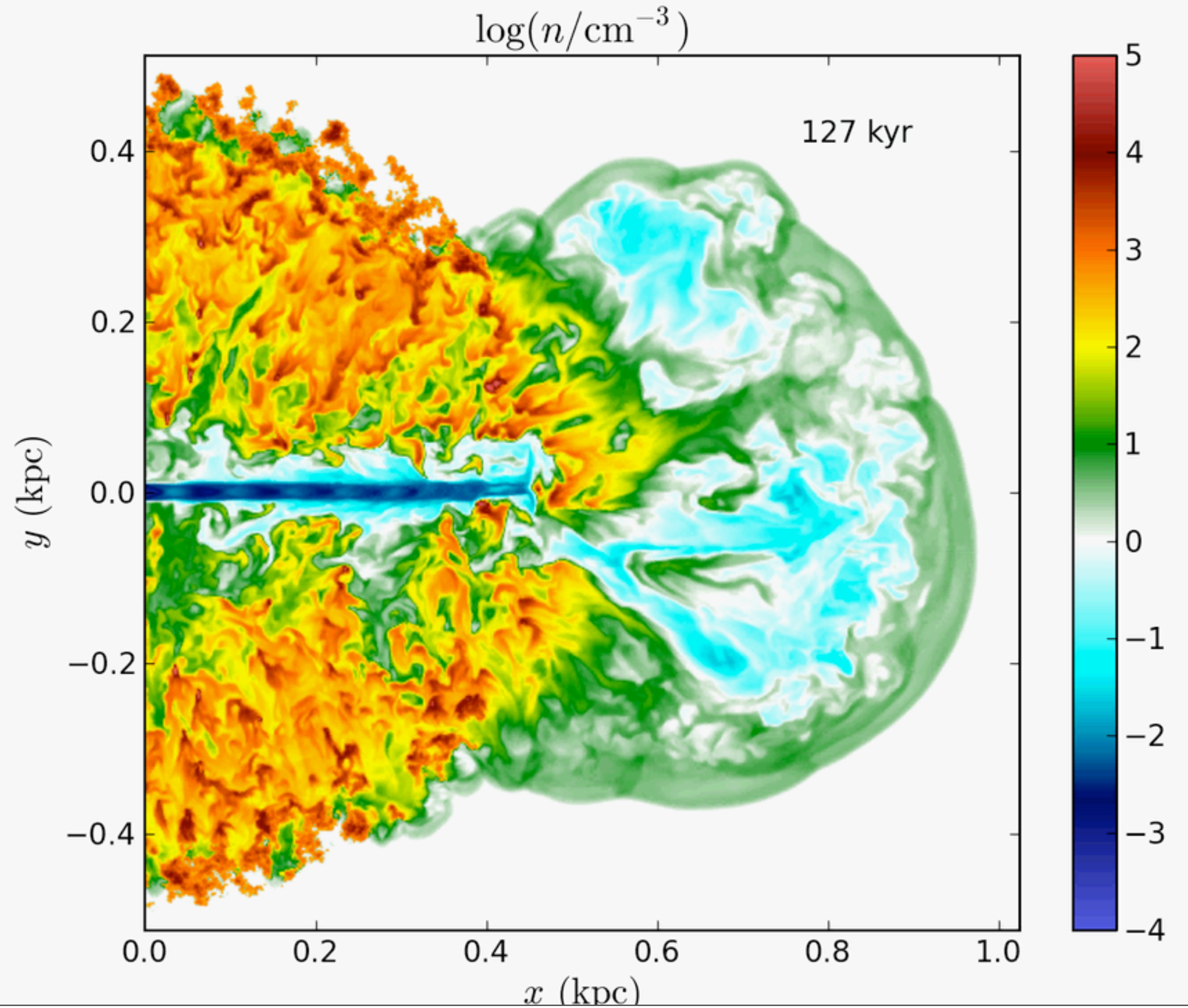
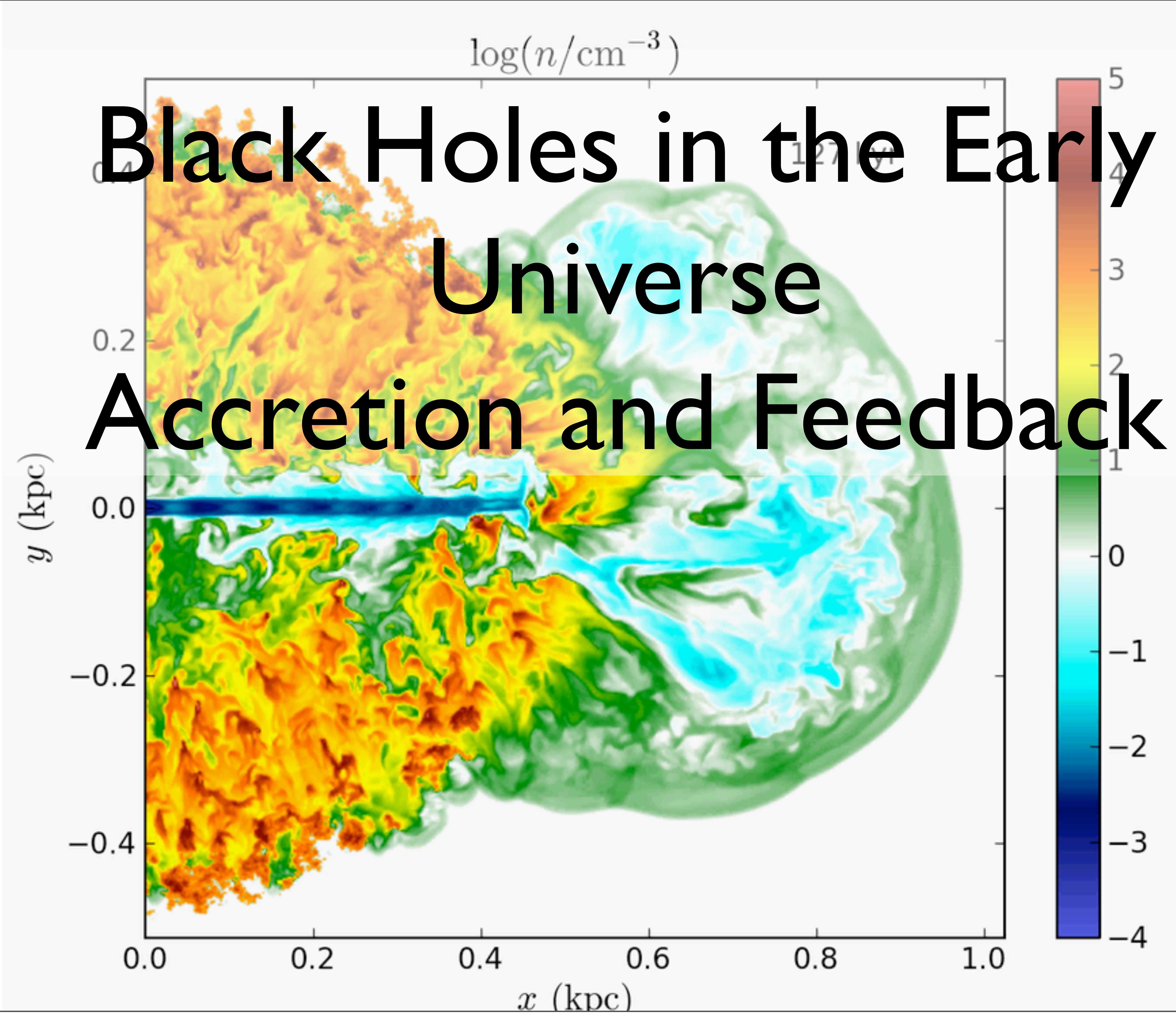


$\log(n/\mathrm{cm}^{-3})$
127 kyr
0.4
0.2
0.0
−0.2
−0.4
y (kpc)
0.0
0.2
0.4
0.6
0.8
1.0
x (kpc)
5
4
3
2
1
0
−1
−2
−3
−4

Black Holes in the Early Universe

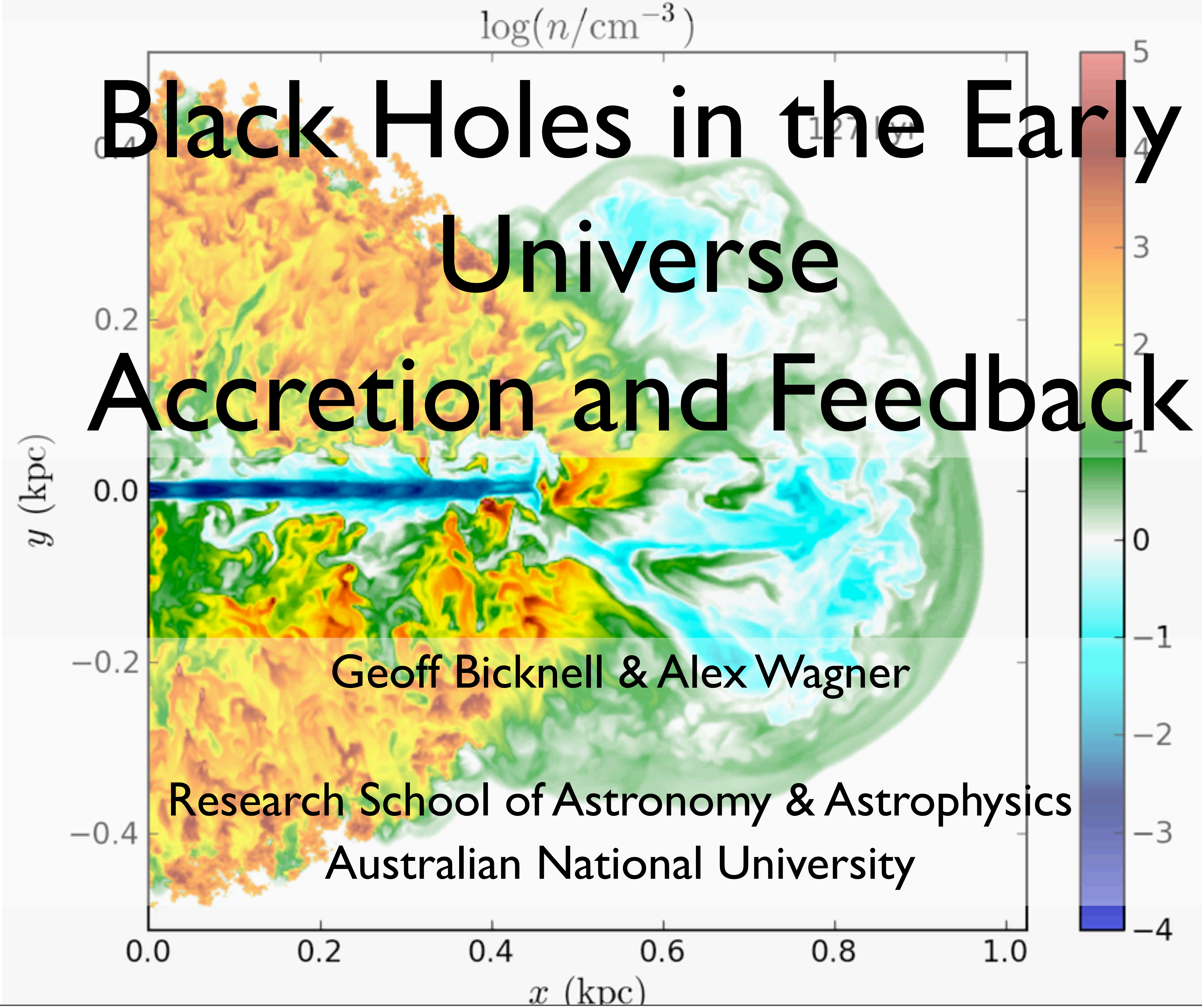
Accretion and Feedback



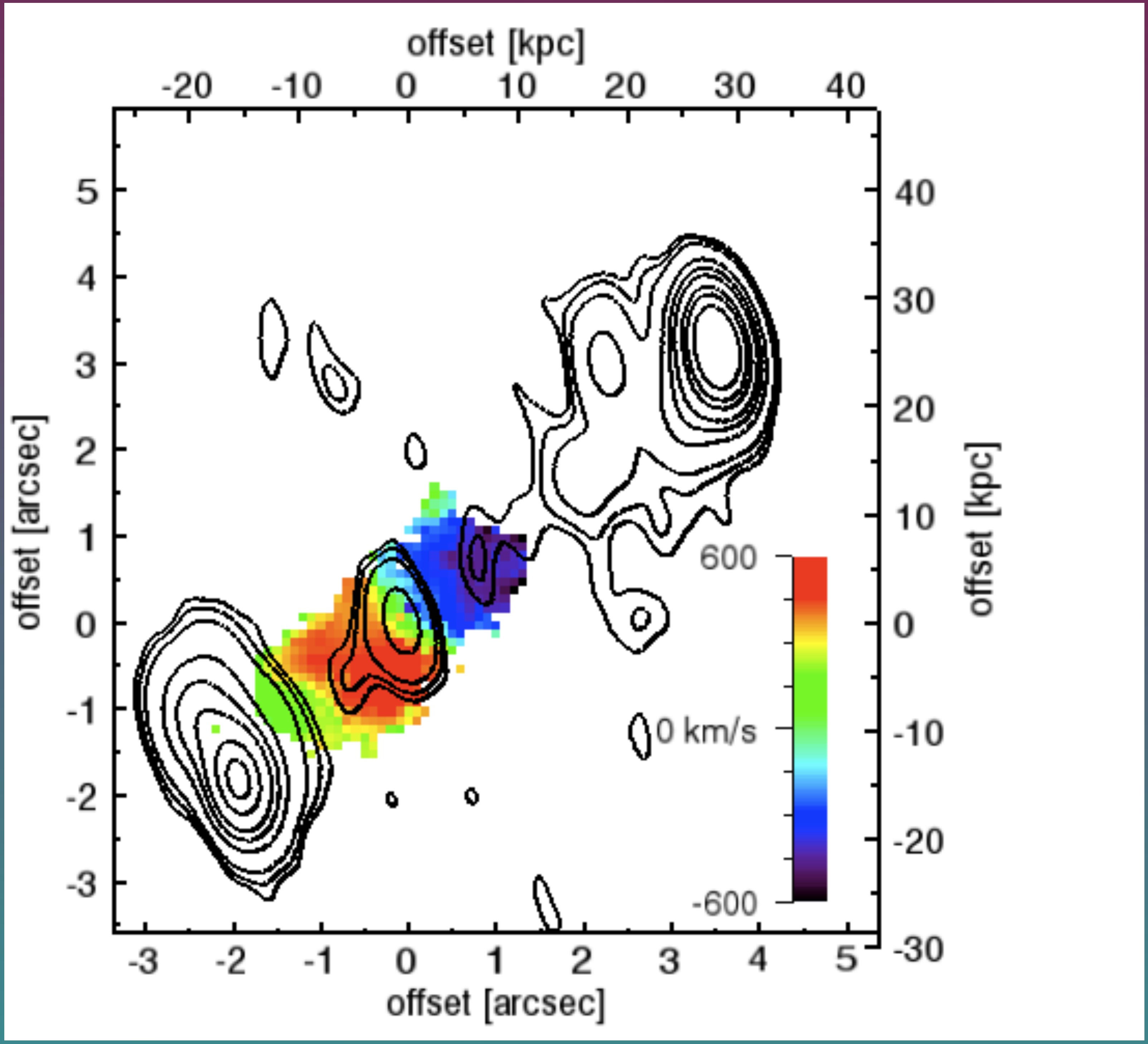
Black Holes in the Early Universe
Accretion and Feedback

Geoff Bicknell & Alex Wagner

Research School of Astronomy & Astrophysics
Australian National University



High redshift radio galaxies: AGN Feedback



z=2.42 radio galaxy MRC0406-244

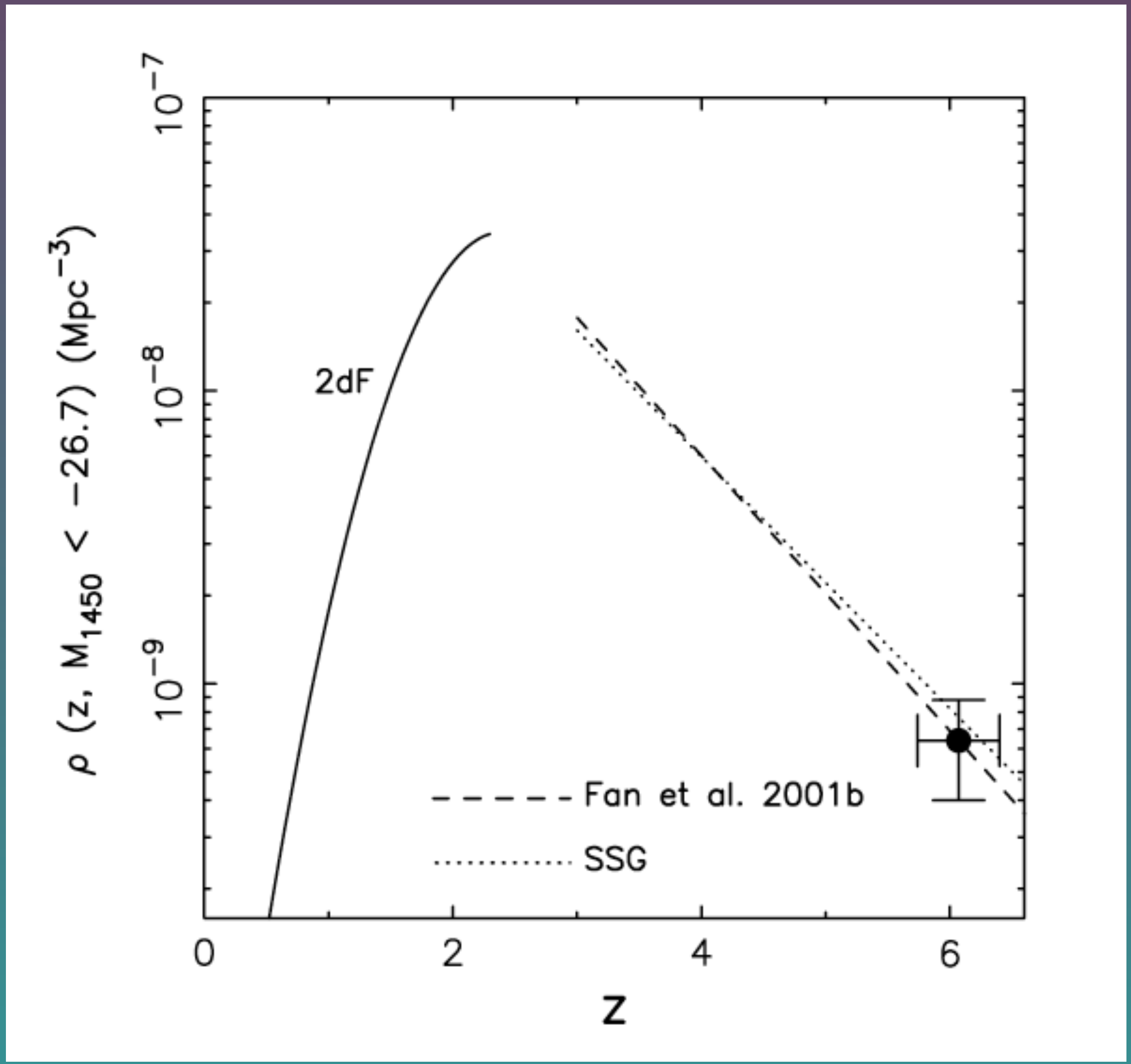
Nesvadba et al. 2009

Feedback from radio galaxies at z ~1-3 requires black holes ~ 10^9 solar masses

What is the origin of these black holes?

Black holes in the early universe

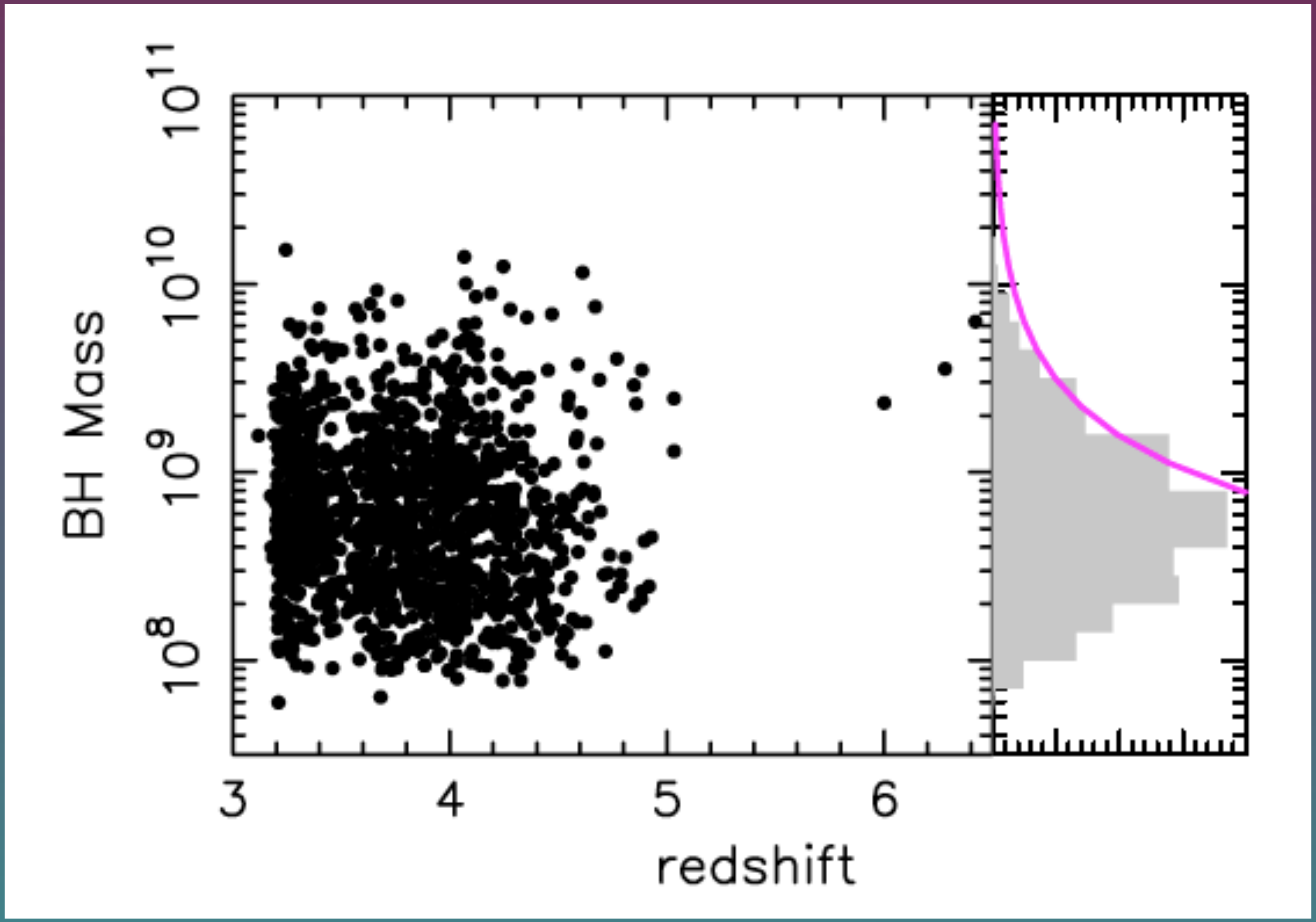
Fan 2006: The discovery of luminous quasars in SDSS at z > 6 indicates the existence billion-solar-mass black holes at the end of reionization epoch.



Comoving spatial density of quasars at M_{1450} < -26.7

Fan 2006, New Astr. Rev. **50**, 665

Black hole masses

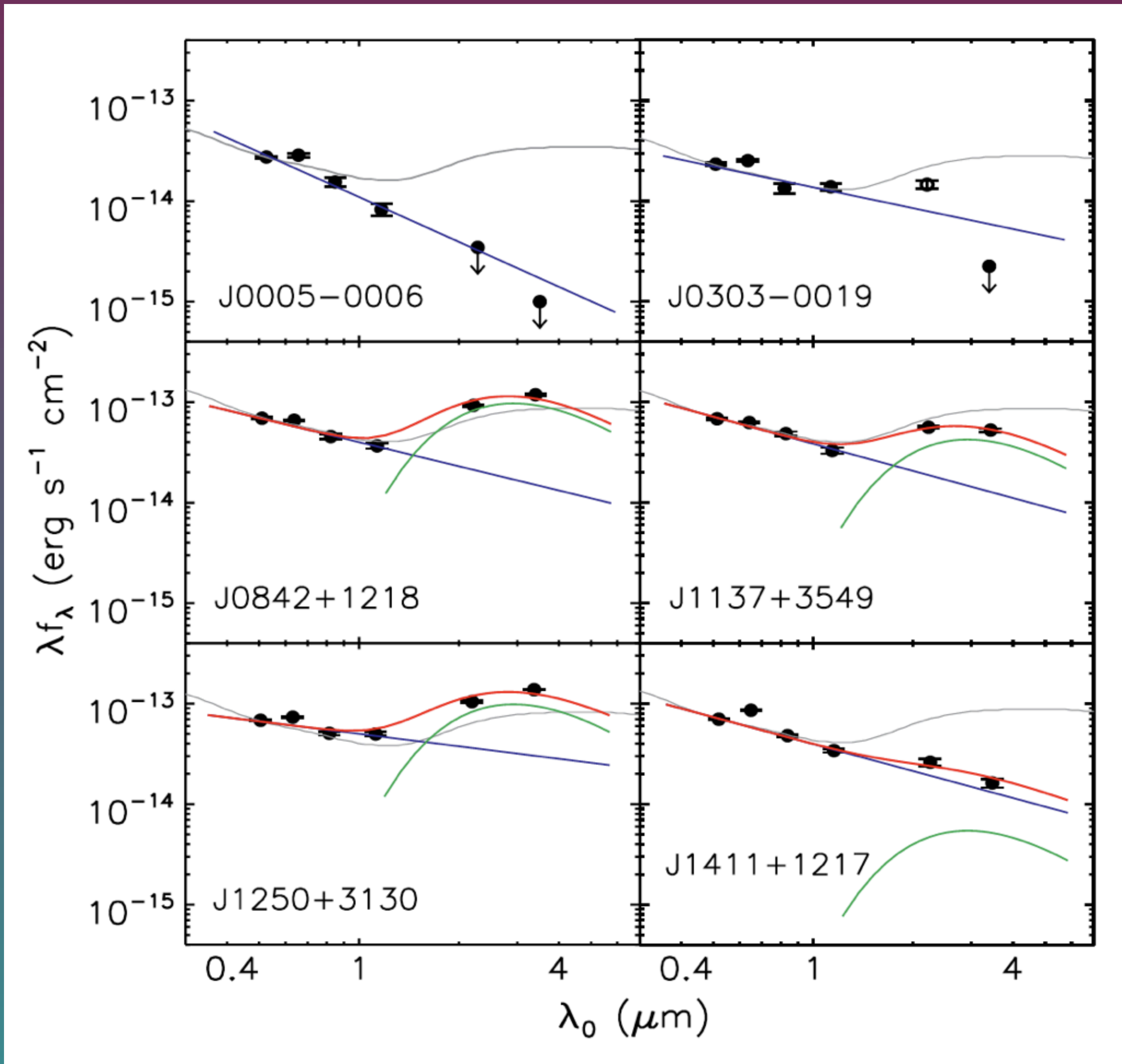


Distribution of black hole masses for z>3

From Fan, 2006

Black hole masses up to ~ 10^{10} solar masses

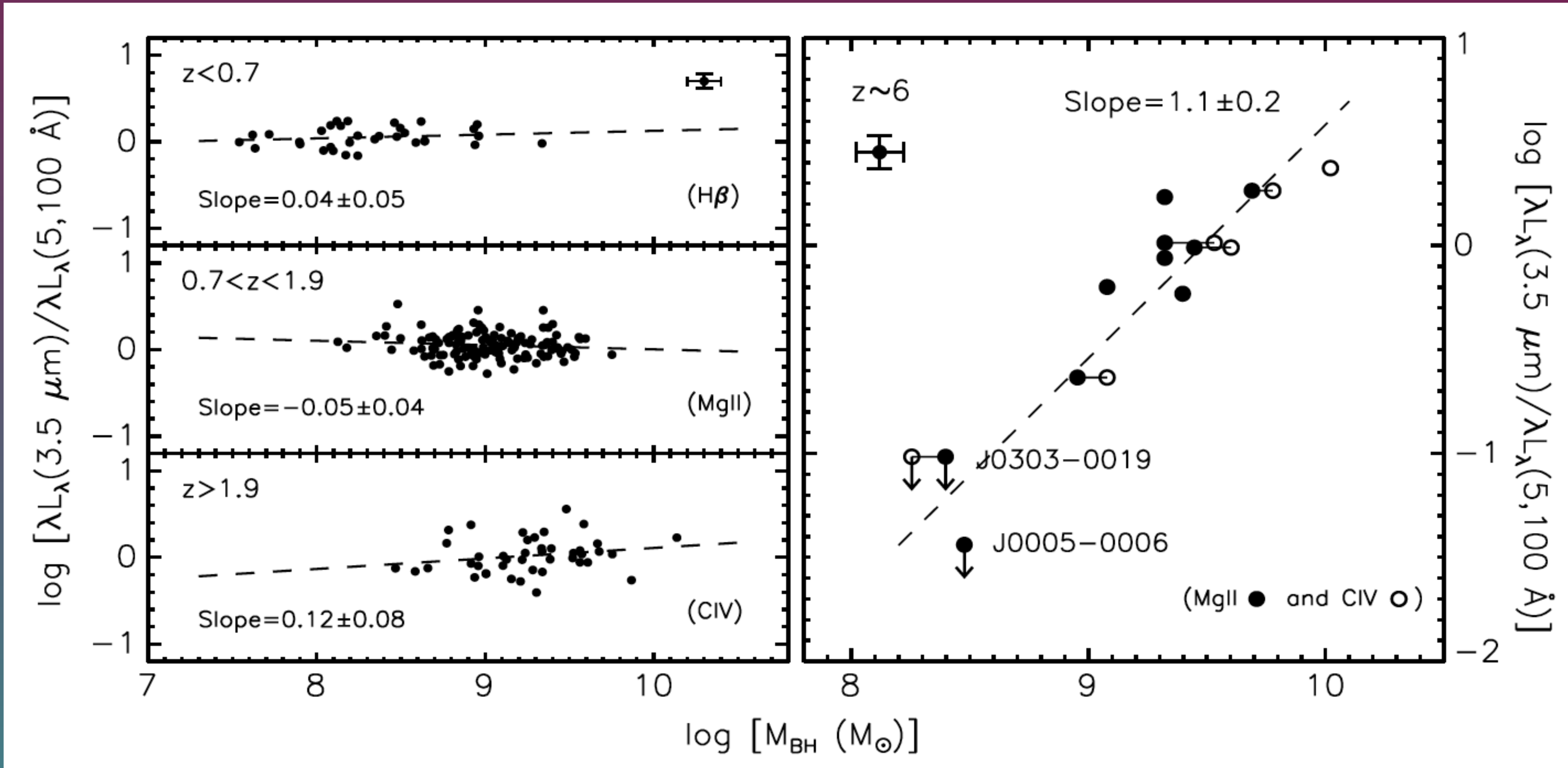
Dust-free quasars – further evidence of evolution



Jiang, Fan, Brandt et al.
Nature 2010

- Disk emission
- Dust emission
- Low z quasars

Correlation between dust and black hole mass



- Correlation between measure of dust and black hole mass
- Formation of dust in quasar outflows? (Elvis et al. 2007)

Alternative to quasar outflow model

Gall, Anderson and Hjorth, 2011

- Rapid dust formation possible when SFR > 10^3 solar masses per year
- Models require top heavy IMF
- Input from SNe not AGB stars
- Does not rule out quasar outflow model

Growth by accretion (Shapiro ApJ 2005)

$$\text{Radiative efficiency:} \quad \epsilon_r = \frac{L}{\dot{M}_0 c^2}$$

$$\text{Normalised luminosity:} \quad \dot{m} = \frac{L}{L_{\rm Edd}}$$

$$\text{Accretion rate:} \quad \frac{dM}{dt} = (1-\epsilon_r)\dot{M}_0 = \frac{\dot{m}(1-\epsilon_r)}{\epsilon_r}\frac{M}{\tau}$$

$$\text{Accretion time scale:} \quad \tau = \frac{c\sigma_T}{4\pi G m_p} = 4.5 \times 10^8 \text{ yrs}$$

Radiative efficiency

Comparison of quasar luminosity density with SMBH density at $z<5$ implies radiative efficiency $\varepsilon_r > 0.1$

(Soltan 1982; Aller & Richstone 2002; Elvis, Risaliti & Zamorani 2002; Yu & Tremaine 2002; Marconi 2004).

Time to grow a black hole by accretion

$$t - t_0 = 4.5 \times 10^8 \text{ yrs} \left(\frac{\epsilon_r}{1 - \epsilon_r} \right) \frac{1}{\dot{m}} \ln \left(\frac{M}{M_0} \right)$$

$$\epsilon_r = 0.1 \quad \dot{m} = 1$$

$$M = 5 \times 10^9 M_\odot \quad M_0 = 100 M_\odot \quad \Rightarrow \quad 8.9 \times 10^8 \text{ yrs}$$
$$M = 1 \times 10^{10} M_\odot \quad M_0 = 100 M_\odot \quad \Rightarrow \quad 1.6 \times 10^9 \text{ yrs}$$

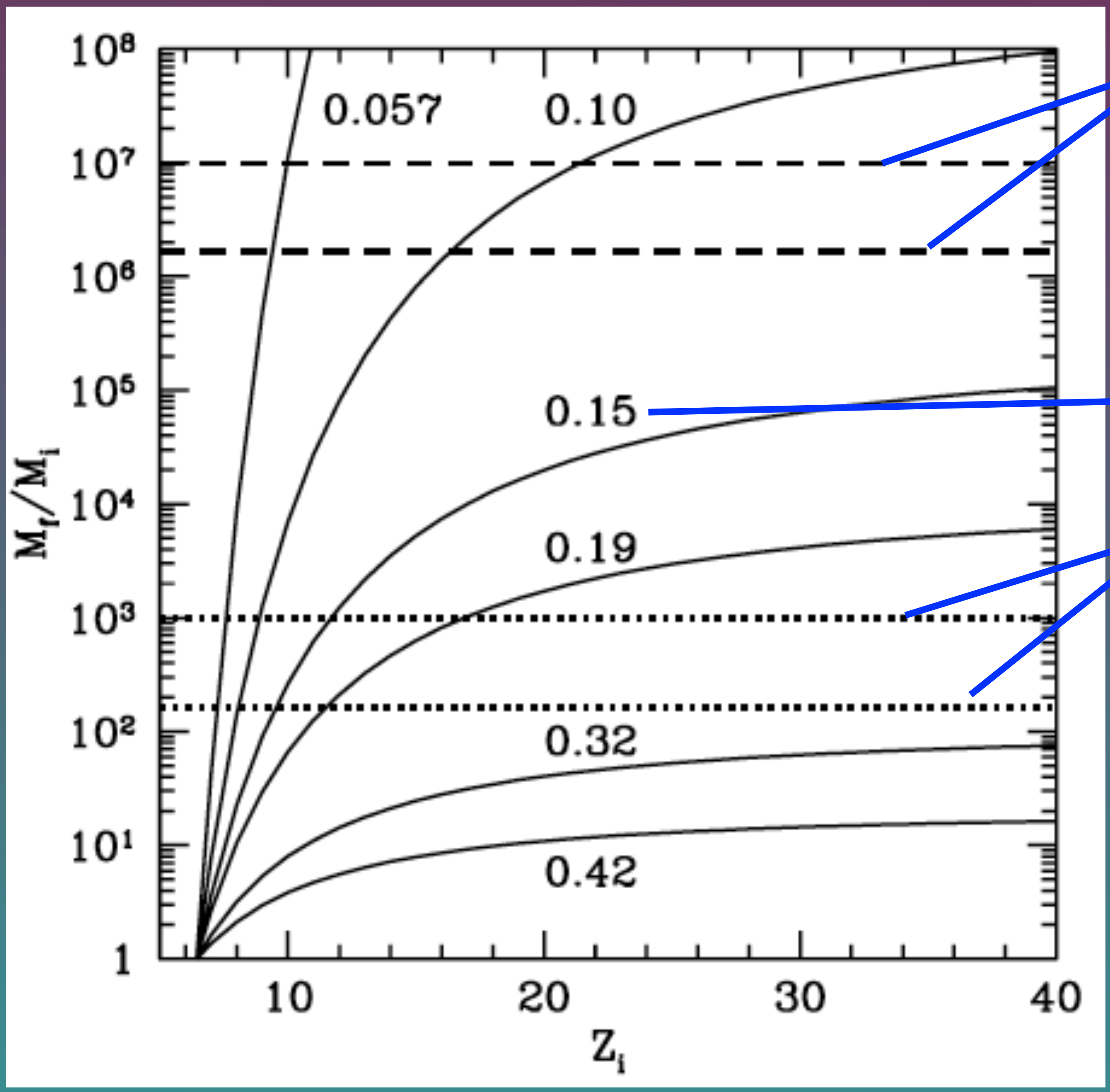
Time available

$$z = 6 \Rightarrow t = 9.5 \times 10^8 \text{ yr}$$
$$z = 3 \Rightarrow t = 2.2 \times 10^9 \text{ yr}$$

Effect of black hole spin: Amplification at z=6.43

Black hole spin increases radiative efficiency up to 0.42

Black hole amplification



Amplification required from accretion alone $100<M_0<600$

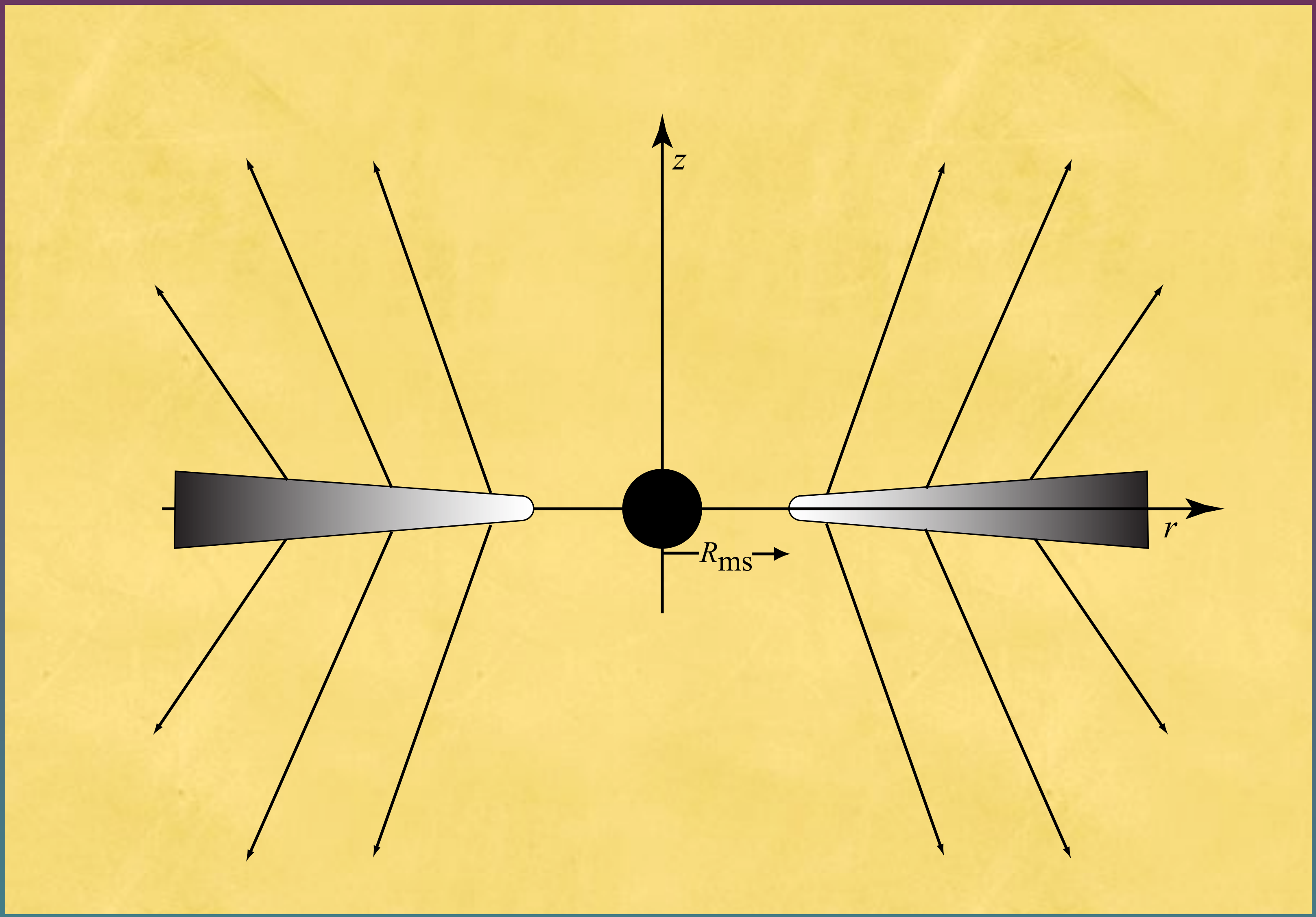
Efficiency

Amplification required assuming mergers account for growth $\sim 10^4$ in black hole mass

Initial redshift

THE AUSTRALIAN NATIONAL UNIVERSITY

Enhancement of accretion by jets/winds (Jolley & Kuncic 2008)



Gravitational power directed into wind or jet decreases the radiative luminosity

=> Accretion rate larger for given luminosity

Modification of black hole growth

$$\text{Accretion efficiency} = \epsilon_a = \text{Radiative} + \text{Jet efficiency} = \epsilon_r + \epsilon_j$$

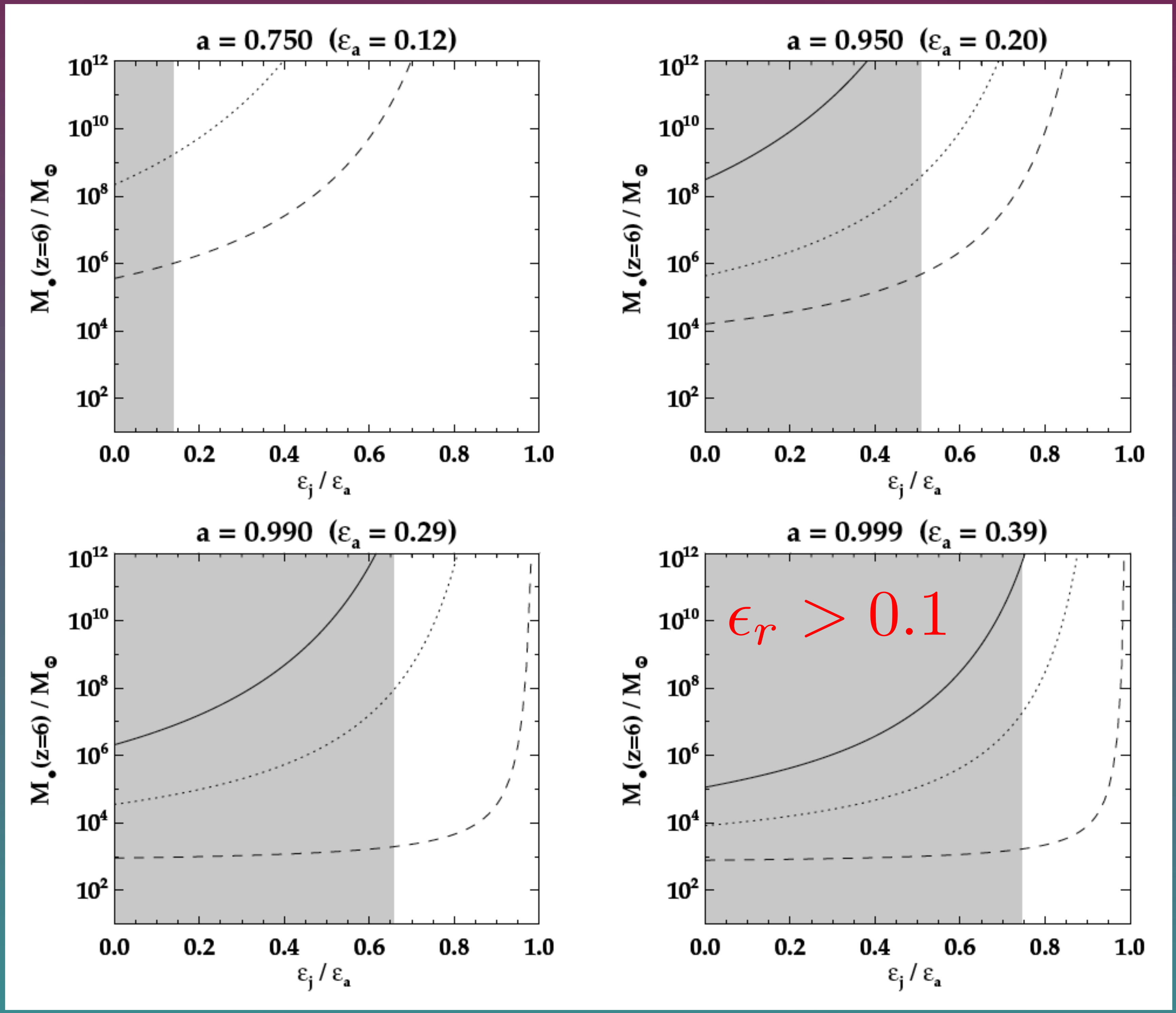
$$\frac{dM}{dt} = \frac{\dot{m}(1-\epsilon_a)}{\epsilon_r}\frac{M}{\tau}$$

$$\Rightarrow t - t_0 = 4.5 \times 10^8 \text{ yrs} \frac{\epsilon_a}{1-\epsilon_a}(1-\epsilon_j/\epsilon_a)\frac{1}{\dot{m}} \ln\left(\frac{M}{M_0}\right)$$

Effect of jet/wind is to reduce accretion time for a given luminosity

Black hole mass at z=6

$M(z=6)/M_0$



ϵ_j/ϵ_a

Research School of Astronomy & Astrophysics

THE AUSTRALIAN NATIONAL UNIVERSITY

Implications for AGN feedback

Kinetic luminosity of jet/wind

$$L_{\rm wind} = 5.5 \times 10^{47}\ {\rm ergs\,s^{-1}} \frac{\epsilon_w}{\epsilon_a} \frac{\epsilon_w/0.42}{\epsilon_r/0.1}\, \dot{m} \left(\frac{M}{10^9\ M_\odot} \right)$$

Powerful jets/winds such as this relevant for AGN feedback

In this case winds may be more likely since, even at high z, most quasars are radio quiet.

So far .....

- Straightforward black hole growth by accretion difficult
- Driving black hole growth by Poynting-flux dominated jets/winds assists the formation of supermassive black holes by z~3, but still involves accretion at the Eddington limit
- Winds have other benefits
  - Feedback in early epochs
  - Early creation of dust

Next ....

Radio-Mode Feedback

The violent universe

The violent universe

- "....We see gas being churned by explosions and huge black holes in the center of the cluster. We see how it's cooling down and how the cooling is being balanced by tremendous outbursts of jets and bubbles of hot gas..."

The violent universe

- "....We see gas being churned by explosions and huge black holes in the center of the cluster. We see how it's cooling down and how the cooling is being balanced by tremendous outbursts of jets and bubbles of hot gas..."

– Martin Rees quoted in review by McNamara & Nulsen *Heating hot atmospheres by active galactic nuclei*

Issues in Galaxy Formation (see Croton et al. '06)

Issues in Galaxy Formation (see Croton et al. '06)

- Hierarchical merging predicts more high mass galaxies than are observed (exponential cutoff in Schecter luminosity function)

Issues in Galaxy Formation (see Croton et al. '06)

- Hierarchical merging predicts more high mass galaxies than are observed (exponential cutoff in Schecter luminosity function)
- Requires feedback in addition to that provided by supernovae => Regulation of star formation

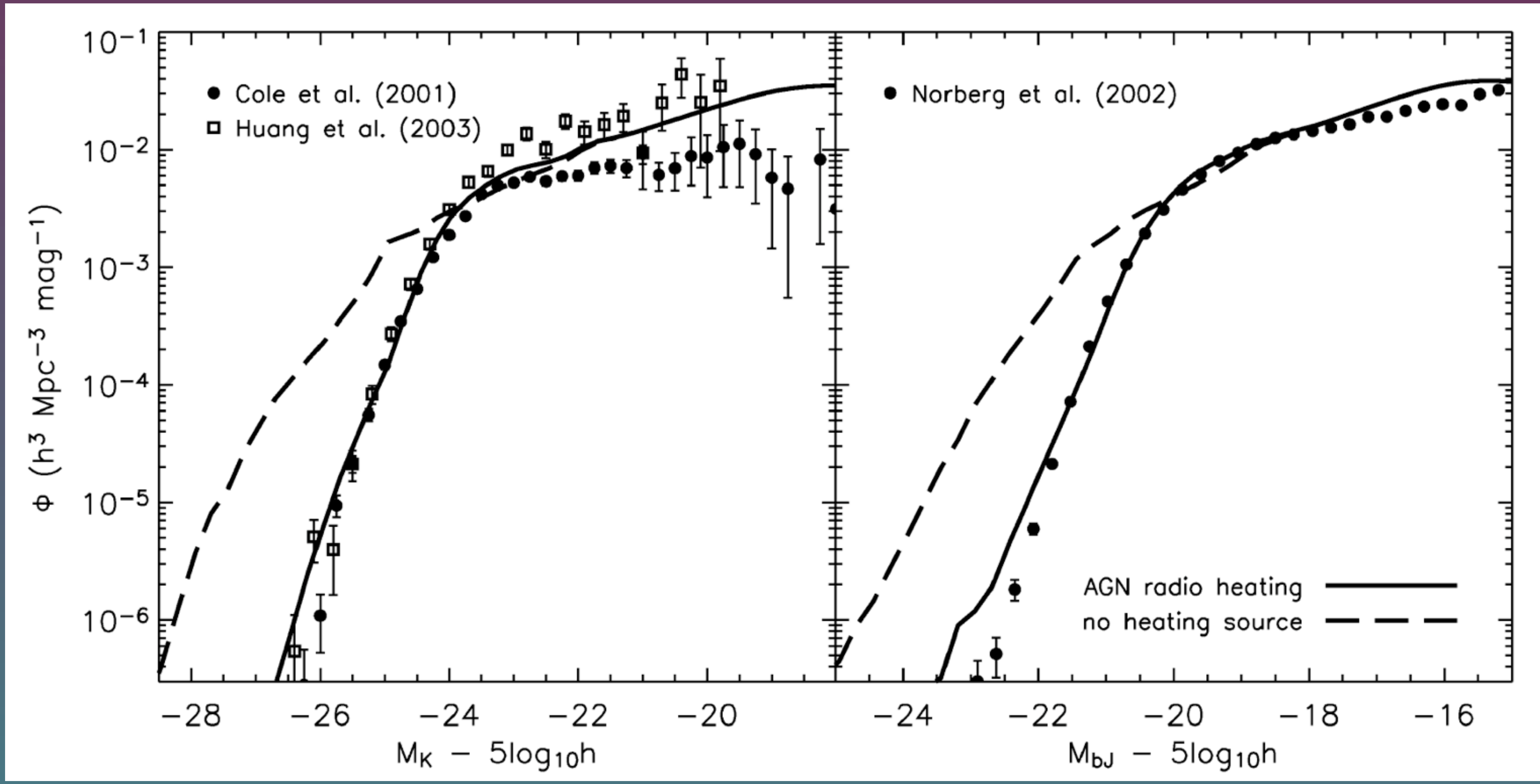
Issues in Galaxy Formation (see Croton et al. '06)

- Hierarchical merging predicts more high mass galaxies than are observed (exponential cutoff in Schecter luminosity function)
- Requires feedback in addition to that provided by supernovae => Regulation of star formation
- Downsizing: Star formation and AGN activity takes place more vigorously and in higher mass objects at z ~ 1-2. Thereafter there is a downsizing in the amount of activity that takes place.

Galaxy downsizing – semi-analytic models

Croton et al. 2006: Effect of "radio-mode" feedback on galaxy formation

Feedback produces an exponential cutoff in luminosity distribution at bright end

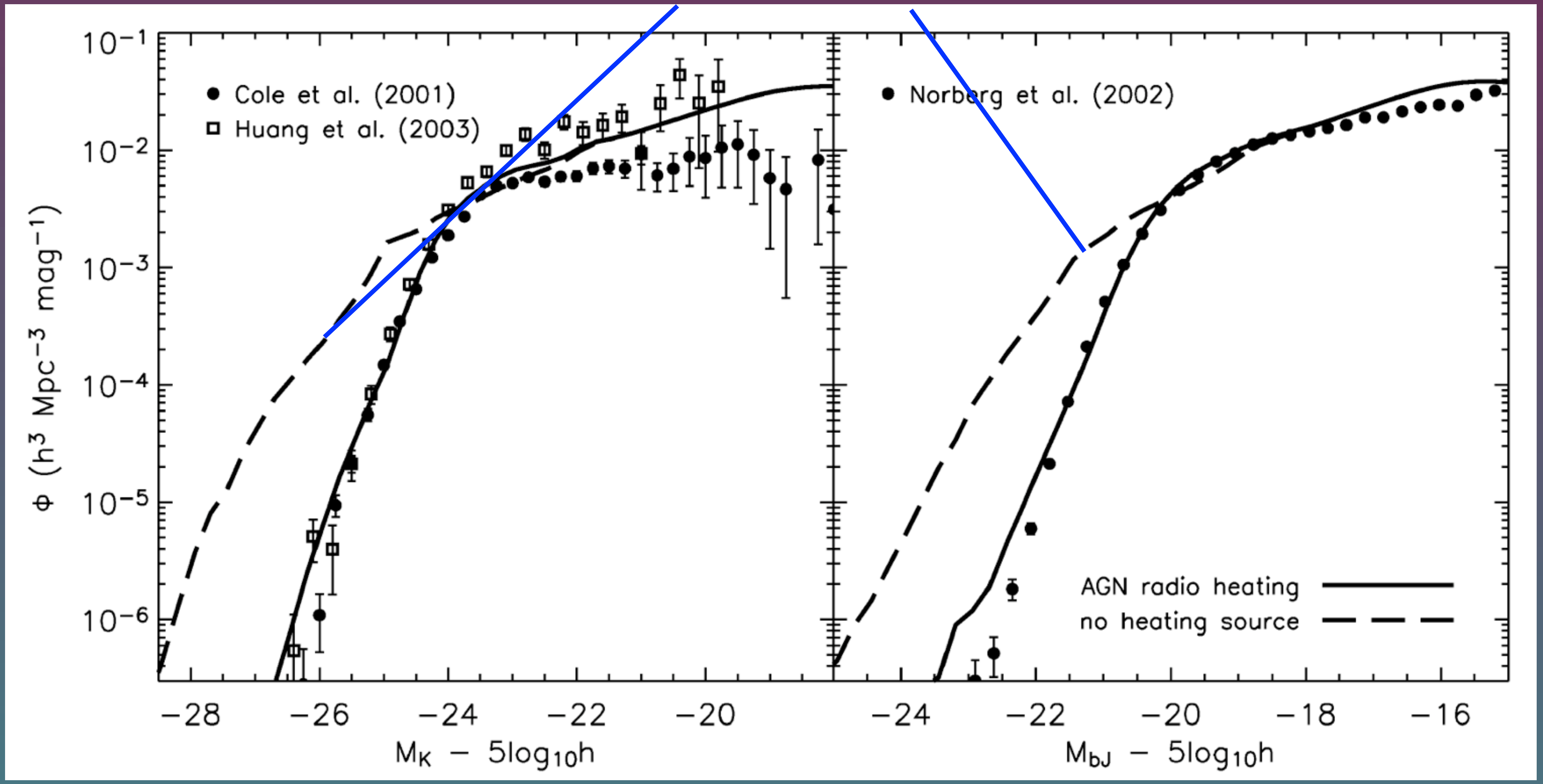


Galaxy downsizing – semi-analytic models

Croton et al. 2006: Effect of “radio-mode” feedback on galaxy formation

Feedback produces an exponential cutoff in luminosity distribution at bright end

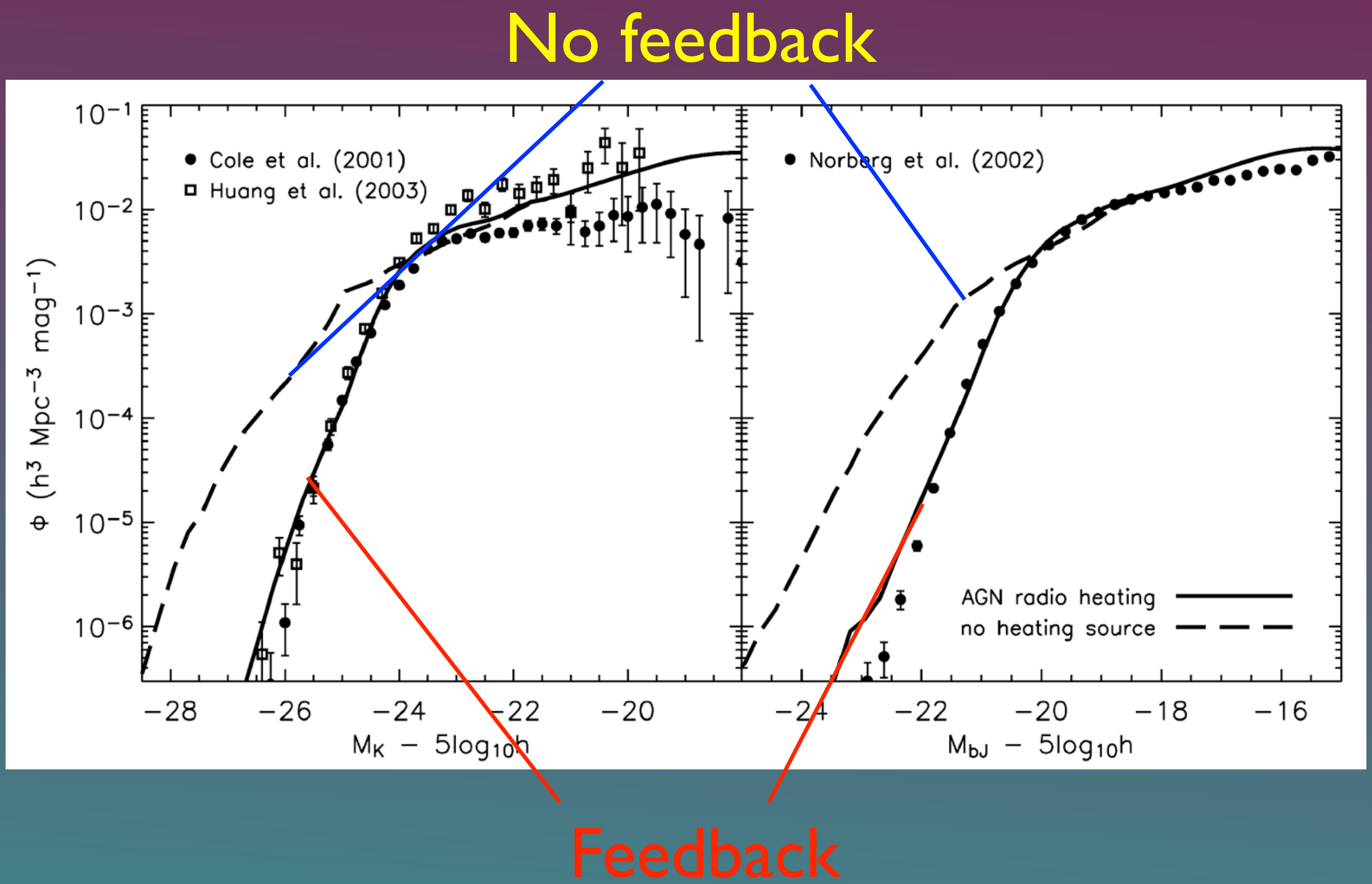
No feedback



Galaxy downsizing – semi-analytic models

Croton et al. 2006: Effect of "radio-mode" feedback on galaxy formation

Feedback produces an exponential cutoff in luminosity distribution at bright end

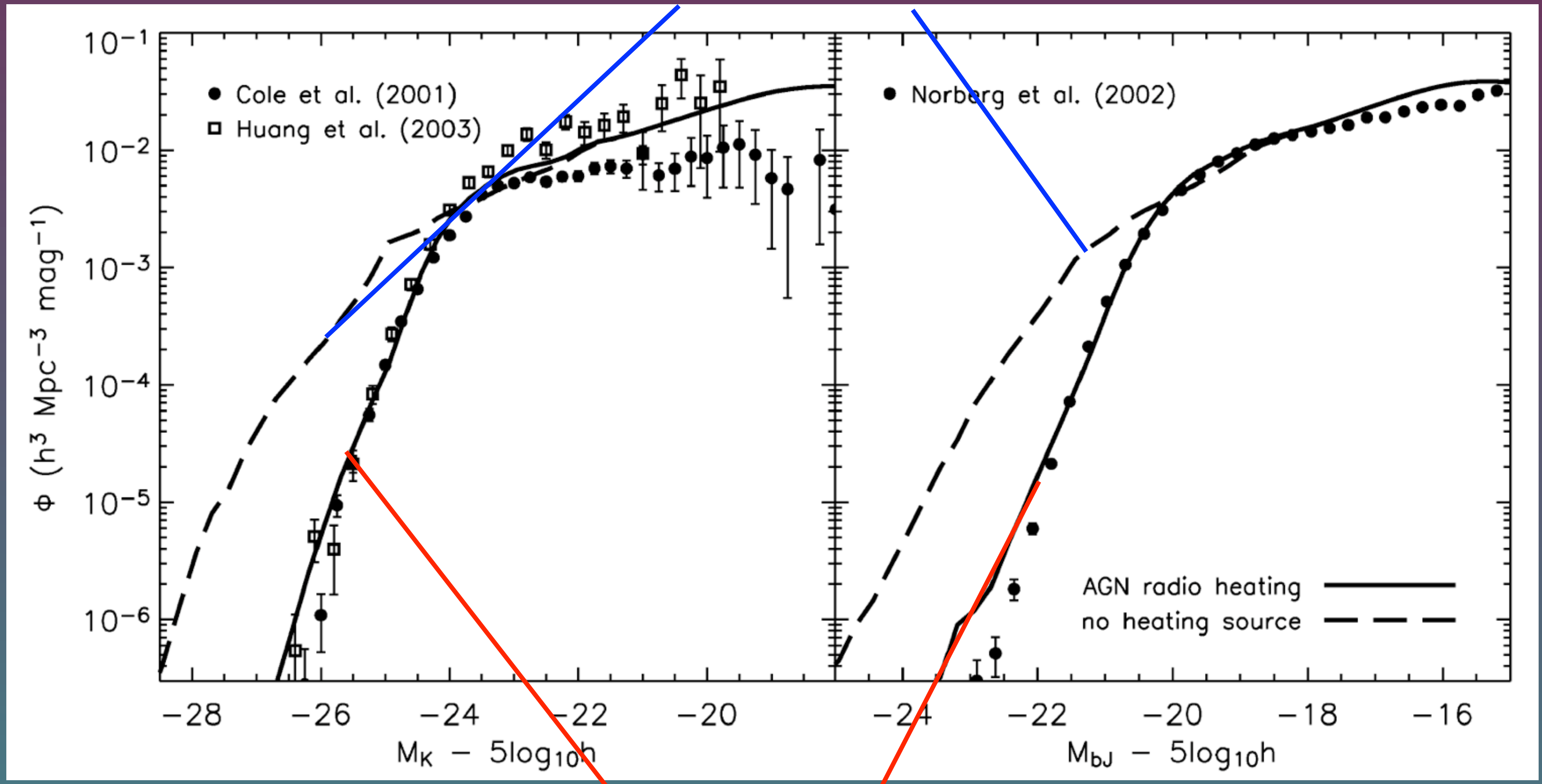


Galaxy downsizing – semi-analytic models

Croton et al. 2006: Effect of "radio-mode" feedback on galaxy formation

Feedback produces an exponential cutoff in luminosity distribution at bright end

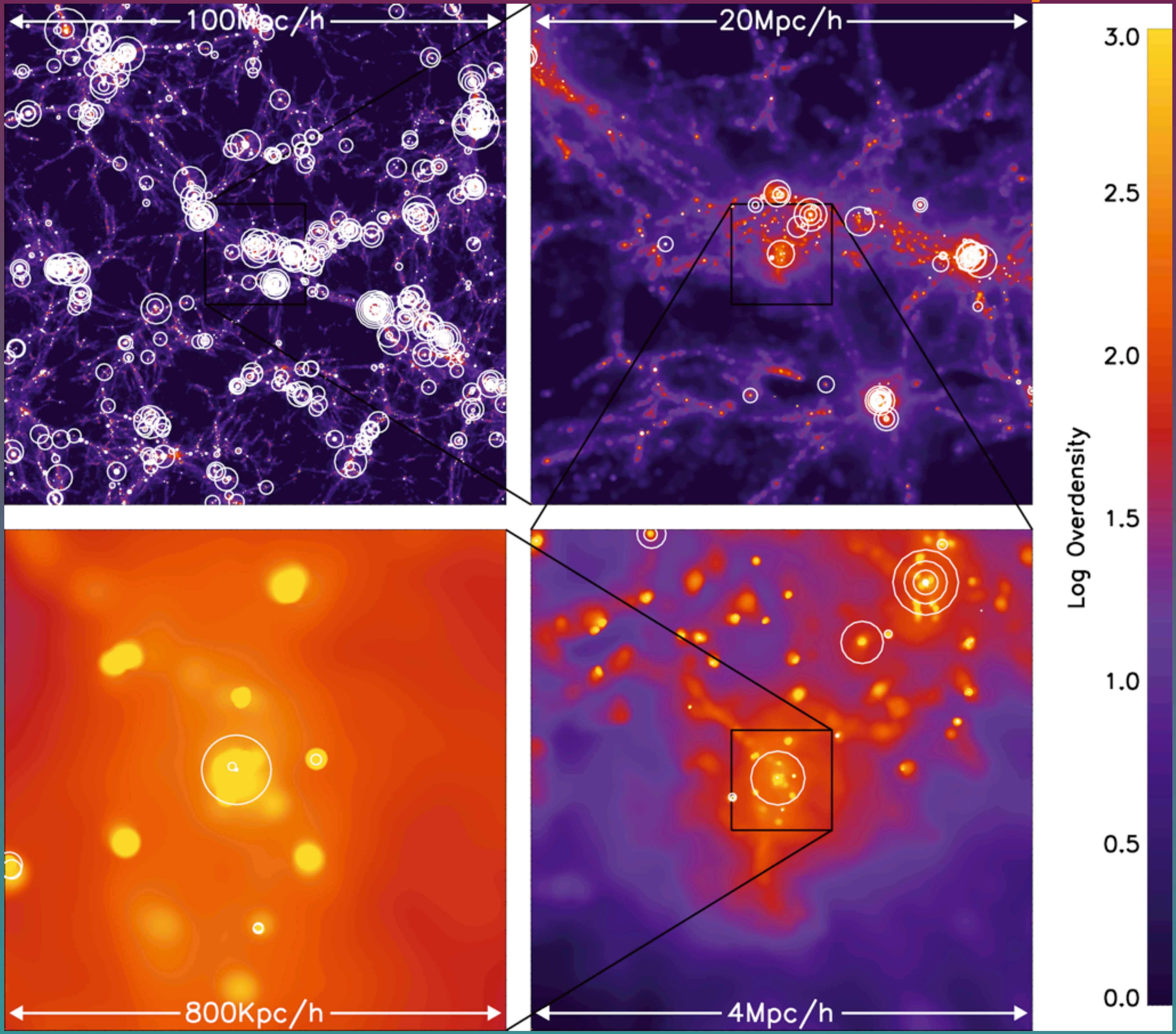
No feedback



Feedback

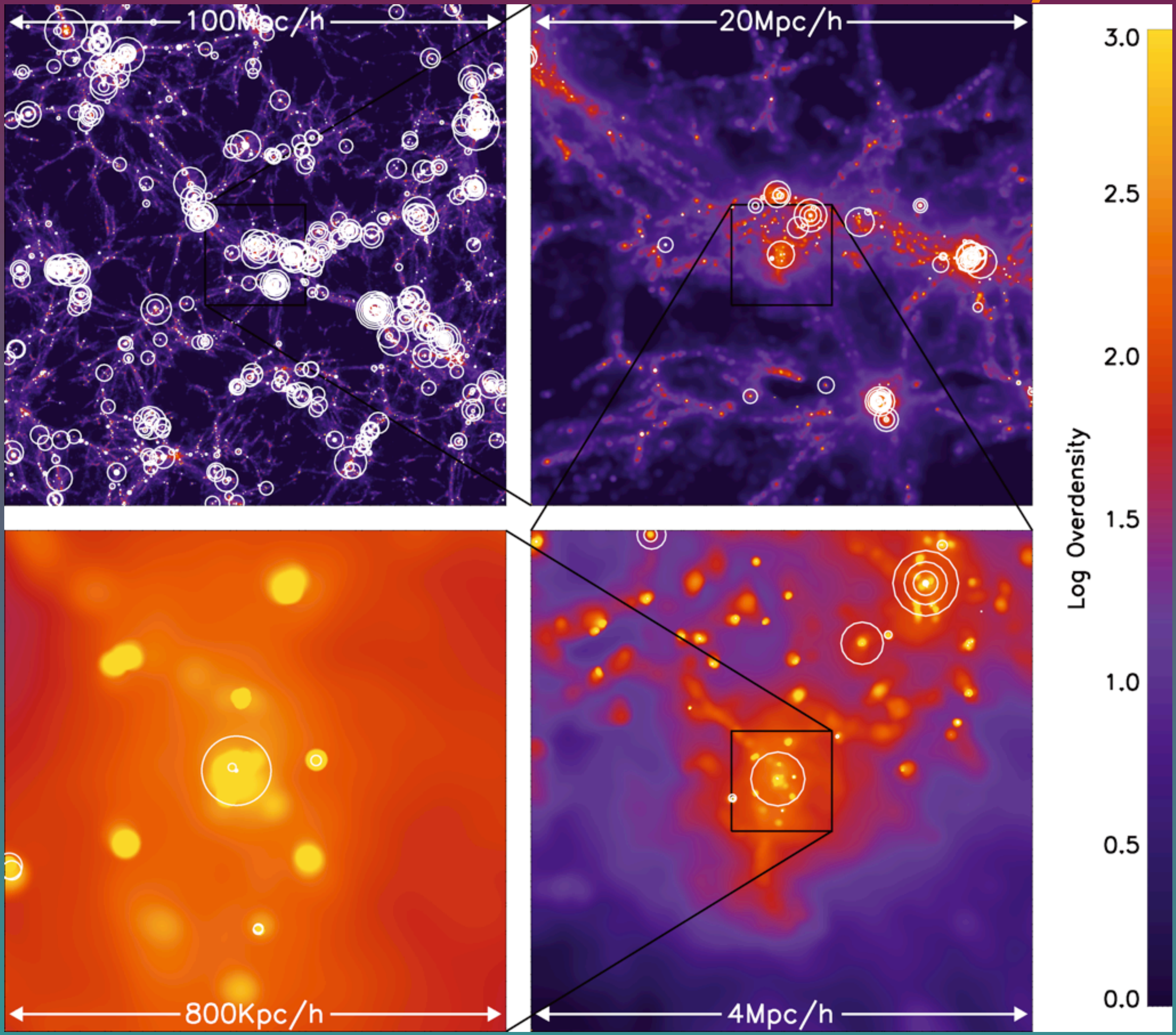
Accretion rate "orders of magnitude" below Eddington
=> Low-powered radio galaxies providing the feedback

SPH simulations – Booth & Schaye 2009



See also Schaye et al. 2010

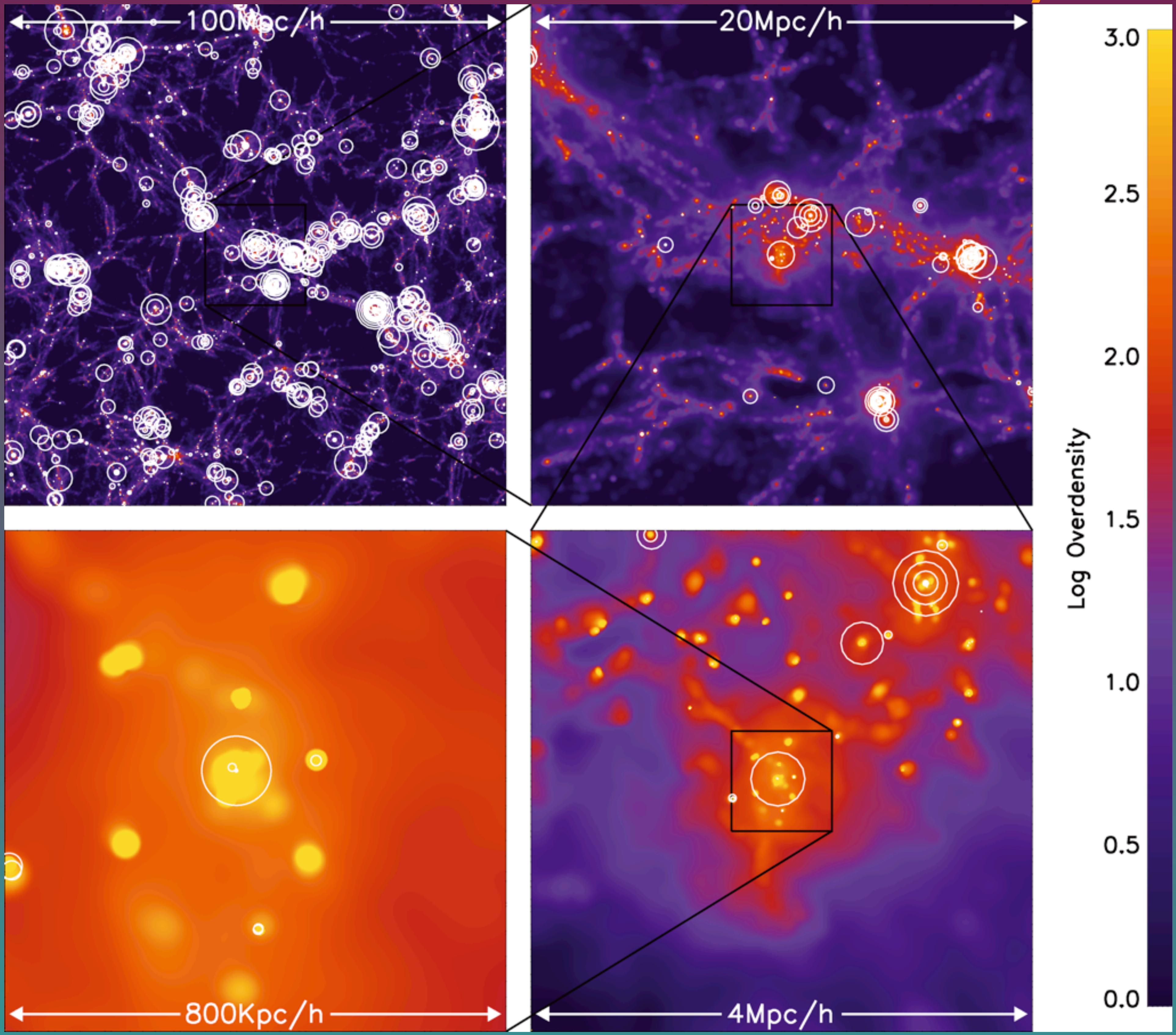
SPH simulations – Booth & Schaye 2009



"Sub-grid" prescriptions for effect of black hole on surrounding ISM

See also Schaye et al. 2010

SPH simulations – Booth & Schaye 2009

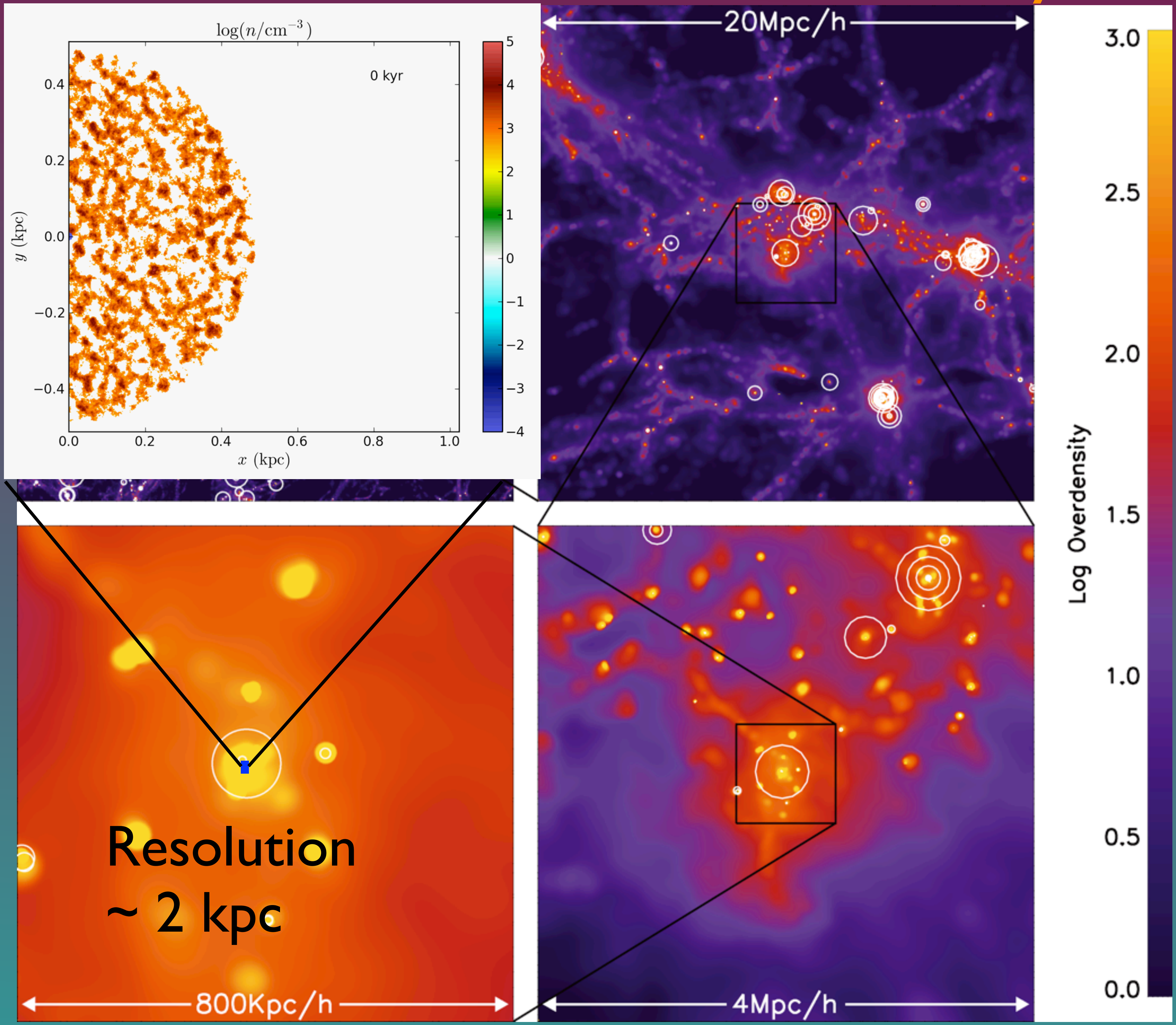


"Sub-grid" prescriptions for effect of black hole on surrounding ISM

Accretion rate ~ 100 x Bondi rate

See also Schaye et al. 2010

SPH simulations – Booth & Schaye 2009

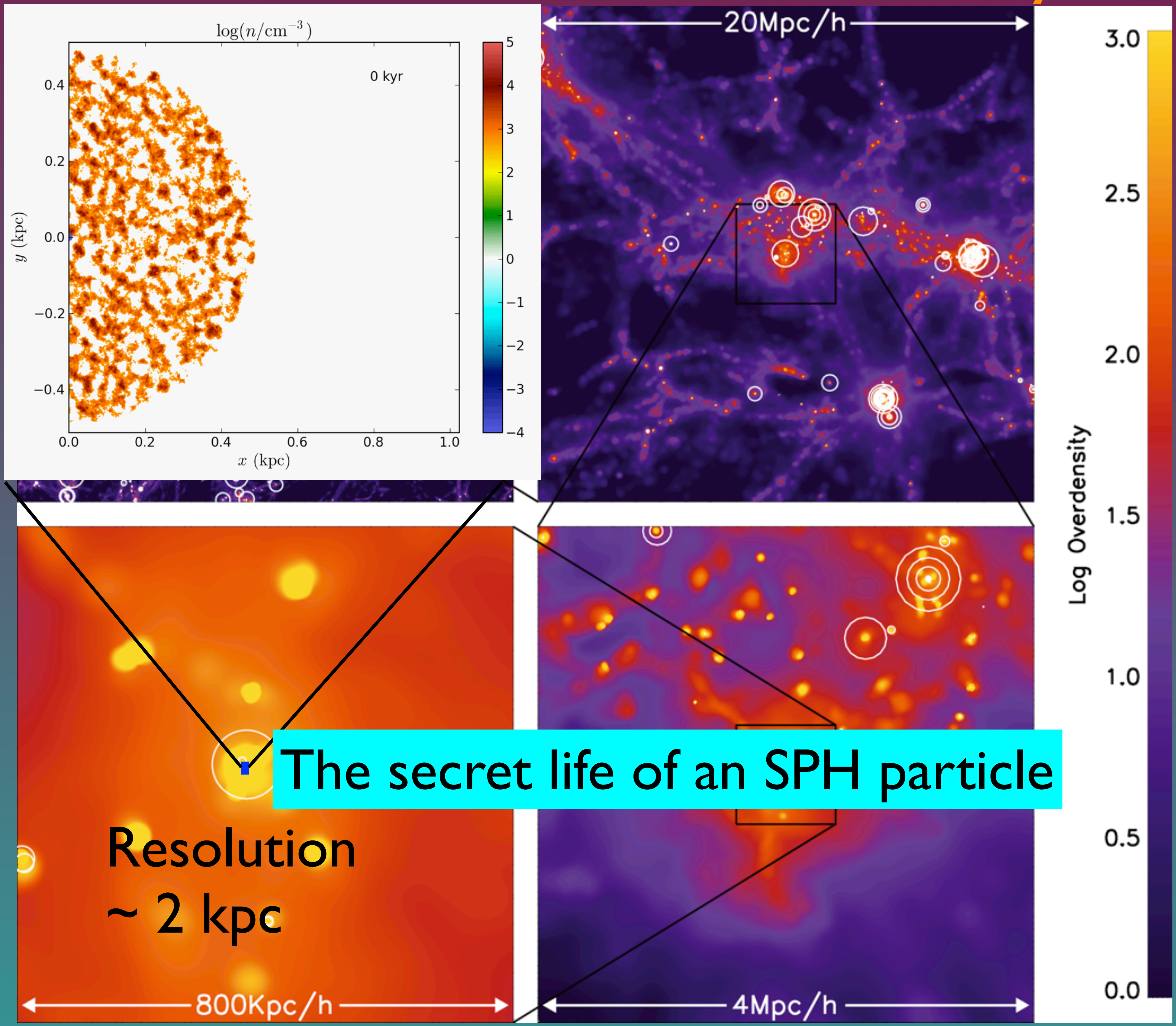


"Sub-grid" prescriptions for effect of black hole on surrounding ISM

Accretion rate ~ 100 x Bondi rate

See also Schaye et al. 2010

SPH simulations – Booth & Schaye 2009

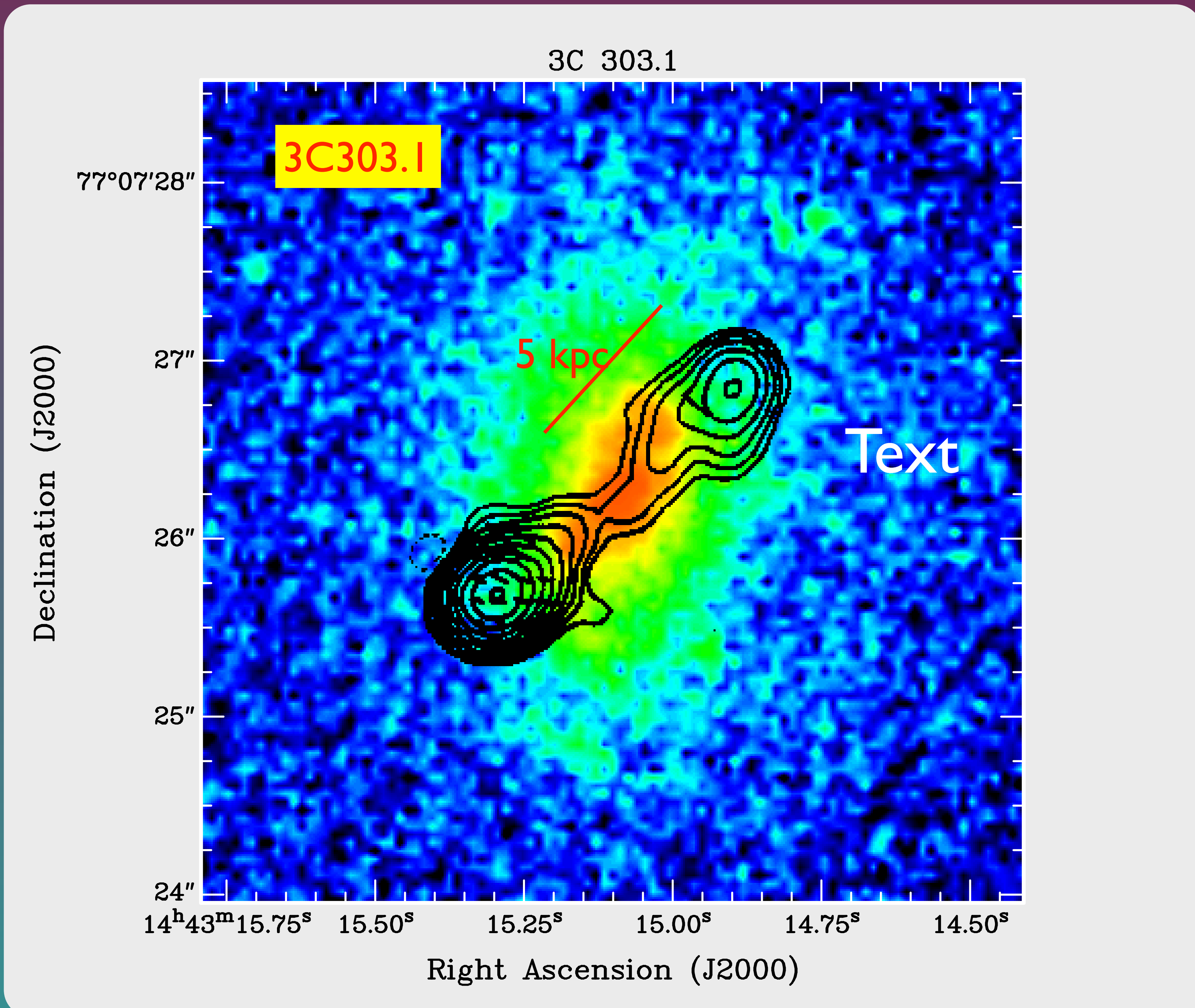


"Sub-grid" prescriptions for effect of black hole on surrounding ISM

Accretion rate ~ 100 x Bondi rate

See also Schaye et al. 2010

Feedback in action: GPS and CSS sources

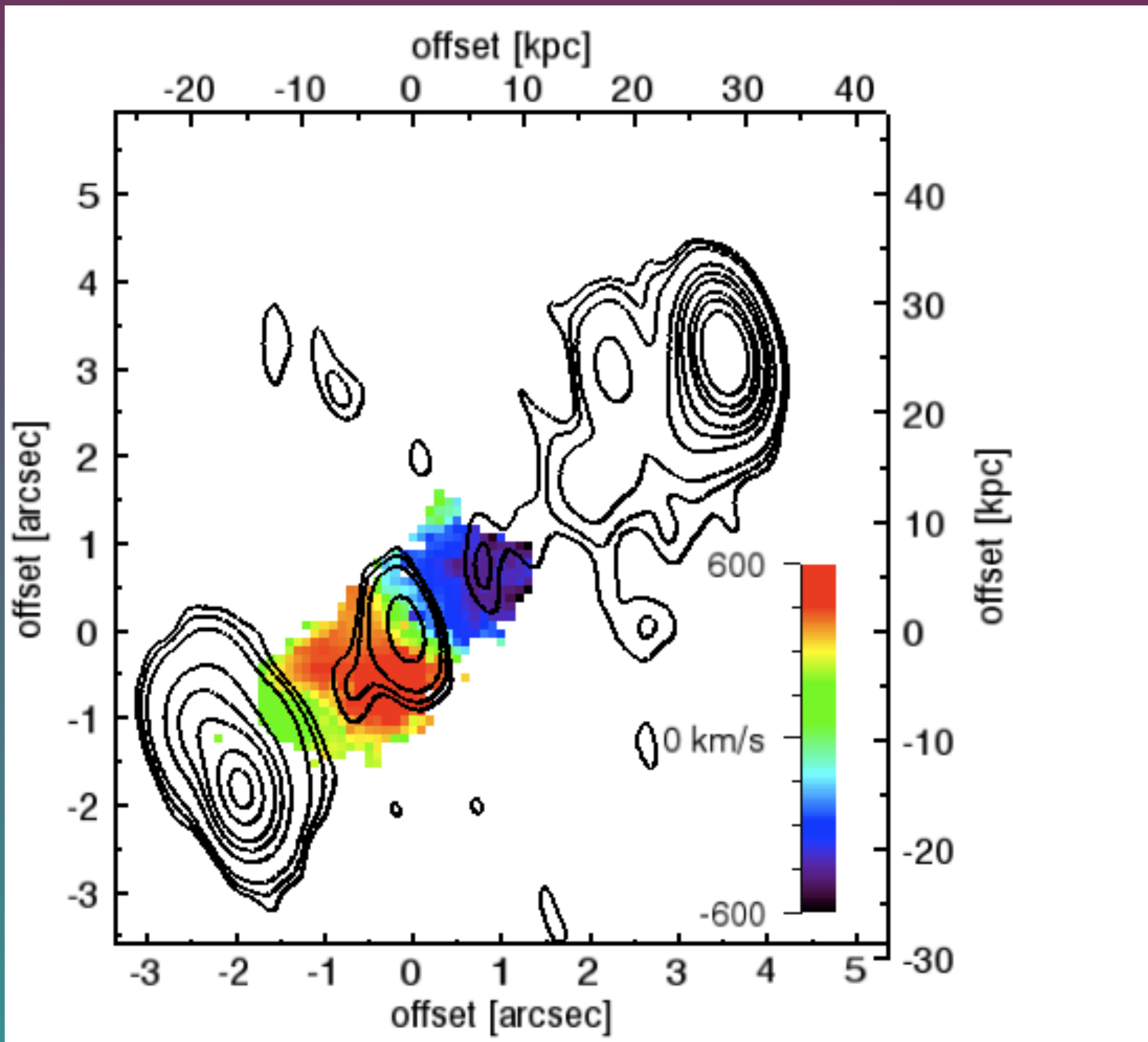


O'Dea et al. 1999

z=0.267

CSS Radio Galaxy Evidence for shocks and star formation

High redshift radio galaxies: MRC 0406-244

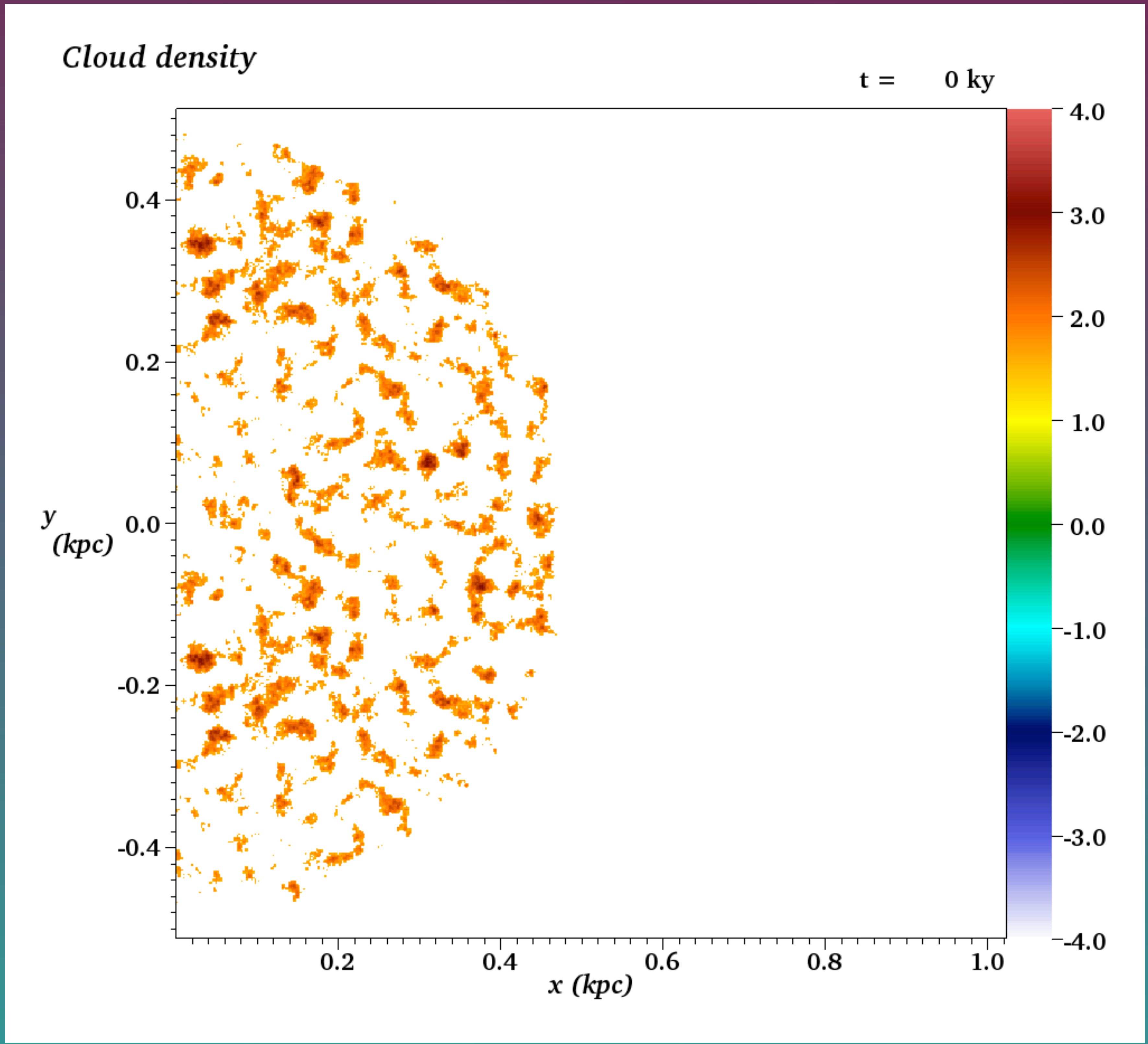


z=2.42 radio galaxy MRC0406-244

Nesvadba et al. 2009

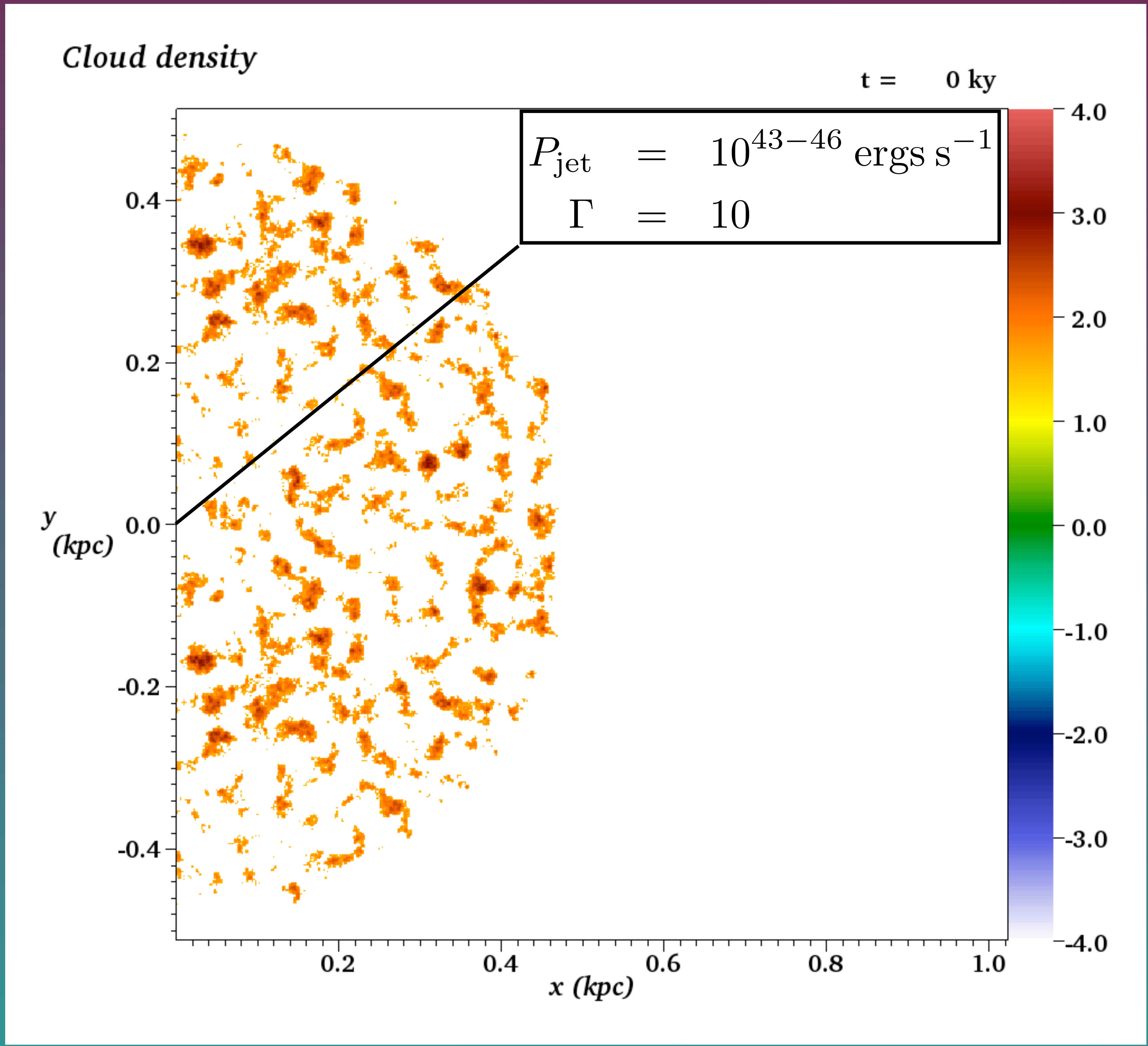
Simulations of jet-ISM interactions (Wagner & GB, ApJ Feb 2011)

log(density)



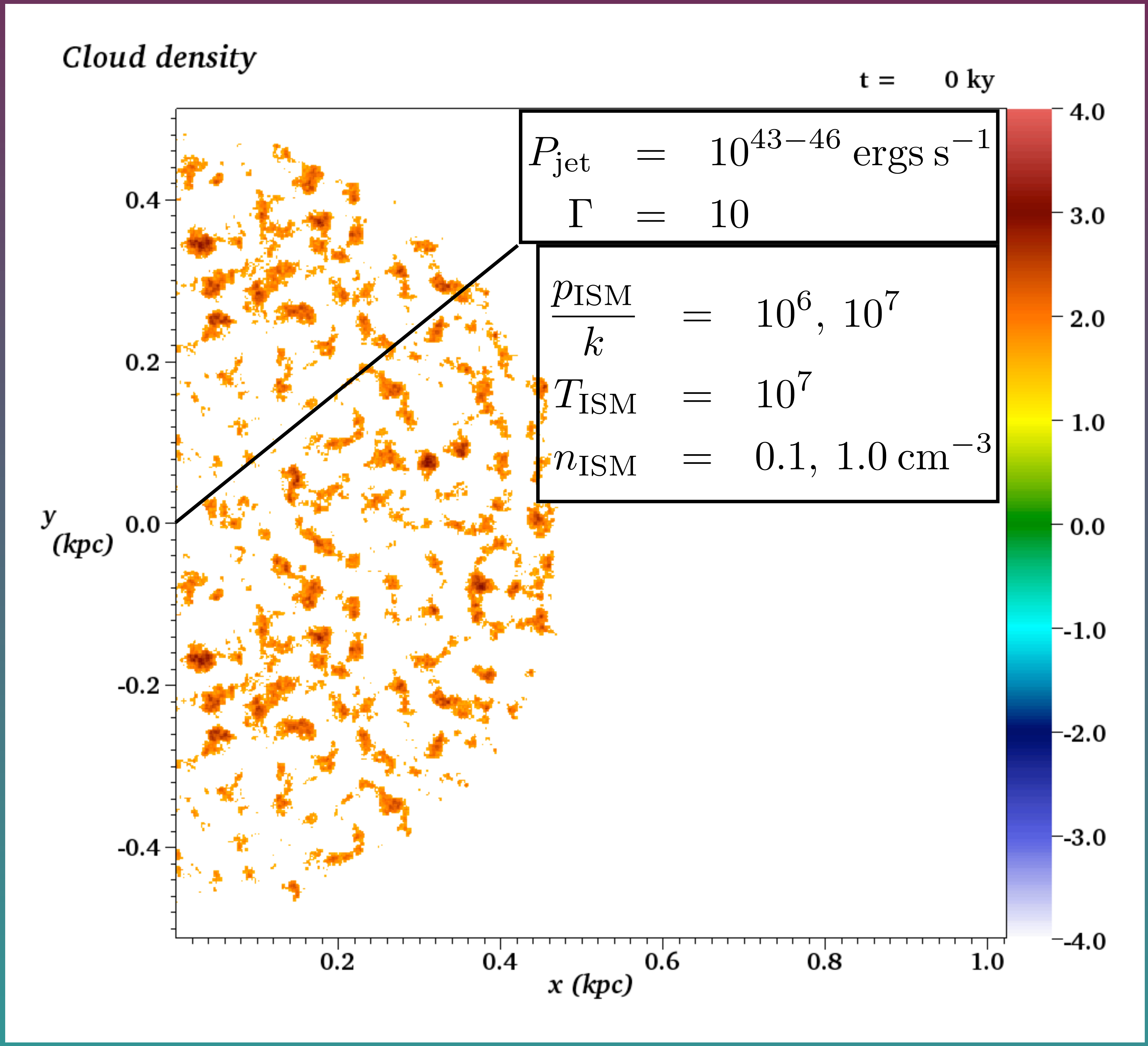
Simulations of jet-ISM interactions (Wagner & GB, ApJ Feb 2011)

log(density)



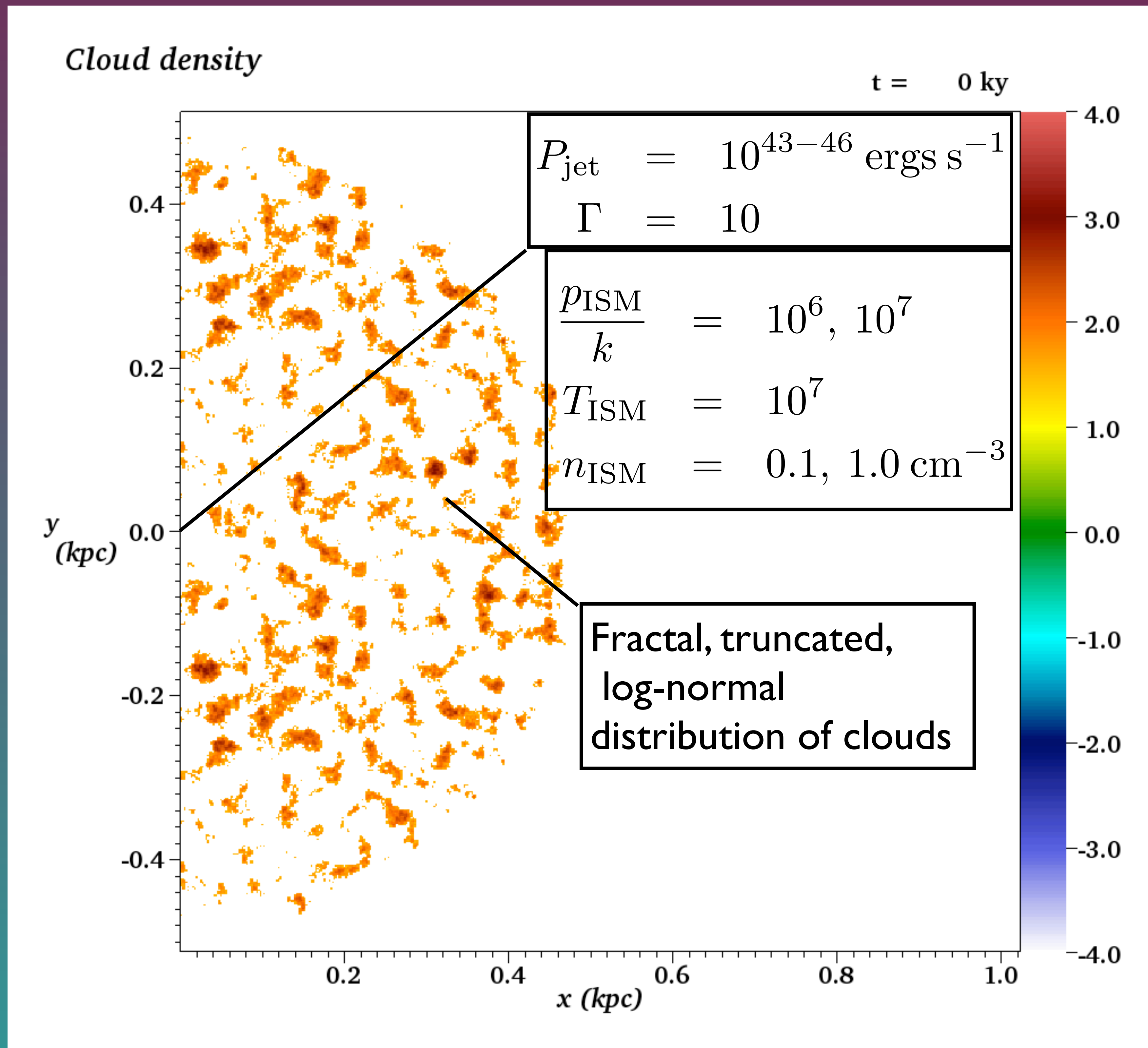
Simulations of jet-ISM interactions (Wagner & GB, ApJ Feb 2011)

log(density)



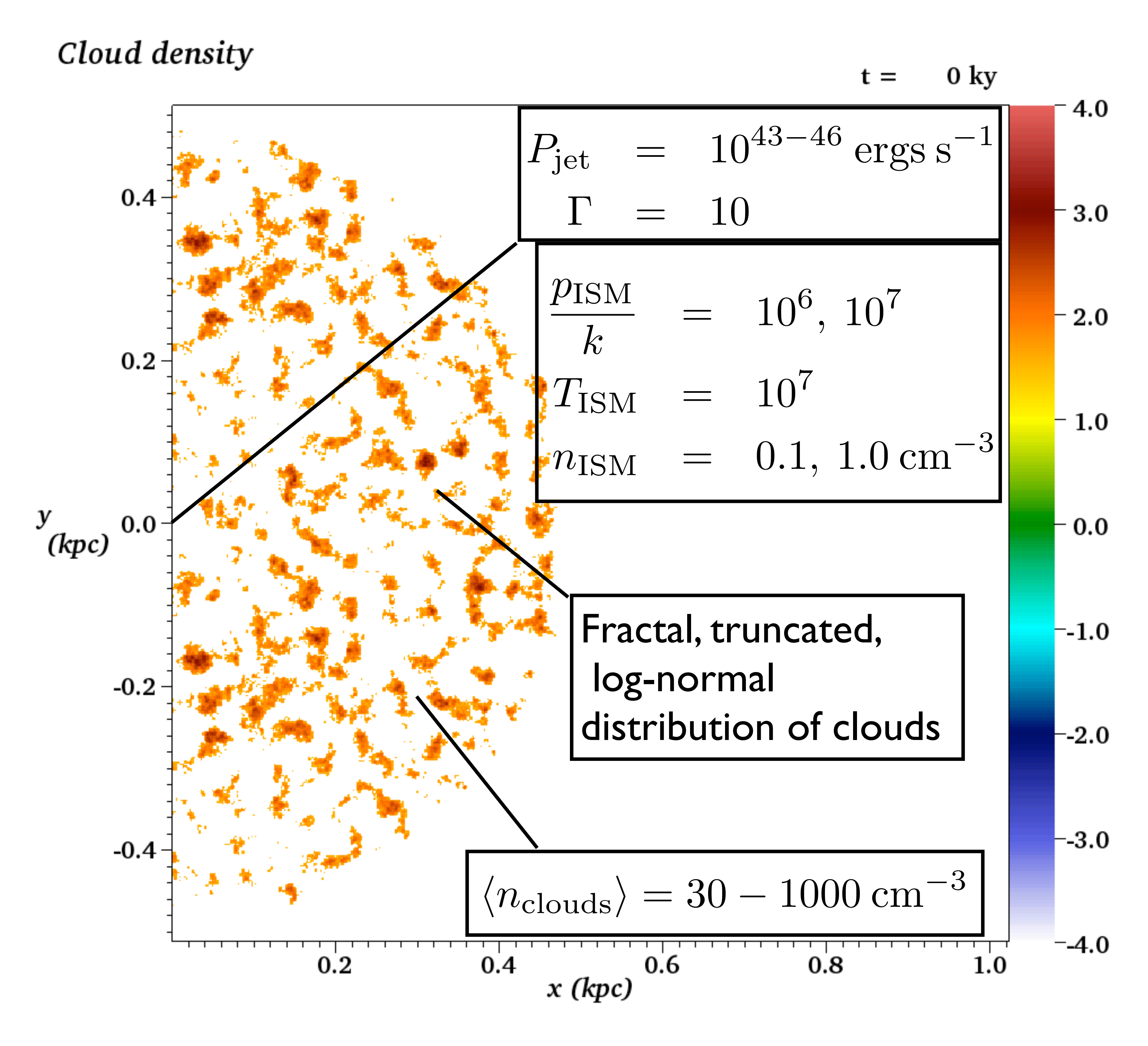
Simulations of jet-ISM interactions (Wagner & GB, ApJ Feb 2011)

log(density)



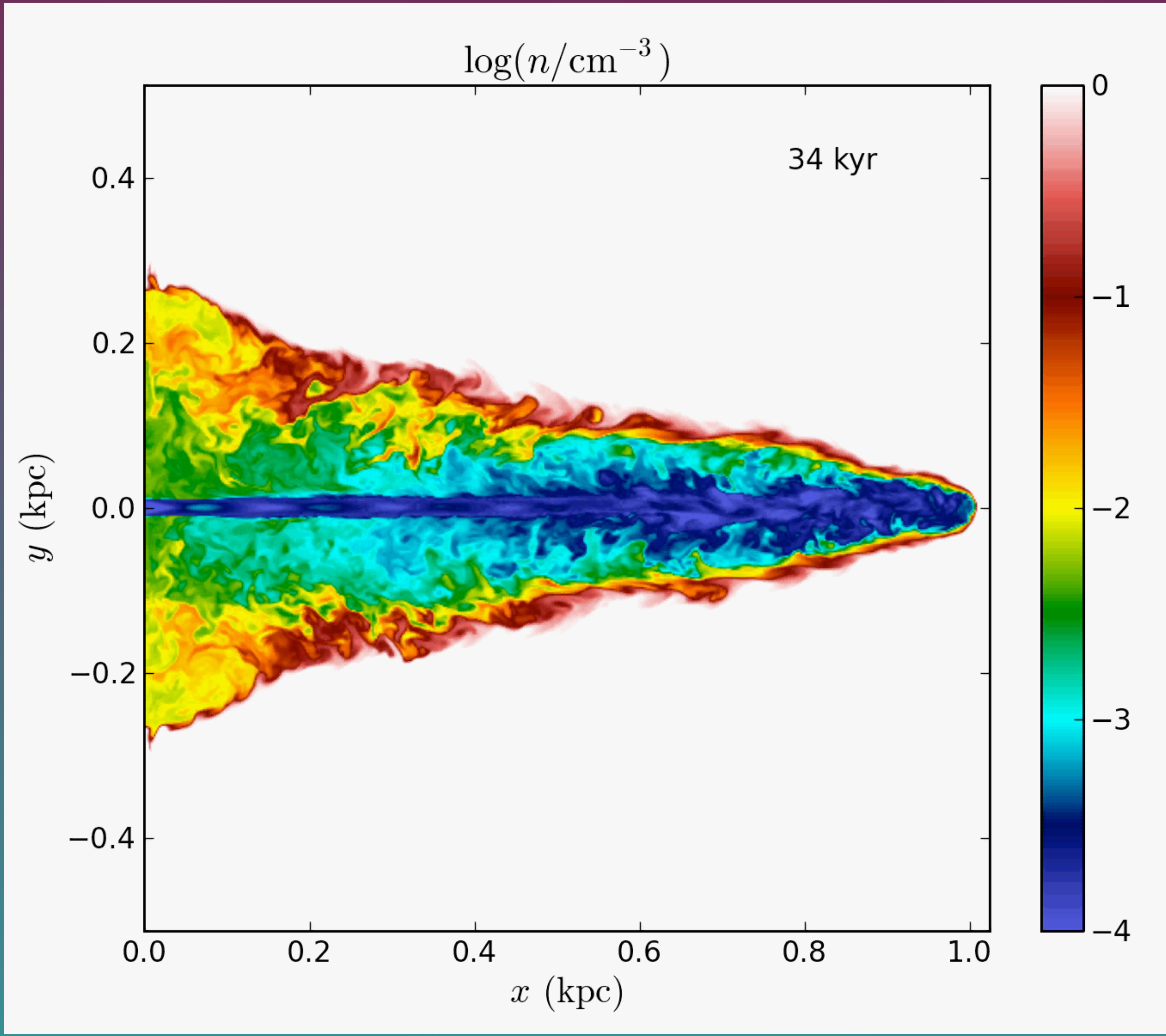
Simulations of jet-ISM interactions (Wagner & GB, ApJ Feb 2011)

log(density)



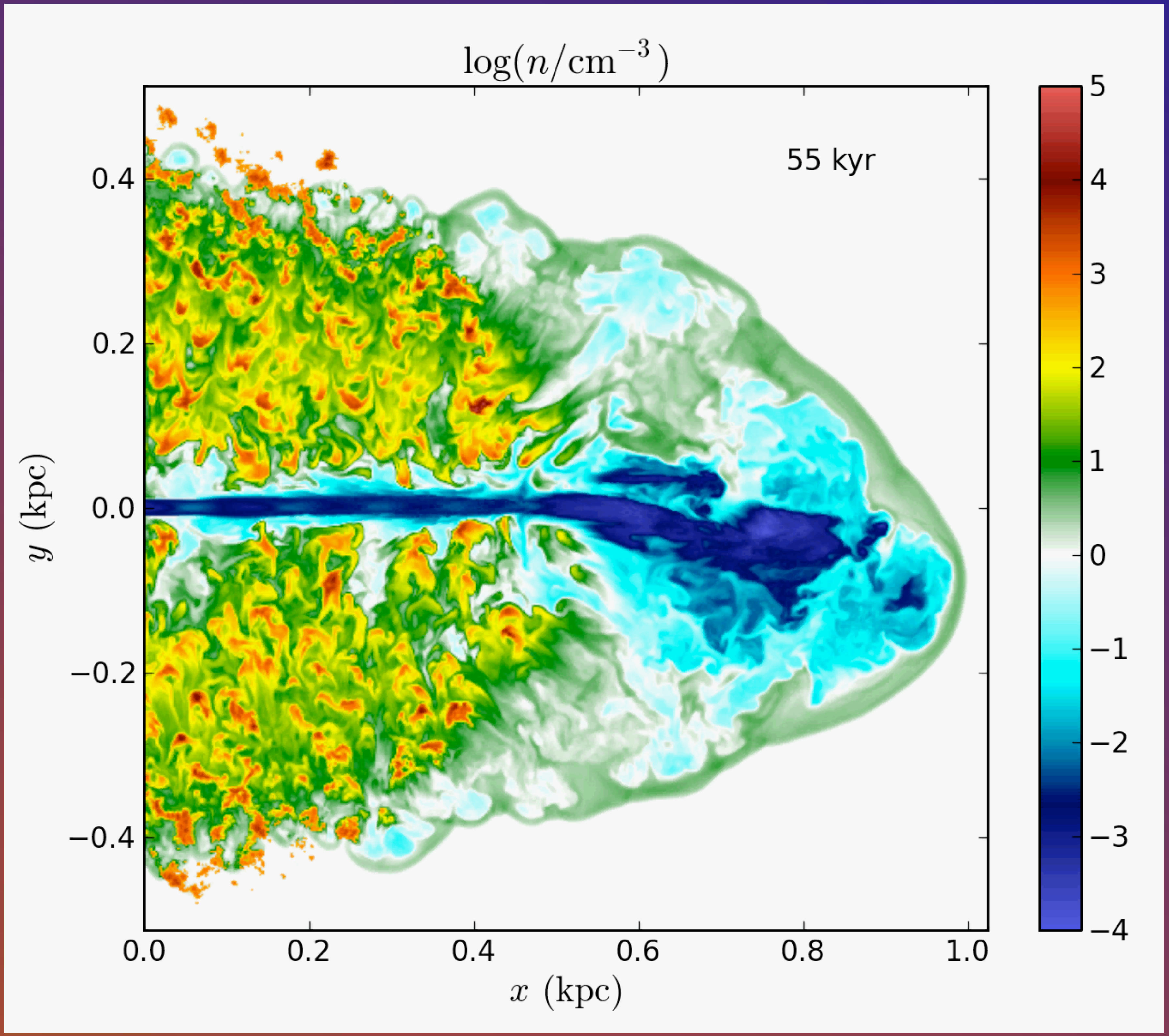
“Standard” jet

“Standard” jet

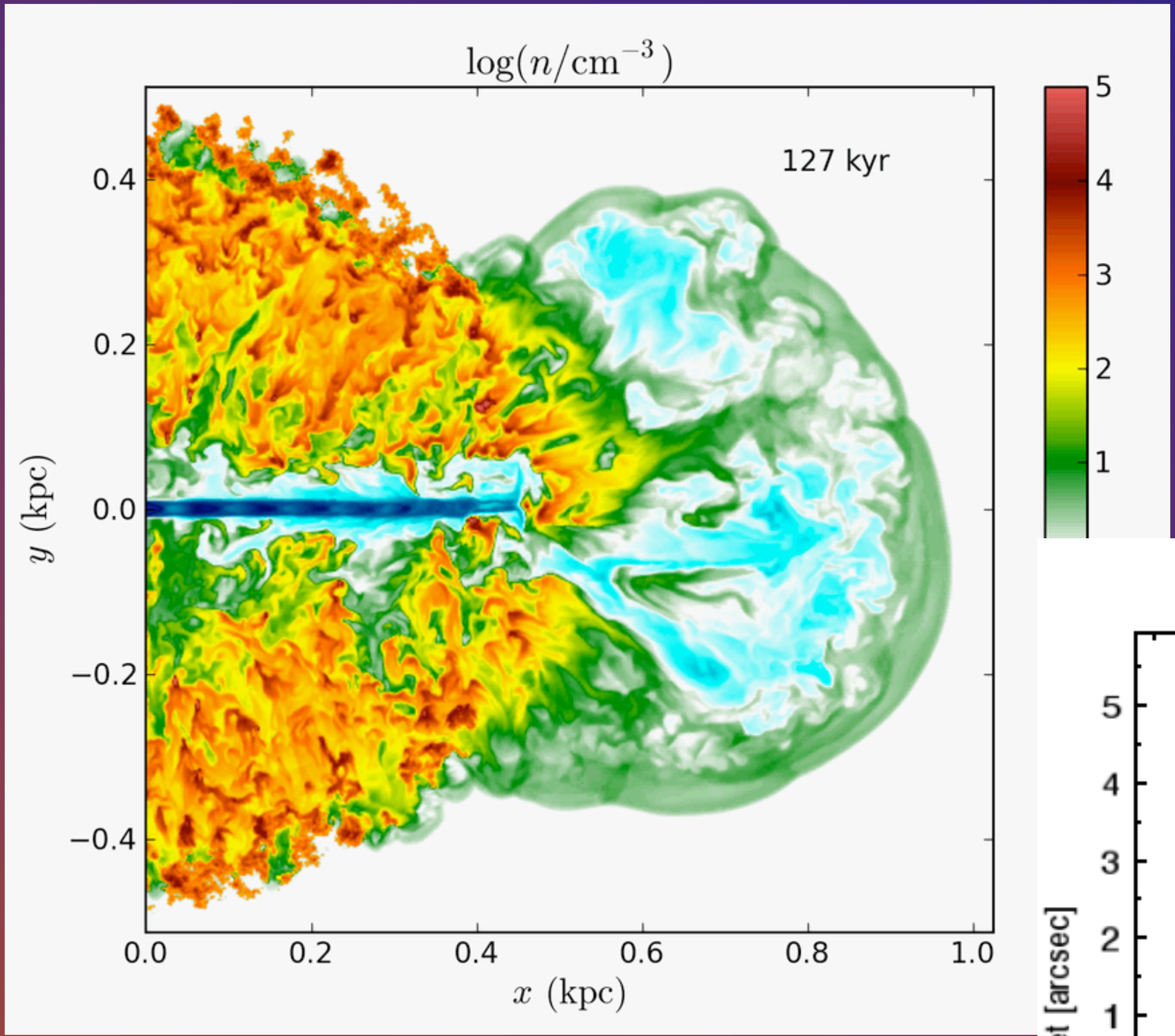


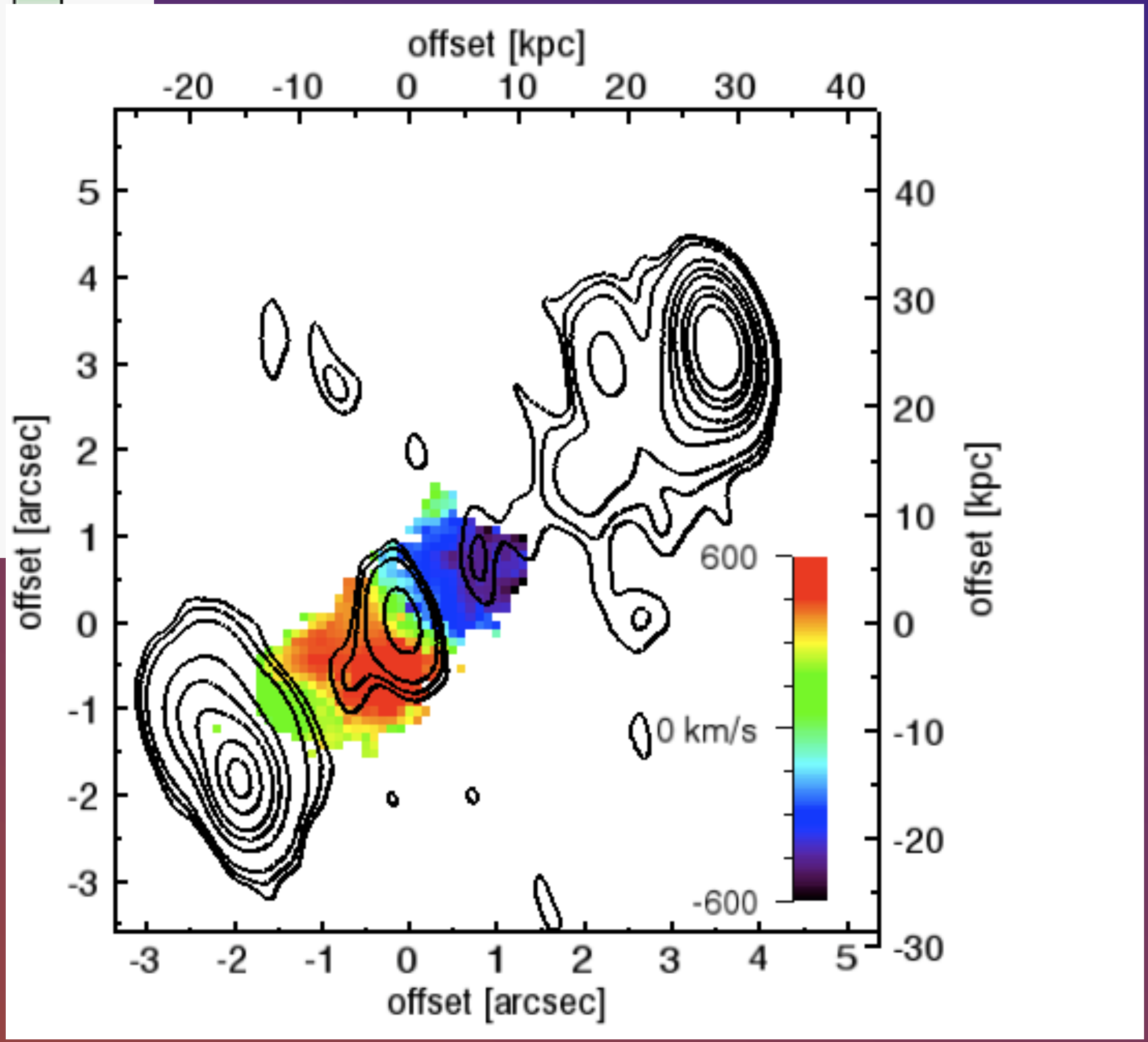
$$P_{\rm jet} = 10^{46}\,{\rm ergs\,s^{-1}} \quad {\rm p/k} = 10^7 \quad \langle {\rm n_{clouds}} \rangle = 10^3\,{\rm cm^{-3}} \quad {\rm f_V} = 0.13$$

$$P_{\rm jet} = 10^{46}\,{\rm ergs\,s^{-1}} \quad {\rm p/k} = 10^{7} \quad \langle {\rm n_{clouds}} \rangle = 10^{3}\,{\rm cm^{-3}} \quad {\rm f_V} = 0.13$$



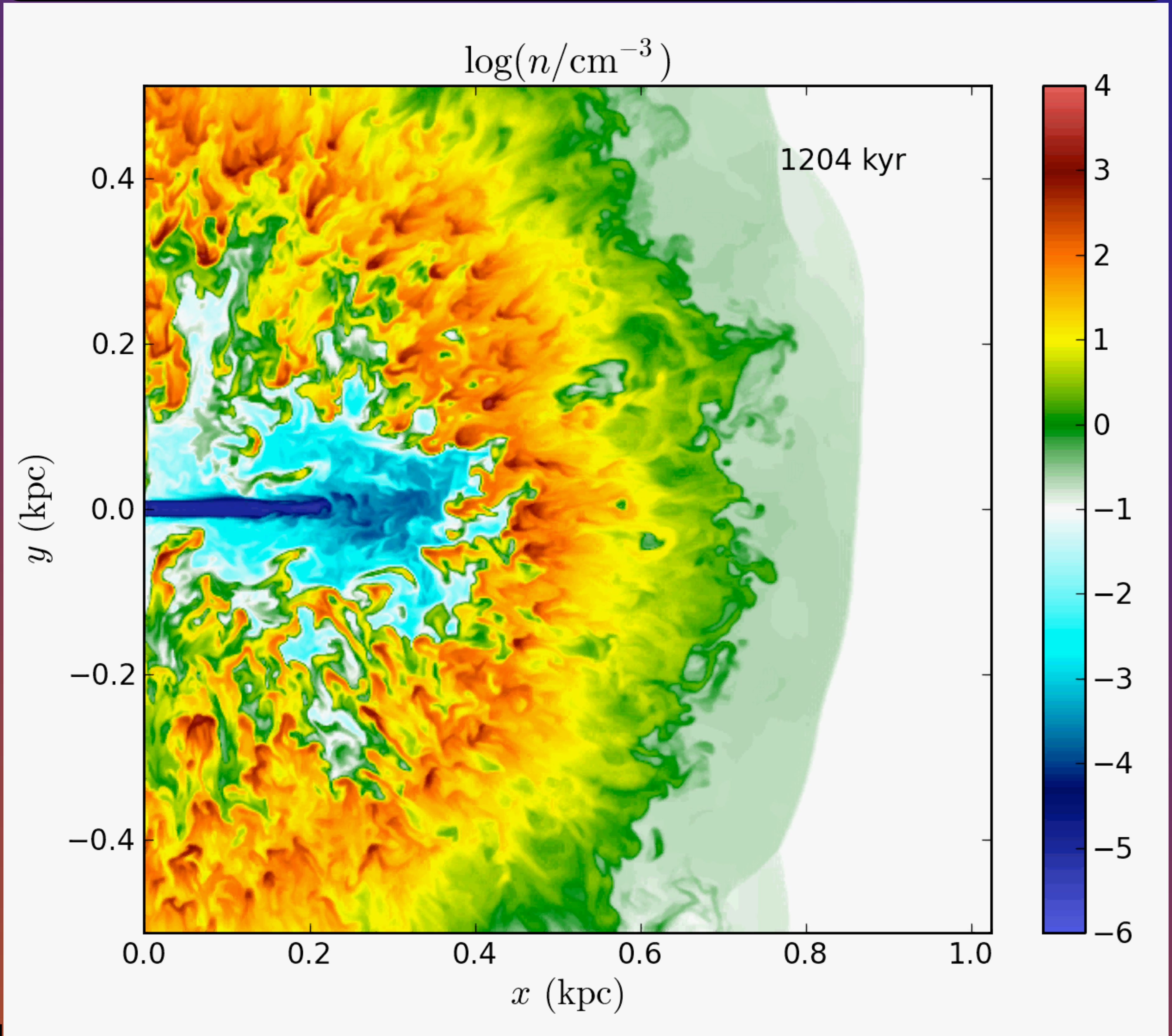
Comparison with MRC 0406-244



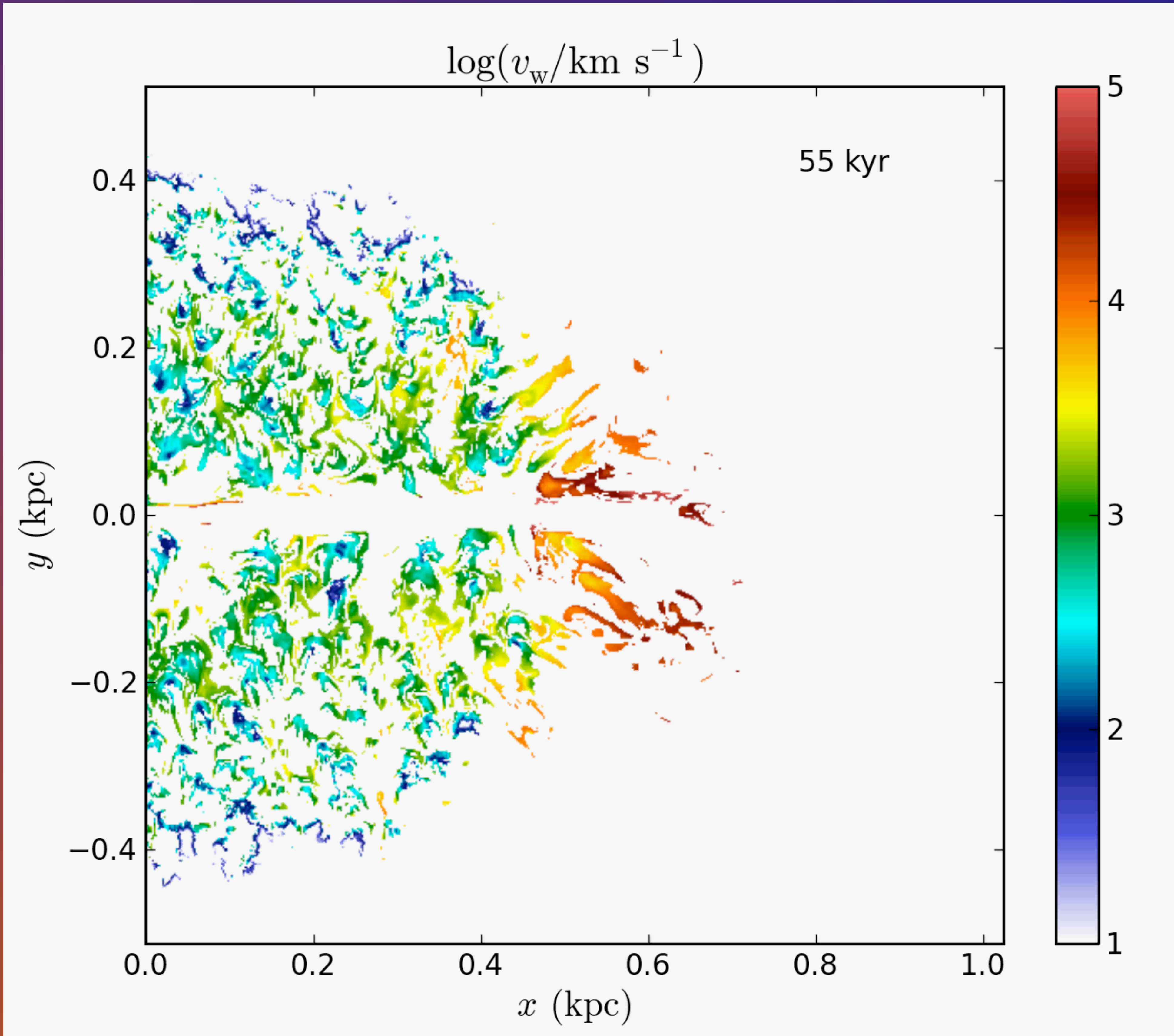


$$P_{\mathrm{jet}} = 10^{43}\,\mathrm{ergs\,s^{-1}} \quad \mathrm{p/k} = 10^6 \quad \langle \mathrm{n_{clouds}} \rangle = 10^2\,\mathrm{cm^{-3}} \quad \mathrm{f_V} = 0.42$$

$P_{\rm jet} = 10^{43}\ {\rm ergs\ s^{-1}}\quad {\rm p/k} = 10^6\quad \langle {\rm n_{clouds}} \rangle = 10^2\ {\rm cm^{-3}}\quad {\rm f_V} = 0.42$



log[v_w (km/s)]


$\log(v_w/\mathrm{km\ s^{-1}})$
55 kyr
0.4
0.2
0.0
−0.2
−0.4
y (kpc)
0.0
0.2
0.4
0.6
0.8
1.0
x (kpc)
5
4
3
2
1

log[v_w (km/s)]

Criterion for inhibition of star formation

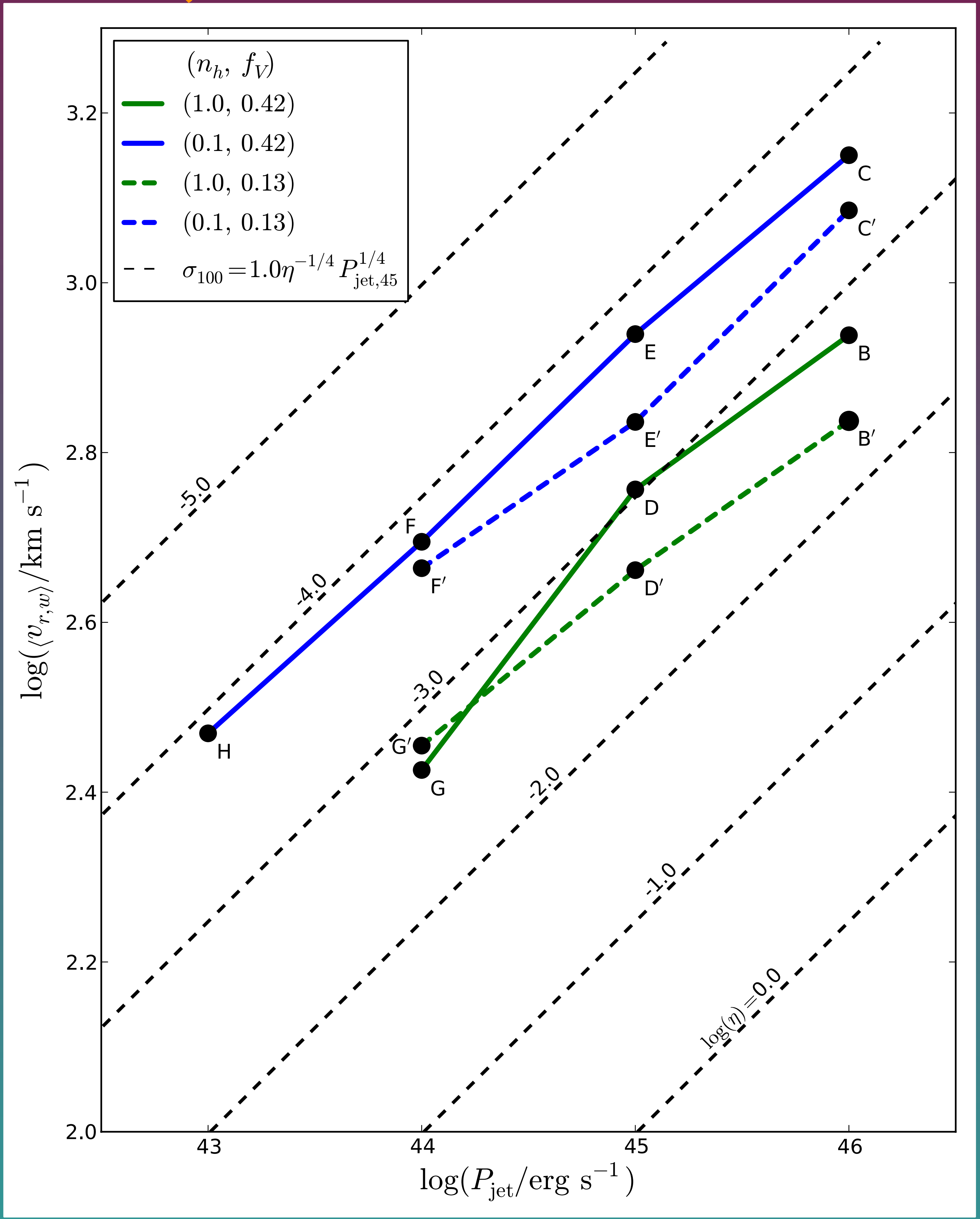
Parametrize jet in terms of Eddington luminosity:

$$\eta = \frac{P_{\rm jet}}{L_{\rm Edd}}$$

Mean radial velocity of clouds exceeds velocity dispersion

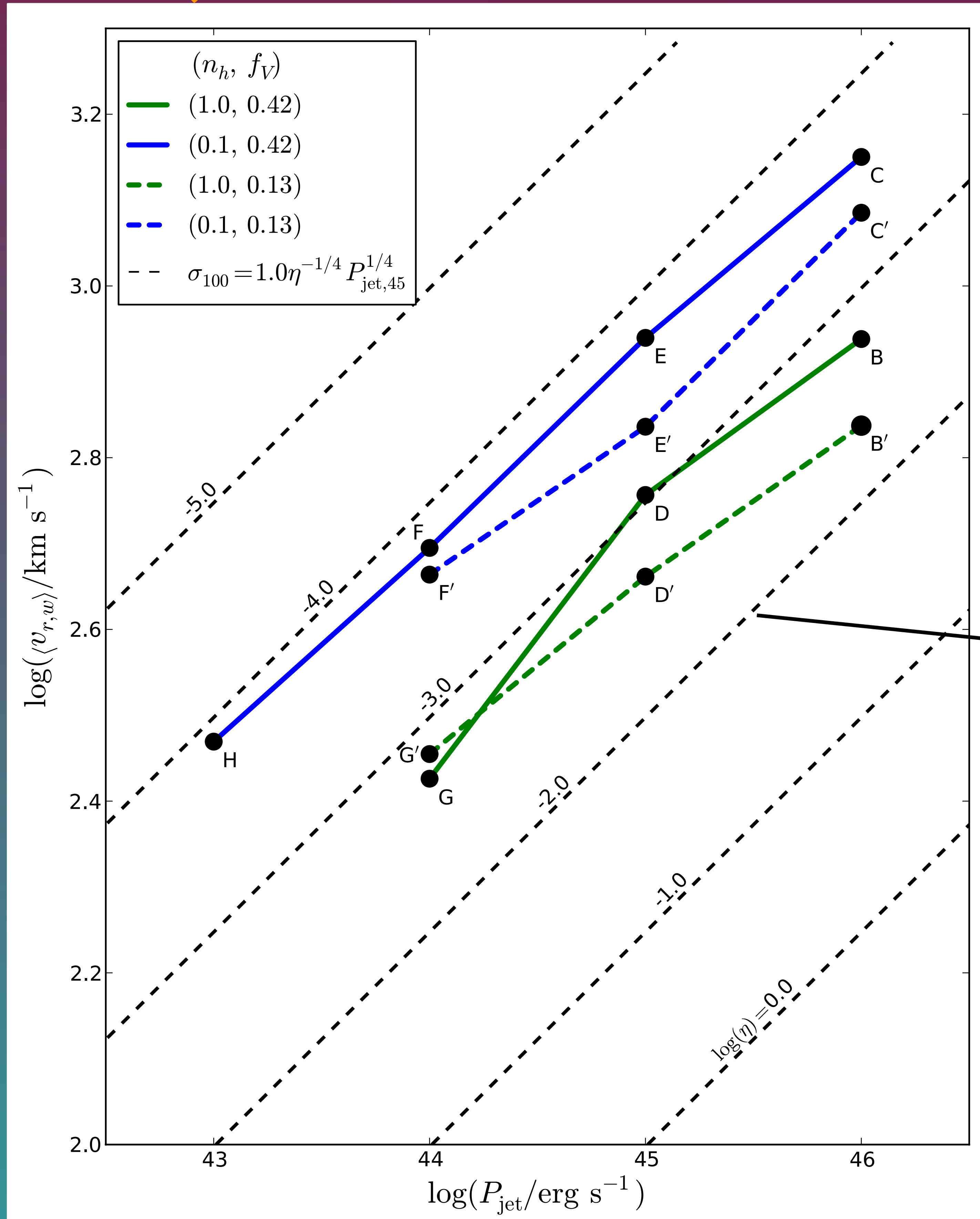
$$\langle v_{\rm cloud} \rangle > \sigma \approx 100\, \eta^{-1/4}\, P_{\rm jet,45}^{1/4} \;\; {\rm km\, s^{-1}}$$

Effectiveness of jet feedback



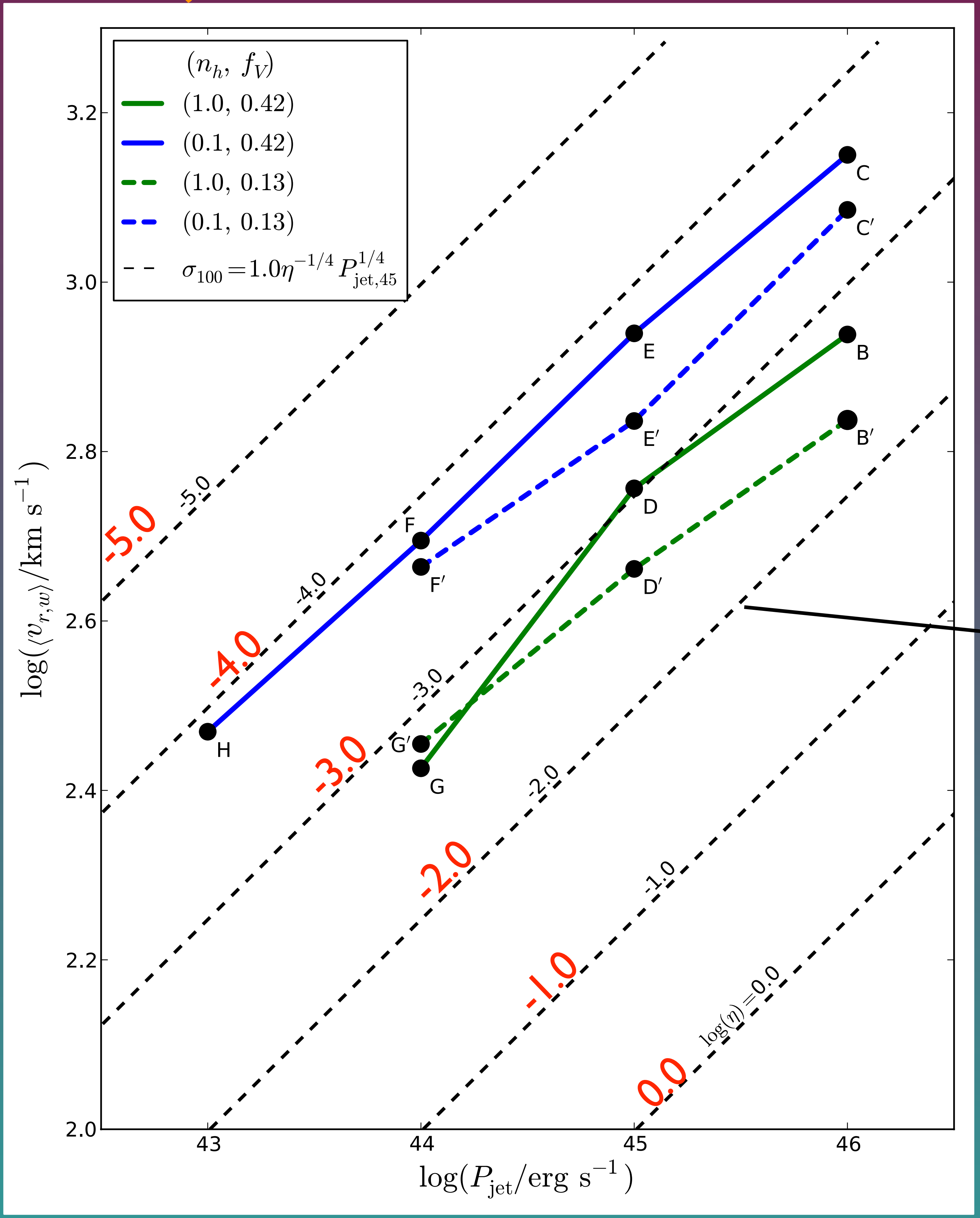
Research School of Astronomy & Astrophysics

Effectiveness of jet feedback



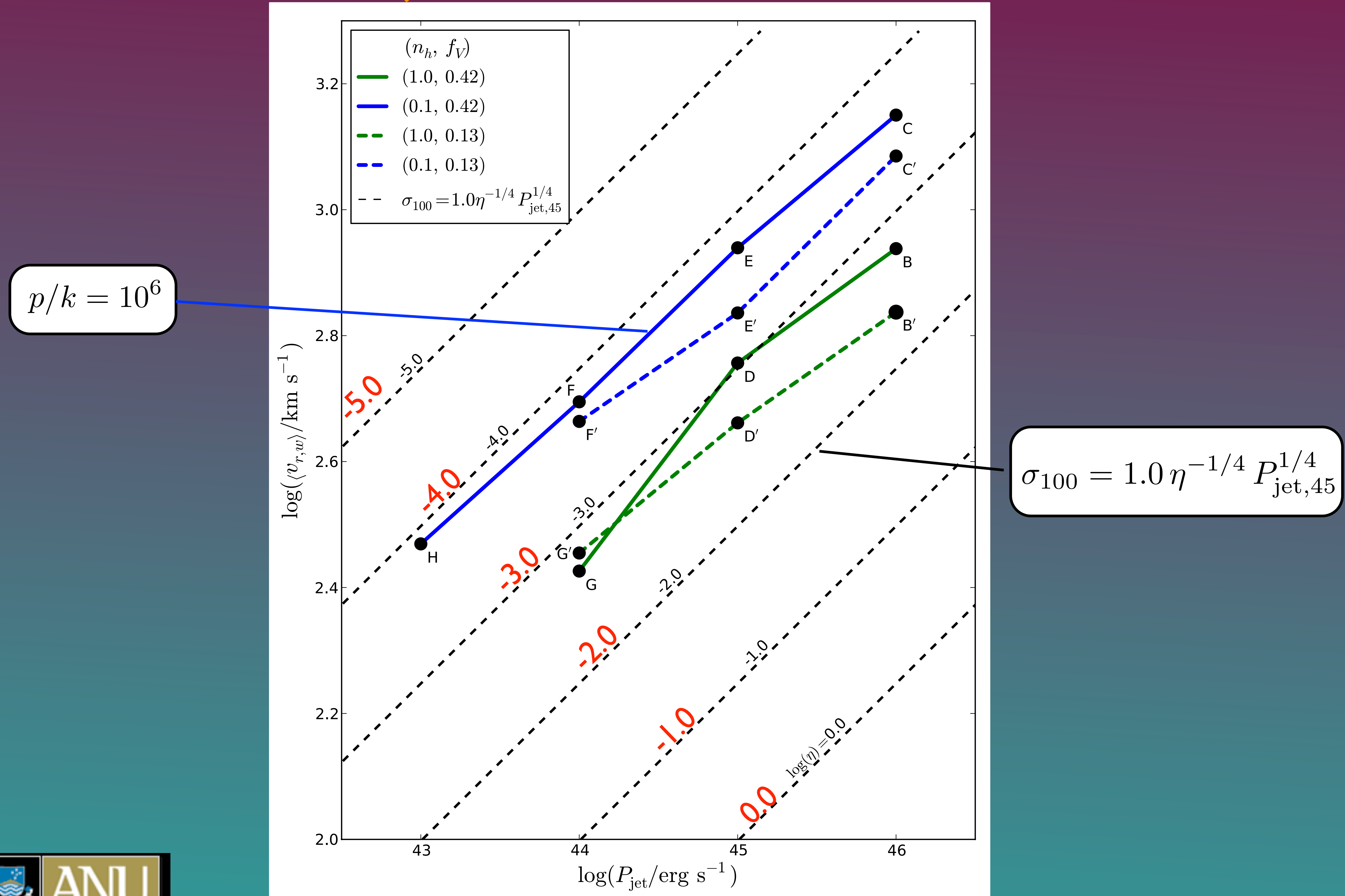
$$\sigma_{100} = 1.0\,\eta^{-1/4}\,P_{\rm jet,45}^{1/4}$$

Effectiveness of jet feedback

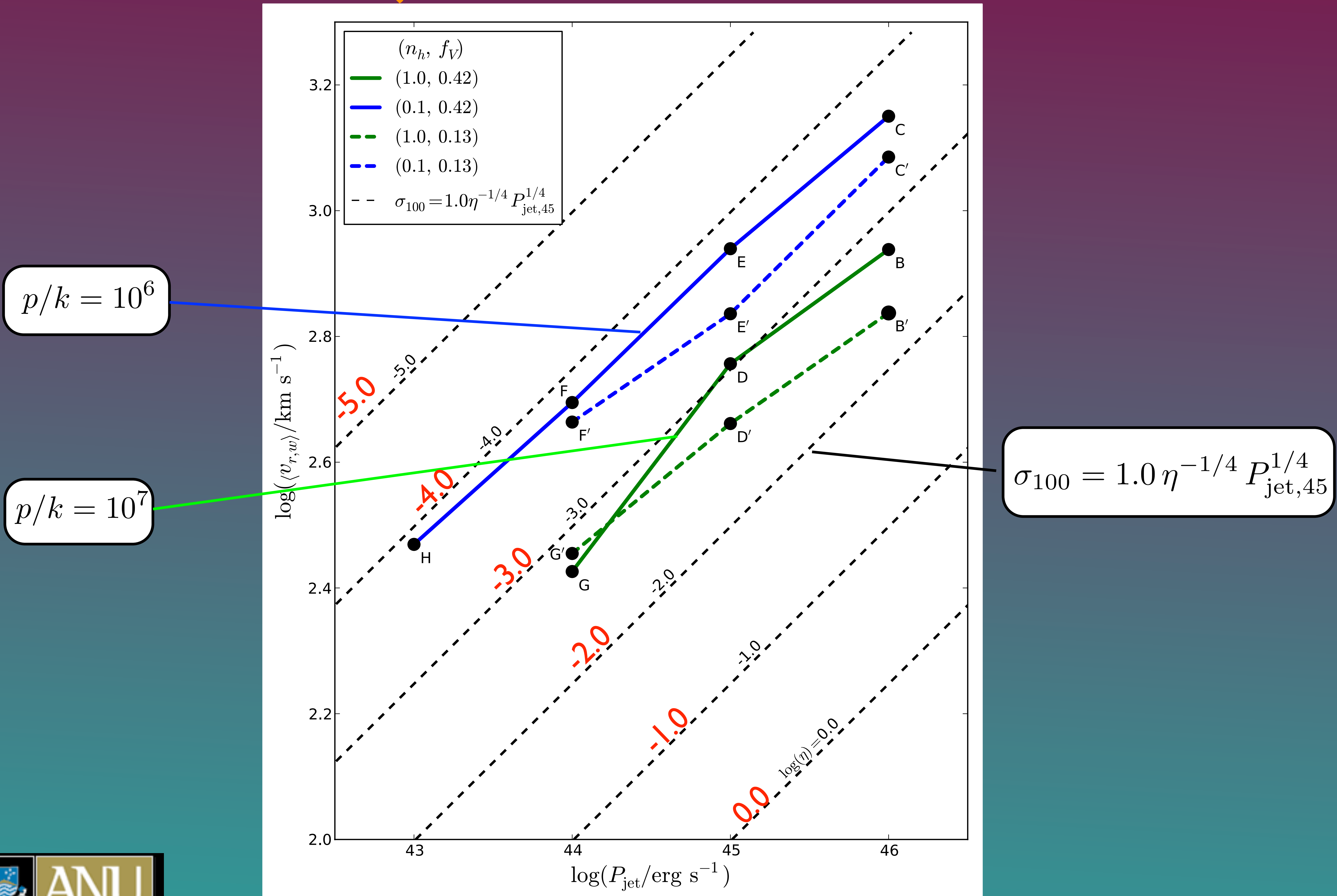


$$\sigma_{100} = 1.0\,\eta^{-1/4}\,P_{\rm jet,45}^{1/4}$$

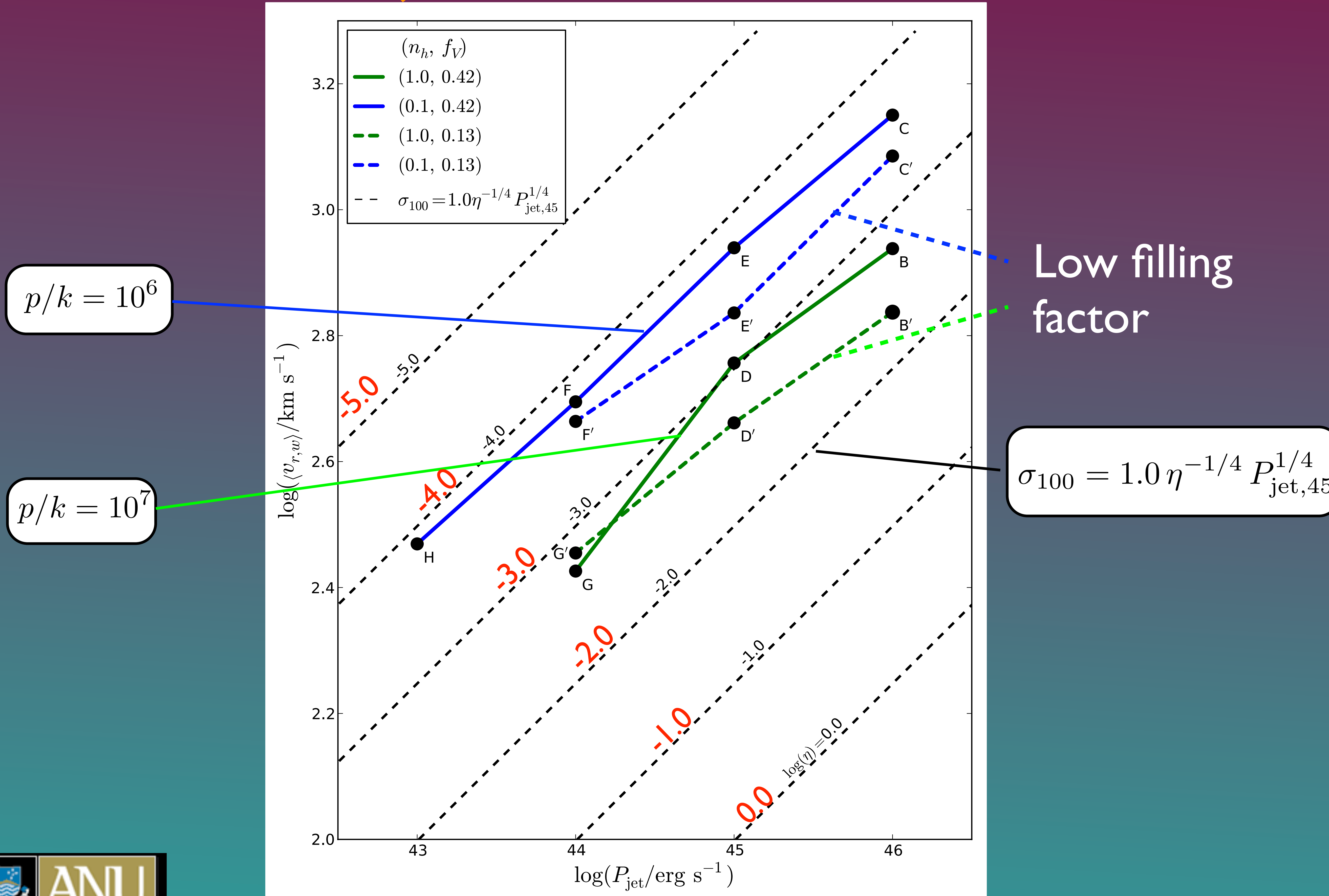
Effectiveness of jet feedback



Effectiveness of jet feedback



Effectiveness of jet feedback



THE AUSTRALIAN NATIONAL UNIVERSITY

Research School of Astronomy & Astrophysics

Eddington factor – velocity dispersion

Parametrize jet power in terms of Eddington luminosity

Eddington factor – velocity dispersion

Parametrize jet power in terms of Eddington luminosity

$$P_{\rm jet} = 1.3 \times 10^{38}\, \eta\, \frac{M_{\rm bh}}{M_\odot}\, {\rm ergs\, s}^{-1}$$

Eddington factor – velocity dispersion

Parametrize jet power in terms of Eddington luminosity

Eddington factor

$$P_{\rm jet} = 1.3 \times 10^{38}\, \eta\, \frac{M_{\rm bh}}{M_\odot}\, {\rm ergs\, s^{-1}}$$

Eddington factor – velocity dispersion

Parametrize jet power in terms of Eddington luminosity

Eddington factor

$$P_{\rm jet} = 1.3 \times 10^{38}\, \eta\, \frac{M_{\rm bh}}{M_\odot}\ {\rm ergs\, s^{-1}}$$

M-σ relation

$$\frac{M_{\rm bh}}{M_\odot} \approx 8.1 \times 10^{6} \left(\frac{\sigma}{100\ {\rm km\, s^{-1}}} \right)^4$$

Eddington factor – velocity dispersion

Parametrize jet power in terms of Eddington luminosity

Eddington factor

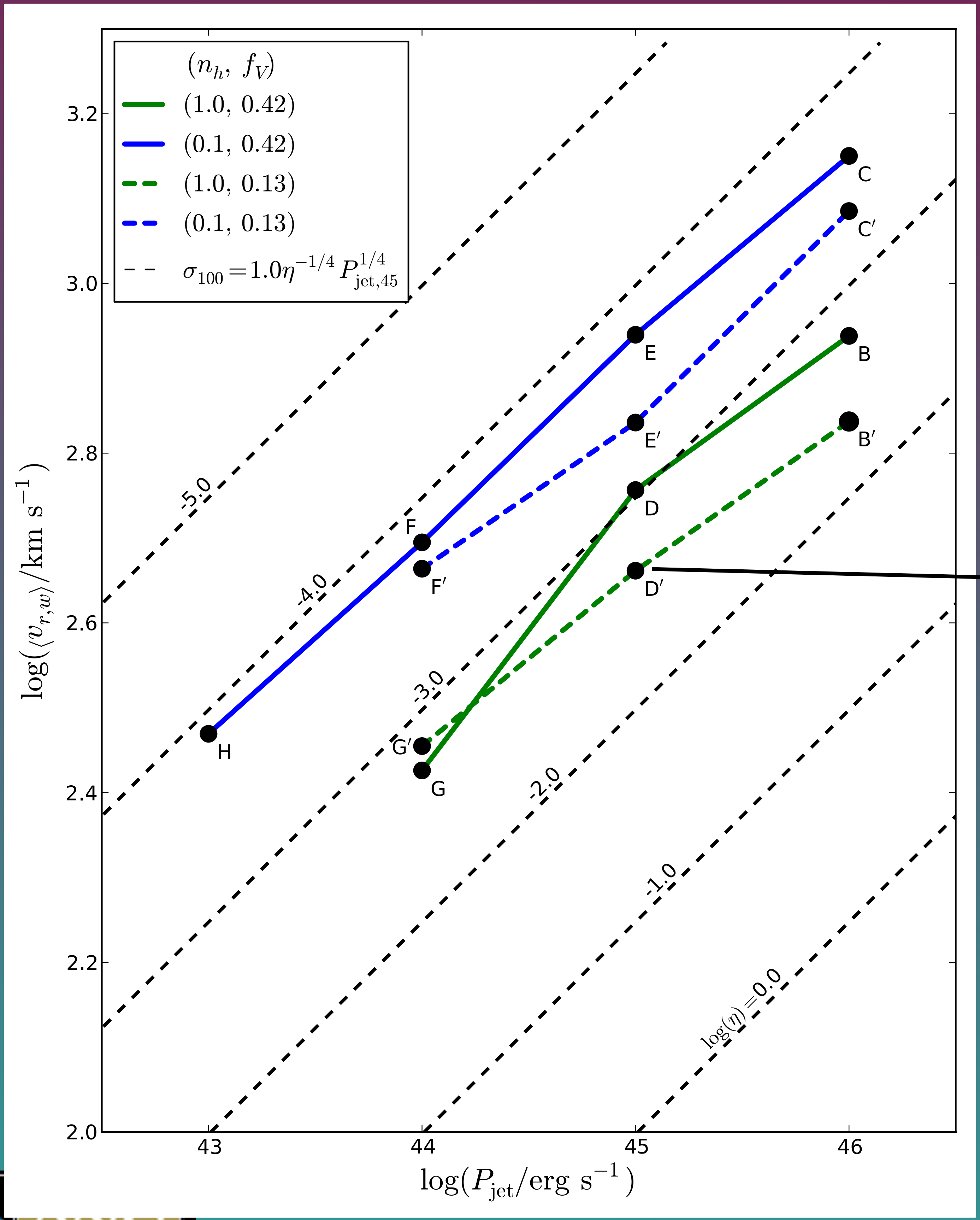
$$P_{\rm jet} = 1.3 \times 10^{38}\, \eta\, \frac{M_{\rm bh}}{M_\odot}\ {\rm ergs\, s^{-1}}$$

M-σ relation

$$\frac{M_{\rm bh}}{M_\odot} \approx 8.1 \times 10^6 \left(\frac{\sigma}{100\ {\rm km\, s^{-1}}} \right)^4$$

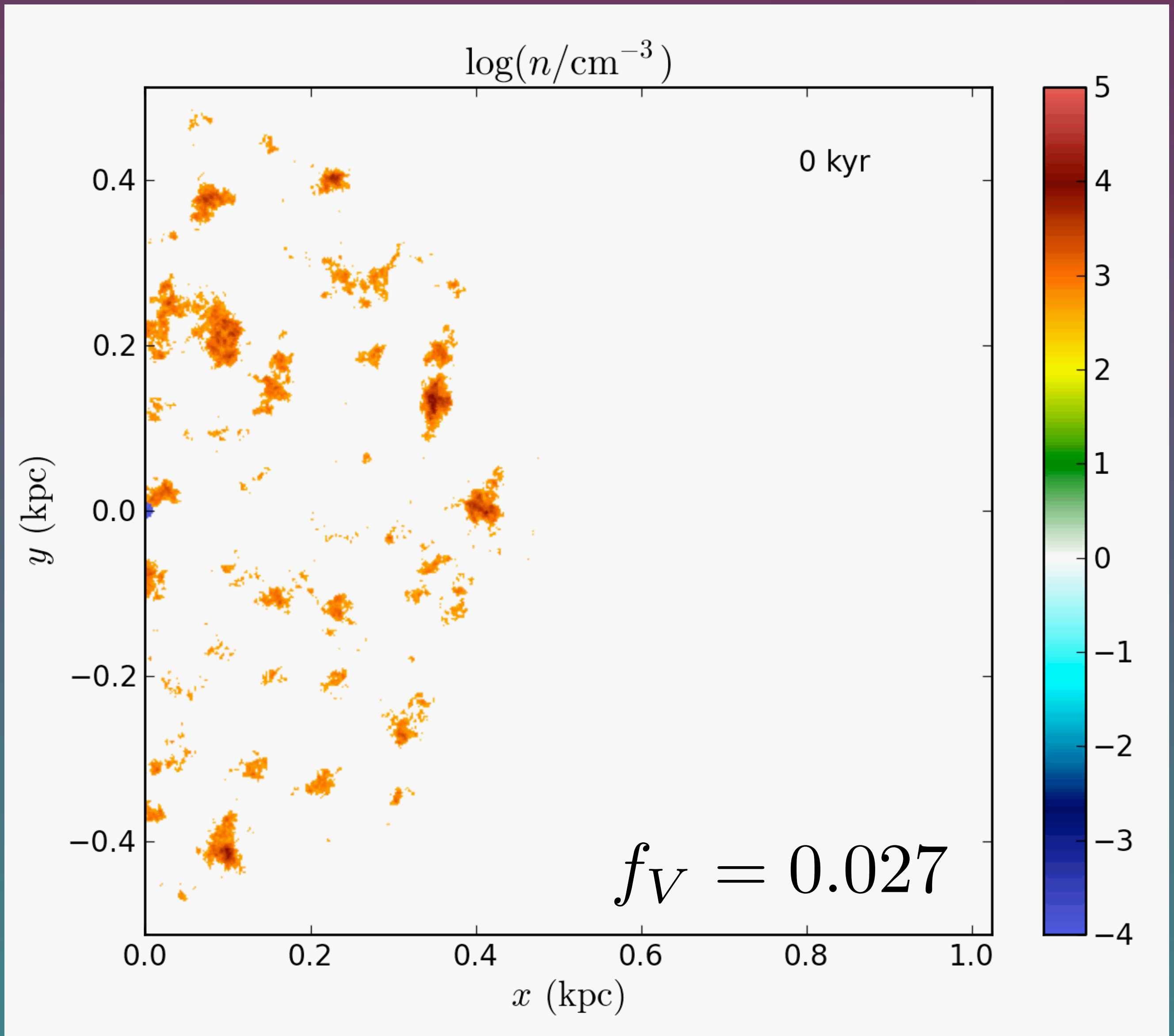
$$\Rightarrow \left(\frac{\sigma}{100\ {\rm km\, s^{-1}}} \right) \approx 1.0\, \eta^{-1/4}\, P_{\rm jet,45}^{1/4}$$

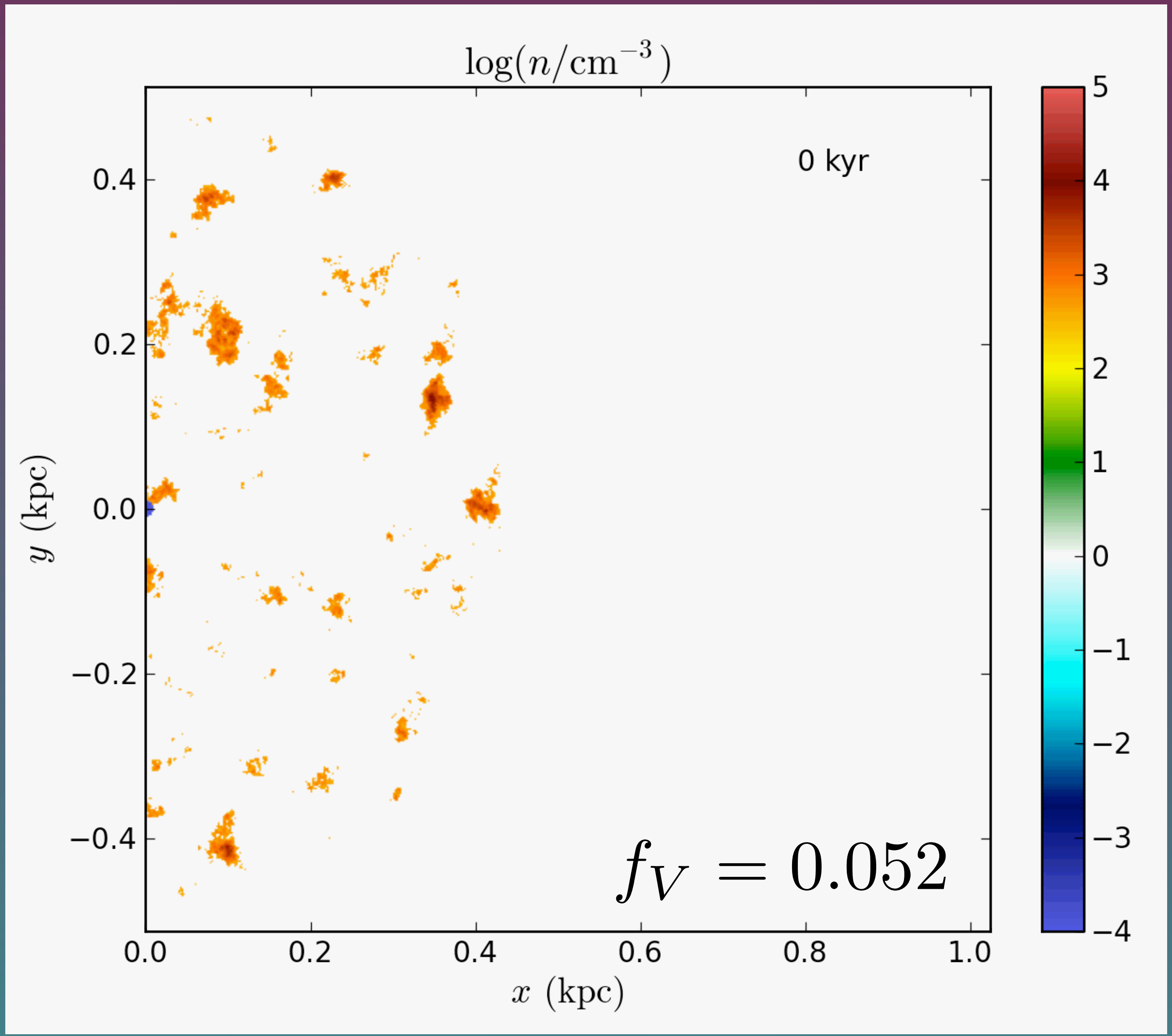
Recent low filling factor simulation



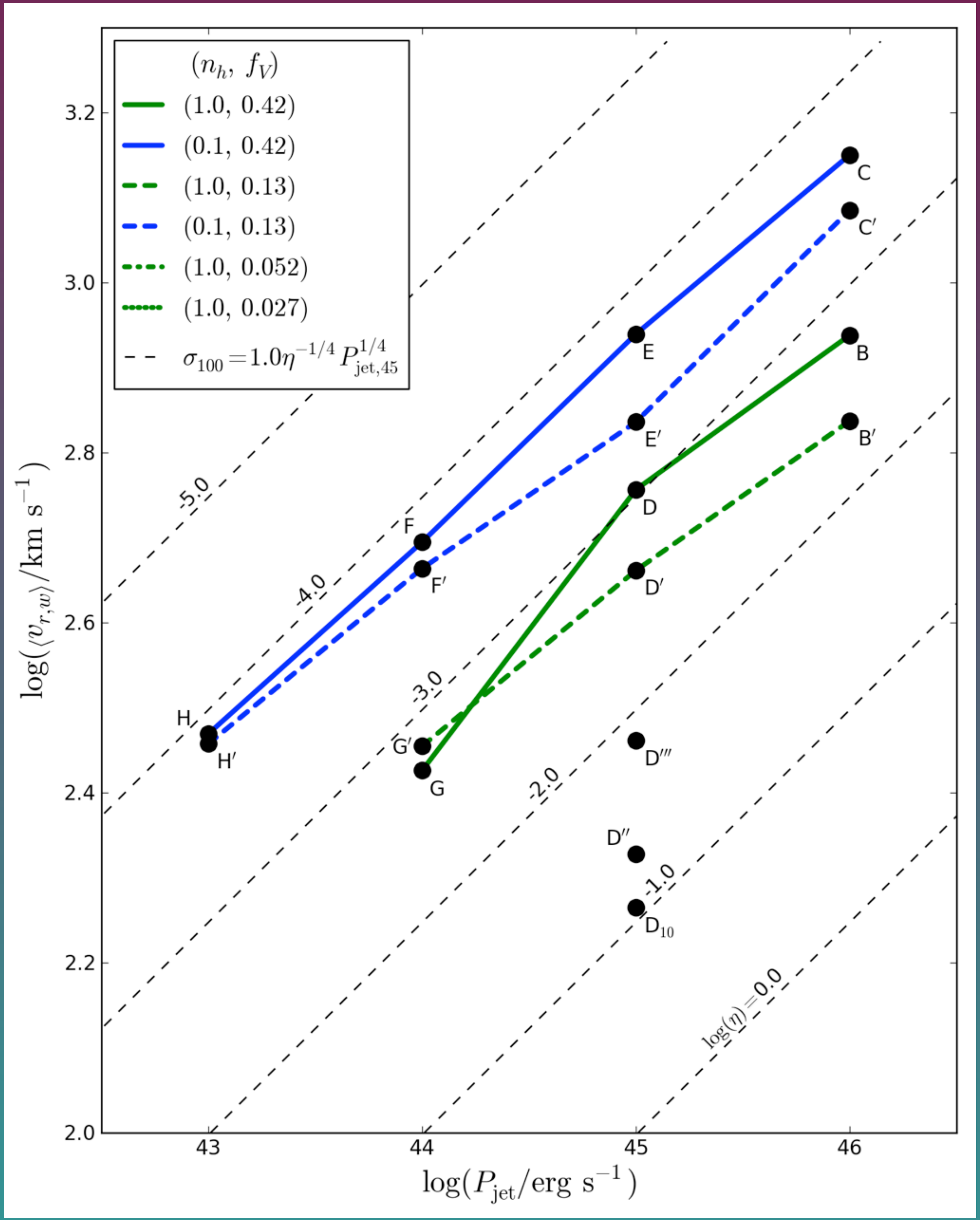
D" continues this sequence to low filling factor

Lower filling factor



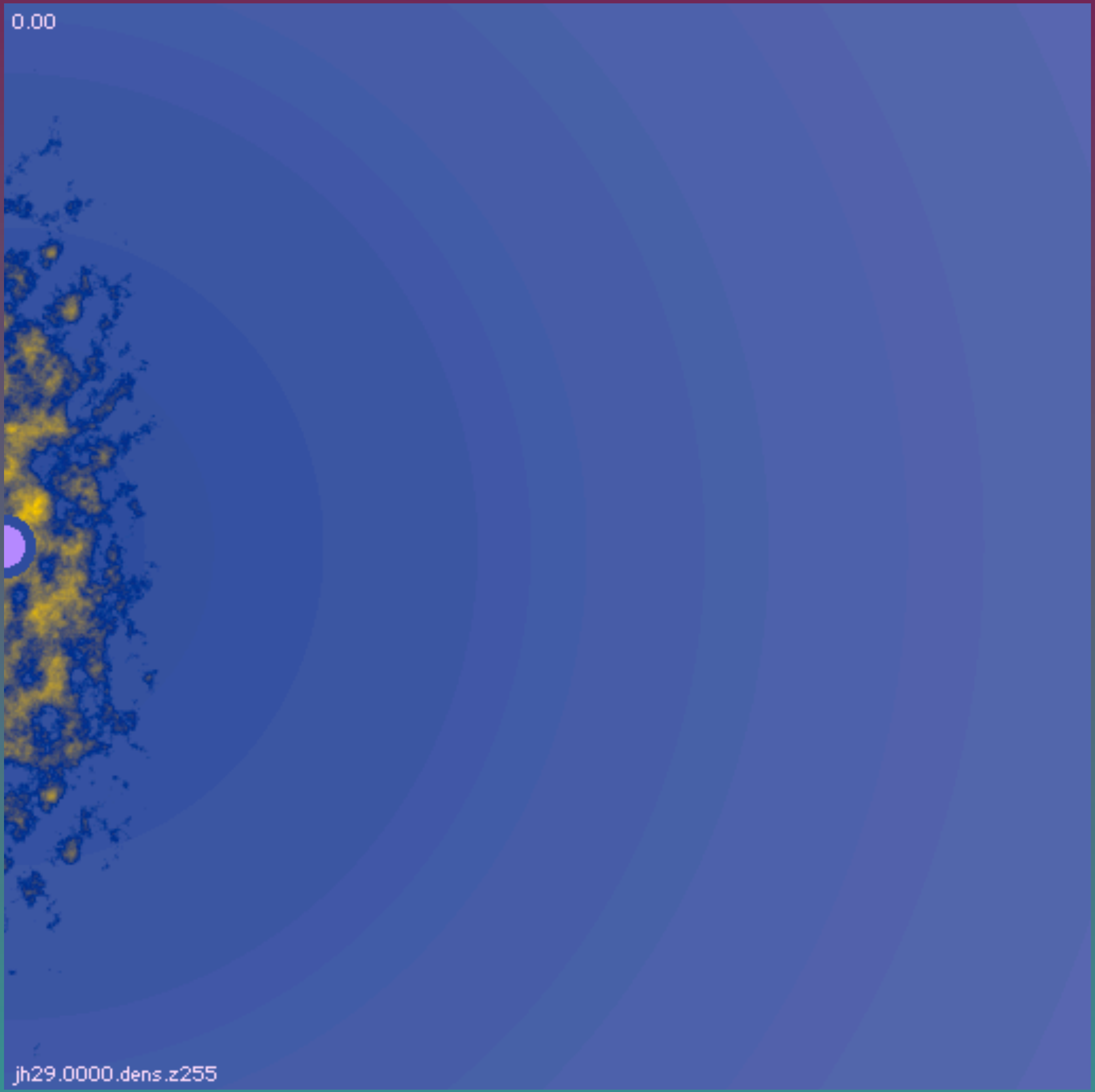


Revised speed – power diagram



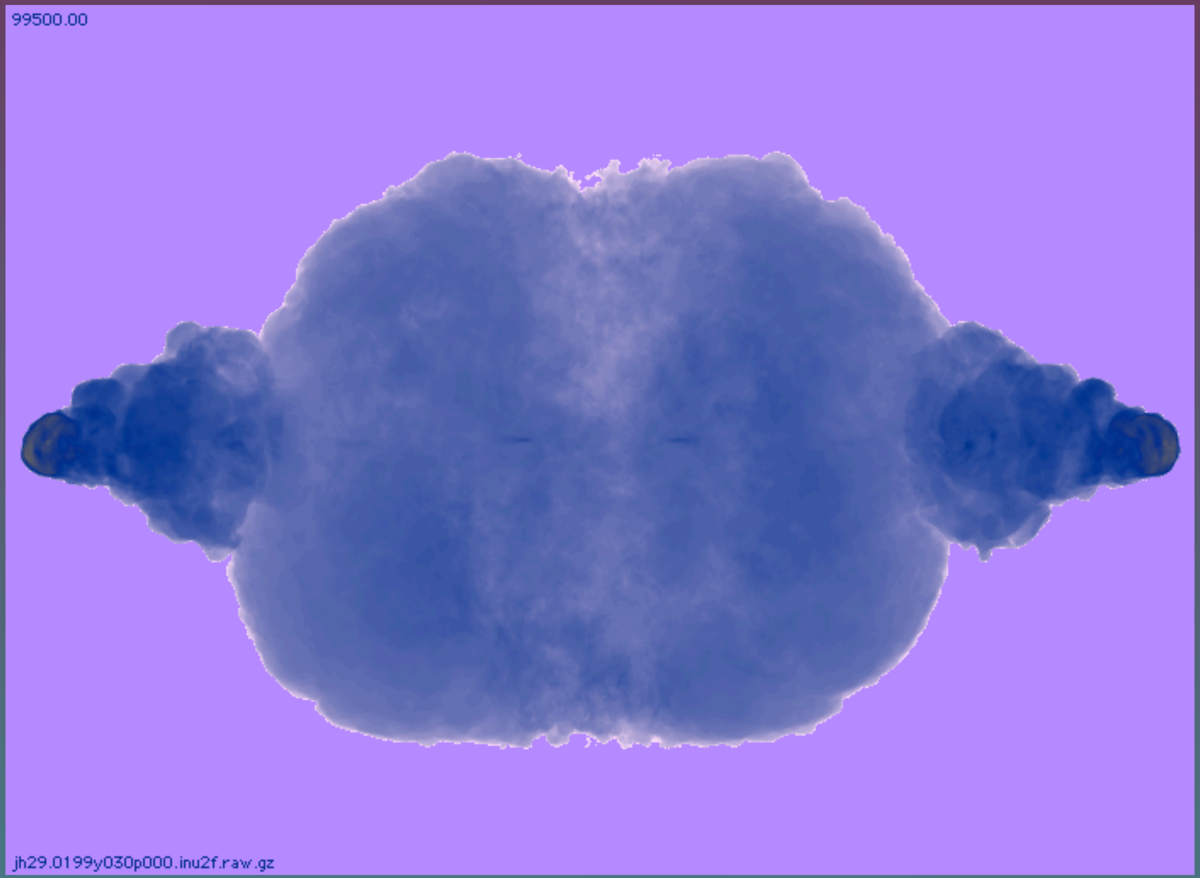
Jet-Disk interaction

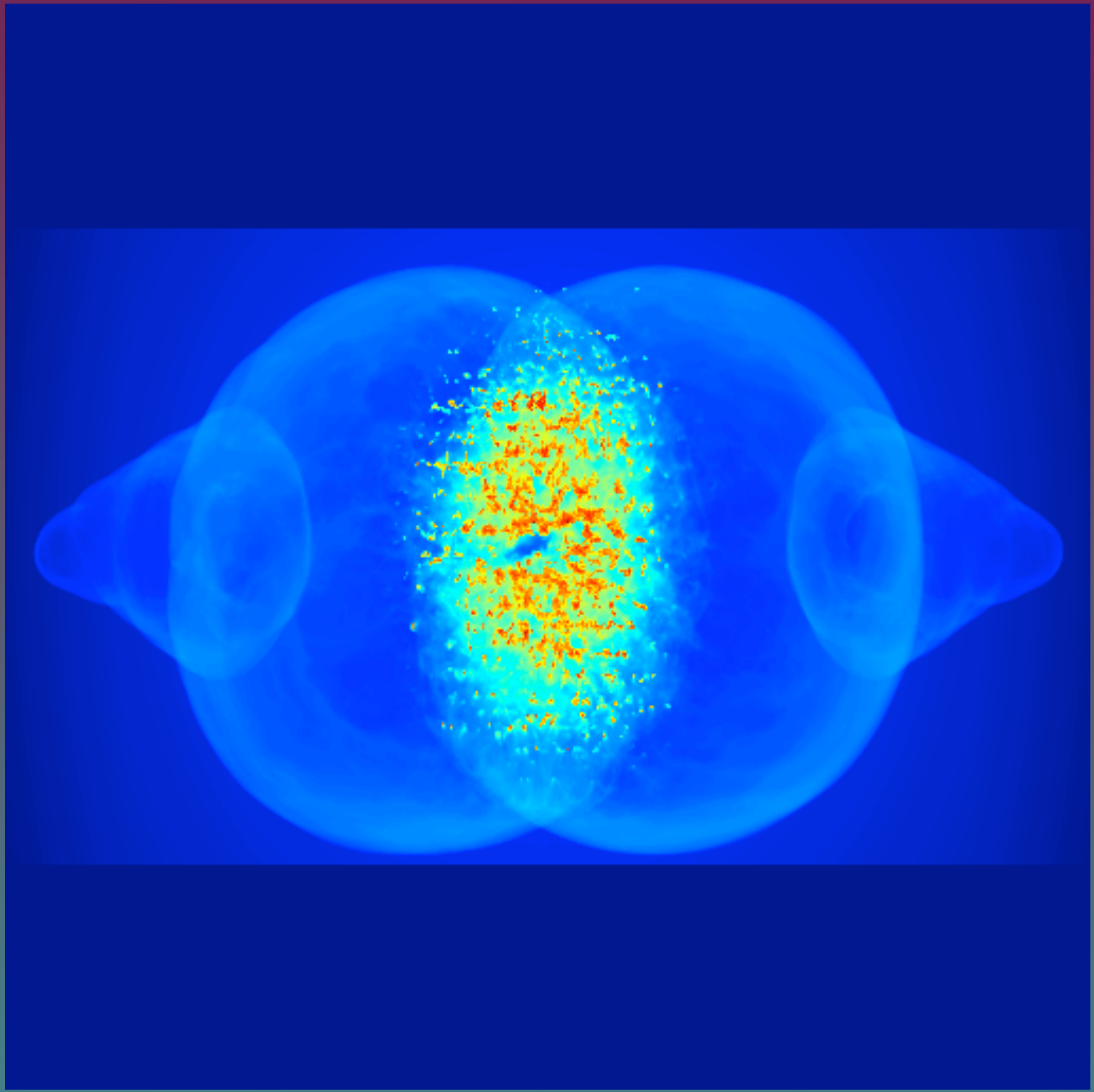
Density



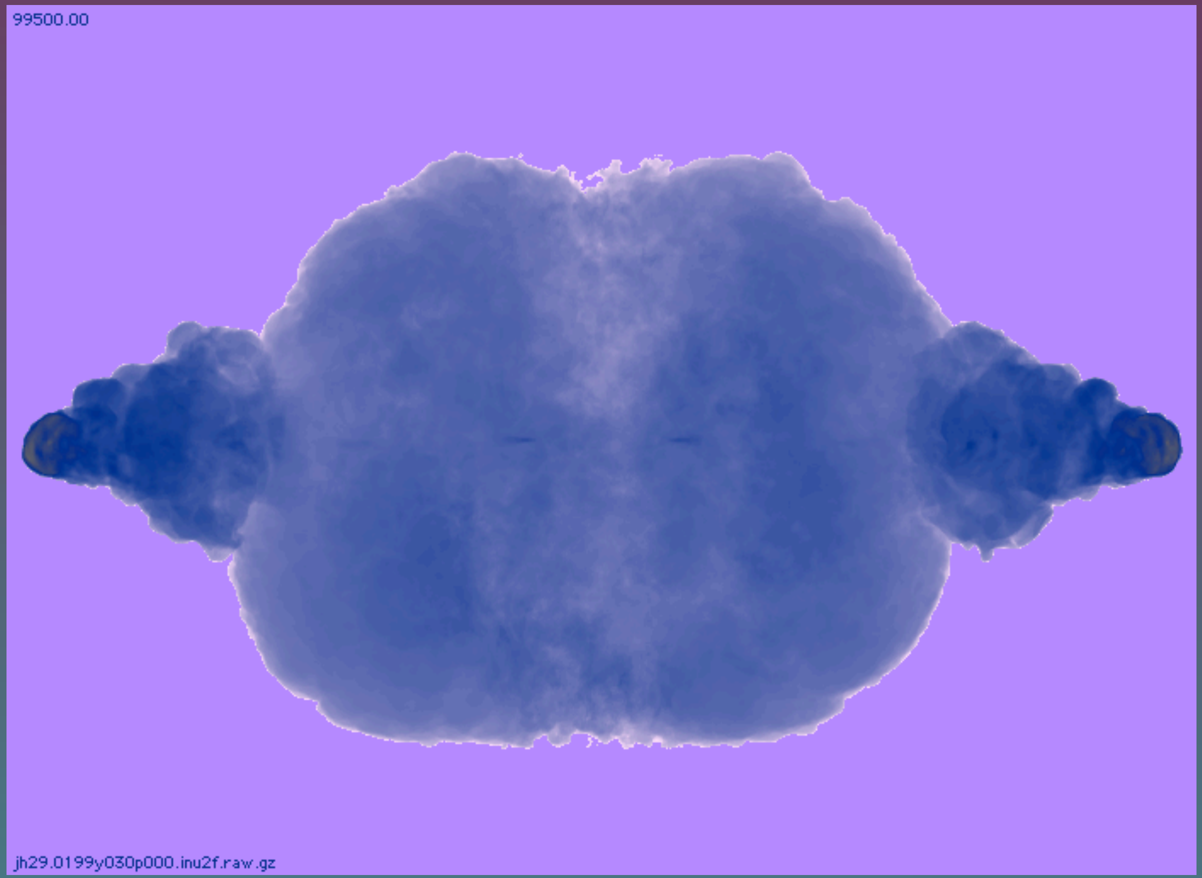
Radio and X-ray surface brightness

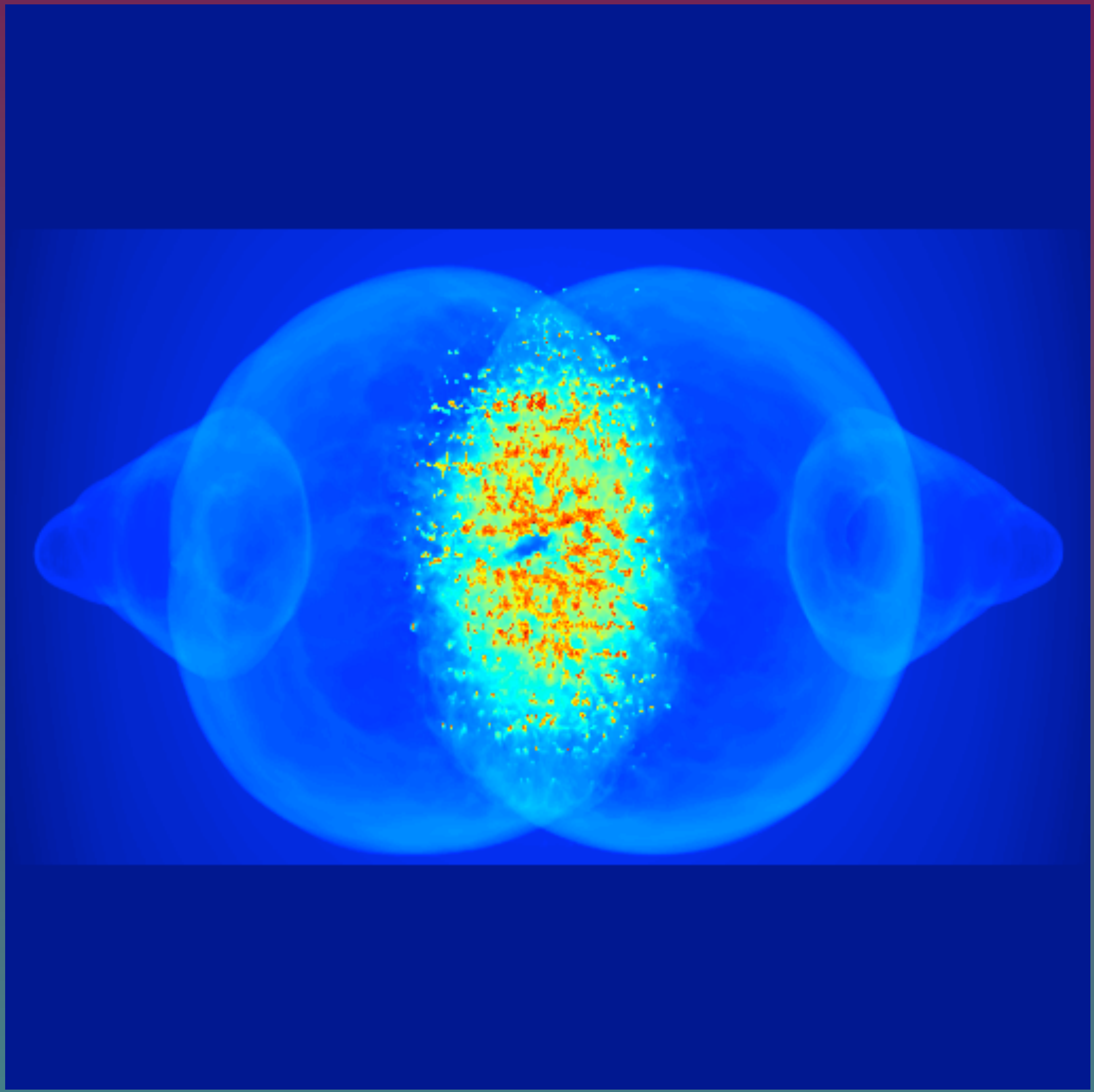
Radio and X-ray surface brightness





Radio and X-ray surface brightness





Simulations and observations GPS/CSO 4C31.04

Sutherland & GB 2007

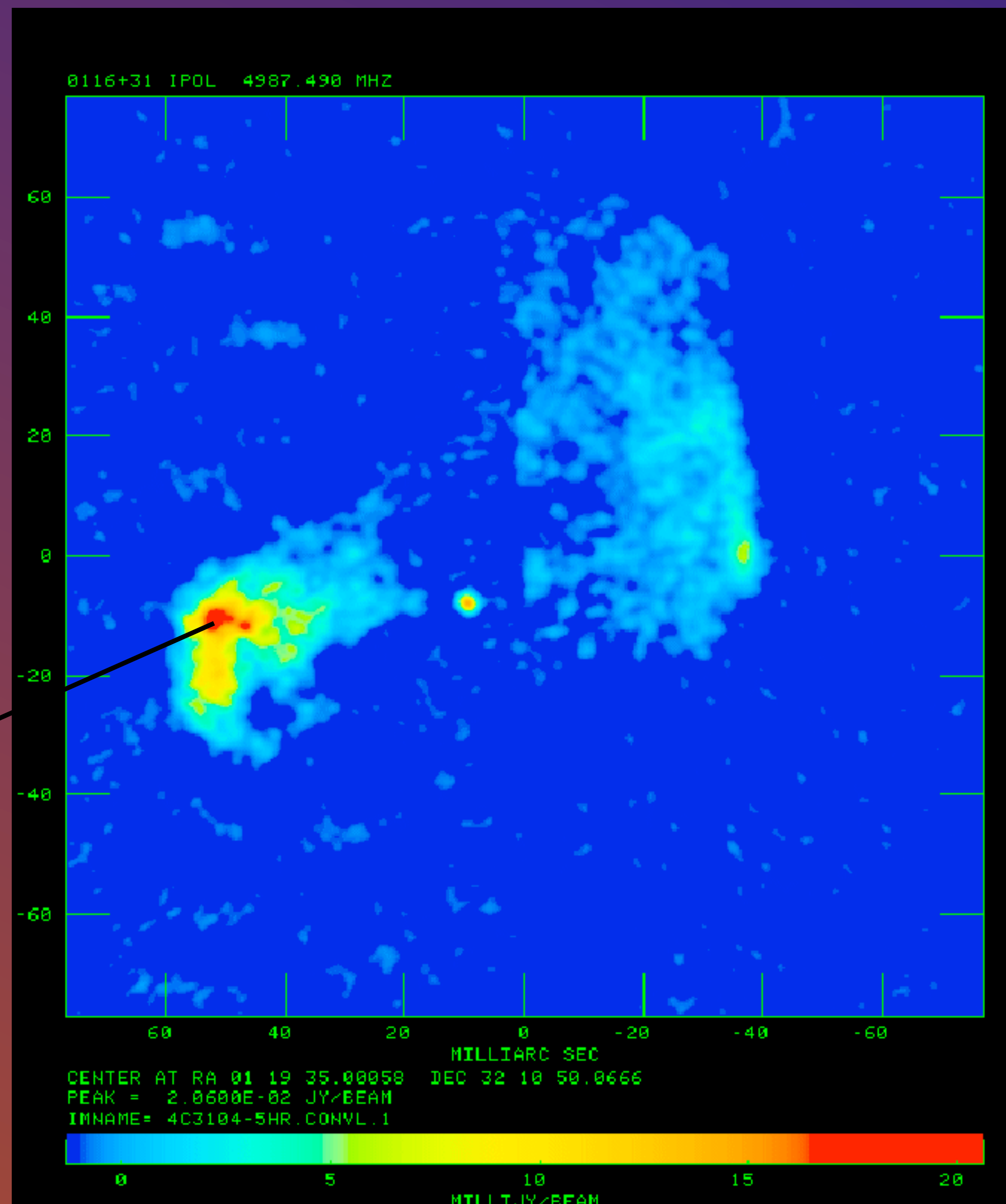


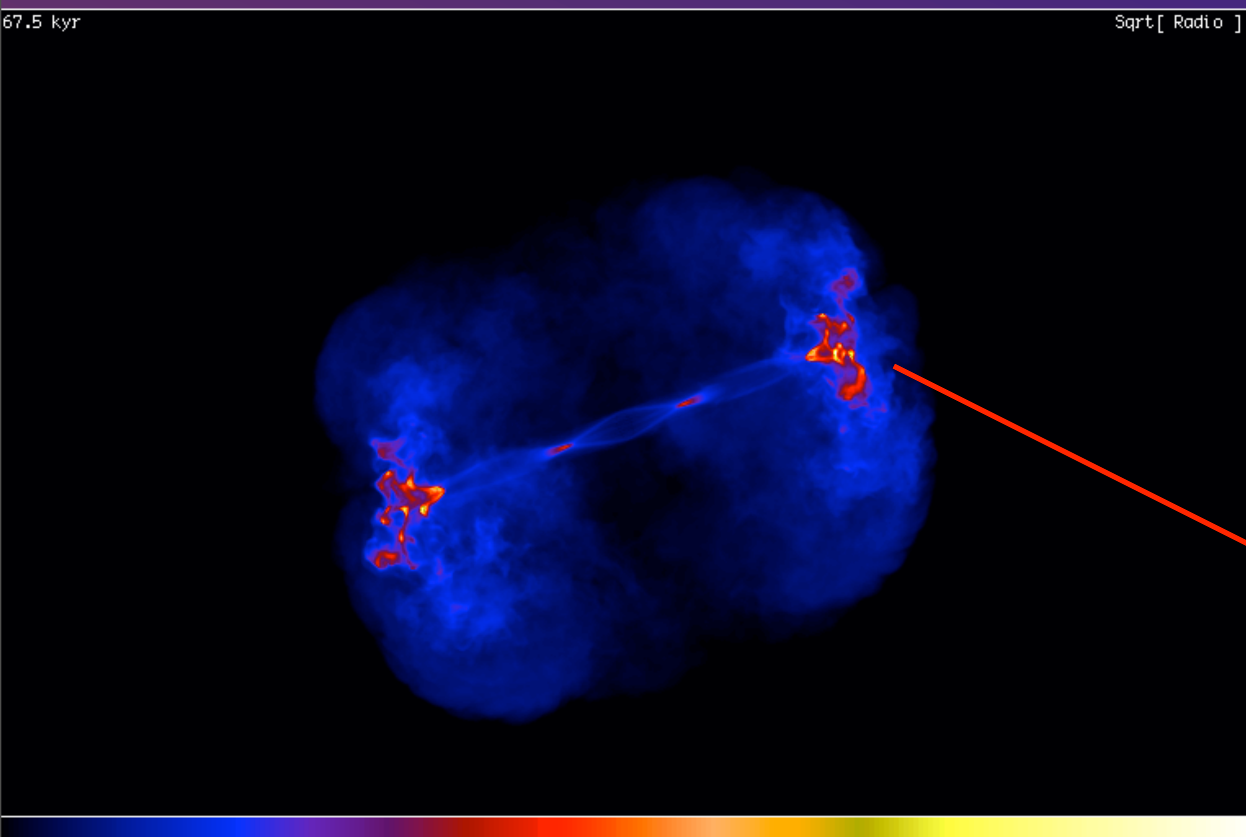
Image courtesy of NRAO/AUI and Gabriele Giovannini, et al.

10 mas = 11.4 pc

$v \sim 0.4c$

Reconciles difference between dynamic and spectral ages

Simulations and observations GPS/CSO 4C31.04



Sutherland & GB 2007

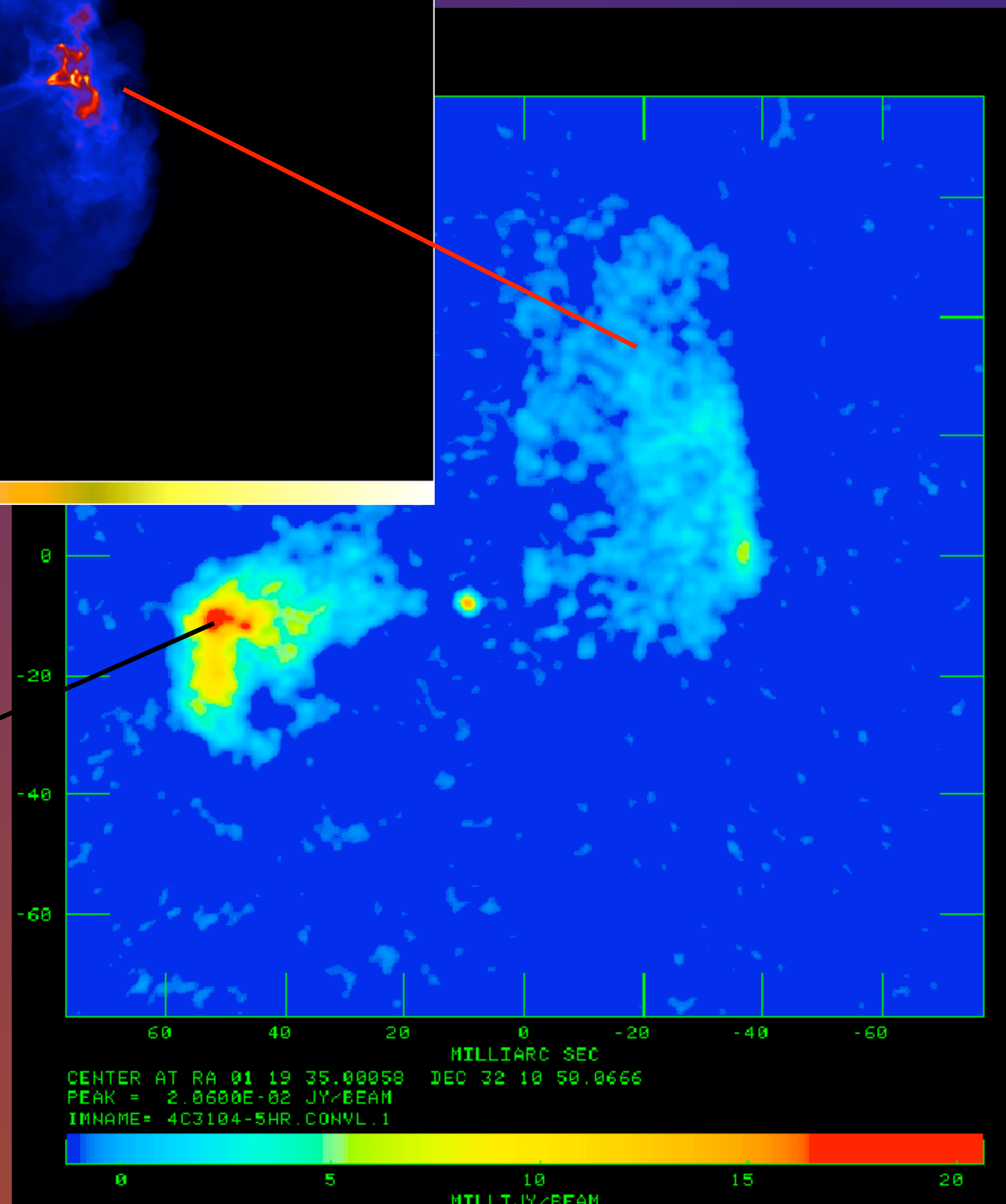


Image courtesy of NRAO/AUI and Gabriele Giovannini, et al.

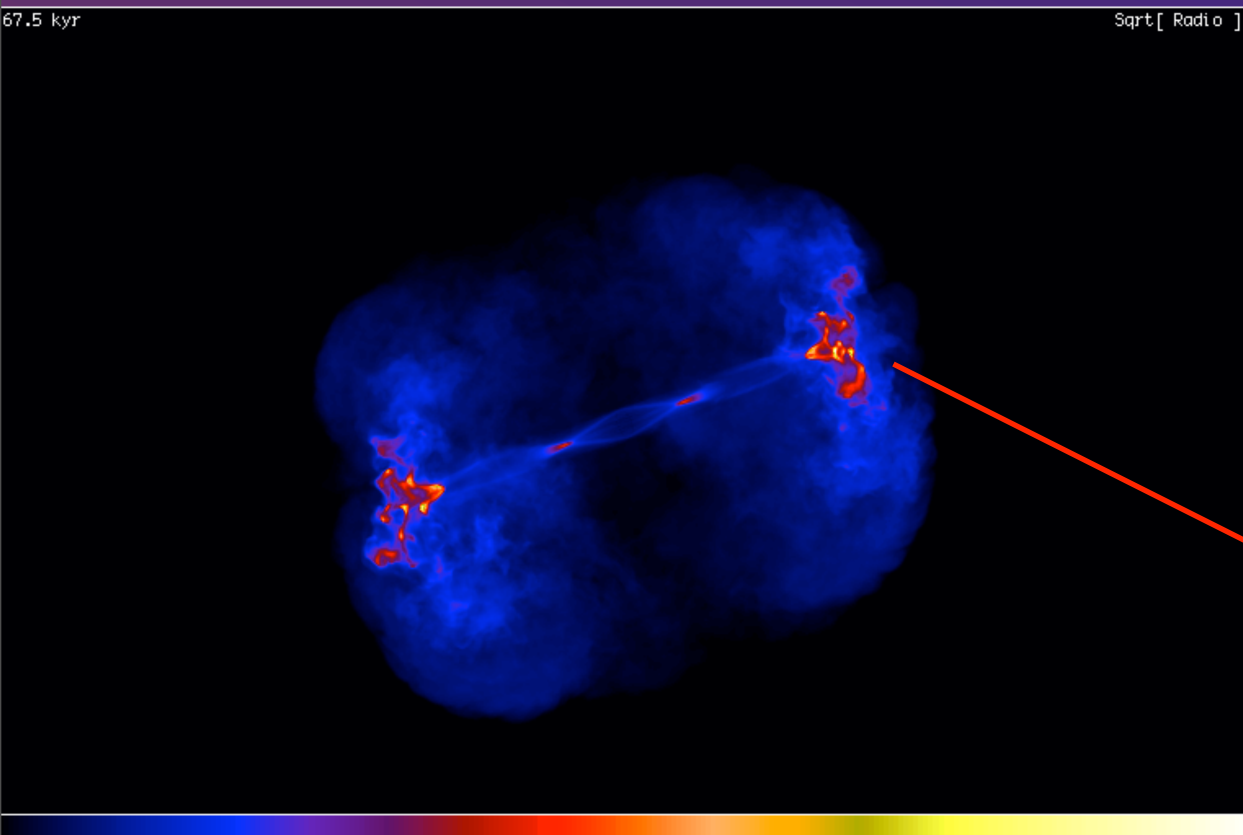
10 mas = 11.4 pc

$v \sim 0.4c$

Reconciles difference between dynamic and spectral ages

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

Simulations and observations GPS/CSO 4C31.04



Sutherland & GB 2007

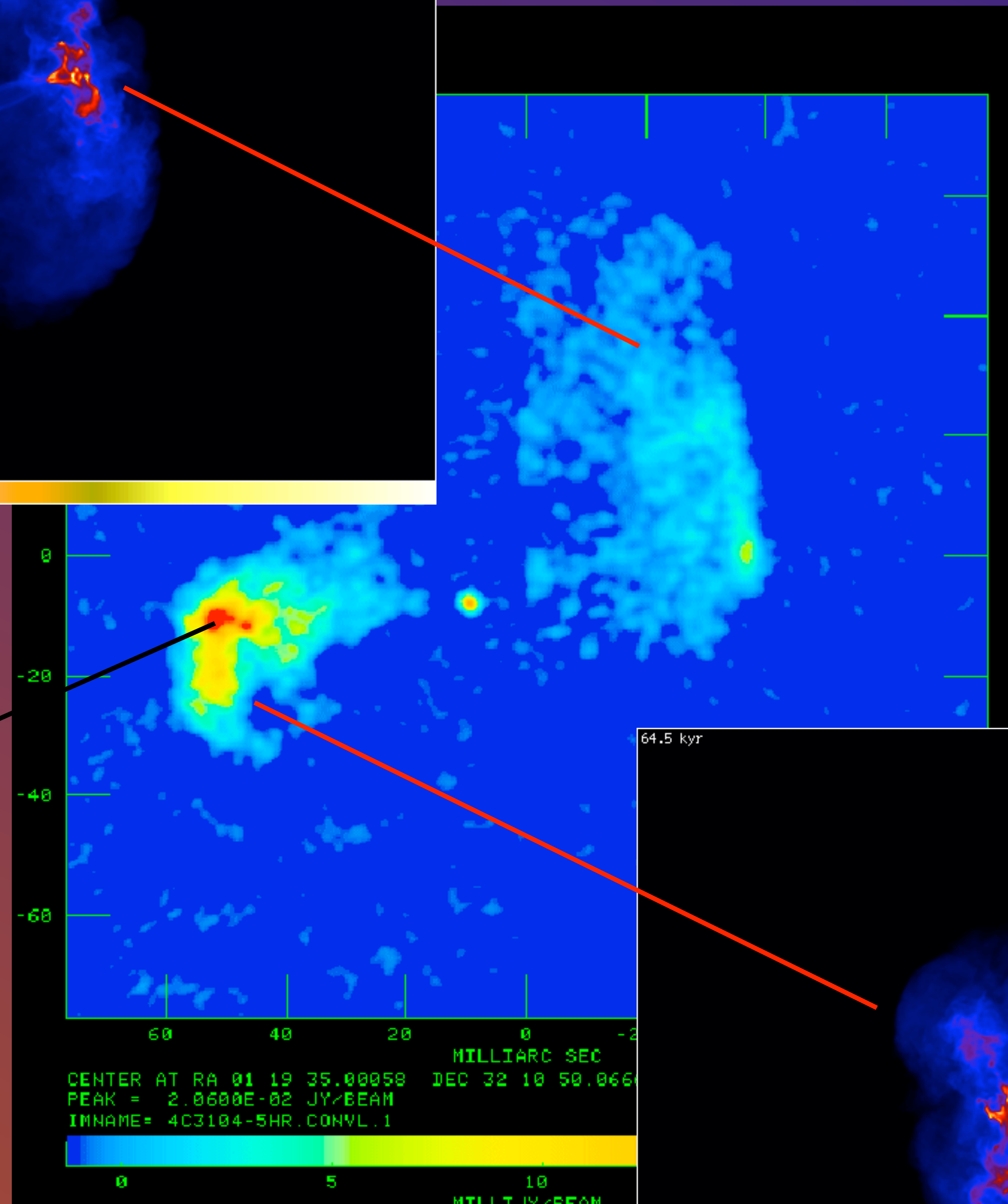
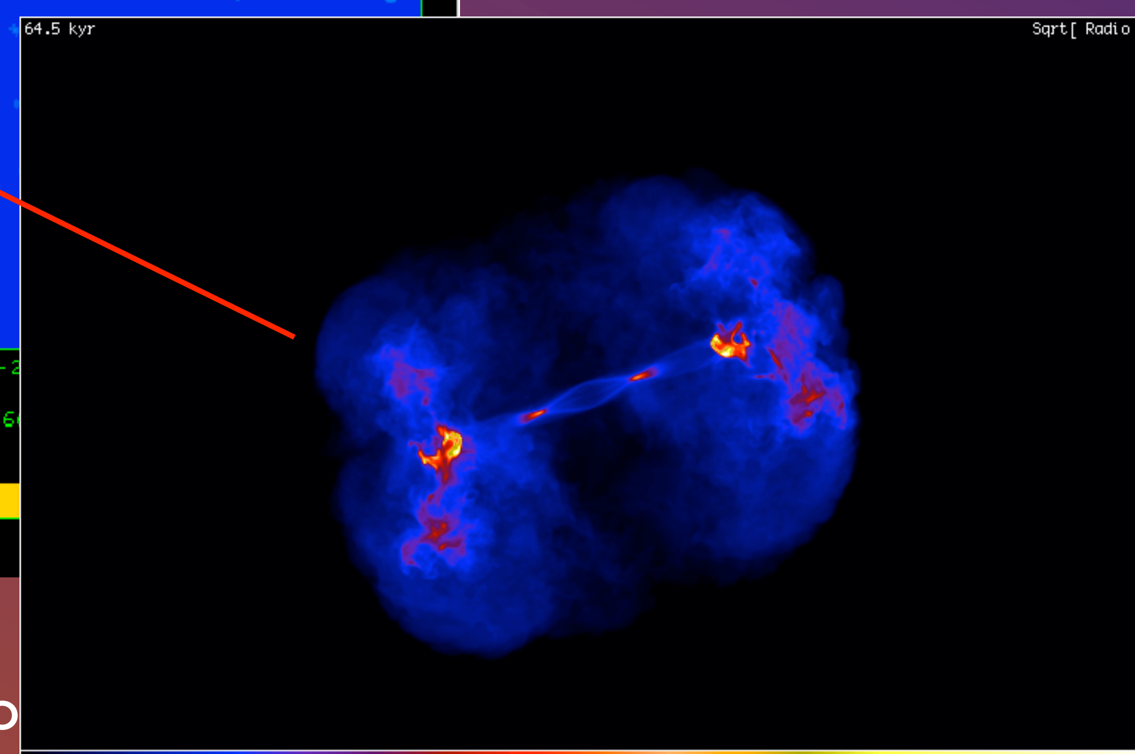


Image courtesy of NRAO/AUI and Gabriele Giovannini, et al.

10 mas = 11.4 pc

$v \sim 0.4c$

Reconciles difference between dynamic and spectral ages



ANU THE AUSTRALIAN NATIONAL UNIVERSITY

Supporting evidence for Jet-ISM interactions from observations of ellipticals

- Kormendy et al., 2009, find that ellipticals with $-21.54 < M_V < -15.53$ have "extra light" indicative of starbursts in "wet mergers".
- For $M_V < -21.66$ no evidence of recent star formation
- AGN more effective in providing feedback in bright ellipticals
- Kormendy et al. interpreted in terms of high p/k of X-ray emitting ISM => more obstructive working surface for jet outflow
- Jet – clumpy ISM interaction provides a more natural explanation

Main points

- Jets with Eddington factor > 10^{-3} – 10^{-2} may disperse gas in the core of an evolving galaxy but porosity increases the critical Eddington factor
- Jets in a clumpy medium process all of the ISM
- Jets of all powers in excess of 10^{43} ergs s^{-1} could play a role
- Large fraction of the radio galaxy population involved

- Increasing influence of radio galaxies at high redshift in view of the evolving radio luminosity function (Sadler et al. 2007)
- Important to consider the radio morphology of radio galaxies when assessing the role of AGN in influencing the evolution of the hosts