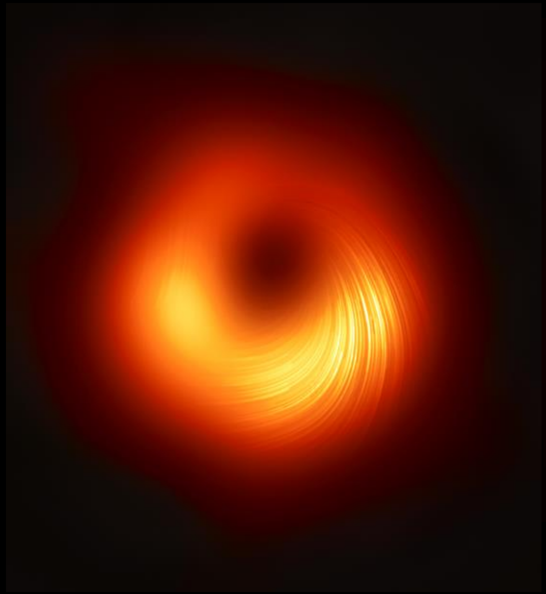
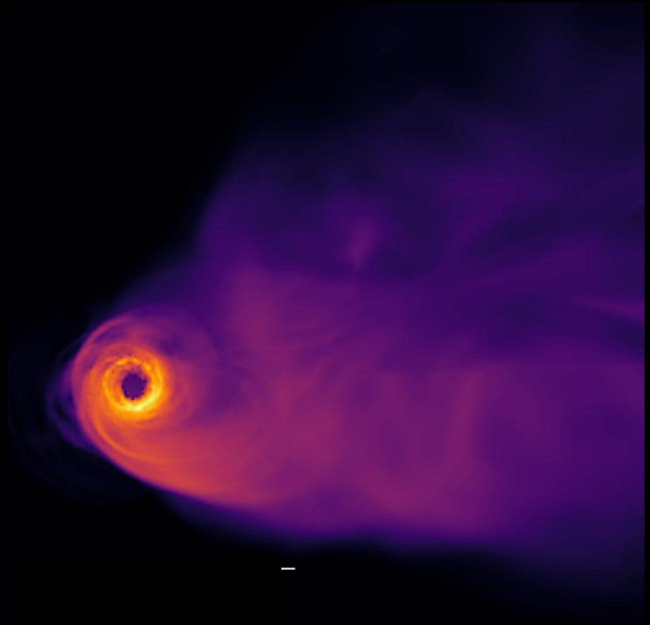
The black-hole jet connection in simulations of M87

Andrew Chael
Princeton Gravity Initiative

02/28/2023





Princeton gravity Initiative

Event Horizon Telescope

M87 & M87*

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

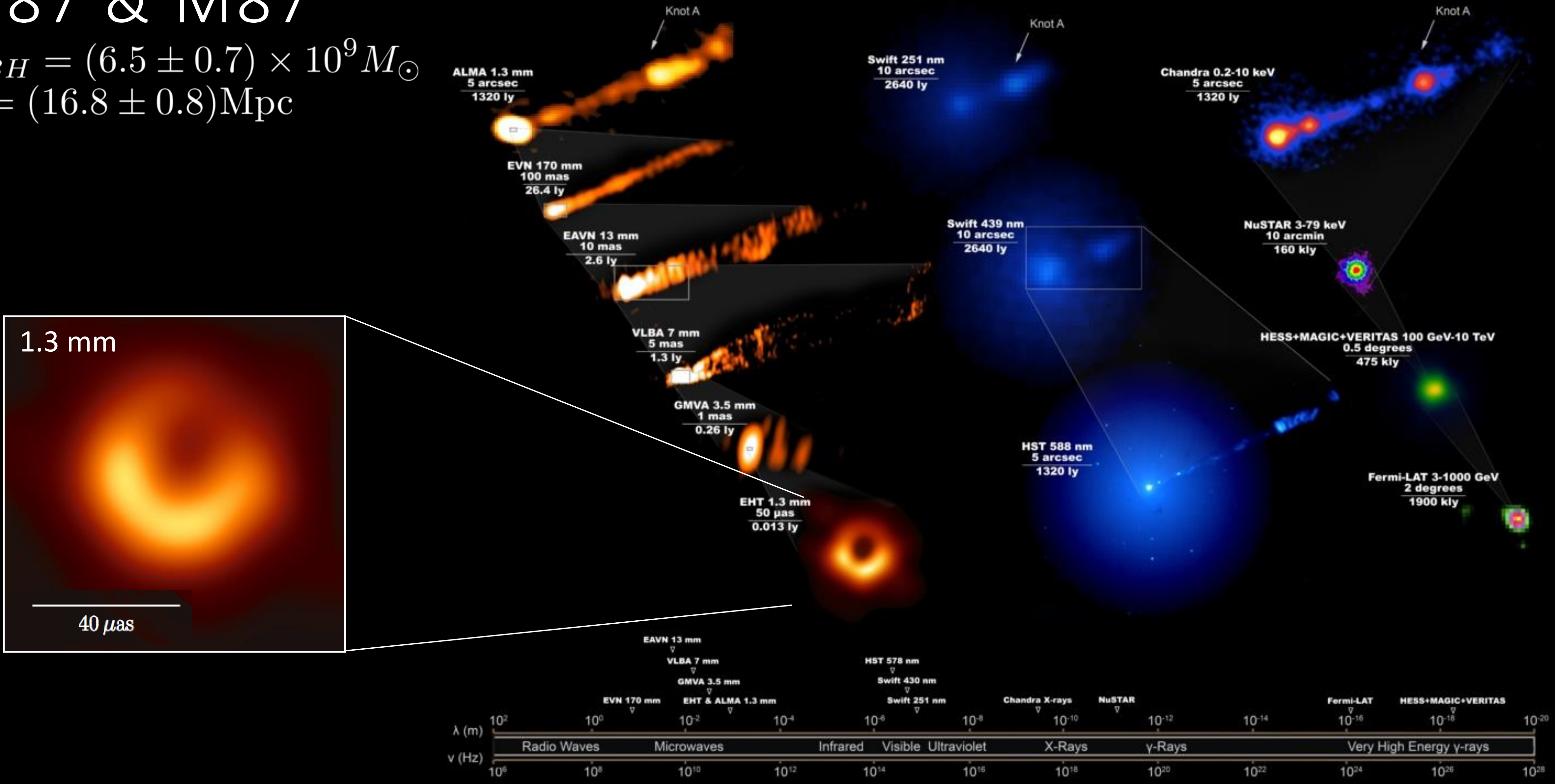
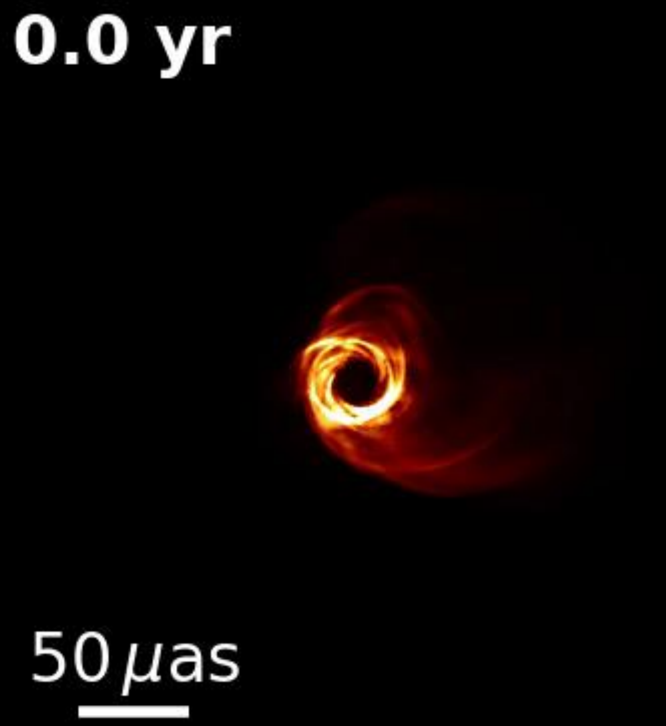


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

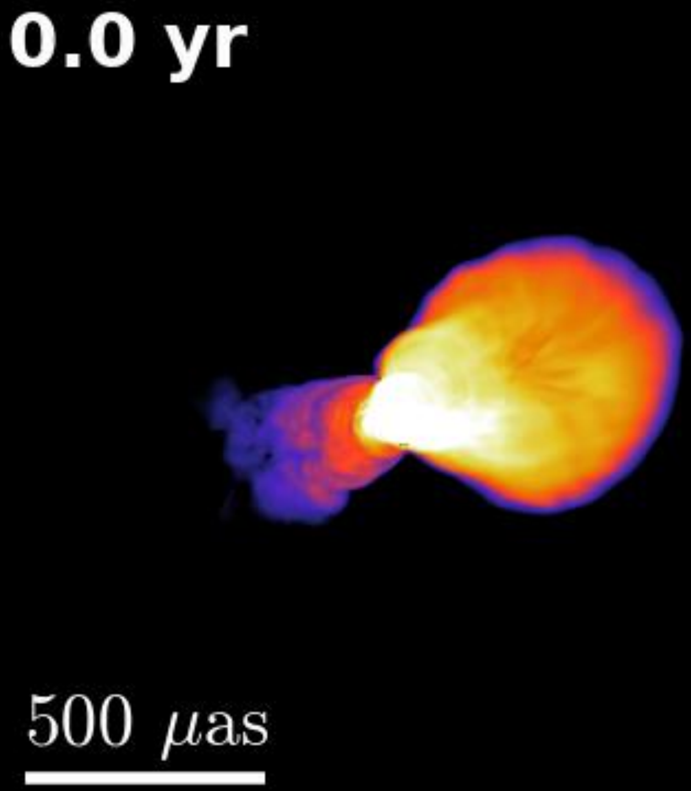
Credit: EHTC, NASA/Swift; NASA/Fermi; Caltech-NuSTAR; CXC; CfA-VERITAS; MAGIC; HESS: arXiv 2104.06855

Takeaway

230 GHz



43 GHz



Progress in modeling EHT sources requires us to **look beyond the shadow** and at launching point and **compare simulations to jet observations d**ownstream

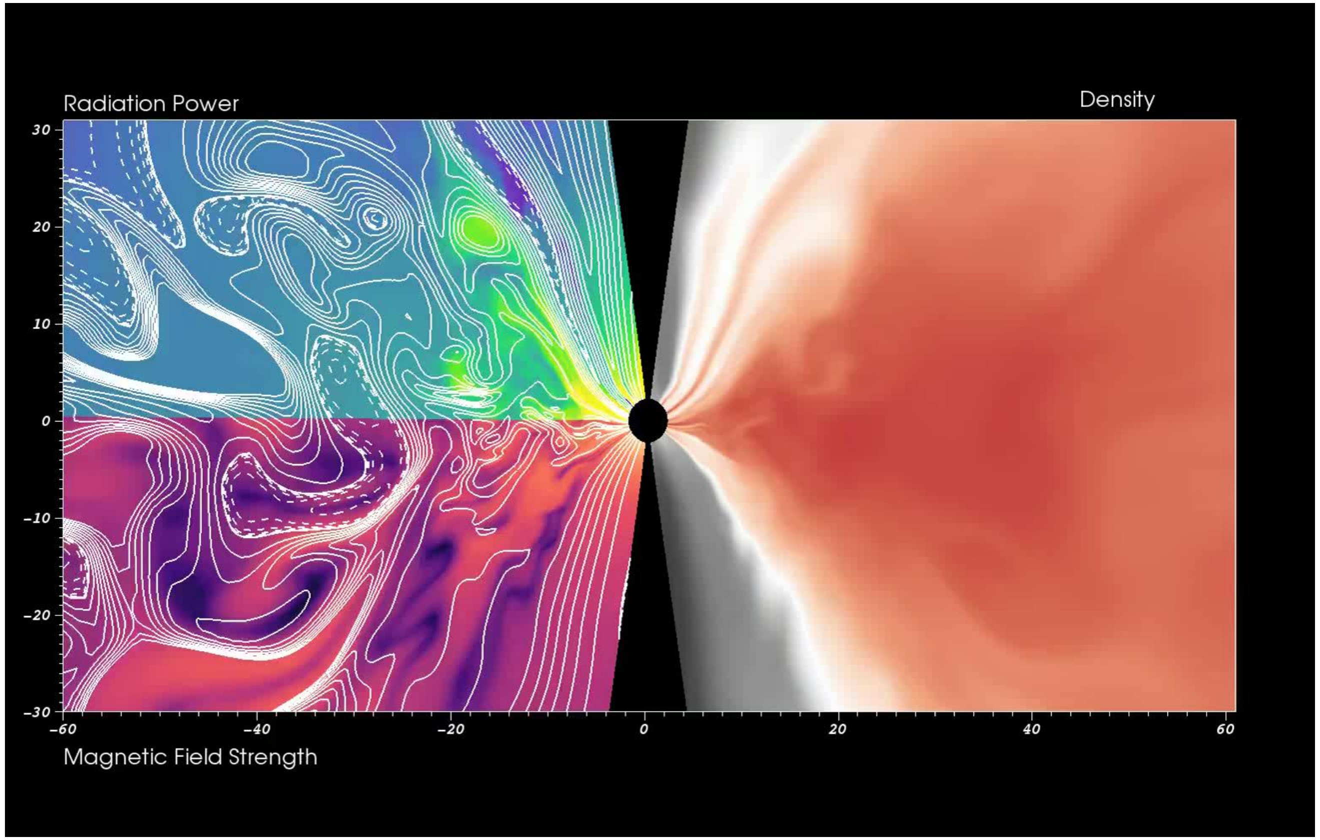
Chael+ 2019

Outline

1. Radiative, Two-Temperature Simulations of M87*
2. Observables, this generation and next
3. Hybrid GRMHD+Force-Free Simulations of Jet Launching

GRMHD and Two-Temperature GRMHD Simulations of M87

Why GRMHD Simulations?



- **G**eneral **R**elativistic **M**agneto**H**ydro**D**ynamic simulations solve the coupled equations of plasma and magnetic fields in the Kerr spacetime

- GRMHD simulations are the primary theoretical tool for interpreting EHT images.

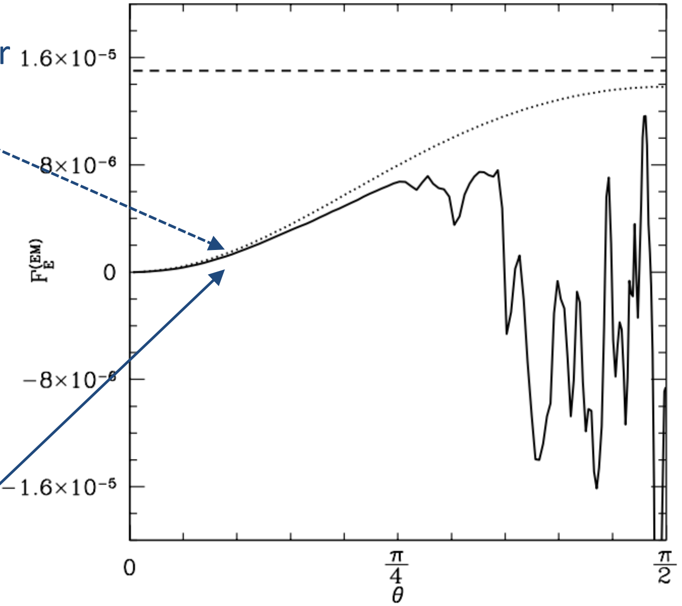
- GRMHD simulations naturally **couple the accretion disk, black hole, and jet**
  - Jet launching in simulations is universal and driven by BH spin

Movie Credit: **Chael**+ 201

GRMHD simulations naturally produce BZ jets

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

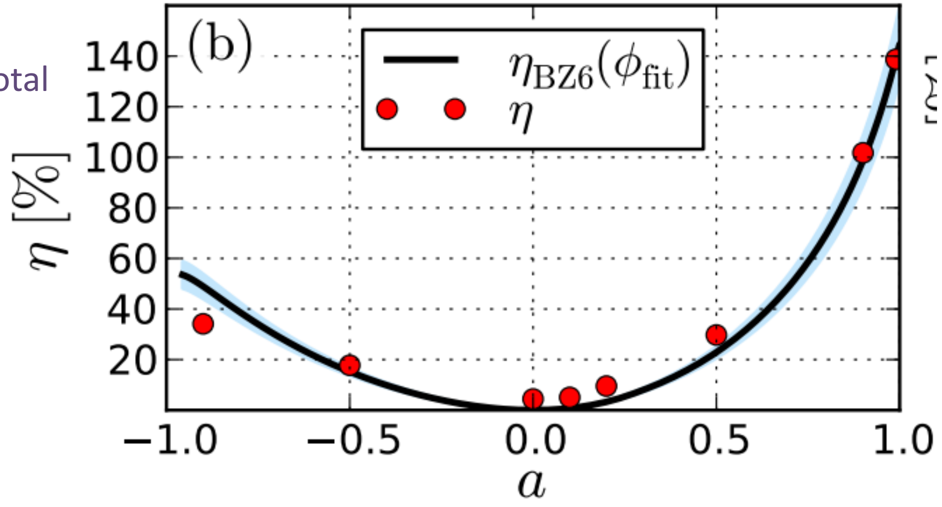
McKinney & Gammie 2004



BZ prediction for outward energy flux at the horizon

Simulation

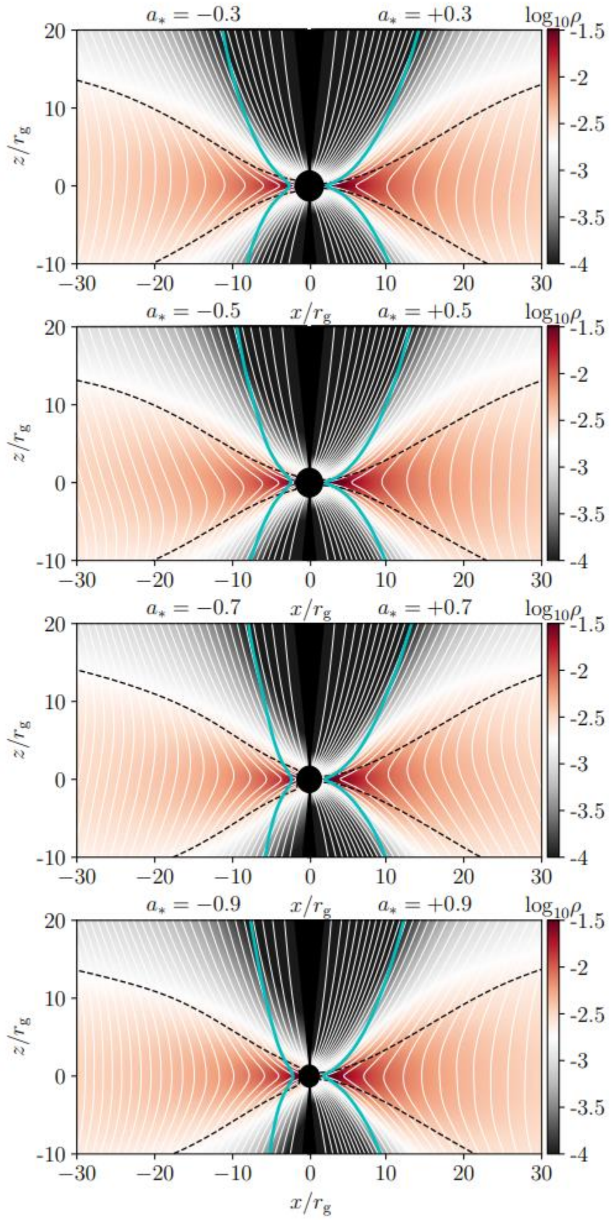
Tchekhovskoy+ 2012



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….

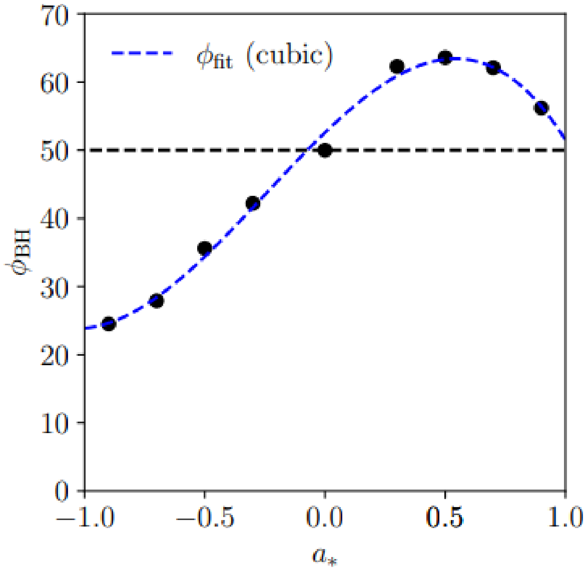
Jet Power in long-duration MAD Simulations



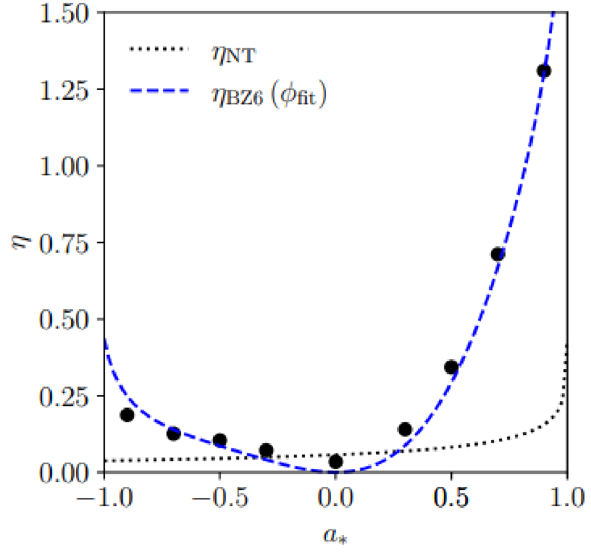
Time-and azimuth-averaged simulation data

- 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



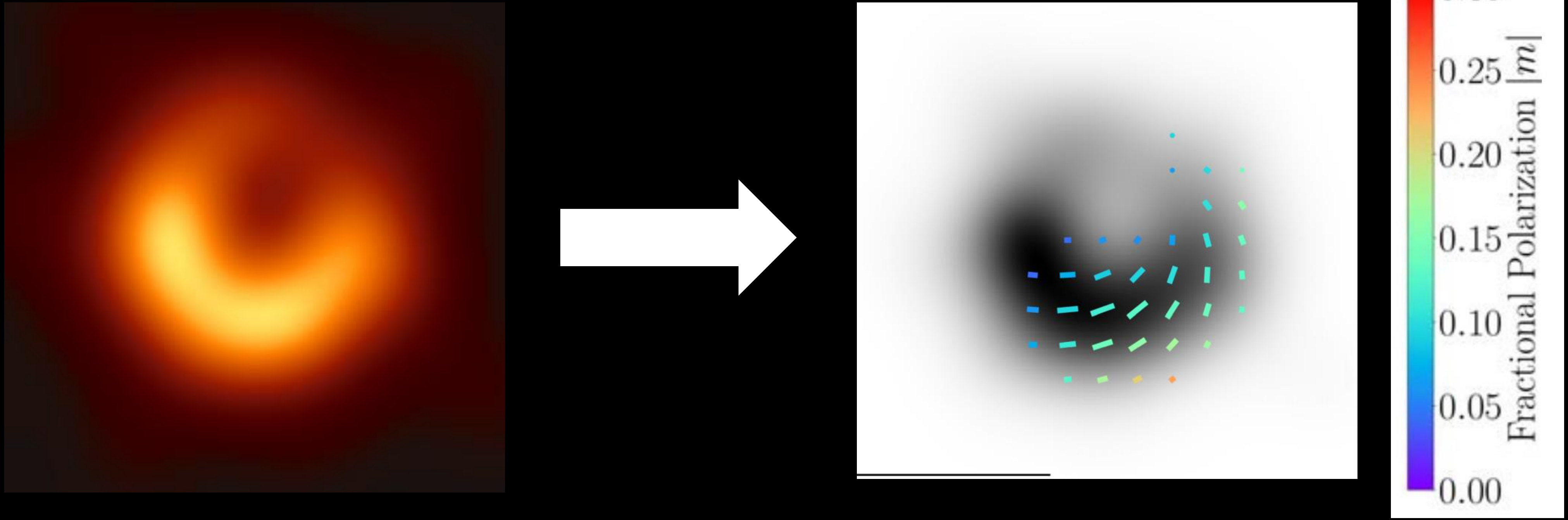
Jet efficiency



BH spin

R. Narayan, **A. Chael**, K. Chatterjee, A. Ricarte, B. Curd, 2022

Polarimetric images of M87* tell us about magnetic fields at the horizon



Total intensity

Linear Polarization

- Polarization is concentrated in the southwest
- Polarization angle structure is predominantly **helical**
- Overall level of polarization is **somewhat weak**, ~15 %

EHTC+ 2021 Papers VII & VIII

Polarimetric simulation scoring

- Scoring with multiple approaches **all strongly favor a magnetically arrested accretion flow**

- Implications for accretion and jet launching:
  - Narrows M87*'s allowed accretion rate by 2 orders of magnitude:

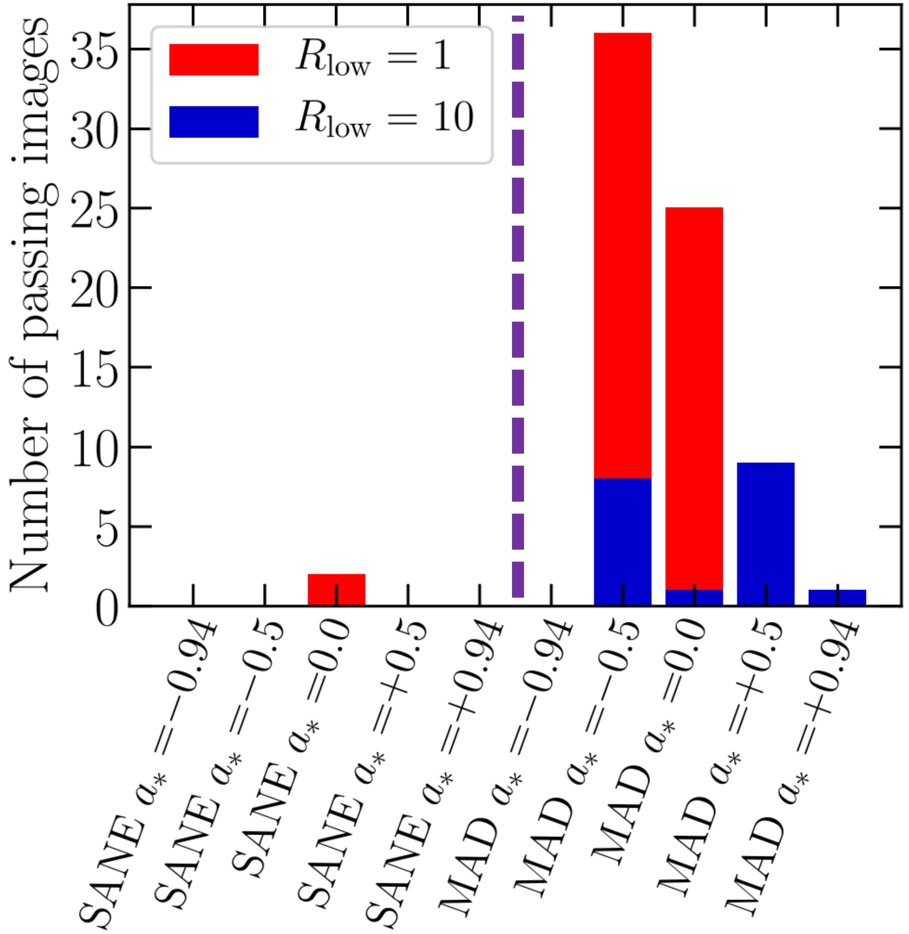
$$\dot{M} \simeq (3-20)\times 10^{-4} M_\odot\ \mathrm{yr}^{-1}$$

$$\left(\dot{M}_{\mathrm{Edd}} = 137 M_\odot\ \mathrm{yr}^{-1}\right)$$

  - Strong fields **more easily launch jets** at lower values of BH spin
  - **M87's radiative efficiency is high, ~1%** (see also Ryan+ 2018)

Weak-field

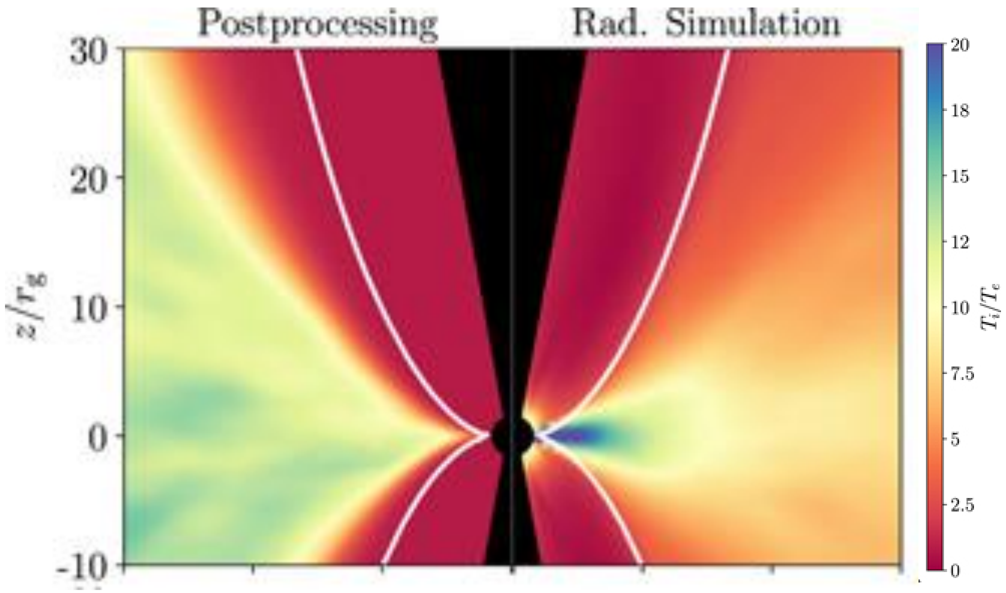
Magnetically arrested



EHTC+ 2021 Paper VIII

Electron Heating and Cooling

ion-to-electron temperature ratio



Simulations with radiation & heating can produce very different emission profiles than are found in postprocessing techniques!

- M87* and Sgr A* have two-temperature plasmas

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

- EHT analysis fixes T_e locally in **postprocessing:**
  - **Major uncertainty** in EHT analysis
  - Most GRMHD simulations **don’t produce bright jets!**

- Radiative, Two-Temperature GRMHD includes **heating and cooling self-consistently**:
  - Sub-grid plasma heating model still uncertain

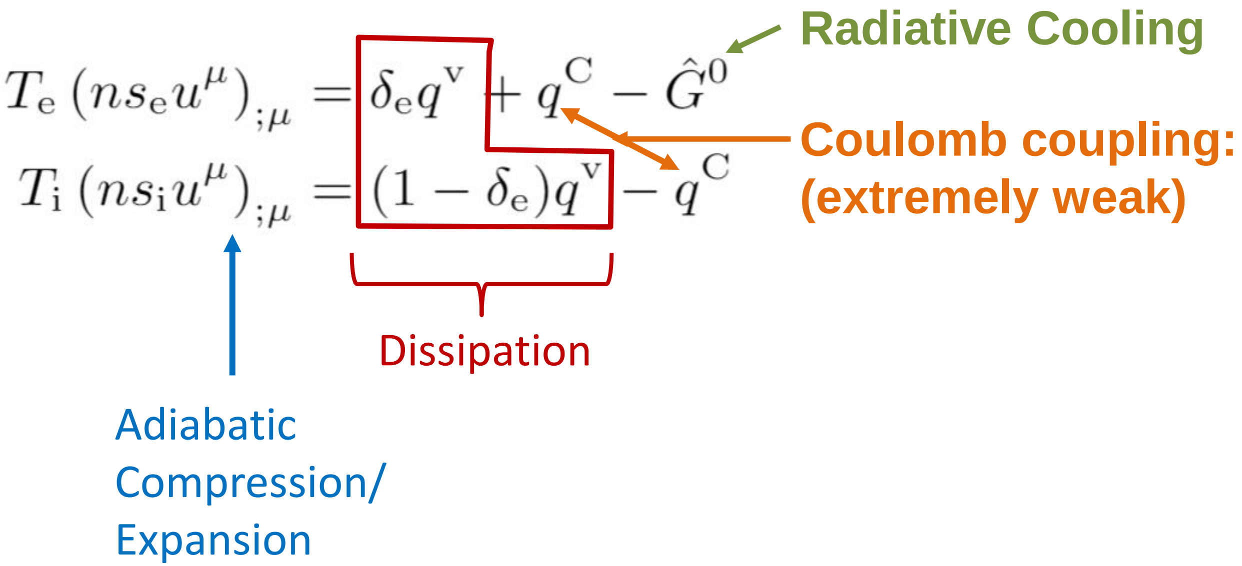
Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019, 2023 (in prep),**
Dexter+ 2020,2021, Mizuno+ 2021

Two-Temperature GRRMHD Simulations

- Using the GRRMHD code `KORAL`: (Sądowski+ 2013, 2015, 2017, Chael+ 2017)

- Includes **radiative feedback** on gas energy-momentum.
  -- M87’s accretion rate is high enough that radiative feedback is important (Ryan+ 2018, EHTC+ 2019,2021)

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



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

Radiative Cooling

Coulomb coupling: (extremely weak)

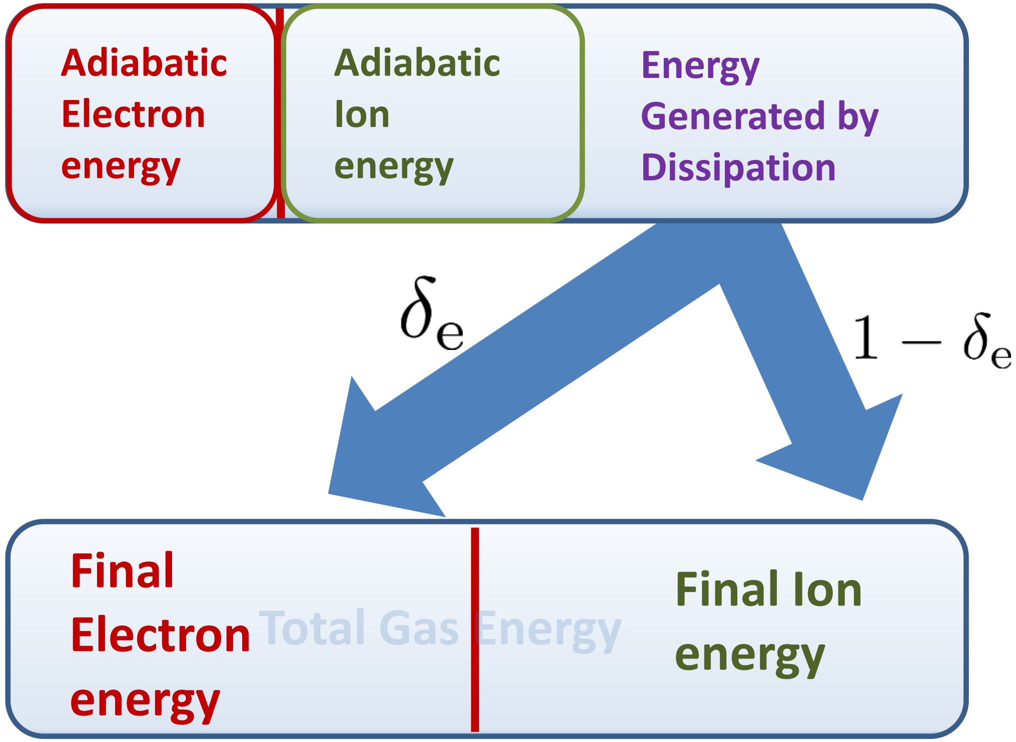
Dissipation

Adiabatic Compression/ Expansion

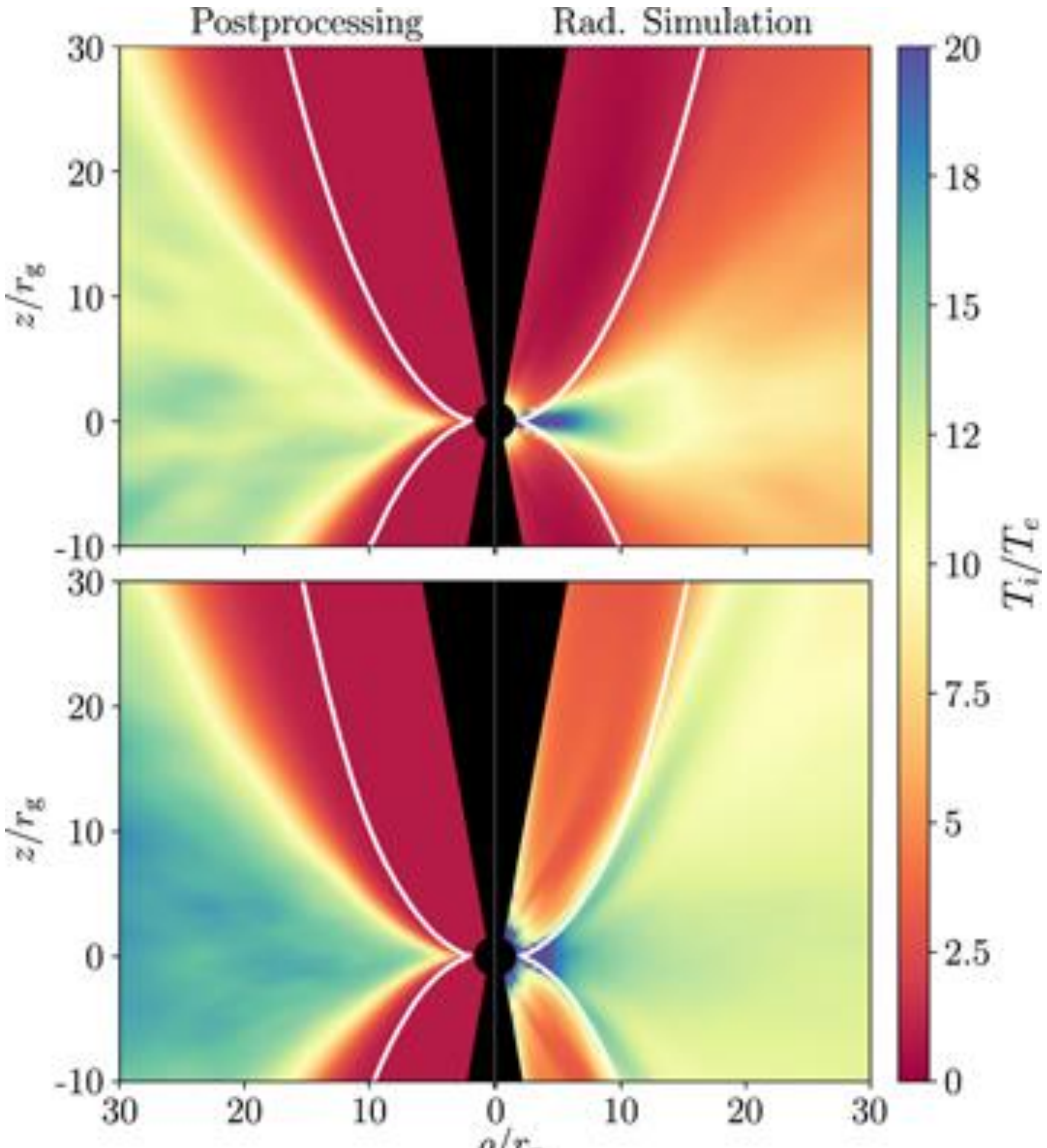
Electron & Ion Heating

- The **total** dissipative heating in the simulation is internal energy of the total gas minus the energy of the components **evolved adiabatically.**

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



Electron Heating and Cooling



- In EHTC Paper VIII we compared average temperature ratios in radiative simulations to **best match** using Rhigh/Rlow prescription

- Rhigh/Rlow model cannot produce structure in temperature ratio distribution seen in radiative simulations

- Radiative simulations have cooler electrons close to the horizon and along the jet sheath than is seen in postprocessing (with Rlow=1)

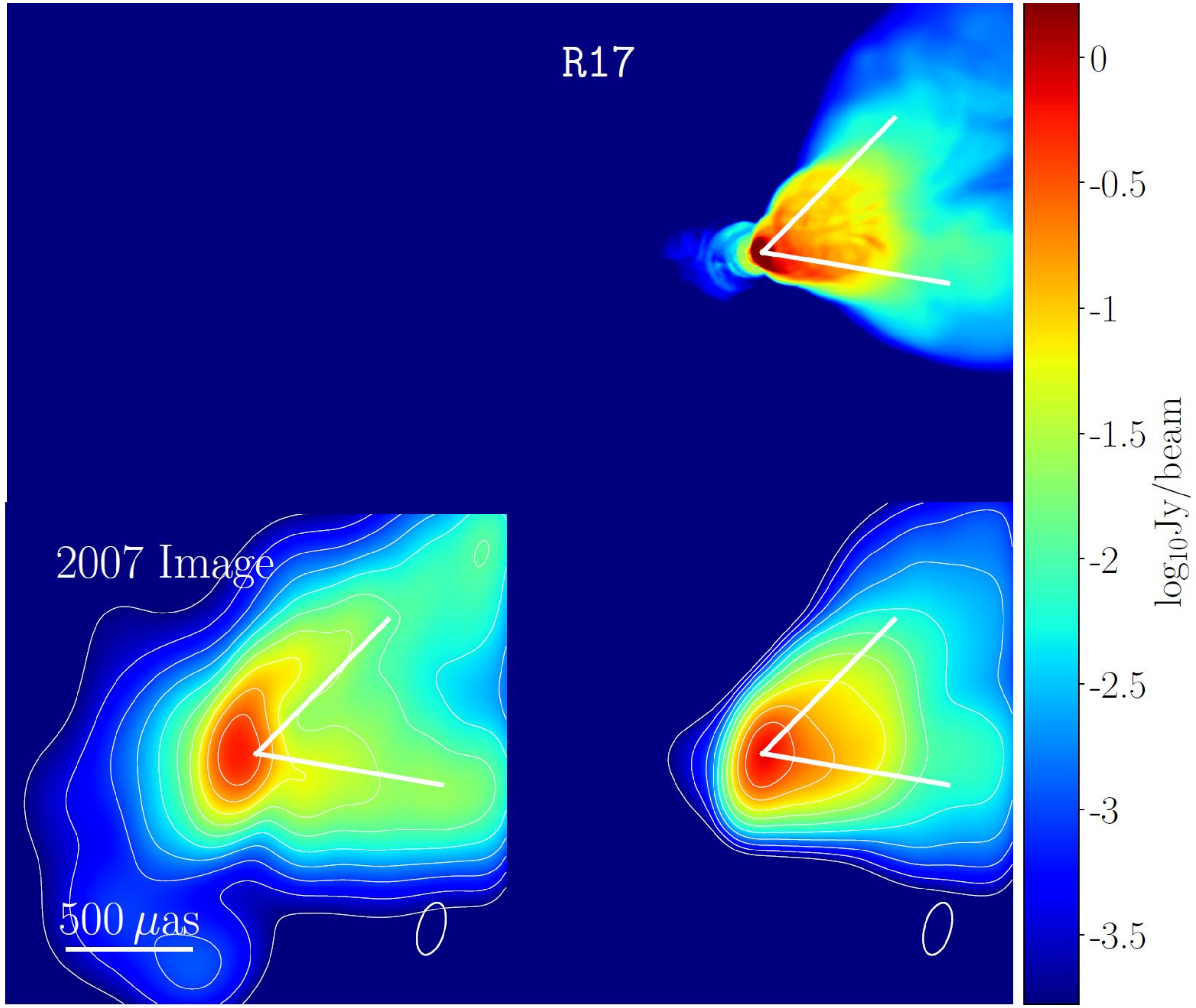
Ressler+ 2015, 2017, Sadowski+ 2017, Ryan+ 2018, **Chael+ 2018, 2019, 2023 (in prep),**
Dexter+ 2020,2021, Mizuno+ 2021

43 GHz jets from M87 GRMHD Simulations

Simulation

High Resolution

VLBA Resolution



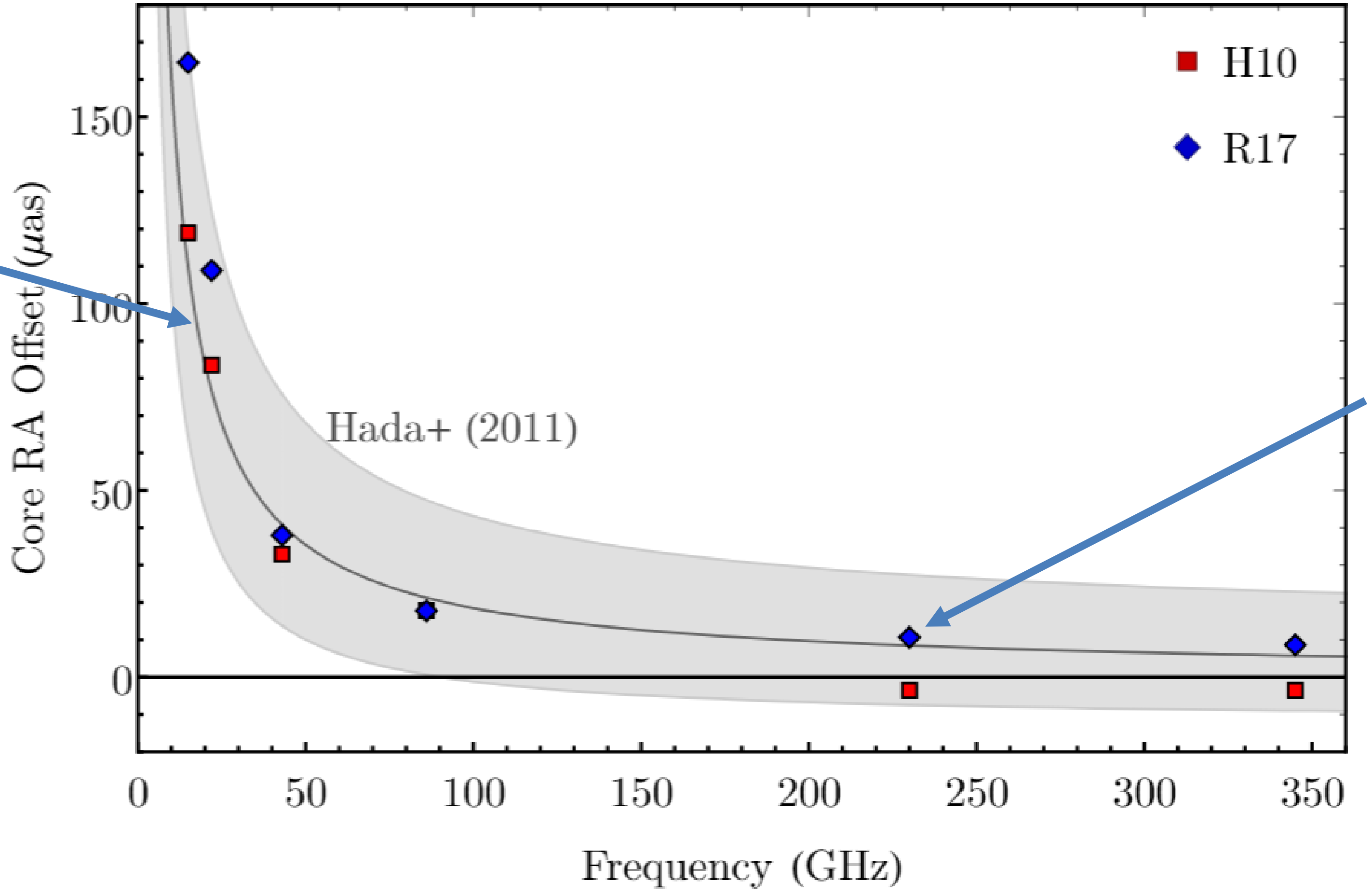
Jets in magnetically arrested GRMHD simulations of M87 run to large distances naturally produce:

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

Observed limb-brightening remains hard to reproduce!!

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

M87 Core-Shift



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

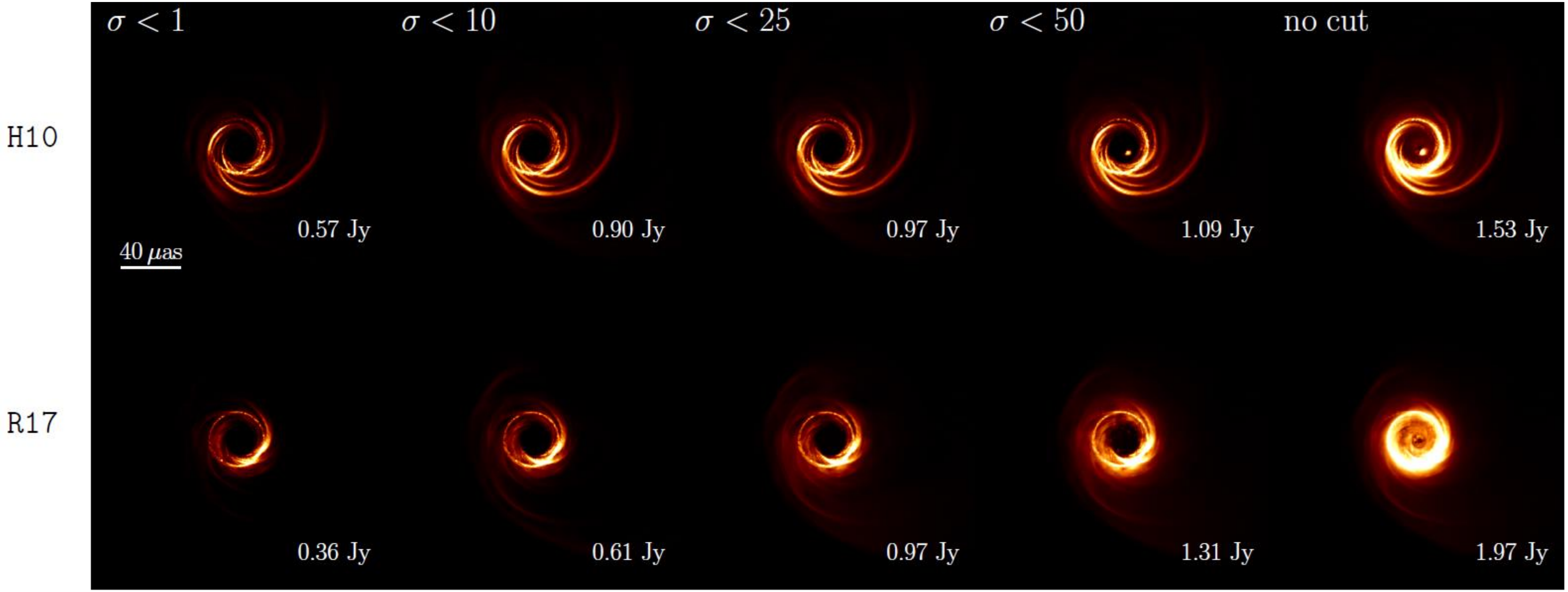
At 230 GHz and higher, the core is coincident with the black hole

Agreement with measured core shift up to cm wavelengths.

Hada+ 2011

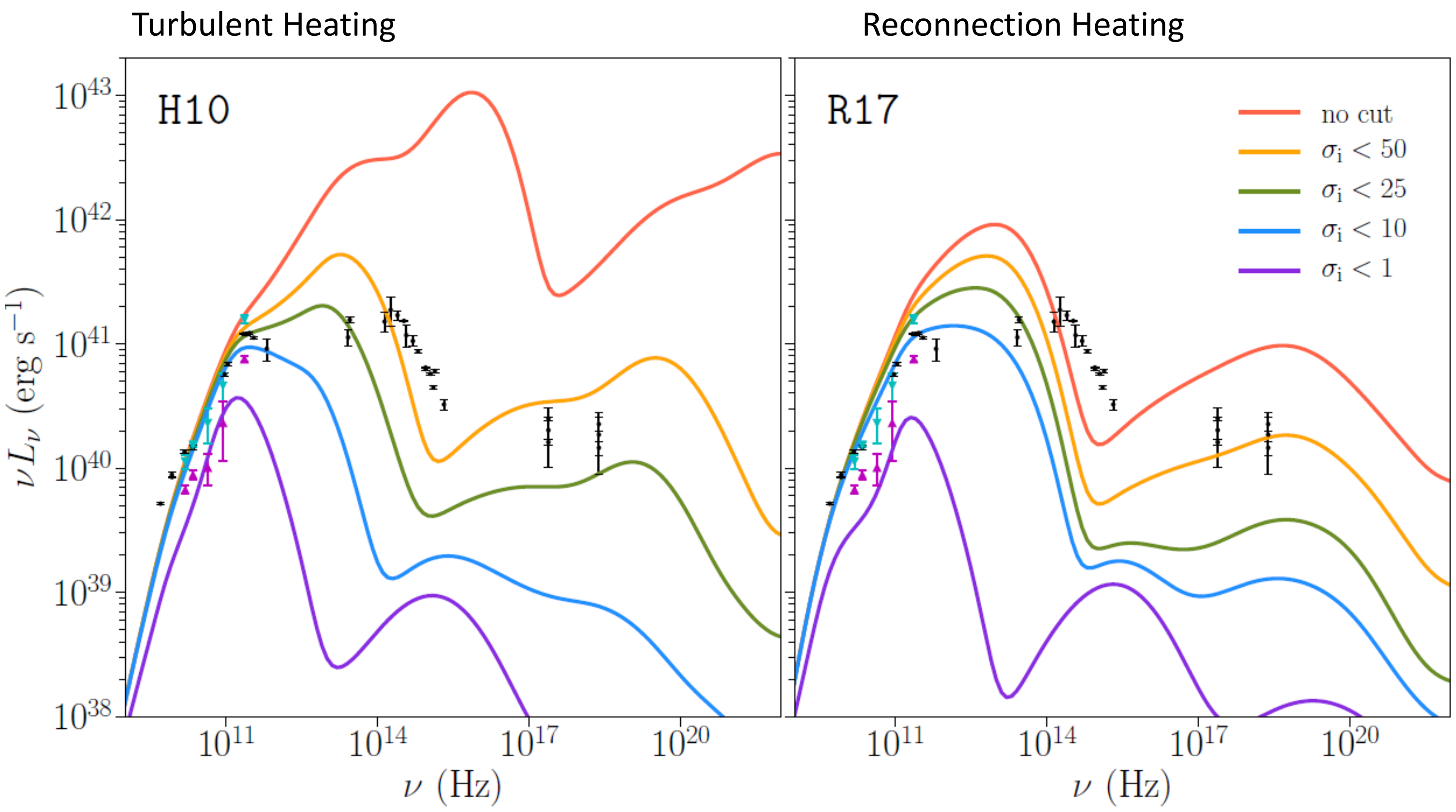
Image Credit: Chael+ 2019

230 GHz images – dependence on σ_i cut



230 GHz images are not to sensitive to sigma-cut, up to sigma=50

Major uncertainty in simulations: σ_{i} cut


Turbulent Heating

Reconnection Heating

- 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 $\sigma_{\mathrm{i}} \leq 25$
- **SED 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

Coming soon:
library of two-temperature MAD simulations of M87*

- 10 BH spins (a=-0.9,-0.7,-0.5,-0.4,-0.1,0,0.1,0.3,0.5,0.7,0.9)

- 2 electron heating models (Kawazura+2020, Zhdankin+ 2019)
  + standard GRMHD comparison

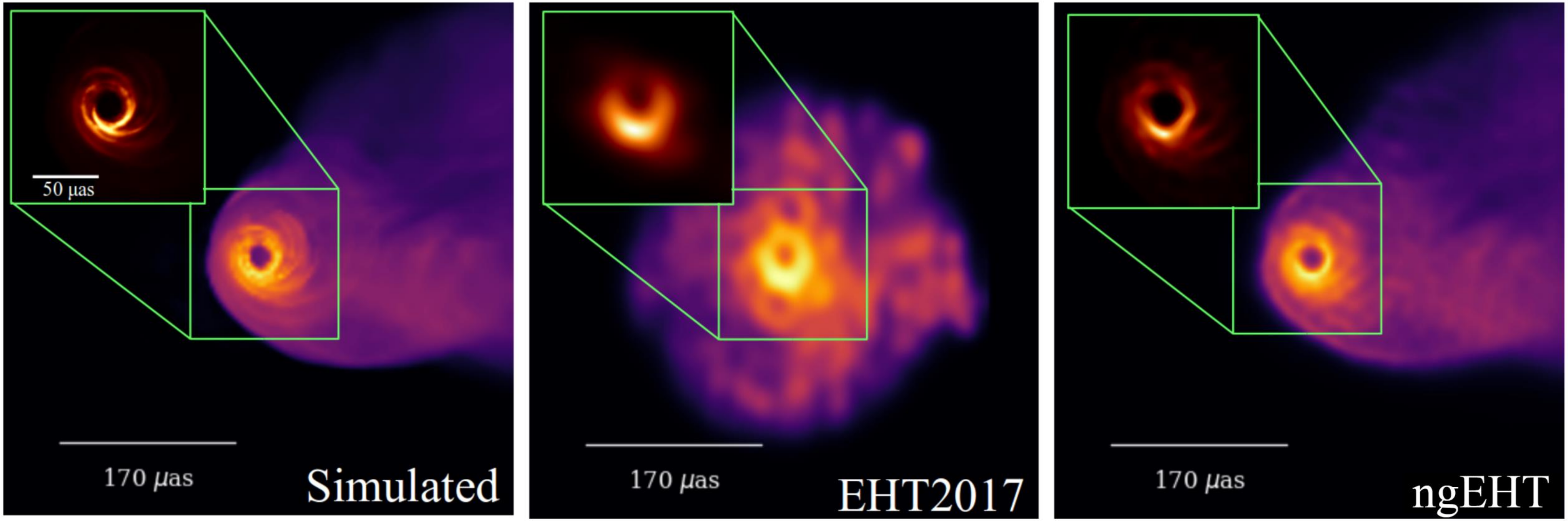
- Run to 25,000 M

- Questions:
  - Is the jet power-spin relationship affected by cooling/radiative feedback?
  - How is image/jet morphology at high dynamic range affected by radiation physics?
  - Is the relationship between beta2 and spin robust to changes in heating/cooling?
  - Others?

- First results soon!

Observables for this generation and the next

EHT/ngEHT will illuminate the BH-jet connection



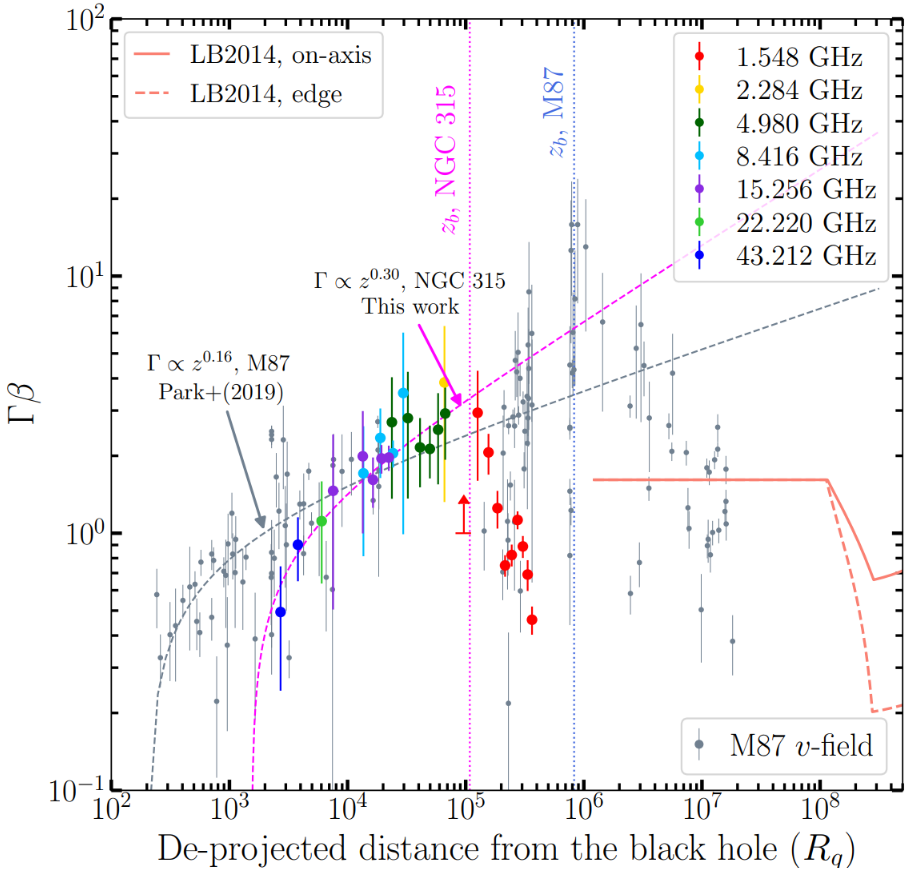
Increased *(u,v)* coverage from new sites in ngEHT will enhance **dynamic range**

Going to 345 GHz will increase **resolution**

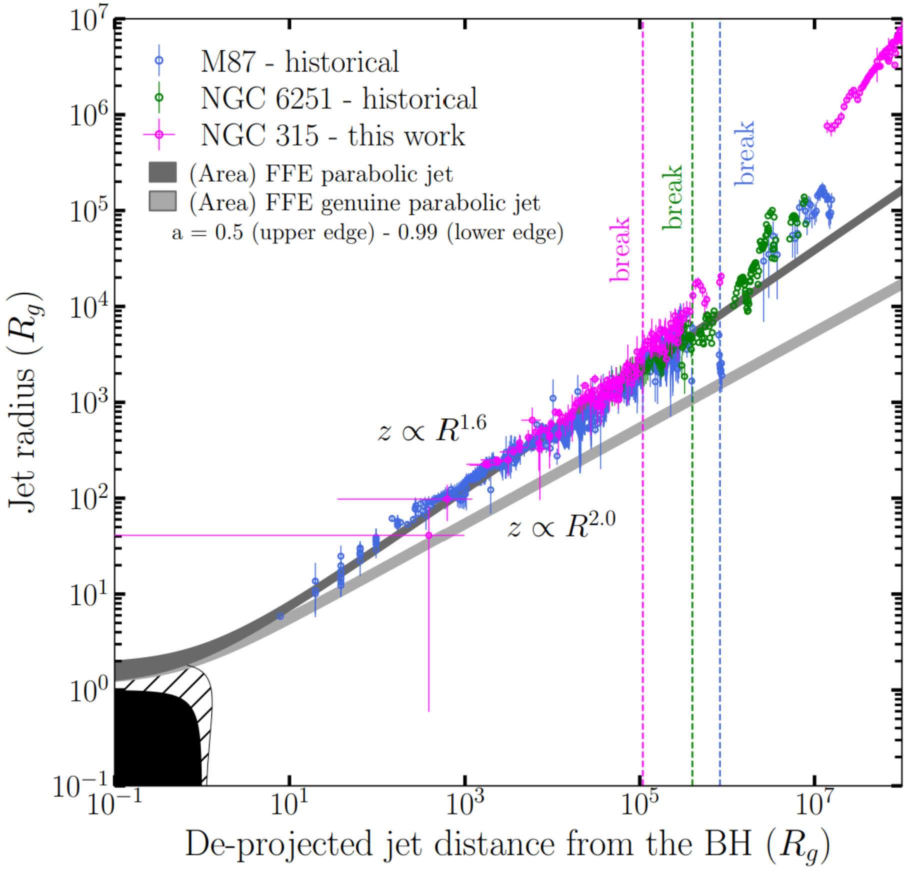
Blackburn+ 2020
Simulation : Chael+ **2019**, **Chael**+ 2021
Imaging: Chael+ **2022** in prep

Jet observables we should be comparing to

Jets show consistent acceleration profiles and deceleration at the bondi radius



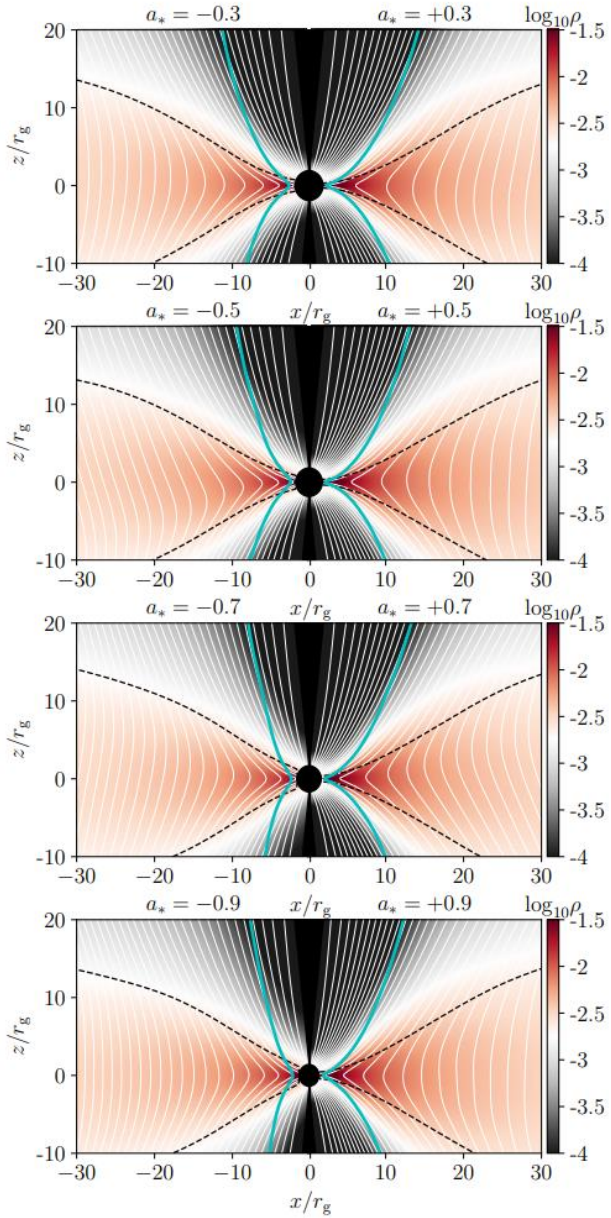
Jet opening angle is tracked over orders in magnitude from jet base in several sources



- **Need to link** jet launching and jet propagation observations to multi-scale jet simulations from launching to past Bondi radius

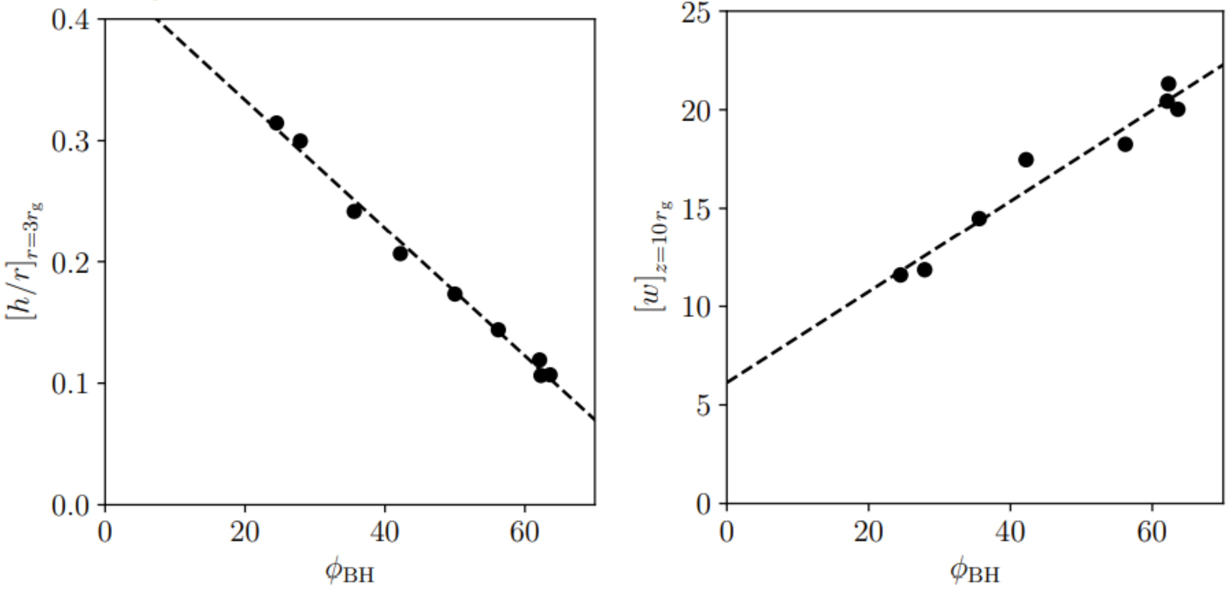
Park+ 2020

Jet Power & Width in long-duration MAD Simulations



Time-and azimuth-averaged simulation data

- Jet width at the base **increases** with BH magnetic flux
- Disk height near the BH **decreases** with flux
- Both could potentially be observable with future EHT/ngEHT observations!



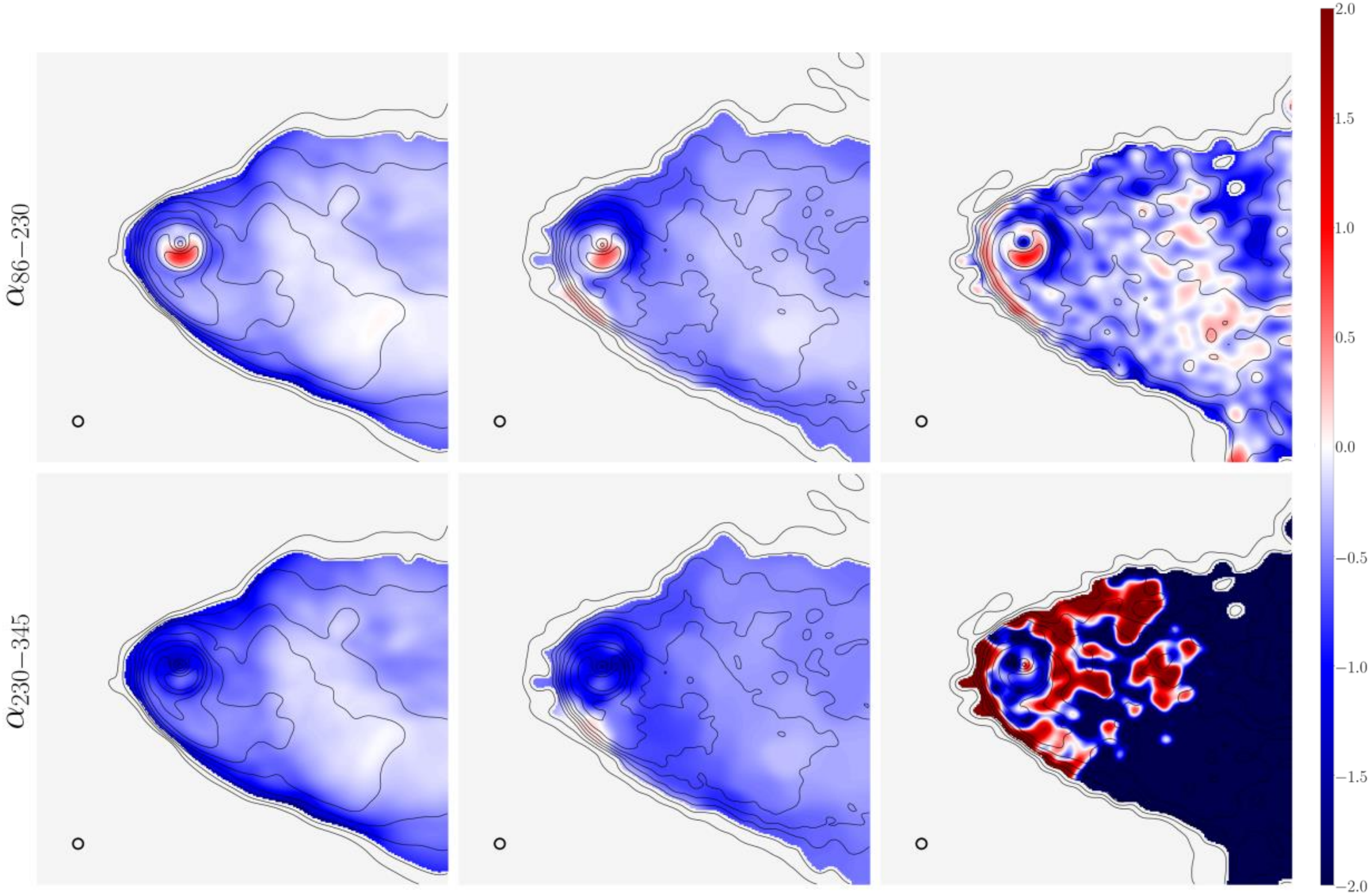
Disk height

Jet width

BH magnetic flux

R. Narayan, A. Chael, K. Chatterjee, A. Ricarte, B. Curd
arXiv: 2108.12380

ngEHT multi-frequency imaging: recovering spectral index



Multi-frequency ngEHT images can probe the **electron temperature and distribution function** in the disk, jet, and interface

Chael+ 2023 in press
Simulation: Chael+ 2019

Hybrid GRMHD+Force-Free Simulations

Hybrid GRMHD+Force Free Simulations

- In real BH accretion systems, we expect very large σ in the jet region
- Here, where $T^{\mu\nu}_{\mathrm{EM}} \gg T^{\mu\nu}_{\mathrm{MAT}}$, the dynamics may better be defined by force-free electrodynamics:

$$\nabla_\mu T^{\mu\nu}_{\mathrm{EM}} = J_\mu F^{\mu\nu} = 0.$$

$$\nabla_\mu {}^\star F^{\mu\nu} = 0$$

- In this region, we can imagine the B-field and velocity are defined by the force-free equations and that the evolution of the fluid density and energy density are **decoupled** from the EM field

- **Goal**: Can we modify GRMHD codes to:
    - Transition to force-free evolution in the jet region
    - Decouple matter from fields in this region
    - Remove the requirement for density floors
    - Without major code modifications?

Chael+ in prep

Our approach for hybrid GRMHD+FF in KORAL

- One set of primitives $\rho,\ u_{\rm int},\ \tilde{u}^i,\ B^i$ everywhere
- Set a transition magnetization $\sigma_{\rm trans} = 50$
- Evolve two sets of conserved quantities derived from the same primitives:
  - $$\underbrace{\rho u^0, B^i}_{\text{Used for both}} \qquad \underbrace{T^0_{\ 0\ {\rm tot}}, T^0_{\ i\ {\rm tot}}}_{\text{Used for GRMHD}} \qquad \underbrace{T^0_{\ i\ {\rm EM}}, b^0, (\rho s)u^0}_{\text{Used for force-free}}$$

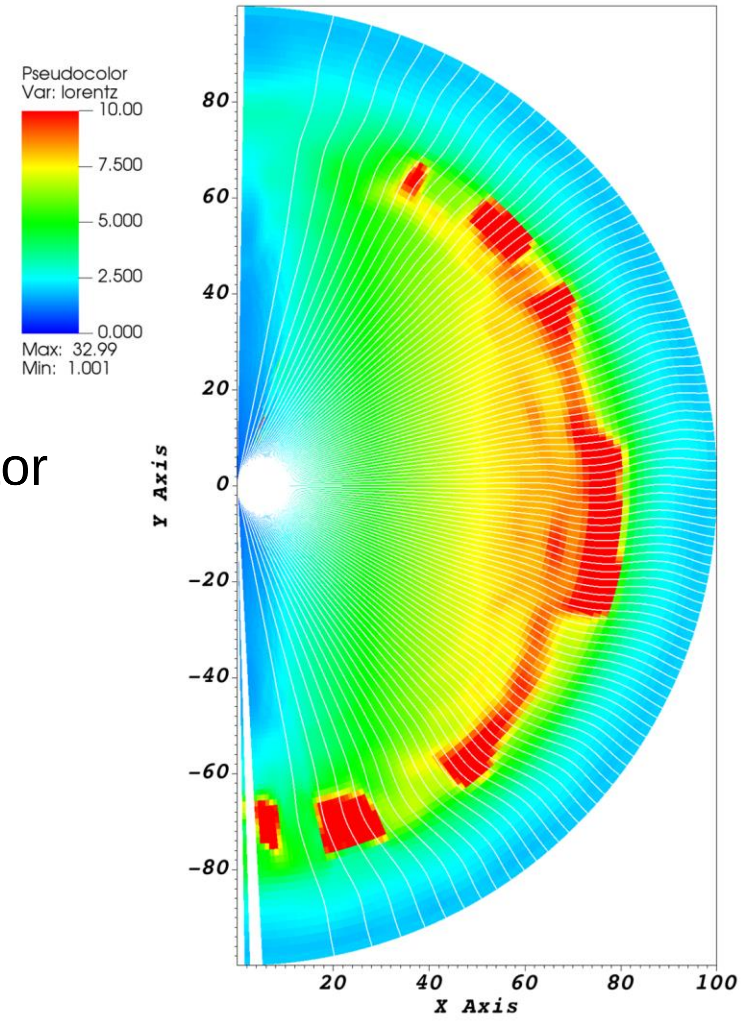
- Below $\sigma < \sigma_{\rm trans}$, invert conserved->prim using GRMHD as normal
- Above $\sigma > \sigma_{\rm trans}$, invert conserved->prim using decoupled FF
  - Gas energy density is evolved **adiabatically** to minimize dissipation
  - We can make the transition a **hard cut** or **smooth it out** using a weighted average

$$\mathbf{P}(\mathbf{U}) = (1 - f(\sigma))\mathbf{P}\left(\mathbf{U}_{\rm MHD}\right) + f(\sigma)\mathbf{P}\left(\mathbf{U}_{\rm FF}\right)$$

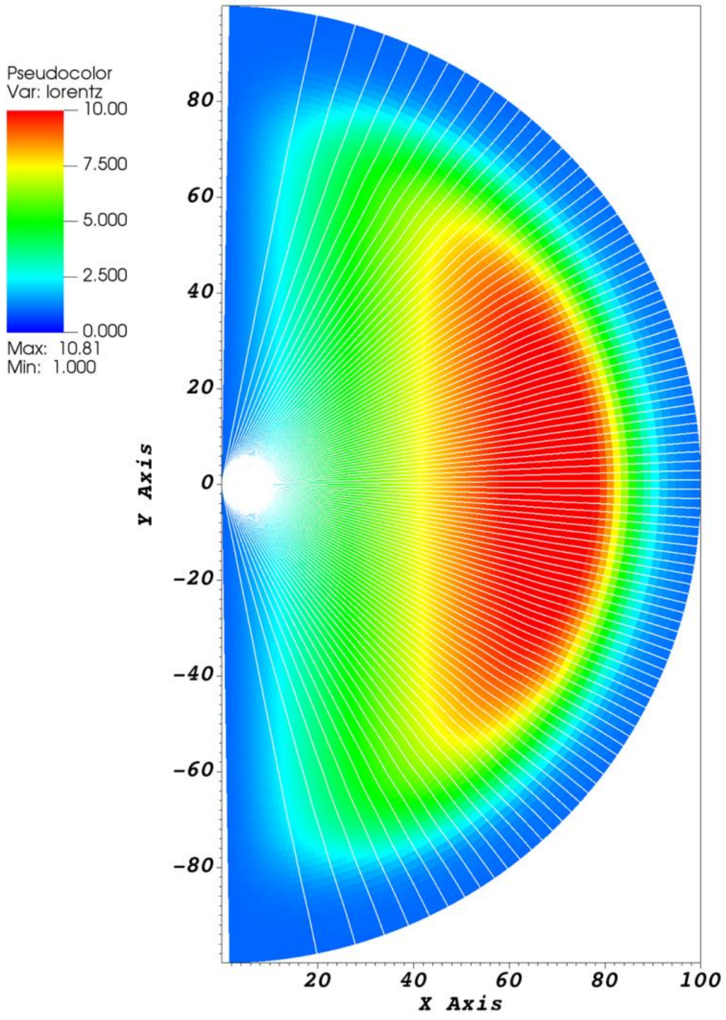
Chael+ in prep

Force-Free Monopole in **KORAL_FF**

Lorentz Factor



GRMHD



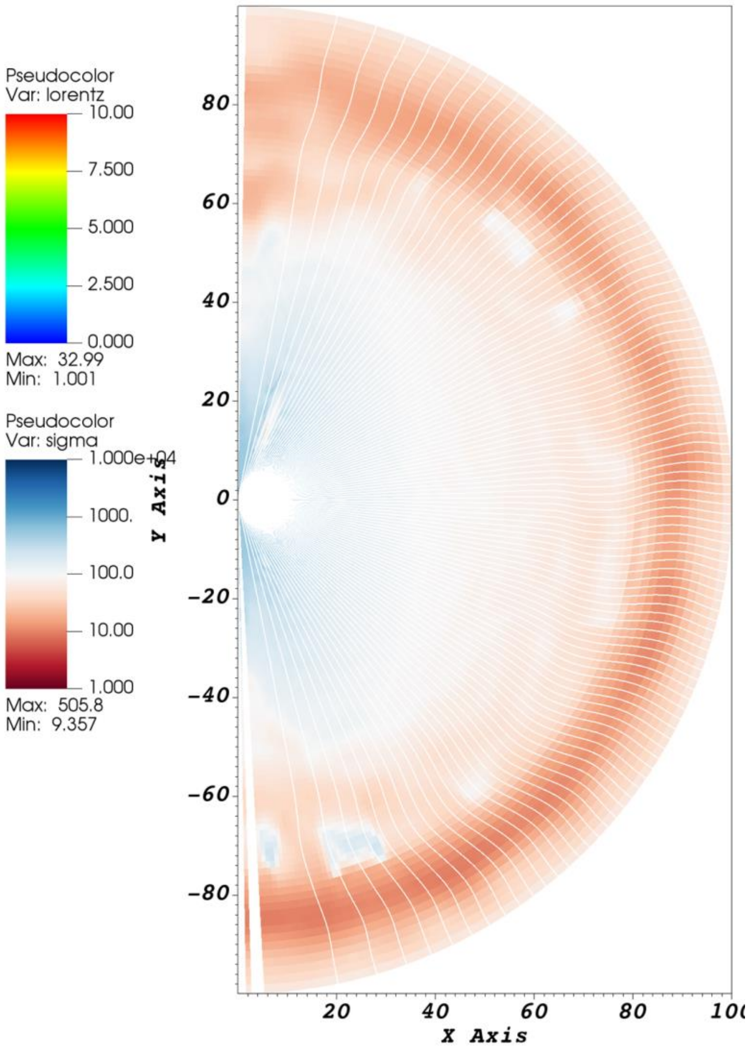
Hybrid Force-Free

Spin =
0.94
t=100 M

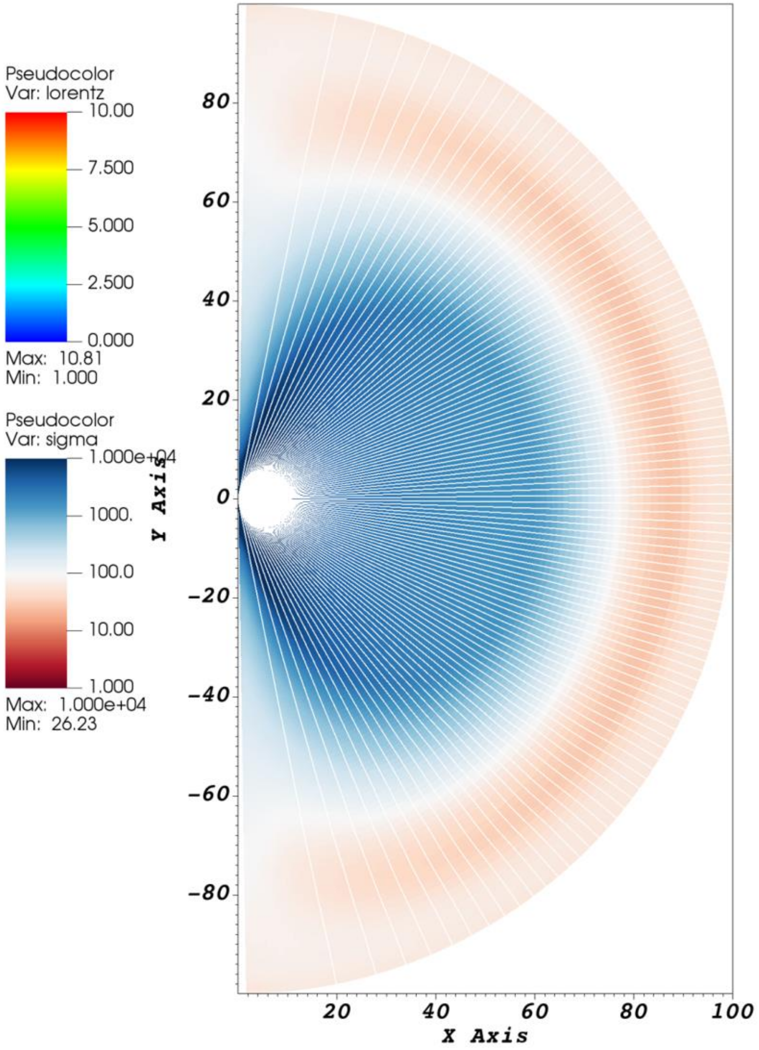
Chael+ in prep

Force-Free Monopole in **KORAL_FF**

Magnetization
σ



GRMHD

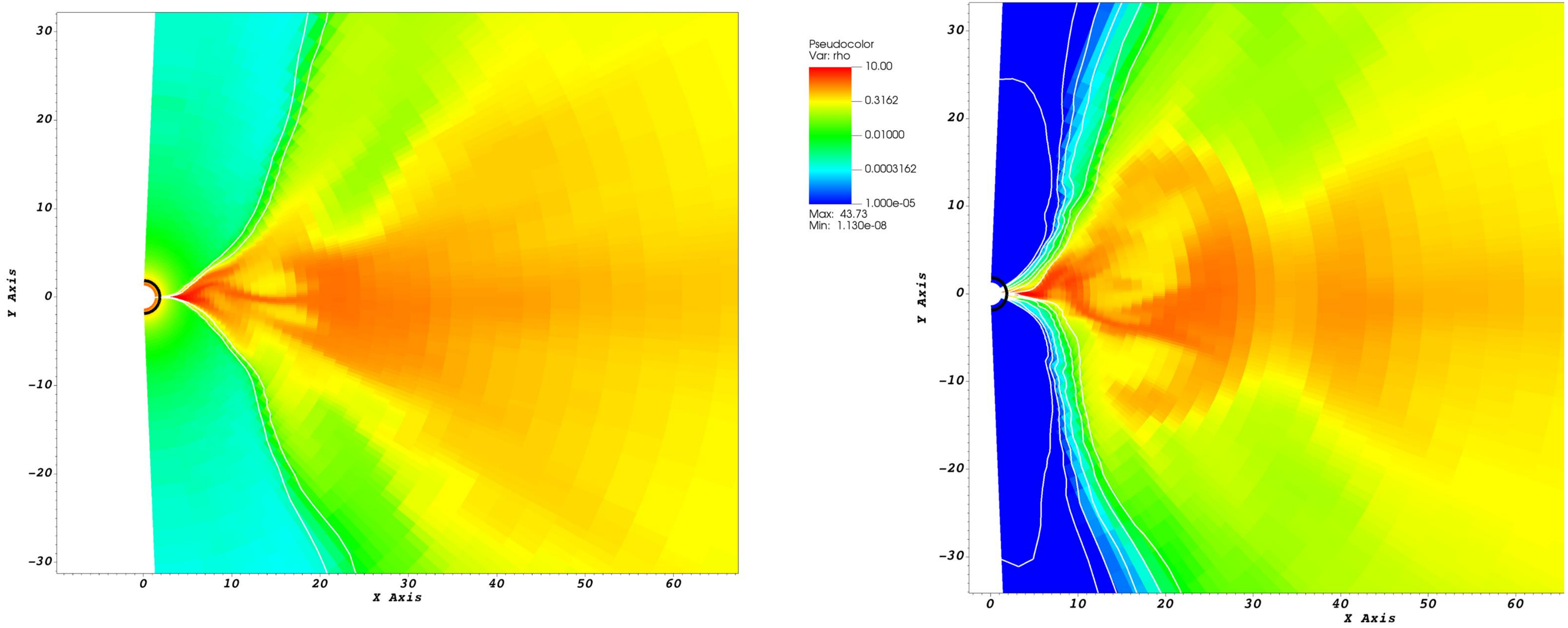


Hybrid Force-Free

Spin =
0.94
t=100 M

Chael+ in prep

3D MAD Simulation Comparison: density



GRMHD

GRMHD+FF

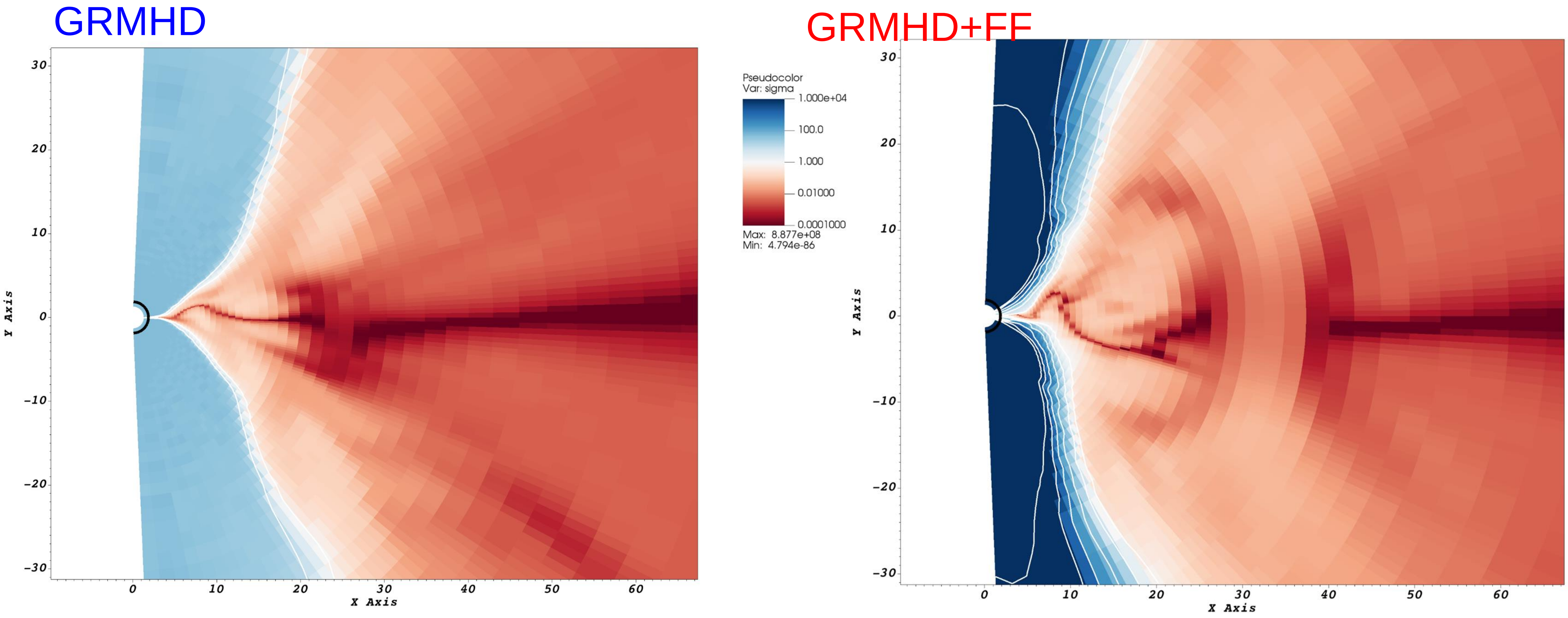
GRMHD capped at sigma=50

GRMHD+FF reaches sigma~10^9

Contours at sigma=1,10,100,1000….

Chael+ in prep

3D MAD Simulation Comparison: sigma



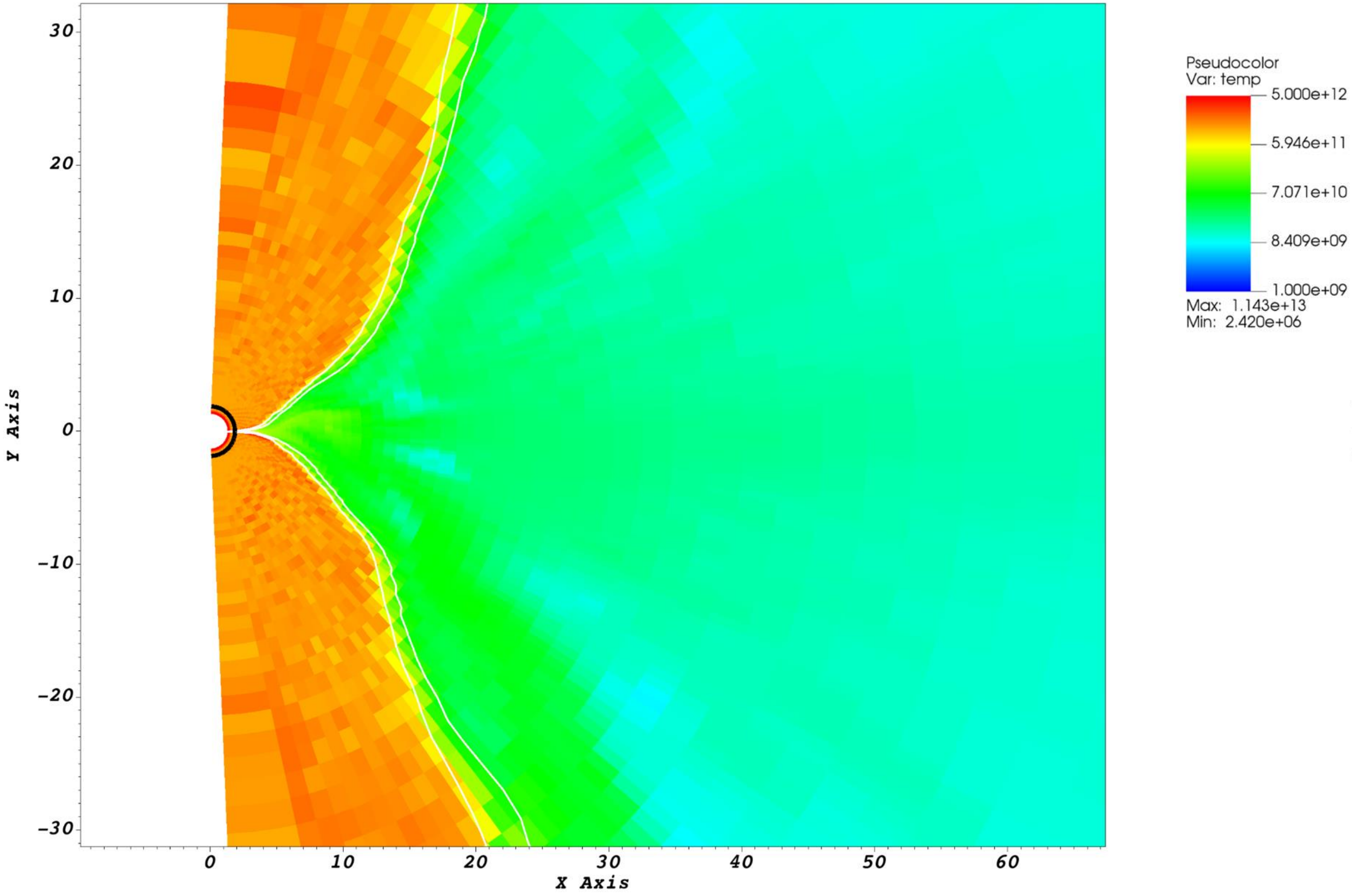
GRMHD capped at sigma=50
Jet lorentz factor limited to ~5 by r=10,000 M

GRMHD+FF reaches sigma~10^9
Jet lorentz factor reaches ~13 by r=10,000 M

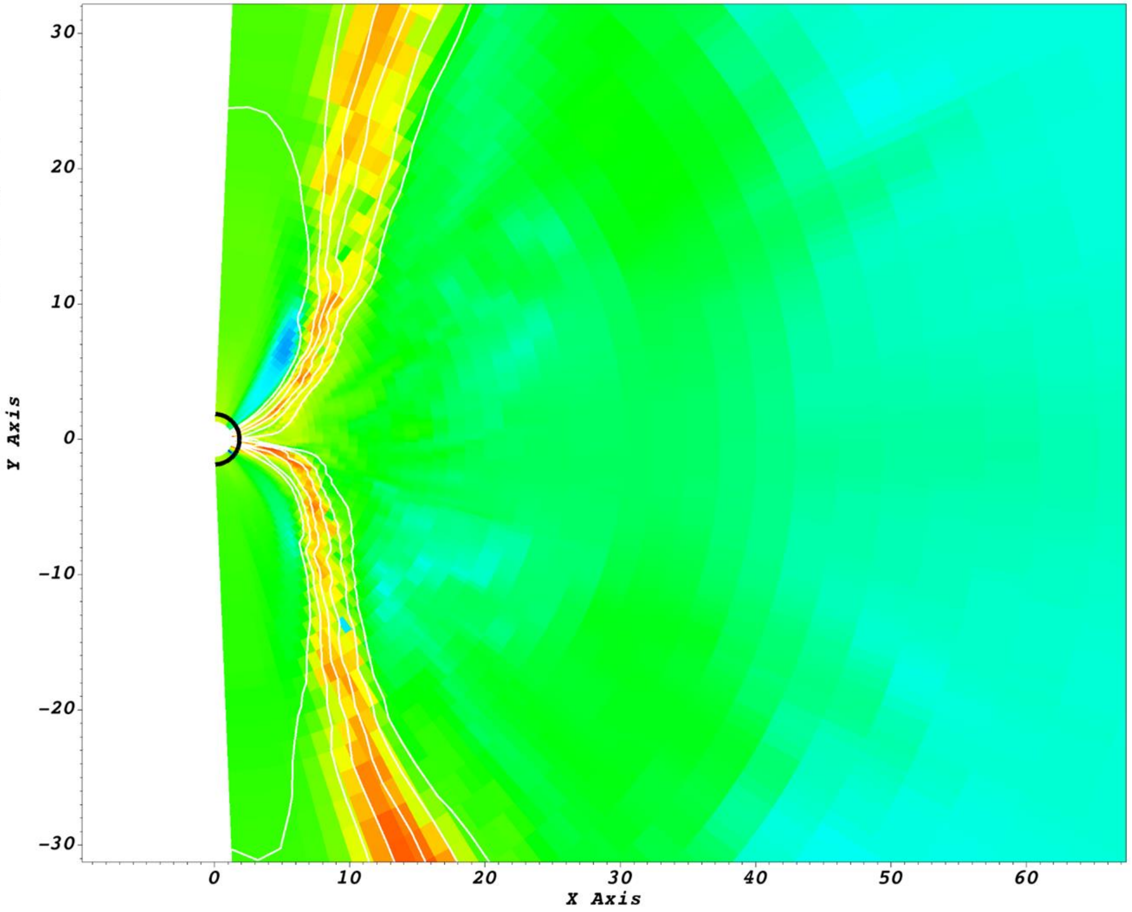
Contours at sigma=1,10,100,1000….

Chael+ in prep

3D MAD Simulation Comparison: temperature



GRMHD has hot material completely filling jet



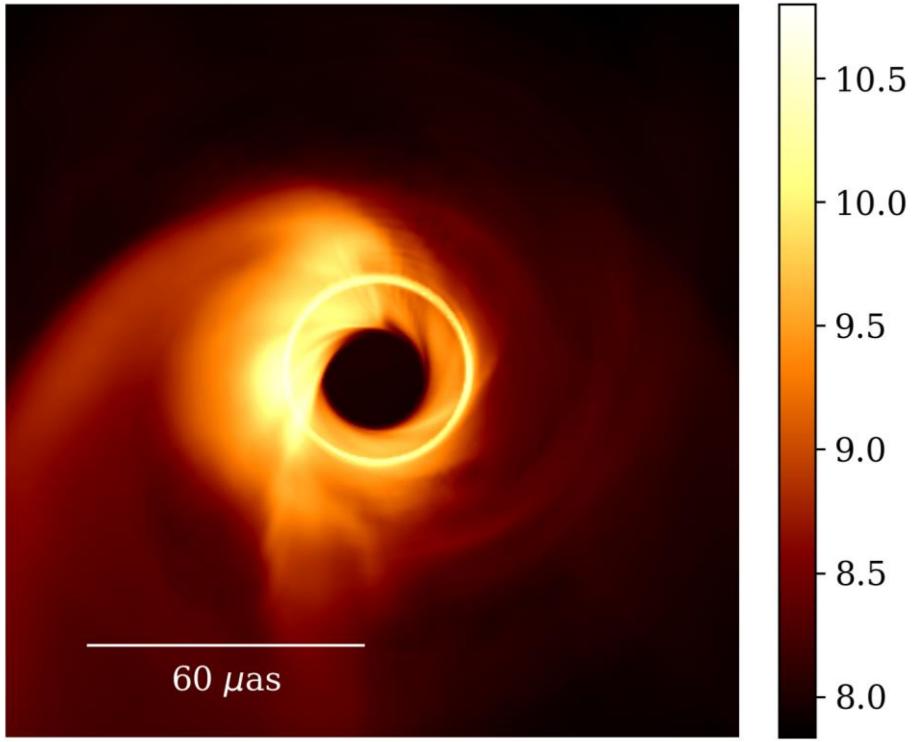
GRMHD+FF has hot material only in sigma transition region
Adiabatic evolution in the jet core keeps material cold

Contours at sigma=1,10,100,1000….

230 GHz Image comparison (snapshot, sigmacut=25)

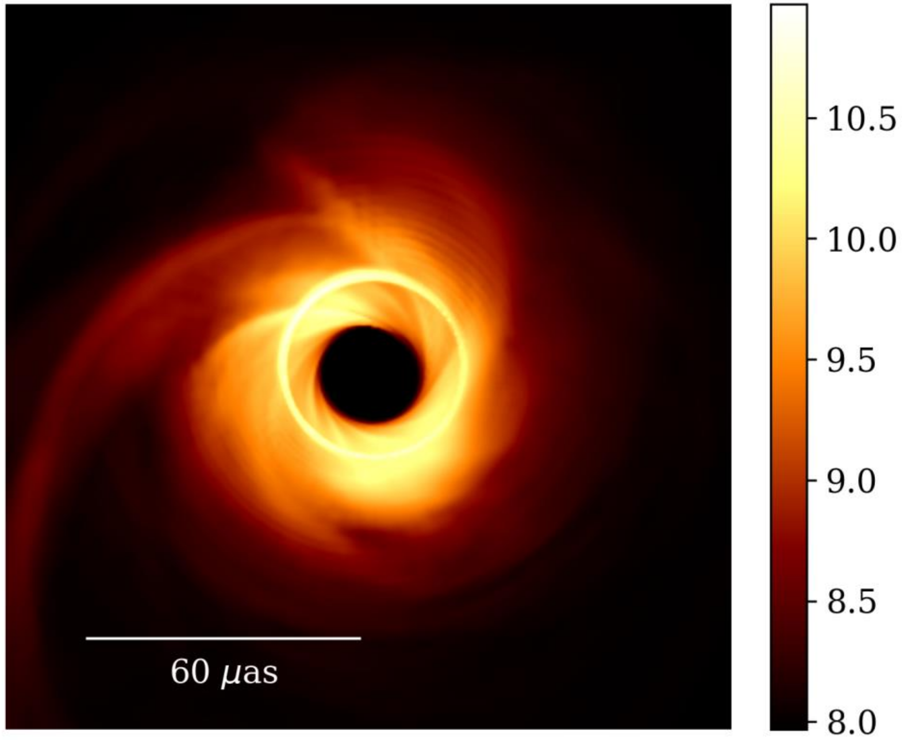
Log scale

GRMHD



t=7950

GRMHD+FF



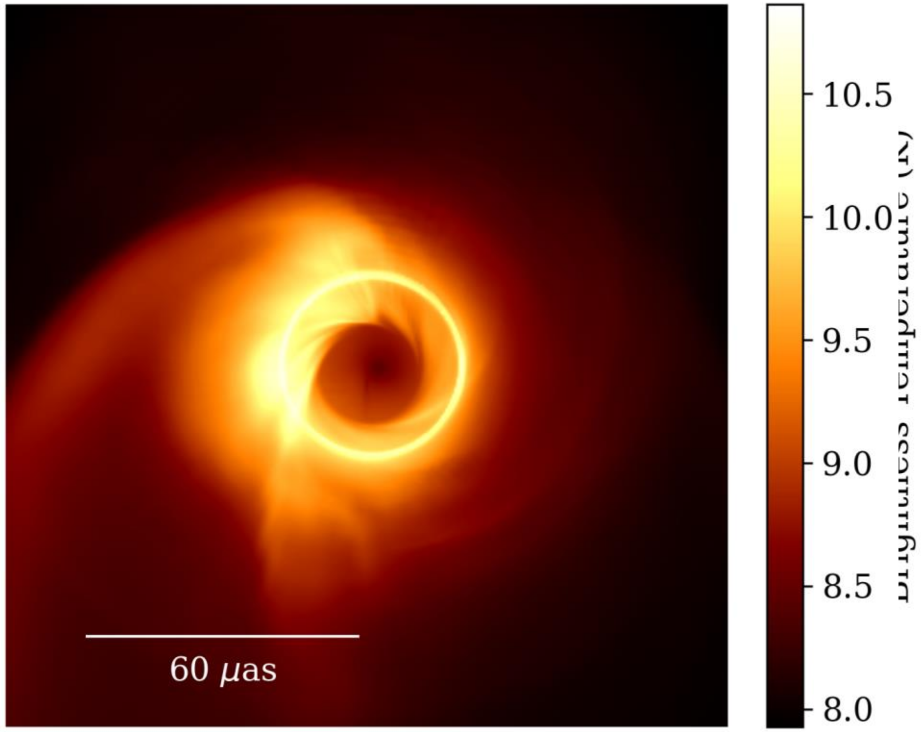
t=9160

note: using maximum flux point for both (arbitrary)

230 GHz Image comparison (snapshot, NO sigmacut)

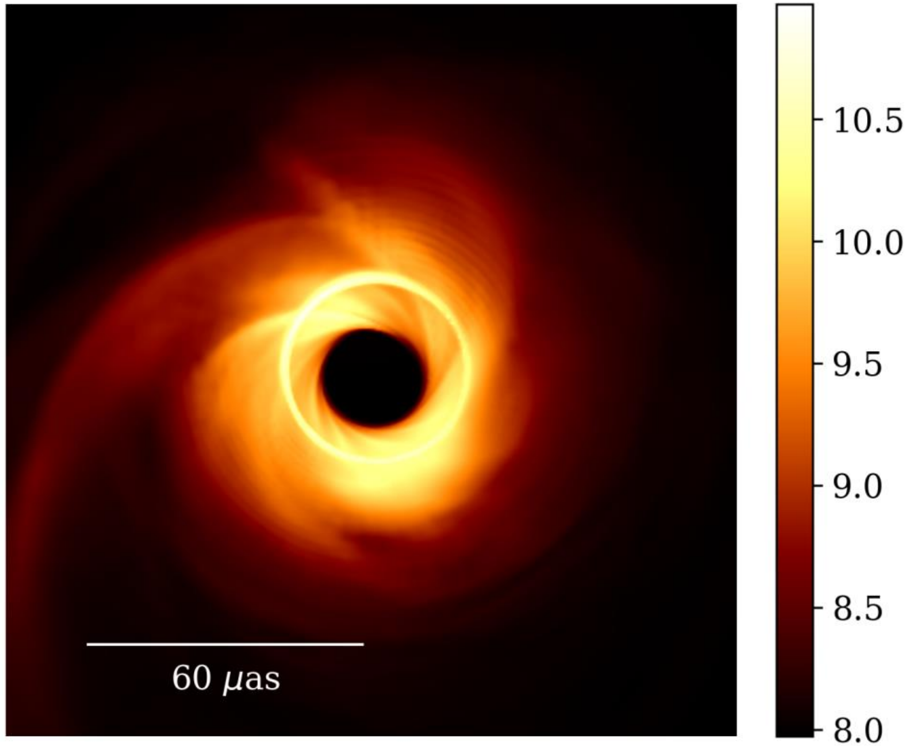
Log scale

GRMHD



t=7950

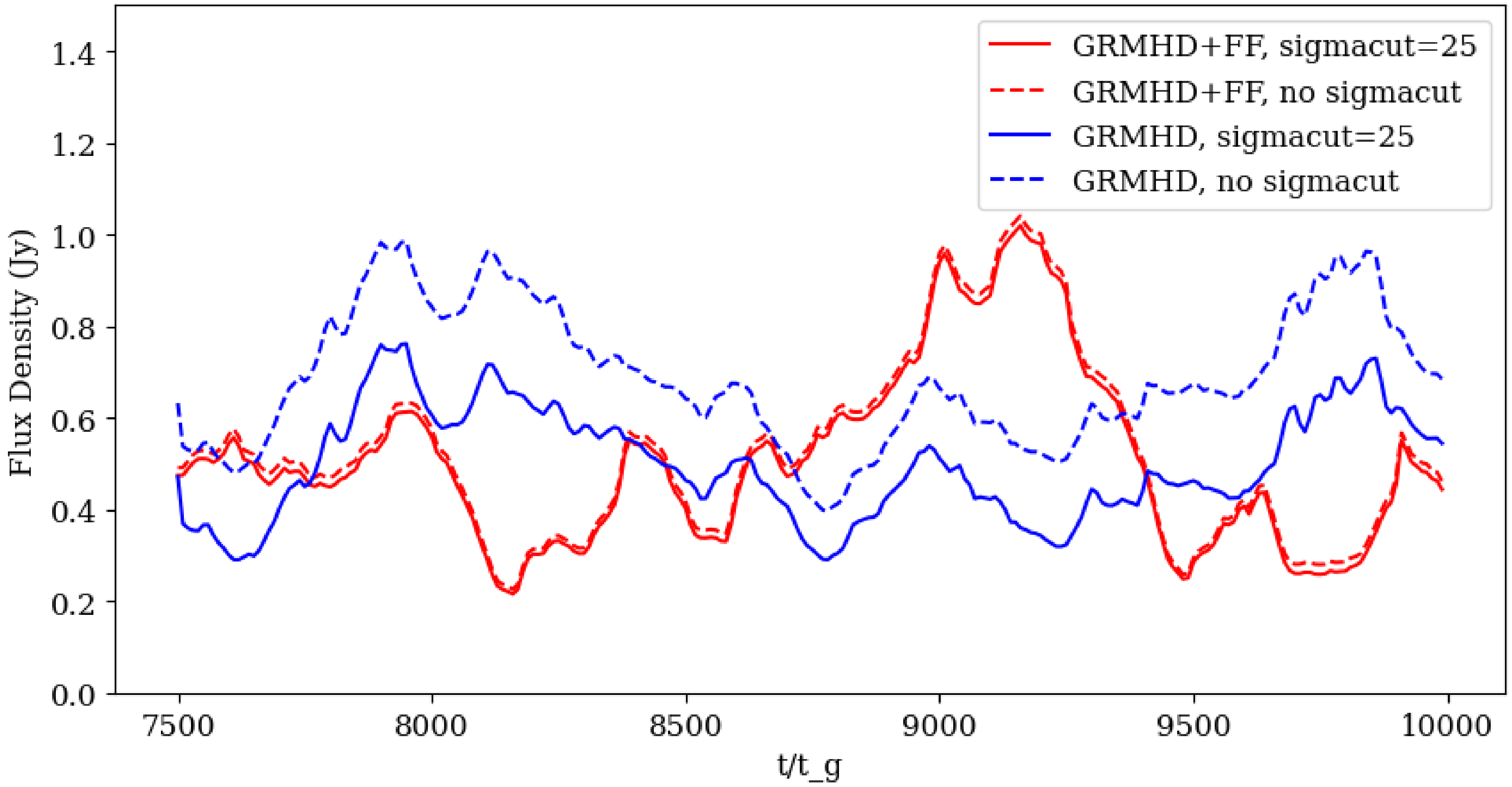
GRMHD+FF



t=9160

In log scale, can see emission from floor material in MHD, not present in MHD+FF

230 GHz Total flux



FF treatment suppresses significant emission from high sigma region

Is the full SED more stable to sigma cut as well?

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.
- Need systematic comparison of GRMHD to observables at a range of scales to understand jet-launching
- Future observables from EHT/ngEHT:
  - Jet collimation and acceleration profiles at launching point
  - Spectral index maps
- Hybrid GRMHD+GRFF offers a new way to investigate effects of floors on GRMHD simulations/images.