Modeling the inner part of the jet in M87: confronting jet morphology with theory

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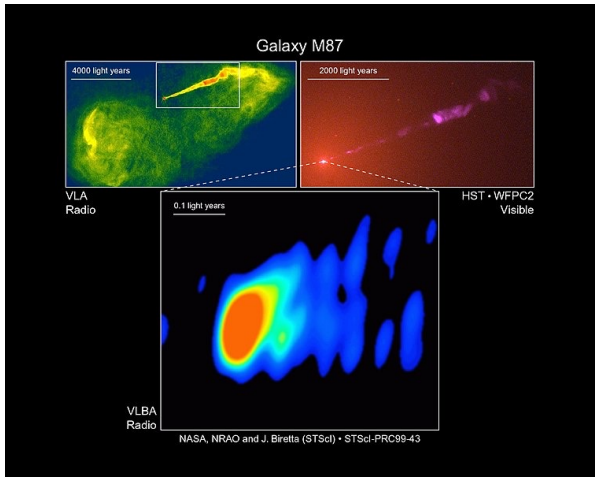
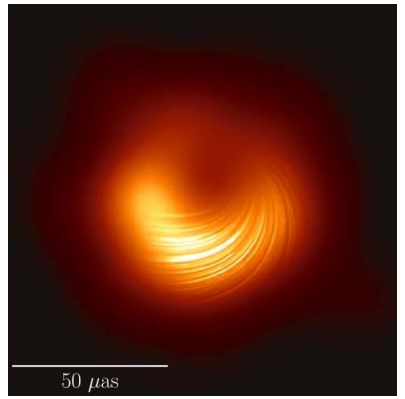
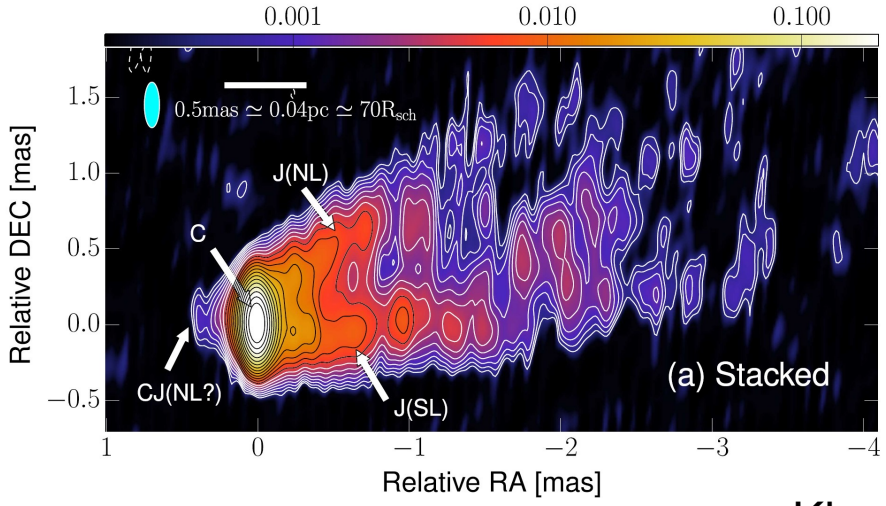
The Observation of M87 Jet

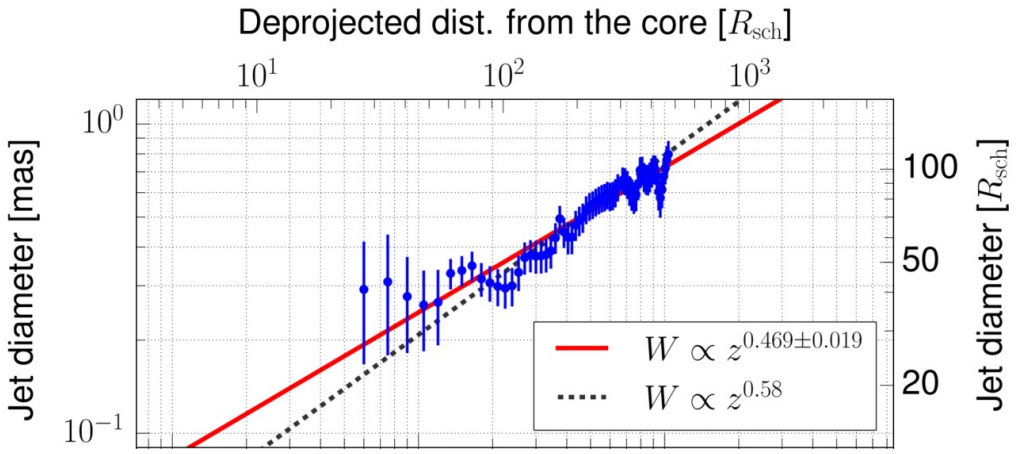
1) Elongated structure
2) limb-brightened jet morphology
3) Jet width: parabolic shape





EHT. 2021

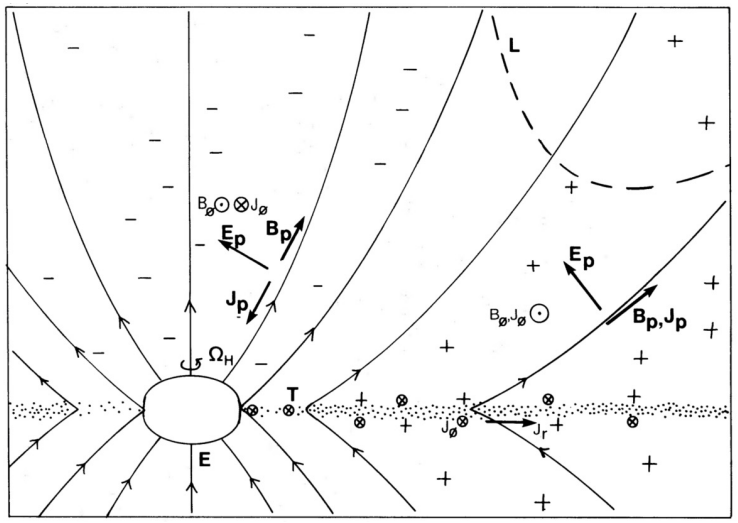




Kim et al. 2018

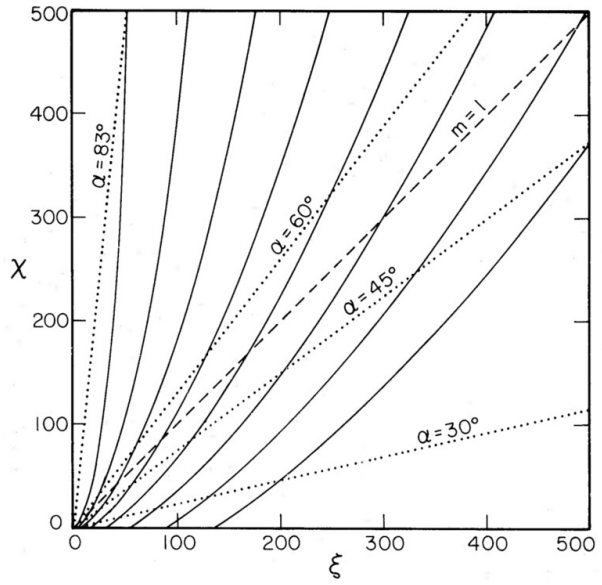
Two open questions of jet physics

1) BZ-jet or BP jet ?



Blandford, Znajek . 1977

Extracting **BH** rotational energy through magnetic field lines

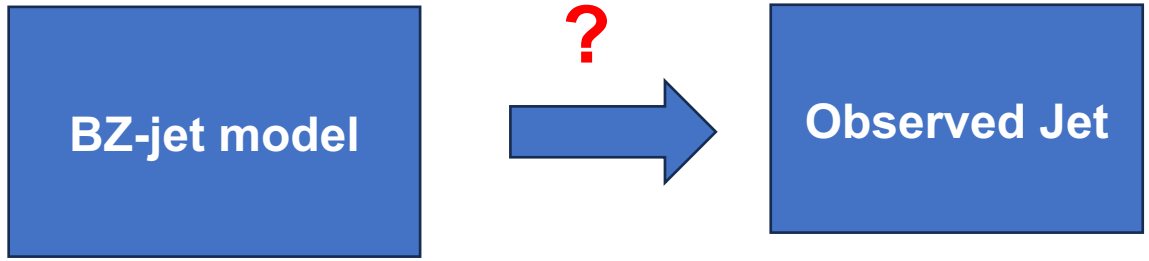


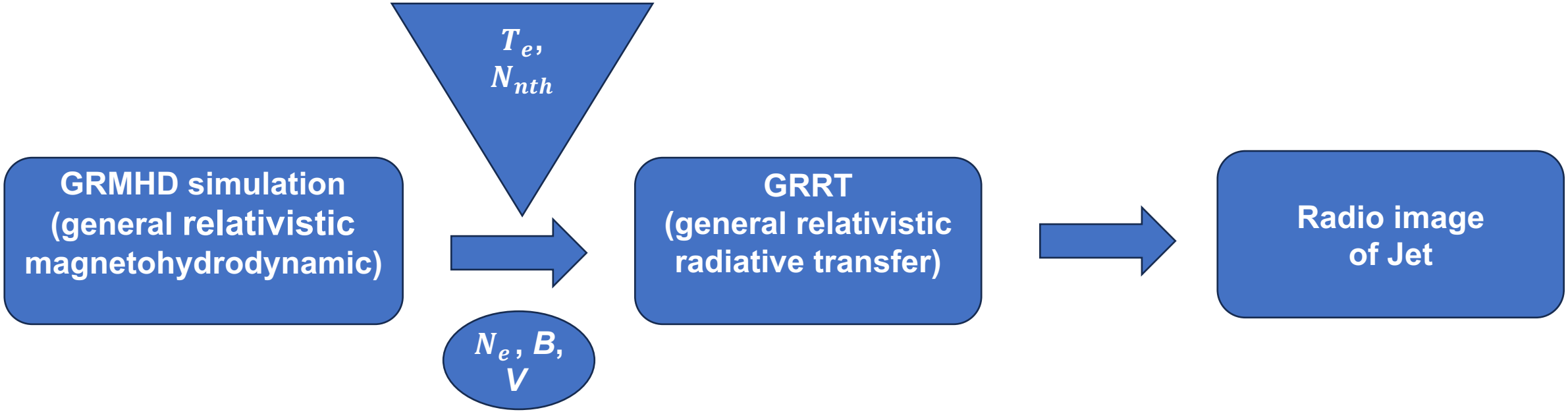
Blandford, Payne. 1977

Extracting **disc** rotational energy through magnetic field lines

Two open questions of jet physics

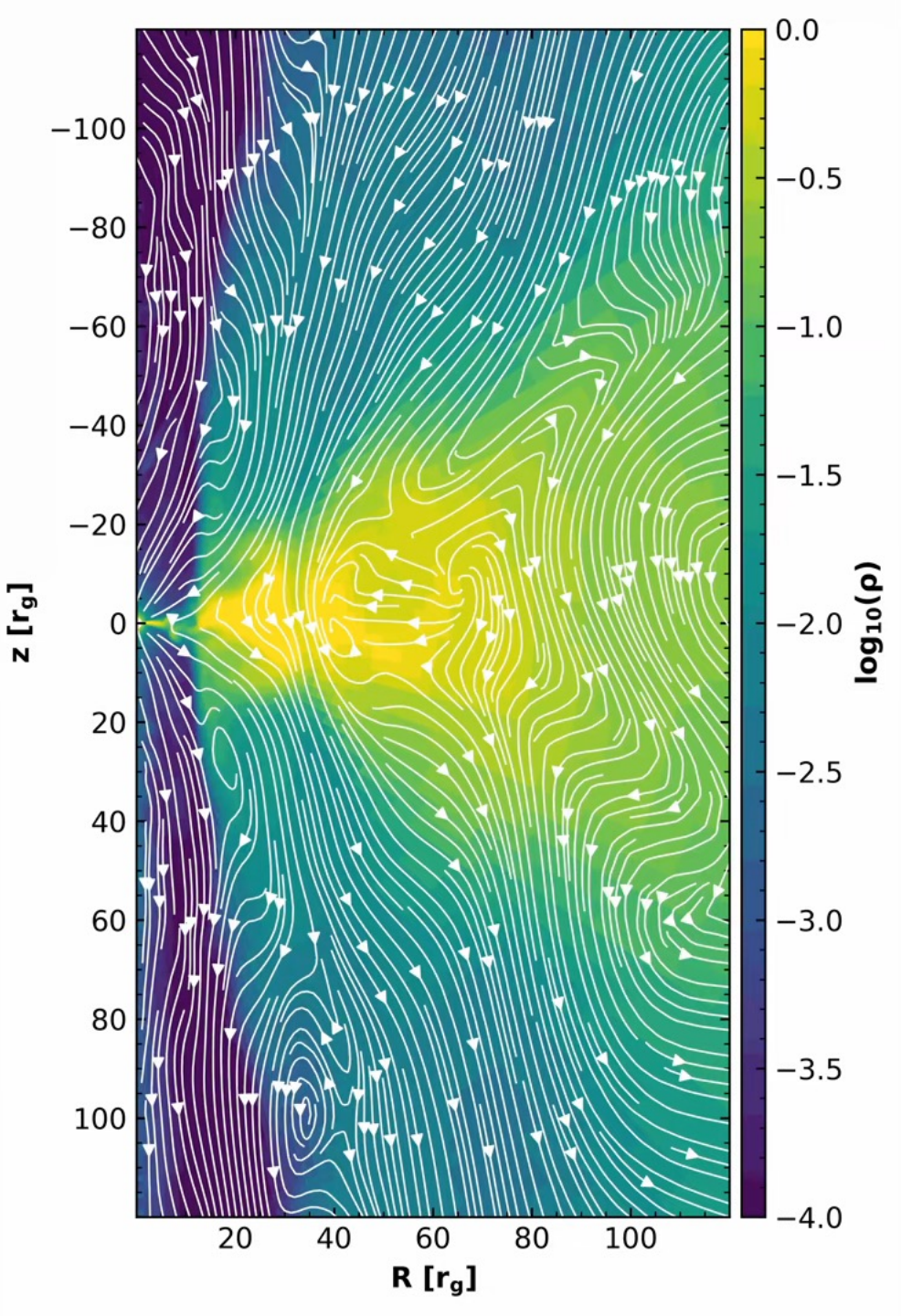
2) Whether BZ-jet can predict the observed morphology; or, how is the radiation of jet produced?





Simulation setup

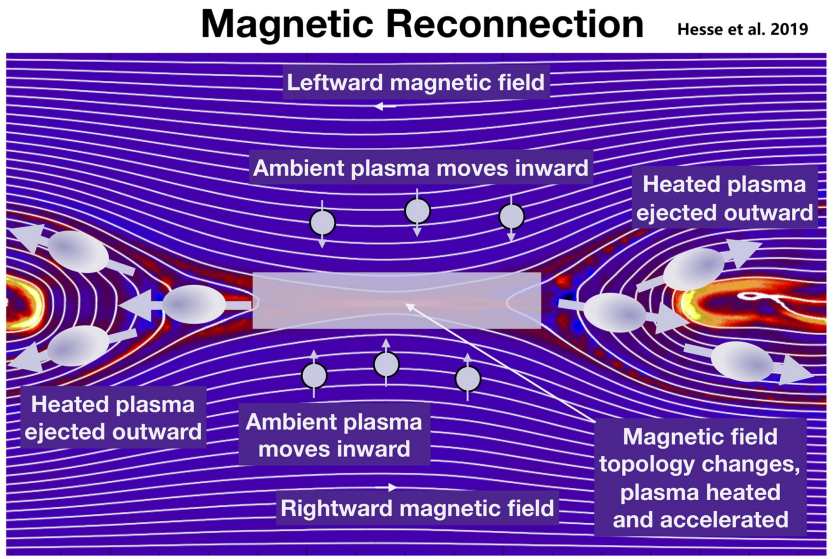
- Code: Athena++
- MAD98: 1408X512X256
- MAD00,MAD05,SANE98: 880X256X128
- GRRT: IPOLE



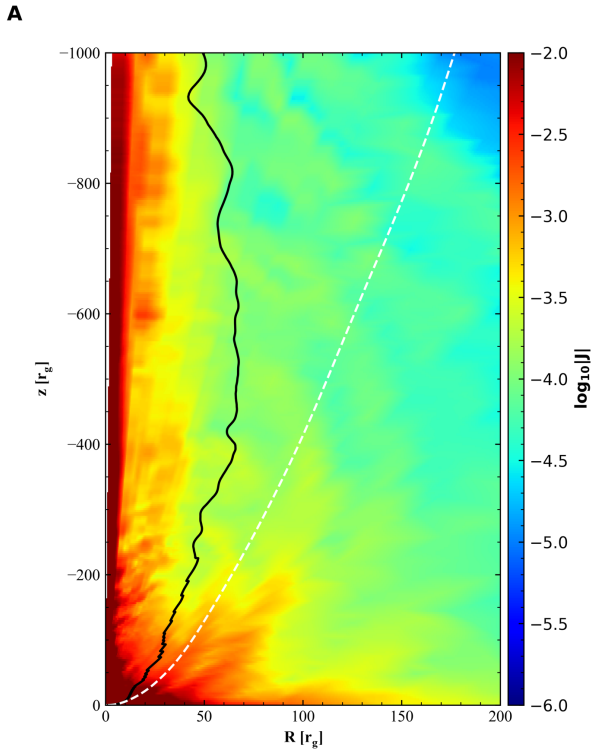
Our basic theory of Non-thermal electrons

Magnetic flux eruption near the EH

Magnetic Reconnection in Jet

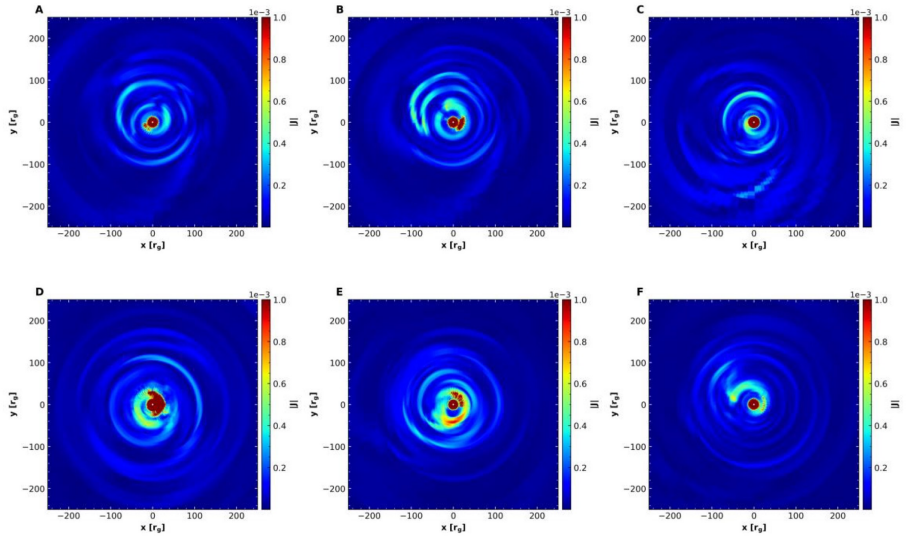


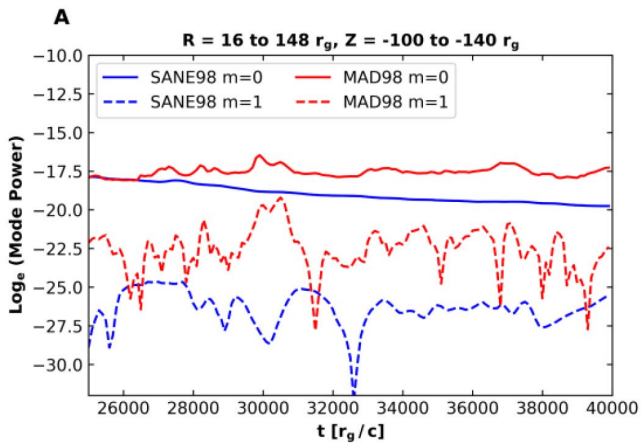
- Acceleration rate: $\propto (J/J_0)^2$

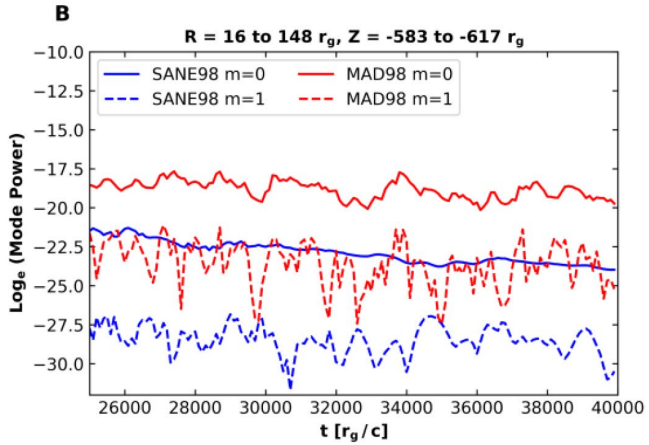


The physical origin of magnetic reconnection in the jet

- Same as magnetic eruption
  - Non-axisymmetric features
  - Variability timescale
- Both in small and larger radius







- Magnetic flux eruption in MAD

Current density model

- Temperature of electrons:

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

- Pow-law distribution:

$$\frac{dn_{pl}}{d\gamma} = N_{pl}(p-1)\gamma^{-p}, \quad \gamma_{max} > \gamma > \gamma_{min} .$$

$$p = \frac{1}{\sigma_x + 0.2(1+tanh(b_g))} + 0.04tanh(b_g)\sigma_x + 1.7b_g + 2.1. \qquad \gamma_{min} = 10kT_e/m_ec^2 + 1$$

- Number density of nonthermal electrons:

$$\eta\frac{v_A}{r_z}(N_{tot} - N_{pl})\frac{J^2}{J_0^2} = \frac{N_{pl}}{\tau_{cool}}$$

Image of the Jet

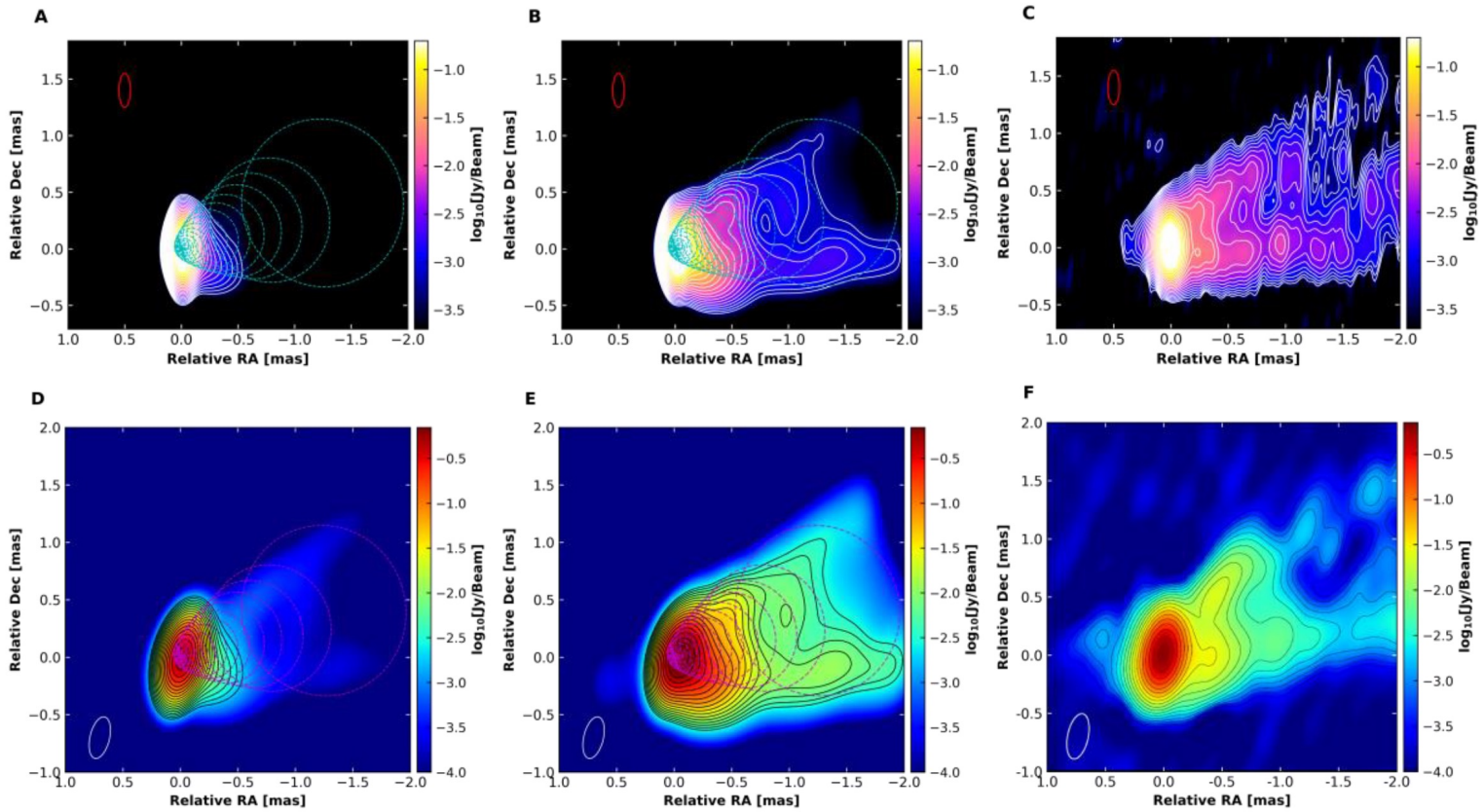
- Thermal:

  no limb-brightening

  short

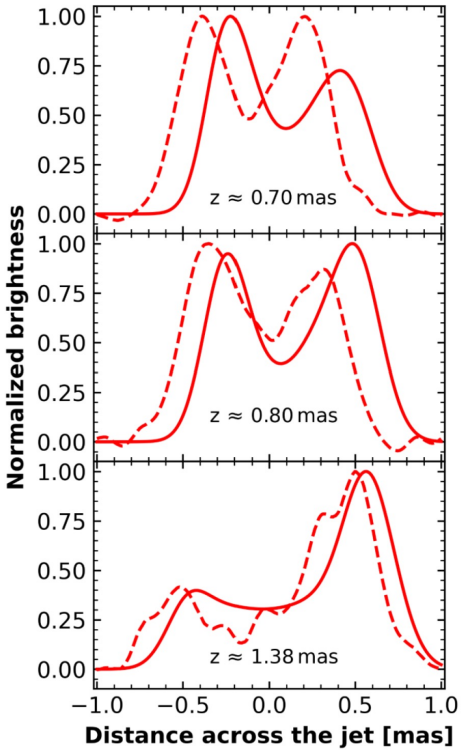
- Current density model:

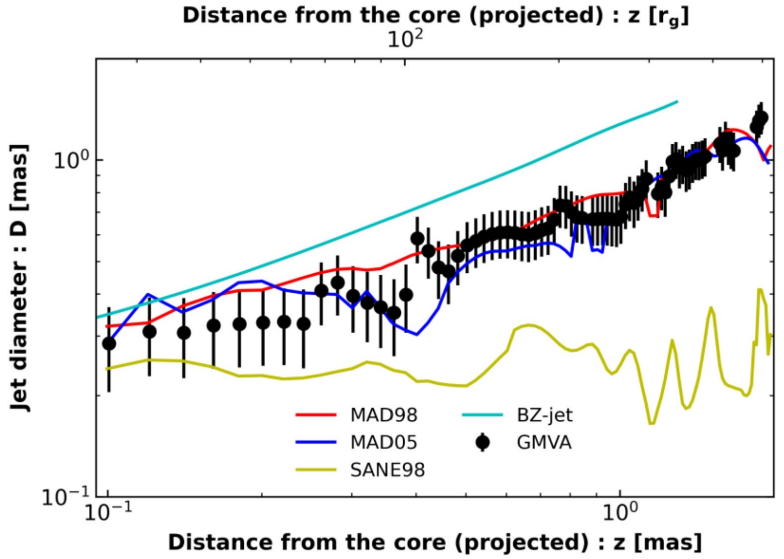
  distinct limb-brightening, elongated jet



Limb-brightening and jet width

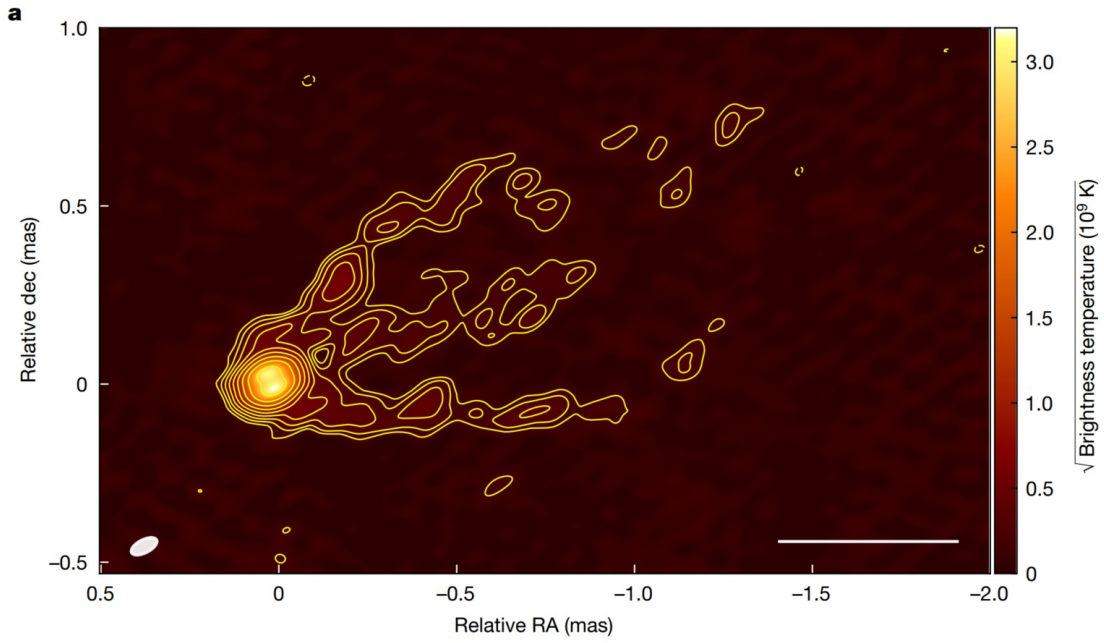
- Distinct limb-brightening feature
- The jet width is consistent with observations and within outer boundary of the BZ jet



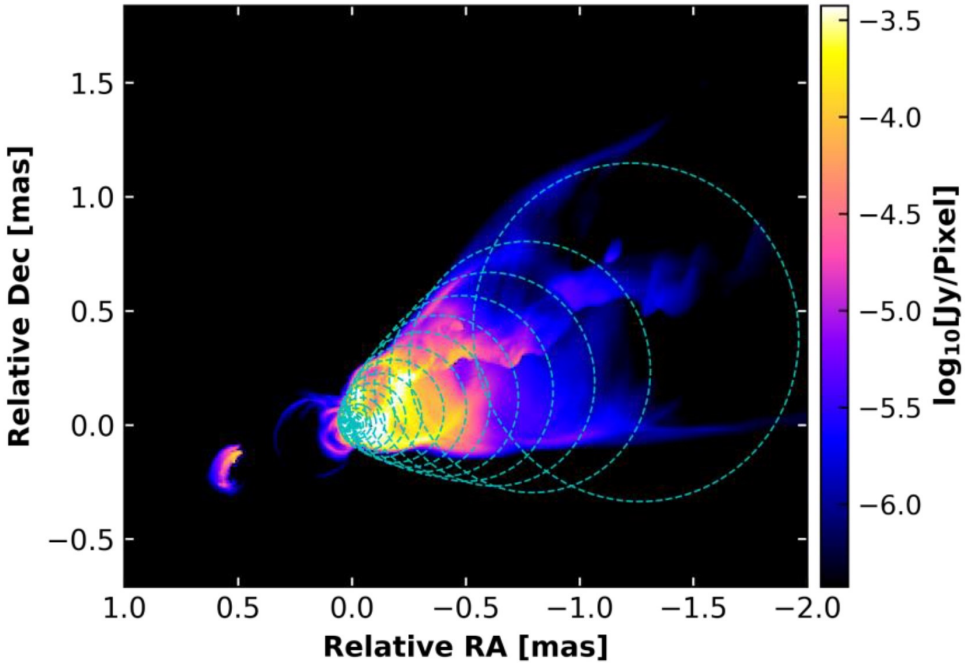


- BZ model can reproduce observed jet morphology

The third ridge

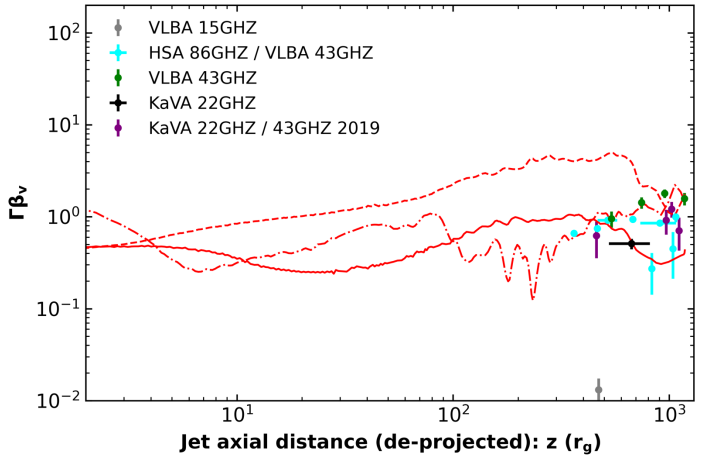


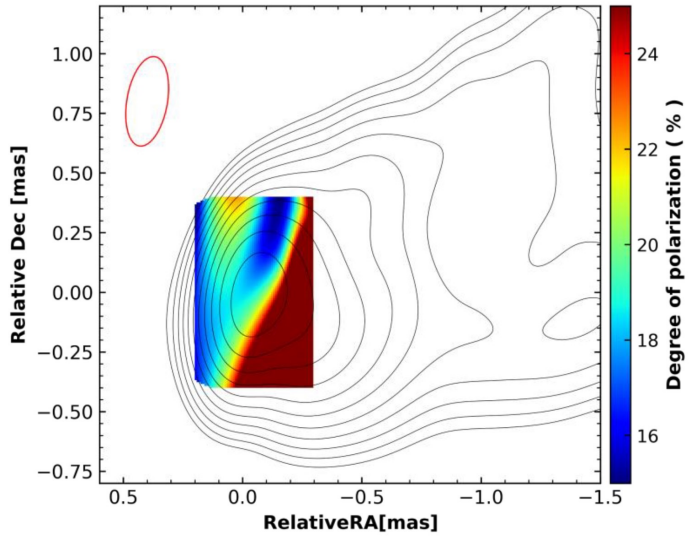
Lu et al, 2023



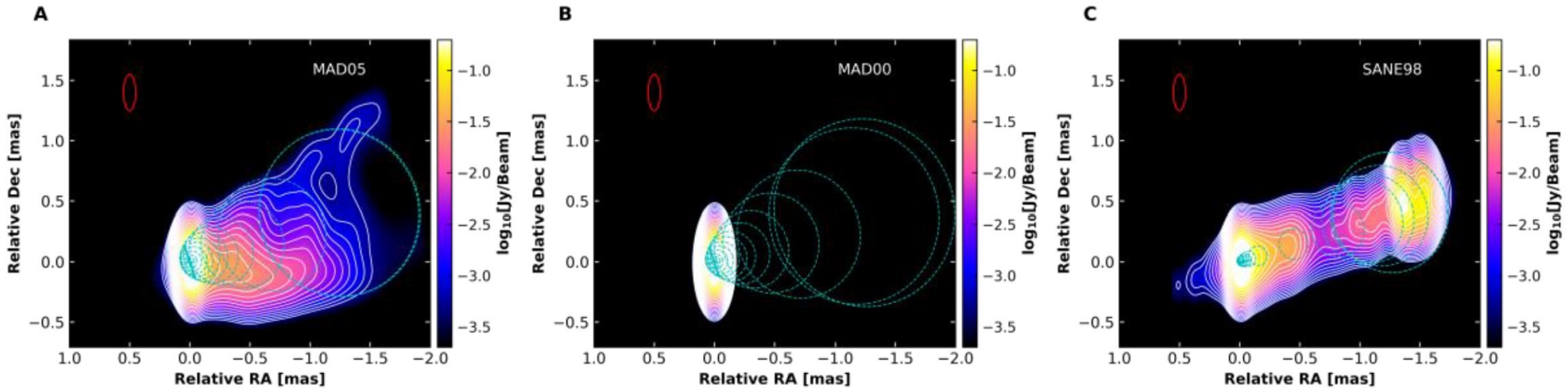
Velocity, power and the polarization degree

- P_{jet} = 6.32×$10^{43} ergs^{-1}$, within the observed range
- Velocity consistent with observations
- Polarization degree higher than observations (due to lack of depolarization from much larger region)





Different accretion modes and black hole spin



- MAD05: N_{nth} layer too thick
- MAD00: N_{nth} too small at larger radius
- SANE98: N_{nth} concentrate in central axis

Two conclusions

- Blandford-Znajek is the mechanism of jet production
- The electron acceleration mechanism is magnetic reconnection which is likely driven by magnetic flux eruption of MAD

Thank you!