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

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(he/him)

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@ PCTS

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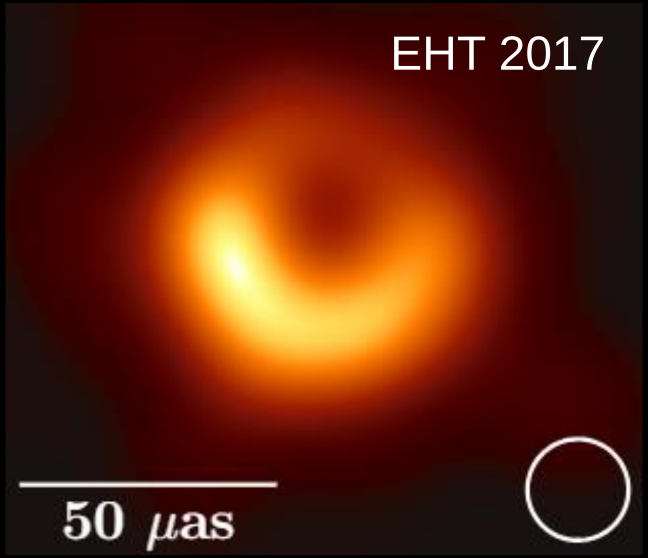
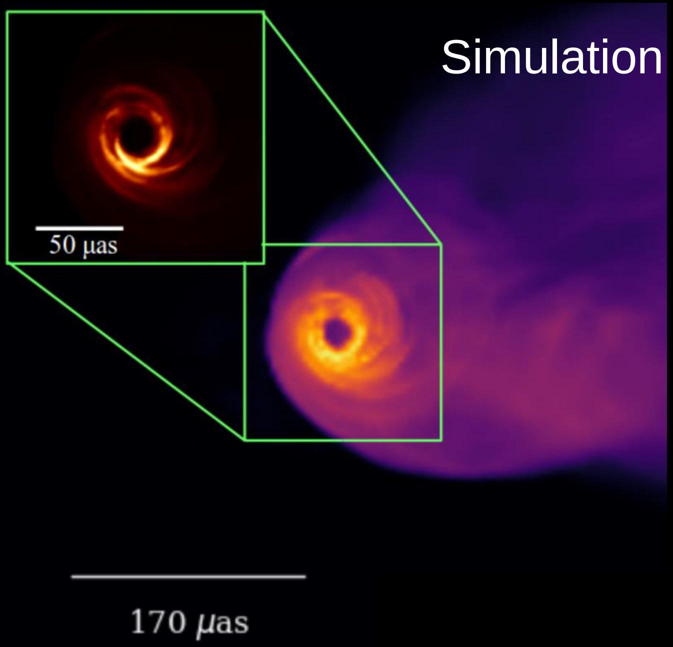




Event Horizon Telescope

The EHT Collaboration

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

Outline

0. EHT intro

1. EHT library simulations / interpreting the image

2. My simulations: connecting to the jet

M87

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

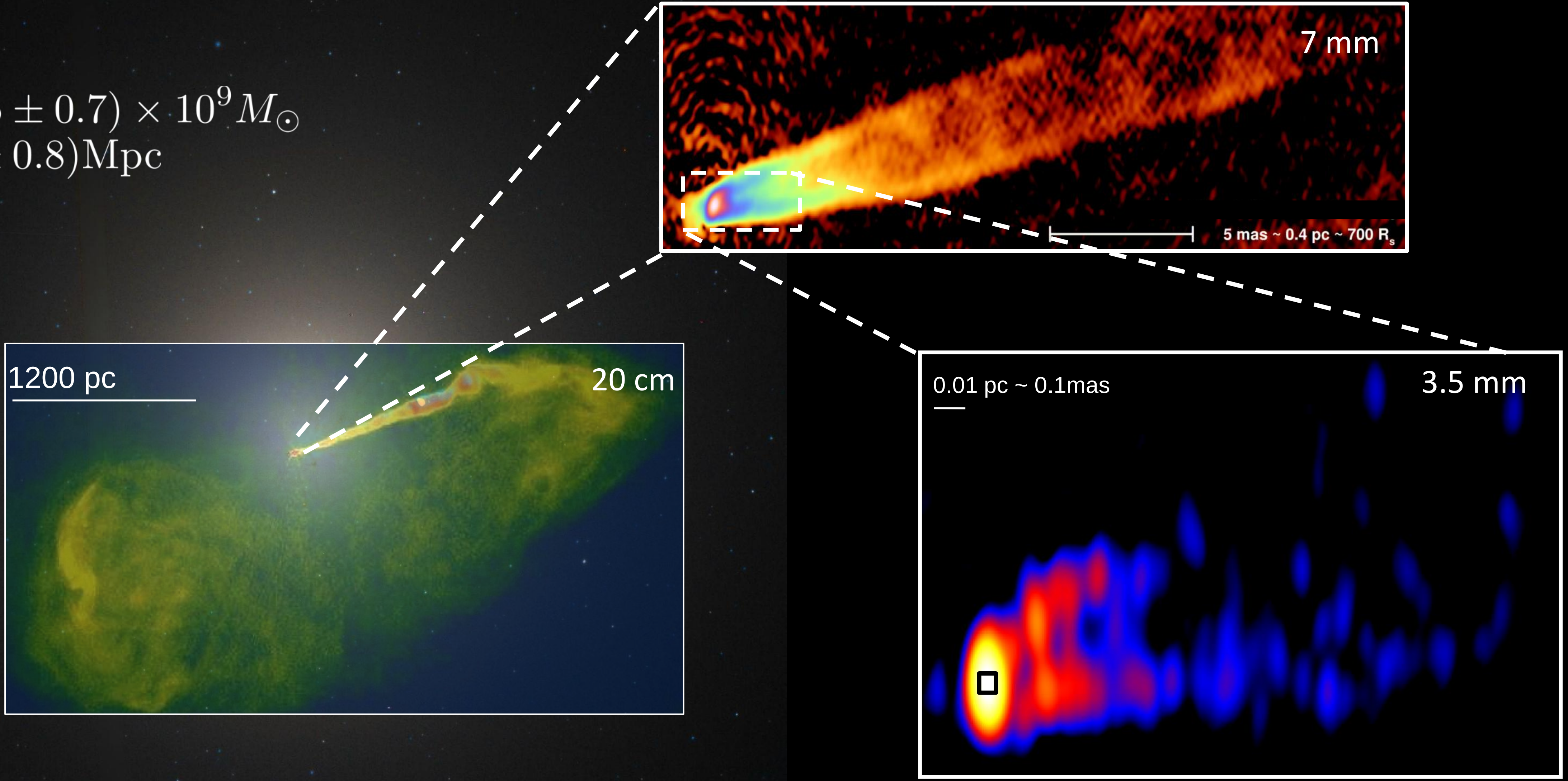
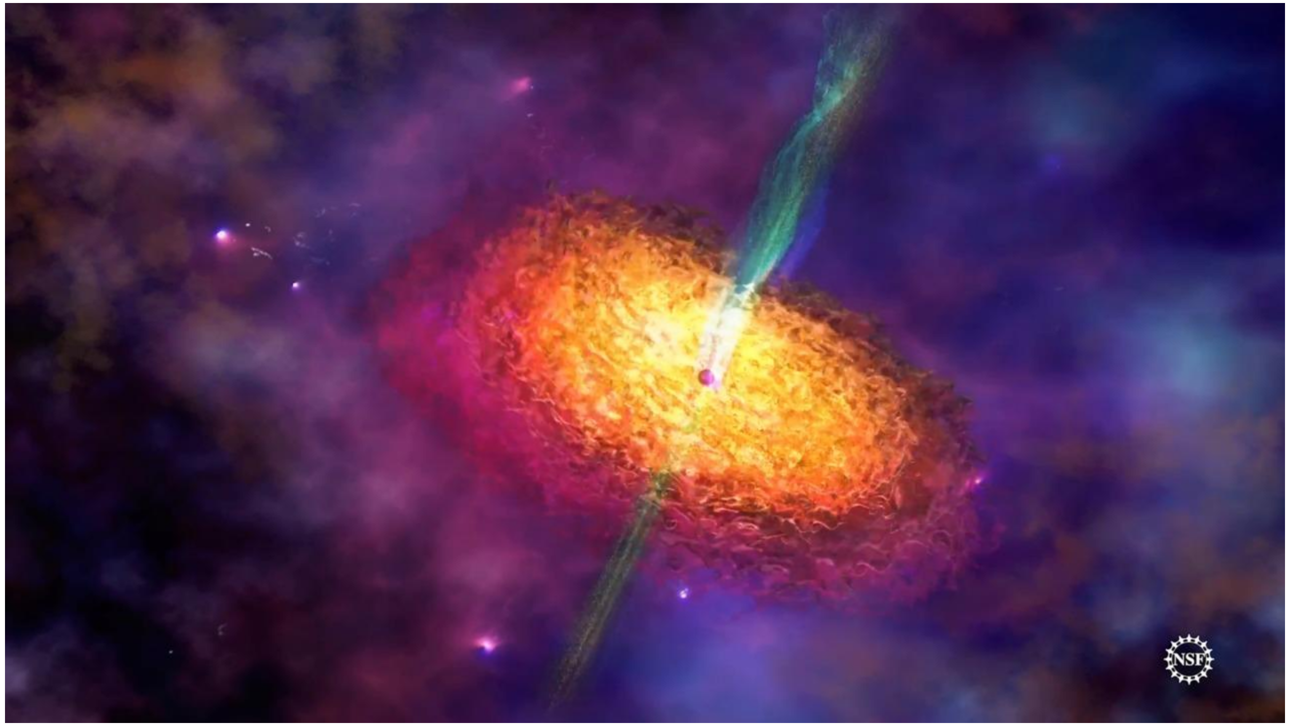


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

At the heart of M87…

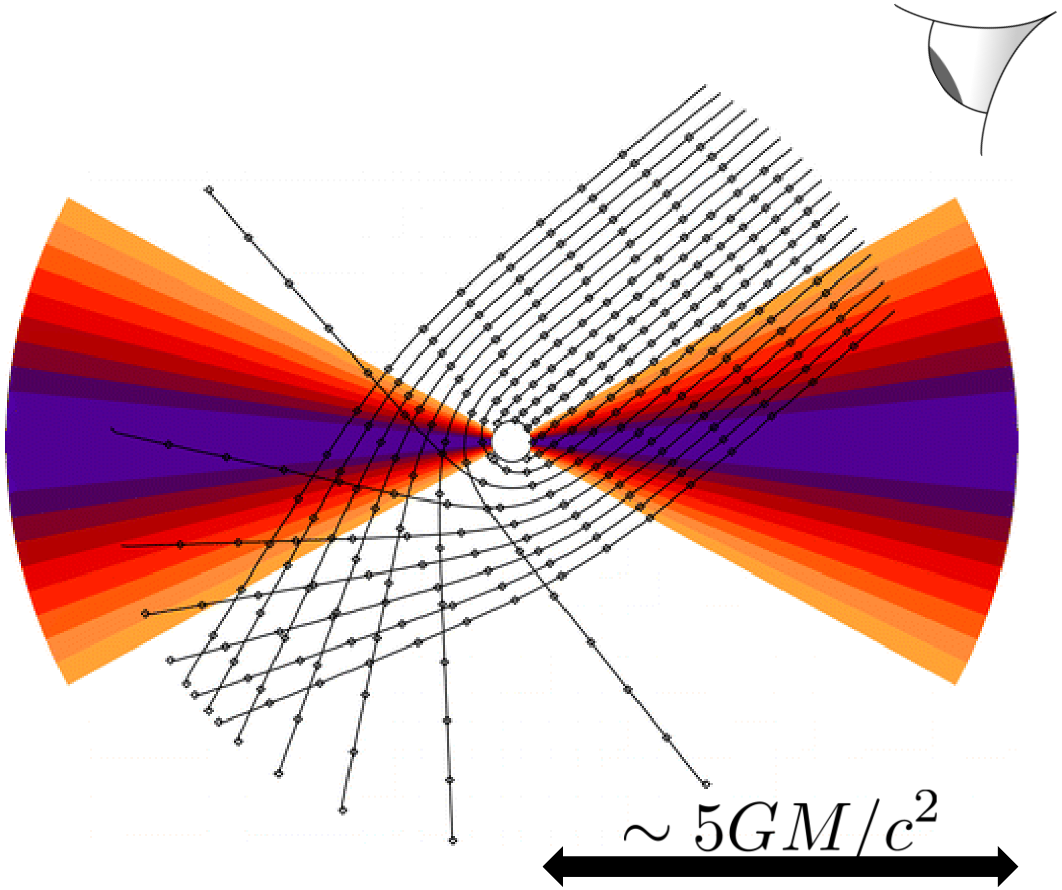
- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Thick accretion flow of hot, ionized plasma ($T \gtrsim 10^{10}\,\mathrm{K}$)
- Launches the powerful relativistic jet ($P_{\rm jet} \geq 10^{42}\ \mathrm{erg\ s^{-1}}$)
  - Extraction of BH spin energy?



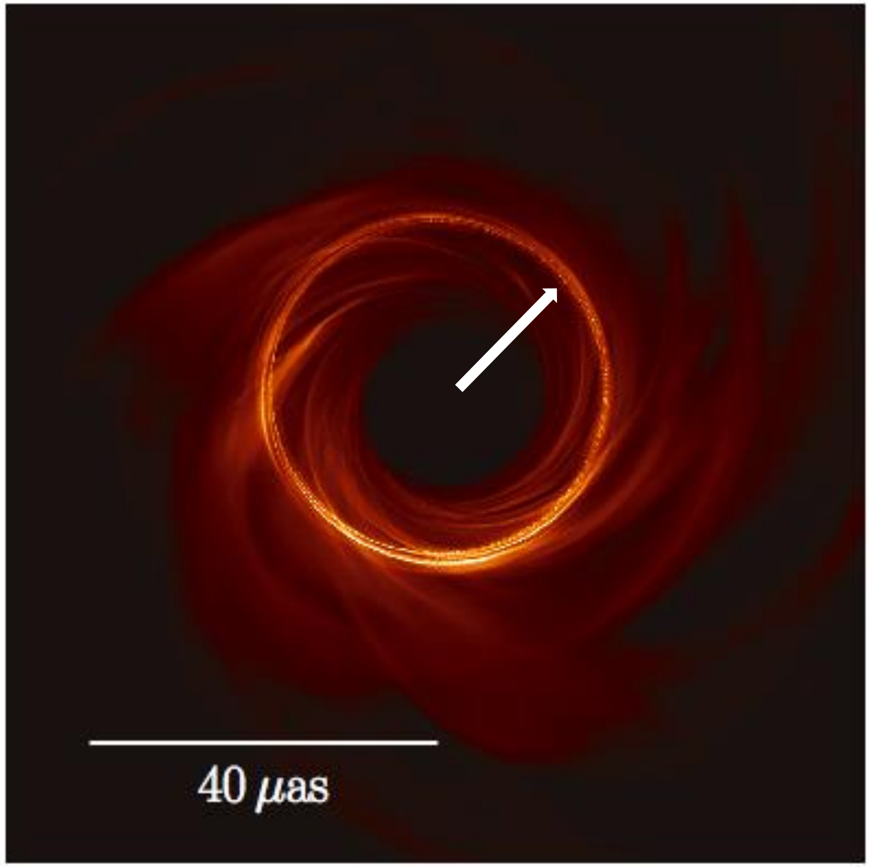
Mass: Gebhardt+ 2011, Walsh+ 2013,
Jet Power: Reynolds+ 1996, Stawarz+ 2006, de Gasperin+ 2012
Simulations: Dexter+2012, Moscibrodzka+2016, Ryan+ 2018

Image credit: National Science Foundation

What does a black hole look like?



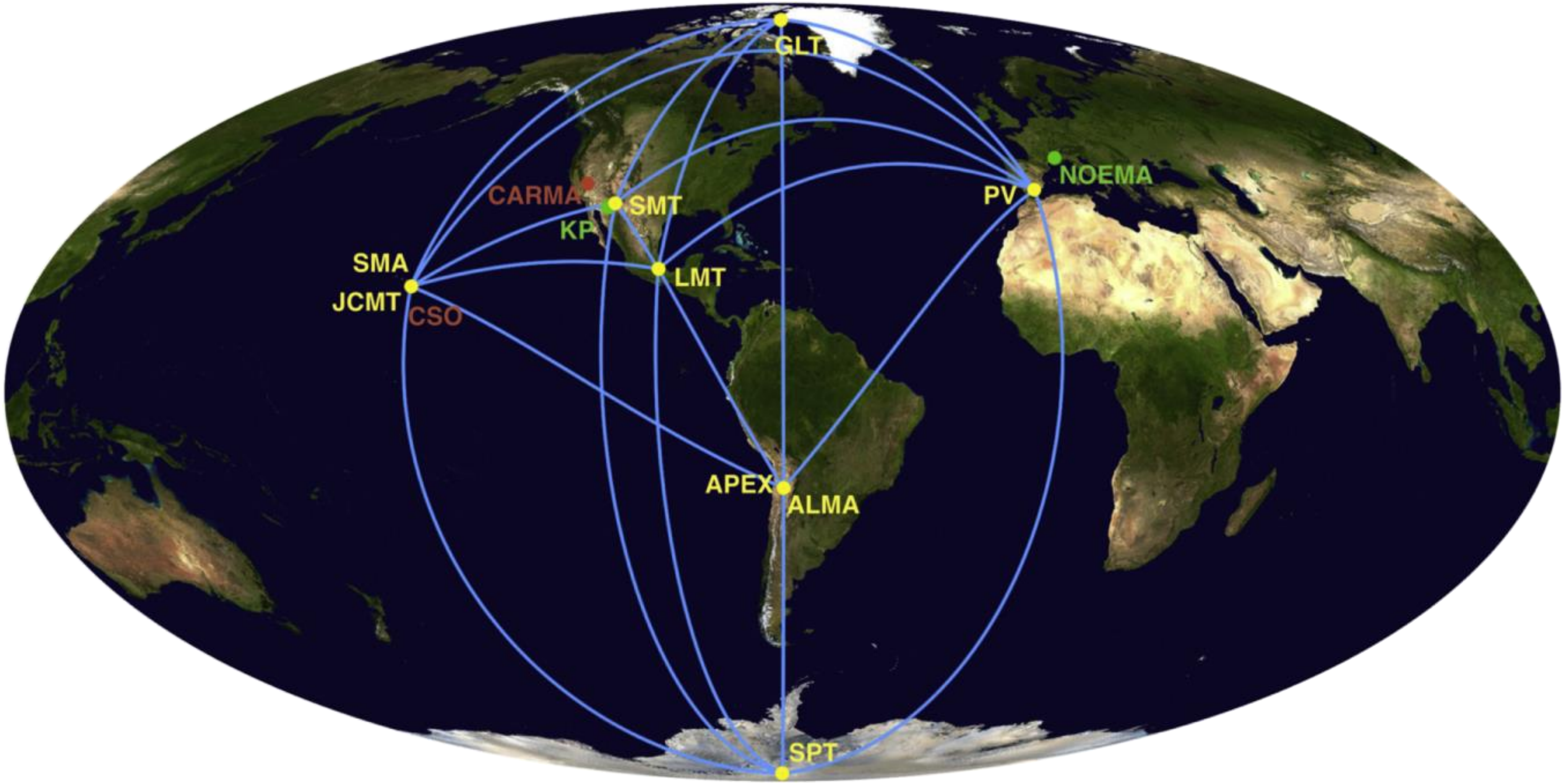
$$r_{\rm shadow} = \sqrt{27}GM/c^2$$



Schnittman+ (2006)

EHTC+ 2019

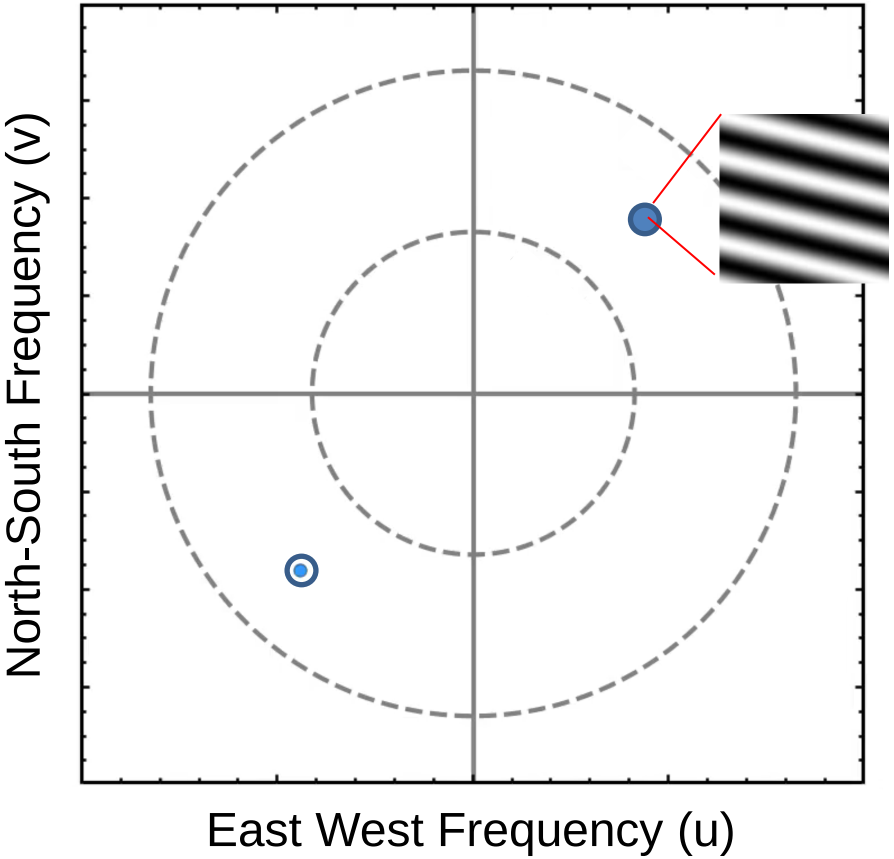
The Event Horizon Telescope



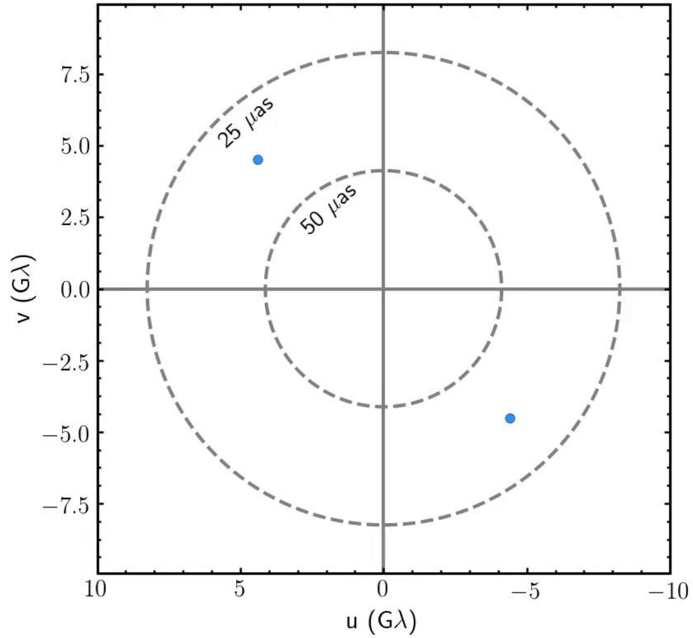
$$\text{Resolution} \approx \frac{\lambda}{d_{\text{Earth}}} \approx \frac{1.3\,\text{mm}}{1.3 \times 10^{10}\,\text{mm}} \approx 20\,\mu\text{as}$$

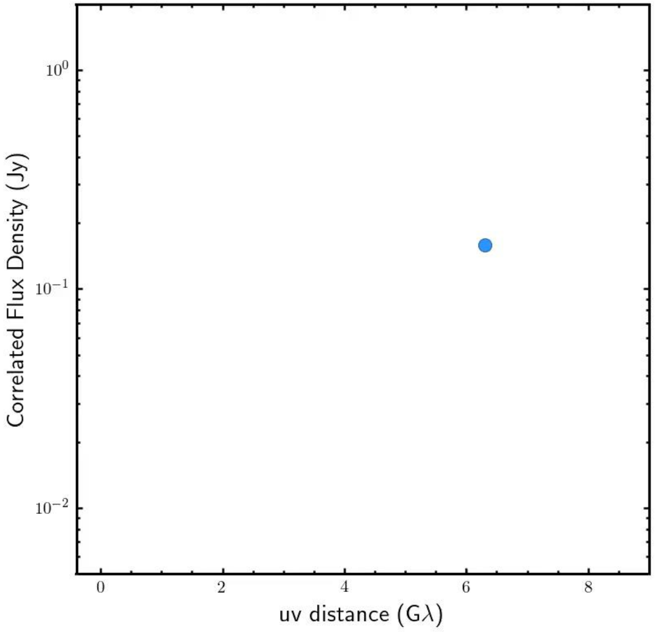
Image Credit:
EHT Collaboration 2019 (Paper II)

Very Long Baseline Interferometry (VLBI)



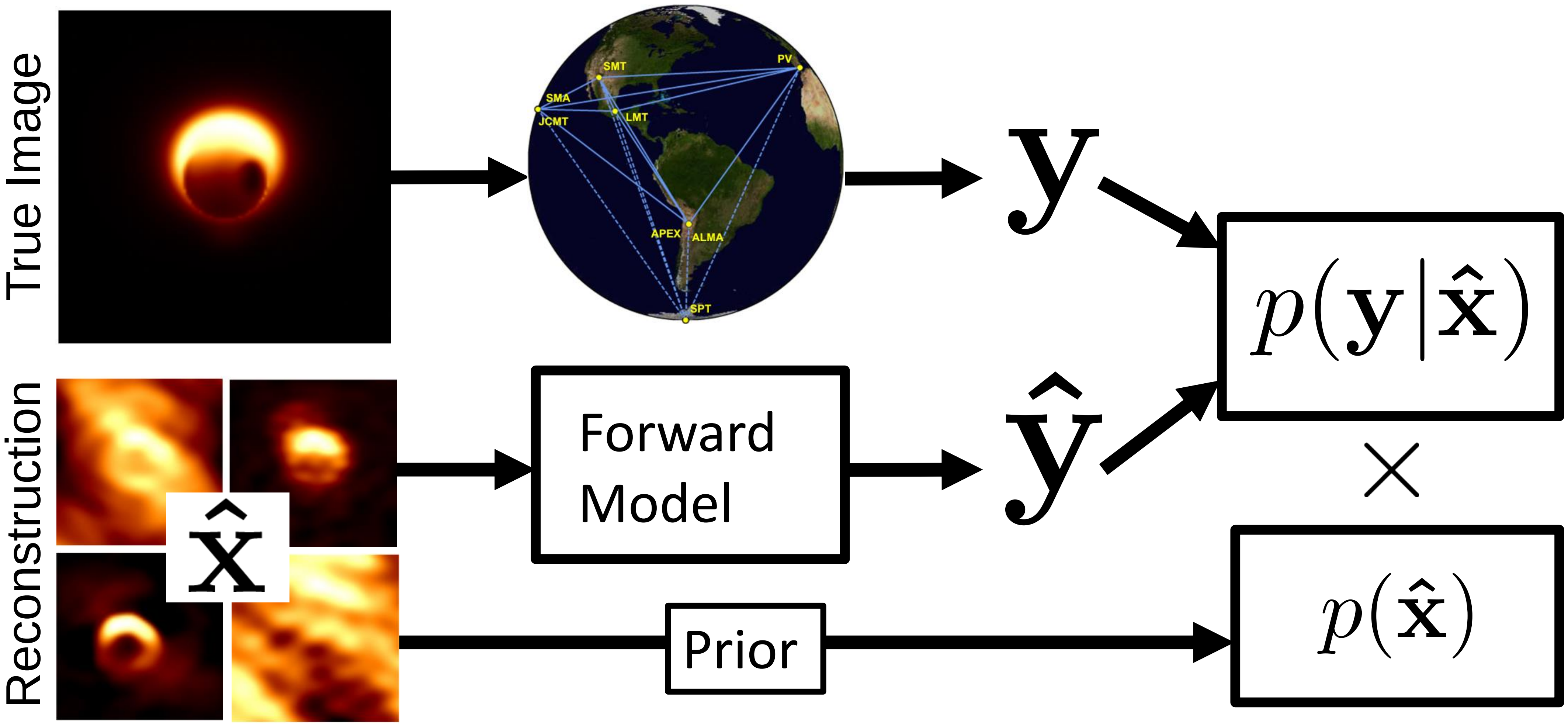
Very Long Baseline Interferometry (VLBI)





Movie Credit: Daniel Palumbo

VLBI Imaging



True Image

Reconstruction

$\hat{\mathbf{x}}$

Forward Model

Prior

$\mathbf{y}$

$\hat{\mathbf{y}}$

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

$\times$

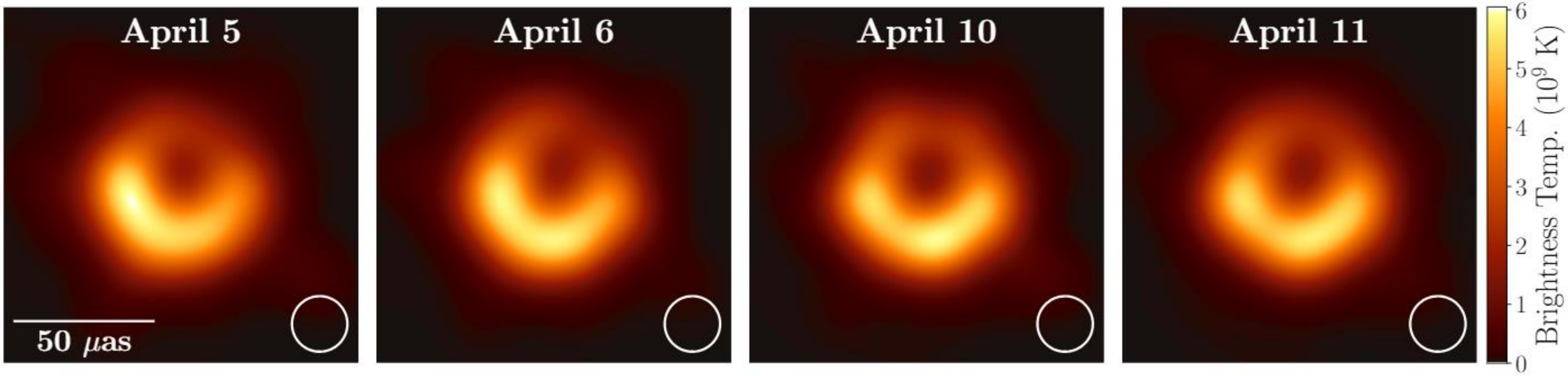
$p(\hat{\mathbf{x}})$

Image Credit: Katie Bouman

Simulation Credit: Avery Broderick

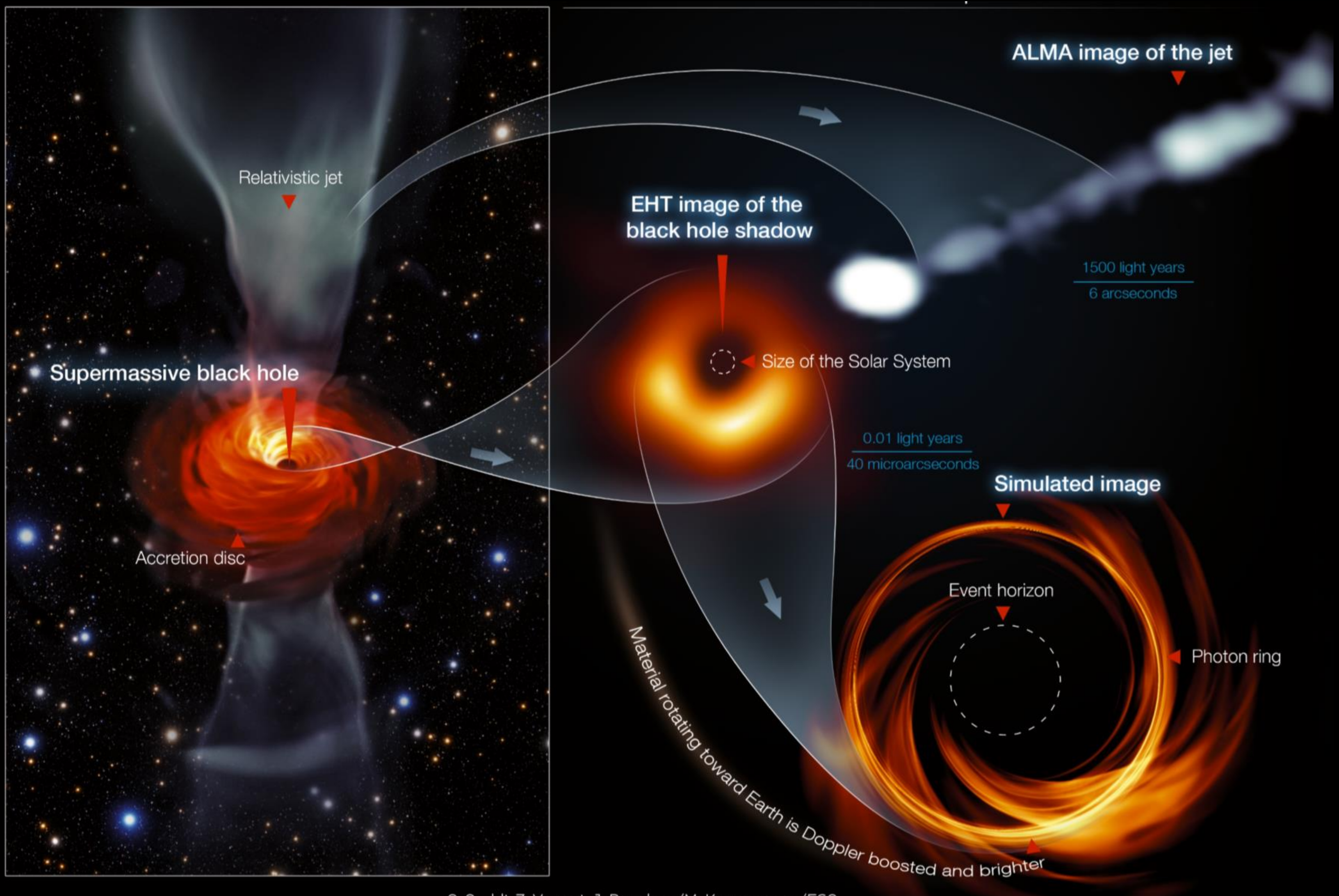
After lots of work….

M87’s black hole across four days in 2017



Consistent structure from night-to-night, **hints of time evolution?**

The EHT images in context

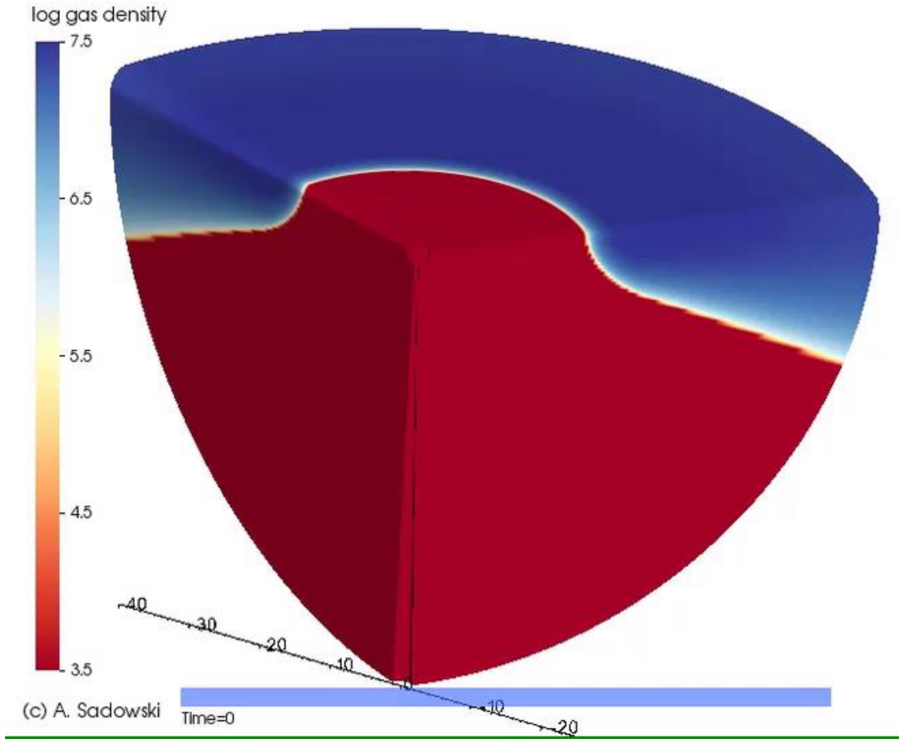


C. Goddi, Z. Younsi, J. Davelaar/M. Kornmesser/ESO

Image Credit: Ciriaco Goddi, Ziri Younsi, Raquel Fraga-Encinas, Jordy Davelaar and ESO

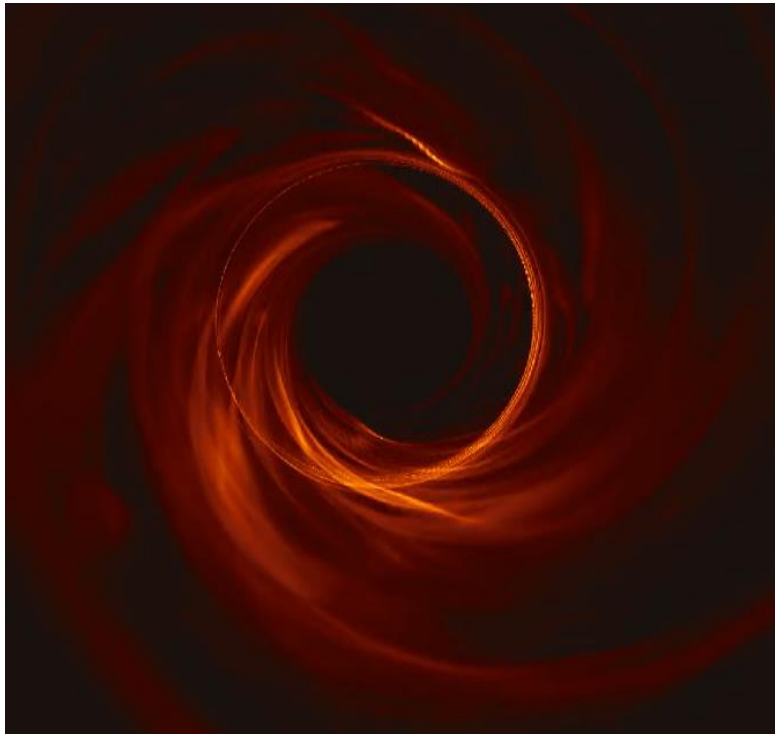
1. How do we interpret EHT images?

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)

What parameters determine the images we see?

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

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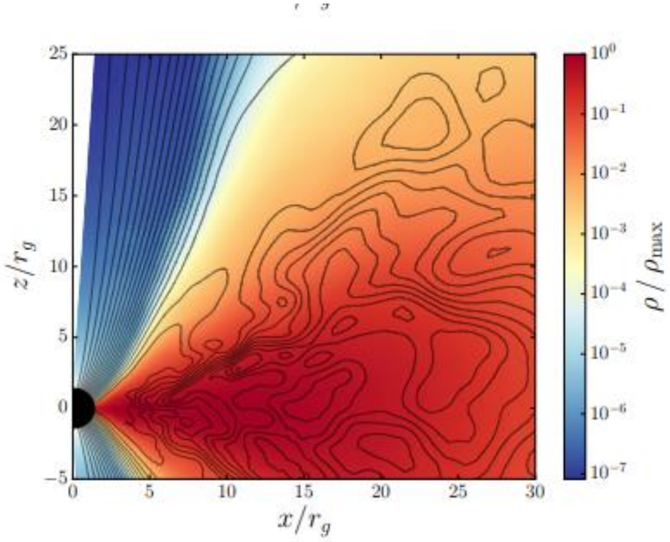
2. (Radiative) Magnetohydrodynamics: $\dot{M}, \Phi_B$
   - - Does the magnetic field arrest accretion?
   - - How does the B-field determine the jet power & shape?

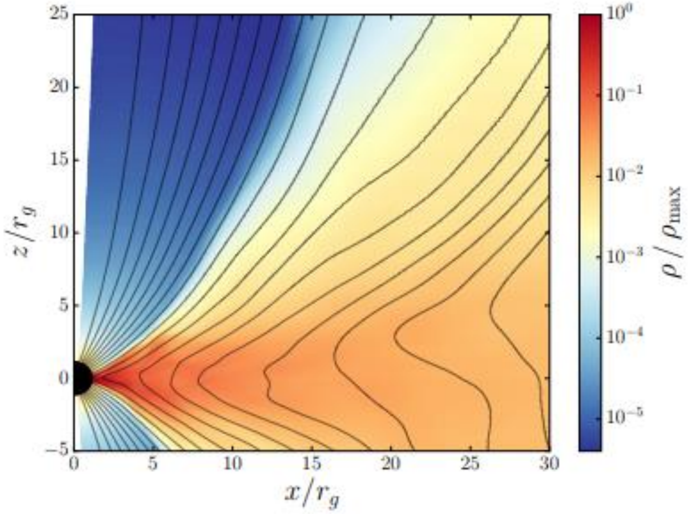
SANE vs MAD

- Two accretion states that depend on the 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

$$\Phi_B/\sqrt{\dot{M}} \approx 50$$

- Blandford-Znajek (1977): Jet is powered by the black hole’s angular momentum:

$$P_{\rm jet} \propto \Phi_B^2 a^2$$

Image credit: Riordan+ 2017

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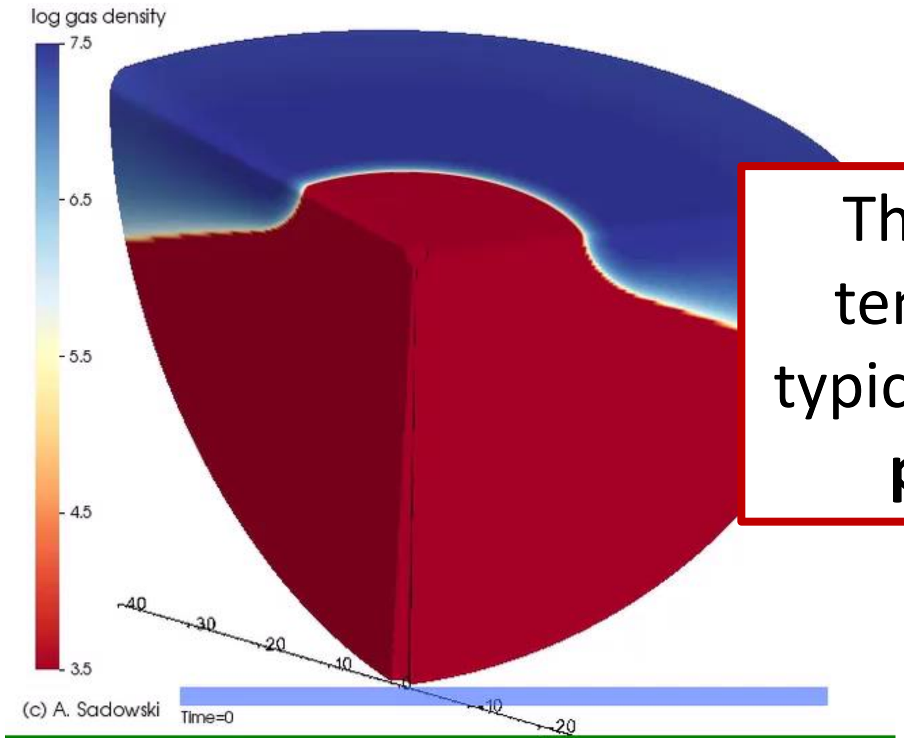
3. **Electron (non)thermodynamics: $T_e, n_e(\gamma)$**
    - **What is the electron temperature?**
    - **What is their distribution function?**

From simulations to observables

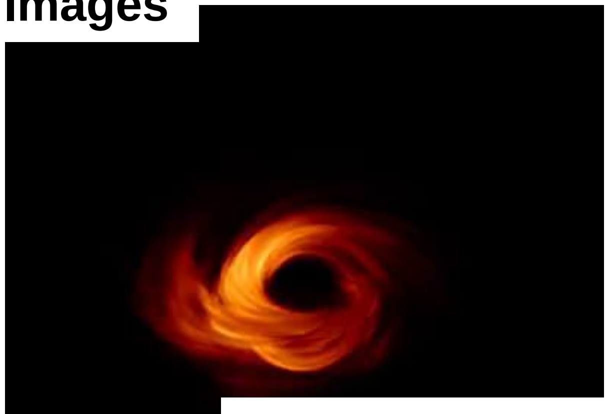


The electron-to-ion temperature ratio is typically set **manually** in **post-processing**

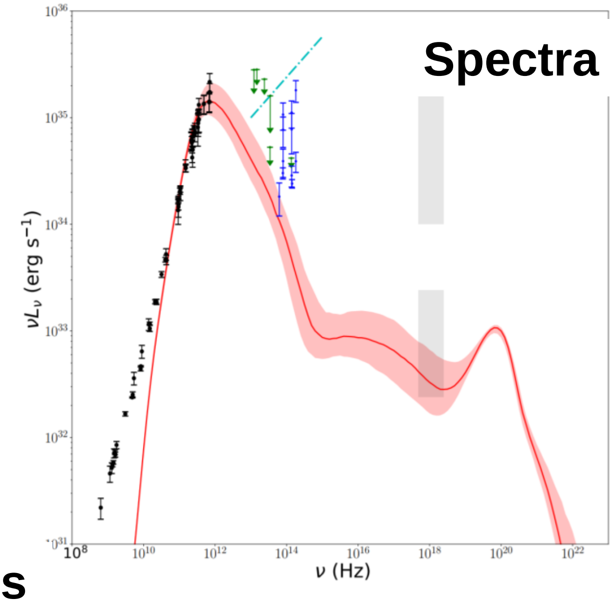
GRMHD Simulations

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

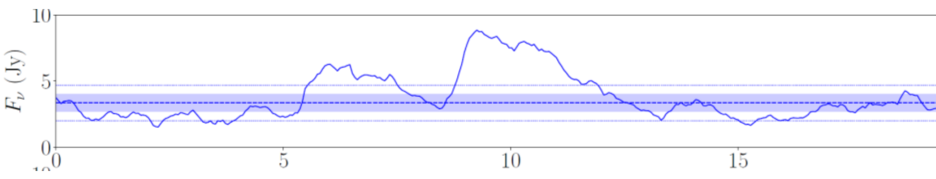
Images



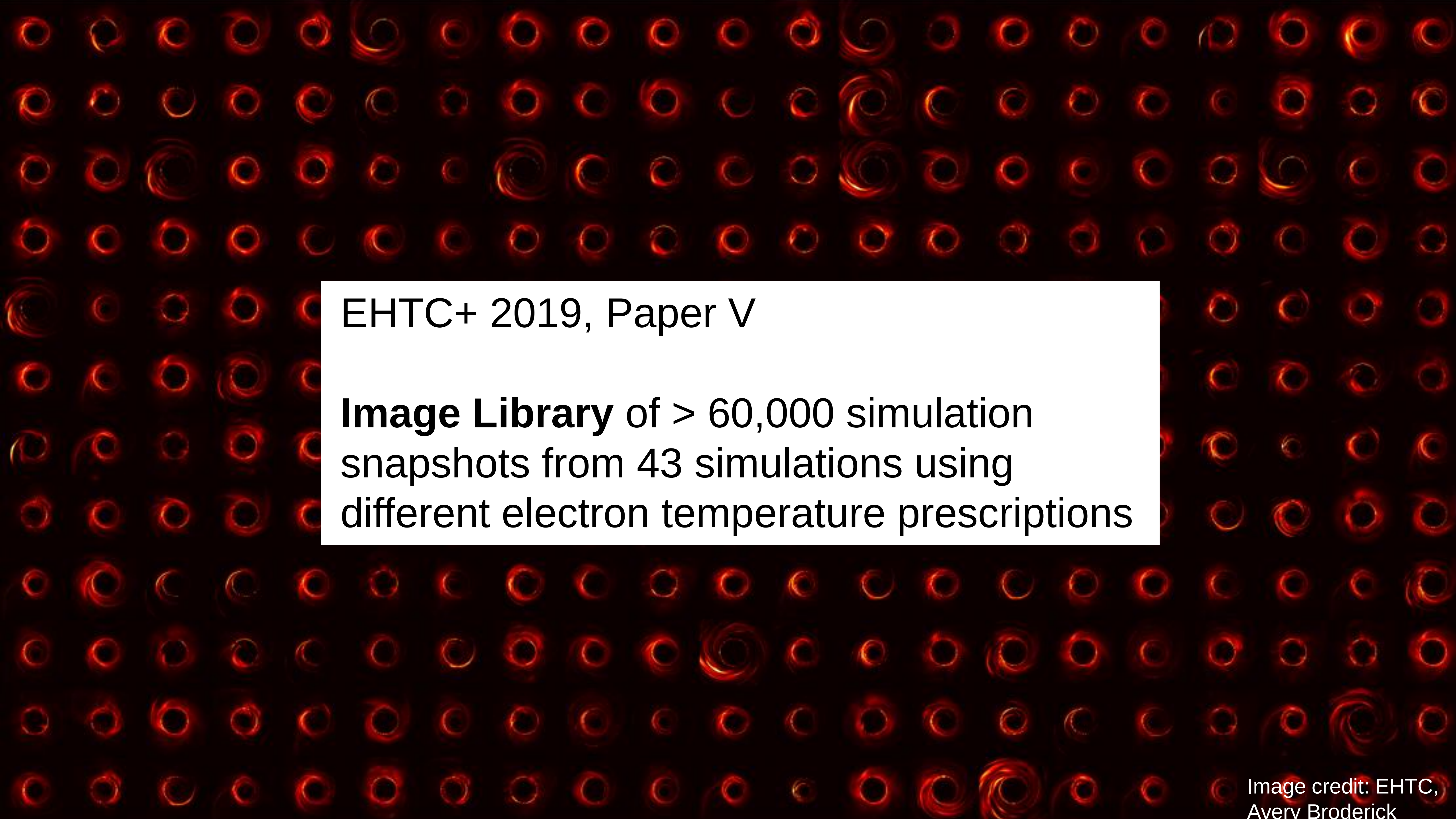
Spectra



Light Curves



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



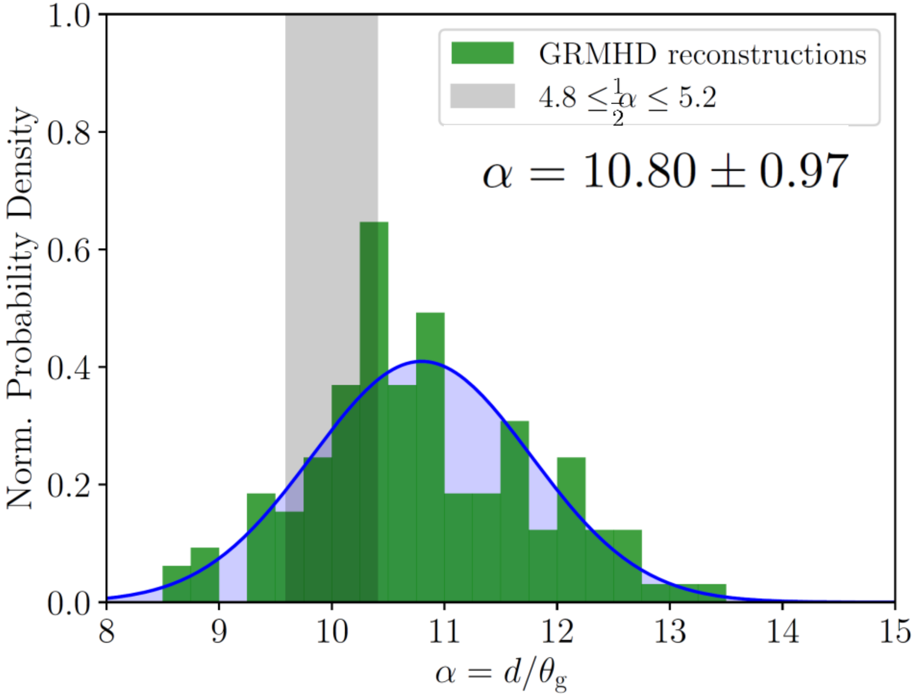
EHTC+ 2019, Paper V

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

Image credit: EHTC,
Avery Broderick

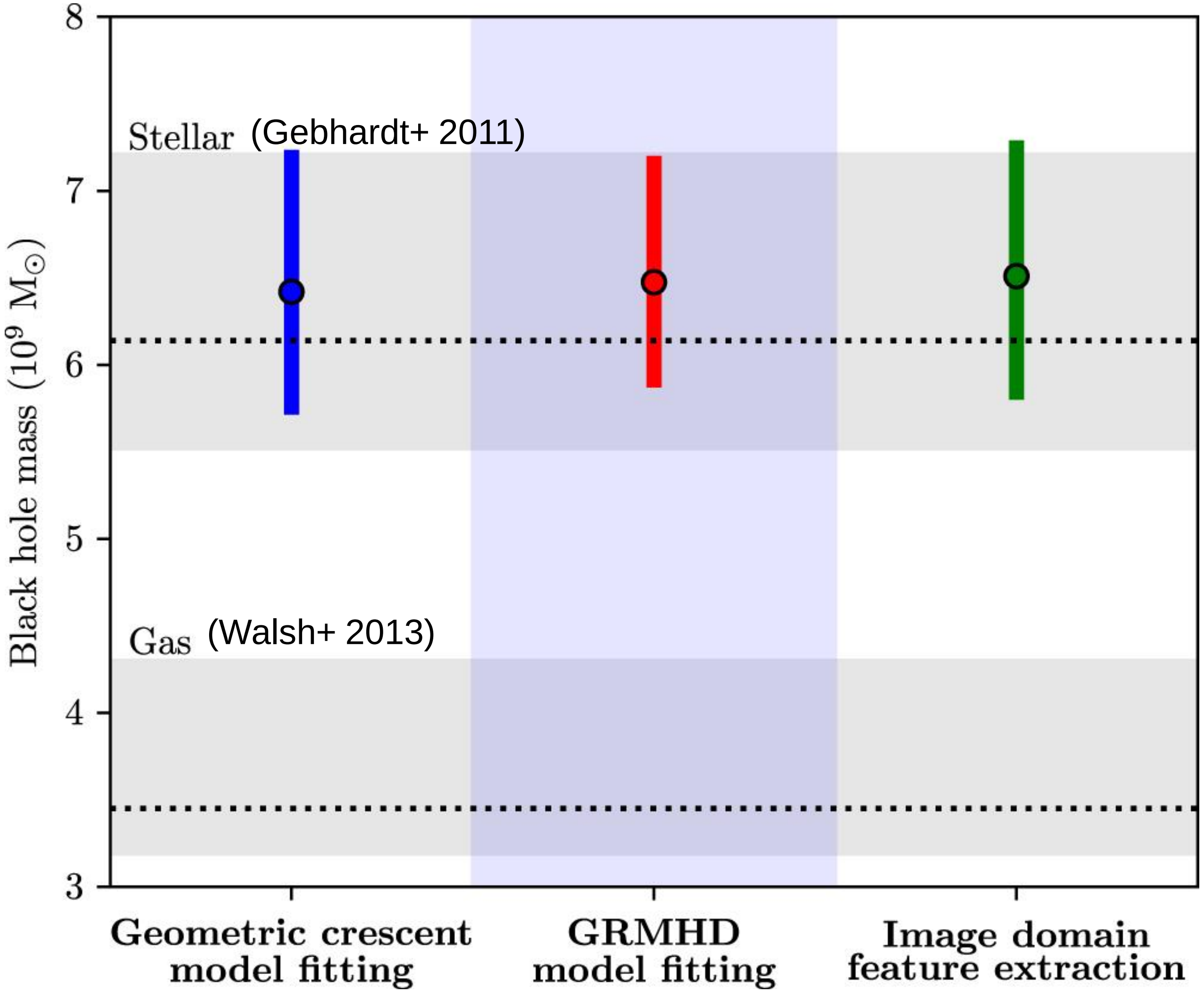
Weighing a black hole

- Emission may not be exactly coincident with the photon ring!
- 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 (including many that fail other tests!)



Weighing a black hole

Paper VI Results from three independent methods

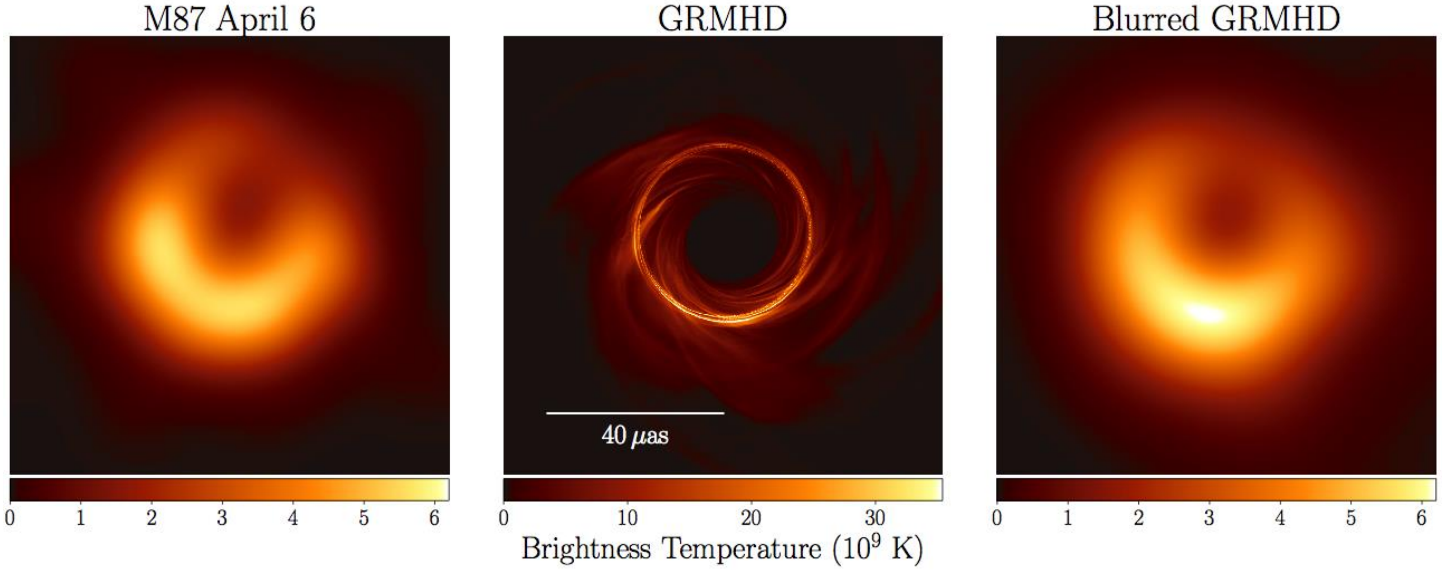


$$M = (6.5 \pm 0.7) \times 10^9\, M_\odot$$

Image Credit:
EHT Collaboration 2019 (Paper VI)

Model Selection

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



EHTC+ Paper V, 2019

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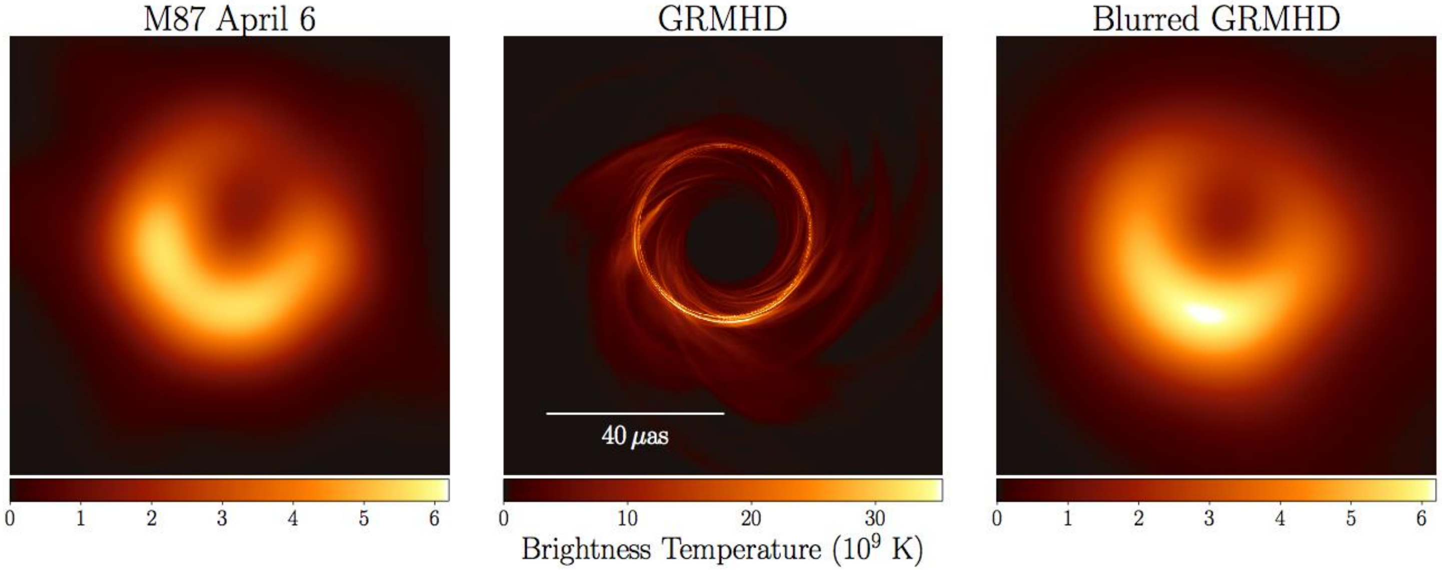
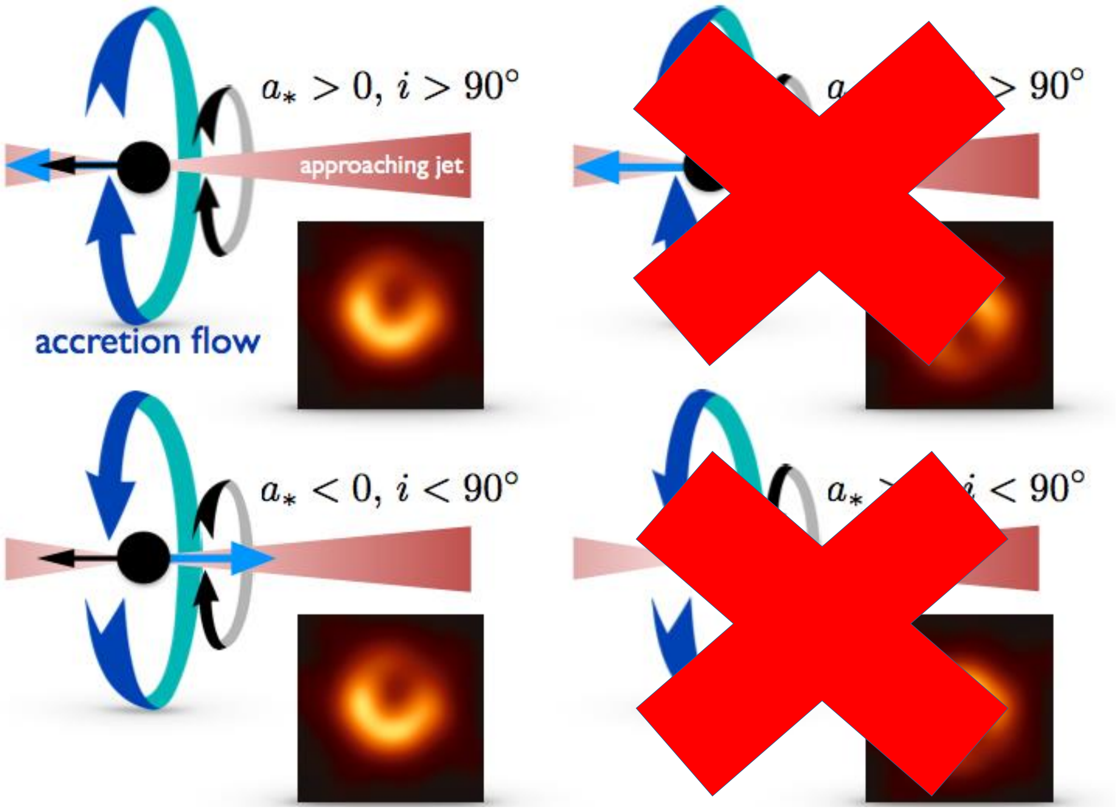


- The **jet power constraint** ($\geq 10^{42}$ erg/sec) rejects all spin 0 models
  SANE models with |a| < 0.5 are rejected.
  Most |a| > 0 MAD models are acceptable.

EHTC+ Paper V, 2019

Ring Asymmetry and Black Hole Spin

It is the **BH angular momentum**, not the **disk angular momentum** that determines the image orientation

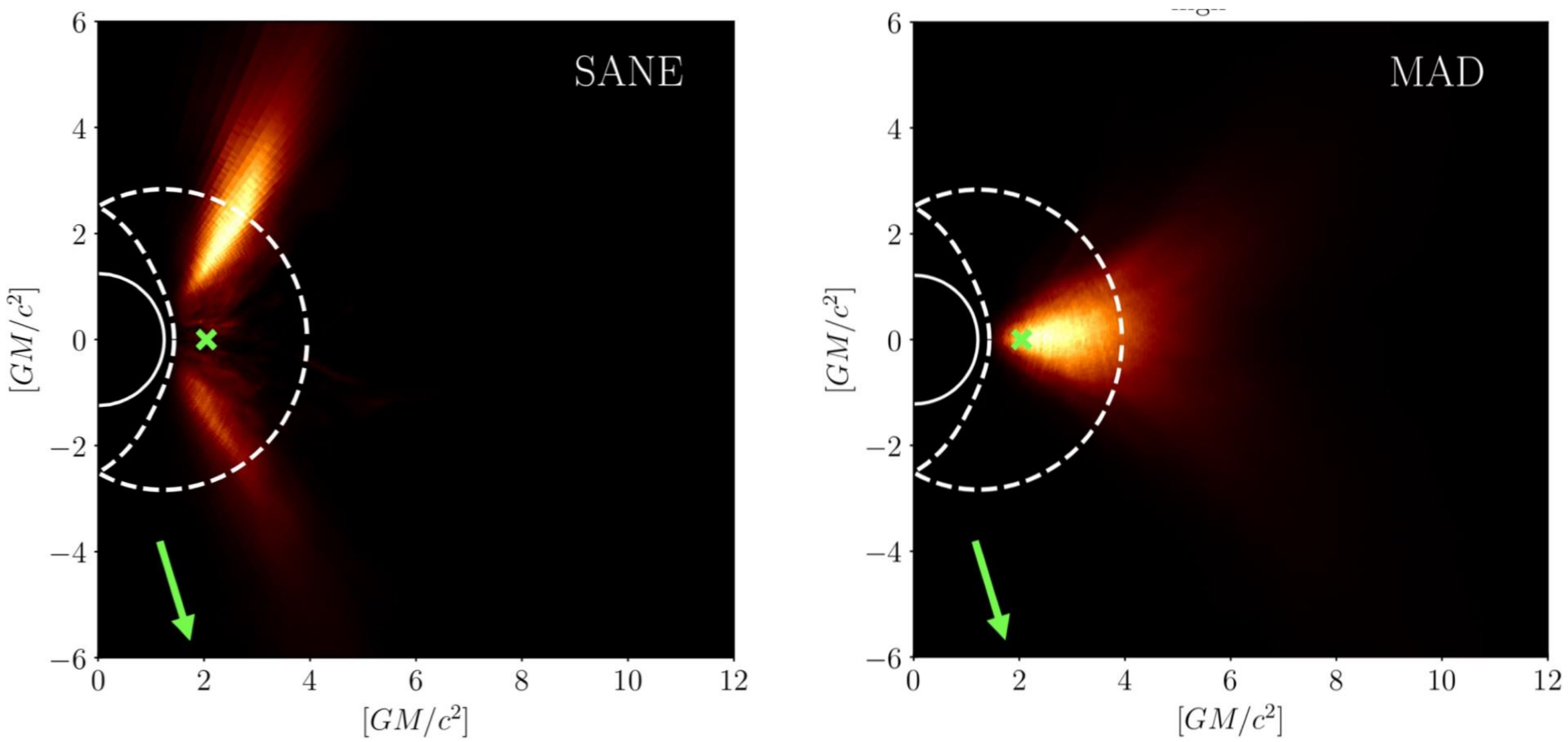


BH spin-away (clockwise rotation) models are strongly favored

EHTC+ 2019, Paper V

Where does the emission come from?

In all surviving models emission region is within ~5 gravitational radii of the black hole



Polarization can distinguish between these scenarios!

EHTC+ 2019, Paper V

2. Going beyond EHT library simulations

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?

M87

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

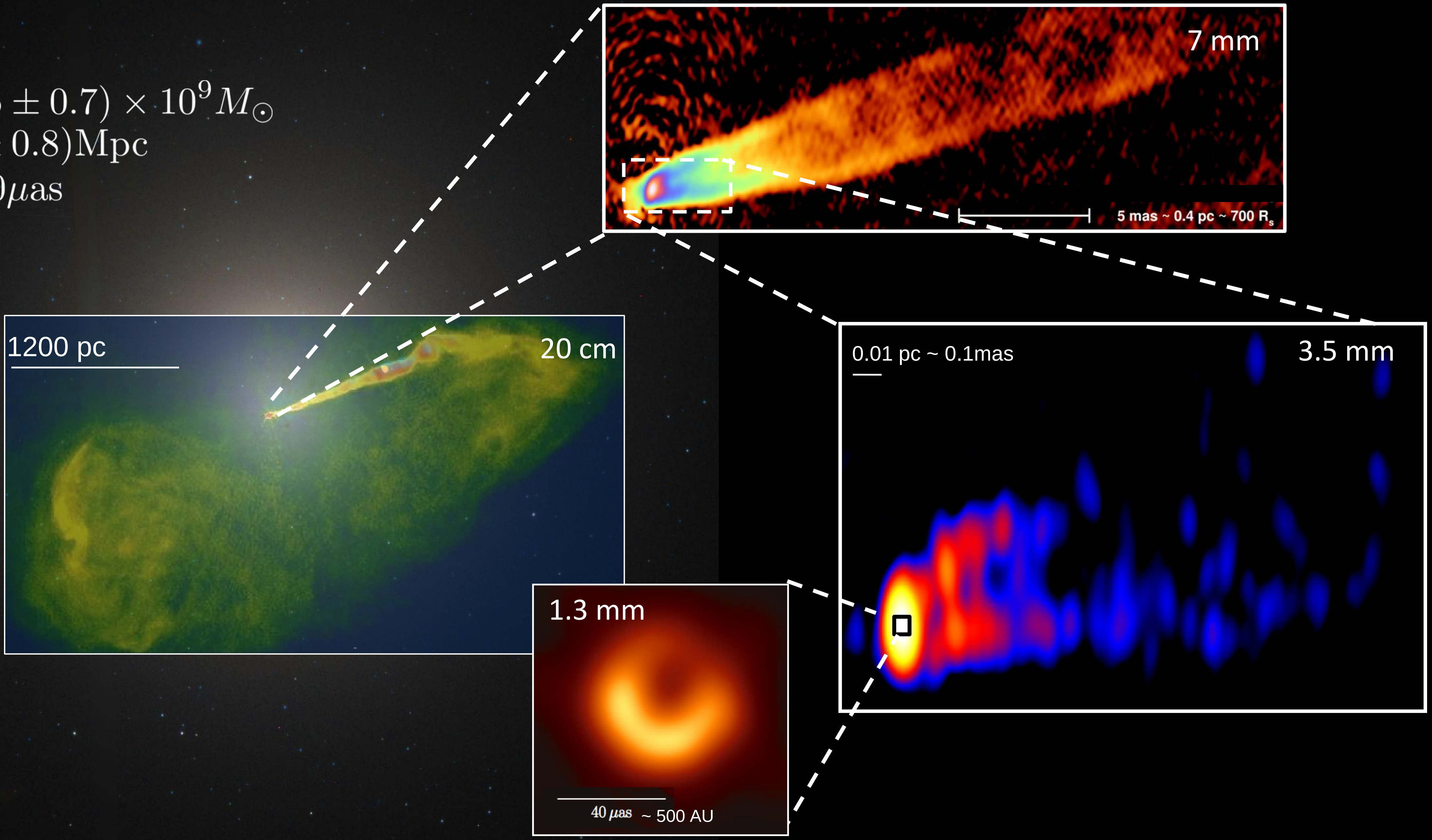


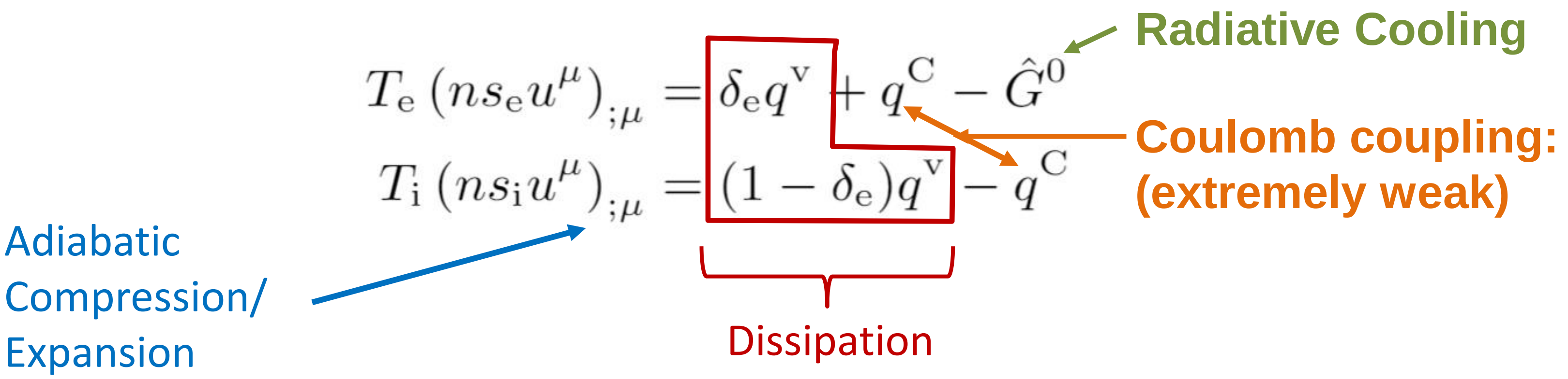
Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

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 covariant 1st law of thermodynamics:



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

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

Radiative Cooling

Coulomb coupling:
(extremely weak)

Adiabatic
Compression/
Expansion

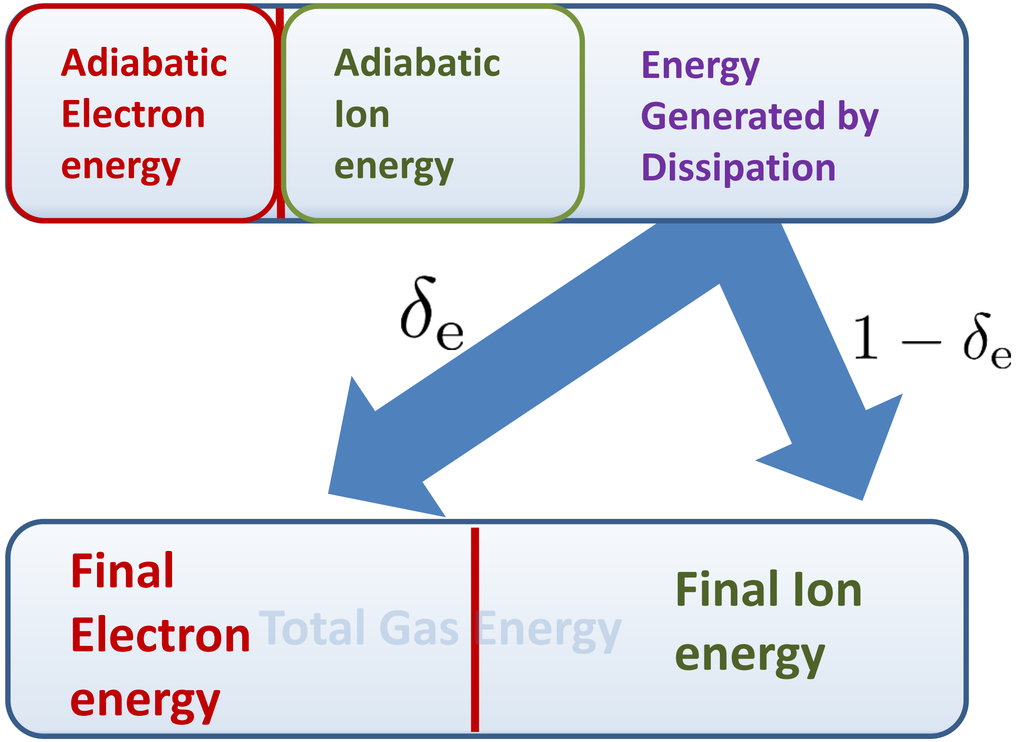
Dissipation

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

Plasma uncertainties: 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.



Exploring Sub-grid Heating Prescriptions

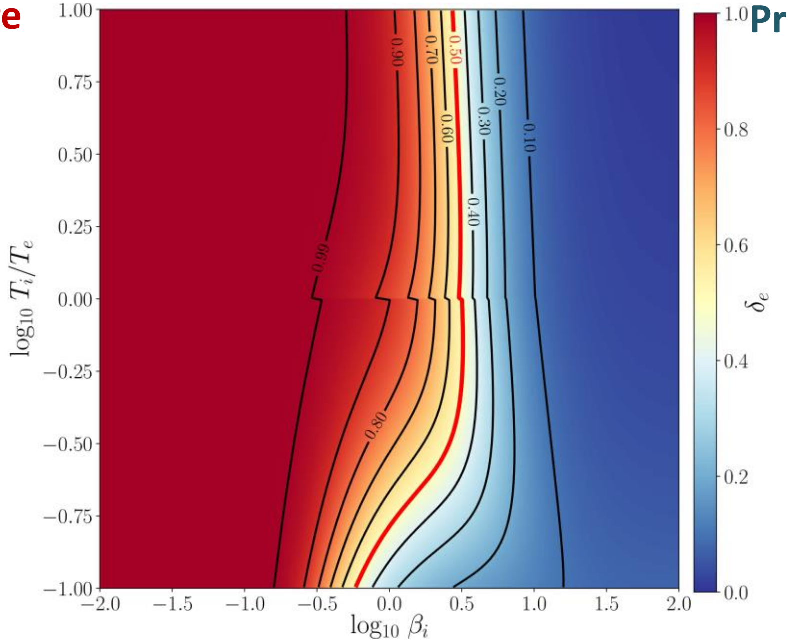
Turbulent Dissipation (Howes 2010)

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

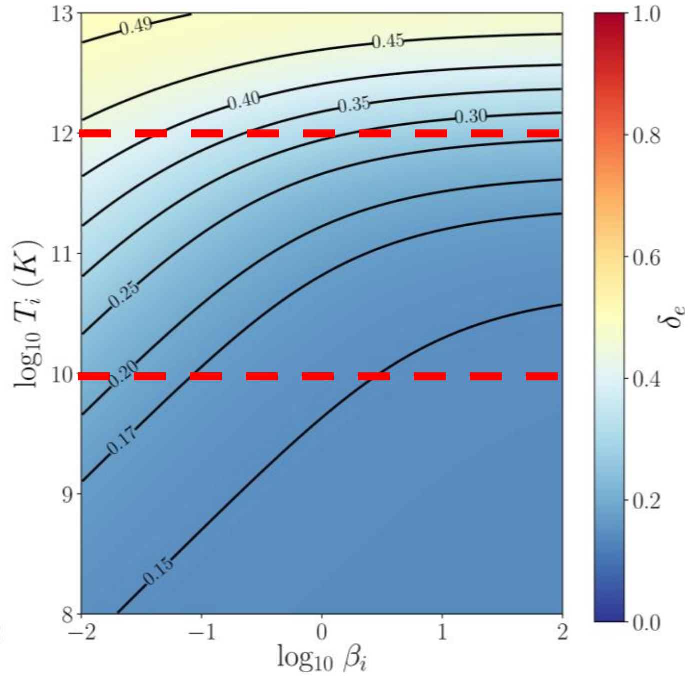
Magnetic Reconnection (Rowan+ 2017)

- 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



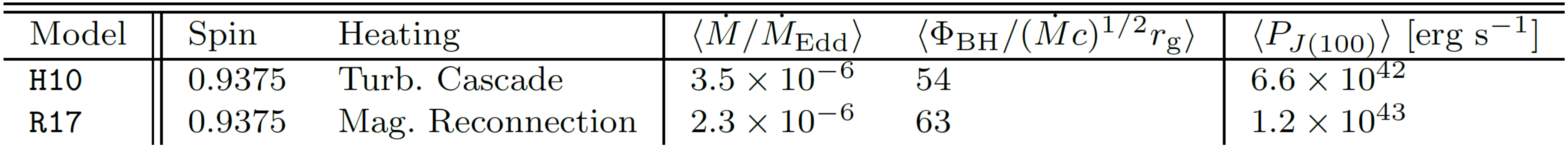
Almost all energy to electrons ⟷ Almost all energy to ions



Relatively flat δ_e over large range of temperature, beta.

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

Two-temperature MAD simulations of M87



Model	Spin	Heating	$\langle \dot{M}/\dot{M}_{\rm Edd} \rangle$	$\langle \Phi_{\rm BH}/(\dot{M}c)^{1/2} r_{\rm g} \rangle$	$\langle P_{J(100)} \rangle$ [erg s^{-1}]
`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}

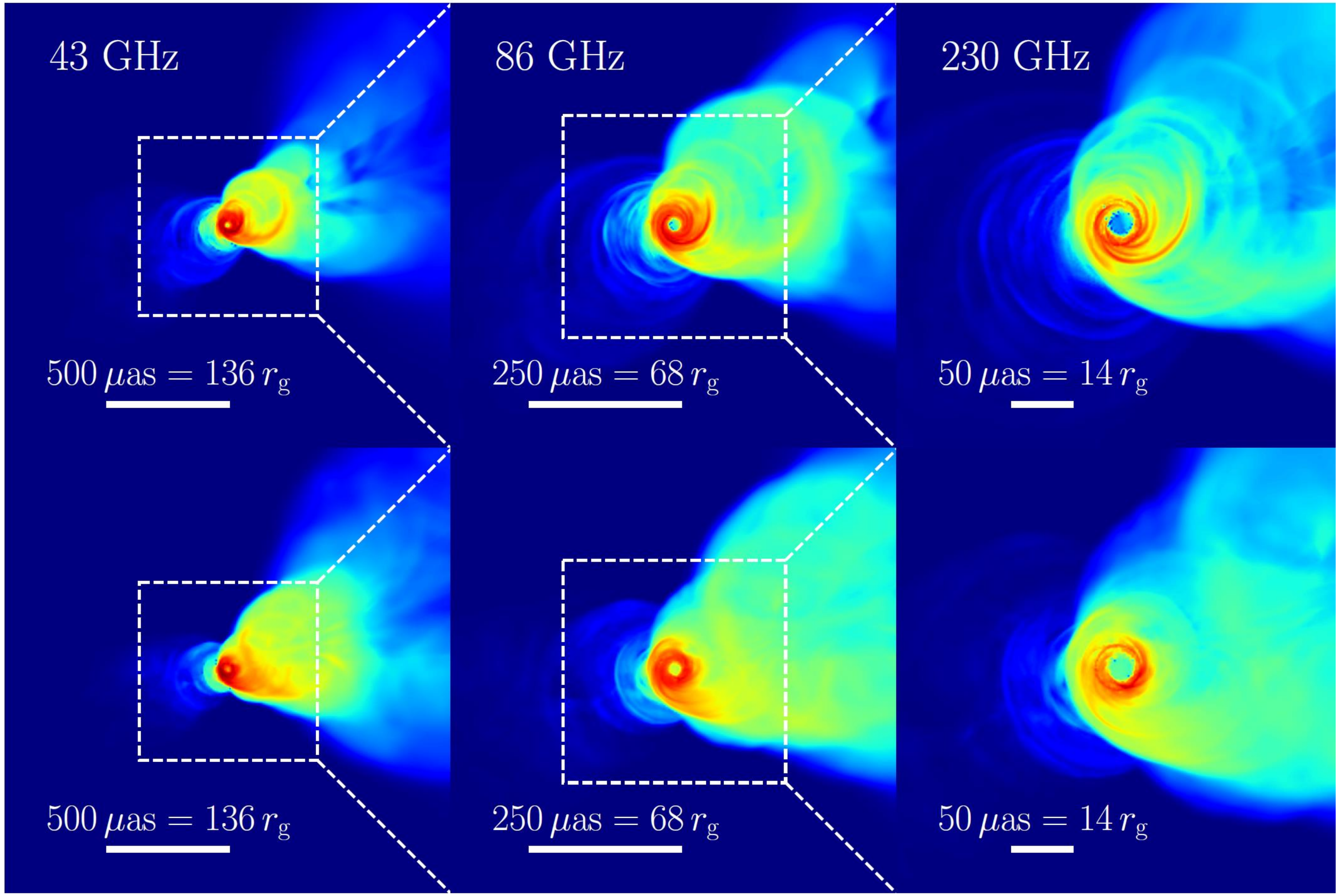
“MAD parameter”

Jet **mechanical** power

- Both simulations are MAD.
- Density is scaled to match 0.98 Jy at 230 GHz.
- The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s.

(Doeleman+ 12, Reynolds+ 1996, Stawartz+ 2006)

M87 Jets at millimeter wavelengths



Turbulent
Heating

Reconnection
Heating

Inclination angle
(down from pole)

17°

Disk/Jet rotation
sense

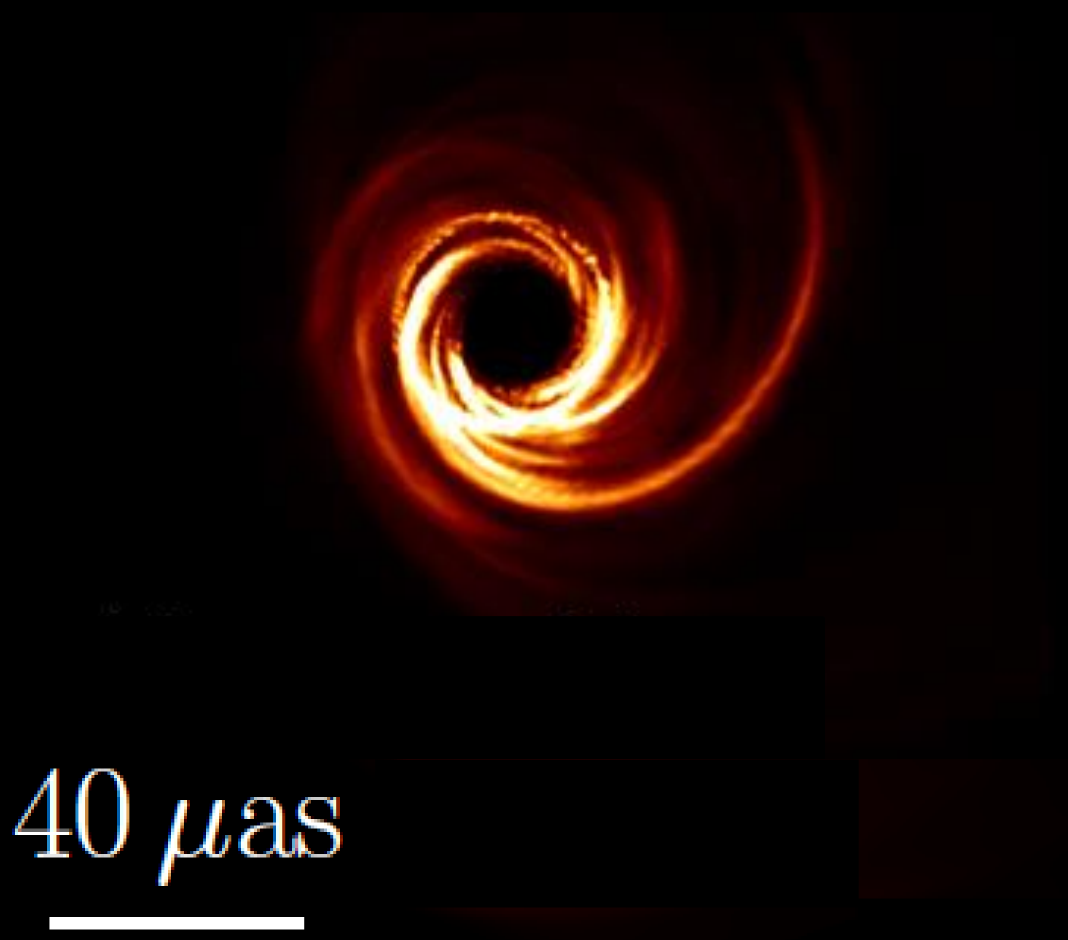
↻

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

Image Credit: Chael+ 2019

230 GHz Images

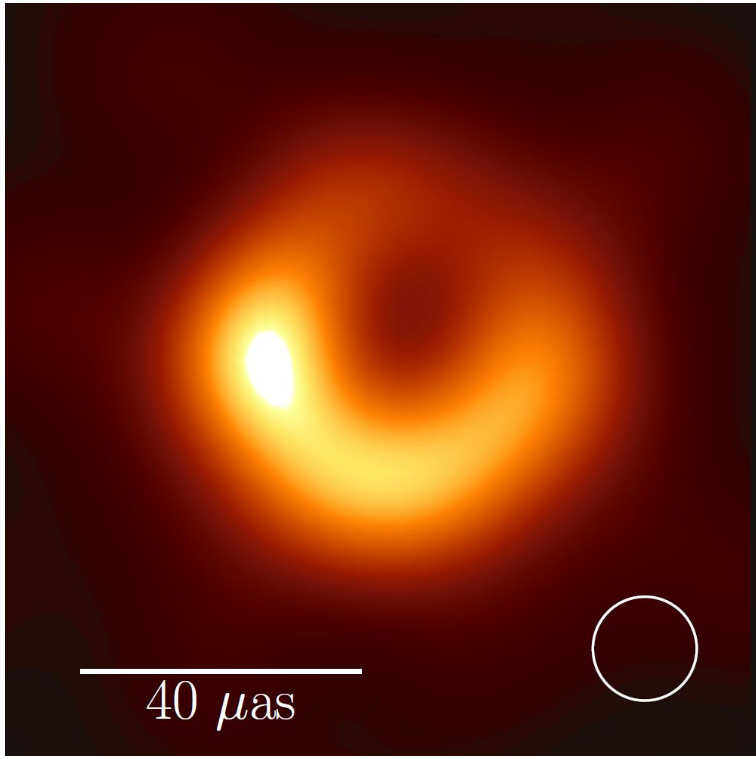
Turbulent Heating



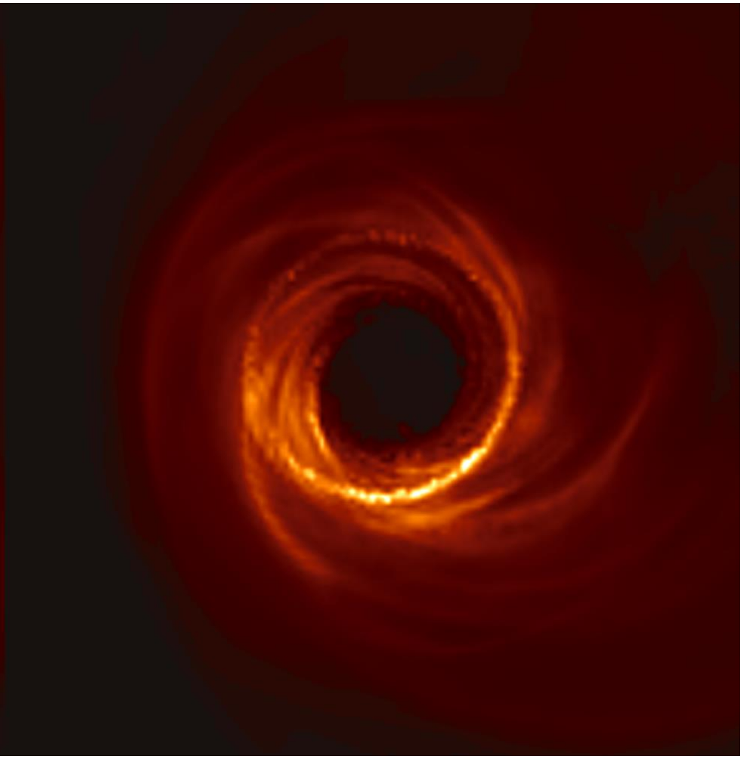
Reconnection Heating

Simulations and Images

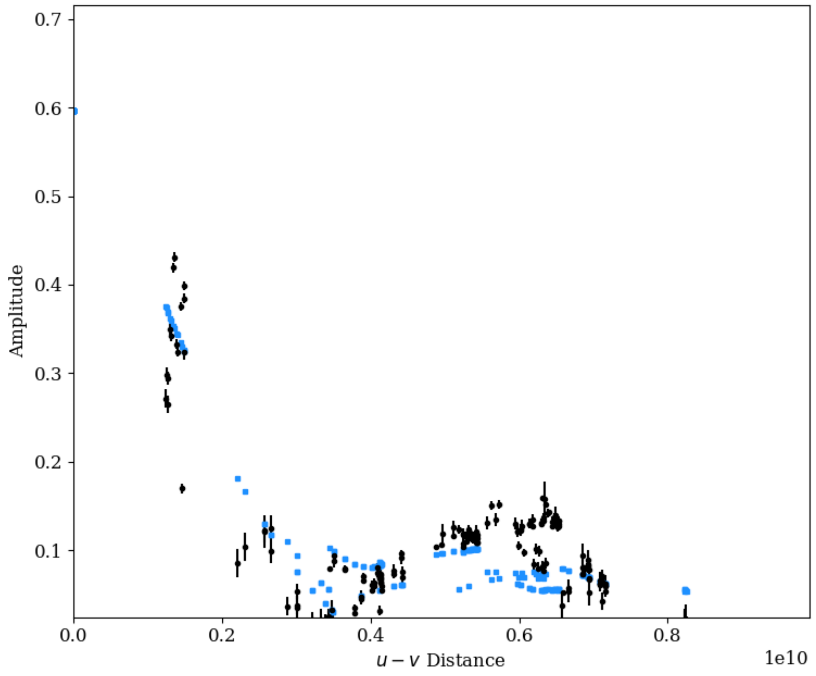
EHT 2017 image



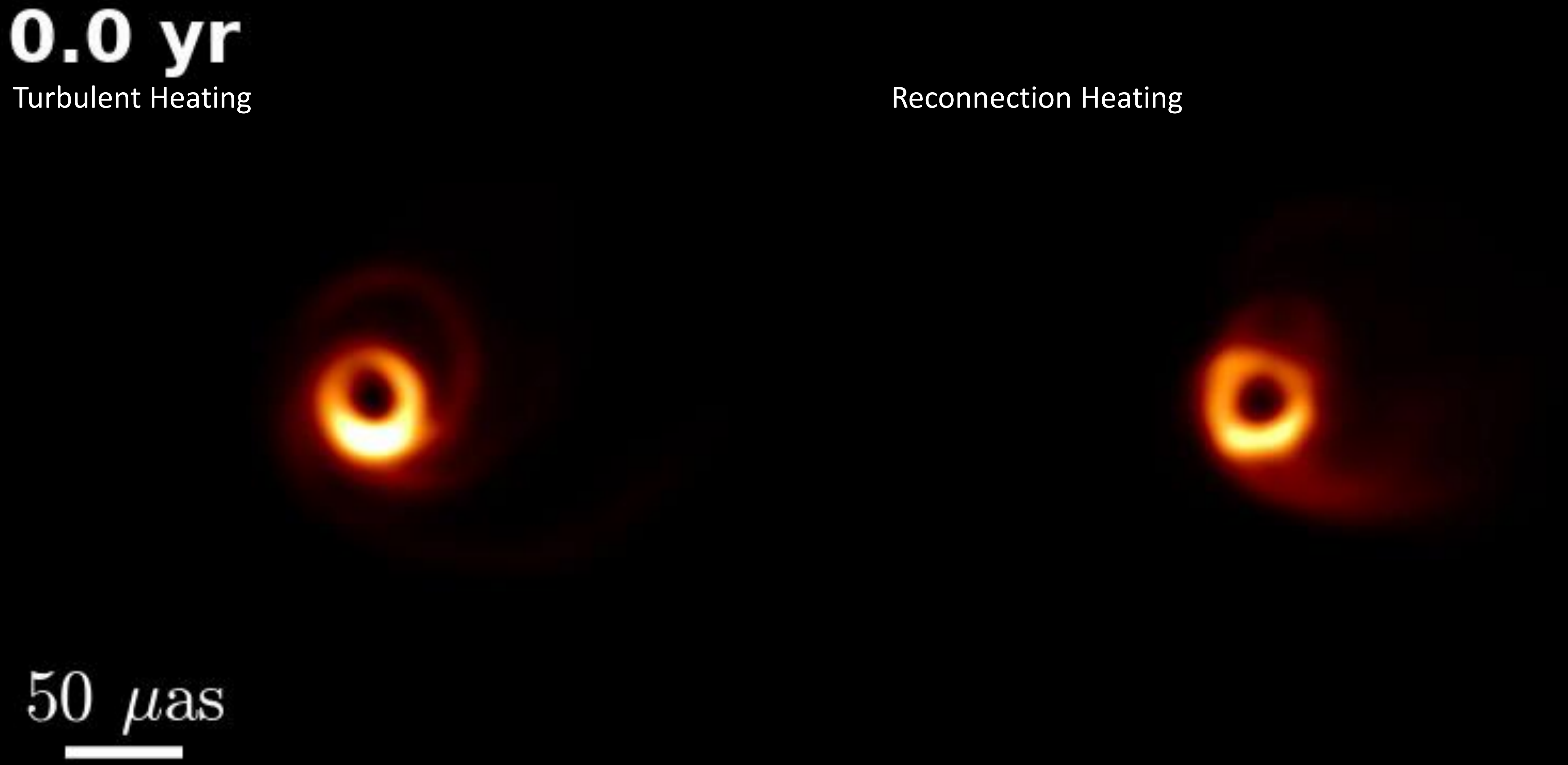
Simulated image
from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes



230 GHz Images & variability

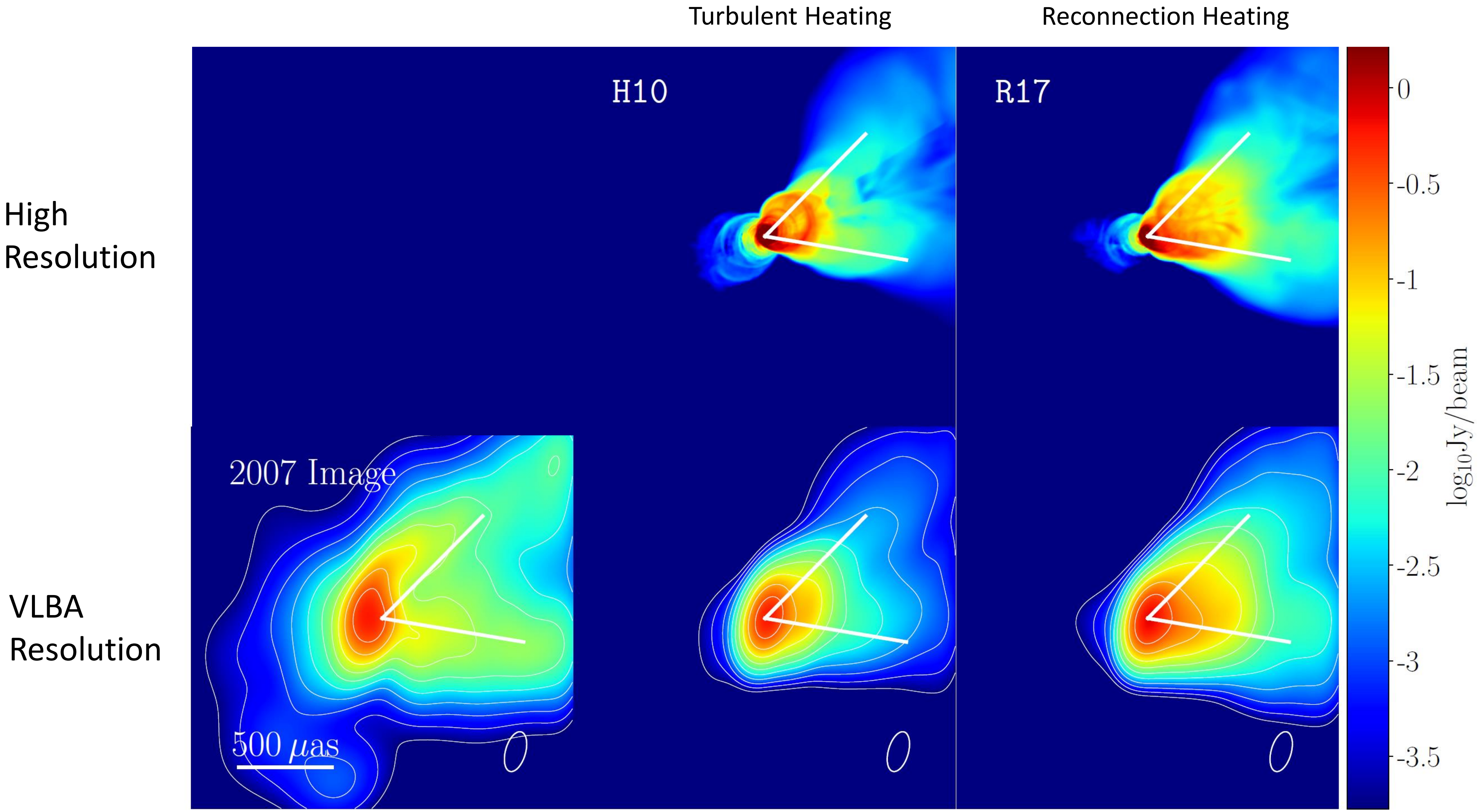


Turbulent Heating

Reconnection Heating

43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

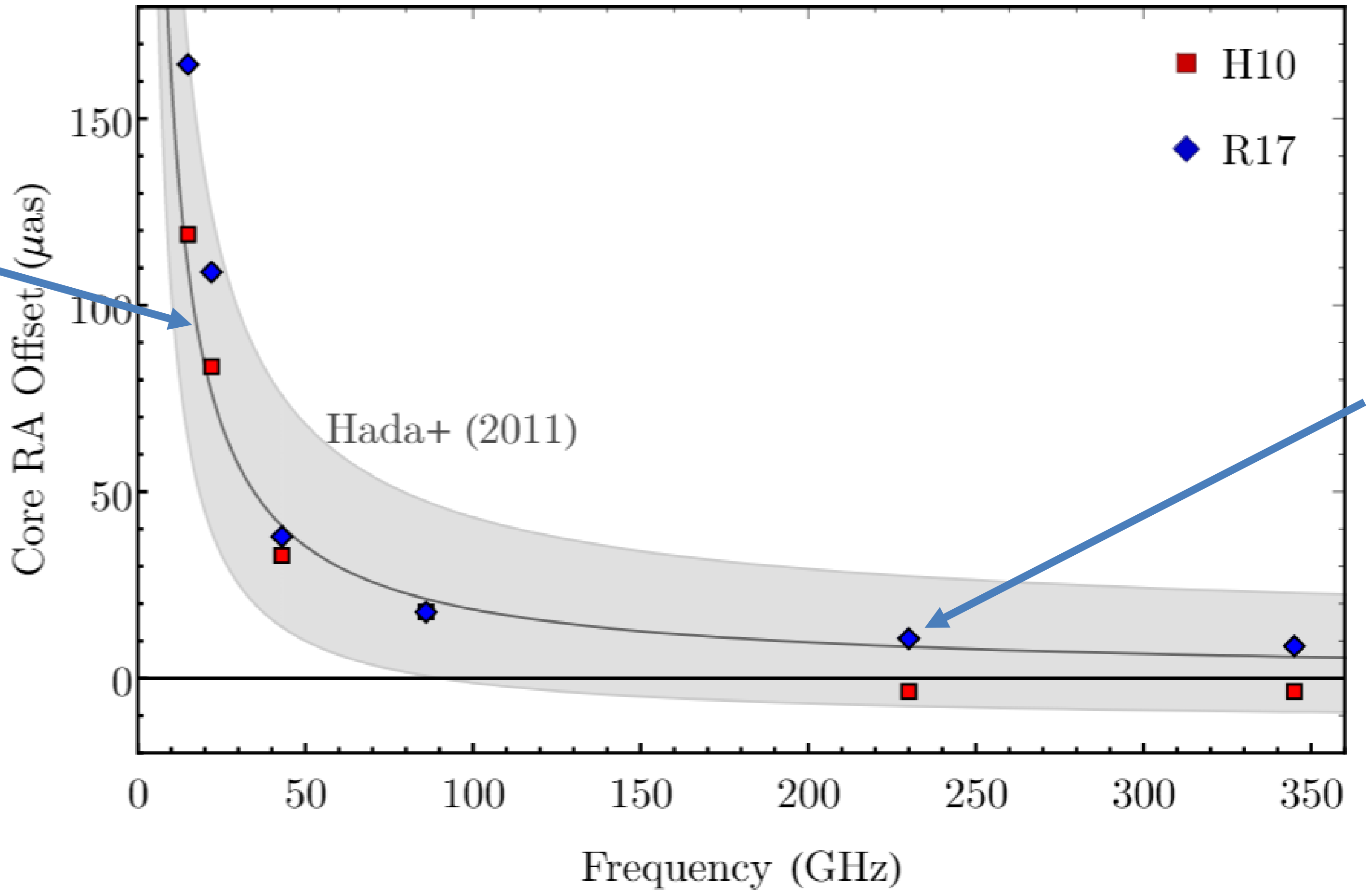
$55°$

(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

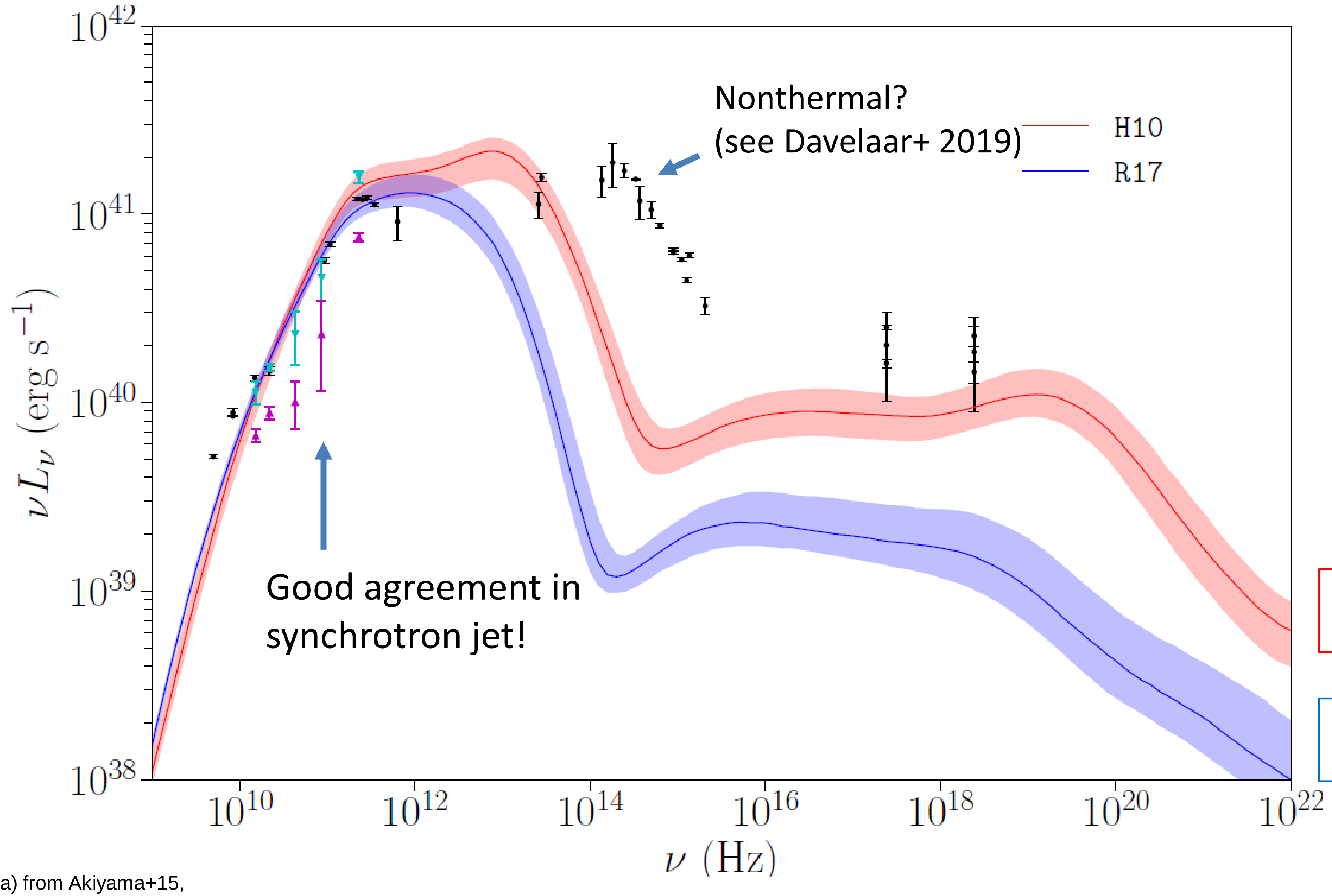
At 230 GHz and higher, the core is coincident with the black hole

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!

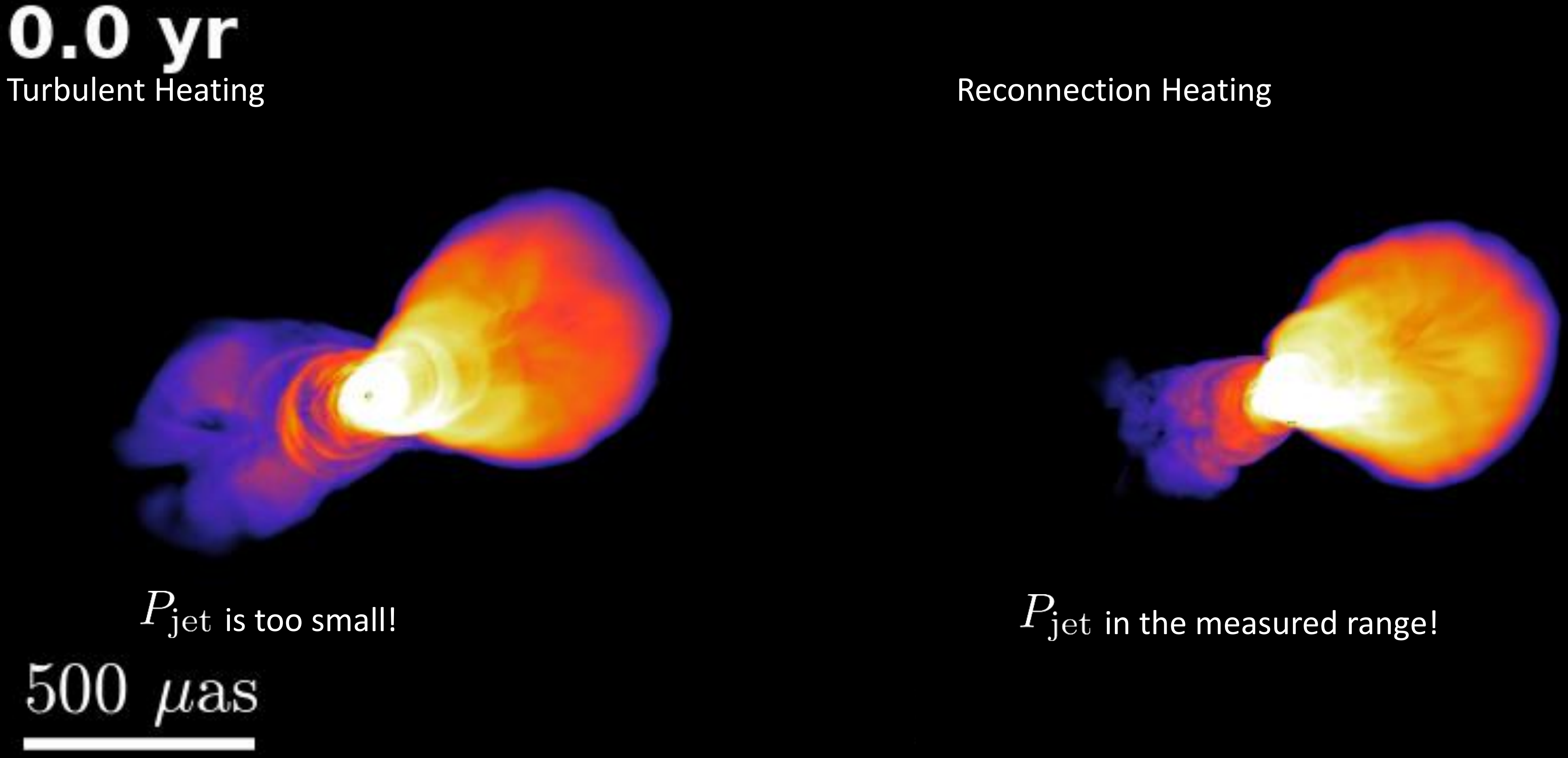
Turbulent Heating

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

43 GHz jets



Turbulent Heating

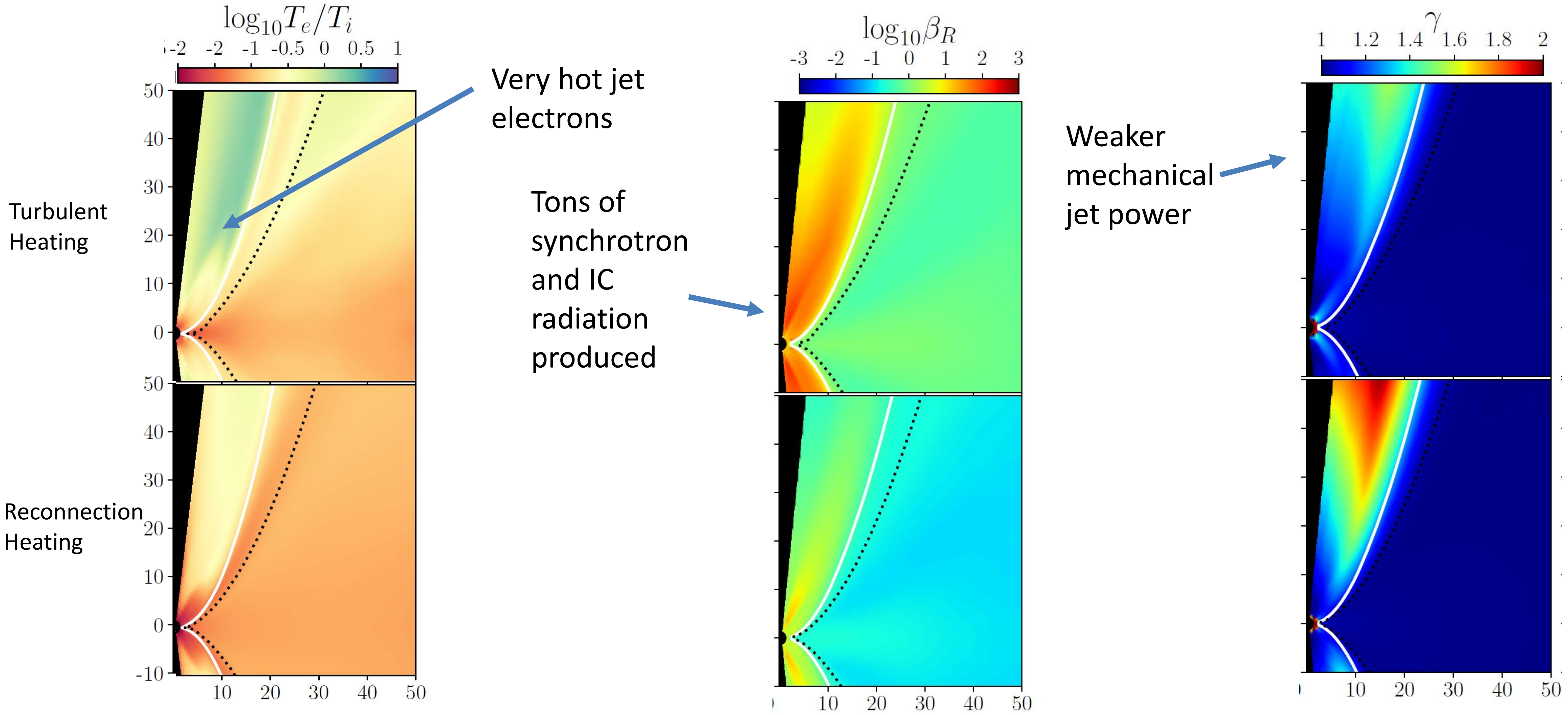
Reconnection Heating

P_{jet} is too small!

P_{jet} in the measured range!

Movie Credit: Chael+ 2019

Electron Heating + Radiation → Jet Dynamics



Very hot jet electrons

Tons of synchrotron and IC radiation produced

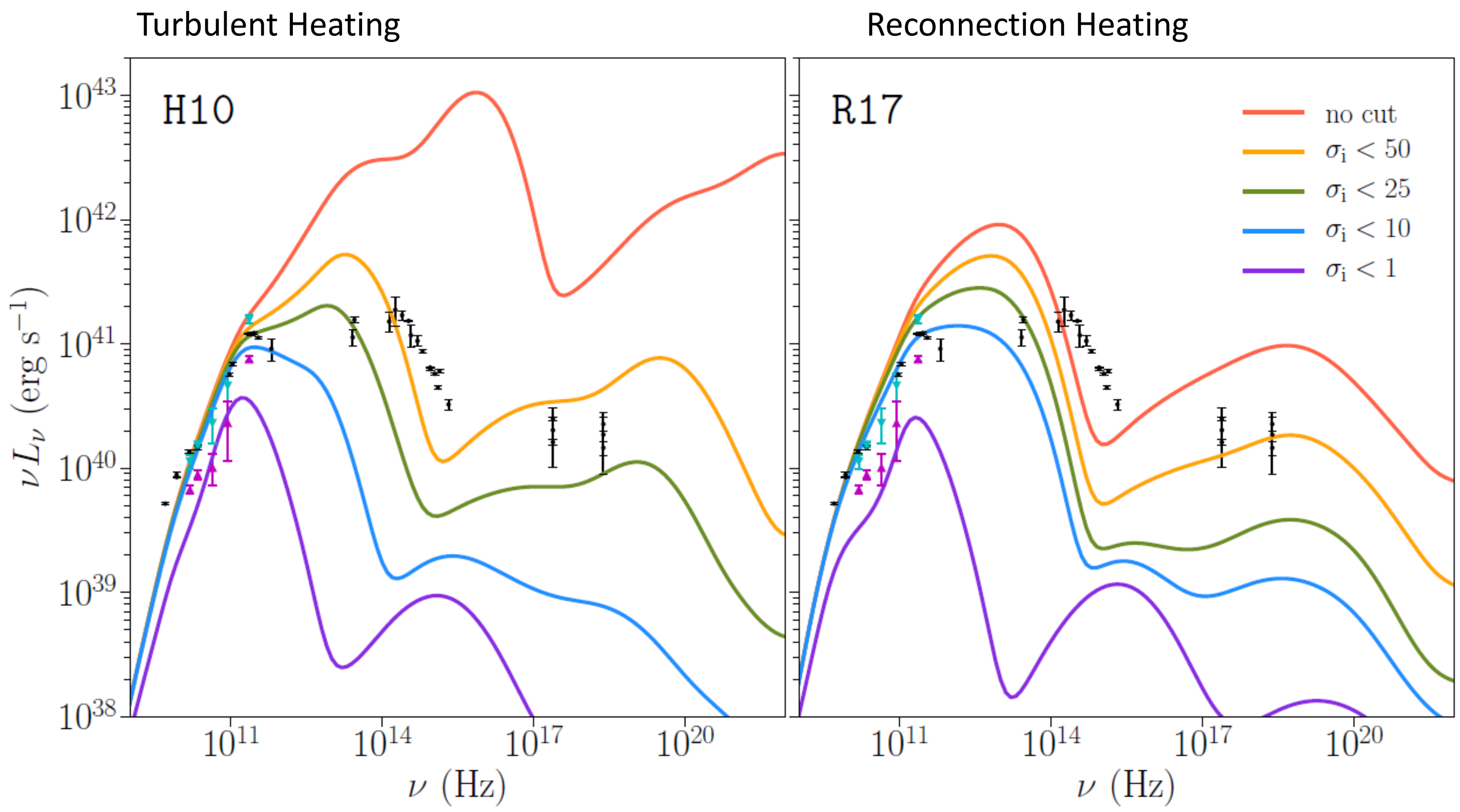
Weaker mechanical jet power

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

Electron Heating + Radiation → Dynamics!

Image Credit: Chael+ 2019

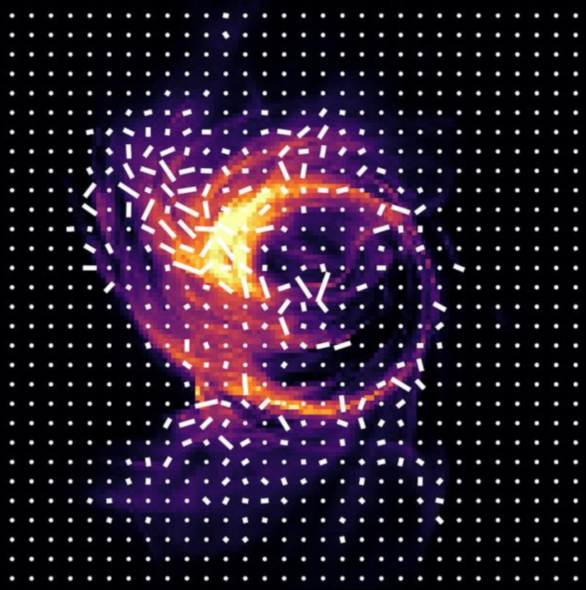
Major uncertainty: Funnel emission/ $\sigma_{\rm i}$ cut



- Density floors are imposed in the simulation inner jet where $\sigma_{\rm i} \geq 100$
- We don't trust radiation from these regions, so when raytracing we only include regions where $\sigma_{\rm i} \leq 25$
- Spectra and images at frequencies $\geq$ 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

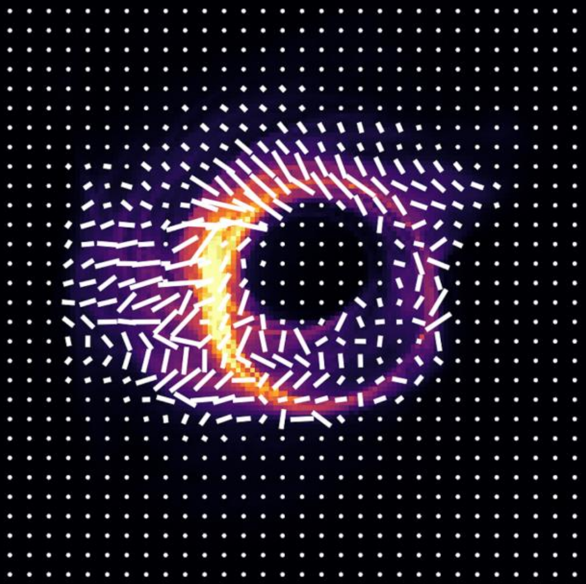
Next steps: Polarization



SANE

-LP < 1%

- Turbulent E-field vector pattern
- high internal RM from hot disk
- (Moscibrodzka & Falcke 2013, Ressler+2015,2017)



MAD

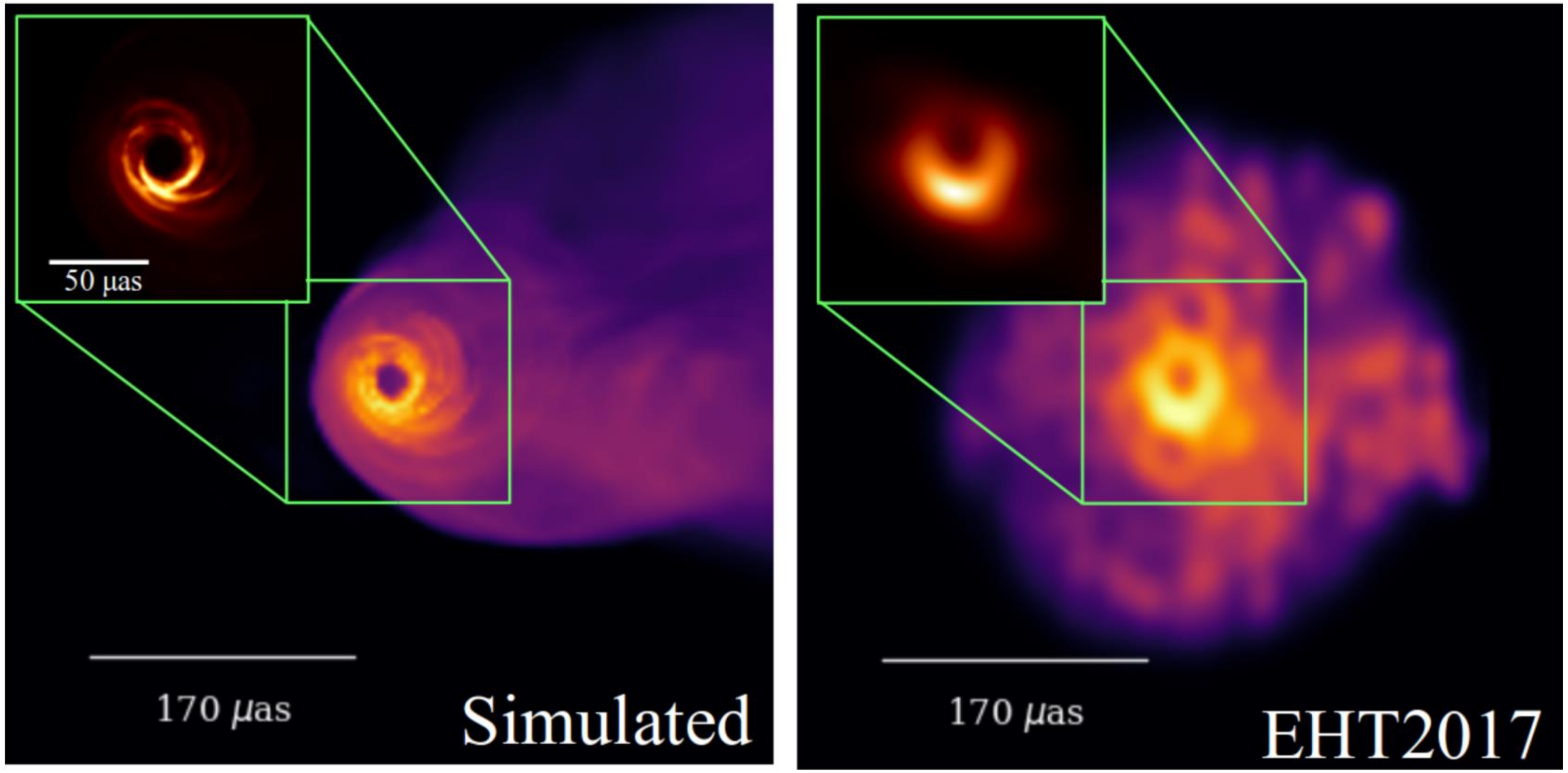
-LP ~ 2-10%

-More coherent E-field vector pattern

-Low RM is mostly external from forward jet (Chael+2019)

Image credit:
Jason Dexter

ngEHT will illuminate the BH-jet connection



The current EHT lacks many <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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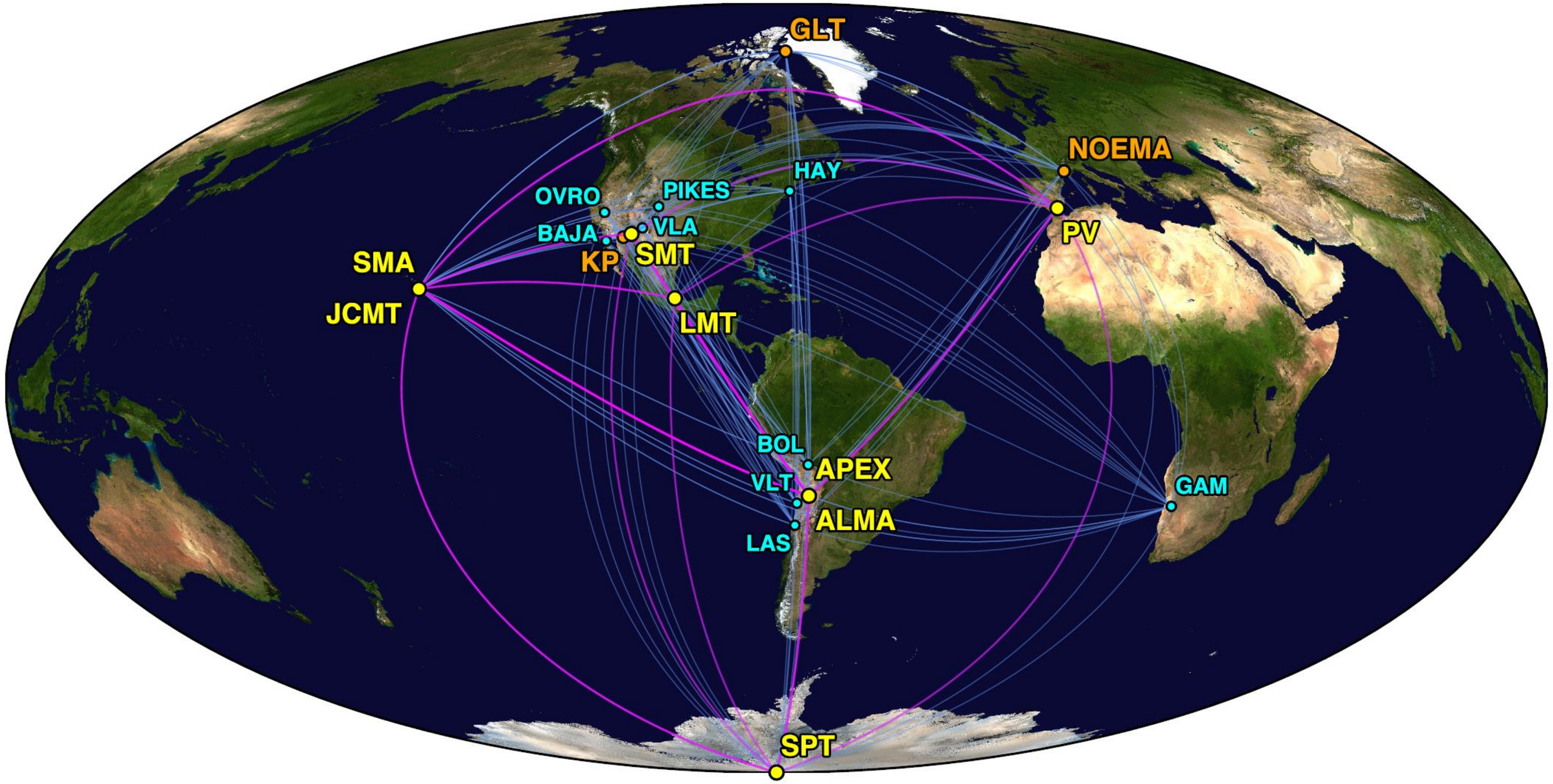

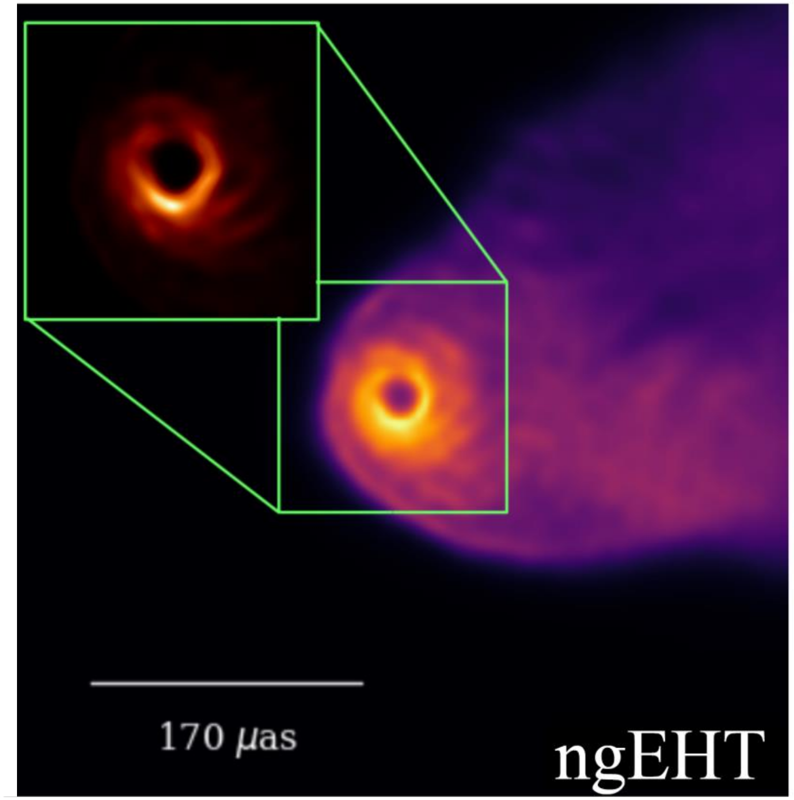

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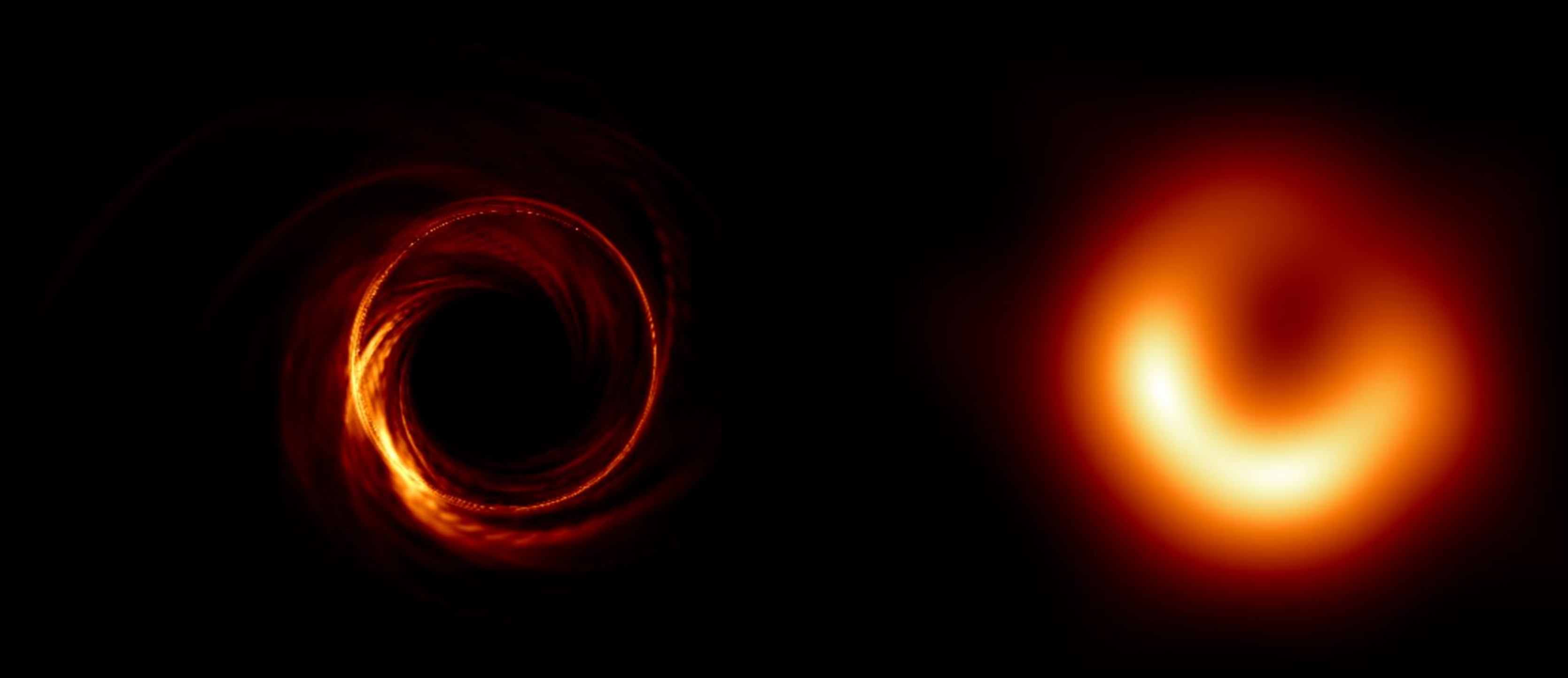
Takeaways

- Global simulations can connect EHT images on horizon scales to the extended jet on ~pc scales.
- Both dissipation and radiation are important in determining the electron temperatures in M87’s accretion flow.
- MAD models produce powerful, wide opening-angle jets which match VLBI observations.
    - But uncertainty about high-magnetization thermodynamics is a big problem.
- M87 Polarization and Sgr A* images are coming soon!

Thank you!



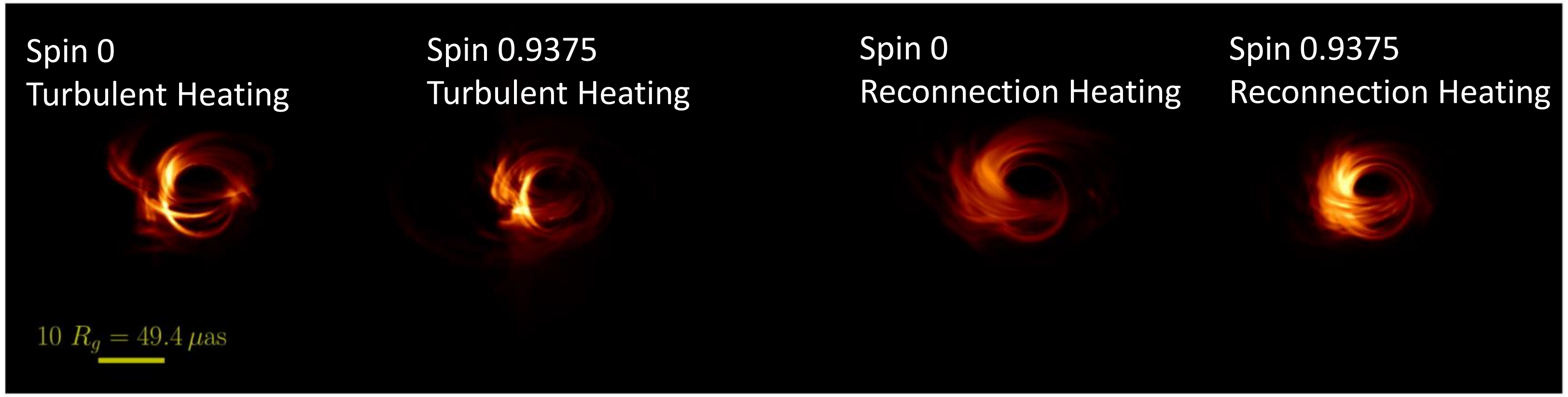
Work with Ramesh Narayan, Michael Johnson,
Katie Bouman, Shep Doeleman, Michael Rowan,
and the entire EHT collaboration

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

Two-temperature simulations of Sgr A*

Image structure with frequency

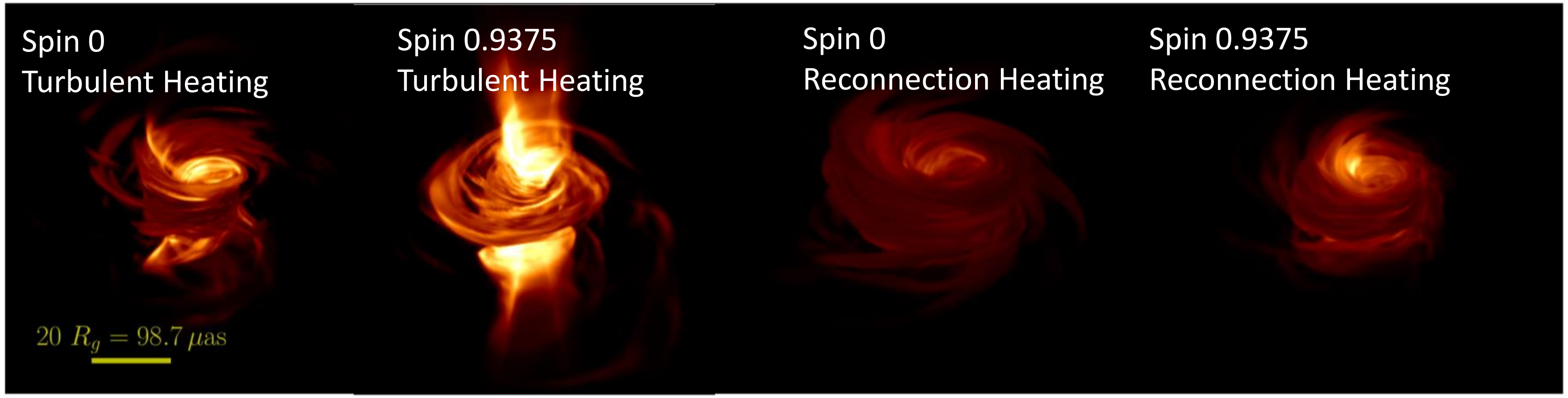
230 GHz



At 230 GHz, both heating prescriptions produce images with **imagable shadows**

Turbulent heating makes lower frequency images jet dominated, **exceeding** measurements of anisotropy
when not viewed face-on
(Johnson+ 2018, Issaoun+ 2018)

43 GHz



Chael+ 2018

Sagittarius A*

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

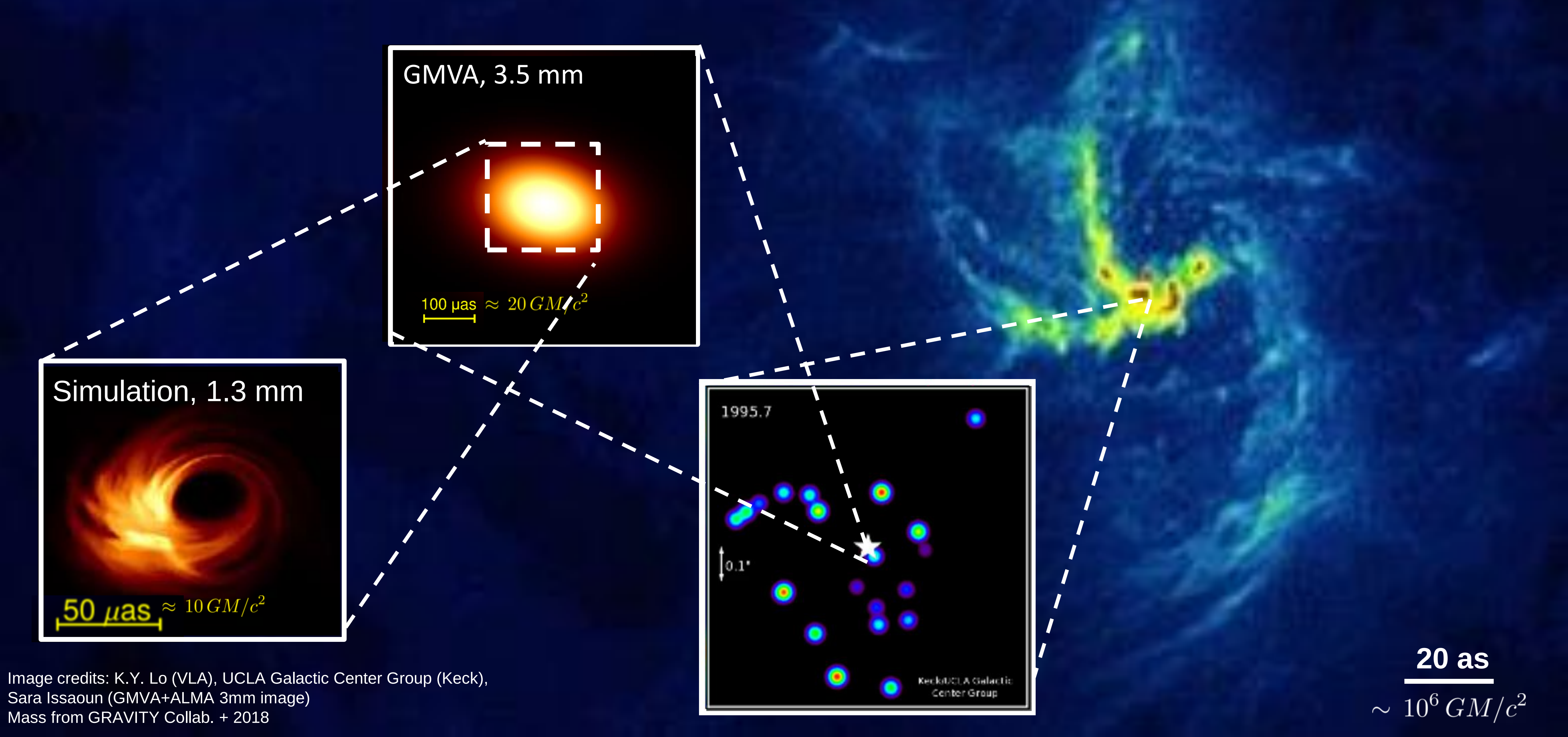
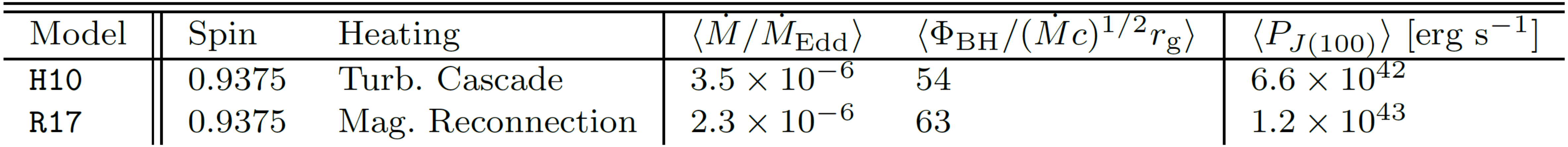


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck),
Sara Issaoun (GMVA+ALMA 3mm image)
Mass from GRAVITY Collab. + 2018

Two-temperature MAD simulations of M87



Model	Spin	Heating	$\langle \dot{M}/\dot{M}_{\rm Edd} \rangle$	$\langle \Phi_{\rm BH}/(\dot{M}c)^{1/2} r_{\rm g} \rangle$	$\langle P_{J(100)} \rangle$ [erg s^{-1}]
`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

- Both simulations are MAD.
- Density is scaled to match 0.98 Jy at 230 GHz.
- The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s.

(Doeleman+ 12, Reynolds+ 1996, Stawartz+ 2006)