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Relativistic Jet Simulations and Modeling on Horizon Scale

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Collaborators:

A. Cruz-Osorio, C. M. Fromm, Z. Younsi, O. Porth, H. Olivares, L. Rezzolla et al.

Cruz-Osorio, Fromm, YM et al. (2022), Nature Astronomy

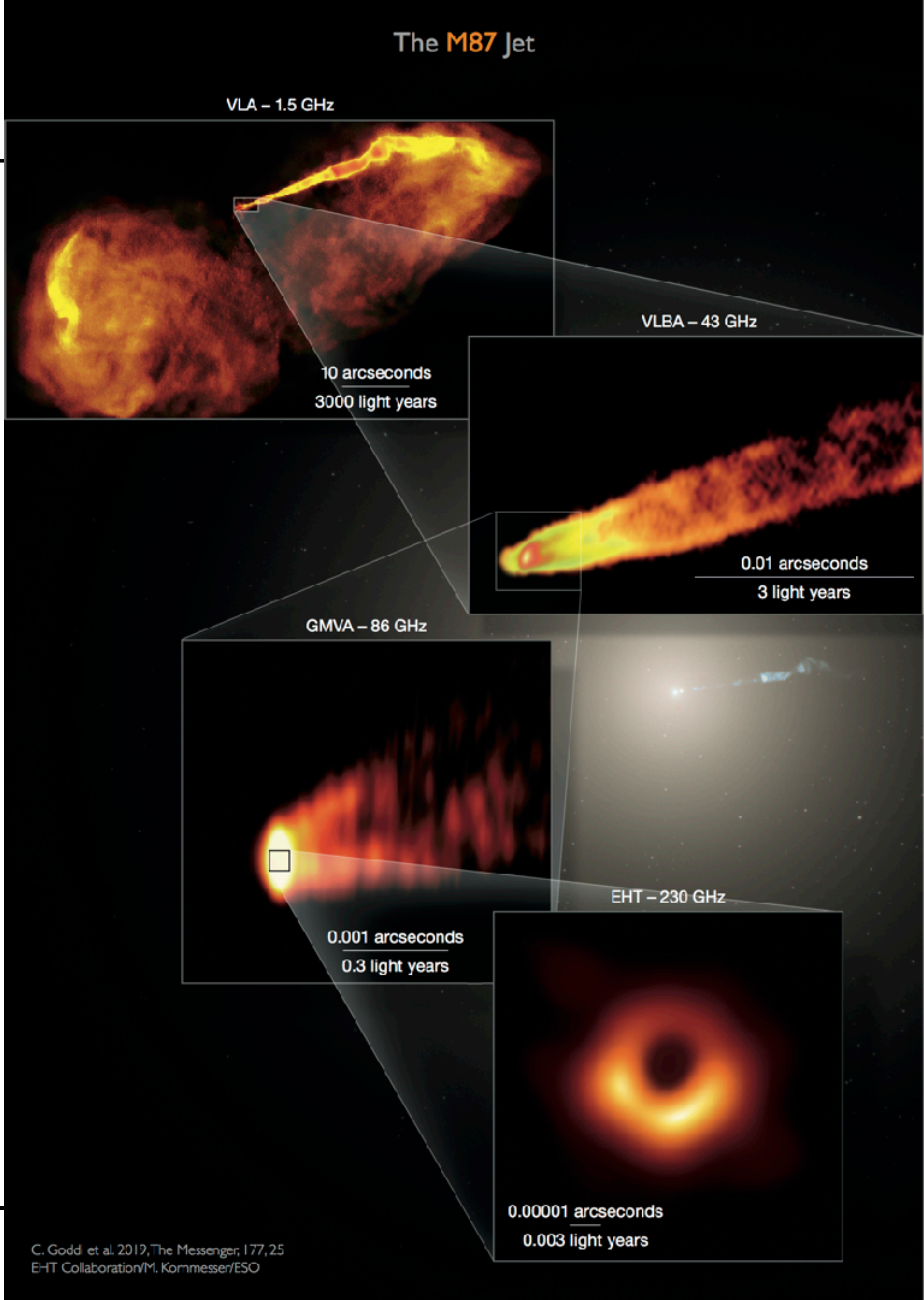
Fromm, Cruz-Osorio, YM et al. (2022), A&A

HEPRO 8, Paris, France, October, 2023

Relativistic Jets

- Outflow of highly collimated plasma
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity ～c
  - Generic systems: Compact object (Neutron Star, Black Hole) + accretion flows
  - Jets are common in the universe

- Key Issues of Relativistic Jets
  - Acceleration & Collimation
  - Propagation & Stability
  - Origin of high energy particle (particle acceleration)



Motivation

- Black holes and relativistic jets are the perfect laboratories to study:
  - Plasma physics
  - Gravitational physics
  - Particle physics

- Observations with recent & future instruments (from radio to γ-ray + multi-messenger):
  - EAVN, VLBA, GMVA, EHT, ngVLA, ngEHT
  - HST, SWIFT
  - Chandra, NuSTAR, IXPE, Athena, eXTP
  - Fermi
  - HESS, MAGIC, VERITAS, LHAASO, CTA
  - Ice Cube, …

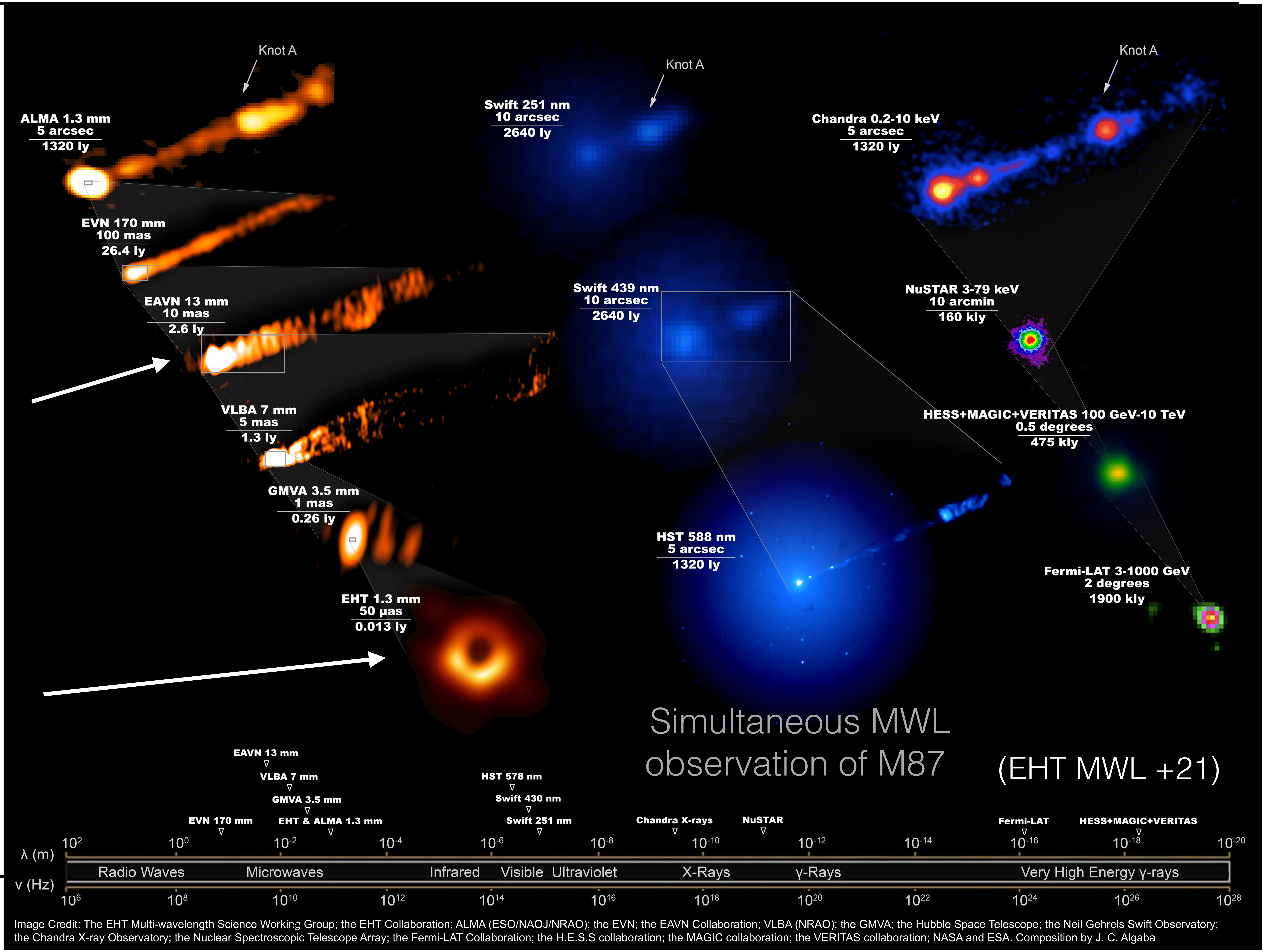
$\Rightarrow$ need tools & methods to interpret the observations & test theoretical models

M87 multi-frequency observations

How good are the models at different frequencies?

non-thermal synchrotron (VLBA spectral index map)

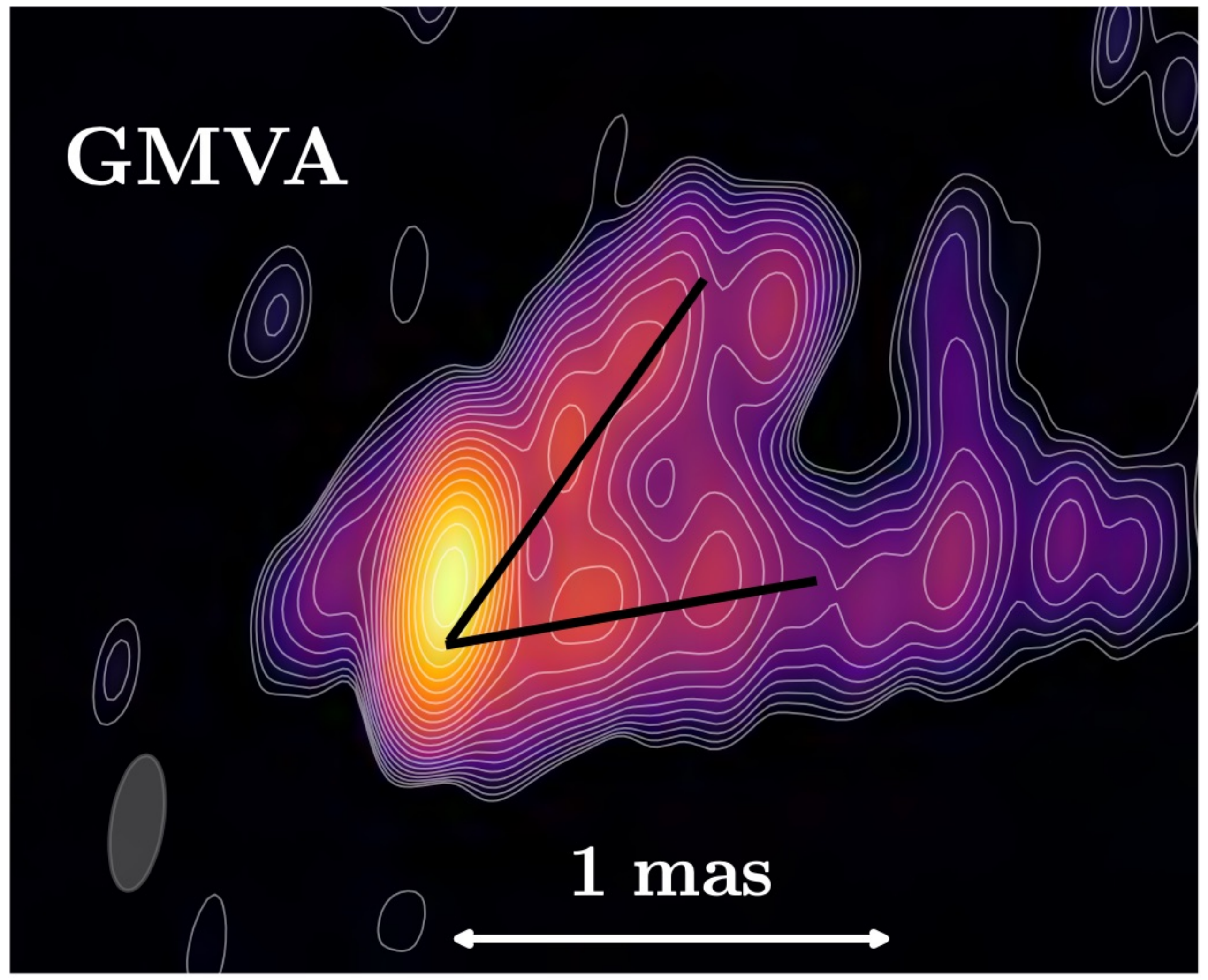
thermal synchrotron (EHT 2019, paper V)



M87 multi-frequency observations

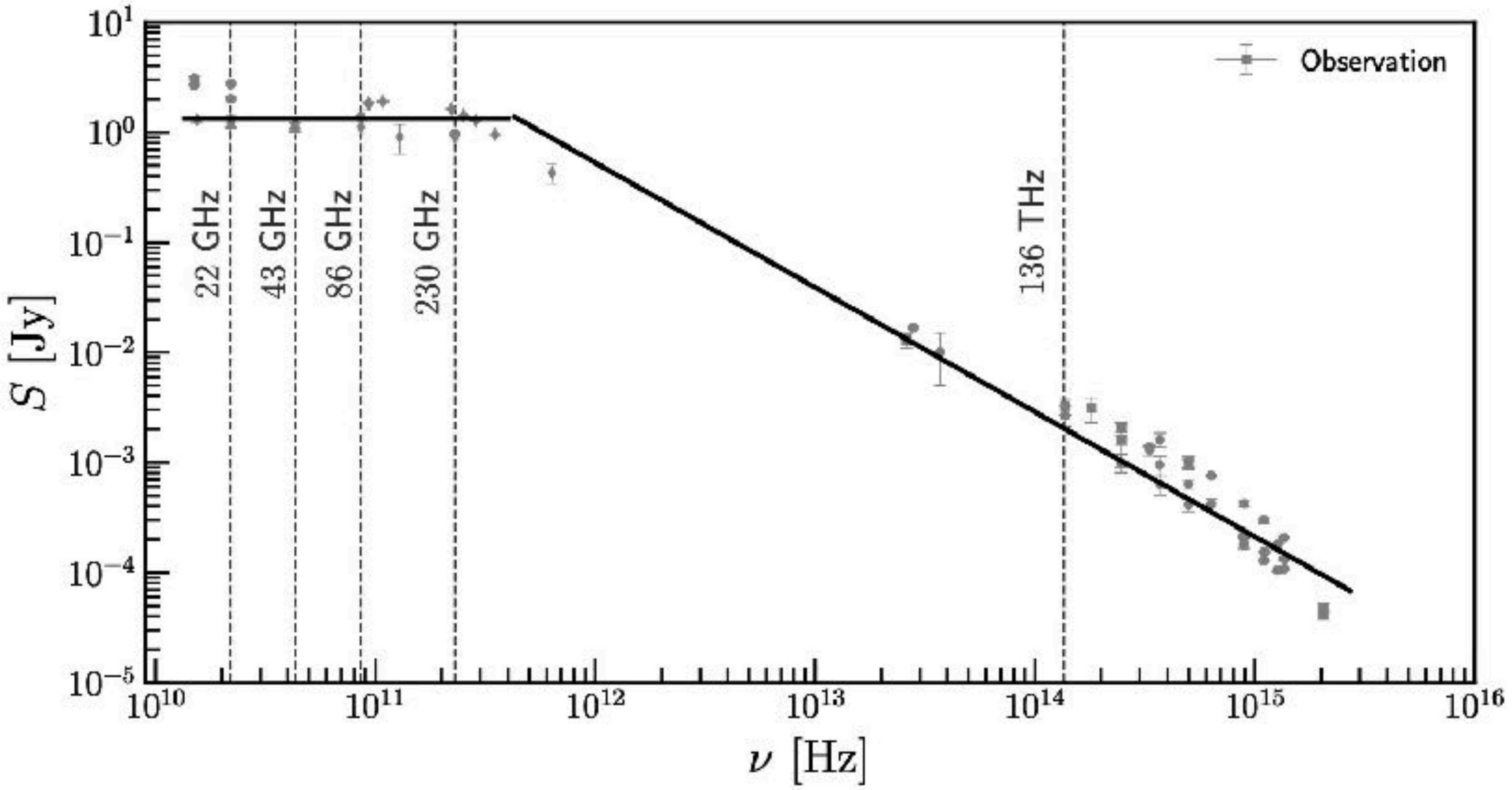
Compare with 86GHz Global Millimetre VLBI observations and board band SED

VLBI @ 86GHz (jet structure)



- wide opening angle
- edge brightening

broad band spectrum



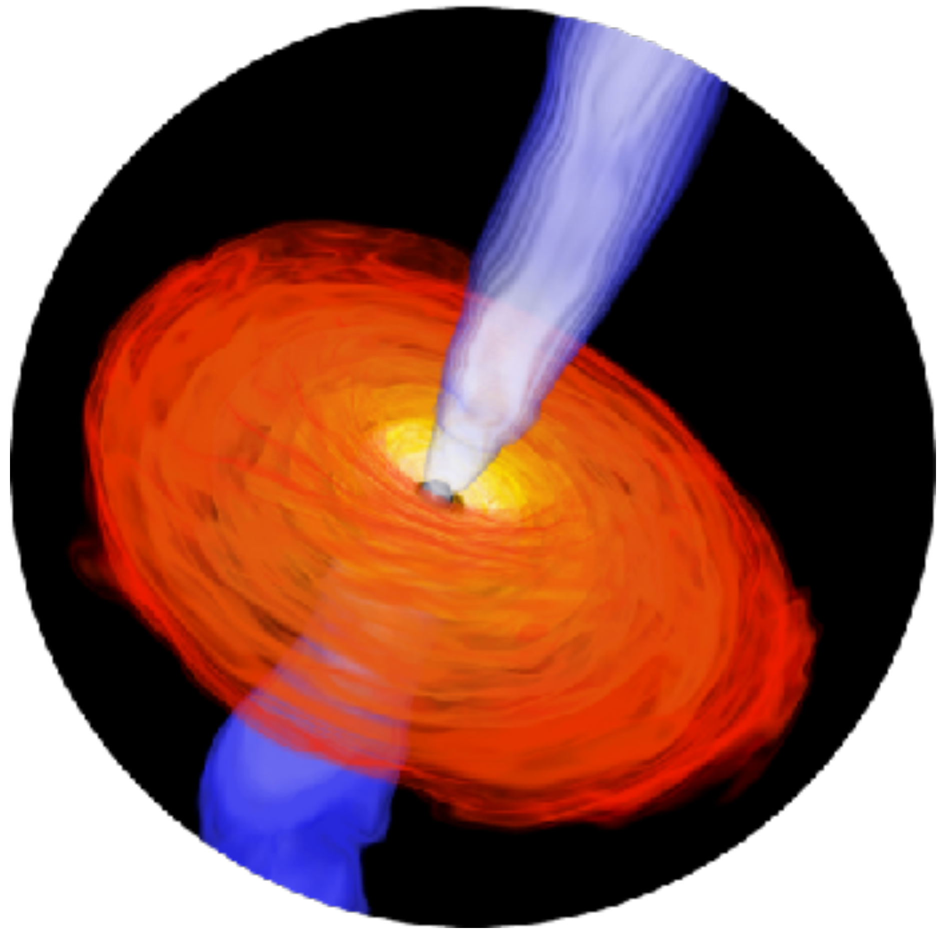
- flat spectrum ($\nu < 10^{12}$ Hz)
- power-law decay spectrum ($\nu > 10^{12}$ Hz)

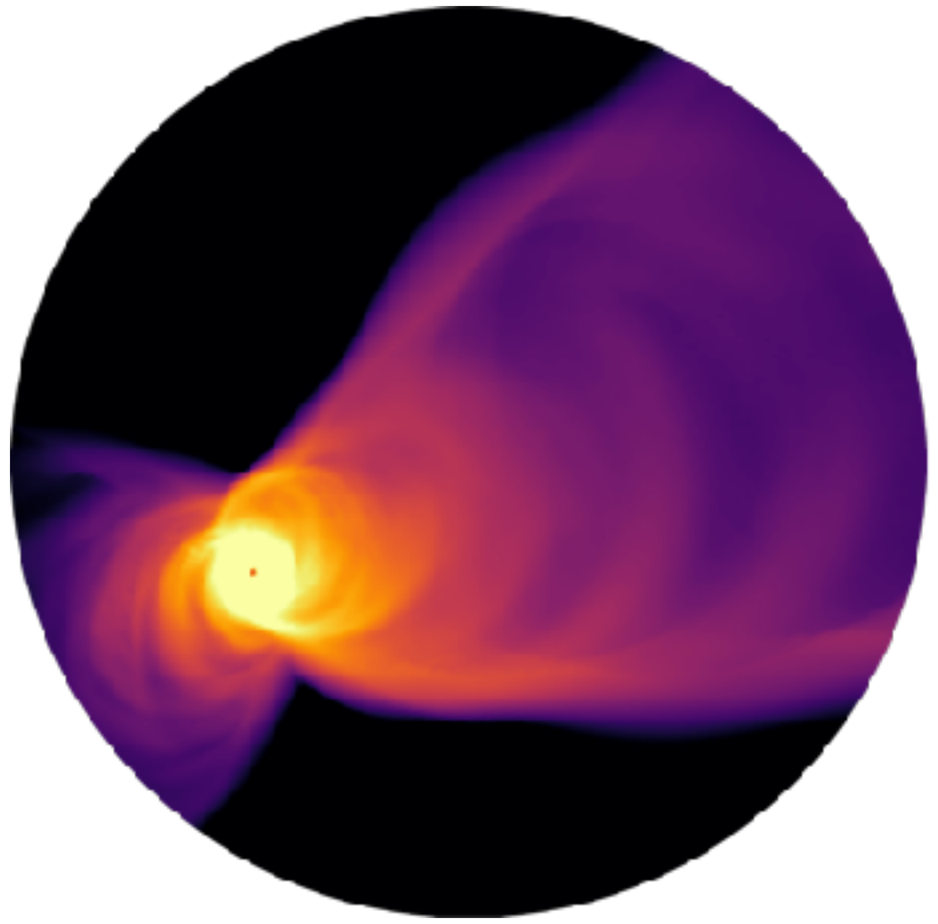
GMVA: Kim et al. 2018
Spectrum: Kim et al. 2018, Prietro et al. 2016, Doeleman et al. 2012, Akiyama et al. 2015

Numerical modeling

GRMHD (BHAC):

- spacetime
- Disk evolution
- Magnetic field
- Jet launching & propagation





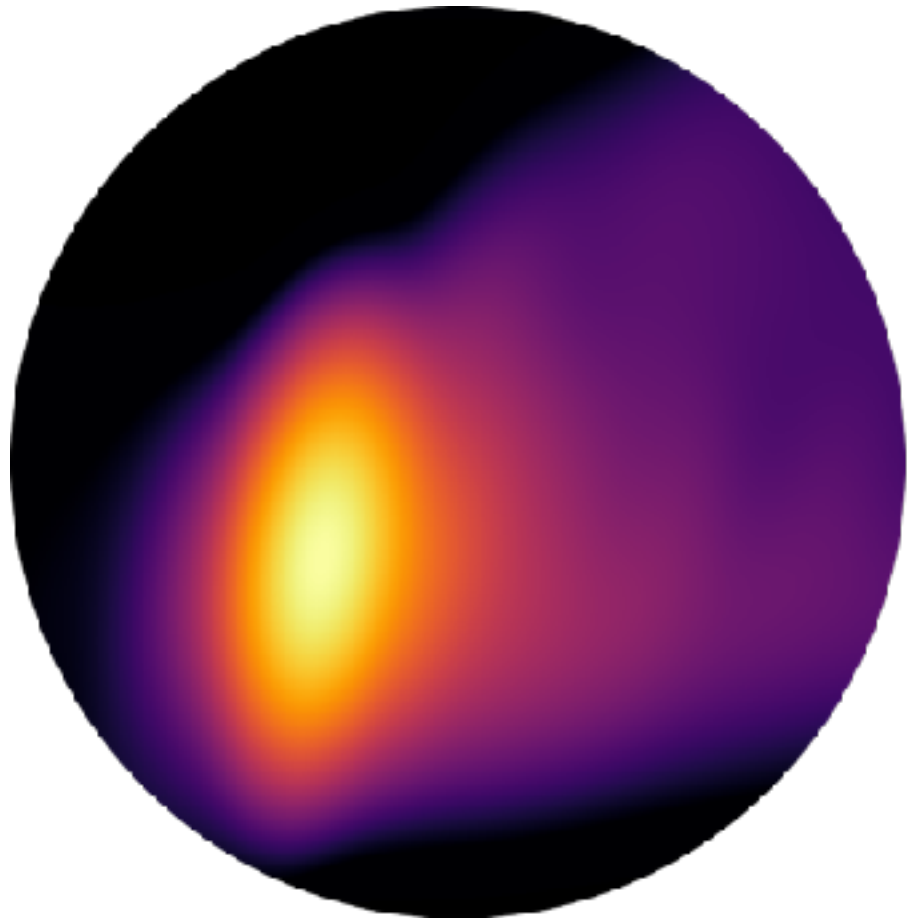
GRRT (BHOSS):

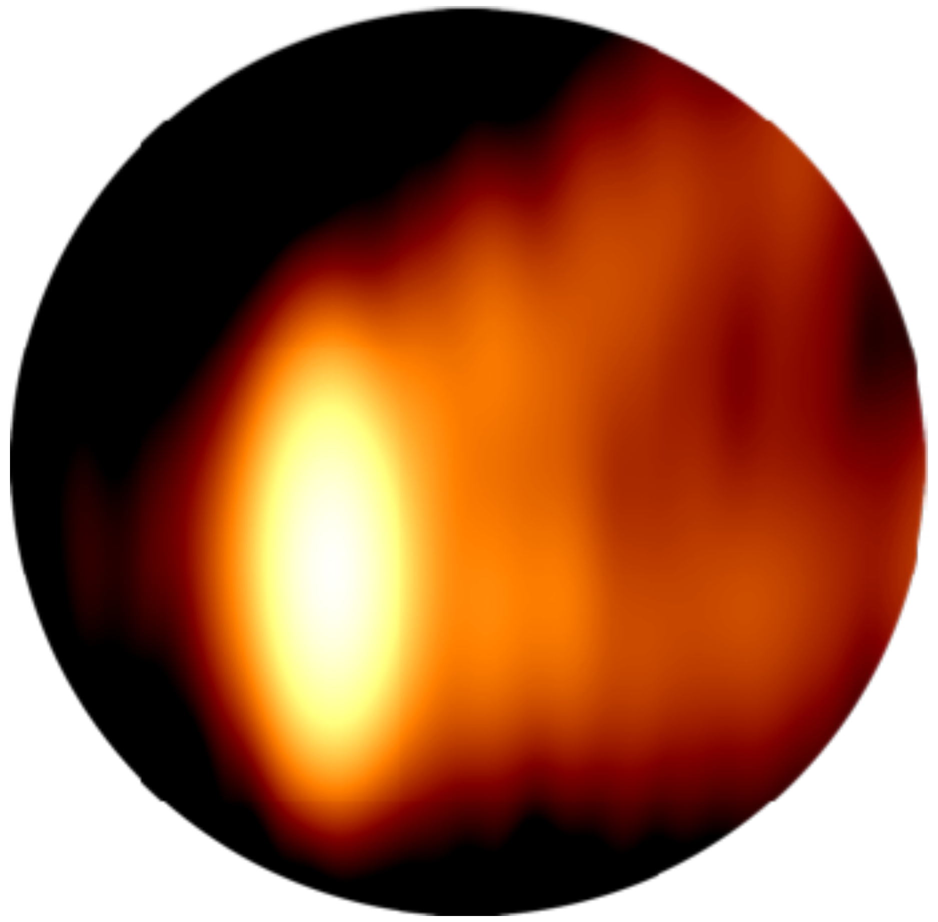
- Mass & distance
- microphysics
- Emission model

post-process

Theoretical prediction (GENA):

- Synthetic data (VLBI observation)
- Image generation





Observations:

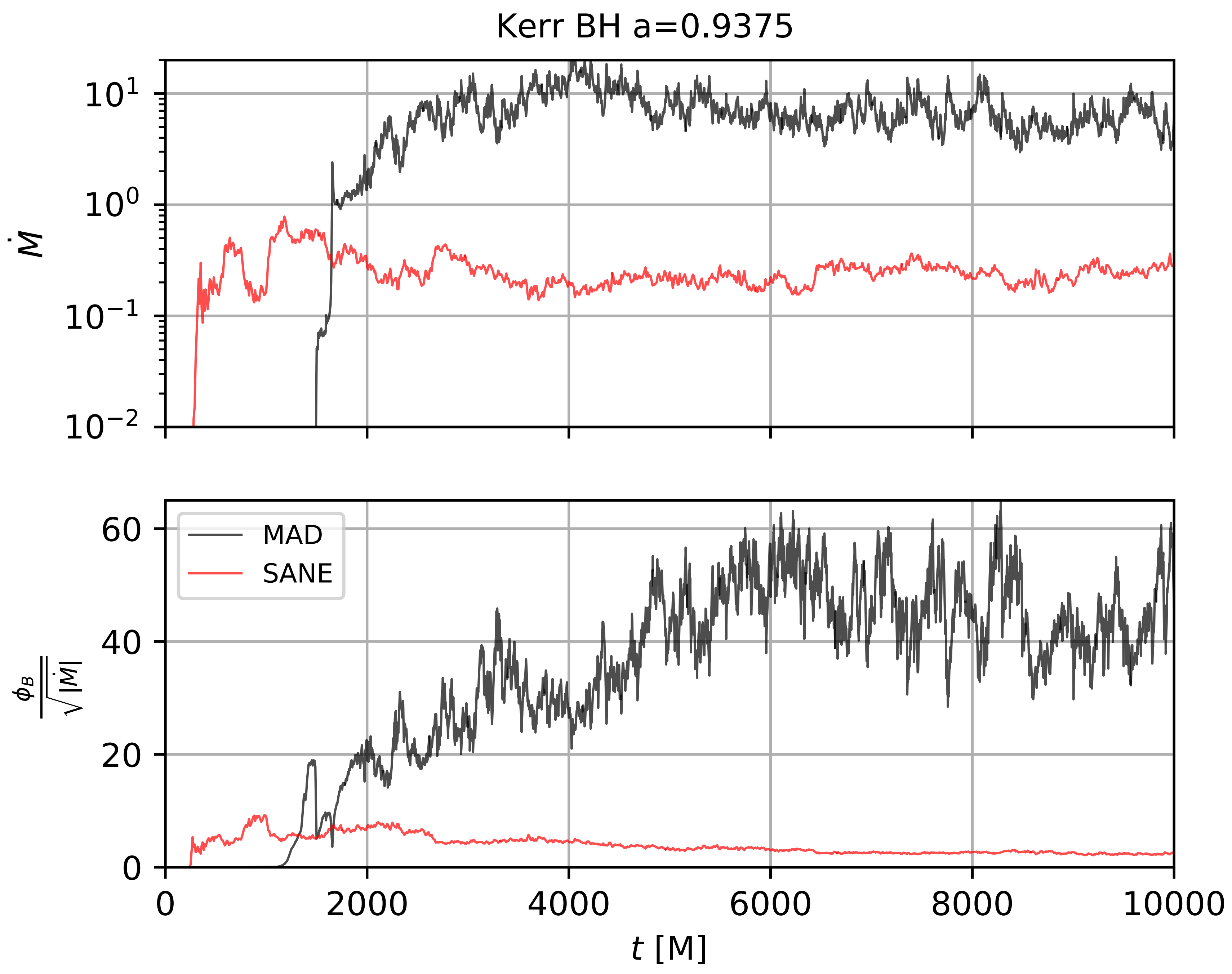
- Data comparison
- Model prediction

BHAC: Porth et al. (17), Olivares et al. (19)
BHOSS: Younsi et al. (21)
GENA: Fromm et al. (19)

MAD vs SANE (GRMHD Simulations)

RIAF model, two extreme situation
Magnetically Arrested Disk (MAD)
Standard And Normal Evolution (SANE)

3D GRMHD simulations with
a=0.94

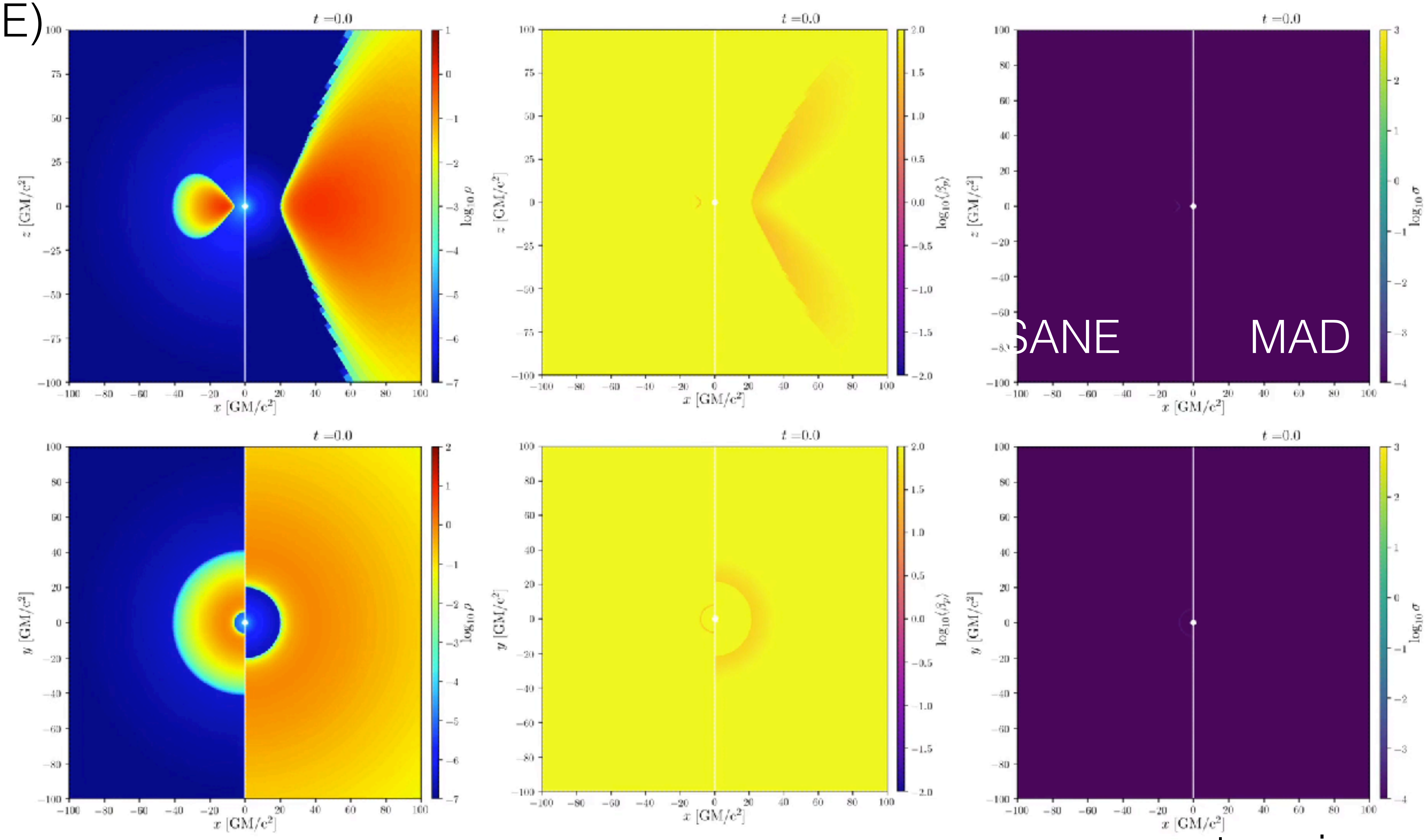


side view

density

plasma beta

magnetisation

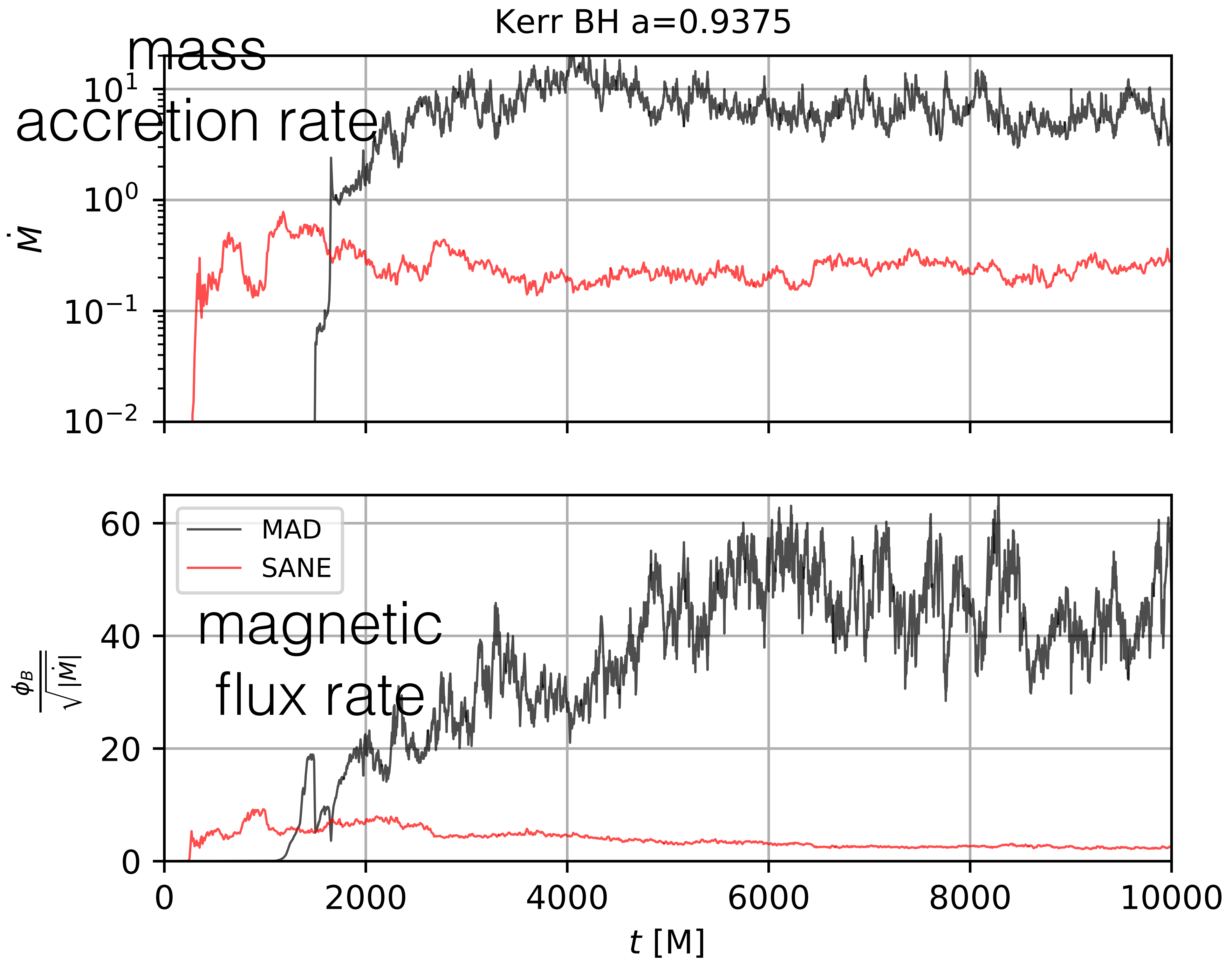


top view

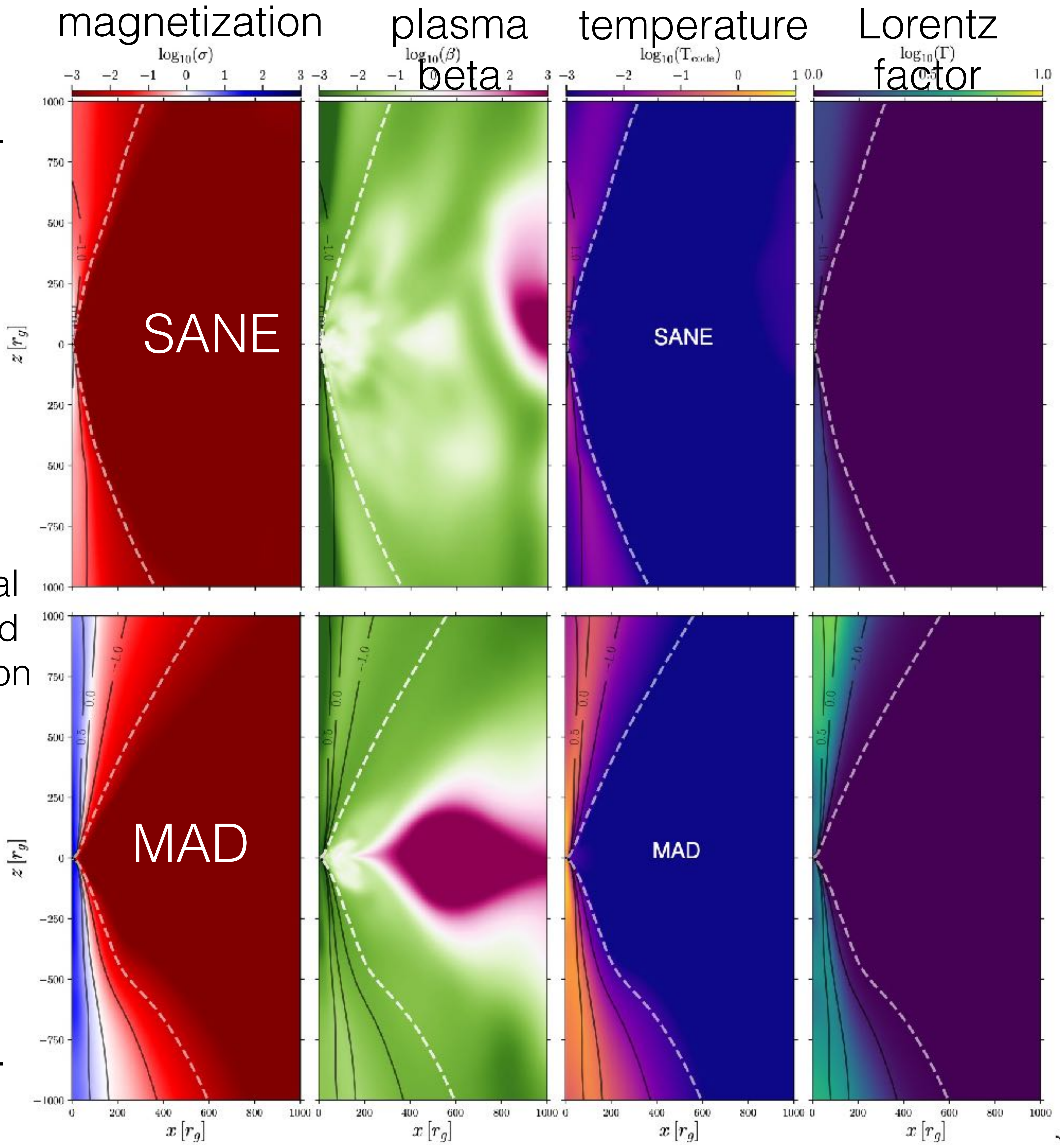
MAD vs SANE

RIAF model, two extreme situation
Magnetically Arrested Disk (MAD)
Standard And Normal Evolution (SANE)

3D GRMHD simulations with
a=0.94



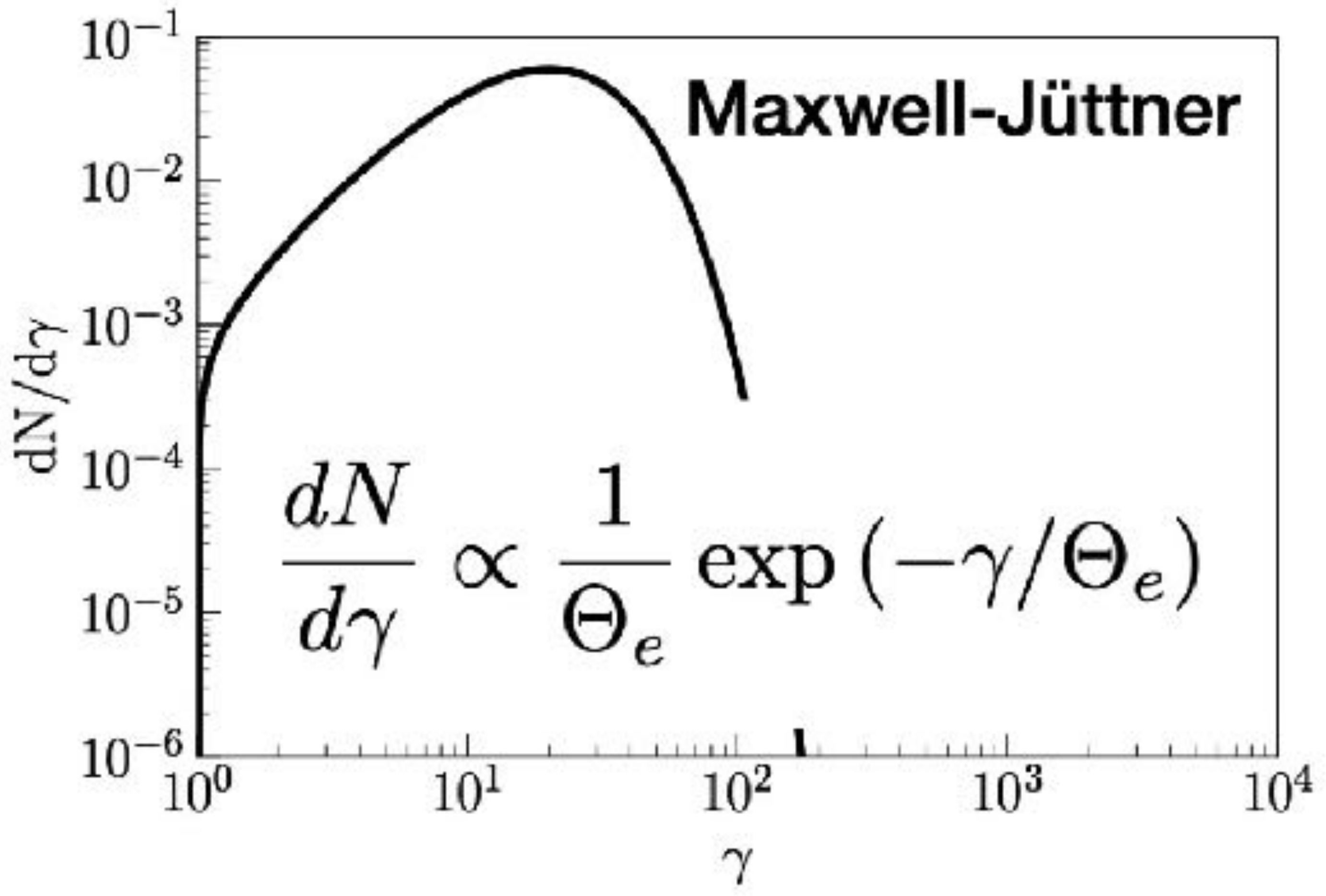
time &
azimuthal
averaged
distribution



GRRT calculation

- Compute the emission structure: BHOSS (Younsi et al. 2021)
- Scale to source: black hole mass, distance, accretion rate, electron distribution function (eDF) & emission process

1) get eDF + emission



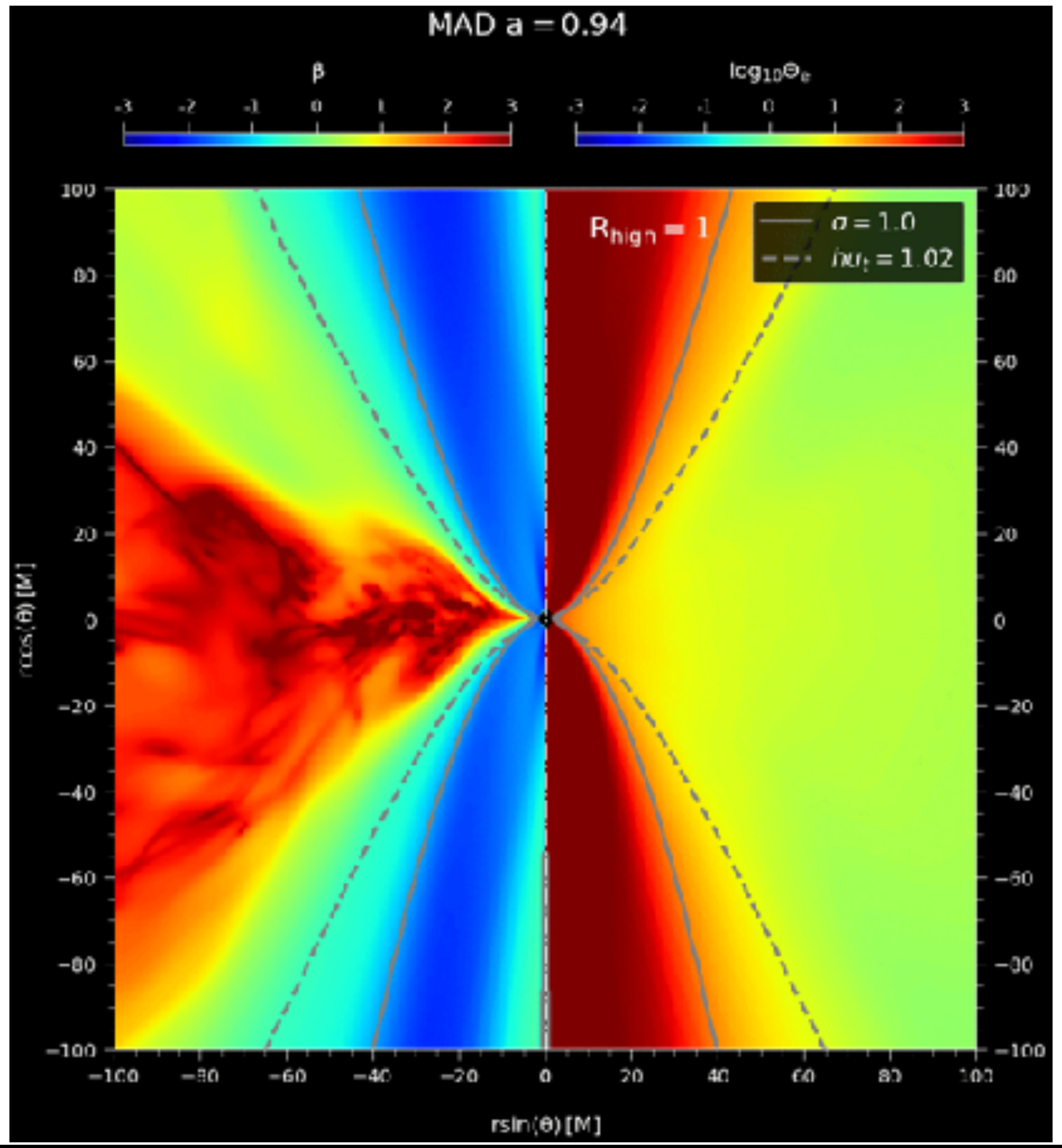
⇒ thermal synchrotron

⇒ electron temp., Θ_e unknown

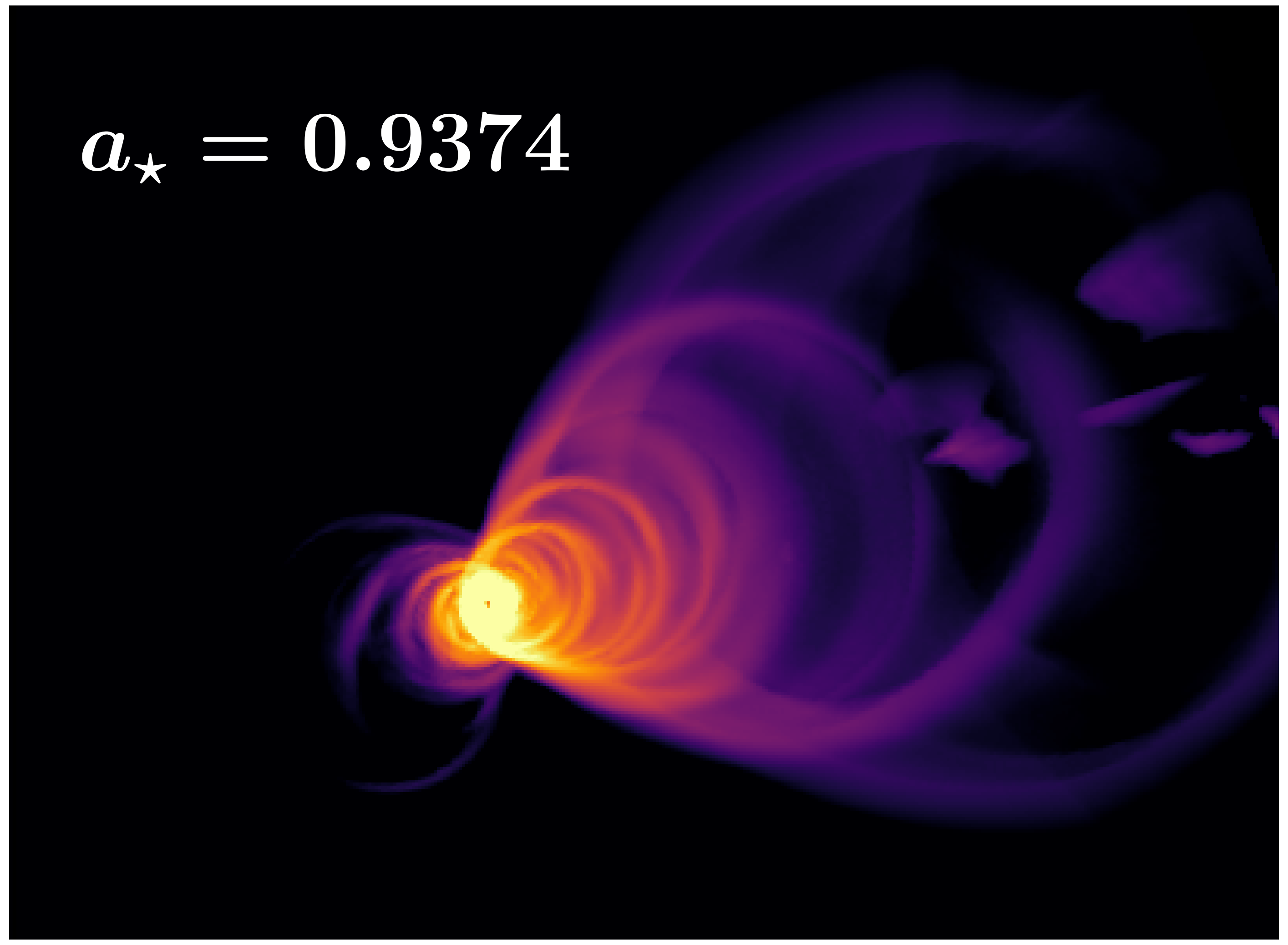
2) connect to GRMHD

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

Moscibrodzka et al. (16)



3) get geodesics + radiation transfer



⇒ emission+absorp. coeffs.

GRRT Jet Modeling for M87

Parameter space:

GRMHD:

- Accretion model: SANE & MAD
- Spin: a=-0.94, -0.5, 0, 0.5, 0.94

GRRT:

- eDF: thermal & non-thermal (kappa)
- R_{low}: 1
- R_{high}: 1, 10, 20, 40, 80, 160
- σ_{cut}: 1, 3, 5, 10

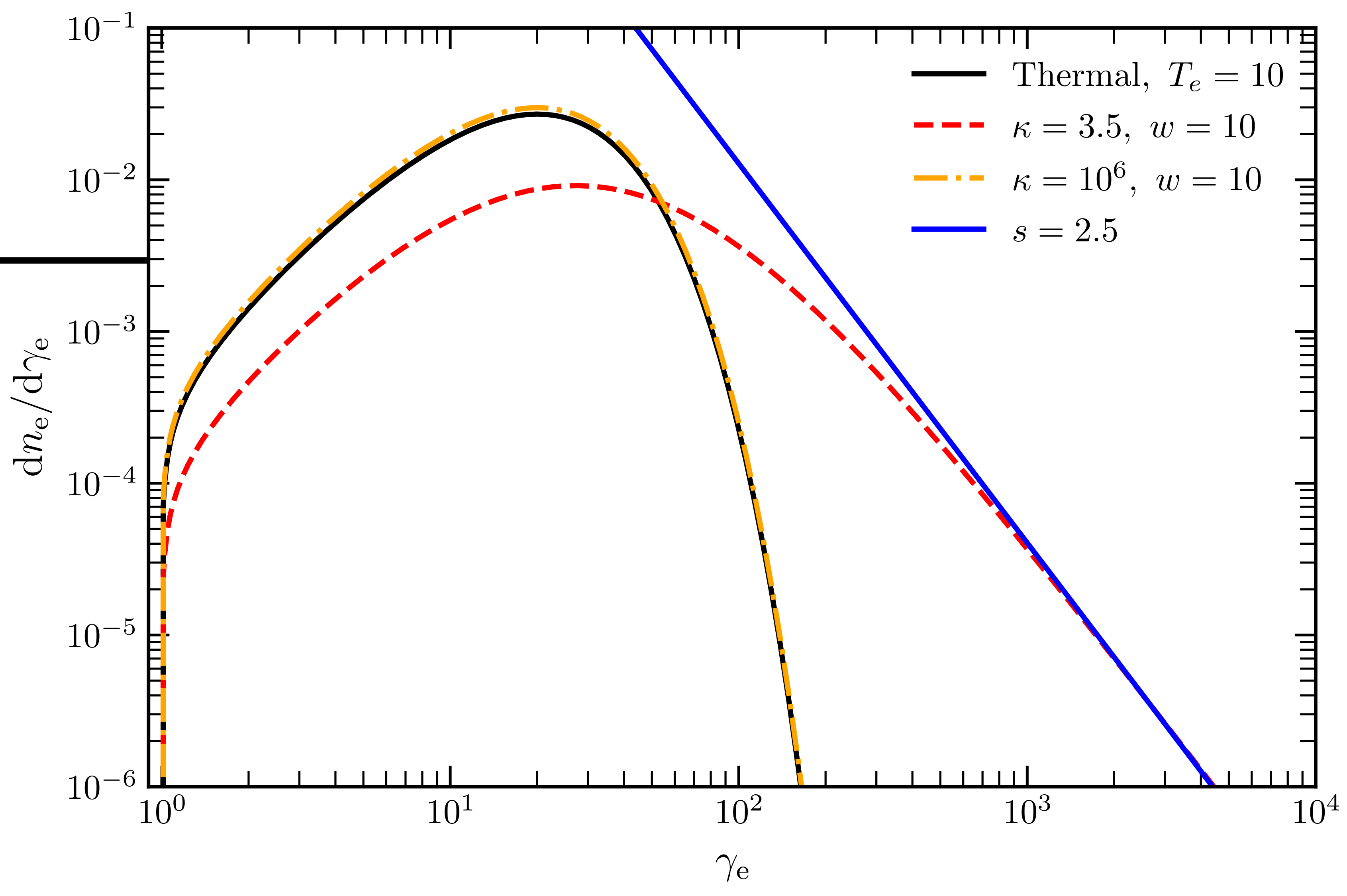
Setup & Analysis:

- M87 mass & distance: M_{BH}=6.5 ± 0.7 x 10^9 $M_\odot$ & 16.8 Kpc
- Inclination angle of 160 deg
- Iterate mass accretion rate to obtain 1.0 Jy at 230 GHz
- Use 200 GRMHD snapshots across 2000 M interval (~ 2 years of observation)
- Compare average spectrum to observed one
- Compute jet width (and opening angle) and compare with data

kappa distribution function

$$\frac{dn_e}{d\gamma} = N\gamma\sqrt{\gamma^2 - 1}\left(1 + \frac{\gamma - 1}{\kappa w}\right)^{-(\kappa+1)}$$

kappa eDF = thermal core + non-thermal tail



- thermal core at low values of the Lorentz factor, asymptotically turns into a power-law
- power-law index, $p=\kappa-1$
- In the limit of $\kappa \rightarrow \infty$, the κ-distribution becomes the Maxwell–Jüttner DF
- $\kappa\ (\beta,\sigma) \leftarrow$ subgrid model from PIC simulation

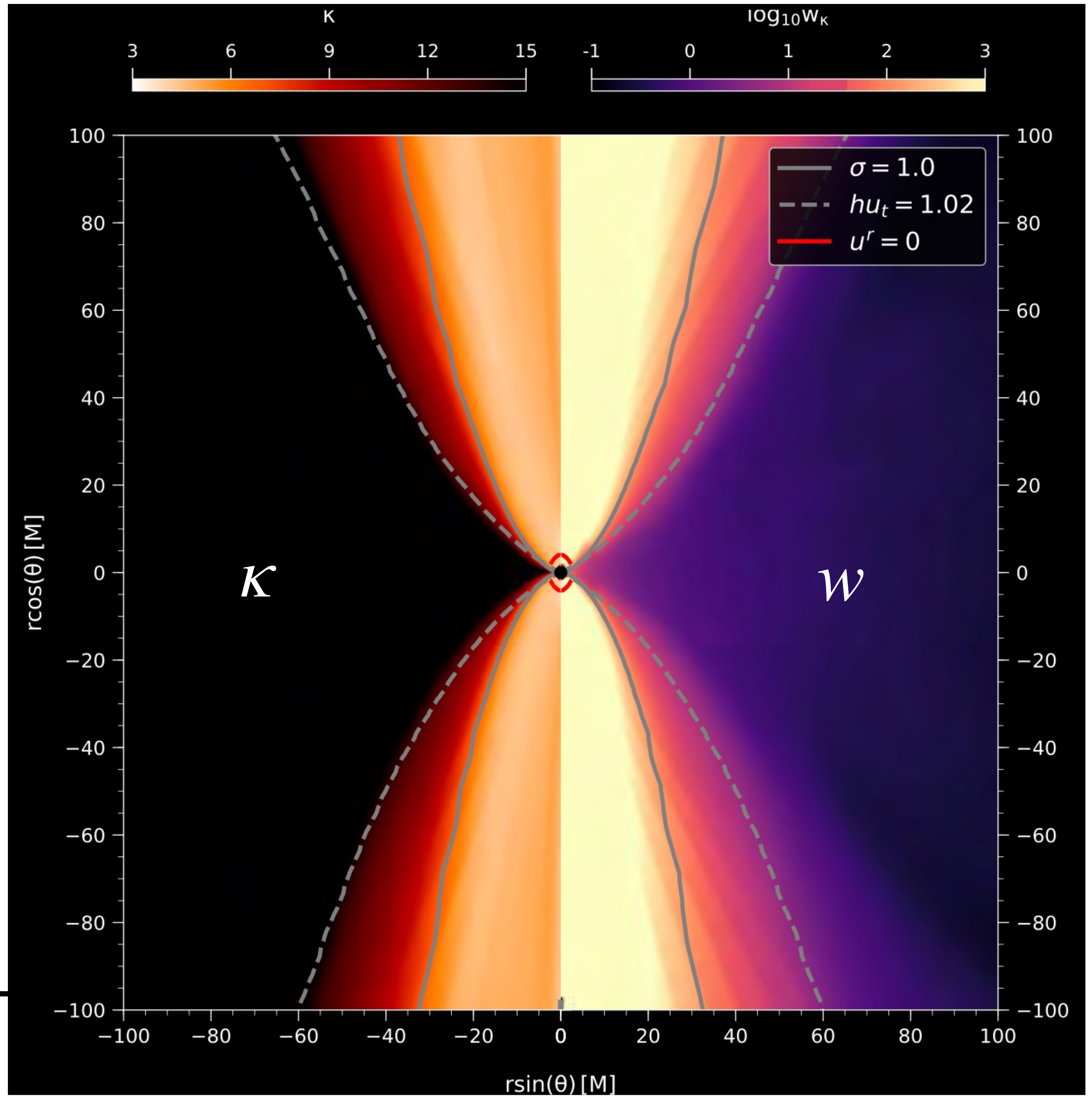
Energy content

$$w = \frac{\kappa - 3}{\kappa}\Theta_e + \tilde{\epsilon}\frac{\kappa - 3}{6\kappa}\frac{m_p}{m_e}\sigma.$$

electron temp., Θ_e : R-beta parameterised prescription

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

→ connect to GRMHD

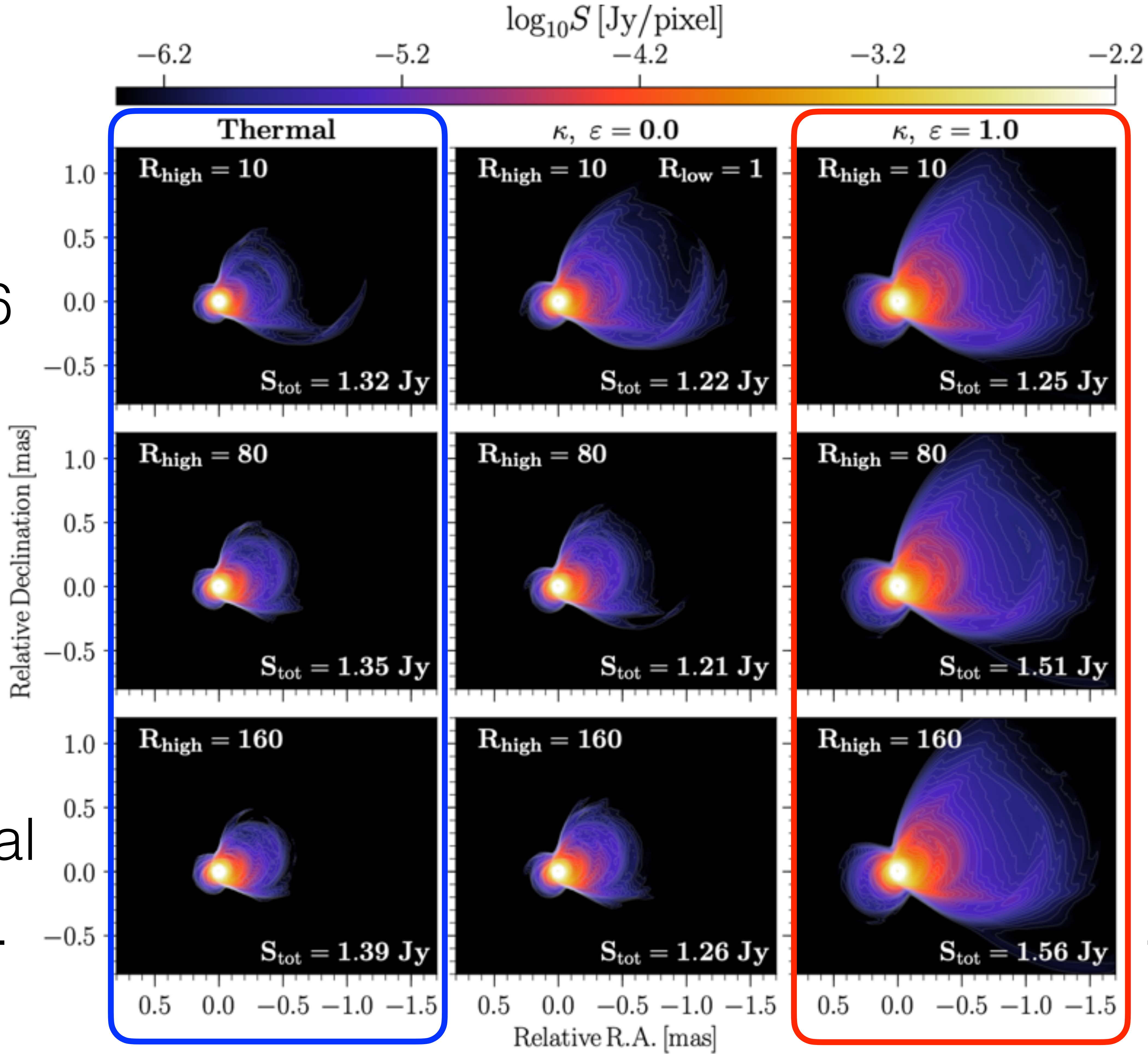


GRRT Jet Modeling of M87

thermal vs kappa eDF

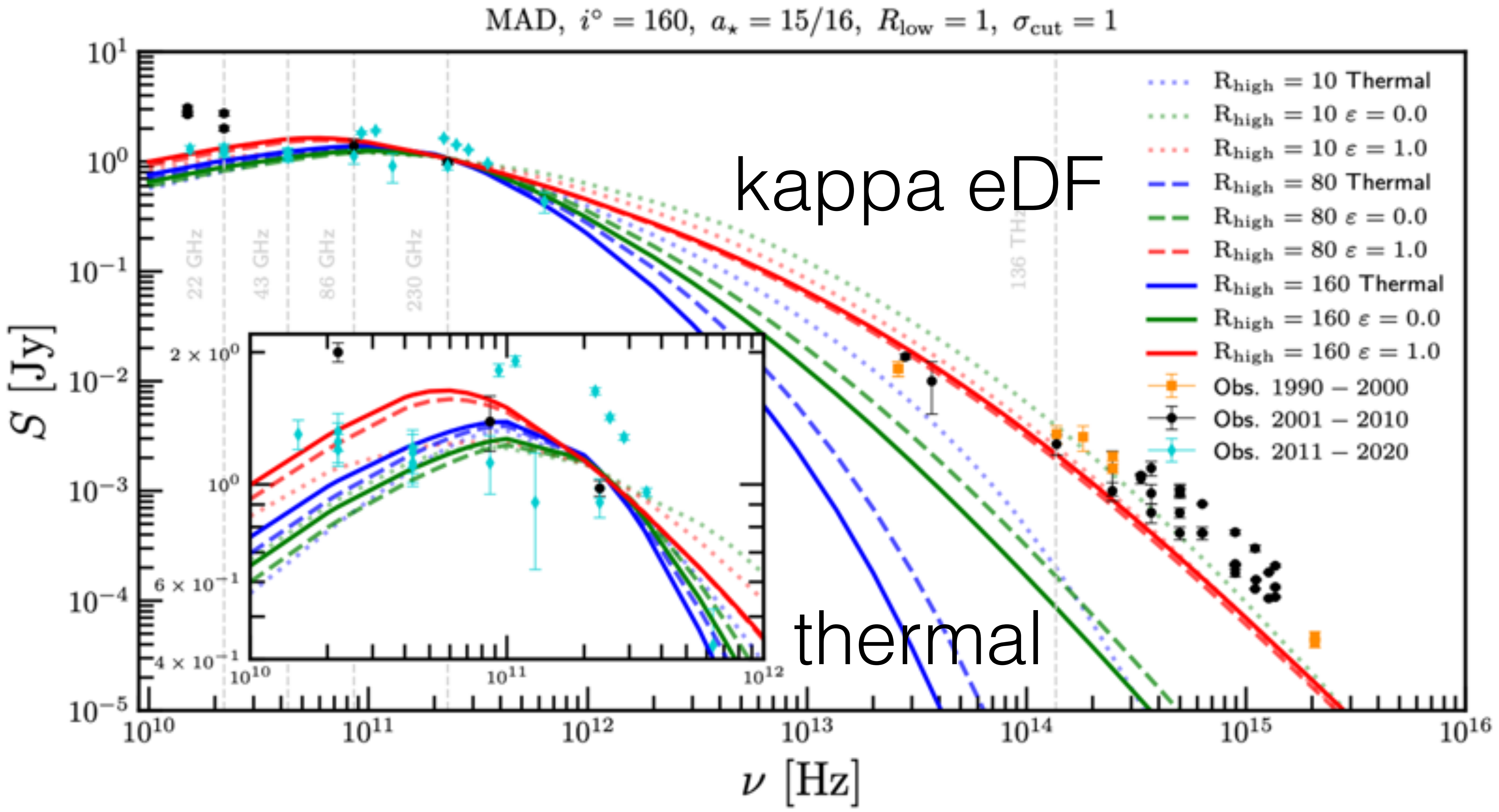
- Thermal eDF can not reproduce broad band SED
- Kappa eDF produces more extended jet emission

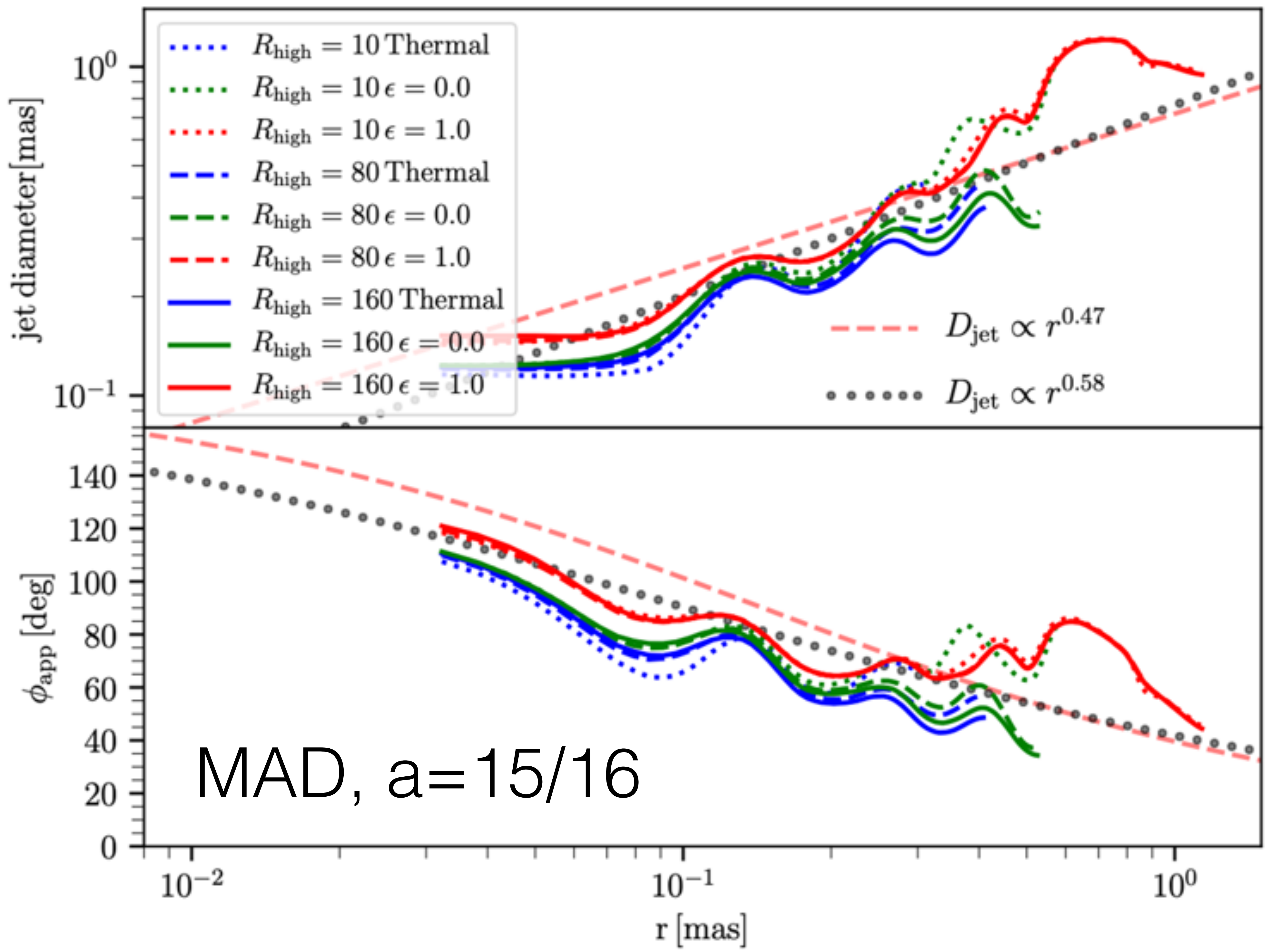
MAD, a=15/16



thermal

kappa eDF



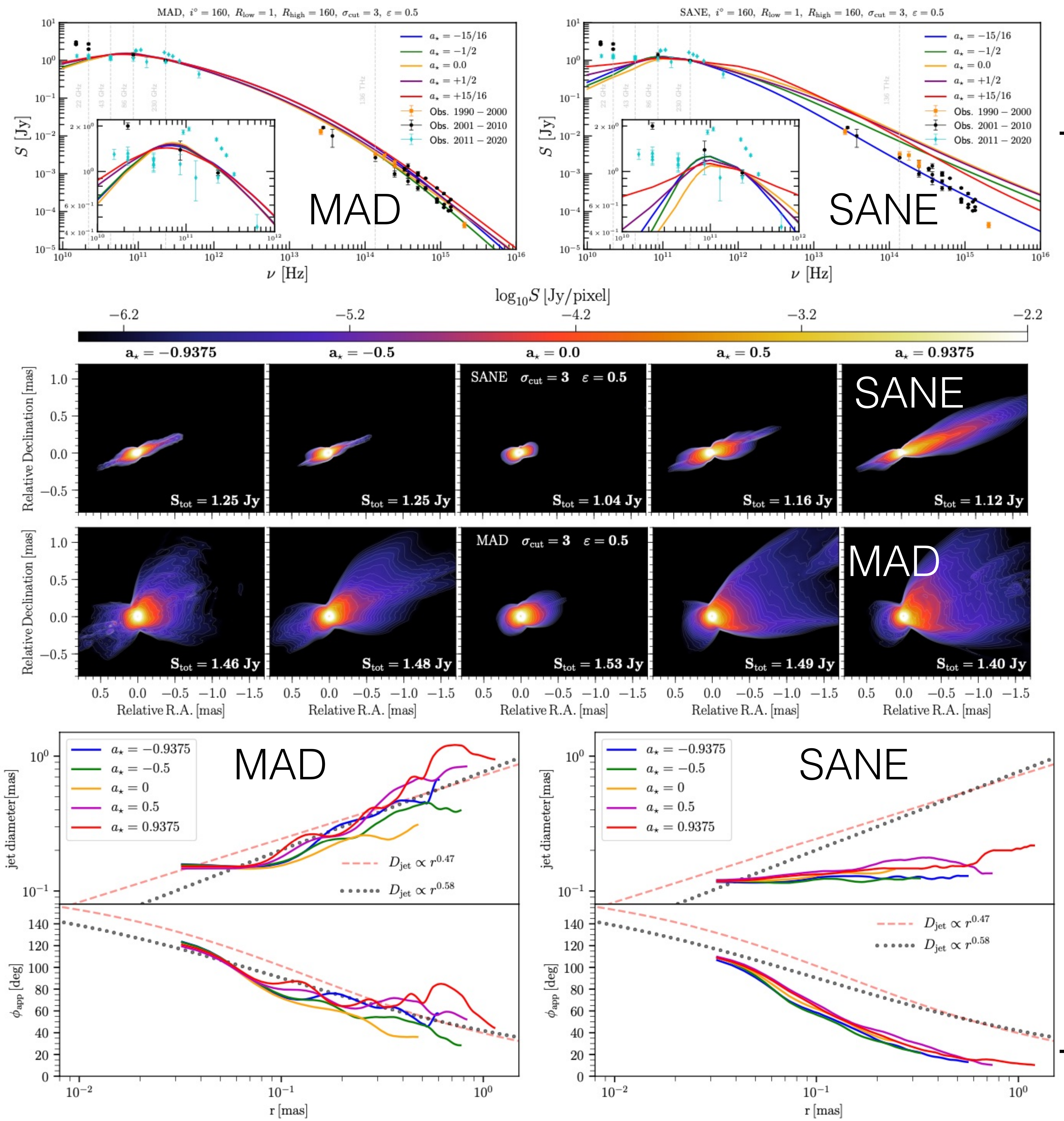


Fromm et al. (2022)

GRRT Jet Modeling of M87

MAD vs SANE

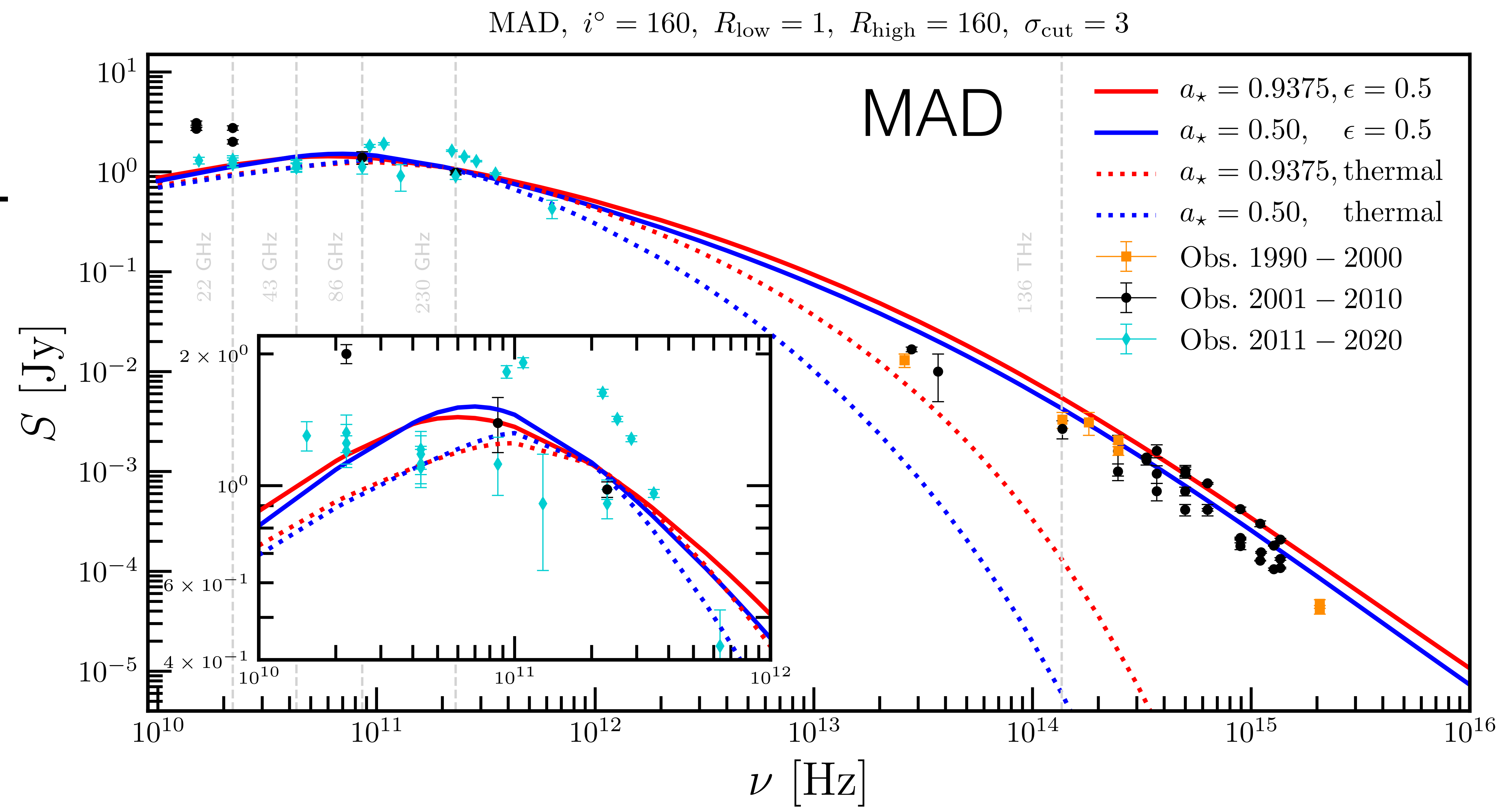
- Both MAD & SANE models can reproduce broadband SED of M87 (using kappa-eDF)
- MAD can make wide jet morphology but SANE can not make wide jet structure
- Lower BH spin case can not make bright extended jet

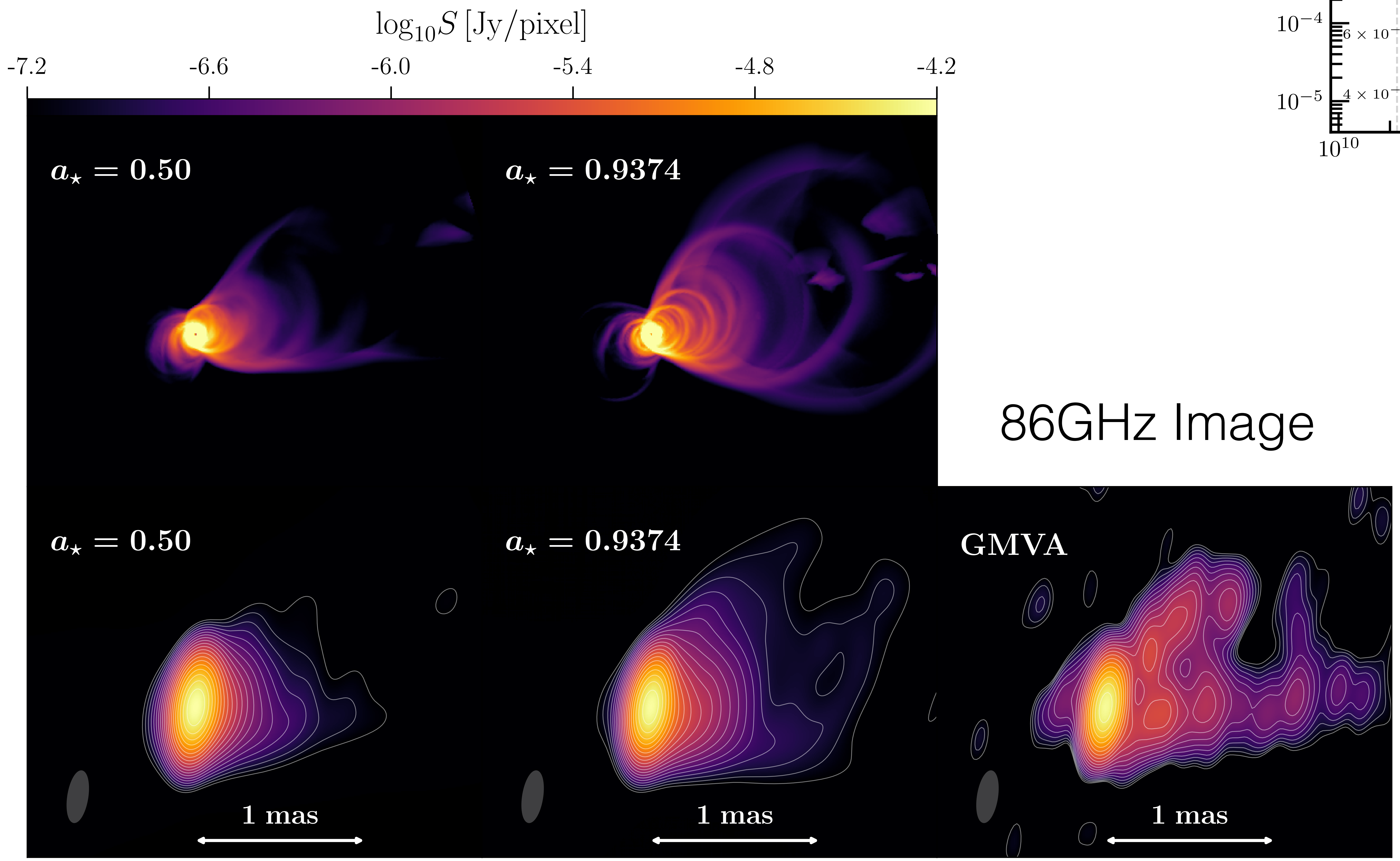


Fromm et al. (22)

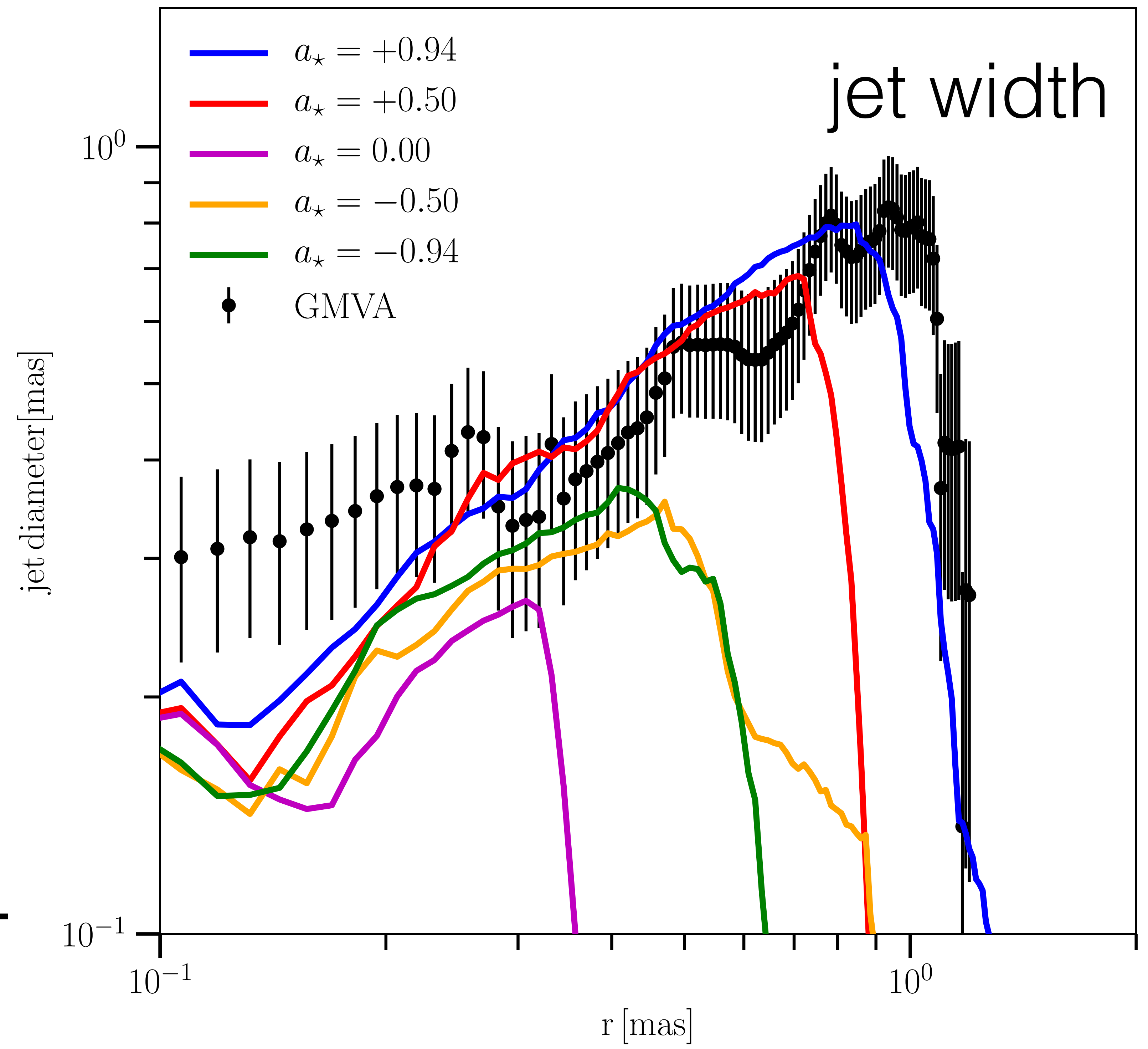
Best Fitting Model

- 3D GRMHD simulations of MAD accretion flows + GRRT calculations (thermal + non-thermal eDF)
- MAD (a=0.94) fits SED & jet morphology at 86GHz
- Still not good to reproduce edge-brightening





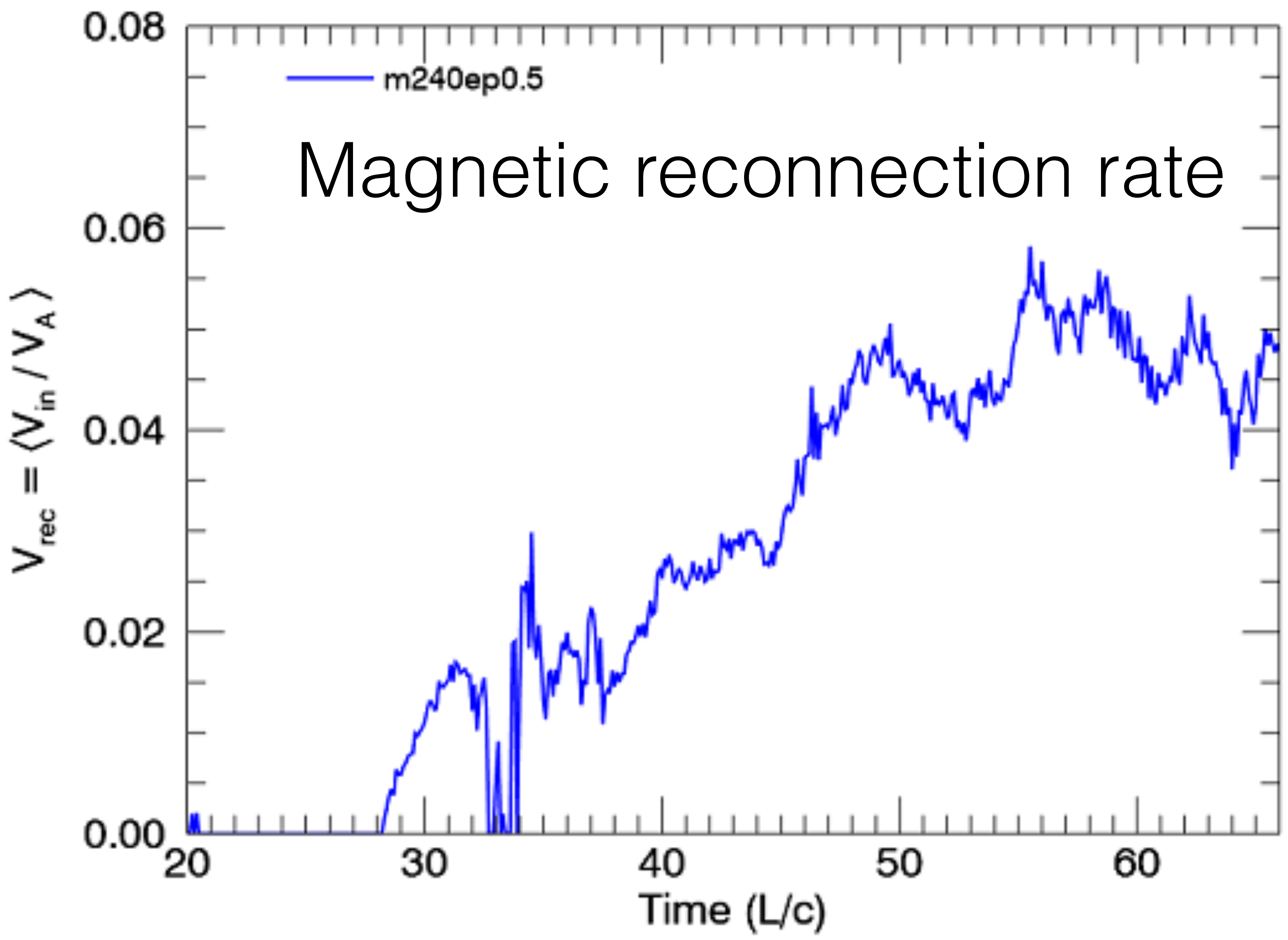
86GHz Image

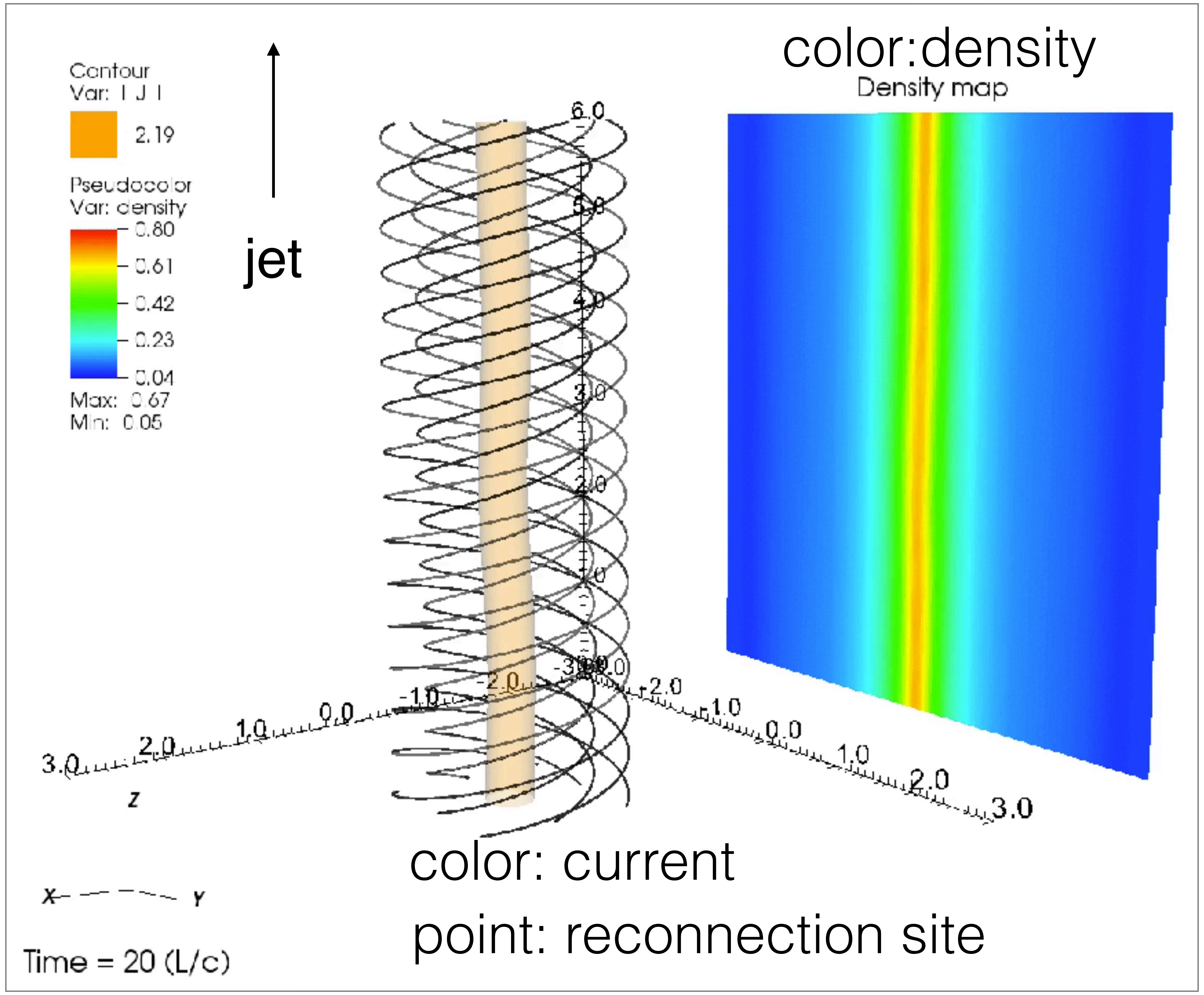


Cruz-Osorio et al. (22)

Magnetic Reconnection in Jets

- Looking for magnetic reconnection site (opposite field topology) in helically twisted jets by CD kink instability
- Calculate reconnection rate, $\langle v_{rec} \rangle \sim 0.05$
- In agreement with relativistic turbulent reconnection simulation (Takamoto+ 15)

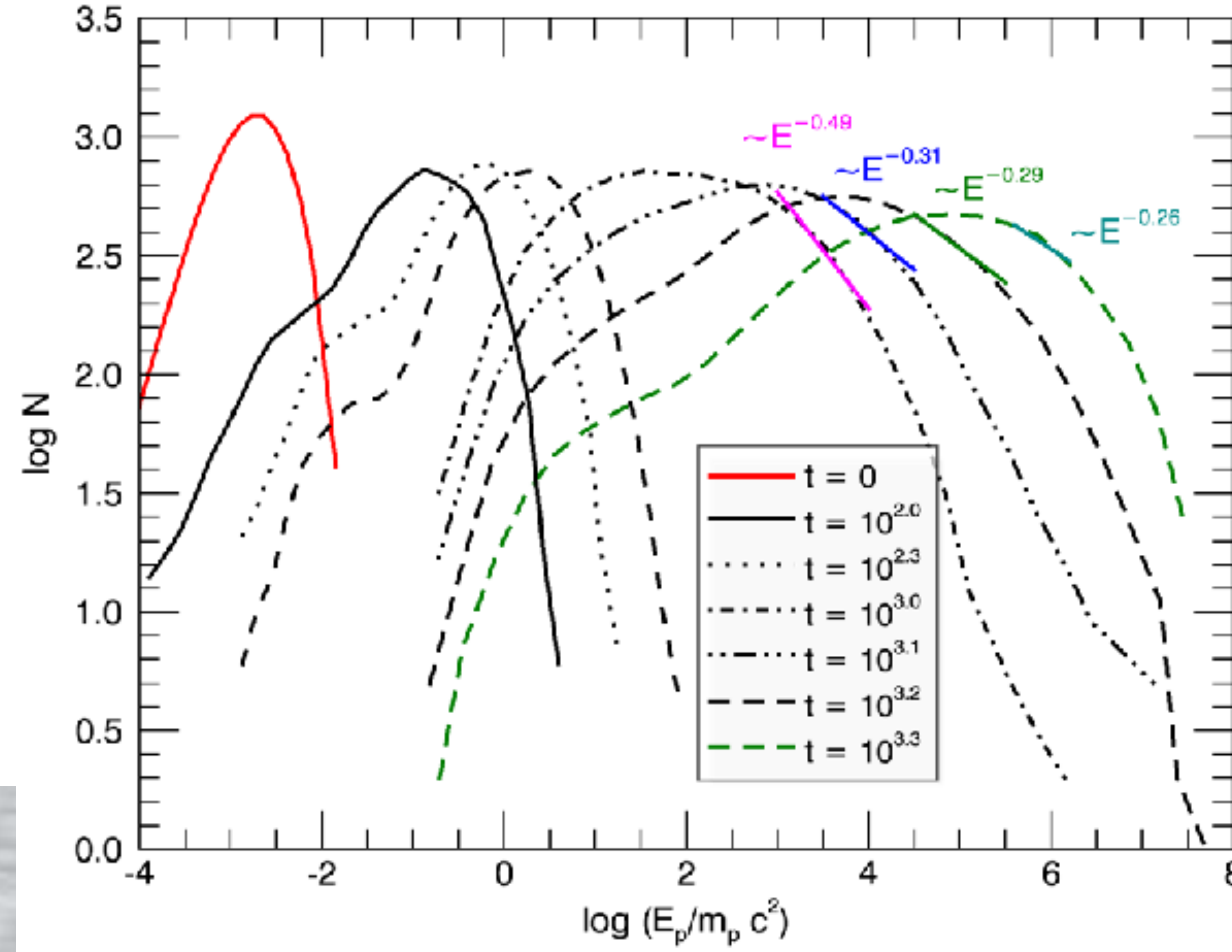


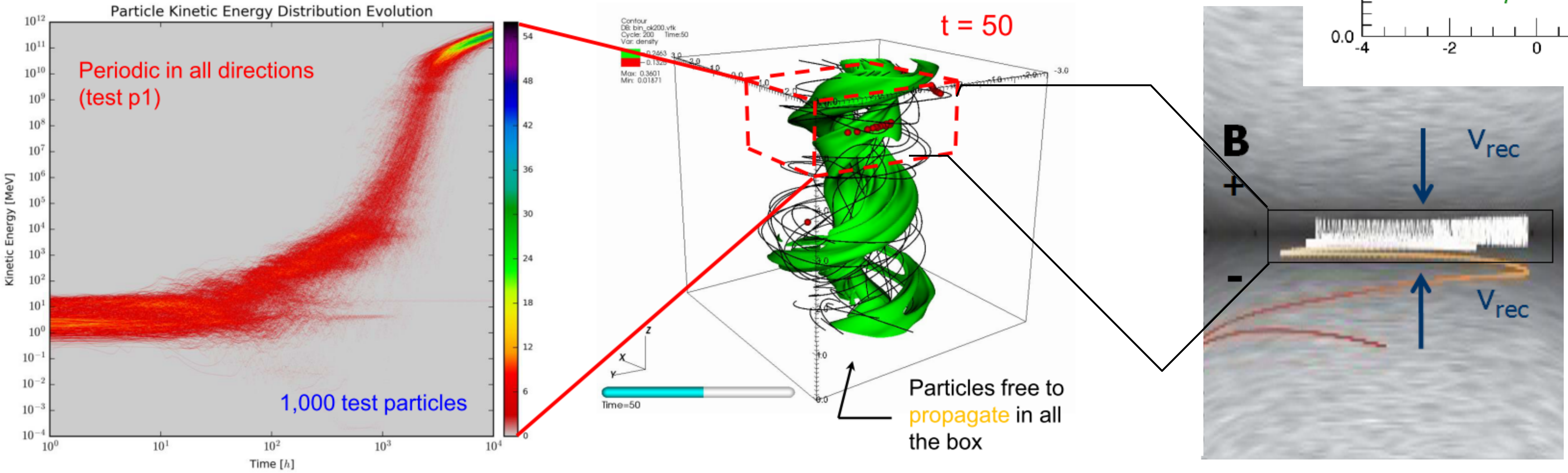


Kadowaki et al. (21)

Particle Acceleration in Jets via CD Kink Instability

- Local magnetic reconnection in jets will heat the plasma and accelerates particles.
- Particle is accelerated via stochastic Fermi-like acceleration in turbulent fields developed by CD kink instability in relativistic jets
- Spectrum becomes flatter tail

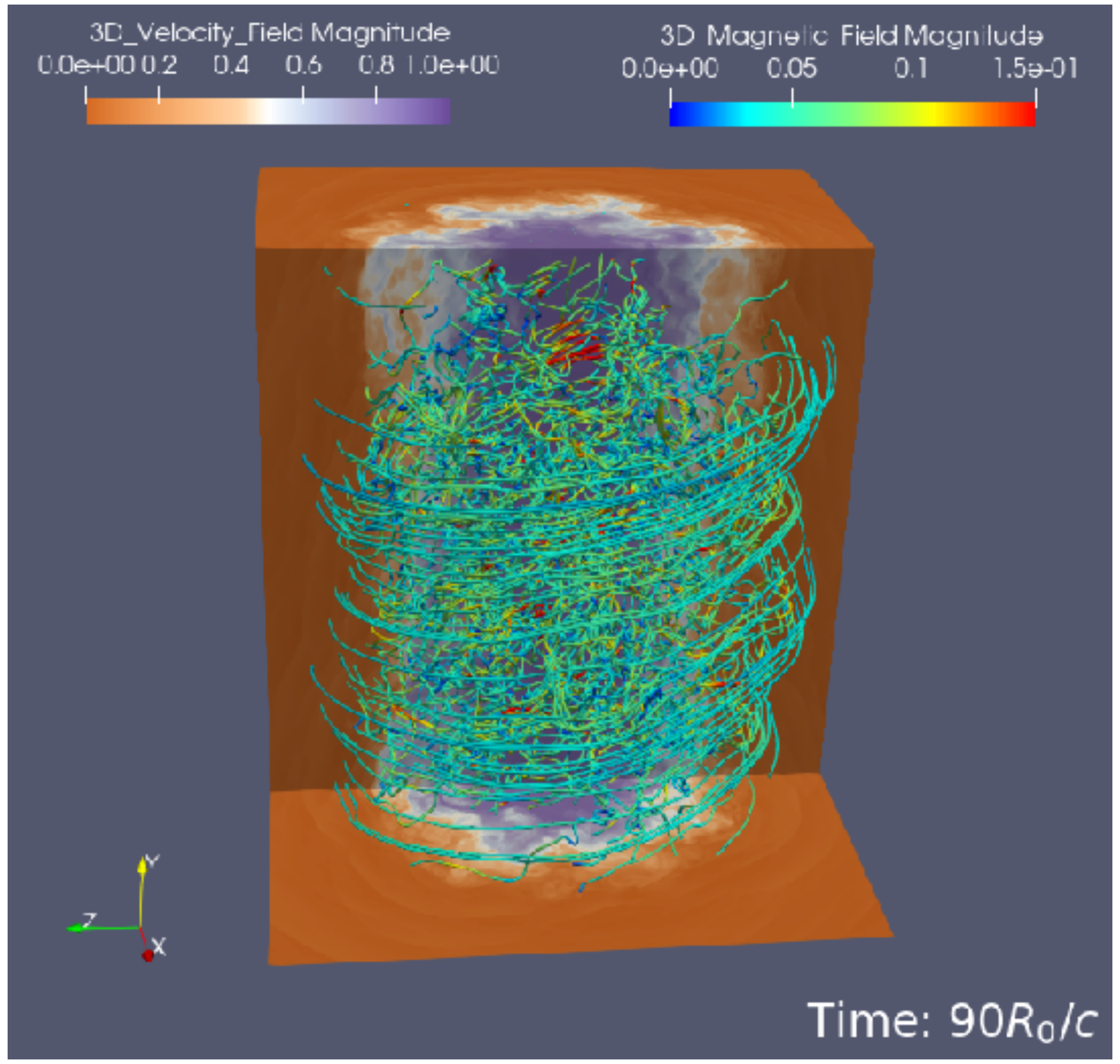


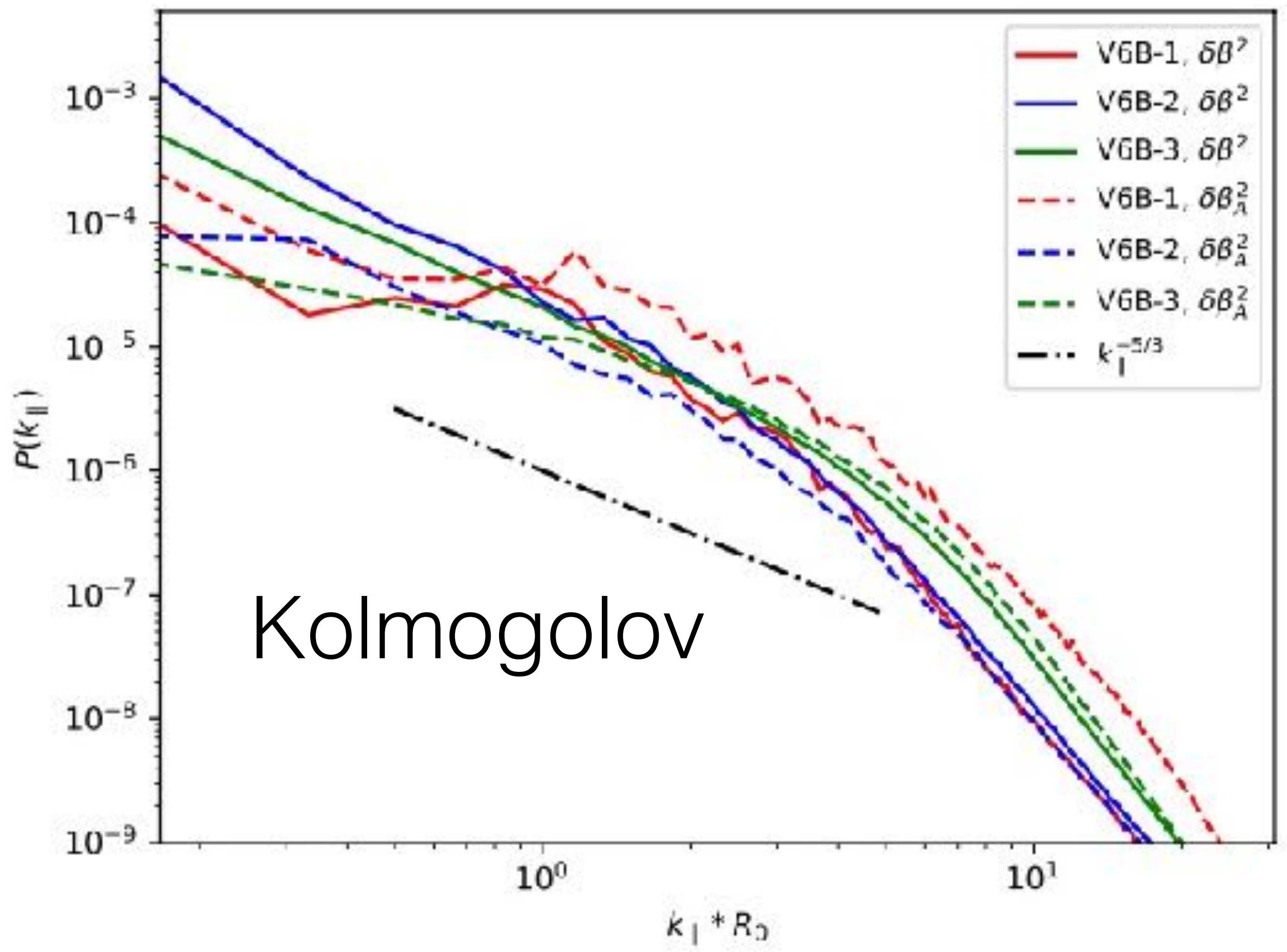


Medina-Torrejon et al. (21)

Particle Acceleration at Jet Shear Region

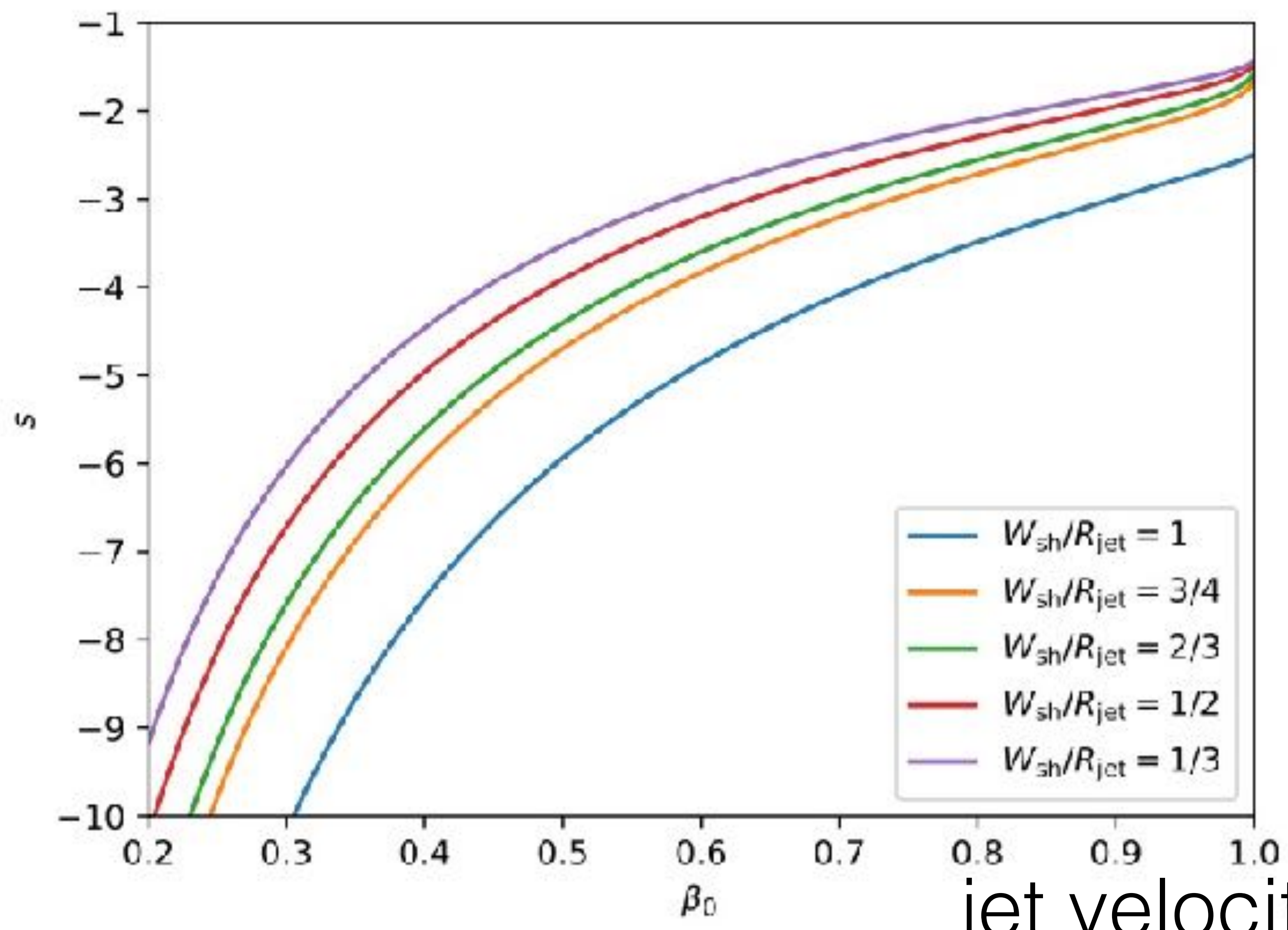
- Simulation: 3DRMHD Jet propagation with magnetic field
- Excite KH Instability at jet shear region with external medium ⇒ make turbulence at jet spine and sheath
- Jet shear region is potential particle acceleration site





Spectrum of turbulent (velocity & B-field)

spectral index



jet velocity

spectral index of shear-accelerated particle distribution

Wang et al. (22)

Summary

✓ Improved numerical modeling of relativistic jets

✓ Direct fitting of observational data with GRMHD/GRRT models

✓ Reproducing broadband spectrum emission & jet morphology (jet width, edge-brightening) of M87 jet

✓ Constrained model parameters (high BH spin is favored)

⦿ Explore more electron temperature models (using two-temperature GRMHD model: YM et al. 21)

⦿ Need more micro-physics such as cooing process (GRMHD + radiative cooling: Dihinghia et al. 22)

⦿ Extent the GRMHD simulations to a larger distance (e.g., 43GHz)

⦿ Compute high-energy emissions (X-ray & gamma-ray)

⦿ Connection to polarimetry