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

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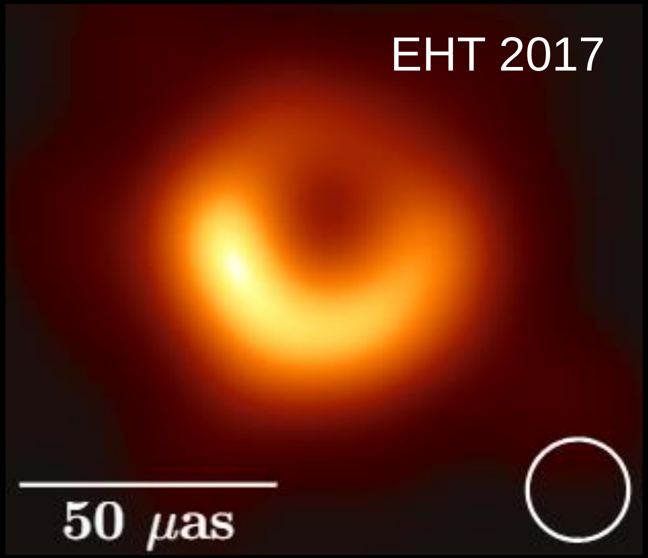
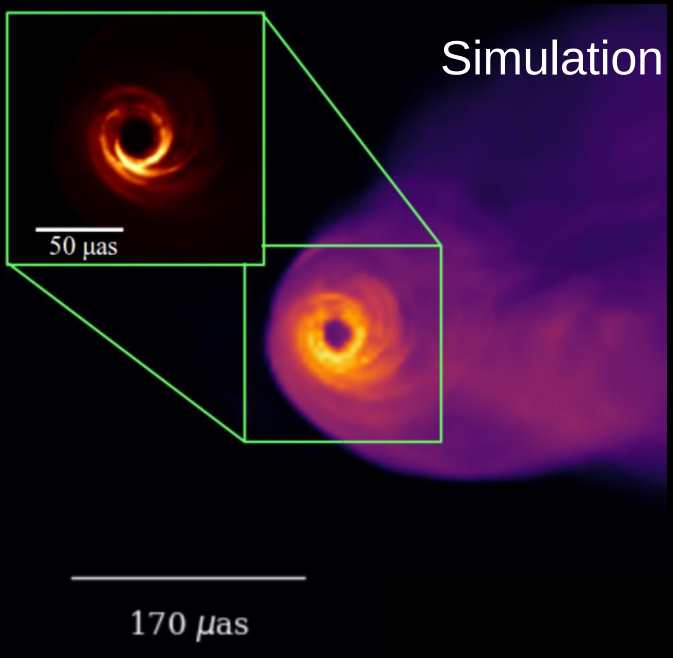




NASA
PRINCETON UNIVERSITY
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN
Event Horizon Telescope

The EHT Collaboration

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

M87

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

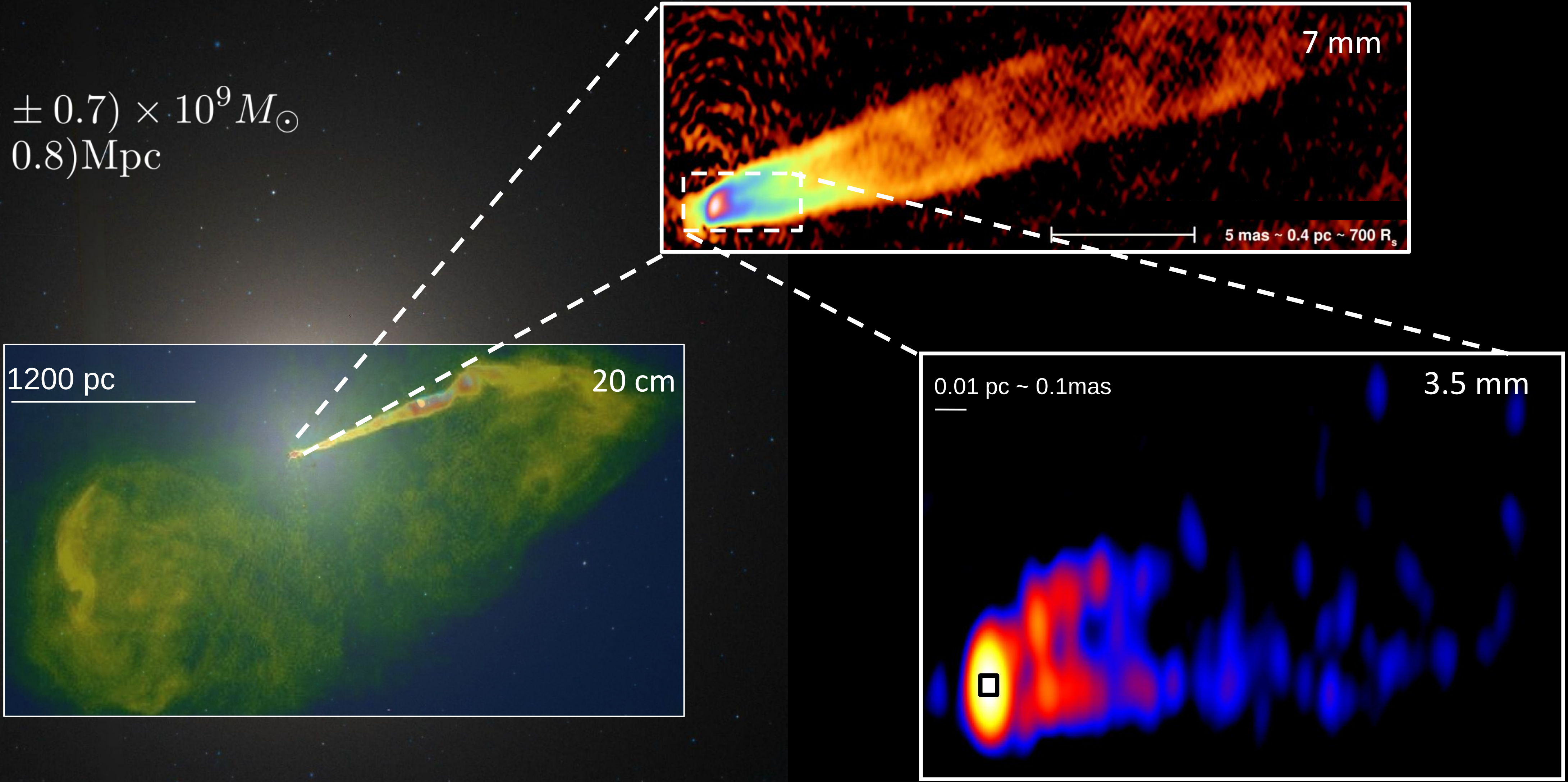


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

At the heart of M87…

- 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?

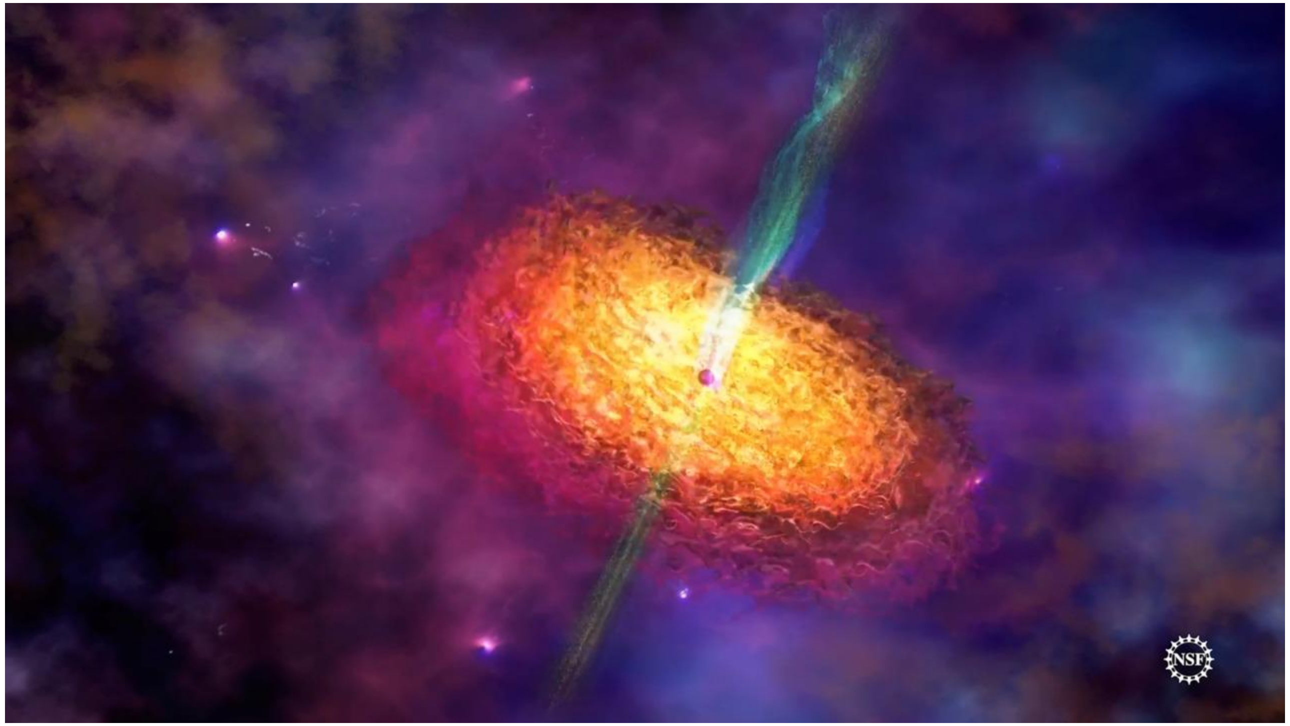
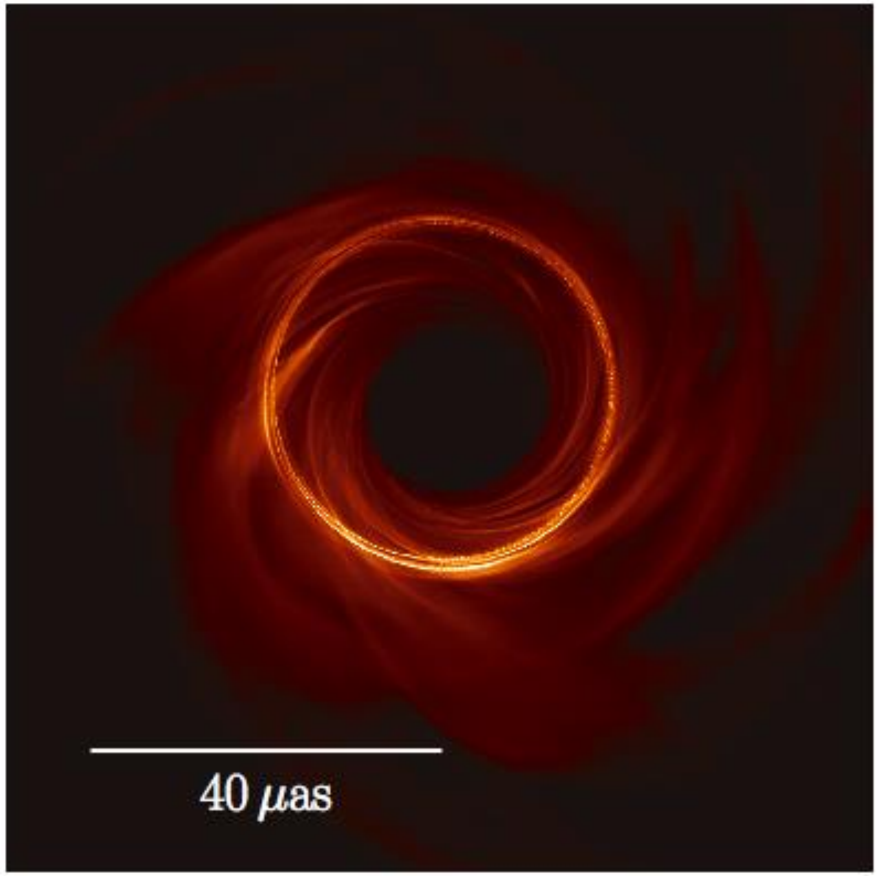


Image credit: National Science Foundation

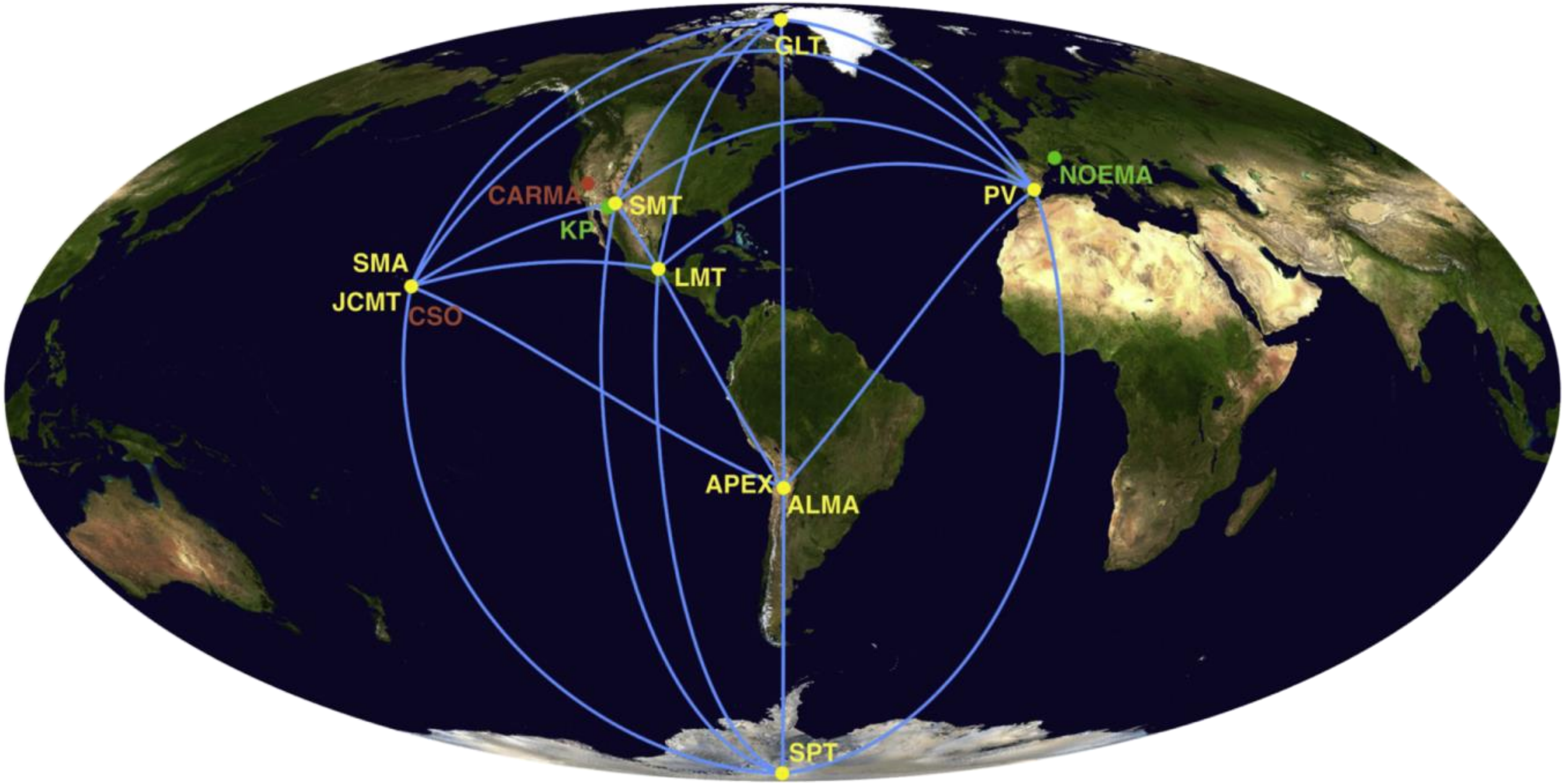
What does a black hole look like?



Modern Simulations
EHTC+ 2019

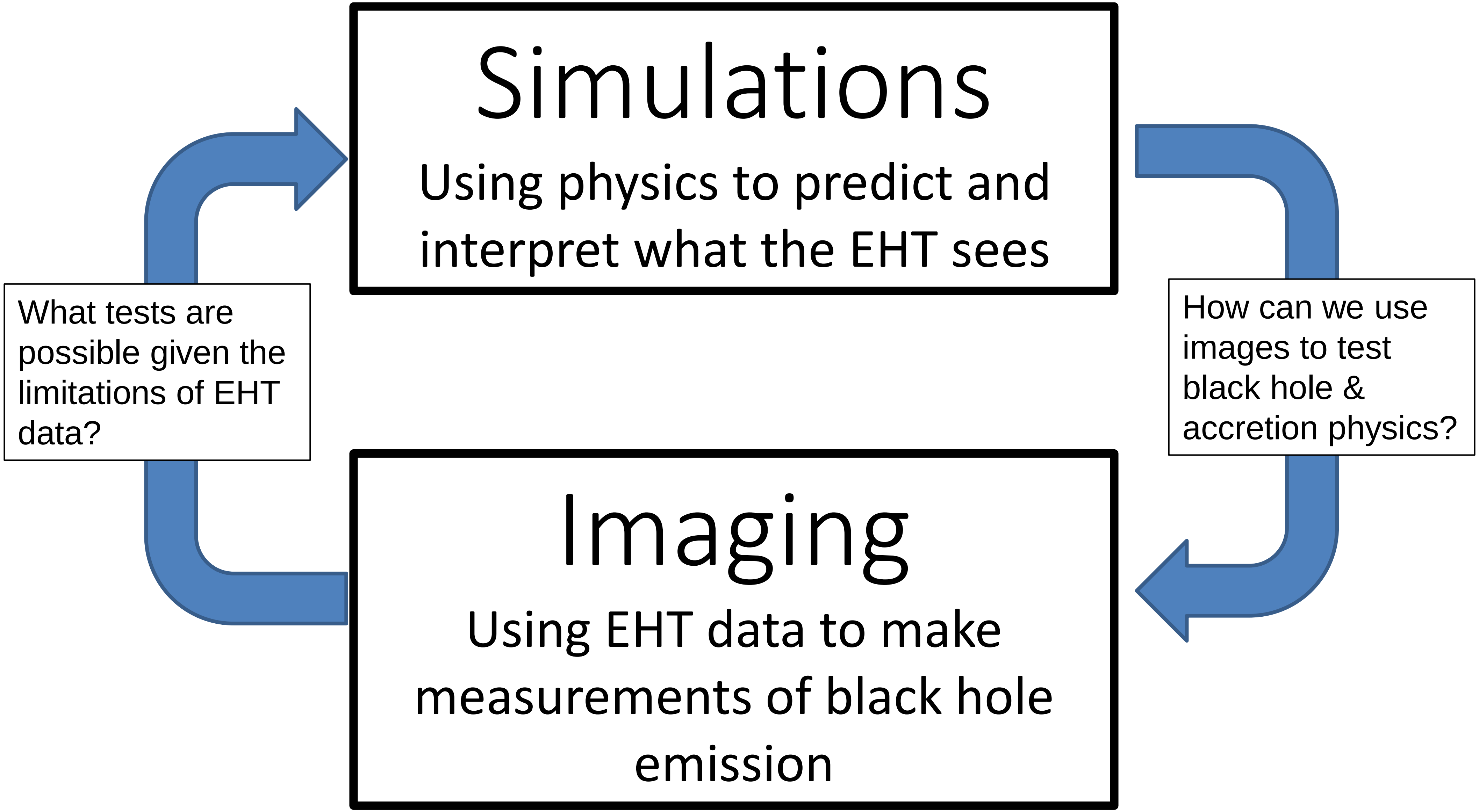
$$r_{\mathrm{shadow}} = \sqrt{27} GM/c^2$$

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

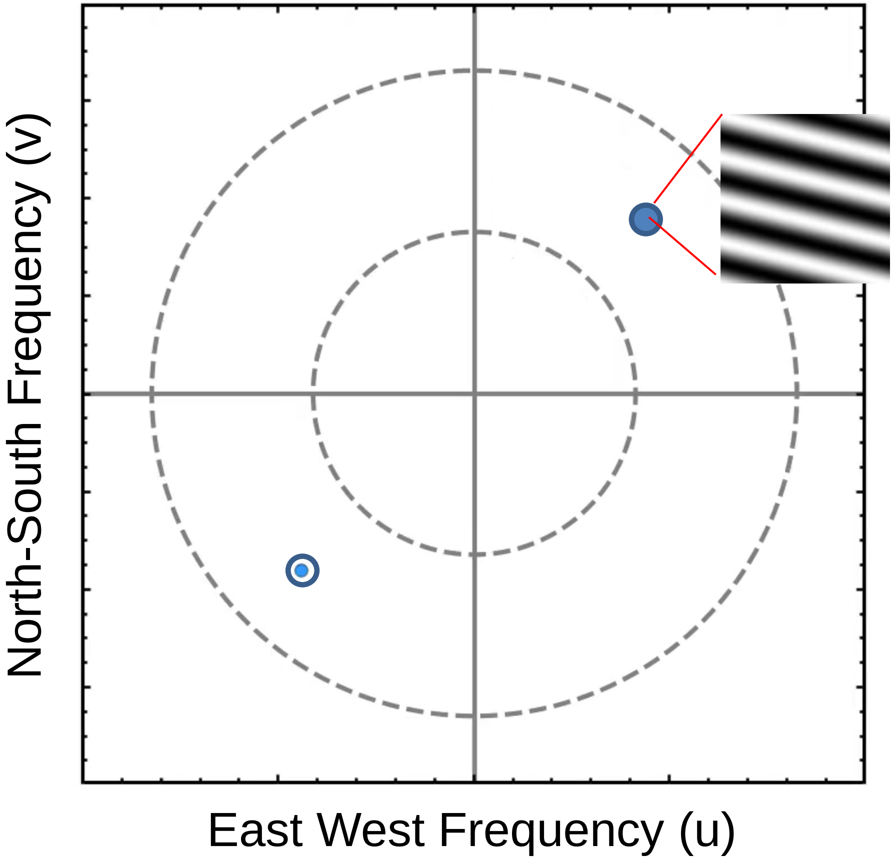
How can we use images to test black hole & accretion physics?

Imaging

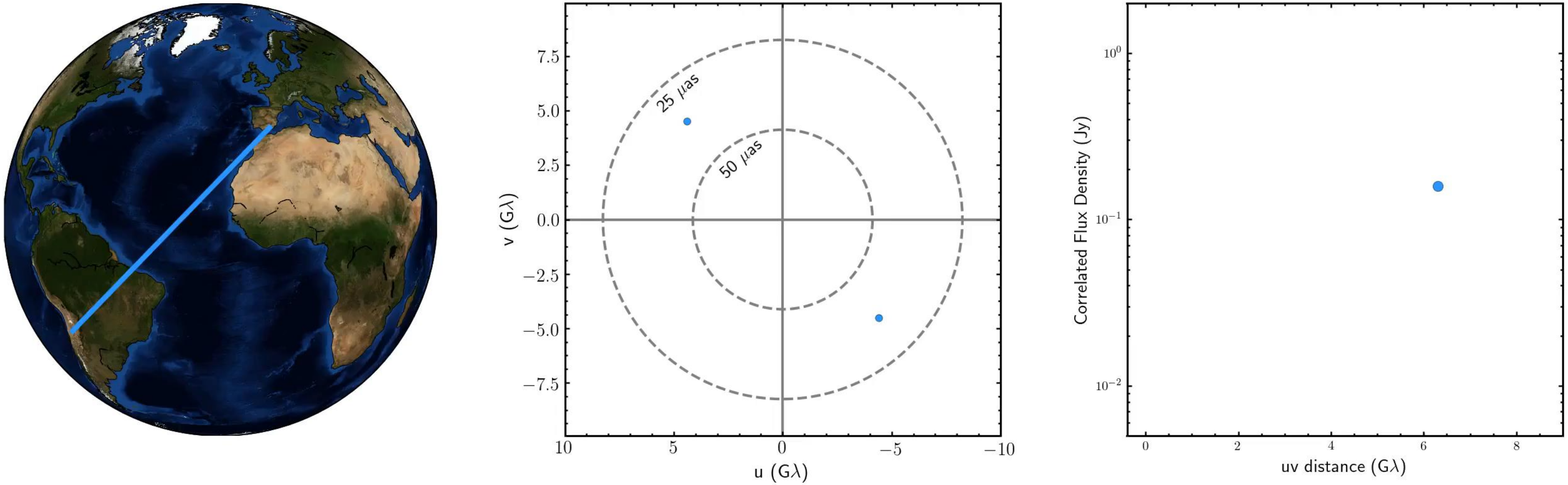
Using EHT data to make measurements of black hole emission

What tests are possible given the limitations of EHT data?

Very Long Baseline Interferometry (VLBI)

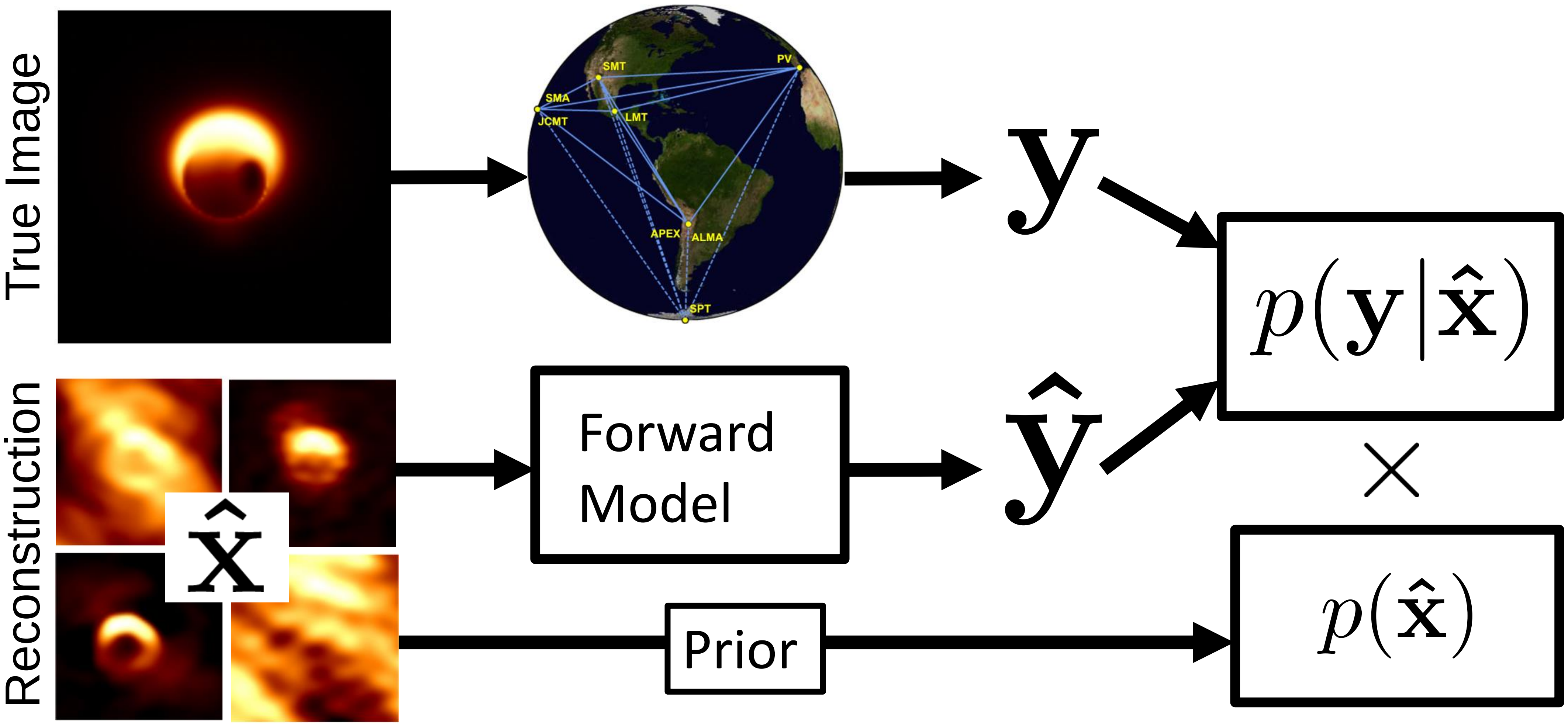


Very Long Baseline Interferometry (VLBI)



Movie Credit: Daniel Palumbo

VLBI Imaging



True Image

$\mathbf{y}$

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

$\times$

Reconstruction

$\hat{\mathbf{x}}$

Forward Model

$\hat{\mathbf{y}}$

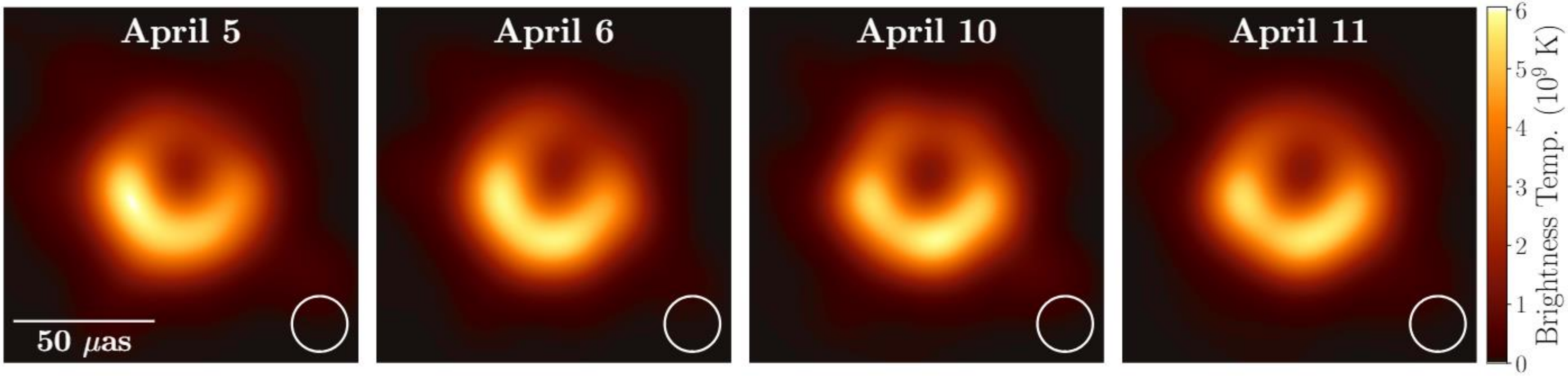
Prior

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

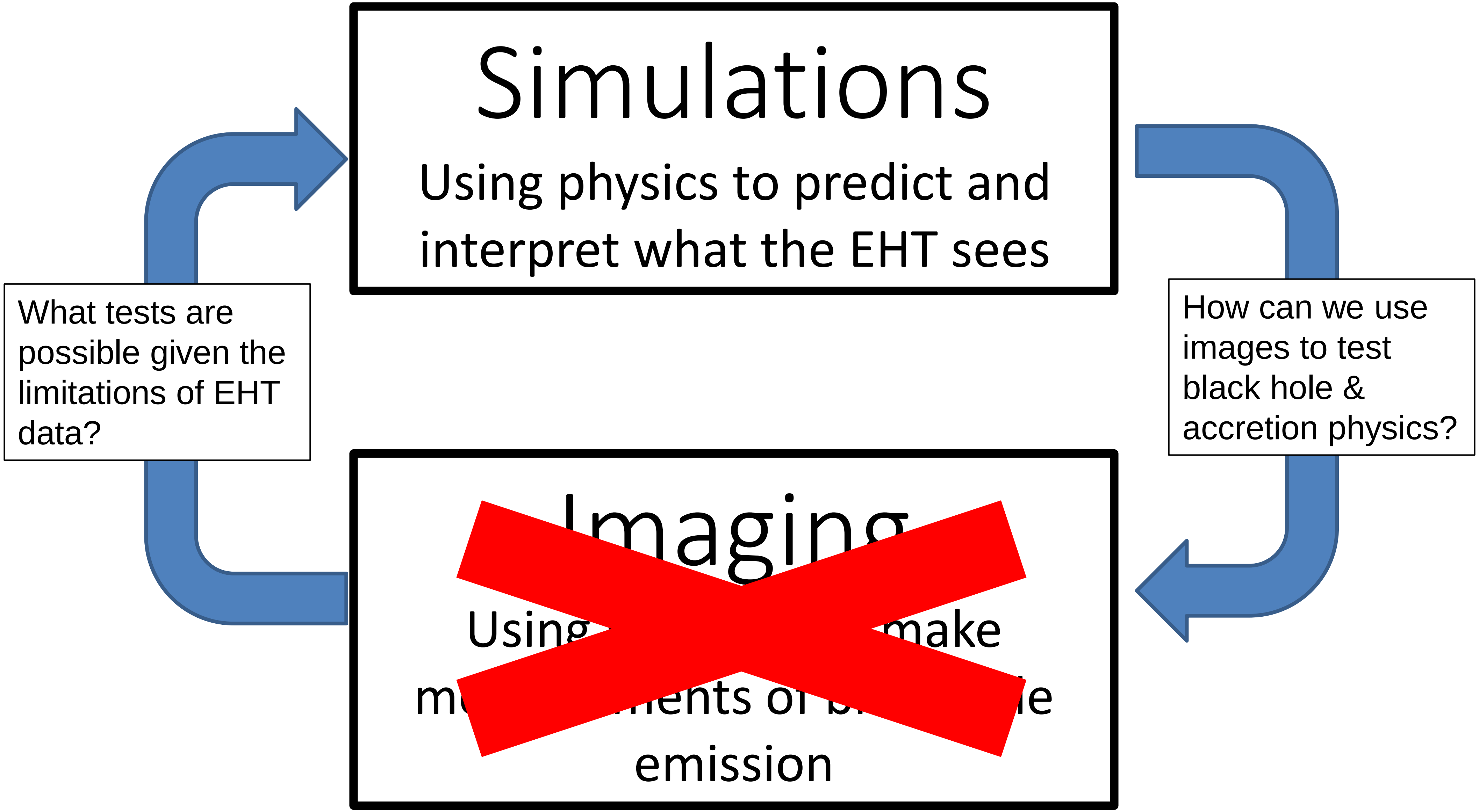
Image Credit: Katie Bouman
Simulation Credit: Avery Broderick

After lots of work….

M87’s black hole across four days in 2017



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



Simulations

Using physics to predict and interpret what the EHT sees

How can we use images to test black hole & accretion physics?

~~Imaging~~

~~Using~~ ~~make~~

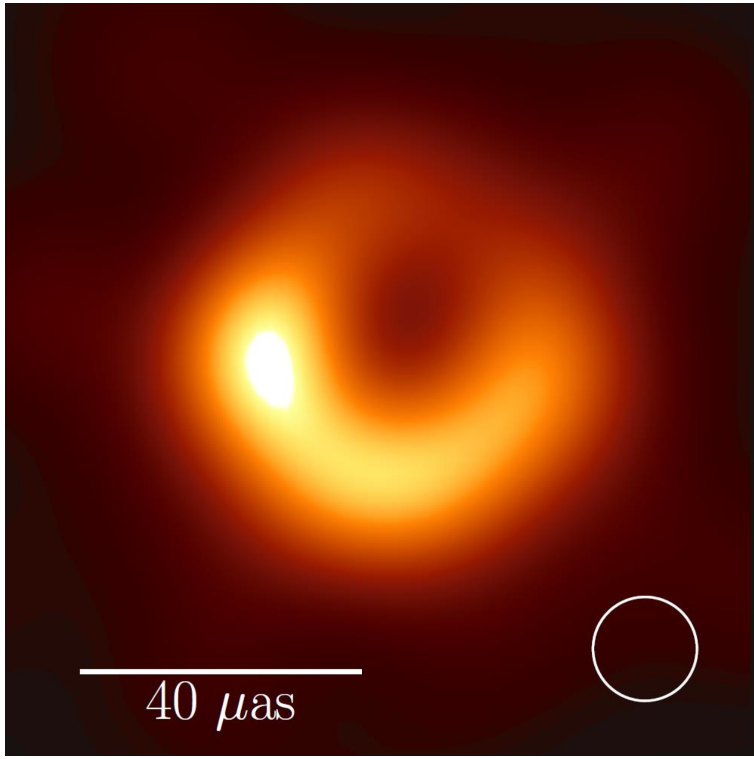
~~m~~ ~~ents of b~~ ~~e~~

~~emission~~

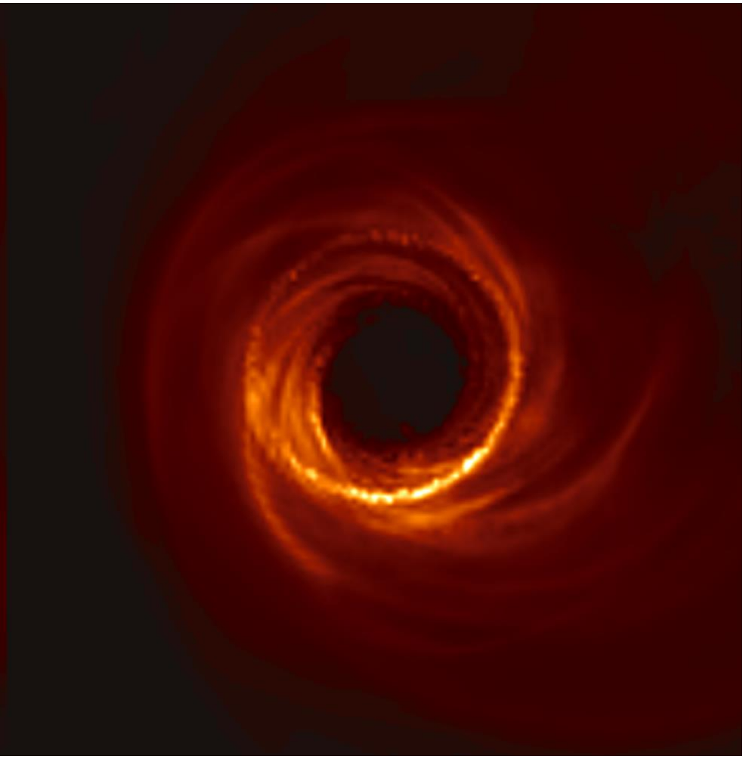
What tests are possible given the limitations of EHT data?

The Black Hole in M87: Simulations and Images

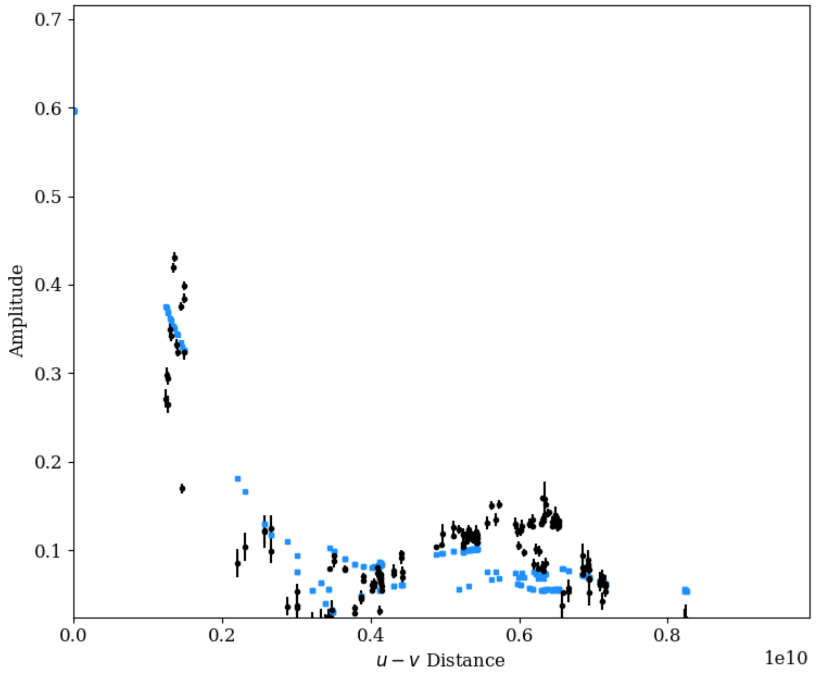
EHT 2017 image



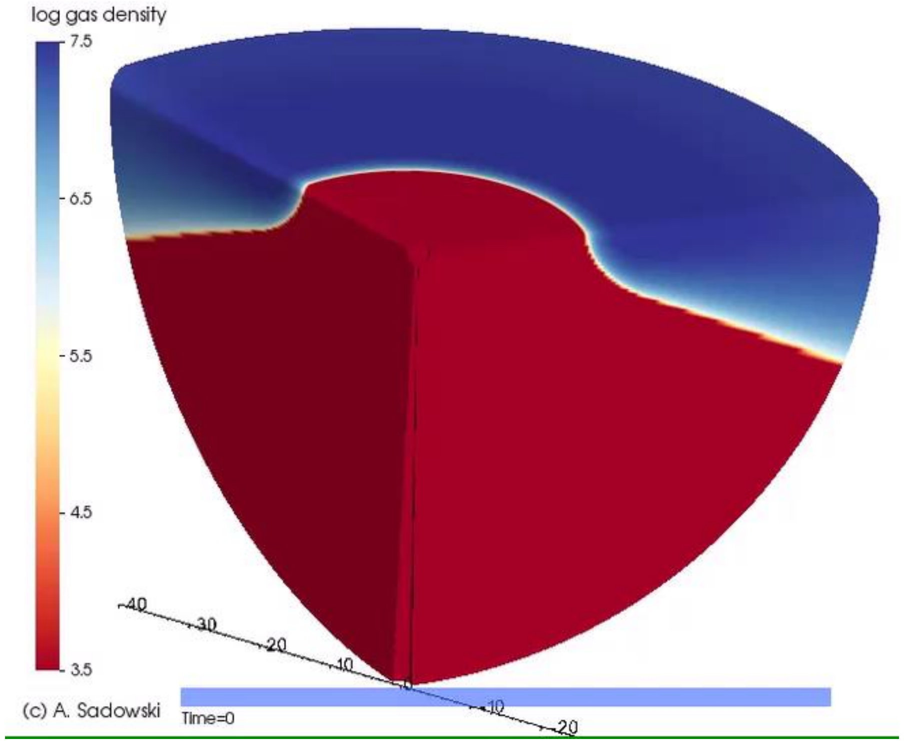
Simulated image from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes

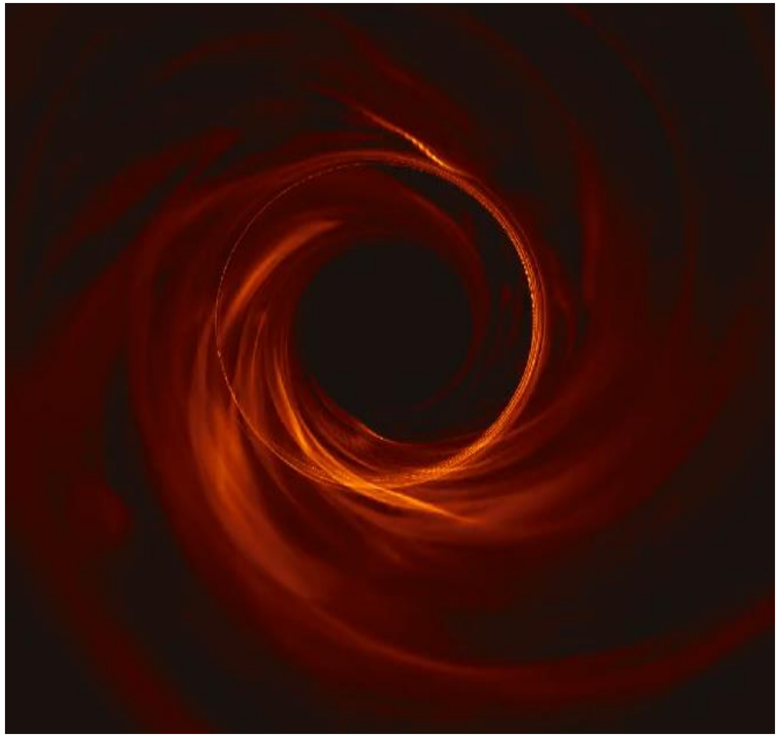


General **R**elativistic **M**agneto**H**ydro**D**ynamics (GRMHD)



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 influence images from simulations?

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

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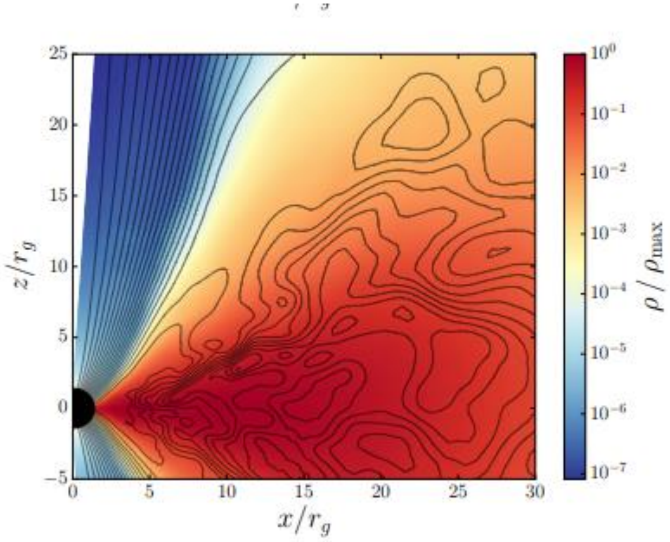
2. (Radiative) Magnetohydrodynamics: $\dot{M}, \Phi_B$
    - Does the magnetic field arrest accretion?
    - How does the B-field determine the jet power & shape?

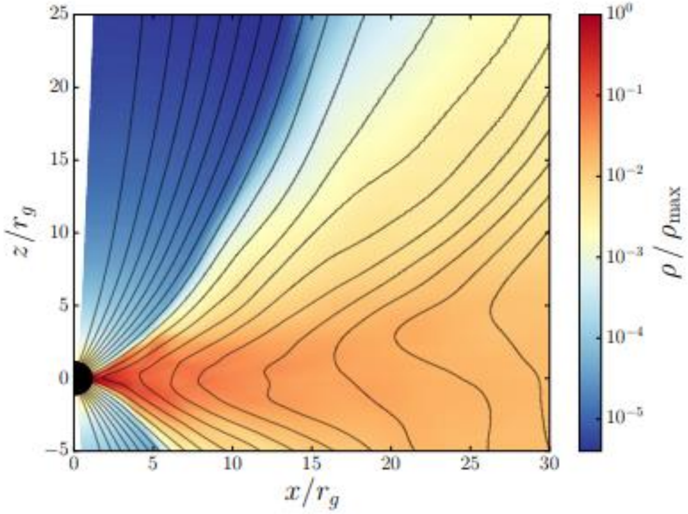
SANE vs MAD

- 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:

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

Image credit: Riordan+ 2017

What parameters influence images from simulations?

1. Spacetime geometry: M, a
    - Liberating potential energy heats the plasma.
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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?**

M87 and Sgr A* are **Two-Temperature** Flows

- Inefficient Coulomb coupling between ions and electrons.

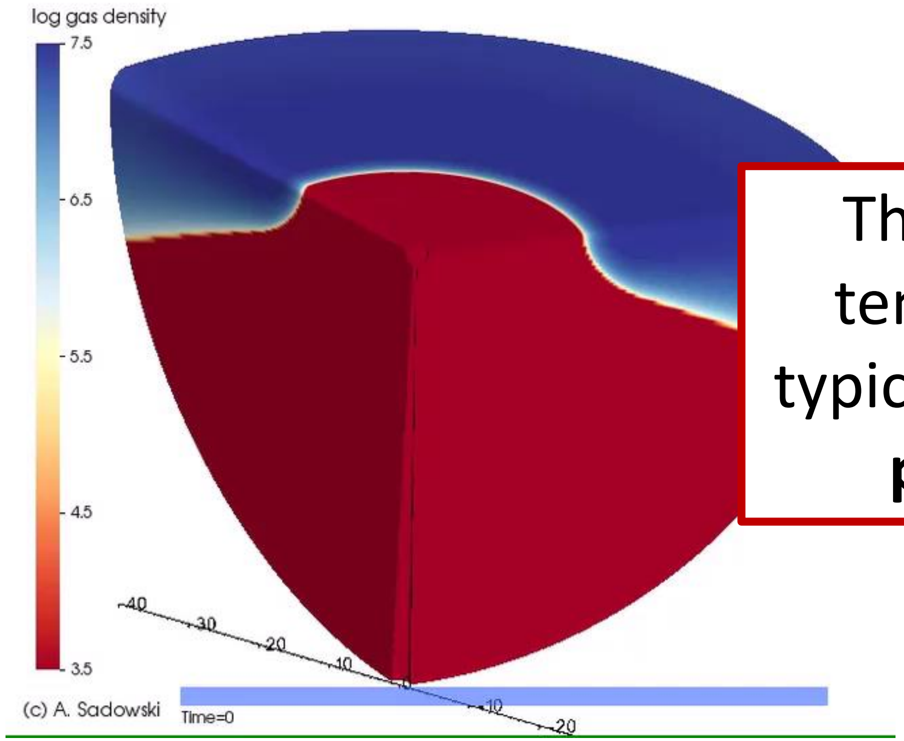
$$T_{\mathrm{e}} \neq T_{\mathrm{i}} \neq T_{\mathrm{gas}}$$

- 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



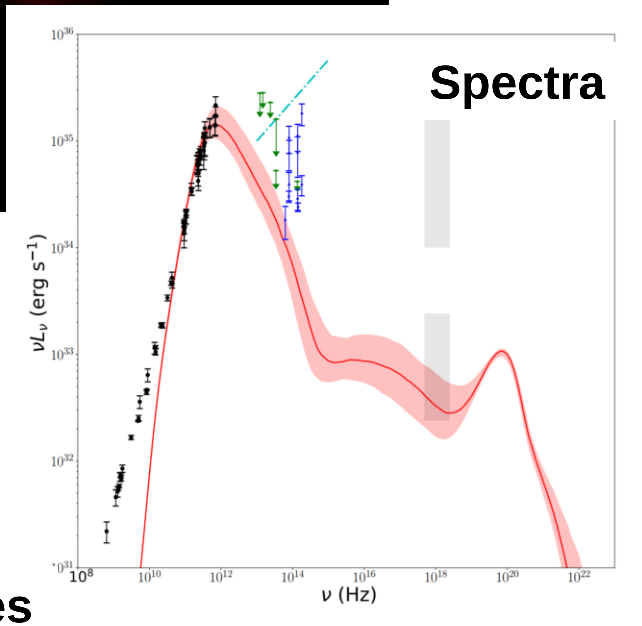
The electron-to-ion temperature ratio is typically set **manually** in **post-processing**

GRMHD Simulations

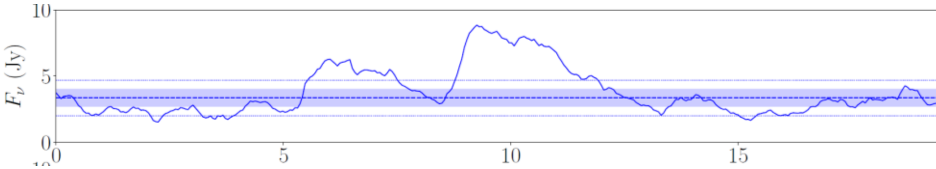
Usually evolve a **single** fluid and magnetic field

Images

Spectra



Light Curves



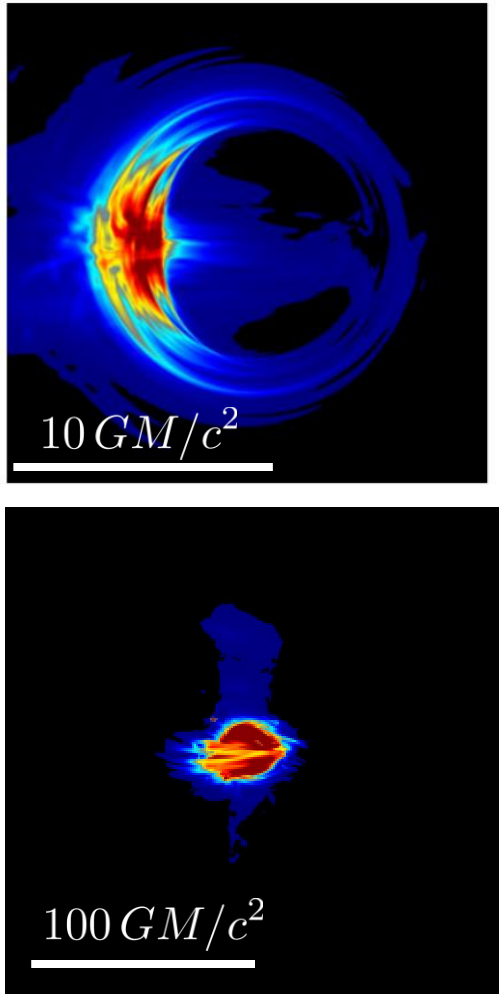
Movie & Image Credits: Aleksander Sądowski, Chael+ 2018b

Setting T_{e} in post-processing

Different Choices → Different Images!

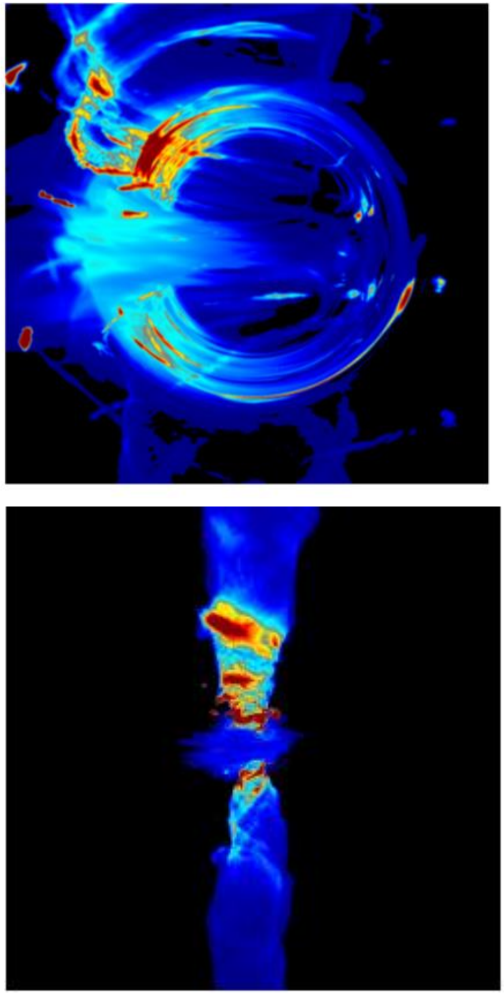
Hot Disk

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



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

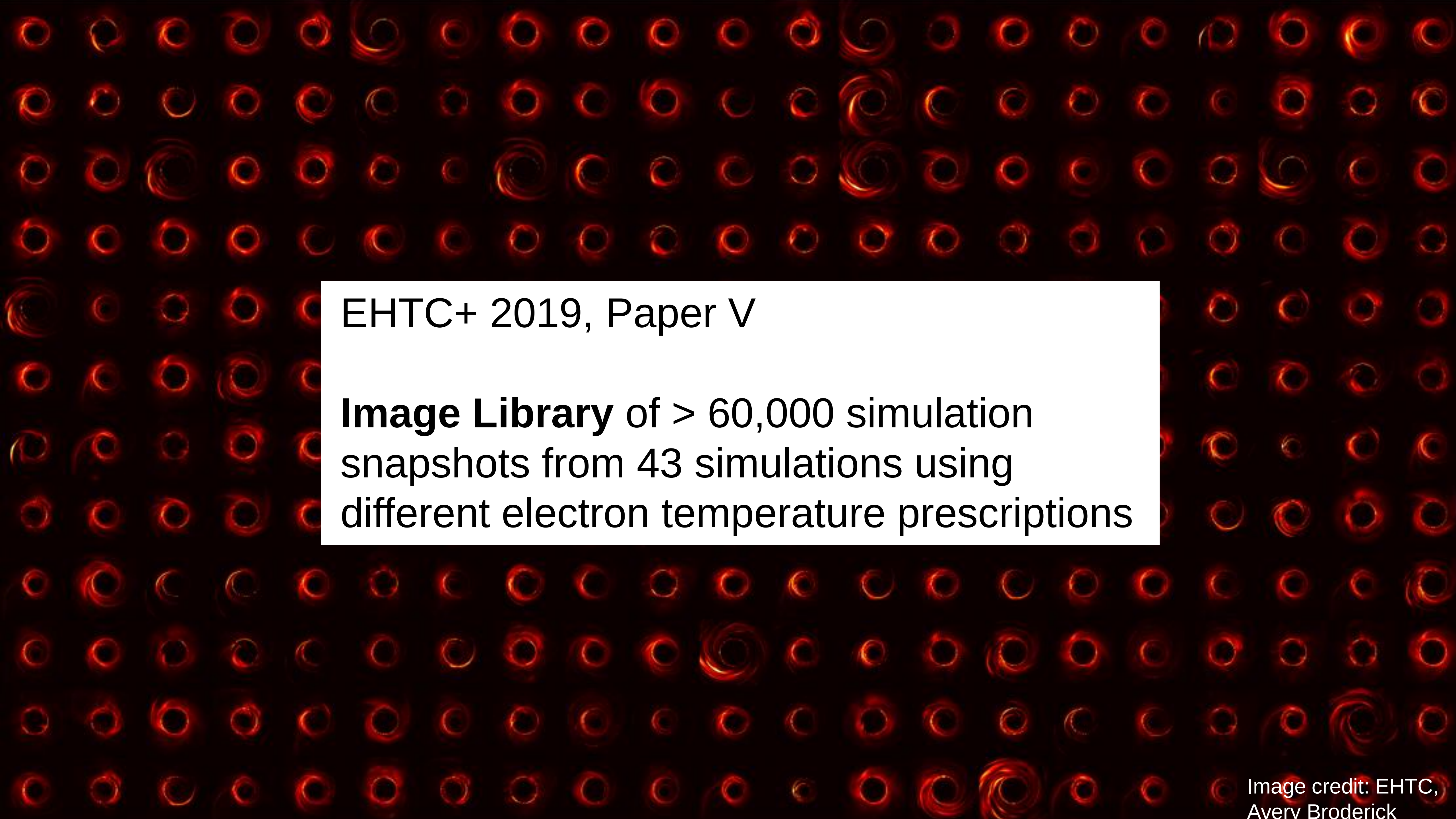
$$\lambda = 7\mathrm{mm}$$



Cool Disk

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

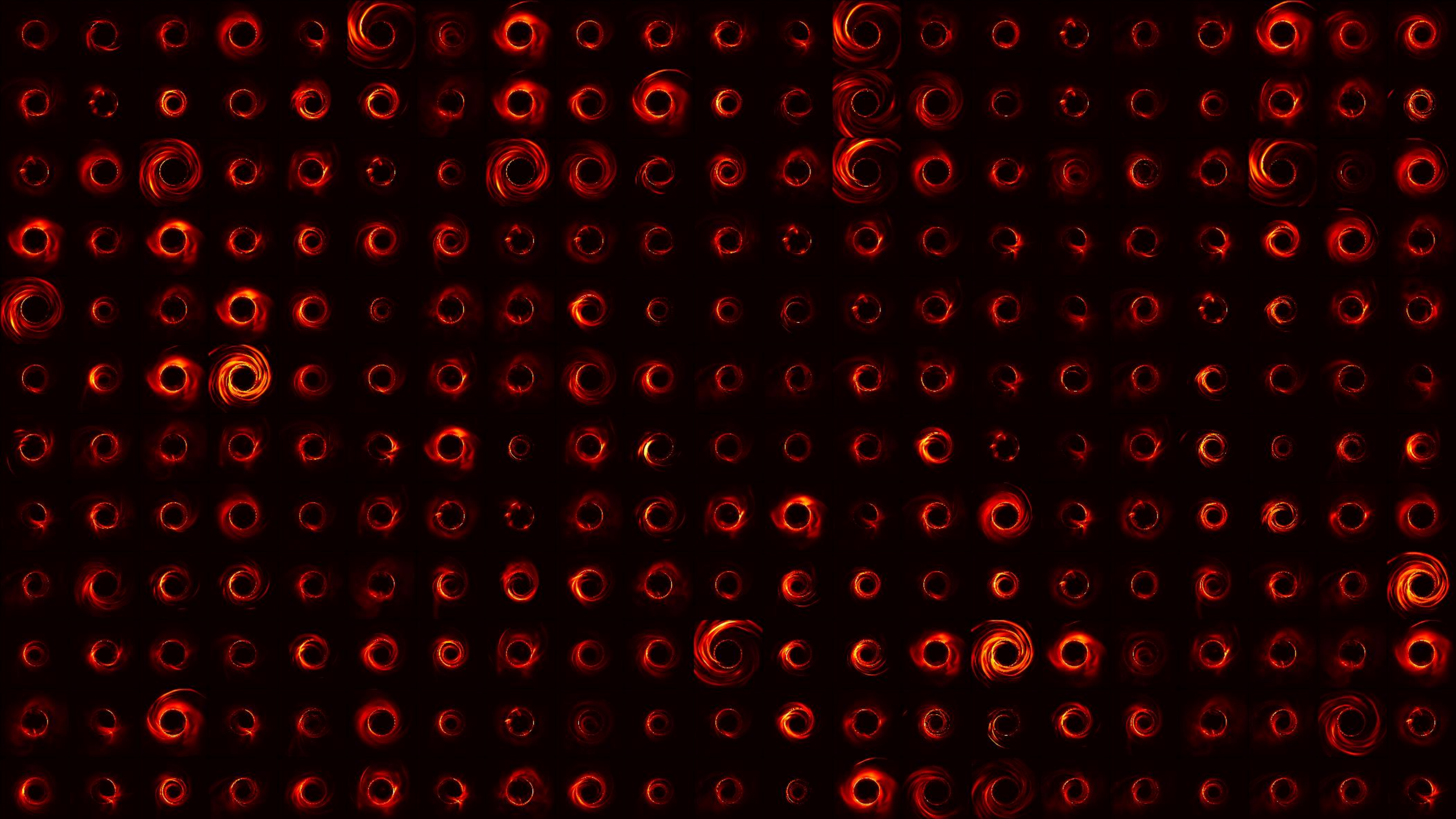
Mościbrodzka+ 2014



EHTC+ 2019, Paper V

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…)

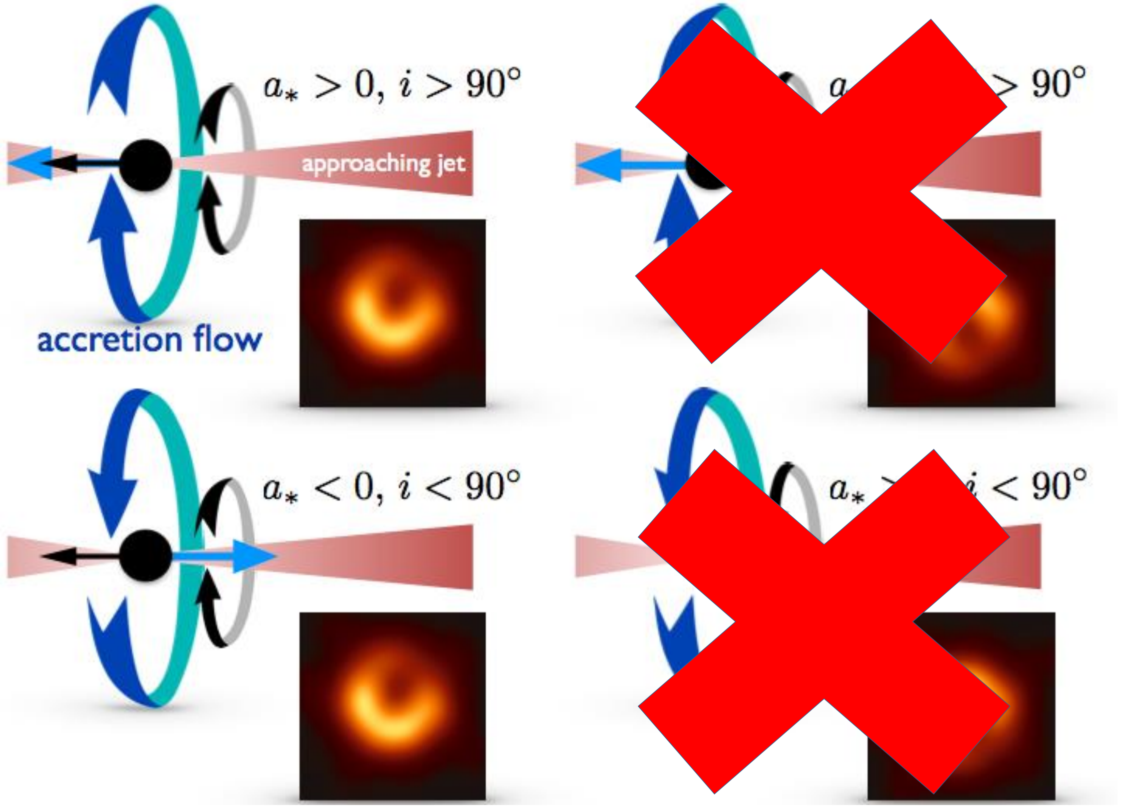
- The jet power constraint (**$\geq 10^{42}$ erg/sec**) rejects all spin 0 models
  SANE models with |a| < 0.5 are rejected.
  Most |a| > 0 MAD models are acceptable.

- Jet power in all surviving models is extracted from BH spin:

Blandford-Znajek (1977): $P_{\rm jet} \propto \Phi_B^2 a^2$

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 Results

- Reason to suspect the system may be MAD and/or high spin

- Electron temperature assumptions are important in determining image structure

- Can we learn more from also comparing to lower frequency images?

M87

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

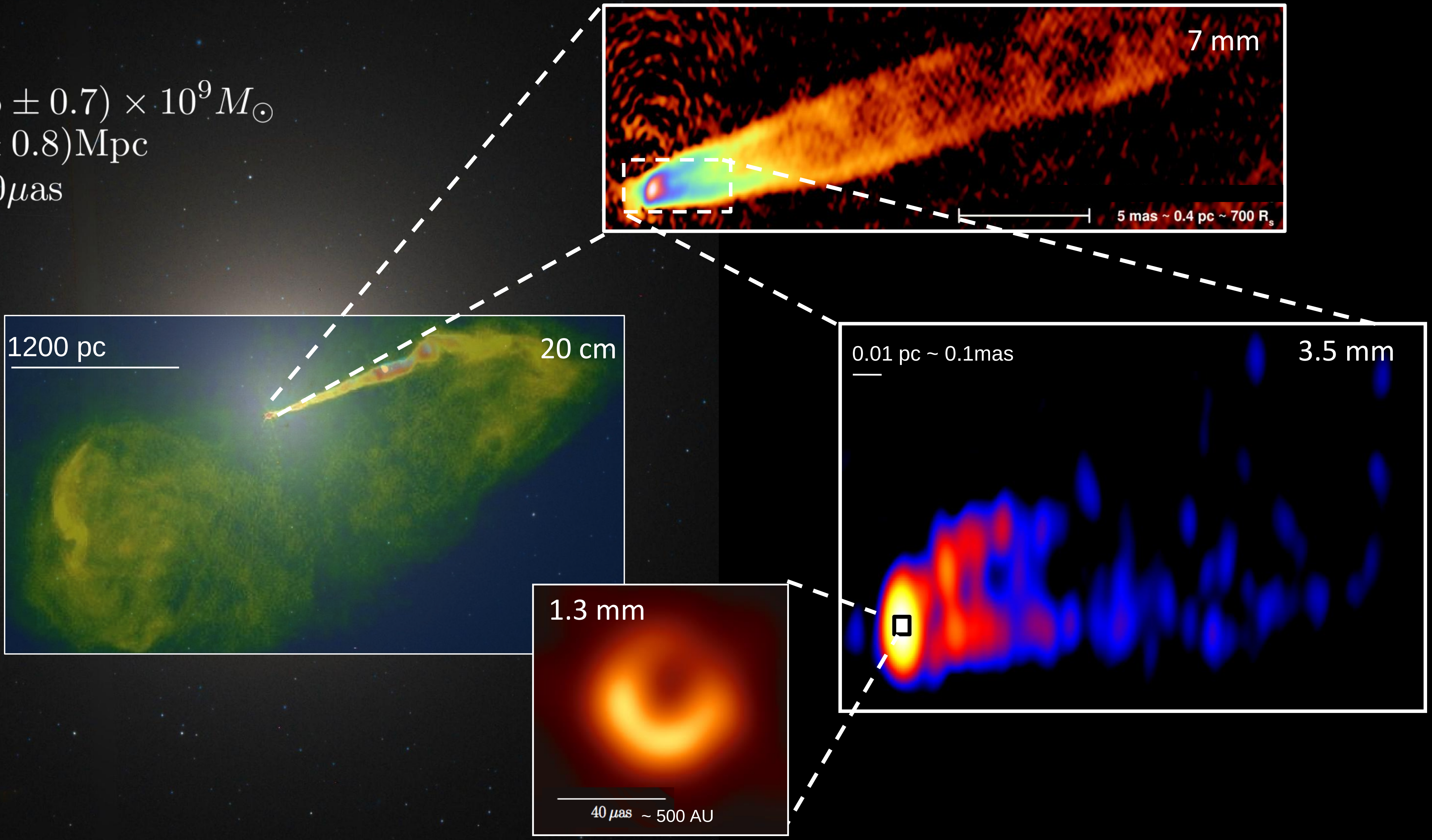


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

Goal: investigate the effects of microscale electron heating in **self-consistent** two-temperature simulations of the EHT targets M87 and Sgr A*.

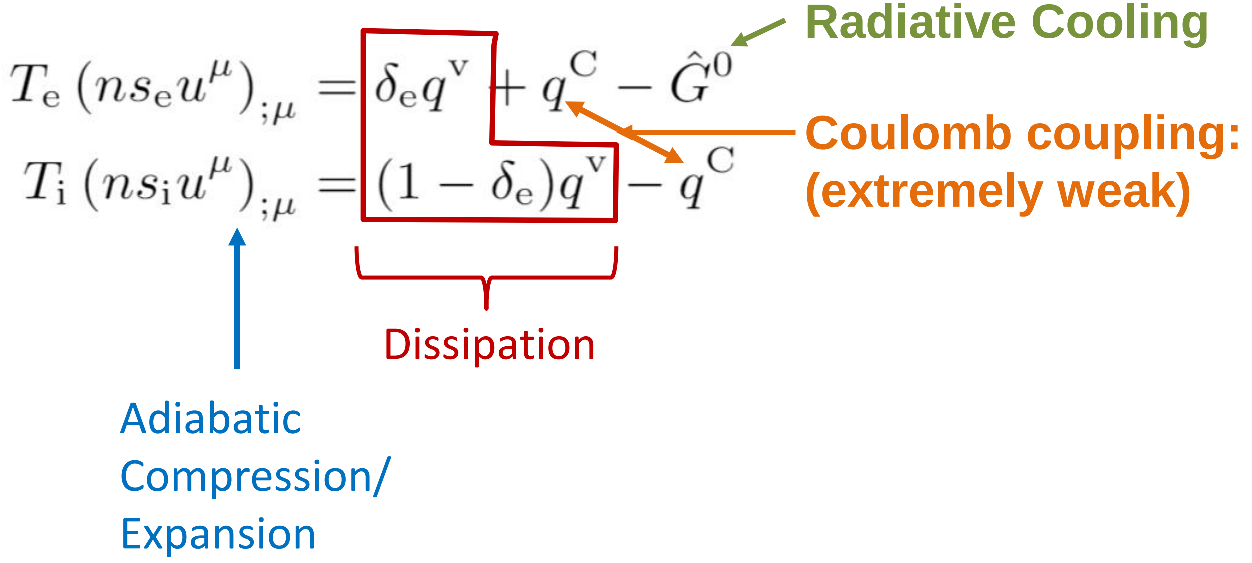
-Using the code KORAL: (Sądowski+ 2013, 2015, 2017)
-Previous work by:
  Ressler+ 2017 (Sgr A*)
  Ryan+ 2018 (M87)

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 covariant 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)

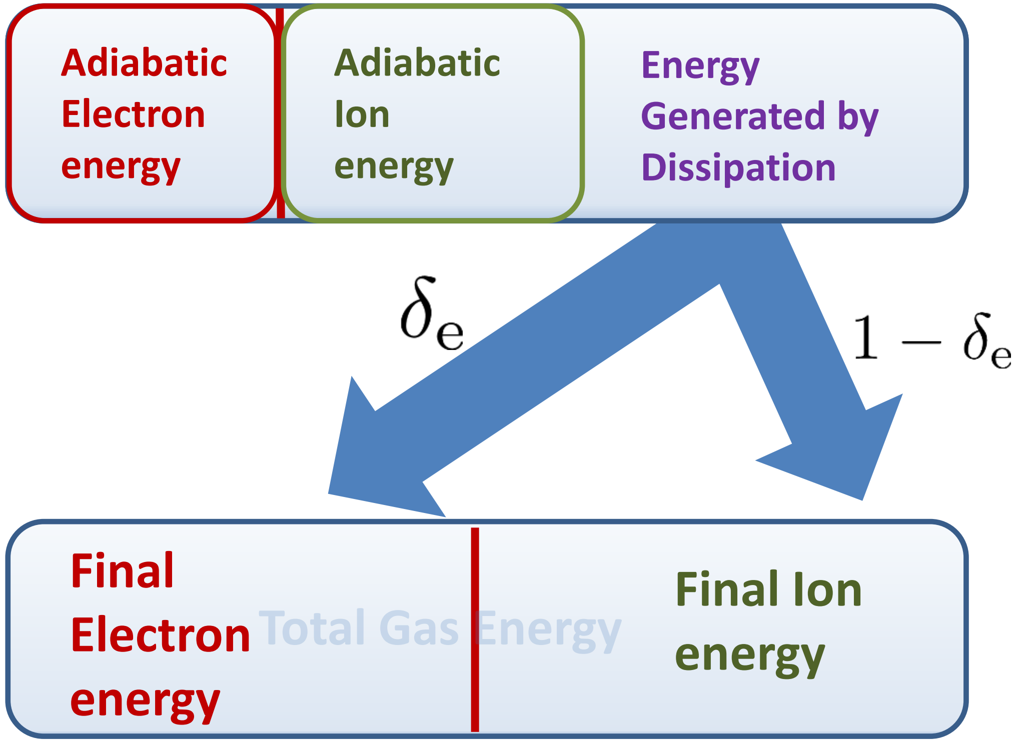
Dissipation

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.

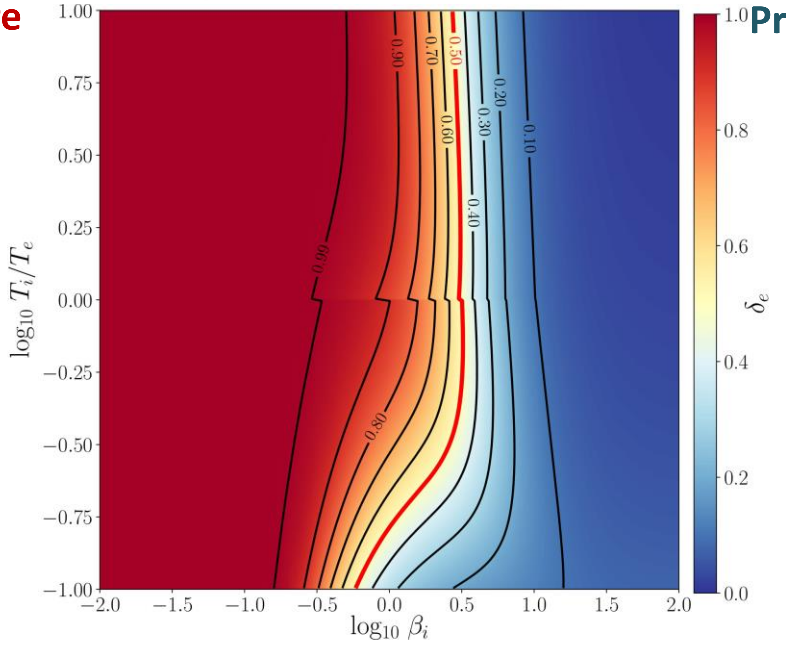


Sub-grid Heating Prescriptions

Turbulent Dissipation (Howes 2010)

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

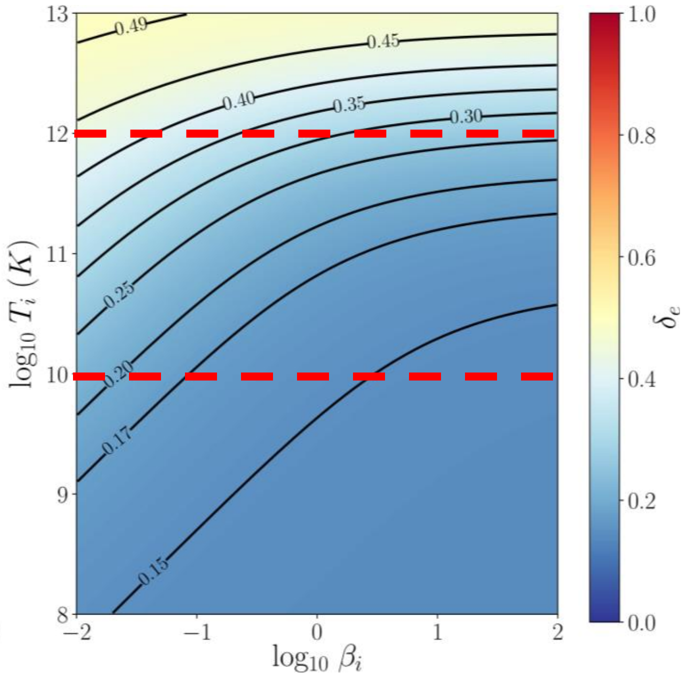
High Magnetic Pressure ⟷ **Low Magnetic Pressure**



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)

Sgr A* Simulations

Sagittarius A*

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

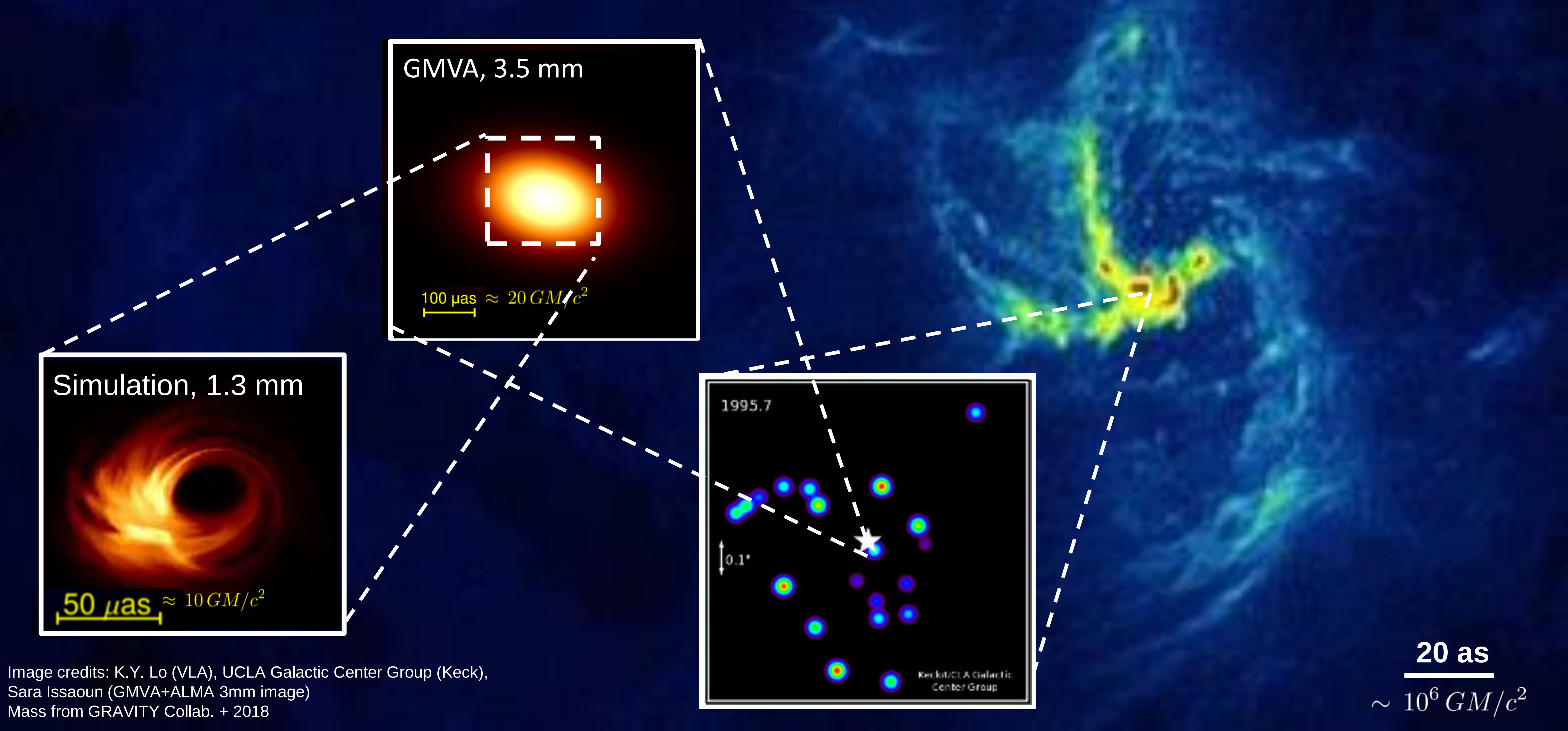
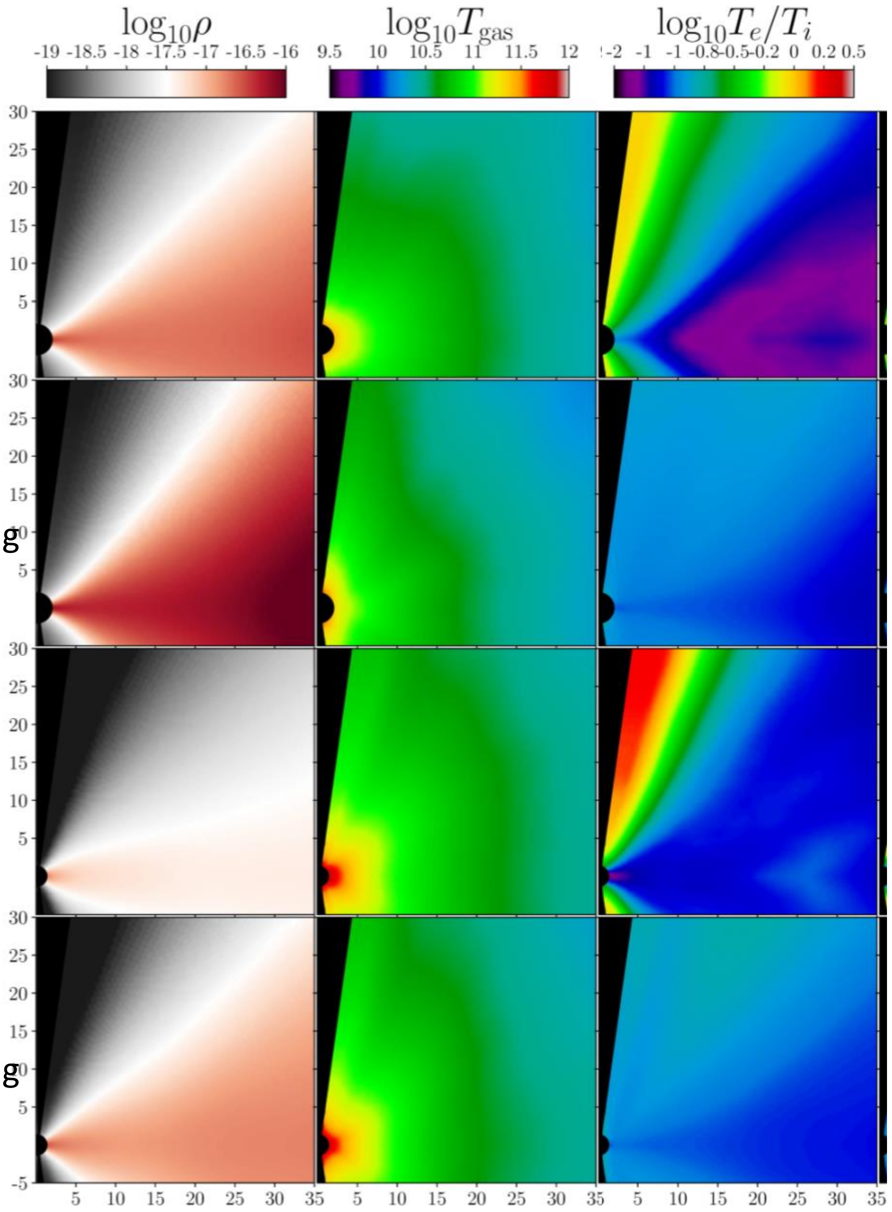


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck),
Sara Issaoun (GMVA+ALMA 3mm image)
Mass from GRAVITY Collab. + 2018

Sgr A*: *Temperature ratio*

All are thick disks: density lower at high spin



Spin 0
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Turbulent Heating

Spin 0.9375
Reconnection Heating

Temperature ratio is **highly stratified with polar angle** for turbulent heating
Electrons are **hotter** than ions in the jet

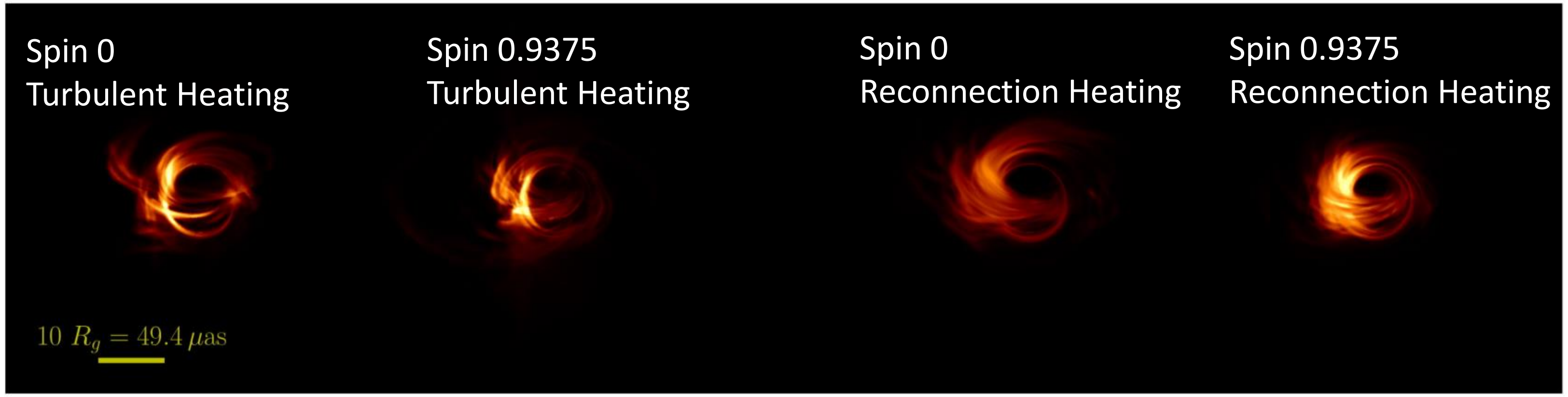
Relatively constant temperature ratio for reconnection
Electrons are cooler everywhere

Image Credit: Chael+2018b

Two-temperature simulations of Sgr A*

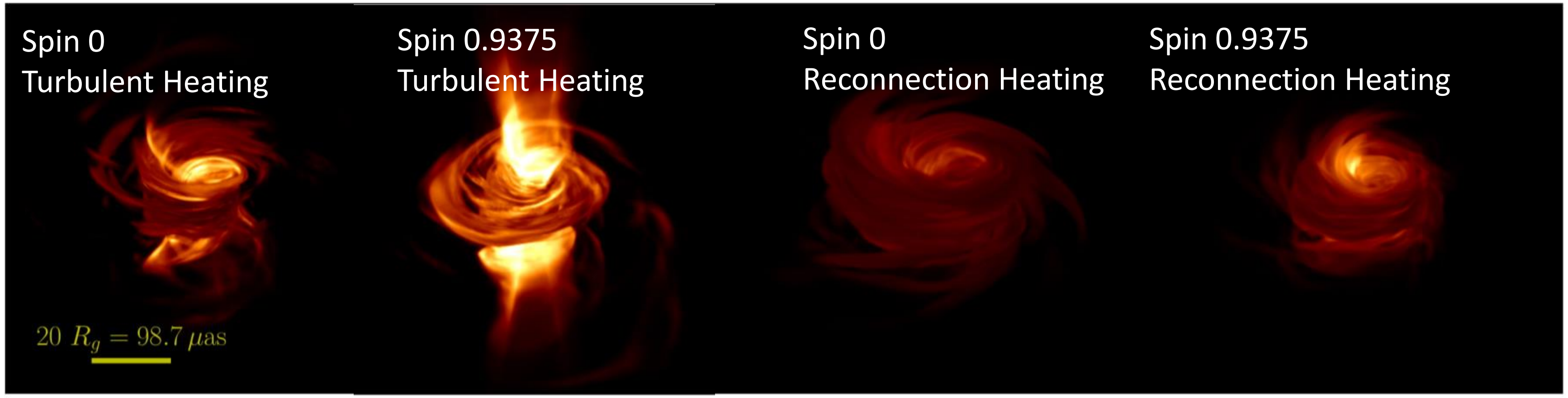
Image structure with frequency

230 GHz



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

43 GHz

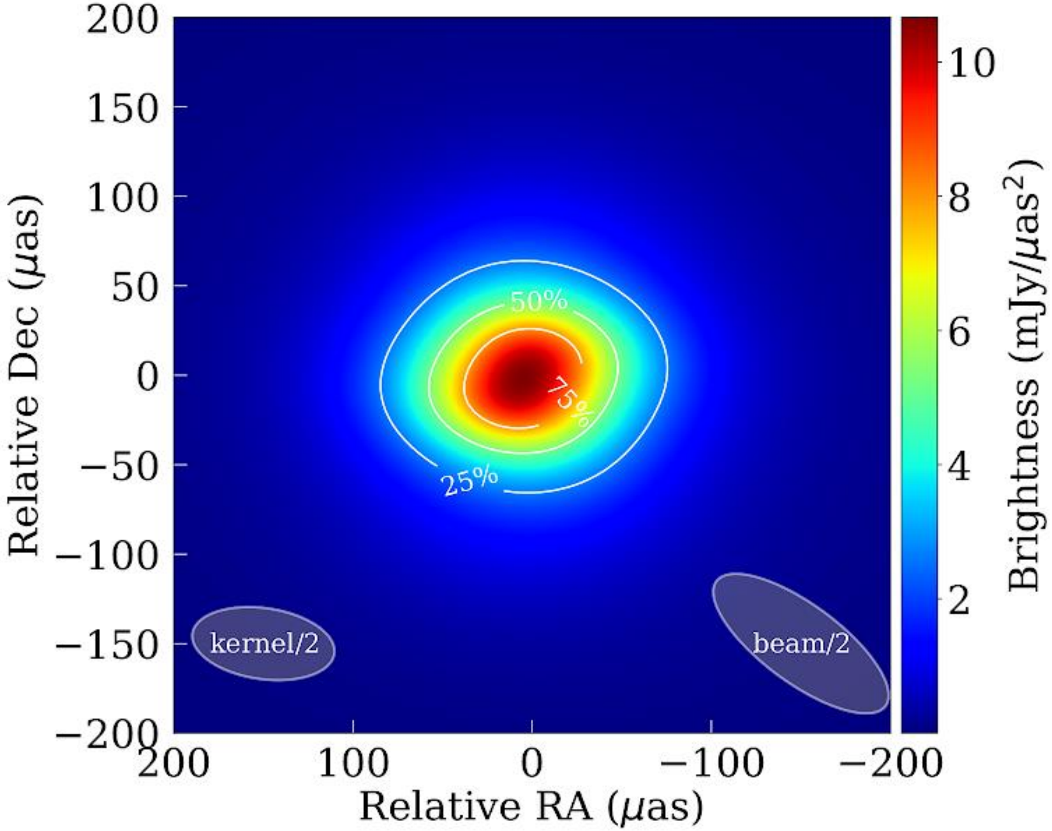


Turbulent heating makes lower frequency images jet dominated, **exceeding** measurements of anisotropy **when not viewed face-on** (Johnson+ 2018, Issaoun+ 2018)

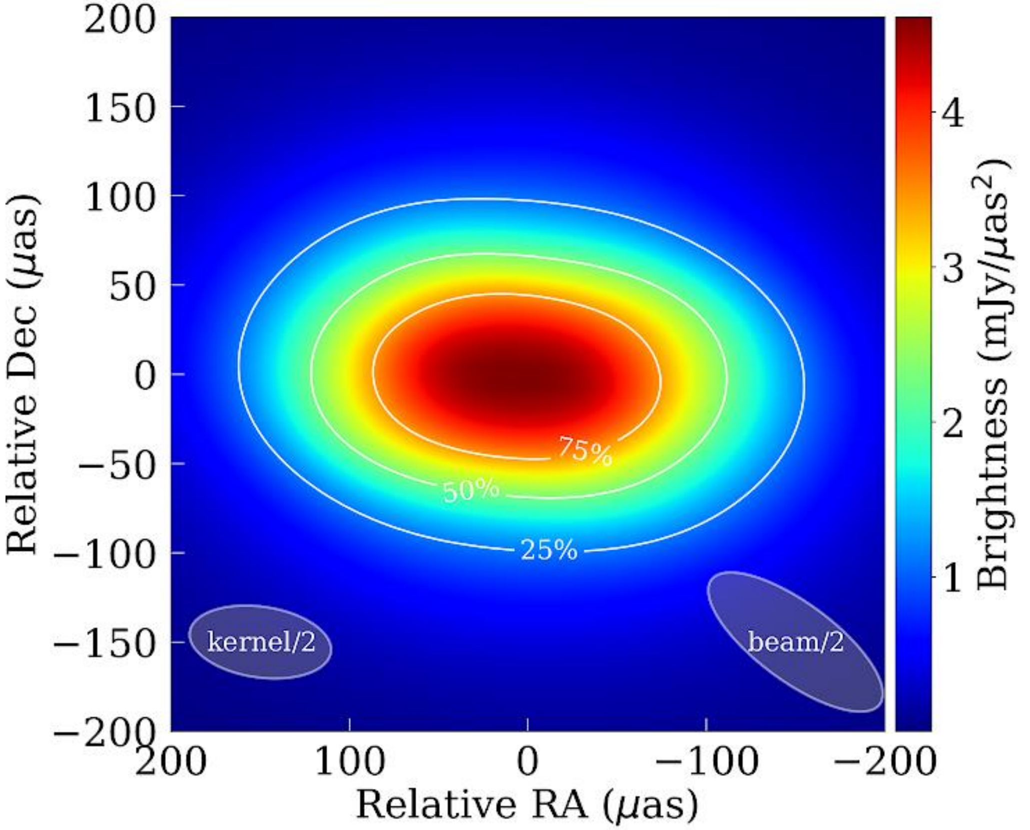
Chael+ 2018

First **Intrinsic** Image of Sgr A* at 3.5 mm

and the first VLBI with ALMA (Issaoun+ 2018)

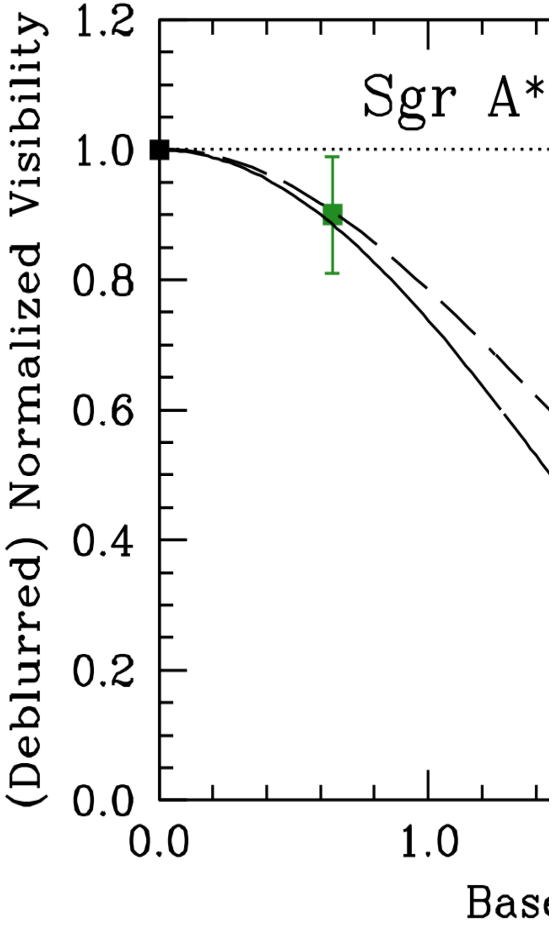

De-scattered

Deblurring and phase correction
(Johnson+ 16)

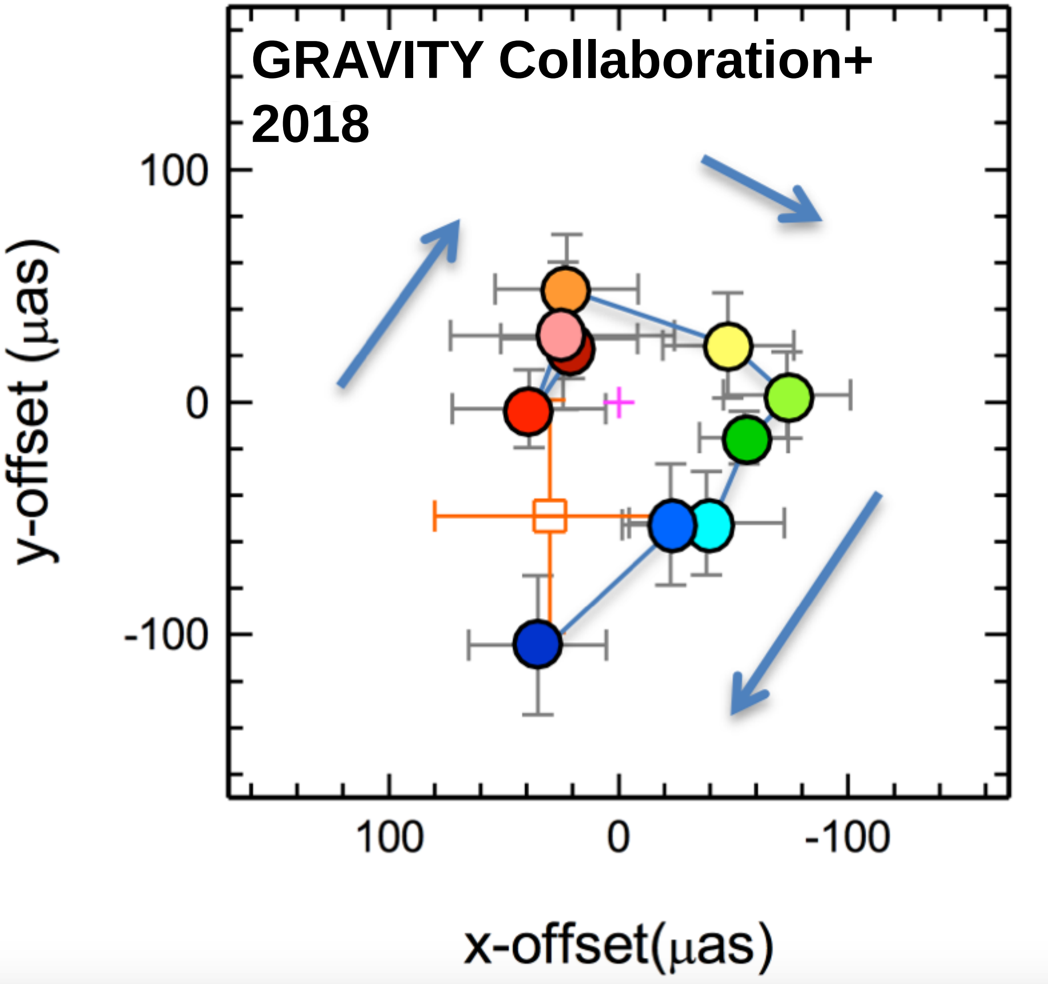

Scattered Image

New constraints on Sgr A* asymmetry at 3.5 mm rule out edge-on jet!

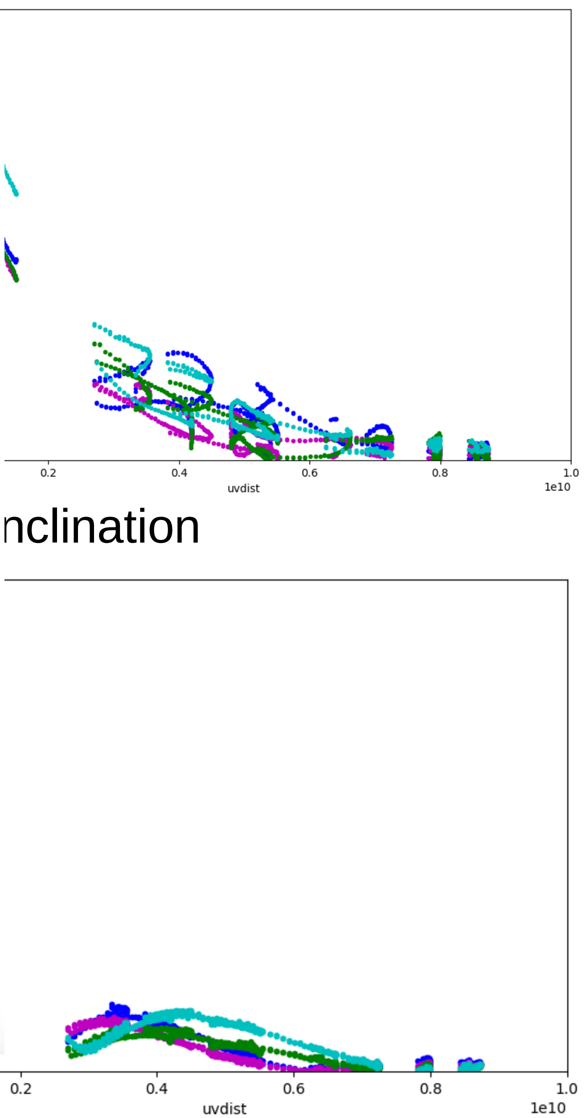
Comparison with EHT 230 GHz measurements: Inclination dependence



Johnson+ (2015)

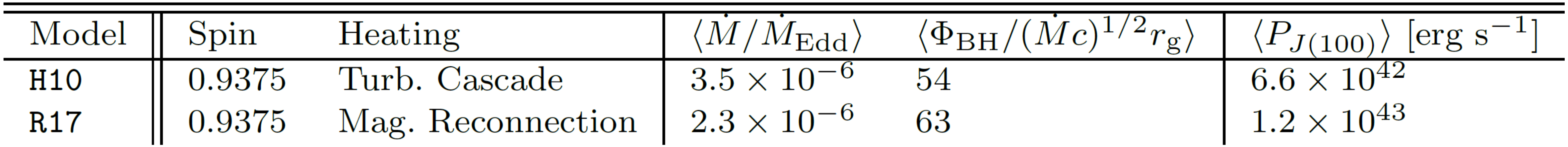


60 degree inclination



M87 Simulations

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

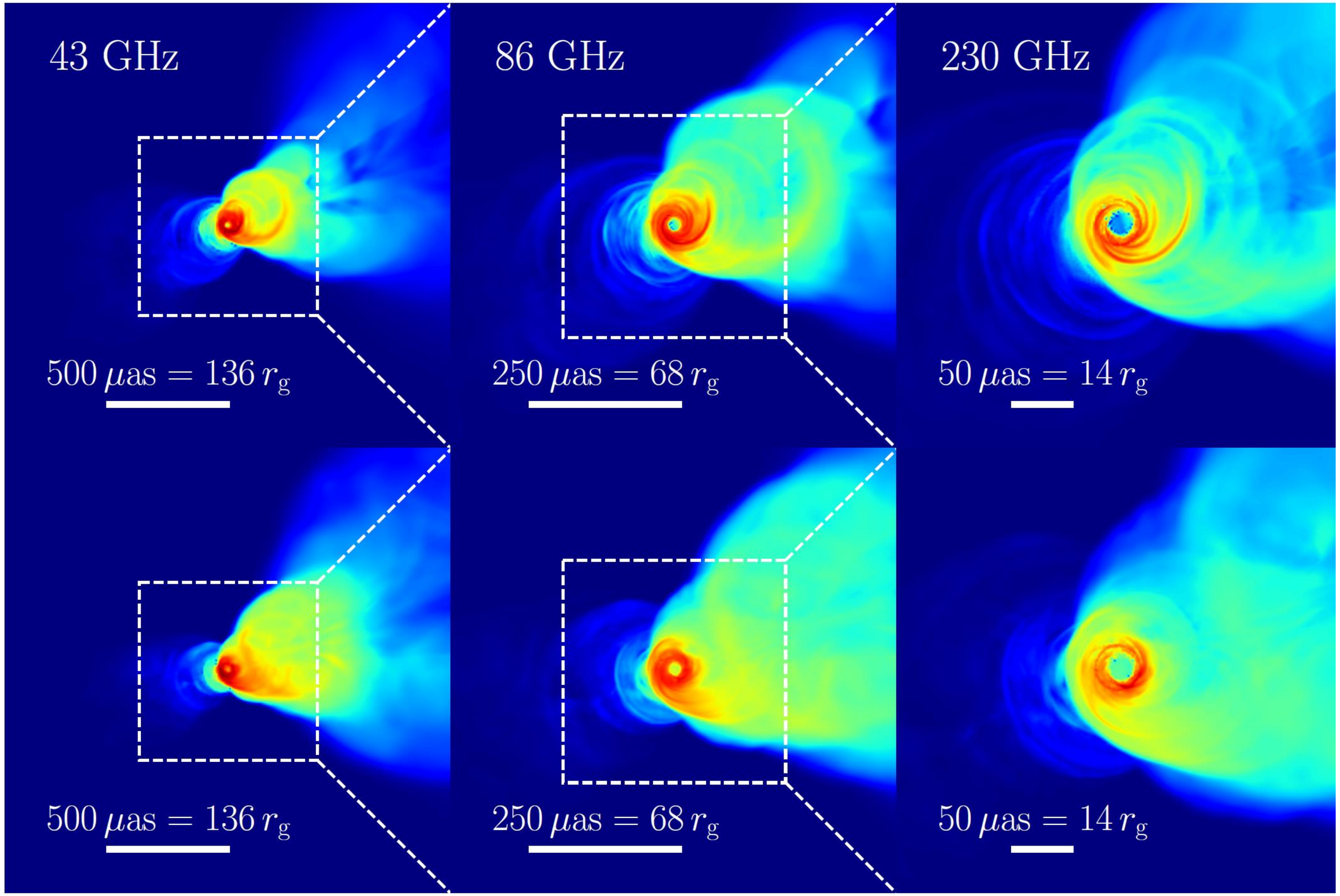
- Both simulations are MAD.
- Density is scaled to match 0.98 Jy at 230 GHz.
- The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s.

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

M87 Jets at millimeter wavelengths

Turbulent Heating

Reconnection Heating



Inclination angle (down from pole)

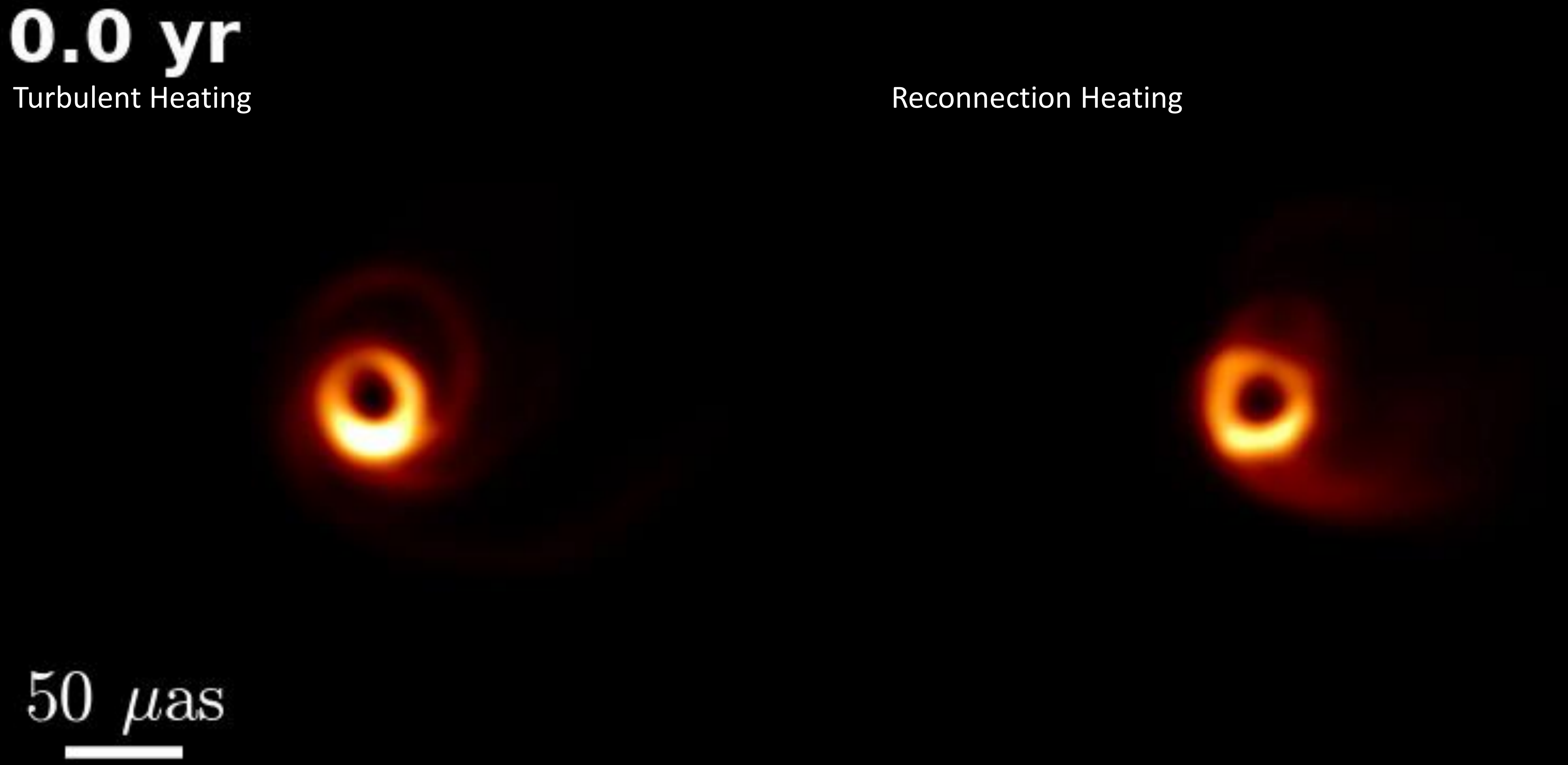
17°

Disk/Jet rotation sense

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

Image Credit: Chael+ 2019

230 GHz Images & variability

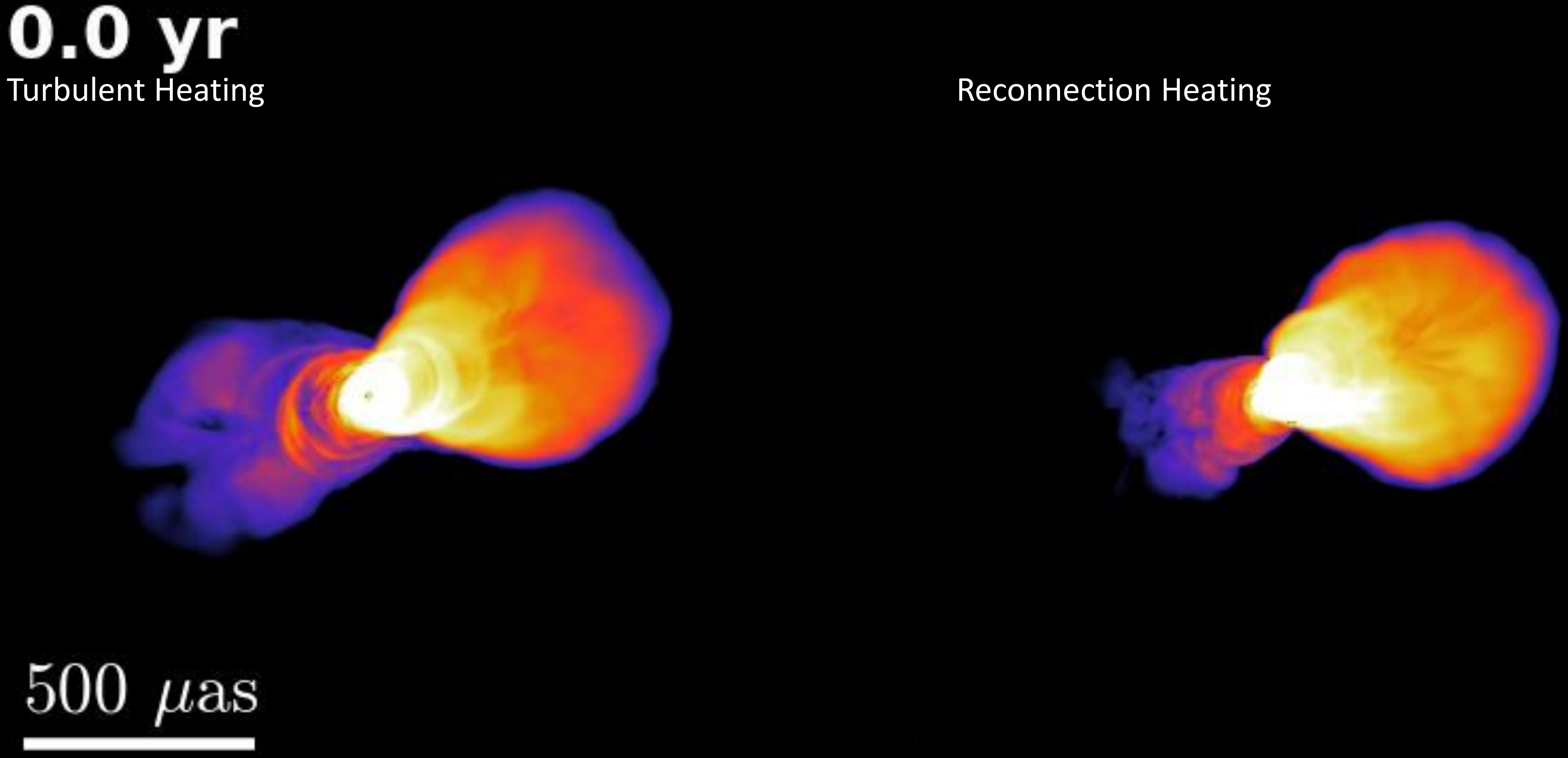


Turbulent Heating

Reconnection Heating

Two-temperature MAD simulations of M87

43 GHz jets



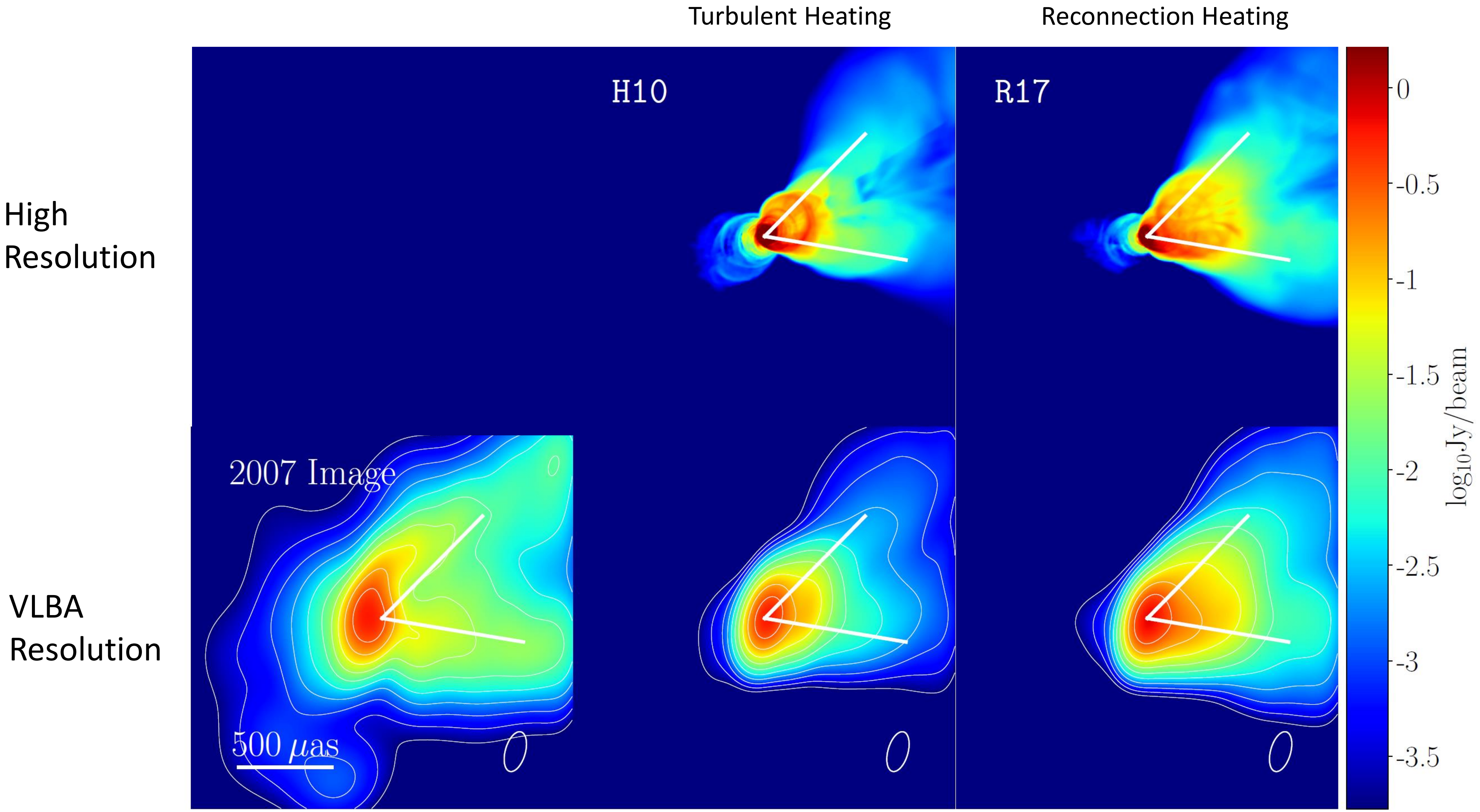
Turbulent Heating

Reconnection Heating

Movie Credit: Chael+ 2019

43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

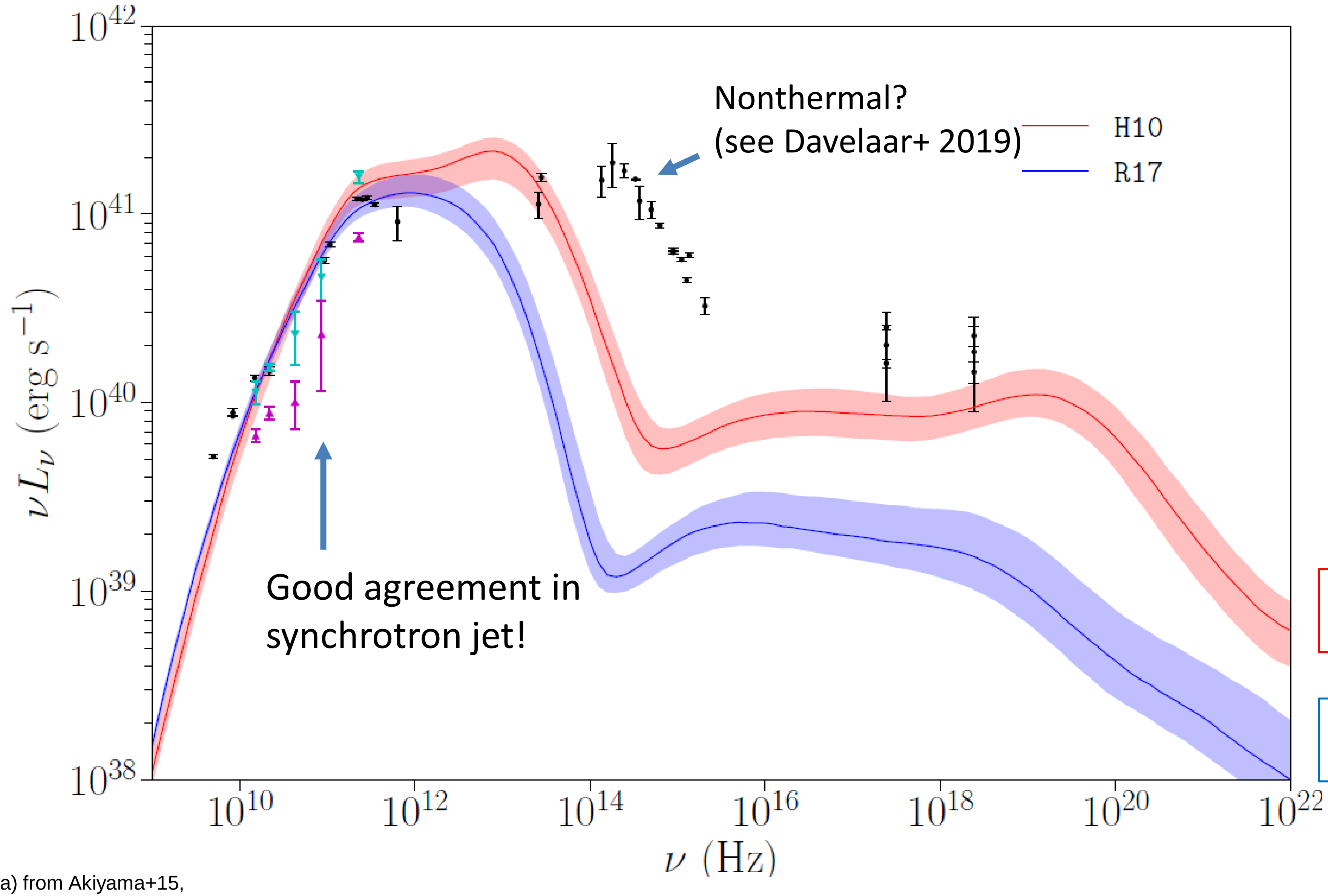
55°

(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 SED



Nonthermal?
(see Davelaar+ 2019)

Good agreement in synchrotron jet!

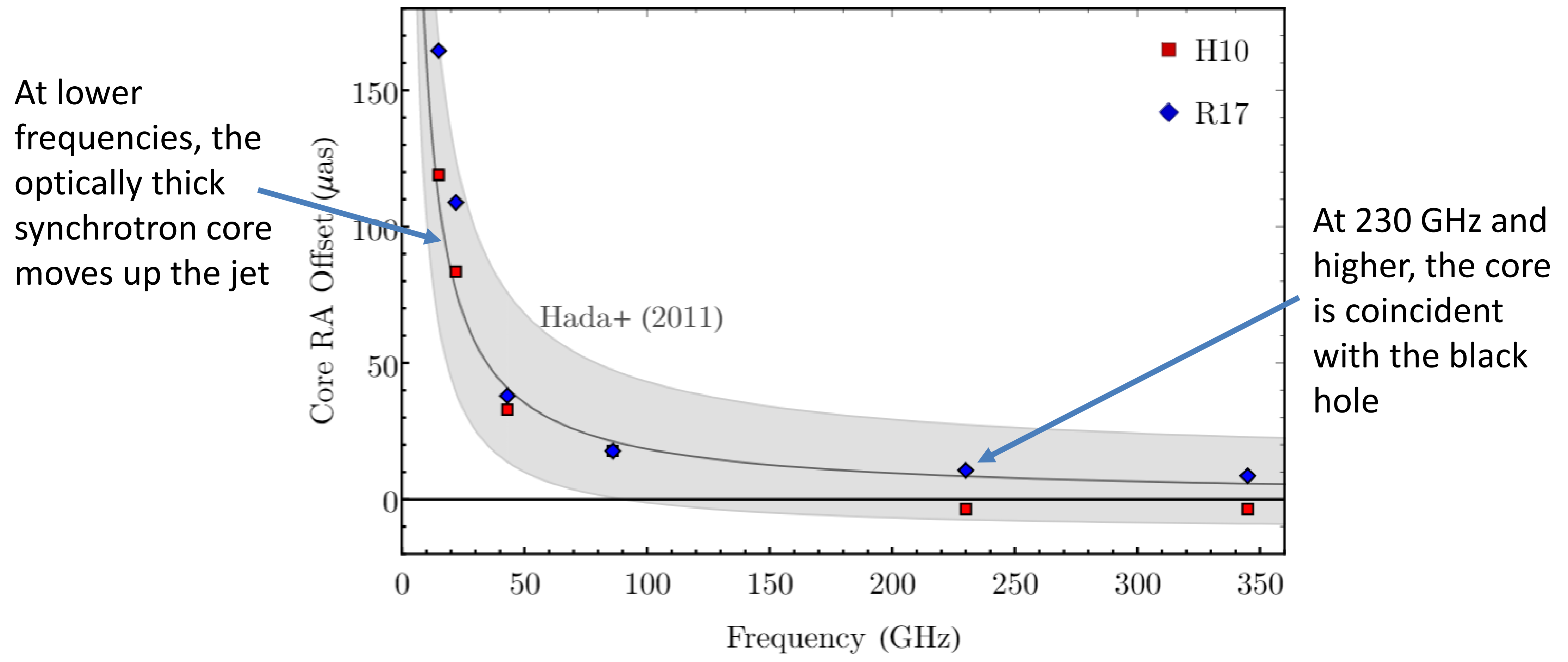
Turbulent Heating

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

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

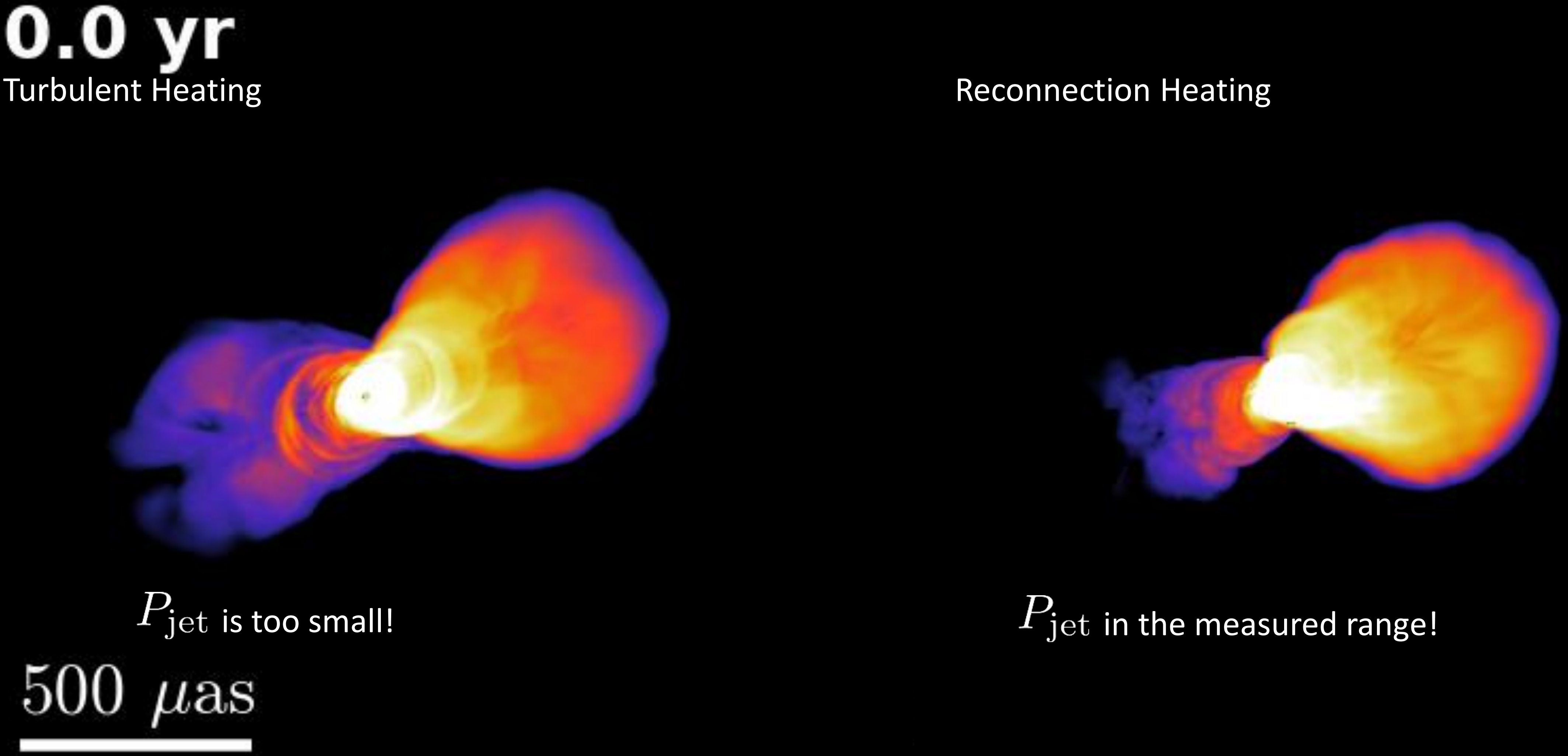
Agreement with measured core shift up to cm wavelengths.

Hada+ 2011

Image Credit: Chael+ 2019

Two-temperature MAD simulations of M87

43 GHz jets



Turbulent Heating

Reconnection Heating

P_{jet} is too small!

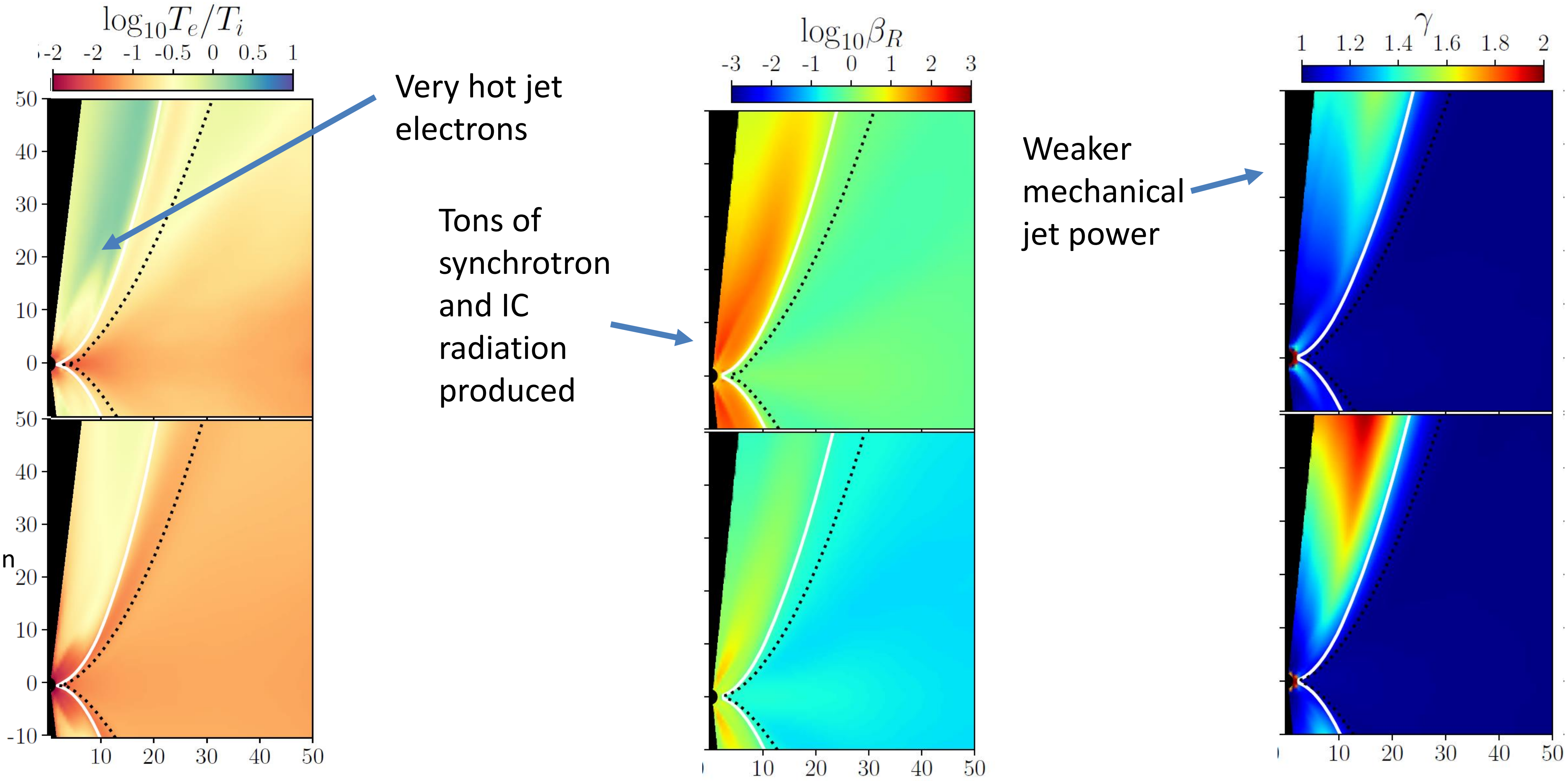
P_{jet} in the measured range!

Movie Credit: Chael+ 2019

Electron Heating + Radiation→ Jet Dynamics

Turbulent Heating

Reconnection Heating



Very hot jet electrons

Tons of synchrotron and IC radiation produced

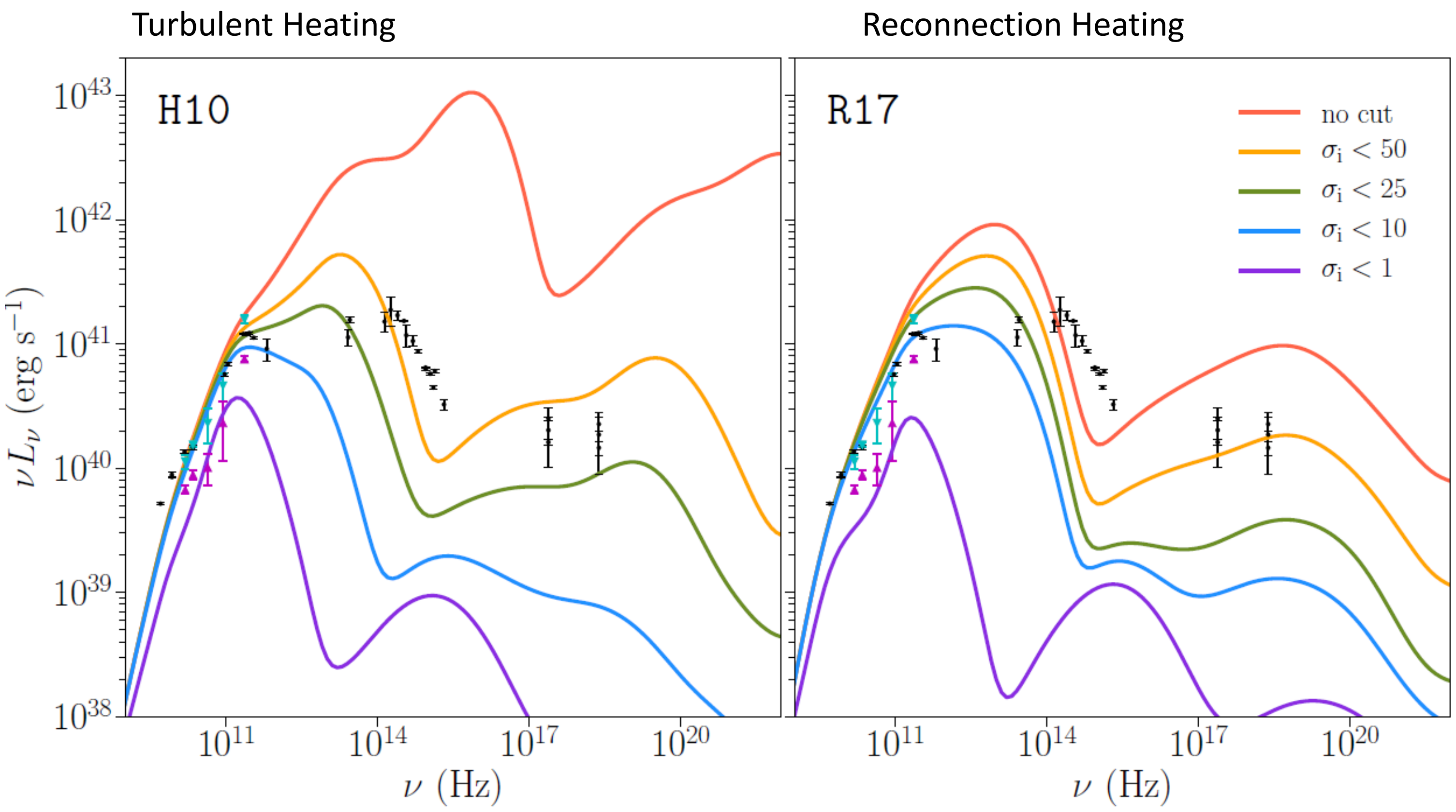
Weaker mechanical jet power

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

Electron Heating + Radiation → Dynamics!

Image Credit: Chael+ 2019

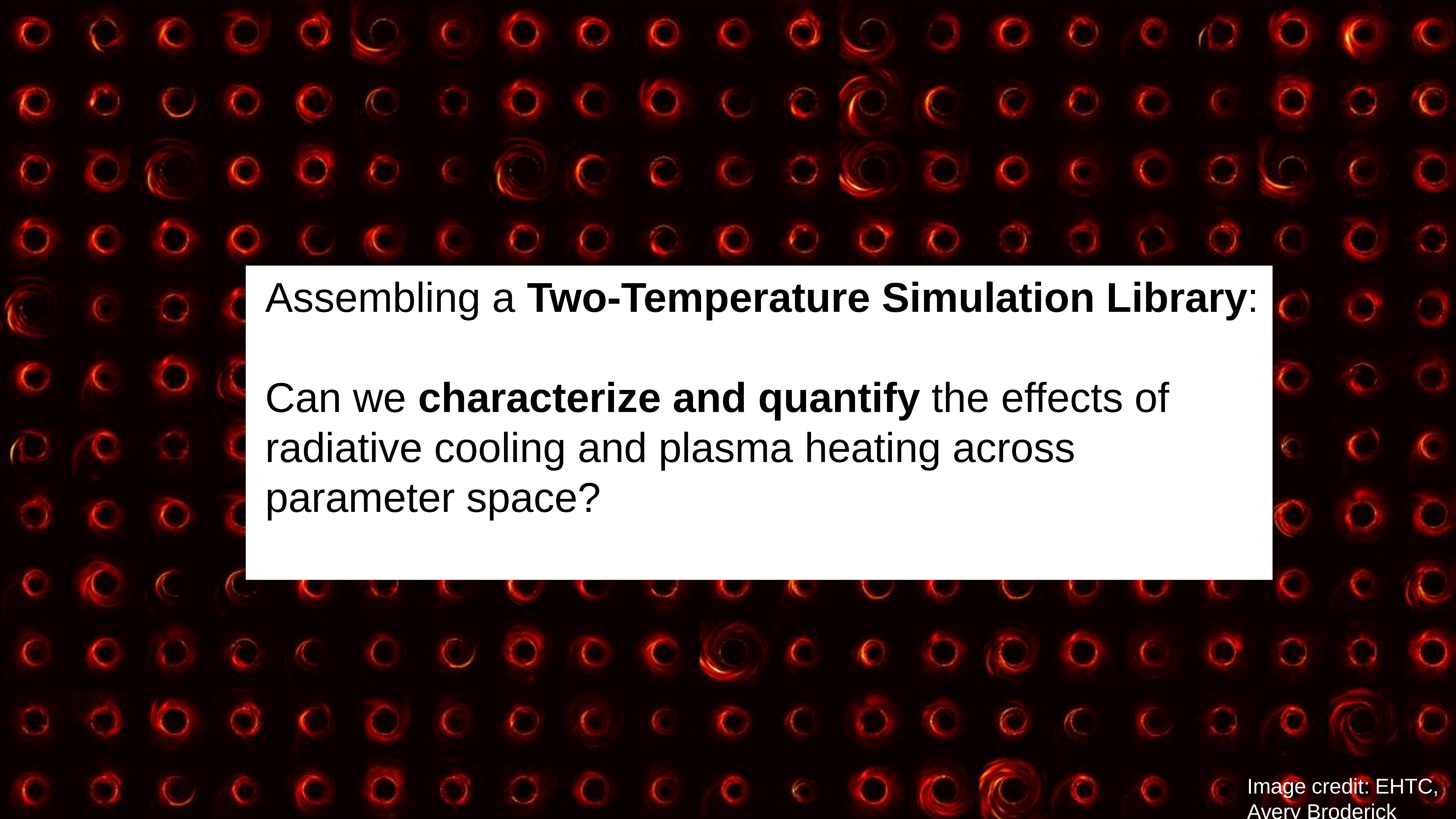
Major uncertainty in simulations: $\sigma_{\rm i}$ cut



- 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 ≥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



Assembling a **Two-Temperature Simulation Library**:

Can we **characterize and quantify** the effects of radiative cooling and plasma heating across parameter space?

Image credit: EHTC, Avery Broderick

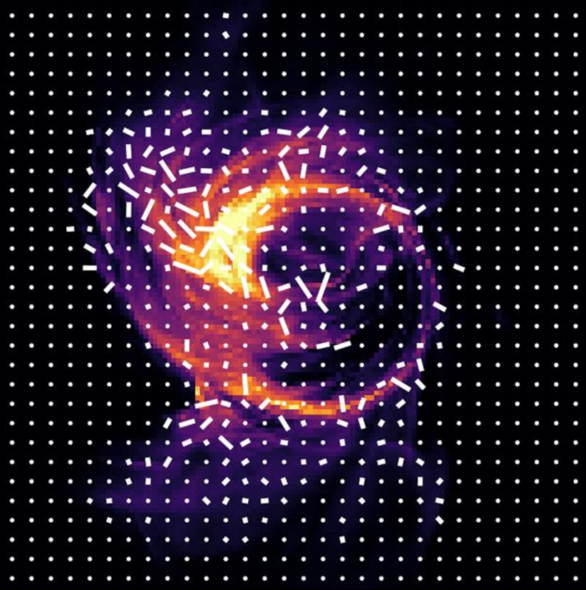
Polarization and e- heating

SANE + Turbulent cascade

-LP < 1%

- Turbulent E-field vector pattern

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



MAD + Reconnection

-LP ~ 2-10%

-More coherent E-field vector pattern

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

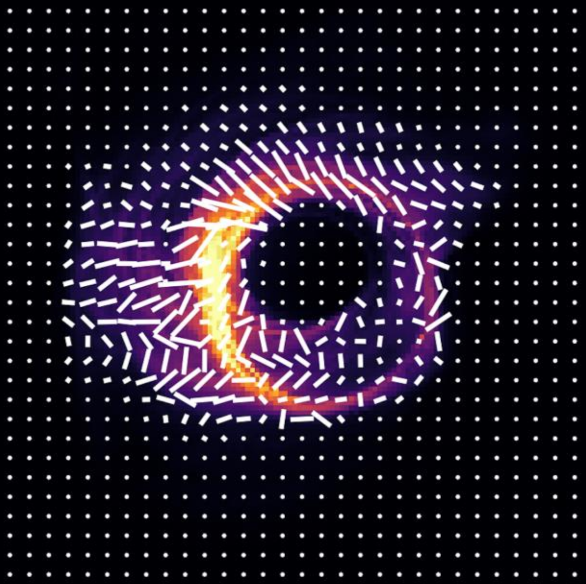
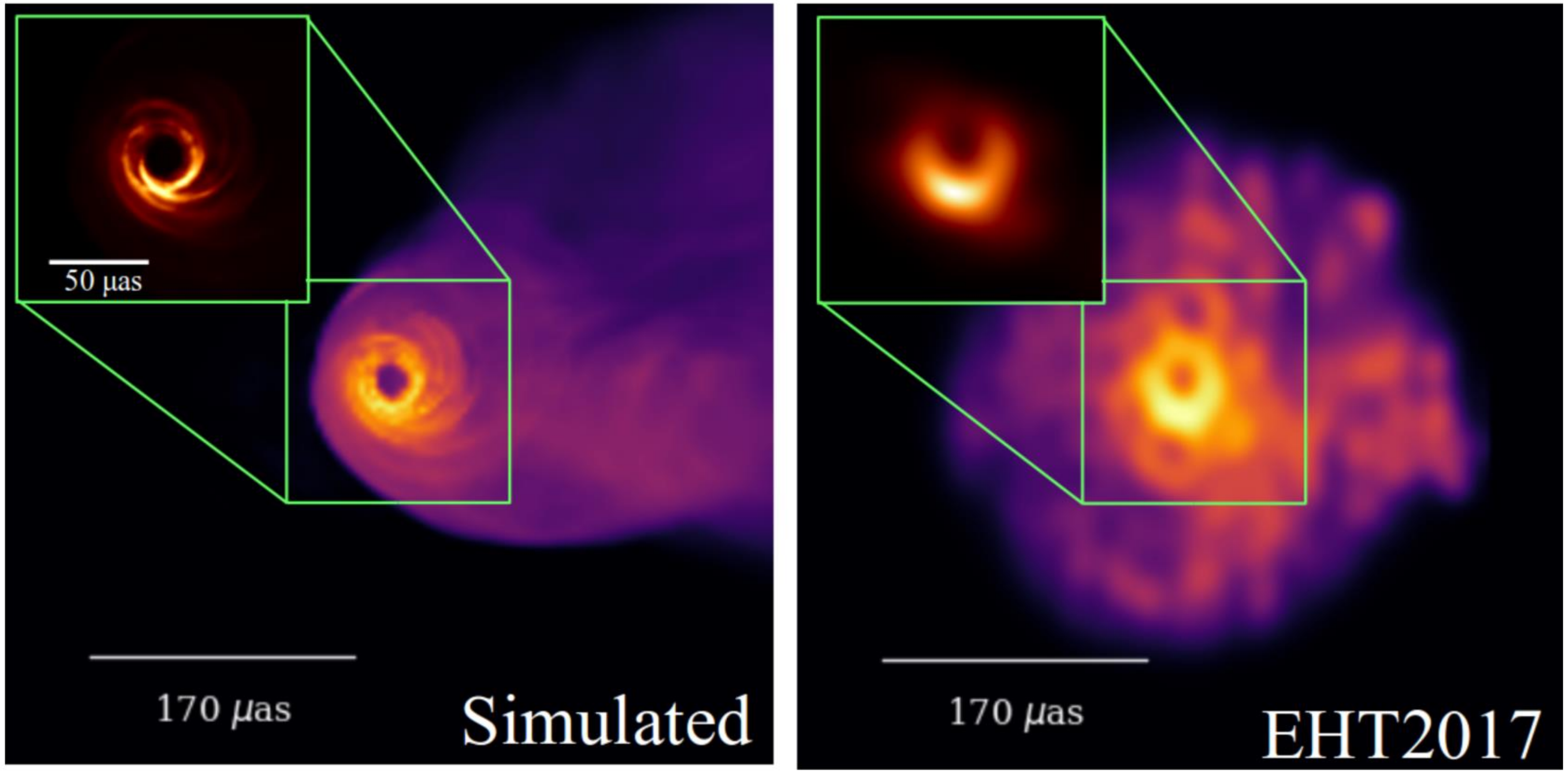


Image credit:
Jason Dexter

Next Steps: EHT Upgrades

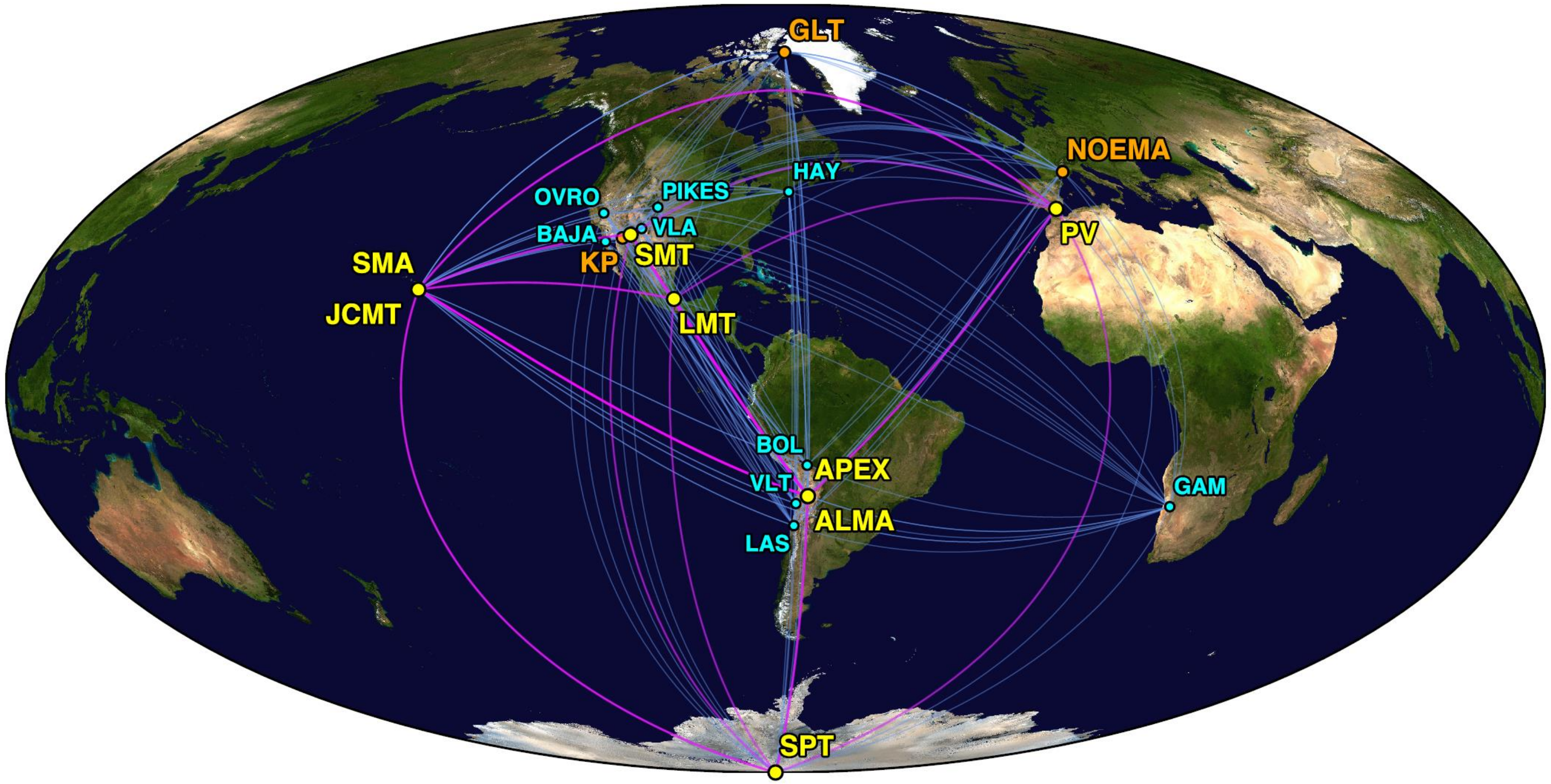


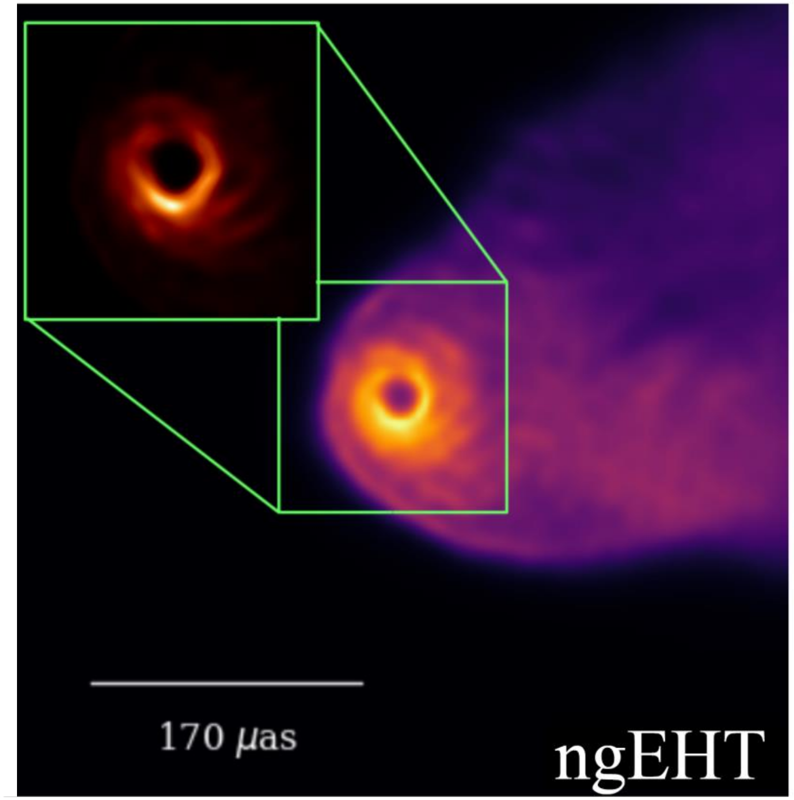
The current EHT lacks many short baselines, which are necessary to detect extended structure.

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)

Next Steps: Enhancing EHT’s dynamic range





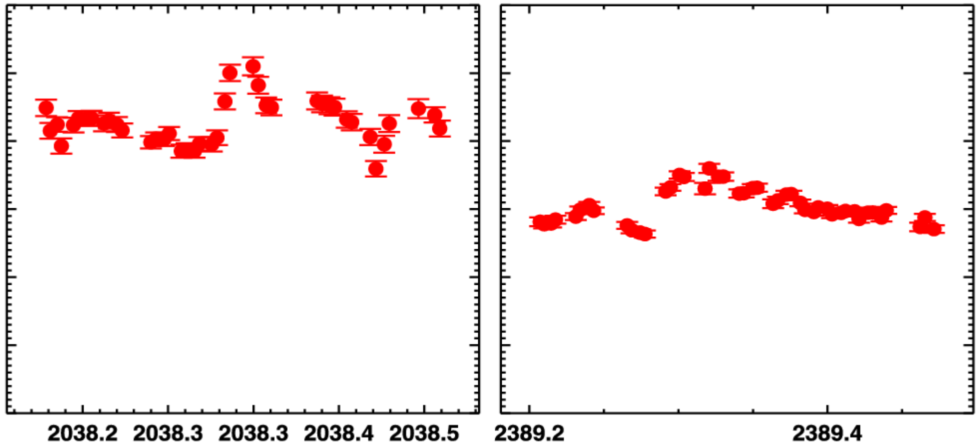
The current EHT lacks <u>short</u> baselines, which are necessary to detect extended structure.

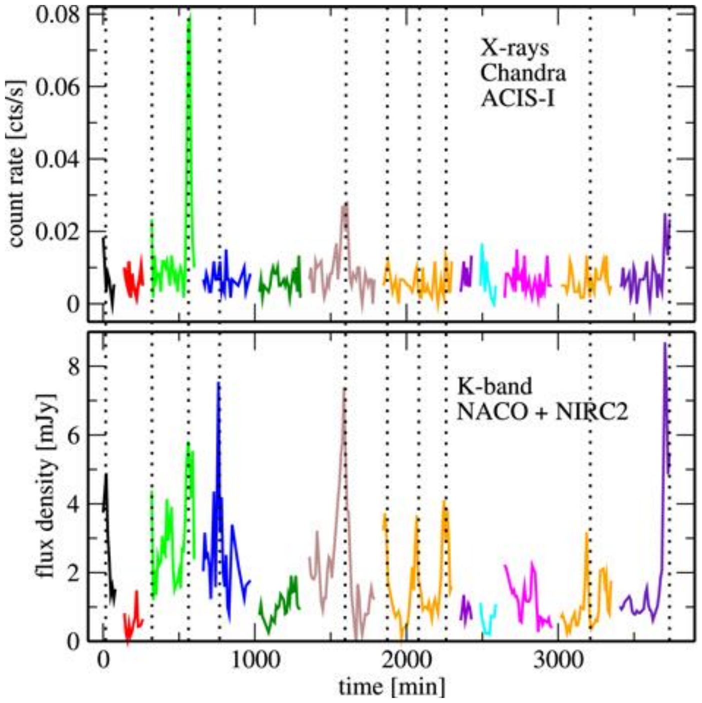
Idea: add many more small, ~6m dishes to the array

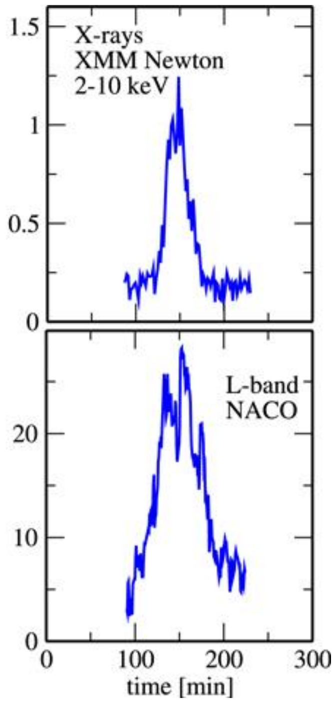
Slide Credit: Michael Johnson
See: EHT Ground Astro2020 APC White Paper
(Blackburn, Doeleman+; arXiv:1909.01411)

Next steps: Sgr A* Dynamics

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





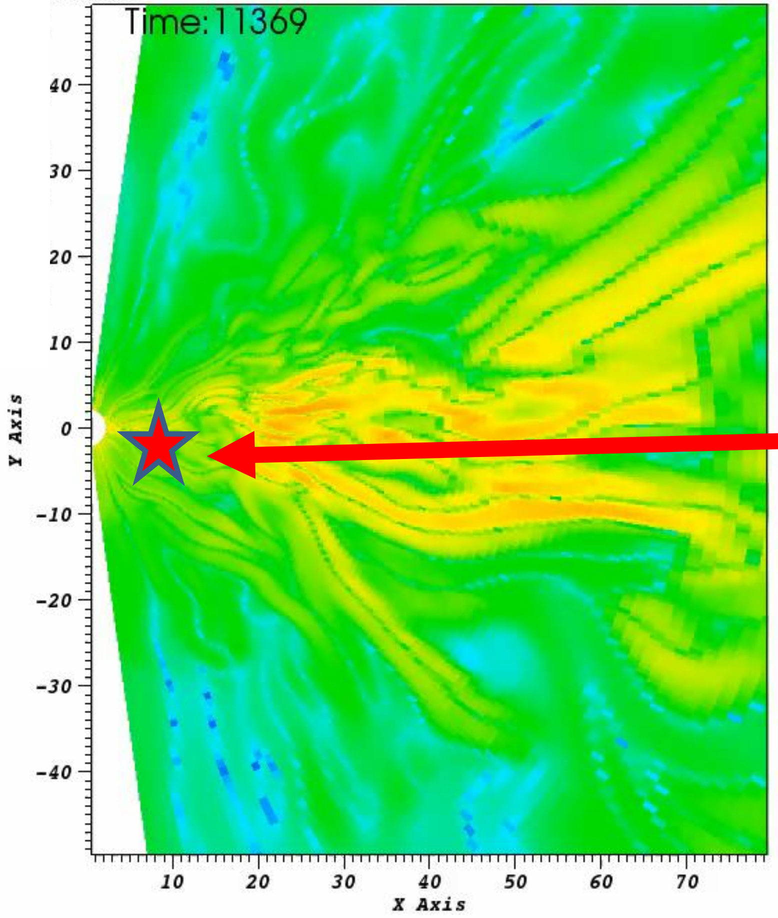


Large amplitude NIR and X-ray variability/flares cannot be produced by thermal electrons in simulations – requires nonthermal particle emission/acceleration.

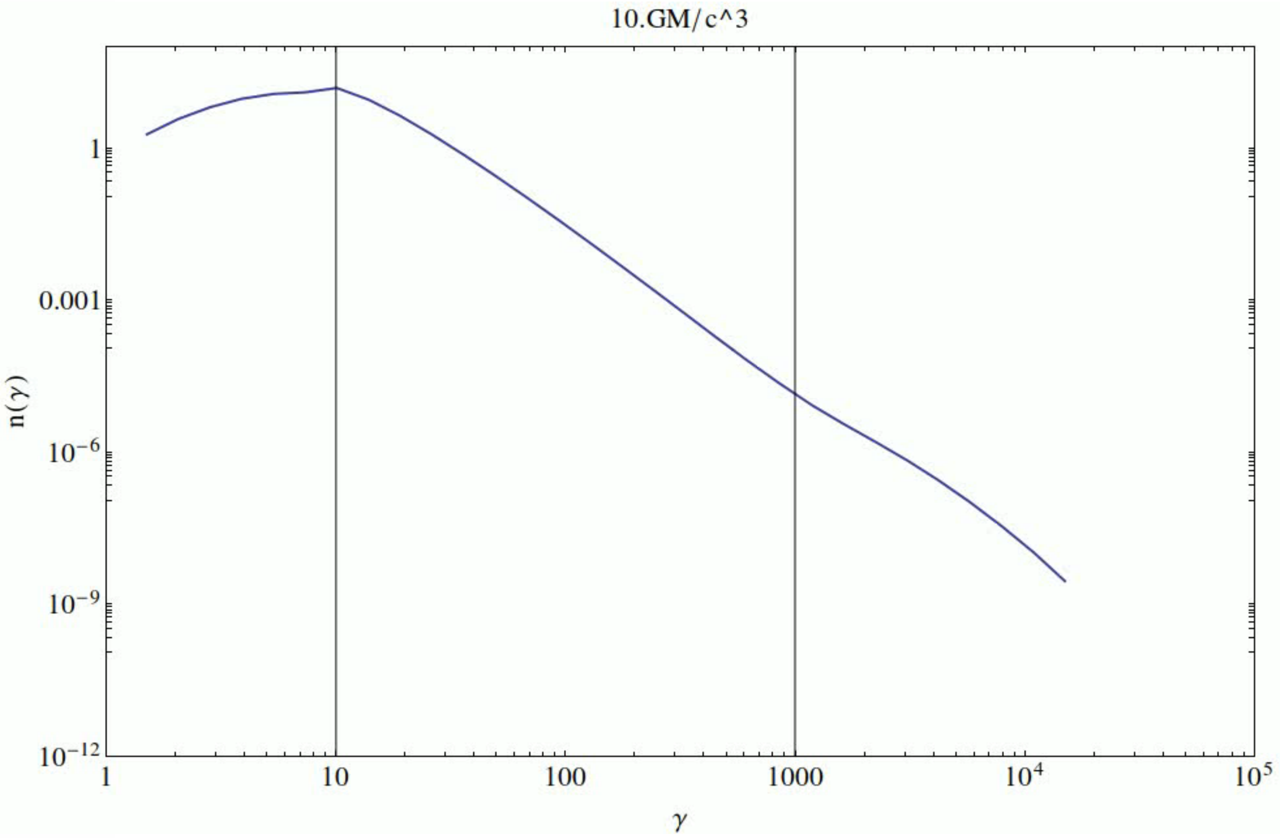
Marrone+2008, Dexter+2014, Fazio+ 2018

Simulating Flares by
Evolving **nonthermal** electron distributions

Radiation Power



Nonthermal distribution @ 10 M



Chael+ 2017

Understanding LLAGN down to horizon scales:

Sgr A's SED*

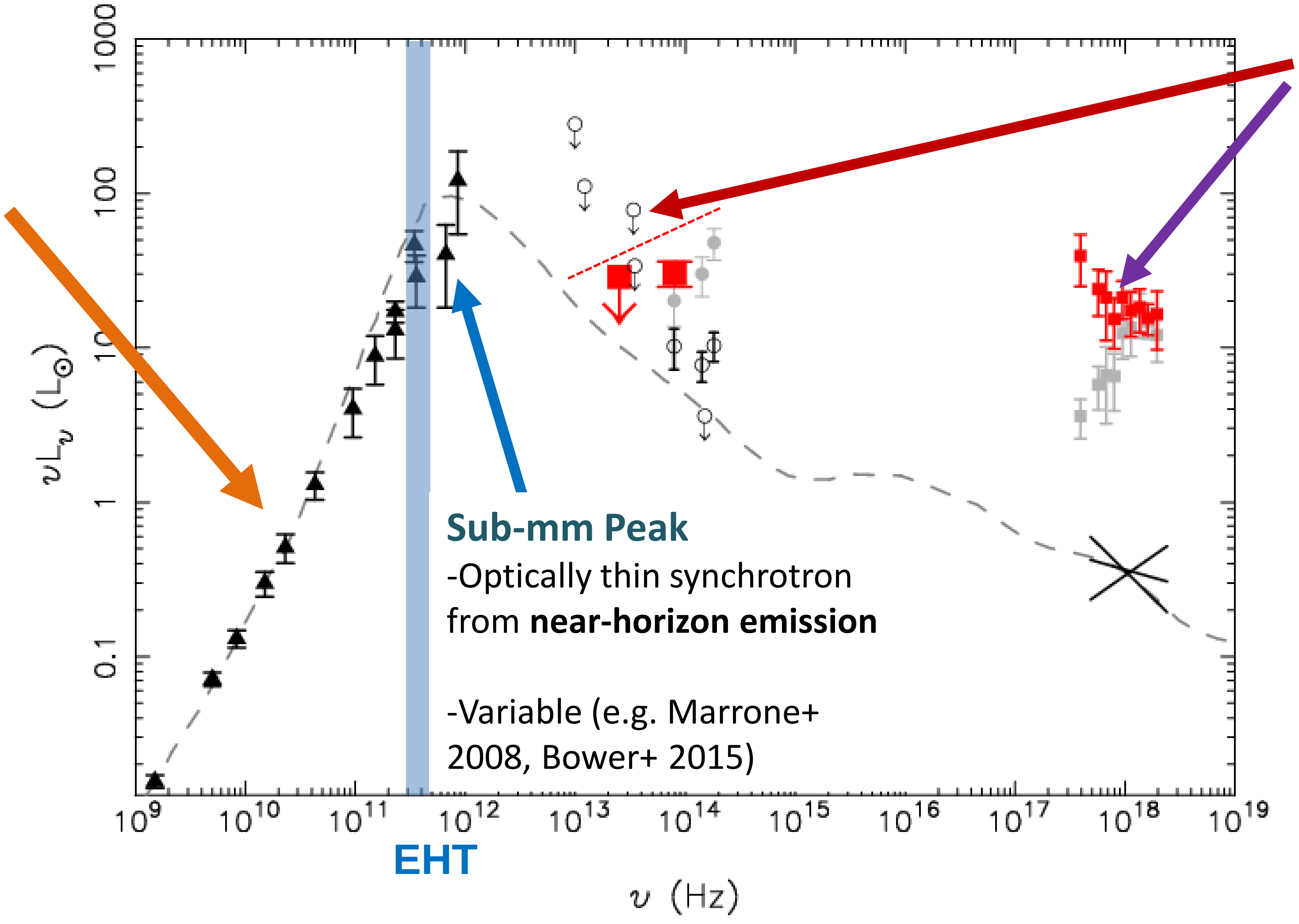
Larger Scales:

"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)

EHT

Close in:

Near-Infrared and X-ray flares:

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

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

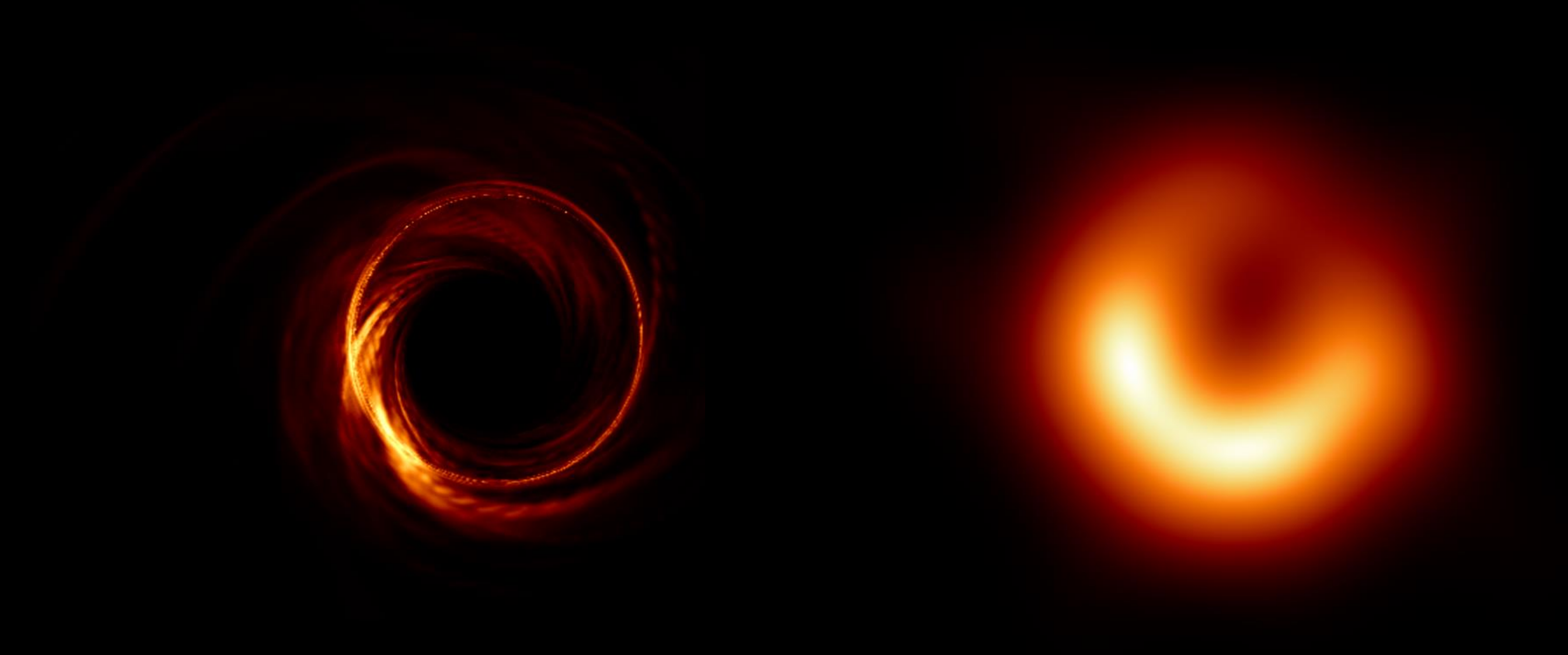
-Measured synchrotron break (e.g. Ponti+ 2017)

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

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