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Idealized Simulations of AGN (Jet) Feedback

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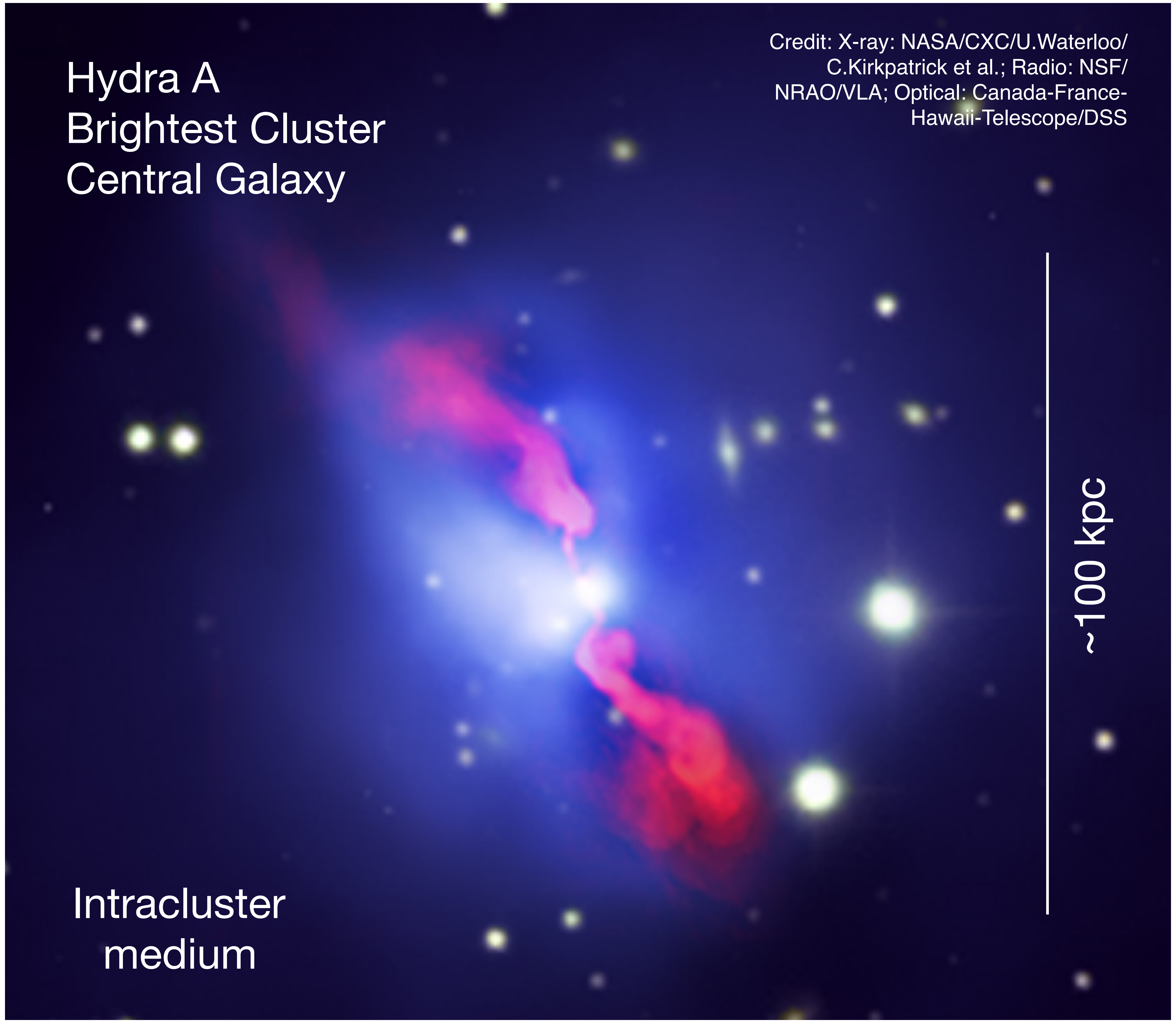
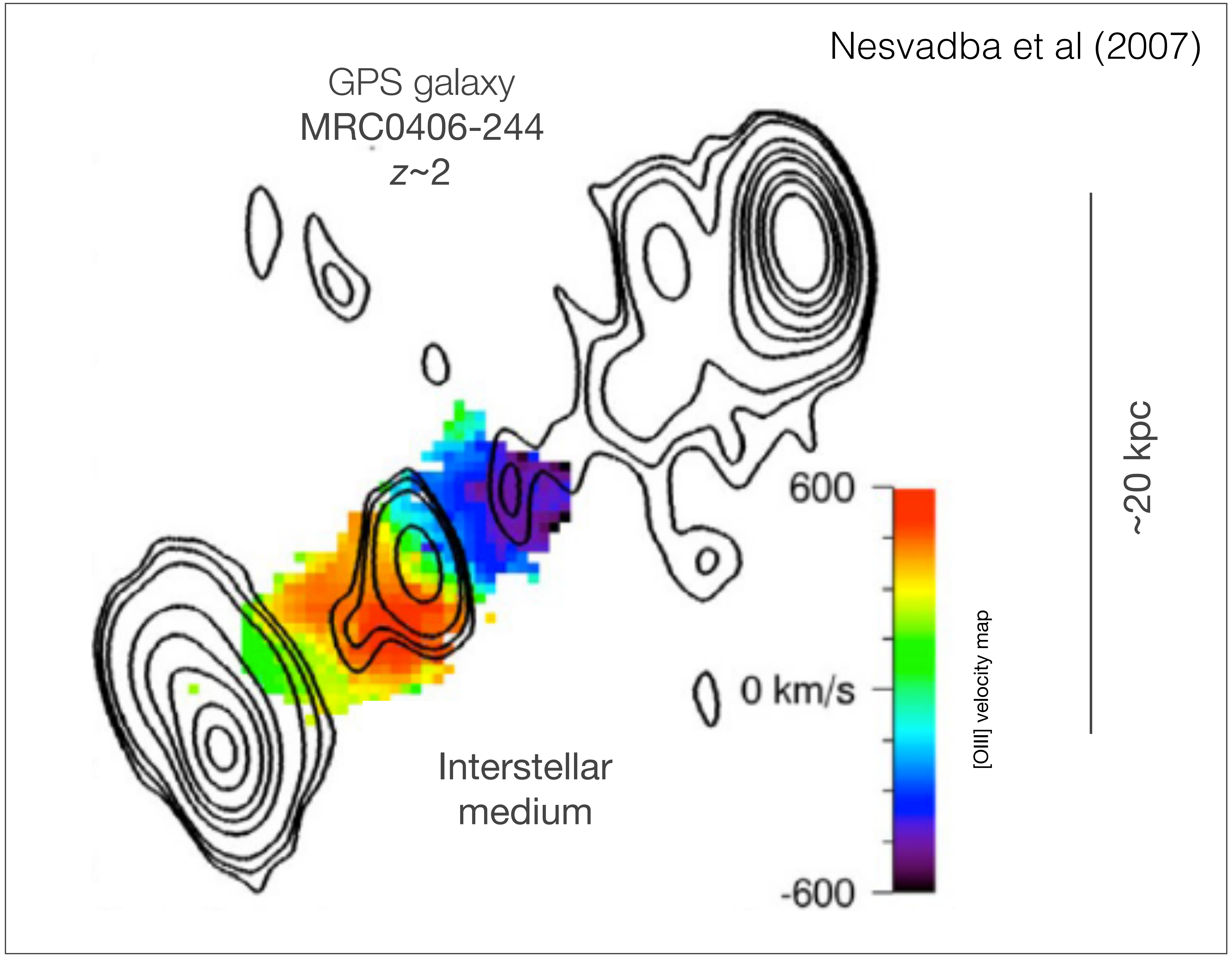
How do AGN jets and winds affect the interstellar medium of galaxies?

Gemini Observatory/AURA, artwork by Lynette Cook

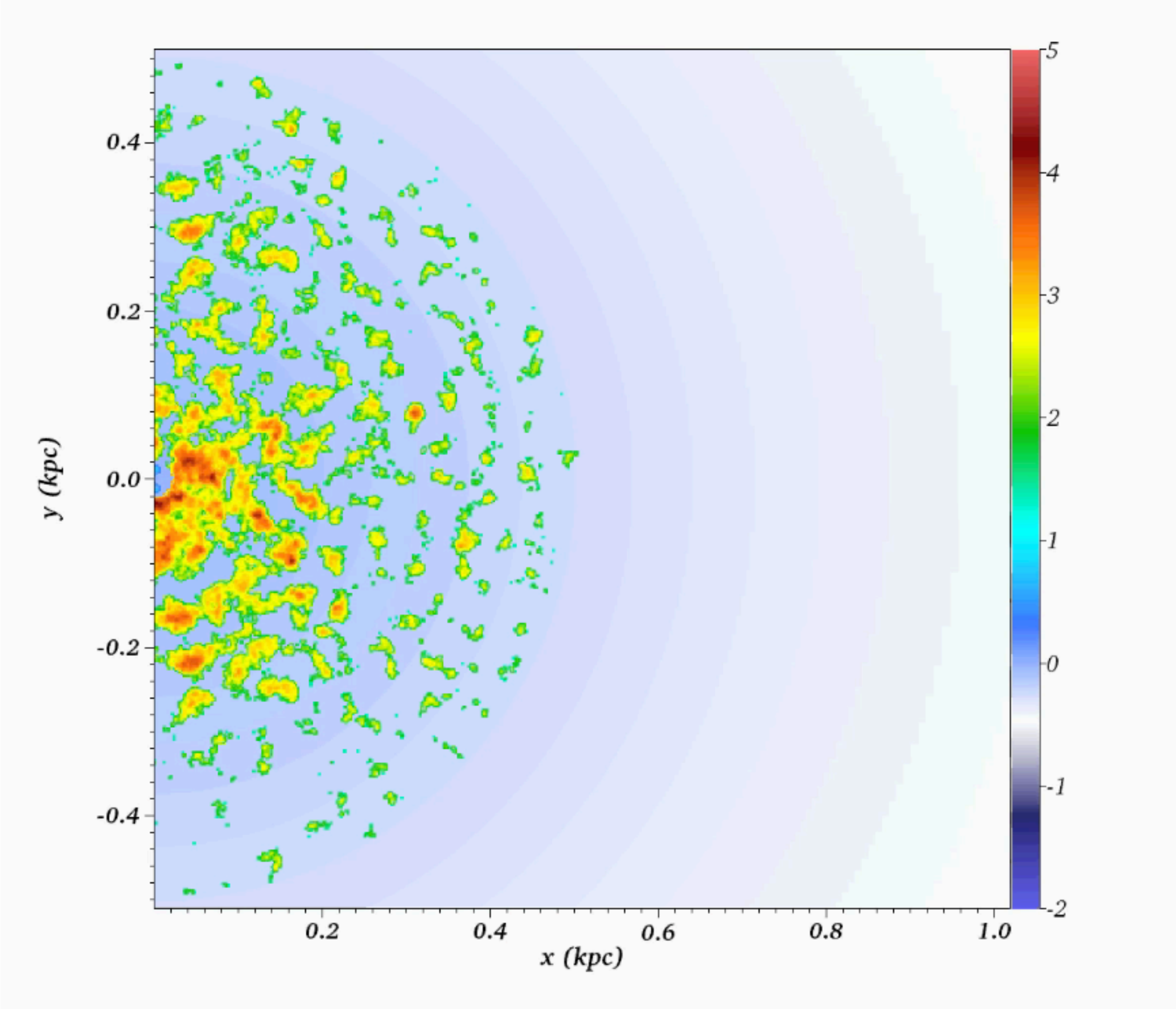
AGN jet feedback - “radio mode” and “quasar mode”





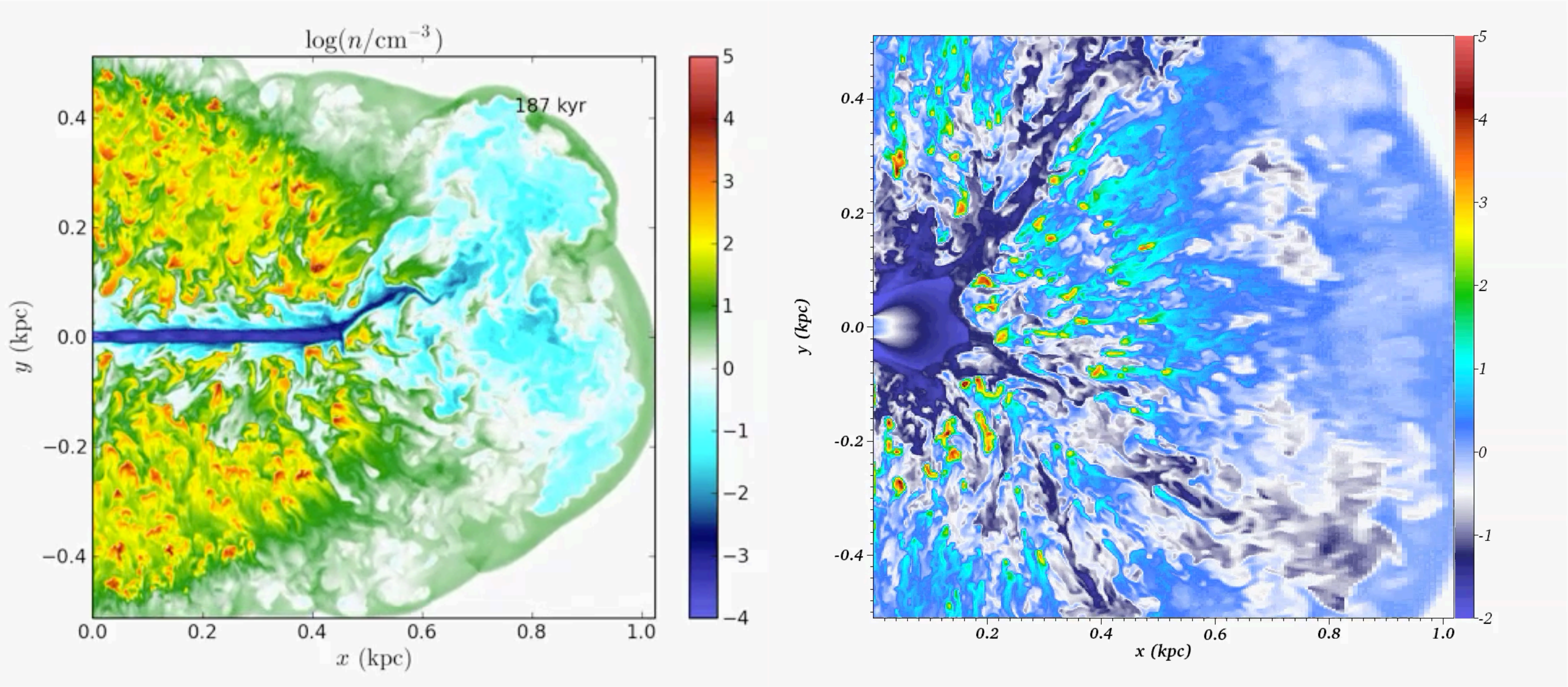
Representative simulation setup

- **Single fluid** for jet and hot and warm gas phases
- Solve **special relativistic fluid equations** in the case of **jets**.
- *Physics (source terms)*:
  - Newtonian **static gravity** (no self-gravity)
  - Optically thin, tabulated NIE **atomic radiative cooling** for solar abundances pre-calculated with MAPPINGS V
- *Setup*:
  - Small central **jet/wind injection** region
  - **Hot**, isothermal, hydrostatic **halo**
  - Clumpy, cold, dense **clouds**…
    - **spatially fractal** distribution *
    - **log-normal density** distribution *
    - are in static pressure equilibrium, or given a Keplerian + random Gaussian velocity
- *Codes*:
  - FLASH 3.x (with Paramesh AMR)
  - PLUTO 4.x (with stretched cartesian grid)
  - RAMSES
  - * pyFC to generate clouds



Idealized simulations of mechanical AGN feedback

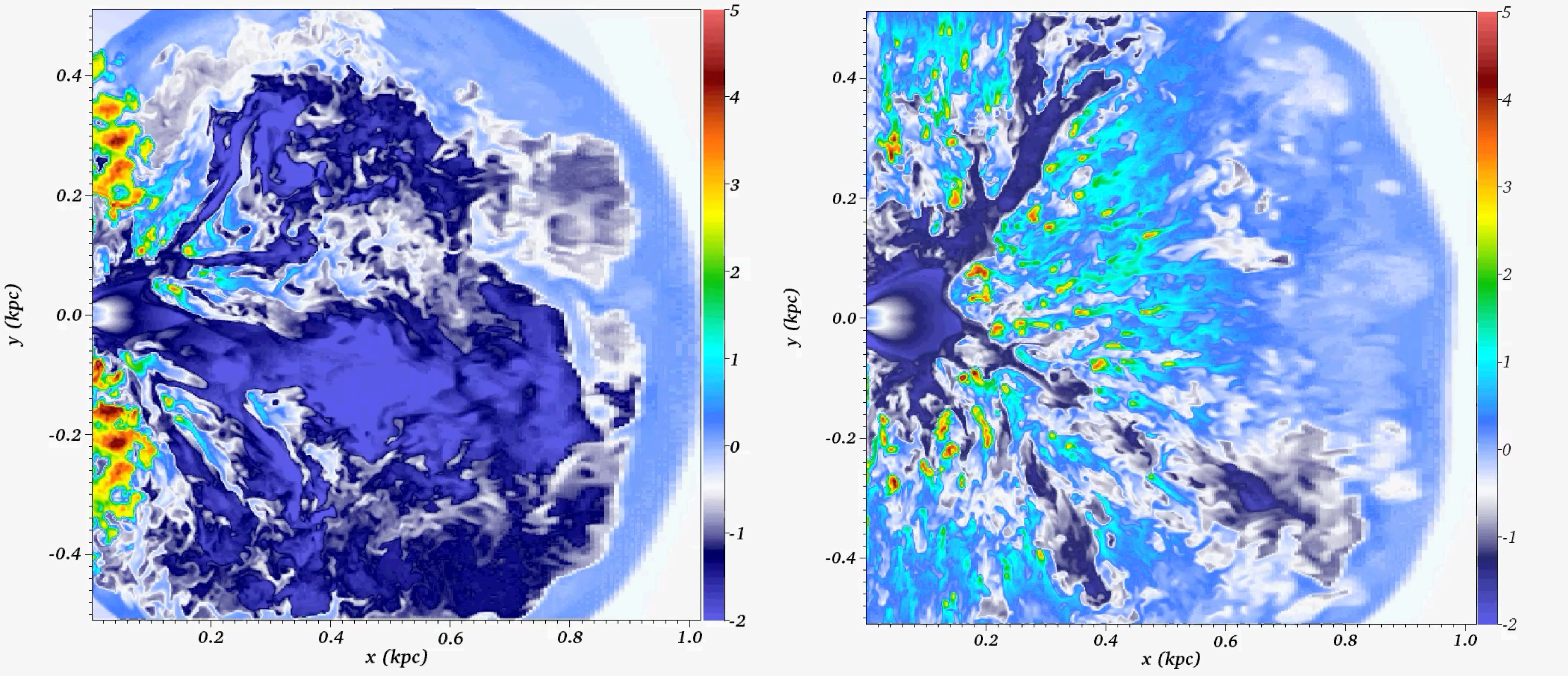
Wagner, Umemura, & Bicknell (2012), Wagner, Umemura, & Bicknell (2013)



- Left: relativistic jet   Right: fast wind (UFO),   Power 10^{45} erg s^{-1}.
- The physics of hydrodynamic energy transfer similar, with the efficiency depending mainly on power and ISM properties

Simulations of feedback by ultra-fast disc-winds

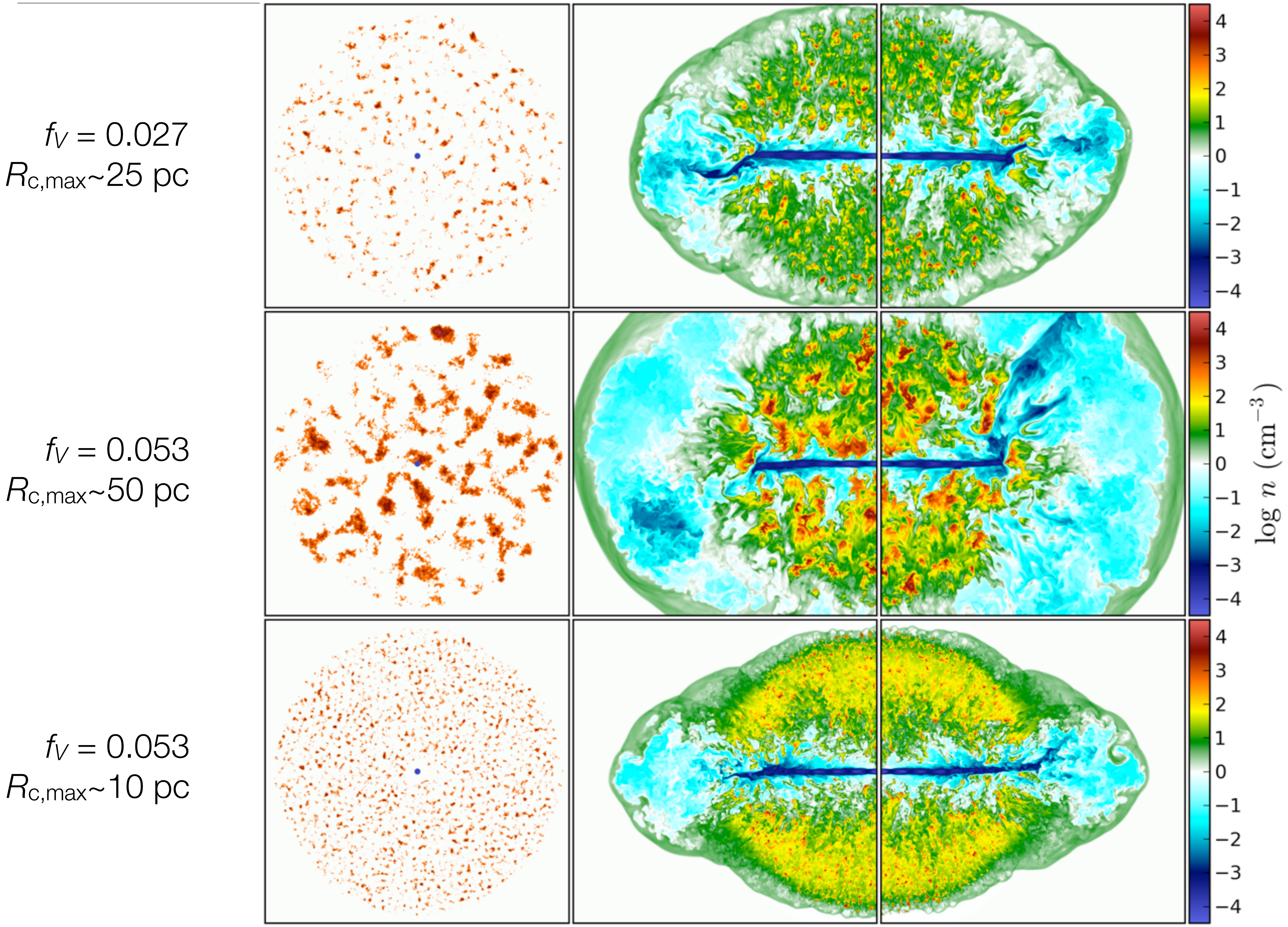
Wagner, Umemura, & Bicknell (2013)



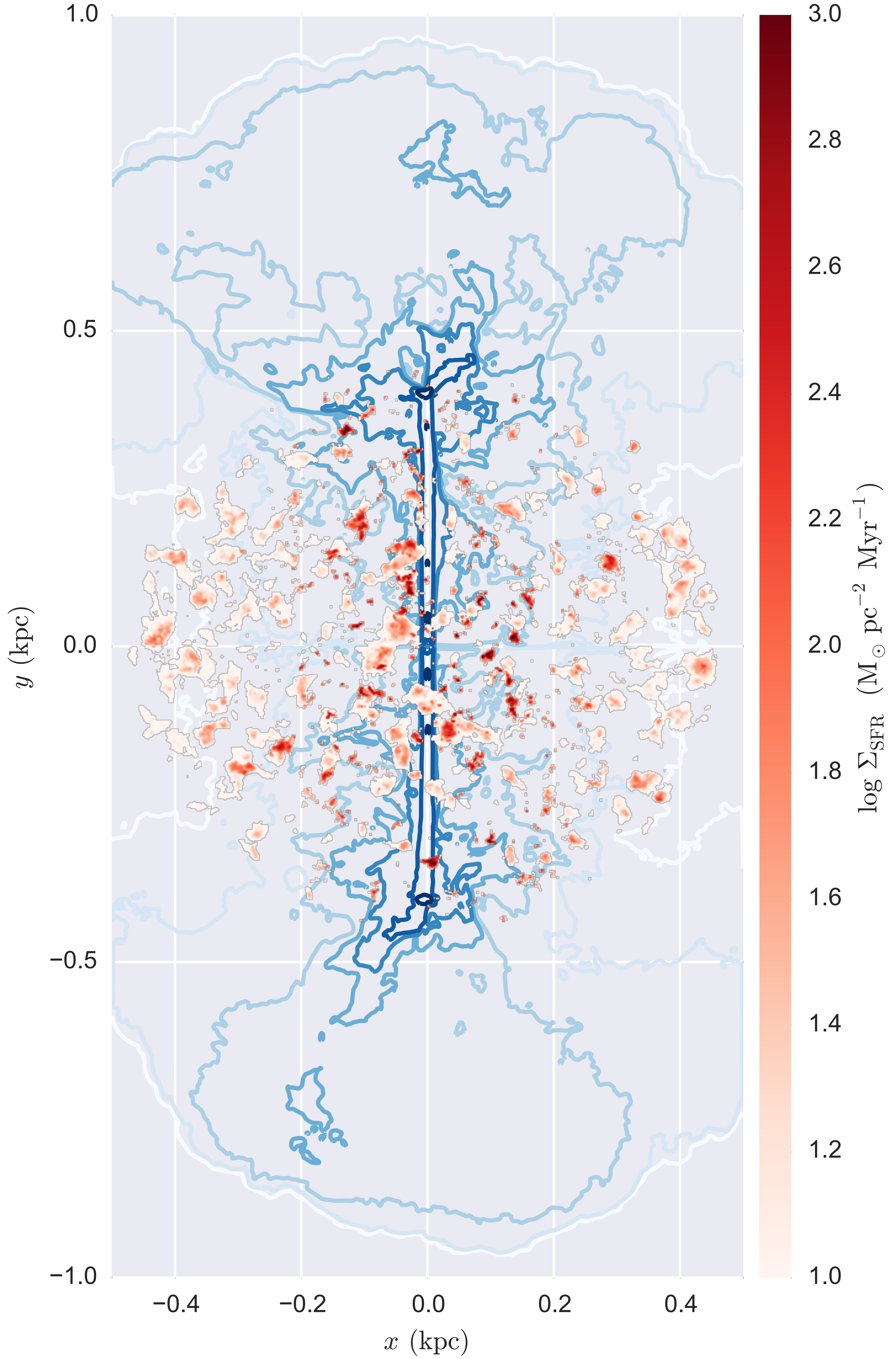
- Comparison between winds in a disc-like gas distribution and a spherical gas distribution.
- In discs, gas at large disc-radii is compressed, while gas near the wind is blown out.

Quasar-mode feedback by AGN jets

(Wagner, Bicknell, & Umemura 2012)



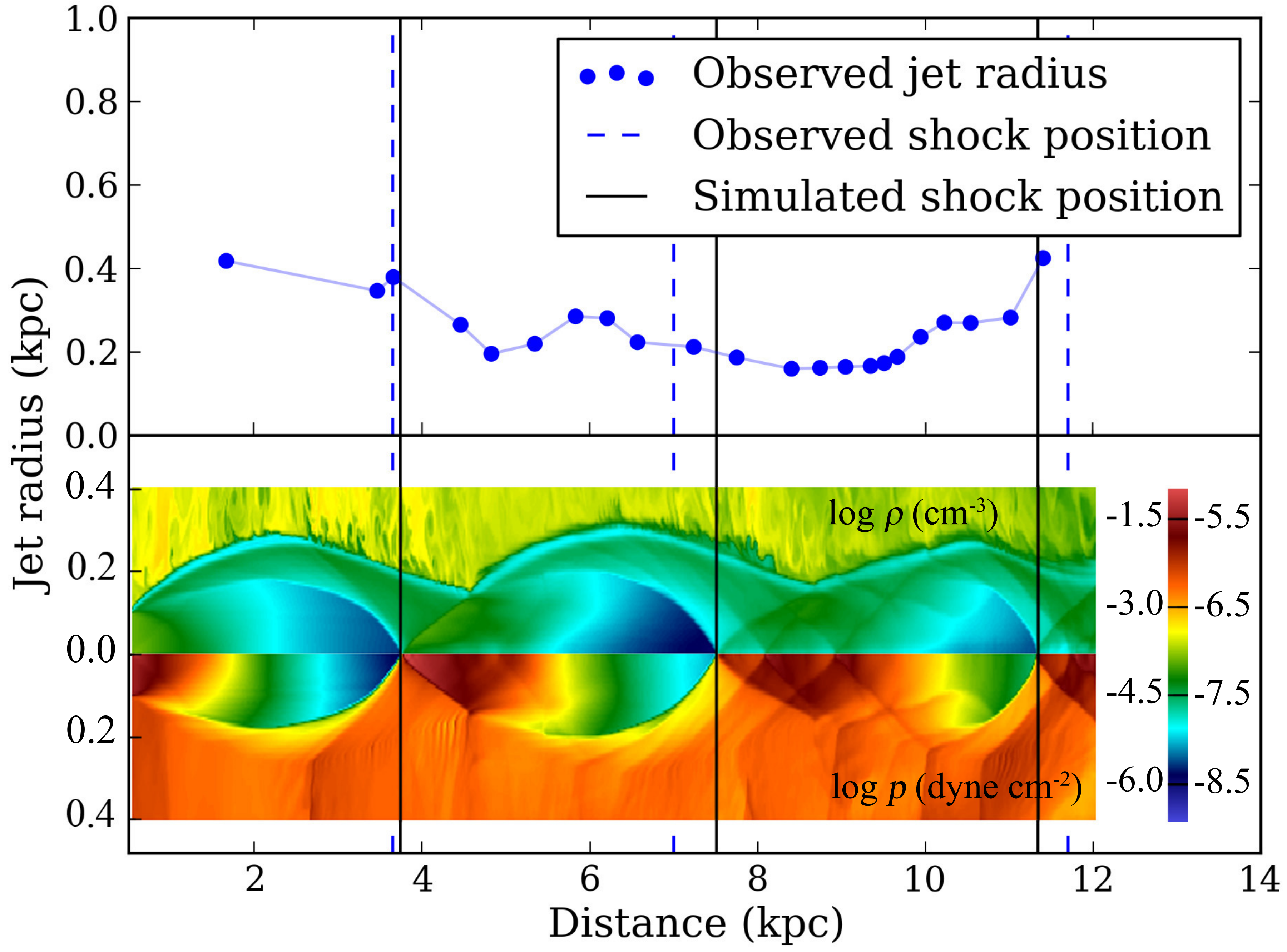
Wagner, Bicknell, Umemura, Silk et al (2016)

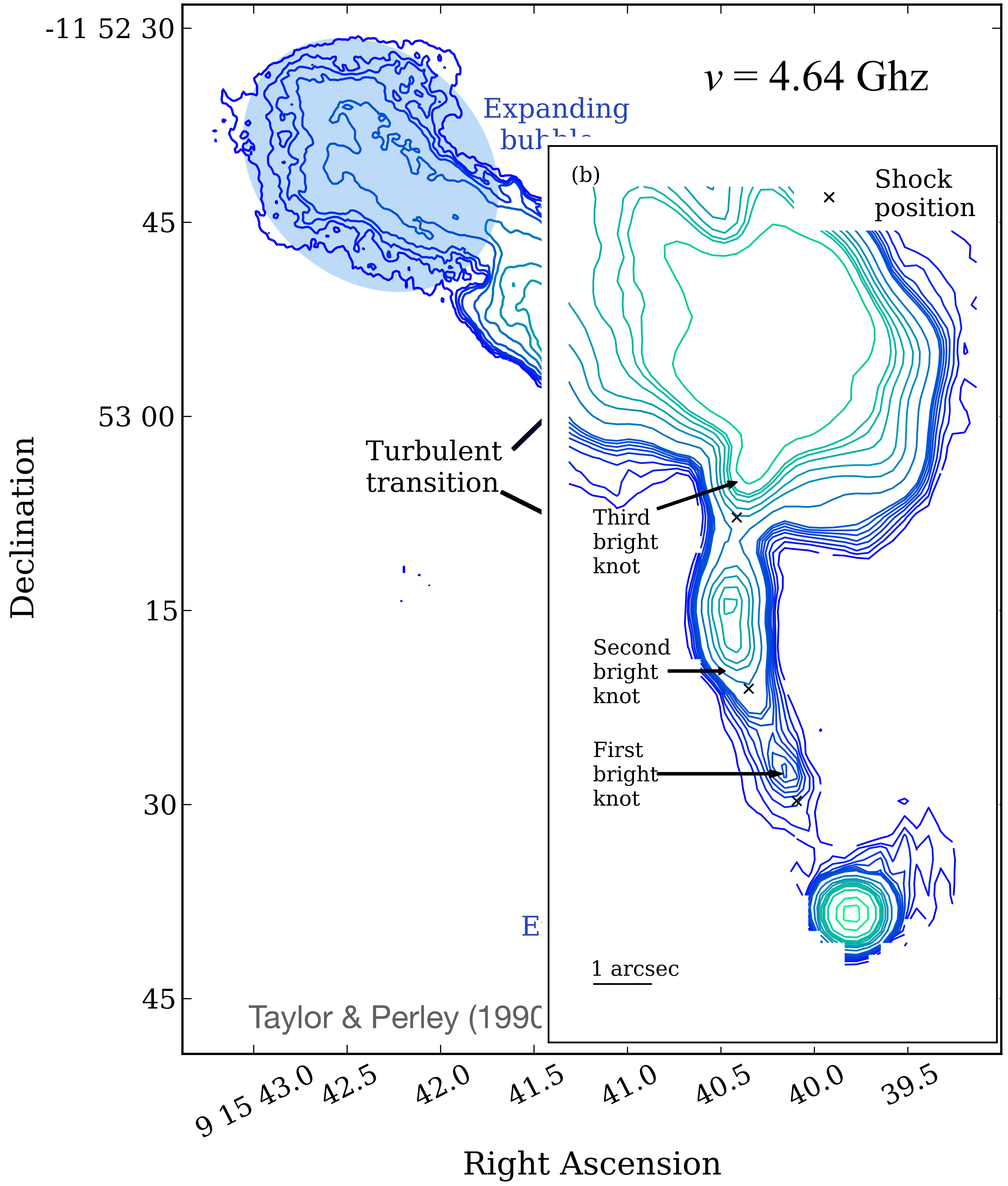


Radio-mode feedback: *Hydra A*

Nawaz, AYW, Bicknell, et al (2014)

- Detailed relativistic hydrodynamical modeling have yielded the **best constraints of jet parameters for Hydra A to date.**
- Parameter survey of *jet power, jet speed, jet composition, and jet pressure* to match **diamond shock** positions and **radius oscillations** of jet stream with observations.

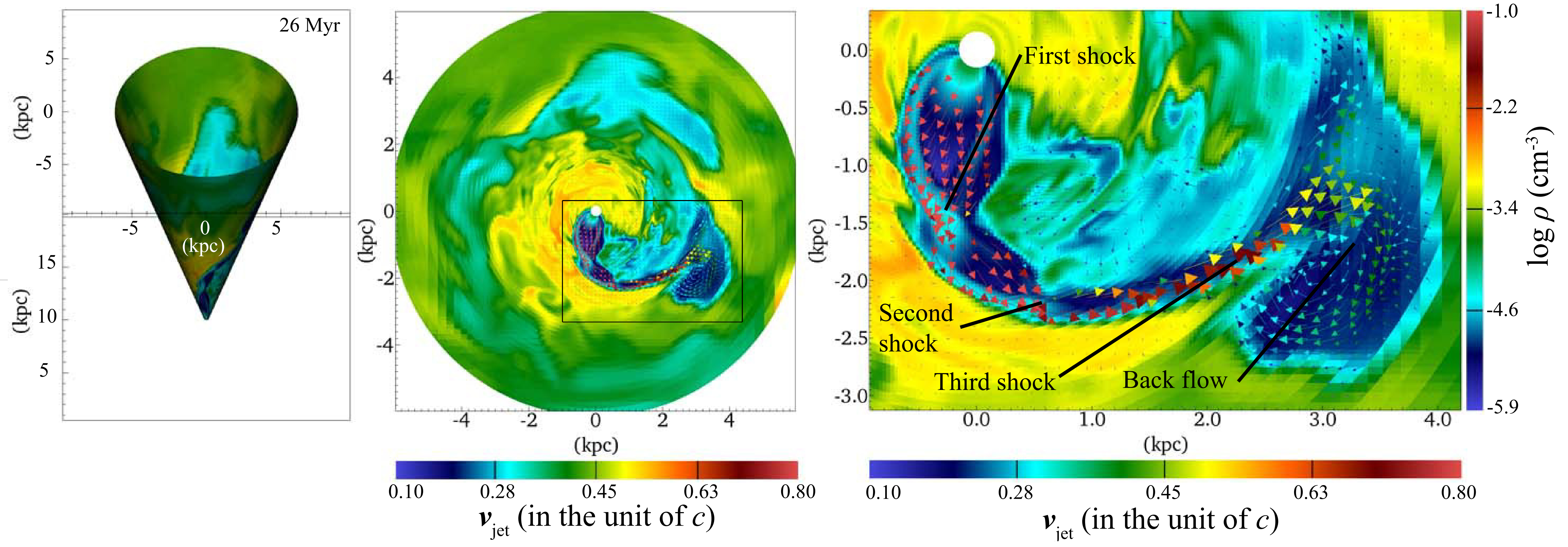




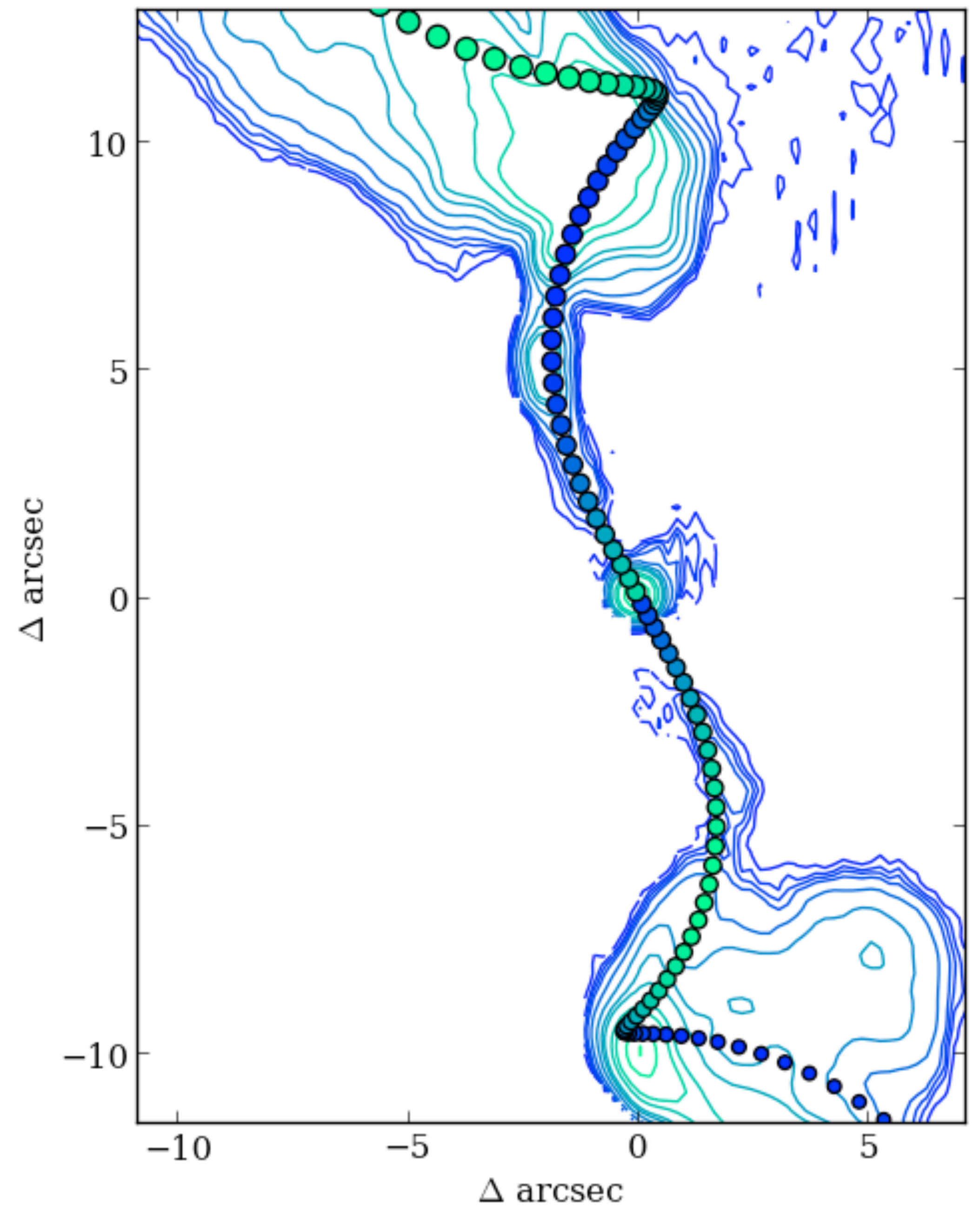
Taylor & Perley (1990

Radio-mode feedback
Hydra A

Nawaz, Bicknell, AYW, et al (2016)



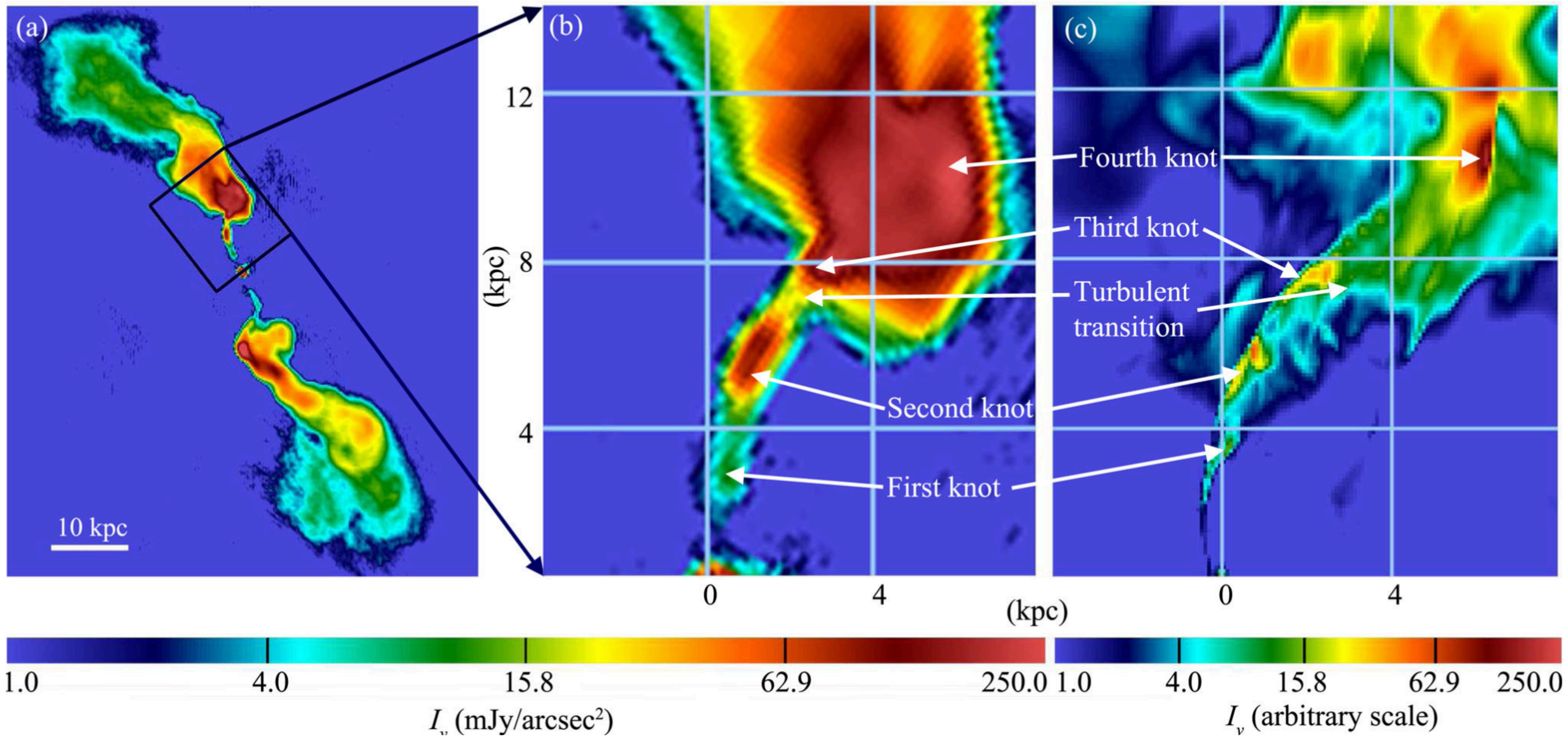
- First and only 3D **precessing jet simulations** of Hydra A.
  - jet curvature
  - transition of jet stream to turbulence, and
  - plume structure.
  - Precession time: ~1 Myr



Radio surface brightness maps

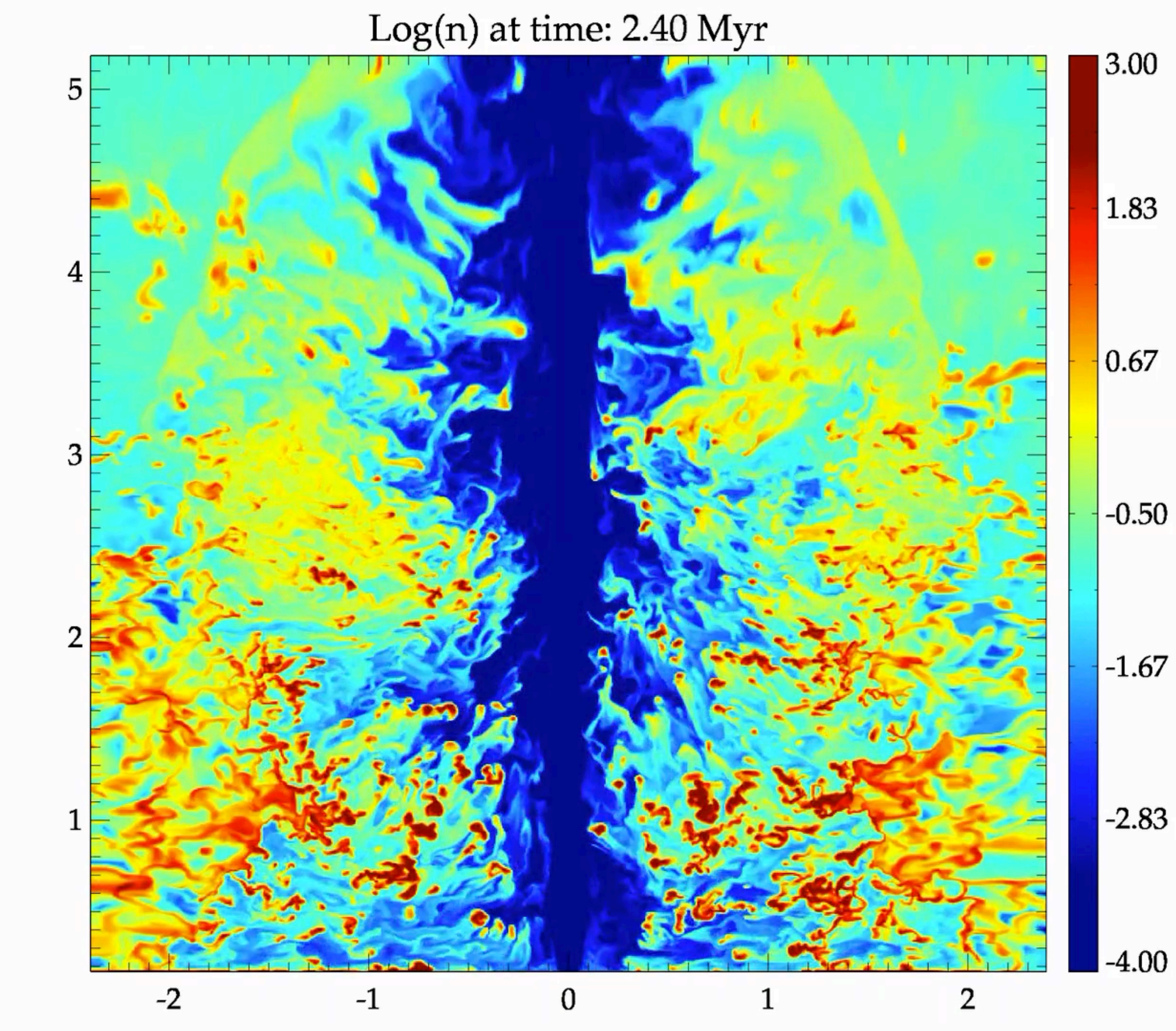
data (Taylor et al 1990)

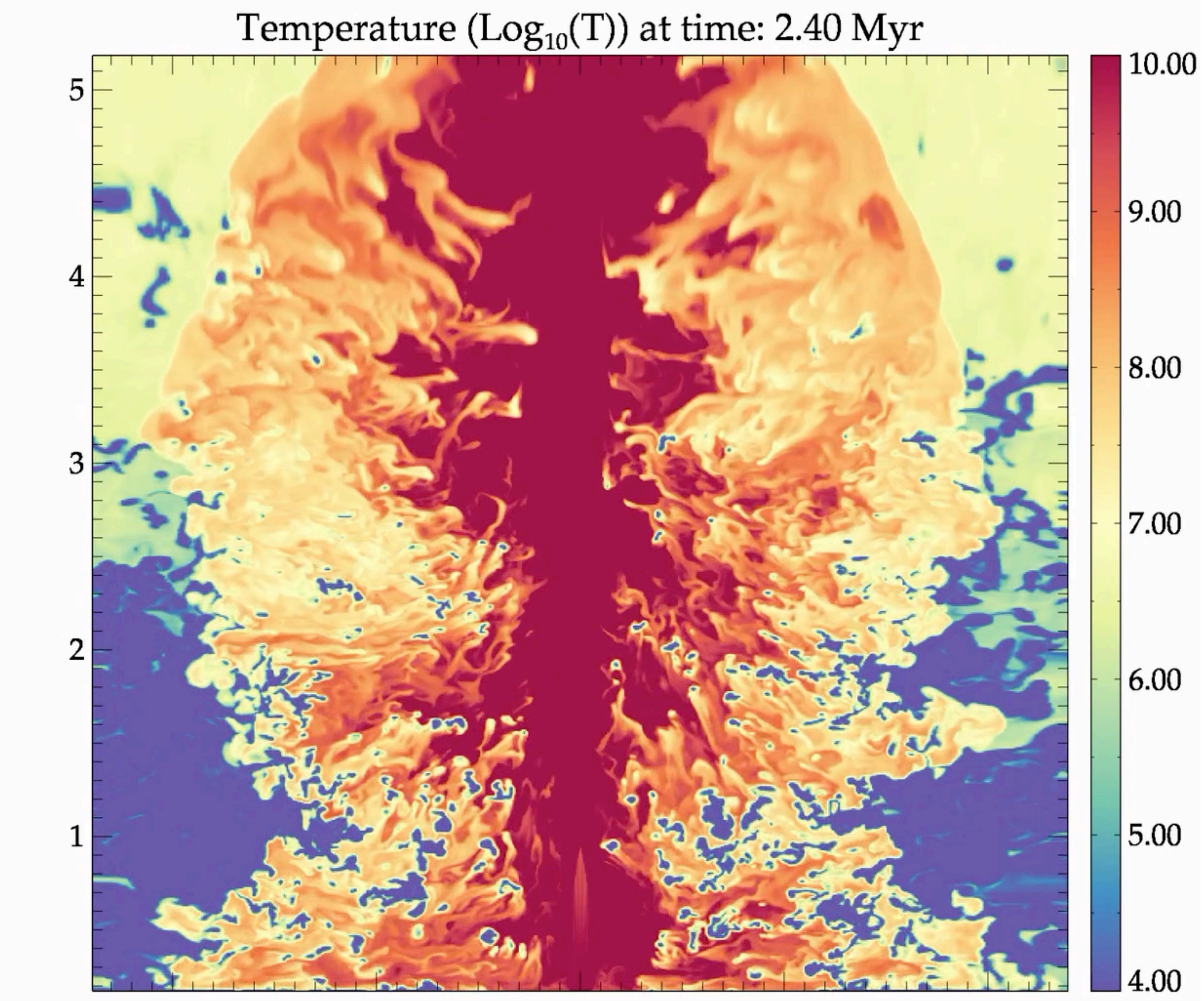
synthetic (simulation)

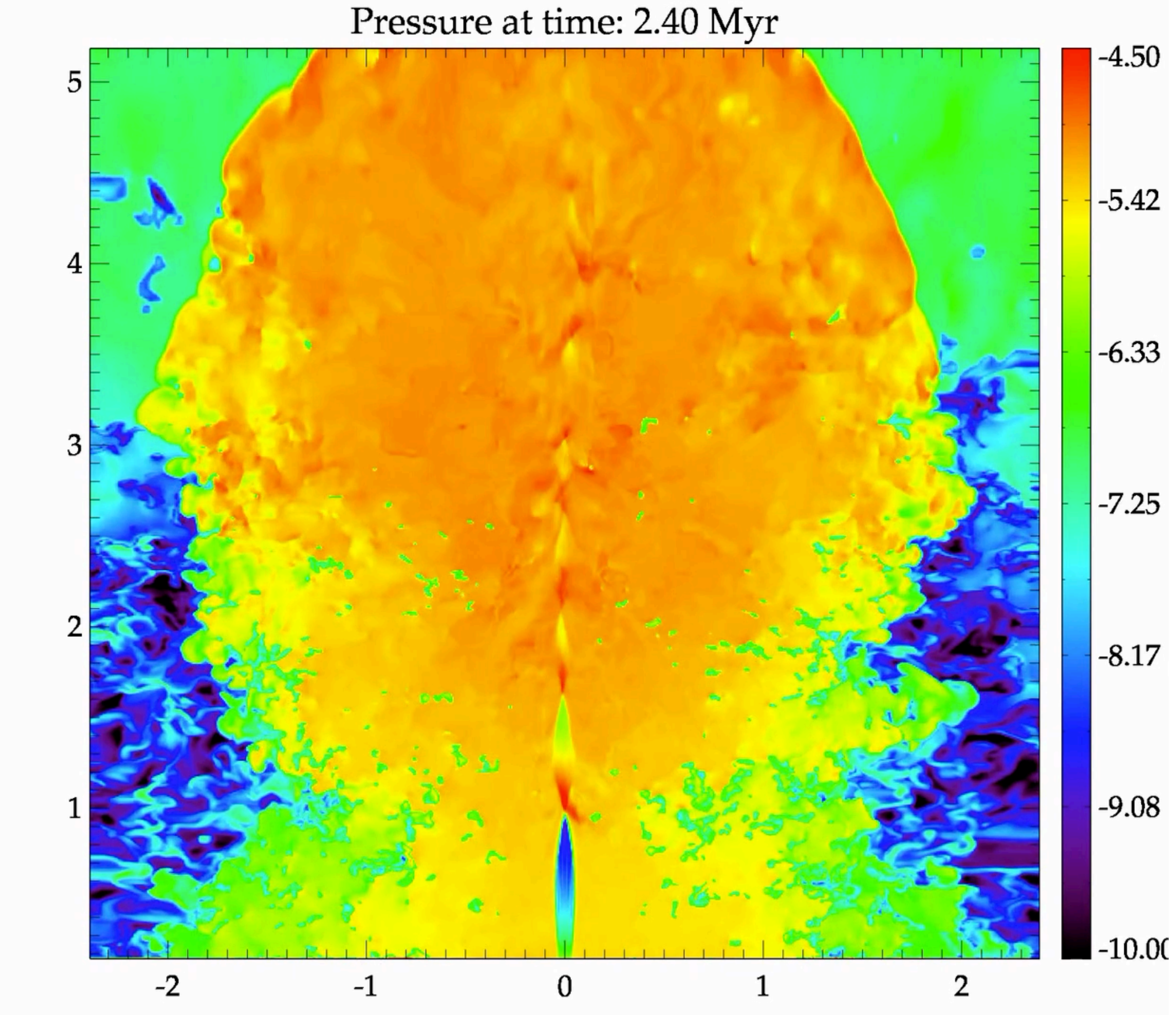


AGN Jet Feedback in spherical, gas-rich forming galaxies

Mukherjee, Bicknell, Wagner, *MNRAS,* 2016



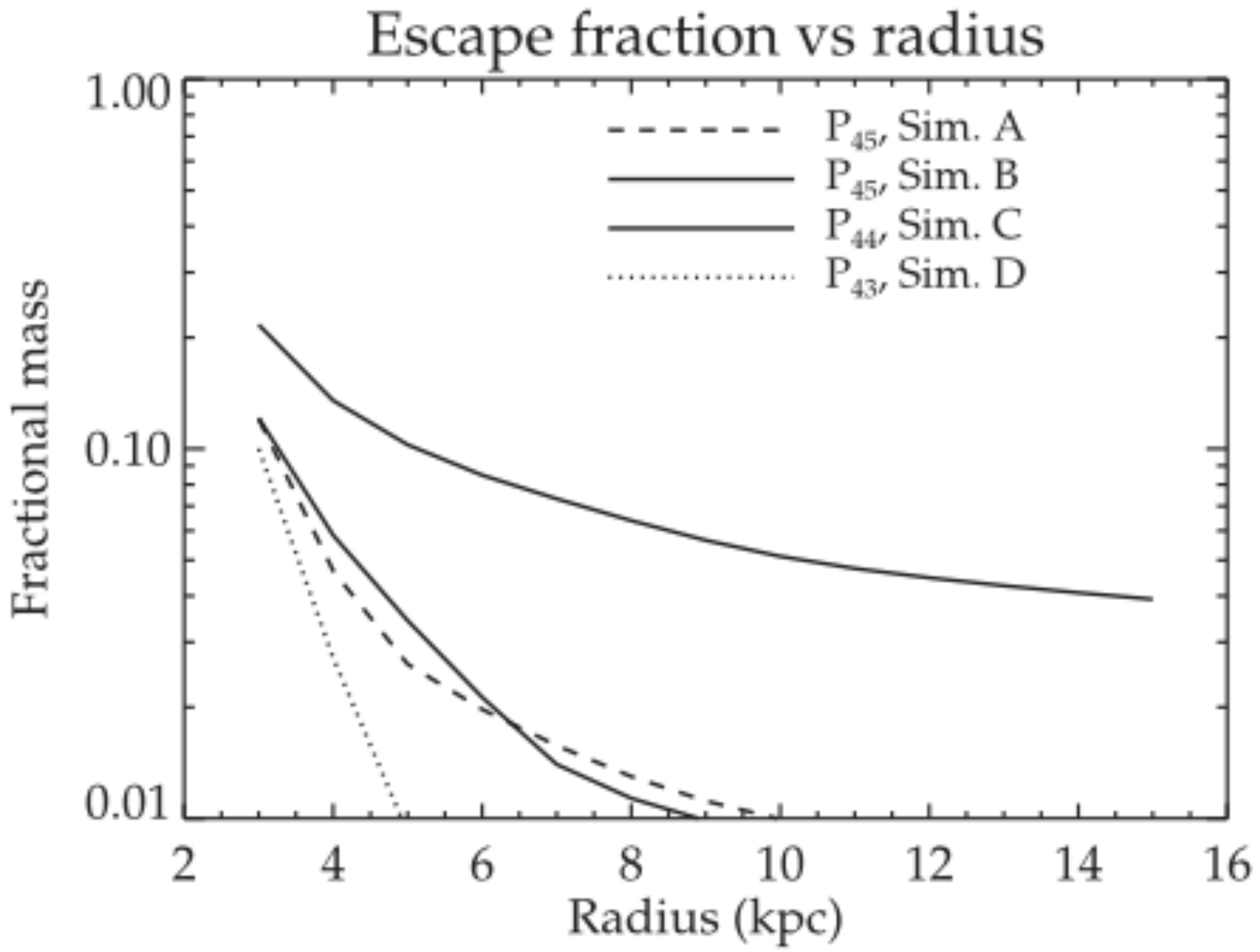


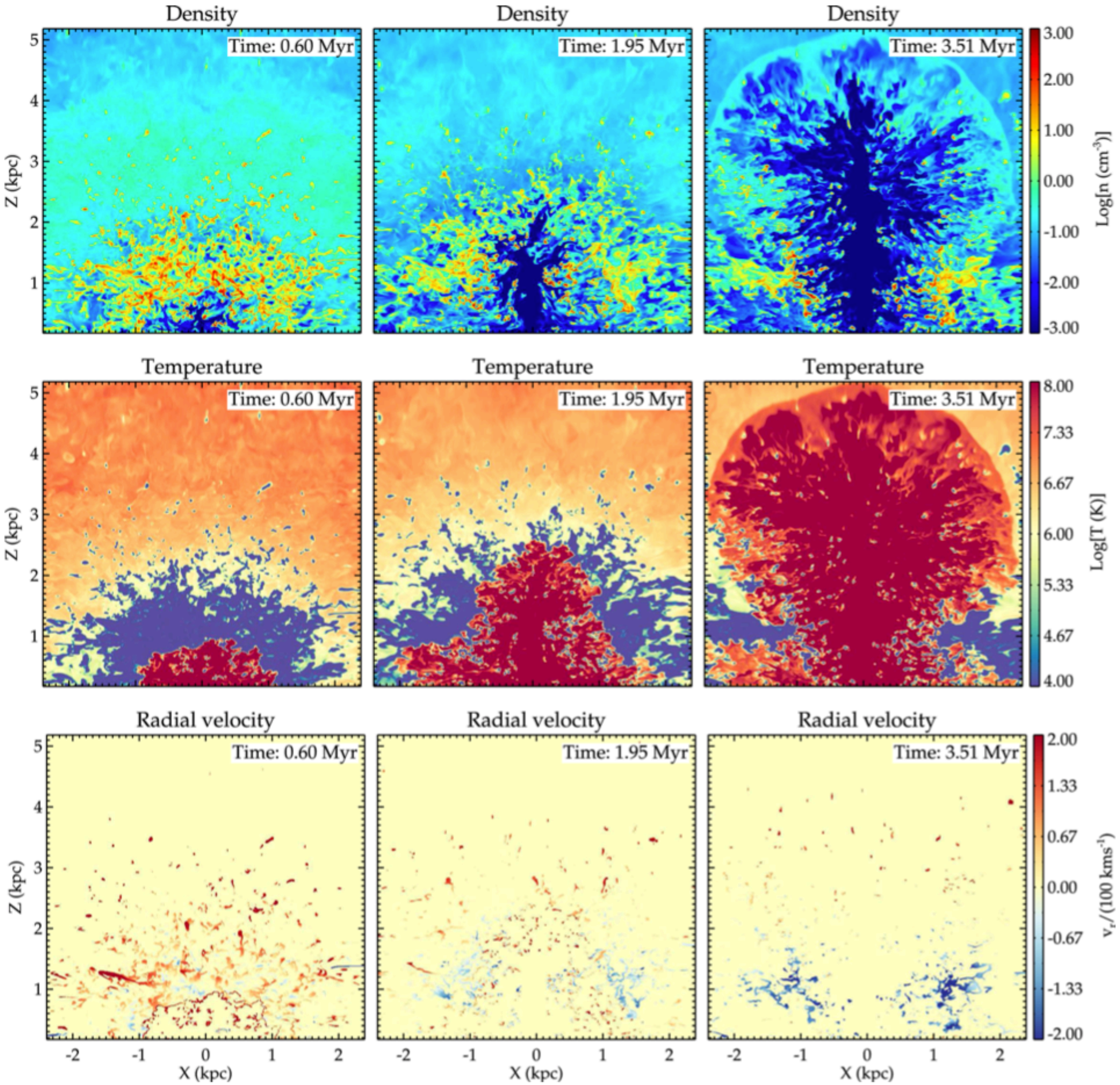


AGN Jet Feedback in spherical, gas-rich forming galaxies

Mukherjee, Bicknell, Wagner, *MNRAS,* 2016

- 20 simulations with **turbulent** interstellar gas, over a 5 kpc volume.
- Strong negative feedback for **P_{jet} > 10^{44} erg s^{-1}**.
- Galactic **fountains**, **stifled** jets (FR0?).
- **Mass ejection** is very inefficient.

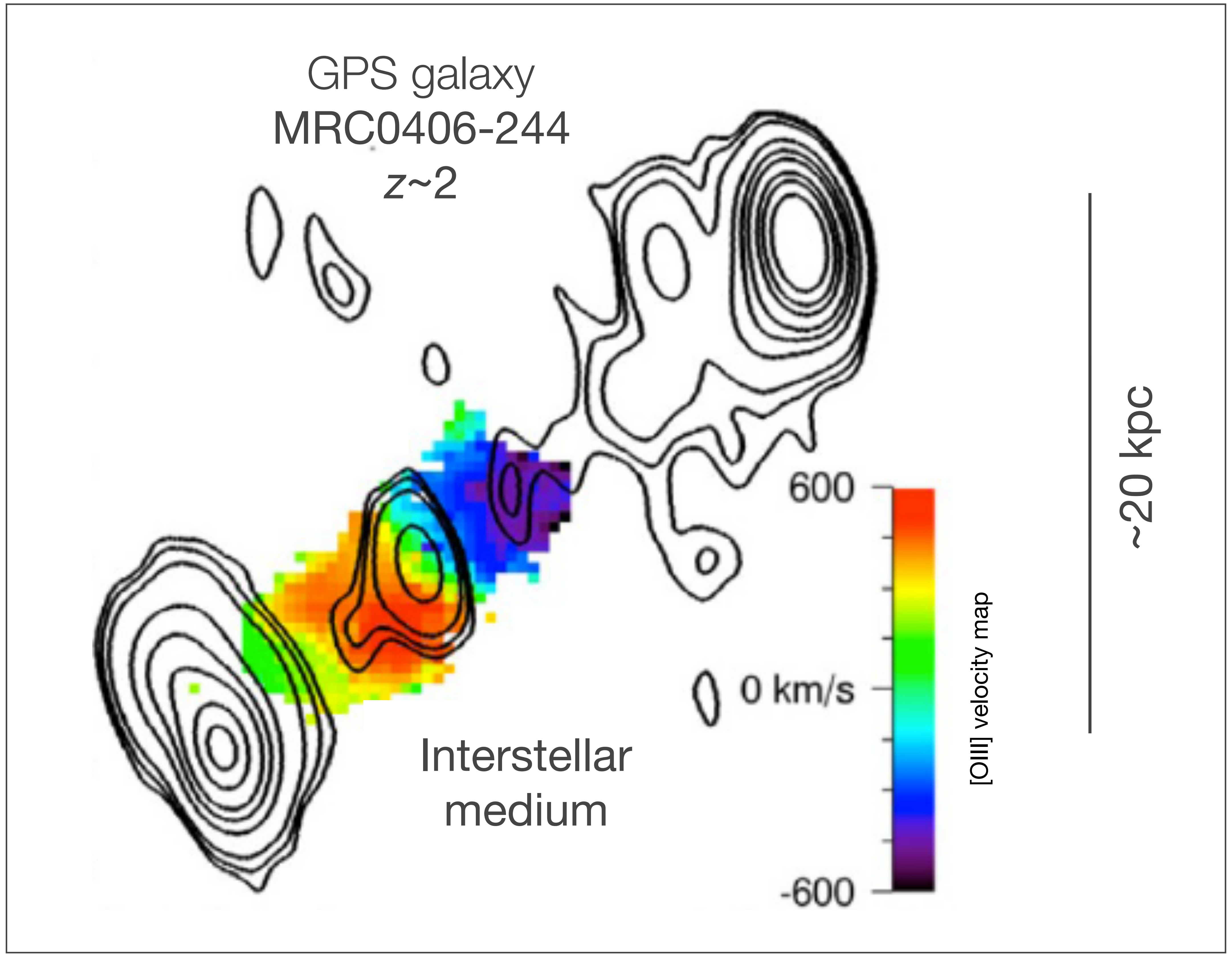


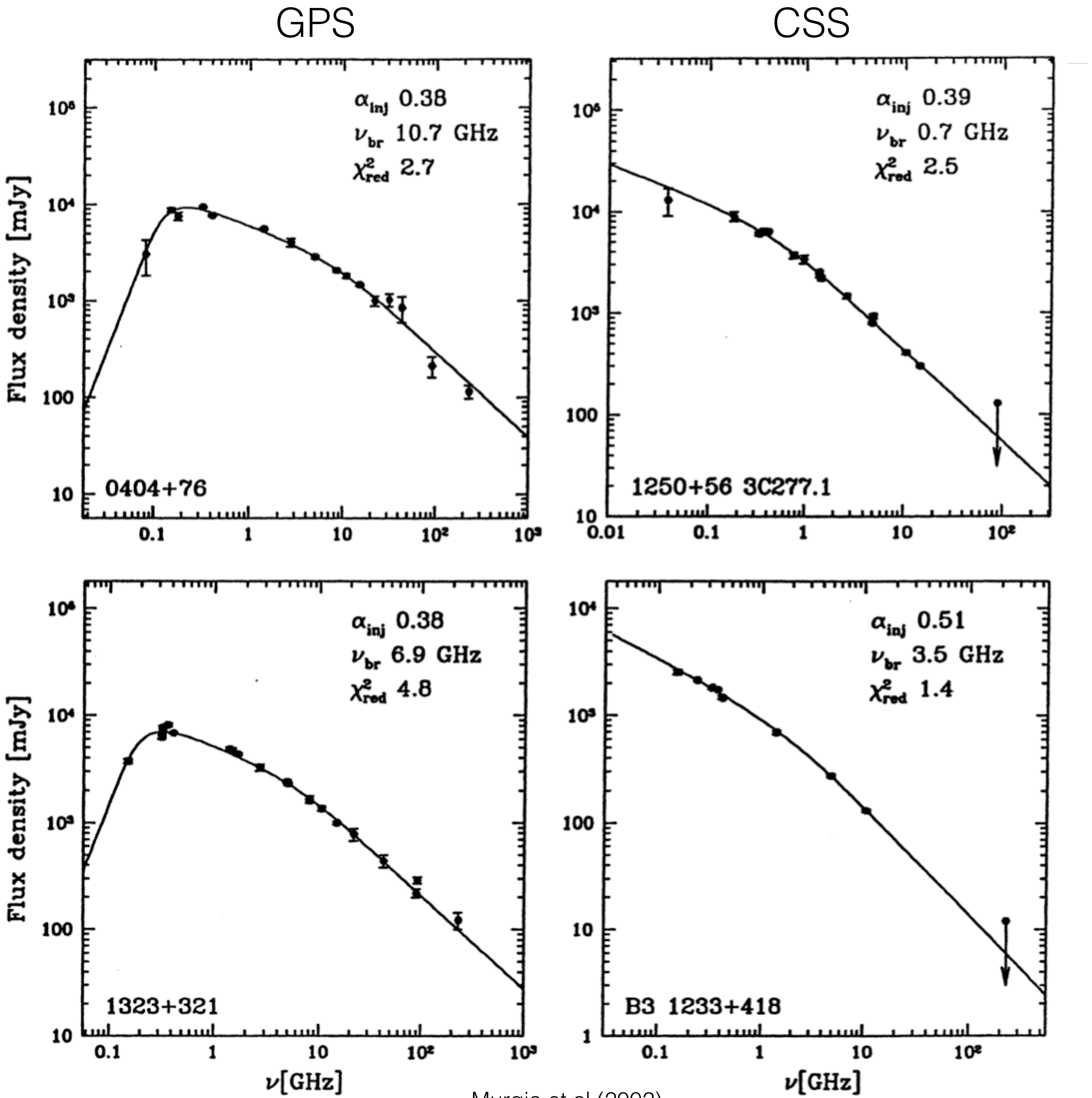


The spectra of GPS and CSS sources explained

Bicknell, Mukherjee, Wagner, et al, *MNRAS,* 2018

- Powerful jet interactions in gas-rich, high-redshift radio galaxies, and **GPS / CSS sources**.



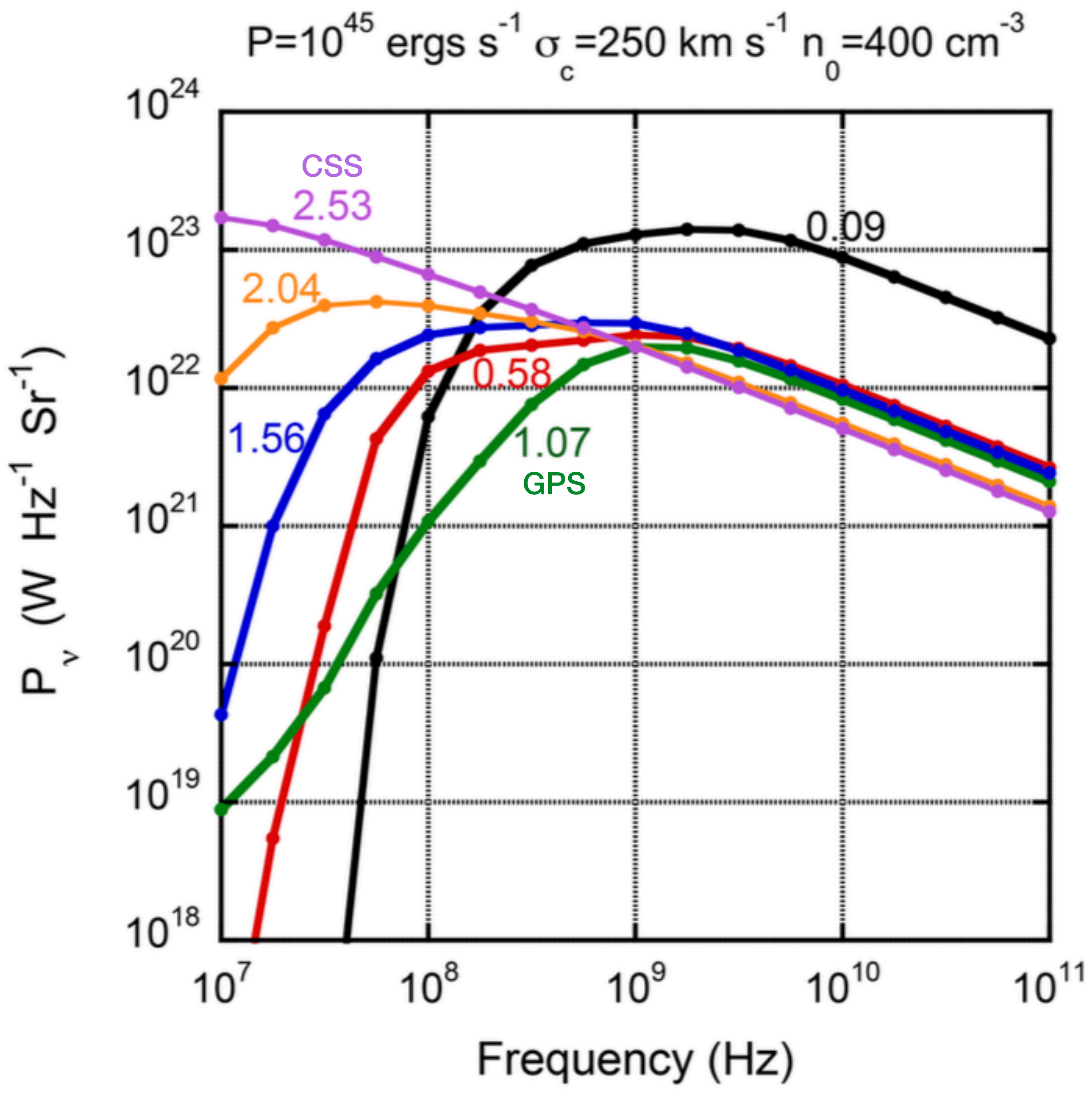


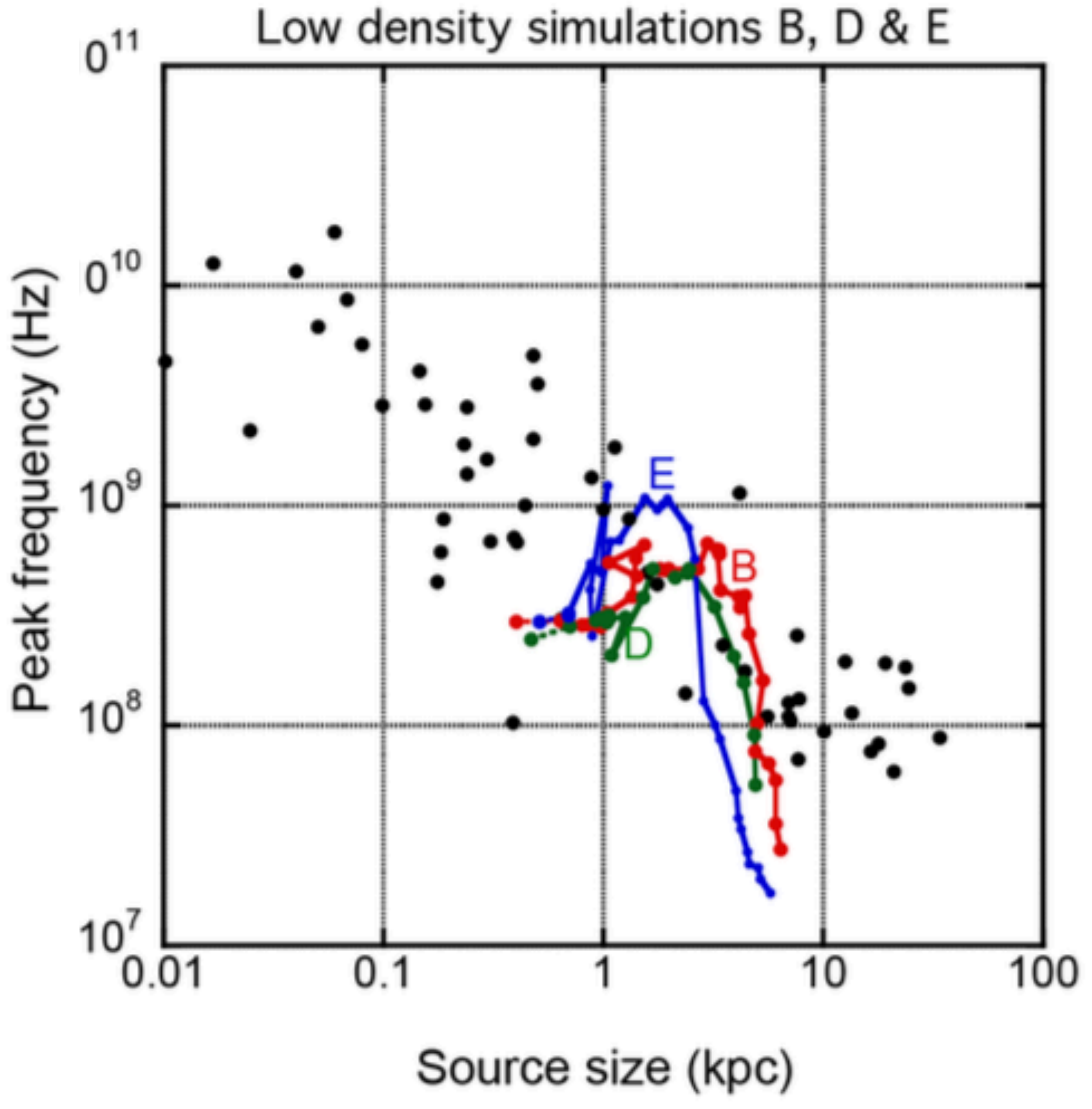
Murgia et al (2002)

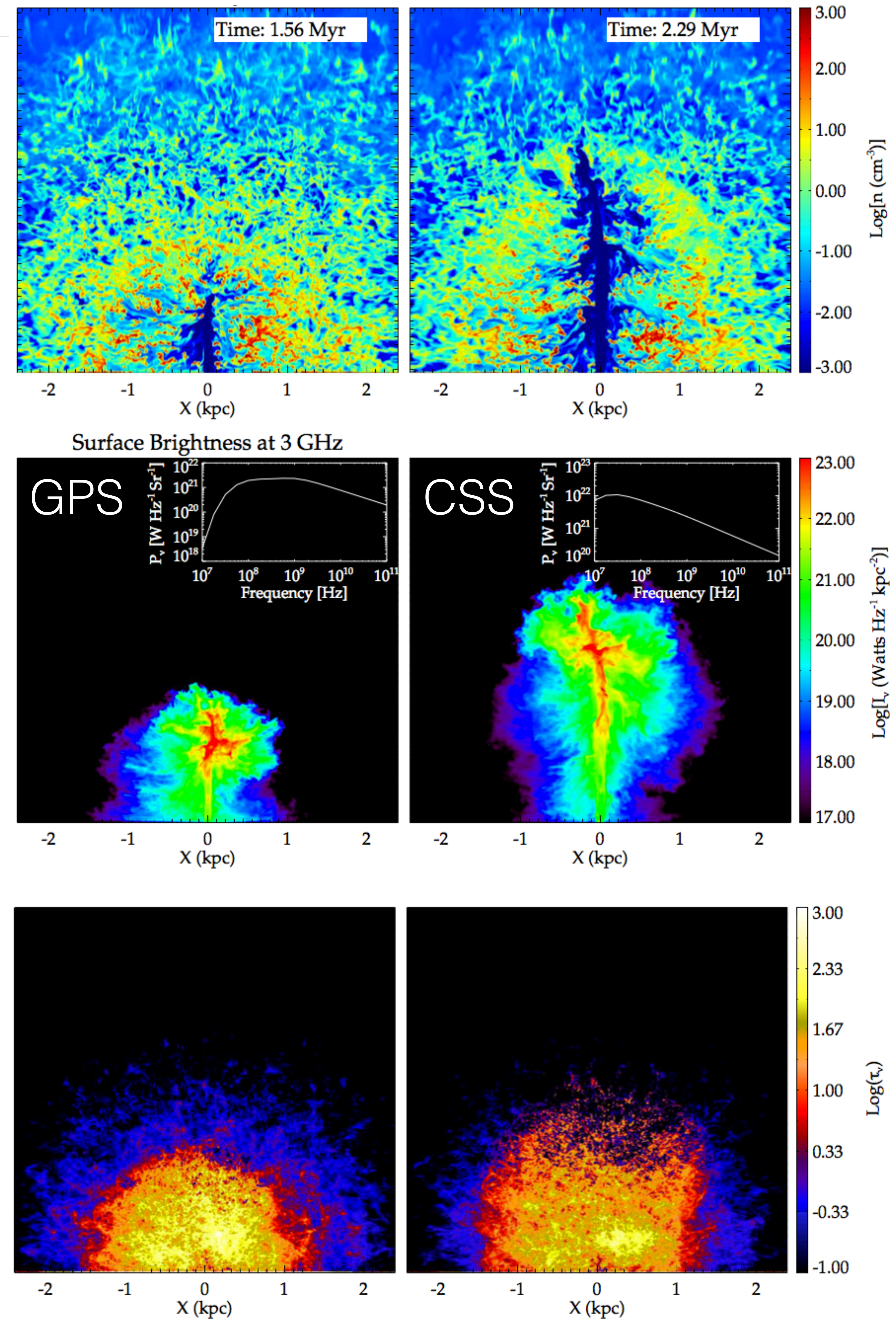
The spectra of GPS and CSS sources explained

Bicknell, Mukherjee, Wagner, et al, *MNRAS,* 2018

- **The shape of GPS and CSS spectra** can be explained through **free-free absorption** through an ISM with a **distribution of optical depths**.
- The **evolution of radio source** explains the **size-turnover frequency relation** in GPS and CSS sources.

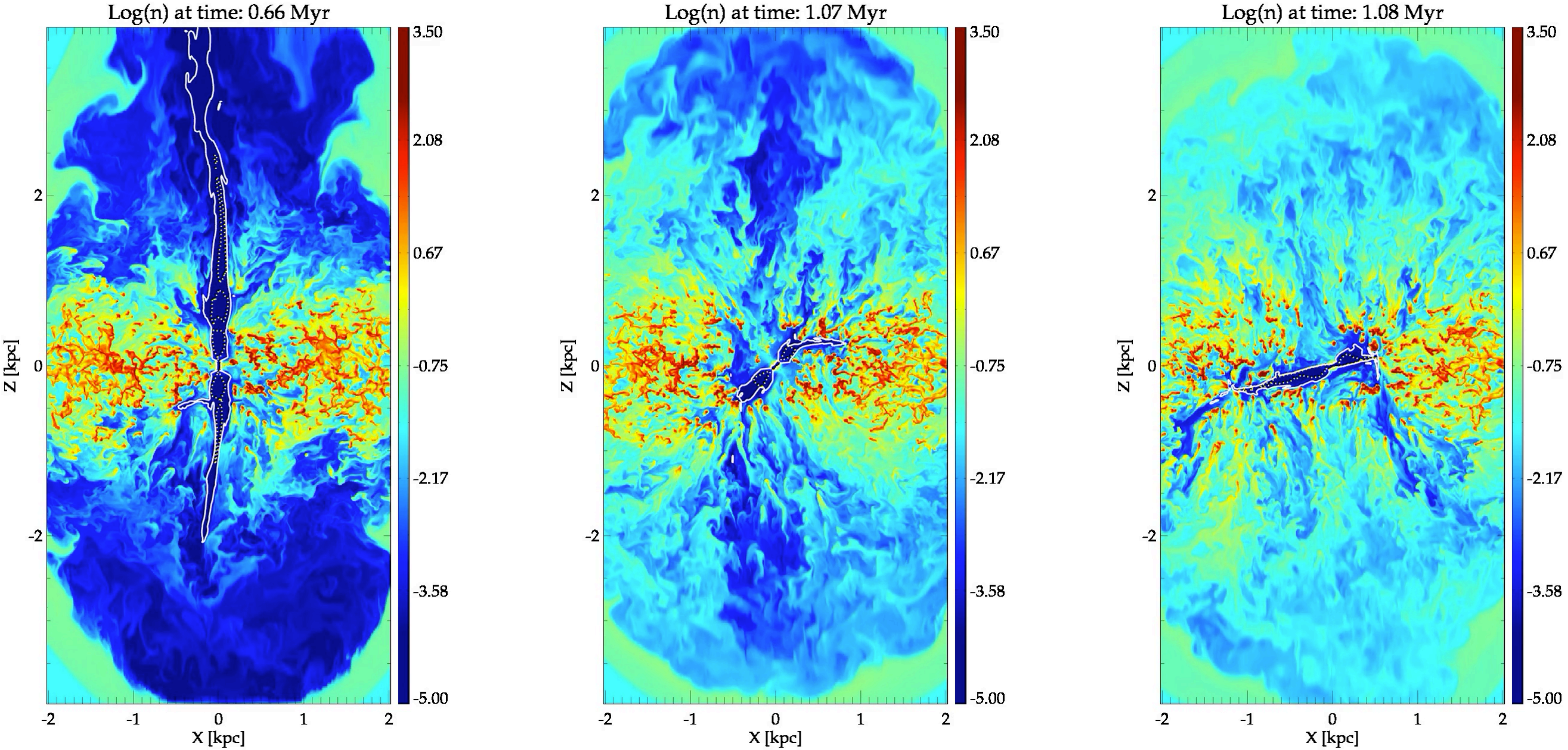






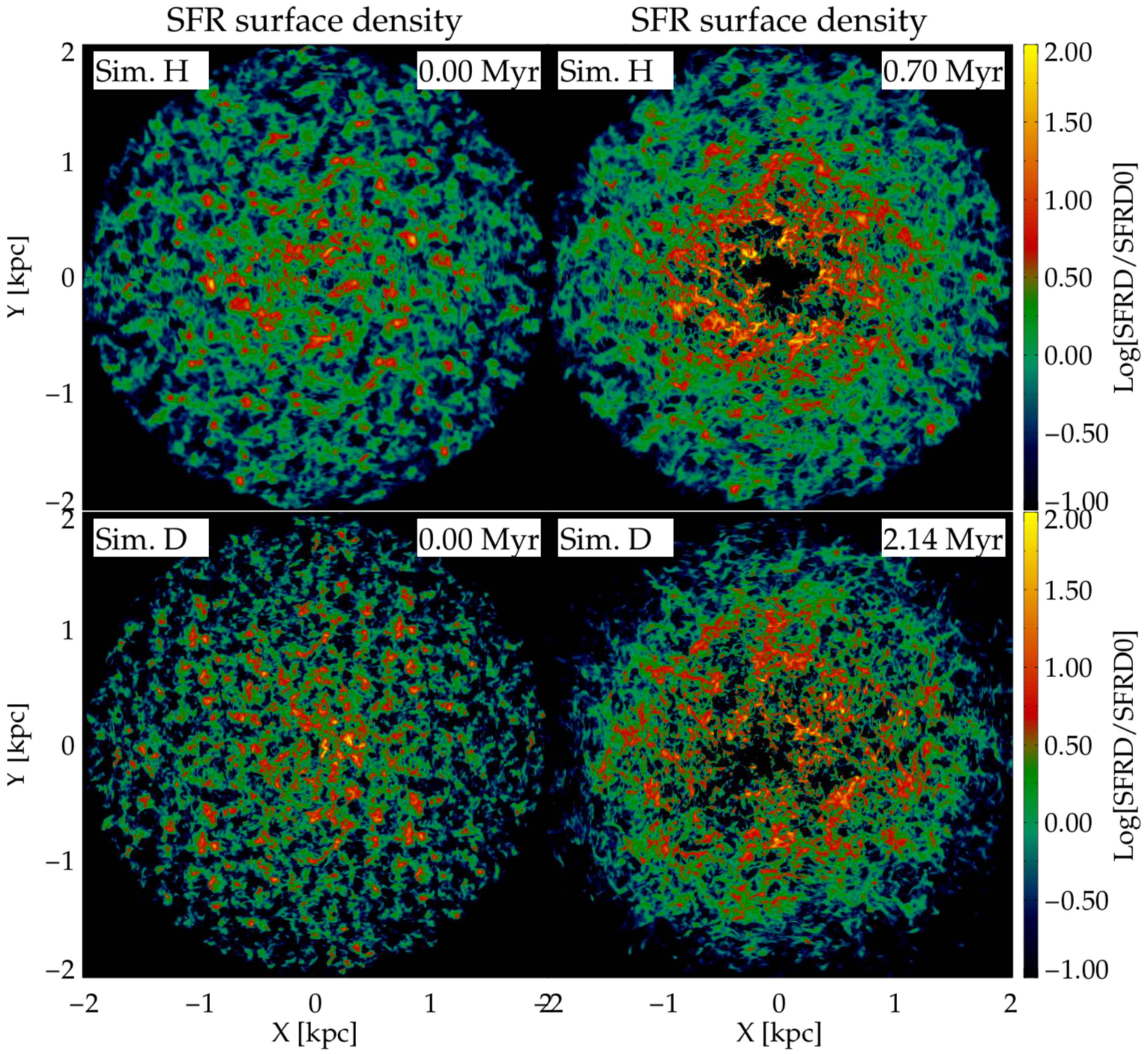
Feedback in disk galaxies *Dependence on jet inclination angle*

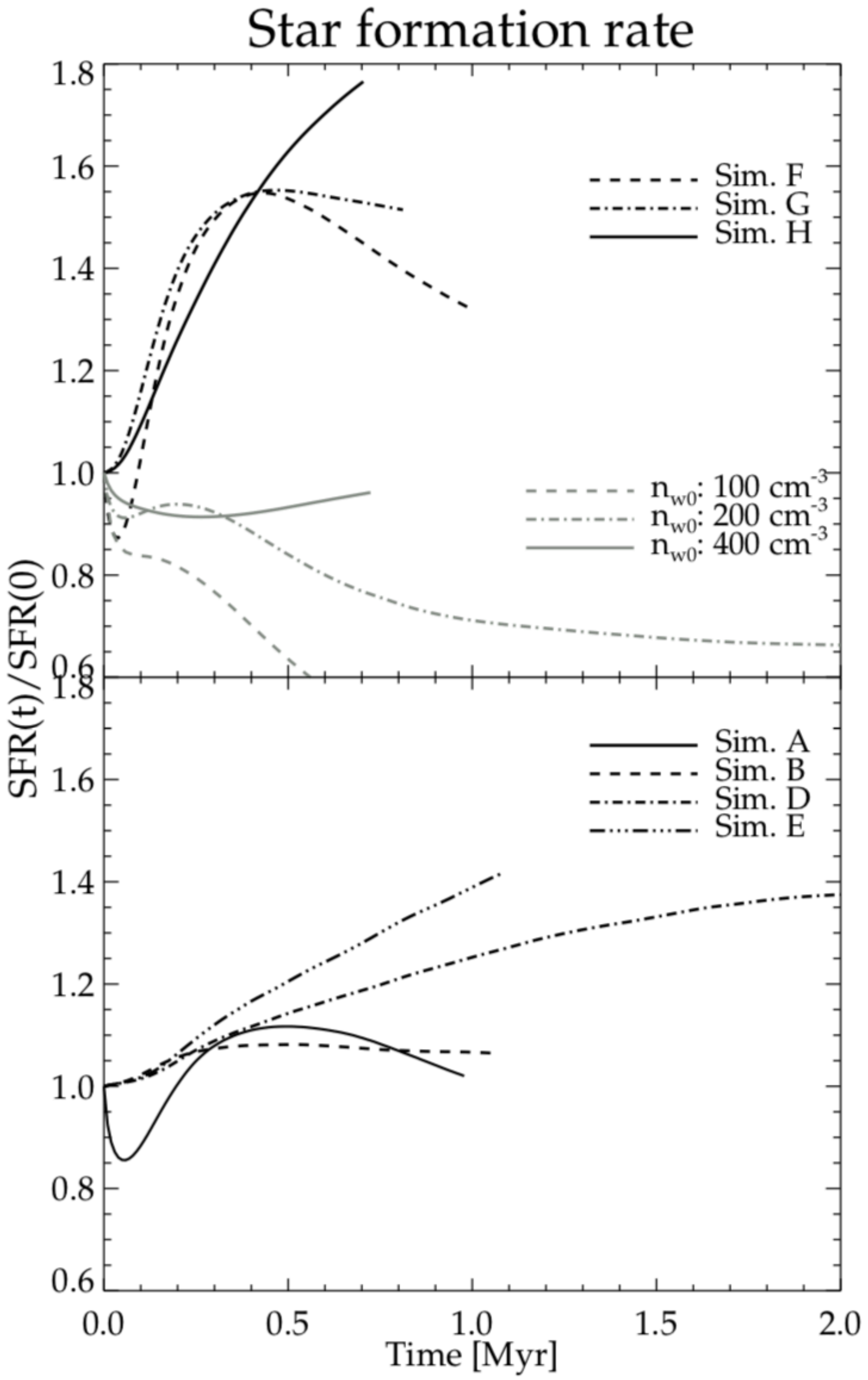
Mukherjee, Wagner, Bicknell, Silk, Sutherland (2018)

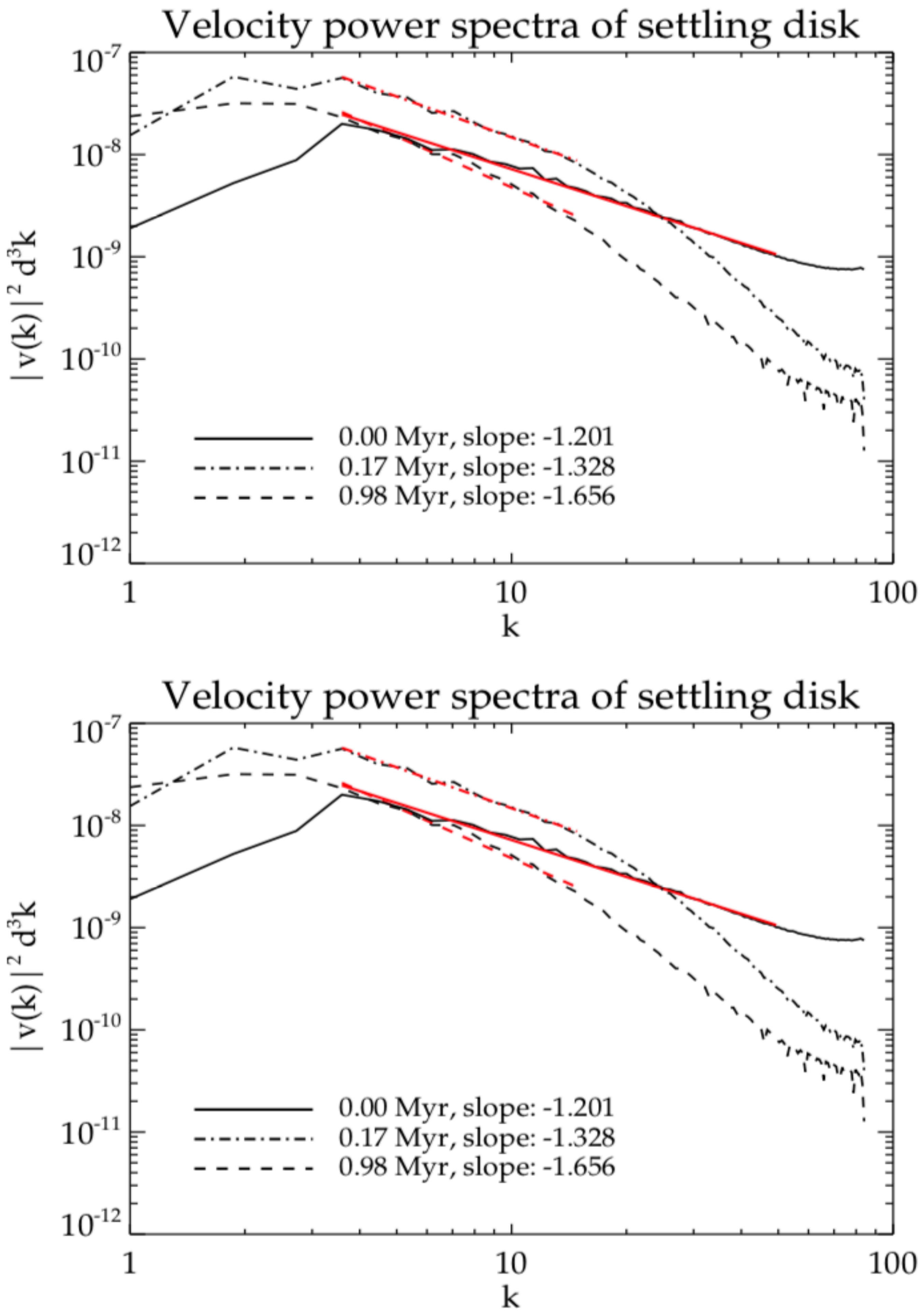


Feedback in disk galaxies *Jet-induced turbulence and star-formation*

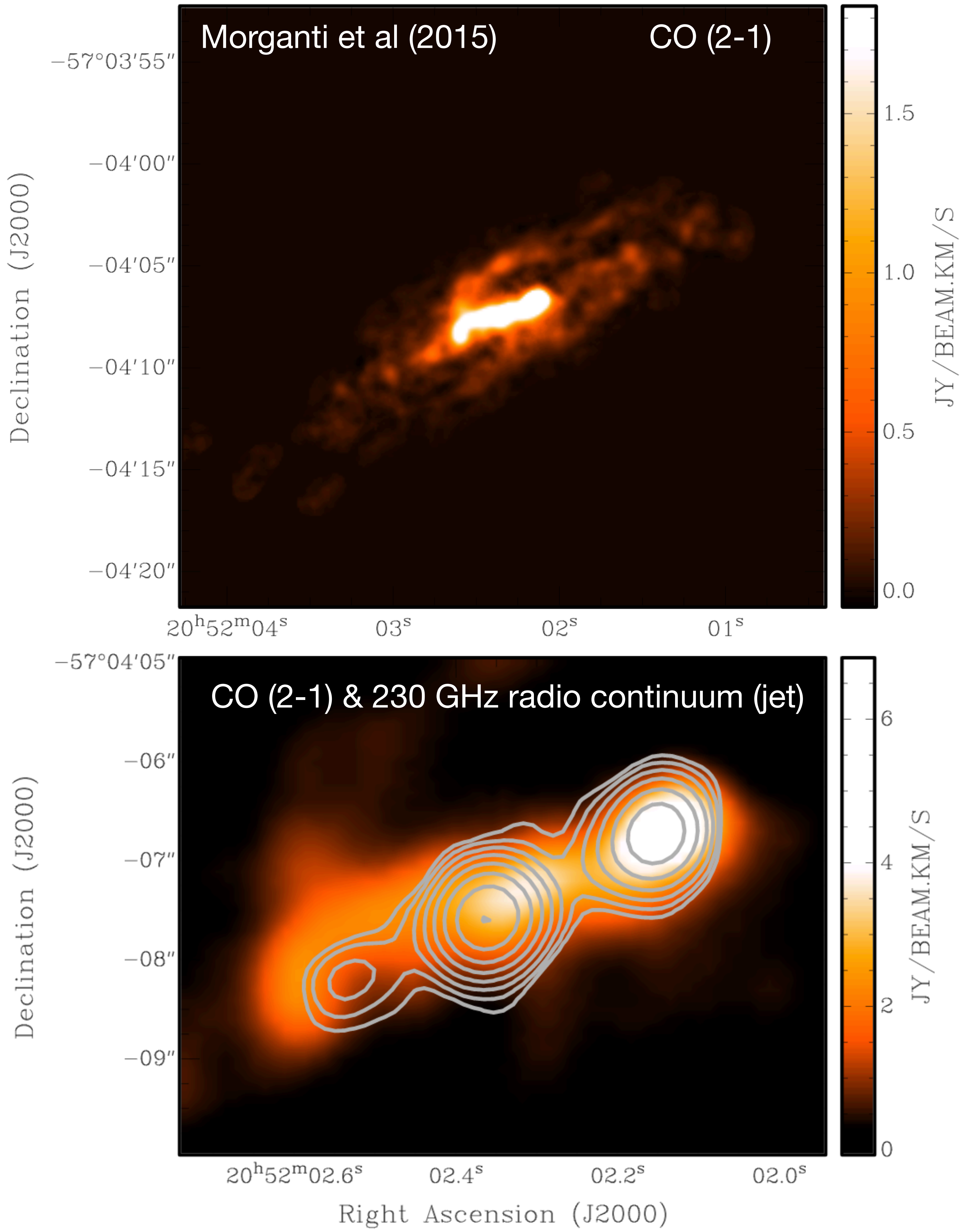
Mukherjee, Wagner, Bicknell, Silk, Sutherland (2018)





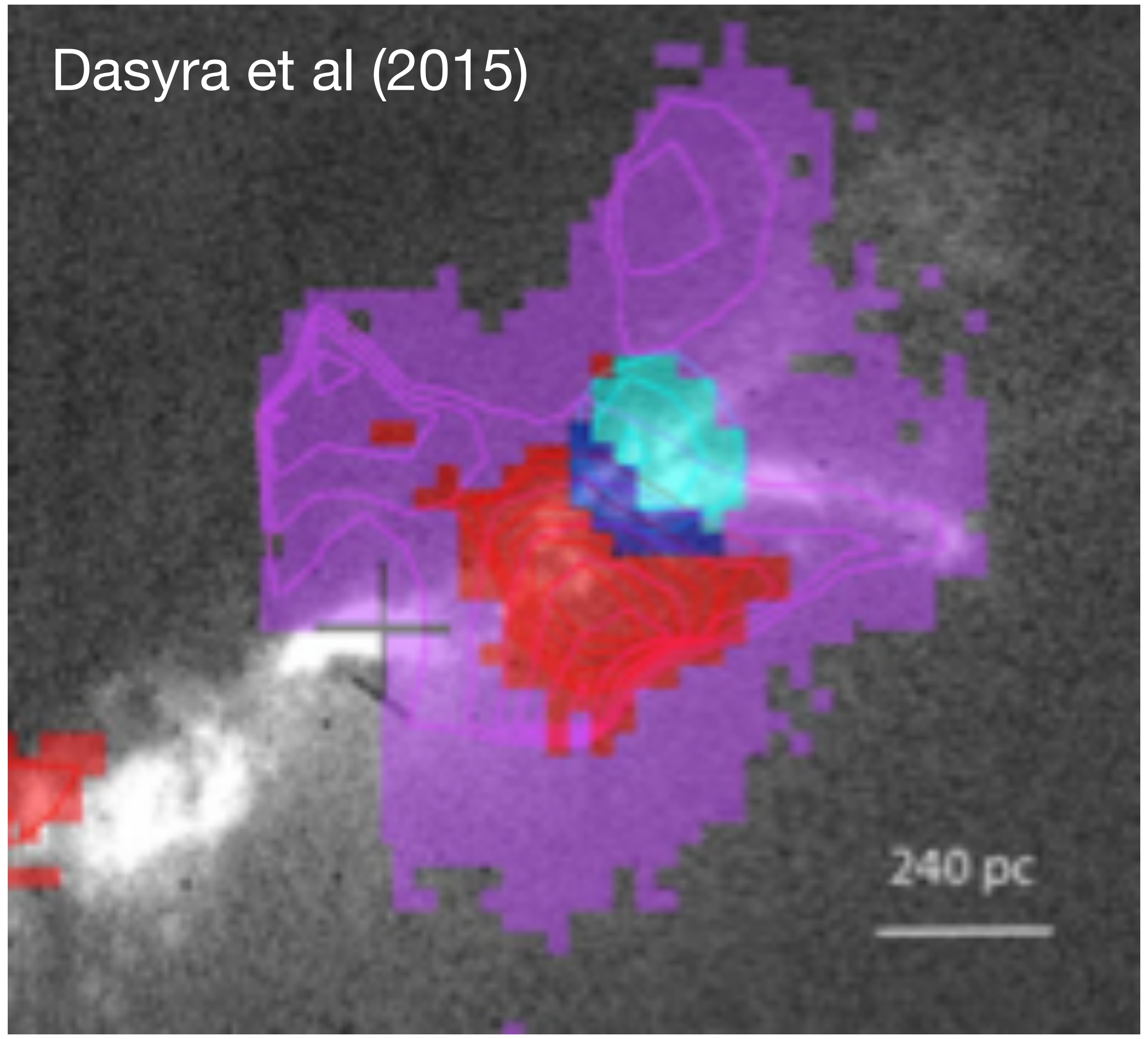


Jet-ISM interactions in IC 5063 — A multiphase view



Multi-phase gas dispersed by jet

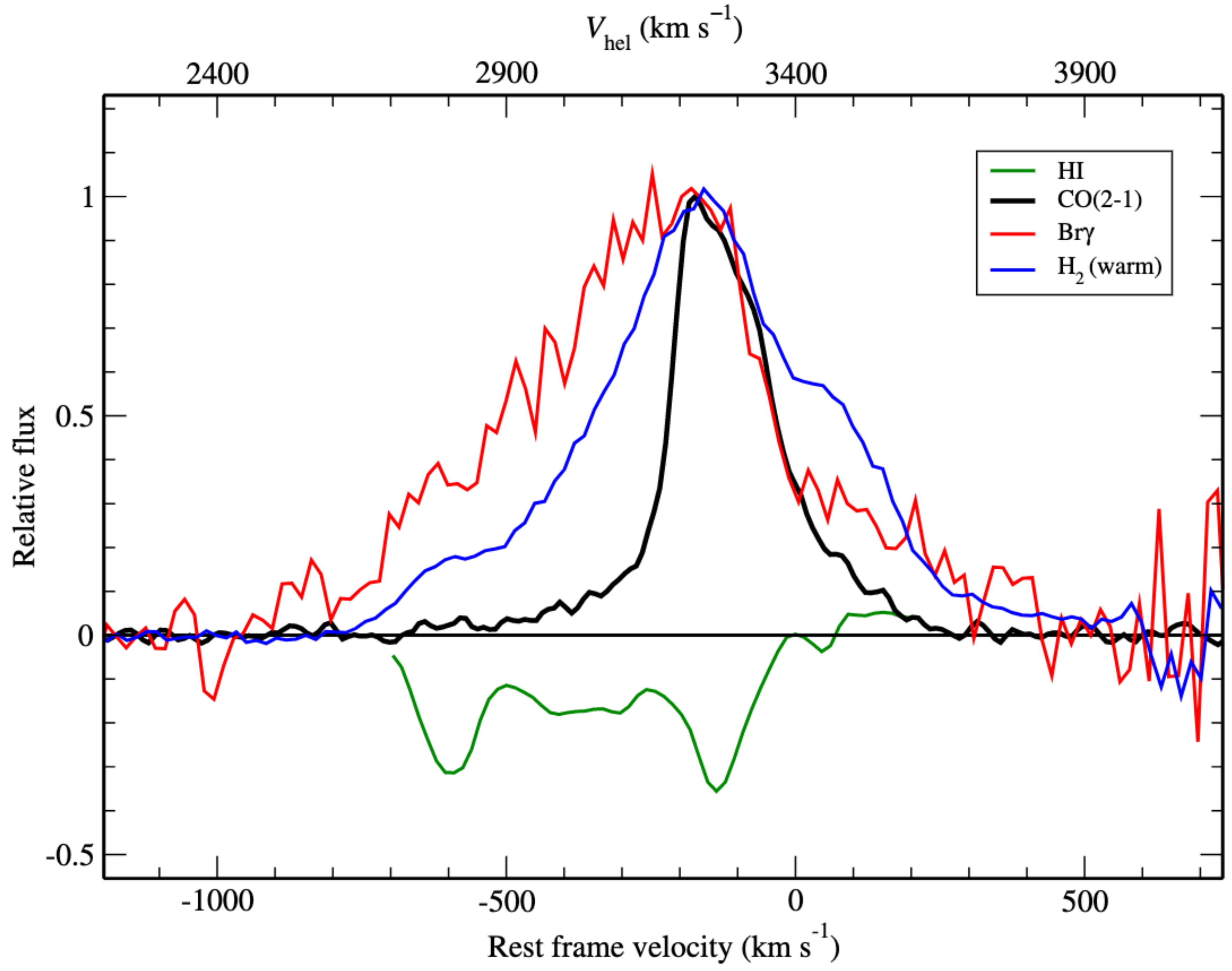
Northwestern hotspot jet-cloud interaction
(ionized and molecular)



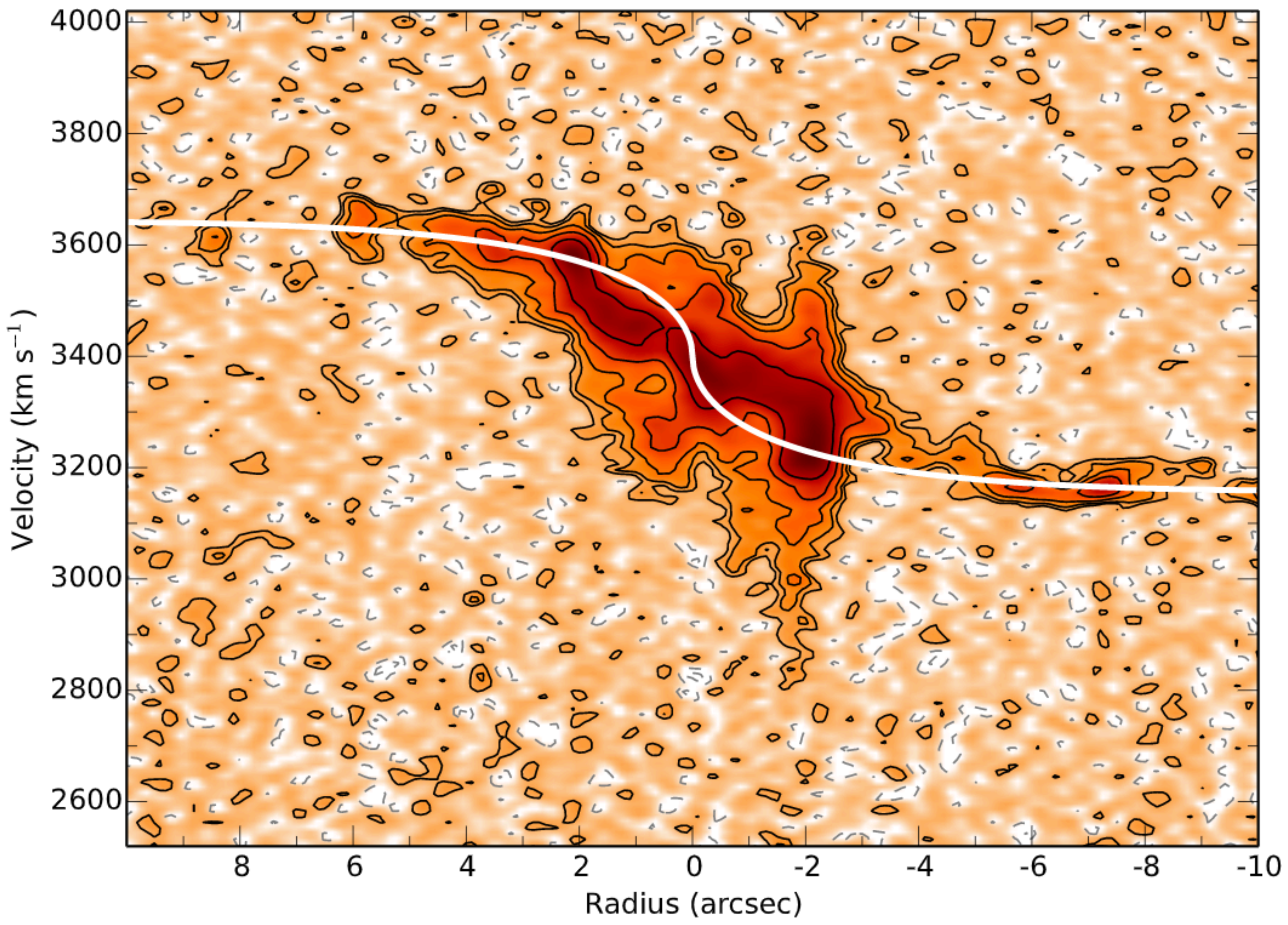
See also Oosterloo et al (2017)

Jet-ISM interactions in IC 5063 — A multiphase view

Normalised spectra of various lines



Position velocity diagram CO(2-1) from ALMA

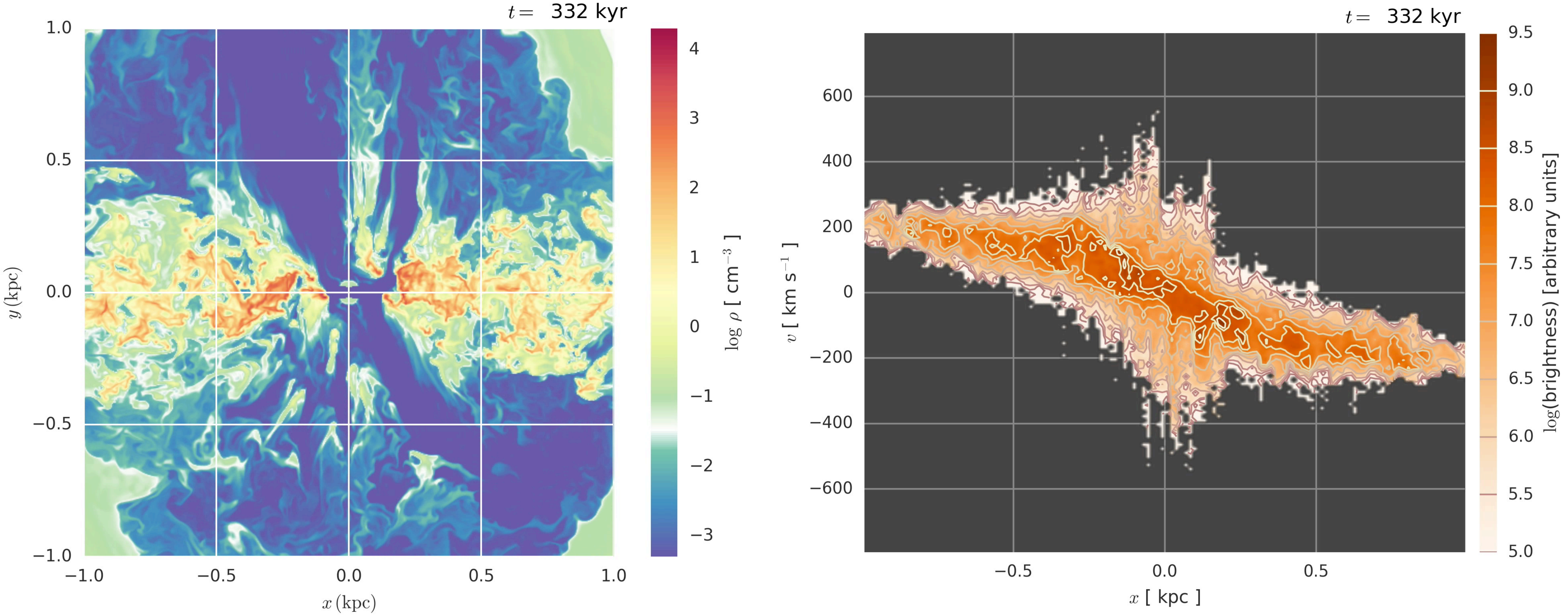


Morganti et al (2015)

- M_{disc} ~ 1×10^9 M$_\odot$; M_{BH} ~ 2.8×10^8 M$_\odot$; L_{Edd} ~ 3.5×10^{46} erg s^{-1}
- $M_{mol,out}$ ~ 1.3–5×10^6 M$_\odot$ ~ $M_{HI,out}$ ~ 3.6×10^6 M$_\odot$; dM/dt ~ 12 M$_\odot$ / yr
- P_{jet} ~ 5×10^{43} erg s^{-1} from radio power scaling relations

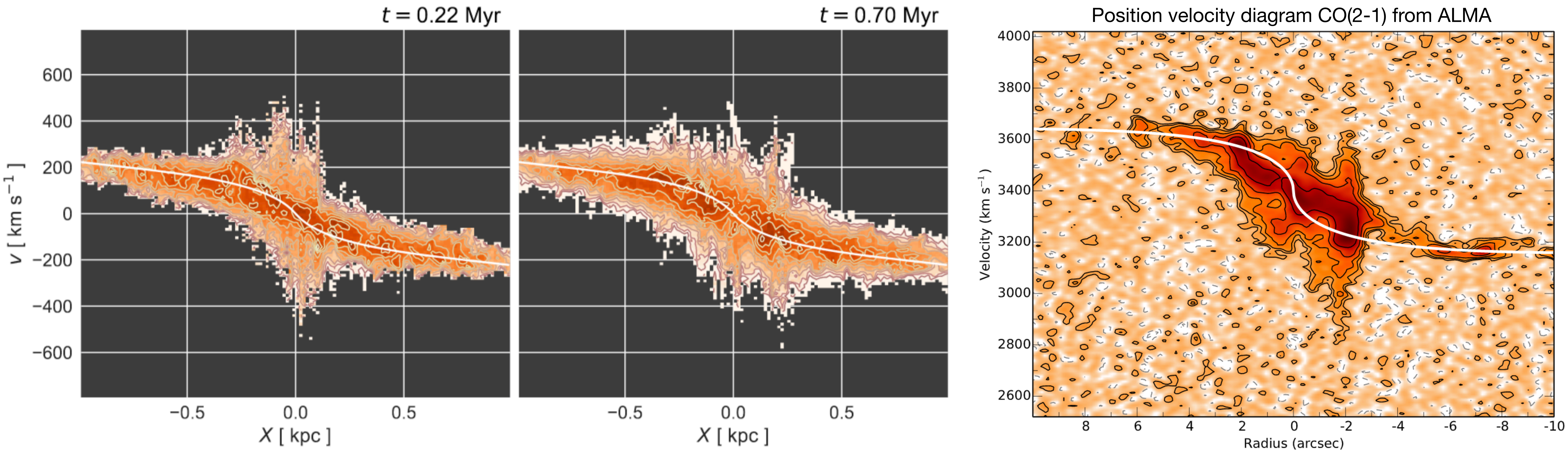
Jet-ISM interactions in IC 5063 — Simulations

(Mukherjee et al 2018b)



Jet-ISM interactions in IC 5063 — Simulations

(Mukherjee et al 2018b)



1. Broadening to a few 100 km s^{-1}
2. Spiky features
3. Strongest feature at jet hotspot
4. Assymmetry
5. Signal in forbidden quadrants
6. Shallower gradient of rotation curve

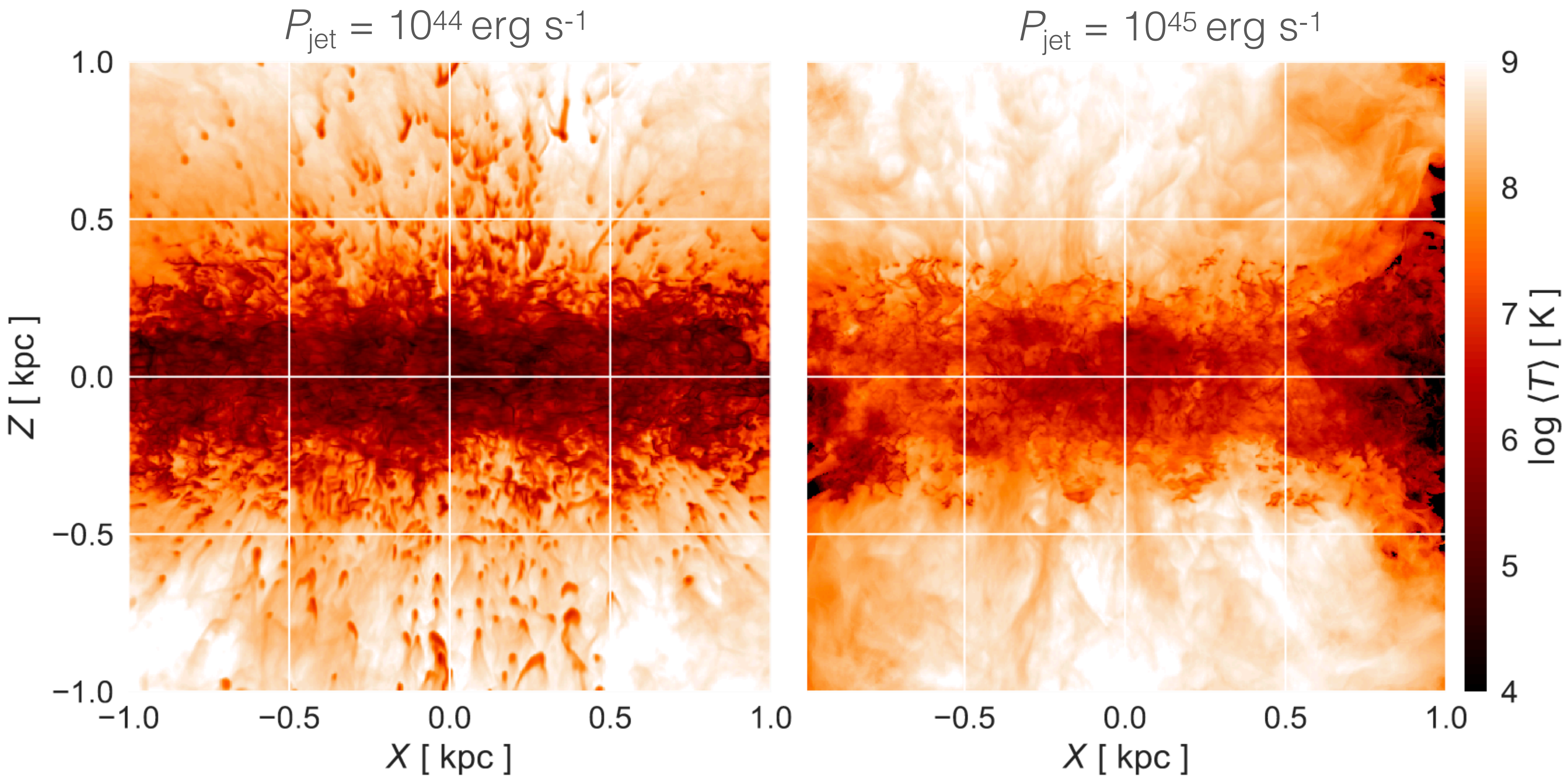
The simulations constrain the clumpiness of the gas

Jet power is revised upward to $P_{\rm jet} > 10^{44}$ erg s^{-1}.

Jet-ISM interactions in IC 5063 — Simulations

(Mukherjee et al 2018b)

- If the power is closer to 10^{44} erg s^{-1}, we expect clumpy filaments lifted off the disc, possibly observable in Hα or [OIII].



Summary

- **AGN jets and winds** interact strongly with the interstellar medium causing positive and negative feedback, often in the same outburst.

- AGN jets induce a lot of **turbulence** in this disc.
  ➡ Unexplored mode of negative and positive feedback

- Jet-ISM interactions of a jet progressing through and dispersing a clumpy ISM can explain the **spectra and the size-turnover-frequency relation of GPS and CCS sources** through the evolving free-free optical depth.

- **A model of IC 5063** with a jet in the plane of the disc explains many of the multiphase observed features, in particular the dynamics of the dense molecular gas.

- *Future work*:
  - **MHD** simulations
  - Simulations of AGN **feedback cycles**,
  - Formulate prescriptions for **sub-grid models of cosmological simulations**