Netherlands Institute for Radio Astronomy

ASTRON

Young radio jets breaking free:

molecular and HI fast outflows in the central regions

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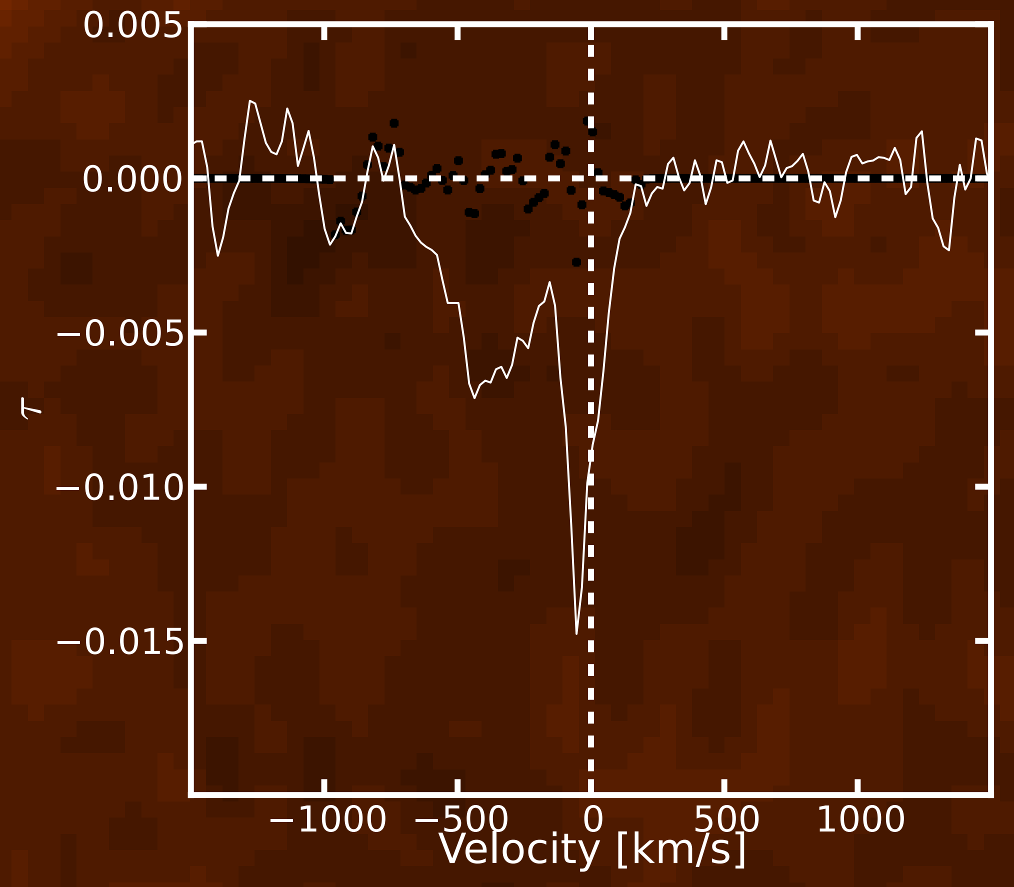


Effect of radio plasma on the (sub) kpc-scale:
Why interesting?

Energetics to **drive outflows:**

long known from ionised gas (optical, X-ray)

➜ but also **atomic neutral hydrogen and molecular:** major component in mass

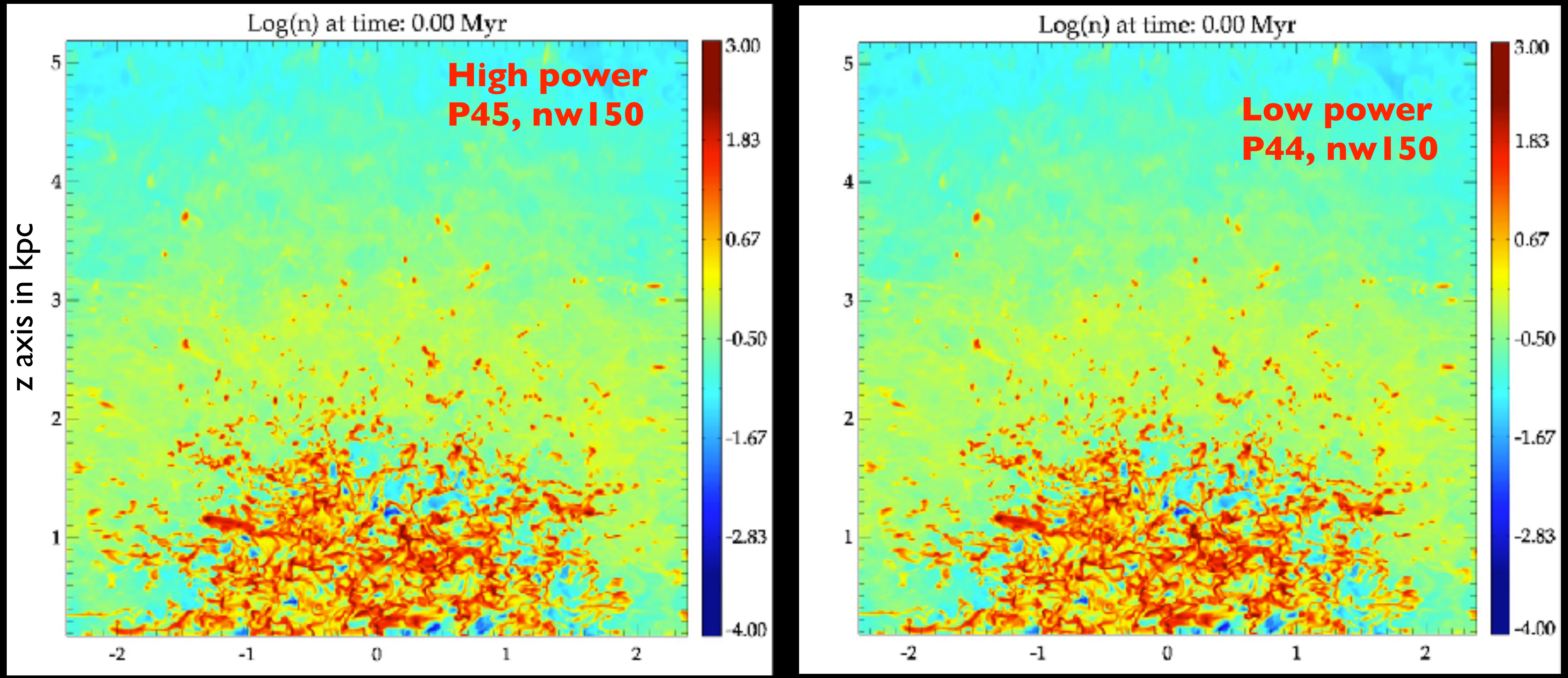
Effects of the cycle of activity

➜ results suggesting **young and restarted having highest impact**

Coupling energy/ISM ➜ **simulations now making predictions** and guiding the observations

Numerical simulations of a newly created radio jet

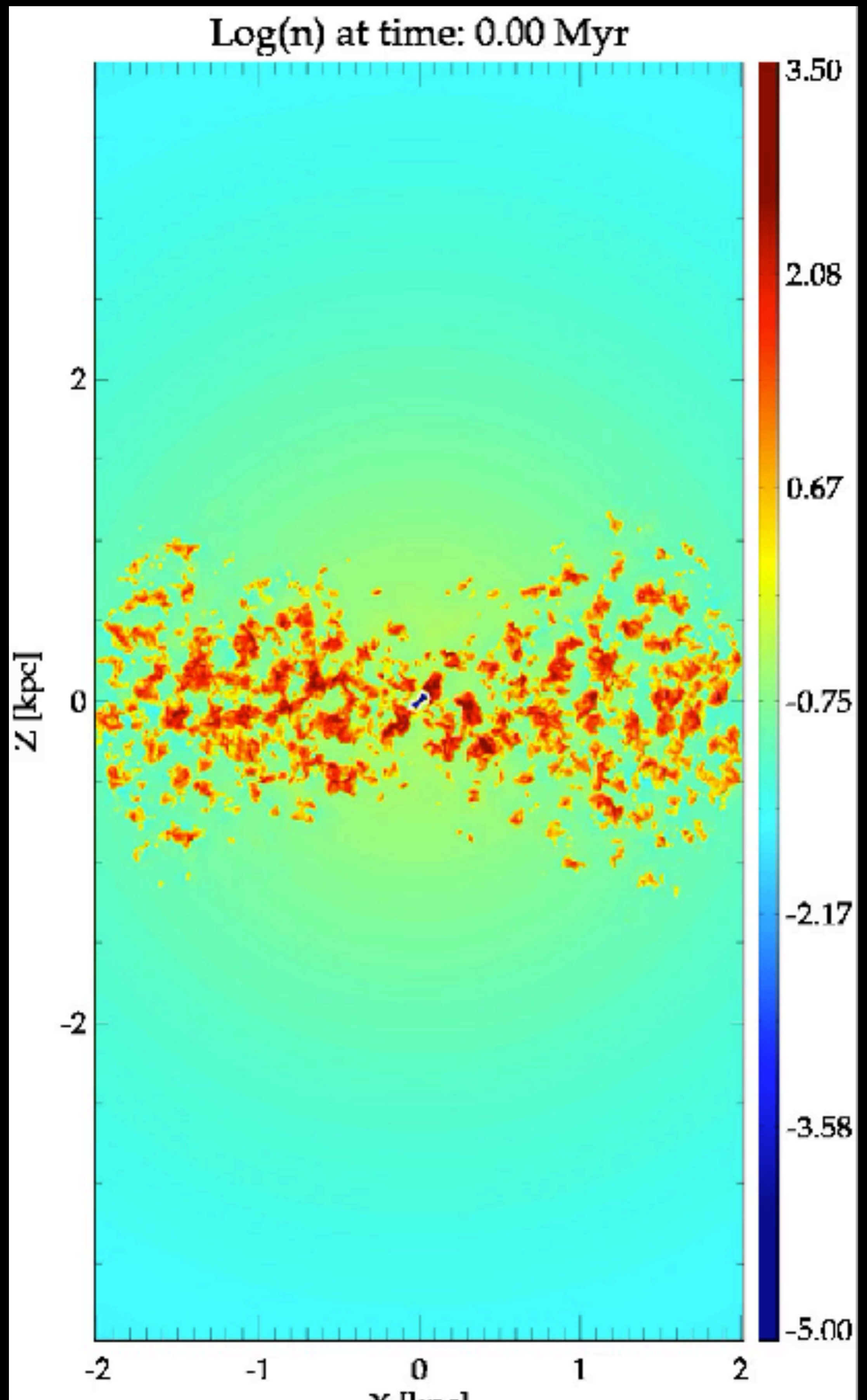
from Wagner & Bicknell 2011, 2012, Mukherjee, Bicknell et al. 2016, 2017, 2018



clumpy medium (spherical distribution), different jet power

Impact of radio jets as on the kinematics of the gas
predicted by numerical simulations:
key parameter the clumpiness of the medium
Large impact also for low luminosity radio AGN

- Jets couple strongly with host's **clumpy ISM**
- Impact dependent on **jet power**
- **Fast multiphase outflows** but not always enough to escape.
- **Low power jets are important!** Couple more with the ISM, will induce more turbulence and more numerous!
- Orientation wrt gas distribution →

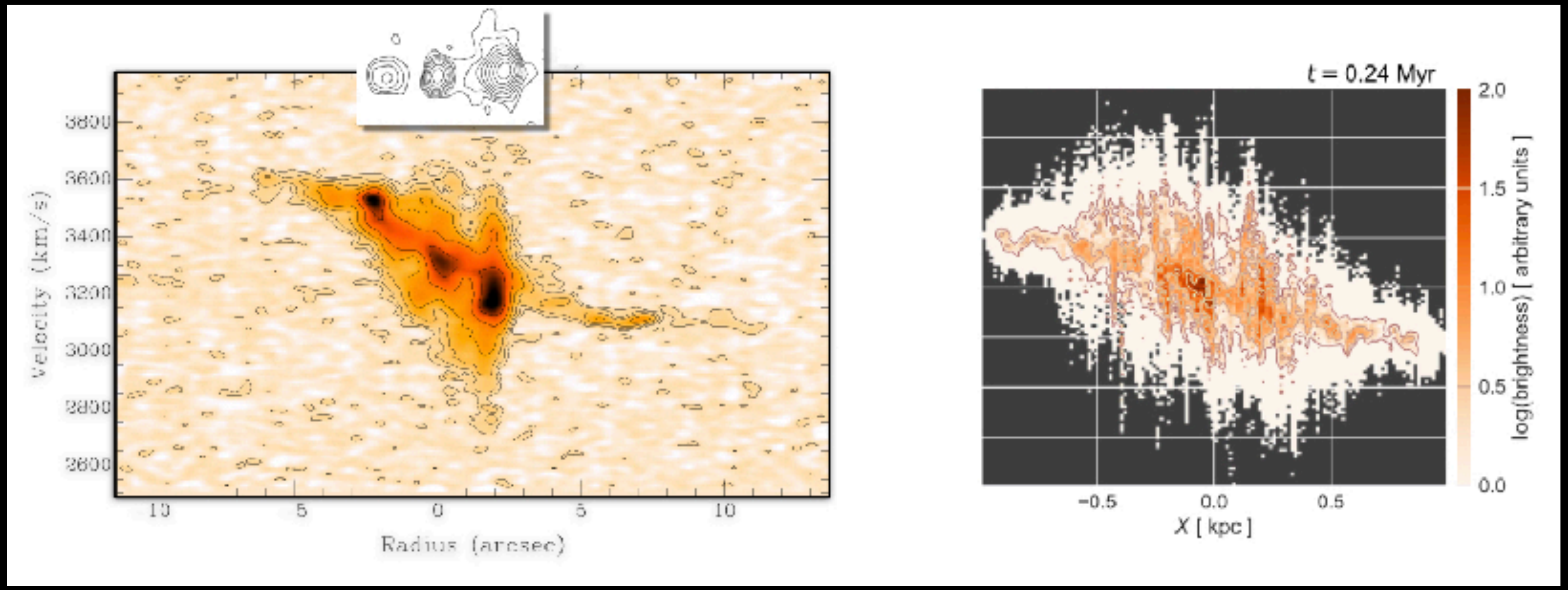


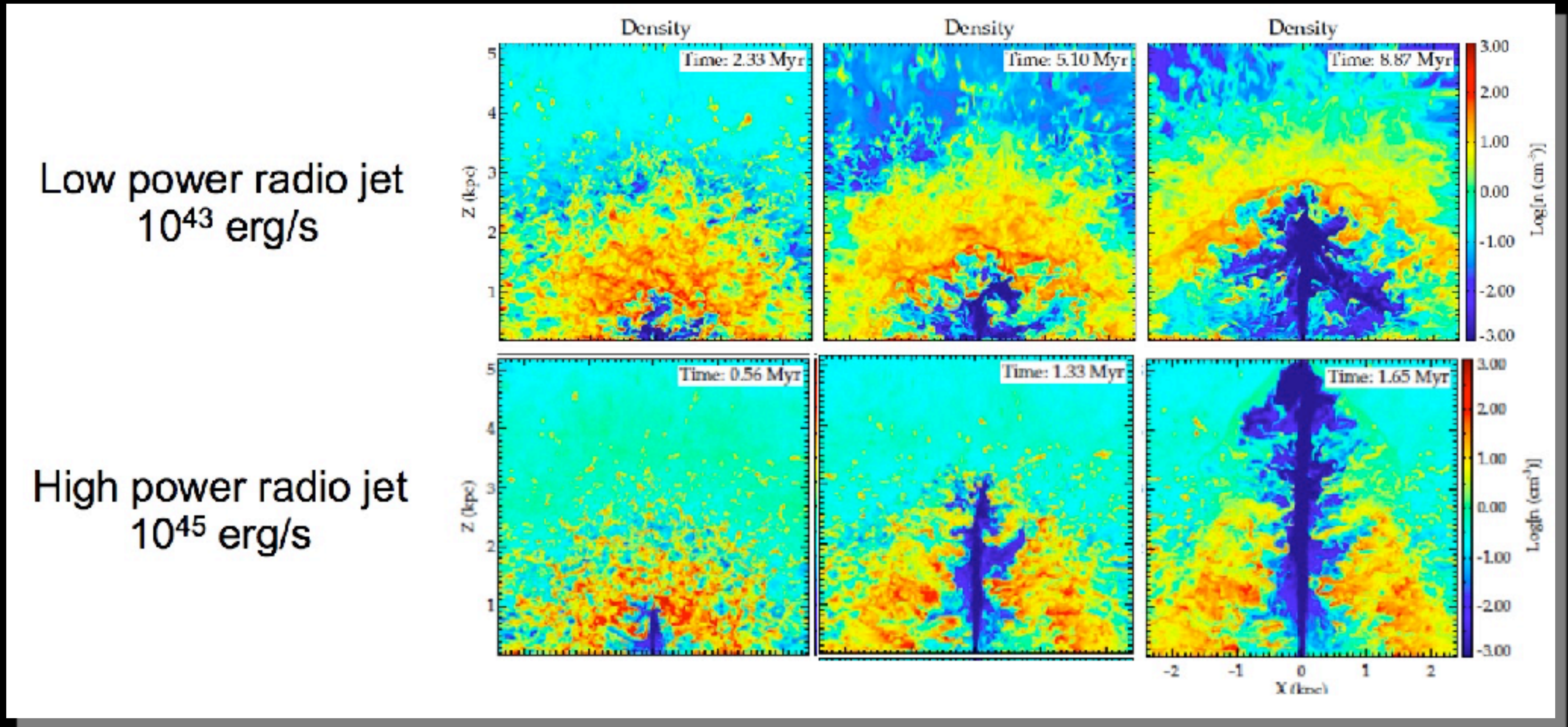
clumpy medium in a disk

Mukherjee et al. 2017 2018

Observations and simulations to quantify the impact of jets

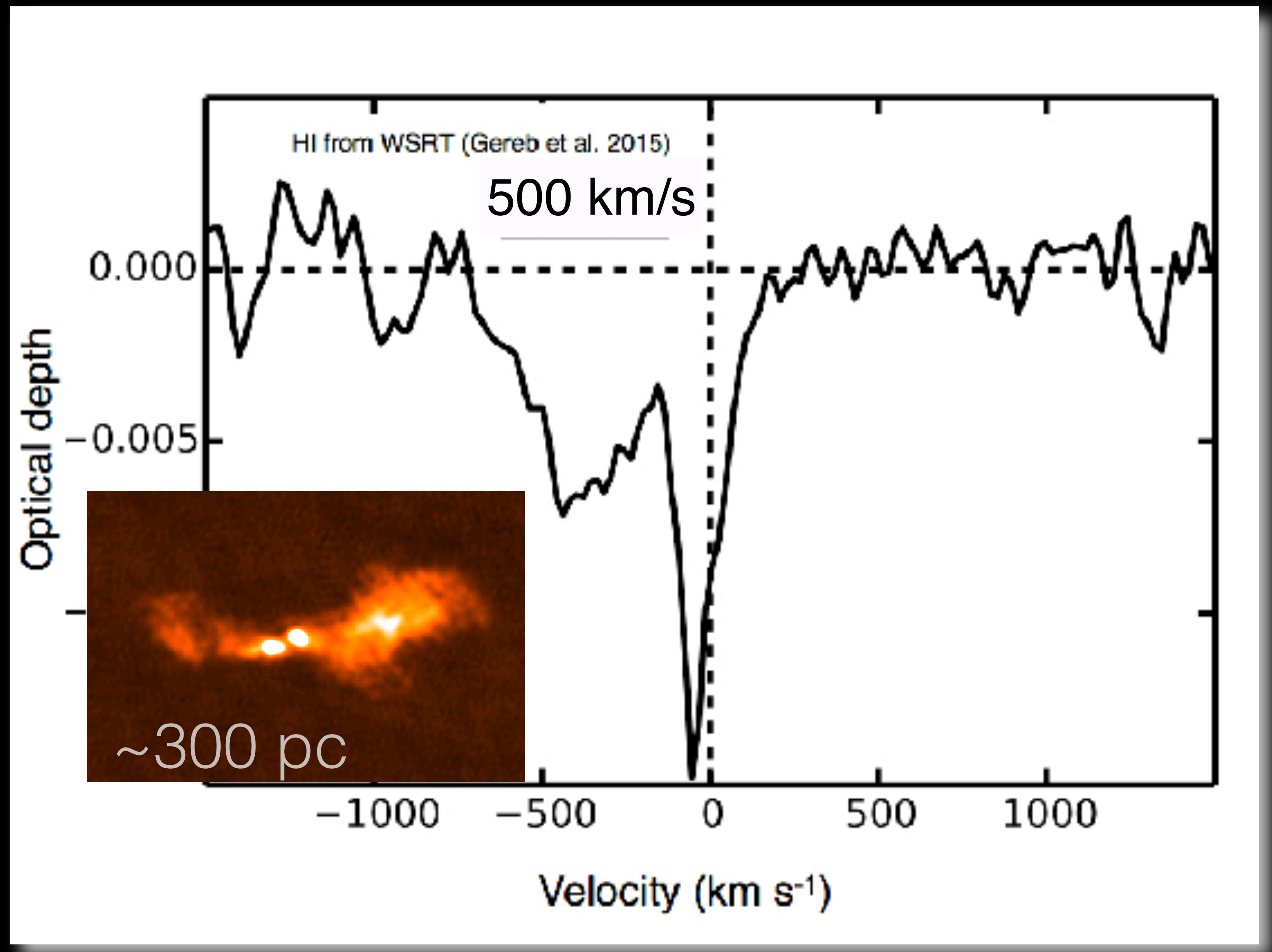
- A large parameter space needs to be covered: evolution with age, jet power, surrounding medium, orientation of the jet
  ➜ using HI and molecular gas (complementary?)
- Important to follow jets in their first phase (or restarted phase)
- Follow the impact using high spatial resolution observations
  ➜ VLBI for HI and ALMA for CO
- Comparison observations/simulations

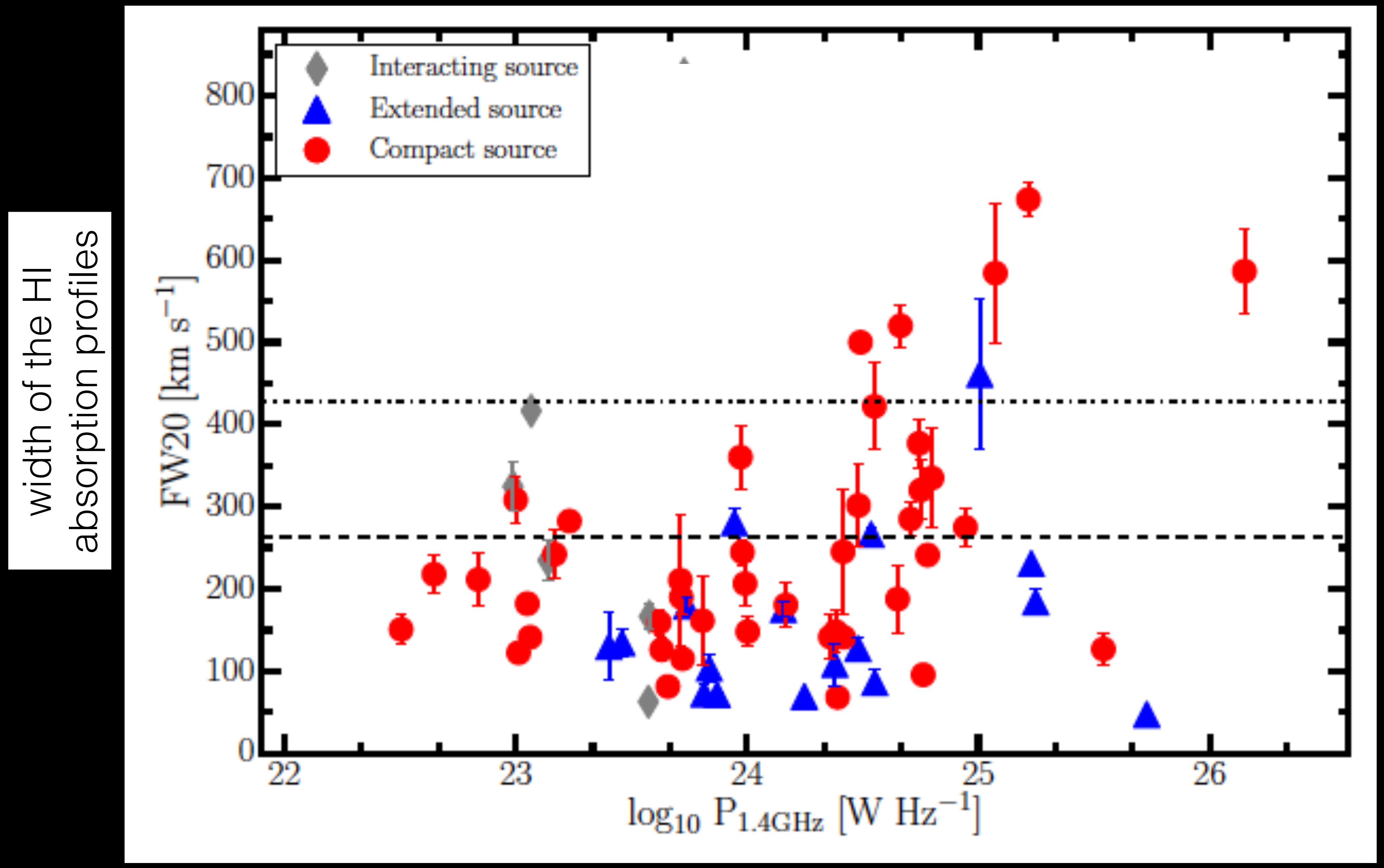




Results from HI outflows

From a pilot survey HI absorption with the WSRT





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

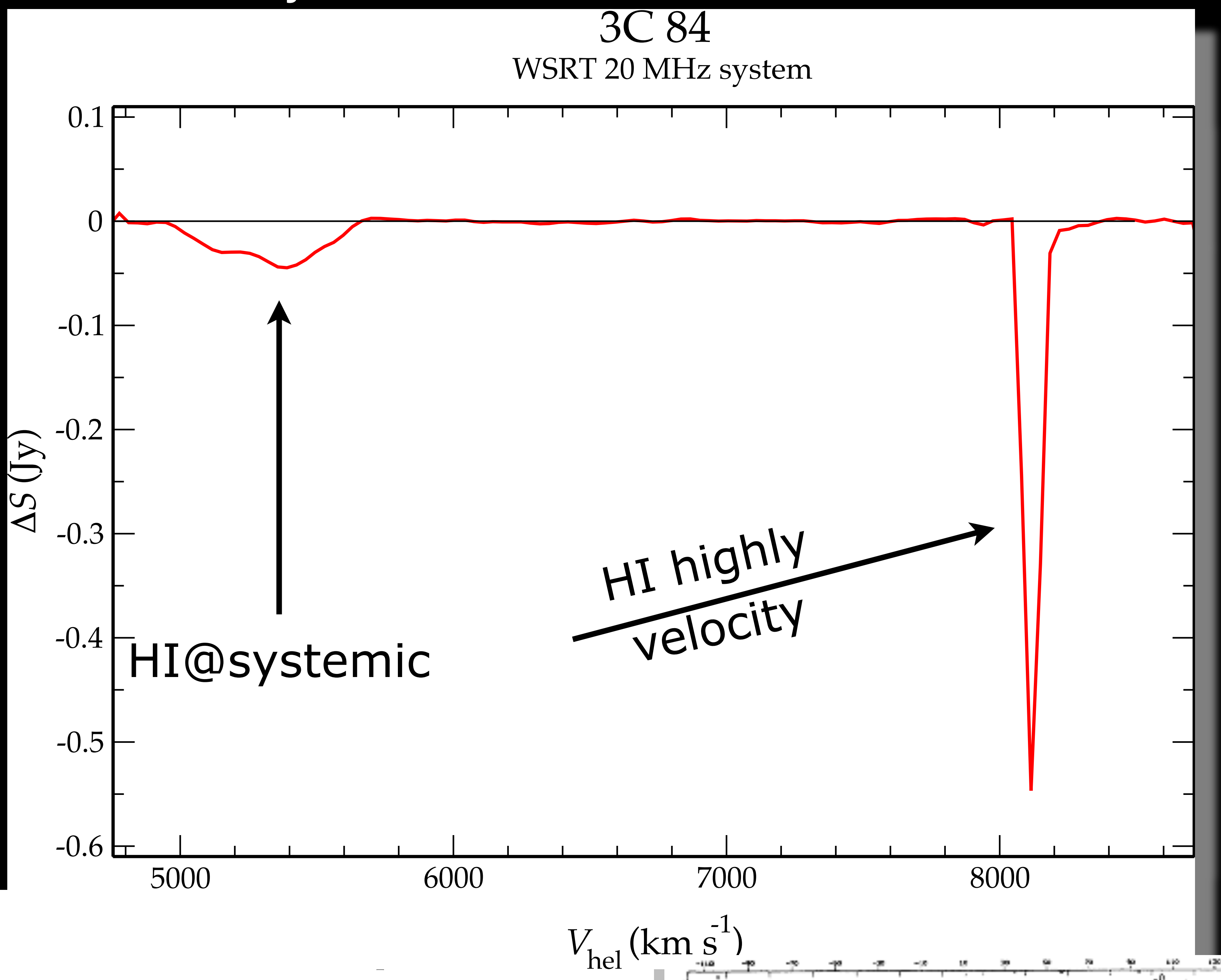
Mass in the HI outflows from a few x10^6 to 10^7 $M_{\odot}$, velocities between a few hundred to ~1300 km/s, mass outflow rates a few to 50 $M_{\odot}$/yr

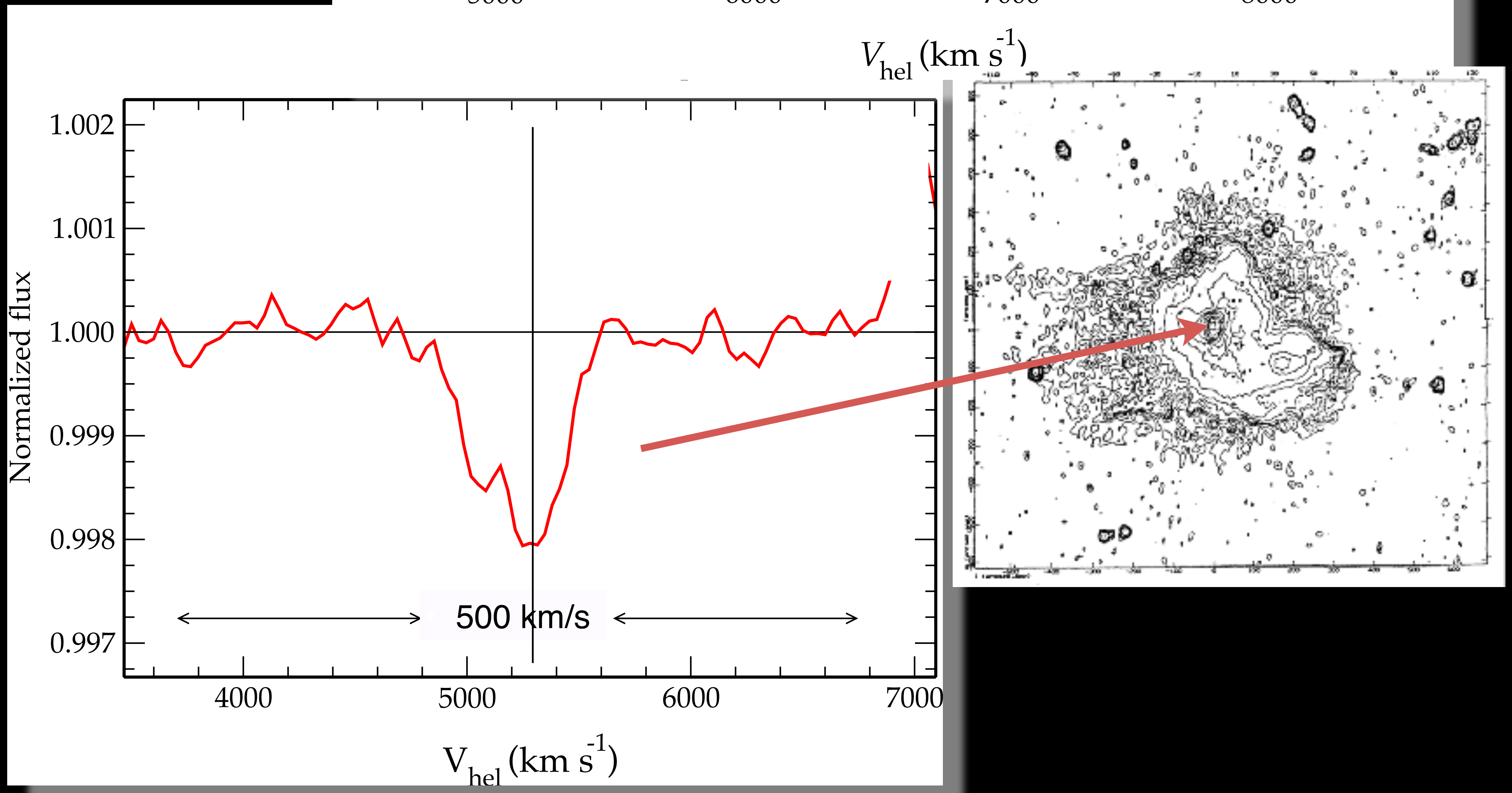
Gereb et al. 2015, Maccagni et al. 2017

Follow up high resolution and molecular gas in progress…

How about 3C84?

Ger de Bruyn & Tom Oosterloo





Radio power 10^{25} W/Hz

- **Two absorbing systems of HI**

  (Jaffe 1990; Sijbring, de Bruyn et al. 1989)

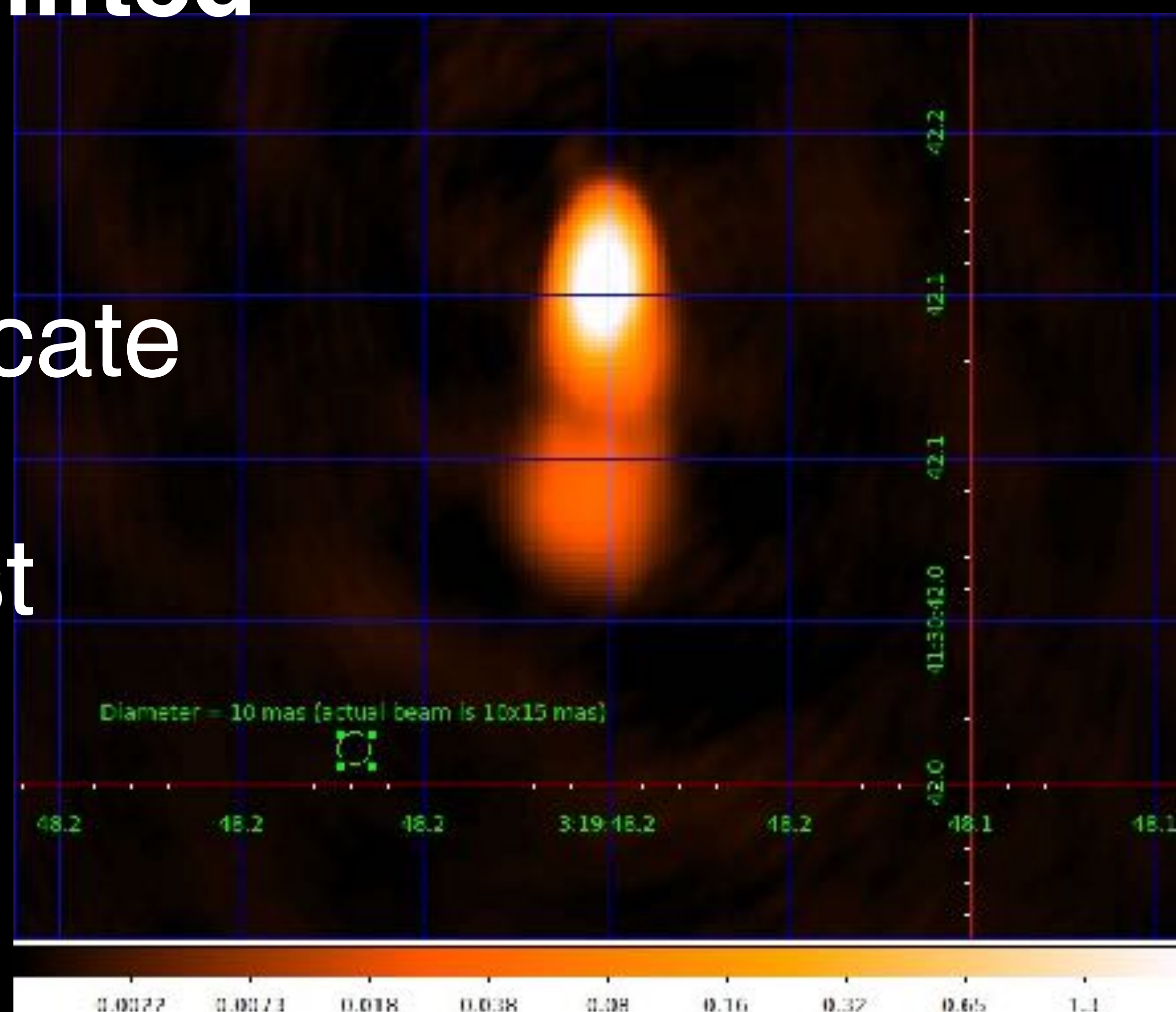
- High-velocity system: chance alignment of foreground gas-rich galaxy? (Momjian et al. 2002)

- Broad (~500 km/s) absorption around systemic velocity: likely combination of large scale and circum-nuclear HI

  BUT

  signs of asymmetry: **blueshifted**

- High resolution required to locate the HI and pin down origin: ruled out absorption against the core? (Oonk, Schulz et al.)



Evolution of the outflows as the source expands?

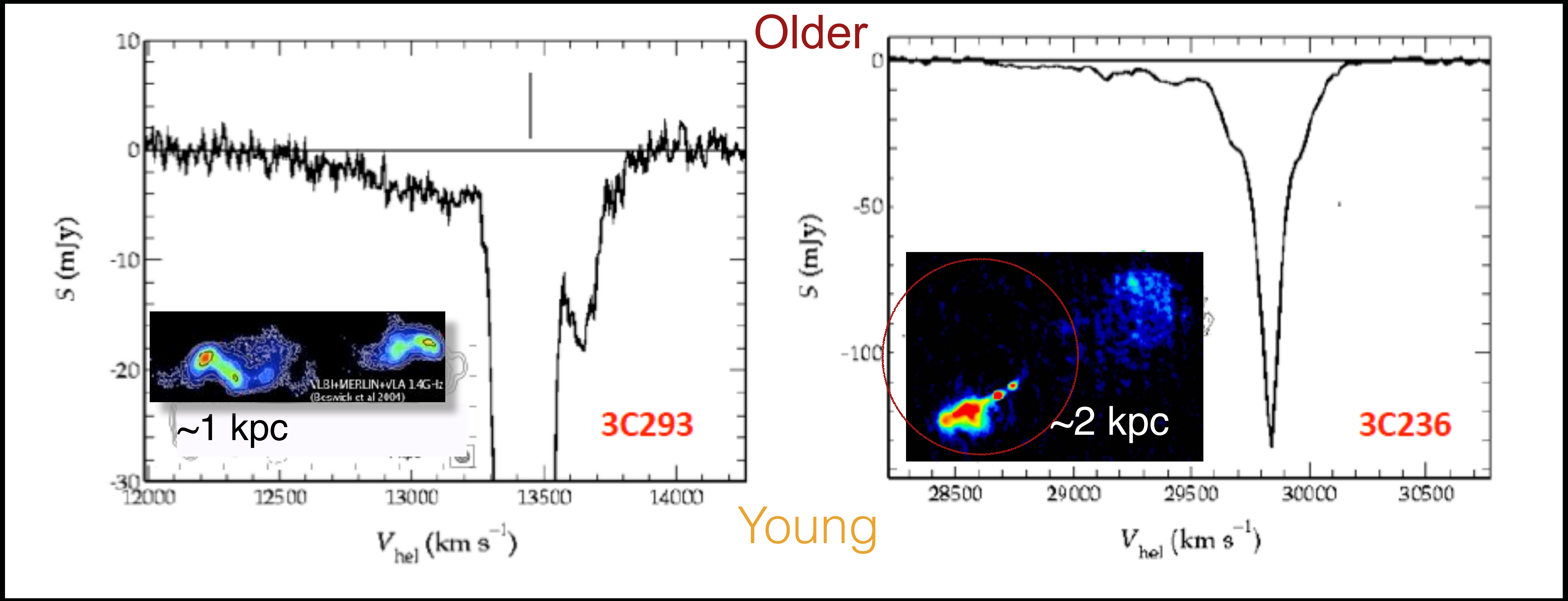
HI outflows traced at high spatial resolution with VLBI (resolution from a few tens to hundred pc)

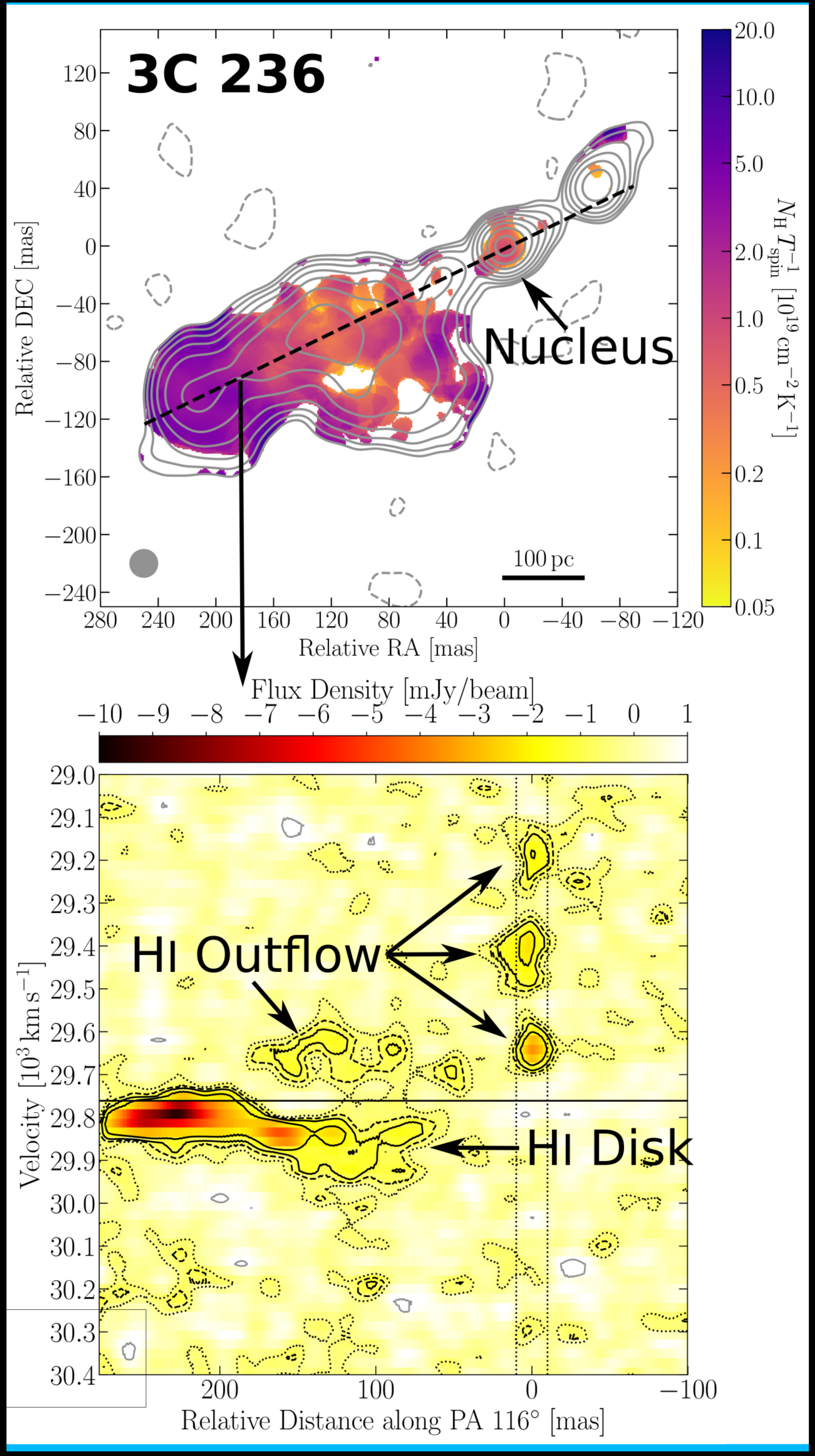
Clumpy medium

Younger: VLBI recovers all flux of the HI outflows

Evolution of the outflows as the source expands?

HI outflows traced at high spatial resolution with VLBI





More evolved (and restarted) sources:

outflows only partly recovered by VLBI: likely mix of compact clouds and diffuse gas

HI clouds (few x 10^4 $M_\odot$) observed in the inner region of the radio galaxy (< 40pc)

Schulz, RM et al. 2018

Some (preliminary) results from HI and VLBI

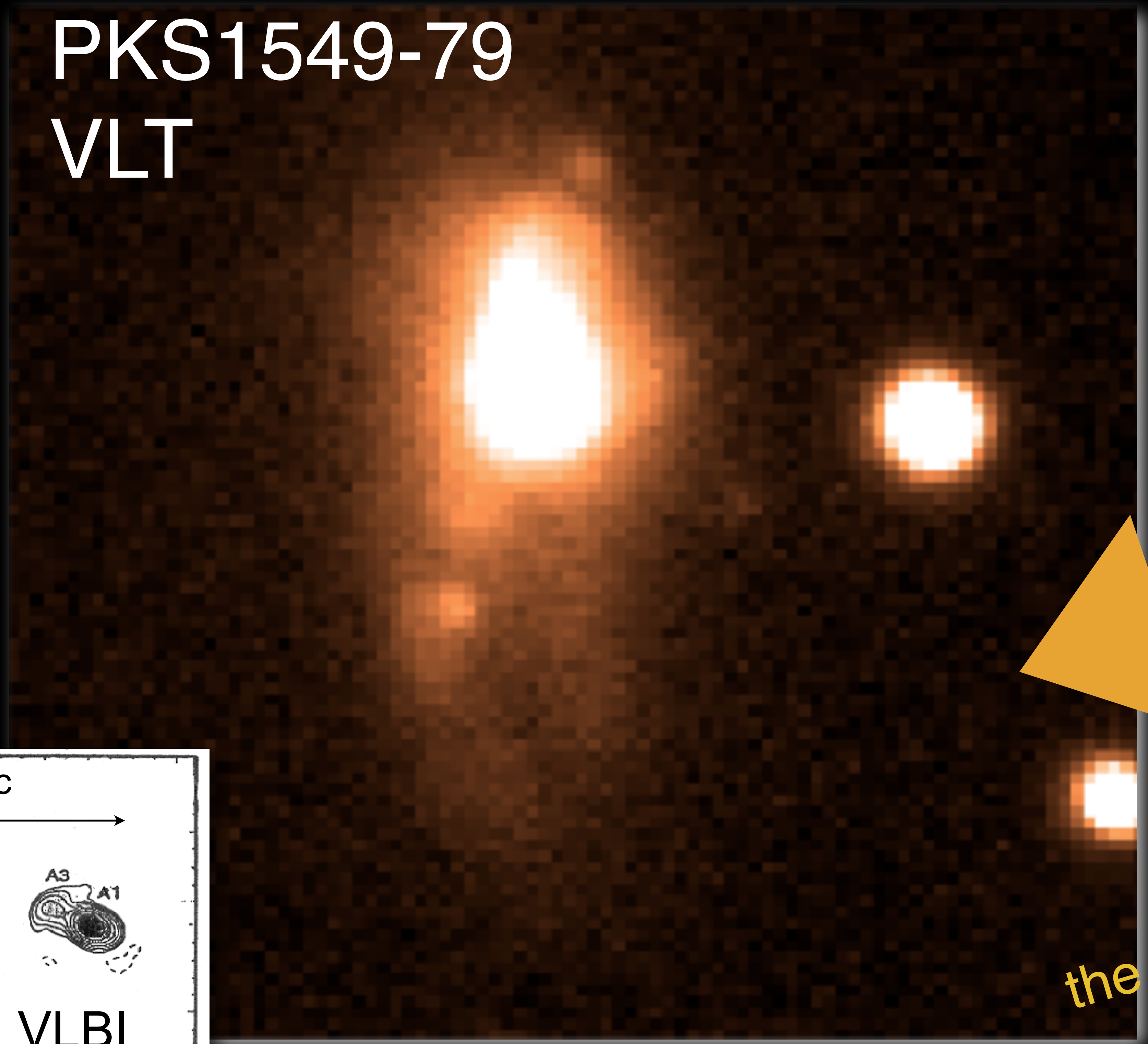
- Signs of clumpy medium in all sources
- Young/smaller sources showing the *most direct sign of interaction*
- Tentative signs of evolution of the outflow: presence of a *diffuse component* - not recovered by the VLBI observations - in larger sources

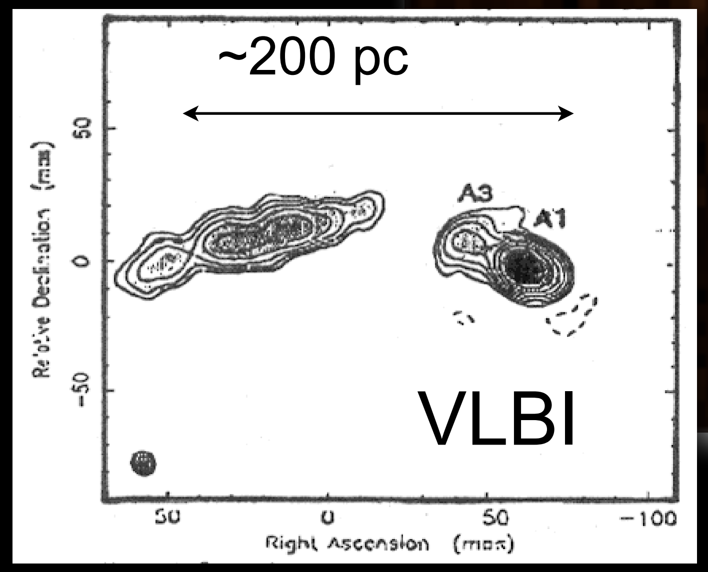
  (3C236, 3C293, B2 0258+35 Murthy et al. in prep.)
- HI outflows are also localised in the nuclear region of the AGN (<40 pc)

  ➜ showing *clumpy structure*

Molecular gas to complete the picture: most massive phase in outflow!

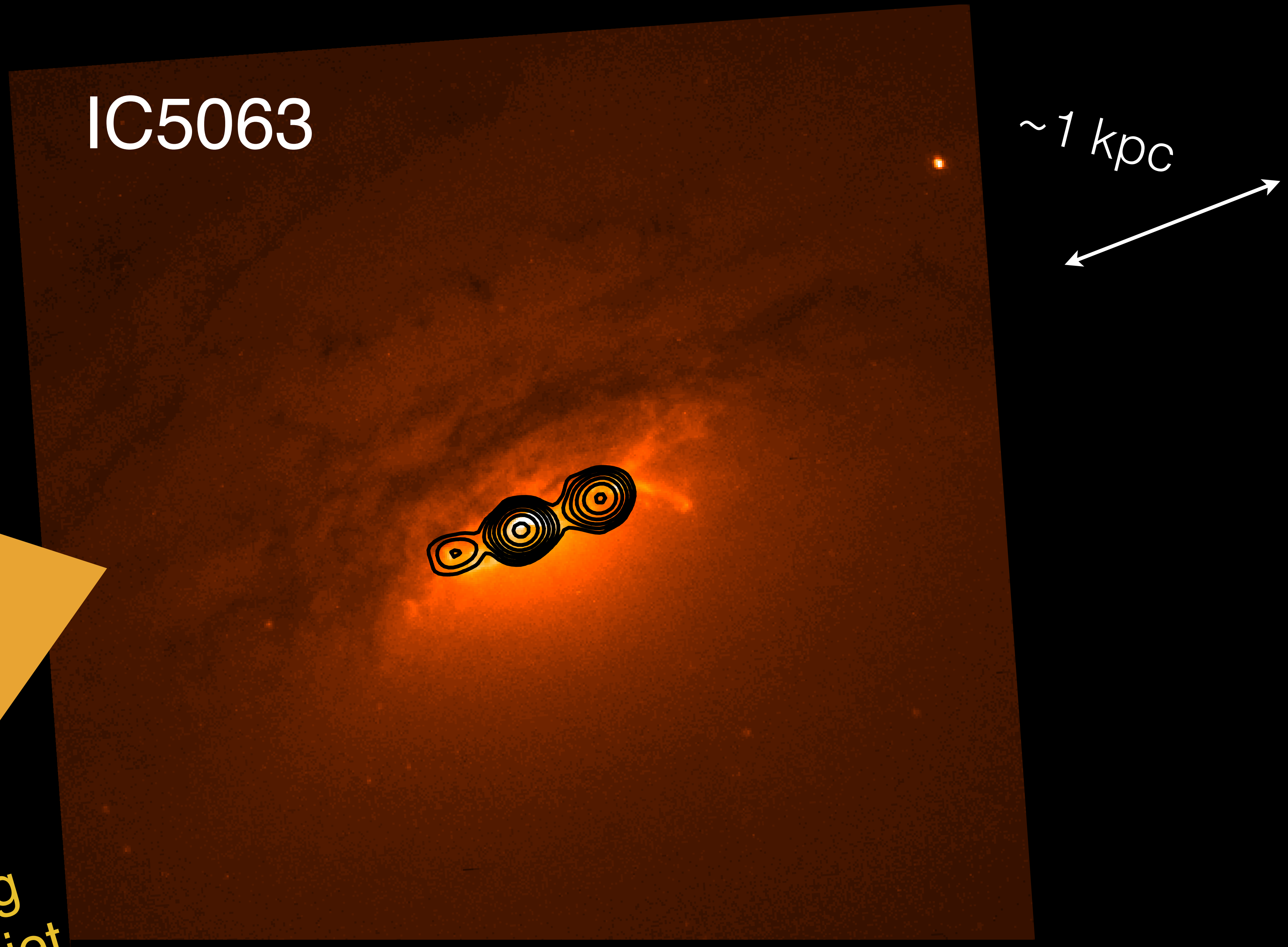
Molecular outflows traced by ALMA





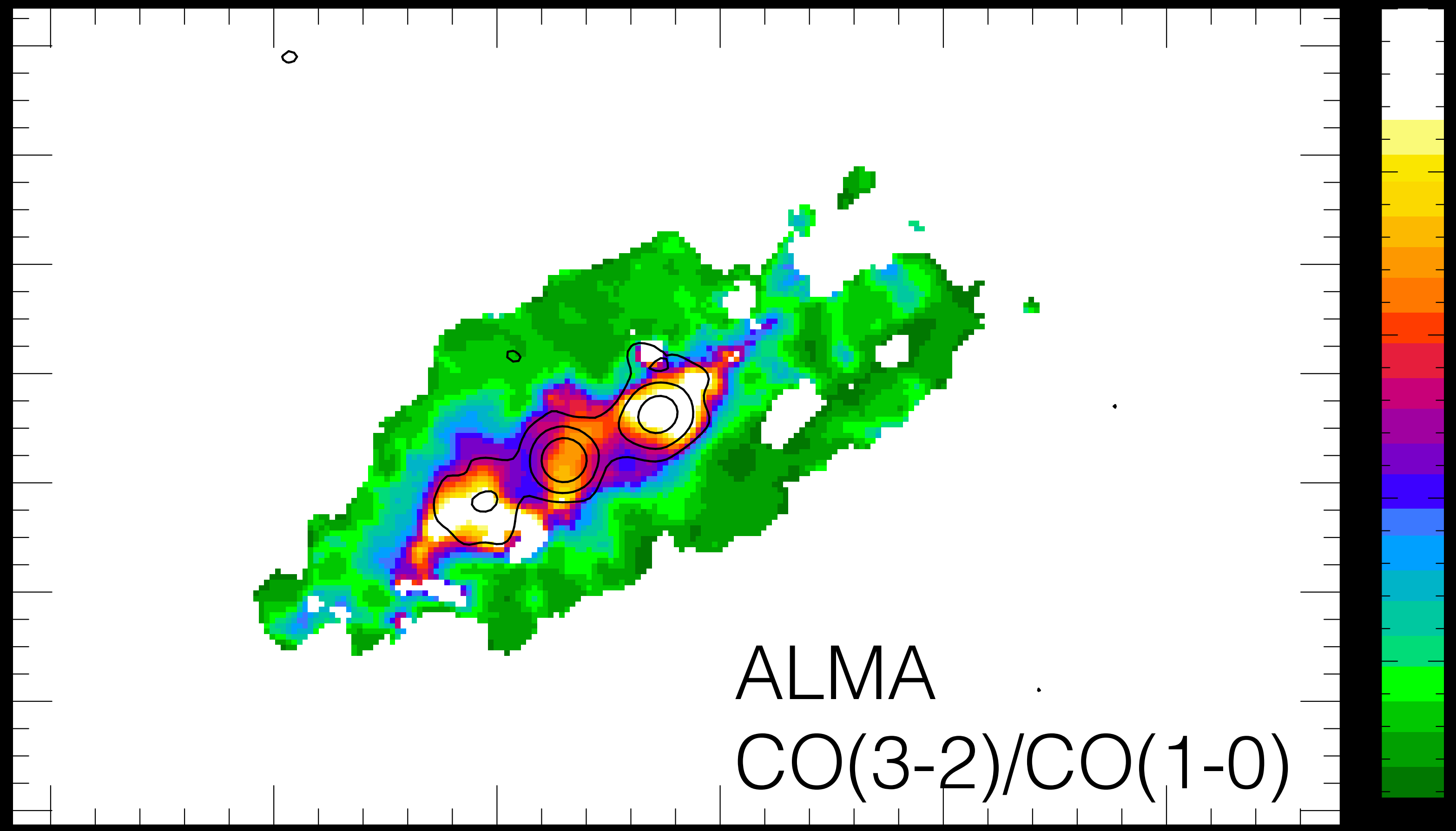
Best case illustrating
the effect of a new-born powerful radio jet

Radio power 10^{26} W/Hz



Morganti et al. 2015, Oosterloo et al. 2017

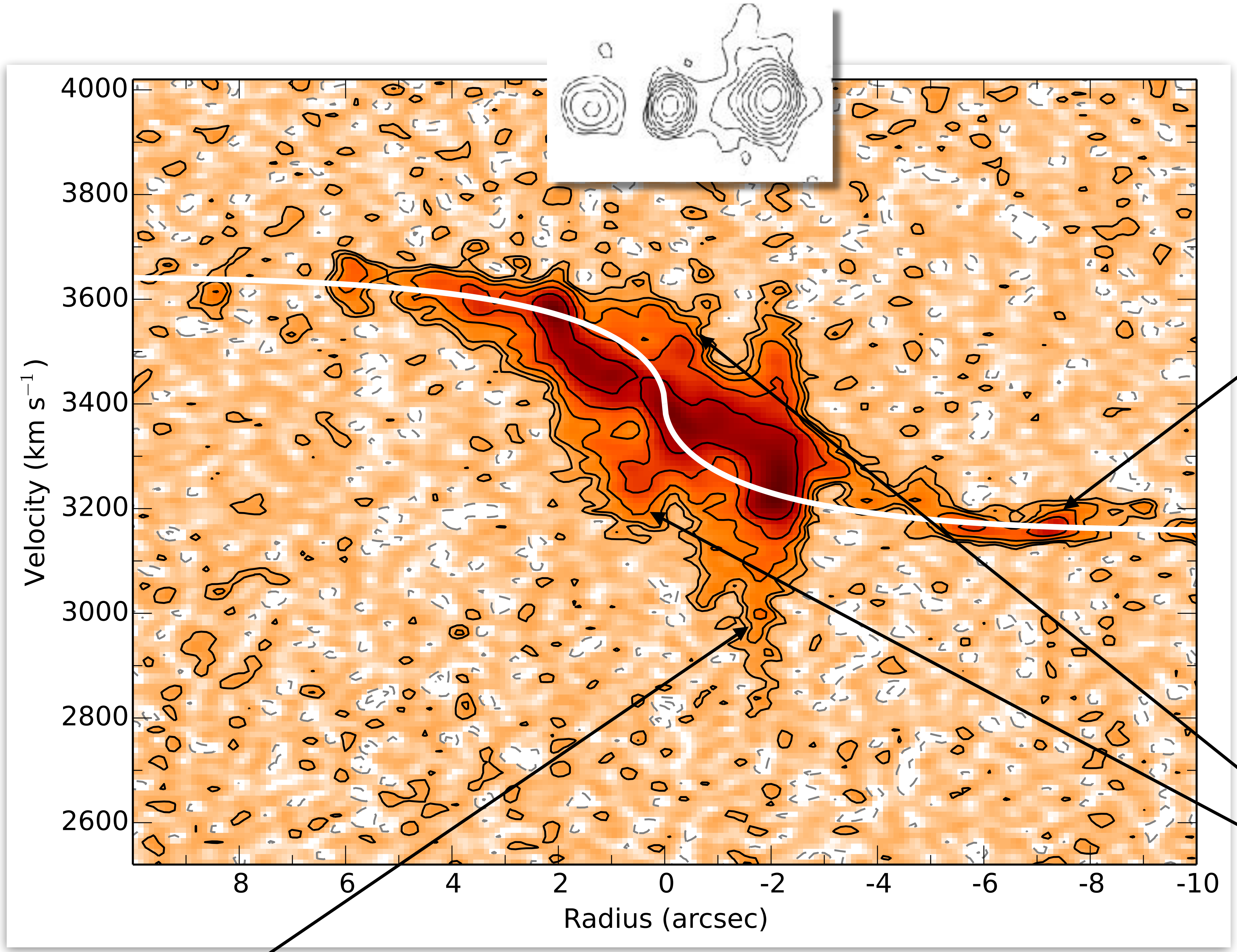
Best case illustrating
the effect of a radio jet



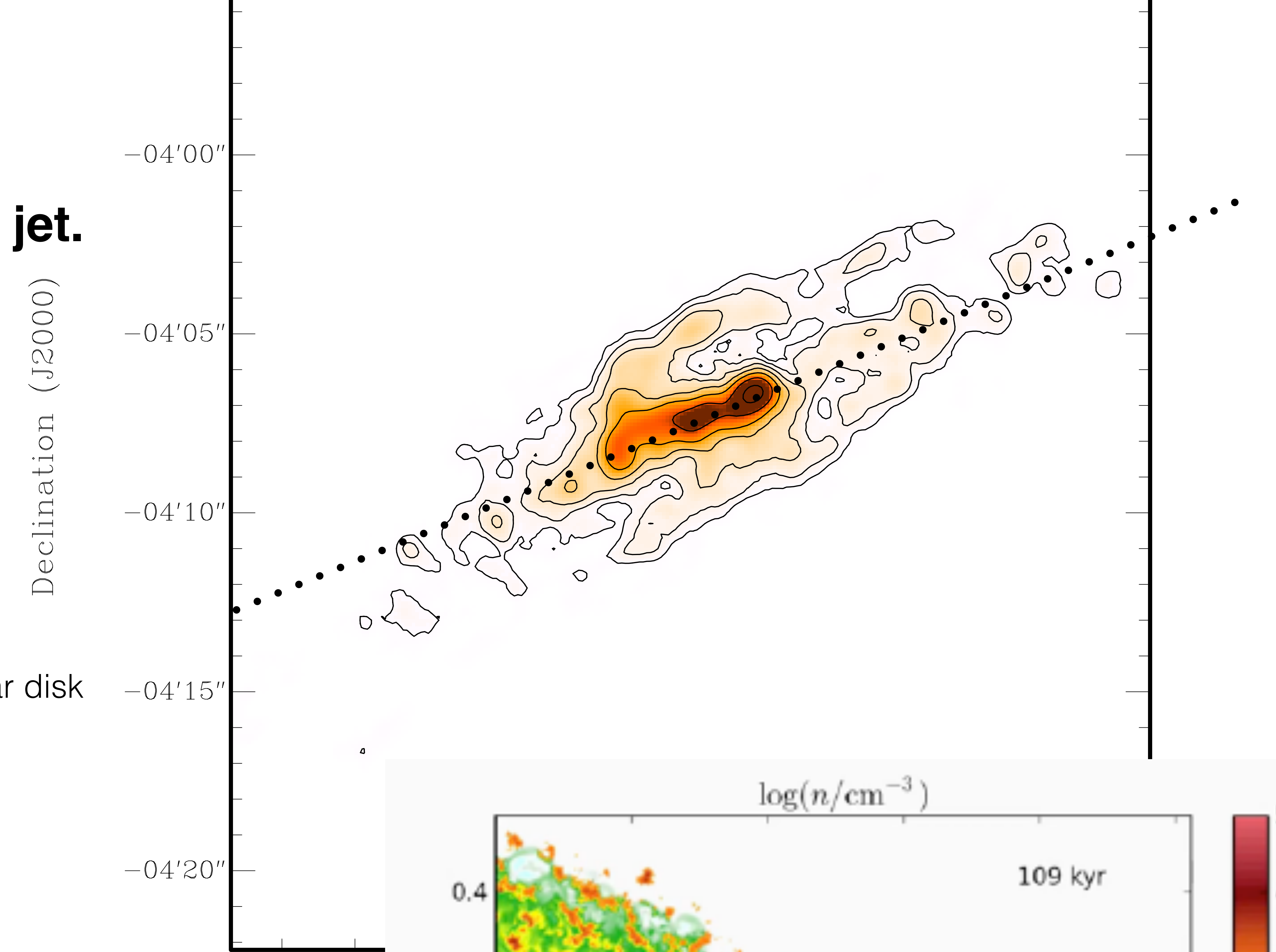
Radio power 10^{24} W/Hz

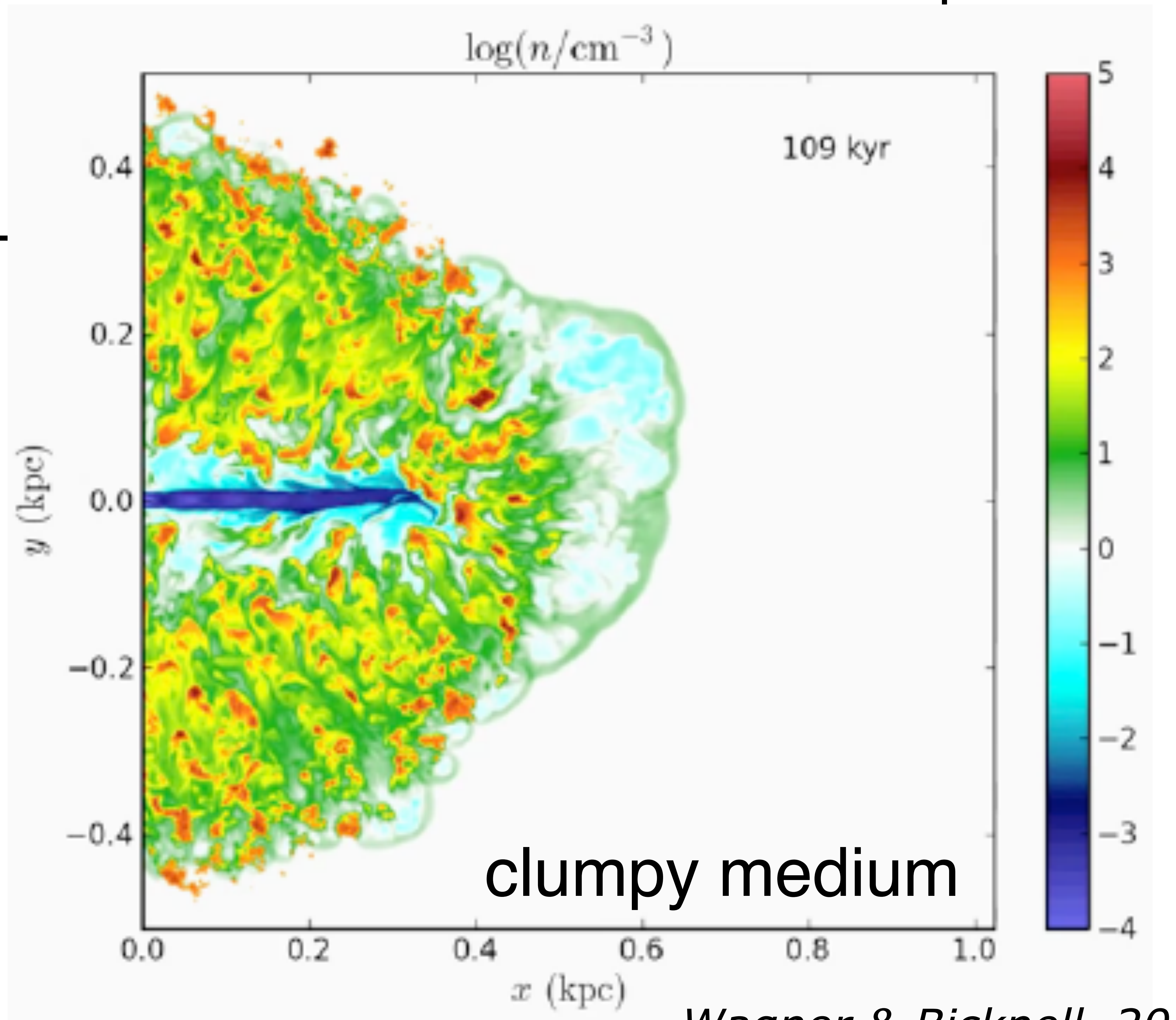
ALMA observations

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



pv diagram of CO(2-1)

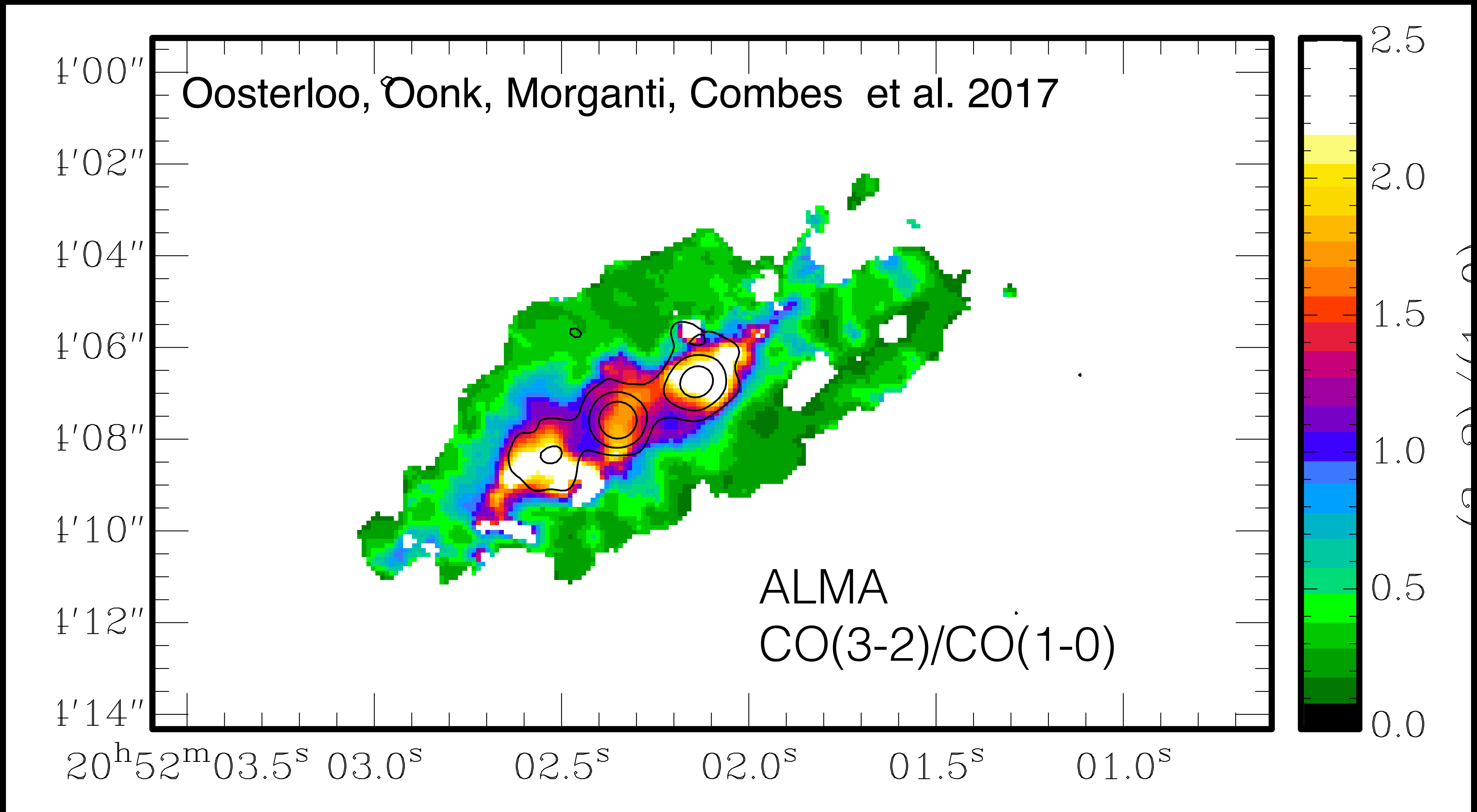




Morganti et al. 2015

Wagner & Bicknell 2012

Impact of the jet as seen by ALMA



Disturbed kinematics
AND
different conditions of the molecular gas
in the jet-affected regions.

Successful modelling as result of the
impact of the jet

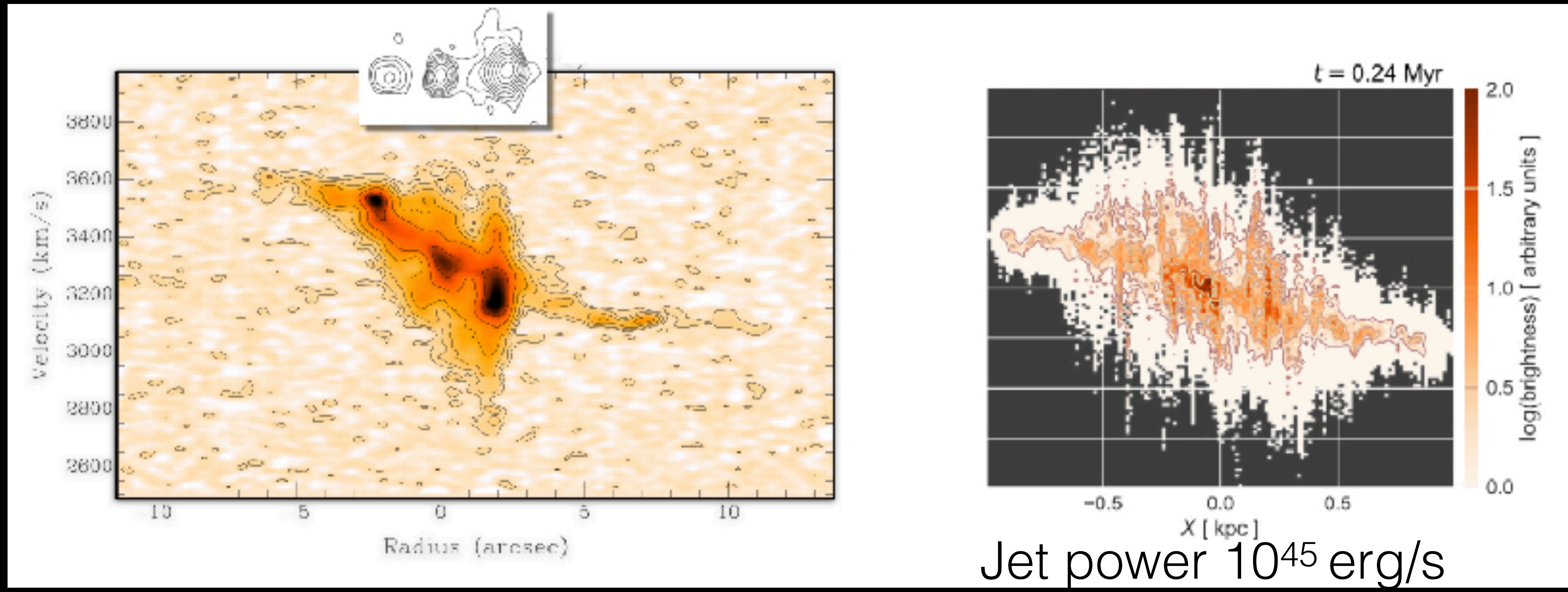
Highest ratios clearly associated with outflow
➔ gas must be optically thin

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

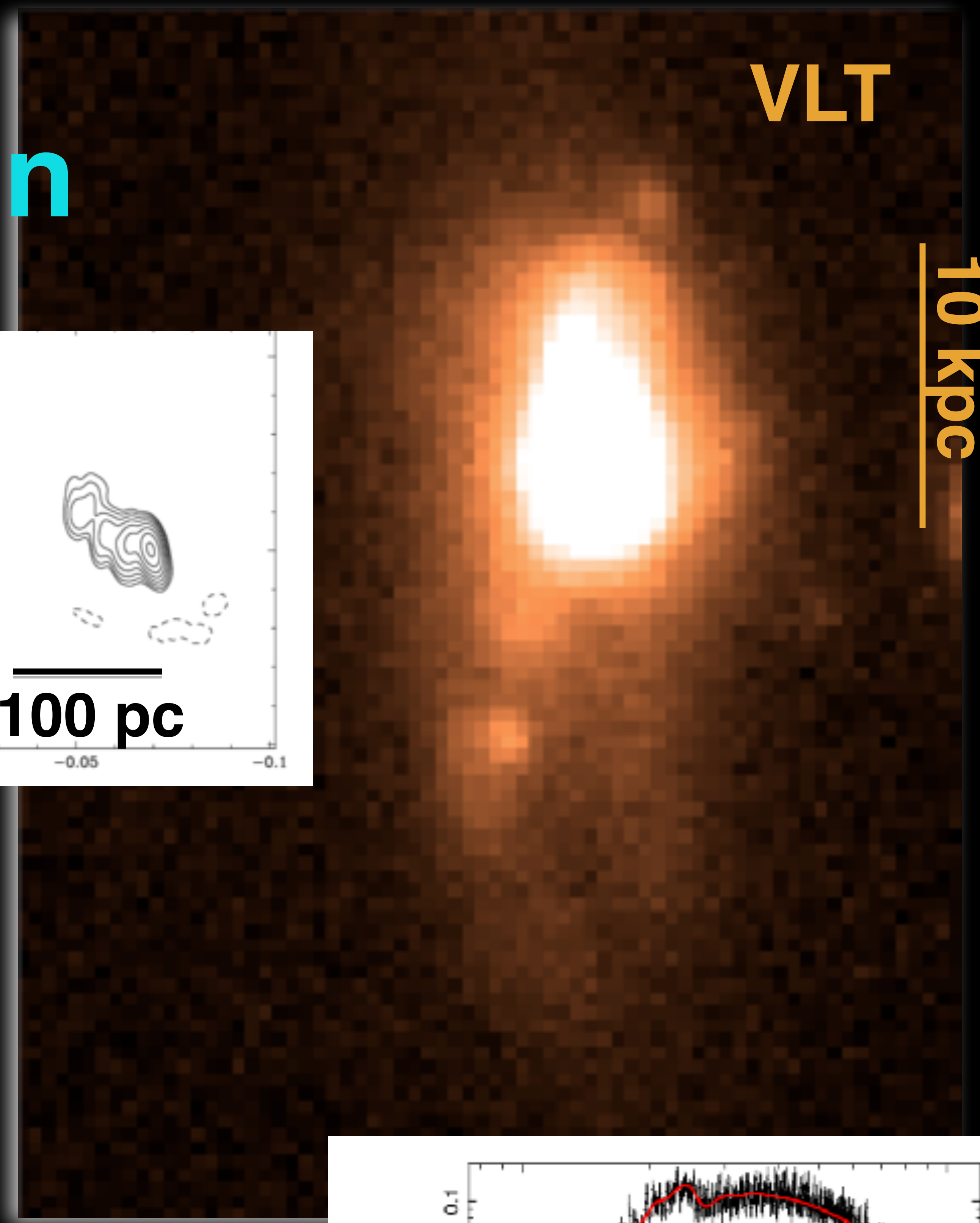
Significant impact of AGN feedback, but only in inner few kpc
Small fraction of the gas will leave the galaxy, main effect of the outflow:
redistribute the gas

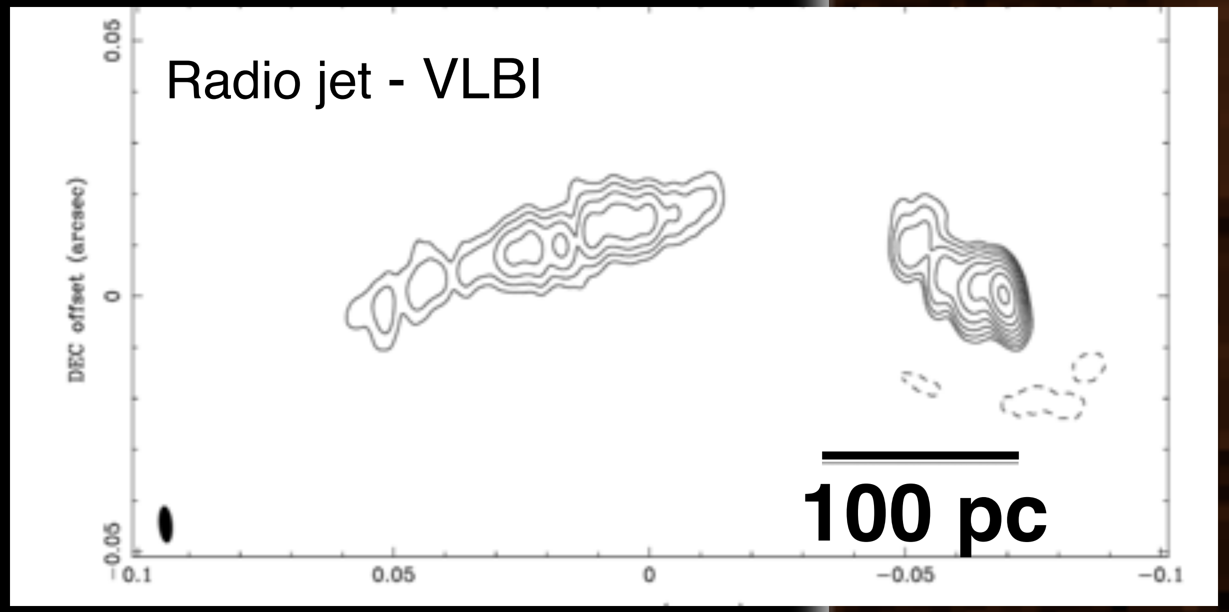
Position-velocity plot of the CO(3-2) ALMA data of IC5063
Data *Modelling*



Mukherjee, Wagner, Bicknell, Morganti et al. 2018

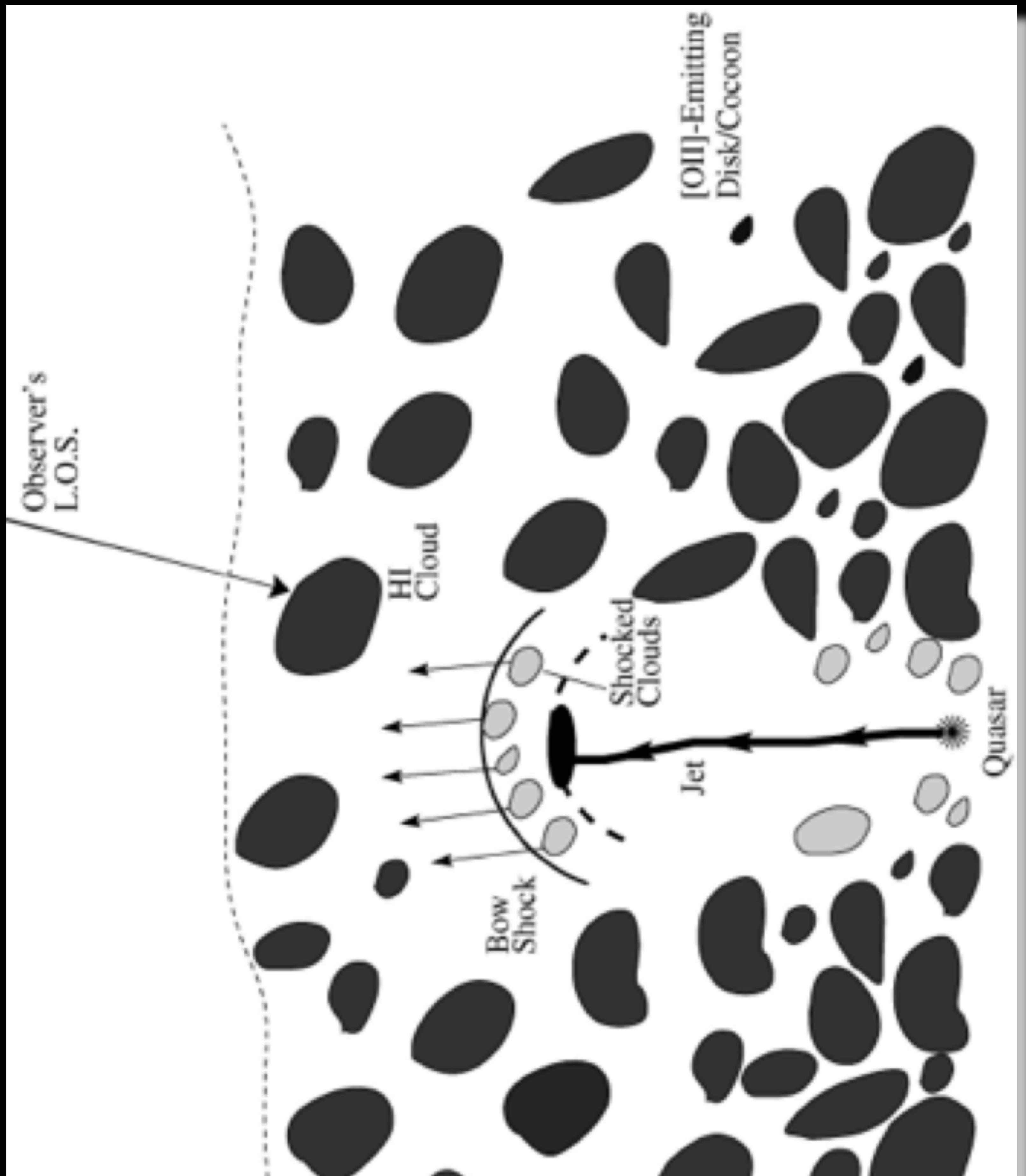
PKS 1549-79 quasar in the early stage of evolution



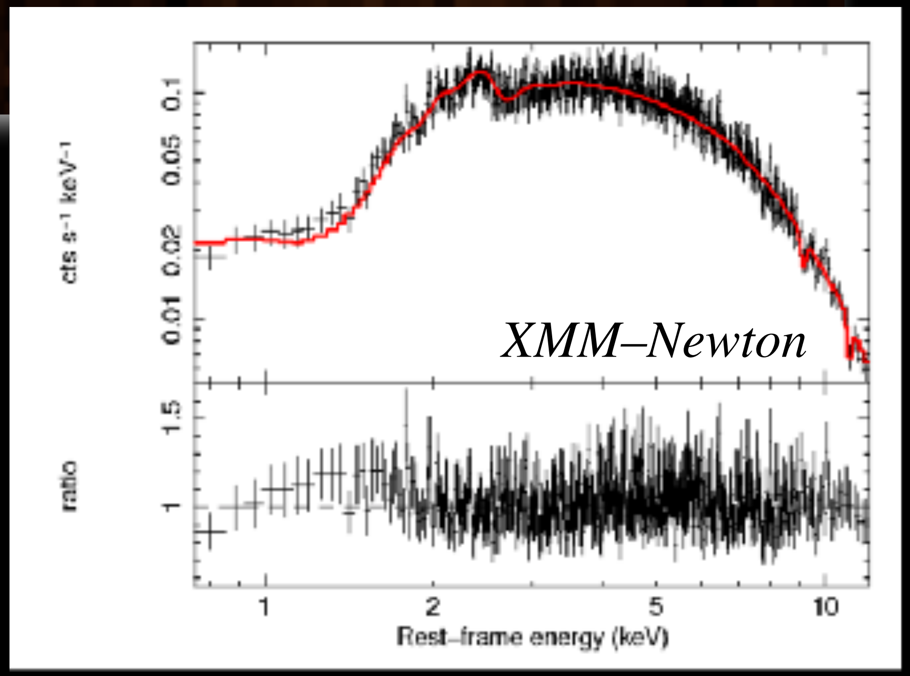


Newly born AGN in an ongoing merger: large cocoon of material still enshrouding the radio source.
Jet clearing the central regions

Holt et al. 2006



Broad, blueshifted optical lines,
high extinction, star formation
Xray UltraFastOutflow (Tombesi et al. 2013), ~0.2c

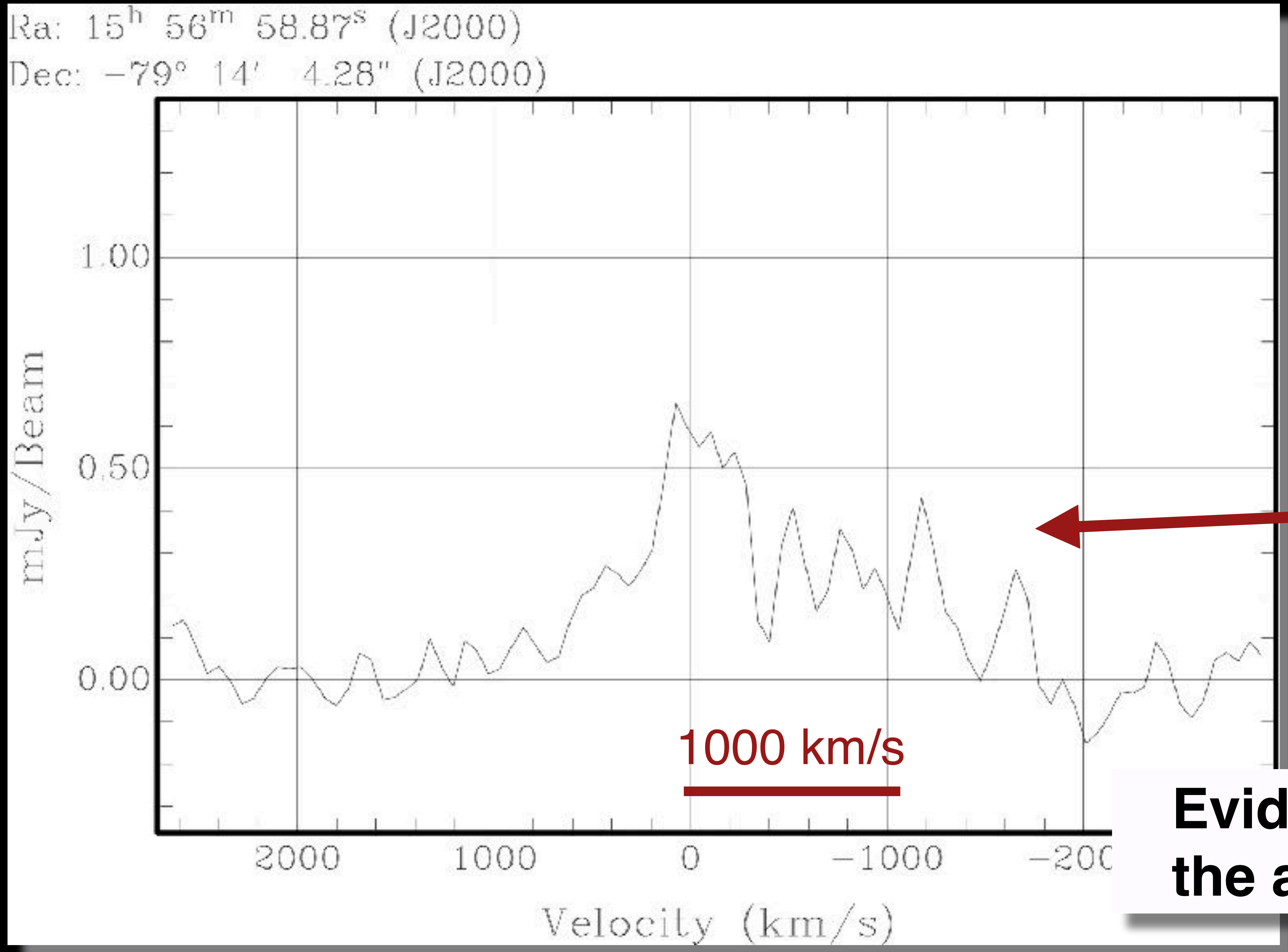


Crucial stage in the evolution, feedback should be at work

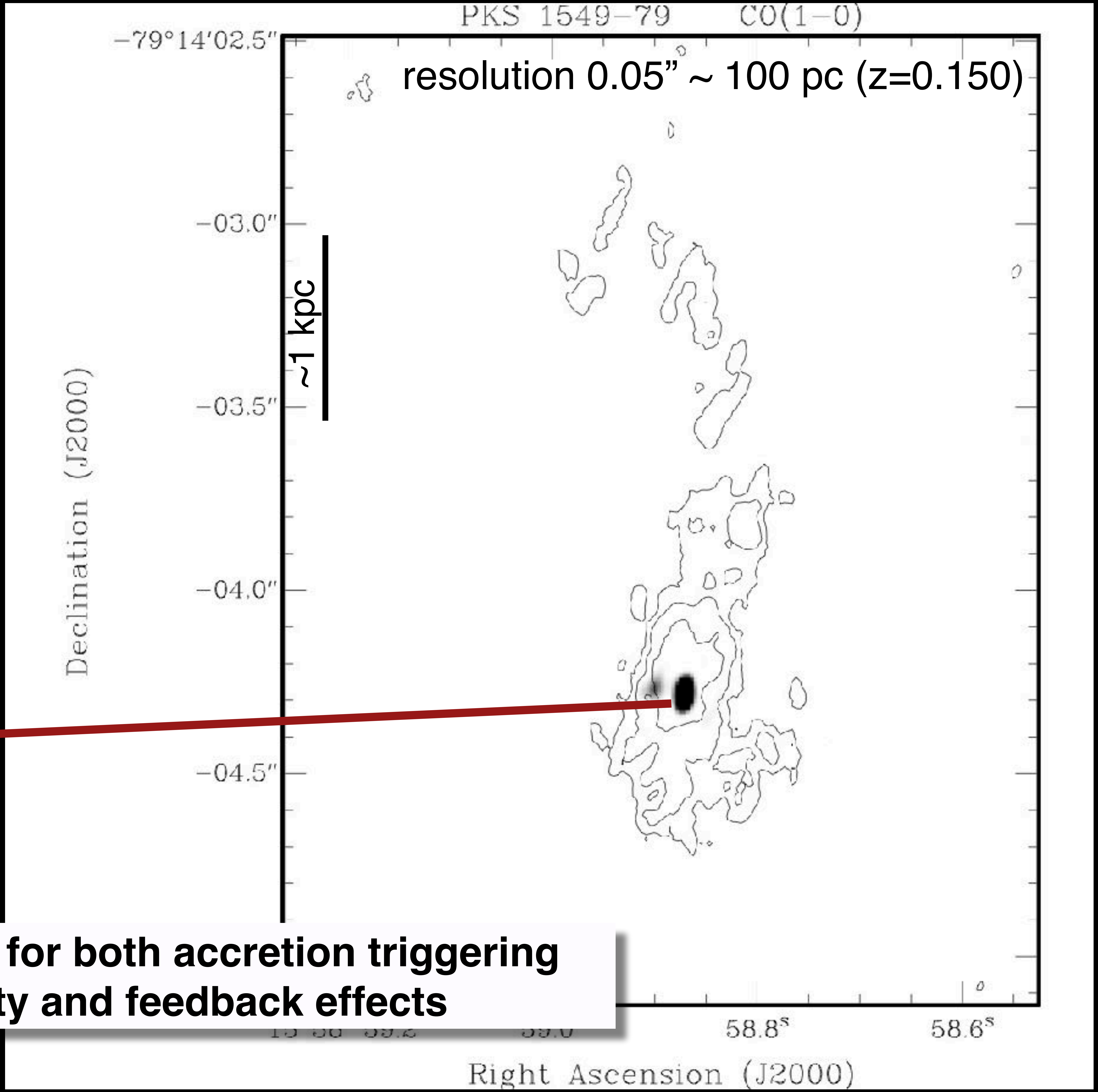
But outflow rate low compared to requirements from cosmological simulations.

PKS 1549-79 quasar in the early stage of evolution

ALMA CO(1-0) detected in emission
Large tail AND fast outflow



Oosterloo, Morganti et al. in prep

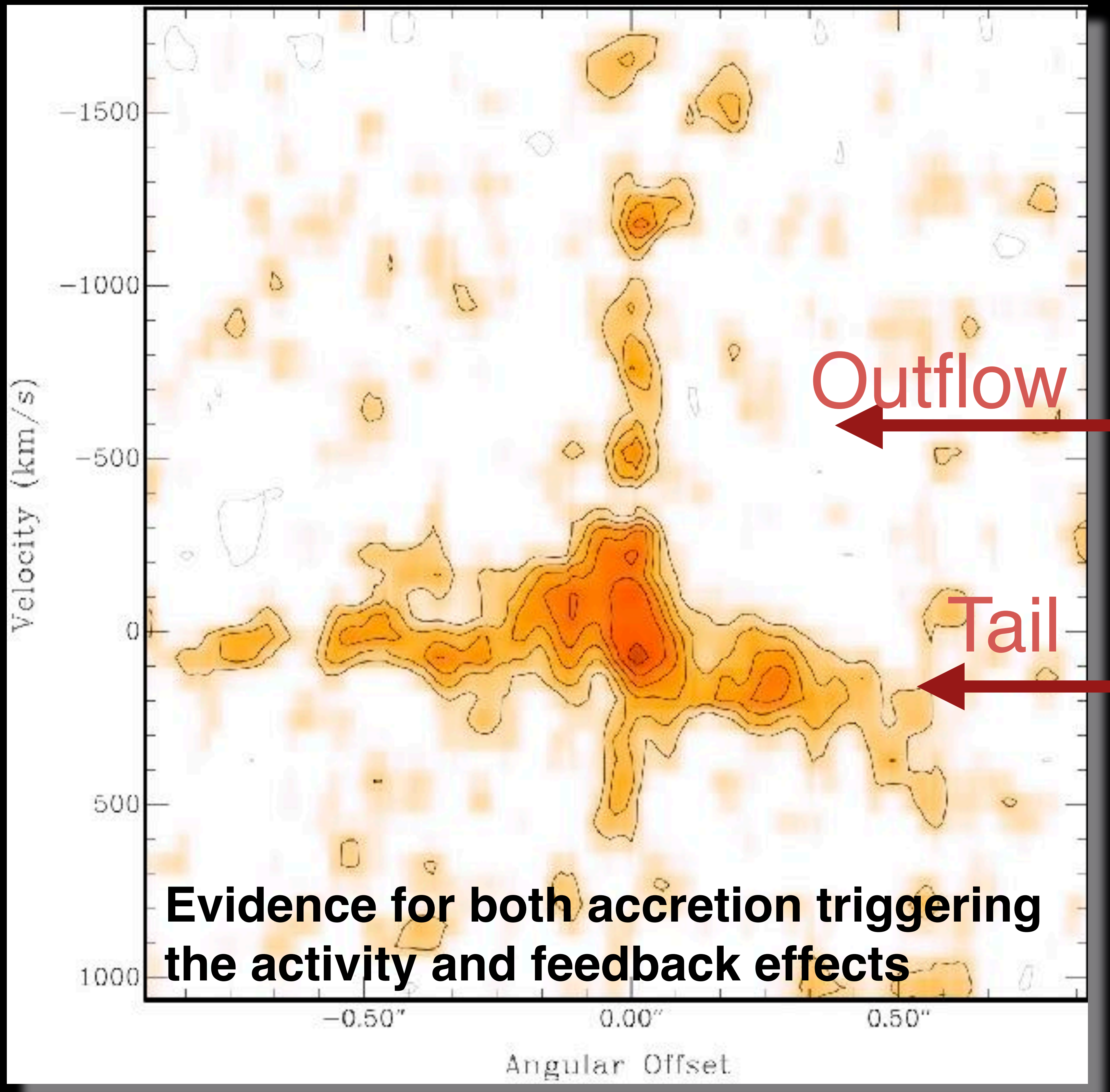


Evidence for both accretion triggering the activity and feedback effects

PKS 1549-79 quasar in the early stage of evolution

Large molecular outflow already in the central regions (<100 pc) ➜ ~100 M⊙/yr

Much higher than in more evolved radio galaxies: enough to produce the expected feedback effects? (more data to come CO(3-2))



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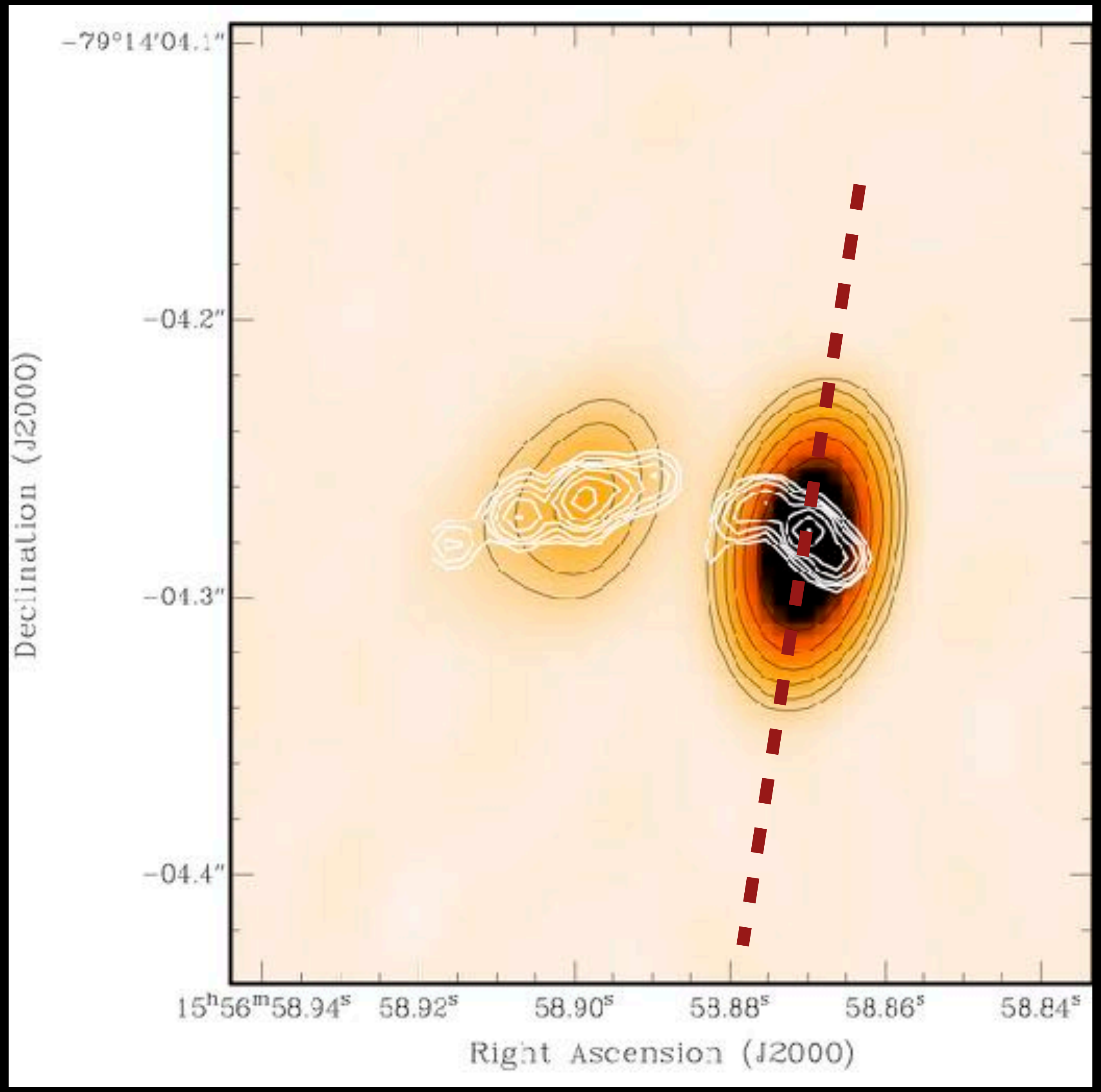
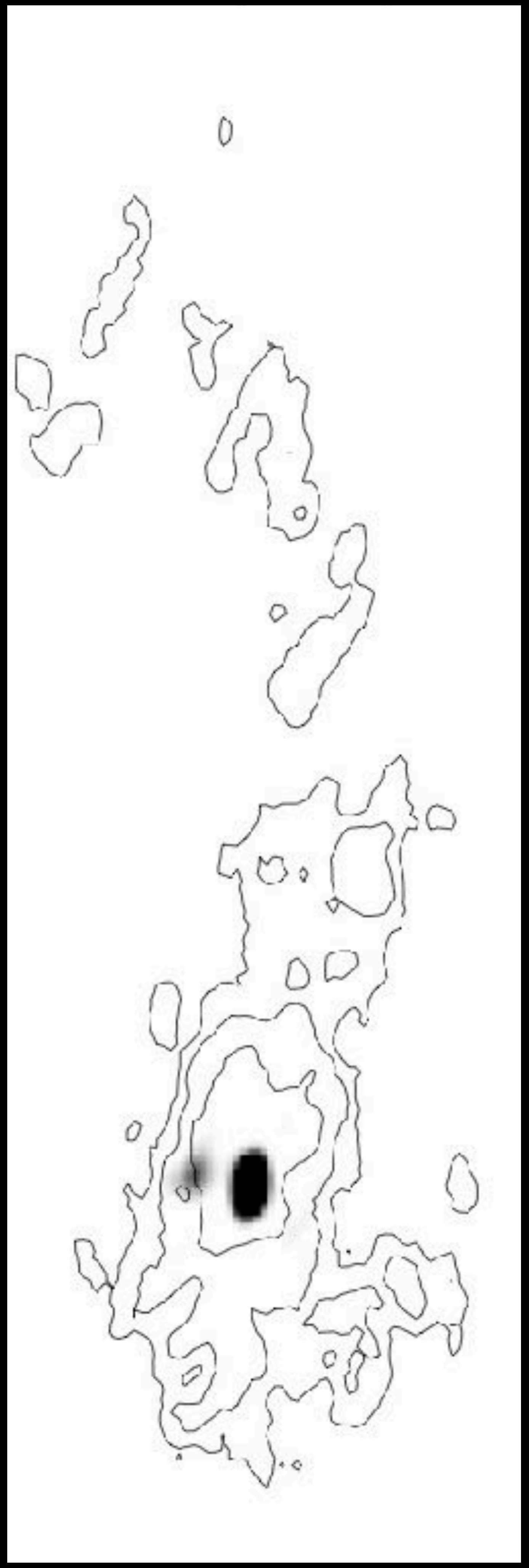




In agreement with simulations: a more powerful source (like PKS1549-79) has a faster/more massive outflow (compared to IC5063)

What have we learned so far about the impact of radio jets

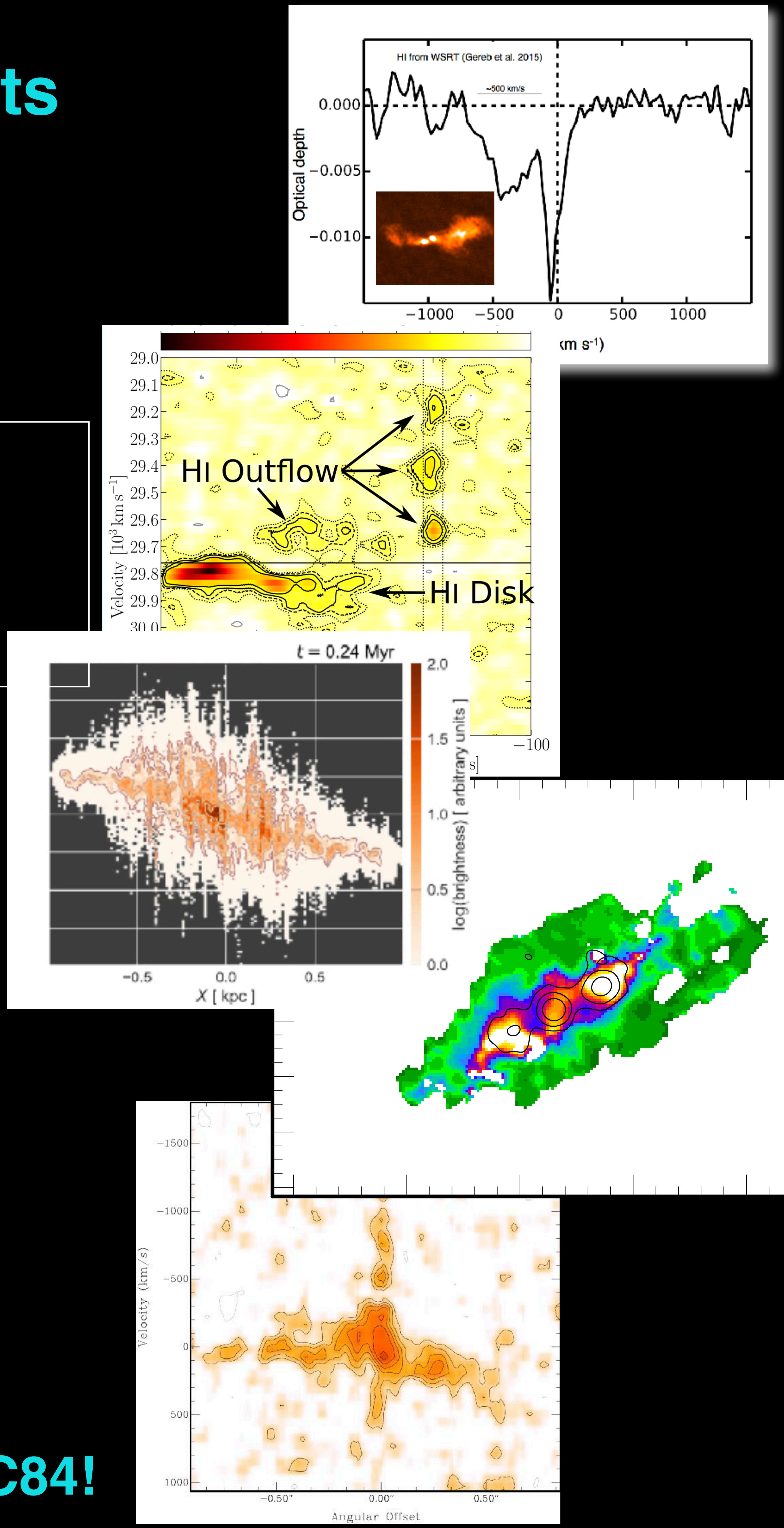
HI and molecular outflows common in young and restarted radio galaxies suggesting a piling up of gas in the centre and the jet clearing it: jets couple well with ISM

Follow up of HI and molecular outflows with high spatial resolution: to first order confirming the predictions of the simulations
➜ the exploration of the parameter space has just started!

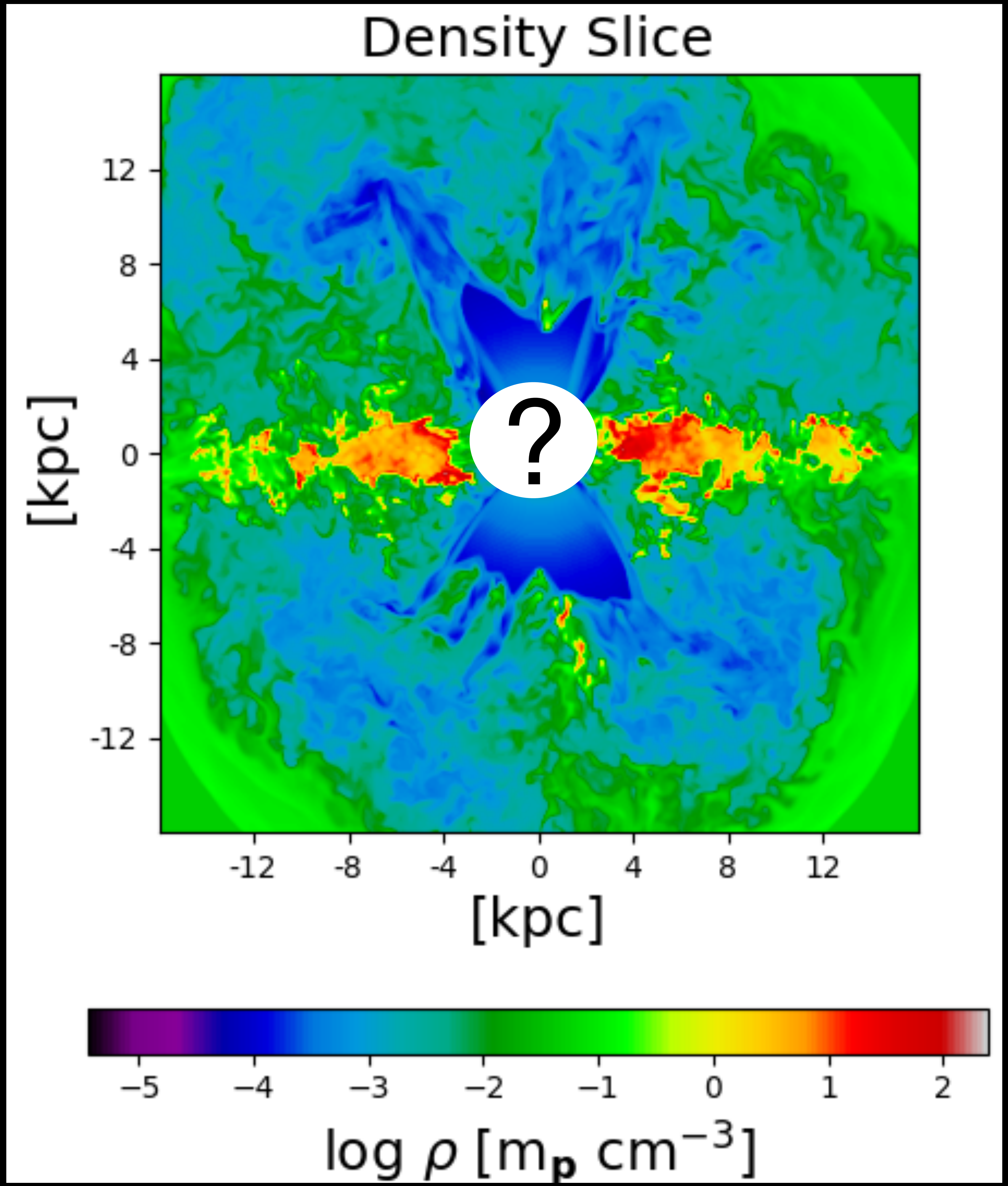
- Clumpy medium seen by HI VLBI image and derived from multiple CO transitions (IC5063)
- Conditions of outflows changing as radio source evolves

- Simulations can explain the kinematics of the molecular gas in IC5063
- Jet affects the kinematics but also the conditions of the gas

- First order trend with jet power: the mass outflow rate is not the only important parameter ➜ inject energy (prevent cooling) and redistribute the gas



The cases explored so far are field galaxies, next goal is to address also cluster galaxies, e.g. 3C84!



Adapted from Dugan

Gas outflows: one of the effects of the energy released by the AGN

Open questions:

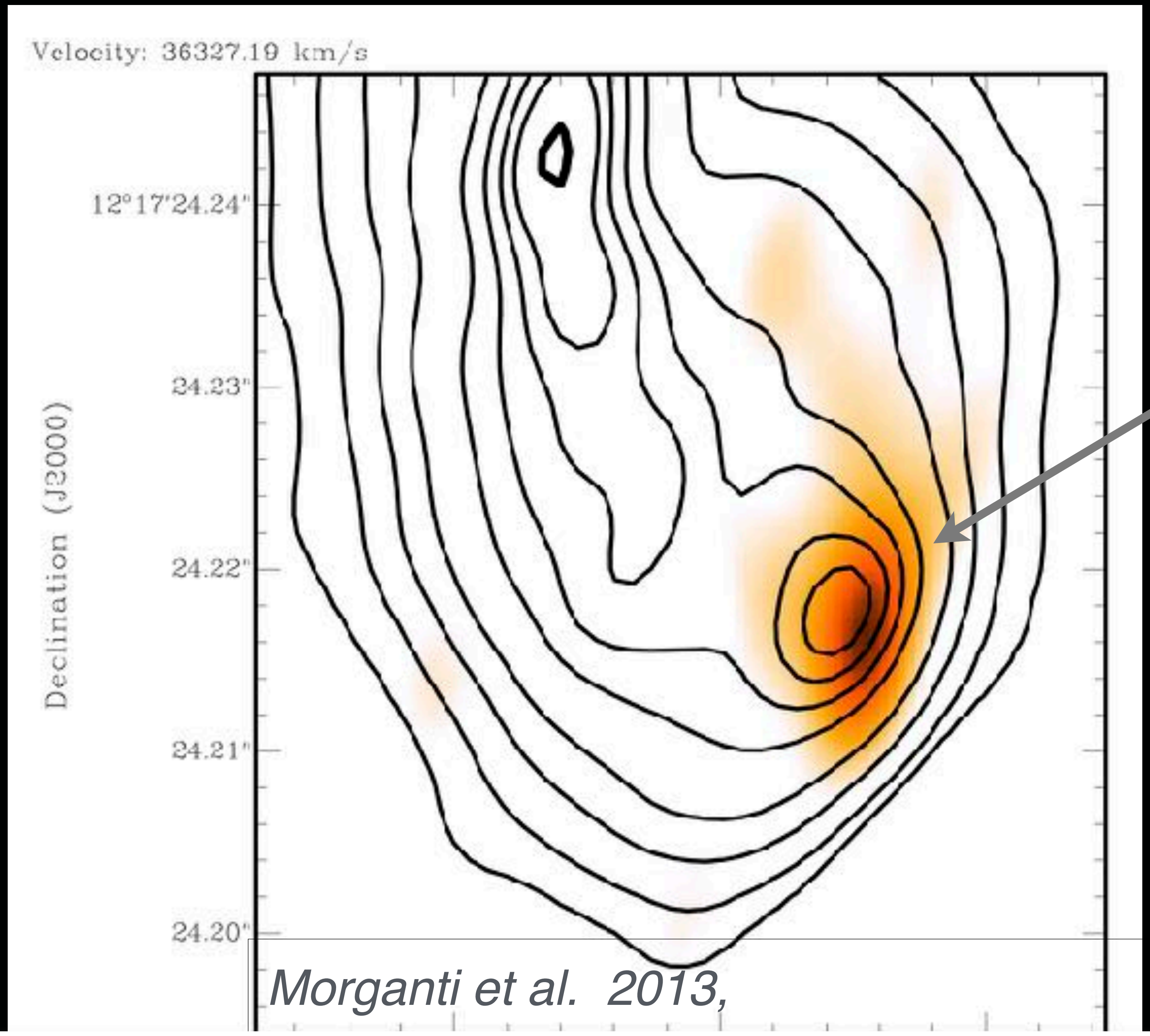
- occurrence of outflows (common? In which type of AGN?)
- long or short duration?
- driving mechanisms? **thermal, radiation, mechanical (jets)**
- location and extent **coincident with bright radio features?**
- physical parameters: velocity, energy, mass, mass outflow rate, structure (diffuse, clumpy?) etc.

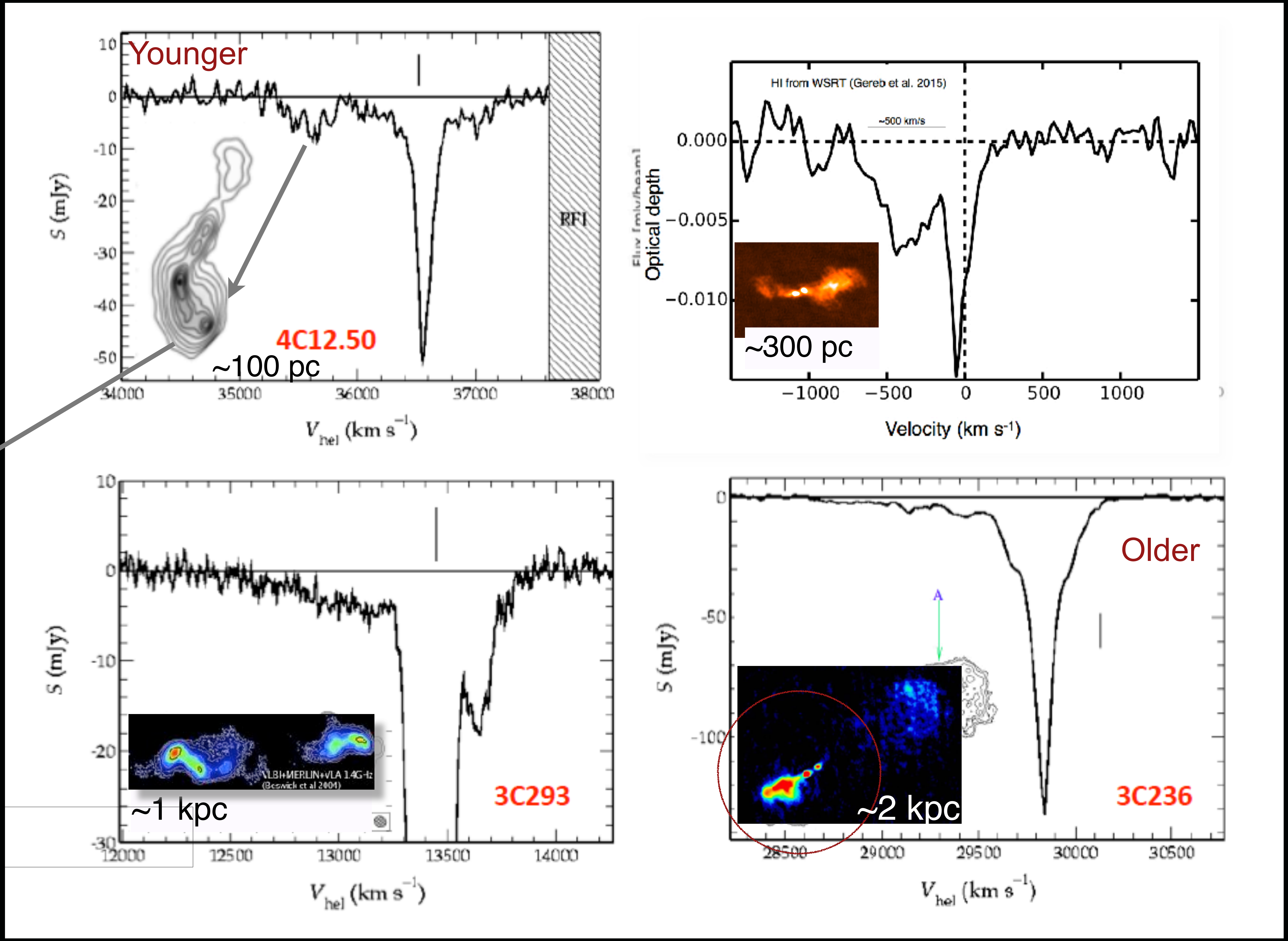
Our goals: **characterise the effects of radio jets using outflows of cold (HI and molecular) gas**

Molecular gas to complete the picture: most massive phase in outflow!
But also tracing different distance from BH compared to ionised (e.g. UFO!)

Evolution in the characteristics of the outflows?

Tracing the HI outflows in young radio sources: evolution of the outflow as the source grows?





Mass of the clouds ~10^4 $M_\odot$

- Mass outflow rate HI ~ 10-20 $M_\odot$/yr
- Kinetic energy flux ~10^{42} erg s^{-1}
- Eddington luminosity $\dot{E}_{kin}/L_{edd}$ ~10^{-4} (few x 10^{-3} L_{boll}
- Mass outflow rate ionised gas ~ 3 $M_\odot$/yr

VLBI project - in progress, Schulz,RM et al.

More transitions:
ALMA observations: CO(1-0), CO(2-1), CO(3-2), 13CO(2-1), HCO+(4-3)

CO(1-0)

CO(2-1)

CO(3-2)

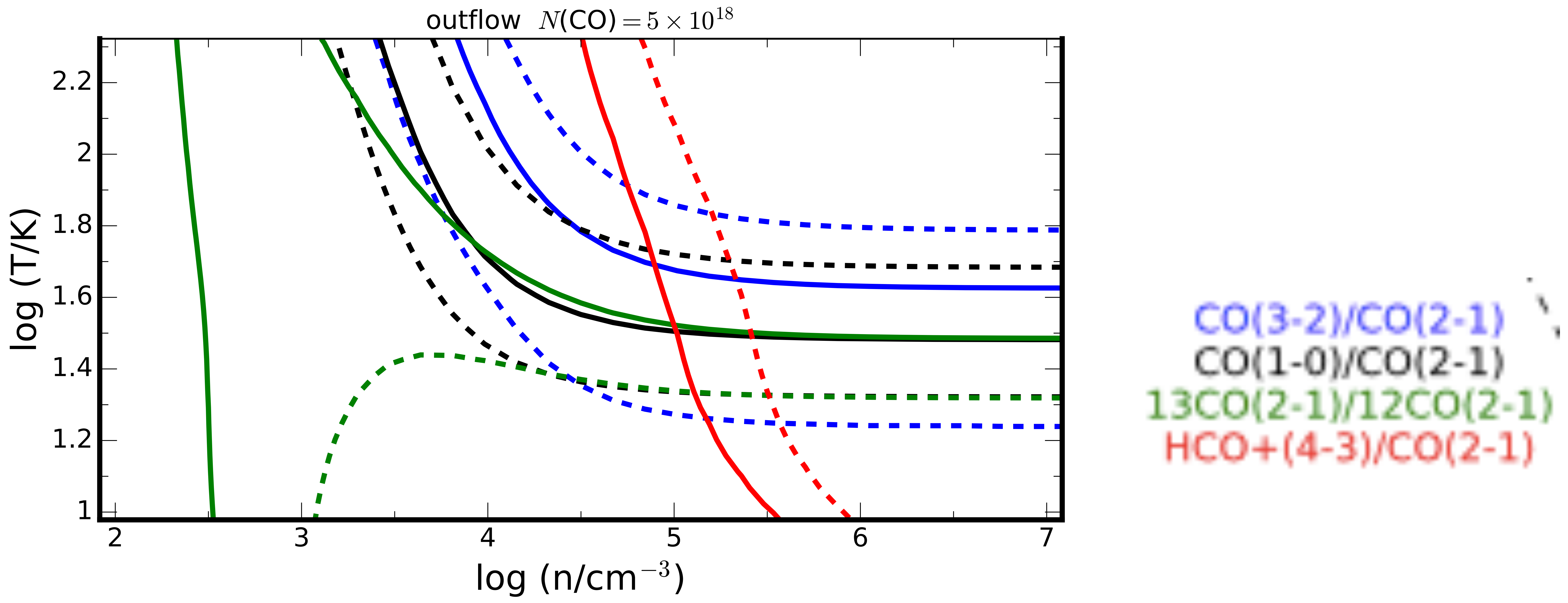
Total intensity images. All panels have the same scaling in K km/s
Clear difference in excitation between jet region and outer disk

Oosterloo et al. 2017

Can do more: RADEX models (non-LTE radiative transfer code; van der Tak+ 2007) to obtain kinetic temperatures and densities

Best results for column density much higher than what observed: clumpy medium!!!

Oosterloo et al. 2017



Kinetic temperatures in the range 20–100 K and densities between 10^5 and 10^6 cm^{-3}.

The resulting pressures are two orders of magnitude higher than in the outer quiescent disk. gas is very clumpy.

The highest pressures are found in the regions with the fastest outflow.