Constraints on mass injection mechanism in M87 jet

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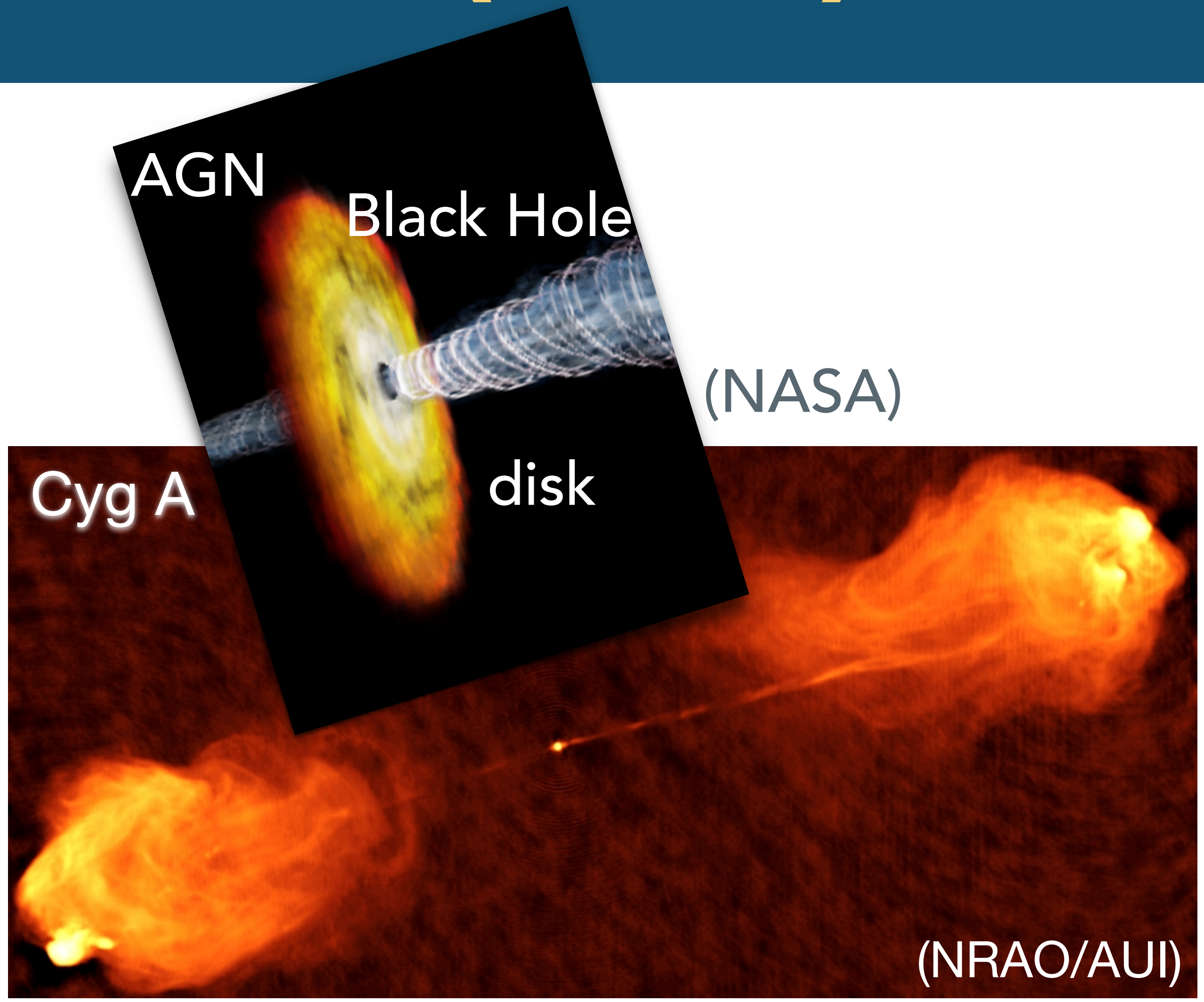
OUTLINE

- 1. Introduction
    - AGN Jets
- 2. Method
    - Jet Model
- 3. Results
    - Reproduction of Jet Image
- 4. Discussion & Summary

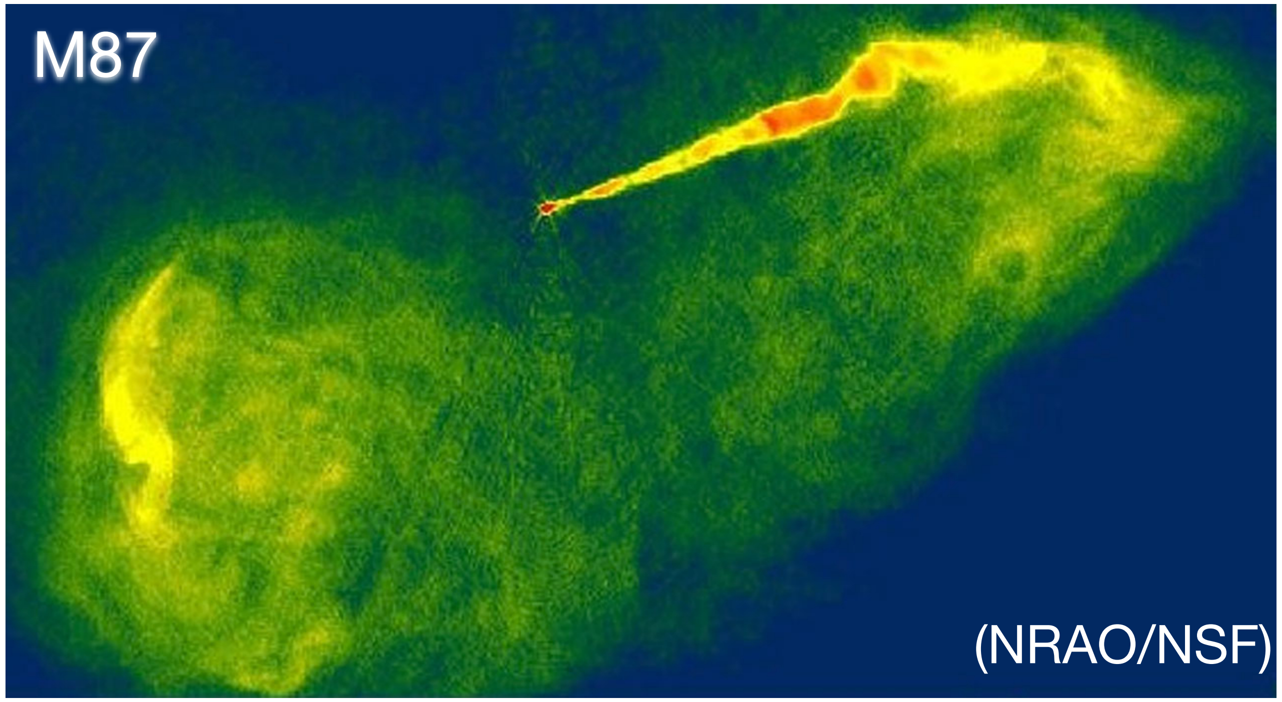
1. Introduction

Active Galactic Nucleus (AGN) Jets



(NASA)

(NRAO/AUI)



(NRAO/NSF)

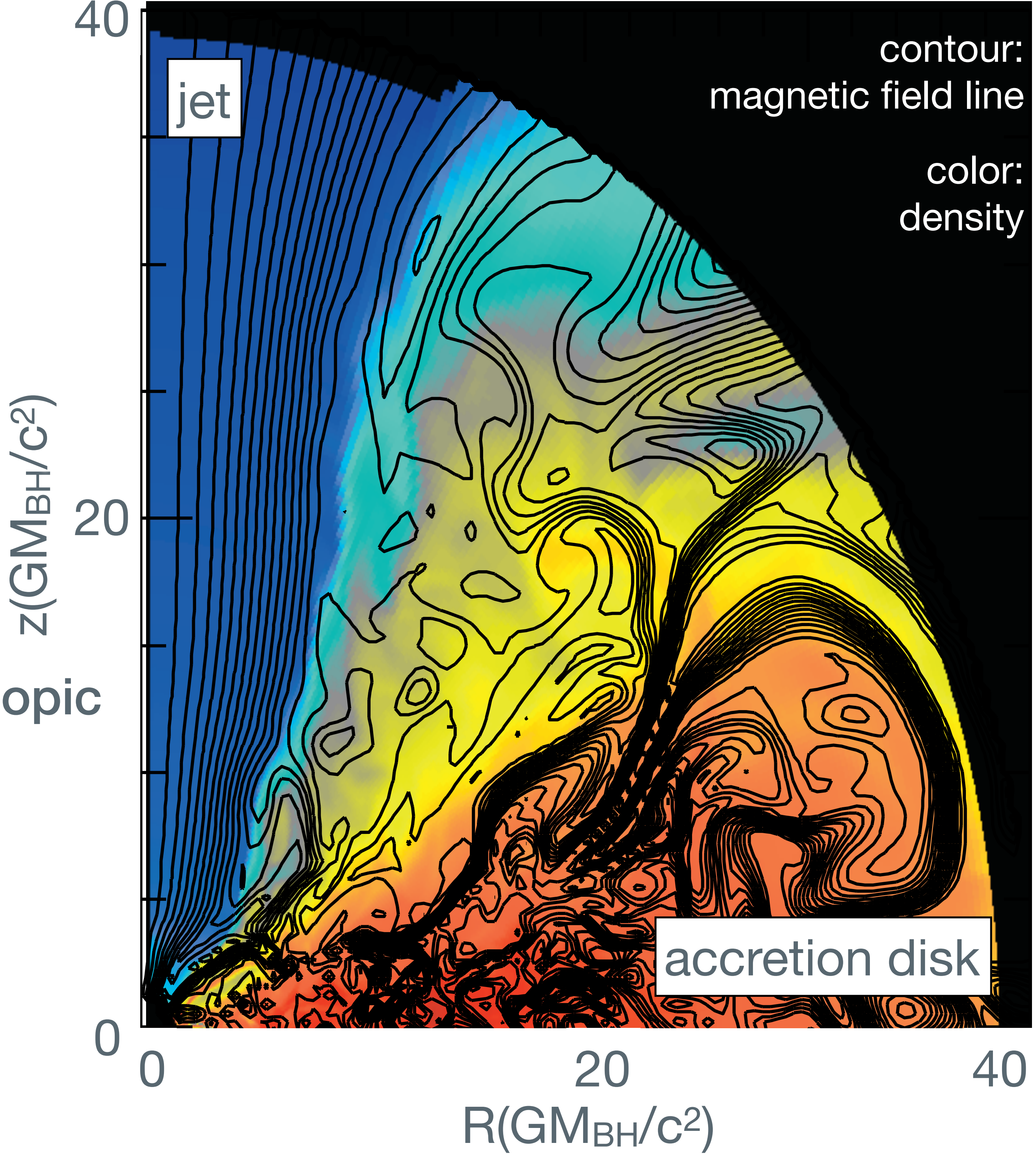
- AGN Jet:
  - relativistic outflow ($\gamma<10$)
  - jet length: ~10kpc-1Mpc
  - tightly collimated (~1°)
  - synchrotron radiation in radio band

Driving Mechanism

- Electromagnetically driven jet
- Energy Source:
  Rotation Energy of
  Blackhole or accretion disk
- B-field collimation
  & density distribution
  ↔Jet power, terminal Lorentz
  factor & radiation

today’s topic

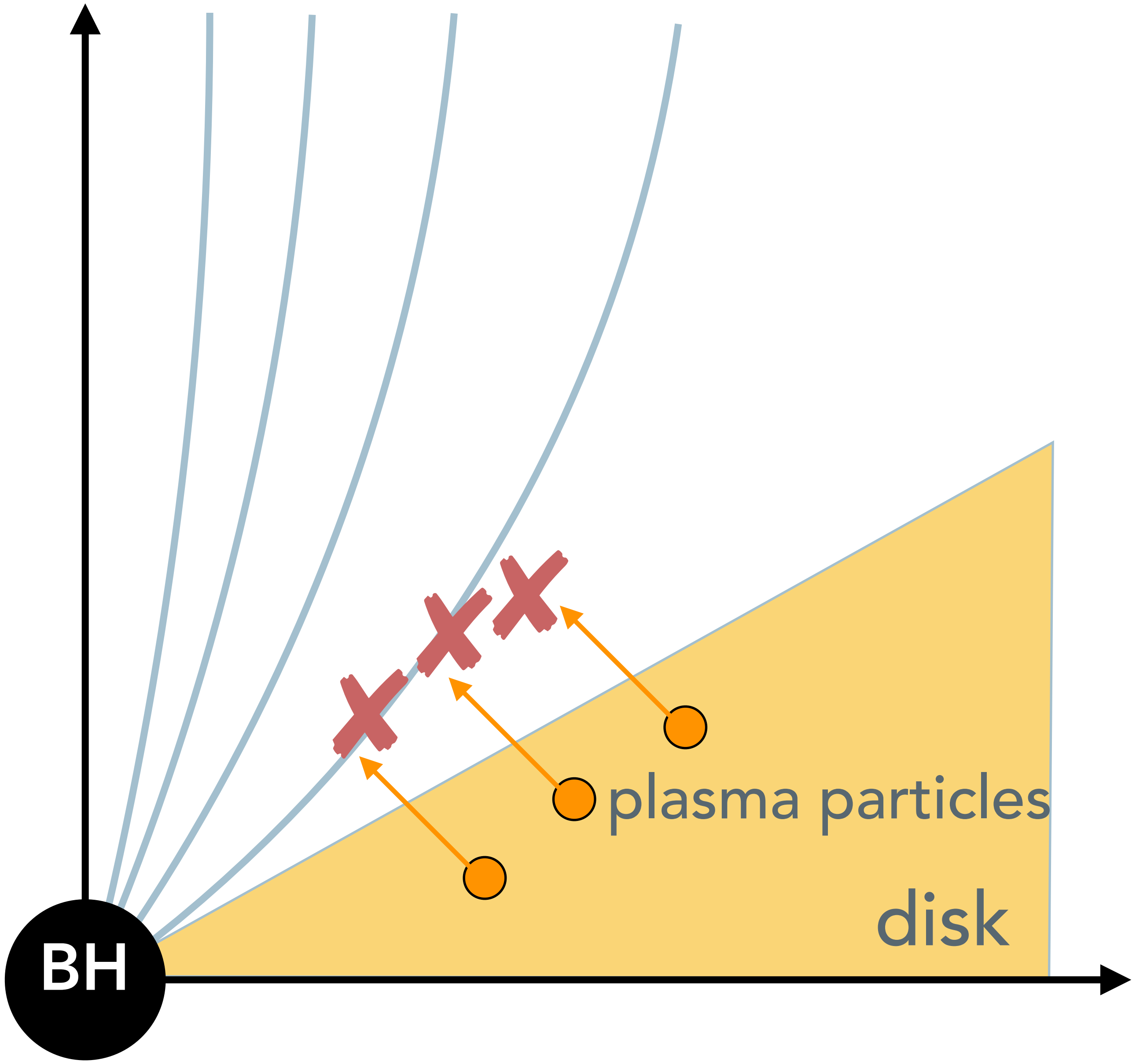
GRMHD simulation (McKinney & Gammie 2004)



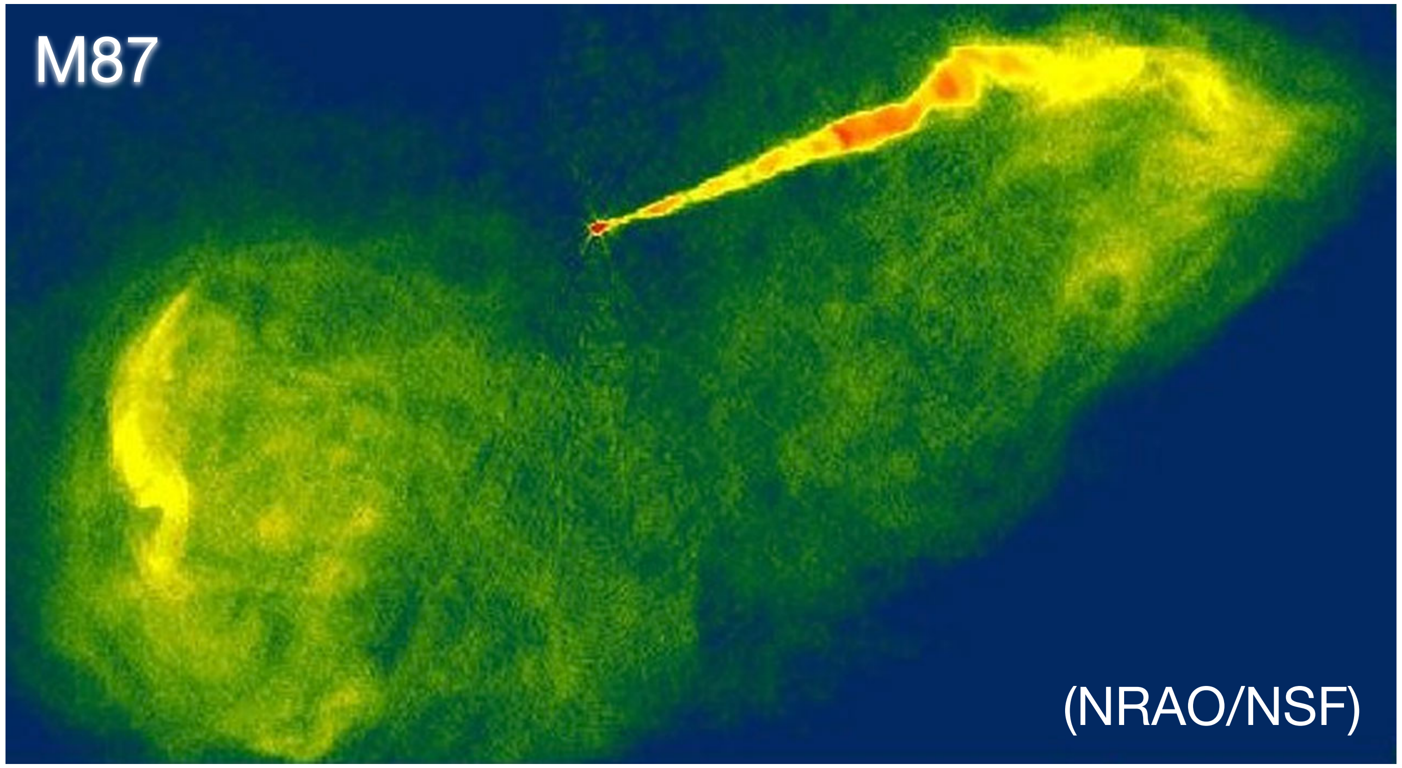
Mass-Loading Problem

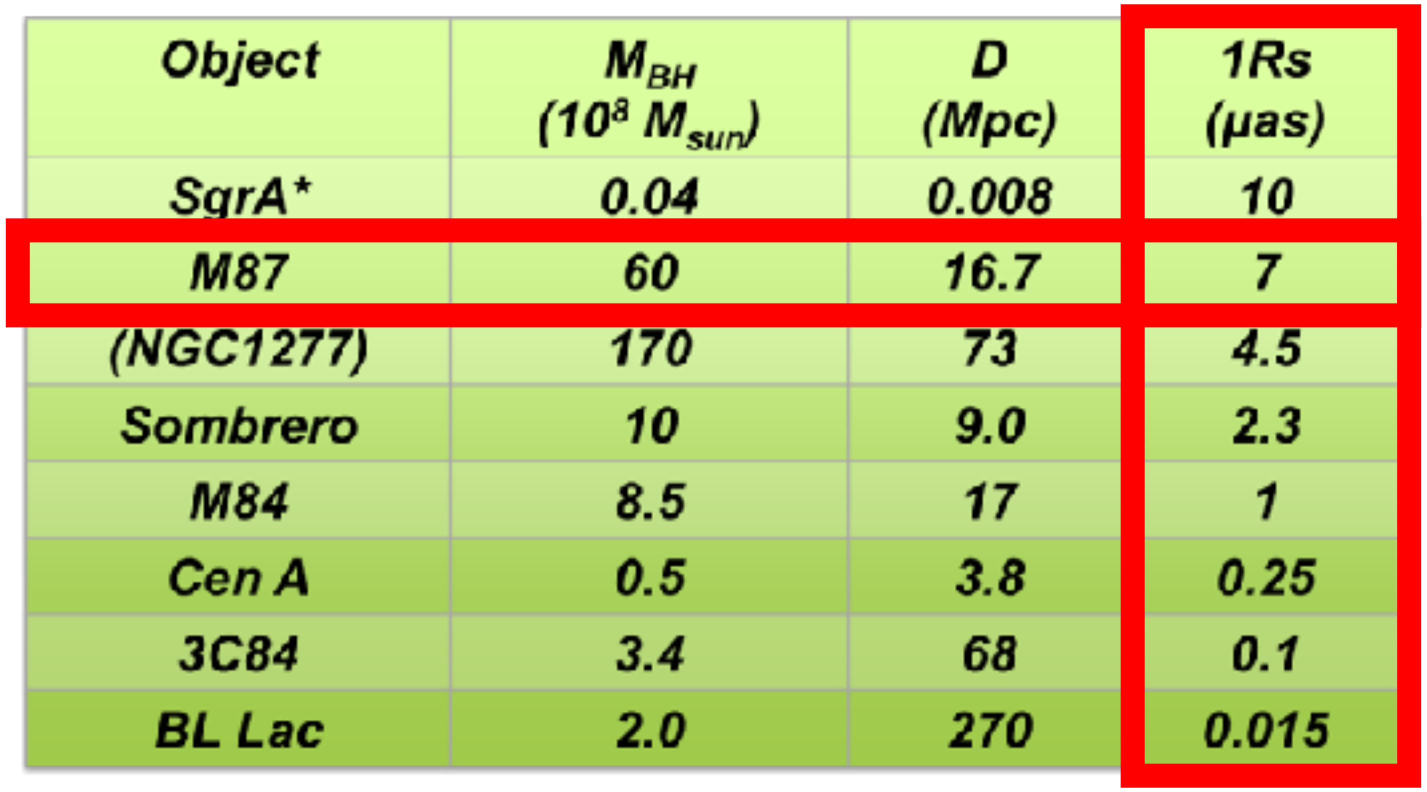
- Strong B-fields prevent plasma injection
- non-thermal injection model: photon-annihilation
- In simulations, density floor is set because of the numerical reason

→We compare the computed jet image with observation, and constrain the density distribution



M87 Jet





Object	M_{BH} (10^8 M_{sun})	D (Mpc)	1Rs (μas)
SgrA*	0.04	0.008	10
M87	60	16.7	7
(NGC1277)	170	73	4.5
Sombrero	10	9.0	2.3
M84	8.5	17	1
Cen A	0.5	3.8	0.25
3C84	3.4	68	0.1
BL Lac	2.0	270	0.015

Table from Hada's Slide

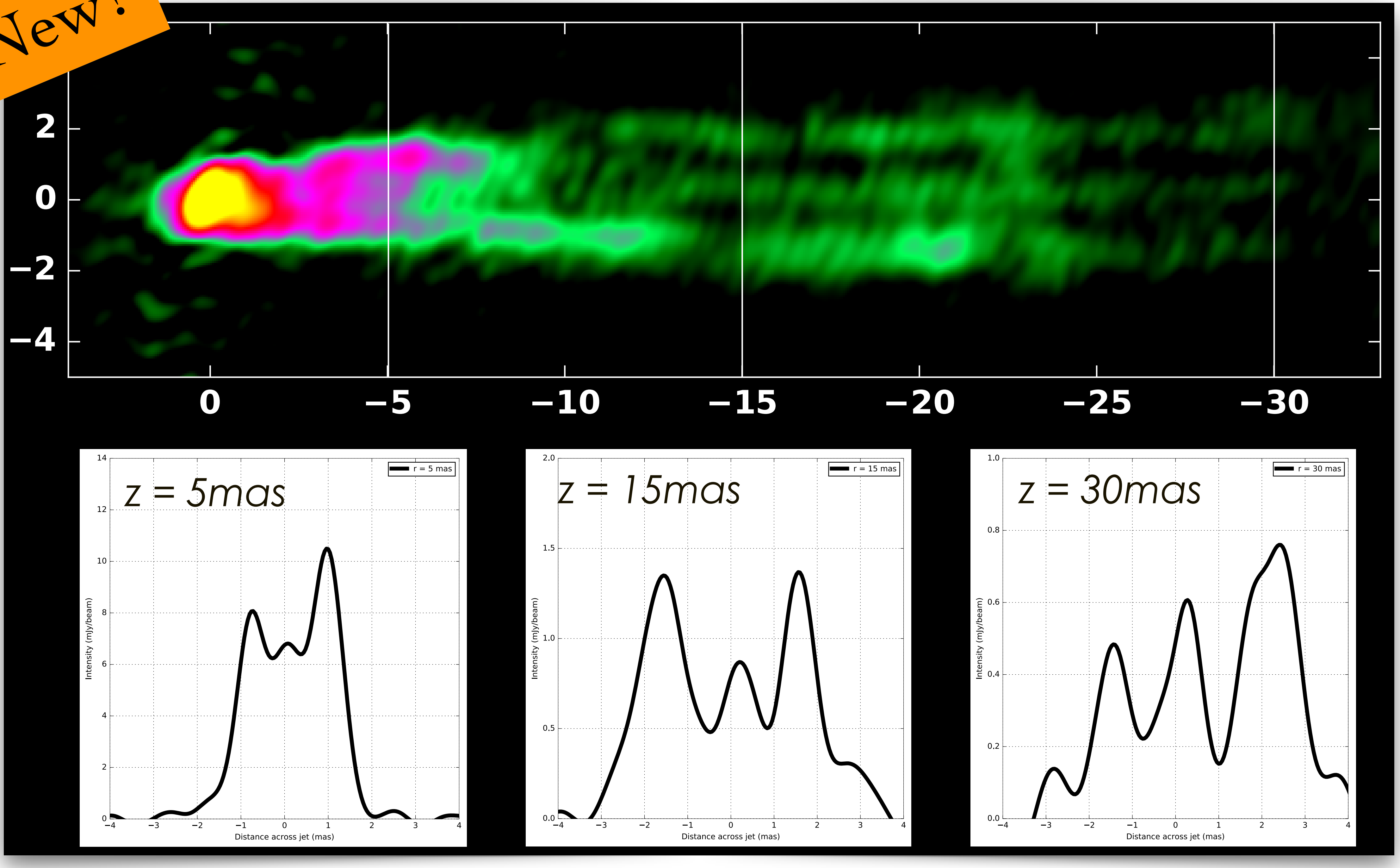
- distance: ~16Mpc
- jet length: ~100kpc
- BH mass: (3-6)x$10^9M_\odot$
- viewing angle: 10°-20°
- **second largest angular sized BH**
- one of the main targets of **Event Horizon Telescope**

Credit: Hotaka Shiokawa

←simulated image

Triple-Ridge Structure

New!

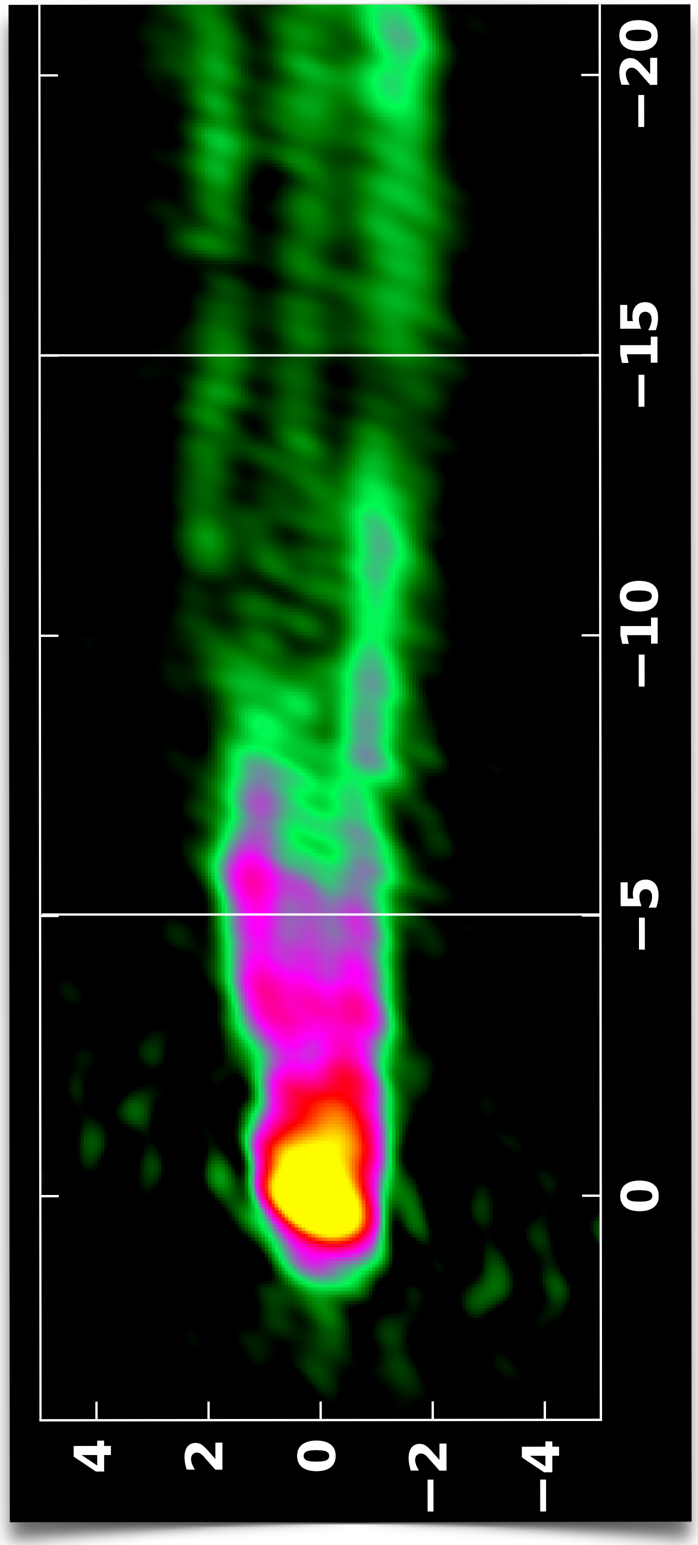


from Hada's slide(see Hada 2017)

Aims of This Study

1. Using a force-free model, we will **explain the triple-ridge structure.**

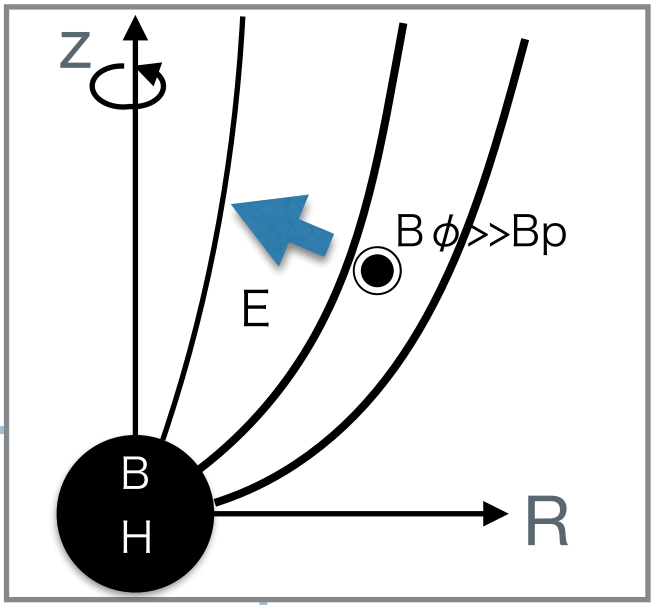
2. We will constrain the density distribution around the blackhole.



2. Method

Force-Free Electromagnetic fields

- steady, axi-symmetric force-free field
  (energy density: EM >> matter)



$$\rho_e \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B} = 0$$

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{B} = 4\pi \boldsymbol{j}$$

$$\nabla \times \boldsymbol{E} = 0$$

$$\int \boldsymbol{B} \cdot d\boldsymbol{S} = 2\pi\Psi$$

$$B_r = r^{\xi-2},$$

$$B_\theta = \frac{\xi\Psi}{r^2 \sin\theta},$$

$$B_\phi = -\frac{2\Omega_F \Psi}{R}$$

$$\boldsymbol{E} = -R\Omega_F \boldsymbol{e}_\phi \times \boldsymbol{B}$$

magnetic field flux

$$\Psi = r^\xi (1 - \cos\theta)$$

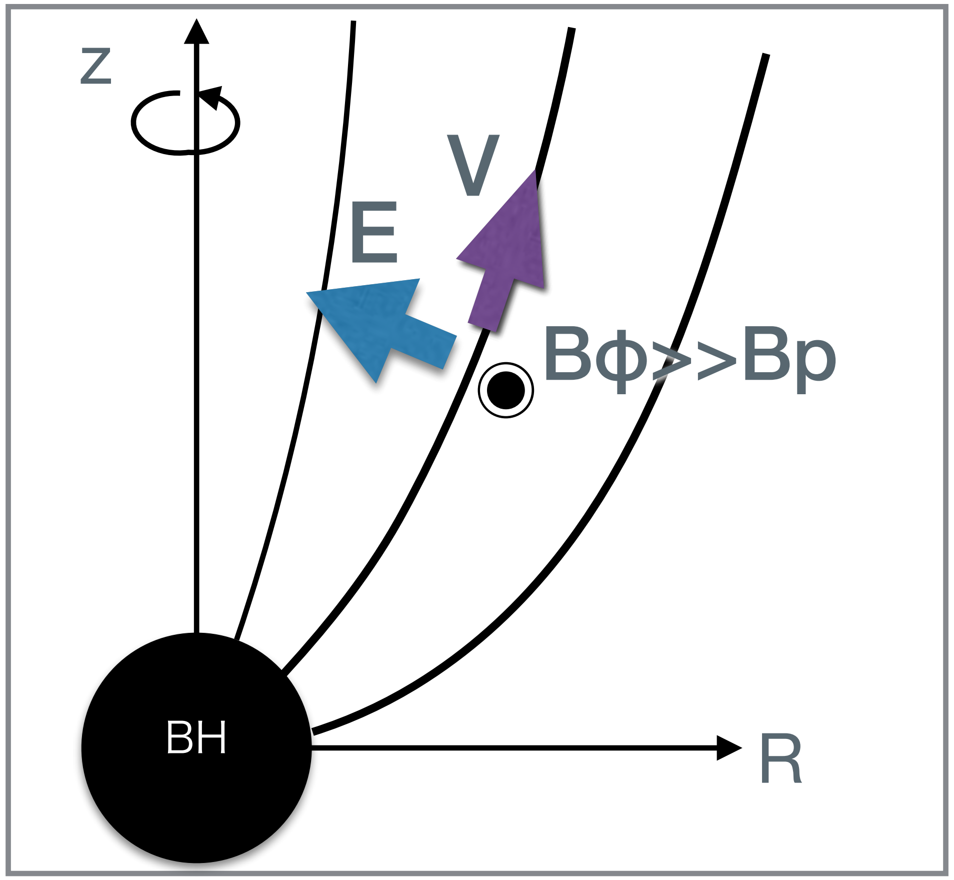
Tchekhovskoy et al. 2008

angular velocity of B-field

$$\Omega_F \sim \Omega_H / 2$$

Blandford & Znajek 1977

Velocity and density



- bulk velocity = drift velocity.

$$\boldsymbol{v} = c\frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2} = R\Omega_F \boldsymbol{e}_\phi - \frac{R\Omega_F B_\phi}{B^2}\boldsymbol{B}$$

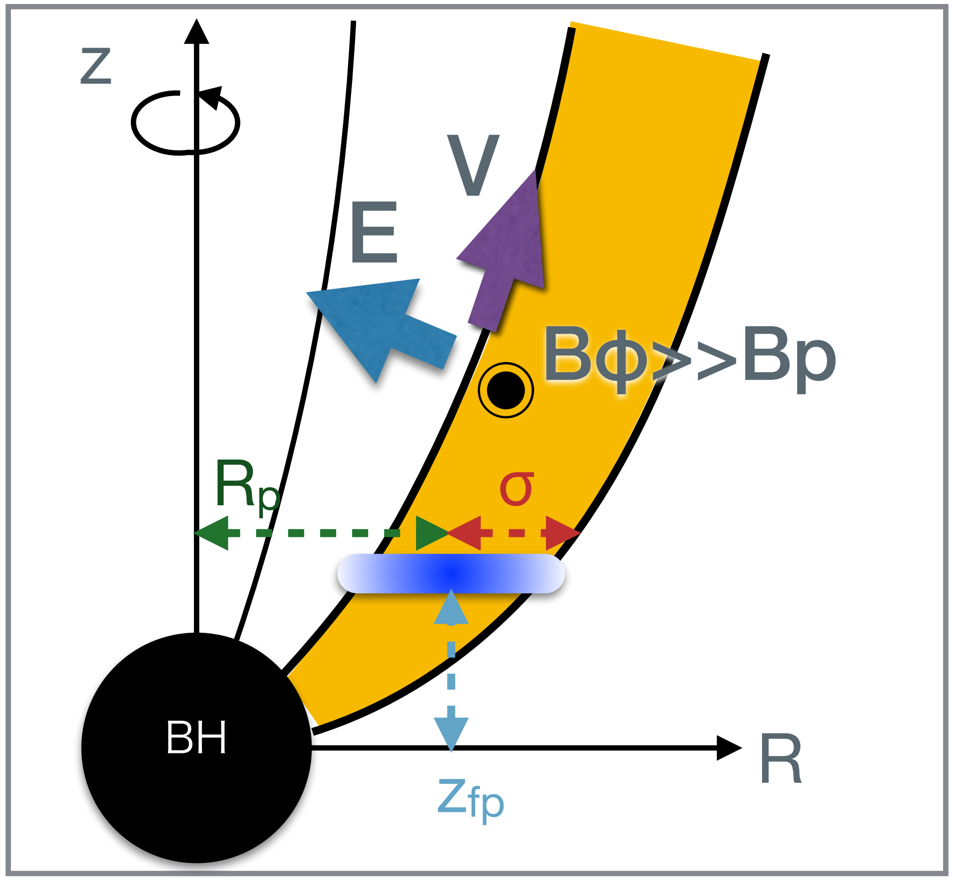
- number density

$$\nabla\cdot(n\boldsymbol{v}) = 0 \rightarrow n/B^2 = \text{const.}$$

along B-field

- we set density distribution at z=z_{fp}
  →obtain density at any point

Non-thermal electron distribution



- density distribution of the non-thermal electron

  at $z=z_{fp}$

$$n_{fp}(R, z_{fp}) = n_{0,fp} \exp\left(\frac{-(R-R_p)^2}{2\sigma^2}\right)$$

(Broderick & Loeb 2009,
K. Takahashi et al. 2018)

- electron's energy density: power-law

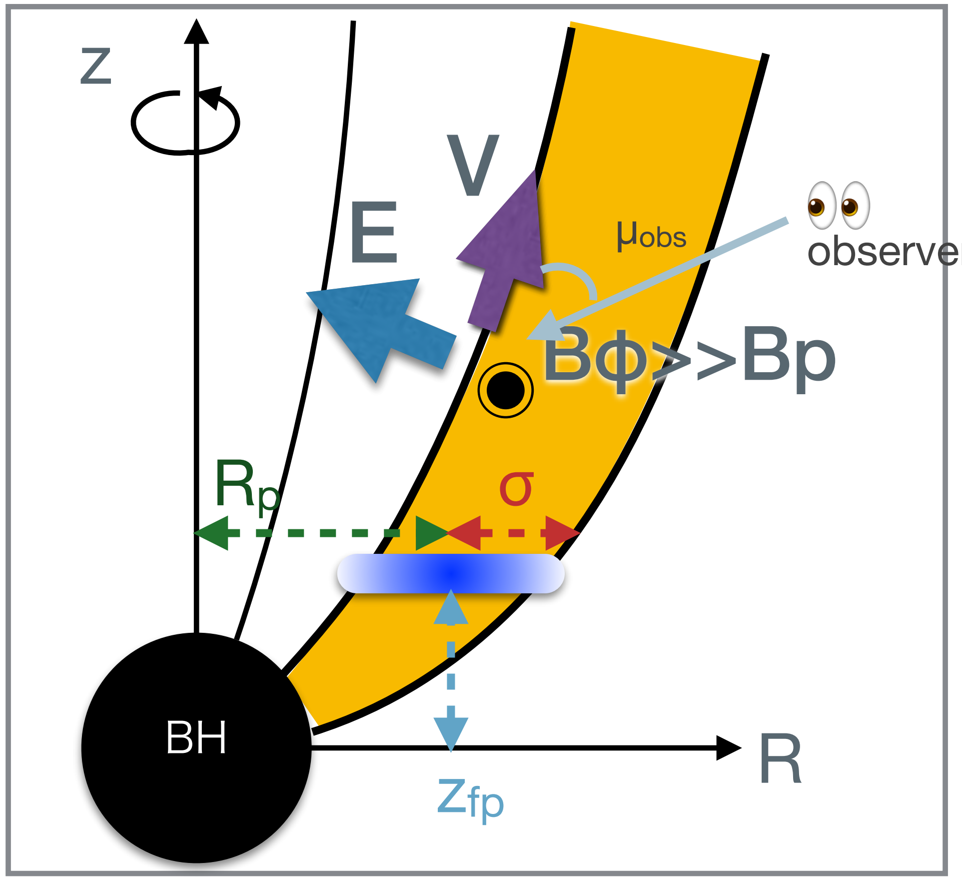
$$f(\gamma_e) = \frac{1}{4\pi} n_{co} \frac{p-1}{\gamma_m^{1-p}} \gamma_e^{-p}$$

$\gamma_m m_e c^2$: minimum energy

$\gamma_m=100$

$p=1.1$

Synchrotron Emission



- Synchrotron radiation in the comoving frame

$$j_{co}(\omega,\alpha) = \left(\frac{n_{co}}{4\pi}\frac{p-1}{\gamma_m^{1-p}}\right)\frac{\sqrt{3}q^3 B\sin\alpha}{2\pi m_e c^2(p+1)}\left(\frac{2m_e c\omega}{3qB_{co}\sin\alpha}\right)^{-\frac{p-1}{2}}$$
$$\times\Gamma\left(\frac{p}{4}+\frac{19}{12}\right)\Gamma\left(\frac{p}{4}-\frac{1}{12}\right)$$

- Lorentz transformation

$$j_{obs} = \frac{1}{\gamma^2(1-\beta\mu_{obs})^3}j_{co}$$

- Intensity

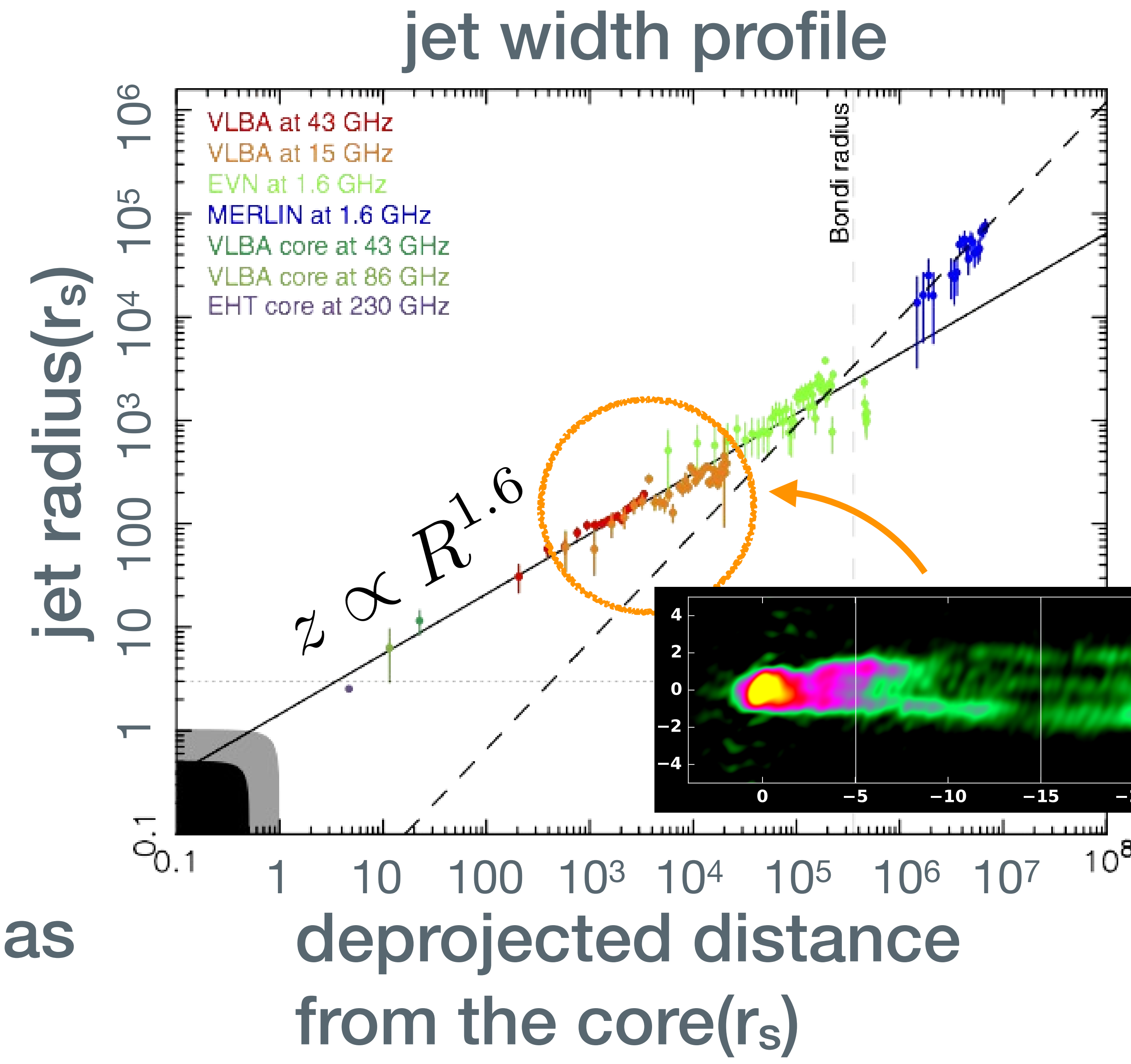
$$I_{obs} = \int j_{obs}ds$$:optically thin

- Convolution with Gaussian beam

$$I(x,y) = \int\int I(x',y')\exp\left[-\frac{(x-x')^2}{2A_x^2}\right]\exp\left[-\frac{(y-y')^2}{2A_y^2}\right]dx'dy'$$

Parameter Set-up

- D = 16.7Mpc
- $M_{BH} = 6.6 \times 10^9 M_\odot$
- $\theta_{view} = 15°$
- BH spin: a = 0.998
- $\Omega_F = 0.5\Omega_H = ac/4r_+$
- ξ = 0.75 (from jet width profile)
- ν = 15GHz (Hada 2017 obs.)
- beam size = 1.14mas x 0.55 mas



3. Results

4. Discussion & Summary

Are the Assumptions Correct?

- steady, axi-symmetric condition
  →no blobs in our jet
- force-free condition
  →invalid in the kinetic-energy dominated (far) region
- energy distribution = const.
  →shock heating, radiative loss, dissipation, and etc…
- triple-ridge structure in other jet?
  →wait for future observations

Summary

- We have shown that the observed triple-ridge jet structure can be explained by the steady axi-symmetric force-free model.

- We have to consider complicated density distributions to fit to the observed triple-ridge.
  →inner ridge: photon injection?
  +outer ridges: reconnection?

- We have to compare the jet dynamics with GRMHD simulations.