Electron heating in simulations of Sgr A* (and M87)

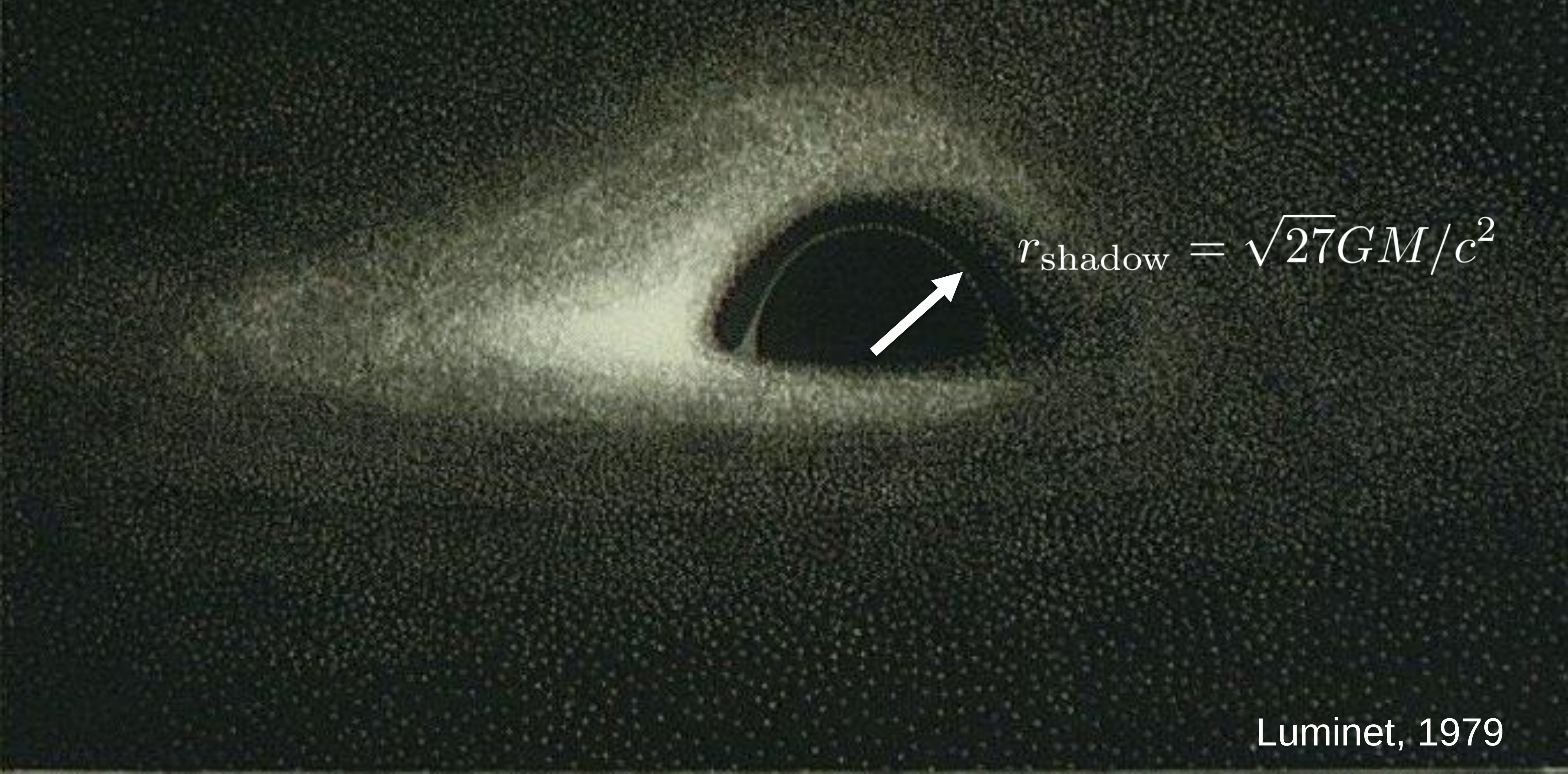
Andrew Chael

Ringberg, November 2, 2018

Event Horizon Telescope

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

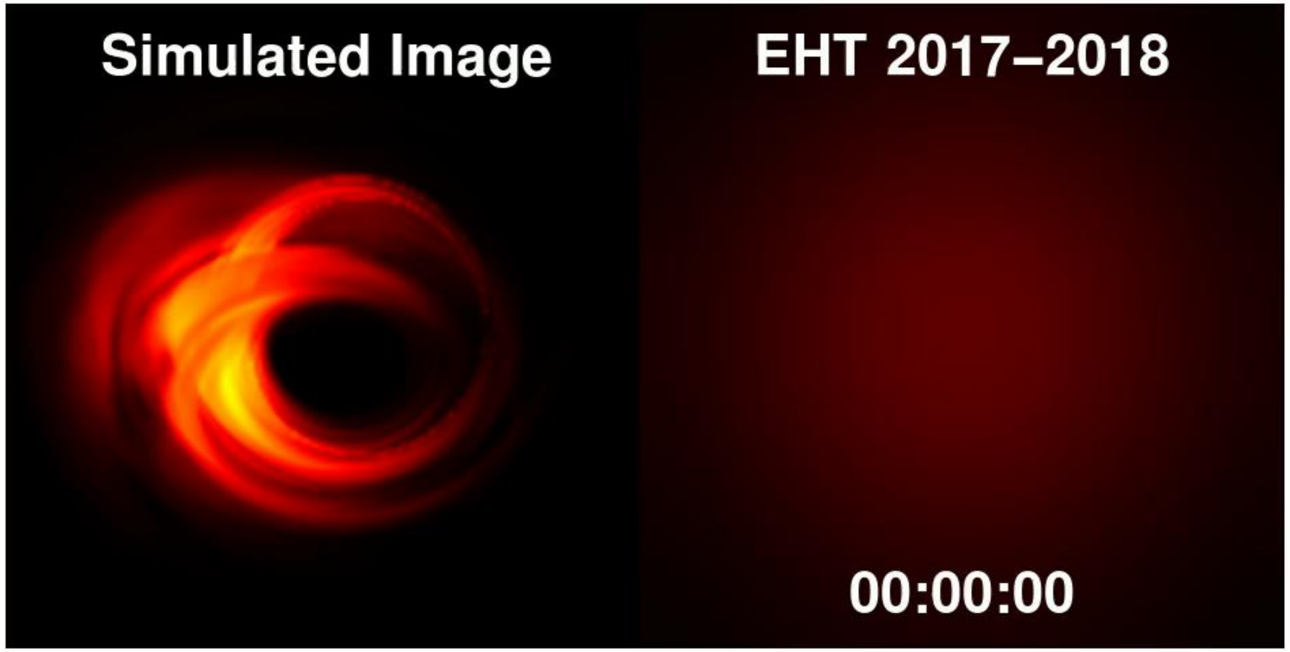
What does a black hole look like?



Luminet, 1979

Black Hole Image Reconstruction with the EHT

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



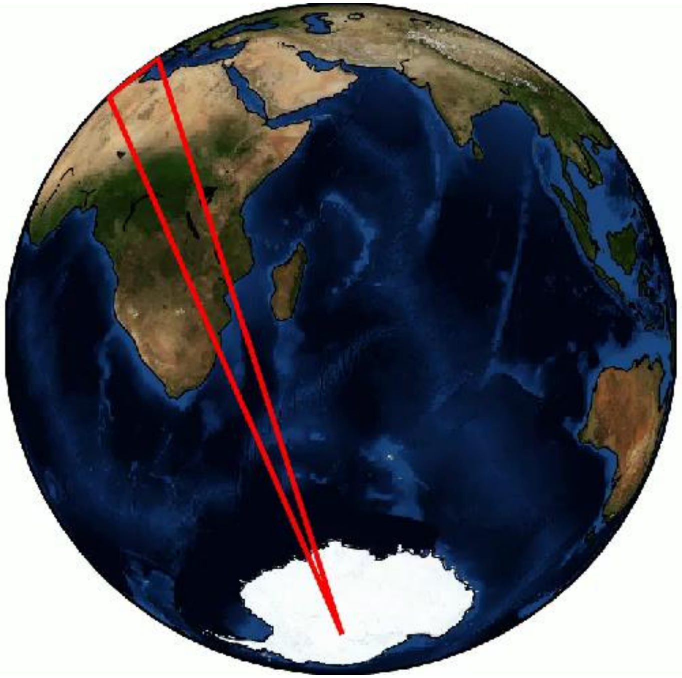


Image Credit:
Jason Dexter, Katie Bouman

Sagittarius A*

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

Gravity Collaboration, 2018

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

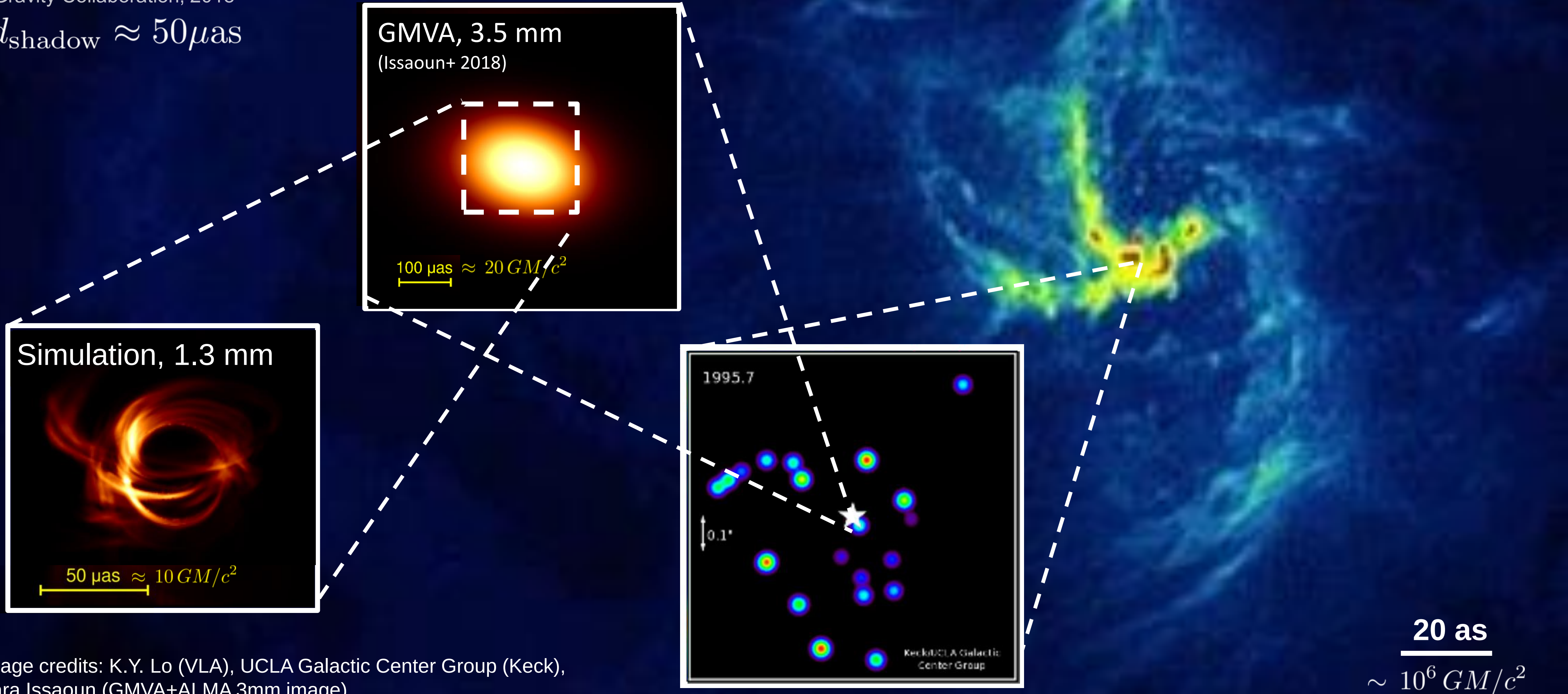


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)

M87

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

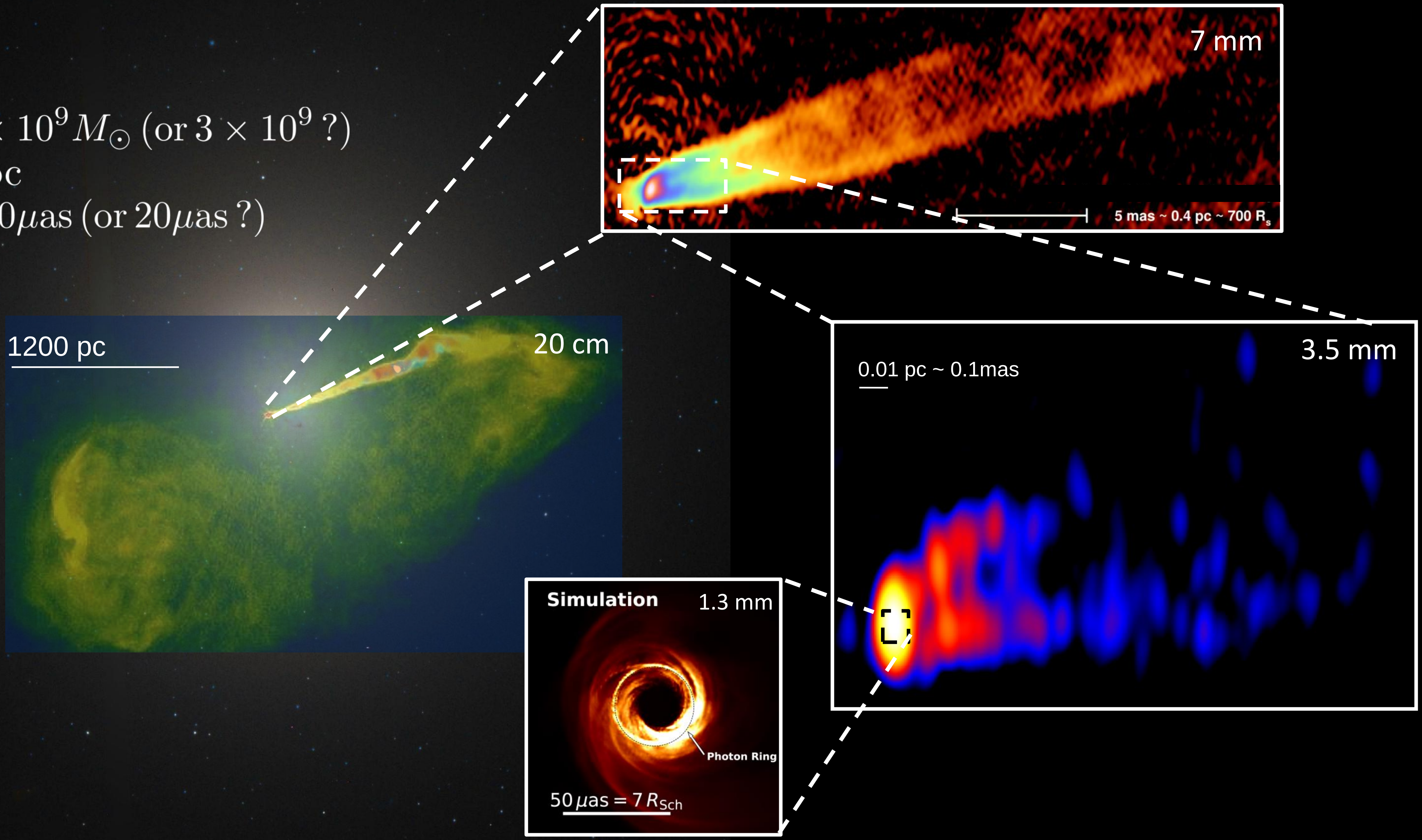


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm)

What will the EHT see?

1. Spacetime geometry
   -The shadow of the black hole. Spin?

2. Fluid dynamics
   -How is stuff moving? Jet/disk/outflow?

3. Electron (non)thermodynamics.
   -Where are the emitting electrons?
   -What is their distribution?

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

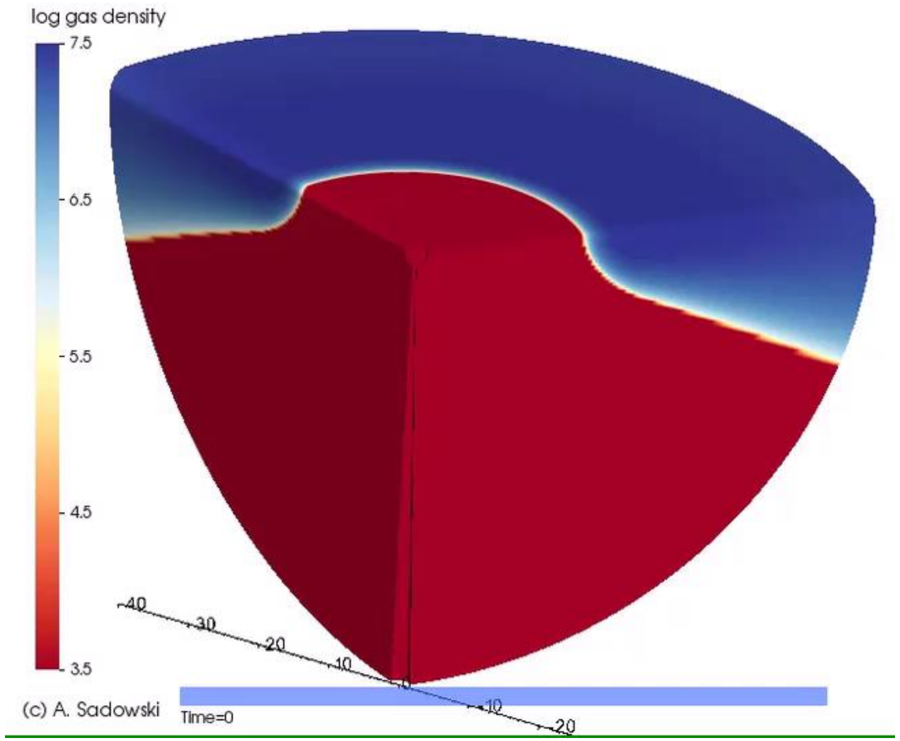
- Low densities in hot flows
  → inefficient Coulomb coupling between ions and electrons.

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

- But if electrons are **heated** much more, they can remain hotter.

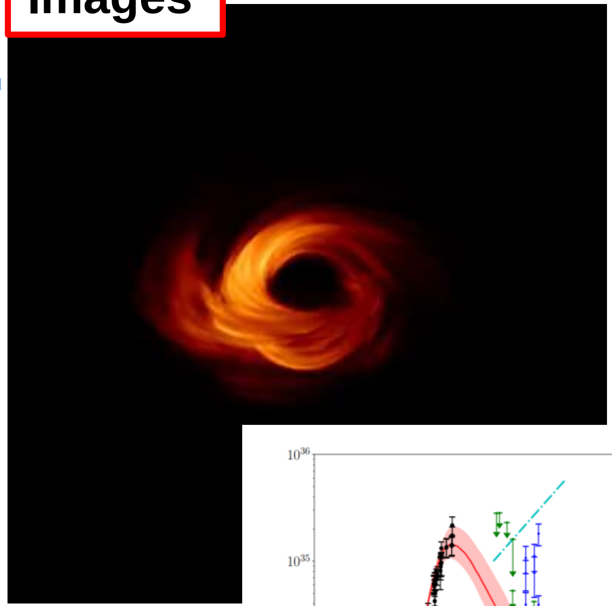
Mahadevan+ 97,98, Sądowski+ 17, Ressler+ 15,17, Ryan+ 18

From simulations to observables

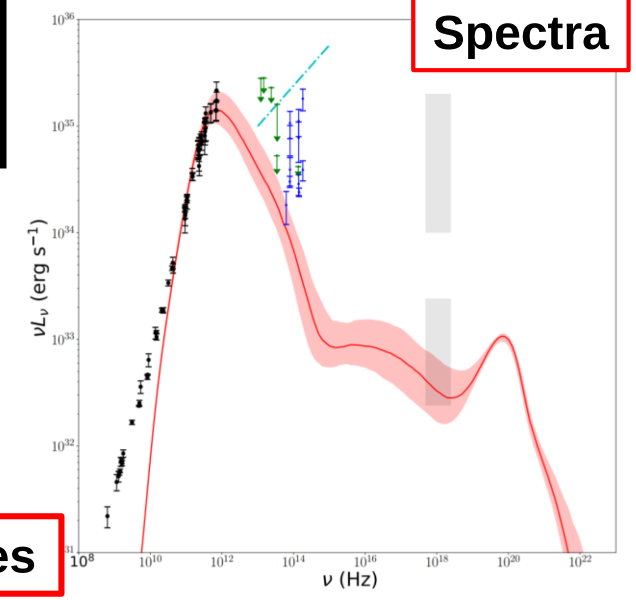


T_e?

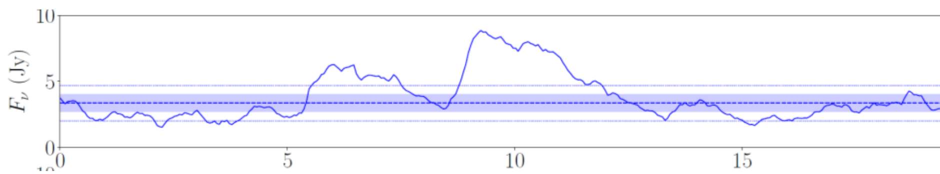
Images



Spectra



Light Curves



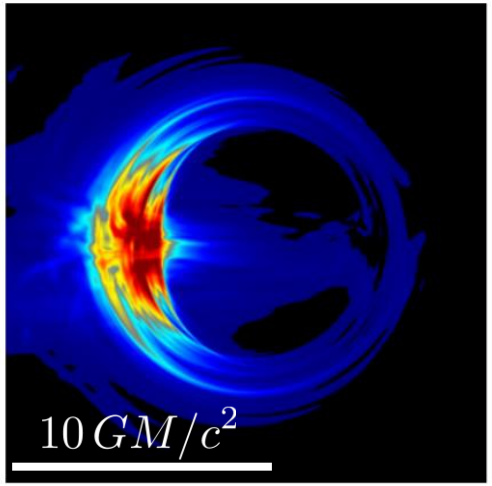
GRMHD Simulations

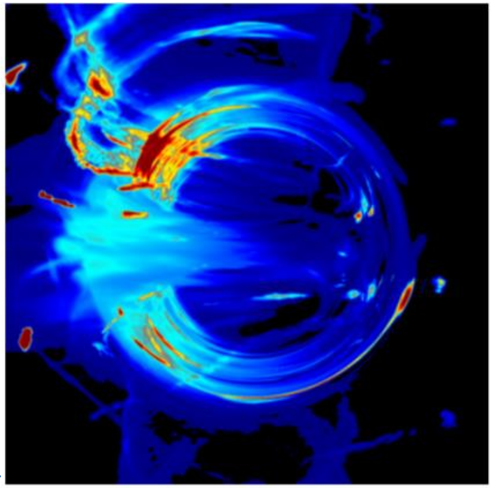
Usually evolve a **single** fluid and magnetic field

Fixed temperature ratios in postprocessing.

(Mościbrodzka+ 2014)

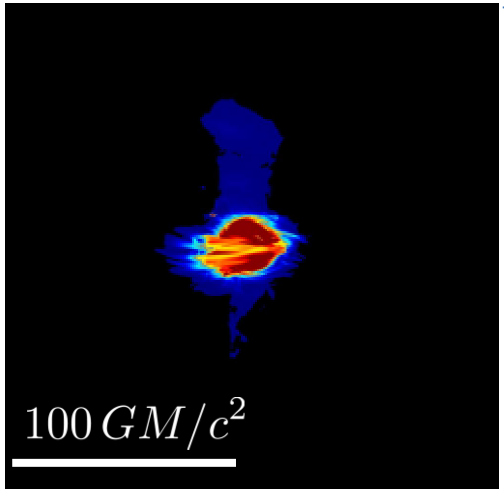
$\lambda = 1.3\text{mm}$

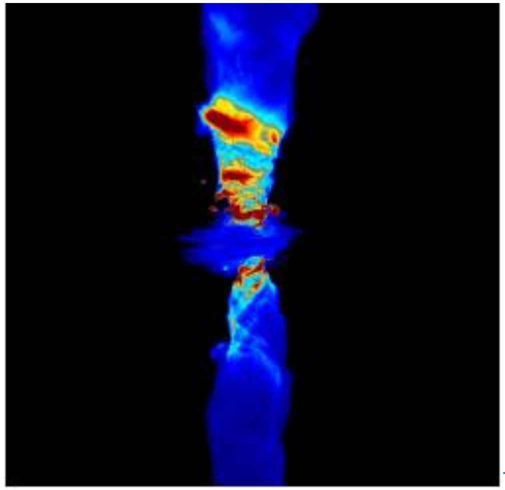




$$\left(\frac{T_e}{T_i}\right)_{\text{disk}} = 0.2$$

$$\left(\frac{T_e}{T_i}\right)_{\text{disk}} = 0.04$$





$\lambda = 7\text{mm}$

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

also: Dexter+2010, Moscibrodzka+ 2009, 2013, 2014, Chan+ 2015a, 2015b, Scherbakov+2012 ...

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+ 2013, 2015, 2017)

-See also previous work by:

Ressler+ 2017 (Sgr A*)

Ryan+ 2018 (M87)

Two-Temperature GRRMHD Simulations

- Total fluid quantities are evolved as in single-temperature GRRMHD
- Electron and ion energy densities are evolved via the 1st law of thermodynamics:

$$T_\mathrm{e}\,(n s_\mathrm{e} u^\mu)_{;\mu} = \delta_\mathrm{e} q^\mathrm{v} + q^\mathrm{C} - \hat{G}^0$$
$$T_\mathrm{i}\,(n s_\mathrm{i} u^\mu)_{;\mu} = (1-\delta_\mathrm{e}) q^\mathrm{v} - q^\mathrm{C}$$

Radiation: weak

Coulomb Coupling: weaker

Viscous dissipation

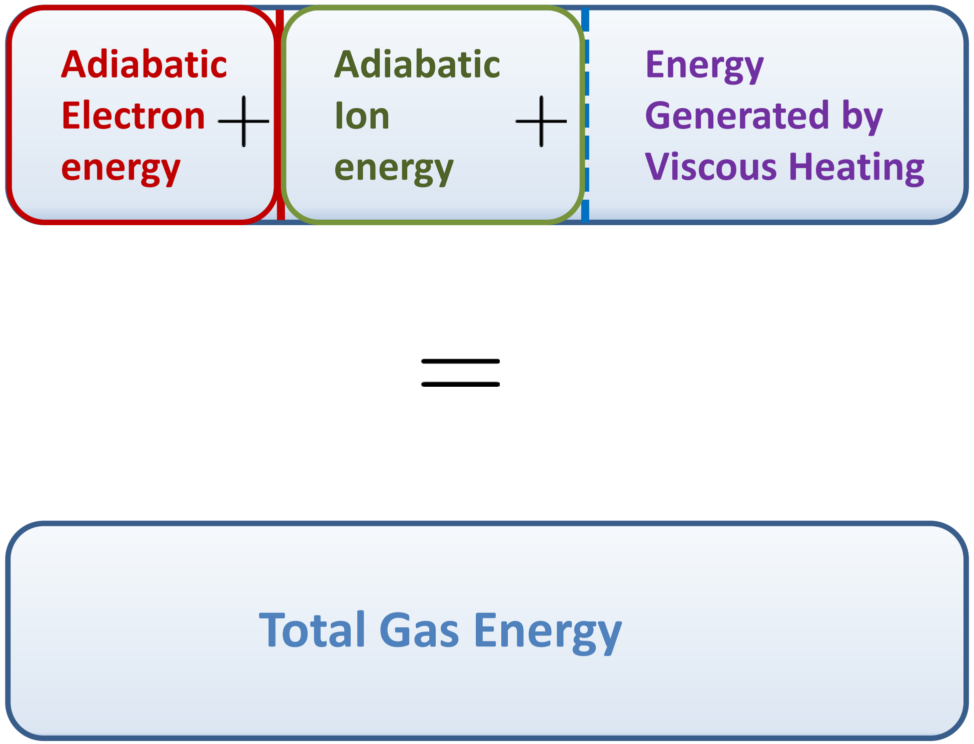
"$T\,\mathrm{d}S$"

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.**

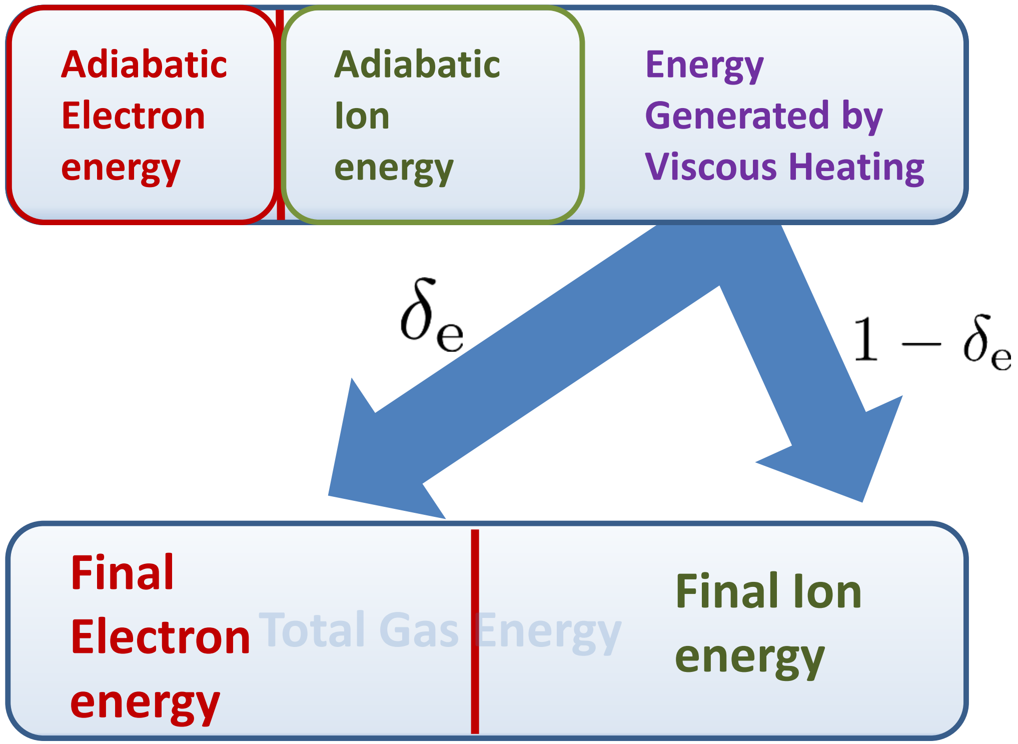
$$q^{\mathrm{v}} = \frac{1}{\Delta\tau}\left[u - u_{\mathrm{i\,adiab}} - u_{\mathrm{e\,adiab}}\right]$$



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.**

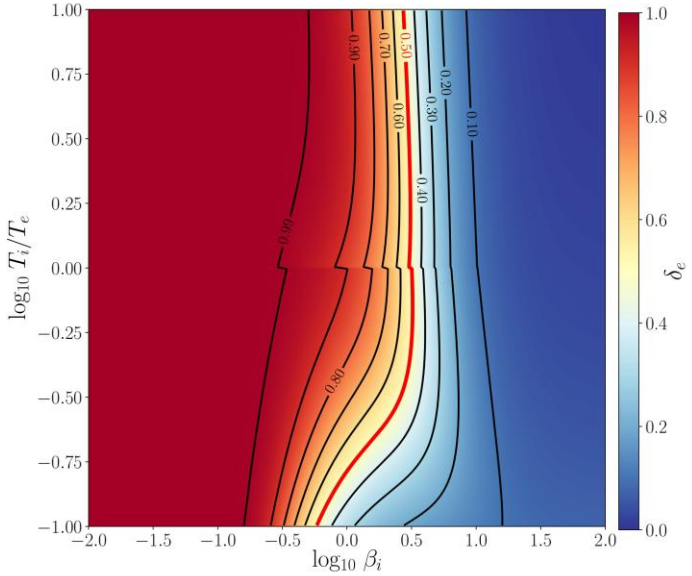
- **Sub-grid physics** must be used to determine what fraction of the dissipation goes into the electrons.



Sub-grid Heating Prescriptions

Landau-Damped Turbulent Cascade (Howes 2010)

- Non-relativistic physics .
- Predominantly heats electrons when magnetic pressure is high, and vice versa



Almost all energy to electrons ⟷ Almost all energy to ions

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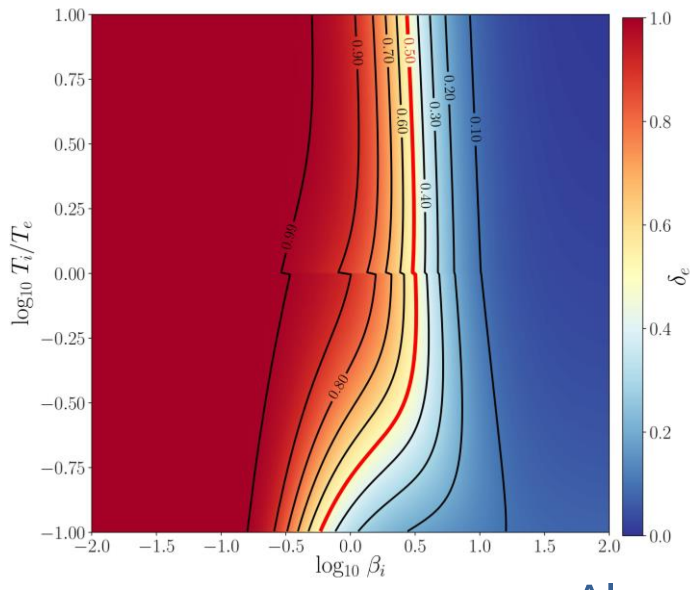
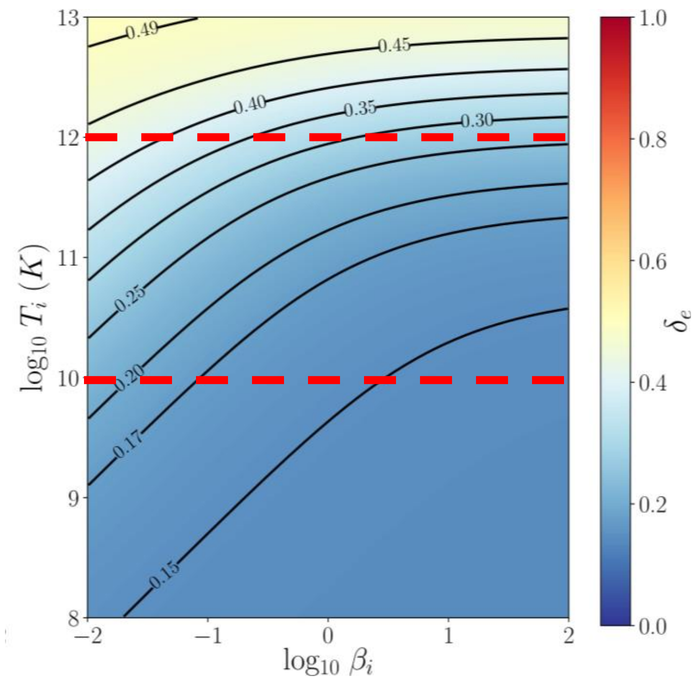


Almost all energy to electrons ⟷ Almost all energy to ions

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 over significant range of temperature, beta.

also: Kawazura+ 2018 (turbulent damping) Werner+ 2018 (reconnection)

Sgr A*

(Chael+ 2018b, 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.
- Natural disk-jet structure.
- Q: Is this structure dependent on electron heating & B field strength?

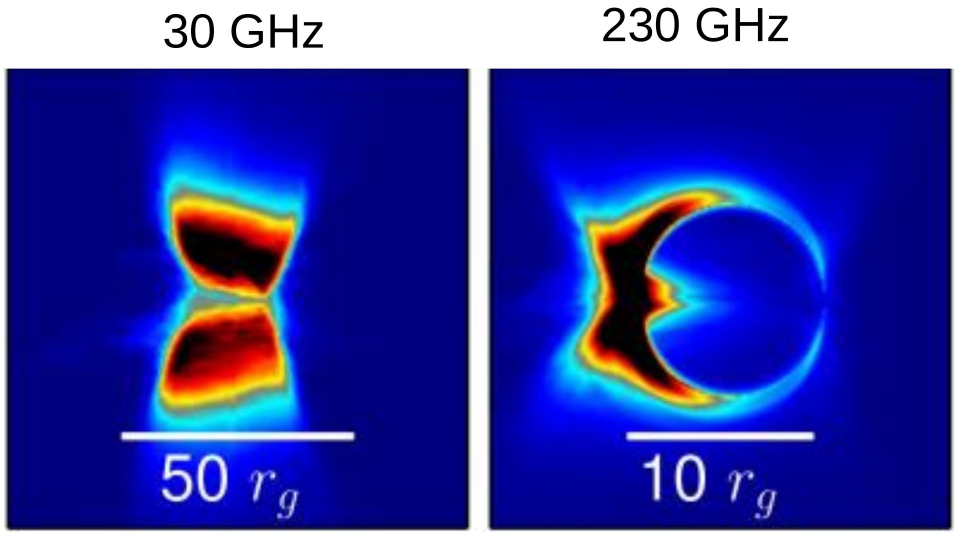


Image credit: Ressler et al. 2017

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 3.5 Jy at 230 GHz (Bower+ 2015).

Sgr A*: *Temperature ratio*

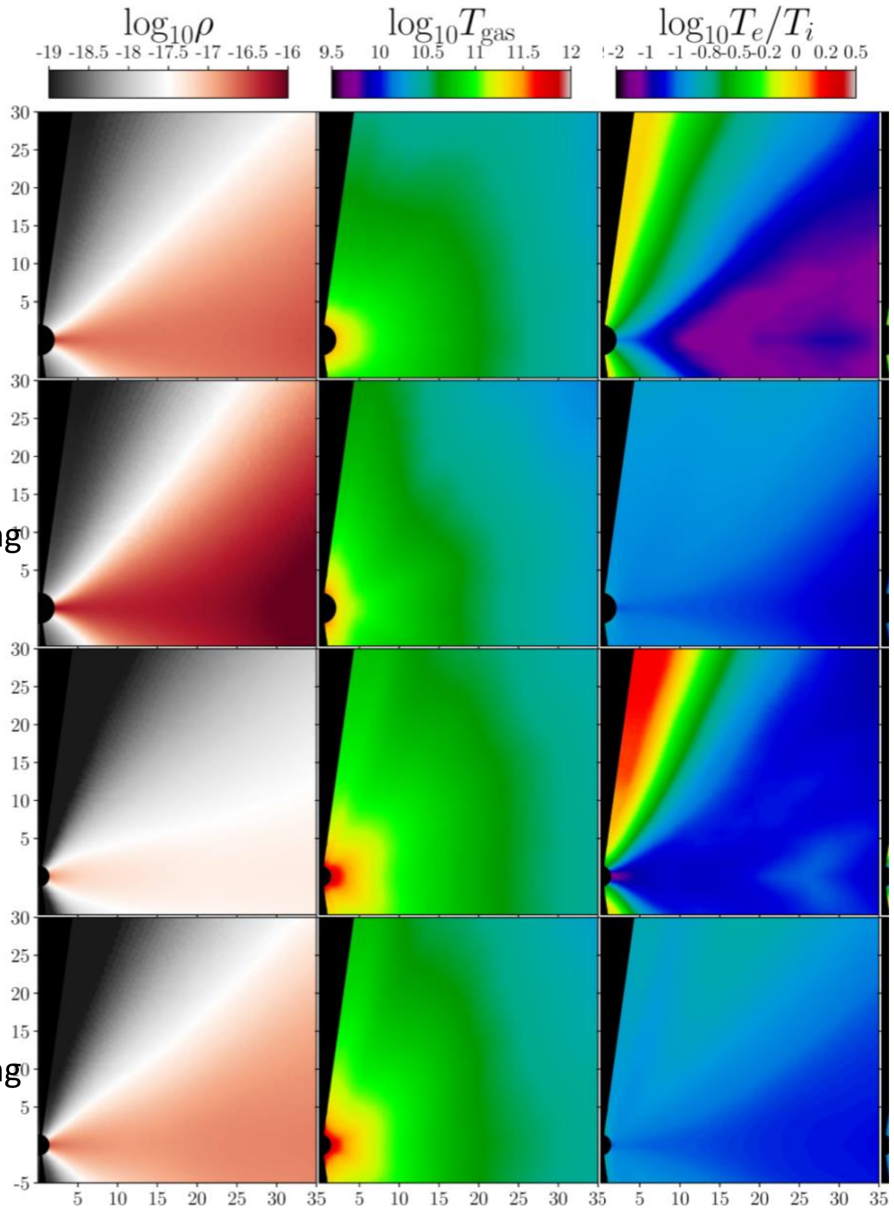
All are thick disks: density lower at high spin

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

230 GHz mm movies

Spin 0
Turbulent
Heating

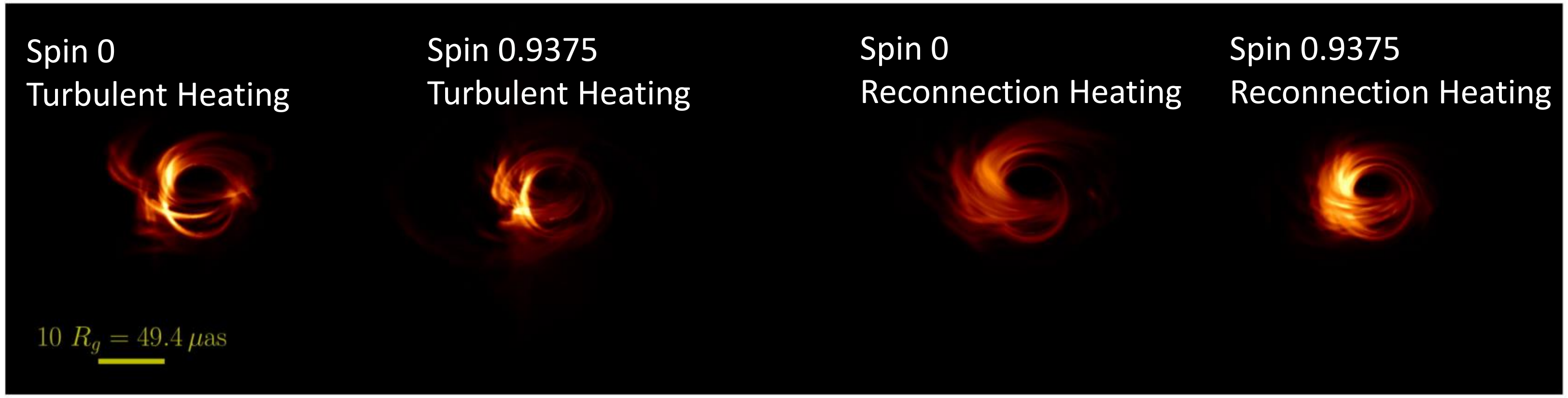
Spin 0.9375
Turbulent
Heating

Spin 0
Reconnection
Heating

Spin 0.9375
Reconnection
Heating

Image structure with frequency

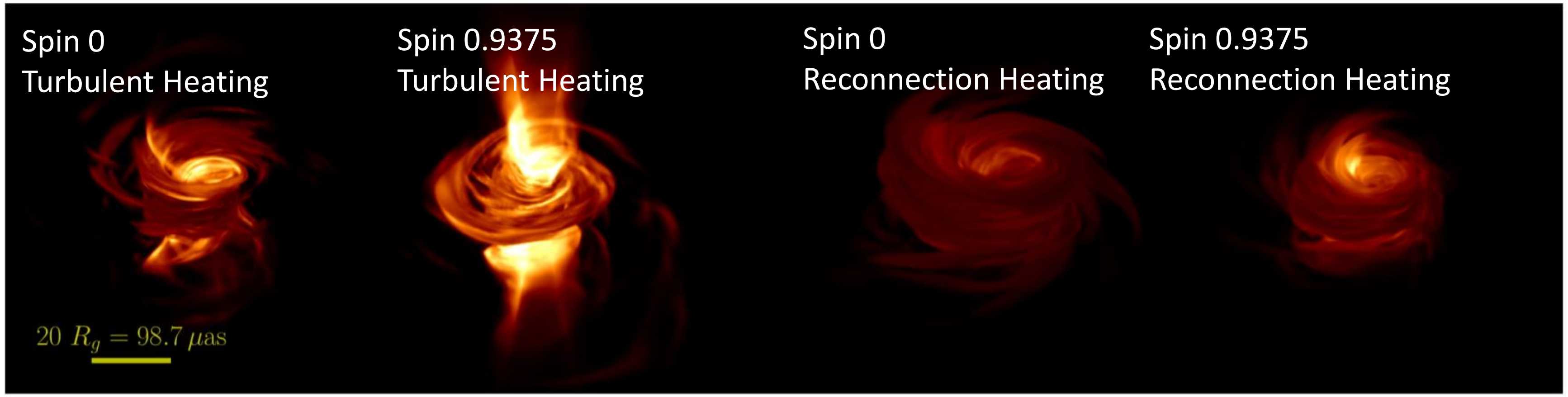
230 GHz



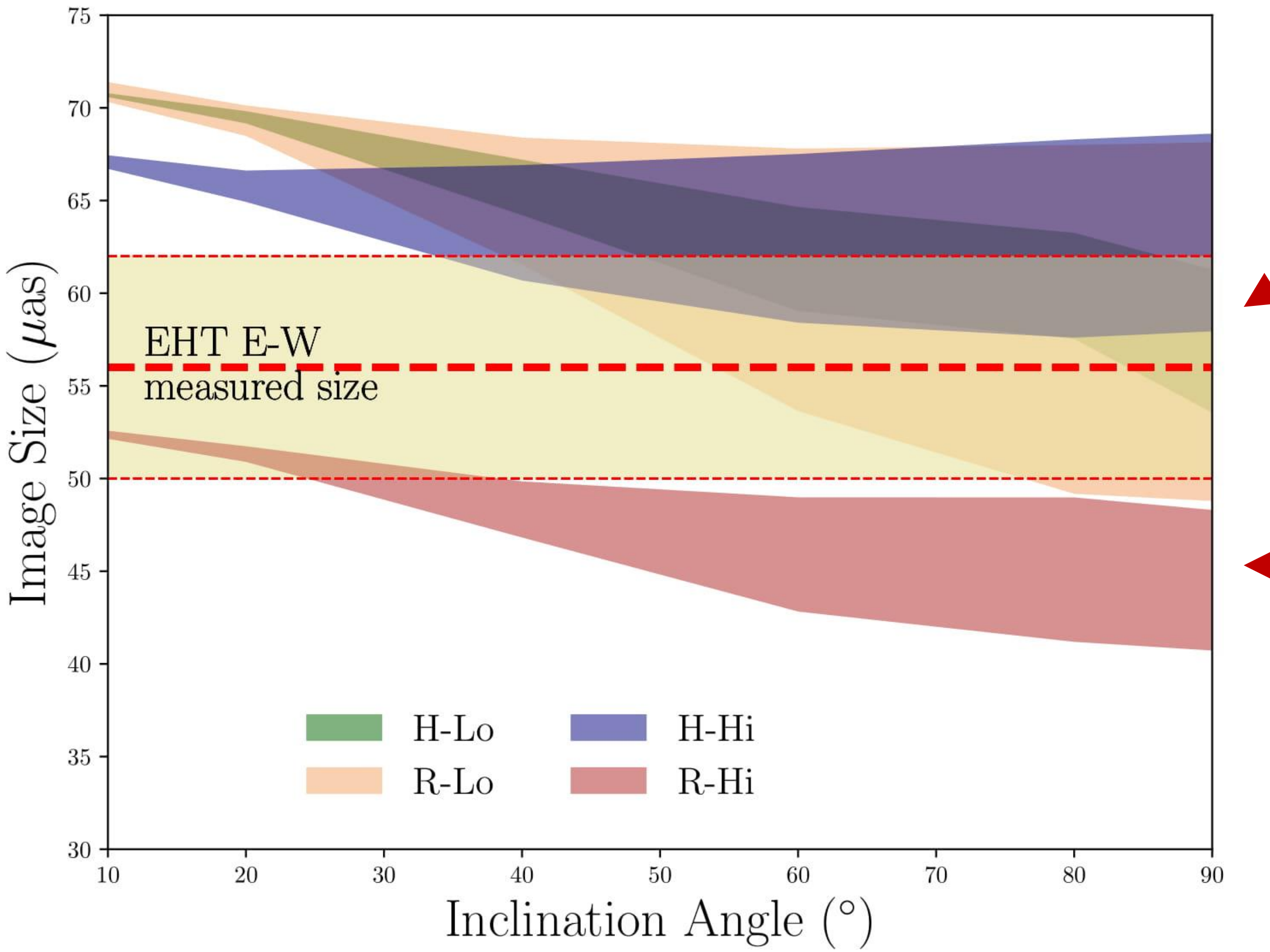
Where the EHT observes at 230 GHz, both heating prescriptions produce images with **distinct black hole shadows**

Turbulent heating makes lower frequency images anisotropic and jet dominated – **exceeding** estimates of intrinsic anisotropy when viewed at high inclination (Johnson+ 2018, Issaoun+ 2018)

43 GHz



EHT 230 GHz size



Most models are consistent with measured size over a range of inclinations

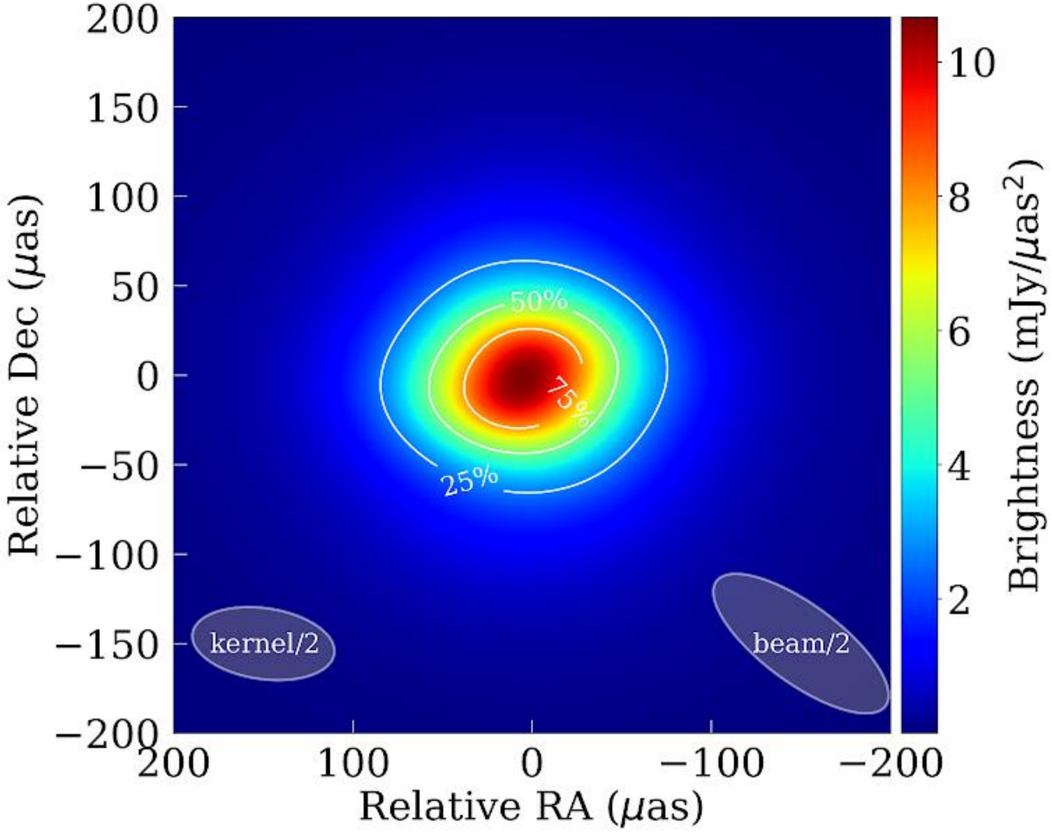
R-Hi is the most compact, so it is only consistent with the measured size near-face on

(Johnson+ 2018)

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

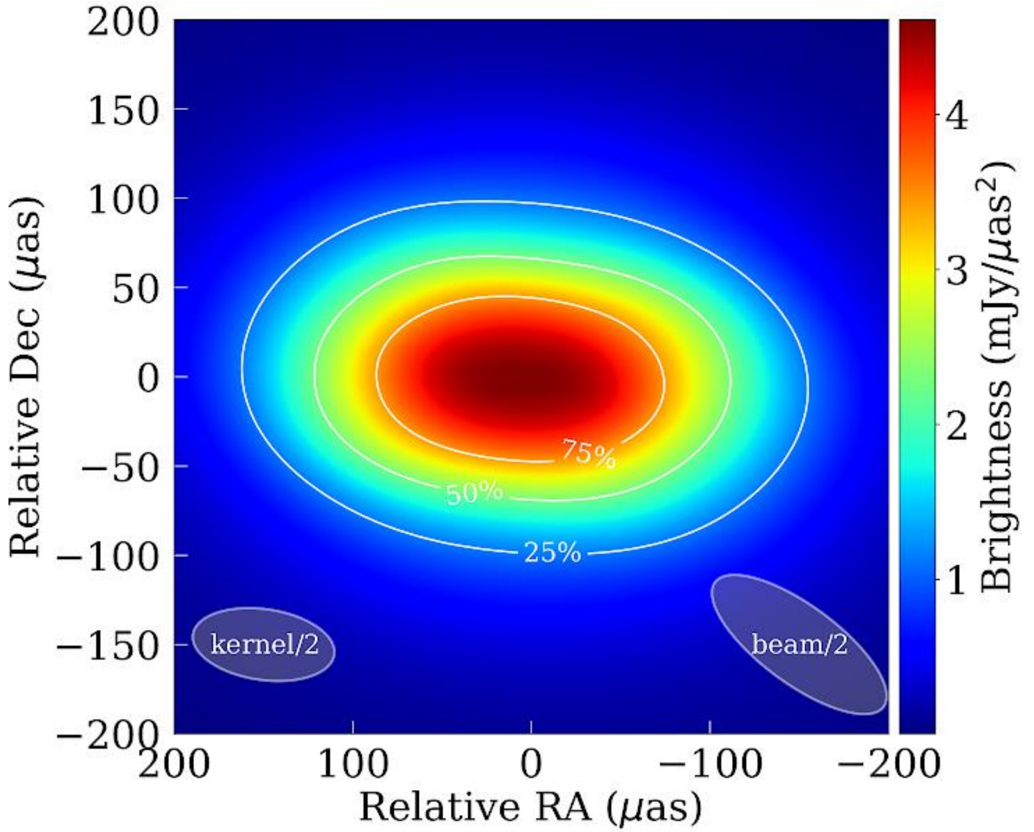
and the first VLBI with ALMA (Issaoun+ 2018)

De-scattered



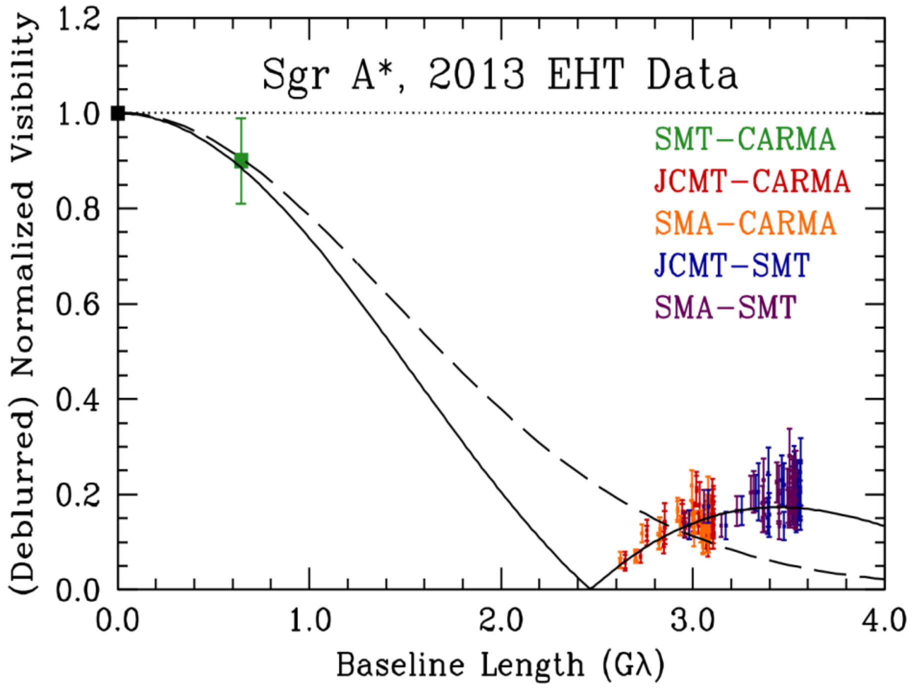
Deblurring and phase correction (Johnson+ 16)

Scattered Image

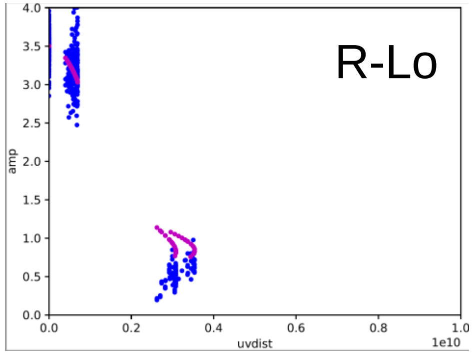


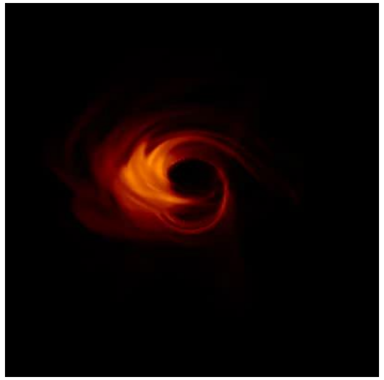
New constraints on Sgr A* asymmetry at 3.5 mm rule out edge-on jet!

Comparison with EHT 2013 visibilities.

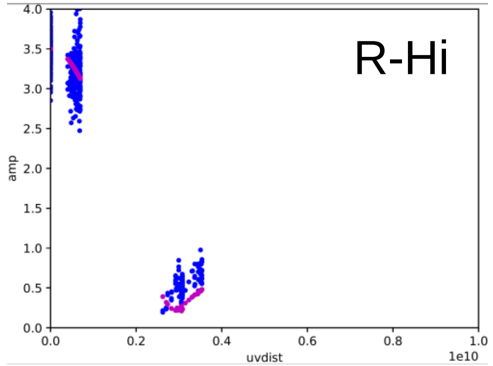


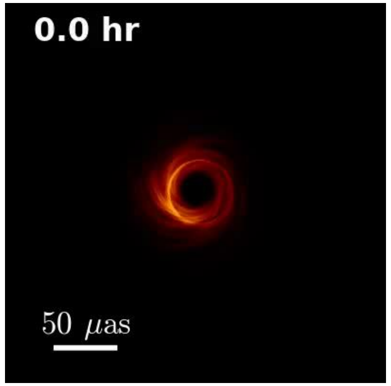
60 degree inclination – no visibility null





10 degree inclination – visibility null from symmetric ring





Johnson+ (2015) (Also Lu+ 2018)

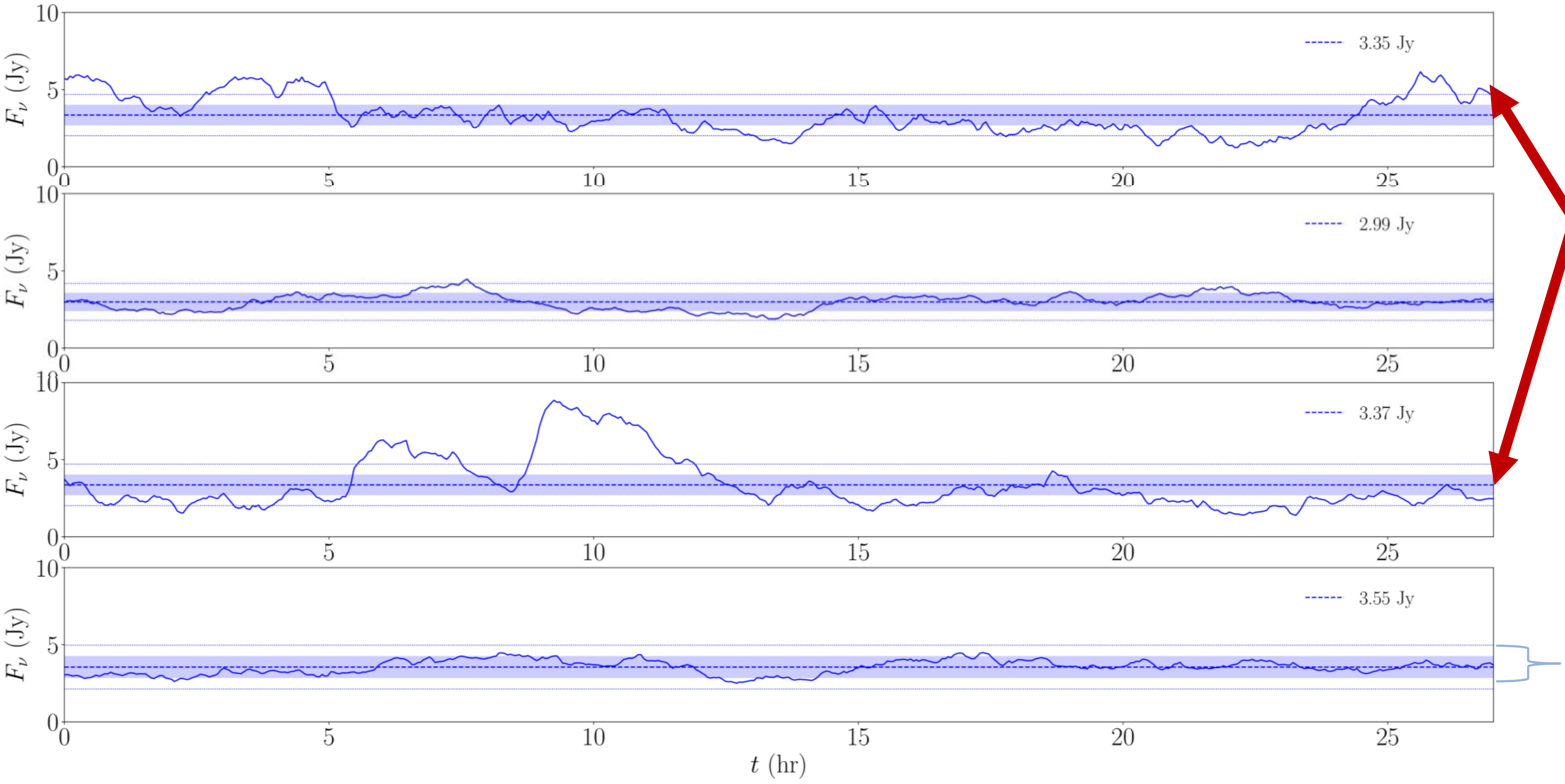
Sgr A*: 230 GHz variability

Spin 0
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Turbulent Heating

Spin 0.9375
Reconnection Heating



Turbulent Heated disks **exceed** observed variability

Rough estimate of 230 GHz intraday RMS flux variability (Bower et al. 2015)

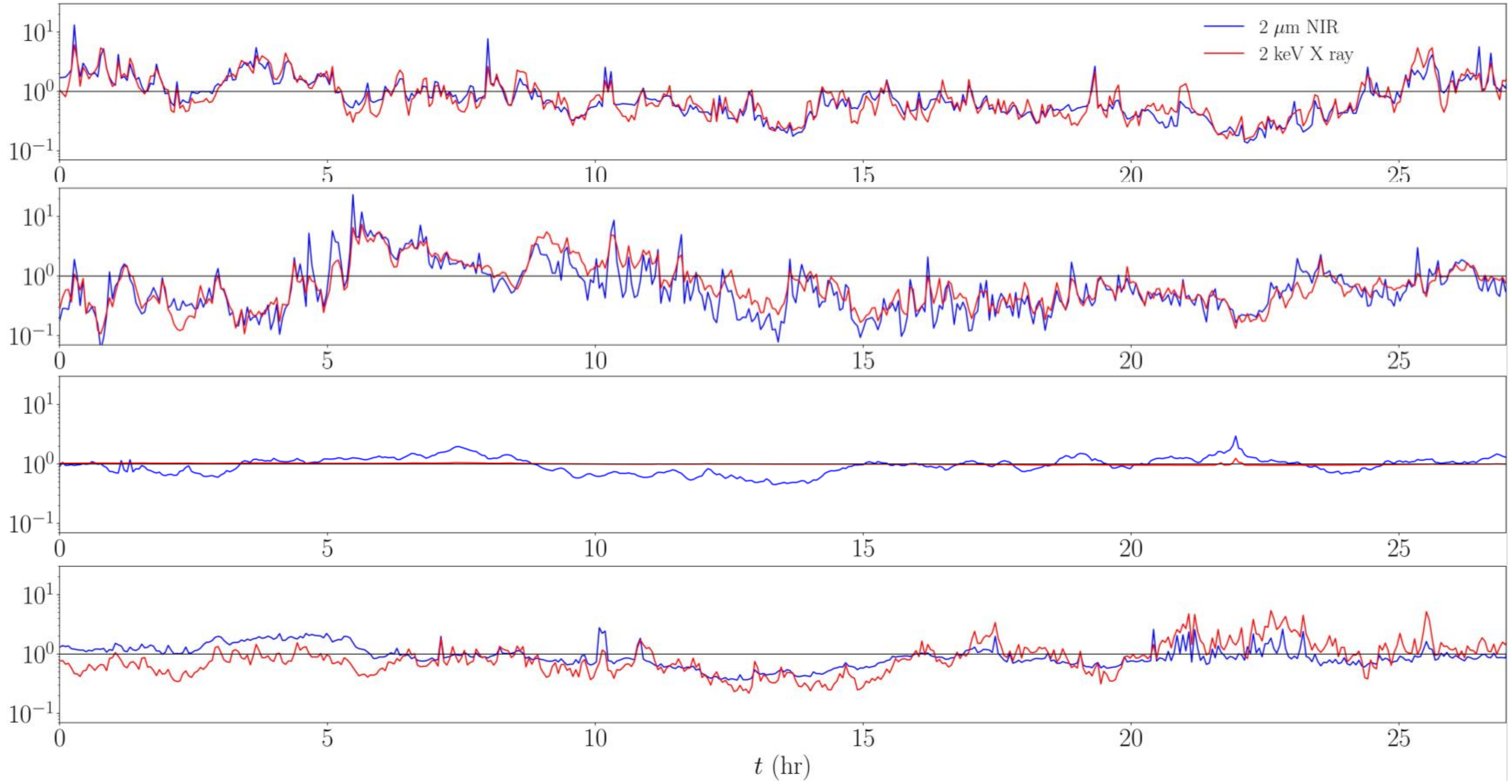
IR and X-ray variability: **no flares**

Spin 0
Turbulent Heating

Spin 0.9375
Turbulent Heating

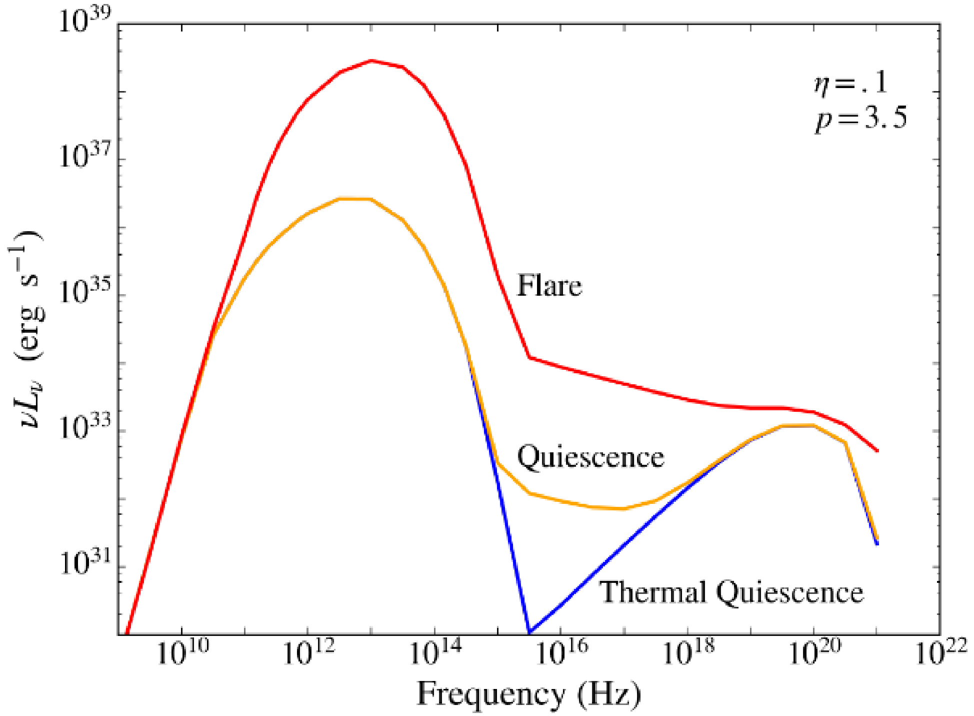
Spin 0
Reconnection Heating

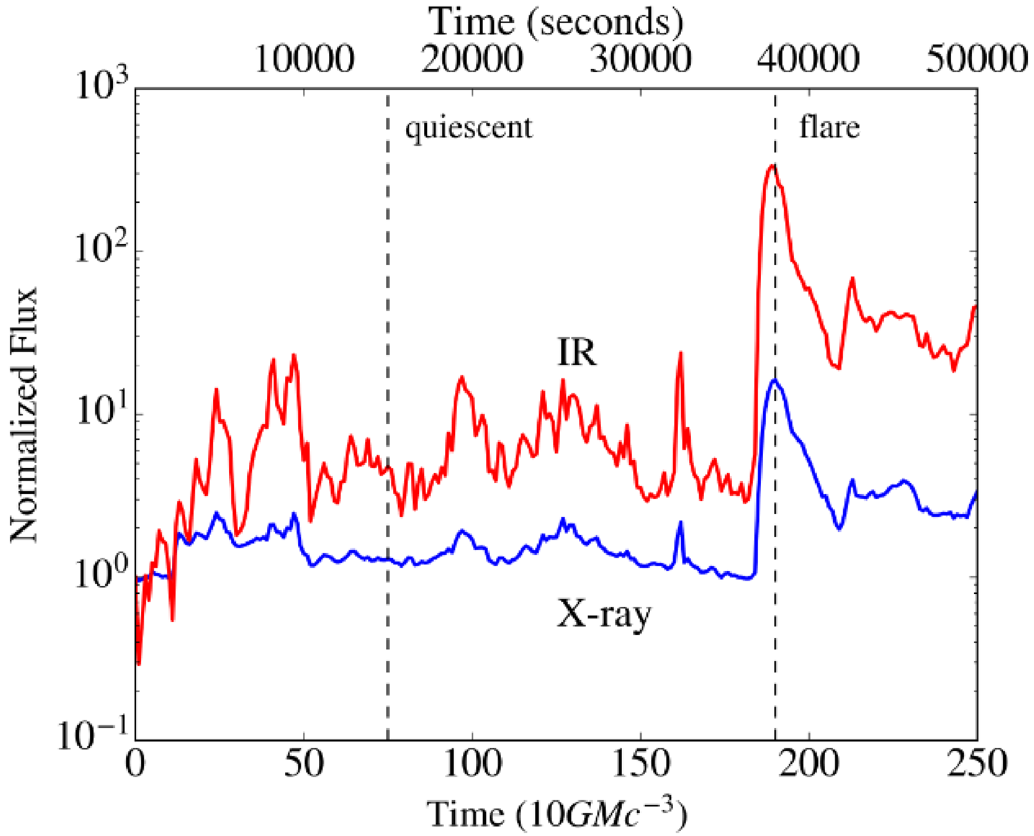
Spin 0.9375
Reconnection Heating



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

Nonthermal distributions added in postprocessing can produce correlated NIR & X-ray flares

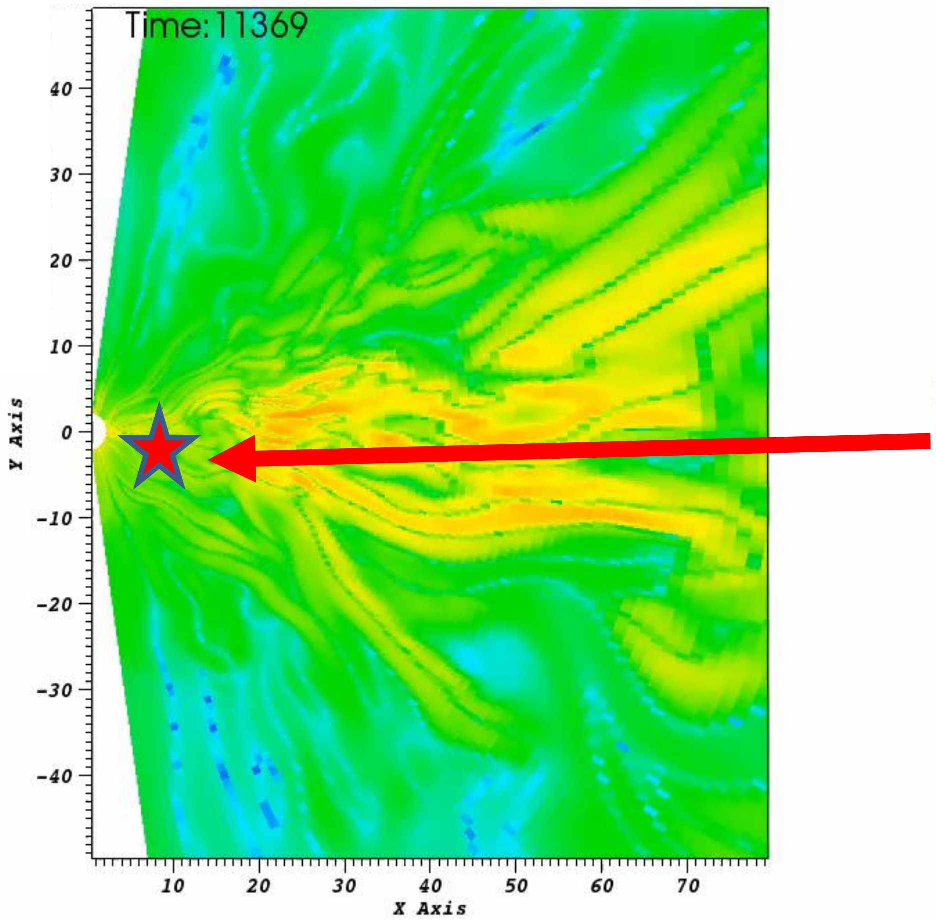




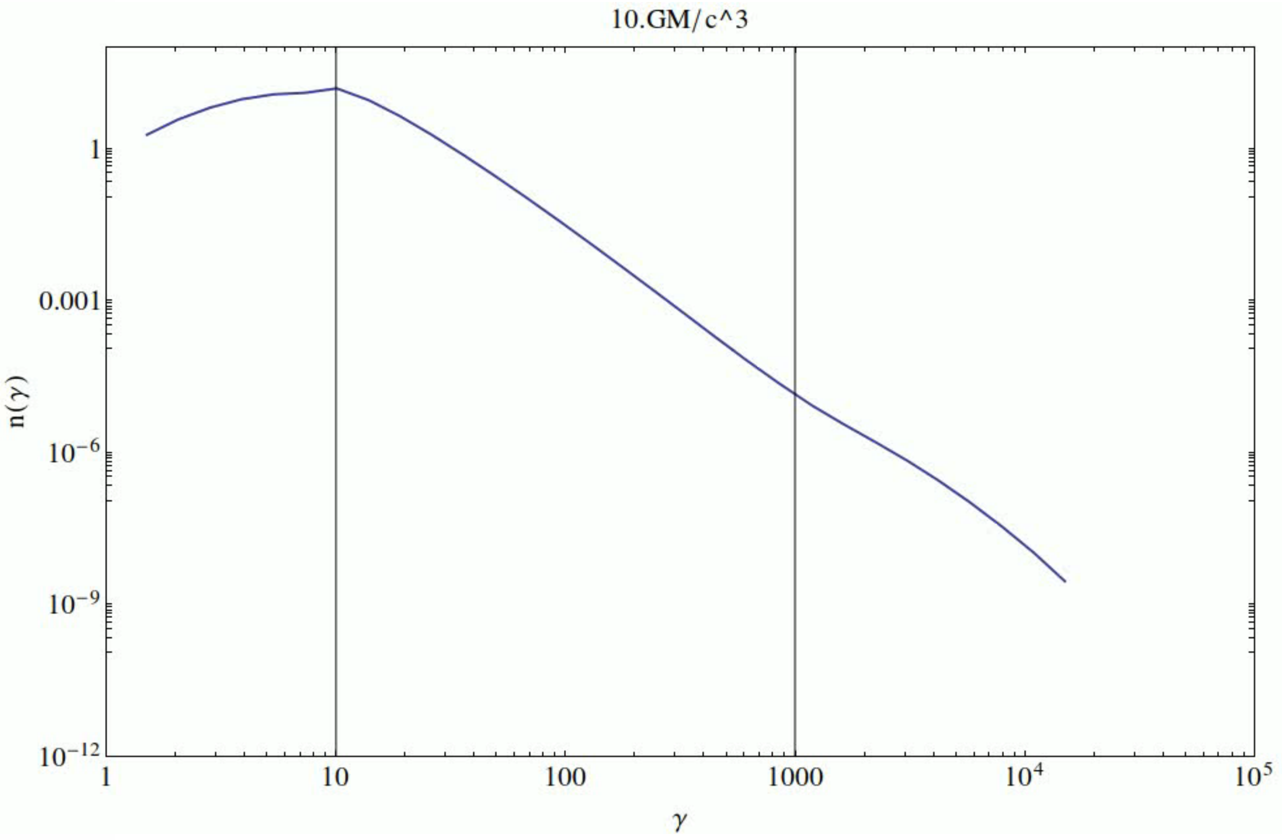
Ball+ 2016

Evolving **nonthermal** electrons in simulations
(Chael+ 2017)

Radiation Power



Nonthermal distribution @ 10 M



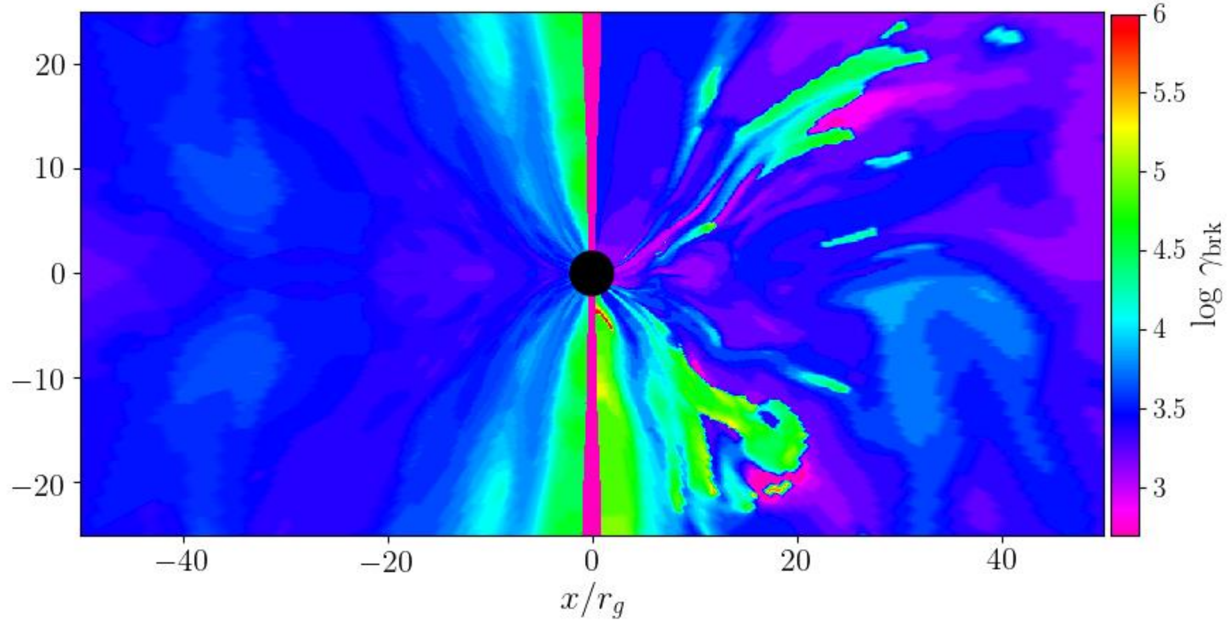
Chael+ 2017
arXiv 1704.05092

Evolving **nonthermal** electrons in simulations
(Chael+ 2017)

- New method to self-consistently evolve non-thermal spectra in parallel with two-temperature fluid.

Spatial distribution of nonthermal cooling break energy

Time-averaged



Snapshot

- First 3D simulations with realistic electron acceleration (Ball+ 2018) coming soon!
  - Ball+ 2018: Magnetic reconnection PIC simulations give $p = 2.5$ (Ponti+ 2017) at $\sigma \approx 1$
  - Jet sheath as acceleration site?

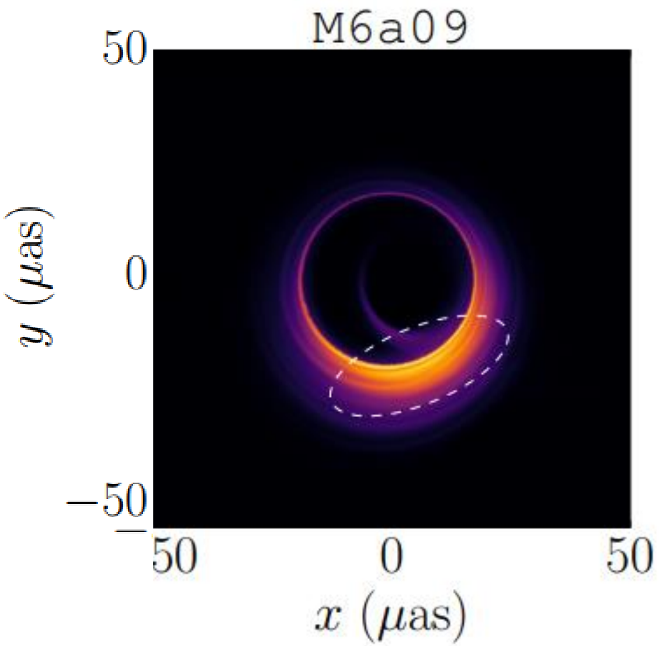
Chael+ 2017
arXiv 1704.05092

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 **relatively weak**, jet angle is **narrow.**



Ryan+ 2018, also Dexter+ 2012, Moscibrodzka+ 2016, 2017

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" (bracket under the $\langle \Phi_{\rm BH}/(\dot{M}c)^{1/2} r_{\rm g} \rangle$ column)

Jet **mechanical** power (bracket under the $\langle P_{J(100)} \rangle$ column)

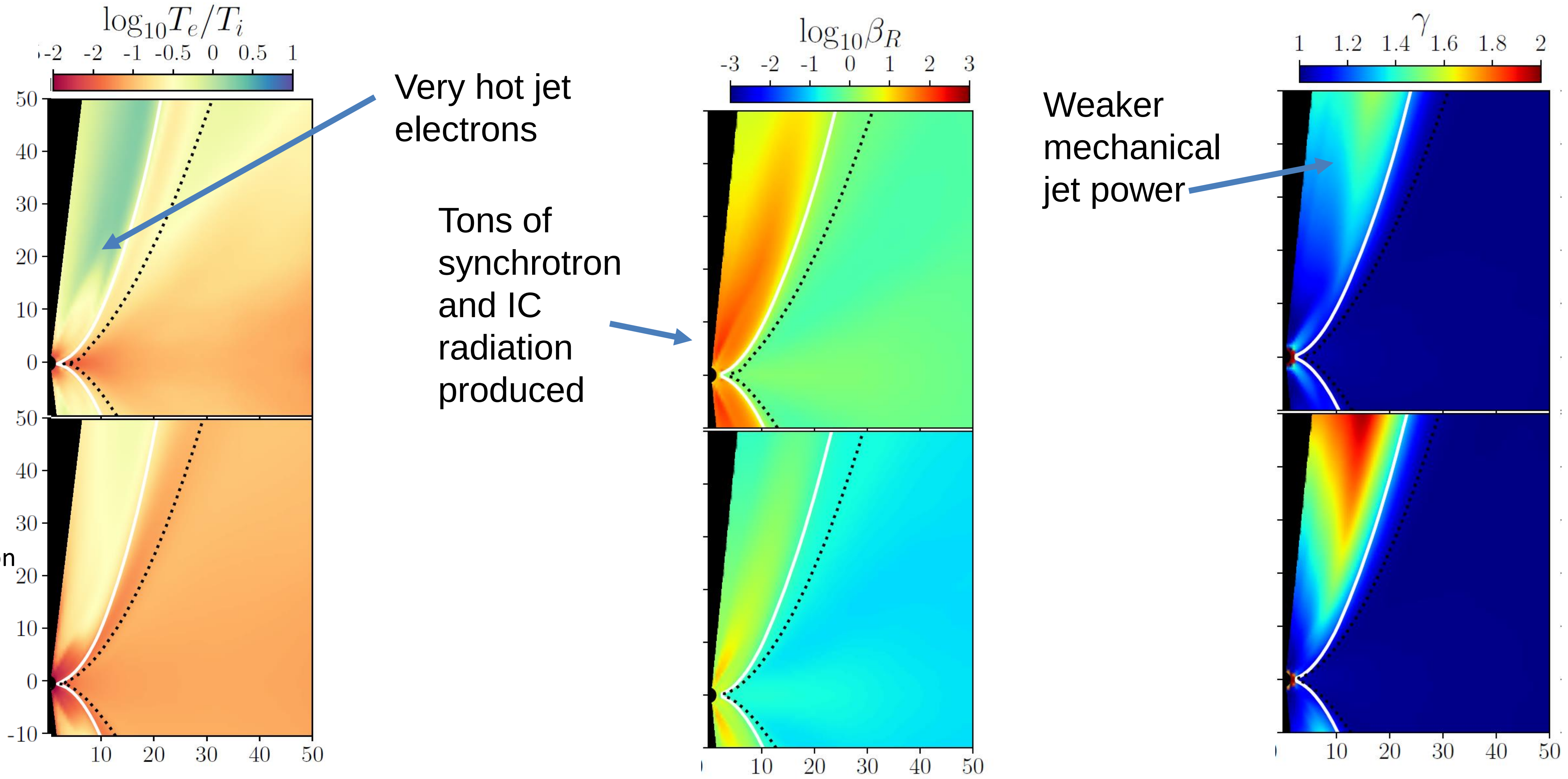
- Both simulations are MAD.
- Density is scaled to match 0.98 Jy at 230 GHz.
- The mechanical jet power in R17 is in the measured range of 10^{43}–10^{44} erg/s.

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

Electron Heating → Jet Dynamics

Turbulent Heating

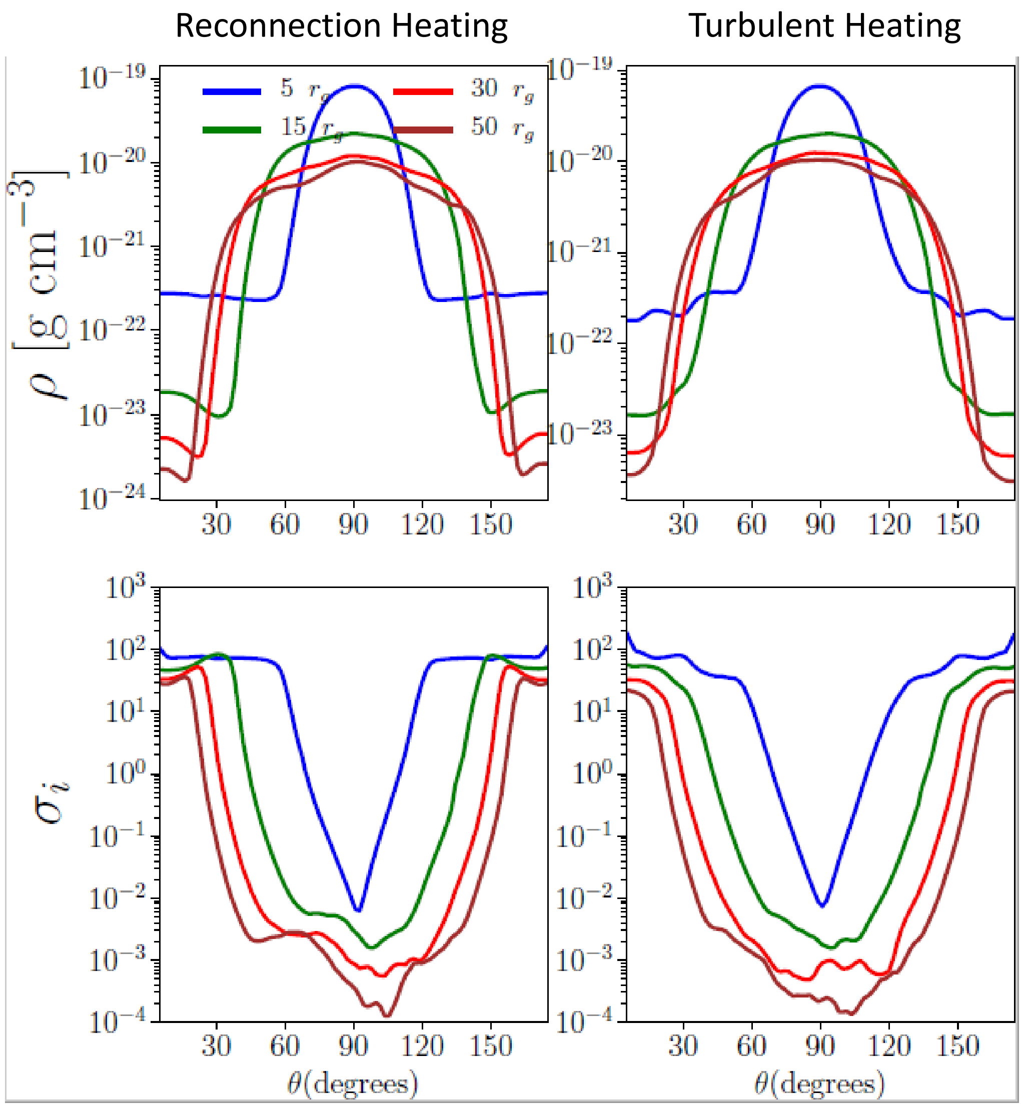
Reconnection Heating



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

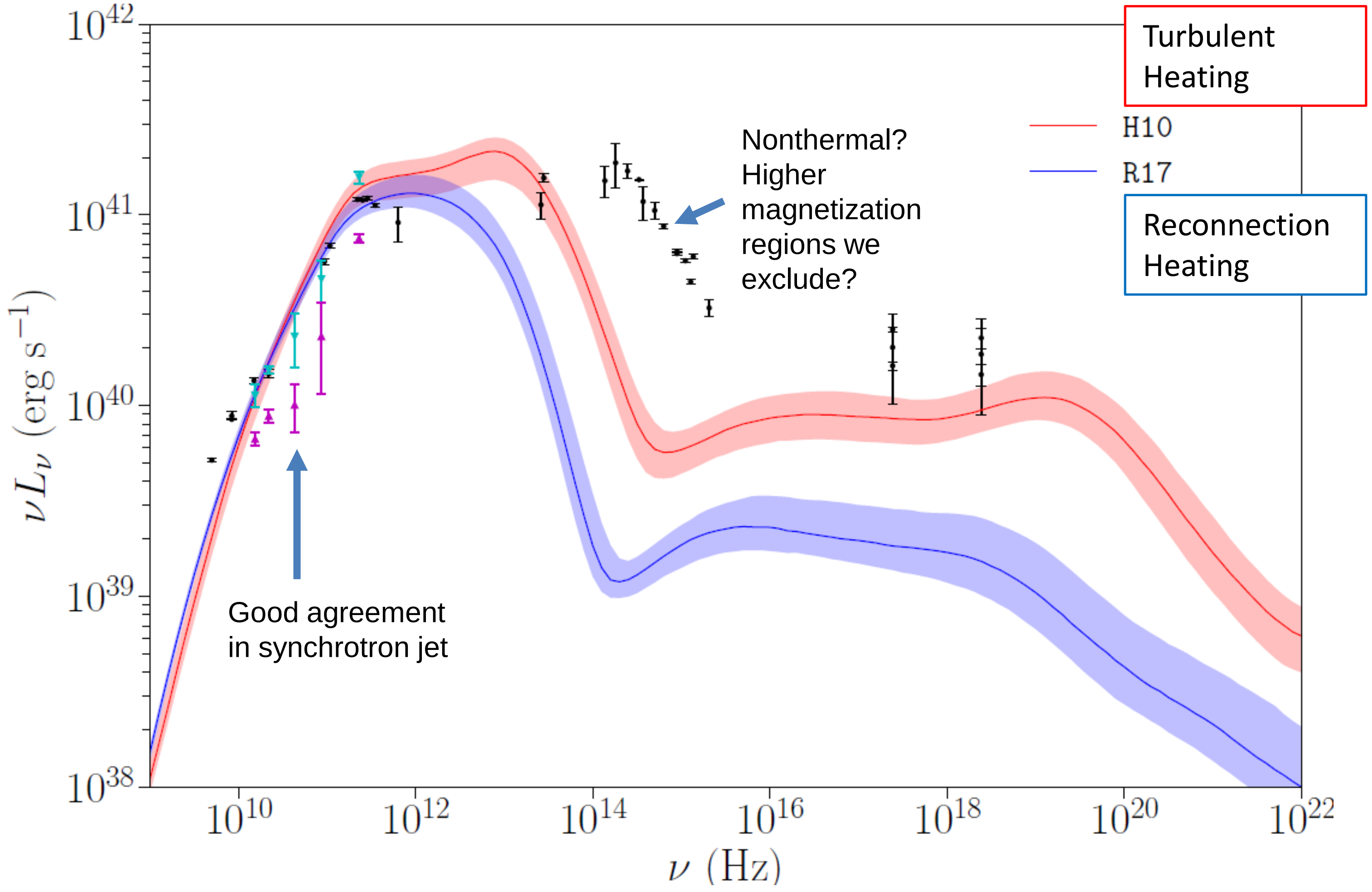
Electron Heating + Radiation → Dynamics!

Density floors: σ_{i} cut in radiative transfer



- Density floors are imposed in the simulation inner jet where $\sigma_{\mathrm{i}} \geq 100$
- We don't trust radiation from these regions, so when raytracing we only include regions where $\sigma_{\mathrm{i}} \leq 25$
- Spectra and images at frequencies $\geq$ 230 GHz depend strongly on the choice of cut!

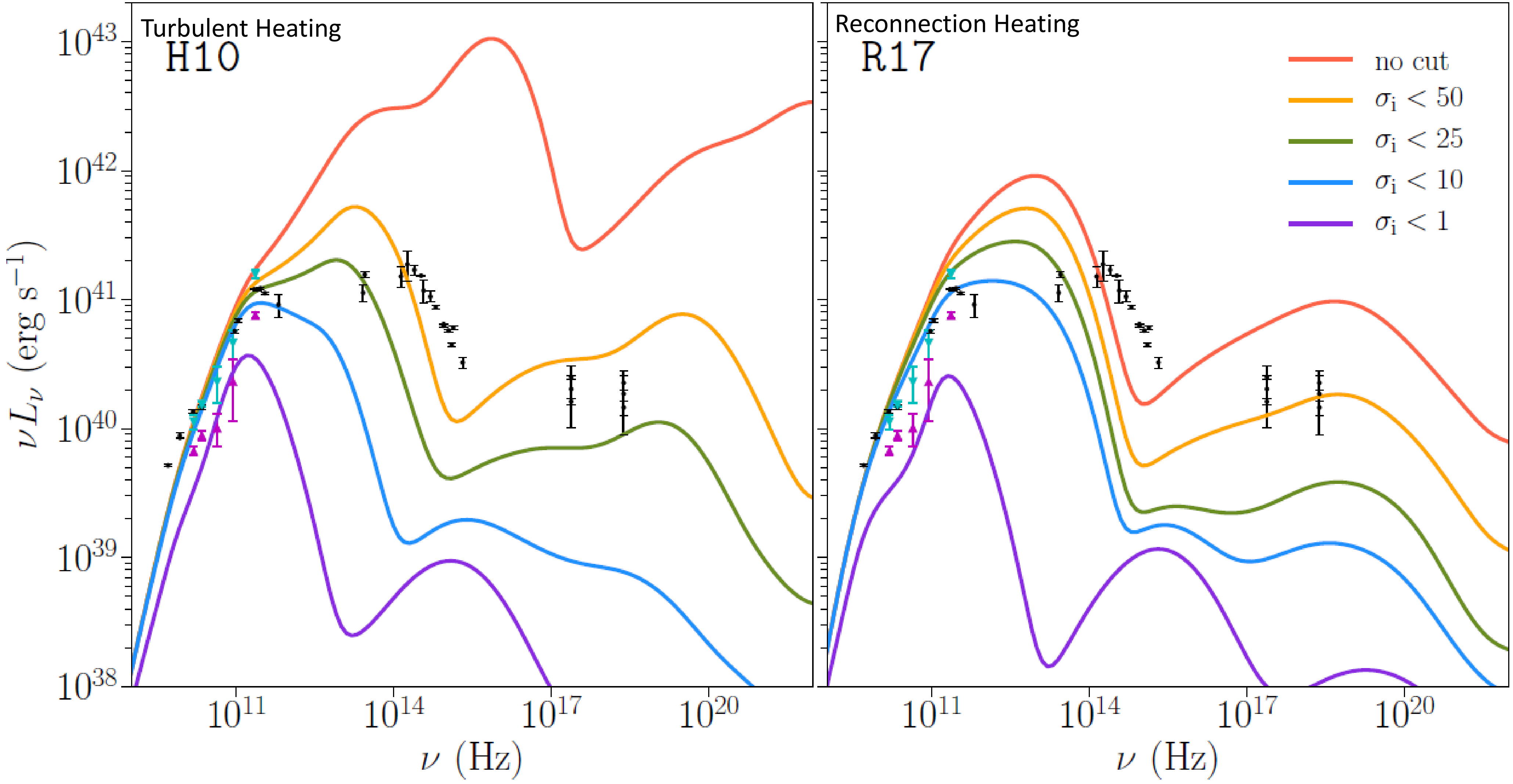
M87 Spectrum



Data from Prieto+16

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

M87 Spectra: dependence on σ_i cut

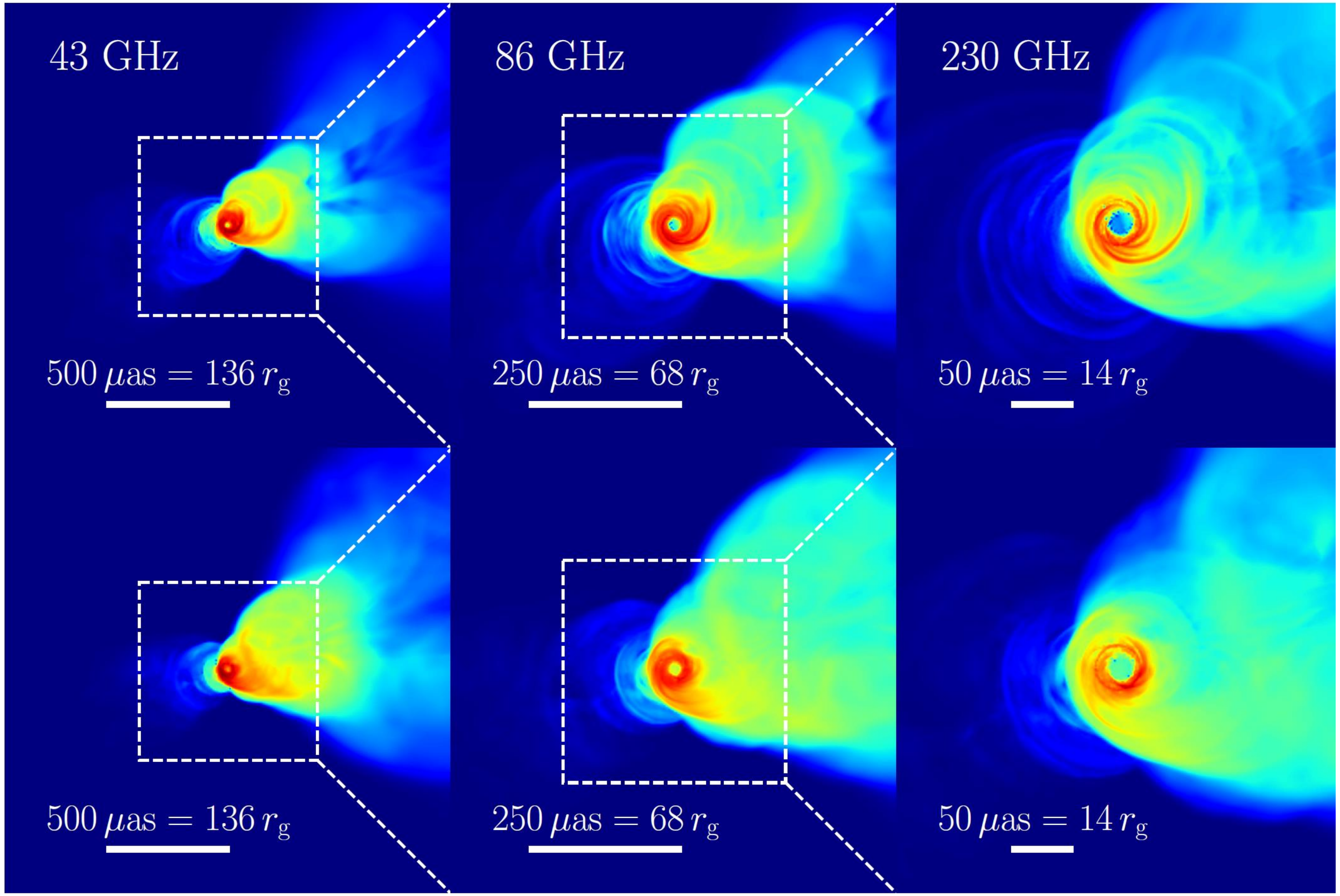


Data from Prieto+16
New points (cyan and magenta) from Akiyama+15, Doeleman+12, Walker+18, Kim+18, and MOJAVE

M87 Jets at millimeter wavelengths

Turbulent Heating

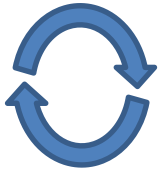
Reconnection Heating



Inclination angle (down from pole)

$17°$

Disk/Jet rotation sense



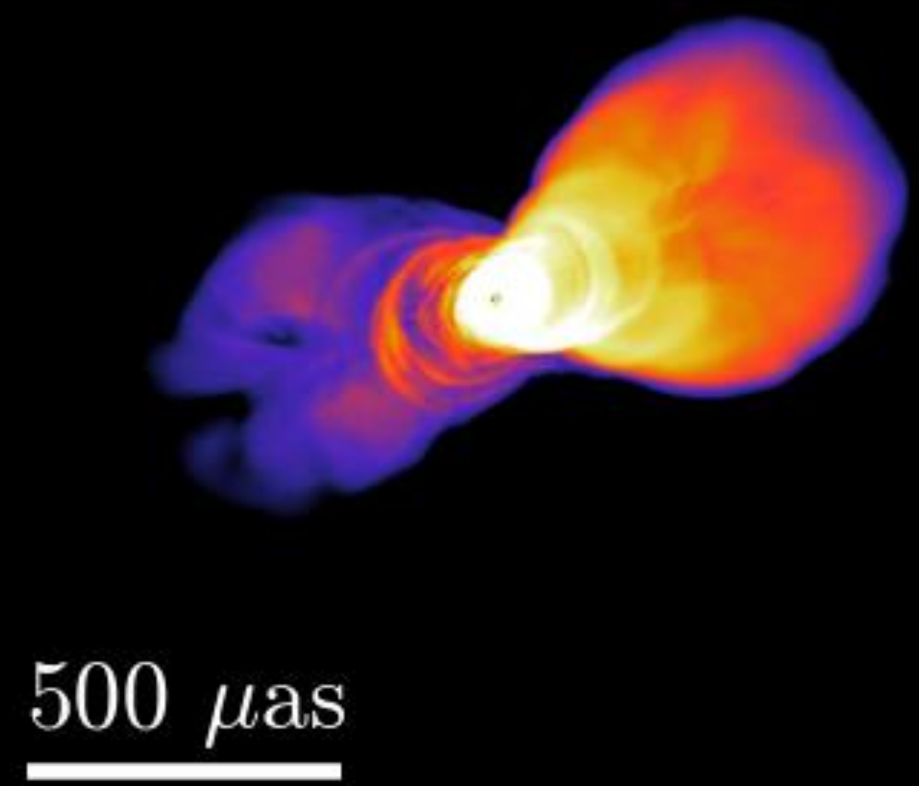
(Values from Walker+ 18)

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

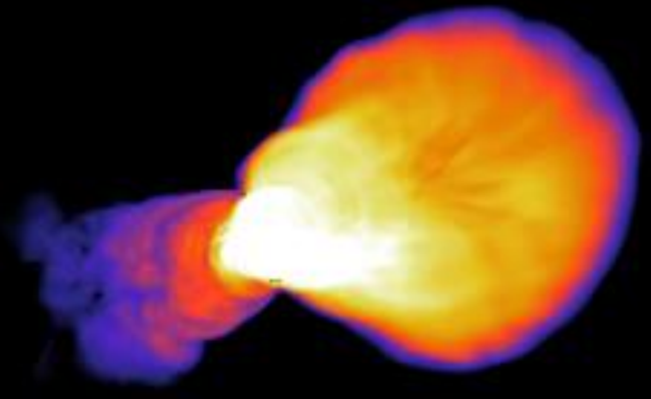
43 GHz jets

0.0 yr

Turbulent Heating

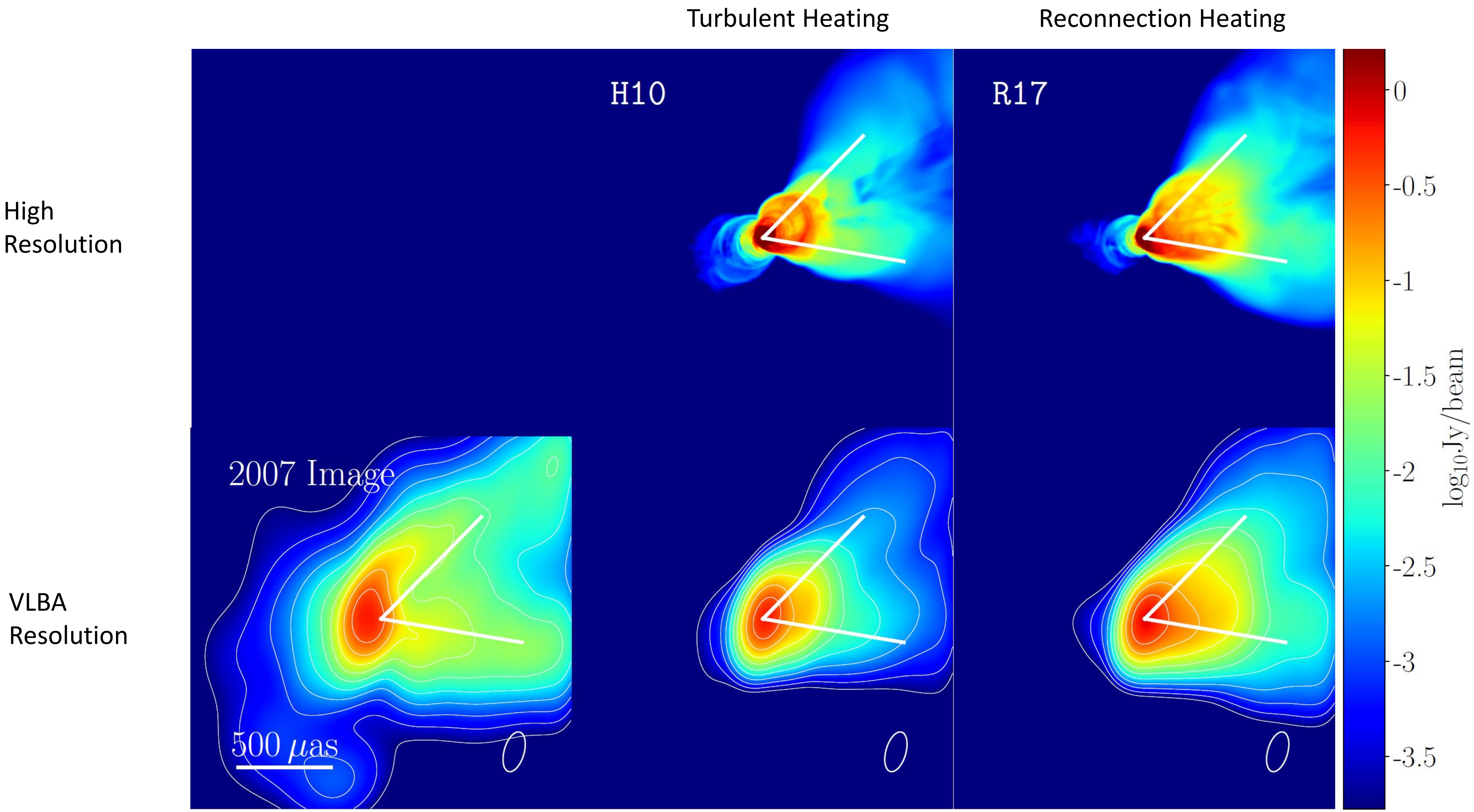


Reconnection Heating



43 GHz images – comparison with VLBA

Walker+ 2018



Apparent opening angle at 43 GHz:

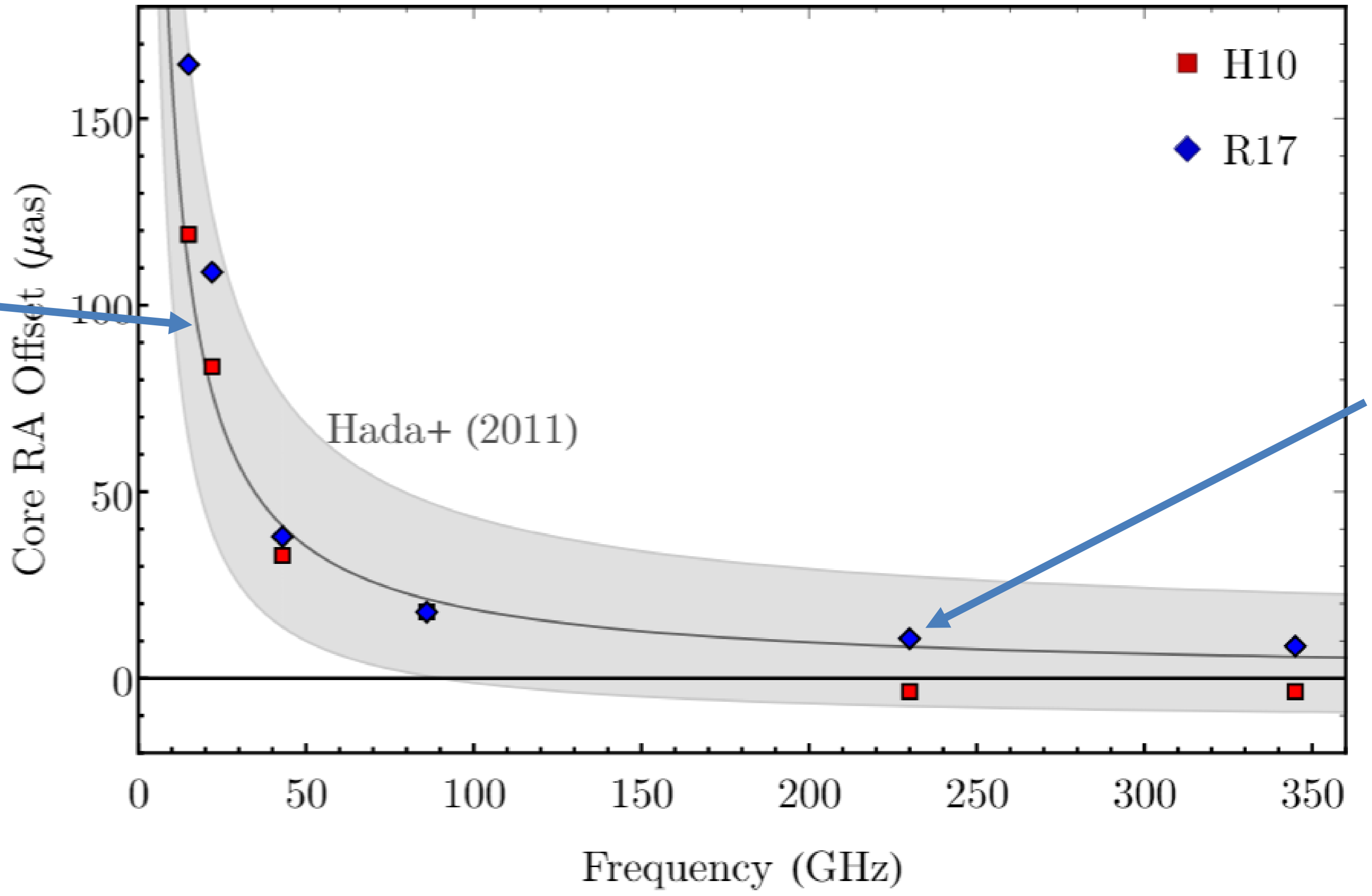
$55°$

(Walker+ 2018)

Walker+ 2018, Kim+ 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

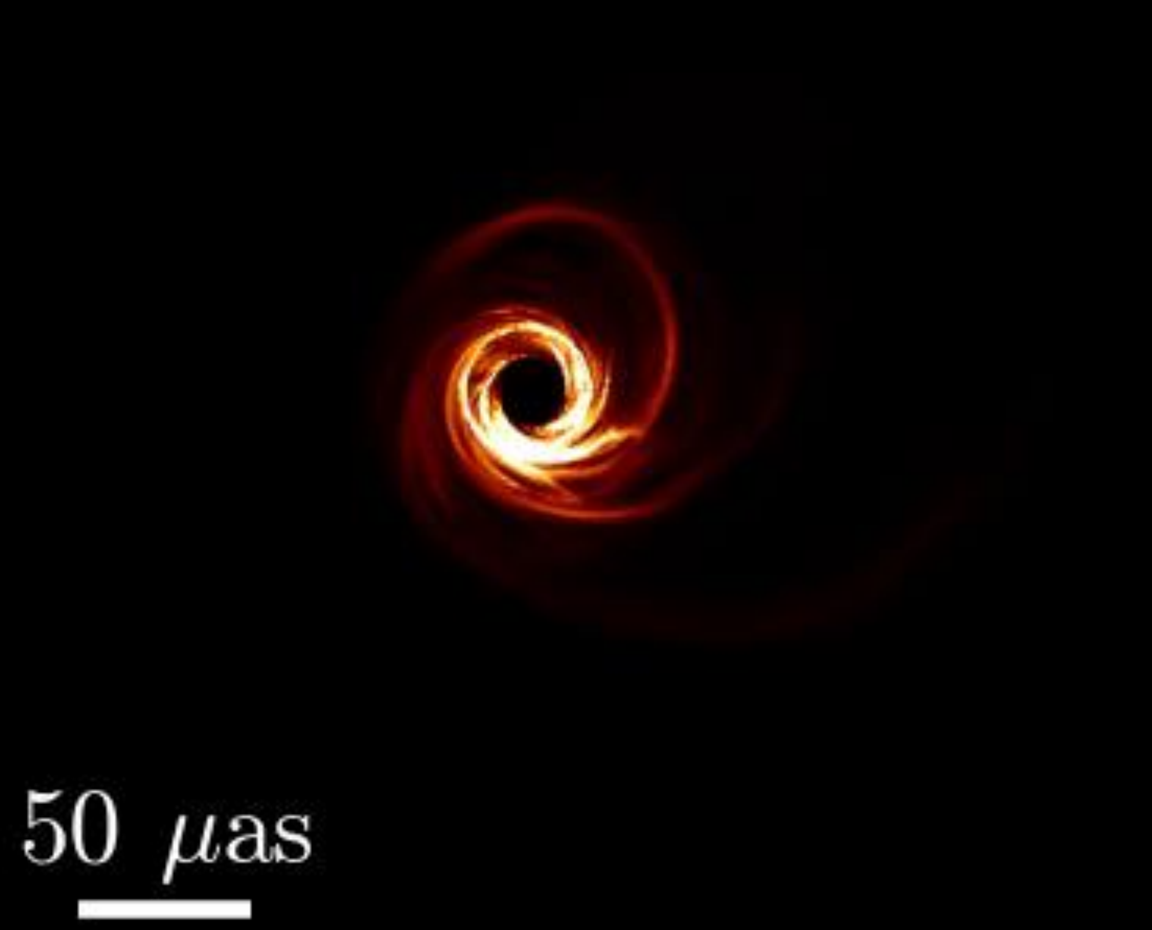
Agreement with measured core shift down to cm wavelengths.

Hada+ 2011

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

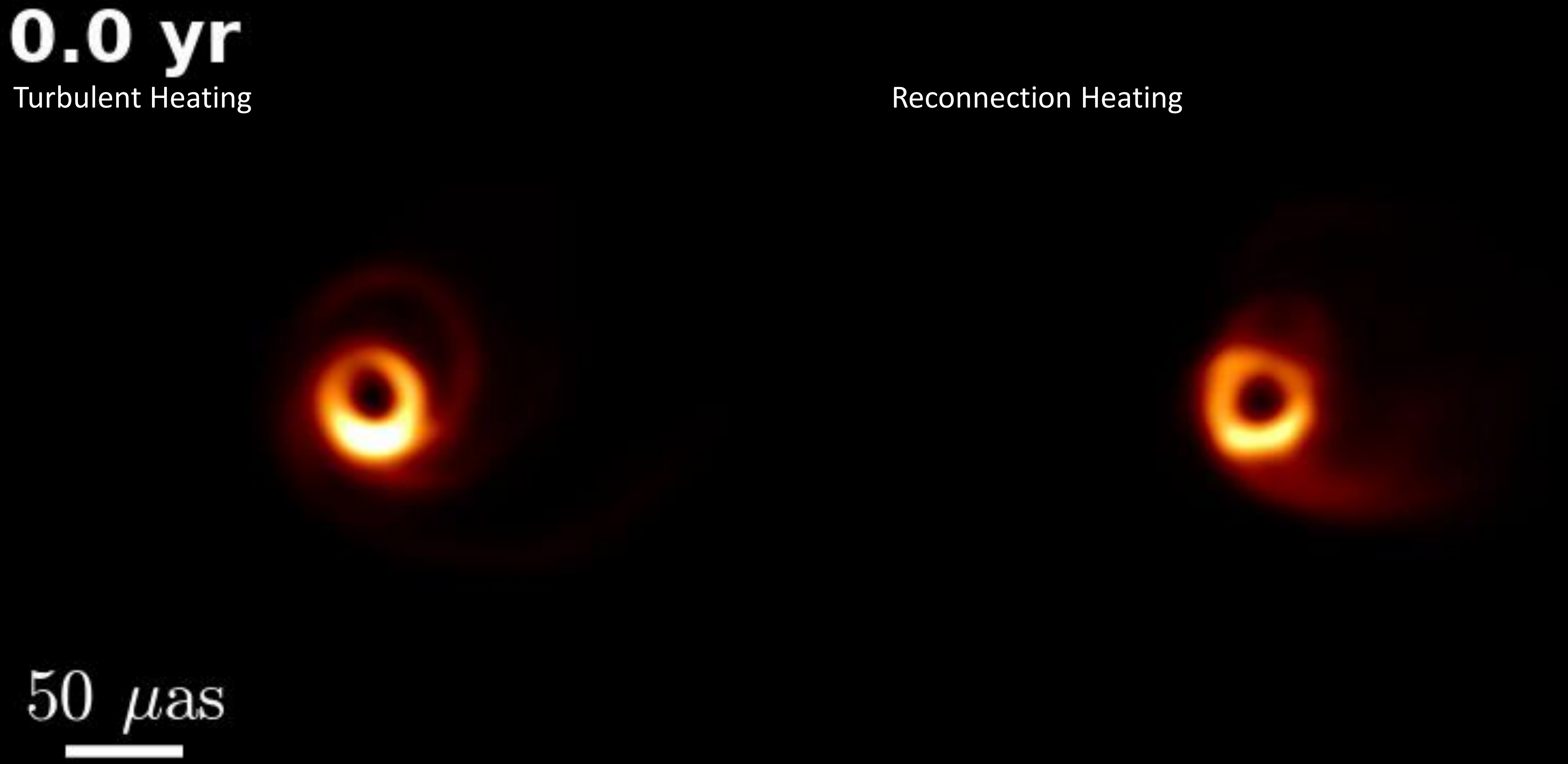
0.0 yr

Turbulent Heating

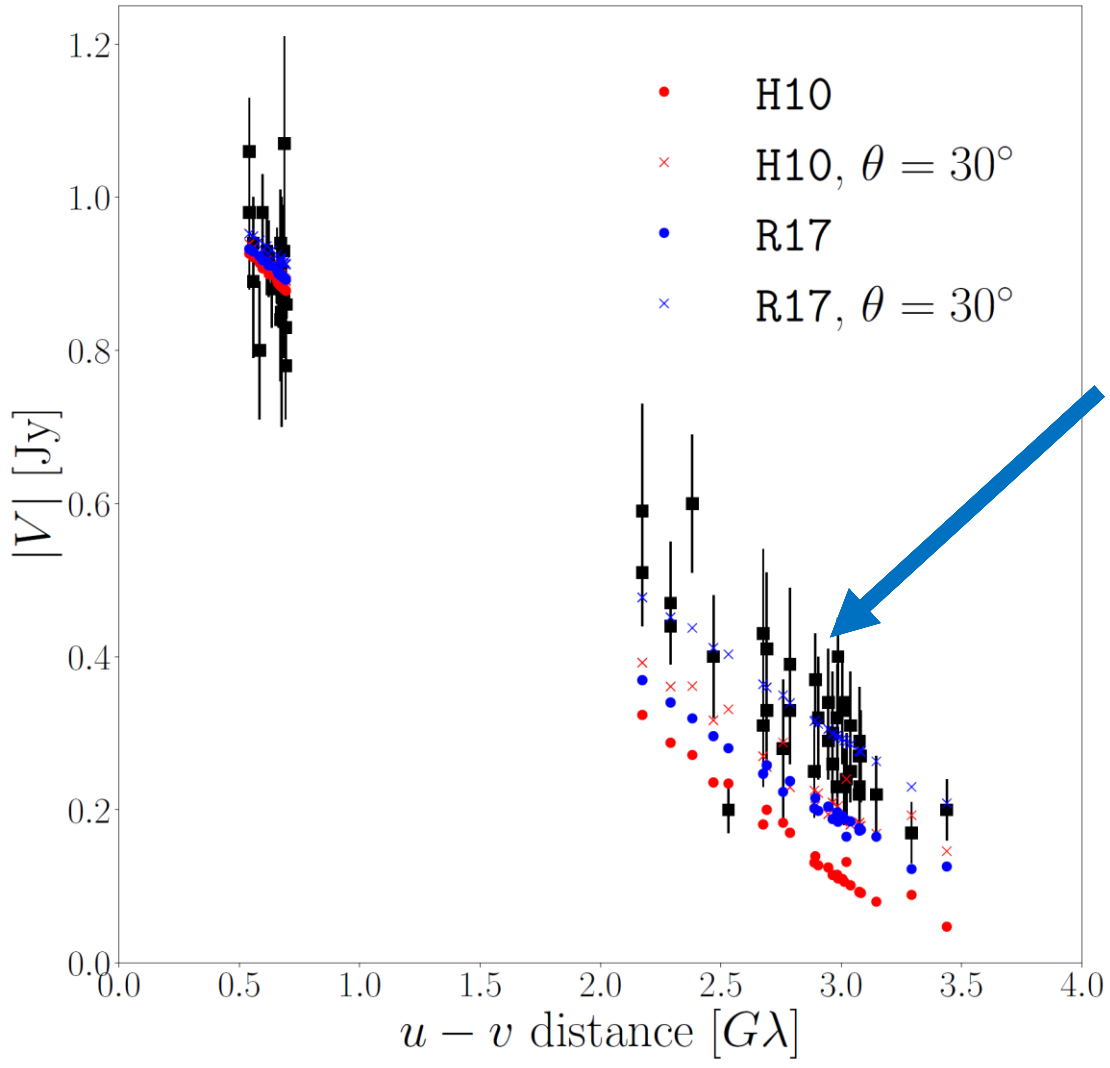


Reconnection Heating

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



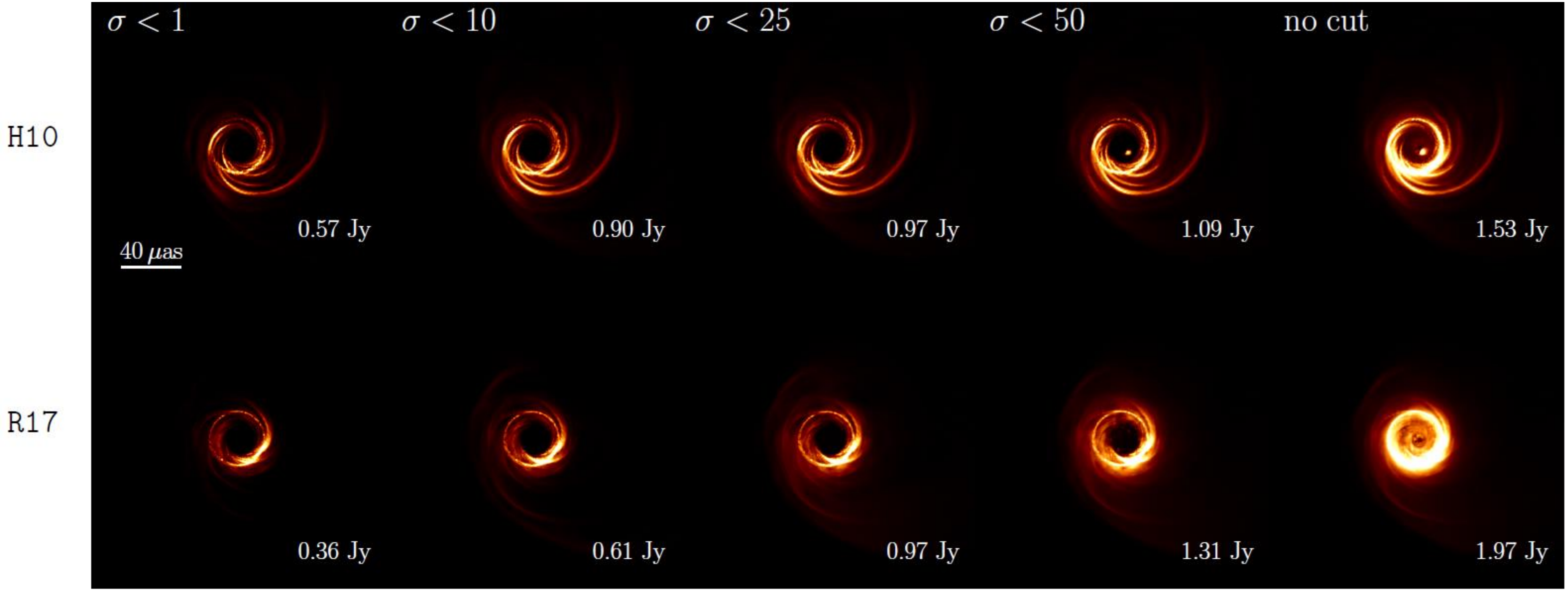
Current 230 GHz images are too big!



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.

230 GHz images – dependence on σ_i cut



The image becomes more compact & counterjet dominated when we include more high-magnetization emission from the jet base!

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 soon!

First EHT images on the way!

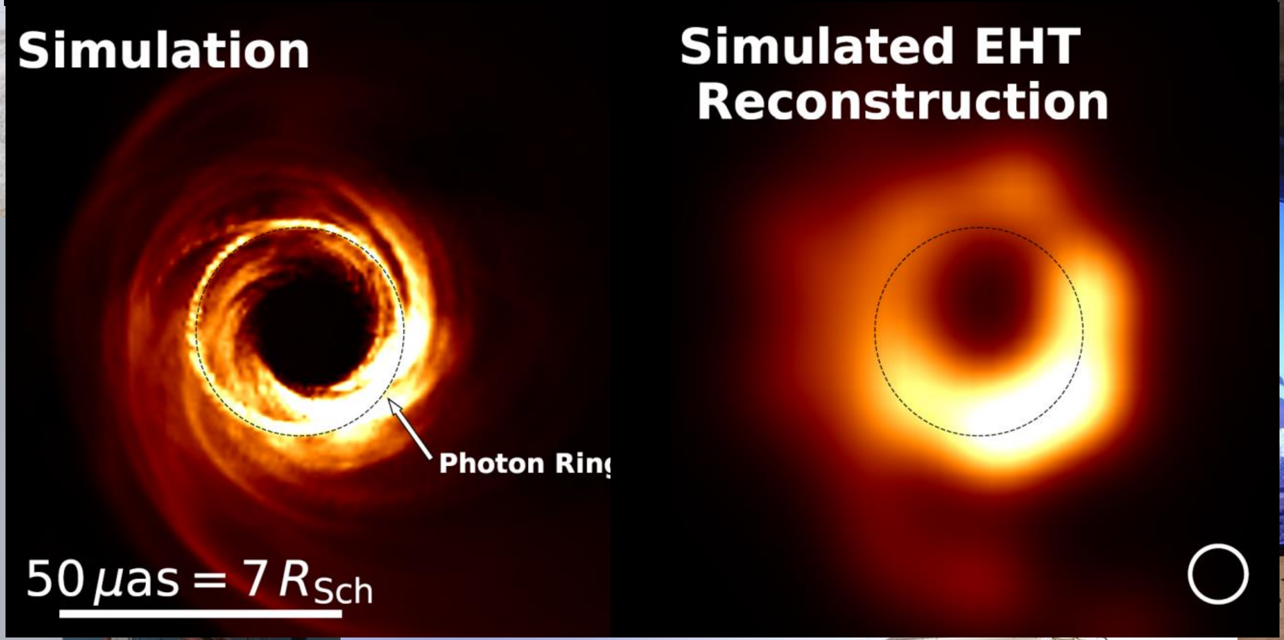


Image credits: Dan Marrone,
David Michalik,Atish Kamble, Junhan Kim , Salvaor Sanchez,
Helge Rottman , Katie Bouman, MIT Haystack Observatory

Thank You!