Supermassive black holes and relativistic jets: Insights from Simulations and EHT observations

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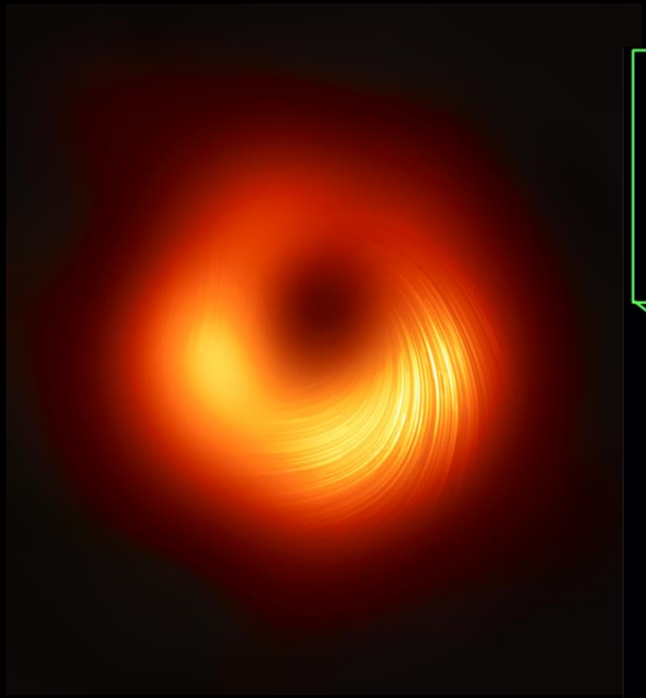
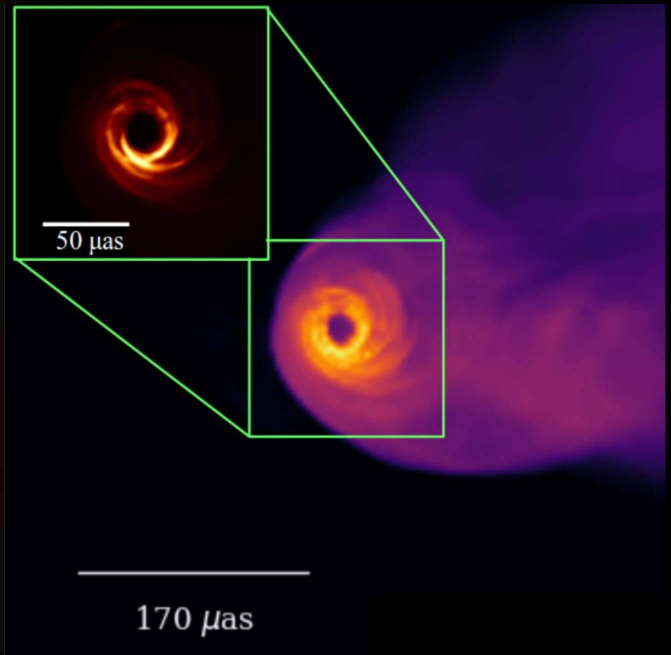




NASA Hubble Fellowship Program

Event Horizon Telescope

The EHT Collaboration

Sgr A*

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

Gravity Collaboration, 2018

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

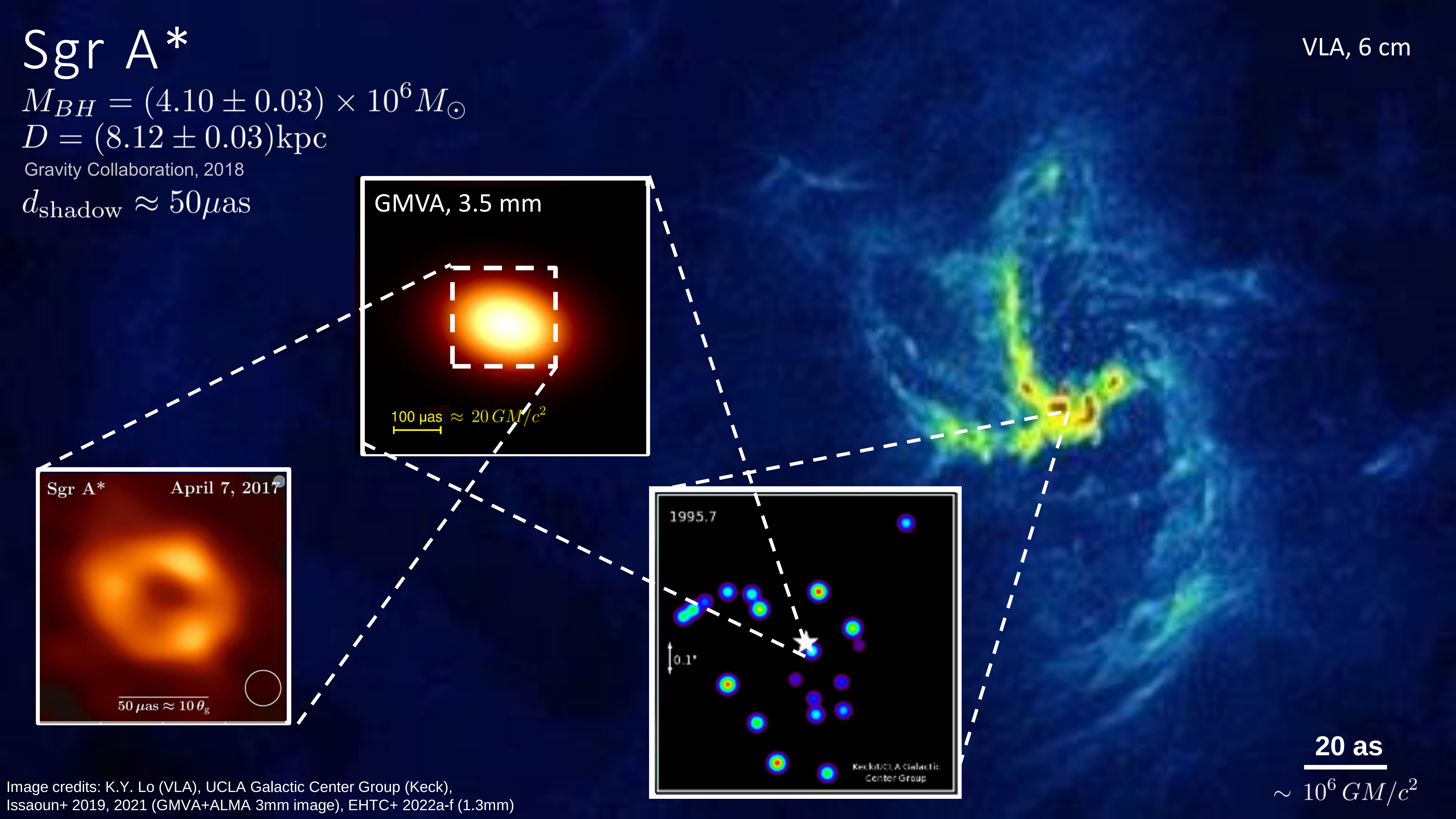
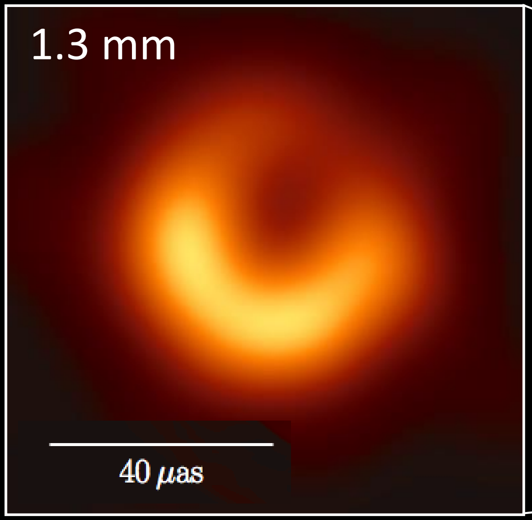
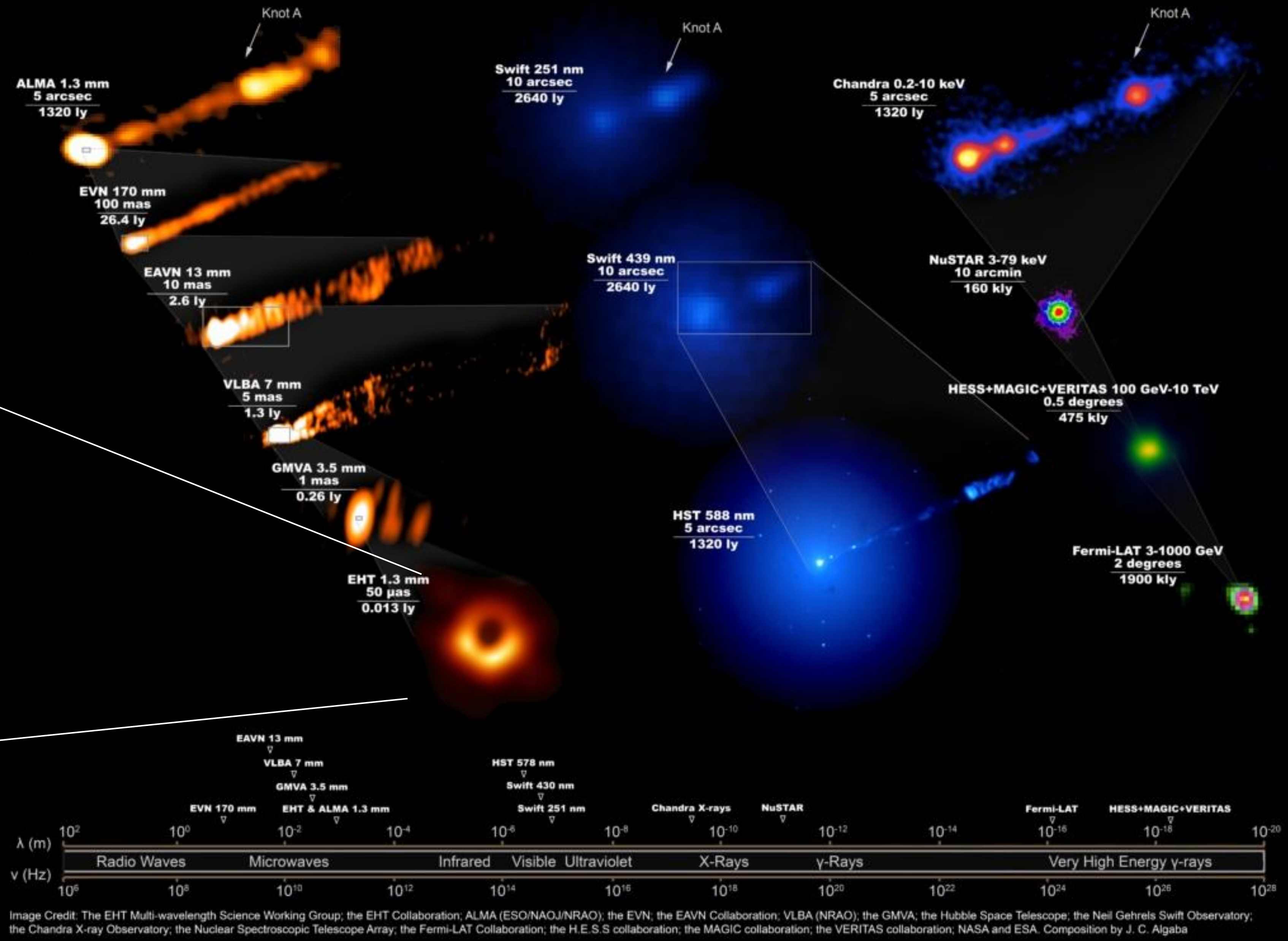


Image credits: K.Y. Lo (VLA), UCLA Galactic Center Group (Keck), Issaoun+ 2019, 2021 (GMVA+ALMA 3mm image), EHTC+ 2022a-f (1.3mm)

M87 & M87*

$M_{BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$
$D = (16.8 \pm 0.8)\mathrm{Mpc}$





Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Outline

1. Why GRMHD Simulations?

2. Comparing GRMHD Simulations to M87 Observations

3. Jets from M87 GRMHD Simulations

4. Future Directions

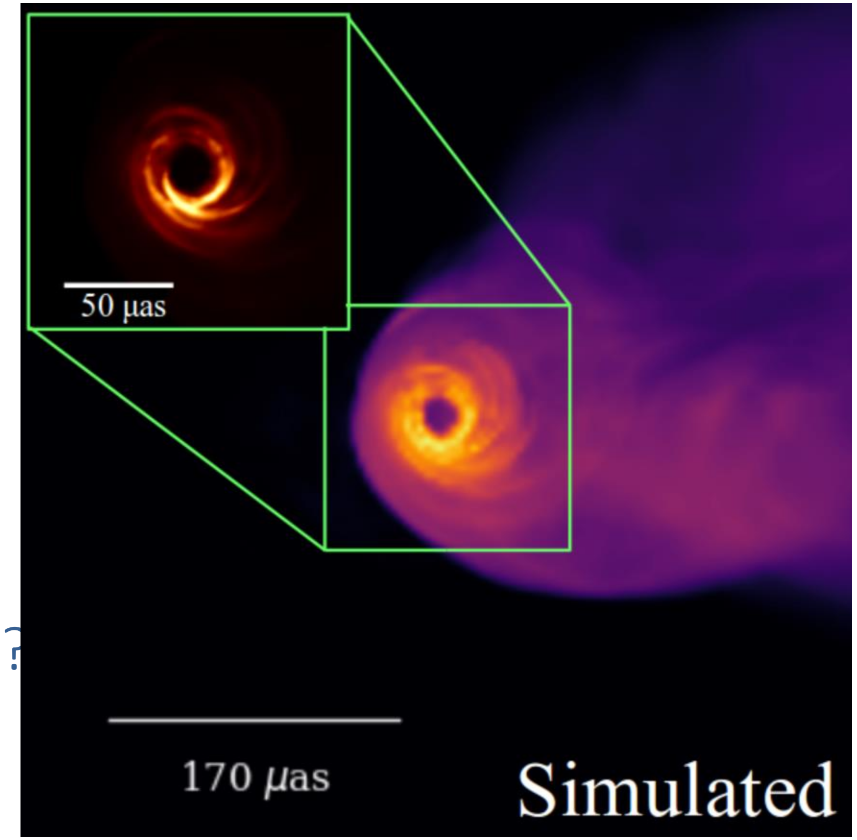
At the heart of M87…

What we know:

- Supermassive black hole with mass $M \approx 6 \times 10^9 M_\odot$
- Synchrotron Emission from very hot ($T \gtrsim 10^{10}\,\mathrm{K}$) plasma close to the event horizon
- Launches a powerful relativistic jet ($P_{\rm jet} \geq 10^{42}$ erg s^{-1})

Open Questions:

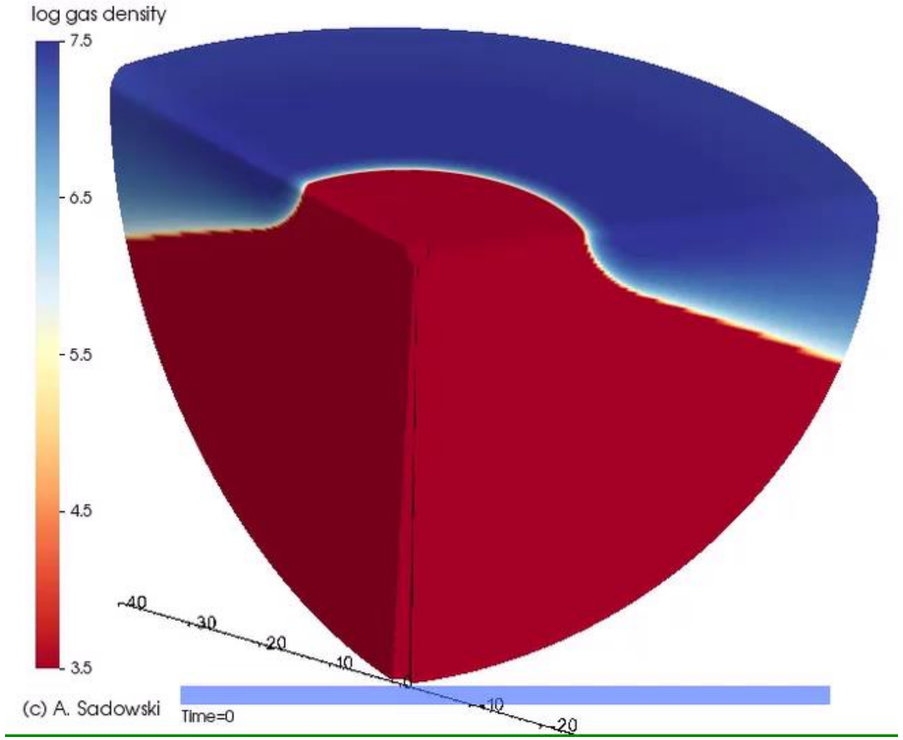
- What is the strength and configuration of the magnetic field?
- How is the jet launched? Can we observe jet launching with the EHT?
- What is the temperature and distribution of the emitting particles? How are they set by plasma physics?
- What powers flares in M87* and Sgr A*?



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, Cruz-Osario+ 2022, Fromm+ 2022, many others...

Image credit: Andrew Chael, Lindy Blackburn

Why GRMHD Simulations?



General **R**elativistic **M**agneto**H**ydro**D**ynamics
Solves the coupled equations of fluid and magnetic field in Kerr spacetime

- GRMHD Simulations are a primary theoretical tool for investigating the physics of accretion and jet launching near supermassive black holes and interpreting EHT images.
- GRMHD simulations naturally **couple the accretion disk, black hole, and jet**
  - Jet launching is universal and driven by BH spin
- GRMHD Simulations are naturally **turbulent** and **dynamic**
  - we know source variability is a critical feature of Sgr A* and M87

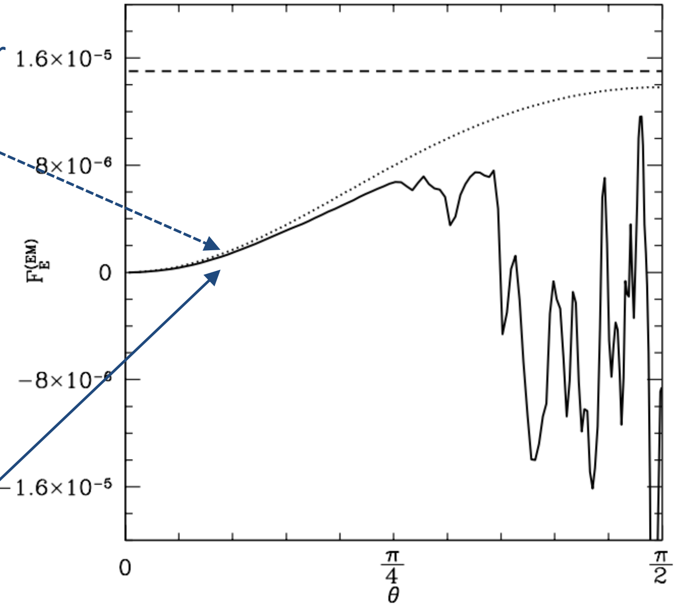
Movie Credits: Aleksander Sądowski (left) George Wong/Ben Prather (right)

GRMHD simulations naturally produce BZ jets

- Jets are produced universally in GRMHD simulations
- They are **powered by the black hole spin** (Blandford & Znajek 1977)

McKinney & Gammie 2004

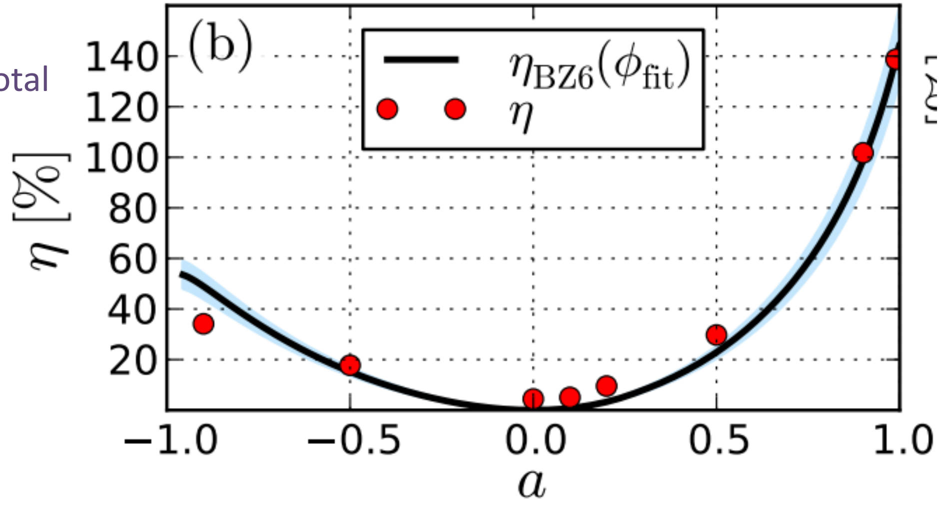
BZ prediction for outward energy flux at the horizon



Simulation

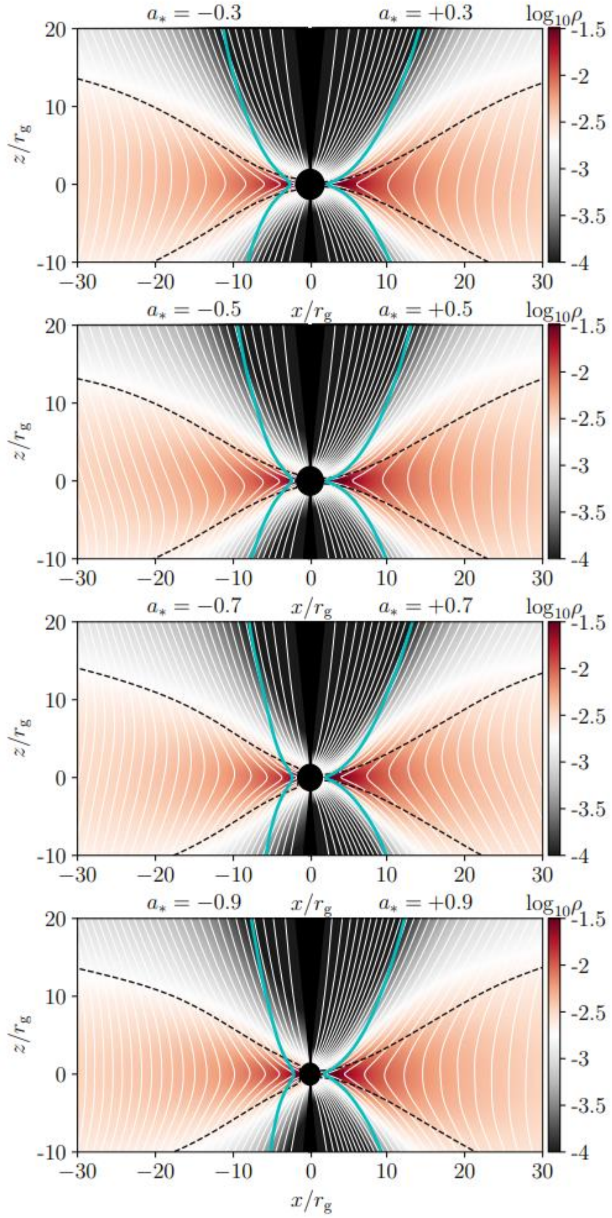
Tchekhovskoy+ 2012

Jet power / total inflow power



Also: Hawley+ 2006, Noble+ 2009, Penna+ 2010, McKinney+ 2012, Sadowski+ 2013, Moscibrodzka+ 2016, EHTC+ 2019, Porth+ 2019, Wong+ 2021, Narayan+ 2021, many others….

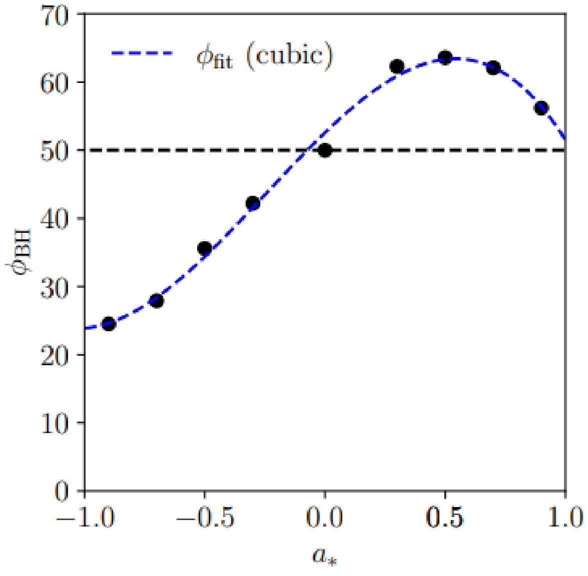
Jet Power in long-duration MAD Simulations



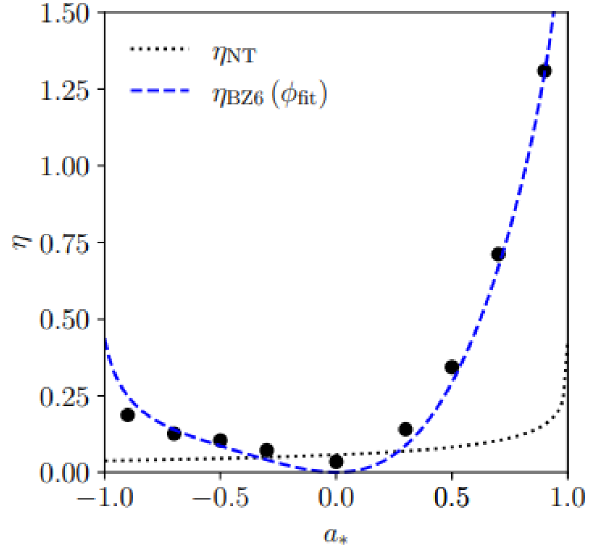
Time-and azimuth-averaged simulation data

- We see agreement with BZ jet power prediction in 8 v**ery-long-duration simulations** (10^5 t_g) of magnetically arrested accretion

Magnetic flux though the horizon

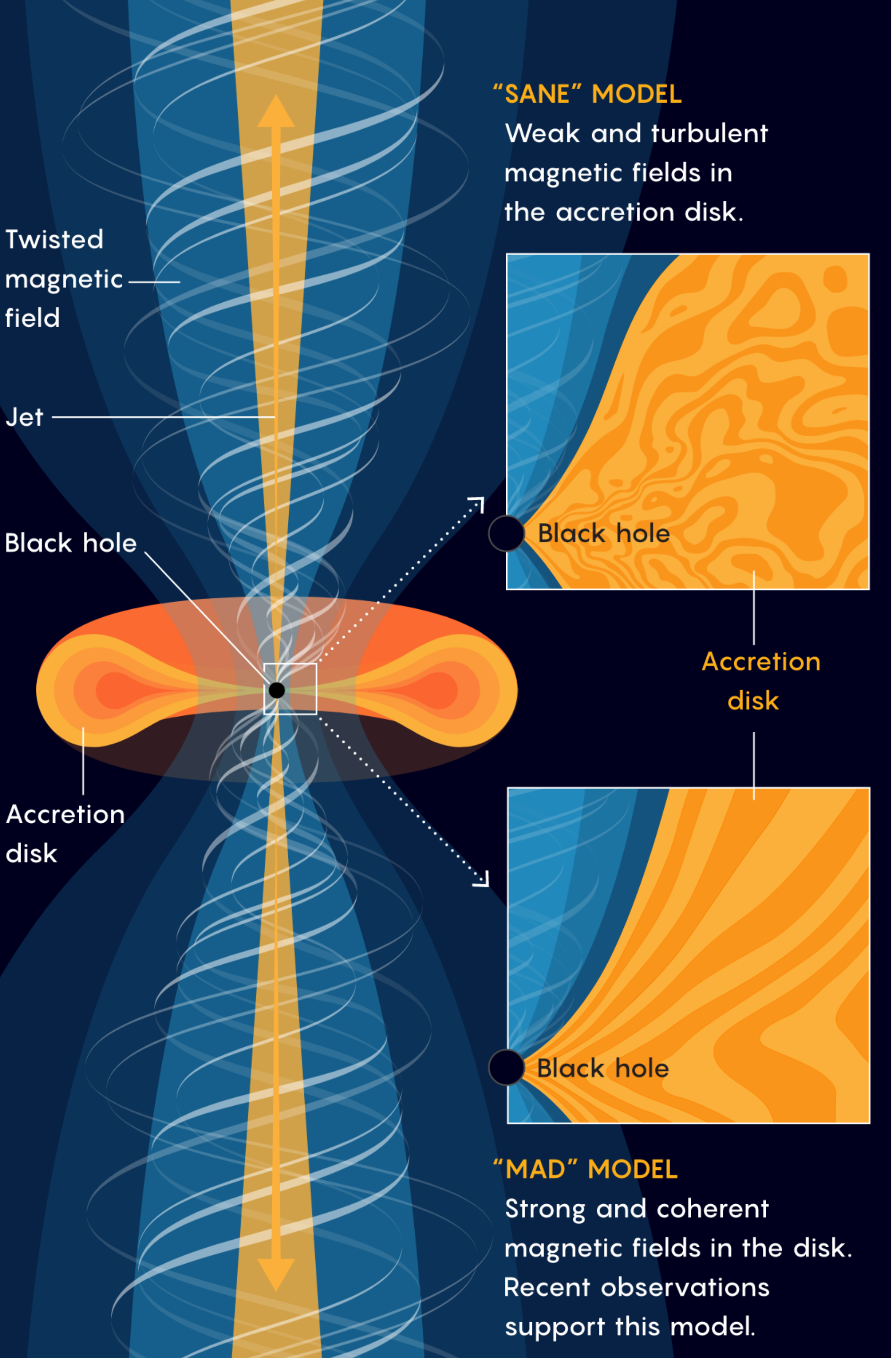


Jet efficiency



BH spin

R. Narayan, **A. Chael**, K. Chatterjee, A. Ricarte, B. Curd, 2021



Magnetic field structure in GRMHD

Simulations show two accretion states that depend on the accumulated magnetic flux on horizon

Magnetic fields are weak and turbulent

"SANE" – Standard and "Normal" Evolution

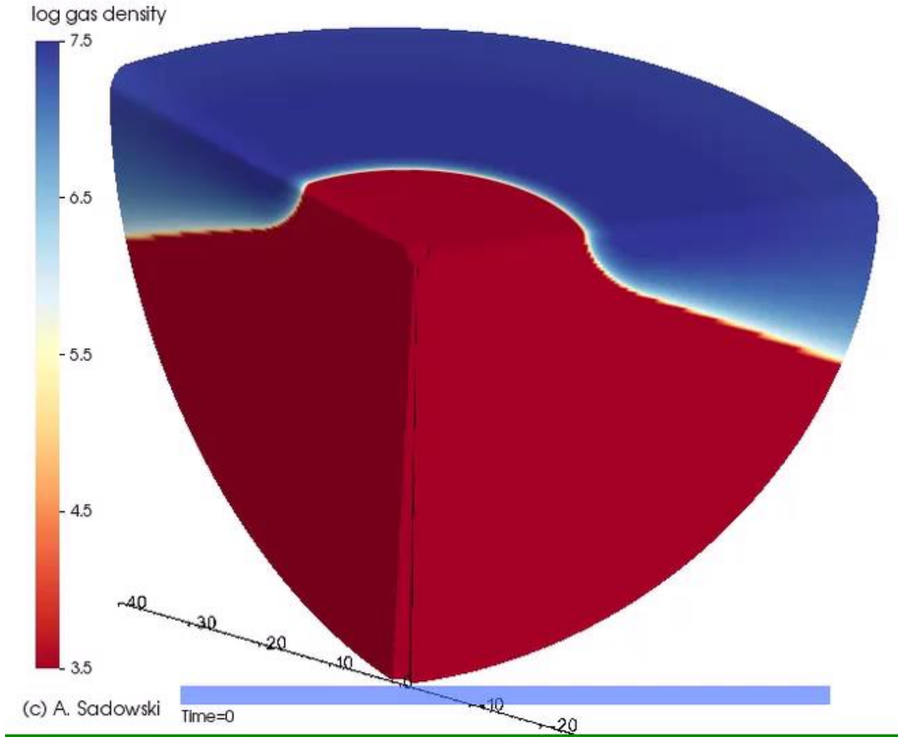
Strong, coherent magnetic fields build up on the horizon

"MAD" - Magnetically Arrested Disk

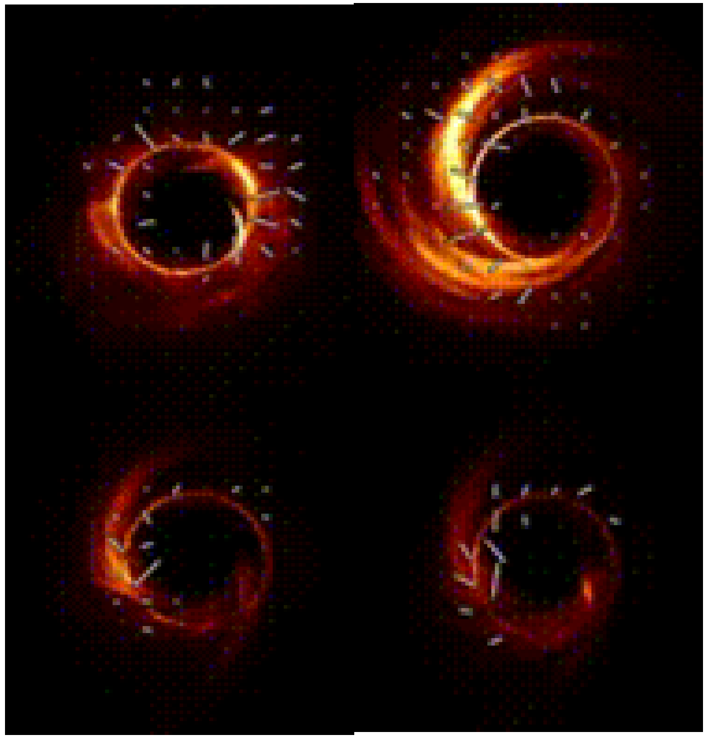
Note: 'strong' fields mean ~10-50 G at the horizon for M87*

Igumenschchev 1977, Narayan+2003, Tchekhovskoy+2011, Narayan+ 2012
Image credit: O'Riordan+ 2017, Quanta Magazine

Comparing EHT images to simulations



$T_e?$

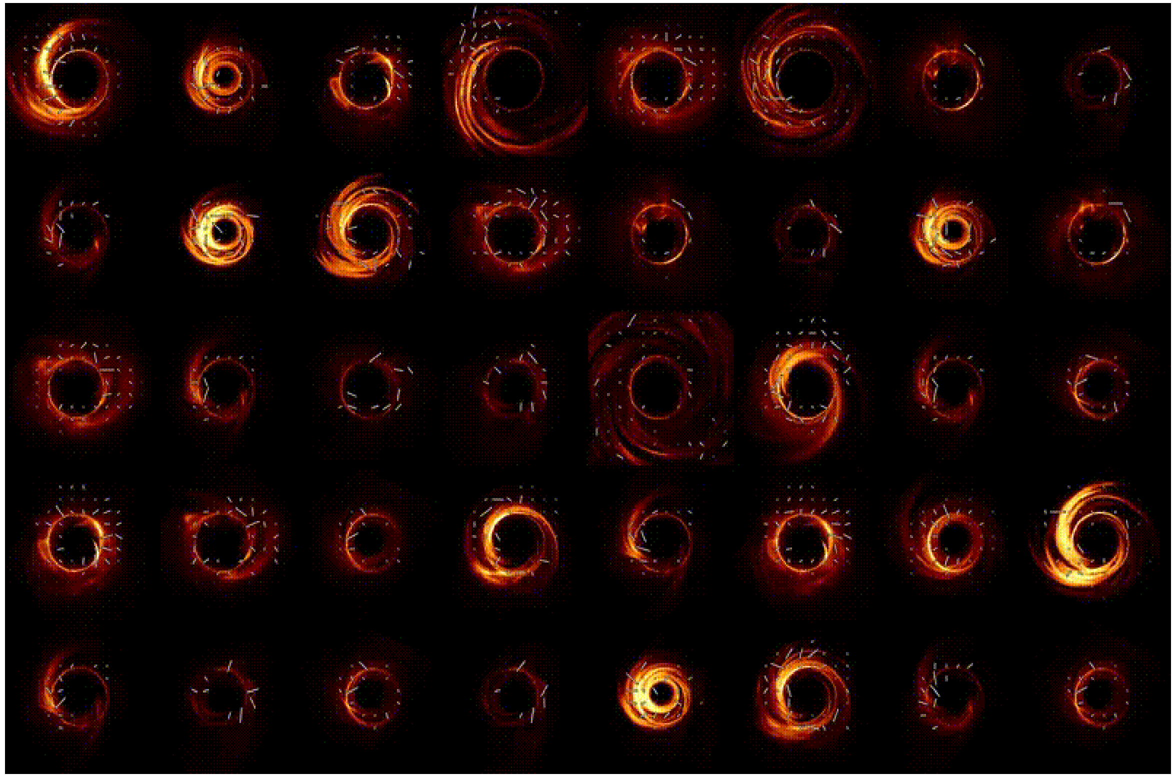


General **R**elativistic **M**agneto**H**ydro**D**ynamics
- solve coupled equations of fluid and magnetic field in Kerr spacetime

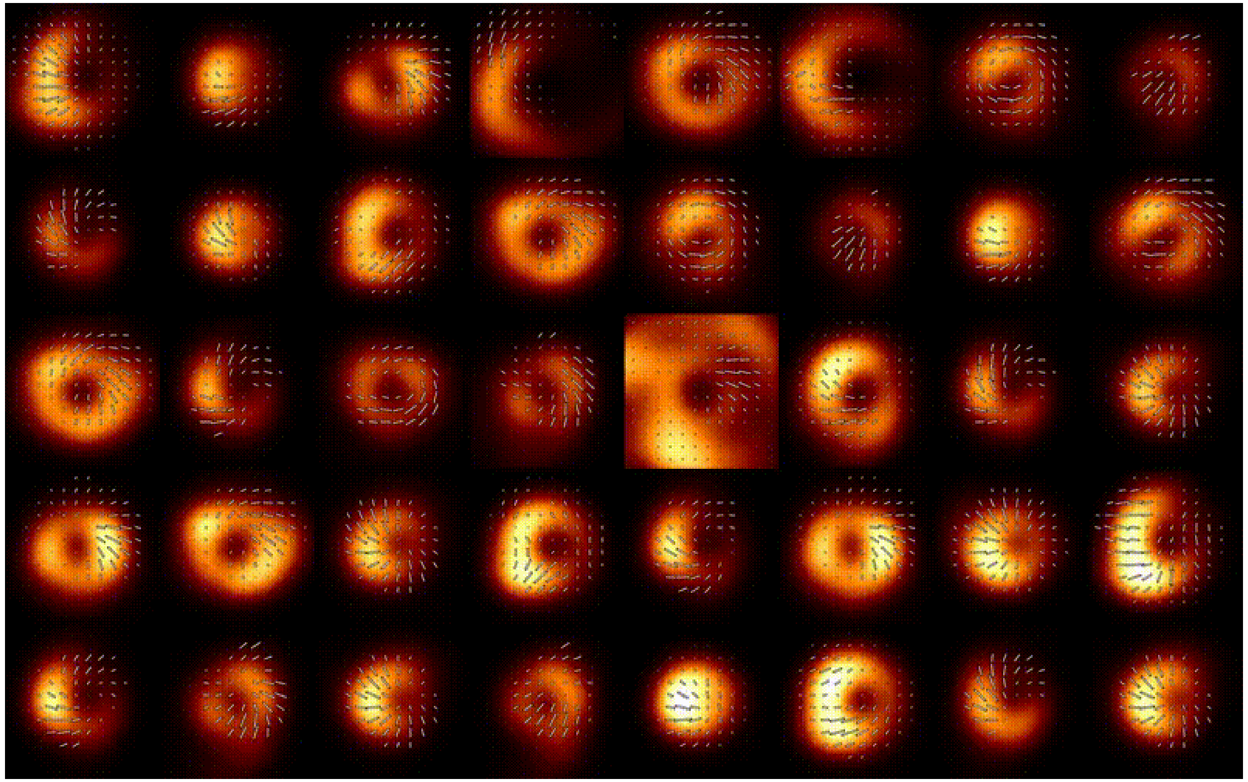
General **R**elativistic **R**adiative **T**ransfer
- solve for the polarized synchrotron radiation (including light bending and Faraday rotation)

Movie Credits: Aleksander Sądowski (left) George Wong/Ben Prather (right)

EHT GRMHD Simulation library
72k images



native resolution



EHT resolution

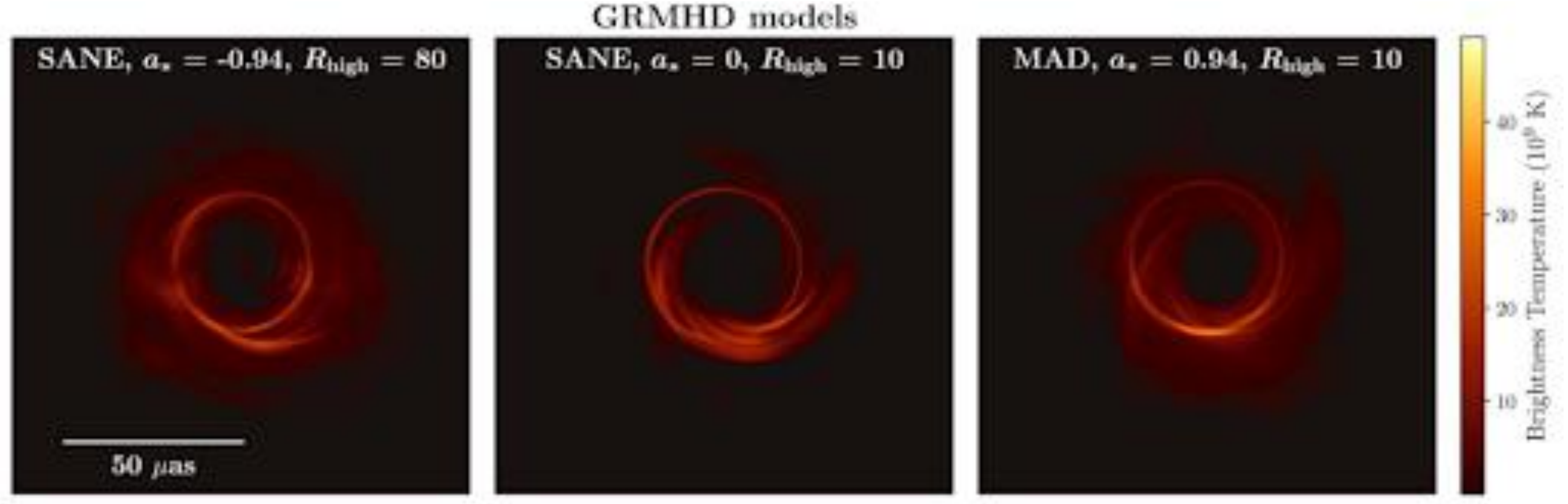
Images modeled with the ipole GRRT code (Moscibrodzka & Gammie 2018)
Two-temperature plasma model from Moscibrodzka et al. 2016

$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta^2}{1+\beta^2} + R_{\rm low}\frac{1}{1+\beta^2}$$

Animation credit: George Wong/ Ben Prather

Scoring M87 GRMHD Simulations: before polarization

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

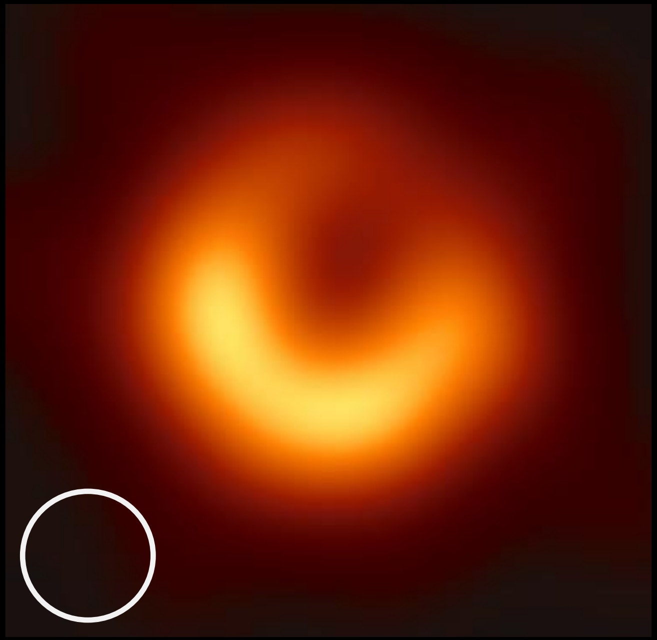


- The **jet power constraint** (≥ 10^{42} erg/sec) rejects all spin 0 models
  SANE models with |a| < 0.5 are rejected.
  Most |a| > 0 MAD models are acceptable.

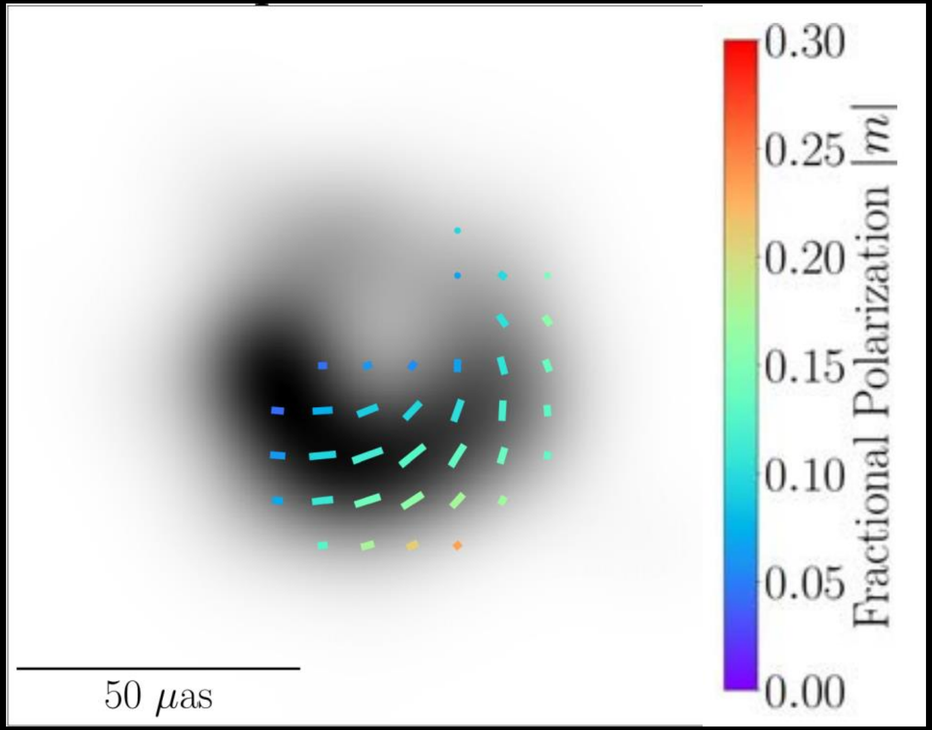
EHTC+ Paper V, 2019

EHT Polarization images are much more informative!

Total intensity



Linear Polarization



EHT Paper V (2019)
- Accretion flow is hot and dilute
- BH spin vector pointed away
- **Many simulation models fit the data**

EHT Paper VIII (2021)
- **strongly constrains the nature of BH magnetic fields**

EHTC+ Paper IV (2019) VII (2021)

Scoring simulations with polarization

Unresolved linear polarization fraction

$$|m|_{\rm net} = \frac{\sqrt{\left(\sum_i Q_i\right)^2 + \left(\sum_i U_i\right)^2}}{\sum_i I_i}$$

Unresolved circular polarization fraction (from ALMA)

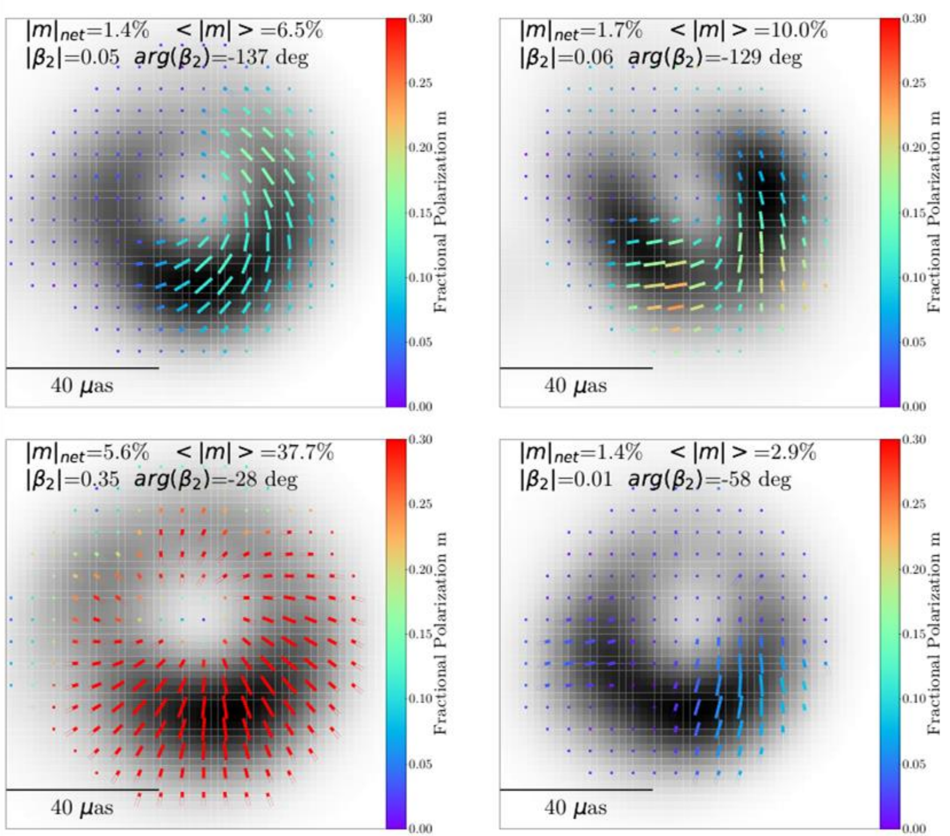
$$|v|_{\rm net} = \frac{\left|\sum_i V_i\right|}{\sum_i I_i}$$

Average resolved polarization fraction

$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Azimuthal structure
2nd Fourier mode

$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P(\rho, \varphi)\, e^{-2i\varphi}\; \rho\, d\varphi\, d\rho$$

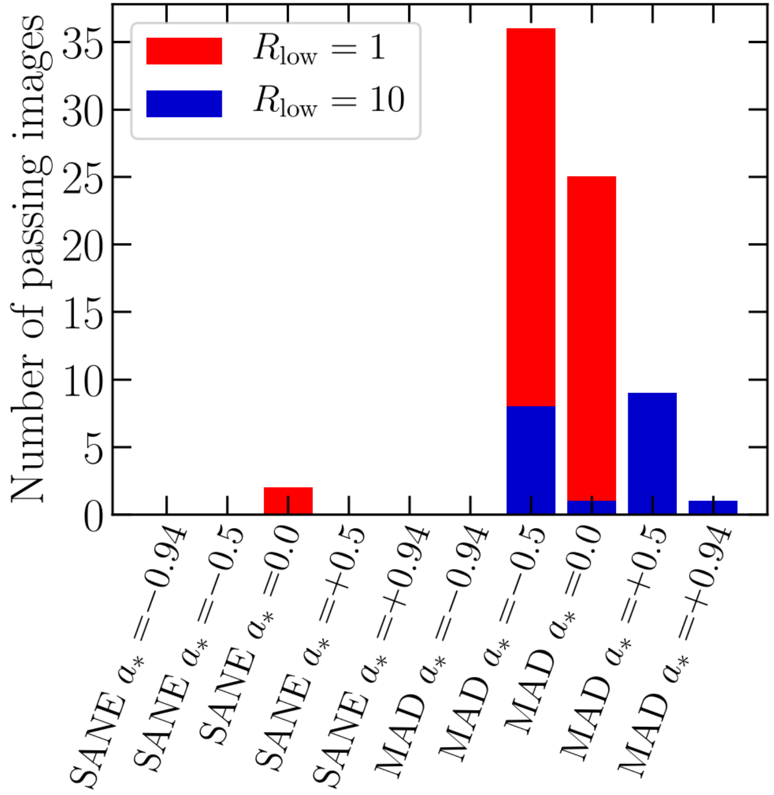


GRMHD images can be **strongly** or **weakly** polarized: with **patterns** that are radial/toroidal/helical

EHTC+ 2021 Paper VIII

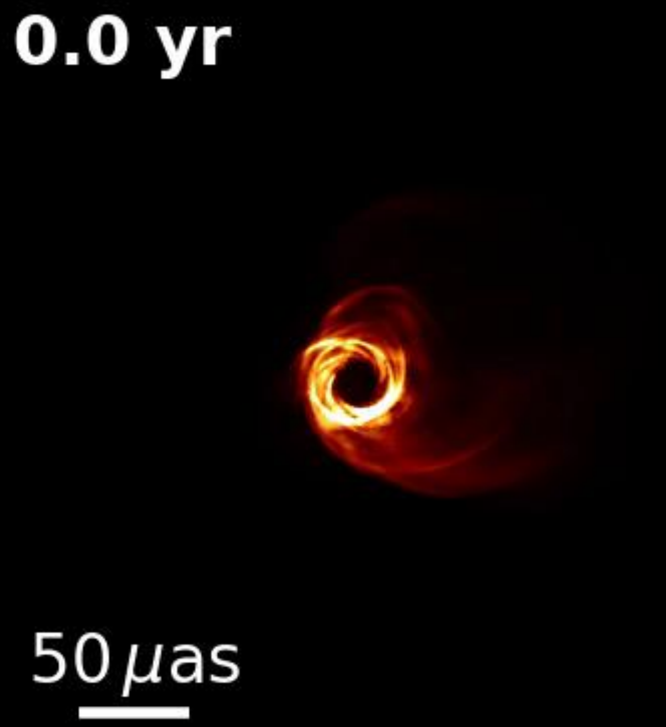
Polarimetric simulation scoring

- Only 73 / 72,000 images satisfy all constraints simultaneously!
- All but 2 of the passing images are from magnetically arrested simulations
- **All scoring approaches strongly favor magnetically arrested (MAD) simulations**
- An additional constraint on the jet power rejects all non-MAD simulations and all spin-zero simulations.



MAD simulation jets at large distances

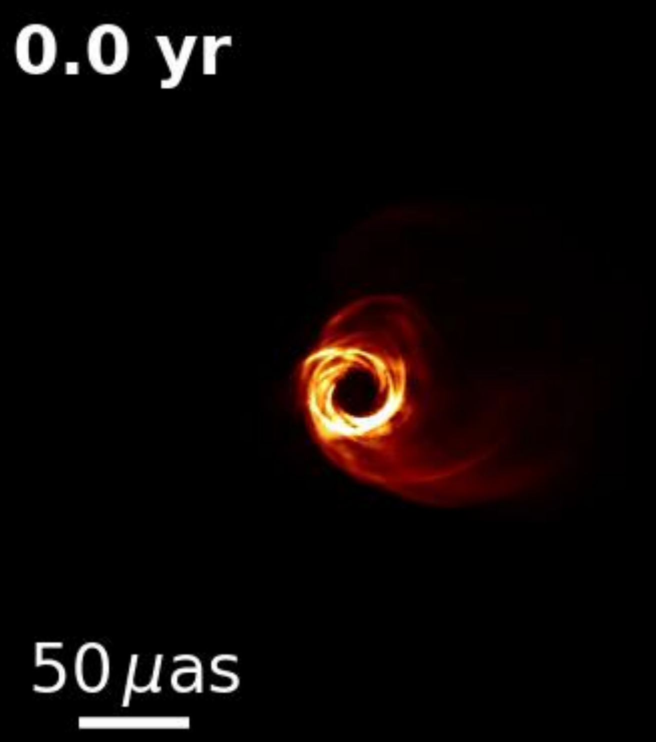
230 GHz



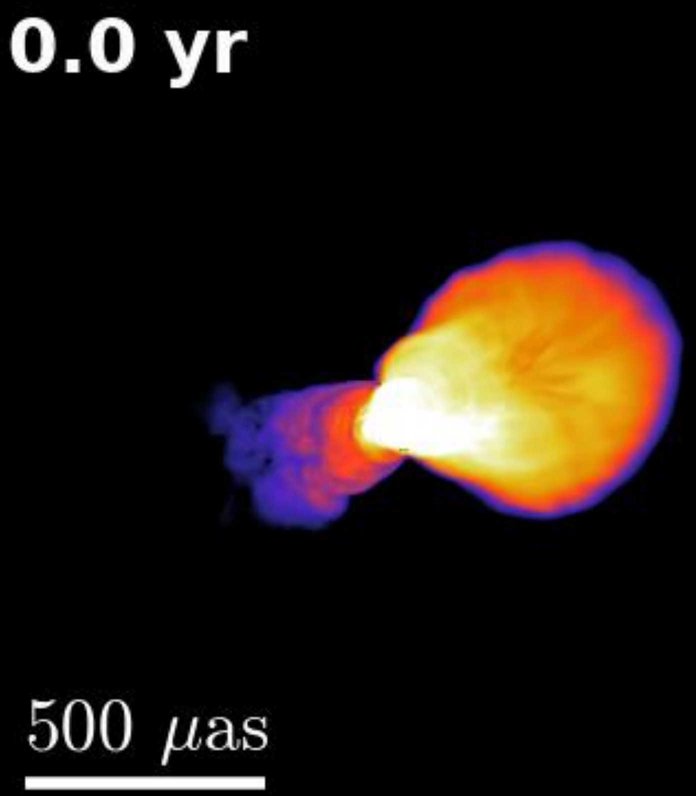
Chael+ 2019

MAD simulation jets at large distances

230 GHz



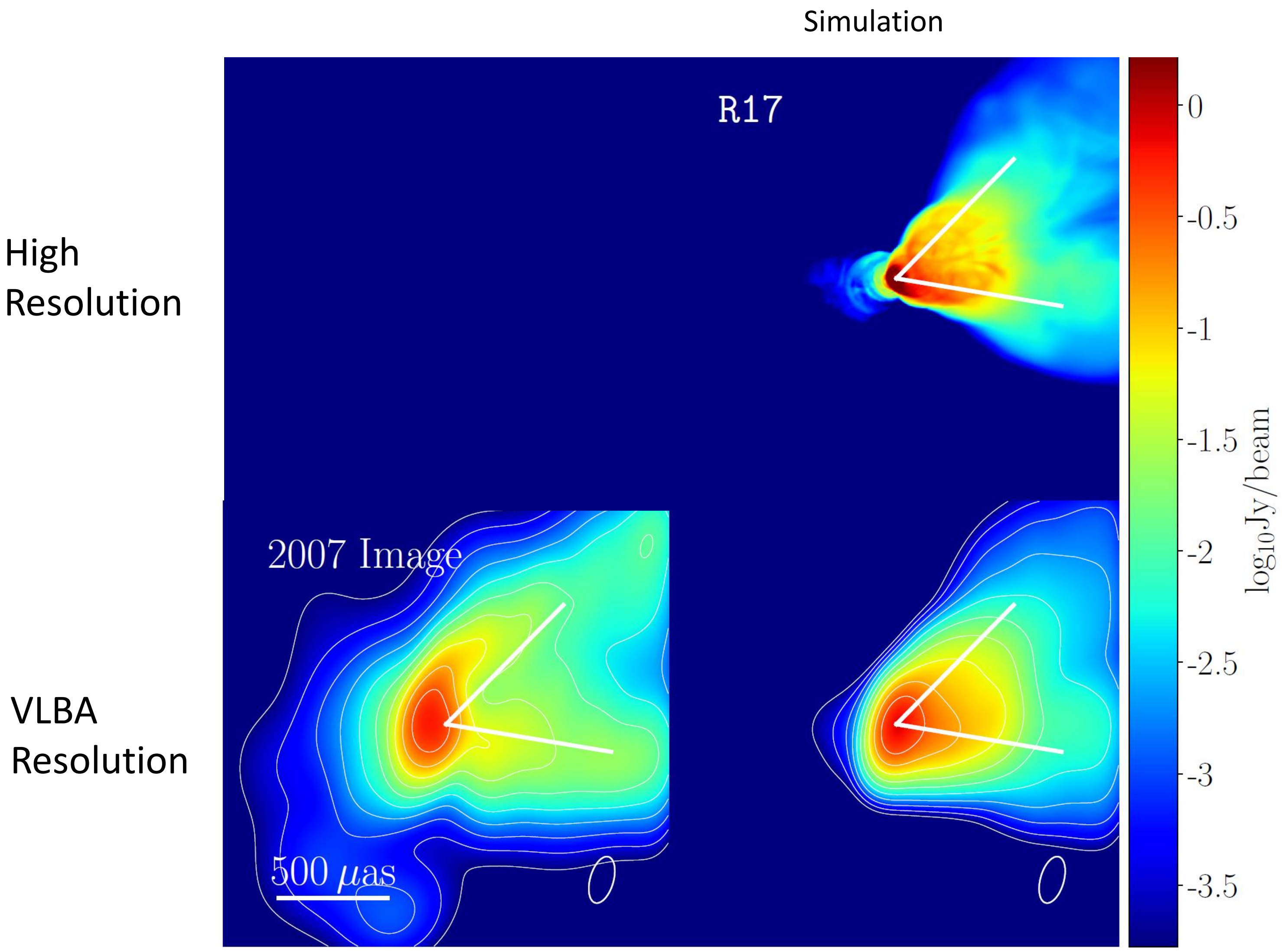
43 GHz



$P_{\rm jet}$ in the measured range for M87!

Chael+ 2019

43 GHz jets from M87 GRMHD Simulations



Jets in magnetically arrested GRMHD simulations of M87 run to large distances naturally produce:

- jet power in measured range from BZ
- observed wide-opening angle morphology
- observed core-shift

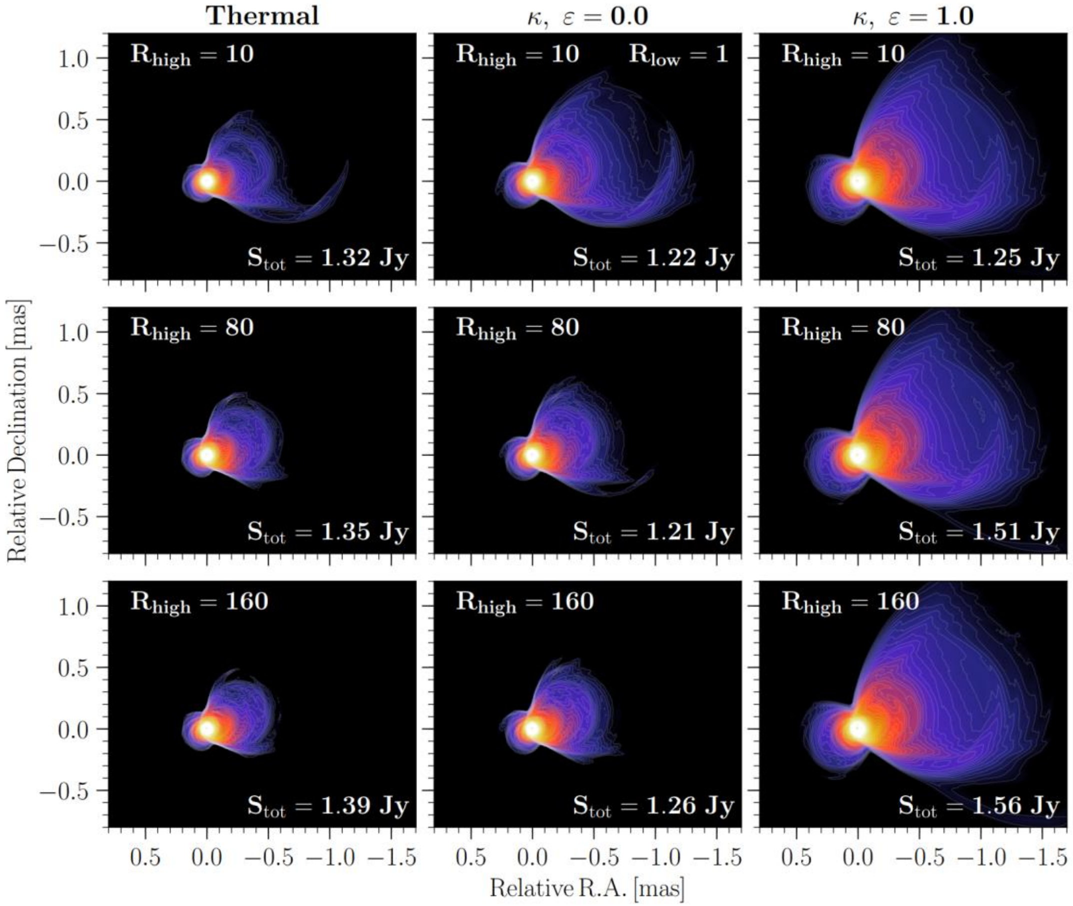
Observed limb-brightening hard to reproduce

- Incorrect modeling of electron distributions?

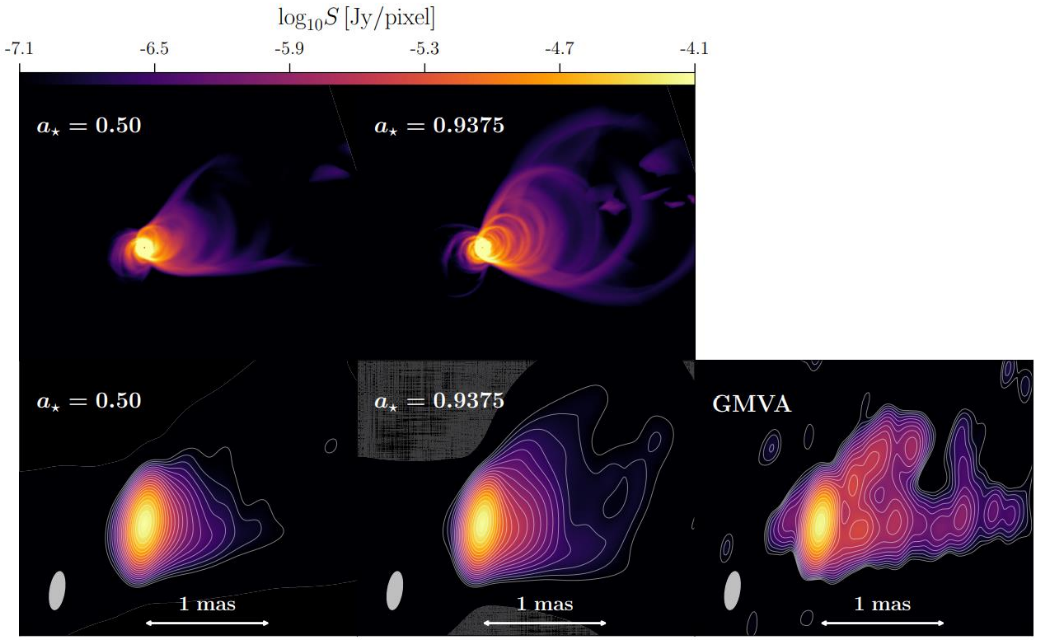
Chael+ 2019
VLBA Image Credit: **Chael**+ 2018a
Original VLBA data: Walker+ 2018

Large-scale jets from M87 GRMHD Simulations

Fromm+ 2021



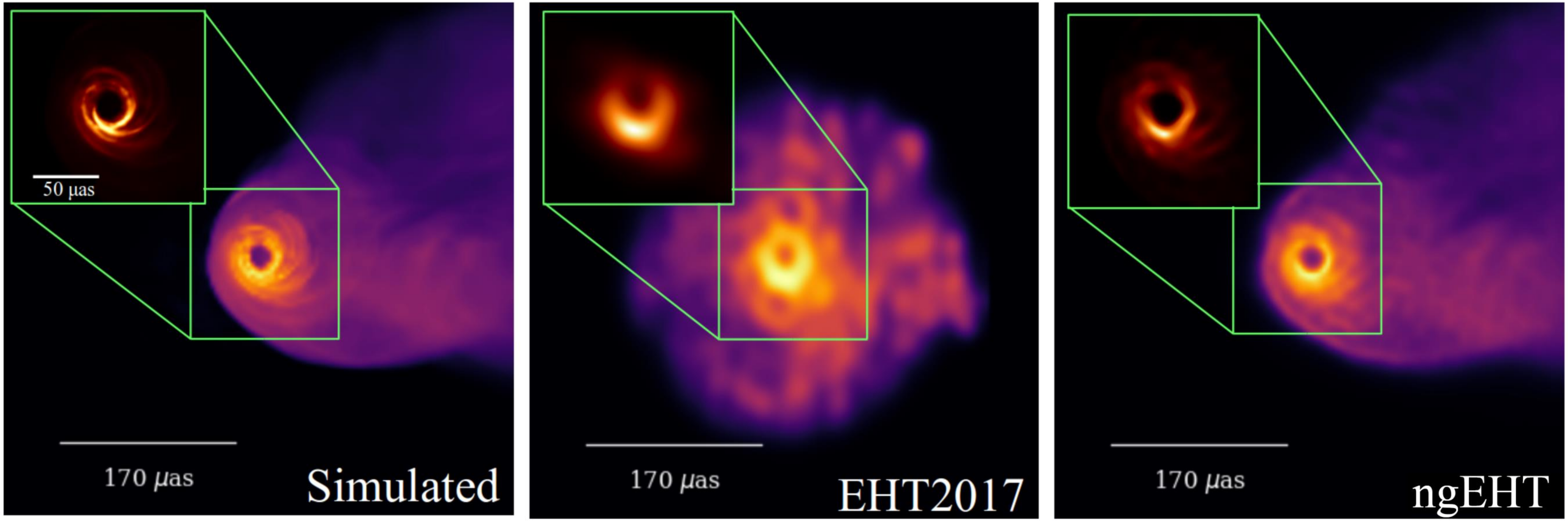
Cruz-Osorio+ 2021



How does the electron distribution function affect the jet morphology?
How is the electron distribution set by sub-grid physics?

Also: Moscibrodzka+ 2016, Davelaar+ 2019, Chatterjee+ 2020….

ngEHT will illuminate the BH-jet connection

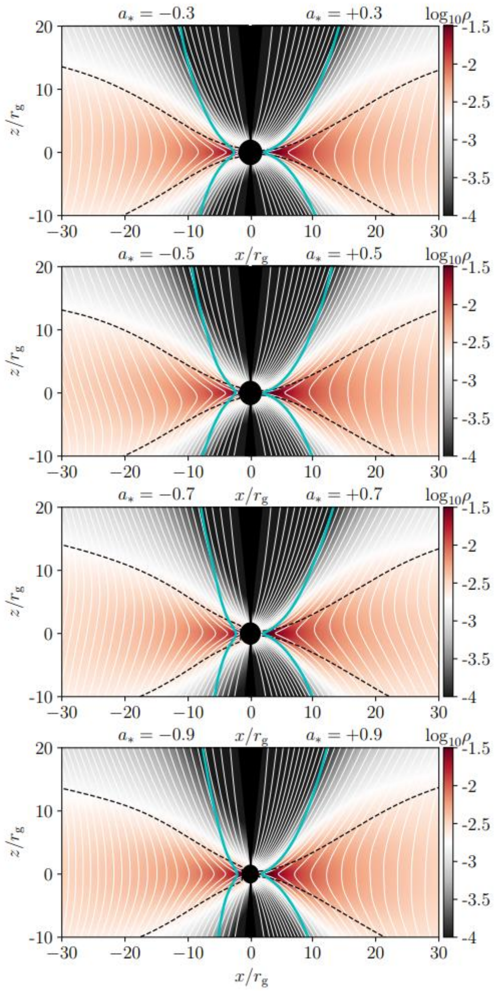


Increased *(u,v)* coverage from new sites in ngEHT will enhance **dynamic range**

Going to 345 GHz will increase **resolution**

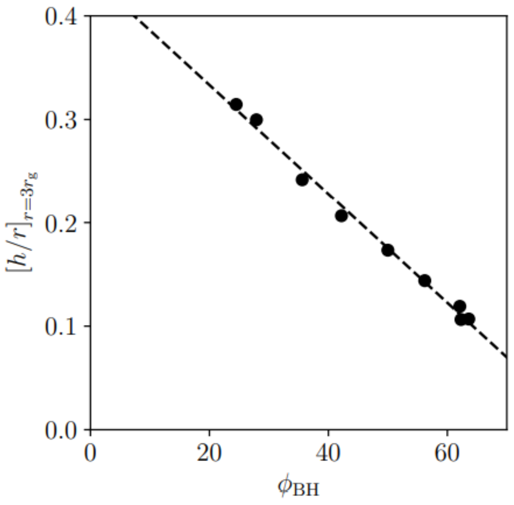
Blackburn+ 2020
Simulation : Chael+ **2019**, **Chael**+ 2021
Imaging: Chael+ **2022** in prep

Jet Power & Width in long-duration MAD Simulations

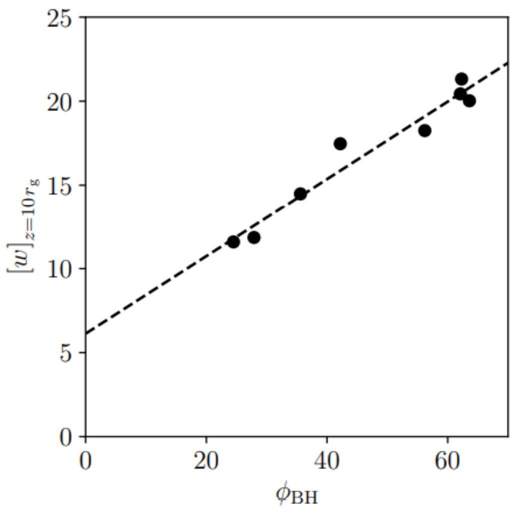


- Jet width at the base **increases** with BH magnetic flux
- Disk height near the BH **decreases** with flux
- Saturated flux is **correlated with spin**
- Could potentially be observable with future EHT observations!

Disk height

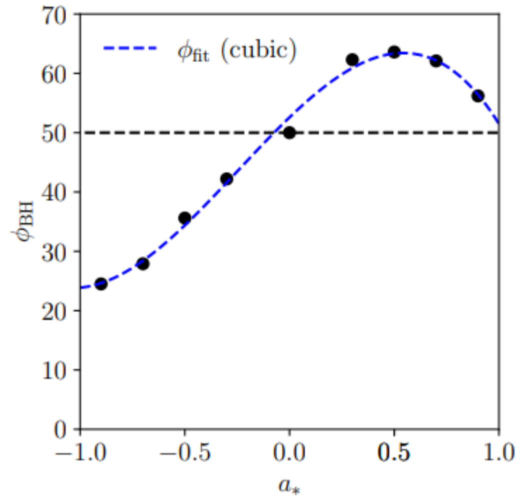


Jet width



BH magnetic flux

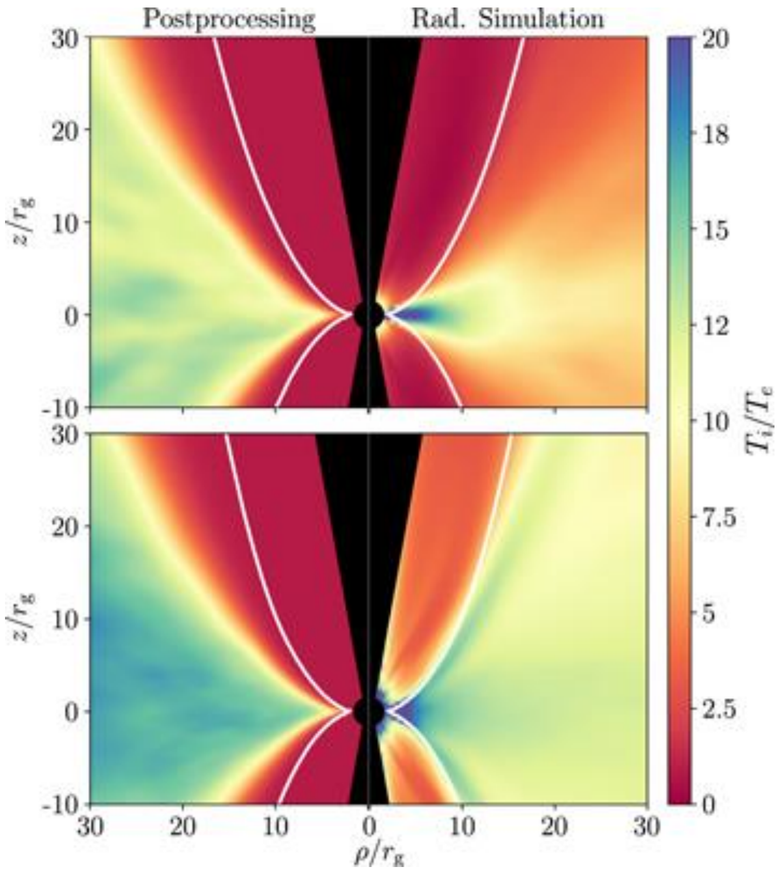
BH magnetic flux



BH spin

R. Narayan, A. **Chael**, K. Chatterjee, A. Ricarte, B. Curd 2021

Ongoing Work: Heating and Cooling



Simulations with radiation & heating can produce very different emission than common postprocessing techniques!

- M87* and Sgr A* have **two-temperature** accretion flows

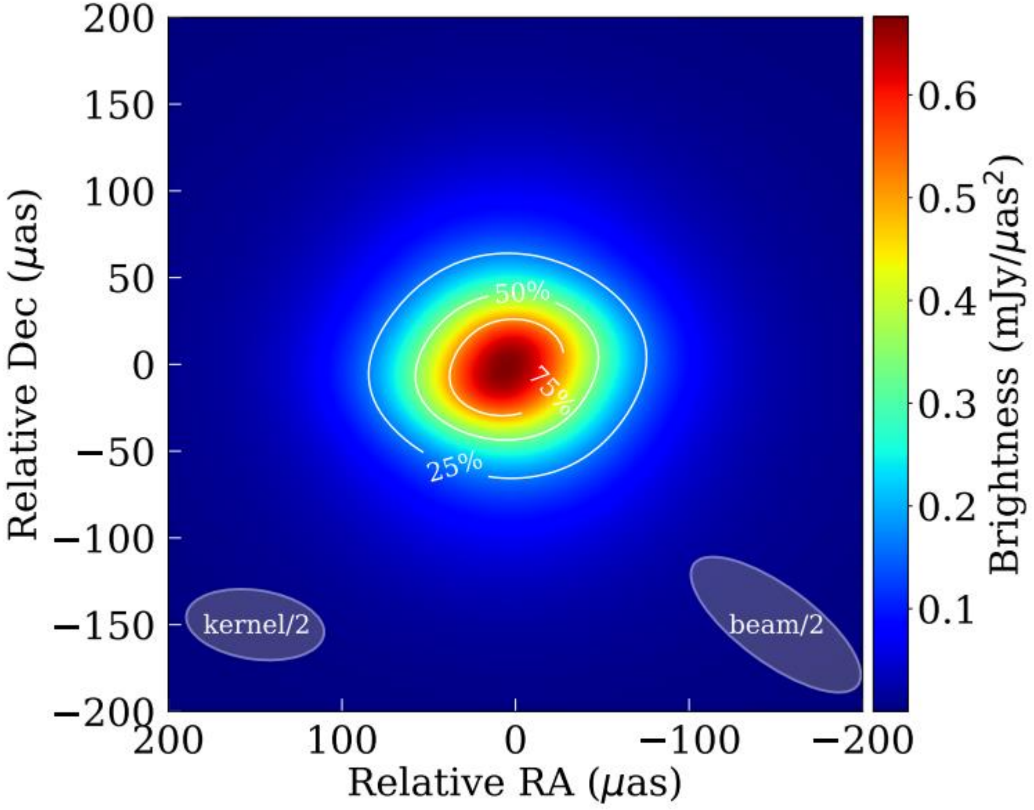
$$T_{\mathrm{e}} \neq T_{\mathrm{i}} \neq T_{\mathrm{gas}}$$

- Radiative **cooling is important** (particularly for M87*)
- Many different prescriptions in the literature for **plasma heating/acceleration at microscopic scales**
- Most GRMHD analysis includes these effects only approximately in postprocessing

EHTC+ 2021 VIII

Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael**+ 2018, 2019, Dexter+ 2020,2021, Mizuno+ 2021,…

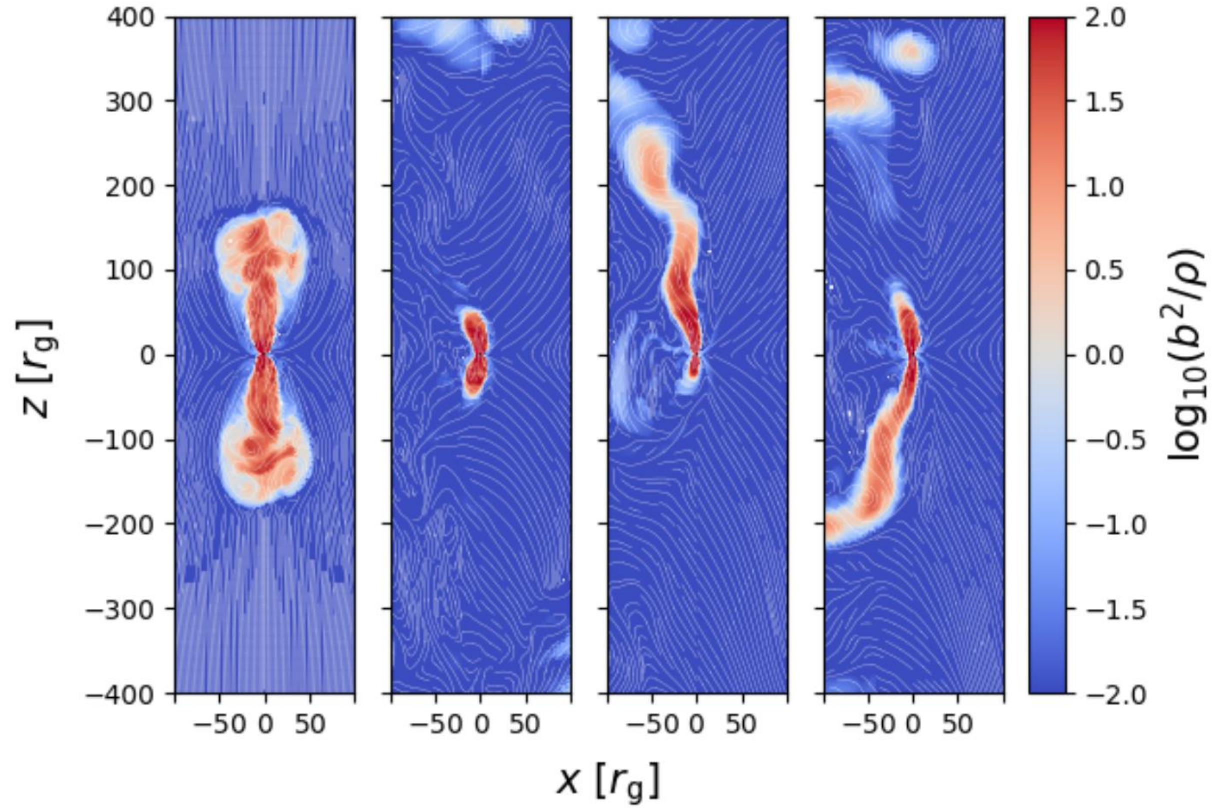
Ongoing Work: Initial Conditions

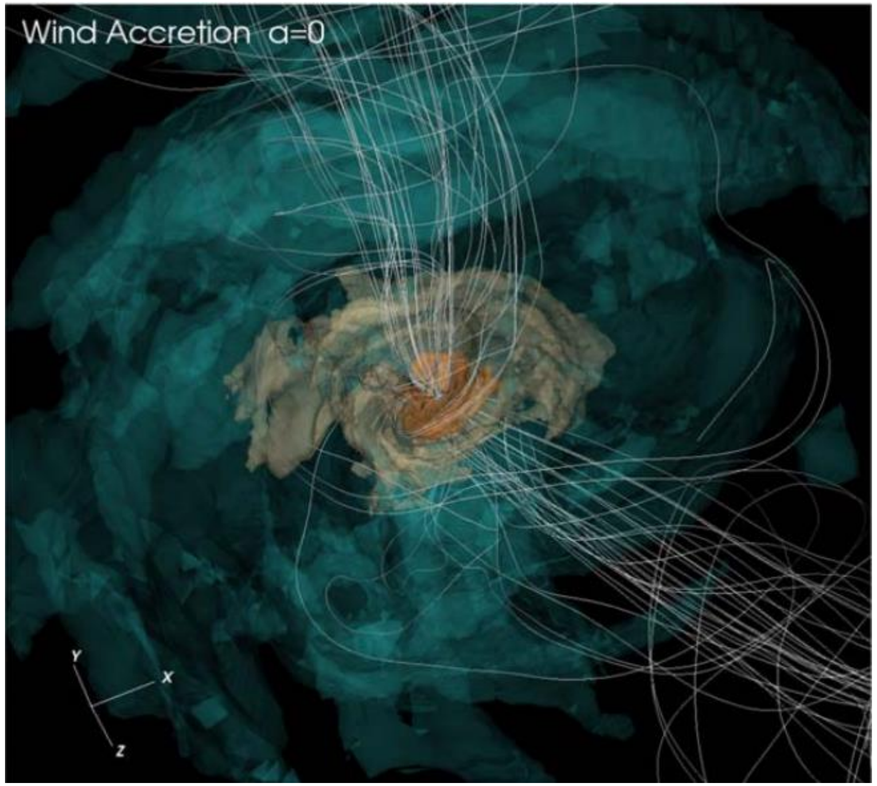


- Where is the jet in Sgr A*?
- 86 GHz image is one of the tightest constraints for Sgr A* (rejects 42% of all models), mainly because of prominence of the jet.
- Issaoun+ 2019, 2021 interpretation – jet is either faint or pointed face on.

Issaoun+ 2019, 2021,
EHTC+ 2022e

Ongoing Work: Initial Conditions



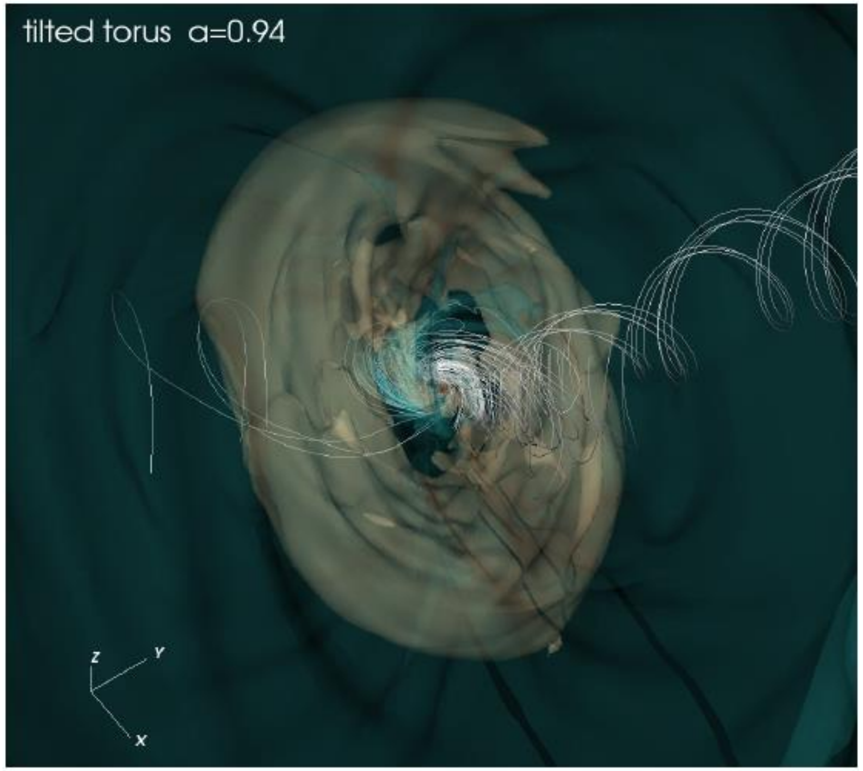


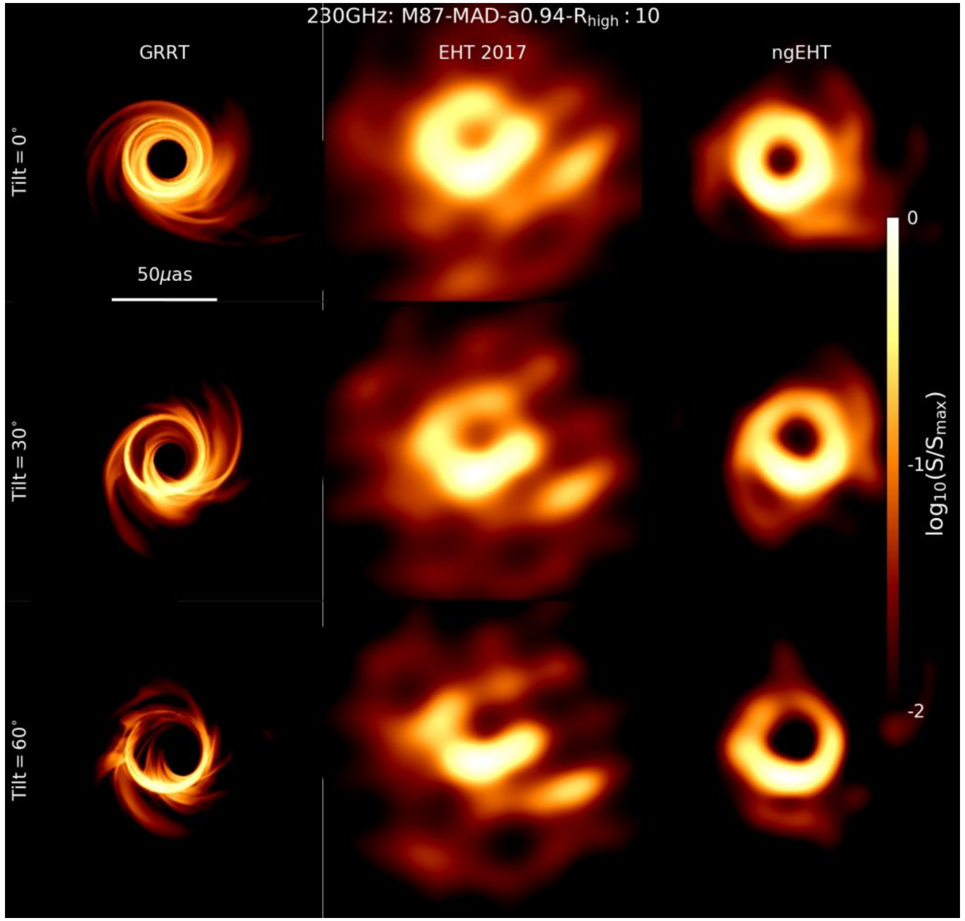
- Standard GRMHD initial conditions are an orbiting torus in the midplane
- Work on more realistic initial conditions from Wolf-Rayet outflows in galactic center shows gas inflow may have less net angular momentum
- These conditions may frustrate emergence of a large-scale jet

Ressler+ 2018, 2019, 2020, 2021

Ongoing Work:
Misaligned disks and jets

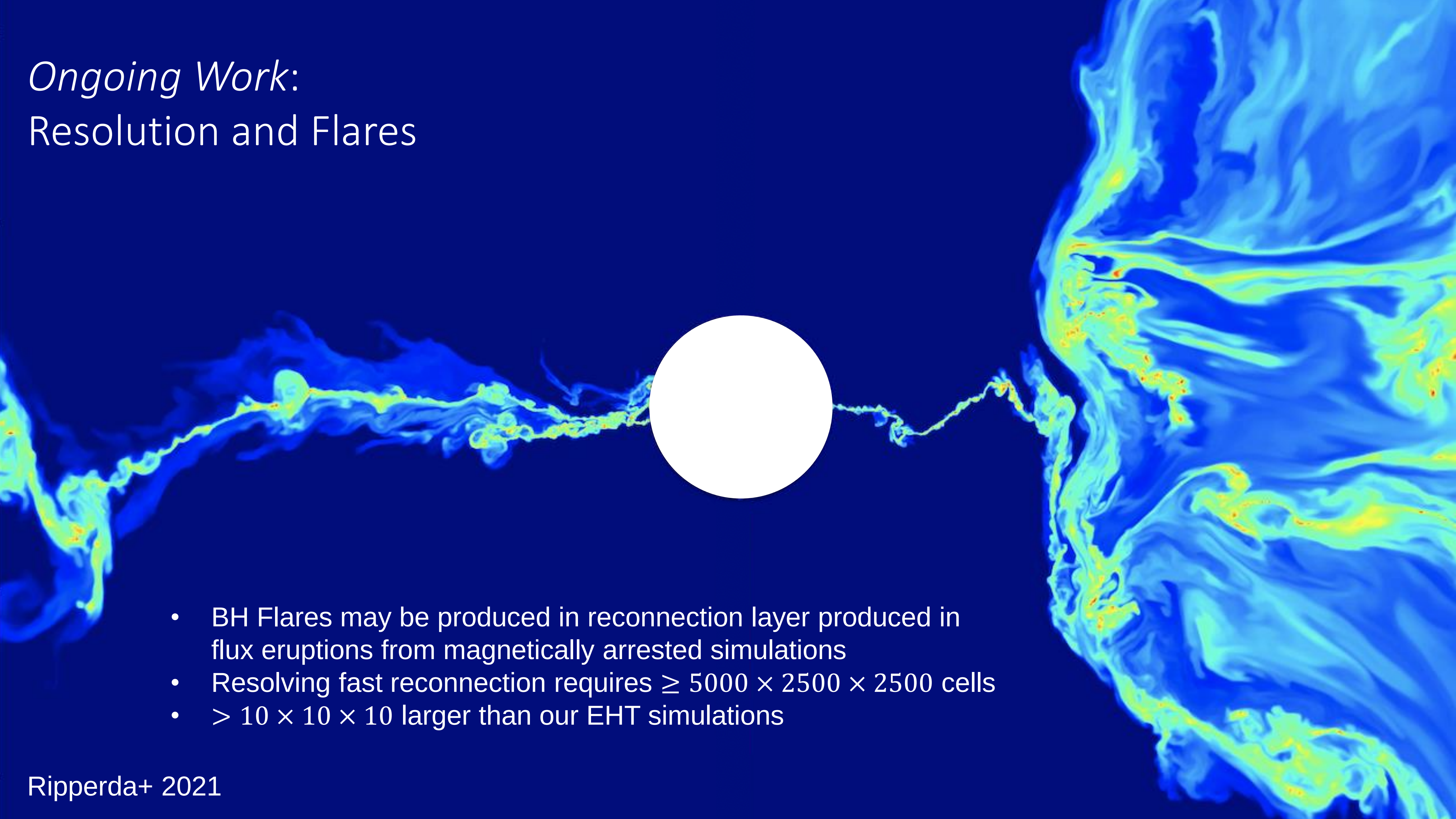
Liska+18, Chatterjee+20, EHT Sgr A* Paper V





Future observations with EHT can potentially track twists in the jet, constraining misalignment

Credit: Chatterjee, Raymond, Palumbo, ngEHT team



Ongoing Work: Resolution and Flares

- BH Flares may be produced in reconnection layer produced in flux eruptions from magnetically arrested simulations
- Resolving fast reconnection requires $\geq 5000 \times 2500 \times 2500$ cells
- $> 10 \times 10 \times 10$ larger than our EHT simulations

Ripperda+ 2021

Summary

- GRMHD simulations are the main theoretical instrument for interpreting EHT results.
- EHT polarimetric images of M87 strongly prefer a magnetically arrested accretion flow.
- GRMHD simulations of magnetically arrested disks naturally produce strong jets via the BZ mechanism.
- Direct comparison of simulations to observations now possible from the black hole out to large distances (>1 pc for M87).
- Future EHT or ngEHT observations will directly observe the disk-jet connection in M87.
- Exciting new frontiers and open questions:

  Electron heating and cooling – *will better modeling change our interpretation?*

  Initial conditions – *can they frustrate the emergence of a jet?*

  Disk tilt – *how does it change EHT images and large-scale features?*

  High resolution – *are BH flares naturally produced in magnetically arrested disks?*