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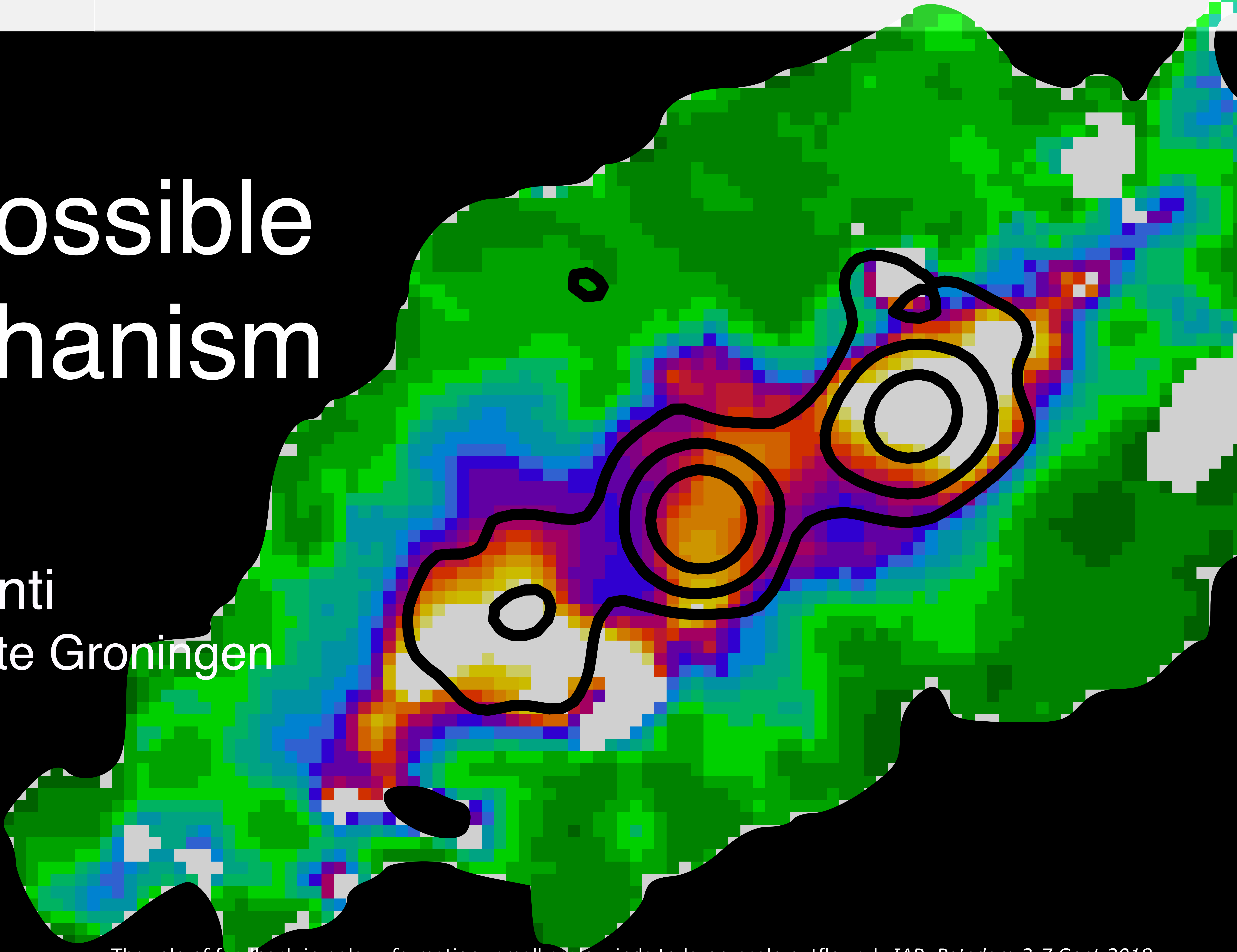
AGN jets as possible feedback mechanism

Mukherjee et al.

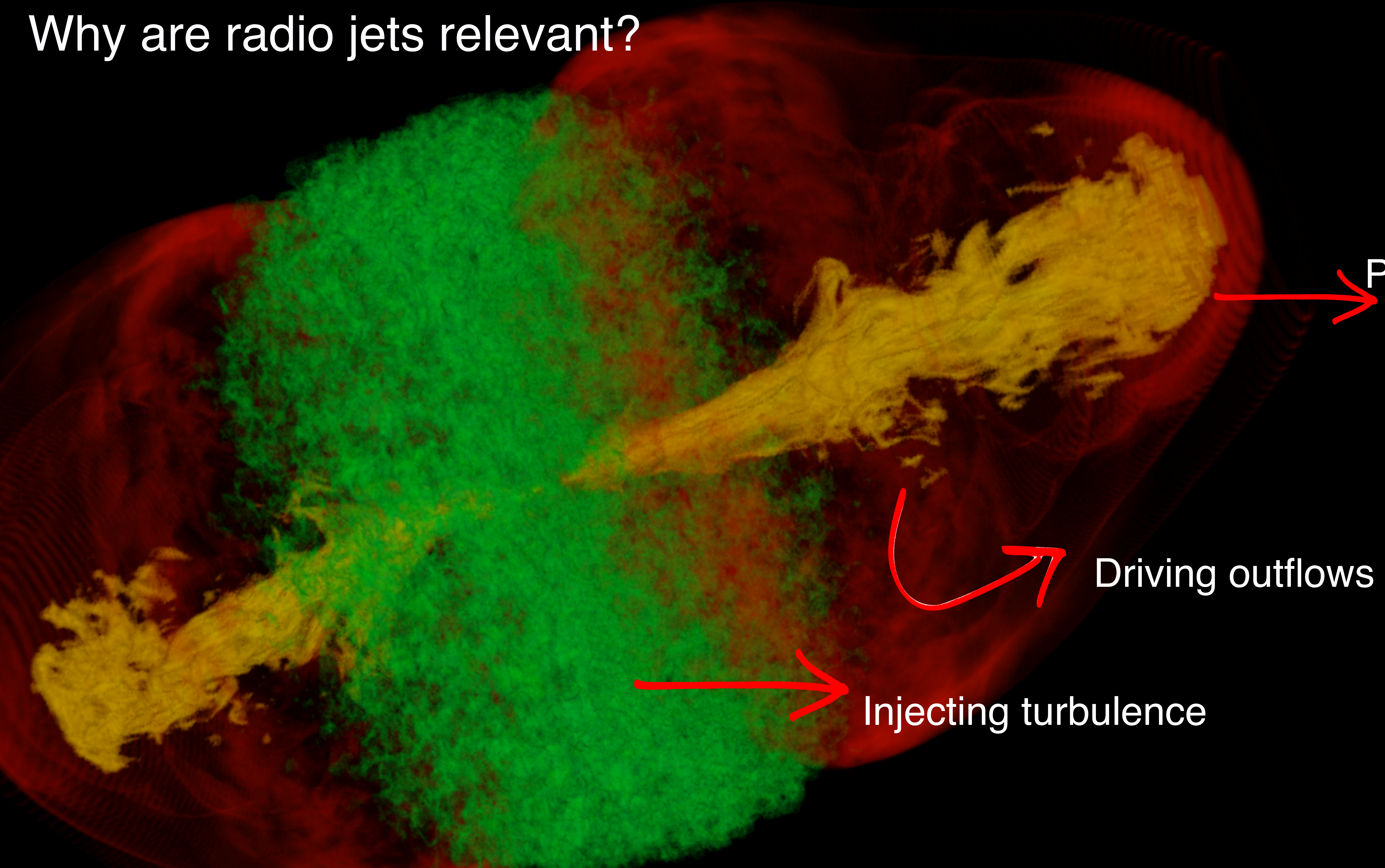
R. Morganti,
ASTRON and Kapteyn Institute Groningen

AGN jets as possible feedback mechanism



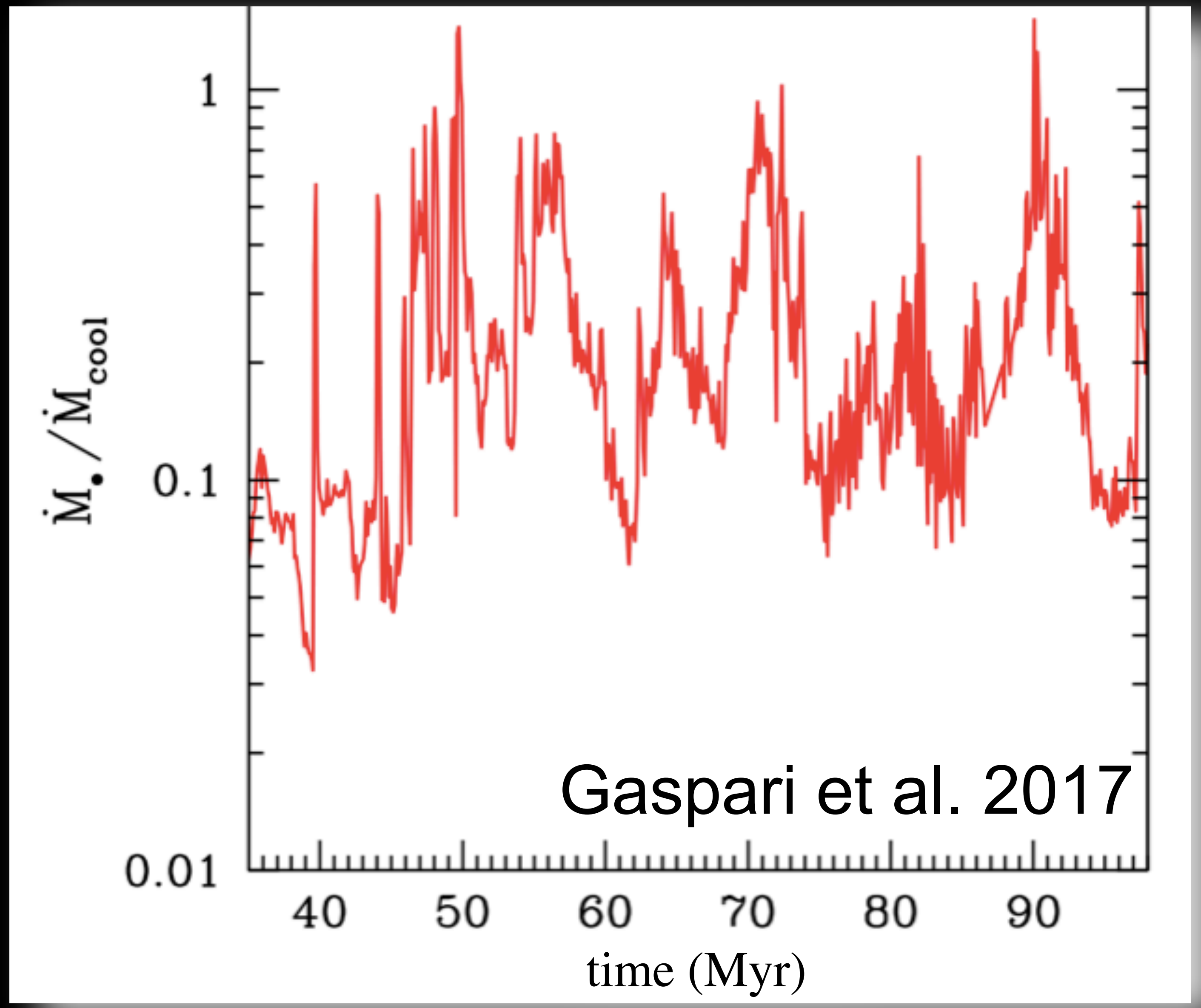
Raffaella Morganti
ASTRON and Kapteyn Institute Groningen

Why are radio jets relevant?

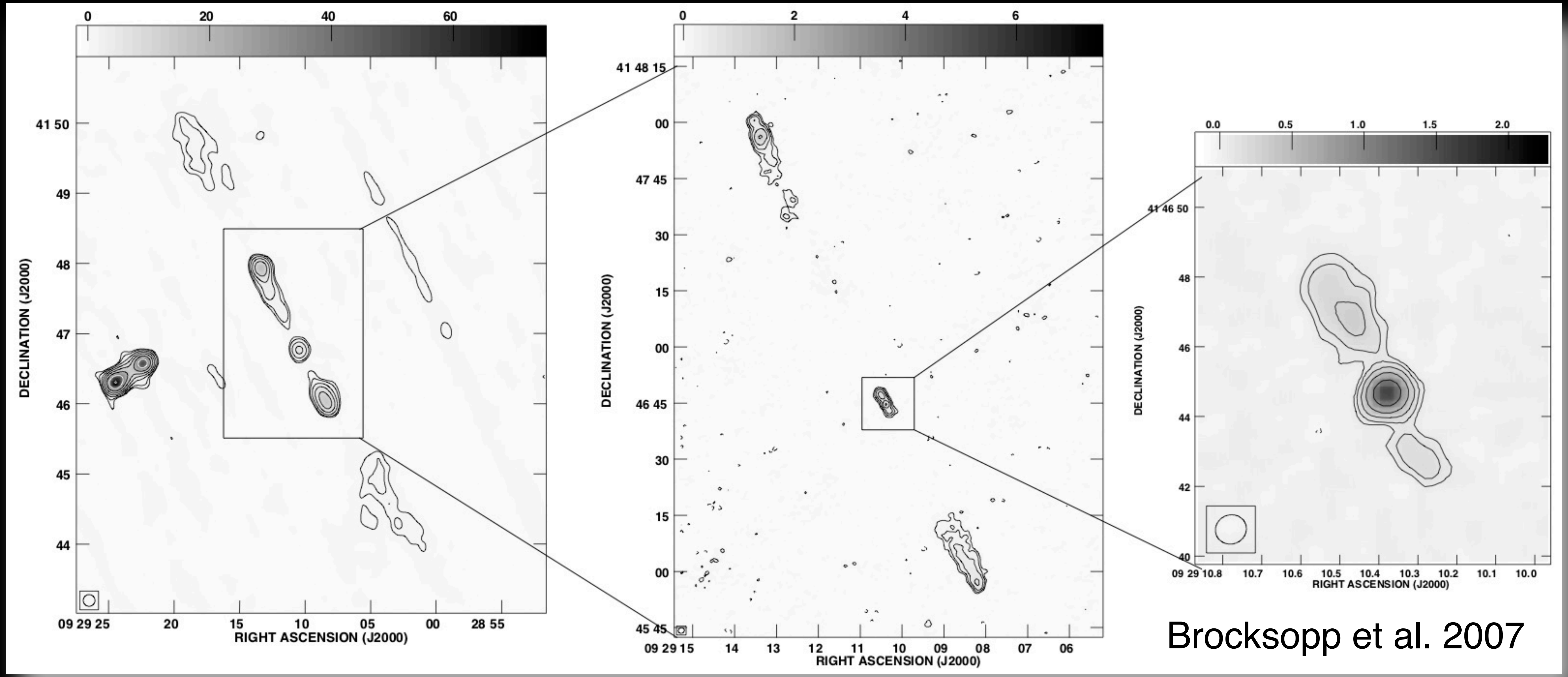


…do we see evidence for all these processes?

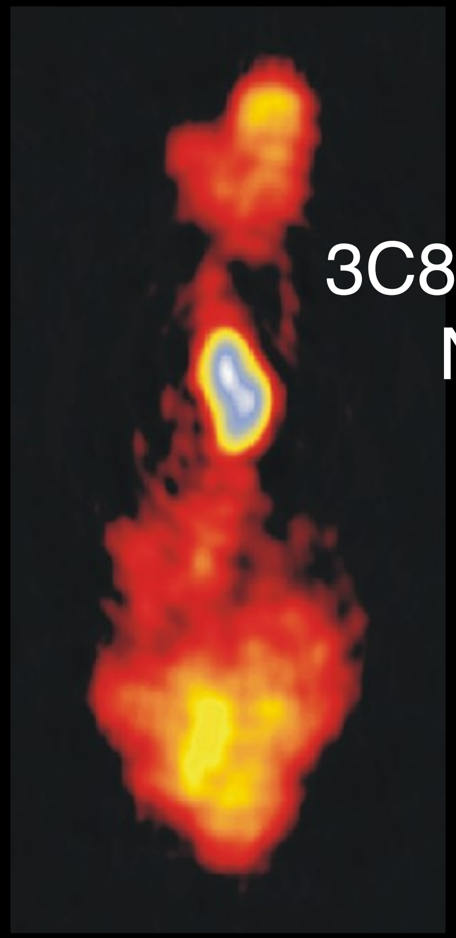
Duty-cycle of the AGN



The duty cycle of activity and quiescence predicted from simulations of chaotic cold accretion (Gaspari et al. 2017)
See also Ciotti et al. 2010).



Restarting radio AGN, e.g. double-double radio sources
High duty cycle in cool core clusters

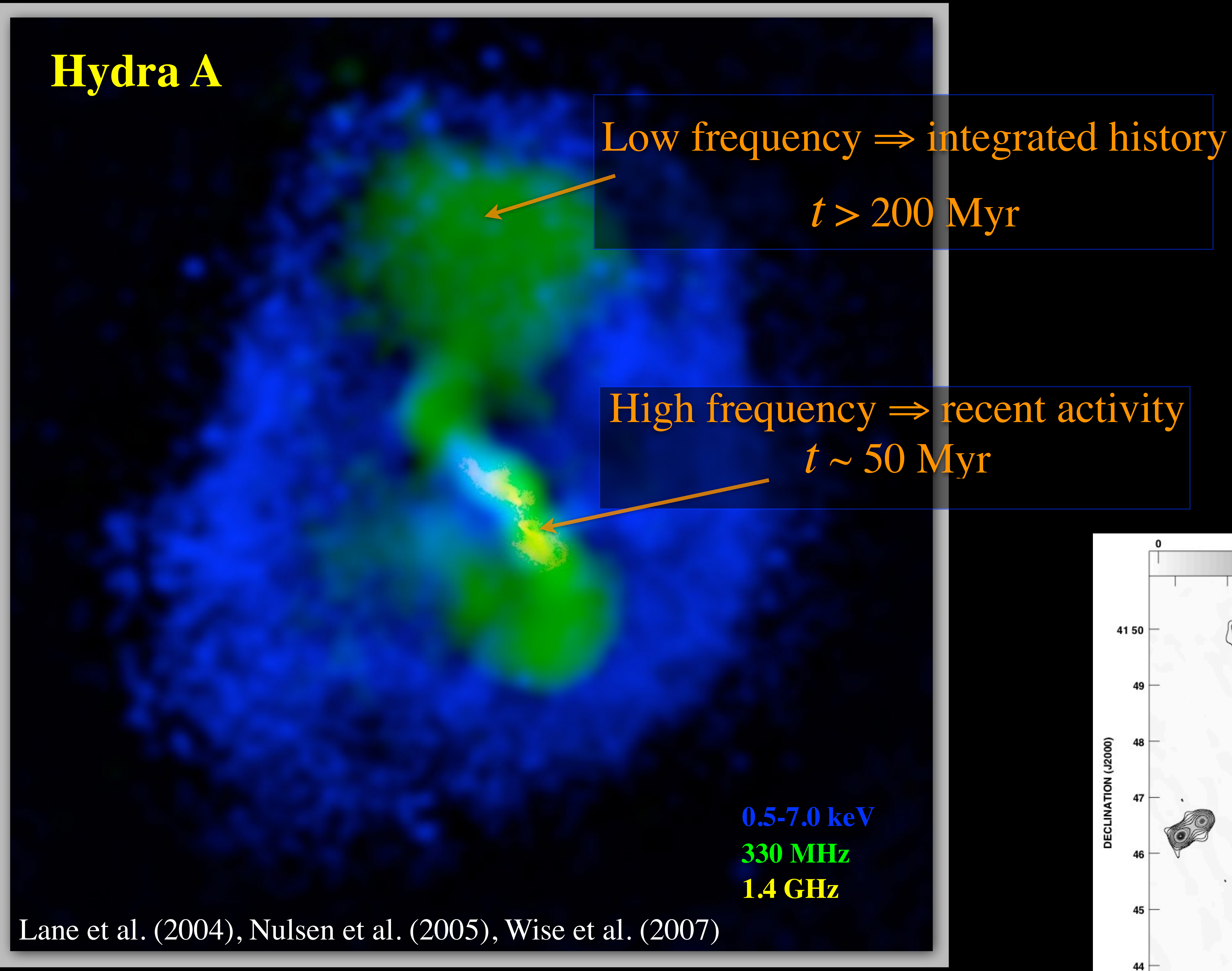


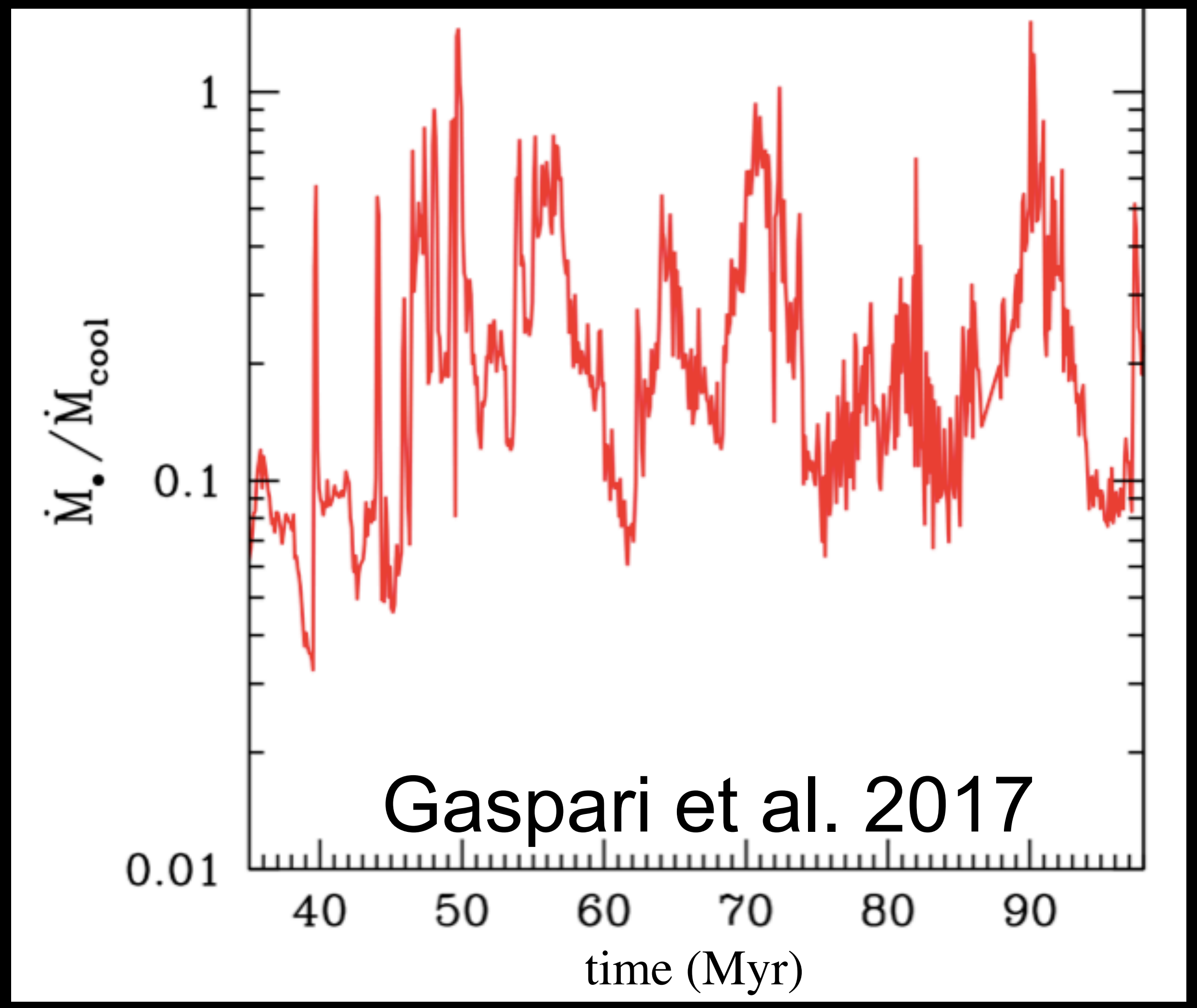
3C84 (Perseus A)
Nagai et al.

See also Archaeology of active galaxies across the electromagnetic spectrum Nat.Astronomy, Morganti 2017

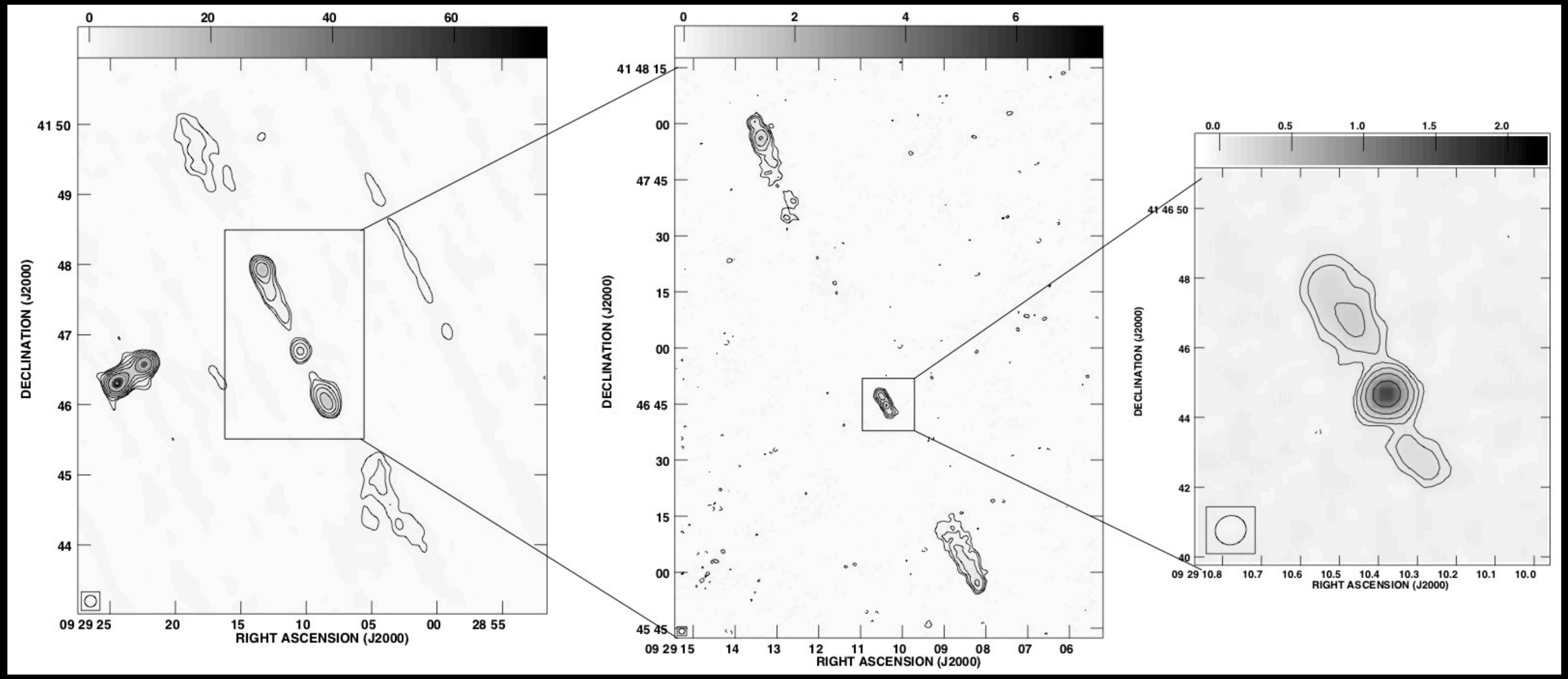
Duty-cycle of the AGN

See Archaeology of active galaxies across the electromagnetic spectrum Nat.Astronomy, Morganti 2017





the duty cycle of activity and quiescence predicted from simulations of chaotic cold accretion. Evolution of the accretion rate (including turbulence, cooling, AGN heating and rotation) as a fraction of the cooling rate. This illustrates the changes in accretion rate (and therefore level of activity) on short timescales.

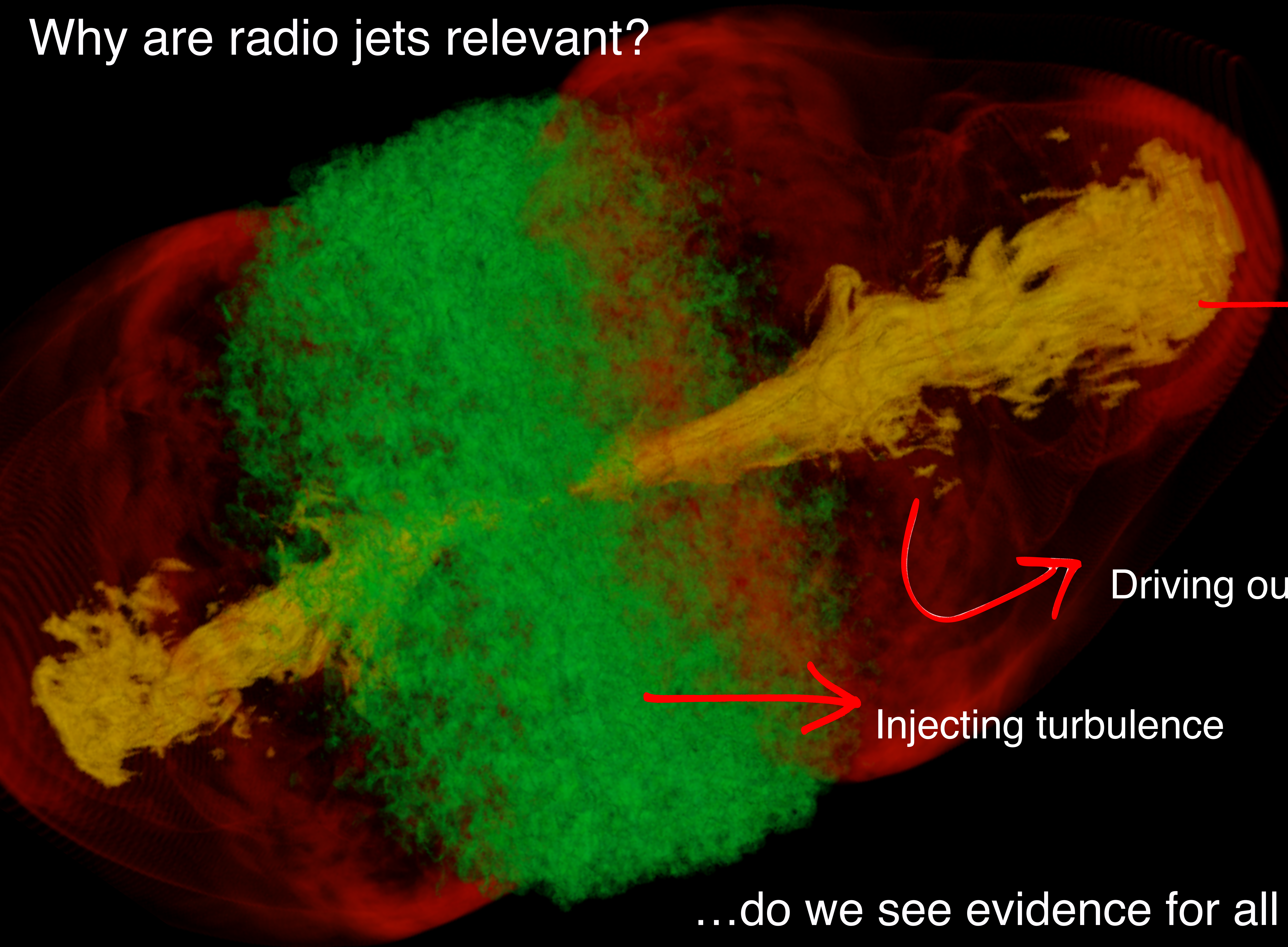


Double-double radio sources (Credits: Brocksopp et al. 2007)

A variety of radio structures and ages

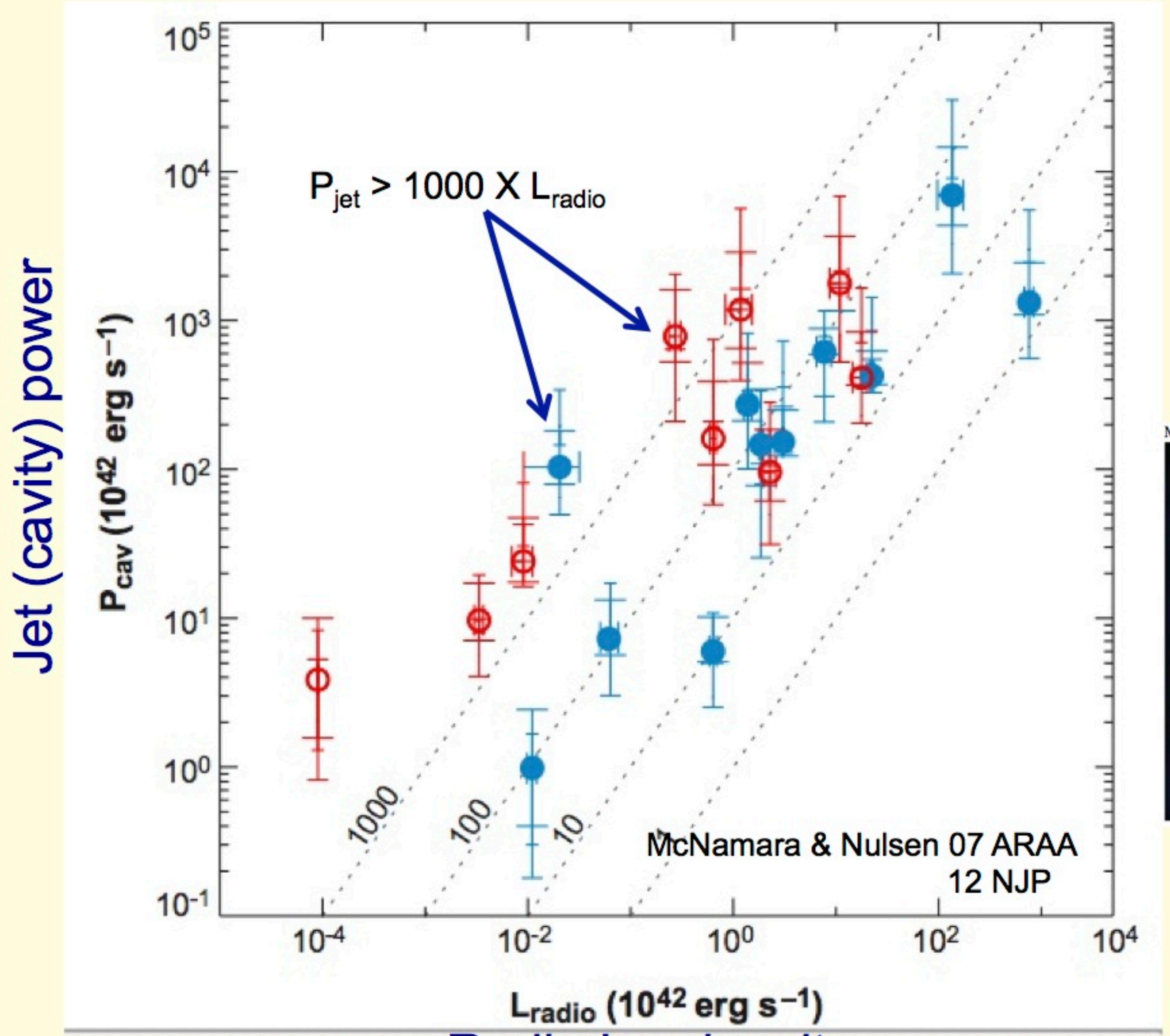
More numerous,
interacting longer with ISM

Why are radio jets relevant?

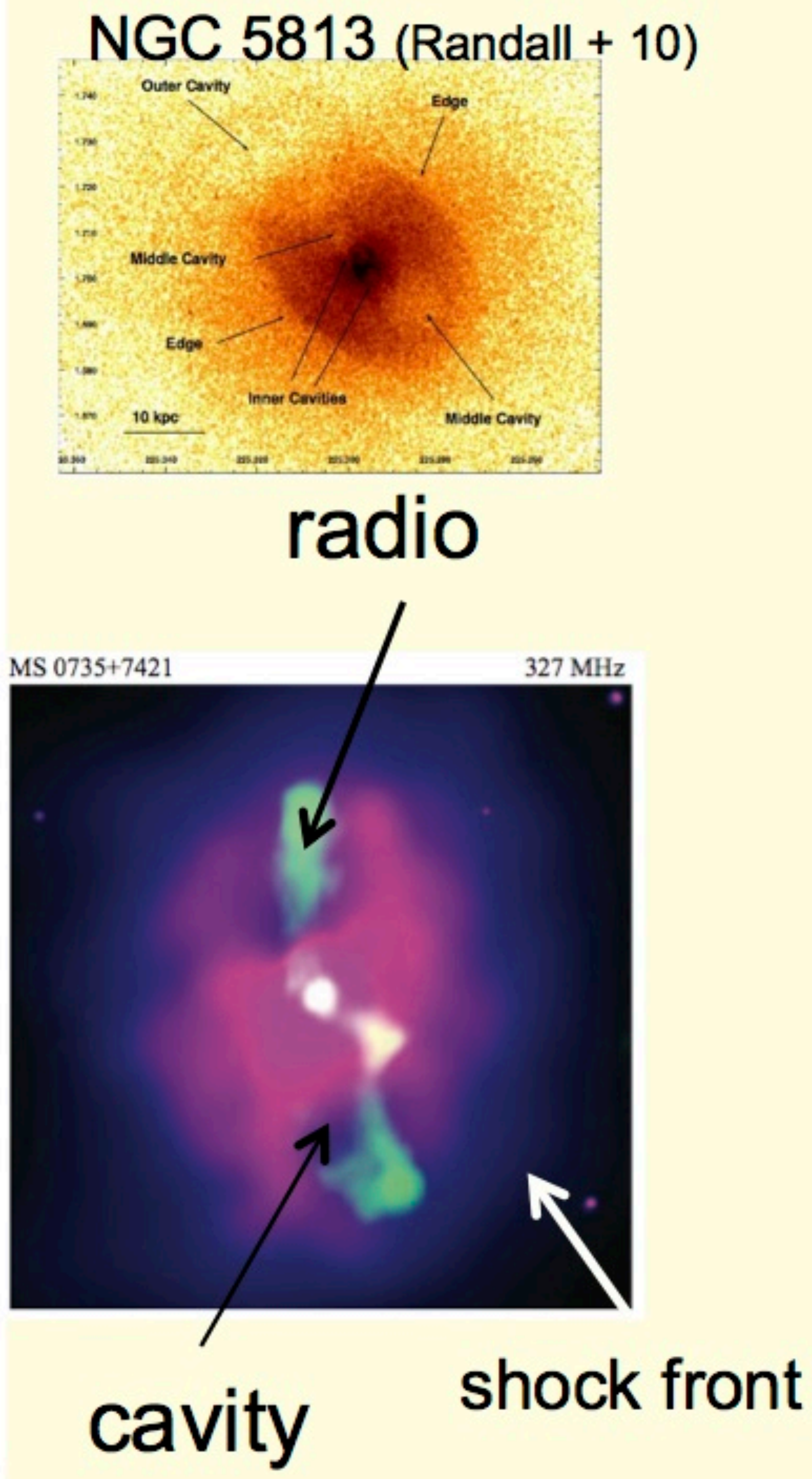


…do we see evidence for all these processes?

Mechanical power dramatically exceeds synchrotron power



Radio Luminosity



Birzan + 04

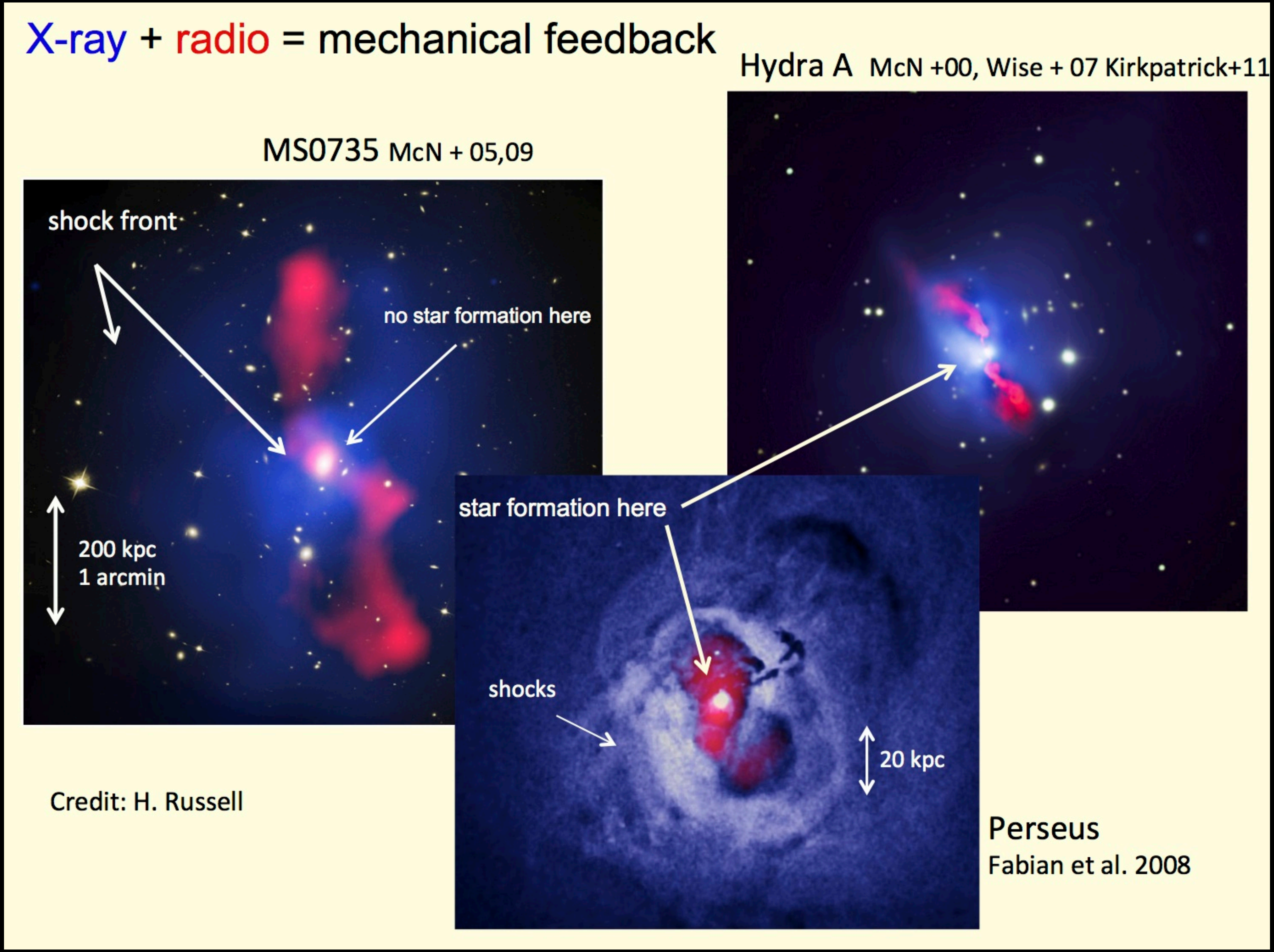
Key breakthrough: even weak radio sources mechanically powerful enoughto regulate or quench cooling, X-ray atmospheres

SMBHs in galaxies with no optical/UV AGN may be rapidly accreting!

Cygnus A

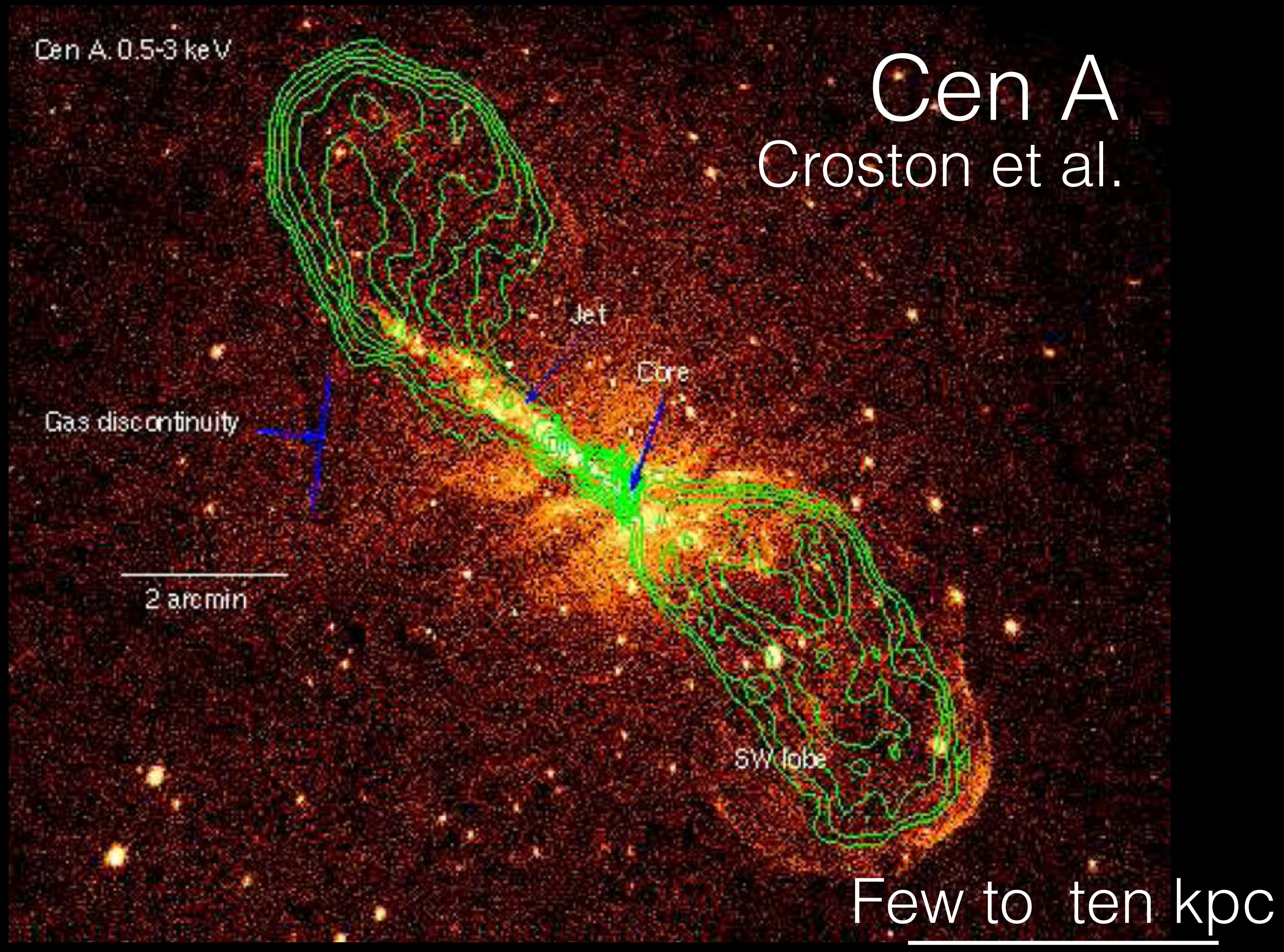
Energies associated with the X-ray cavities and shocks: ~10^{59} - 10^{62} erg

Effect of jets on large-scale hot gas



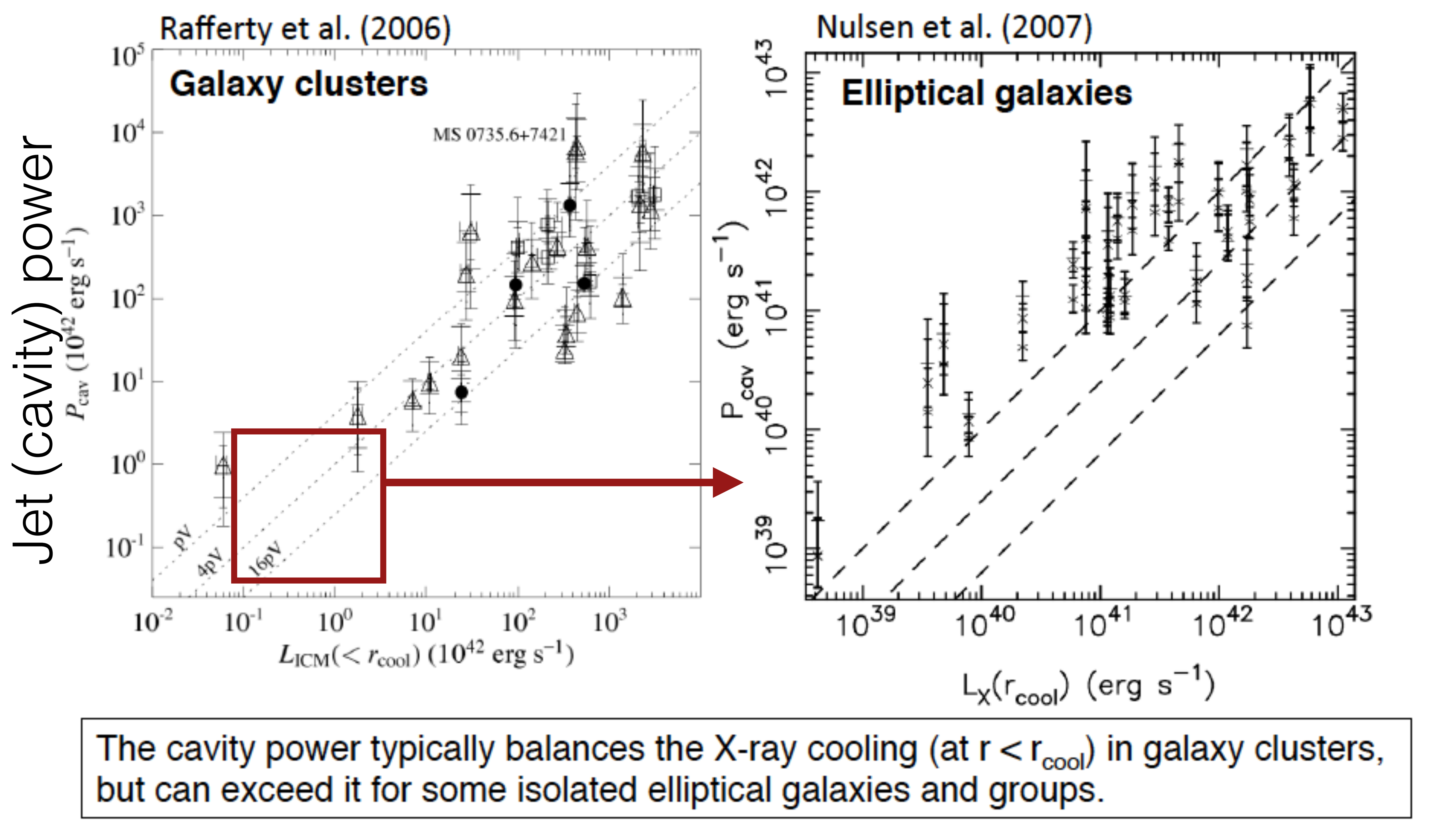
Cygnus A
LOFAR+Chandra
Wise et al., McKean et al.

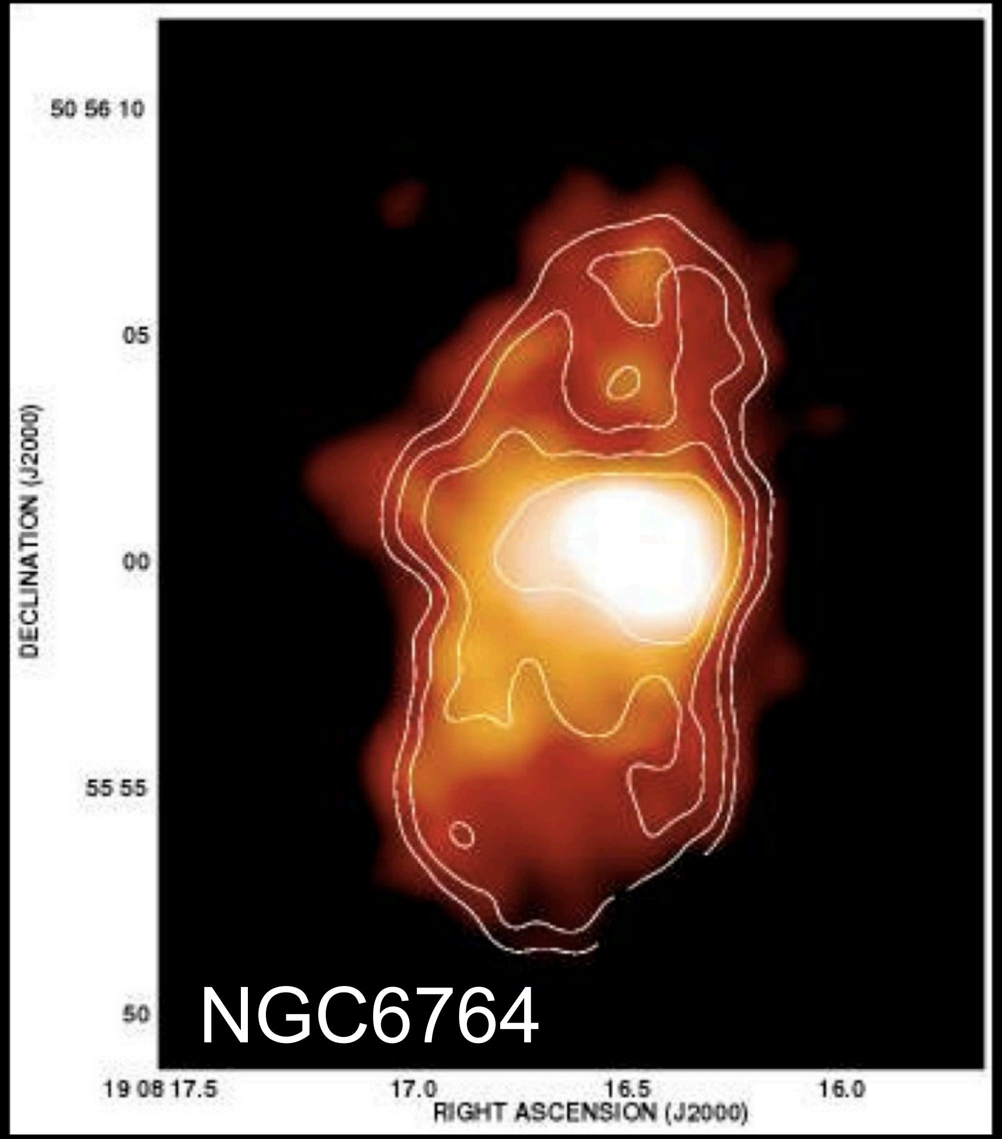
Also relevant on galaxy scales…

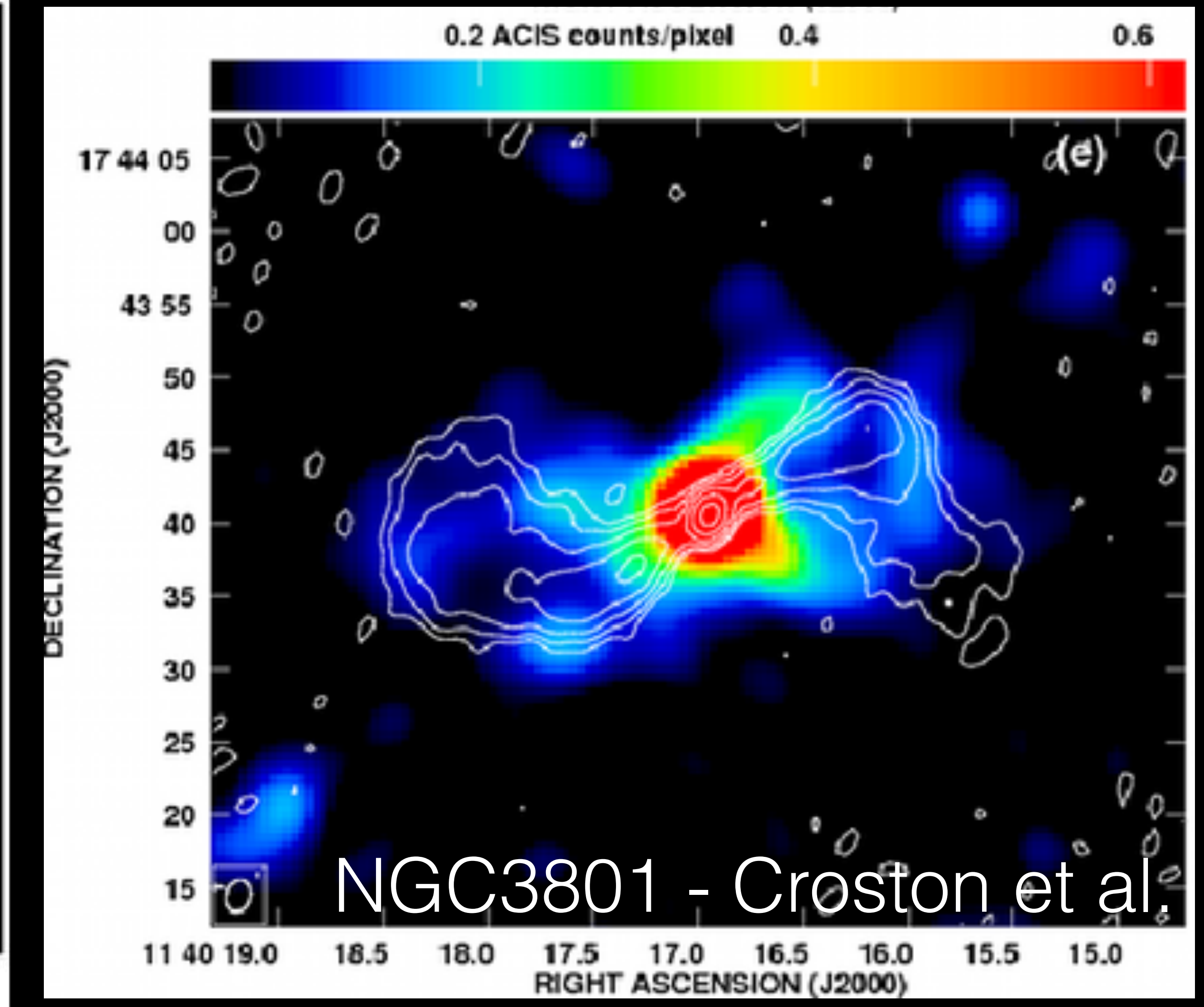


Croston et al. 2008 ApJ 688 190

Jet power ➜ about 1% in jet luminosity
(see McNamara 2012, Birzan, Cavagnolo et al. 2010)
➜ but conversion **very** uncertain (Godfrey et al. 2016)



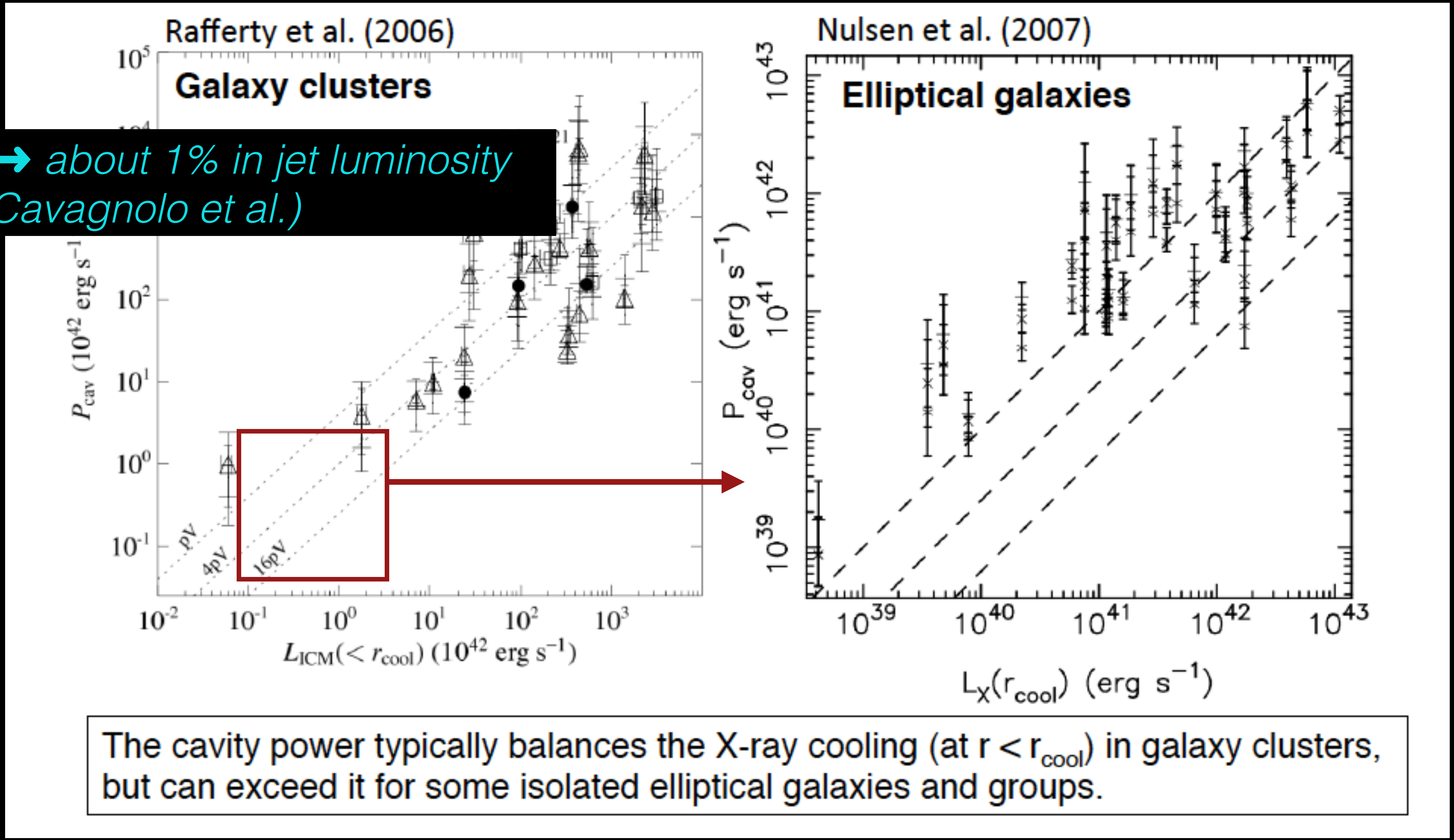




Mechanical power largely exceed synchrotron power: even for weak radio sources the mechanically powerful enough to balance the cooling

See also poster of Anna Ogorzalek et al.

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



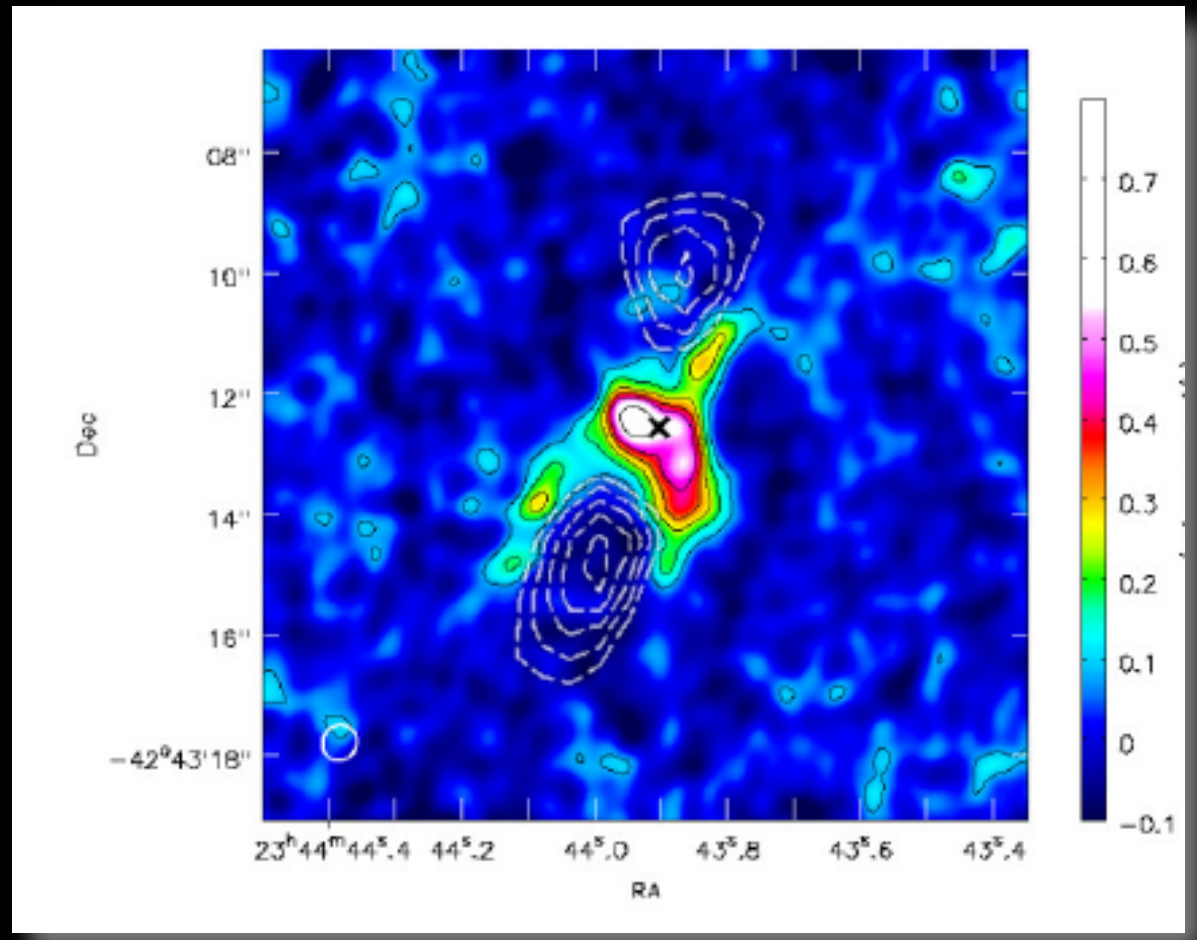
Mechanical power largely exceed synchrotron power: even weak radio sources mechanically powerful enough

McNamara et al. 2012

Jet-inflated X-ray cavities: summary

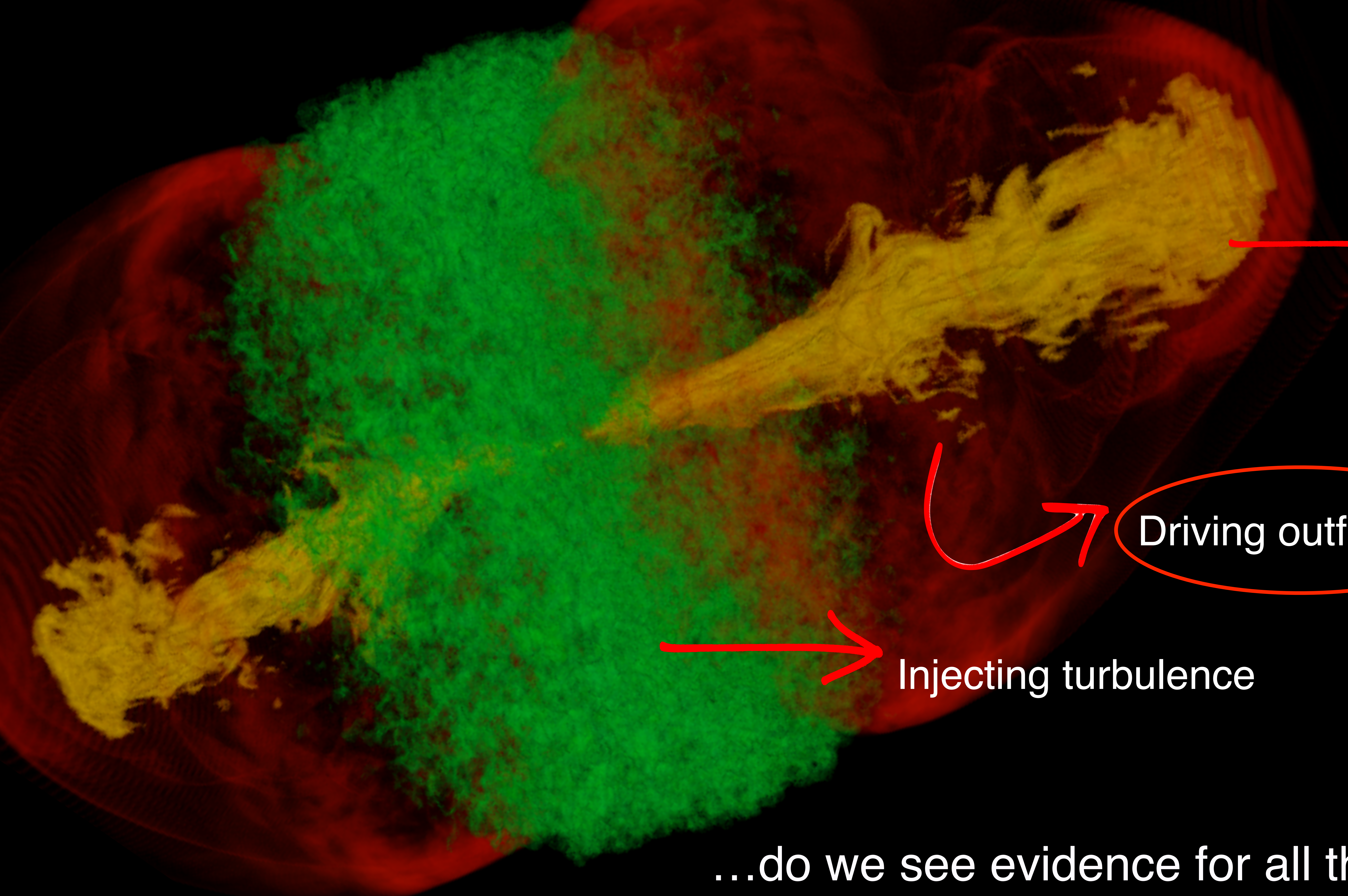
- X-ray cavities detected in ~50% of galaxy clusters, groups and individual galaxies
- Scales ~1 - 200 kpc
- Associated cavity power is often sufficient to balance the X-ray cooling
- Can be important even in moderate radio luminosity objects

- Coupling radio bubbles - cold gas ➜ molecular gas lifted by the radio bubble
- New possibilities open up by ALMA
- Velocity not high enough to escape so gas will fall back: cycle of activity is needed



ALMA (CO(3-2)
Russell et al. 2016

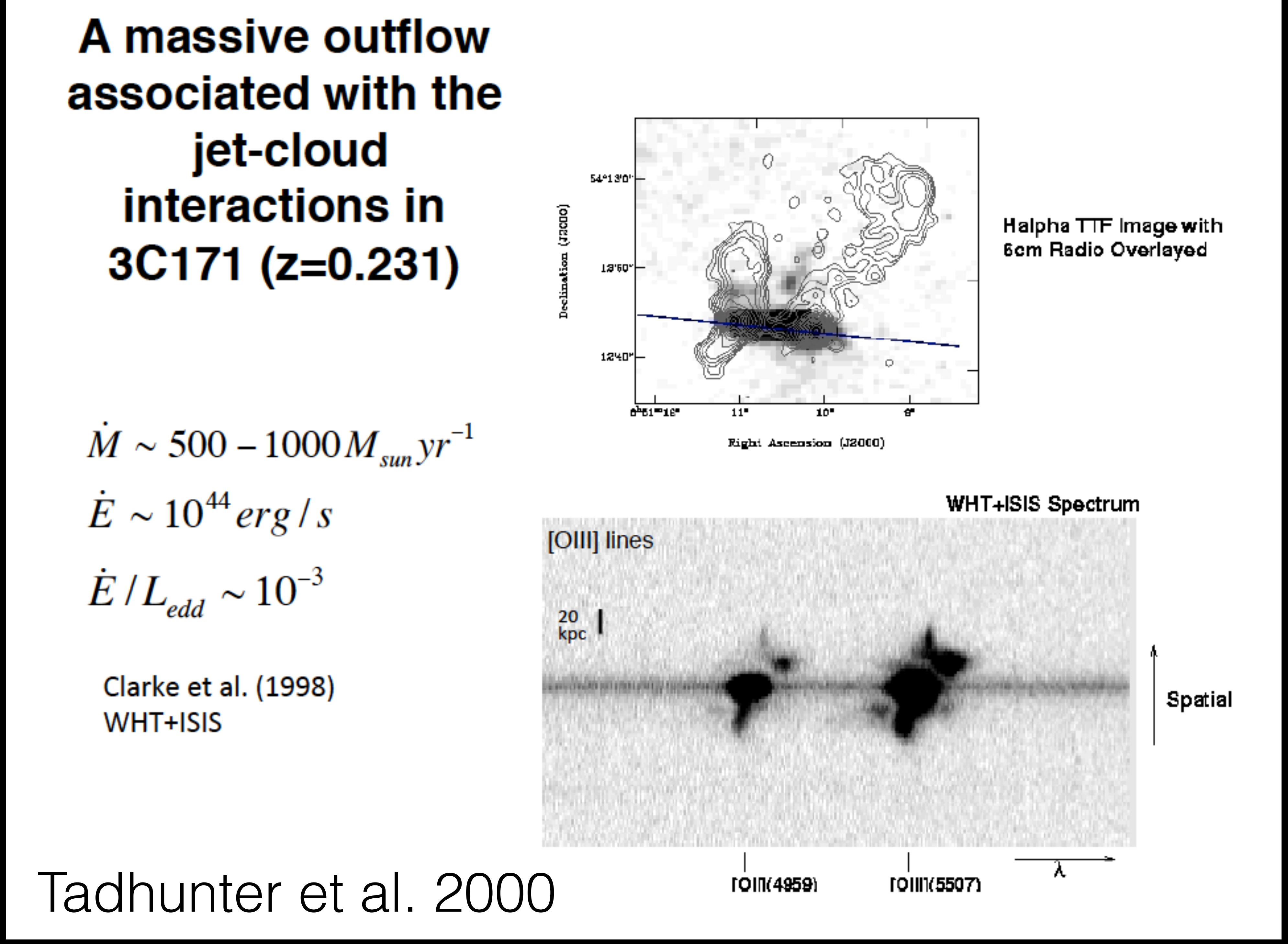
Why are radio jets relevant?

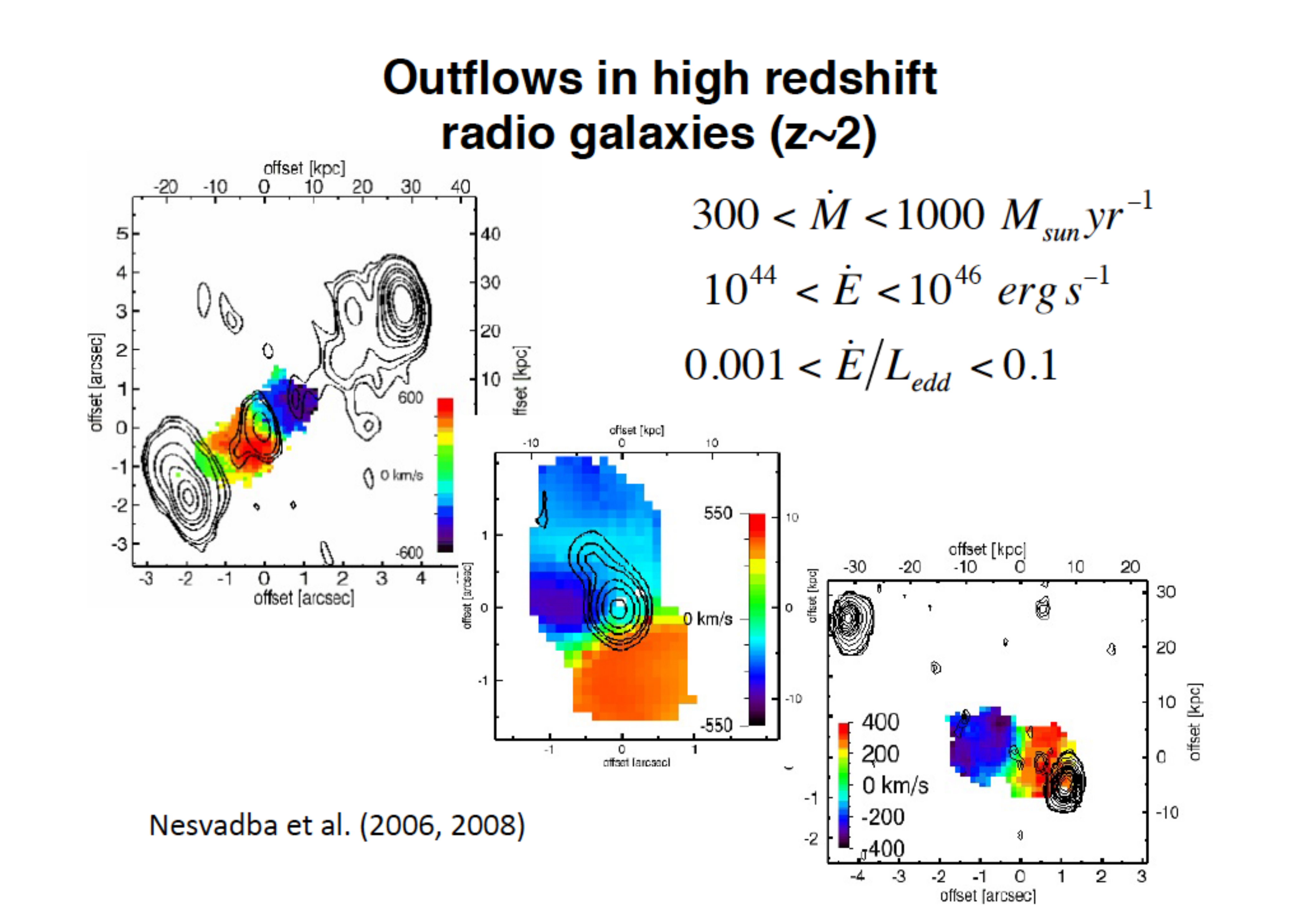


…do we see evidence for all these processes?

Radio plasma affecting the ISM known since long time....

Gas affected by the interaction with the radio plasma
➜ strongly disturbed kinematics

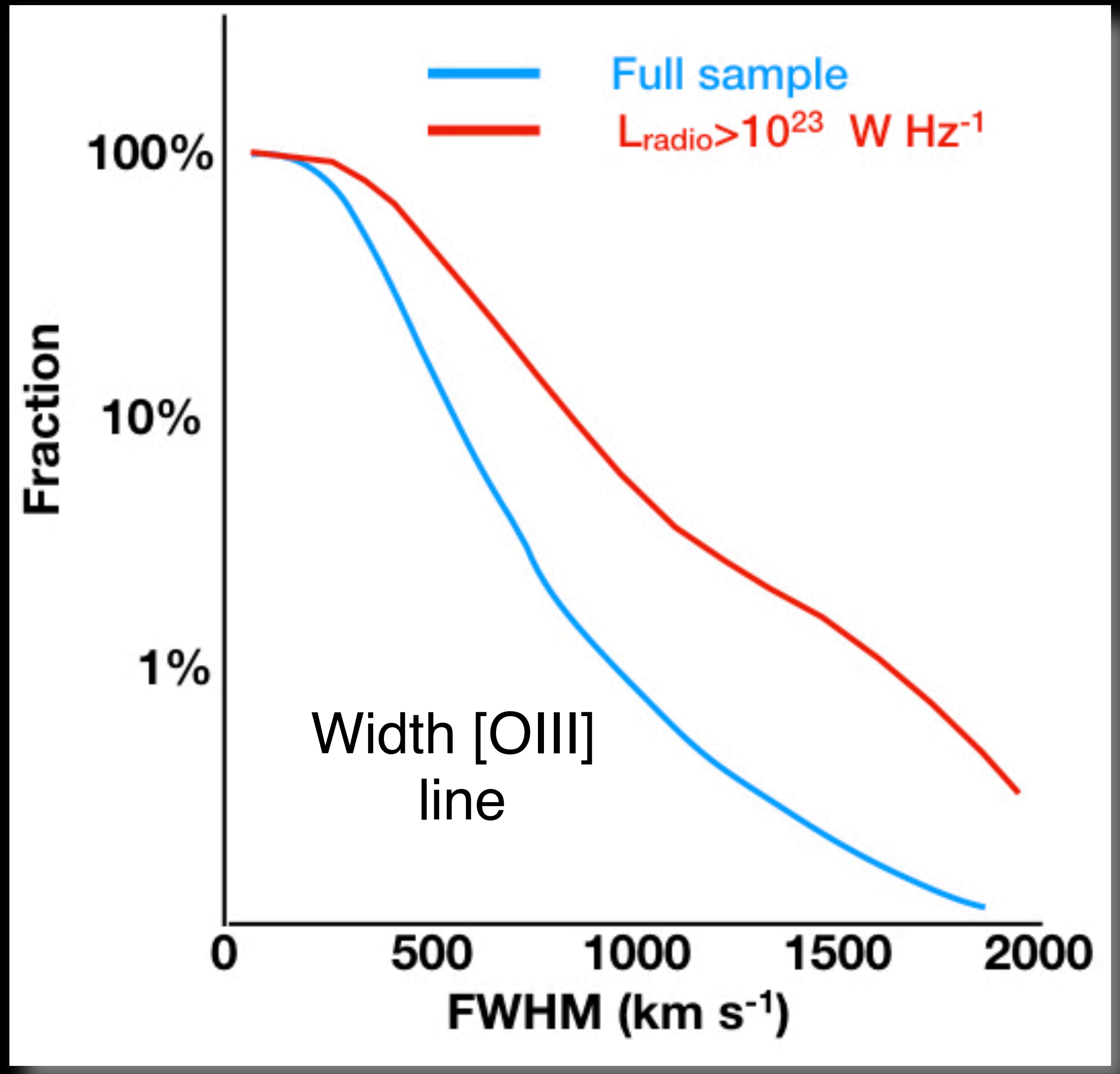




Limited to high radio power? Too rare to be interesting?
Jets too collimated to have an impact?

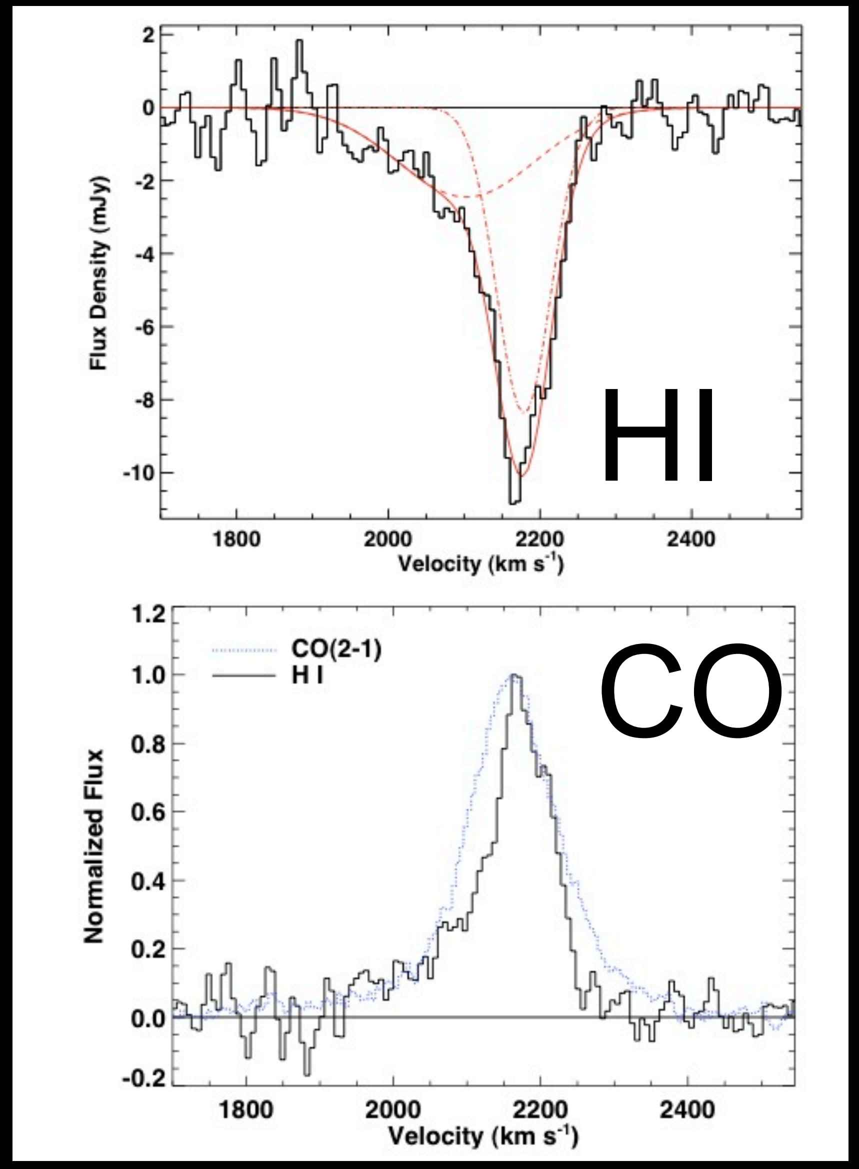
What has recently changed?

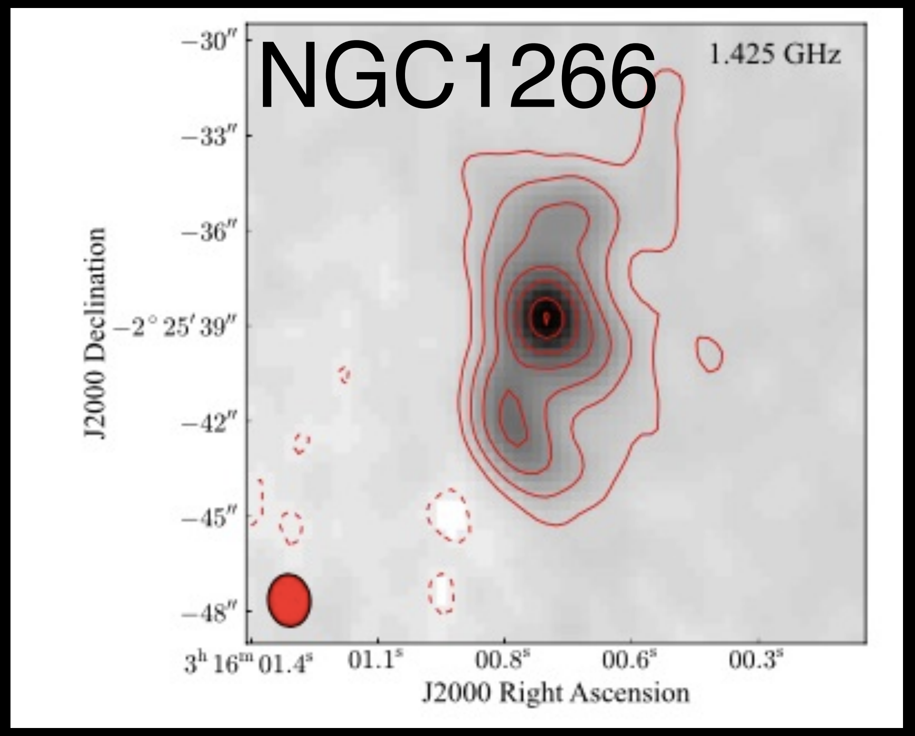
- Effects are seen in a broad range of radio sources: also in not radio-selected samples
- Effects are seen from low power jets: the so called radio-quiet!



Optical AGN from SDSS, Mullaney et al. 2013

- Outflows from ionised gas typically have modest mass outflow rates: much larger energetics associated with cold gas (HI and molecular)
- …and advances in the numerical simulations describing jet expansion





Alatalo et al. 2012

Radio power $10^{21.5}$ W/Hz

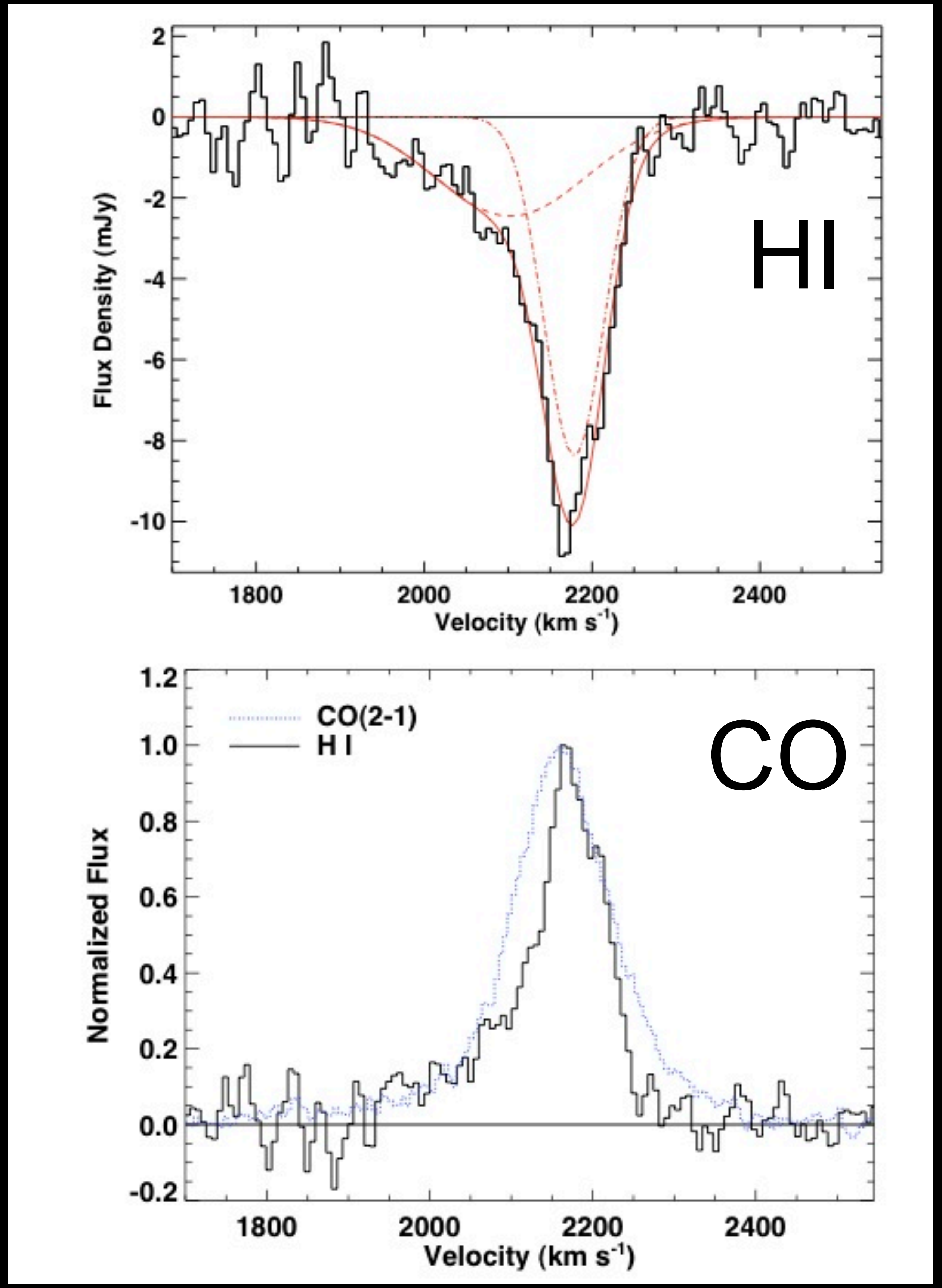
Predictions from simulations tested using cold gas

NGC1266: a more “normal” galaxy

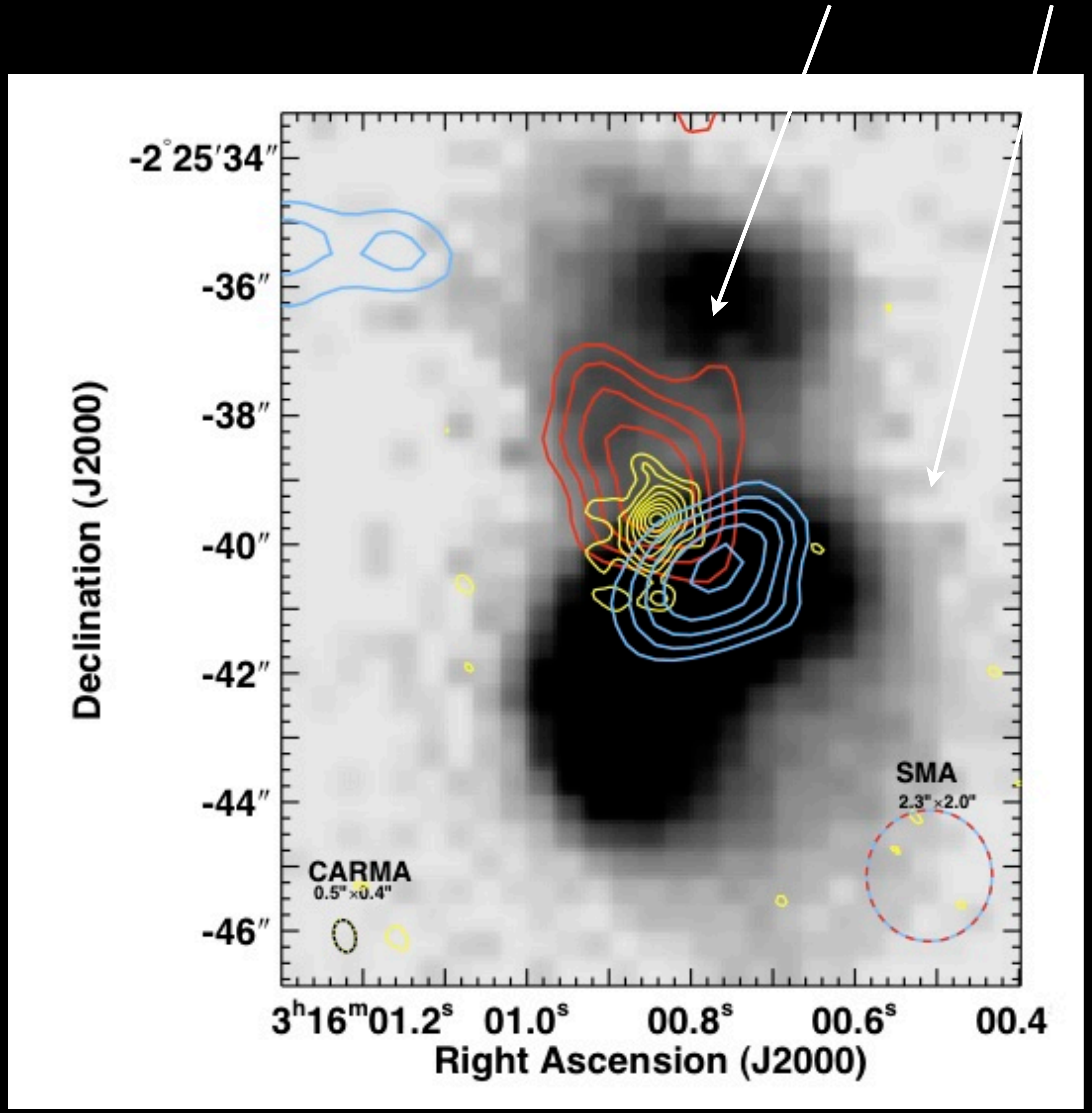
- A relatively quiet and boring early-type galaxy
- Weak radio source (about 10^{21} W/Hz)
- mass ouflow rate in CO ~ 13 M_{sun}/yr

Gas depletion time-scale 85 Myr

It shows that outflows may be found also in relatively “normal” galaxies: weak (radio) AGN, no starburst, no interaction!



CO outflow



Alatalo et al. 2011

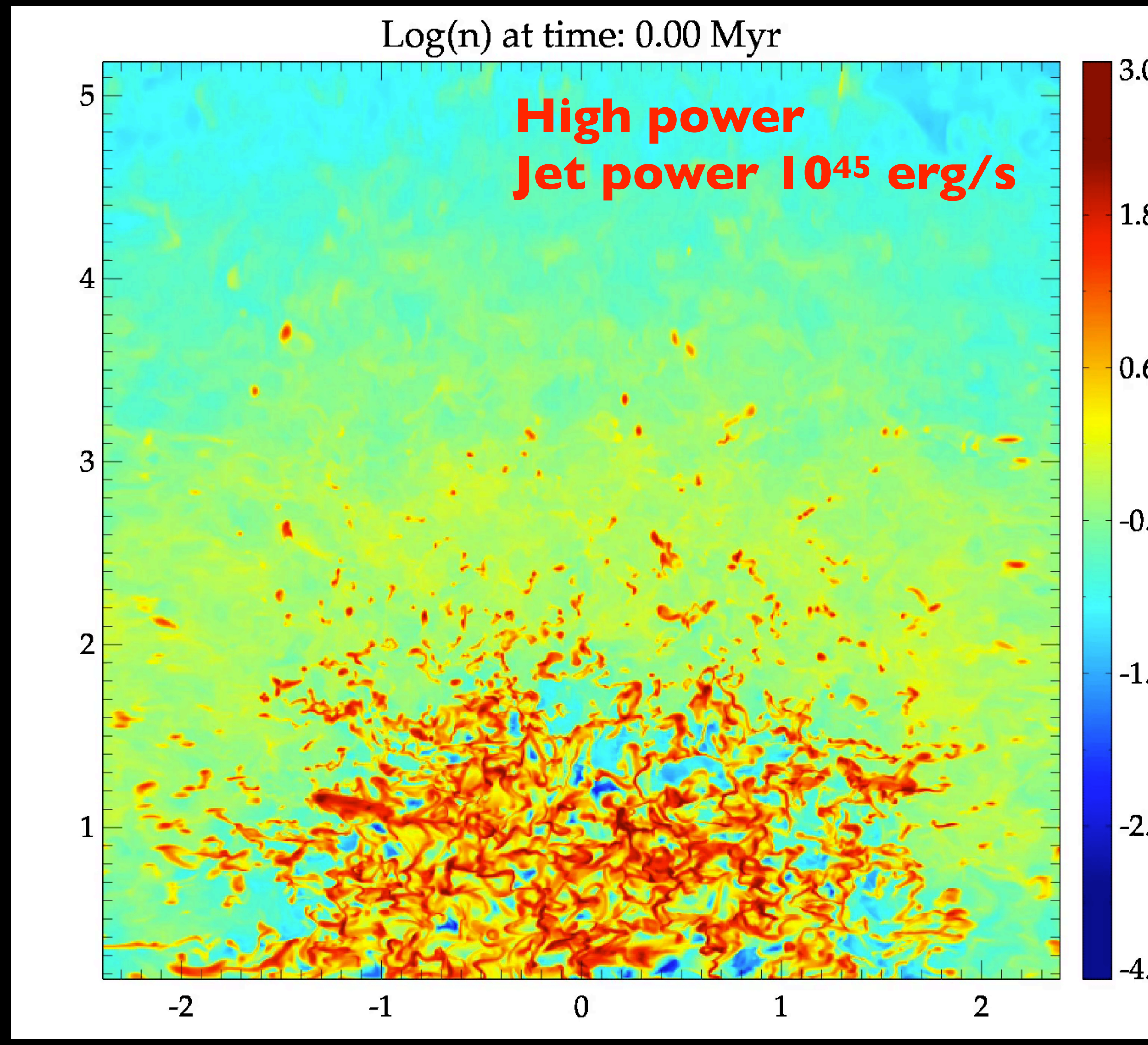
Numerical simulations of a newly created radio jet

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

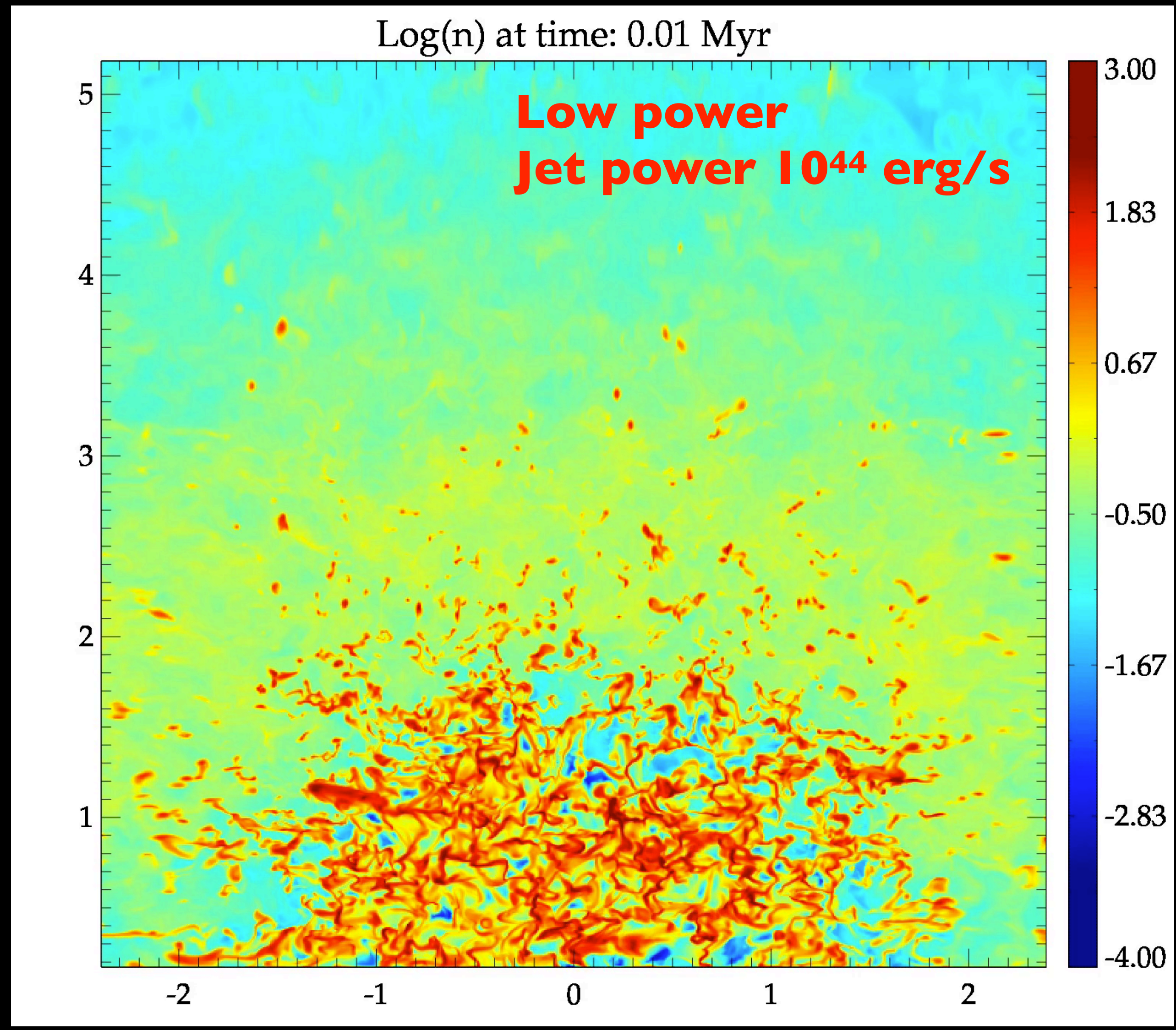
Impact of radio jets as on the kinematics of the gas predicted by numerical simulations: large range of parameter-space to explore!

- 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 cloud* (Wagner et al. 2012).
- A newly created jet (or restarted) jet has the largest impact
- Effect depends on **jet power: low power jets are important!** Couple more with the ISM, will induce more turbulence and they are more numerous!

  Change in balance outflows vs turbulence?
- **Fast multiphase outflows** but not always enough to escape.
- Orientation jet expansion wrt gas distribution



clumpy medium (spherical distribution), different jet power



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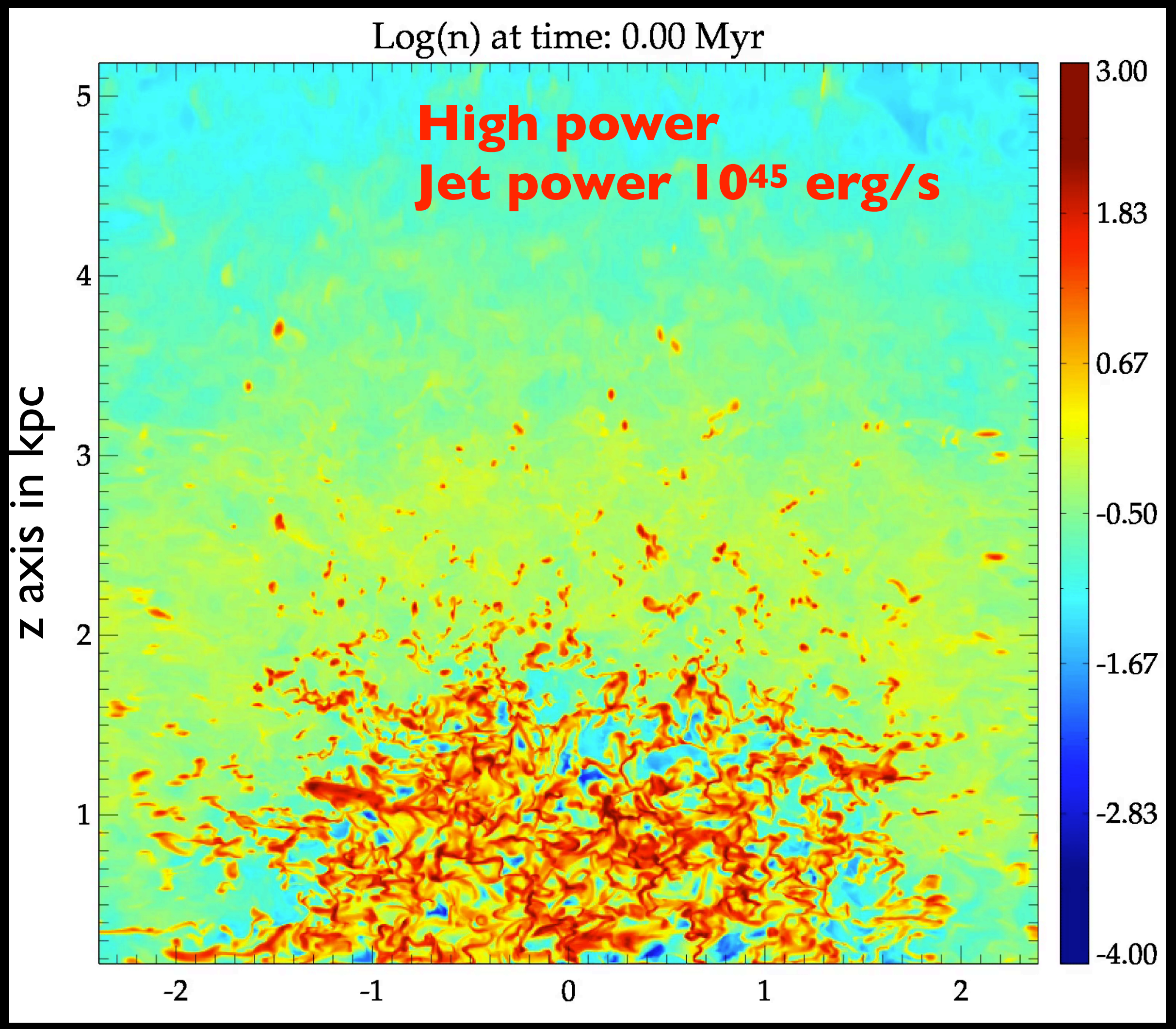

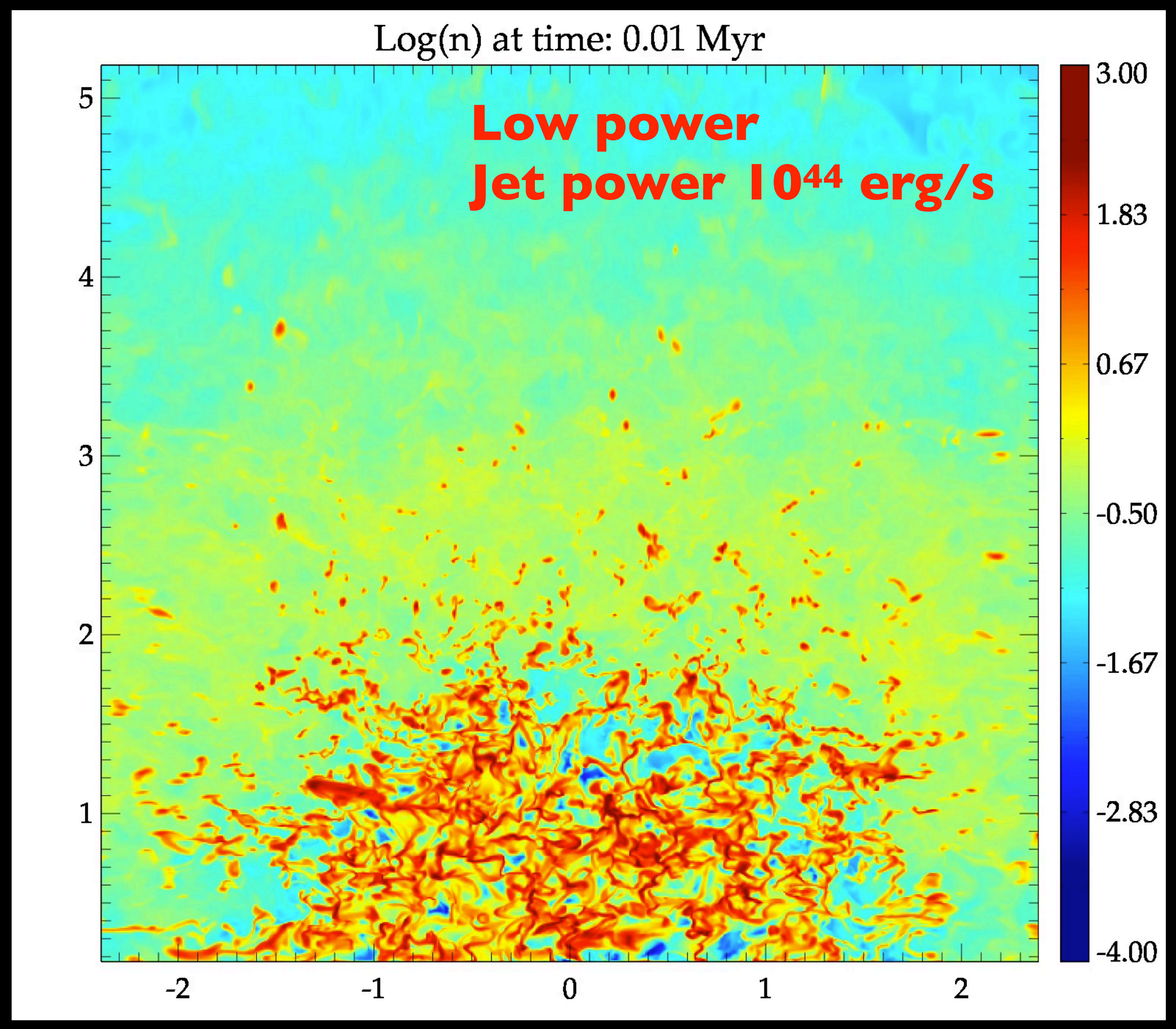

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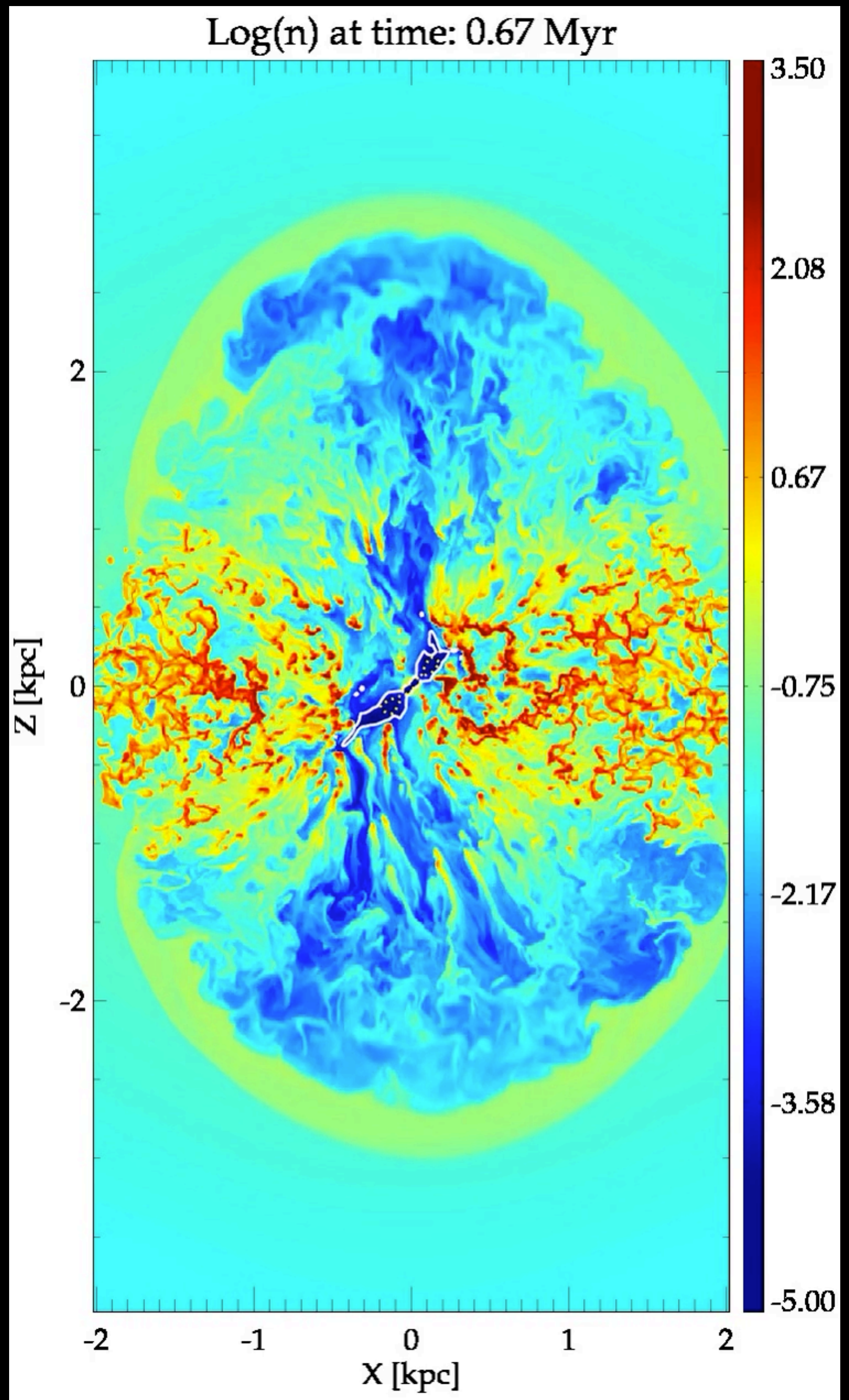

Mukherjee et al. 2017 2018

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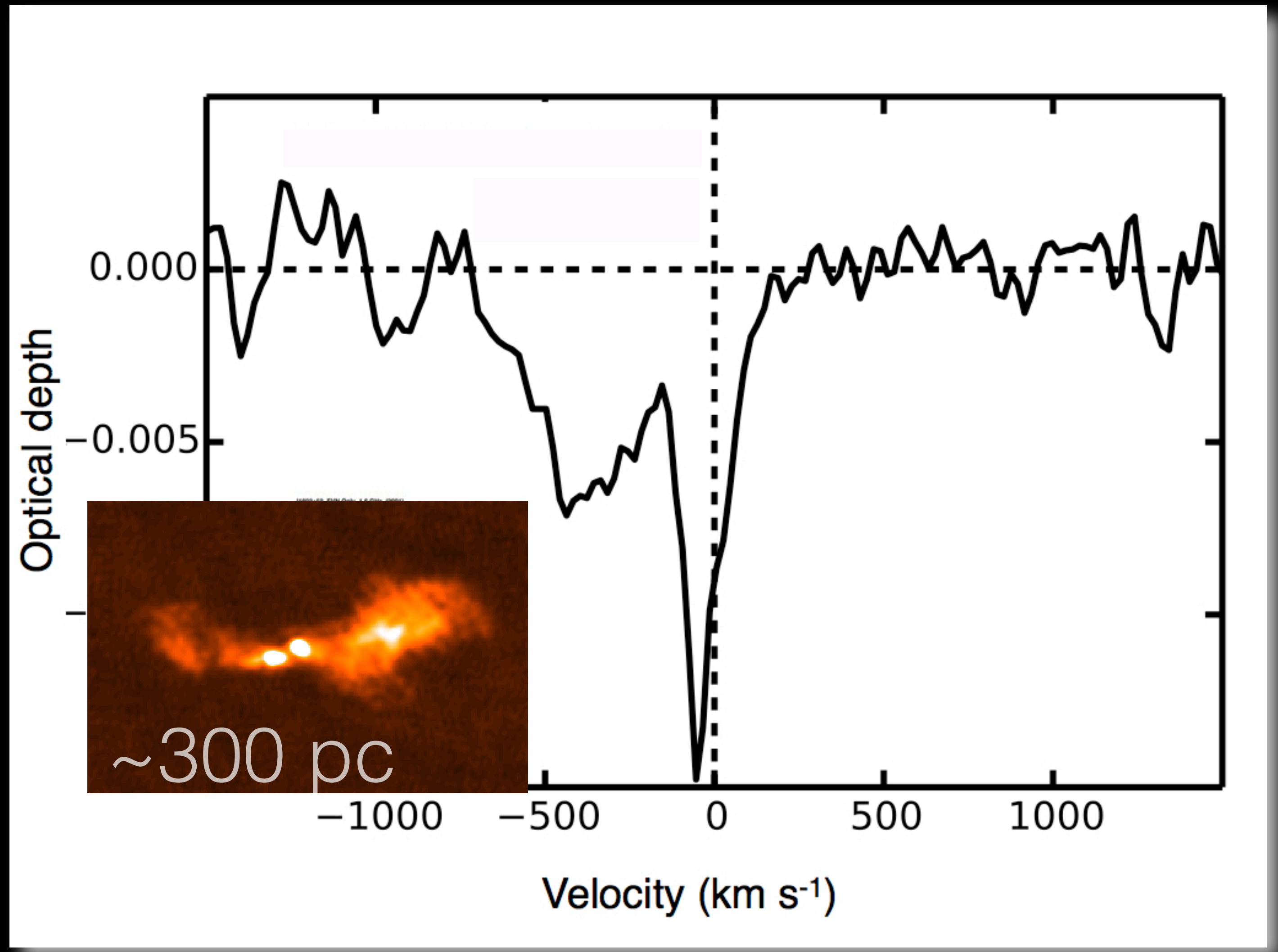
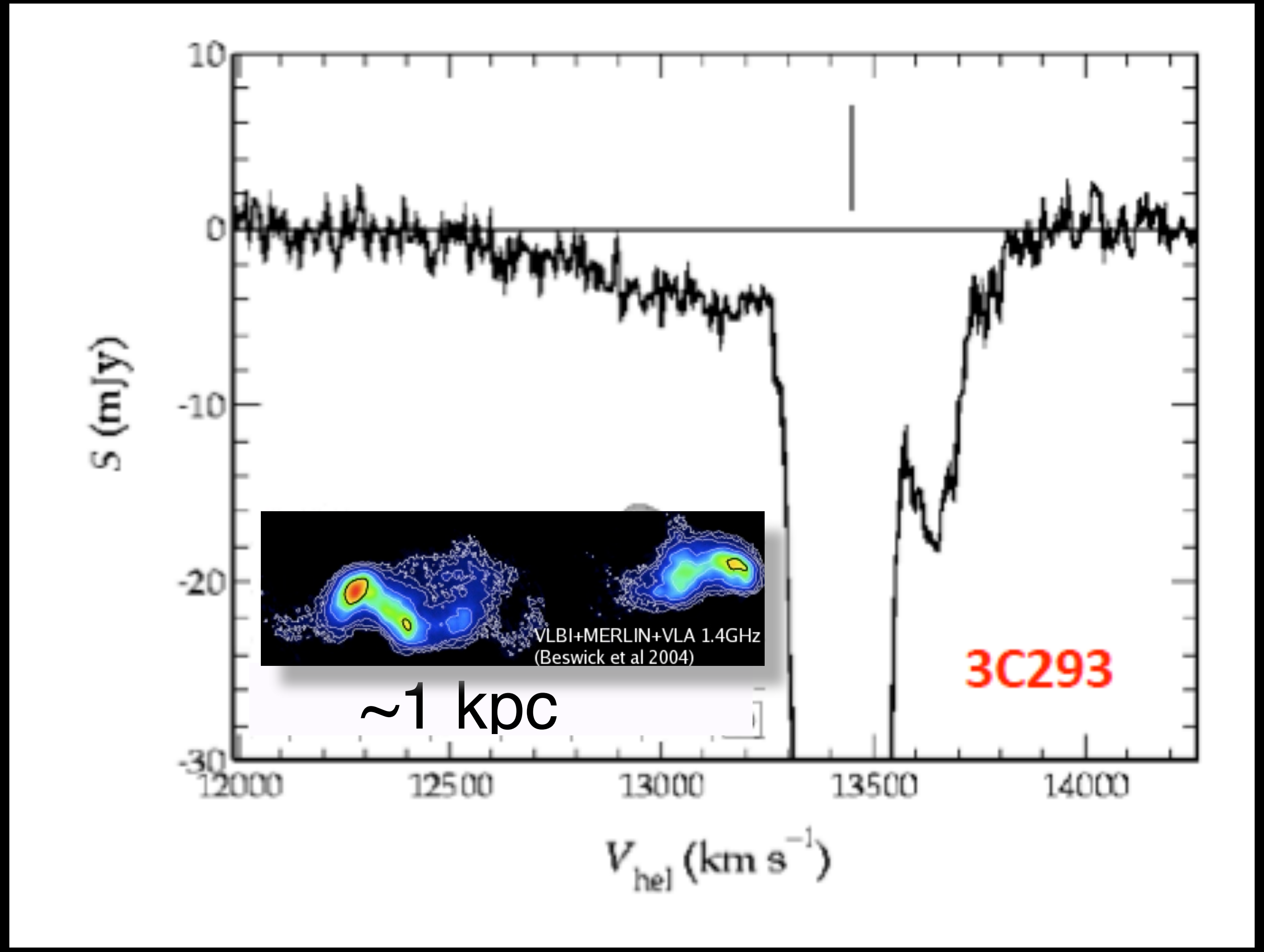
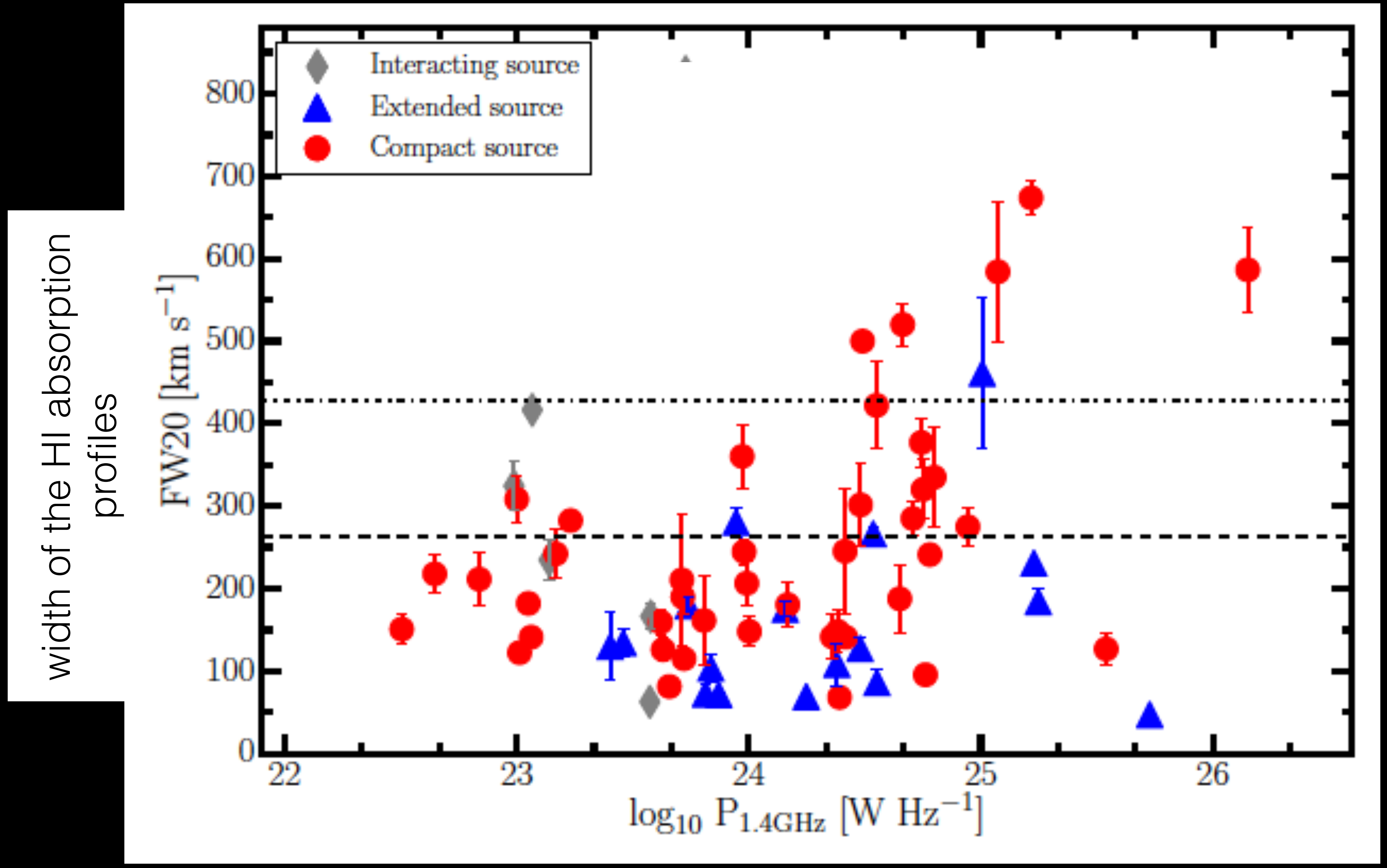
clumpy medium in a disk

Young (and restarted) radio sources effective in producing outflows

Gereb et al. 2015, Maccagni et al. 2017







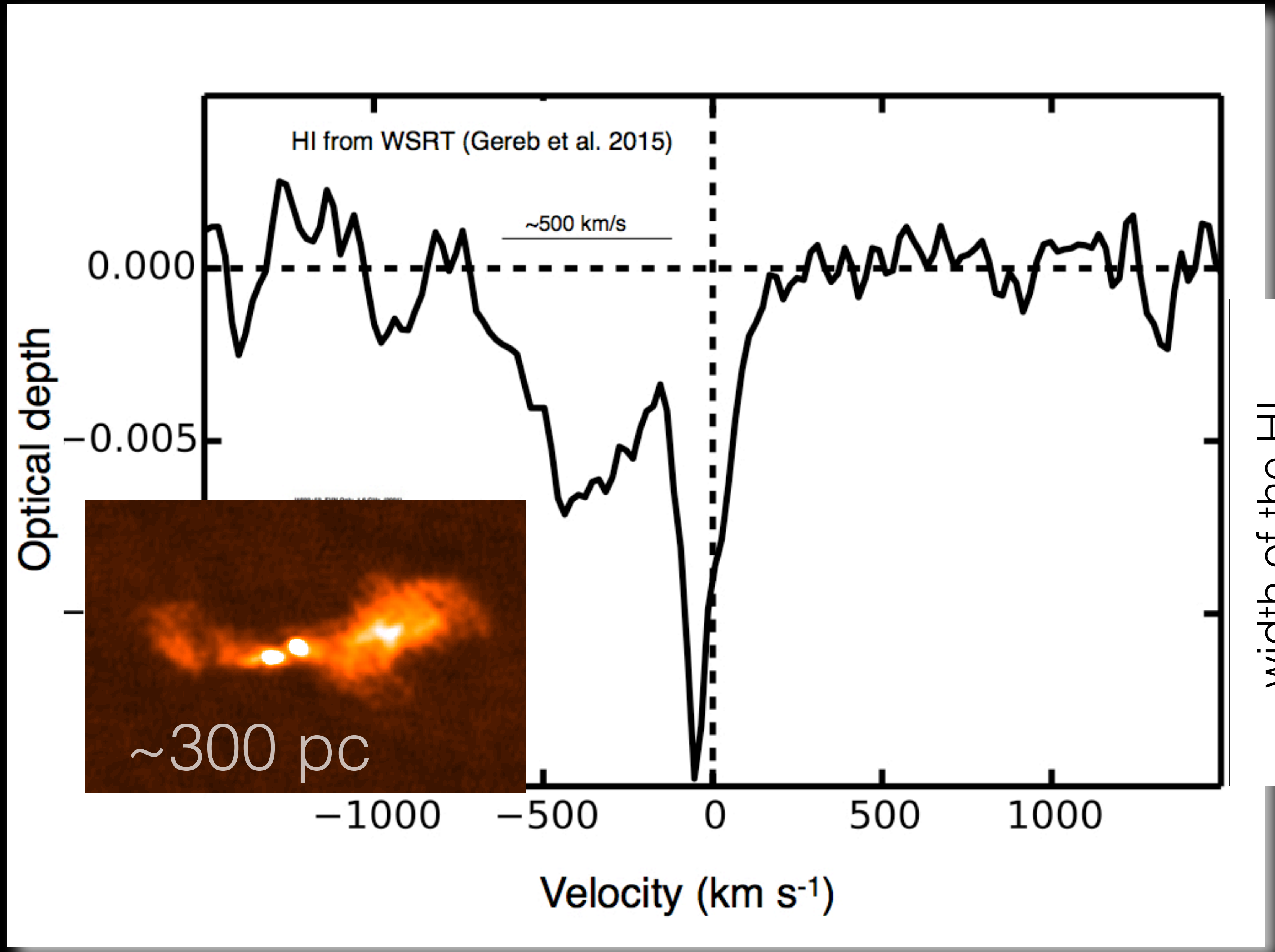
15% of HI detections show HI outflow (500-1300 km/s)

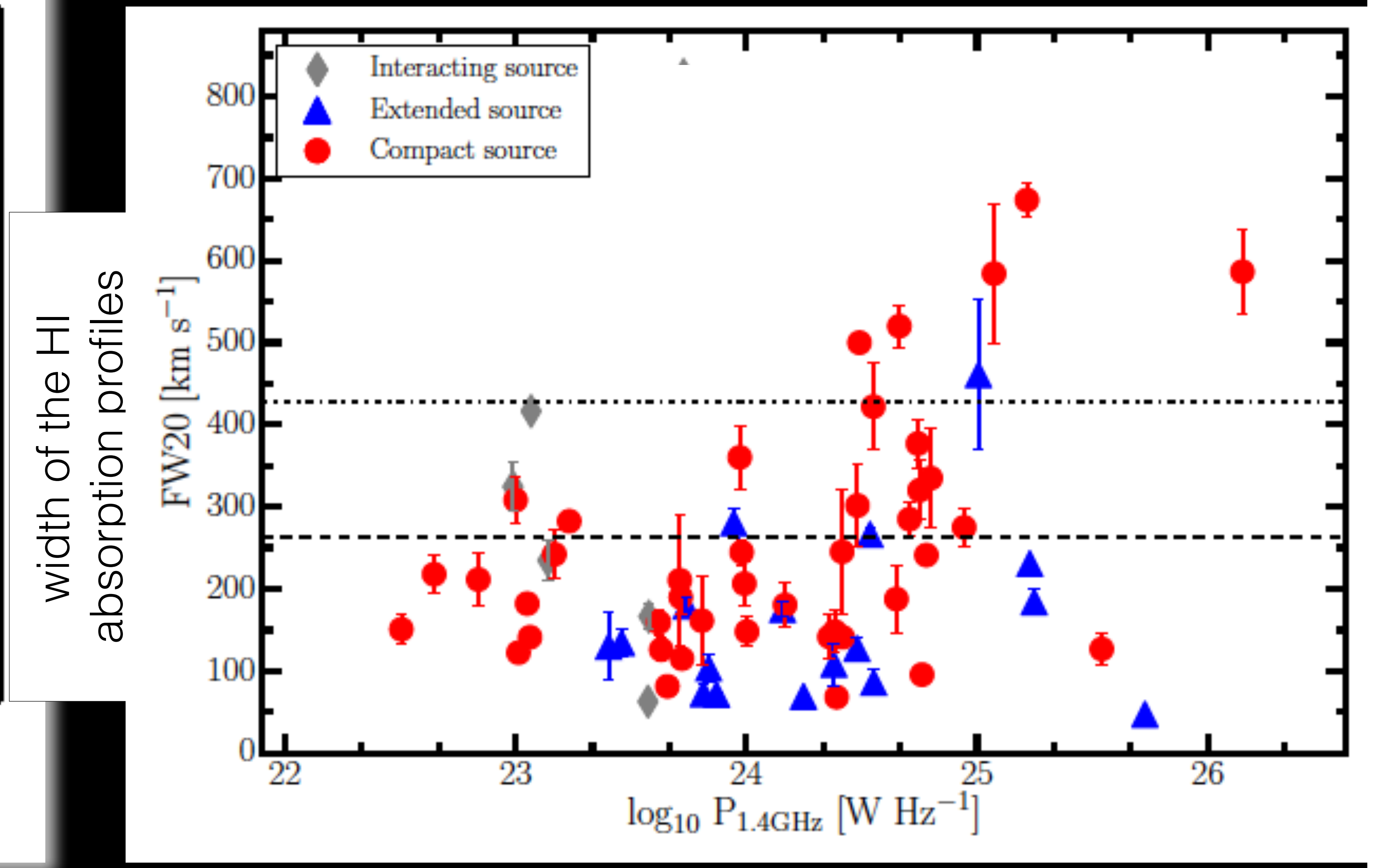
higher detection rate for
young (and restarted) radio galaxies

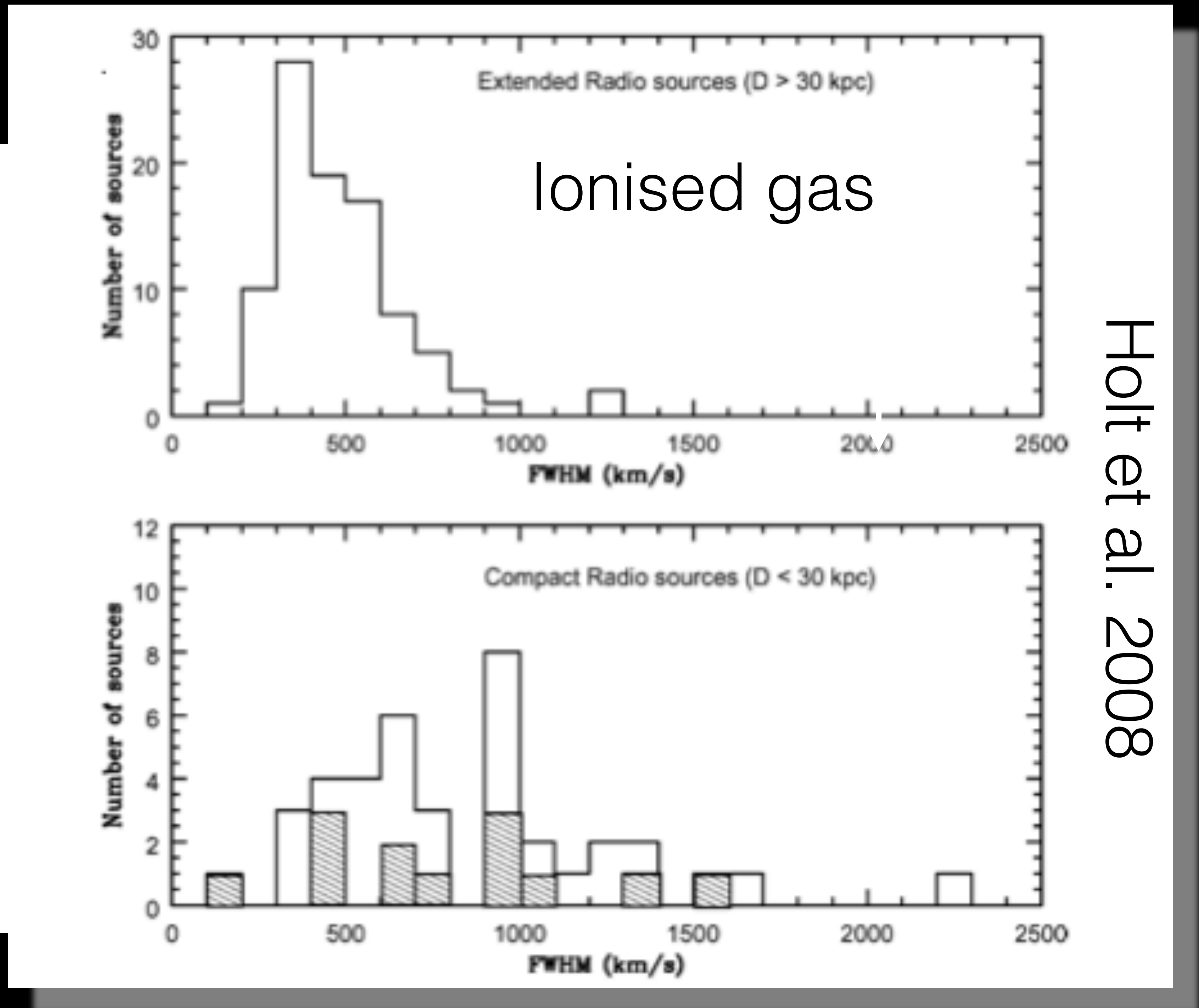
(consistent with results from the ionised gas, e.g. Holt et al. 2008)

Mass in the HI outflows from a few x10^6 to 10^7 $M_\odot$; **mass outflow rates** up to 20-50 $M_\odot$/yr
For HI outflows $\dot{E}_{kin}/L_{edd}$ ~10^{-4} (few x 10^{-3} bolometric luminosity)

Young (and restarted) radio sources more effective?







Gereb et al. 2015, Maccagni et al. 2017

15% of HI detections show HI outflow (500-1000 km/s)

higher detection rate for
young (and restarted) radio galaxies

consistent with results on the ionised gas

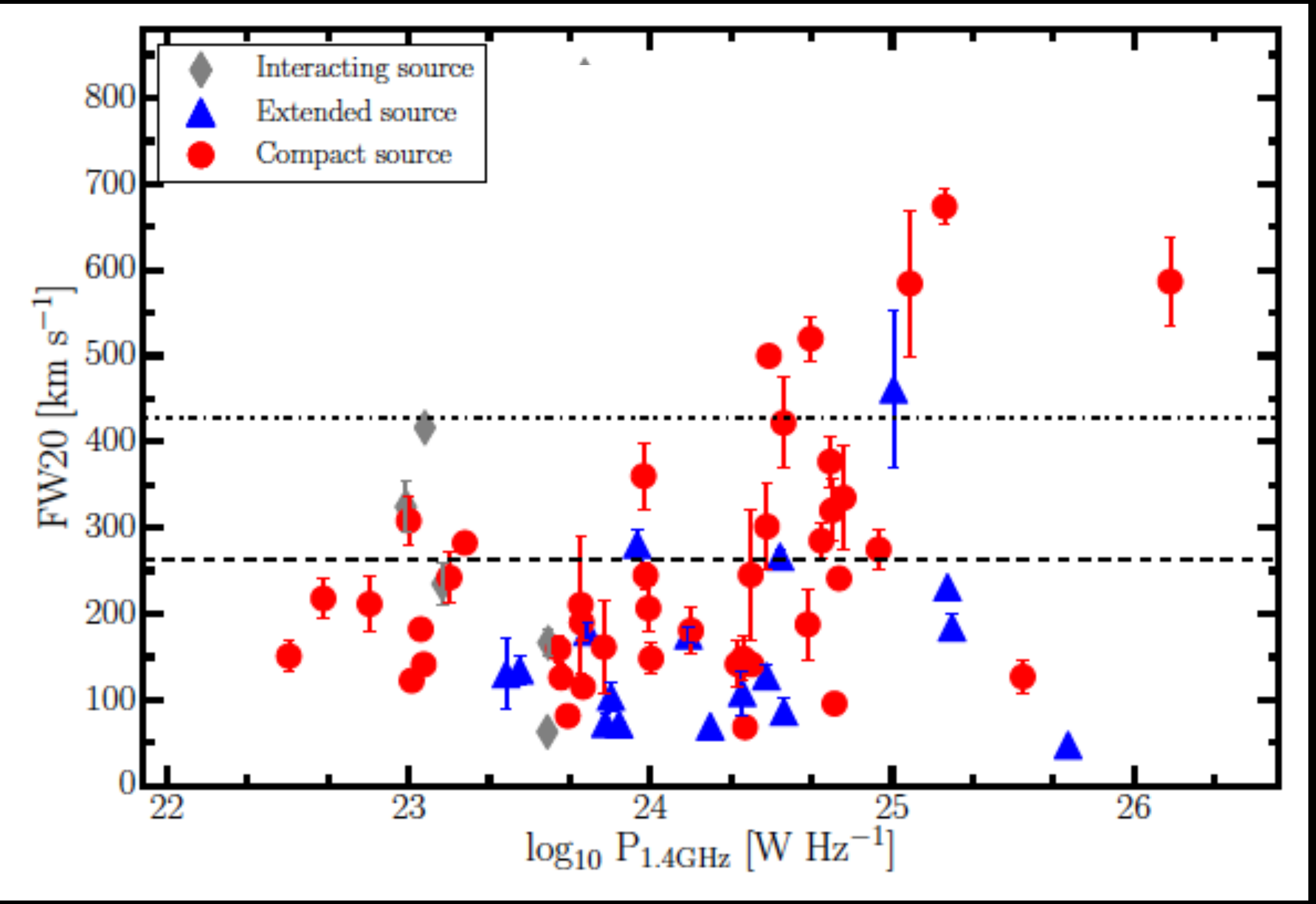
HI outflows: mass in the HI outflows from a few $x10^6$ to 10^7 $M_\odot$;
velocities between a few hundred and ~1300 km/s; **mass outflow rates** up to 20-50 $M_\odot$/yr
For HI outflows $\dot{E}_{kin}/L_{edd}$ ~10^{-4} (few x 10^{-3} bolometric luminosity)

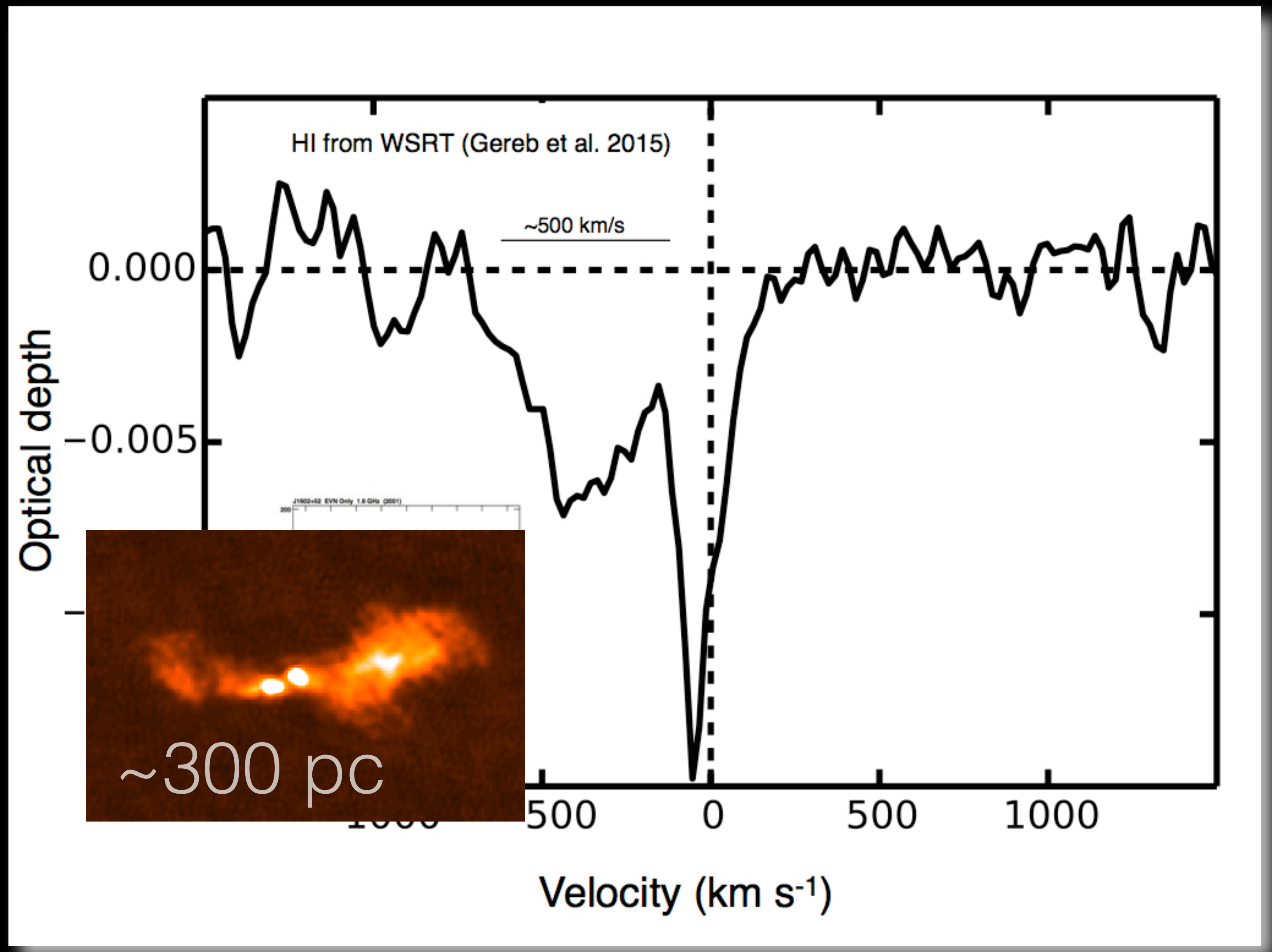
1

What is the occurrence of HI outflows?

From a pilot survey HI absorption with the WSRT in preparation for Apertif

width of the HI absorption profiles





at least ~5% of the all sources (15% of HI detections) show HI outflow (500-1000 km/s)

higher detection rate for young (and restarted) radio galaxies

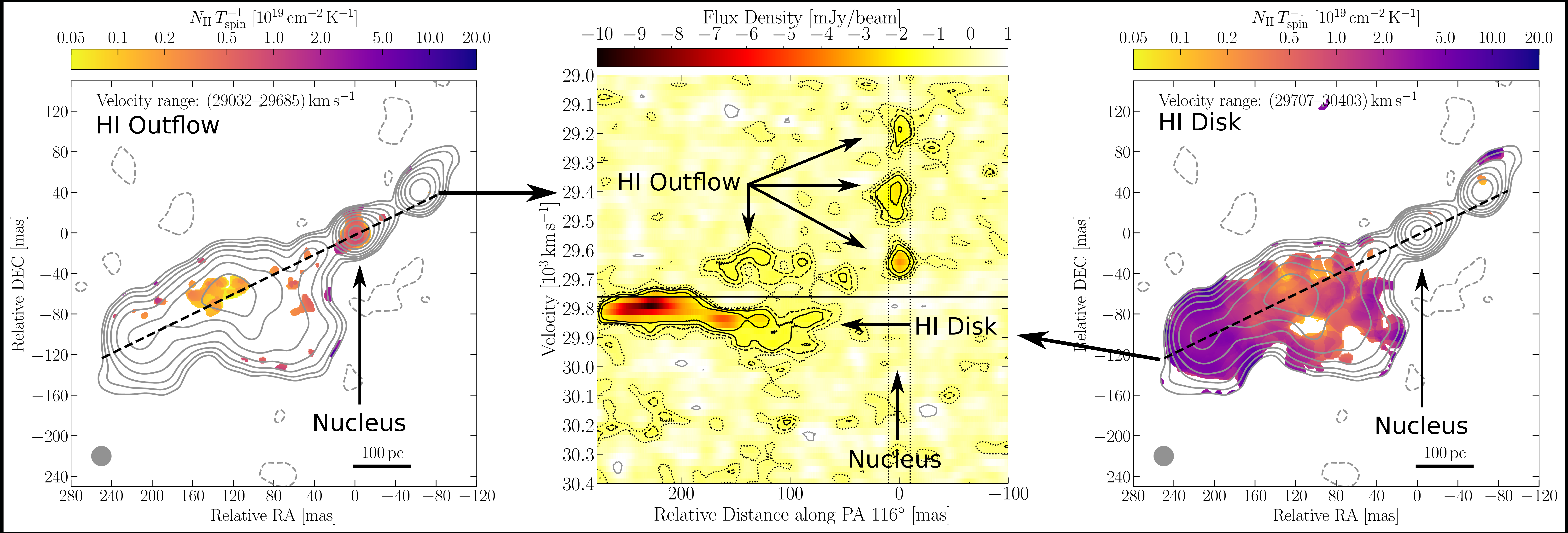
Mass in the HI outflows from a few x10^6 to 10^7 $M_\odot$, velocities between a few hundred to ~1300 km/s, mass outflow rates a few to 50 $M_\odot$/yr

Gereb et al. 2015, Maccagni et al. 2017

Tracing the clumpy medium at pc resolution

HI VLBI observations (resolution ~10 pc)

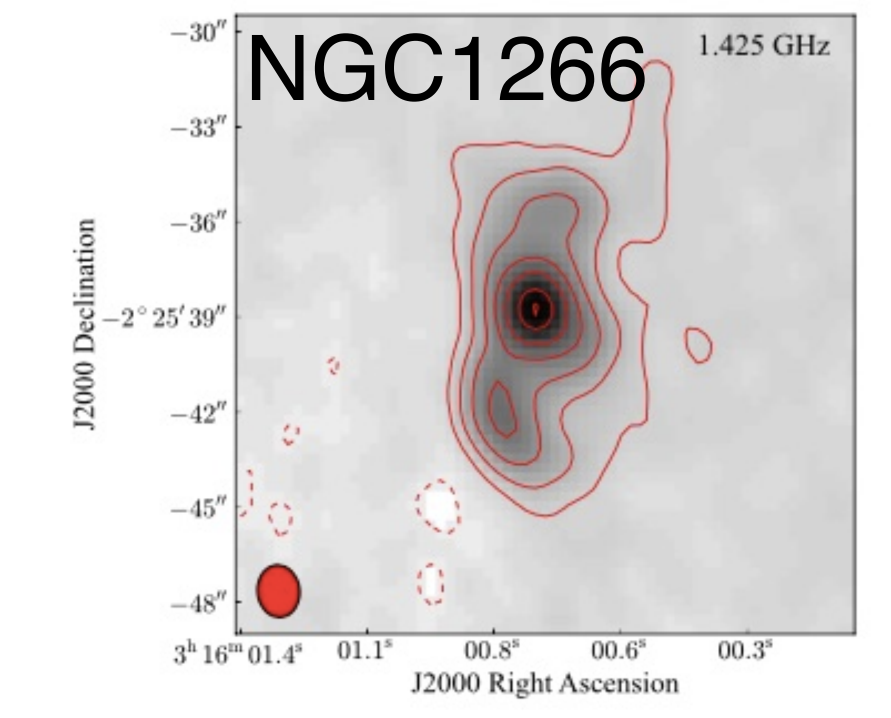
HI clouds outflowing at ~ 600 km/s observed already in the inner few x 10 pc from the nucleus (< 40pc).
Average density of the HI clouds n_e ~150-300 cm^{-3} (0.28–1.5 x 10^4 $M_{\odot}$)



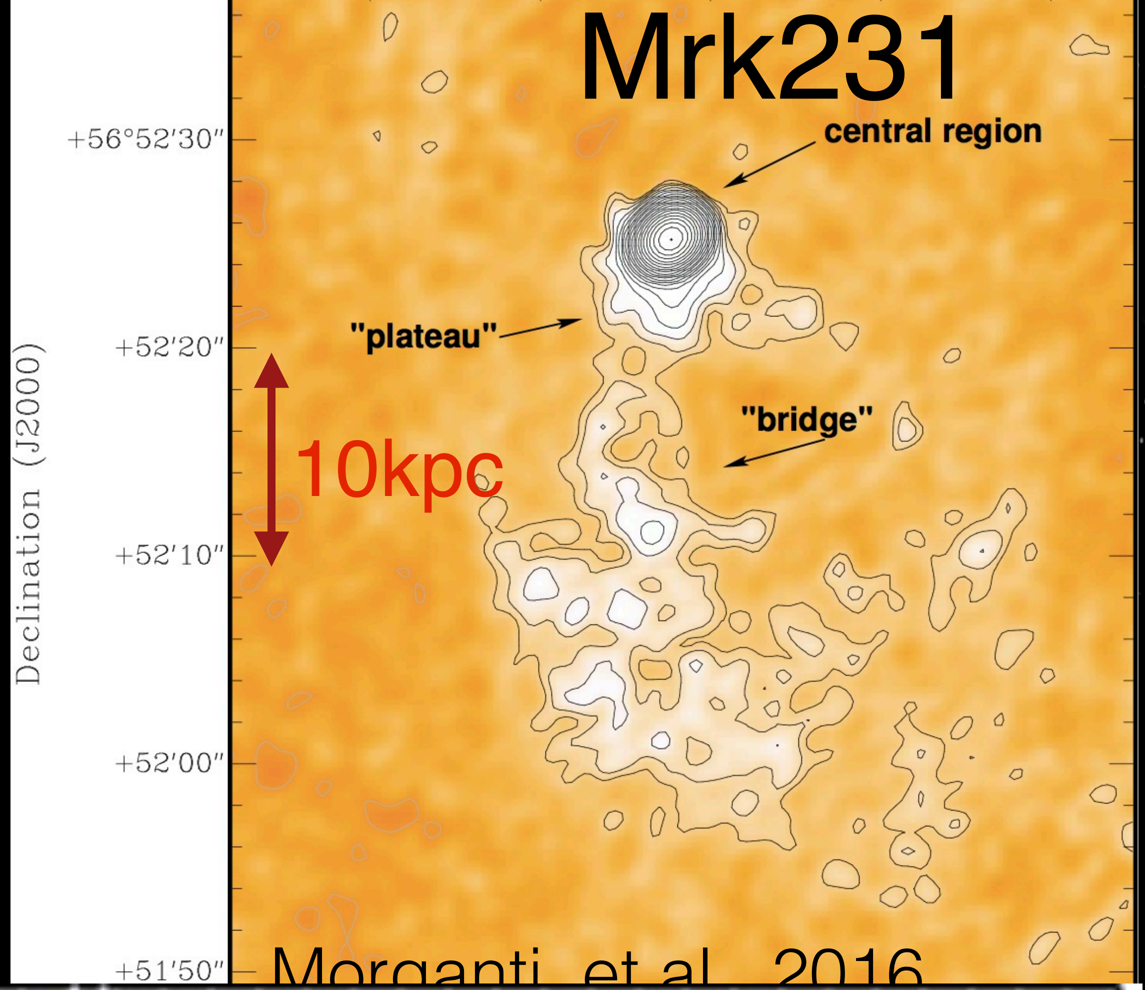
Case of the radio galaxy 3C236

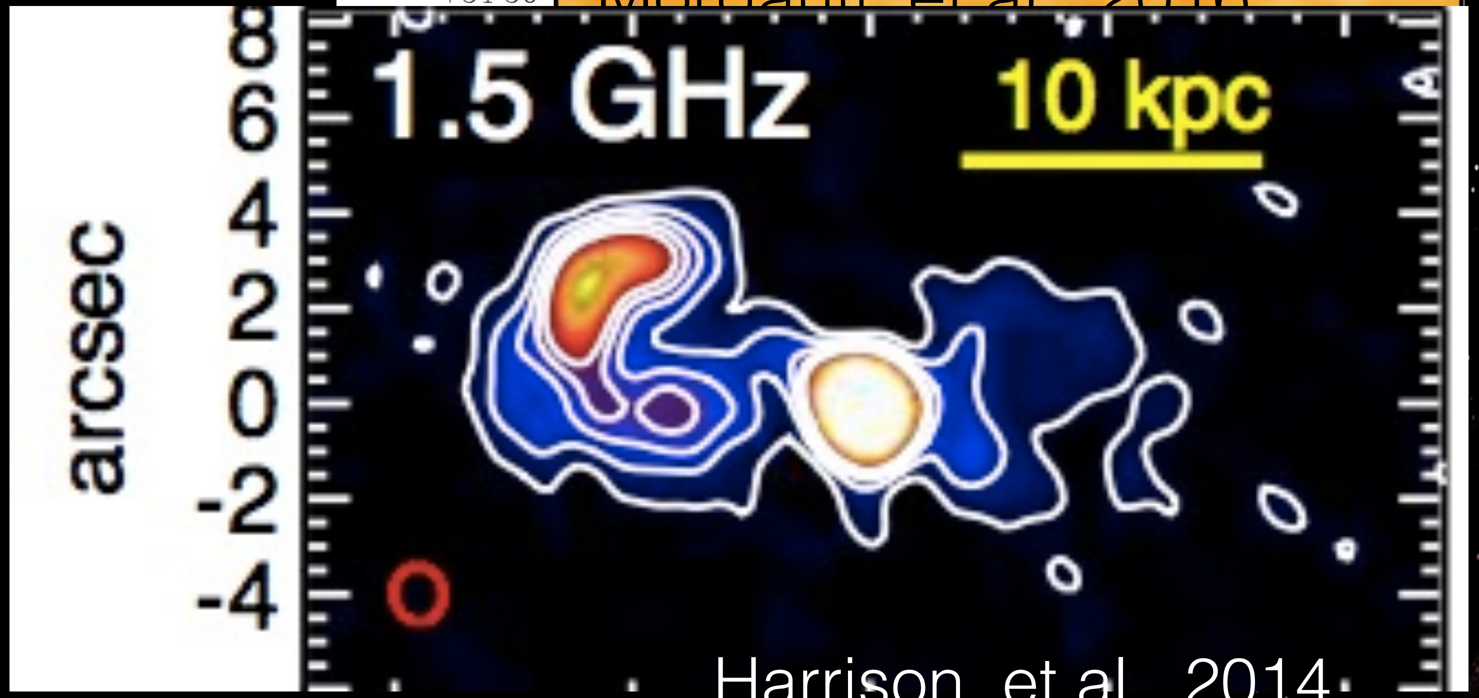
Schulz, RM et al. 2018 (arXiv:1806.06653)

radio quiet?

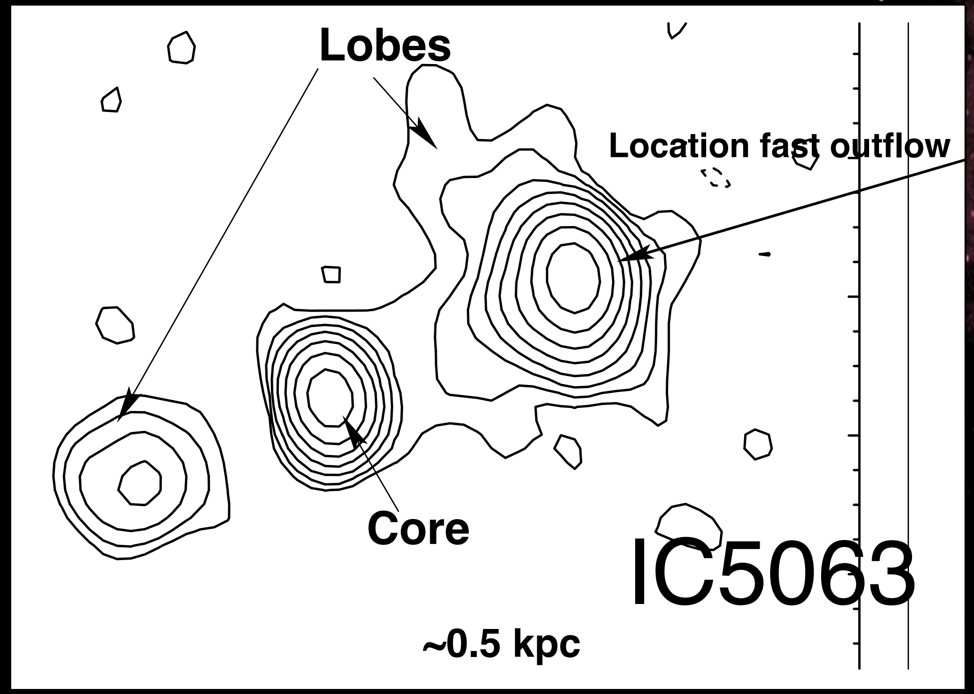


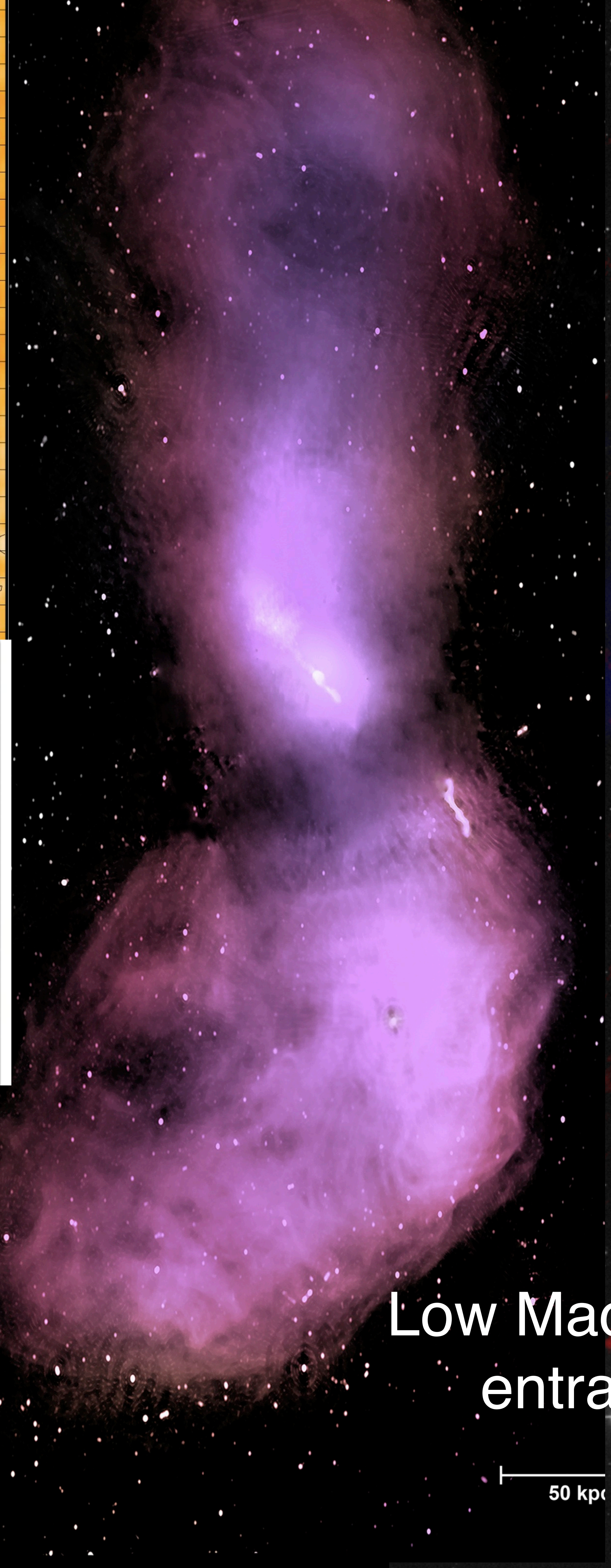
Alatalo et al. 2012



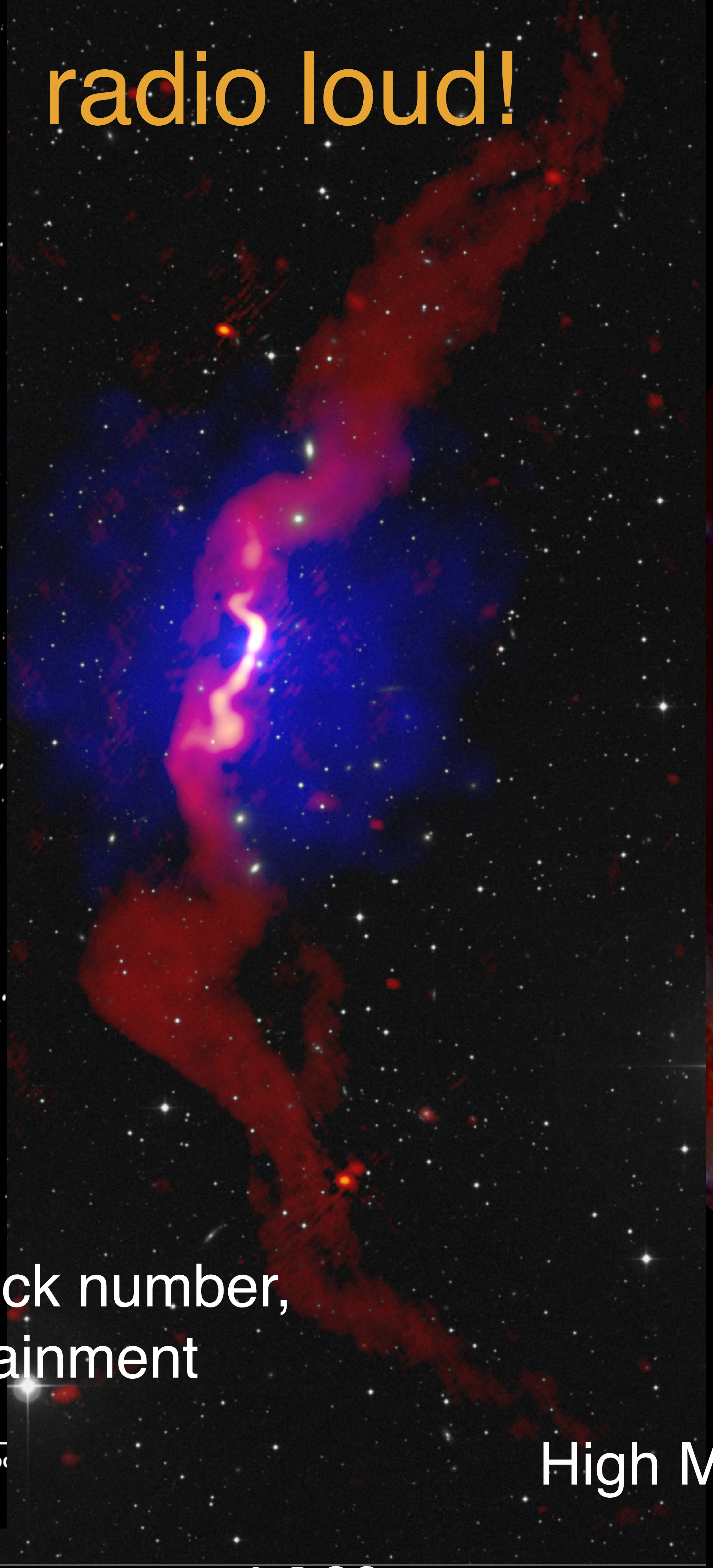


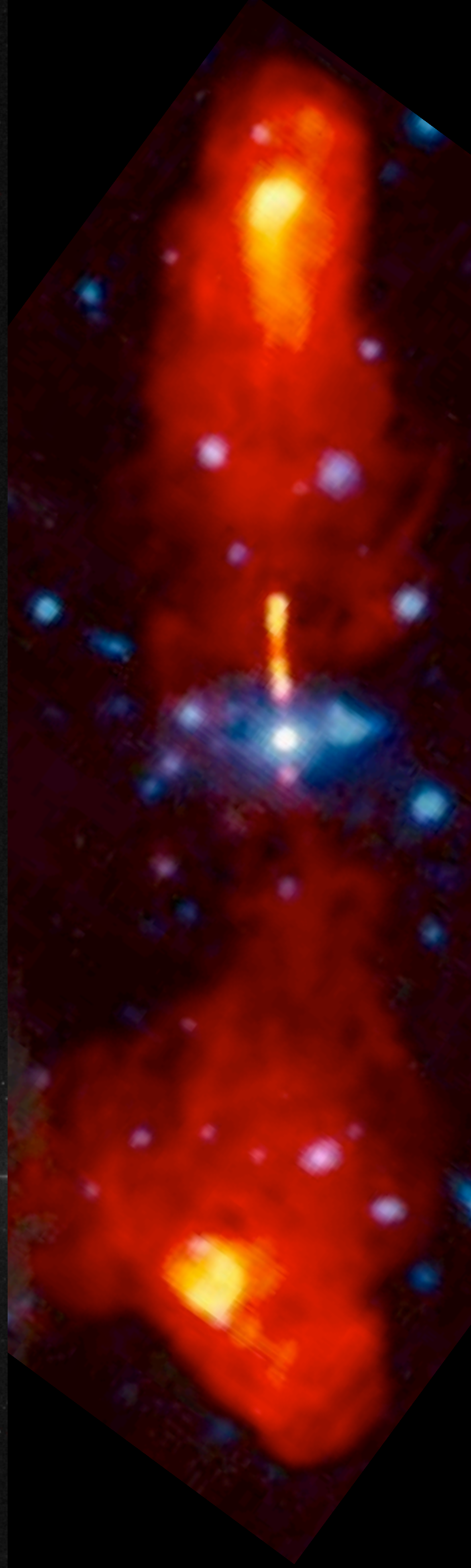
Low velocities of the radio plasma,
high entrainment
(of thermal component),
[very poorly collimated small jets or quasar wind creating radio bubbles?]





radio loud!





Low Mack number,
entrainment

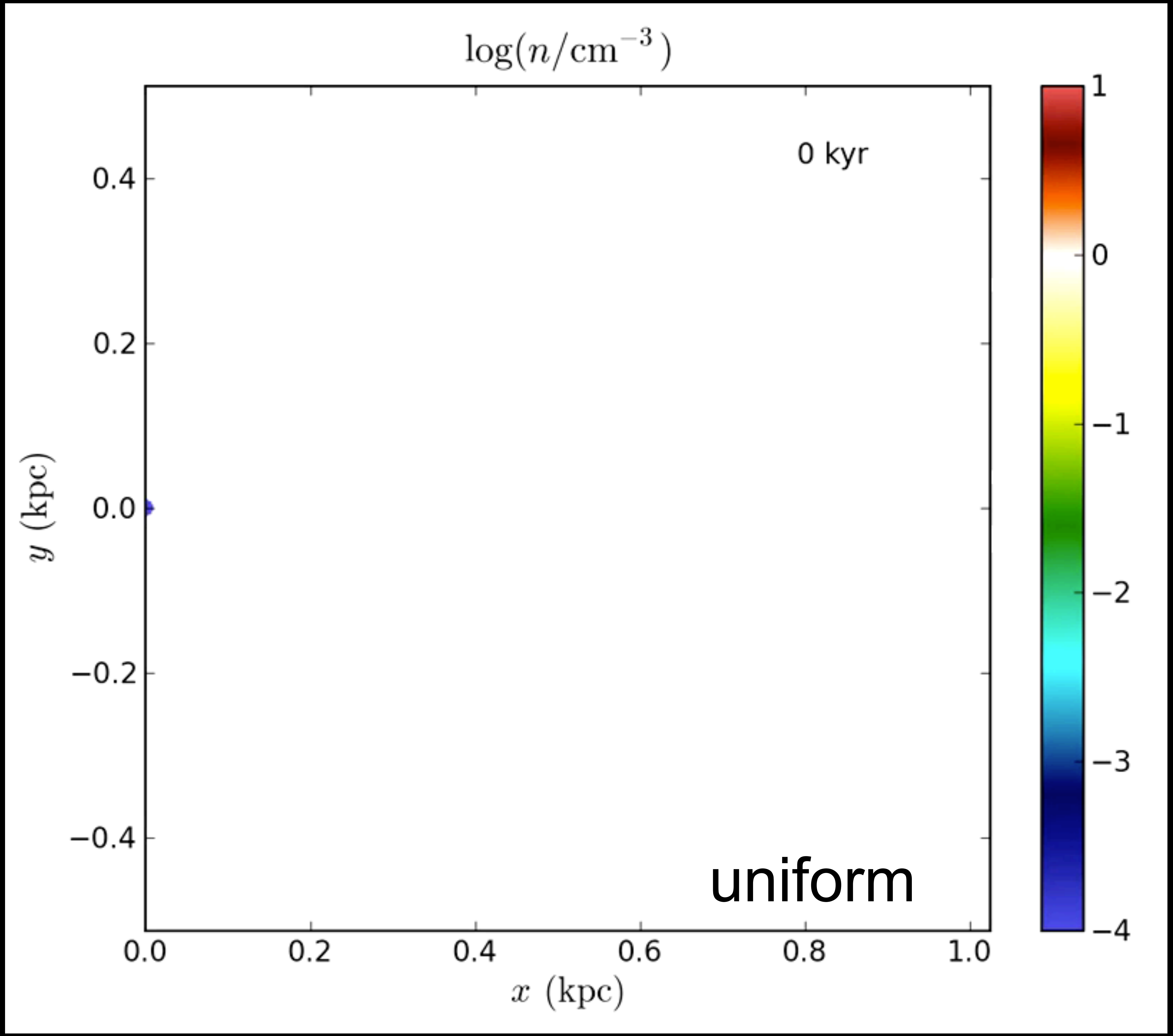
High Mack number

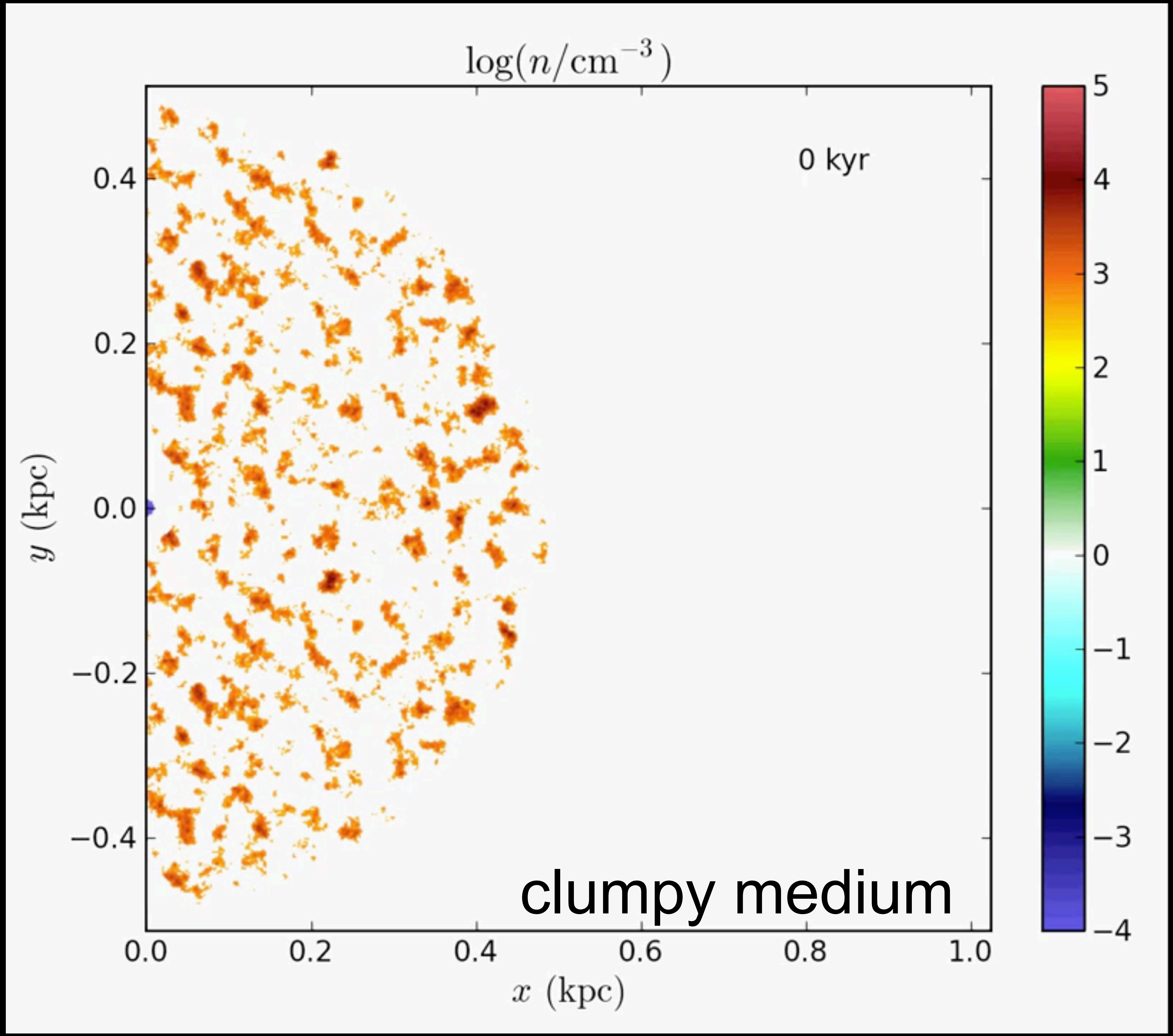
10^{21} 10^{23} 10^{24} 10^{25} 10^{26} W/Hz

radio power

3×10^{42} - 5×10^{43} erg/s transition FRI/II

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.)

Exploring the effects of radio plasma

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

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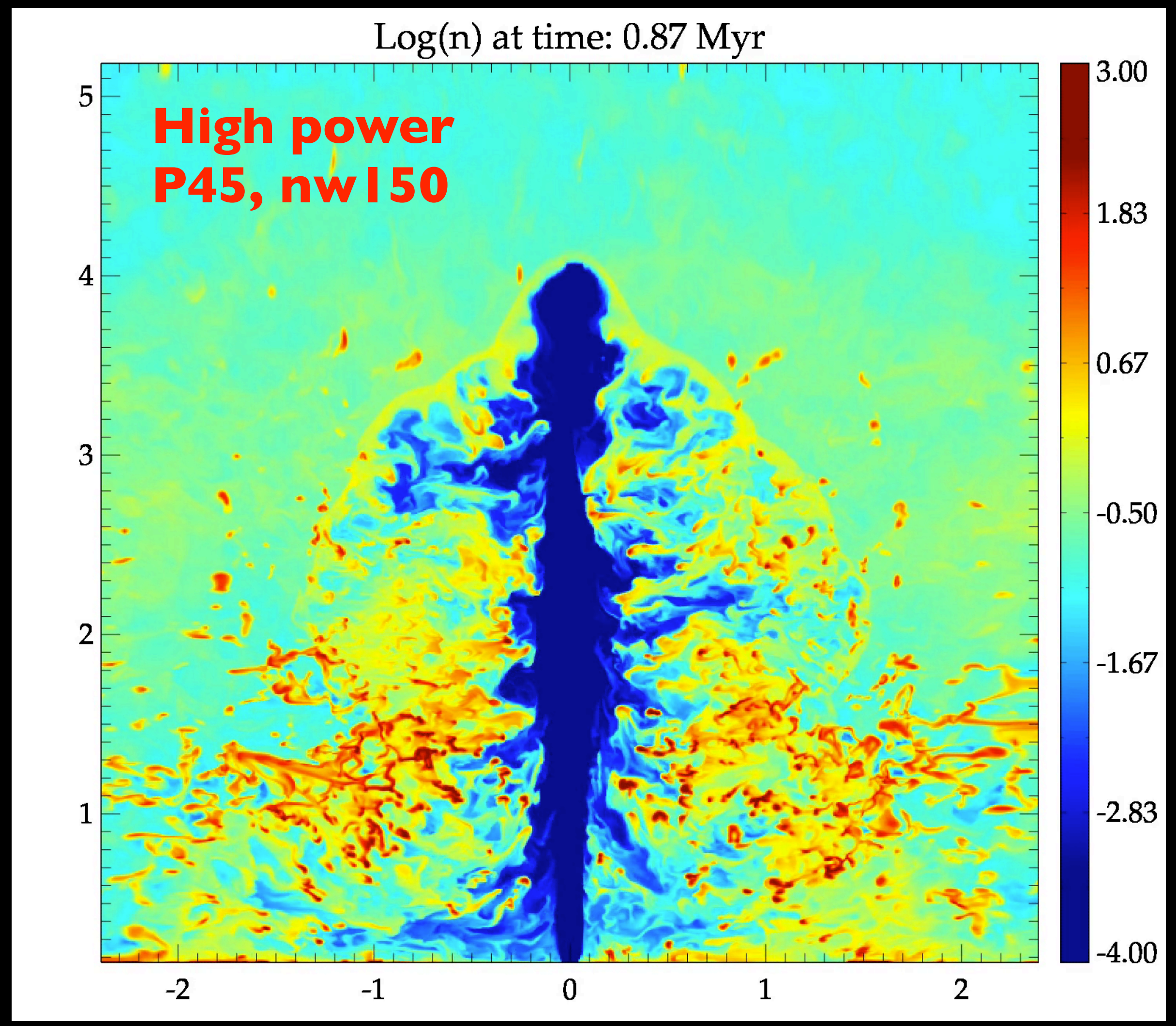
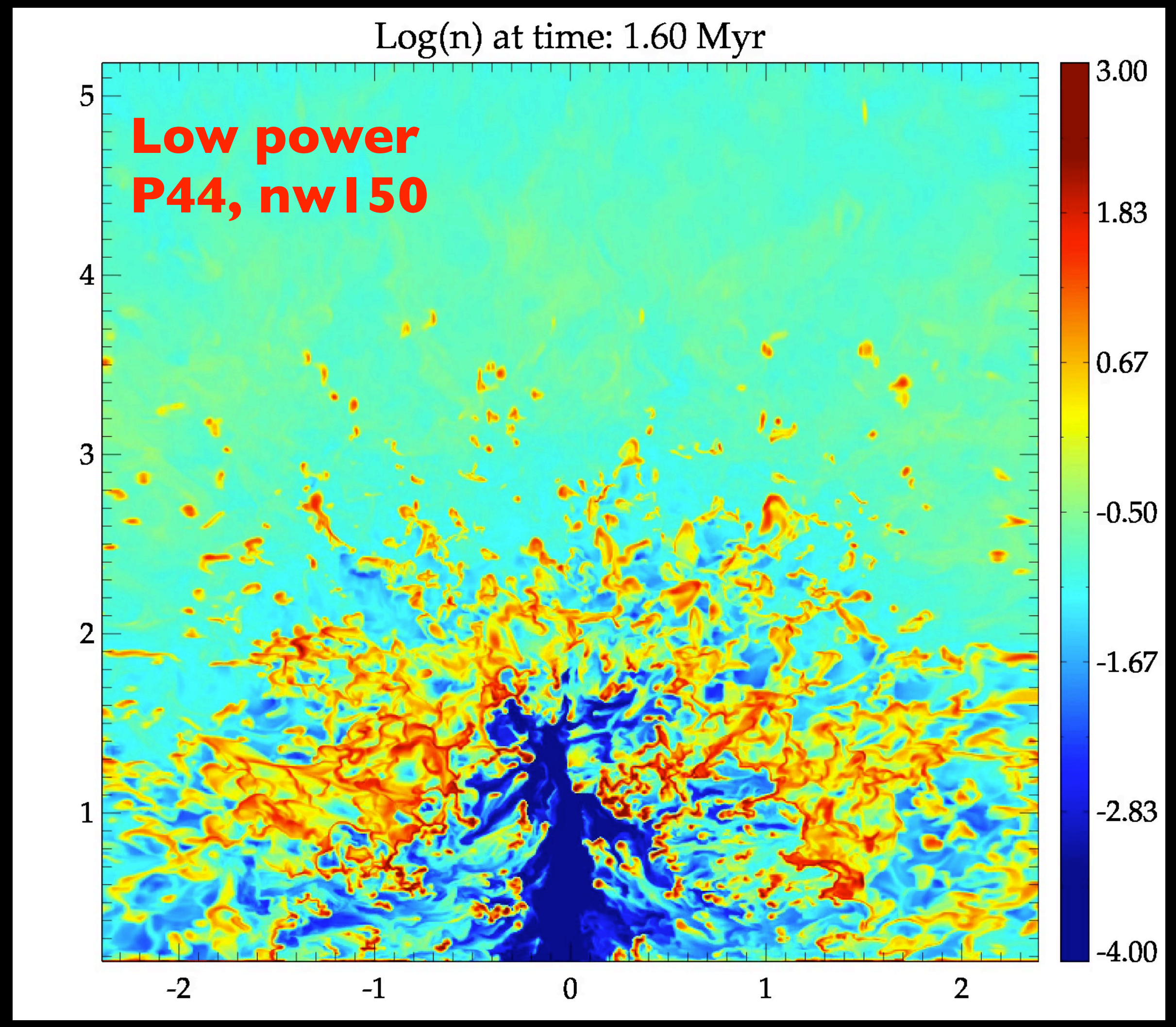




clumpy medium (spherical distribution), different jet power

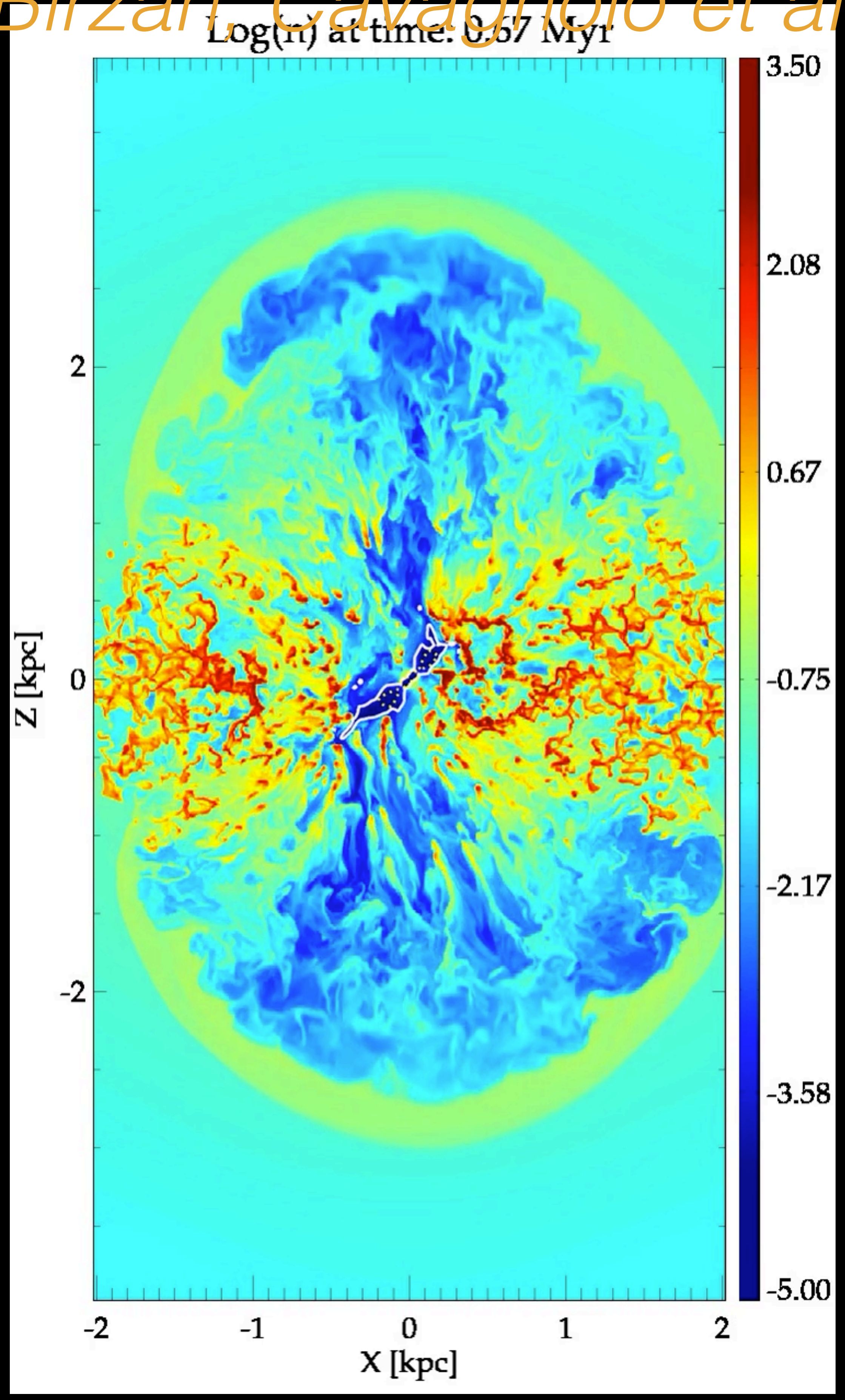
- Dependence on jet power and jet-ISM orientation

  Change in balance outflows vs turbulence?

- Low power jets are important! Couple more with the ISM, will induce more turbulence and they are more numerous!

- Orientation wrt gas distribution →

LARGE RANGE OF PARAMETER SPACE TO EXPLORE!!

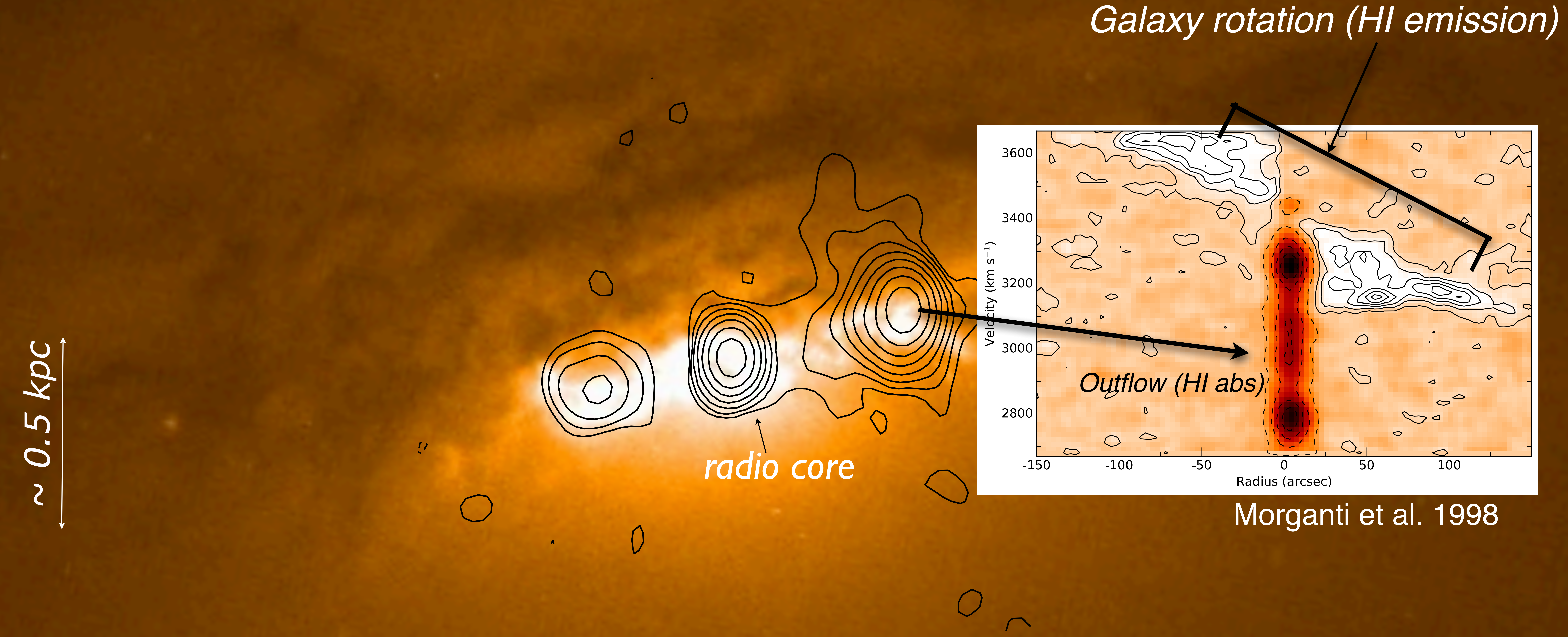


clumpy medium in a disk

Mukherjee et al. 2017, 2018

A case study: IC5063

Seyfert 2 (similar to NGC1068) strong optical AGN and radio power 3×10^{23} W/Hz @ 1.4GHz

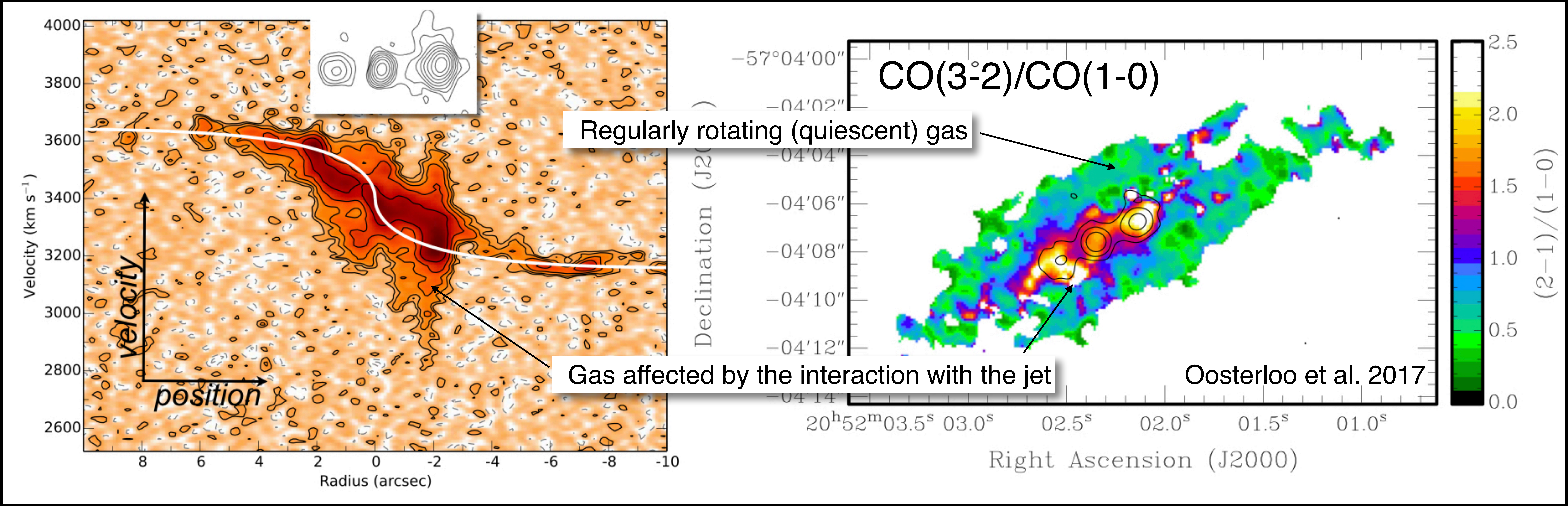


Morganti et al. 1998

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

Tadhunter, Morganti et al. 2014 Nature

Jet interacting affecting the molecular gas



➡ Multi-phase outflow driven by the radio jet
➡ Interaction affecting the kinematics and the physical conditions of the gas
(excitation, optically thin, high pressure, clumpy)

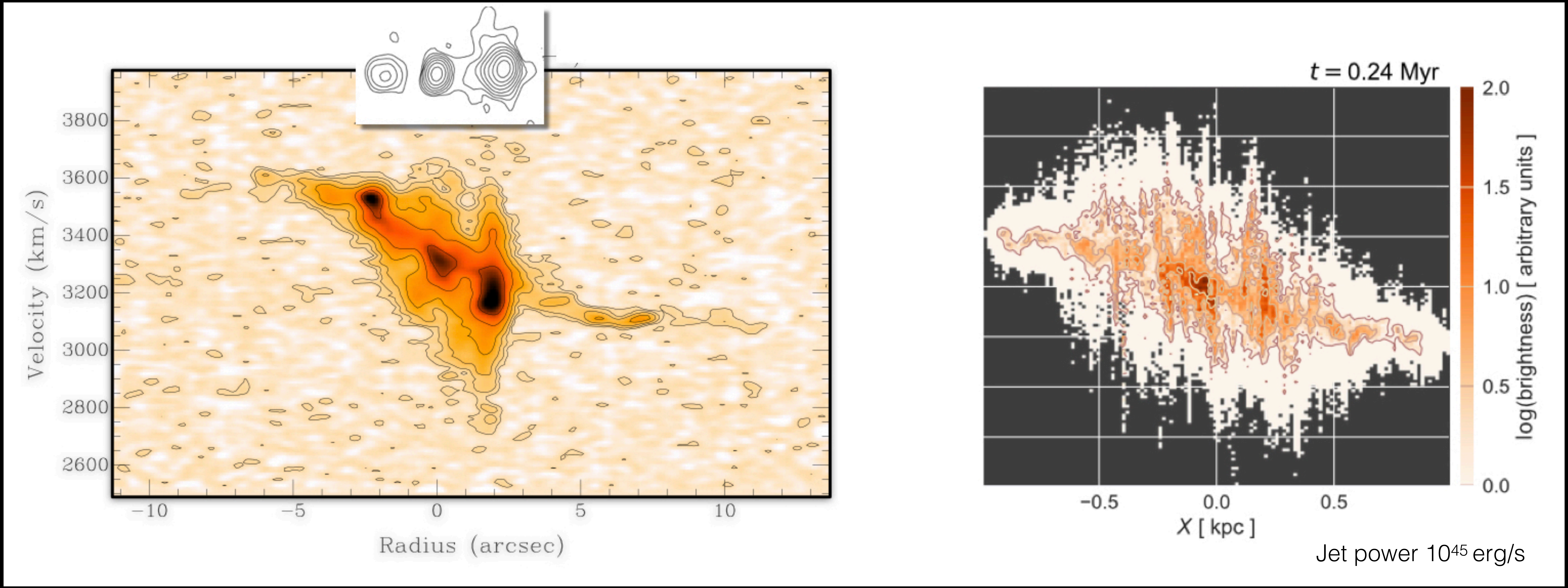
To first order described by the simulations

Kinetic temperatures in the range 20–100 K
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 $M_\odot$
Mass outflow rate ~10 $M_\odot$/yr

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

Data *Modelling*



Mukherjee, Wagner, Bicknell, RM et al. 2018

Which parameters can be derived....

Ionised gas: typical mass outflow rates low (<1 $M_\odot$/yr) but could be much larger when detected on larger scales: are the outflows really important or is “maintenance mode” the main role of radio plasma?

For HI outflows $\dot{E}_{kin}/L_{edd} \sim 10^{-4}$ (few x 10^{-3} bolometric luminosity)

Molecular gas: very limited statistics ➜ similarities with the kinematics of the HI and a few cases of jet-induced molecular outflows

➜ gas forming in situ: cooling after the shock *(see Richings, A. J. & Faucher-Giguere 2017)* *=> molecular final product*

IC5063: clear case of jet-driven outflow, affecting gas properties. Important for a realistic estimate of the mass outflow rate. Most of the gas affected by the jet will not leave the galaxy.

Parameters of the jet-driven outflows

3C293

- Mass outflow rate (from HI) ~ 50 $M_\odot$/yr
- Outflow kinetic power ~10^{43} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ ~10^{-3} (~ 10^{-2} bolometric luminosity)
- Jet power Q_{jet} ~ 2 x 10^{44} erg/s

4C12.50

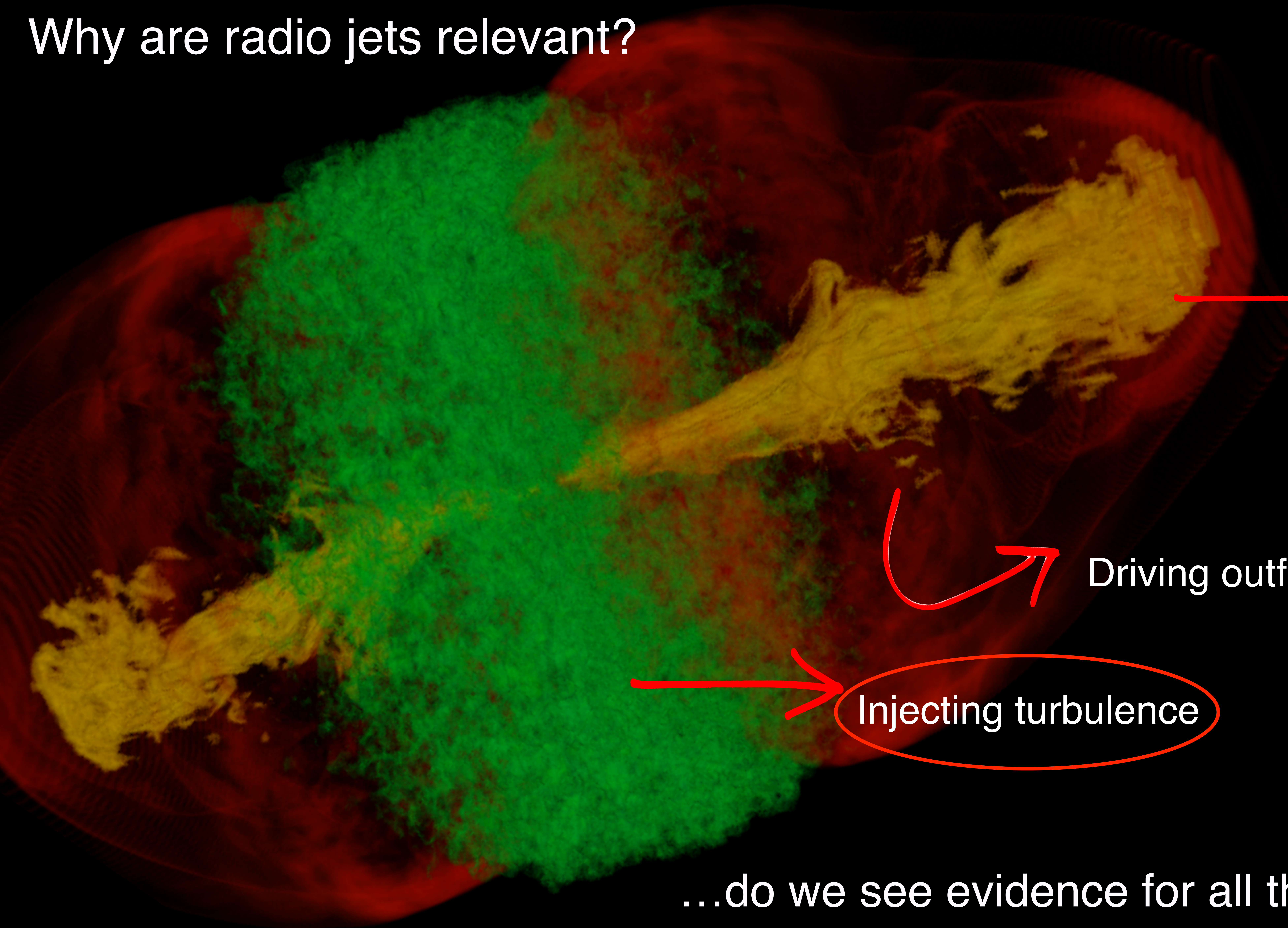
- Mass outflow rate ~ 10-20 $M_\odot$/yr
- Outflow kinetic power ~10^{42} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ ~10^{-4} (few x 10^{-3} bolometric luminosity)
- Jet power Q_{jet} ~ 4 x 10^{44} erg/s

IC5063

- Mass outflow rate (molecular gas) ~ 12 - 30 $M_\odot$/yr
- Outflow kinetic power (HI + CO) ~ 8 x 10^{42} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ = ~10^{-4} (few x 10^{-2} bolometric luminosity)
- Jet power Q_{jet} ~ 5 x 10^{43} erg/s

➔ most of the gas is not leaving but "relocated"

Why are radio jets relevant?



Preventing cooling
(maintenance)

Driving outflows

Injecting turbulence

…do we see evidence for all these processes?

From IC5063: only a small fraction of gas (~0.1% of total ISM) is leaving the galaxy, the rest “rains” back
Main effect of the jet-ISM interaction: relocating the gas/inducing turbulence

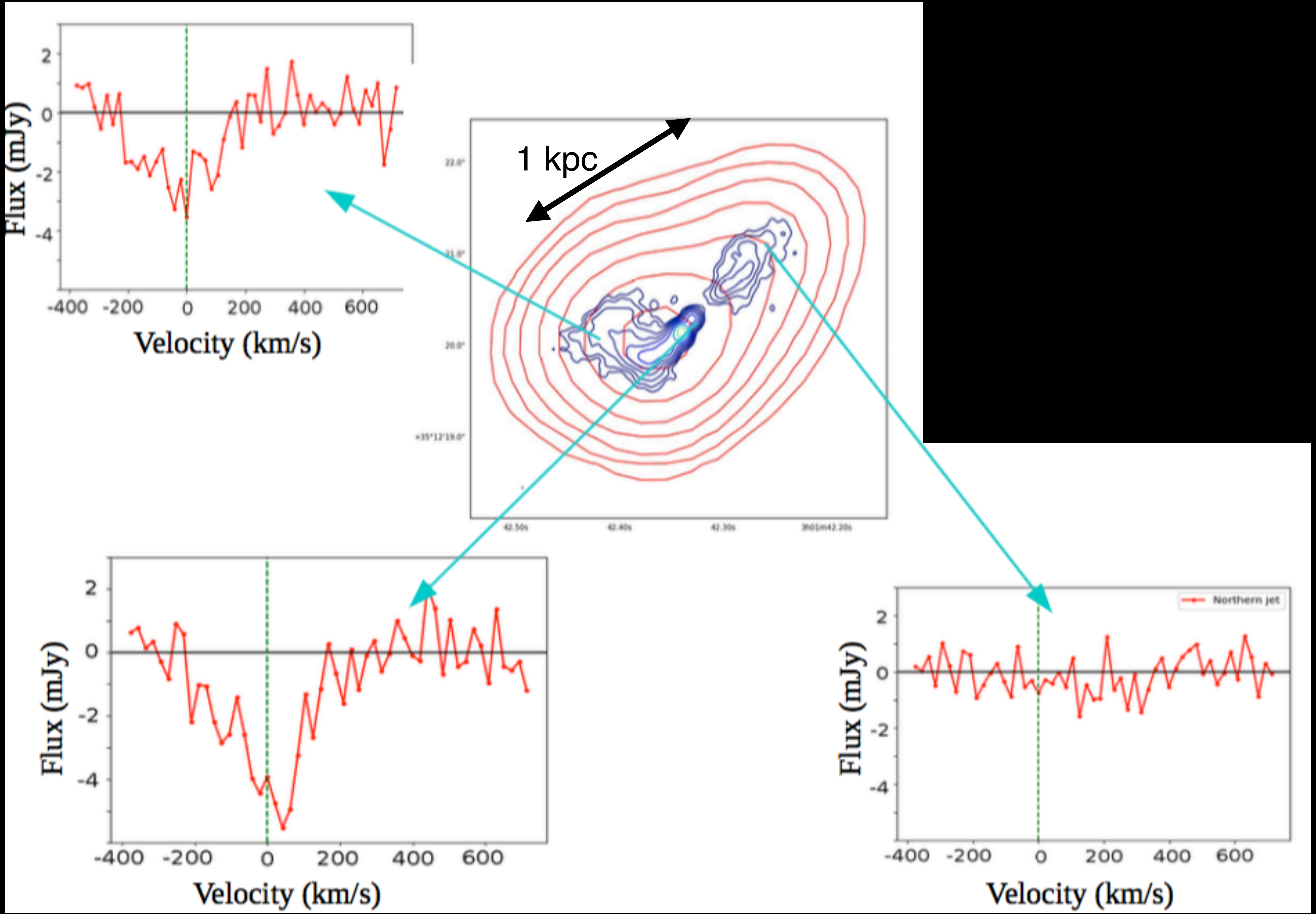
Discussed by Nicole N., Pierre Guillard et al. (e.g. 3C326)

Dependence on radio power

The case of B2 0258+35 (low luminosity jet 1.7x10[24] W/Hz)

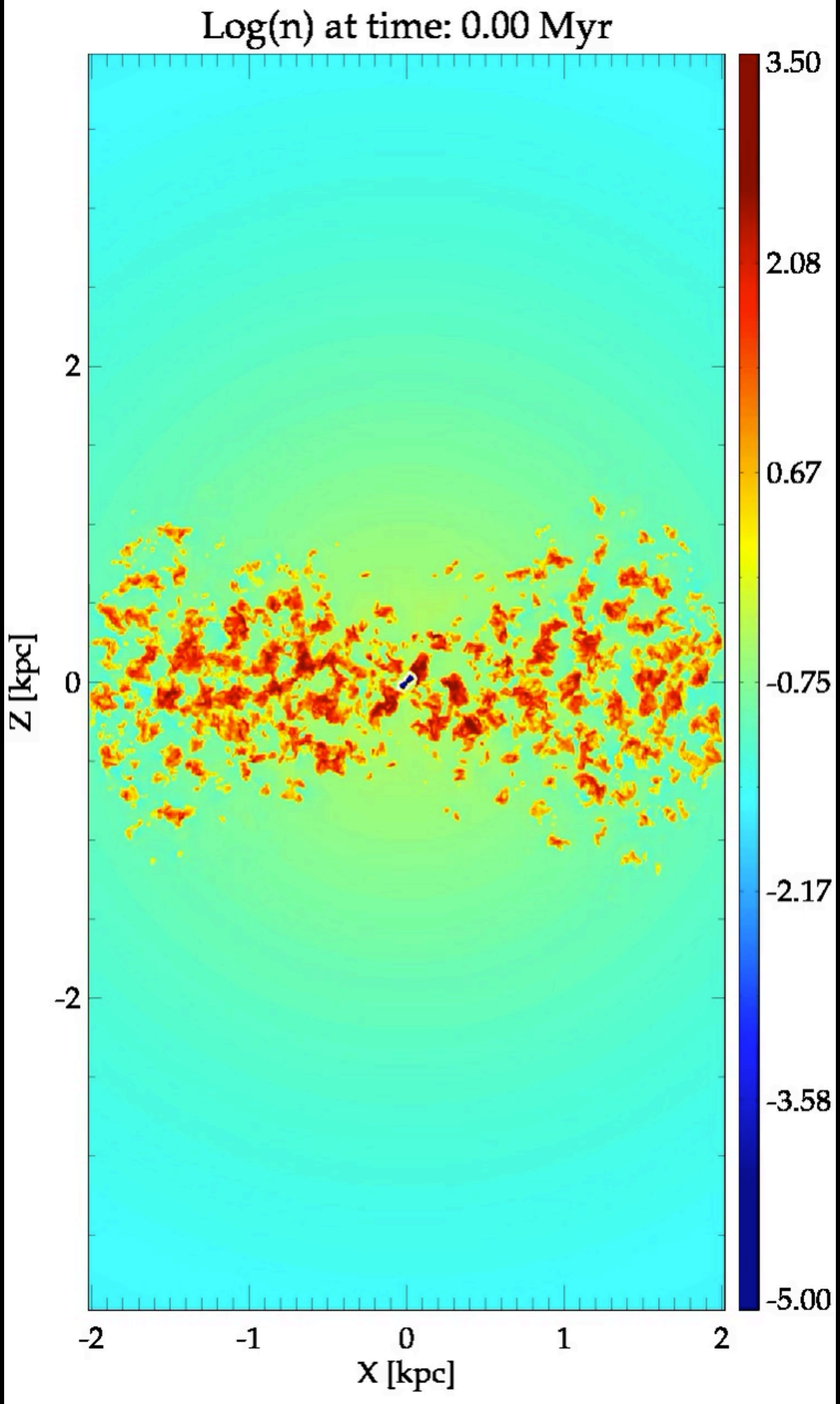
Murthy et al. in prep.

HI absorption too broad for originating from a *cold* cirumnuclear disk
➜ most likely jets of B2 0258+35 expanding into the disk



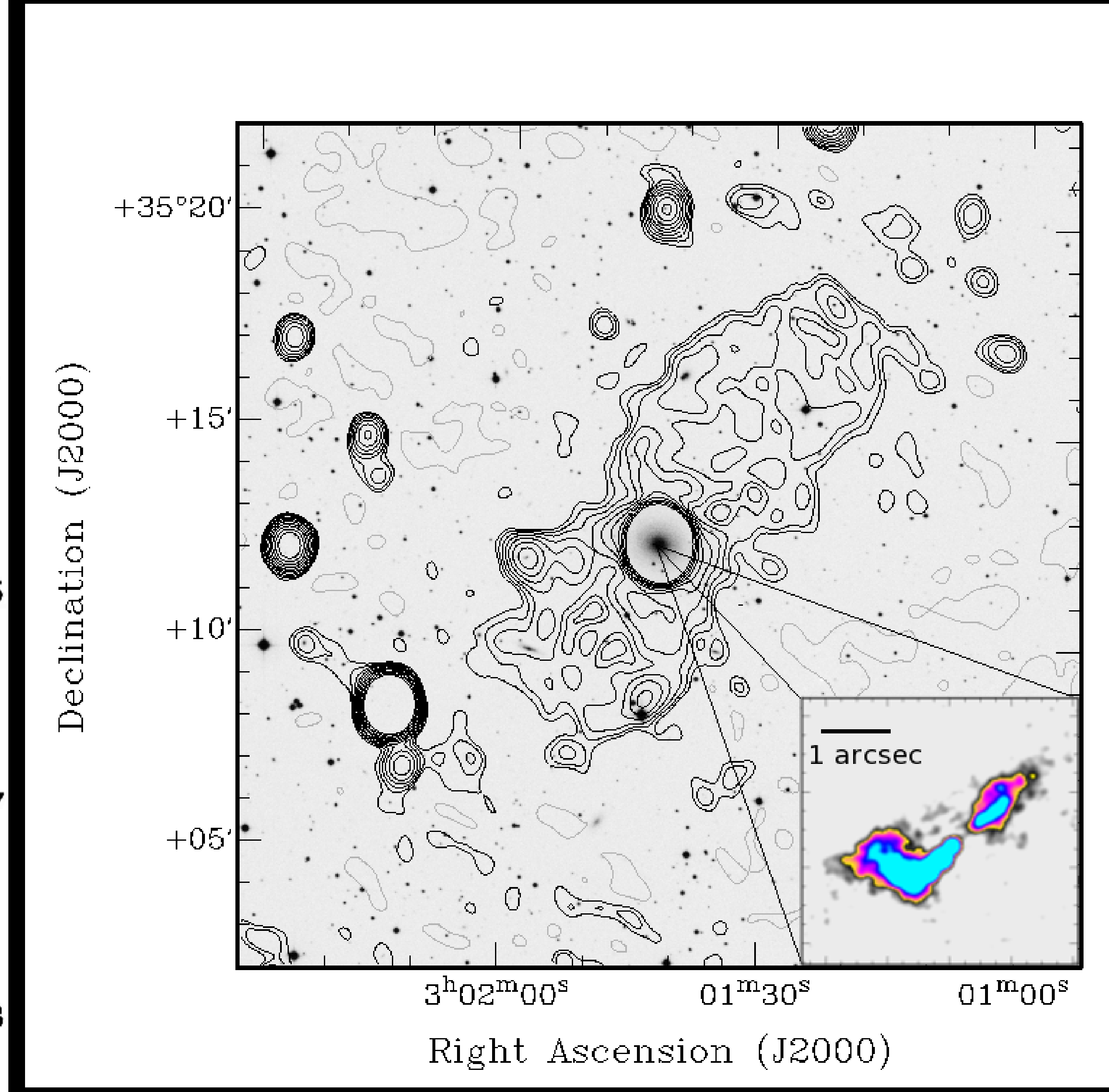
Impact depends on jet power
High jet power drill through easily
Low jet power can cause mostly turbulence

Low radio power jet expanding in a disk:
simulation would predict "leakage" of plasma and thermal gas



Mukherjee et al. 2017 2018

Observable in radio continuum?



Shulevski et al. 2012

Some conclusions on the impact of radio jets :

➜ AGN jets as possible feedback mechanism ➜ YES!

➜ The impact of radio jets should be explored also for "radio quiet" objects!

See also poster of Alberto Rodriguez-Ardila

➜ Also in isolated galaxies, jets can play a role for *maintenance:* we need to know more about this - more deep, high resolution X-ray images required!

➜ Jets coupling well with clumpy ISM - young (restarted) most effective: supported by the observations.

➜ Many signatures of jet/ISM interaction: fast outflows (up to 50 $M_\odot$/yr on sub-kpc scale in cold gas)

➜ But not clear yet the amplitude of the impact: outflowing gas not always leaving the galaxy: importance of relocating the gas and injection of turbulence?

➜ Jet power key parameter in simulations, but difficult to derive especially for low luminosity radio sources

Next step: expand to high redshift!

Thanks!

➡ Paper Nims, Quataet, Faucher-Giguere 2015

$$\nu L_\nu \approx \frac{10^{-2}\,\xi_{-2}\,L_{\rm kin}}{2\,\ln(\gamma_{\rm max})} \quad \text{(synchrotron : radio to X–ray)}$$

$$\approx 10^{-5}\,\xi_{-2}\,L_{\rm AGN}\left(\frac{L_{\rm kin}}{0.05\,L_{\rm AGN}}\right) \quad (\nu \gtrsim \nu_{\rm cool}).$$

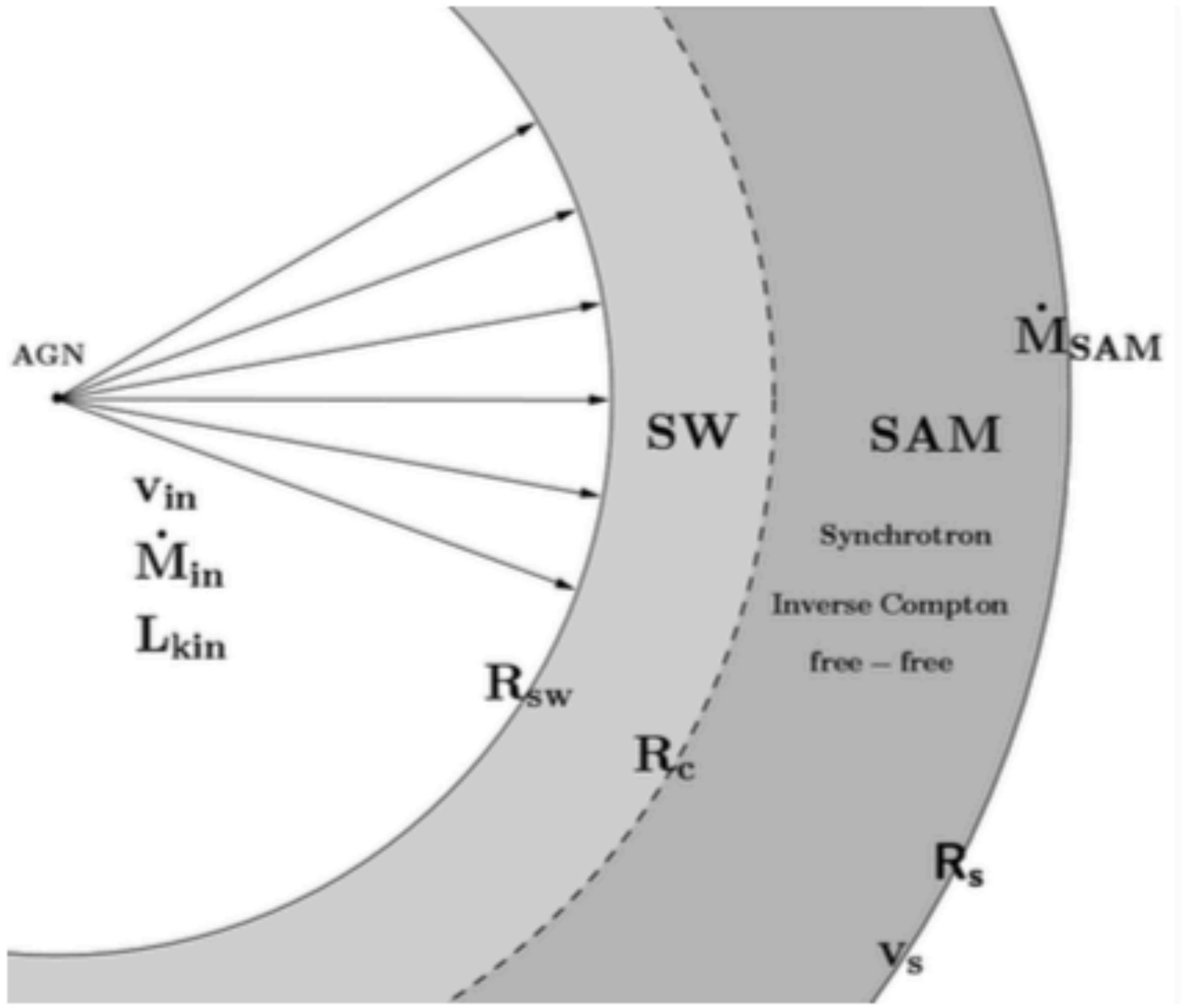


Figure 1. An AGN drives a wind with velocity $v_{\rm in}$, mass-loss rate $\dot{M}_{\rm in}$,

Table 1. Fiducial parameters utilized in analytic estimates.

Parameter	Fiducial value	Units
$L_{\rm AGN}$[1]	10^{46}	erg s^{-1}
$L_{\rm kin}$[2]	0.05	$L_{\rm AGN}$
$n_{\rm H,0}$[3]	10	cm^{-3}
α[3]	1	–
R_0[3]	100	pc
$v_{\rm in}$[4]	0.1	c

[1]Bolometric luminosity of the AGN. [2]Kinetic energy flux supplied by the AGN wind at small radii (see Fig. 1). Approximately half of this energy goes into the forward shock driven into the ambient medium. The other half is thermal energy of the SW bubble. [3]Parameters in the ambient medium density profile; see equation (1). [4]Input speed of the AGN wind on small scales (Fig. 1).

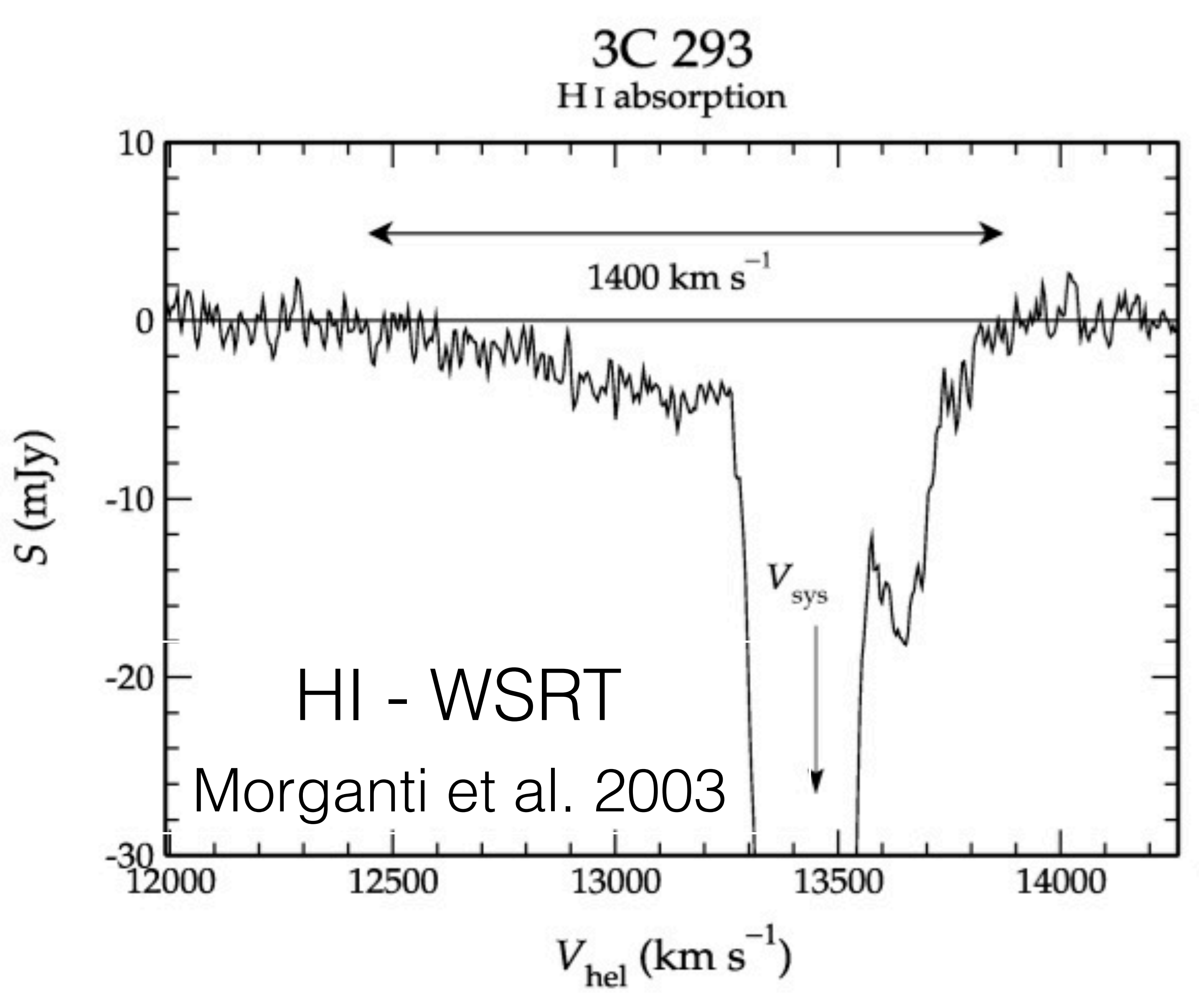
Two clear observational ways of distinguishing between jet-dominated and wind-dominated radio emission are
(1) **the spatial extent of the emission** and
(2) **the spectral indices**, which should be $F \sim \nu^b$ with b=~1 for wind dominated emission

Lack of radio core?

➡ We need some deep, high resolution, multi frequencies radio observations of some promising candidates!!!!!!

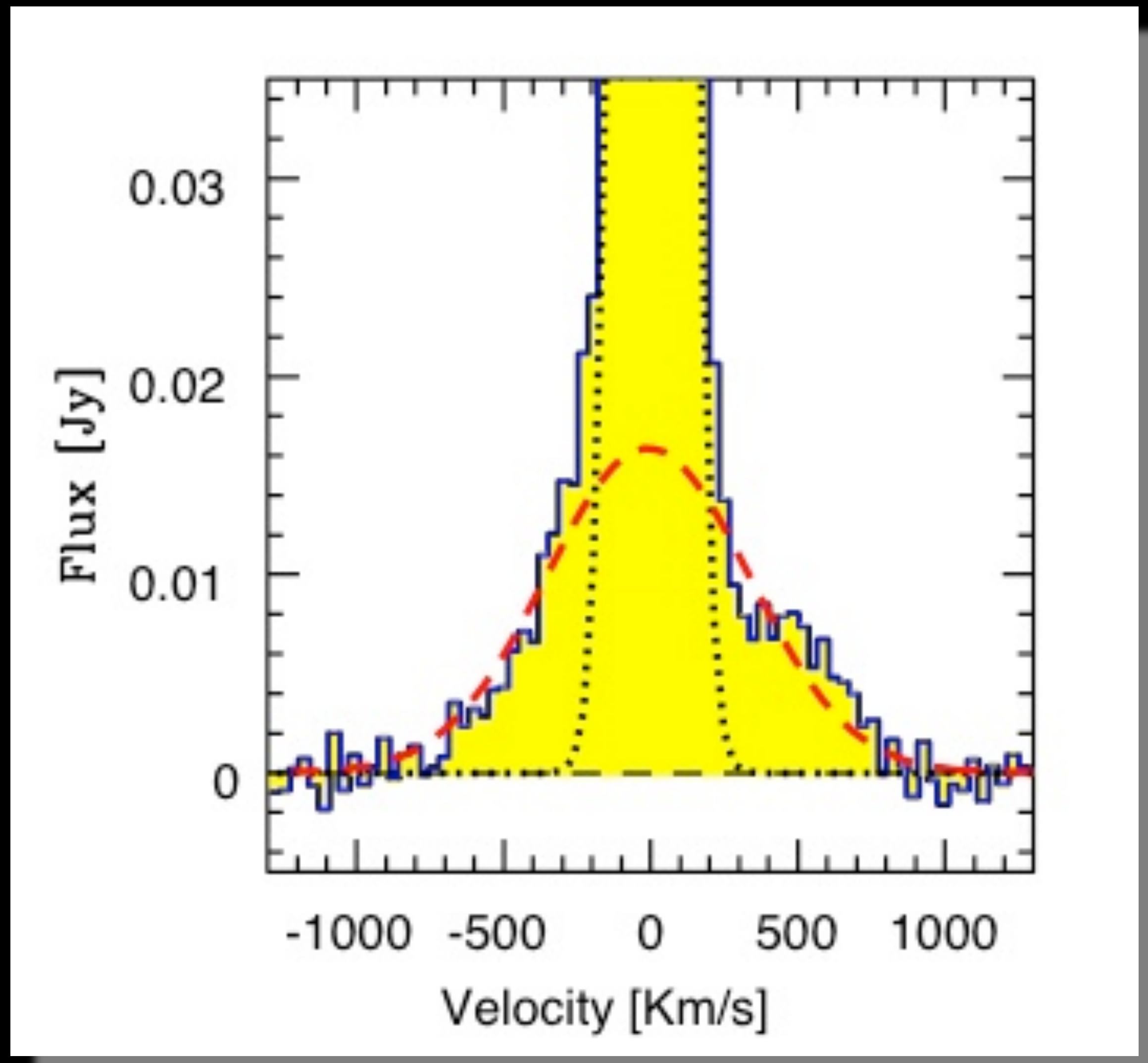
The surprising presence of cold gas (atomic and molecular)

Discovery of a massive component associated with cold gas: HI and molecular

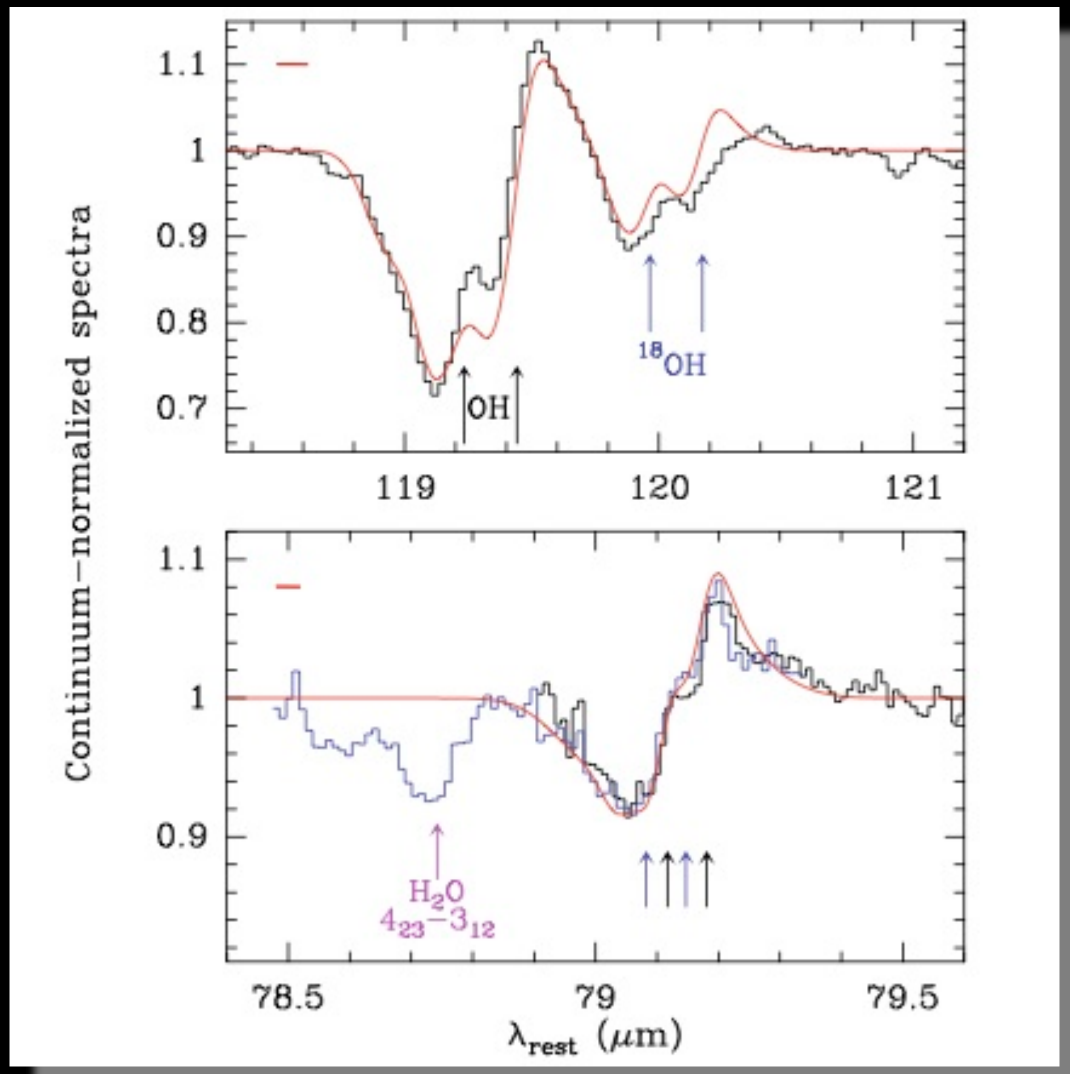


Mrk231

CO - Feruglio et al. 2010

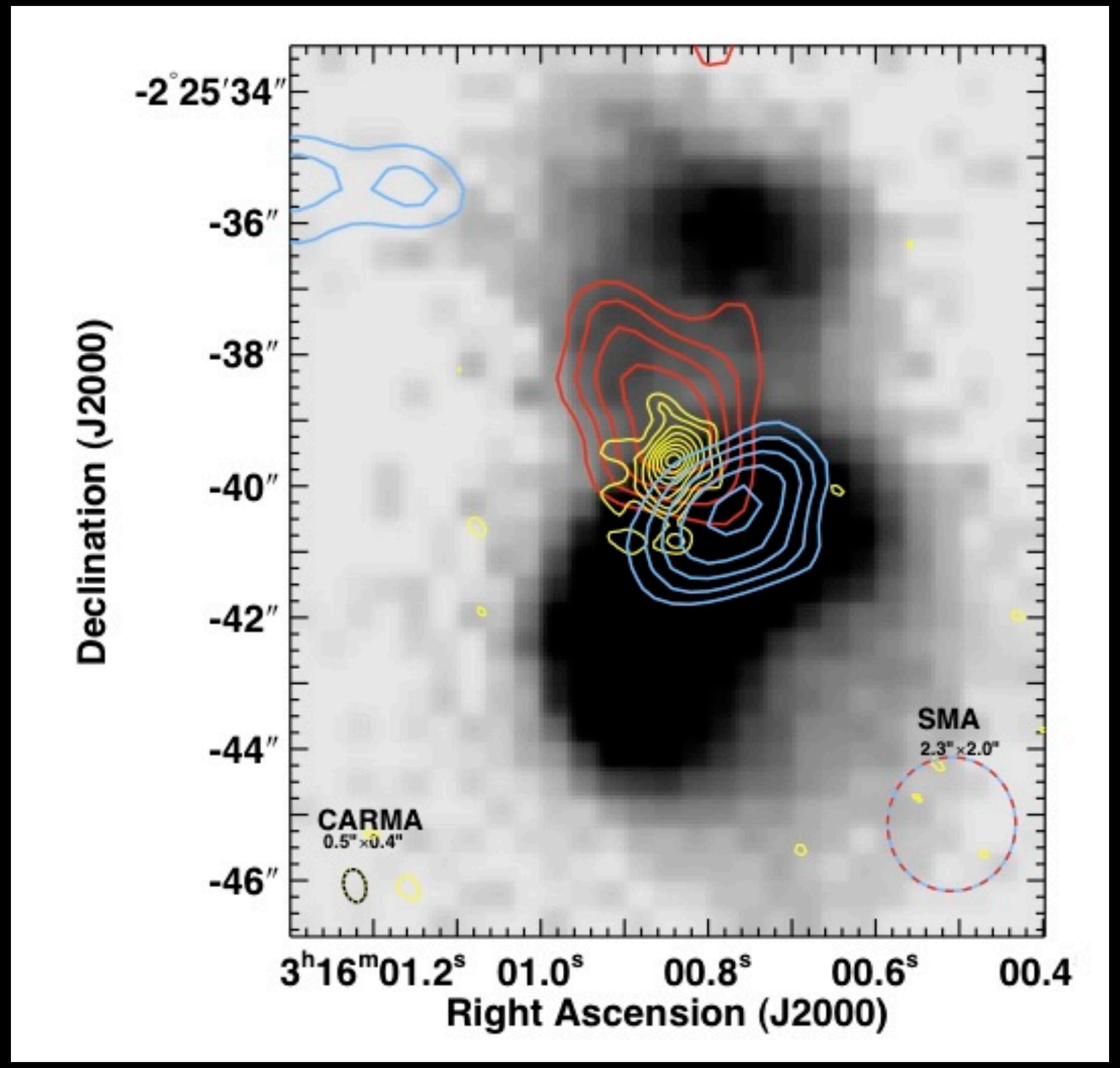


OH - Fischer et al. 2010



NGC1266

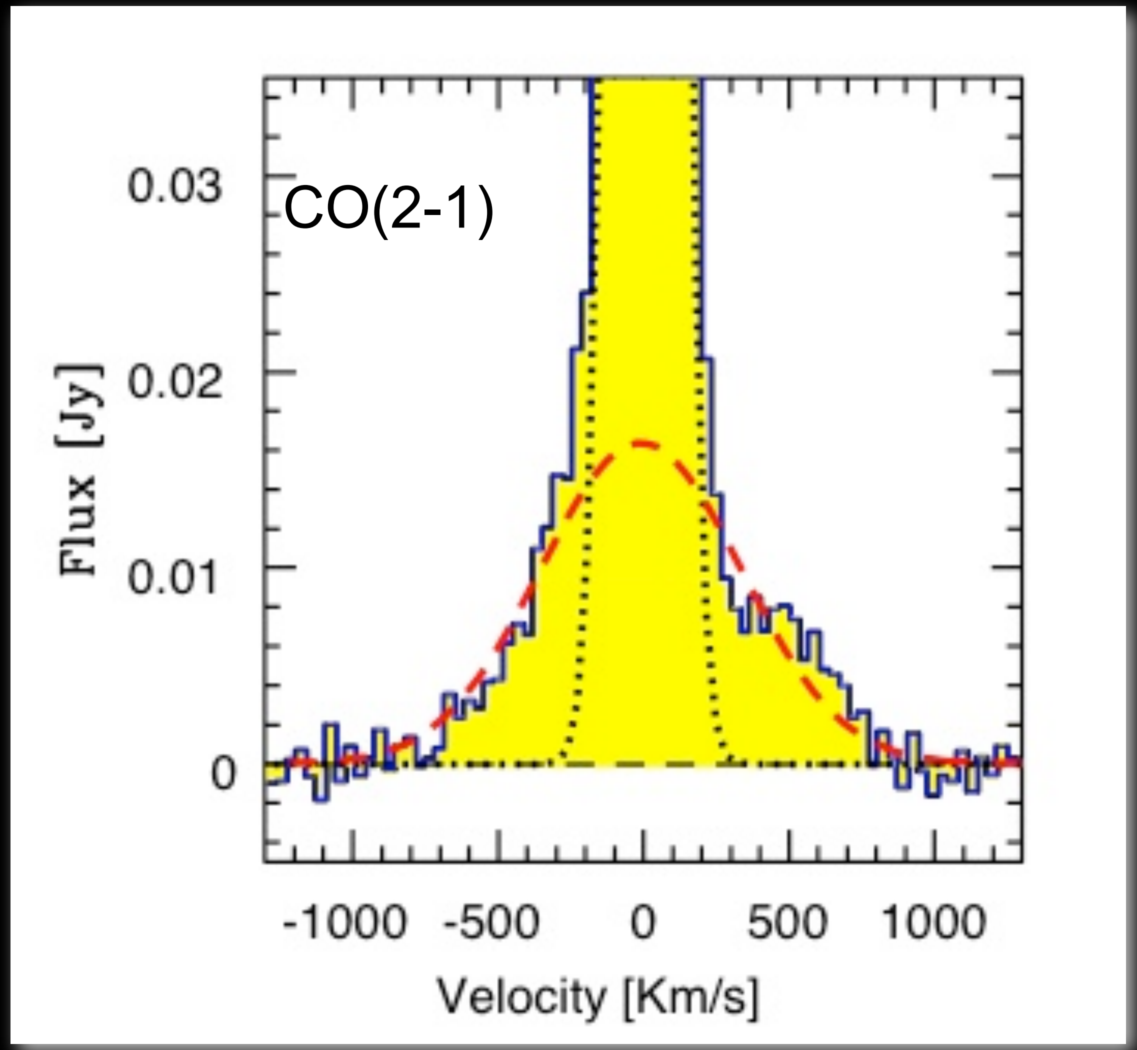
CO - Alatalo et al. 2010

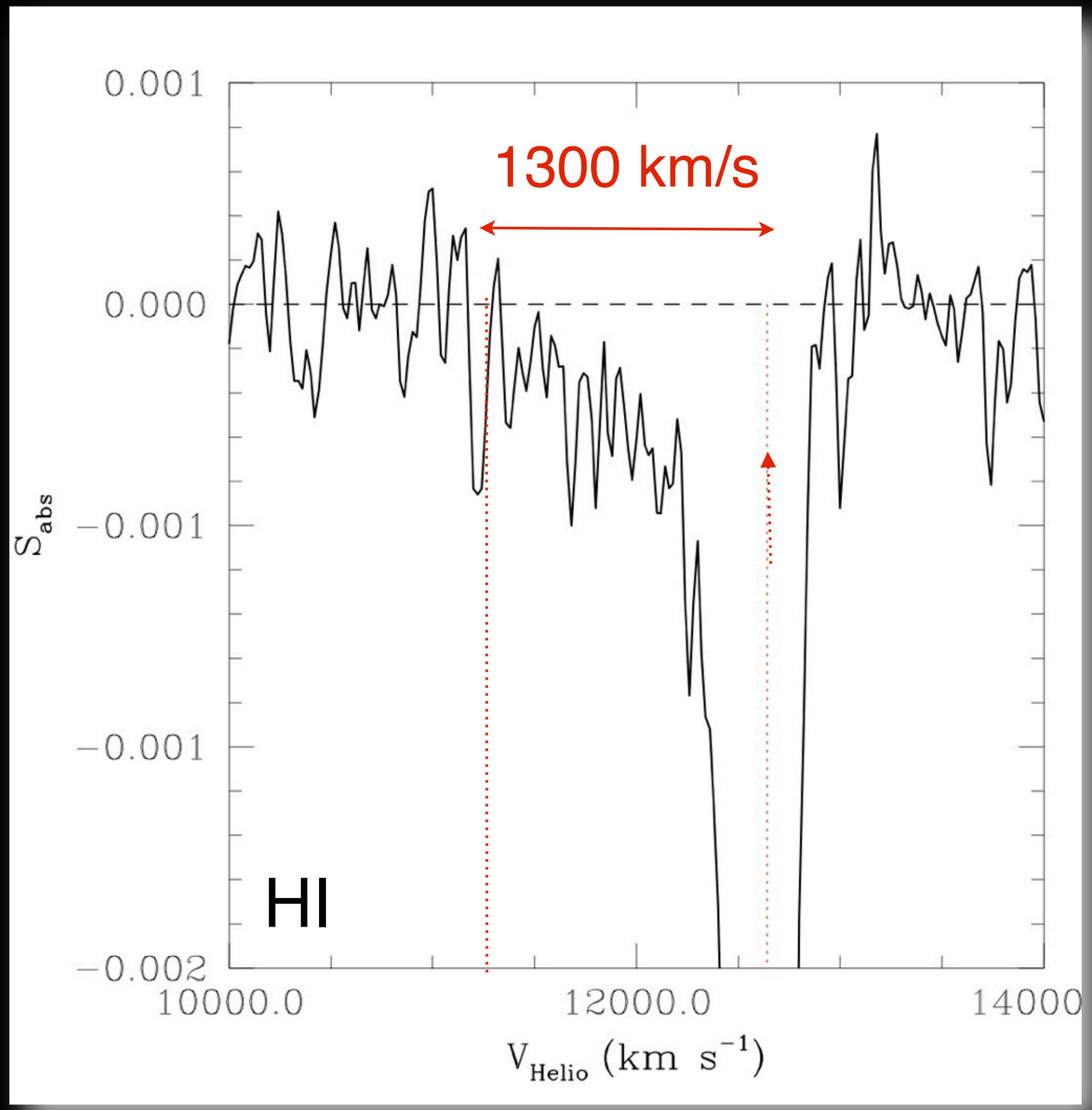


atomic gas (e.g., Rupke & Veilleux 2011, 2013a, 2015; Lehnert et al. 2011; Morganti et al. 2013, 2015), **warm and cold molecular gas** (e.g., Feruglio et al. 2010; Dasyra & Combes 2011; Guillard et al. 2012; Rupke & Veilleux 2013b; García-Burillo et al. 2014; Tadhunter et al. 2014; Cicone et al. 2014; Calderón et al. 2016), **and OH** (e.g., Fischer et al. 2010; Sturm et al. 2011; Veilleux et al. 2013).

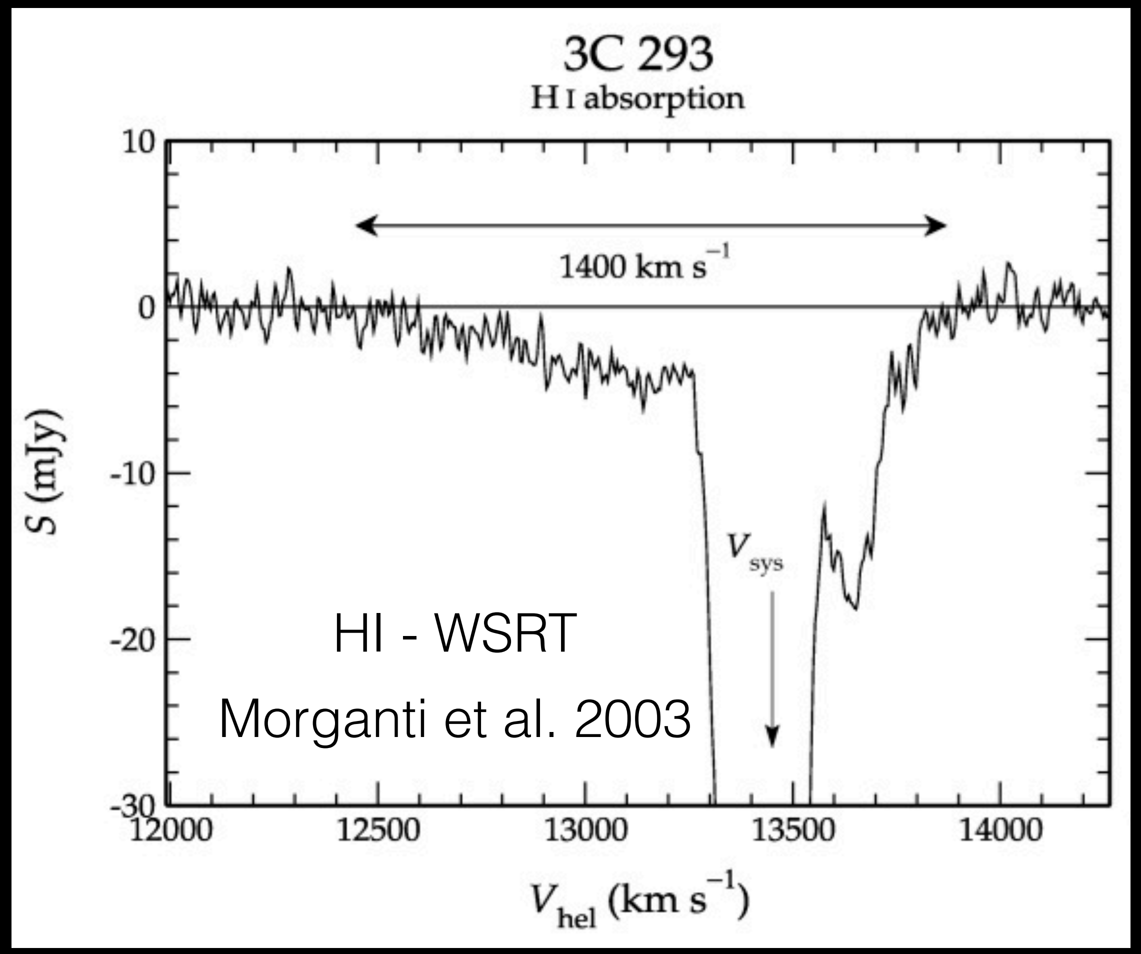
The surprising presence of massive outflows of cold gas (HI and molecular)

Mrk231

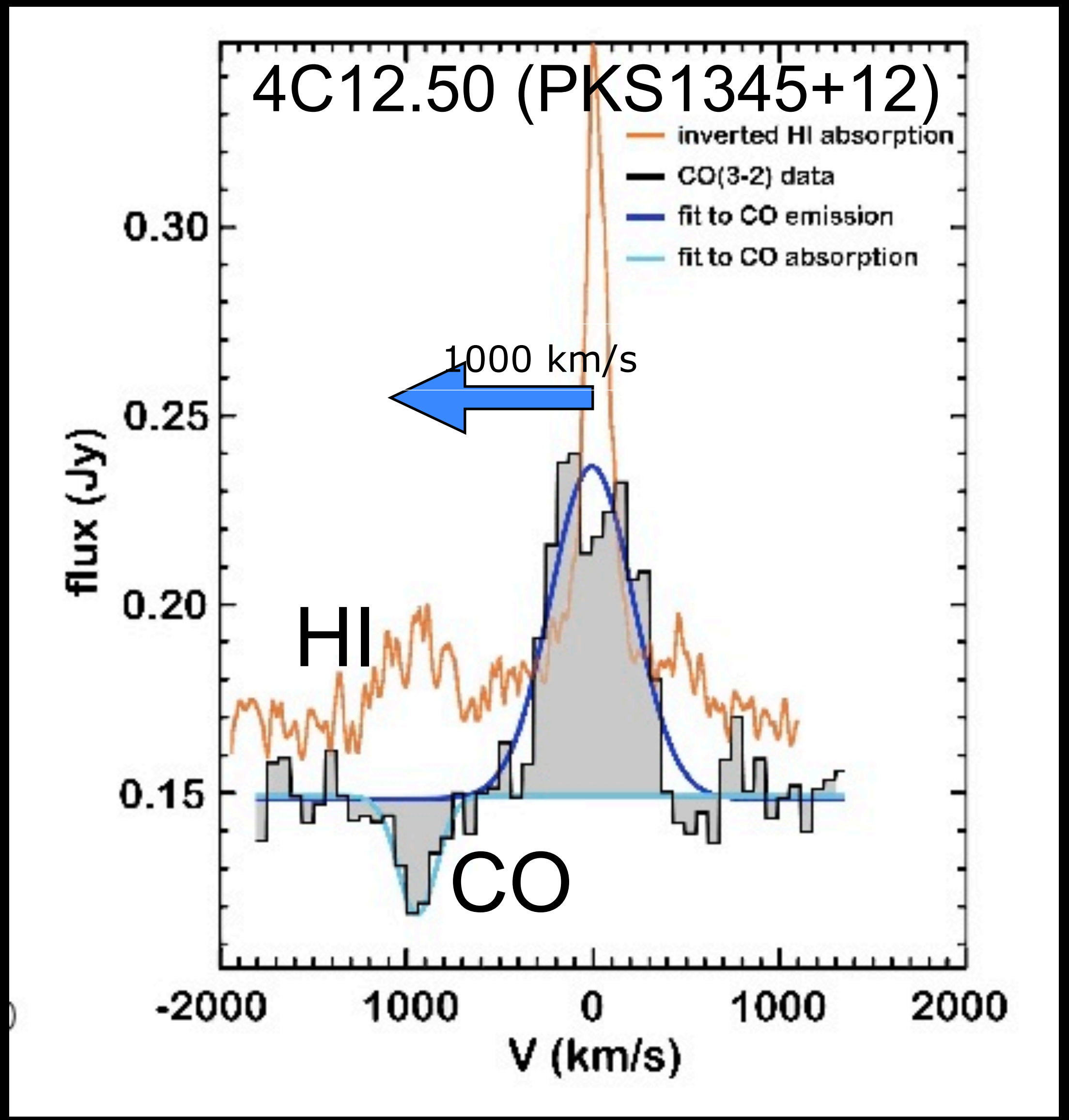


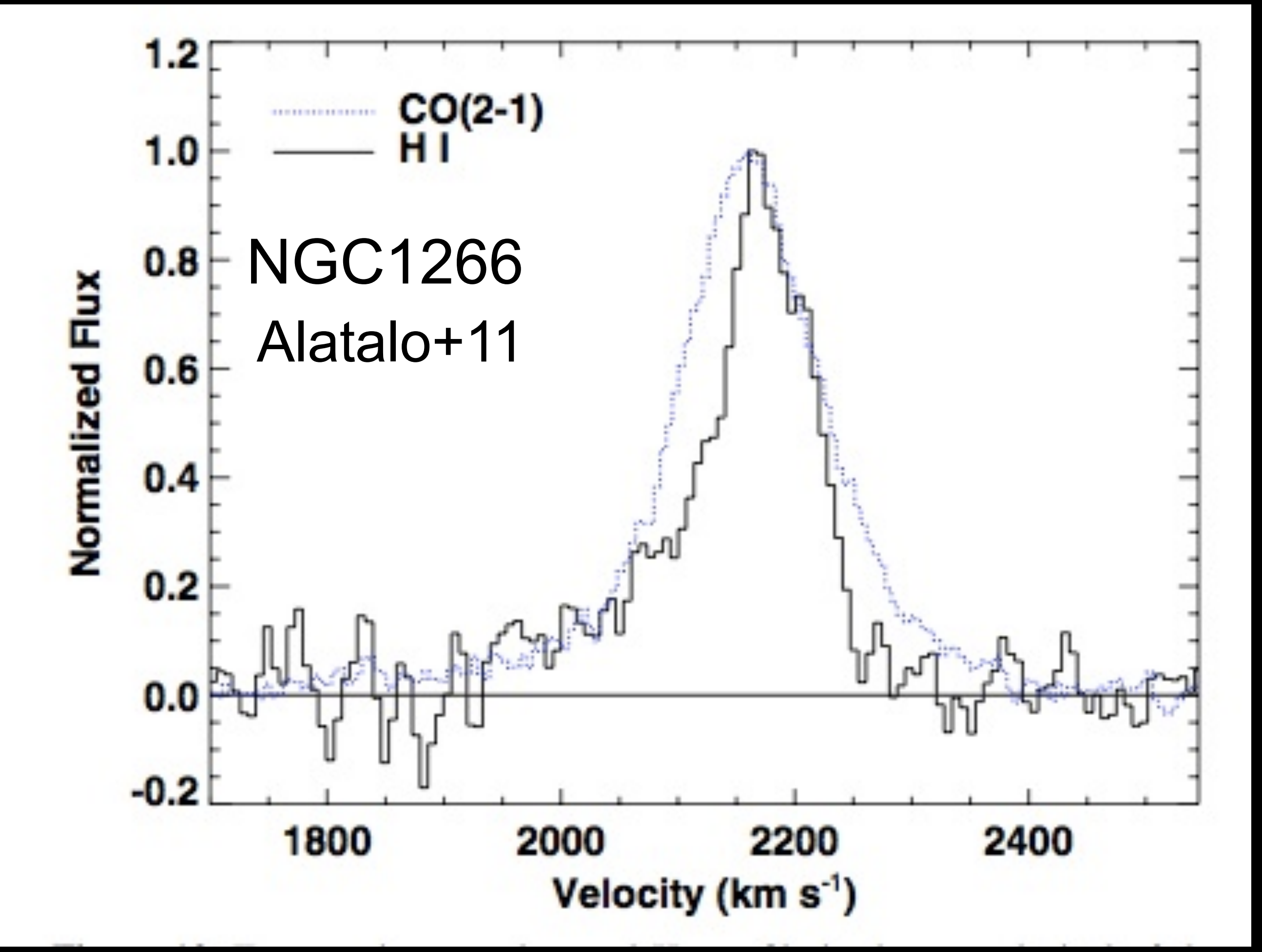


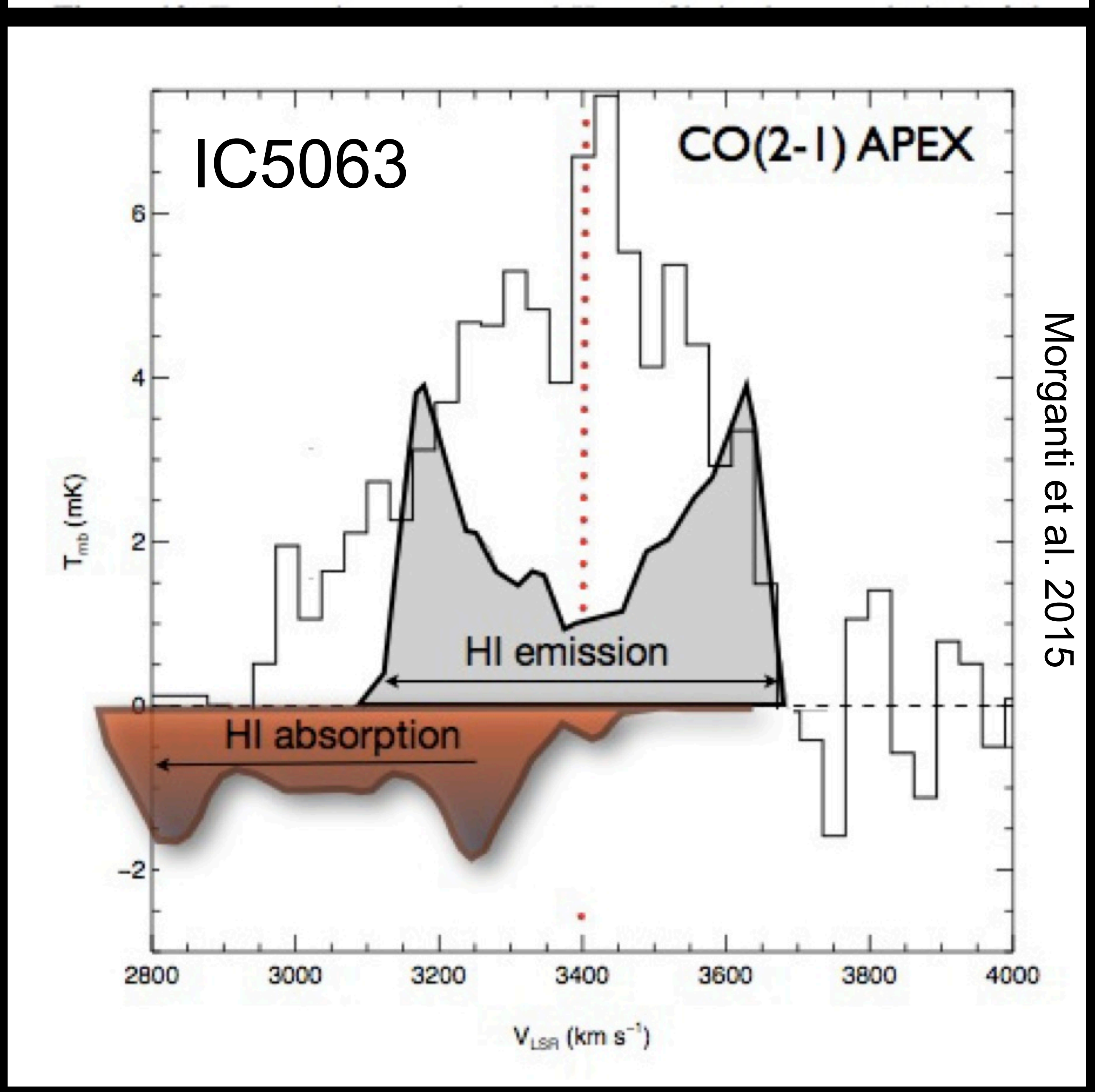
Feruglio et al. 2010
Morganti et al. 2016



Dasyra & Combes 2012
Morganti et al. 2005







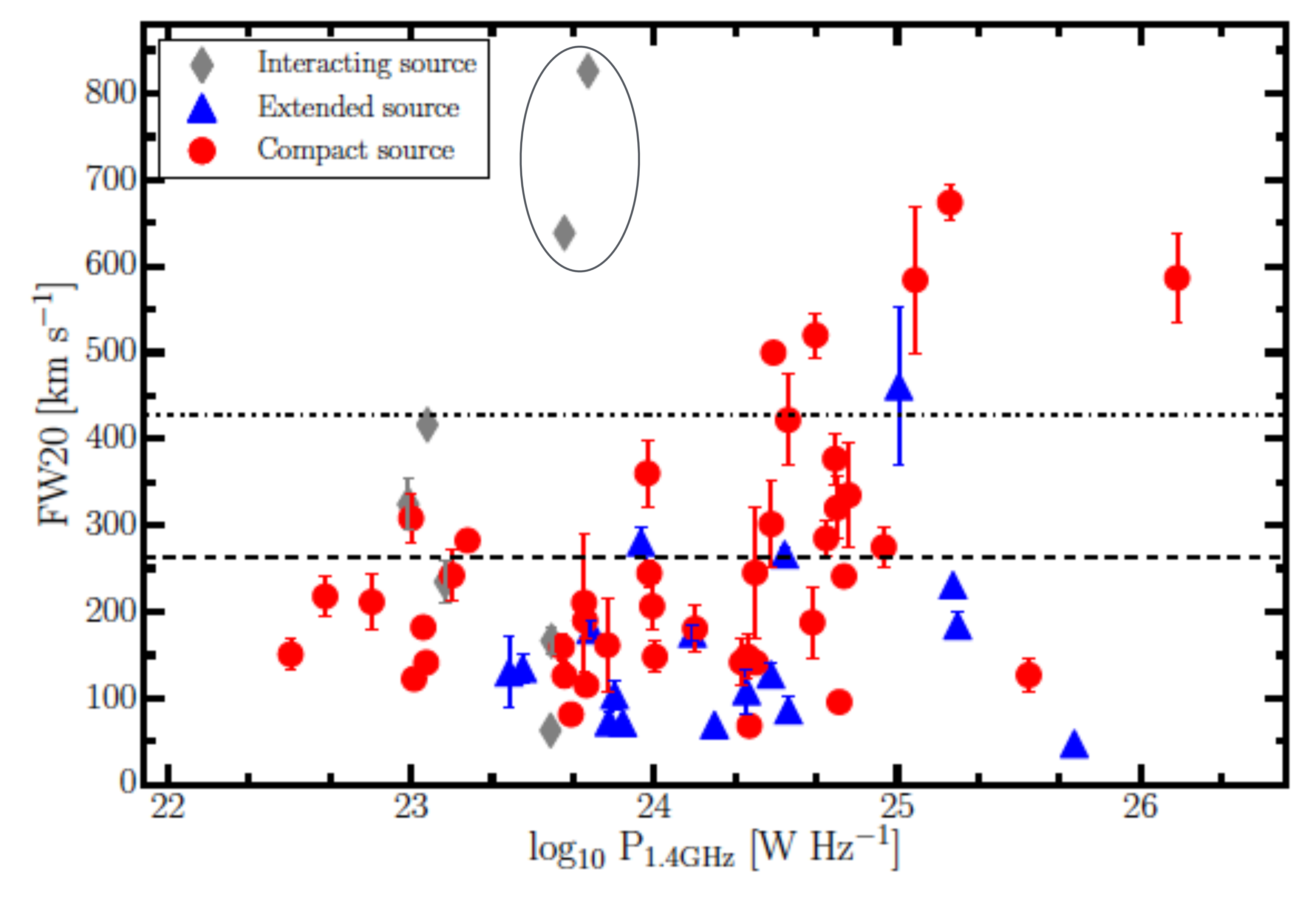
Morganti et al. 2015

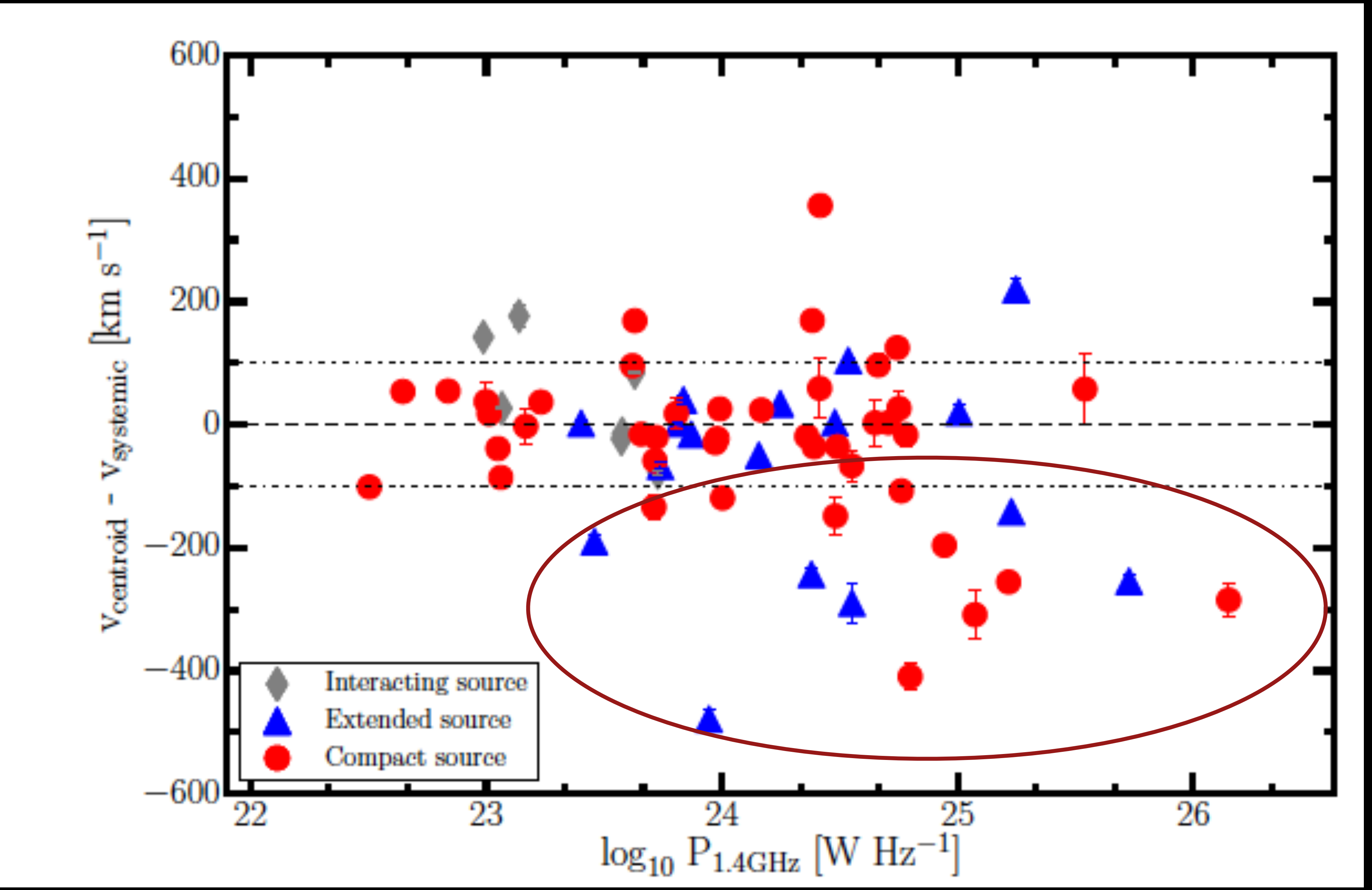
Many studies….

atomic gas (e.g., Rupke & Veilleux 2011, 2013a, 2015; Lehnert et al. 2011; Morganti et al. 2013, 2015), **warm and cold molecular gas** (e.g., Feruglio et al. 2010; Dasyra & Combes 2011; Guillard et al. 2012; Rupke & Veilleux 2013b; García-Burillo et al. 2014; Tadhunter et al. 2014; Cicone et al. 2014; Calderón et al. 2016), **and OH** (e.g., Fischer et al. 2010; Sturm et al. 2011; Veilleux et al. 2013).

What is the occurrence of outflows?
HI outflows from a shallow survey

width of the HI absorption profiles



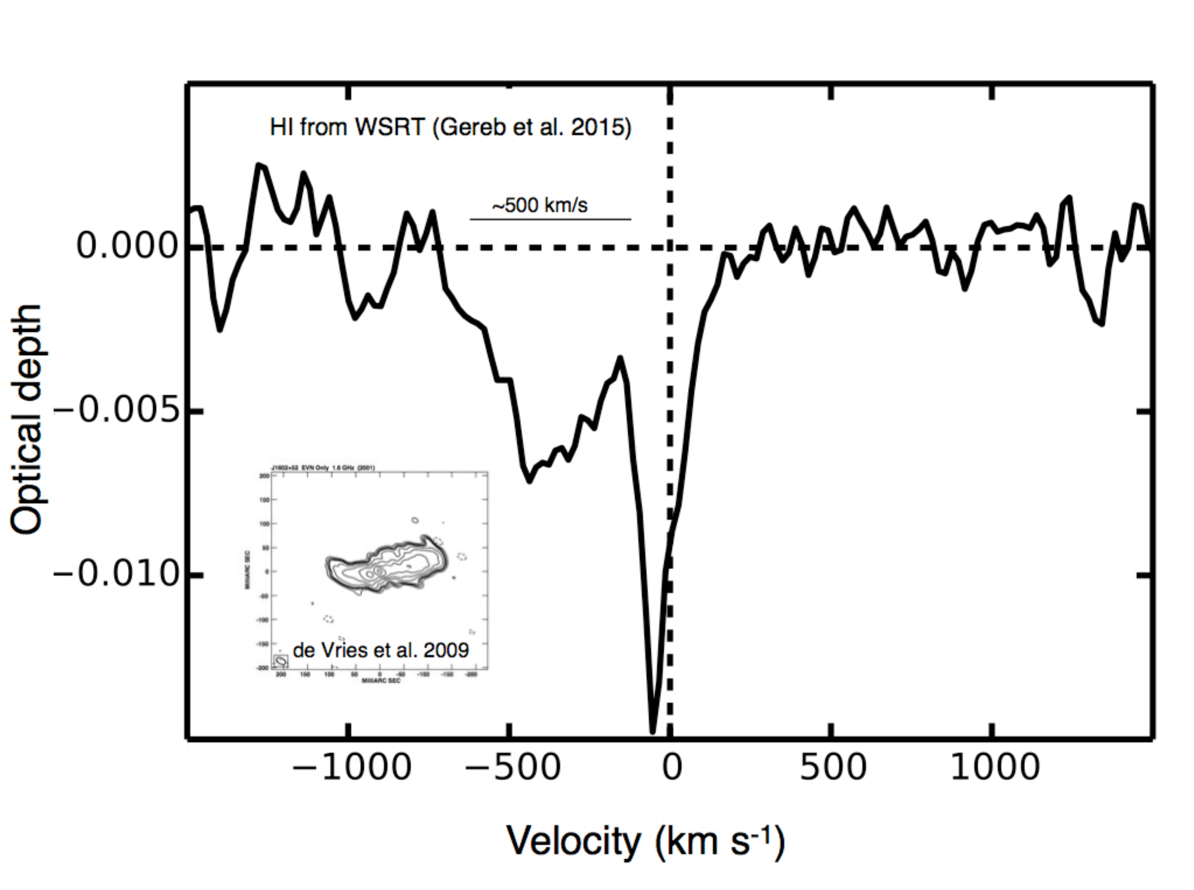


About 27% detection rate of HI
(over all radio powers 10^{22} - 10^{26} W/Hz)
at least ~5% of the all sources show an HI outflow (500-1000 km/s)

➔ if a phase of outflow appears in every object,
then it should last not more than *a few x Myr*

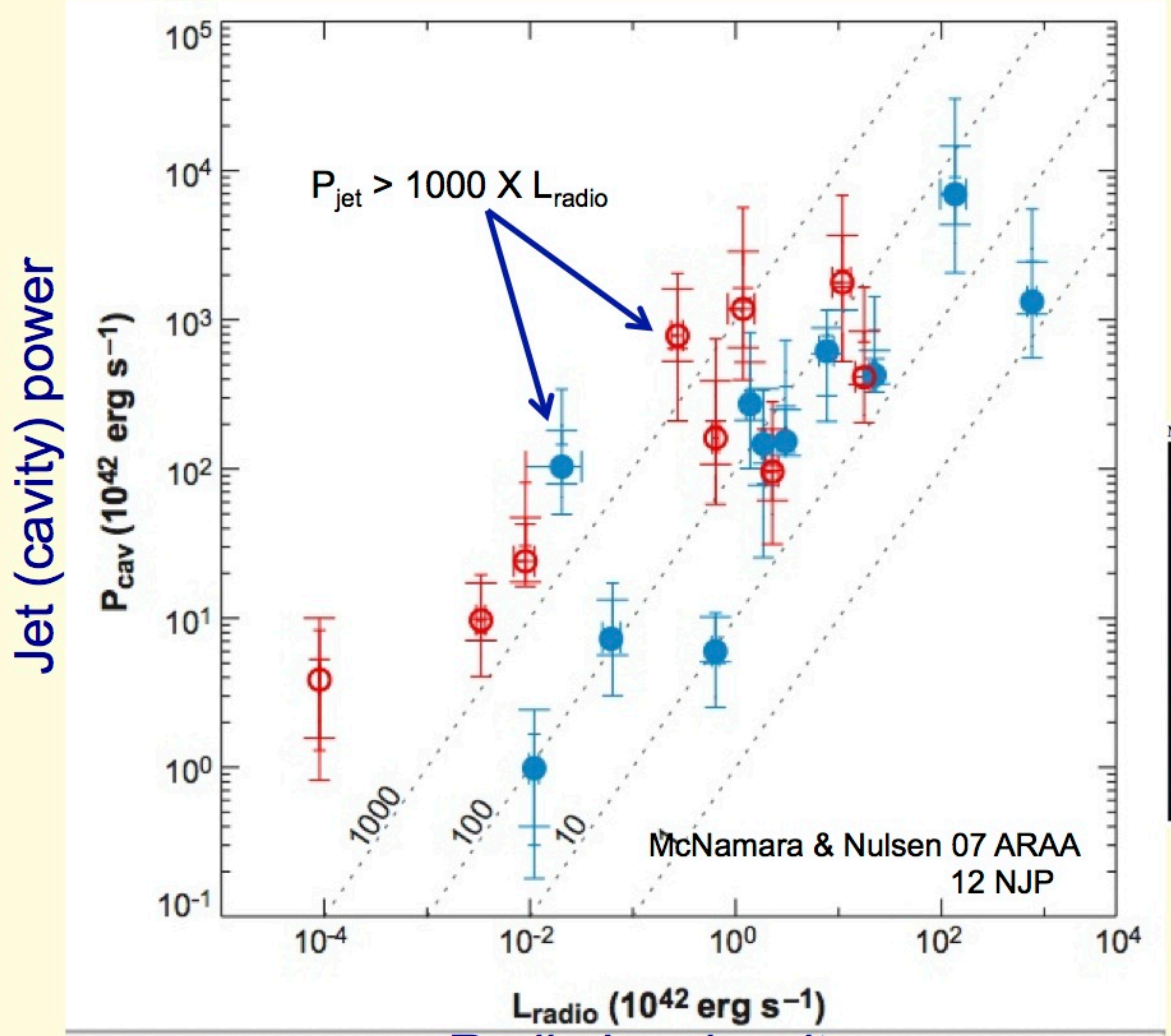
higher detection rate for young radio sources (farIR bright) and for high radio power

Gereb et al. 2015, Maccagni et al. 2017



To be confirmed by the upcoming “blind” HI surveys

Mechanical power dramatically exceeds synchrotron power

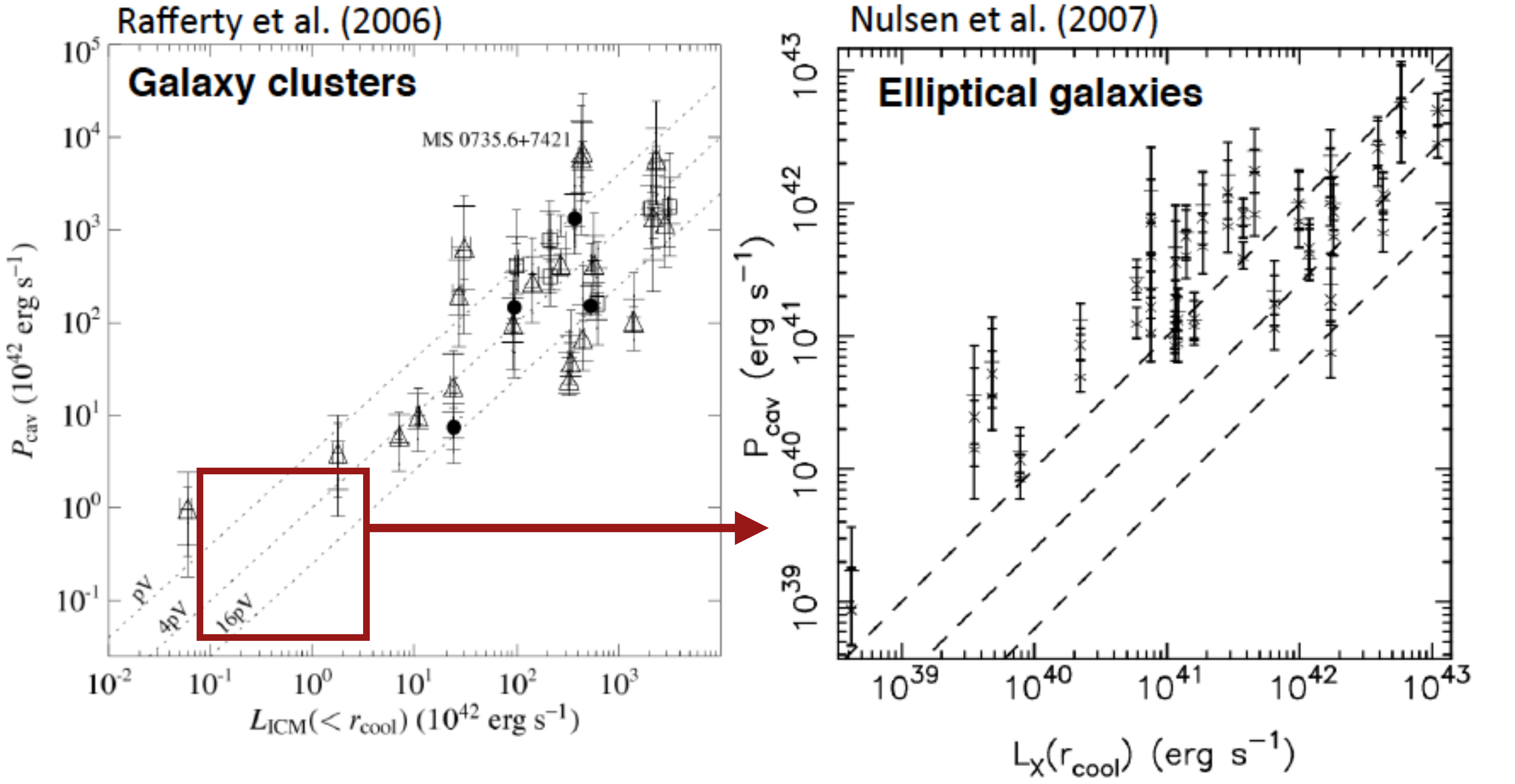


Radio Luminosity

Key breakthrough: even weak radio sources mechanically powerful enoughto regulate or quench cooling, X-ray atmospheres

SMBHs in galaxies with no optical/UV AGN may be rapidly accreting!

Quantifying the feedback effect of the jets on the large-scale hot gas



The cavity power typically balances the X-ray cooling (at r < r_{cool}) in galaxy clusters, but can exceed it for some isolated elliptical galaxies and groups.

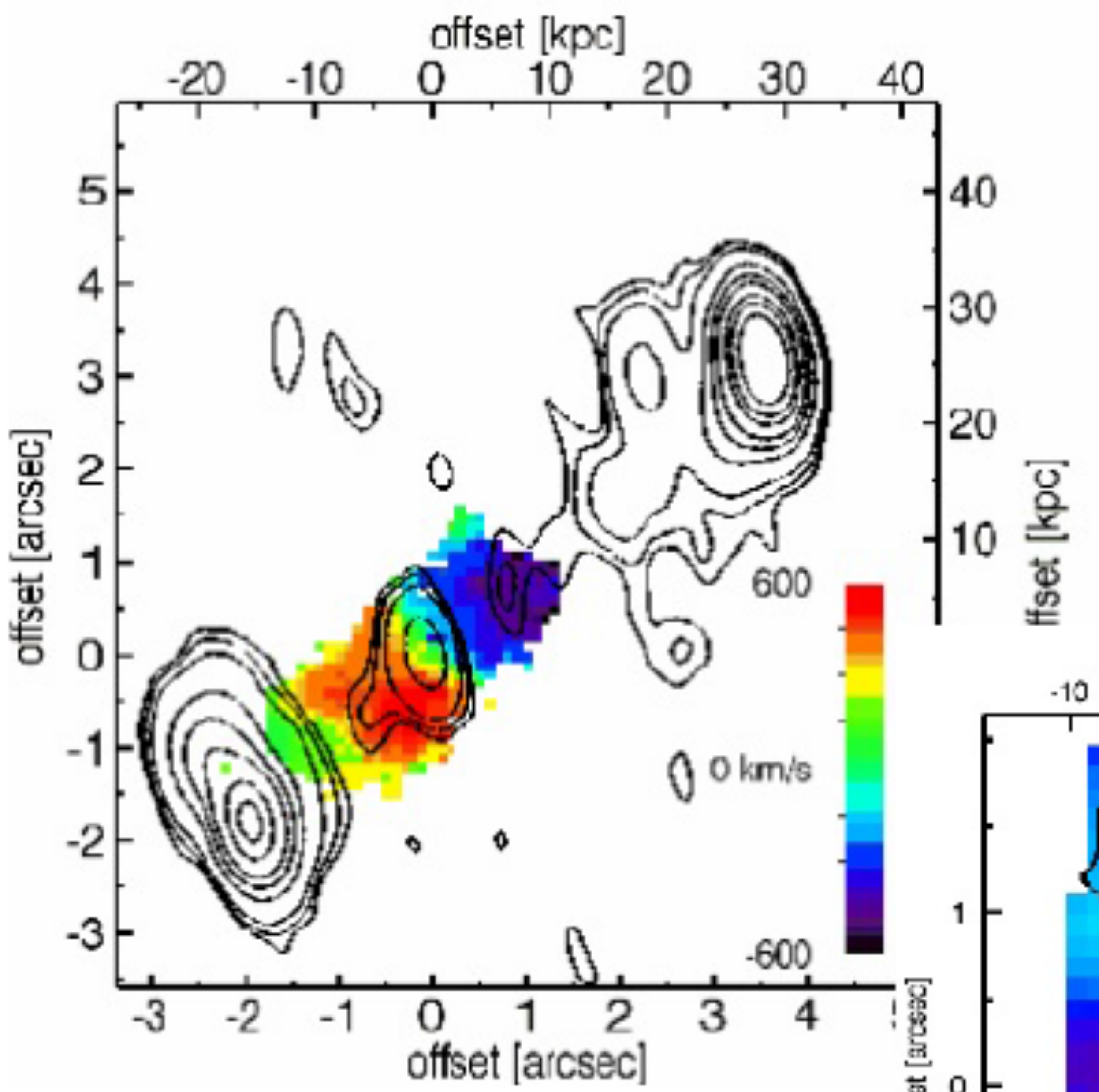
McNamara et al. 2012

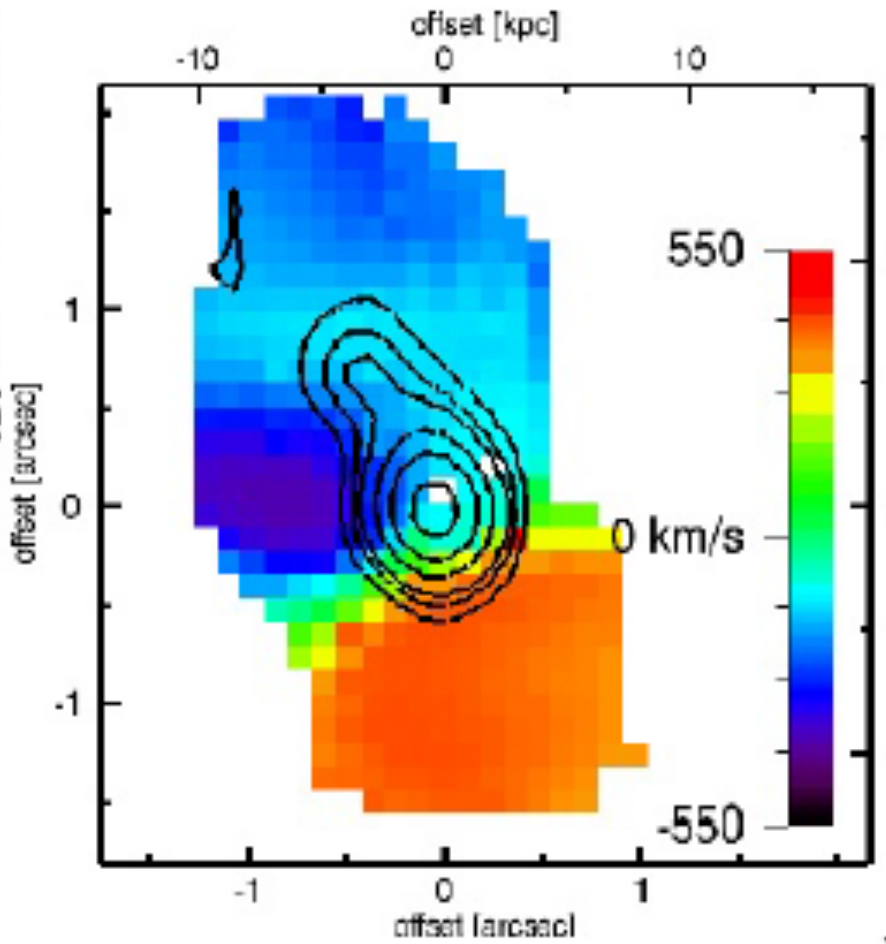
Outflows in high redshift radio galaxies (z~2)

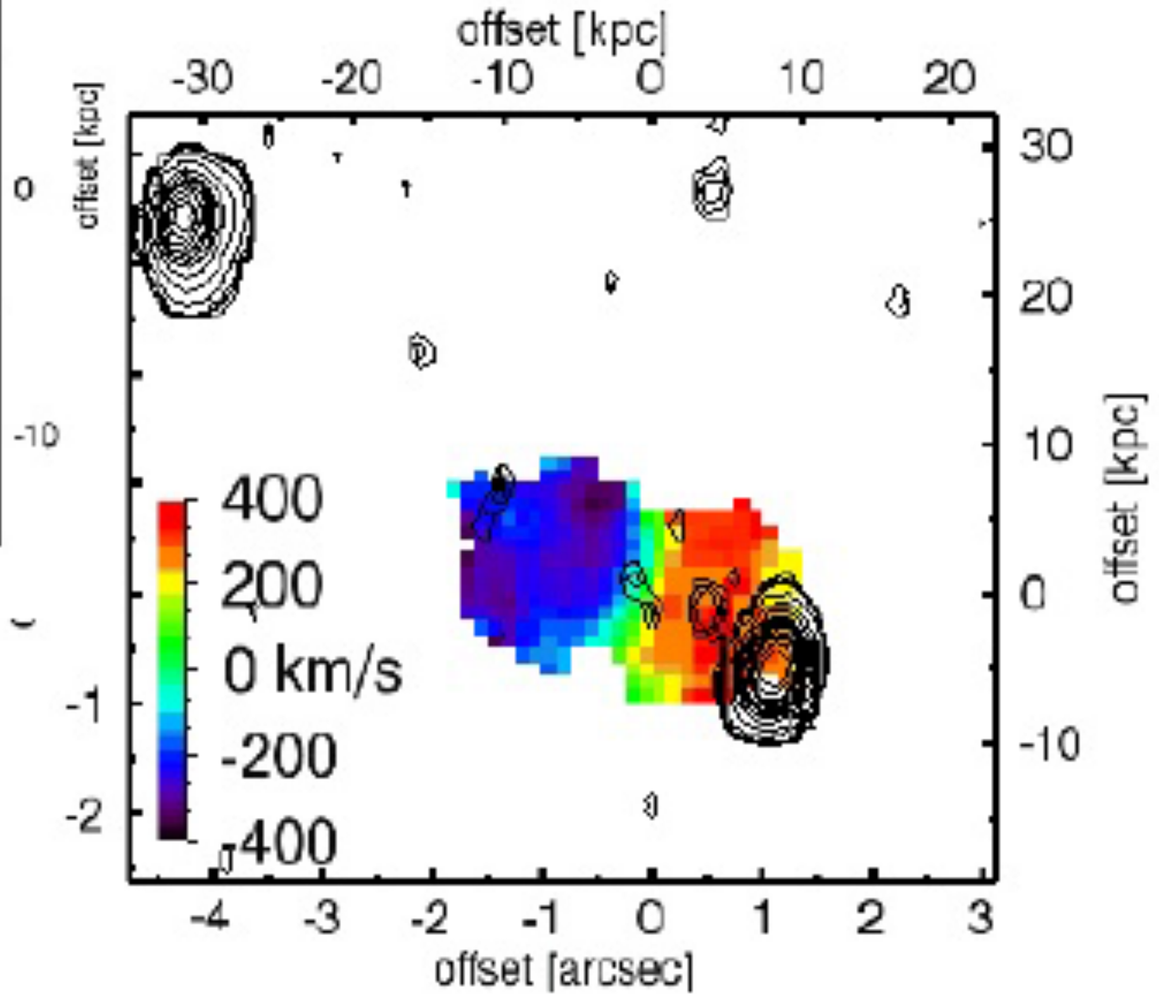
$$300 < \dot{M} < 1000\ M_{sun}\,yr^{-1}$$

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

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







Nesvadba et al. (2006, 2008)

Parameters of the jet-driven outflows

ASTRON

3C293

- Mass outflow rate (from HI) ~ 50 $M_\odot$/yr
- Outflow kinetic power ~10^{43} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ ~10^{-3} (~ 10^{-2} bolometric luminosity)
- Jet power Q_{jet} ~ 2 x 10^{44} erg/s

4C12.50

- Mass outflow rate ~ 10-20 $M_\odot$/yr
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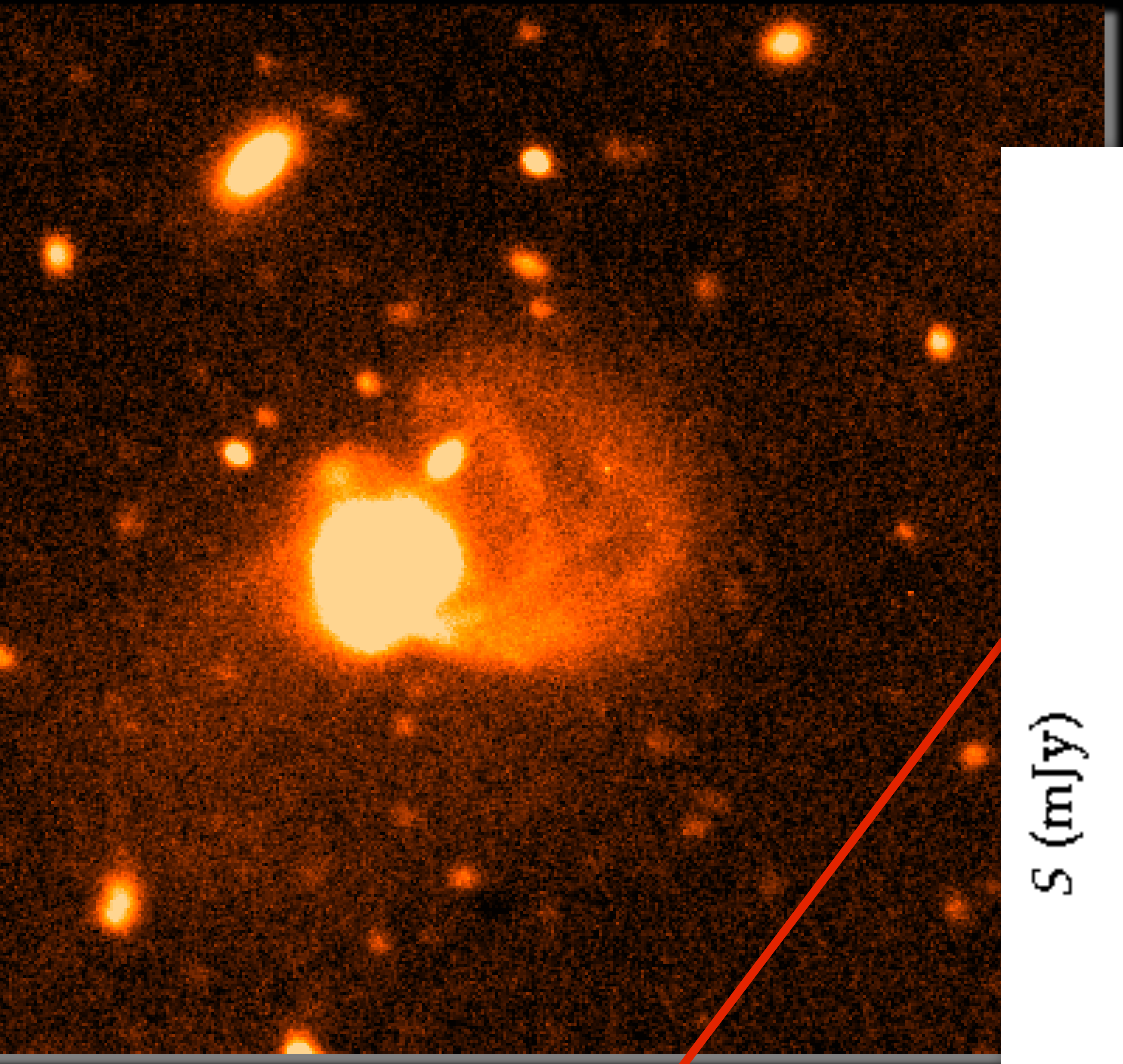
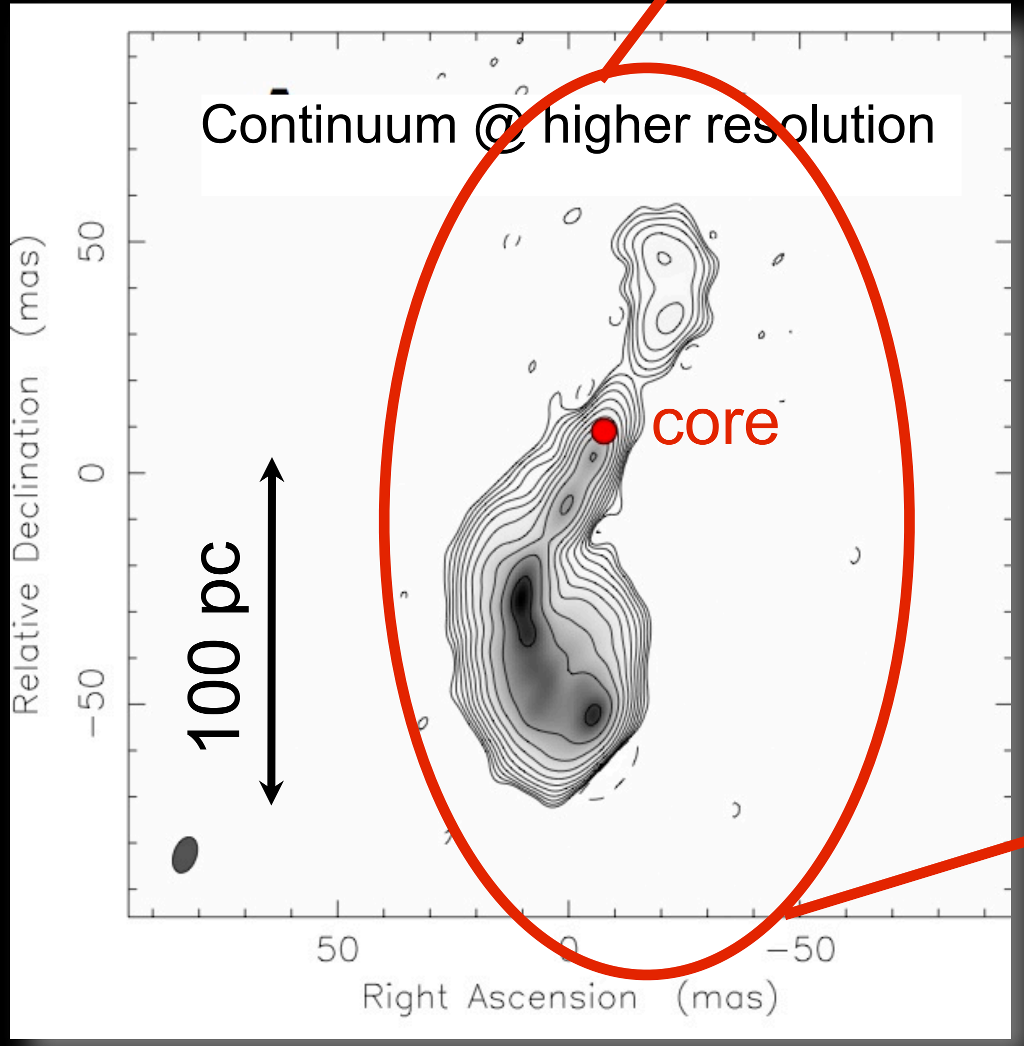
IC5063

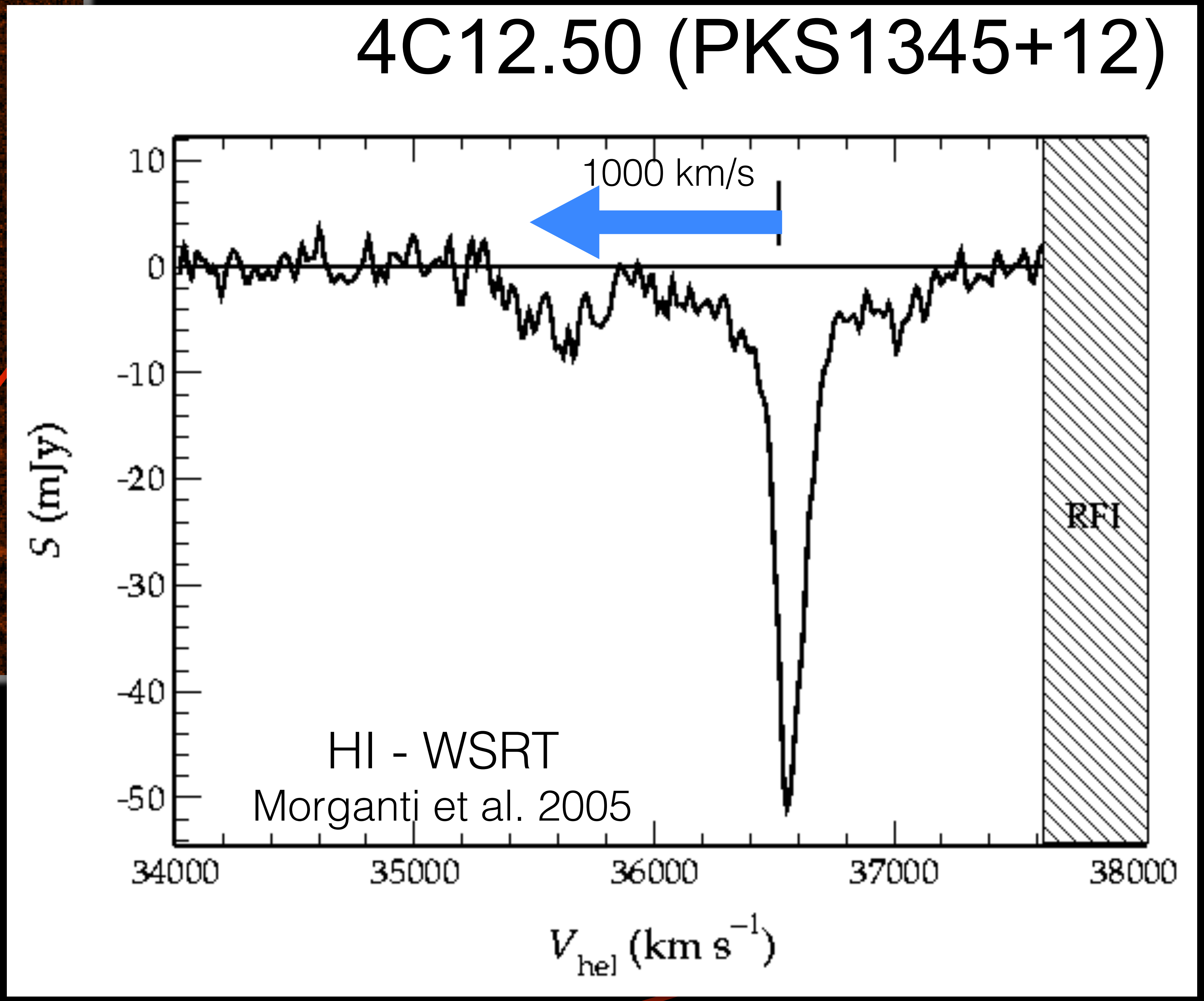
- Mass outflow rate (molecular gas) ~ 12 - 30 $M_\odot$/yr
- Outflow kinetic power (HI + CO) ~ 8 x 10^{42} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ = ~10^{-4} (few x 10^{-2} bolometric luminosity)
- Jet power Q_{jet} ~ 5 x 10^{43} erg/s

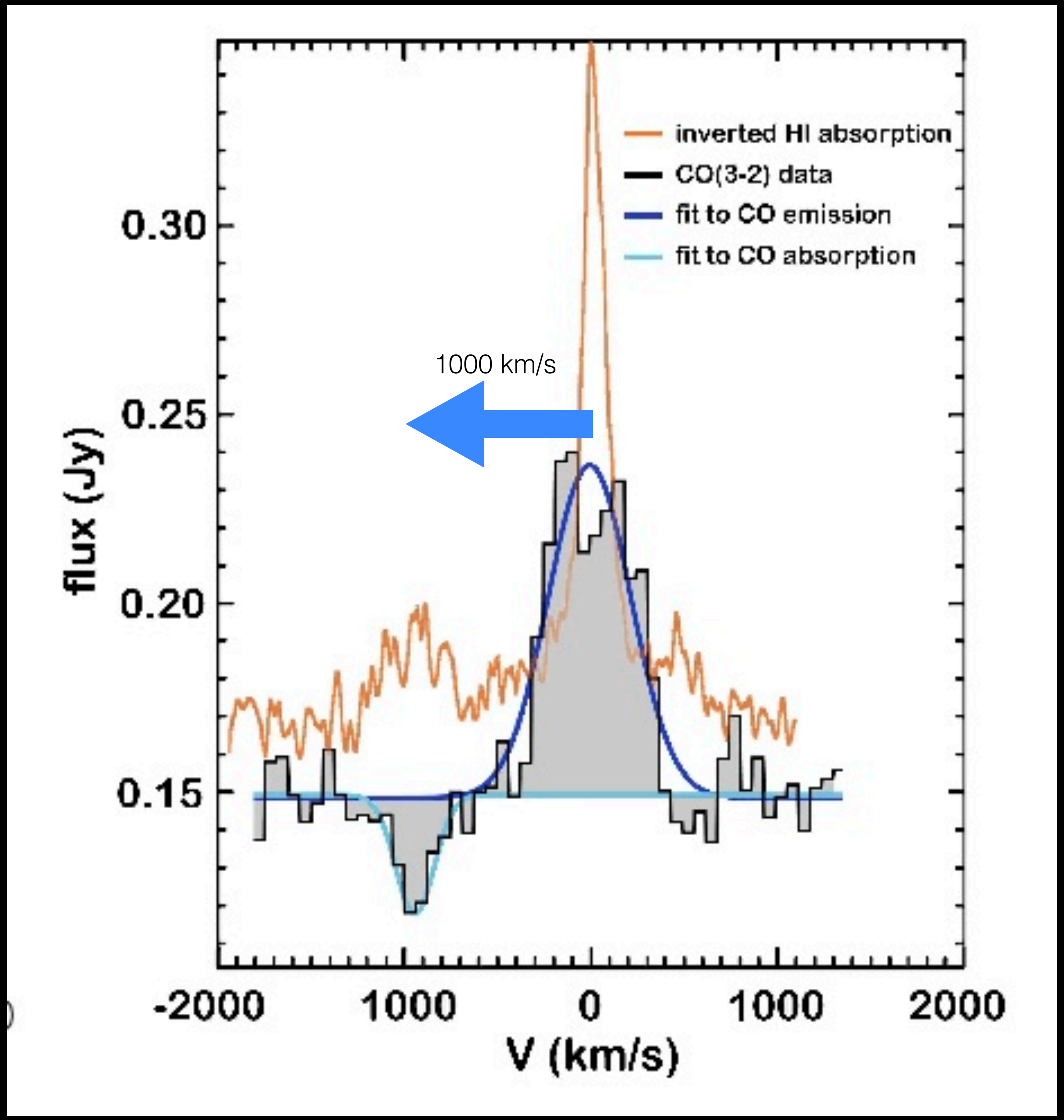
➔ most of the gas is not leaving but "relocated"

Fast outflow of cold gas in 4C12.50 (farIR bright, young radio source)









CO - PdB
Dasyra & Combes 2012

- powerful object $>10^{26}$ W/Hz @ 1.4GHz

Remarkable correspondence between HI and molecular gas
➔ importance of the cold gas
➔ complementarity of the two tracers