Active galactic nuclei at radio wavelengths: properties, life and impact

4) The impact of radio jets on the interstellar medium and galaxy evolution

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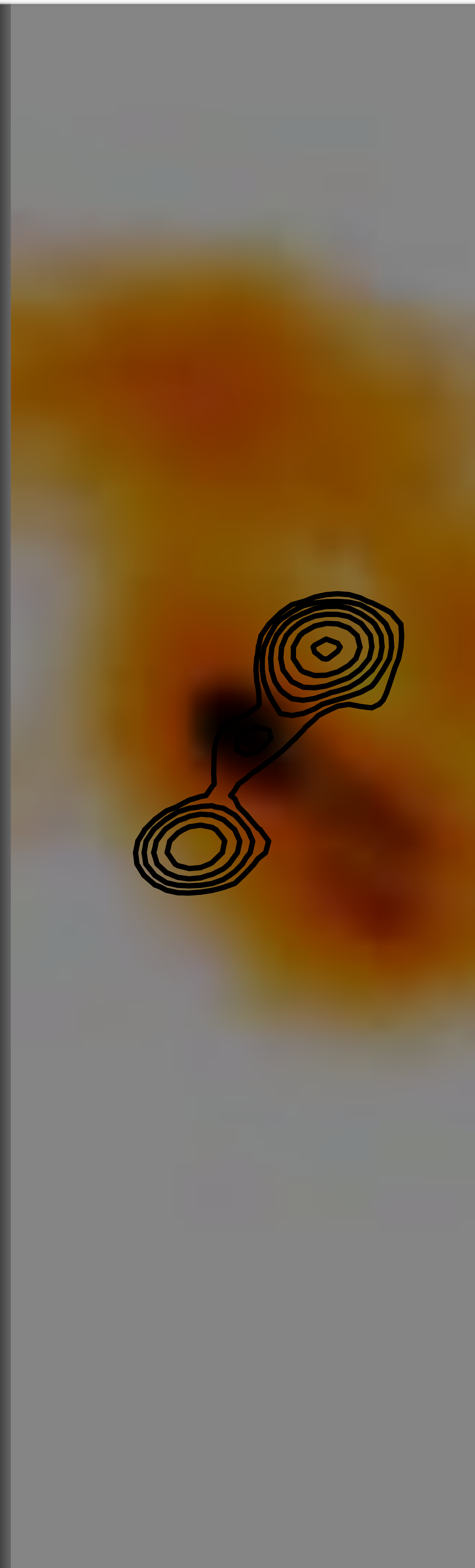
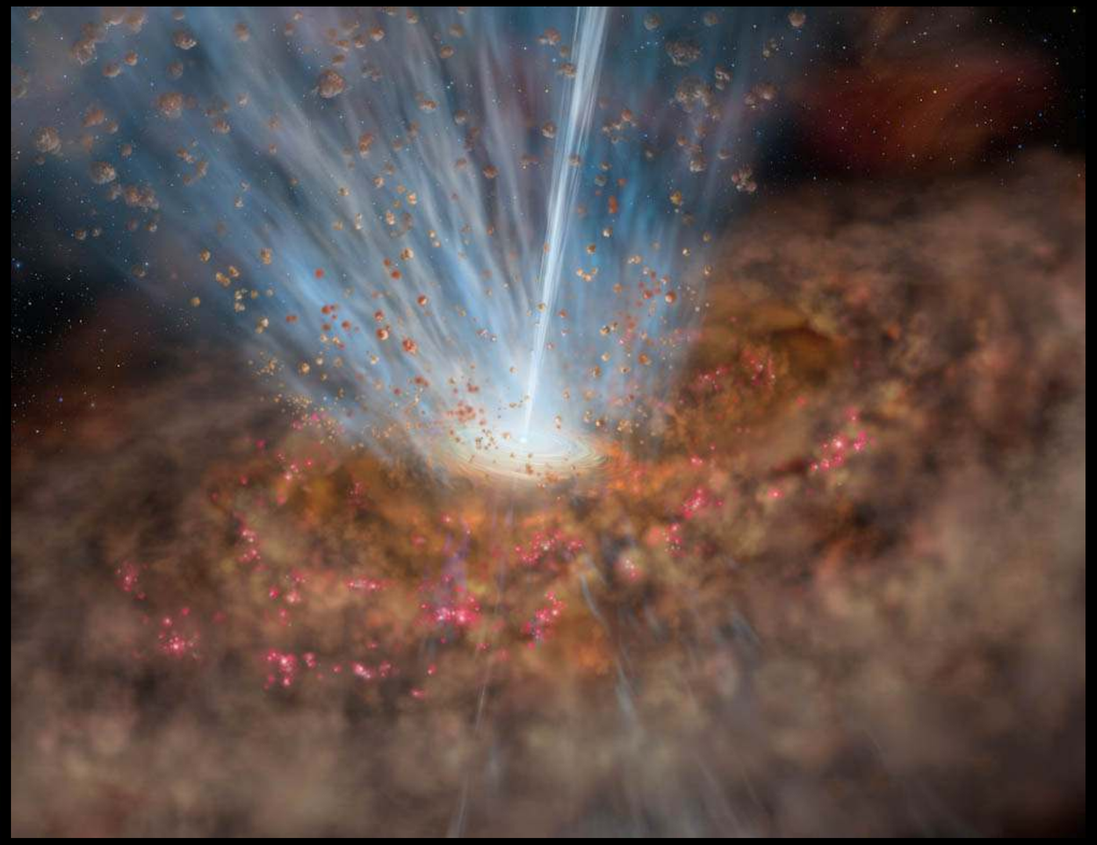


Themes of the lectures

- An introduction to radio-astronomy and radio surveys
- From radio quiet to radio loud AGN: properties and recent results
- Radio galaxies and their life cycle
- **The impact of radio jets on the interstellar medium and galaxy evolution**

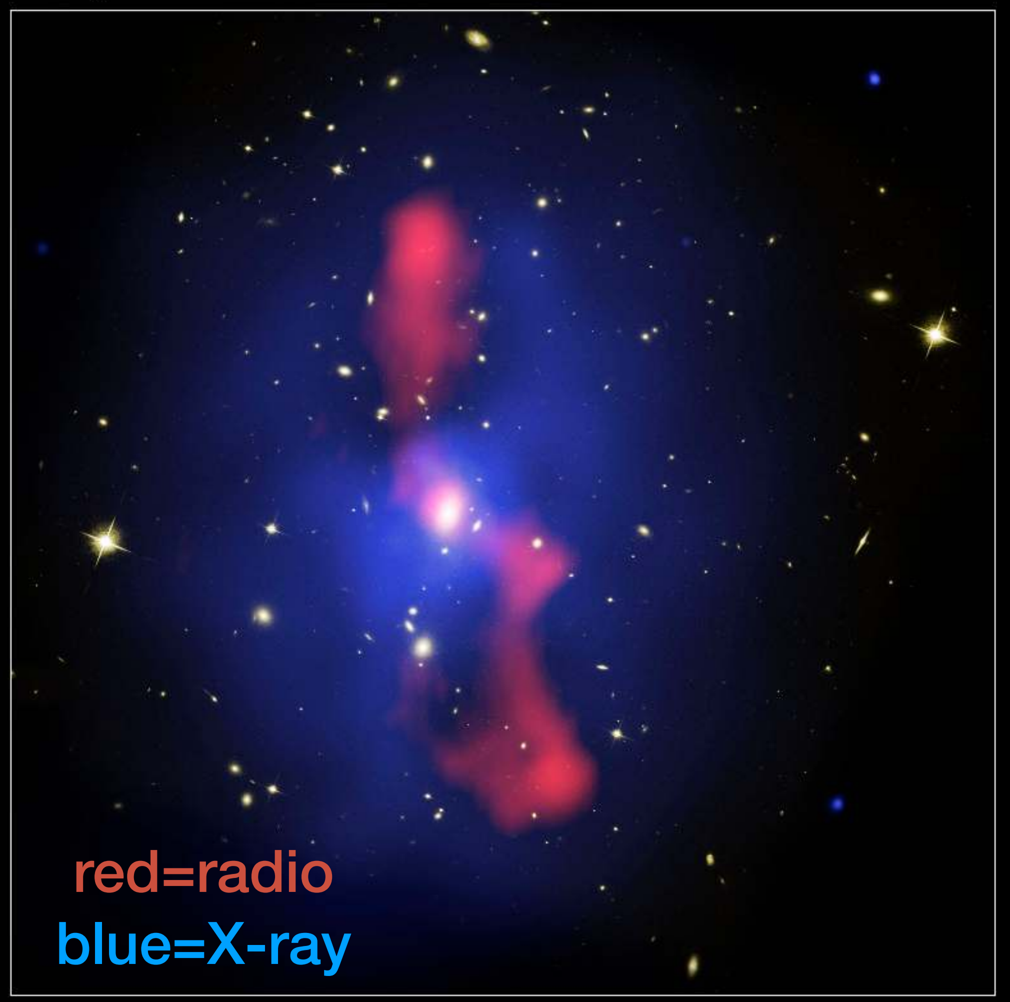
Role of AGN in galaxy evolution: cosmological simulations

Preventing gas from cooling
and/or
ejecting gas (outflows)



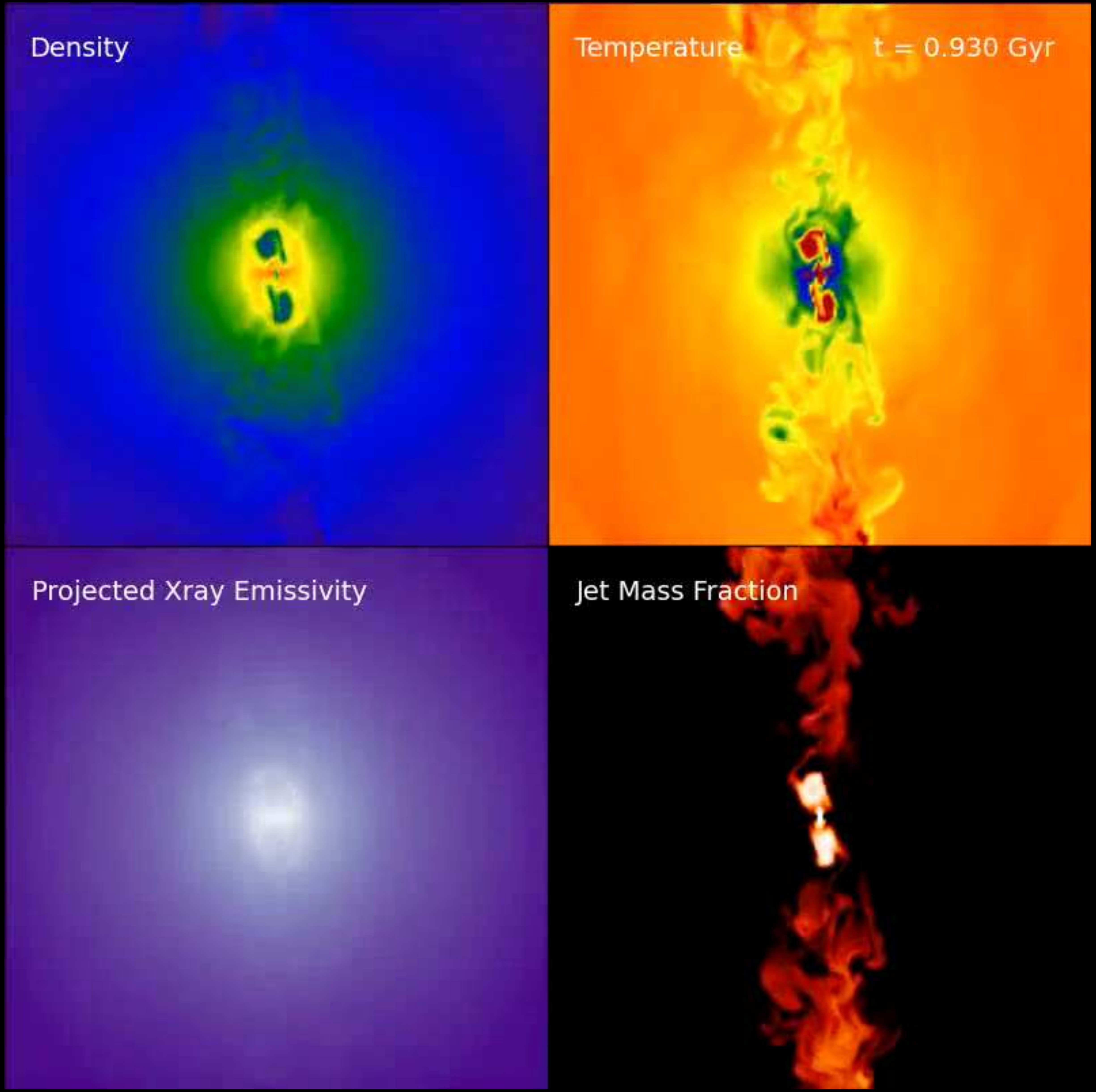
“Quasar” mode

Galaxy Cluster MS 0735.6+7421



NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)

“jet/maintenance” mode
(cluster-scale)



Possibly still the best example of AGN feedback

Large scale radio AGN feedback → these simulations have demonstrated the cooling offset and accretion balance in large clusters over long time scales (Yang and Reynolds 2016)

Is the dichotomy
(outflows from radiation and “maintenance” from radio)
realistic?

radio jets connect the small and large scales:
can they also produce outflows on galaxy
scales?

gas outflows not only driven by radiation but also by jets?
would expand the number of AGN that can produce “feedback”

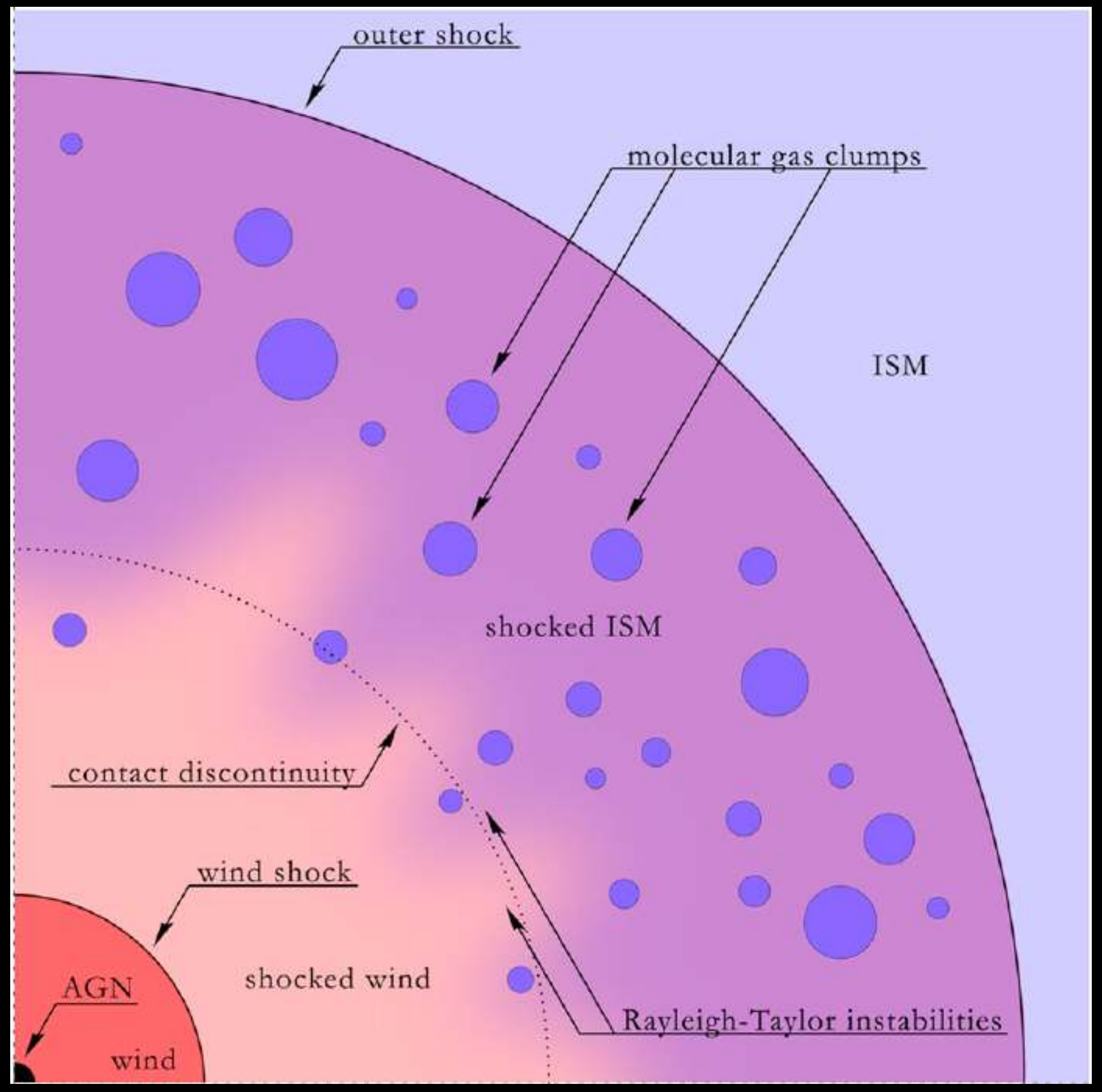
What makes these mechanisms useful for feedback

- **energetics: enough to do the job!**
- **efficient coupling with the ISM needed**
- feedback process has to cover large scales to IGM/ICM

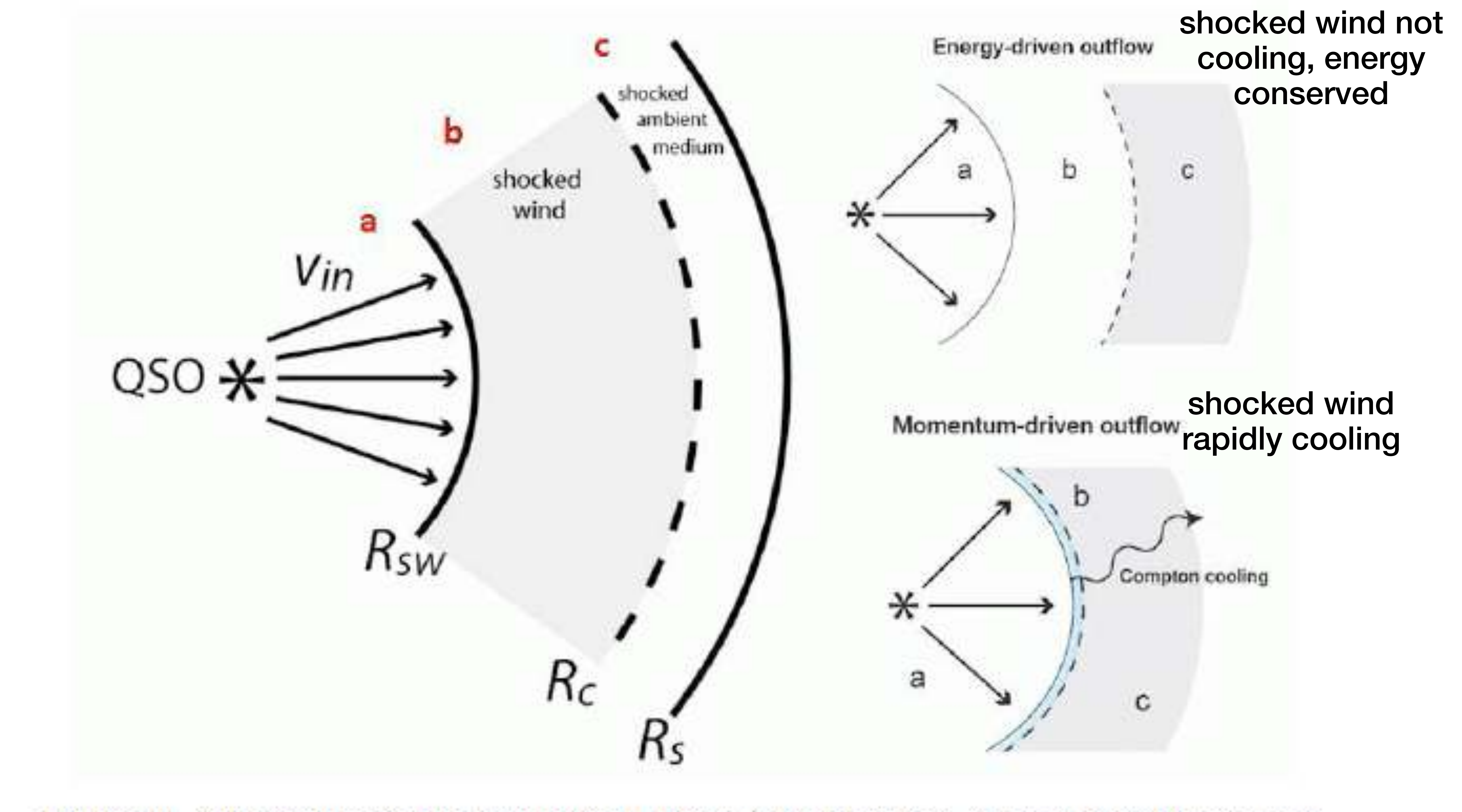
Energetics radiation and winds…

- Radiation pressure can launch (wide) winds from the accretion disk ➜ wind shocks against the surrounding gas and drives an outflow. Efficient cooling can trigger the collapse of gas in clumps.
- Coupling of AGN radiation to the dust in the wind

Zubovas & King 2014



Costa et al. 2014, Faucher-Giguere & Quataert 2012



shocked wind not cooling, energy conserved

shocked wind rapidly cooling

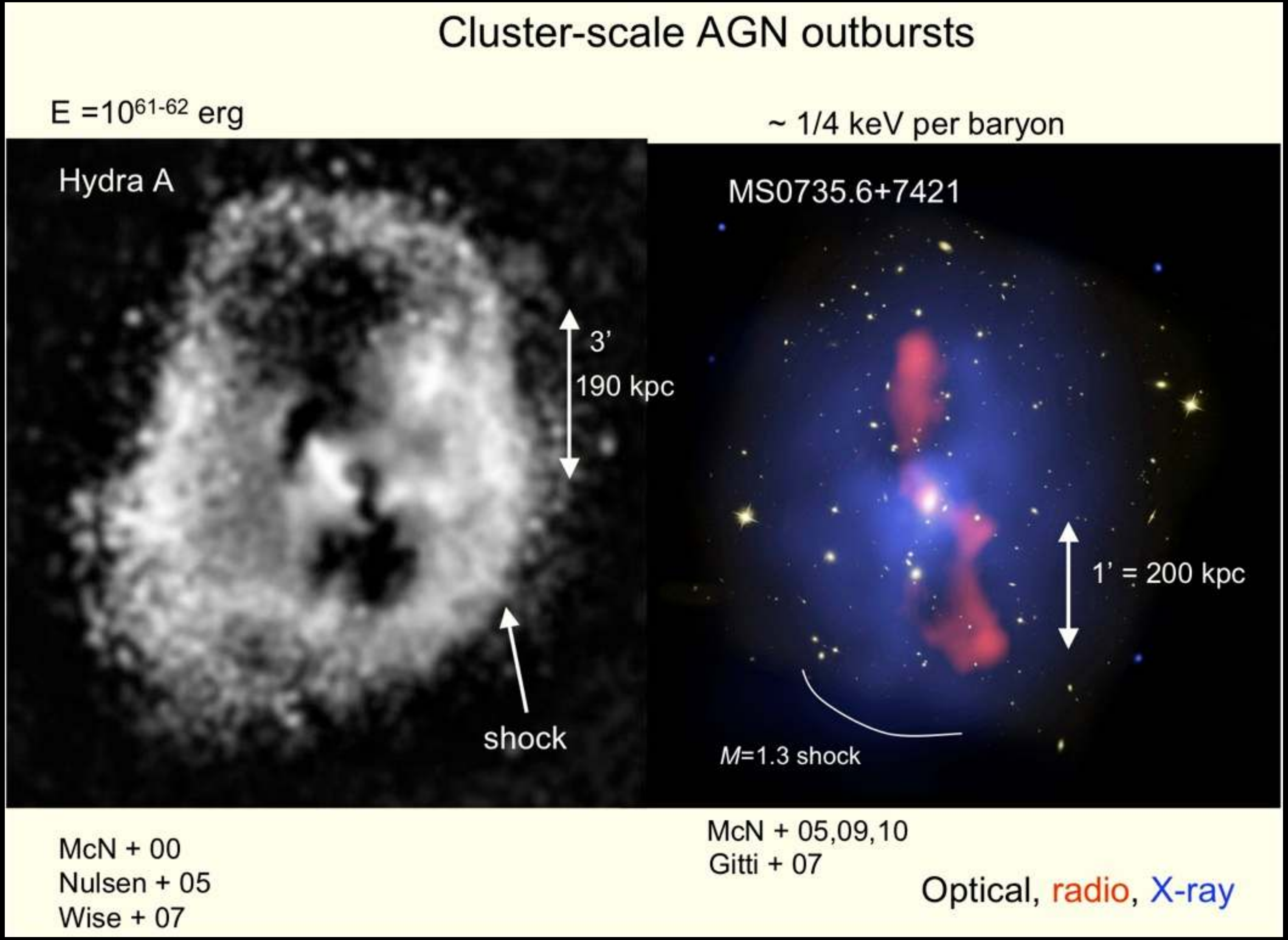
$L_{AGN} = \eta \dot{M}_{BH} c^2$

L_{bol} ➙ fraction of L_{Edd} depending on the efficiency of the accretion

(radiative efficient vs radiative inefficient), see Les 2

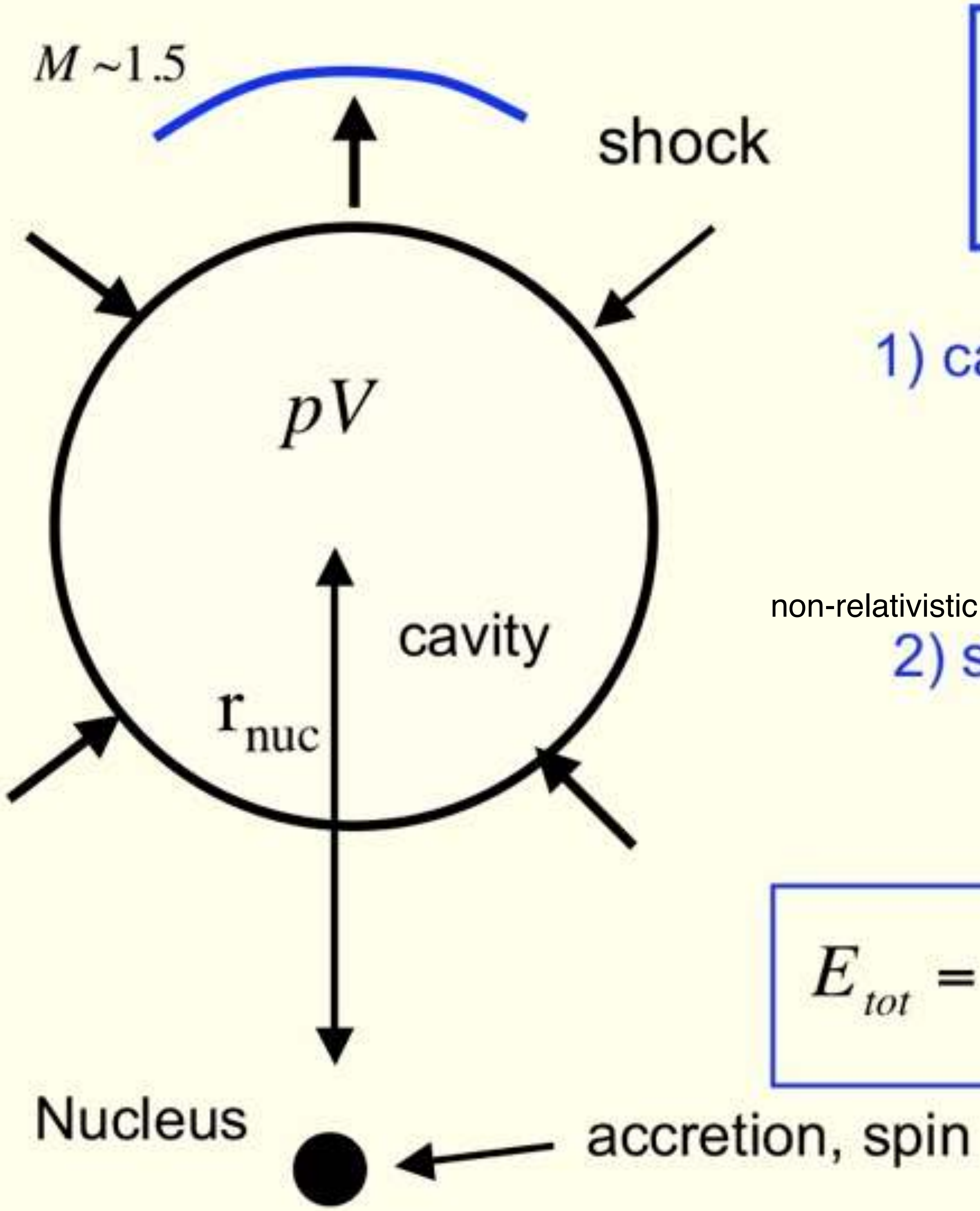
Energetics of the jets

the X-ray cavities used as calorimeter as one of the methods to derived the jet power from cavities



Measuring Jet Power with X-ray Cavities

Ages: as the time required for it to reach its projected location assuming it traveled at the sound speed or as the time for the cavity to rise buoyantly to its present location



- *energy & age measured directly*
- measure total (not synchrotron) power

total enthalpy, i.e., the pV work plus the internal energy that provides the pressure supporting the cavities

1) cavity

$$E_{cav} = \frac{\gamma pV}{\gamma - 1} = 2.5pV - 4pV \qquad t_{cav} = r_{nuc}/v_{buoy}$$

non-relativistic plasma (gamma = 5/3)

relativistic plasma (gamma = 4/3) or

2) shock

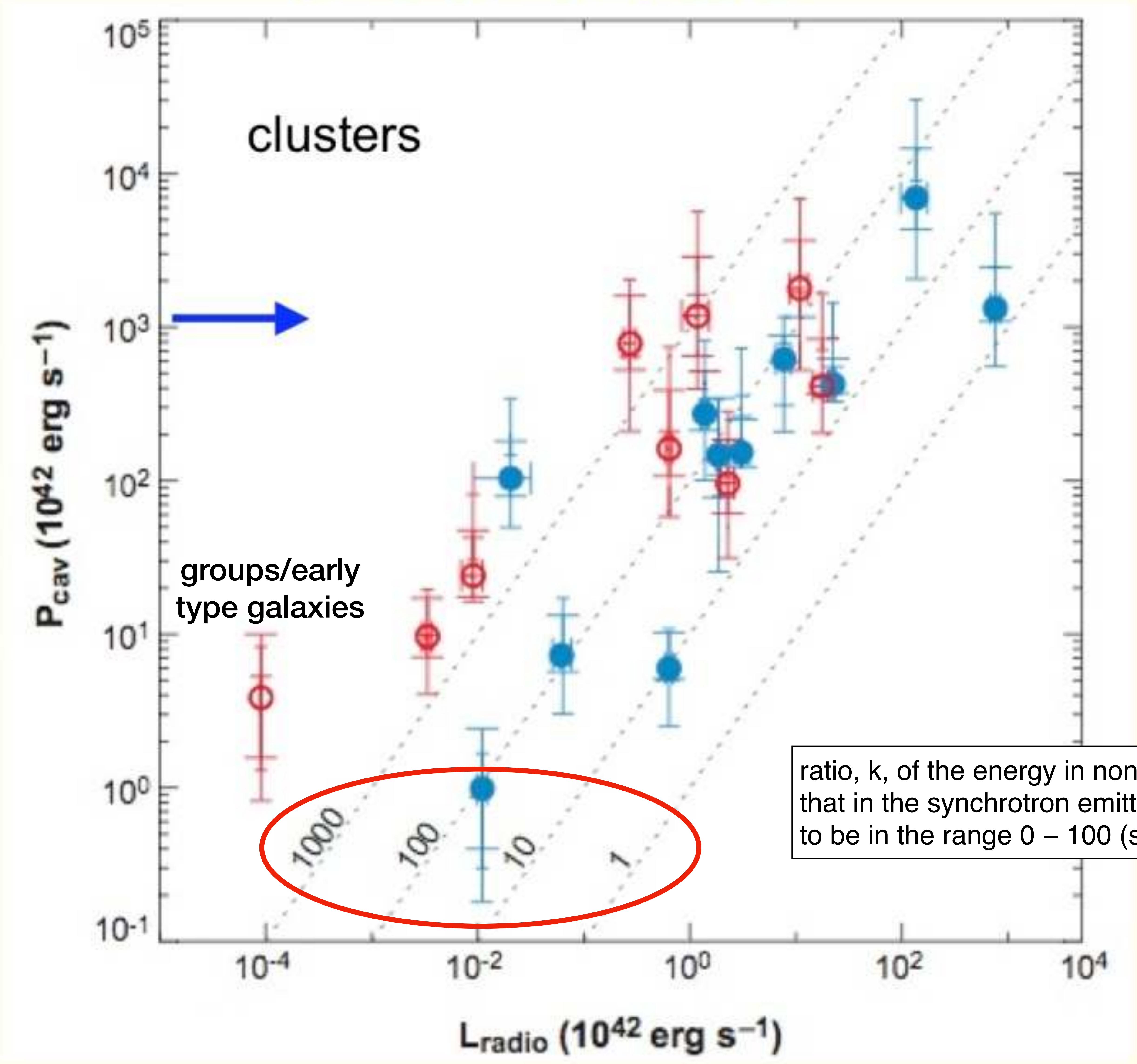
$$E_{shock} \approx \Delta pV \qquad t_{shock} \approx r_{shock}/c_s$$

$$\boxed{E_{tot} = E_{cav} + E_{shock} + (E_{photon}) = 10^{55} - 10^{62} erg}$$

McNamara + 00,01, Birzan + 04

Radio Calorimetry: low radiative efficiency, mechanically-dominated, *powerful, 'heavy lobes'*

jet (cavity) power



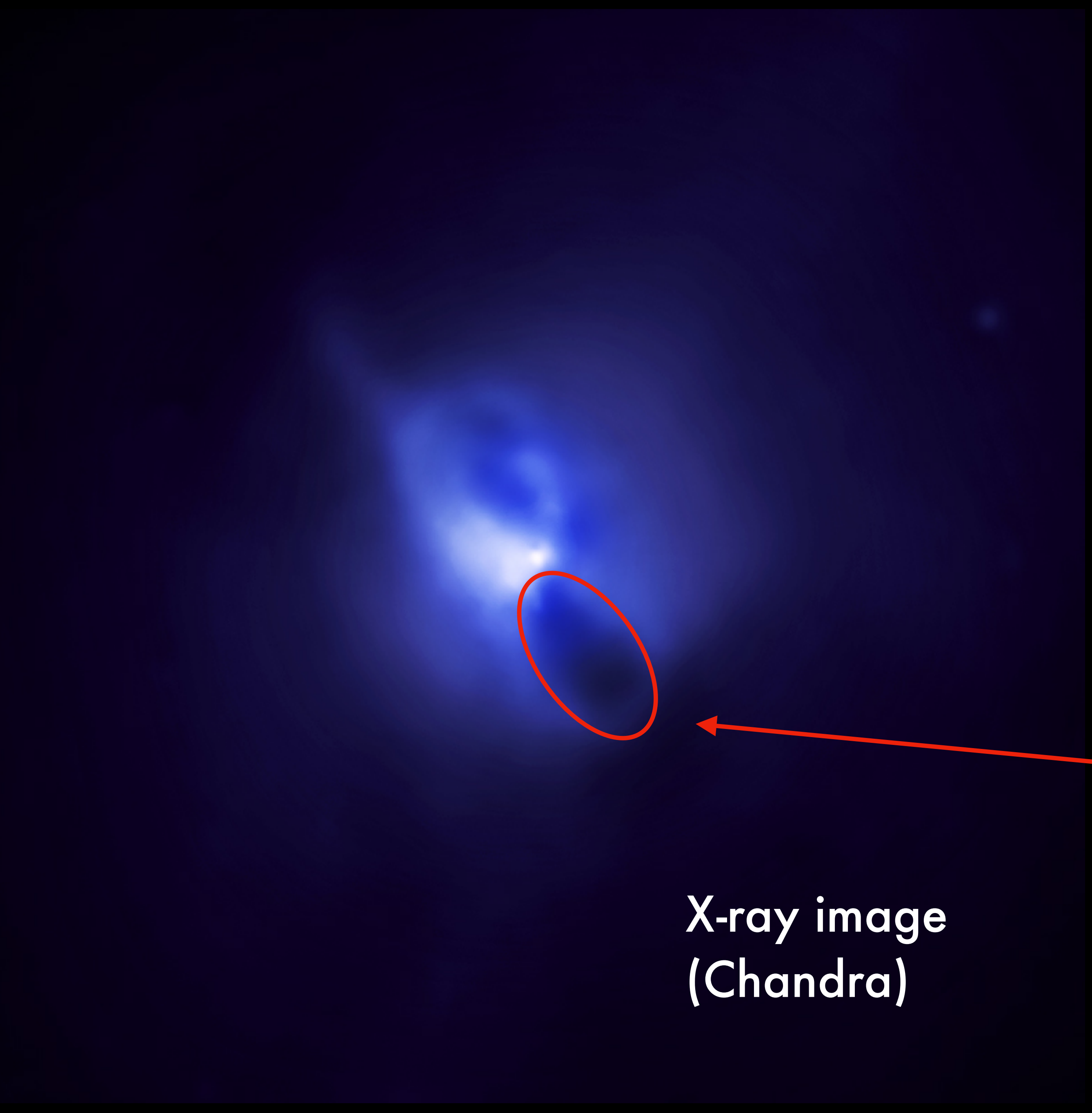
ratio, k, of the energy in non-radiating particles to that in the synchrotron emitting electrons, assumed to be in the range 0 – 100 (see Willott et al. 1999)

radio synchrotron power

McNamara & Nulsen, 07 ARA&A

Birzan + 04, 08

An example: Hydra A



X-ray image
(Chandra)

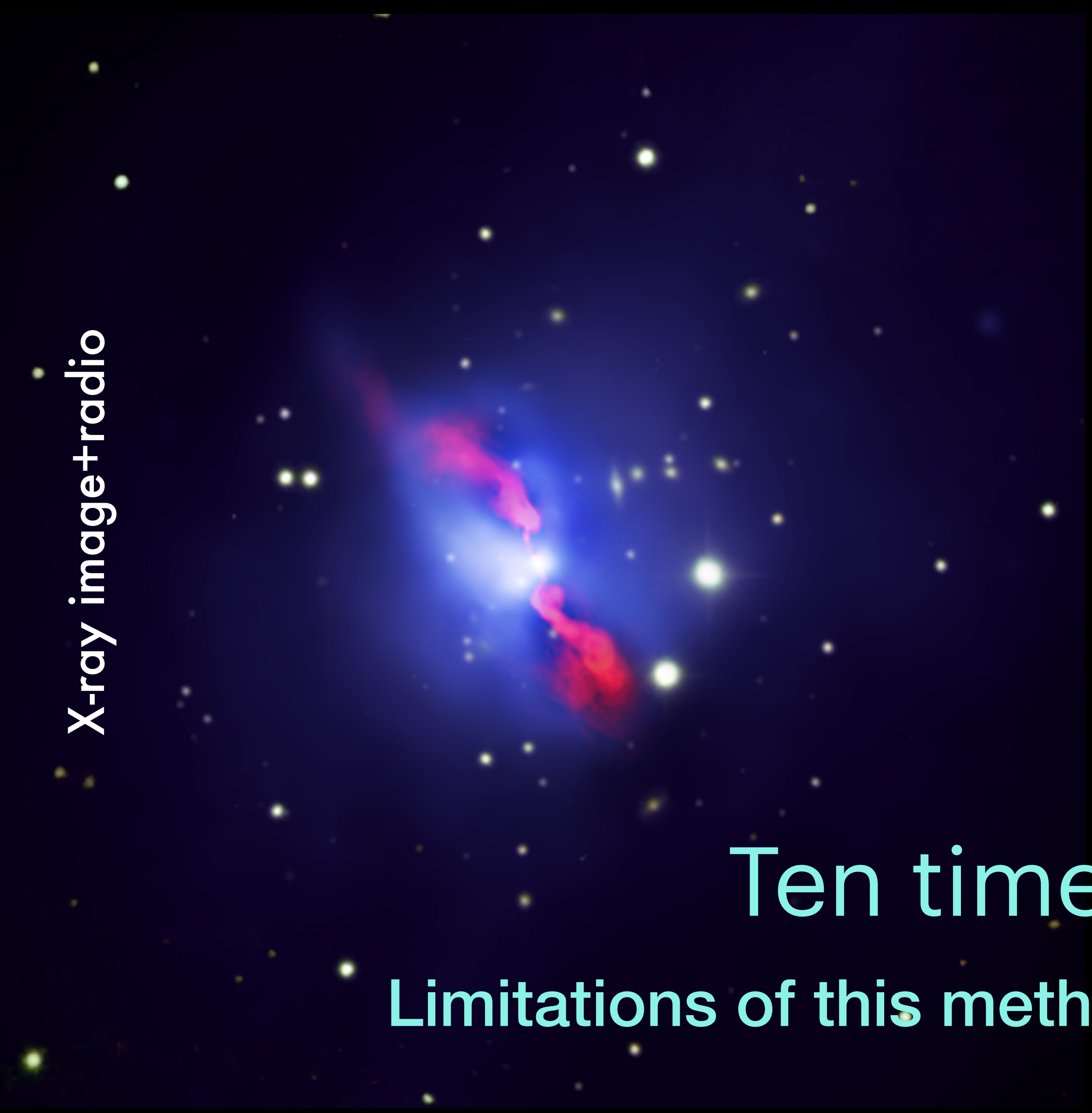
electron density ➔ $n_e \sim 0.023\ \mathrm{cm}^{-3}$
temperature ➔ $kT = 3.4$ KeV
pressure ➔ 2.8×10^{-10} erg cm^{-2}

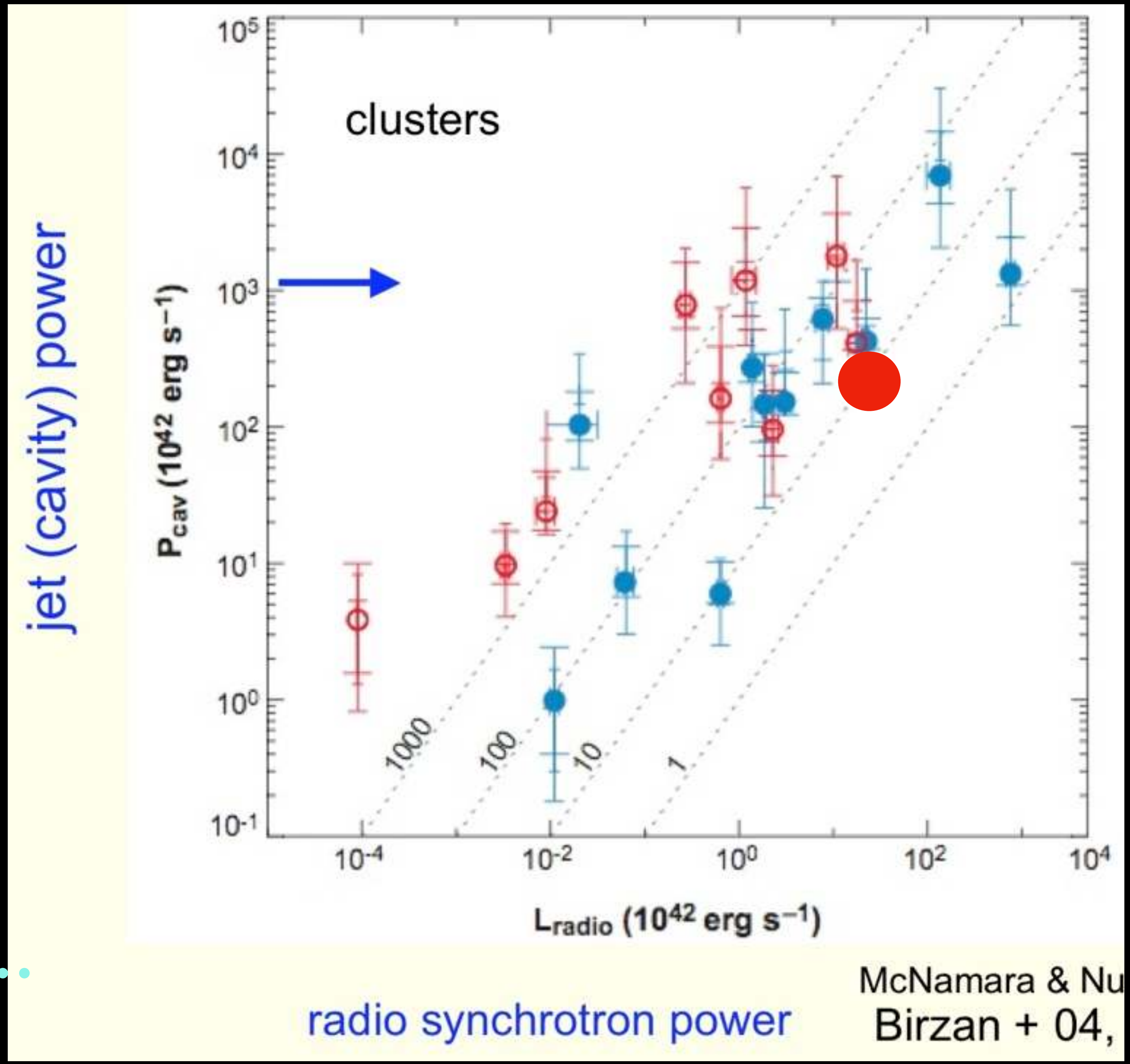
over which Volume?
sphere ~15 kpc ➔ $pV \sim 1.2 \times 10^{59}$ ergs

no signs of shocks, only subsonic motion of the gas

Cavities can take 2×10^7 yr to form
(expanding at about sound speed)

needs 2×10^{44} erg s^{-1} of jet power to maintain the cavity





McNamara & Nu
Birzan + 04,

Ten times more jet power than radio luminosity…

Limitations of this method for in particular for low luminosity (radio-quite) sources

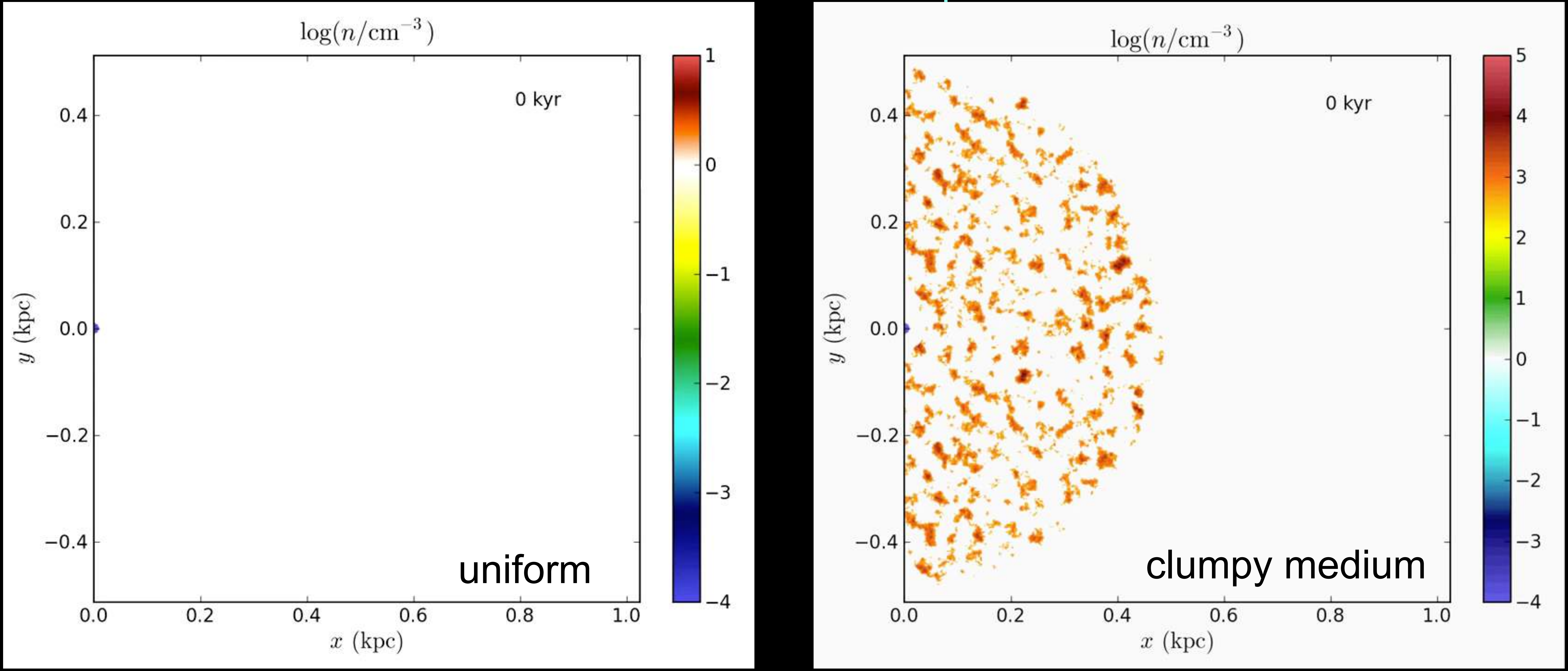
What makes these mechanism useful for feedback

- energetics: enough to do the job!
- **efficient coupling with the ISM needed for the jets**
- feedback process has to cover large scales to IGM/ICM

Coupling efficiency for the jets

Impact of radio jets as predicted by numerical simulations:

key parameter the clumpiness of the medium ➜ Importance of the ISM



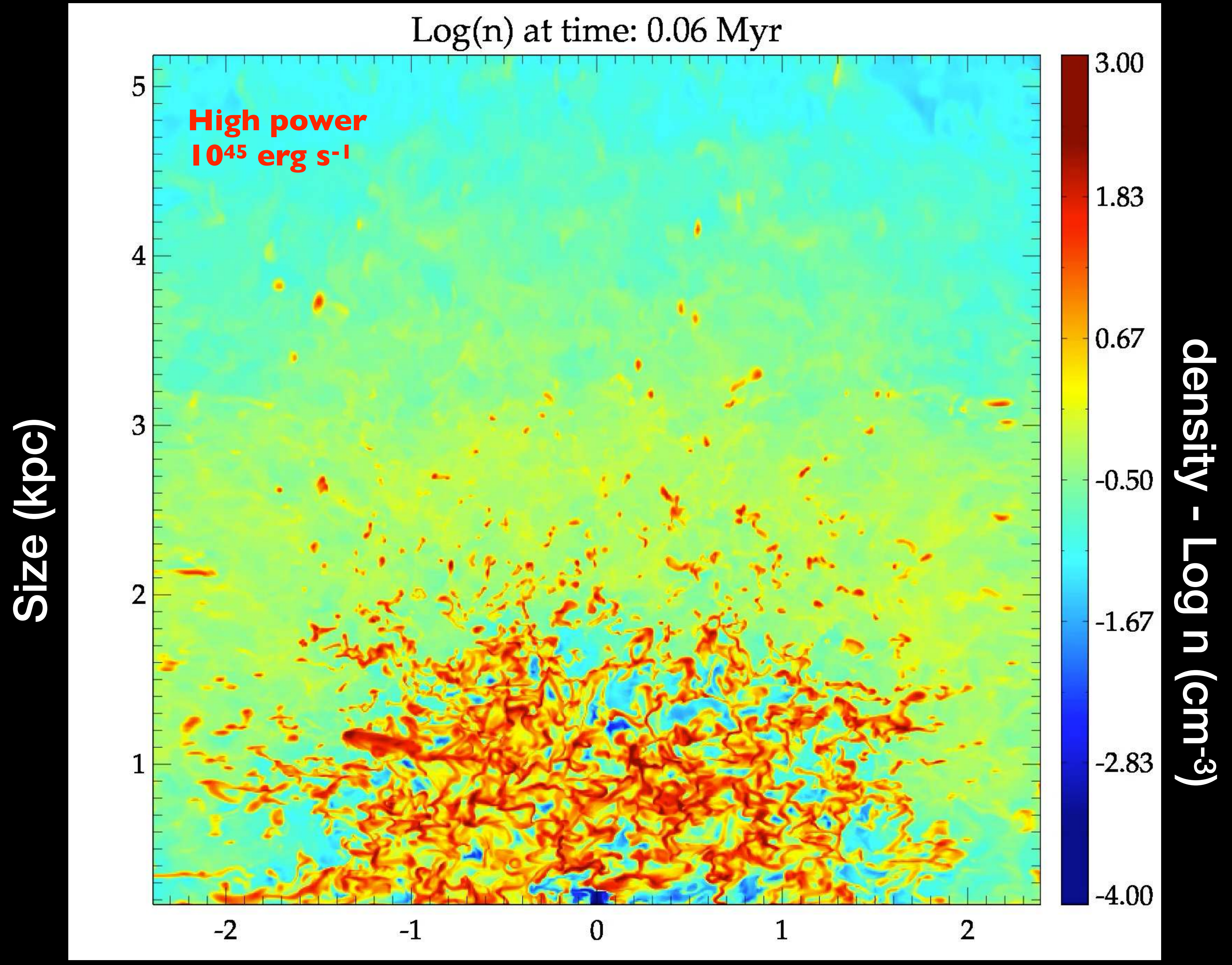
Numerical simulation of a newly created radio jet
Wagner & Bicknell 2011, 2012

Jet power 10^{45} erg/s ➜ about 1% in jet luminosity (McNamara, Birzan, Cavagnolo et al.)

Predictions from simulations

- Jets couple strongly with host's clumpy ISM: whatever the initial narrowness of the jet, the flow is broadened by the interaction with the first clouds (Wagner et al. 2012).
- Outflows expected especially in the initial phase of evolution of a jet (few Myr). Originating from both low and high-power jets
- Multi-phases gas tracing this interaction

from Wagner & Bicknell 2011, 2012;
Mukherjee, Bicknell et al. 2016, 2017, 2018
But similar results also from Cielo et al. 2018



clumpy medium (spherical distribution), high jet power

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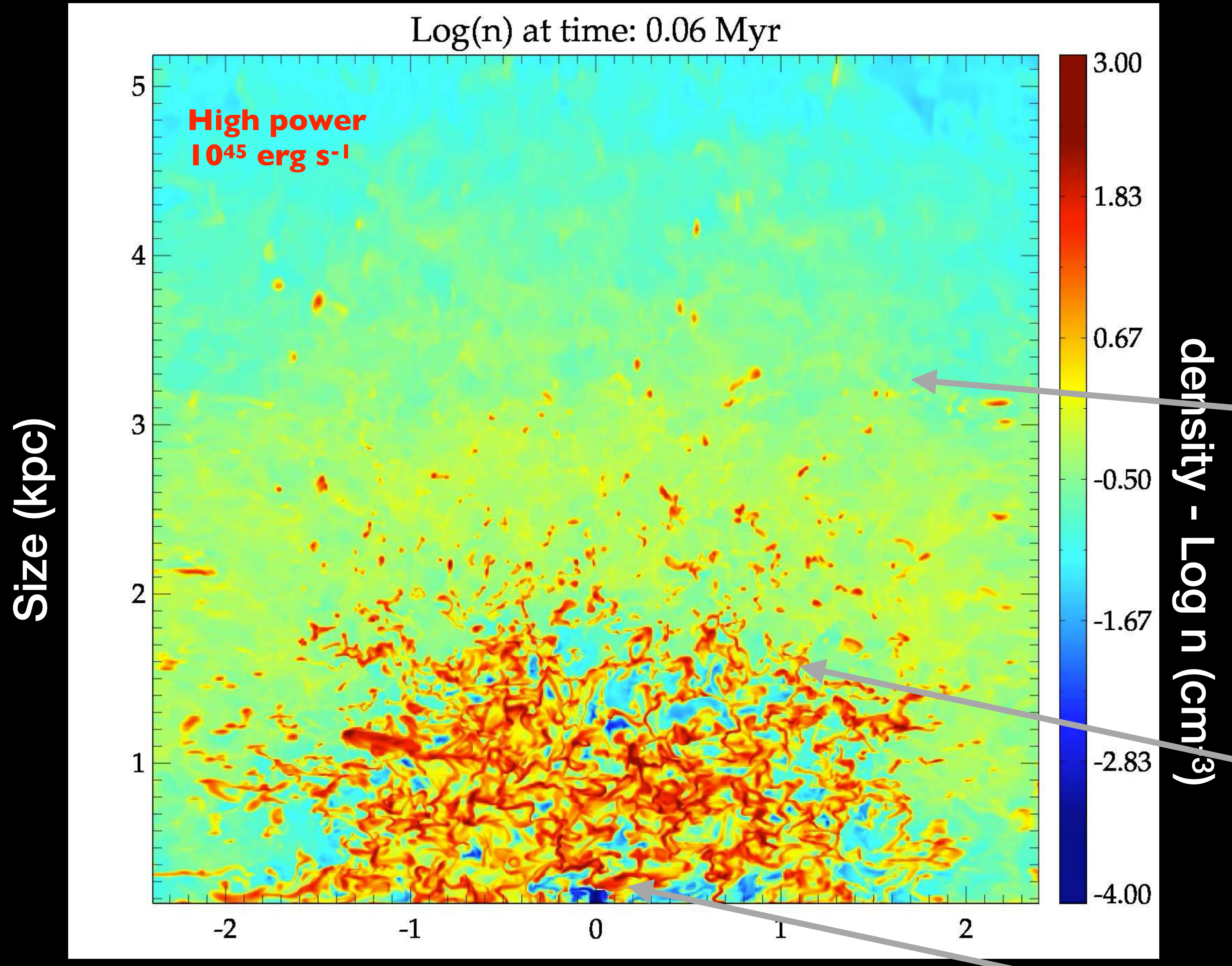


Cocoon of shocked gas (including hot, X-ray gas)

Clouds (partly) shred and accelerated by the direct interaction (warm ionized gas)

High density gas:
fast cooling,
molecular/HI outflows

clumpy medium (spherical distribution), high jet power

A complex parameter space to explore!

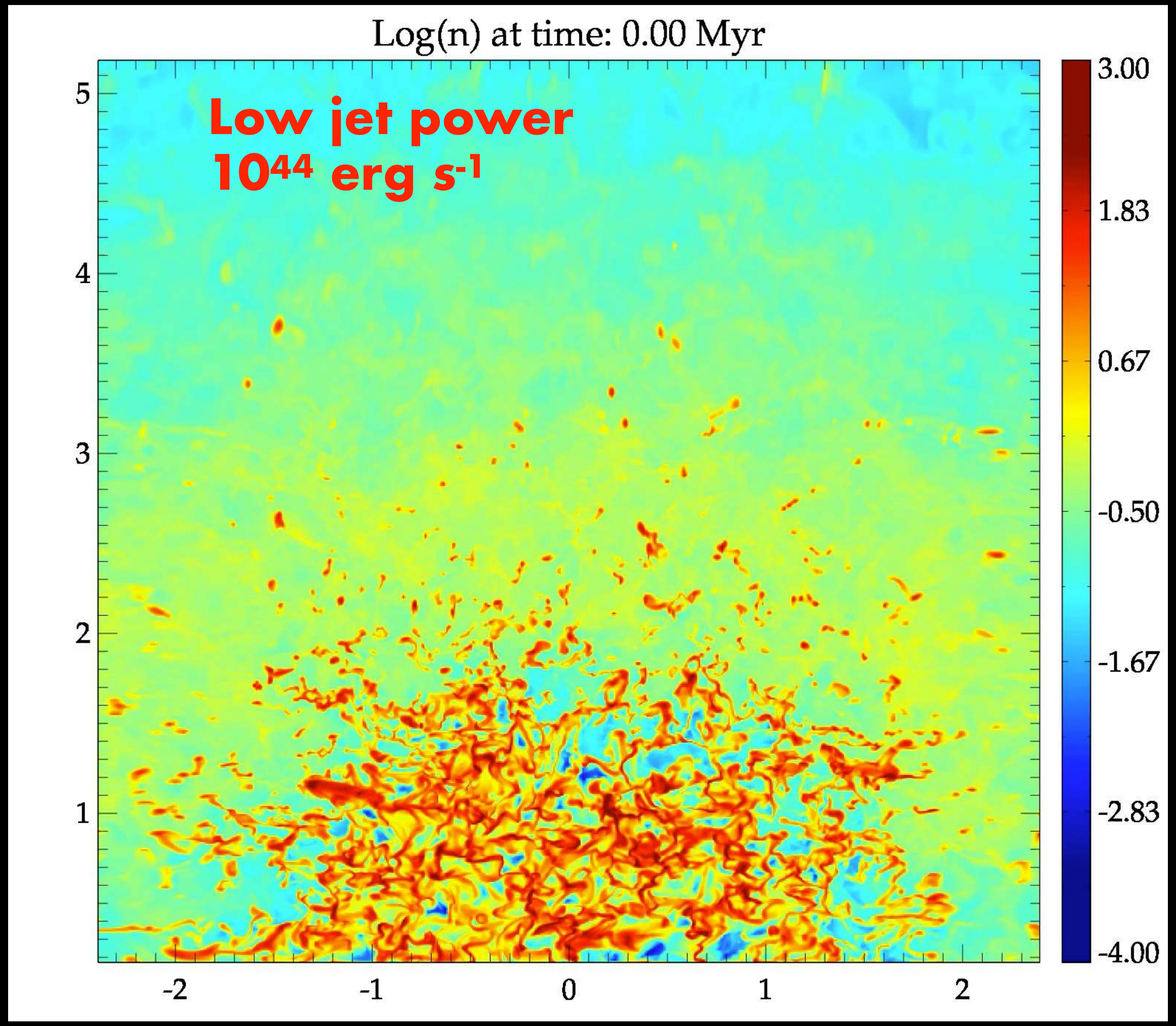
jet power

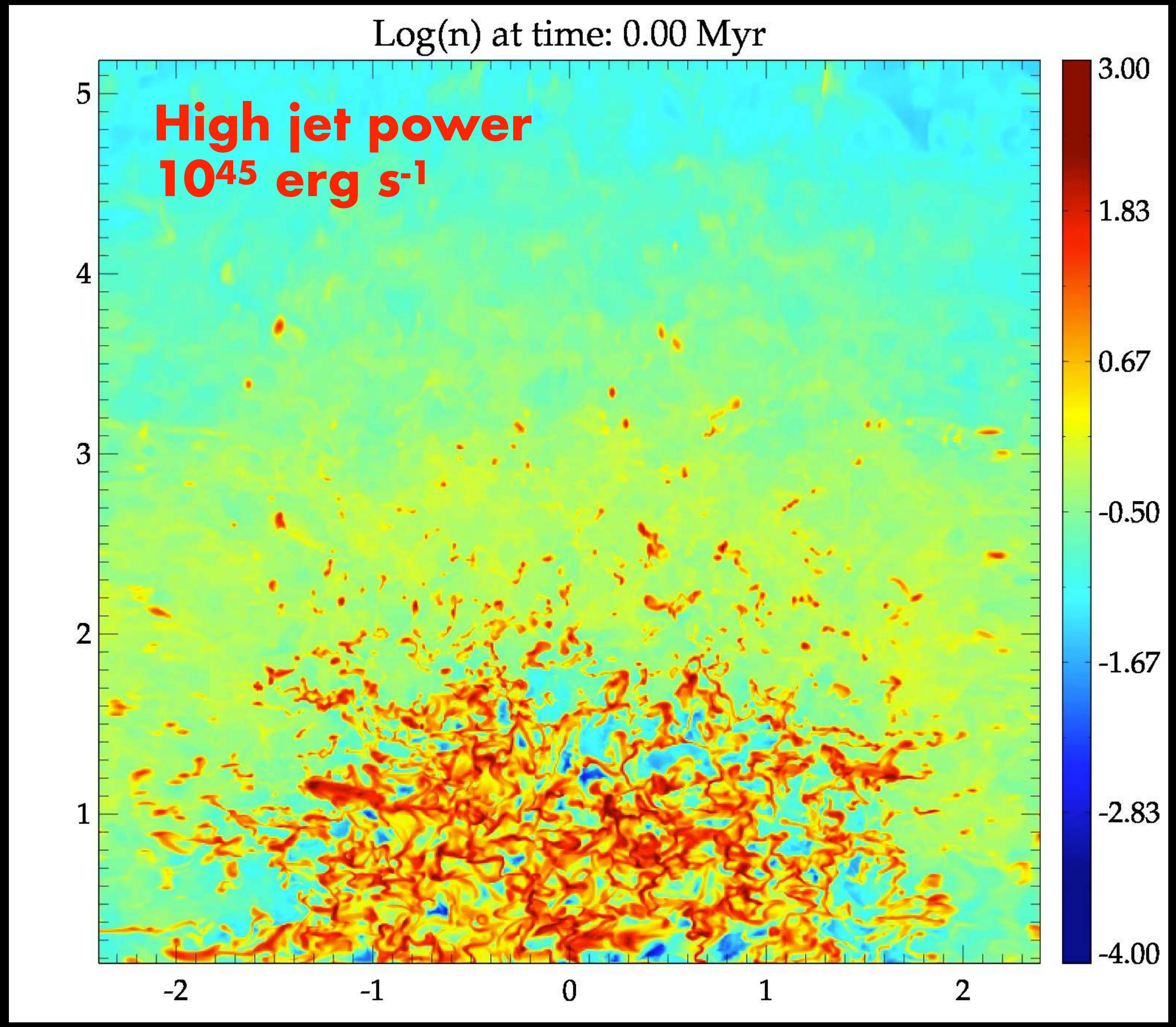
ages

10^8 yr

Effect depends on **jet power:**
low power jets are important!
Couple more with the ISM, will
induce more turbulence and
they are more numerous!

from Wagner & Bicknell 2011, 2012,
Mukherjee, Bicknell et al. 2016, 2017, 2018





$<10^6$ yr

10^{21} radio quiet 10^{23} 10^{24} 10^{25} 10^{26} radio loud W/Hz

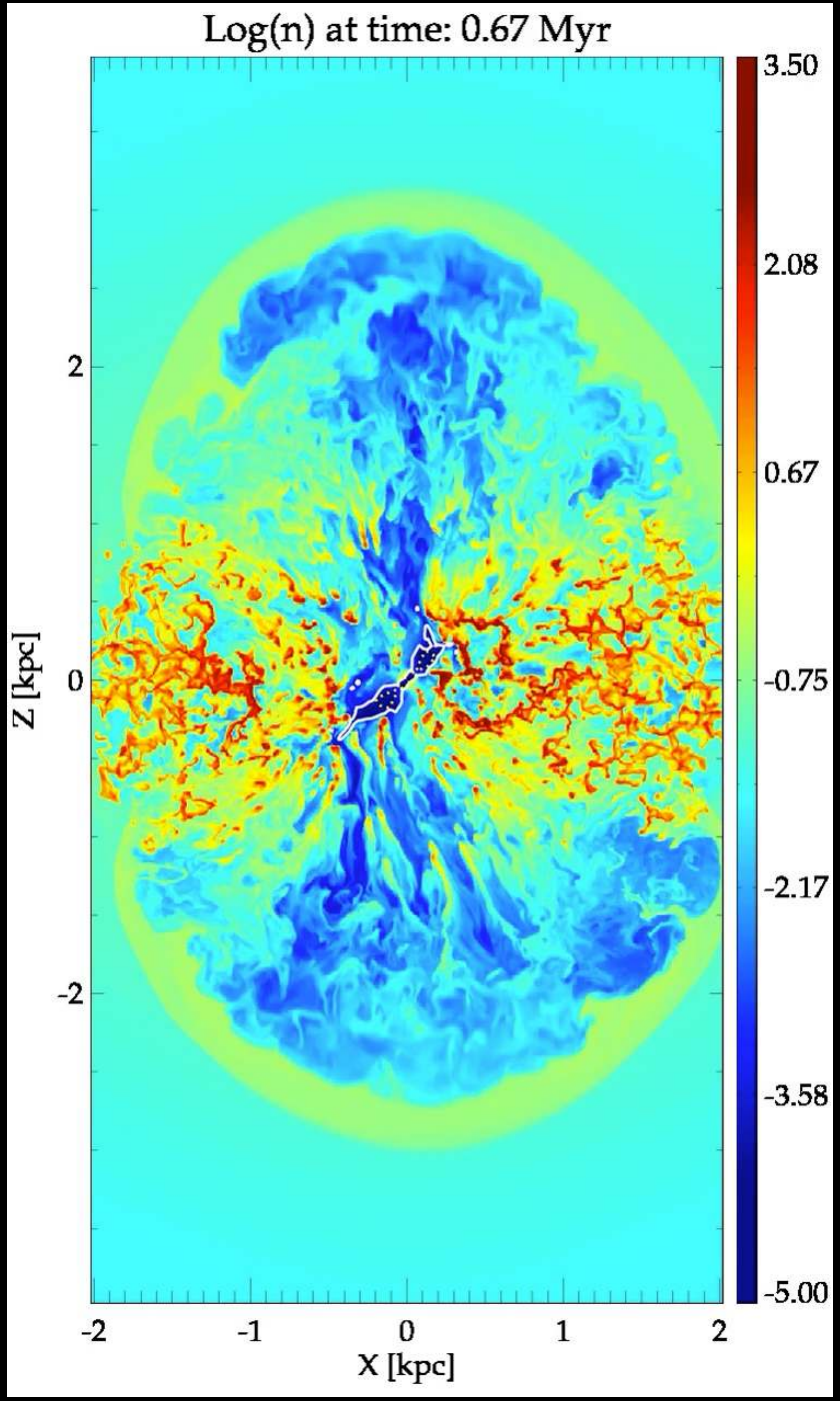
More numerous,
interacting longer with ISM

radio power
jet power

A complex parameter space to explore!

jet orientation

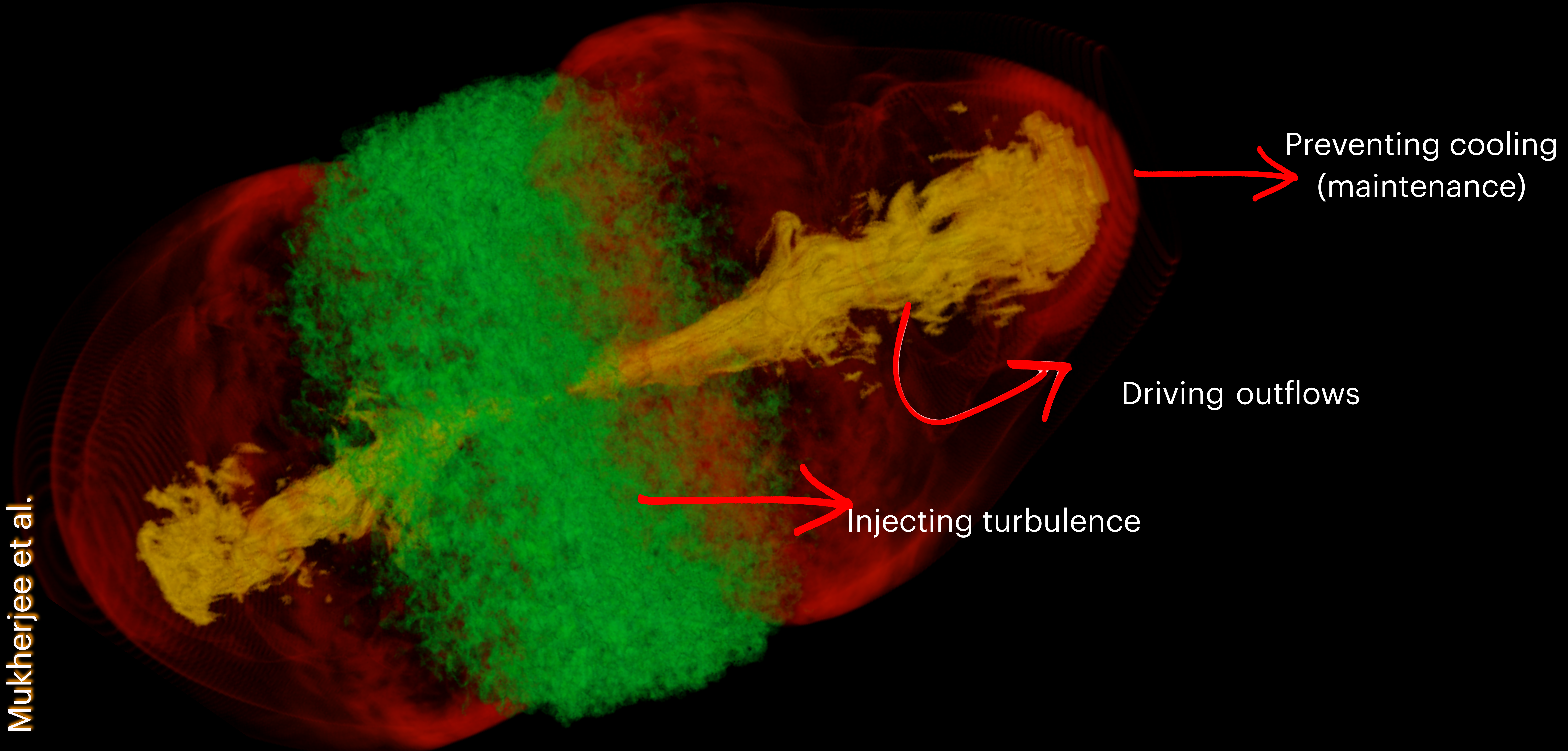
- Orientation of the jet wrt gas distribution



Mukherjee et al. 2017, 2018

clumpy medium in a disk

In summary: multiple ways in which a jet can impact the interstellar medium of the host galaxy, including producing outflows



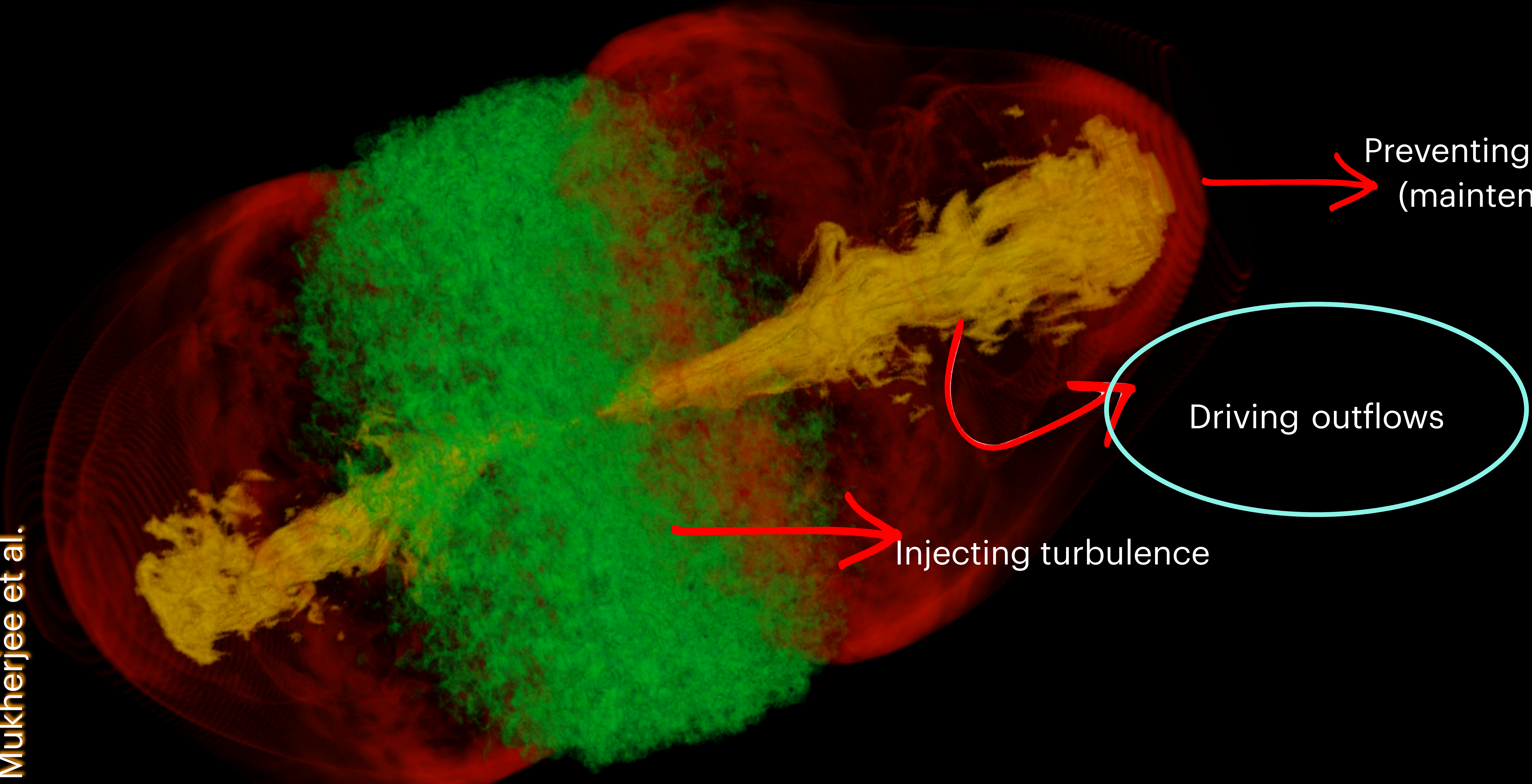
Preventing cooling
(maintenance)

Driving outflows

Injecting turbulence

Mukherjee et al.

In summary: multiple ways in which a jet can impact the interstellar medium of the host galaxy, including producing outflows



Preventing cooling
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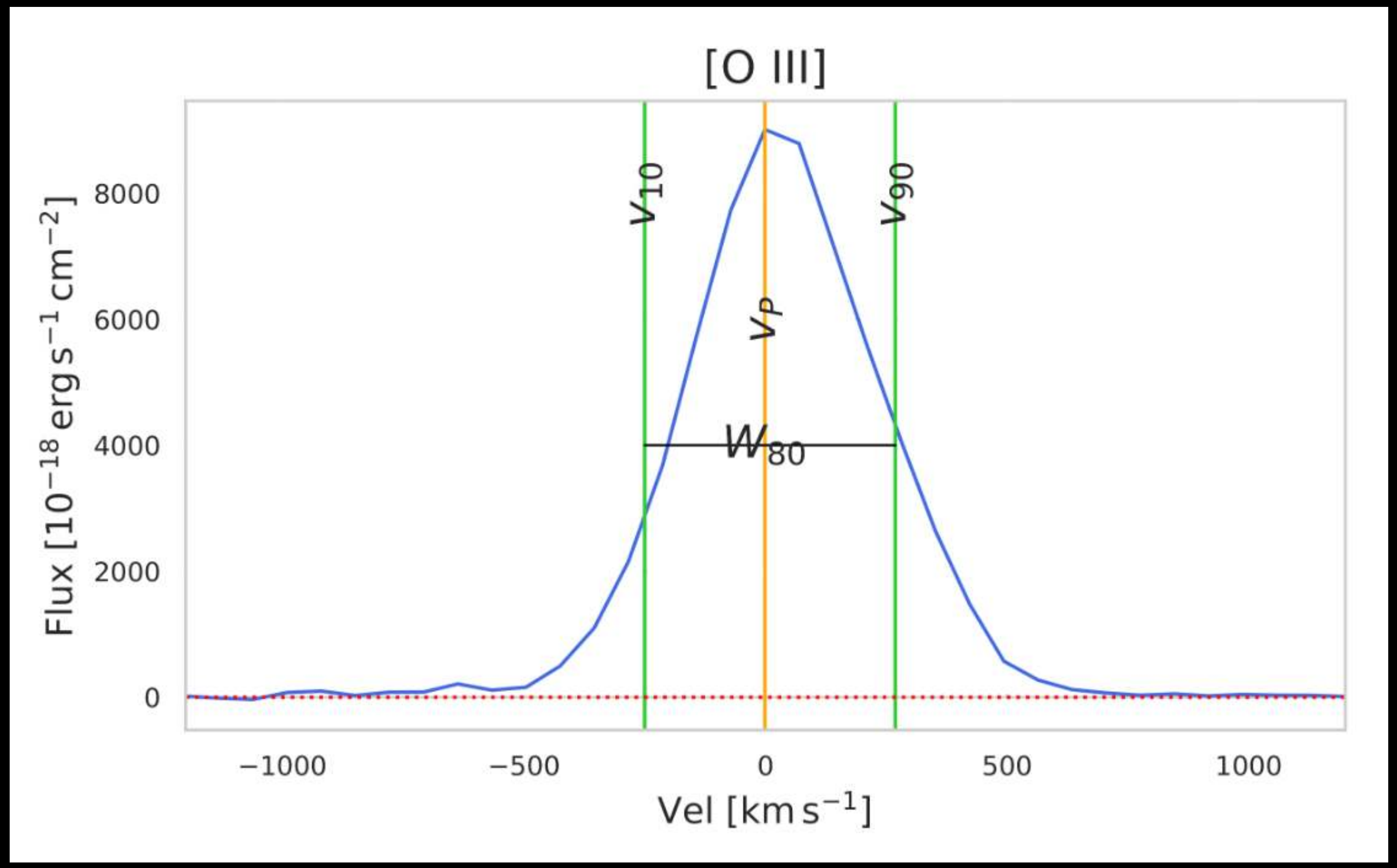
Mukherjee et al.

Parameters that can be derived (I)



Speranza et al. 2021

Outflowing gas: gas with kinematics deviating from quiescent e.g. regularly rotating, typically identified by broad wings in emission/absorption lines

- location, velocity, density of the outflow
- velocity higher than escape velocity?

Mass outflow rate $\dot{M}_{out} \propto \frac{M_{out} v_{out}}{r_{out}}$

Mass outflow rate

Kinetic power $\dot{E}_{kin} \propto \frac{\dot{M}_{out}}{2}(v_{out}^2 + \sigma_{out}^2)$

Velocity dispersion outflow

other formula have also been used, see Harrison et al. 2018 Nat Astr for more about parameters of the outflows

Parameters that can be derived (II)

- L_{edd} and L_{bol} of the AGN

  $L_{edd} = 1.26 \times 10^{38}$ x BH mass (erg/s)

  L_{bol} ➔ bolometric luminosity of the AGN

Ratio of the two gives indication of Eddington rate of the accretion

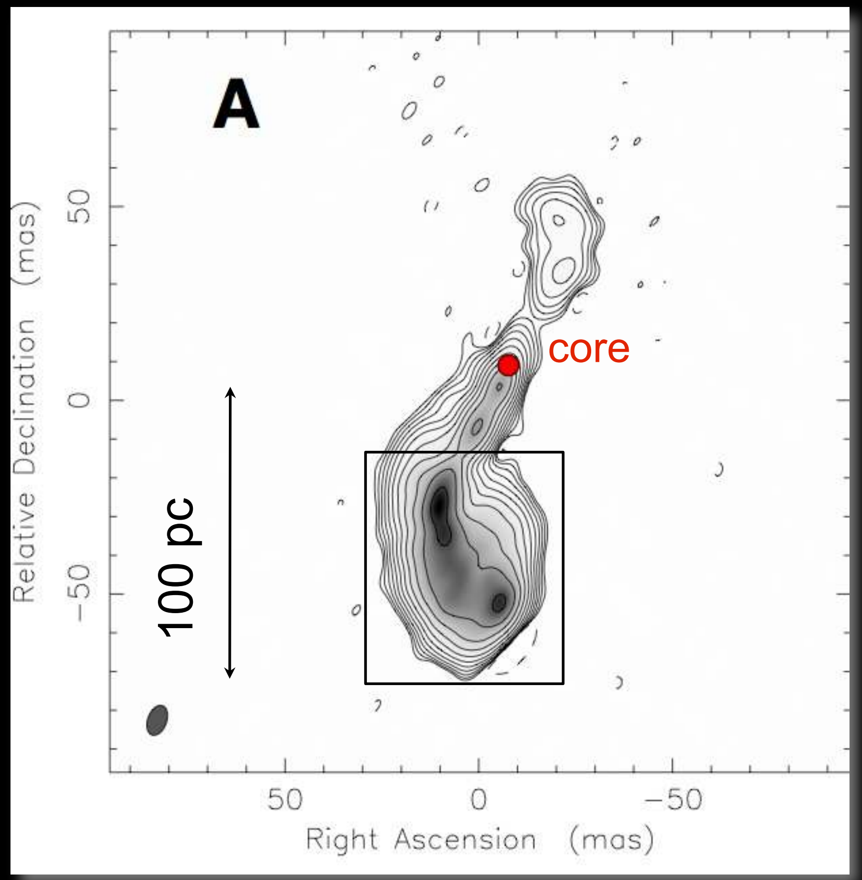
Kinetic energy of the gas outflow should be a significant fraction of the bolometric luminosity if effective in preventing, e.g. the growing on the SMBH, or even larger to affect star formation in the host galaxy

Kinetic energy of the outflow to be compared to L_{edd} and L_{bol}
➔ models of galaxy formation requires about 5% of Edd luminosity in outflows

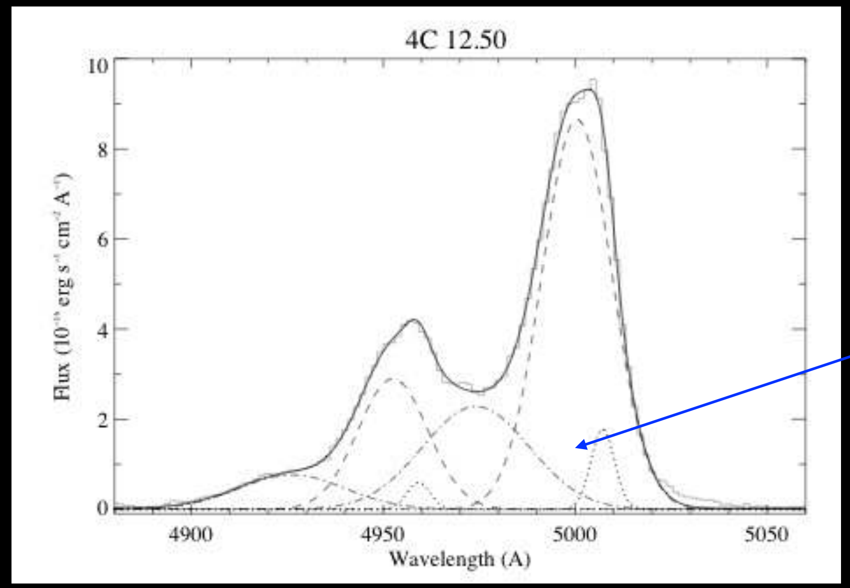
Mass outflow rate can be compared with star formation rate in the galaxy
➙ although not a direct indication of quenching of star formation (different time scales)

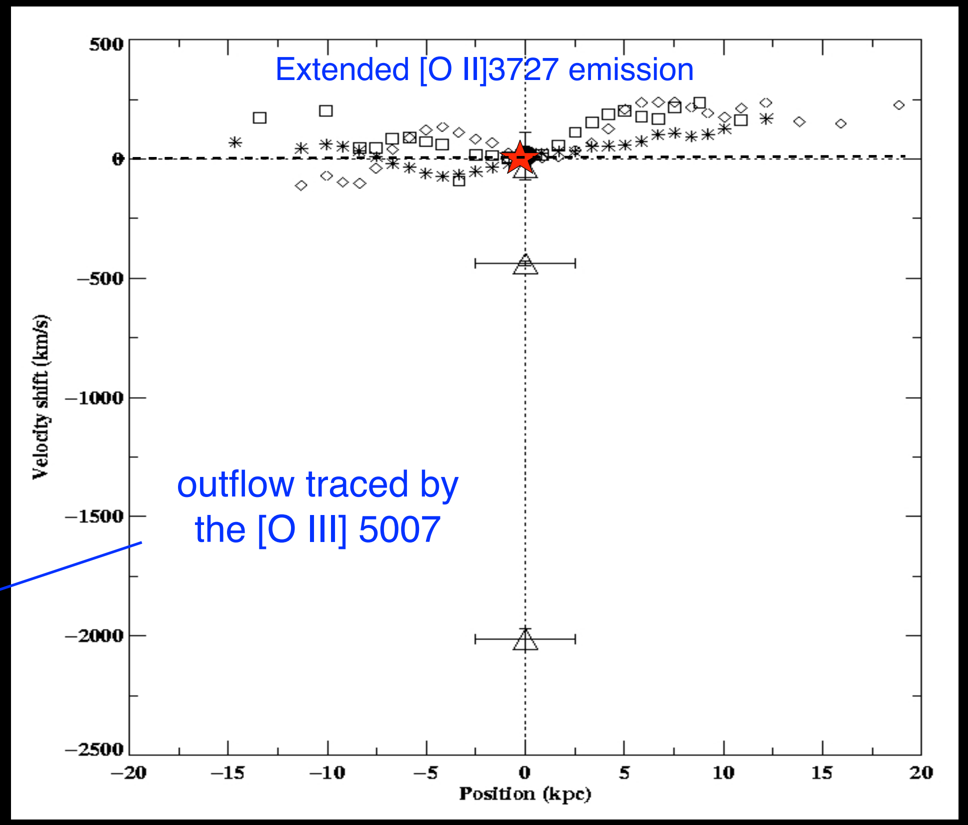
Radio jets known to affect the ISM since long time....

young radio source 4C12.50

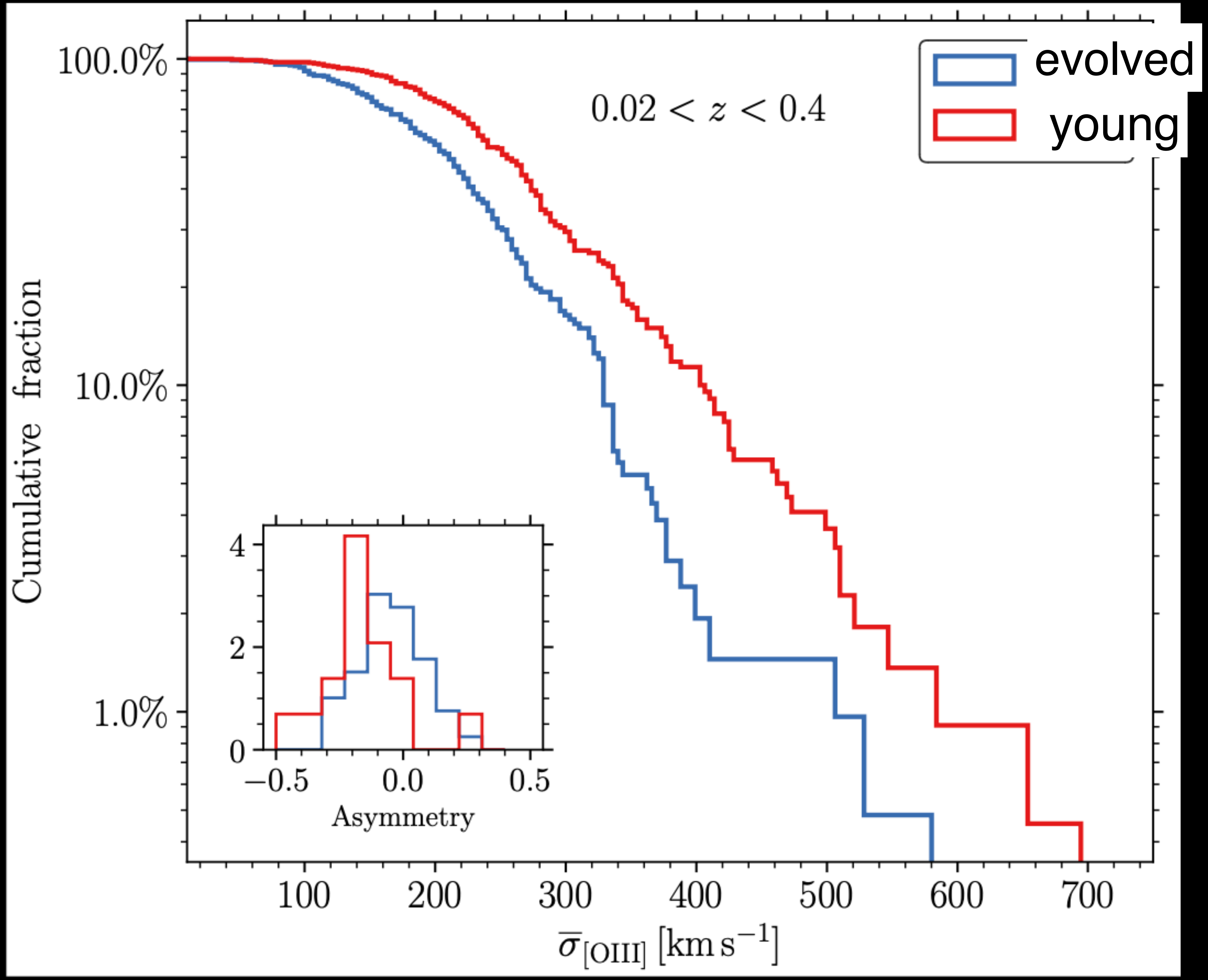


[OIII]





Holt et al. 2007, 2011



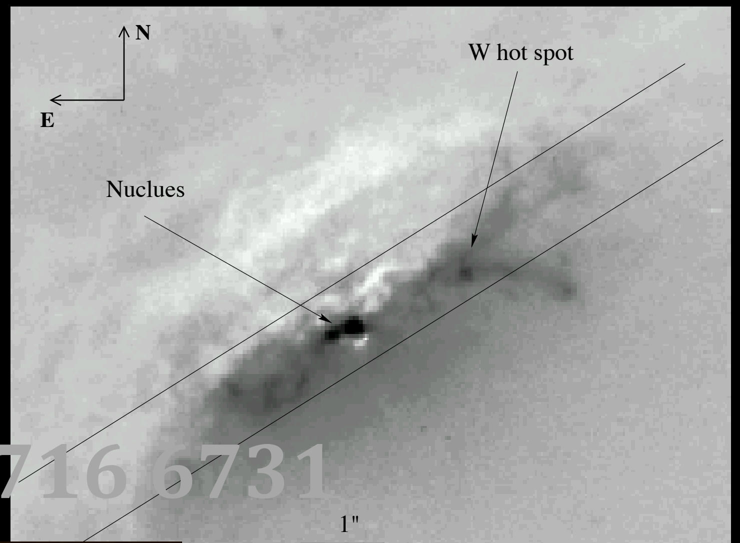
Kukreti et al.

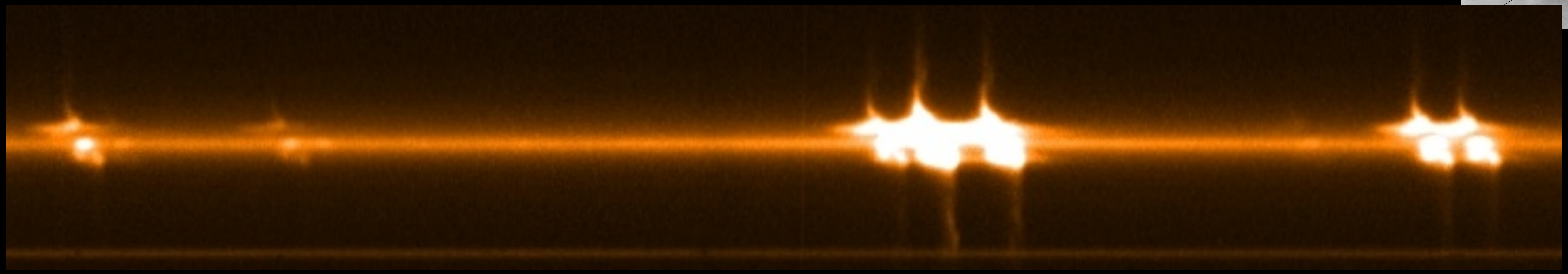
outflows larger and more common in young (or restarted) radio galaxies
many studies available

(see O'Dea & Saikia 2022 for a review of young radio sources)

Outflows in warm (ionised) gas

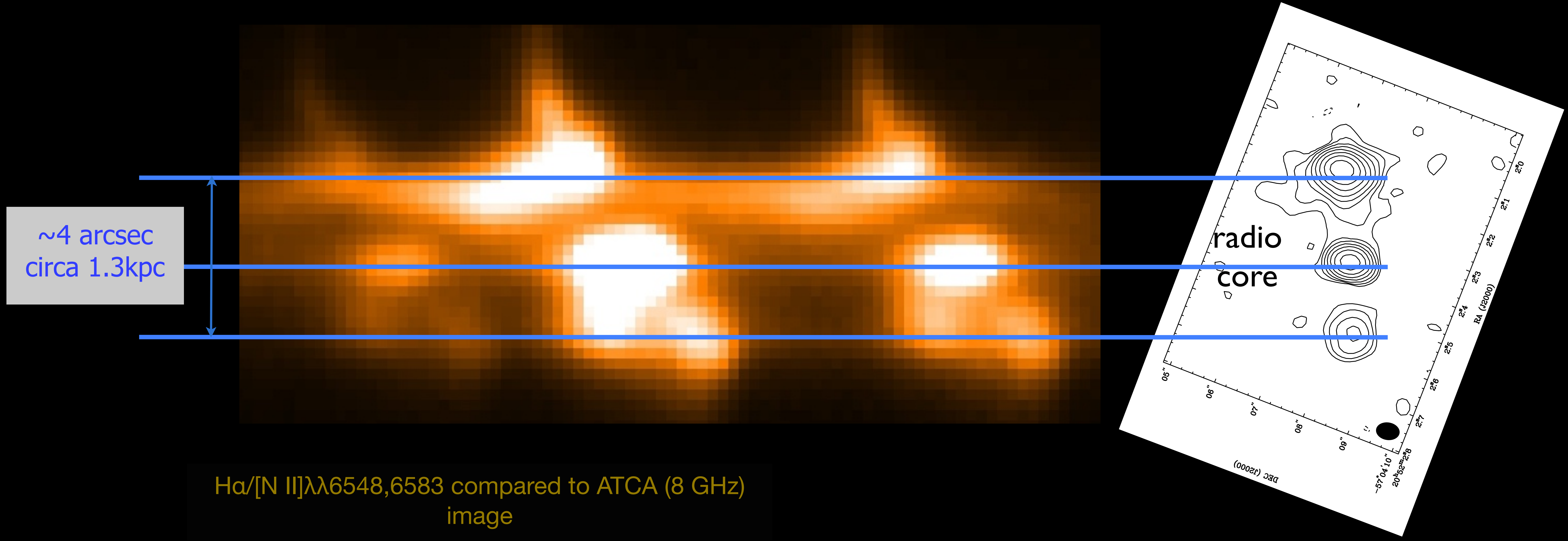
most of the studies on this phase of the gas….





part of 2D spectrum (red)

pix scale: 0.27 arcsec/pix



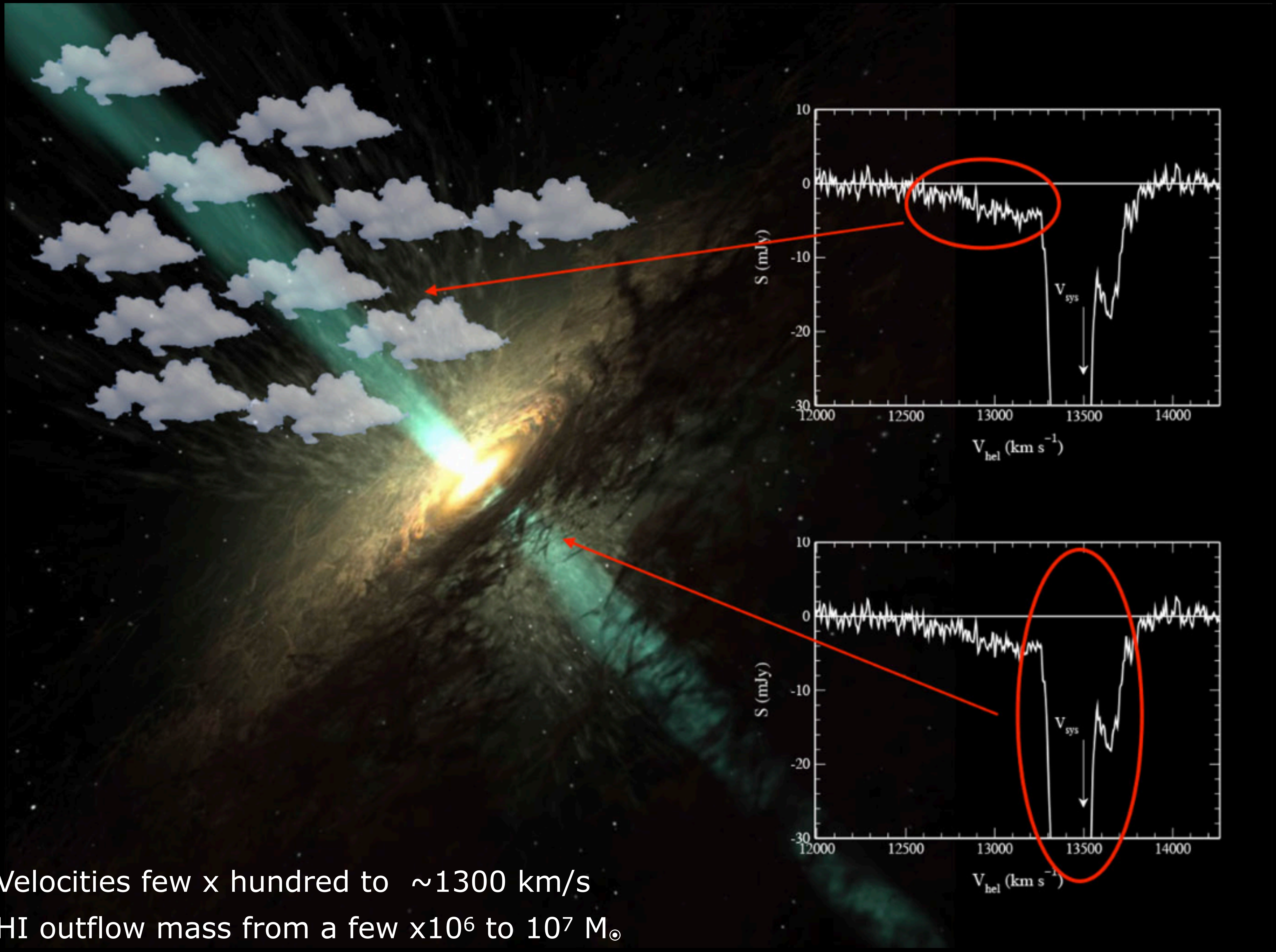
Hα/[N II]λλ6548,6583 compared to ATCA (8 GHz) image

IC5063 - Holt et al.

…but mass of the gas in the outflow of ionised gas very modest, fraction of $M_\odot$/yr

The discovery that cold gas can also trace outflows!

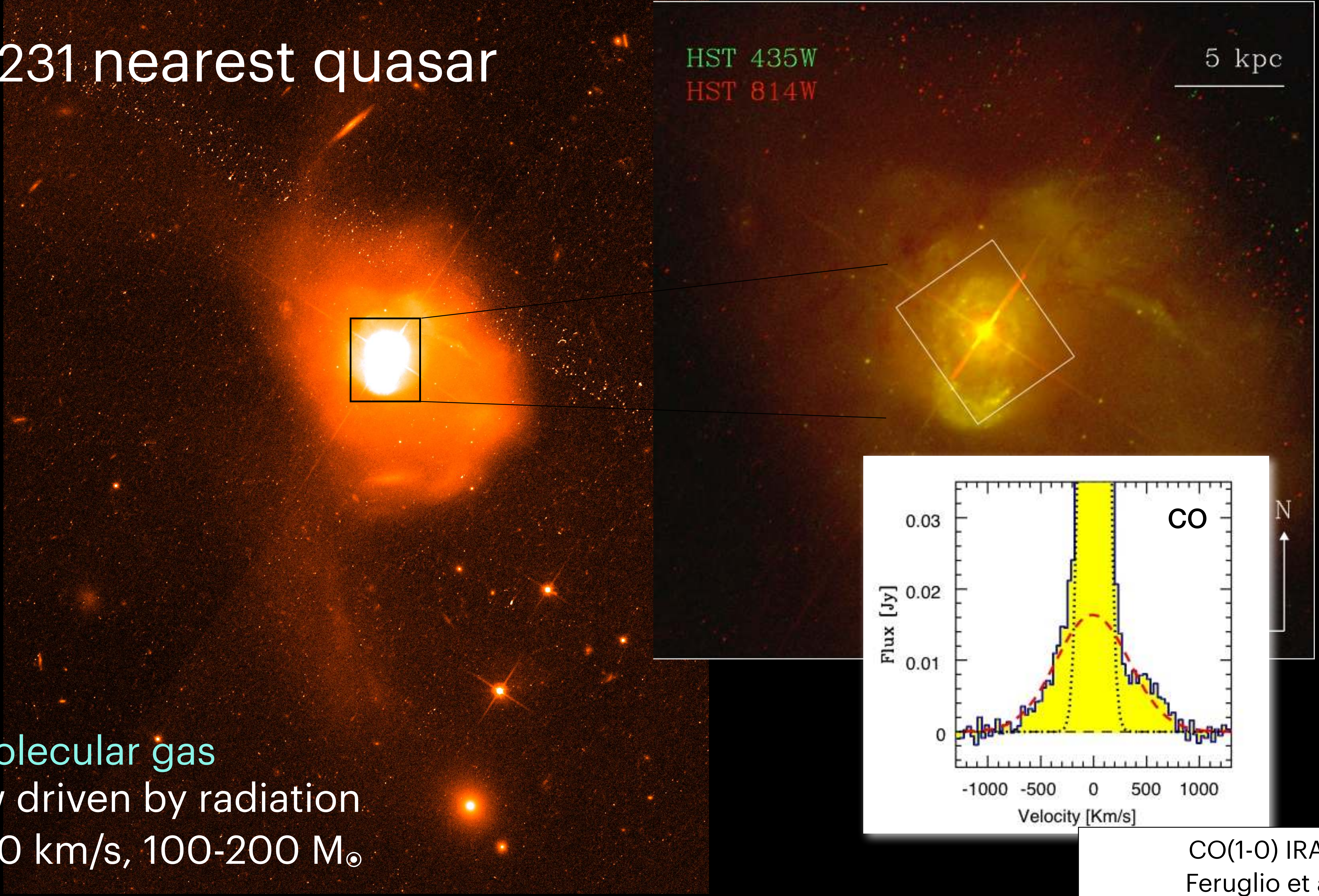
Morganti et al. 2005, Morganti & Oosterloo 2018



HI absorption outflow driven by a jet

- Velocities few x hundred to ~1300 km/s
- HI outflow mass from a few $x10^6$ to 10^7 $M_\odot$
- Mass outflow rate ➔ a few to ~ 30 $M_\odot$/yr

Mrk 231 nearest quasar



CO(1-0) IRAM PdBI
Feruglio et al. 2010

cold molecular gas
outflow driven by radiation
of ~1500 km/s, 100-200 $M_\odot$

- how can HI and cold molecular gas be present in such harsh environments?

Gas outflows are multi-phases but in the last years the cold gas has become more relevant

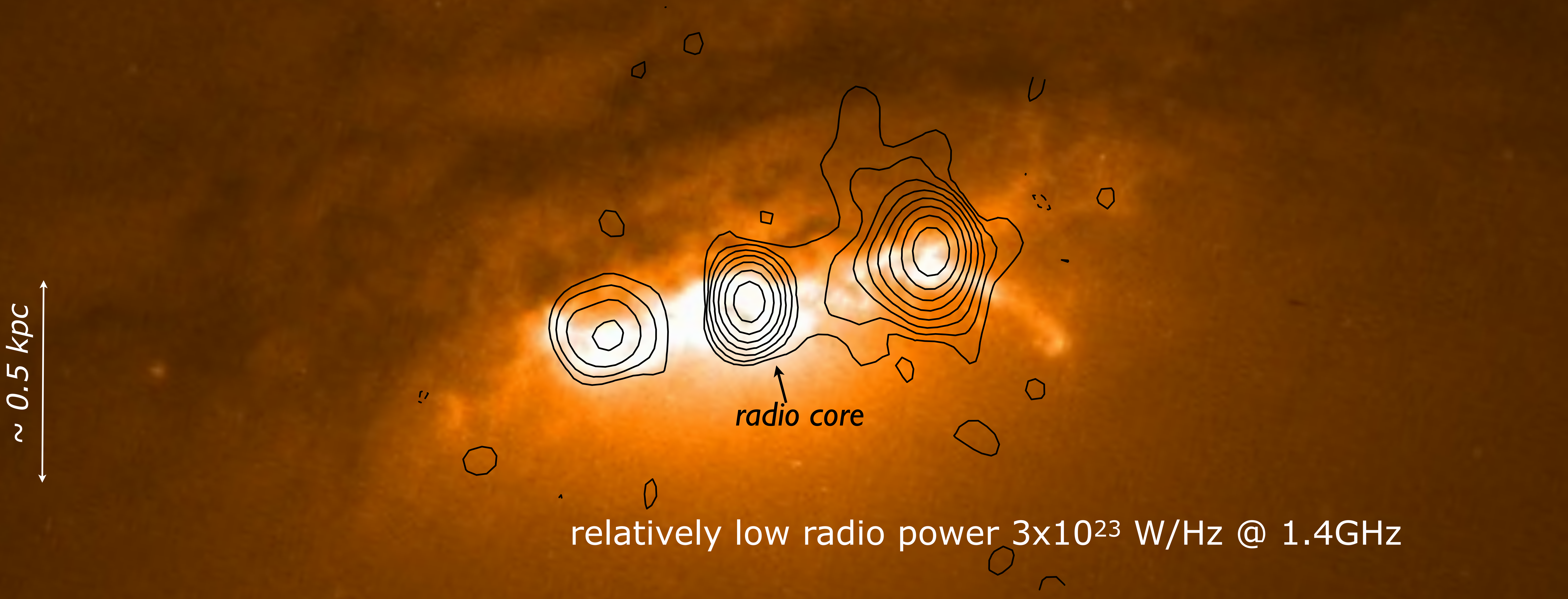
could be the most massive component of outflows and contribute most to feedback

⇩

major role of ALMA very high spatial resolution can be reac
the interaction jet/ISM can be studied in detail

Effect of radio jets
The case of IC5063

Seyfert 2 (similar to NGC1068) strong optical AGN and radio power 3x10^{23} W/Hz @ 1.4GHz



HST image and ATCA radio at 17GHz

relatively low radio power 3x10^{23} W/Hz @ 1.4GHz

Known multi-phase gas outflow (HI, ionised gas and warm molecular)

ALMA CO(2-1)

Cycle 1 - 31 antennas

0.6 arcsec resolution

Morganti et al. 2015

CO total intensity

noise 0.3 mJy/b/ch and 30 microJy continuum

ALMA CO(2-1)

Cycle 1 - 31 antennas

0.6 arcsec resolution

Morganti et al. 2015

CO wrapping around the continuum
Bright region close to the location
of the W hot-spot

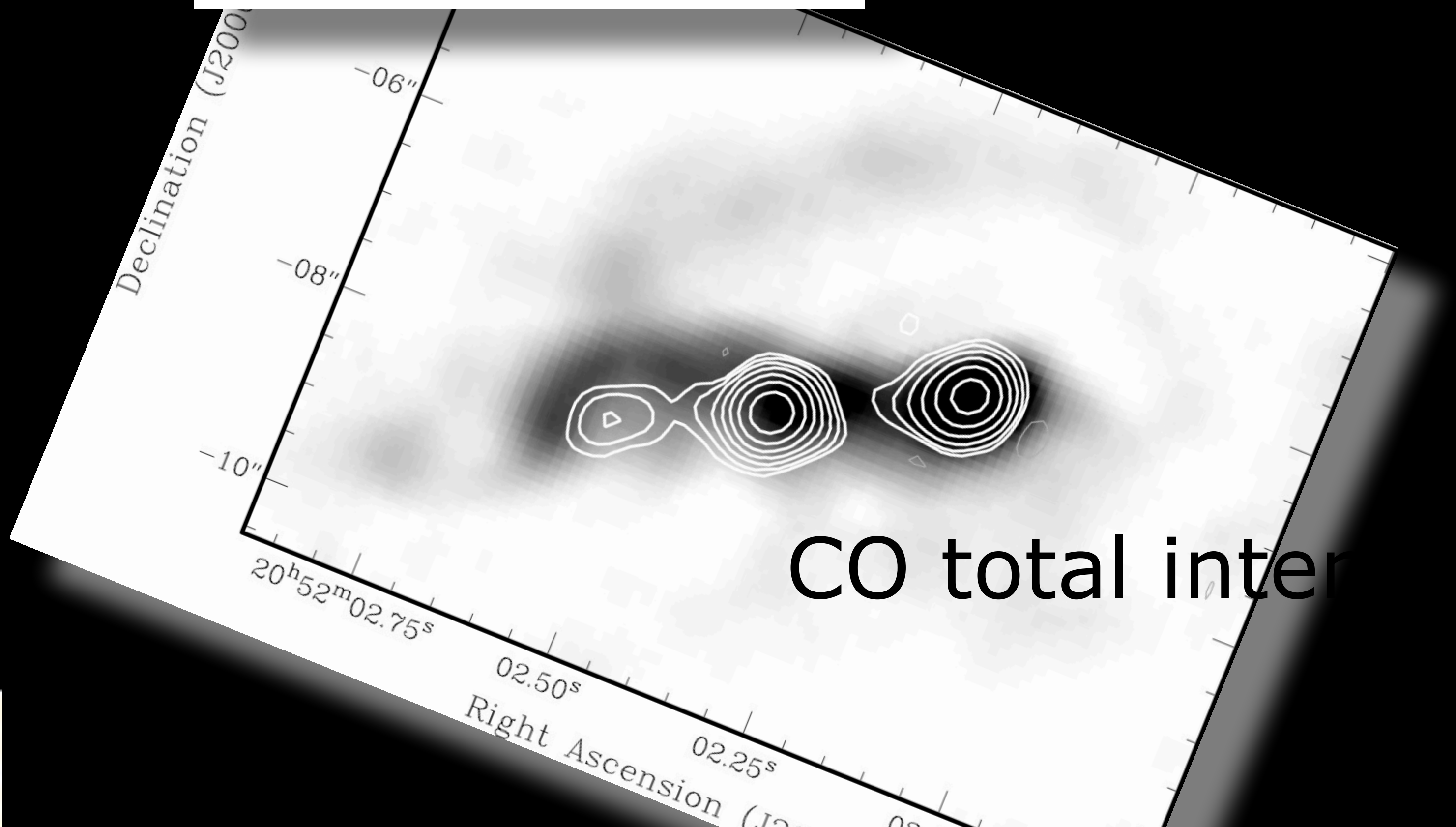
CO total intensity

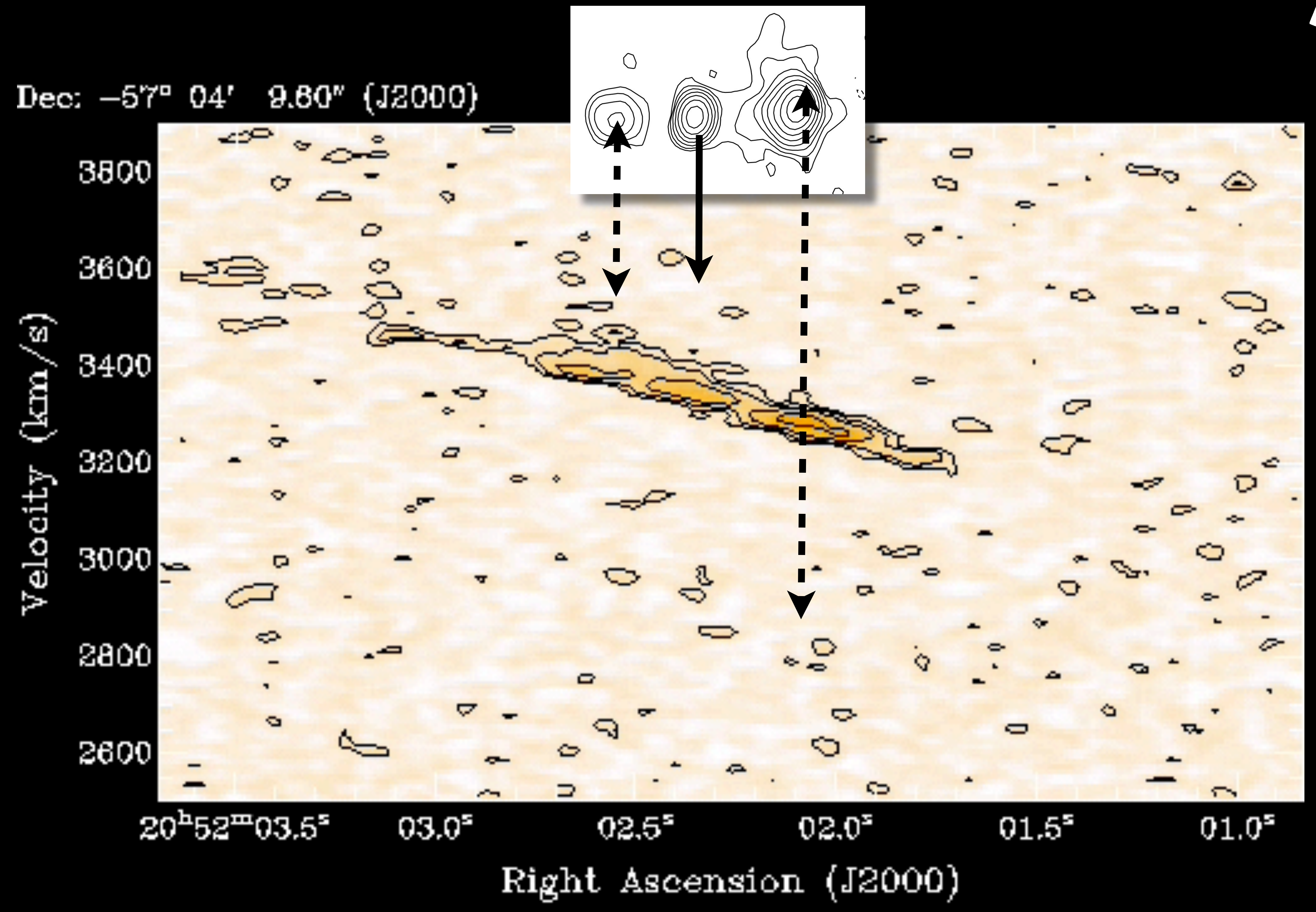
noise 0.3 mJy/b/ch   and 30 microJy continuum

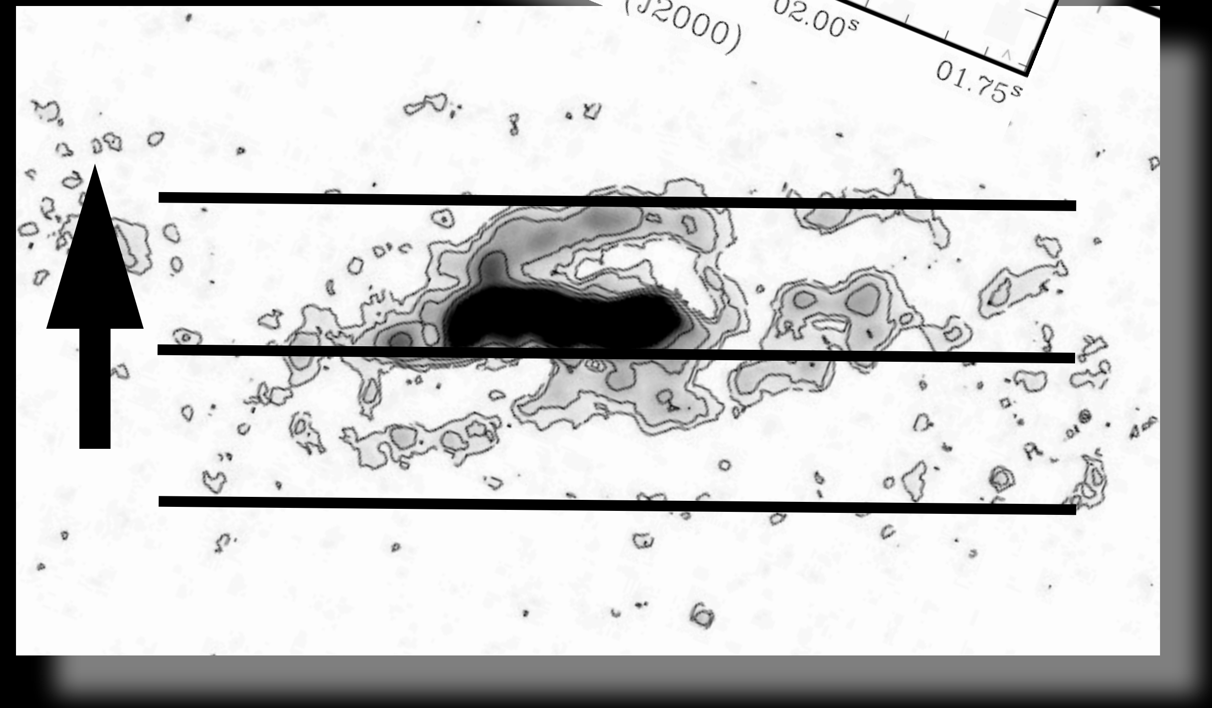
ALMA CO(2-1) - 0.6 arcsec resolution

illustrating the full complexity of the kinematics of the molecular gas

CO total intensity(grey)
+radio
continuum(contours)





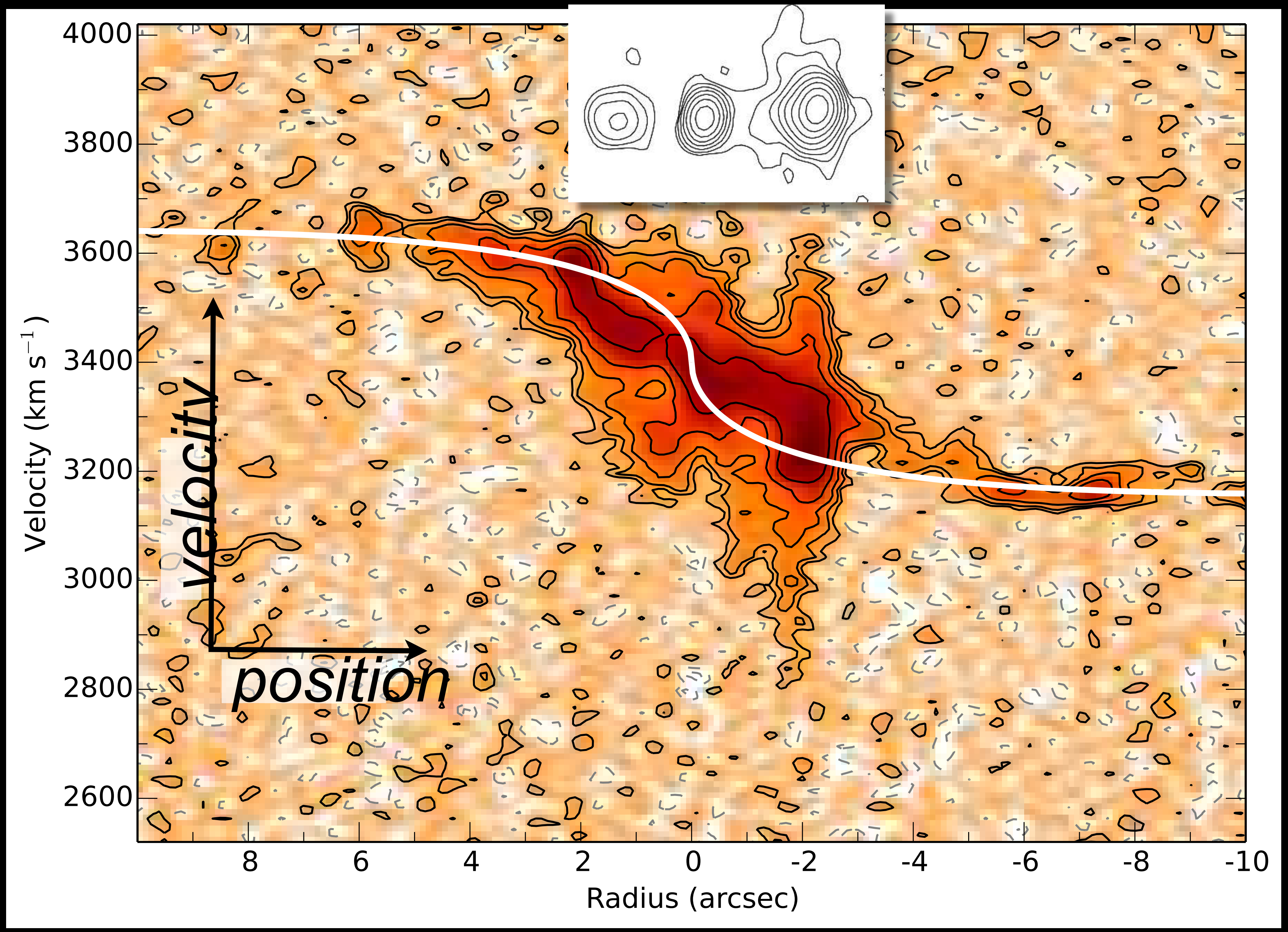


radio source rotated in EW direction to more easily slice along major axis.

position-velocity plot at the along the radio axis

IC5063 - ALMA CO(2-1) Morganti et al. 2015

Kinematically disturbed molecular gas all along the radio jet



rotation curve from photometry overplotted

- Mass outflow rate: molecular gas ~ 12 - 30 $M_\odot$/yr
- ionised gas ~ 0.08 $M_\odot$/yr
- Outflow kinetic power (HI + CO) ~ 8 x 10^{42} erg s^{-1}
- AGN bolometric luminosity L_{bol} ~ 2 - 7.6 x10^{44} erg/s
- Jet power Q_{jet} ~ 9 x10^{43} - 7 x10^{44} erg/s

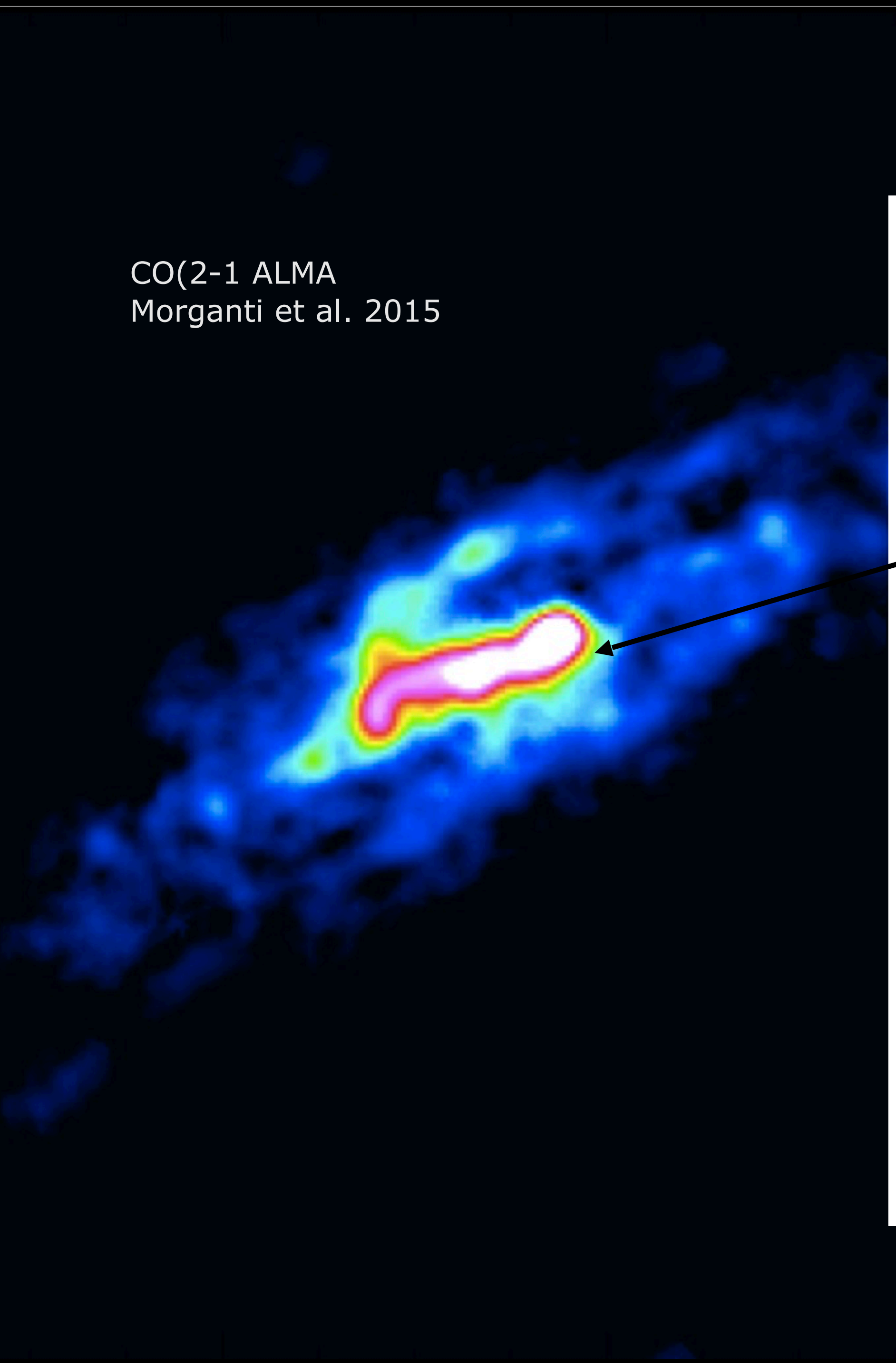
mass of the cold molecular outflow ~ 10^7 M_{sun}

➔ much higher than the warm H_2 and [OIII] and somewhat larger than of the HI outflow

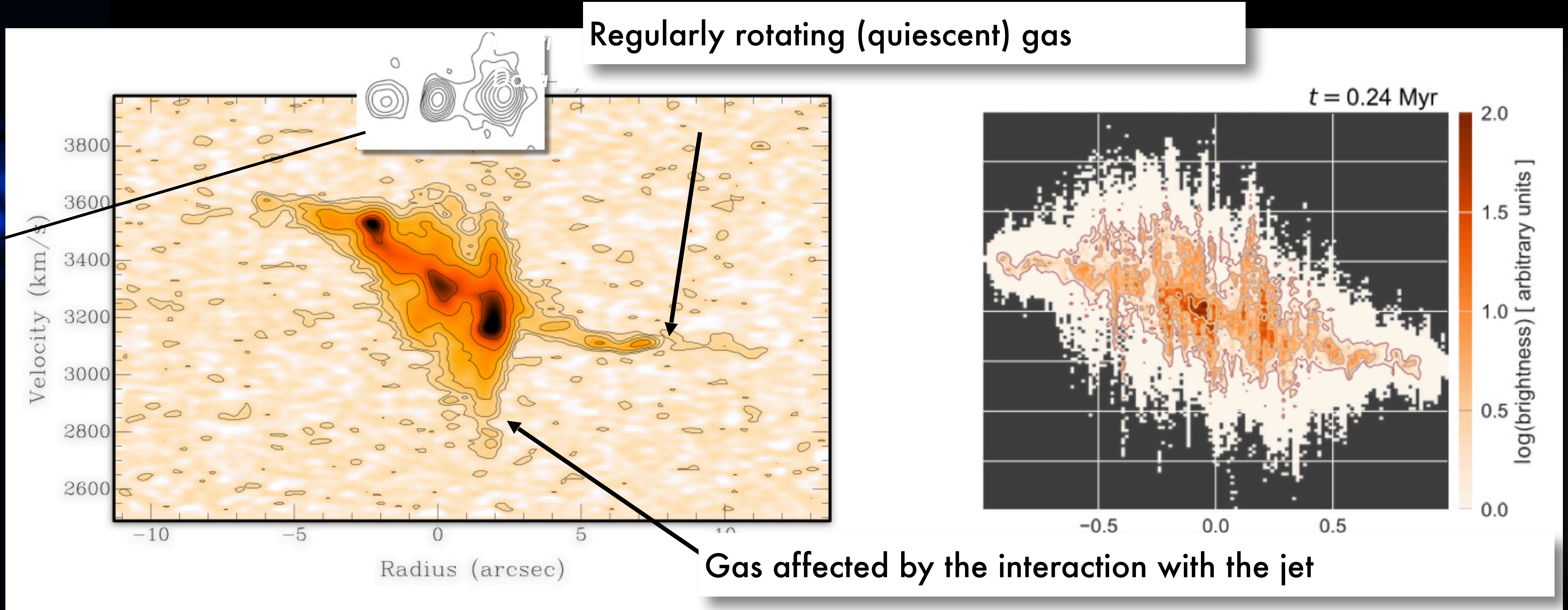
➔ most of the cold molecular outflow is due to fast cooling after the passage of a shock

but only a small fraction of the gas will actually leave the galaxy: mostly raining back

IC5063: showing the impact of (low power) jets ...



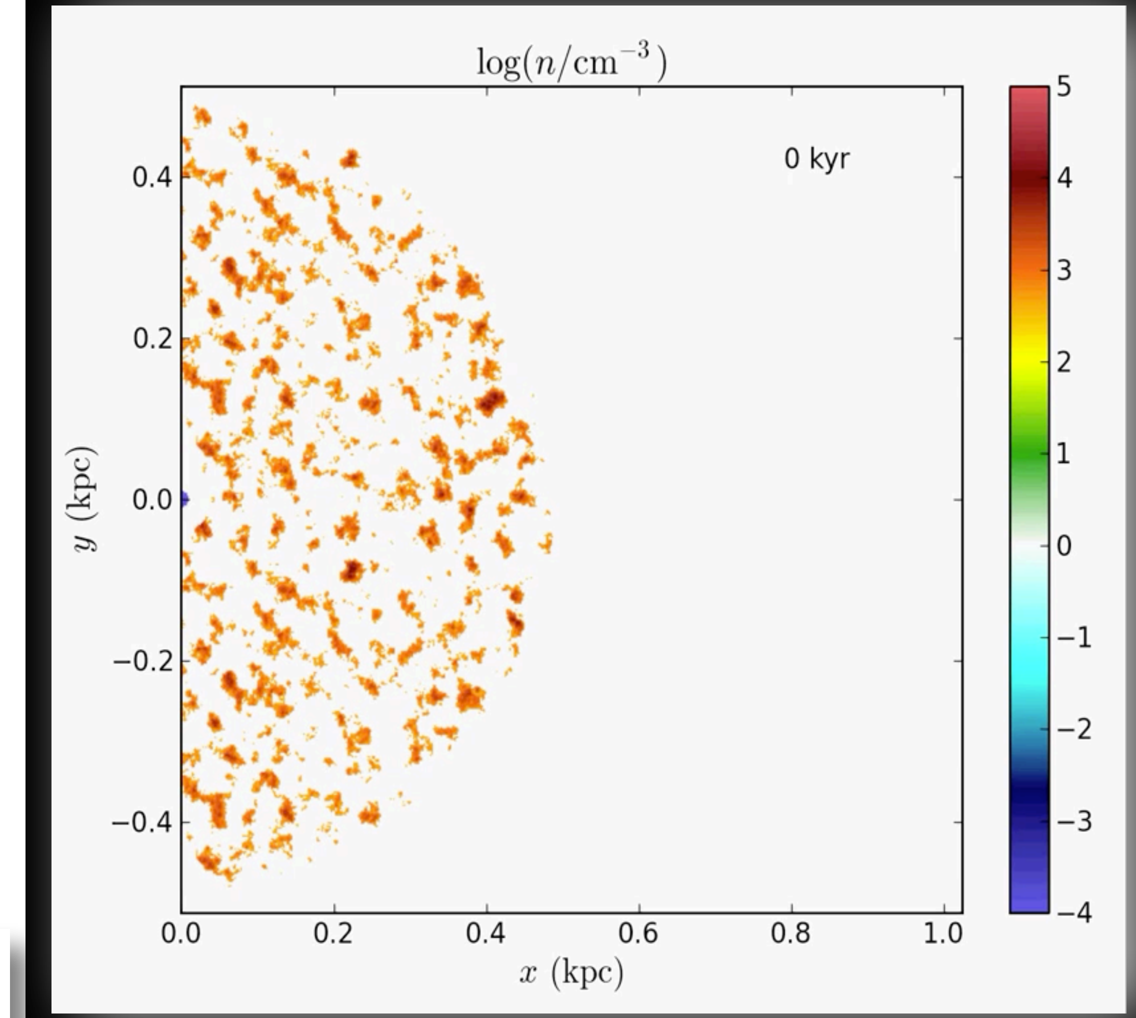
CO(2-1 ALMA
Morganti et al. 2015



Regularly rotating (quiescent) gas

Gas affected by the interaction with the jet

Wagner & Bicknell 2012



Mukherjee, Wagner, Bicknell, Morganti et al. 2018

Outflows of molecular gas found in a growing number of objects: this phase represents the most massive component of the outflows
➝ resulting from gas rapidly cooling after being dissociated by the interaction

Many cases of massive outflows driven by jets (based on spatial coincidence), including low-power (radio-quiet) jets

but the outflows are limited to region < 1 kpc in size!

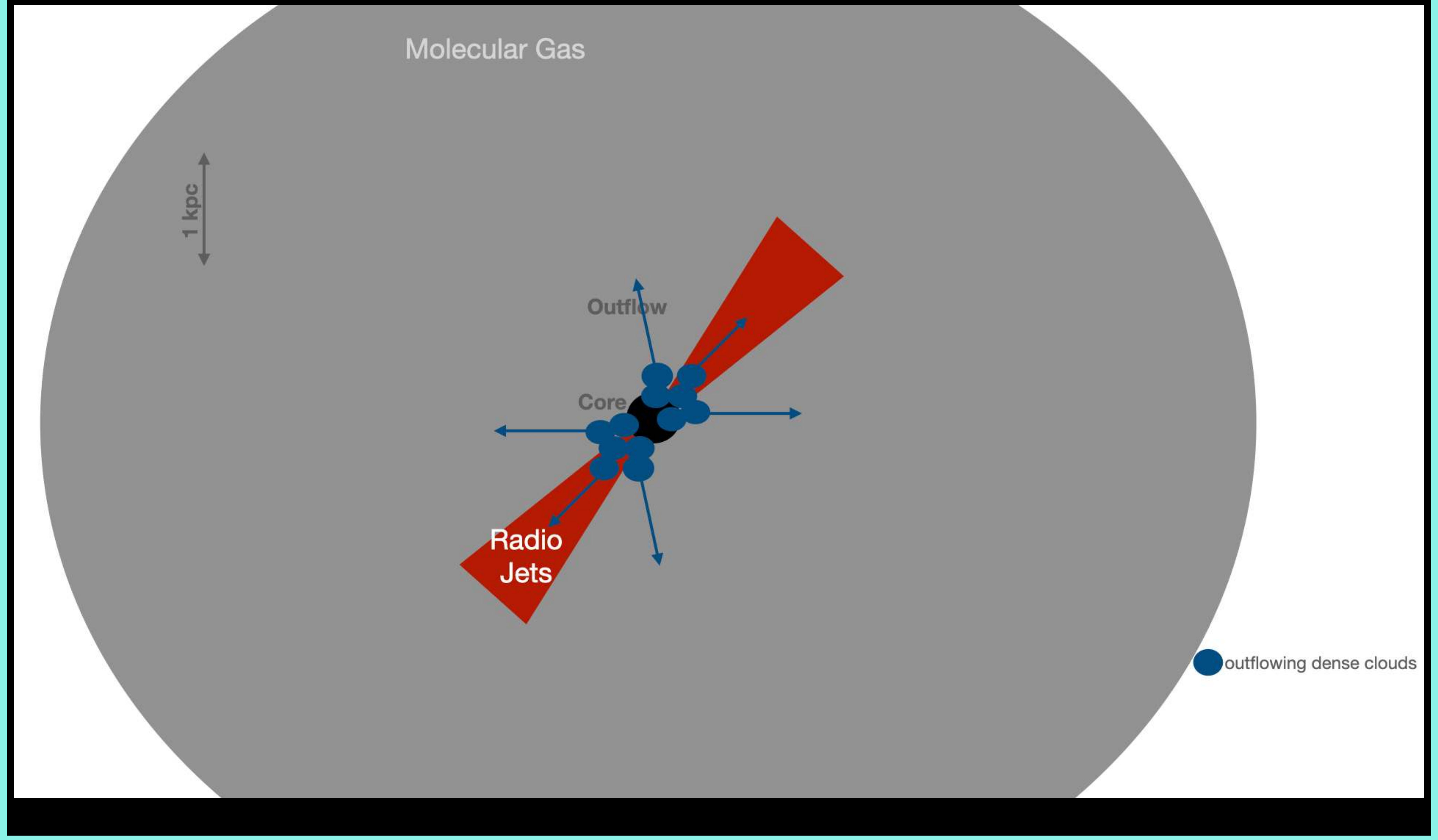
⇩

Outflows **are not the whole story** in order to provide the negative feedback required by cosmological simulations

A possible scenario: not only outflows …

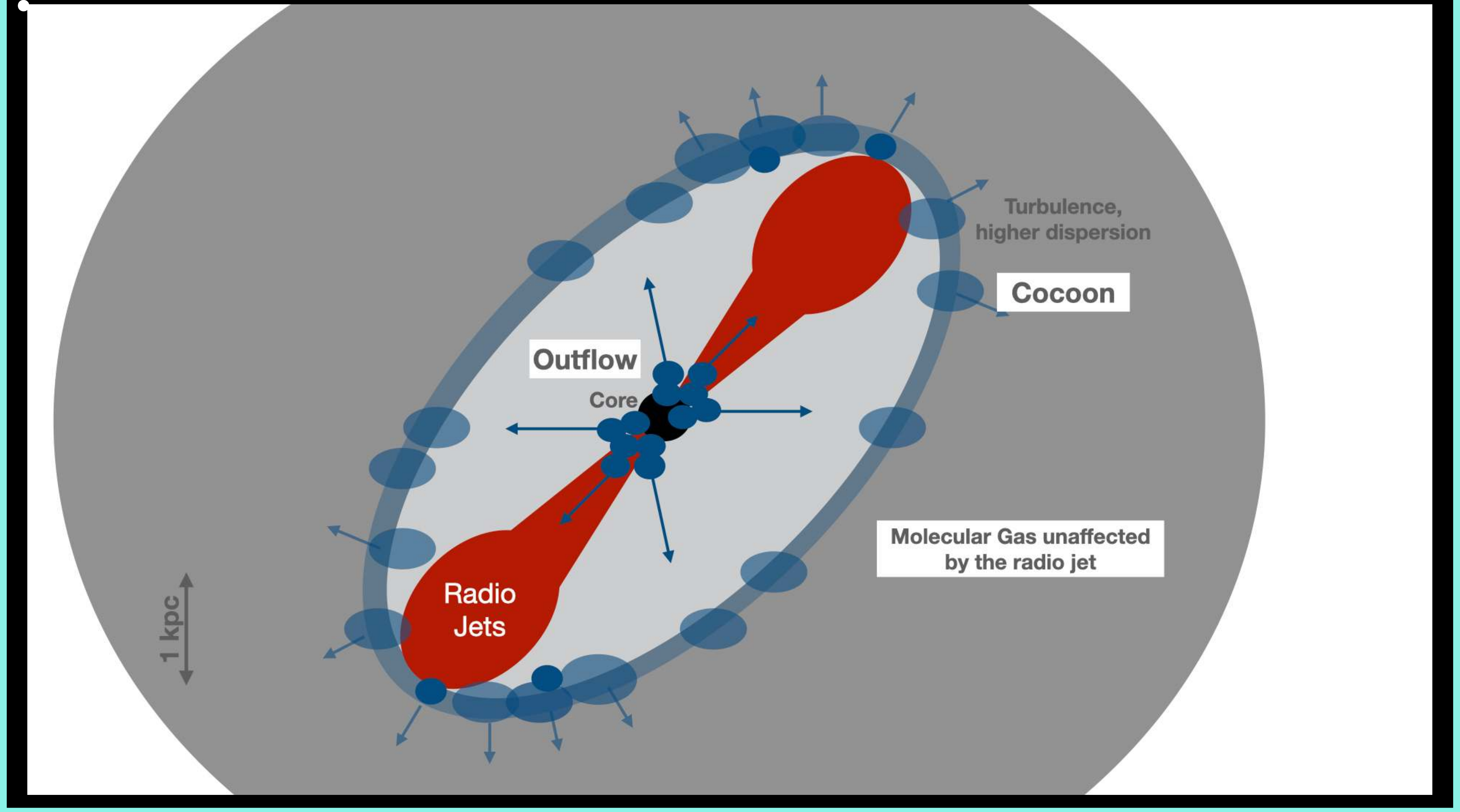
consistent with predictions from simulations
of jet-ISM interaction
transition from *outflows* to *maintenance* mode

- **In the inner, sub-kiloparsec, region** the main effect is the **direct interaction** with the newly born jet (fast cooling of the dense gas)



- **Larger distances: the coupling between the radio plasma and the ISM changes**
- Jet drives mild shocks creating a cocoon of shocked gas: molecular gas interacting with the (slowing) expanding jet cocoon

→ increasing turbulence



Final remarks....

- AGN are considered to play a key role in galaxy evolution but not all aspects of how this happens are clear

- AGN-driven outflows are common but their properties do not appear to fully match the requirements from simulations ➙ many different at high redshift?

- While trying to understand this, we are learning **a lot** of new things about AGN: for example the presence of outflows of cold/molecular gas!

- Radio jets, including low luminosity (radio-quiet) sources, are now recognised to play a role. The connection between evolutionary stage and impact may suggest a more complex interplay than what implemented in the simulations

Future….

- Importance of multi-wavelength observations: surveys/databases/archives allow you to do this more easily than ever before

- When possible, select samples in areas with many ancillary data - a growing number is becoming available: it can save a lot of time and troubles!!
  Build on the work of others to move forward!

- Radio AGN (continuum emission) ➙ I focused on LOFAR, i.e. northern hemisphere where most of the radio astronomy has been done so far (NVSS, FIRST 1.4GHz surveys etc.) but in the southern telescopes like MeerKat are becoming available:
  a lot of potential for future projects…

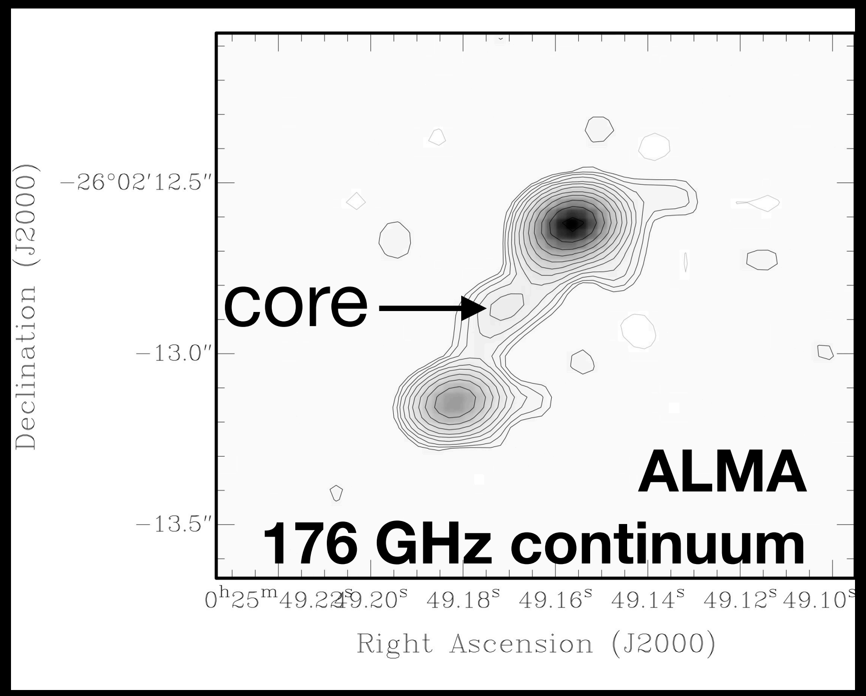
- ALMA (studies of the gas) ➙ enormous potentials by tracing the molecular gas with very high spatial resolution (and by using the many molecular lines available): key for a detailed localisation of the disturbed gas and ond comparison e.g. with radio

PKS 0023-26 view by ALMA

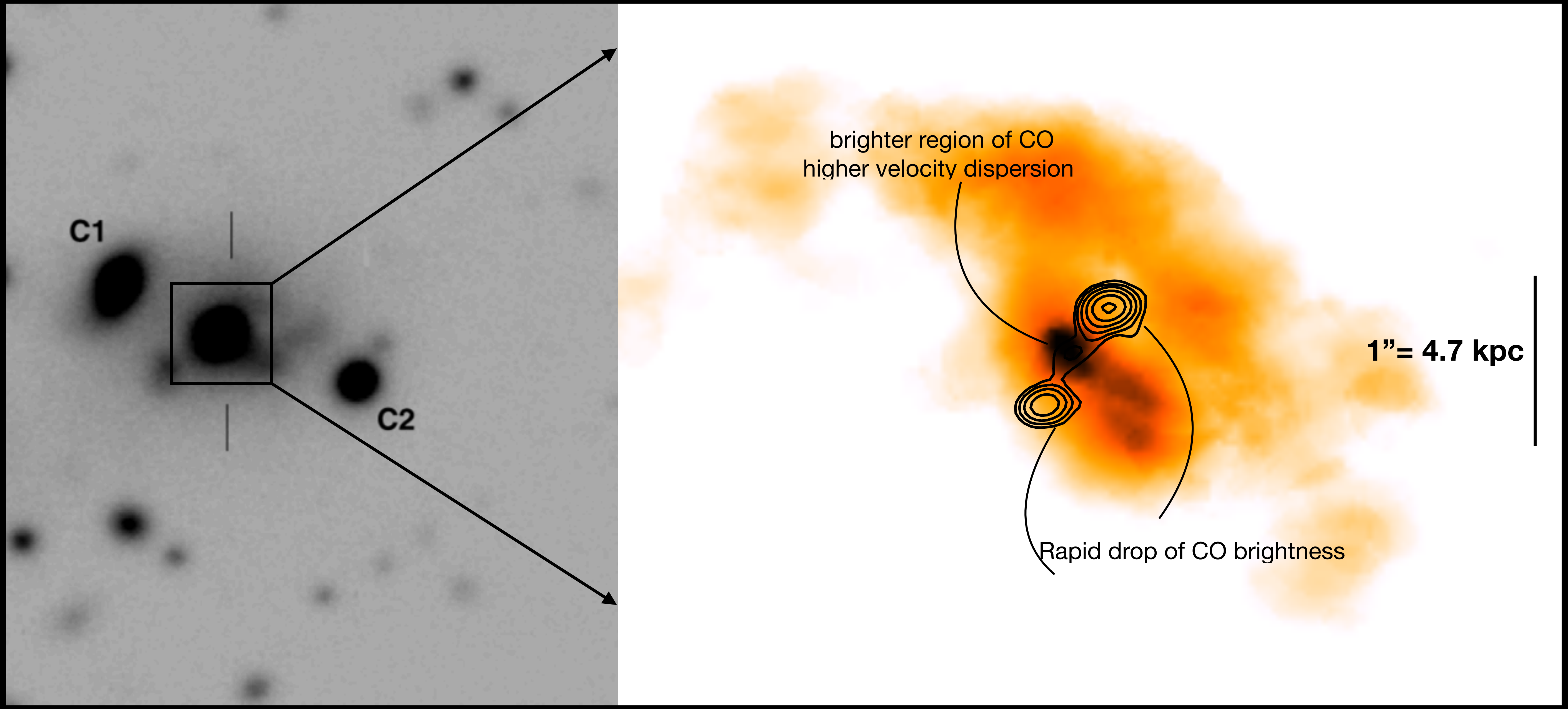
(z = 0.321)

Young but **evolved** powerful jet (~ 4 kpc)
Also powerful optical AGN
Ideal system for the study of the impact of the (radio) AGN on "galactic" scales

radio continuum



ALMA view: CO(2-1), 0.2 arcsec resolution

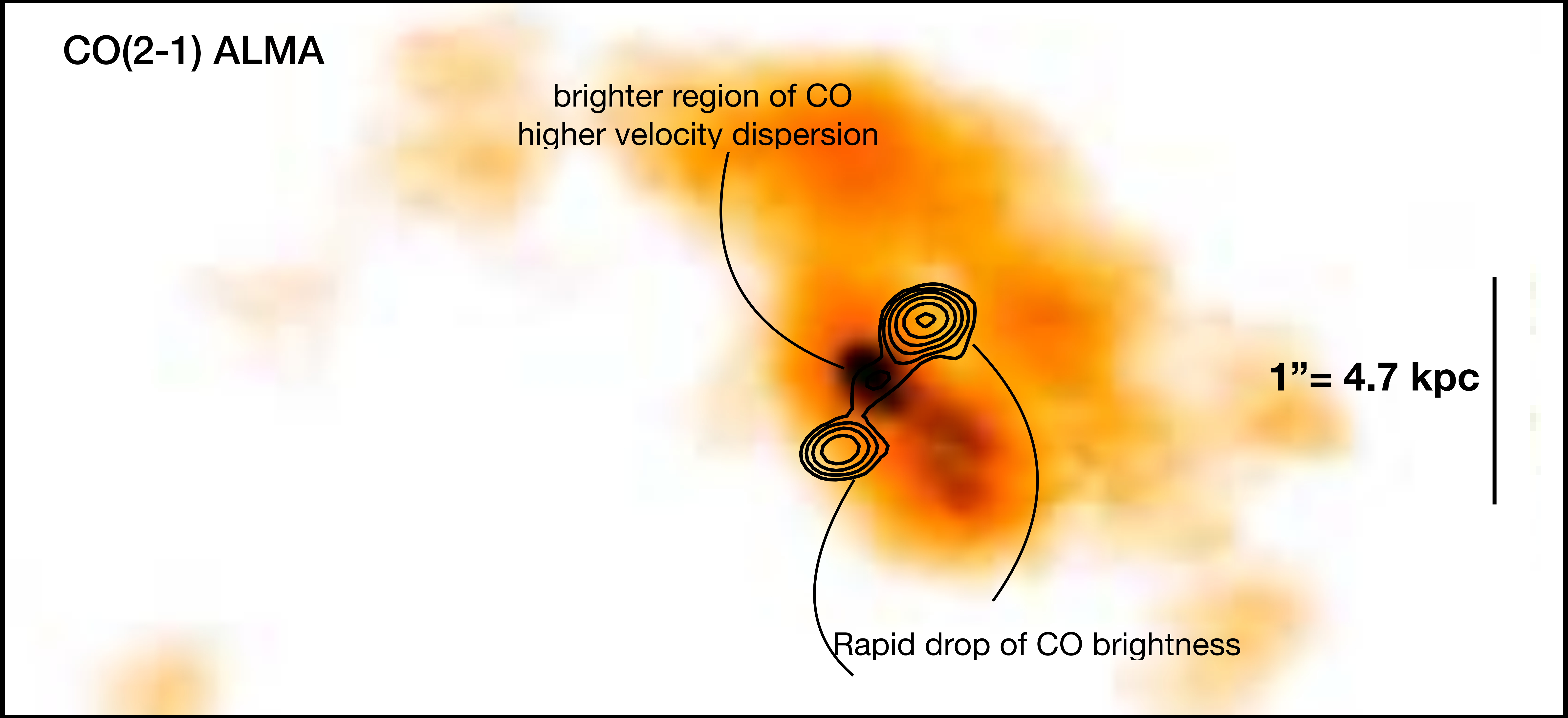


Morganti et al. 2021

- Total mass of molecular gas:
  3×10^{10} $M_\odot$ for $\alpha_{CO} = 4.3$ $M_\odot$ (K km s^{-1} $pc^2)^{-1}$
  → distributed on ~20 kpc, with tidal streams
- Bright central region of molecular gas
  → piling up of gas or effect of higher excitation due to AGN
- Low brightness at the location of the lobes

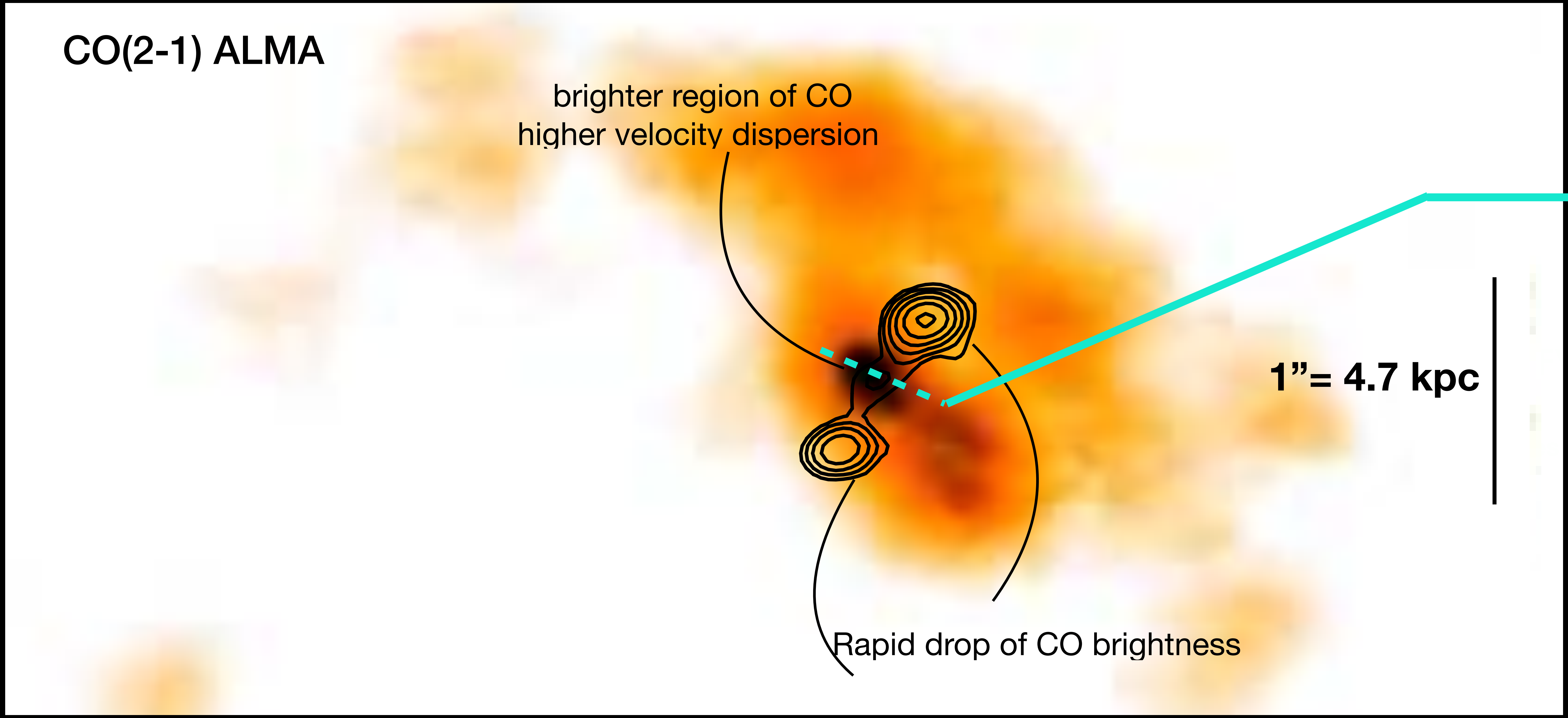
PKS 0023-26

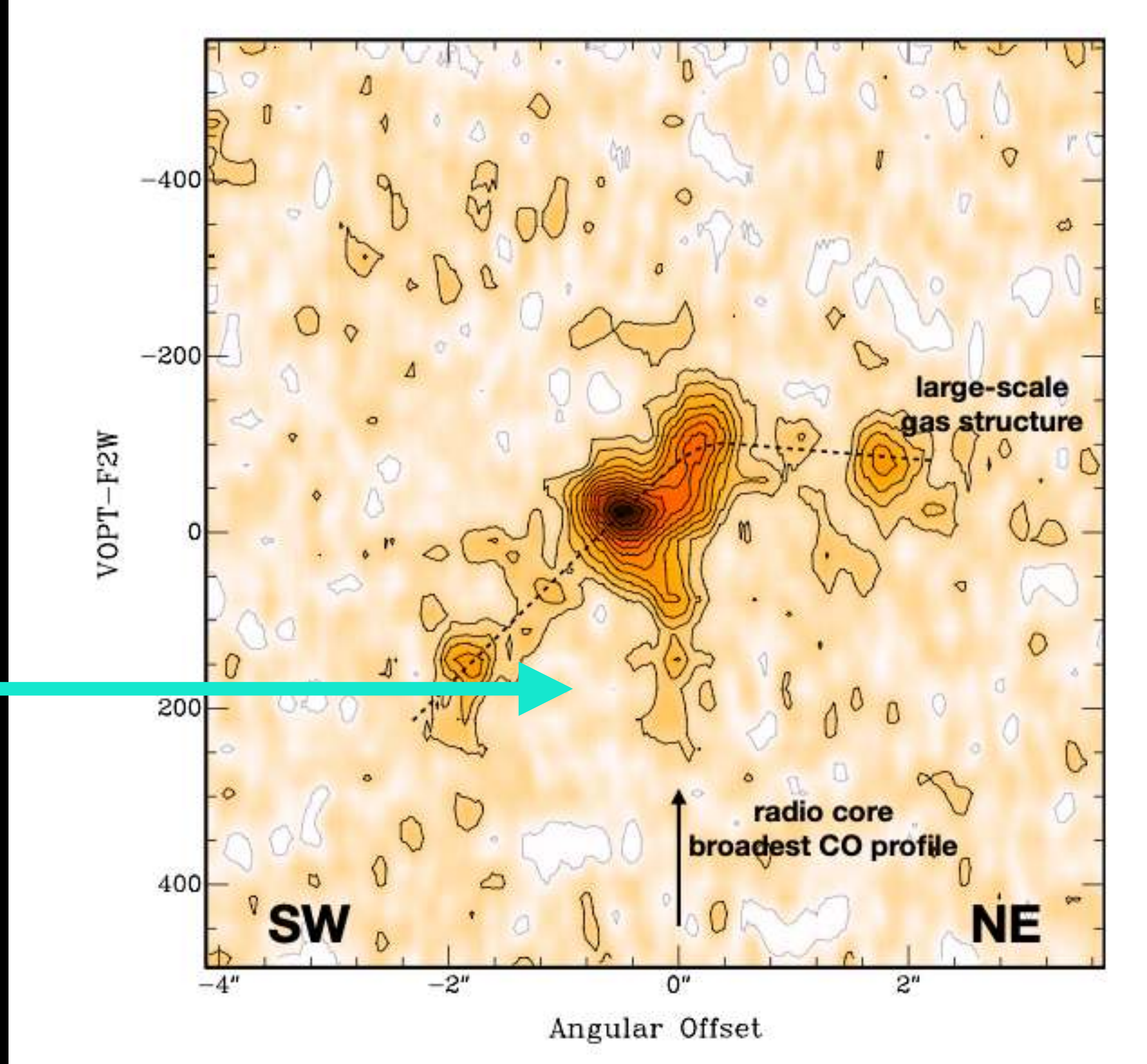
Morganti et al. 2021 A&A



PKS 0023-26

Morganti et al. 2021 A&A



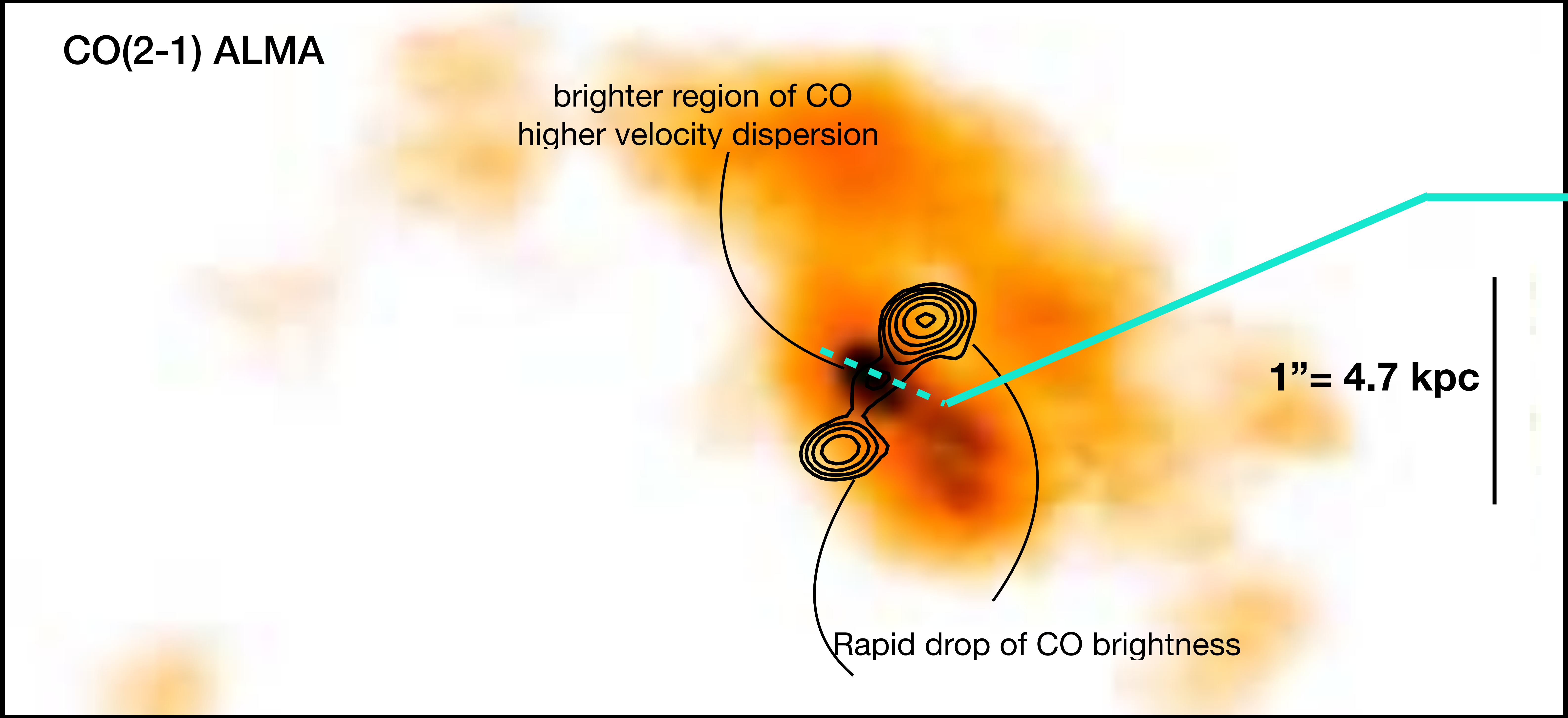


FWZI ~ 500 km/s

Higher velocity in the central (sub-kpc) region

PKS 0023-26

Morganti et al. 2021 A&A

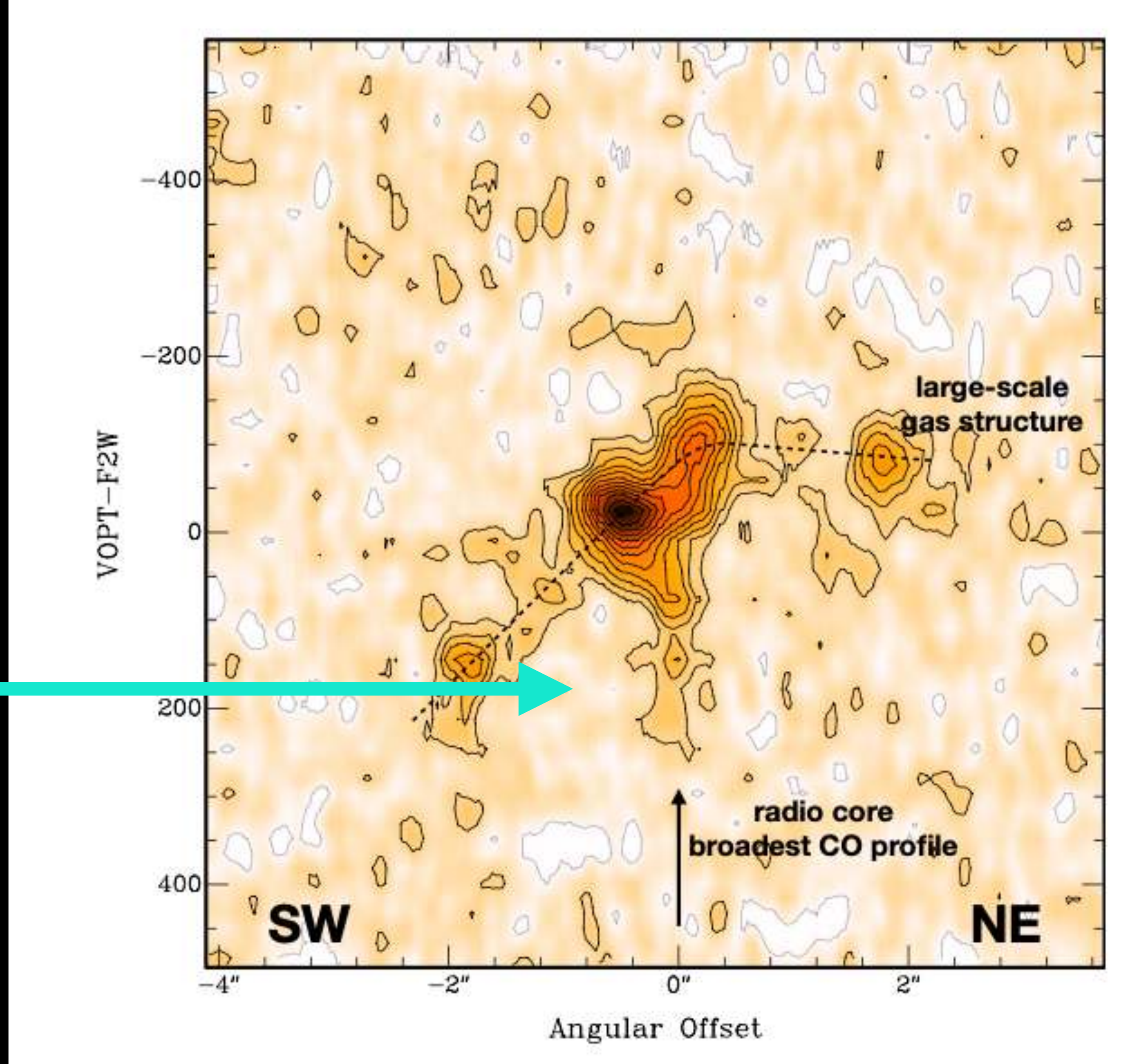


CO(2-1) ALMA

brighter region of CO
higher velocity dispersion

Rapid drop of CO brightness

1”= 4.7 kpc



FWZI ~ 500 km/s

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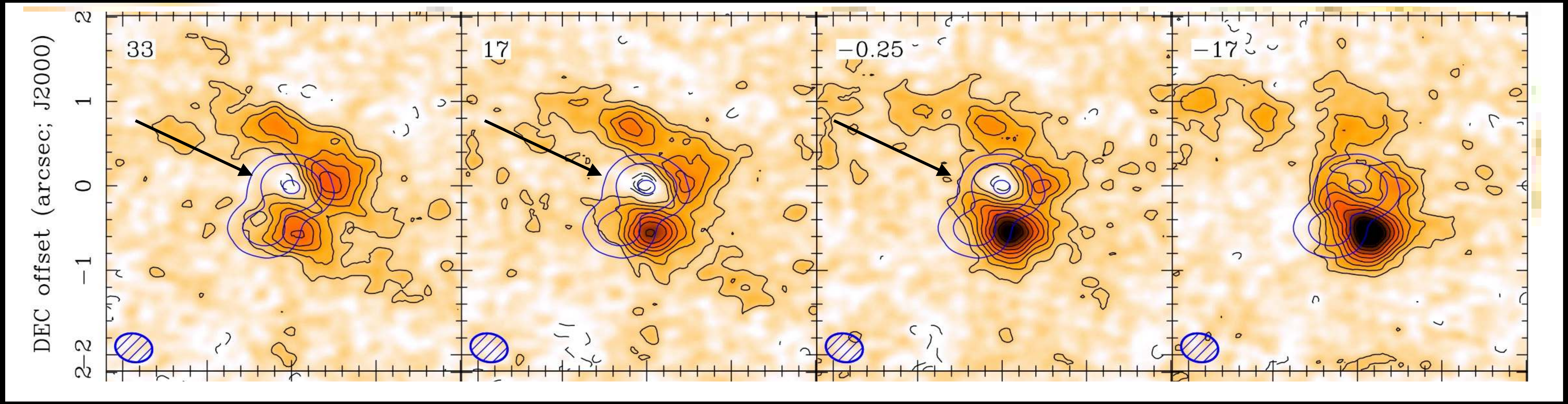
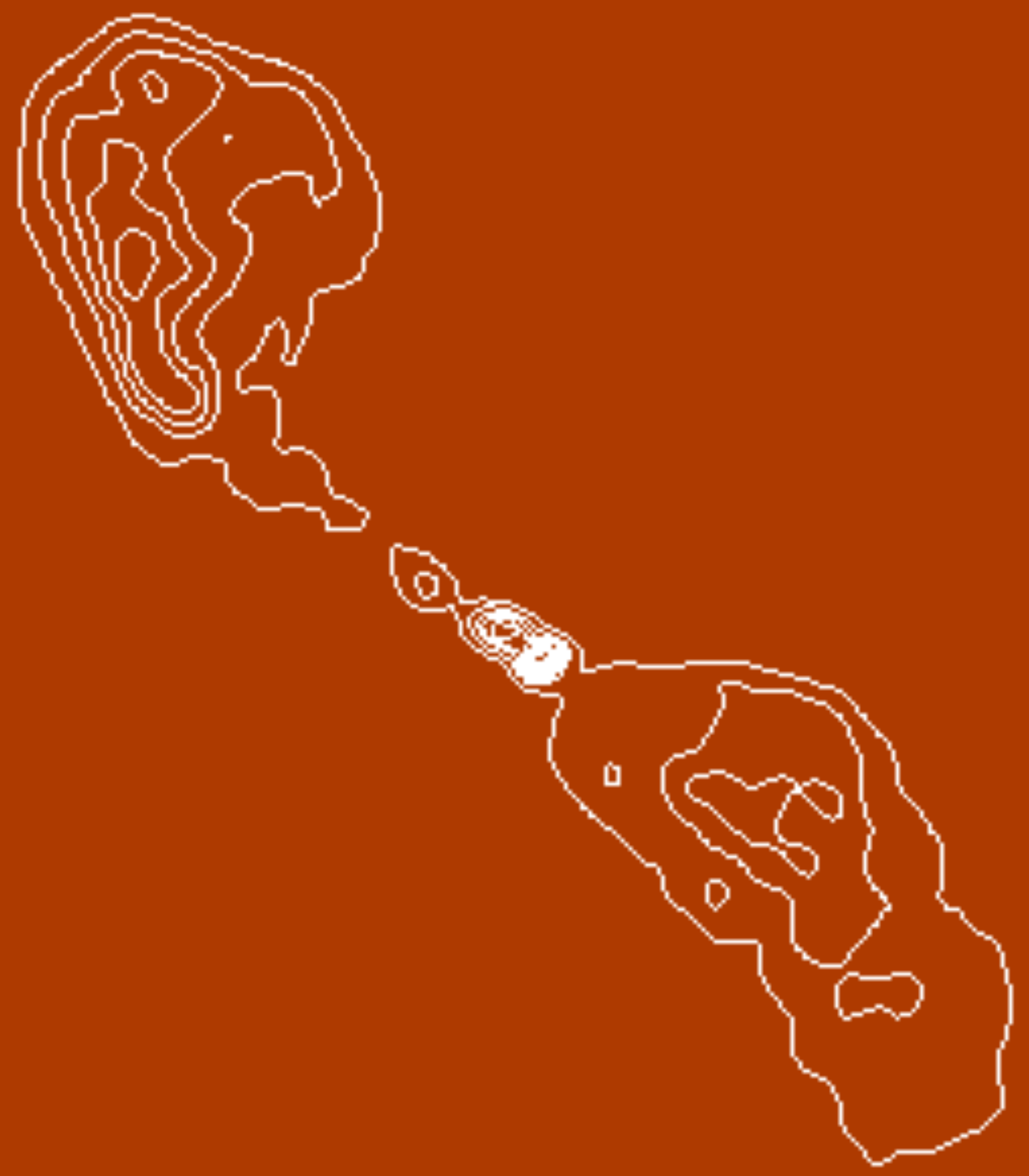


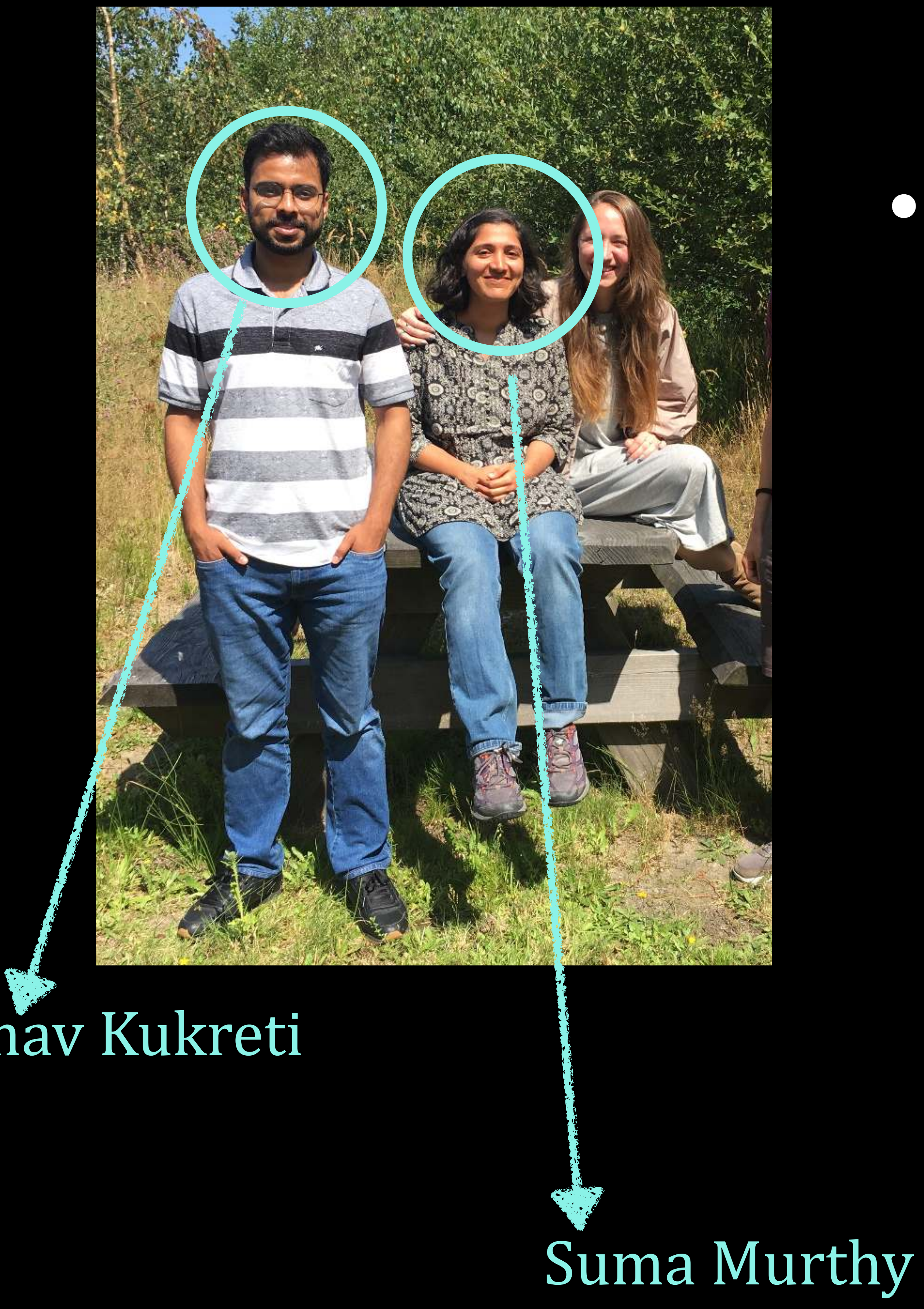
High velocity dispersion at the location of the radio emission but no fast, massive molecular outflow detected, despite powerful radiative AGN and powerful radio jet

radio plasma disturbing the molecular gas
➙ mild interaction
dispersing and heating
pre-existent molecular gas and pushing the gas aside



derive key quantities….

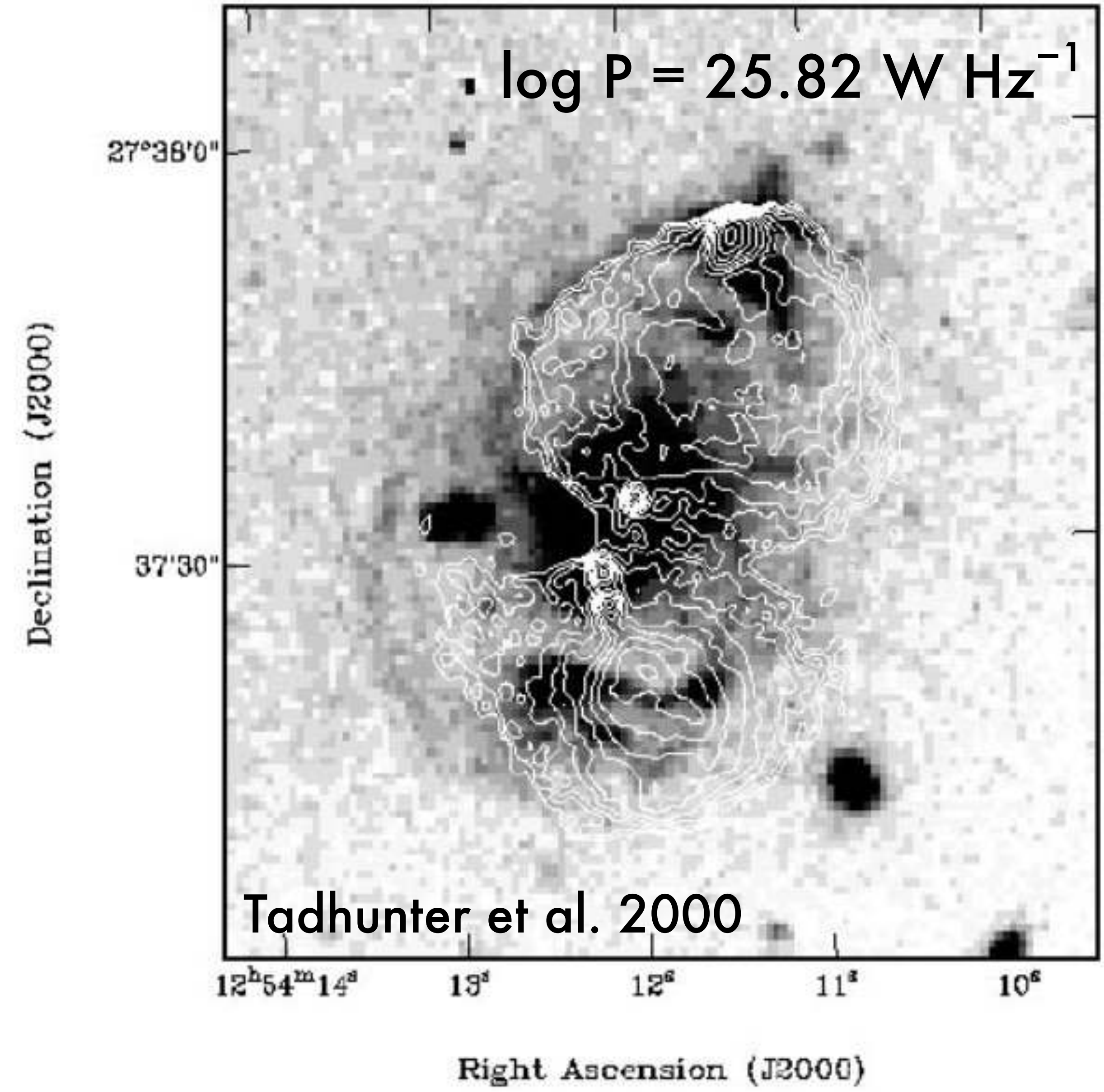
- outflow rate (and limitations…)
- kinetic energy
- jet power
- ….



- Appendix Luke 5063
-

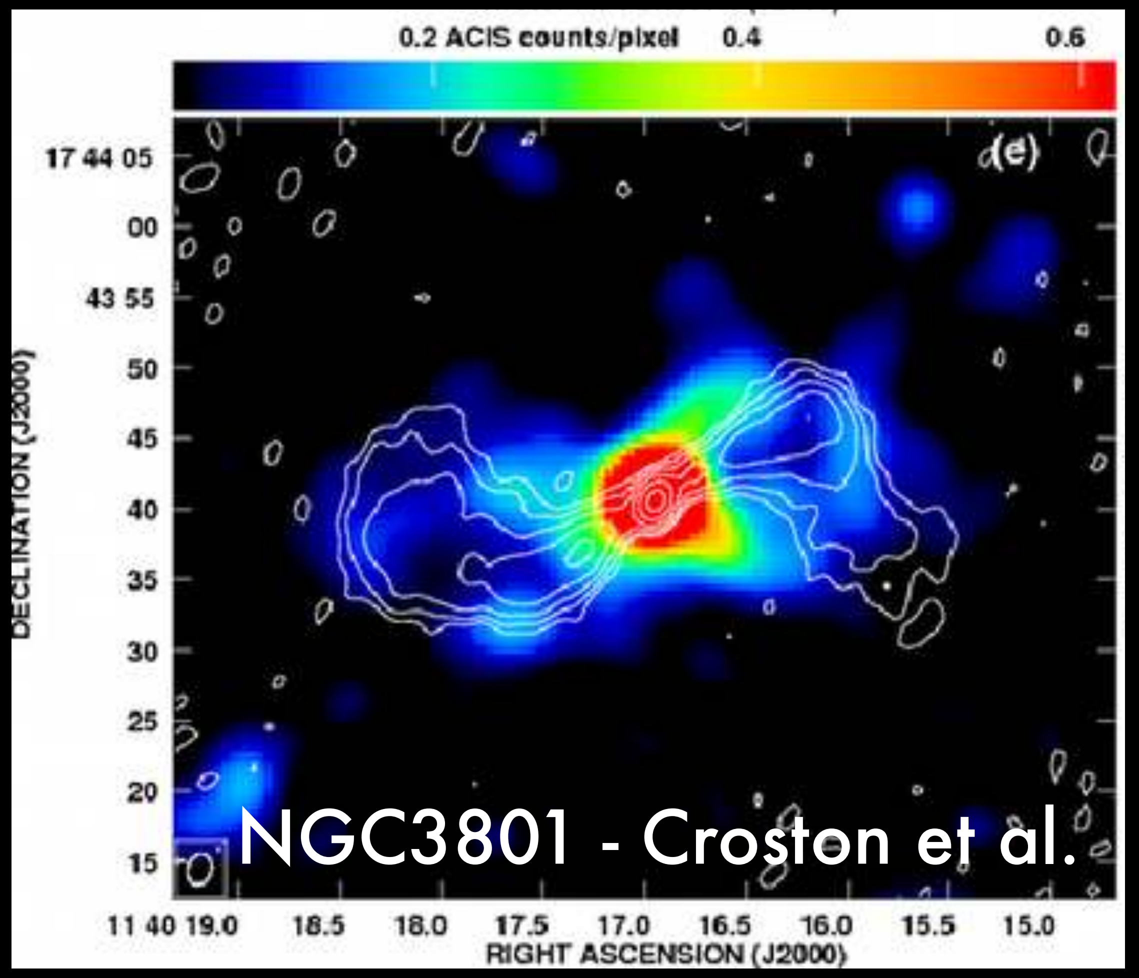
Radio jets known to affect the ISM since long time....

Expanding radio plasma jet/lobes affecting the distribution and kinematics of the surrounding gas



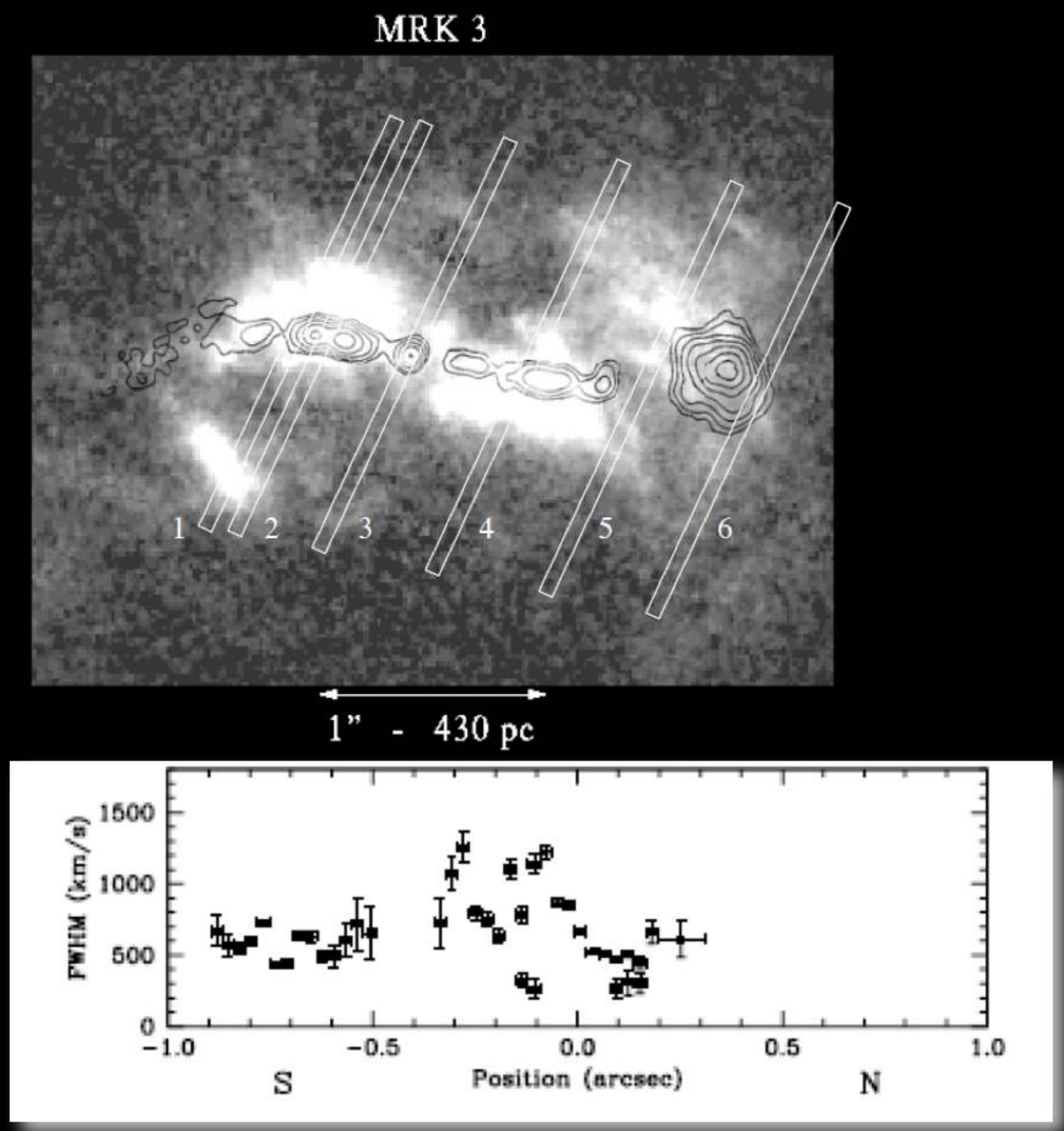
log P = 25.82 W Hz^{-1}

Tadhunter et al. 2000

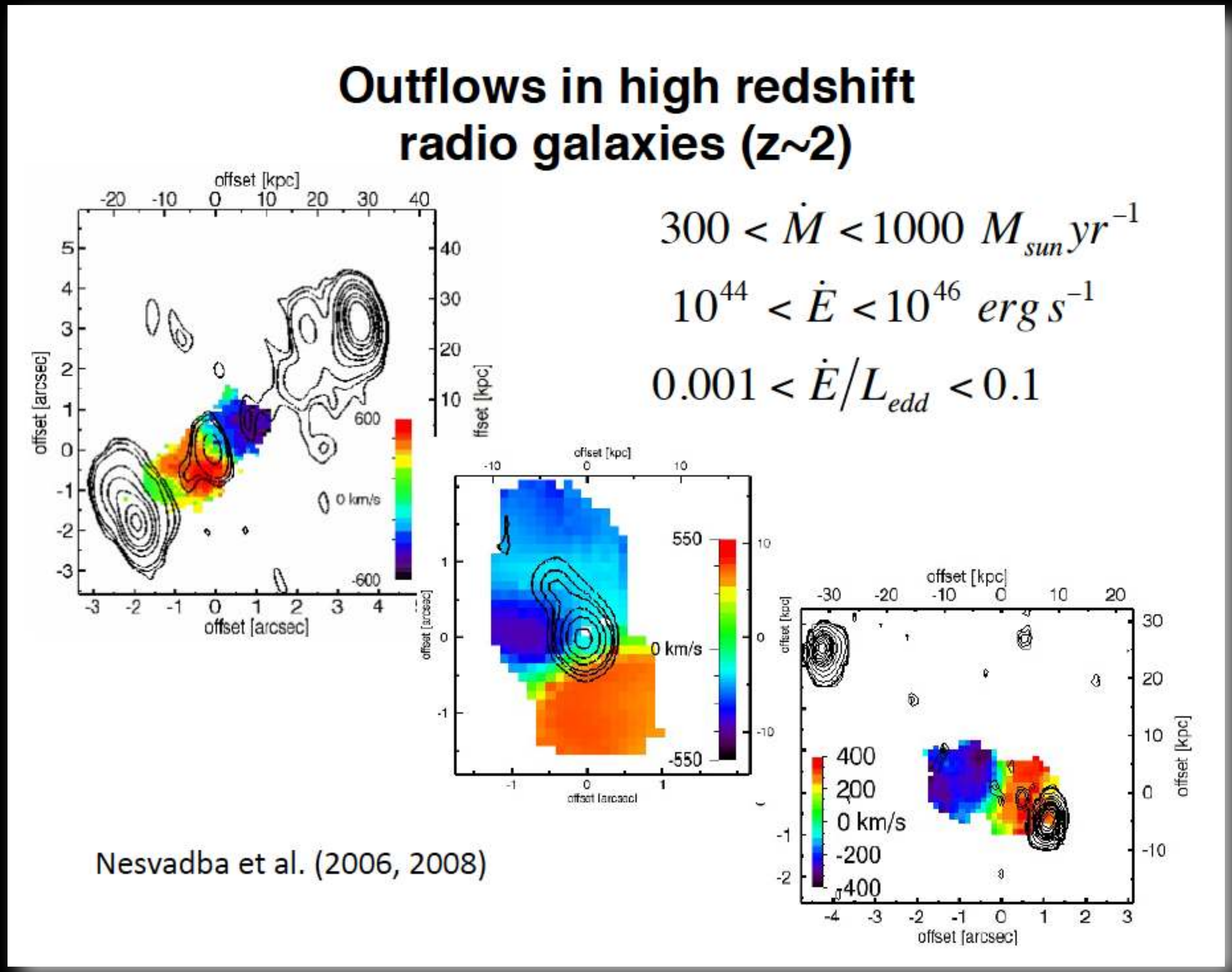


NGC3801 - Croston et al.

See also Capetti et al, Axon et al. and many many others



Capetti et al. 1999



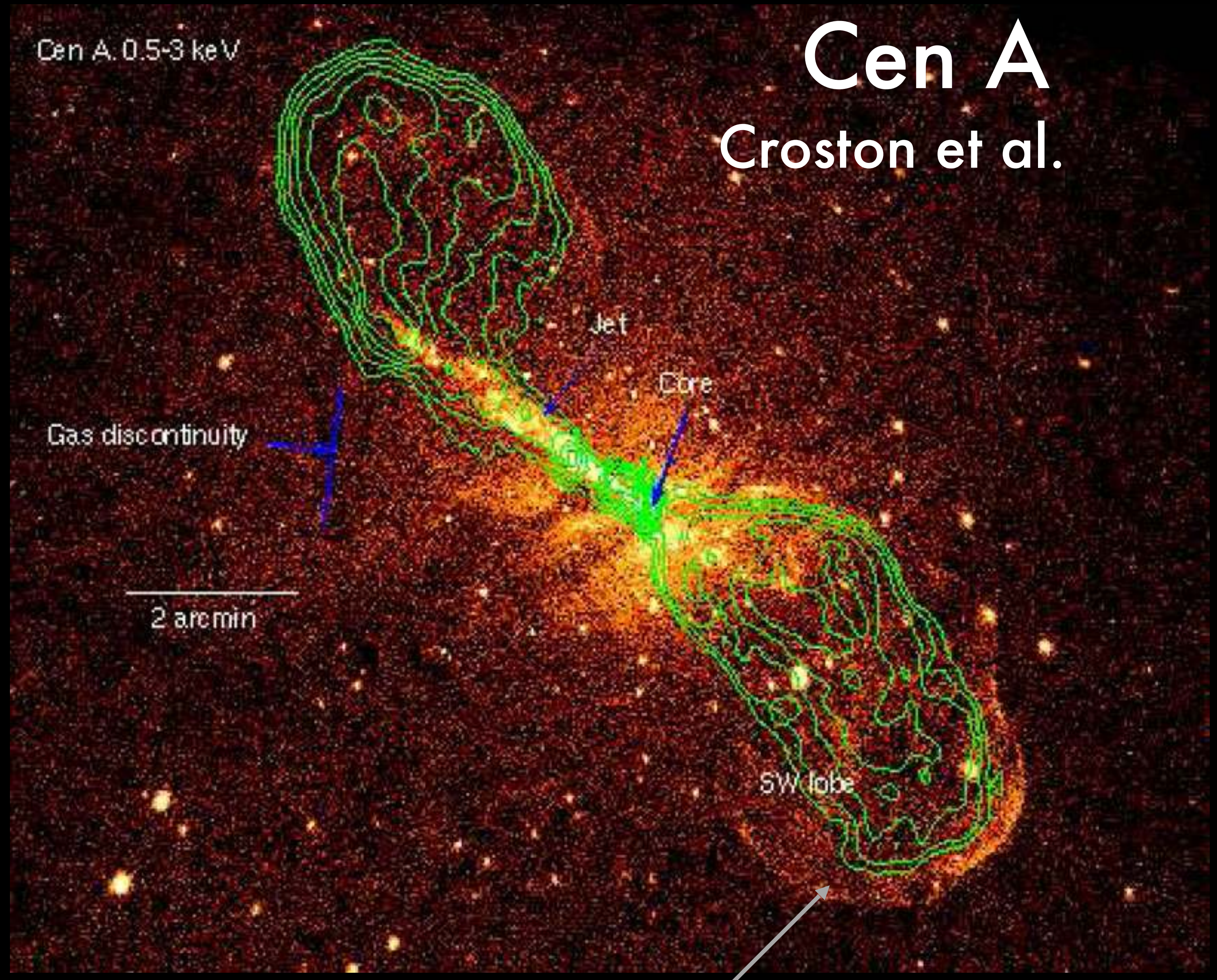
Outflows in high redshift radio galaxies (z~2)

$$300 < \dot{M} < 1000\ M_{sun} yr^{-1}$$

$$10^{44} < \dot{E} < 10^{46}\ erg\ s^{-1}$$

$$0.001 < \dot{E}/L_{edd} < 0.1$$

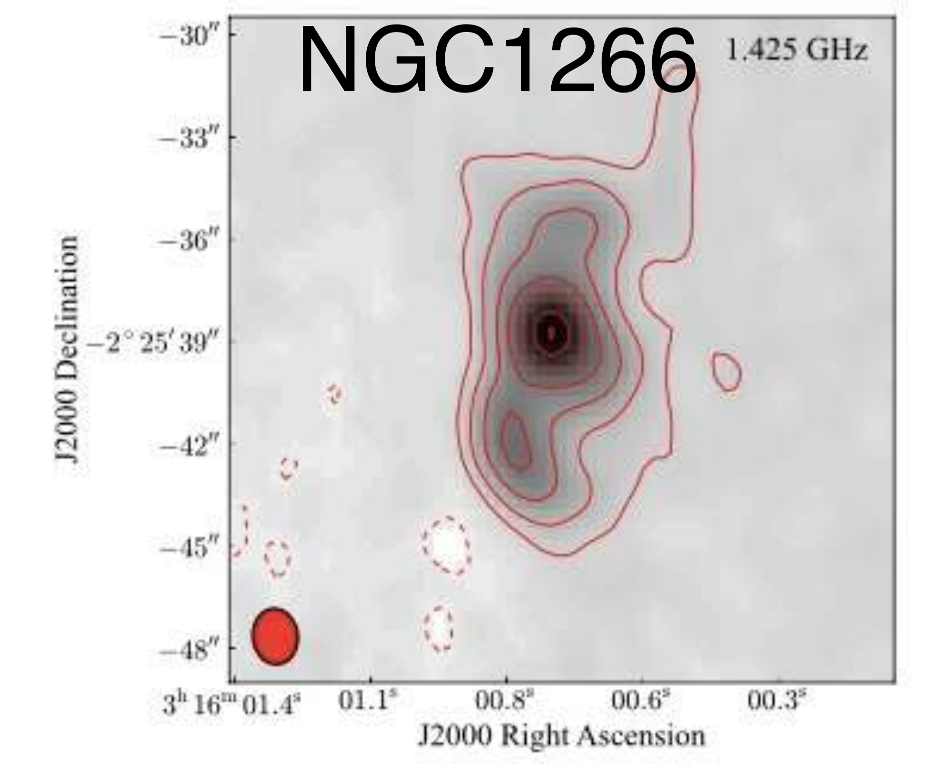
Nesvadba et al. (2006, 2008)



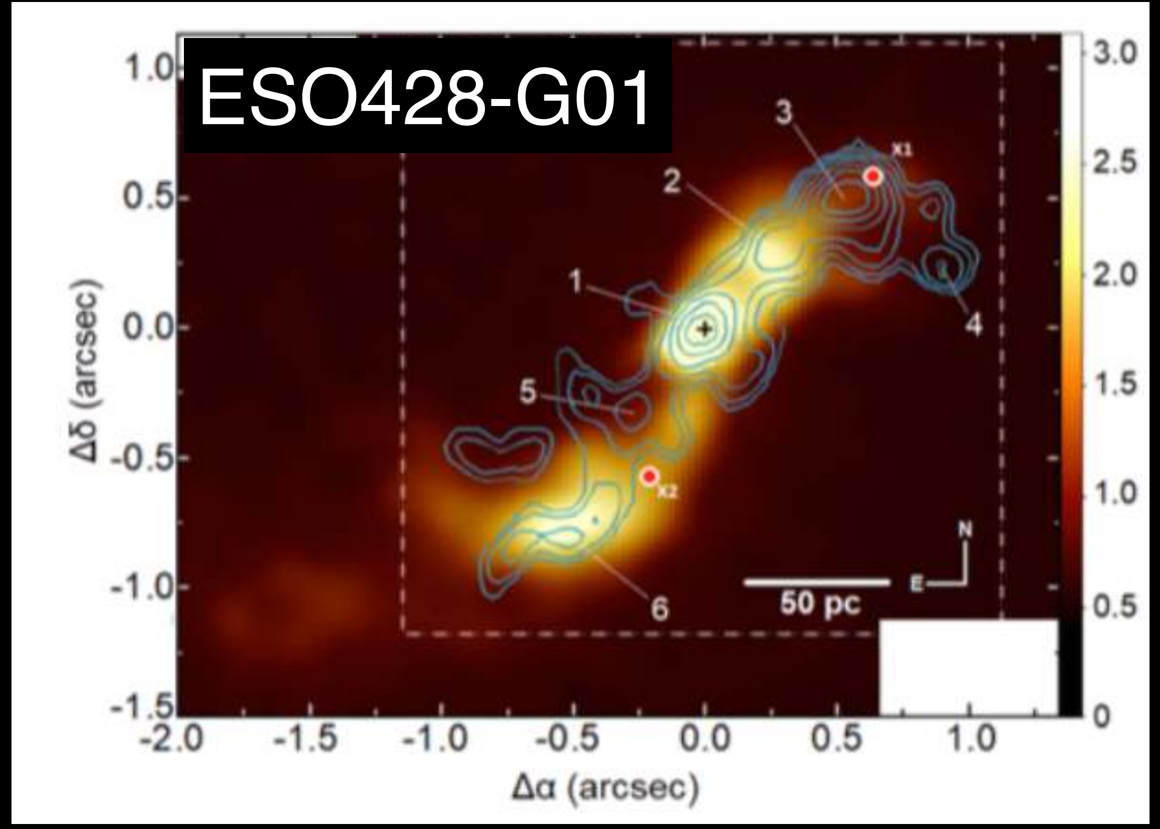
Cen A

Croston et al.

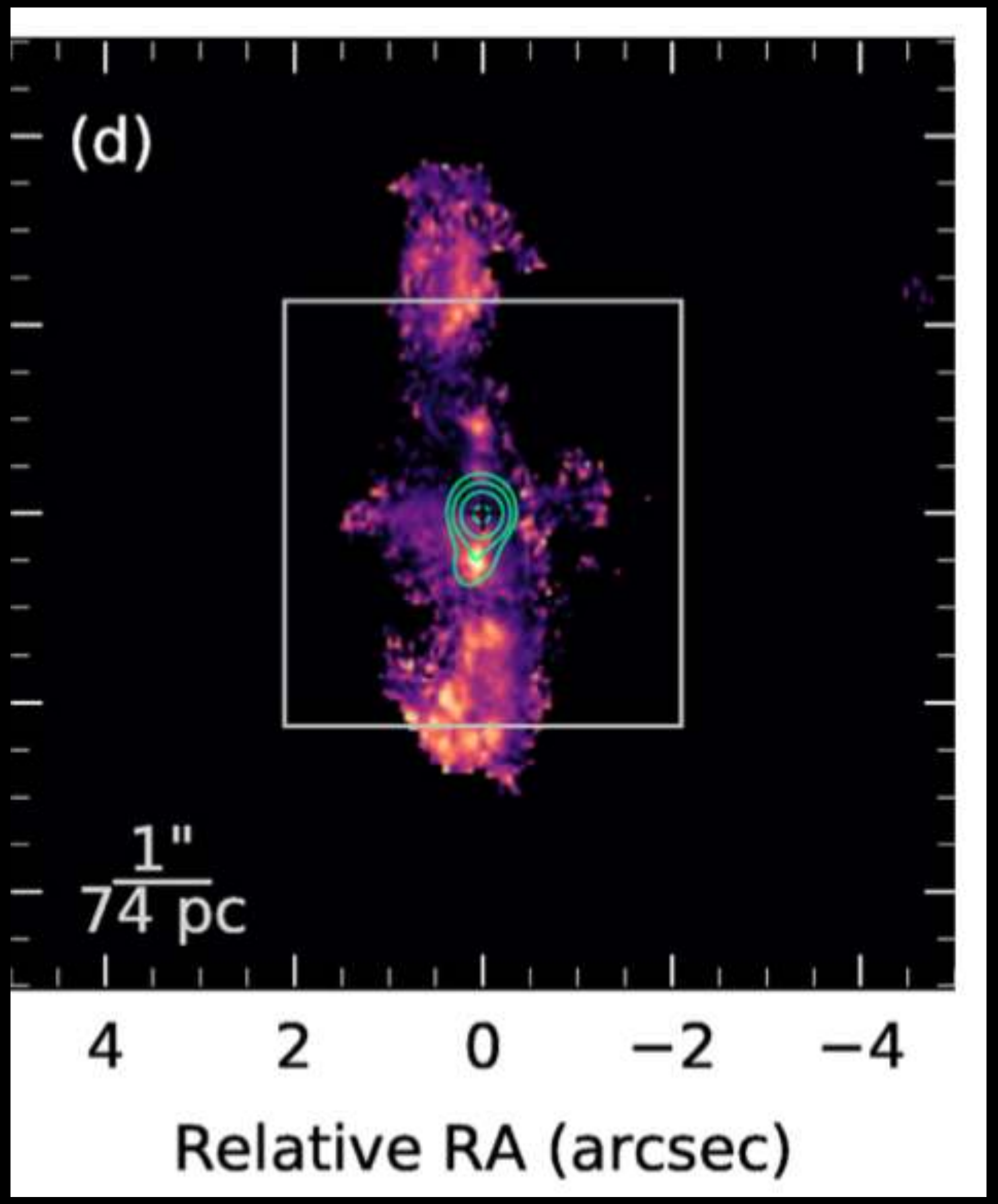
Lobe is expanding to the south-west with a velocity of ~2600 km s^{-1}, roughly Mach 8 relative to the ambient medium.



Alatalo et al. 2012

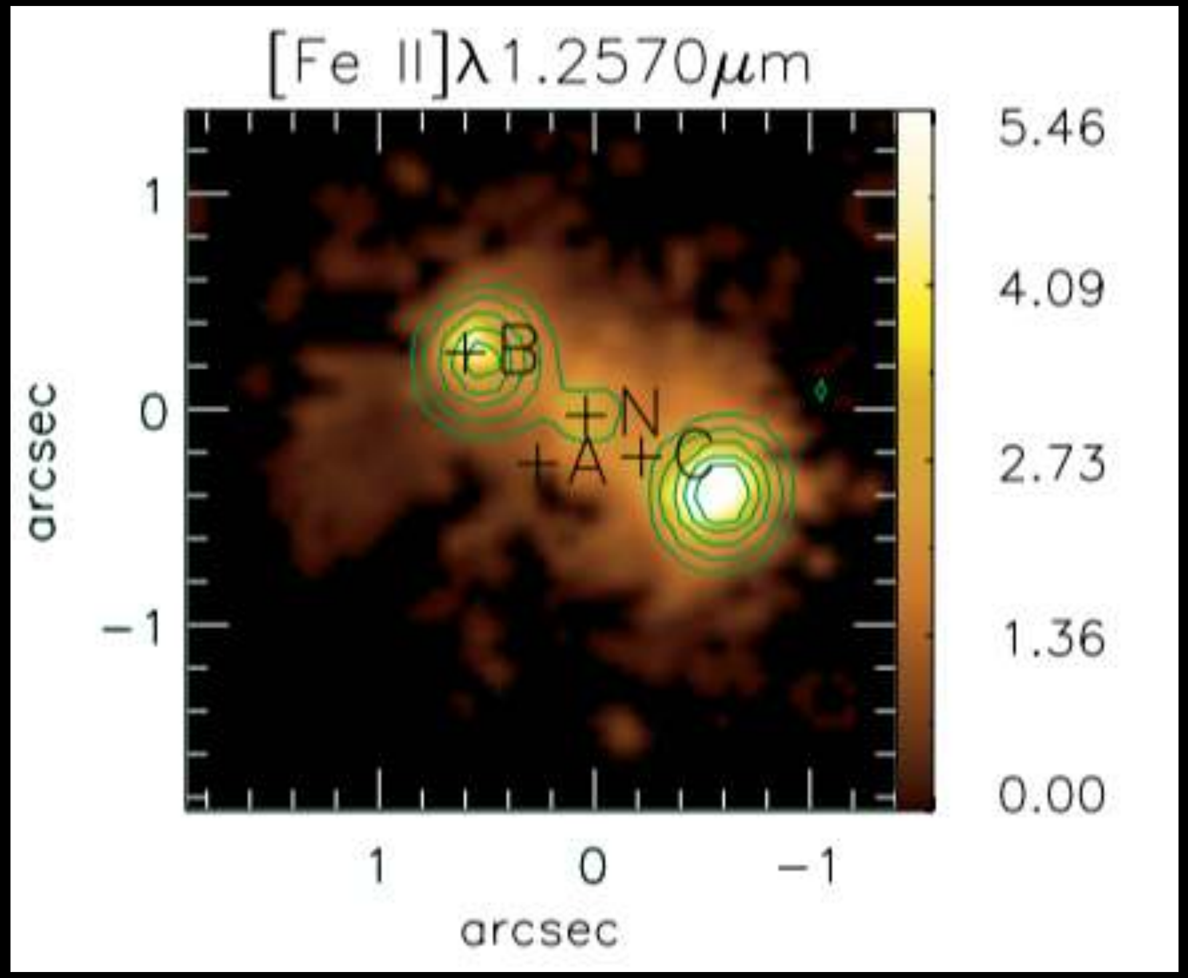


May, Rodriguez-Ardila, Prieto et al. 2018 et al.

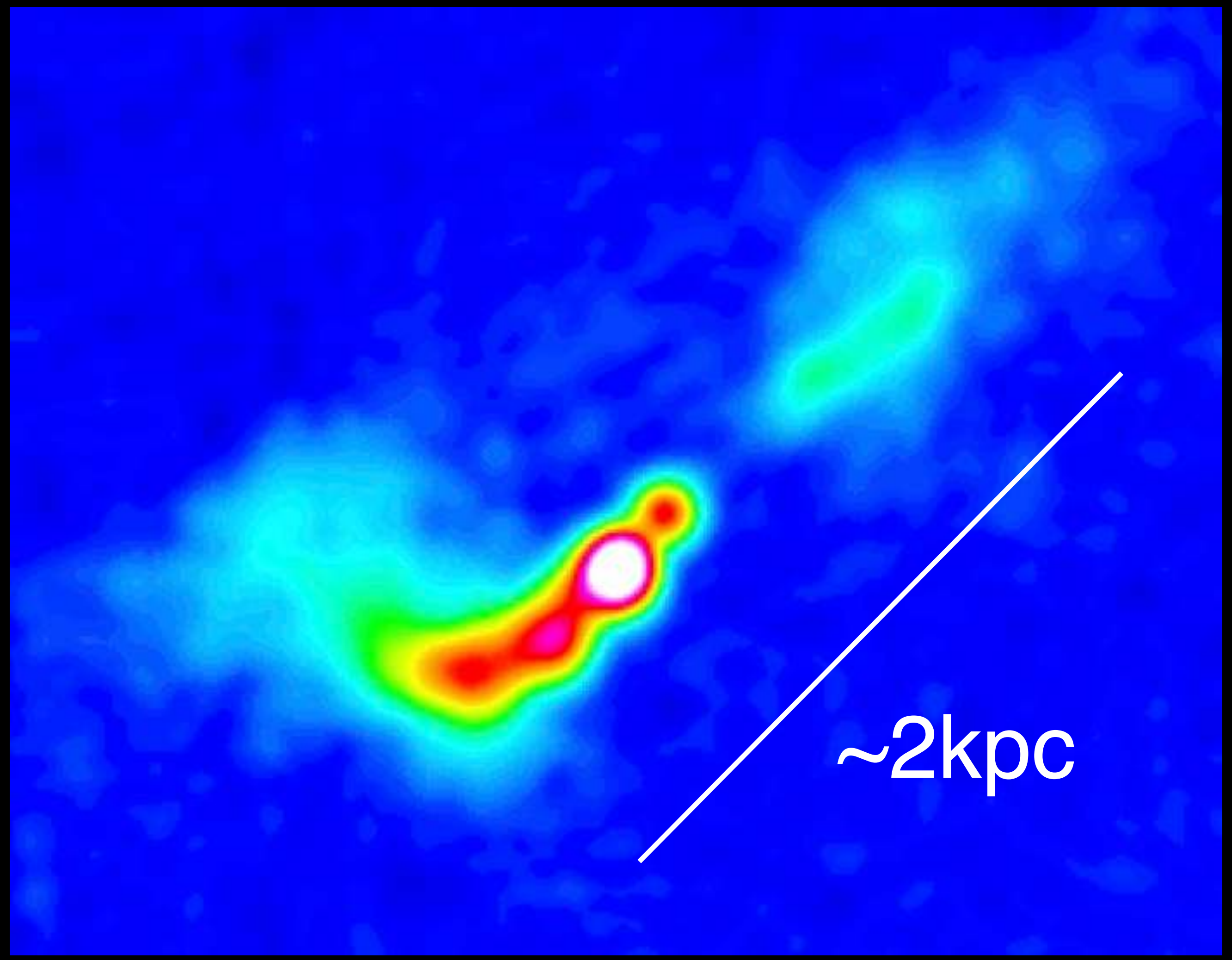


NGC1386 Rodríguez-Ardila et al.

Growing number of "radio-quiet" (comparable radio power as IC5063)
and LLAGN where a low power jet could be responsible
for driving a cocoon of disturbed/ionized gas



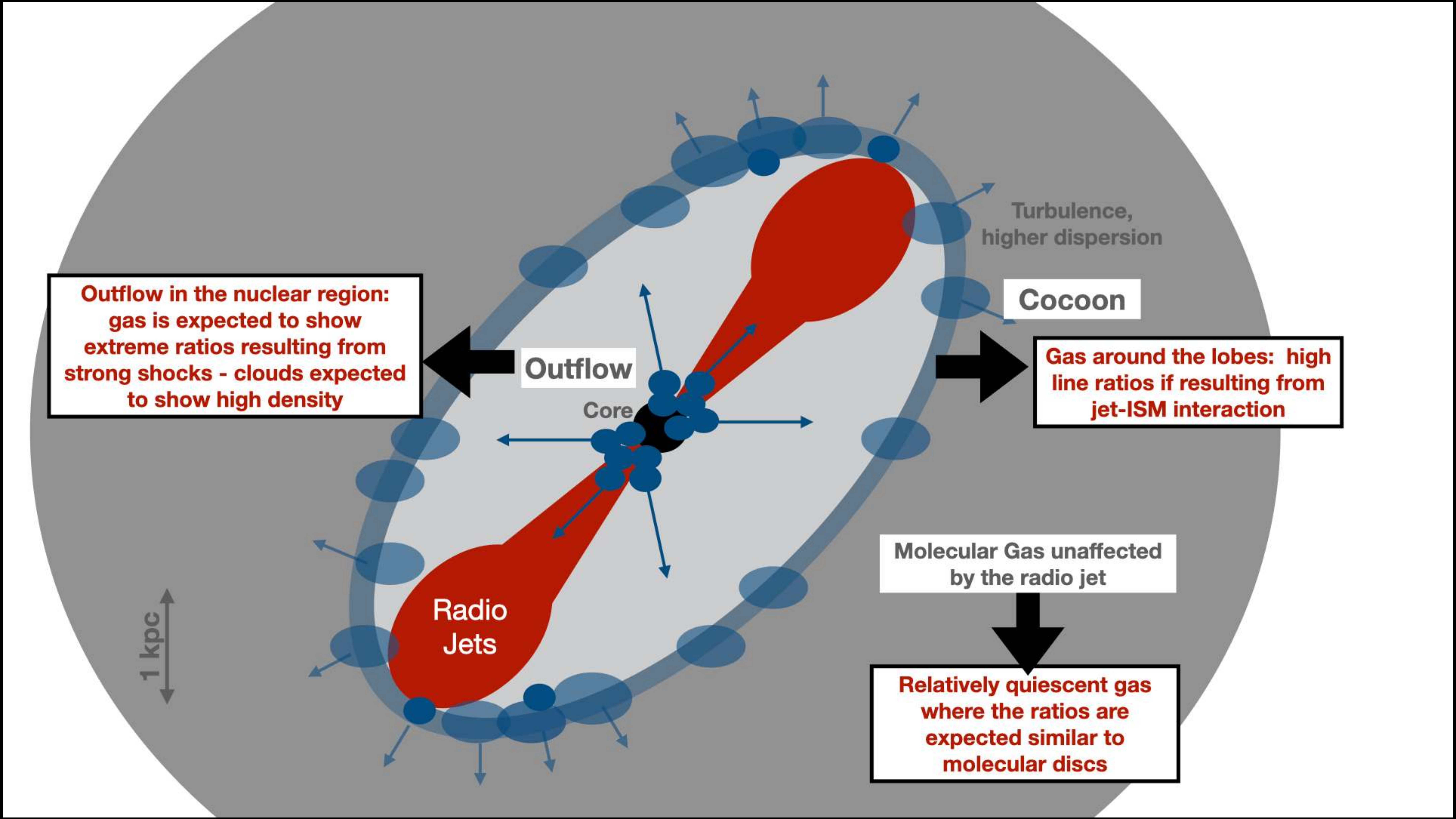
Riffel et al. 2014 - NGC5929
outflow also perpendicular to the radio jet



Murthy et al. 2019

And many others....
e.g. NGC613, Combes' presentation

Not a large amount of gas leaving the galaxy: relevance for feedback?



Outflow in the nuclear region: gas is expected to show extreme ratios resulting from strong shocks - clouds expected to show high density

Gas around the lobes: high line ratios if resulting from jet-ISM interaction

Molecular Gas unaffected by the radio jet

Relatively quiescent gas where the ratios are expected similar to molecular discs