What will the Event Horizon Telescope see?

Electron heating in simulations of Sgr A and M87*

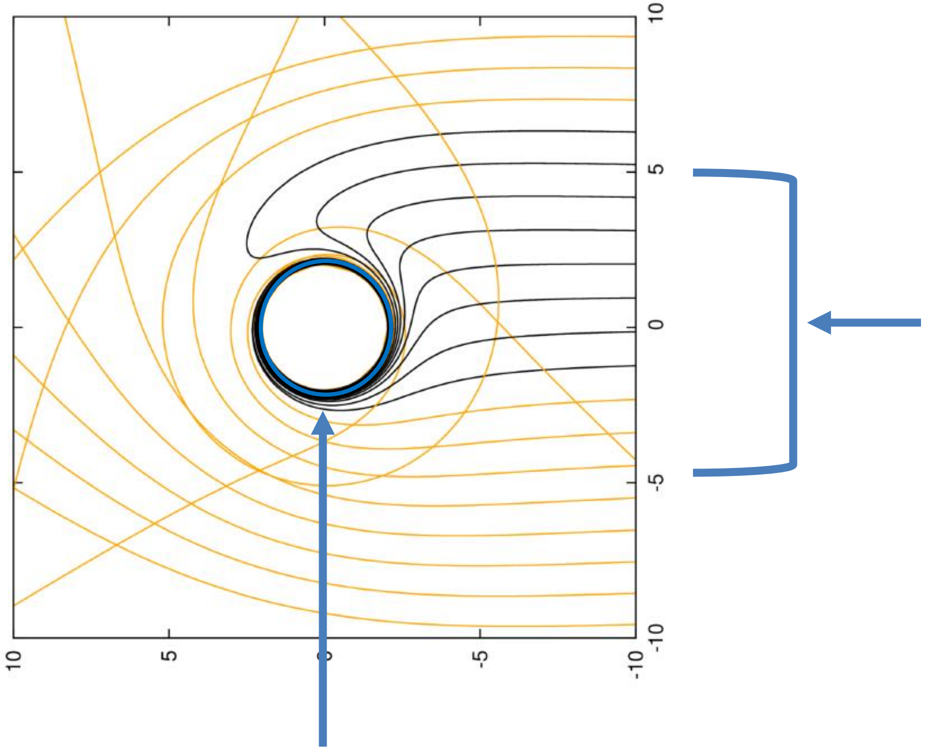
Andrew Chael

Columbia, November 29, 2018

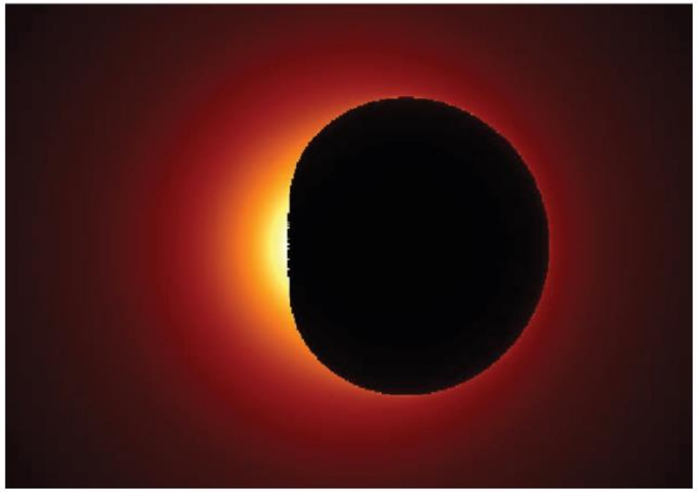
Event Horizon Telescope

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

What does a black hole look like?



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



Bardeen 1973

phot

> “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

What does a black hole look like?

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

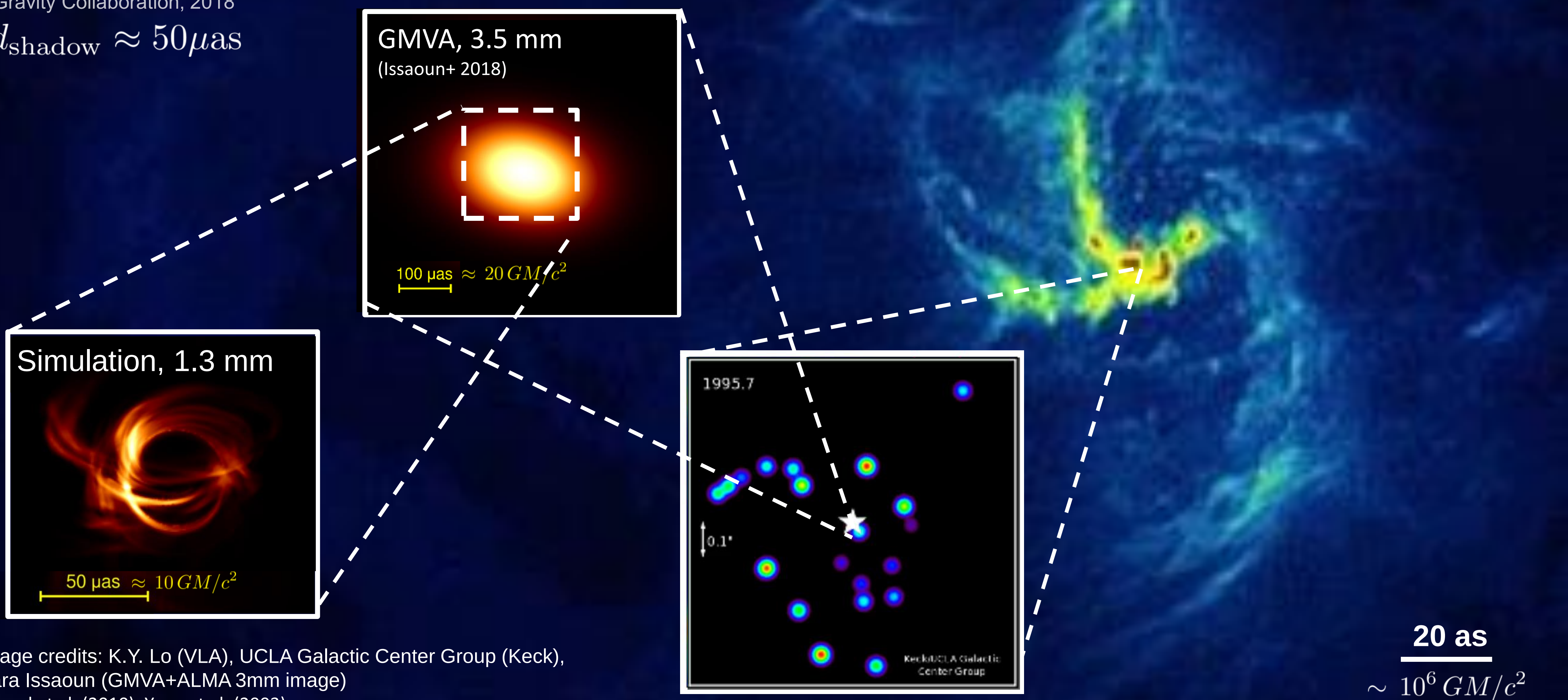
Luminet, 1979

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

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



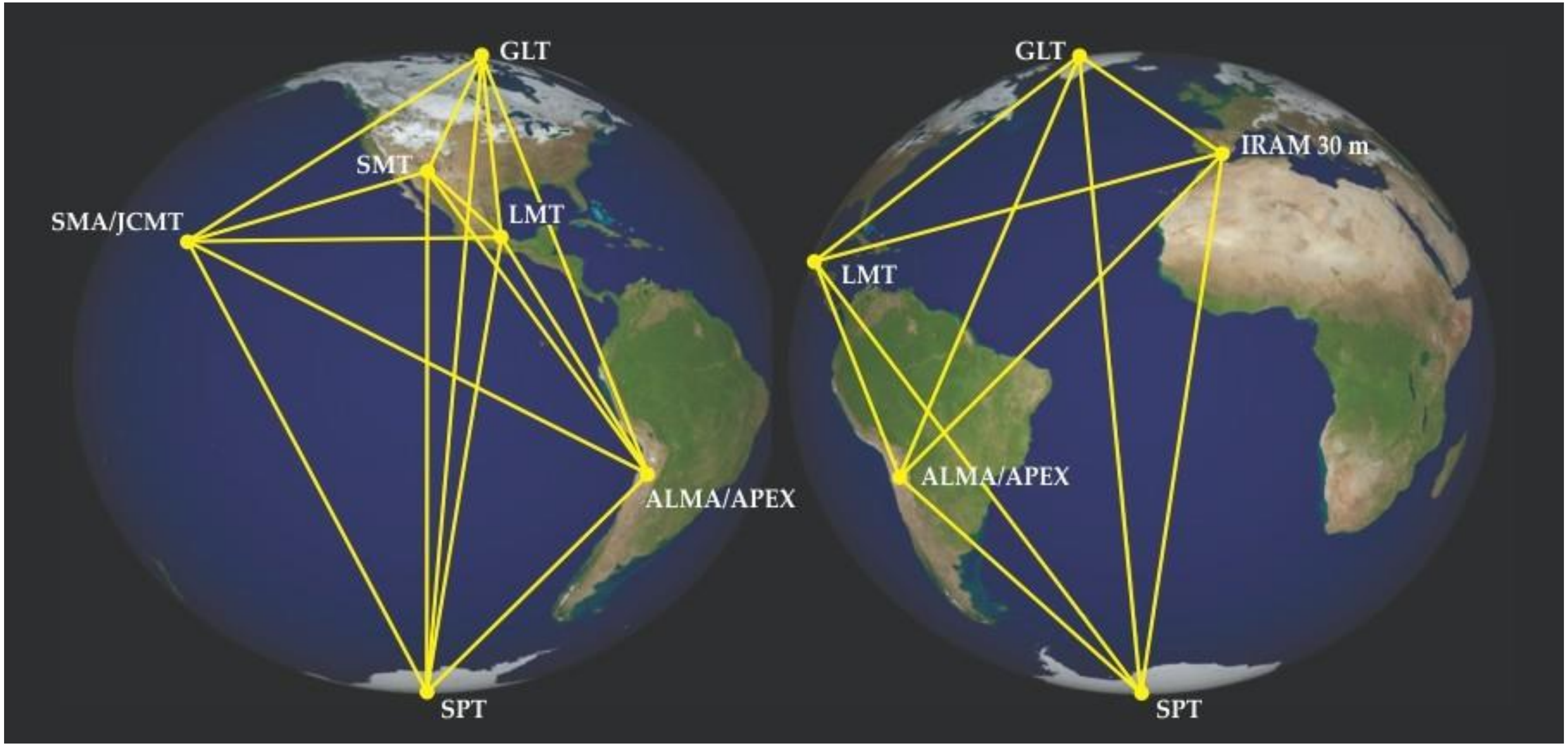
VLA, 6 cm

GMVA, 3.5 mm
(Issaoun+ 2018)

Simulation, 1.3 mm

Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Sara Issaoun (GMVA+ALMA 3mm image)
Genzel et al. (2010), Yuan et al. (2003).

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: Lindy Blackburn

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

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 function?

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

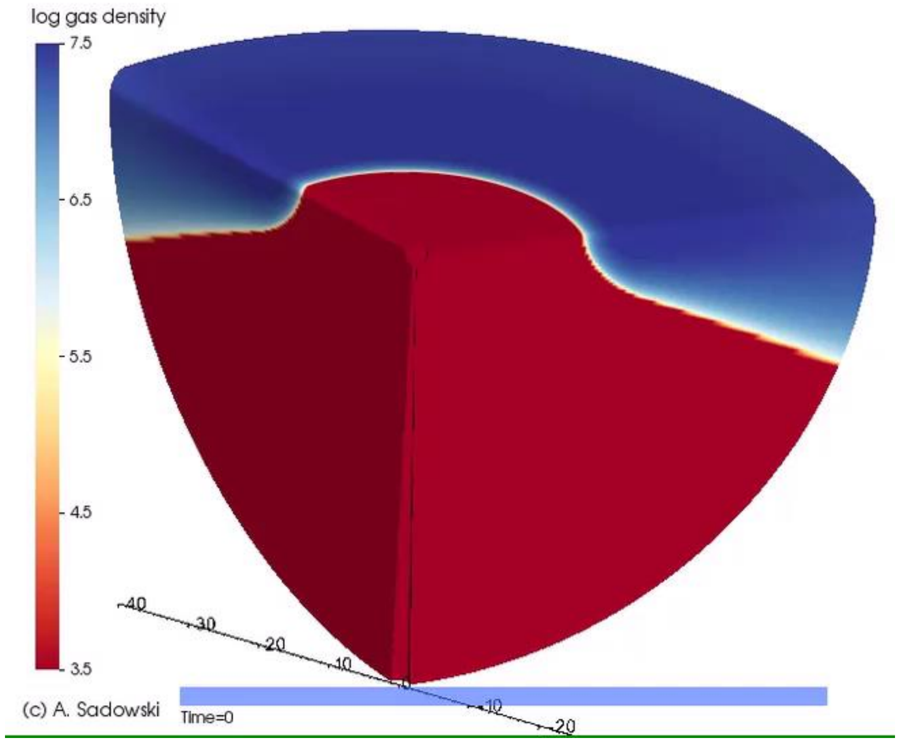
- Low densities in hot flows
  → inefficient Coulomb coupling between ions and electrons.

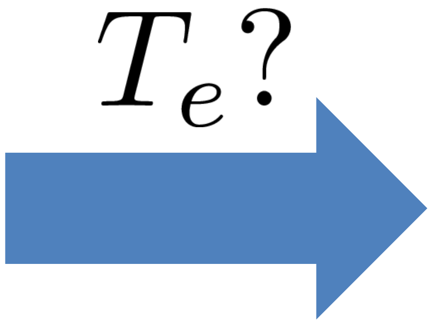
- Generally expect electrons to be **cooler** than ions.

- 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

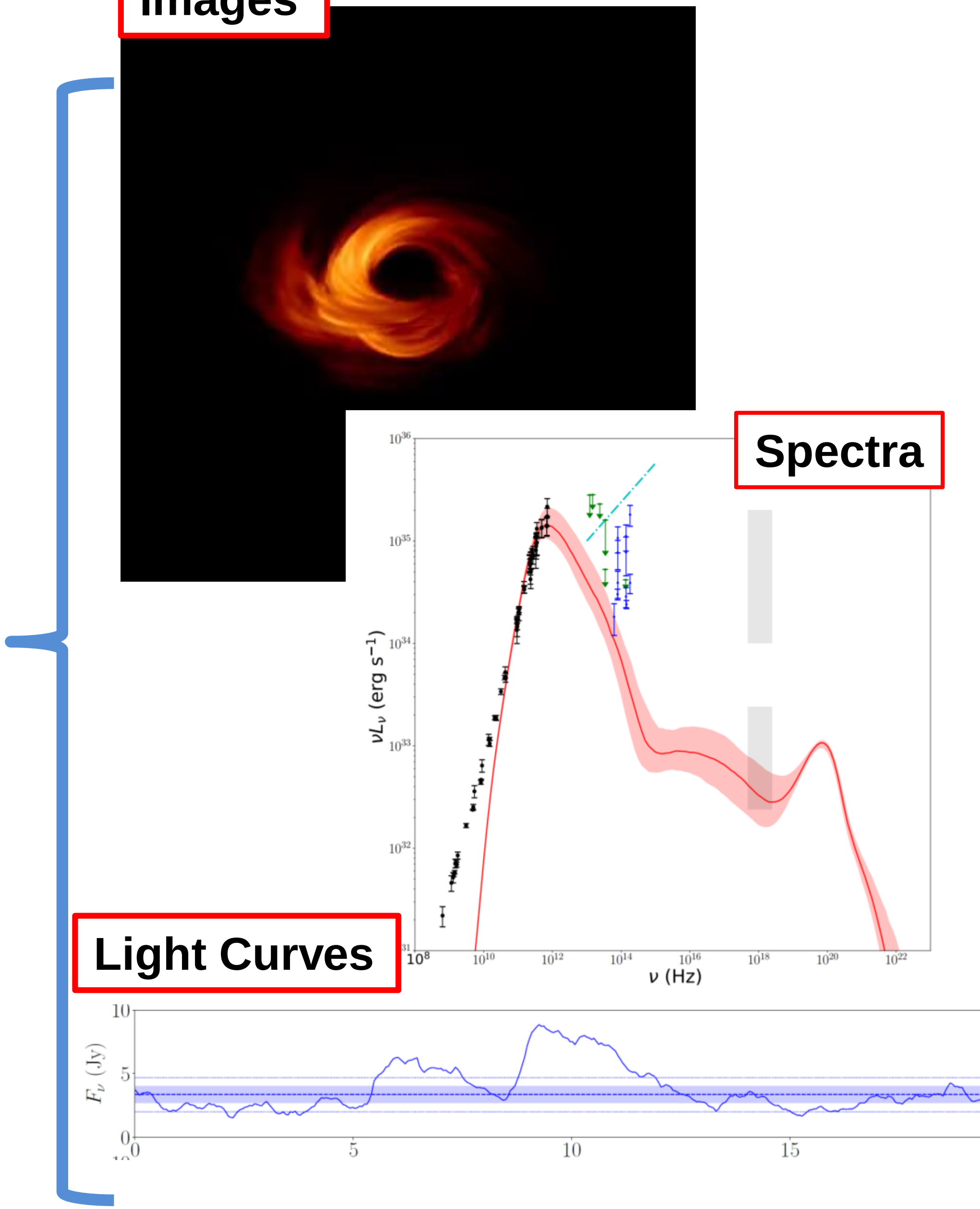



T_e?

Images

Spectra

Light Curves



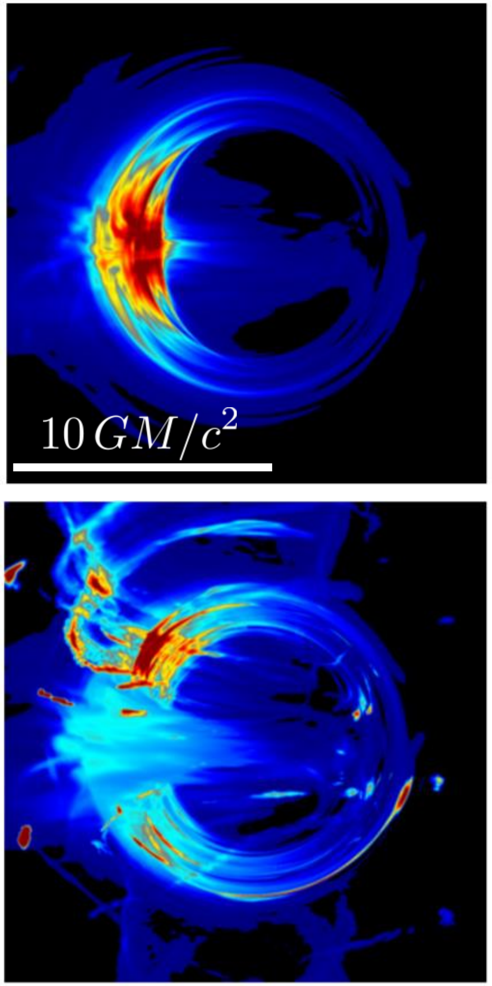
GRMHD Simulations

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

Fixed temperature ratios in postprocessing.

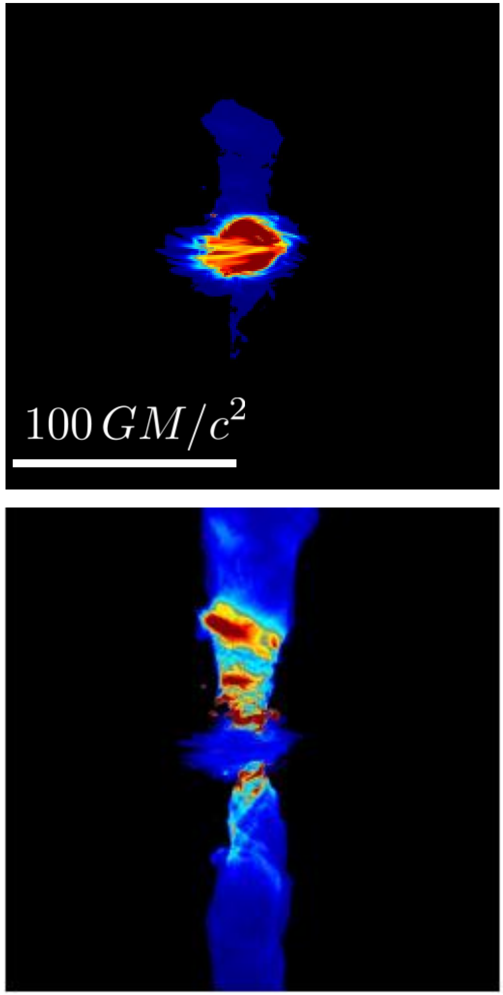
(Mościbrodzka+ 2014)

$\lambda = 1.3\text{mm}$



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

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



$\lambda = 7\text{mm}$

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

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

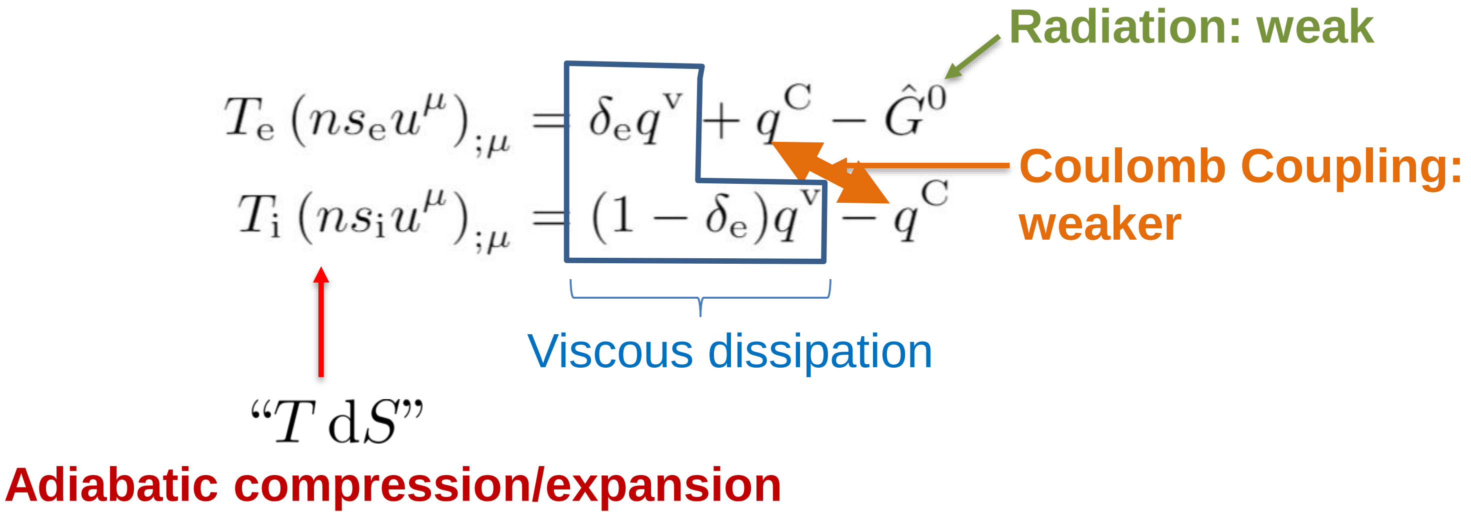
Goal: investigate the effects of microscale electron heating in **self-consistent** two-temperature simulations of the EHT targets Sgr A* and M87.

-Using the code KORAL: (Sądowski+ 2013, 2015, 2017)
-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.**

Adiabatic Electron energy + **Adiabatic Ion energy** + **Energy Generated by Viscous Heating**

=

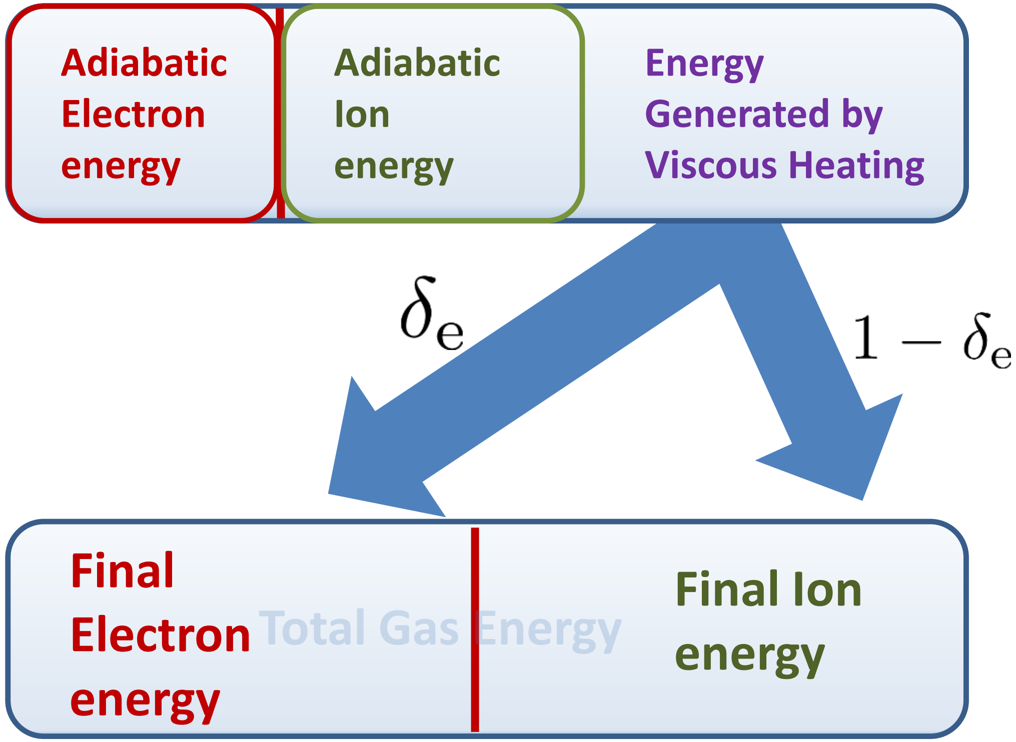
Total Gas Energy

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

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.**

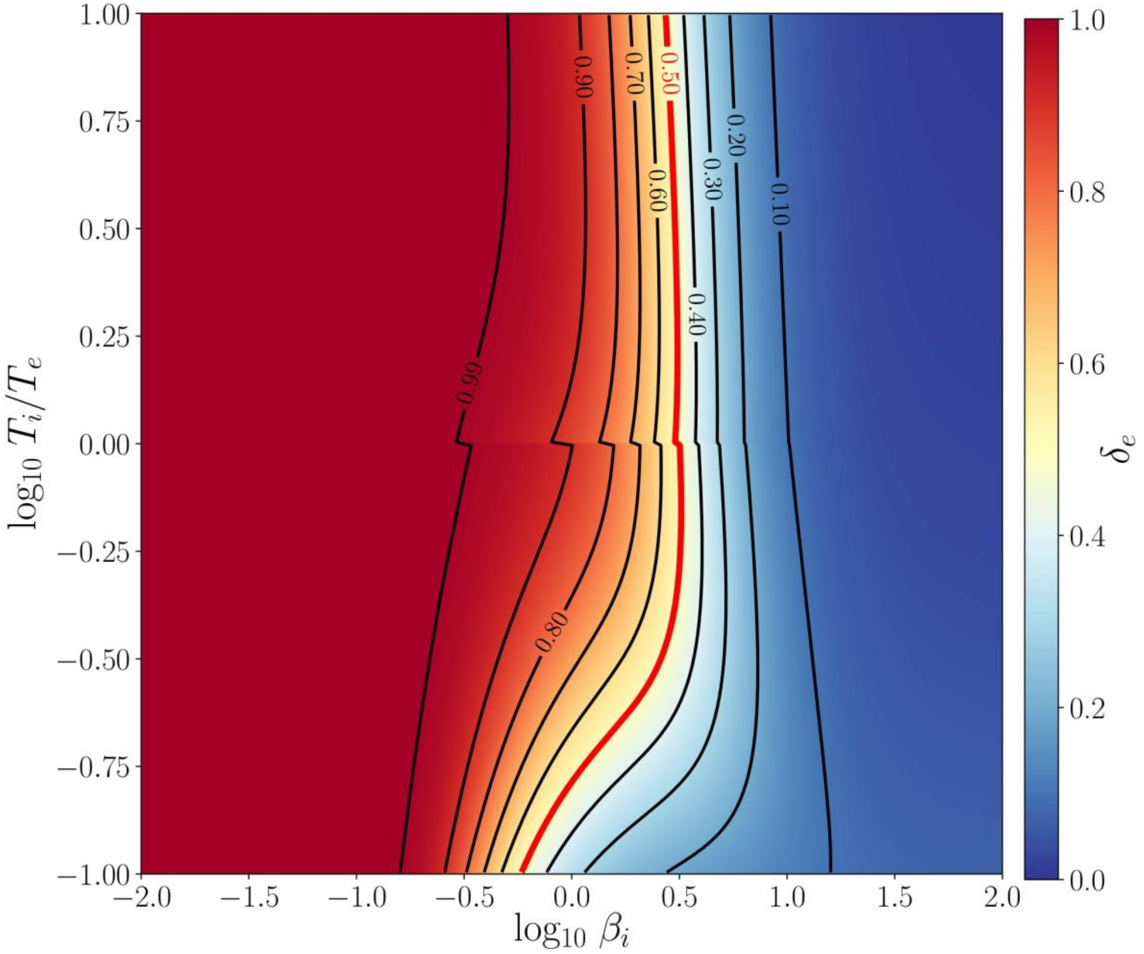
- **Sub-grid physics** must be used to determine what fraction of the dissipation goes into the electrons.



Sub-grid Heating Prescription #1

Landau-Damped Cascade (Howes 2010)

- Turbulent cascade of energy to small scales truncated by Landau damping.
- Predominantly heats electrons when magnetic pressure exceeds thermal (low beta).
- Used in all previous work (Sadowski 2016, Ressler 2015, 2017)



Almost all energy to electrons ↔ Almost all energy to ions

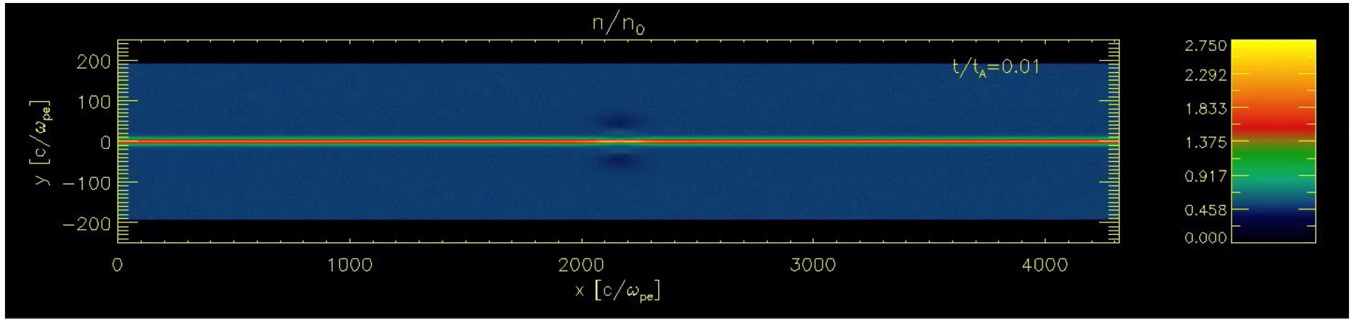
See also: Kawazura+ 2018

Sub-grid Heating Prescription #2

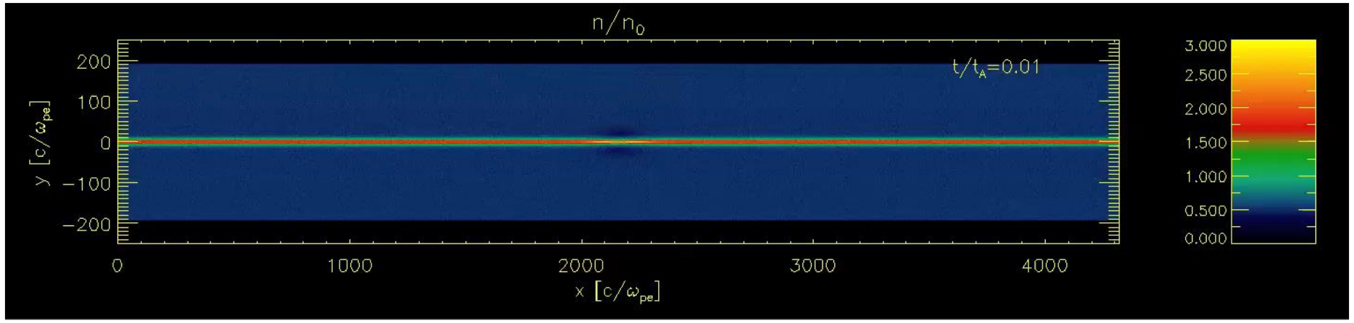
Magnetic Reconnection (Rowan 2017)

- Idea: subgrid turbulence may be truncated by magnetic reconnection
- Fit to Particle-in-Cell simulation results at trans-relativistic ranges of temperature, magnetization.
- **Always** puts more heat into ions
- Constant nonzero δ_e at low magnetization.

High-beta reconnection



Low-beta reconnection



Video credit: Michael Rowan
See also: Werner+ 2018

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?

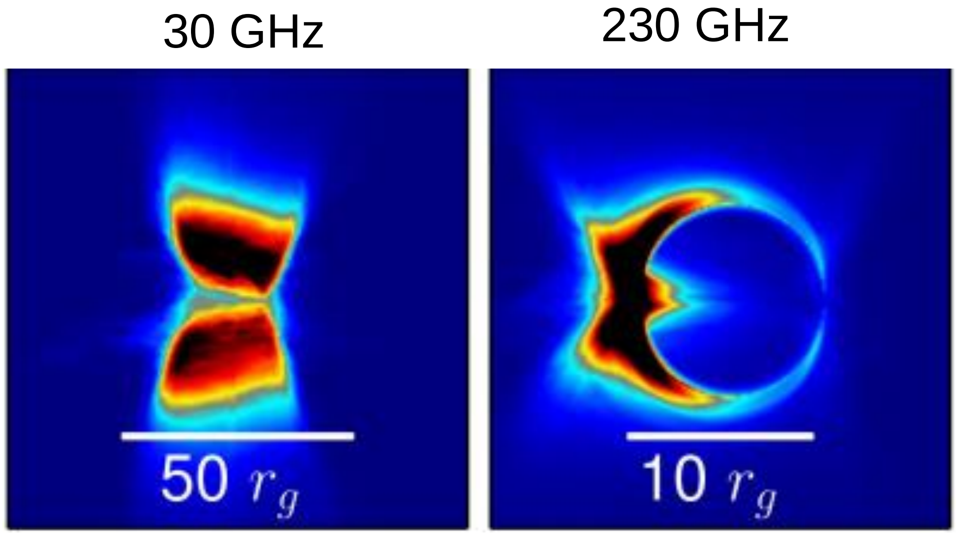
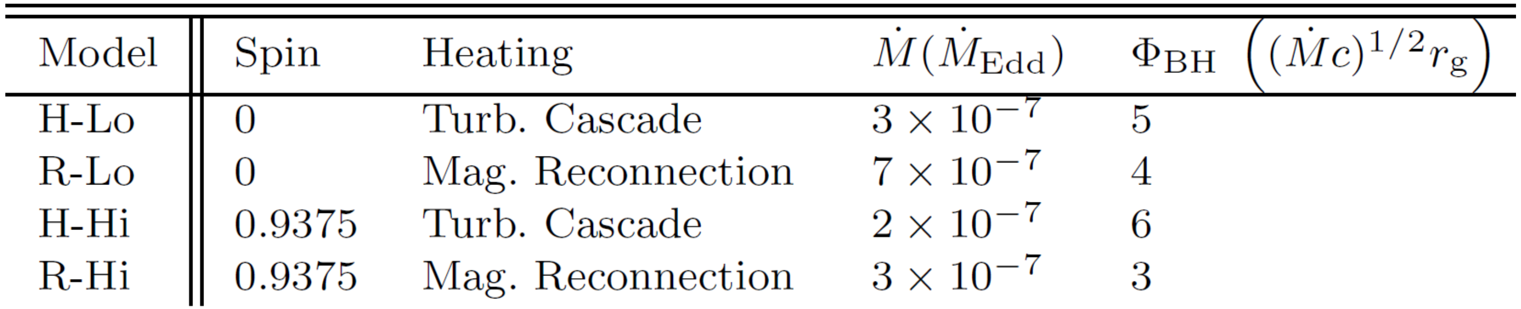


Image credit: Ressler et al. 2017

Four 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	$\dot{M}\,(\dot{M}_{\mathrm{Edd}})$	$\Phi_{\mathrm{BH}}\ \left((\dot{M}c)^{1/2}r_{\mathrm{g}}\right)$
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*

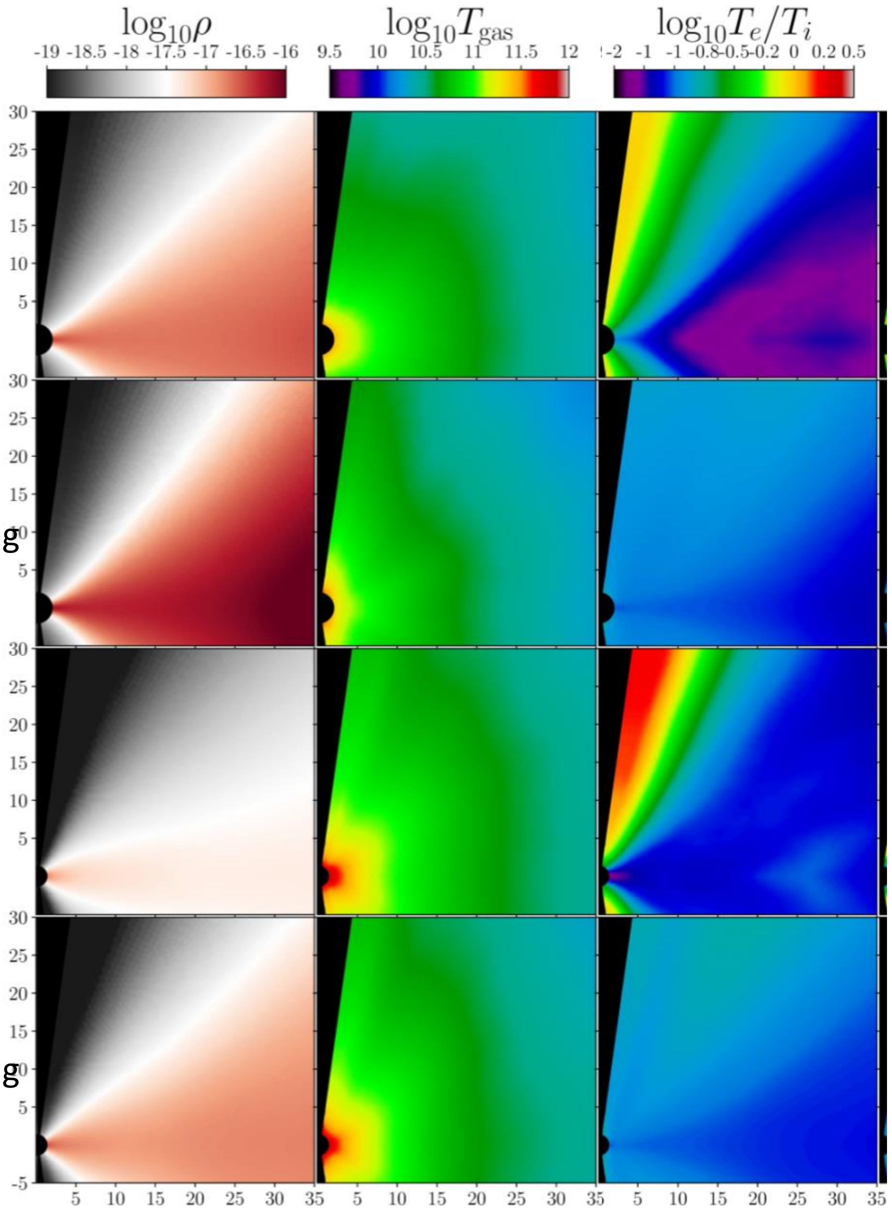
All are thick disks: density lower at high spin

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

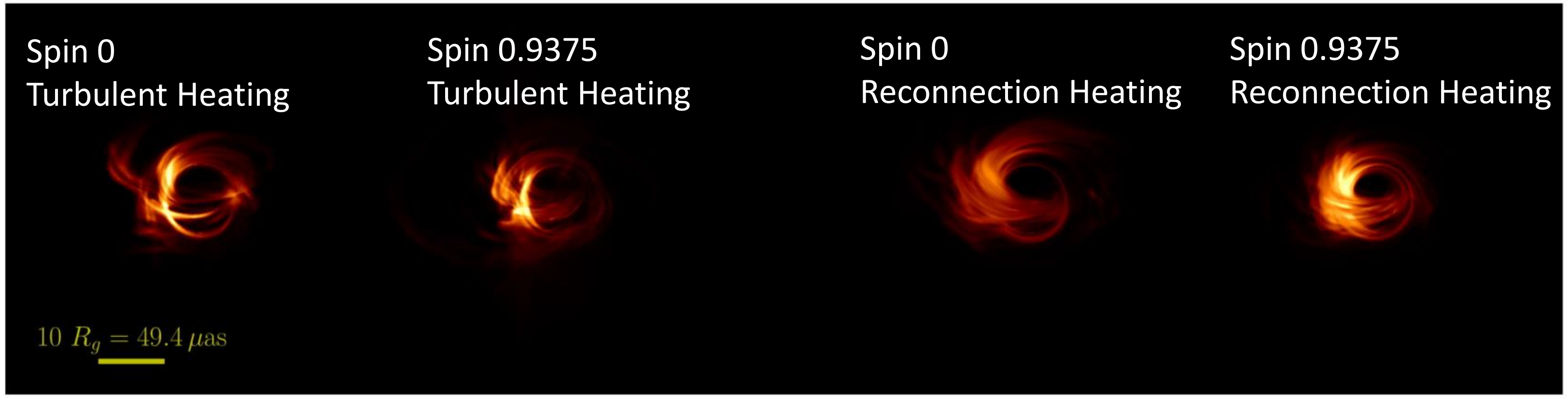
Spin 0.9375
Turbulent
Heating

Spin 0
Reconnection
Heating

Spin 0.9375
Reconnection
Heating

Image structure with frequency

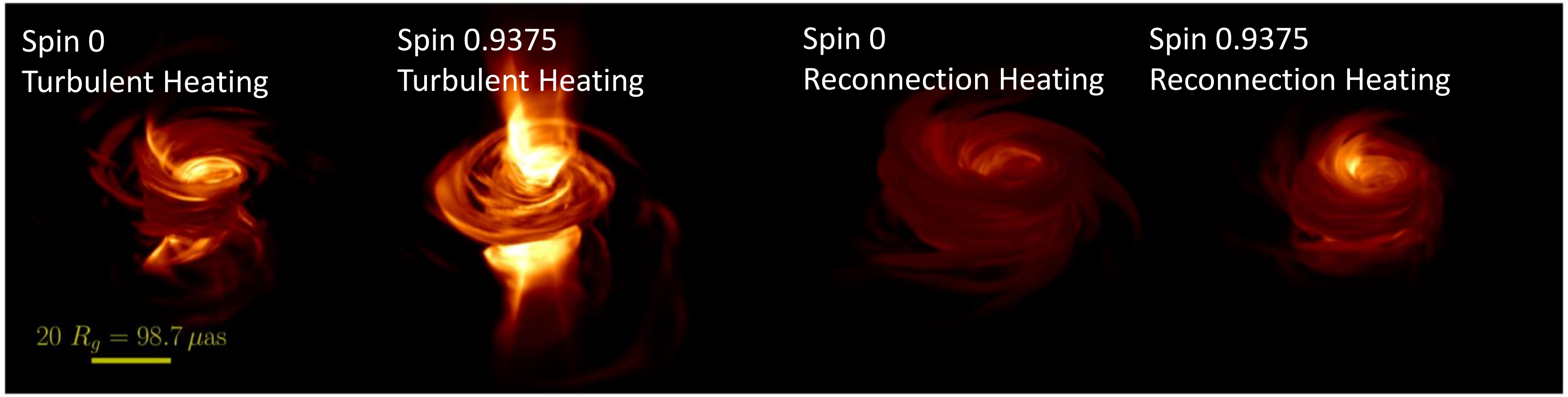
230 GHz



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

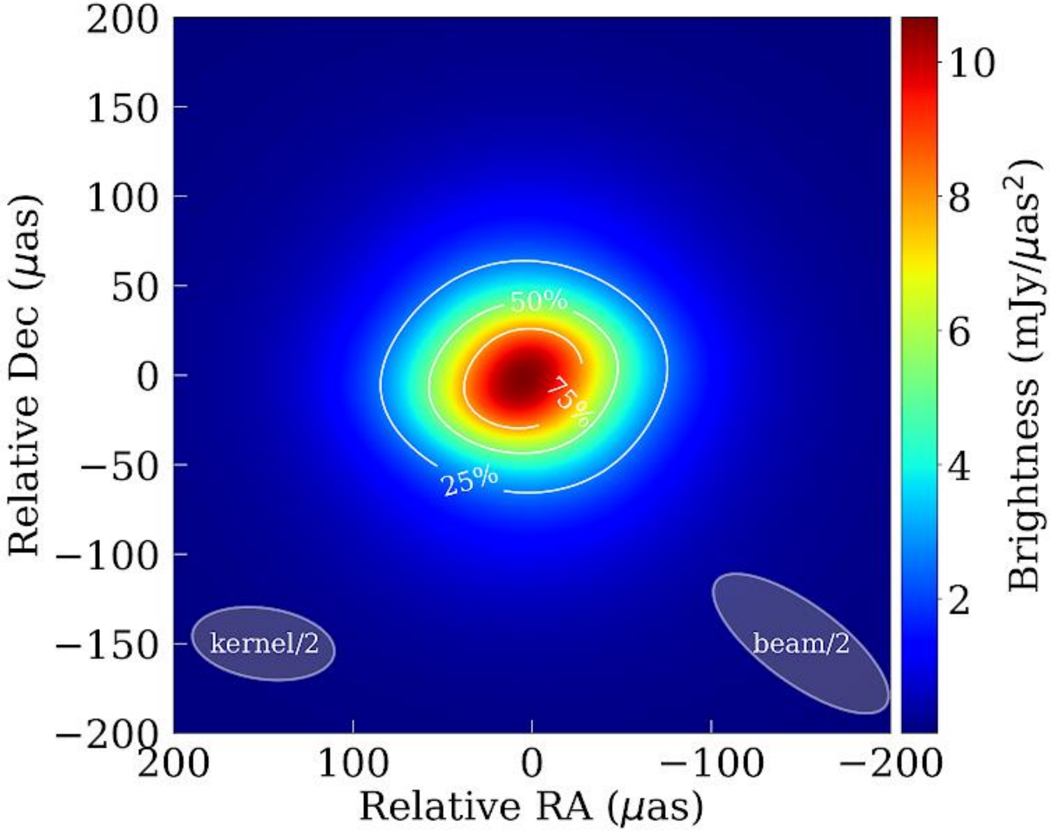
Turbulent heating makes lower frequency images anisotropic and jet dominated – **exceeding** estimates of intrinsic anisotropy when viewed at high inclination
(Johnson+ 2018, Issaoun+ 2018)

43 GHz



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

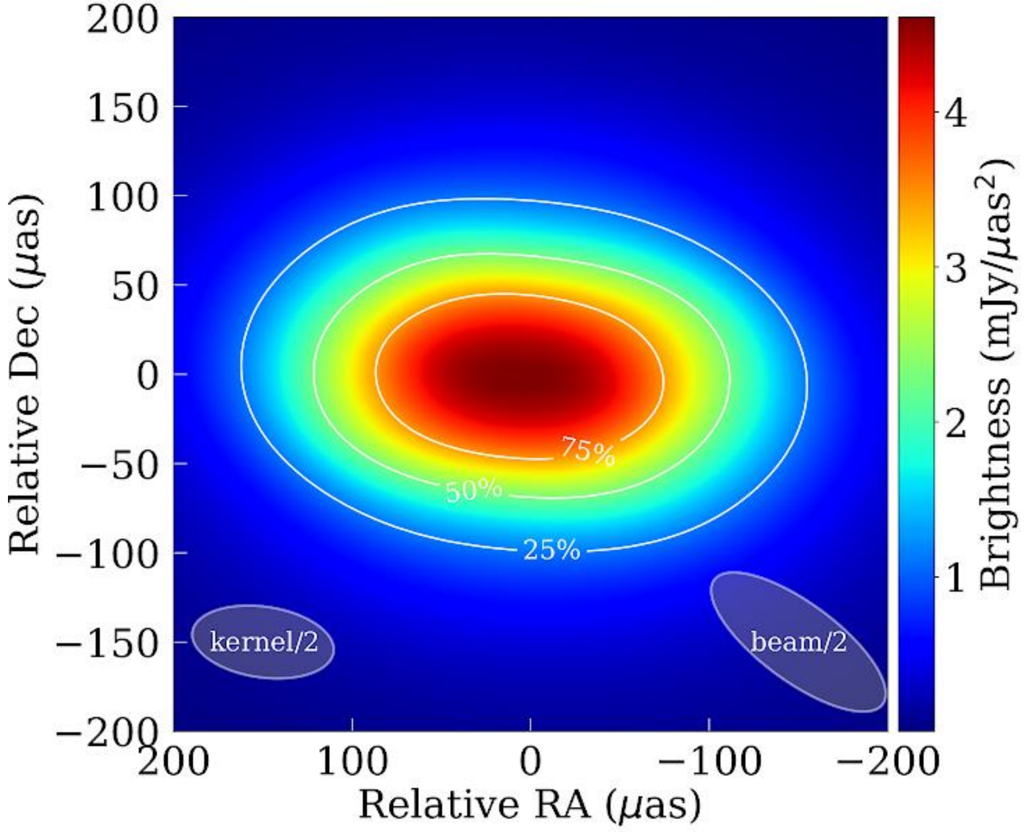
and the first VLBI with ALMA (Issaoun+ 2018)



De-scattered

Deblurring and phase correction

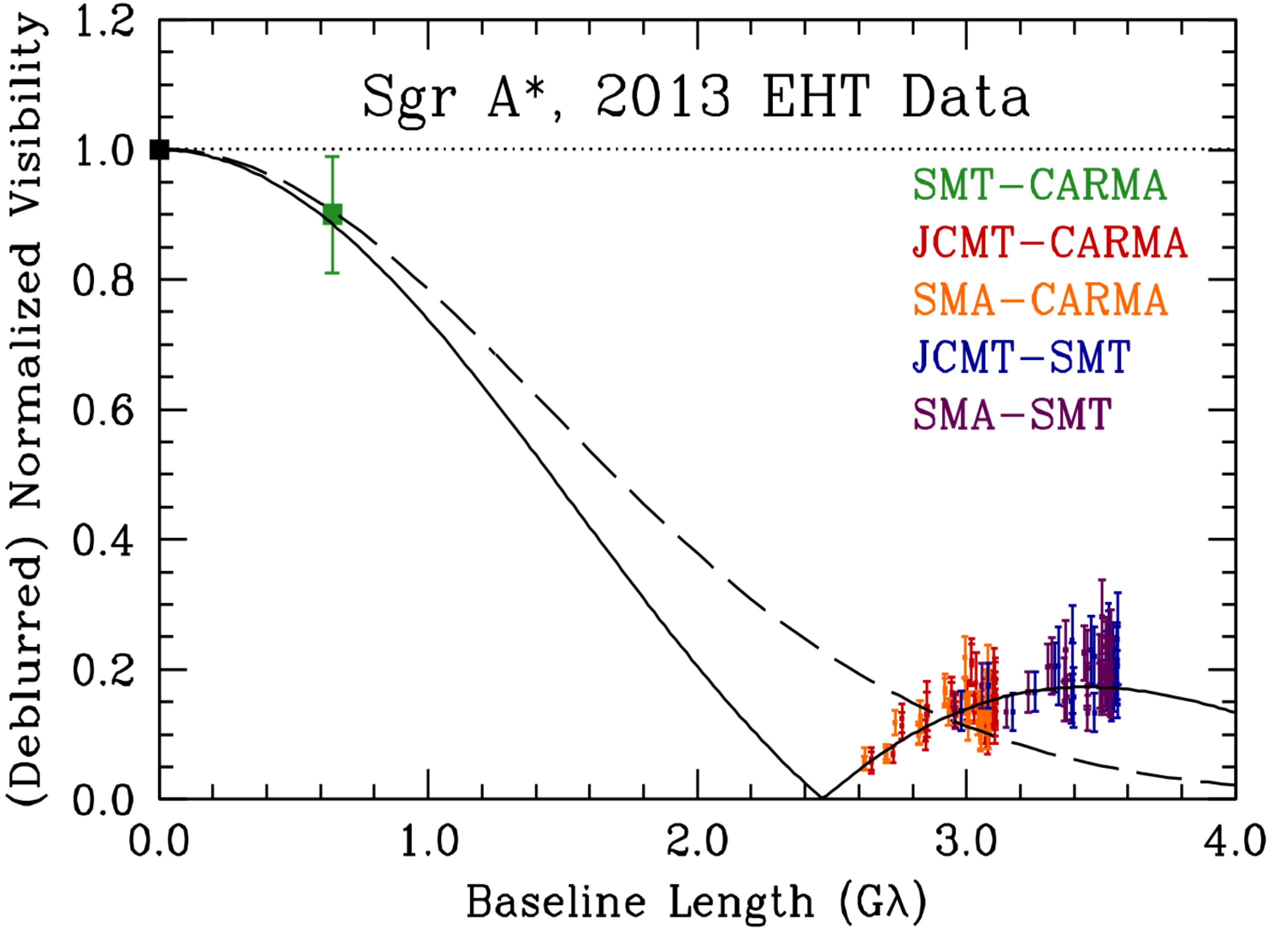
(Johnson+ 16)



Scattered Image

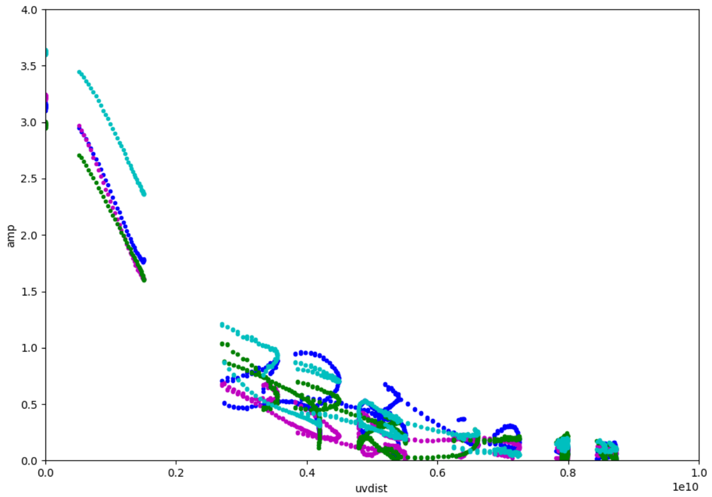
New constraints on Sgr A* asymmetry at 3.5 mm rule out edge-on jet!

Comparison with EHT 230 GHz measurements: Evidence for low inclination?

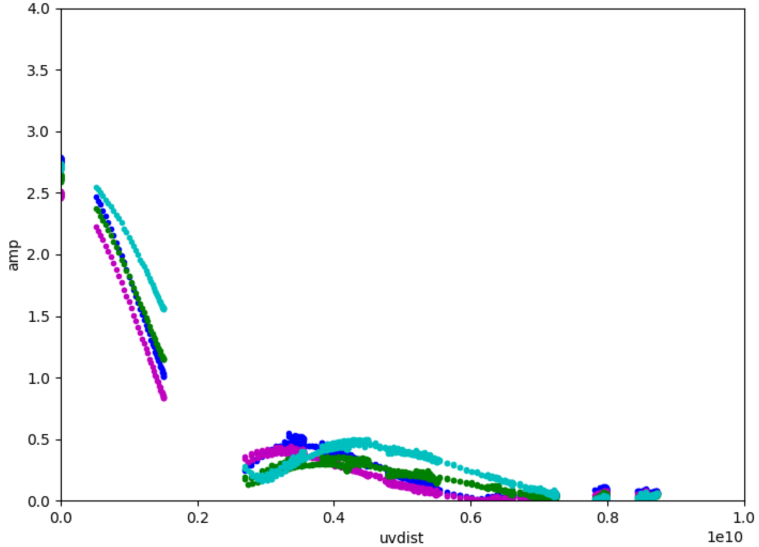


Johnson+ (2015)

60 degree inclination



10 degree inclination



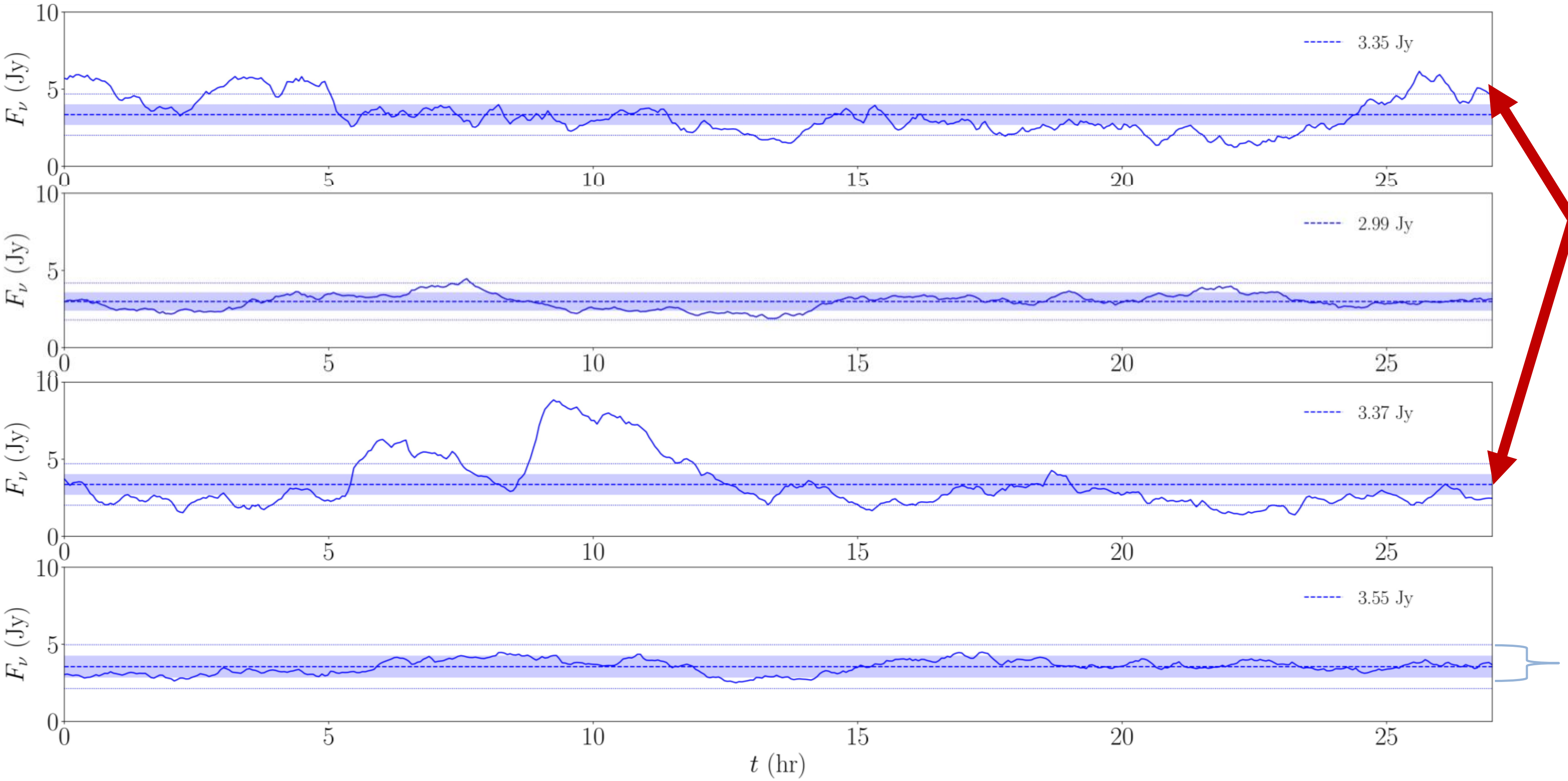
Sgr A*: 230 GHz variability

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)

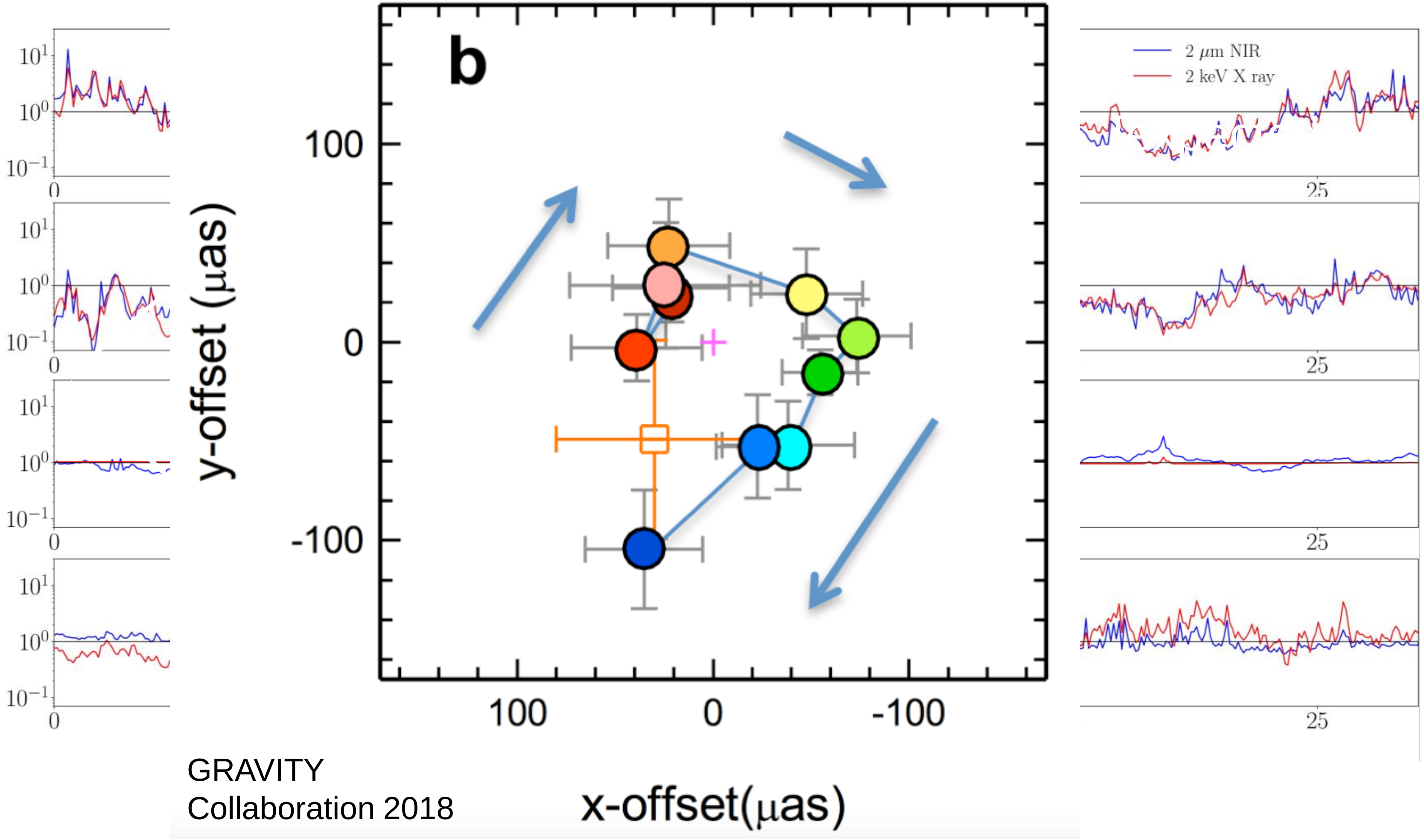
IR and X-ray variability: **no flares**

Spin 0
Turbulent Heating

Spin 0.9375
Turbulent Heating

Spin 0
Reconnection Heating

Spin 0.9375
Reconnection Heating



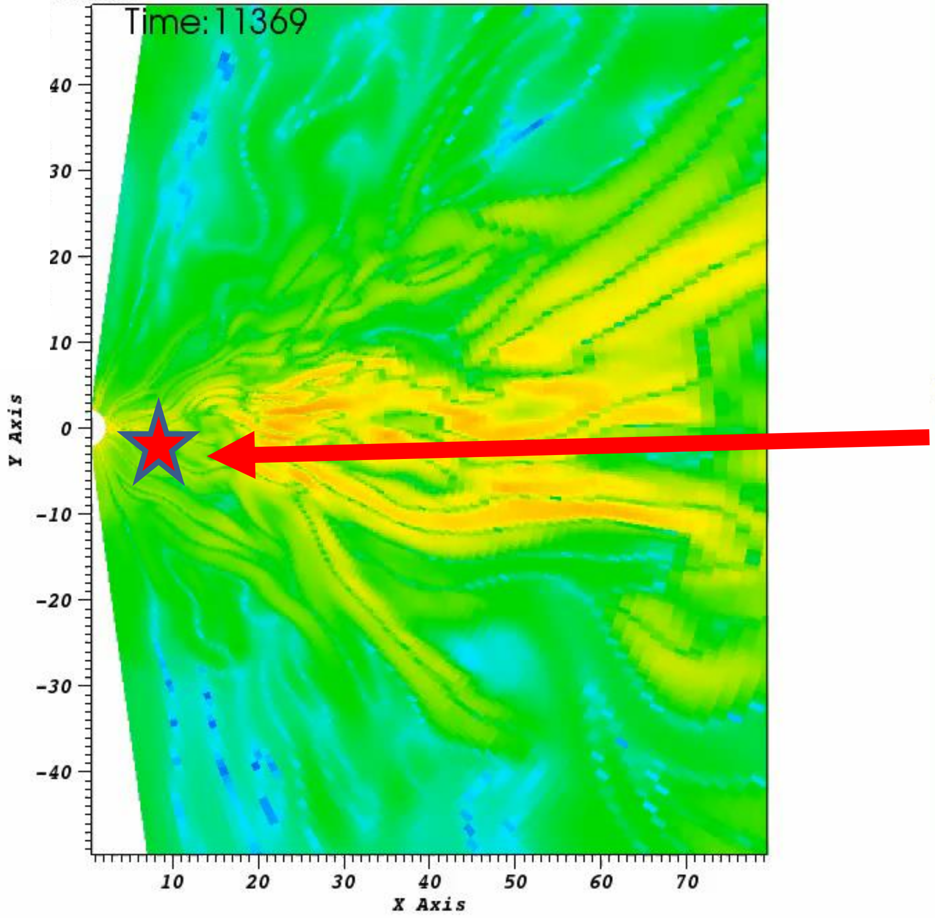
GRAVITY
Collaboration 2018

No models reproduce strong IR and X-ray flares →Nonthermal Electrons (e.g. Ball+ 2016)

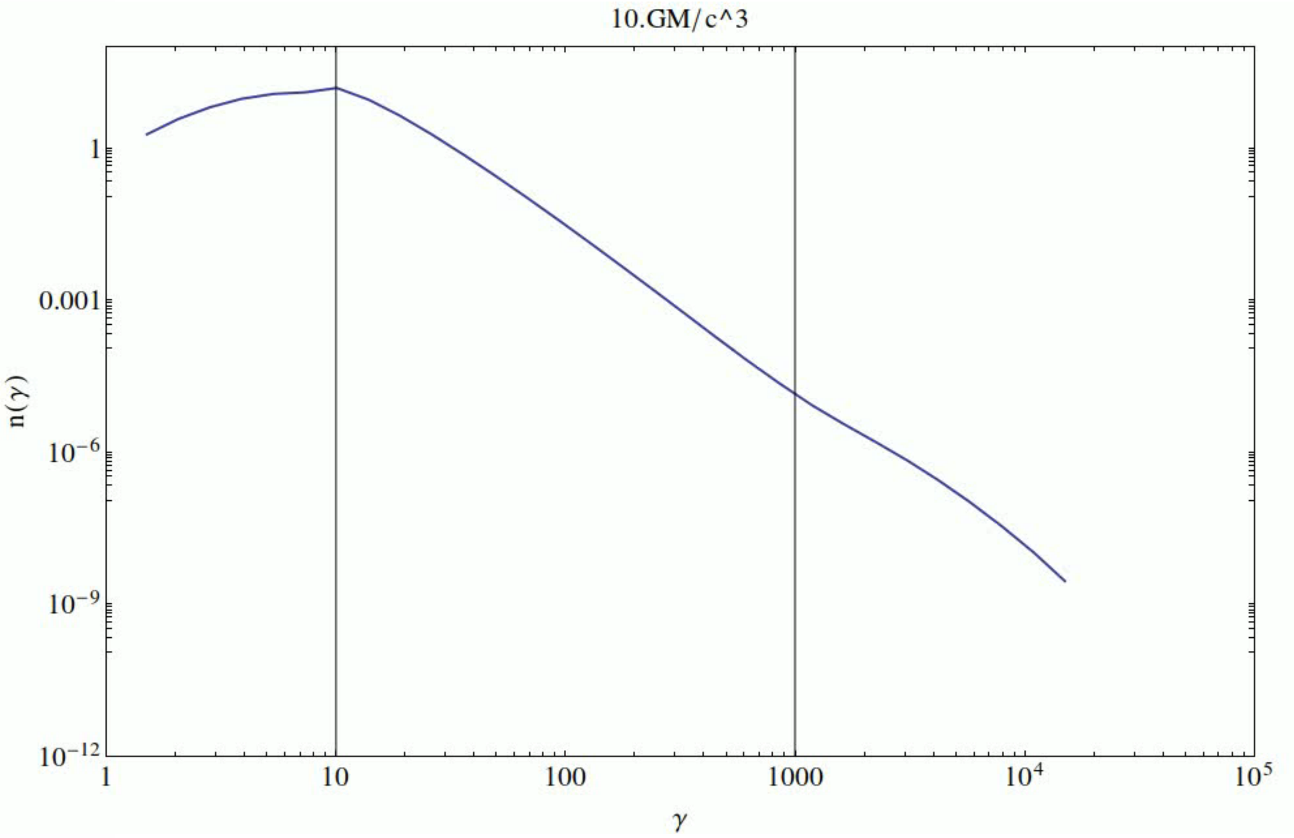
Simulating Flares: Evolving **nonthermal** electrons

(Method: Chael+ 2017)

Radiation Power



Nonthermal distribution @ 10 M



Chael+ 2017
arXiv 1704.05092

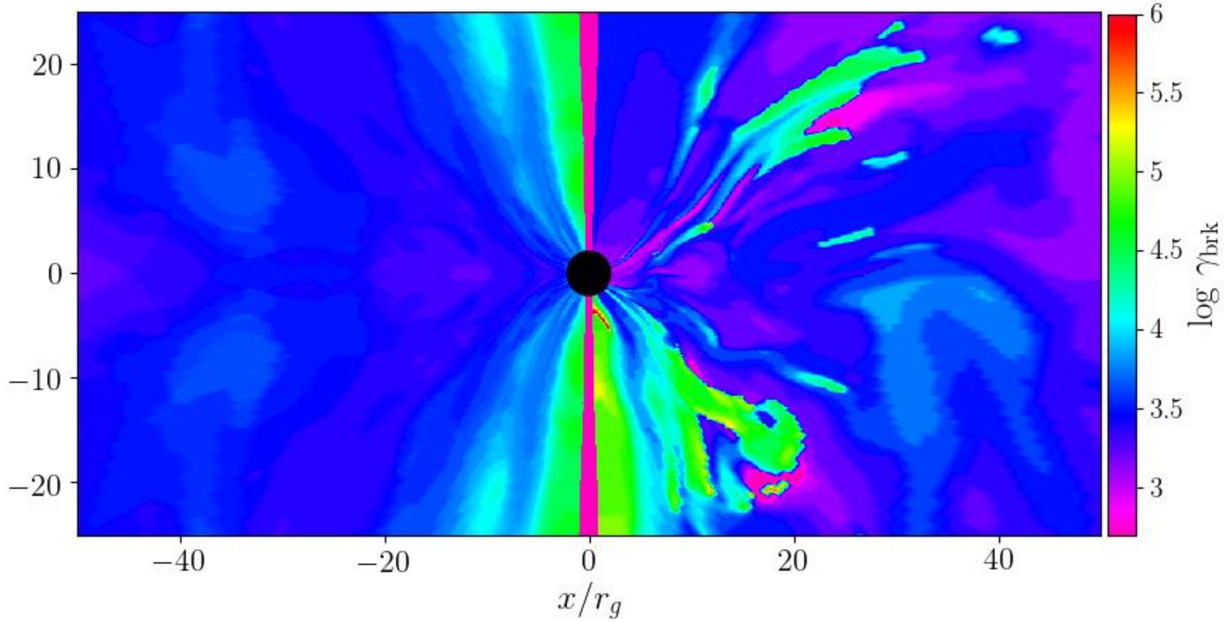
Evolving **nonthermal** electrons in simulations

(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



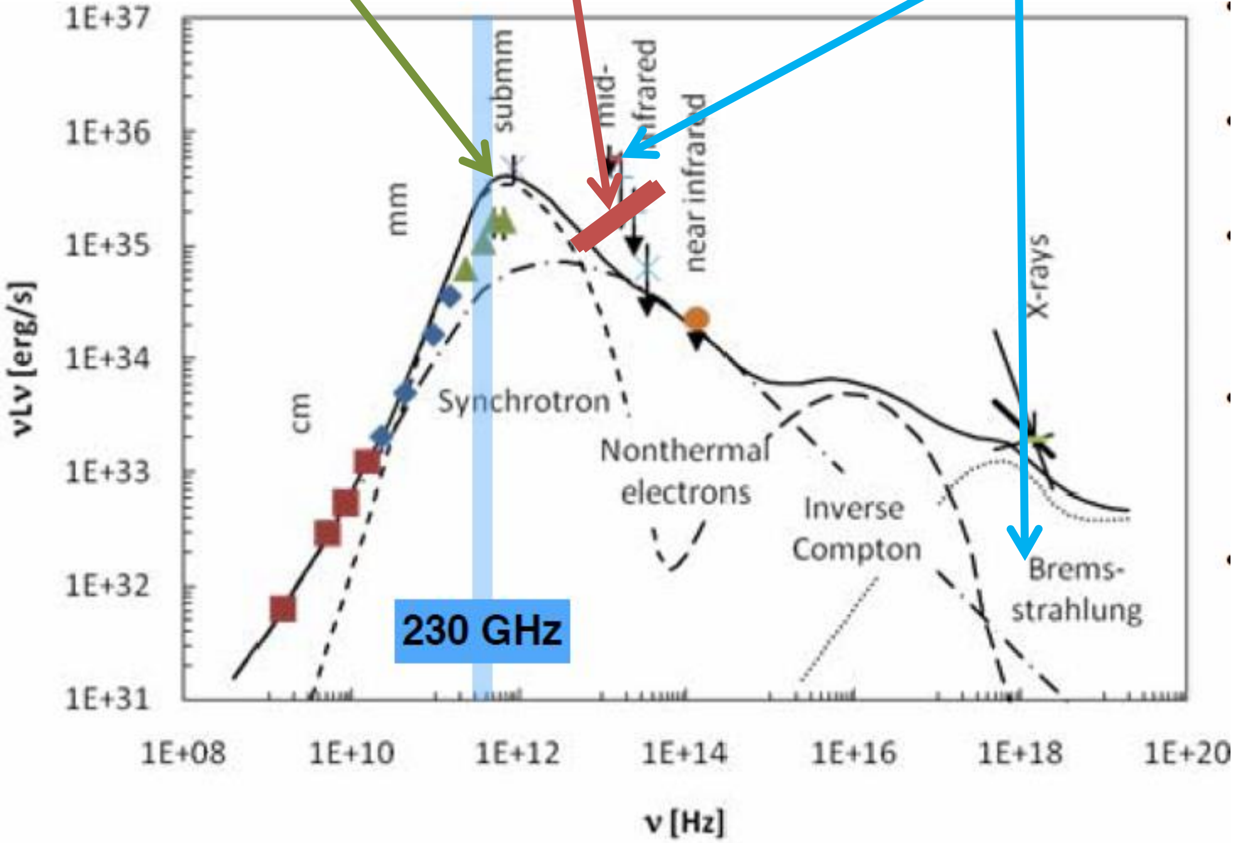
Snapshot

- 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

Sgr A* Spectrum & Variability

- Radio: self-absorbed optically thick synchrotron.
- Sub-mm: Peaks and transitions from optically thick → optically thin synchrotron.
  - Variable, RMS ~ 20%
- NIR and X-ray: strongly variable.
  - X-ray flares can exceed 100x quiescence
  - Flares are correlated
  - Measured synchrotron break between IR and X-ray? (Ponti et al. 2017)



Positive, consistent IR spectral index in flares

Weak variability at peak

Correlated flares w/ large amplitude from IR to X-Ray

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

M87

(Chael+ 2018b, arXiv: 1810.01983)

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 $20\mu\mathrm{as}$?)

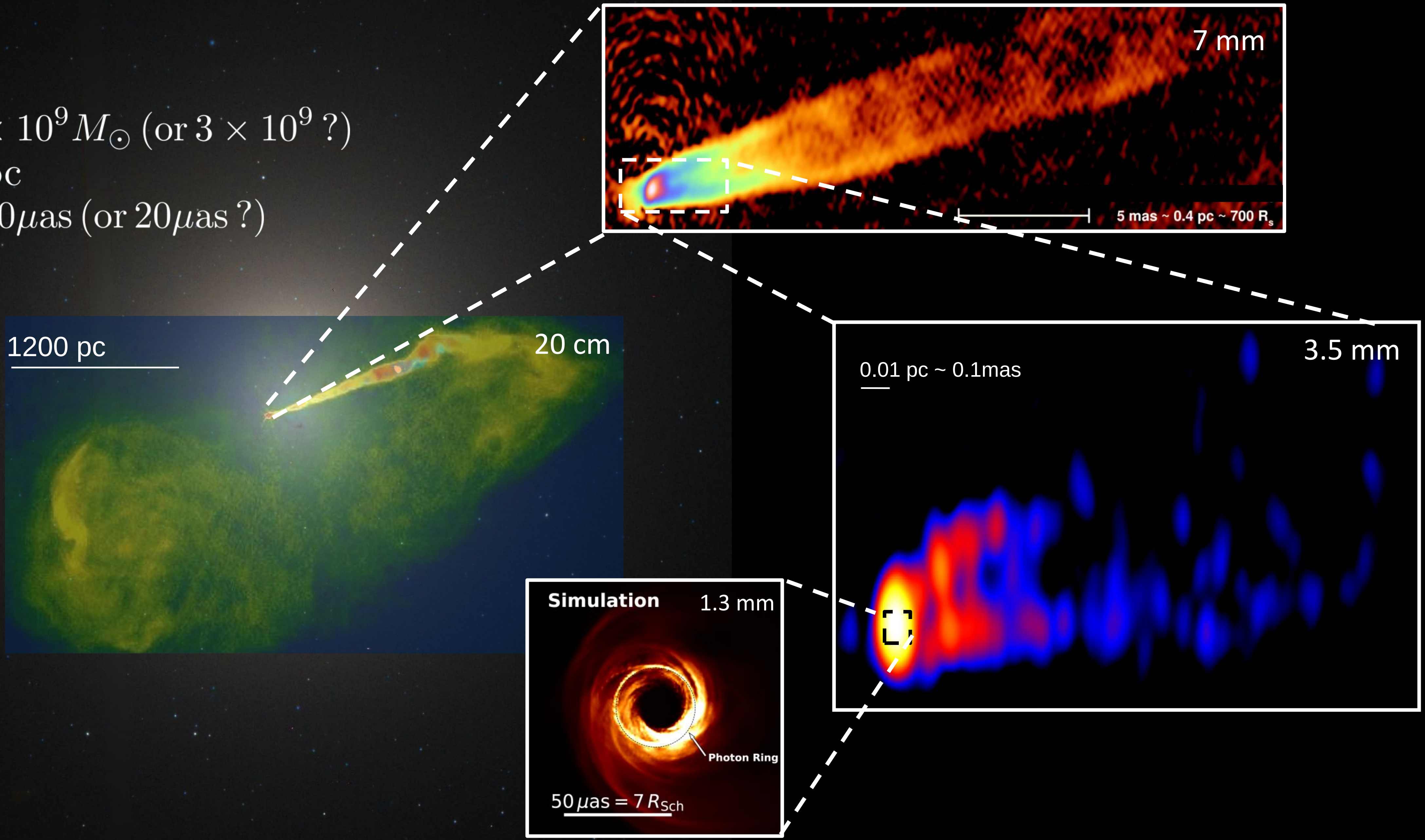
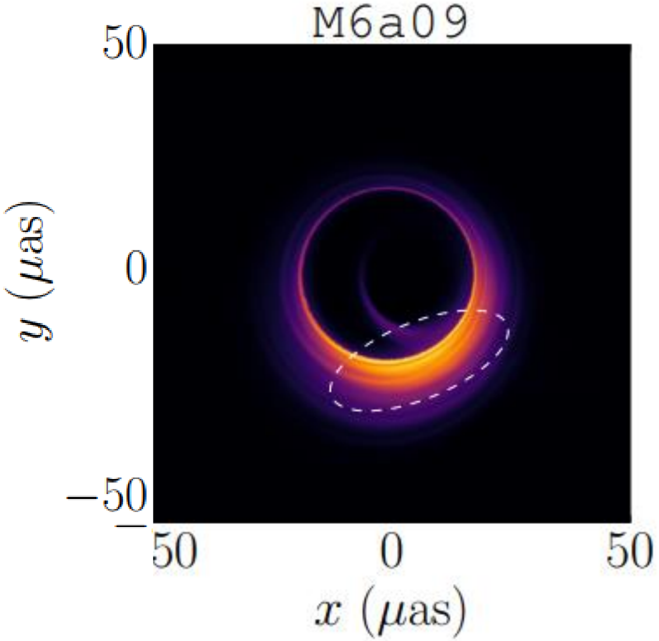


Image Credits: NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm)

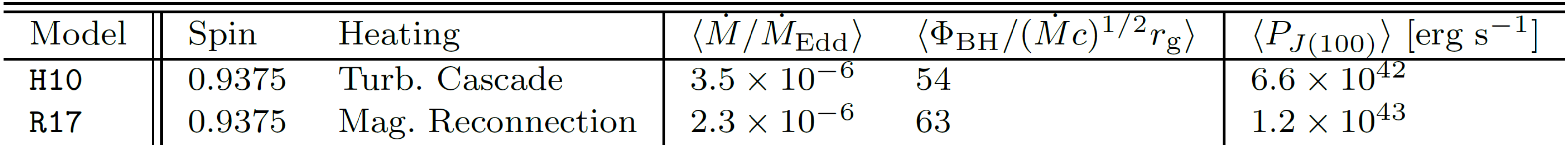
Previous work: *Ryan et al. 2018*

- 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

Two M87 Simulations



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

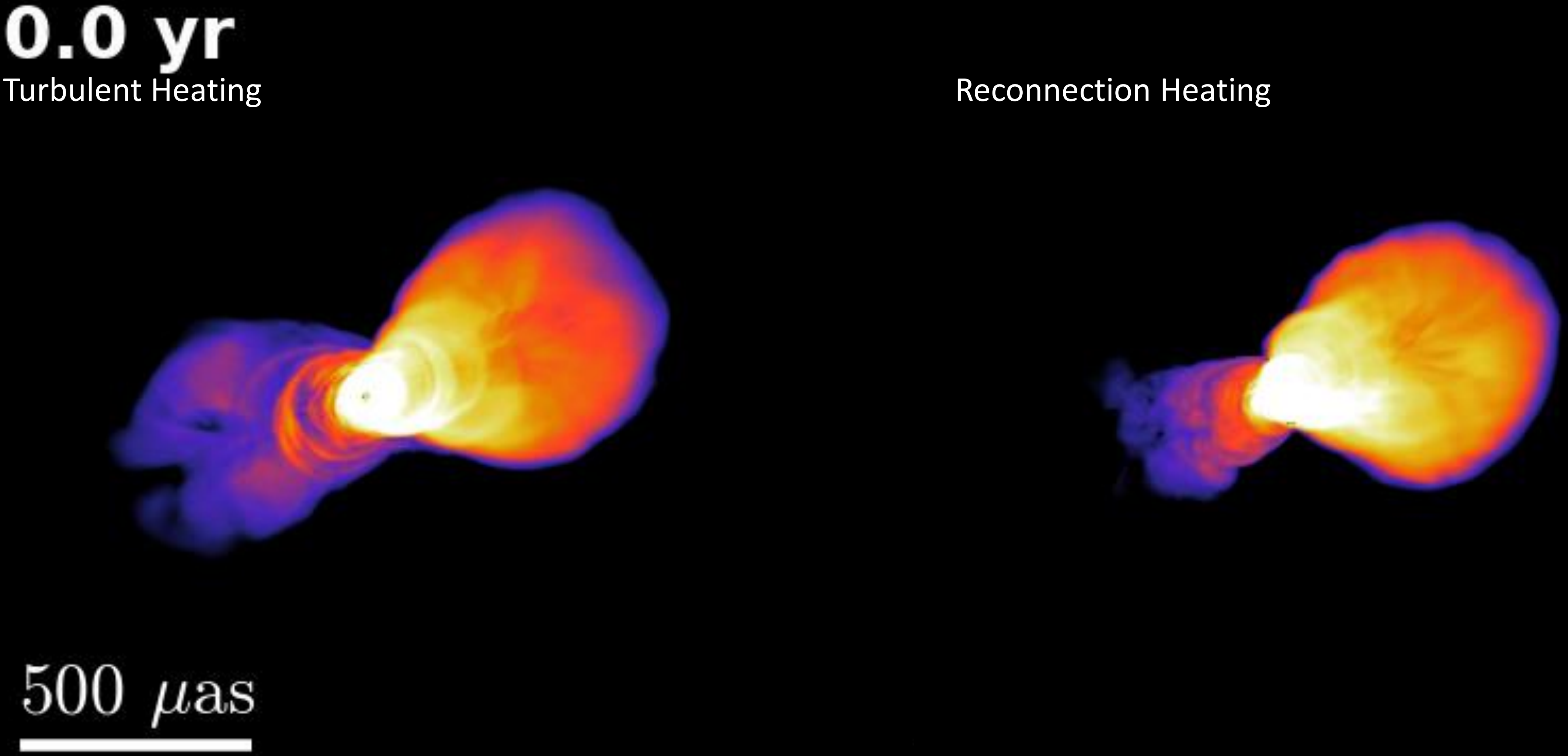
“MAD parameter”

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 simulations: 43 GHz jets

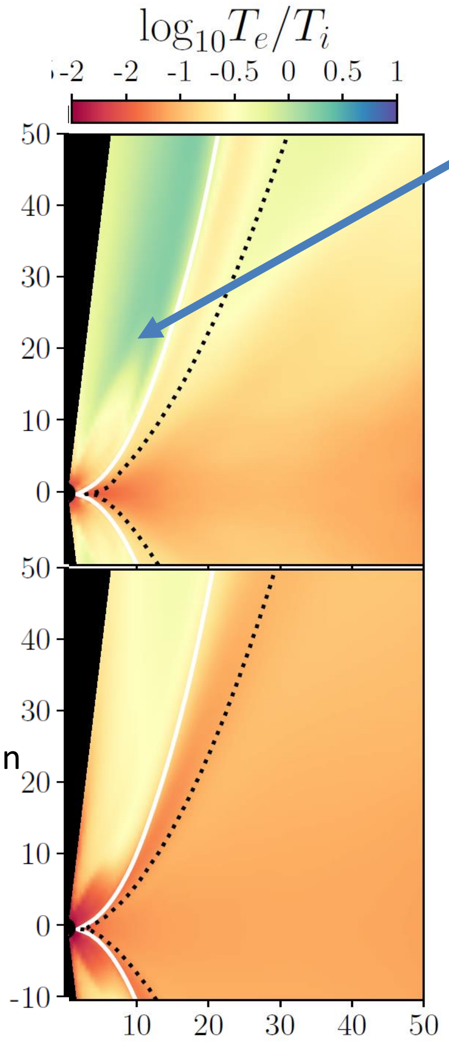

Turbulent Heating

Reconnection Heating

Electron Heating → Jet Dynamics

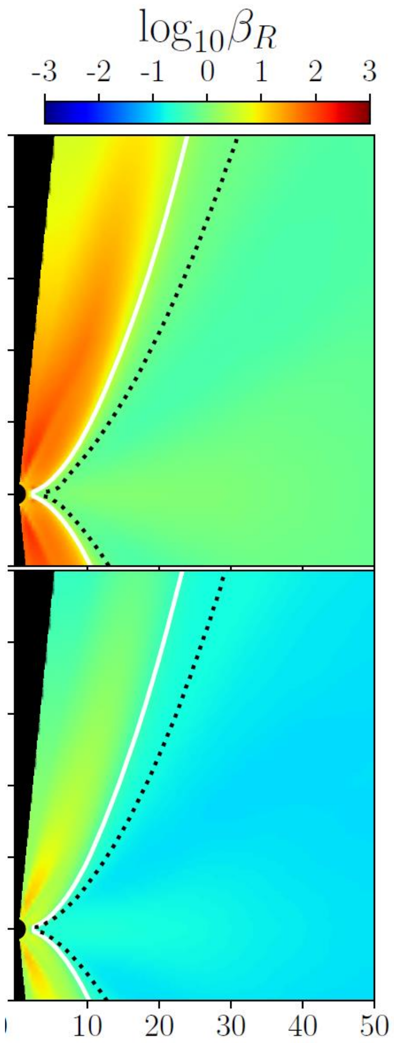
Turbulent Heating

Reconnection Heating

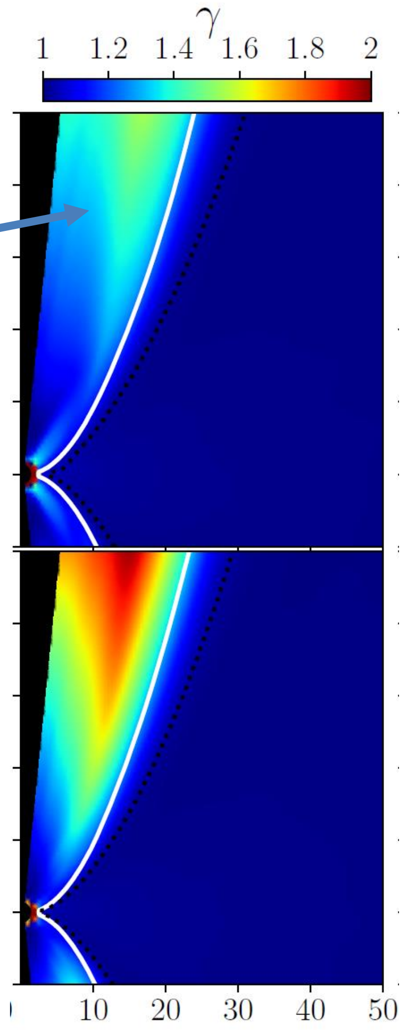


Very hot jet electrons

Tons of synchrotron and IC radiation produced



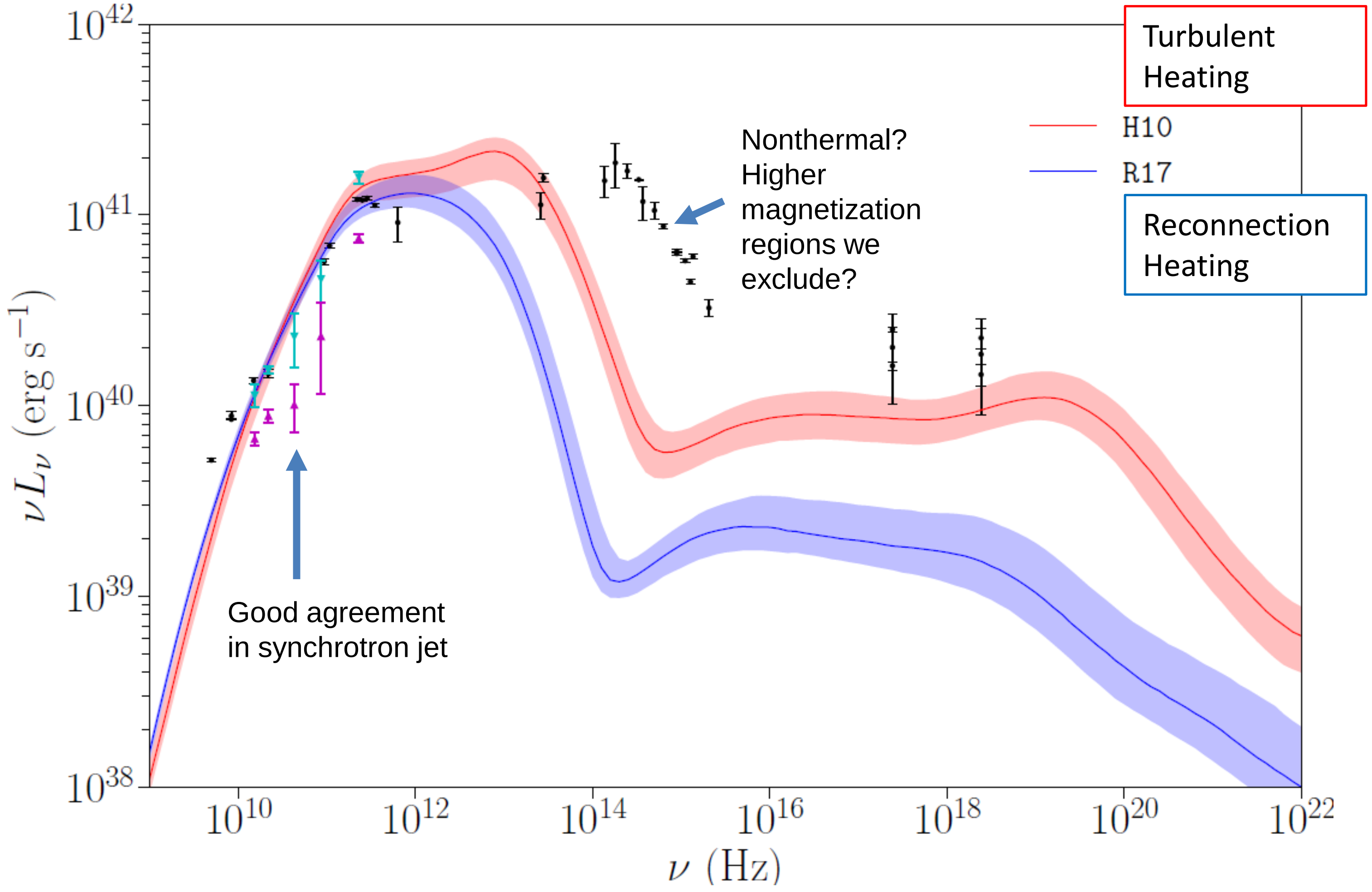
Weaker mechanical jet power



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

Electron Heating + Radiation → Dynamics!

M87 Spectrum



Turbulent Heating

Reconnection Heating

Nonthermal? Higher magnetization regions we exclude?

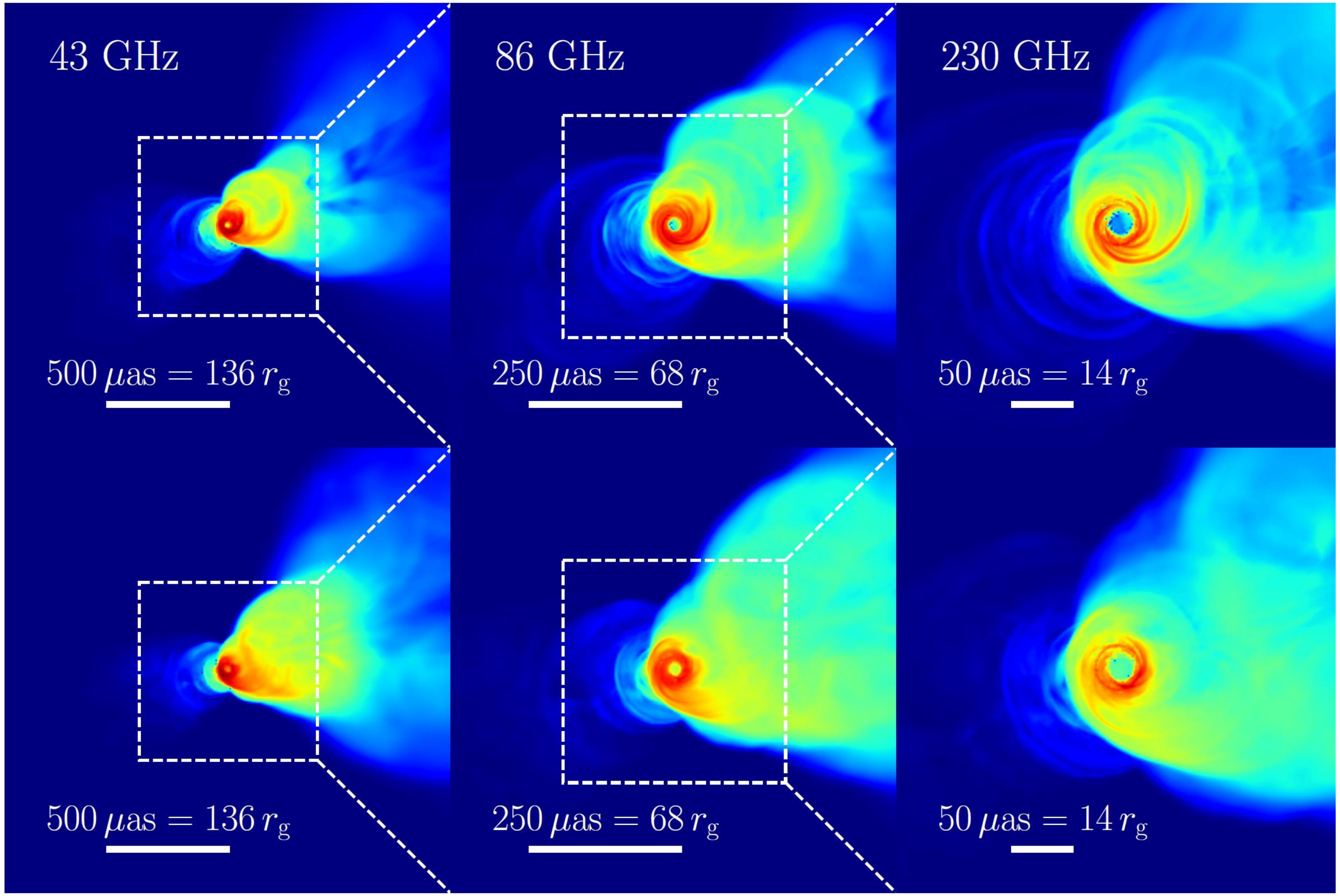
Good agreement in synchrotron jet

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

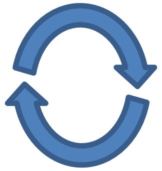
Reconnection Heating



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 images – comparison with VLBA

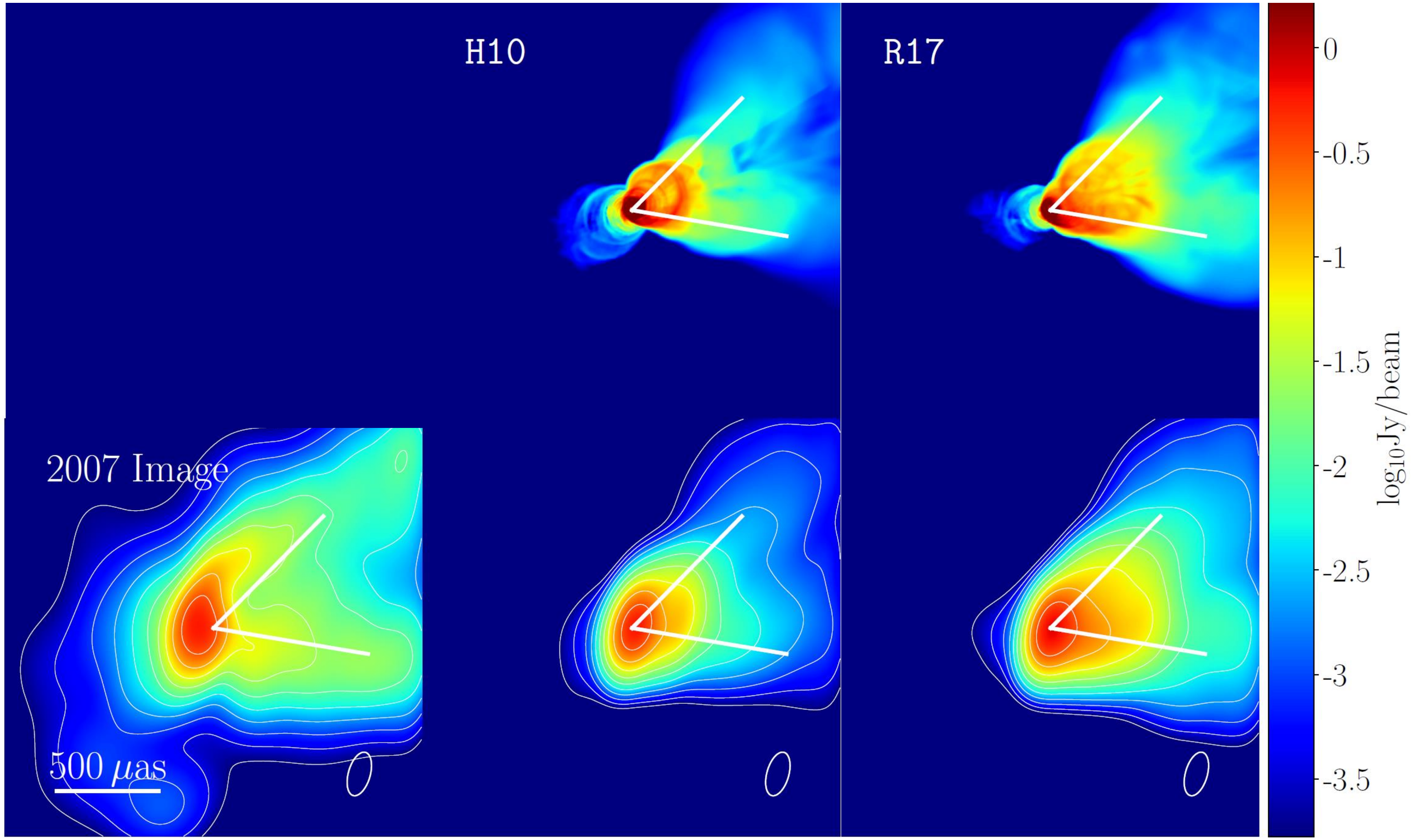
Walker+ 2018

Turbulent Heating

Reconnection Heating

High Resolution

VLBA Resolution



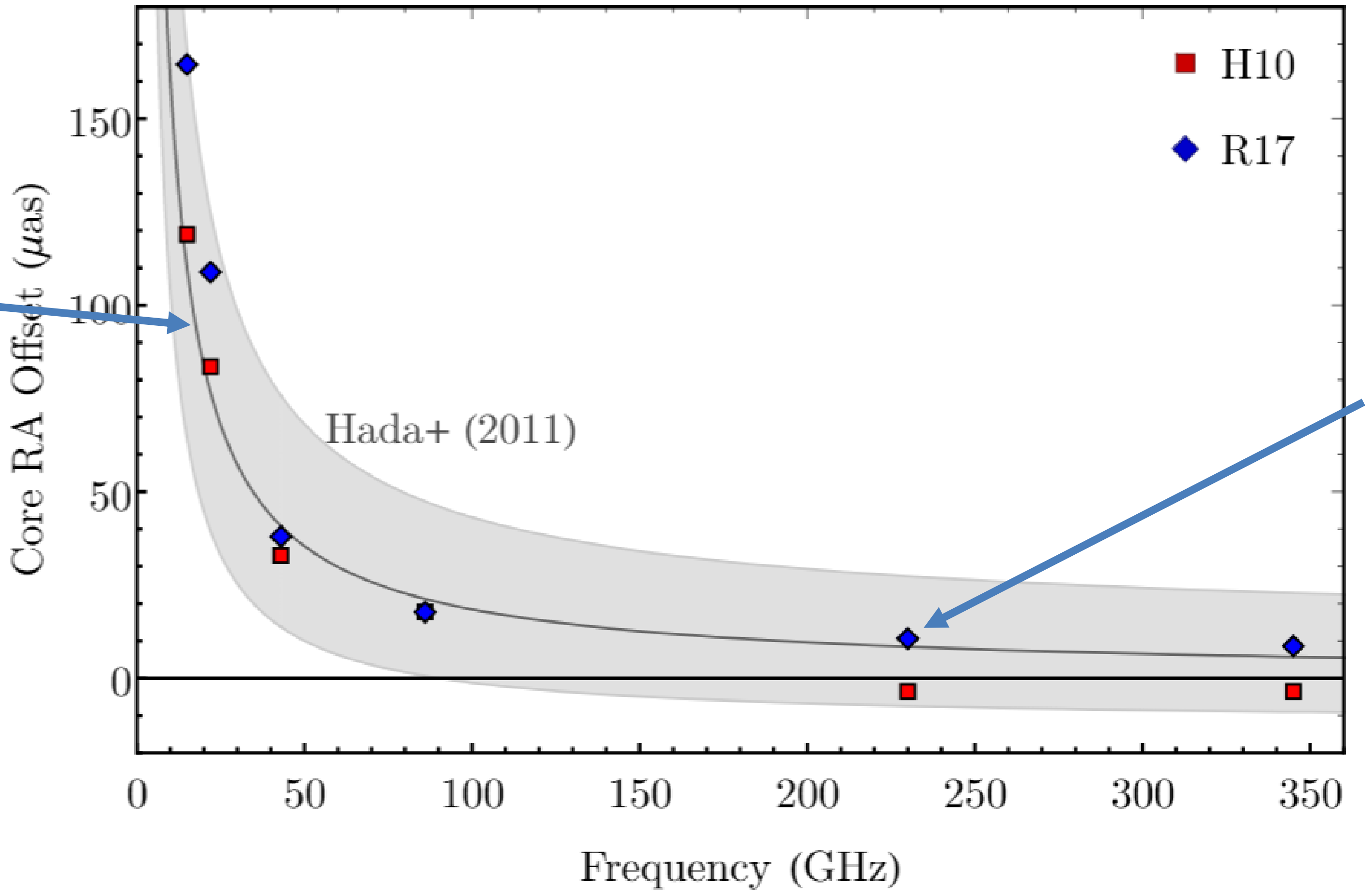
Apparent opening angle at 43 GHz:

55°

(Walker+ 2018)

Walker+ 2018, Kim+ 2018

M87 Core Shift



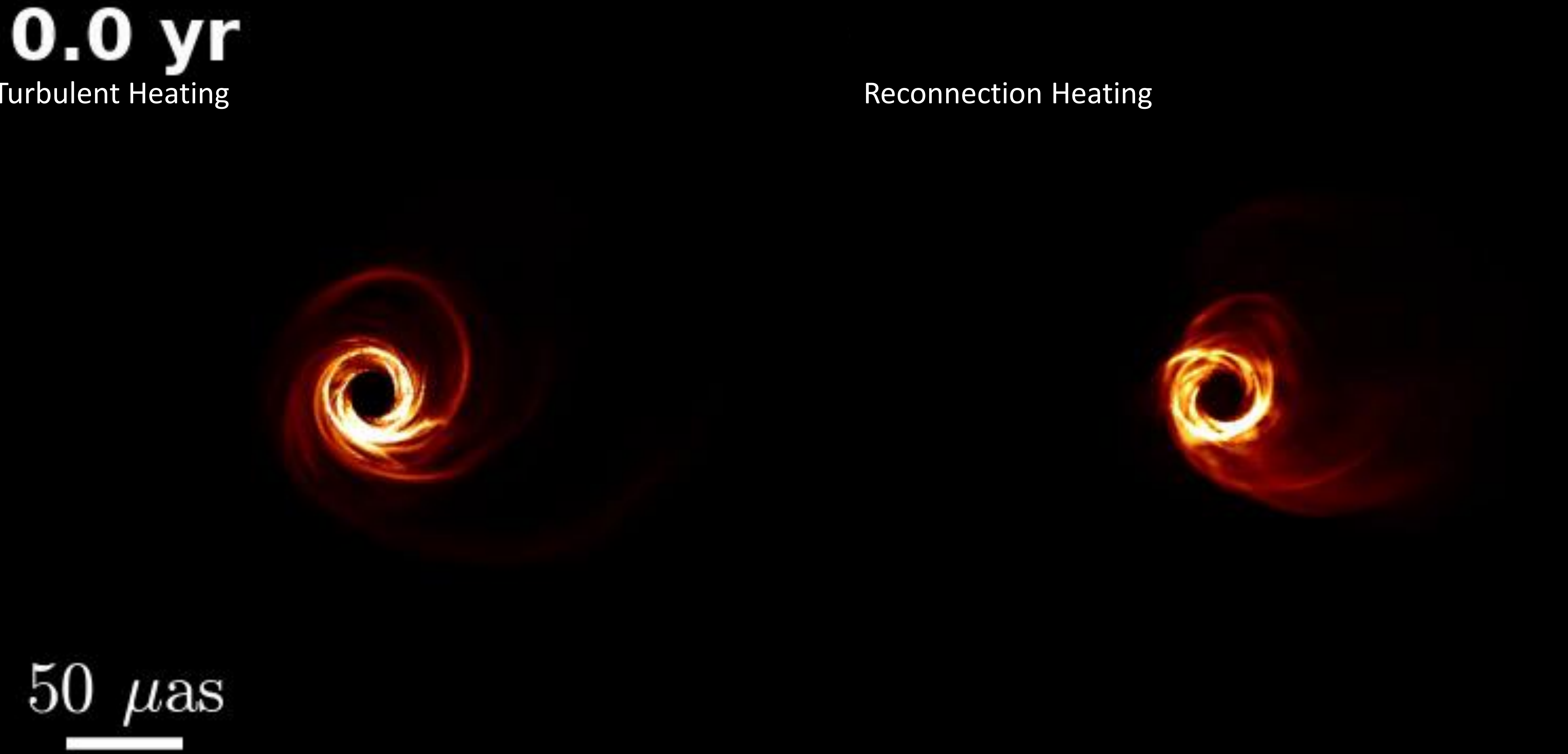
At lower frequencies, the optically thick synchrotron core moves up the jet

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?



Turbulent Heating

Reconnection Heating

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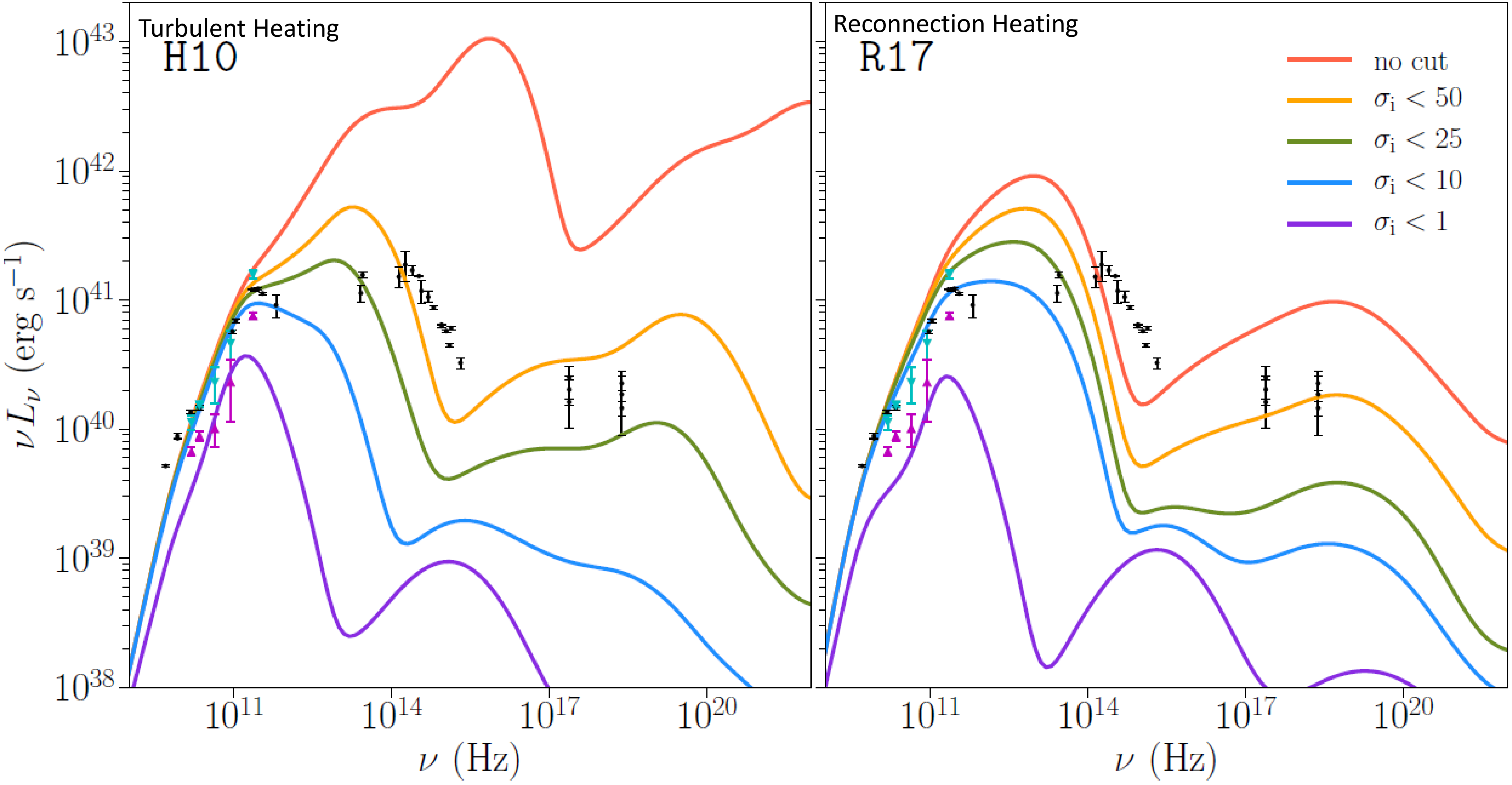
Turbulent Heating

Reconnection Heating

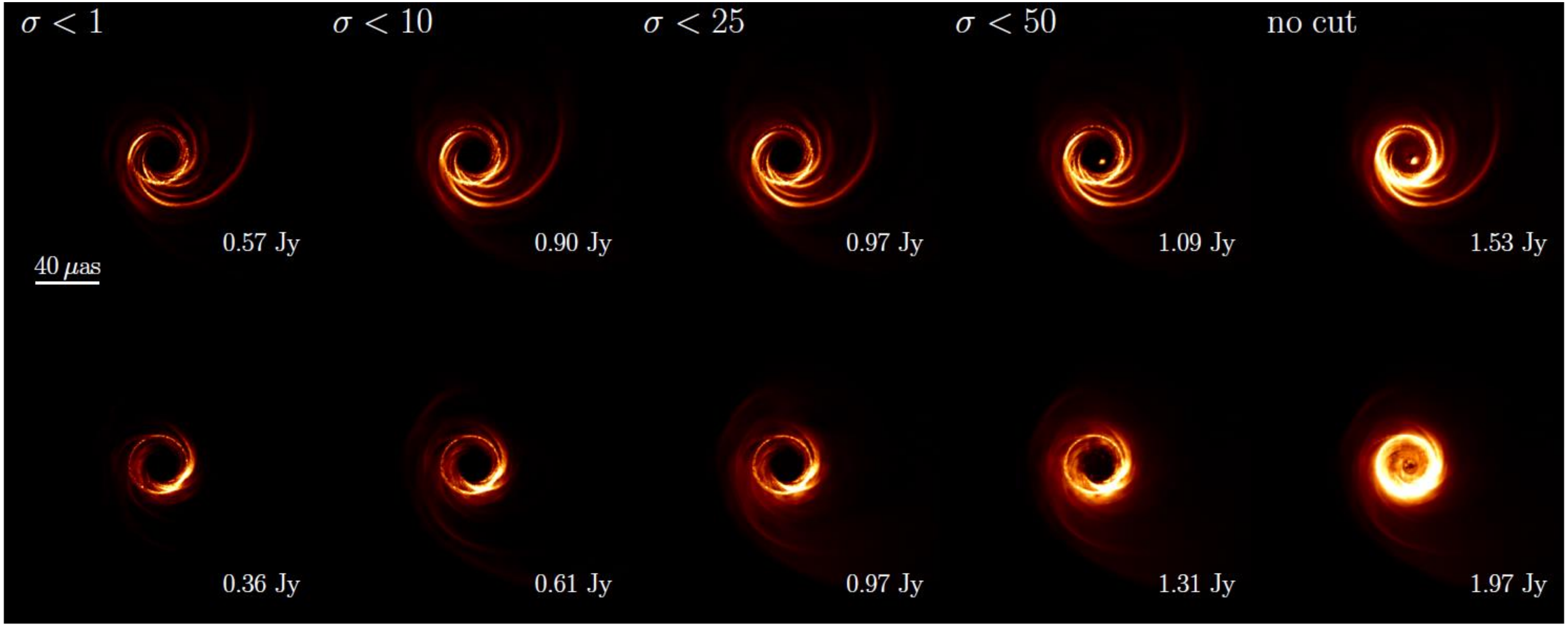
M87 Spectra: dependence on $\sigma_{\rm i}$ cut



Data from Prieto+16

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

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.

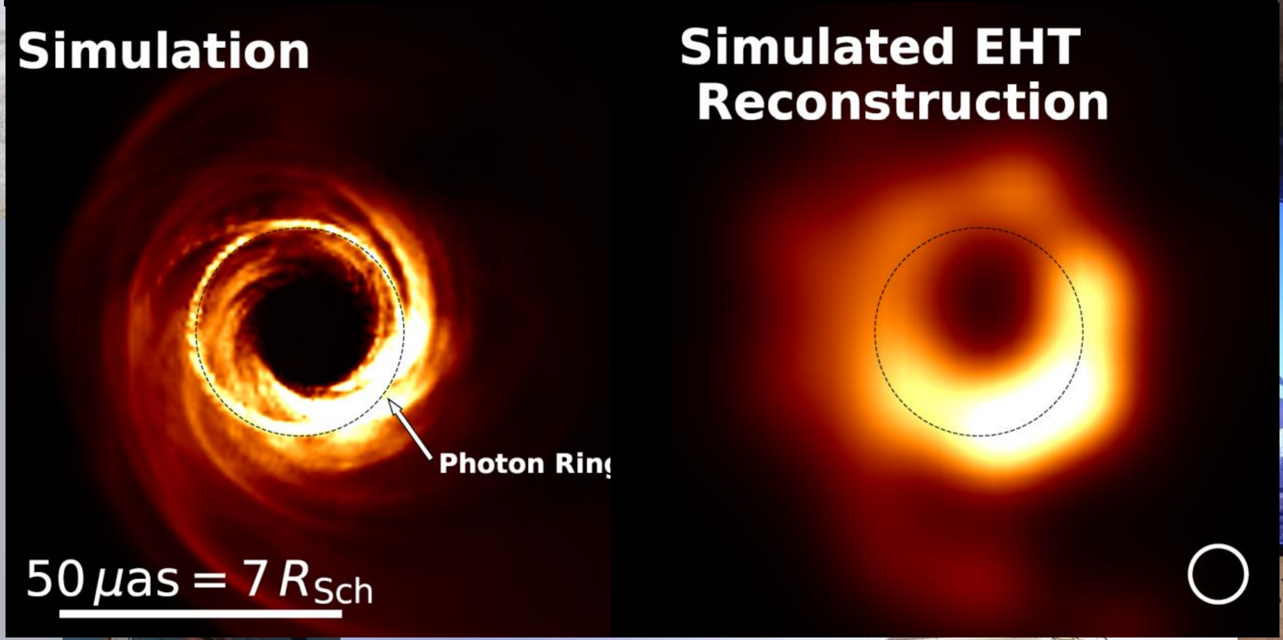
- For **Sgr A*:**
  - Turbulent heating produces a disk-jet structure, which is too anisotropic (when viewed-edge on.)

- 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!



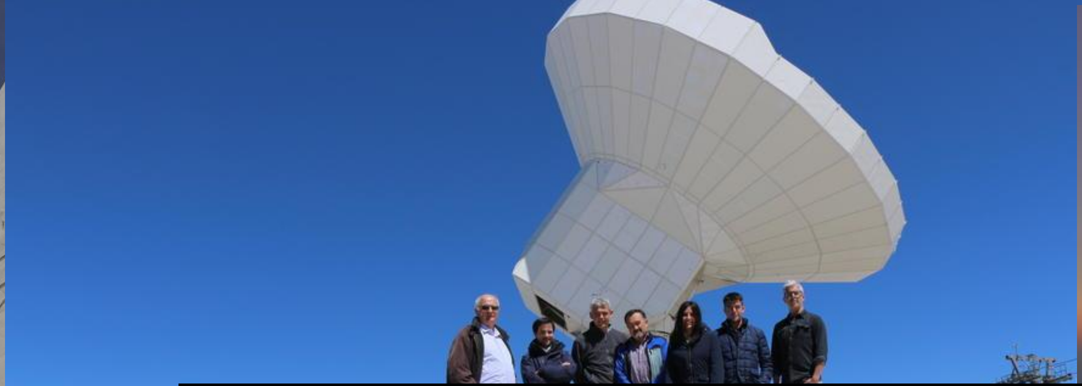


Image credits: Dan Marrone,
David Michalik,Atish Kamble, Junhan Kim , Salvaor Sanchez,
Helge Rottman , Katie Bouman, MIT Haystack Observatory

Thank You!