Evolution of Jets in a Clumpy Environment

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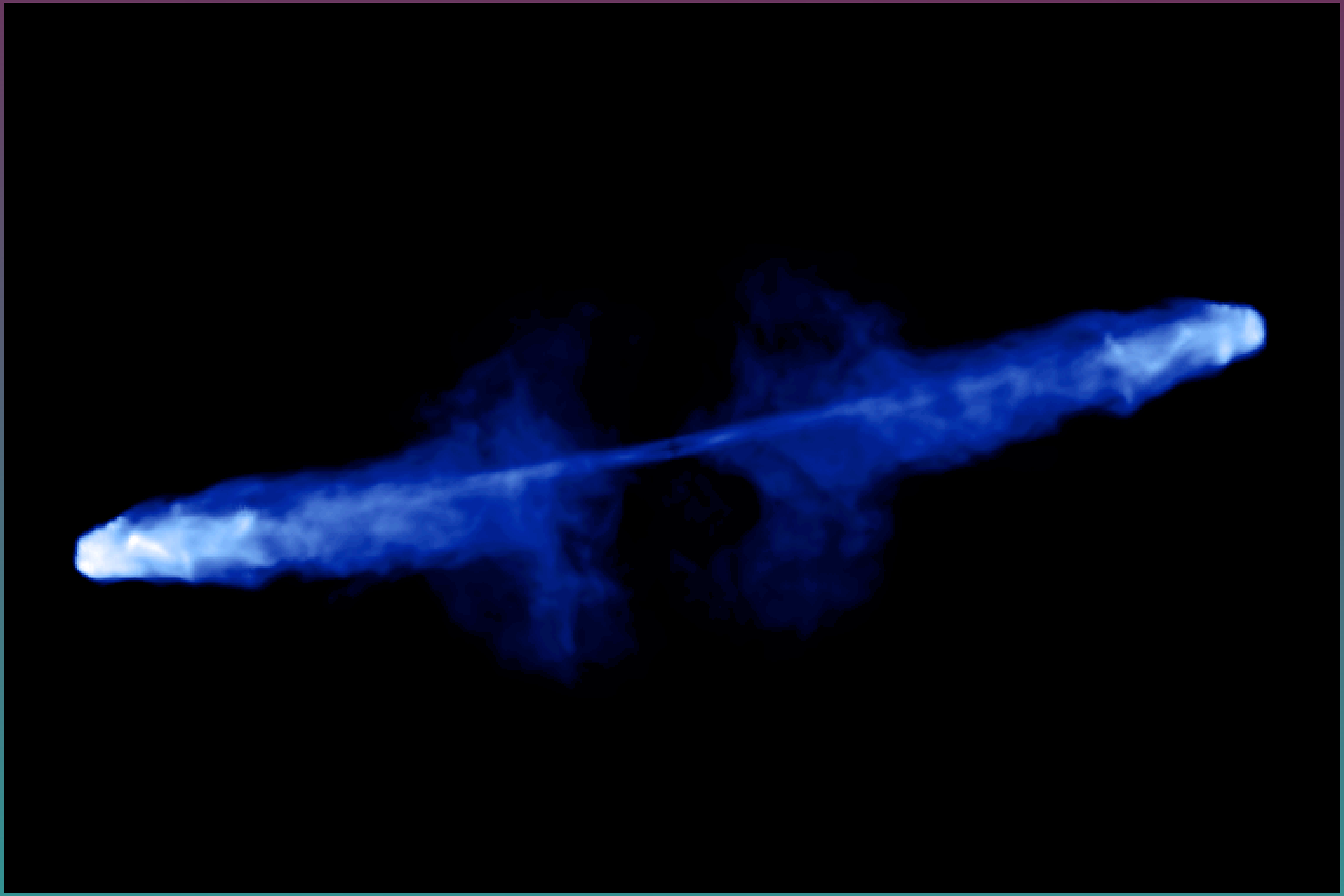
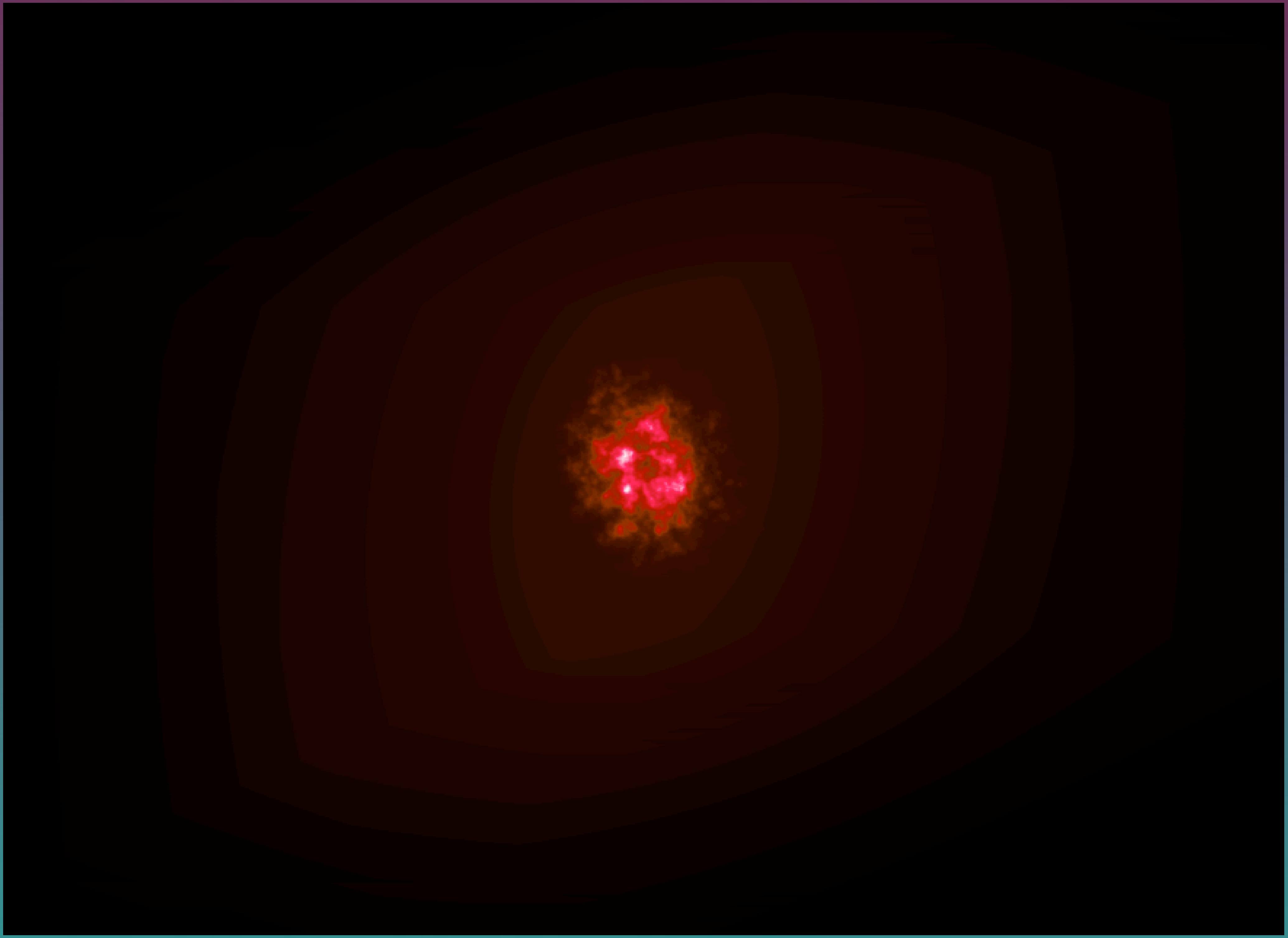
Supersonic jet in inhomogeneous medium

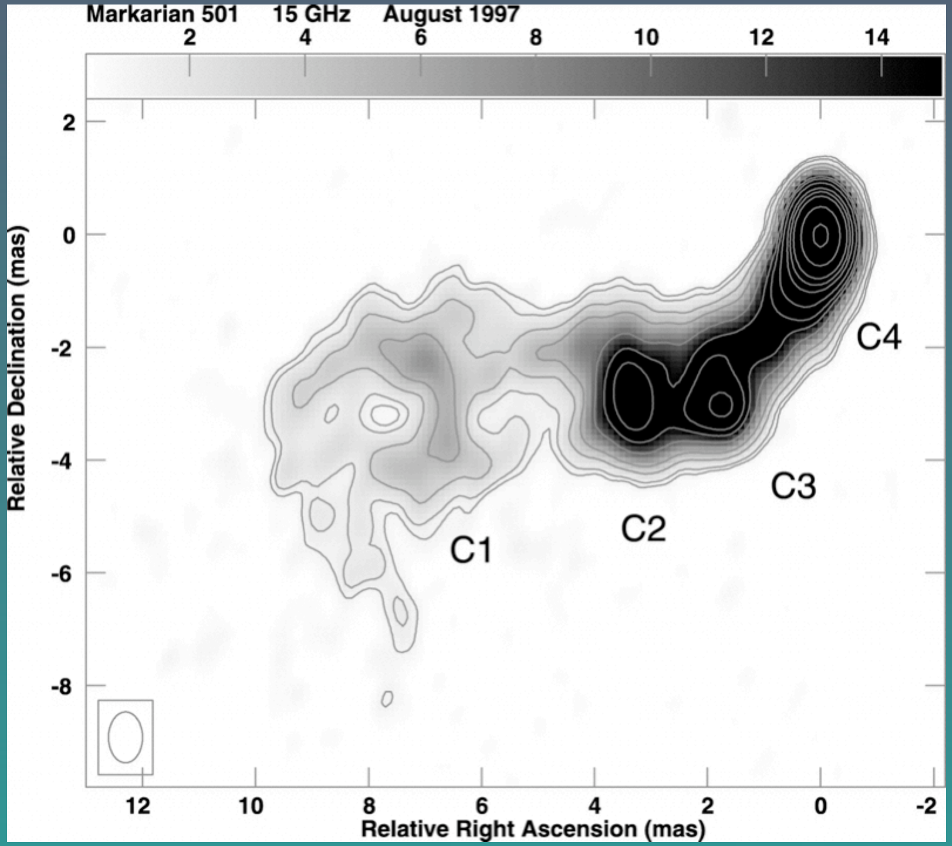


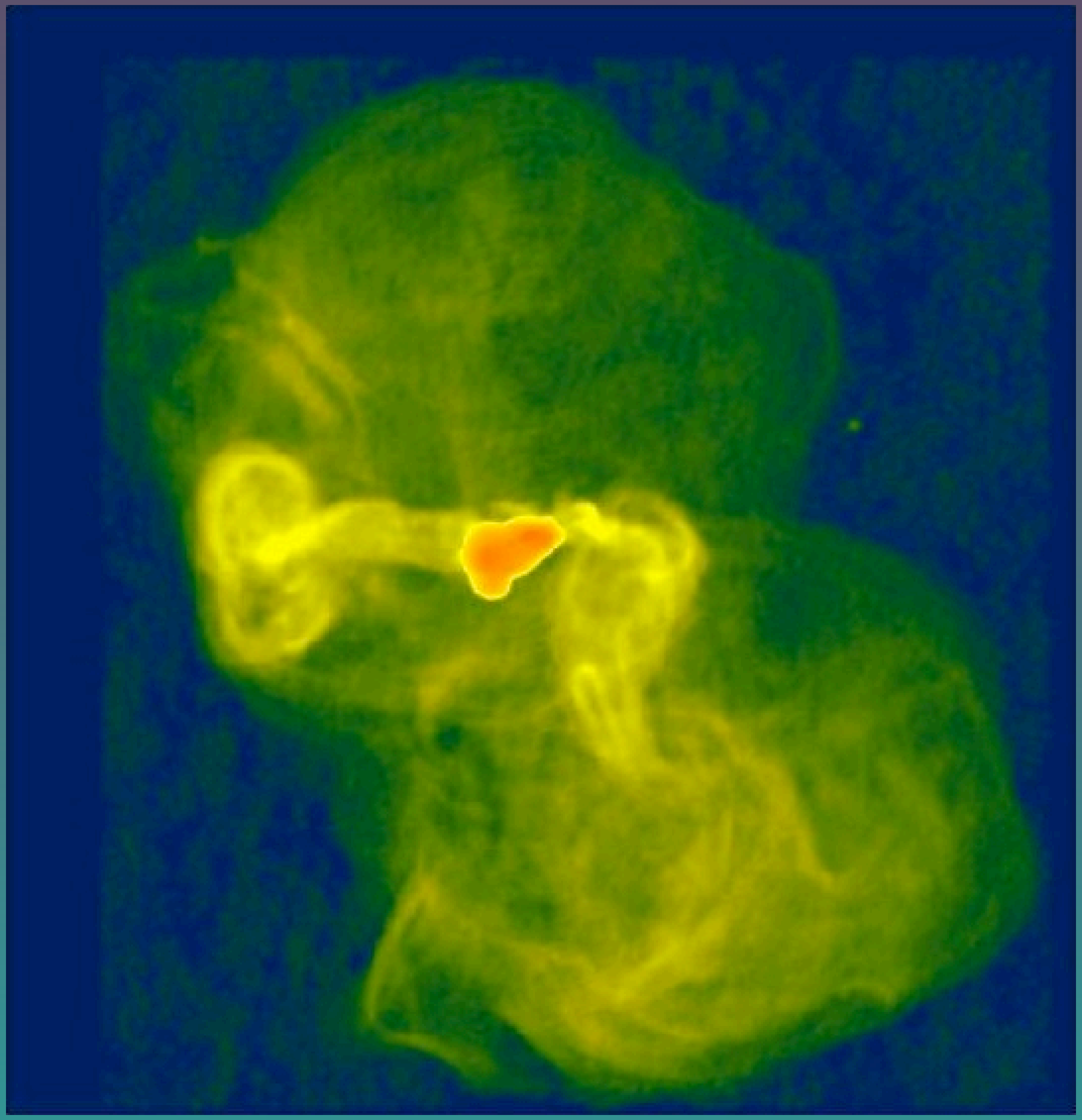
An emerging radio galaxy in X-rays



Background & motivation

- GPS and CSS sources - clear evidence for interaction with environment
- High redshift radio galaxies – jet-cloud interactions e.g. 4C41.17
- Numerous radio galaxies bear the imprint of jet/clumpy medium interactions (M87, Cen A, MKN 421, MKN 501, ...)

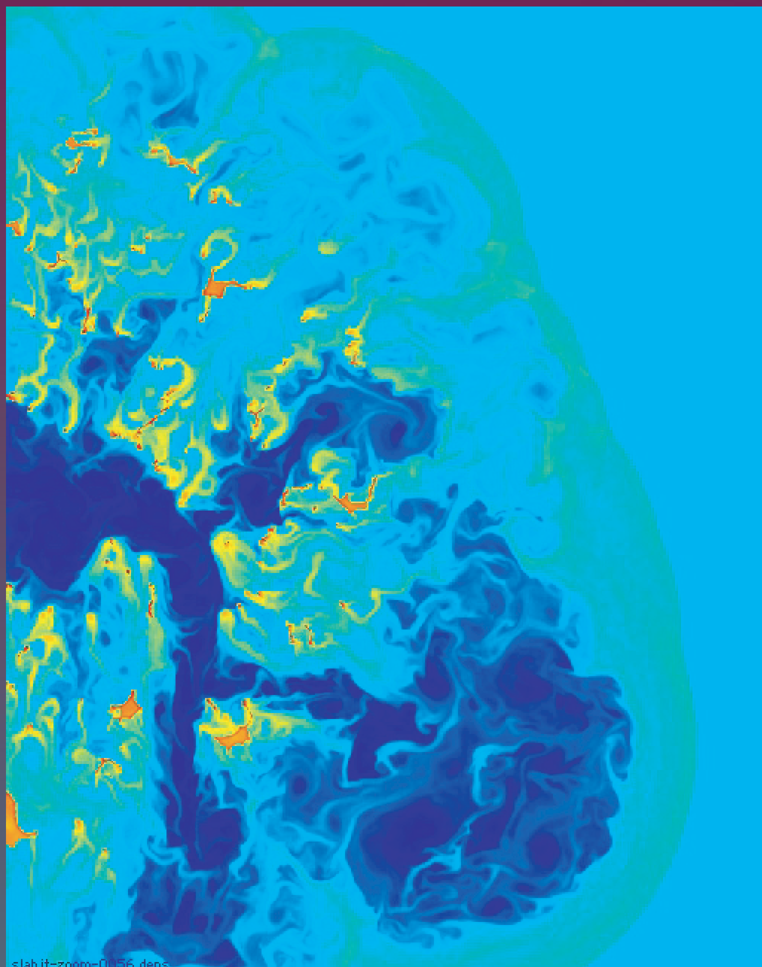


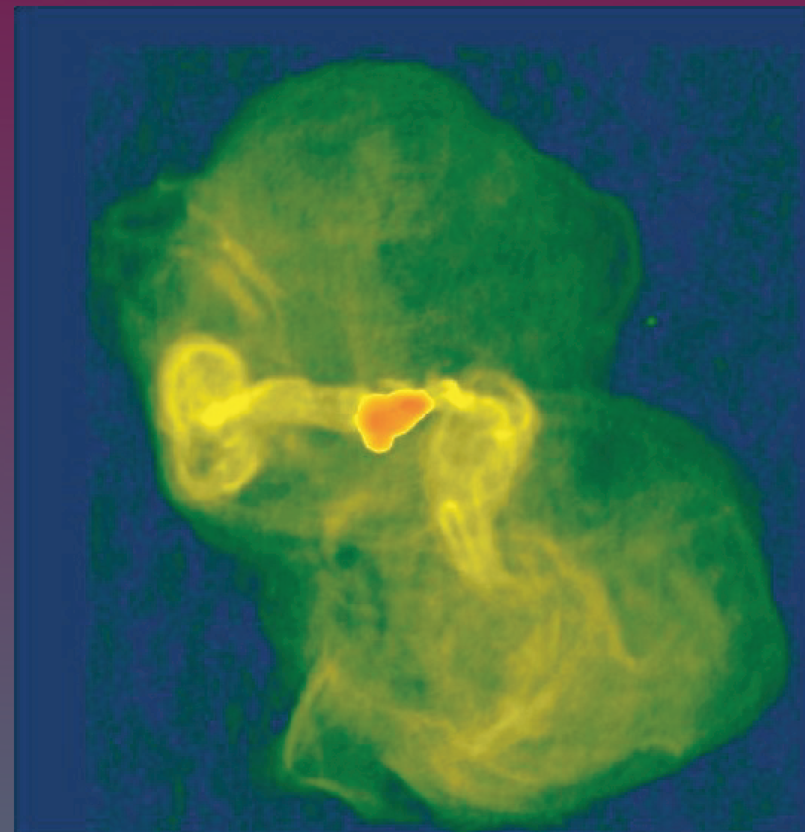


Further motivation

- Many examples of FR2 interactions leading to emission lines (Morganti, Tadhunter etc.)
- Indicator of the environment in which young radio galaxies are formed e.g mergers
- Interaction between AGN and forming galaxies – probably the basis for the Magorrian relation
- The baryon mass fraction in galaxies: – probably a result of outflows – starbursts in dwarf galaxies - AGN in massive galaxies

2D comparisons





M 87

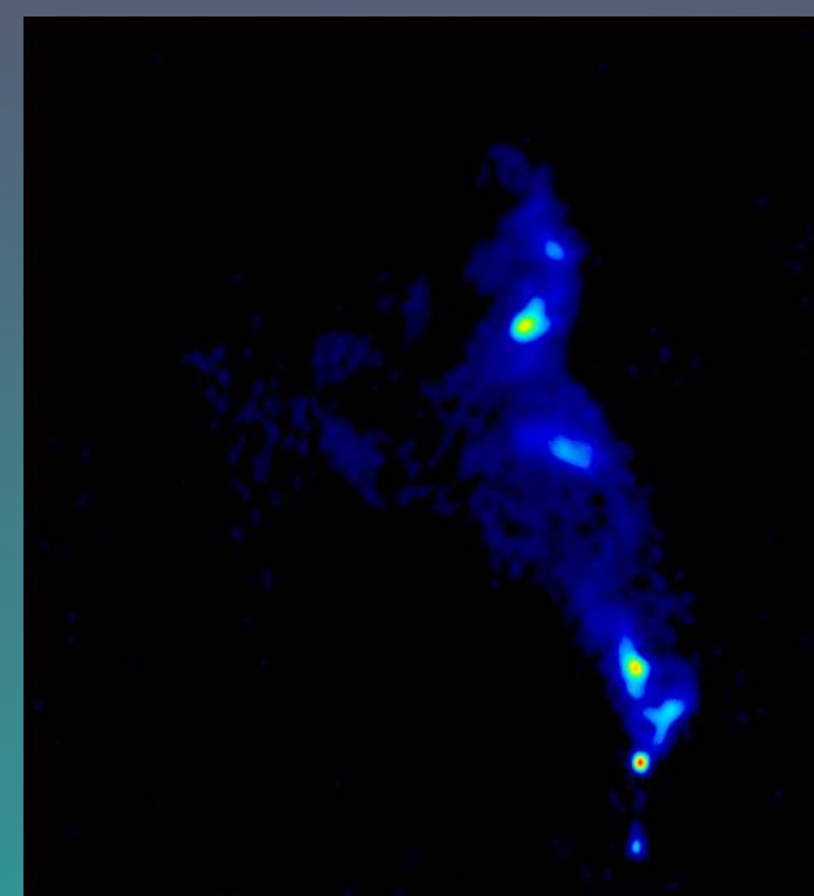
Large filling factor

"Flood and channel"

3C 48

Small filling factor

Buoyant plume



Technical features

- 3D; ppmlr hydro; thermal cooling
- Constant hot gas density replaced by atmosphere in potential well
- Self-consistent potential corresponding to light and dark matter
- Log–normal distribution of clouds with a power-law distribution in Fourier space (cf clouds in Earth's atmosphere)
- X-ray emission calculated using MAPPINGS code

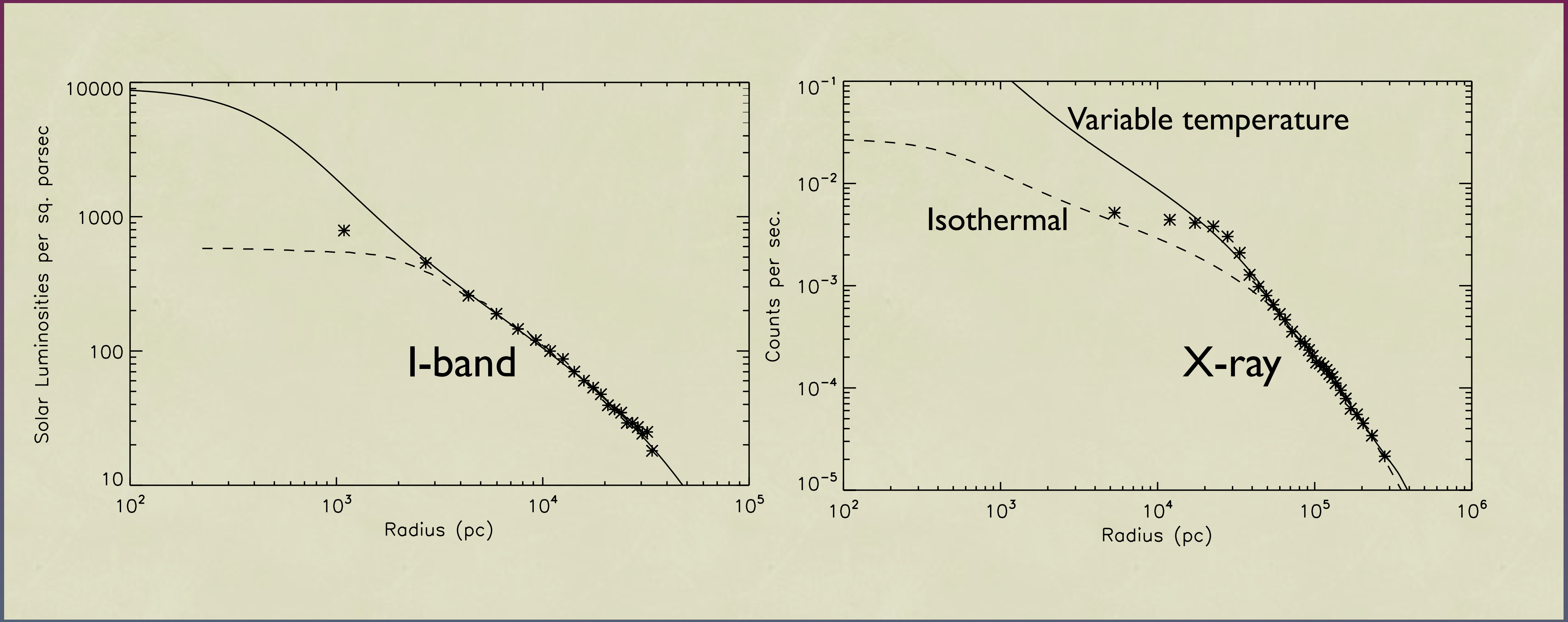
Double isothermal potential (cf Saglia et al.)

$$
\begin{aligned}
f_{\rm dark}(E) &\propto \exp(-E/\sigma_d^2) \\
f_{\rm lum}(E) &\propto \exp(-E/\sigma_{\rm l}^2) \\
E &= \frac{1}{2}v^2 + \phi \\
\nabla^2 \phi &= 4\pi G \rho
\end{aligned}
$$

PARAMETERS

- Dark matter & luminous matter velocity dispersions
- Dark matter and luminous matter core radii
- => Dark matter and luminous densities

Cygnus A I-band and X-ray profiles



Data: Westergard & Barthel; Carilli Smith & Wilson

Observed and inferred parameters

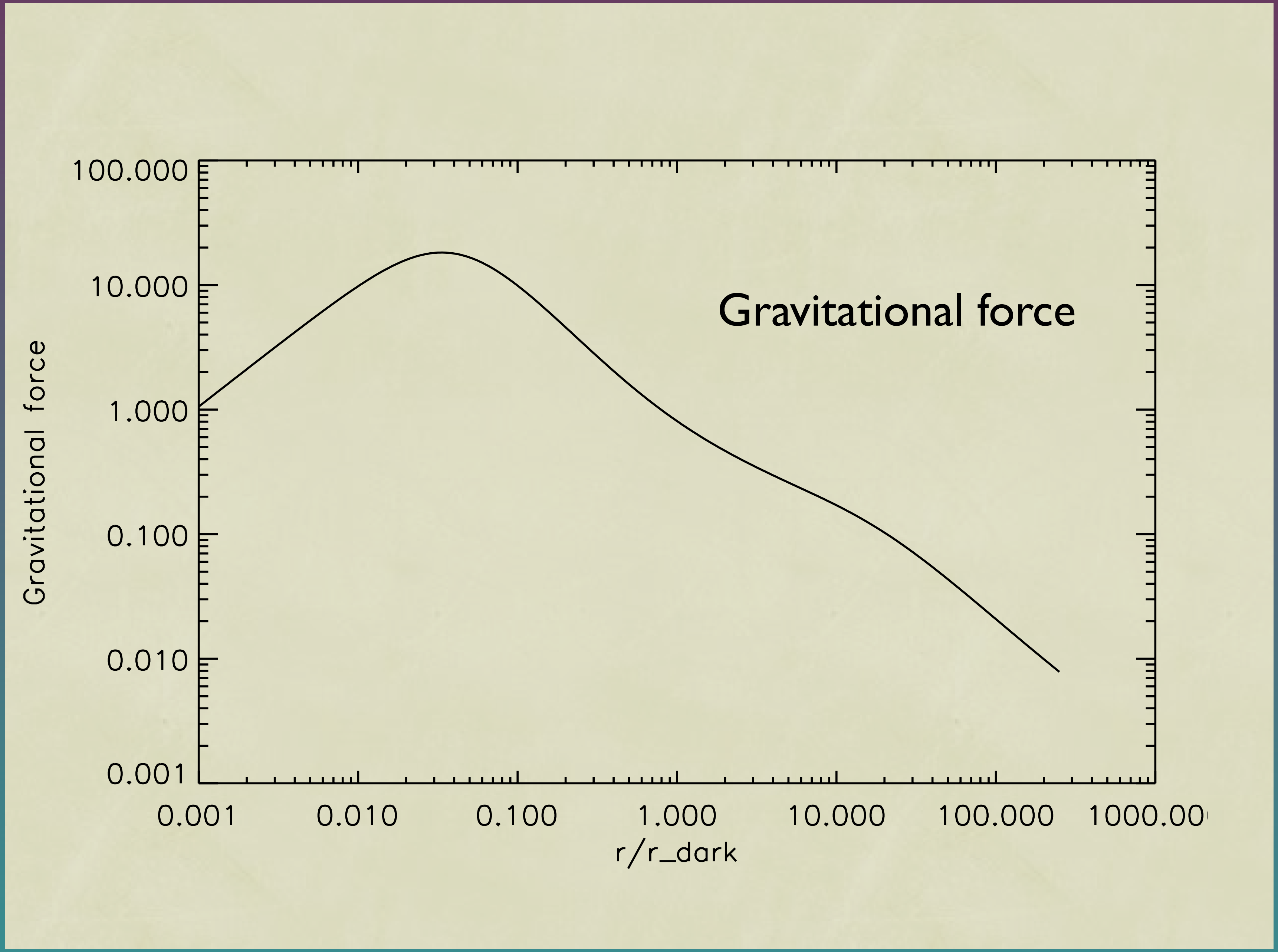
$$r_{\rm lum} = 500\ {\rm pc} \qquad r_{\rm dark} = 15\ {\rm kpc}$$

$$\beta = \frac{T_{\rm vir}}{T} = \frac{\mu m_p \sigma_{\rm dark}^2}{kT_\infty} \approx 0.9 \qquad T_\infty \approx 9 \times 10^7\ {\rm K}$$

$$\sigma_{\rm lum} \approx 620\ {\rm km\ s}^{-1} \qquad \sigma_{\rm dark} \approx 1000\ {\rm km\ s}^{-1}$$

Densities: $\rho_{\rm lum} \approx 260\ M_\odot\ {\rm pc}^{-3}$ $\rho_{\rm dark} \approx 0.74\ M_\odot\ {\rm pc}^{-3}$

Generic luminous + dark matter potential



$$\frac{r_{\rm lum}}{r_{\rm dark}} = 0.1$$

$$\frac{\sigma_{\rm lum}}{\sigma_{\rm dark}} = 0.5$$

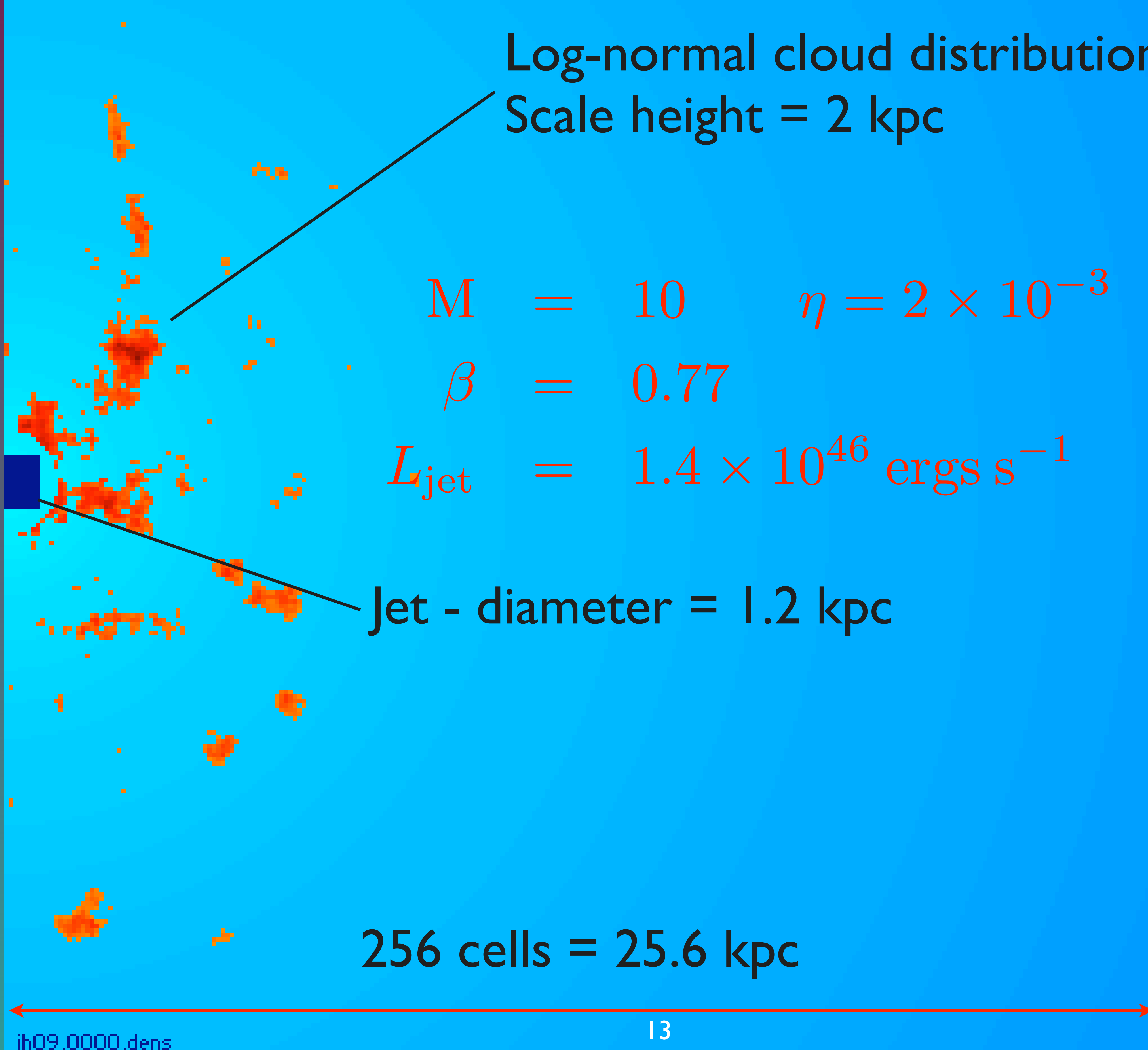
(Ad hoc) Initial conditions

- Likely origin of gas a minor or major merger
- Adopt ad hoc distributions of gas that are more or less consistent with reasonable physical constraints
- Single point statistic of density: log-normal distribution
- Two point statistics described by $\rho(\mathbf{k}) \propto k^{-5/3}$

Mean density

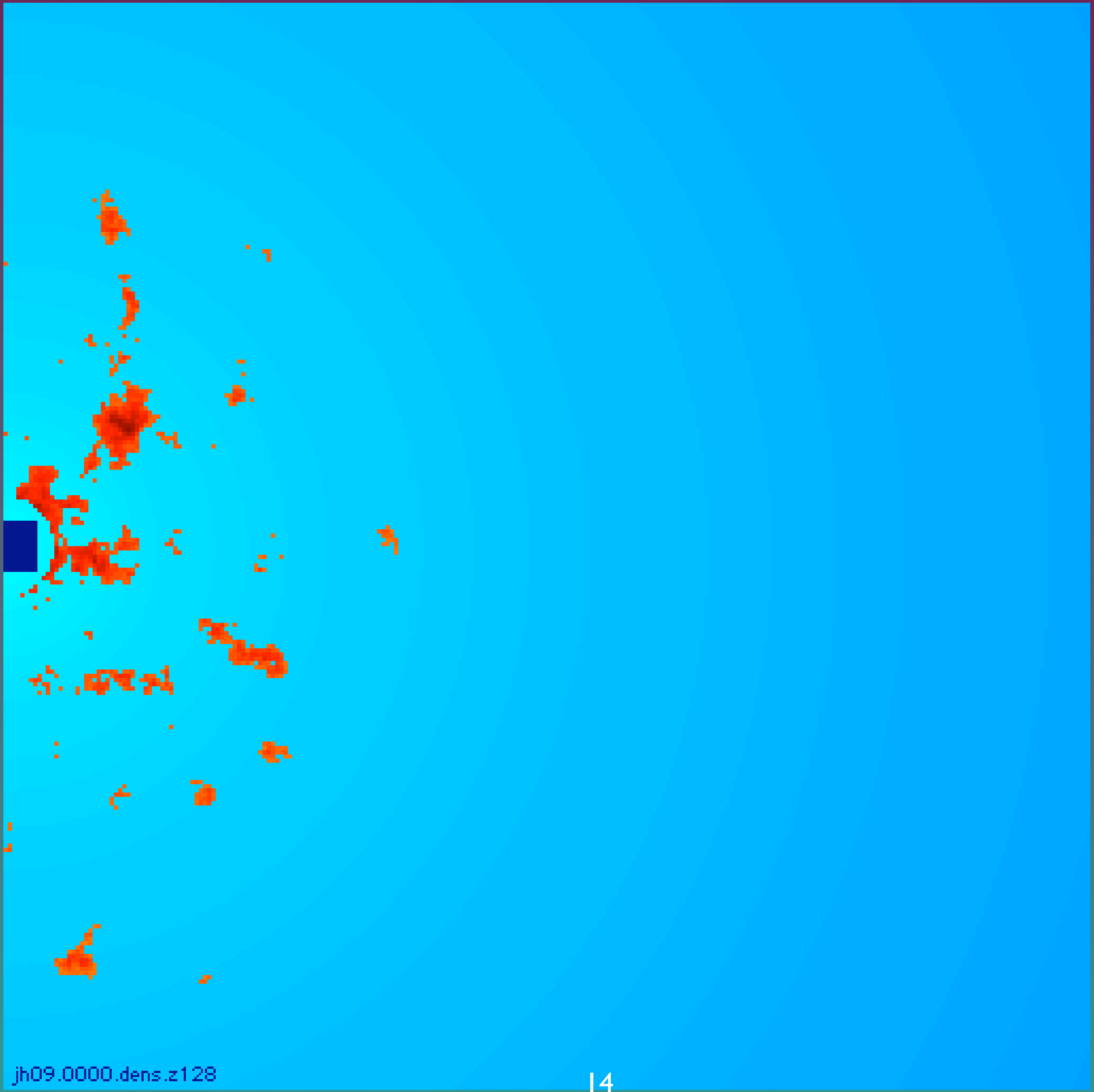
Spherical distribution $\bar{\rho}(\mathbf{r}) = \bar{\rho}_0 \times \exp(-r/h)$

Initial configuration

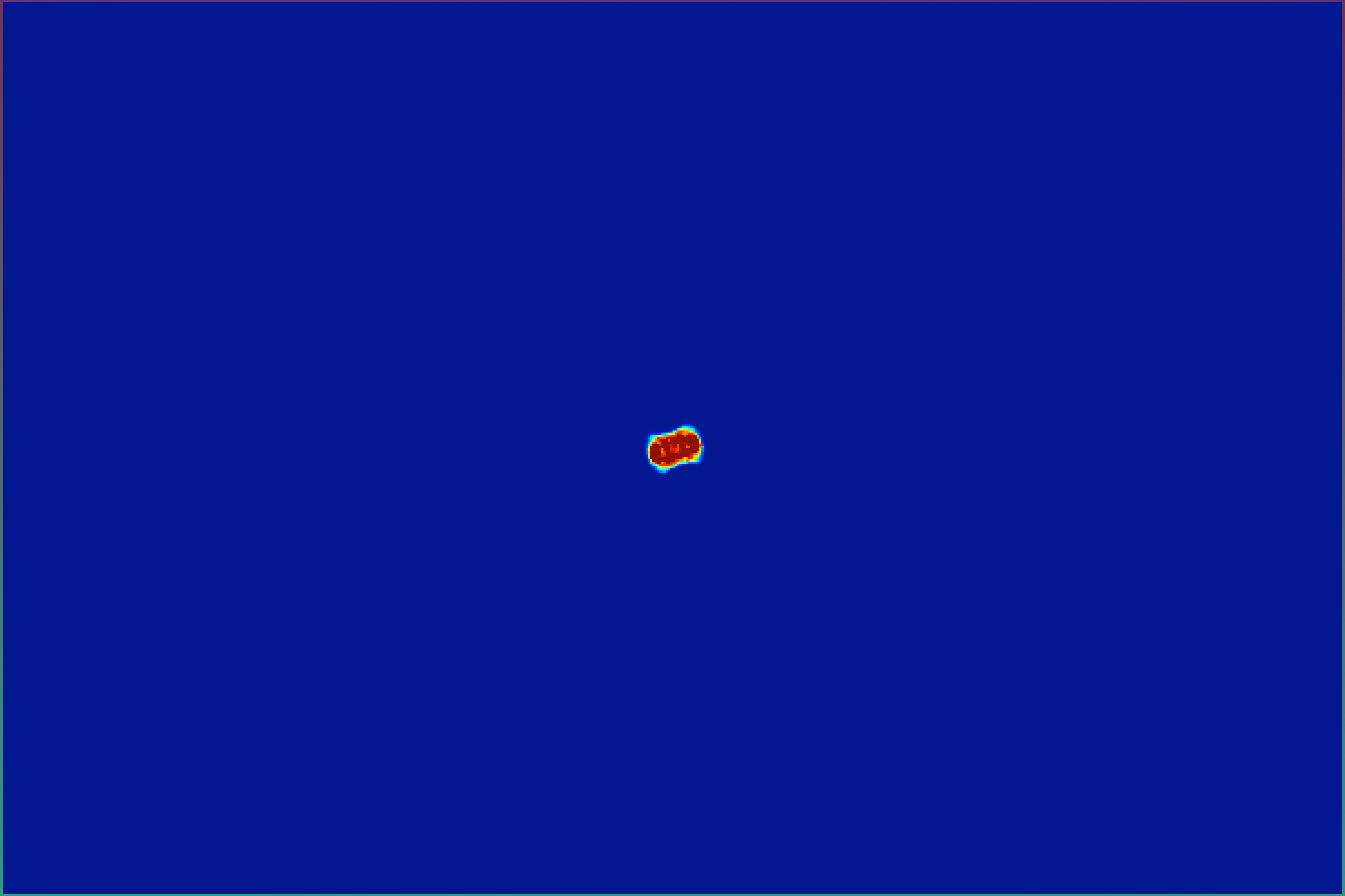


$$
\begin{aligned}
M &= 10 \qquad \eta = 2 \times 10^{-3} \\
\beta &= 0.77 \\
L_{\rm jet} &= 1.4 \times 10^{46}\ {\rm ergs\,s^{-1}}
\end{aligned}
$$

Evolution of density



Radio emission



Initial disk-like density distributions

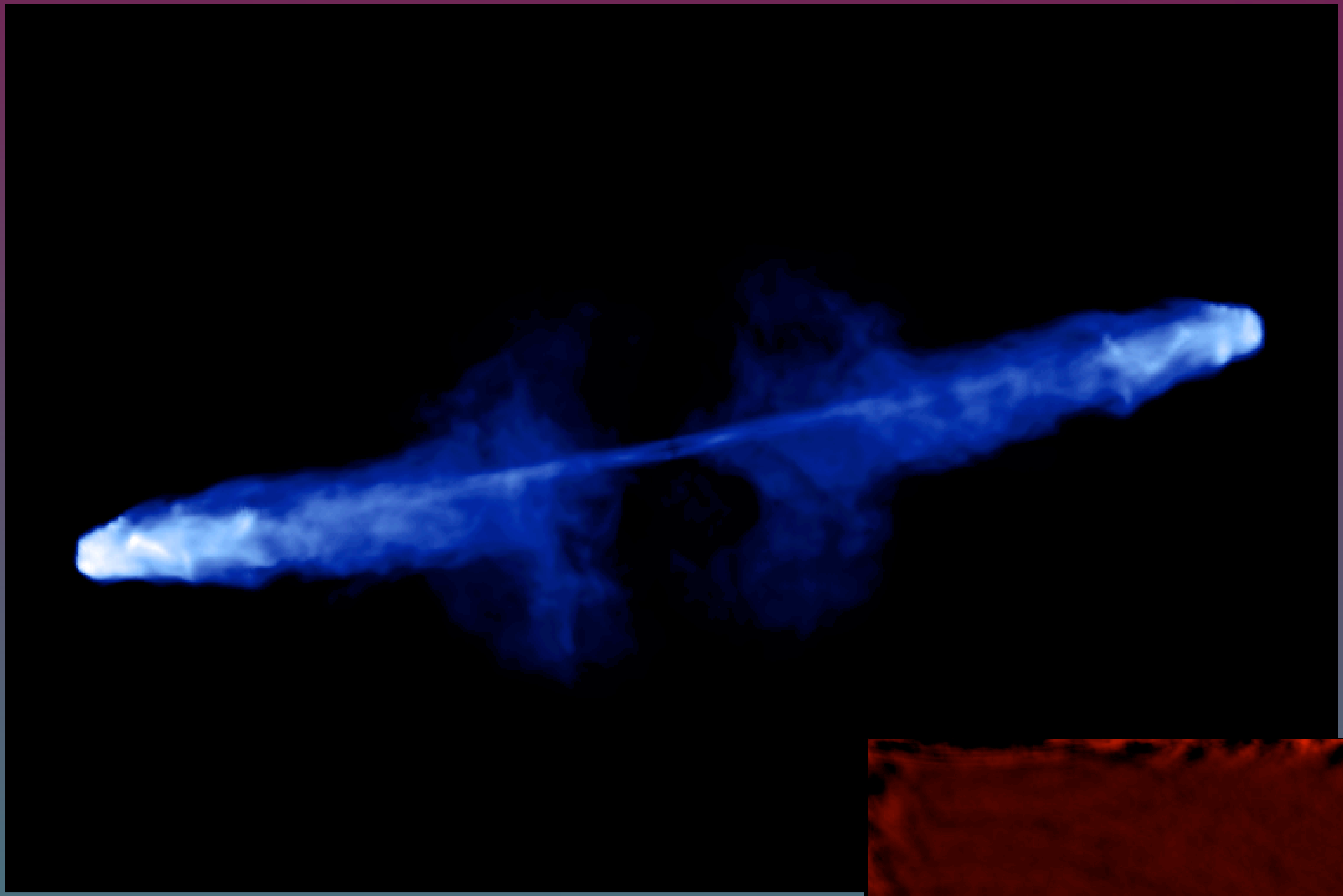
Modified Keplerian

$$\tilde{v}_\phi = e\, v_{\rm Kepler}(r)$$

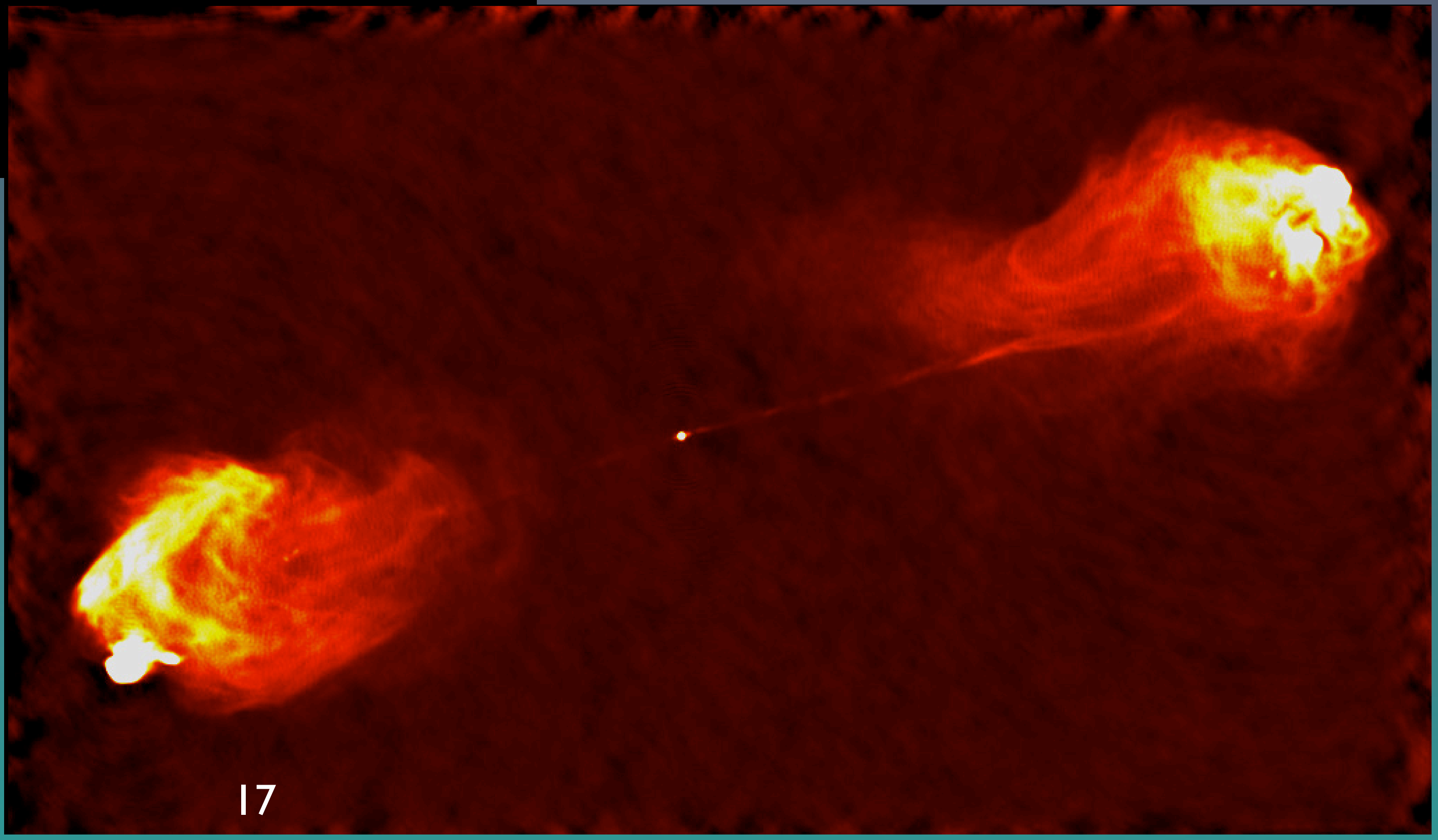
$$\frac{\bar{\rho}(r,z)}{\bar{\rho}(0,0)} = \exp\left[\frac{\phi(r,z) - e^2\phi(r,0) - (1-e^2)\phi(0,0)}{\sigma_g^2}\right]$$

$$\sigma_g^2 = \frac{kT}{\mu m_p} + \sigma_t^2$$

Simulation with disk of warm gas

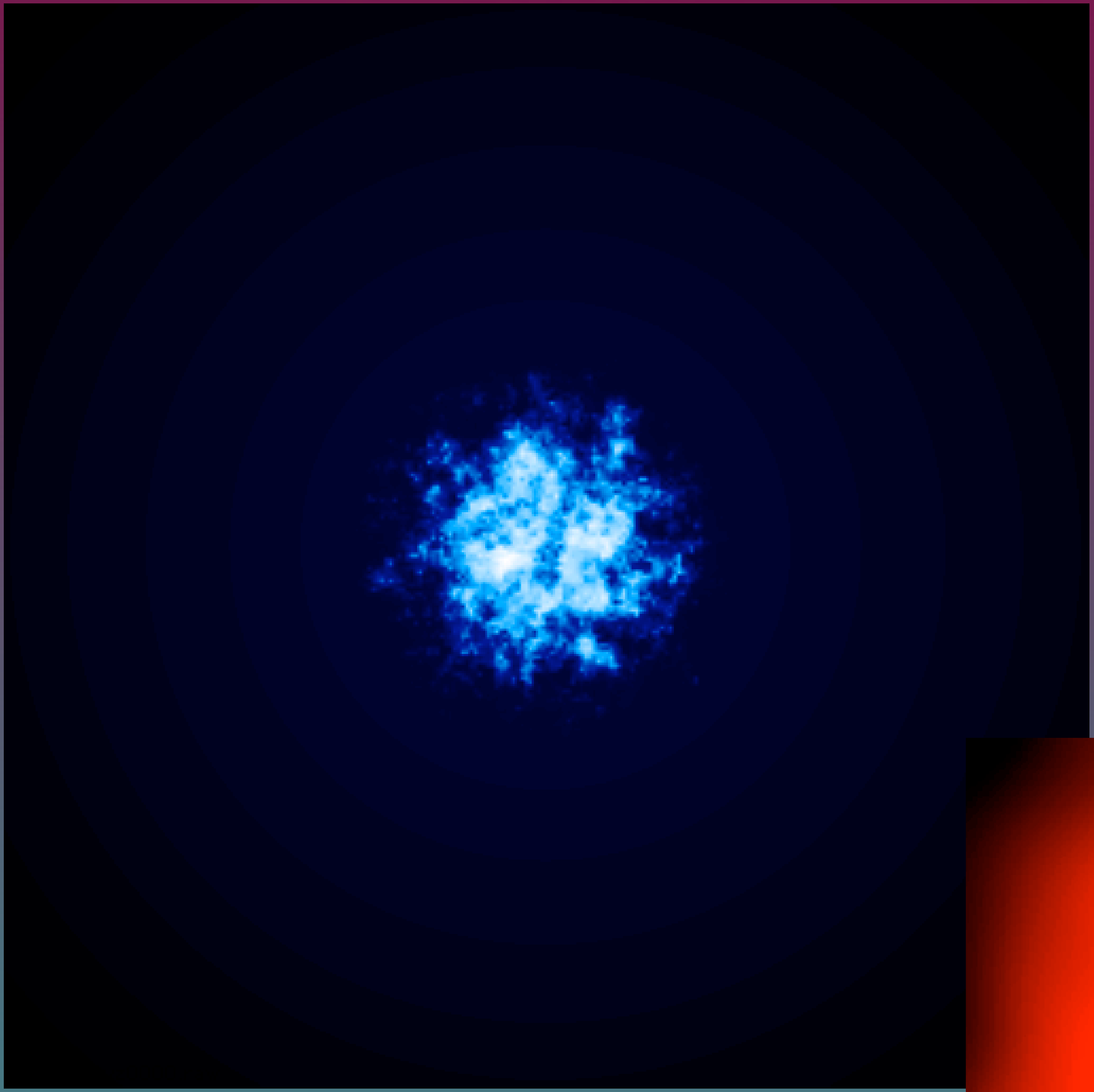


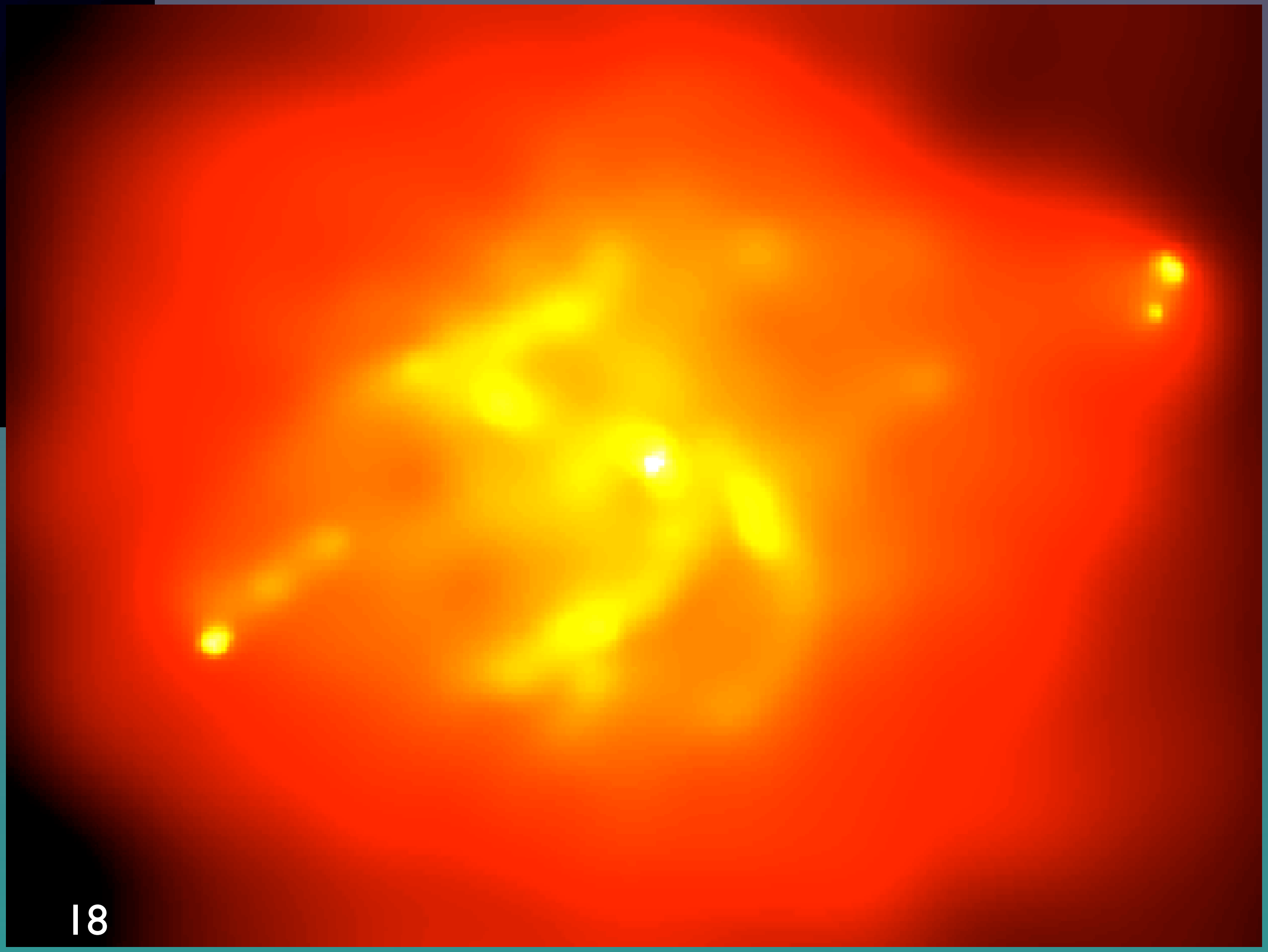
Synthetic radio image



Cygnus A

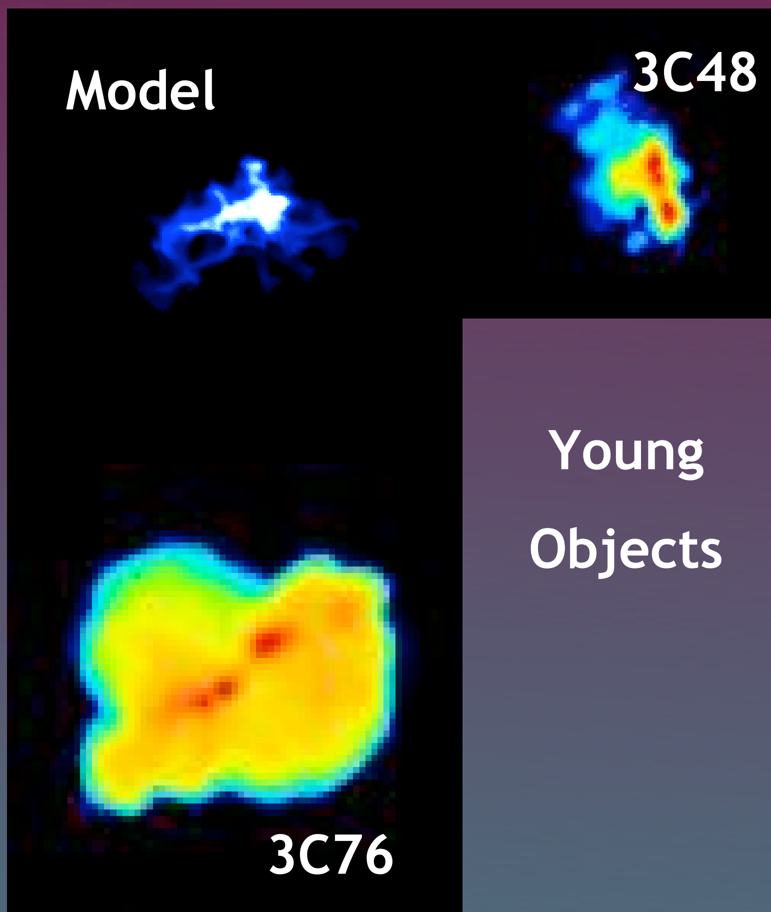
Evolution of thermal emission



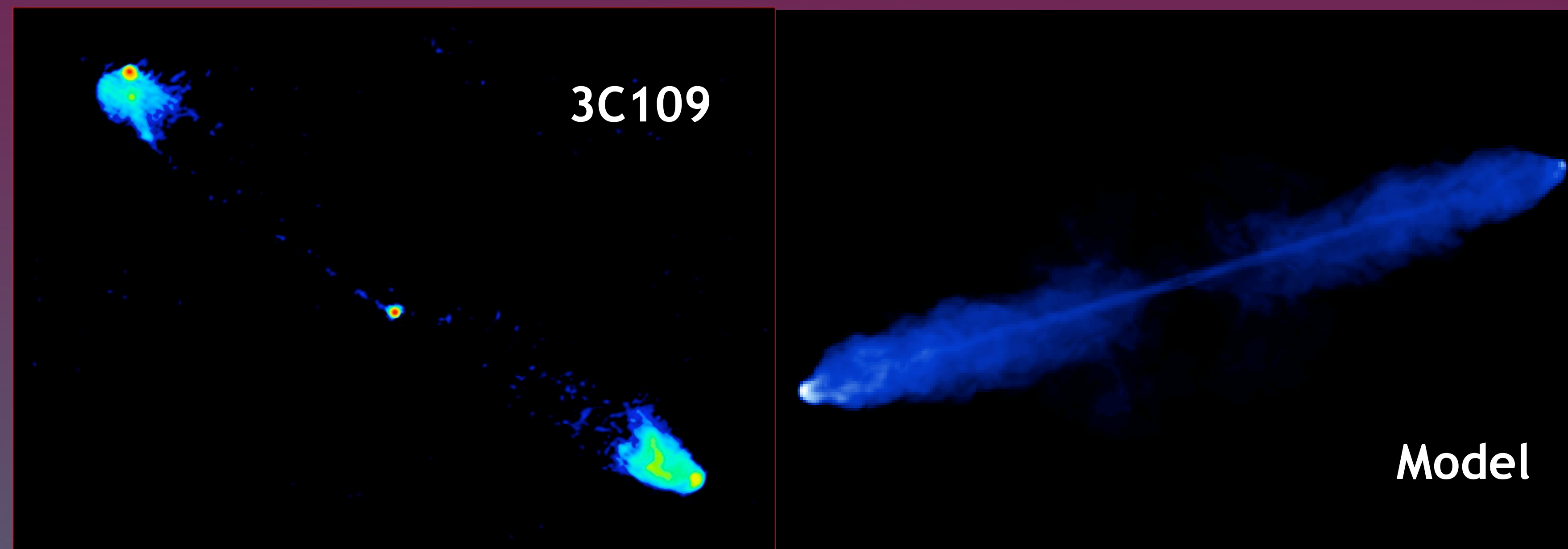


Chandra X-ray image of Cygnus A

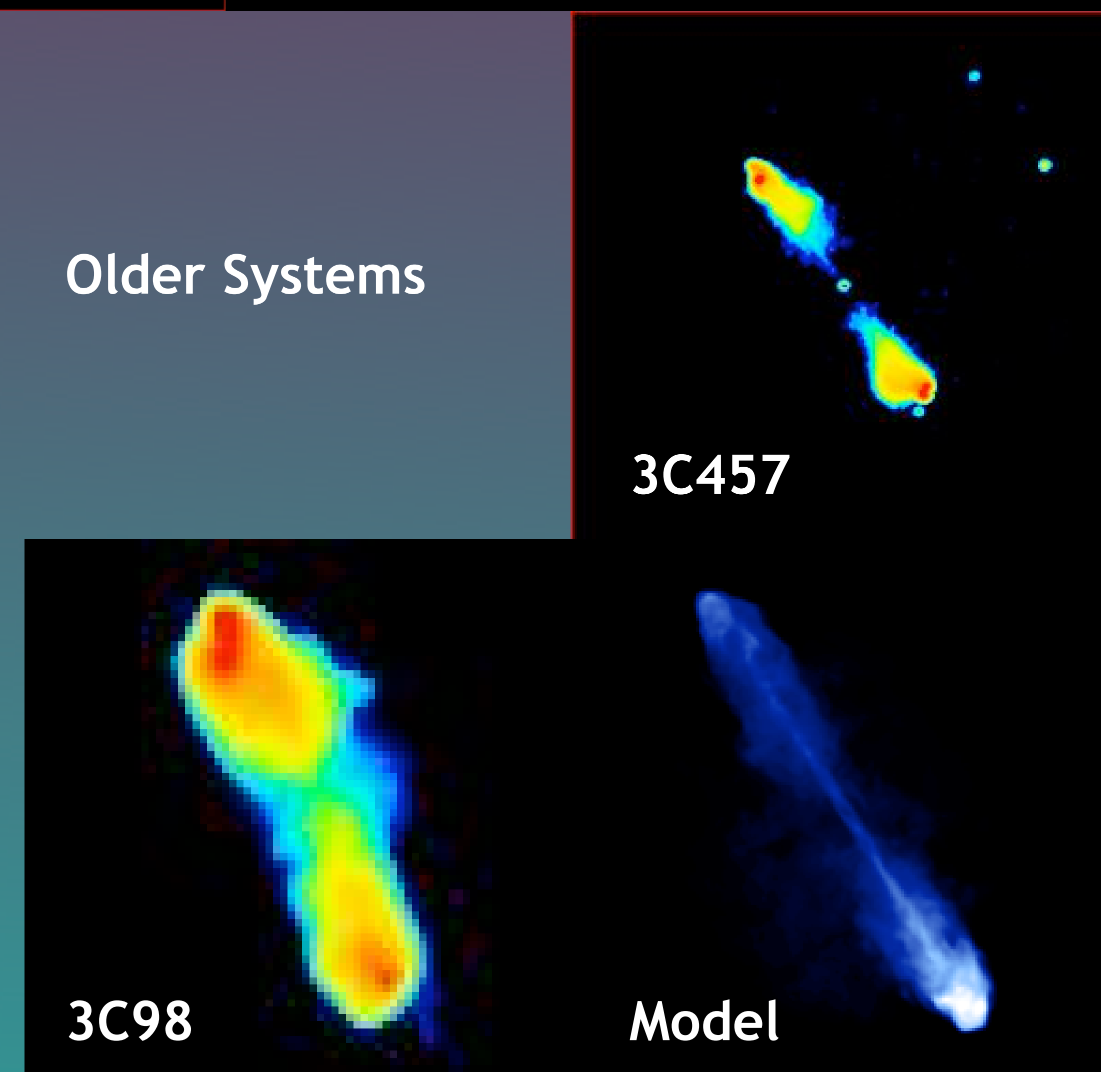
Evolutionary sequence



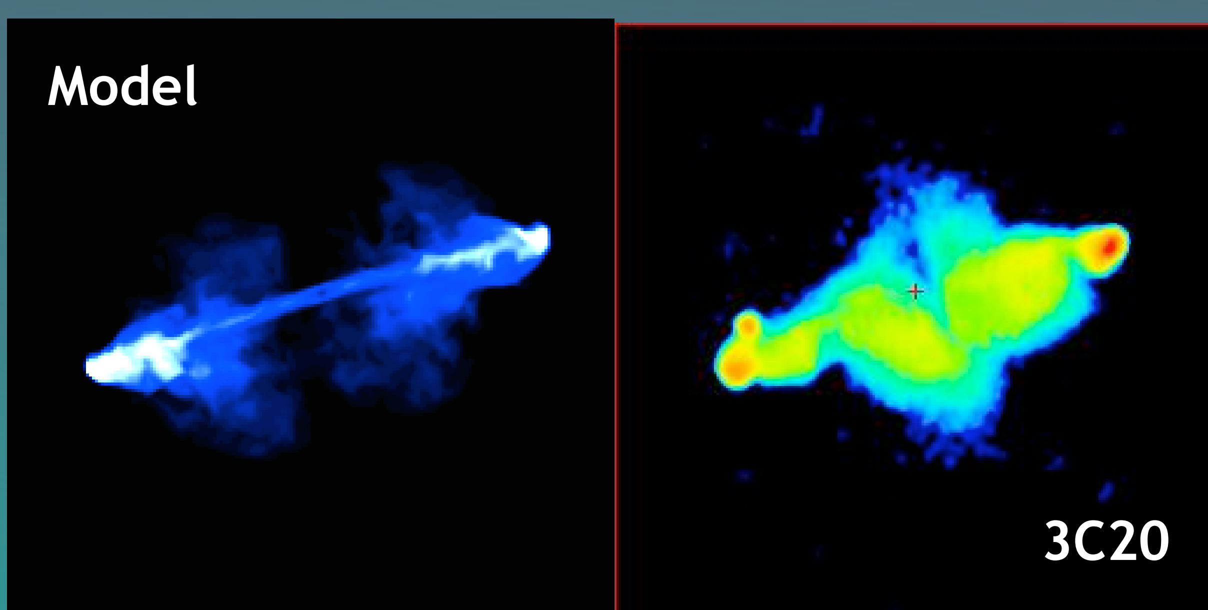
Young Objects



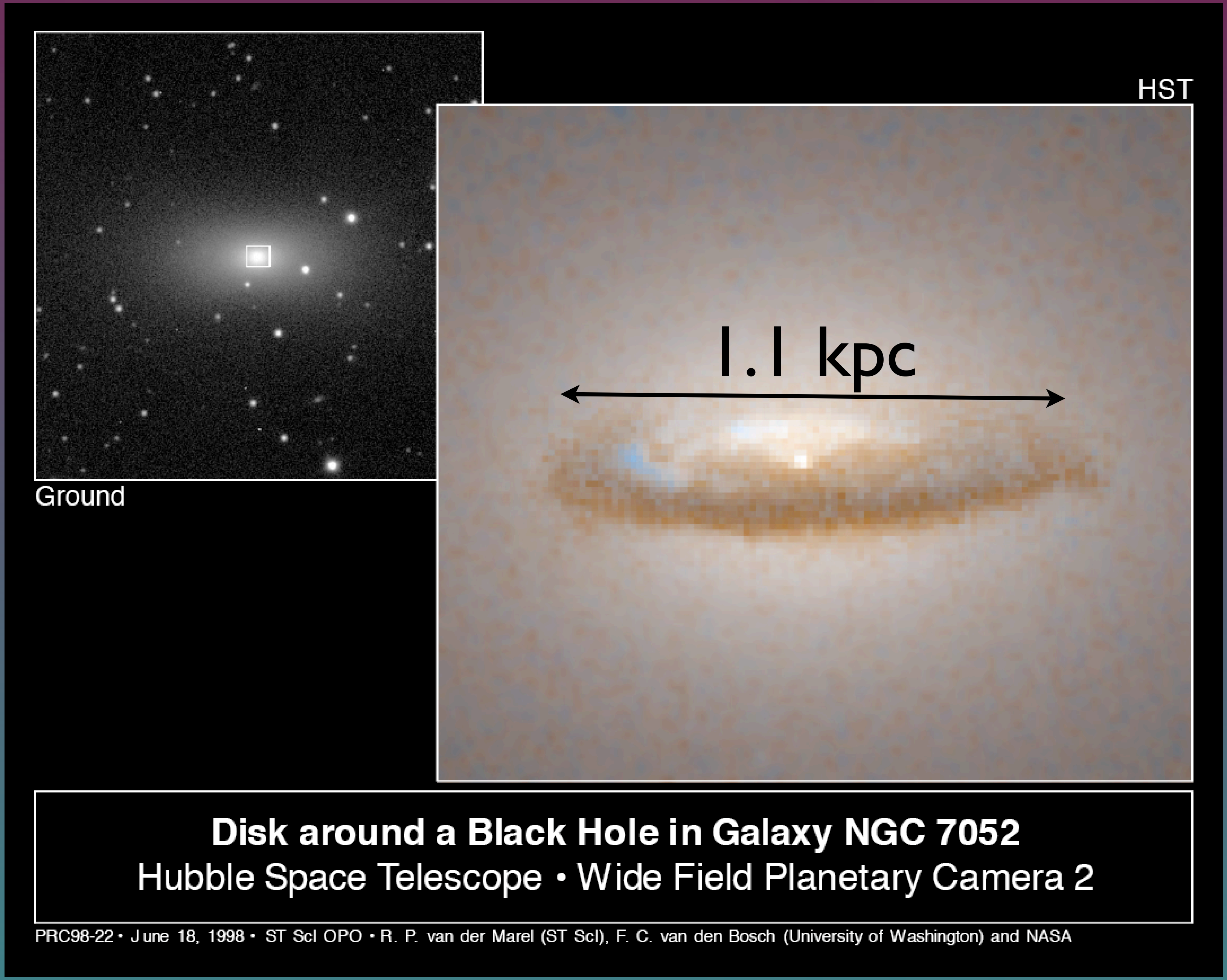
Older Systems



Intermediate Ages



Large scale accretion disk



NGC 7502: Velocity dispersion ~ 70 km s^{-1}
Van der Marel and Van den Bosch 98

Density distribution in kpc-scale accretion disk

$$\tilde{v}_\phi = v_{\rm Kepler}(r)$$

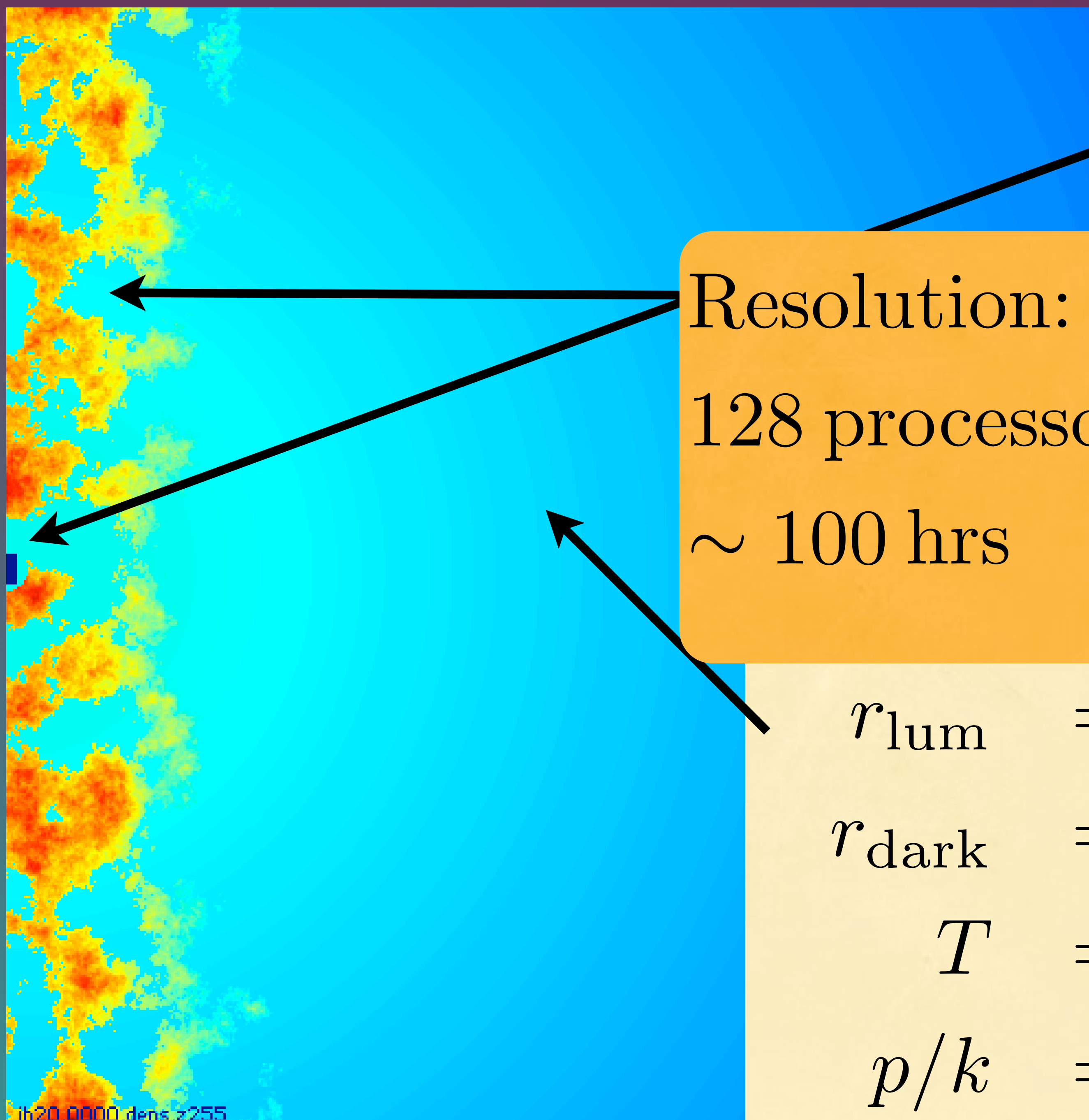
$$\bar{\rho}(r,z) = \bar{\rho}(r)\ \exp\left(-\frac{z^2}{h^2}\right)$$

$$\bar{\rho}(r) = \frac{\dot{M}_a/\alpha}{(2\pi)^{3/2}}\frac{1}{\sigma_g^3}\frac{GM}{r^3}$$

$$h^2 = \frac{2\sigma_g^2 r^3}{GM(r)} \qquad \sigma_g^2 = \frac{kT}{\mu m_p} + \sigma_t^2$$

$$\alpha = \frac{\langle \rho v_r' v_\phi' \rangle}{\langle \rho v'^2 \rangle}$$

Jet / kpc-scale accretion disc



$$M = 28.9$$

Log-normal, power-law distribution:

$$\sigma_{\rm turb} = 50\,{\rm km\,s^{-1}}$$

$\tilde{}$ ... K ... s s^{-1}

... $\rm cm^{-3}$

... $\rm M_\odot\ yr^{-1}$

Resolution: $512 \times 512 \times 512$

128 processors

~ 100 hrs

$$r_{\rm lum} = 500\,{\rm pc} \quad \sigma_{\rm lum} = 300\,{\rm km\,s^{-1}}$$

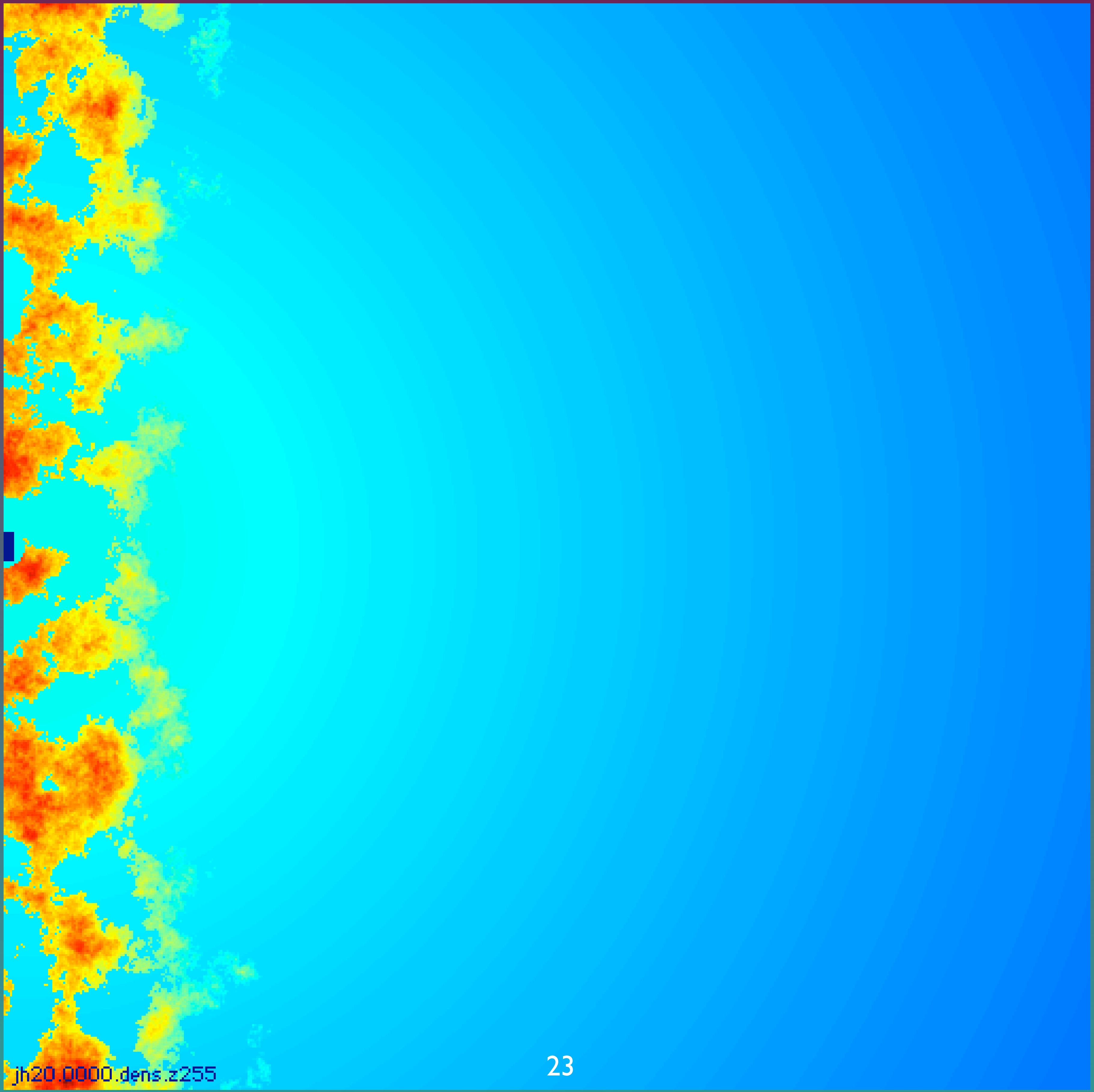
$$r_{\rm dark} = 5\,{\rm kpc} \quad \sigma_{\rm dark} = 600\,{\rm km\,s^{-1}}$$

$$T = 6.74 \times 10^6\,{\rm K}$$

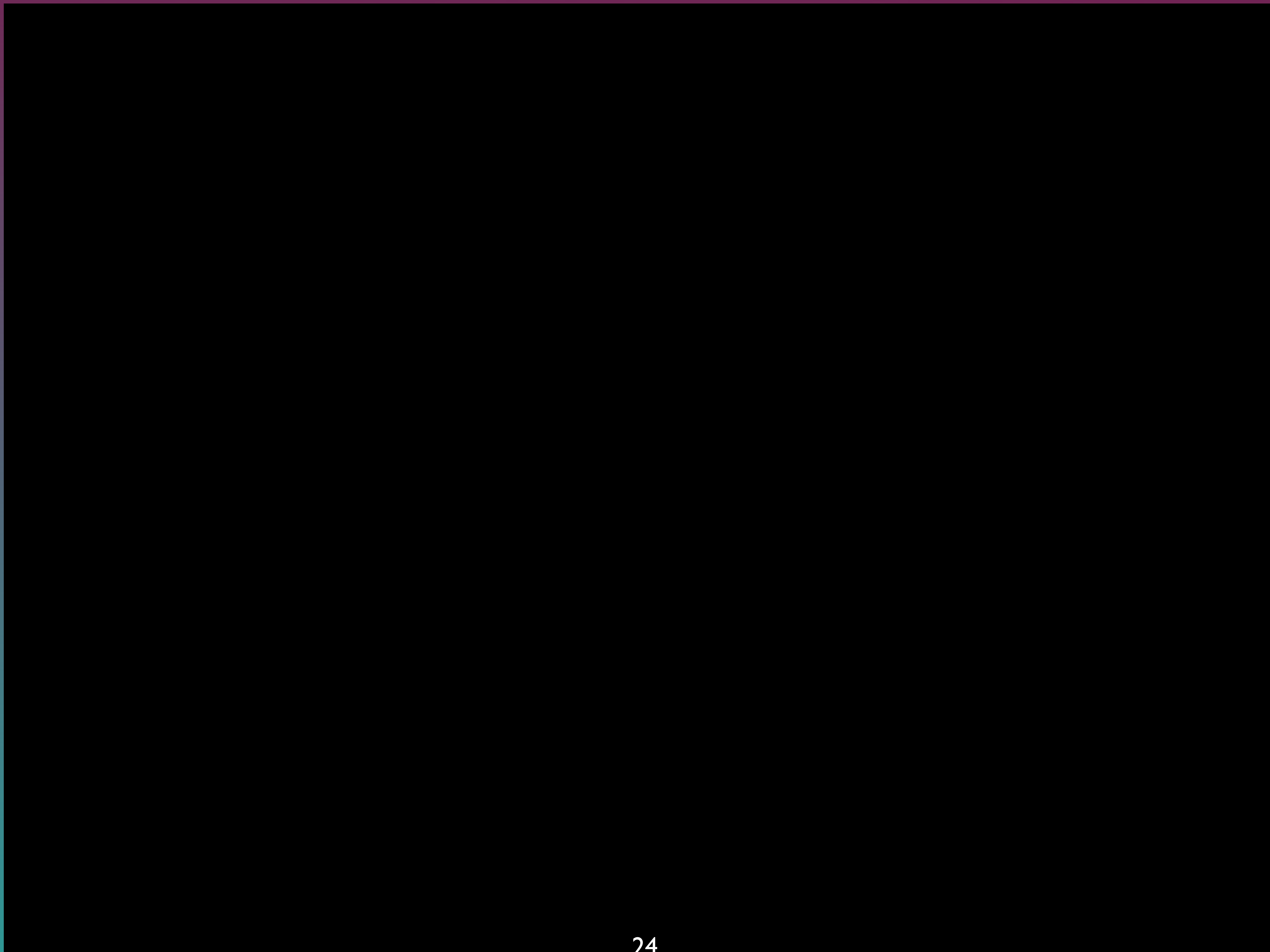
$$p/k = 2 \times 10^7$$

$$n_0 = 2.97\,{\rm cm^{-3}}$$

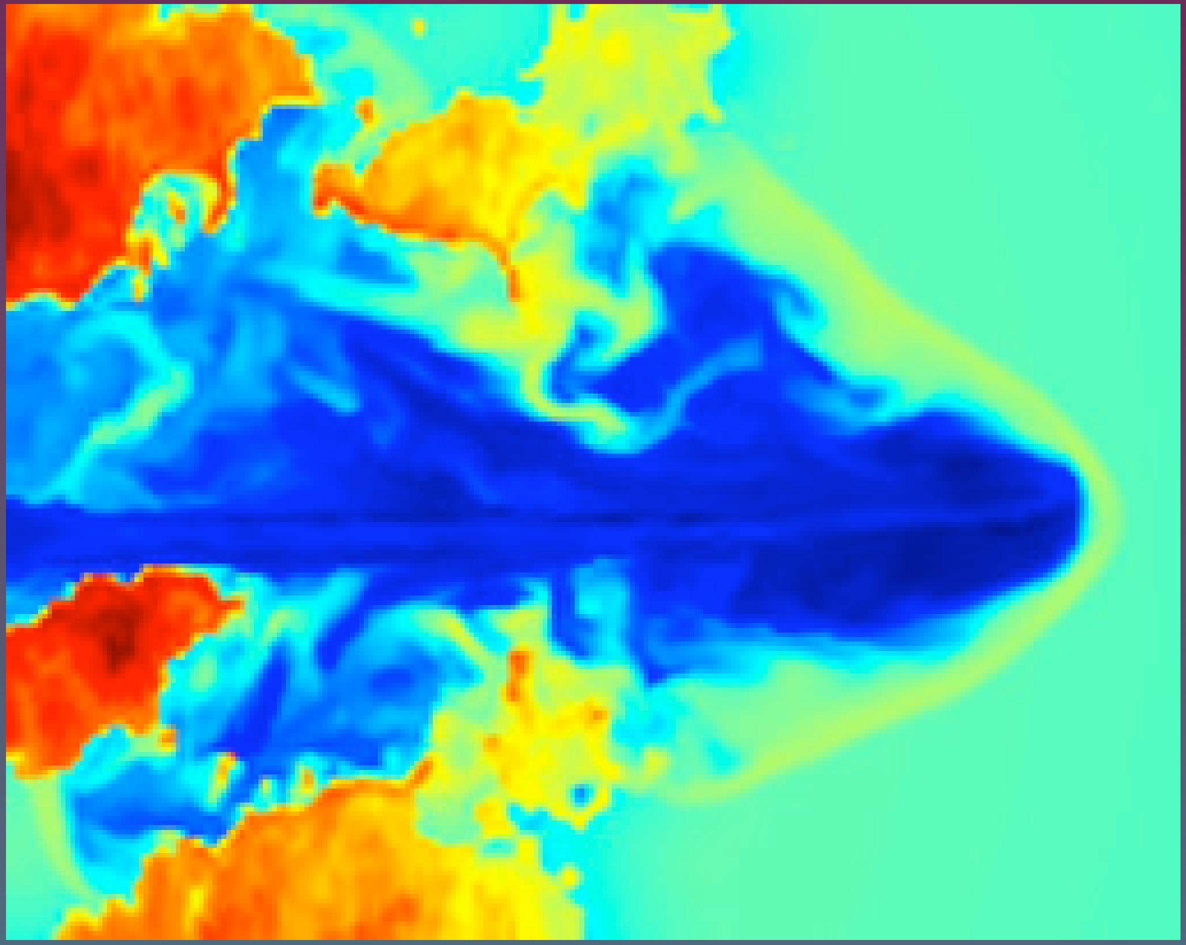
Evolution of mid-plane density



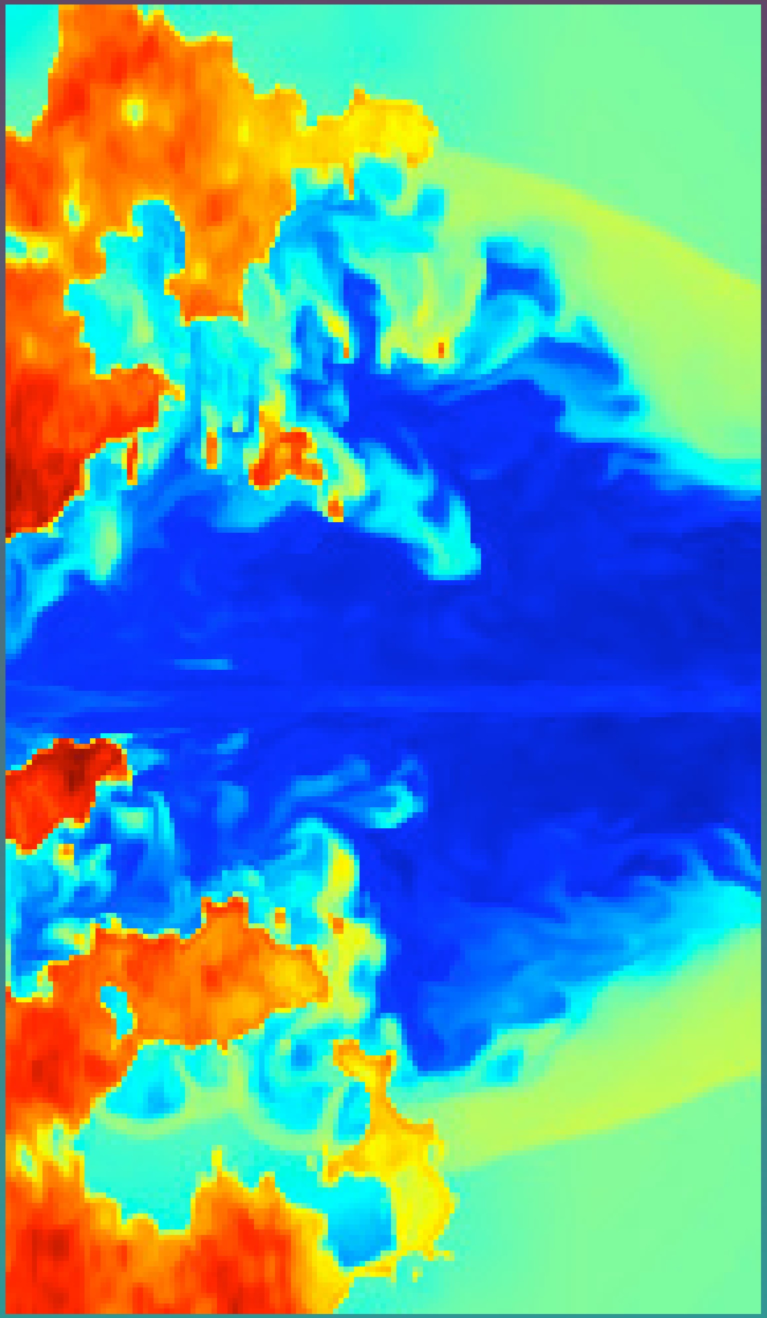
Synthetic radio movie



Radiative shocks

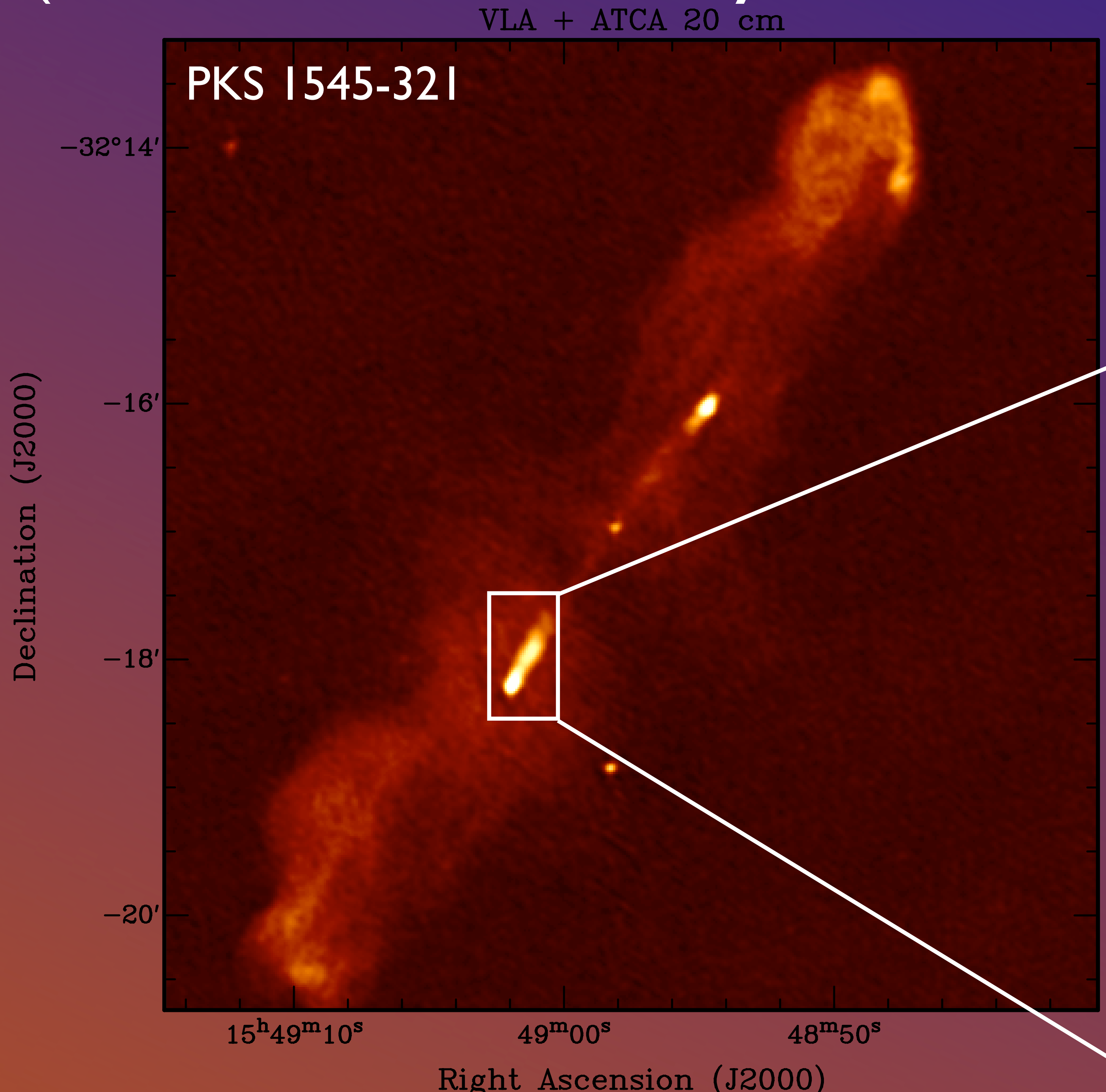


Early



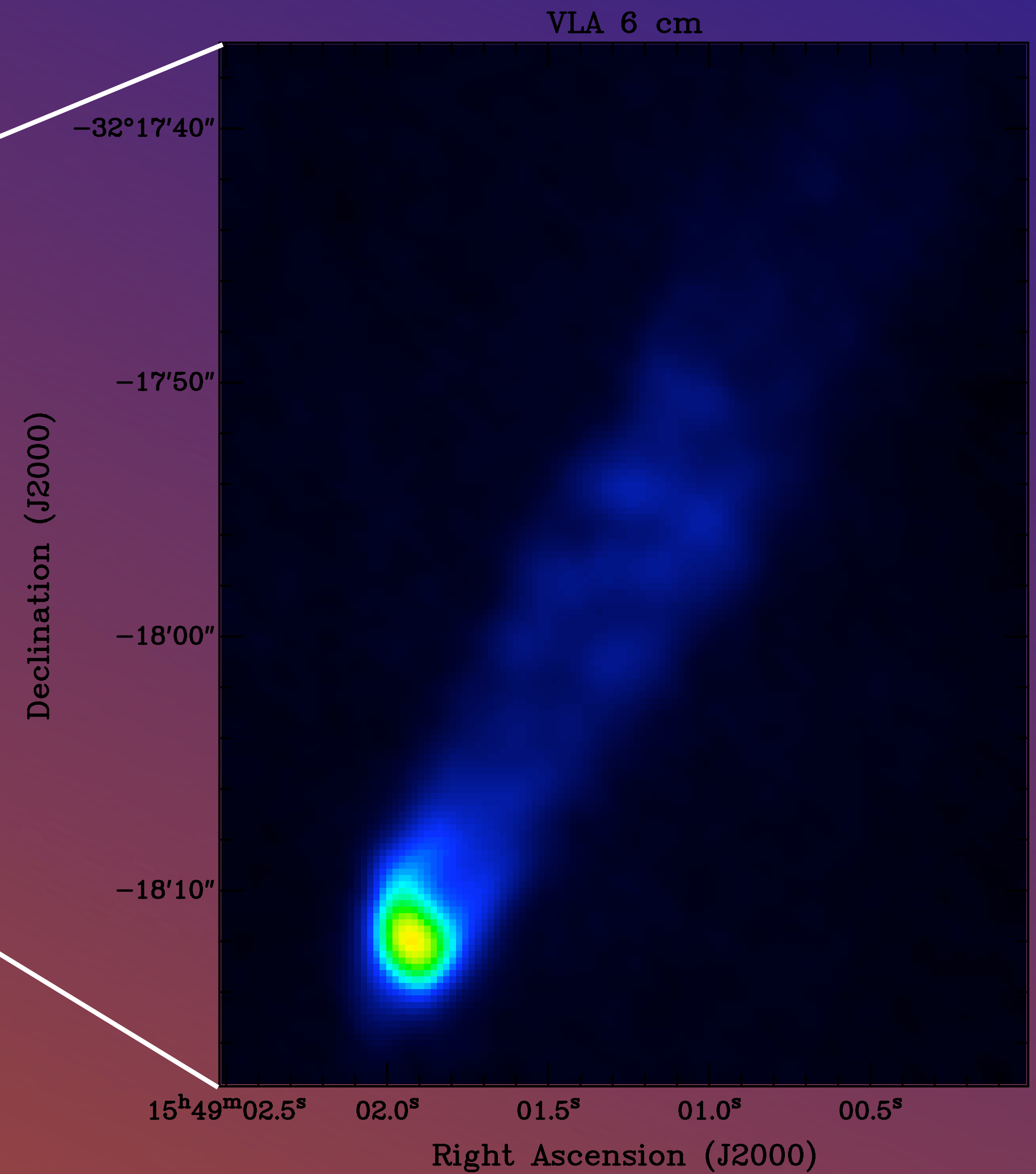
Late

A hyper-relativistic jet in a restarting Radio Galaxy
(Safouris, Subrahmanyan, GB, Saripalli, Sutherland)

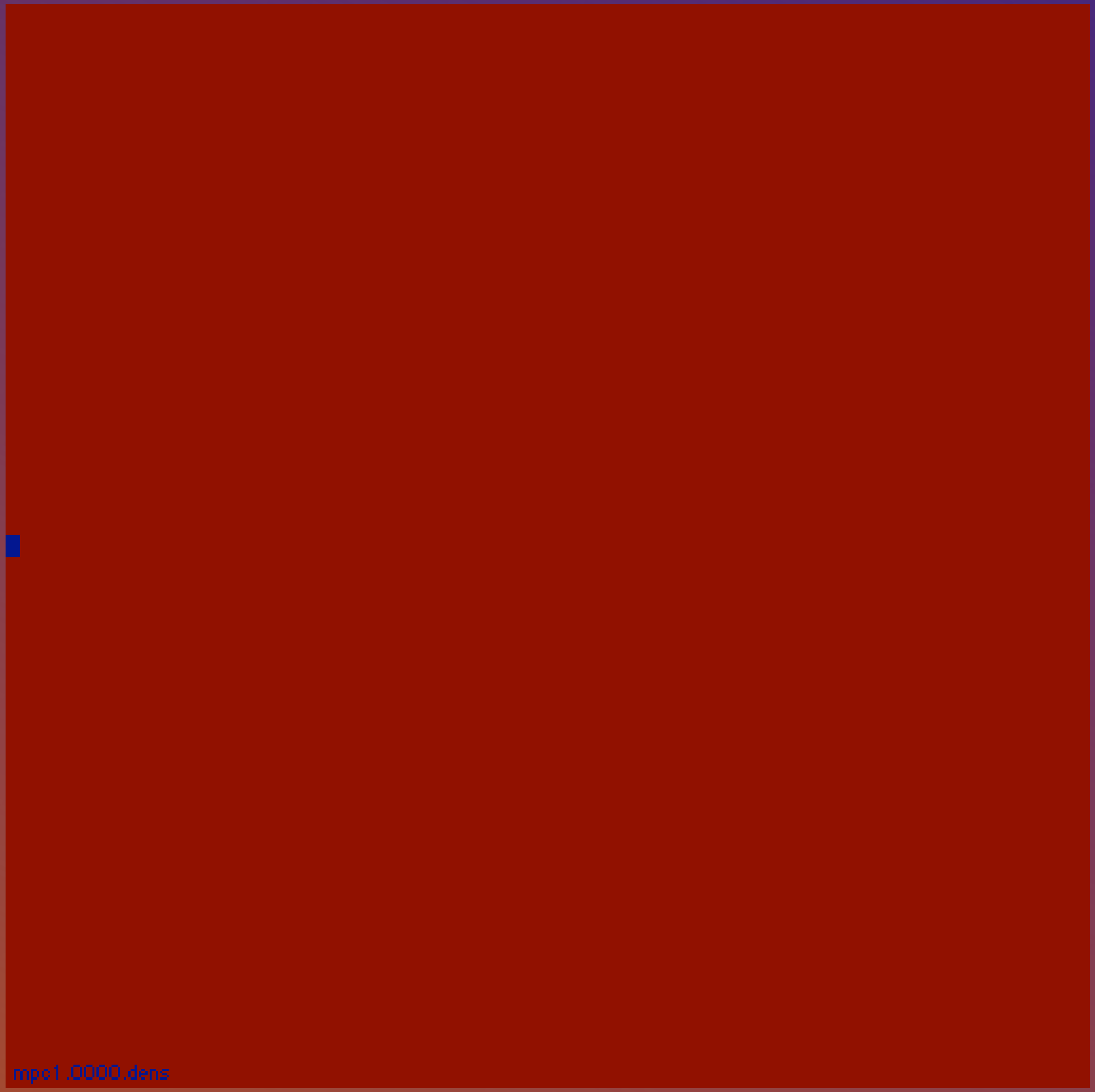


VLA + ATCA 20 cm

VLA 6 cm



Simulation of a hypersonic restarting jet

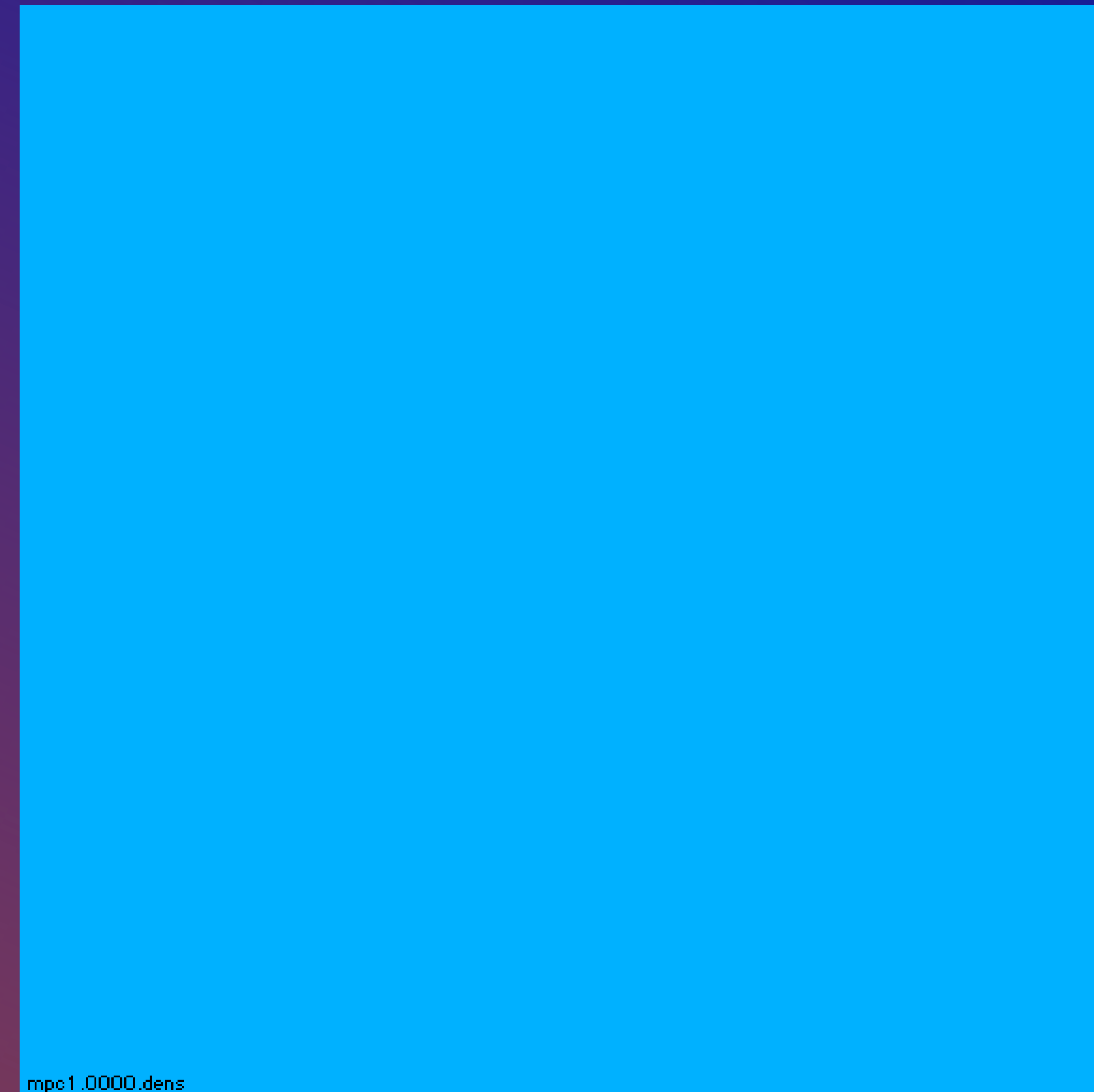


$$
\begin{aligned}
M &= 30 \\
\eta &= 10^{-2}
\end{aligned}
$$

Jet within pre-existing cocoon

$$\begin{aligned} M &= 30 \\ \eta &= 1 \end{aligned}$$

Use simulation to determine ratio of cocoon to jet diameters



$$4pAc\beta\left[\Gamma^2 + (\Gamma - 1)\Gamma\chi\right] \times \text{Age} \times \text{Adiabatic Factor}$$

$$\simeq \text{Energy deposited within new cocoon}$$

$$\Rightarrow \Gamma \approx 20$$

Summary

- Wide variety of morphologies possible when relativistic jets interact with cloudy medium

- Various structures can be identified which are similar to evolutionary phases in FR2 evolution – signature of initial interaction with disk

- Spherical distribution of clumpy gas builds up halo of old particles

- Disk-like distribution shows persistent X-ray emission from shocked disk

- Shocked emission due to direct jet-cloud encounters and interaction with cocoon

- High Lorentz factors possible on scales of 100 kpc in Mpc scale radio galaxies