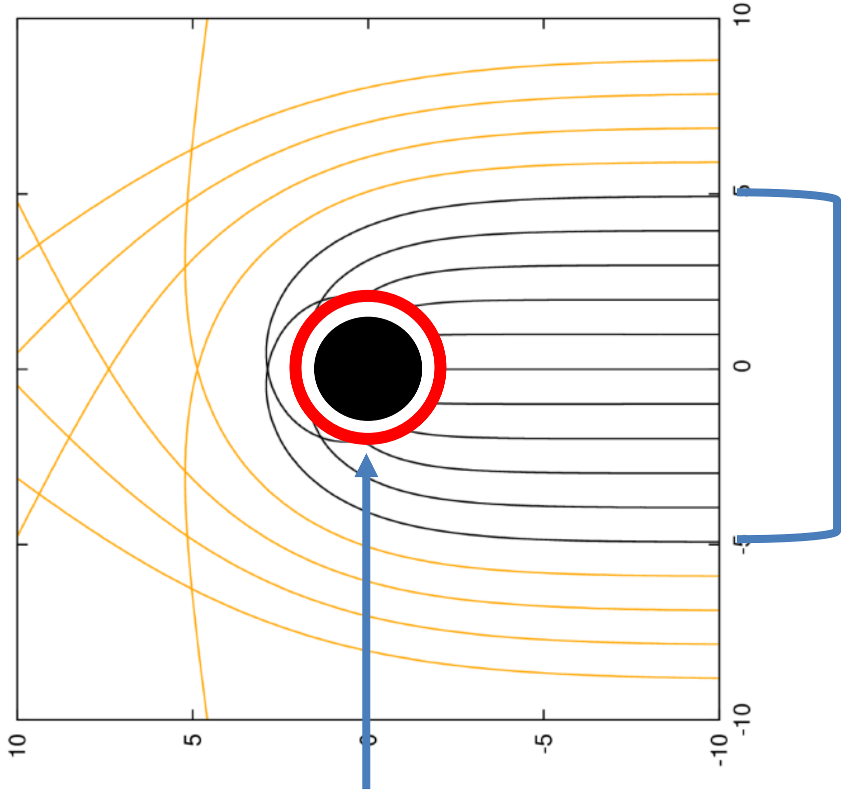


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

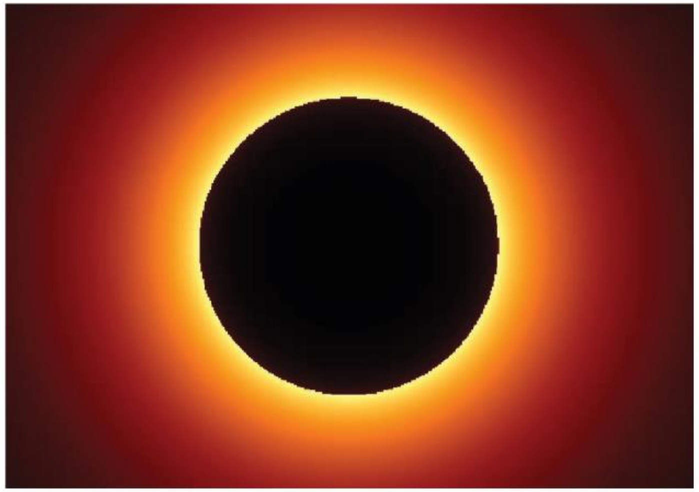

Animation Credit: NSF

The Black Hole Shadow



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

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

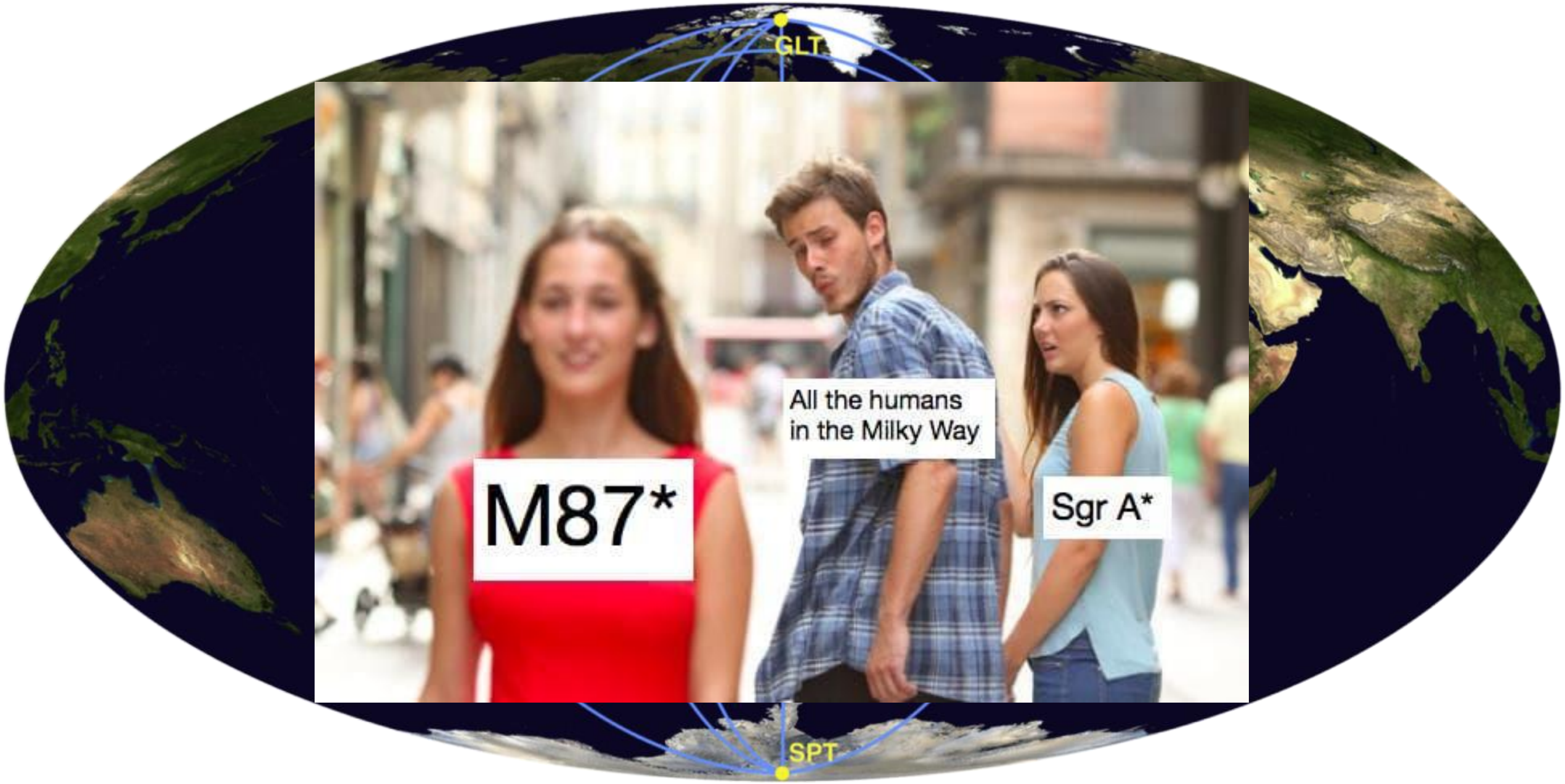


Sgr A*: d ≈ 50 μas

M87: d ≈ 40 μas

Image credit: Keiichi Asada

The Event Horizon Telescope



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

Image Credit:
EHT Collaboration 2019 (Paper II)

M87

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

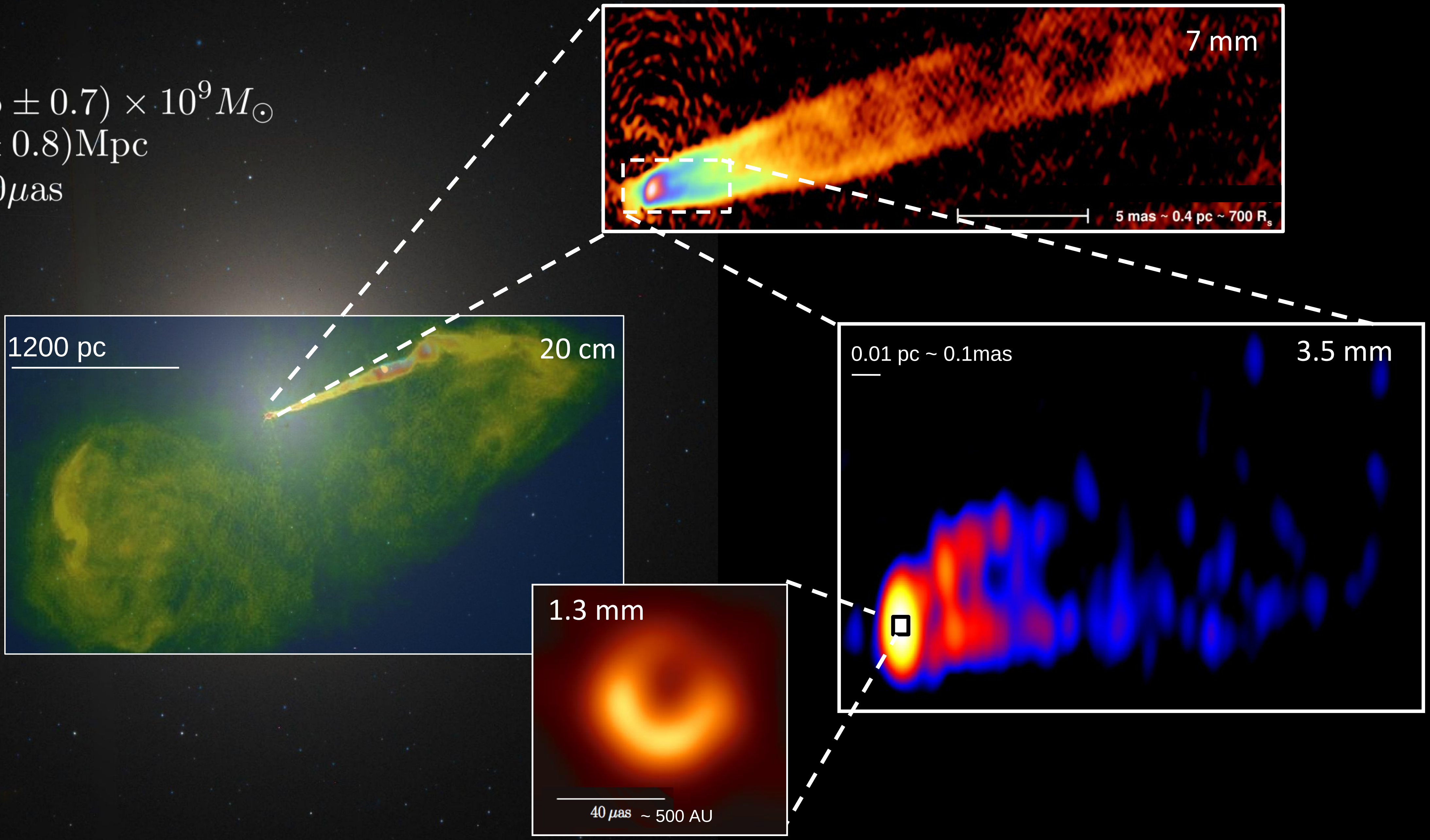
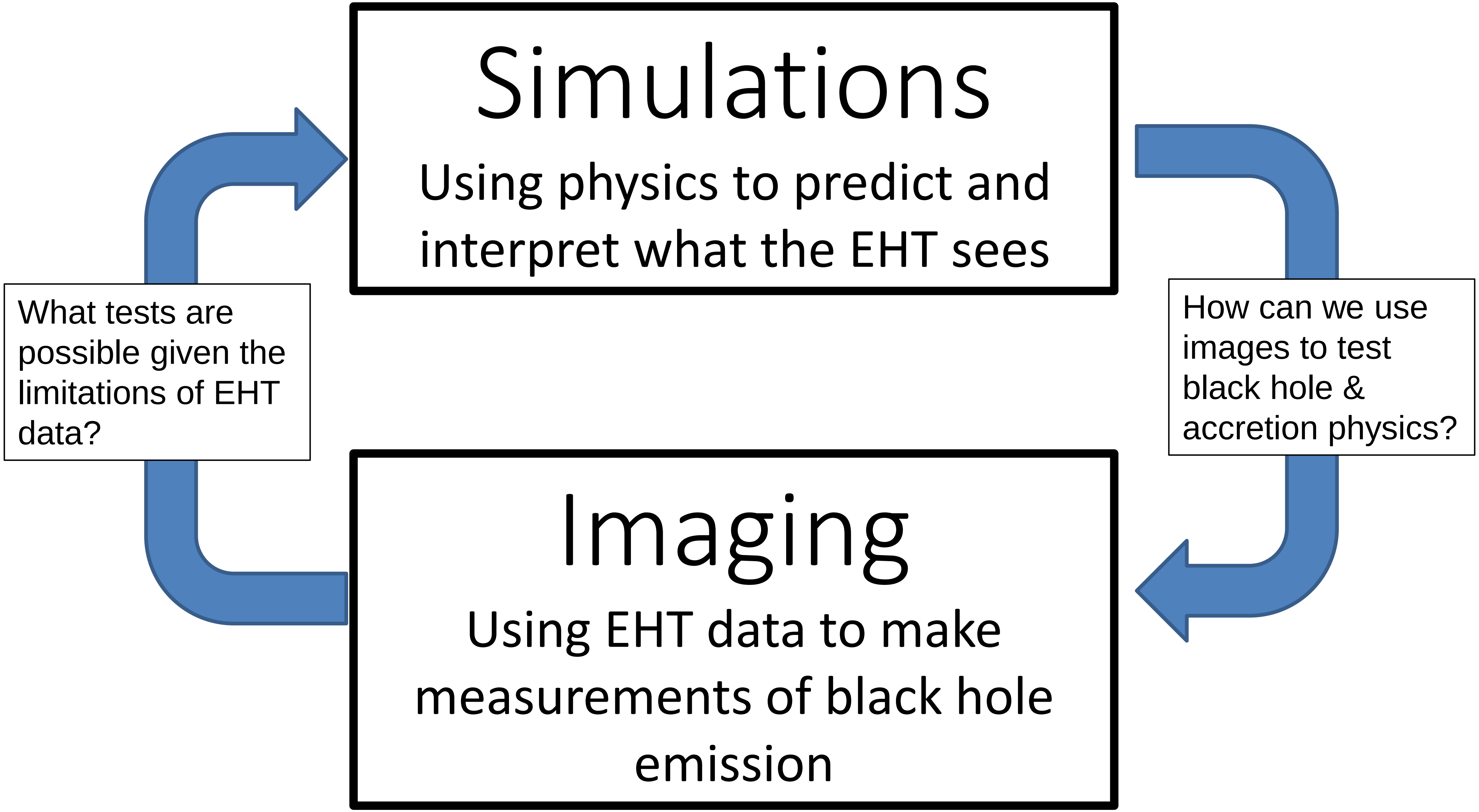


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)


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`
- Sgr A* and Nonthermal Electrons
- MAD Simulations of M87

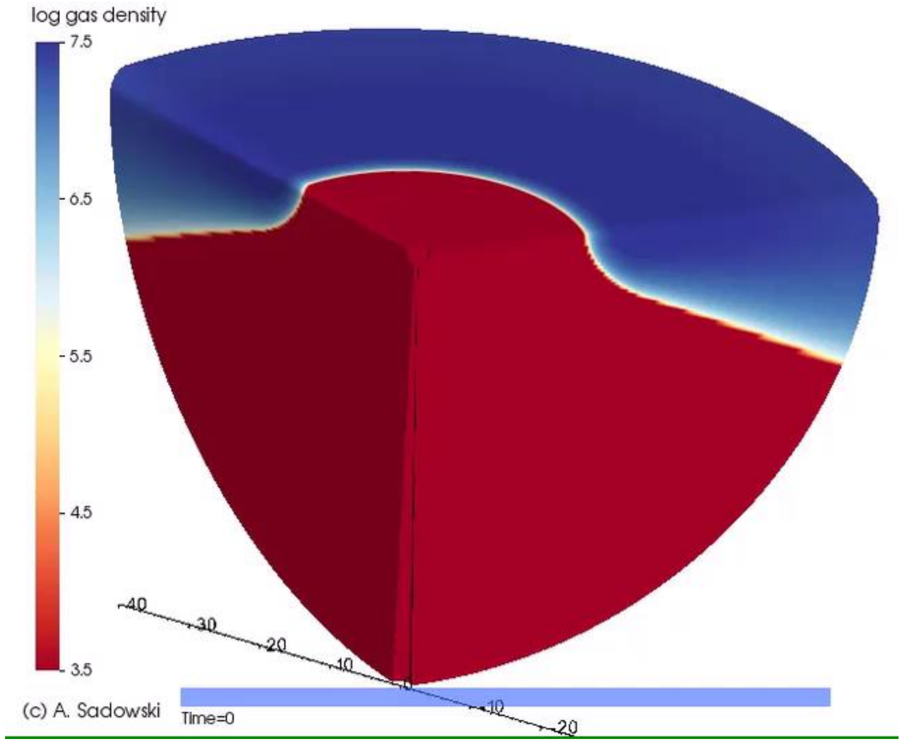
II. Imaging

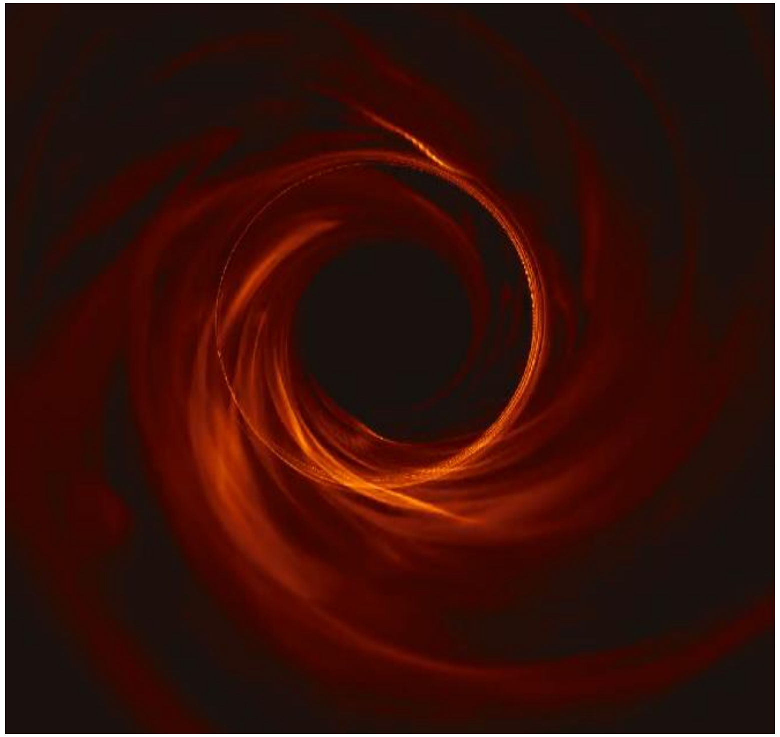
- Regularized Maximum Likelihood
- The eht-imaging library
- EHT Images of M87

Part I:
Simulating Accretion Flows with Electron Physics

General Relativistic MagnetoHydroDynamics

General Relativistic Ray Tracing





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

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.

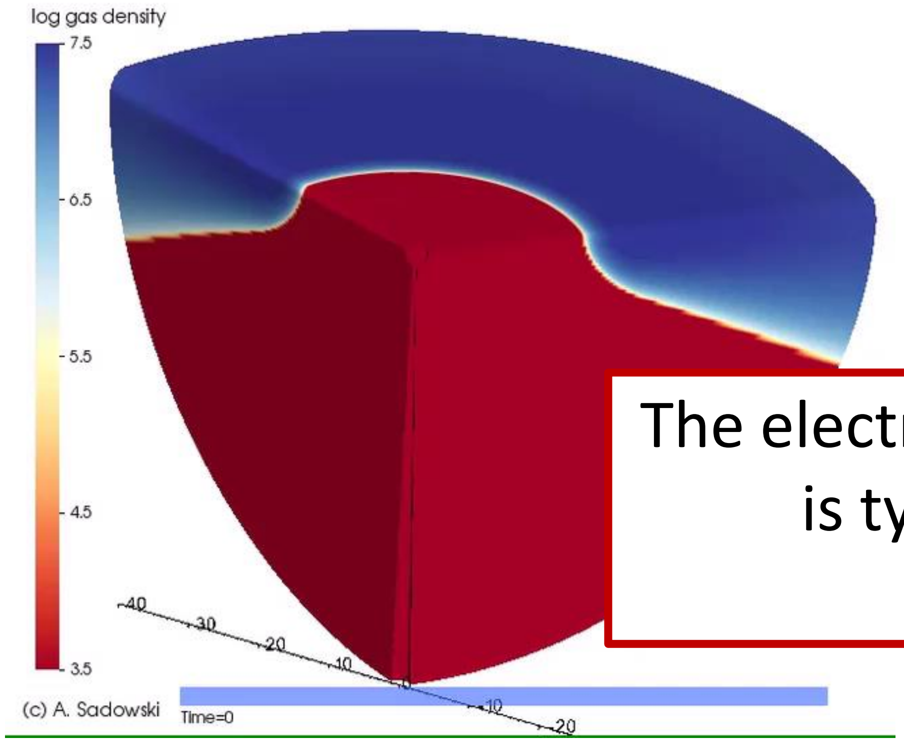
$$T_{\mathrm{e}} \neq T_{\mathrm{i}} \neq T_{\mathrm{gas}}$$

- 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



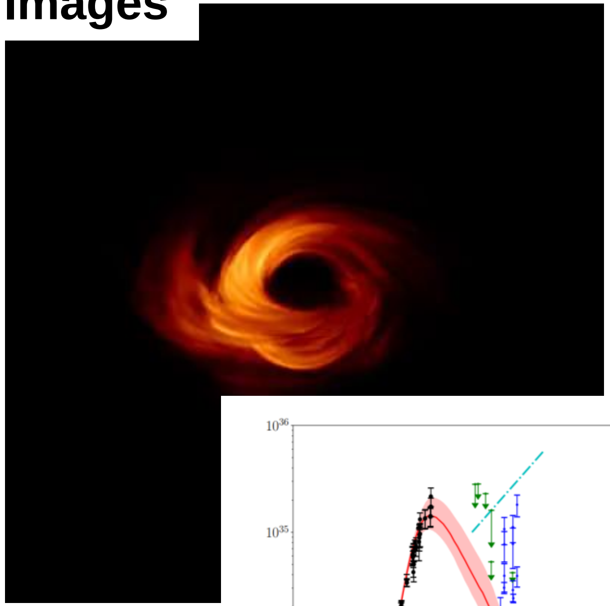
GRMHD Simulations

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

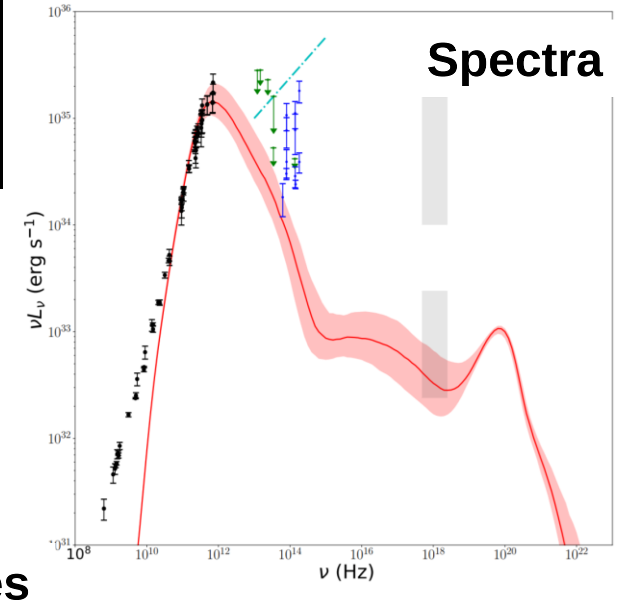
T_e?

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

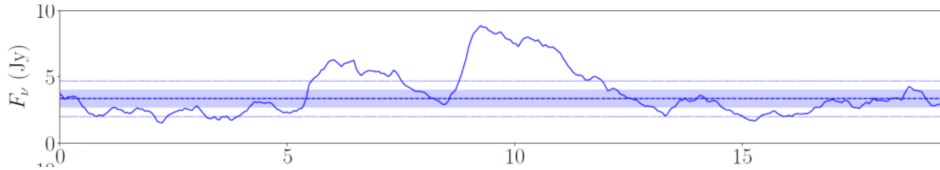
Images



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:

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

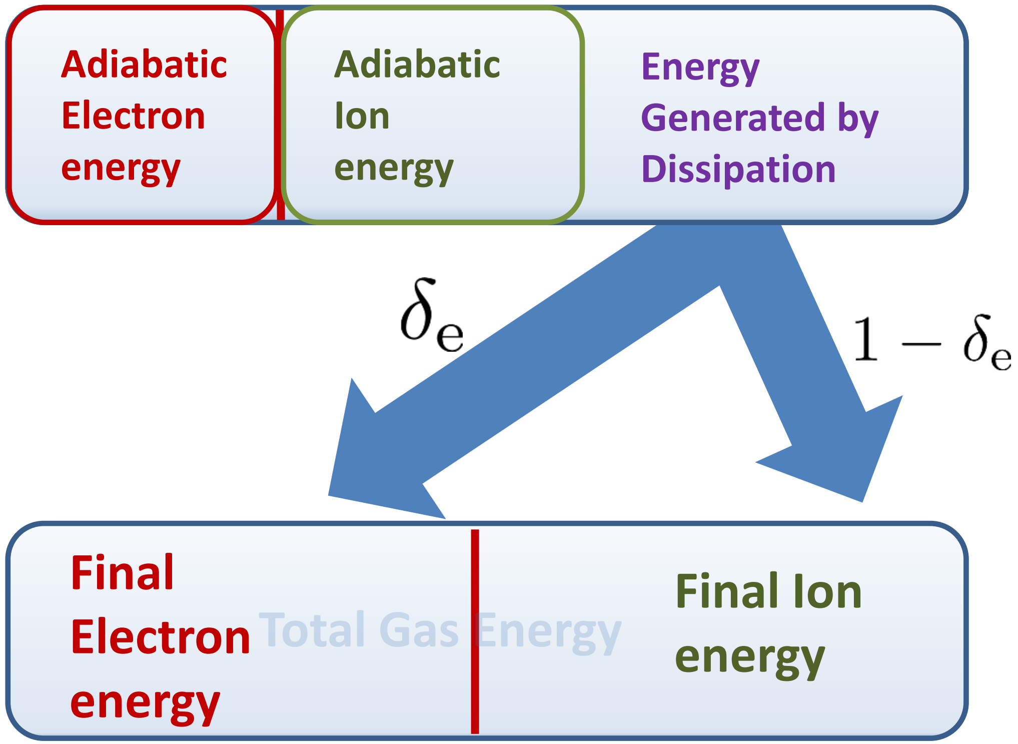
Adiabatic Compression and Expansion

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

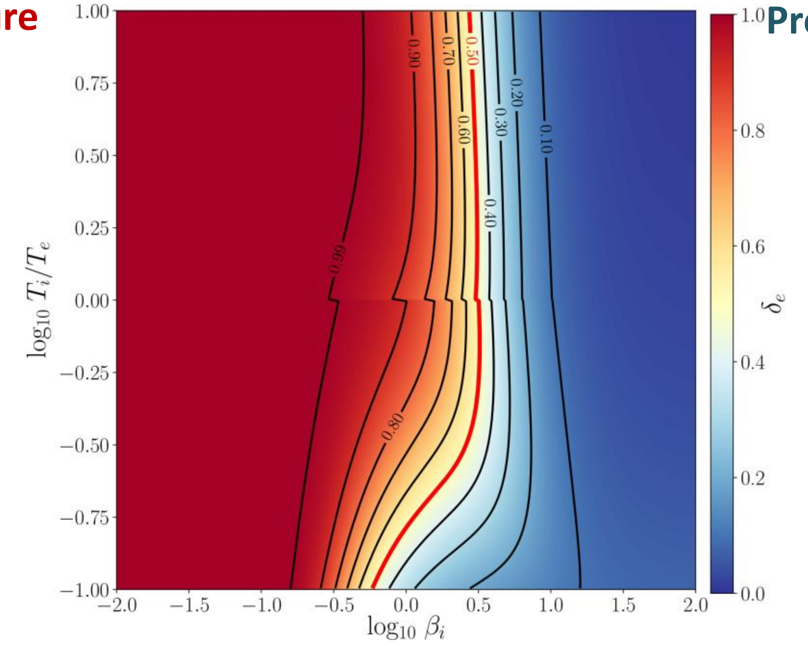
Turbulent Dissipation (Howes 2010)

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

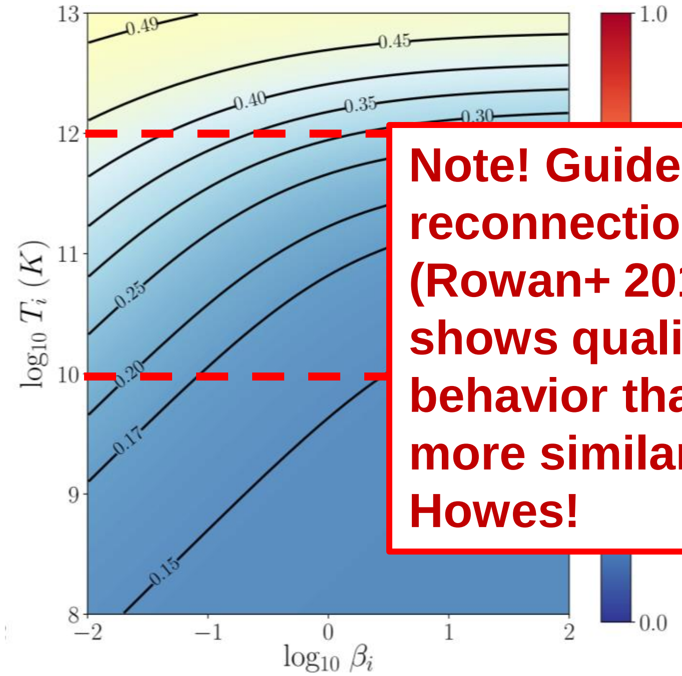
Magnetic Reconnection (Rowan+ 2017)

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

High Magnetic Pressure ⟷ Low Magnetic Pressure



Almost all energy to electrons ⟷ Almost all energy to ions



...ively flat δ_e ...large range of ...erature, beta.

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

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

Sgr A* Simulations

Previous work:

Ressler+ 2017

- A 3D, two-temperature simulation using the Howes+ 2010 prescription

- Results in a Natural “disk-jet” structure.

- Question: Is this structure dependent on electron heating?

30 GHz 230 GHz

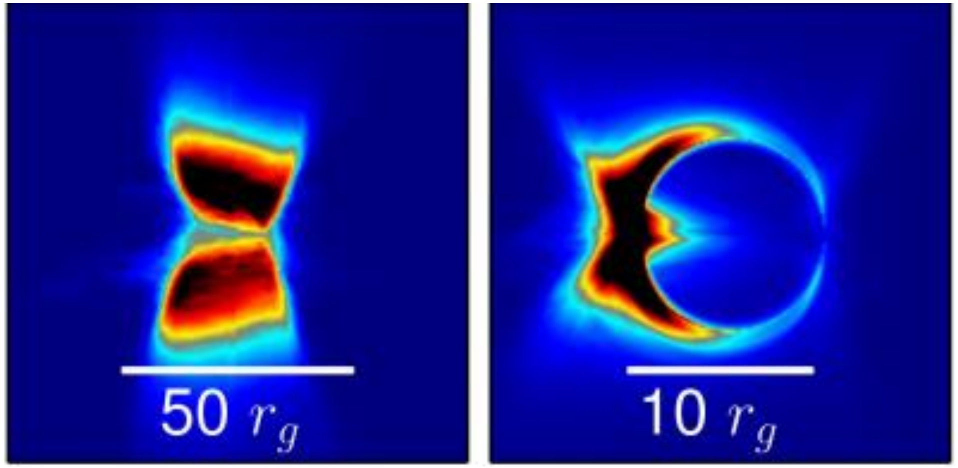


Image credit: Ressler+ 2017

Four Sgr A* Simulations

Spin 0
Turbulent
Heating

Spin 0.9375
Turbulent
Heating

All low magnetic flux (SANE)

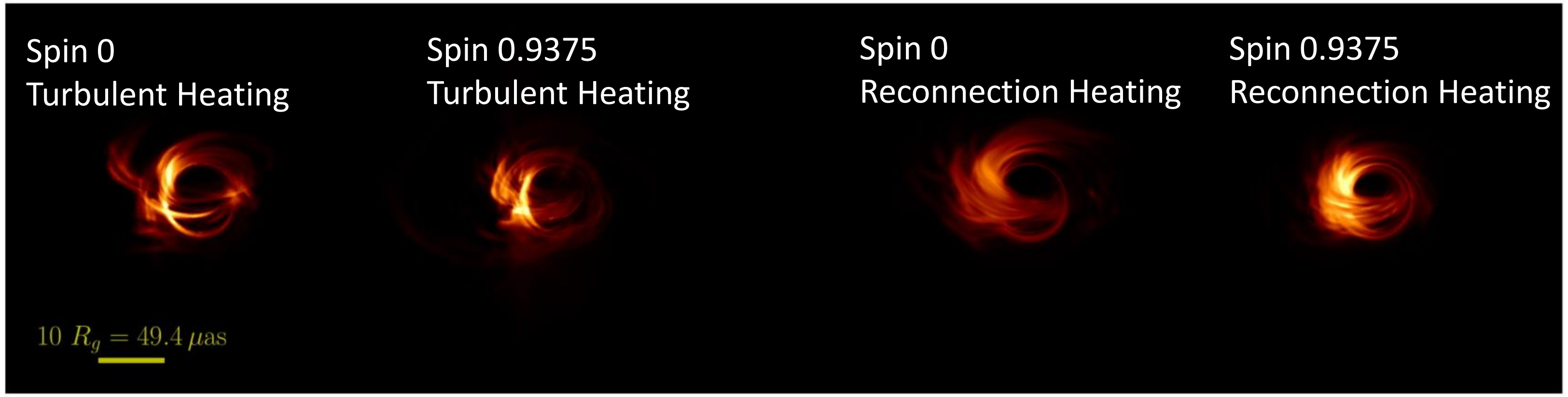
Spin 0
Reconnection
Heating

Spin 0.9375
Reconnection
Heating

Movie Credit: Chael+2018b

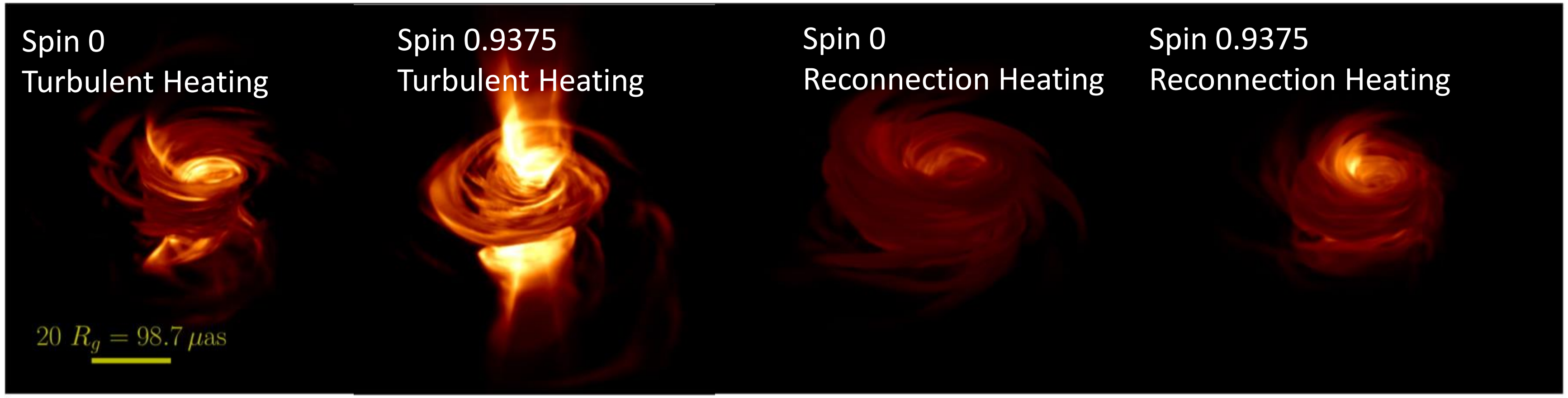
Sgr A*: *Image structure with frequency*

230 GHz



Where the EHT observes at 230 GHz, both heating prescriptions produce images with
distinct black hole shadows

43 GHz



Turbulent heating makes lower frequency images anisotropic and jet dominated –
exceeding estimates of intrinsic anisotropy when viewed edge-on (Johnson+ 2018, Issaoun+ 2018)

Image Credit: Chael+2018b

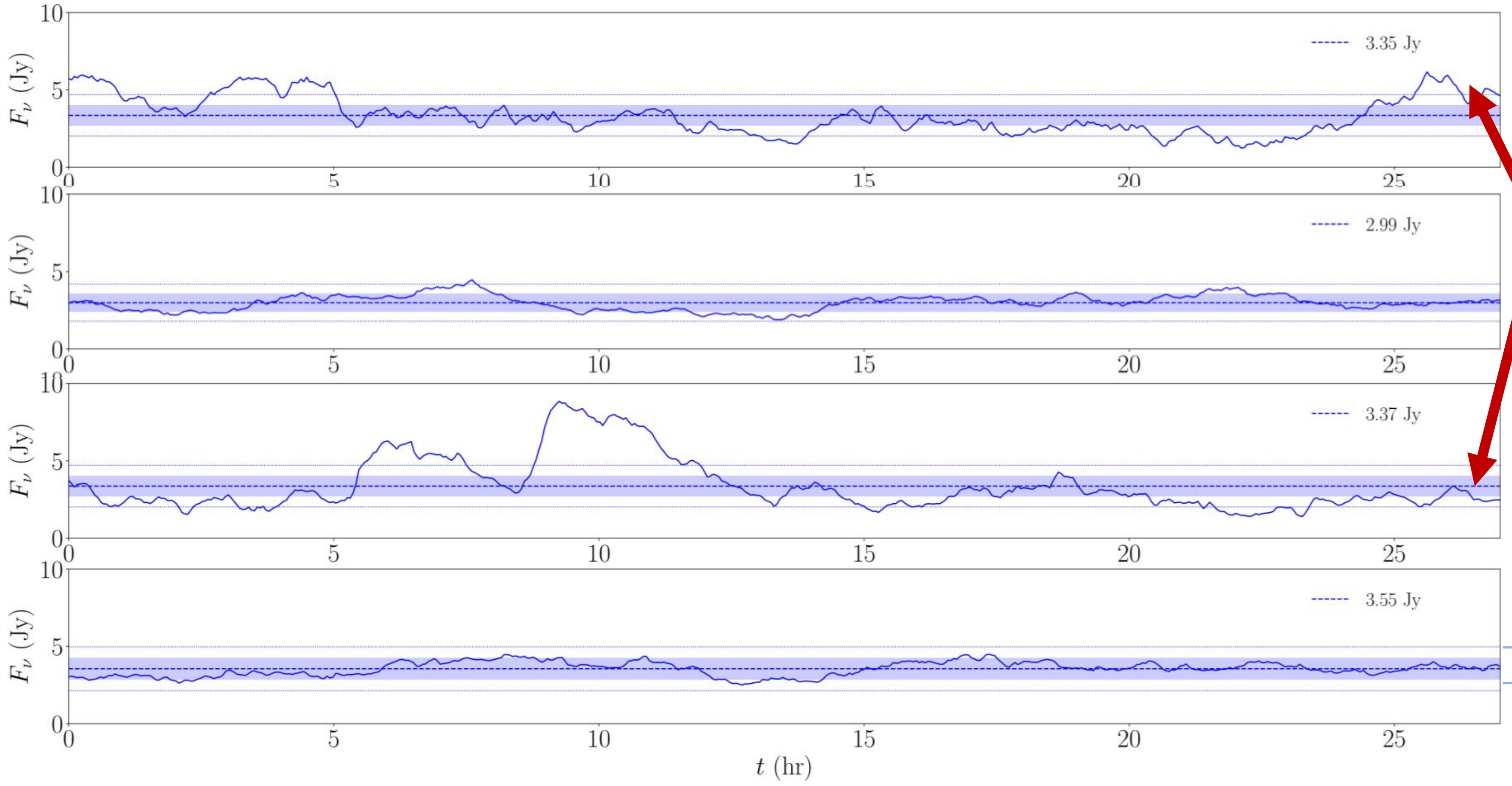
Sgr A*: *230 GHz variability*

Spin 0
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Turbulent Heating

Spin 0.9375
Reconnection Heating



Turbulent heated disks **exceed** observed 230 GHz variability

Rough estimate of 230 GHz intraday RMS flux variability (Bower et al. 2015)

Image Credit: Chael+2018b

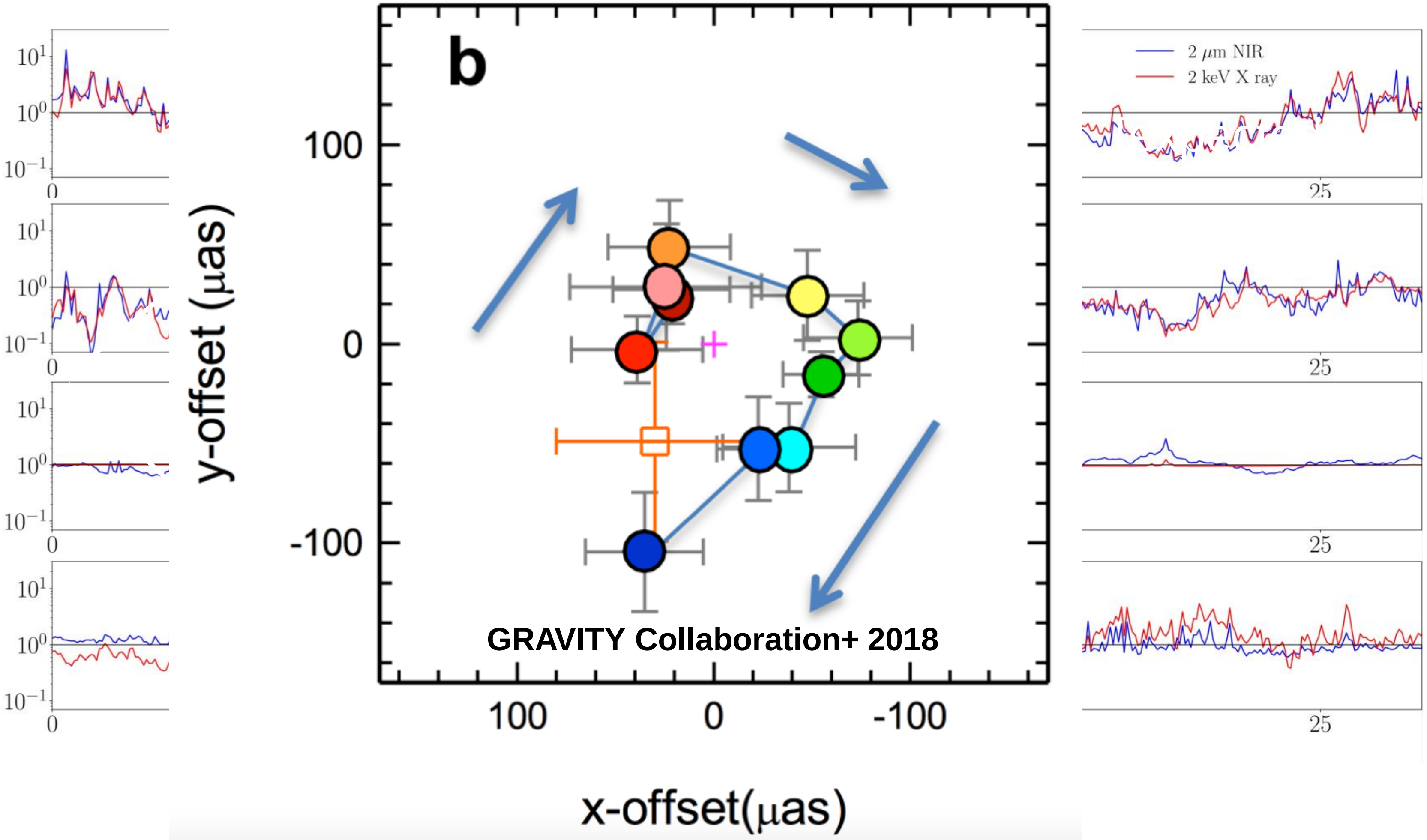
Sgr A*: *IR and X-Ray variability*

Spin 0
Turbulent Heating

Spin 0.9375
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Reconnection Heating



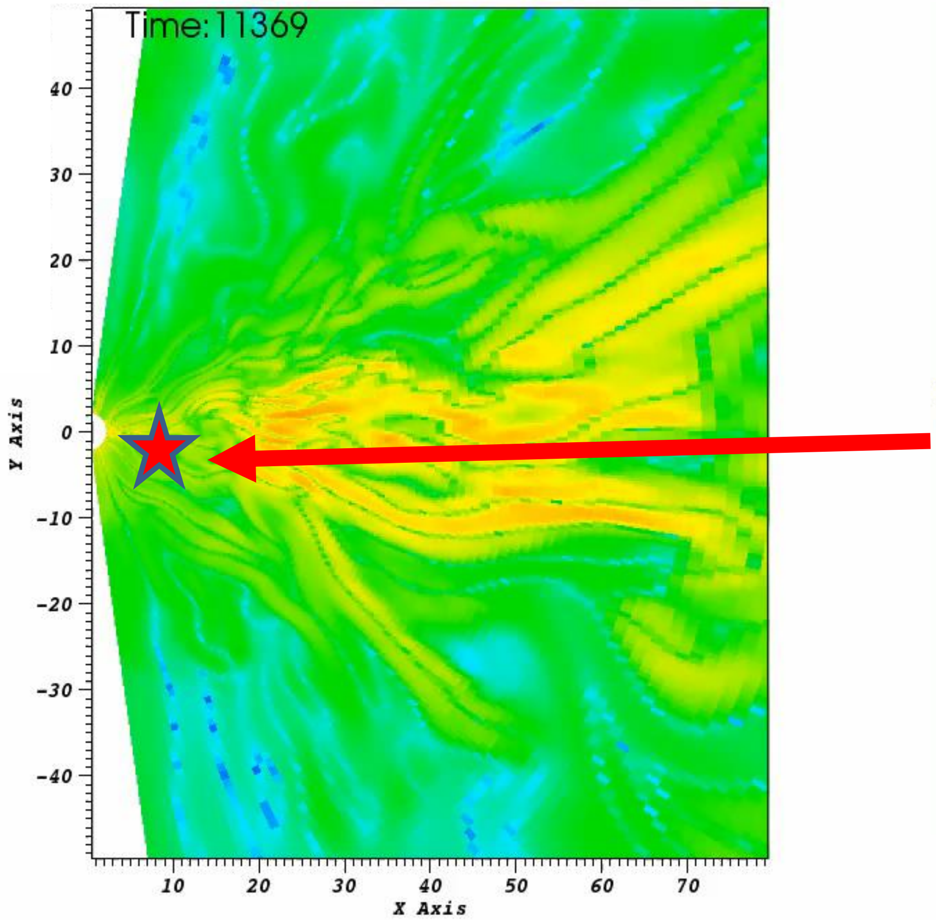
No models reproduce strong IR and X-ray flares

→Nonthermal Electrons (e.g. Ball+ 2016)

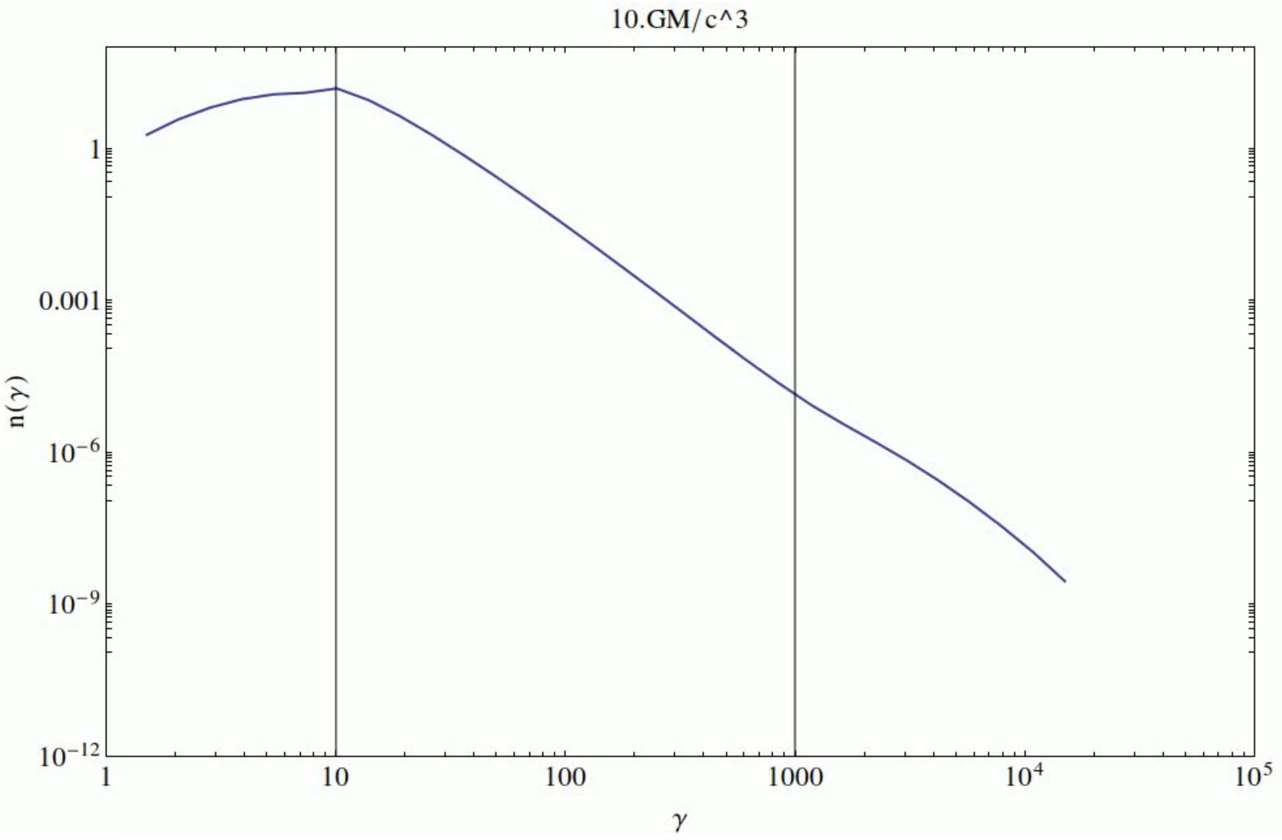
Image Credit: Chael+2018b, Gravity Collaboration+ 2018a

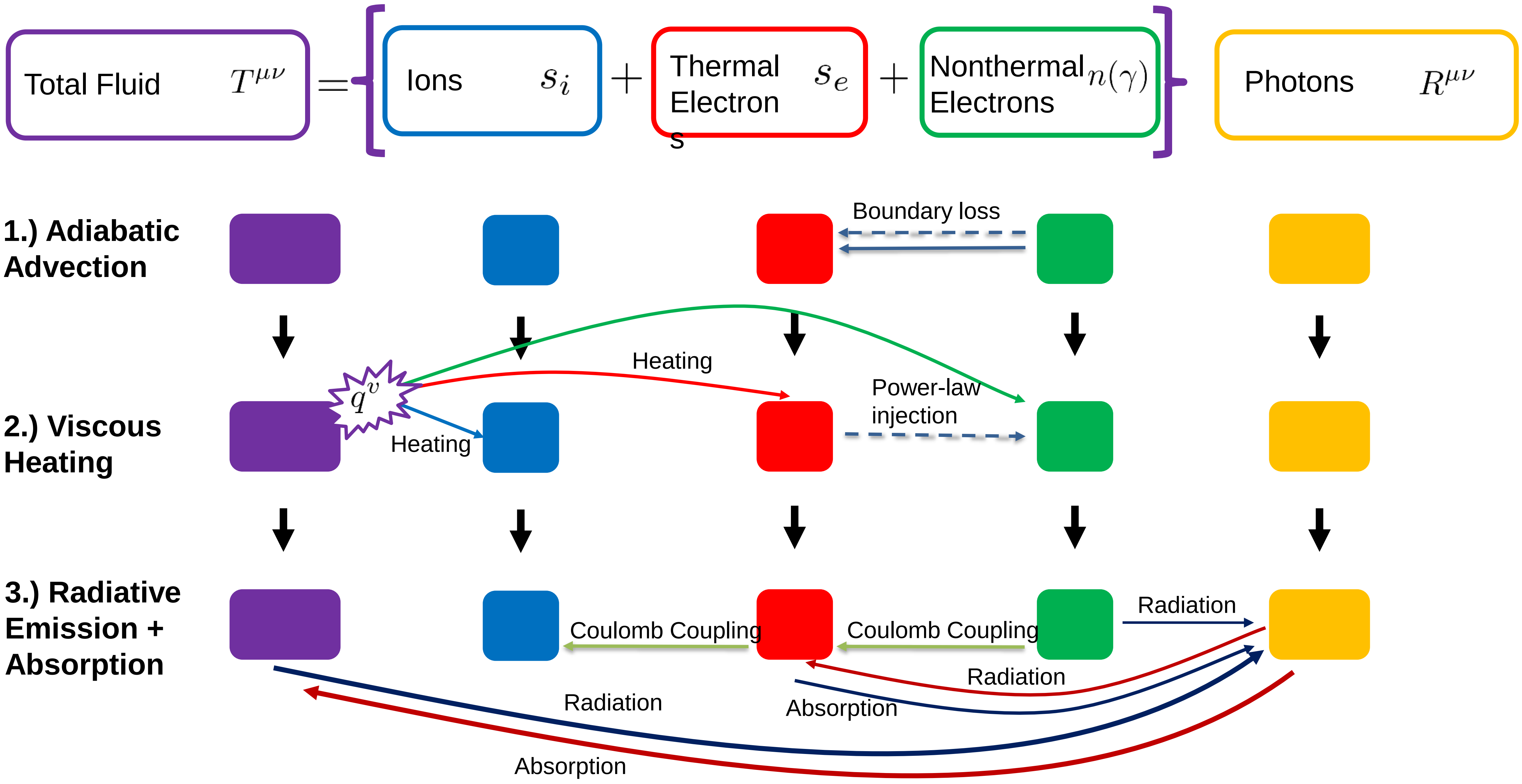
Simulating Flares: Evolving **nonthermal** electrons

Radiation Power



Nonthermal distribution @ 10 M





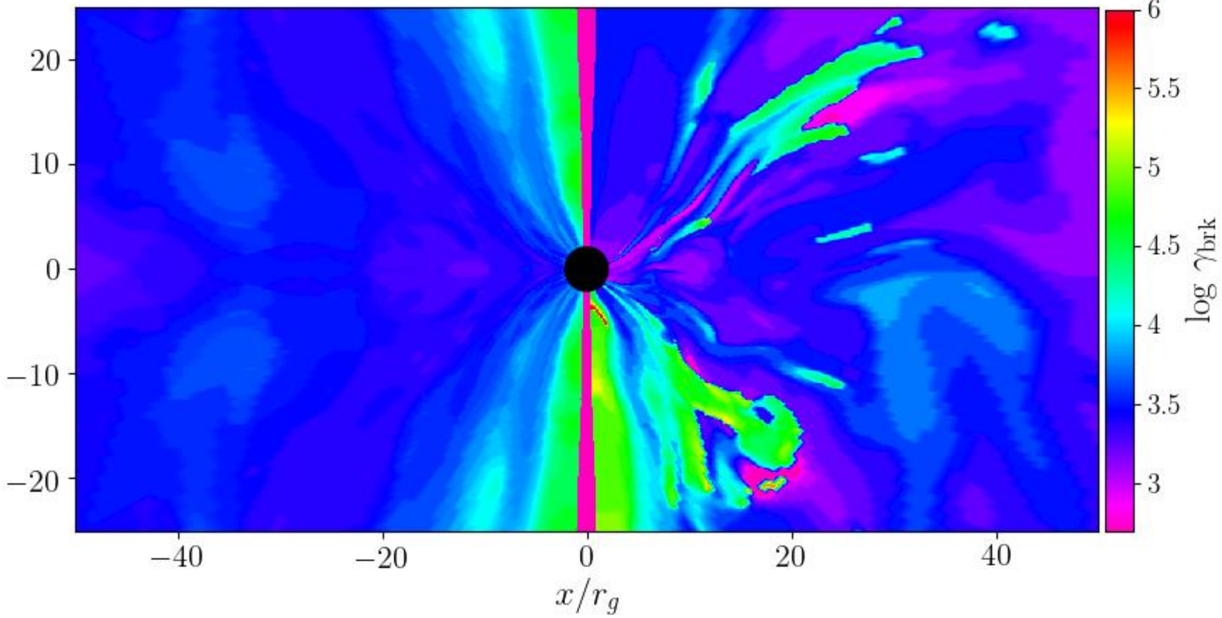
Total Fluid $T^{\mu\nu}$
$=$
Ions s_i
$+$
Thermal Electrons s_e
$+$
Nonthermal Electrons $n(\gamma)$
Photons $R^{\mu\nu}$
1.) Adiabatic Advection
Boundary loss
2.) Viscous Heating
q^v
Heating
Heating
Power-law injection
3.) Radiative Emission + Absorption
Coulomb Coupling
Coulomb Coupling
Radiation
Radiation
Absorption
Radiation
Absorption

Evolving **nonthermal** electrons in simulations

- New method to self-consistently evolve non-thermal spectra in parallel with two-temperature fluid.

Spatial distribution of nonthermal cooling break energy

Time-averaged



Snapshot

- First 3D simulations with realistic electron acceleration are on the way!
  - (Ball+ 2018): Magnetic reconnection PIC simulations give $p = 2.5$ (Ponti+ 2017) at $\sigma \approx 1$
  - Jet sheath as acceleration site?

Image Credit: Chael+ 2017

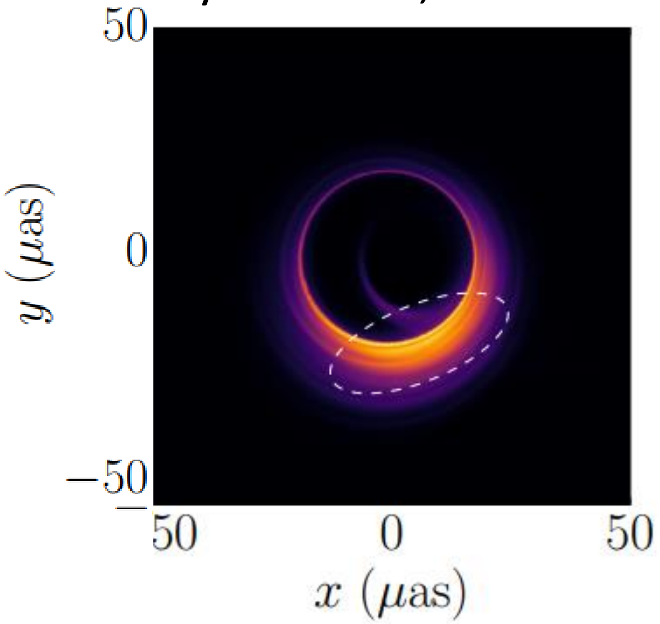
M87 Simulations

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

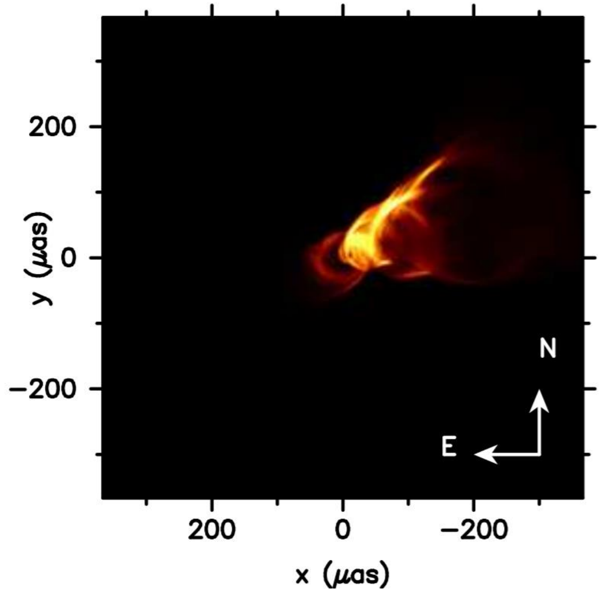
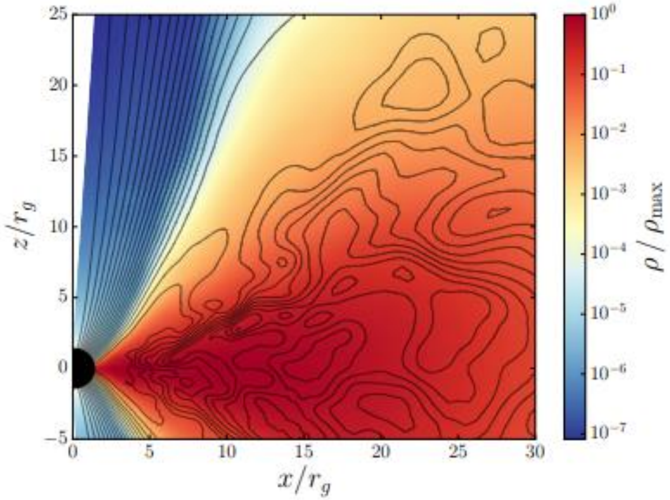


Image Credit: Ryan+ 2018, Moscibrodzka+ 2016
Also: Dexter+ 2012,, 2017

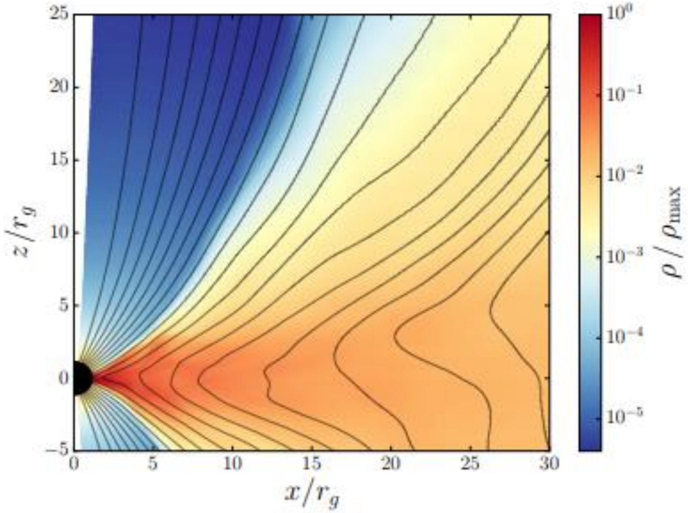
SANE vs MAD

- Two accretion states according to accumulated magnetic flux on horizon:

Magnetic fields are turbulent



SANE: Standard And Normal Evolution



MAD: Magnetically Arrested Disk

Coherent magnetic fields build up on the horizon

- Blandford-Znajek (1977): $P_{\rm jet} \propto \Phi_{\rm mag}^2 \Omega_{\rm H}^2$

Magnetic flux

Angular velocity of the horizon

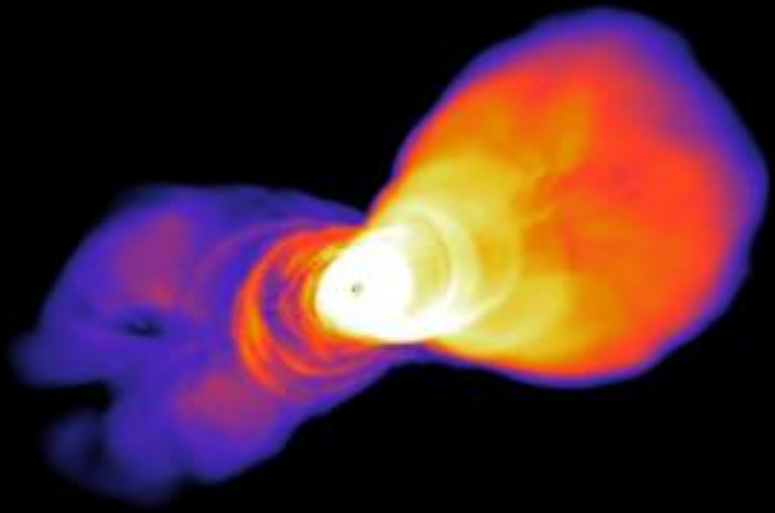
Image credit: Riordan+ 2017

Two M87 simulations

43 GHz jets

0.0 yr

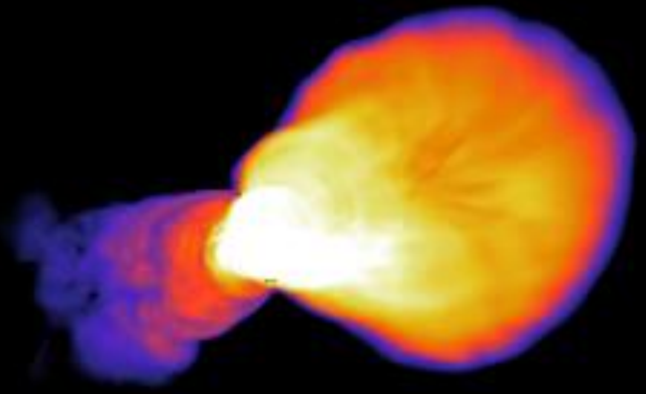
Turbulent Heating



$P_{\rm jet}$ is too small!

$500\ \mu$as

Reconnection Heating



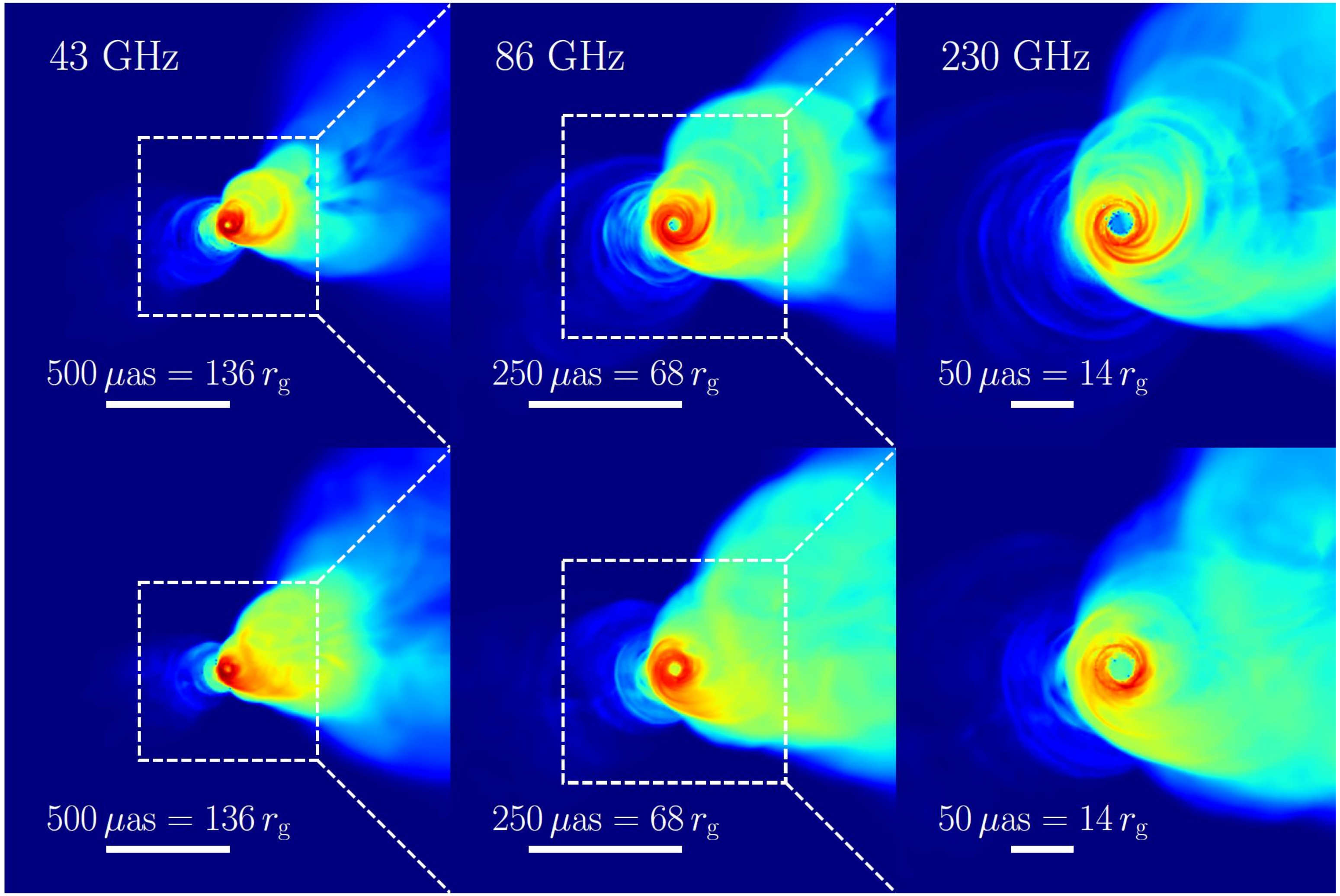
$P_{\rm jet}$ in the measured range!

Movie Credit: Chael+ 2019

M87 Jets at millimeter wavelengths

Turbulent Heating

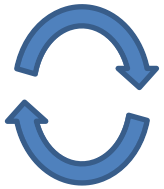
Reconnection Heating



Inclination angle (down from pole)

17°

Disk/Jet rotation sense

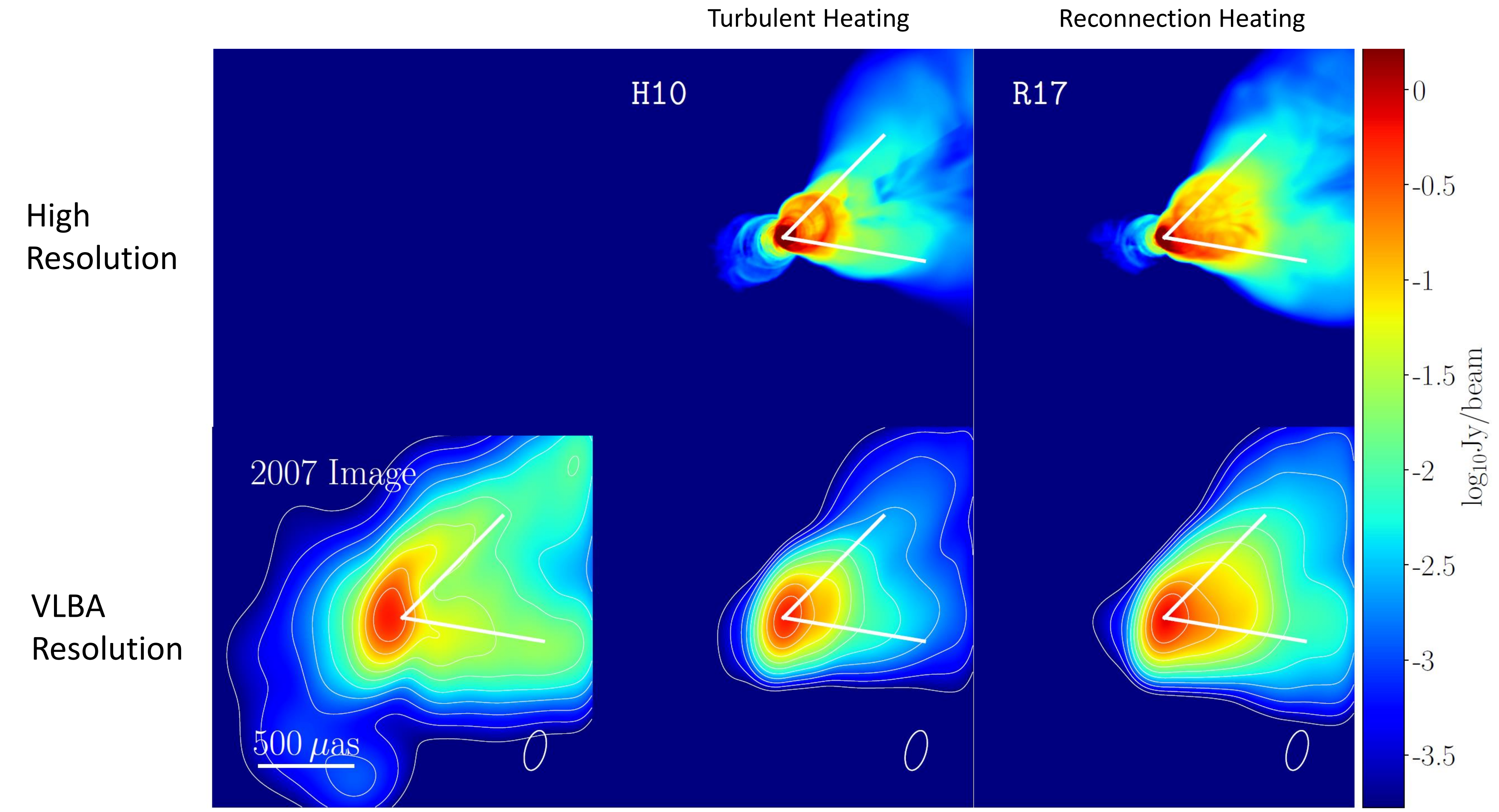


Wide apparent opening angles get **larger** with increasing frequency

Image Credit: Chael+ 2019

43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

$55°$

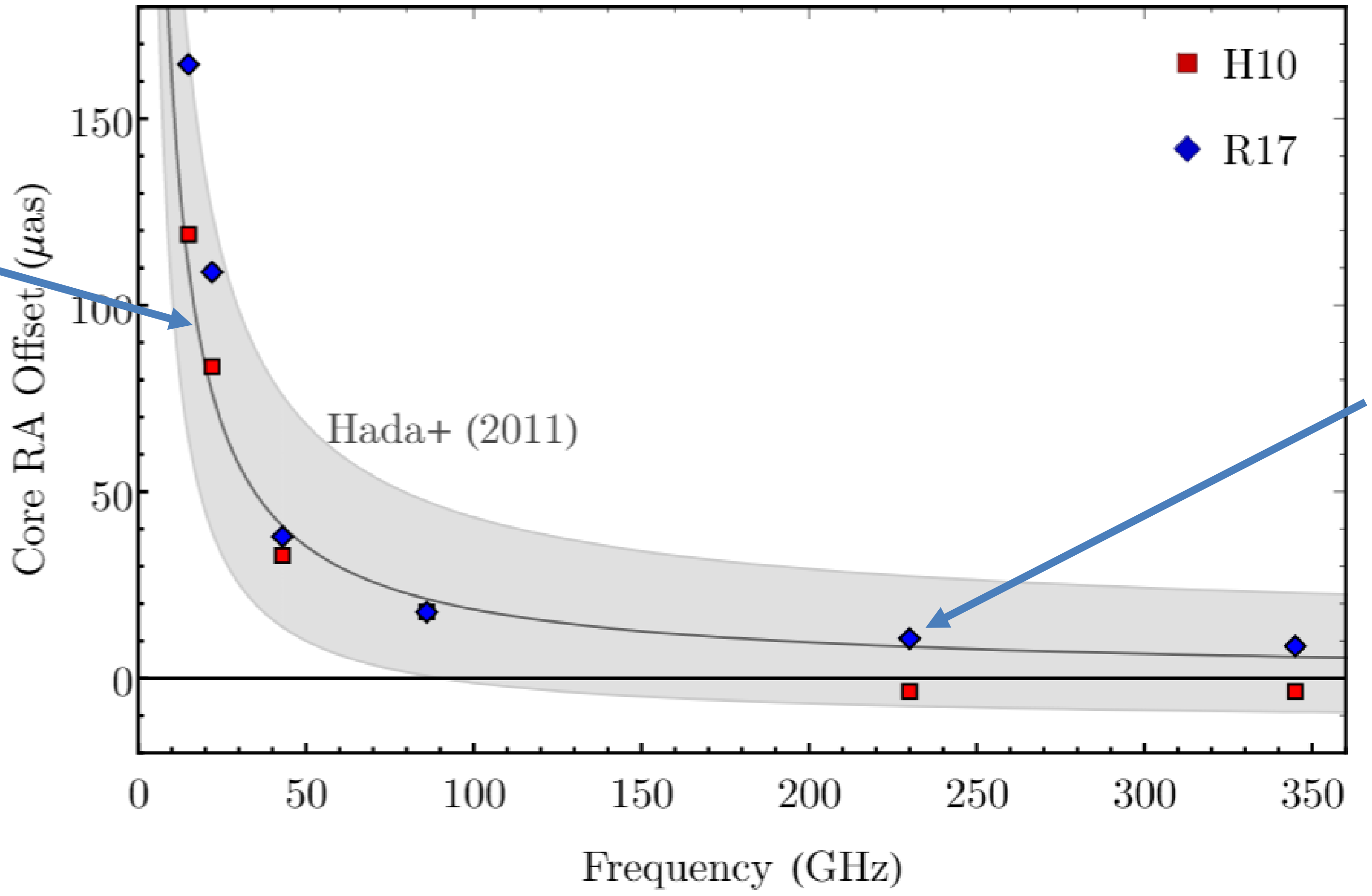
(Walker+ 2018)

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

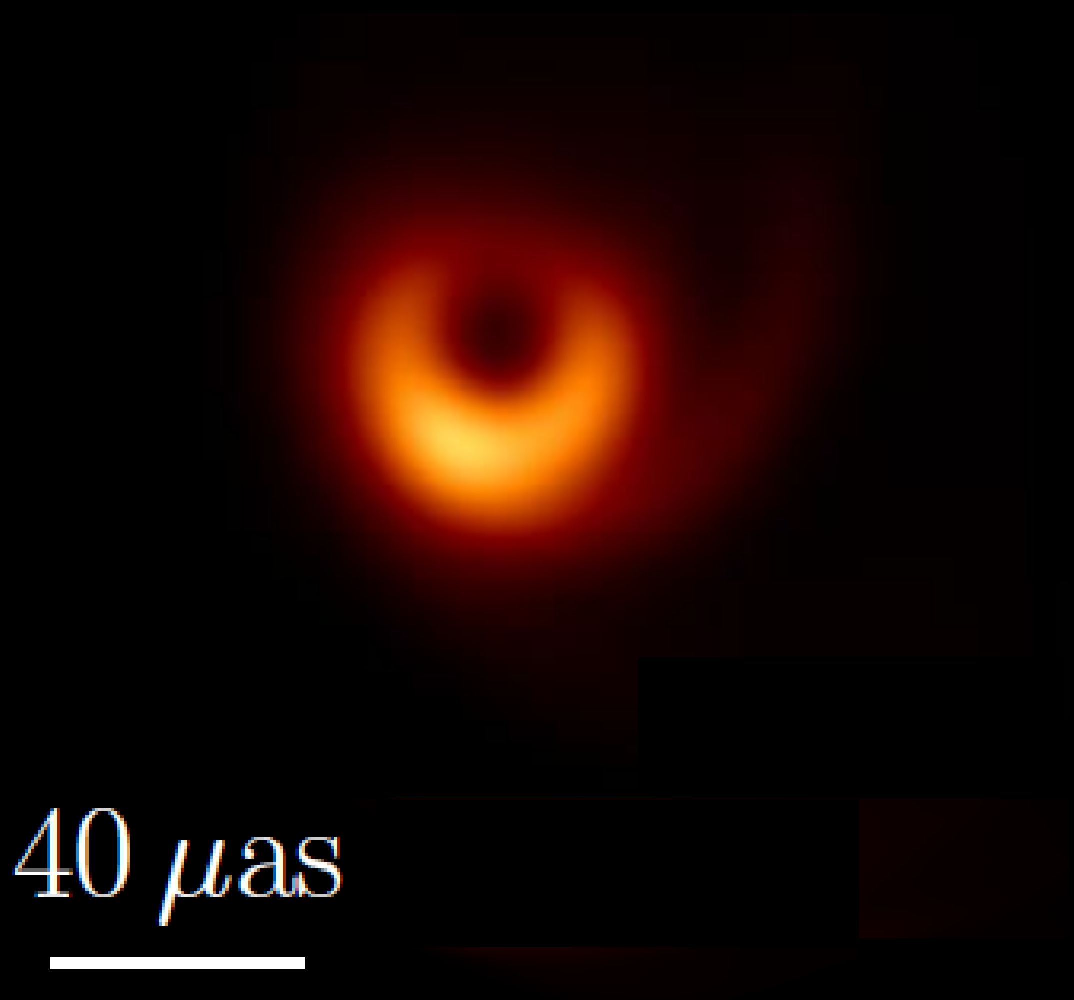
Turbulent Heating

Reconnection Heating

$40\ \mu\mathrm{as}$

230 GHz Images

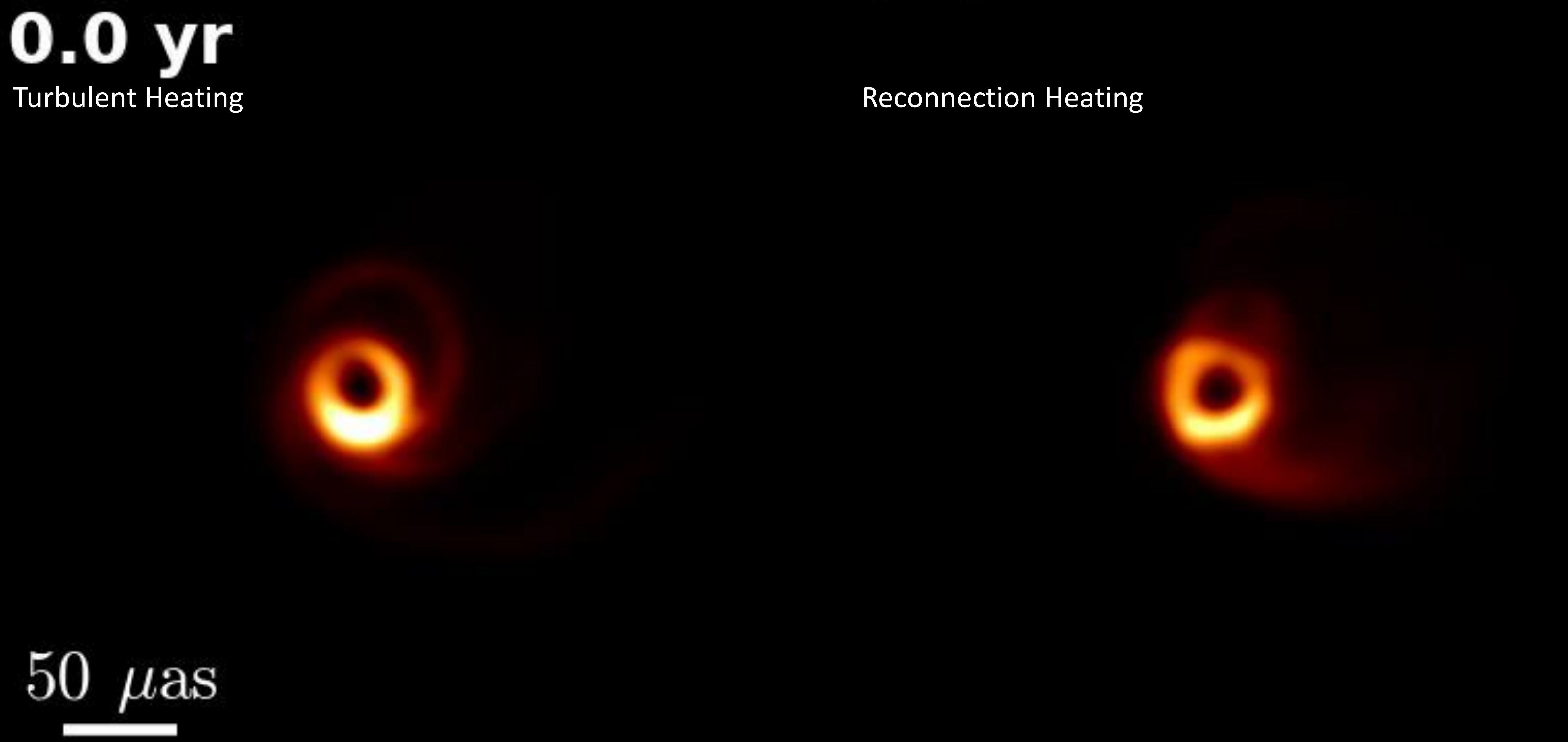
Turbulent Heating



Reconnection Heating

Image Credit: Chael+ 2019

230 GHz Images



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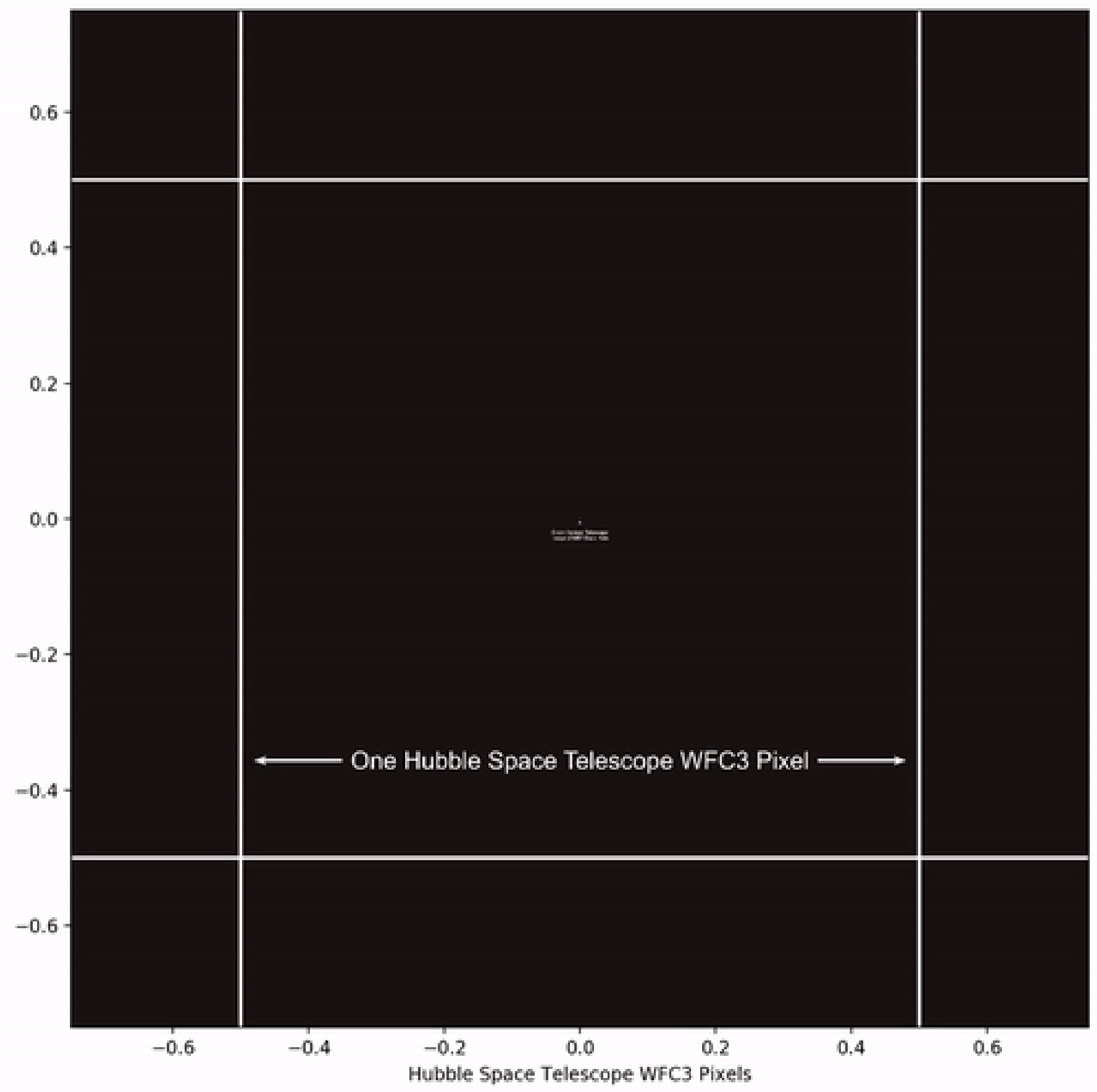
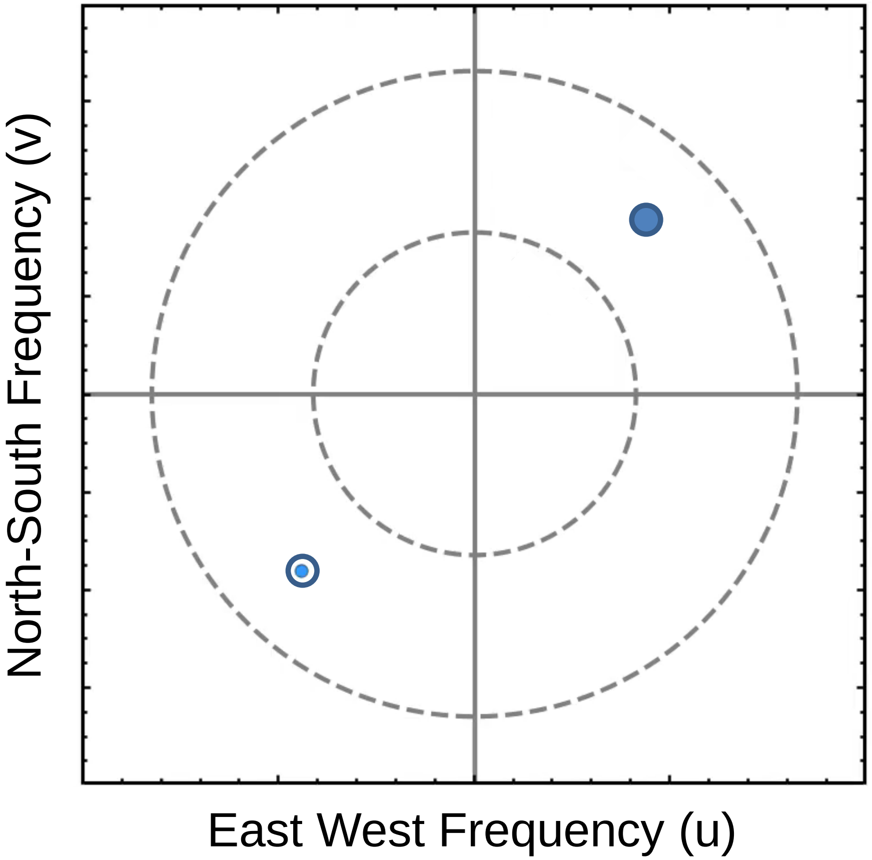
Part II:
Imaging a Supermassive Black Hole

How small is 40 microarcseconds?



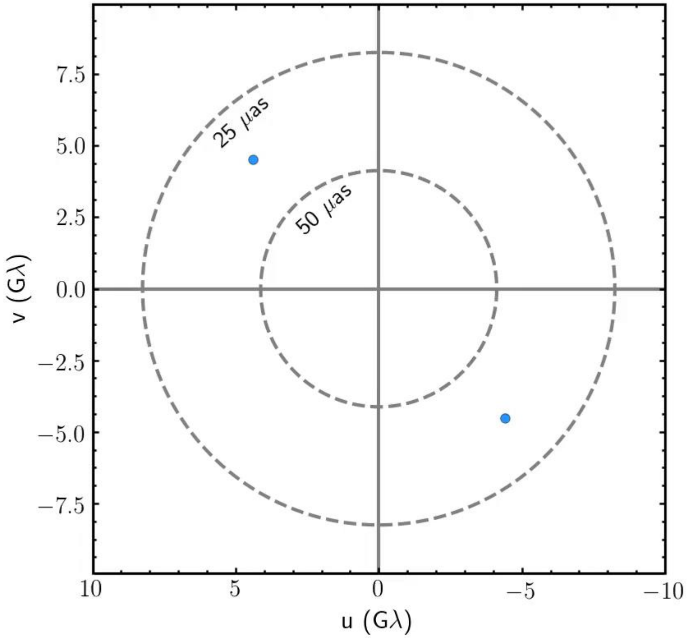
Animation credit: Alex Parker

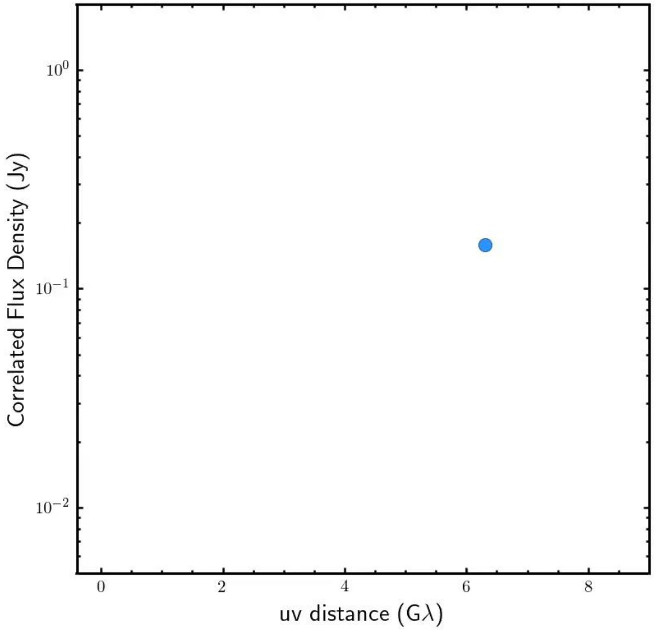
Very Long Baseline Interferometry (VLBI)



Slide Credit: Katie Bouman

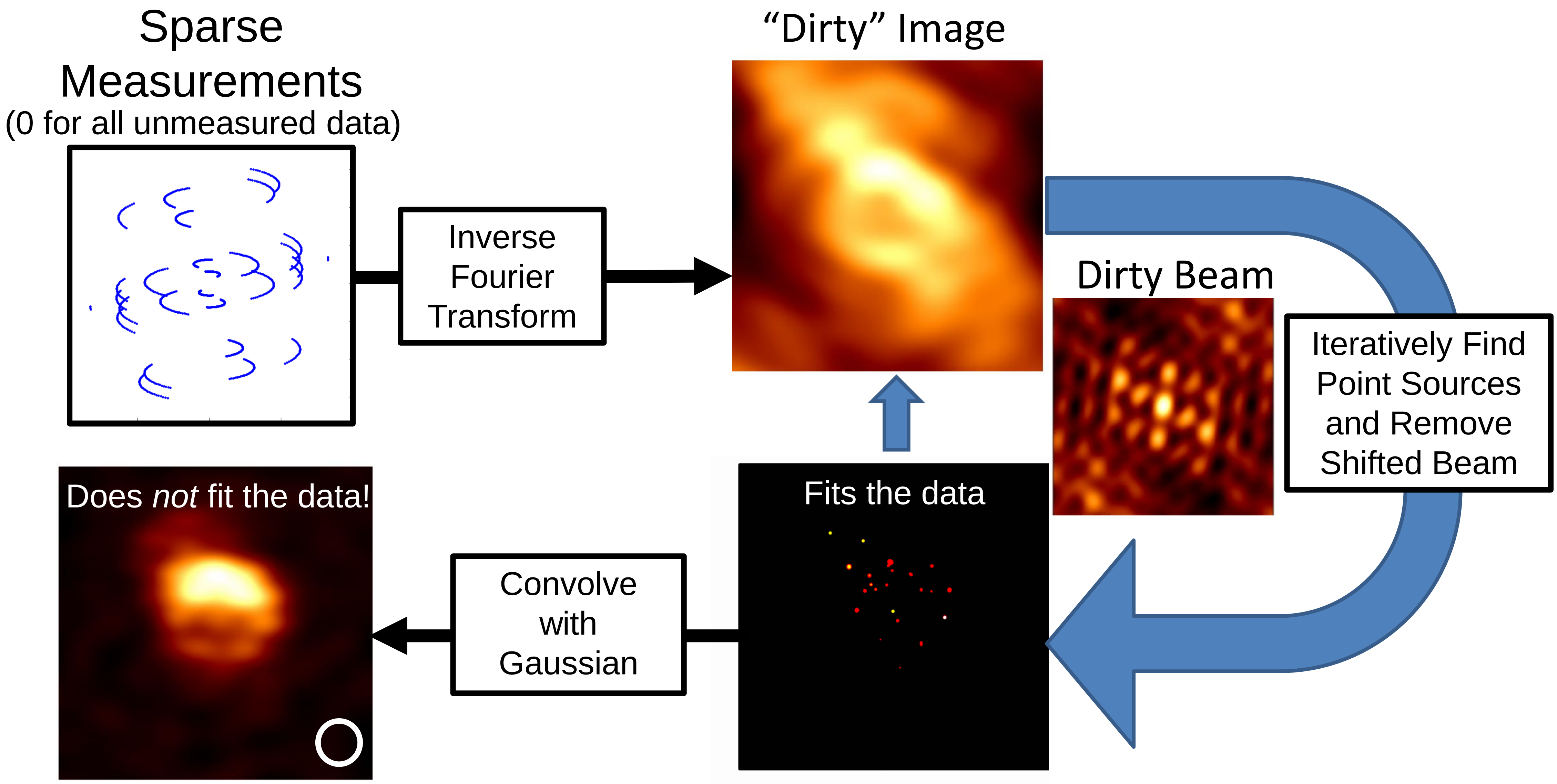
Earth Rotation Aperture Synthesis





Movie Credit: Daniel Palumbo

Traditional Approach: CLEAN



Simulation Credit: Avery Broderick

Closure Quantities

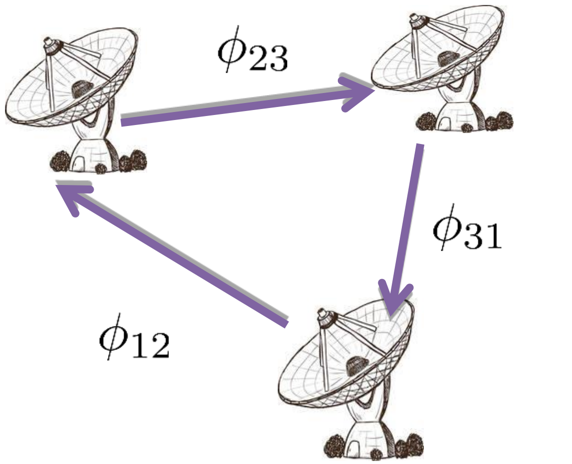
- Visibilities are corrupted by **station-based** gain errors

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

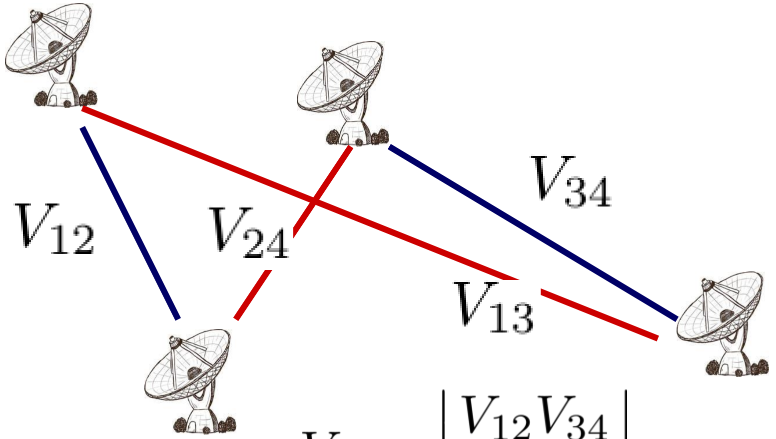
Amplitude: slower, from incorrect sensitivity

Phase: fast, from atmosphere

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



$$\psi_C = \phi_{12} + \phi_{23} + \phi_{31}$$



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

“Bayesian” Model Inversion

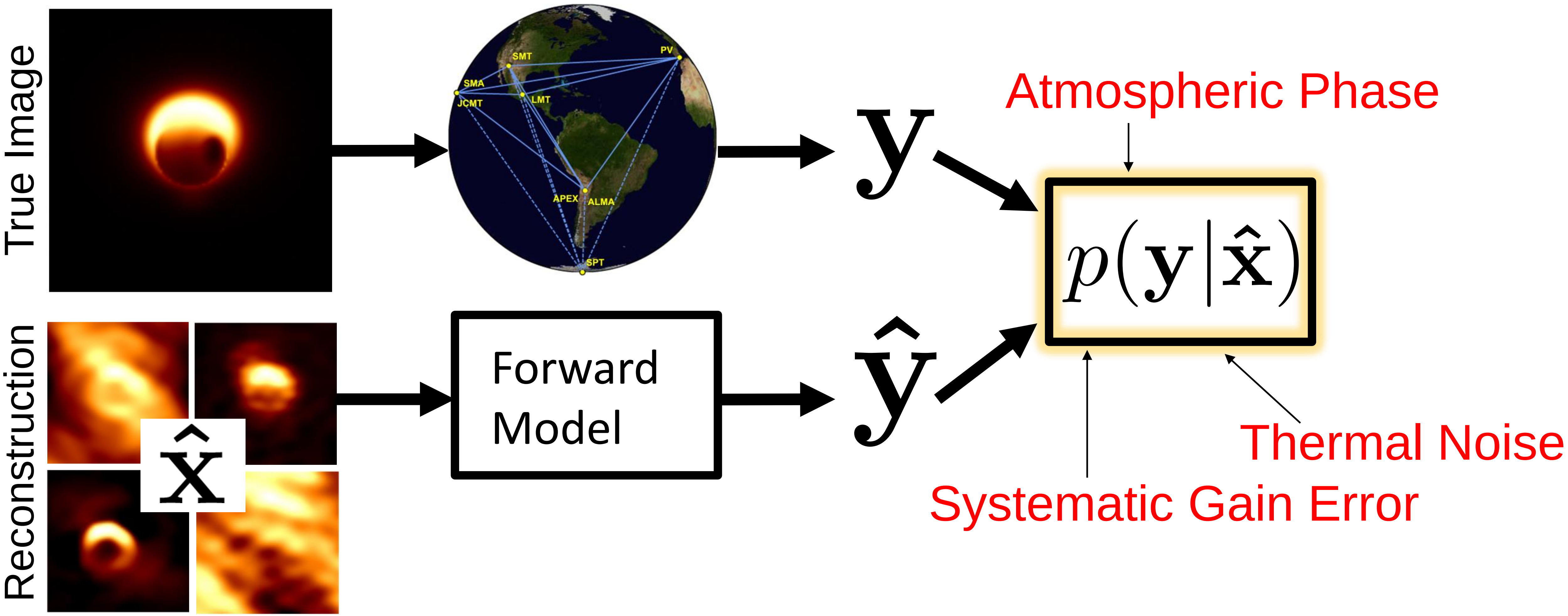


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

“Bayesian” Model Inversion

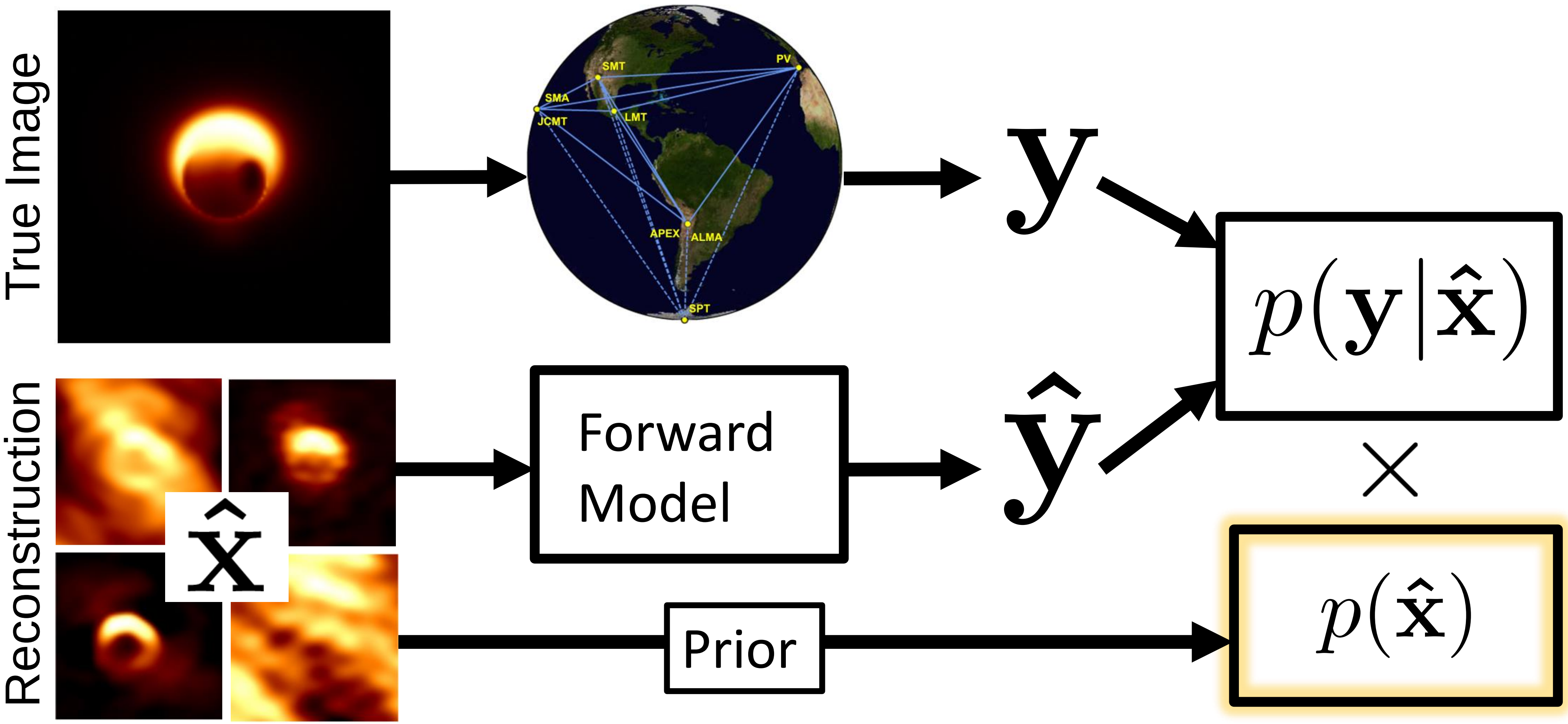


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

Regularized Maximum Likelihood

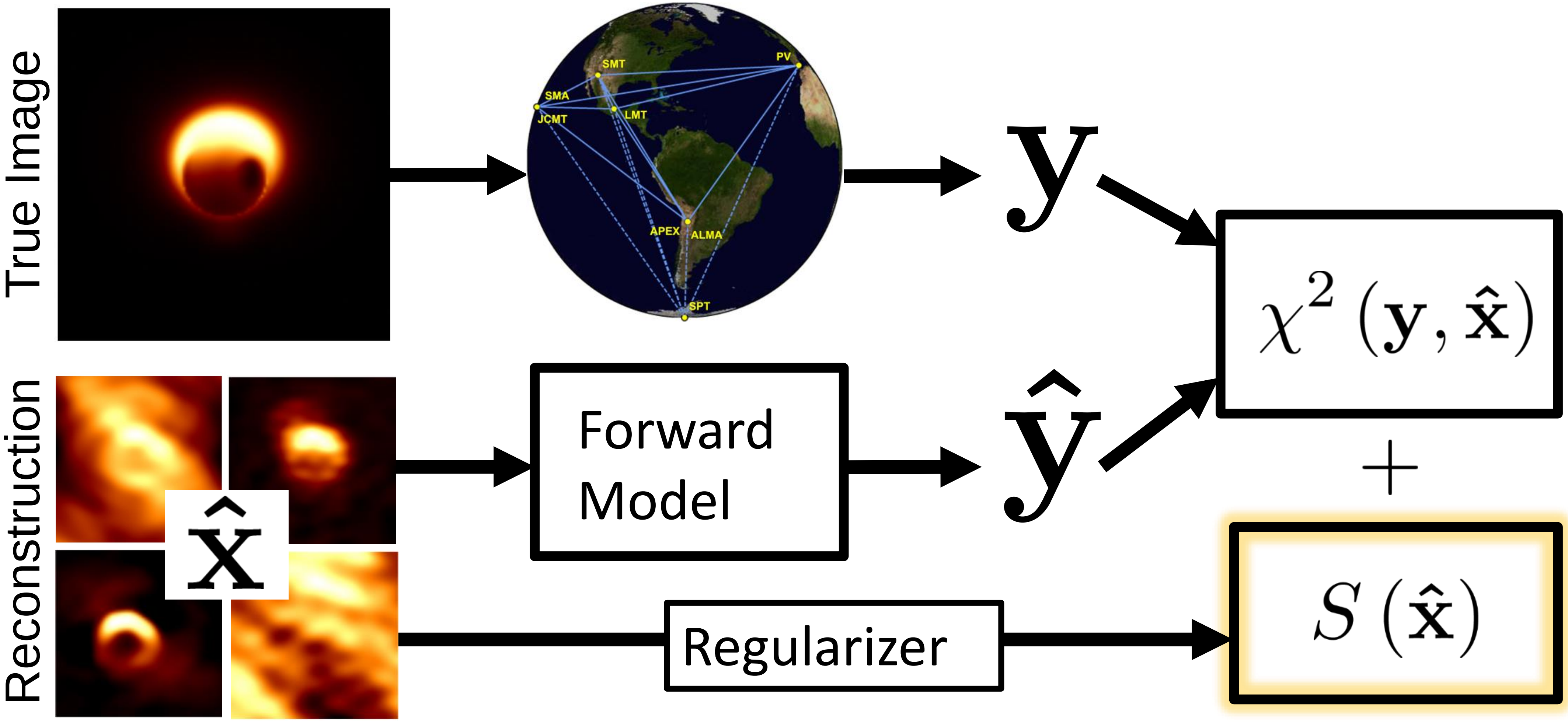


Image Credit: Katie Bouman

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

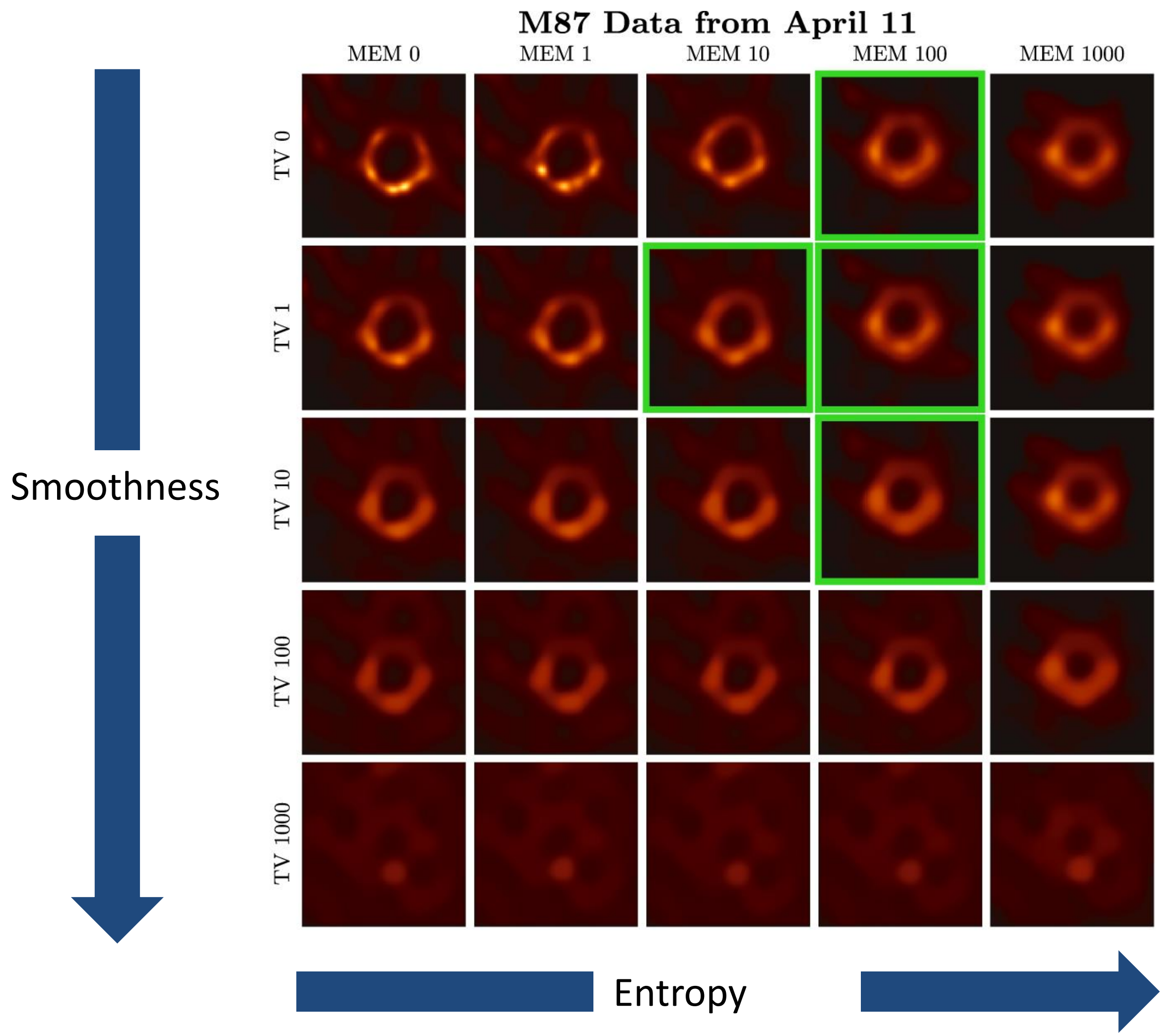


Image Credit: EHT Collaboration 2019 (Paper IV)

Imaging with Regularized Maximum Likelihood

"hyperparameters"

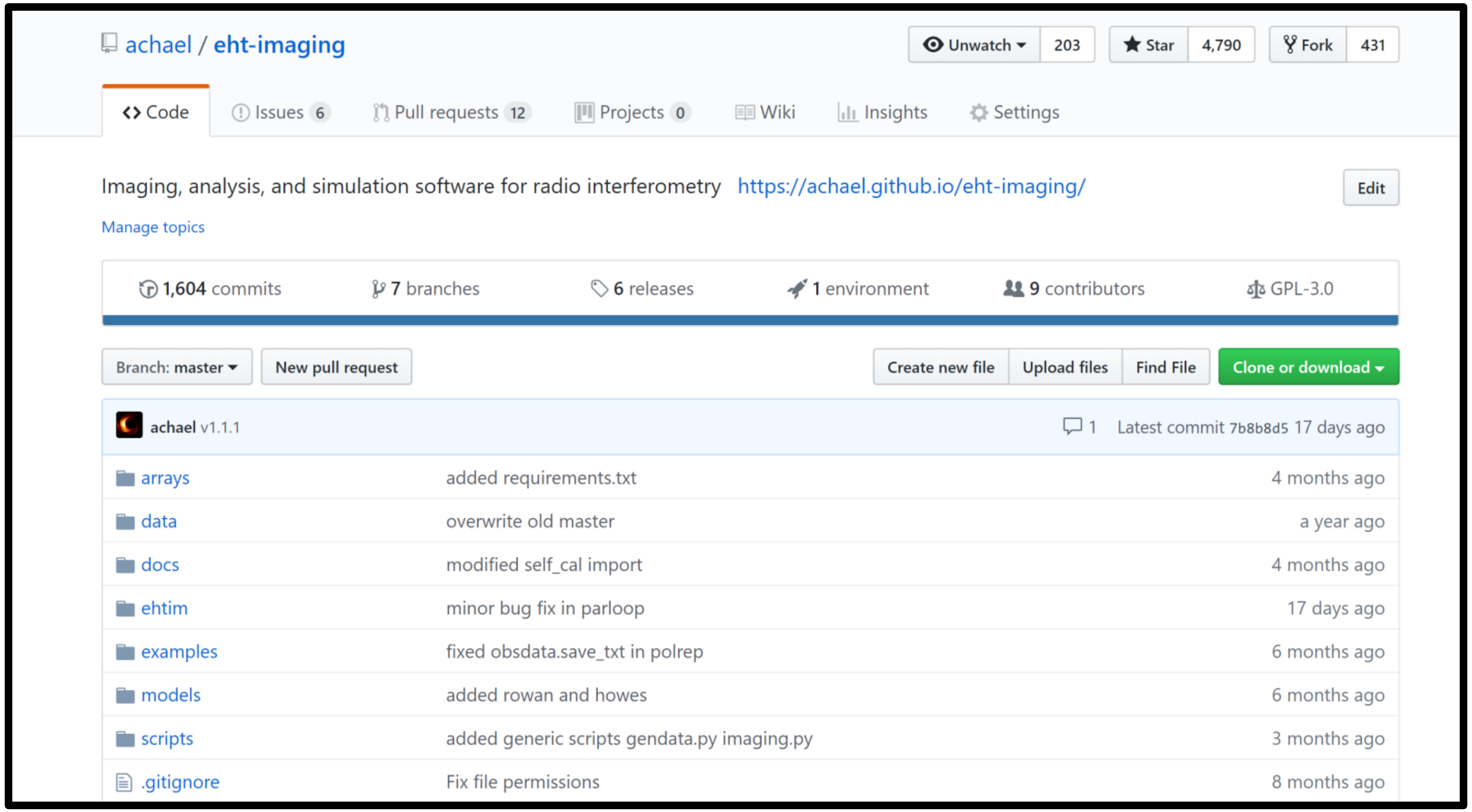
Minimize: $$J(\mathbf{I}) = \sum_{\text{data terms}} \alpha_D \chi^2_D\left(\mathbf{I}, \mathbf{d}\right) - \sum_{\text{regularizers}} \beta_R S_R\left(\mathbf{I}\right).$$

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

Regularizers

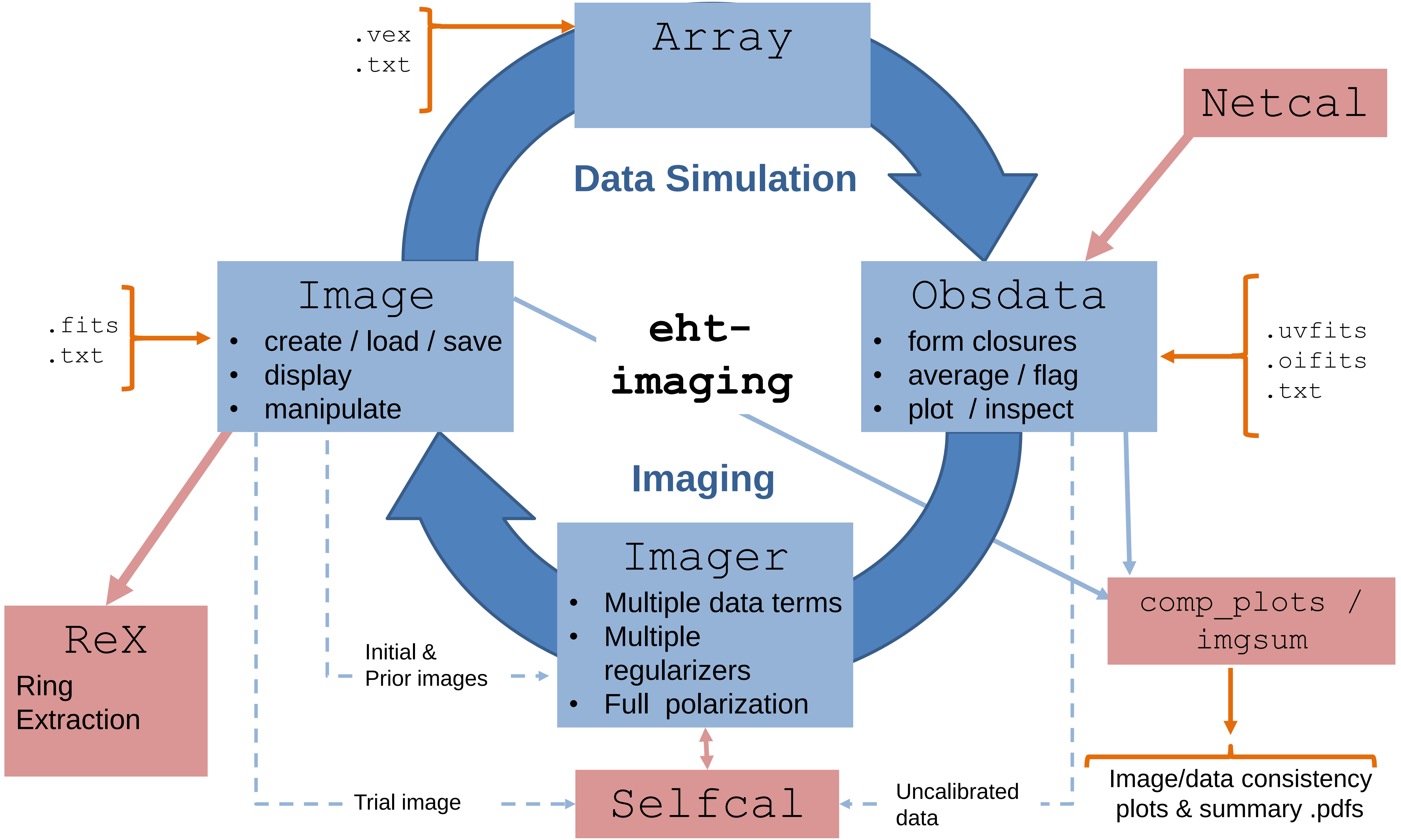
- Flexible framework enables development of new data and regularizer terms
- Hyperparameters weight relative importance of the different terms.
- Implemented in `eht-imaging` (Chael+ 2016,18,19) and `SMILI` (Akiyama+ 2017a,b) software libraries.

The `eht-imaging` software library



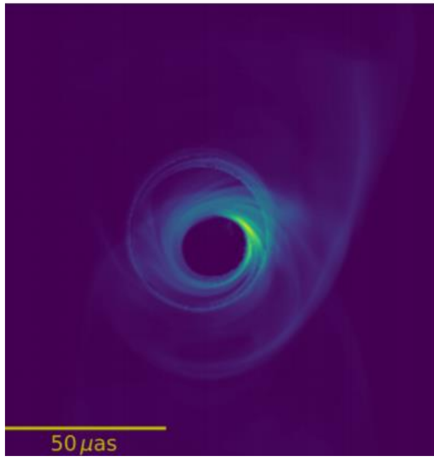
- Python software to image, analyze, and simulate interferometric data
- Flexible framework for developing new tools – e.g. polarimetric imaging, dynamical imaging.
- Used in 18 published papers (including all 5/6 EHT result papers)

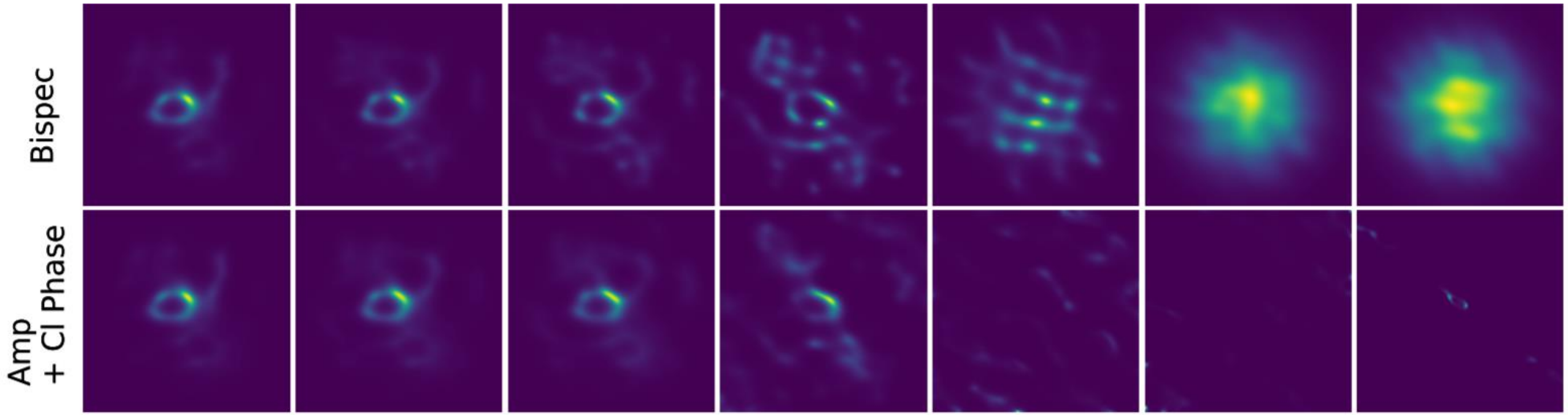
https://github.com/achael/eht-imaging



.vex
.txt
Array
Netcal
Data Simulation
.fits
.txt
Image
• create / load / save
• display
• manipulate
eht-
imaging
Obsdata
• form closures
• average / flag
• plot / inspect
.uvfits
.oifits
.txt
Imaging
Imager
• Multiple data terms
• Multiple regularizers
• Full polarization
comp_plots /
imgsum
ReX
Ring
Extraction
Initial &
Prior images
Image/data consistency
plots & summary .pdfs
Trial image
Selfcal
Uncalibrated
data

Closure-only imaging





0% 5% 10% 25% 50% 75% 100%

Increasing Gain Calibration Error

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

Closure-Only & RML Imaging have wide applicability!

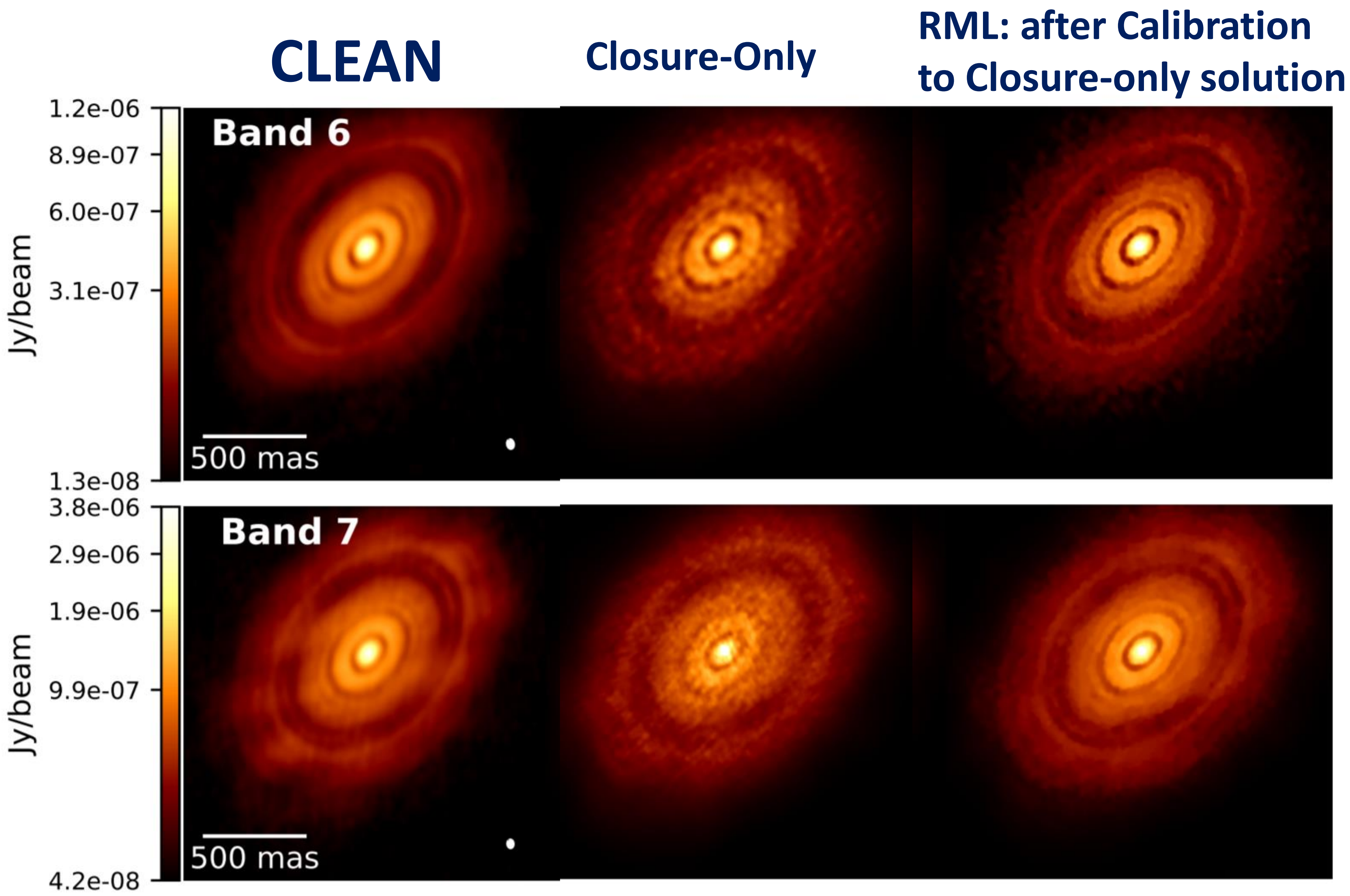


Image Credit: Chael+ 2018a

Imaging M87 with the EHT

BHI, July 2018

EHT 2017

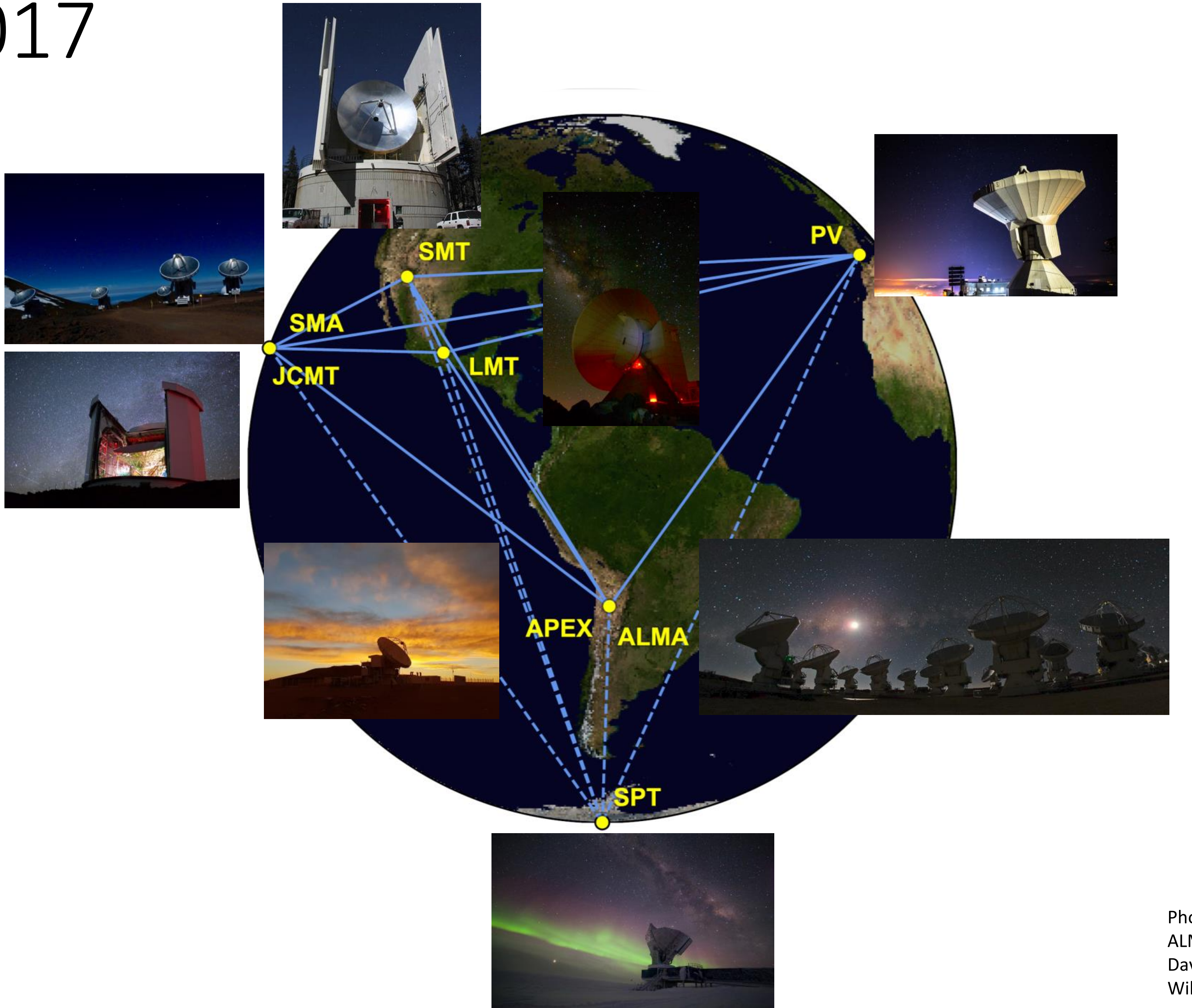
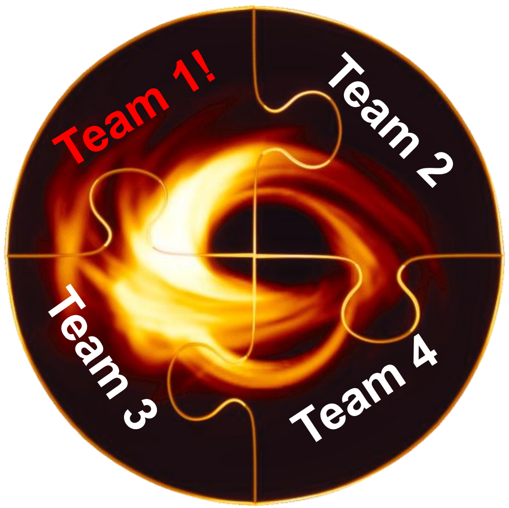
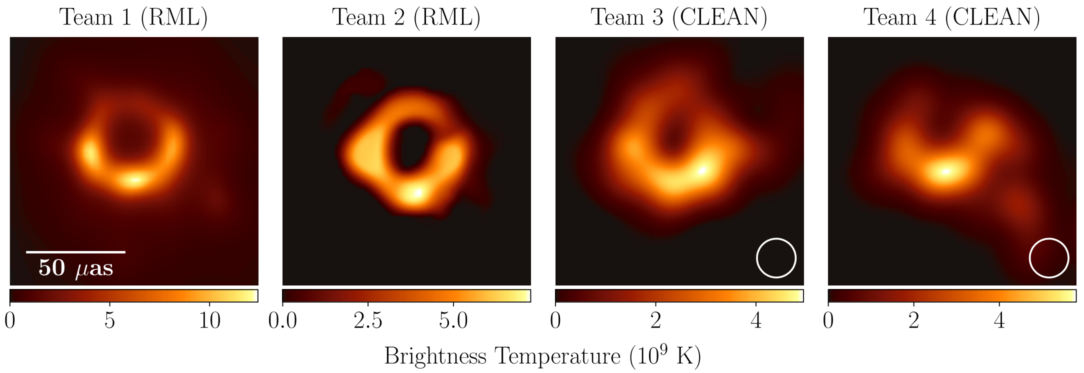


Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

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

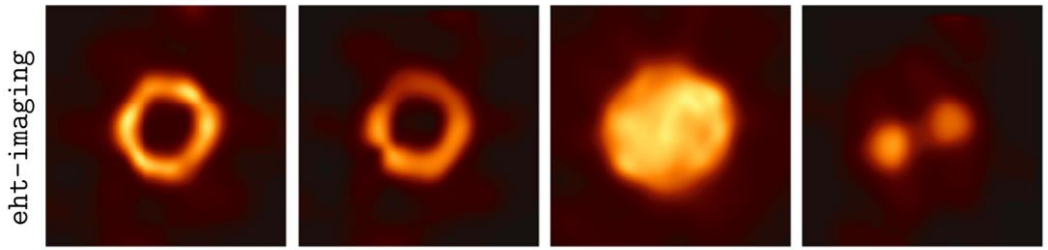
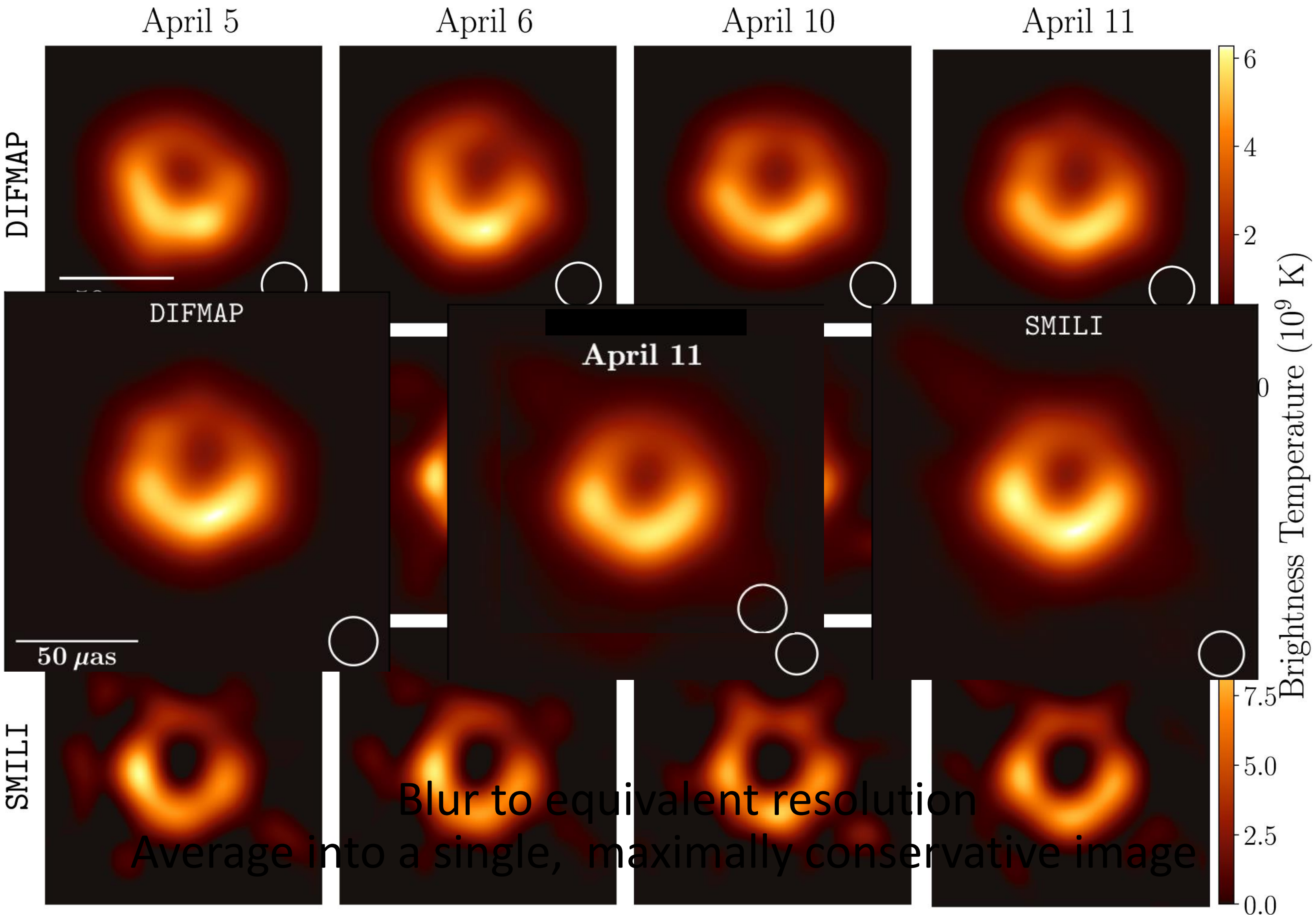


Image Credit: EHT Collaboration 2019 (Paper IV)

Three pipelines, four days



Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

Measuring Features of a Ring

- Measuring characteristic features tells us how consistent the reconstructions are across methods and time

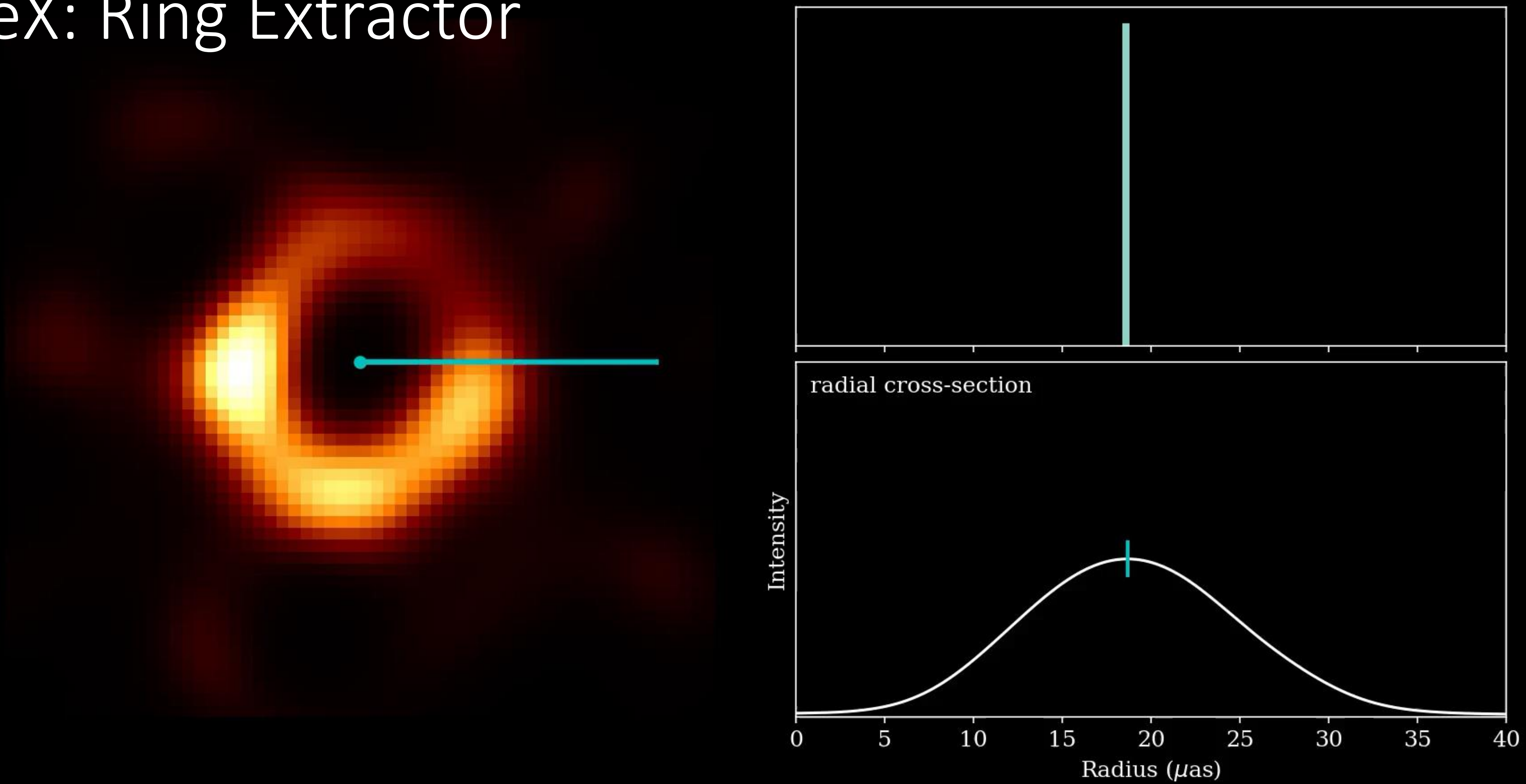
- **Five** characteristic features:
  - Diameter d
  - Width w
  - Orientation angle η
  - Asymmetry A
  - Central Contrast f_{C}

- 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

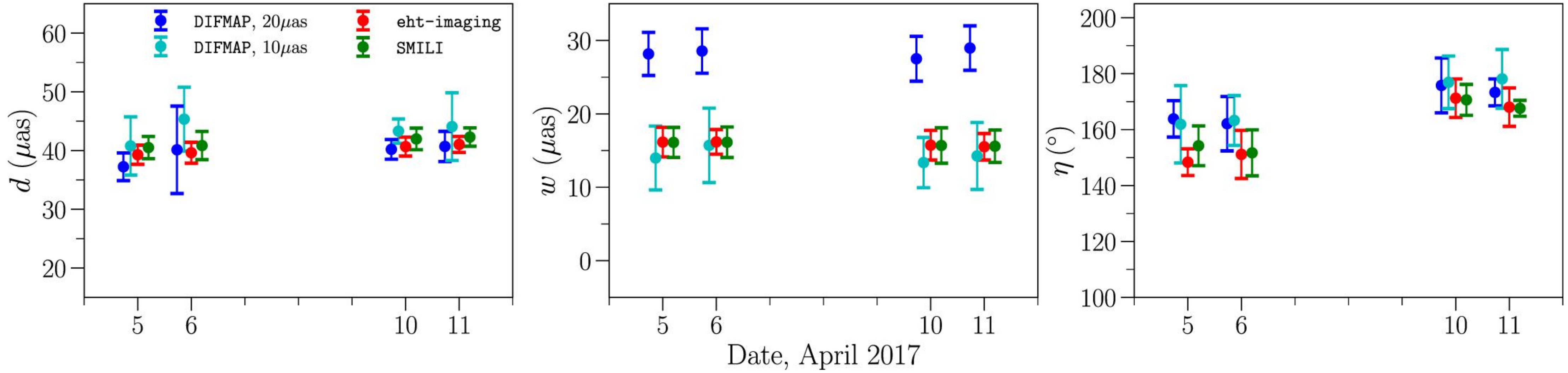
ReX: Ring Extractor



Animation Credit: Dom Pesce

M87 Ring Properties

Diameter　　　　Width　　　　Angle

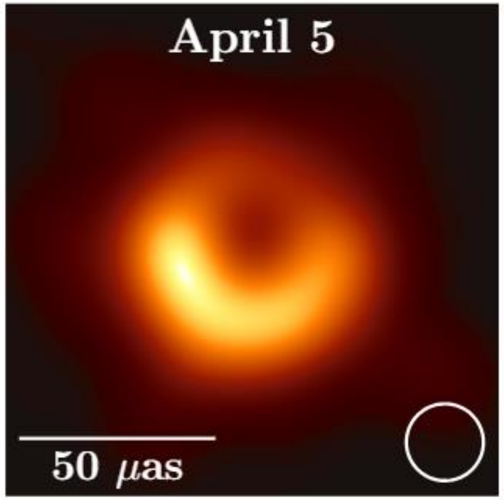


- Diameter $d \approx 41\ \mu\mathrm{as}$ is consistent across time and method
- Ring width is resolution dependent, and is at best an upper limit.
- Orientation angle shows tentative $\approx 20^\circ$ CCW shift from April 5 - 11

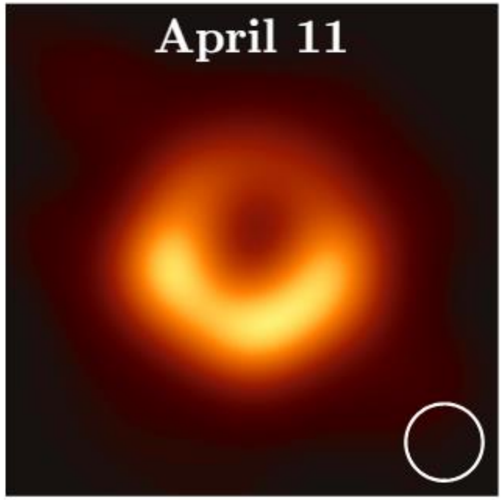
Image Credit:
EHT Collaboration 2019 (Paper V)

Time Variability?

M87



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



Simulation

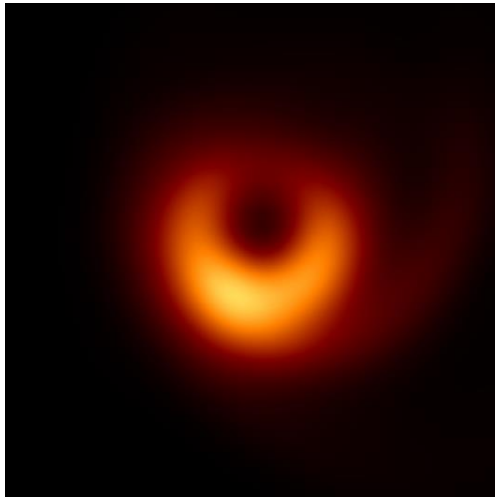
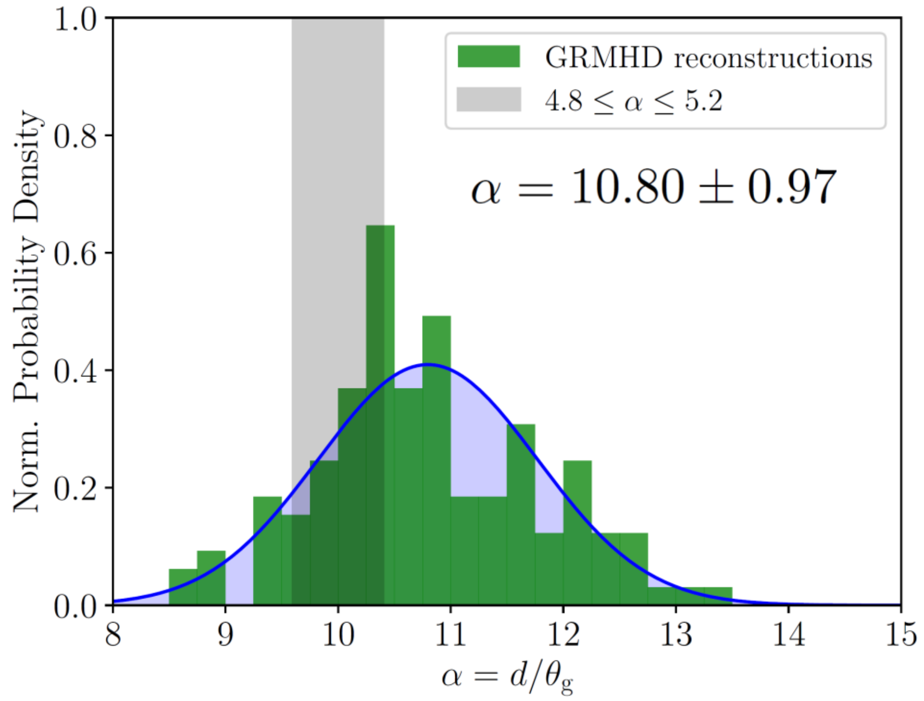


Image Credit: EHT Collaboration 2019 (Paper IV), Chael+ 2019

Weighing a black hole

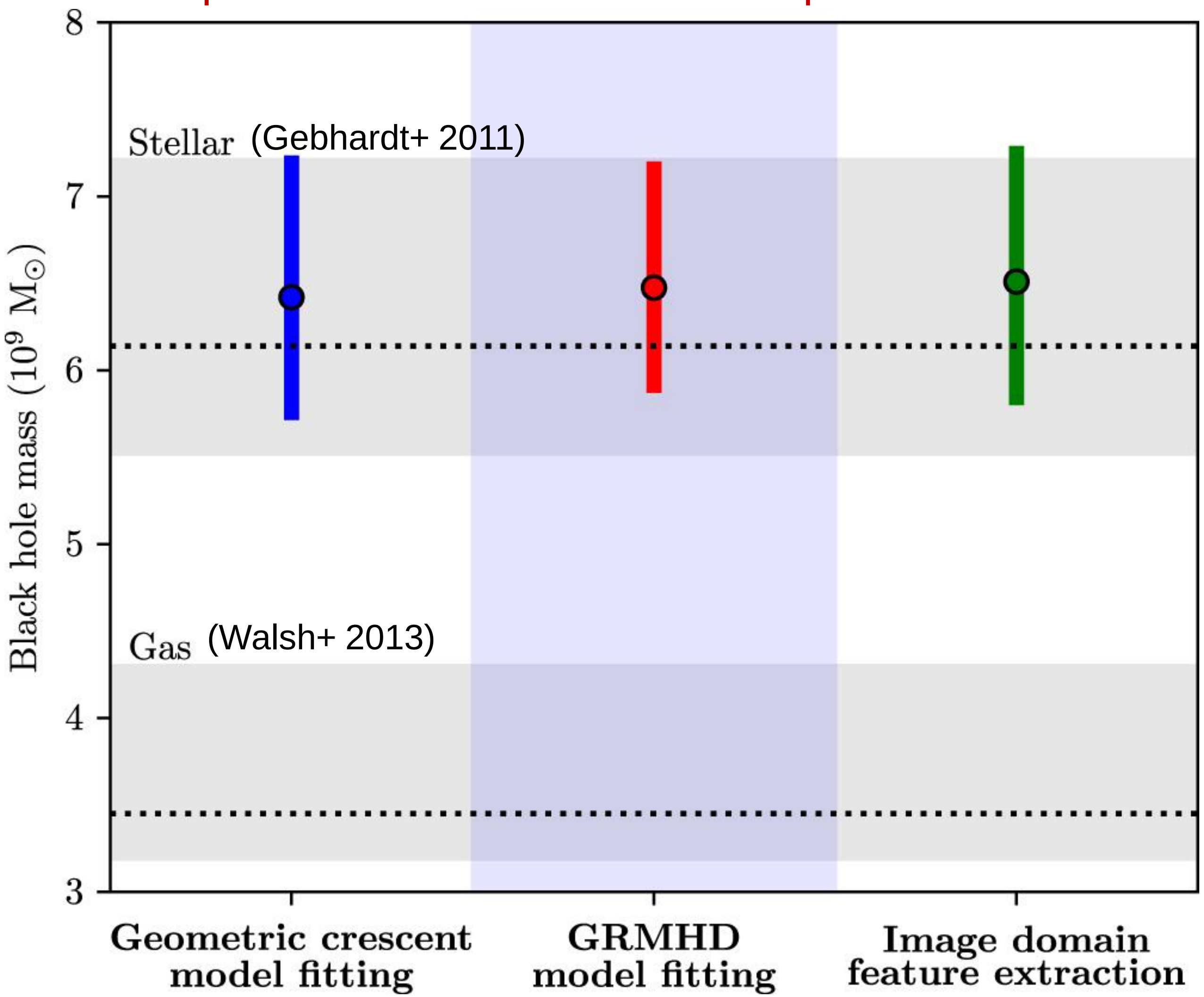
- The mass is proportional to the distance and diameter: $M = \frac{c^2 D}{G}\frac{d}{\alpha}$
- α can be biased by resolution and structure → Calibrate α with a library of GRMHD images



- After calibration, `eht-imaging` gives $M = (6.47 \pm 0.62) \times 10^9\, M_\odot$

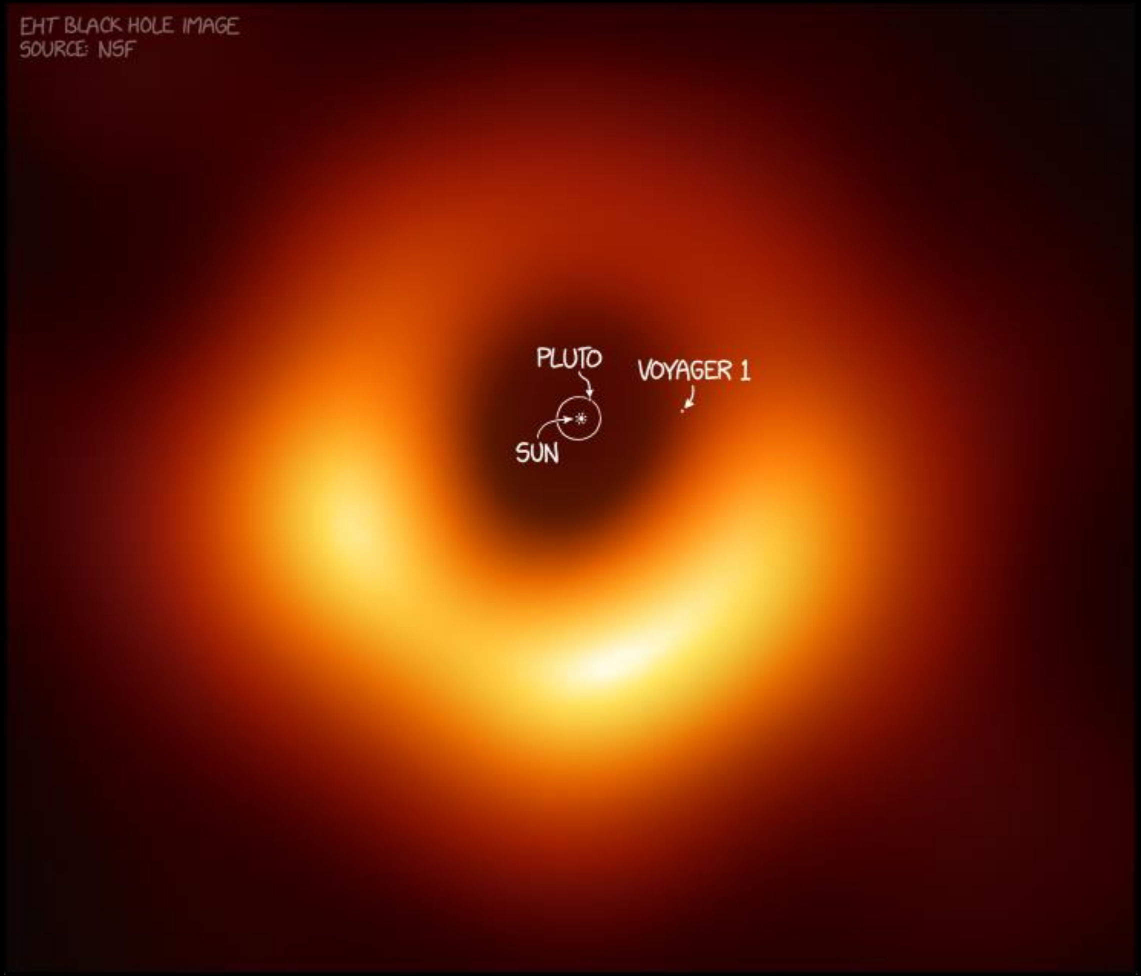
Weighing a black hole

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)



$$M = (6.5 \pm 0.7) \times 10^9 \, M_\odot$$
$$R_{\mathrm{Sch}} = 128 \, \mathrm{AU}$$

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

Outline

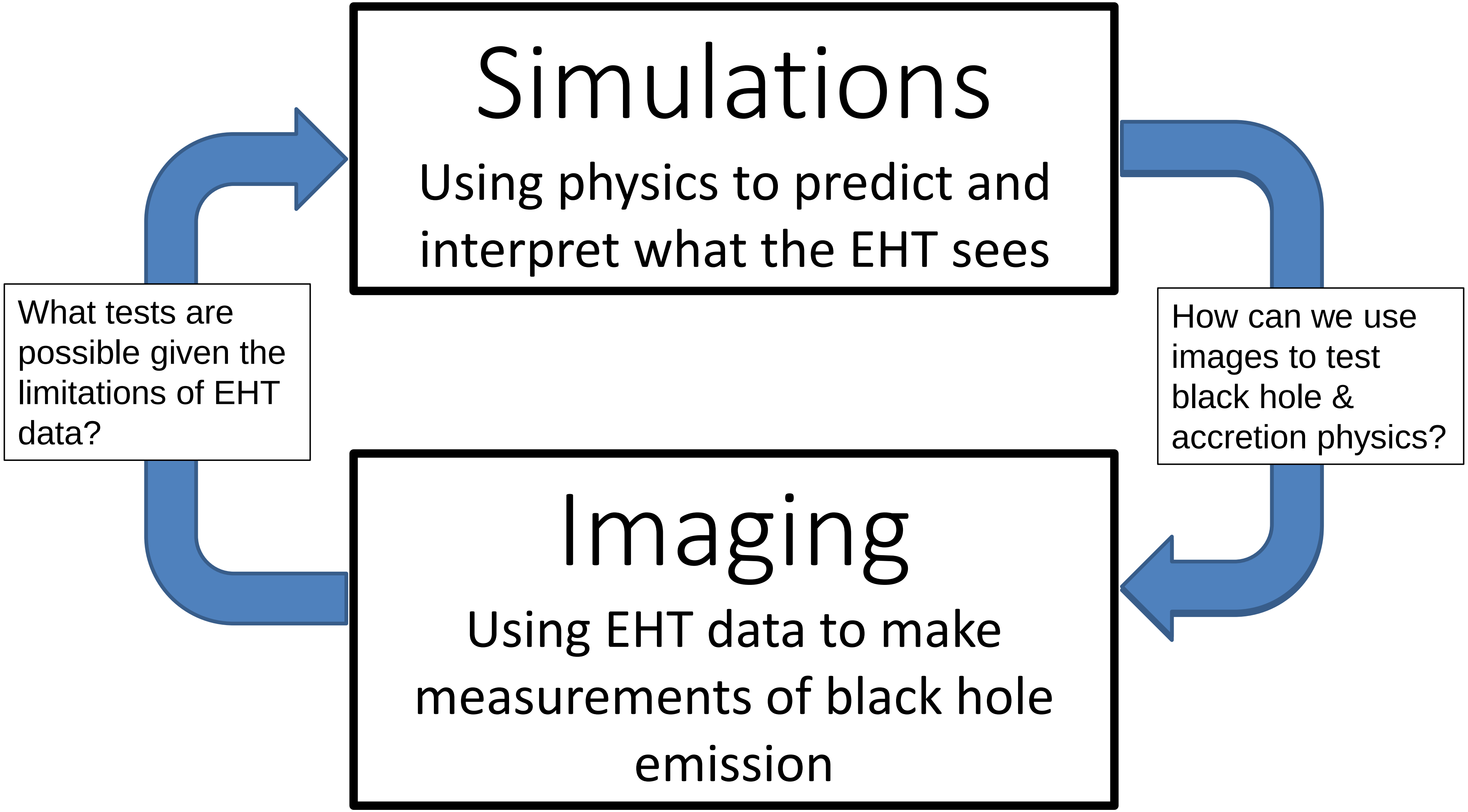
Introduction

I. Simulations

- Two-temperature simulations in `KORAL`
- Sgr A* and Nonthermal Electrons
- MAD Simulations of M87

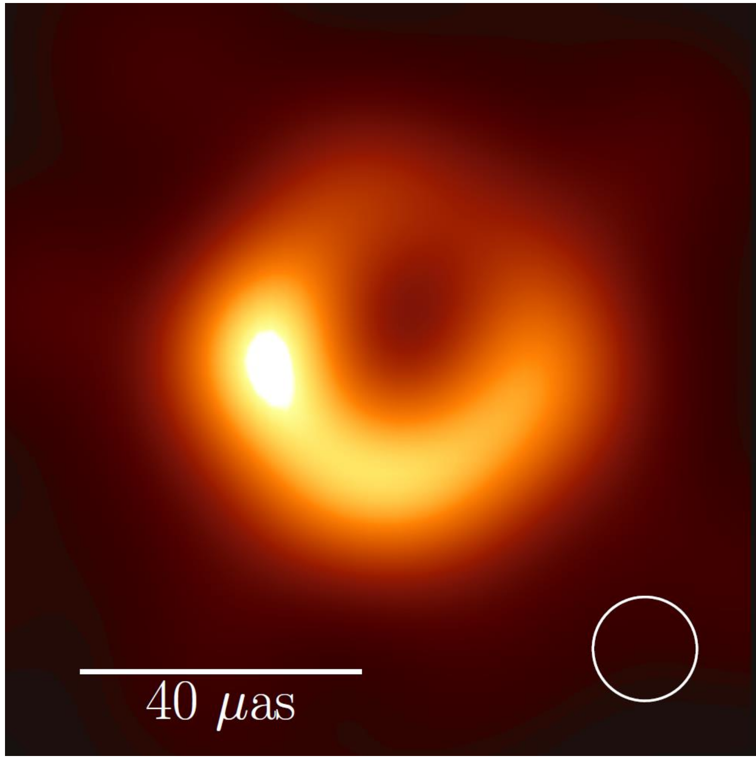
II. Imaging

- Regularized Maximum Likelihood
- The eht-imaging library
- EHT Images of M87

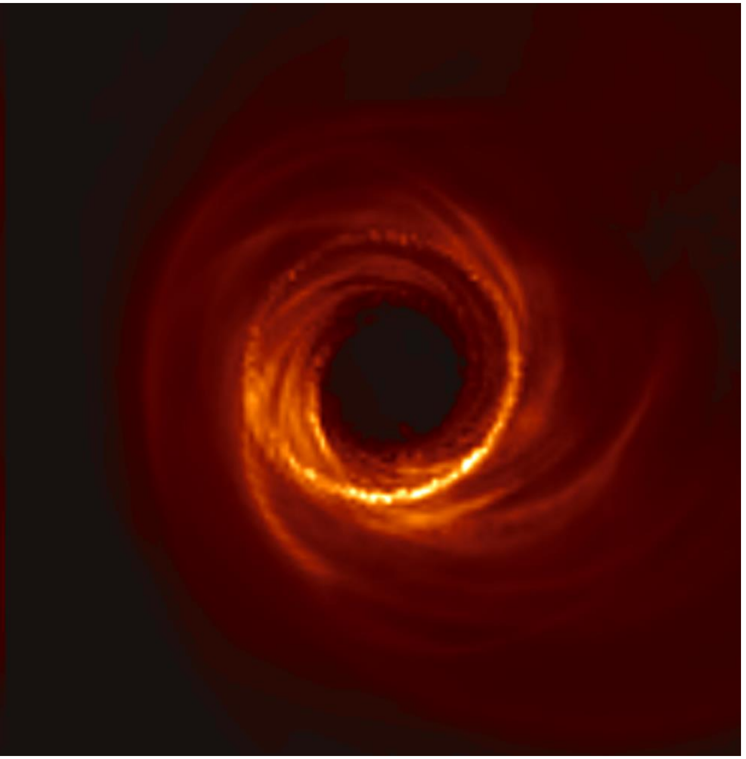

Simulations
Using physics to predict and interpret what the EHT sees
How can we use images to test black hole & accretion physics?
Imaging
Using EHT data to make measurements of black hole emission
What tests are possible given the limitations of EHT data?

The Black Hole in M87: Simulations and Images

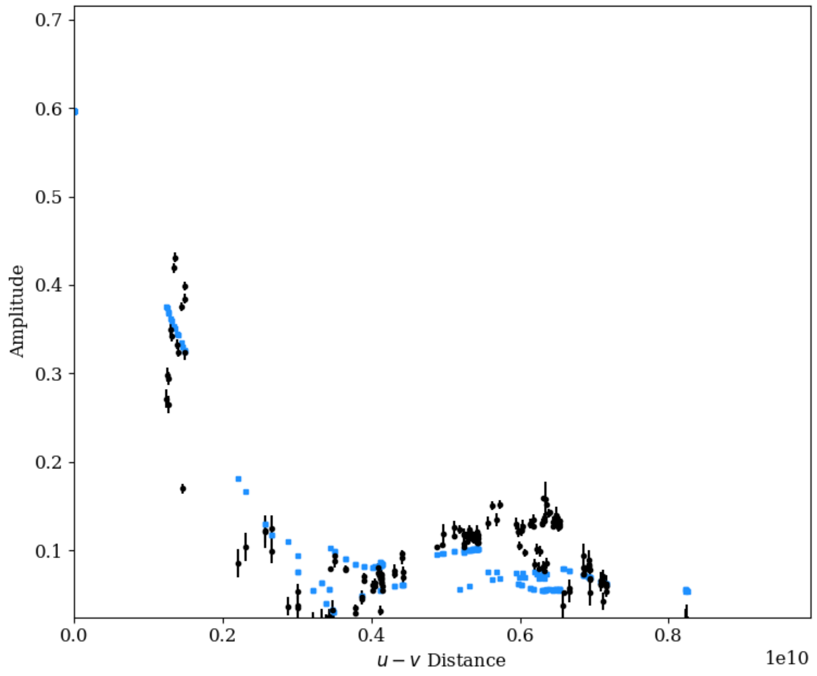
EHT 2017 image



Simulated image from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes

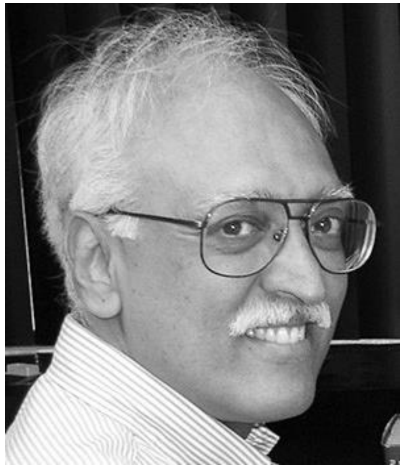


Thank you

Acknowledgements

My Committee


Cora Dvorkin


Ramesh Narayan


Shep Doeleman

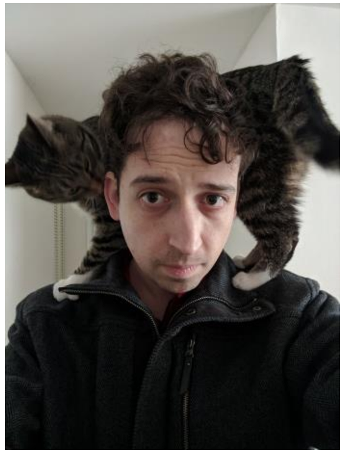

Michael D. Johnson


Peter Galison

My Family

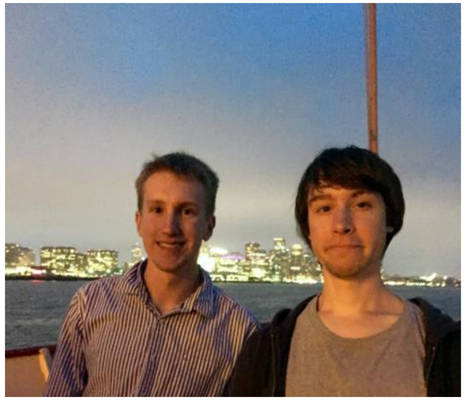
Mom & Dad

Nathan



Jason

My Friends and Fellow Grad Students



Michael

Brandon

Ron, Lan, James, Ceci, & Maryrose

Dan, Mallika, Sam,
Rachel, Charlotte, Tom,
Steve, Fadi, & Amelia

Dunster House

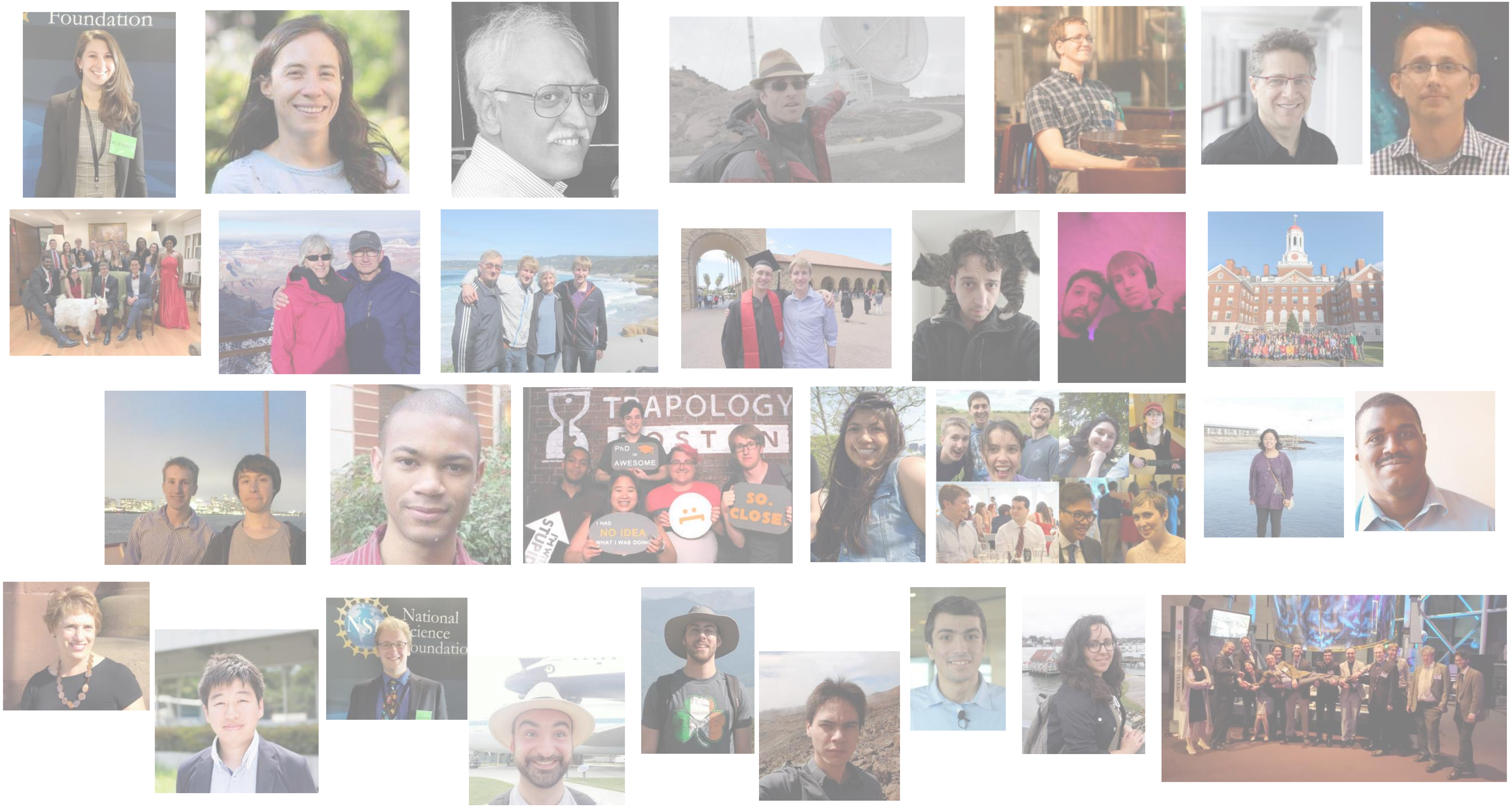
Tutors & Staff

Gregory

Jennifer

Students

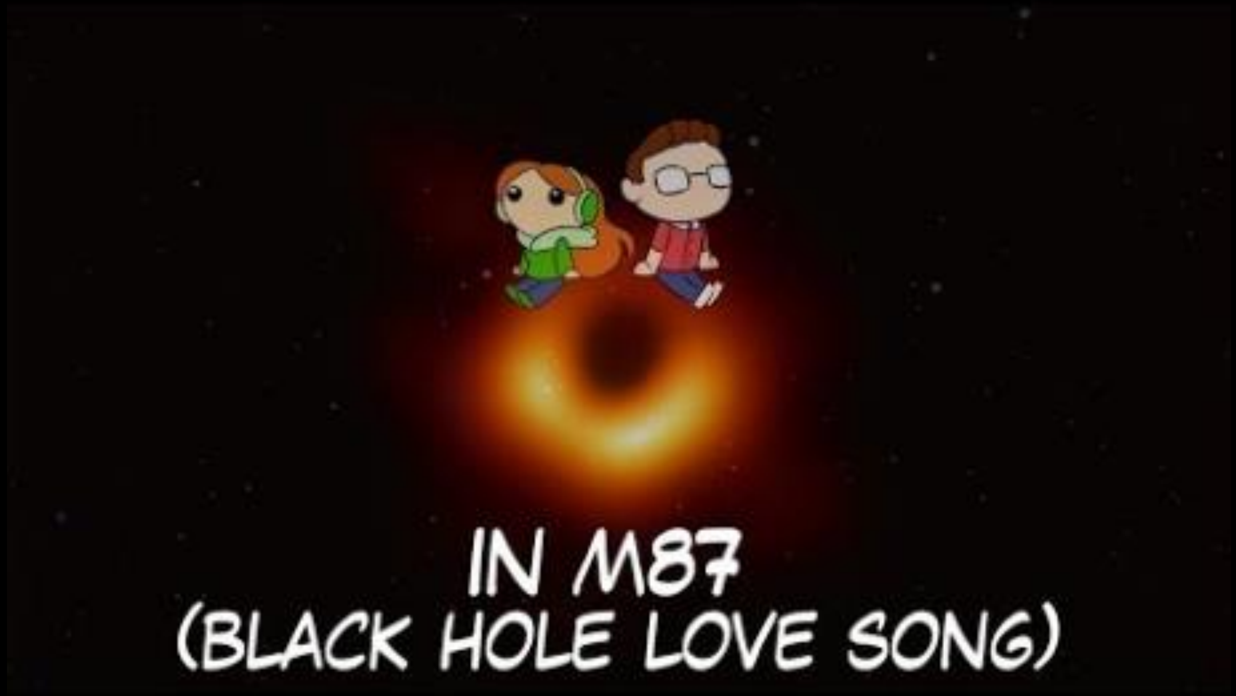
SAO EHT & Friends


Foundation
PhD IN AWESOME
I HAD NO IDEA WHAT I WAS DOING
SO. CLOSE.
National

oration


SENORGIF.COM
Event Horizon Telescope
Collaboration Meeting
Welcome to Nijmege
Radboud University
Event Horizon Telescope
Collaboration Meeting
Welcome to Nijmegen!
♪It's only smooth, smooth sailing from now on♪


Thank You!
FRIENDSHIP
THE WALL STREET JOURNAL



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