Towards Understanding Black Hole Accretion and Jet Launching: Linking Simulations to EHT Images

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(he/him)
On behalf of the EHT collaboration

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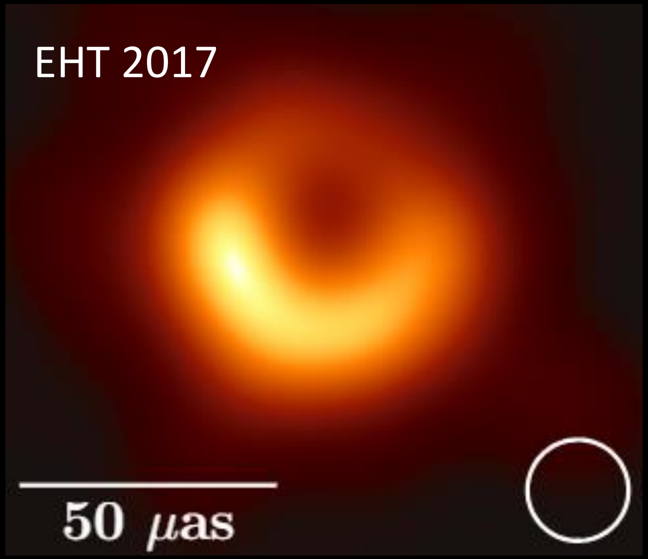
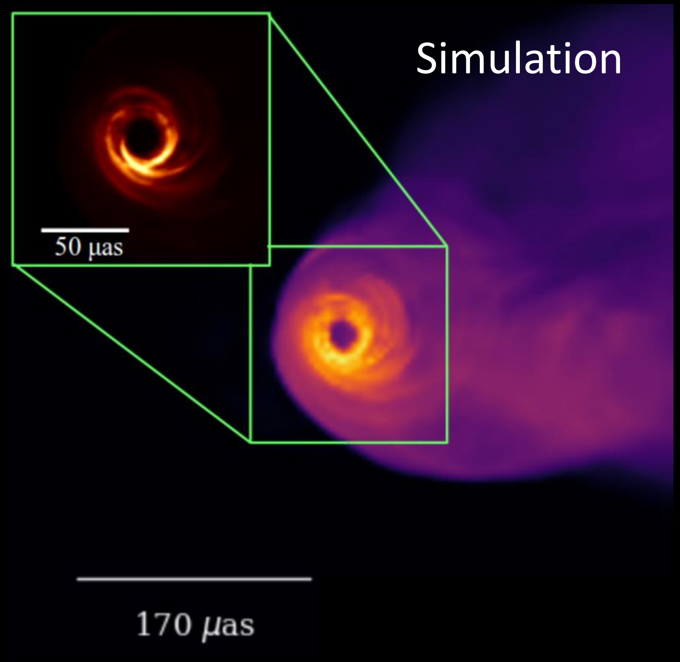
April 18, 2020





Event Horizon Telescope

The EHT Collaboration

Outline

1. Interpreting the EHT image with GRMHD Simulations

2. Going Further
    - Polarization
    - Larger scales
    - Dynamics & Sgr A* Flares
    - Plasma Physics

1. How do we interpret the EHT M87 Image?

M87

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

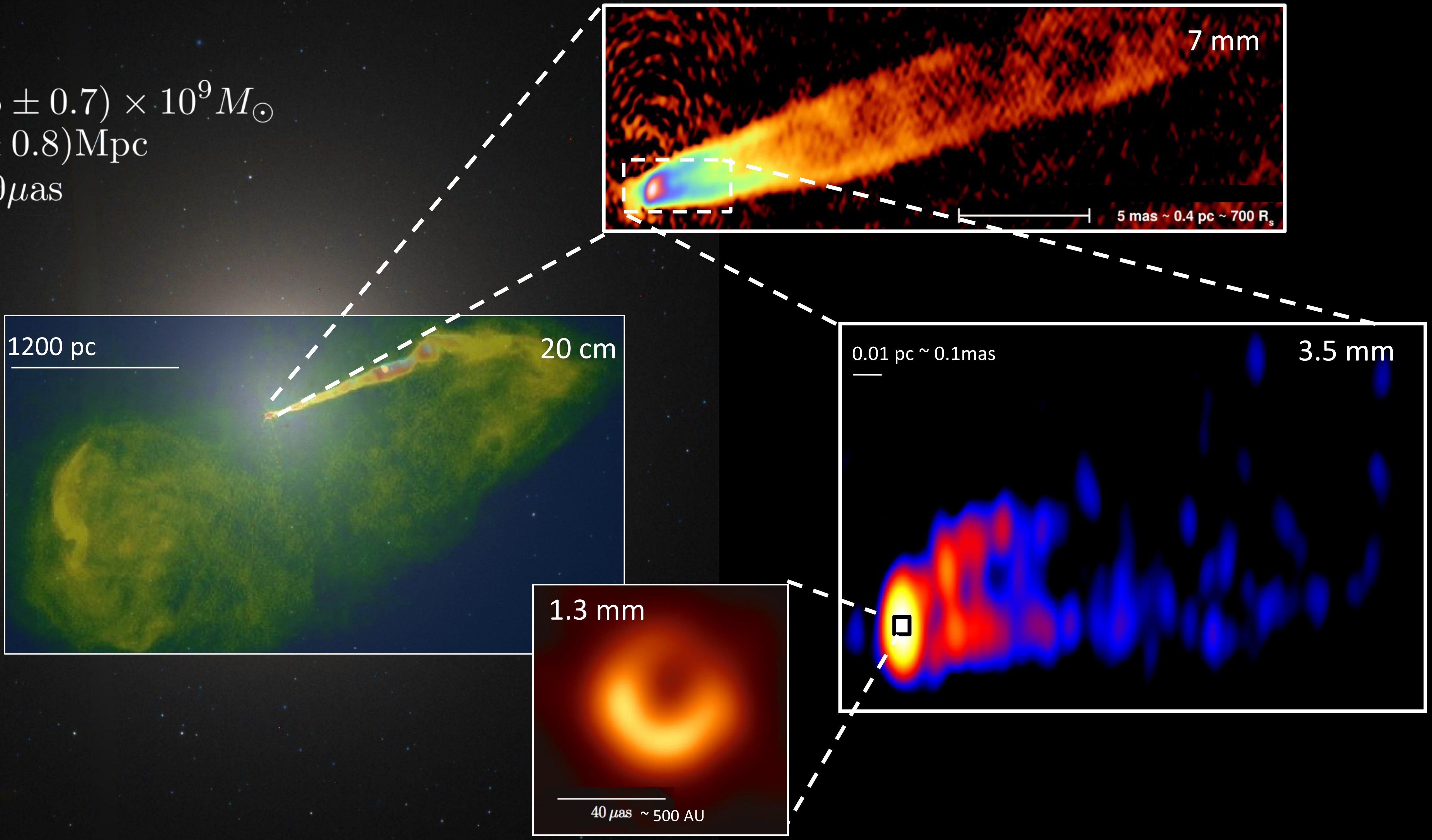
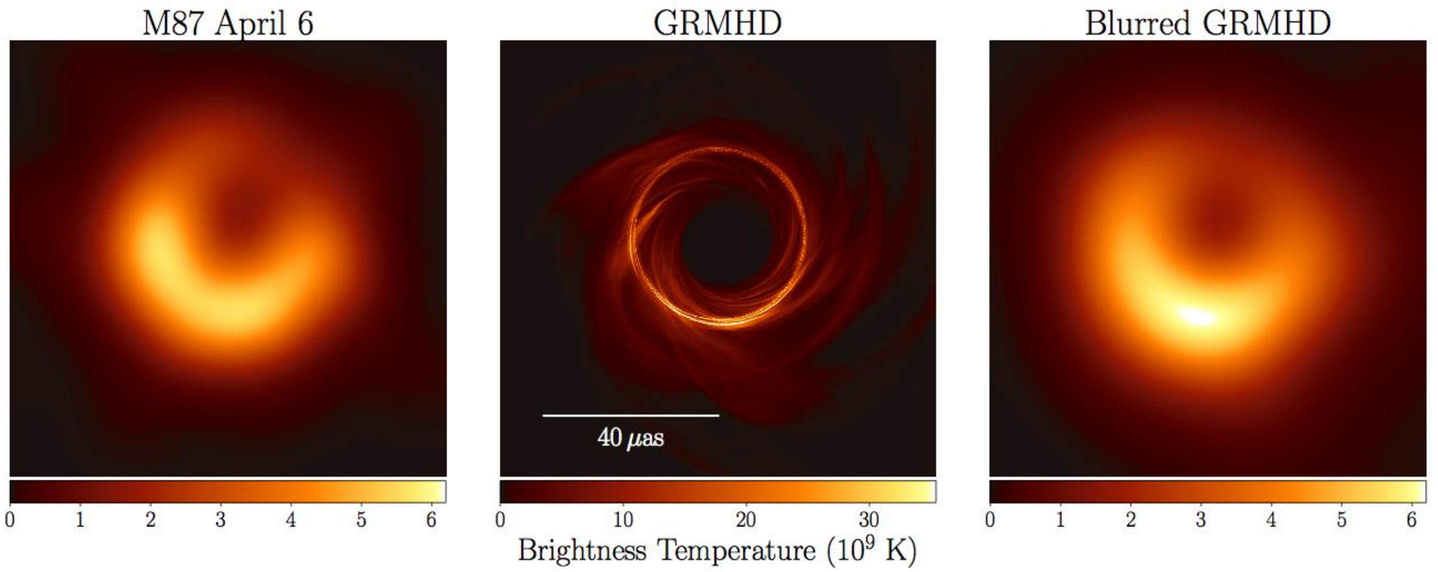


Image Credits: HST(Optical), NRAO (VLA),
Craig Walker (7mm VLBA), Kazuhiro Hada (VLBA+GBT 3mm),
EHT (1.3 mm)

At the heart of M87…

- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$

- Thick accretion flow of hot, ionized plasma ($T \gtrsim 10^{10}\,\mathrm{K}$)



- Launches a powerful relativistic jet ($P_{\rm jet} \geq 10^{42}$ erg s^{-1})
  - Extraction of BH spin energy?

Mass: Gebhardt+ 2011, Walsh+ 2013,
Jet Power: Reynolds+ 1996, Stawarz+ 2006, de Gasperin+ 2012
Simulations: Dexter+2012, Mościbrodzka+2016, Ryan+ 2018, Chael+ 2019, Davelaar+ 2019 ….

Image credit: EHTC+ 2019 Paper V

What parameters determine the images we see?

1. Spacetime geometry: M, a
    - Liberating potential energy heats the plasma.
    - Extraction of spin energy

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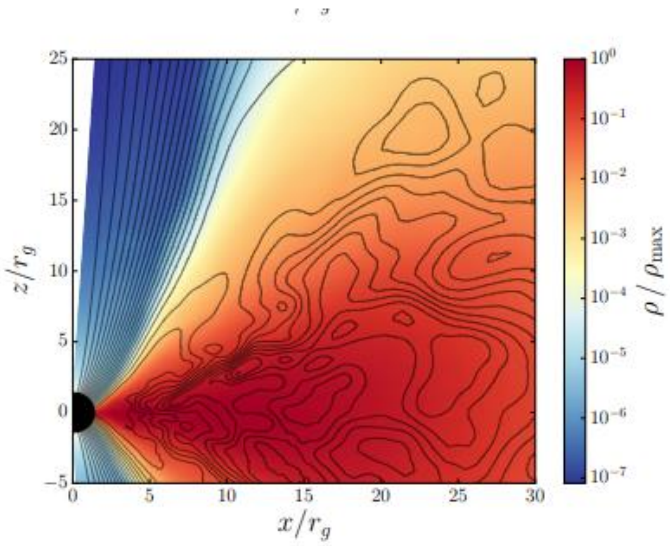
2. (Radiative) Magnetohydrodynamics: $\dot{M}, \Phi_B$
    - Does the magnetic field arrest accretion?
    - How does the B-field determine the jet power & shape?

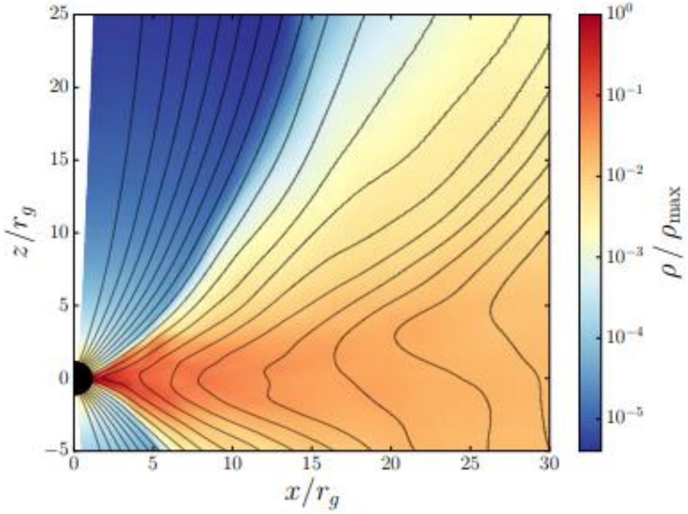
SANE vs MAD

- 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:

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

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012
Image credit: Riordan+ 2017

What parameters determine the images we see?

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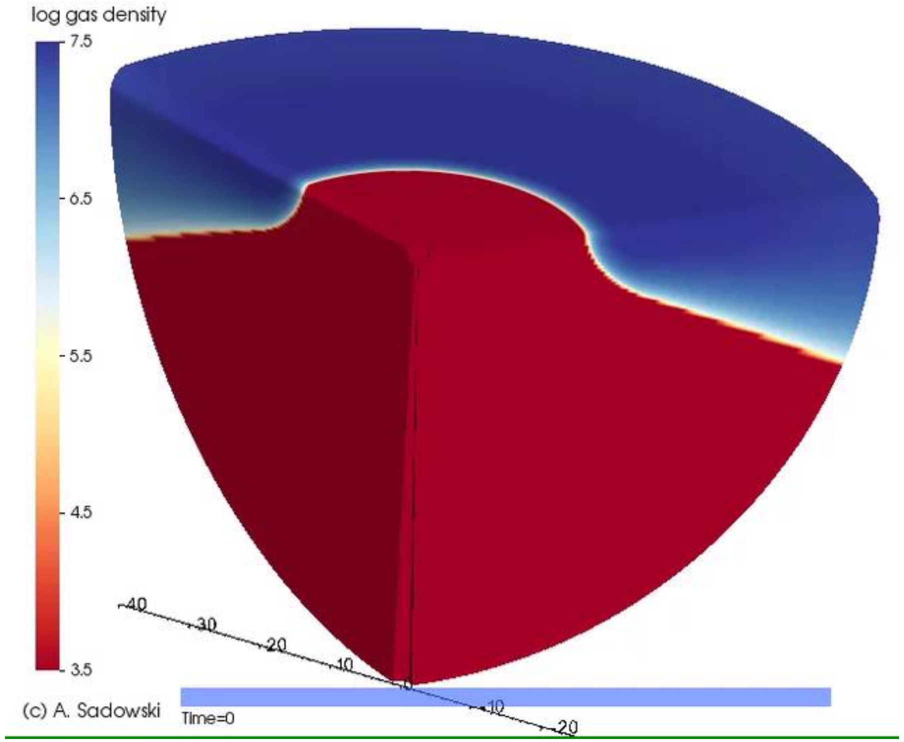
2. (Radiative) Magnetohydrodynamics: $\dot{M}, \Phi_B$
   - Does the magnetic field arrest accretion?
   - How does the B-field determine the jet power & shape?

3. Electron distribution functions: $T_e, n_e(\gamma)$
   - Electrons and ions are not in equilibrium in hot flows
   - What is the electron temperature?
   - Is there a nonthermal population?

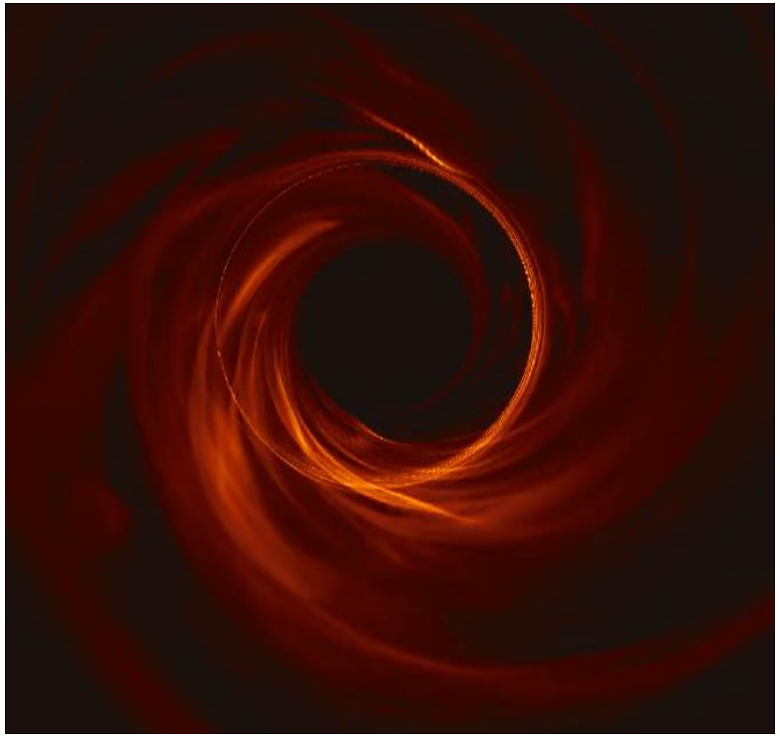
General **R**elativistic **M**agneto**H**ydro**D**ynamics (GRMHD)



Solves coupled equations of fluid dynamics and magnetic field in Kerr spacetime

$T_e?$

General **R**elativistic **R**ay **T**racing (GRRT)

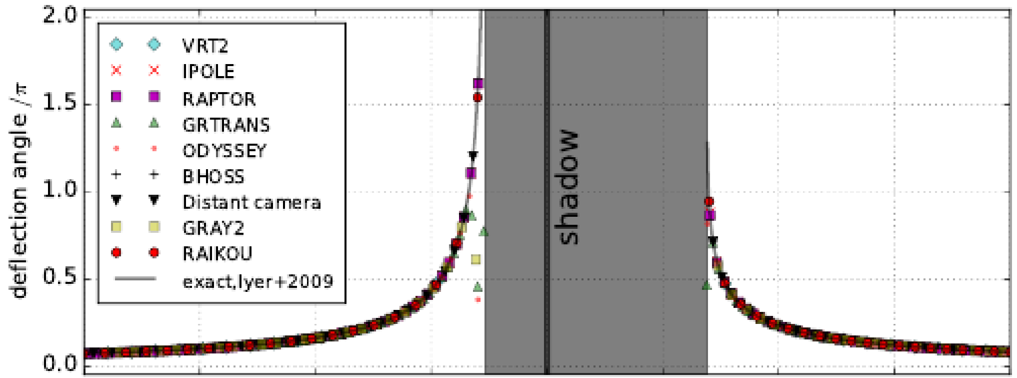


Tracks light rays and solves for the emitted radiation

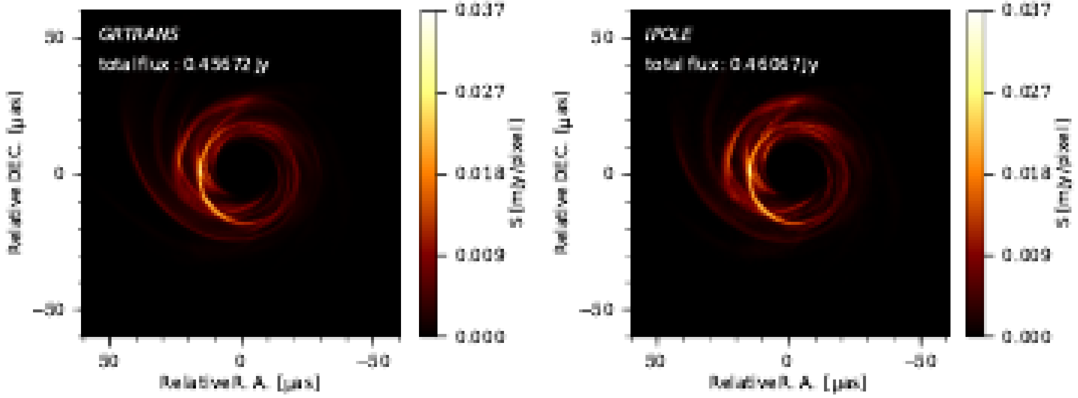
Movie Credits: Aleksander Sądowski,
EHT Collaboration 2019 (Paper V)

Validating GRRT codes

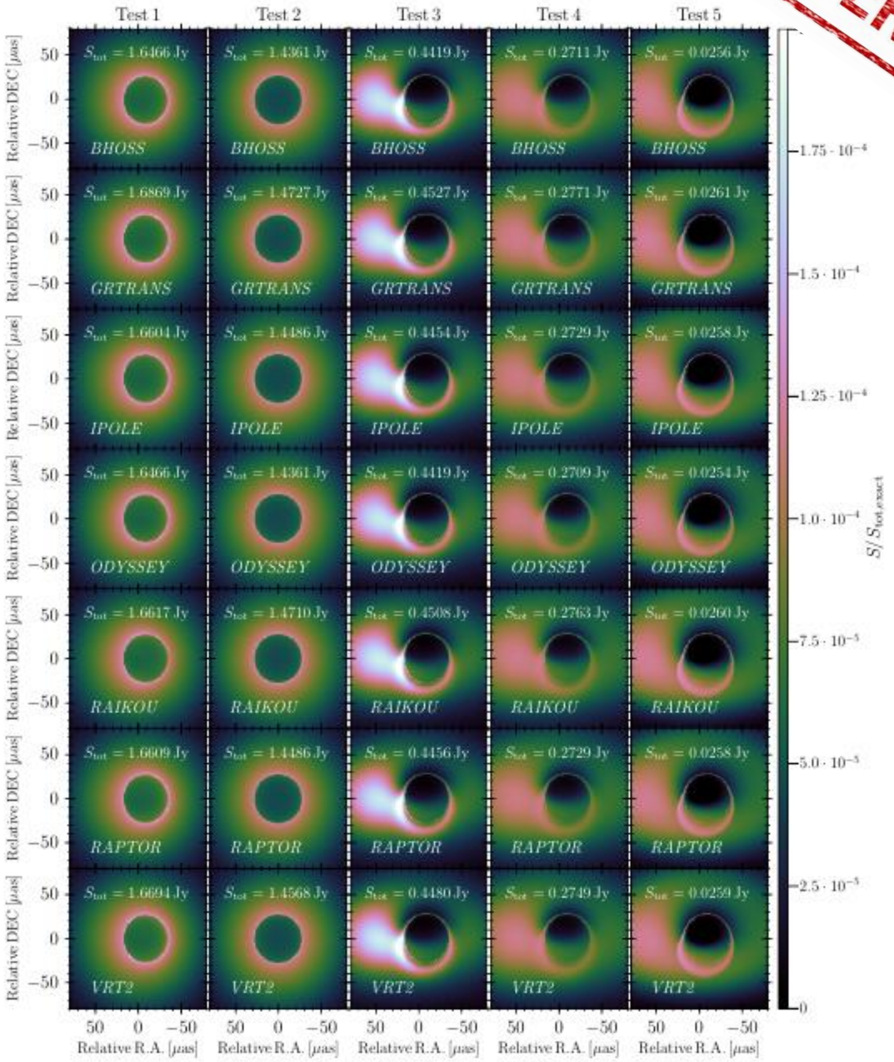
VERIFIED



Deflection Angle Test



GRMHD Image Tests

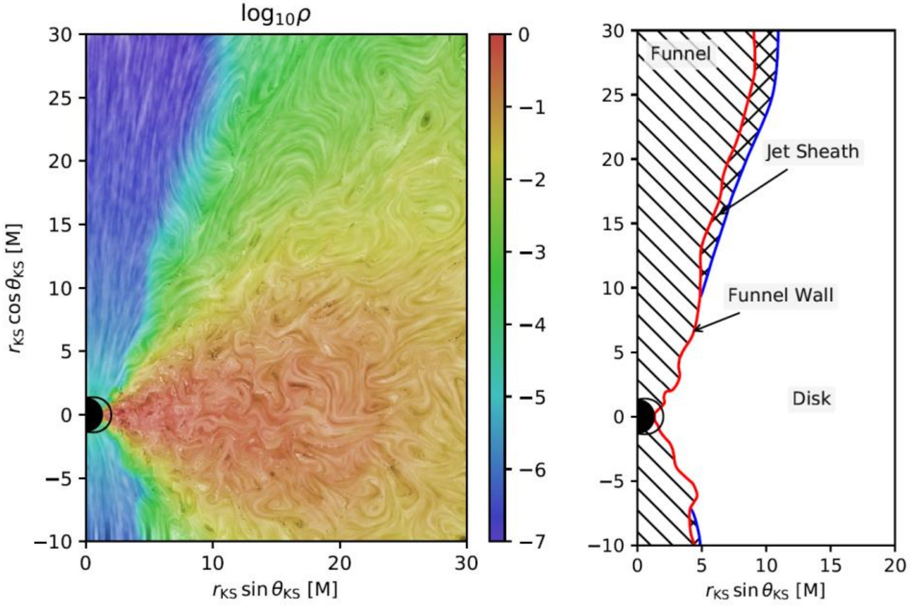


Analytic Model Tests

Gold+ EHTC 2020 (in prep)

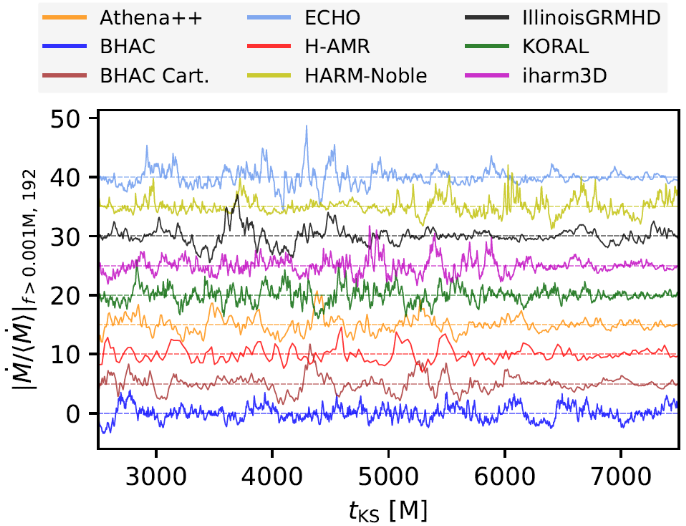
Validating GRMHD codes

VERIFIED

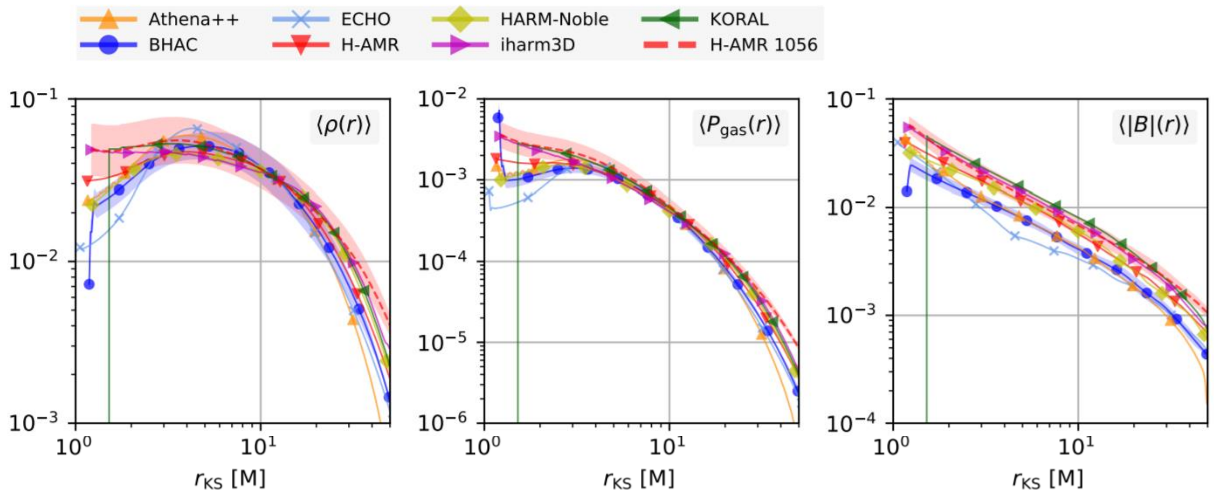


SANE disk test problem.
9 codes used different grids, reconstruction schemes, numerical floors, boundary conditions

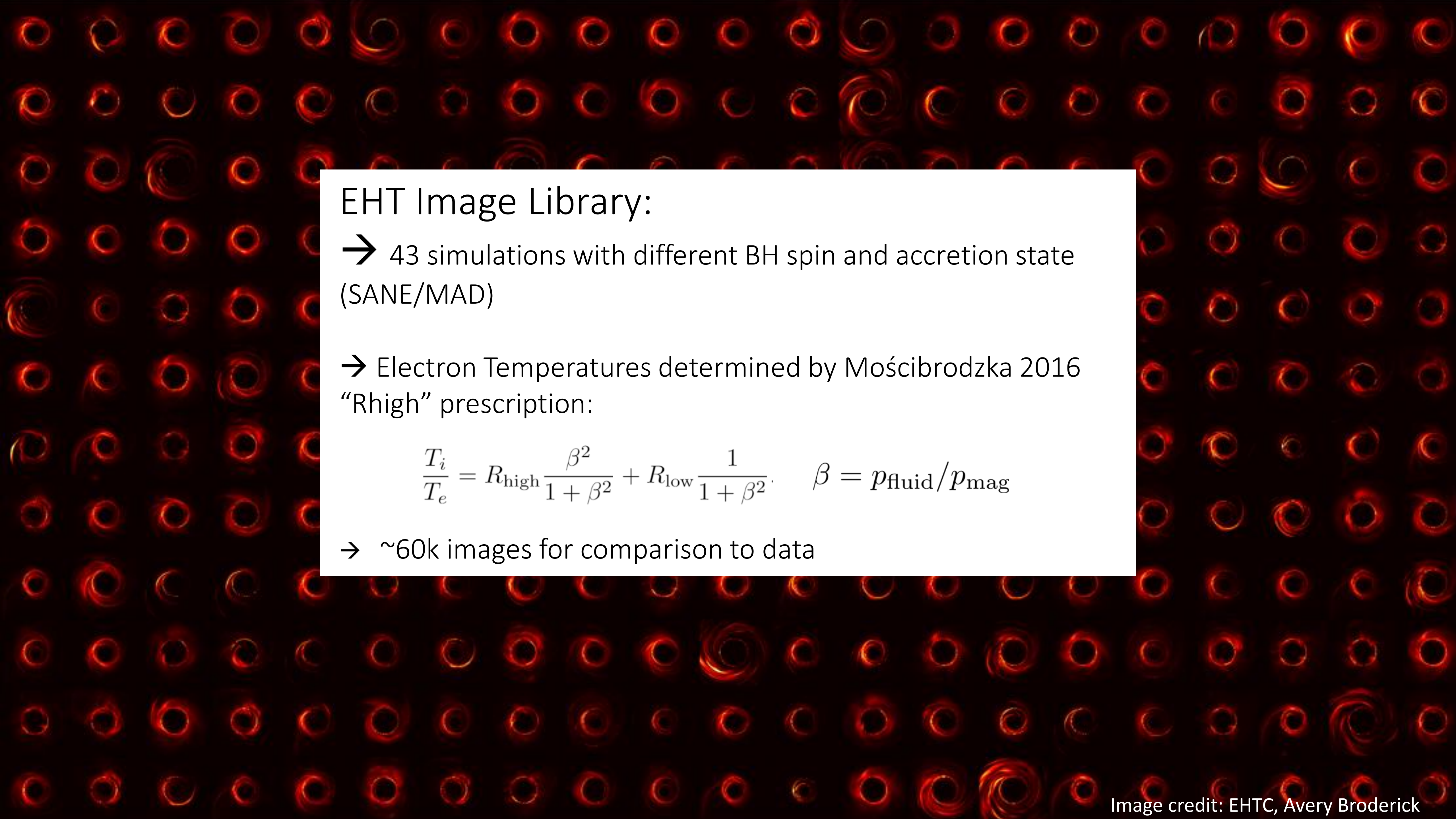
Porth+ EHTC 2020
1904.04923



Codes differ in turbulent realizations…



… but produce consistent disk and jet profiles



EHT Image Library:

→ 43 simulations with different BH spin and accretion state (SANE/MAD)

→ Electron Temperatures determined by Mościbrodzka 2016 “Rhigh” prescription:

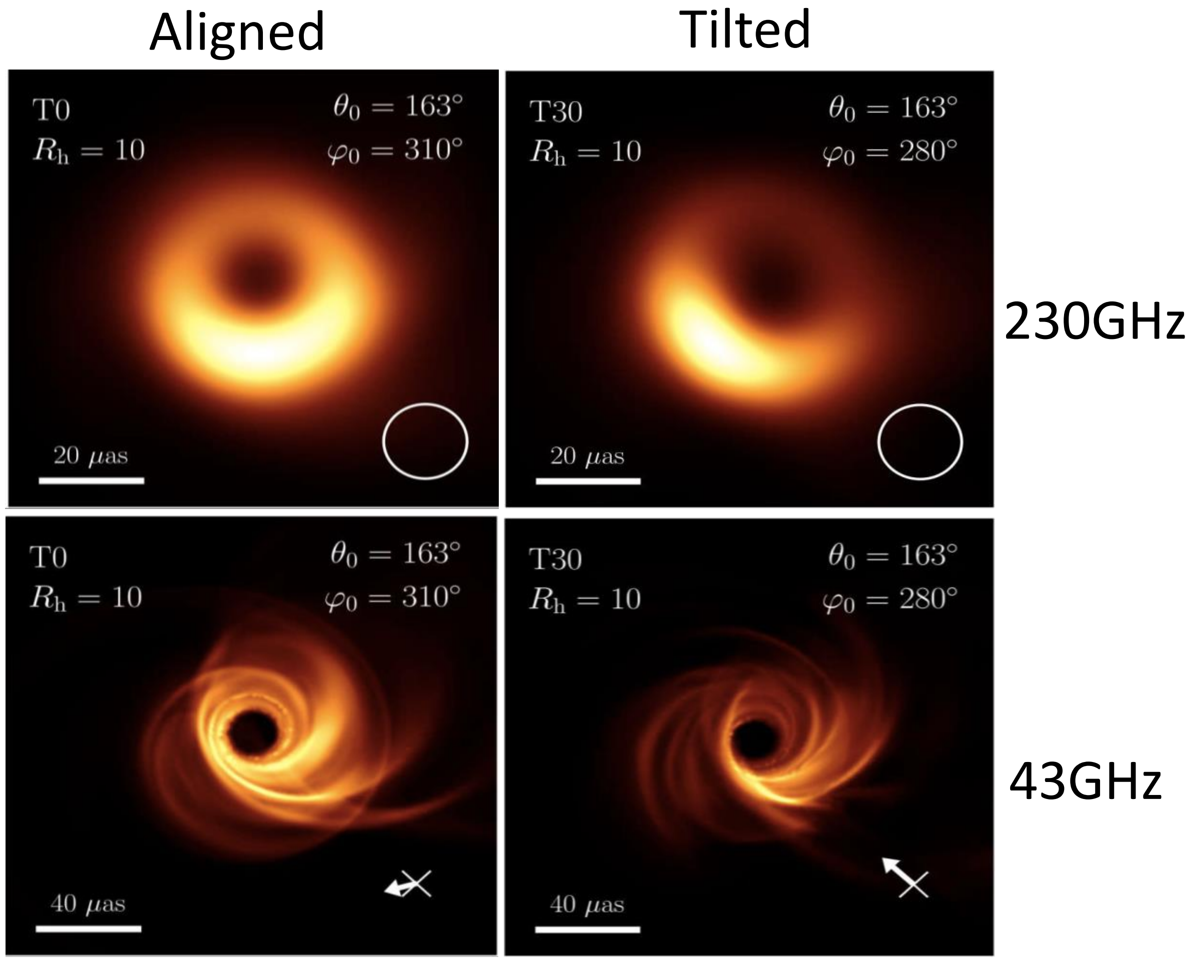
$$\frac{T_i}{T_e} = R_{\mathrm{high}}\frac{\beta^2}{1+\beta^2} + R_{\mathrm{low}}\frac{1}{1+\beta^2} \qquad \beta = p_{\mathrm{fluid}}/p_{\mathrm{mag}}$$

→ ~60k images for comparison to data

Image credit: EHTC, Avery Broderick

Caveat: EHT simulation library has no tilted disks

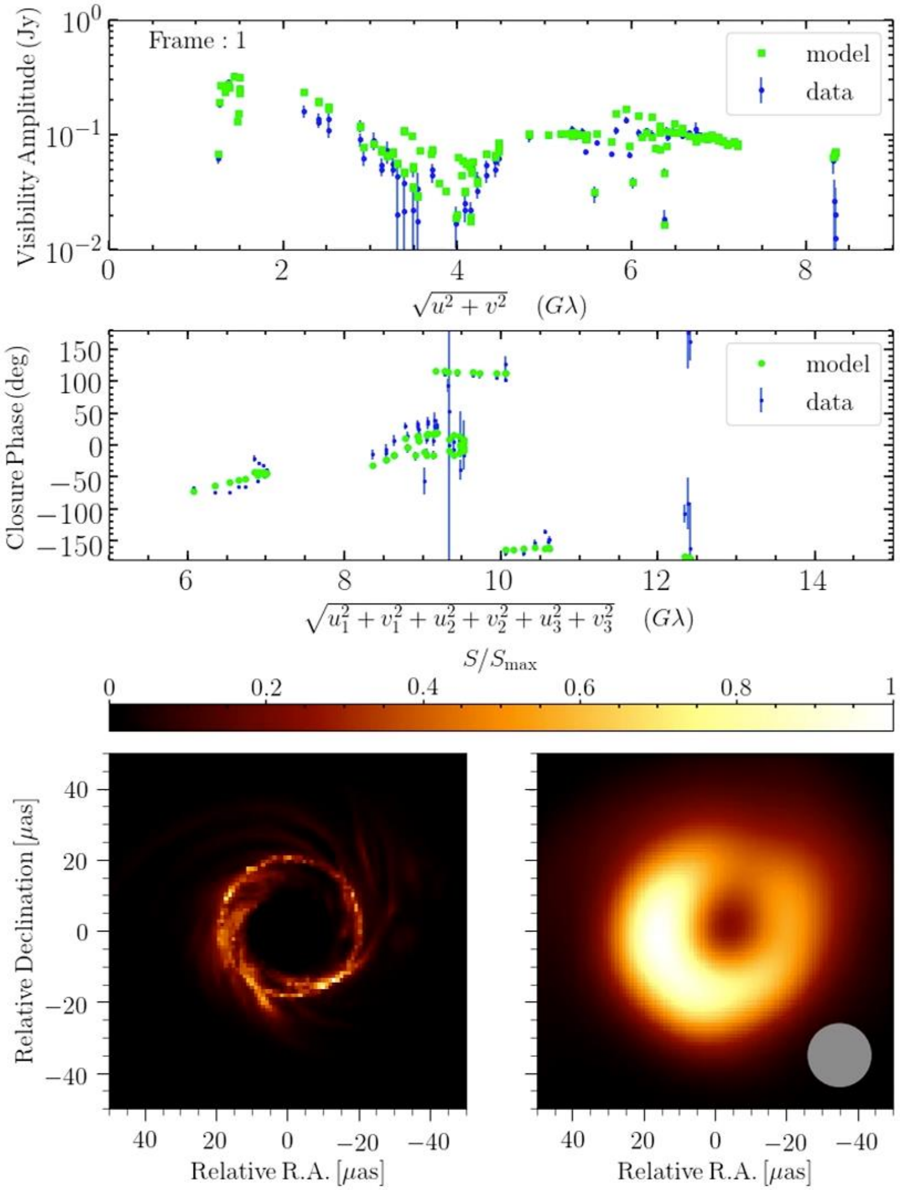
- All EHT library simulations have disk angular momentum **parallel/antiparallel** to BH spin axis
- In tilted-disk simulations, **lensing** of the inner disk/jet base can result in vastly different 230 GHz images even though 43 GHz images are similar
- Need a library of tilted disk systems!



Chatterjee+20
2002.08386

also: Fragile+07, Dexter+11, McKinney+13, Liska+18, White+19,+20

Fitting Simulations to EHT observations



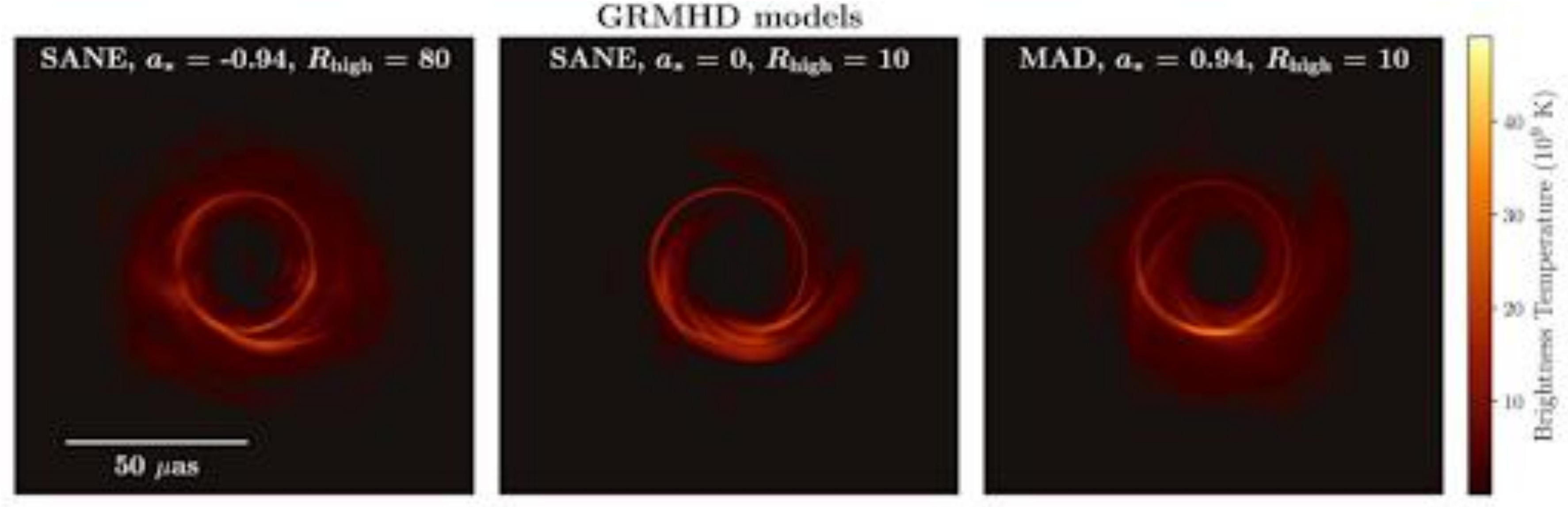
- We fit frames to data by varying the **angular size, total flux, and sky position angle**

- Since each simulation runs for only a limited time, no single frame is likely to exactly match the observations

- **Average Image Scoring**: given a distribution of fit statistics to many frames from a given simulation, how likely are we to get a good fit if the underlying simulation ran forever?

Model Selection

- Most models can be made to fit EHT observations alone by tweaking free parameters (mass, PA, total flux density)



- The **jet power constraint** (≥ 10^{42} erg/sec) rejects all spin 0 models

  SANE models with |a| < 0.5 are rejected.
  Most |a| > 0 MAD models are acceptable.

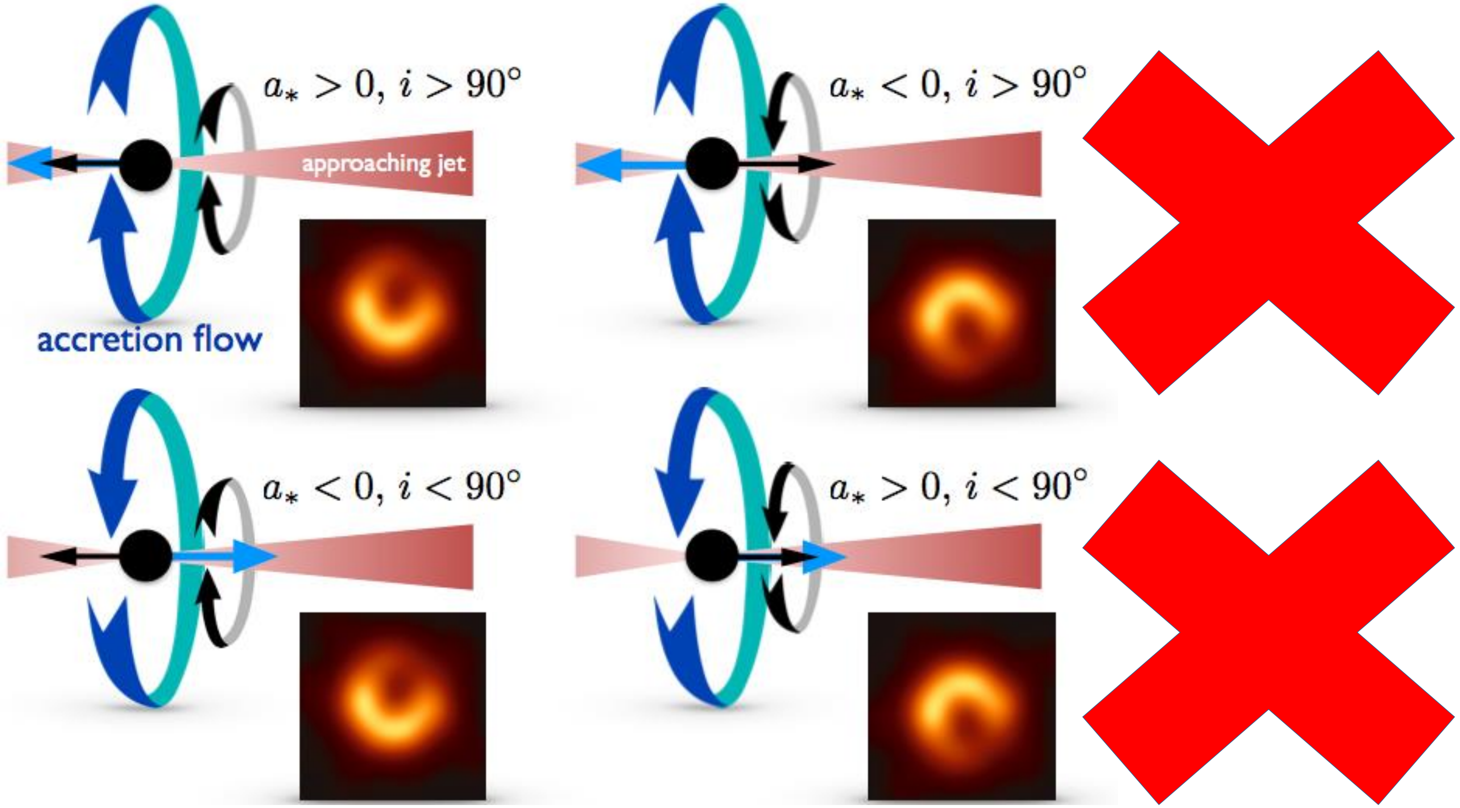
- In all successful models, jet is **driven by extraction of black hole spin energy**

Blandford-Znajek (1977): $P_{\rm jet} \propto \Phi_B^2 a^2$

EHTC+ Paper V, 2019

Ring Asymmetry and Black Hole Spin

It is the **BH angular momentum**, not the **disk angular momentum** that determines the image orientation

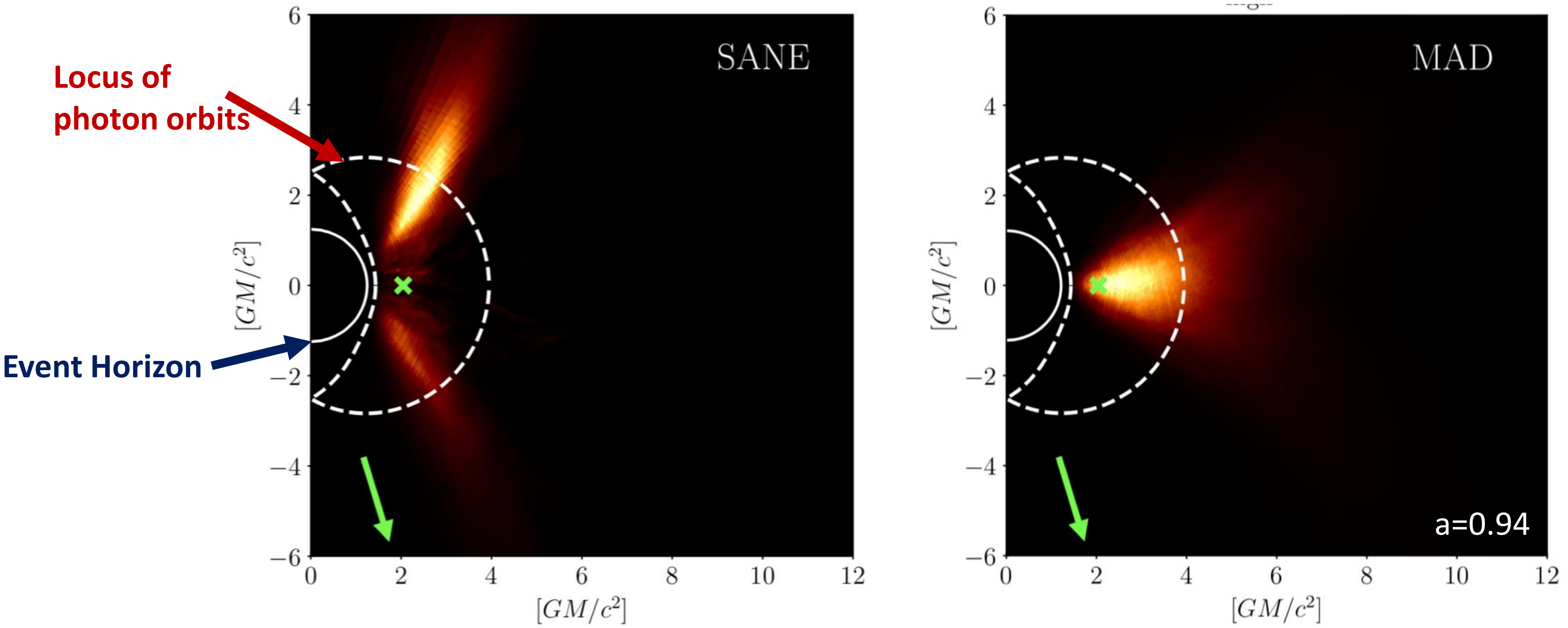


BH spin-away (clockwise rotation) models are strongly favored

EHTC+ 2019, Paper V

Where does the emission come from?

In all surviving models emission region is within ~5 gravitational radii of the black hole



Locus of photon orbits

Event Horizon

Typical plasma parameters: $T_e \sim 10^{12}\,\mathrm{K}\,,\; B \sim 5\,\mathrm{G}\,,\; n_e \sim 10^4\,\mathrm{cm}^{-3}$

Polarization can help distinguish between these scenarios!

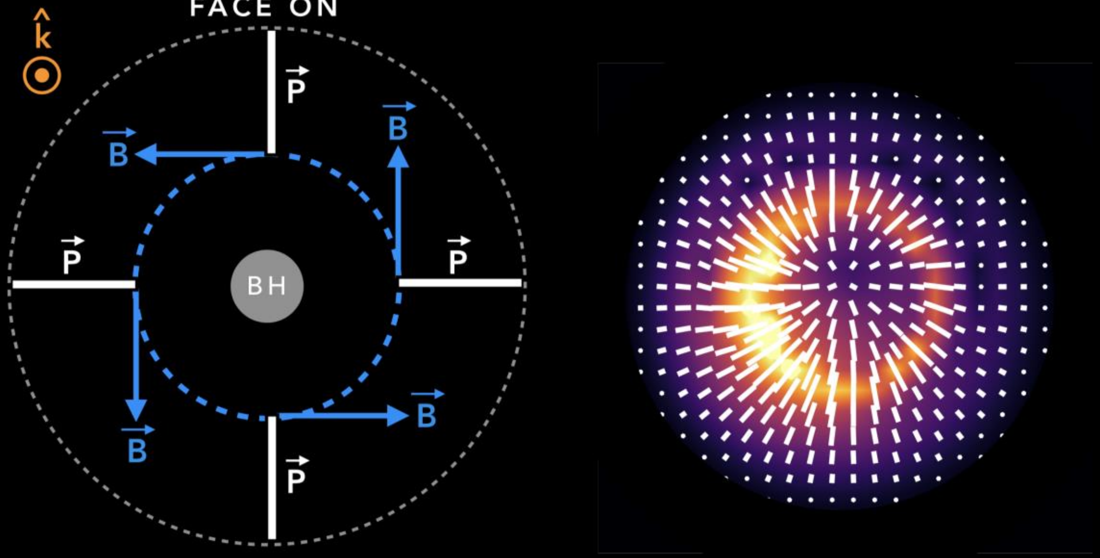
EHTC+ 2019, Paper V

2. Going Further

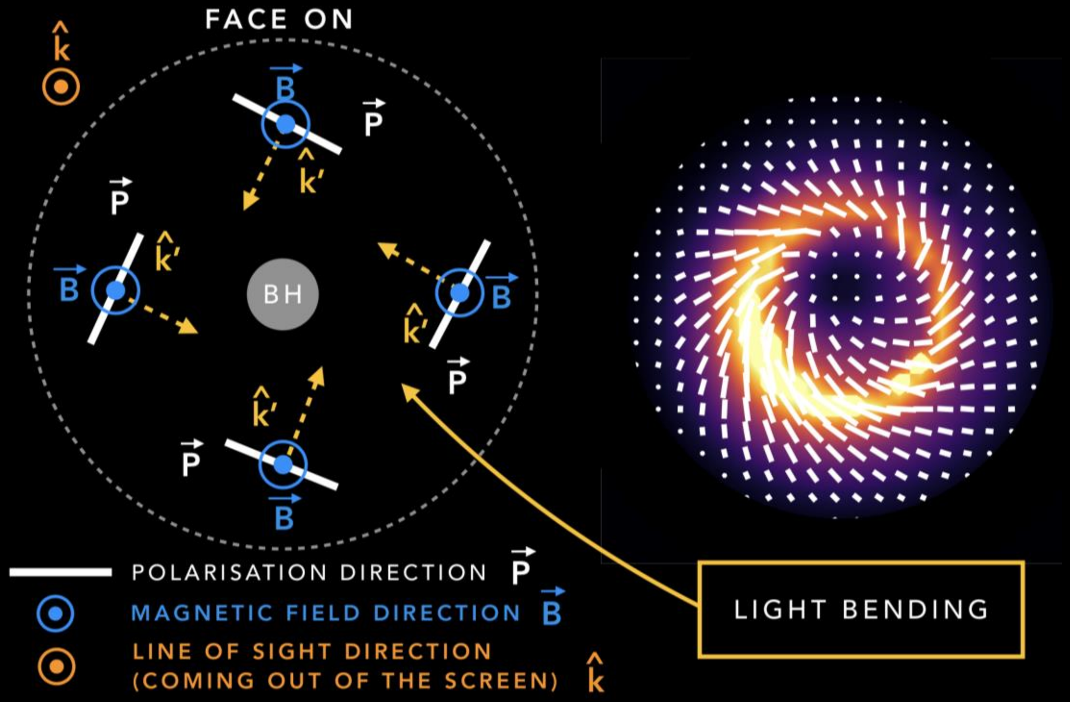
Polarization, Large Scales, Dynamics, Plasma Physics

Polarization: Traces magnetic fields

Toroidal Field: ~SANE like



Vertical field: ~MAD like



Vertical field scenario would be unpolarized without GR!

Image credit: Alejandra Jiménez-Rosales

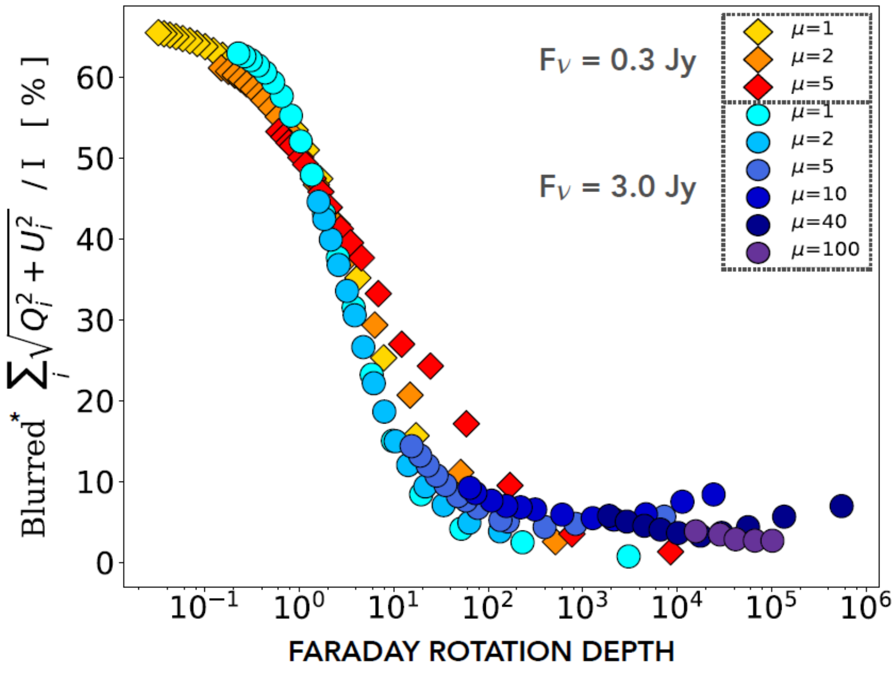
Polarization: Faraday Effects

Optical depth to Internal Faraday Rotation:

$$\tau_{\rm FR} \sim \left(\frac{R}{R_{\rm Sch}}\right)\left(\frac{n_e}{10^6\,{\rm cm^{-3}}}\right)^{3/2}\left(\frac{\theta_e}{10}\right)^{-2}\left(\frac{\beta}{10}\right)^{-1/2}$$

Increasing Faraday Depth
→ more image depolarization

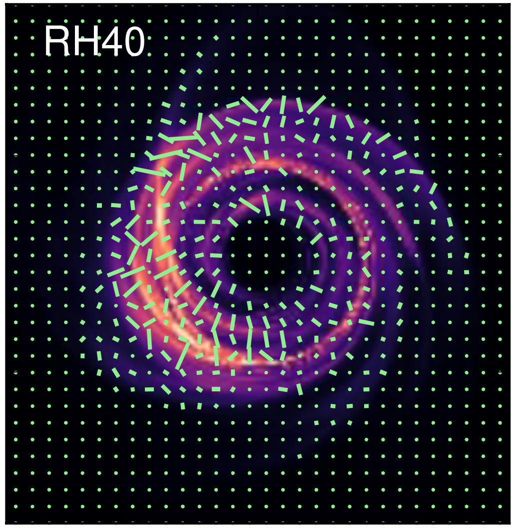
μ = **T**



Jiménez-Rosales+ 2018

The amount of internal Faraday rotation depends on emission origin

Broderick & Loeb 2009
Forward jet: LP~10%



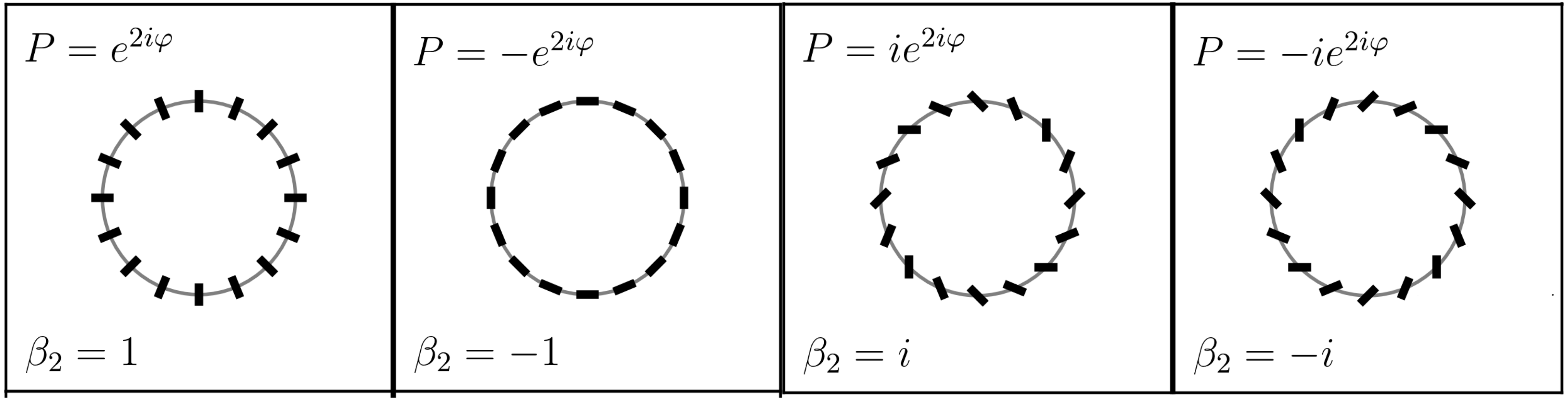
Mościbrodzka+ 2017
Counter jet: LP~1%

Polarization: Pattern Trends in the Image Library

- Fourier decomposition of azimuthal polarized flux:

$$\beta_m = \frac{1}{I_{\rm ann}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_{0}^{2\pi} P(\rho, \varphi)\, e^{-im\varphi}\, \rho\, \mathrm{d}\varphi\, \mathrm{d}\rho,$$

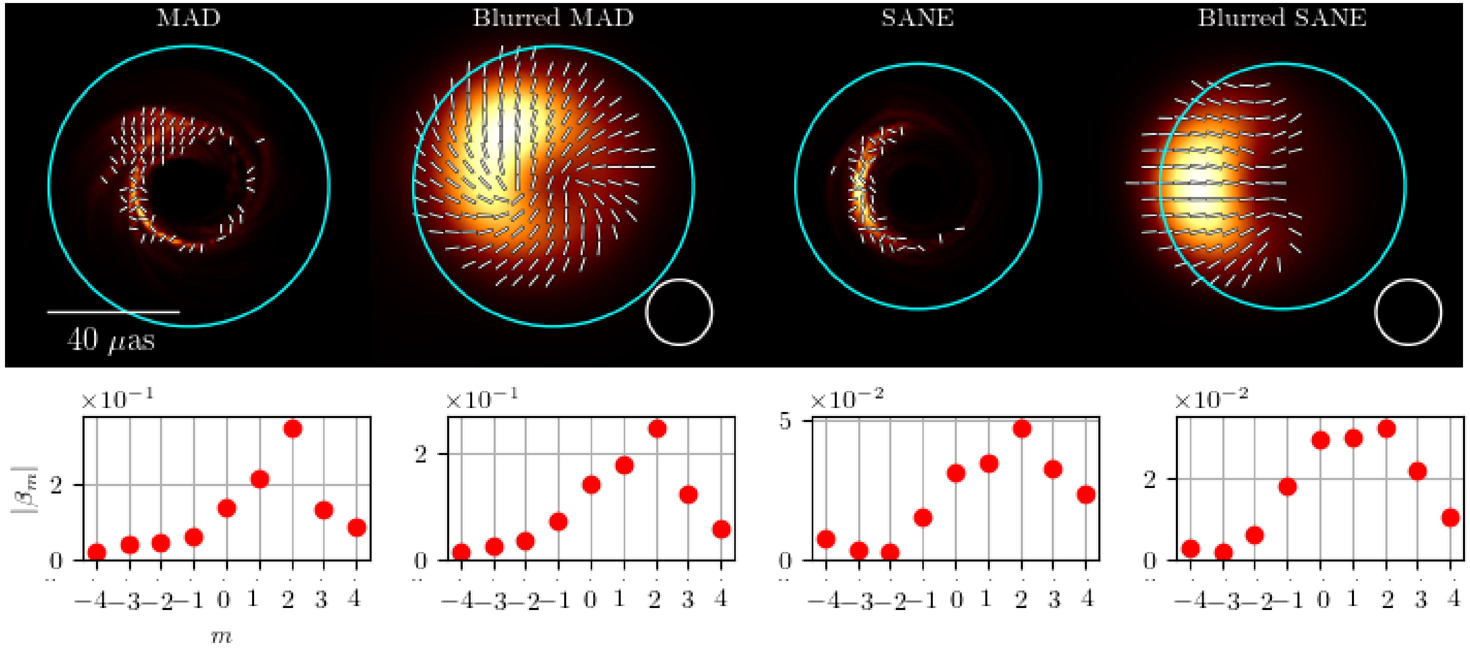
- *m*=2 mode picks out rotationally symmetric part (equivalent to E & B modes)

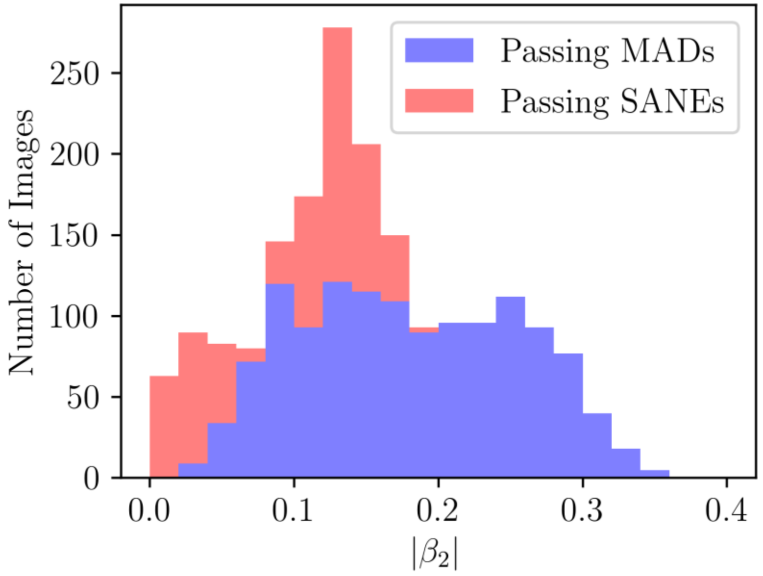


Palumbo+ 2020
2004.01751

Polarization: Pattern Trends in the Image Library

- MADs tend to have more power in m=2 mode, prefer toroidal or twisty EVPA patterns:

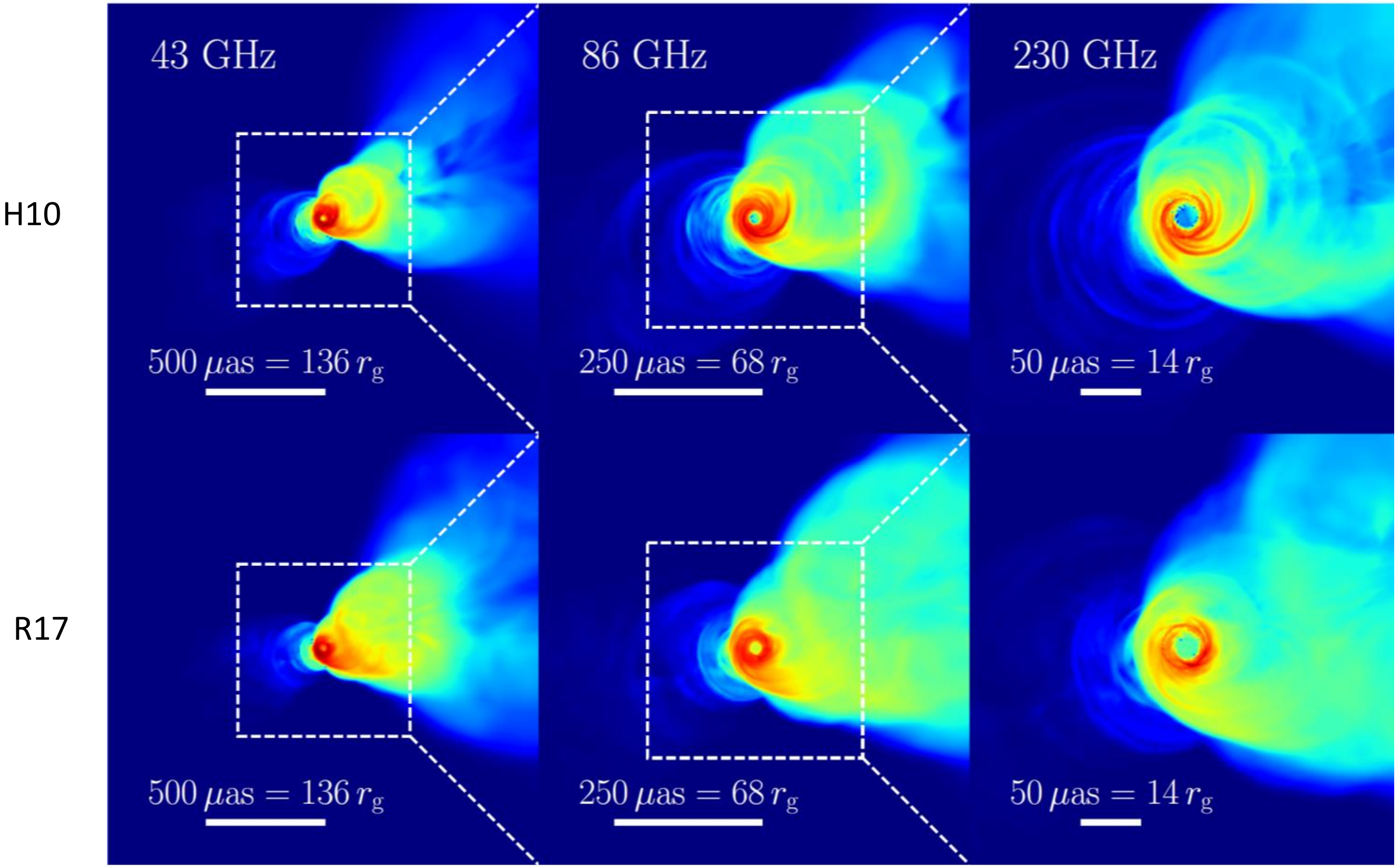




- Azimuthal decomposition of polarized flux can help to distinguish between accretion states

Palumbo+ 2020
2004.01751

Connecting to Larger Scales: Radiative MAD jet simulations



Inclination angle
(down from pole)

17°

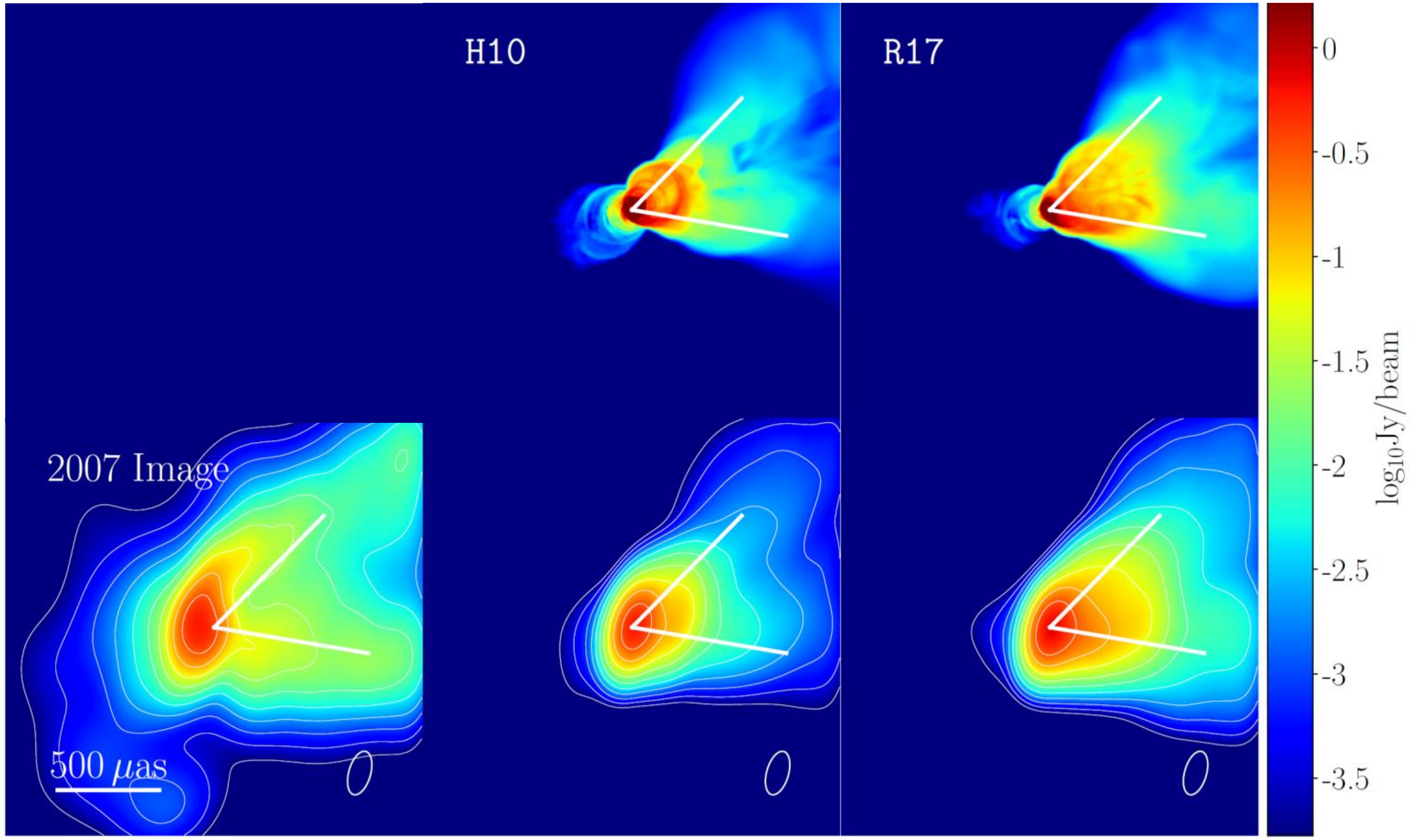
Wide apparent opening angles get **larger** with increasing frequency

Chael+ 2019: 1810.01983

Connecting to Larger Scales:
Radiative MAD jet simulations at 43 GHz

High Resolution

VLBA Resolution



Apparent opening angle at 43 GHz:

$55°$

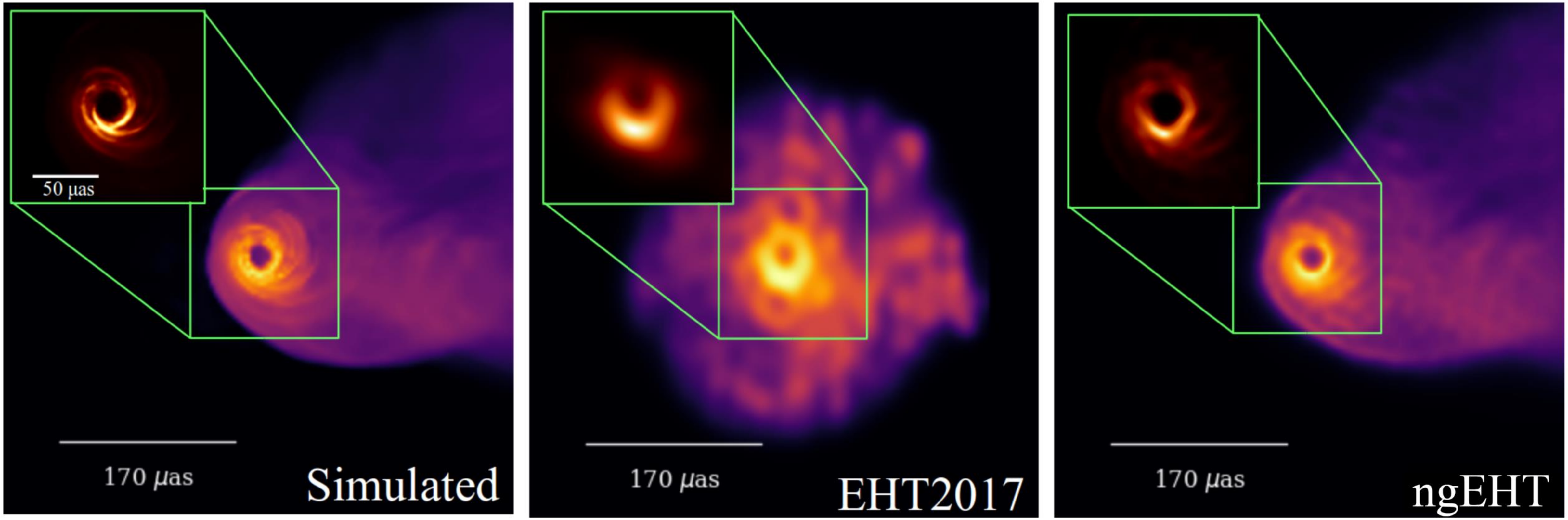
(Walker+ 2018)

The mechanical jet power in R17 is in the measured range of 10^{43} – 10^{44} erg/s!

Chael+ 2019: 1810.01983

VLBA Image Credit: Chael+ 2018a
Original VLBA data: Walker+ 2018

Connecting to Larger Scales:
ngEHT will illuminate the BH-jet connection

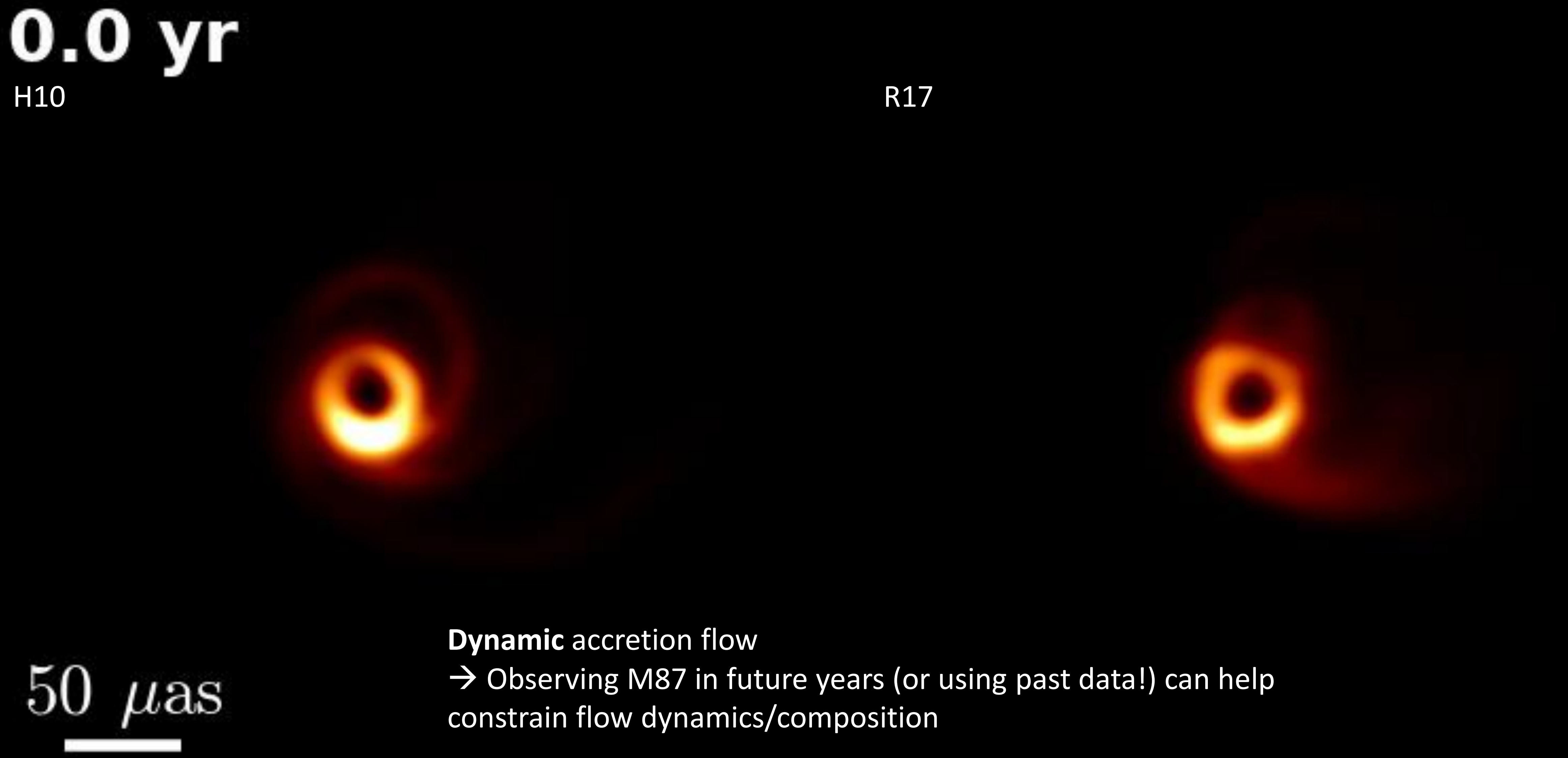


The current EHT lacks <u>short</u> baselines, which are necessary to detect extended structure.

With more dishes added to the array, we will be able to observe the BH-jet connection near the horizon

Image Credit: Michael Johnson
EHT Astro2020 APC White Paper
(Blackburn, Doeleman+; 1909.01411)

Time variability: M87



Dynamic accretion flow
→ Observing M87 in future years (or using past data!) can help constrain flow dynamics/composition

Chael+ 2019: 1810.01983

Time variability: Sgr A*

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

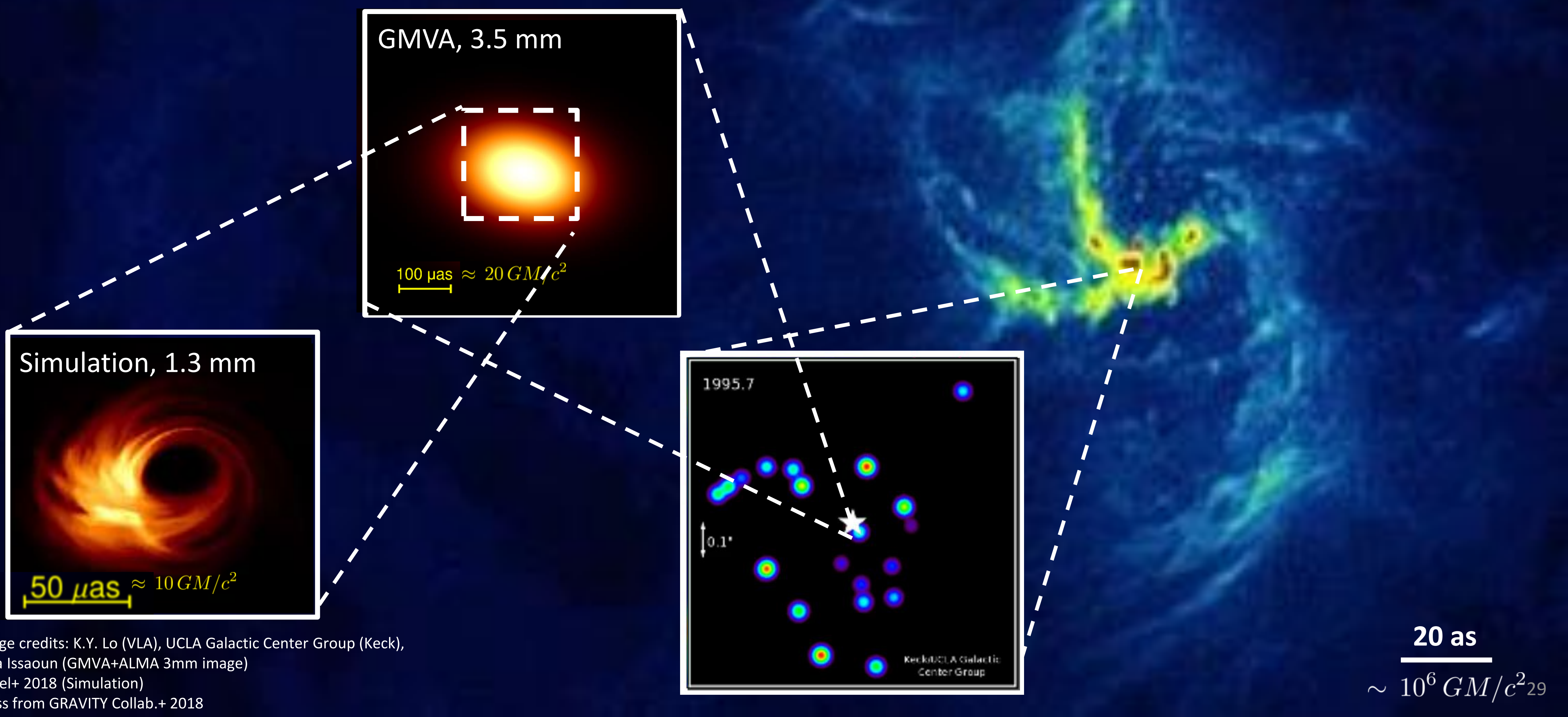
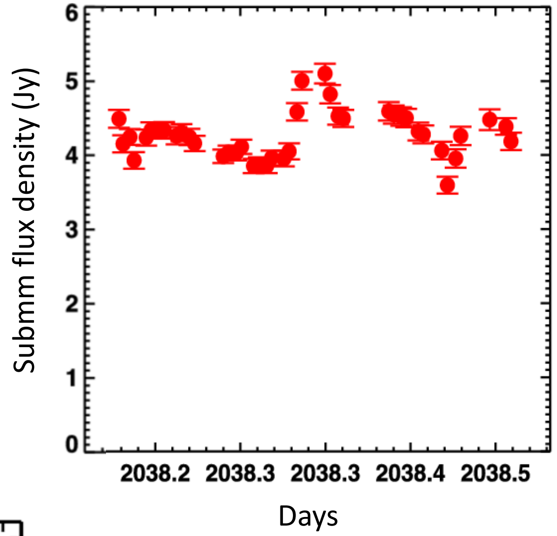
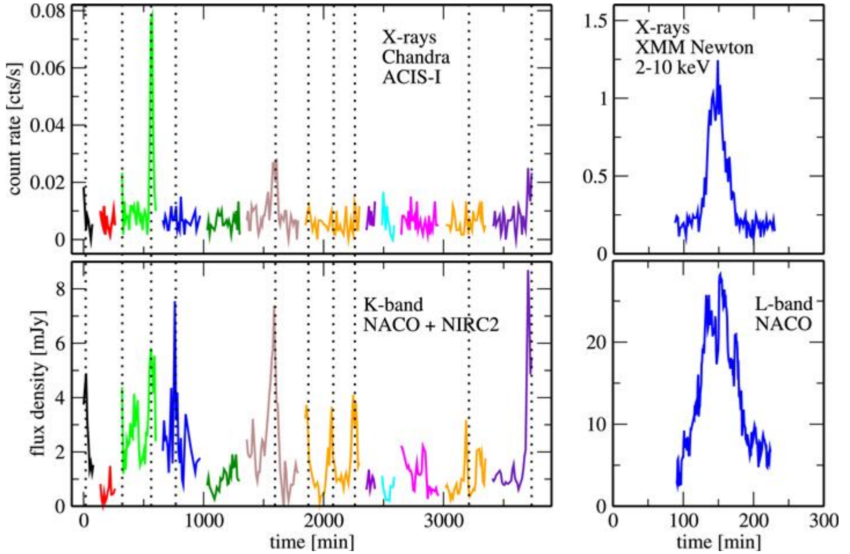


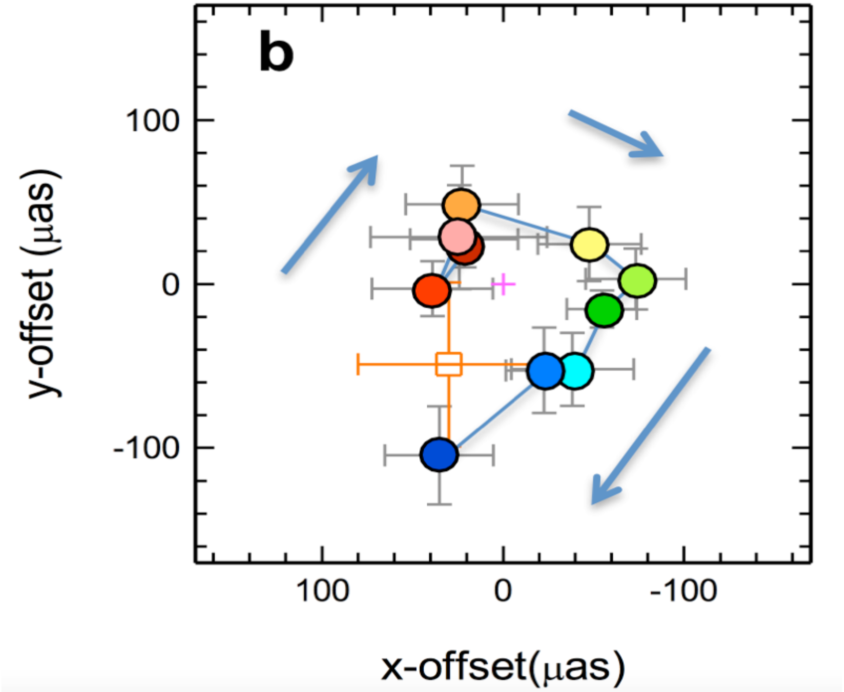
Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck),
Sara Issaoun (GMVA+ALMA 3mm image)
Chael+ 2018 (Simulation)
Mass from GRAVITY Collab.+ 2018

Time variability: Sgr A* Flares

- Intra-day 1.3 mm variability in Sgr A* on minute-hour timescales makes imaging very hard!





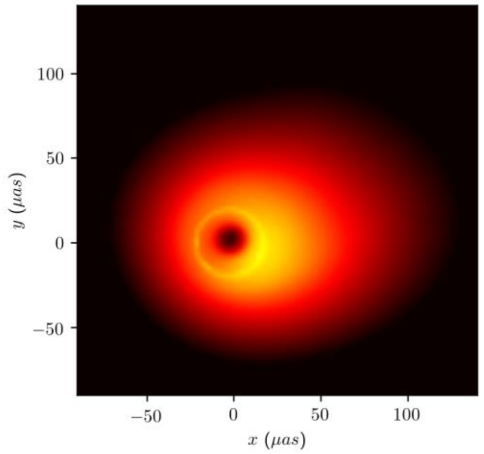


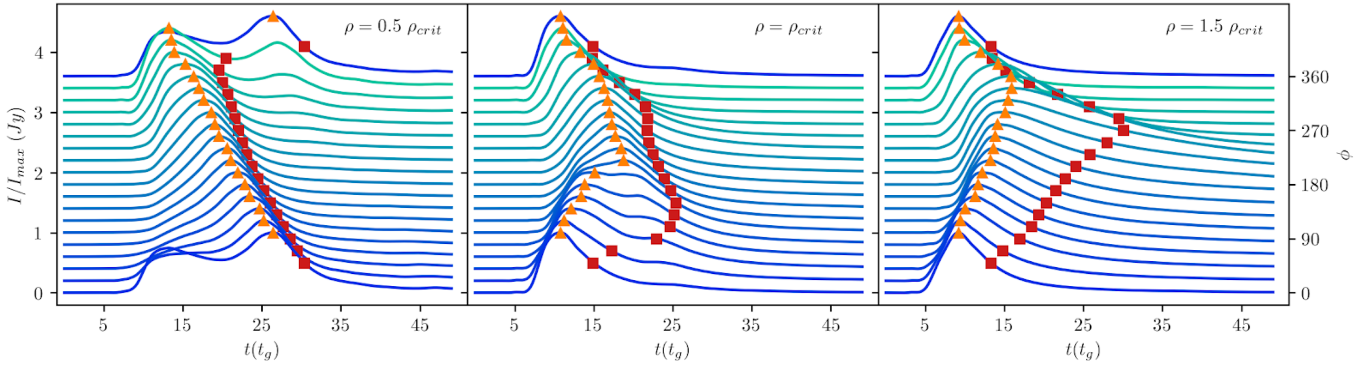
- GRAVITY NIR Interferometry: flares rotate near the horizon, $R \sim 3-5\,R_{\rm Sch}\,,\; v \sim 0.2-0.3c$

Marrone+2008, Dexter+2014, Fazio+ 2018, GRAVITY Collab+ 2018b

Time variability: Tracking coherent flares in M87 & Sgr A*

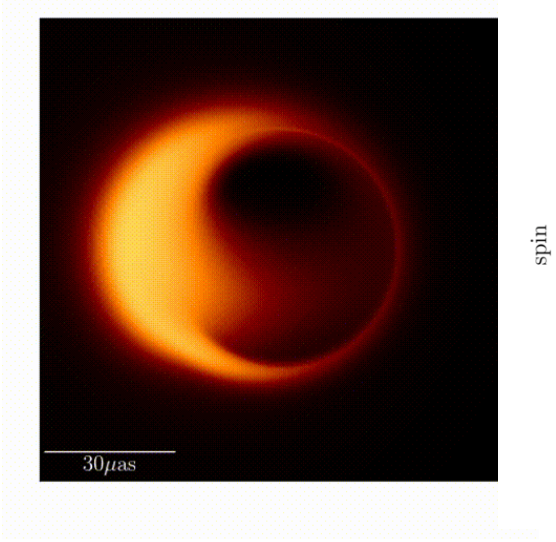
- In M87, flares emitted in a BH driven jet have more complex & longer-lived signatures than those emitted in a disk wind

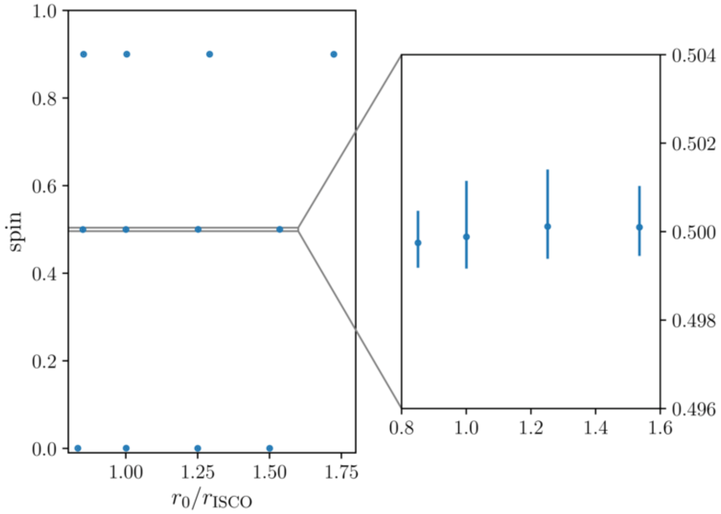




Flares in BH jet last longer and experience lensing could be tracked/imaged in EHT campaign

Flares in disk wind are shorter-lived





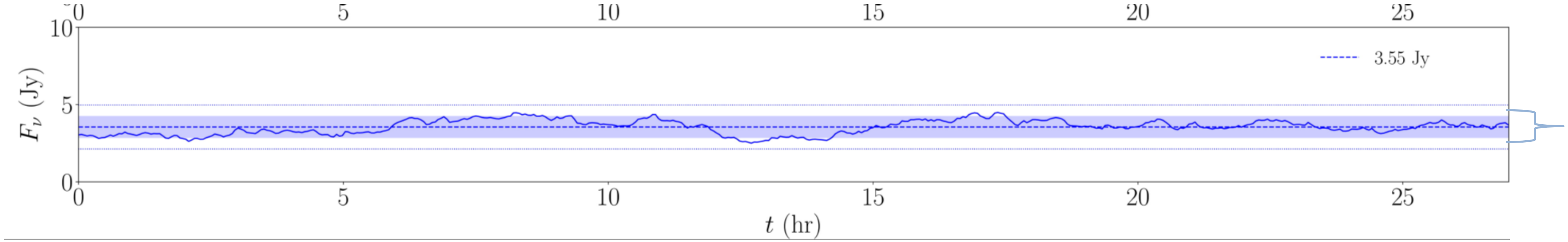
- In Sgr A*, repeated observations might catch flares at different initial radii and probe different radial slices of spacetime

→ could enable a precise spin measurement **if** flares can be associated to orbiting compact emission regions.

Tiede+ 2020: 2002.05735
Jeter+ 2020: 1804.05861

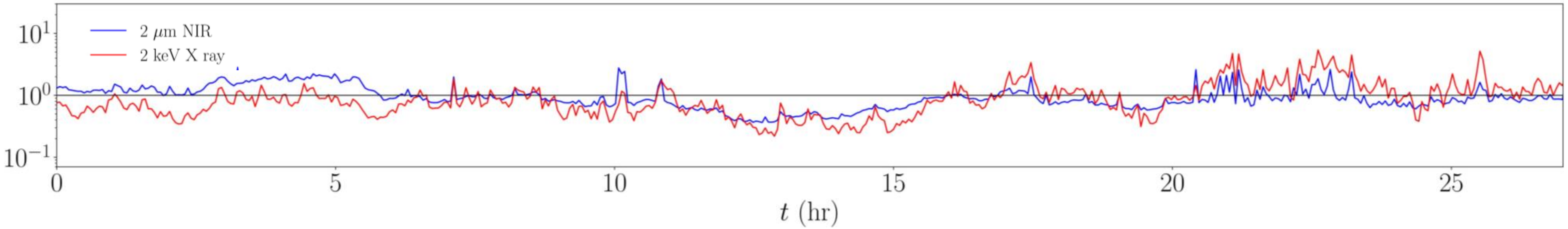
Time variability:
Thermal simulations can’t produce strong flares

1.3 mm



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

Normalized NIR/
X-ray



Flares require rapid **nonthermal** particle acceleration
(e.g. Ball+ 2016)

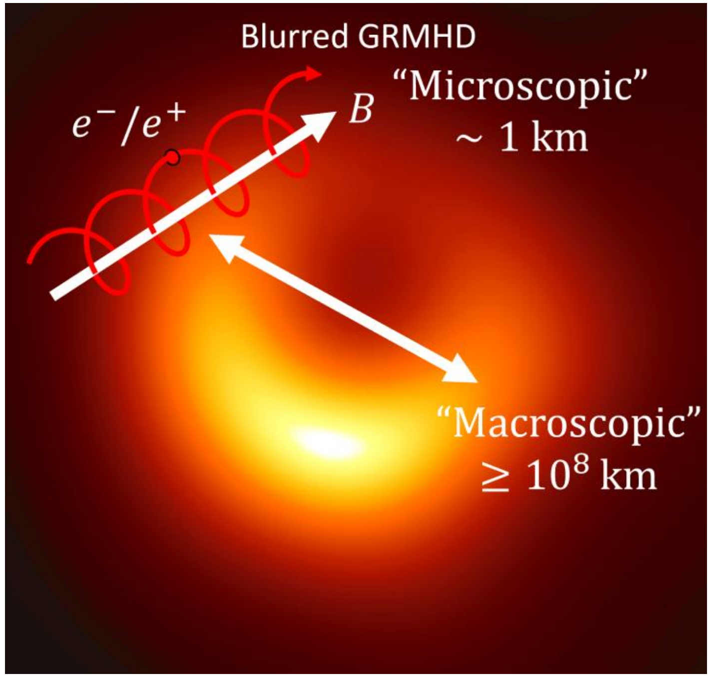
Chael+ 2018, 1804.06416

Plasma physics:
A major uncertainty & opportunity!

- Inefficient Coulomb coupling between ions and electrons:

$$T_{\mathrm{e}} \neq T_{\mathrm{i}}$$

- Generally expect electrons to be **cooler** than ions, but if electrons are **heated** much more, they can remain hotter.
- The electron temperature is sensitive to microscopic plasma processes, and electrons may not completey thermalize!

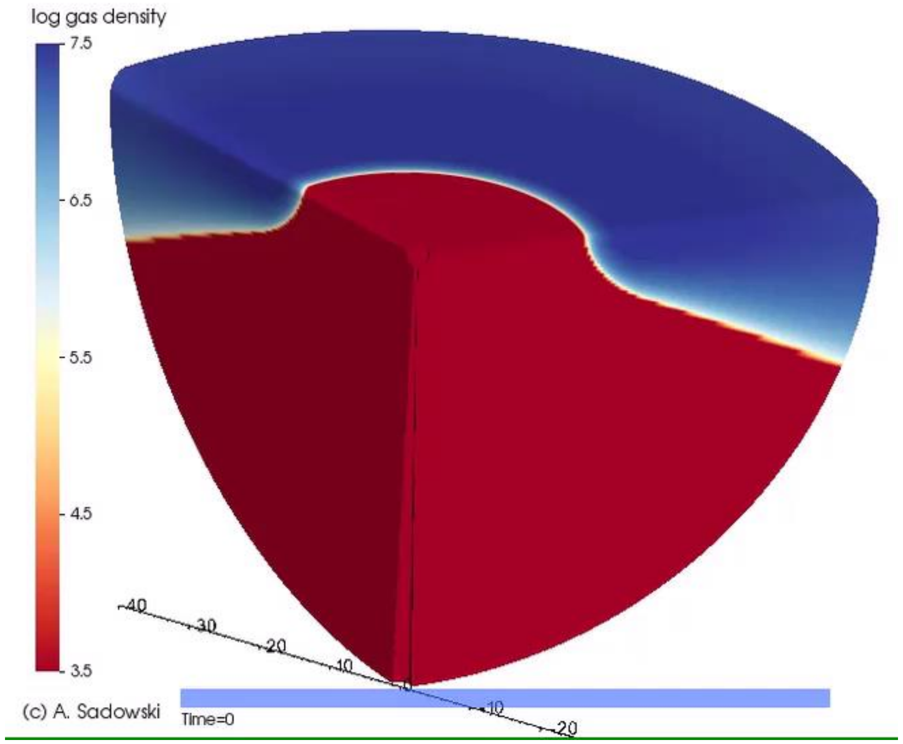


Huge scale separation in hot accretion flows

Image credit: Bart Ripperda

Plasma physics:
Adding electron temperatures to GRMHD Simulations

GRMHD

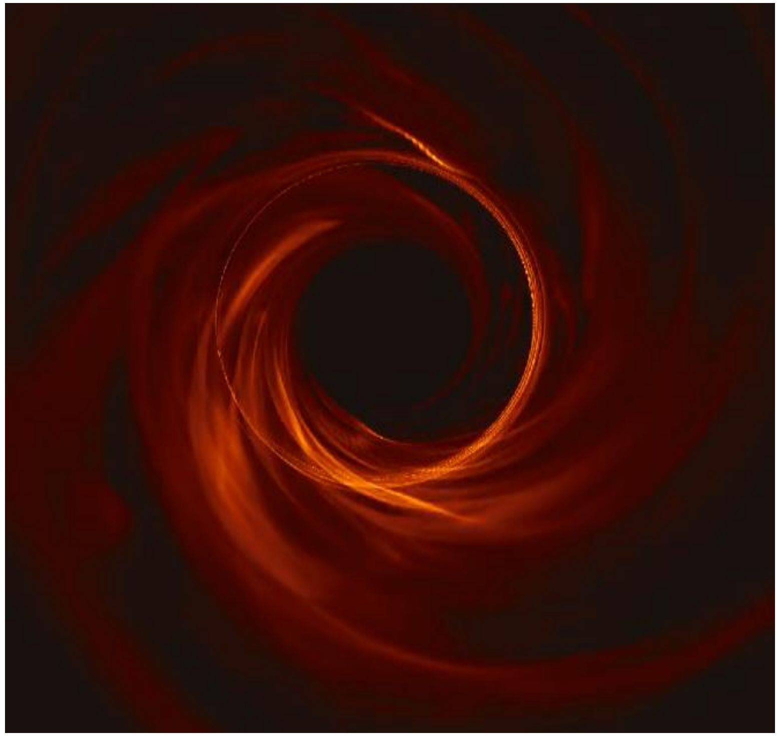


Evolves a **coupled** electron-ion fluid and magnetic field

$T_e?$

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

GRRT

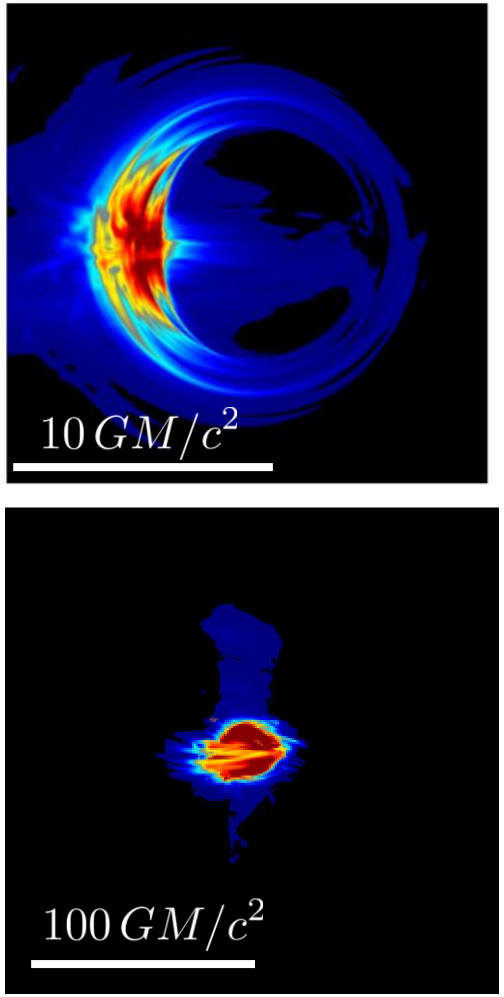


Movie Credits: Aleksander Sądowski, EHT Collaboration 2019 (Paper V)

Plasma physics:
Adding electron temperatures to GRMHD Simulations

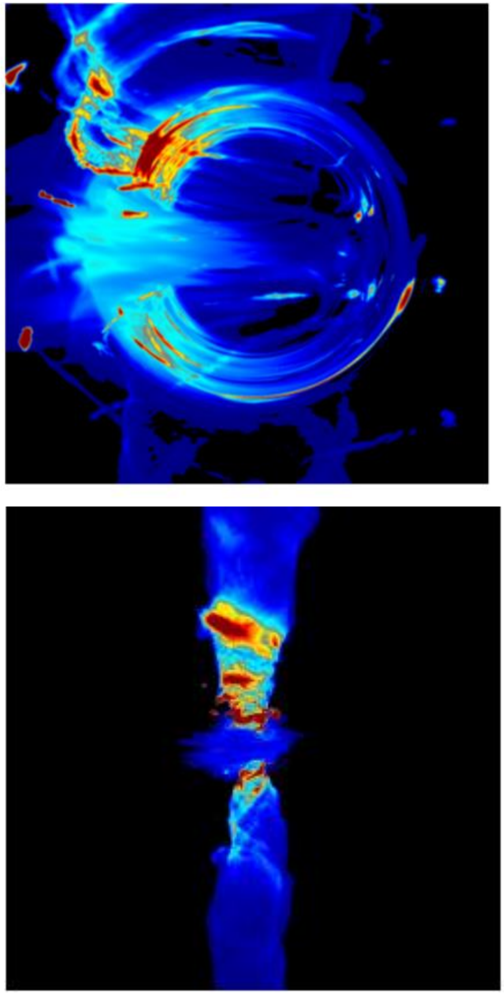
Hot Disk

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



$$\lambda = 1.3\text{mm}$$

$$\lambda = 7\text{mm}$$



Cool Disk

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

Mościbrodzka+ 2014

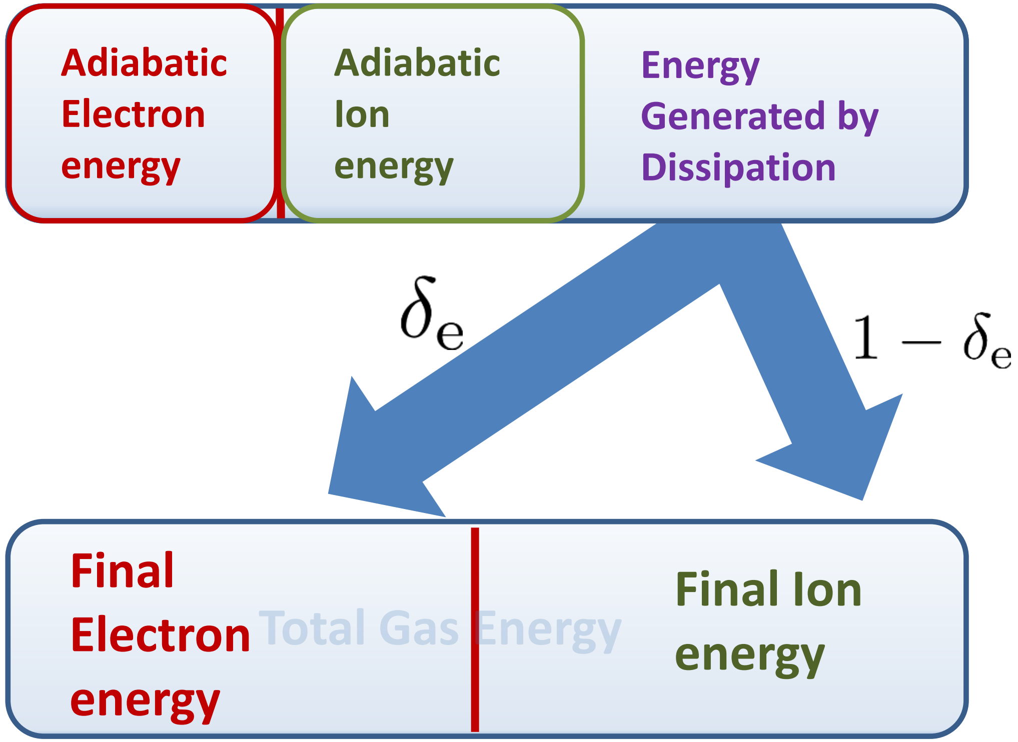
Plasma physics: Electron & Ion Heating in radiative simulations

- Include **electrons, ions, and photons** as additional populations in simulations:

  - Emitting electrons cool from radiation and gain energy in microscopic plasma heating

  - M87’s accretion rate is high enough that radiative feedback is important! (Ryan+ 2018, EHTC+ 2019)

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



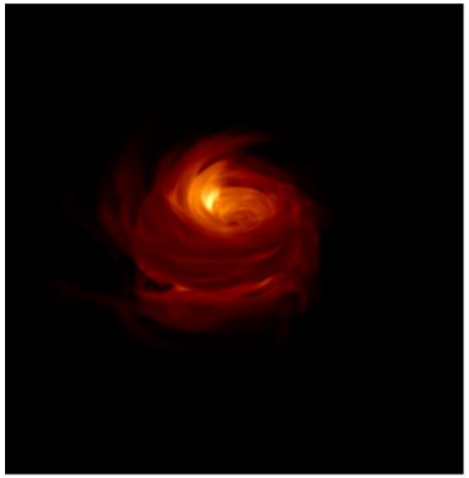
e.g. Ressler+ 2015, 17, Sadowski+ 2017, Ryan+ 2018, Chael+ 2018,19, Dexter+ 2020

Plasma physics:
Exploring different sub-grid models for electron heating

- What dissipative mechanism truncates the turbulent cascade at small scales?
- Options: magnetic reconnection (e.g. Rowan 2017), Landau damping (e.g. Howes+ 2010), Fermi-type acceleration (e.g. Zhdankin+ 2019)
- Radiative simulations allow us to incorporate different heating models self-consistently, but there is a large parameter space of heating models, but

43 GHz images of Sgr A* Simulations

Heating from sub-grid Landau damping – hotter electrons in the jet

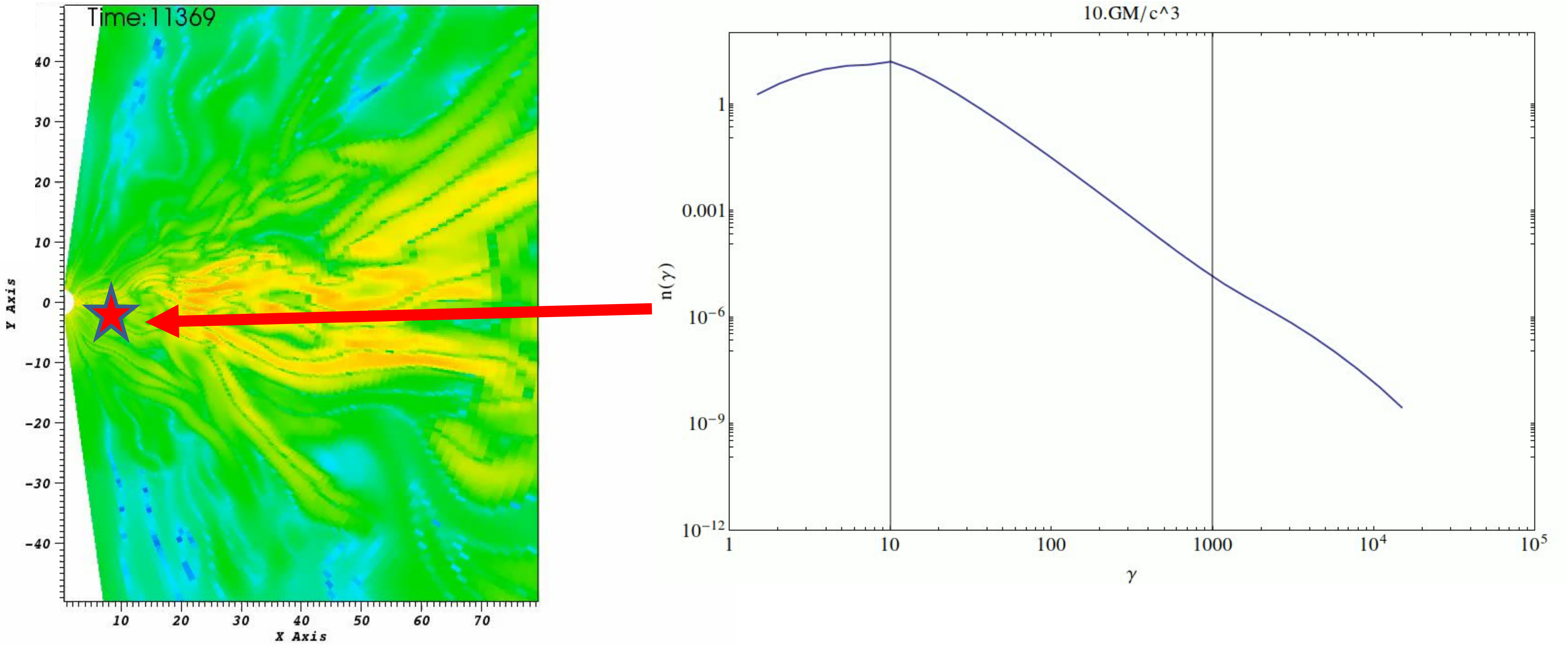


Heating from sub-grid reconnection -- hotter electrons in the disk

Chael+ 2018, 1804.06416

See also Ressler+ 2017, Ryan+ 2018, Chael+ 2019, Dexter+ 2020

Plasma physics: Simulating Sgr A* Flares by evolving the EDF

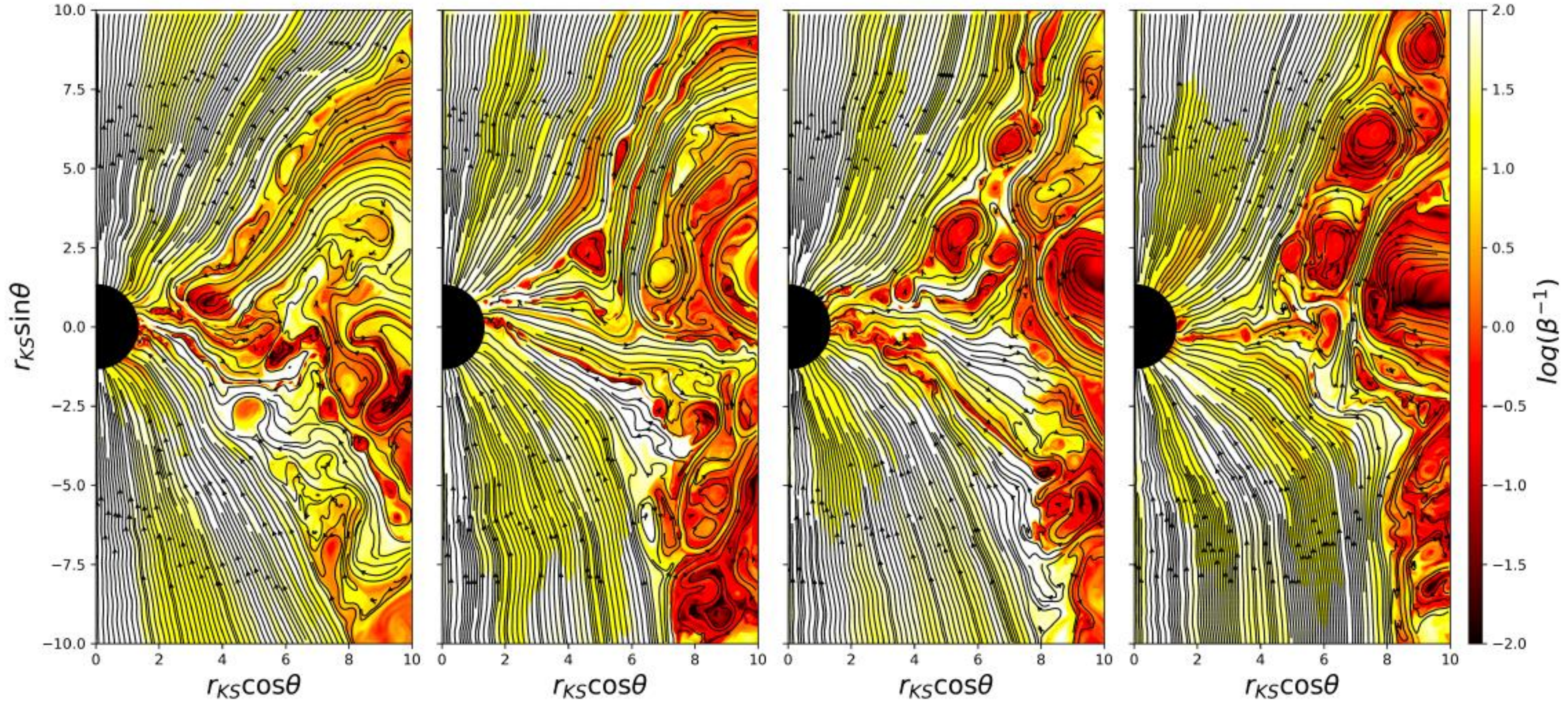


Radiation Power

Nonthermal distribution @ 10 M

Chael+ 2017

Plasma physics:
Reconnection events in resistive GRMHD



Ripperda+ 2020
2003.04330

The goal:
Understanding accretion flows & jets at all scales

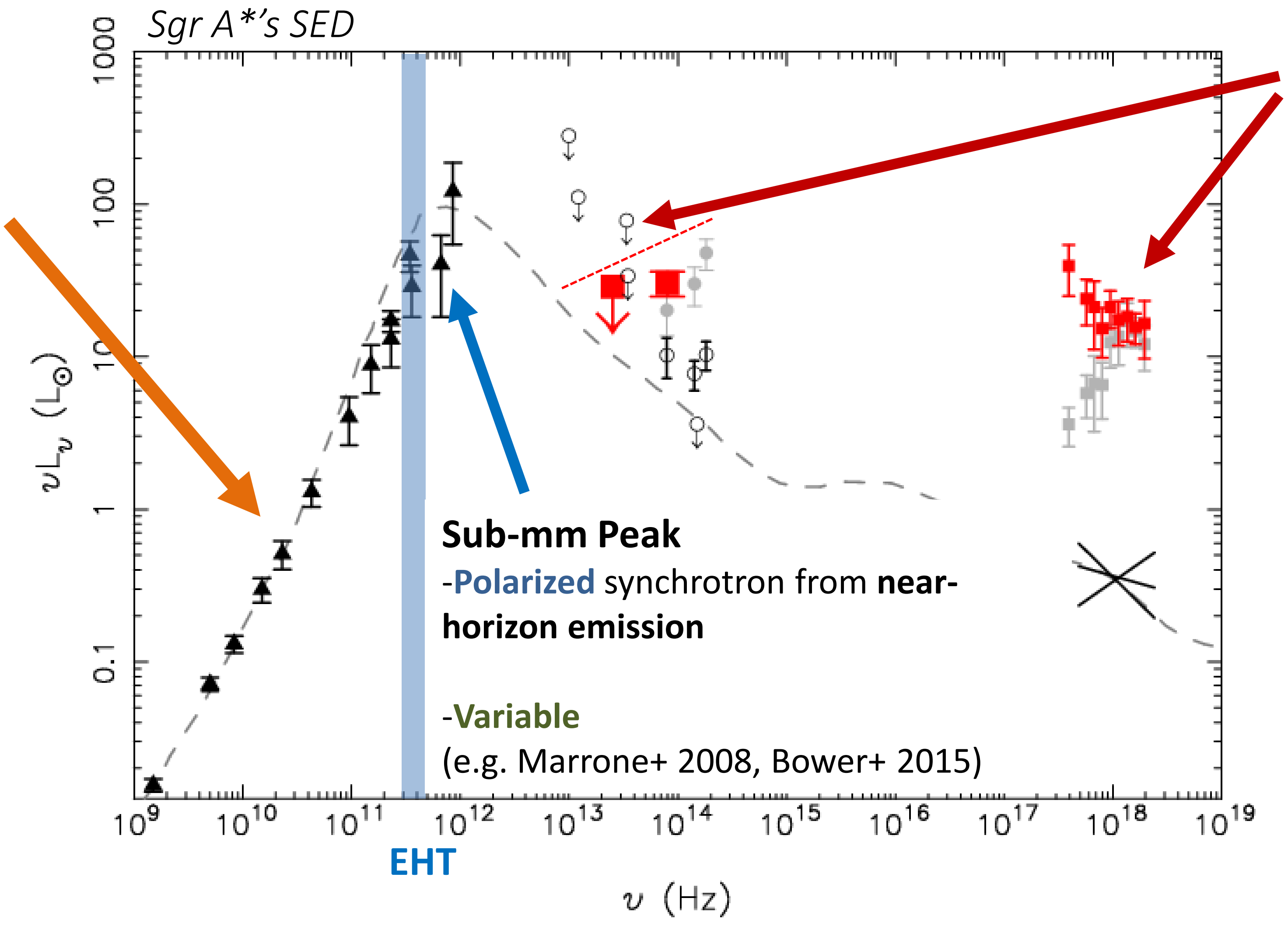
Larger Scales:

“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

-**Polarized** synchrotron from **near-horizon emission**

-**Variable**

(e.g. Marrone+ 2008, Bower+ 2015)

Close in:

Near-Infrared and X-ray flares and dynamics from nonthermal particles/acceleration

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

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

- Spatially resolved trajectories (GRAVITY+ 2018)

Image Credit: Dodds-Eden+ (2009)

Also: Flacke & Markoff (2000), Yuan+ (2003), Genzel+ (2010)

Takeaways

- GRMHD simulations are a powerful tool for connecting EHT images to plasma flows around black holes
- Polarization will be particularly powerful to disentangle different accretion scenarios
- Extended jet simulations can connect EHT images on horizon scales to the extended jet on large (up to ~pc) scales: EHT upgrades will directly reveal the BH / jet connection.
- Strong Sgr A* flares require emitting populations not captured in thermal GRMHD → more EHT data will mean opportunities to explore & constrain plasma microphysics

Thank you!