3) Radio jets and their impact in galaxy evolution

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

Themes of the lectures

- ➡ Active galactic nuclei (AGN): introduction of their properties
- ➡ Structure of radio AGN and their life cycle
- ➡ Radio jets and their impact in galaxy evolution

3) Radio jets and their impact in galaxy evolution

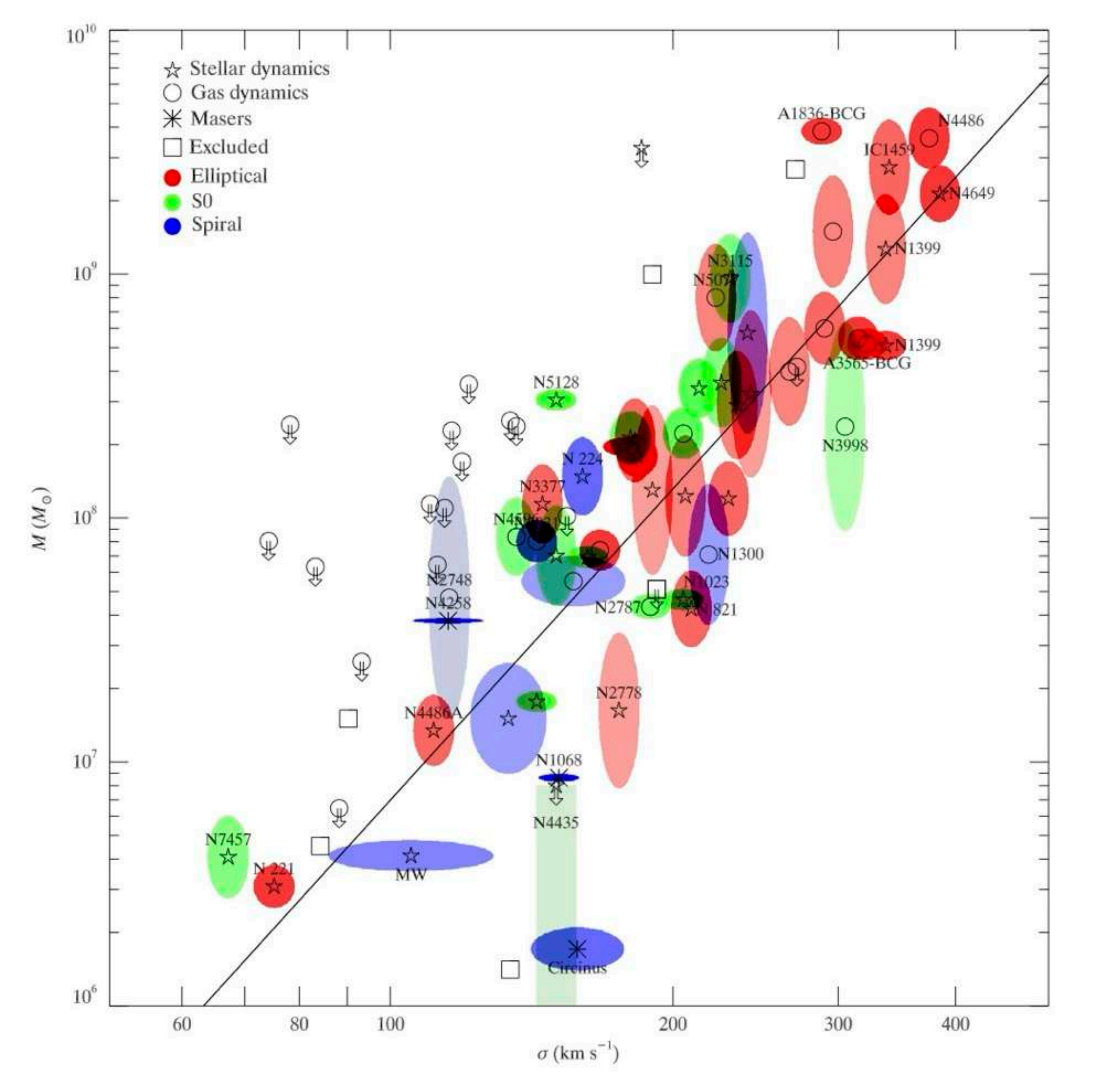
Plan of this lesson

a) Radio AGN and their gaseous environment
b) AGN feedback and the various modes of impact of an AGN
c) Radio jets and cluster cavities
d) Radio jets driving gas outflows
e) The impact of jets in a broader picture

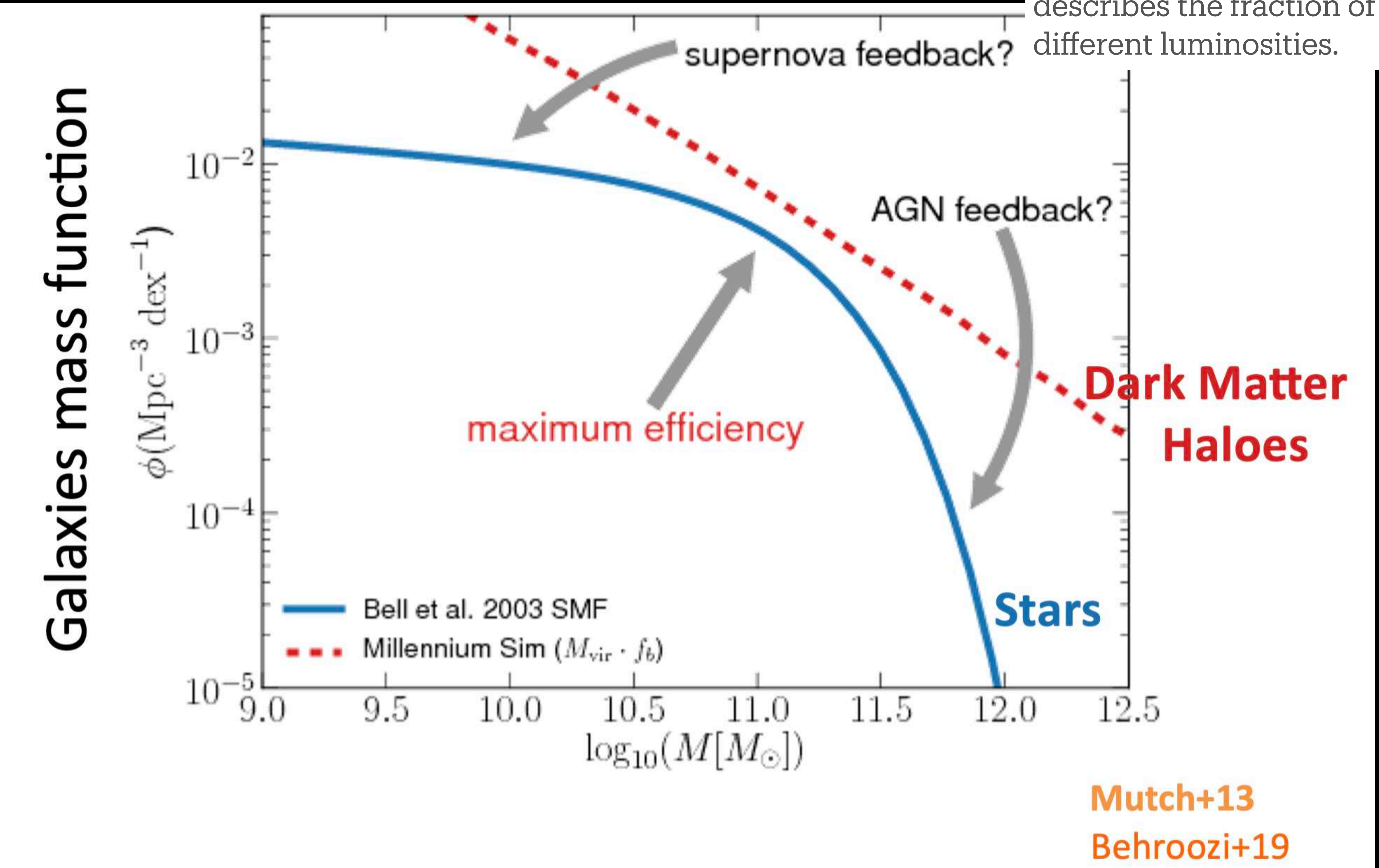
Feedback required for reproducing the properties of observed galaxies

- clear relationship between mass of spheroidal component of host galaxy and black-hole mass
- indicates connection between galaxy formation (star formation) and growth/evolution of central black-hole
- simulations require extra ingredients to reproduce galaxy luminosity function and cooling flow problem…

galaxy luminosity function which describes the fraction of galaxies of different luminosities.



Gebhardt et al. 2000; Ferrarese & Merritt 2000, Gültekin et al. 2009



cosmological models derive too many big galaxies and too many dwarf galaxies

a) Radio AGN and their gaseous environment

Galaxies have large reservoirs of gas (in different phases, from hot to cold)...

even early-type galaxies have a large reservoir of gas

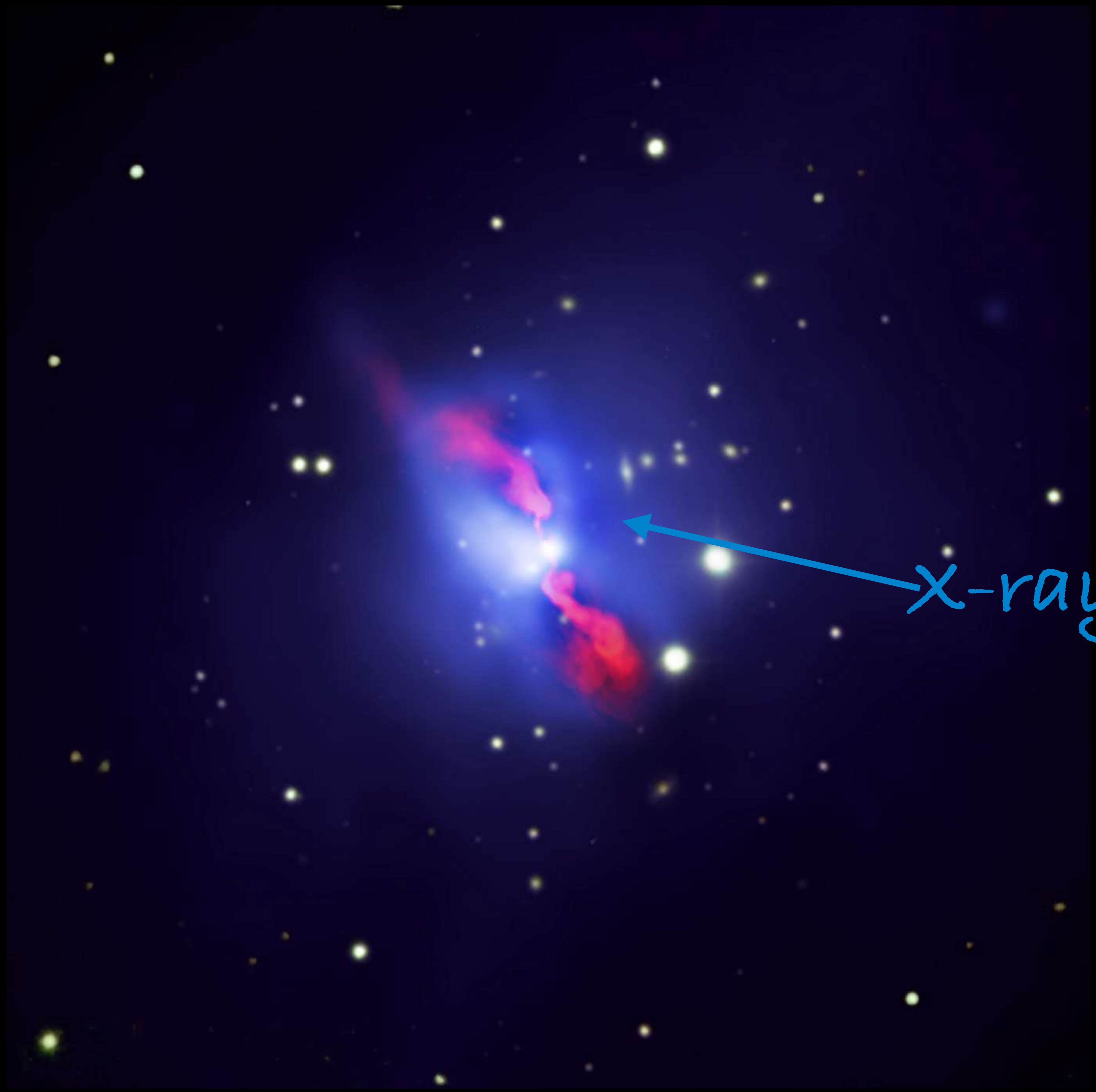
→ mass loss from evolving stars (possibly enough for low luminosity AGN)

→ from major or minor galaxy mergers → can bring more gas ...

→ cooling of gas from the hot (X-ray) halo

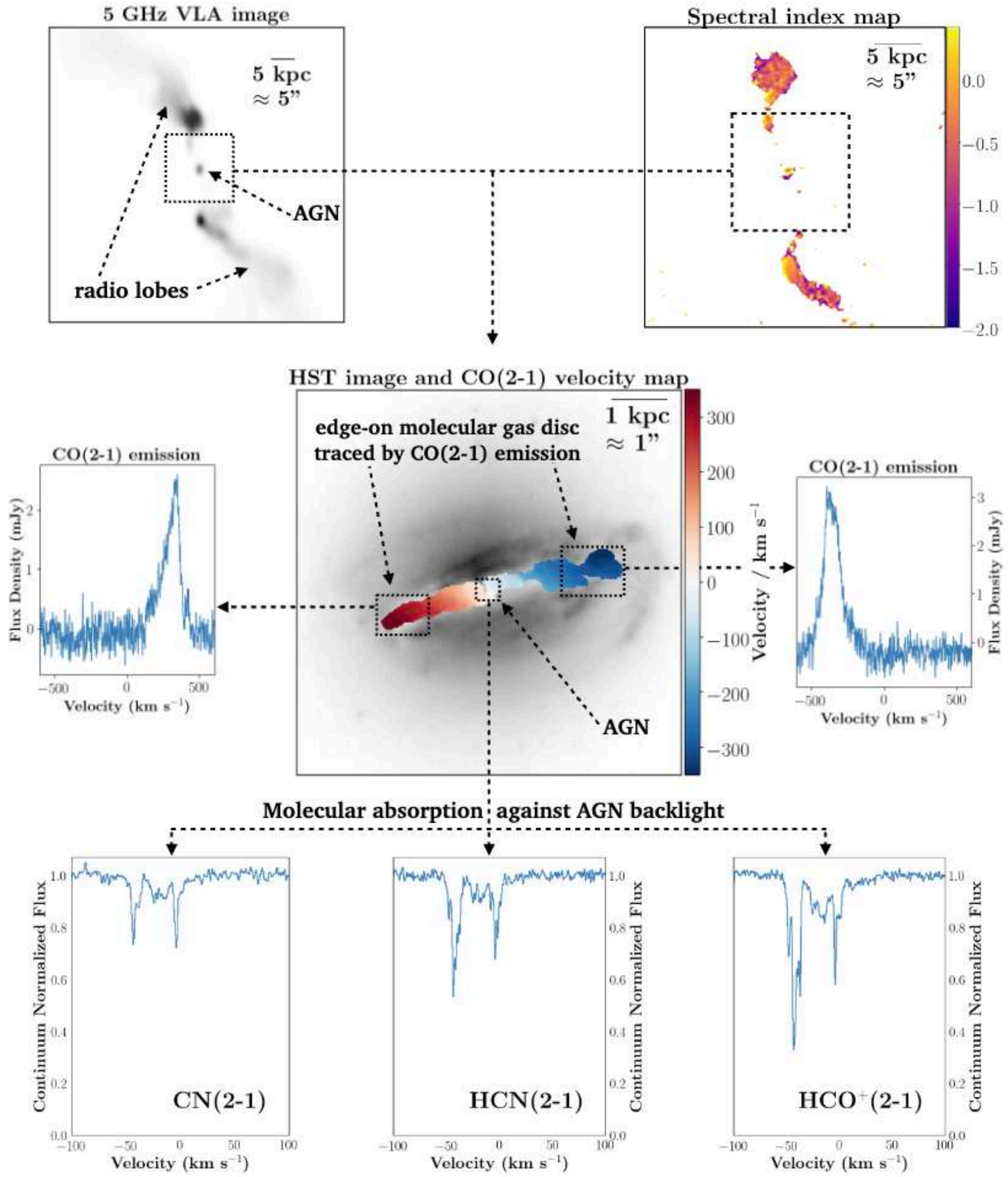
potentially available for forming stars and accrete on the BH:
how can these be regulated?

...medium where the radio plasma is embedded



Wise et al. 2007

cold molecular gas



Rose et al. 2020

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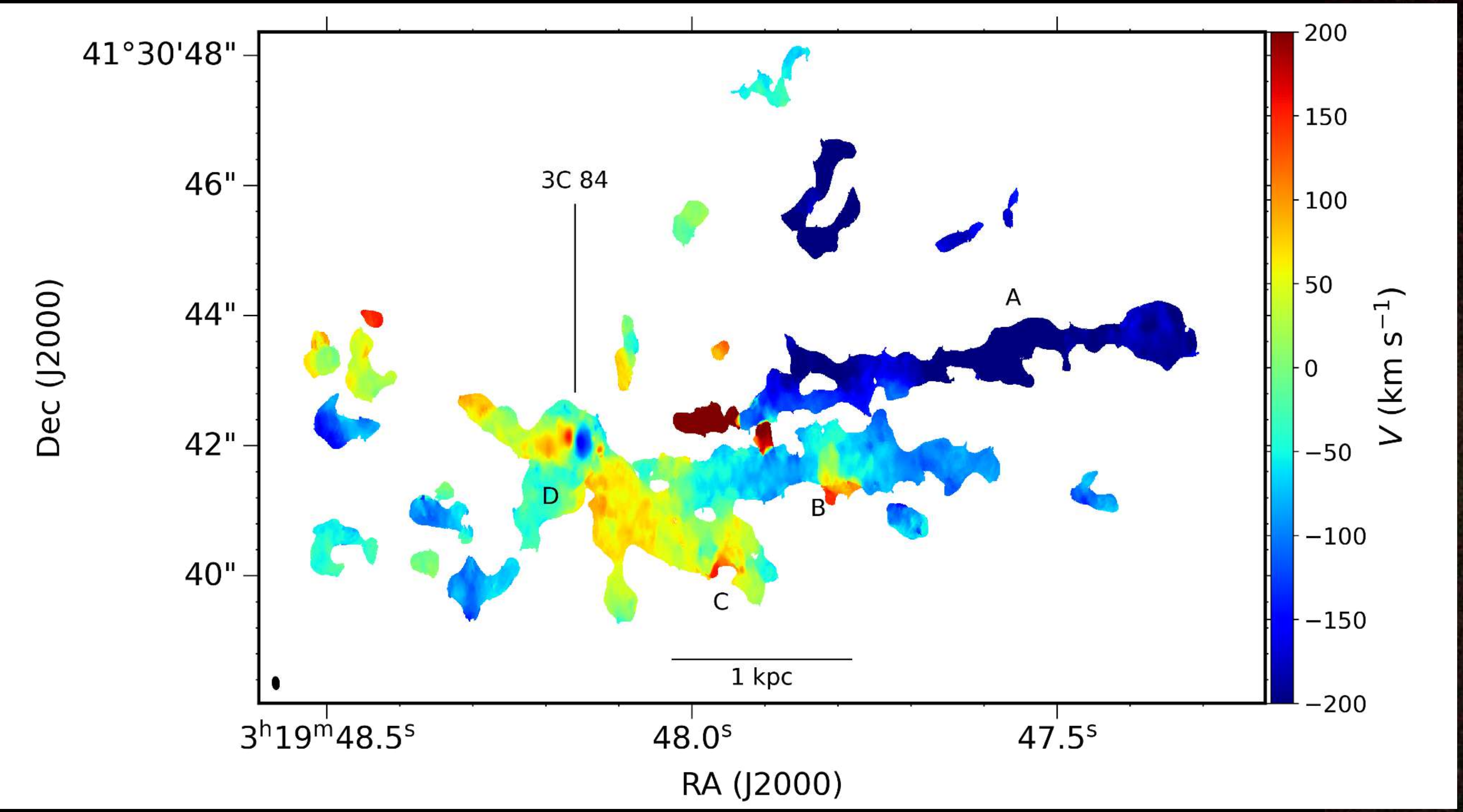
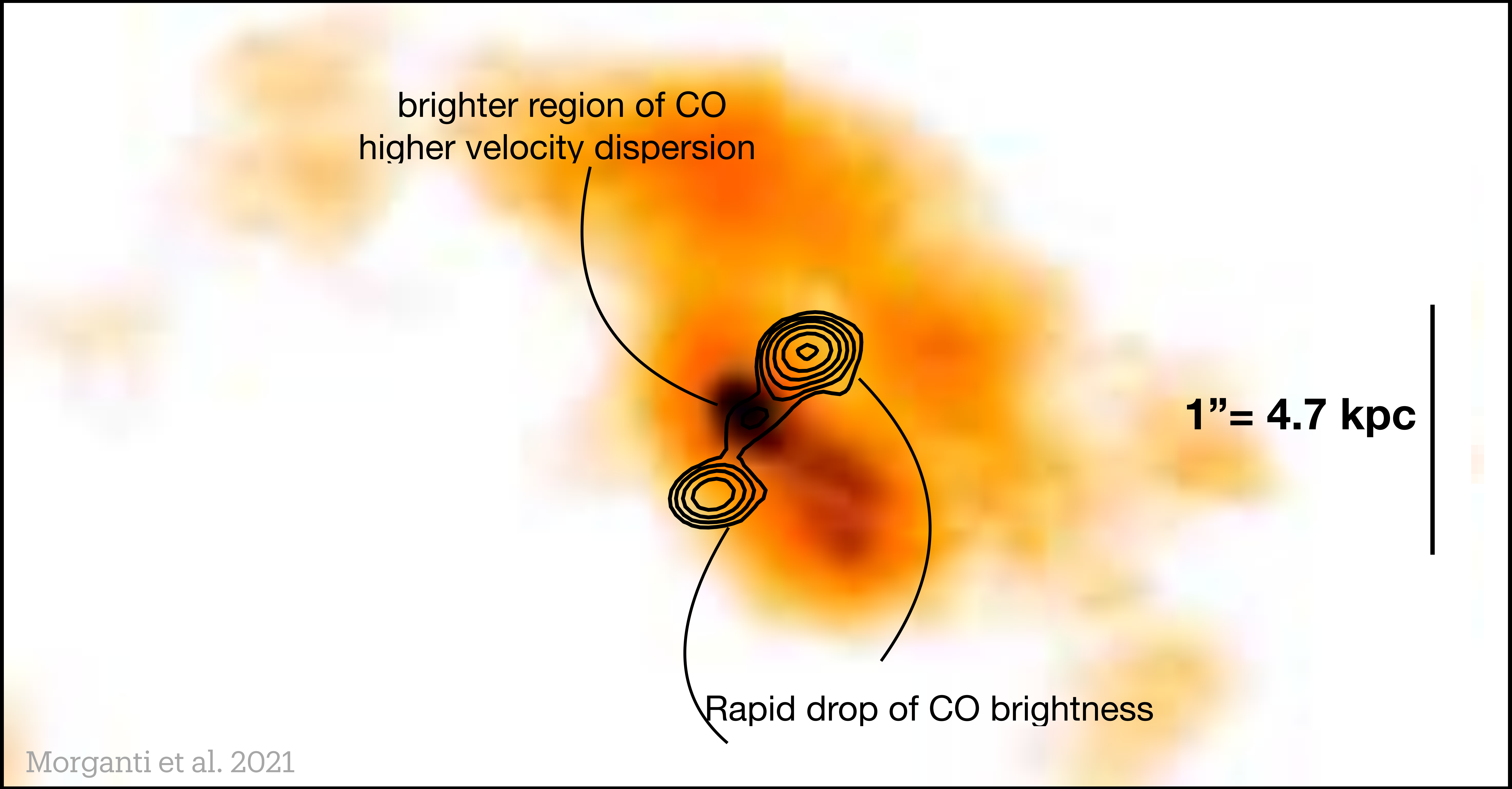


Cold molecular gas - ALMA
high resolution - 30 pc -
Oosterloo et al. 2023

Hα image (Conselice+ 01)

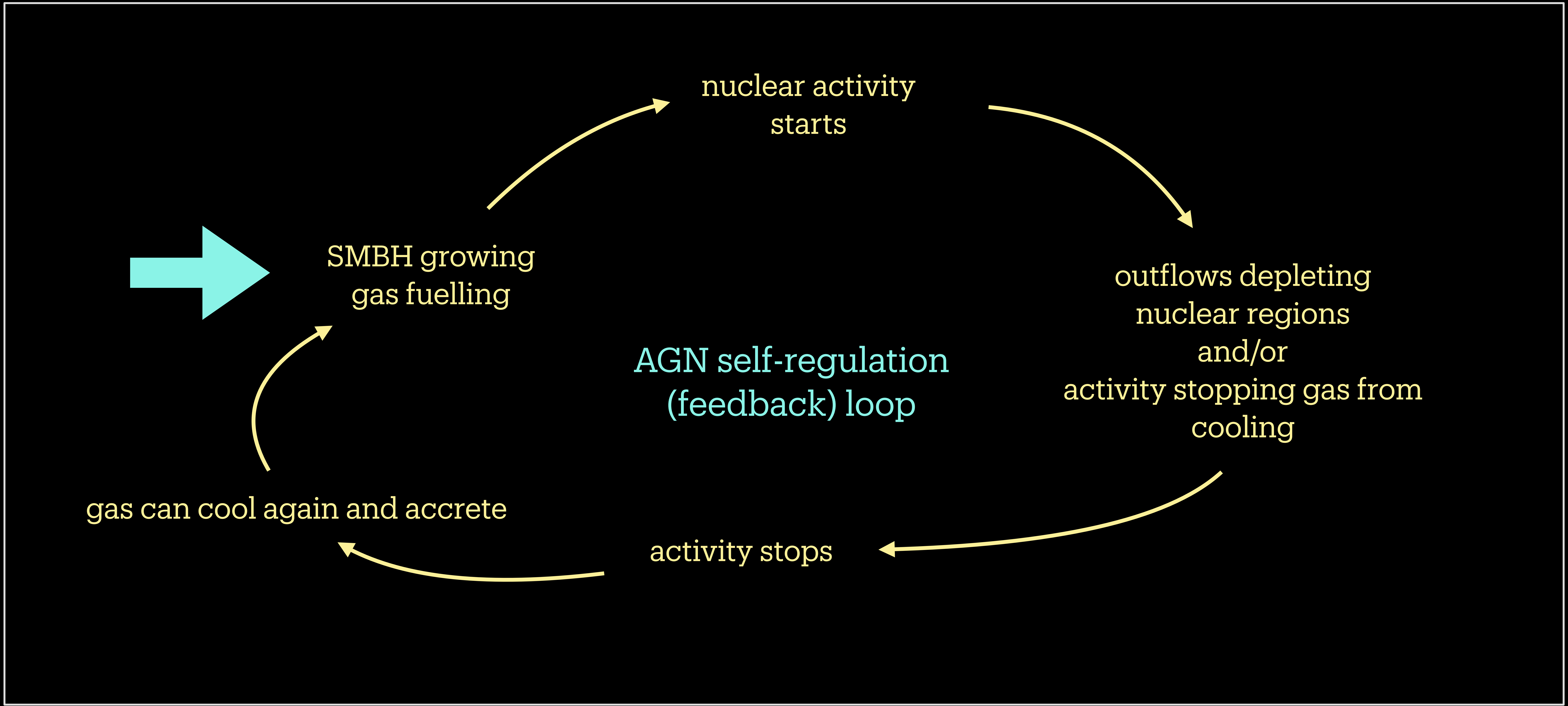
PKS 0023-26 view by ALMA in CO(2-1)



~10^{10} $M_{\odot}$ cold molecular gas

b) AGN feedback and the various modes of impact of an AGN

A basic self-regulating feedback loop...



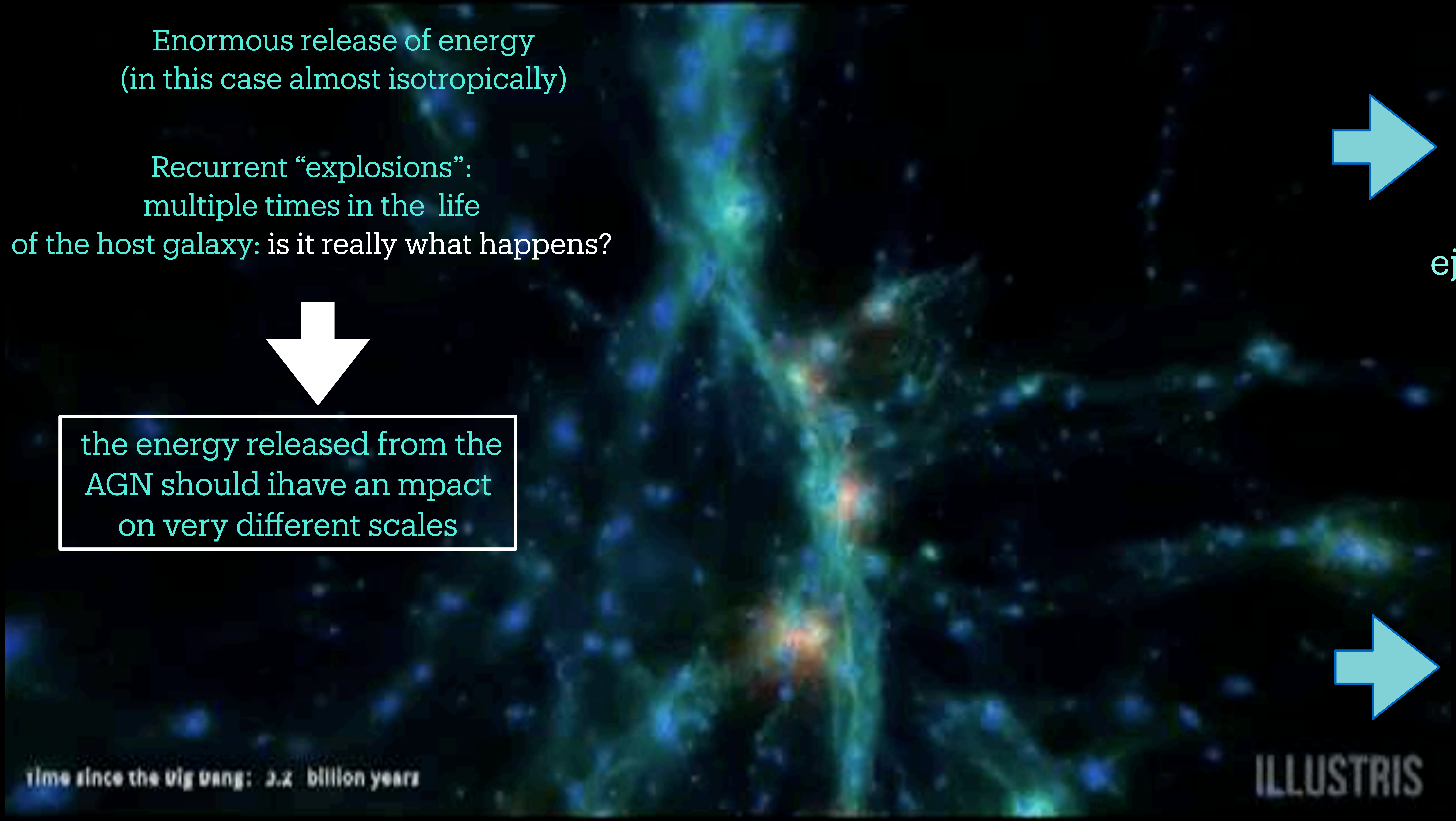
Role of AGN in galaxy evolution: cosmological simulations

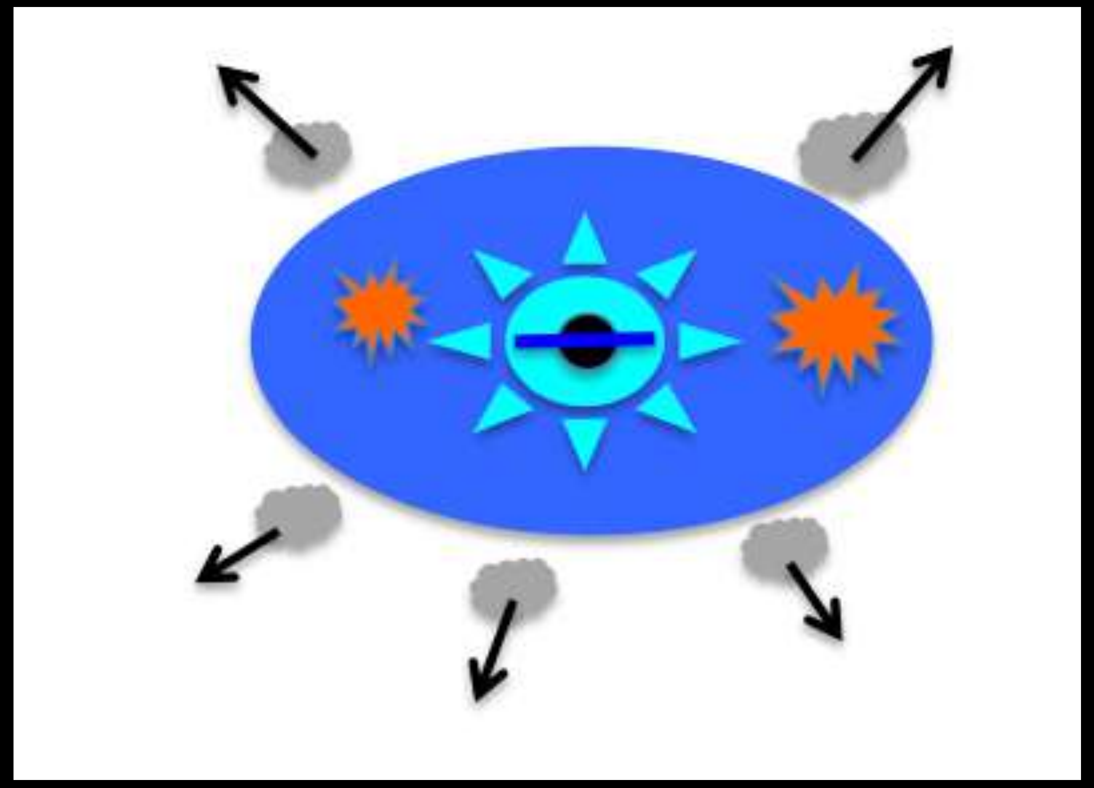
Points to notice:

Enormous release of energy
(in this case almost isotropically)

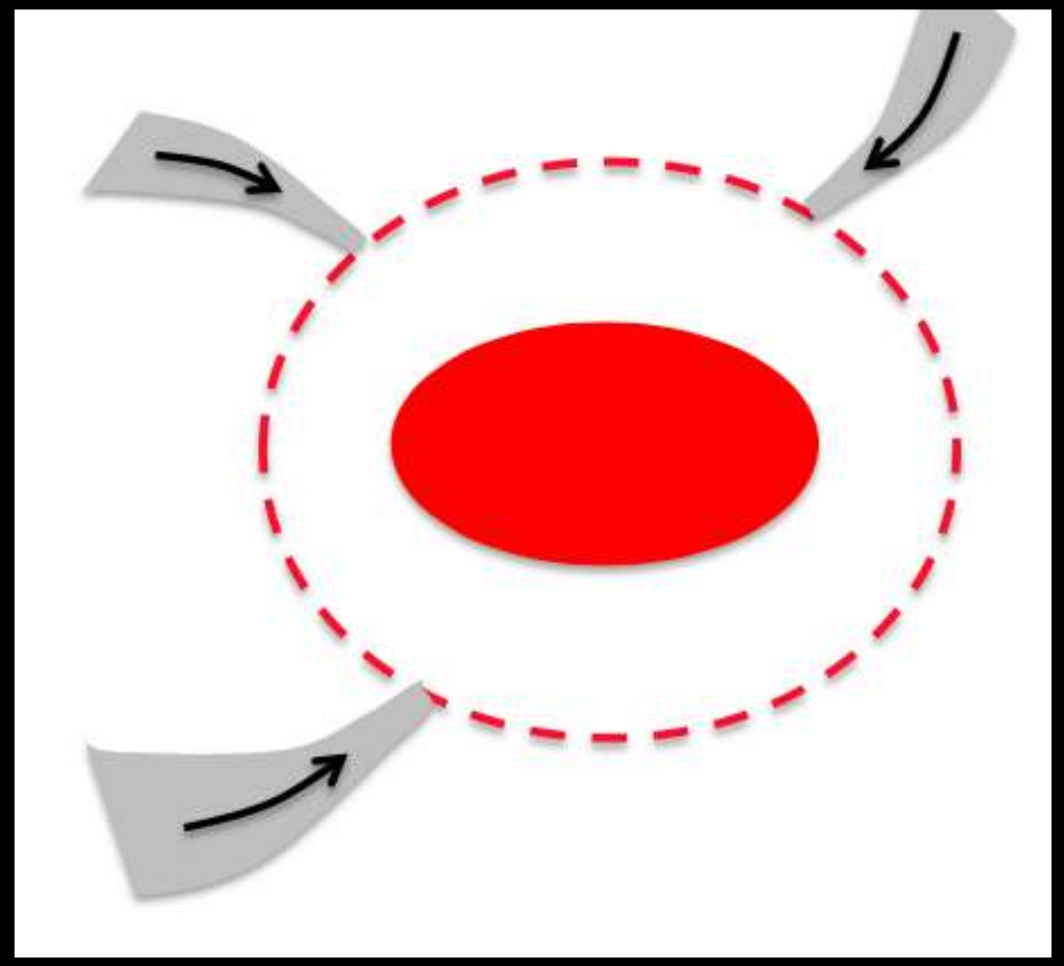
Recurrent “explosions”:
multiple times in the life
of the host galaxy: is it really what happens?

the energy released from the the AGN should ihave an mpact on very different scales





ejecting mode (gas outflows)



“maintenance” mode
preventing gas from cooling/halt gas supply

from R. Maiolino lectures

Radio jets can connect small and large scales

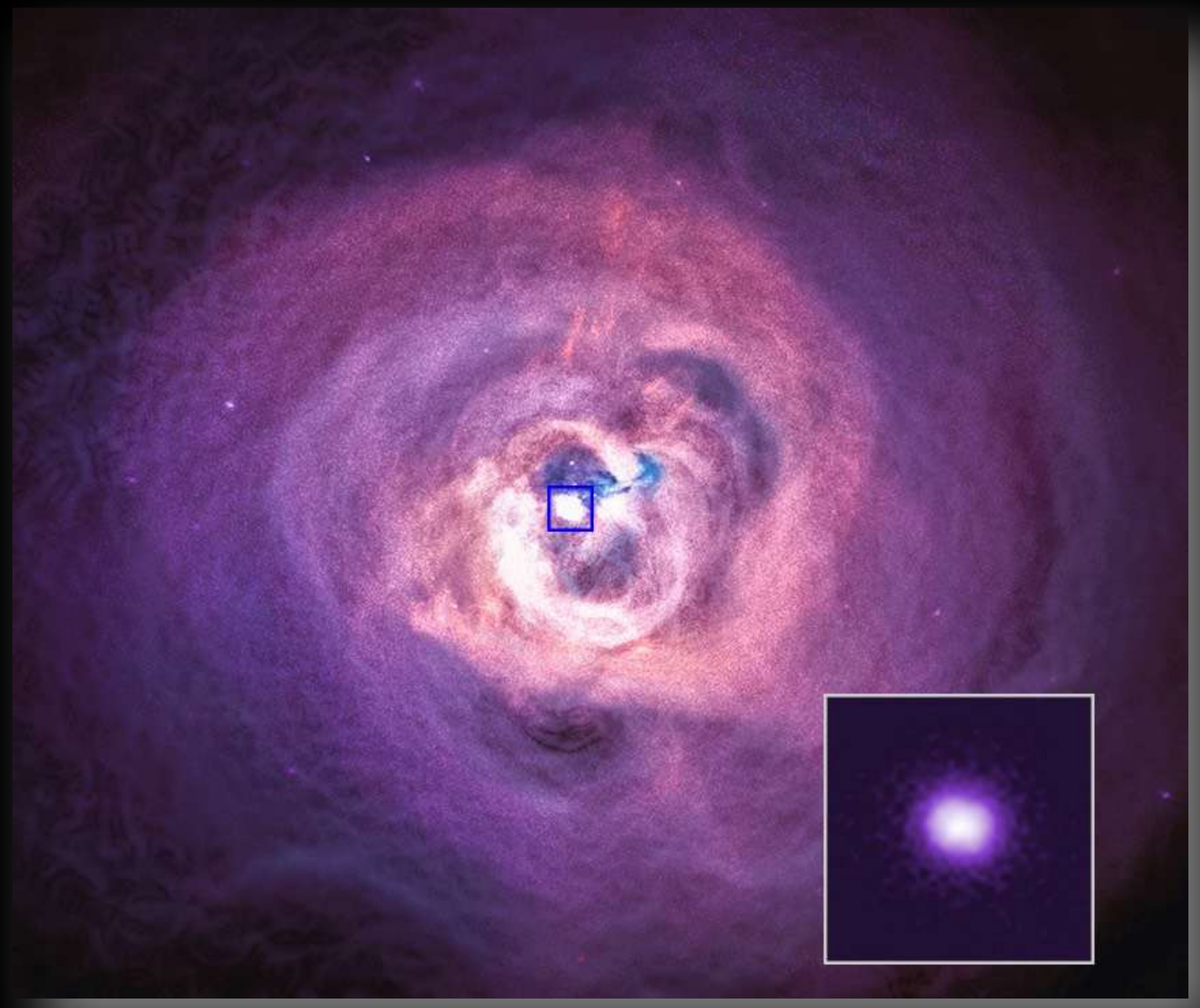
radio AGN (jets) considered key for the "maintenance" mode but
they can also drive gas outflows
we will see they role in both feedback modes

↓

but is their impact enough?

c) Radio jets and cluster cavities

1) Radio plasma preventing the cooling of the gas: possibly the best example of AGN feedback....



Starting point: issue with cooling flow in clusters of galaxies

+ hot (X-ray) gas should cool ($t_{cool}<10^9$ yr) and pile up in the centre of clusters ➙ highly enhancing star formation
(this should also happen in massive ellipticals)

➙ *this is not observed!* *(cooling flow problem)*

although some cold molecular gas is observed (Russell et al. 2019)

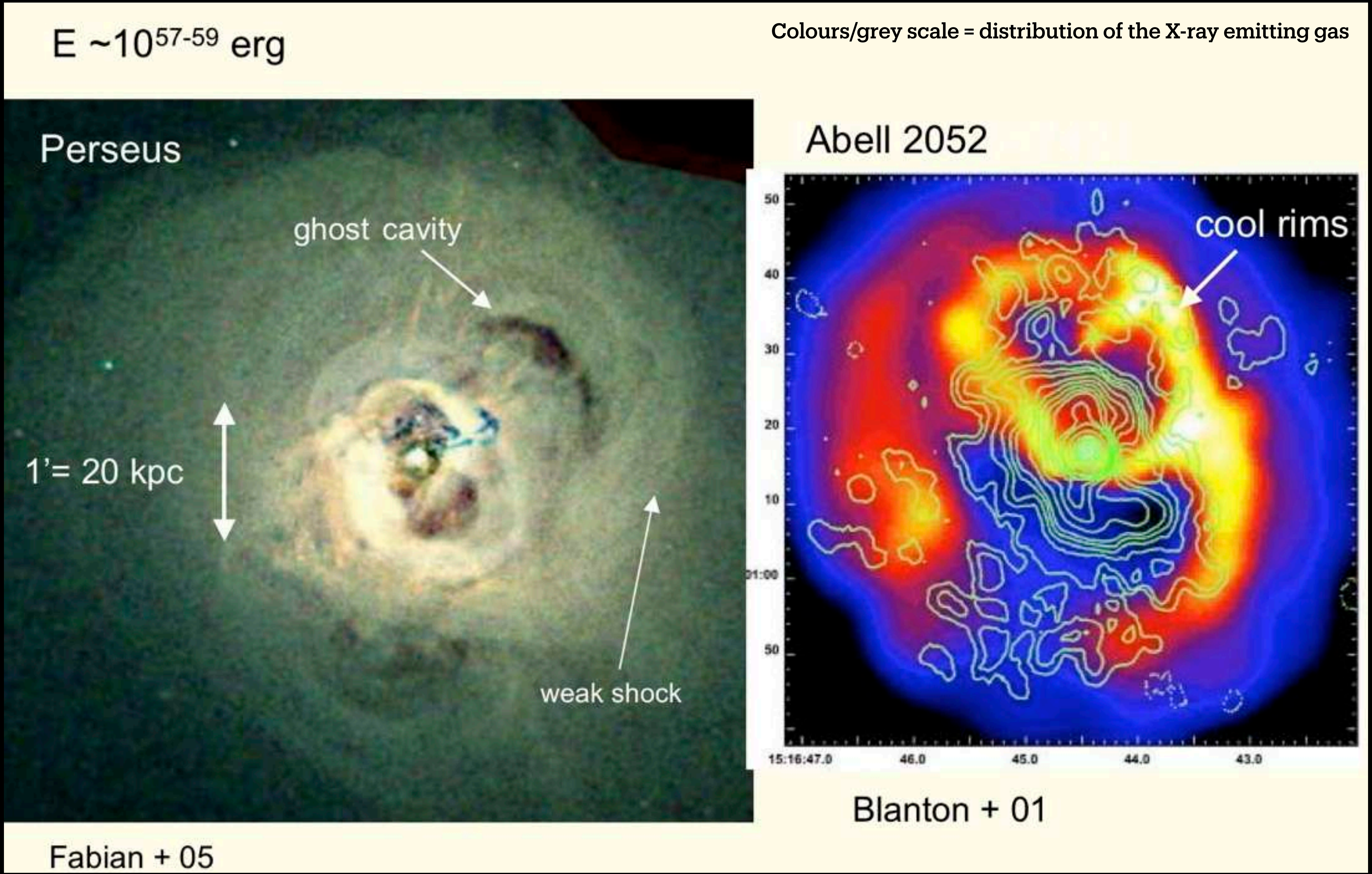
+ solved by the action of AGN

+ feedback loop

Bîrzan et al. 2004, 2008, review McNamara et al. 2012

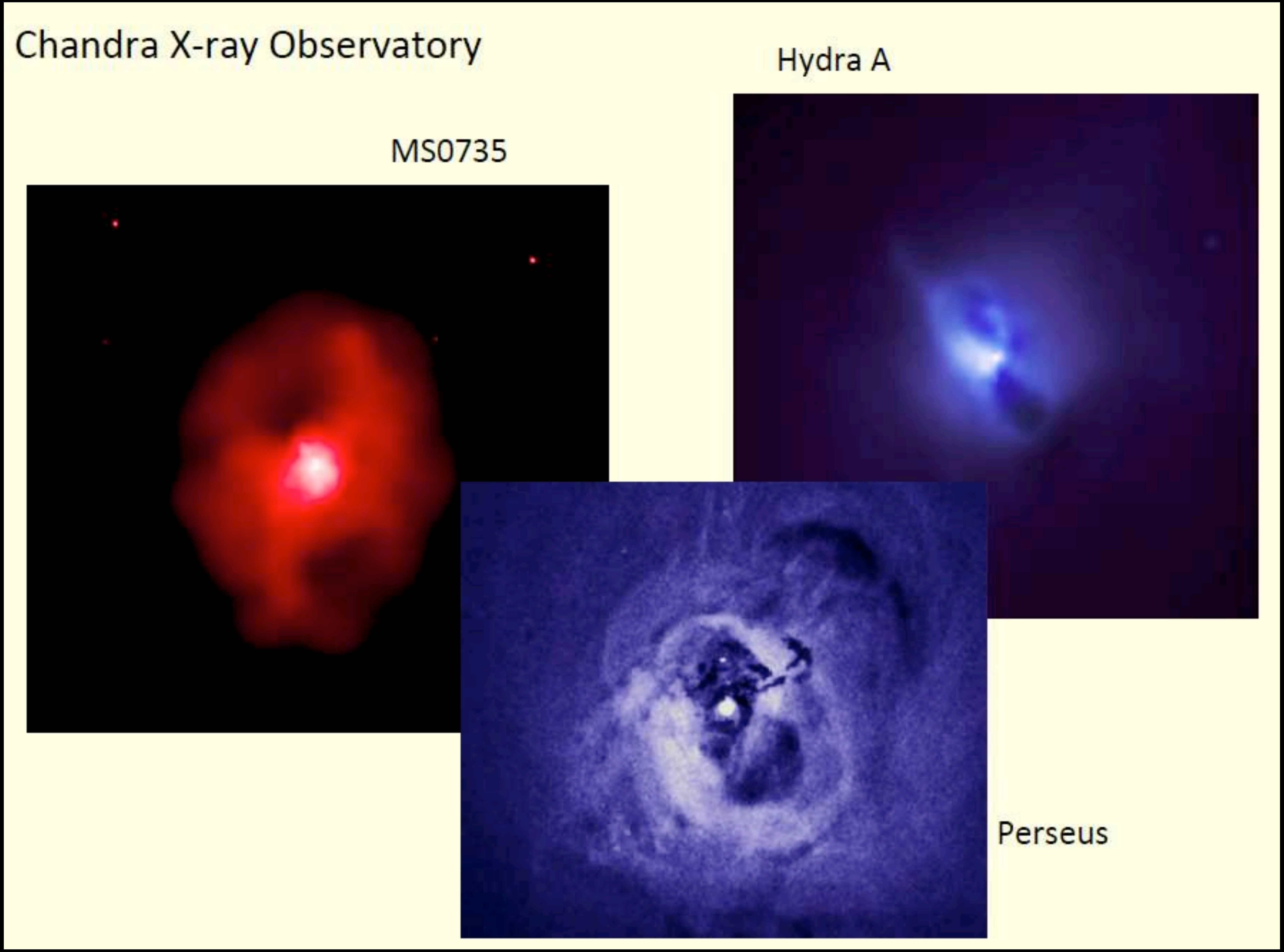
How is this loop observed?
Cavities in the inter-galactic hot medium

X-ray observations have revealed hot bubbles and cavities in the hot intergalactic medium: these cavities are often filled with radio plasma from the radio AGN



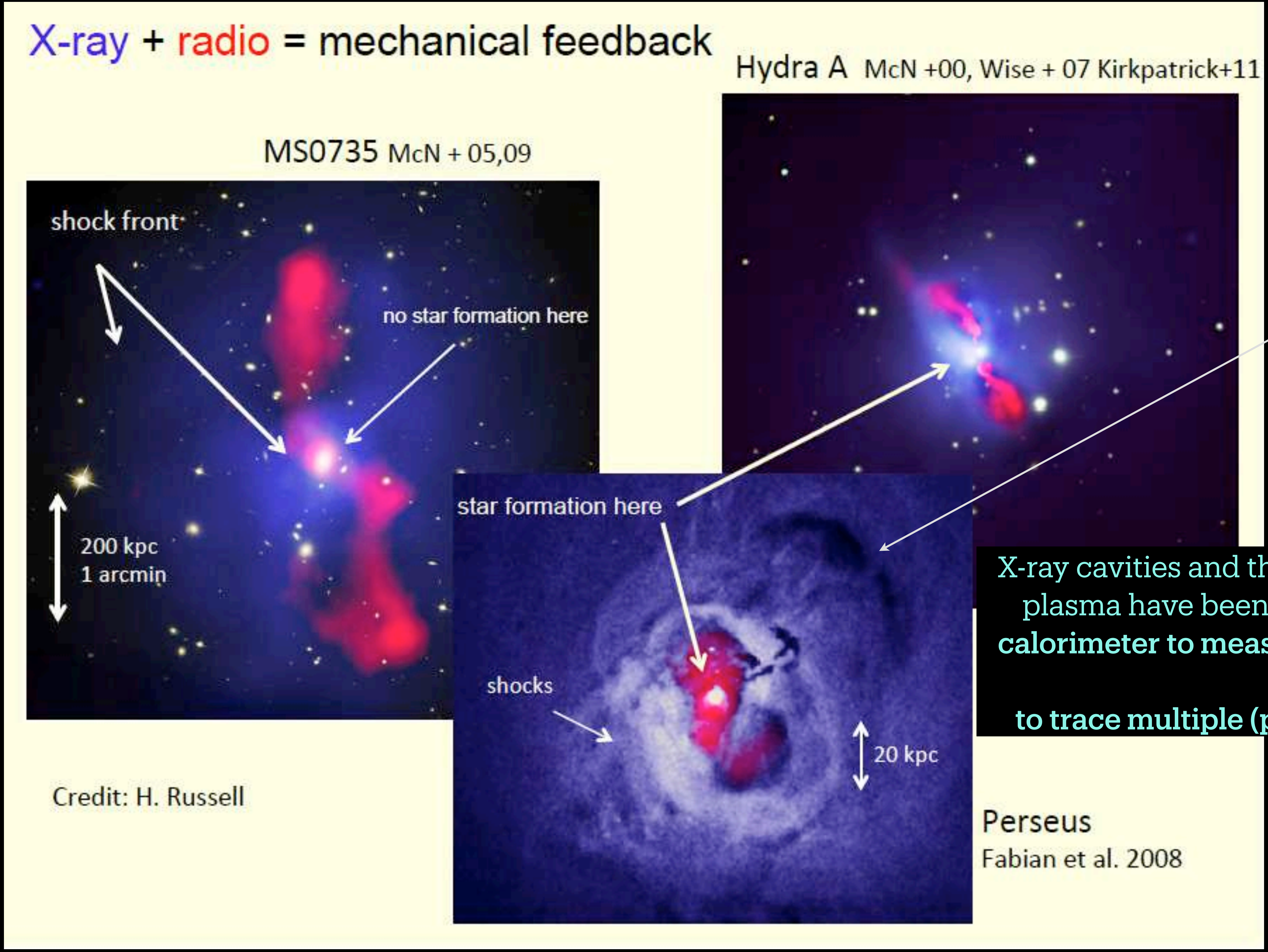
Radio galaxies in cluster: key objects for feedback

often bright cluster galaxies in the centre of gas-rich clusters



X-ray cavities filled by radio plasma

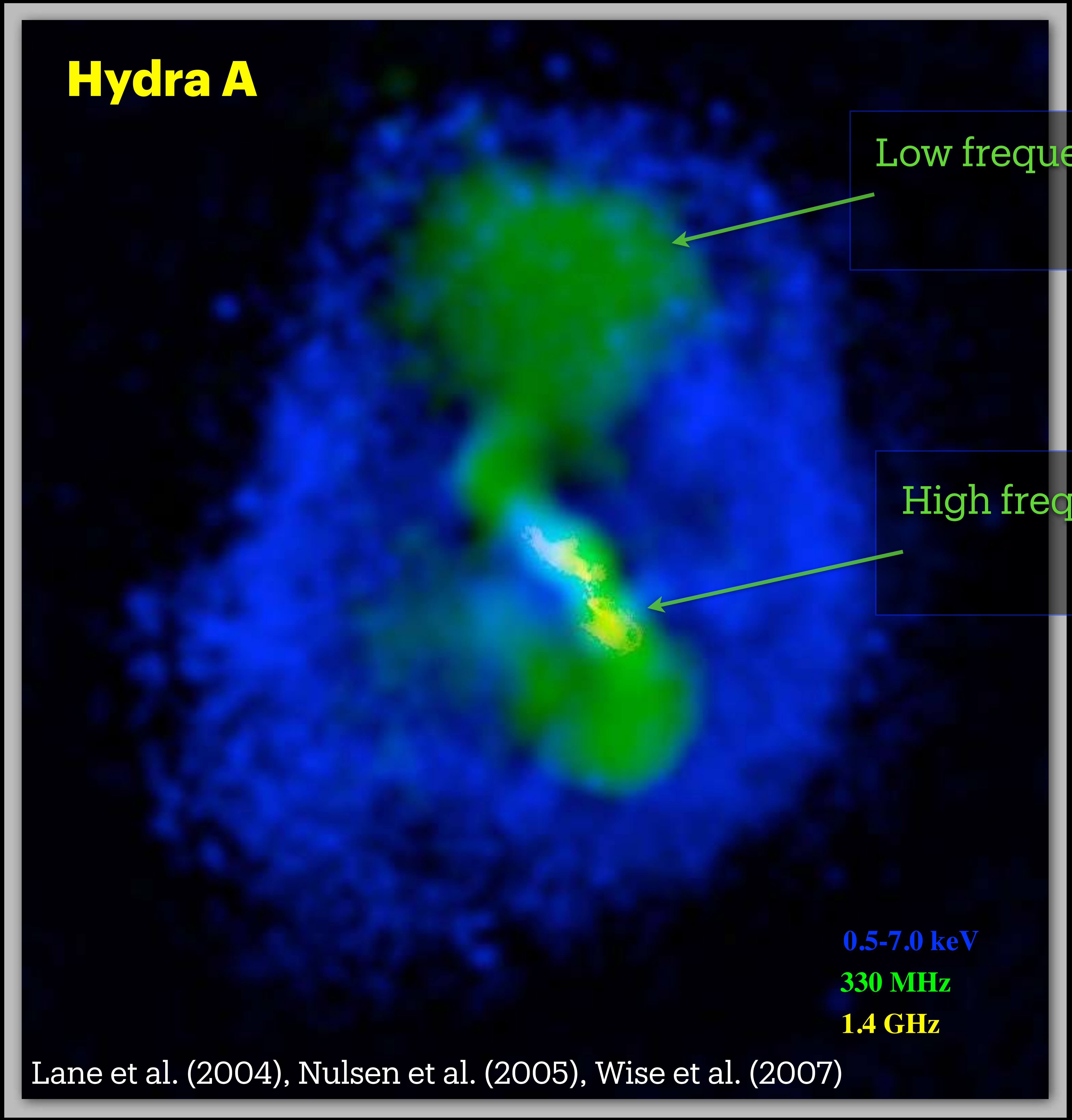
X-ray gas pushed out of the cavities and compressed into shells by the radio plasma ejected by the central AGN



ghost cavities

X-ray cavities and their connection with radio plasma have been crucial for two reasons:
calorimeter to measure the energy deposition
and
to trace multiple (past) phases of activity...

Cavity Systems: tracing the history of (integrated) AGN output - complementary to spectral index



From radio

Low frequency ⇒ integrated history
t > 200 Myr
outer cavities

High frequency ⇒ recent activity
t ~ 50 Myr
inner cavities

Low frequency radio observations (150MHz) sensitive the the old plasma

Diffuse emission
Steep spectrum

From X-ray

Ages of cavities derived with three different methods: 1) as the time required for it to reach its projected location assuming it traveled at the sound speed; 2) as the time for the cavity to rise buoyantly to its present location; 3) the refill time-scale

➙ inner cavities 50-100 Myr

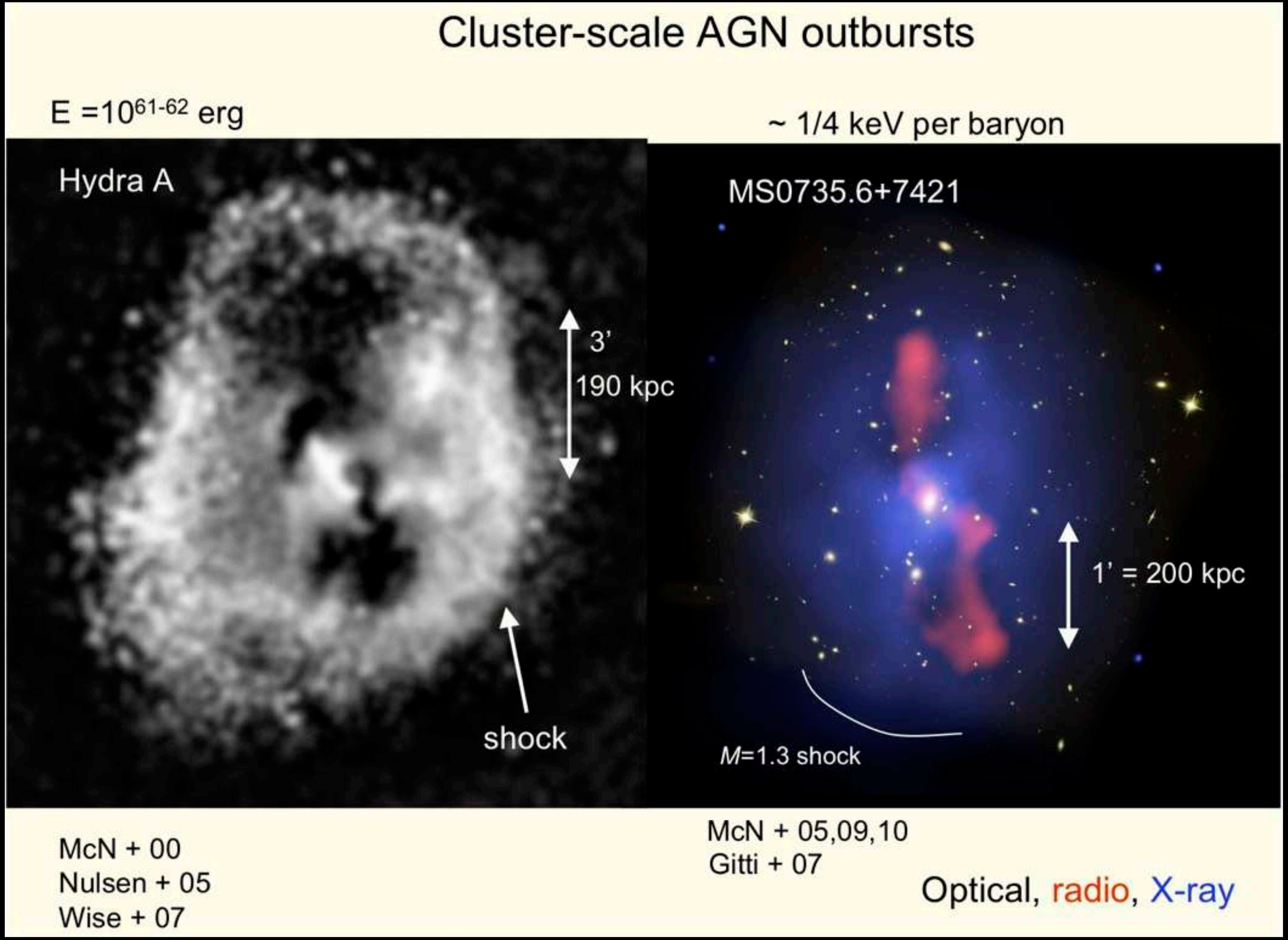
➙ outer cavities 100 - 200 Myr

(McNamara et al. 2000; Nulsen et al. 2002, Wise et al. 2007).

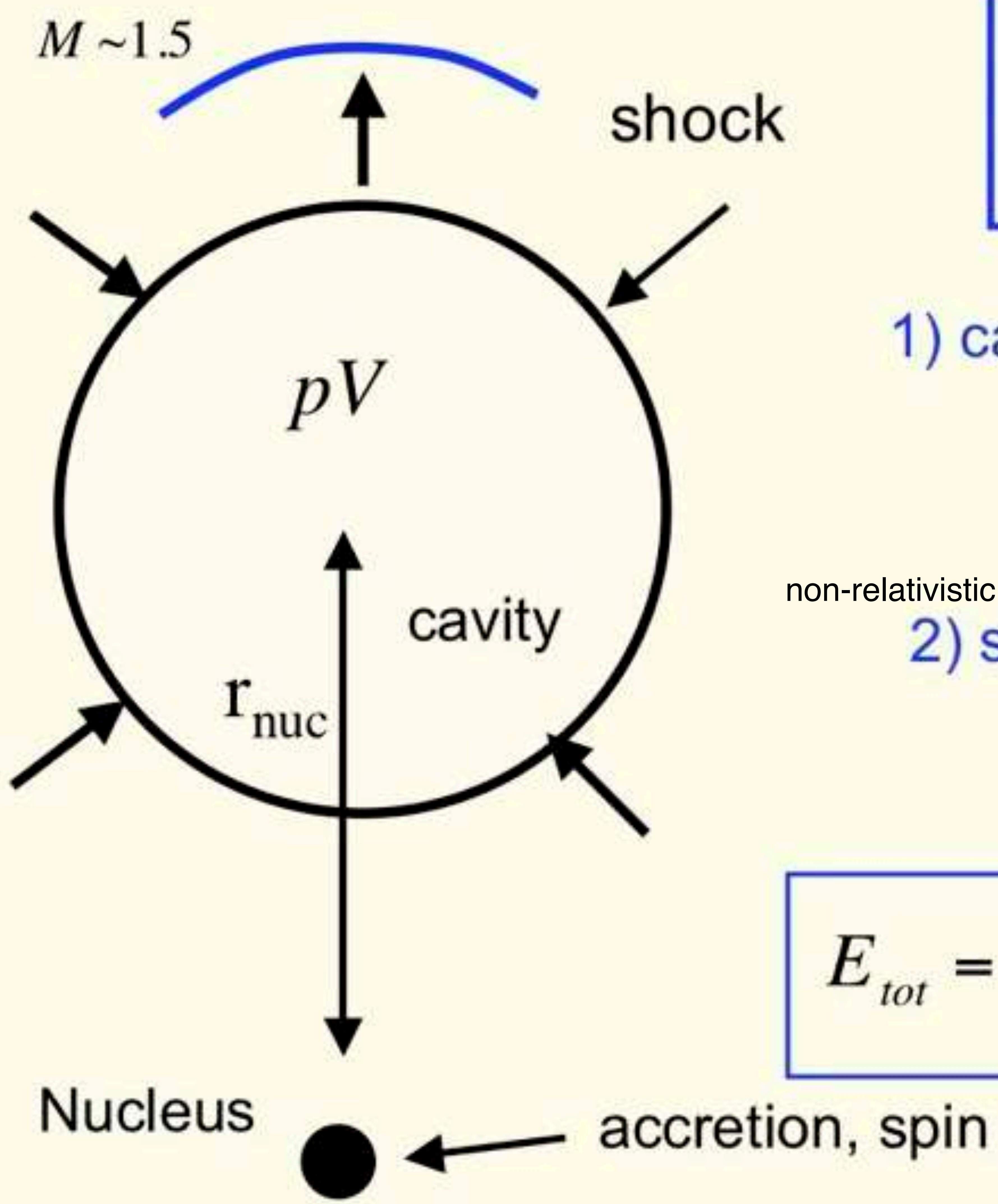
consistent with the time of the radio emission derived from the radio spectrum

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



- *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

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

non-relativistic plasma (gamma = 5/3) relativistic plasma (gamma = 4/3) or

2) shock

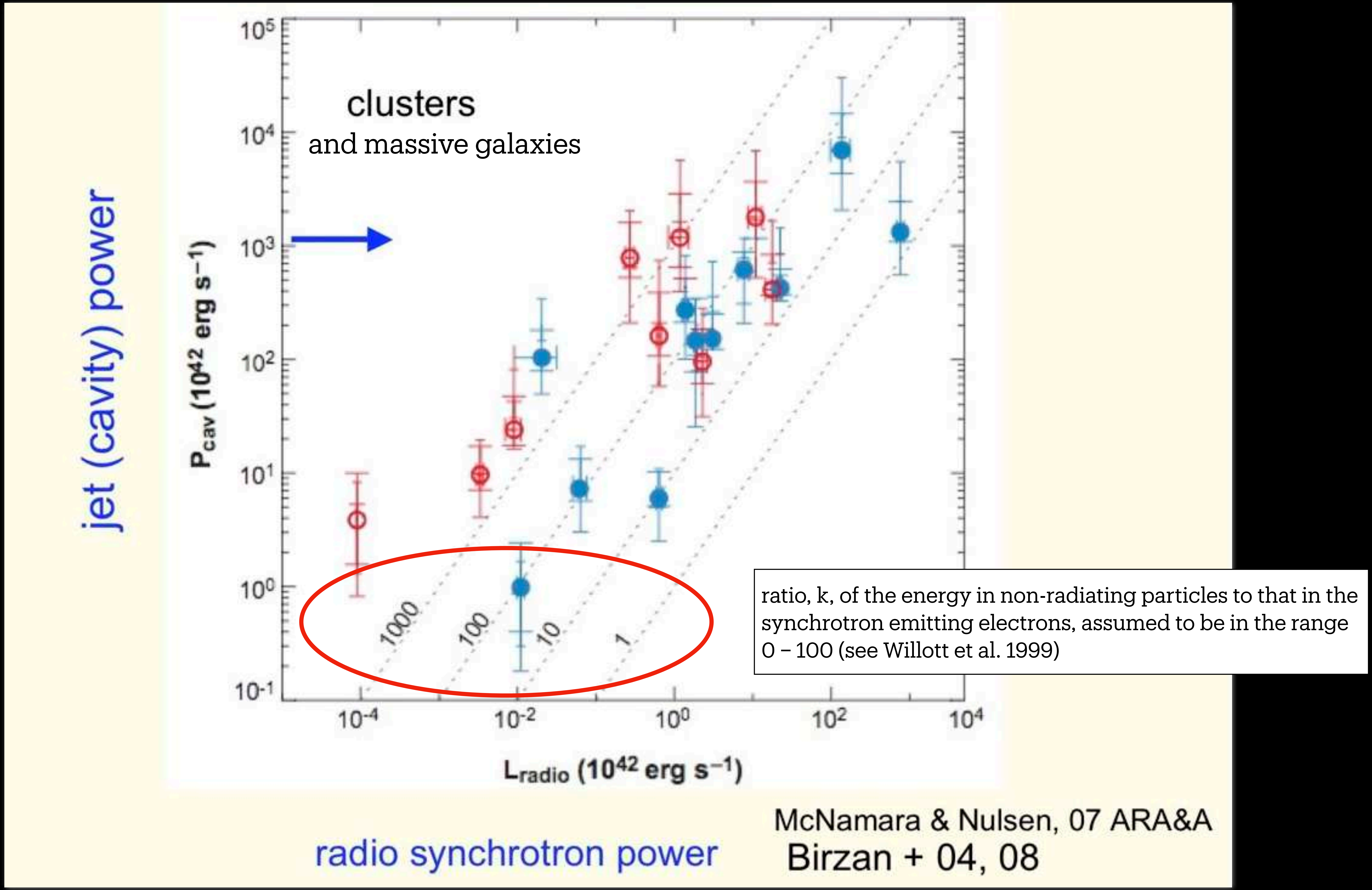
$$E_{shock} \approx \Delta p V \qquad t_{shock} \approx r_{shock}/c_s$$

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

→ Volume of the bubble x Surrounding pressure (density and temperature of the thermal gas)/Age cavity
McNamara et al. 2000, 2001; Birzan et al. 2004 and many others McNamara review 2012

Energy needed to form the cavities ➙ total energy in the jets

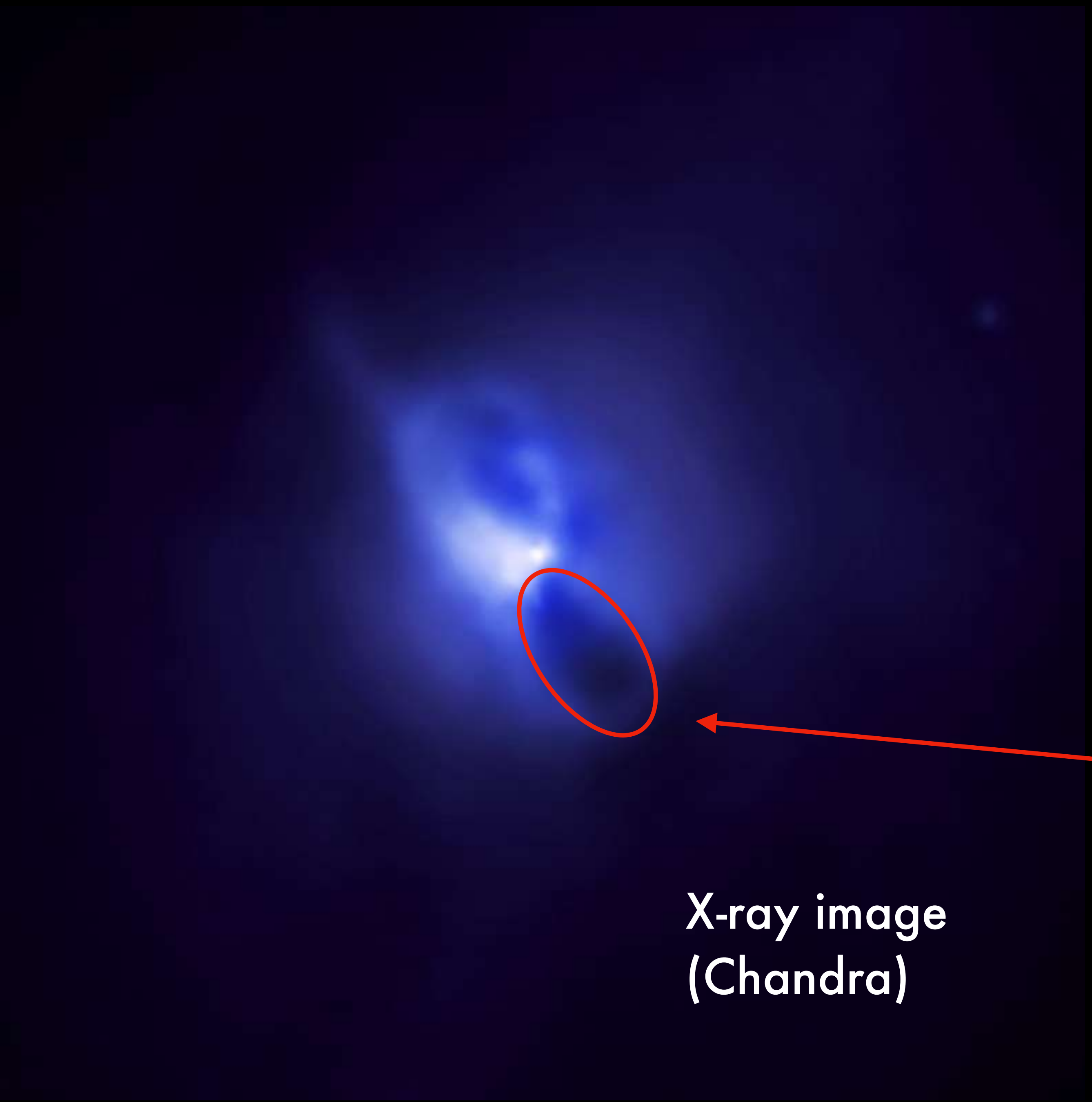
(i.e. not only the energy which is radiated)



Energy of the cavity expansion = Jet power

➙ Volume of the bubble x Surrounding pressure (density and temperature of the thermal gas)/Age cavity

An example: Hydra A



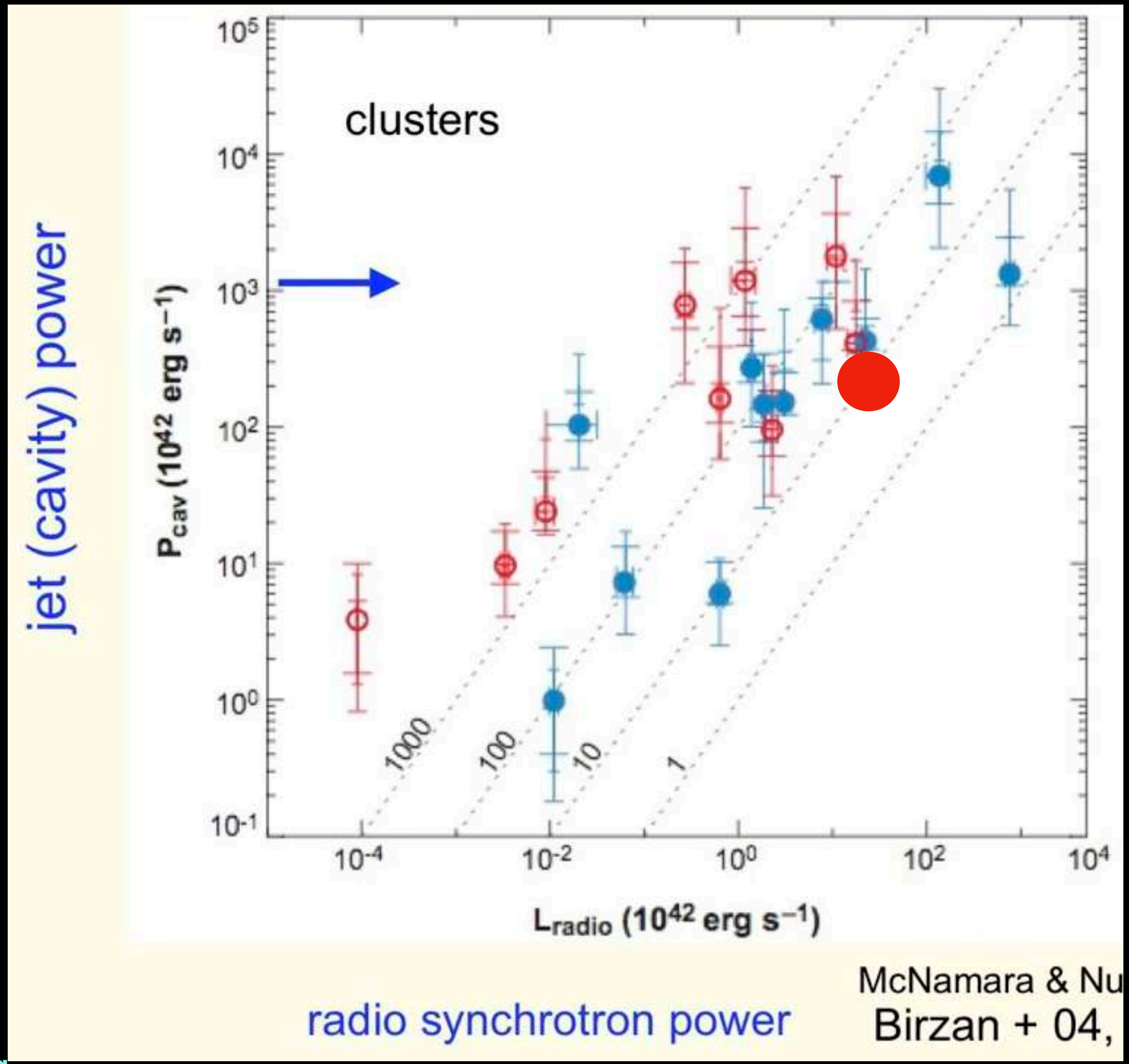
electron density ➔ n_e ~0.023 cm^{-3}
temperature ➔ kT = 3.4 KeV
pressure ➔ 2.8 x 10^{-10} erg cm^{-2}

over which Volume?
sphere ~15 kpc ➔ pV ~ 1.2 x 10^{59} ergs

no signs of shocks, only subsonic motion of the gas

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

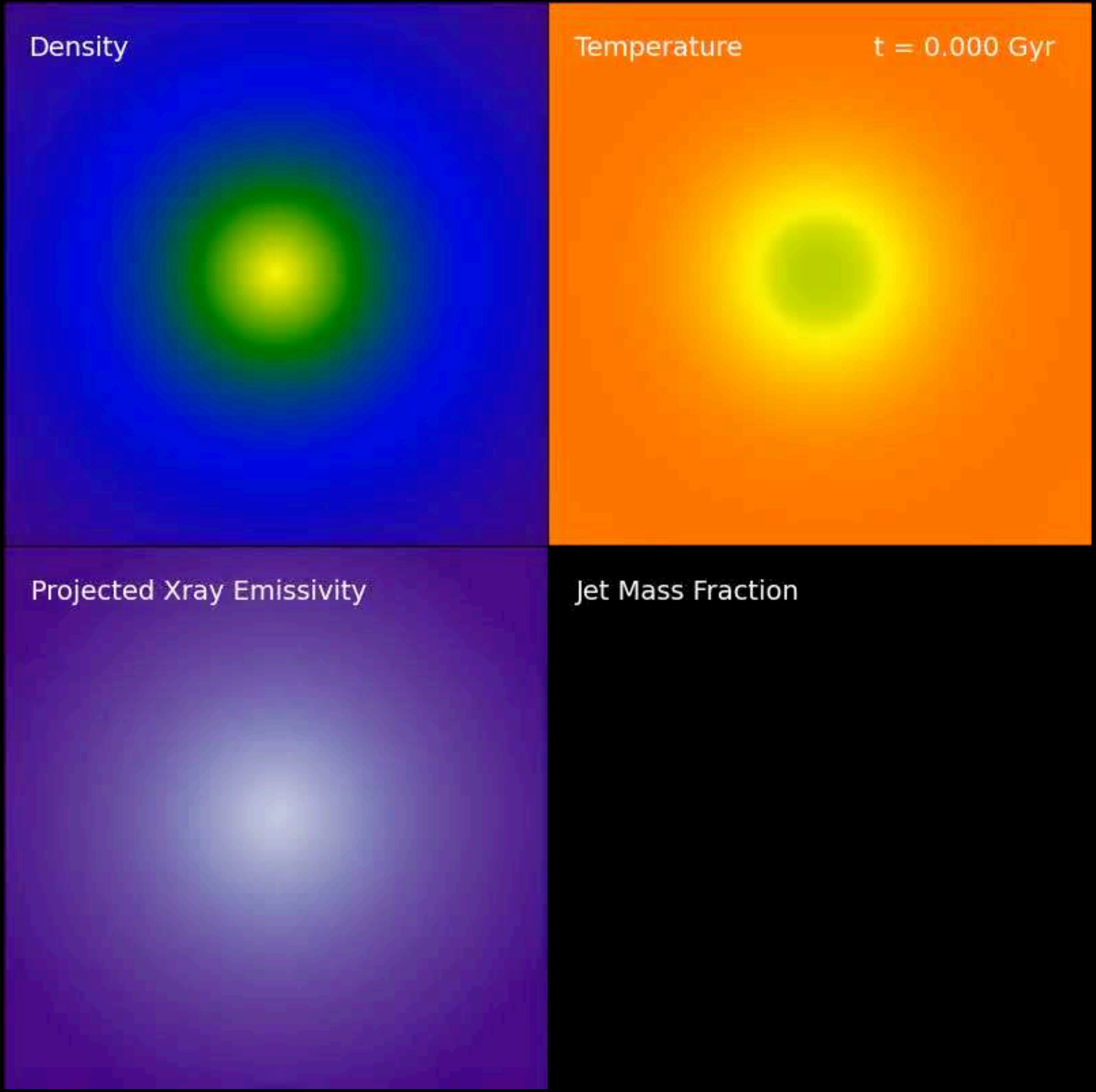
needs 2 x 10^{44} erg s^{-1} of jet power to maintain the cavity



Ten times more jet power than radio luminosity...

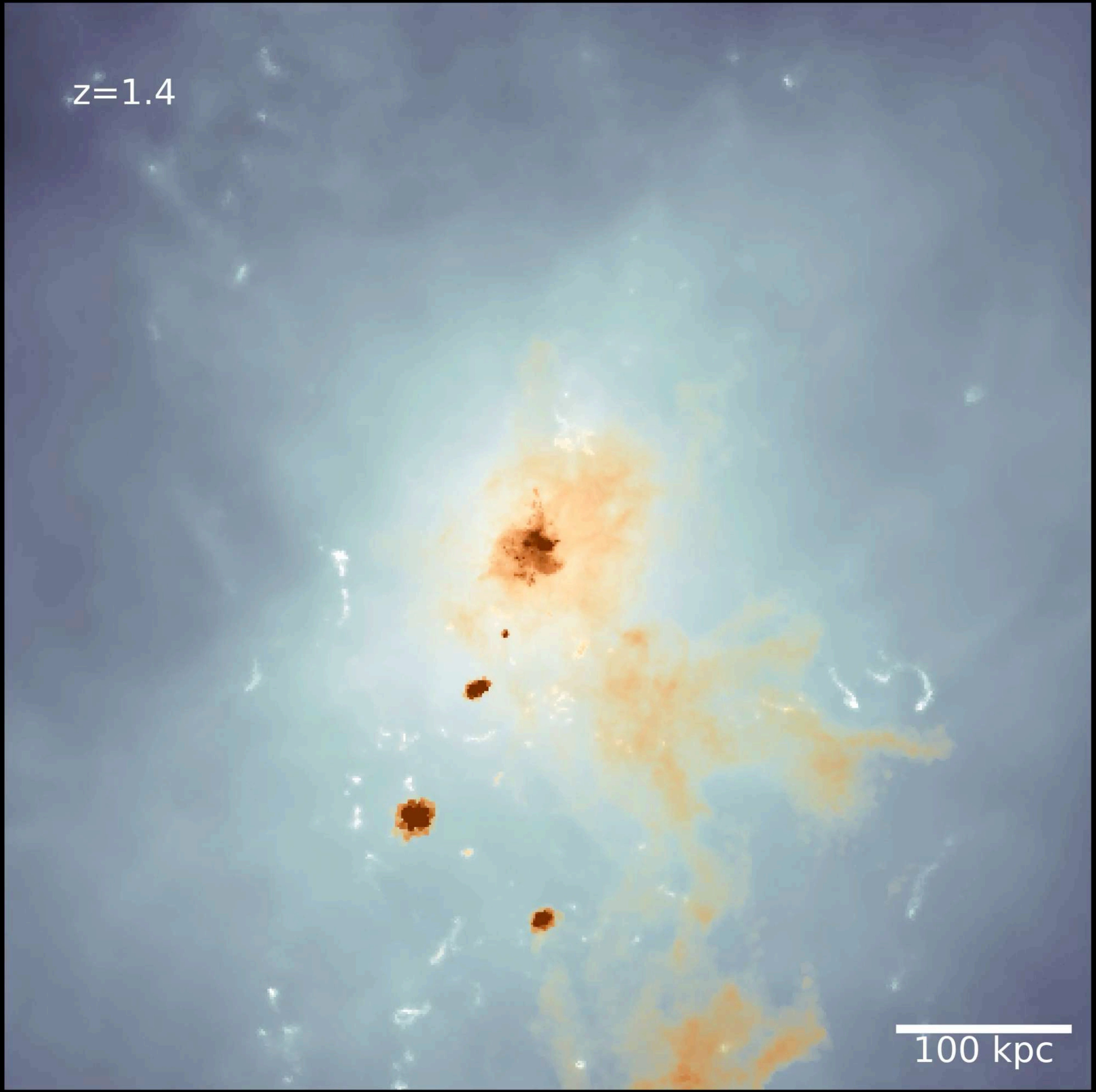
Limitations of this method for in particular for low luminosity (radio-quite) sources

From the simulations



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)

Cosmological simulations are starting to include this

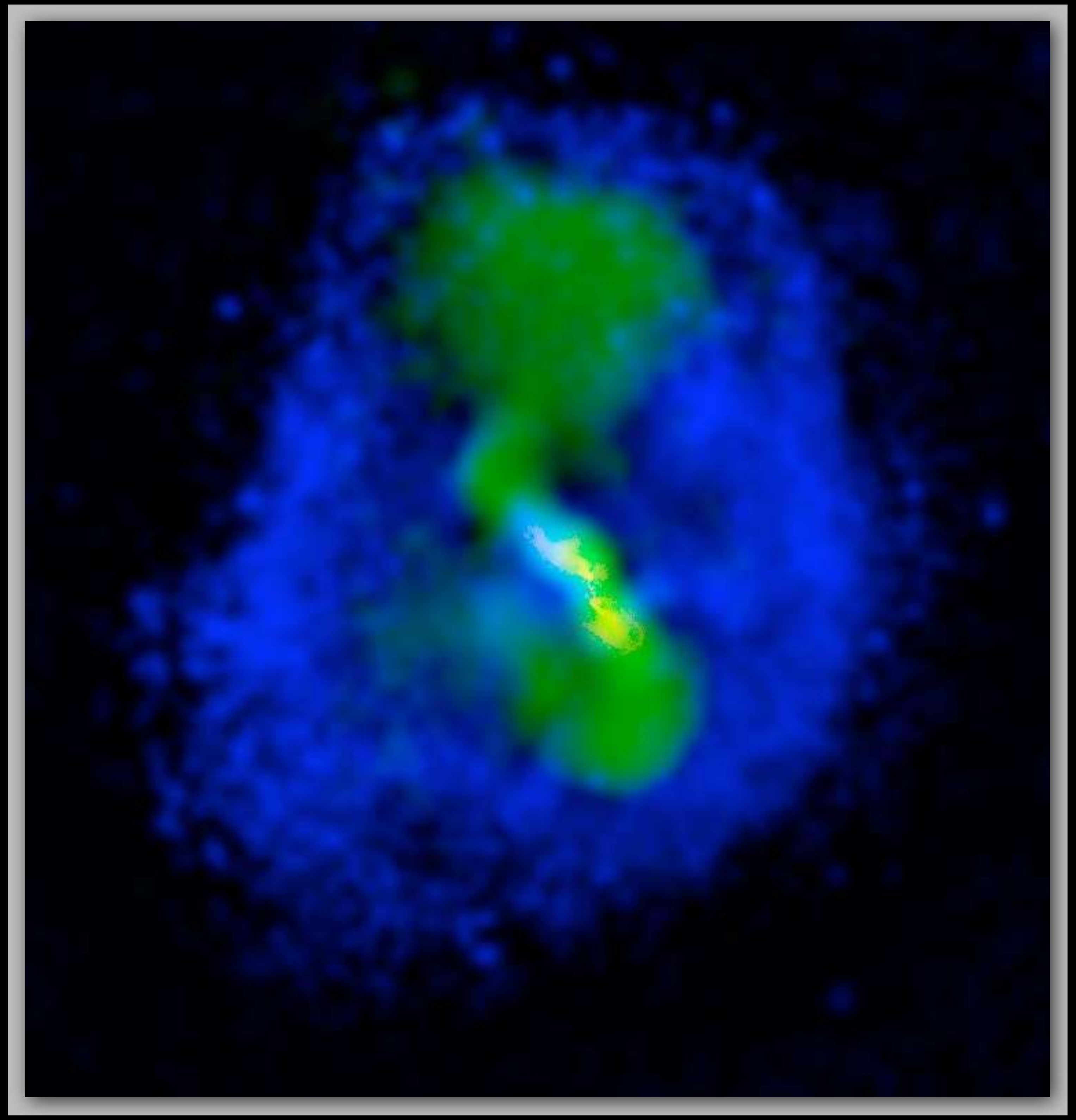


A movie of a cosmological zoom simulation of a 10^{15} $M_{\odot}$ galaxy cluster, with a sidelength of 1.5 Mpc.
White: column density of the ICM gas,
Red: material from AGN jet feedback.

The red “jet” material is decaying over a few 100 Myr timescale (evolution of the cluster over 7-8 Gyr or so), so the jets from AGNs (not only in the central AGN) have to continuously restart,
The resulting morphology is highly dependent on the intra-cluster turbulence on these large scales.

Weinberger et al. in prep

Are you still with me?



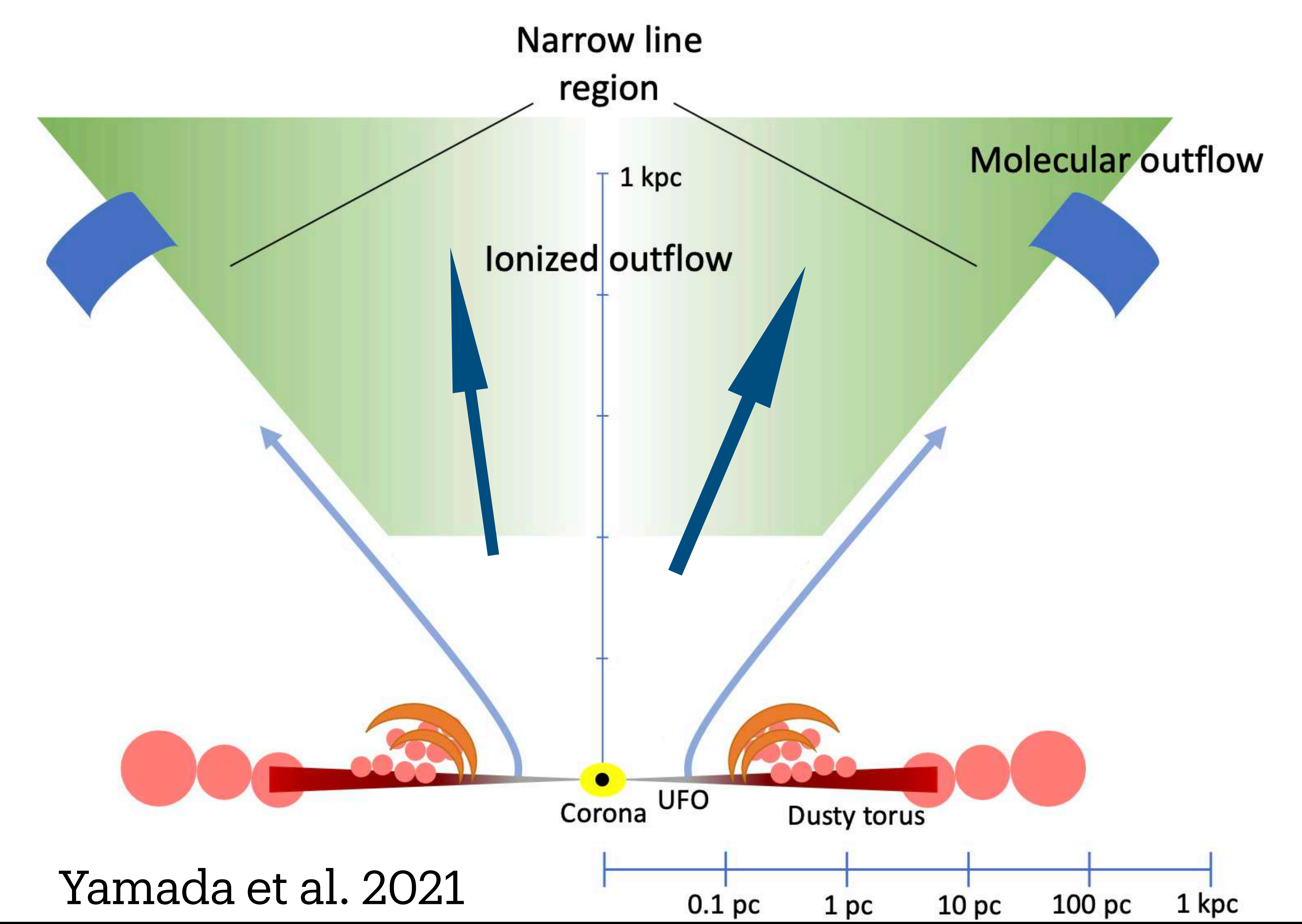
- Radio plasma can halt the cooling of the ICM/IGM, therefore stopping the accretion on the galaxy of fuel for new star-formation
- Typical time scales derived for the cavities up to few x10^8 years: to first order consistent when derived in different ways (cavities vs spectral indices).
  Multiple cavities observed indicating that the process has been recurrent (with the direction of the jet that can change!)
- Jet power much higher than energy measured from radio luminosity: important for the energetics of this process

d) Radio jets driving gas outflows

Expel the gas via outflows

Outflows on different scales and of different phases of the gas

- Nuclear winds ➙ X-ray absorption (10^7 K) Ultrafast outflows (UFO) ⟶ sub-pc scale
- Outflows of ionised gas ➙ emission lines (10^4 K) ⟶ up to many kpc
- Outflows of COLD (and even molecular!) gas (100 - 1000 K) ⟶ up to kpc ⬅



Yamada et al. 2021

see also review Harrison & Ramos Almeida 2024

Parameters that can be derived

- uncertainties: location, velocity, density of the outflow

requires high spatial resolution to measure the radius of the outflowing region

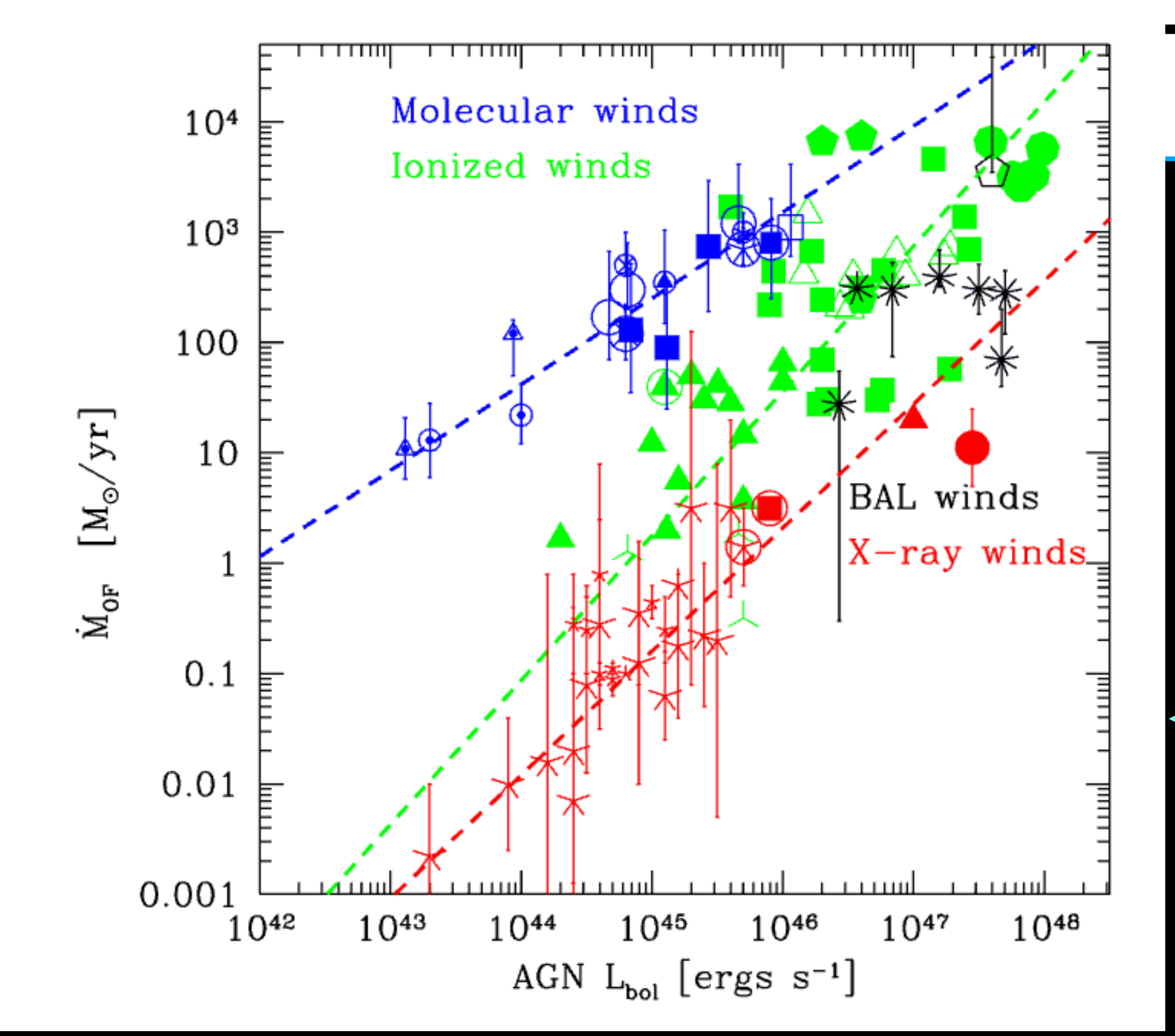
Mass outflow rate $$\dot{M}_{out} \propto \frac{M_{out} v_{out}}{r_{out}}$$ $M_{\odot}$/yr

Mass outflow rate

Velocity dispersion outflow

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

Harrison et al. 2018 for more about parameters of the outflows



Extreme cases: high luminosity end of AGN (radiative mode)+ULIRG interesting correlations
Fiore et al. 2017

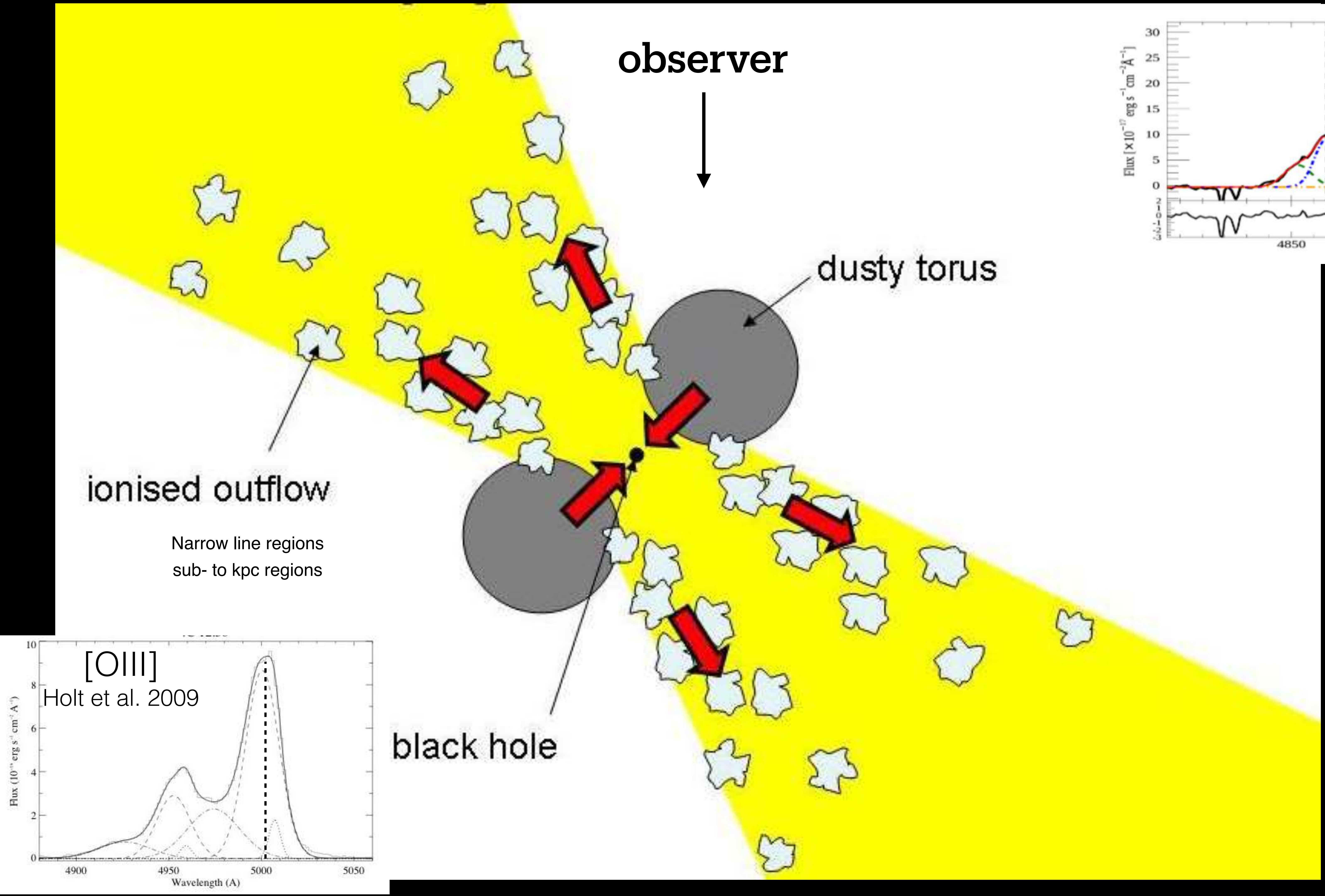
More commonly found values of mass outflow rate:
from <0.1 $M_{\odot}$/yr (ionised gas)
to many tens/hundred $M_{\odot}$/yr molecular gas

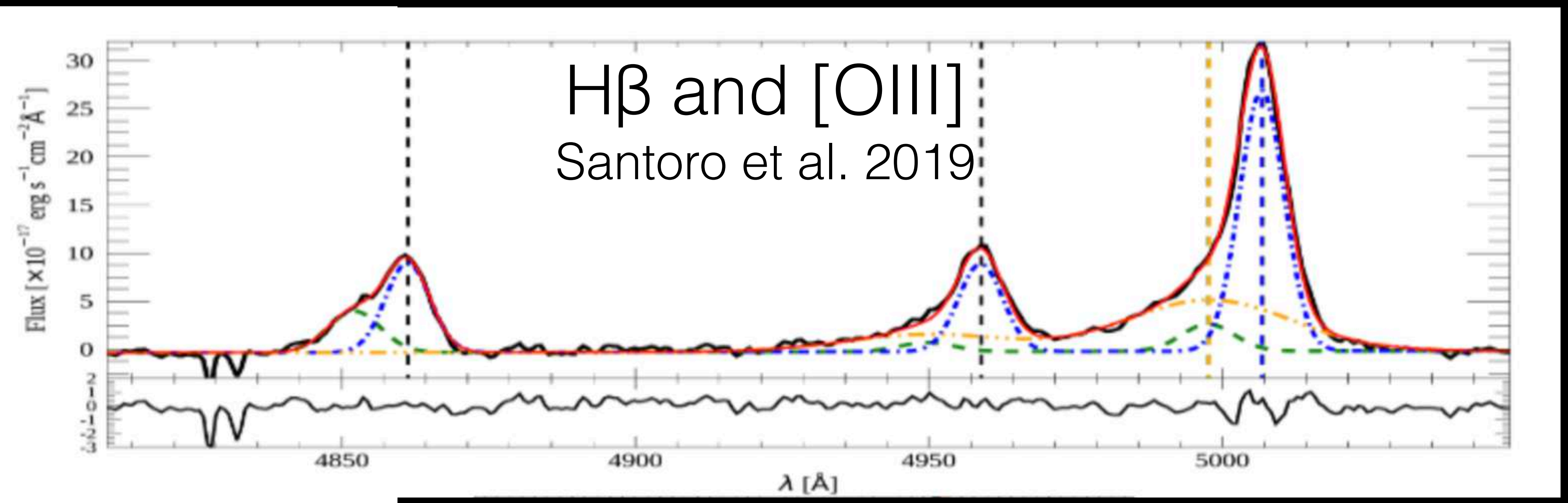
Molecular outflows typically more massive but over a smaller radius (compared to ionised gas)

Outflows of warm ionised gas: quite common in AGN

how do we recognise an outflow?

Velocities up to FWM~2000km/s





shape of the lines very asymmetric and blueshifted
OR
broad width of forbidden lines

Width larger than typical rotation of the galaxy or deviating from the regular rotation

Properties:

velocities up to > thousands km/s

mass outflow rates: typically at most few $M_{\odot}$/yr, higher in the most luminous AGN

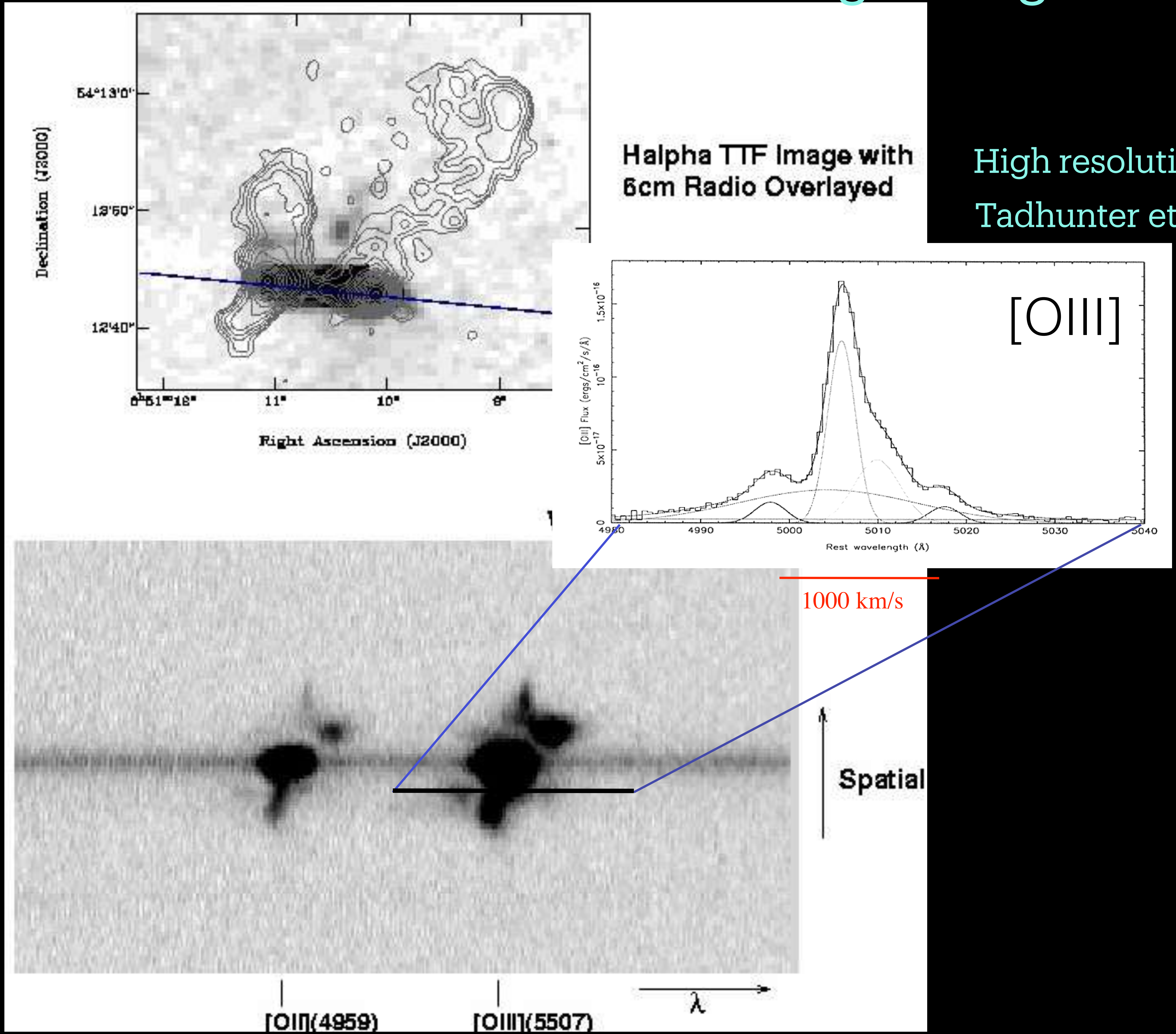
→ but uncertainties due to poor knowledge of gas density and geometry

Outflows of warm ionised gas

extending to larger radii (many kpc)

High resolution spectroscopy of 3C171

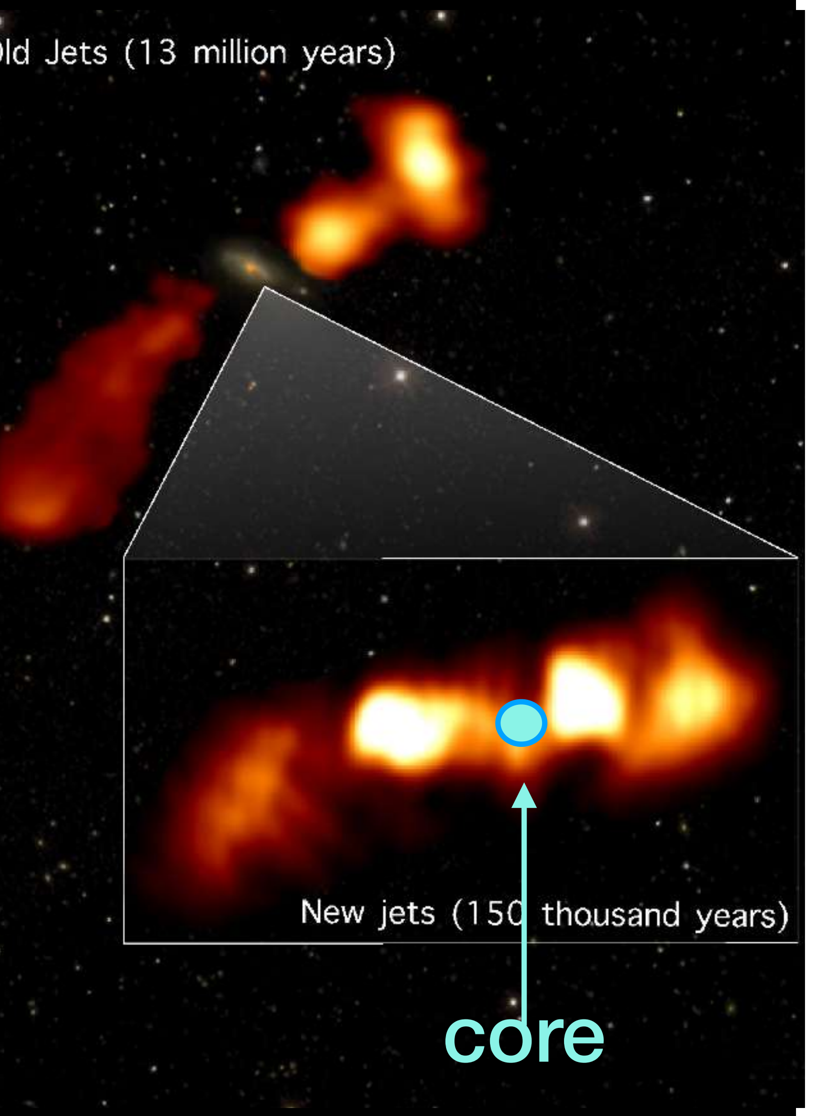
Tadhunter et al.

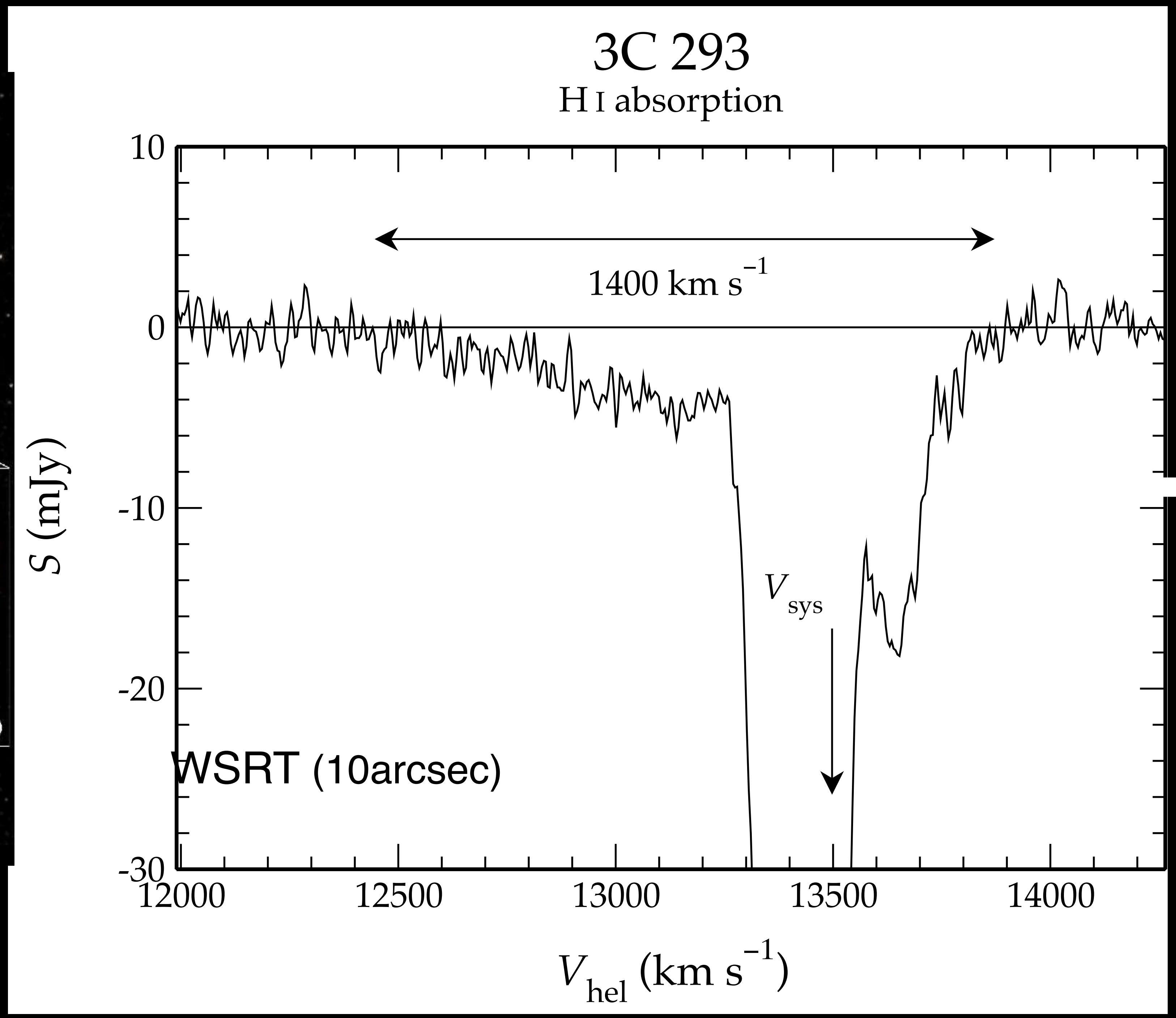


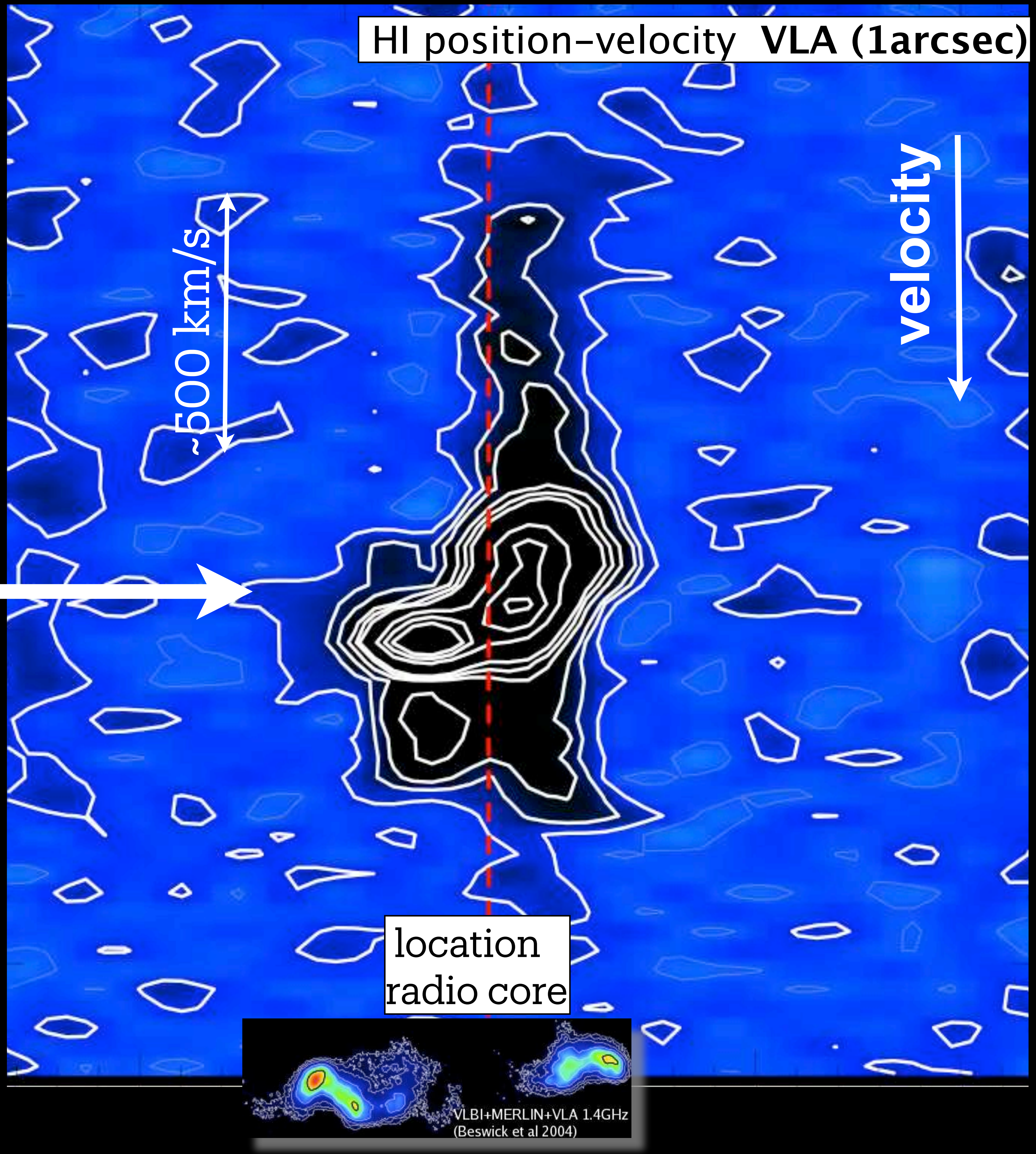
Not only ionised gas: also neutral and molecular

Atomic neutral hydrogen (HI) observed in absorption

Morganti et al. 2003, 2005, 2018







Mahony, Morganti et al. 2013

HI absorption against the radio continuum inner lobes: highlights the role of radio jets

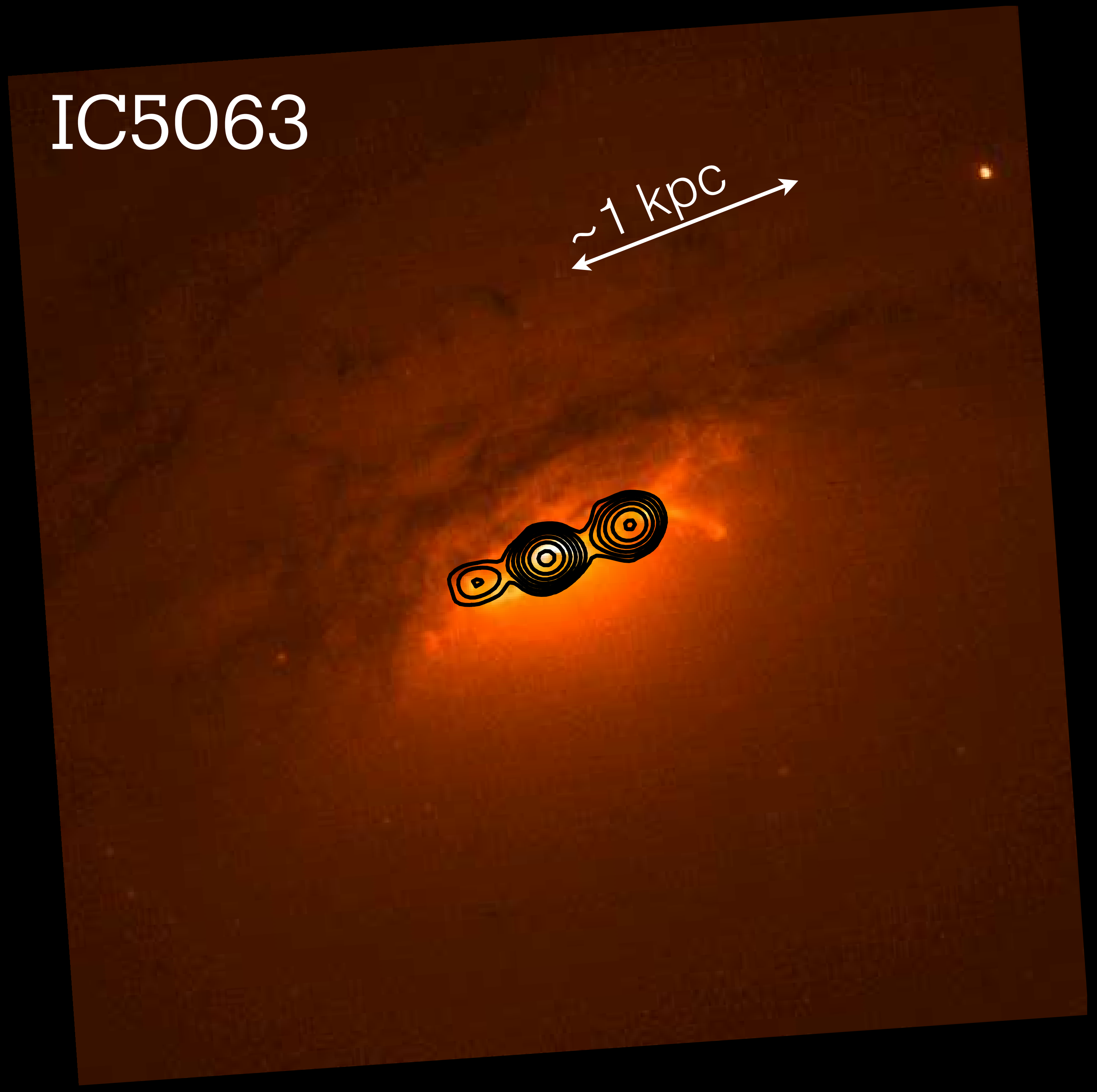
HI outflow mass from a few x 10^6 to 10^7 $M_\odot$

mass outflow rates: up ot few tens $M_\odot$/yr,

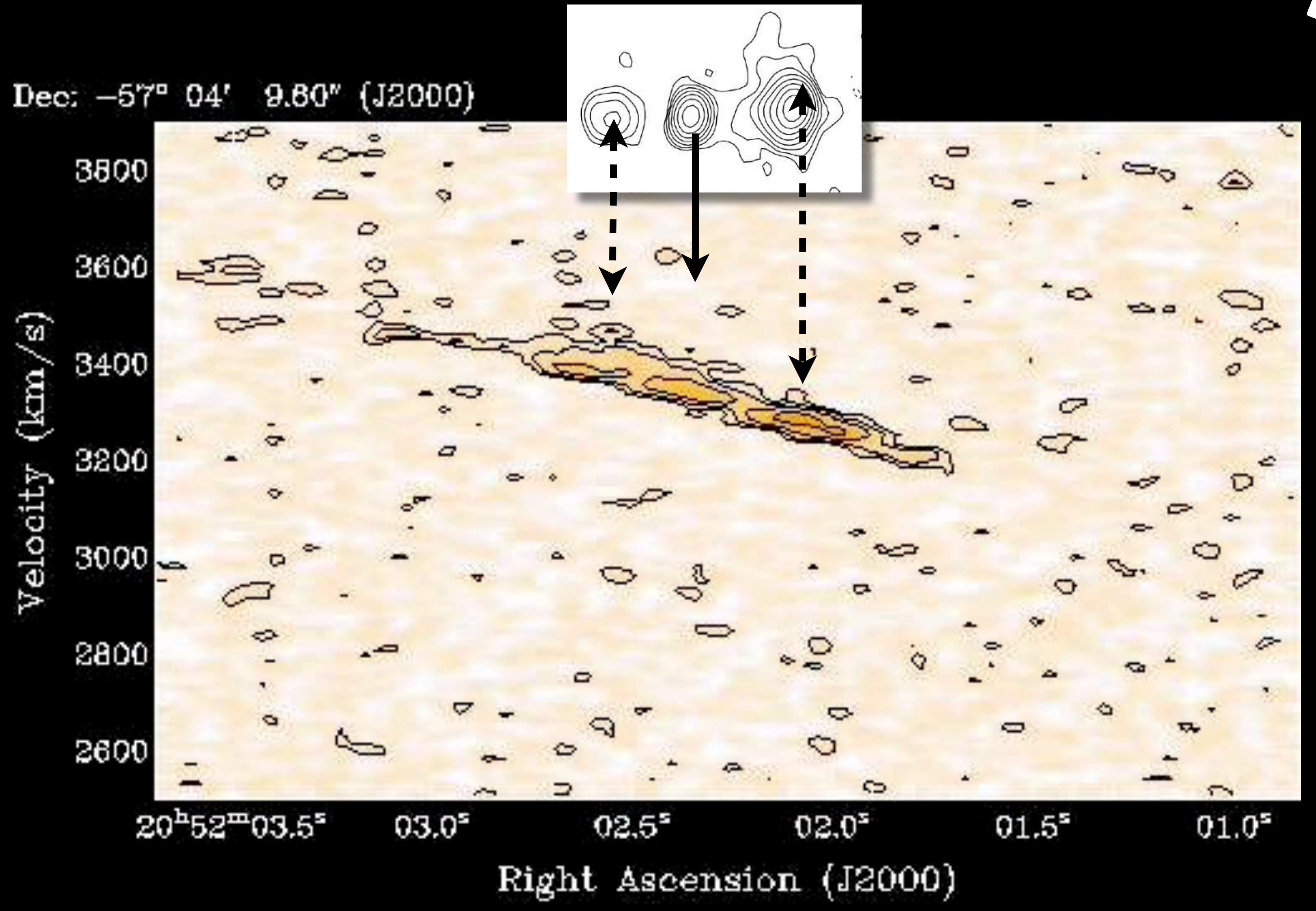
- Outflow kinetic power ~10^{43} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ ~10^{-3}
- Jet power Q_{jet} ~ 2 x 10^{44} erg/s

Molecular outflows in AGN traced by ALMA

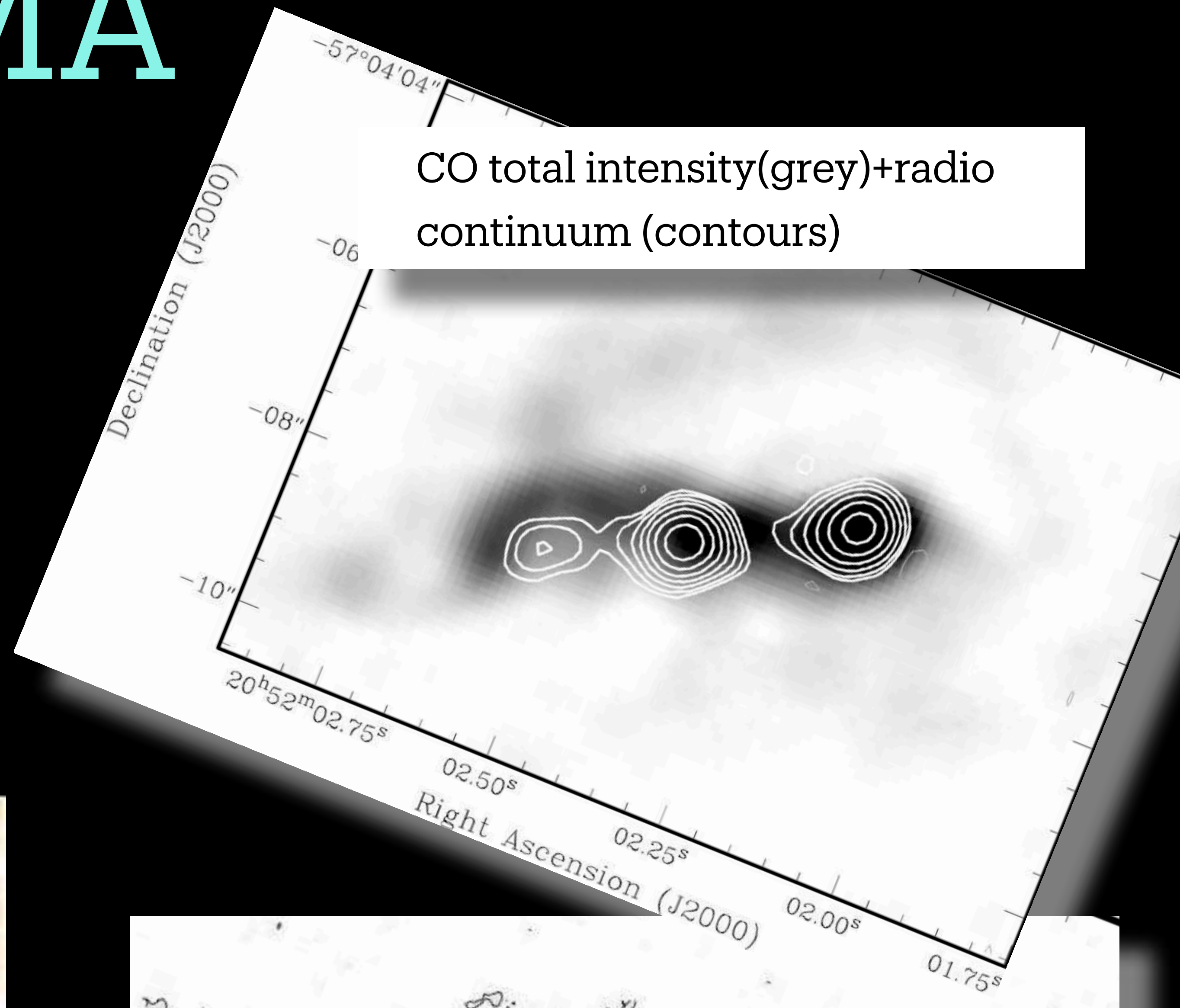
illustrating the full complexity of the kinematics of the molecular gas

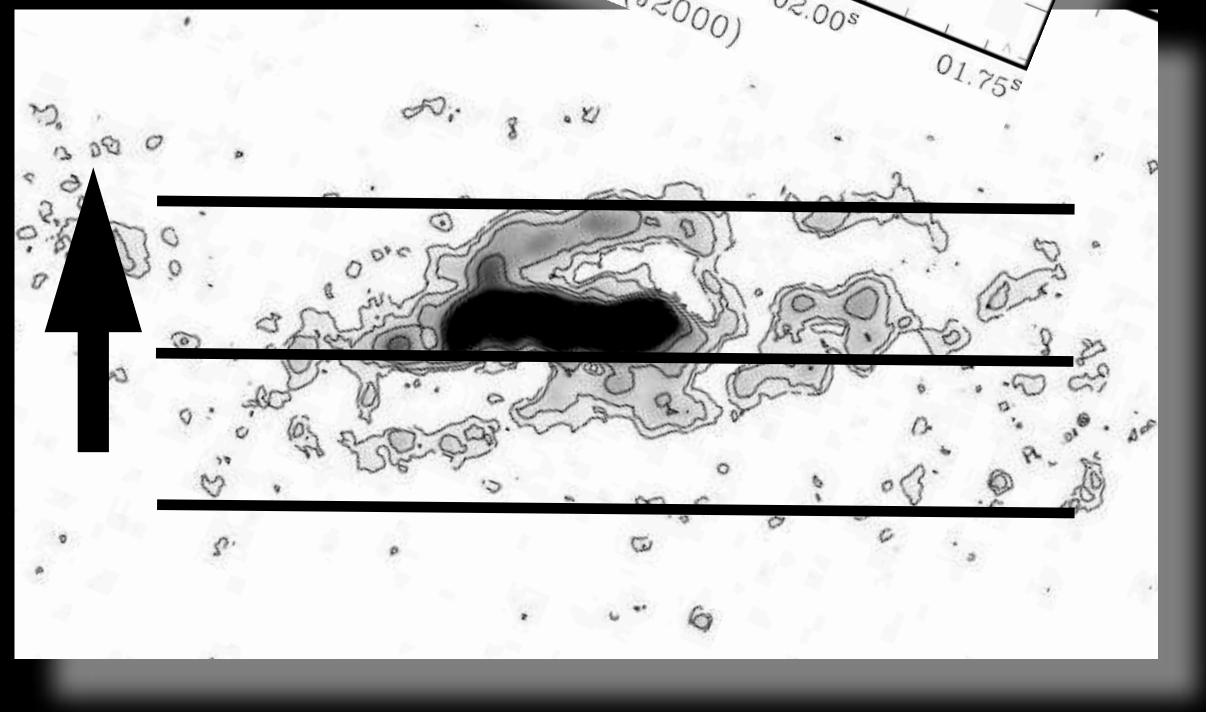


low luminosity radio jet



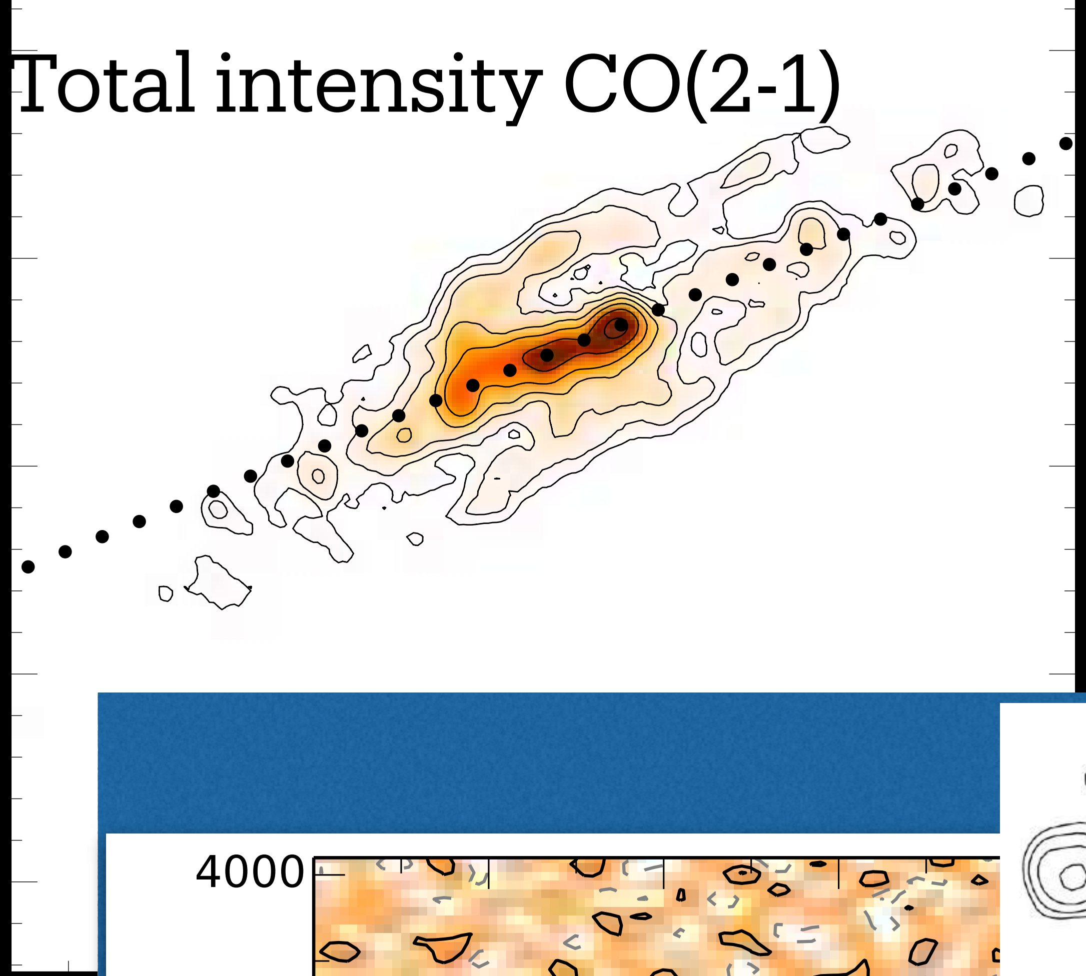
position-velocity plot along the radio axis

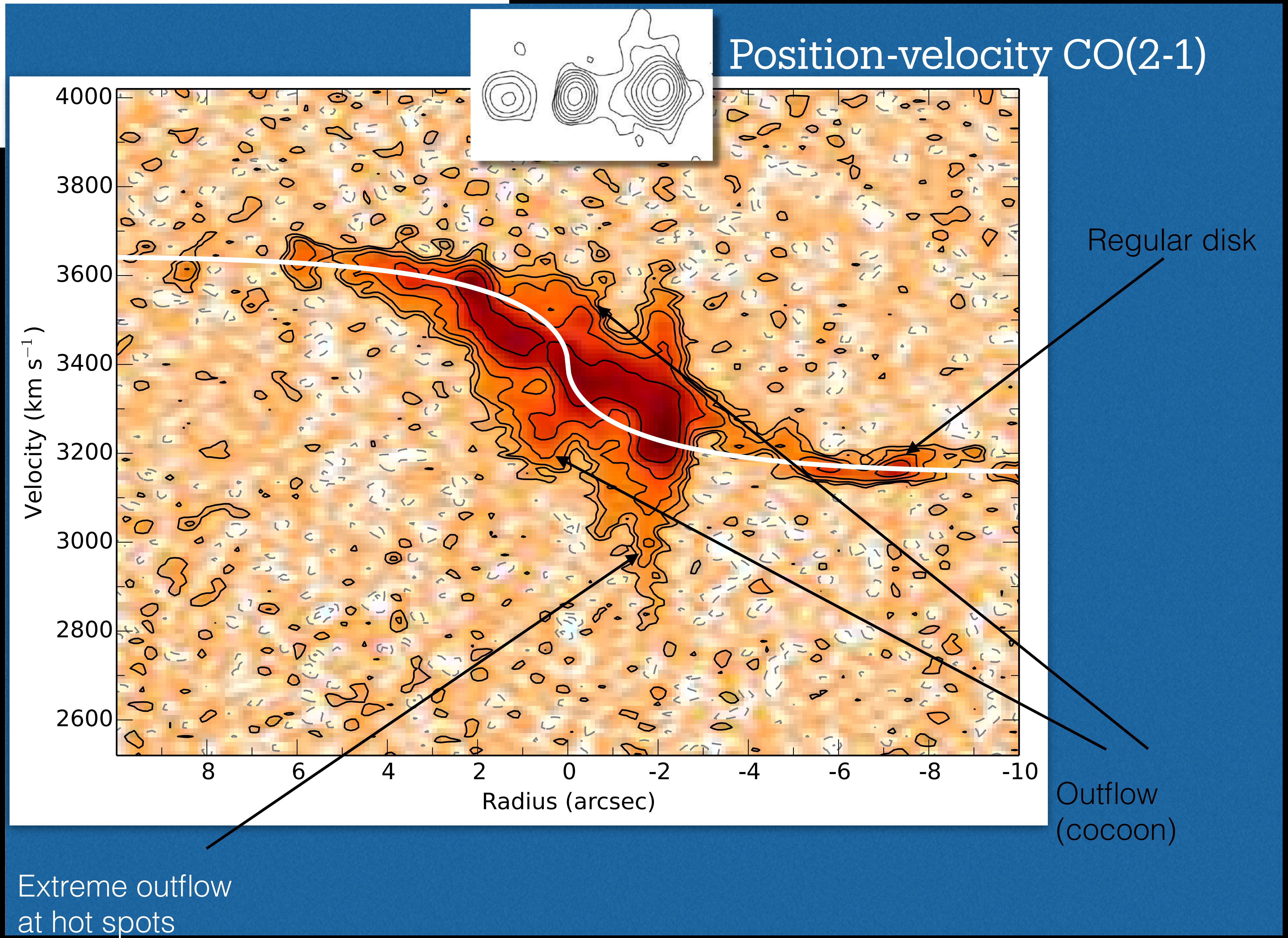




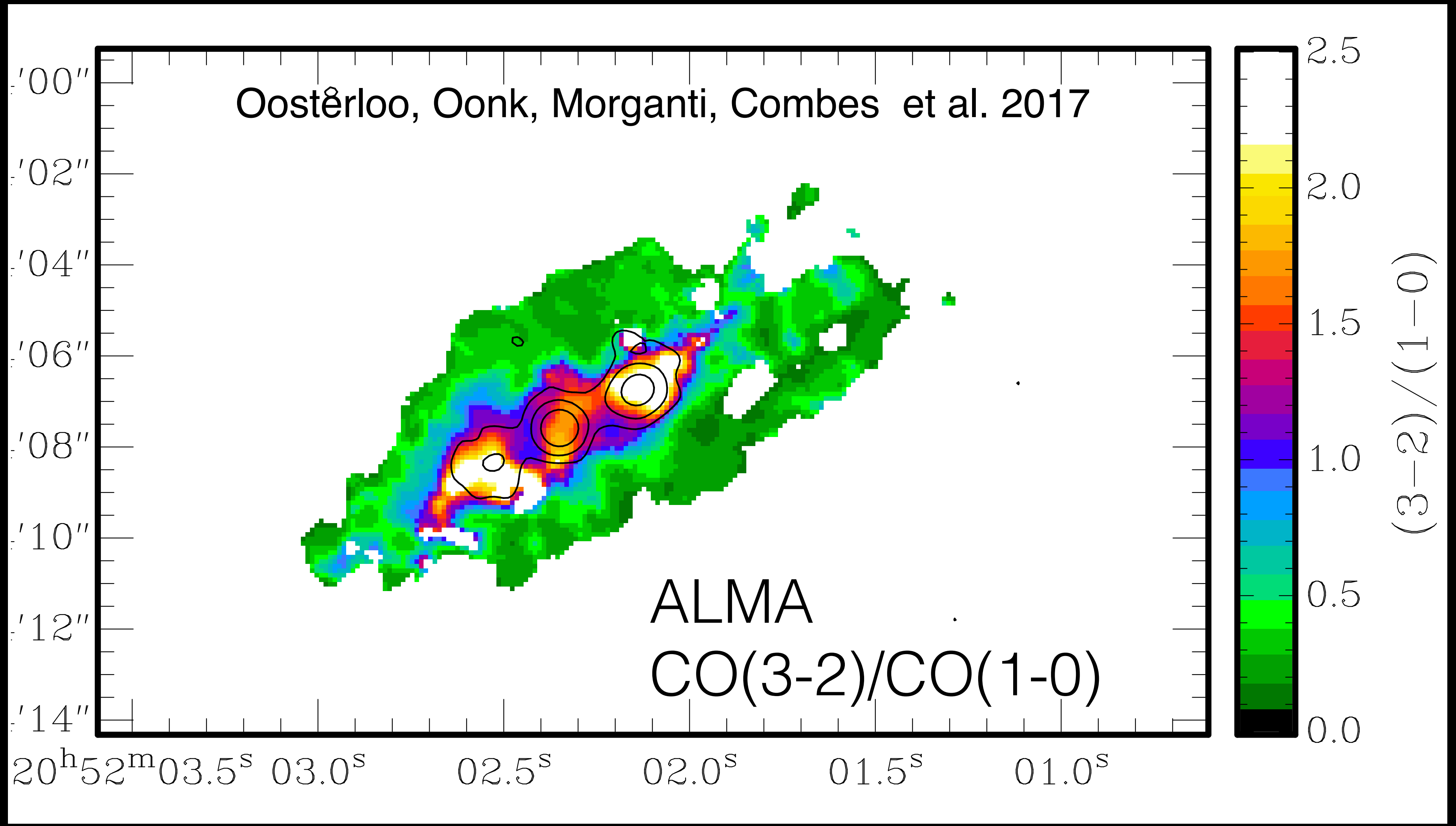
Impact of the jet as seen by ALMA:
Disturbed kinematics AND different conditions

now seen in a growing number of objects (e.g. Audibert et al., Murthy et al.)





Strong molecular outflow exactly coinciding with the radio jet.
Outflow is also lateral and driven by cocoon inflated by jet



Highest ratios clearly associated with outflow → gas must have high temperature and be optically thin

Kinetic temperatures in the range 20–100 K and densities between 10^5 and 10^6 cm^{-3}
(best fit of ratio line transitions suggests a clumpy medium)

Mass of outflowing gas few x 10^6 $M_\odot$; ~0.1% of total ISM
Mass outflow rate ~10 $M_\odot$/yr
Significant impact of AGN feedback, but only in inner few kpc

Small fraction of the gas will leave the galaxy, main effect of the outflow: redistribute the gas + expanding shocked bubble

Origine of the outflows

radiation
and
radio jets

Radiation-driven outflows

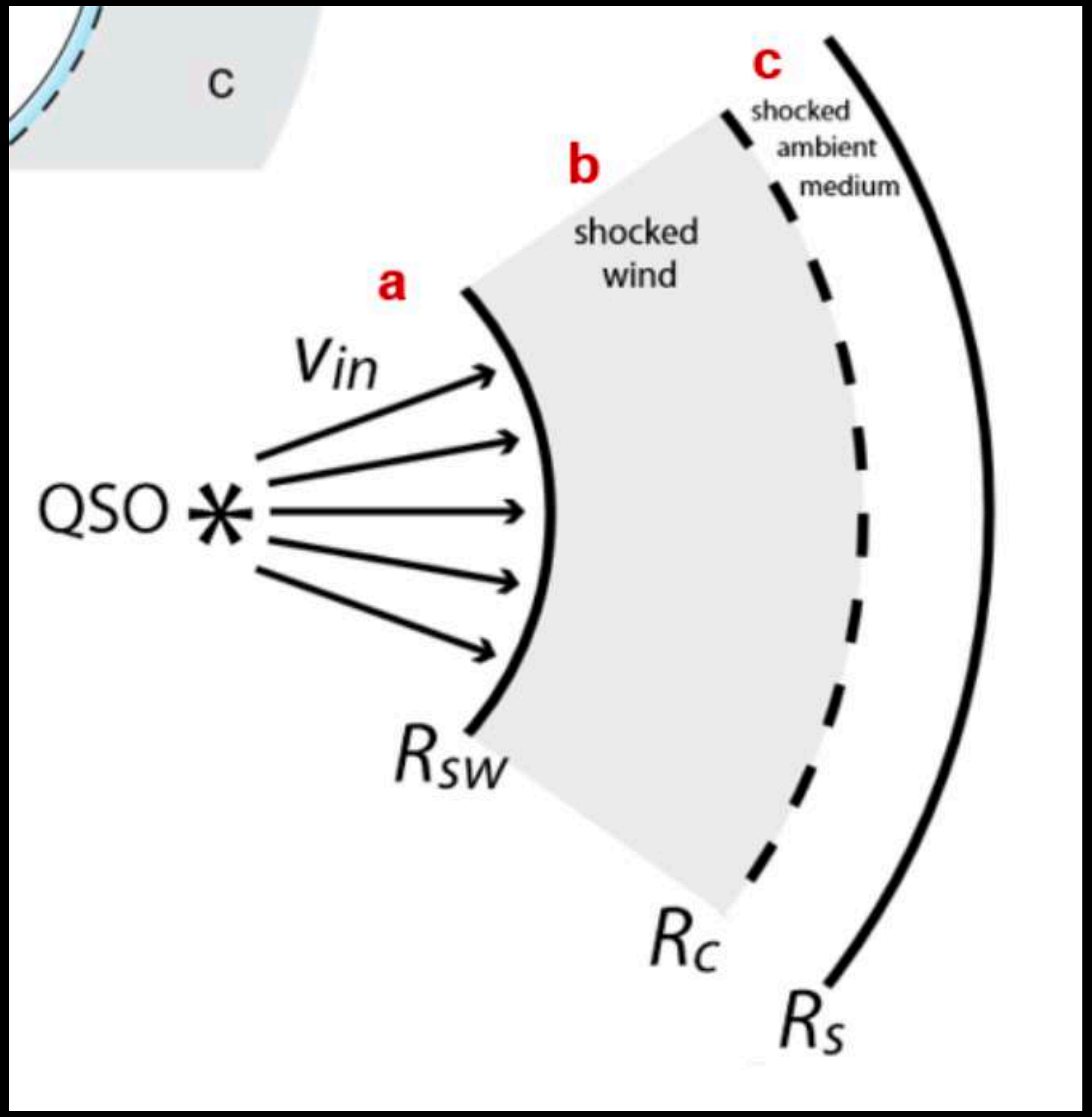
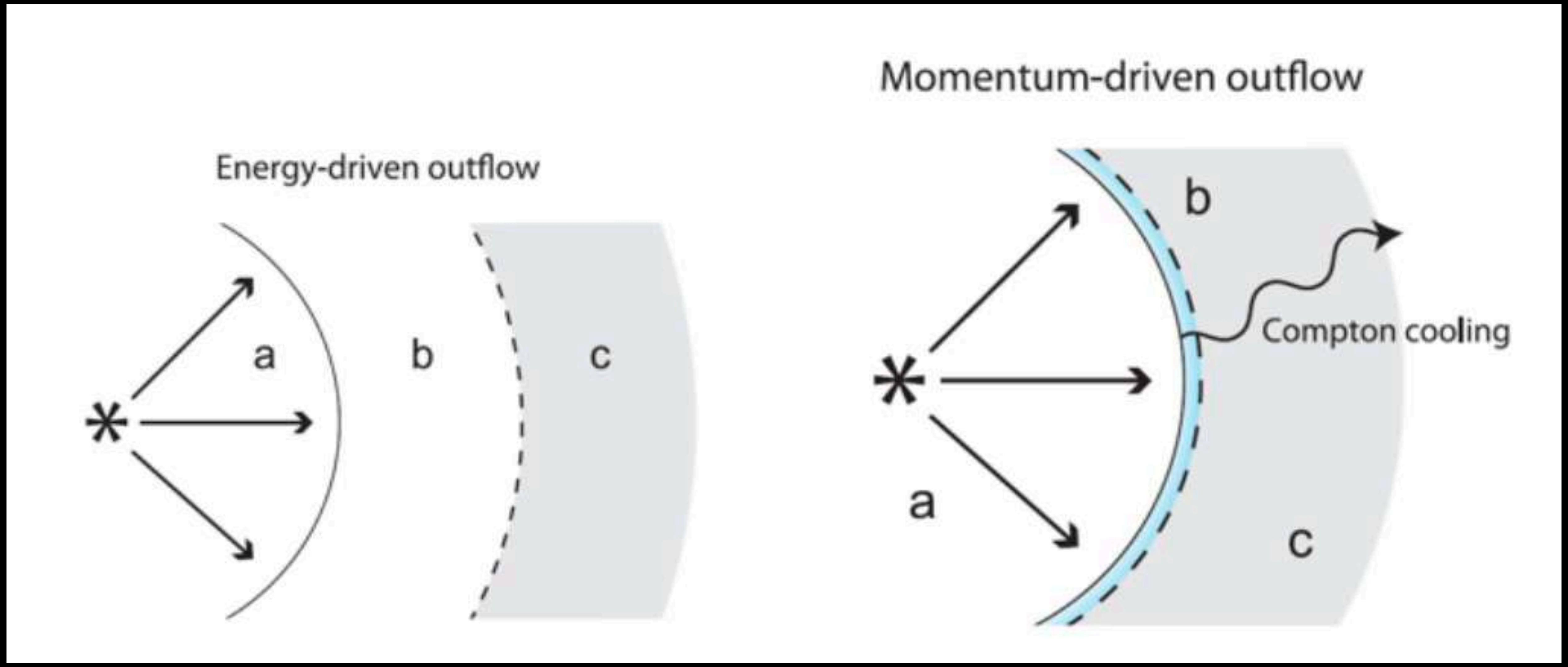


Diagram (right) of the various outflow phases around an AGN in the radiative phase (quasar mode). Rc is the discontinuity surface, Rs the shock in the interstellar medium, RSW the reverse shock towards the relativistic wind. Reproduced from Faucher-Giguère & Quataert (2012). Richings and Faucher-Giguère 2017

gas outflows not isotropic



from F. Combes

The zone "a" is characterised by the initial speed Vin, then the zone "b" of the shocked wind, which can be considerably reduced in volume, if the cooling is effective, as in the hypothesis of a momentum- conserving flow, which does not conserve energy. Faucher-Giguère & Quataert (2012)

A wind is launched in the accretion disc (radiation pressure especially in the highly efficient AGN) V_{in} can be 0.1 c (as observed in UFO) - interaction with the medium produce the first shock (R_{SW}) and the shocked-wind zone.

If adiabatic ➝ energy-driven outflow ➝ part of the energy is spent in to inflate the bubble/push the ambient medium ➝ the momentum of the outflow is boosted.

If cooling/radiating by inverse Compton ➝ momentum-driven outflow

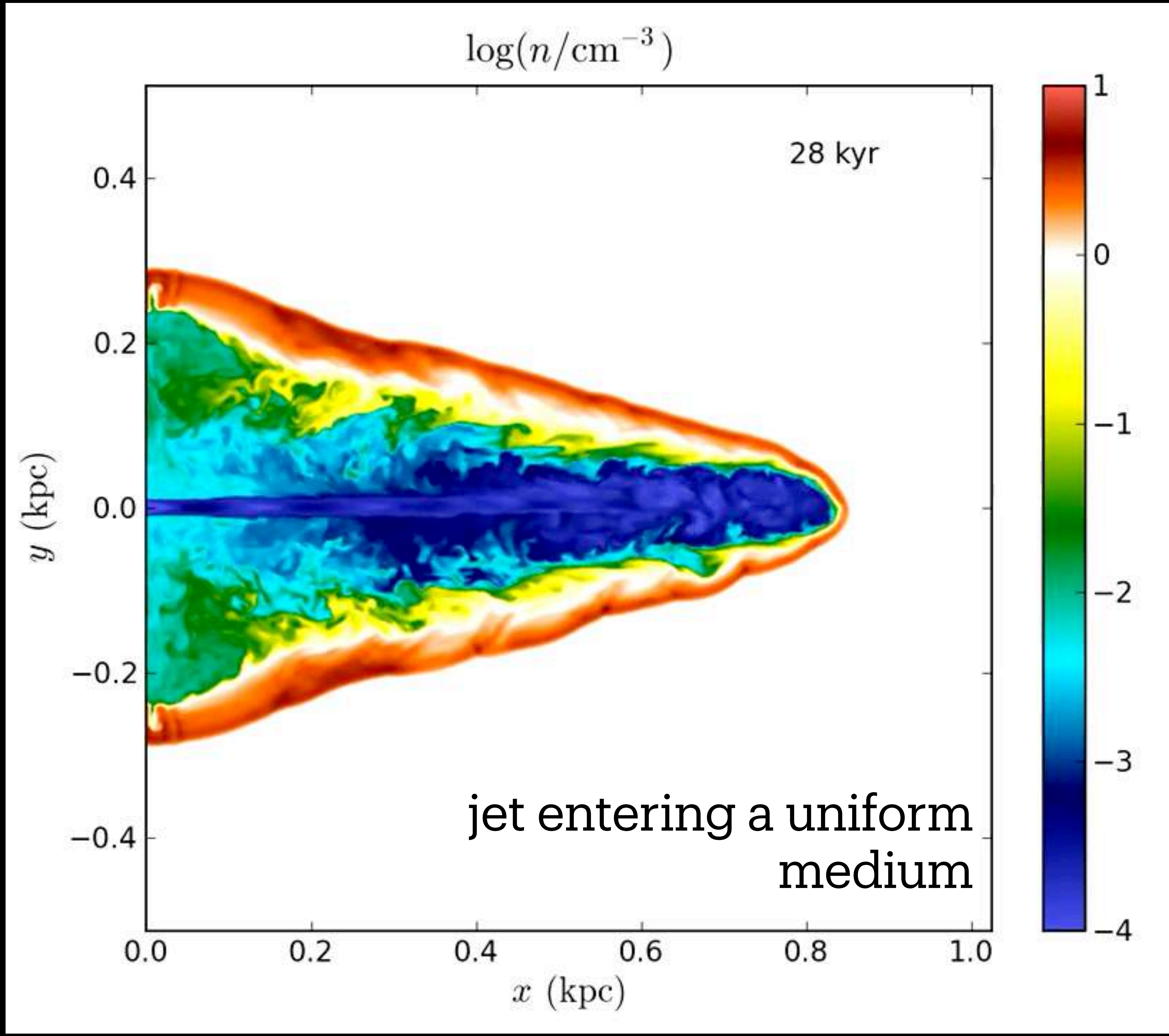
→ BUT can radio jets drive gas outflows?

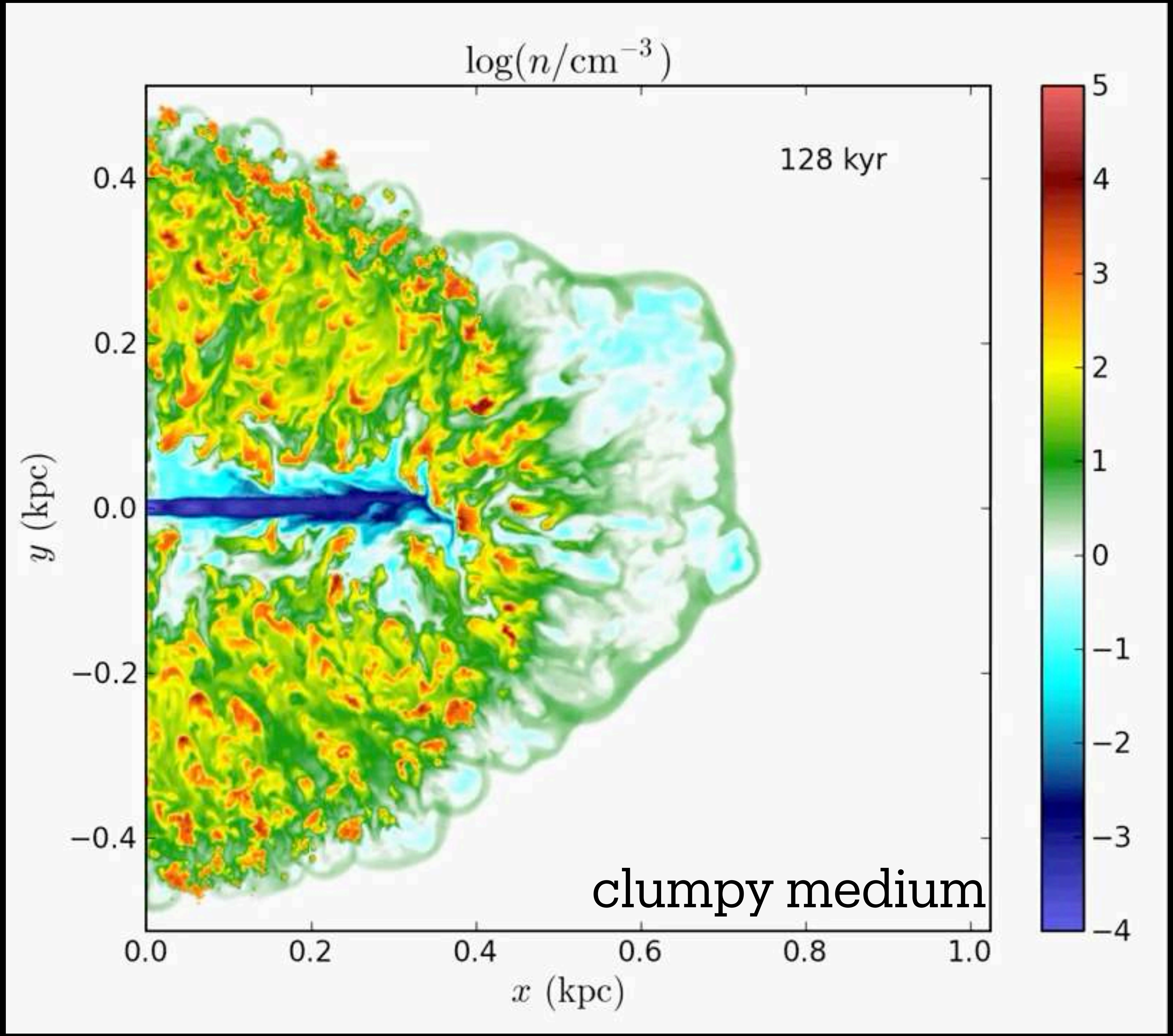
... jets were never considered to be able until more realistic simulations appeared!

Sutherland & Bicknell 2007 onwards ...

Jet-driven outflows in more realistic medium: higher coupling efficiency for the jets

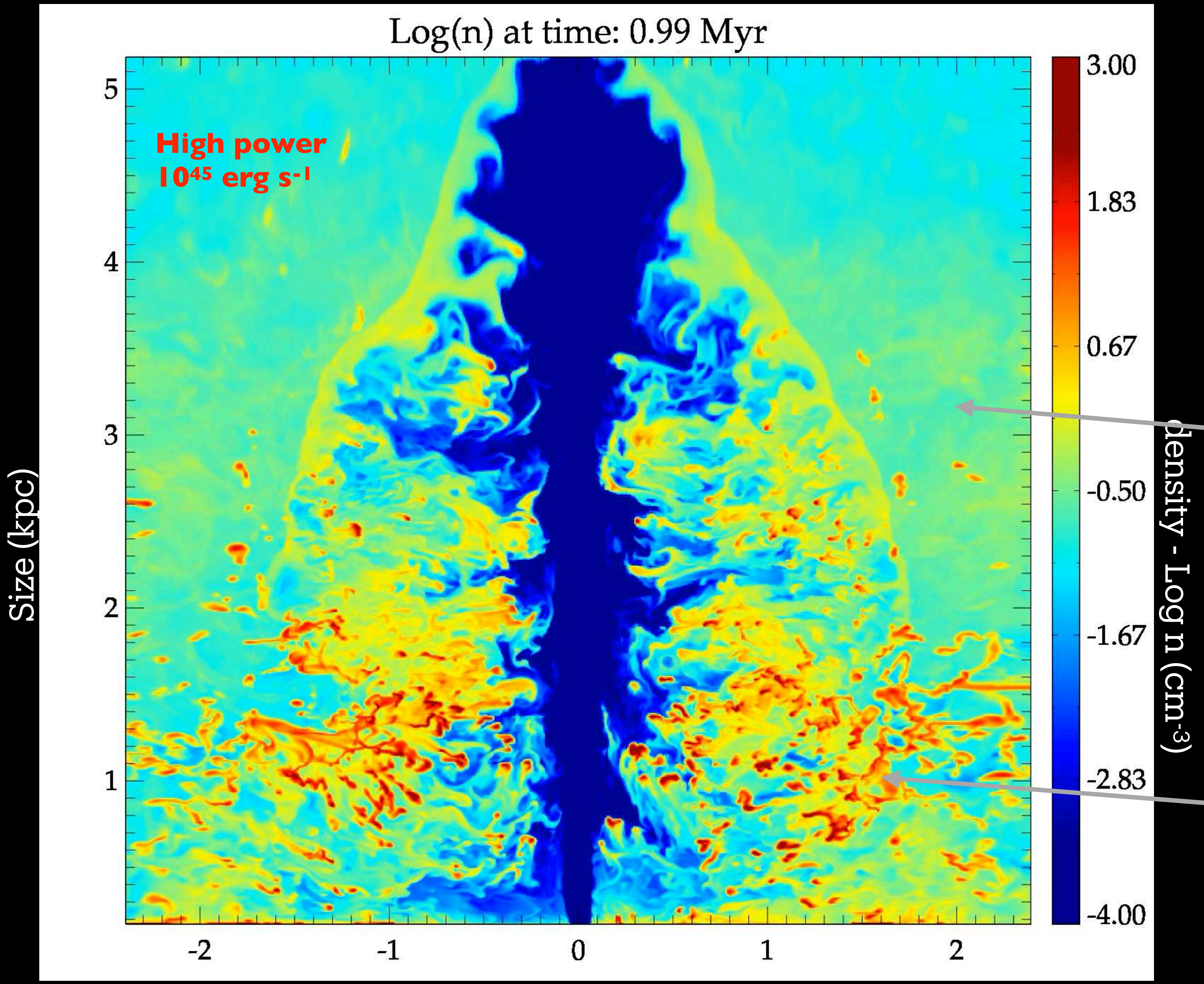
Impact of radio jets as predicted by numerical simulations:
key parameter the clumpiness of the medium





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

Jet-driven outflows



clumpy medium (spherical distribution), high jet power

Mukherjee, Bicknell et al. 2016, 2017, 2018

from Wagner & Bicknell 2011, 2012;
Mukherjee, Bicknell et al. 2016, 2017, 2018
see also from Cielo et al. 2018, Dutta et al. 2023, Perucho 2023

- predictions from realistic simulations show that jets can efficiently couple with ISM
  ➙ jets can produce outflows
  AND cocoon of shocked gas on galaxy scale

Cocoon of shocked gas

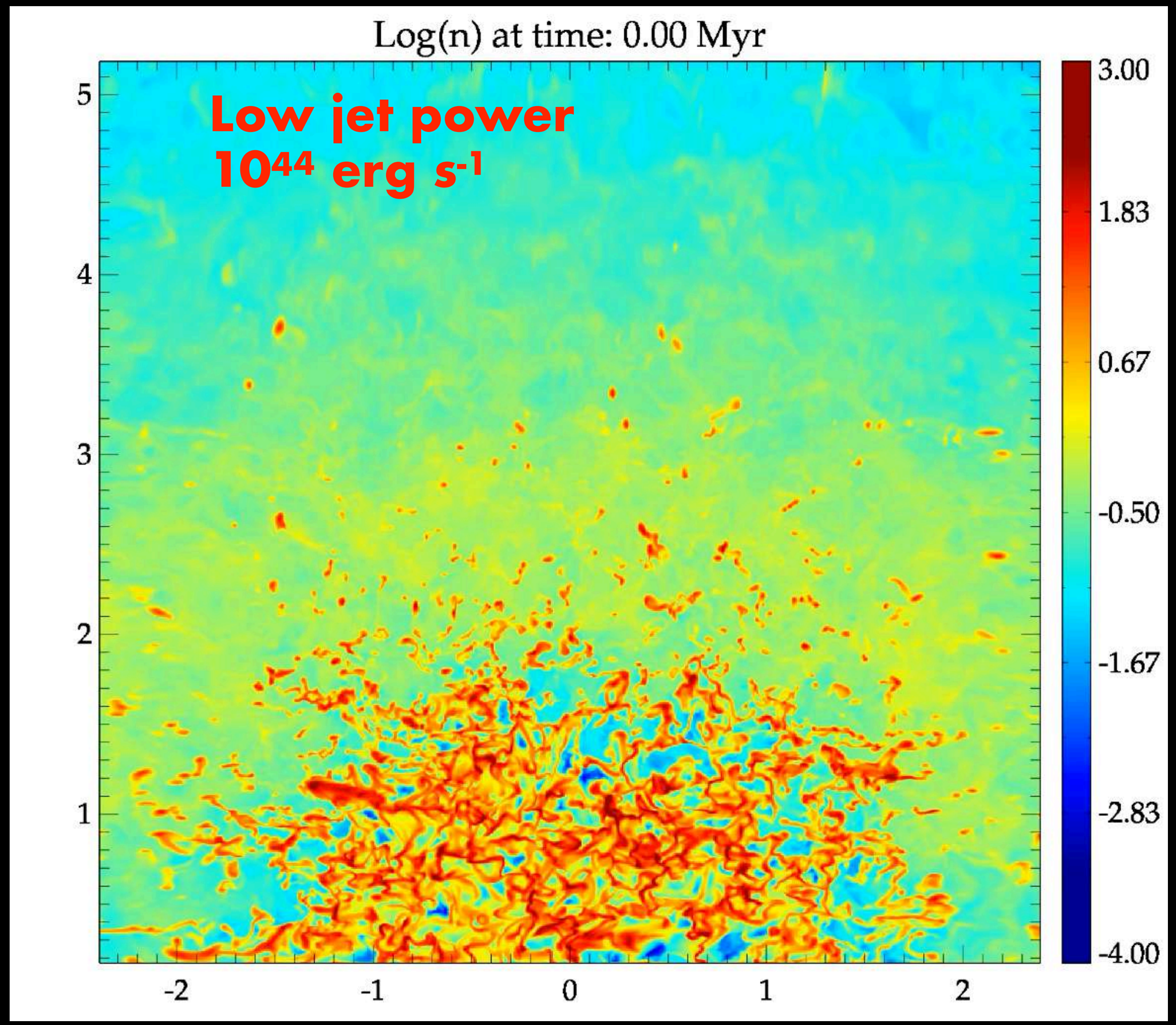
Clouds (partly) shred and accelerated by the direct interaction

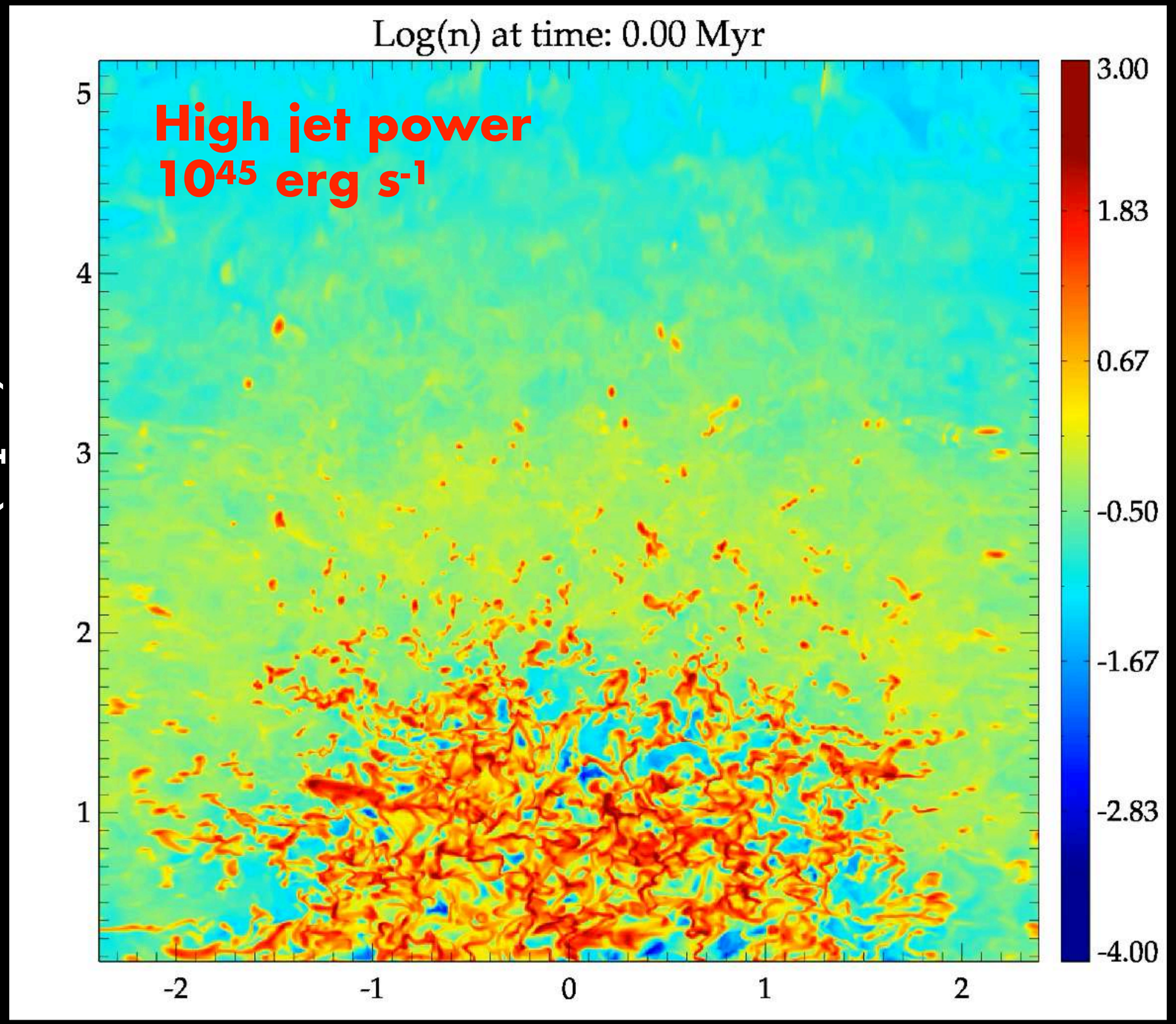
Jet-driven outflows

ages

10^8 yr

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

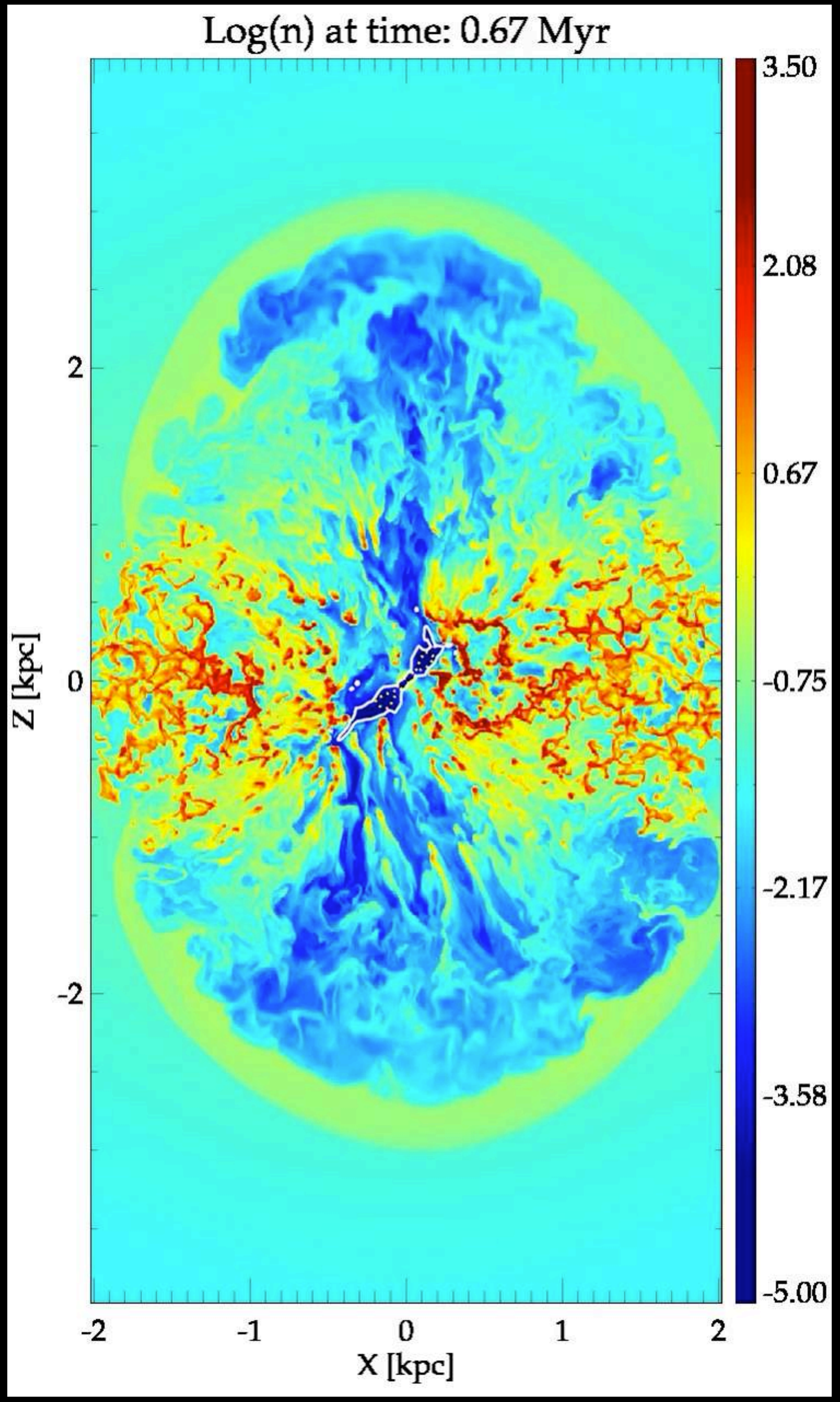
Less powerful jet: more numerous and takes longer
to "break free" while depositing energy in the ISM

Powerful, relativistic jet
Jet power = 10^{45} erg/s
the jet is very light and overpressured

radio power
jet power

A complex parameter space to explore!

- Orientation of the jet wrt gas distribution



Mukherjee et al. 2017, 2018

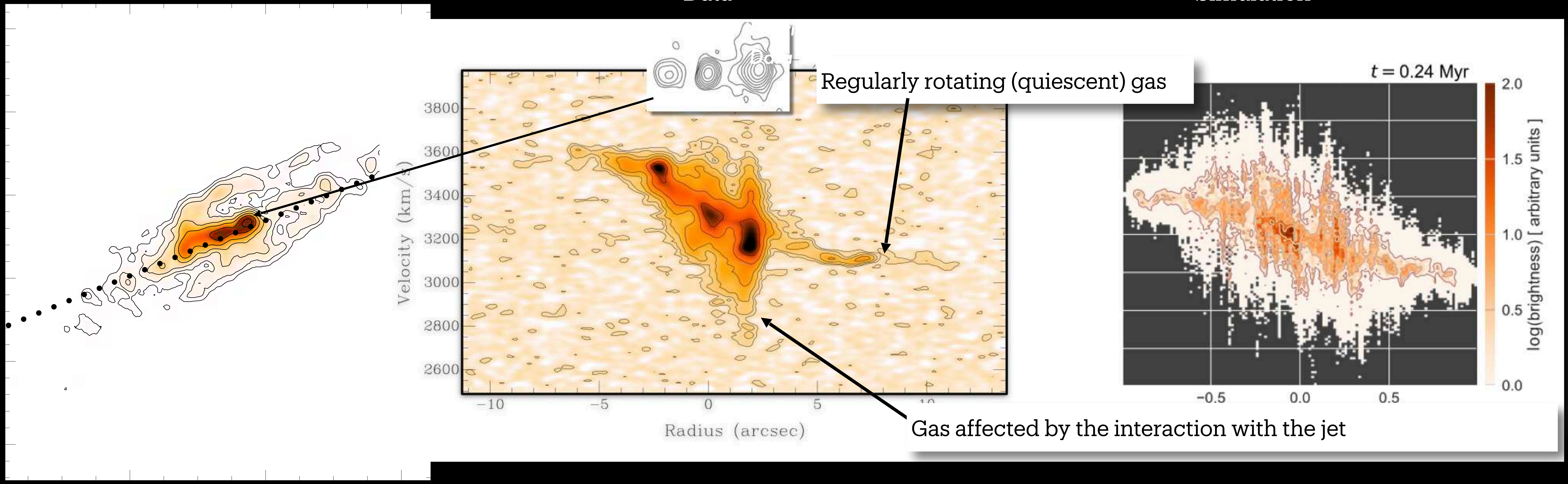
clumpy medium in a disk

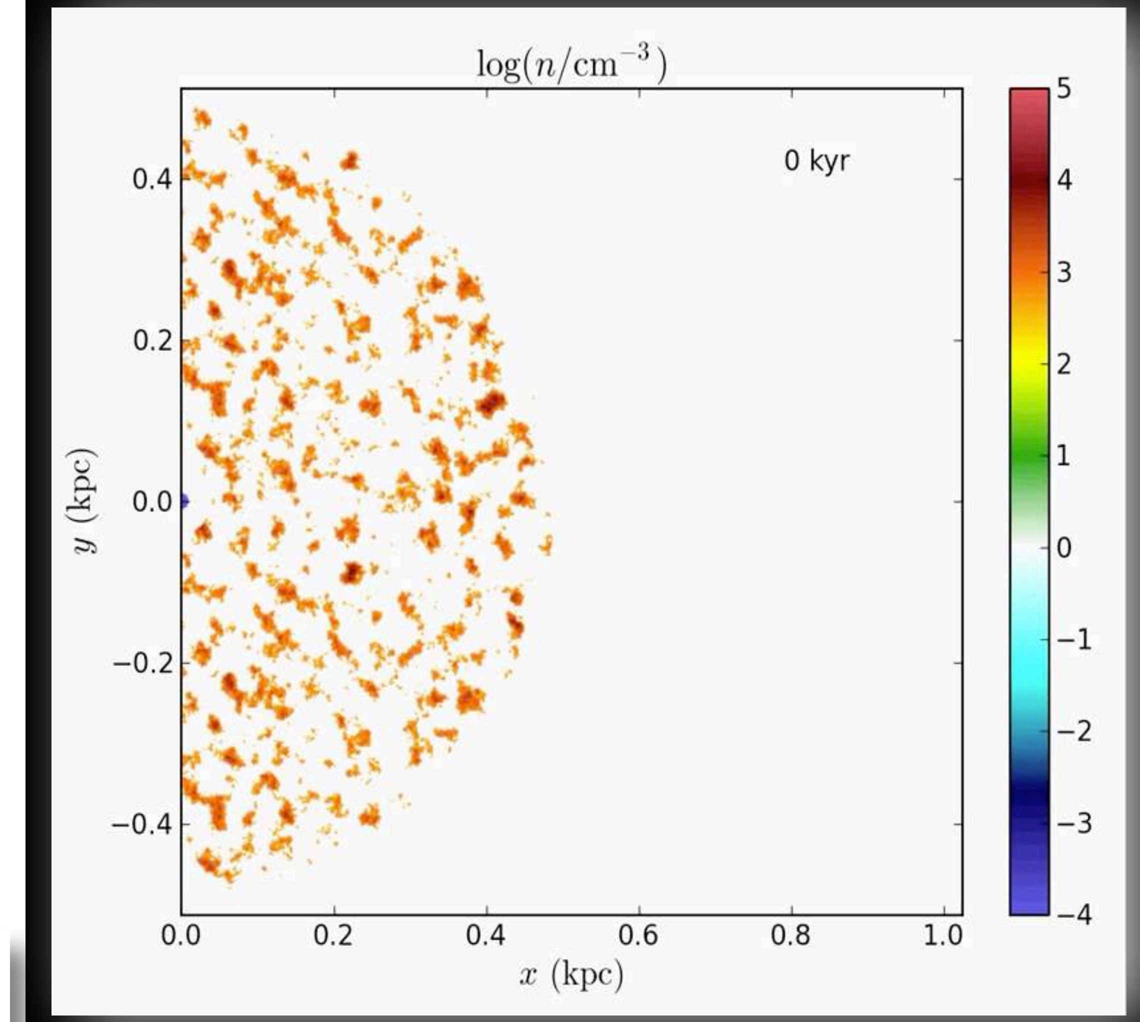
The importance of comparing data and model: IC5063

CO(2-1 ALMA

Position-velocity plot of the CO(3-2) ALMA data of IC5063

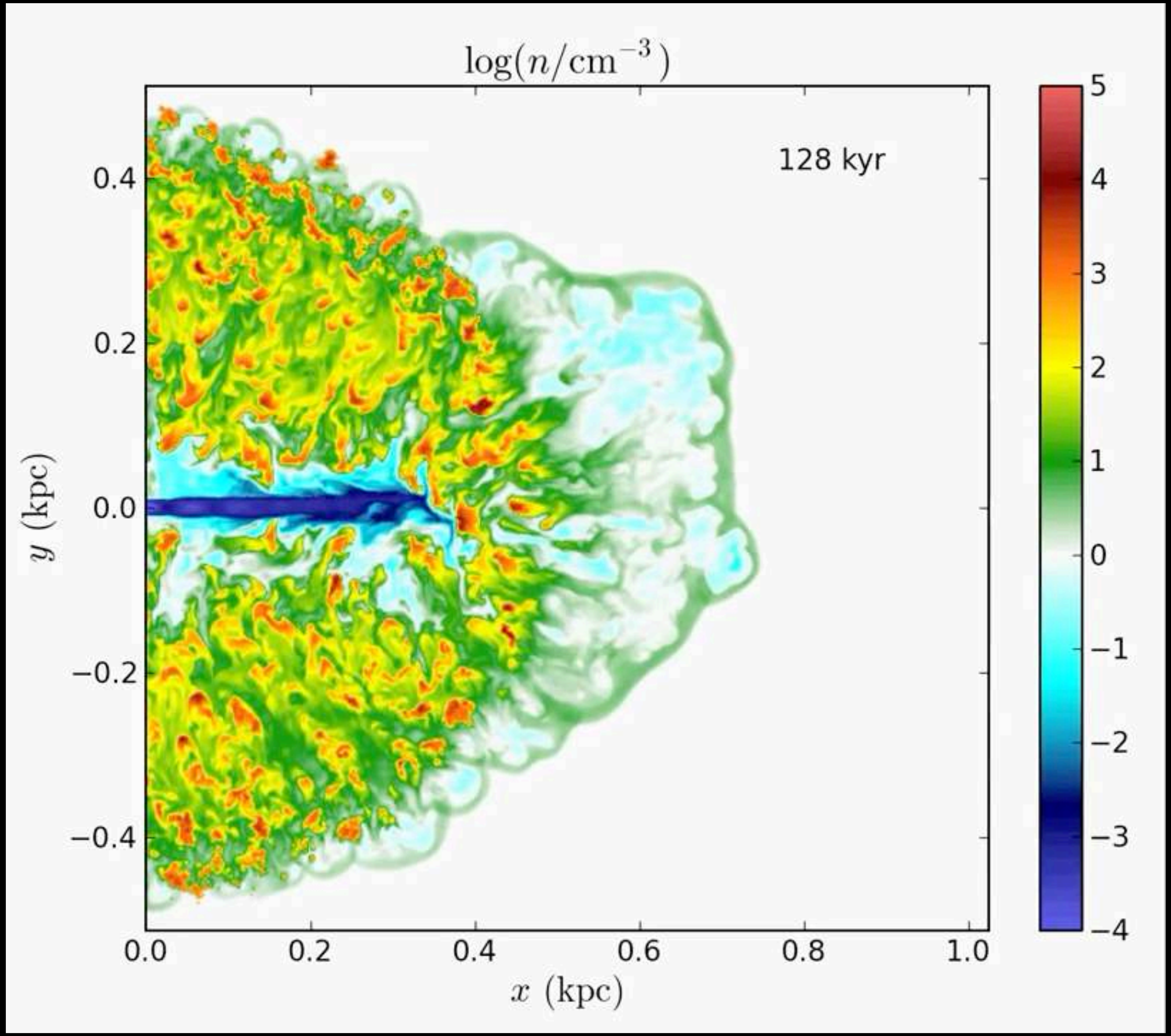
Data *Simulation*





Mukherjee, Wagner, Bicknell, Morganti et al. 2018

Are you still with me?



- new simulations have shown that jet can have an impact also on galactic scales
- radio plasma driving outflows: effective because not only the head of the jet is producing the interaction - cocoon of disturbed gas (over a larger volume)
- also low luminosity jets (radio quiet sources) can produce outflows
- particularly effective in the early (young) phase of the jet

e) The impact of AGN and jets in a broader picture

But not all consistent with the cosmological simulations

Comparison with L_{edd} and L_{bol} ➙ models of galaxy formation requires about 5% of Edd luminosity in outflows: this is not found

see di Matteo et al. 2005

Although coupling AGN energy and multi-phase gas is observed, the efficiency can be low ➙ large fraction of energy can escape to CGM

Region affected by the outflow often limited to (sub)kpc regions

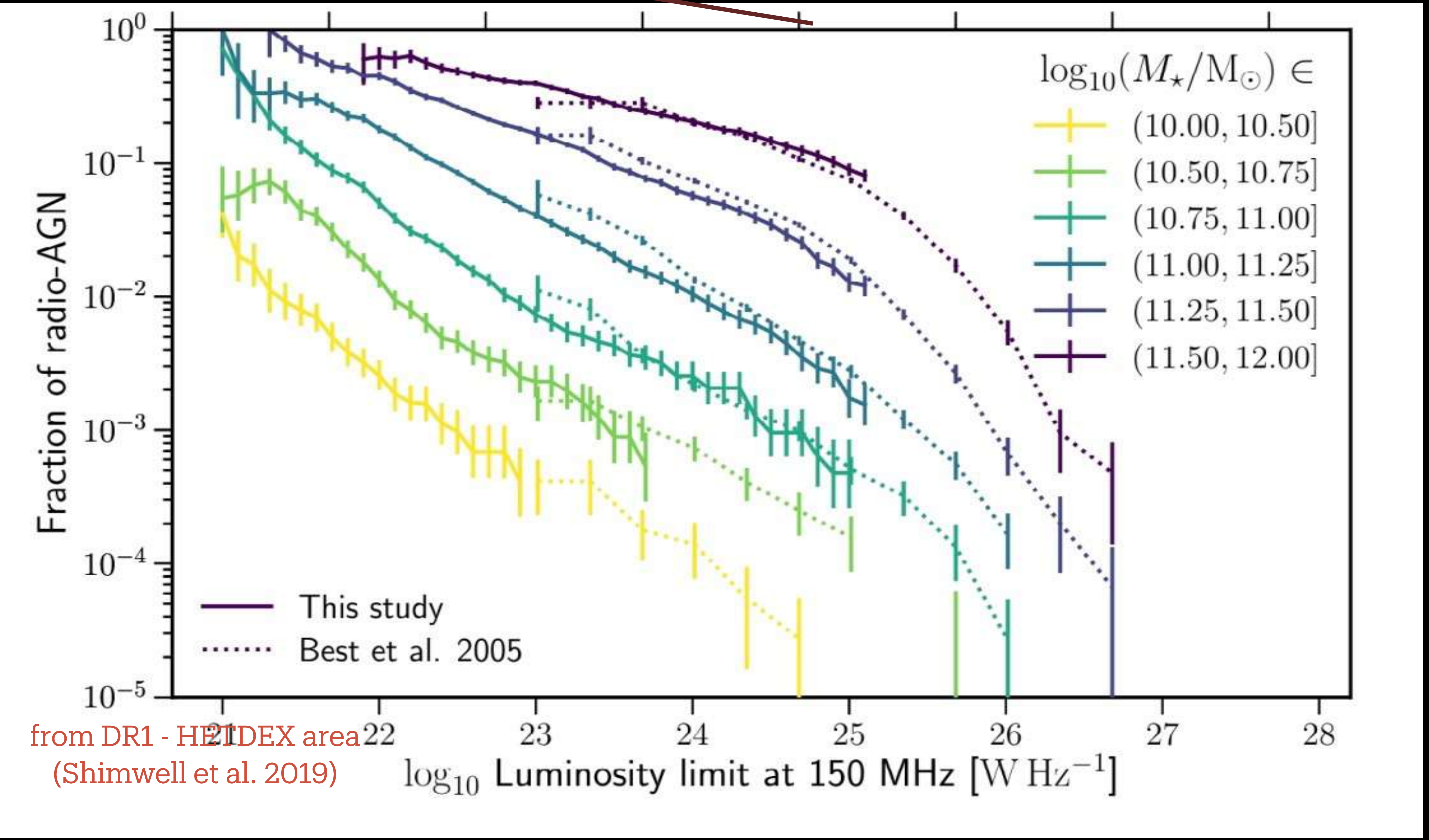
Velocities of the outflow not enough for a substantial amount of gas to leave the galaxy ➙ outflowing gas reaching escape velocity only in less than 5% of the cases fountain ➙ delay star formation.

Gas outflows alone do not seem to be enough for quenching star formation

which process is the dominant for AGN feedback not yet completely clear

Kinetic energy injected by the radio jets: main mode of feedback?

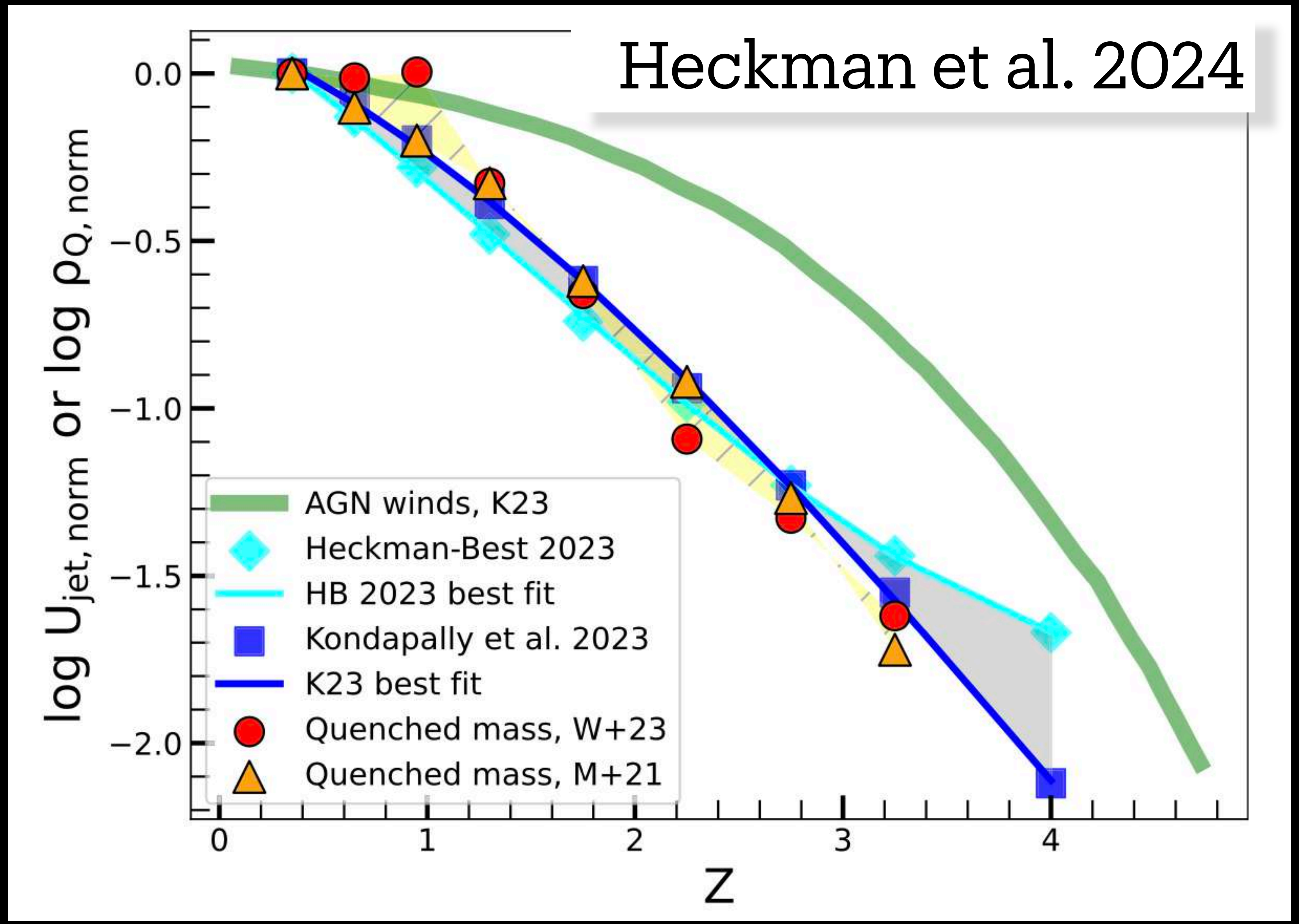
Best et al. 2005; Sabater et al. 2019



Luminosity function of radio AGN - dependence on stellar mass - fraction changing with radio power.

The fraction can be used to derive the fraction of time a radio AGN is "on" (active) under the assumption that every massive galaxy becomes a radio source during its life ➙ then the fraction of radio AGN tell us about what fraction of time the source is "on"

- radio synchrotron luminosity converted in jet power (using correlation from the X-ray cavities)
- values applied to the measured radio luminosity function ➙ integrated amount of jet kinetic energy injection per co-moving volume element per Gyr



Cumulative amount of stellar mass in quiescent massive galaxies, normalized to its value at z = 0.35 compared with the kinetic energy injected by radio jets

In summary:

- Relevance of radio AGN in galaxy evolution ➙ required by cosmological simulations
- Radio jets can impact small and large scales in different ways
- X-ray cavities as calorimeter: can be used to derive the jet power
- Radio jets (even in radio quiet AGN) can drive outflows ➙ more realistic simulations can explain that (at least from the kinematic point of view)
  ➙ First phase of the jet important for feedback
- Still work to be done to understand how AGN feedback works:
  some interesting challenges for the young astronomers! Good luck!
- BUT on the way to do this we have had some extremely interesting/unexpected additions in our understanding of AGN (e.g. presence of fast outflows of cold gas)


A big thank to the organisers
(especially Ciriaco and the LOC)
for taking care of us so well!