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

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(he/him/his)

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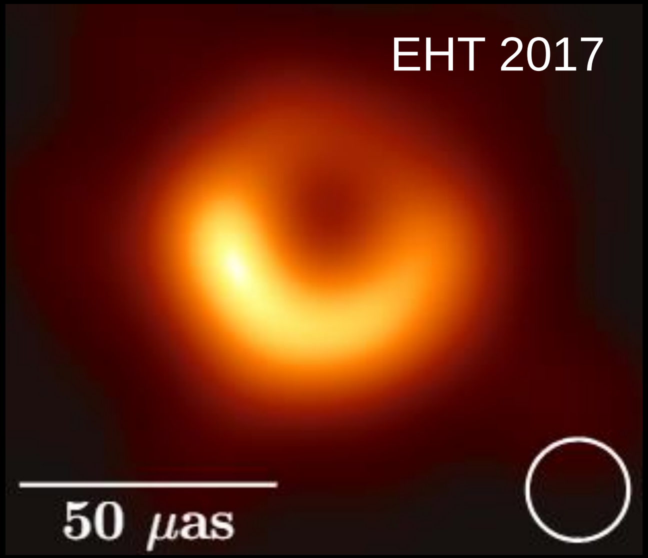
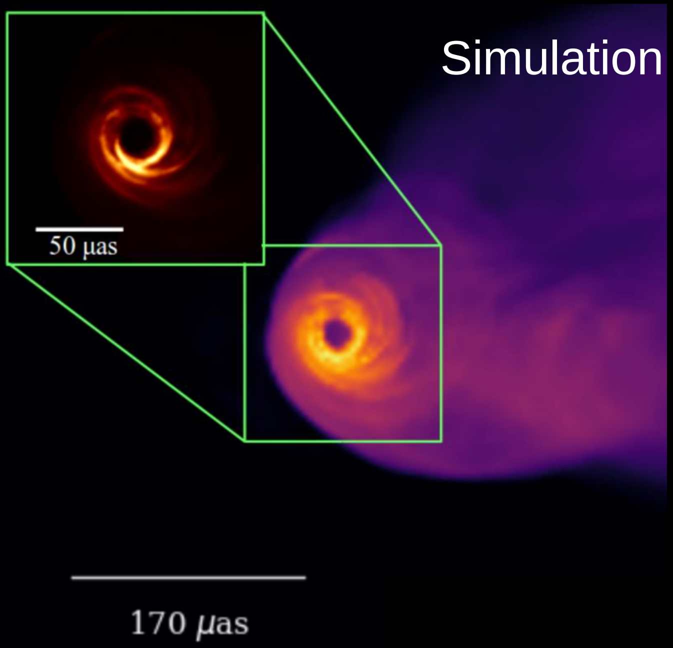
October 24, 2019





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

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

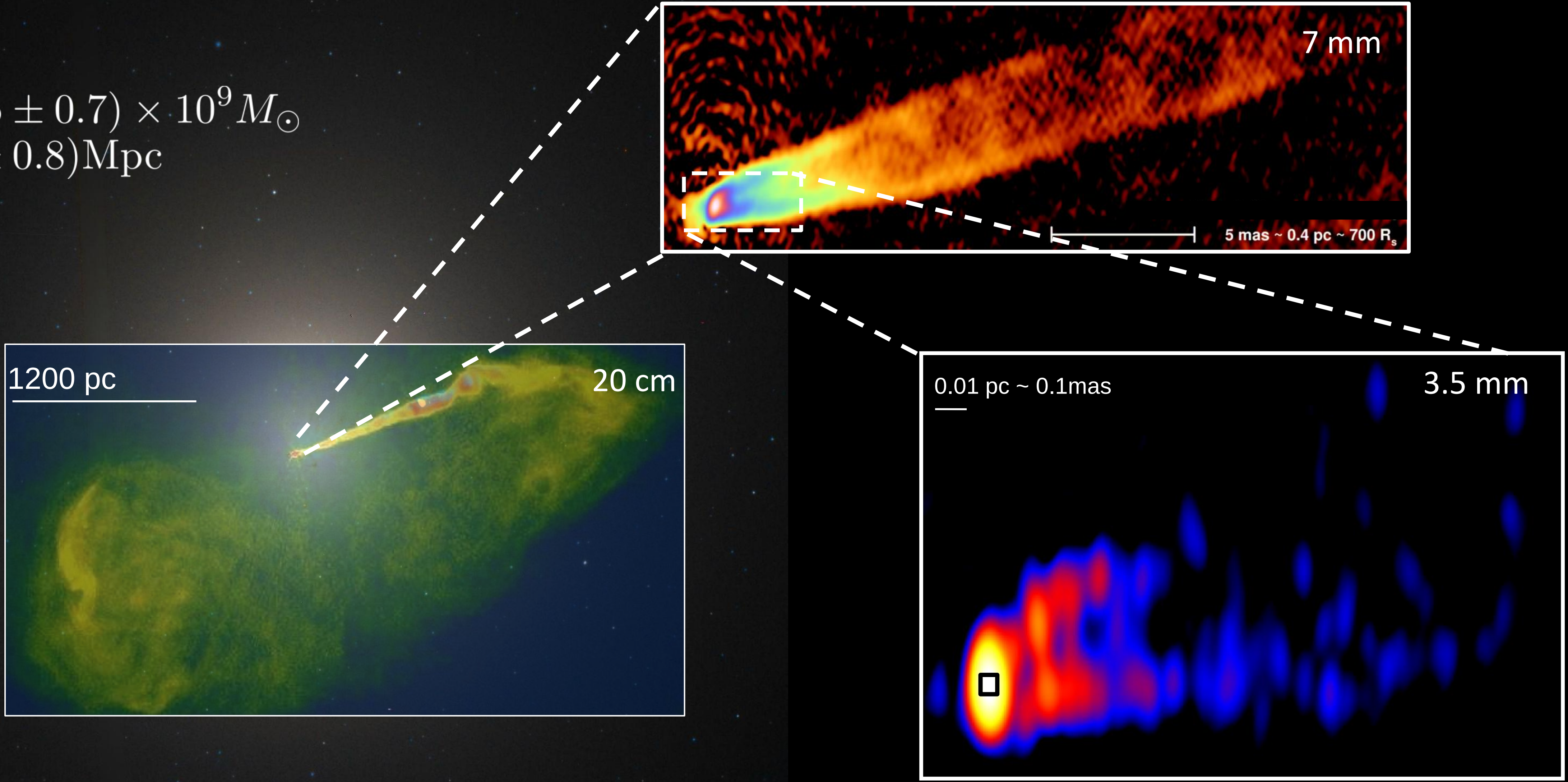


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

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?

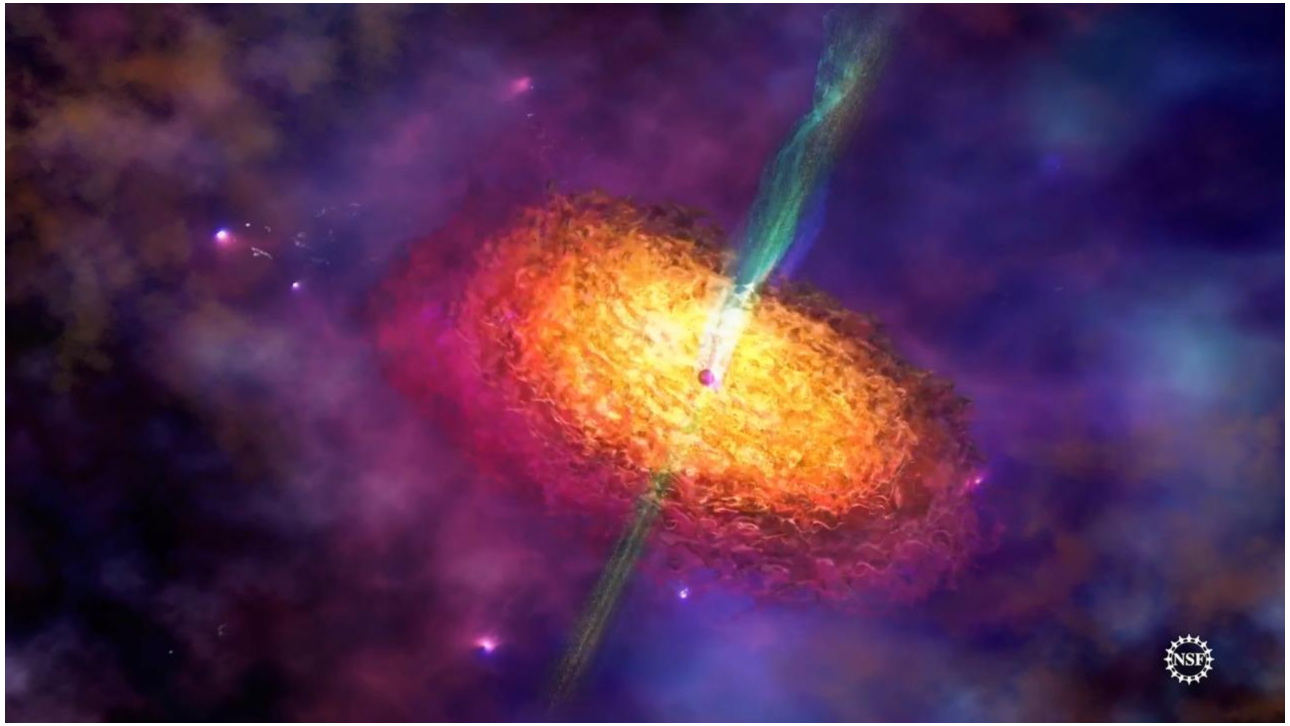
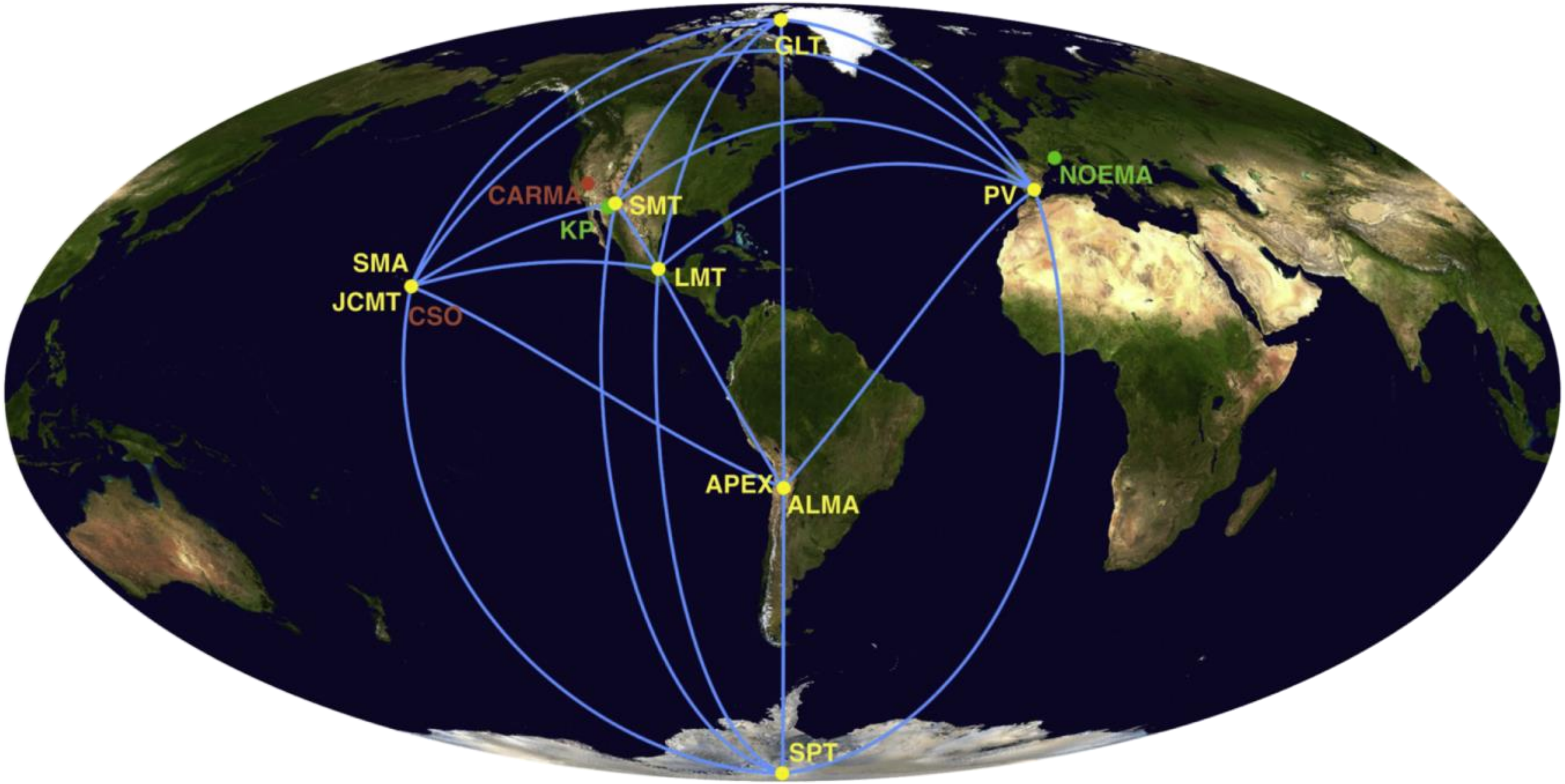


Image credit: National Science Foundation

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

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

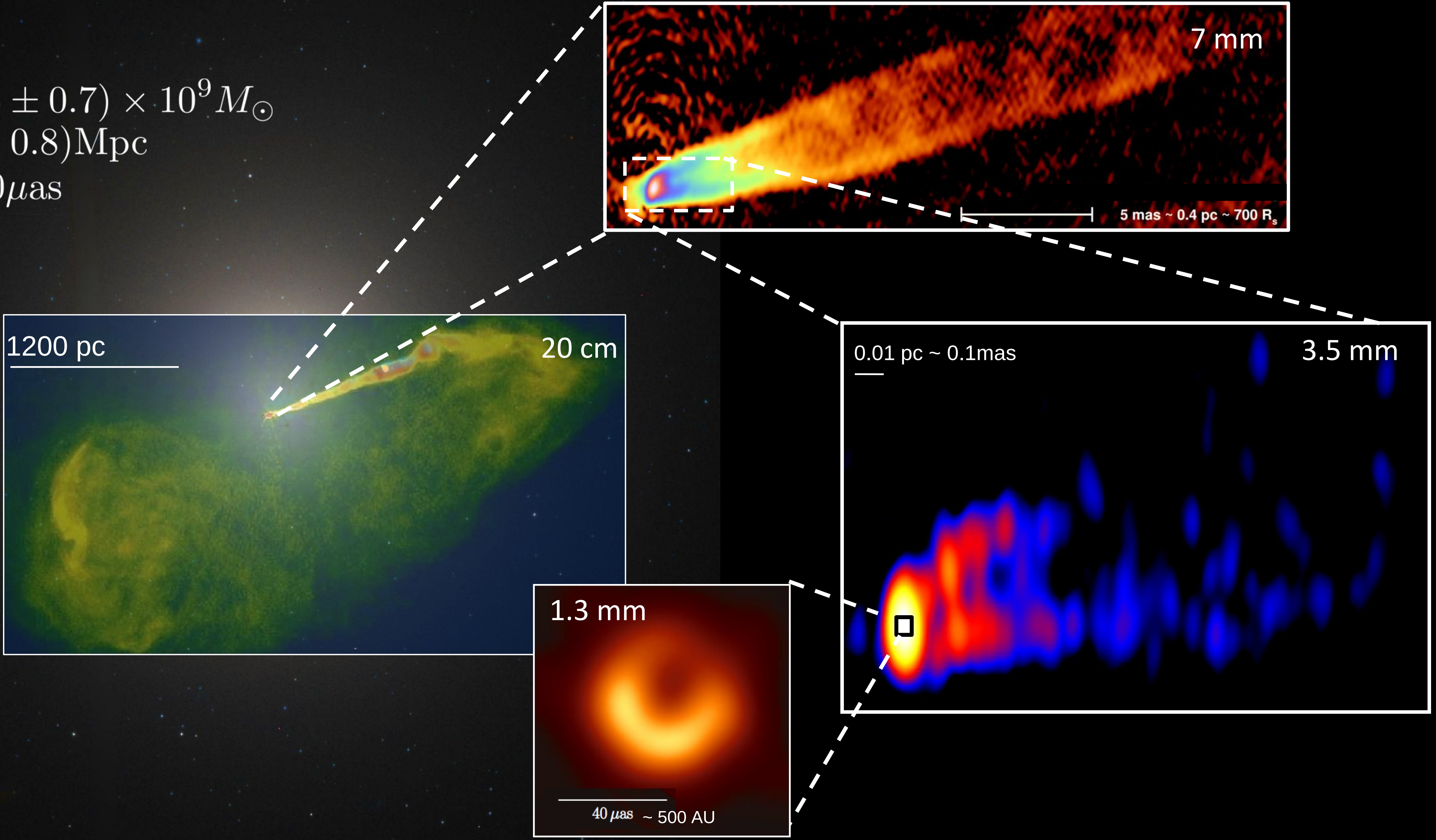


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

Understanding LLAGN down to horizon scales:

Sgr A's SED*

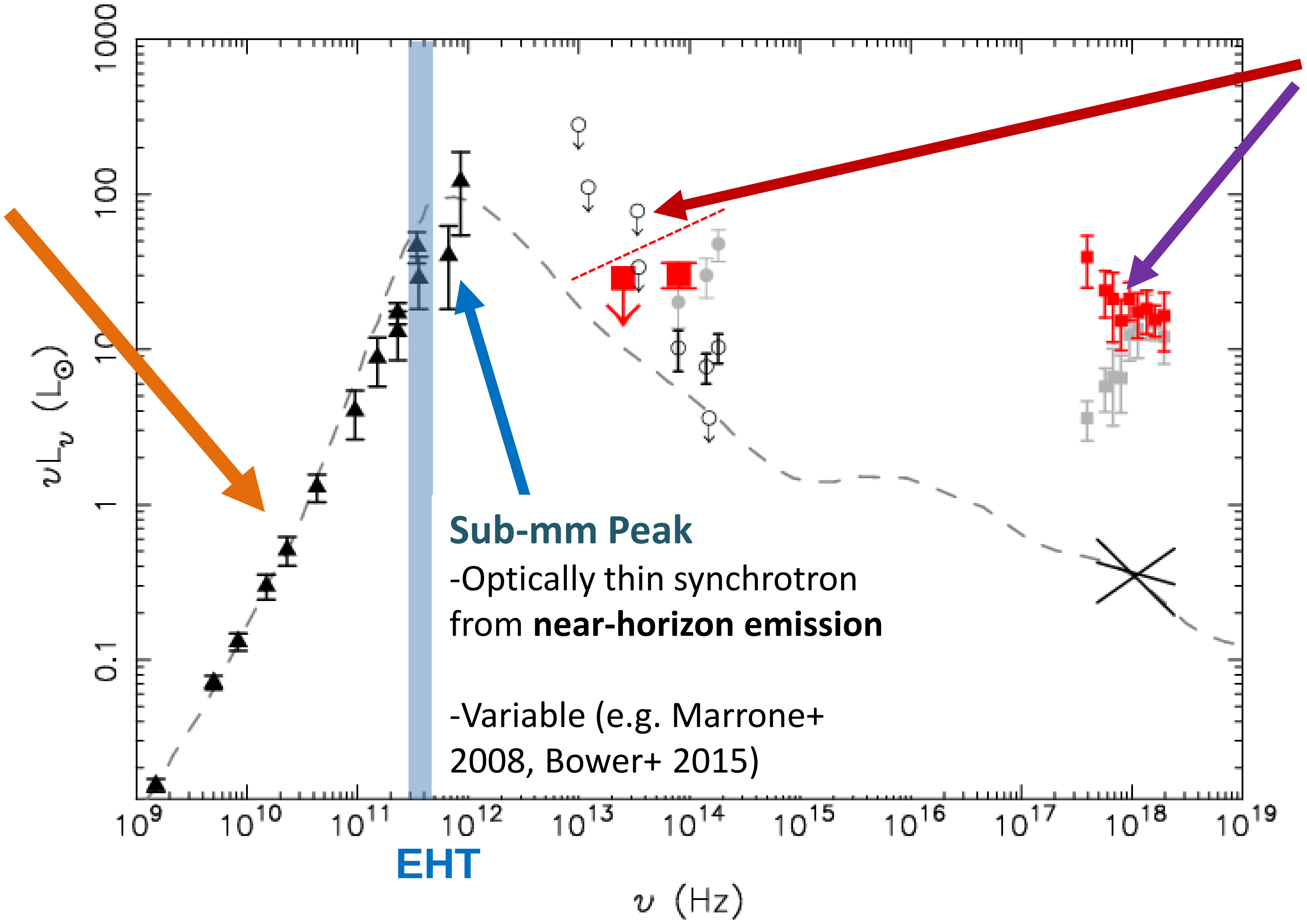
Larger Scales:

"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)

Close in:

Near-Infrared and X-ray flares:

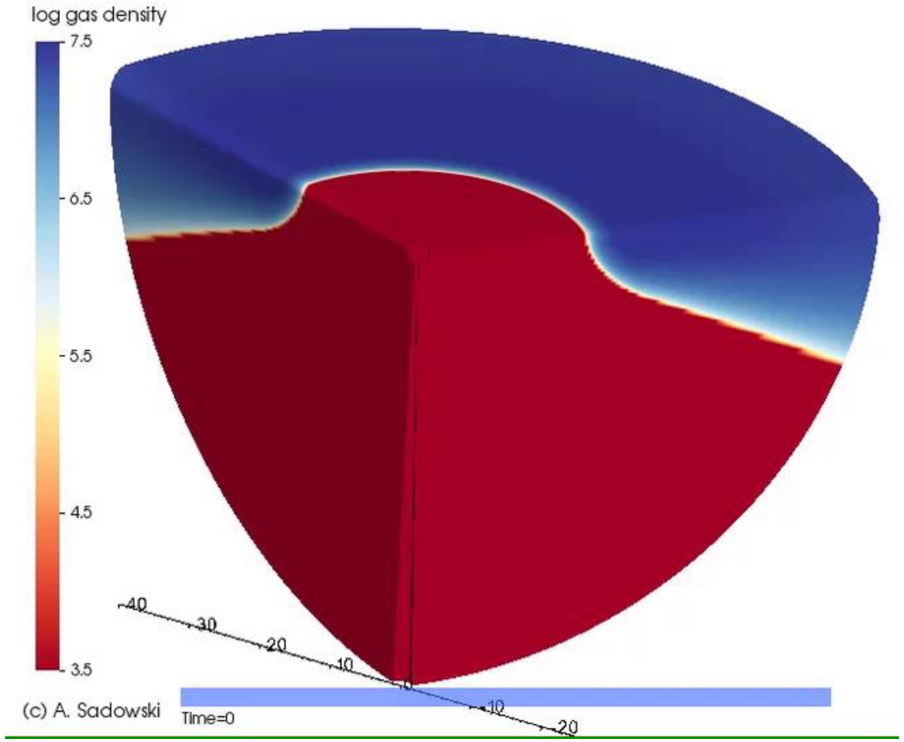
-Strong & correlated (e.g. Eckart 2004)

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

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

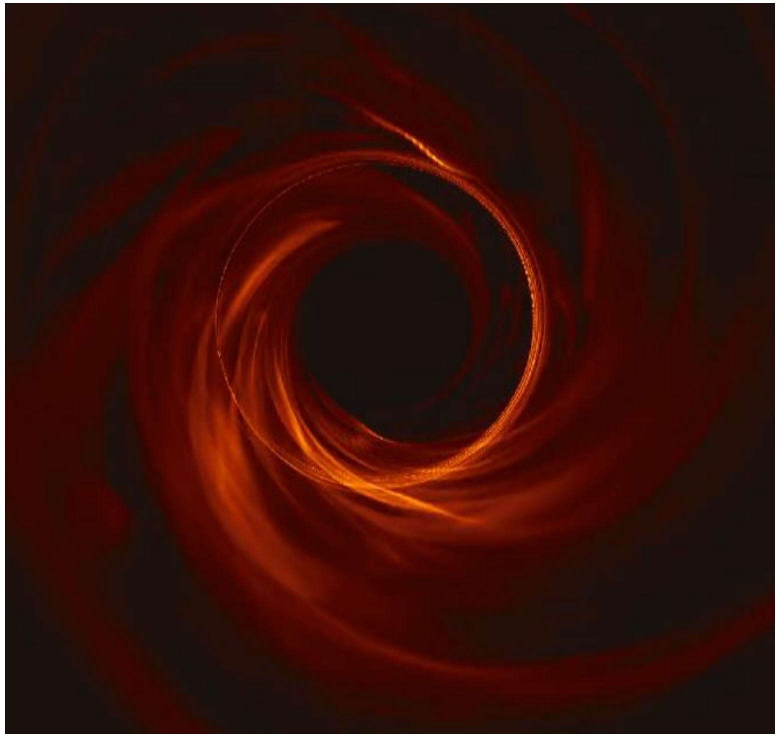
Image Credit: Dodds-Eden+ (2009)
Also: Flacke & Markoff (2000), Yuan+ (2003), Genzel+ (2010)

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

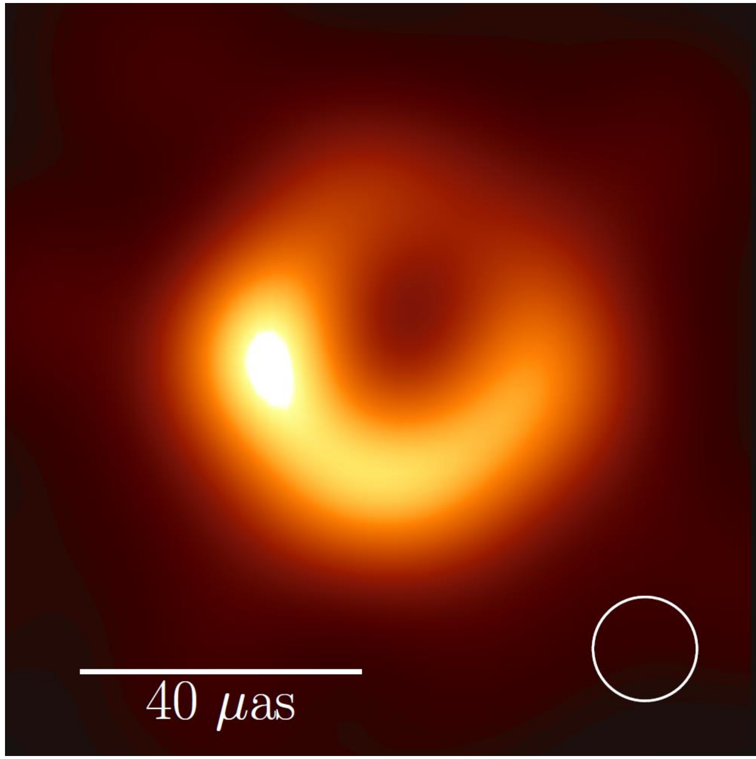


Tracks light rays and solves for the emitted radiation

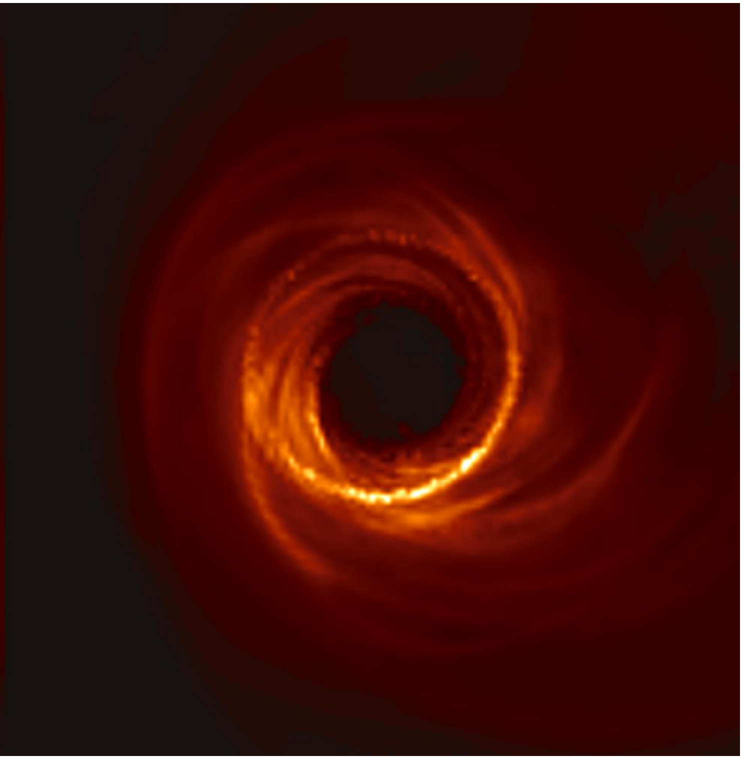
Movie Credits: Aleksander Sądowski,
EHT Collaboration 2019 (Paper V)

The Black Hole in M87: Simulations and Images

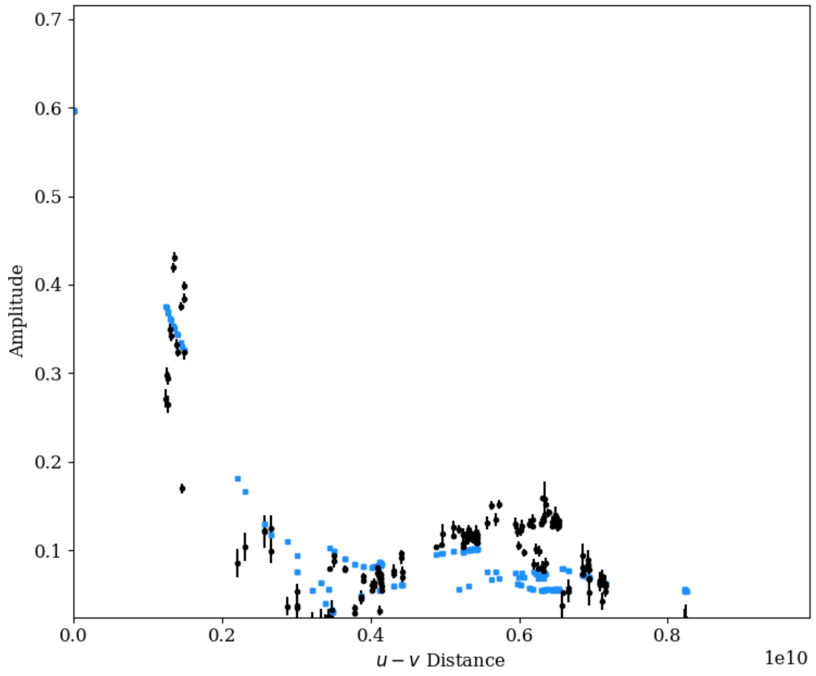
EHT 2017 image



Simulated image
from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes



What parameters influence images from simulations?

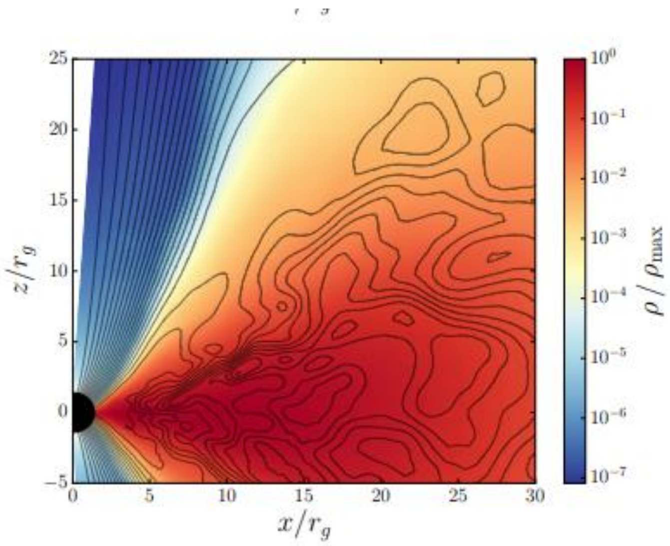
1. Spacetime geometry: M, a
    - -Liberating potential energy heats the plasma.
    - -Photons follow null geodesics.

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

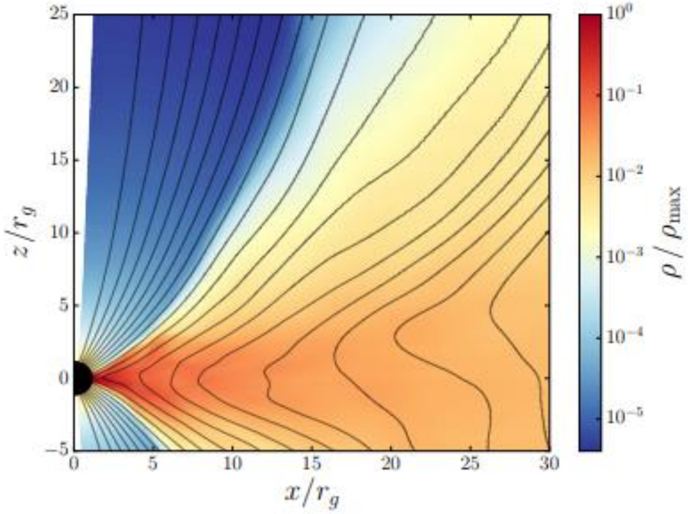
SANE vs MAD

- 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:

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

Image credit: Riordan+ 2017

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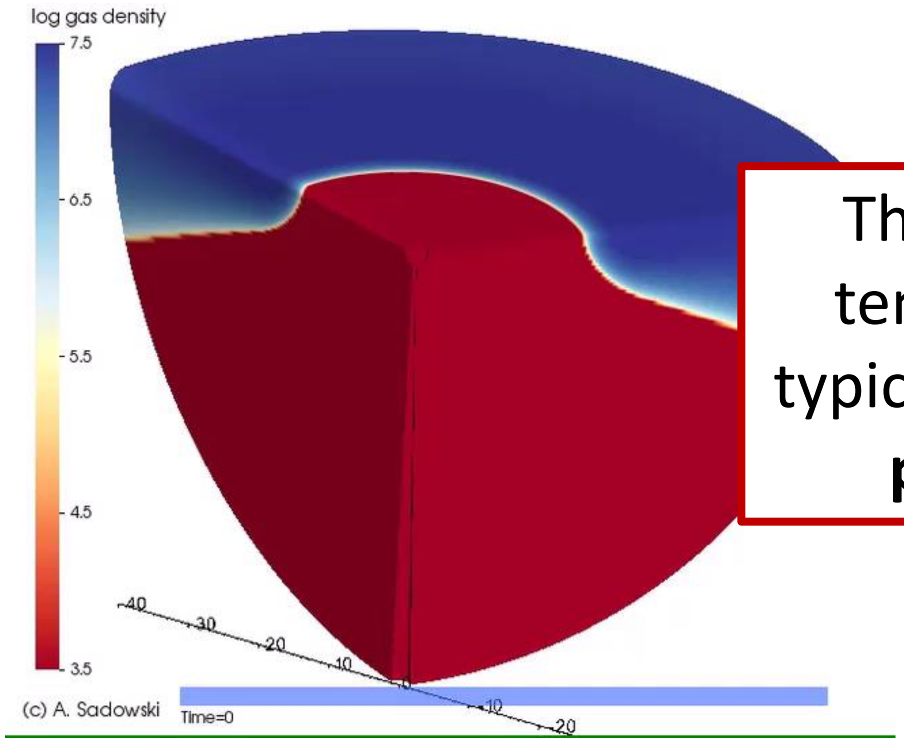
2. (Radiative) Magnetohydrodynamics: $\dot{M}, \Phi_B$
   - - Does the magnetic field arrest accretion?
   - - How does the B-field determine the jet power & shape?

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**

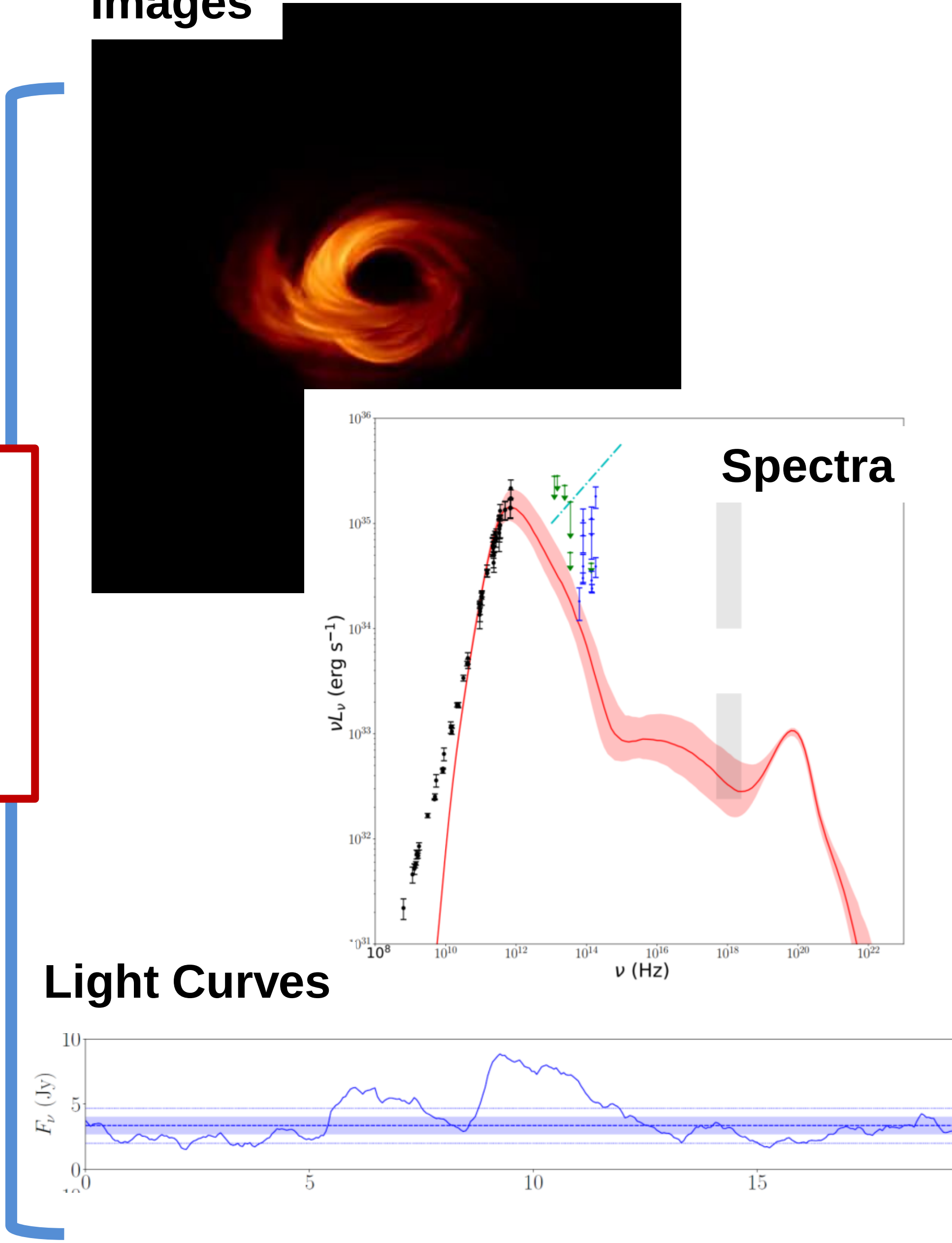
GRMHD Simulations

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

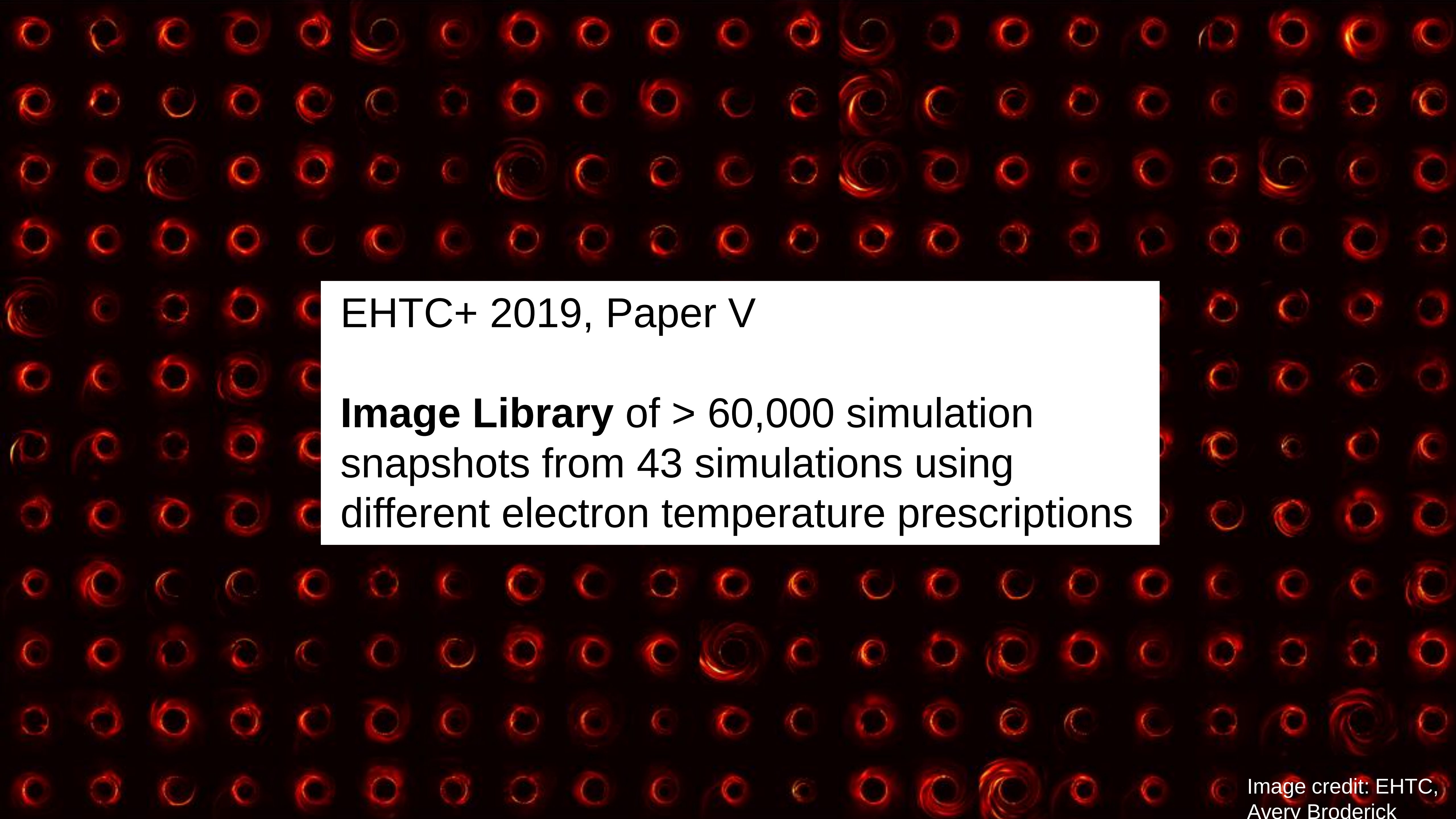
Images

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

EHTC+ 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.

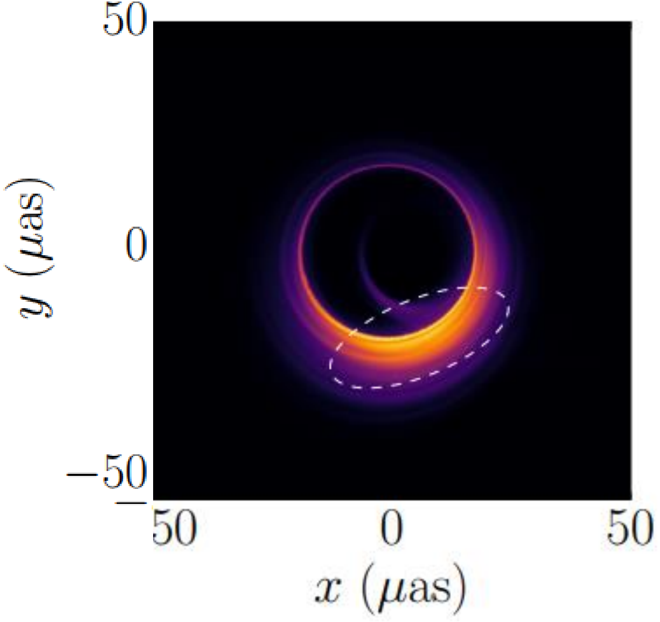
- Reason to suspect the system may be MAD, and self-consistent electron temperatures from simulations may be important
  - -Can we learn more from also comparing to lower frequency images?

SANE simulations of M87:

Ryan+ 2018 / Mościbrodzka+ 2016

- Radiative cooling determines the disk temperature.
- Jet powers **too weak:** $P_{\mathrm{jet,M87}} = 10^{43} - 10^{44}\,\mathrm{erg\,s^{-1}}$
- Jet opening angle is **too narrow:** $\theta_{\mathrm{jet,\,43\,GHz}} \approx 55^{\circ}$

Ryan+ 2018, 230 GHz



Mościbrodzka + 2016, 43 GHz

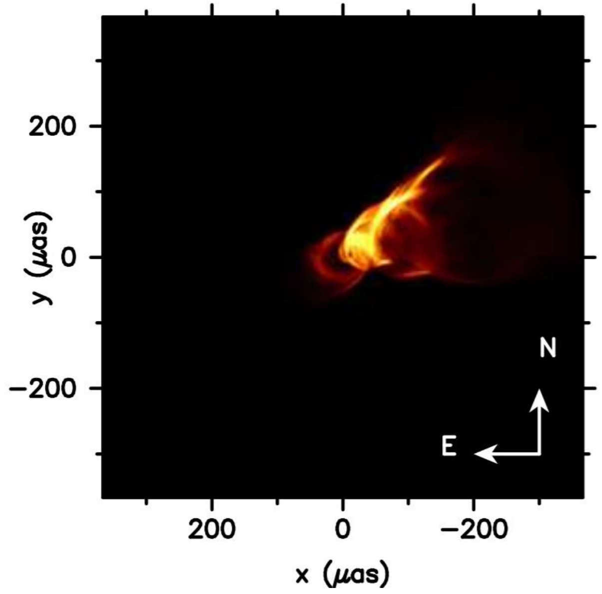


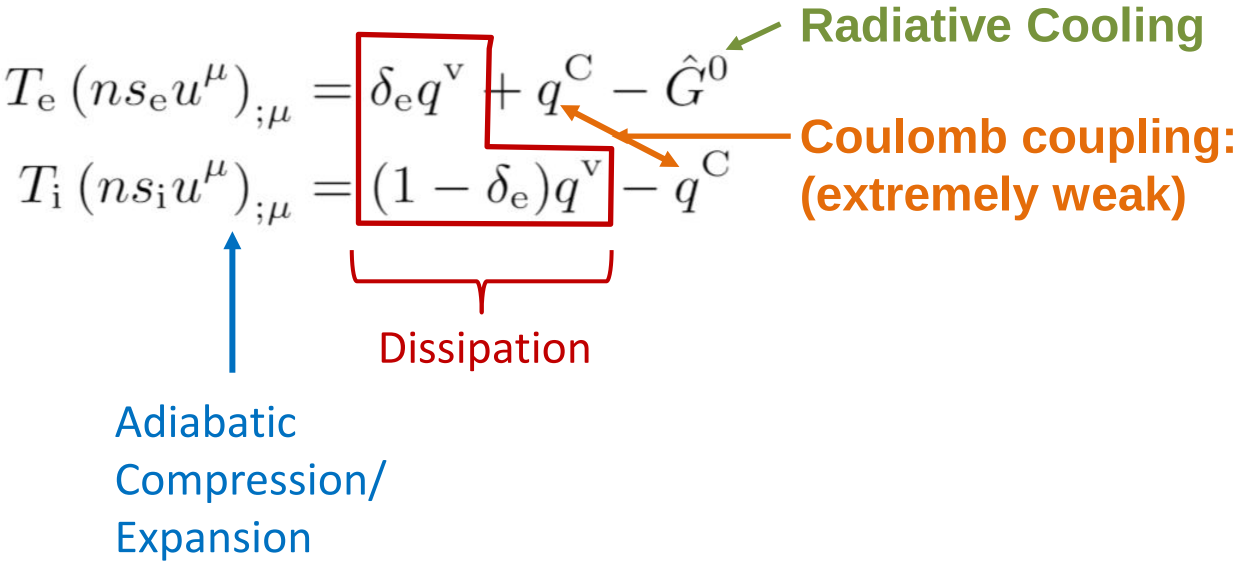
Image Credit: Ryan+ 2018, Moscibrodzka+ 2016
Also: Dexter+ 2012, 2017

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:



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

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

Radiative Cooling

Coulomb coupling:
(extremely weak)

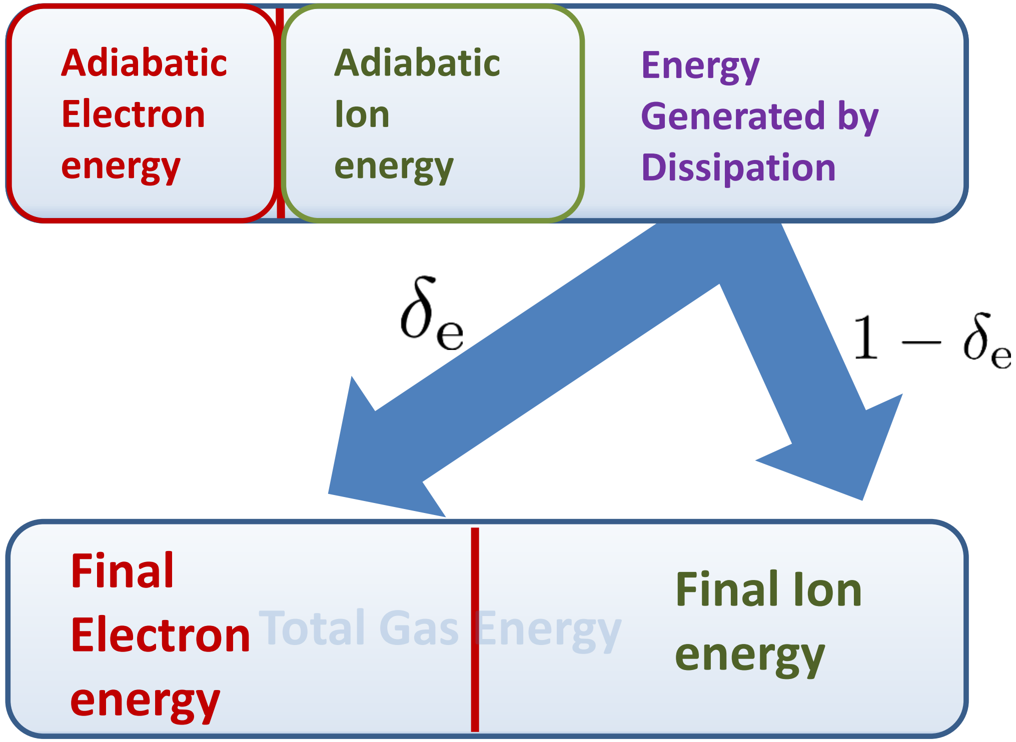
Dissipation

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.

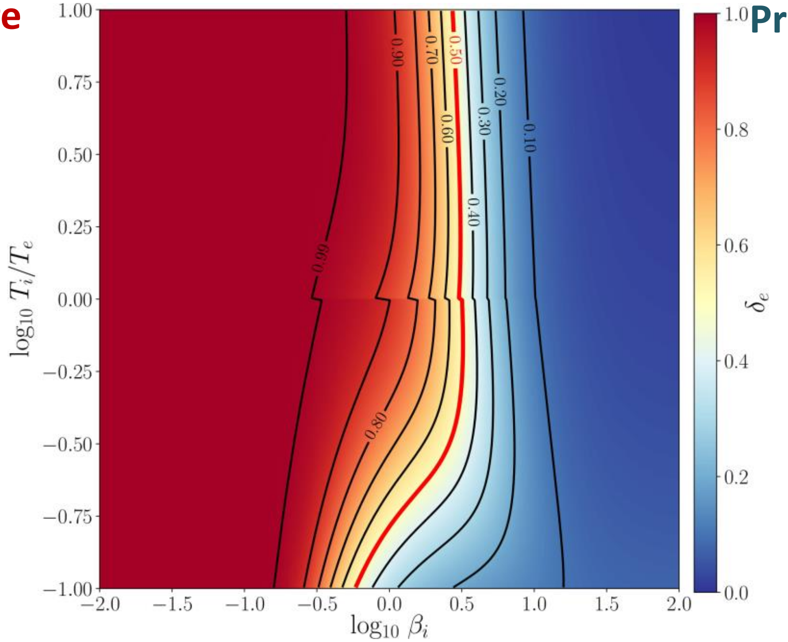


Sub-grid Heating Prescriptions

Turbulent Dissipation (Howes 2010)

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

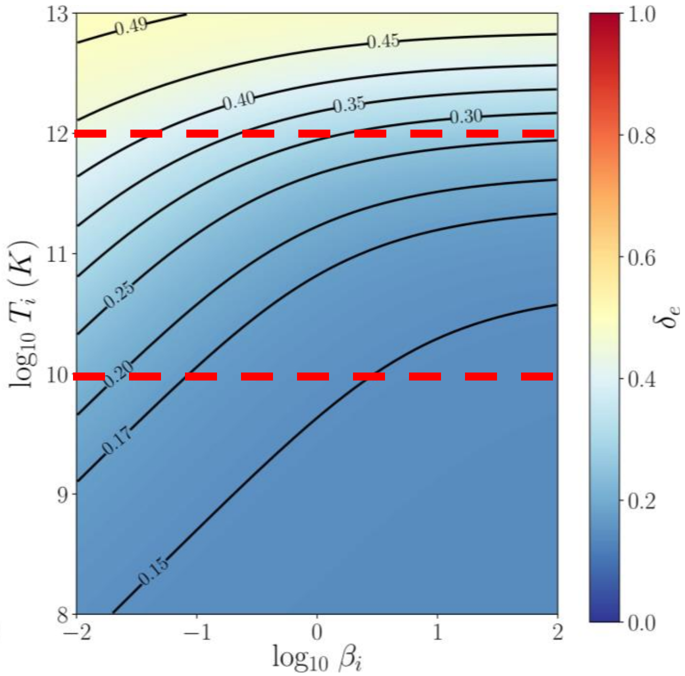
High Magnetic Pressure ⟷ **Low Magnetic Pressure**



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.



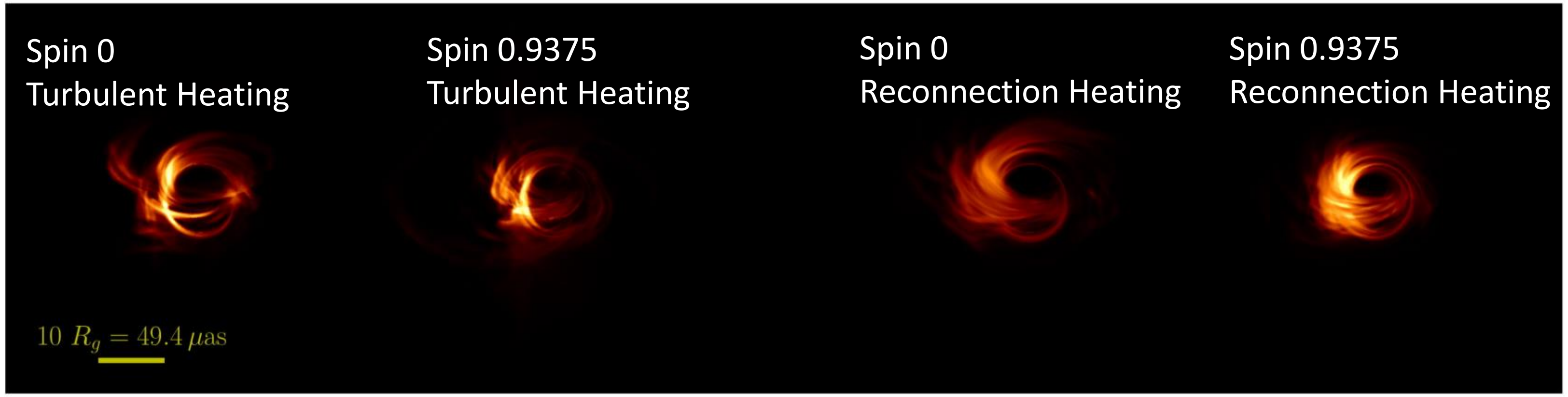
Relatively flat δ_e over large range of temperature, beta.

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

Two-temperature simulations of Sgr A*

Image structure with frequency

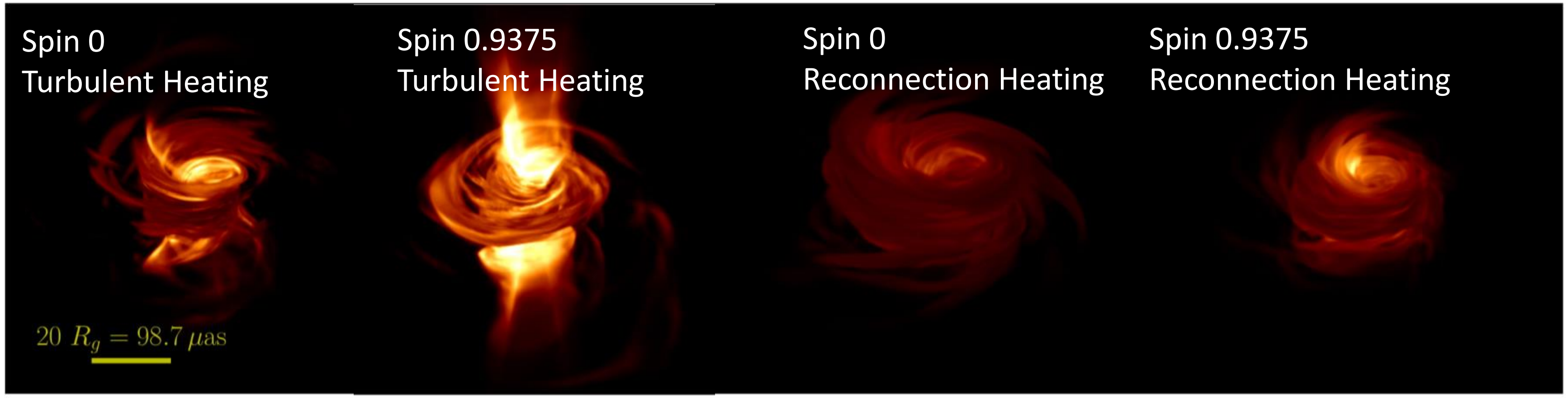
230 GHz



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*

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

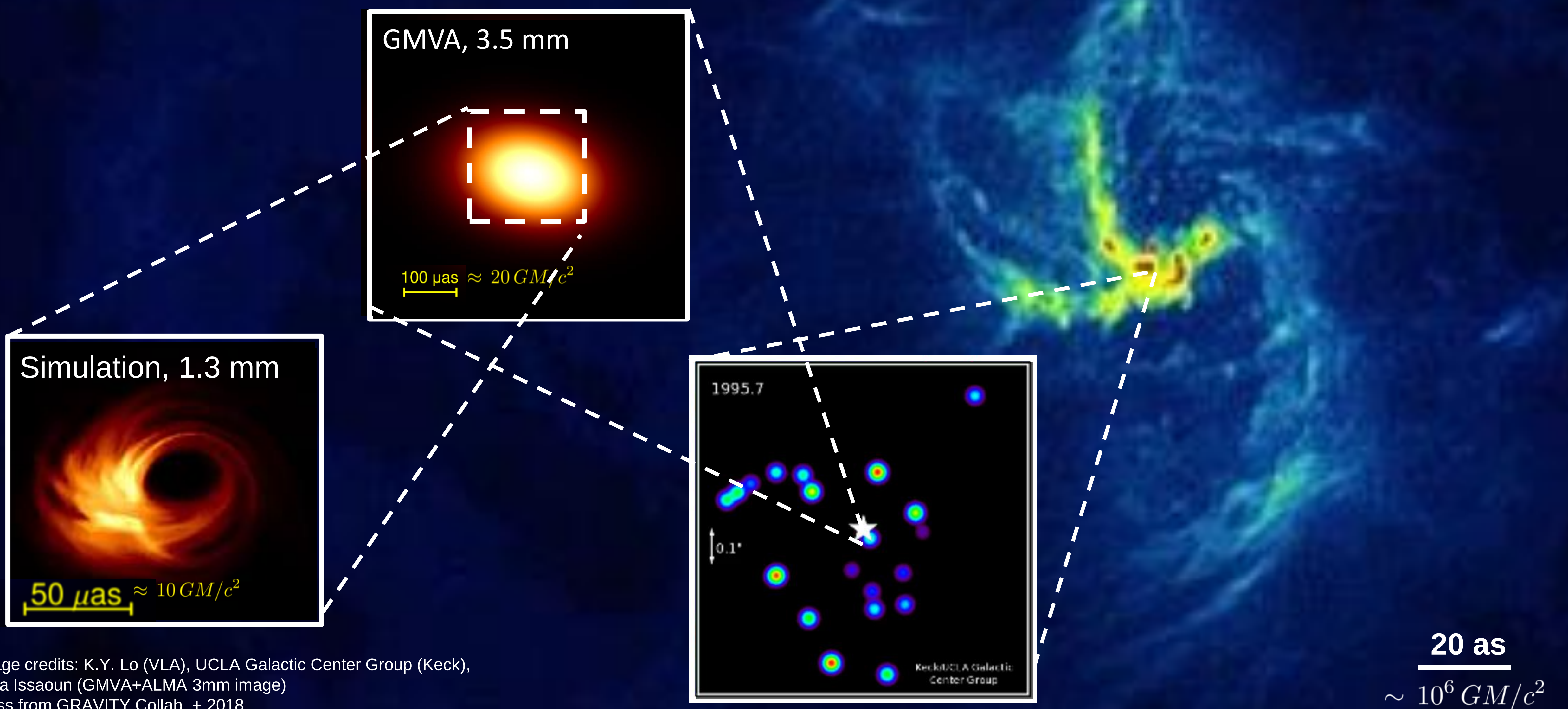
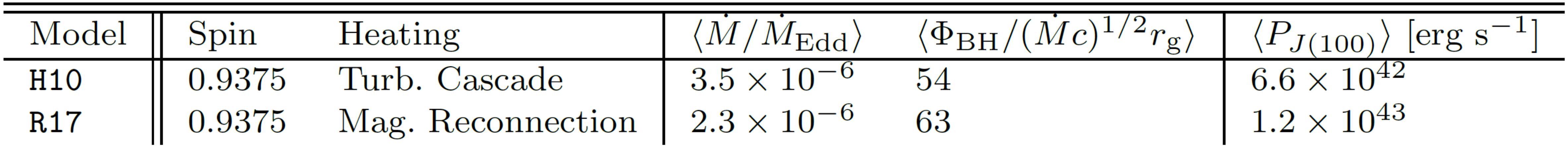


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)
Mass from GRAVITY Collab. + 2018

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”

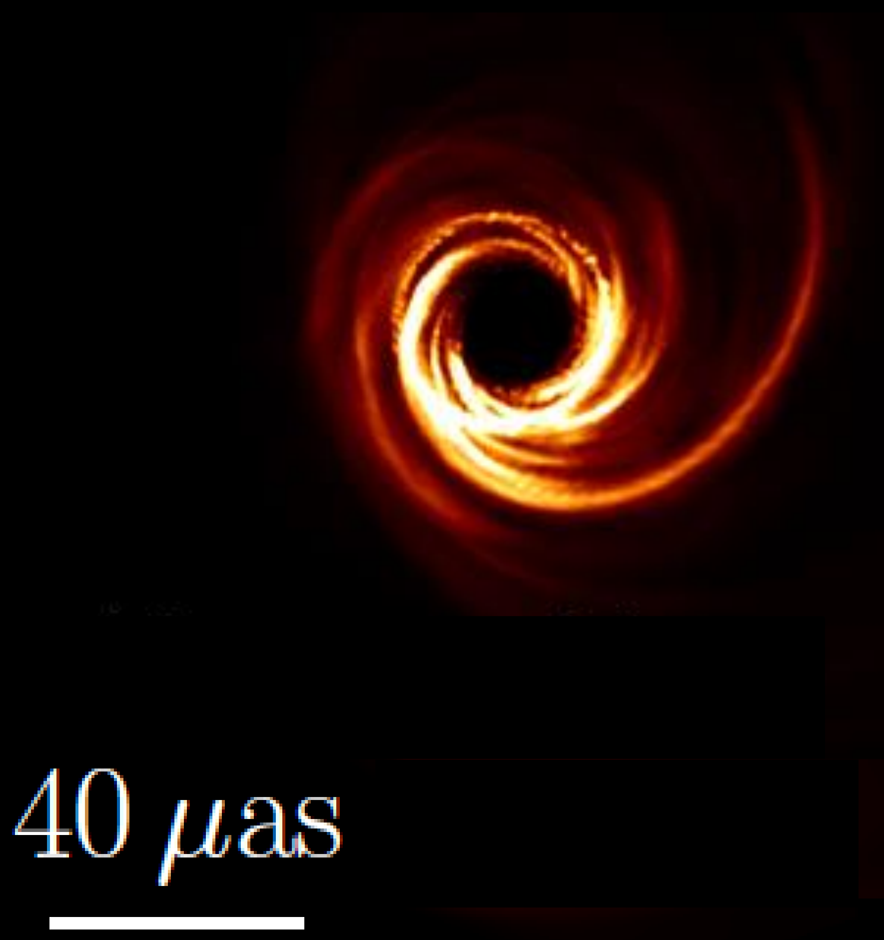
Jet **mechanical** power

- 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)

230 GHz Images

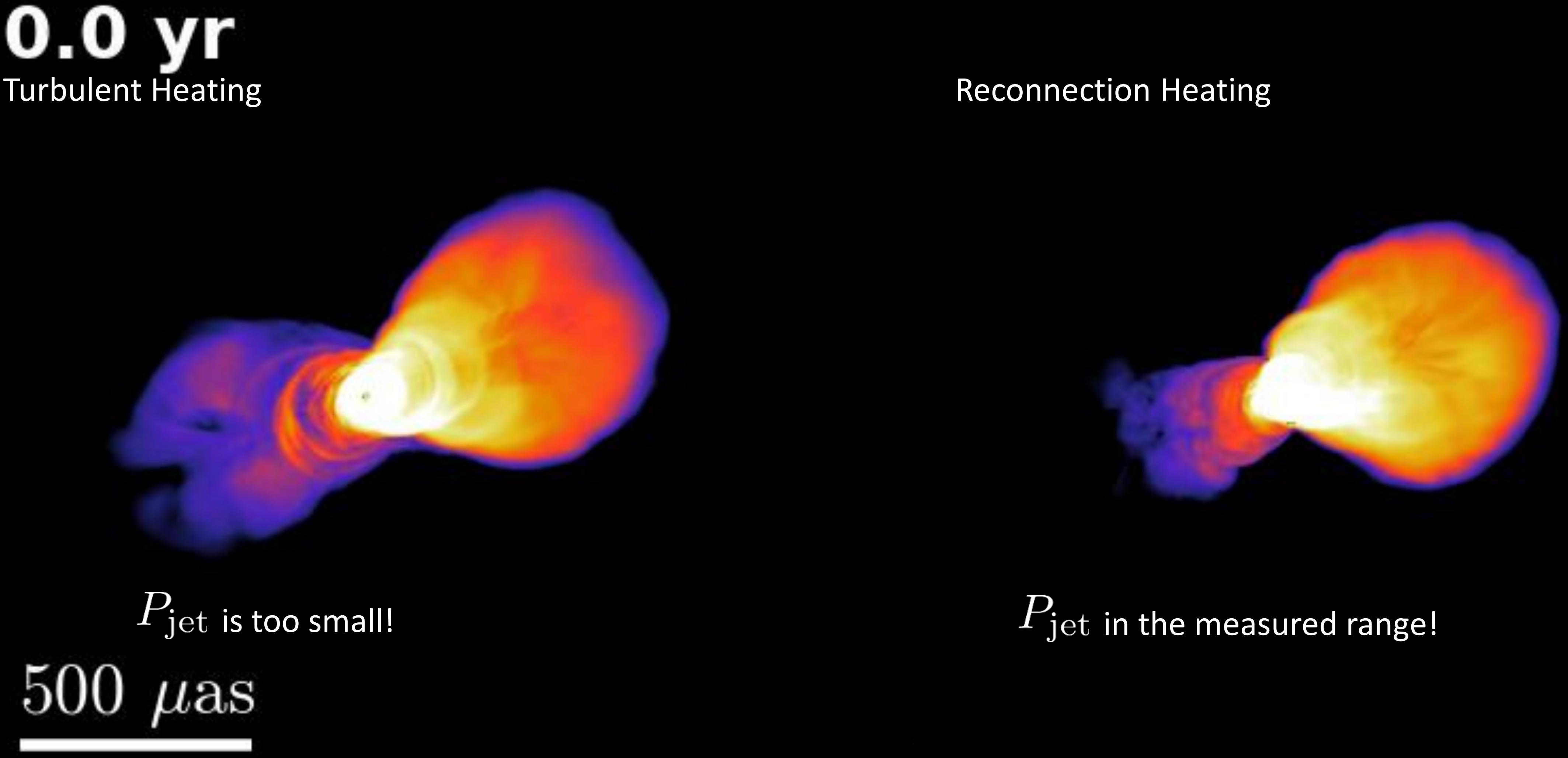
Turbulent Heating



Reconnection Heating

Two-temperature MAD simulations of M87

43 GHz jets



Turbulent Heating

Reconnection Heating

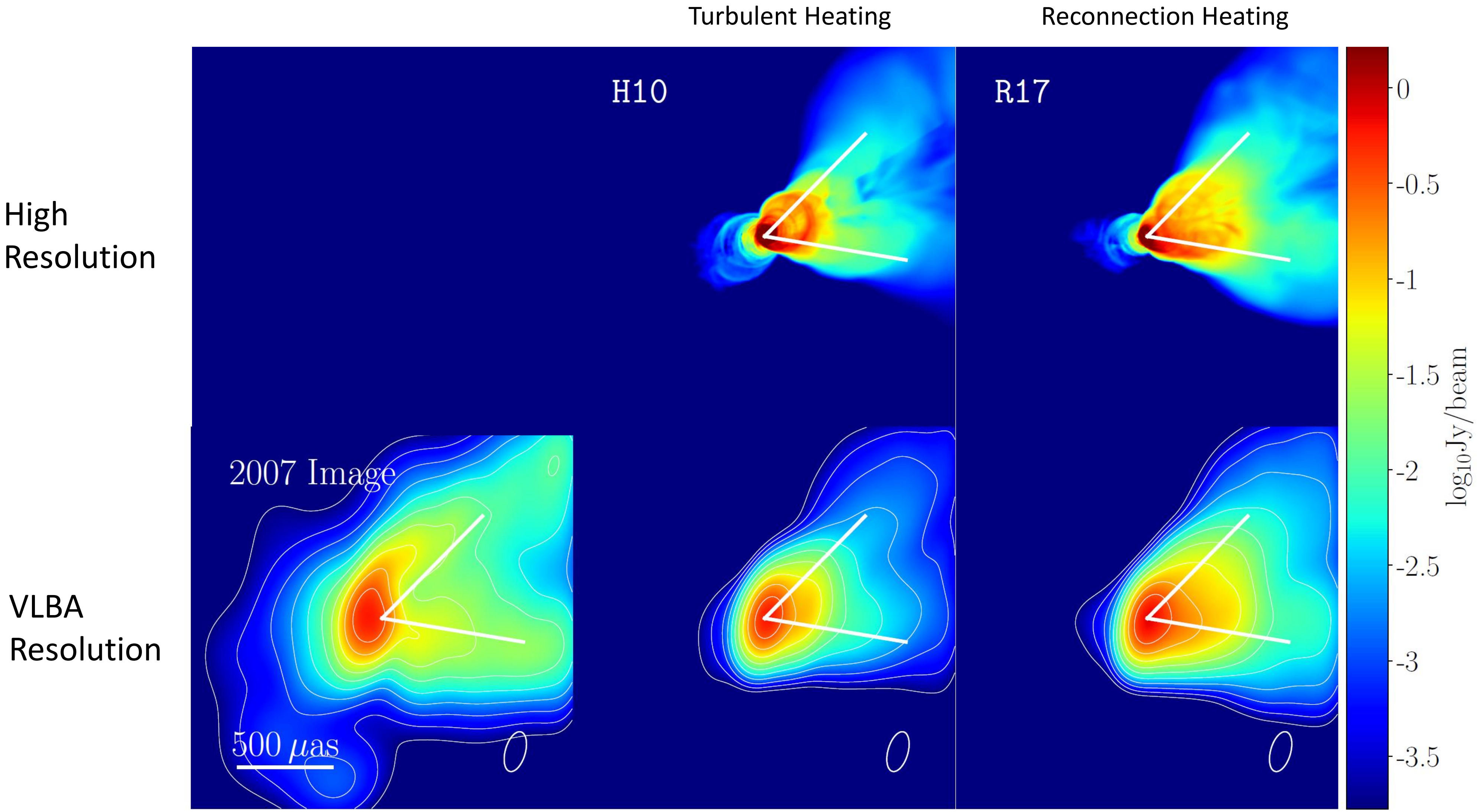
$P_{\rm jet}$ is too small!

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

Movie Credit: Chael+ 2019

43 GHz images – comparison with VLBI

Walker+ 2018



Apparent opening angle at 43 GHz:

55°

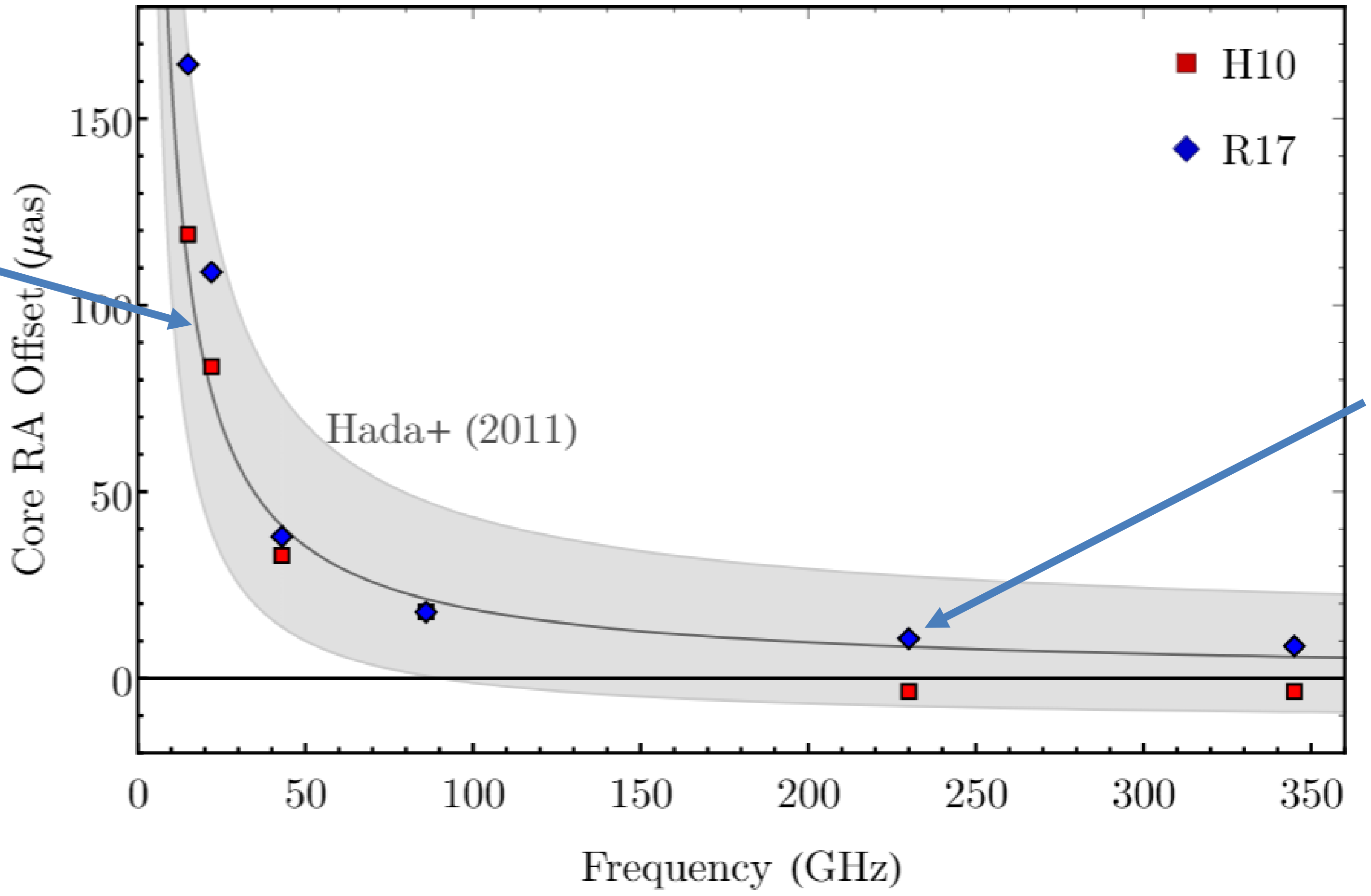
(Walker+ 2018)

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 Core-Shift

At lower frequencies, the optically thick synchrotron core moves up the jet



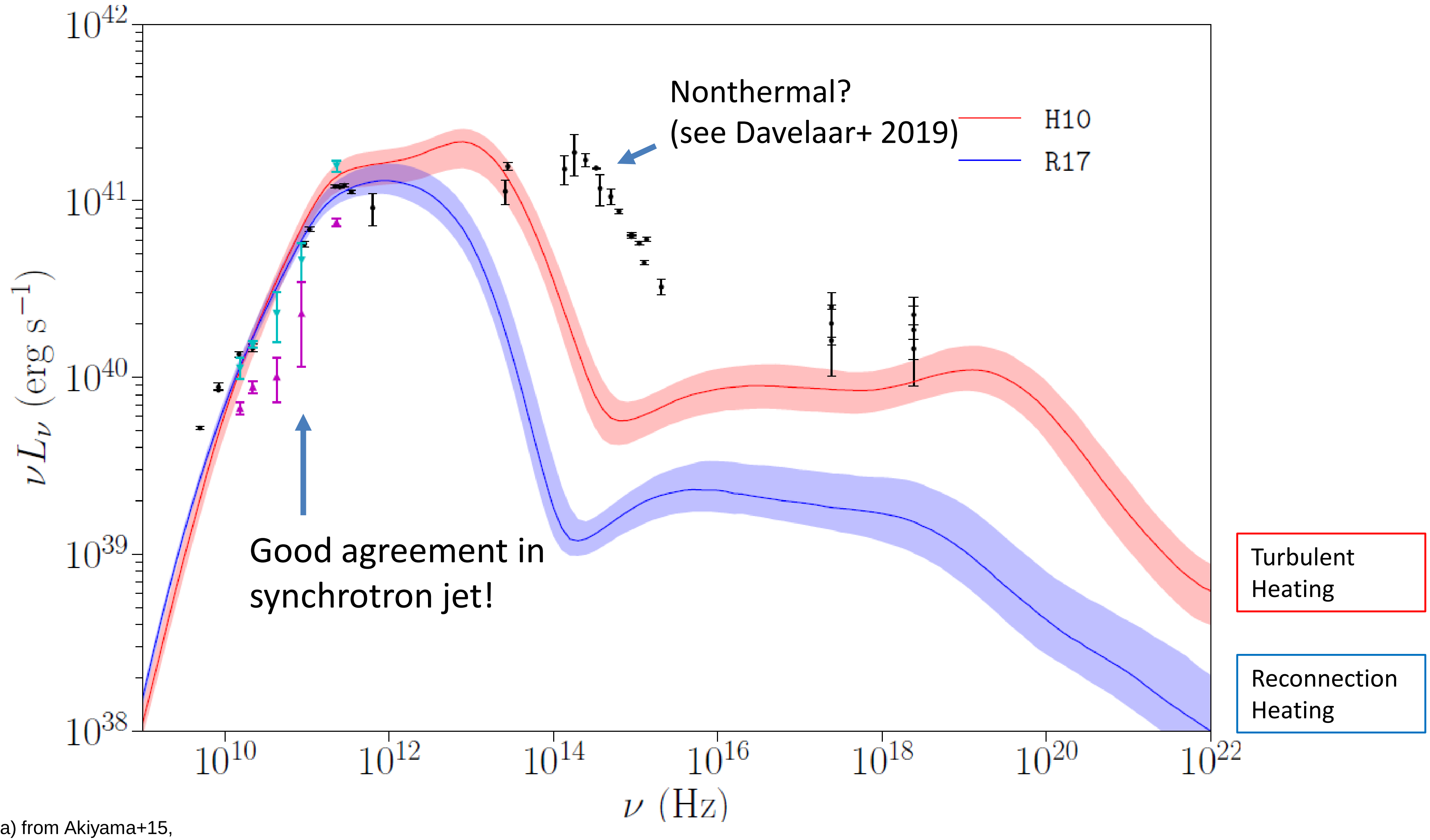
At 230 GHz and higher, the core is coincident with the black hole

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

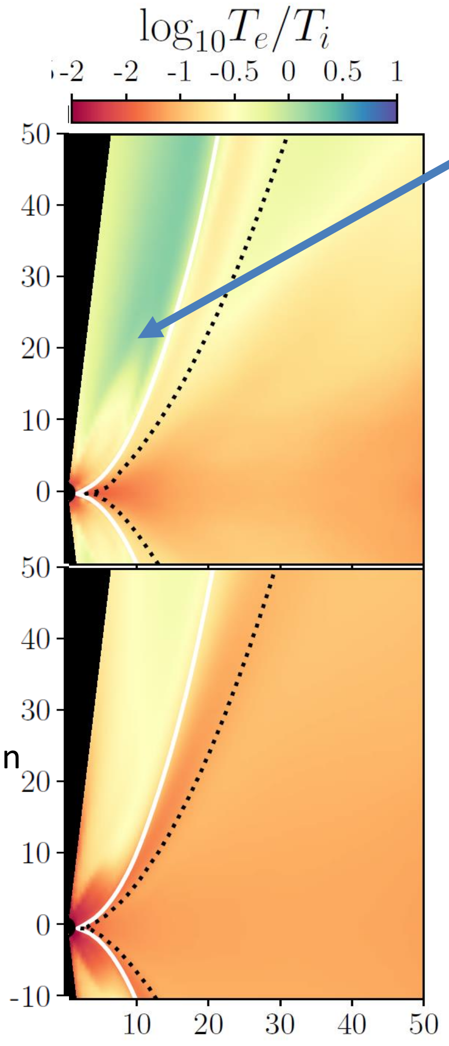
Data from Prieto+16
New points (cyan and magenta) from Akiyama+15, Doeleman+12, Walker+18, Kim+18, and MOJAVE

Image Credit: Chael+ 2019

Electron Heating + Radiation → Jet Dynamics

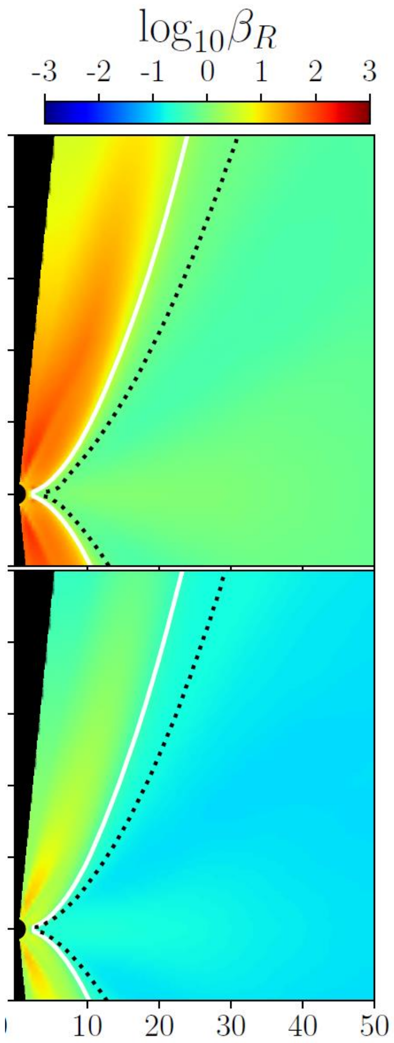
Turbulent Heating

Reconnection Heating

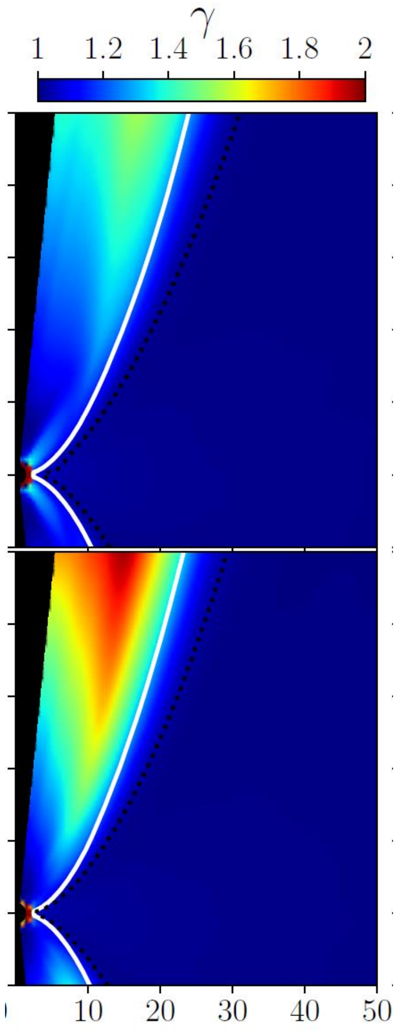


Very hot jet electrons

Tons of synchrotron and IC radiation produced



Weaker mechanical jet power

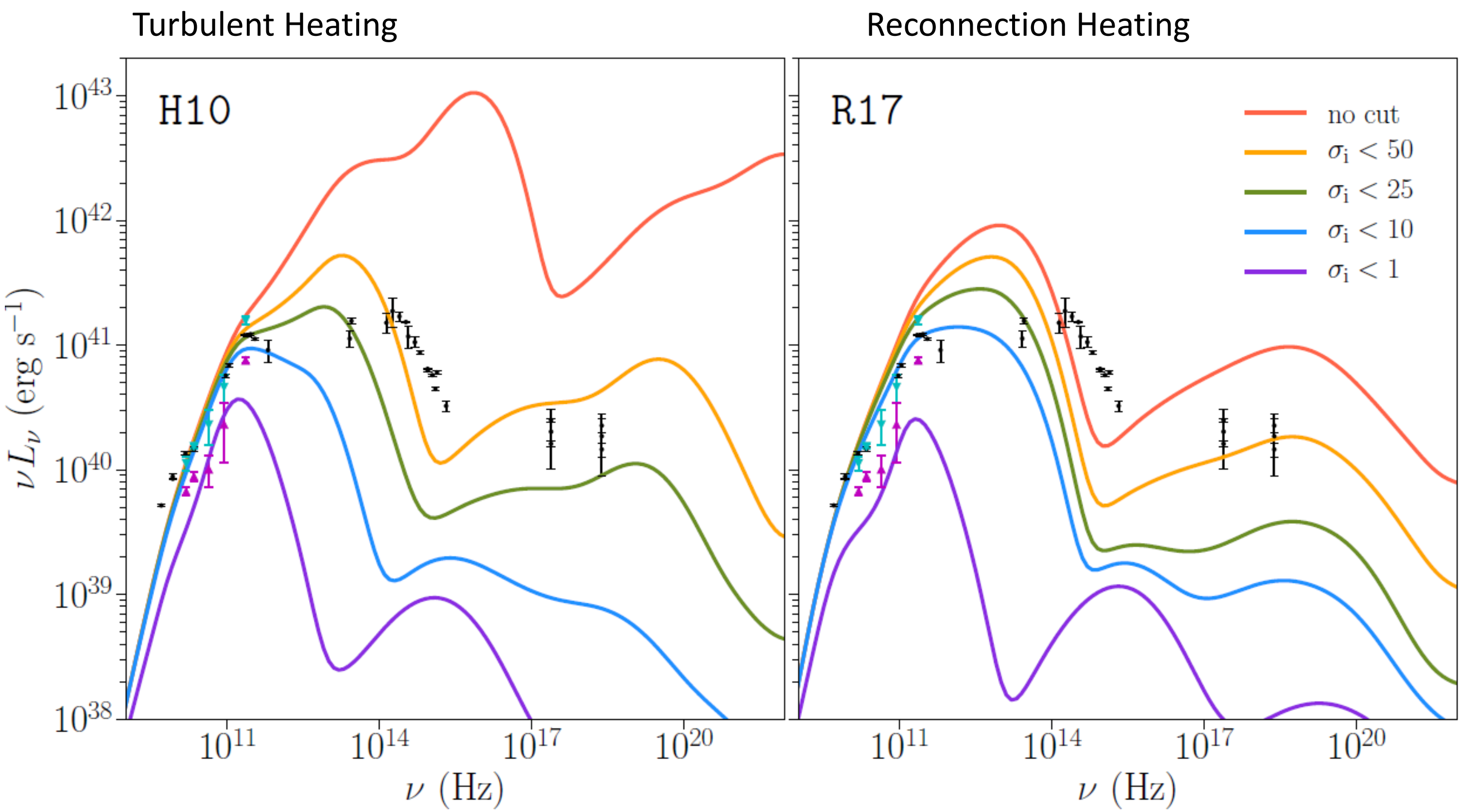


Turbulent heating produces too much radiation at the jet base, which saps the jet power

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 $\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

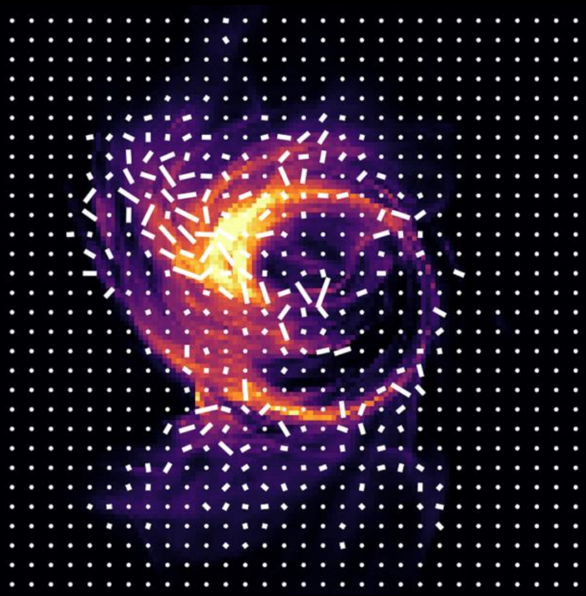
Polarization and e- heating

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)

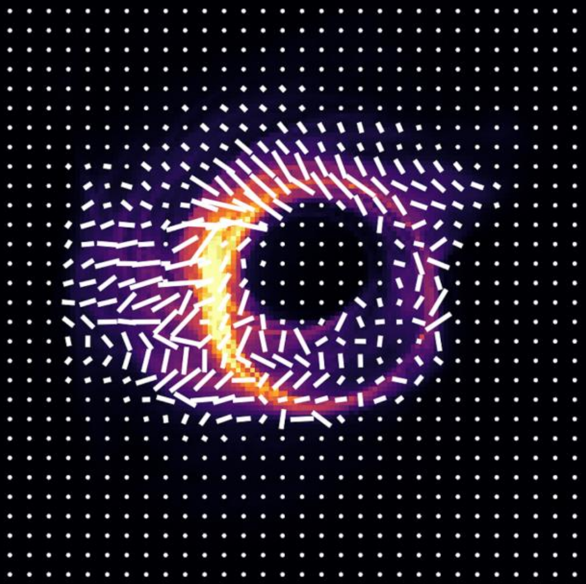
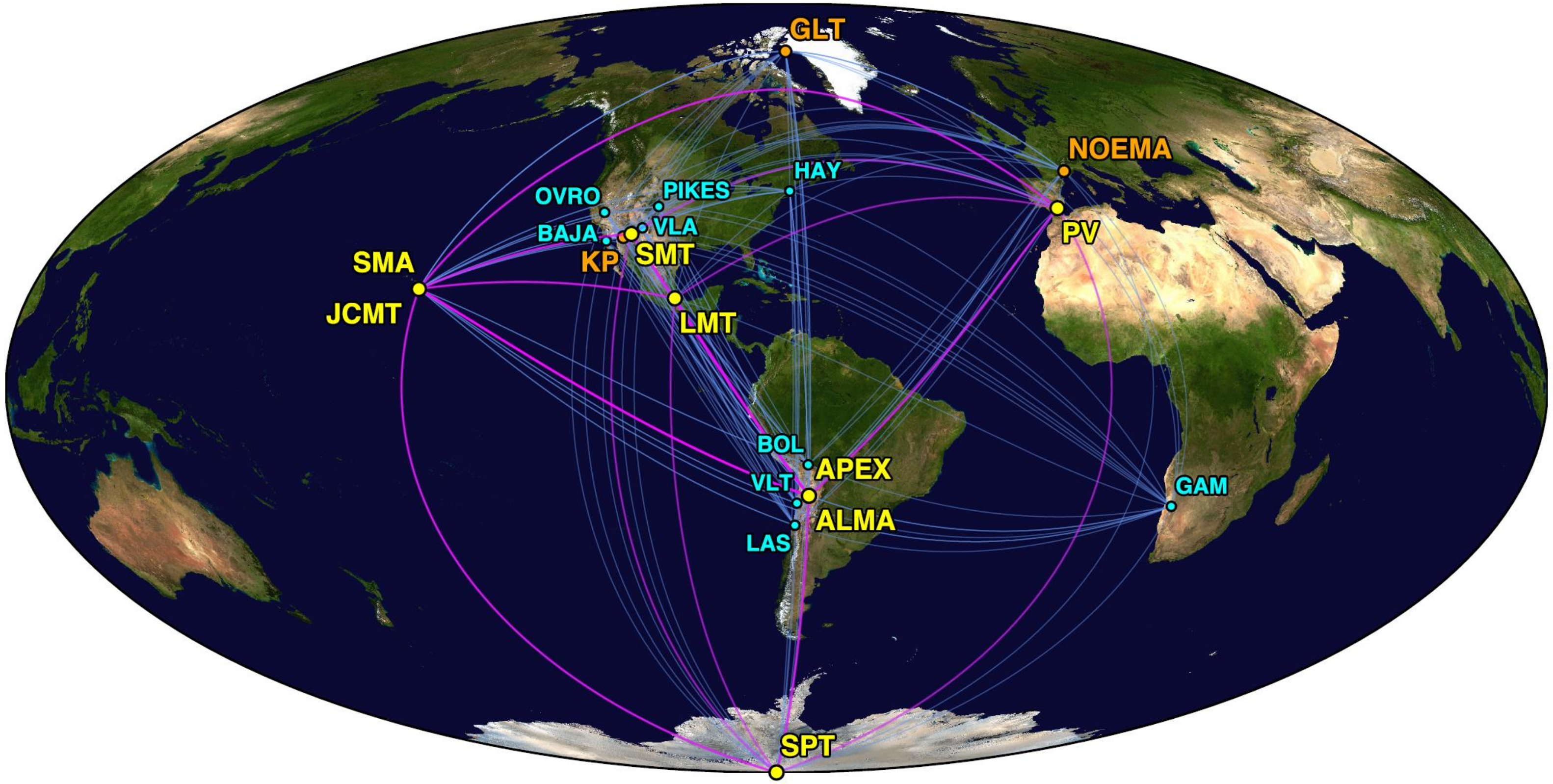
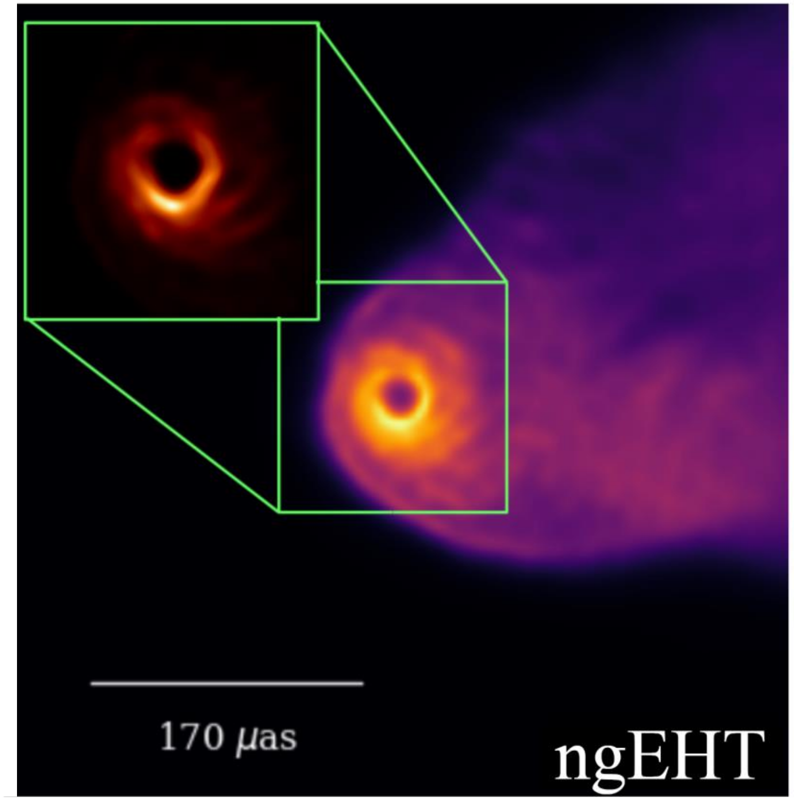


Image credit:
Jason Dexter

Next Steps: Enhancing EHT’s dynamic range





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

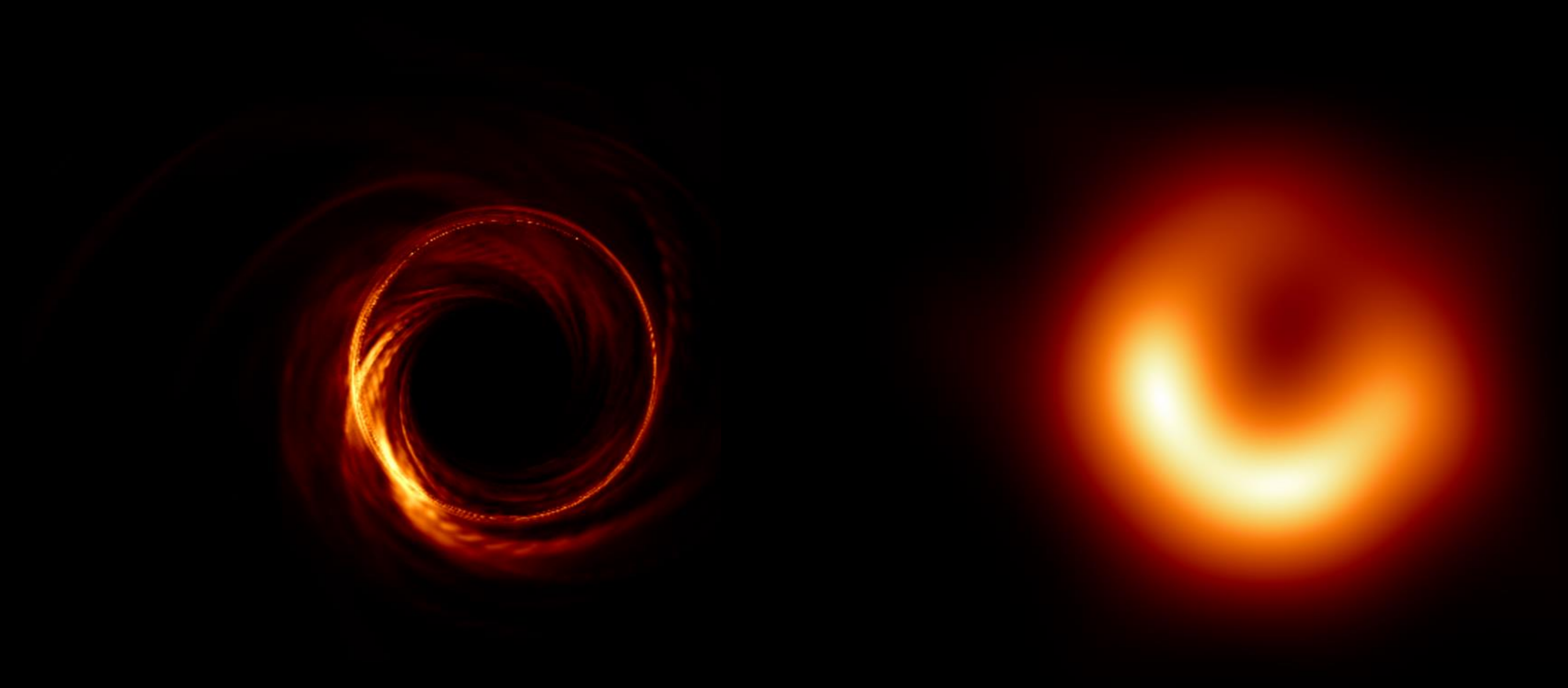
Idea: add many more small, ~6m dishes to the array

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

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