The Black Hole and Jet in M87: Linking Simulations and VLBI images

Andrew Chael
NHFP Einstein Fellow, Princeton University

Waterloo, October 2, 2019

PRINCETON CENTER FOR THEORETICAL SCIENCE

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HARVARD & SMITHSONIAN

Event Horizon Telescope

The Black Hole and Jet in M87:
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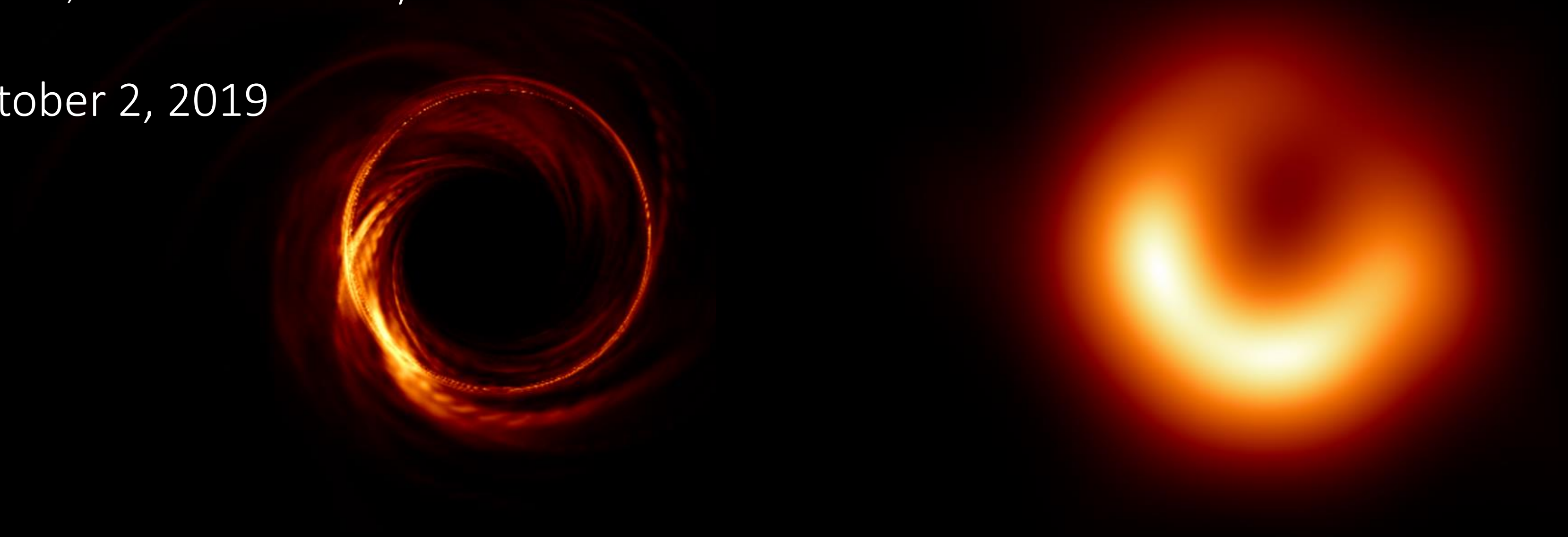


Work with Ramesh Narayan, Michael Johnson,
Katie Bouman, Shep Doeleman, Michael Rowan,
and the entire EHT collaboration

arXiv: 1803.07088, 1810.01983
EHTC+ 2019, Papers I-VI (ApJL 875)
my thesis! https://achael.github.io/_pages/pubs

The EHT Collaboration

M87

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

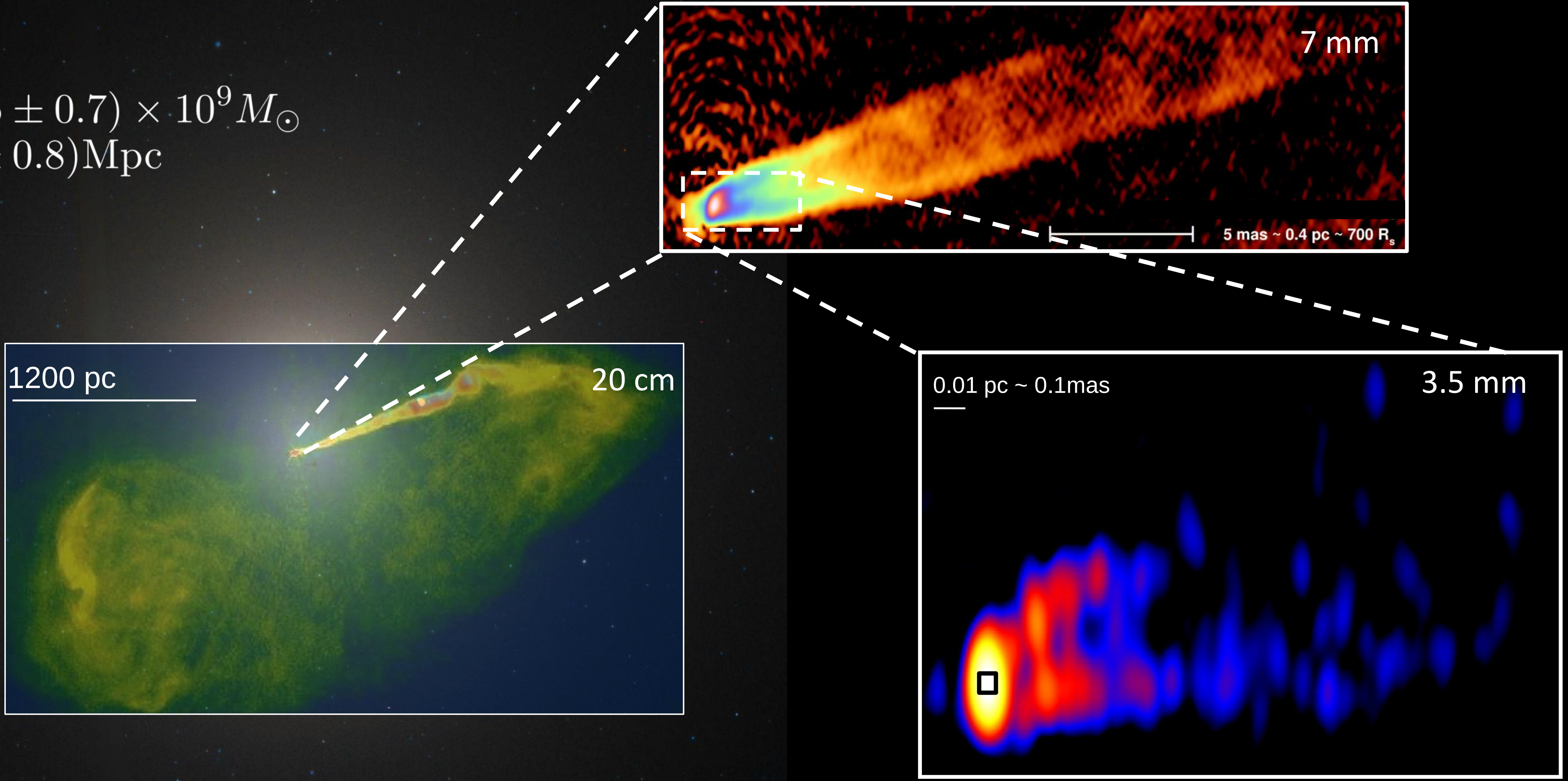


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

At the core of M87

- Thick accretion flow of hot, ionized plasma ($T \gtrsim 10^{10}\,\mathrm{K}$)
- Launches the powerful relativistic jet (≥ 10^{42} erg/sec)
- Strong and turbulent magnetic fields? Extraction of BH spin energy via the Blandford-Znajek process?

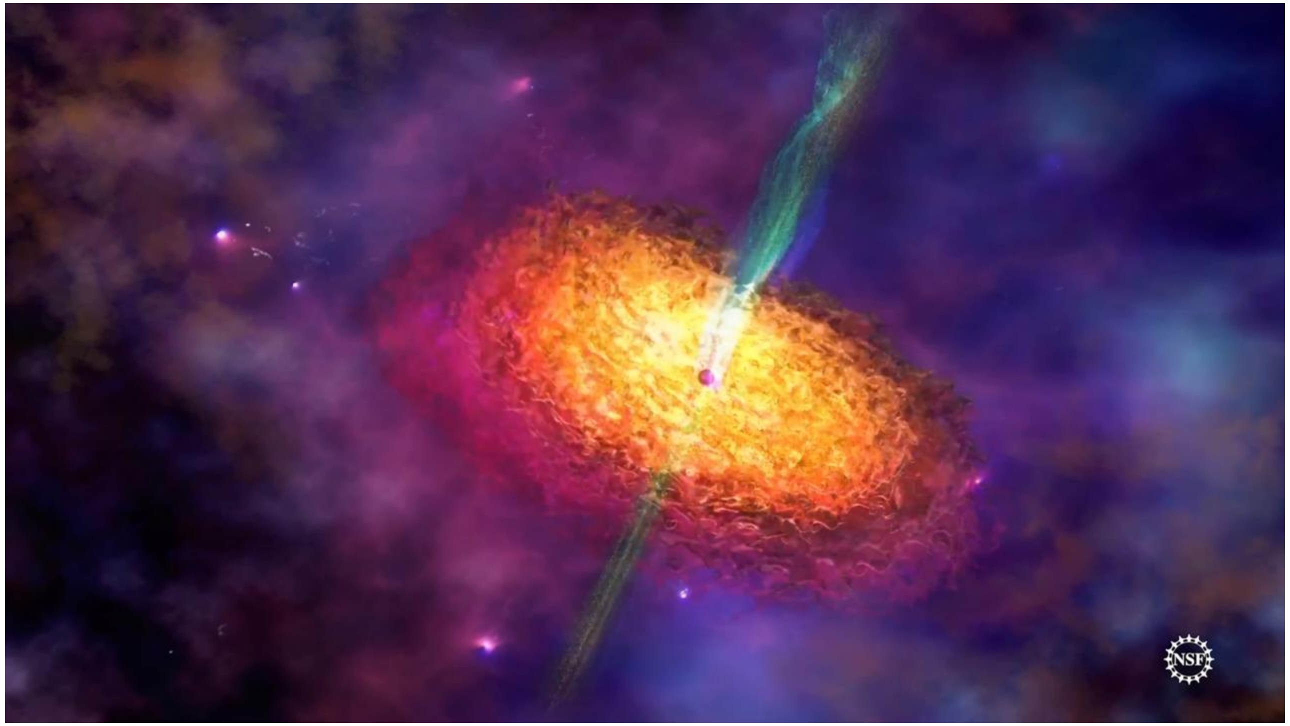
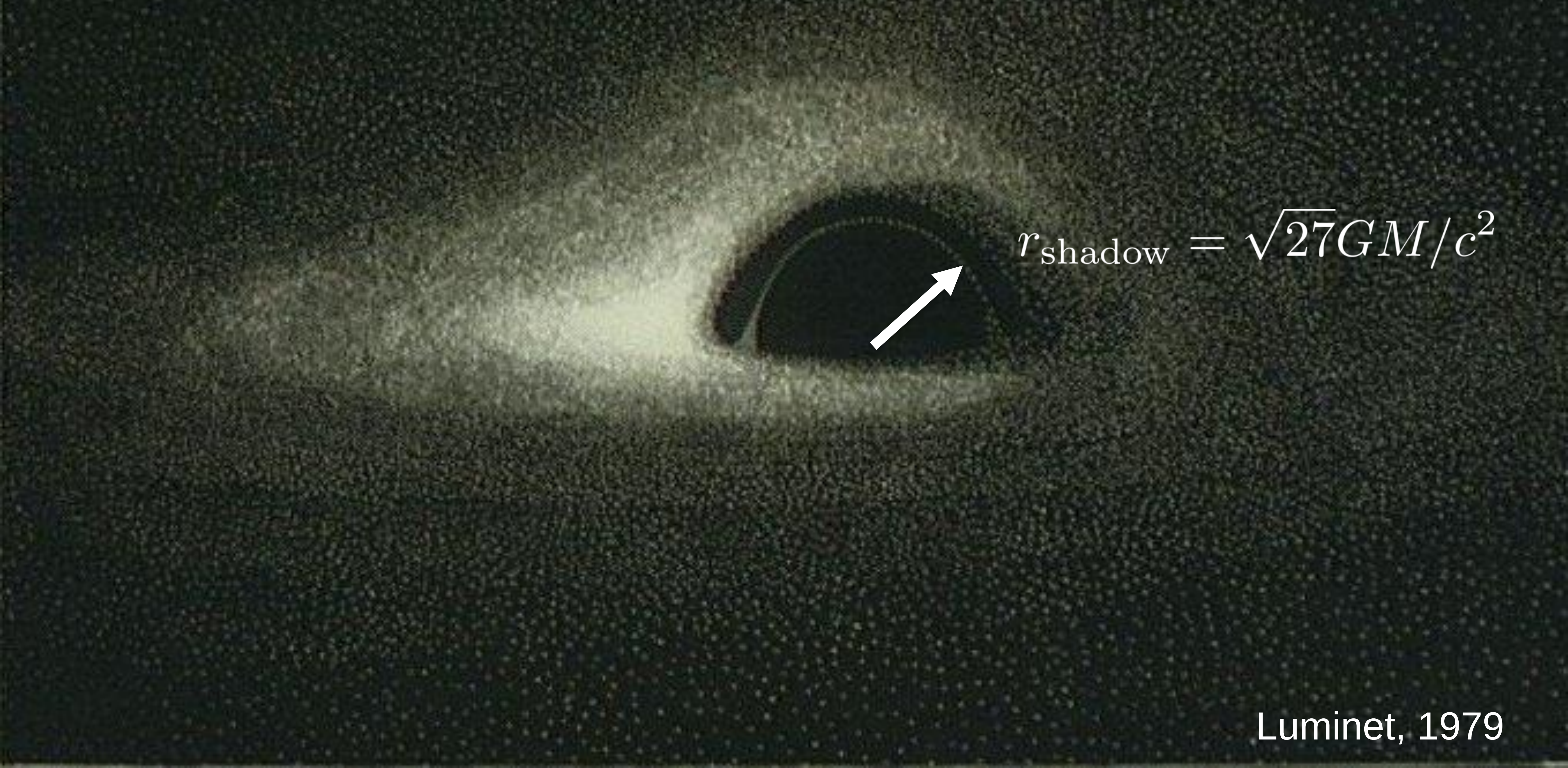


Image credit: National Science Foundation

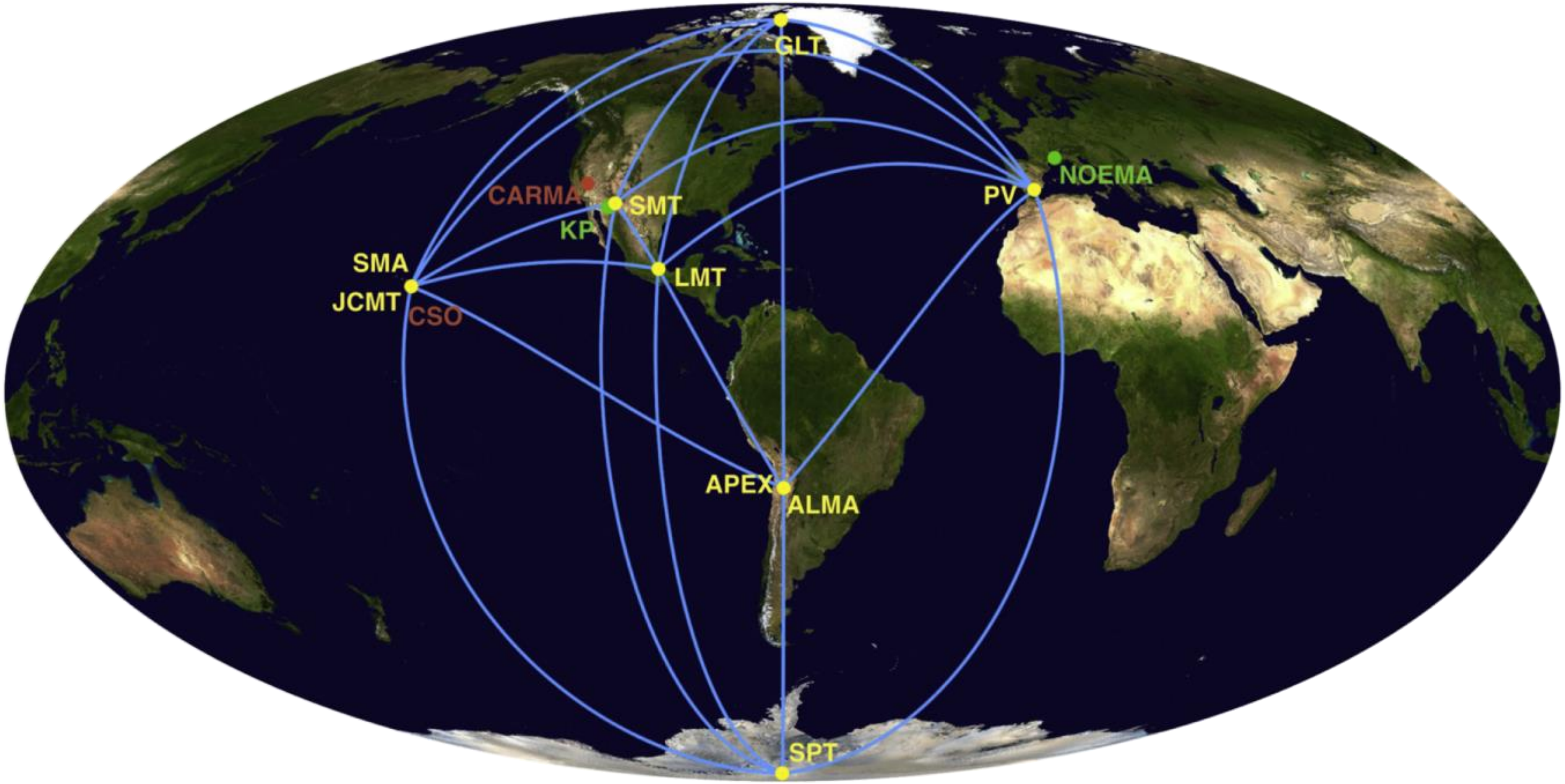
What does a black hole look like close up?



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

Luminet, 1979

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

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

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

$d_{\mathrm{shadow}} \approx 40\mu\mathrm{as}$

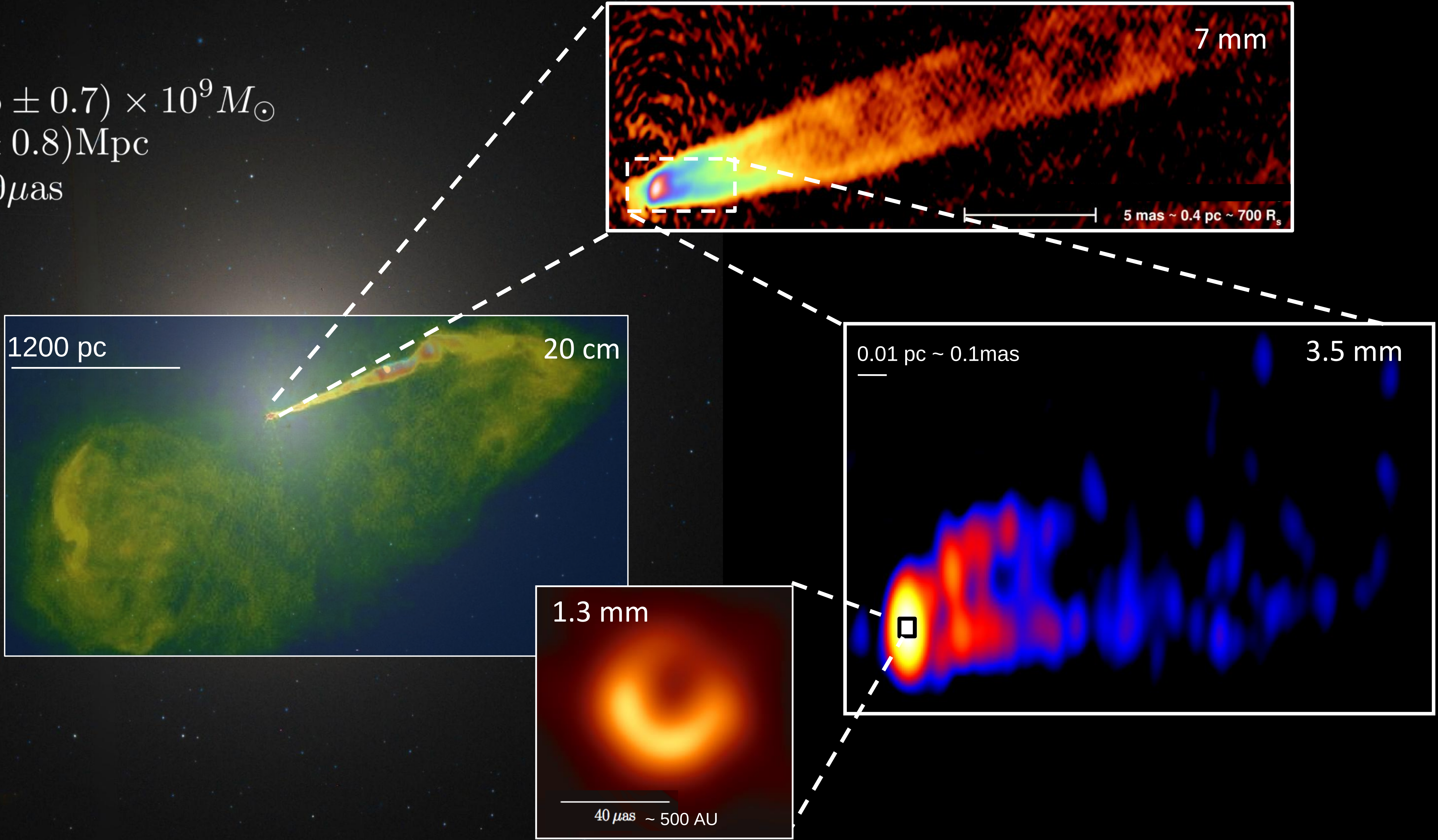
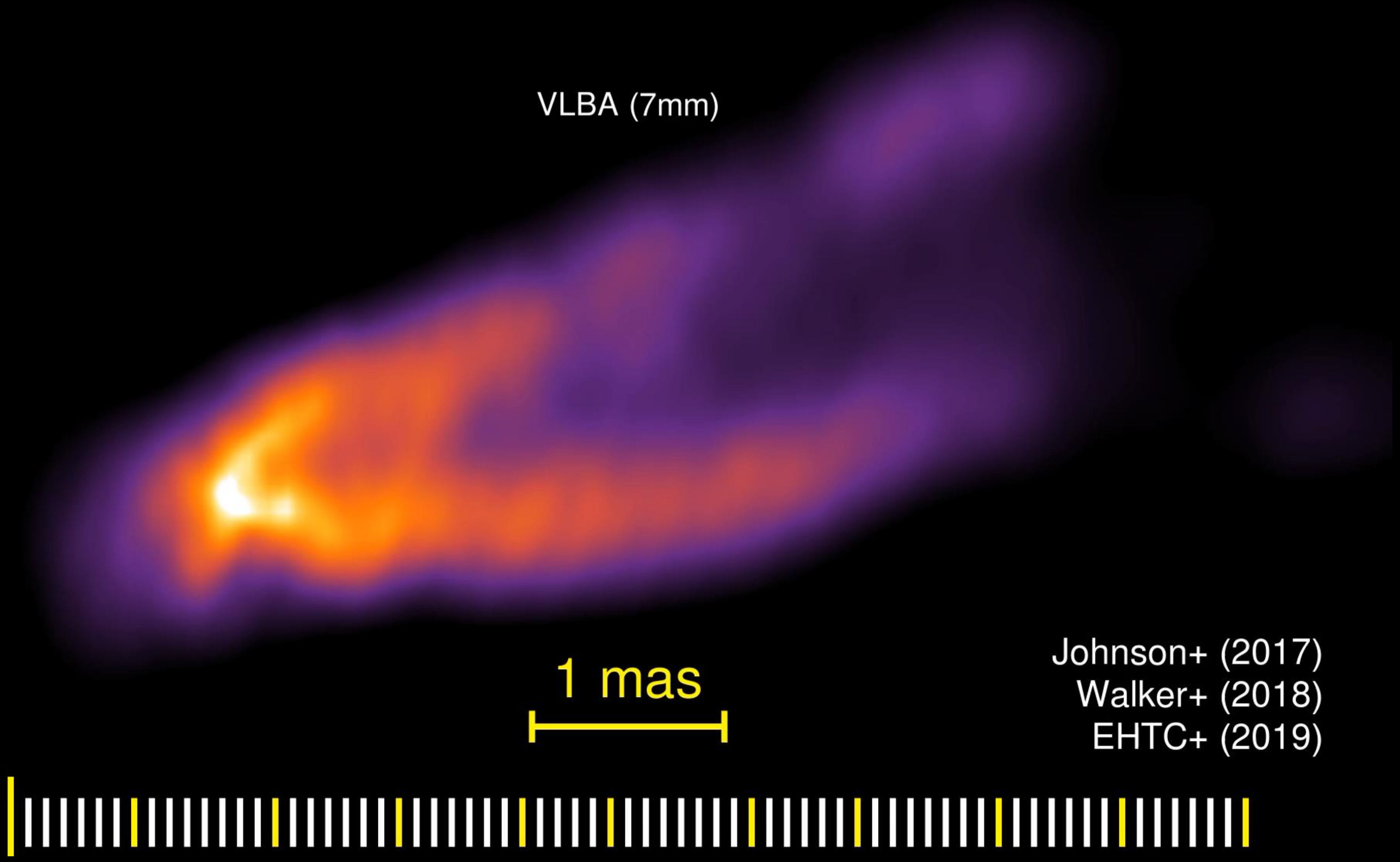


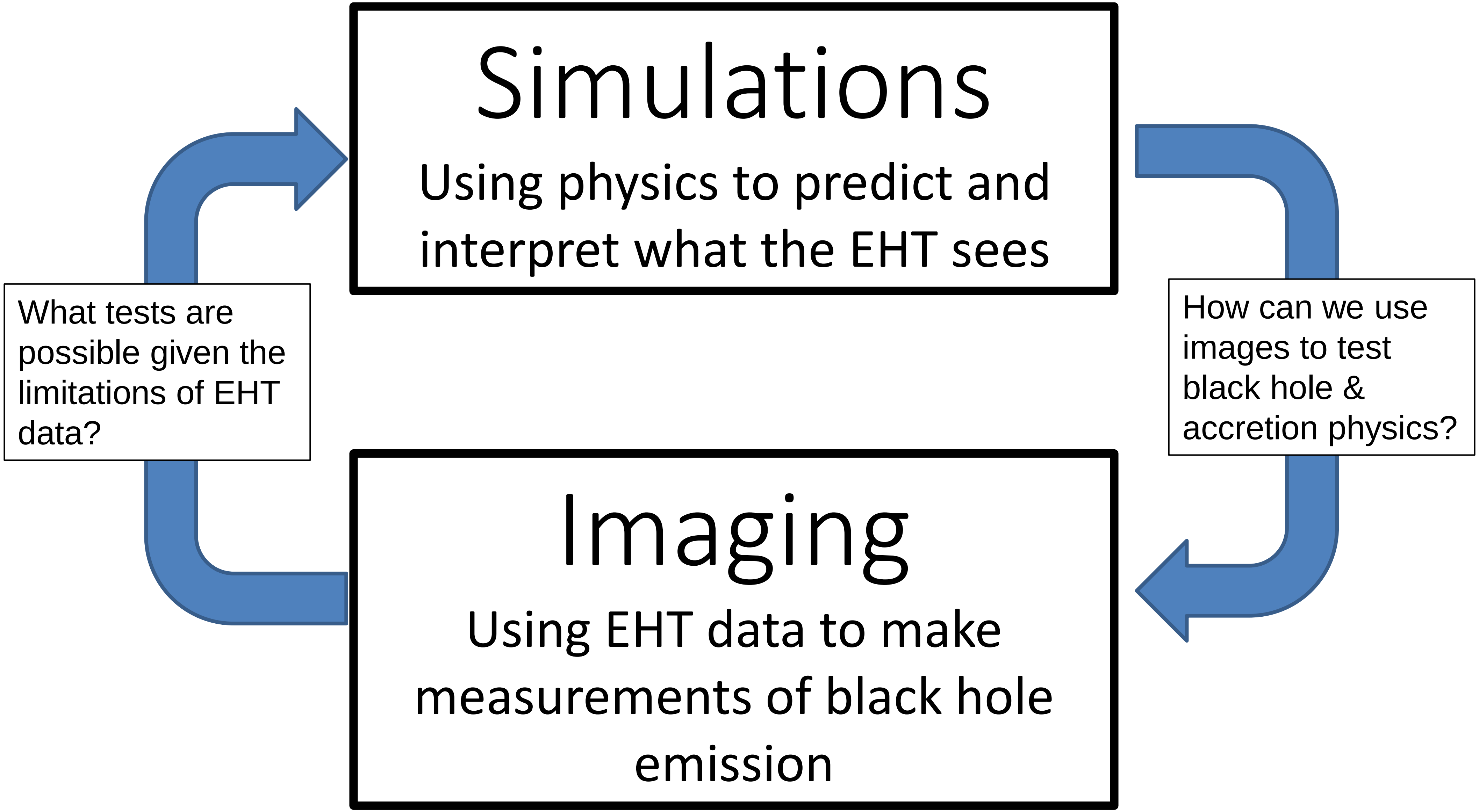
Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

01/27/07



Johnson+ (2017)
Walker+ (2018)
EHTC+ (2019)

Video Credit: Michael Johnson



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

I. Imaging M87

- Regularized Maximum Likelihood
- The eht-imaging library
- EHT Images of M87 and the BH mass

II. Simulating M87

- Two-temperature simulations in KORAL
- MAD Simulations of M87
- Connecting simulations to images at multiple scales

III. Next Steps

- Polarization
- Dynamics and Nonthermal electrons
- Expanding the EHT

EHT 2017

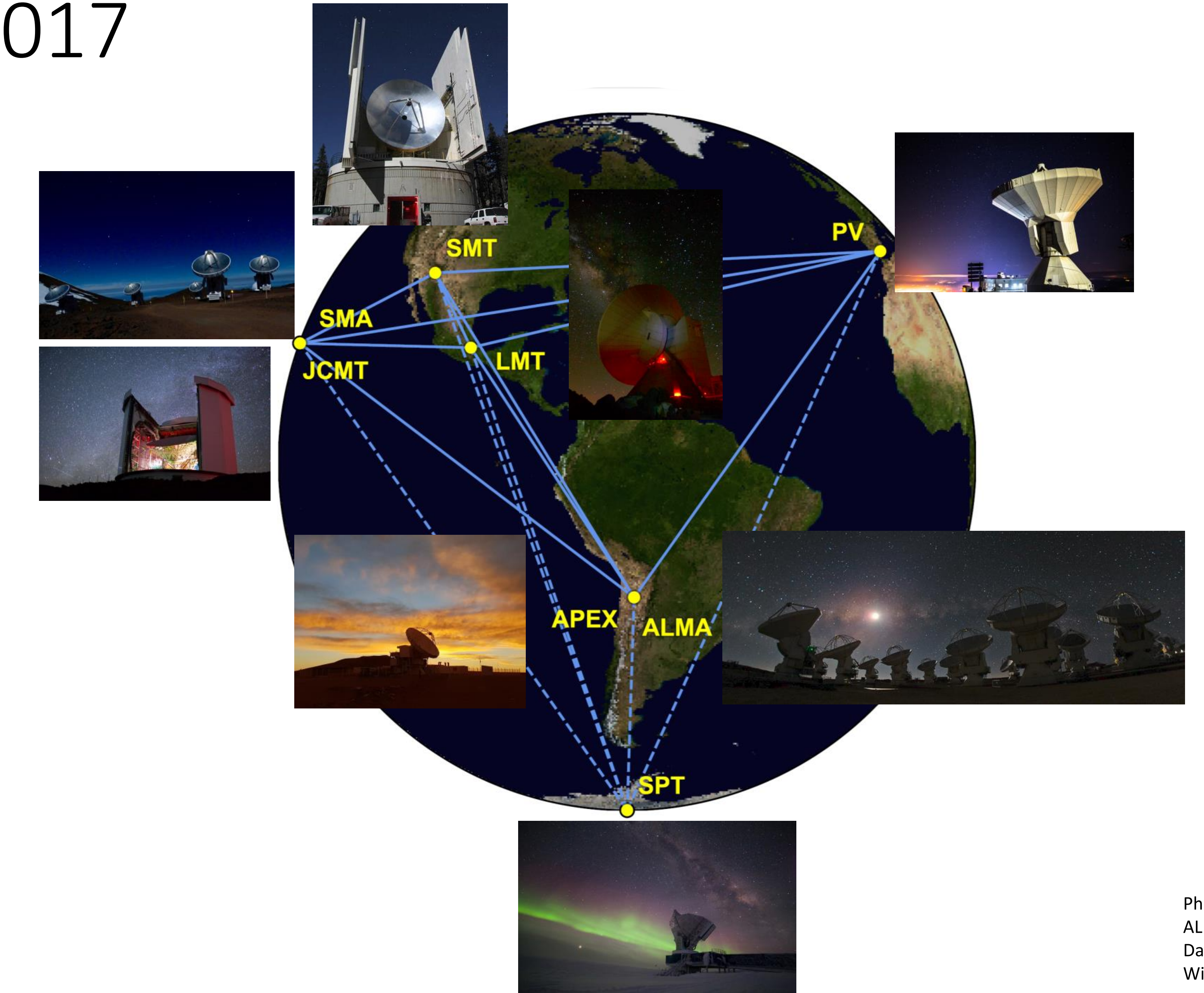
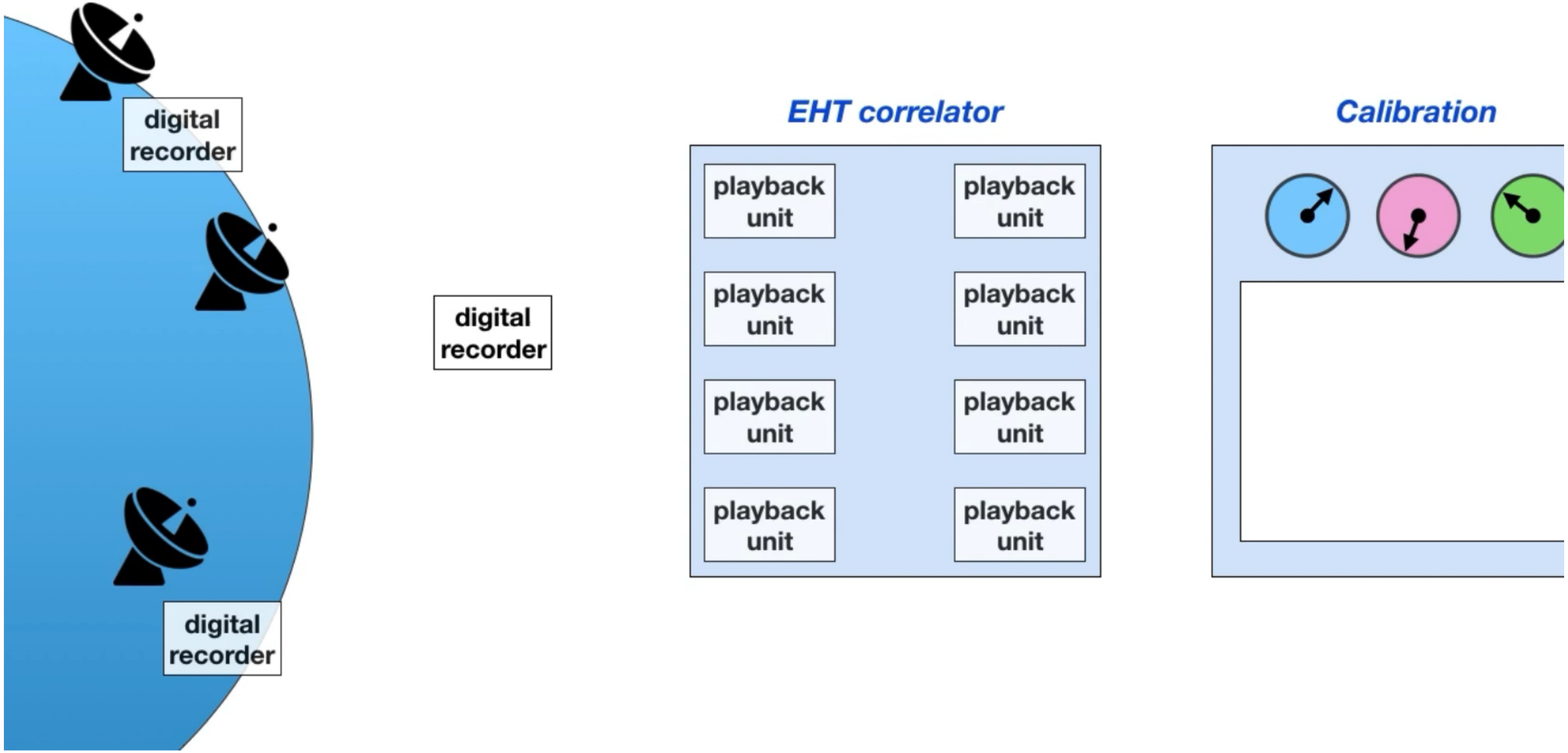


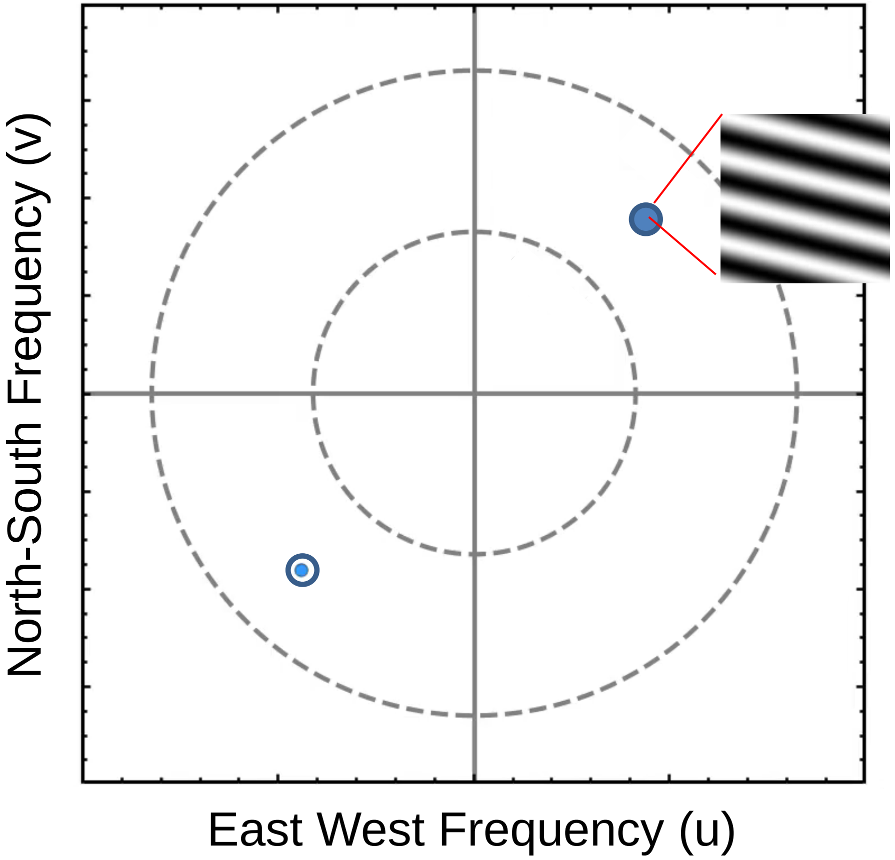
Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

The EHT data path

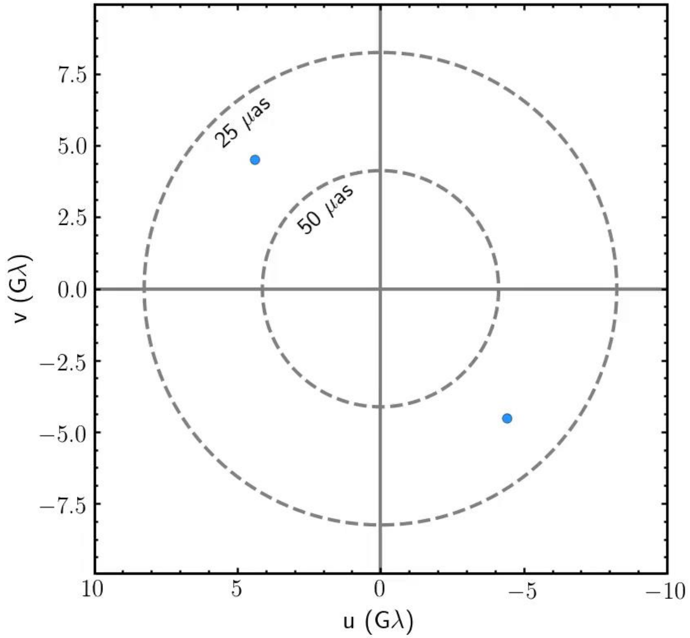


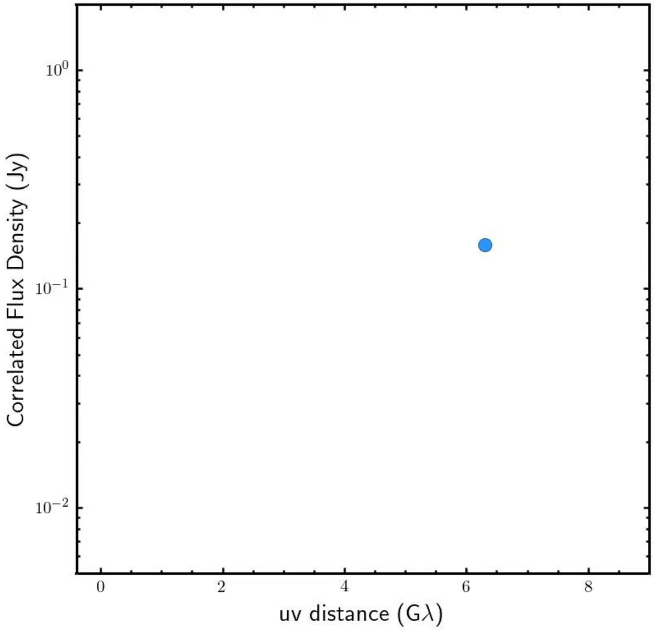
Animation credit: Lindy Blackburn

Very Long Baseline Interferometry (VLBI)



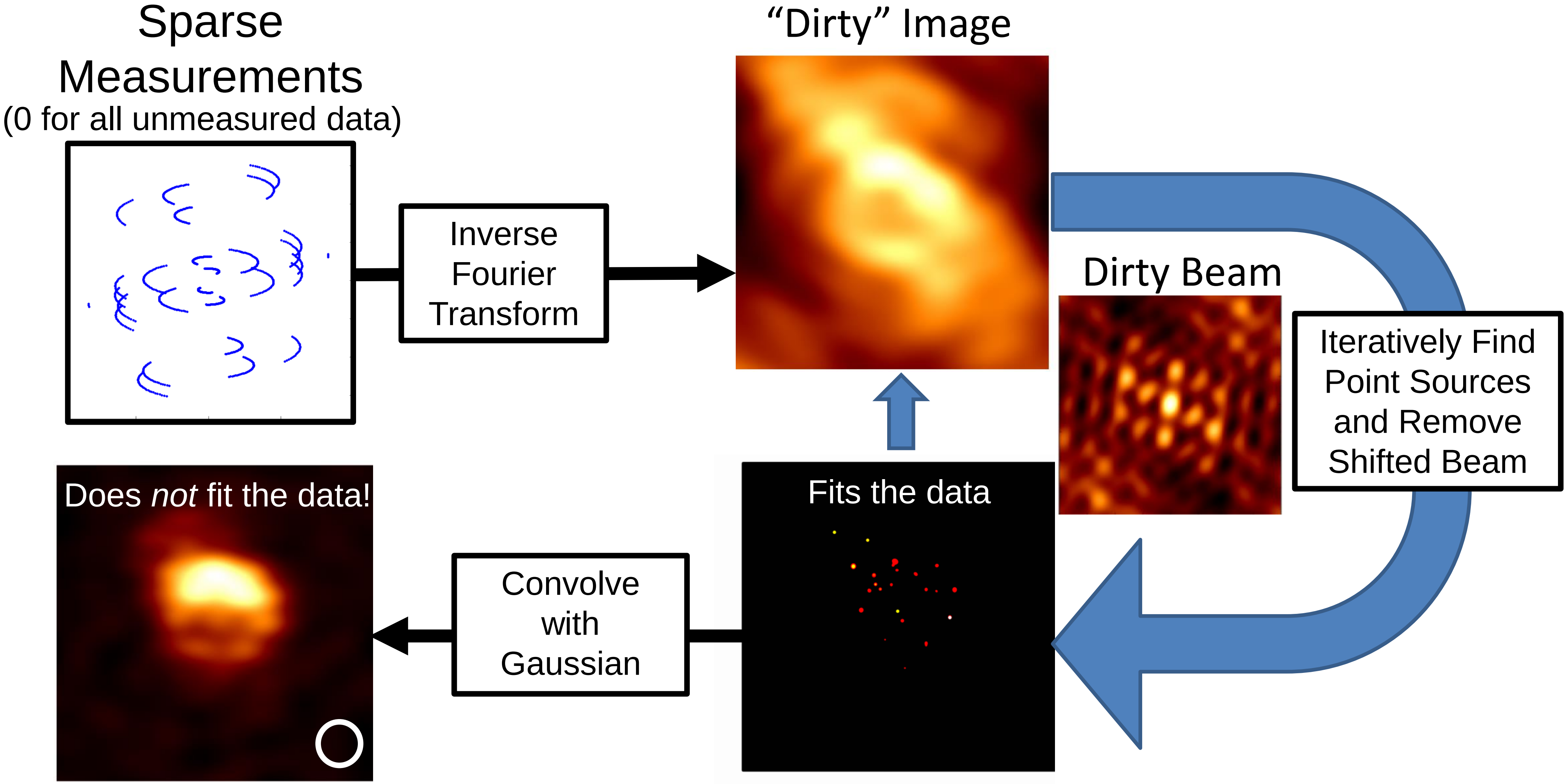
Very Long Baseline Interferometry (VLBI)





Movie Credit: Daniel Palumbo

Traditional Approach: CLEAN



Sparse Measurements
(0 for all unmeasured data)

Inverse Fourier Transform

“Dirty” Image

Dirty Beam

Iteratively Find Point Sources and Remove Shifted Beam

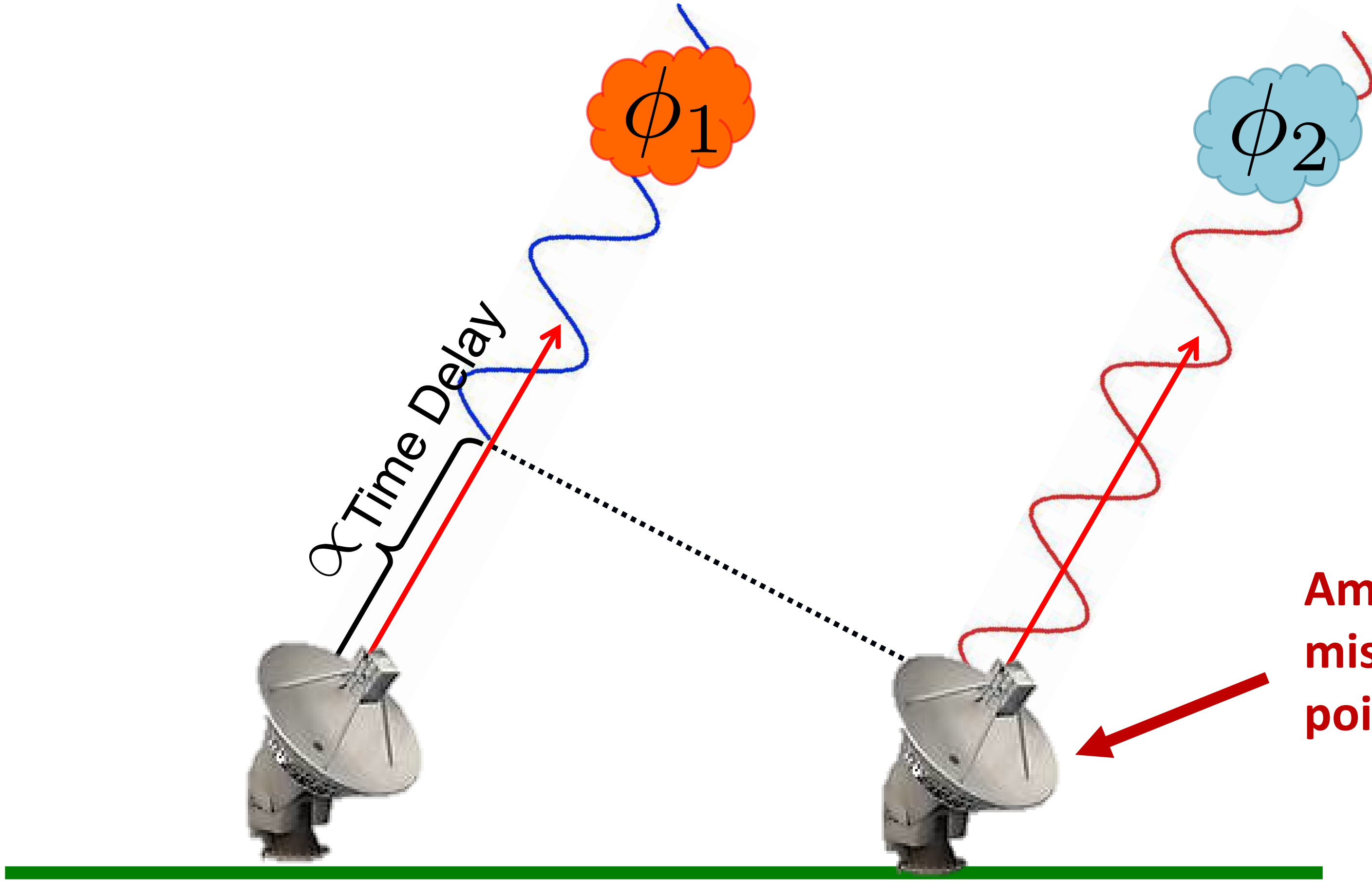
Fits the data

Convolve with Gaussian

Does *not* fit the data!

Simulation Credit: Avery Broderick

Station-based errors



Phase errors from the atmosphere (fast)

Amplitude error from miscalibration / errors in pointing

+ Thermal noise (subdominant)

Closure Quantities

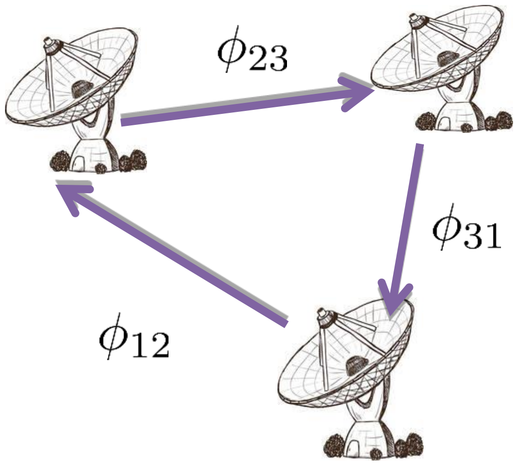
- Visibilities are corrupted by **station-based** gain errors

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

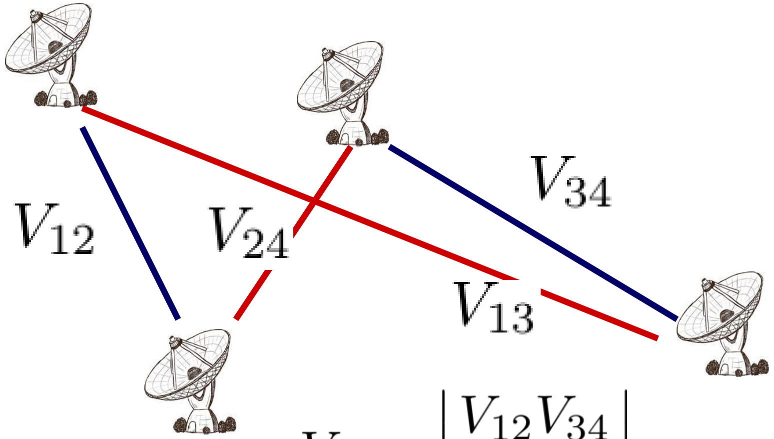
Amplitude: slower, from incorrect sensitivity

Phase: fast, from atmosphere

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

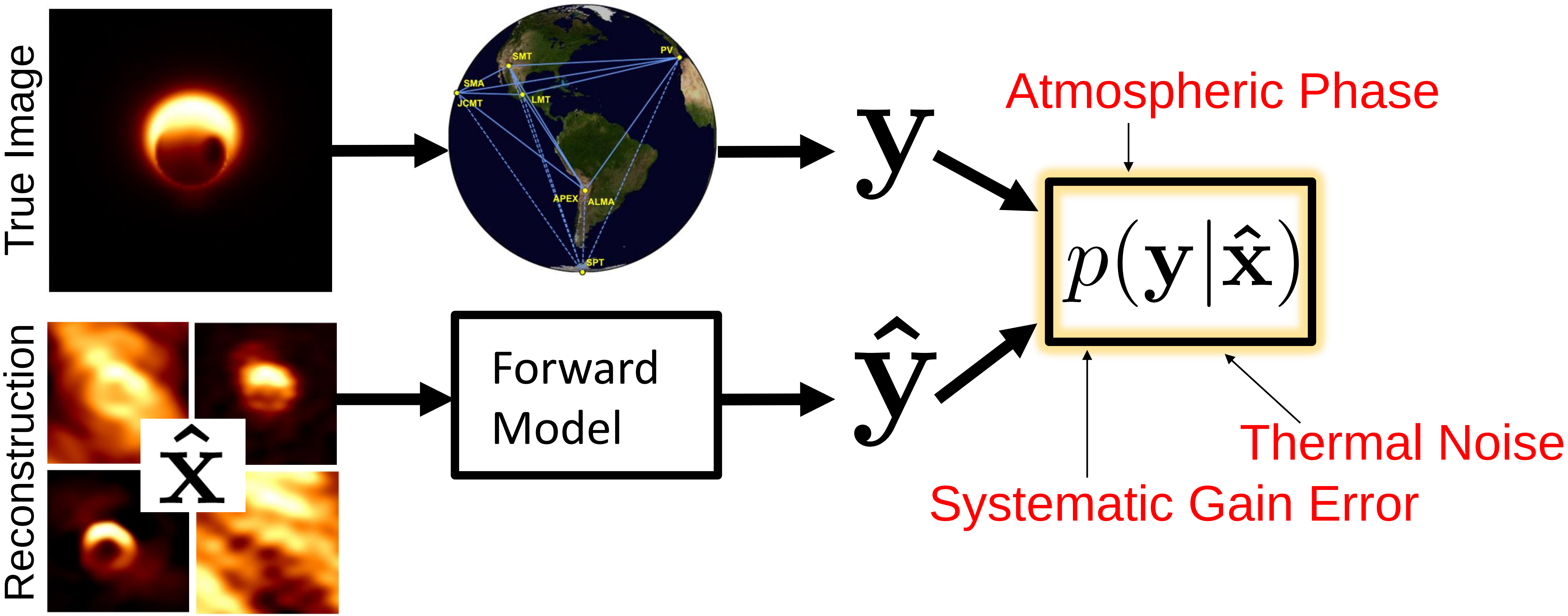


$$\psi_{\text{C}} = \phi_{12} + \phi_{23} + \phi_{31}$$



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

“Bayesian” Imaging



True Image

$\mathbf{y}$

Reconstruction

$\hat{\mathbf{x}}$

Forward Model

$\hat{\mathbf{y}}$

$p(\mathbf{y}|\hat{\mathbf{x}})$

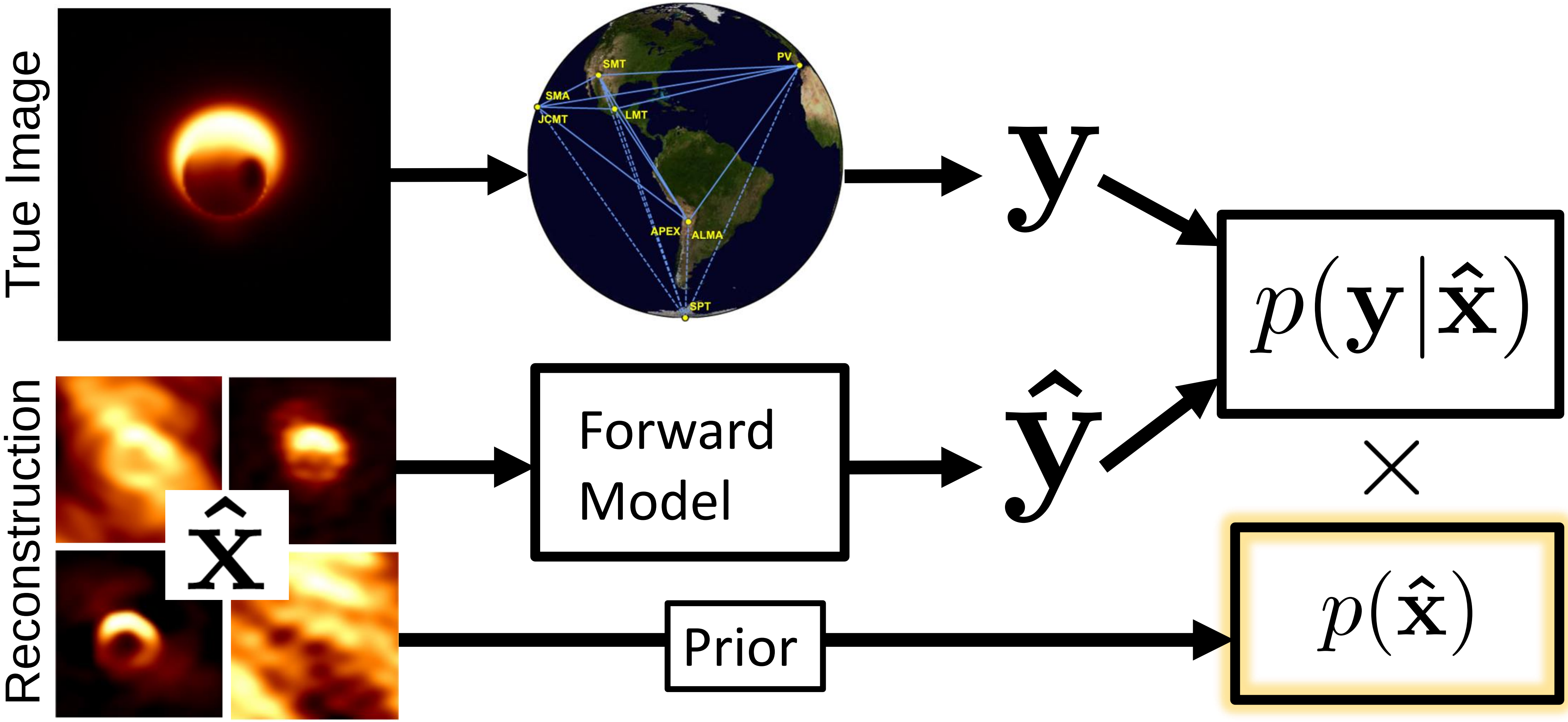
Atmospheric Phase

Thermal Noise

Systematic Gain Error

Image Credit: Katie Bouman
Simulation Credit: Avery Broderick

“Bayesian” Imaging



True Image

Reconstruction

$\hat{\mathbf{x}}$

Forward Model

Prior

$\mathbf{y}$

$\hat{\mathbf{y}}$

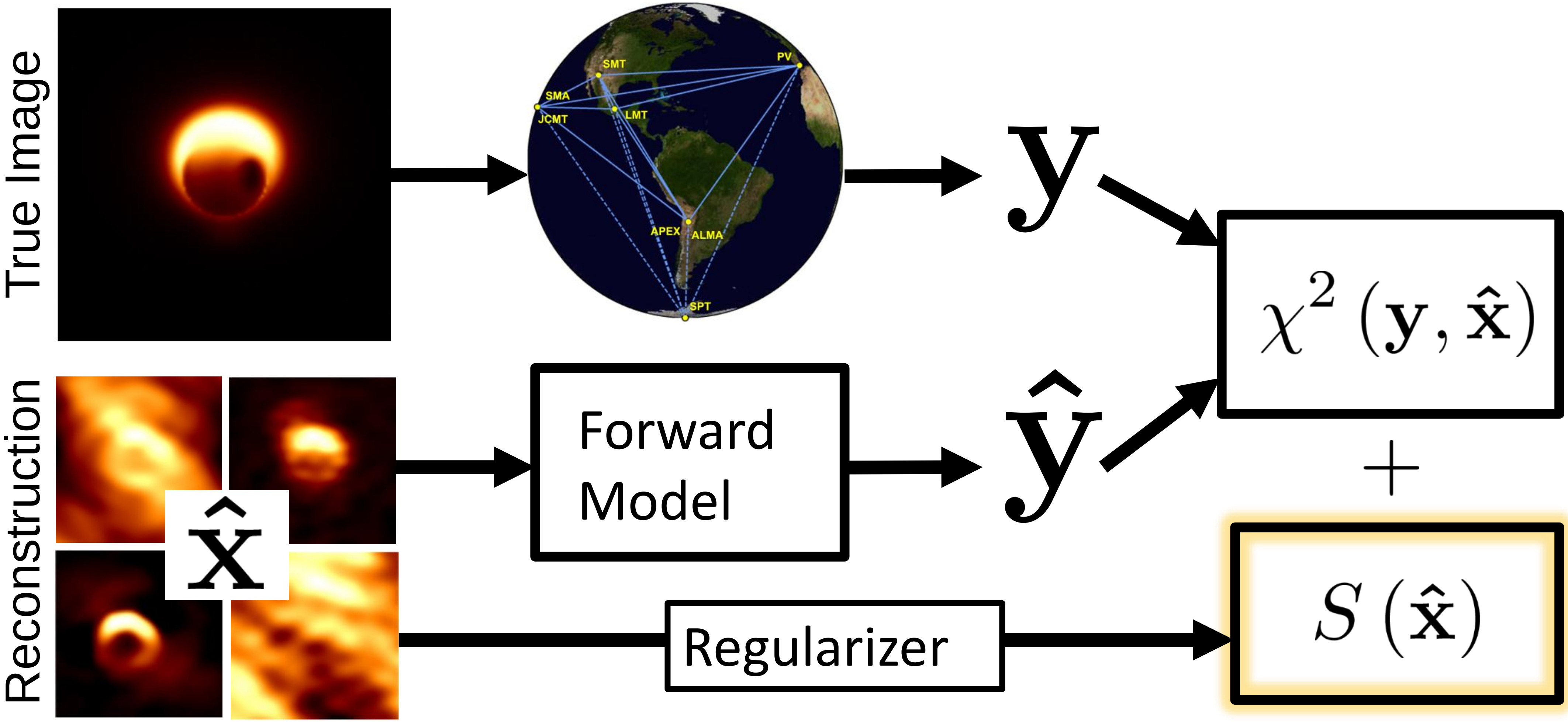
$p(\mathbf{y}|\hat{\mathbf{x}})$

$\times$

$p(\hat{\mathbf{x}})$

Image Credit: Katie Bouman
Simulation Credit: Avery Broderick

Regularized Maximum Likelihood



True Image

Reconstruction

$\hat{\mathbf{x}}$

Forward Model

Regularizer

$\mathbf{y}$

$\hat{\mathbf{y}}$

$$\chi^2\left(\mathbf{y}, \hat{\mathbf{x}}\right)$$

$$+$$

$$S\left(\hat{\mathbf{x}}\right)$$

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

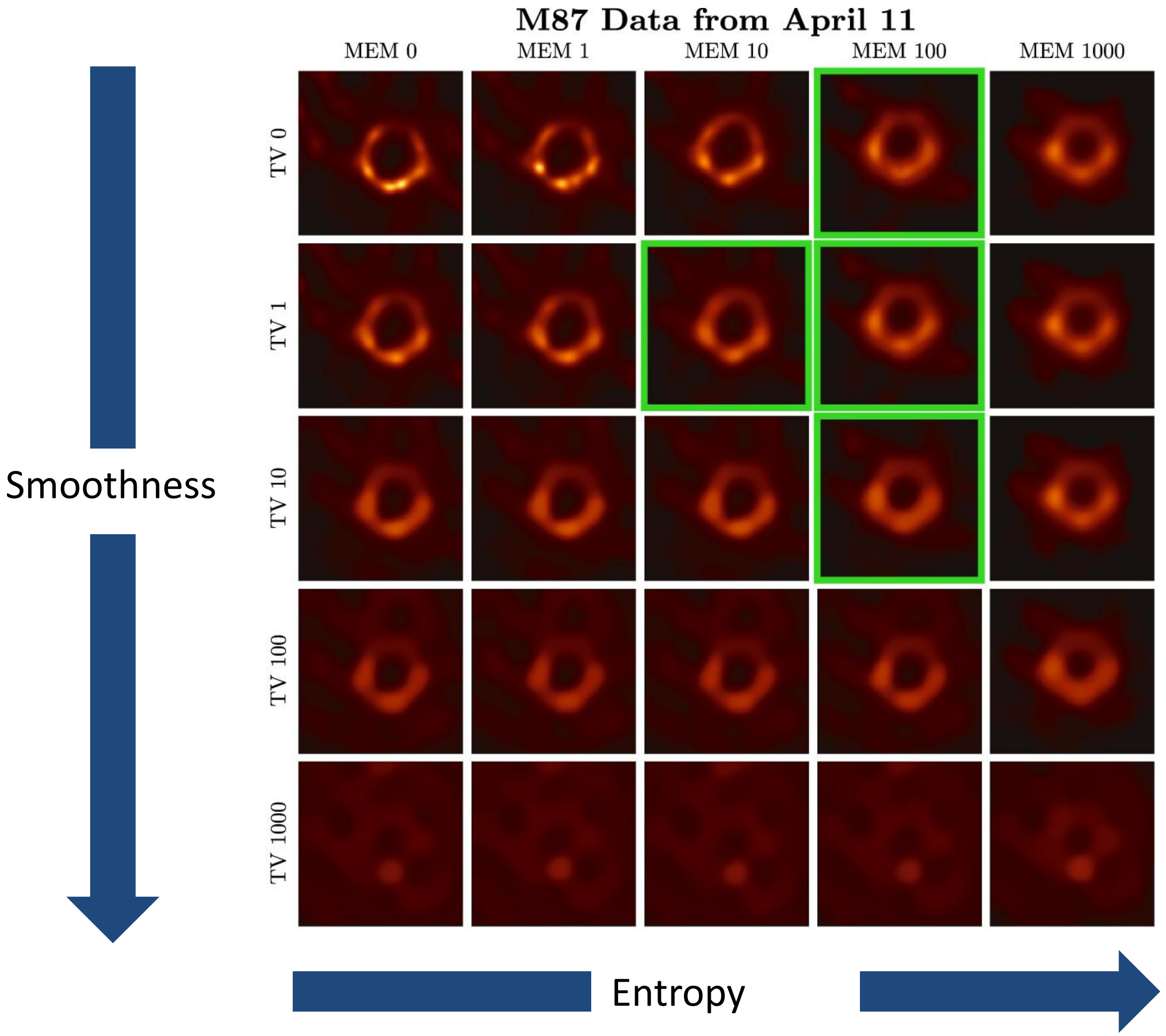
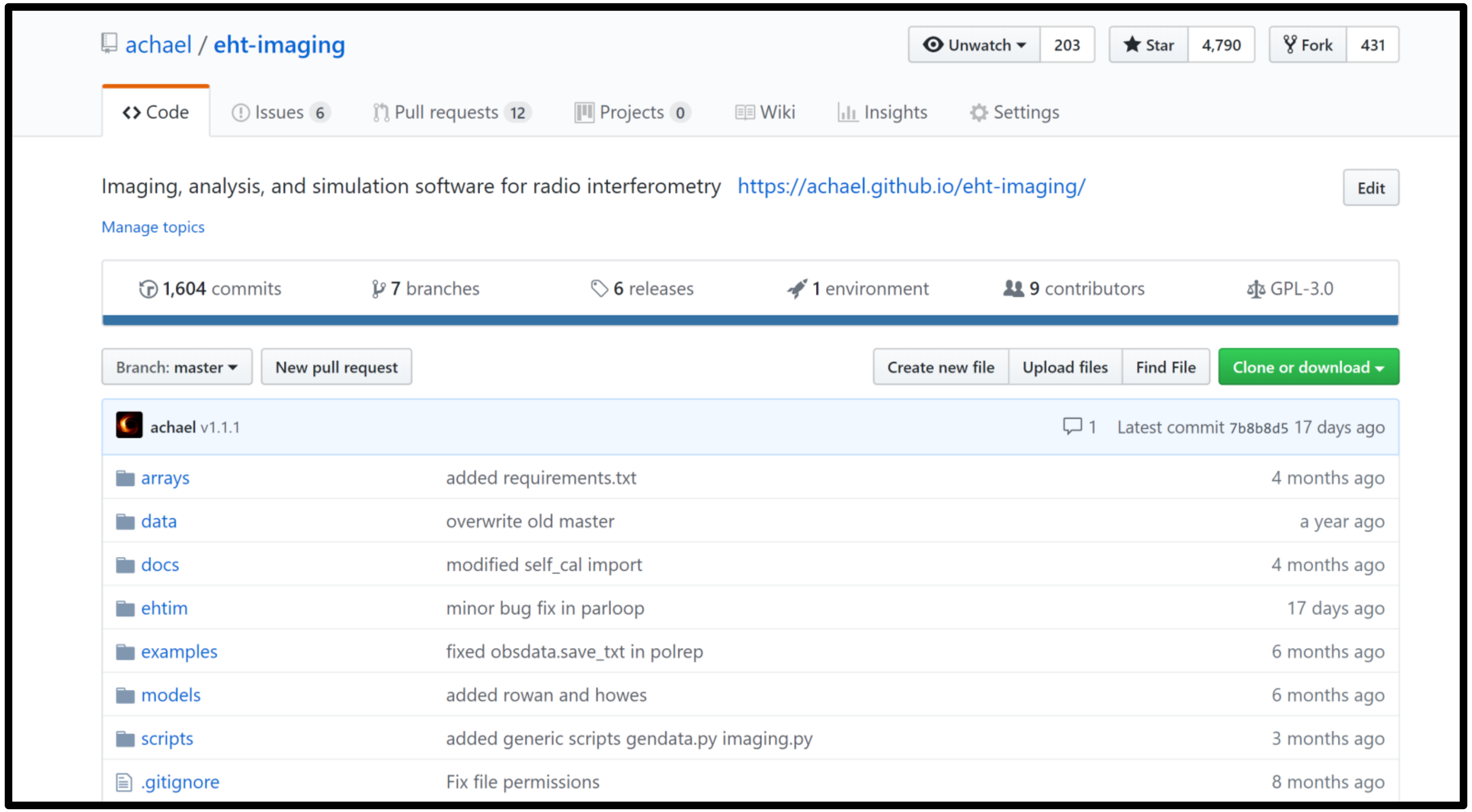


Image Credit: EHT Collaboration 2019 (Paper IV)

The `eht-imaging` software library



Imaging, analysis, and simulation software for radio interferometry https://achael.github.io/eht-imaging/

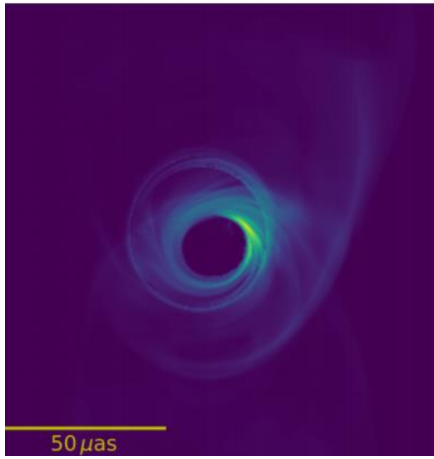
achael v1.1.1 — 1 — Latest commit 7b8b8d5 17 days ago

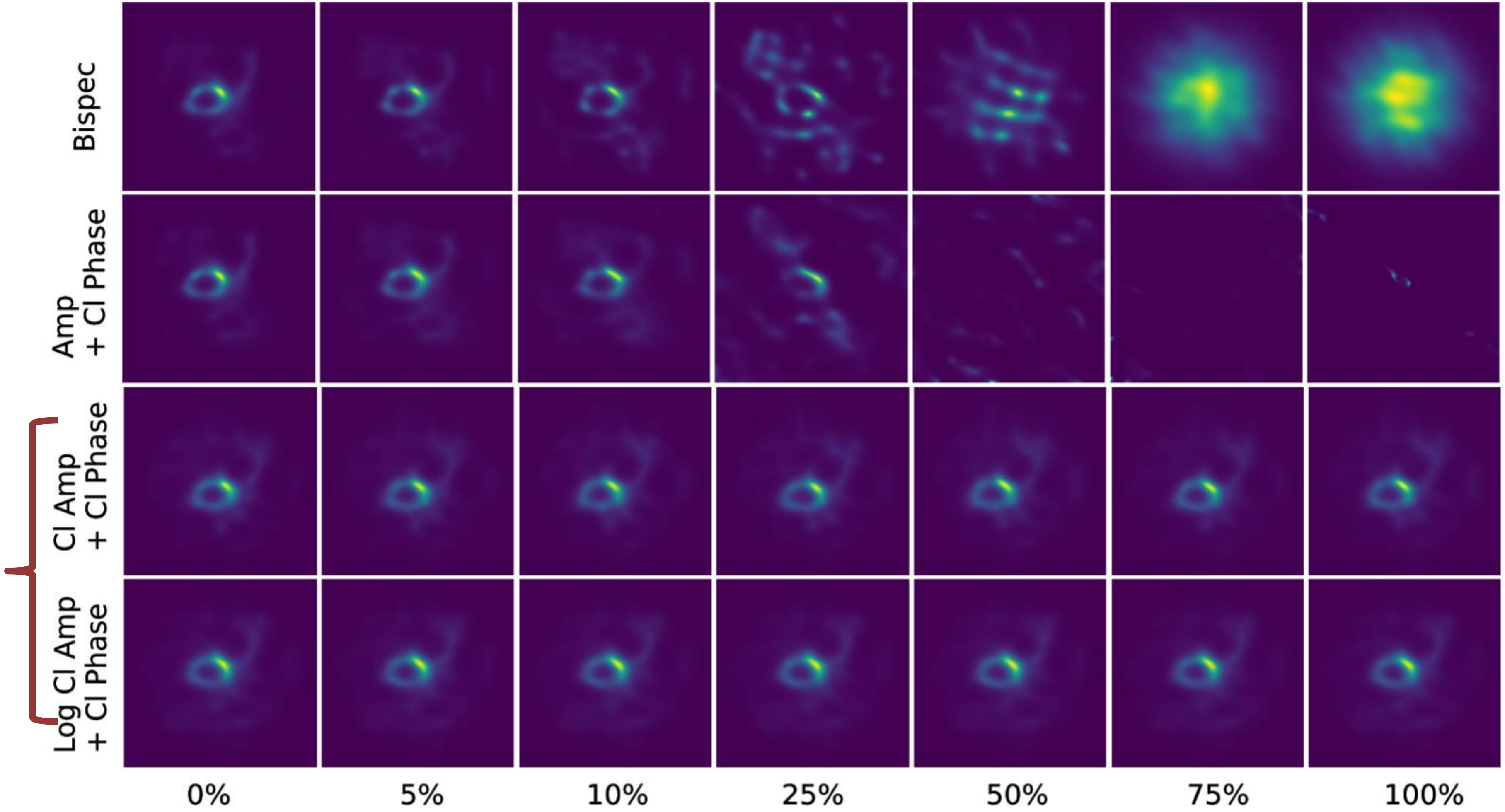
arrays	added requirements.txt	4 months ago
data	overwrite old master	a year ago
docs	modified self_cal import	4 months ago
ehtim	minor bug fix in parloop	17 days ago
examples	fixed obsdata.save_txt in polrep	6 months ago
models	added rowan and howes	6 months ago
scripts	added generic scripts gendata.py imaging.py	3 months ago
.gitignore	Fix file permissions	8 months ago

- 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

Closure imaging in interferometry





Closure Methods

Increasing Gain Calibration Error

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

RML Imaging
has wide applicability!

M87 jet at 7mm with the VLBA

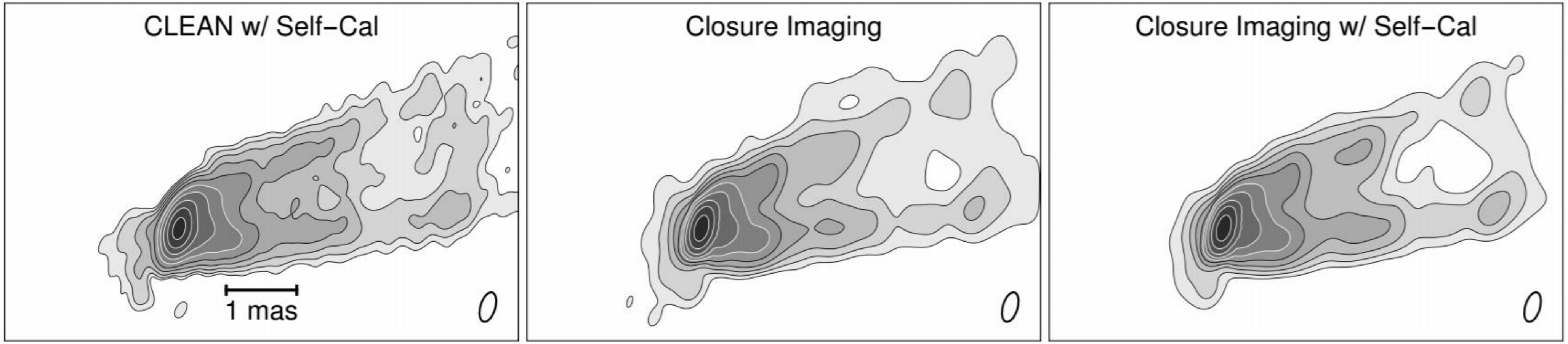


Image Credit: Chael+ 2018a,
Walker+ 2018

RML Imaging
has wide applicability!

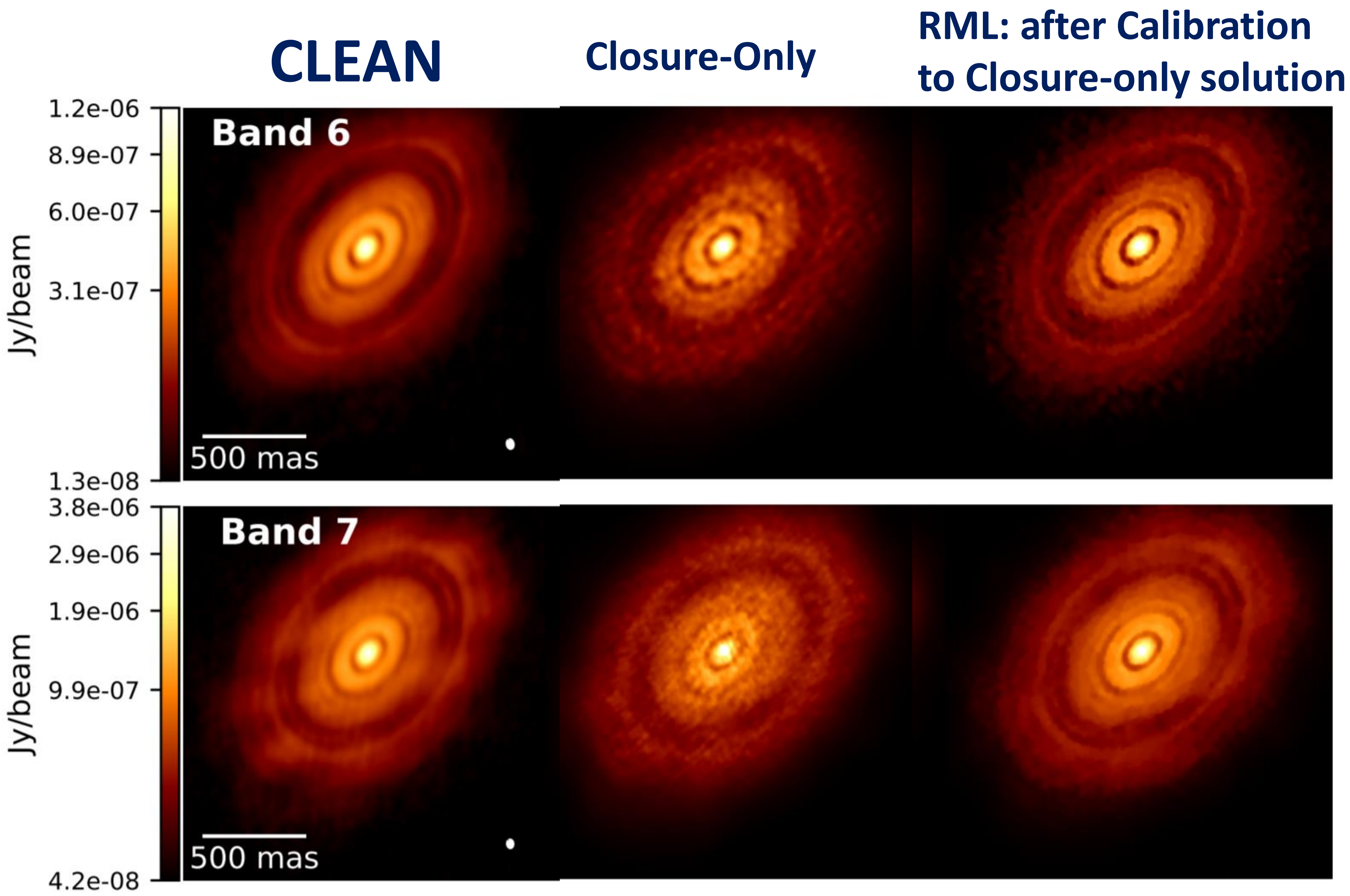


Image Credit: Chael+ 2018a,
ALMA Partnership+ 2015

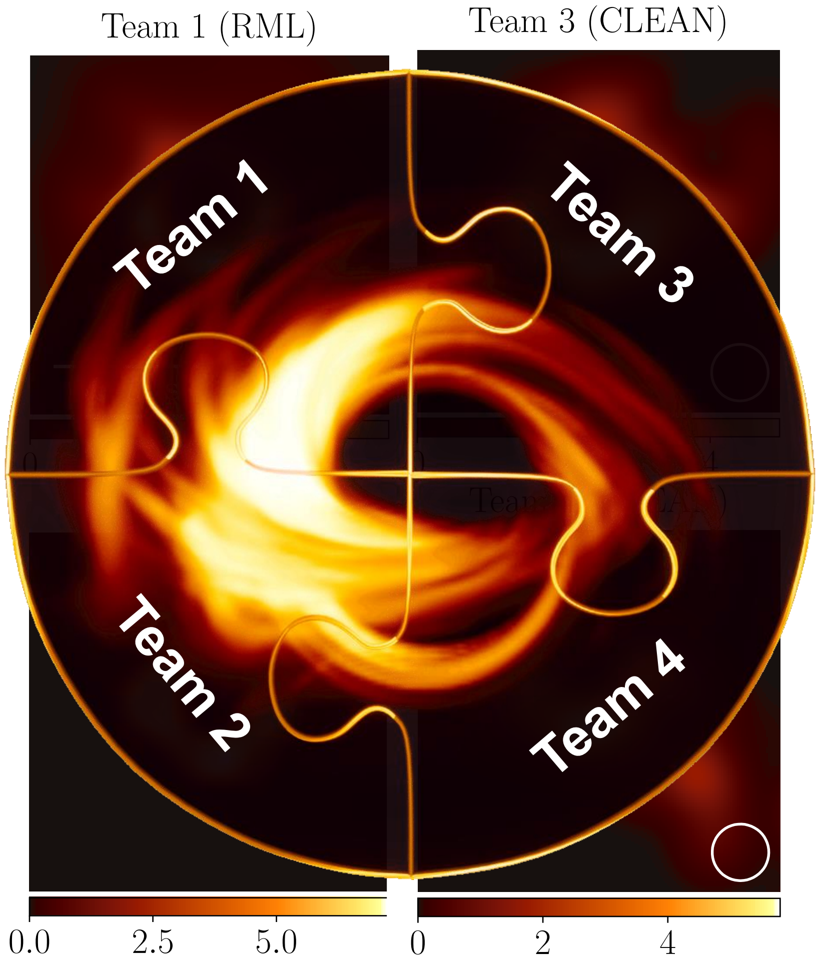
Imaging M87 with the EHT

BHI, July 2018

Two stages of imaging M87

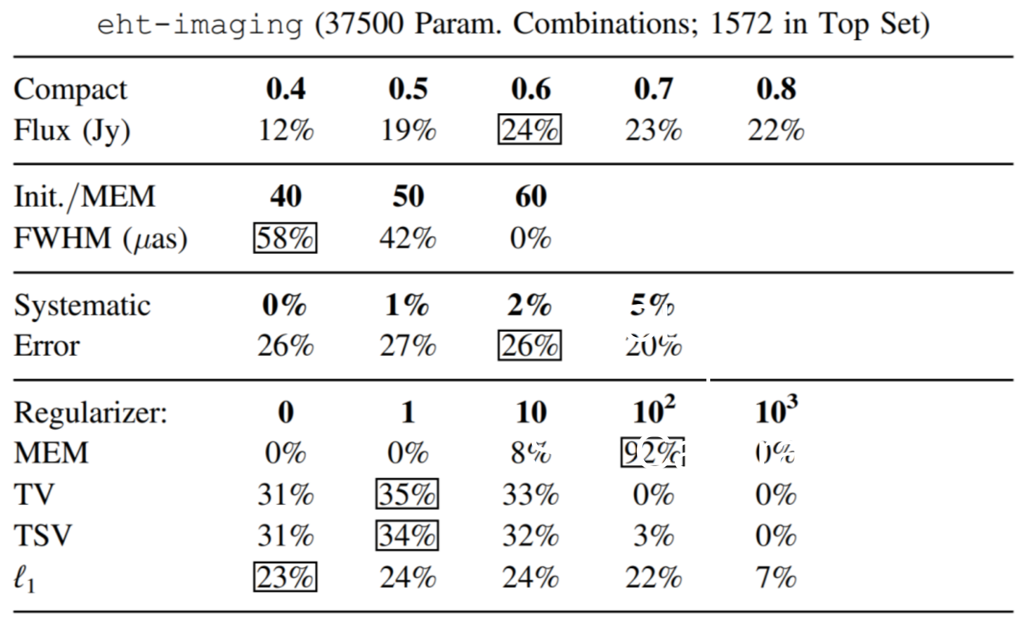
Stage 1: **Blind Imaging**

RML



CLEAN

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



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

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

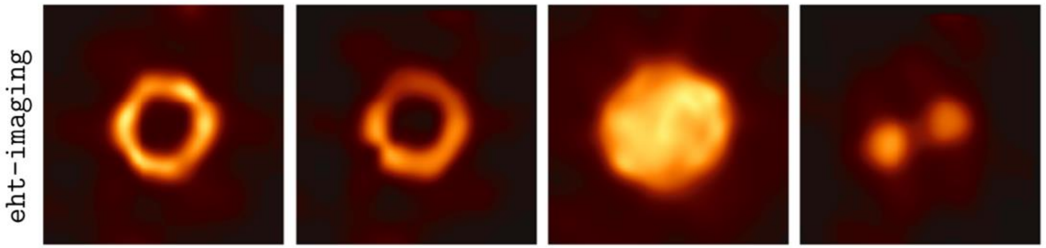
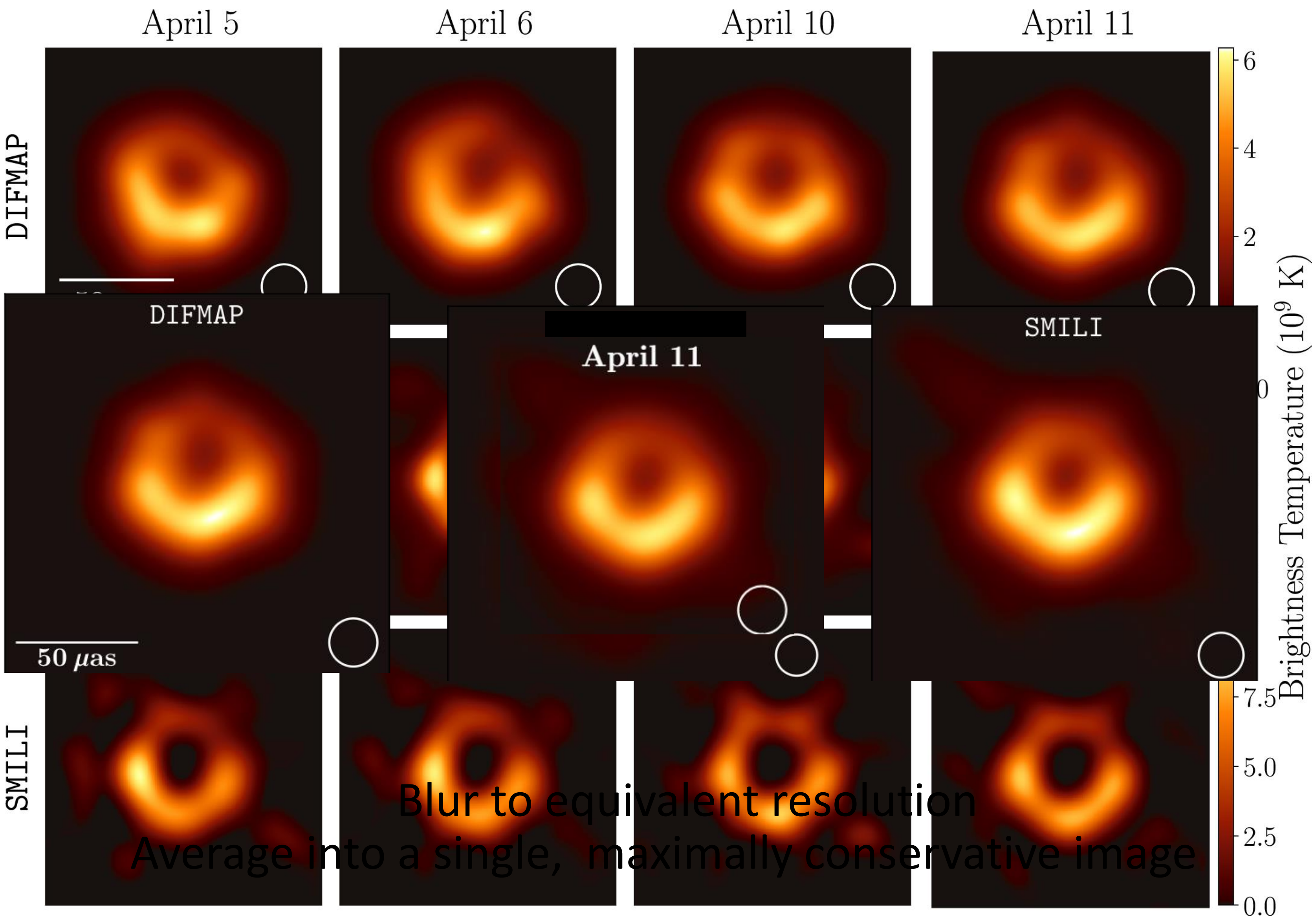


Image Credit: EHT Collaboration 2019 (Paper IV)

Three pipelines, four days

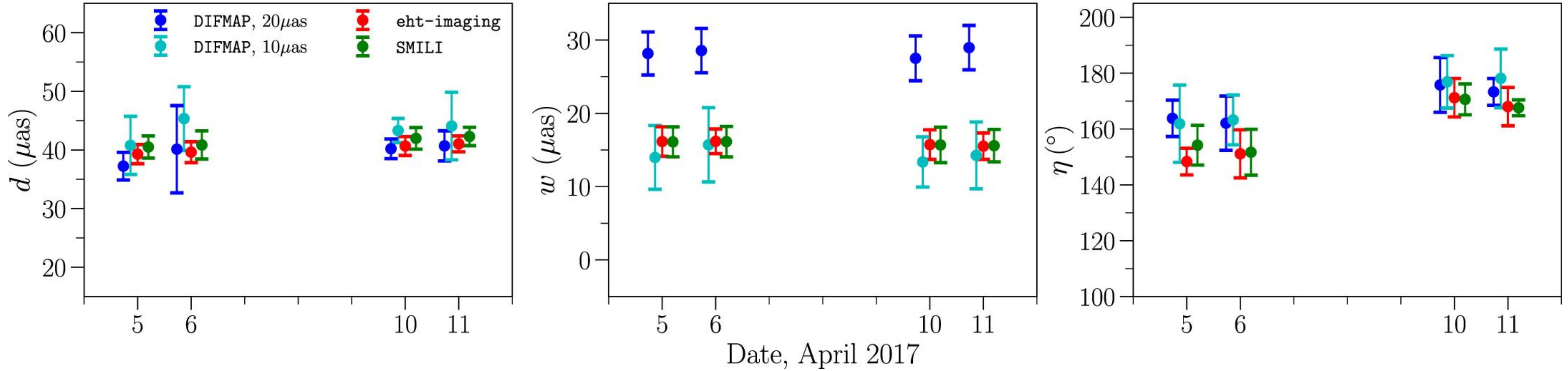


Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

M87 Ring Properties



Diameter

Width

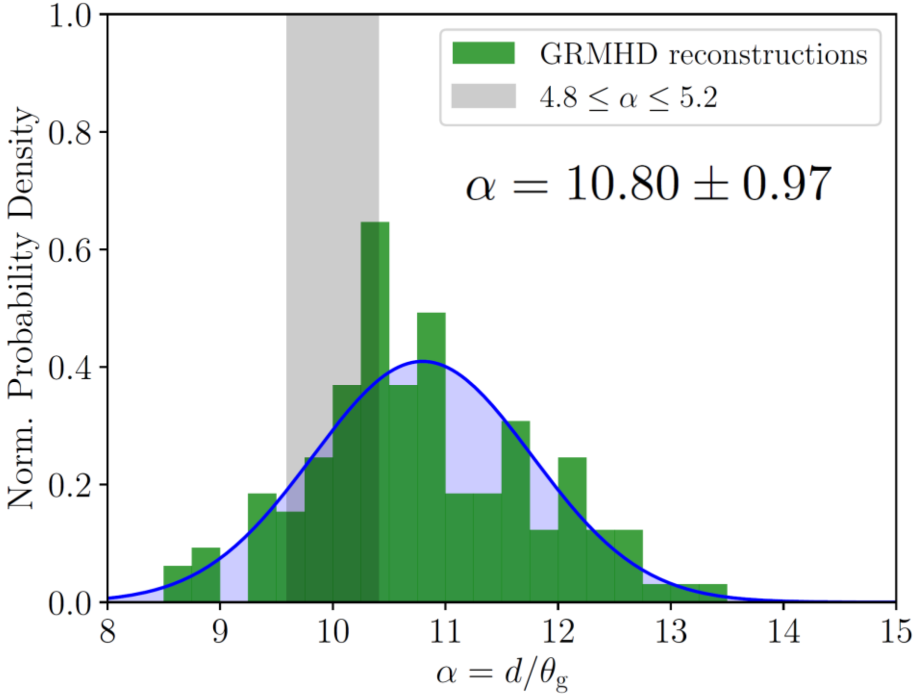
Angle

- 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)

Weighing a black hole

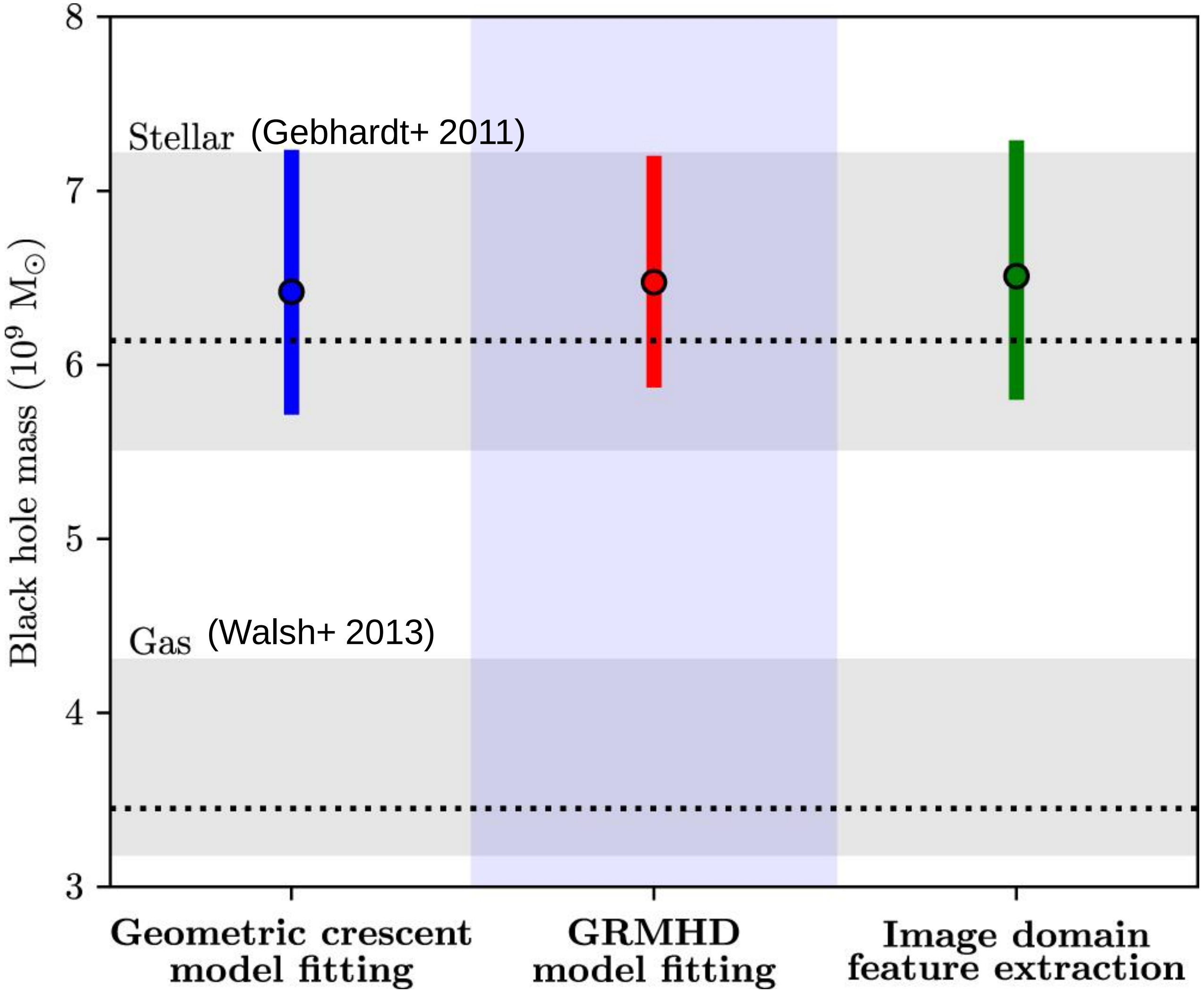
- The mass is proportional to the distance and diameter: $M = \frac{c^2 D}{G} \frac{d}{\alpha}$
- α can be biased by resolution and structure → Calibrate α with a library of simulation images



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

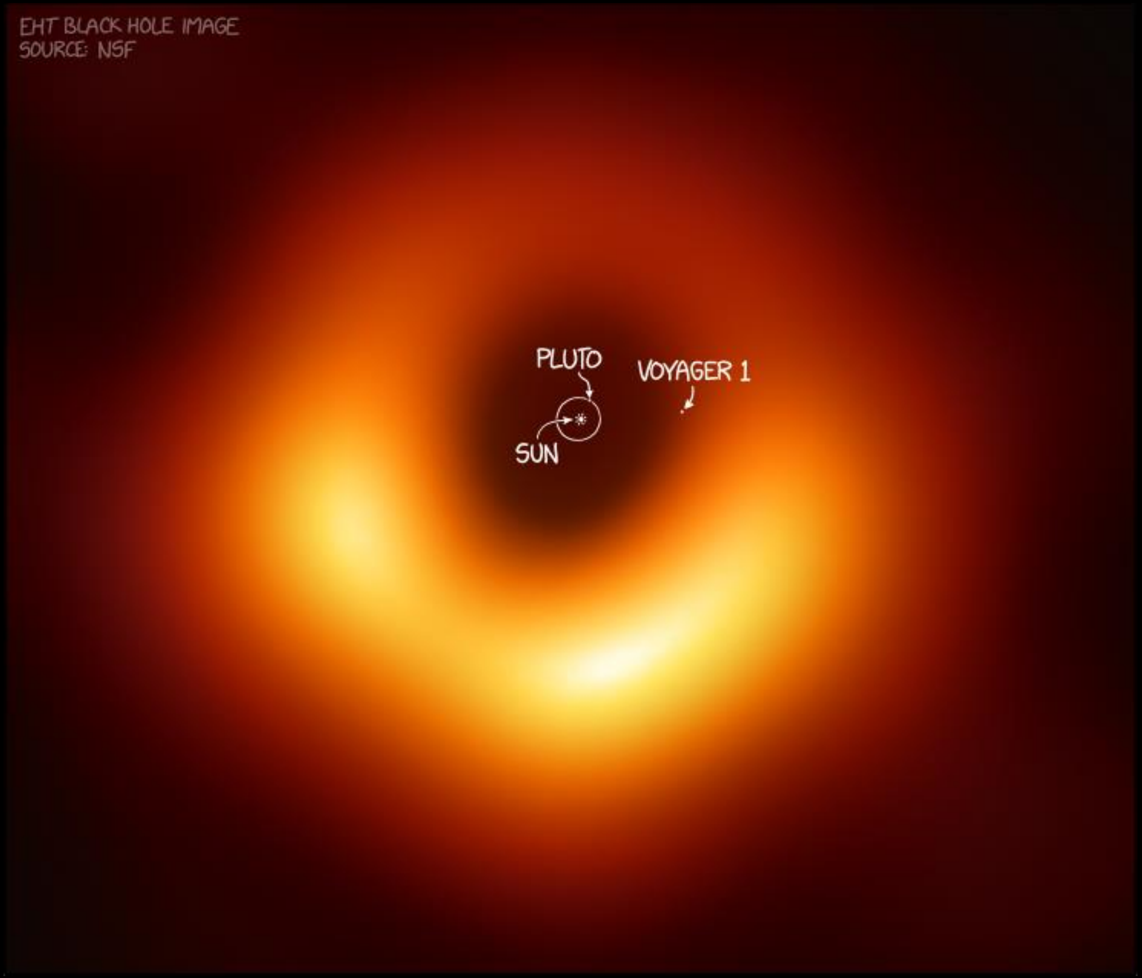
Weighing a black hole

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)



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

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

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

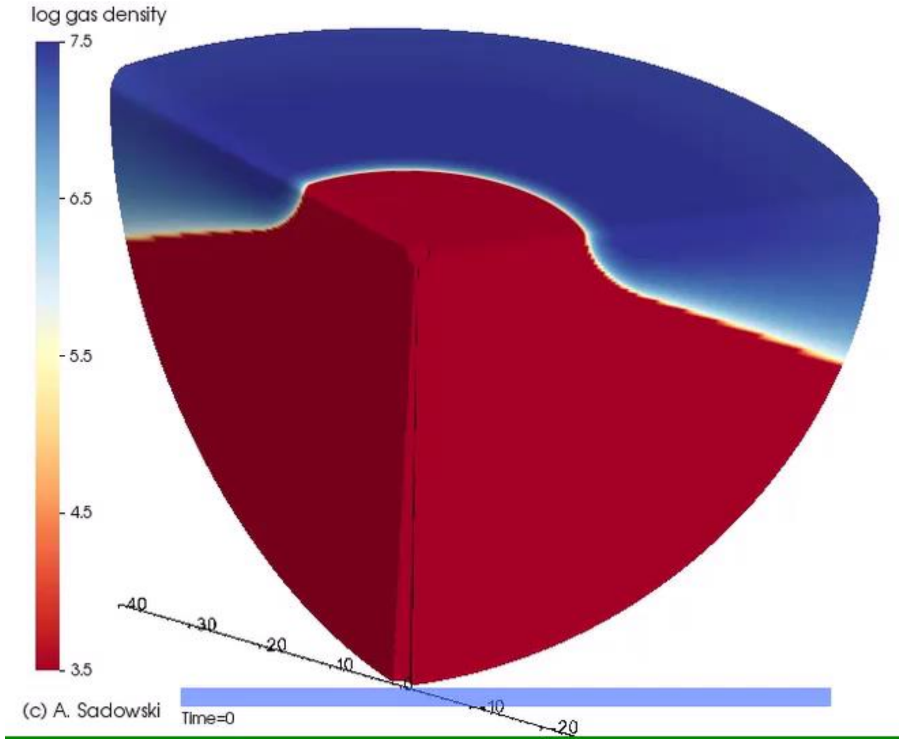
Outline

✓ I. Imaging M87
- Regularized Maximum Likelihood
- The eht-imaging library
- EHT Images of M87 and the BH mass

II. Simulating M87
- Two-temperature simulations in KORAL
- MAD Simulations of M87
- Connecting simulations to images at multiple scales

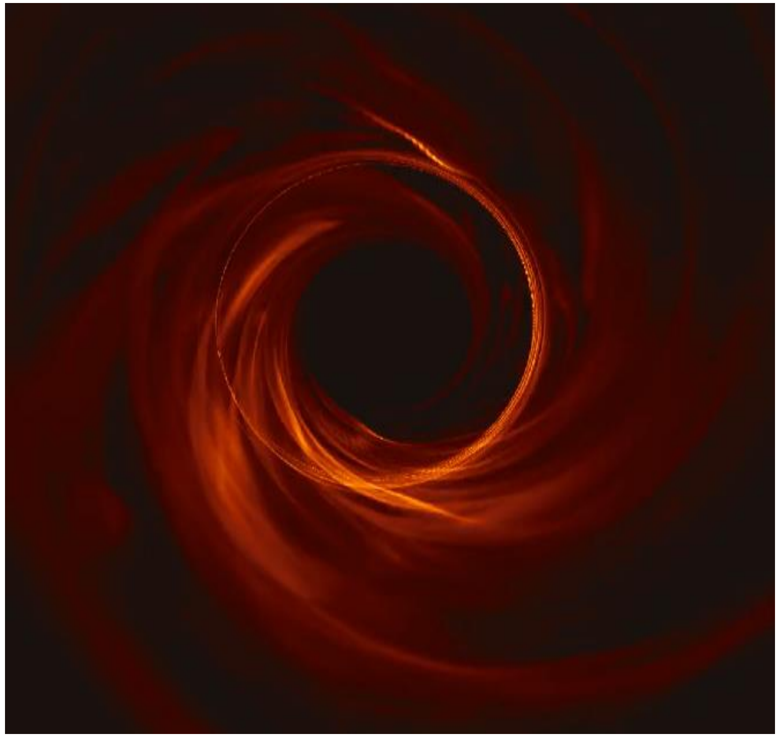
III. Next Steps
- Polarization
- Dynamics and Nonthermal electrons
- Expanding the EHT

General **R**elativistic **M**agneto**H**ydro**D**ynamics (GRMHD)



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

General **R**elativistic **R**ay **T**racing



Tracks light rays and solves for the emitted radiation

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

Simulations: What does the EHT see?

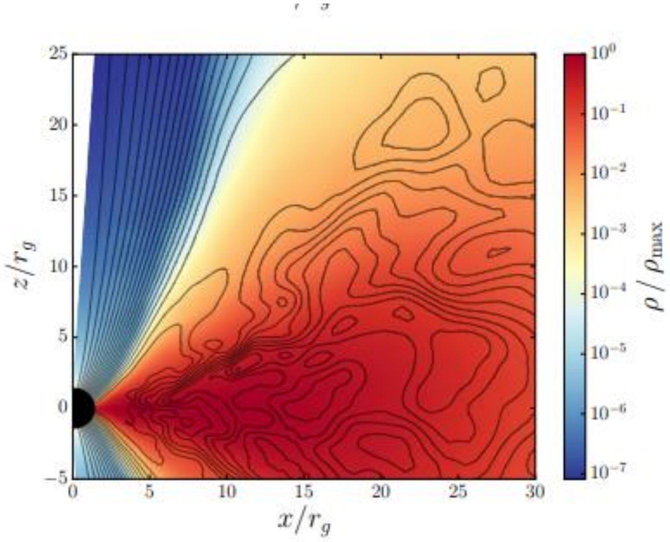
1. Spacetime geometry
    - -The gravity and shadow of the black hole.

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

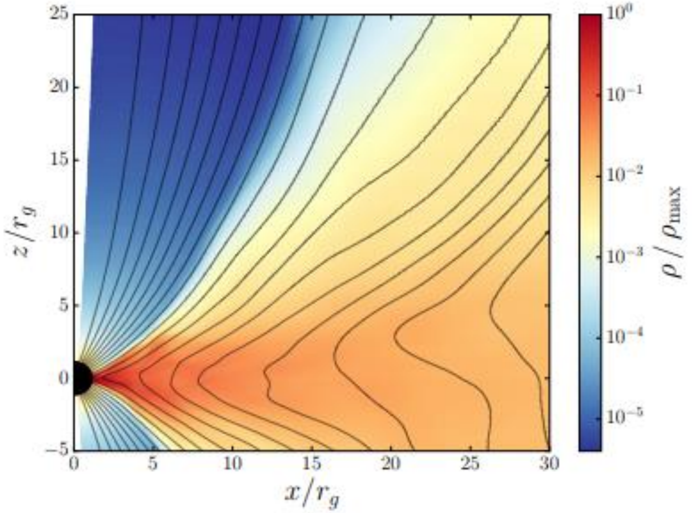
SANE vs MAD

- 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): $P_{\rm jet} \propto \Phi^2_{\rm mag}\Omega^2_{\rm H}$

Magnetic flux

Angular velocity of the horizon

Image credit: Riordan+ 2017

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.

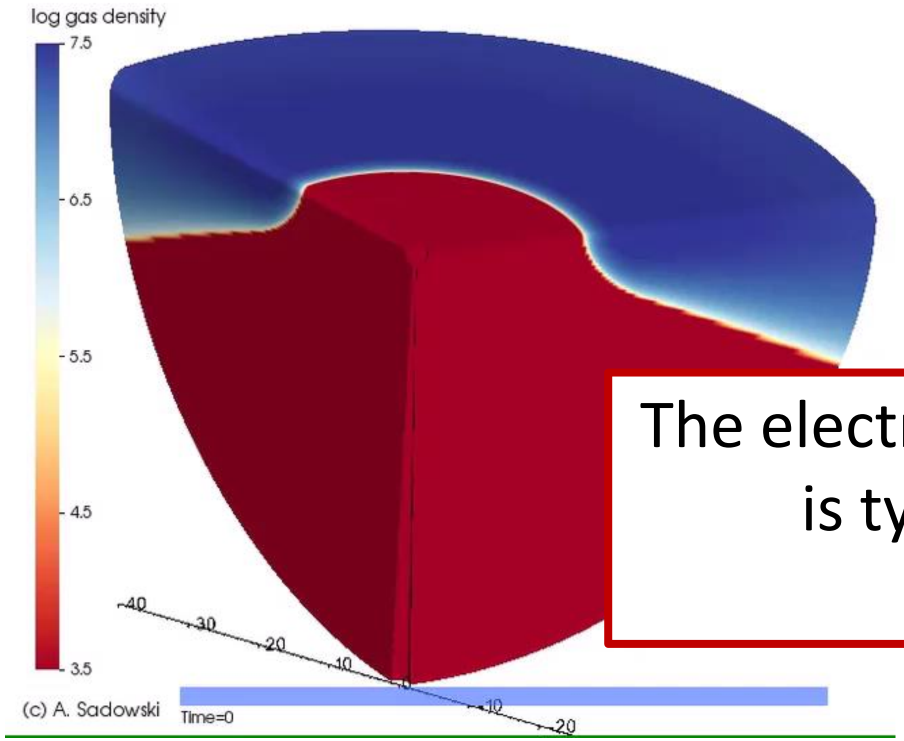
$$T_{\mathrm{e}} \neq T_{\mathrm{i}} \neq T_{\mathrm{gas}}$$

- 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



$T_e?$

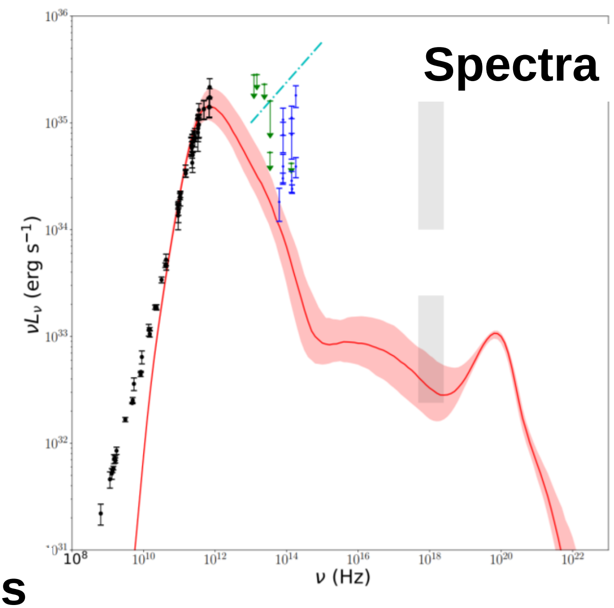
The electron-to-ion temperature ratio is typically set **manually** in **post-processing**

GRMHD Simulations

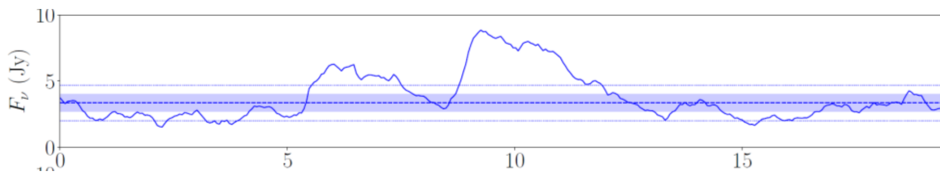
Usually evolve a **single** fluid and magnetic field

Images

Spectra



Light Curves



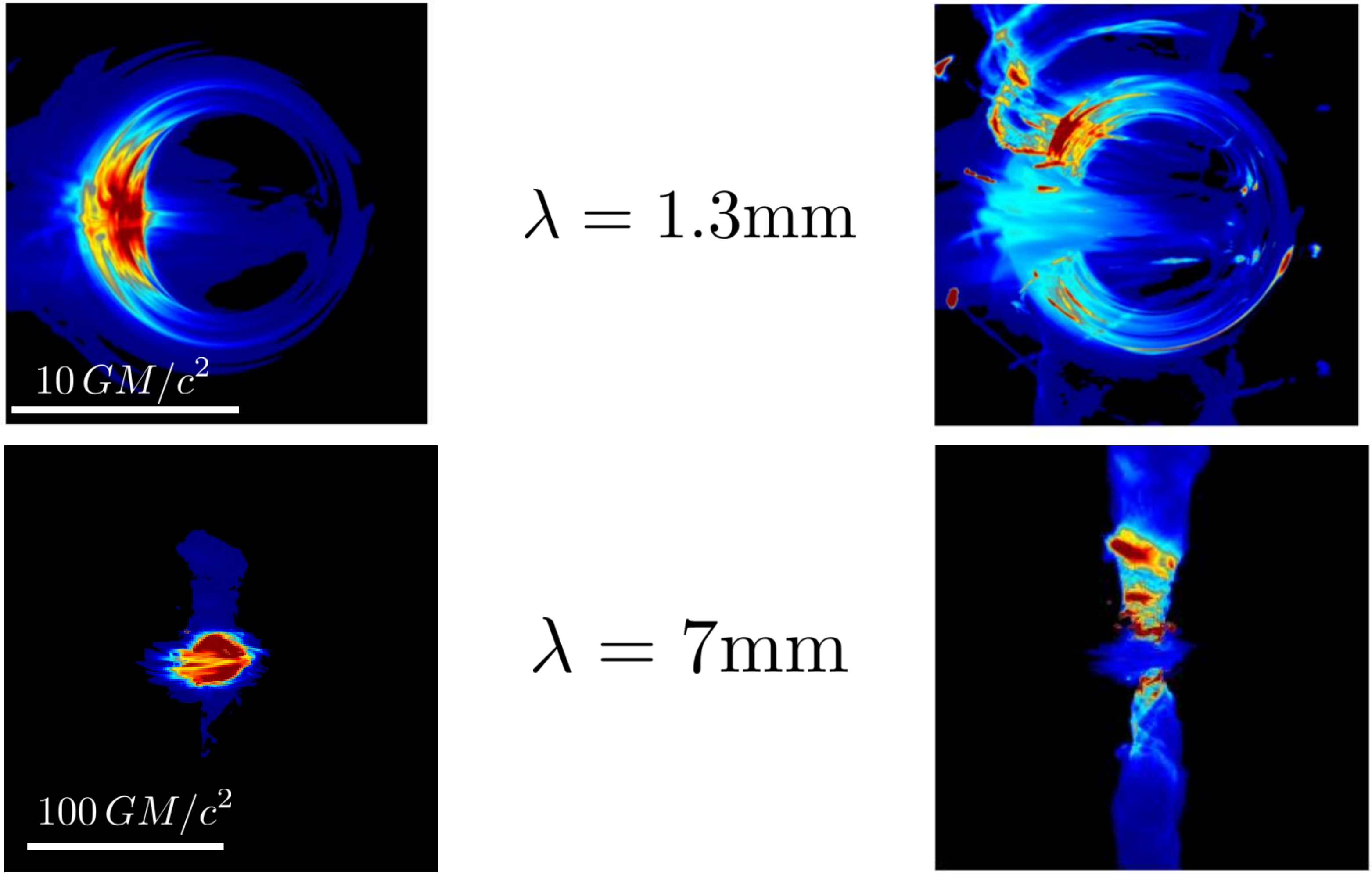
Movie & Image Credits: Aleksander Sądowski, Chael+ 2018b

Setting T_e in post-processing

Different Choices → Different Images!

Hot Disk

$$\frac{T_e}{T_i} = 0.2$$



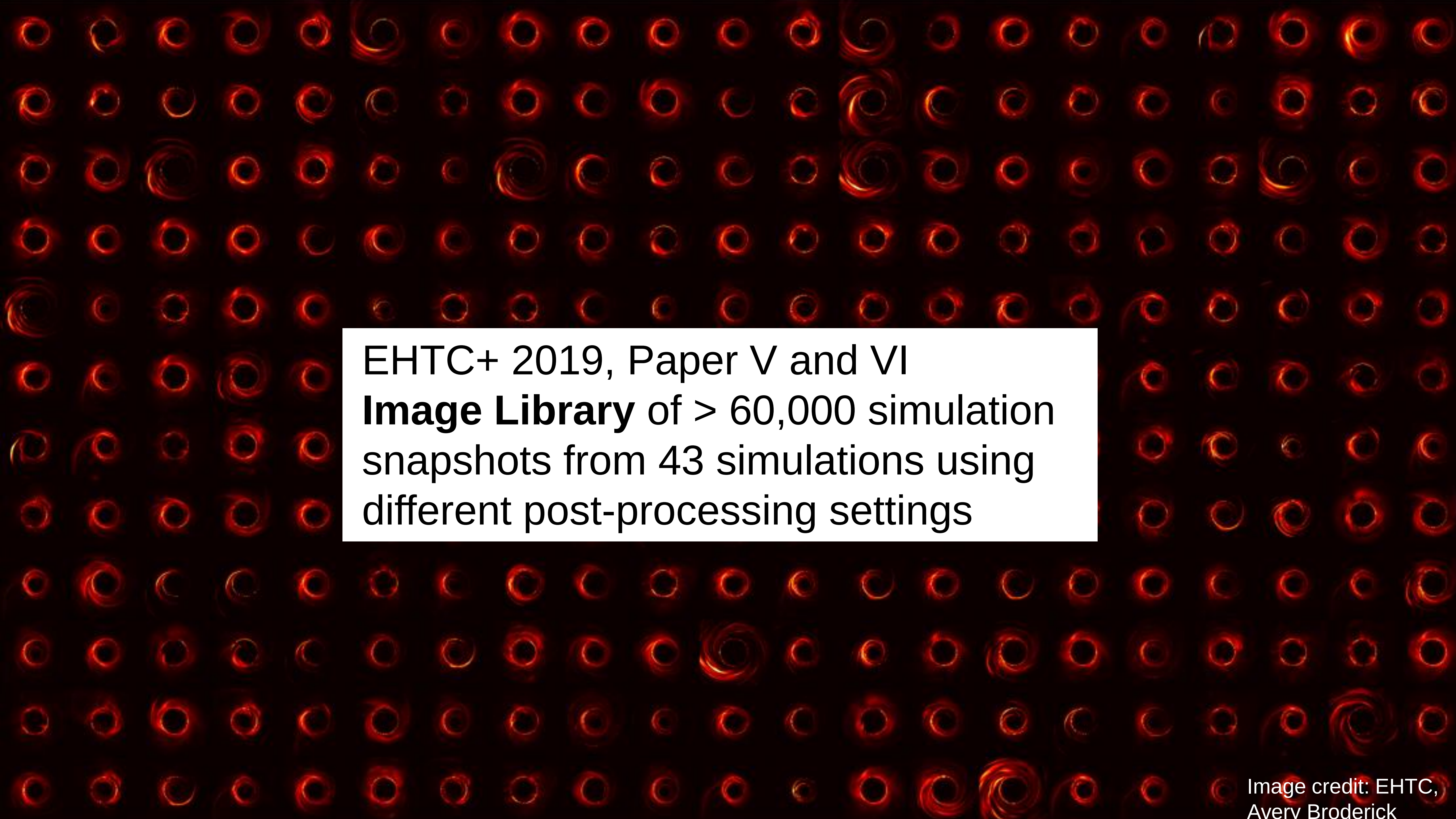
$$\lambda = 1.3\mathrm{mm}$$

$$\lambda = 7\mathrm{mm}$$

Cool Disk

$$\frac{T_e}{T_i} = 0.04$$

Mościbrodzka+ 2014



EHTC+ 2019, Paper V and VI

Image Library of > 60,000 simulation snapshots from 43 simulations using different post-processing settings

Image credit: EHTC, Avery Broderick

Lessons from EHTC+ 2019 Paper V

- Most models can be made to fit EHT observations alone by tweaking free parameters (mass, orientation, electron temperature…)

- The jet power constraint (**$\geq 10^{42}$ erg/sec**) rejects all spin 0 models
  - SANE models with |a| < 0.5 are rejected.
  - Most |a| > 0 MAD models are acceptable.

- Reason to suspect the system may be MAD, and self-consistent electron temperatures from simulations may be important
  - -Can we learn more from also comparing to lower frequency images?

Two-Temperature GRRMHD Simulations

- Using the code `KORAL`: (Sądowski+ 2013, 2015, 2017, Chael+ 2017)
- **Include radiative feedback on gas energy and momentum (through M1 closure)**
- Electron and ion energy densities are evolved via the covariant 1st law of thermodynamics:

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

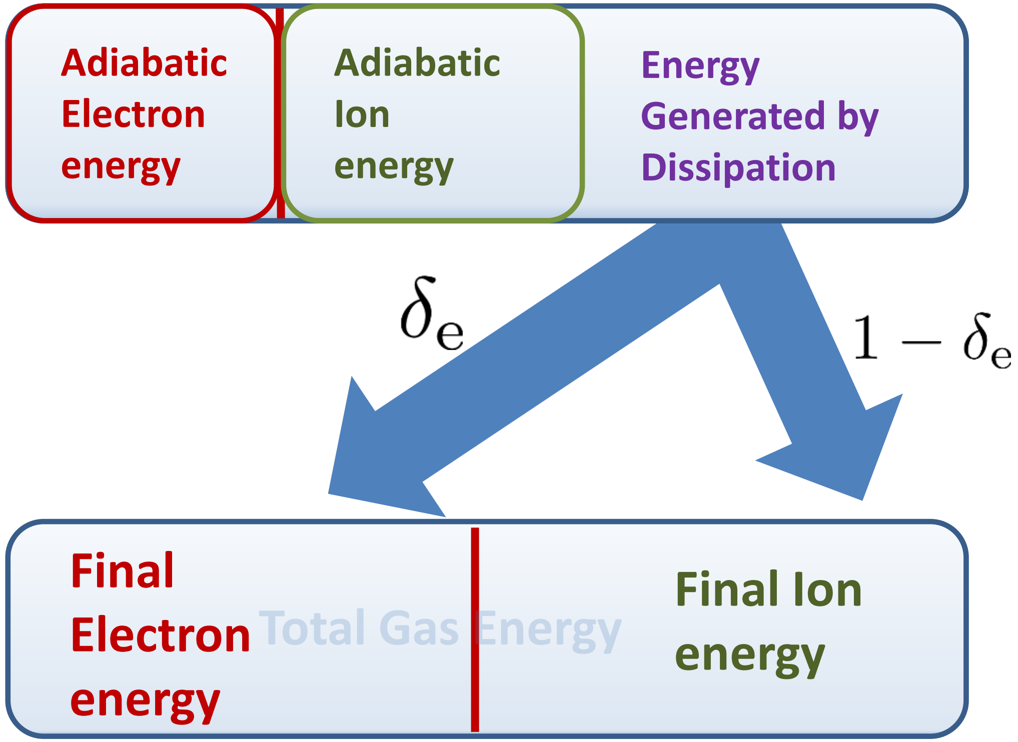
Adiabatic Compression and Expansion

Entropy Generated Through Dissipation
And lost through radiative cooling

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.



Adiabatic Electron energy

Adiabatic Ion energy

Energy Generated by Dissipation

$\delta_{\rm e}$

$1 - \delta_{\rm e}$

Final Electron energy

Total Gas Energy

Final Ion energy

Sub-grid Heating Prescriptions

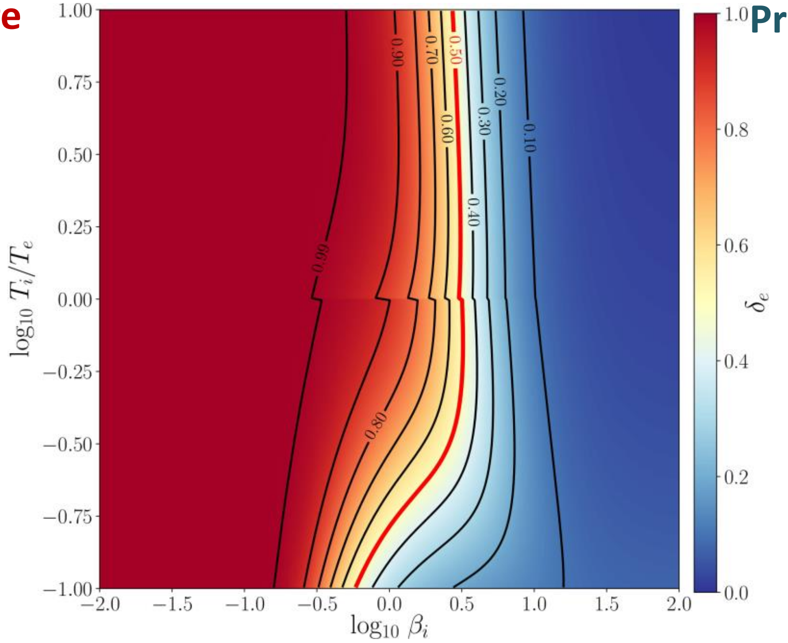
Turbulent Dissipation (Howes 2010)

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

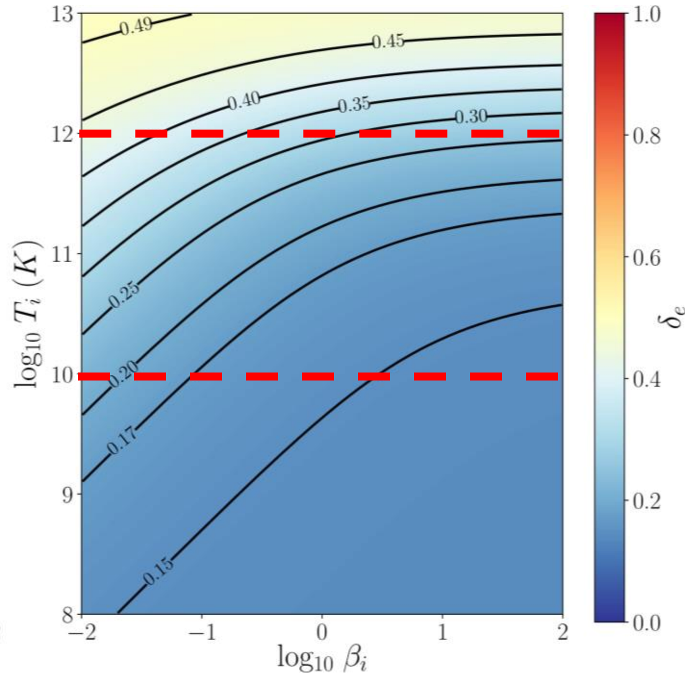
Magnetic Reconnection (Rowan+ 2017)

- 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



Relatively flat δ_e over large range of temperature, beta.

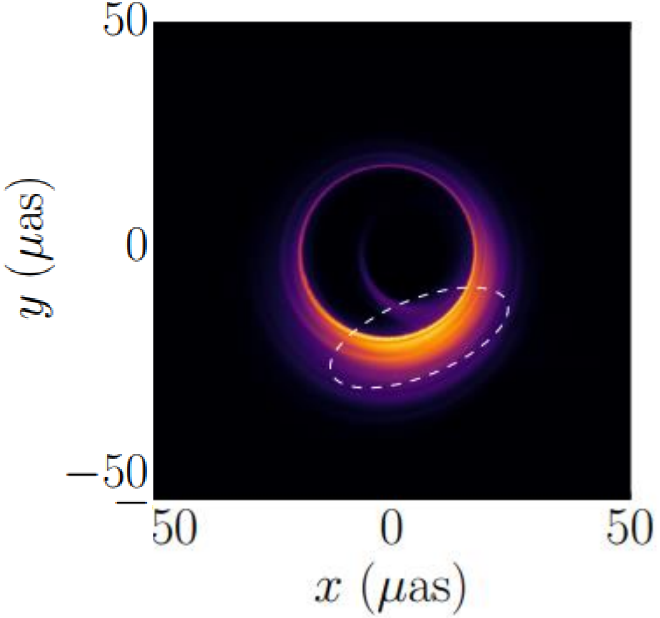
Image Credit: Chael+ 2018b
see also: Kawazura+ 2018 (turbulent damping). Werner+ 2018 (reconnection)

Previous simulations:

Mościbrodzka+ 2016, Ryan+ 2018

- Both are SANE 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

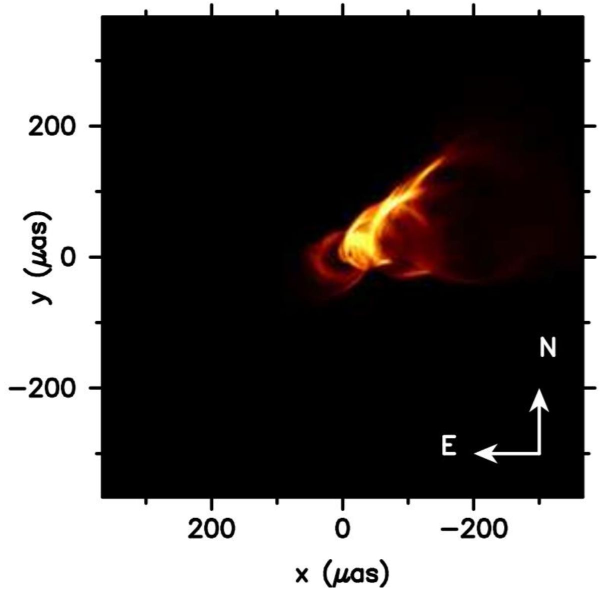


Image Credit: Ryan+ 2018, Moscibrodzka+ 2016
Also: Dexter+ 2012,, 2017

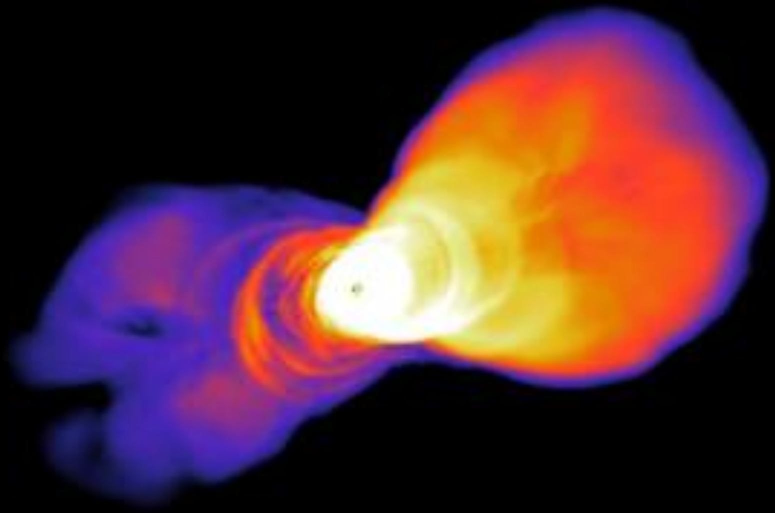
Two M87 simulations

43 GHz jets

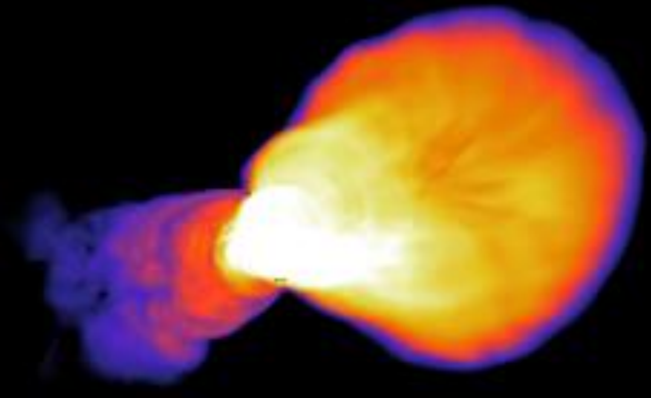
0.0 yr

Turbulent Heating

Reconnection Heating



P_{jet} is too small!



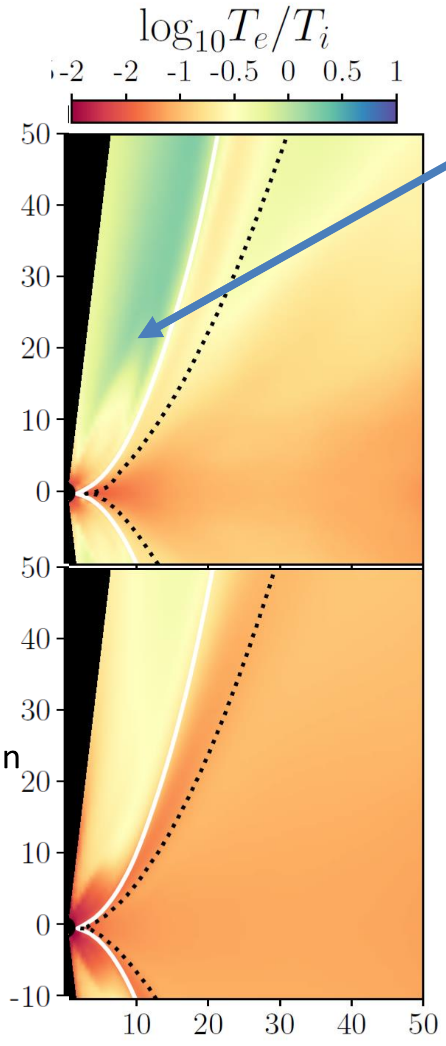
P_{jet} in the measured range!

Movie Credit: Chael+ 2019

Electron Heating + Radiation → Jet Dynamics

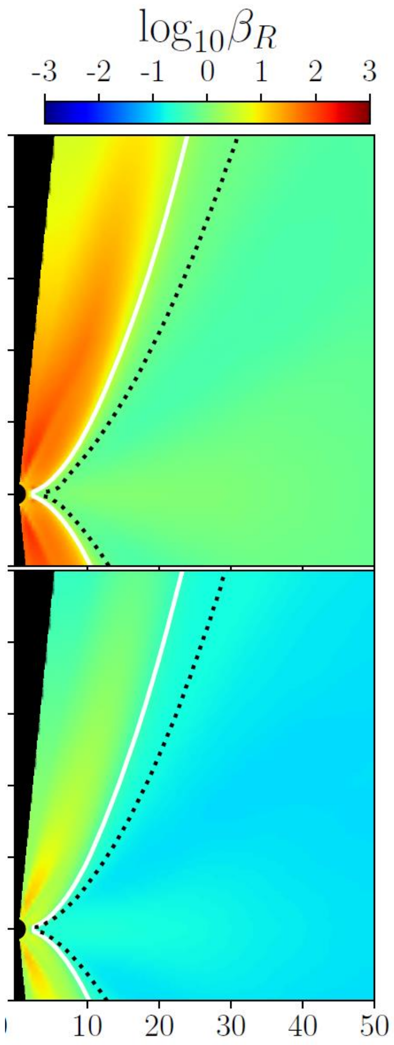
Turbulent Heating

Reconnection Heating

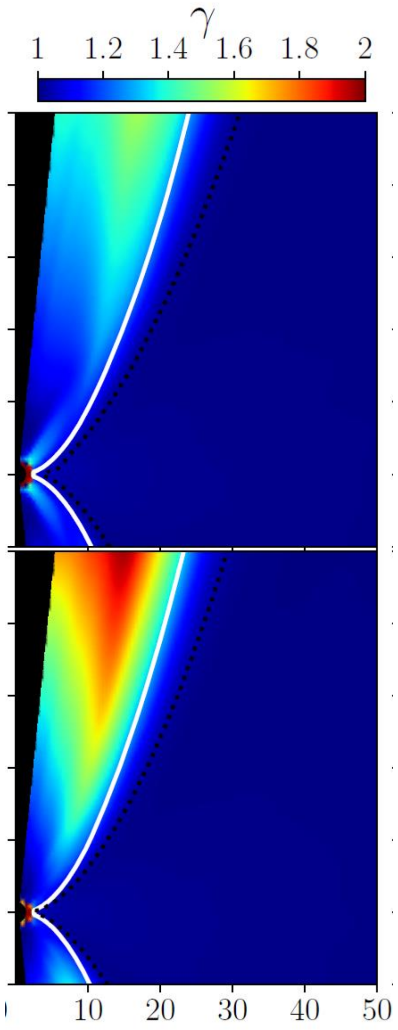


Very hot jet electrons

Tons of synchrotron and IC radiation produced



Weaker mechanical jet power



Turbulent heating produces too much radiation at the jet base, which saps the jet power

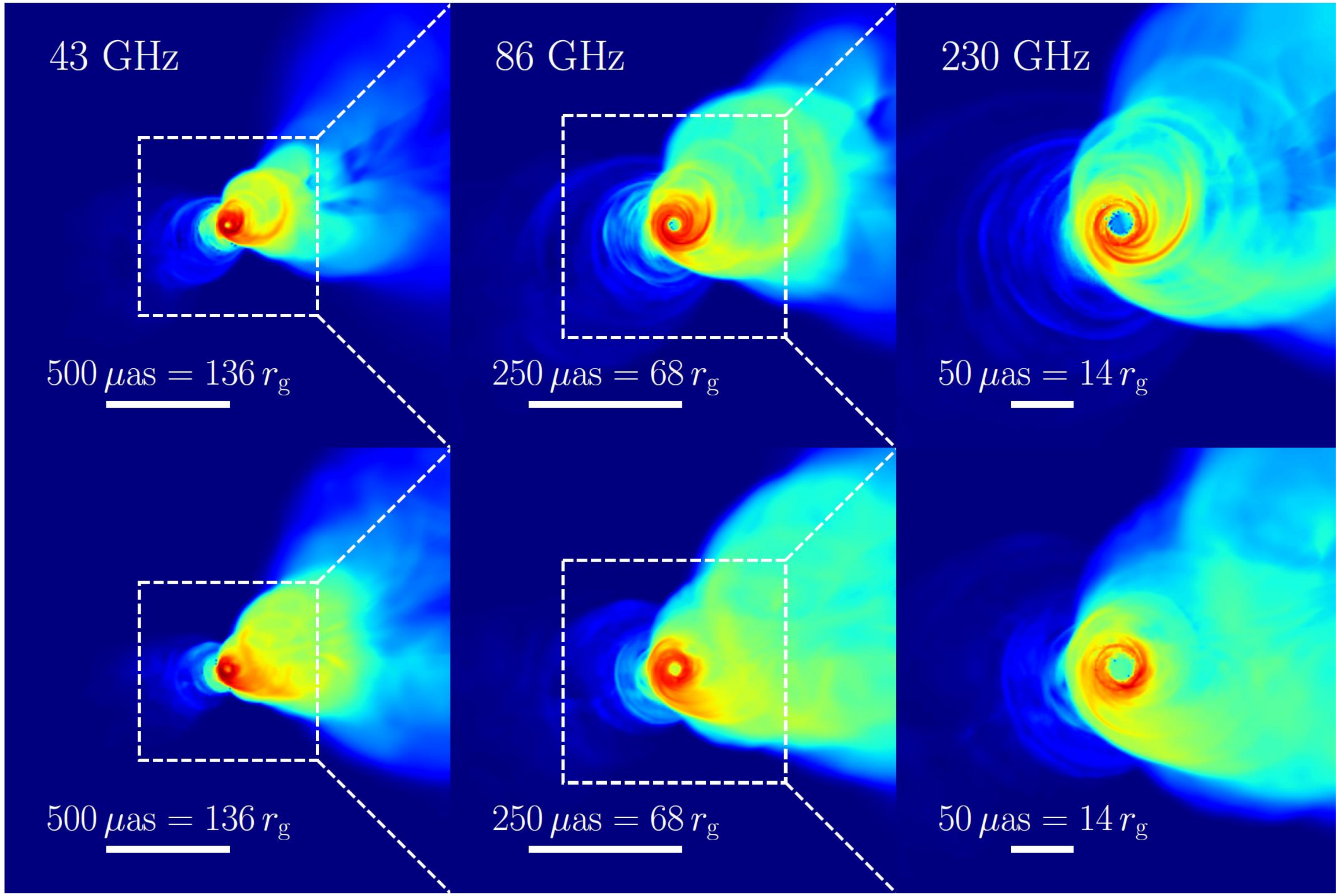
Electron Heating + Radiation → Dynamics!

Image Credit: Chael+ 2019

M87 Jets at millimeter wavelengths

Turbulent Heating

Reconnection Heating



Inclination angle (down from pole)

17°

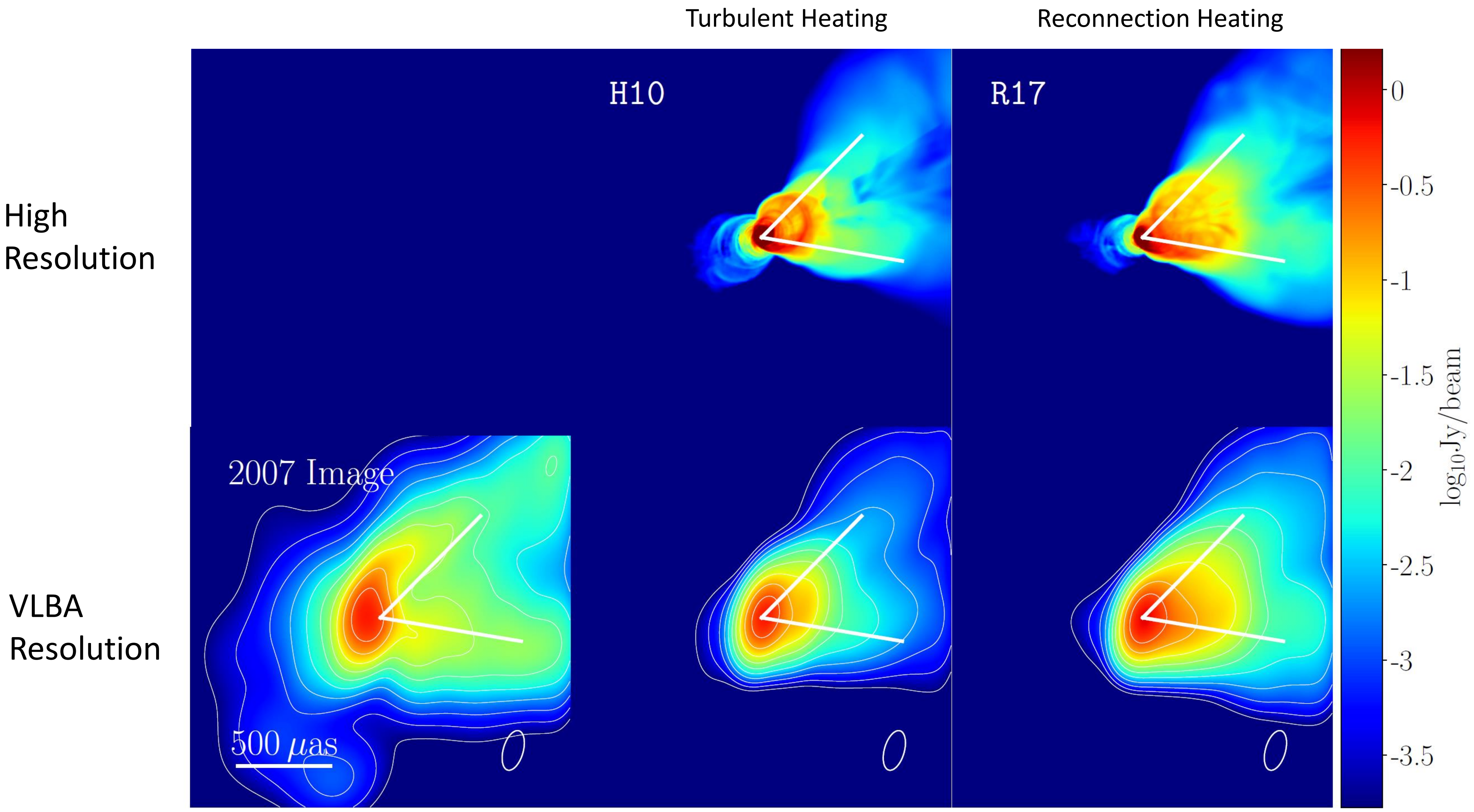
Disk/Jet rotation sense

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°

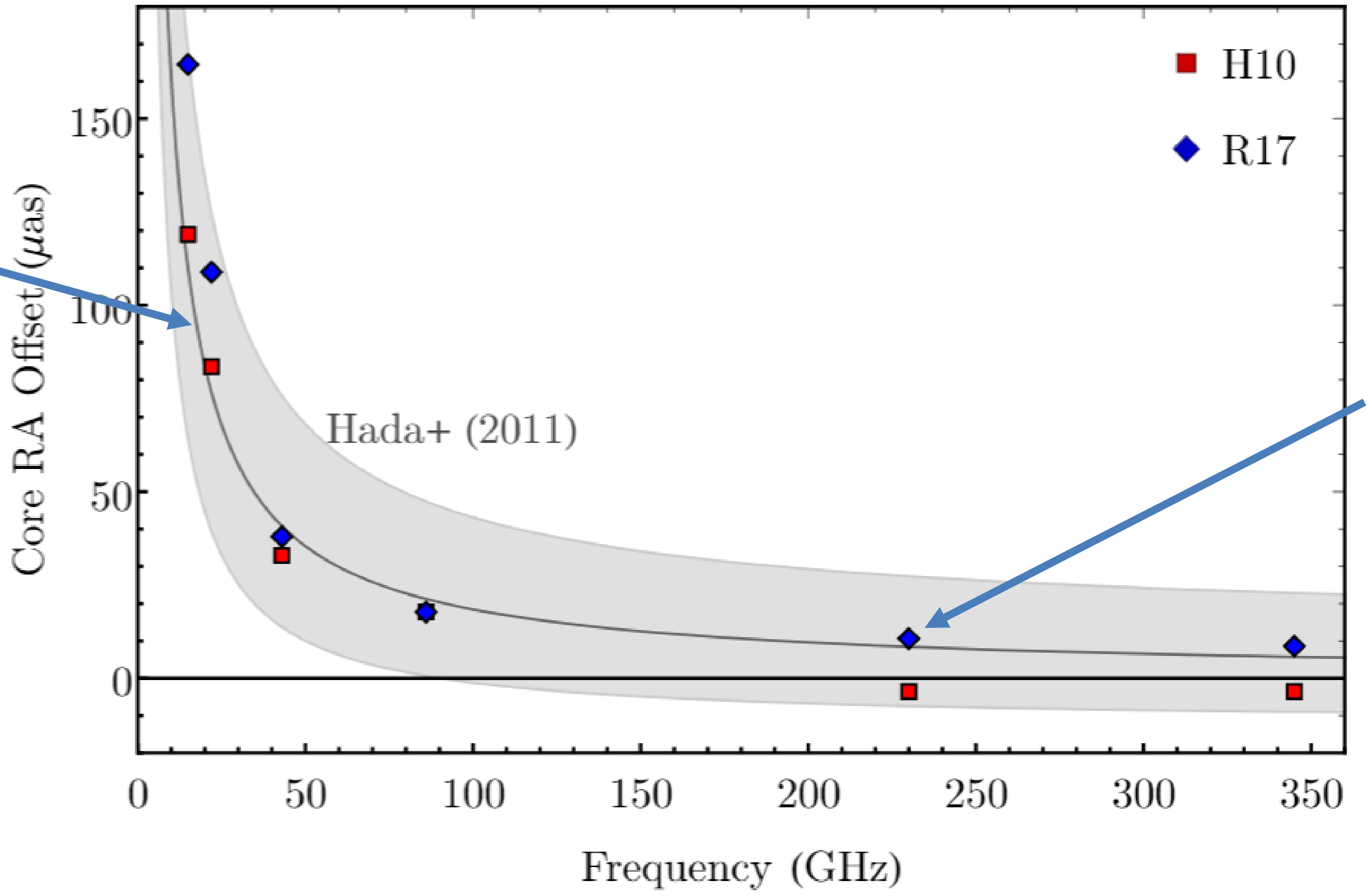
(Walker+ 2018)

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



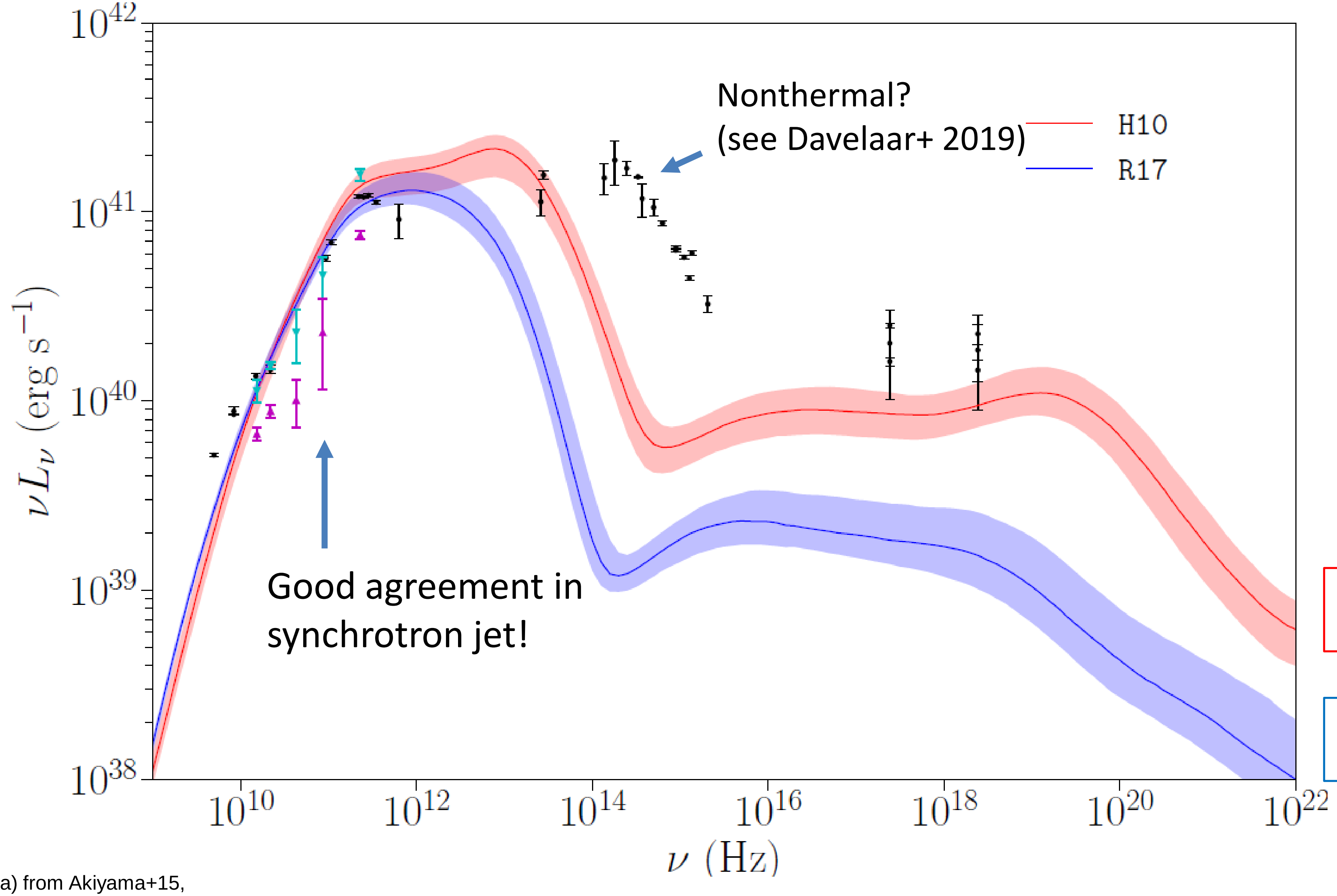
At 230 GHz and higher, the core is coincident with the black hole

Agreement with measured core shift up to cm wavelengths.

Hada+ 2011

Image Credit: Chael+ 2019

M87 SED



Nonthermal?
(see Davelaar+ 2019)

Good agreement in synchrotron jet!

Turbulent Heating

Reconnection Heating

Data from Prieto+16
New points (cyan and magenta) from Akiyama+15, Doeleman+12, Walker+18, Kim+18, and MOJAVE

Image Credit: Chael+ 2019

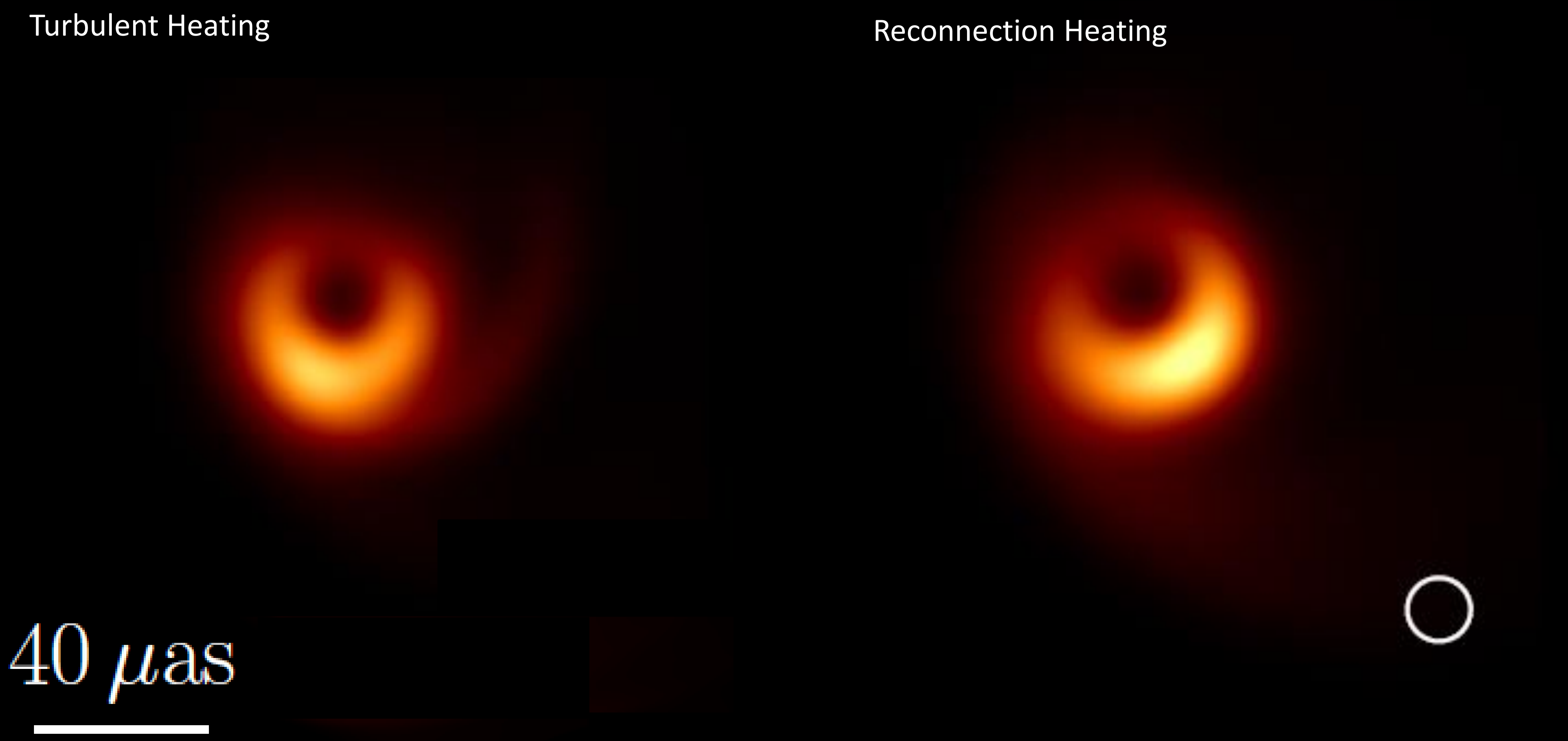
230 GHz Images

Turbulent Heating

Reconnection Heating

40 μas

230 GHz Images

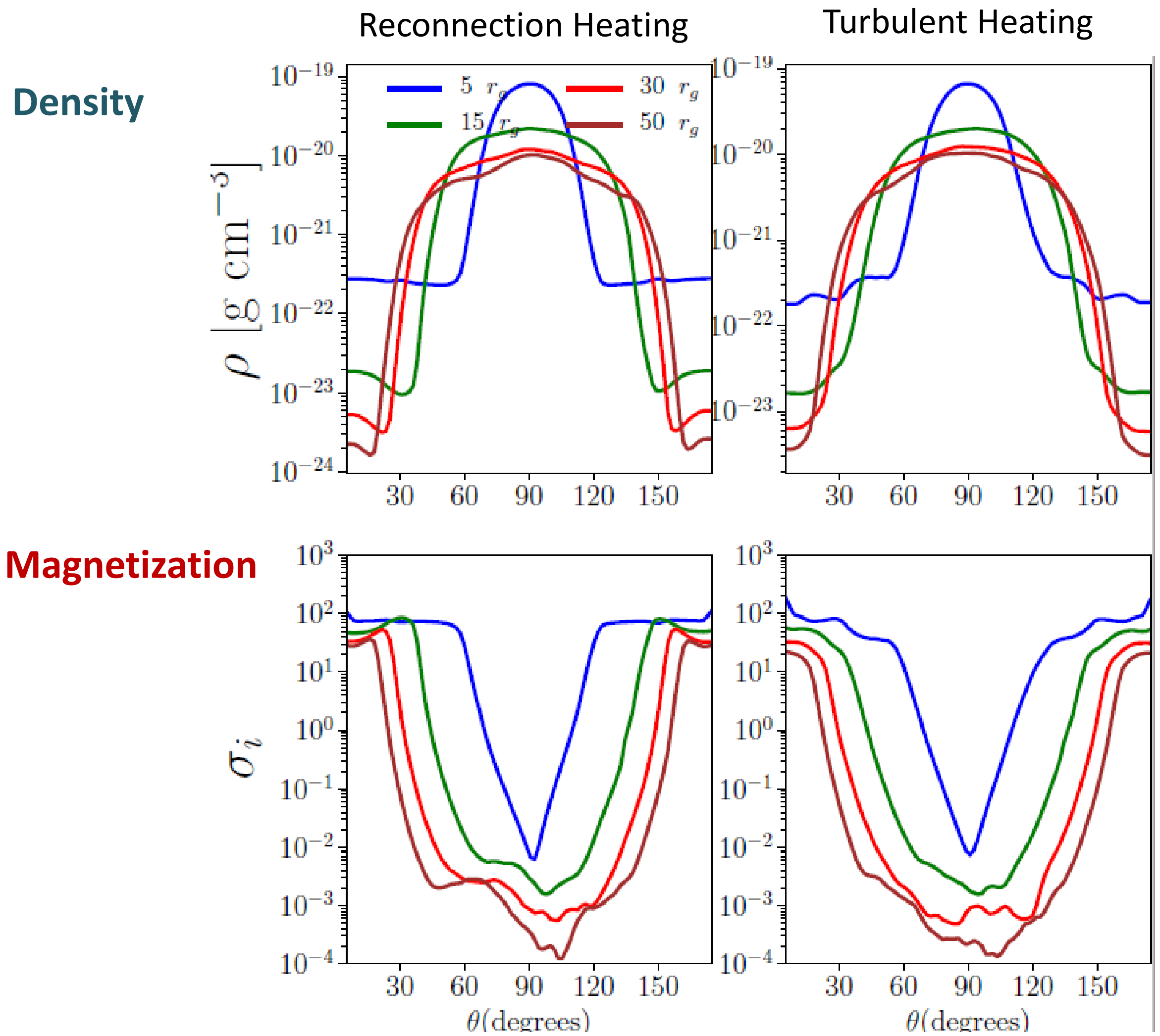


Turbulent Heating

Reconnection Heating

Image Credit: Chael+ 2019

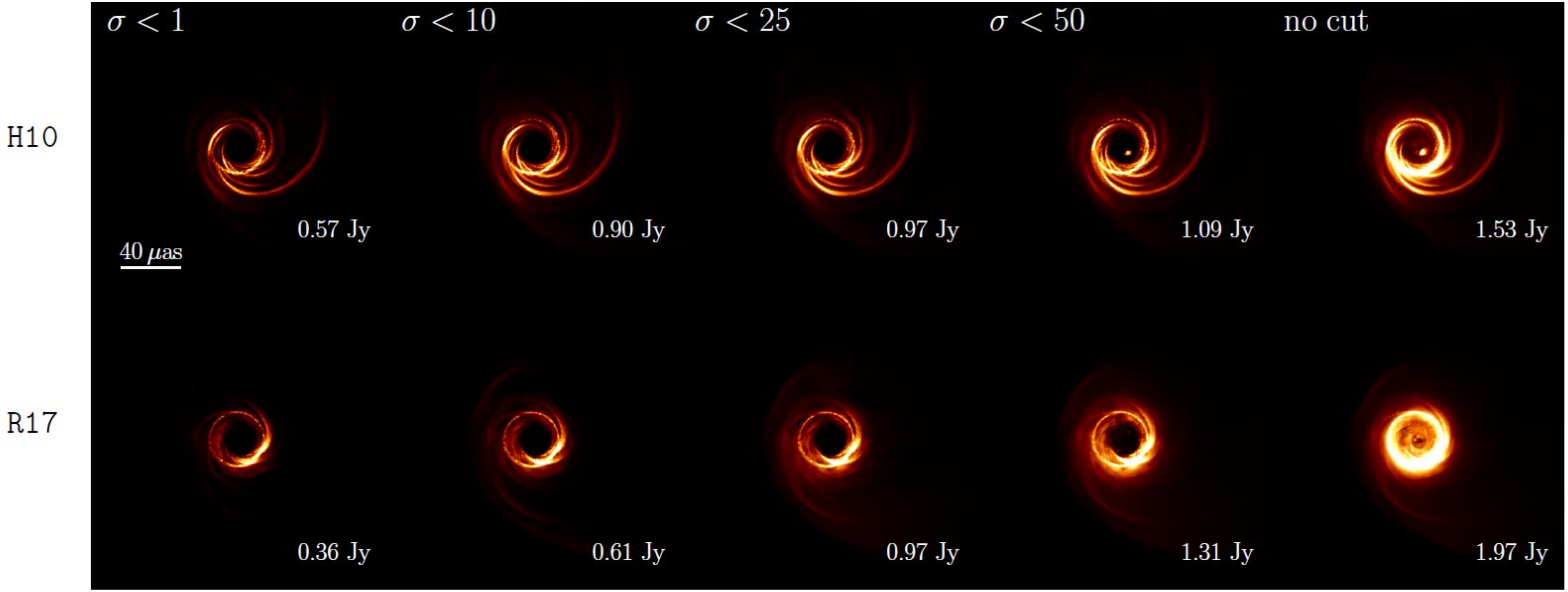
A word of catuion: σ_i cut



- Density floors are imposed in the simulation inner jet where $\sigma_\mathrm{i} \geq 100$
- We don't trust radiation from these regions, so when raytracing we only include regions where $\sigma_\mathrm{i} \leq 25$
- Spectra and images at frequencies $\geq$ 230 GHz depend strongly on the choice of cut!

Image Credit: Chael+ 2019

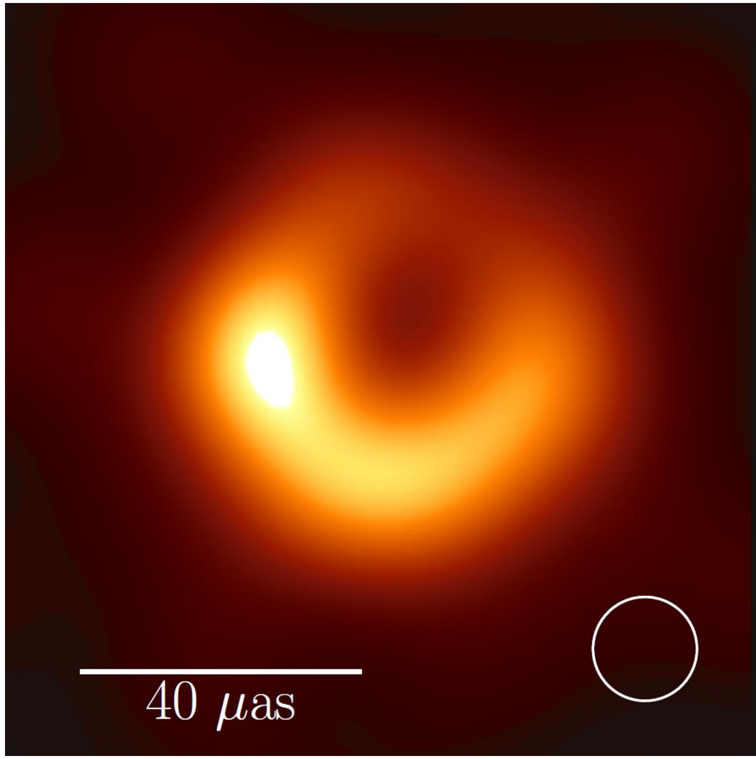
230 GHz images – dependence on σ_{i} cut



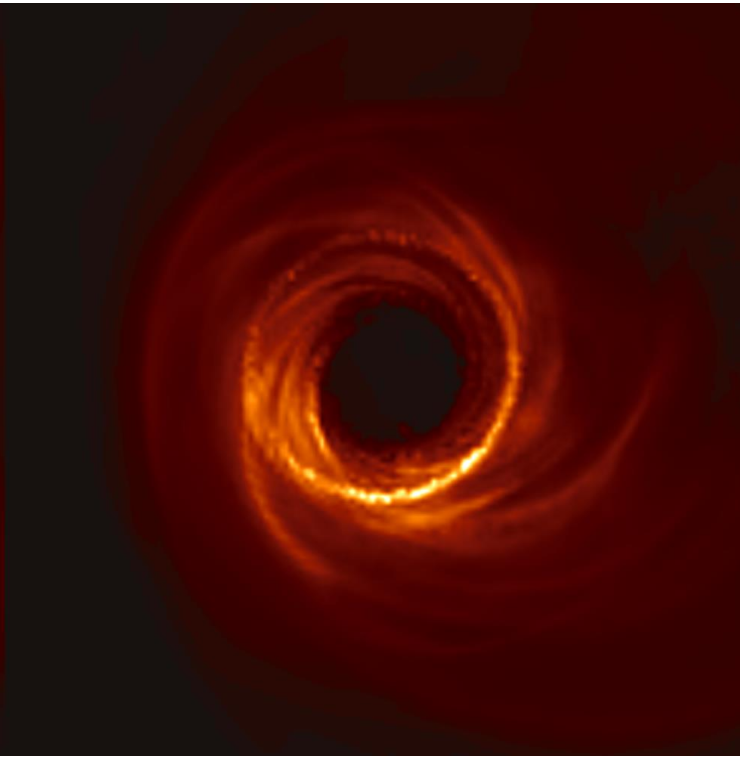
The image becomes more compact & counterjet dominated when we include more high-magnetization emission from the jet base!

The Black Hole in M87: Simulations and Images

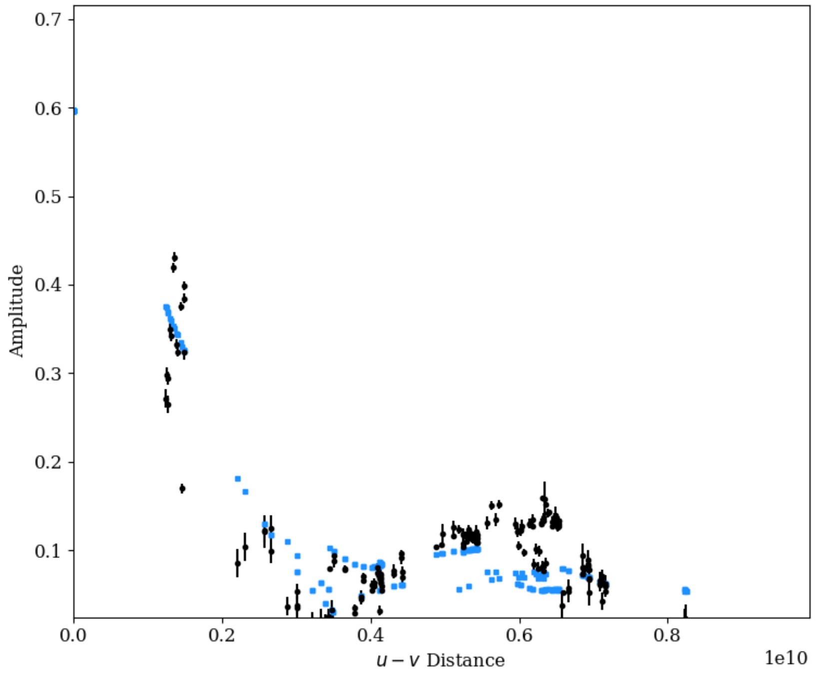
EHT 2017 image



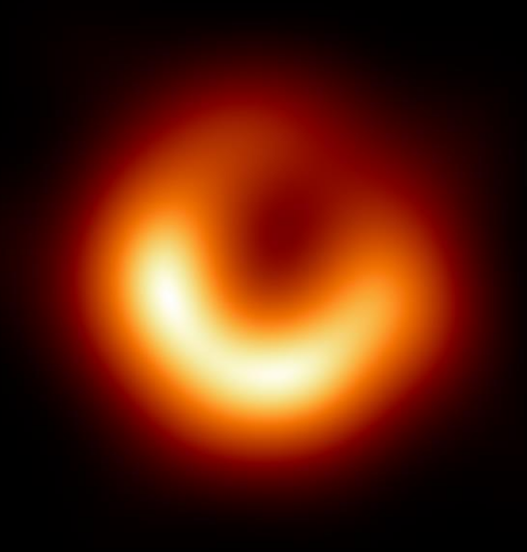
Simulated image from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes



Outline



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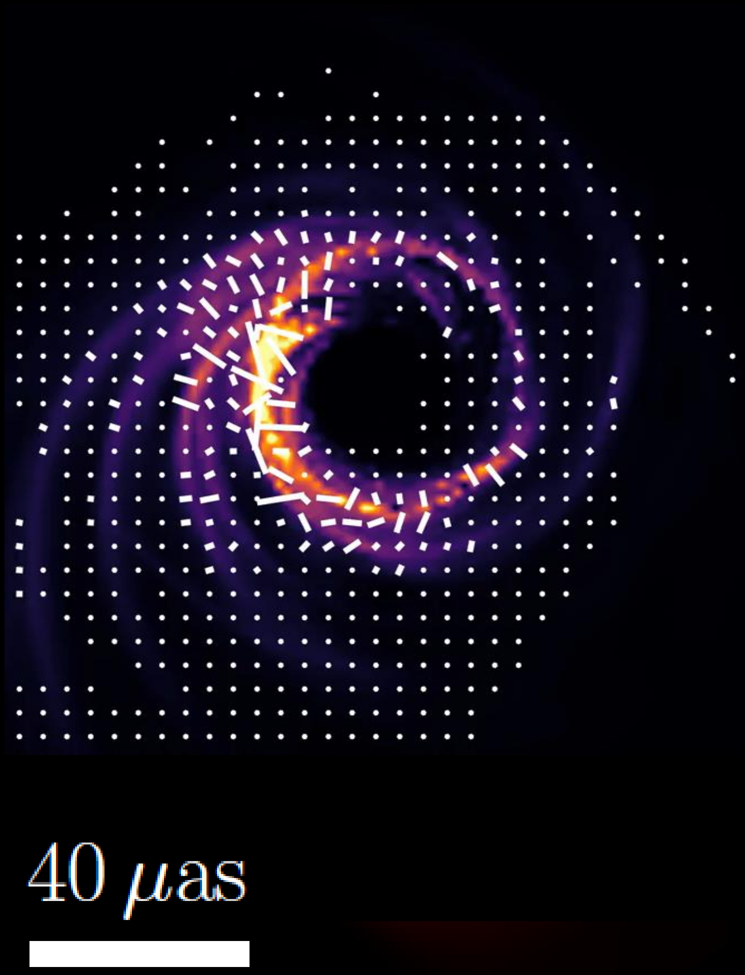
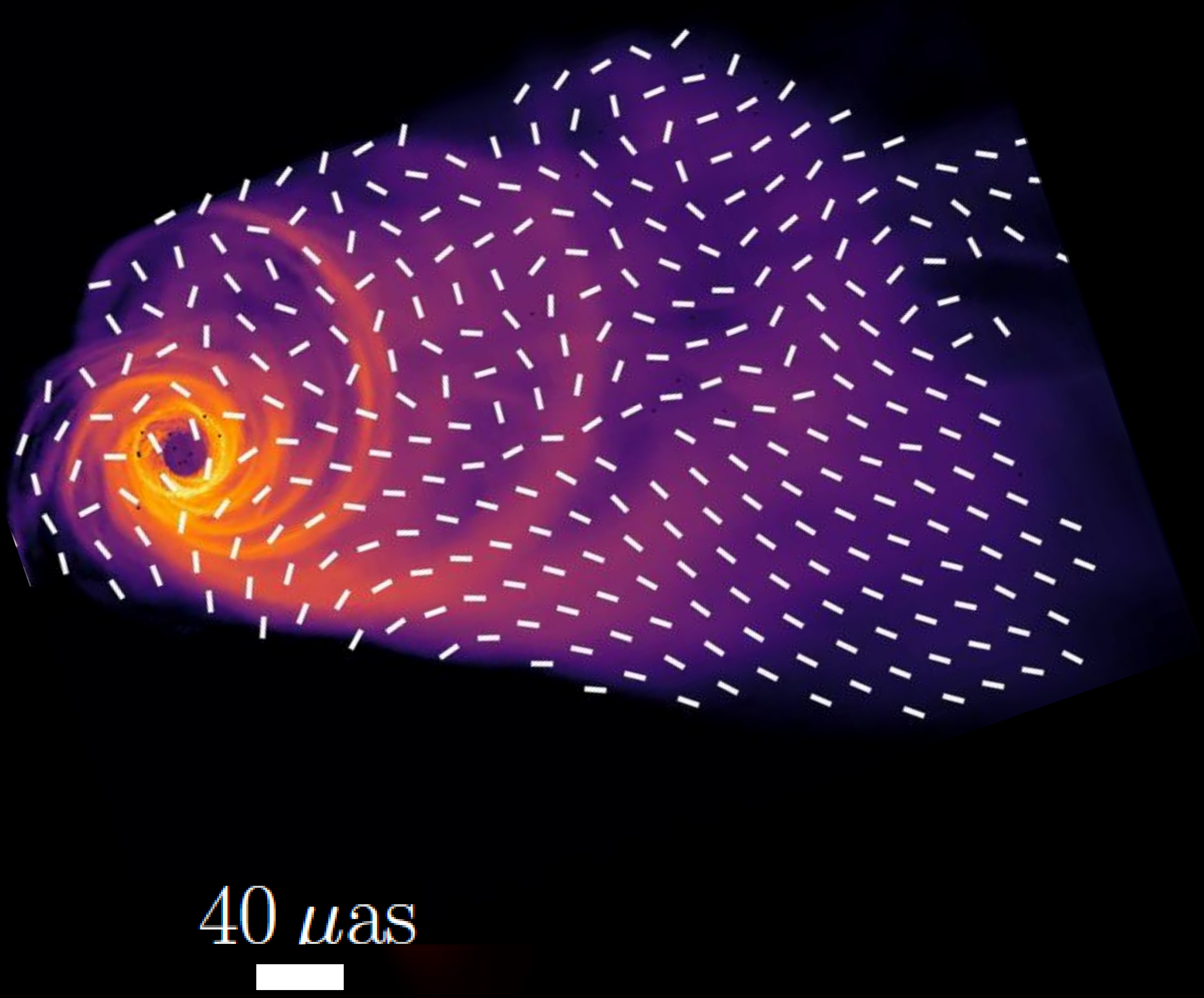
- Polarization
- Dynamics and Nonthermal electrons
- Expanding the EHT

Next Steps: Polarization!





Polarization and e- heating

SANE + Turbulent cascade

-LP < 1%

- high internal RM does not follow lambda^2
(Moscibrodzka & Falcke 2013, Ressler+2015,2017)

MAD + Reconnection

-LP ~ 2-10%

-low RM is mostly external from forward jet– follows lambda^2
(Chael+2018)

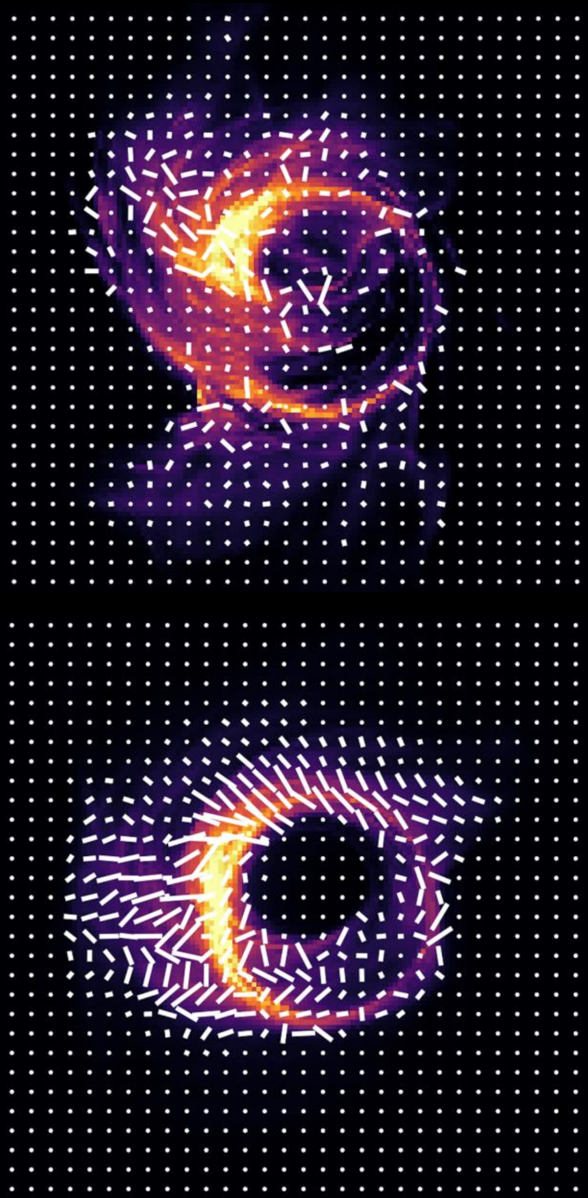
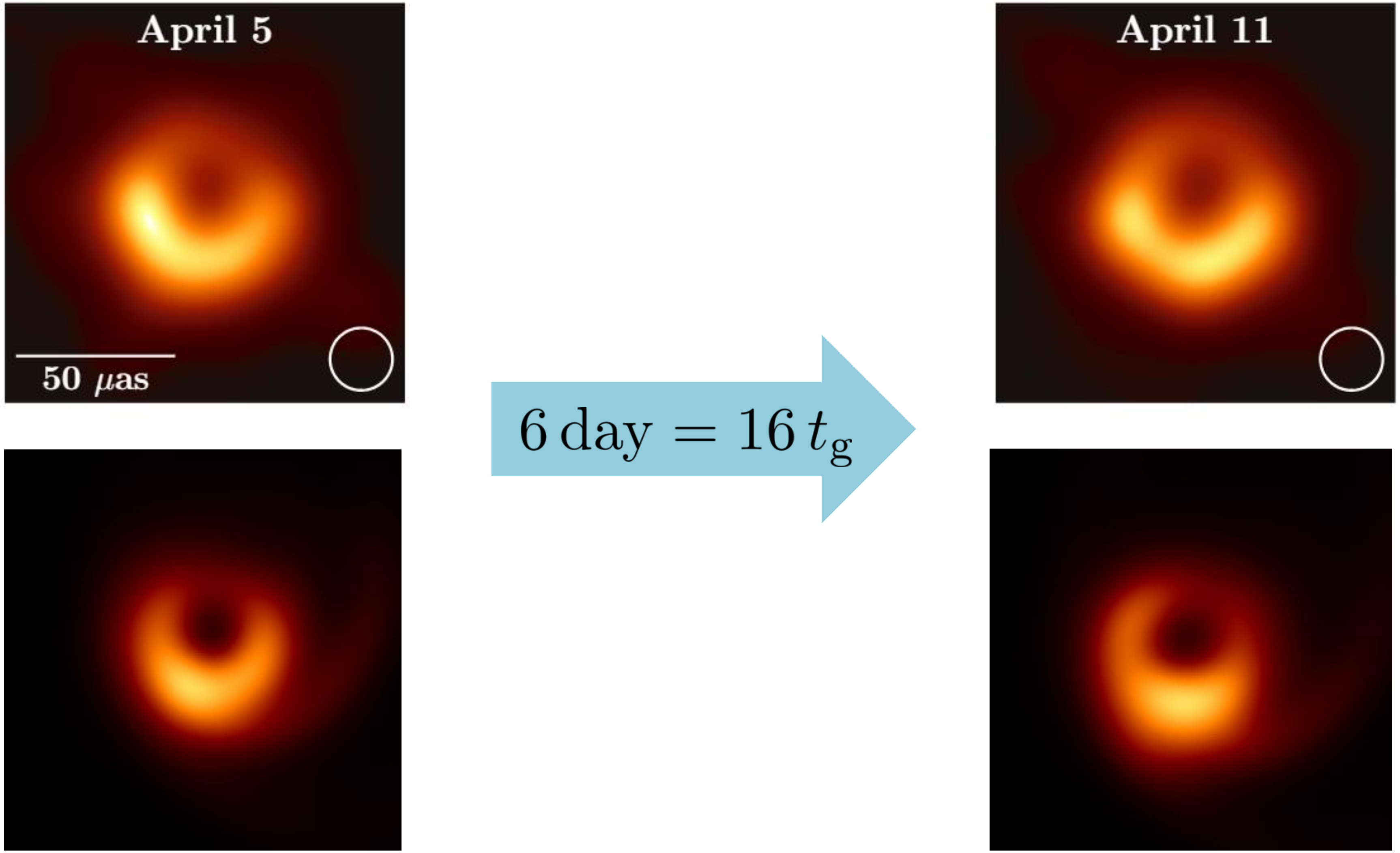


Image credit:
Jason Dexter

Time Variability?

M87

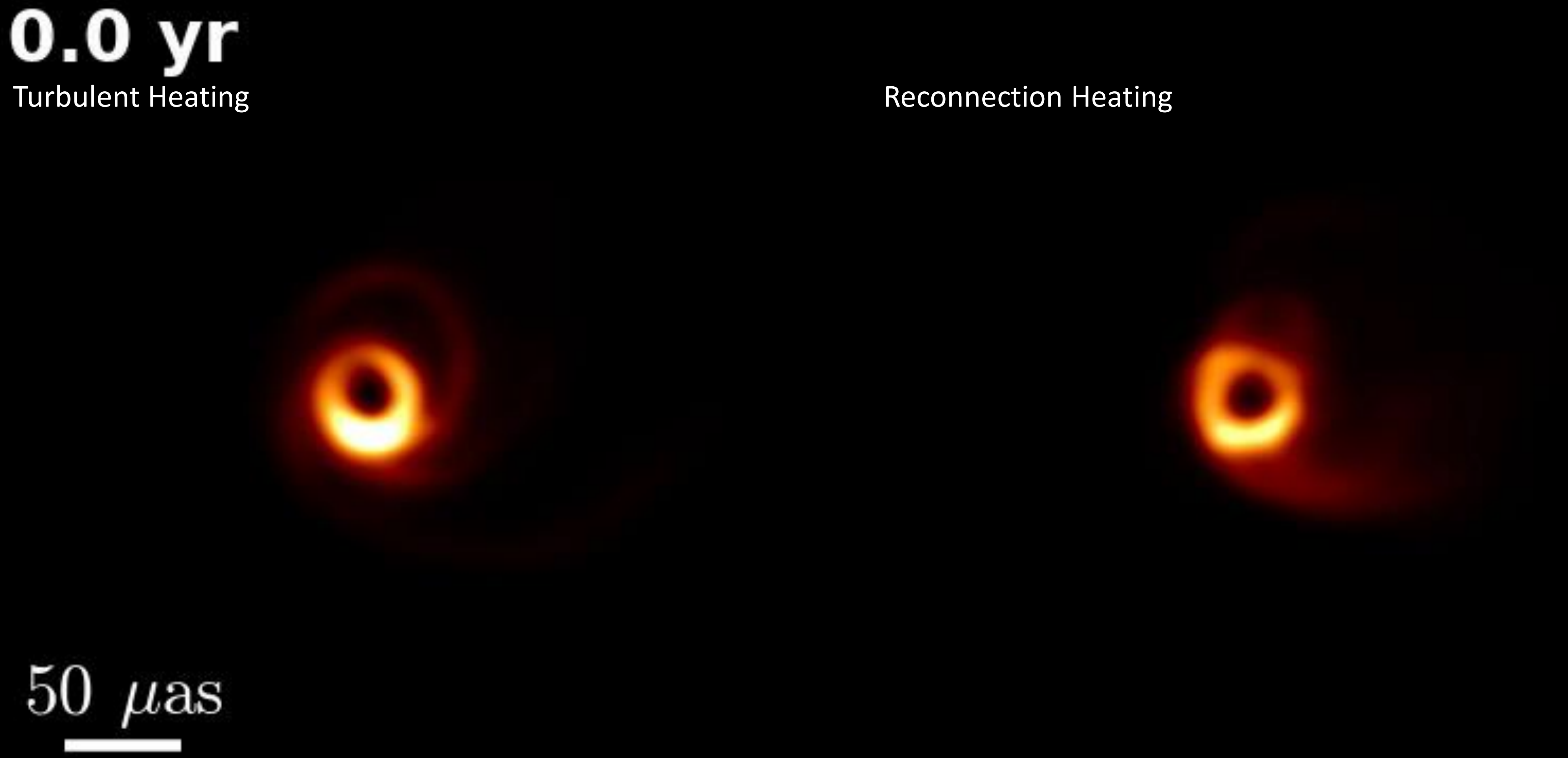
Simulation



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

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

Next steps: Dynamics



Turbulent Heating

Reconnection Heating

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

$$d_{\mathrm{shadow}} \approx 50\mu\mathrm{as}$$

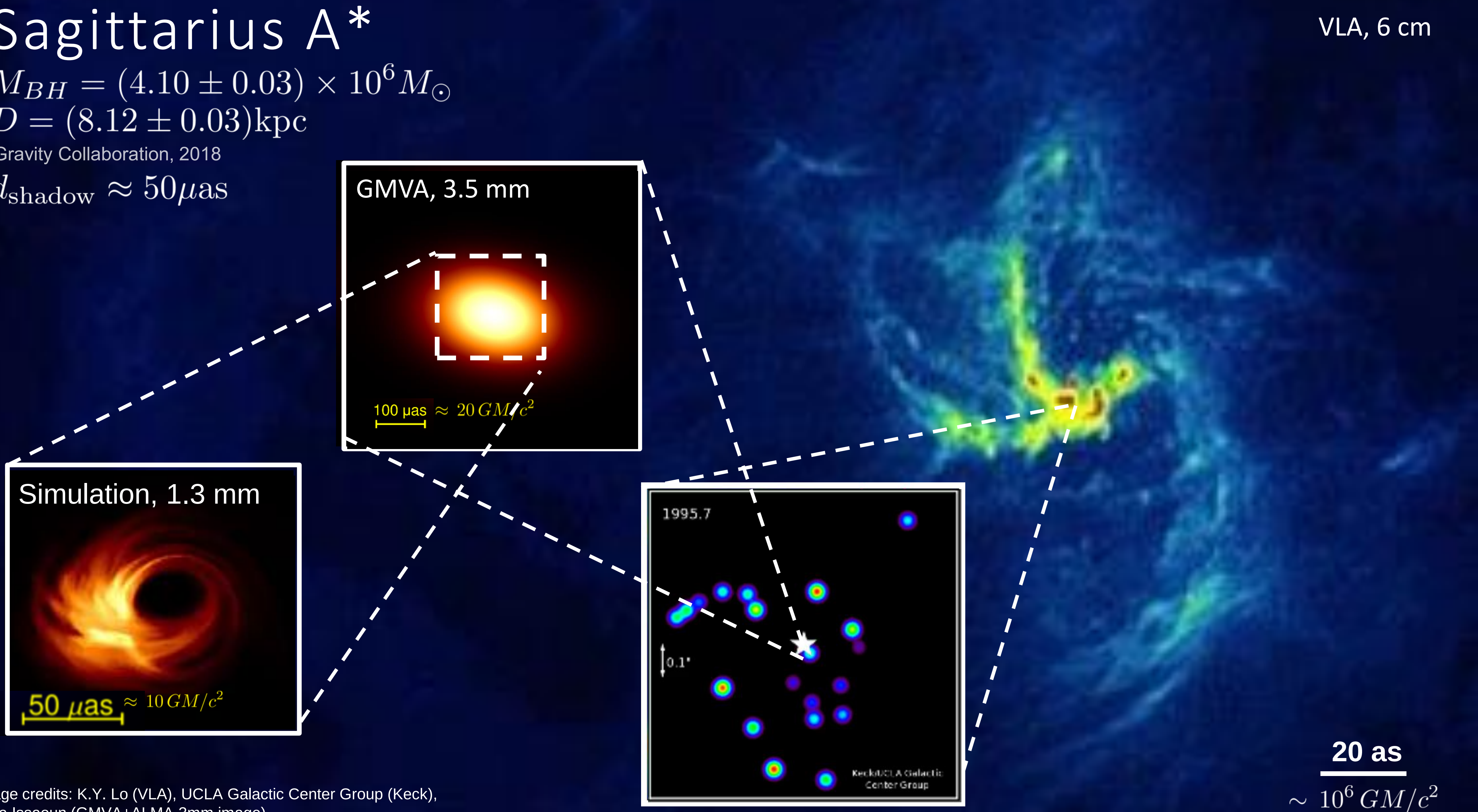
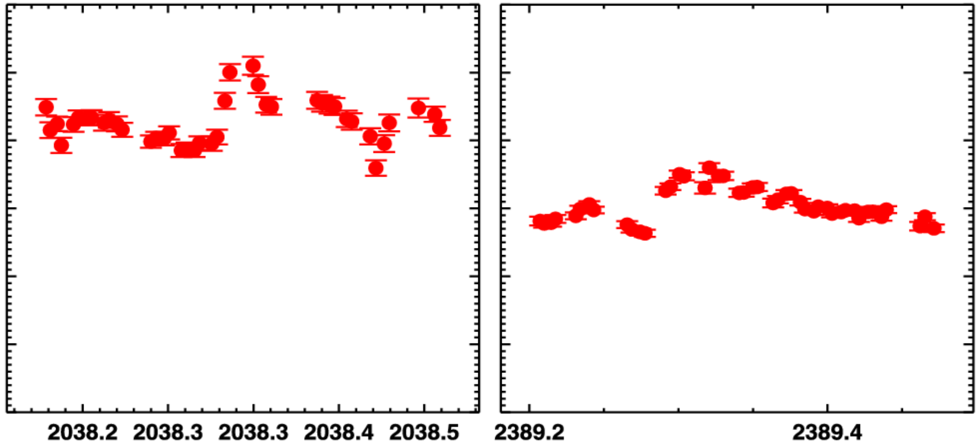
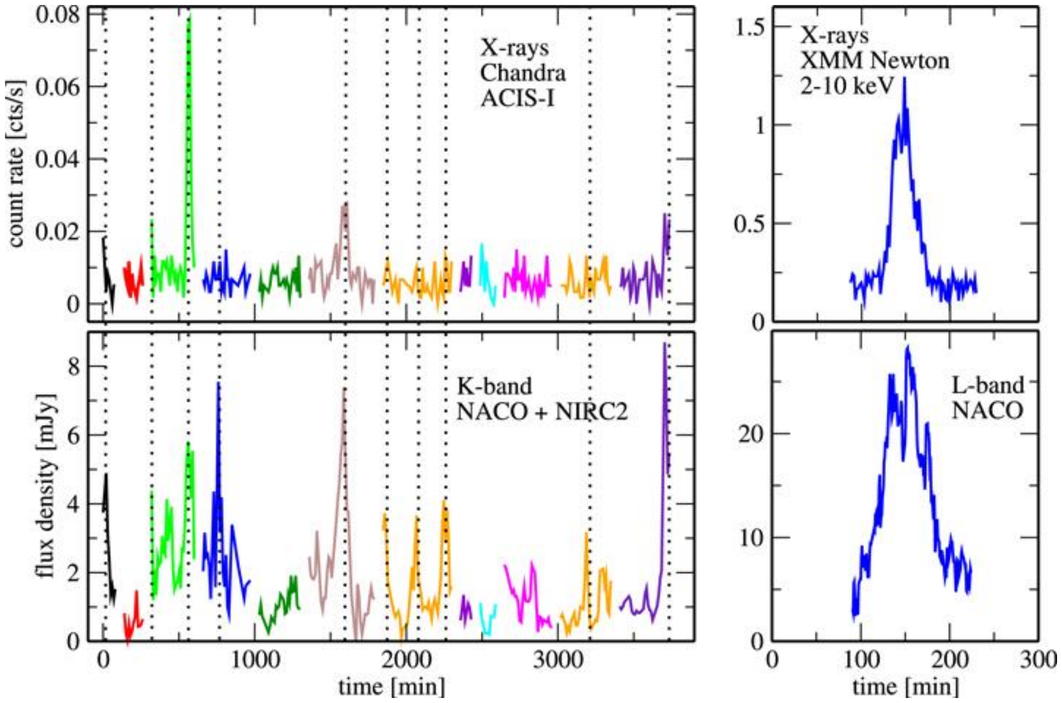


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

Next steps: Sgr A* Dynamics

Intra-day 1.3 mm variability in Sgr A* on minute-hour timescales makes imaging hard!



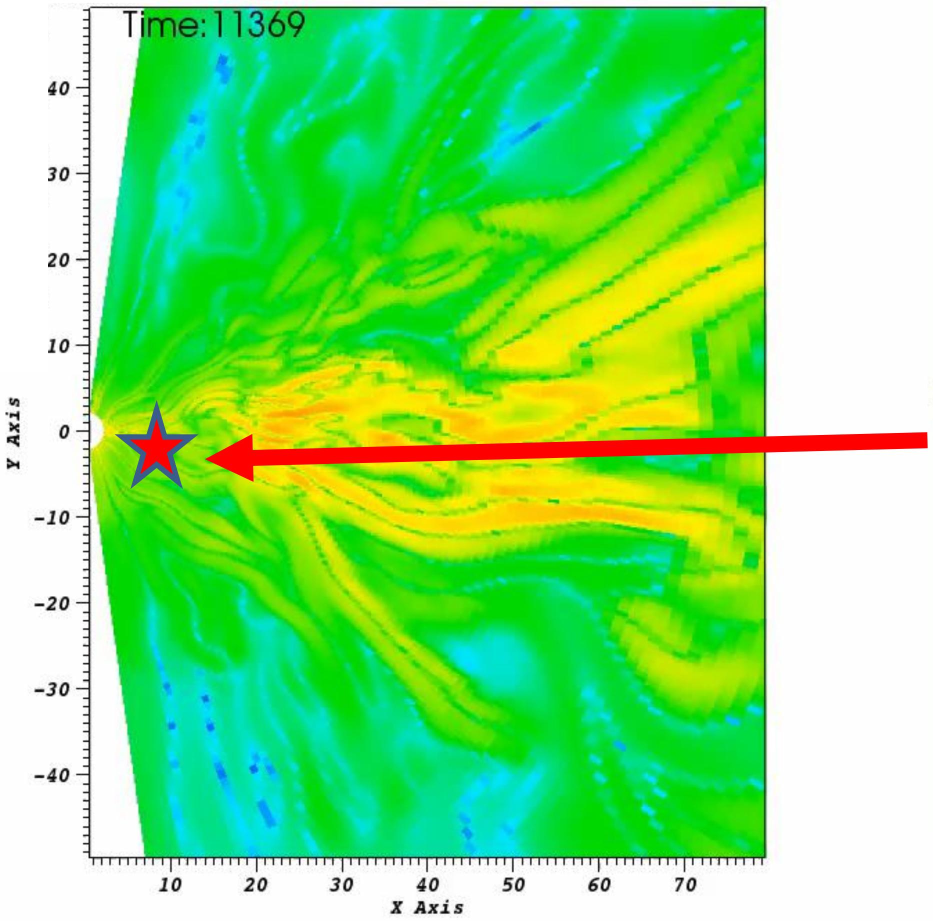


Large amplitude NIR and X-ray variability/flares cannot be produced by thermal electrons in GRMHD – require nonthermal emission?

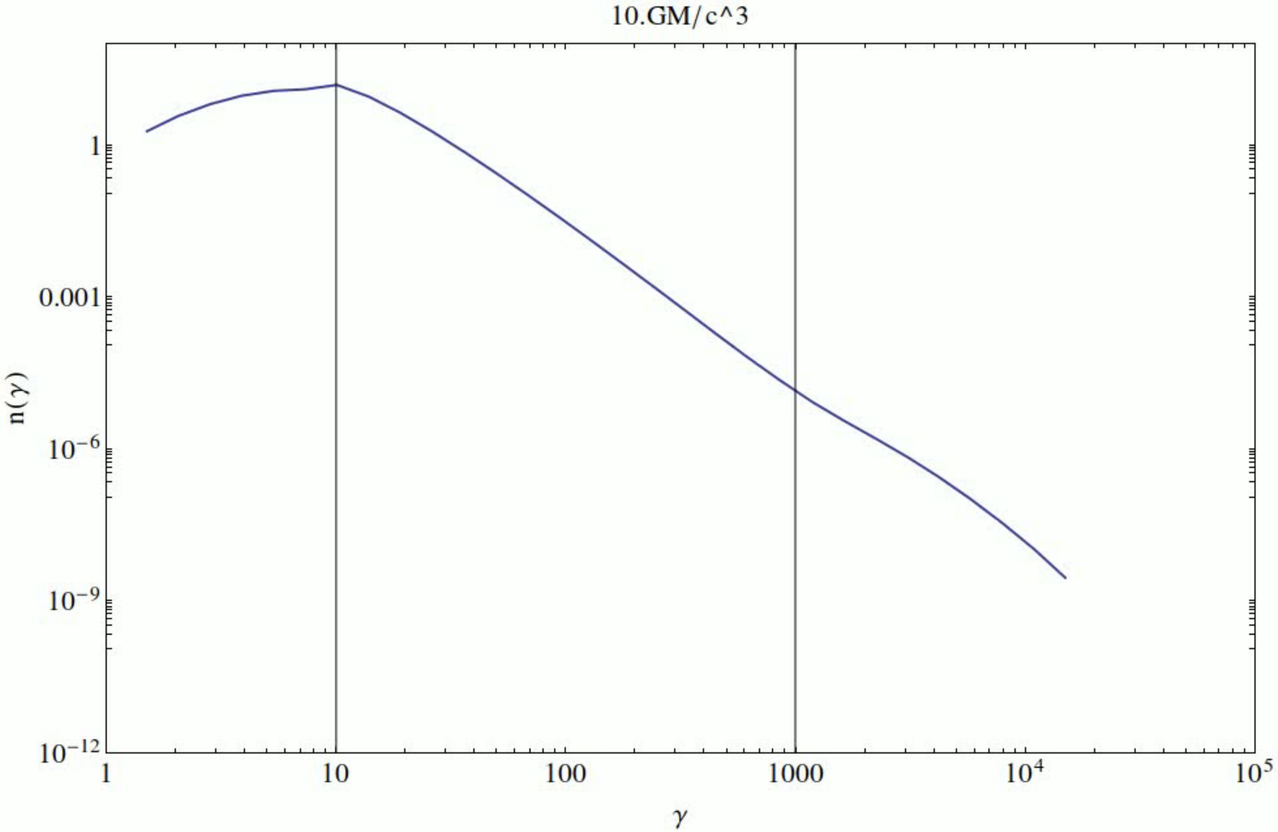
Marrone+2008, Dexter+2014, Fazio+ 2018

Simulating Flares: Evolving **nonthermal** electrons

Radiation Power



Nonthermal distribution @ 10 M



Chael+ 2017

Understanding LLAGN down to horizon scales:

Sgr A's SED and Variability*

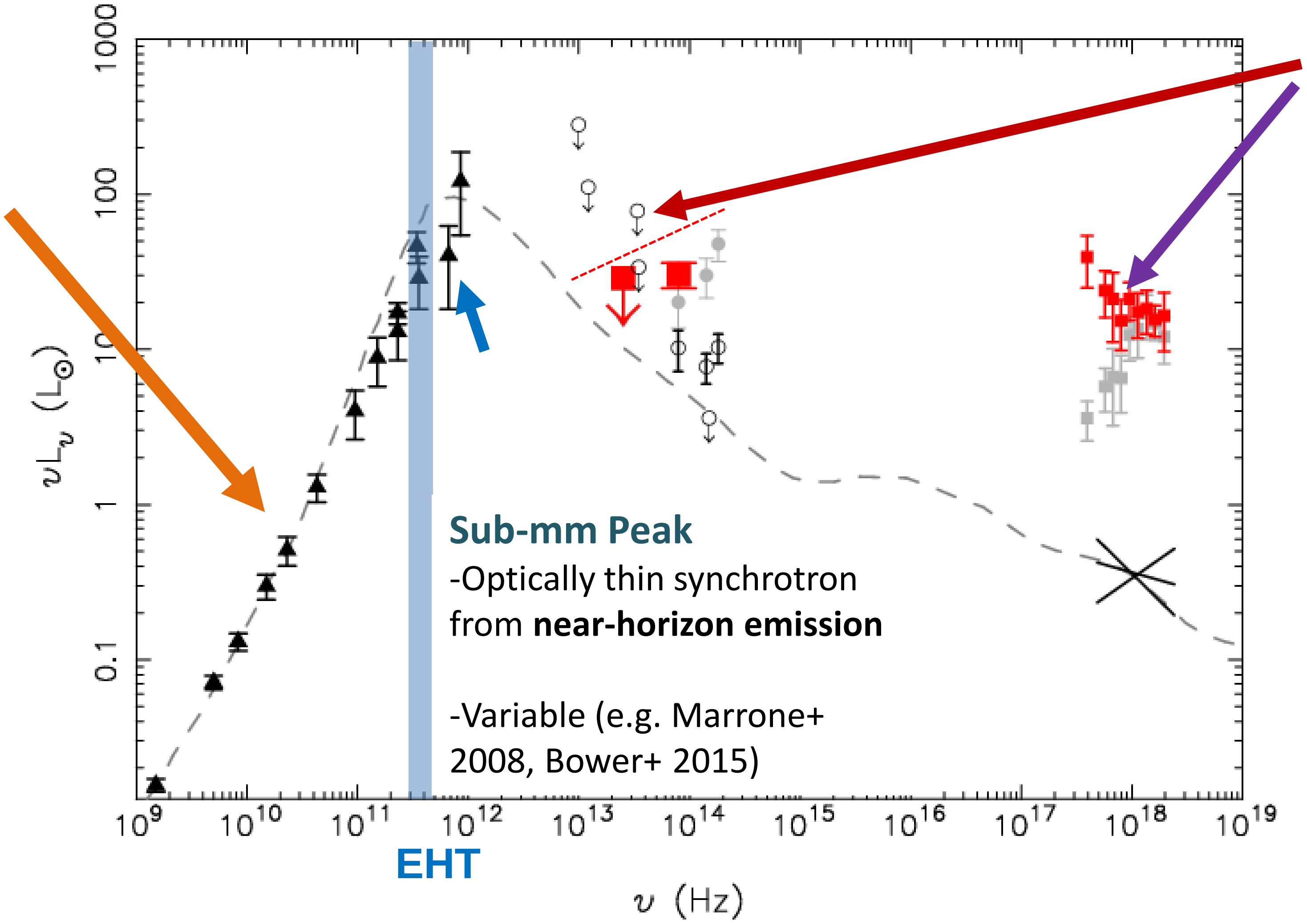
Larger Scales:

"Flat" Radio Spectrum:

-Self-absorbed synchrotron from a thick accretion disk? (e.g. Narayan+ 1995)

-Or a large-scale outflow? (e.g. Falcke & Markoff 2000)

-Nonthermal electrons? (e.g. Ozel+ 2000)



Sub-mm Peak

-Optically thin synchrotron from **near-horizon emission**

-Variable (e.g. Marrone+ 2008, Bower+ 2015)

Close in:

Near-Infrared and X-ray flares:

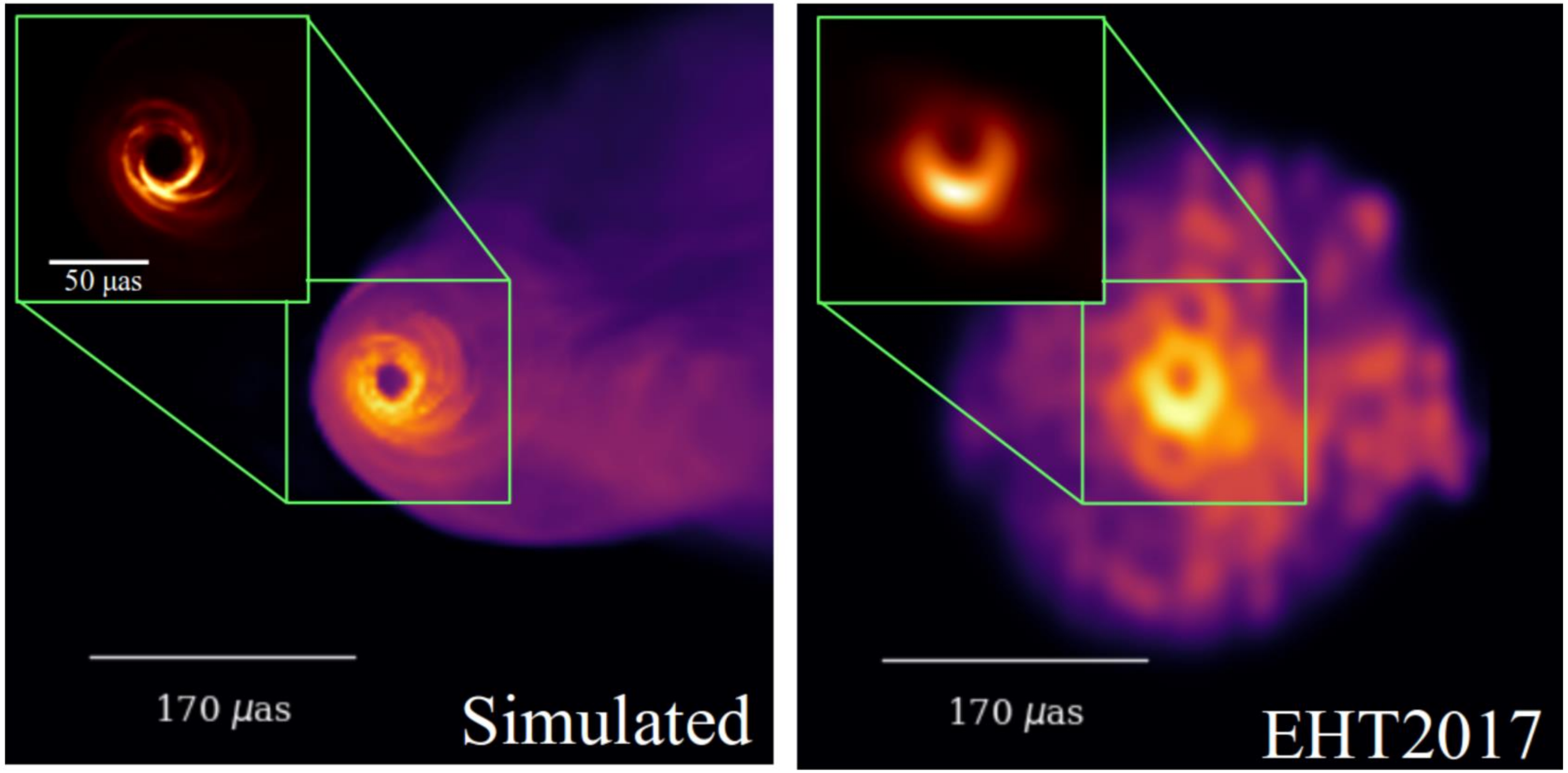
-Strong & correlated (e.g. Eckart 2004)

-Positive NIR spectral index: (e.g. Gillessen+ 2016)

-Measured synchrotron break (e.g. Ponti+ 2017)

Image Credit: Dodds-Eden+ (2009)
Also: Flacke & Markoff (2000), Yuan+ (2003), Genzel+ (2010)

Next Steps: EHT Upgrades



The current EHT lacks <u>short</u> baselines, which are necessary to detect extended structure.

Idea: add many more small, ~6m dishes to the array

Slide Credit: Michael Johnson
See: EHT Ground Astro2020 APC White Paper
(Blackburn, Doeleman+; arXiv:1909.01411)

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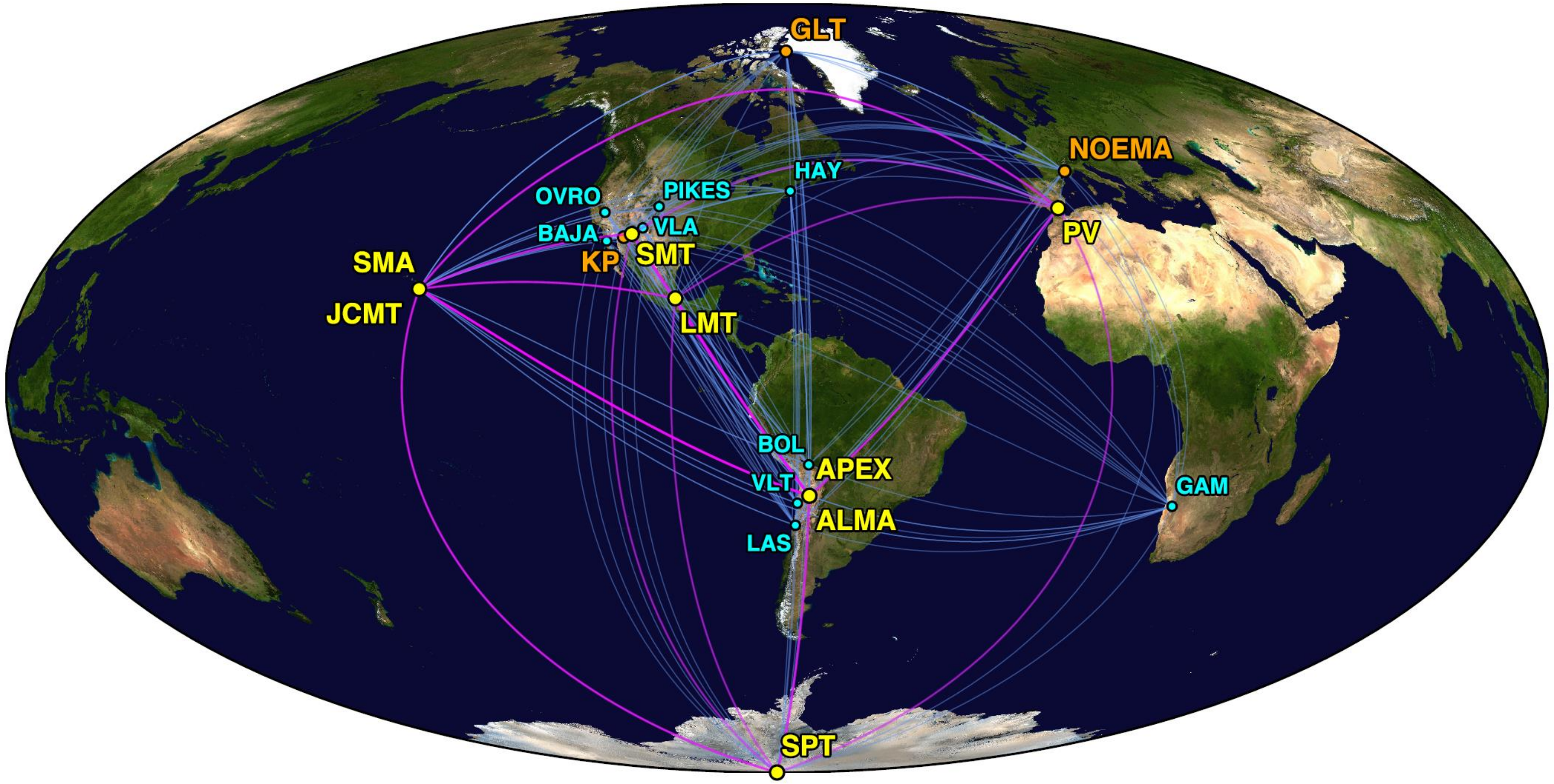

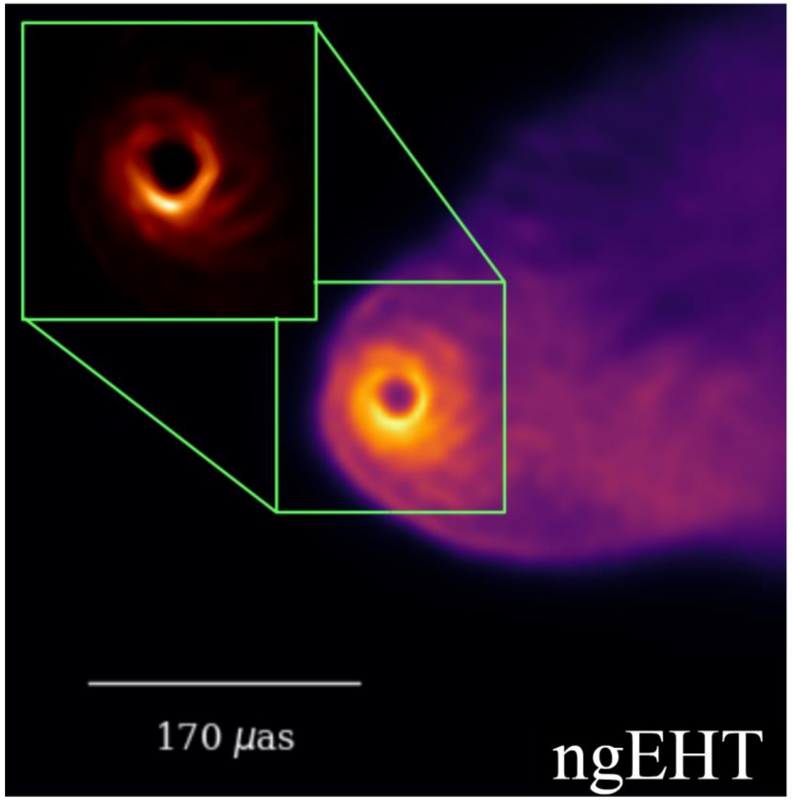

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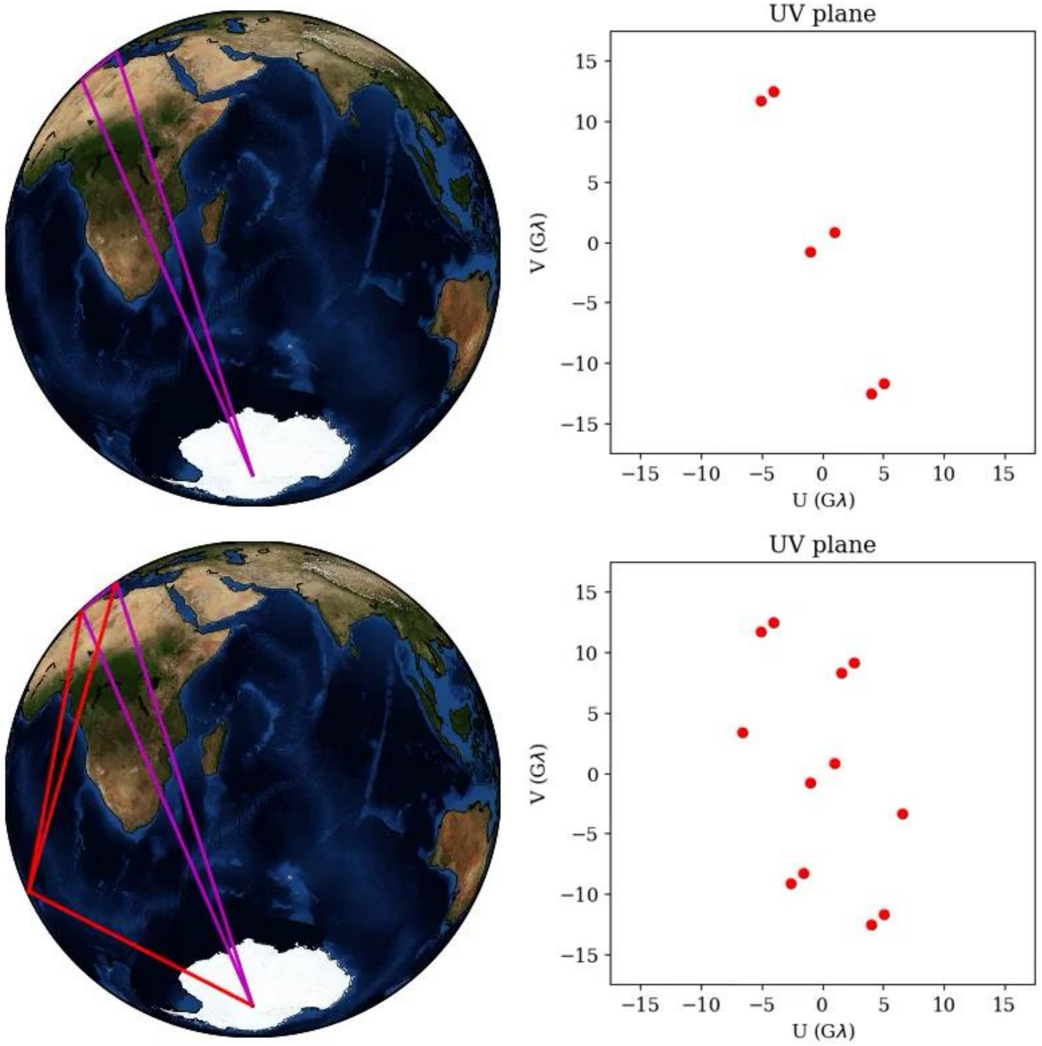
Future: Space VLBI with the EHT

	LEO	High MEO / GEO	Higher Orbits
Resolution	Not much better than ground-only	Several times ground-only	Higher
Gaps in (u,v) Coverage	Negligible	Manageable	Extreme
Speed of (u,v) Coverage	Fast	~Daily	Slow

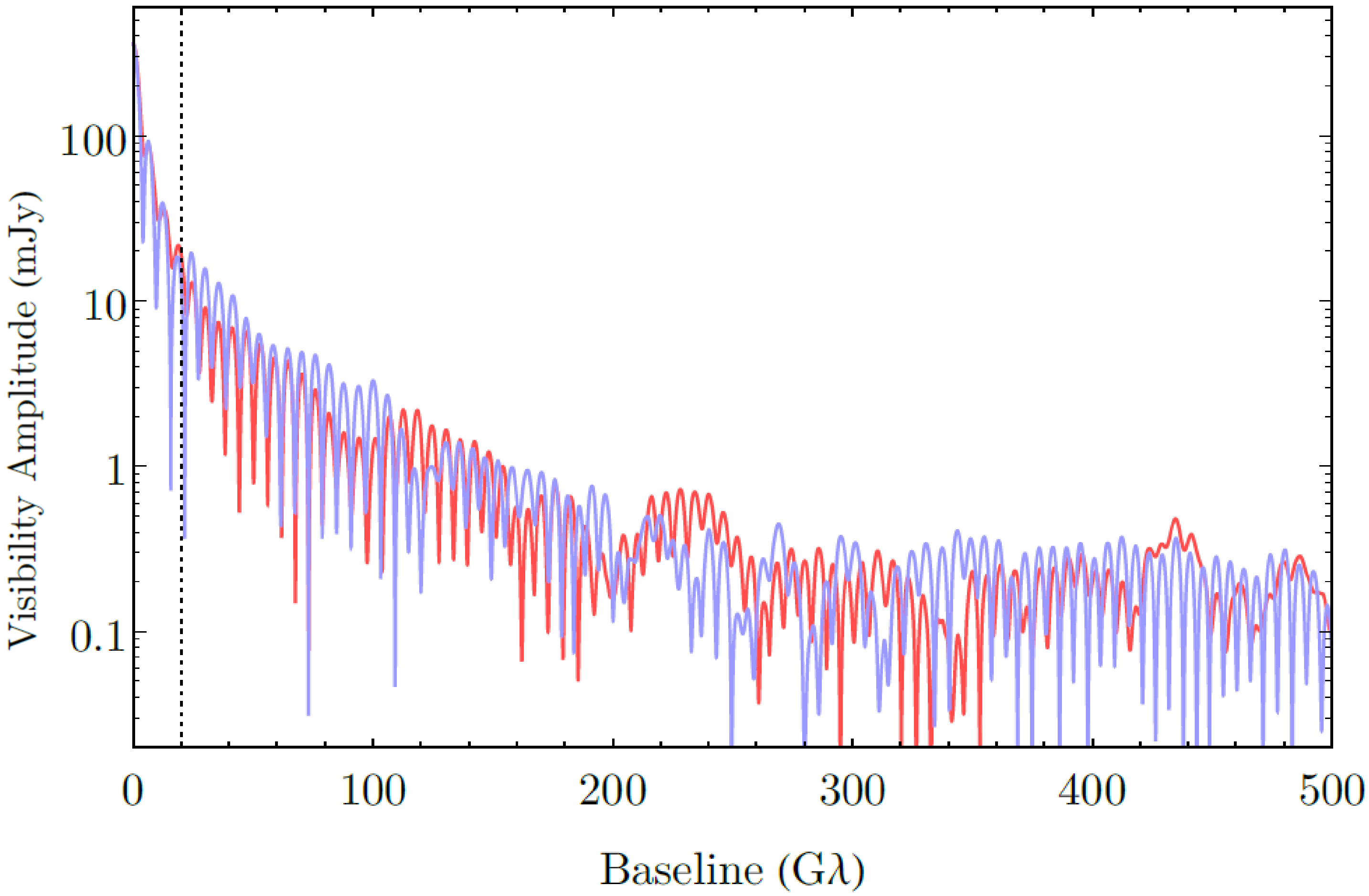


See: EHT Space Astro2020 APC White Papers

- Haworth, Johnson+; arXiv:1909.01405
- Pesce+; arXiv:1909.01408

Image Credits: Vincent Fish, Daniel Palumbo

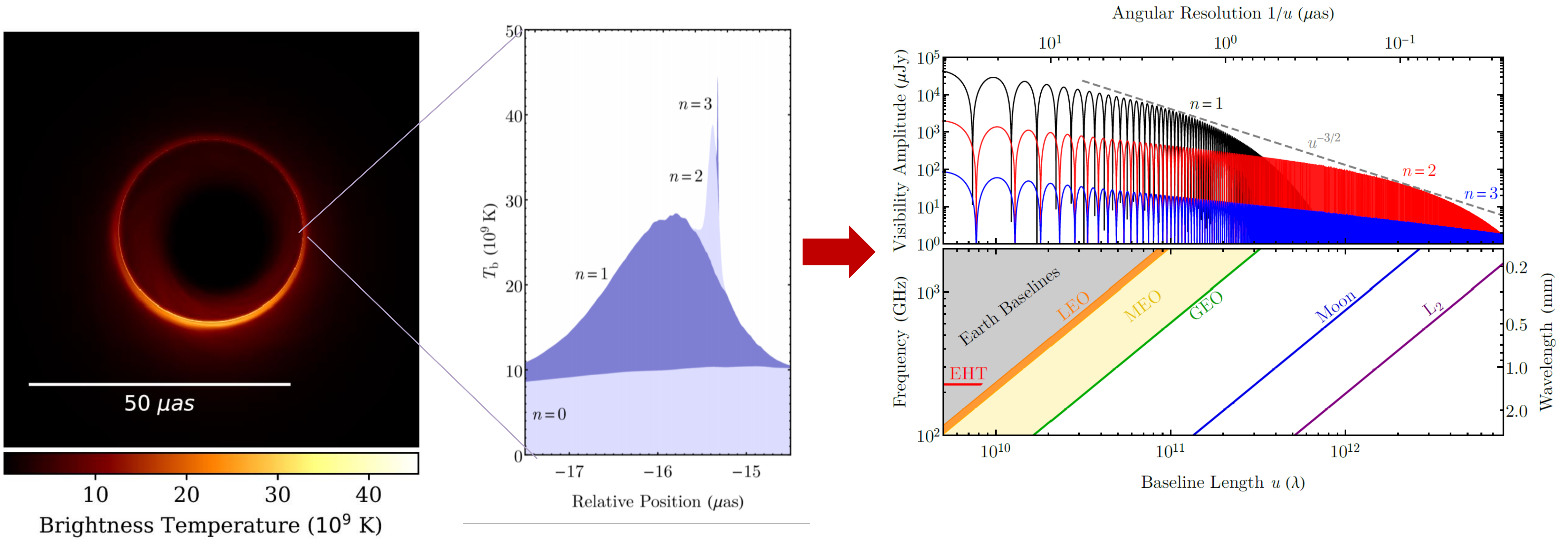
Future: Extremely LBI measures the photon ring precisely



Simulated visibility amplitudes – ringing from narrow structures on extremely long baselines!

Johnson+ 2019, arXiv: 1907.04329

Future: Extremely LBI measures the photon ring precisely



Longer and longer baselines measure narrower and narrower subrings – each from a different number of photon windings!

Johnson+ 2019,
arXiv: 1907.04329

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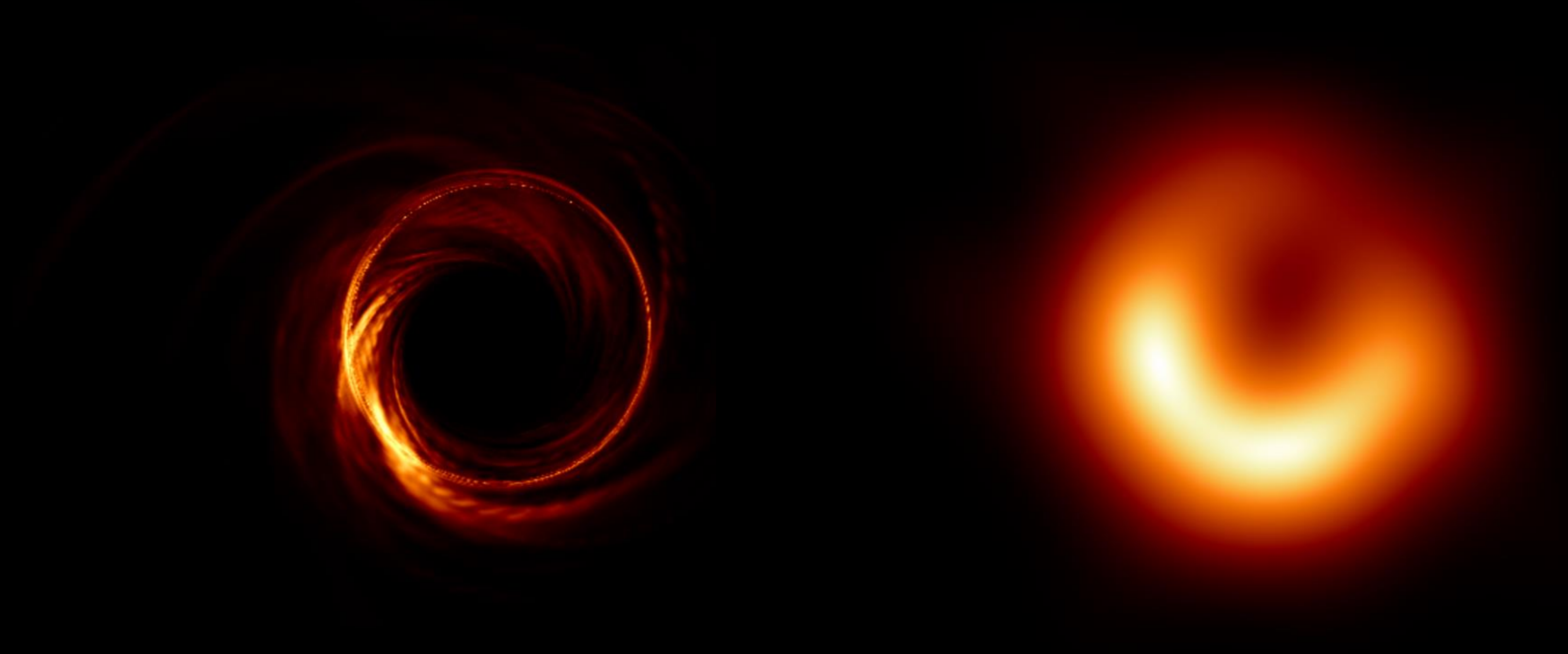
Thank you!



Work with Ramesh Narayan, Michael Johnson,
Katie Bouman, Shep Doeleman, Michael Rowan,
and the entire EHT collaboration

arXiv: 1803.07088, 1810.01983
EHTC+ 2019, Papers I-VI (ApJL 875)
my thesis! https://achael.github.io/_pages/pubs