Simulating and Imaging Supermassive Black Hole Accretion Flows

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(he/him)

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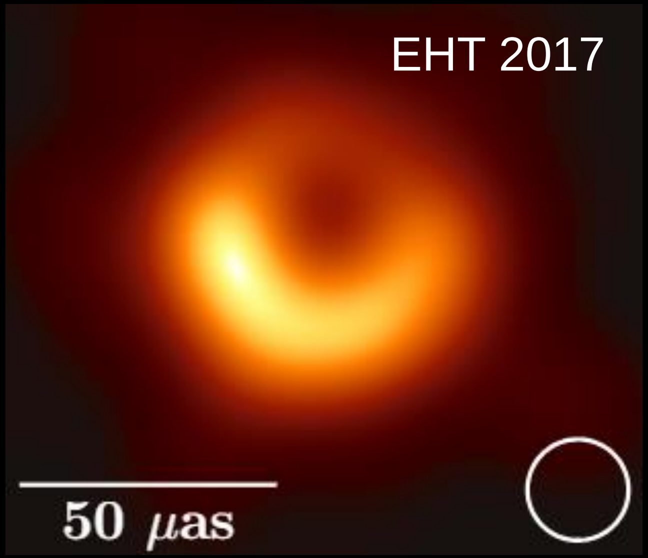
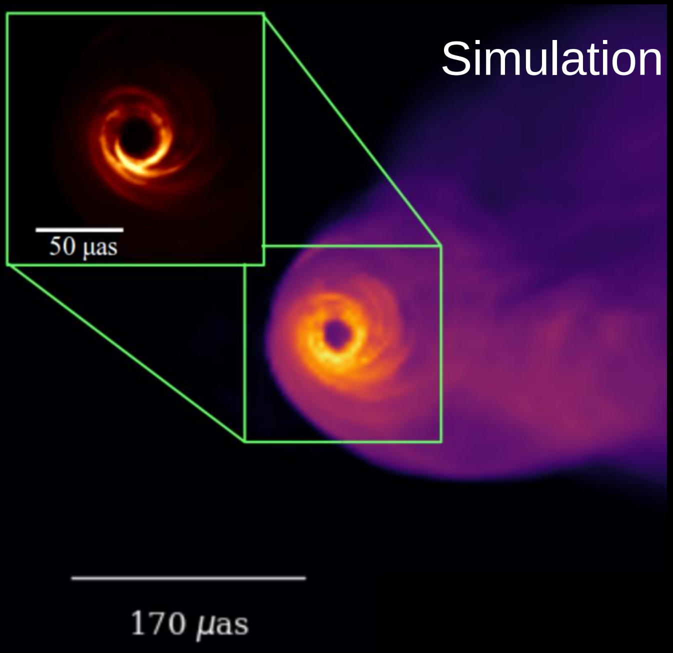
January 9, 2020



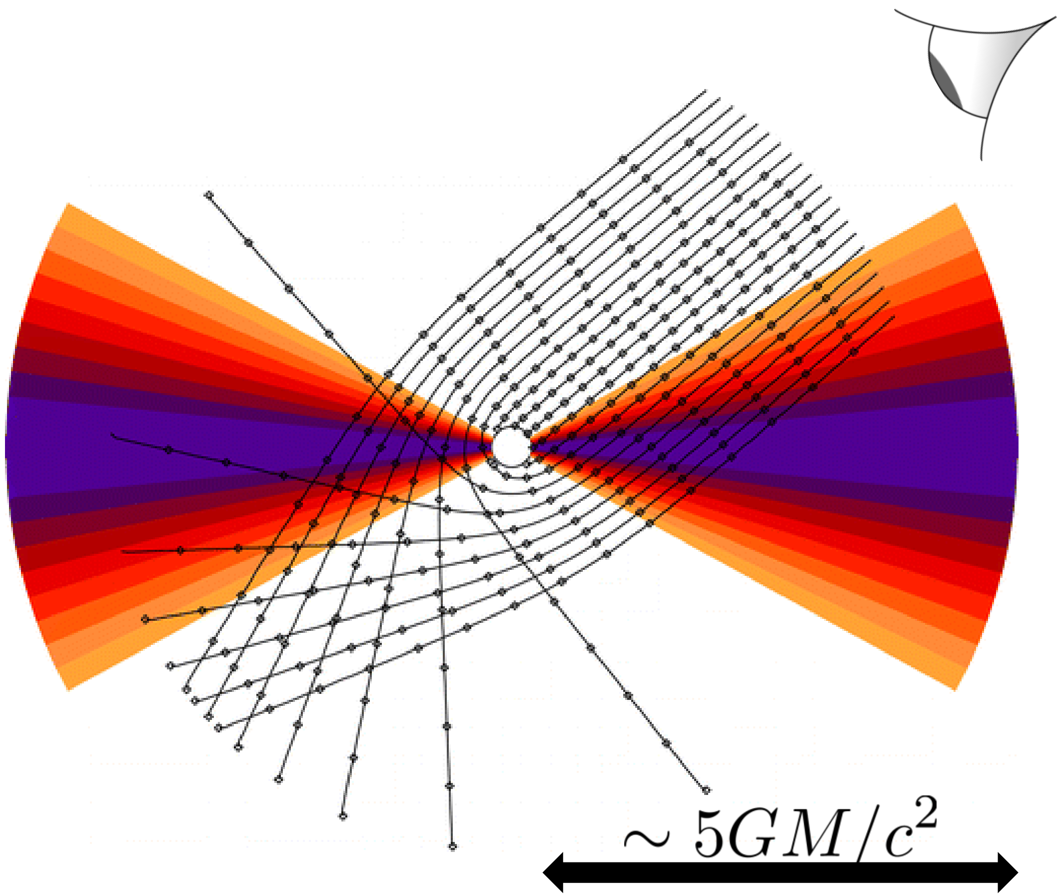


NASA PRINCETON UNIVERSITY CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN Event Horizon Telescope

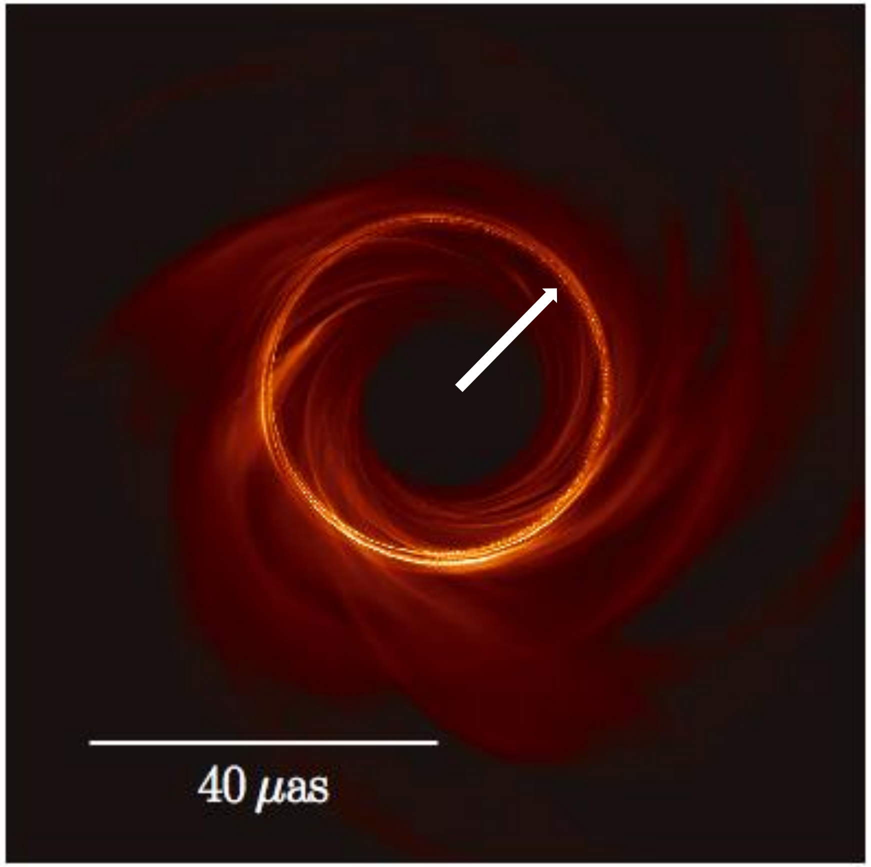
The EHT Collaboration

In particular: Ramesh Narayan, Michael Johnson, Shep Doeleman, Katie Bouman, Kazu Akiyama, Sara Issaoun, and Michael Rowan

What does a black hole look like?



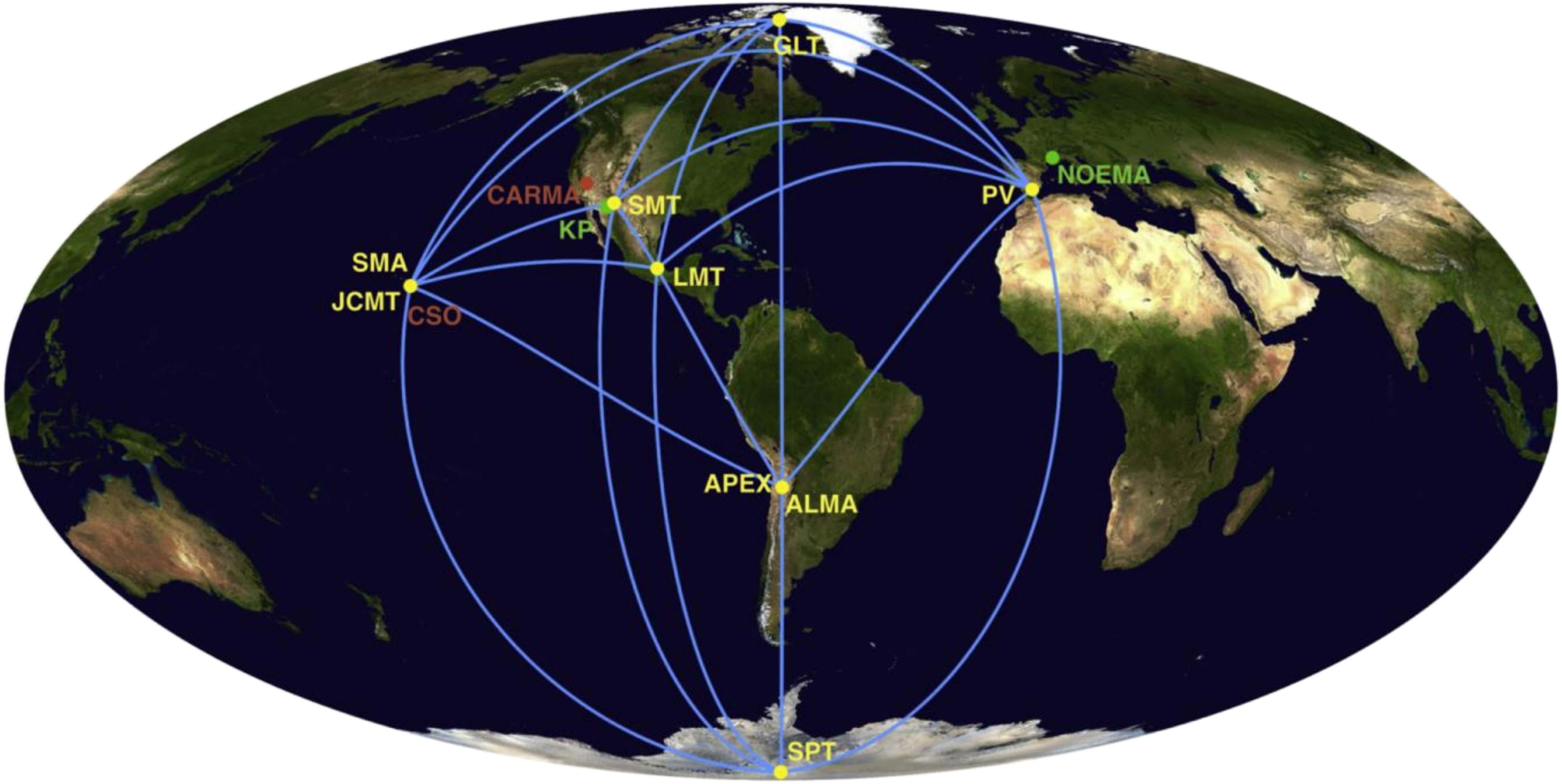
$$r_{\mathrm{shadow}} = \sqrt{27}GM/c^2$$



Schnittman+ (2006)

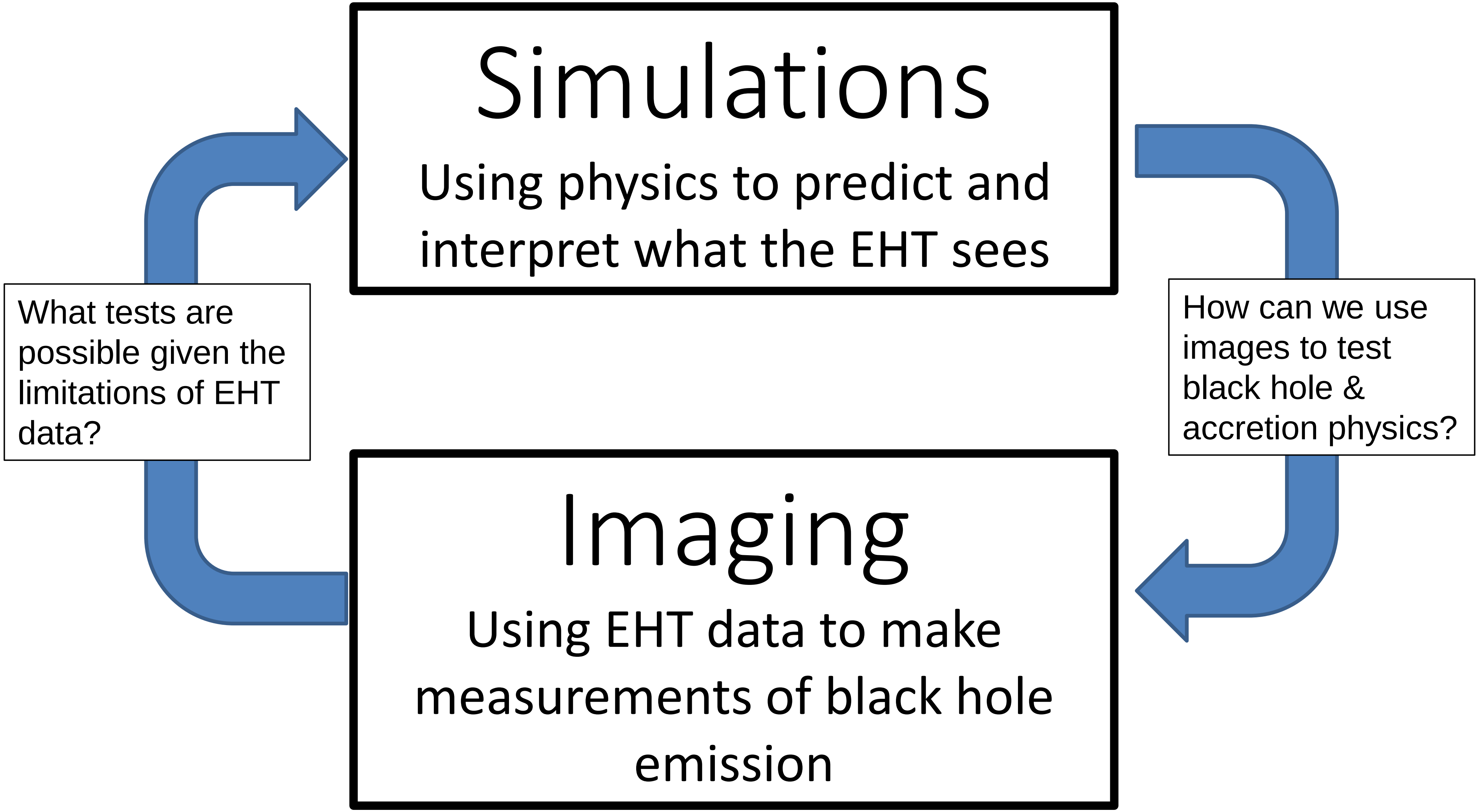
EHTC+ 2019

The Event Horizon Telescope



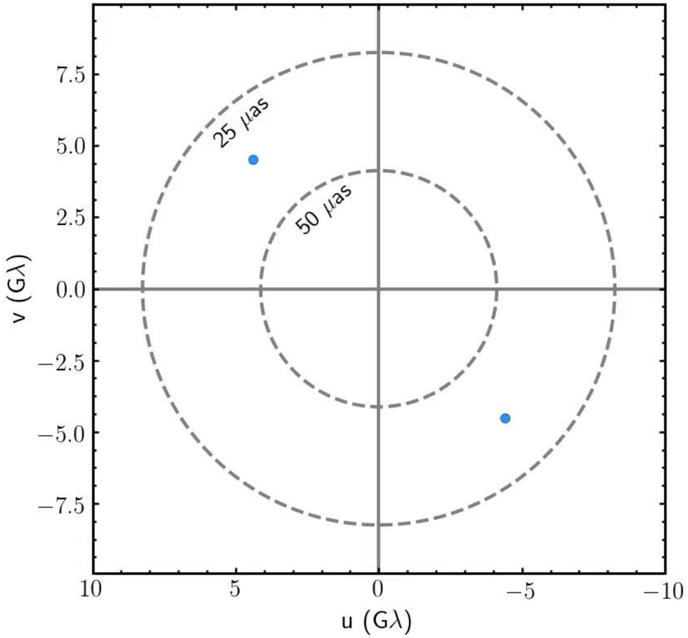
$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

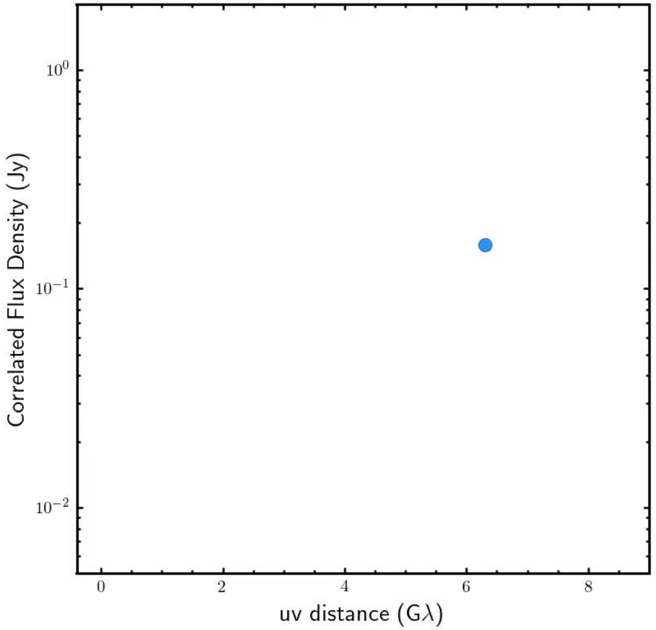
Image Credit:
EHT Collaboration 2019 (Paper II)


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?

Imaging
a supermassive black hole accretion flow

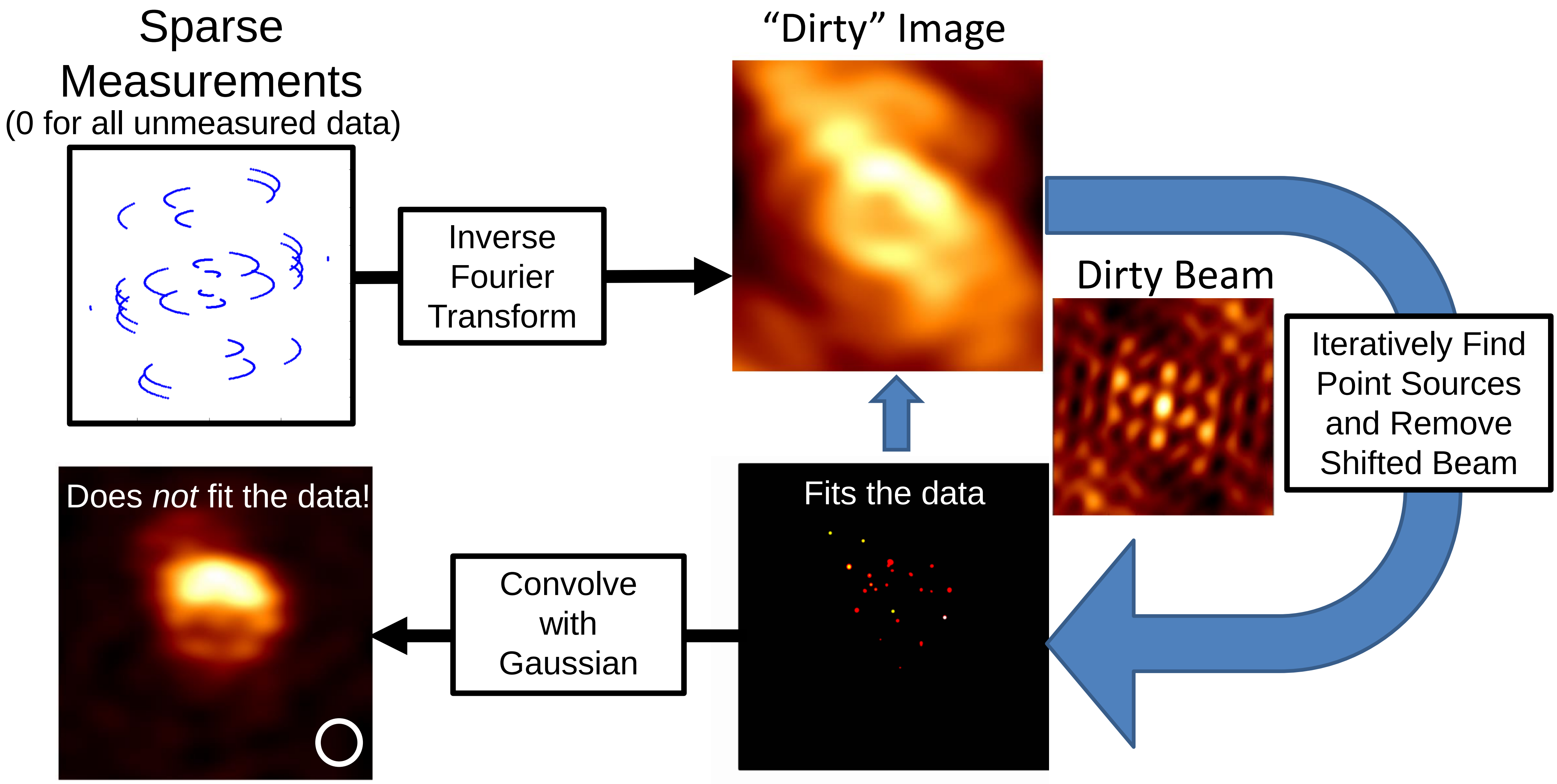
Very Long Baseline Interferometry (VLBI)





Movie Credit: Daniel Palumbo

Traditional Approach: CLEAN



Simulation Credit: Avery Broderick

VLBI Imaging: Bayesian approach

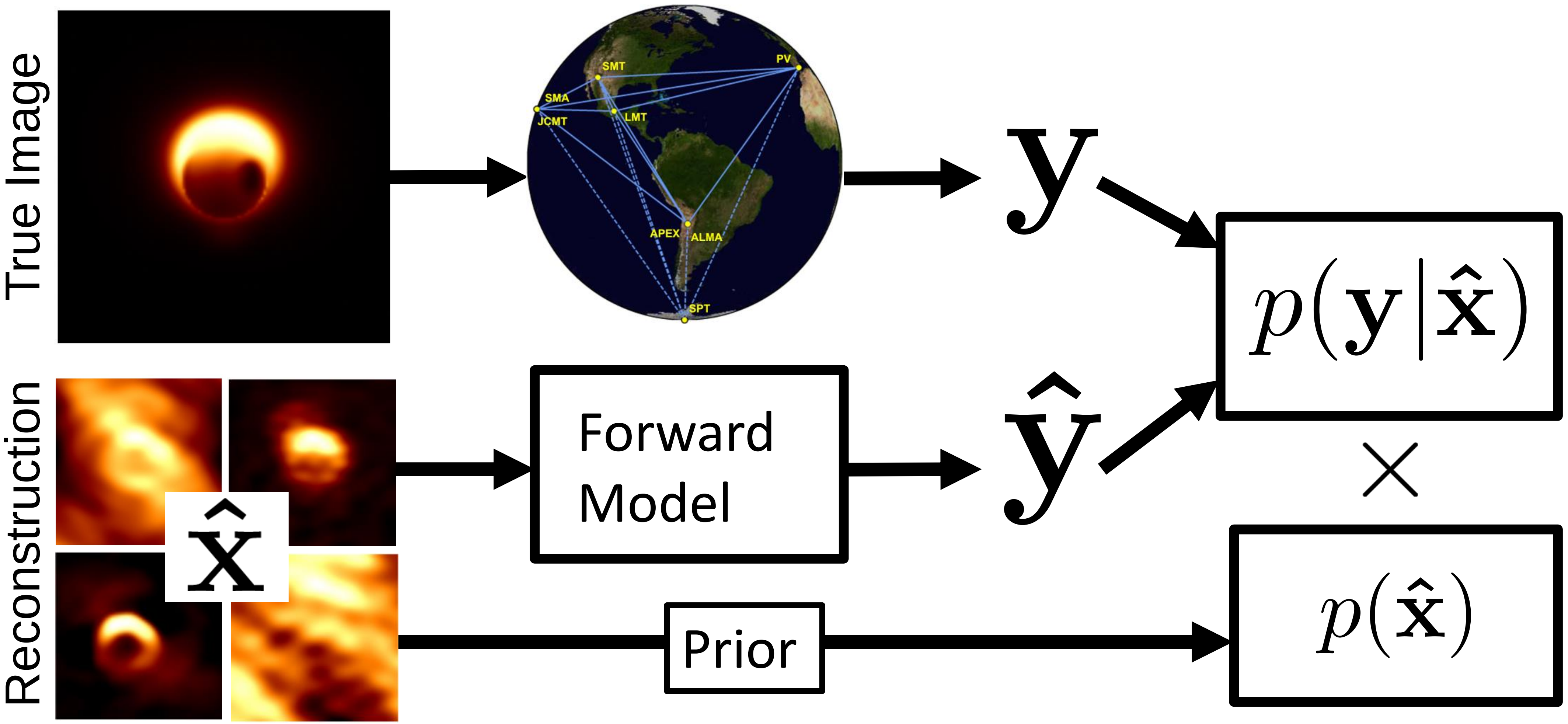


Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

Regularized Maximum Likelihood

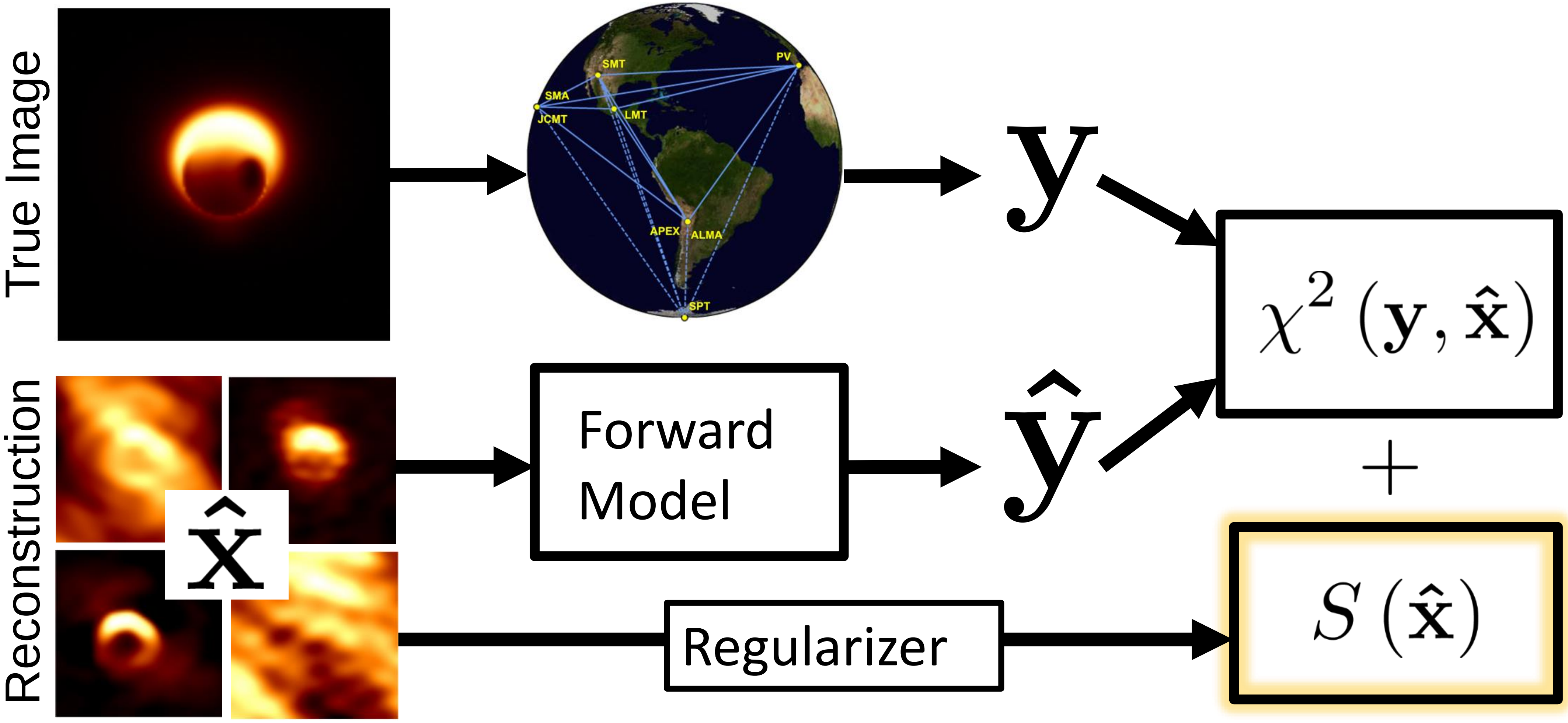


Image Credit: Katie Bouman

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

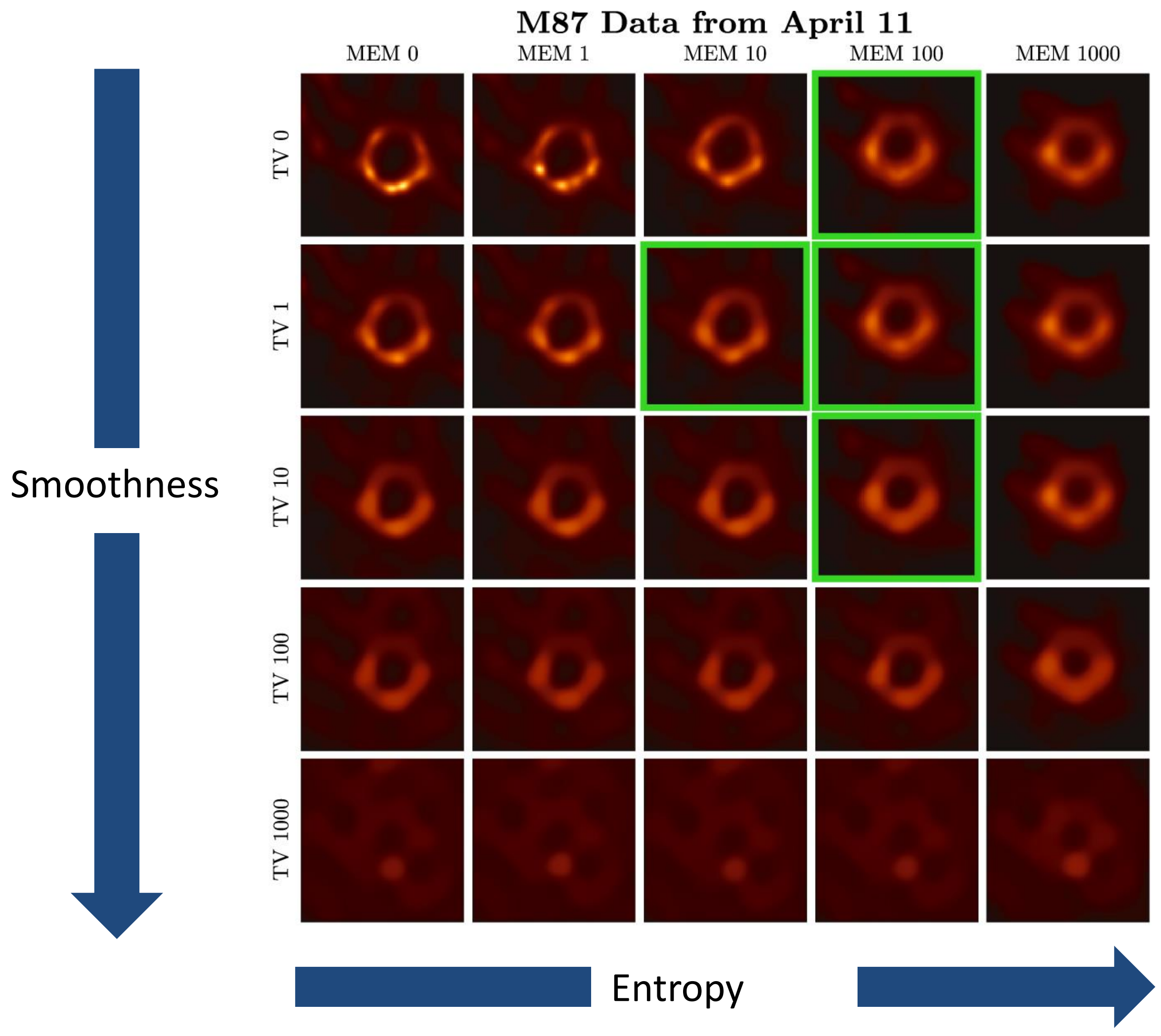
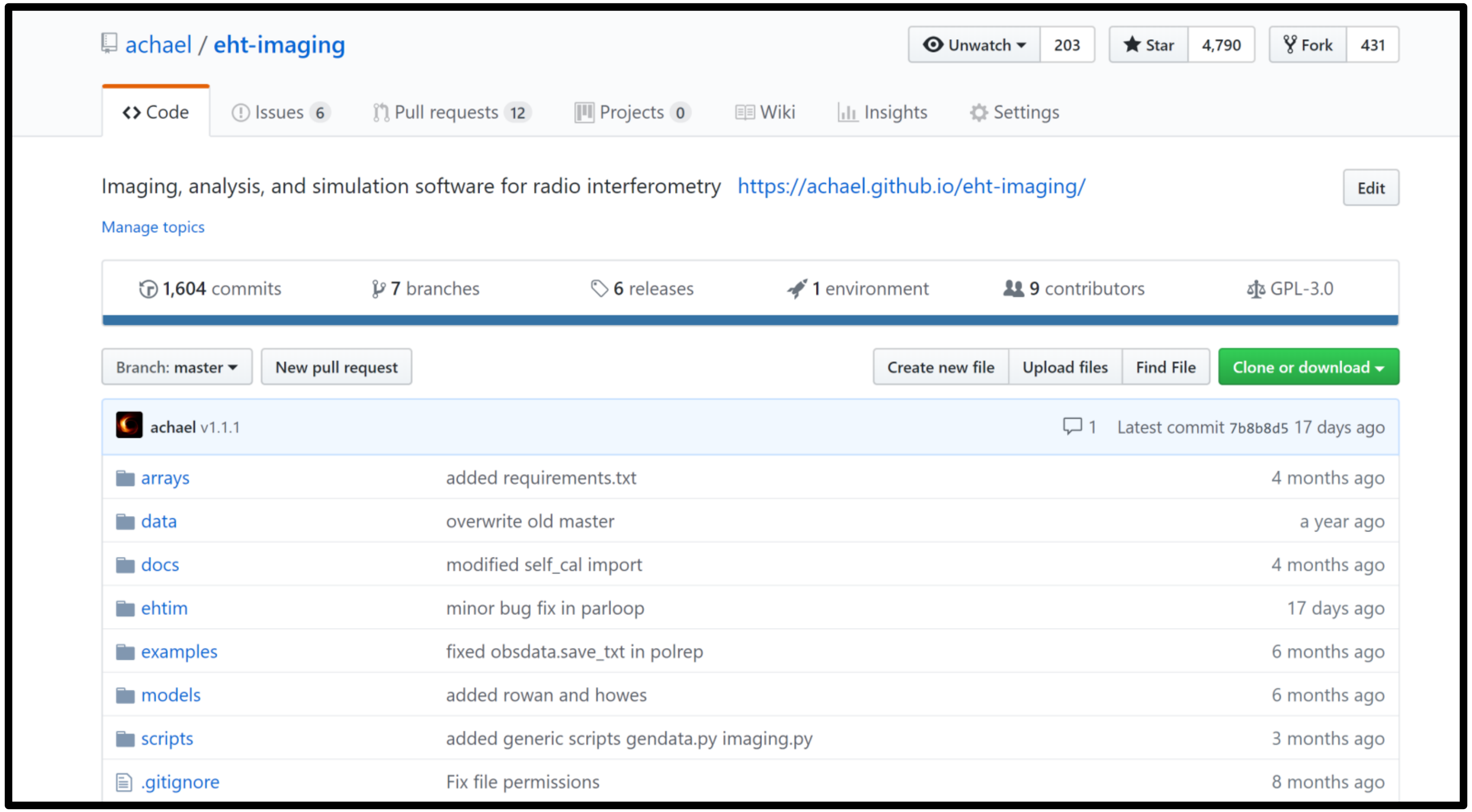


Image Credit: EHT Collaboration 2019 (Paper IV)

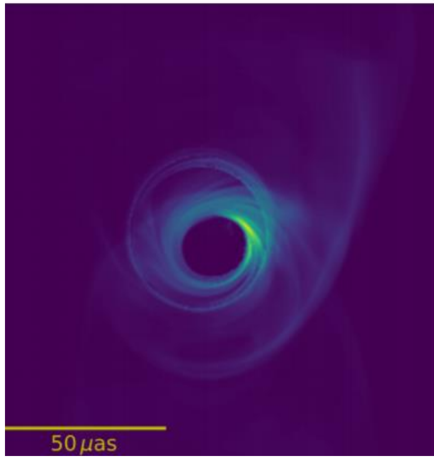
The `eht-imaging` software library

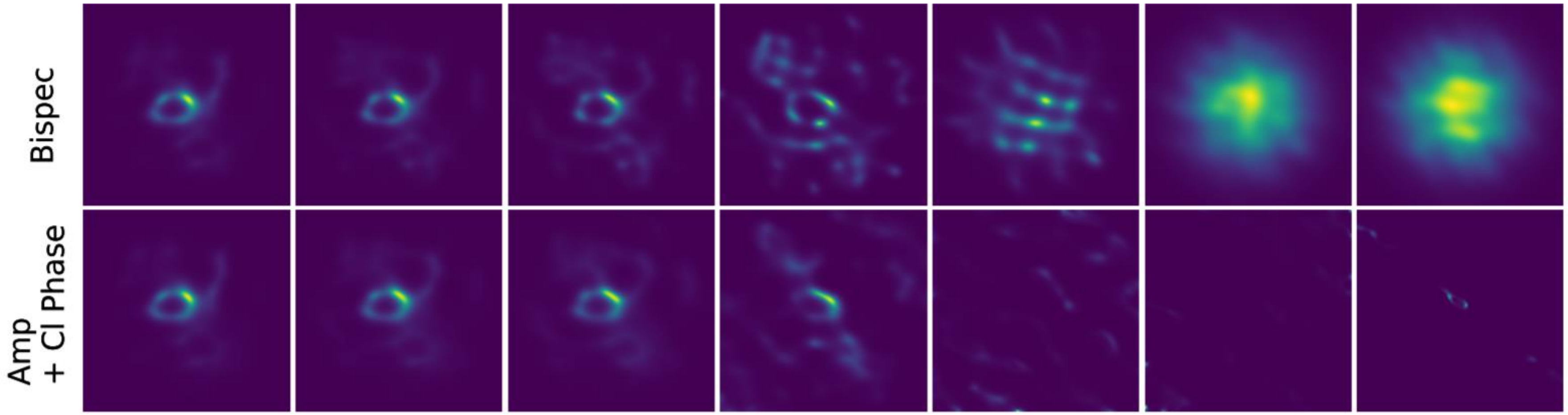


- Python software to image, analyze, and simulate interferometric data
- Flexible framework for developing new tools – e.g. polarimetric imaging, dynamical imaging.
- Used in 18 published papers (including all 5/6 EHT result papers)

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

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!

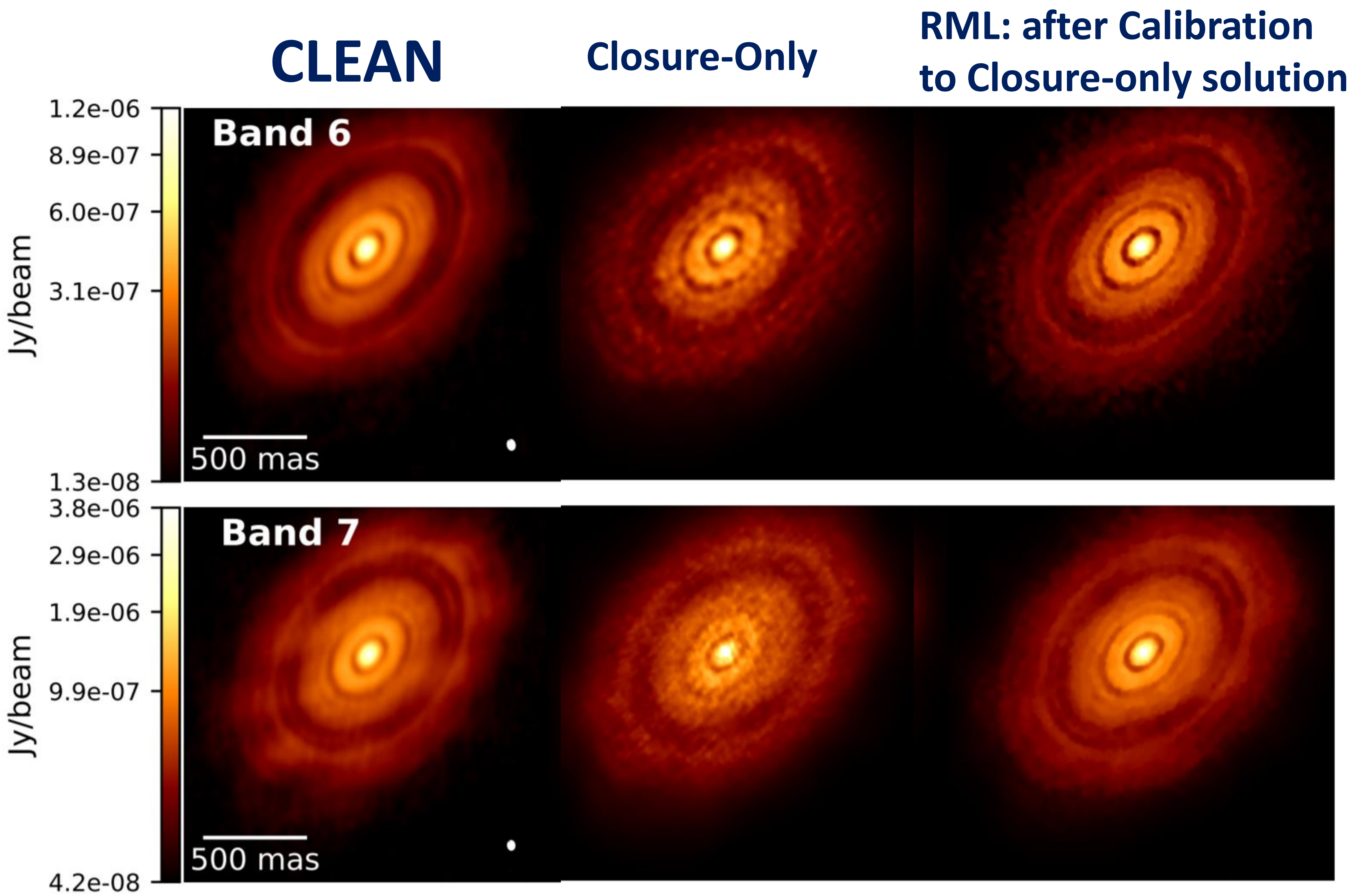


Image Credit: Chael+ 2018a

EHT 2017

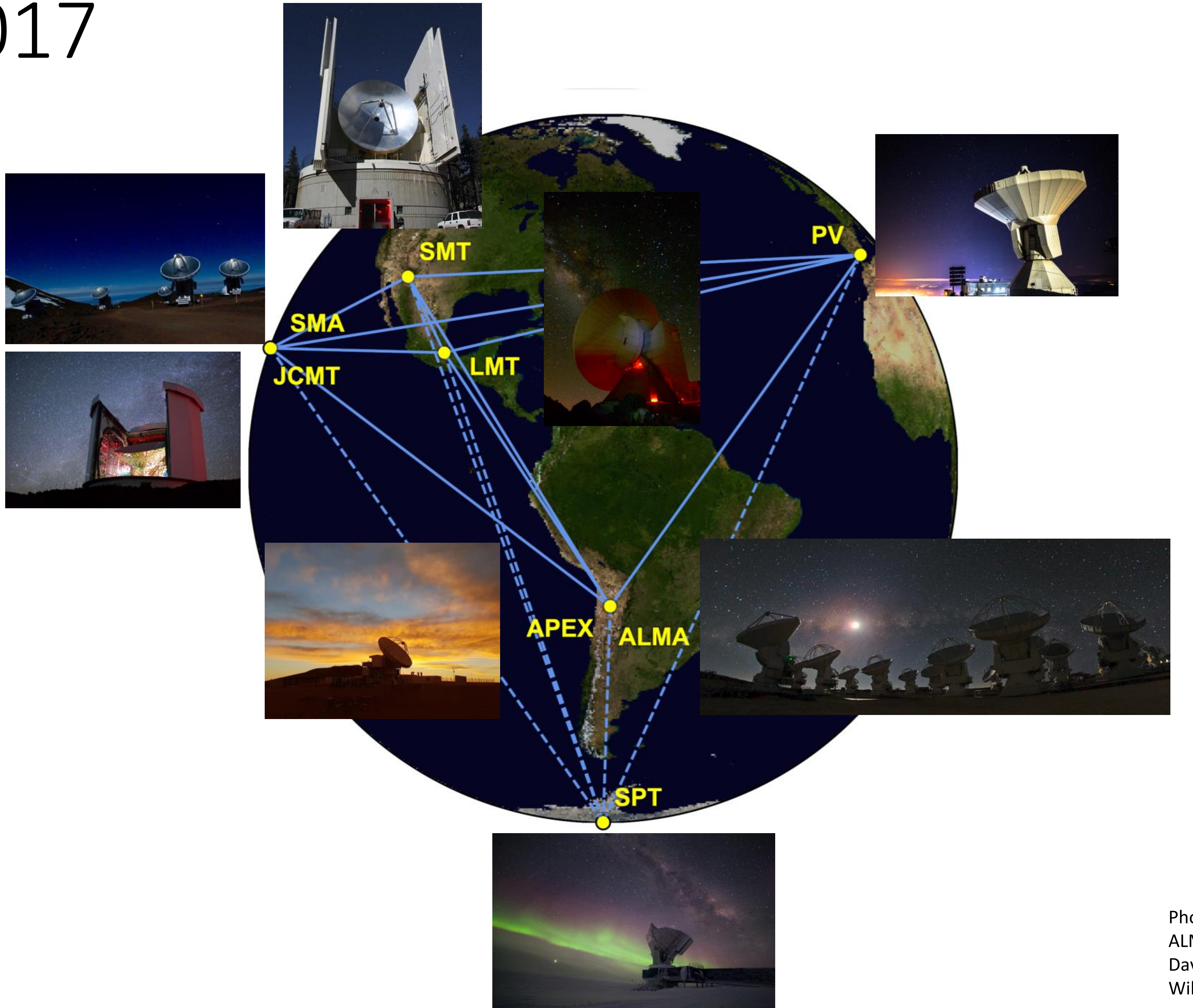
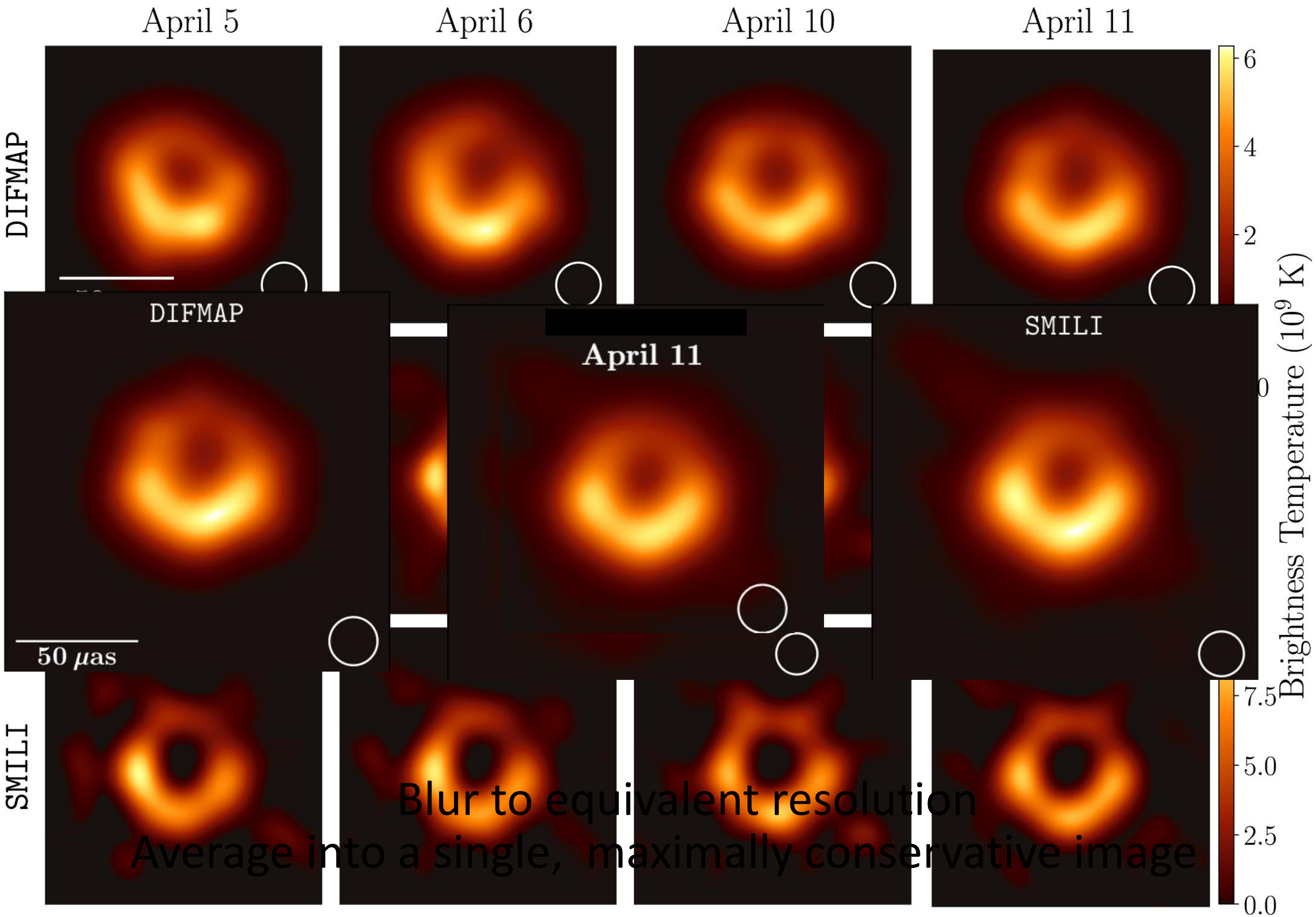


Photo Credits: EHT Collaboration 2019 (Paper III)
ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann,
David Sanchez, Daniel Michalik, Jonathan Weintroub,
William Montgomerie, Tom Folkers, ESO, IRAM

After lots of work….

$\boxed{\text{See special session 429 this afternoon in Room 310!}}$

Three imaging pipelines



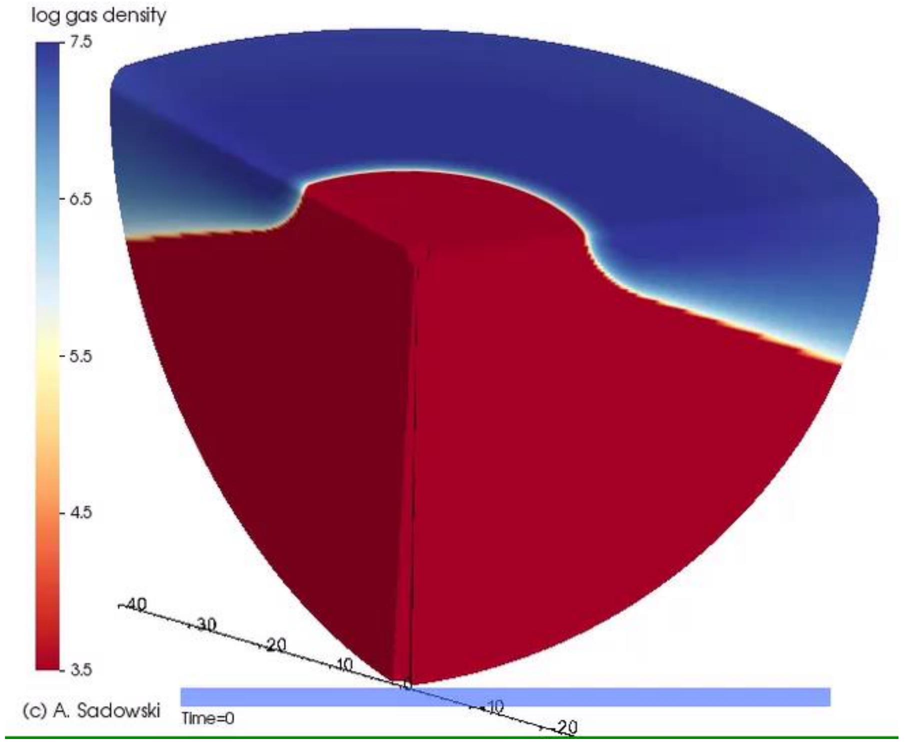
Blur to equivalent resolution

Average into a single, maximally conservative image

Image Credit: EHT Collaboration 2019 (Paper IV)

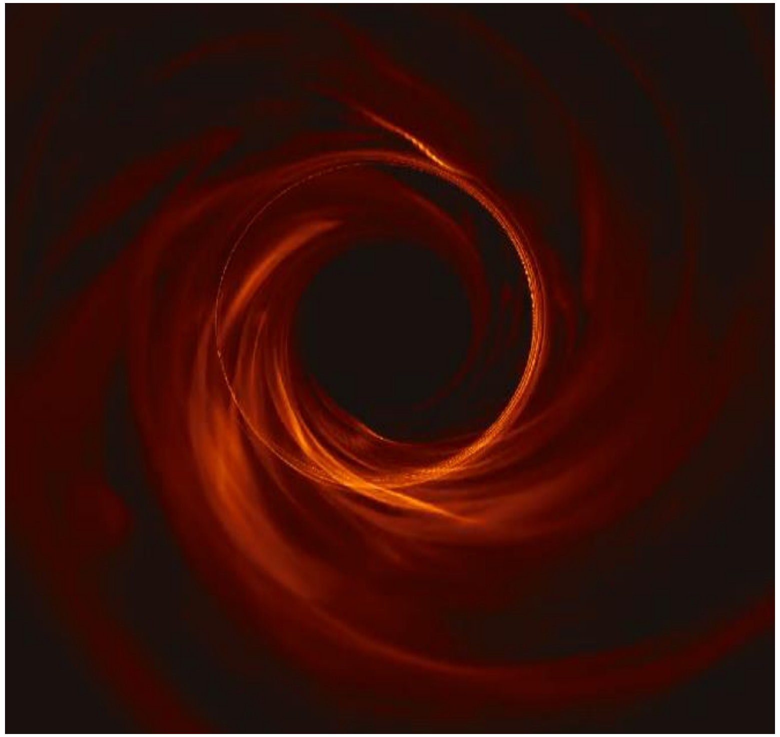
Radiative GRMHD simulations of M87

General Relativistic MagnetoHydroDynamics (GRMHD)



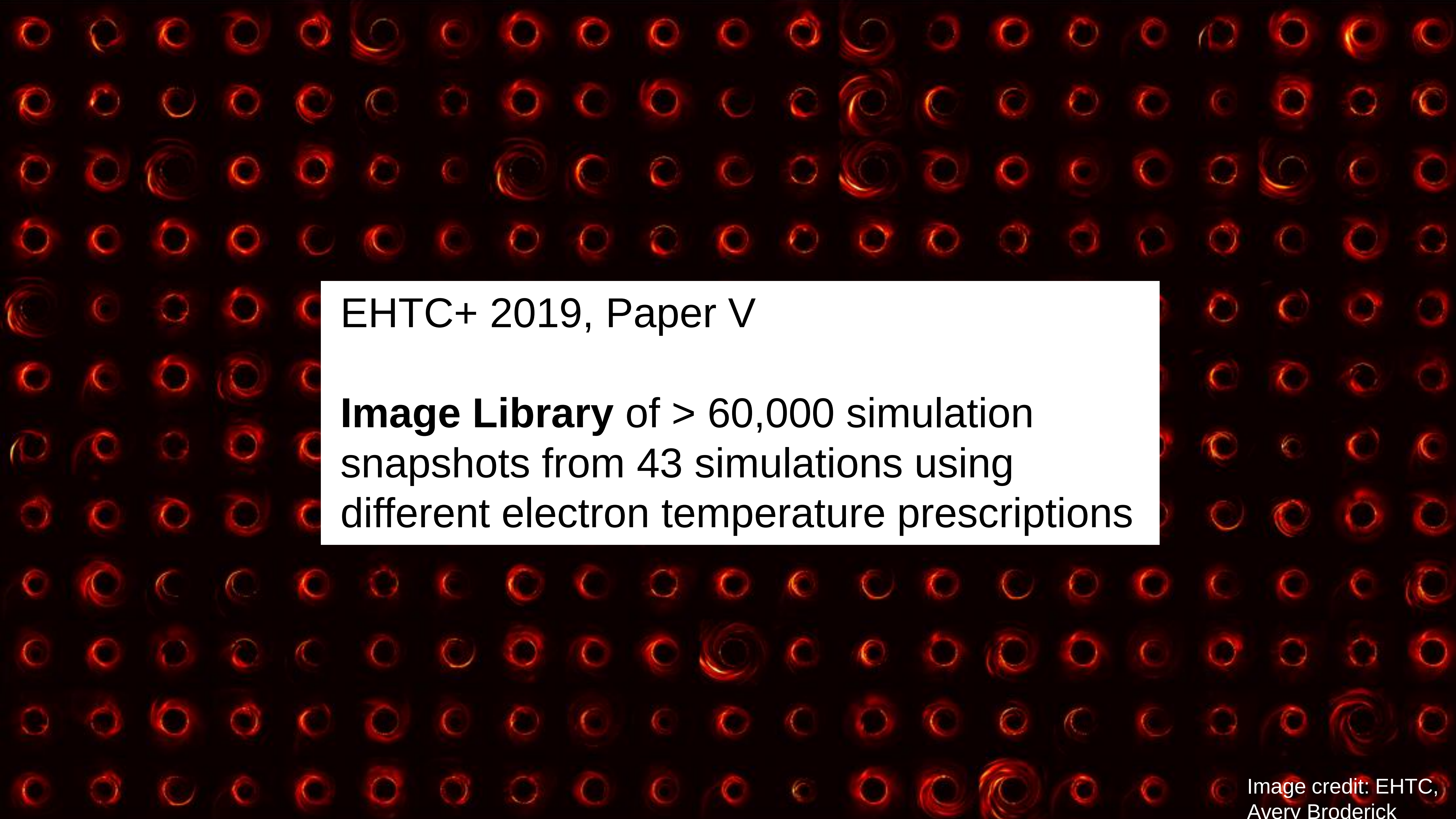
Solves coupled equations of fluid dynamics and magnetic field in a black hole spacetime

General Relativistic Ray Tracing



Tracks light rays and solves for the emitted radiation

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



EHTC+ 2019, Paper V

Image Library of > 60,000 simulation snapshots from 43 simulations using different electron temperature prescriptions

Image credit: EHTC, Avery Broderick

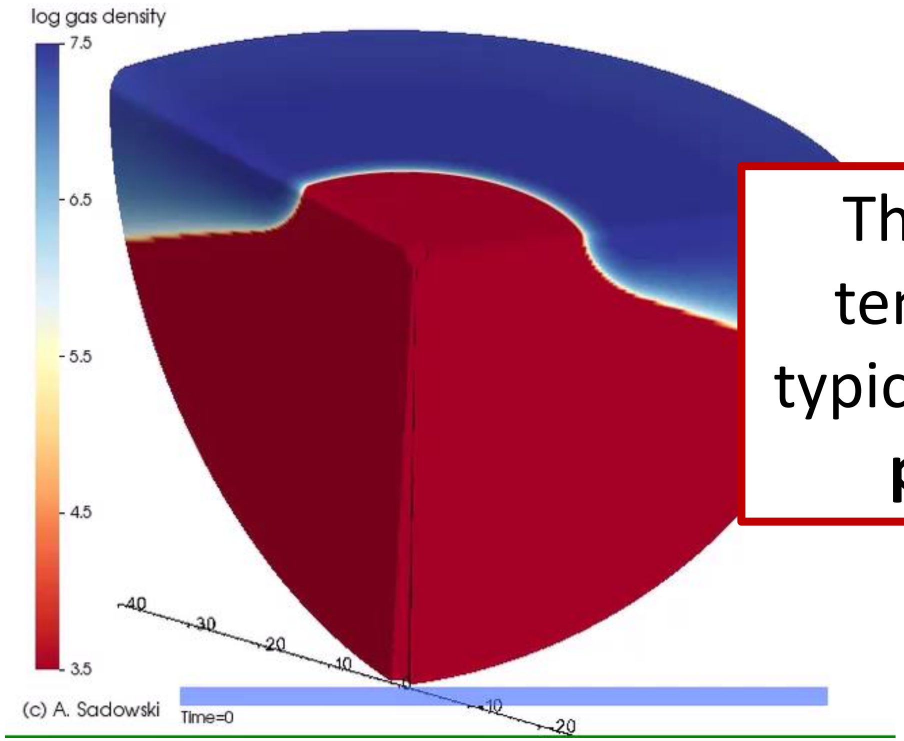
What parameters determine the images we see?

1. Spacetime geometry: M, a
   - Liberating potential energy heats the plasma.
   - Extraction of spin energy

2. (Radiative) Magnetohydrodynamics: $\dot{M}, \Phi_B$
   - Does the magnetic field arrest accretion?
   - How does the B-field determine the jet power & shape?

3. Electron (non)thermodynamics: $T_e, n_e(\gamma)$
   - What is the electron temperature?
   - What is their distribution function?

From simulations to observables

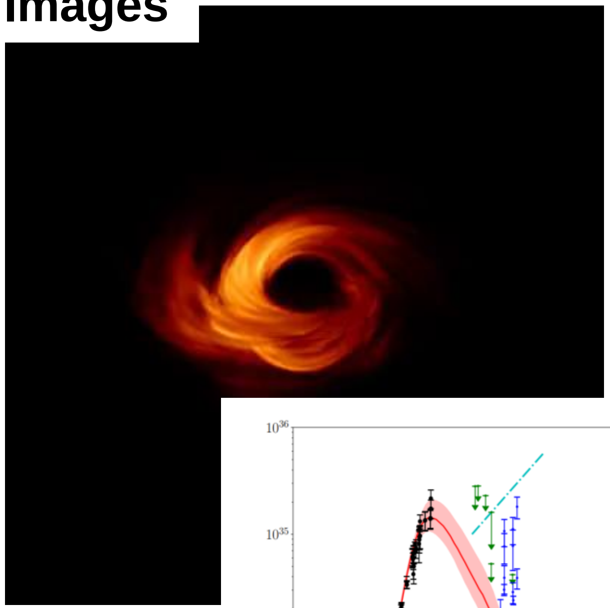


The electron-to-ion temperature ratio is typically set **manually** in **post-processing**

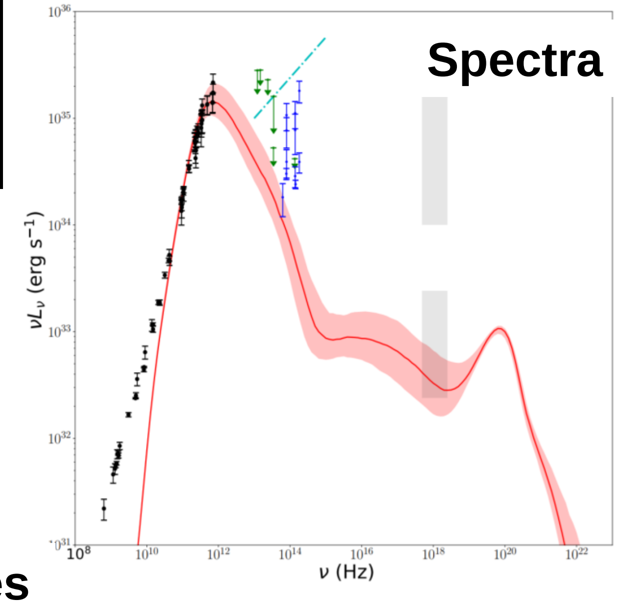
GRMHD Simulations

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

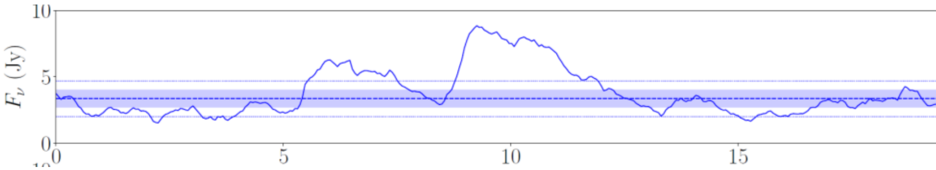
Images



Spectra



Light Curves



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

What can we learn from:

1.) Simulating M87 with electron heating and cooling?

2.) Connecting these simulations to horizon-scale and large-scale jet images?

Two-Temperature GRRMHD Simulations

- Evolve plasma and magnetic field as in standard GRMHD

- But include **radiative feedback** on gas energy-momentum.
  -- M87's radiative efficiency $L/\dot{M}c^2 \sim 1\%$ (Ryan+ 2018, EHTC+ 2019)

- Also evolve electron and ion temperatures via the 1st law of thermodynamics:

Radiative Cooling

$$T_{\rm e}\,(n s_{\rm e} u^{\mu})_{;\mu} = \delta_{\rm e} q^{\rm v} + q^{\rm C} - \hat{G}^0$$

$$T_{\rm i}\,(n s_{\rm i} u^{\mu})_{;\mu} = (1-\delta_{\rm e}) q^{\rm v} - q^{\rm C}$$

Coulomb coupling:
(extremely weak)

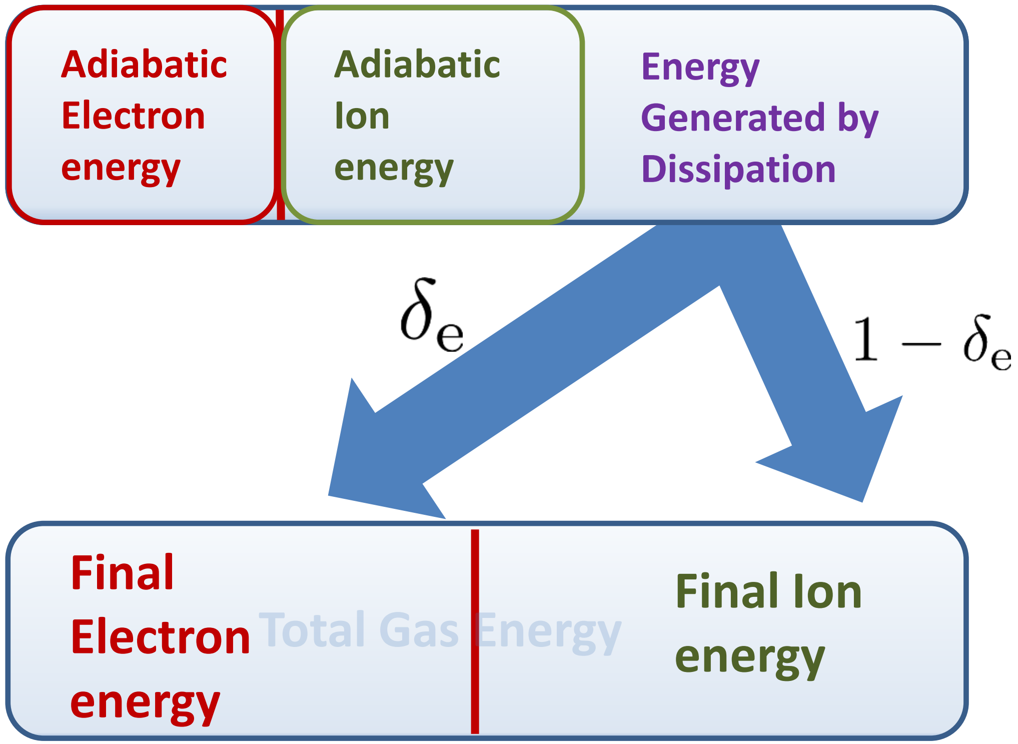
Adiabatic
Compression/
Expansion

Dissipation

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

Plasma uncertainties: Electron & Ion Heating

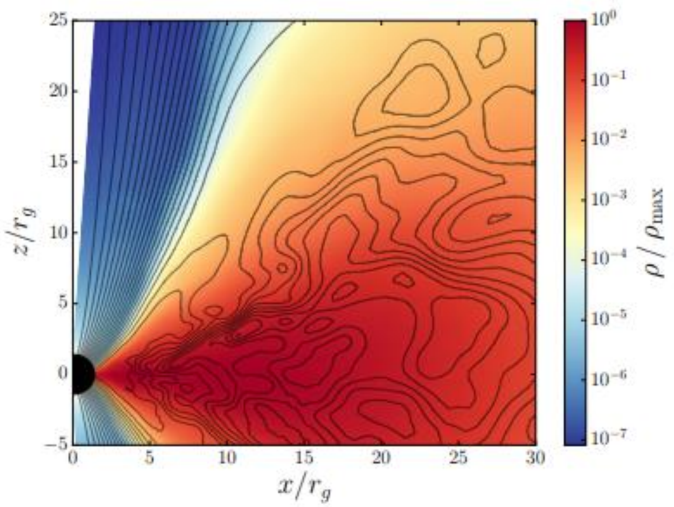
- We can identify the **total** dissipative heating in the simulation but…
- **Sub-grid physics** must be used to determine what fraction of the dissipation goes into the electrons.

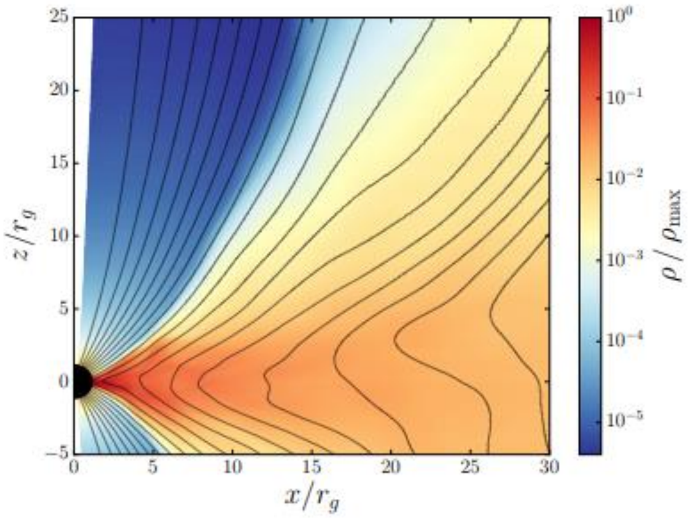


Two-temperature MAD simulations of M87

- Both simulations are in the magnetically arrested (MAD) state.

SANE





MAD

- Two different microphysical plasma heating mechanisms

- Density is scaled to match 0.98 Jy at 230 GHz.

Image credit: Riordan+ 2017

230 GHz Images

0.0 yr

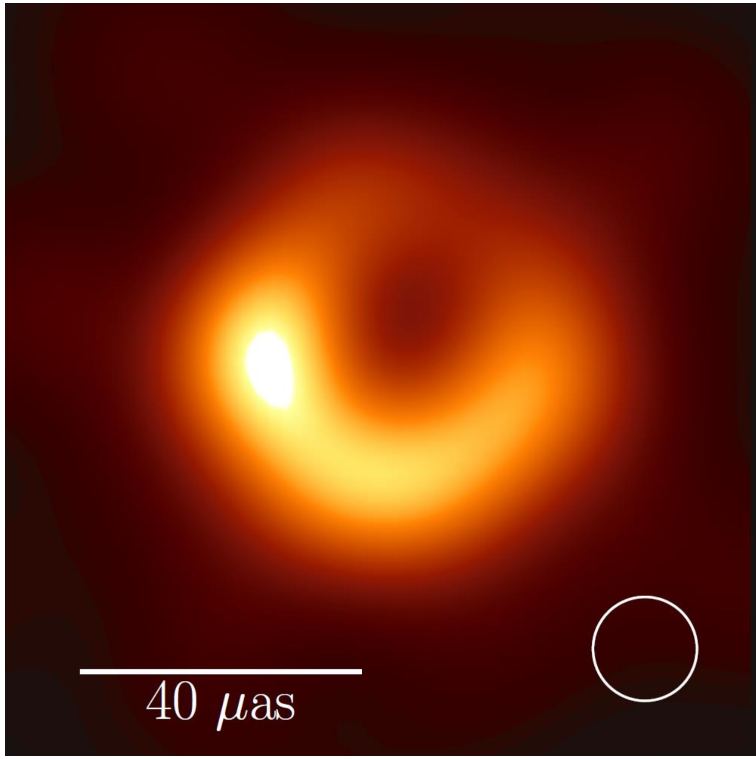
Turbulent Heating

Reconnection Heating

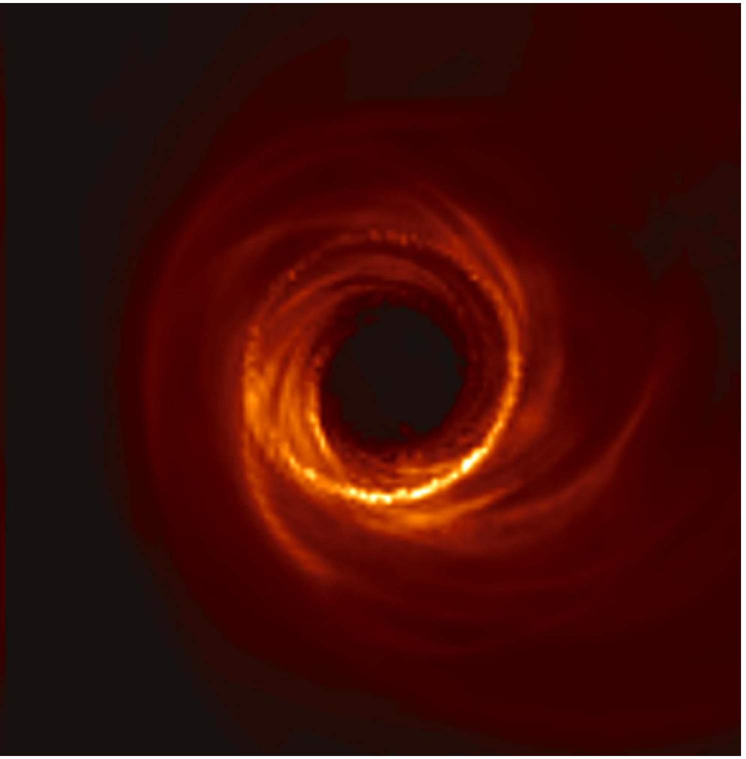
50 μas

Simulations and Images

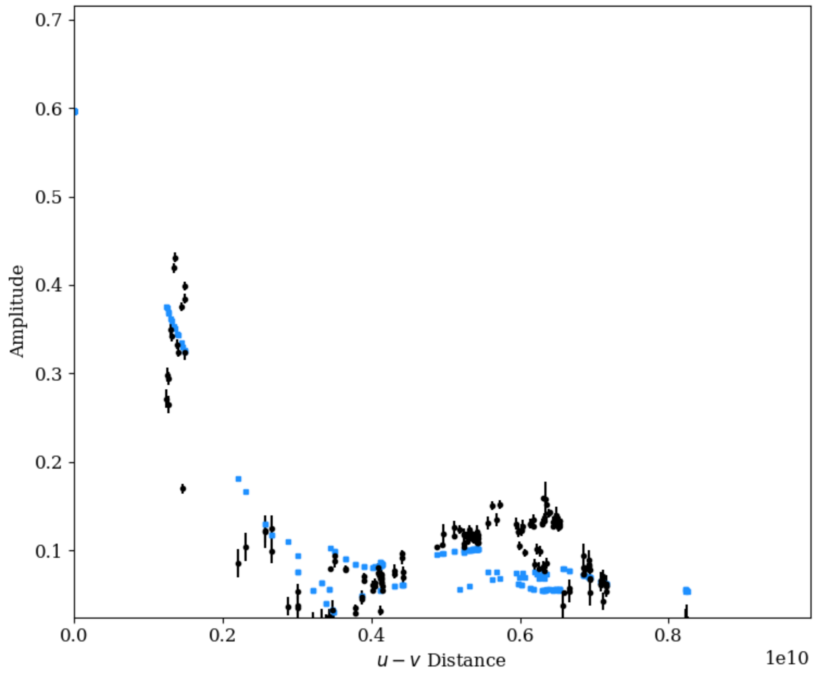
EHT 2017 image



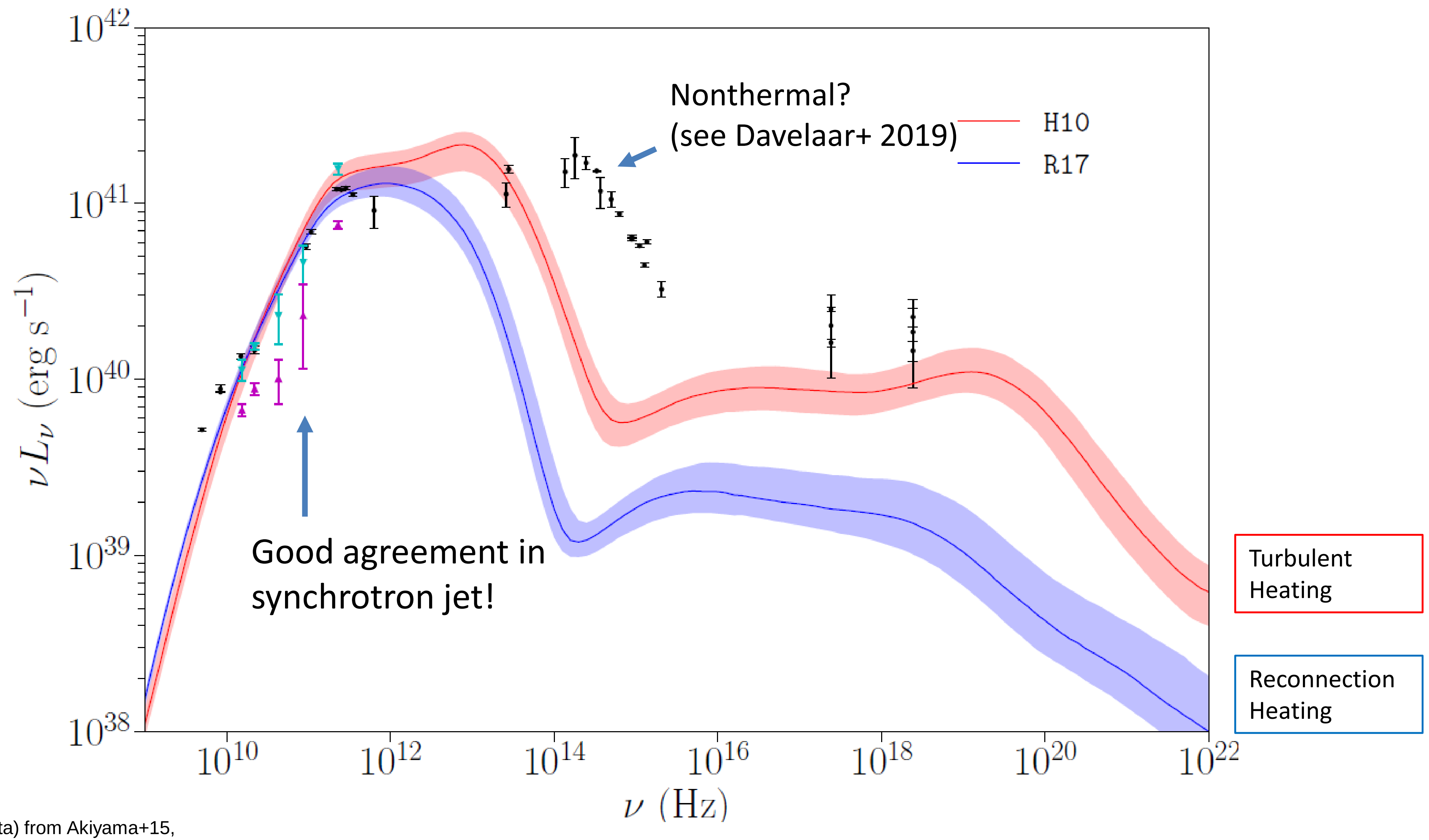
Simulated image
from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes



M87 SED

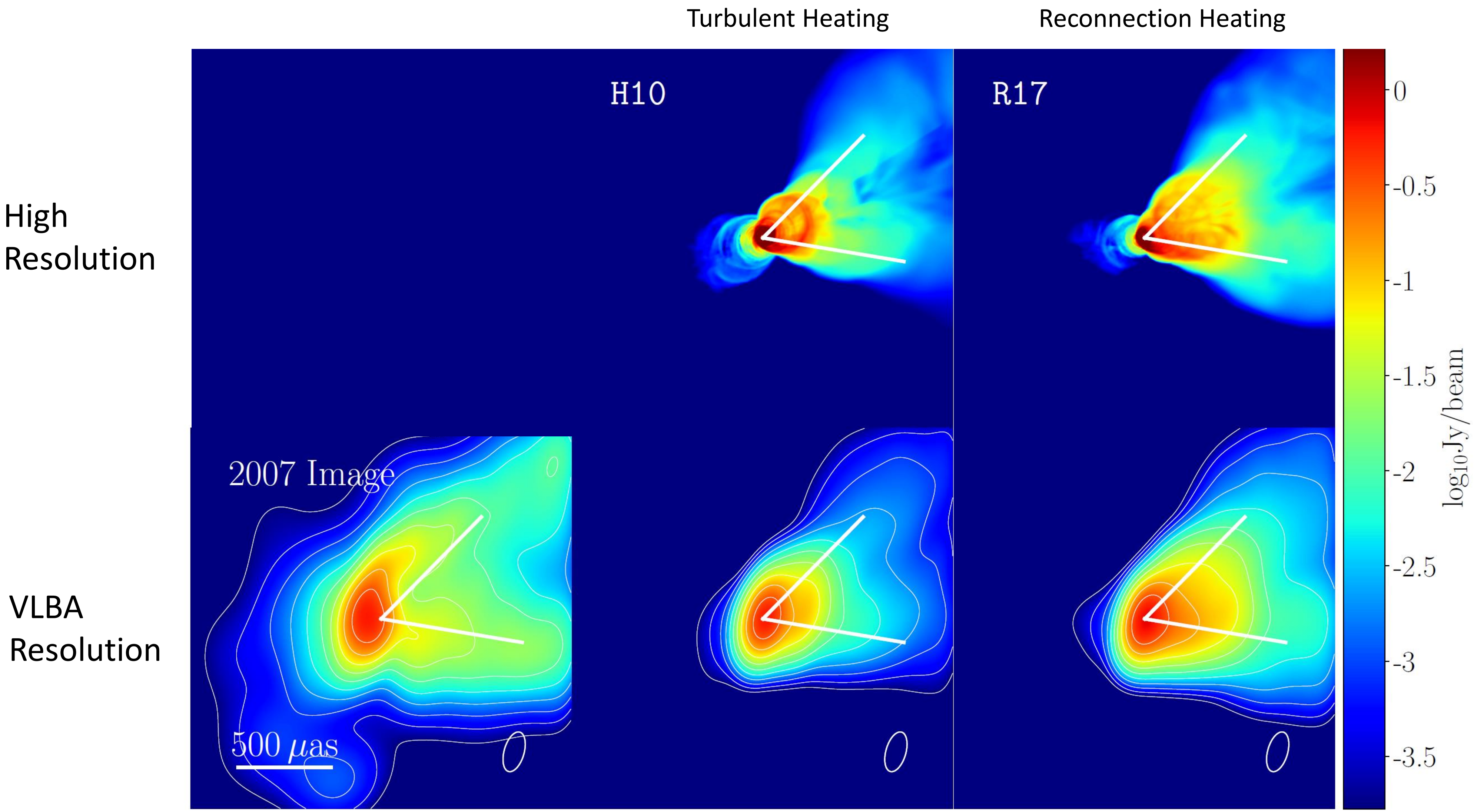


Data from Prieto+16
New points (cyan and magenta) from Akiyama+15, Doeleman+12, Walker+18, Kim+18, and MOJAVE

Image Credit: Chael+ 2019

43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

$55°$

(Walker+ 2018)

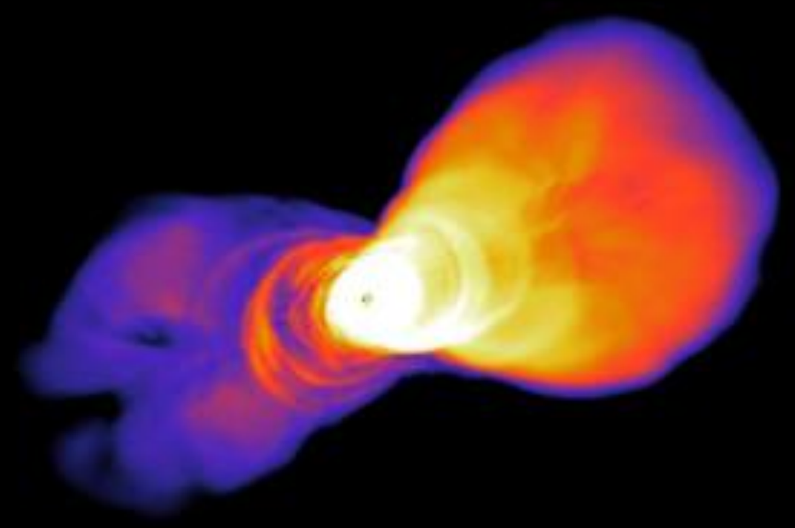
The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s!

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

43 GHz jets

0.0 yr

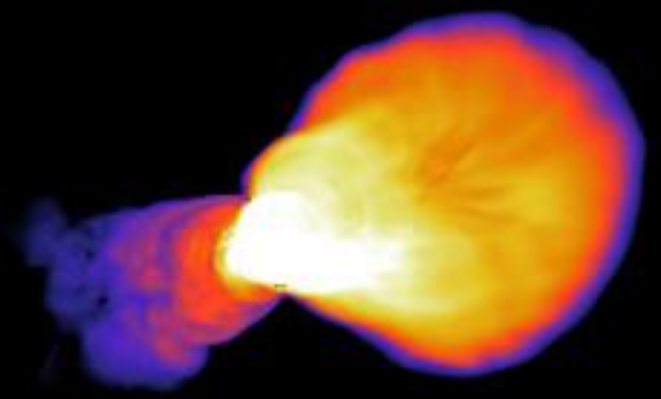
Turbulent Heating



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

$500\ \mu$as

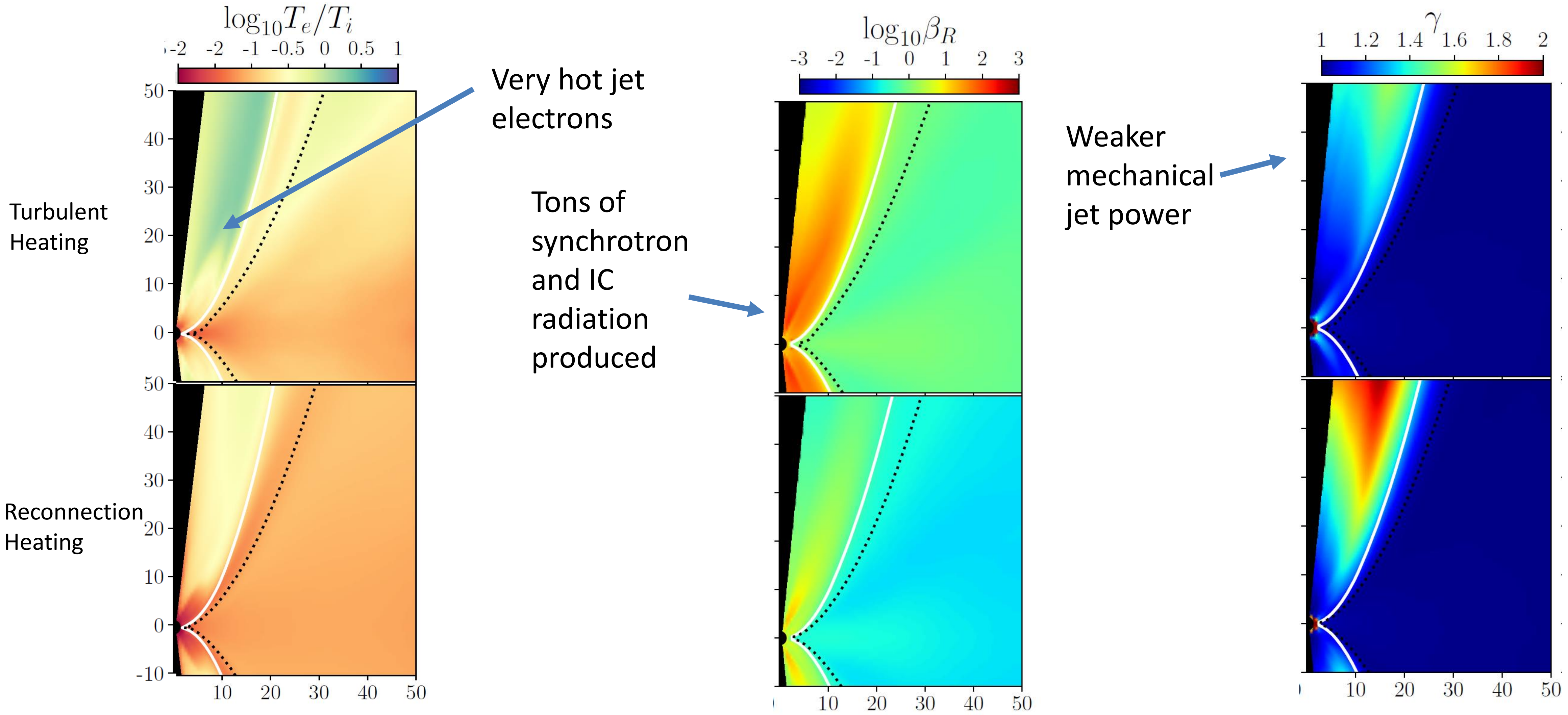
Reconnection Heating



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

Movie Credit: Chael+ 2019

Electron Heating + Radiation → Jet Dynamics

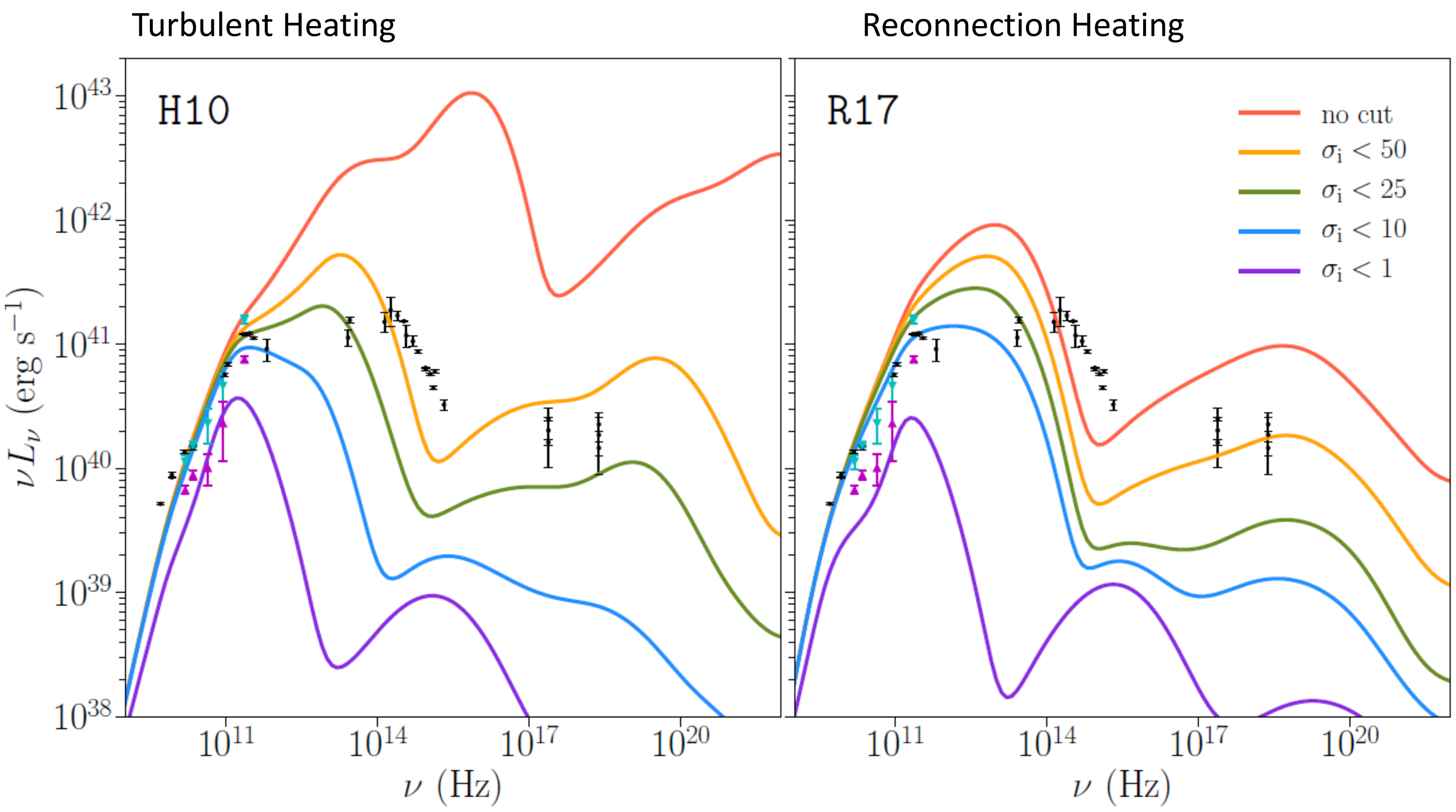


Turbulent heating produces too much radiation at the jet base, which saps the jet power

Electron Heating + Radiation → Dynamics!

Image Credit: Chael+ 2019

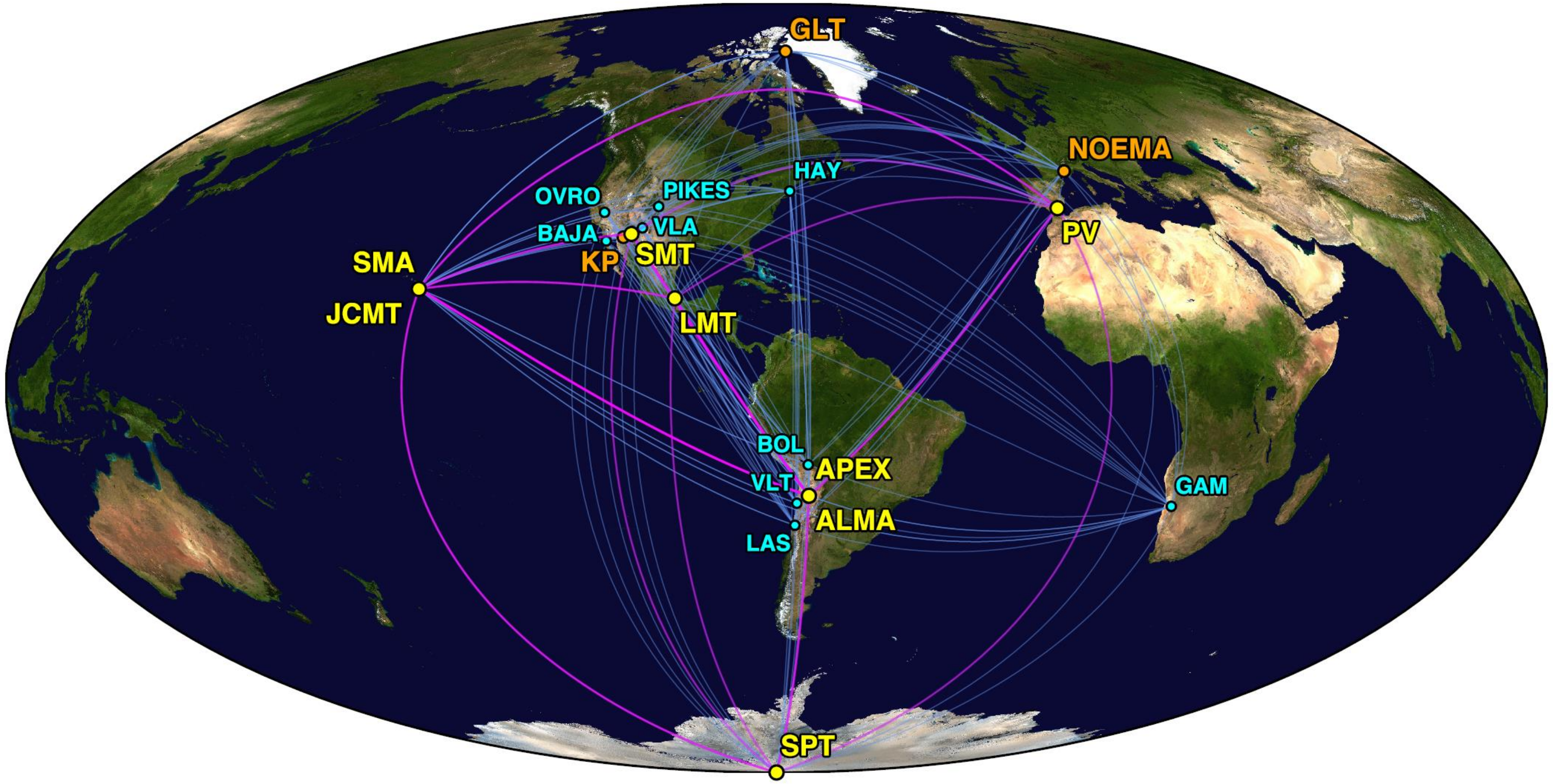
Major uncertainty: Funnel emission

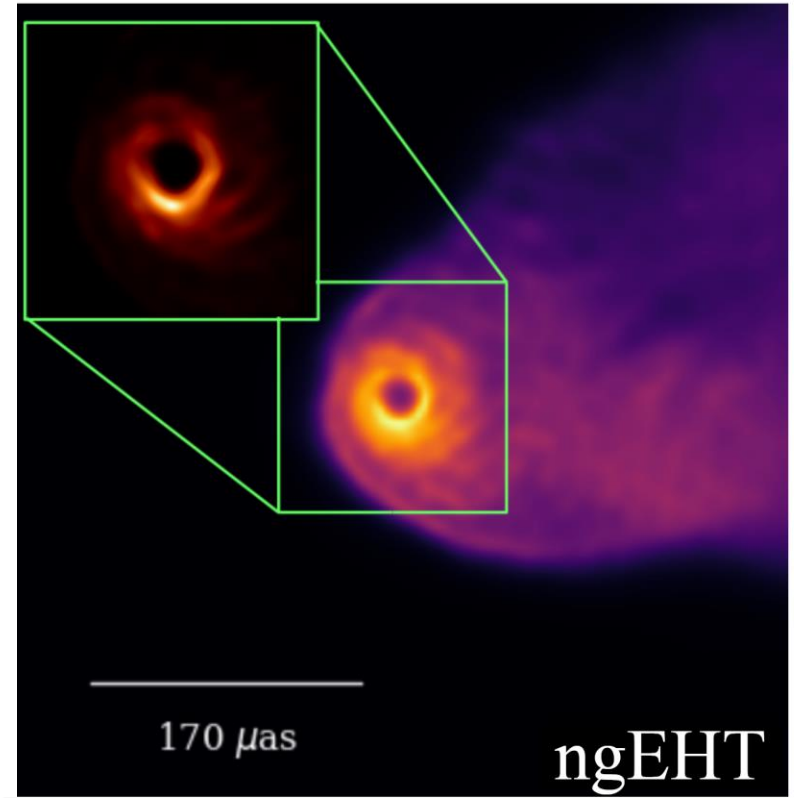


- In the simulation inner jet, the magnetic field is strong, $\sigma_i \geq 1$
- We don't trust the gas thermodynamics in regions with very strong magnetic field, so we only include regions where $\sigma_i \leq 25$
- Spectra and images at frequencies $\gtrsim$230 GHz depend strongly on the choice of cut!

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

ngEHT will illuminate the BH-jet connection





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)

Takeaways

- RML interferometric imaging techniques can produce images with poor amplitude/phase calibration
  - These techniques were critical in producing the EHT M87 image

- Global simulations can connect EHT images on horizon scales to the extended jet on ~pc scales.

- MAD models produce powerful, wide opening-angle jets which match VLBI observations.

  - But uncertainty about high-magnetization thermodynamics is a big problem.

Thank you!

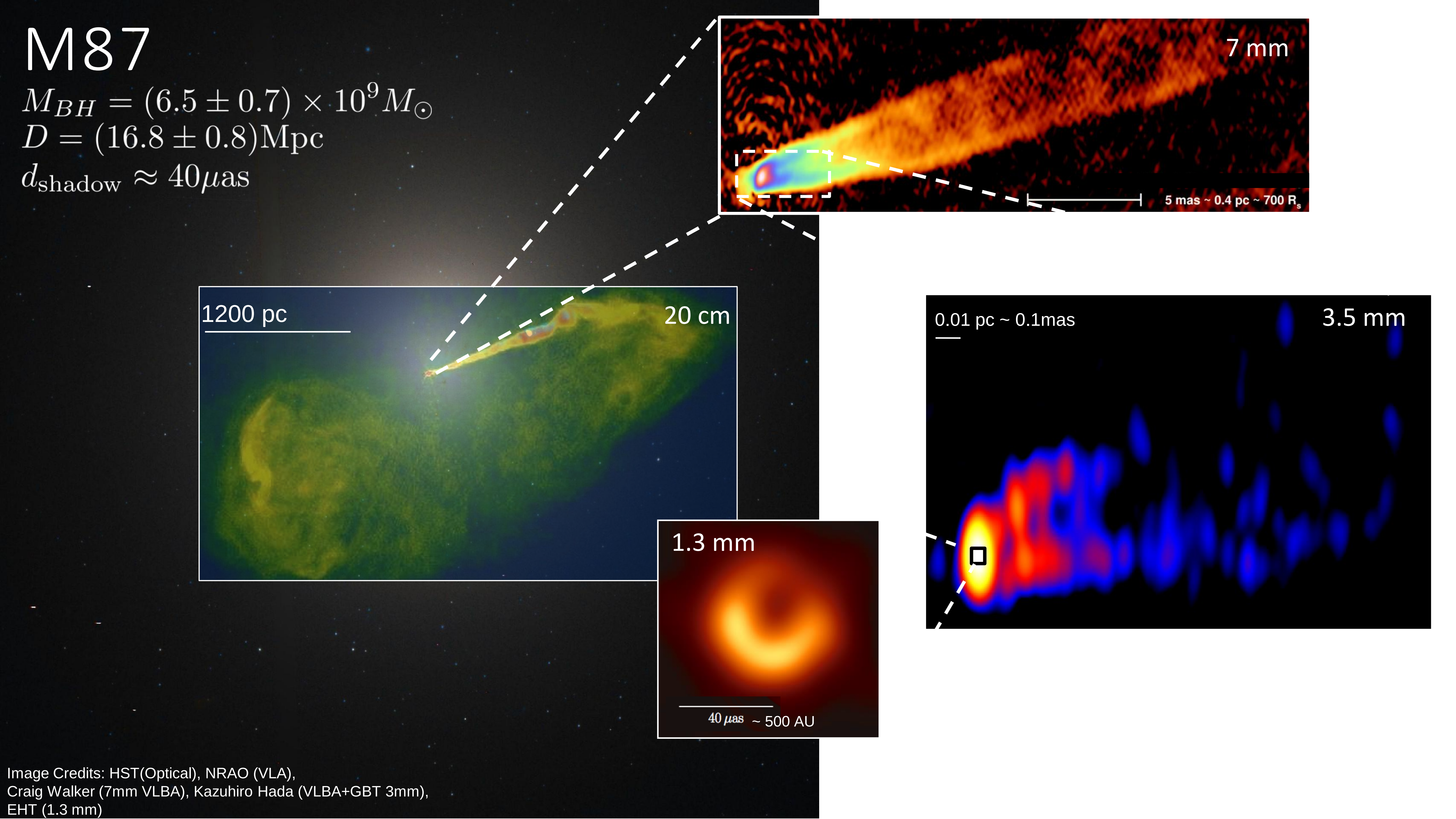
Work with Ramesh Narayan, Michael Johnson,
Katie Bouman, Shep Doeleman, Michael Rowan,
and the entire EHT collaboration

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

Two-temperature MAD simulations of M87

Model	Spin	Heating	$\langle \dot{M}/\dot{M}_{\rm Edd} \rangle$	$\underbrace{\langle \Phi_{\rm BH}/(\dot{M}c)^{1/2} r_{\rm g} \rangle}_{\text{“MAD parameter”}}$	$\underbrace{\langle P_{J(100)} \rangle \text{ [erg s}^{-1}\text{]}}_{\text{Jet mechanical power}}$
H10	0.9375	Turb. Cascade	3.5×10^{-6}	54	6.6×10^{42}
R17	0.9375	Mag. Reconnection	2.3×10^{-6}	63	1.2×10^{43}

“MAD parameter” Jet **mechanical** power


M87
$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$
$d_{\mathrm{shadow}} \approx 40\mu\mathrm{as}$
7 mm
5 mas ~ 0.4 pc ~ 700 R_s
1200 pc
20 cm
0.01 pc ~ 0.1mas
3.5 mm
1.3 mm
40 μas ~ 500 AU
Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)