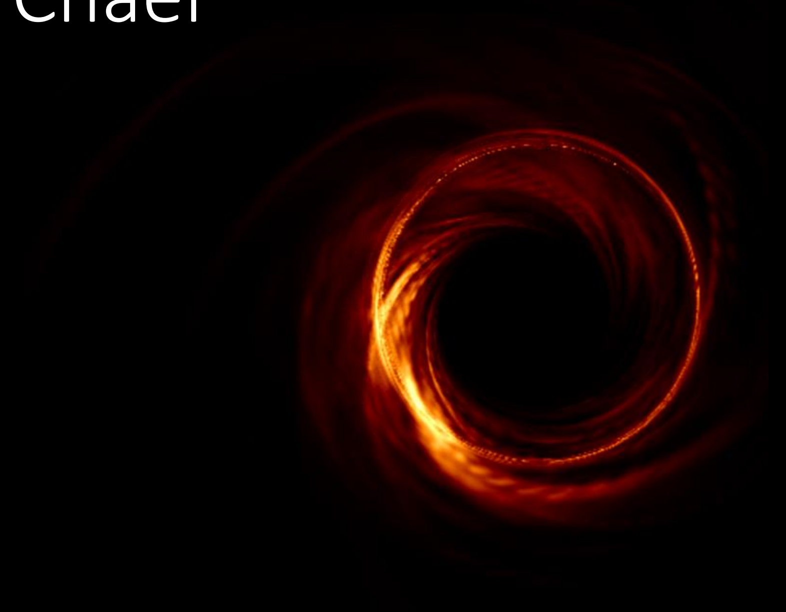
Radiative, two-temperature simulations of the supermassive black hole in M87

Andrew Chael

May 2, 2019



CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Event Horizon Telescope

MNRAS 486 (2019)
arXiv: 1810.01983

M87

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

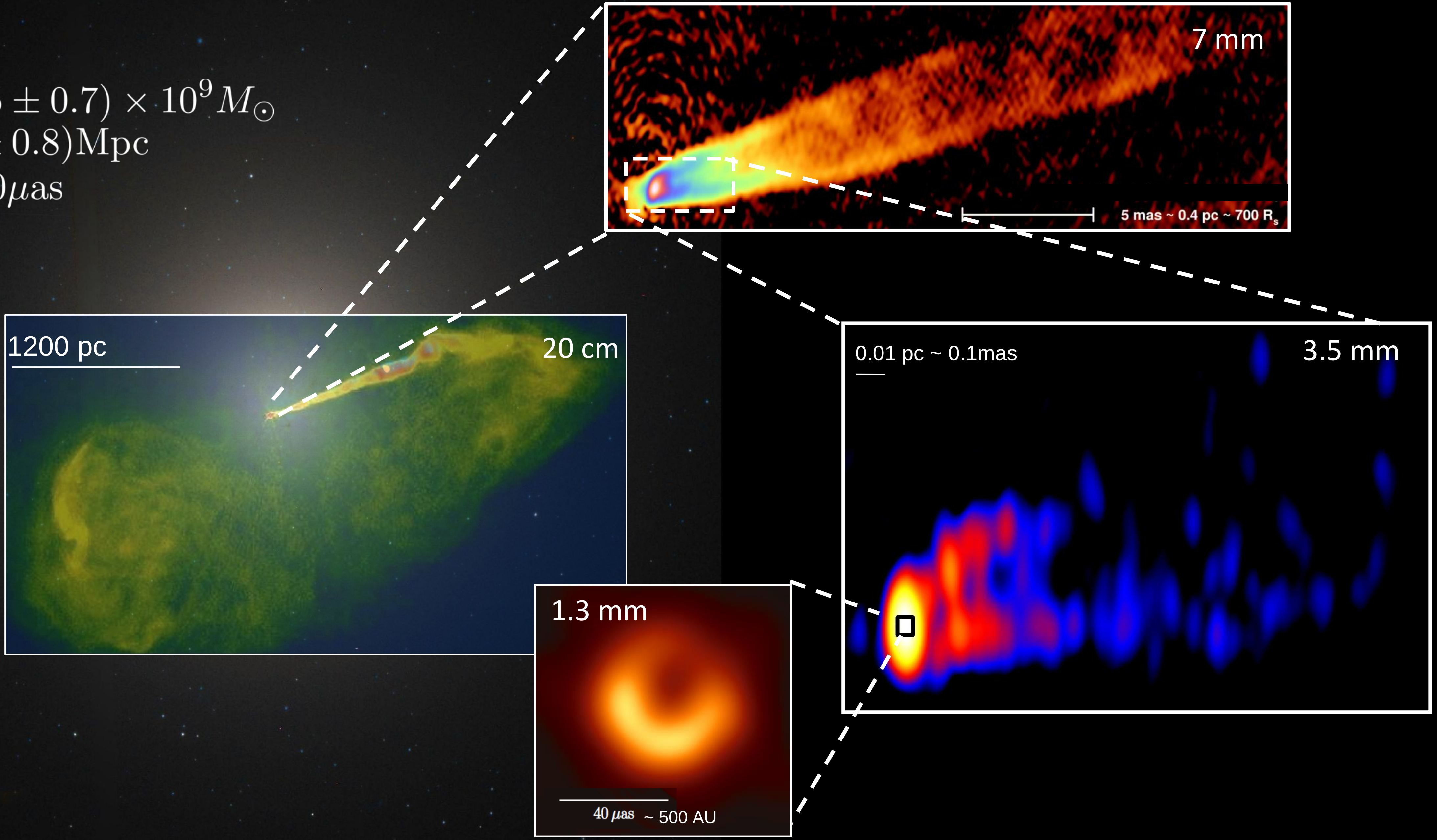
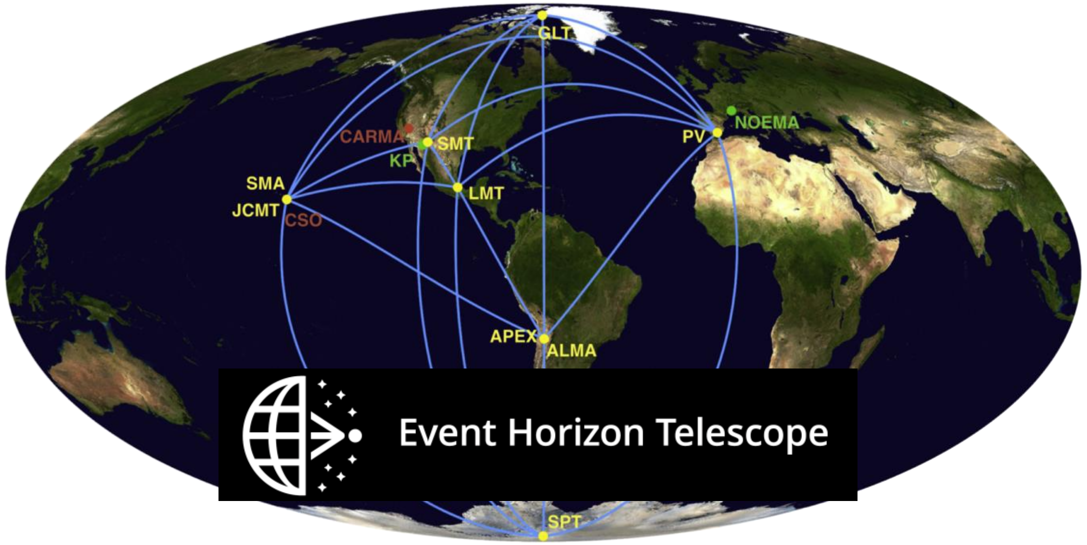


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

Simulations

Using physics to predict and interpret what the EHT sees

What tests are possible given the limitations of EHT data?



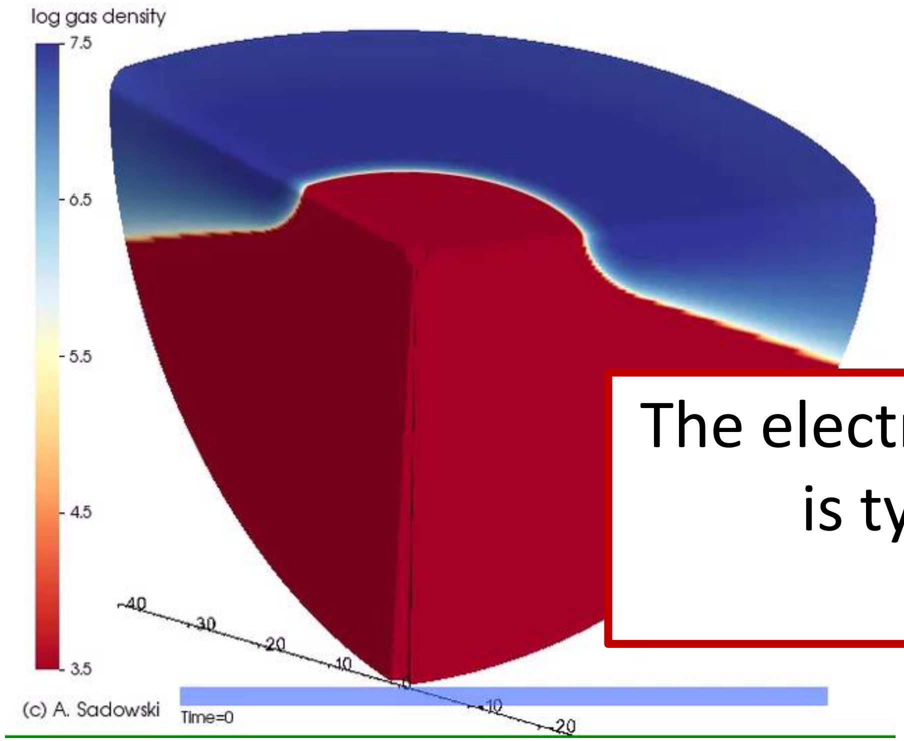
How can we use images to test black hole & accretion physics?

Imaging

Using EHT data to make measurements

Image Credit:
EHT Collaboration 2019 (Paper II)

From simulations to observables



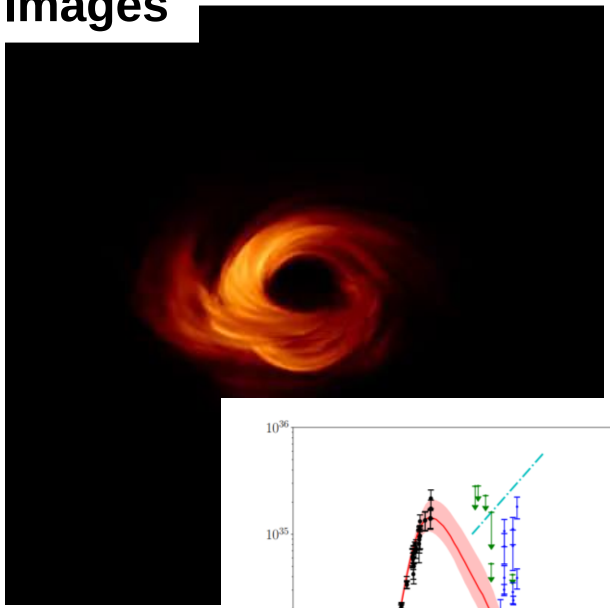
GRMHD Simulations

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

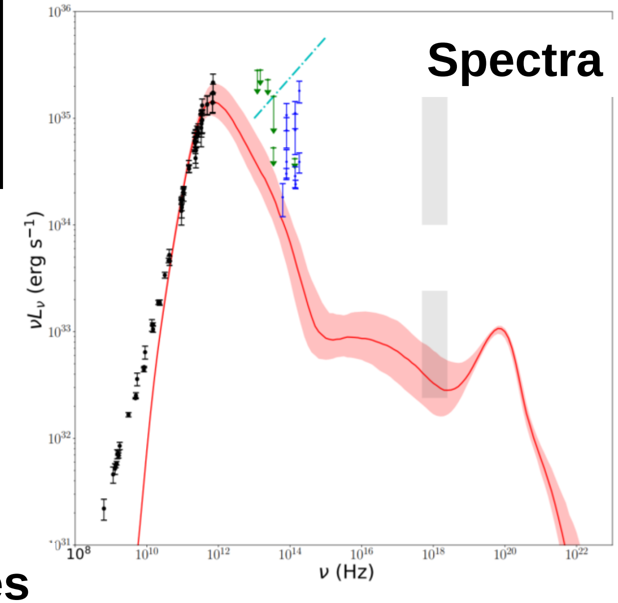
T_e?

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

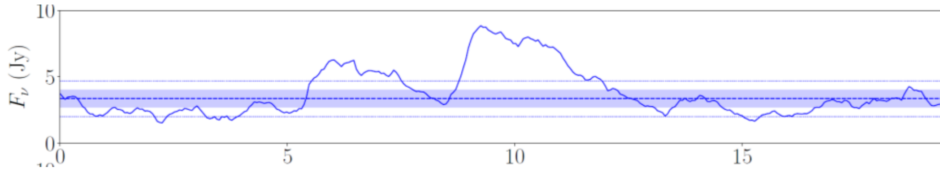
Images



Spectra



Light Curves



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

Two-Temperature GRRMHD Simulations

- Using the **radiative** GRMHD code `KORAL`: (Sądowski+ 2013, 2015, 2017)

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

Radiation

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

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

Coulomb Coupling: extremely weak

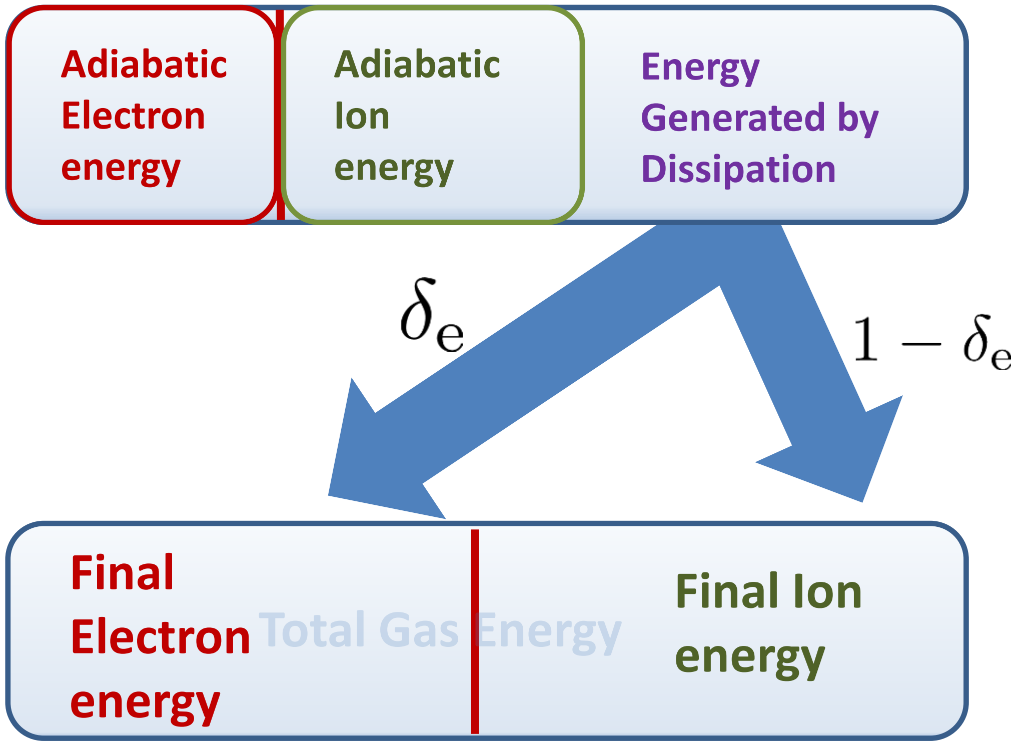
Dissipation

Adiabatic Compression/ Expansion

Electron & Ion Heating

- The **total** dissipation in the simulation is the total internal energy 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.

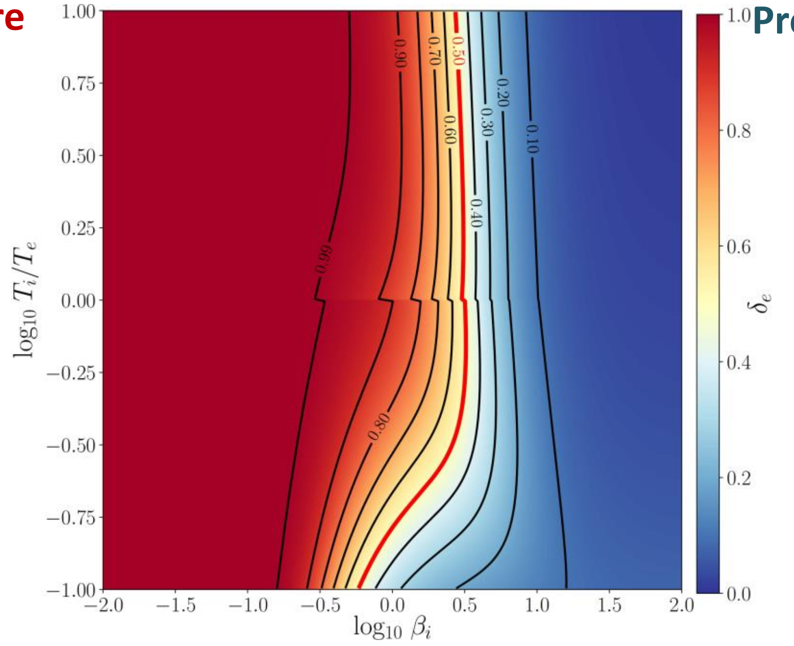


Sub-grid Heating Prescriptions

Turbulent Dissipation (Howes 2010)

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

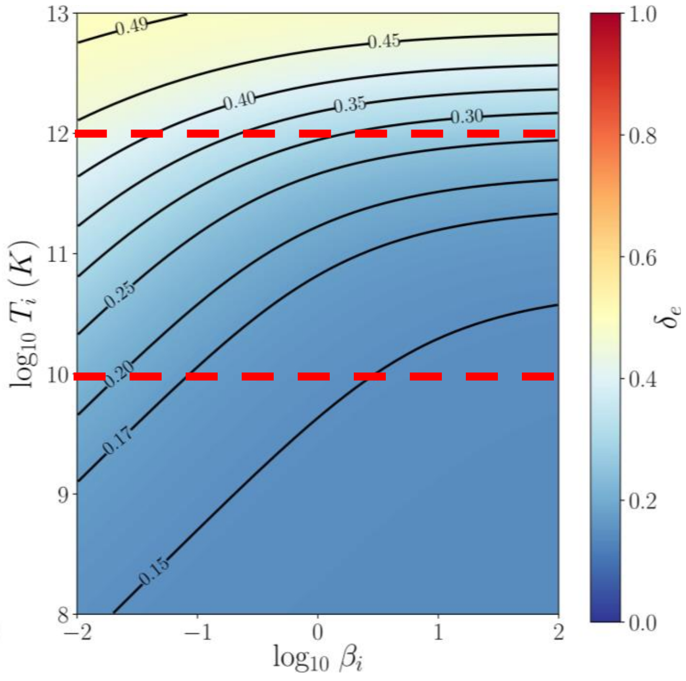
High Magnetic Pressure ⟷ **Low Magnetic Pressure**



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



Relatively flat δ_e over large range of temperature, beta.

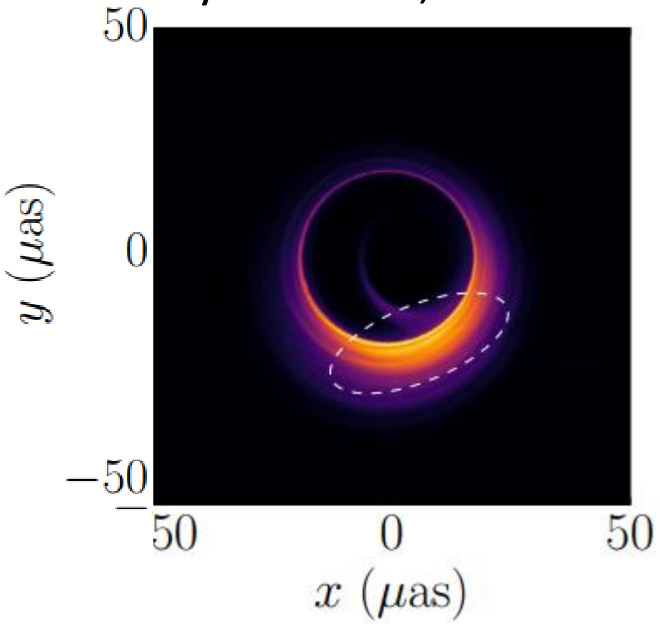
Image Credit: Chael+ 2018b
see also: Kawazura+ 2018 (turbulent damping). Werner+ 2018 (reconnection)

Previous work:

Mościbrodzka+ 2016, Ryan+ 2018

- All simulations with **weak magnetic flux.**
- Radiation feedback becomes important in determining the disk electron 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

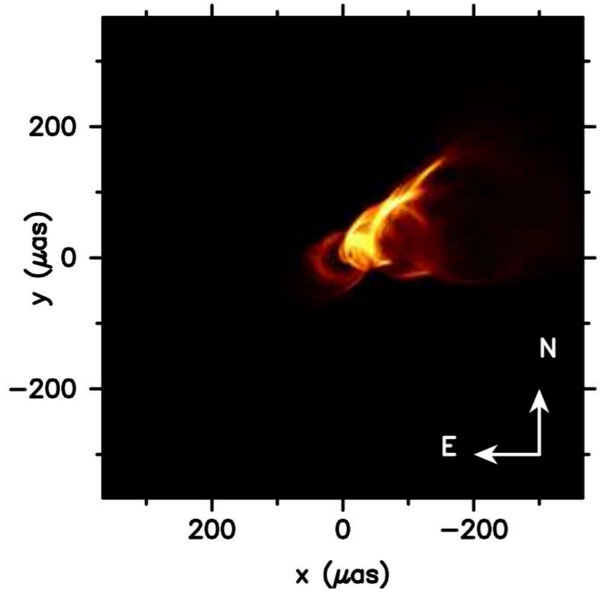


Image Credit: Ryan+ 2018, Moscibrodzka+ 2016
Also: Dexter+ 2012, 2017

Two M87 Simulations

Model	Spin	Heating	$\langle \dot{M}/\dot{M}_{\rm Edd} \rangle$	$\langle \Phi_{\rm BH}/(\dot{M}c)^{1/2} r_{\rm g} \rangle$
H10	0.9375	Turb. Cascade	3.5×10^{-6}	54
R17	0.9375	Mag. Reconnection	2.3×10^{-6}	63

"MAD parameter"

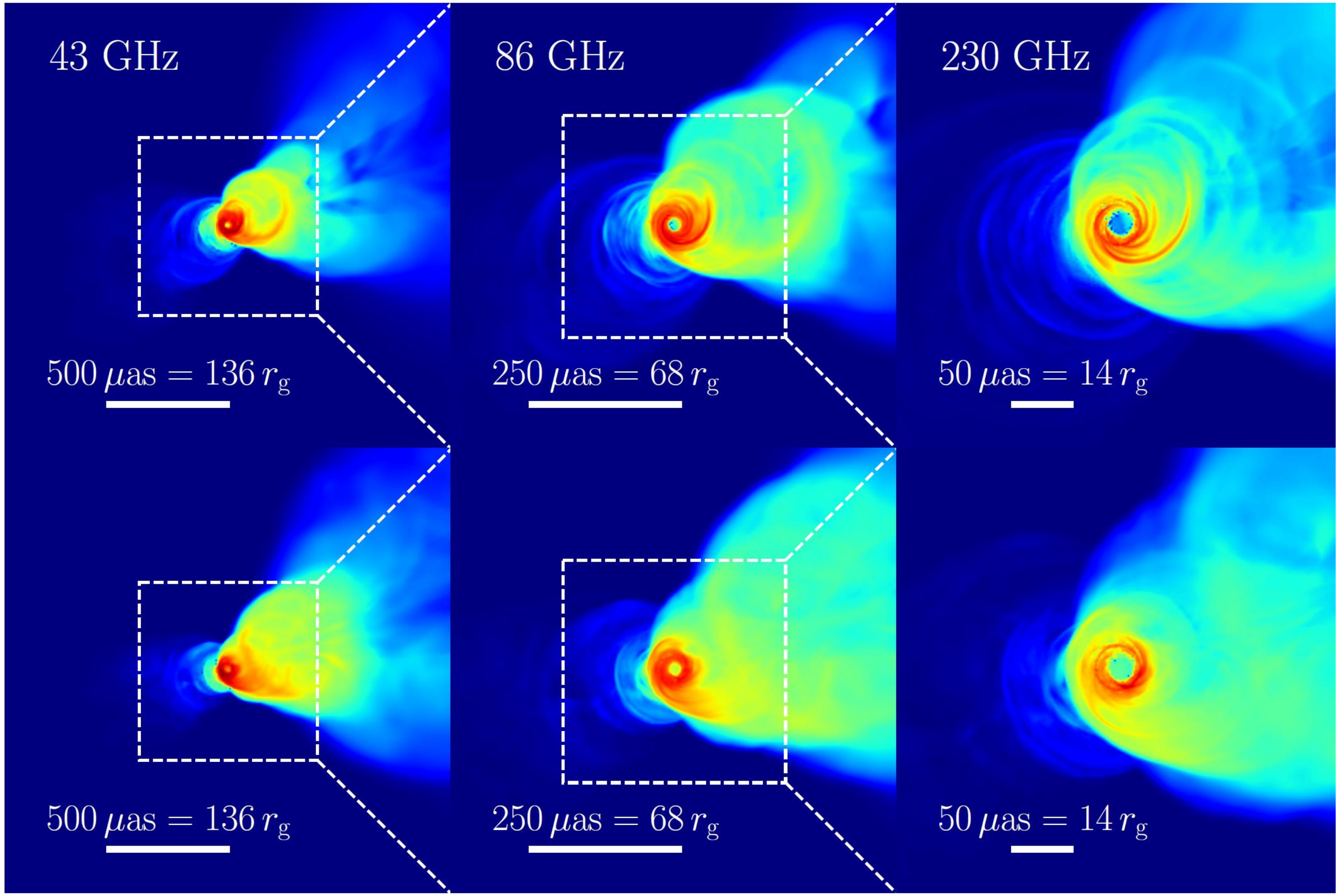
- Both simulations are MAD and accrete at $\sim 10^{-6}\, \dot{M}_{\rm Edd}$
- Density is scaled to match 0.98 Jy at 230 GHz
  - (EHT measurement in 2009-2012; in 2017 the 230 GHz flux density was ~0.6 Jy)

(Doeleman+ 12, Akiyama+ 15)

M87 Jets at millimeter wavelengths

Turbulent Heating

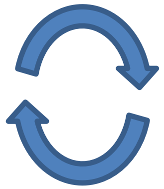
Reconnection Heating



Inclination angle (down from pole)

17°

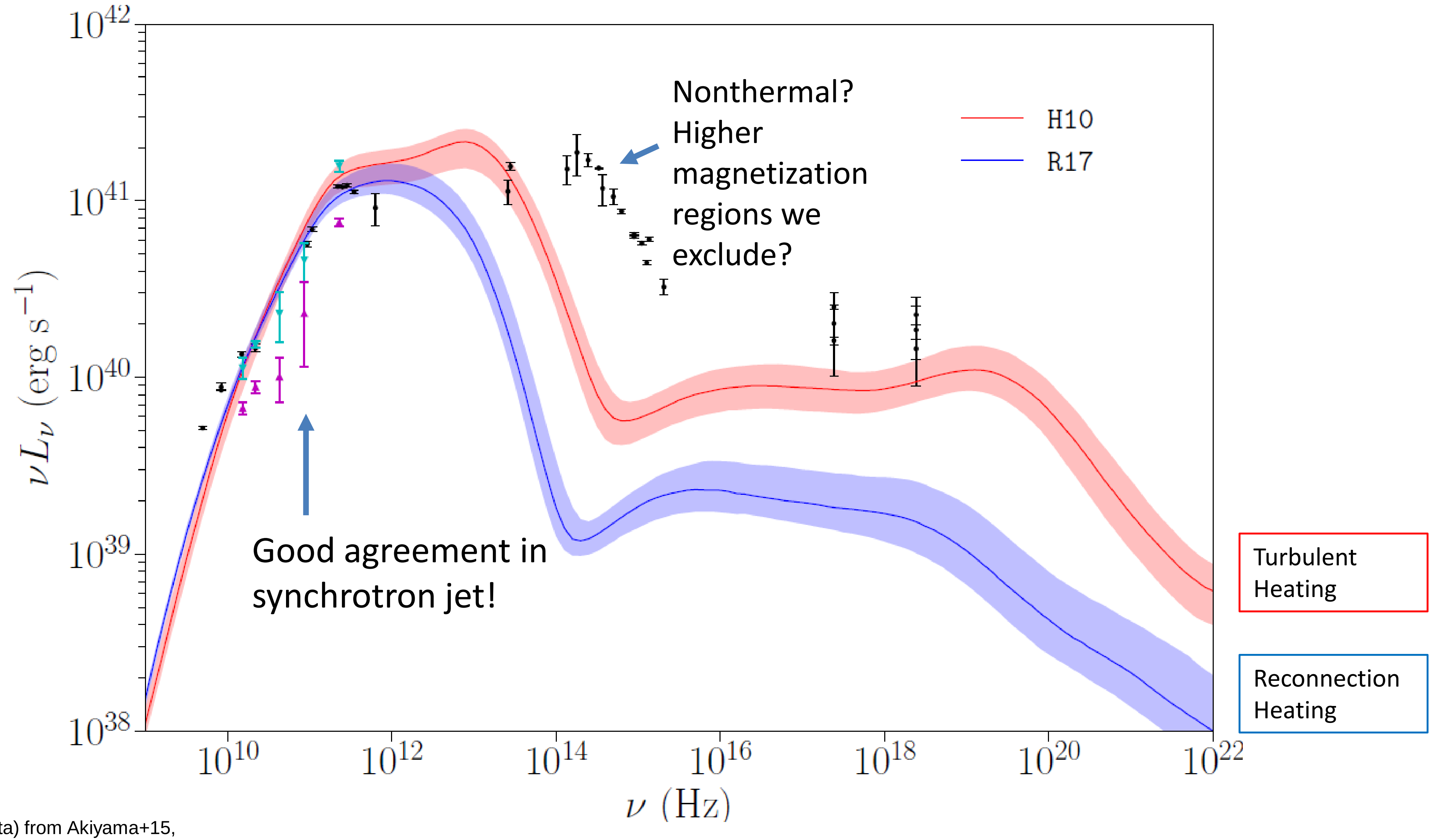
Disk/Jet rotation sense



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

Image Credit: Chael+ 2019

M87 Spectrum



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

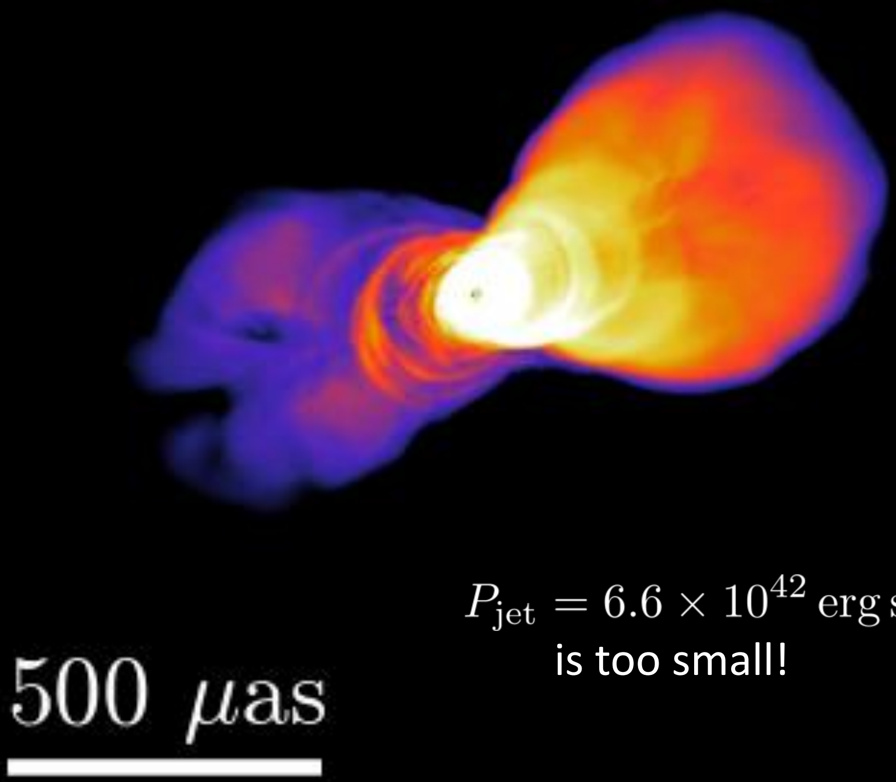
Image Credit: Chael+ 2019

Two M87 simulations

43 GHz jets

0.0 yr

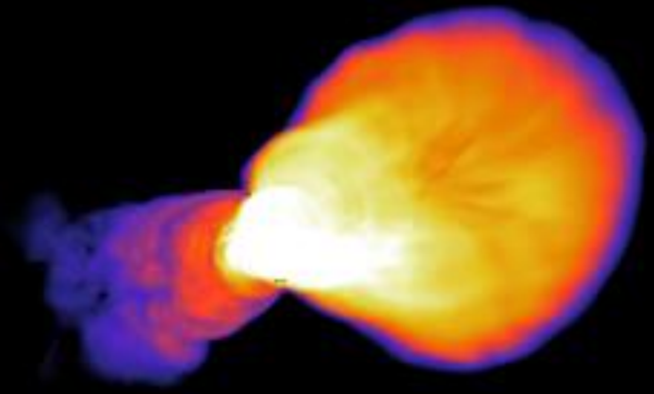
Turbulent Heating



$P_{\rm jet} = 6.6 \times 10^{42}\,{\rm erg\,s^{-1}}$

is too small!

Reconnection Heating



$P_{\rm jet} = 1.2 \times 10^{43}\,{\rm erg\,s^{-1}}$

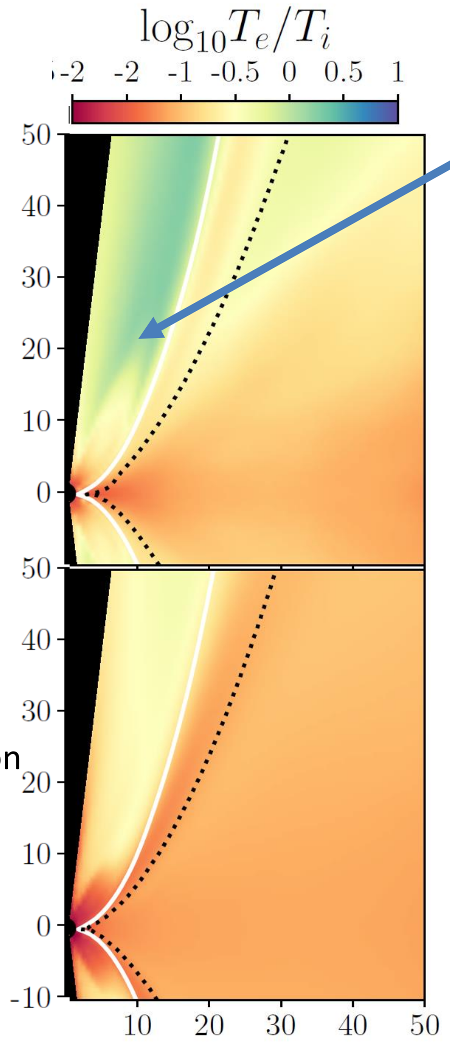
in the measured range!

Movie Credit: Chael+ 2019

Electron Heating → Jet Dynamics

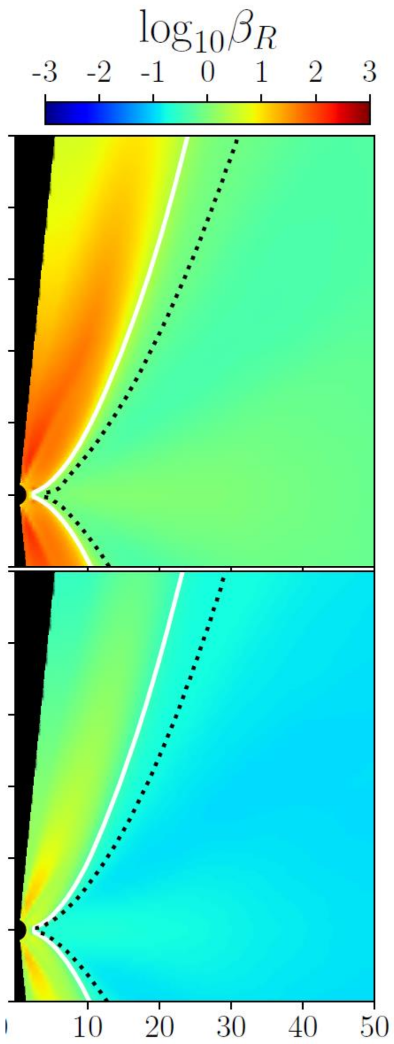
Turbulent Heating

Reconnection Heating

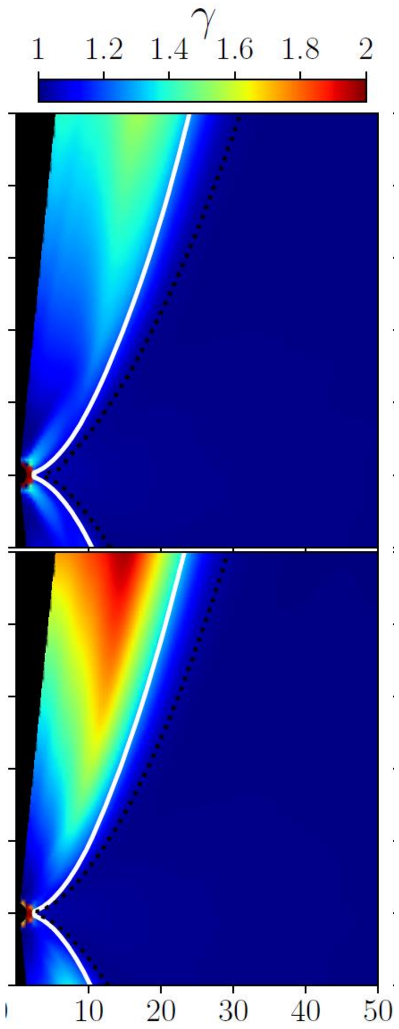


Very hot jet electrons

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

43 GHz images – comparison with VLBA images

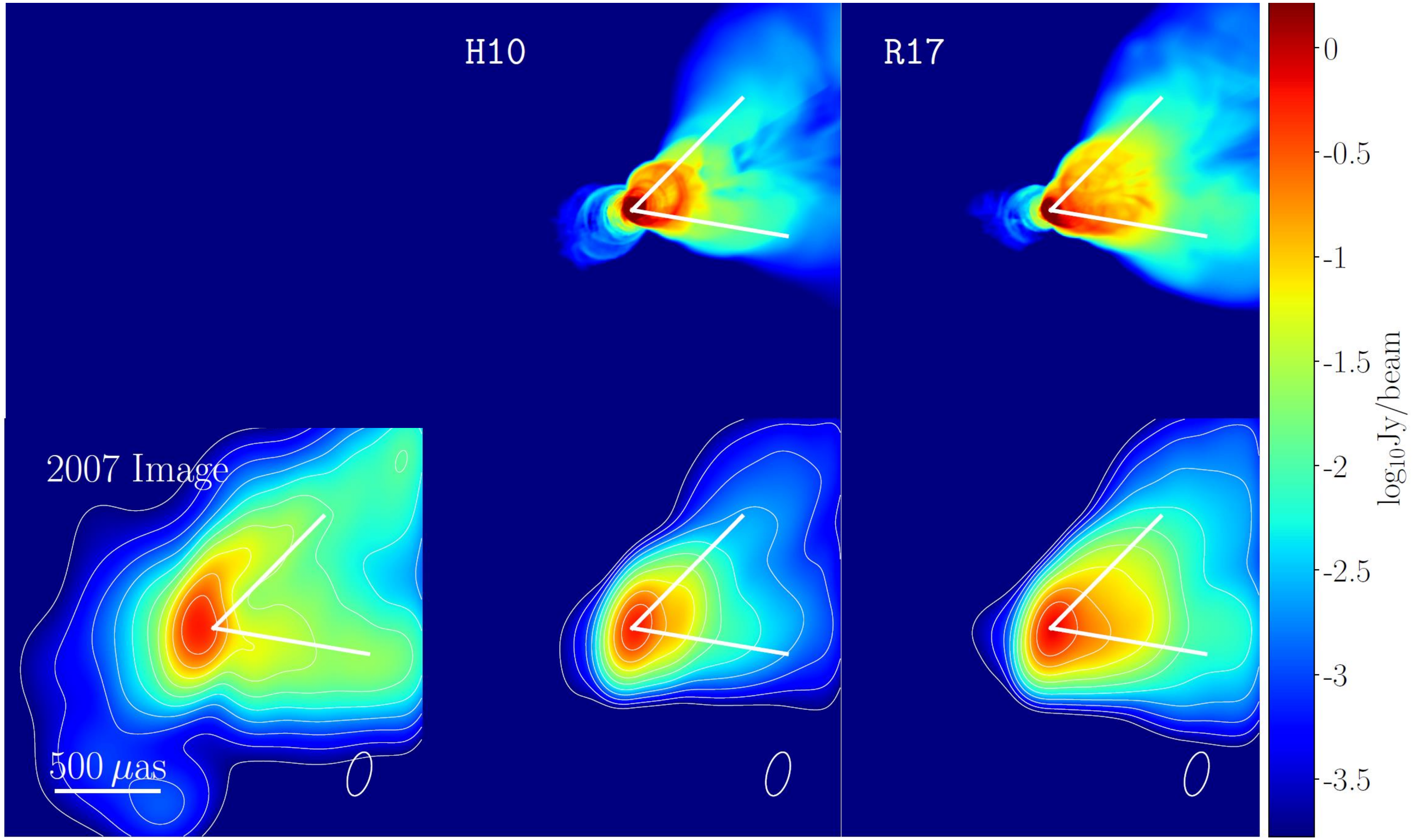
Walker+ 2018

Turbulent Heating

Reconnection Heating

High Resolution

VLBA Resolution



Apparent opening angle at 43 GHz:

$$55°$$

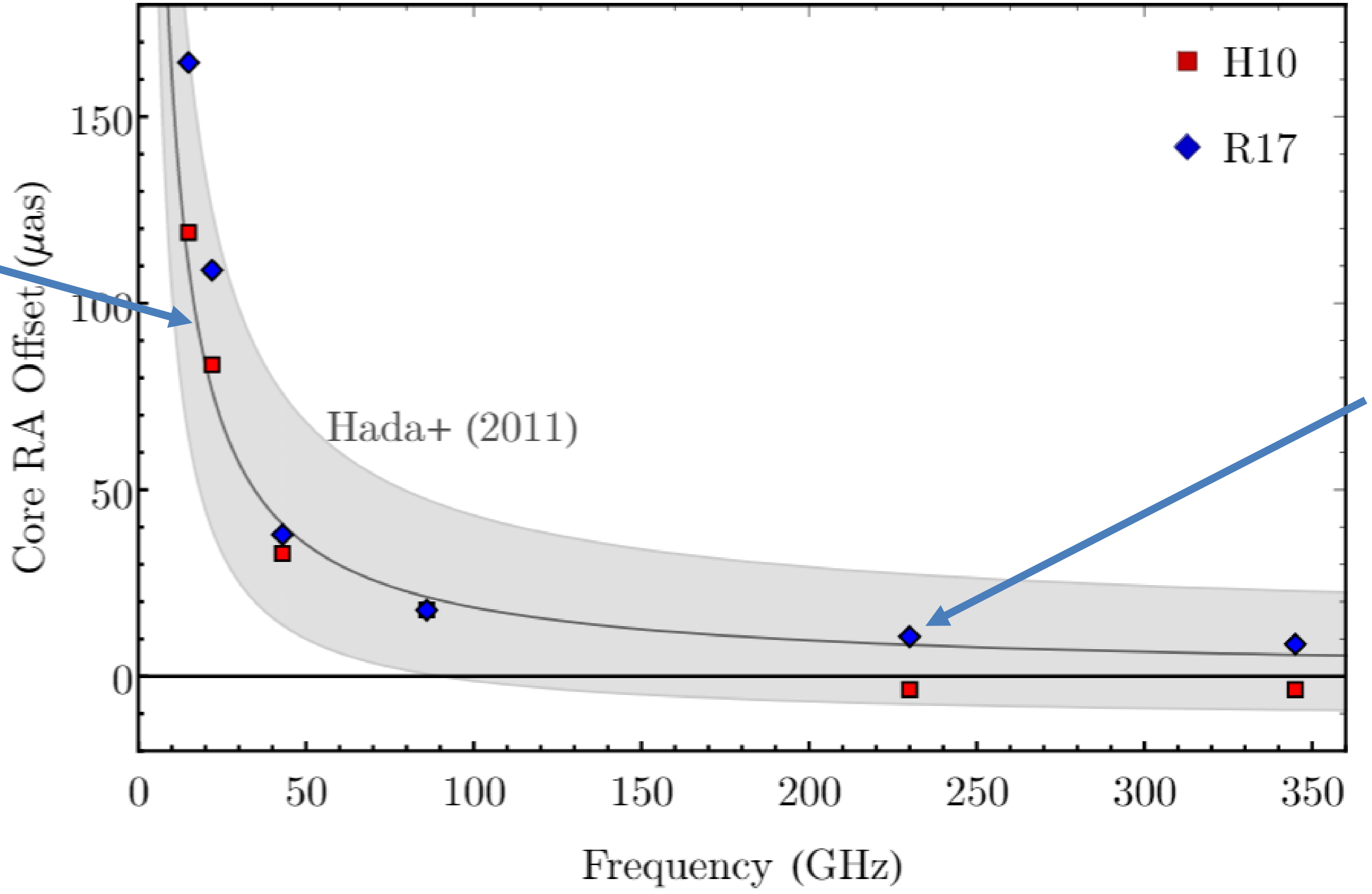
(Walker+ 2018)

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

230 GHz Images

Turbulent Heating

Reconnection Heating

230 GHz Images

Turbulent Heating

Reconnection Heating

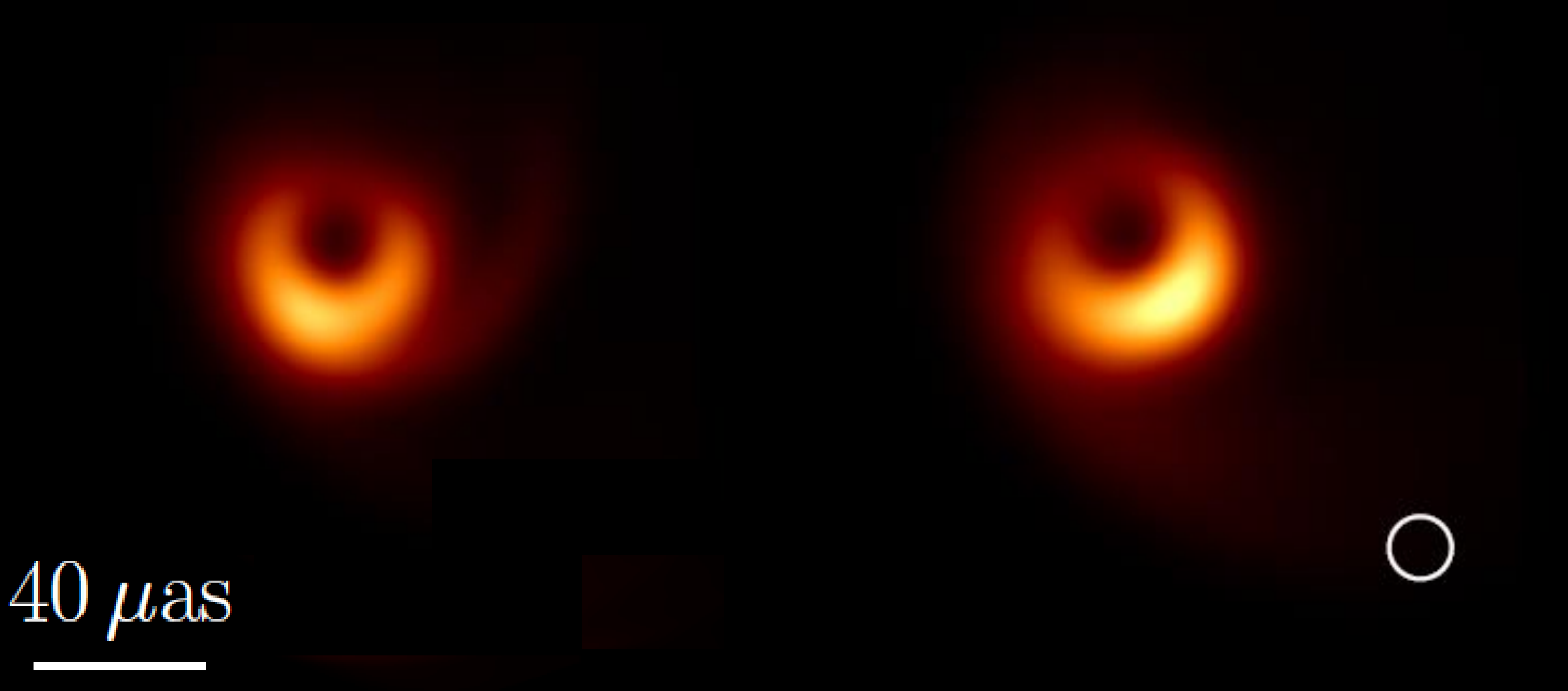
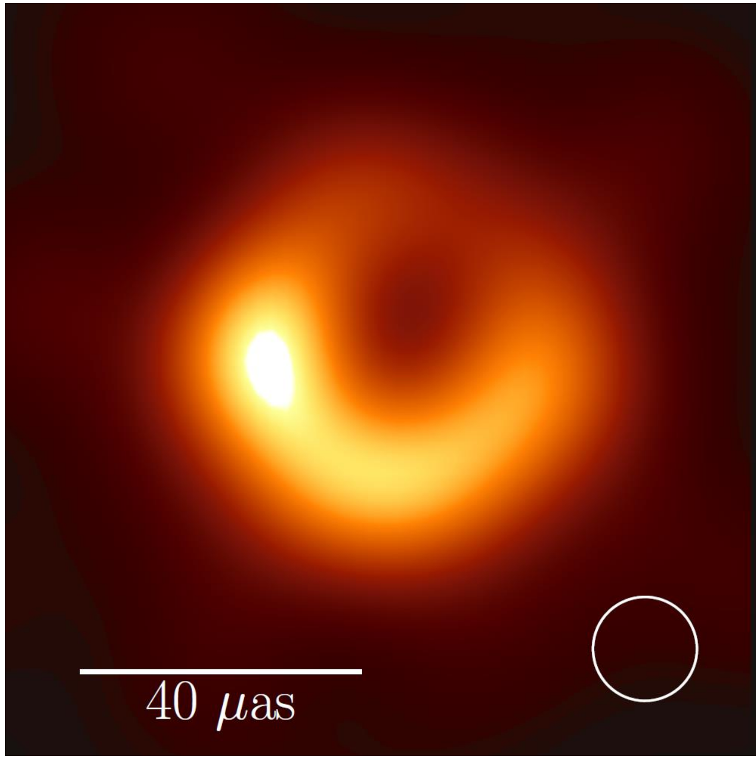


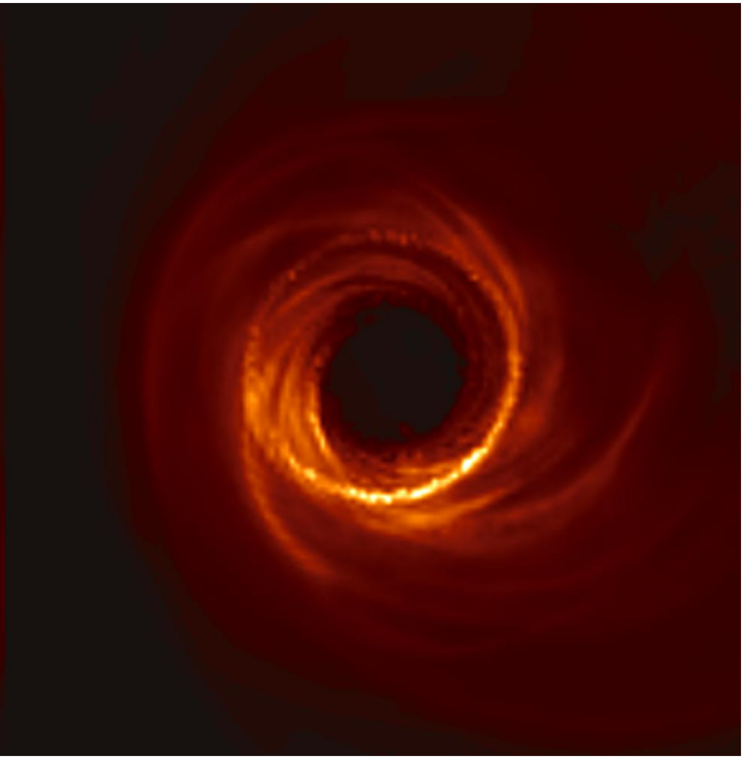
Image Credit: Chael+ 2019

The Black Hole in M87: Simulations and Images

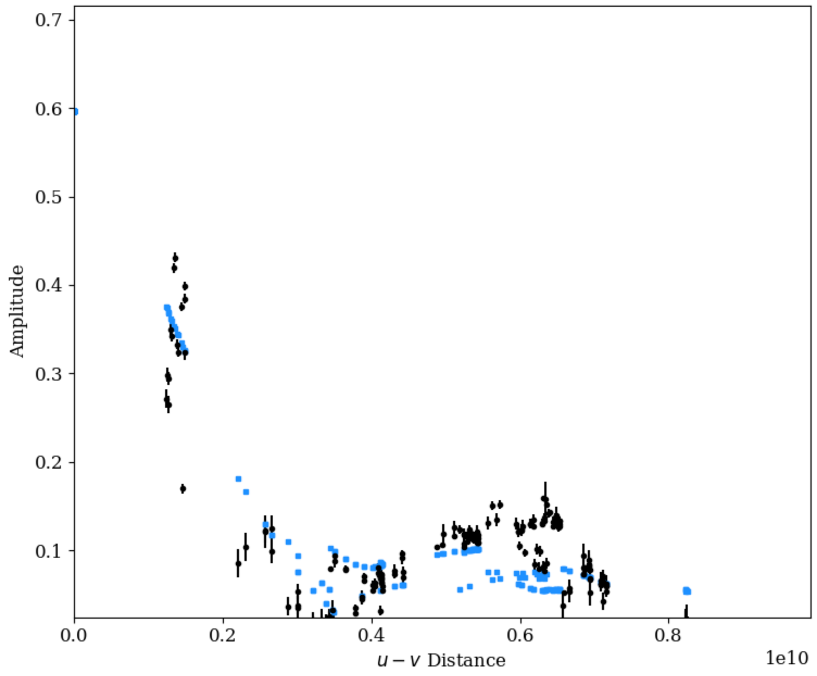
EHT 2017 image



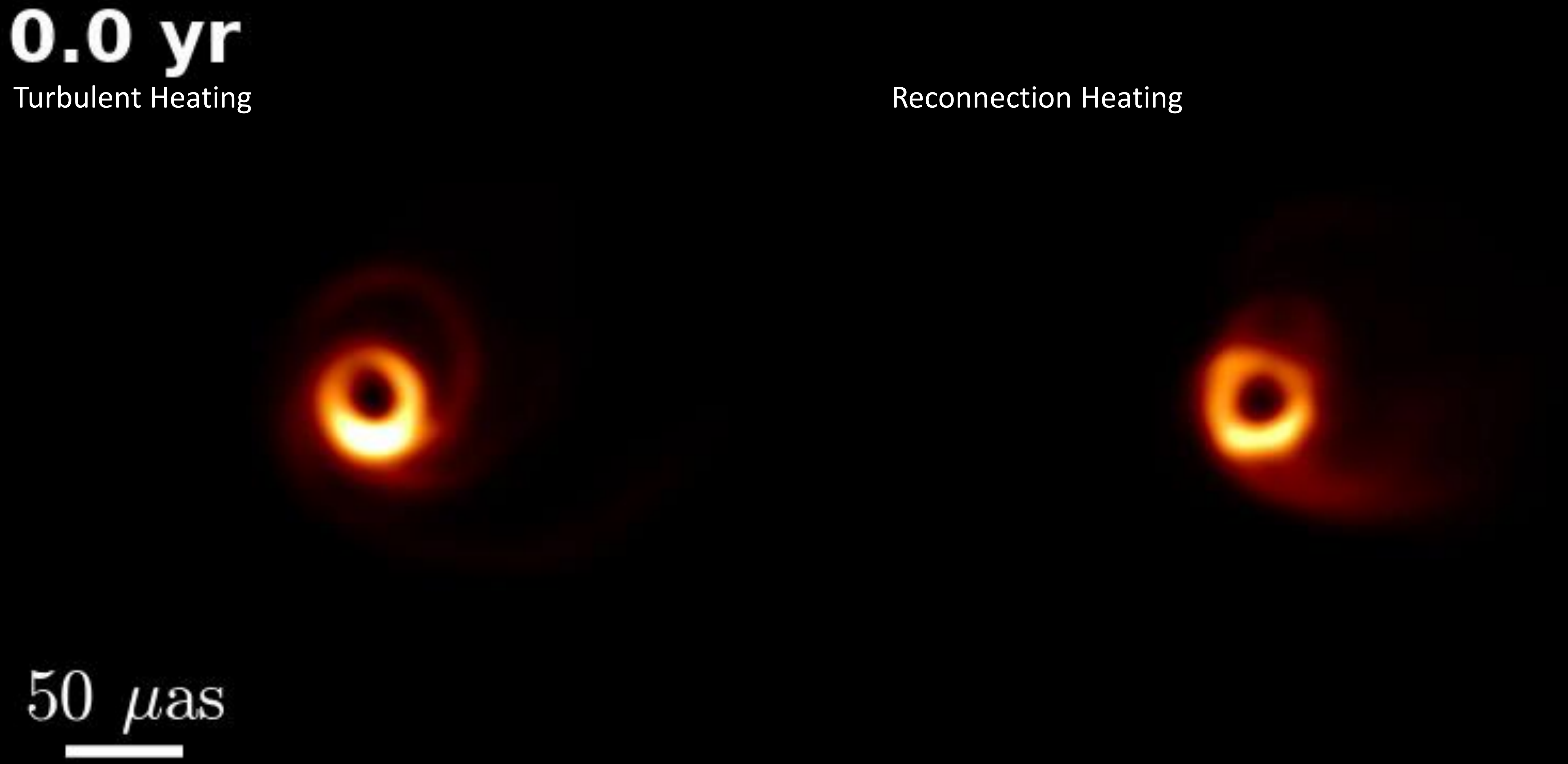
Simulated image from GRMHD model



EHT 2017 visibility amplitudes and model amplitudes



230 GHz Images – Time Evolution



Takeaways

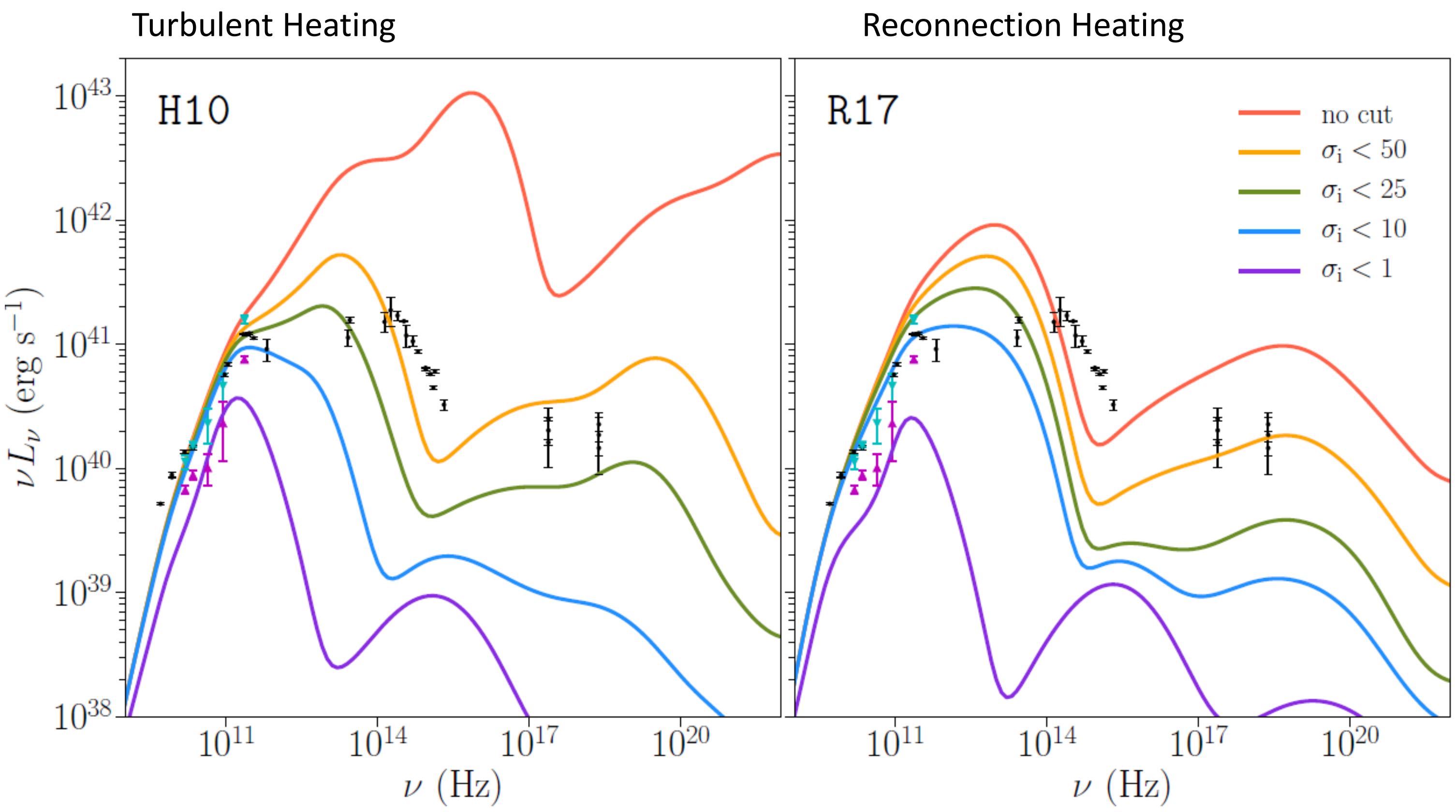
- Both dissipation and radiation are important in determining the electron temperatures in M87’s accretion flow.

- Different plasma heating mechanisms produce qualitatively different images.

- For **M87:**
    - MAD models produce powerful, wide opening-angle jets which match VLBI observations.
    - But turbulent heating produces too much radiation at the jet base.

- EHT images can now be used to investigate jet launching on horizon scales!

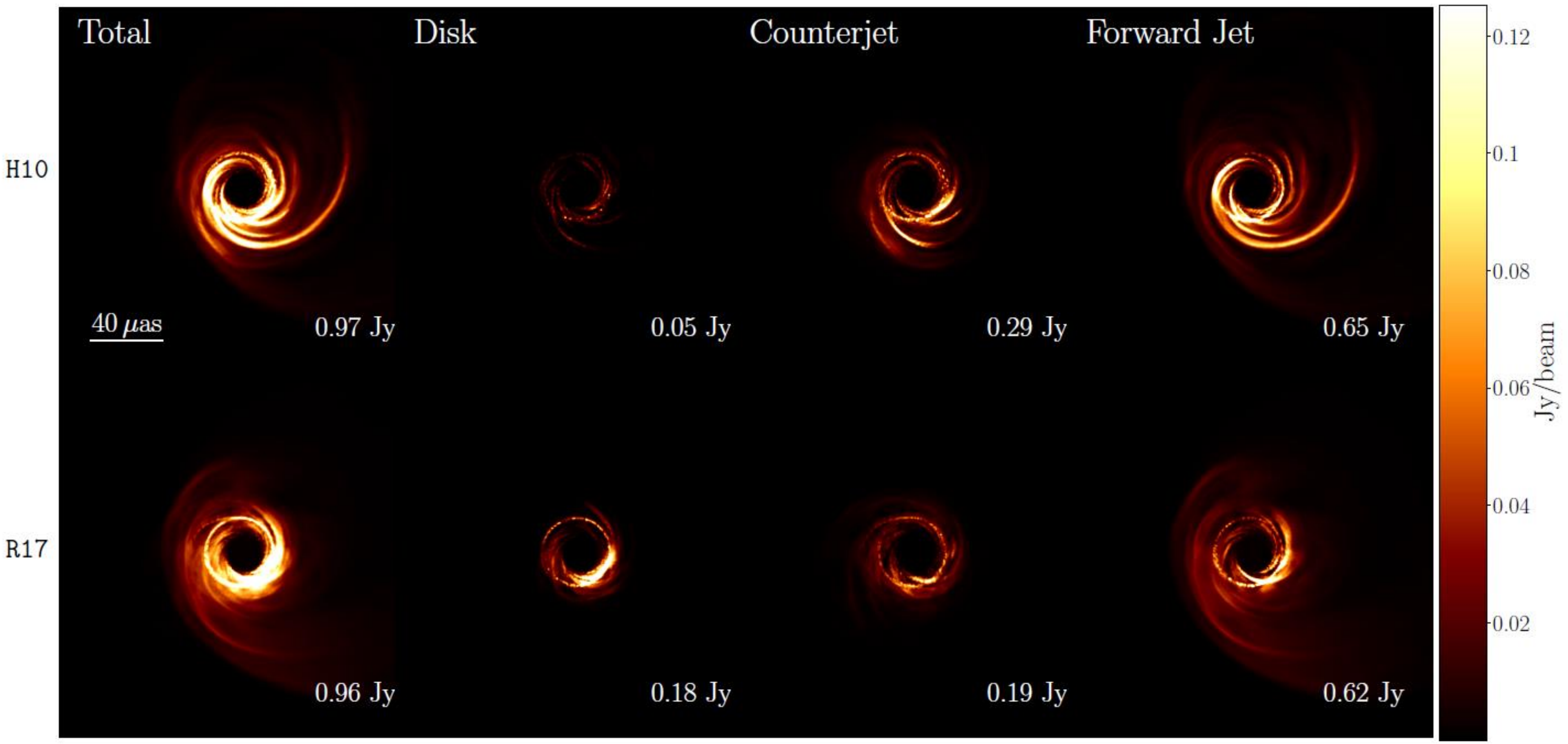
Source of uncertainty: $\sigma_{\rm i}$ cut



- 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

M87 230 GHz images – emission regions



Forward jet dominates the emission.
Secondary component depends on the heating used

Image Credit: Chael+ 2019

EHT Simulation Scoring (Paper V)

- Used a library of 43 pure GRMHD simulations (no radiation/electron heating)
- Produced 60,000 images by varying postprocessing electron heating and inclination angle.
- Found MAD simulations most easily fit the EHT data while satisfying the jet power constraint.

SANE

flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
SANE	-0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	-0.94	10	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	20	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	40	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	-0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	10	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	80	Fail	Pass	Pass	Fail	Fail
SANE	-0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	0	1	Pass	Pass	Pass	Fail	Fail
SANE	0	10	Pass	Pass	Pass	Fail	Fail
SANE	0	20	Pass	Pass	Fail	Fail	Fail
SANE	0	40	Pass	Pass	Pass	Fail	Fail
SANE	0	80	Pass	Pass	Pass	Fail	Fail
SANE	0	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	1	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	10	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	80	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	1	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	10	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	+0.94	160	Pass	Pass	Pass	Pass	**Pass**

MAD

flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
MAD	-0.94	1	Fail	Fail	Pass	Pass	Fail
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MAD	-0.94	20	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	40	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	80	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	160	Fail	Pass	Pass	Pass	Fail
MAD	-0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	-0.5	10	Pass	Pass	Pass	Fail	Fail
MAD	-0.5	20	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	0	1	Pass	Fail	Pass	Fail	Fail
MAD	0	10	Pass	Pass	Pass	Fail	Fail
MAD	0	20	Pass	Pass	Pass	Fail	Fail
MAD	0	40	Pass	Pass	Pass	Fail	Fail
MAD	0	80	Pass	Pass	Pass	Fail	Fail
MAD	0	160	Pass	Pass	Pass	Fail	Fail
MAD	+0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	+0.5	10	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	80	Pass	Pass	Pass	Pass	**Pass**
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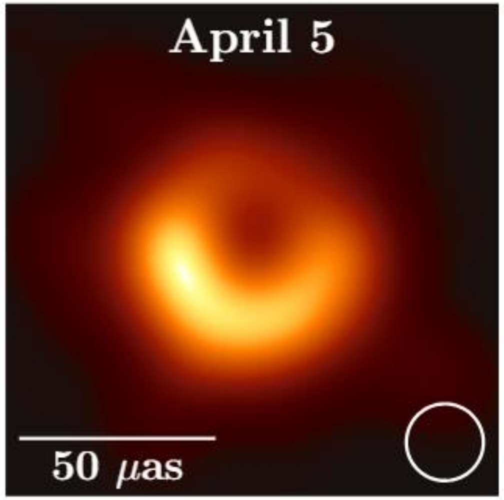
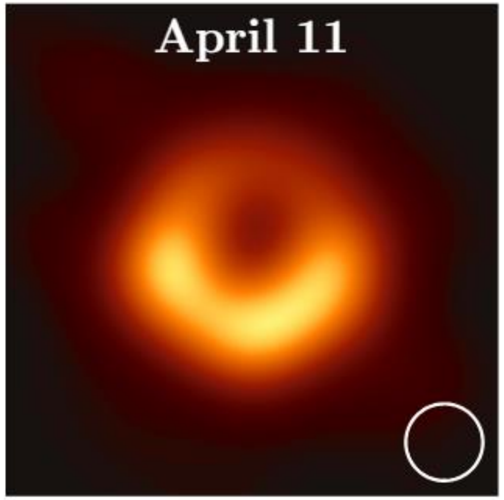
Time Variability?

M87





$$6\,\mathrm{day} = 16\,t_{\mathrm{g}}$$

Simulation

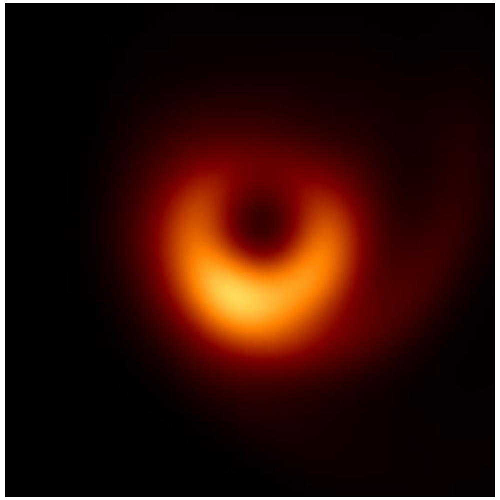
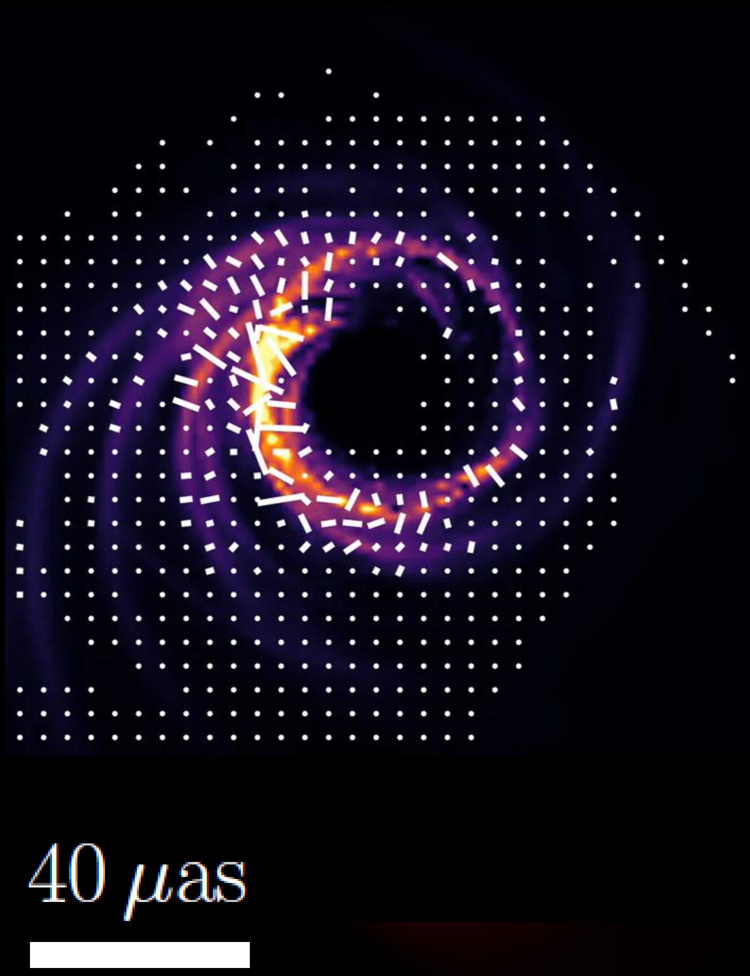
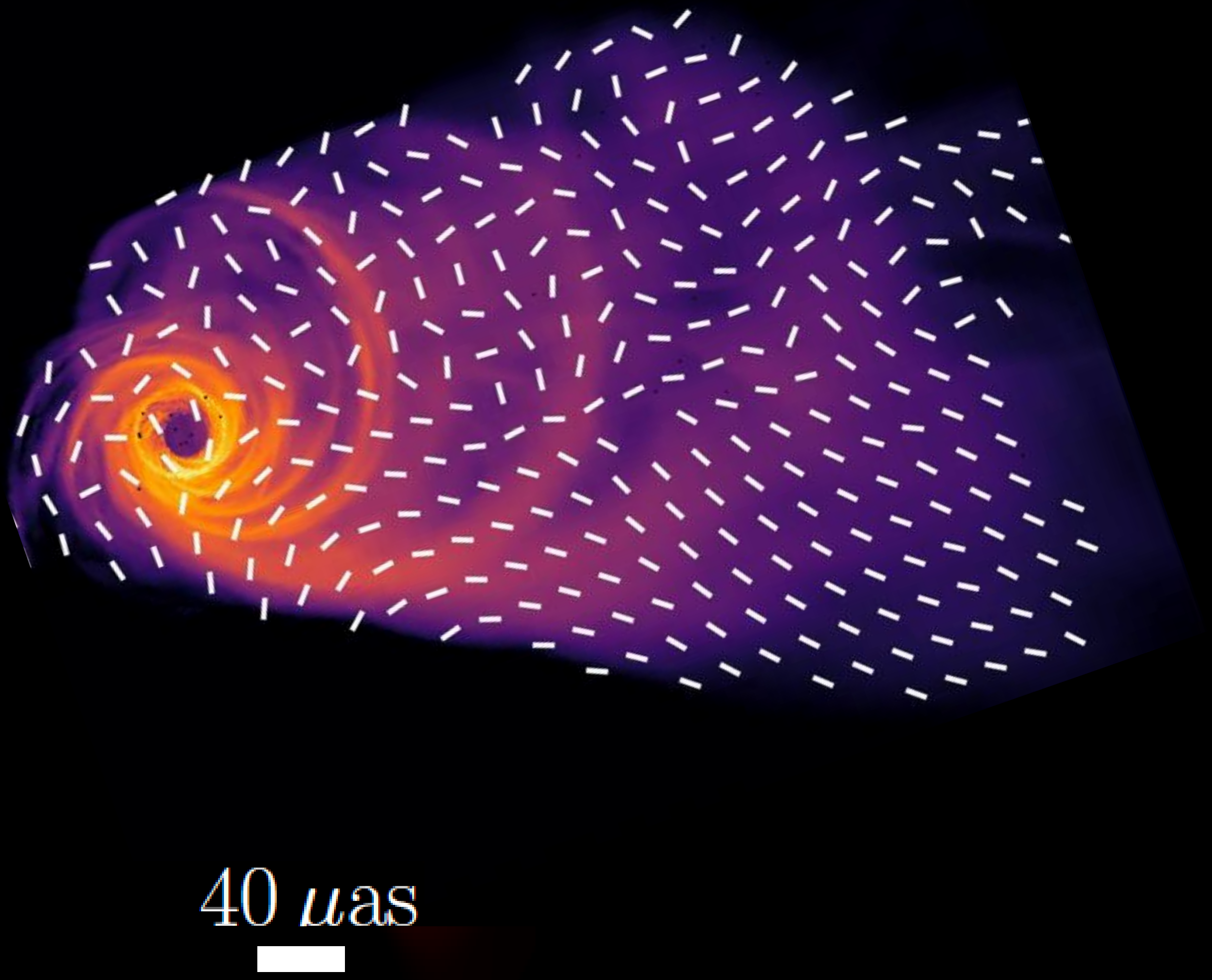


Image Credit: EHT Collaboration 2019 (Paper IV), Chael+ 2019

Next Steps: Polarization!





Movie Credit: Jason Dexter

Source of uncertainty: $\sigma_{\rm i}$ cut

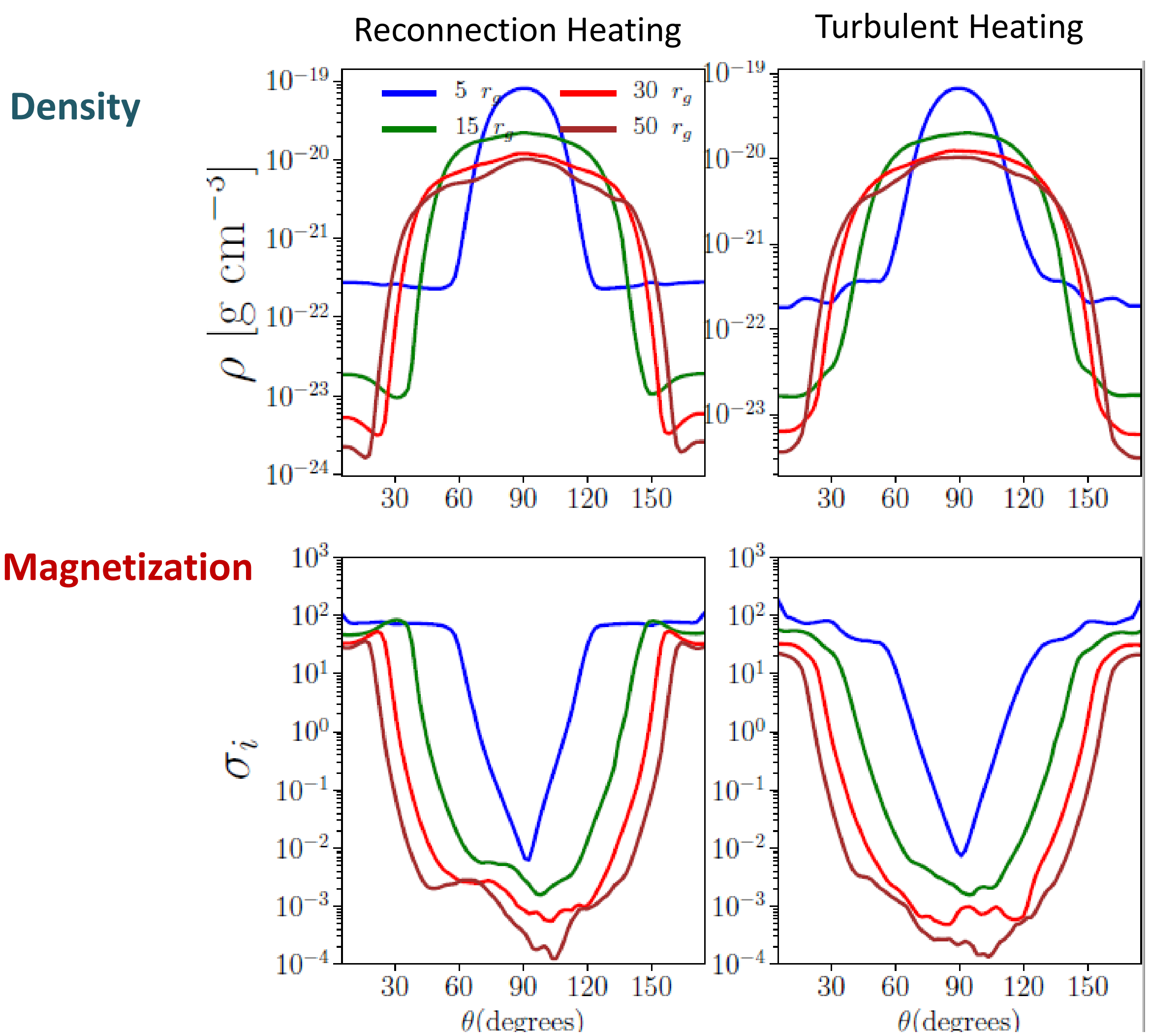


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Image Credit: Chael+ 2019