What will the Event Horizon Telescope see?

Electron heating in simulations of Sgr A and M87*

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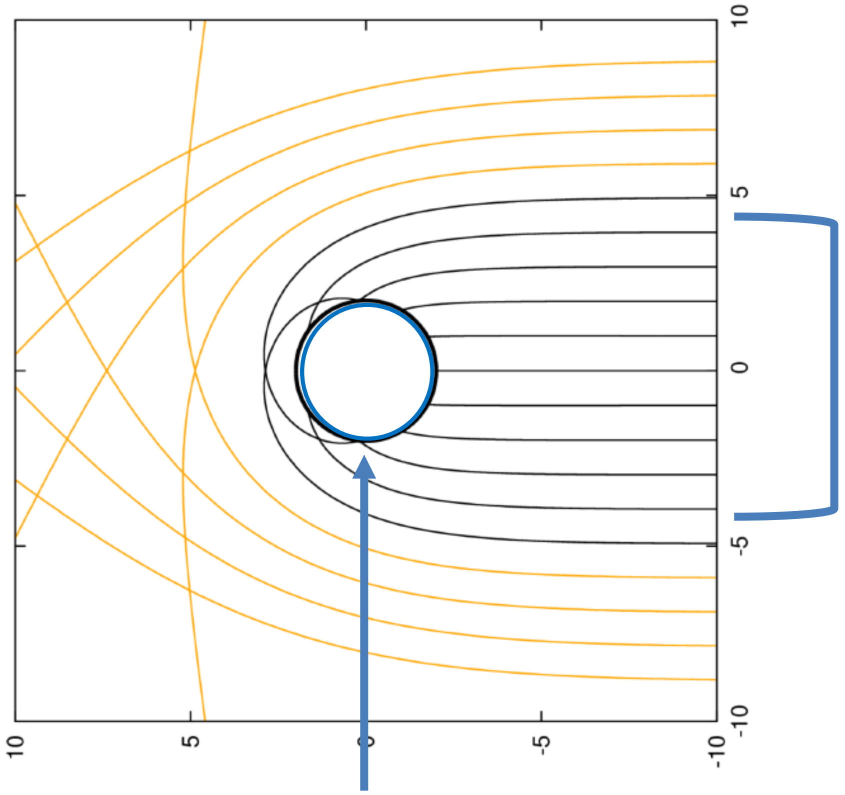
Northwestern CIERA Theory Group
October 19, 2018

arXiv: 1804.06416 and 1810.01983
Work with Ramesh Narayan, Michael Johnson
Michael Rowan, and Lorenzo Sironi

Event Horizon Telescope

What does a black hole look like?



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

photon orbit $r_\gamma = 3GM/c^2$

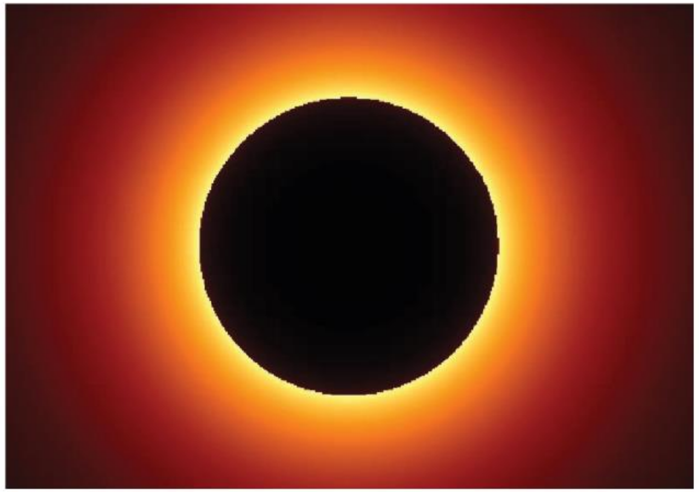
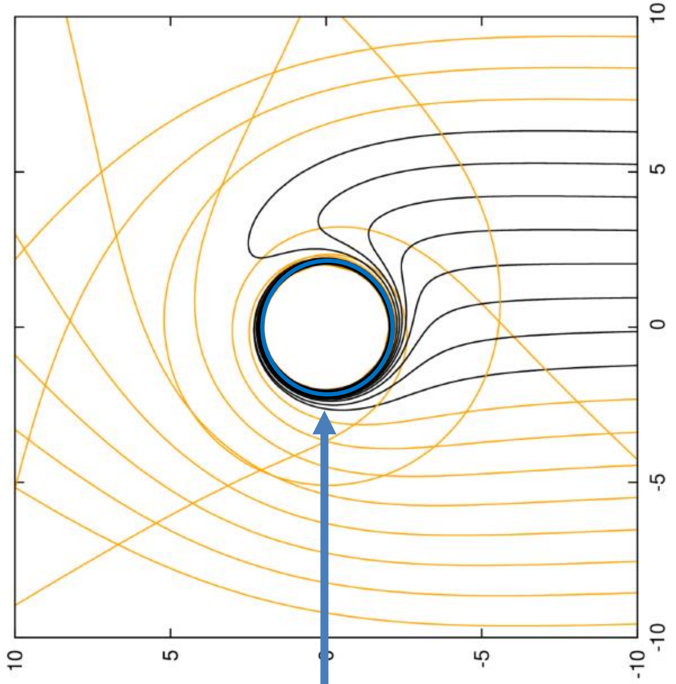
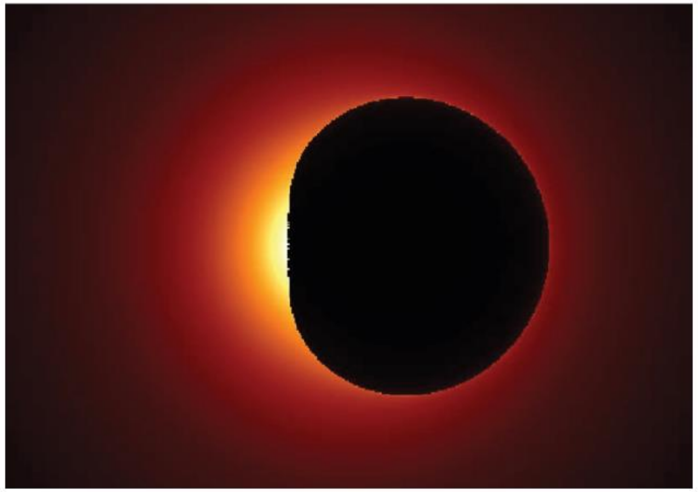


Image credit:
Keiichi Asada

What does a black hole look like?



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



Bardeen 1973

photo

> "It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole... Unfortunately, there seems to be no hope of observing this effect." (Bardeen 1973,1974)

Image credit:
Keiichi Asada

Sagittarius A*

$$M_{BH} = (4.10 \pm 0.03) \times 10^6 M_\odot$$
$$D = (8.12 \pm 0.03)\mathrm{kpc}$$

Gravity Collaboration, 2018

$$d_{\mathrm{shadow}} \approx 50\mu\mathrm{as}$$

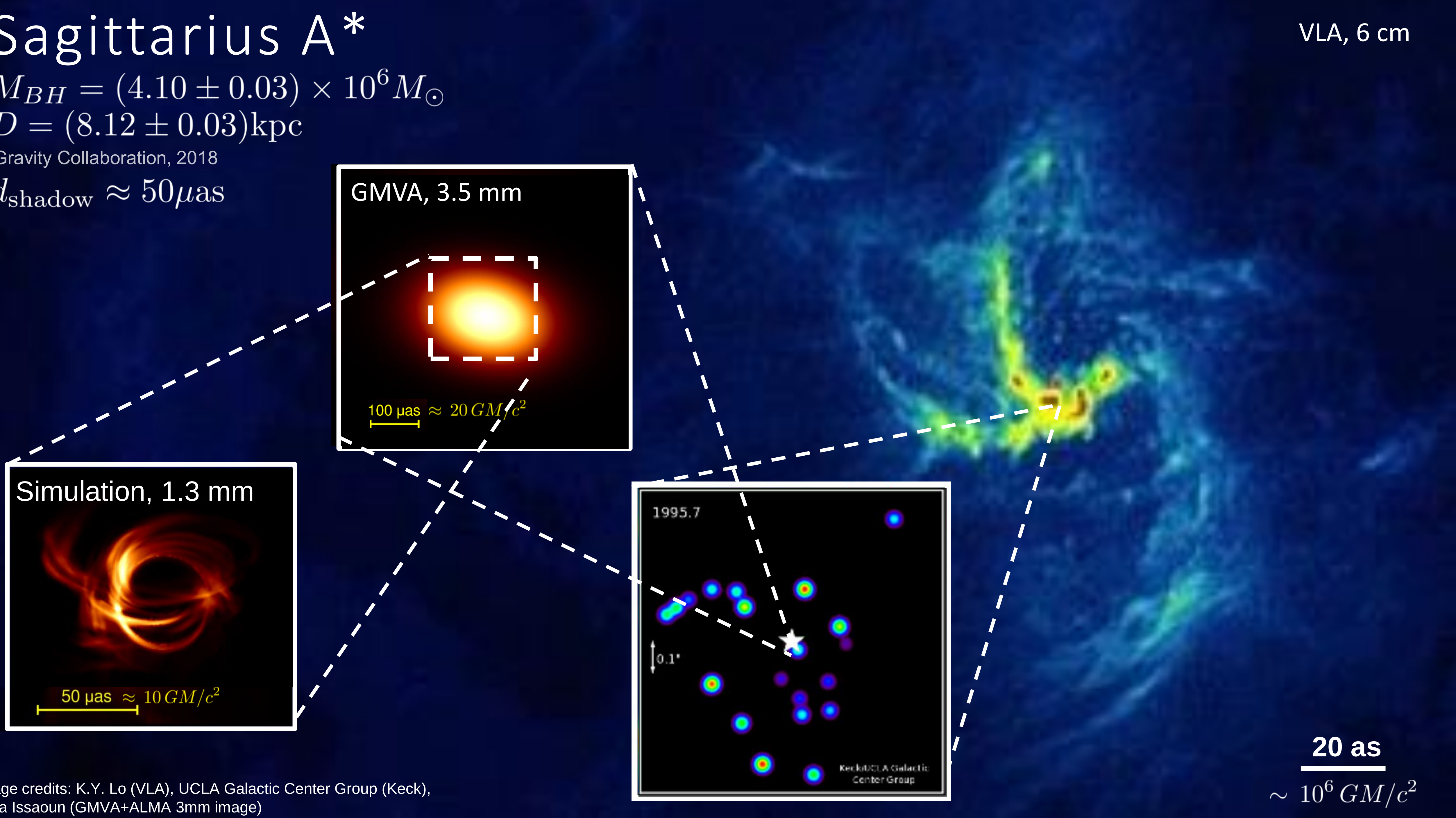


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

M87

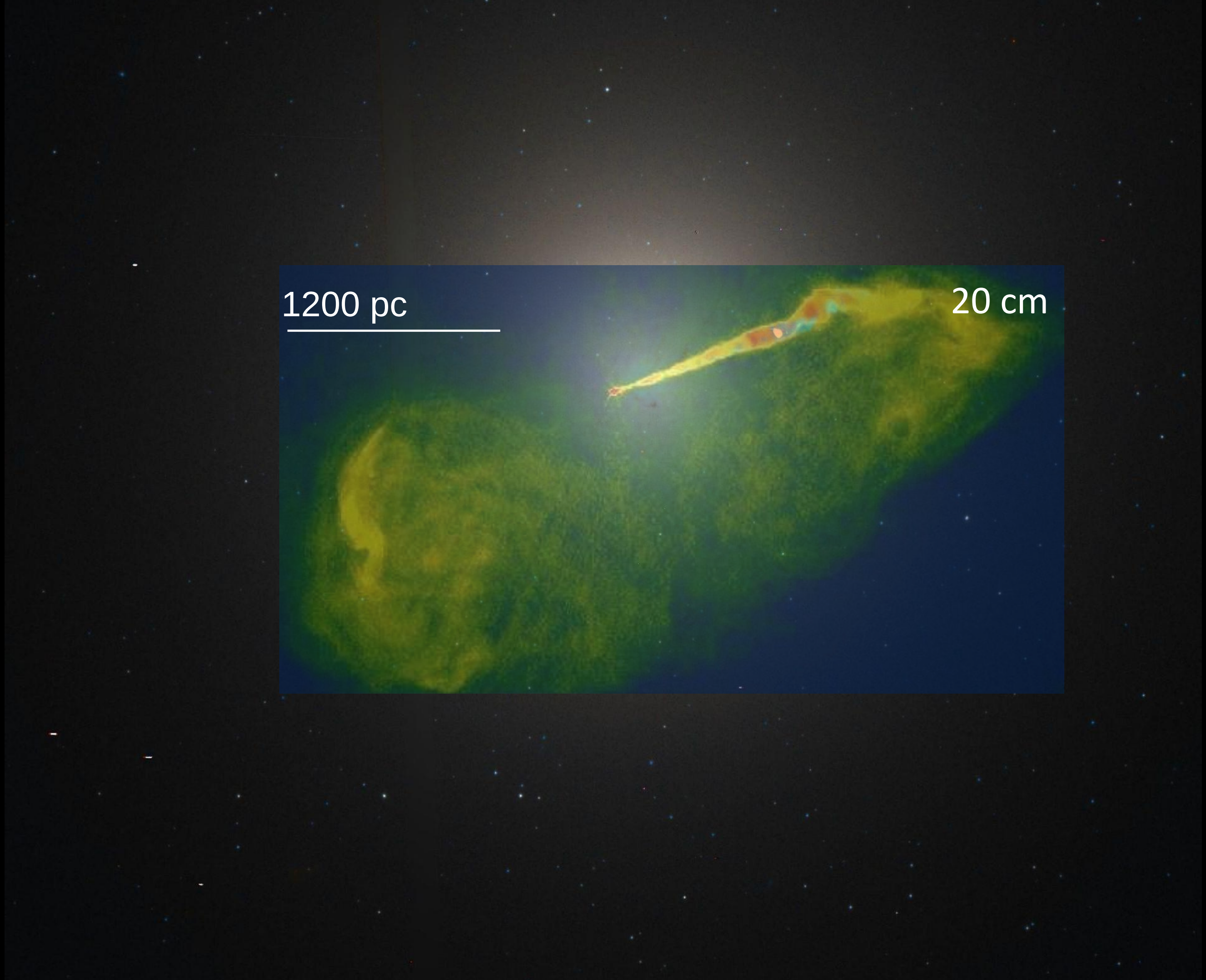


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm)

M87

$M_{BH} \approx 6 \times 10^9 M_\odot$ (or 3×10^9 ?)
$D \approx 17\,\mathrm{Mpc}$
$d_{\mathrm{shadow}} \approx 40\mu\mathrm{as}$ (or $20\mu\mathrm{as}$?)

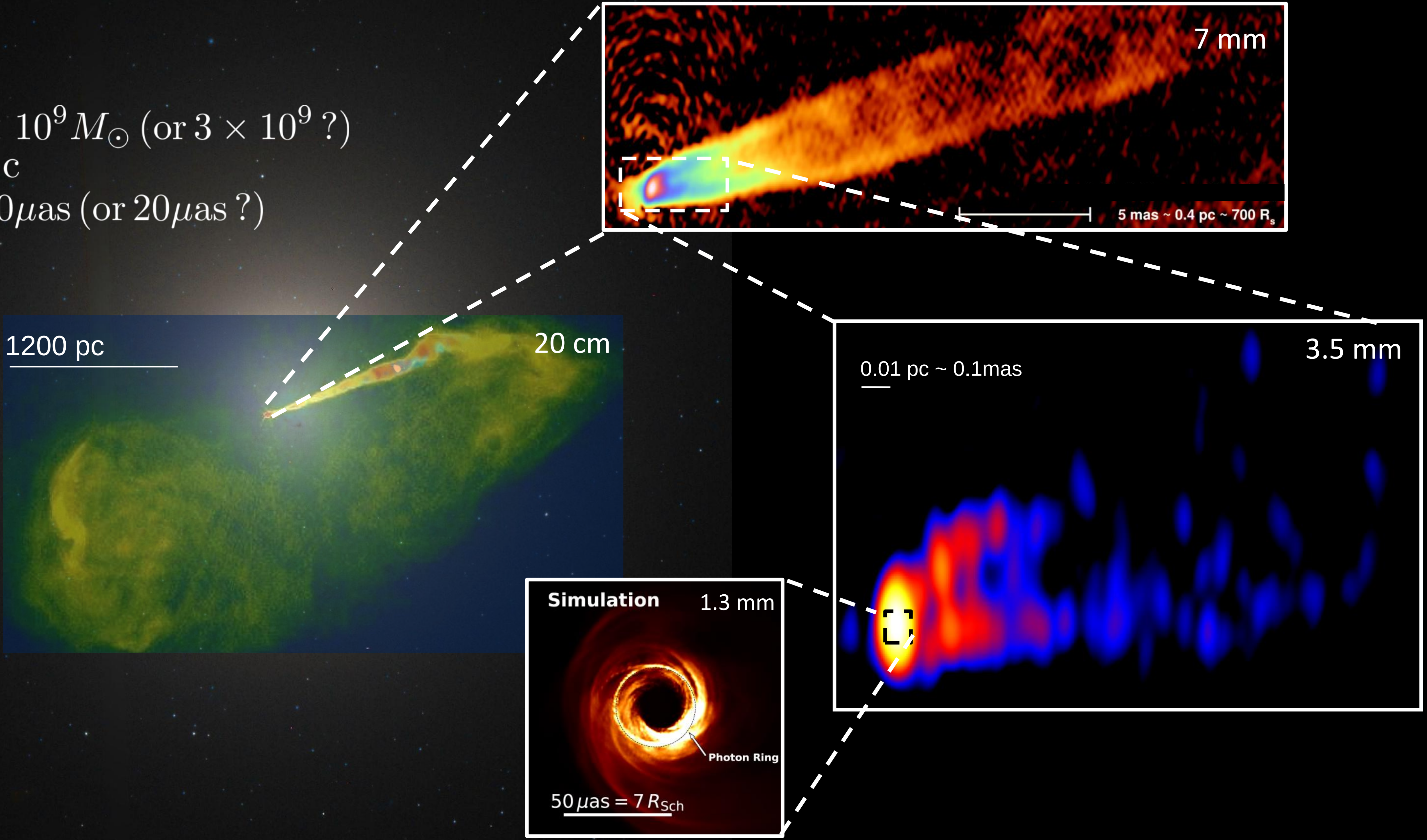
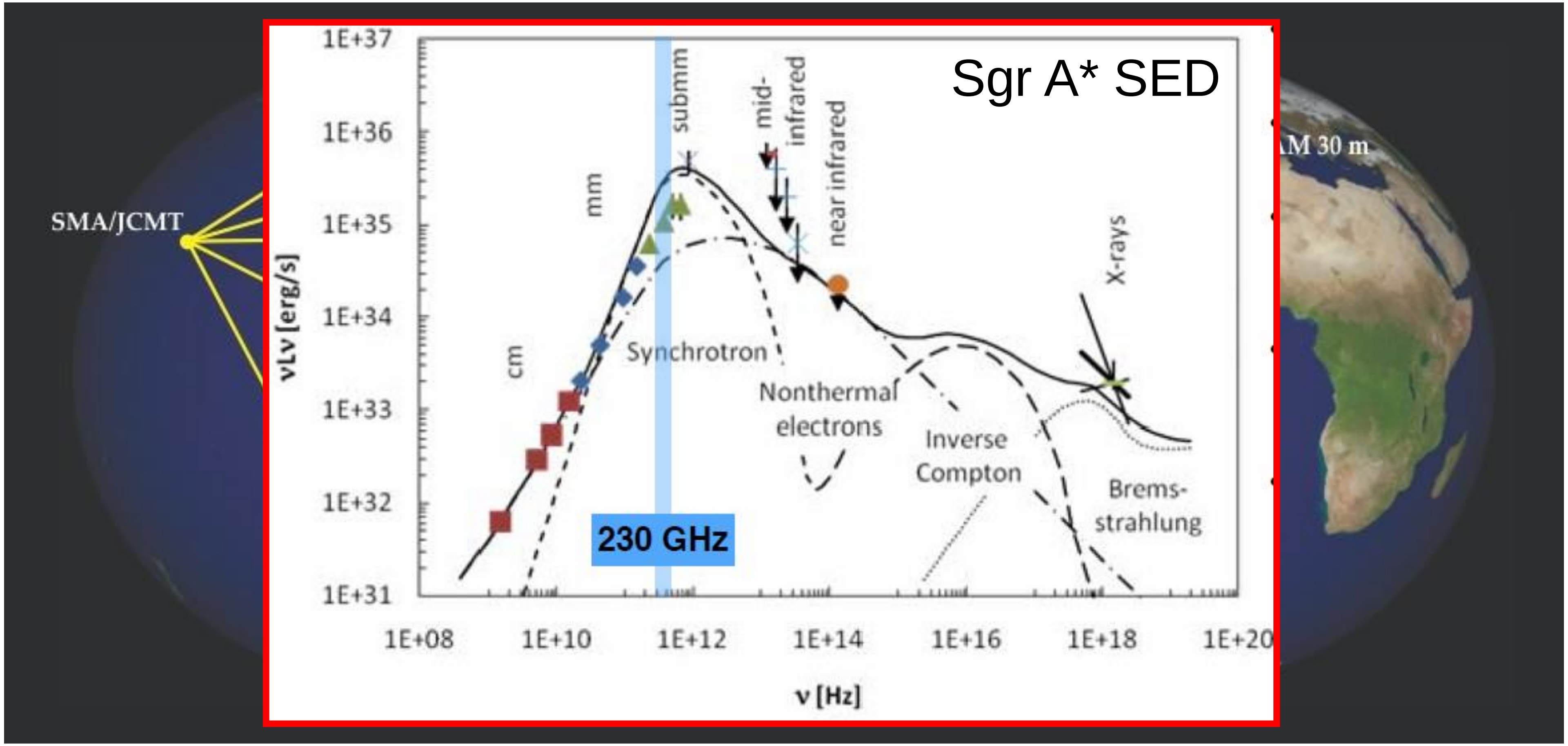


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm)

The Event Horizon Telescope

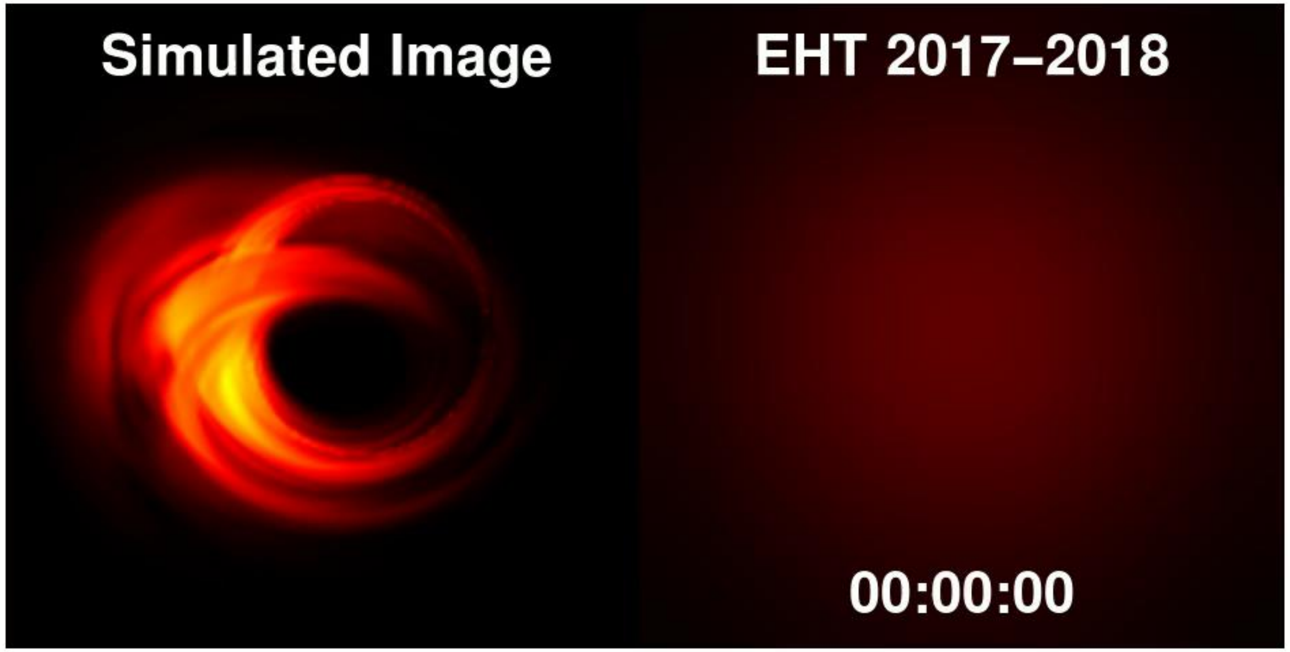


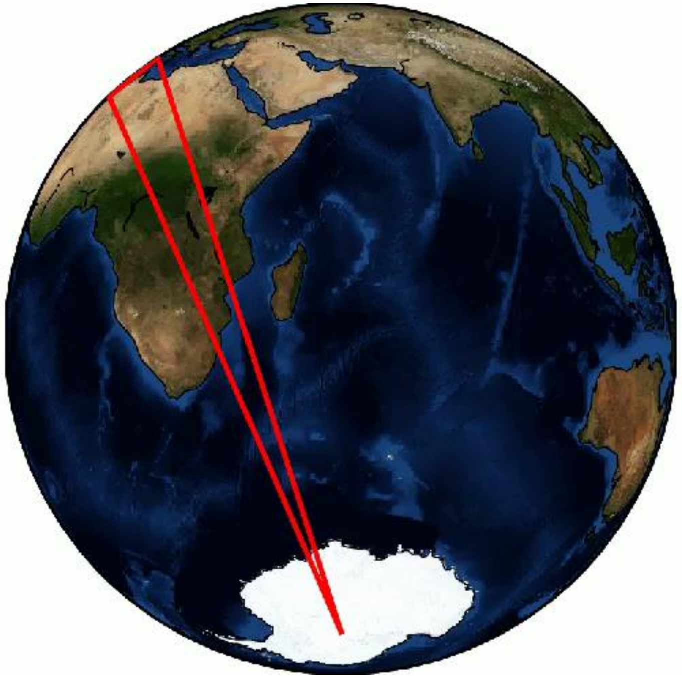
$$\frac{\lambda = 1.3\,\mathrm{mm}}{d_{\mathrm{Earth}} = 1.3 \times 10^{10}\,\mathrm{mm}} \approx 20\mu as$$

Image Credit: Genzel et al. (2010), Yuan et al. (2003).

Black Hole Image Reconstruction with the EHT

(i.e. the other half of my work – ask me more later!)





First images in **early** 2019

Image Credit:
Jason Dexter, Katie Bouman

What will the EHT see?

1.) Spacetime geometry
-The shadow of the black hole.

2.) Fluid dynamics
-How is stuff moving? Jet or disk?

3.) Electron (non)thermodynamics.
Where does the light come from?

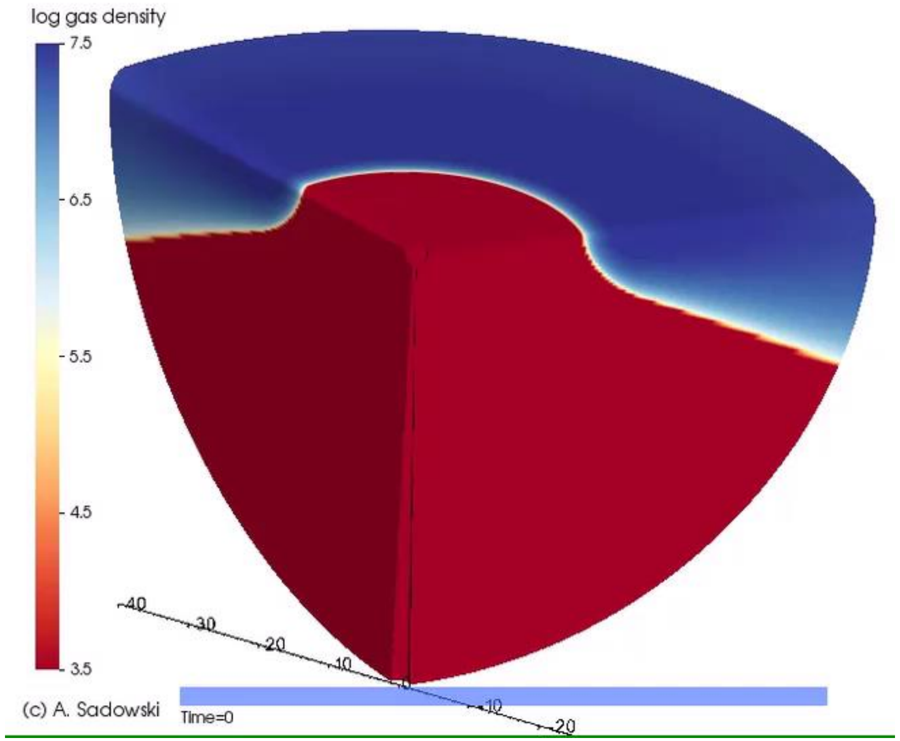
Sgr A* and M87 are **Two-Temperature** Accretion Flows

- Low densities in hot flows
  → inefficient Coulomb coupling between ions and electrons.

- Generally expect electrons to be **cooler** than ions.

- But if electrons are **heated** much more, they can remain hotter than ions for long times.

From simulations to observables

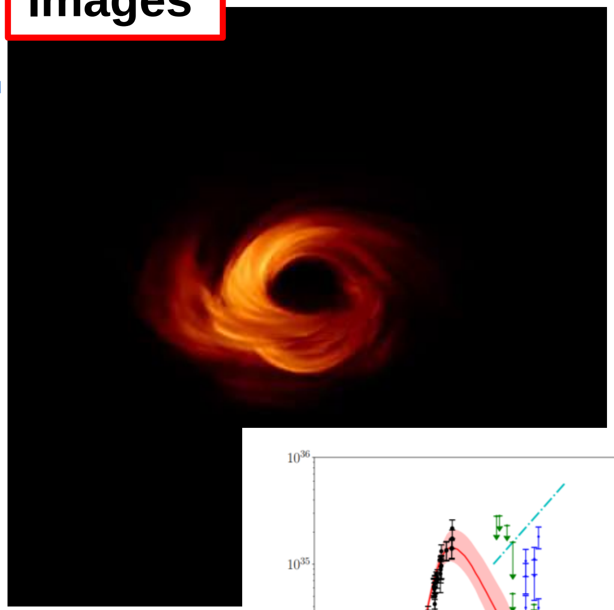


GRMHD Simulations

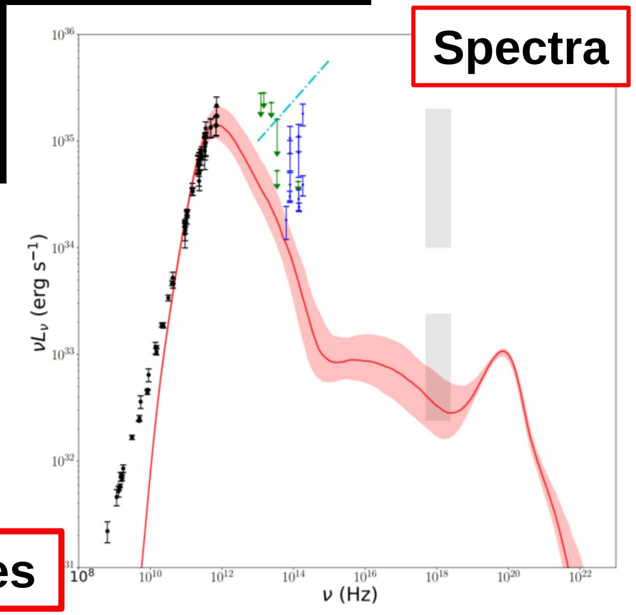
evolve a **single** fluid and magnetic field

T_e?

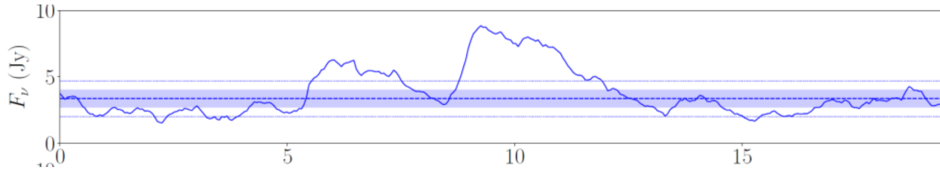
Images



Spectra



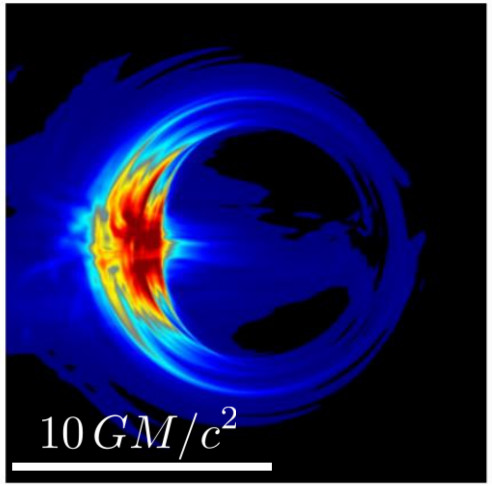
Light Curves



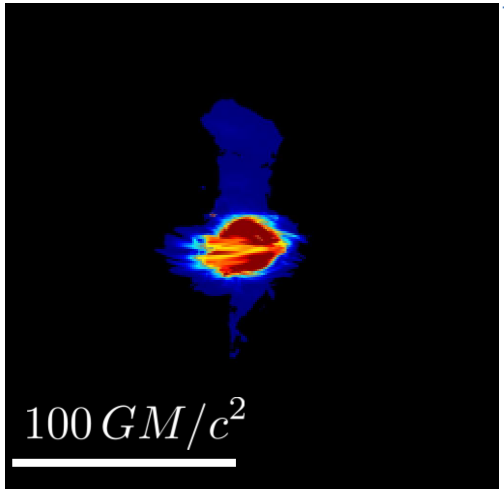
Previous work used **fixed** temperature ratios in postprocessing.

(Mościbrodzka et al. 2014)

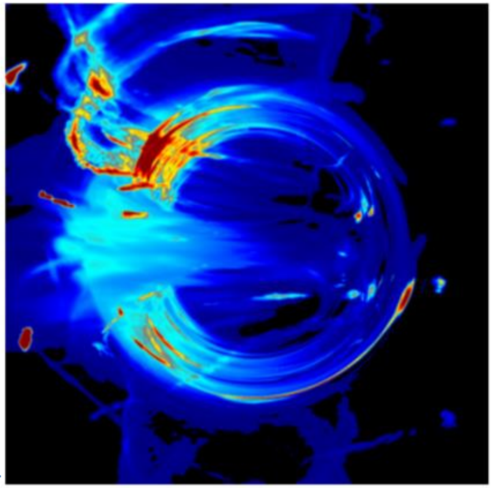
$\lambda = 1.3\text{mm}$



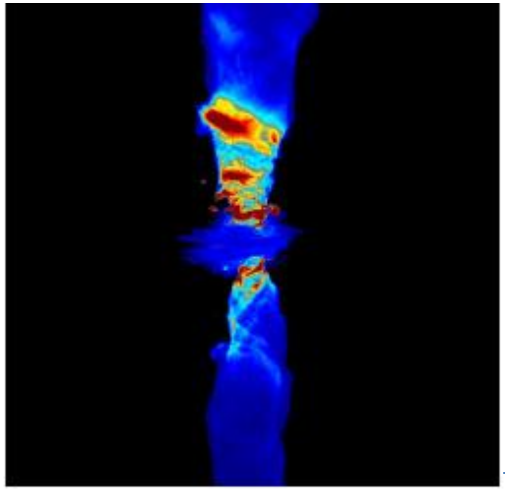
$$\frac{T_e}{T_i} = 0.2$$



$\lambda = 7\text{mm}$



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



Different temperature ratios applied to the same simulation produce quite different images!

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

-Using the code KORAL: (Sądowski et al. 2017)
-See also previous work by:
Ressler et al. 2017 (Sgr A*)
Ryan et al. 2018 (M87)

Two-Temperature GRRMHD Simulations

- Combined fluid quantities are evolved as in single-temperature general relativistic MHD with radiation.

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

Adiabatic compression/expansion

"$T\,\mathrm{d}S$"

Radiation: weak

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

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

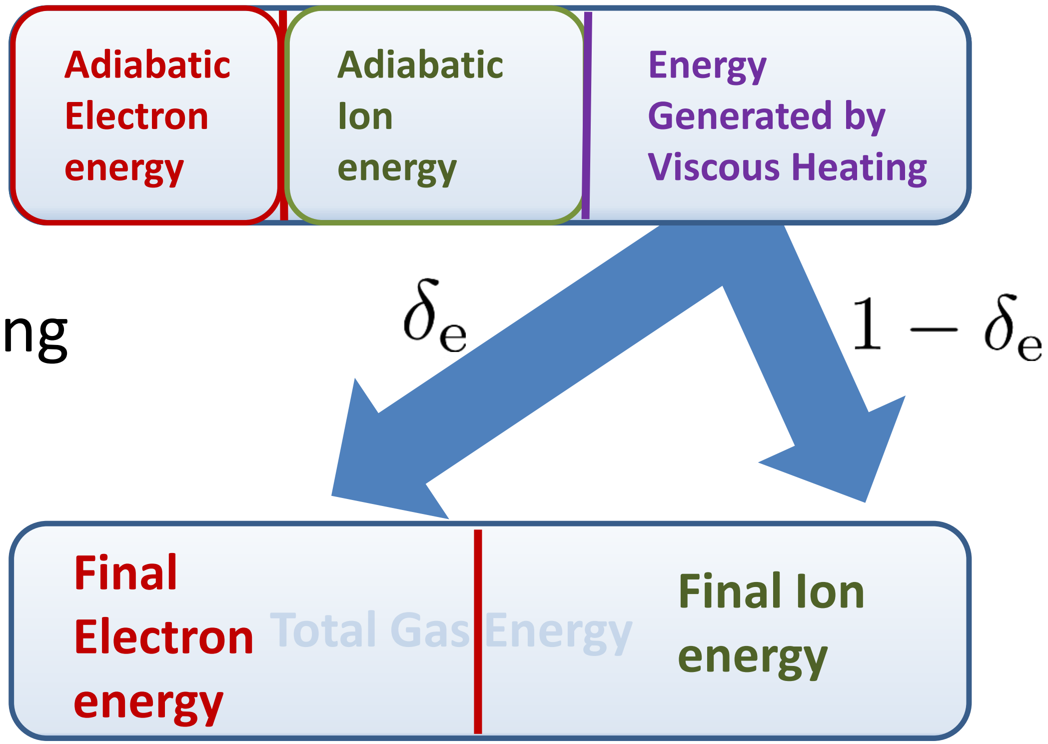
Coulomb Coupling: weaker

Viscous dissipation

- KORAL uses **self-consistent** entropies/adiabatic indices that transition from 5/3 to 4/3 as the species become relativistic.

Sub-grid Heating Prescriptions

Identify **total dissipation** numerically

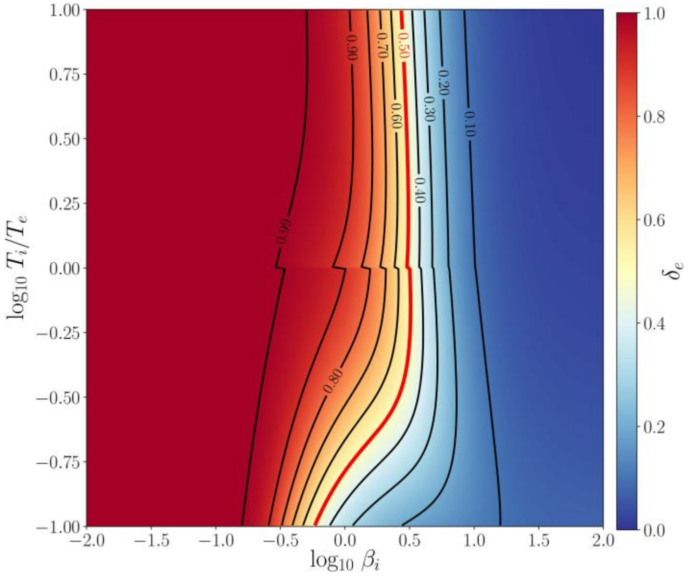


How do we divide heating between the species?

Sub-grid Heating Prescriptions

Landau-Damped Turbulent Cascade
(Howes 2010)

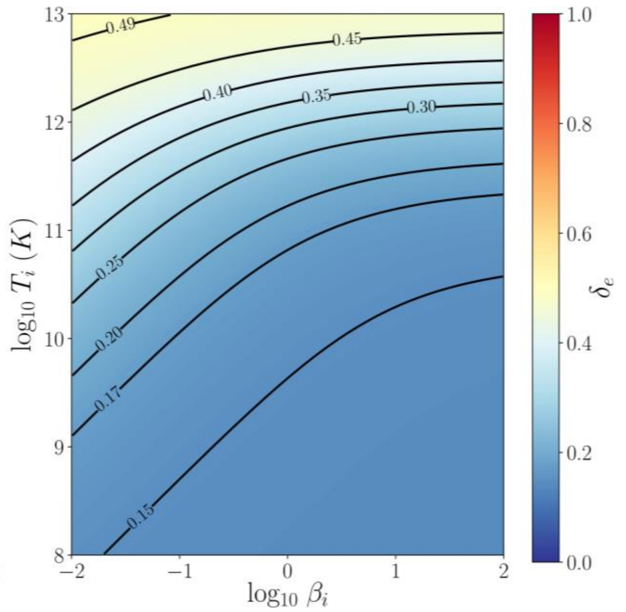
- Based on non-relativistic physics
- Predominantly heats electrons (ions) when magnetic pressure is high (low)



Almost all energy to electrons ↔ Almost all energy to ions

Magnetic Reconnection
(Rowan 2017)

- Based on PIC simulations of trans-relativistic reconnection (appropriate for Sgr A* & M87)
- **Always** puts more heat into ions



Heating varies only a little over a significant range of temperature & plasma-beta.

Sgr A*

(Chael+ 2018a, arXiv: 1804.06416)

Previous work: *Ressler et al. 2017*

- A 3D, two-temperature simulation with relatively high magnetic flux and using the turbulent cascade prescription.
- Recovers a disk-jet structure.
- Is this structure dependent on electron heating & B field strength?

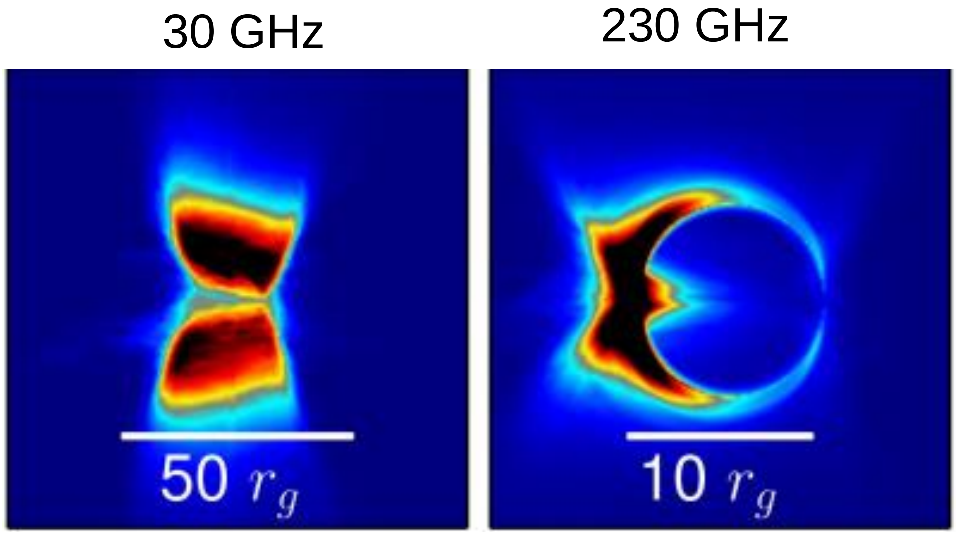


Image credit: Ressler et al. 2017

Our Sgr A* Simulations

- Four 3D simulations using KORAL

– one for each heating prescription at low (0) and high (0.9375) BH spins.

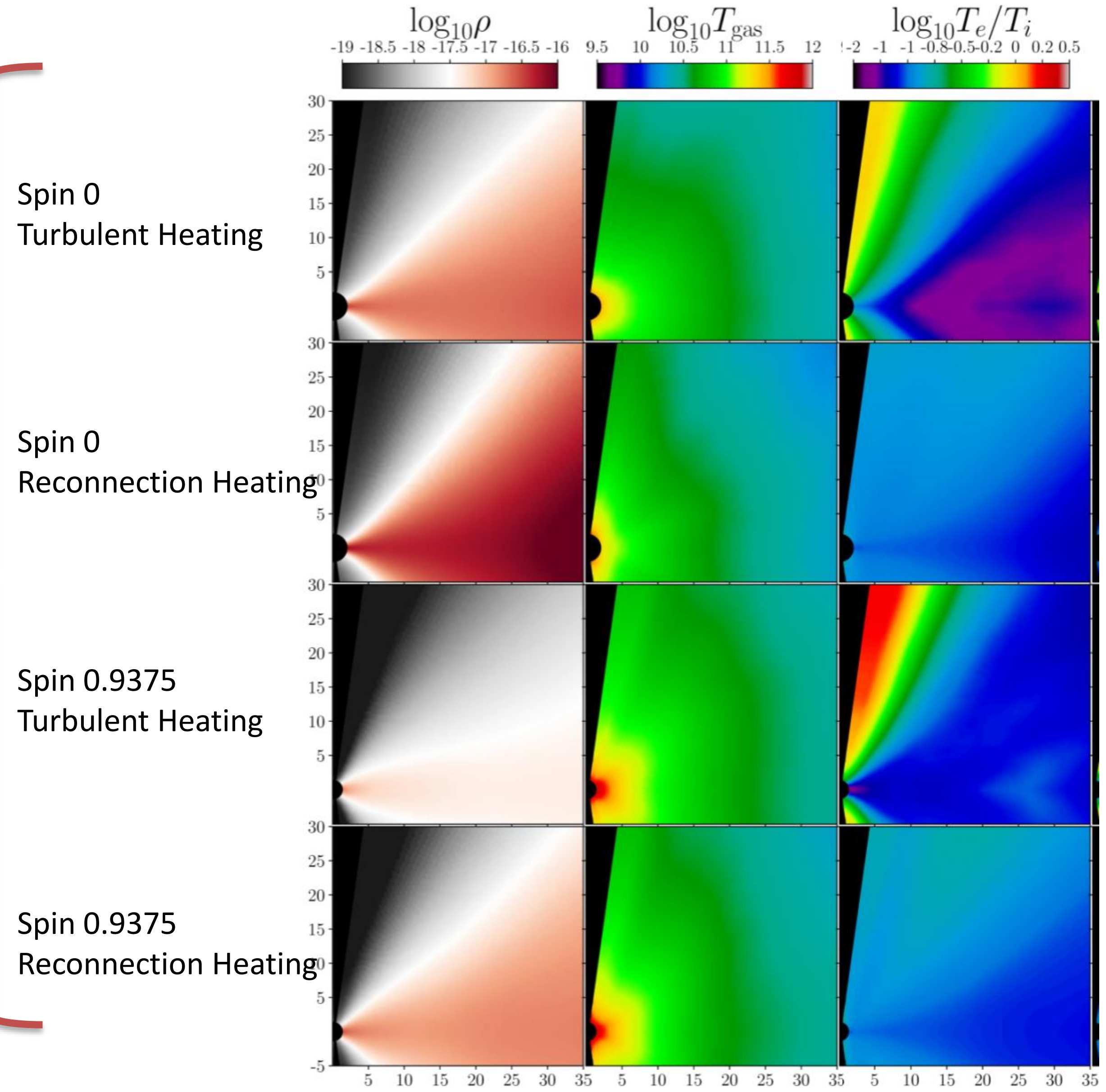
Model	Spin	Heating	$\dot{M}\,(\dot{M}_{\rm Edd})$	$\Phi_{\rm BH}\ \left((\dot{M}c)^{1/2}r_{\rm g}\right)$
H-Lo	0	Turb. Cascade	3×10^{-7}	5
R-Lo	0	Mag. Reconnection	7×10^{-7}	4
H-Hi	0.9375	Turb. Cascade	2×10^{-7}	6
R-Hi	0.9375	Mag. Reconnection	3×10^{-7}	3

Very **low** "MAD parameter"
~50 is saturation value for a
Magnetically Arrested Disk

- Density is scaled to match ~3 Jy at 230 GHz

Sgr A*: *Temperature ratio*

All are thick disks: density lower at high spin



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

1.3 mm movies

Spin 0
Turbulent
Heating

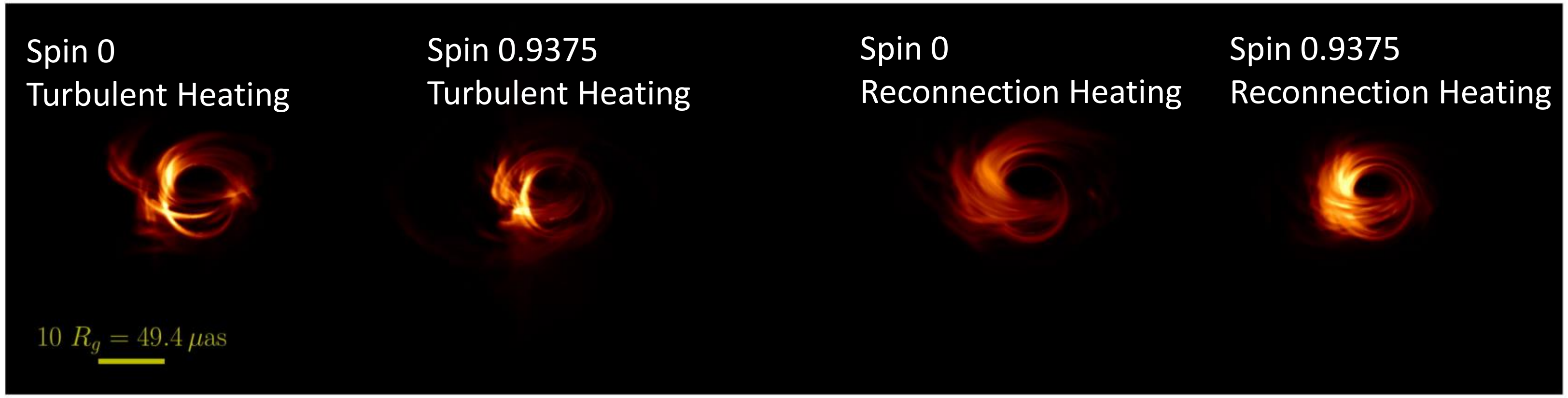
Spin 0.9375
Turbulent
Heating

Spin 0
Reconnection
Heating

Spin 0.9375
Reconnection
Heating

Image structure with frequency

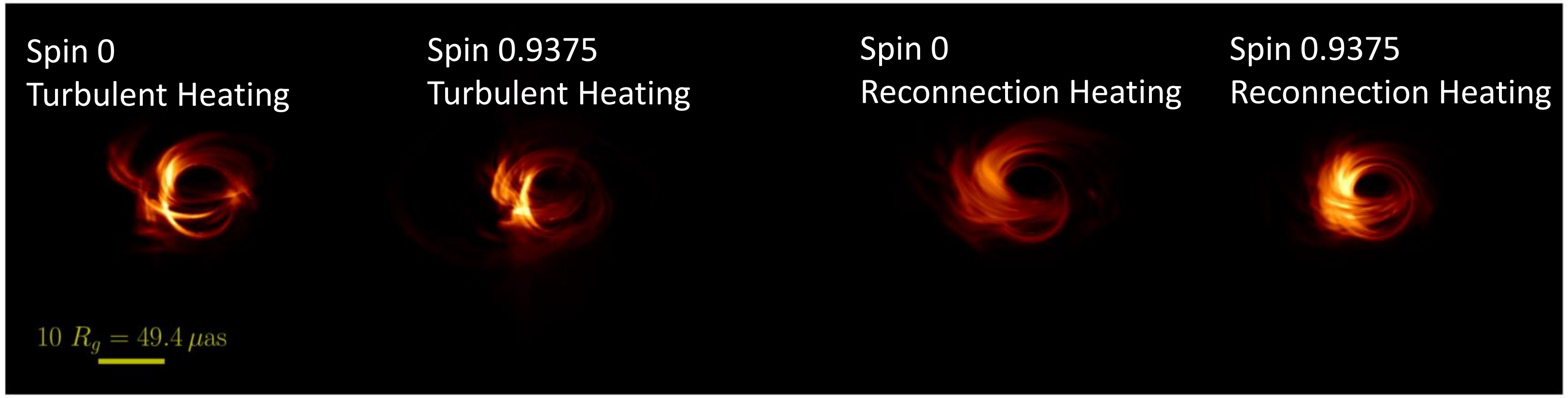
230 GHz



Where the EHT observes at 230 GHz, both heating prescriptions produce images with **distinct black hole shadows**

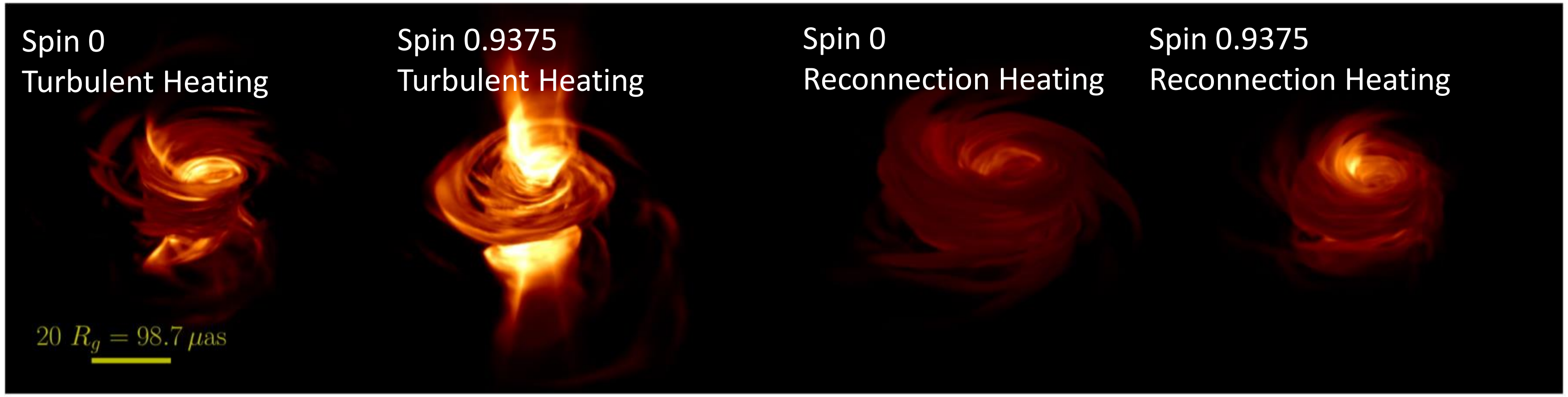
Image structure with frequency

230 GHz



Where the EHT observes at 230 GHz, both heating prescriptions produce images with **distinct black hole shadows**

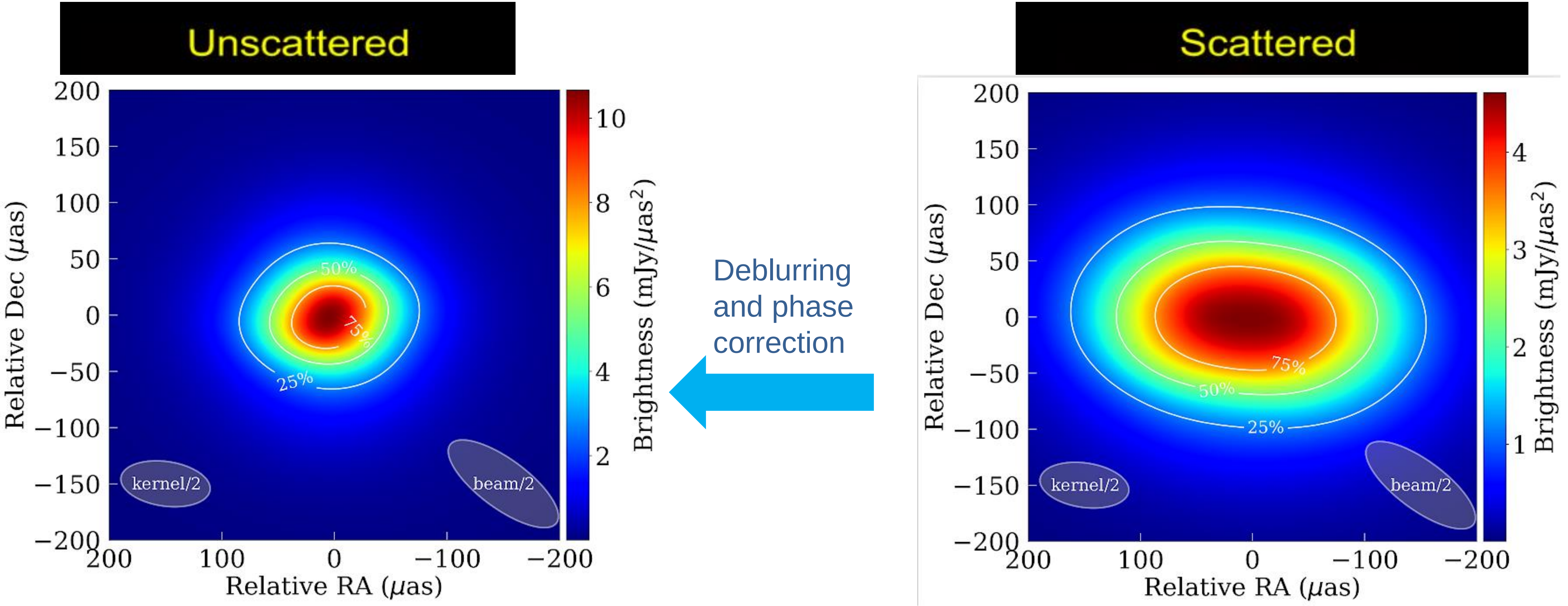
43 GHz



Turbulent heating makes 43 GHz images anisotropic and jet dominated –
exceeding estimates of intrinsic anisotropy
(Johnson et al. 2018,
Issaoun et al. 2018 in prep)

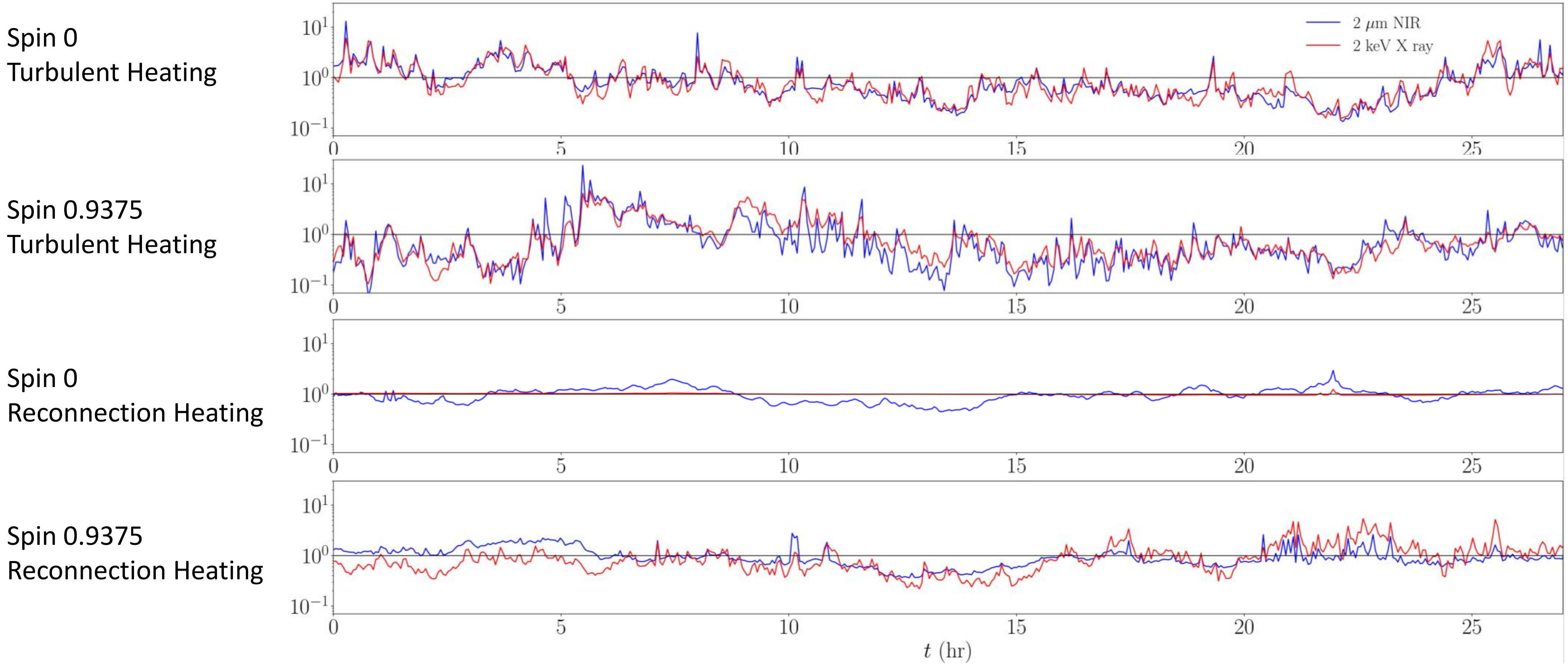
First **Intrinsic** Image of Sgr A* at 3.5 mm

and the first VLBI with ALMA (Issaoun et al. in prep)



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

IR and X-ray variability: **no flares**



No models reproduce strong IR and X-ray flares →Nonthermal Electrons

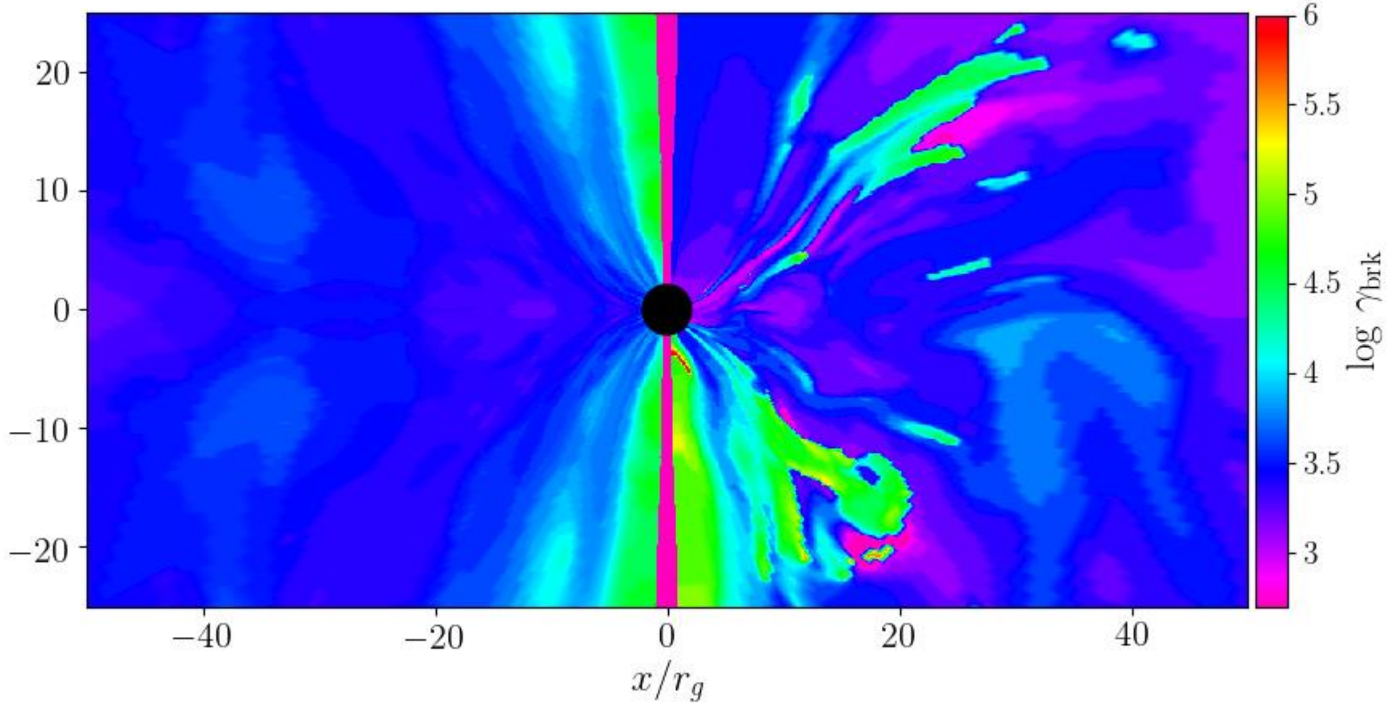
Evolving **nonthermal** electrons in simulations

(Chael et al. 2017, arXiv 1704.05092)

- New method to self-consistently evolve non-thermal spectra in parallel with two-temperature fluid.
- First 3D simulations with realistic electron acceleration coming soon!

Spatial distribution of nonthermal spectral break energy

Time-averaged



Snapshot

M87

(Chael+ 2018b, arXiv: 1810.01983)

Previous work: *Ryan et al. 2018*

- 2D, two-temperature simulations with **weak magnetic flux** and using the turbulent cascade prescription at 2 BH masses.
- Good agreement with previous EHT measurements of image size for high mass case $(6 \times 10^9 M_\odot)$.
- Jet power **too weak**, jet angle **too narrow**

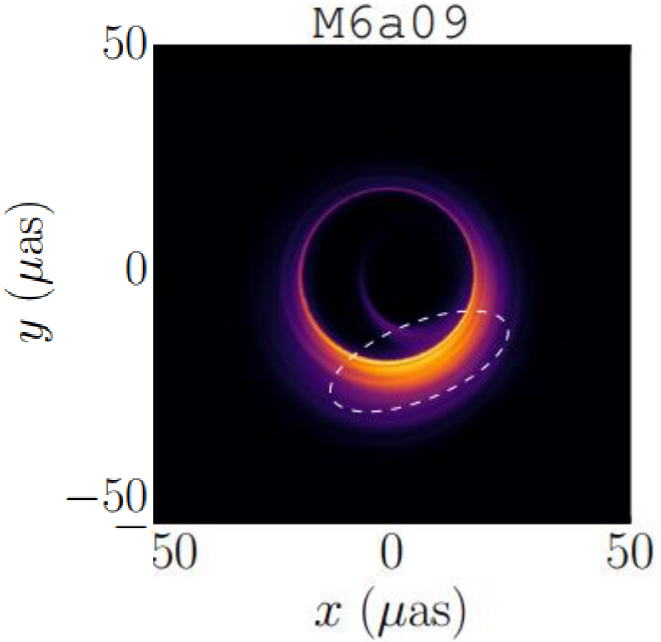


Image credit: Ryan et al. 2018

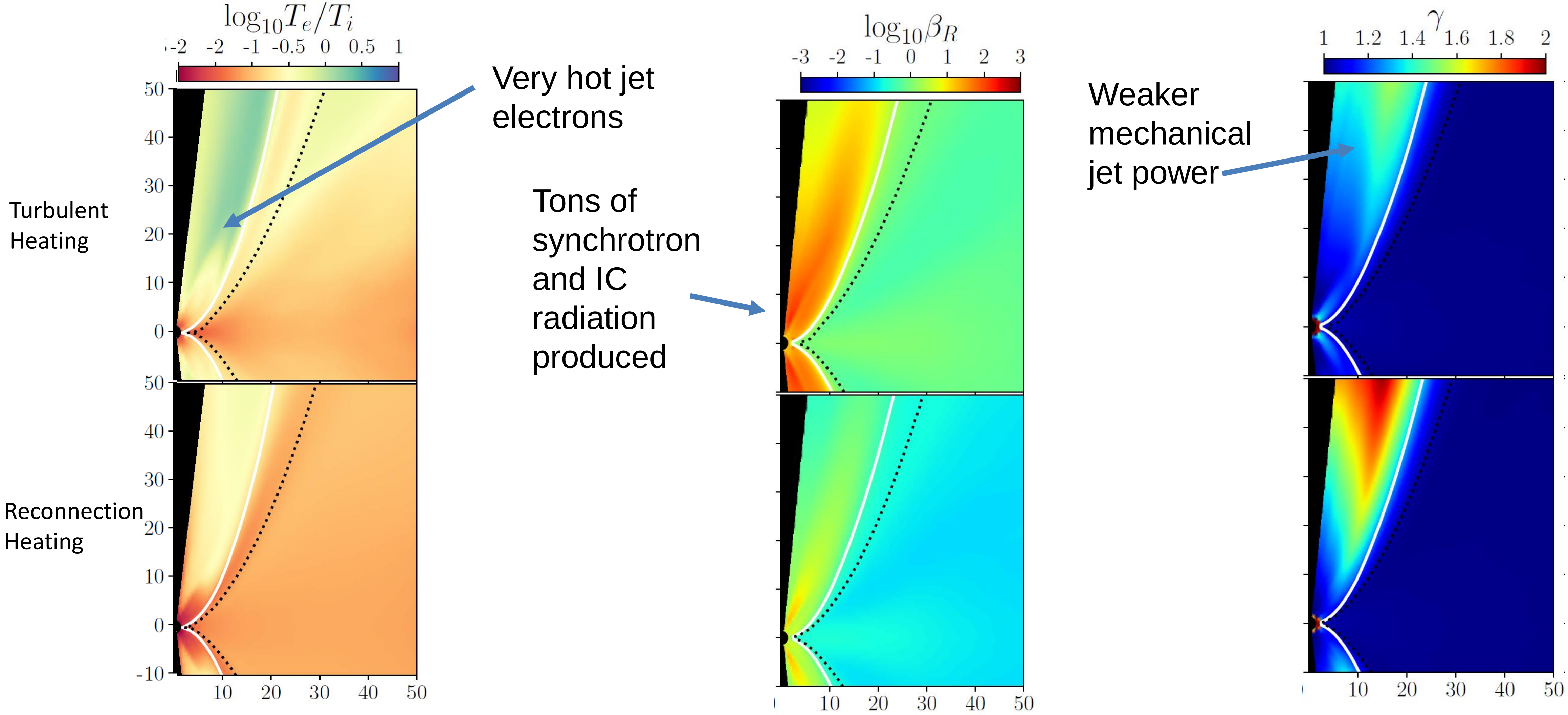
Our M87 Simulations

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

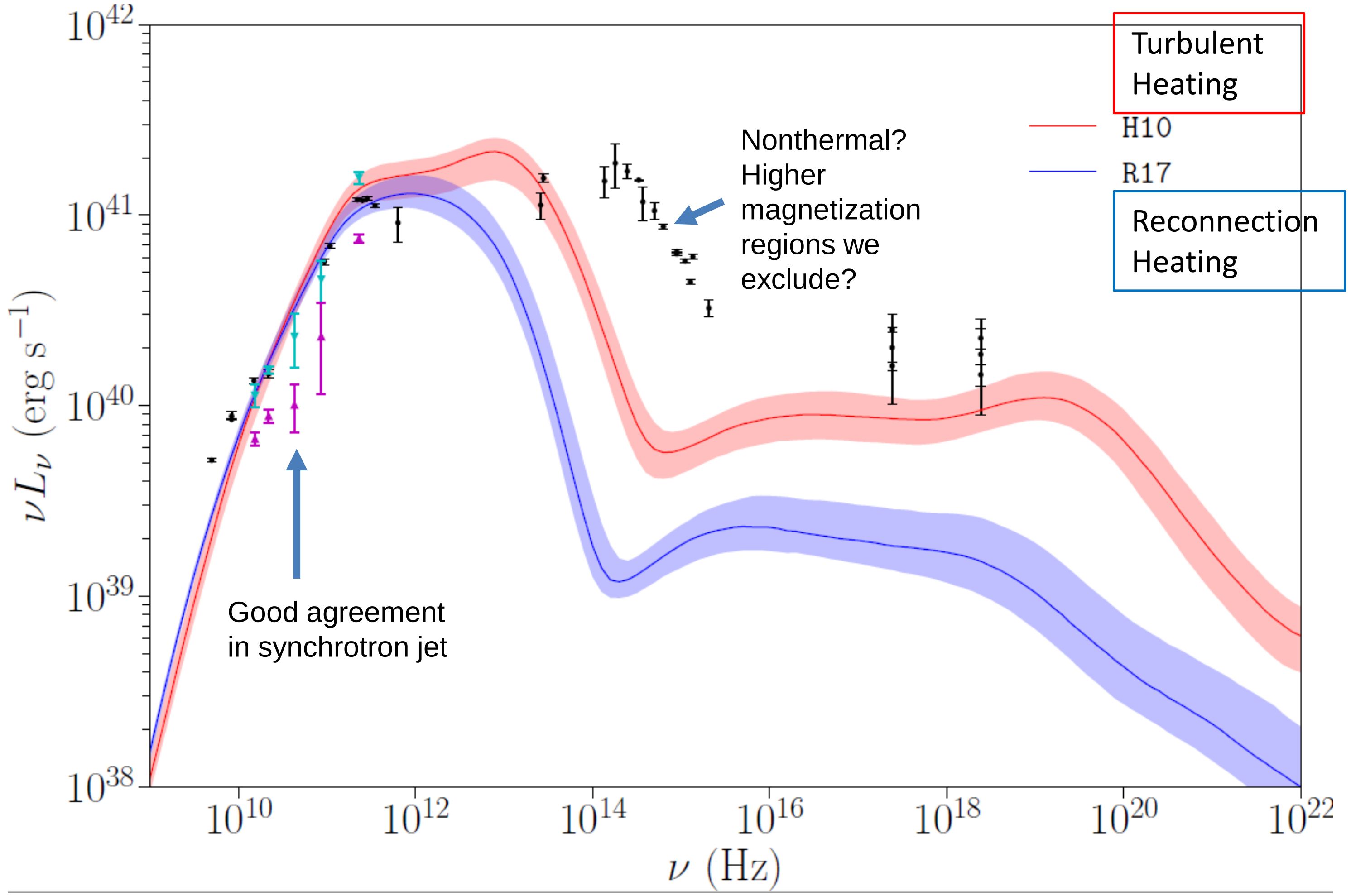
- Both simulations are in the MAD state.
- Density is scaled to match ~ 1 Jy at 230 GHz.
- The mechanical jet power in R17 is in the measured range of 10^{43}–10^{44} erg/s.

Electron Heating → jet dynamics



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

M87 Spectra



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 $\sigma_{\rm i} \leq 25$

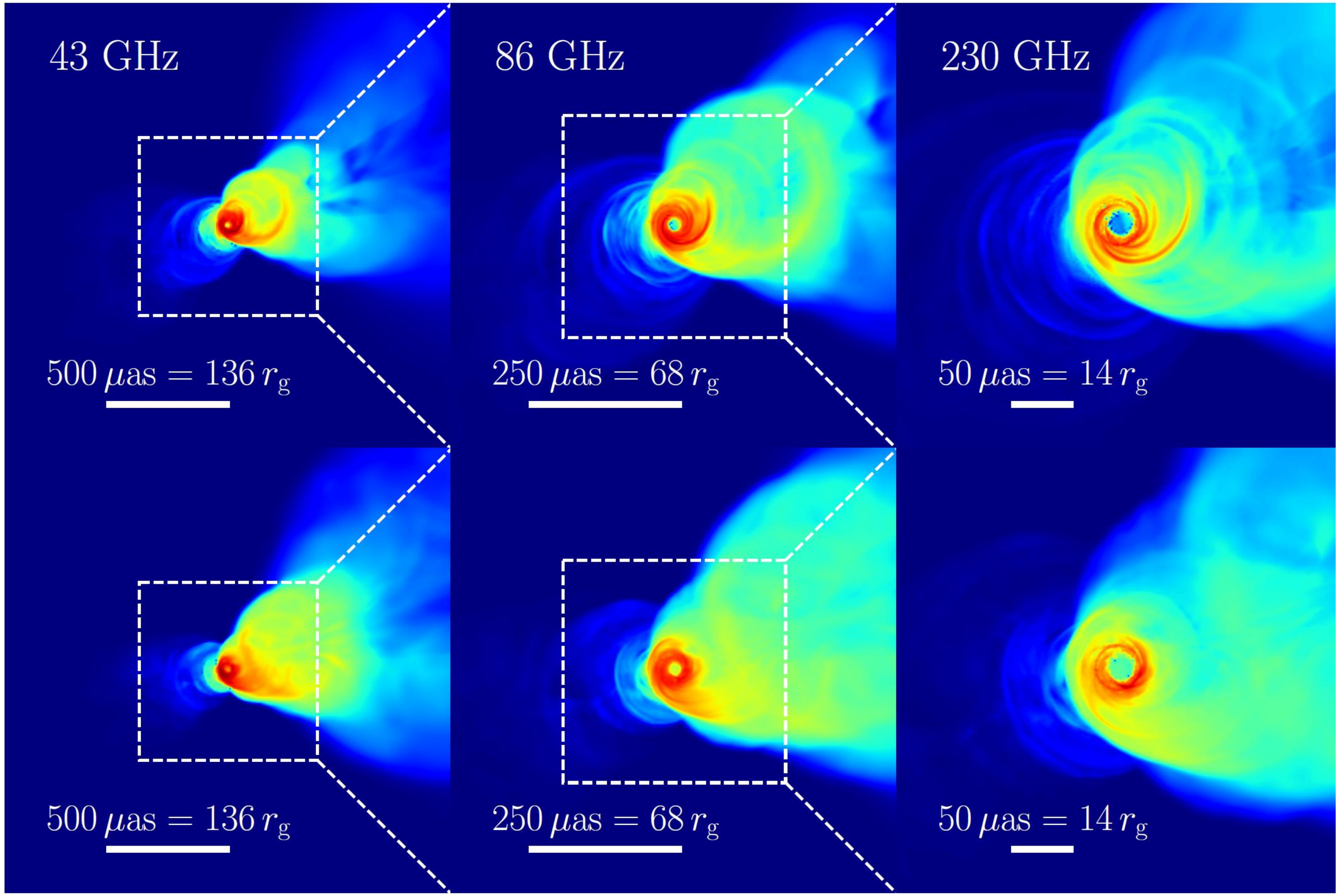
Spectra and images at frequencies $\geq$ 230 GHz depend strongly on the choice of cut!

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

M87 Jets at millimeter wavelengths

Turbulent Heating

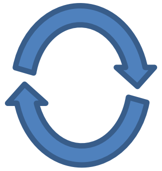
Reconnection Heating



Inclination angle (down from pole)

17°

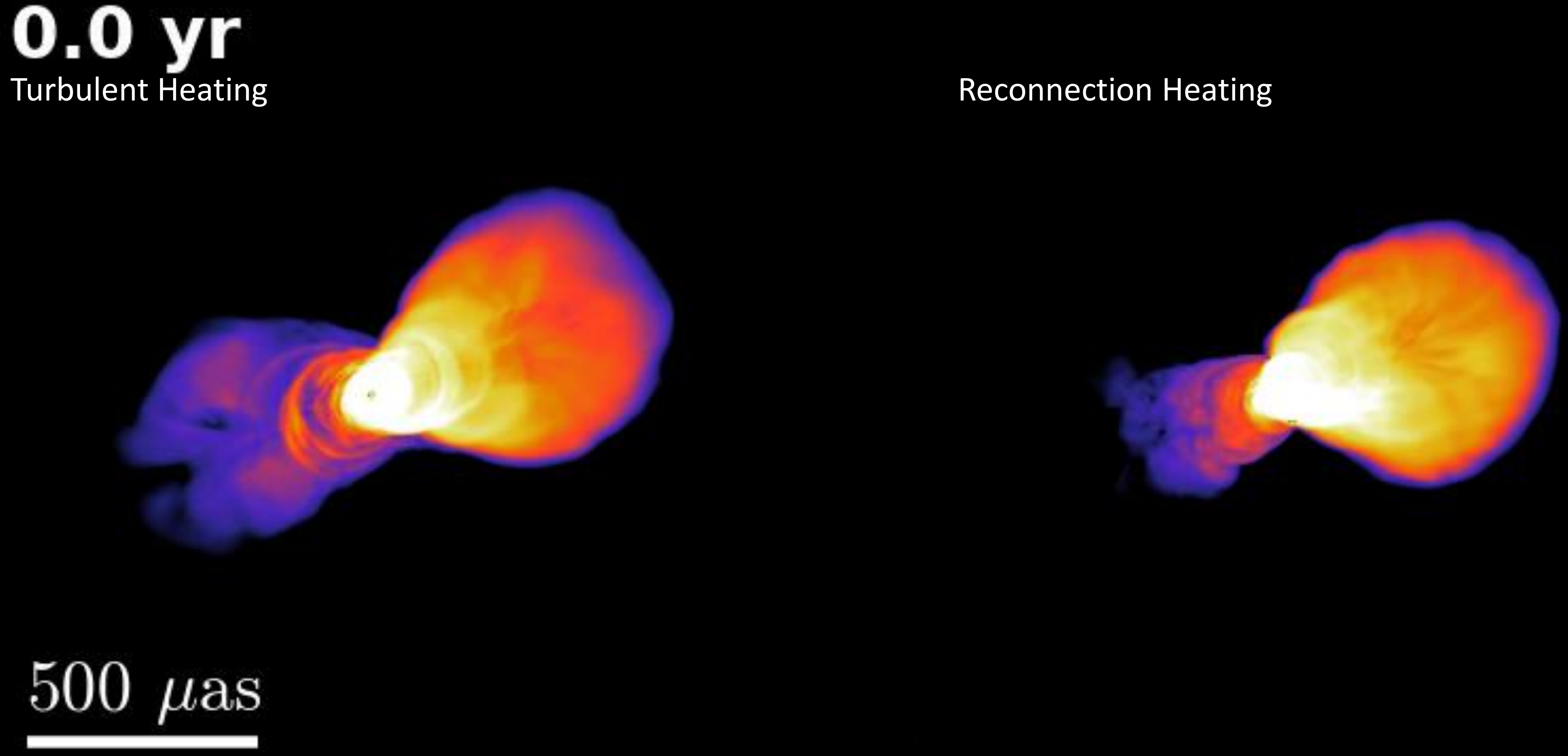
Disk/Jet rotation sense



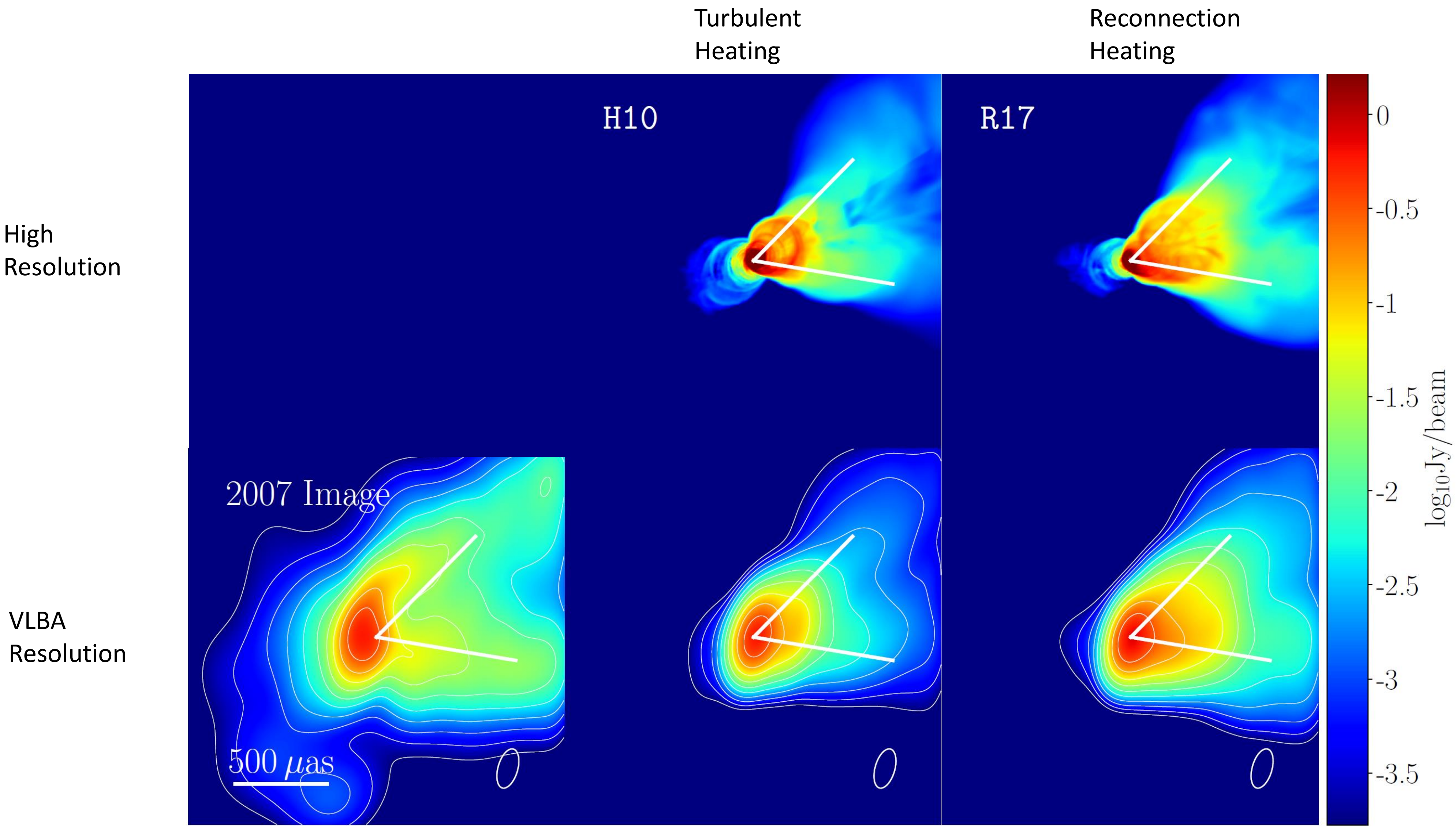
(Values from Walker+ 18)

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

43 GHz jets



43 GHz images – comparison with VLBA



Apparent opening angle at 43 GHz:

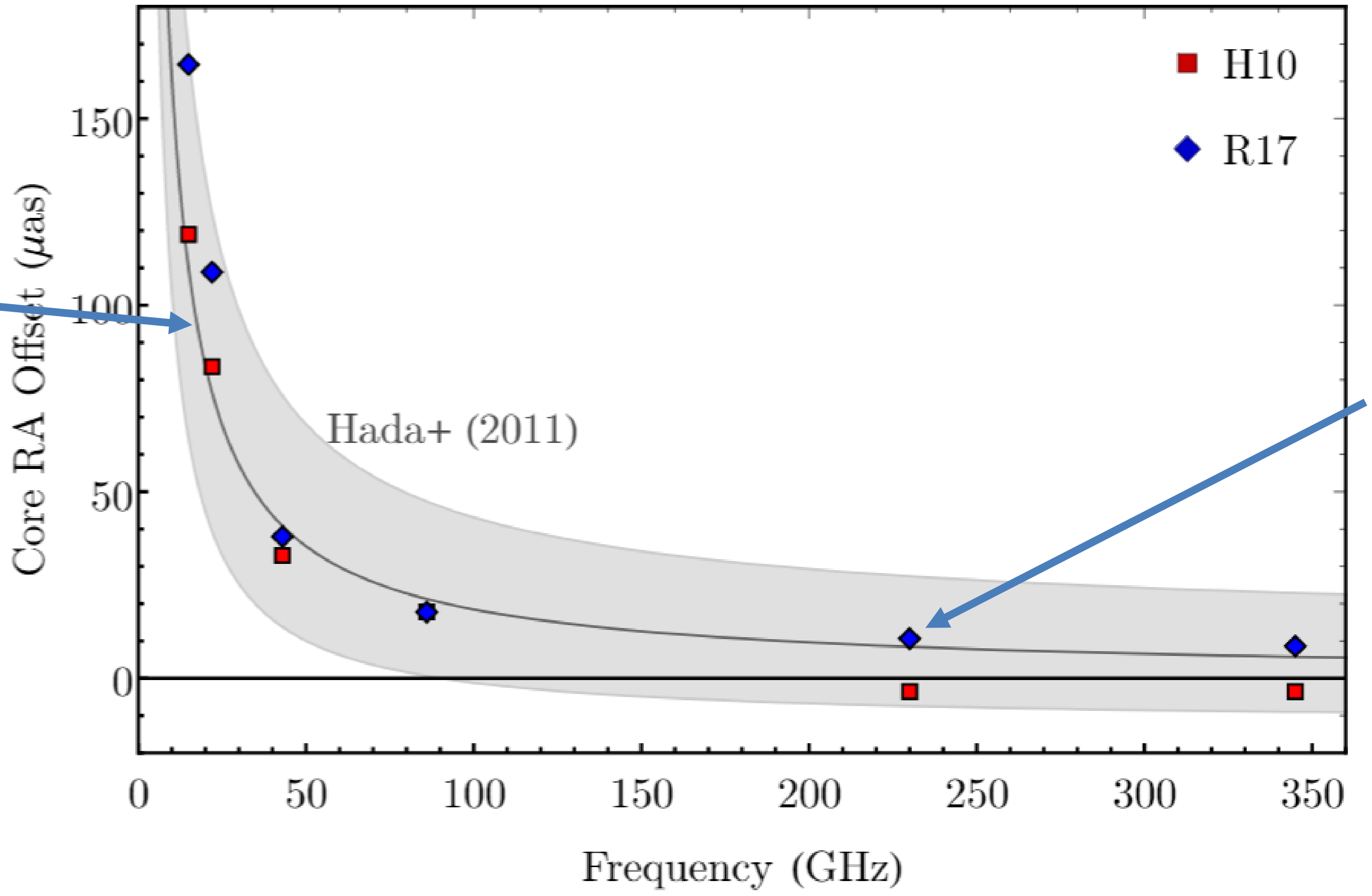
55°

(Walker+ 2018)

Image credit: 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

Good agreement with measured core shift down to cm wavelengths

What will M87 look like to the EHT at 230 GHz?

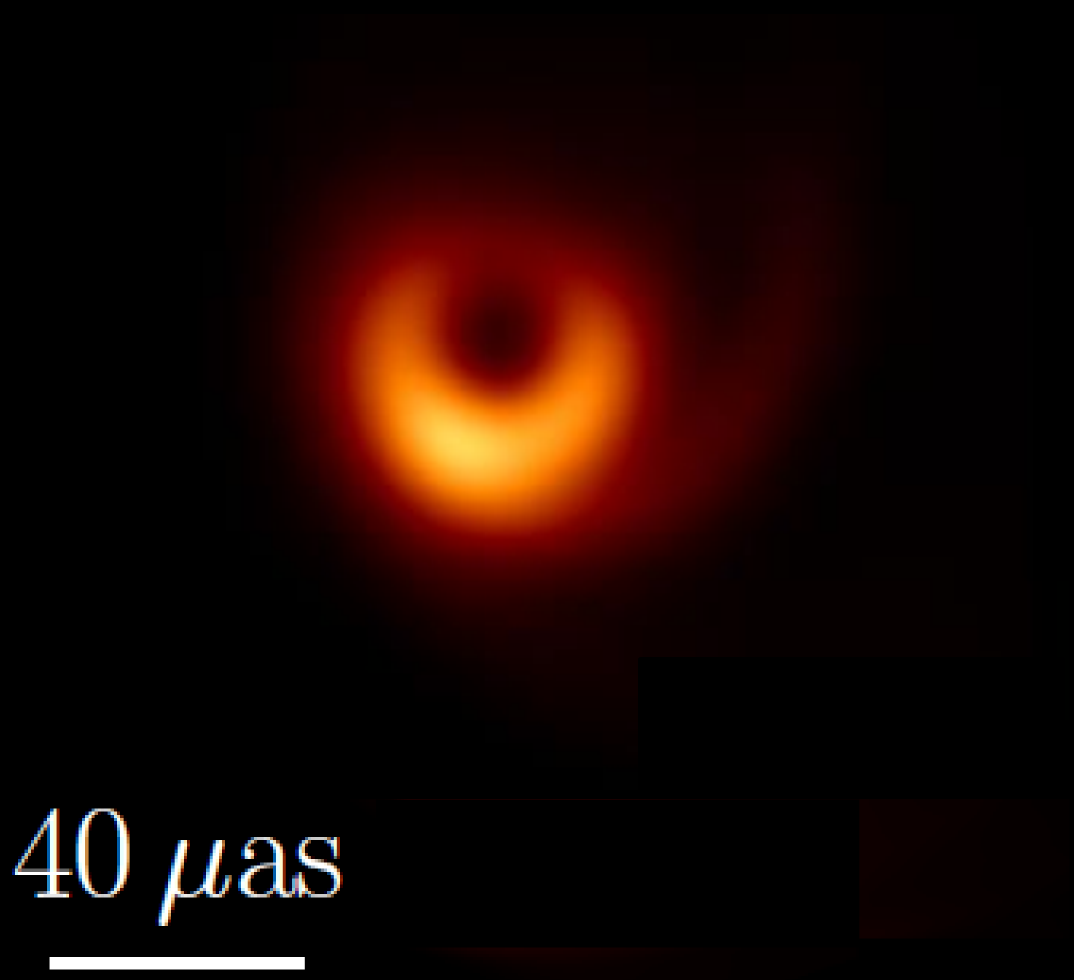
Turbulent Heating

Reconnection Heating

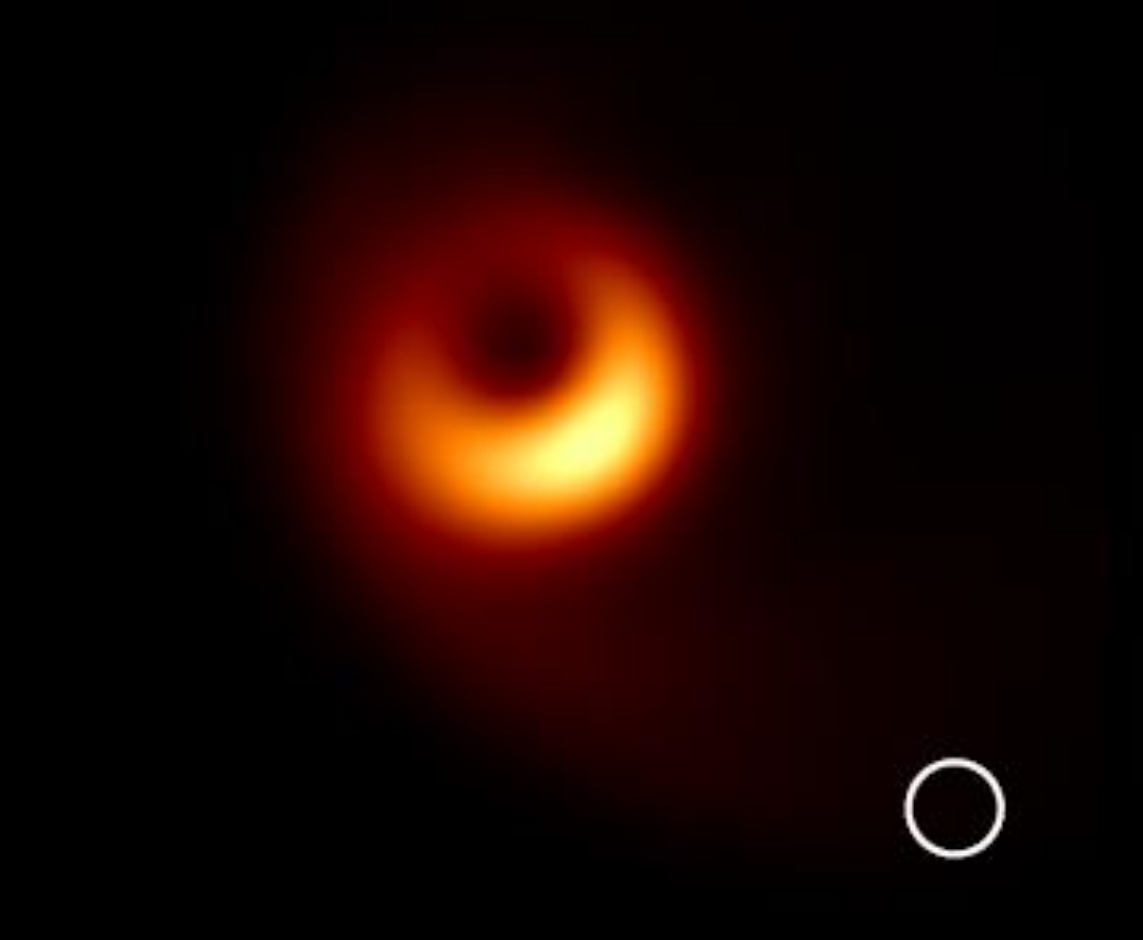
$40\ \mu as$

What will M87 look like to the EHT at 230 GHz?

Turbulent Heating

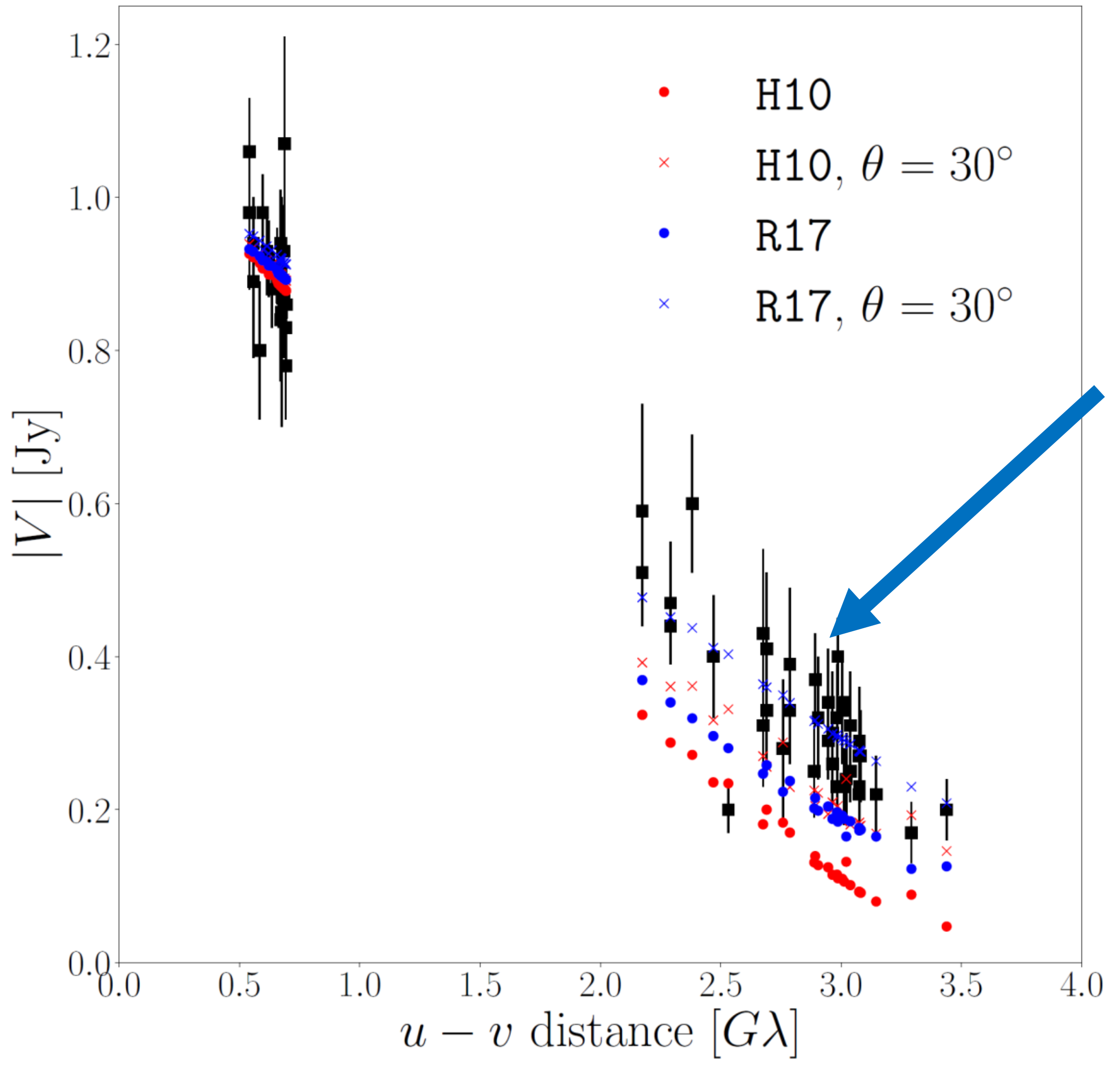


Reconnection Heating



What will M87 look like to the EHT at 230 GHz?

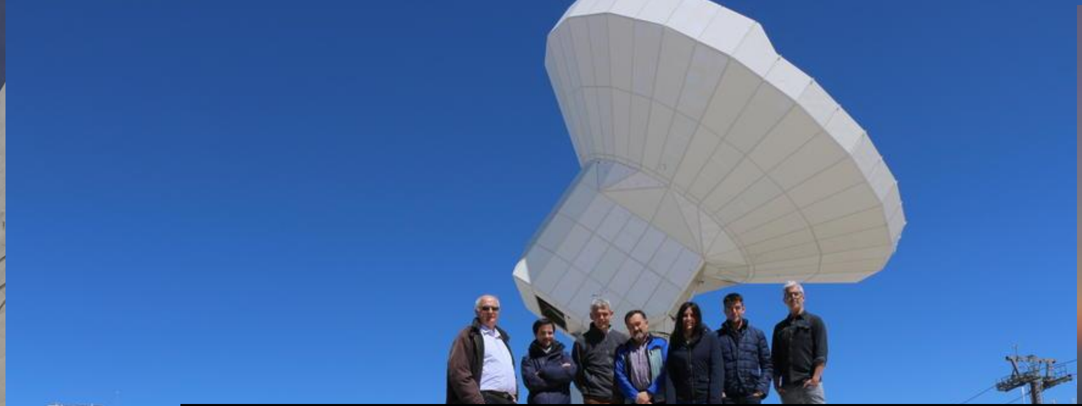
Current 230 GHz images are too big!



2009 and 2012 EHT visibility amplitudes (Doeleman+ 2012, Akiyama+ 2015)

Changing the inclination **or** including more emission from magnetized regions near axis makes the emission more compact.

First EHT images on the way!



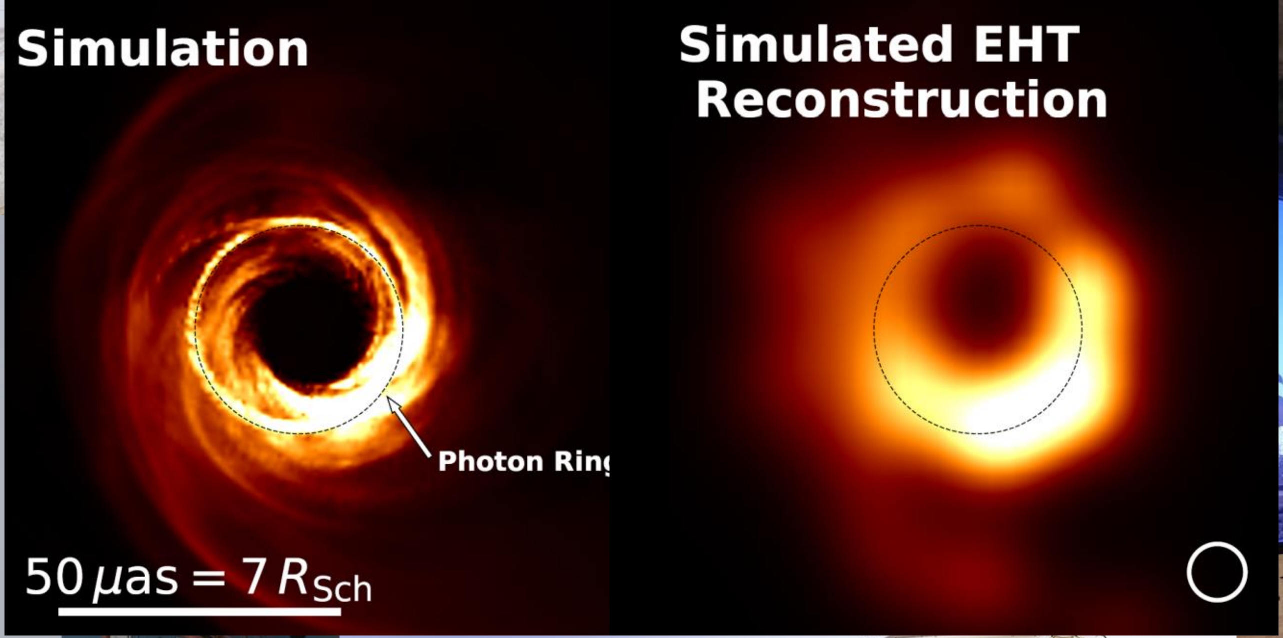


Image credits: Dan Marrone,
David Michalik,Atish Kamble, Junhan Kim , Salvaor Sanchez,
Helge Rottman , Katie Bouman, MIT Haystack Observatory

Takeaways

- Different plasma heating mechanisms produce qualitatively different images.

- For **Sgr A*:**
  - Turbulent heating produces a disk-jet structure, which is too anisotropic (when viewed-edge on.)

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

- Many features remain unexplained by two-temperature models.
  - *Non*thermal electrons.

- EHT images early next year!

Thank You!