# 3D precessing jet simulations for radio galaxy Hydra A

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# AGN-ICM INTERACTION

Aims of this study:

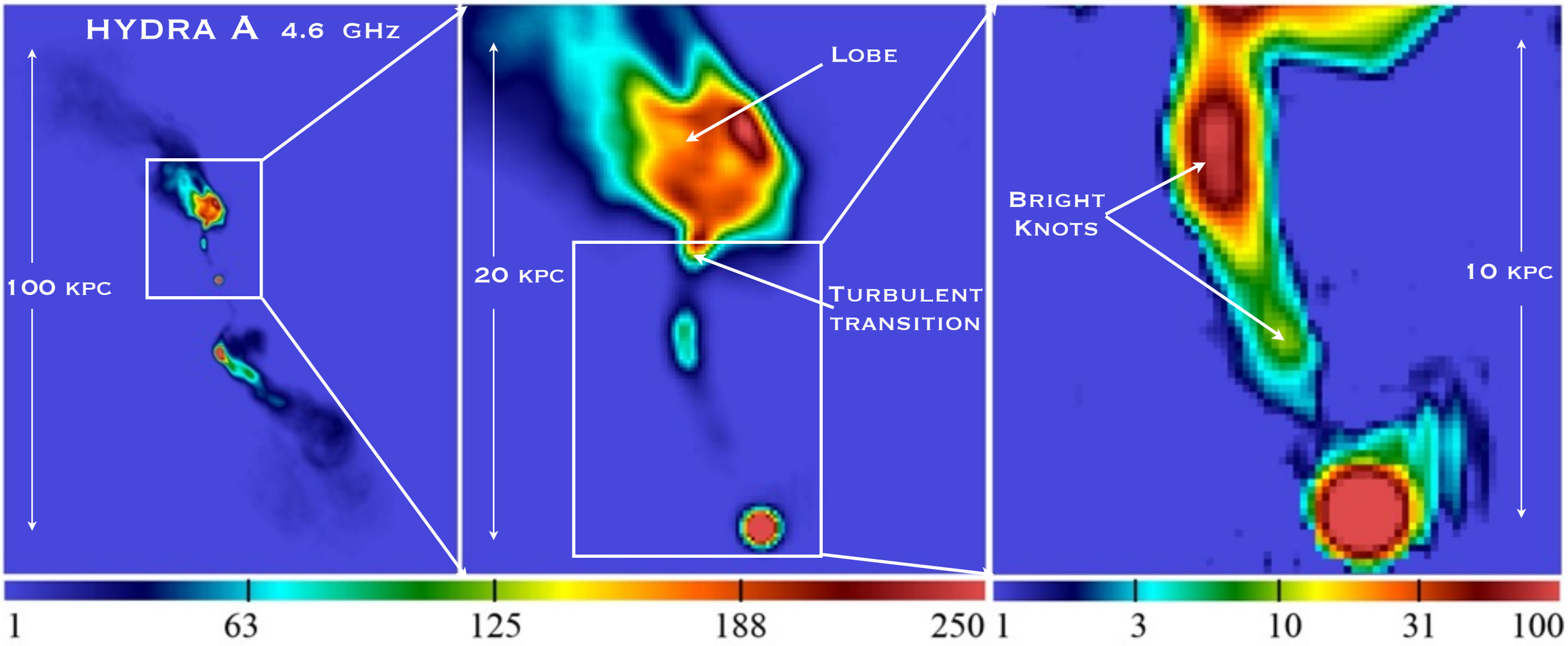
1. Understand the jet energetics and jet components

3. Estimate jet velocity

4. Complex source morphologies

5. Heating of the ICM

# Hydra A: Radio morphology

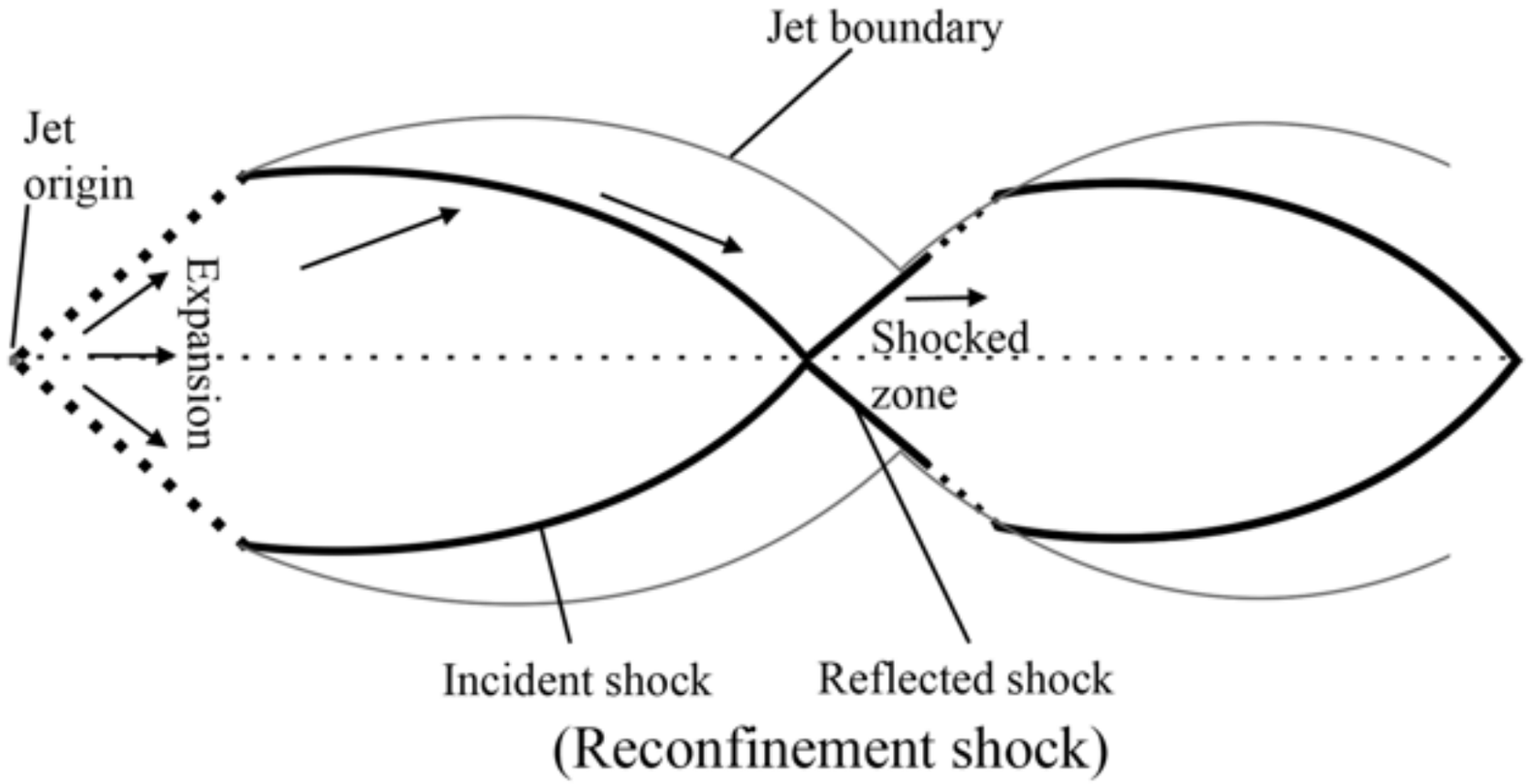



- Four bright knots
- Jet boundary oscillation
- Curved jet
- Turbulent transition

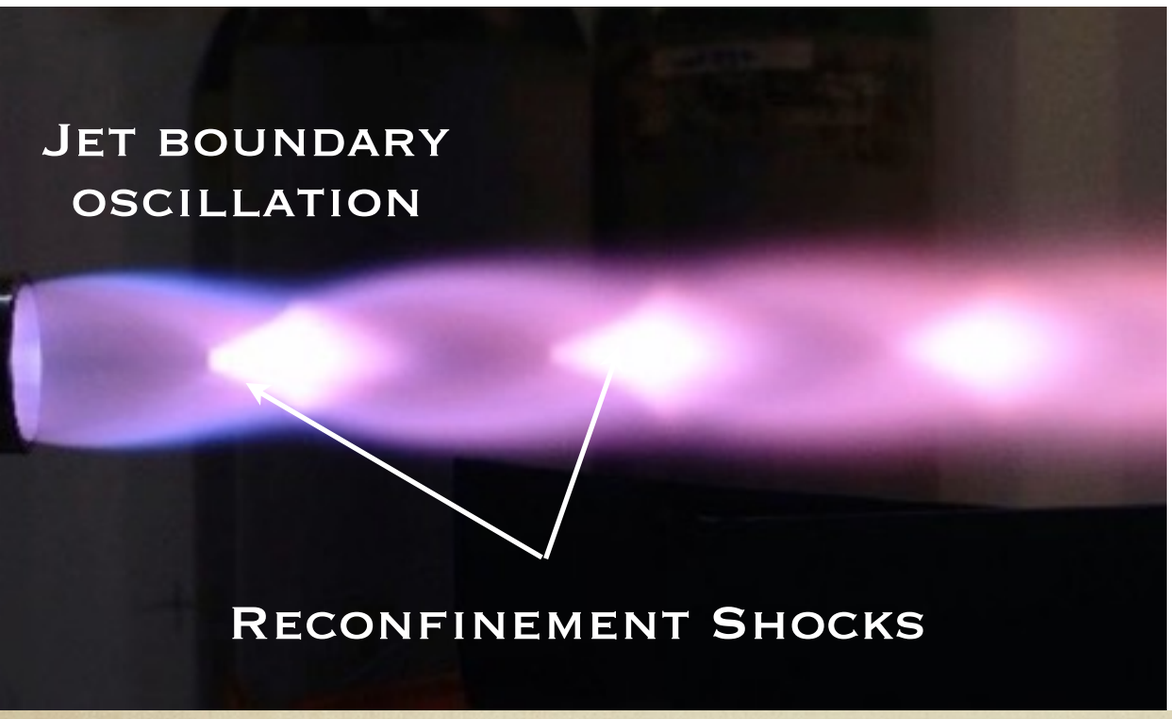
Reconfinement shocks?

Jet Precession?

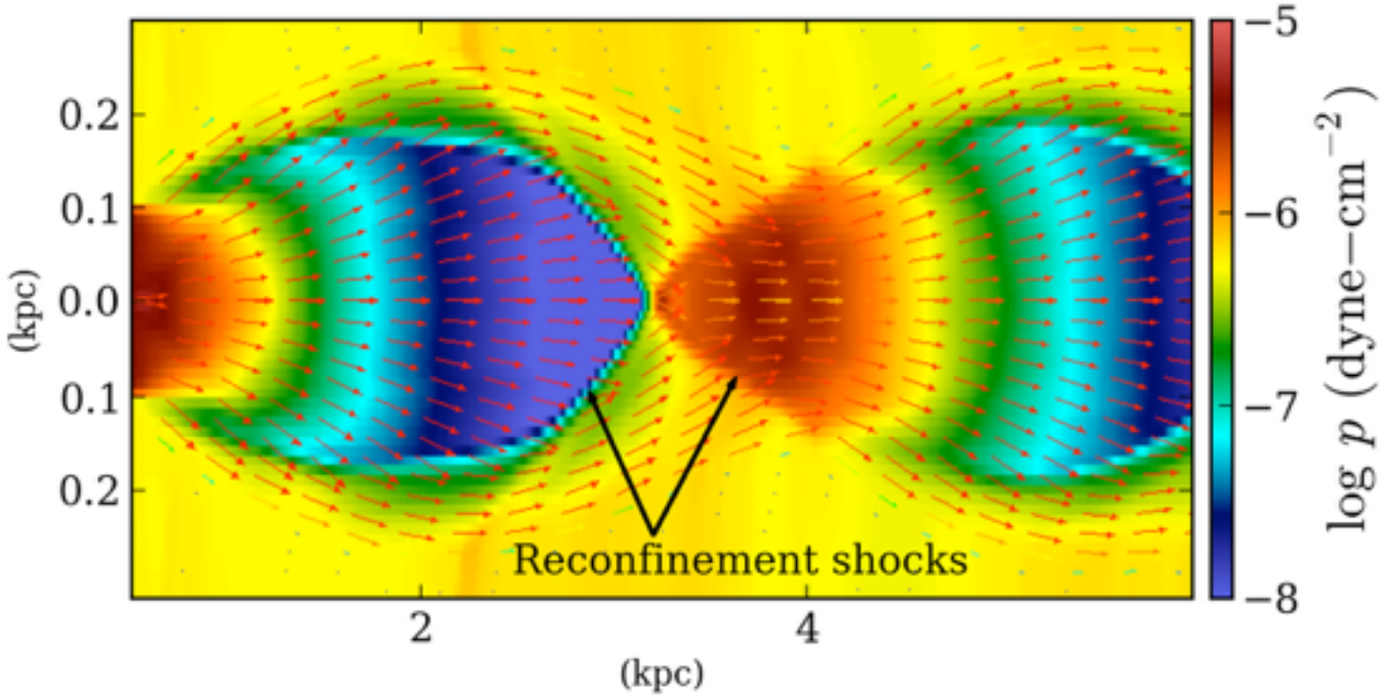
# Reconfinement shocks




- Reconfinement shocks in laboratory jets: (Mach, 1890)
- Astrophysical jet knots are reconfinement shocks. (Norman et al., 1982)




Laboratory jet




Simulated jet

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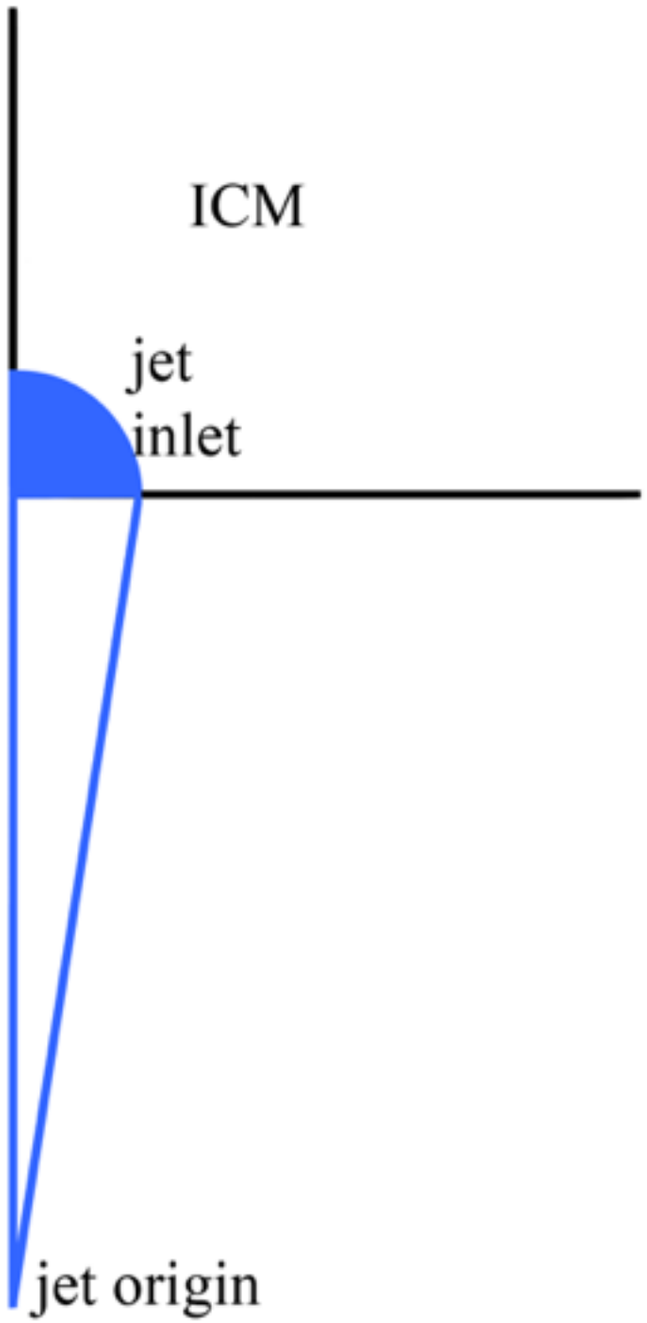
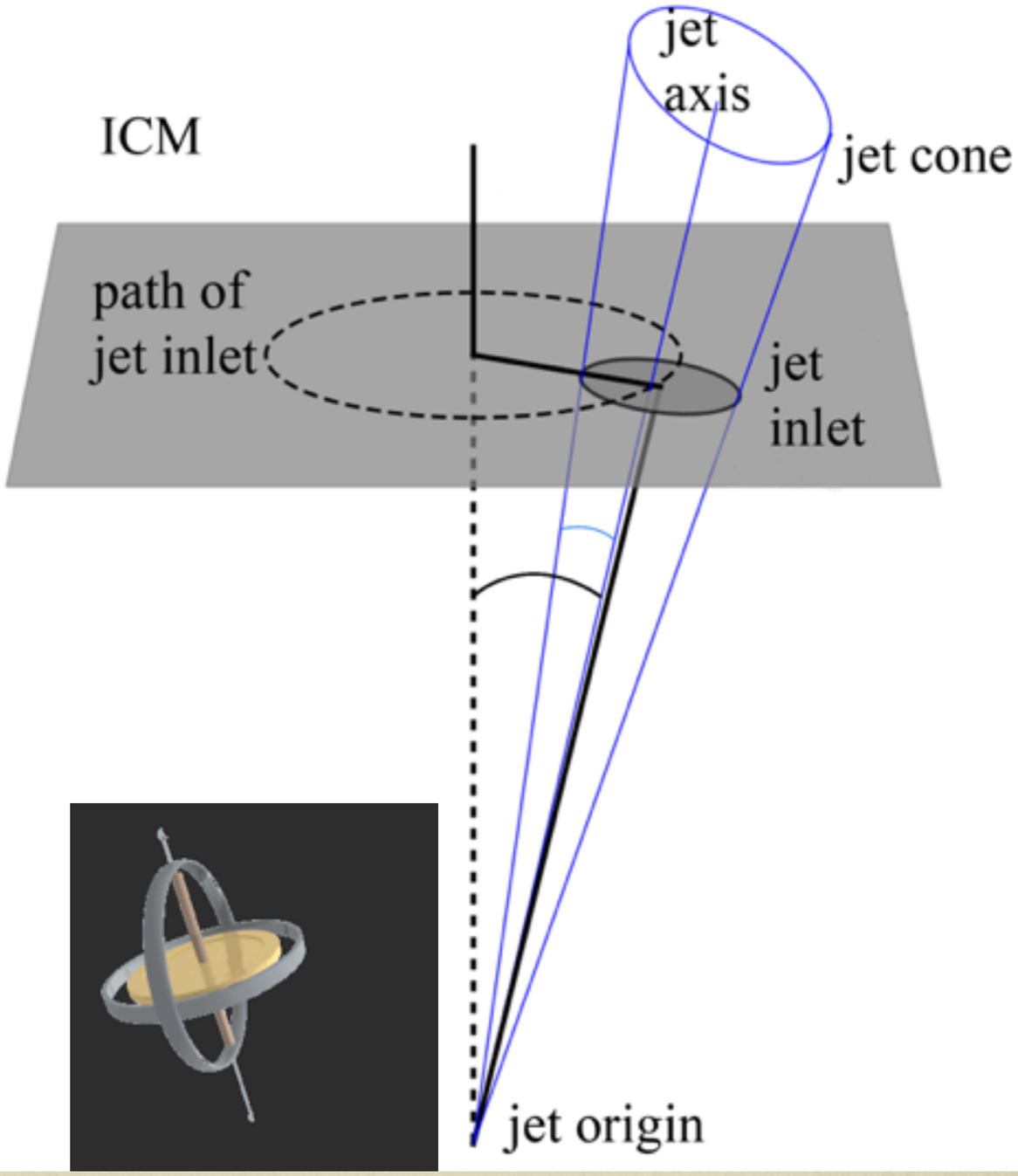
# Model setup

## Axisymmetric model
for inner 10 kpc




## 3D precessing jet model
for inner 30 kpc




code: PLUTO

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# Model setup

## Jet parameters

Power

Pressure

Lorentz factor

Velocity

Jet inlet radius

Density parameter

$$P_{\rm jet} = \frac{\gamma}{\gamma - 1} c \left(p_{\rm jet}\right) \Gamma_{\rm jet}^2 \left(\beta_{\rm jet}\right) \pi \left(r_{\rm jet}^2\right) \left[1 + \frac{\Gamma_{\rm jet} - 1}{\Gamma_{\rm jet}} \chi_{\rm jet}\right]$$

(Bicknell 1995)

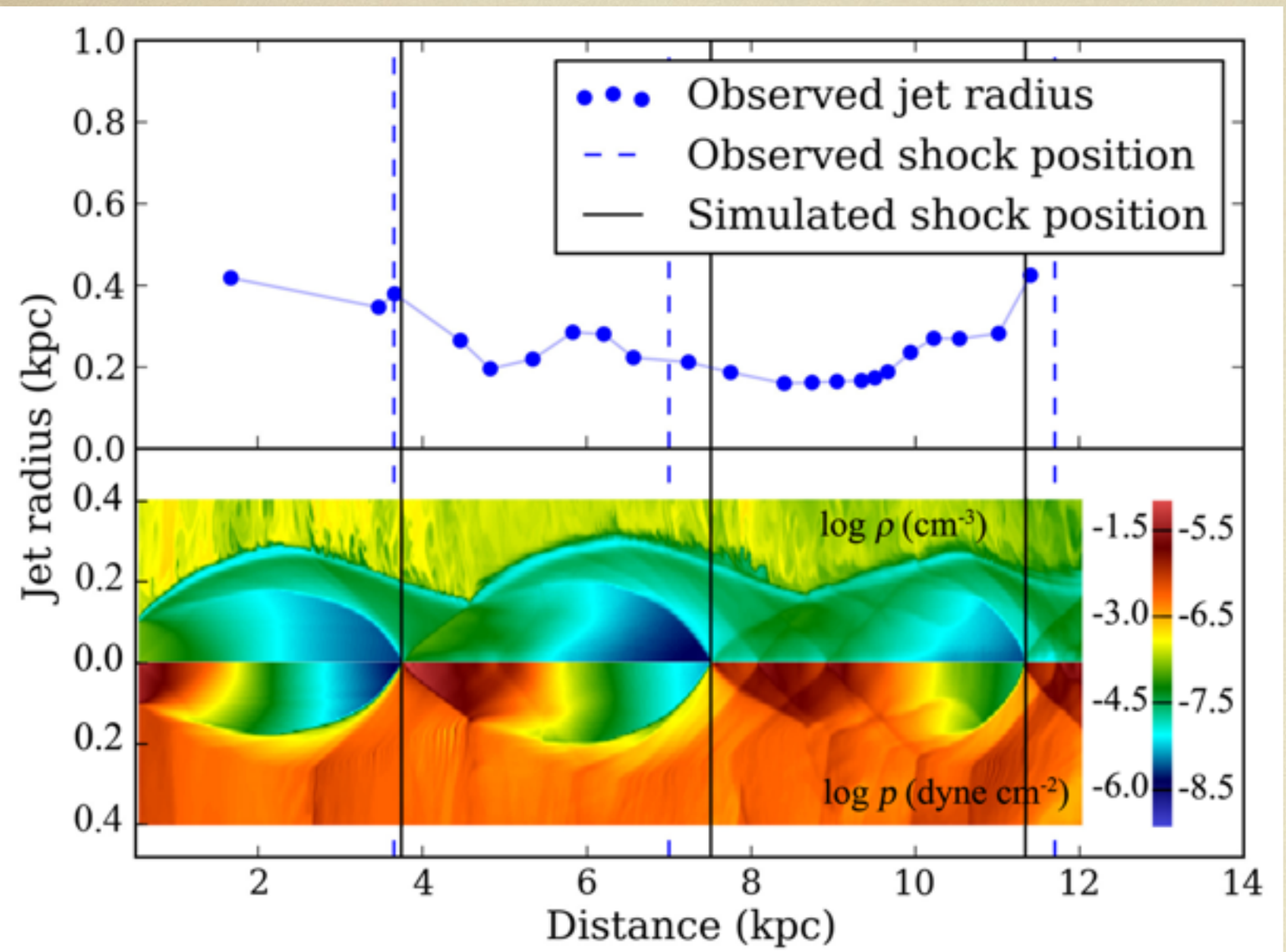
$$\chi_{\rm jet} = \frac{\rho_{\rm jet}\, c^2}{(\varepsilon_{\rm jet} + p_{\rm jet})}$$

Internal energy density

## Intracluster medium

Atmosphere model based on the X-ray data presented in David et al. 2001

# Axisymmetric Model




## Jet velocity from knot location

Natural wavelength of non-relativistic supersonic flow

$$\Lambda / r = 2.6 \sqrt{(M^2 - 1)}$$

Inlet radius

Flow Mach number

(Birkhoff & Zaranantonello 1957)

## Jet composition

Electron-positron jet: $\gamma_1 \sim 1$

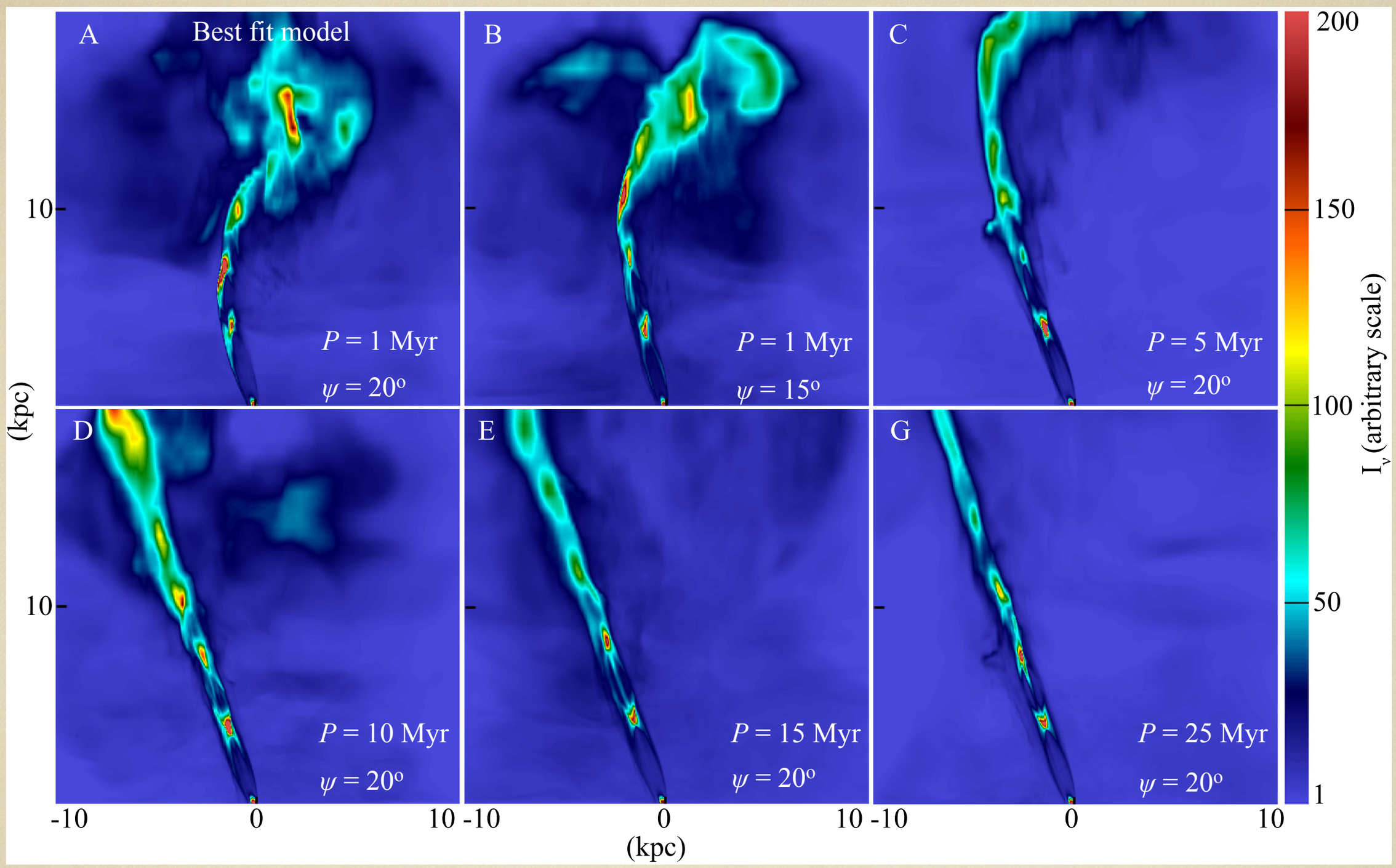
Electron-proton jet: $\gamma_1 \sim 700$

## Best fit values

$$\beta_{\rm jet} = 0.8$$

$$\chi_{\rm jet} = 13$$

# Precessing Jet: Curvature




Best fit parameters

Precession period, $P = 1$ Myr

Precession angle, $\psi = 20^{o}$

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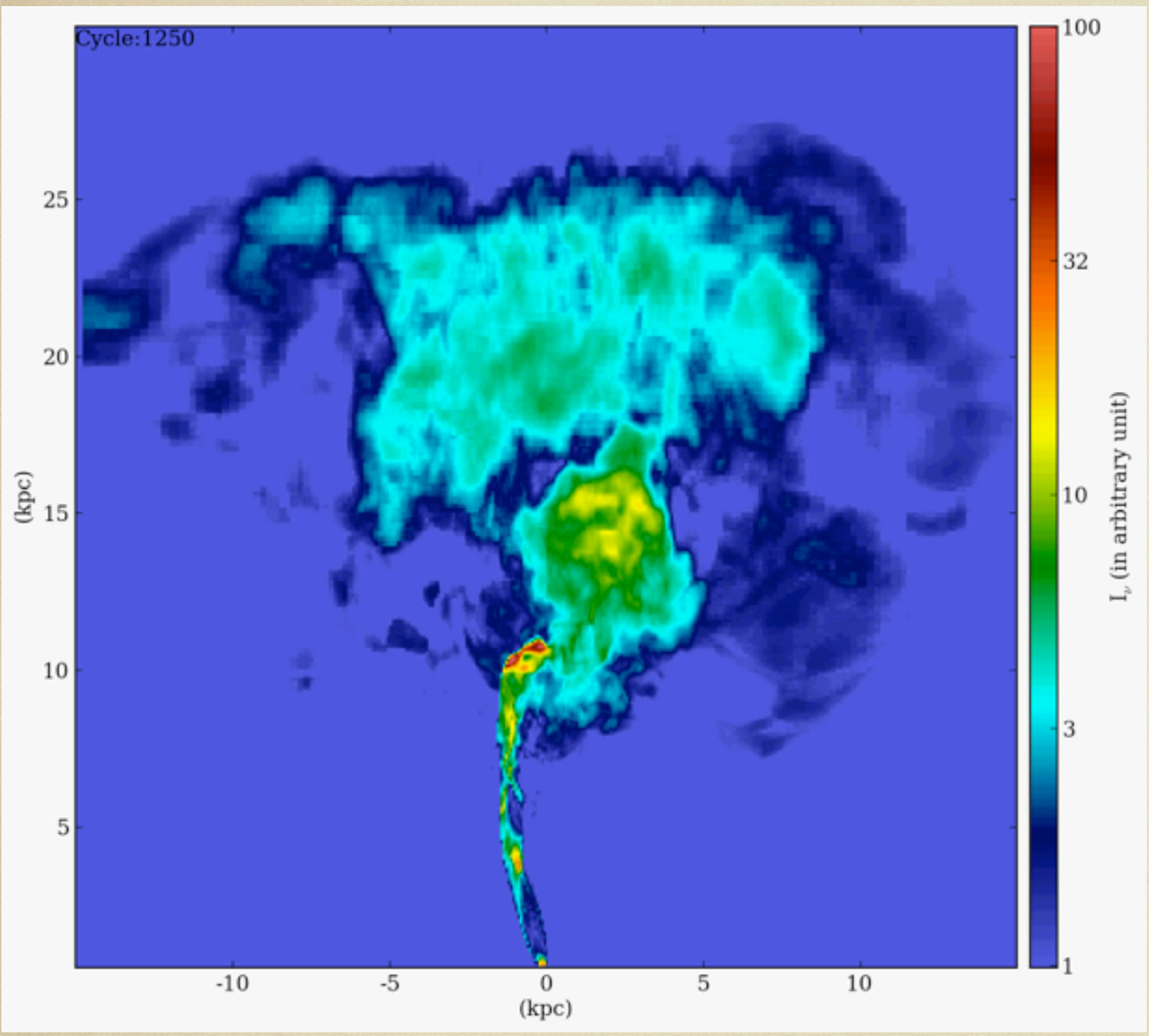
# Evolution of synthetic radio source




Jet parameters:

$P_{jet} = 10^{45}$ ergs/s

$\beta_{jet} = 0.8$

$p_{jet}/p_a = 5$

$\chi_{jet} = 13$

ICM:
Modelled from the X-ray data of David et al. 2001

Grid resolution:
456 x 456 x 456
11 cells across the jet

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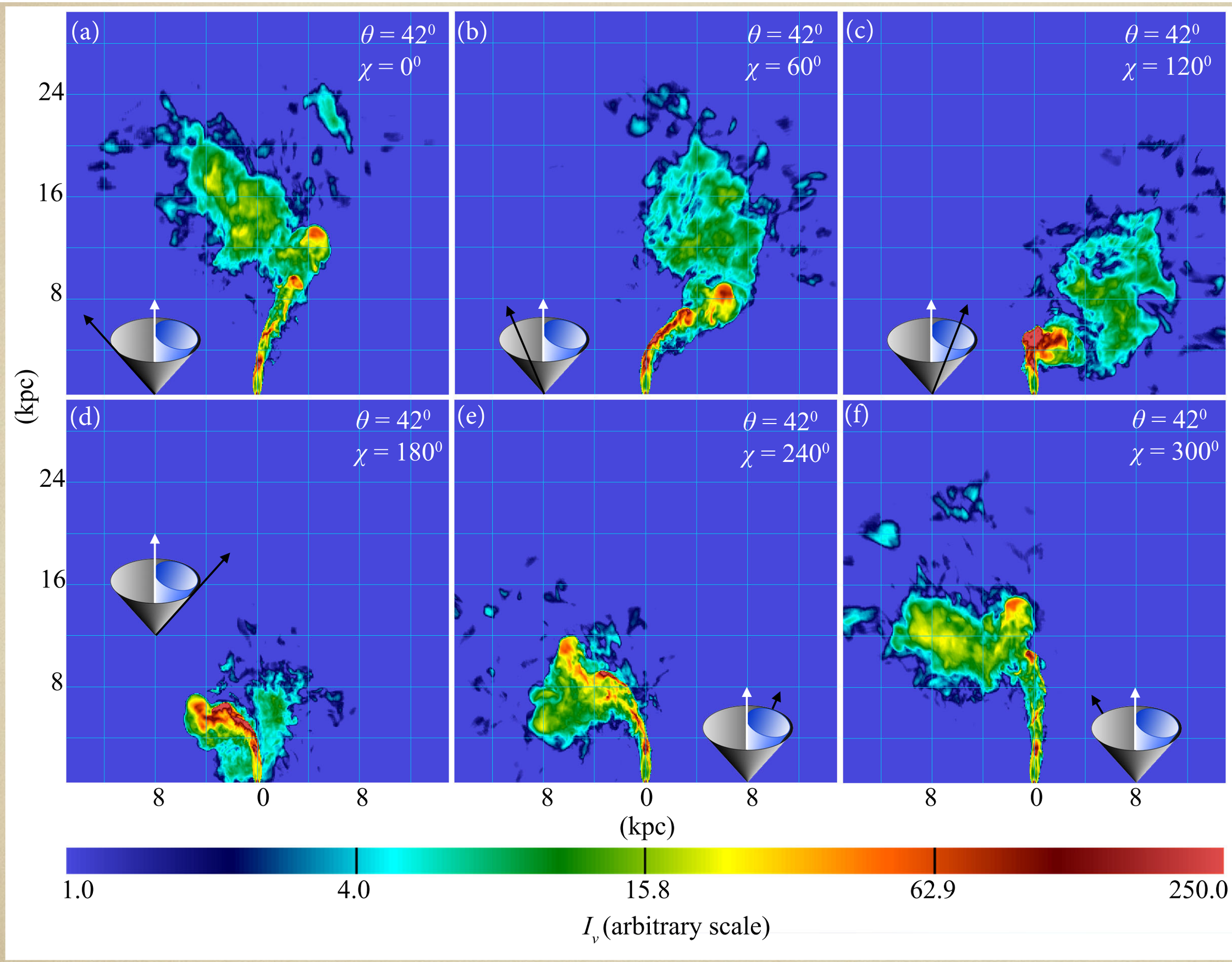
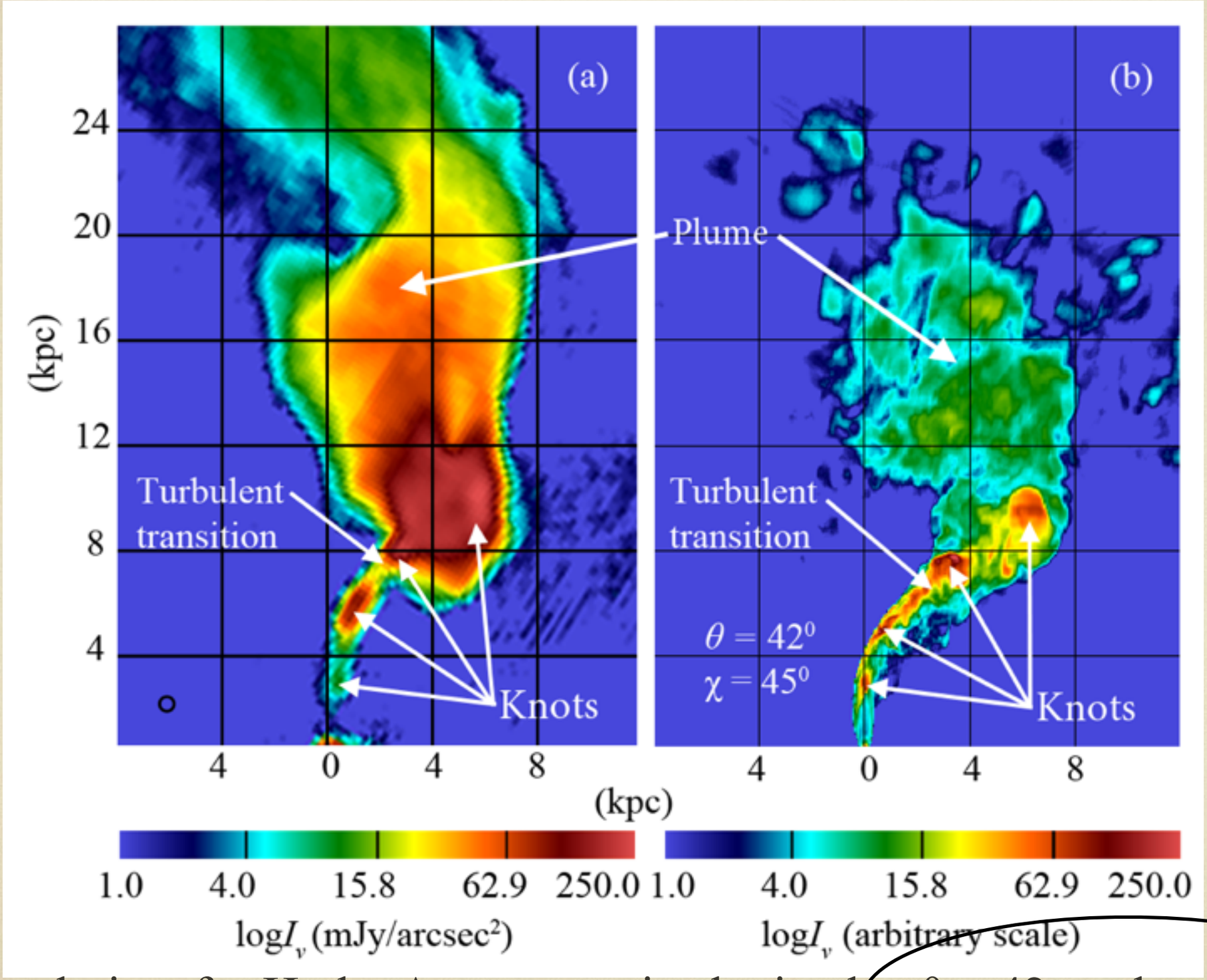
# Complex source morphology



# Precessing Jet: Radio morphology

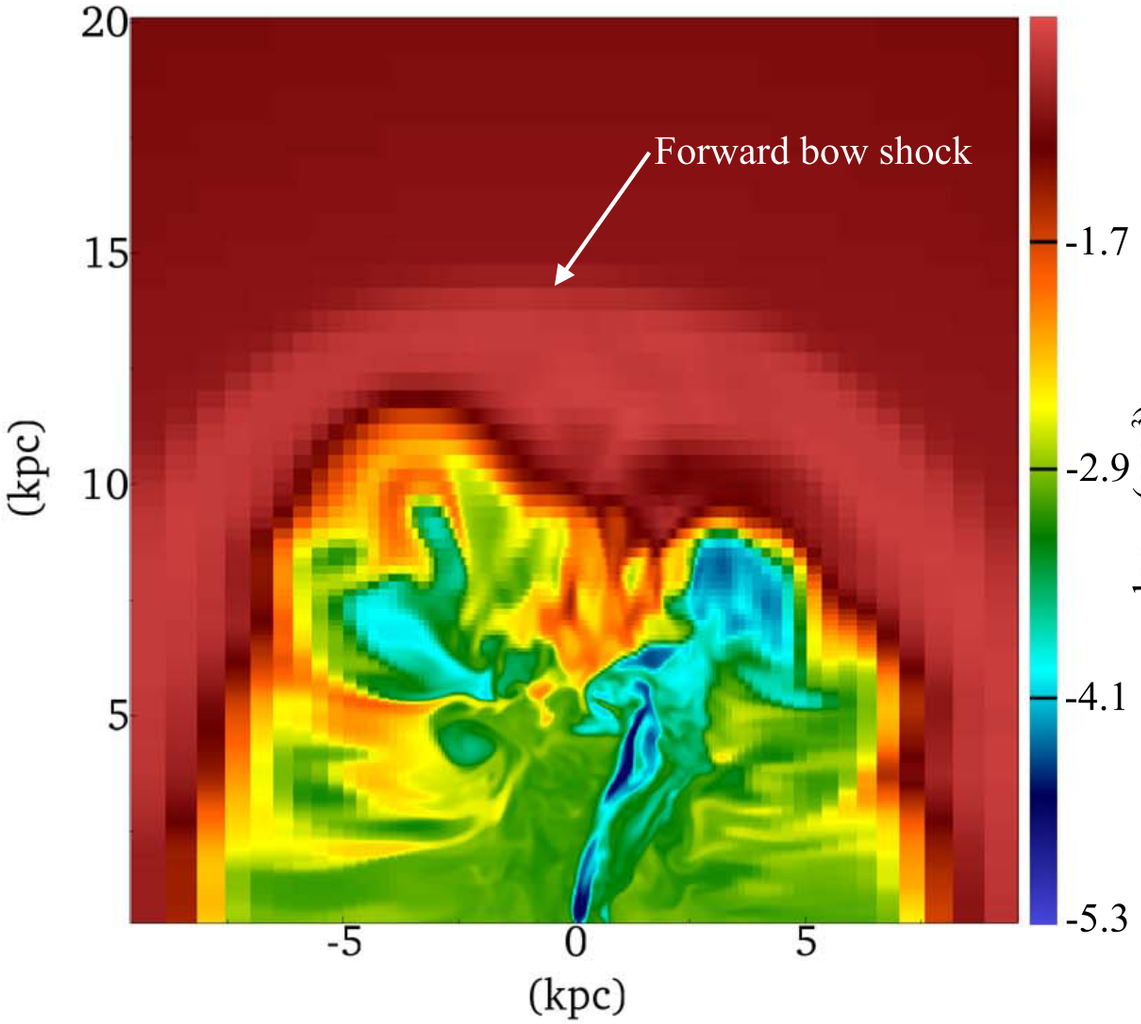
Hydra A northern jet

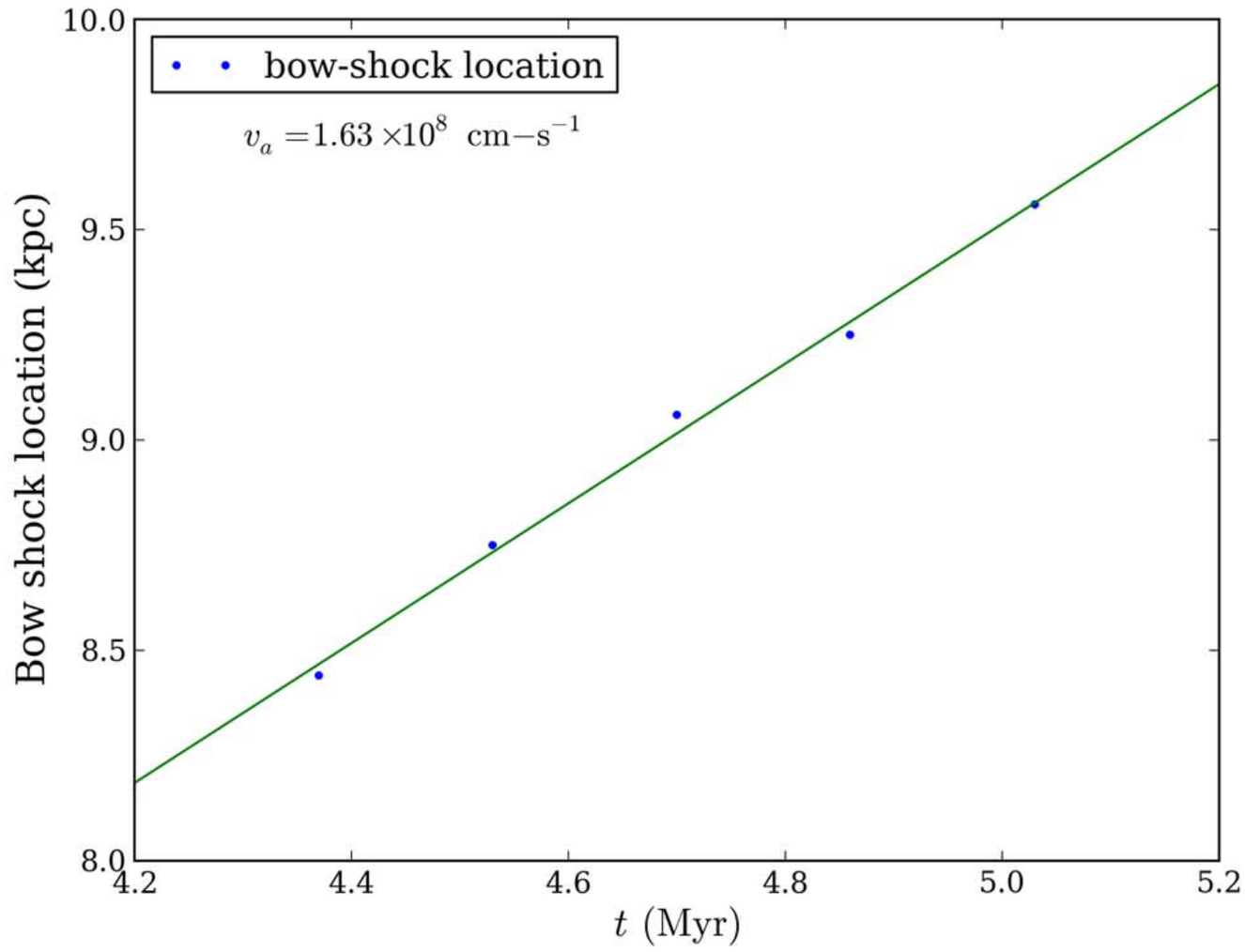
Simulated jet




Optimal view for Hydra A moments is obtained at $\theta = 42^o$ and $\chi = 45^o$ which gives $\omega = 12.5^o$

# Heating of the atmosphere

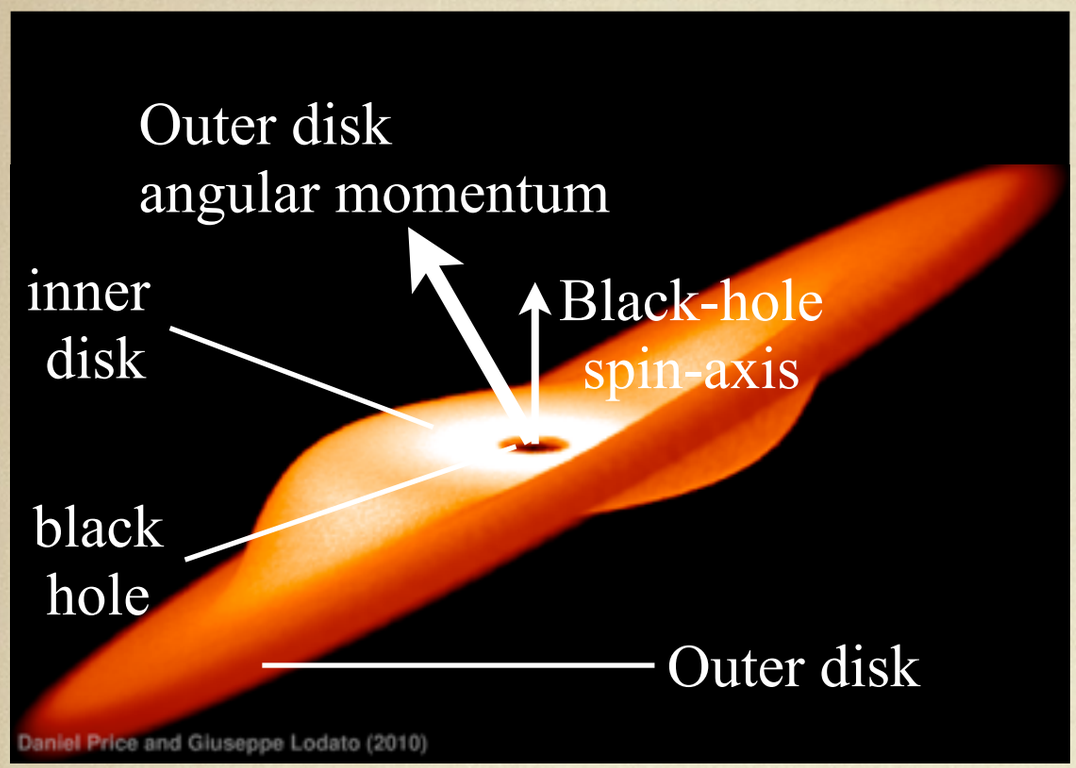



M = 1.85; Pressure jump across shock: 3.4

McNamara et al. 2012 -> Gentle heating

# Jet precession period: Theoretical Time scale




$$t_{\rm align} = 5.6 \times 10^5 a^{1/16} \left(\alpha/0.03\right)^{13/8} \times \left(L/(0.1 L_{\rm E})\right)^{-7/8} M_8^{-1/16} \left(\epsilon/0.3\right)^{7/8} yr$$

(Natarajan & Pringle 1998)

Using Natarajan& Pringle 1998 formula :

$$t_{\rm p} \approx 1.5 \times 10^6 \; a^{2/3} \left(\frac{\alpha}{0.03}\right)^{5/3} \left(\frac{h/r}{0.01}\right)^{2/3} \left(\frac{\epsilon}{0.1}\right) \left(\frac{M_9}{P_{\rm jet,45}}\right) \; \rm yr$$

- $t_{\rm p}$: Precession time-scale
- $a$: Black hole spin parameter
- $\alpha$: Accretion disk paramater
- $h/r$: Disk height at radius $r$
- $\epsilon$: Efficiency parameter
- $M_9$: Black hole mass

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# Summary

1. Bright knots of Hydra A are Reconfinement shocks.

2. Jet Velocity from the spacing of the bright knots and oscillation in the jet radius:

$$\beta = 0.8c$$

(First time used in extragalactic jets)

3. Complex radio morphology is reproduced:
   Jet Precession~1Myr period and 20° precession angle.

4. Gentle Heating of the ICM

5. Theoretical precession time-scale
   of Hydra A jets: 1Myr

# Thank You