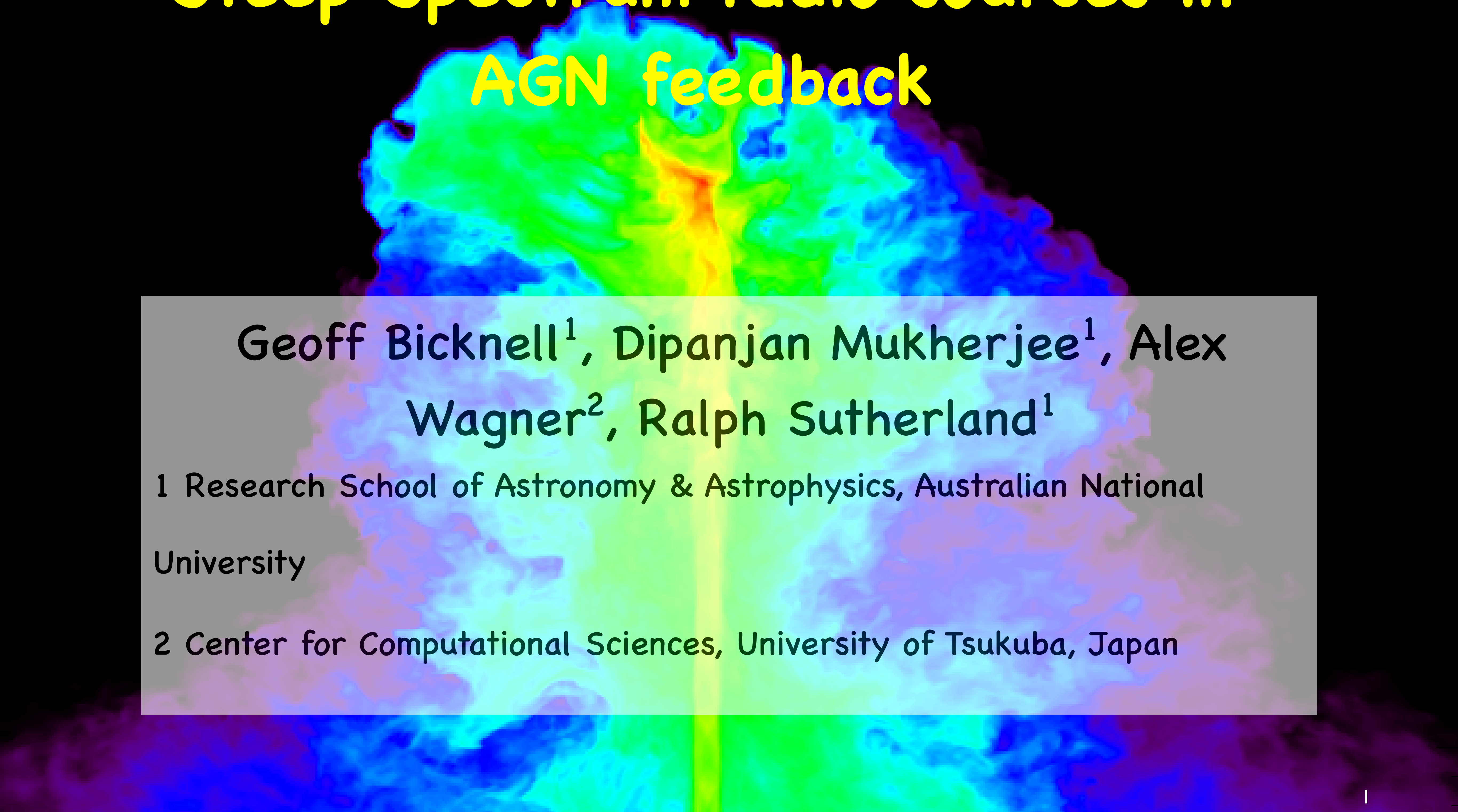
The critical role of Gigahertz Peak Spectrum and Compact Steep Spectrum radio sources in AGN feedback



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Radio galaxies and AGN feedback

- Radio-active phase part of the life-cycle of all galaxies
- Significant amount of energy and momentum injected into the ISM during this phase
- Influence on cooling flows - used in modelling the galaxy luminosity function (Croton+'06)
- Radio galaxies heat cooling flows - prevent further accretion

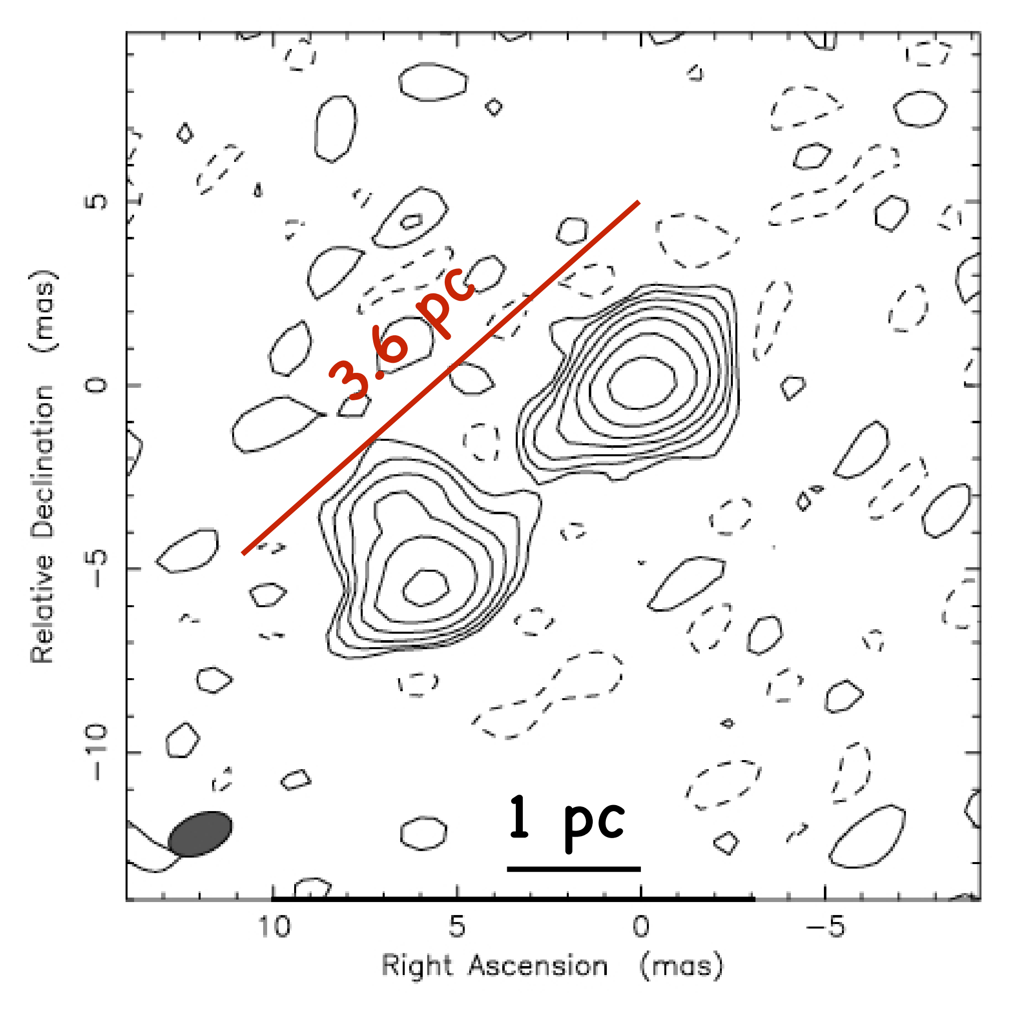
Feedback in other environments

- ISM in evolving galaxies is inhomogeneous (esp. at z~2)
- AGN feedback is not just a matter of heating the ISM and preventing accretion
- Emphasised by the physics of Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum (CSS) sources

Outline

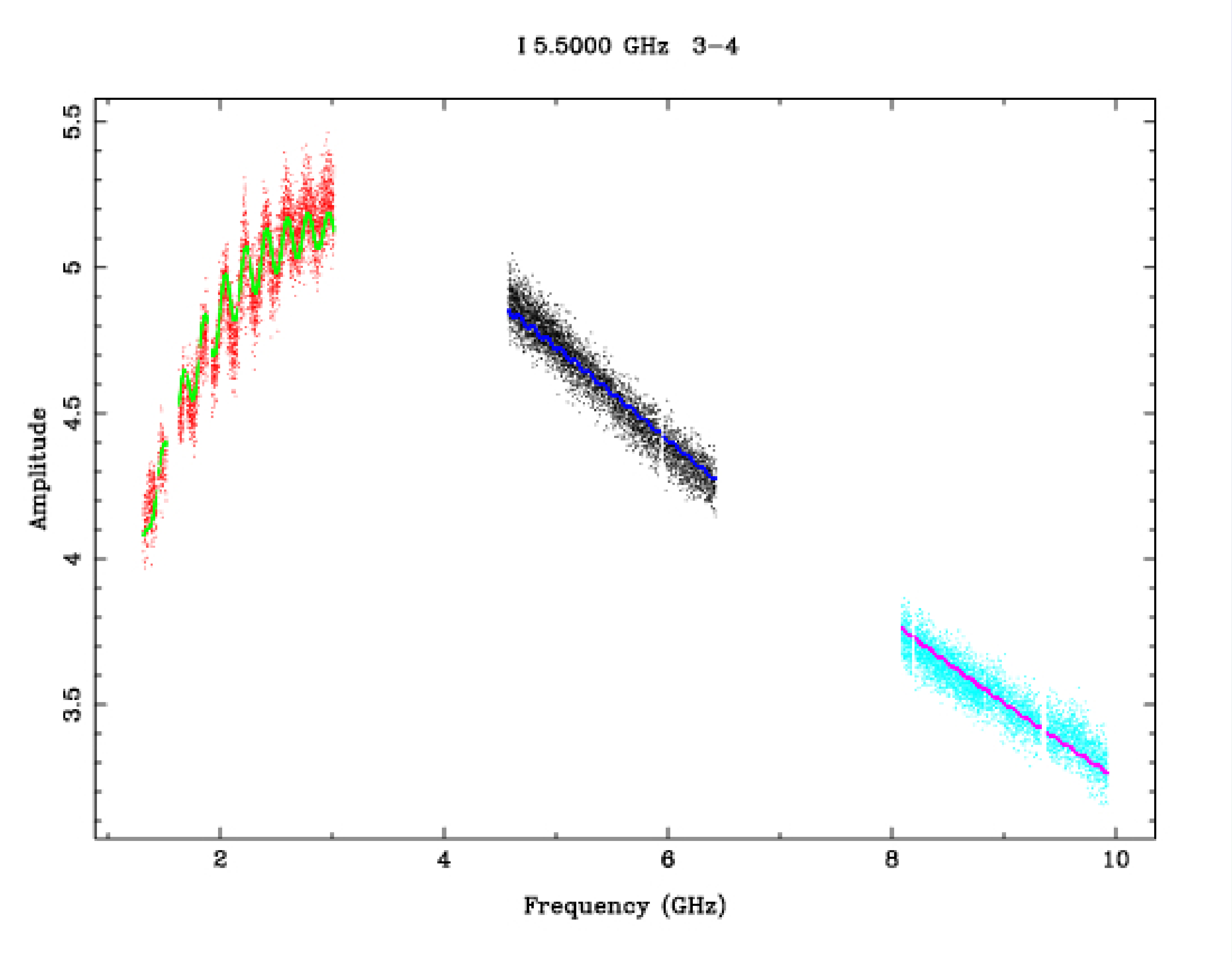
- What are GPS and CSS sources?
- Relativistic jet - ISM interactions
- Evolution of radio spectrum
- Turnover frequency - size relation
- Relevance to AGN feedback

GPS source: PKS 1718-649 Tingay et al. '15

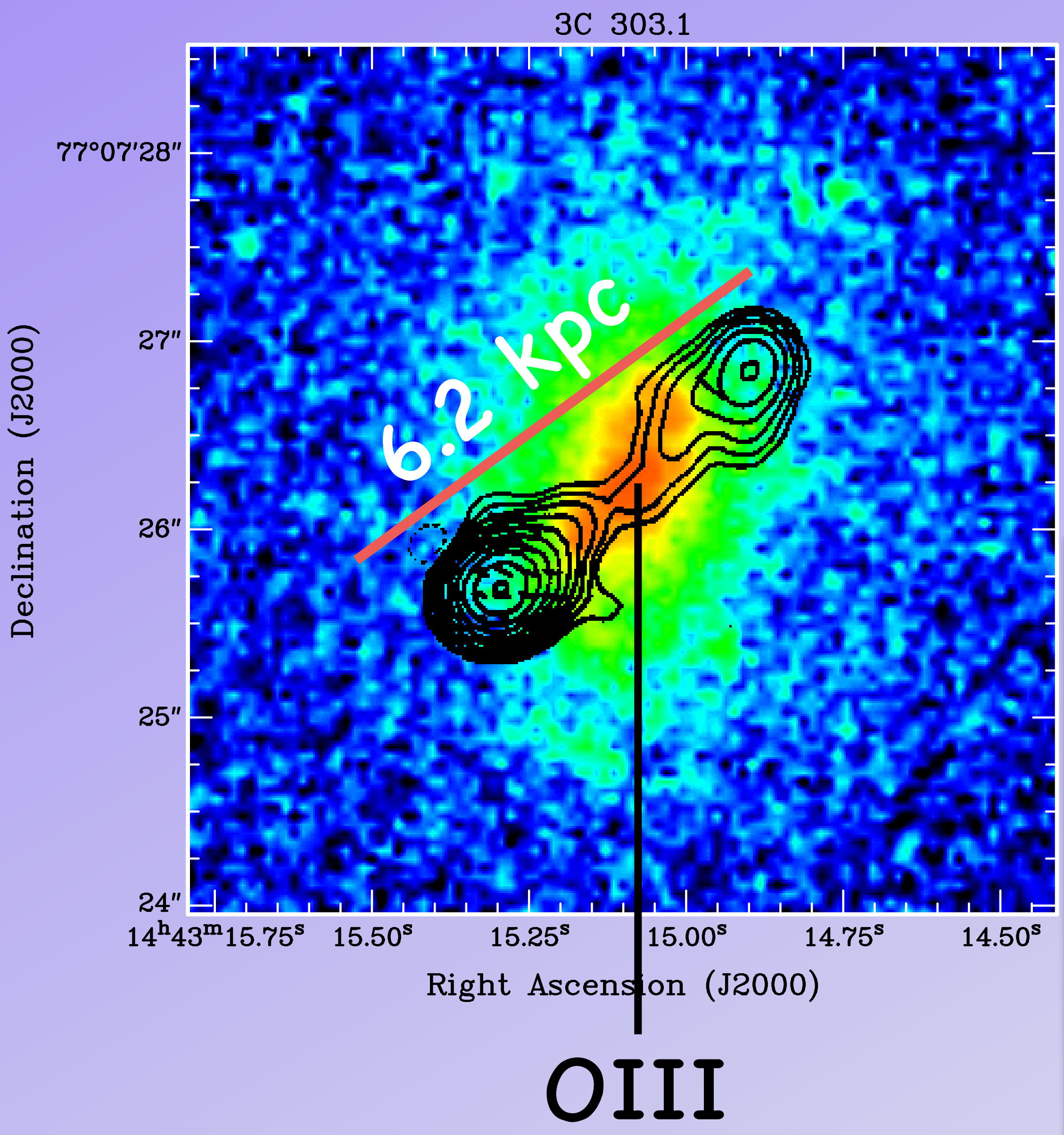


3.6 pc in size

Spectral Turnover at ~ 3 GHz

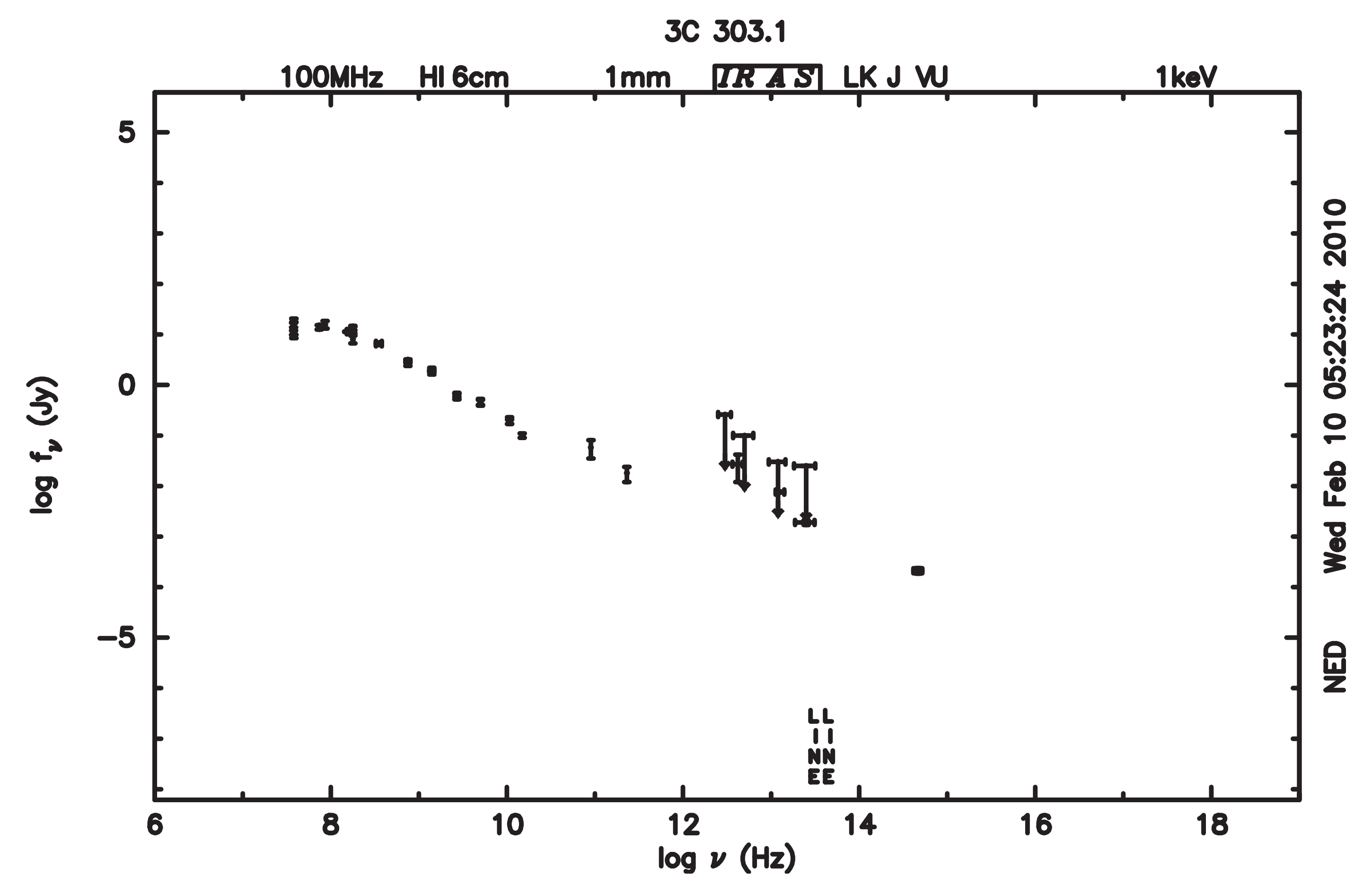


CSS source: 3C303.1; Leahy & Perley '91

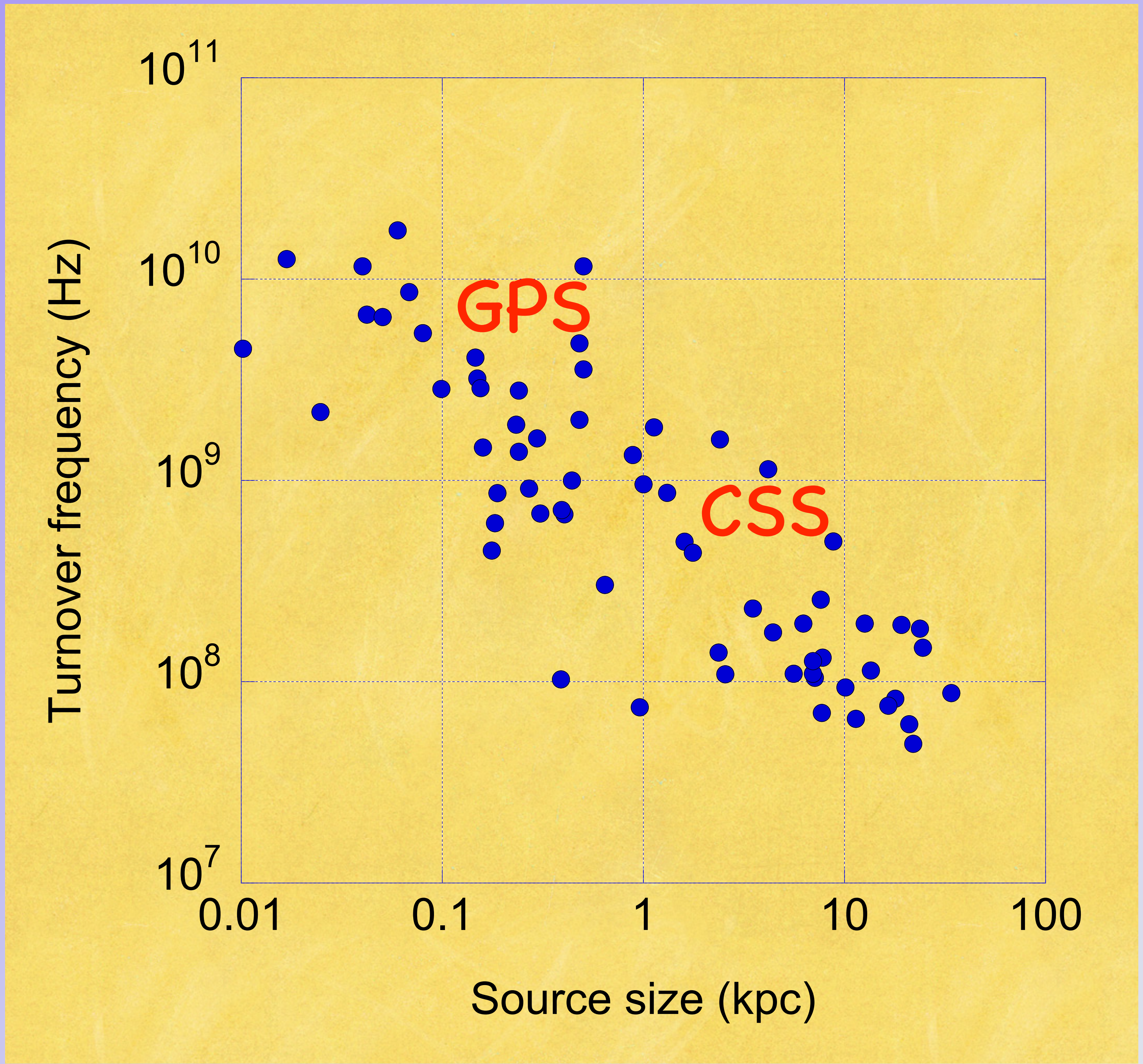


~ 6.2 kpc in size

Spectral turnover at ~ 100 MHz



Turnover frequency – size relation (O'Dea & Baum '97)



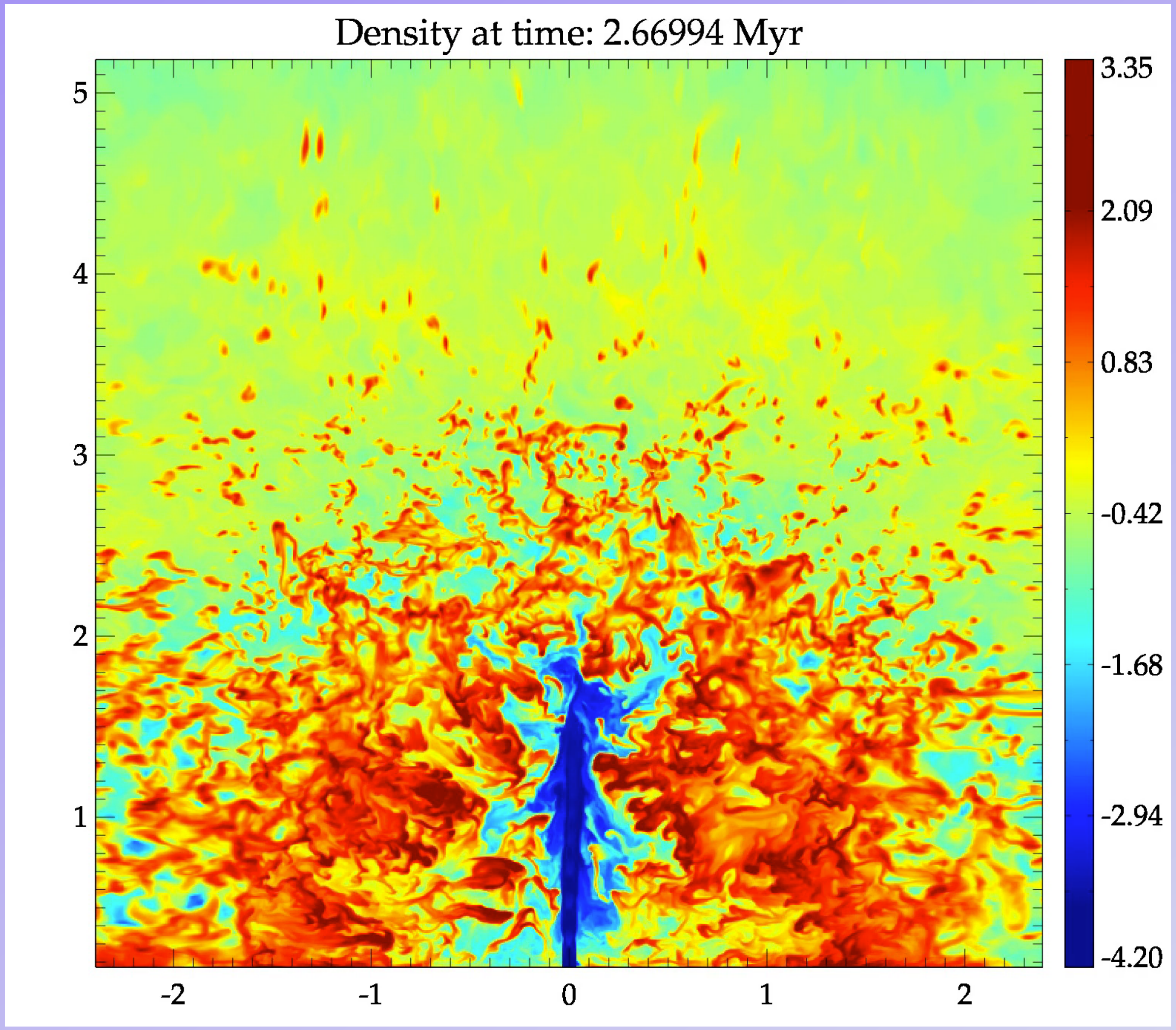
Inverse correlation between turnover frequency and size

GPS and CSS sources represent different evolutionary stages of radio galaxies

Simulations of relativistic jet feedback

- Code: PLUTO Relativistic Hydrodynamics Code – Andrea Mignone et al.
- Thermal cooling using MAPPINGS cooling function – Sutherland & Dopita
- Australian National Computational Infrastructure supercomputer
- See Mukherjee, GB, Wagner & Sutherland, MNRAS, 2016 for simulations

Galaxy & ISM - halo + warm clouds

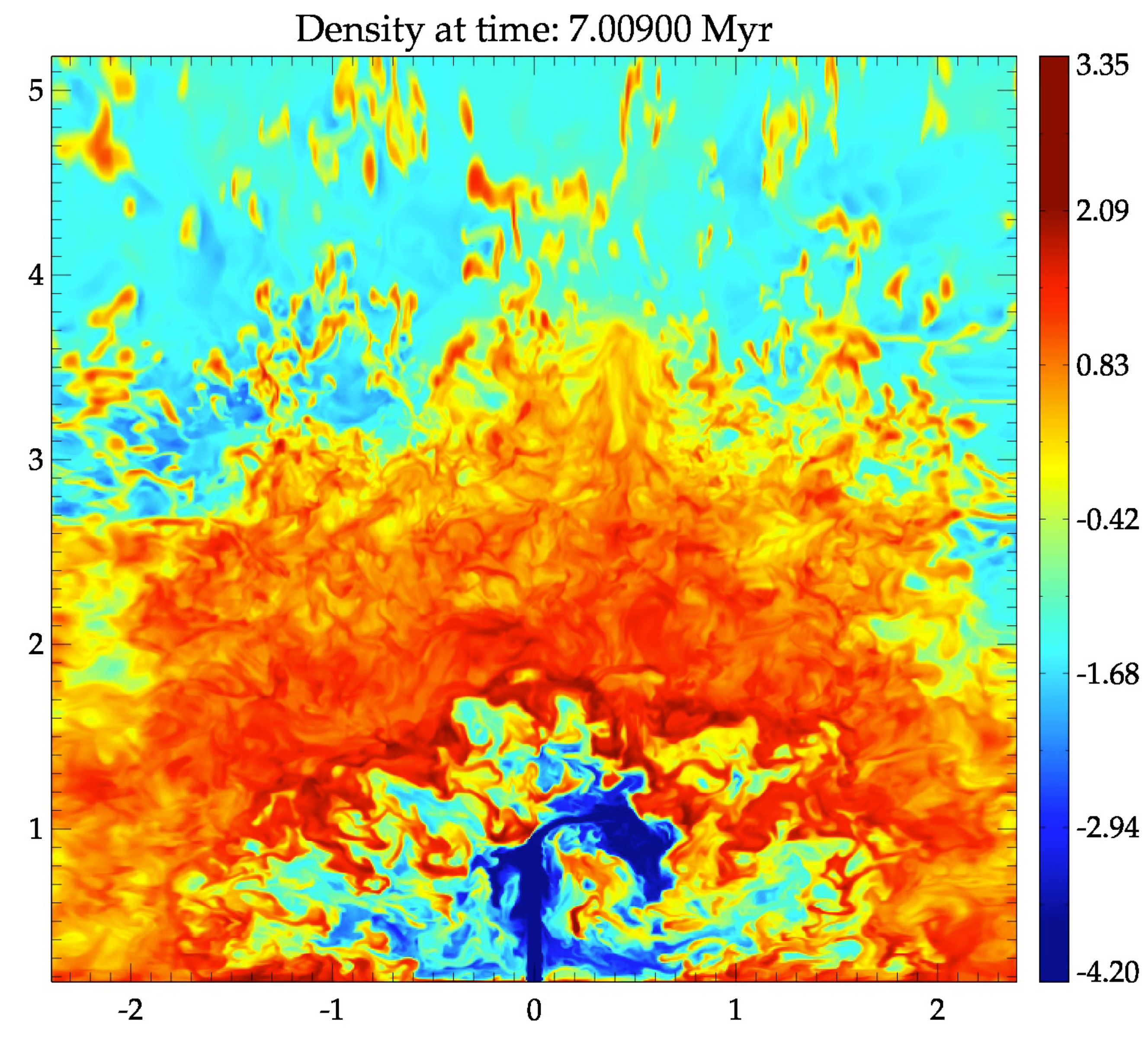


Core radius	1 kpc
Vel. dispersion	250 km/s
Halo temperature	10^7 K
Halo density	n(0) = 0.5 cm^{-3}
Cloud mean temperature	10^4 K
Initial gas turbulent velocity	250 km/s
Initial mean warm no. density	150, 300 cm^{-3}

$$\rho_{\mathrm{warm}} = \mathrm{Log\ normal\ distribution}$$

$$\frac{\rho_{\mathrm{warm}} k T_{\mathrm{warm}}}{\mu m} = p_{\mathrm{halo}}$$

Jet and ISM parameters

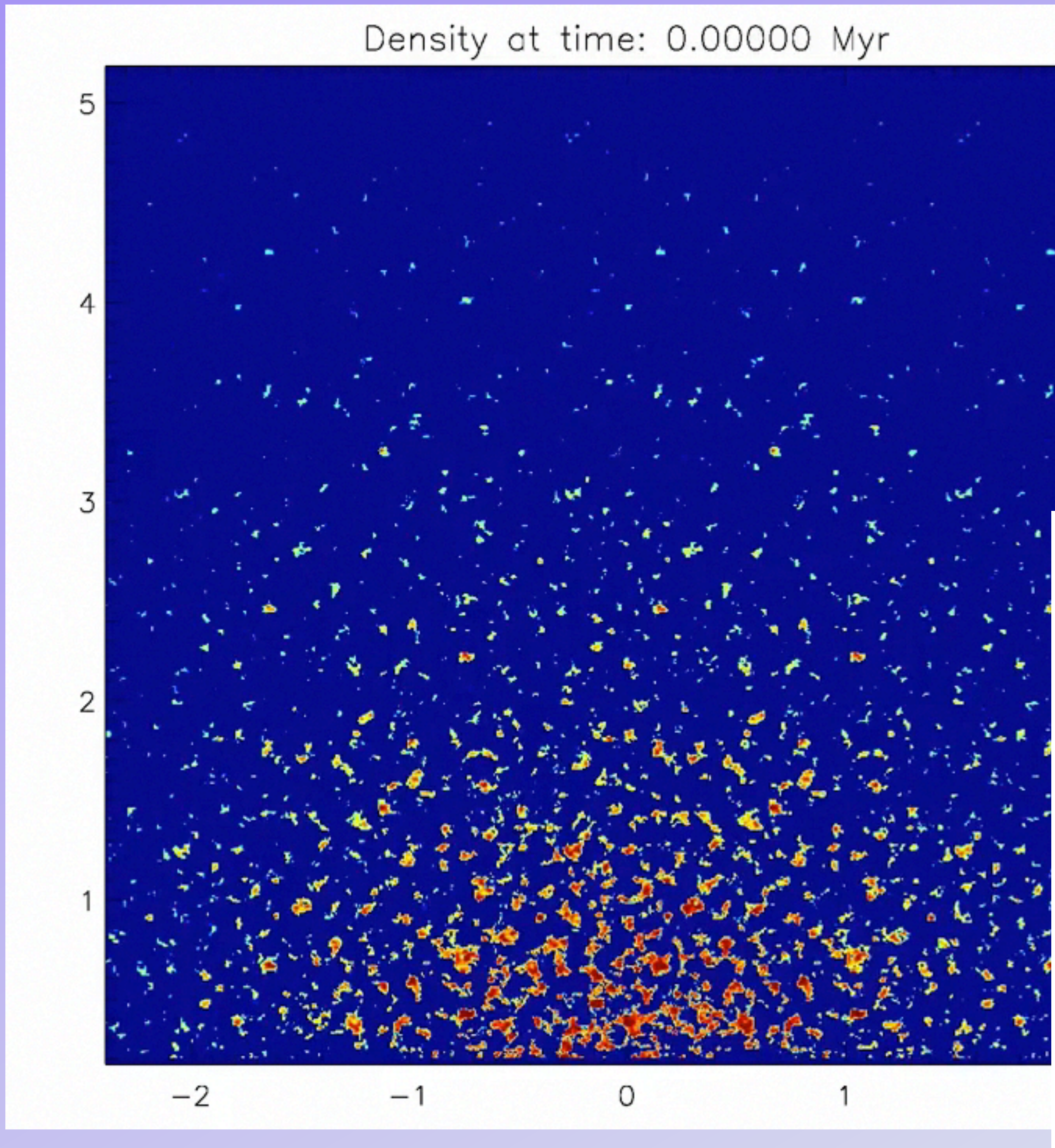


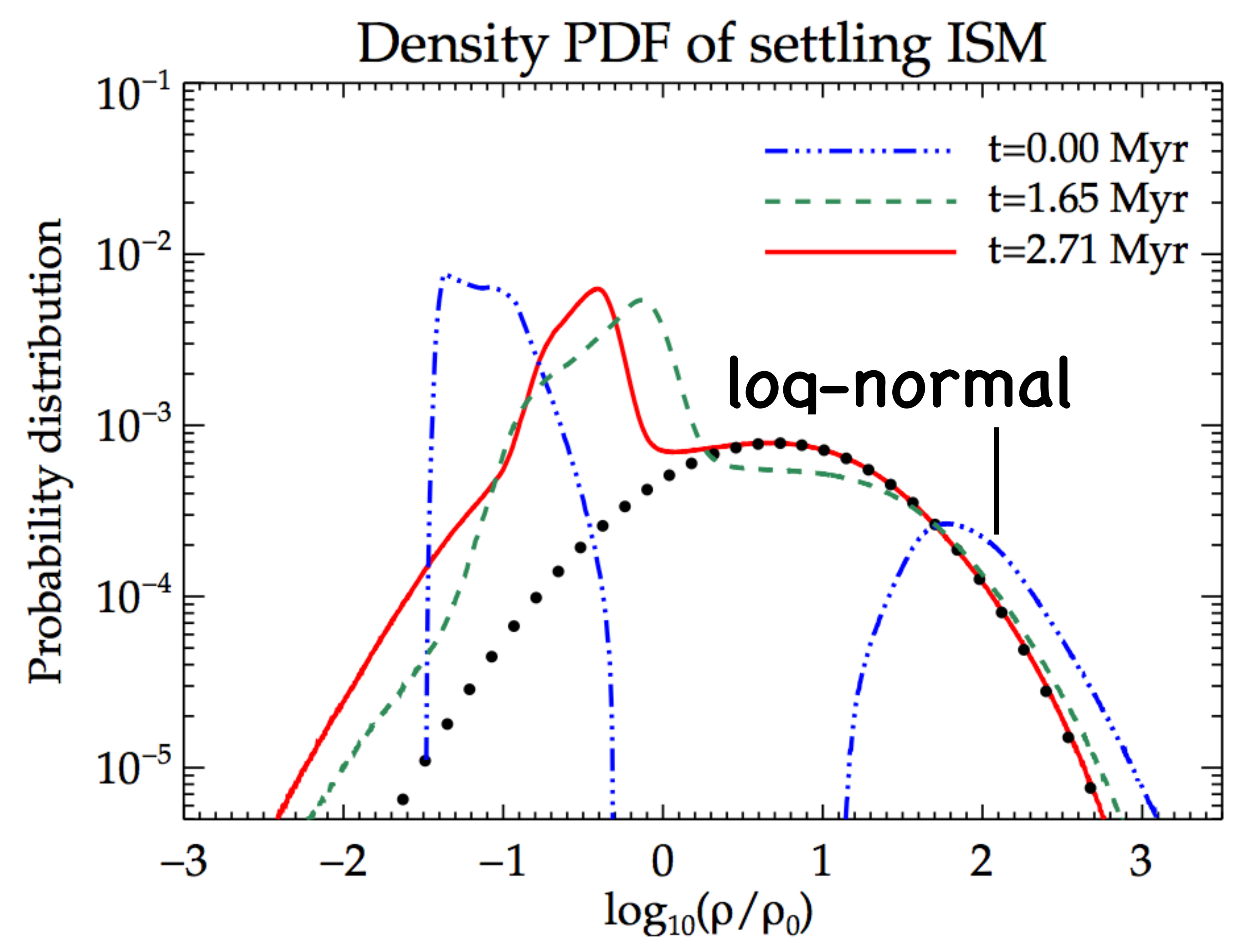
Simulat-ion	Jet Power ergs/s	Lorentz Factor	Initial density cm^{-3}
A	10^{44}	4	150
B	10^{45}	5	150
C	10^{43}	2	300
D	10^{45}	5	300

Densities: Shirazi+ '14; Sanders+ '16

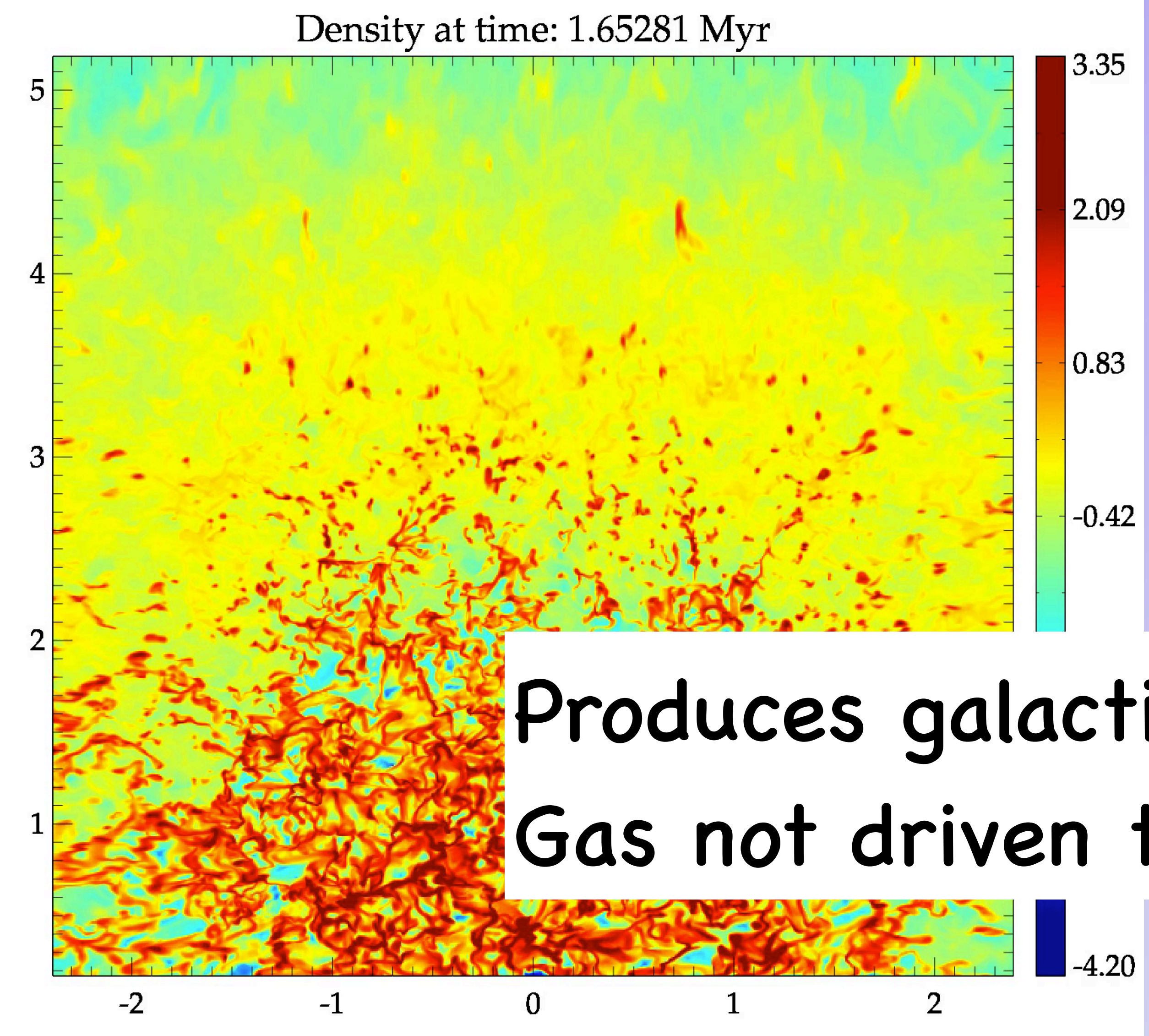
Settling the turbulent ISM

Velocity dispersion of clouds settled to ~100-150 km s^{-1} typical of z~2 galaxies (Förster-Schreiber+ '09)





Density evolution - slices of 3D simulations

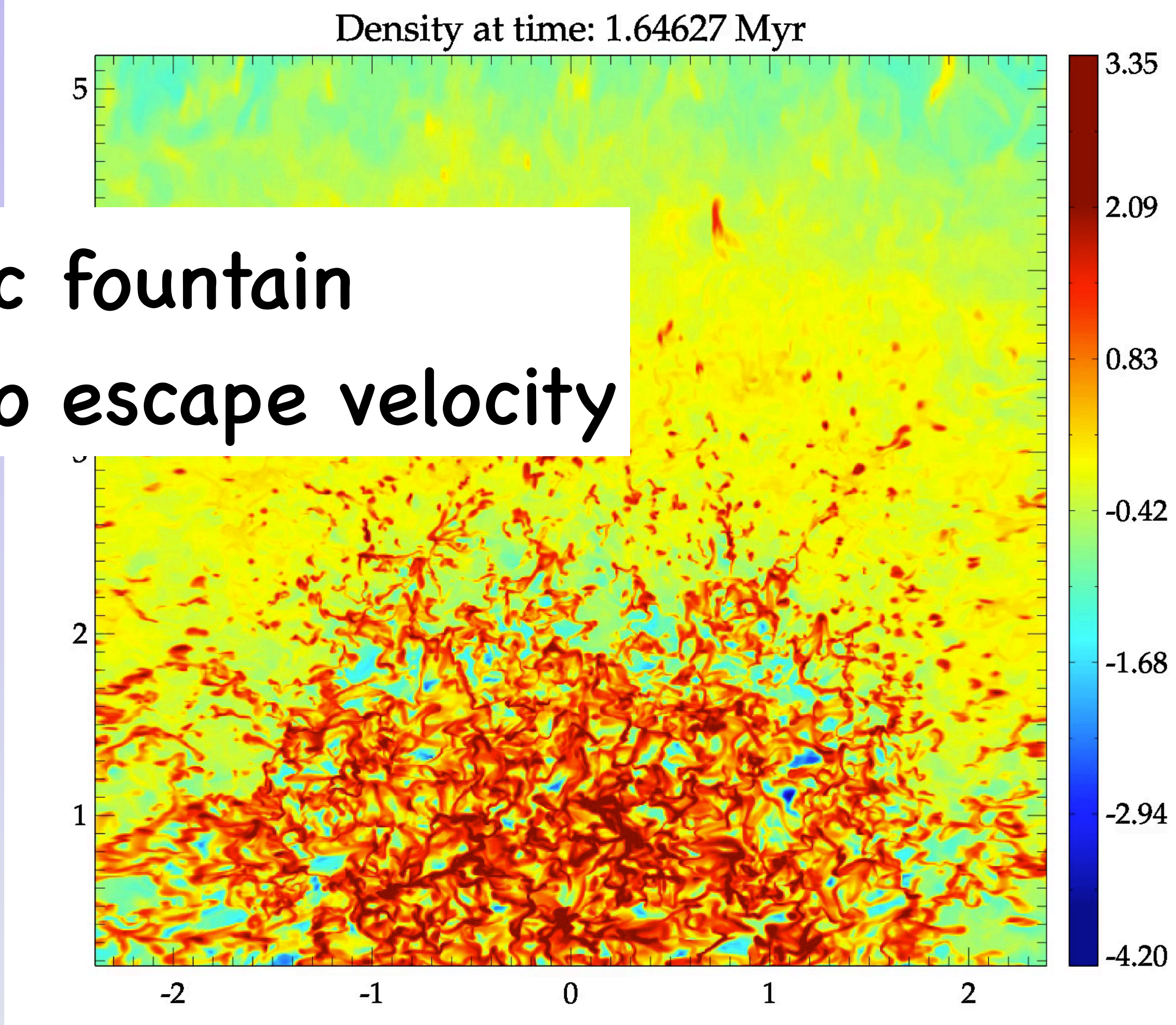

Density at time: 1.65281 Myr

P_{jet} = 10^{45} ergs s^{-1}

$n_{w,0}$ = 300 cm^{-3}

Produces galactic fountain

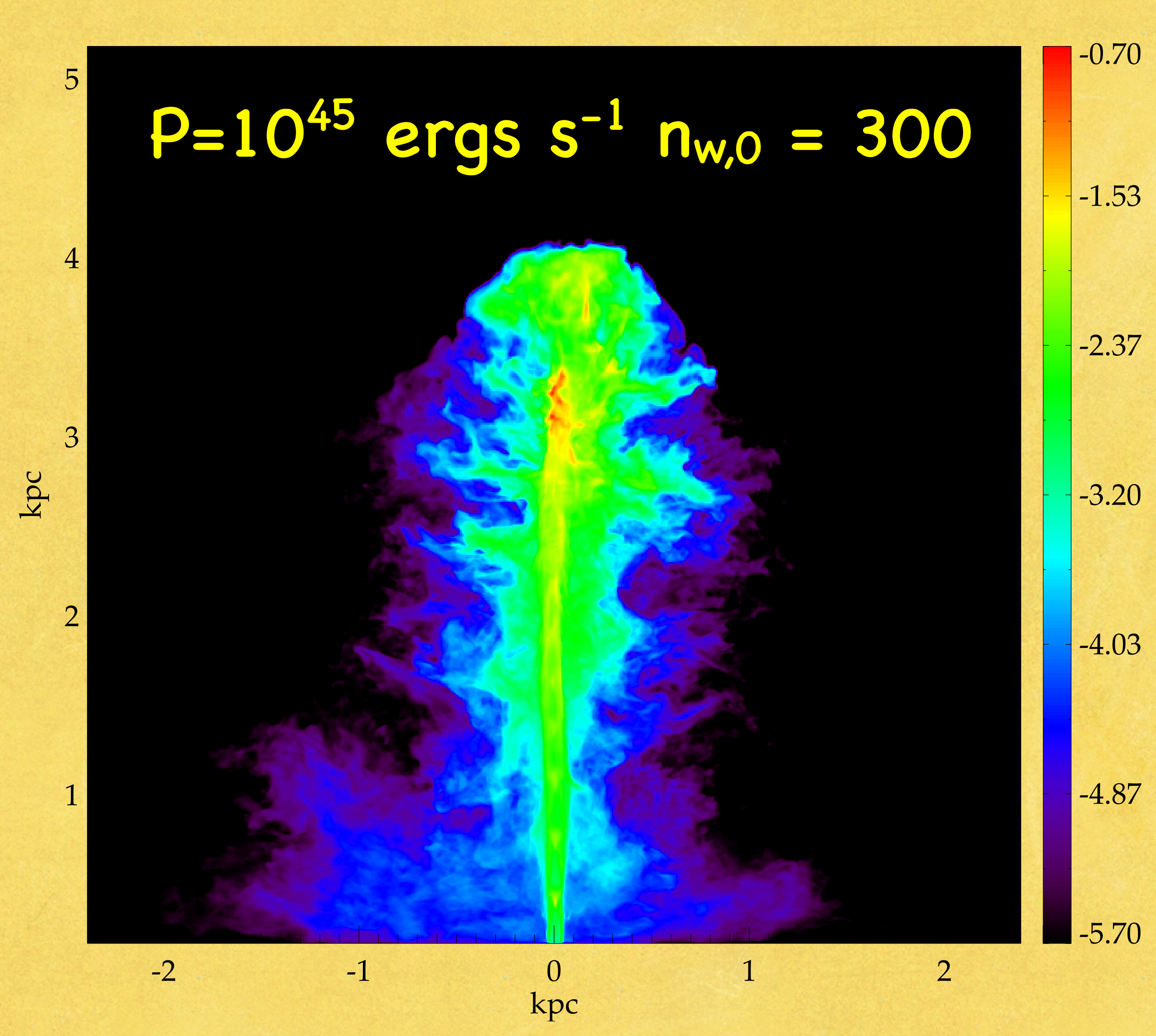
Gas not driven to escape velocity

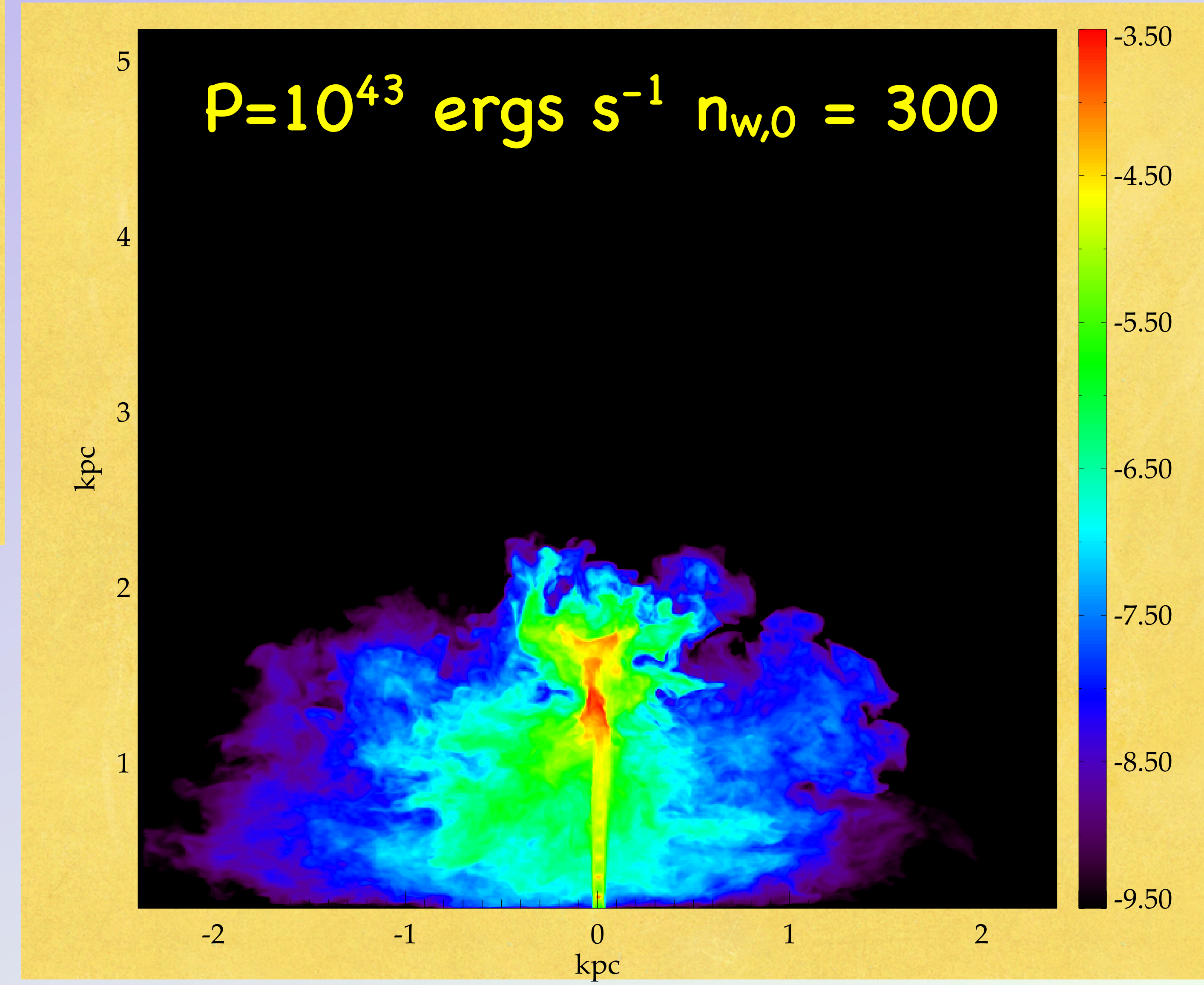

Density at time: 1.64627 Myr

P_{jet} = 10^{43} ergs s^{-1}

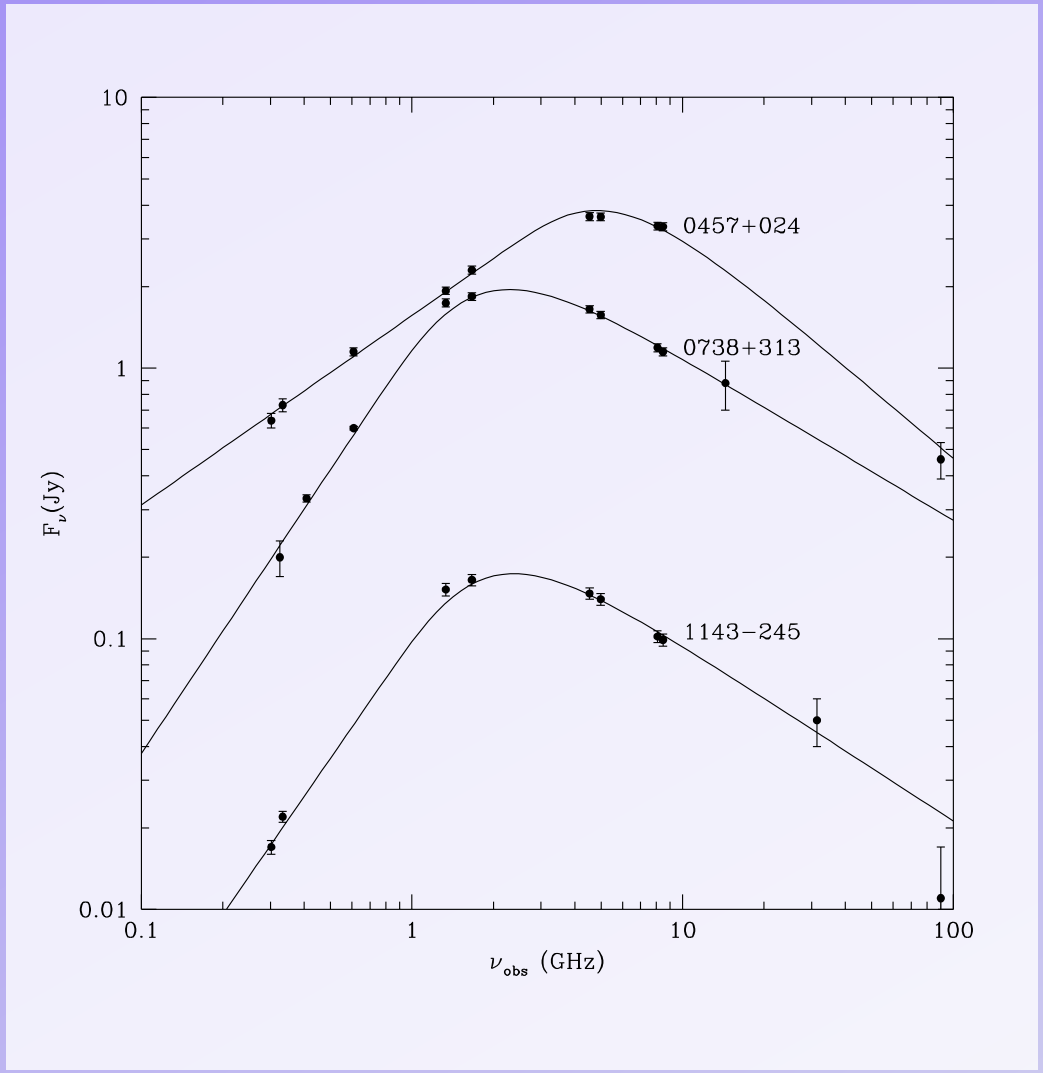
$n_{w,0}$ = 300 cm^{-3}

Surface brightness at 1 GHz



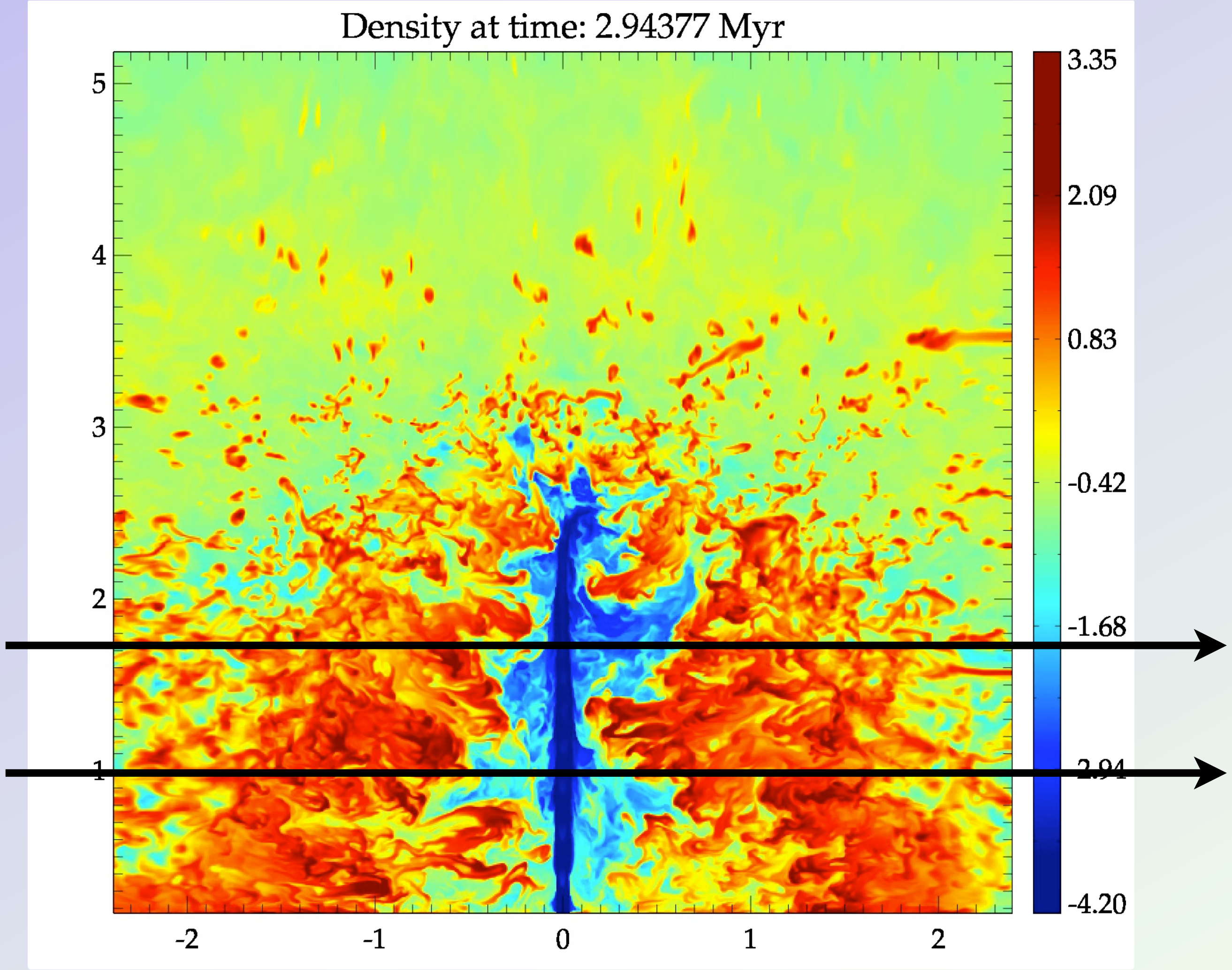


GPS and CSS sources



- Low frequency power-law attributed to distribution of free-free optical depths (GB, Dopita, O'Dea 1997)

Drill through simulation to determine surface brightness and spectrum



Synchrotron emissivity

Assume electron energy density and magnetic energy density proportional to total energy density

Electron energy distribution: $N(\gamma) = K\gamma^{-a} \quad a = 2\alpha + 1$

Doppler factor

Jet tracer

$$\langle j_\nu \rangle = \mathrm{Constants} \times \delta^{2+\alpha}\phi_{\mathrm{jet}}\, f_{\mathrm{e}}\, f_{\mathrm{B}}^{(a+1)/4} \left(\frac{\epsilon_{\mathrm{tot}}}{\epsilon_0}\right)^{(a+5)/4} \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

$$\begin{aligned} \epsilon_e &= f_e \times \epsilon_{\mathrm{tot}} & \qquad \epsilon_B &= f_B \times \epsilon_{\mathrm{tot}} \\ f_e &= 0.1 & \qquad f_B &= 0.3 \end{aligned}$$

Free-free absorption

Density^2 dependence

$$\alpha_\nu(Z) = \text{Constants} \times \left(\frac{kT}{m_\mathrm{e}c^2}\right)^{-3/2} n_\mathrm{e}\, n_\mathrm{i}(Z)\, Z^2\, g_\nu(T,Z)\, \nu^{-2}$$

Frequency dependence

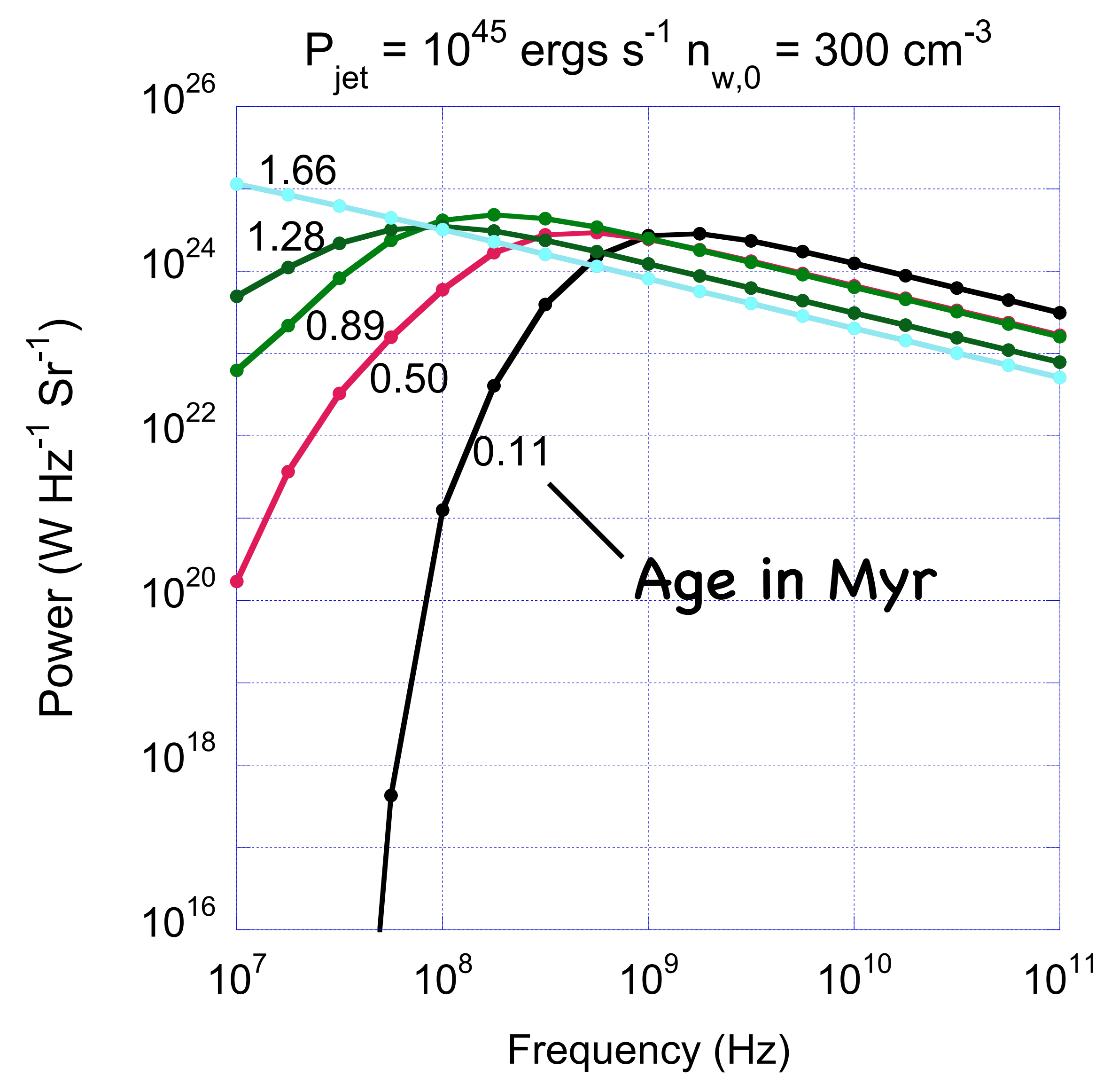
Integrate

$$\frac{dI_\nu}{ds} = \langle j_\nu \rangle - \alpha_\nu I_\nu$$

along rays through volume

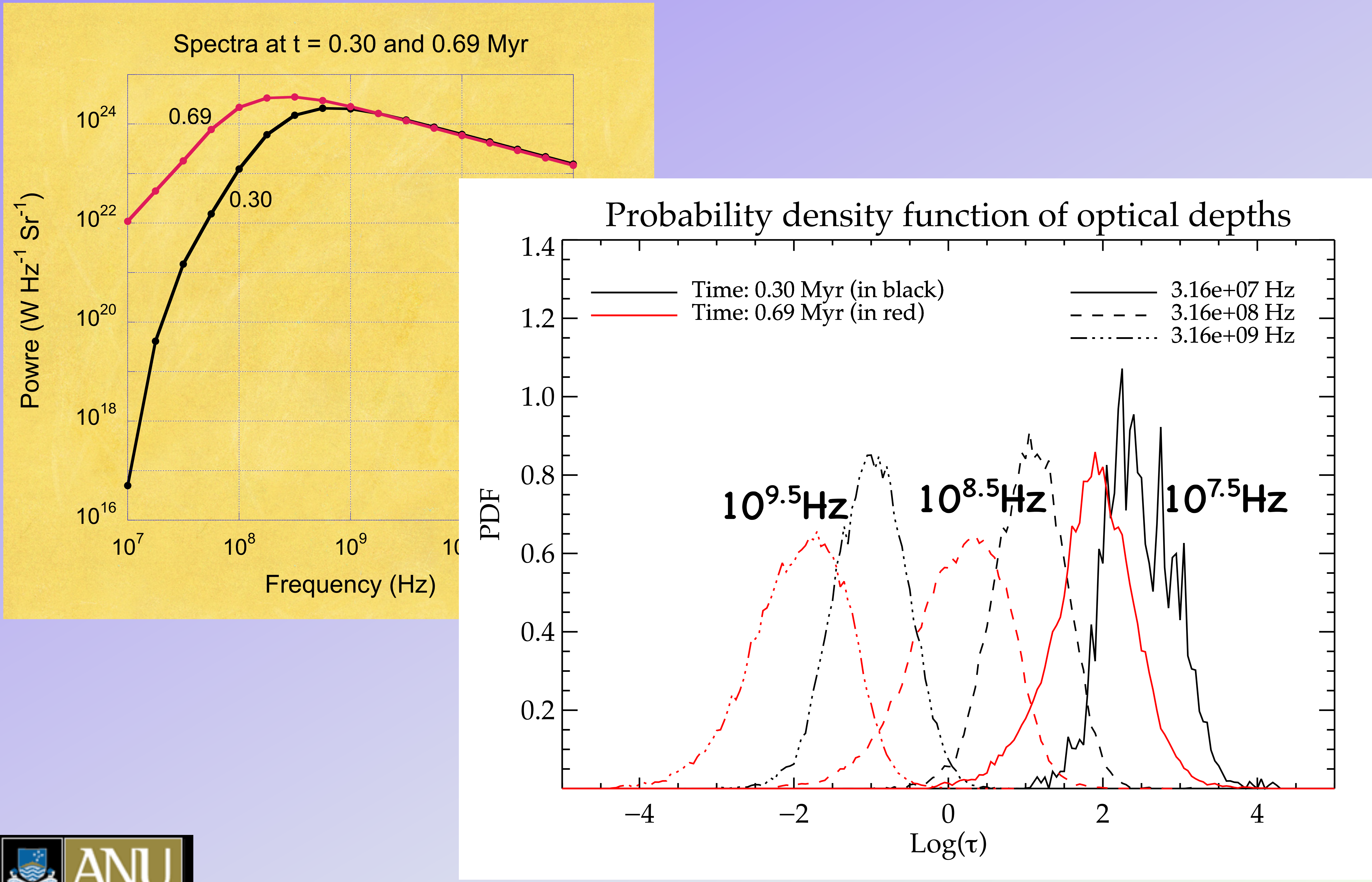
Spectral evolution for

$P_{jet}=10^{45}$ ergs/s $n_{w,0}$ = 300 cm^{-3}

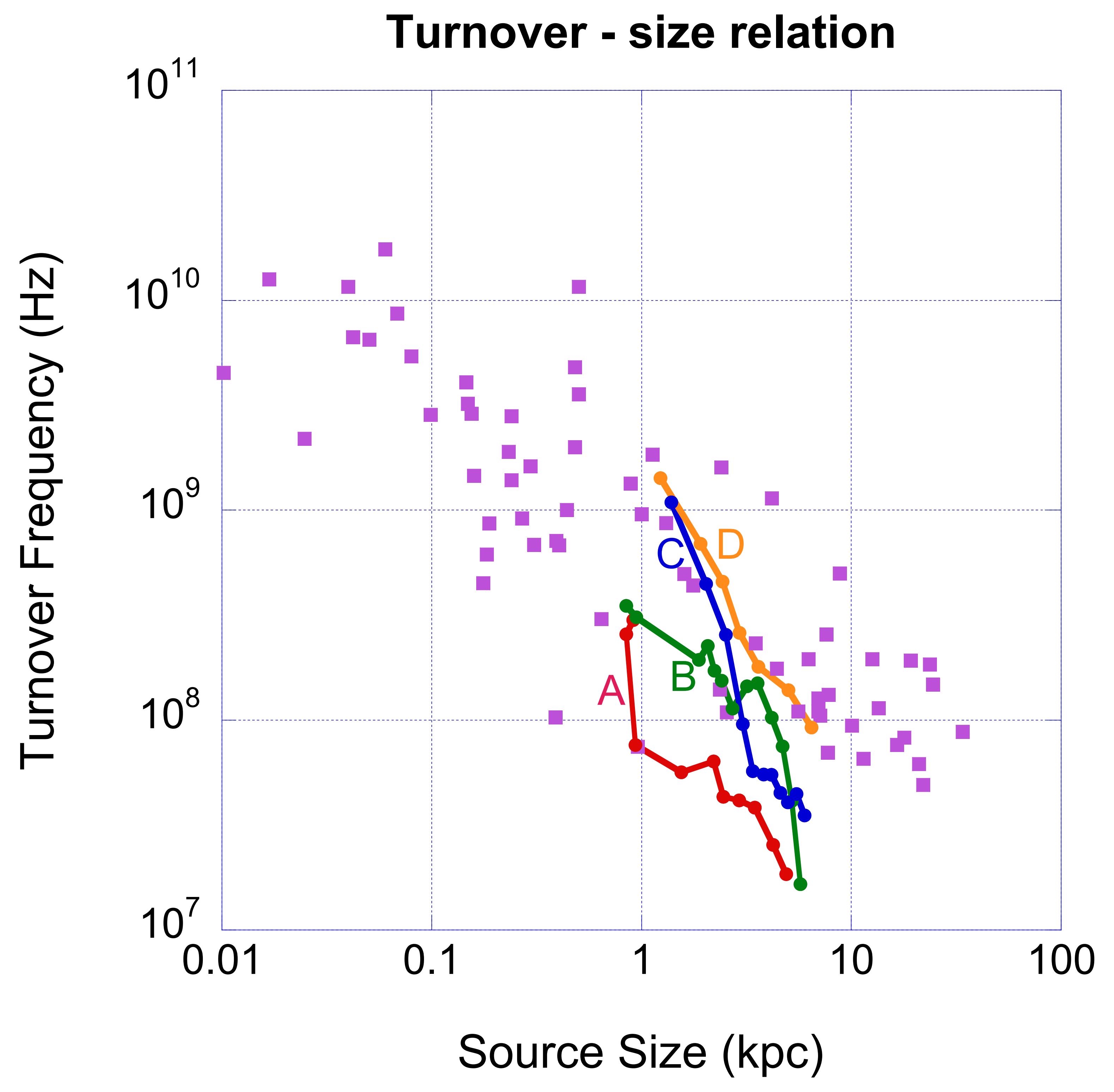


- Peak moves to lower frequencies as source evolves – Effect of decreasing density and path length
- Spectral slope flattens – Effect of increasing dispersion in optical death

Spectrum and optical depth



Turnover frequency – size relation



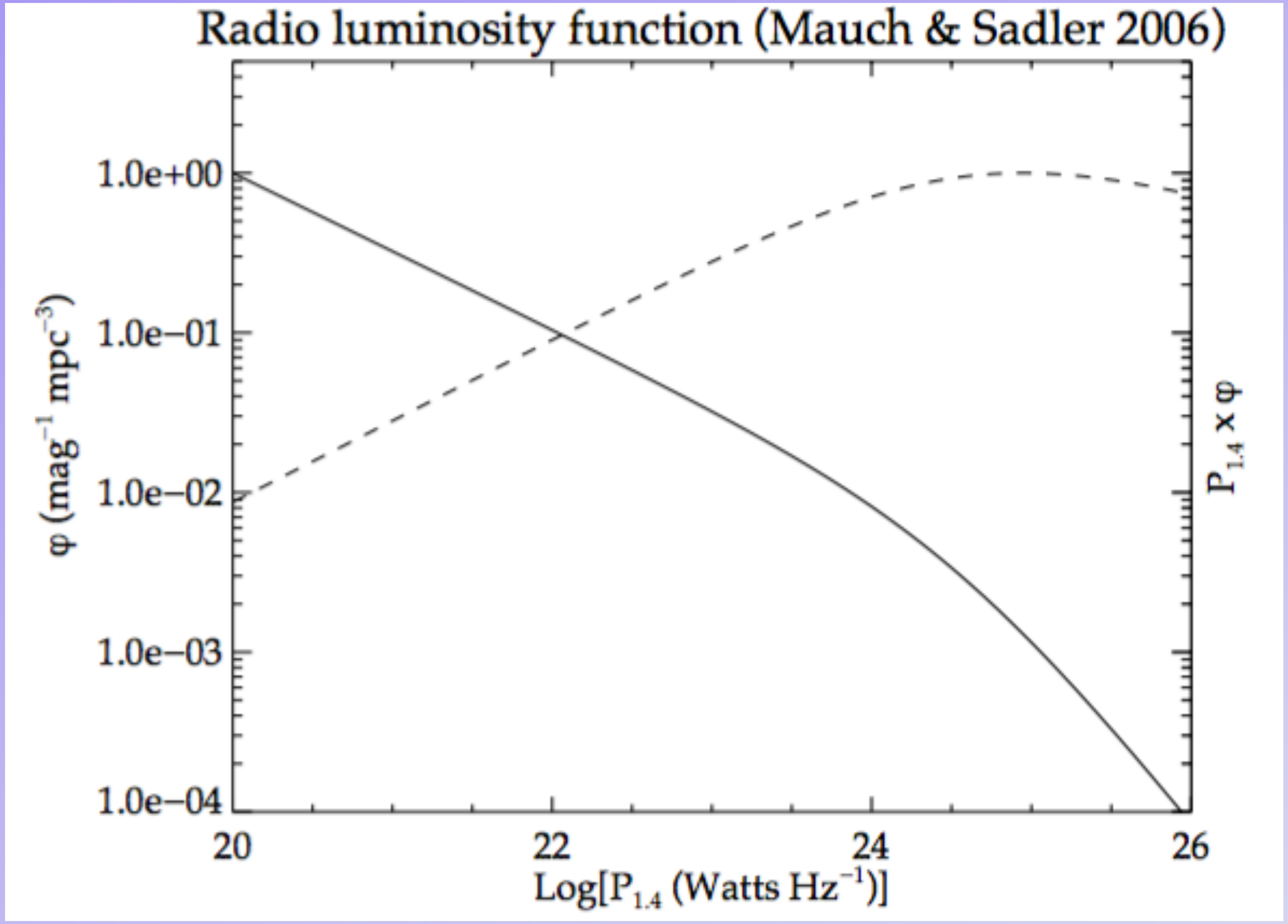
Sim.	Jet Power ergs/s	Initial density cm^{-3}
A	10^{44}	150
B	10^{45}	150
C	10^{43}	300
D	10^{45}	300

Summary

- GPS and CSS sources strongly related to AGN feedback in early stages of galaxy evolution
- Low-powered jets important - FR0 sources?
- Low frequency turnover plausibly related to free-free absorption by inhomogeneous ISM
- Initial density and velocity dispersion of ISM similar to values inferred from optical observations
- Radio spectrum provides independent information on ISM density and spectrum of density fluctuations – important for modelling feedback

Additional slides

Jet power

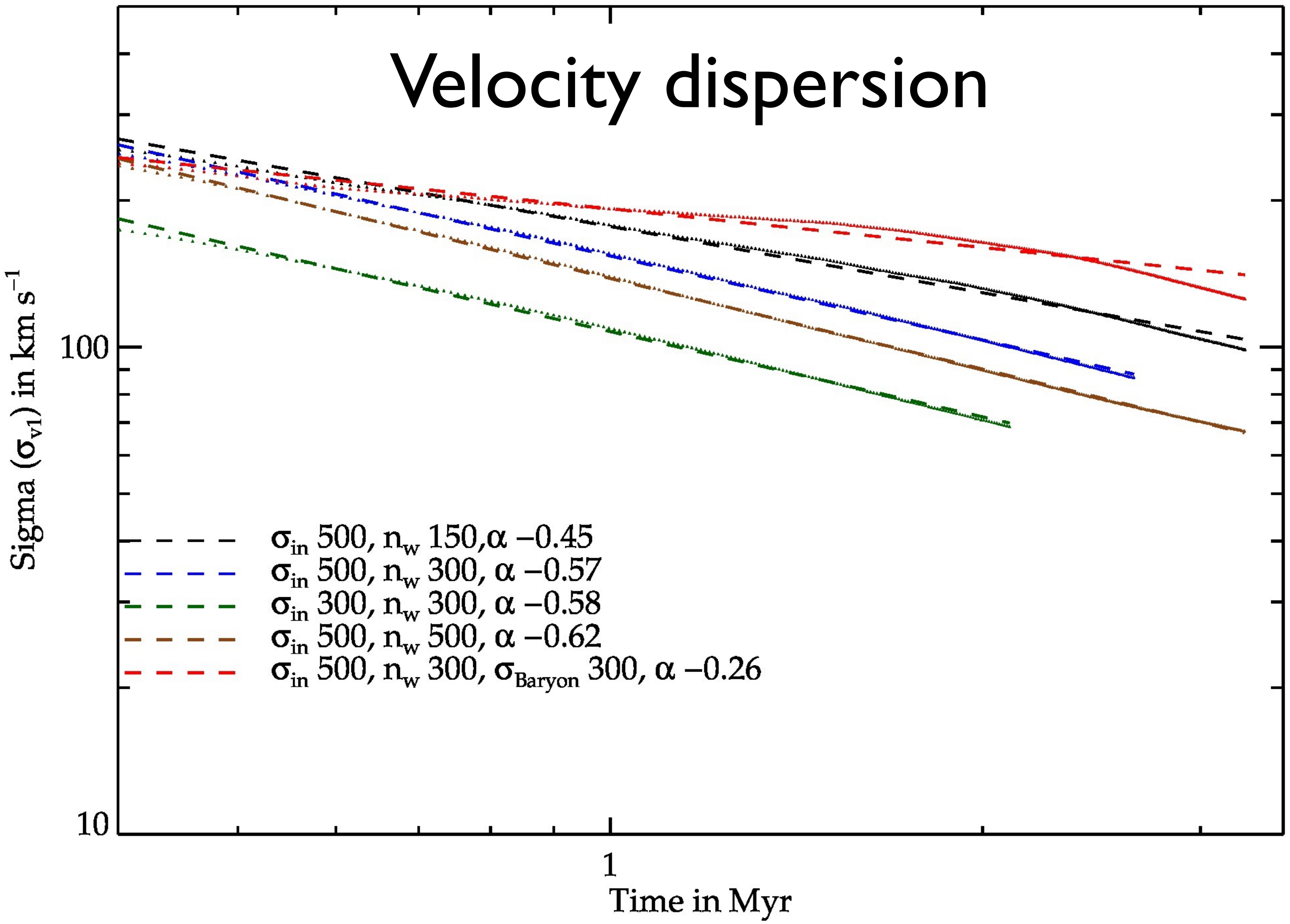


Most important range of 1.4 GHz radio power around

10^{25} W Hz^{-1}

Corresponds to jet power ~ 10^{43-45} ergs s^{-1}

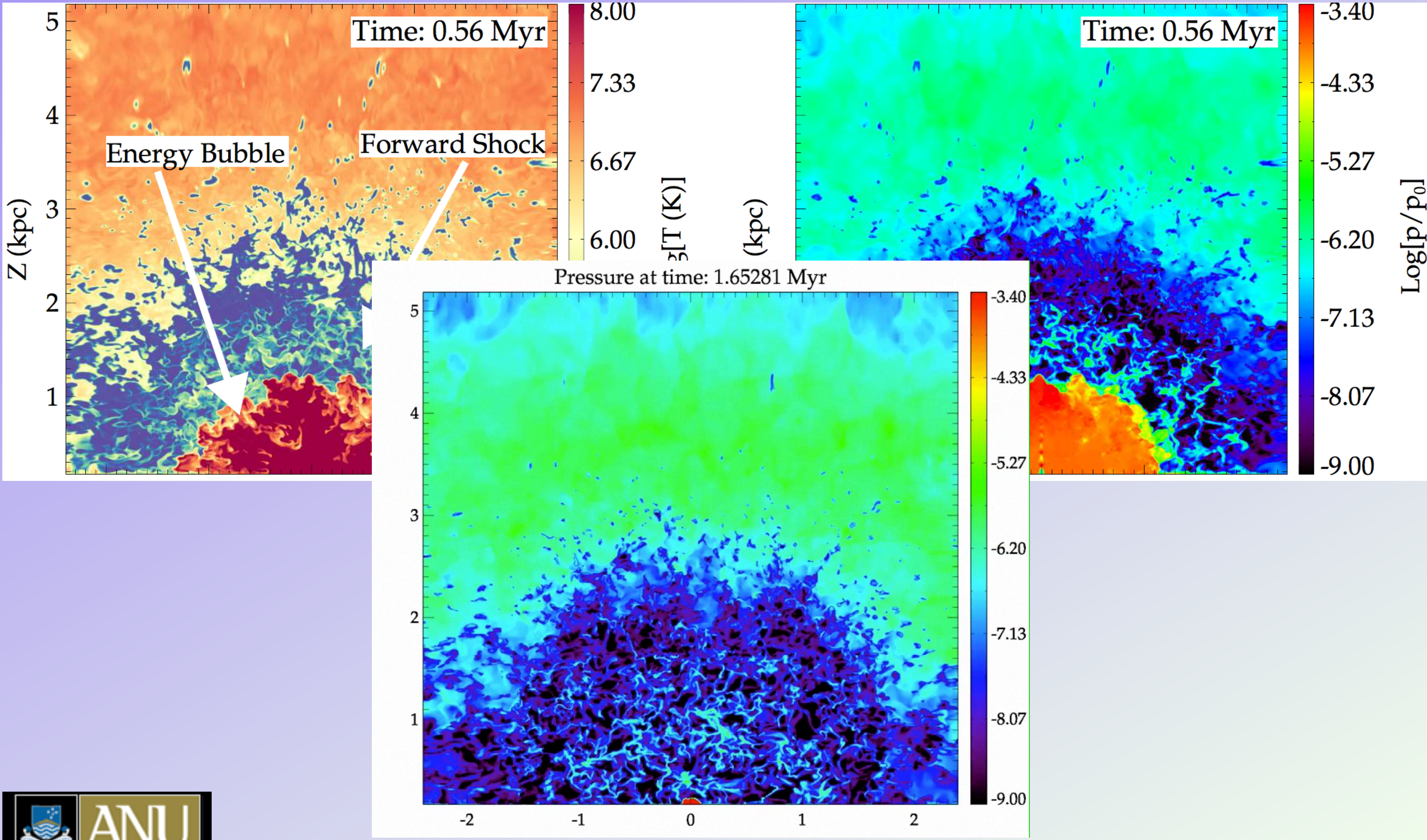
Velocity dispersion



- Initial turbulent set up: lognormal in density, Gaussian in velocity
- Cloud-cloud collisions, shearing and cloud merger result in elongated filaments
- Settled until σ ~ 150-100 km/s

e.g. Förster-Schreiber+ '09

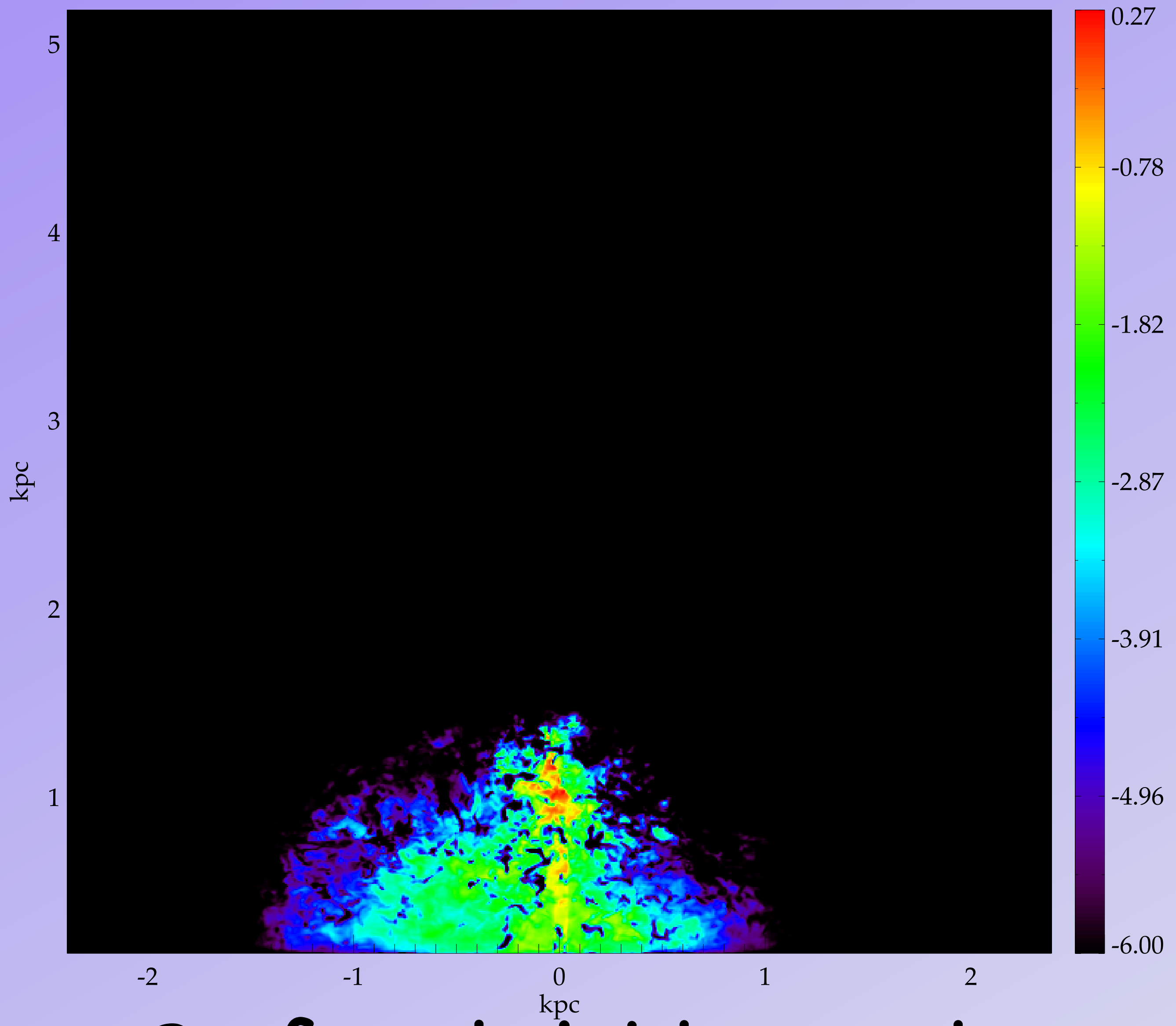
Structure from temperature and pressure



Temperature

Pressure

Surface brightness and optical depth

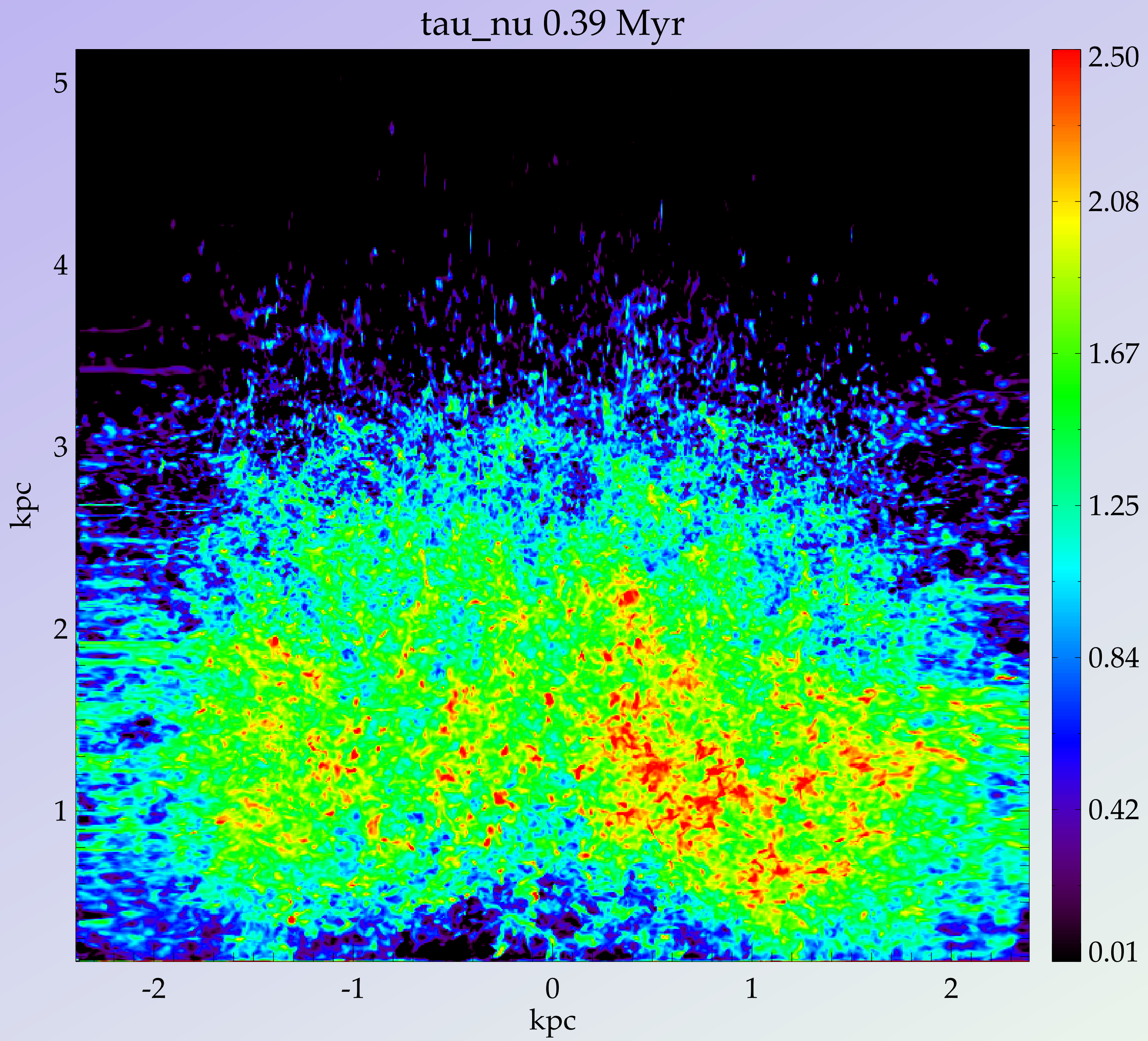


Surface brightness at

τ = 0.39 Myr

Optical depth at

τ = 0.39 Myr



$\Delta\tau \sim 1 - 2.5$