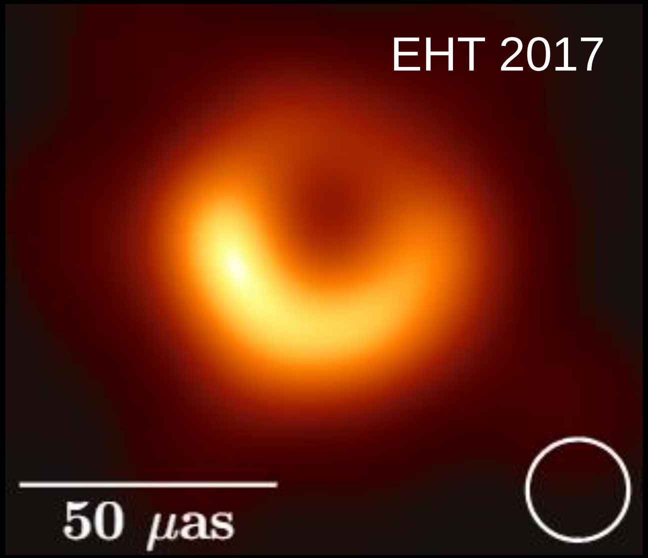
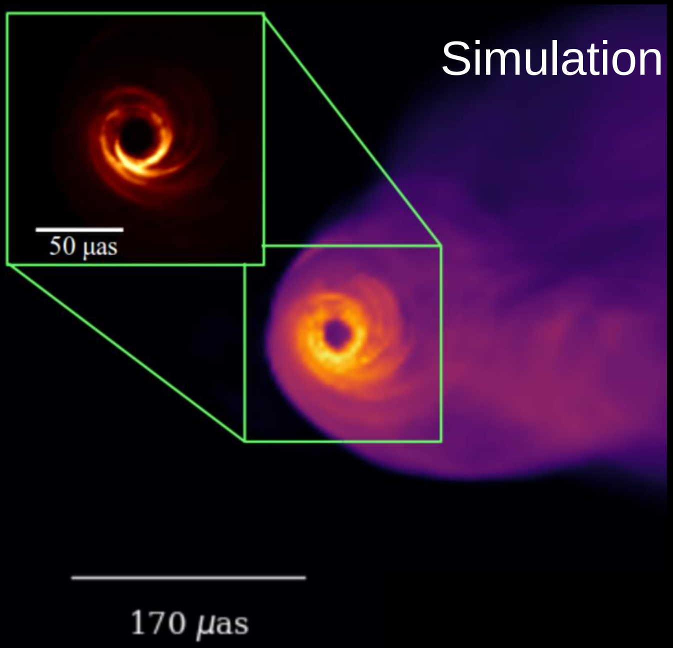
The Black Hole and Jet in M87: Connecting Simulations and VLBI images

Andrew Chael

NHFP Einstein Fellow
Princeton University

JSI Workshop
November 13, 2019





PRINCETON UNIVERSITY

Event Horizon Telescope

M87

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

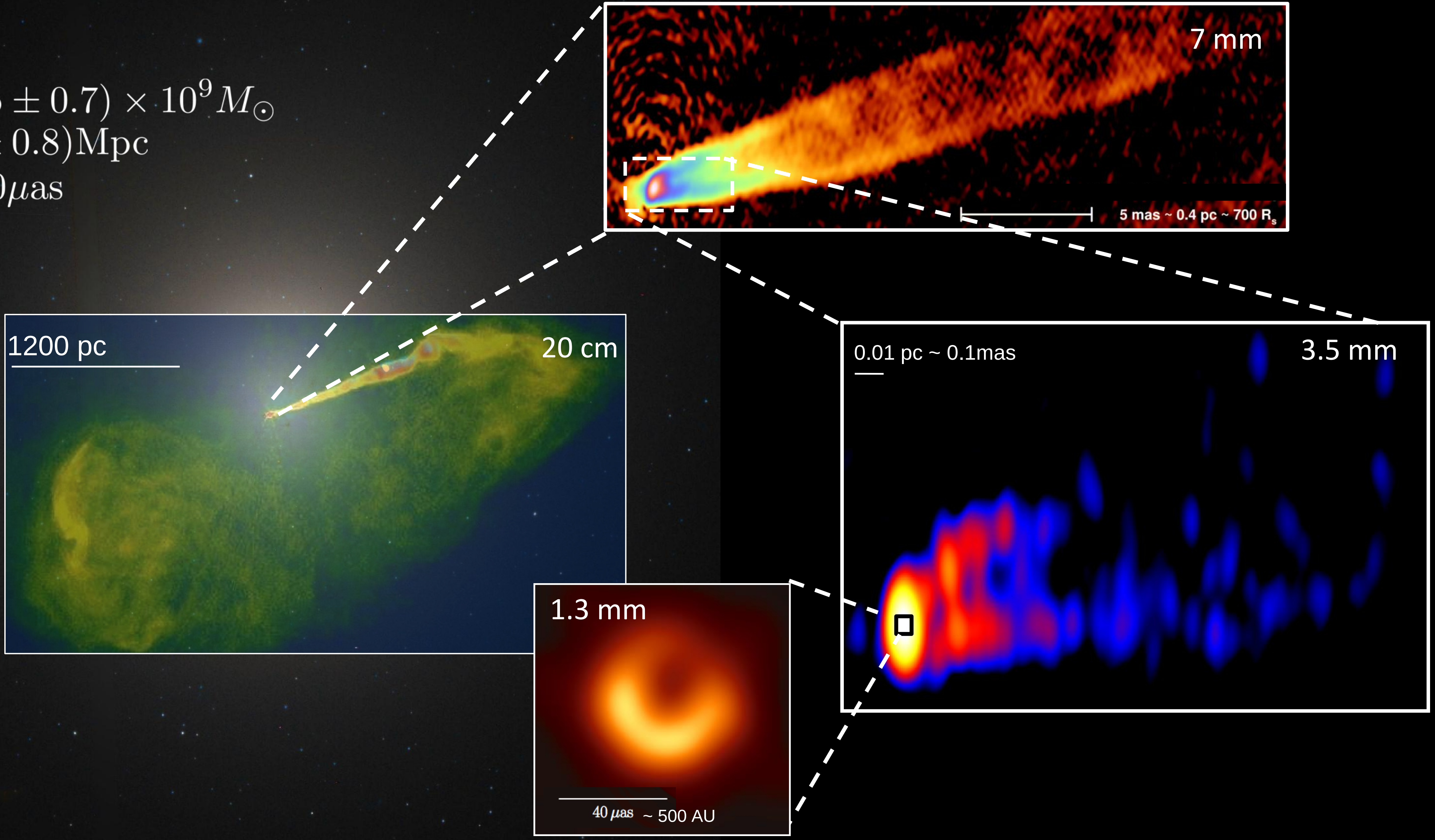


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

What parameters determine the images we see?

1. Spacetime geometry: M, a
   - -Liberating potential energy heats the plasma.
   - -Photons follow null geodesics.

What parameters determine the images we see?

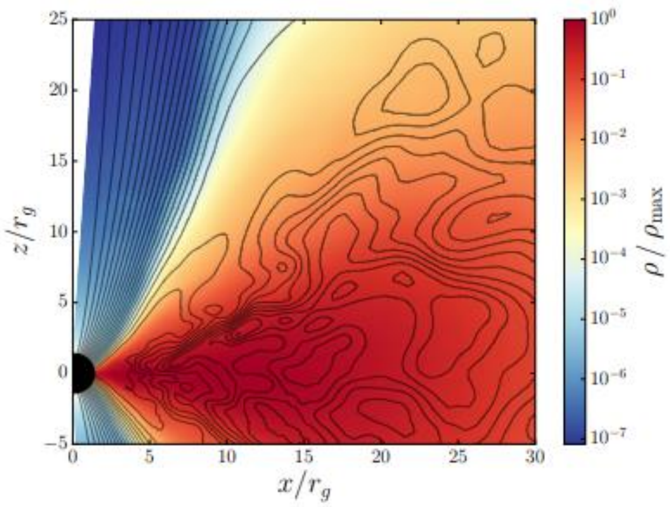
1. Spacetime geometry: M, a
   - Liberating potential energy heats the plasma.
   - Photons follow null geodesics.

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

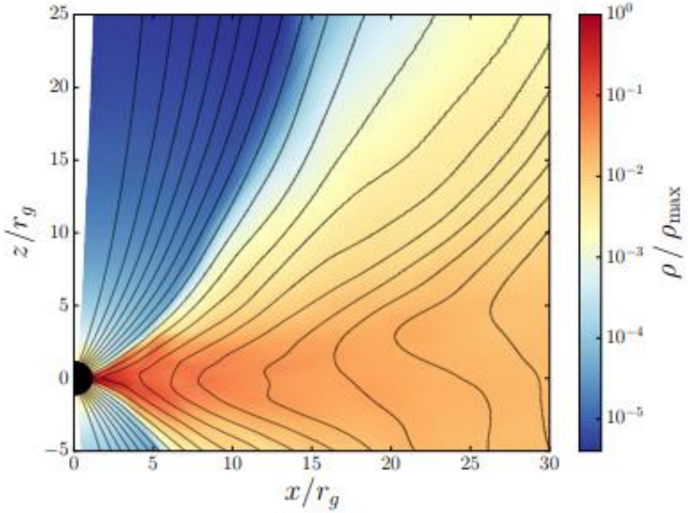
SANE vs MAD

- 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:

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

Image credit: Riordan+ 2017

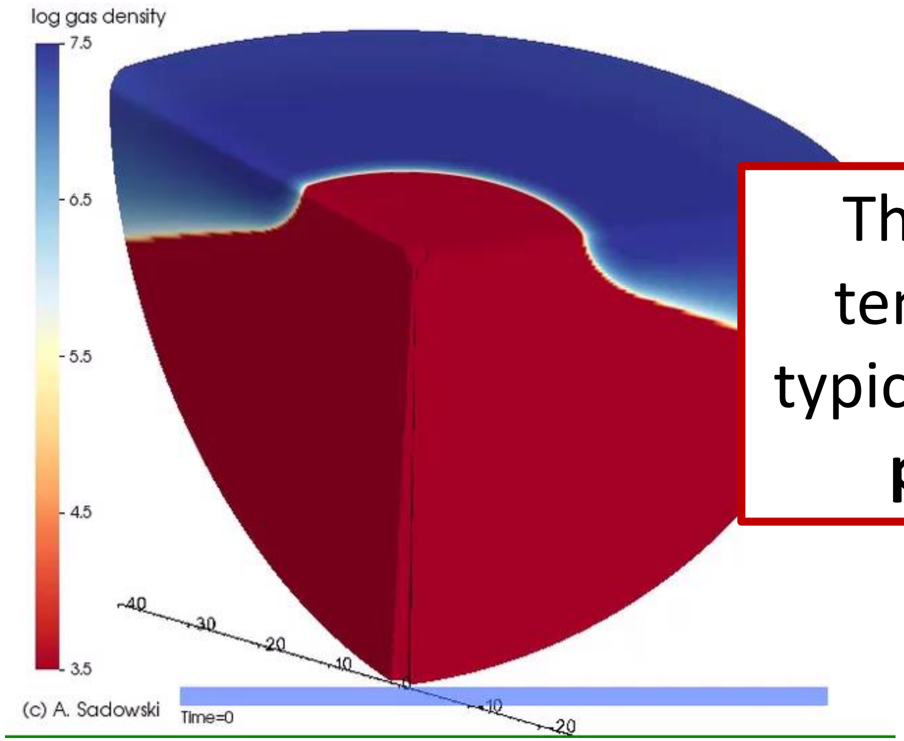
What parameters determine the images we see?

1. Spacetime geometry: M, a
   - Liberating potential energy heats the plasma.
   - Photons follow null geodesics.

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

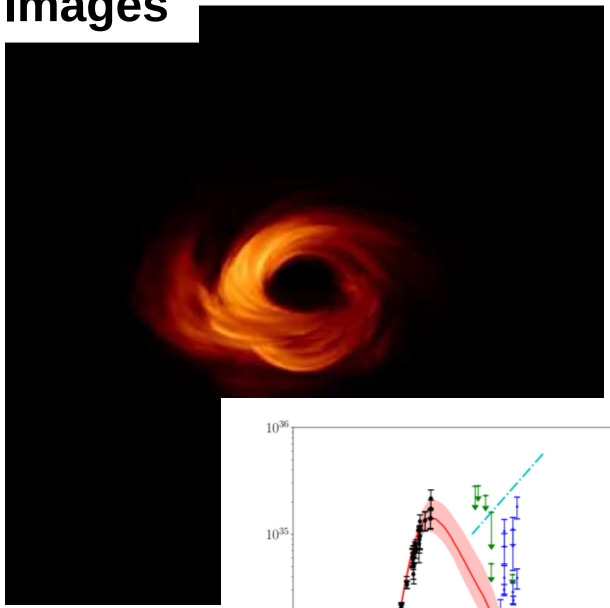


The electron-to-ion temperature ratio is typically set **manually** in **post-processing**

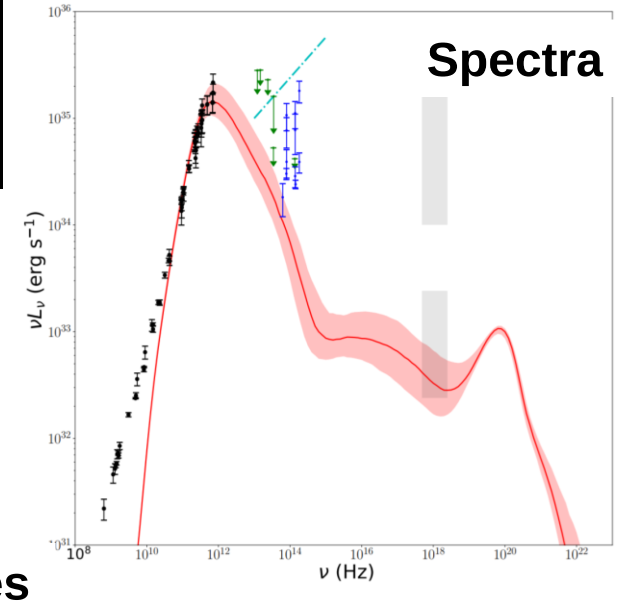
GRMHD Simulations

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

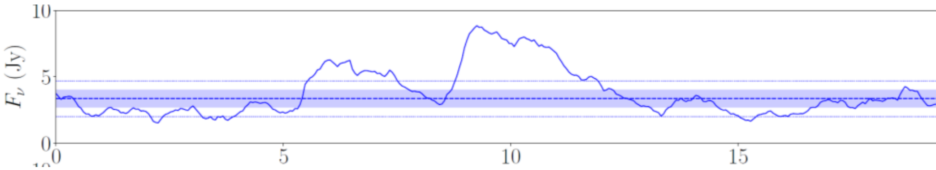
Images



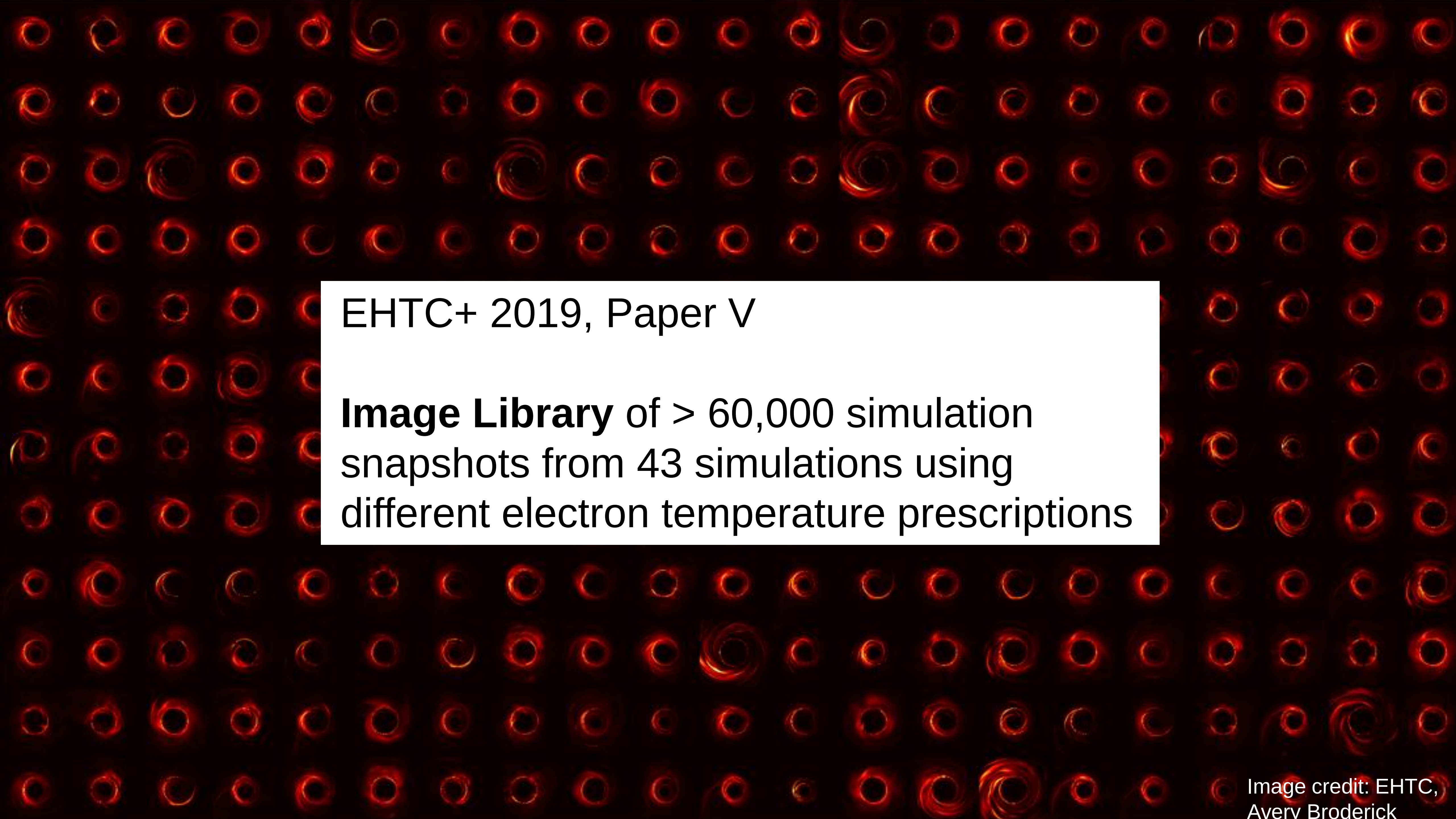
Spectra



Light Curves



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



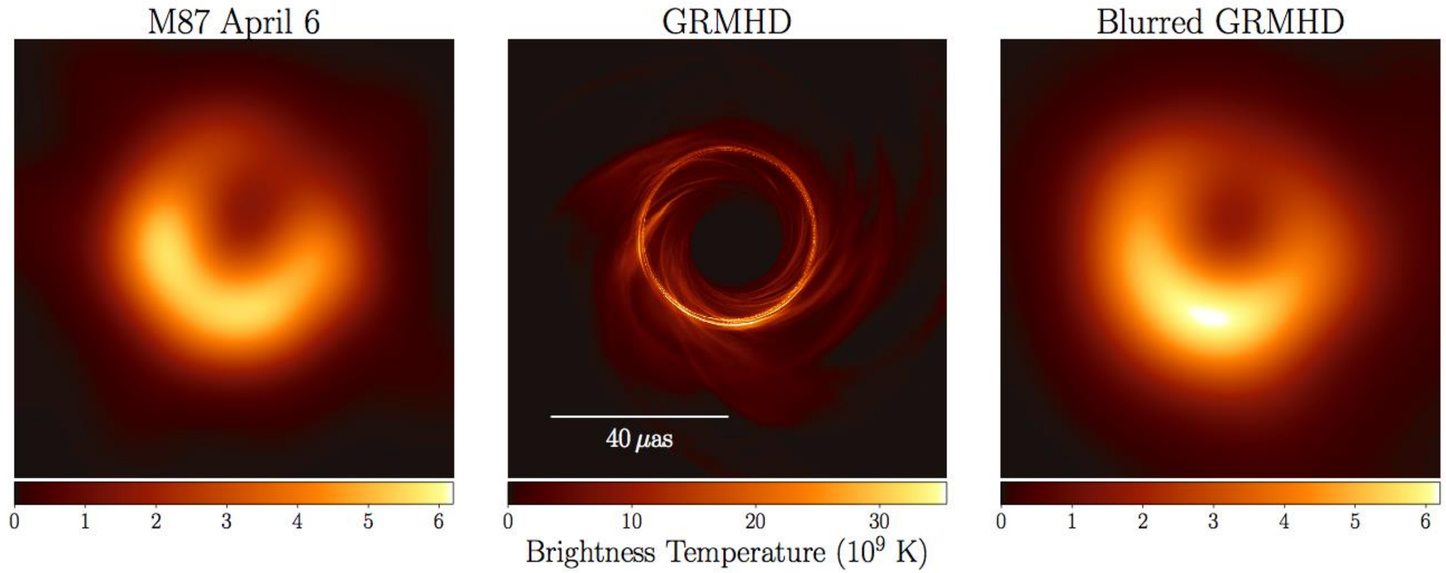
EHTC+ 2019, Paper V

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

Image credit: EHTC, Avery Broderick

EHTC+ 2019 Results

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



- The **jet power constraint** (≥ 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

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

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

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

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

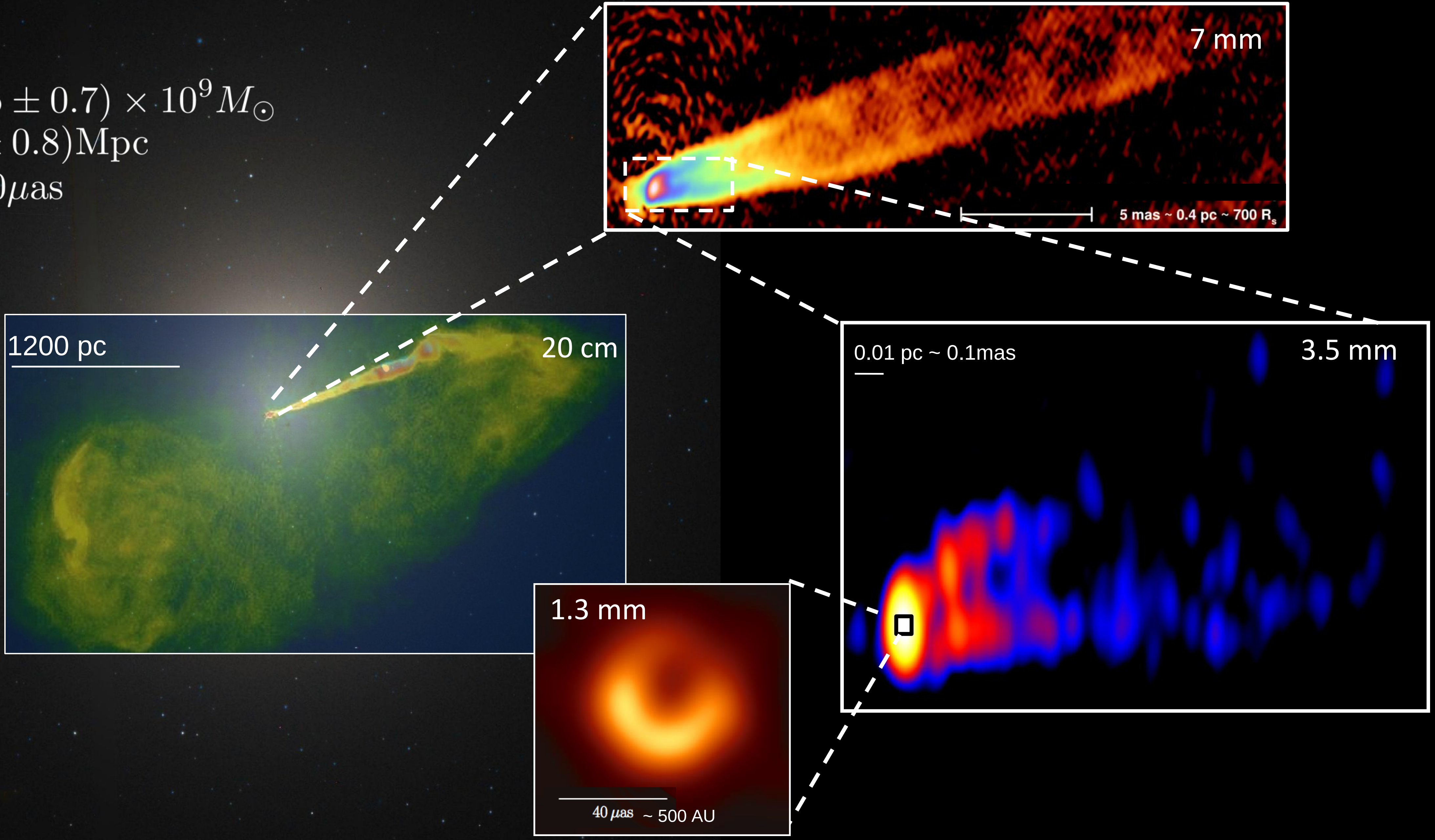


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

Two-Temperature GRRMHD Simulations

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

- Includes **radiative feedback** on gas energy-momentum.
  -- M87's accretion rate is high enough that radiative feedback is important (Ryan+ 2018, EHTC+ 2019)

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

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

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

Radiative Cooling

Coulomb coupling: (extremely weak)

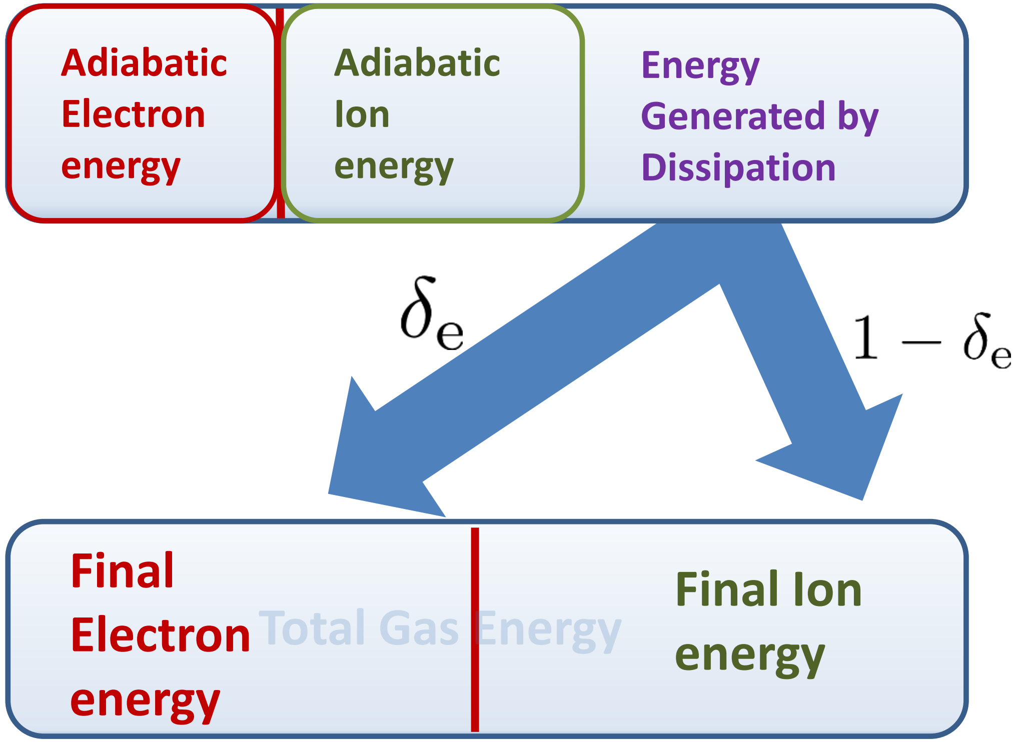
Dissipation

Adiabatic Compression/ Expansion

Electron & Ion Heating

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

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

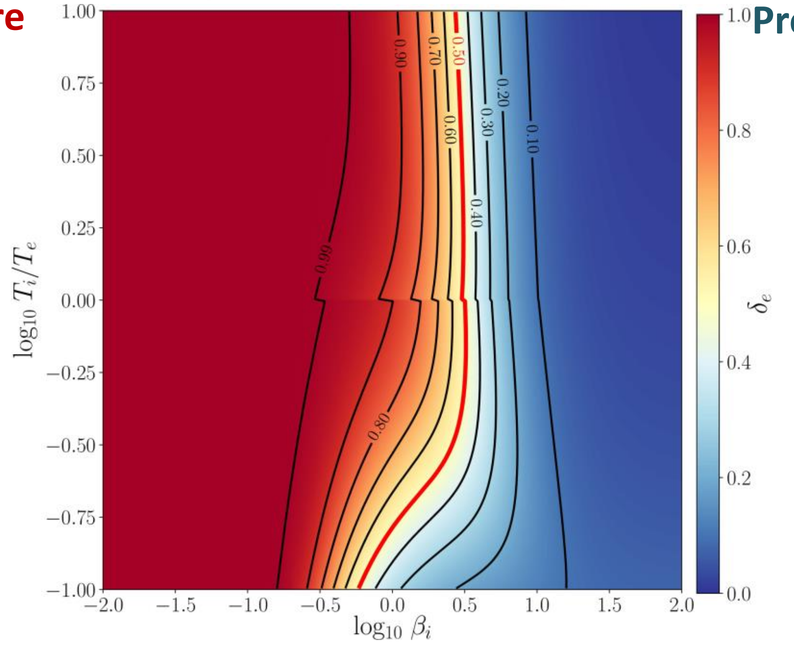


Sub-grid Heating Prescriptions

Turbulent Dissipation (Howes 2010)

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

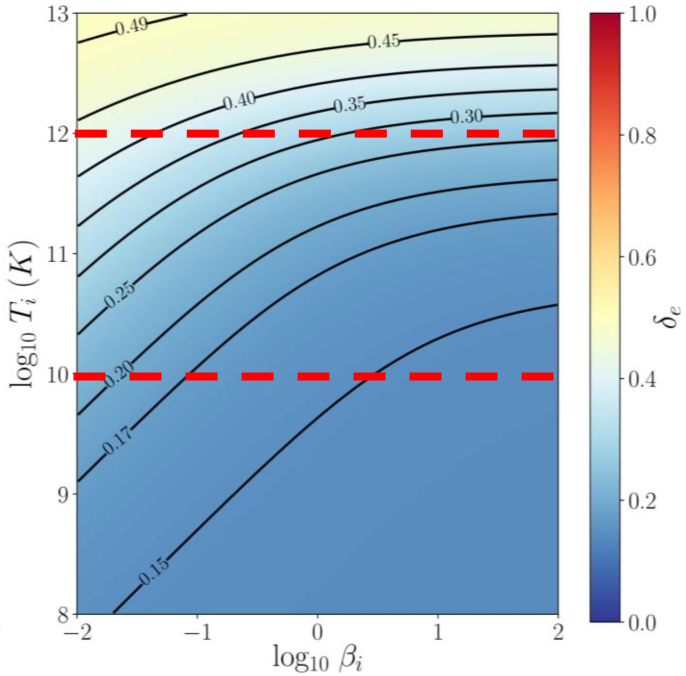
High Magnetic Pressure ↔ Low Magnetic Pressure



Almost all energy to electrons ↔ Almost all energy to ions

Magnetic Reconnection (Rowan+ 2017)

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



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" (for $\langle \Phi_{\rm BH}/(\dot{M}c)^{1/2} r_{\rm g} \rangle$) — Jet **mechanical** power (for $\langle P_{J(100)} \rangle$)

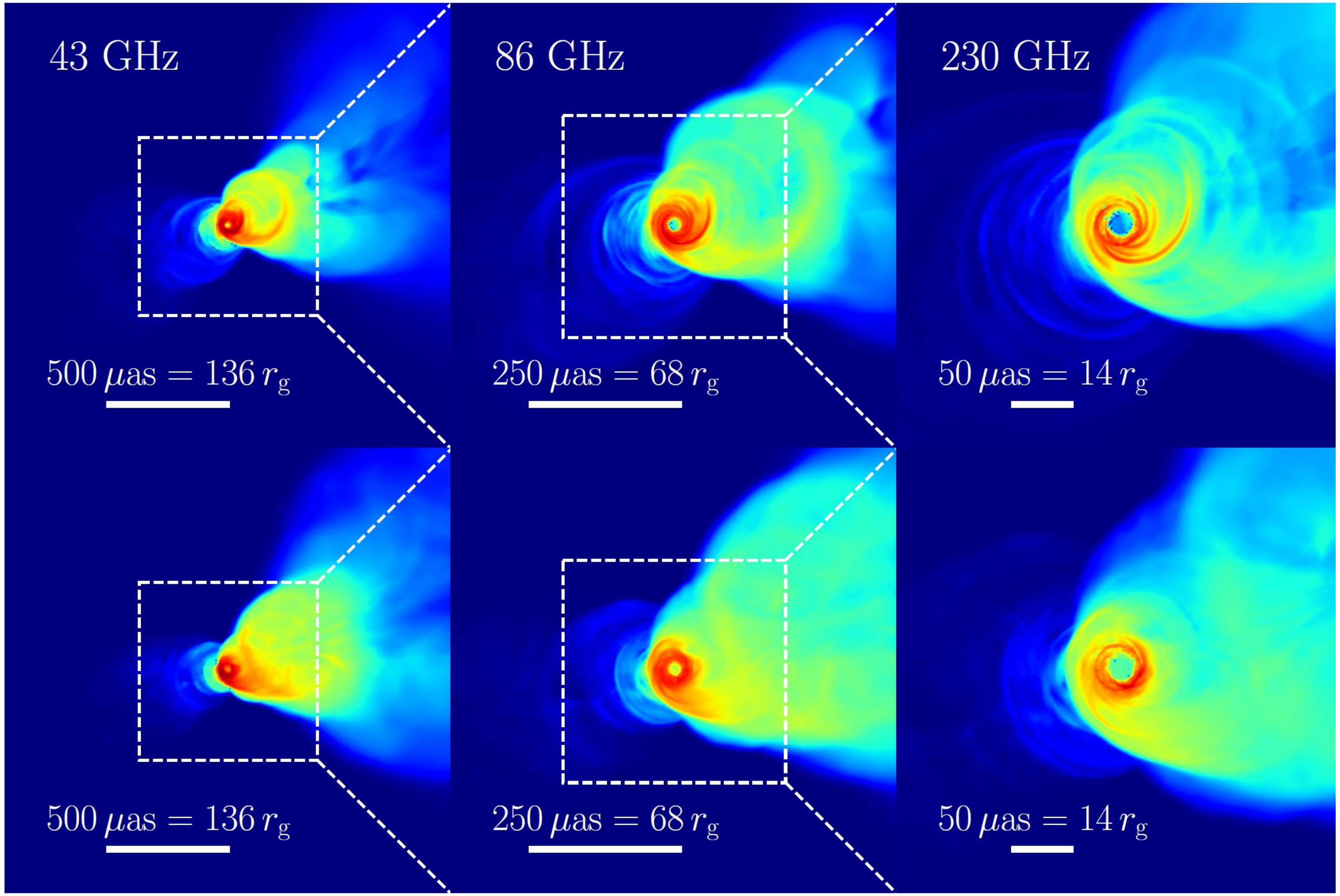
- Both simulations are MAD.
- Density is scaled to match 0.98 Jy at 230 GHz.
- The mechanical jet power in R17 is in the measured range of 10^{43}–10^{44} erg/s.

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

M87 Jets at millimeter wavelengths

Turbulent Heating

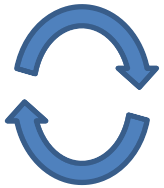
Reconnection Heating



Inclination angle (down from pole)

17°

Disk/Jet rotation sense



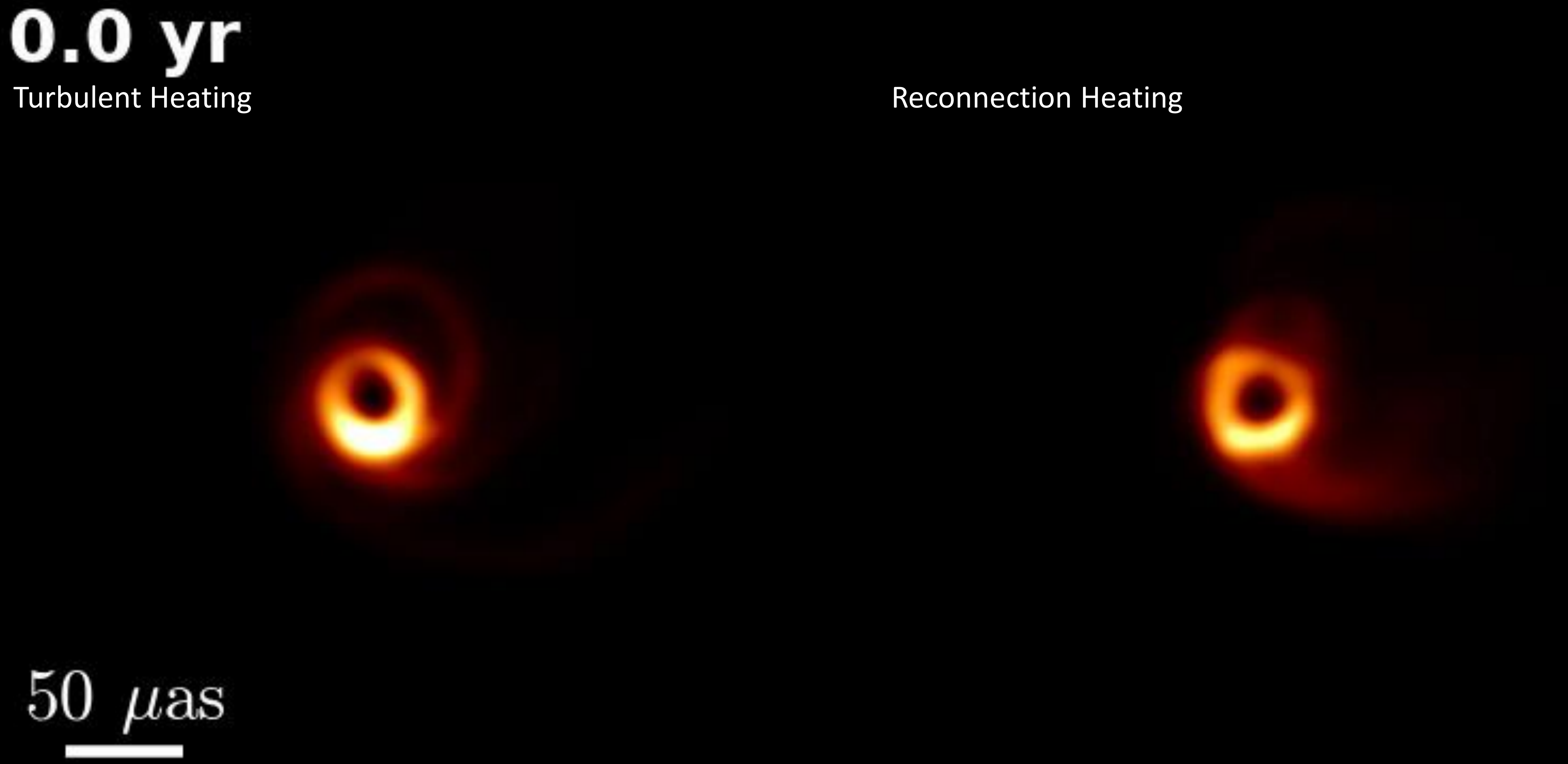
Wide apparent opening angles get **larger** with increasing frequency

Image Credit: Chael+ 2019

230 GHz Images

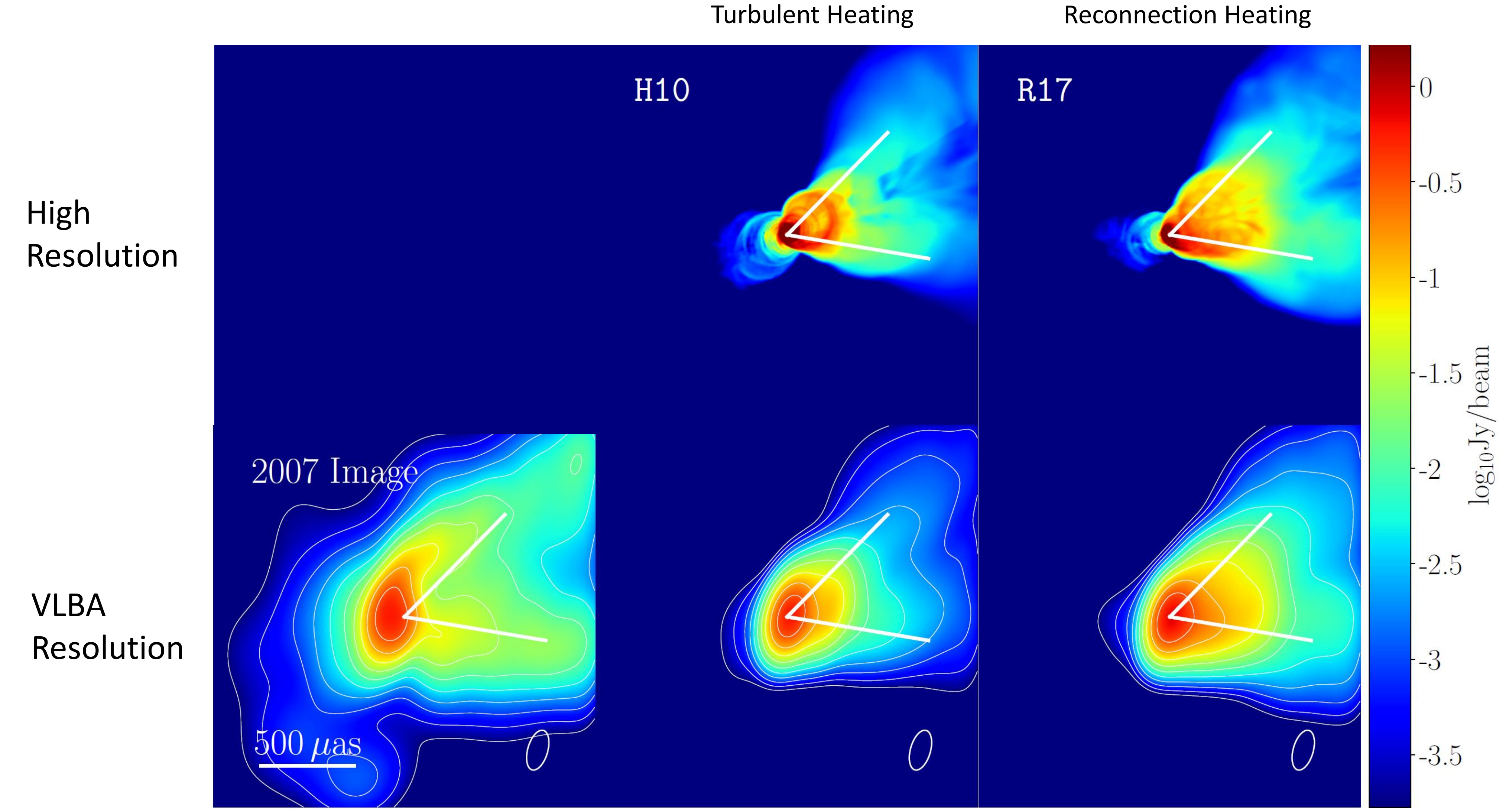
$40\ \mu\text{as}$

230 GHz Images & variability



43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

$55°$

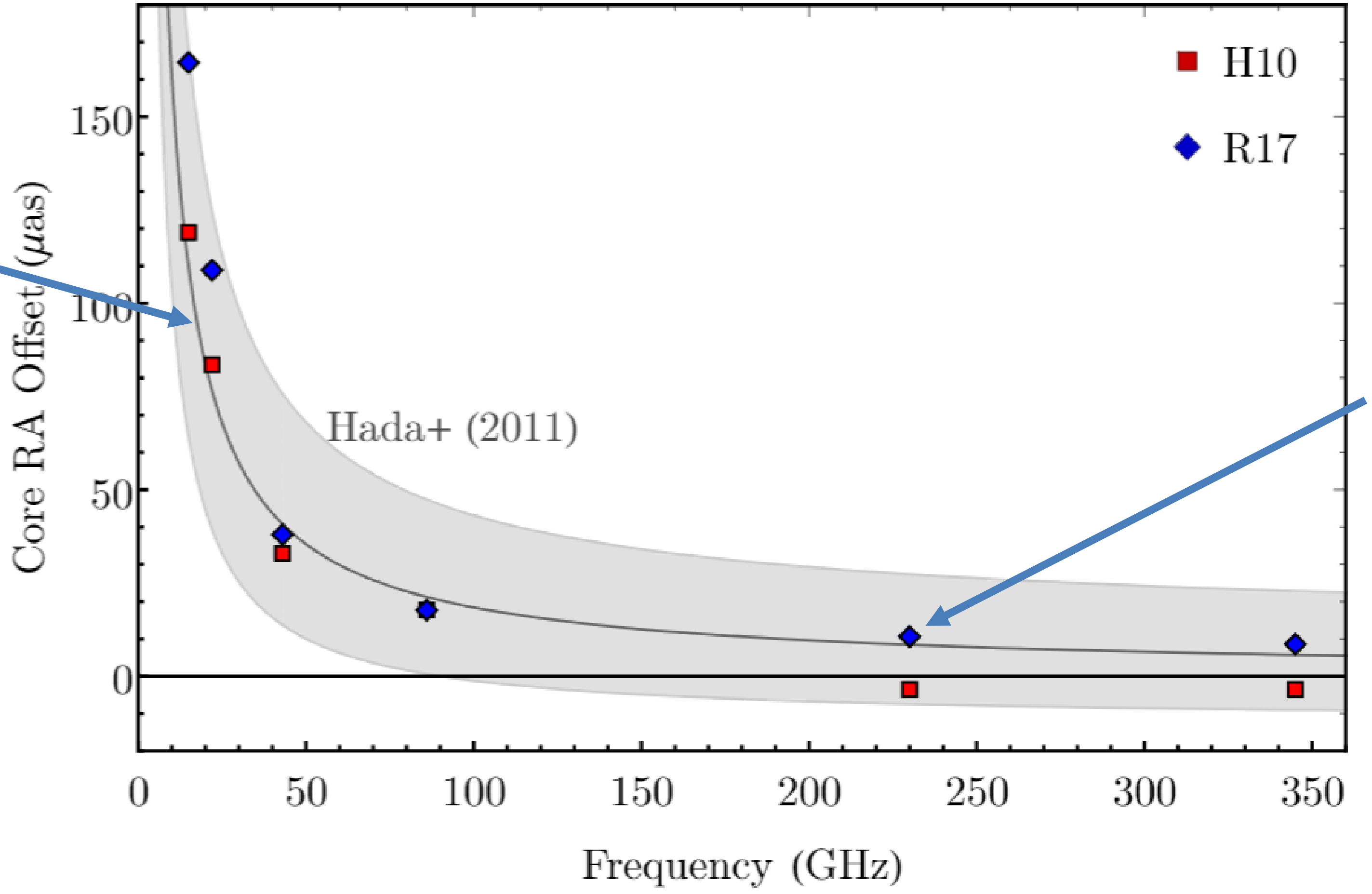
(Walker+ 2018)

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



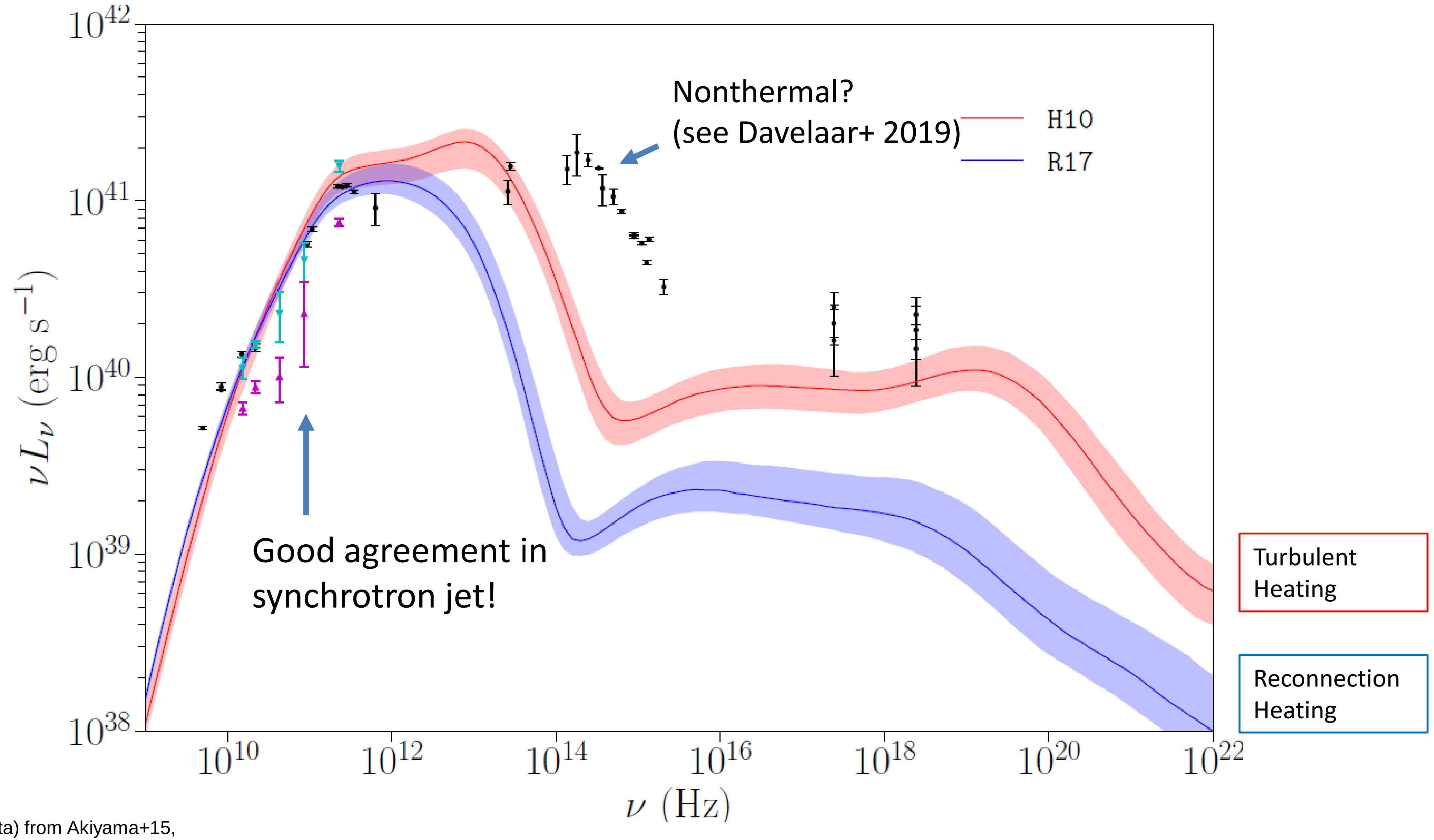
At 230 GHz and higher, the core is coincident with the black hole

Agreement with measured core shift up to cm wavelengths.

Hada+ 2011

Image Credit: Chael+ 2019

M87 SED



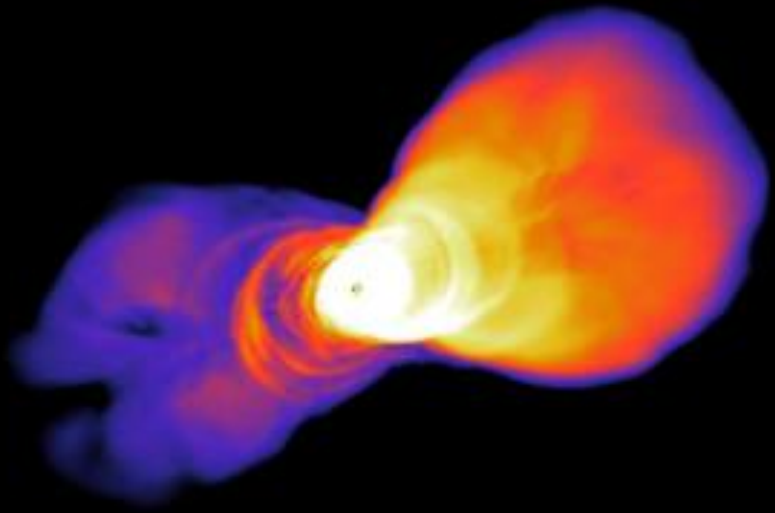
Data from Prieto+16
New points (cyan and magenta) from Akiyama+15, Doeleman+12, Walker+18, Kim+18, and MOJAVE

Image Credit: Chael+ 2019

43 GHz jets

0.0 yr

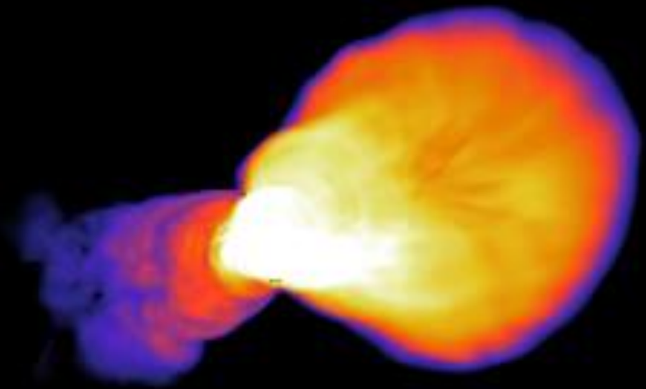
Turbulent Heating



P_{jet} is too small!

$500\ \mu\text{as}$

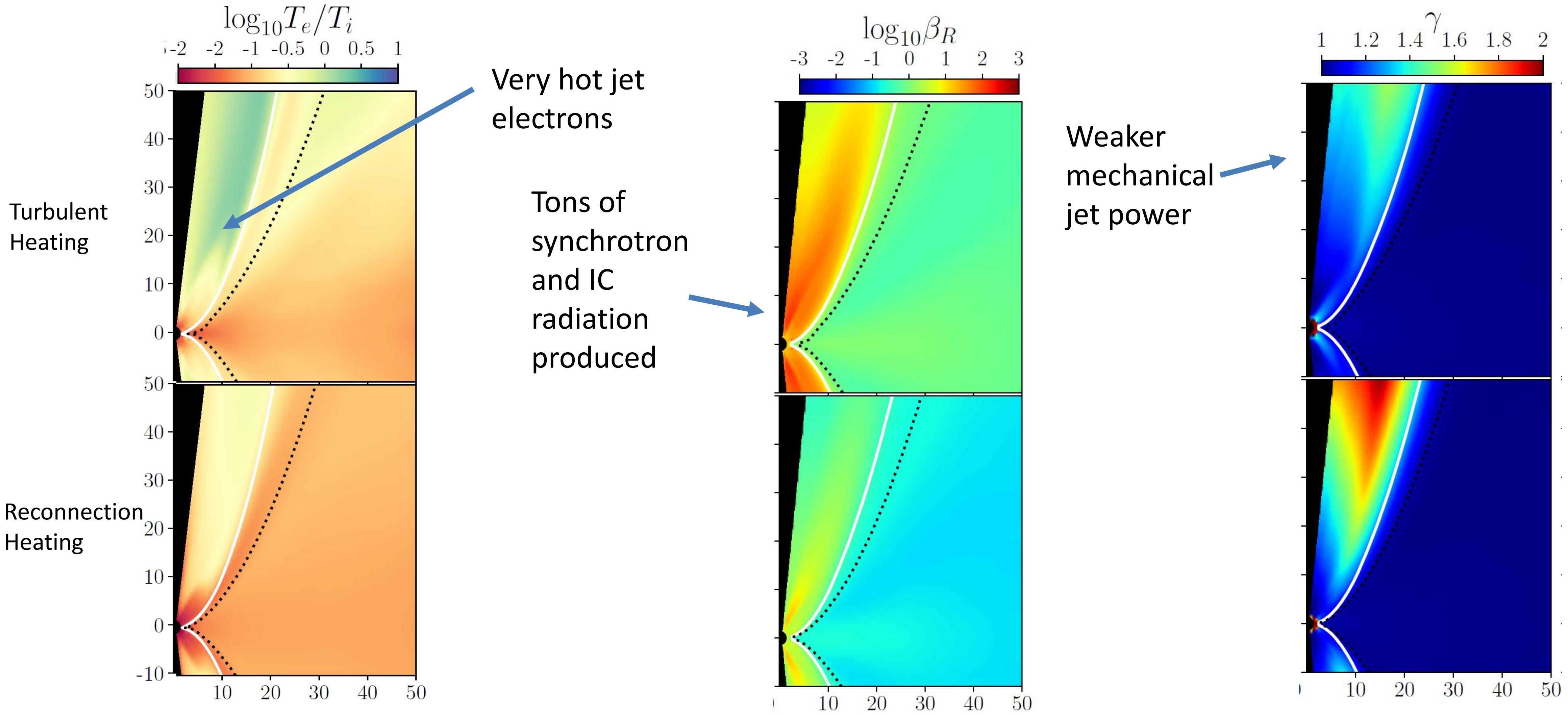
Reconnection Heating



P_{jet} in the measured range!

Movie Credit: Chael+ 2019

Electron Heating + Radiation → Jet Dynamics

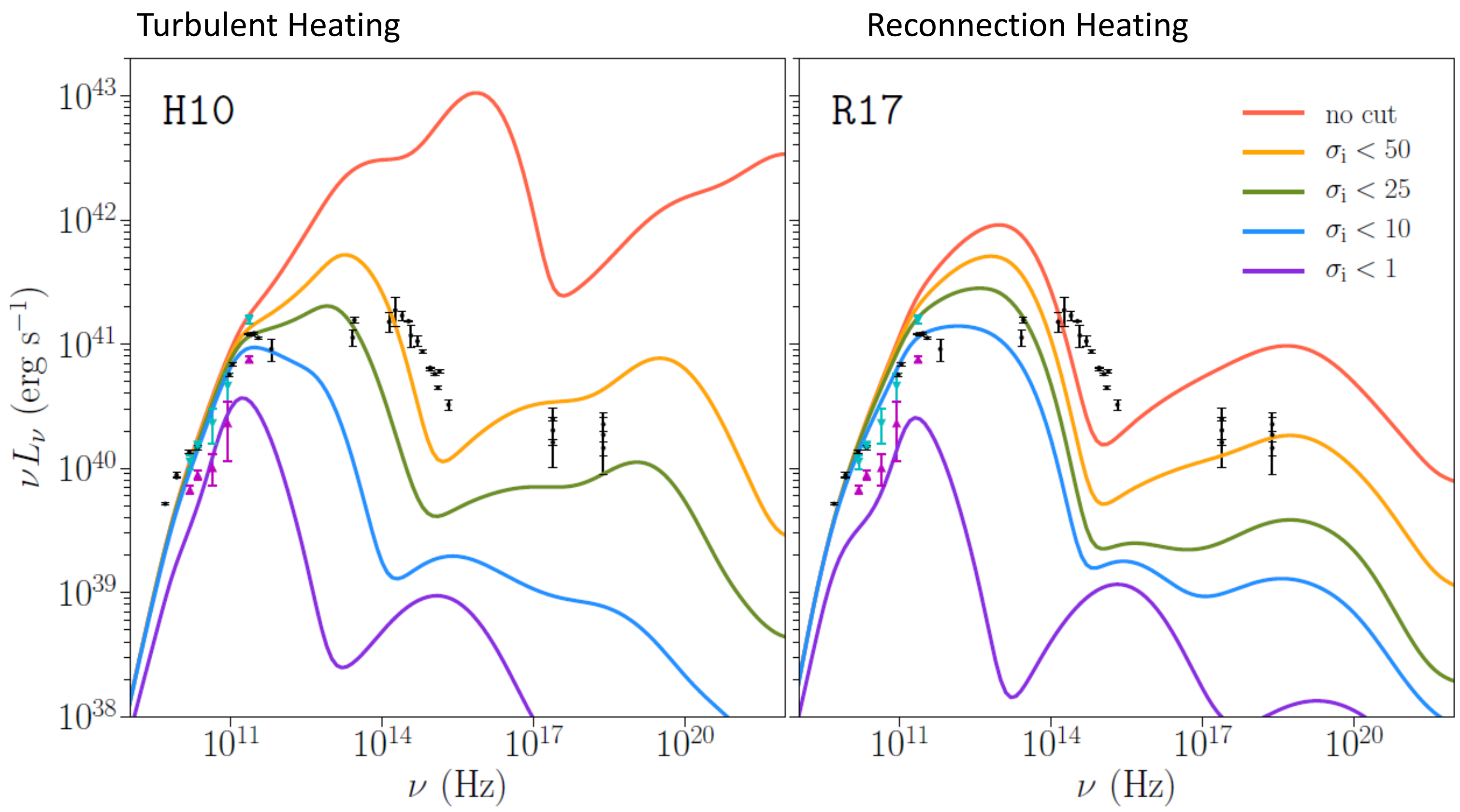


Turbulent heating produces too much radiation at the jet base, which saps the jet power

Electron Heating + Radiation → Dynamics!

Image Credit: Chael+ 2019

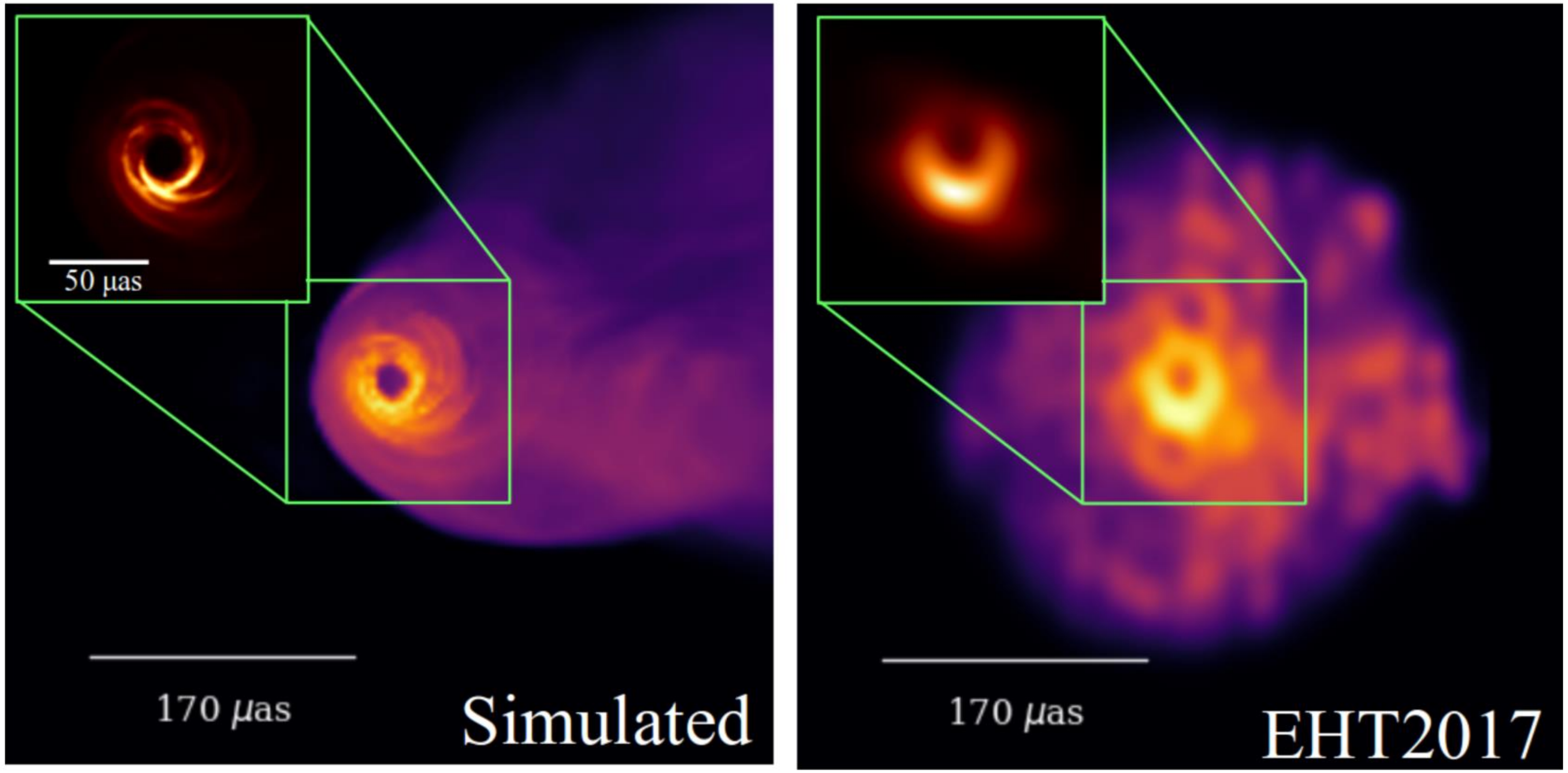
Major uncertainty in simulations: $\sigma_{\rm i}$ cut



- 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

ngEHT will illuminate the BH-jet connection

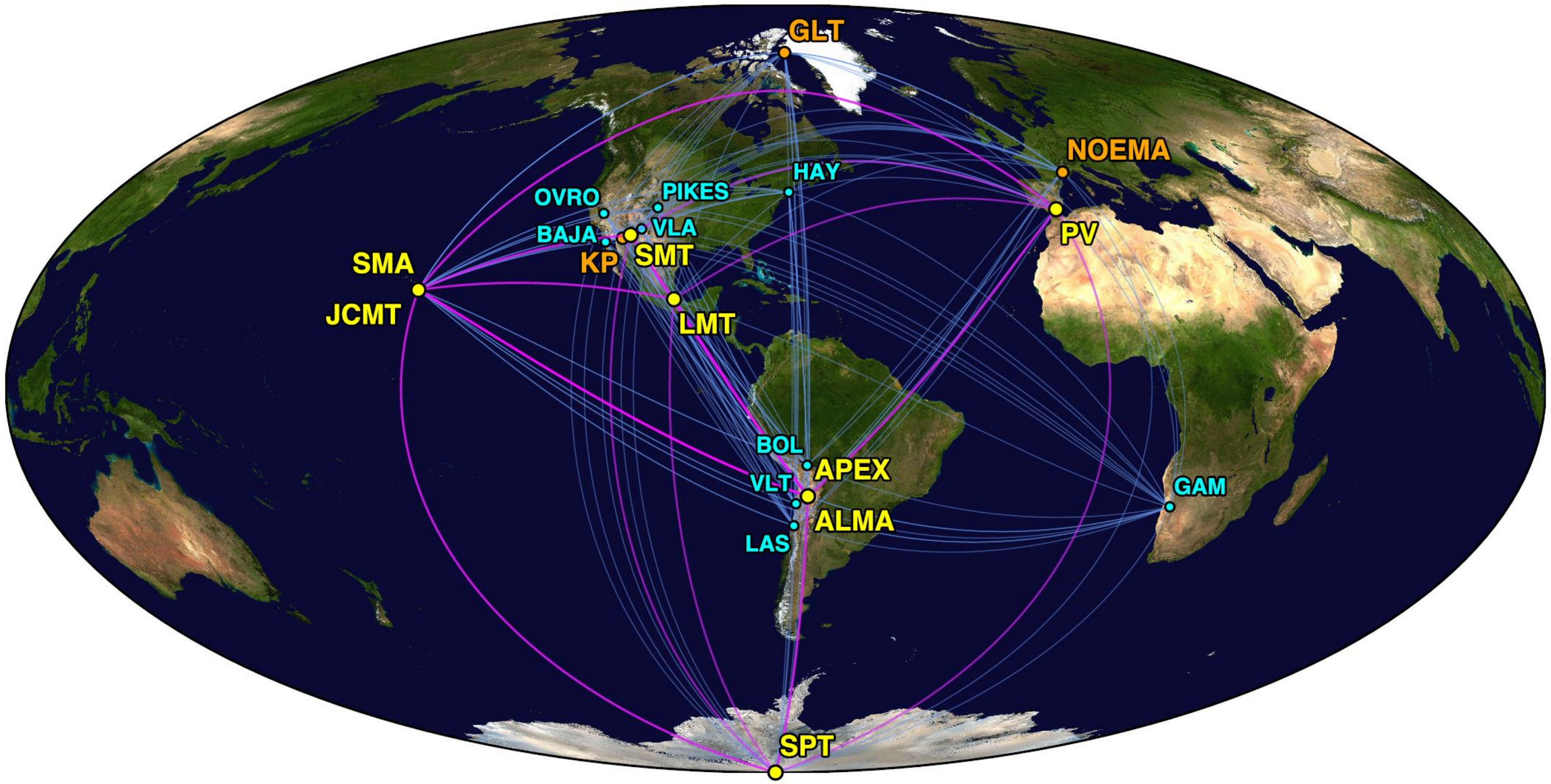


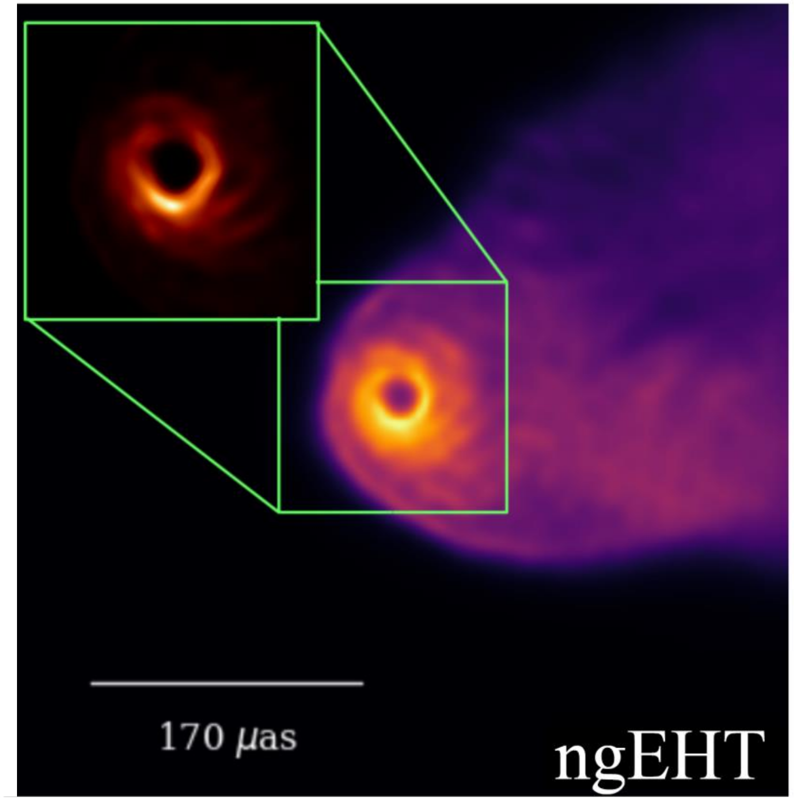
The current EHT lacks many <u>short</u> baselines, which are necessary to detect extended structure.

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)

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

- 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