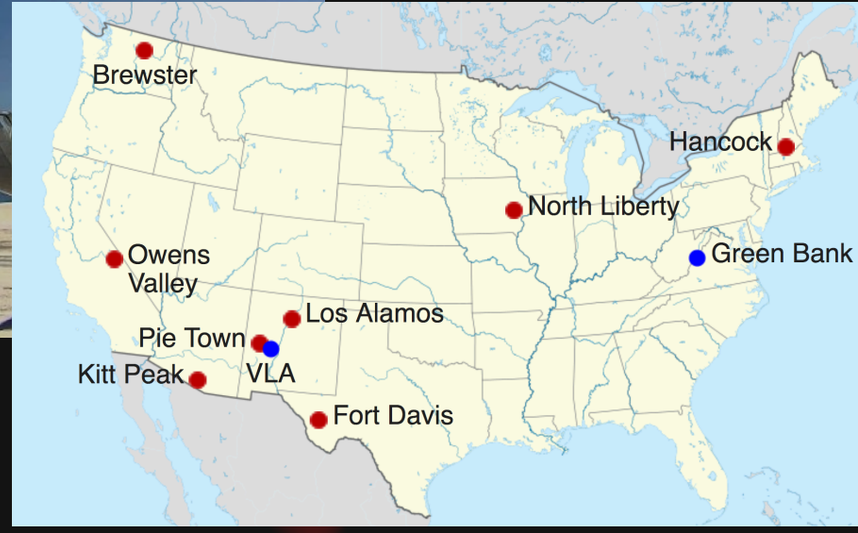


FEEDBACK FROM RADIO AGN

THE CASE OF 4C 31.04

SUMA MURTHY

JIVE
Joint Institute for VLBI ERIC

RAFFAELLA MORGANTI
ZSOLT PARAGI
TOM OOSTERLOO
ROBERT SCHULZ …

AGN – HOST GALAXY INTERPLAY

Gas accretion on to the SMBH (feeding)

↓

AGN

↓

Host galaxy evolution (AGN feedback)

The galactic scale impact of radio jets ignored!

AGN feedback in models of galaxy evolution

Quasar mode

Maintenance mode

Radio AGN prevent the cooling of IGM

These are rare!

GALACTIC-SCALE IMPACT OF RADIO JETS

- Jet-ISM interaction more common

  e.g. Maccagni et al. 2017, Gupta et al. 2006

- Turbulence, multi-phase outflows

  e.g. Zovaro et al 2019, Santoro et al. 2020, Molyneux et al. 2019, Venturi et al. 2021

Cold gas is affected significantly!

e.g. Alatalo et al. 2015, Feruglio et al. 2015, Oosterloo et al. 2018, Morganti et al. 2021, Murthy et al. 2022

THEORETICAL STUDIES OF GALACTIC-SCALE IMPACT OF RADIO JETS

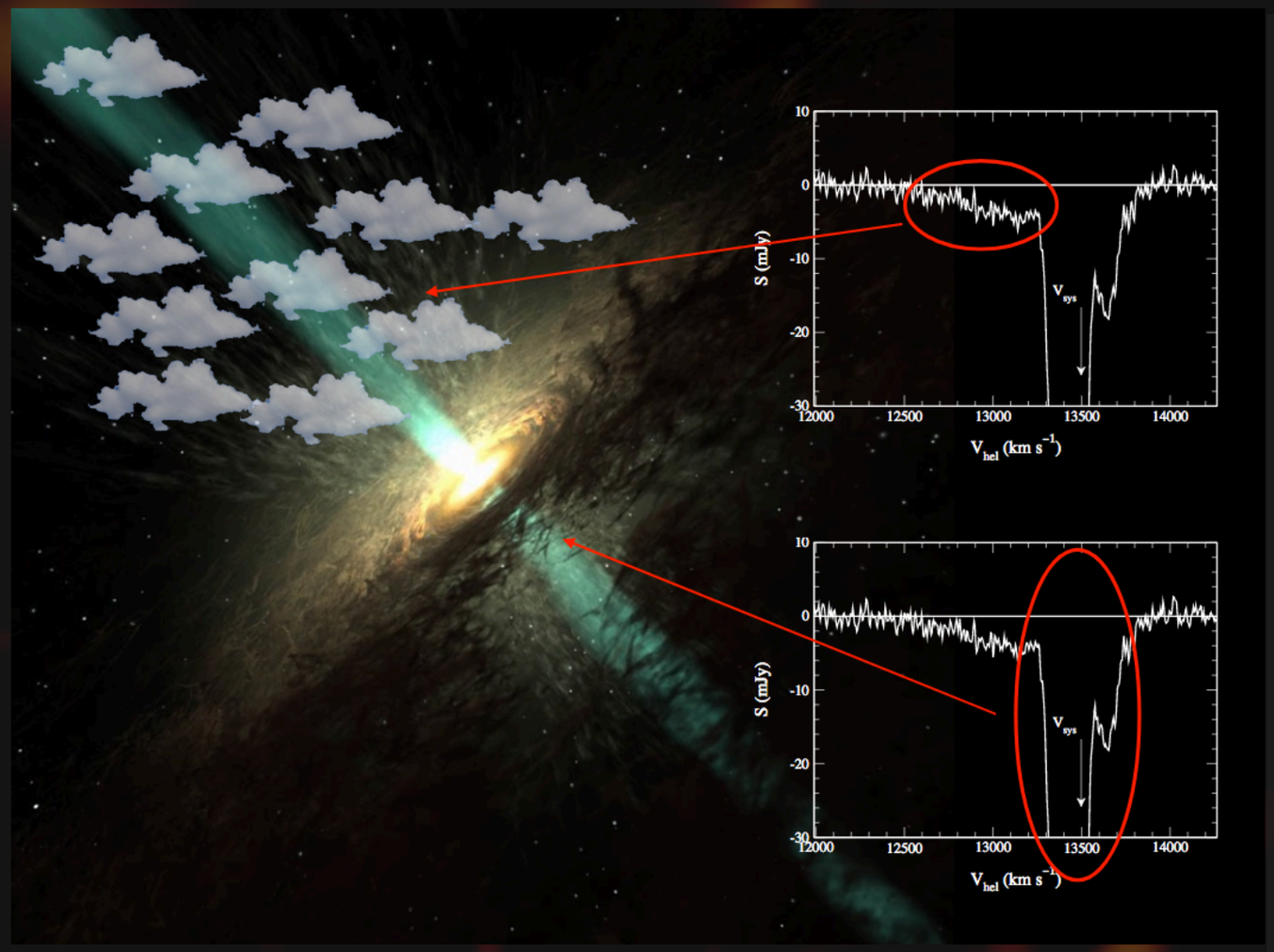
- Impact depends on:
  - Clumpy gas distribution
  - Radio power, age, morphology

e.g. Bicknell et al. 2007, Wagner et al. 2012, Mukherjee et al. 2016,2018

For atomic gas, relevant spatial scales achieved only with VLBI

NEUTRAL ATOMIC GAS

traced via HI 21-cm absorption



Morganti & Oosterloo, 2018

Can go to **high spatial resolution** and redshifts

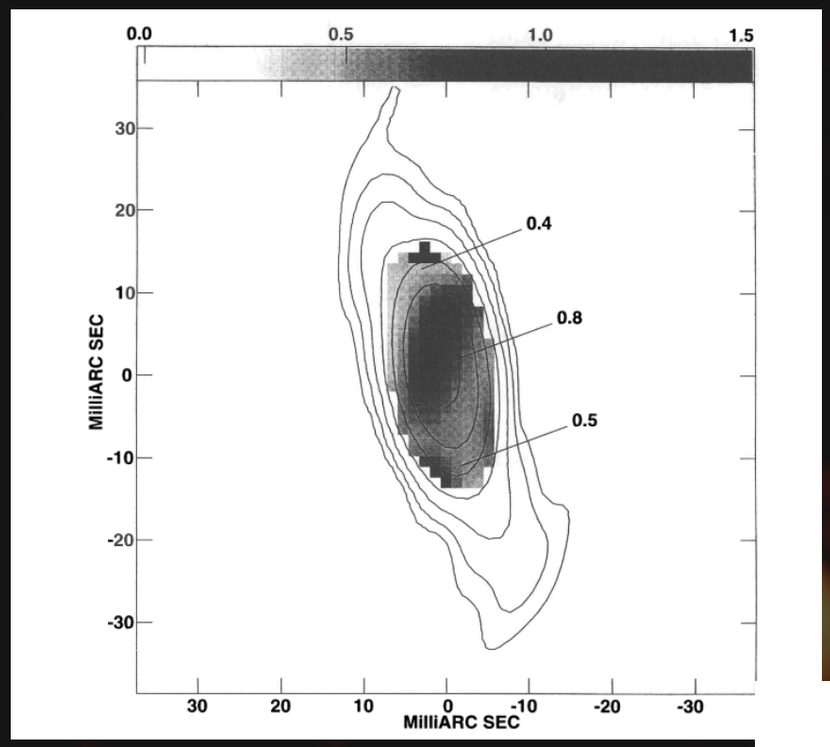
Easier to constrain the kinematics

Complements emission studies at other wavelengths providing better constraints.

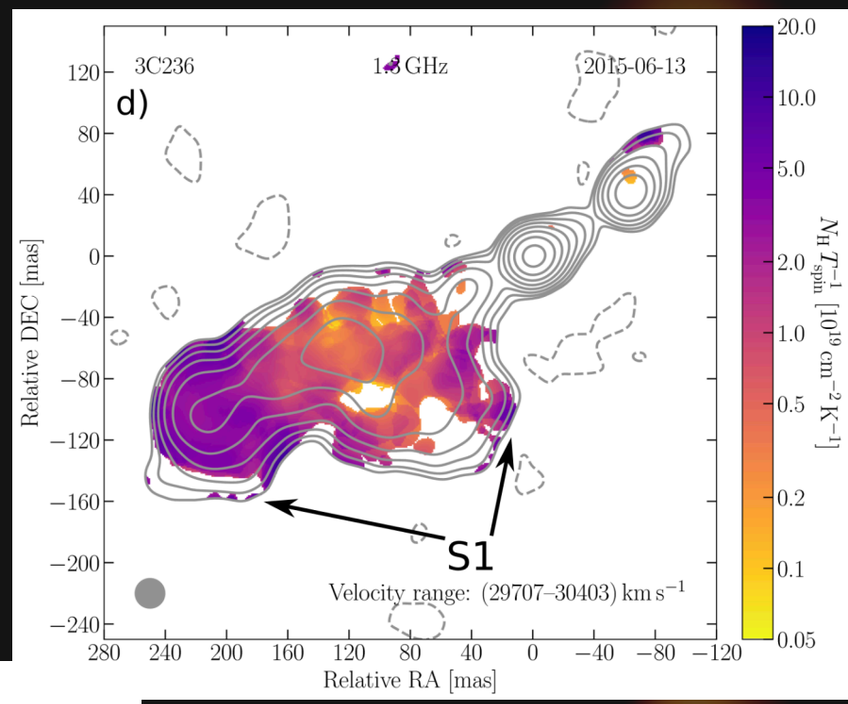
ATOMIC GAS AT PARSEC SCALES

CIRCUMNUCLEAR DISCS

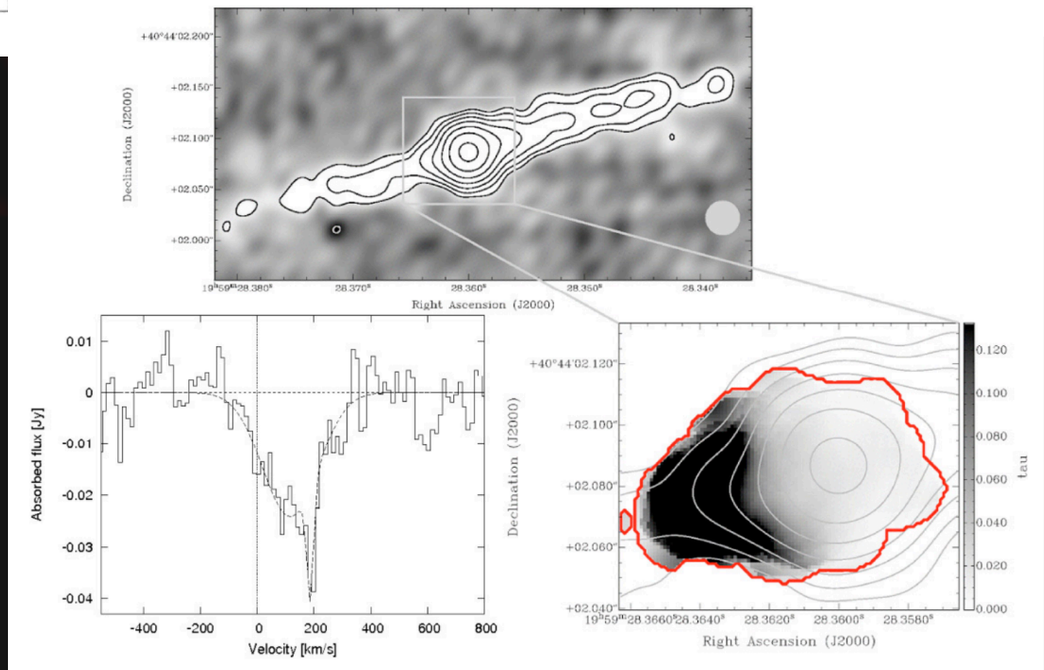
Hydra A: Taylor et al. 1996



3C 236: Schulz et al. 2018

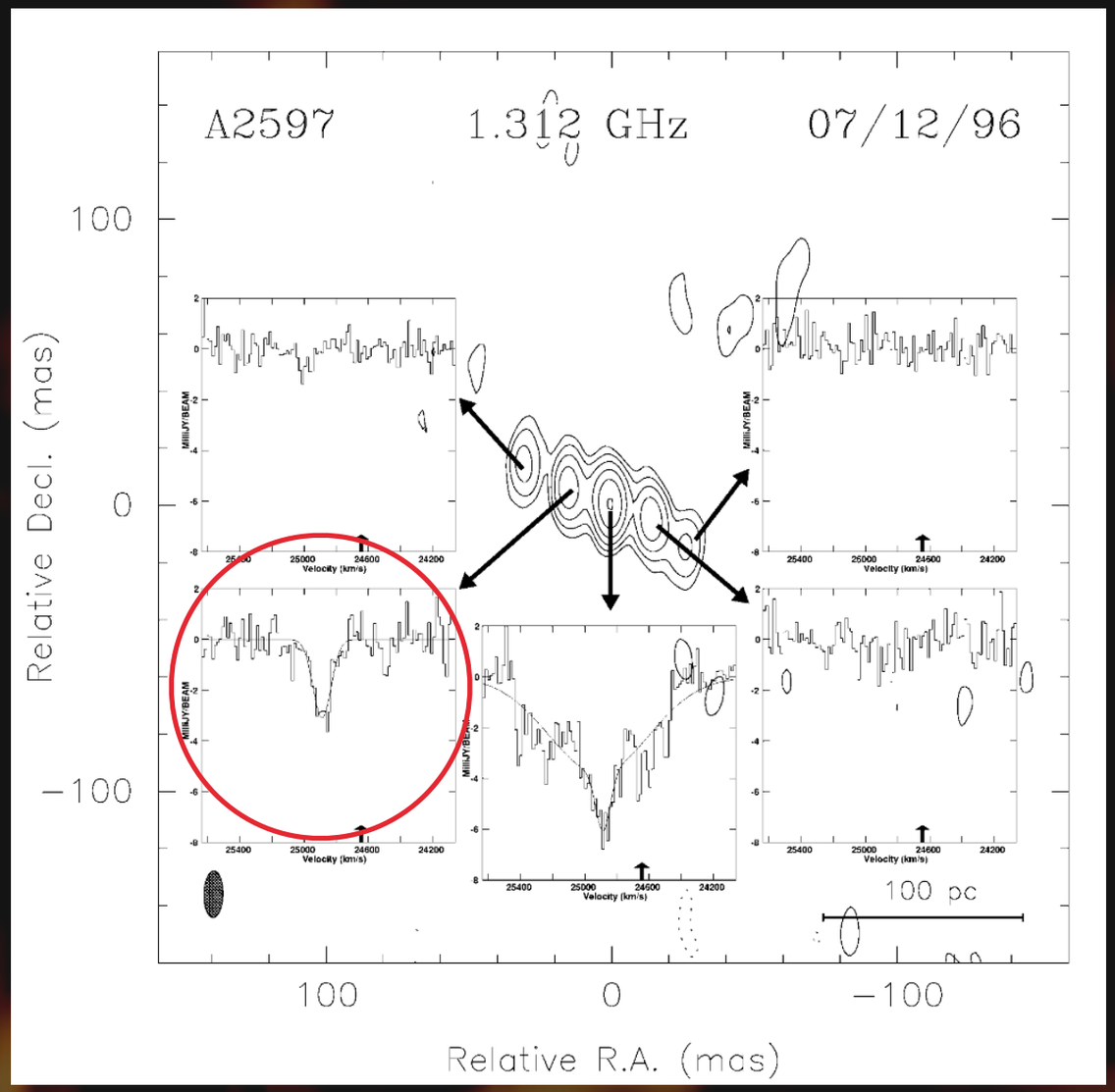


Cygnus A: Struve & Conway, 2010



ATOMIC GAS AT PARSEC SCALES

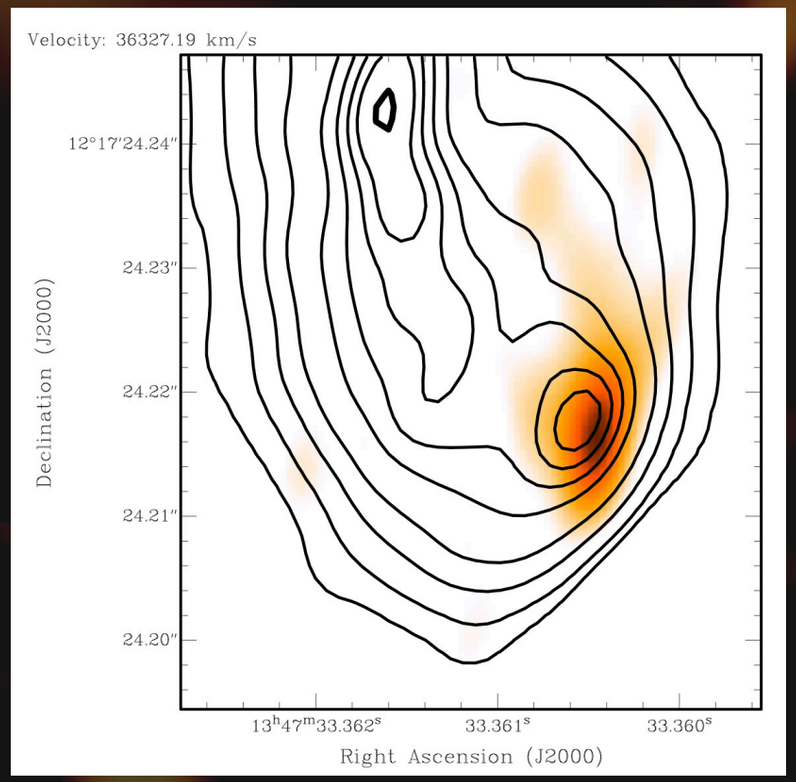
INFALLING GAS



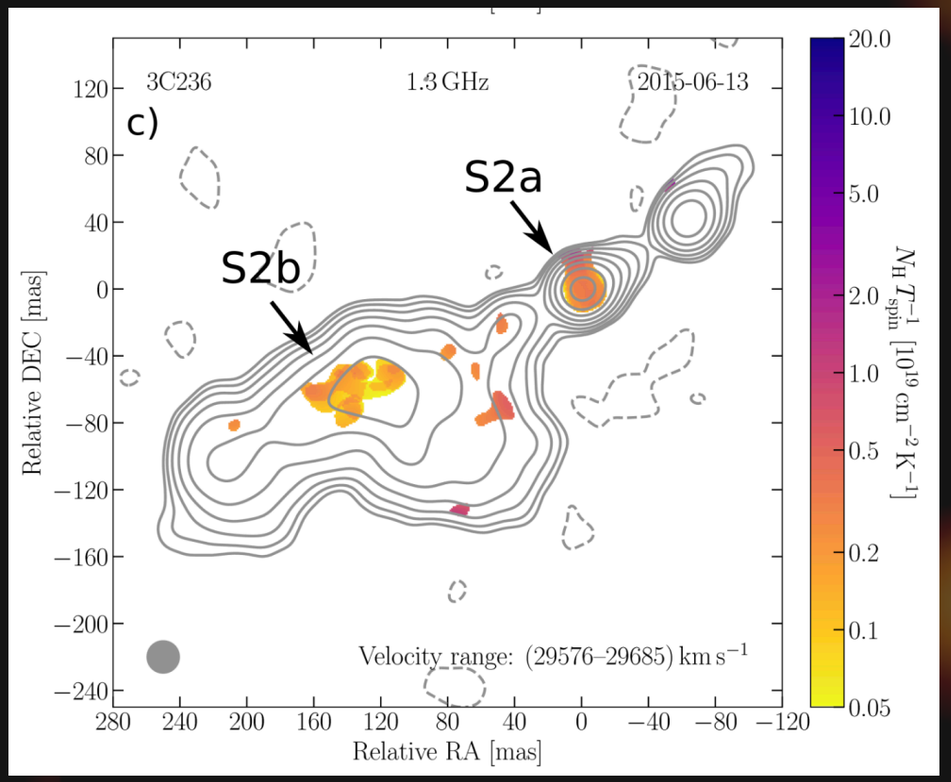
PKS 2322-123: Taylor et al. 1999

ATOMIC GAS AT PARSEC SCALES

OUTFLOWING (CLUMPY) GAS CLOUDS



4C 12.50: Morganti et al. 2013

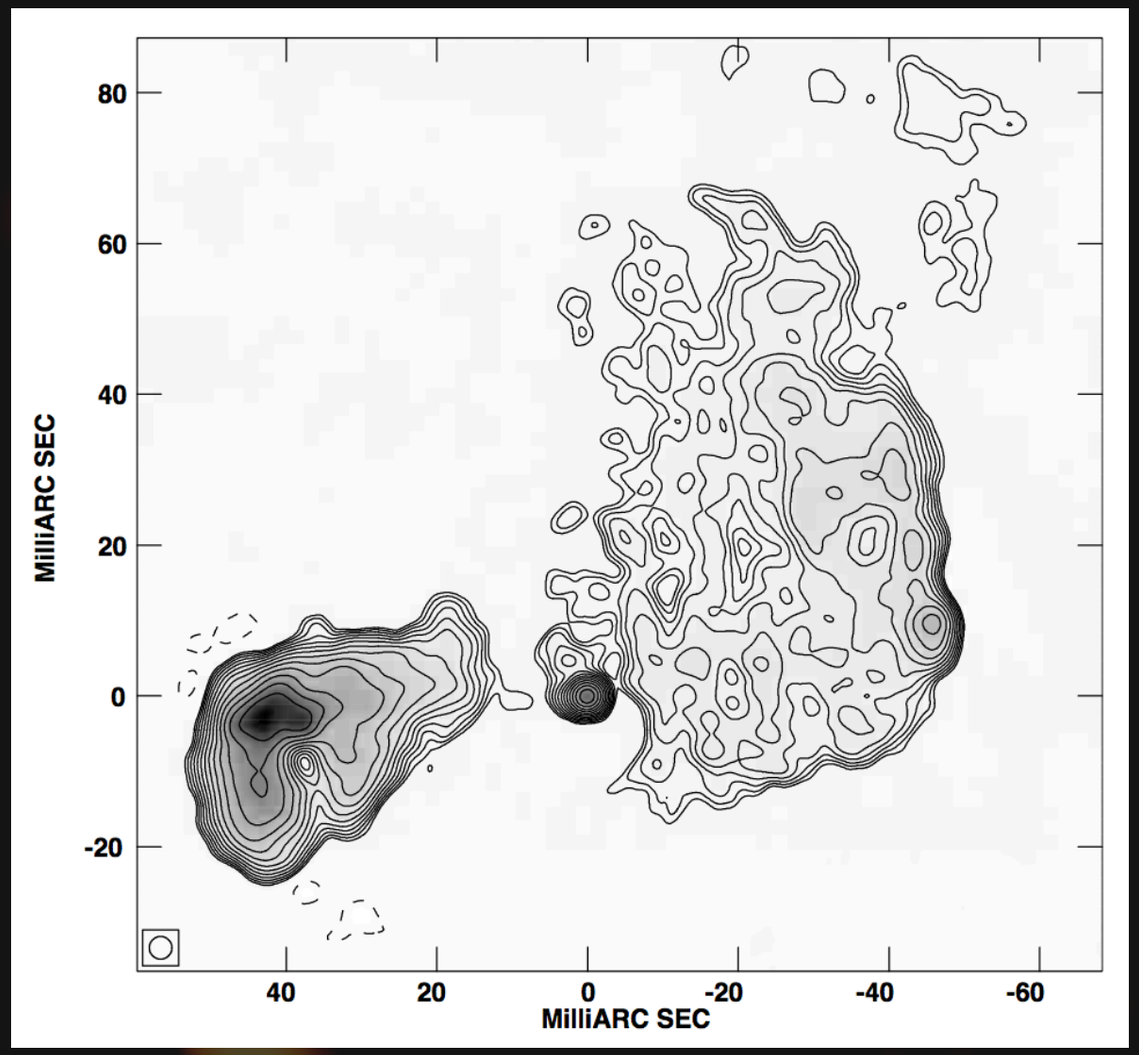


3C 236: Schulz et al. 2018

Need to increase the sample size and the range of parameters covered

Giroletti et al. 2003, A&A

4C 31.04



- $z = 0.0602$
- Compact Steep Spectrum source
- $L_{5GHz} = 10^{25}$ W/Hz
- ~100 pc; 500 to 3000 yr old
- Very asymmetric morphology

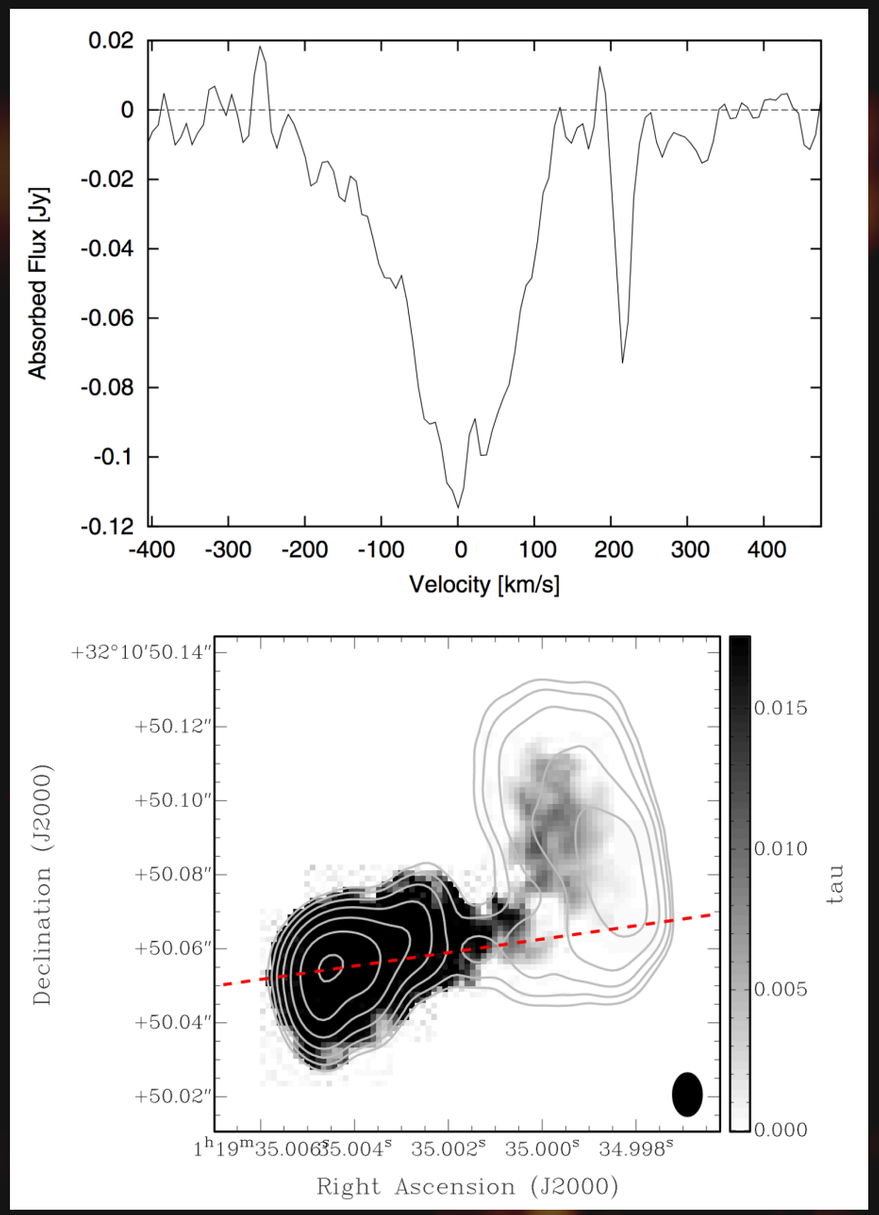
Evidence for strong jet-ISM interaction: disturbed ionised gas, warm molecular gas

Zovaro et al. 2019

Condition of cold gas?

Struve & Conway 2012, A&A

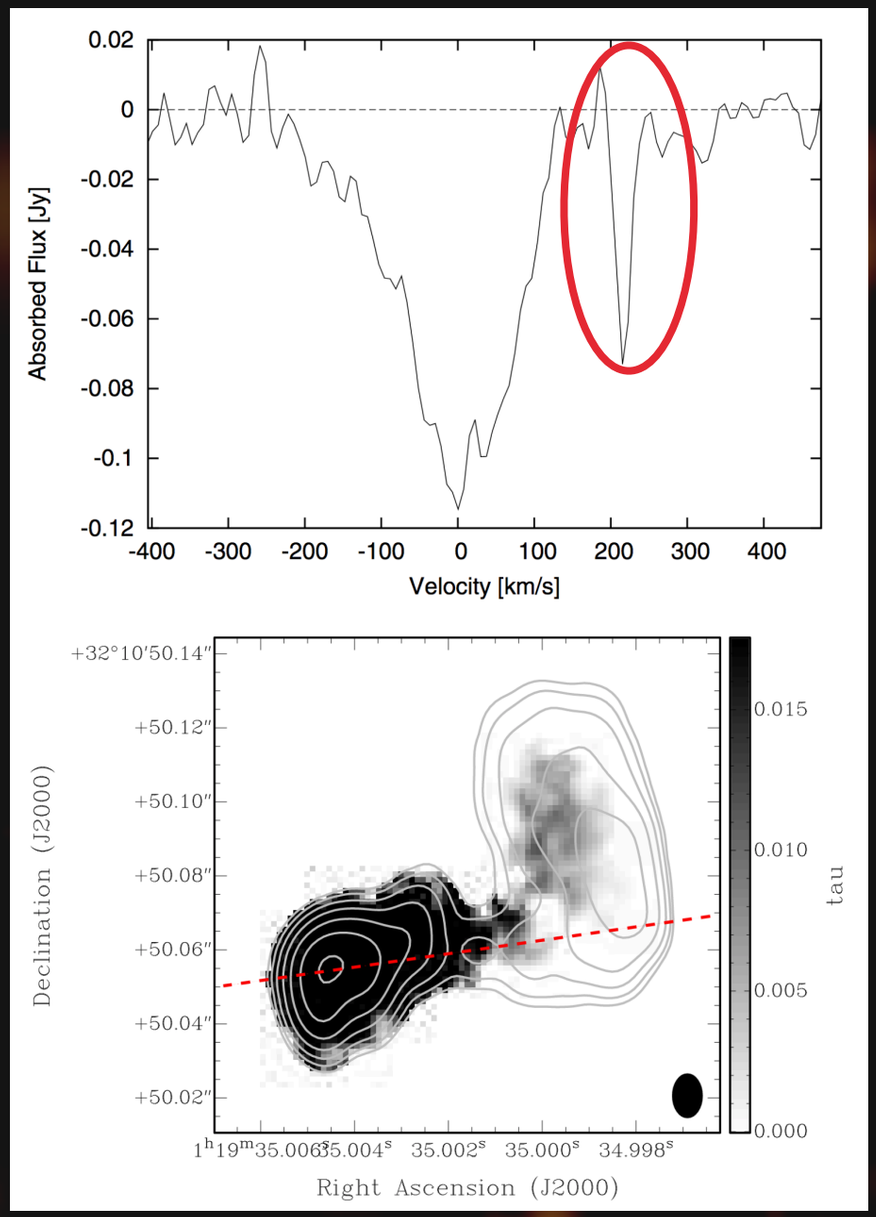
HI ABSORPTION: VLA, VLBA



- VLA: Unresolved absorption
- VLBA:
  - Well resolved HI absorption.
  - Two components:
    - Narrow (FWZI ~30 km/s): cloud> 100 pc away
    - Broad (FWZI ~300 km/s): closer to the nucleus and only against the eastern lobe

Struve & Conway 2012, A&A

HI ABSORPTION: VLA, VLBA



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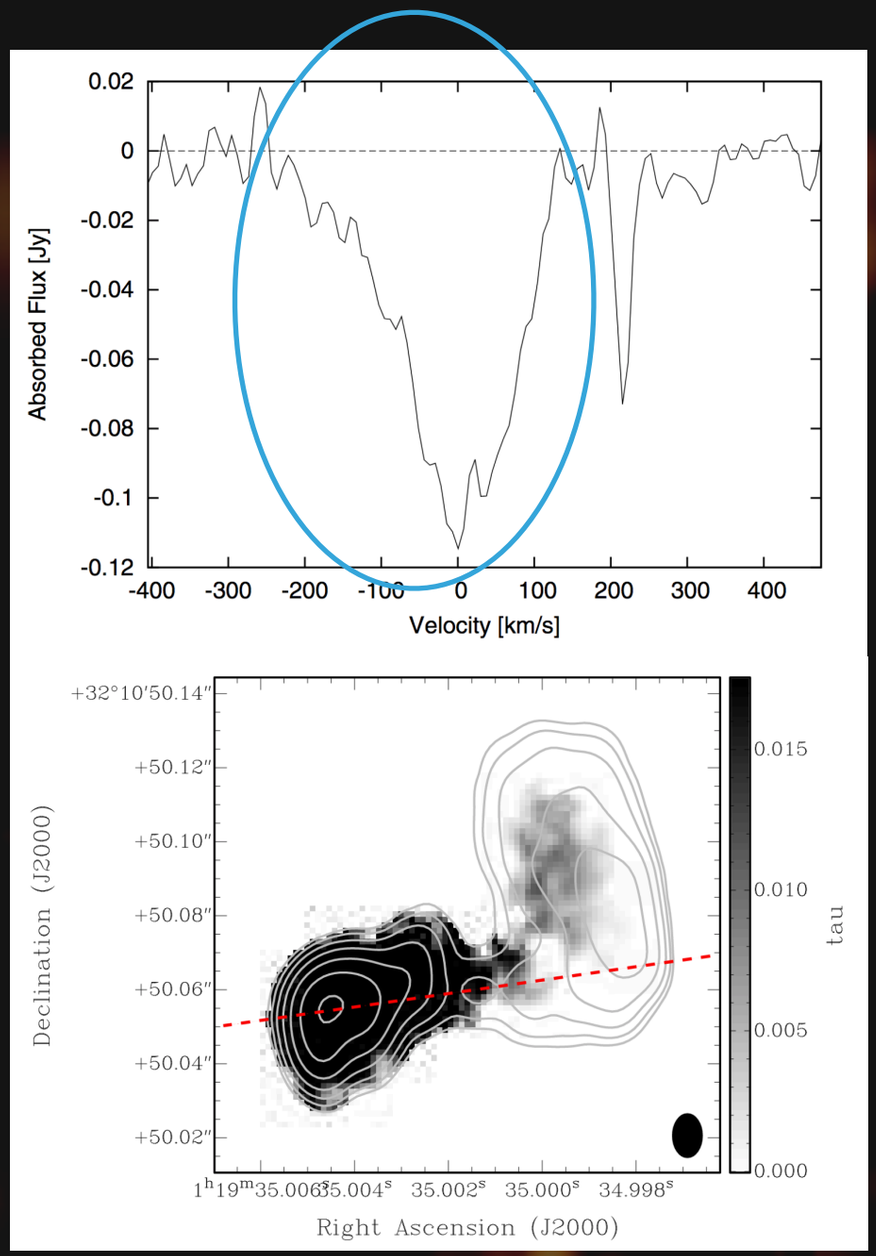

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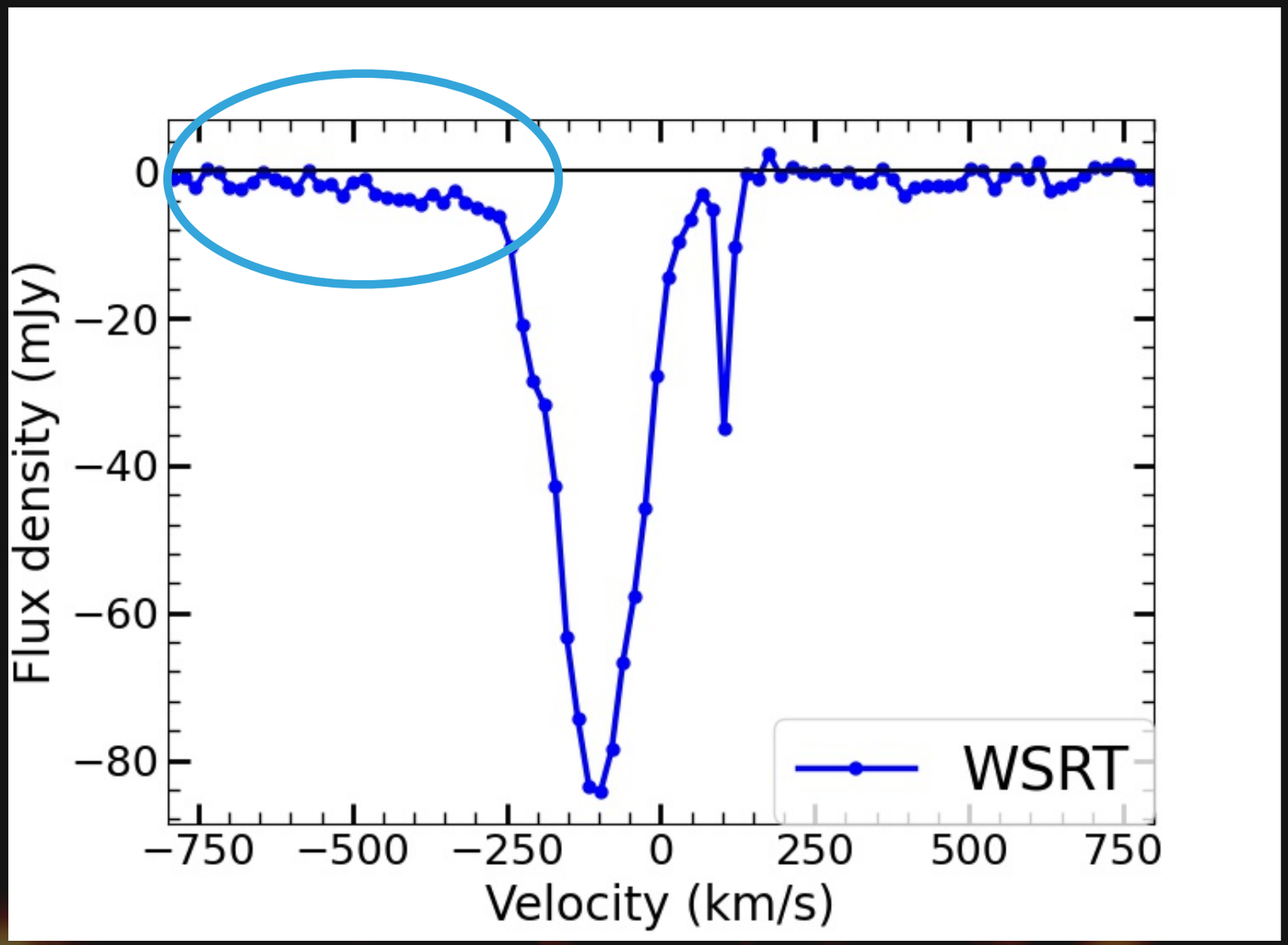
A possible circumnuclear gas disc

Murthy et al. in preparation

HI ABSORPTION (WSRT)



Wide blue-shifted wing

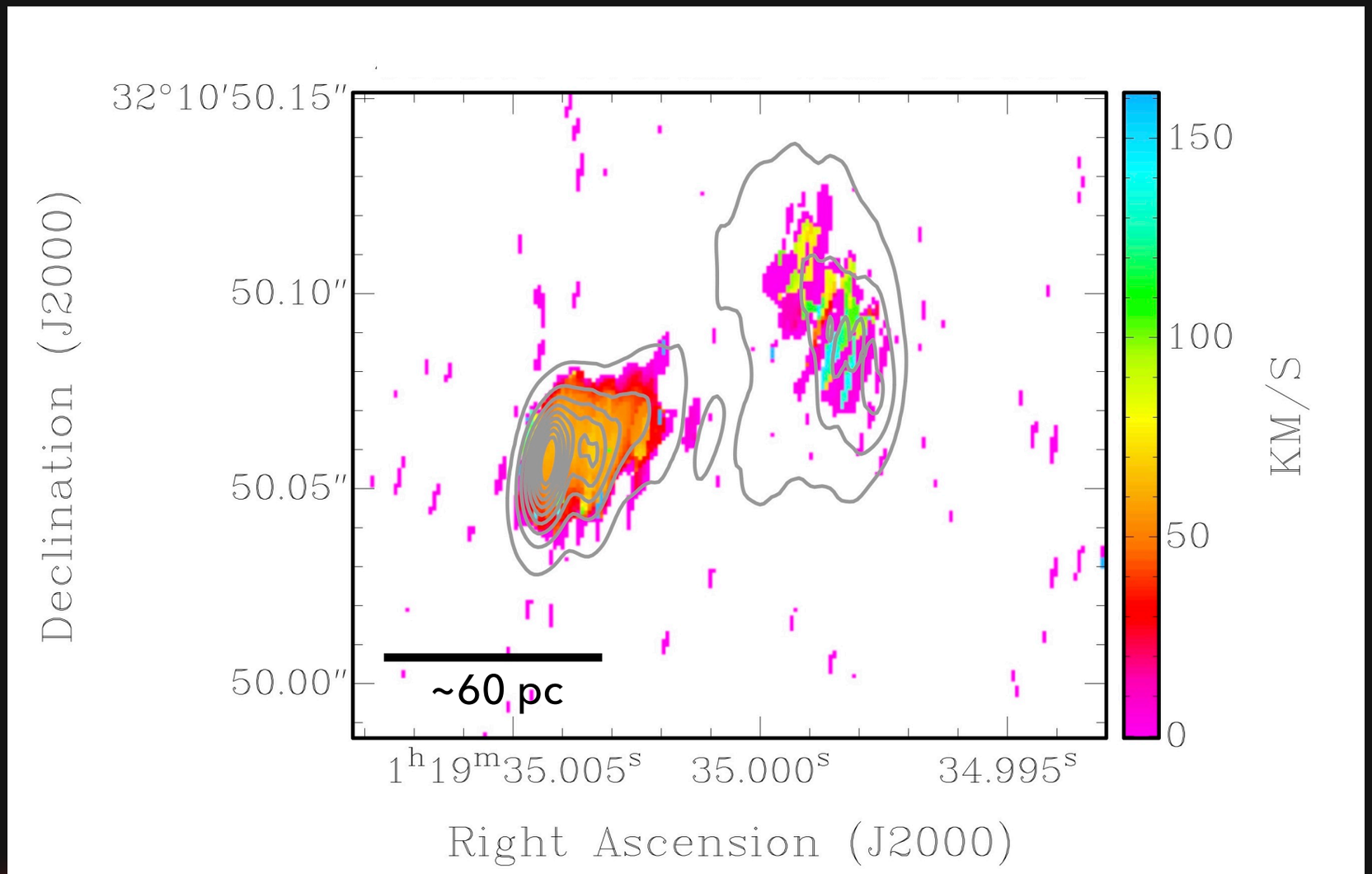
Outflow?

Where is it located?

Need more sensitive pc-scale observations with a wider band

Murthy et al. in preparation

HI ABSORPTION: GLOBAL VLBI



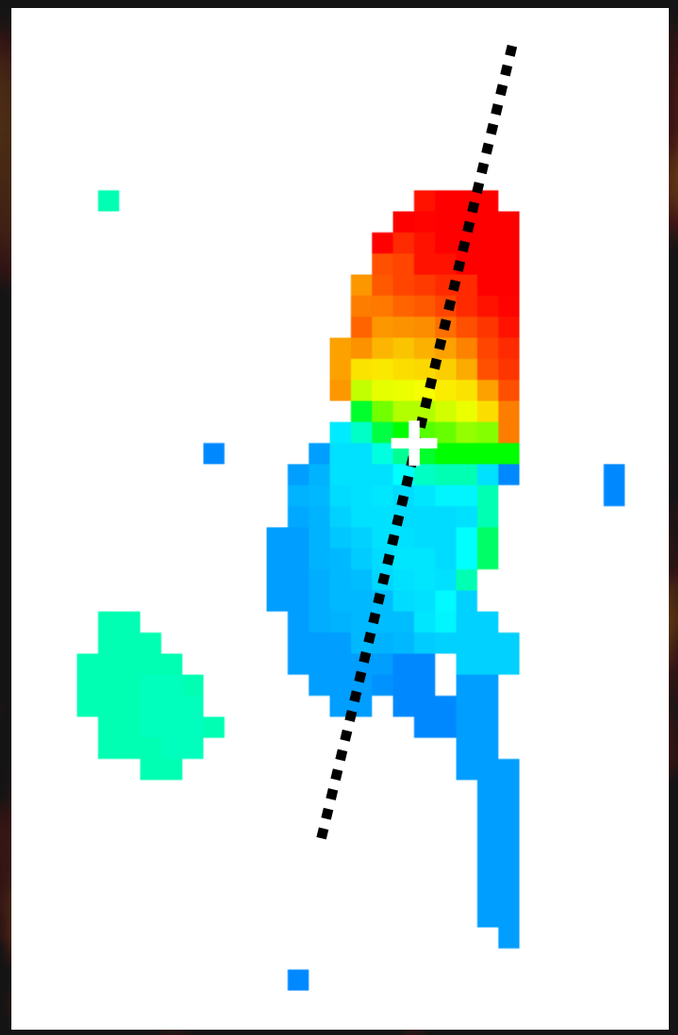
More sensitive observations with wider band

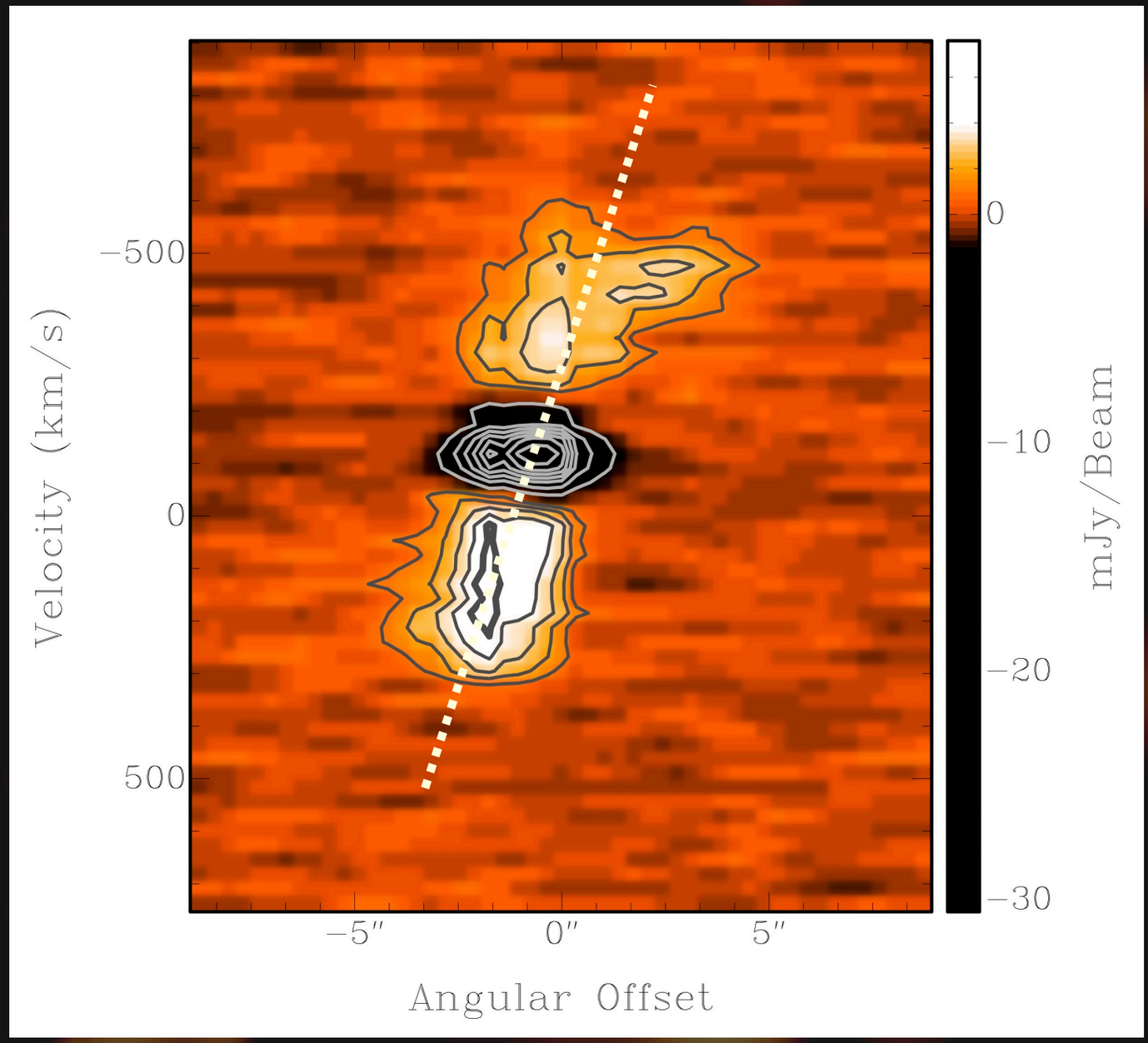
- ~13 hr on-source
- 16 MHz band
- Resolution:
  12 mas x 3 mas
  (~12pc x 3pc)

- HI column density:
  ~ 2×10^{21} cm^{-2}

High velocity dispersion (>50 km/s)
Especially at the eastern hotspot

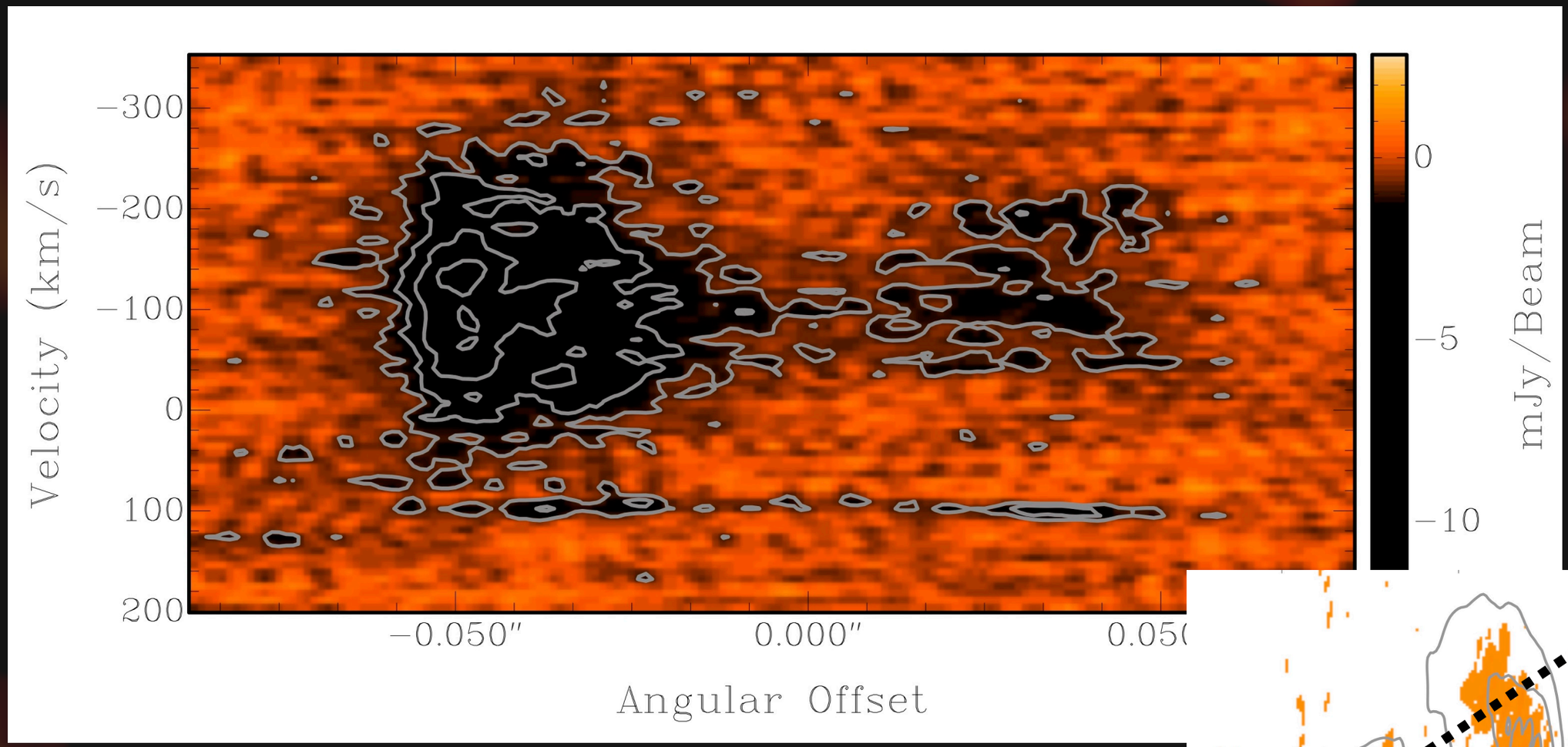
POSITION – VELOCITY PLOTS





Murthy et al. in preparation

HI ABSORPTION: GLOBAL VLBI



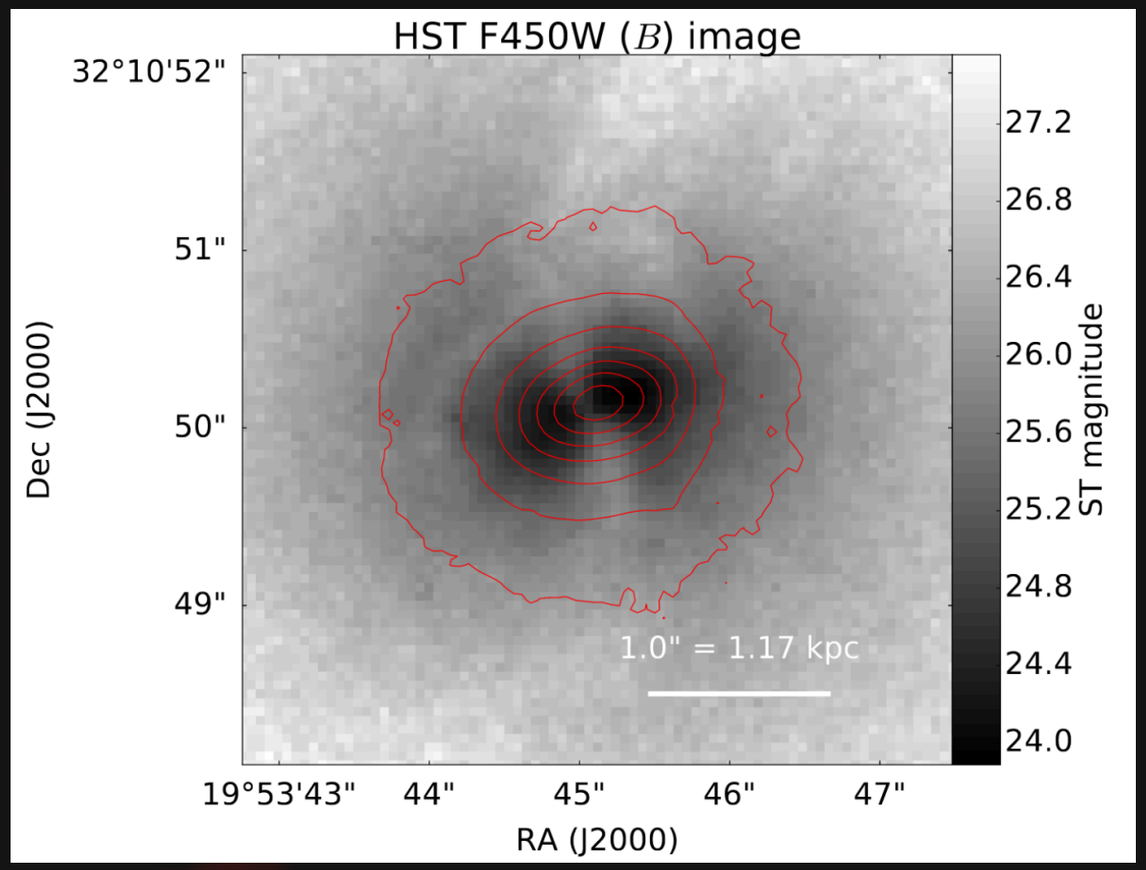
Broad absorption:~130 km/s blue-shifted

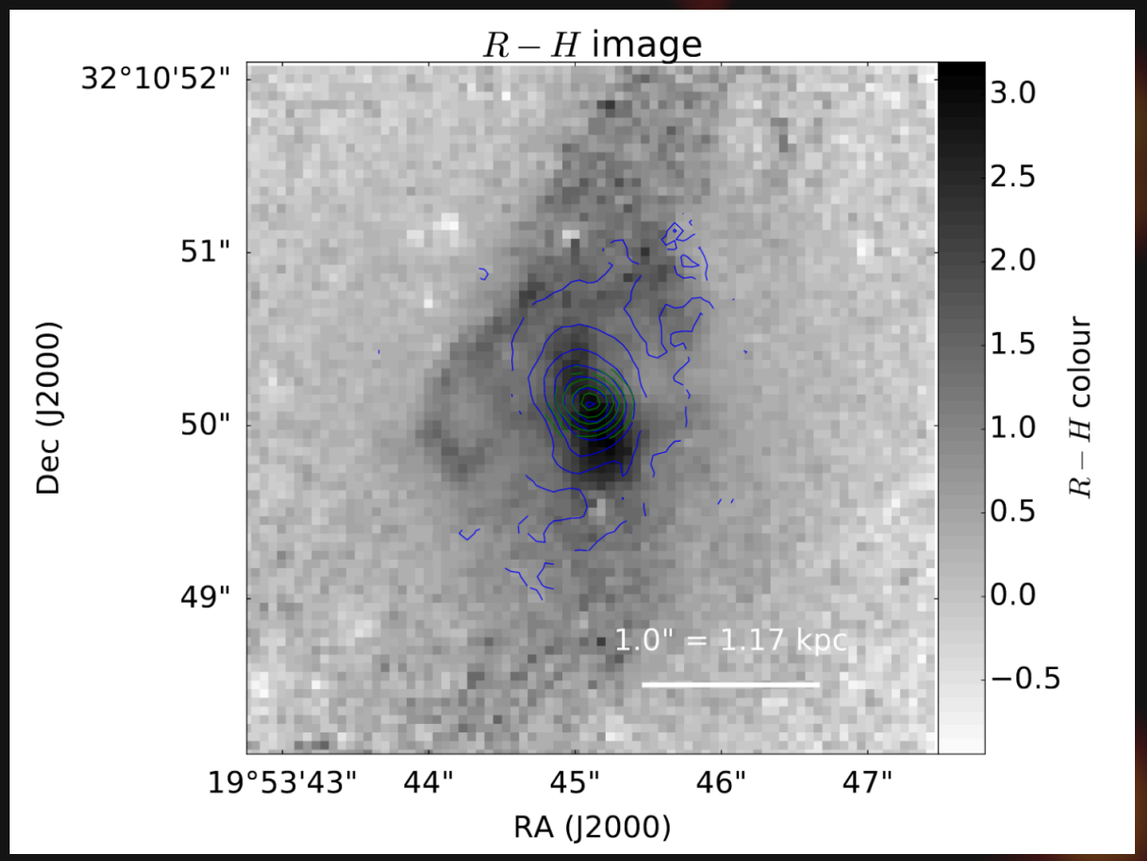
Against both lobes; filament connecting the two

No velocity gradient (over ~100 pc)!

Zovaro et al. 2019, MNRAS

ZOOMING OUT TO KPC SCALES: OTHER PHASES



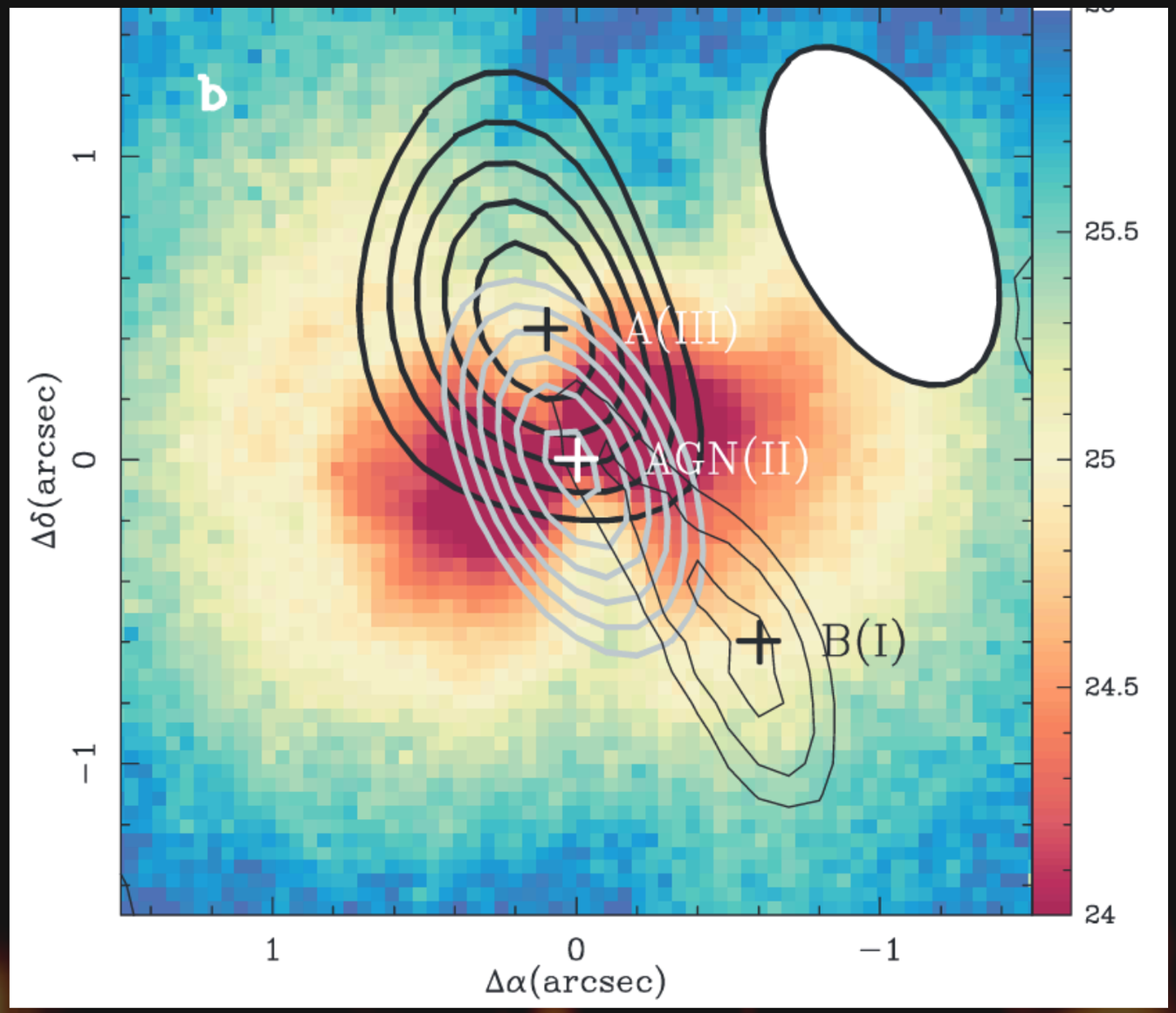


Dust lane along the radio axis

Larger, warped disc perpendicular to the radio axis

Garcia-Burillo et al. 2007, A&A

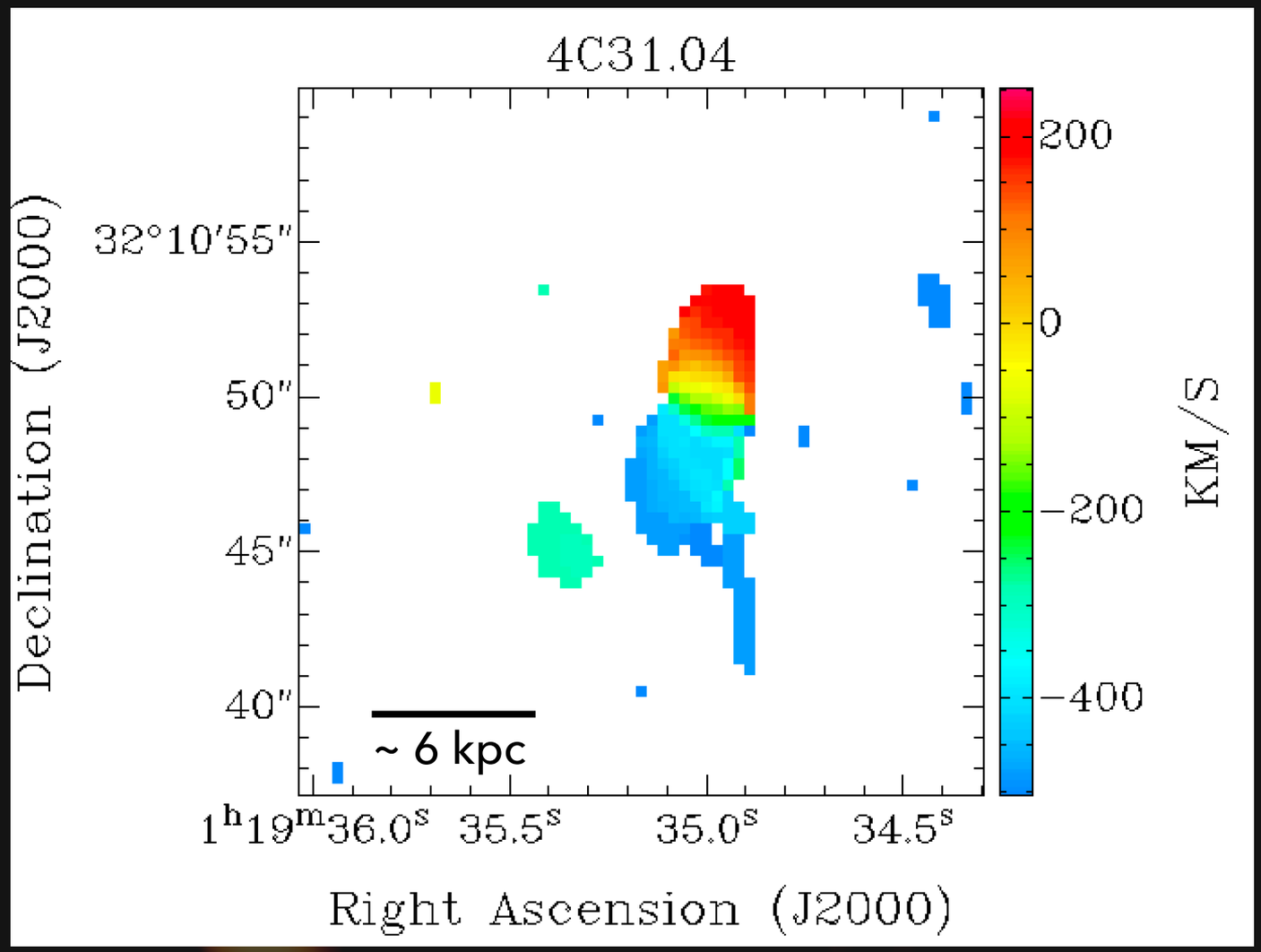
ZOOMING OUT TO KPC SCALES: COLD GAS



- 1.4 kpc HCO^+ disc
- Not dynamically relaxed

Murthy et al. in preparation

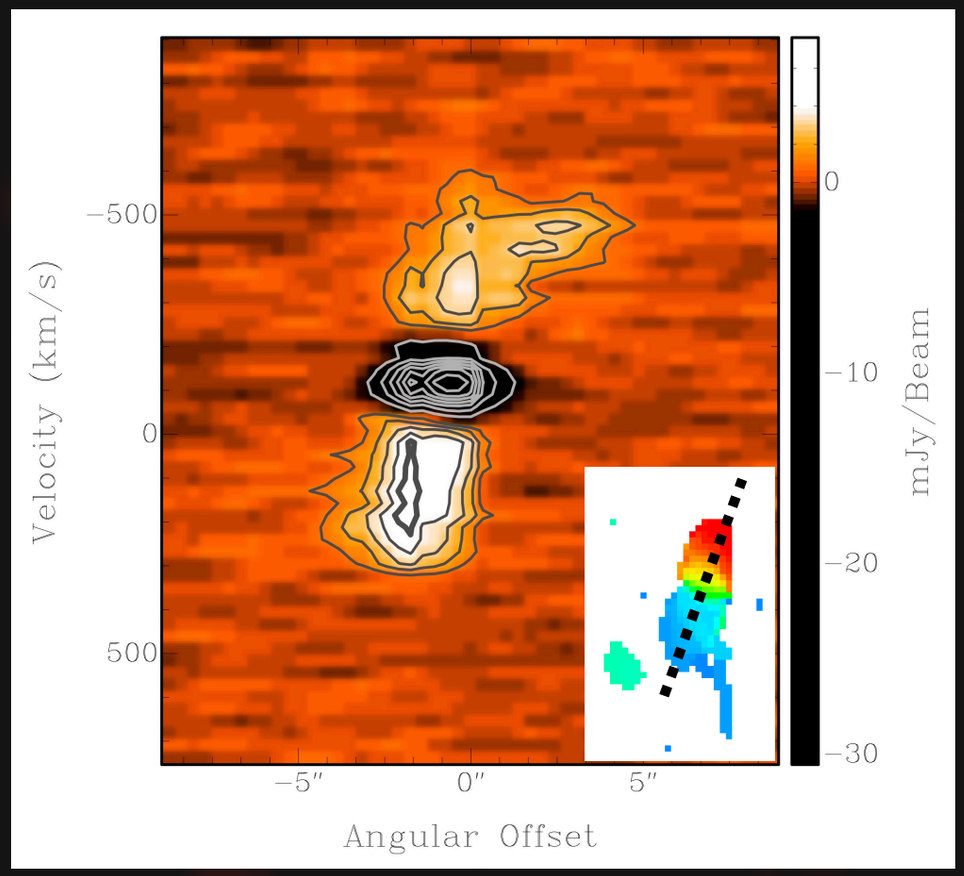
ZOOMING OUT TO KPC SCALES: COLD GAS

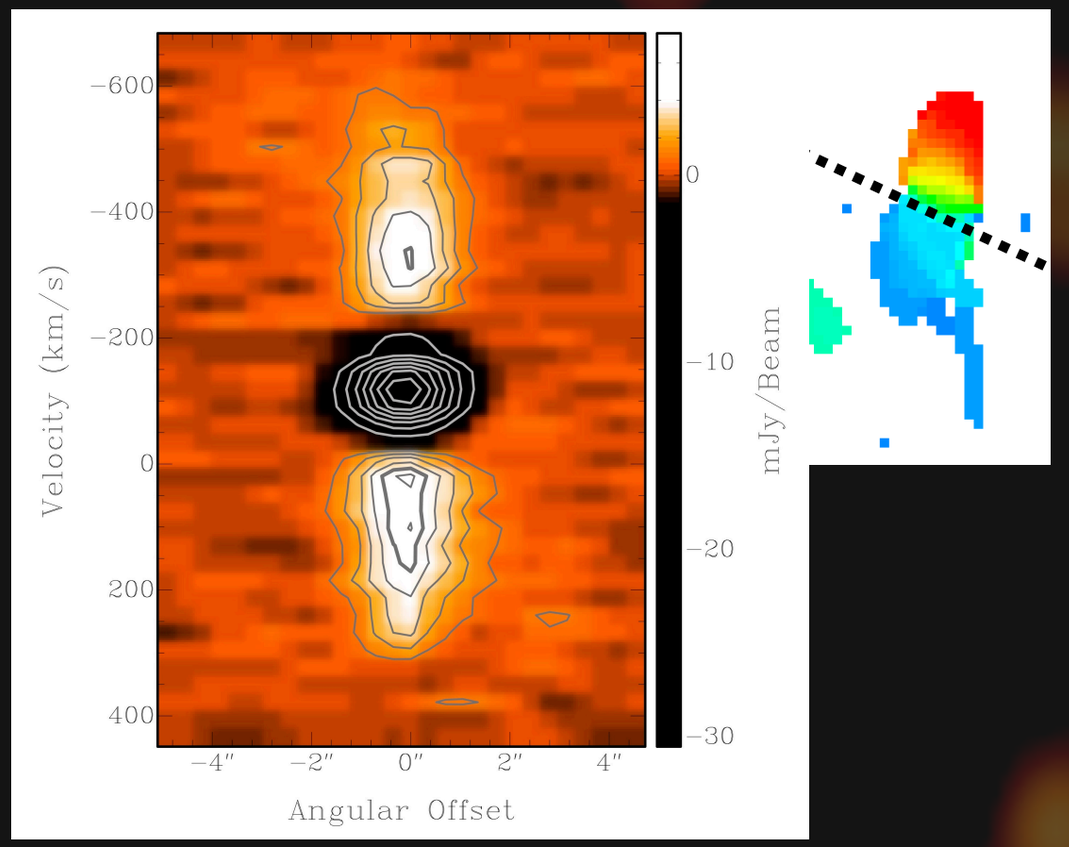


- CO(1–0) with NOEMA
- ~10 kpc disc
- Warped
- Edge-on, regularly rotating

Murthy et al. in preparation

ZOOMING OUT TO KPC SCALES: COLD GAS





Two kinematically distinct structures!

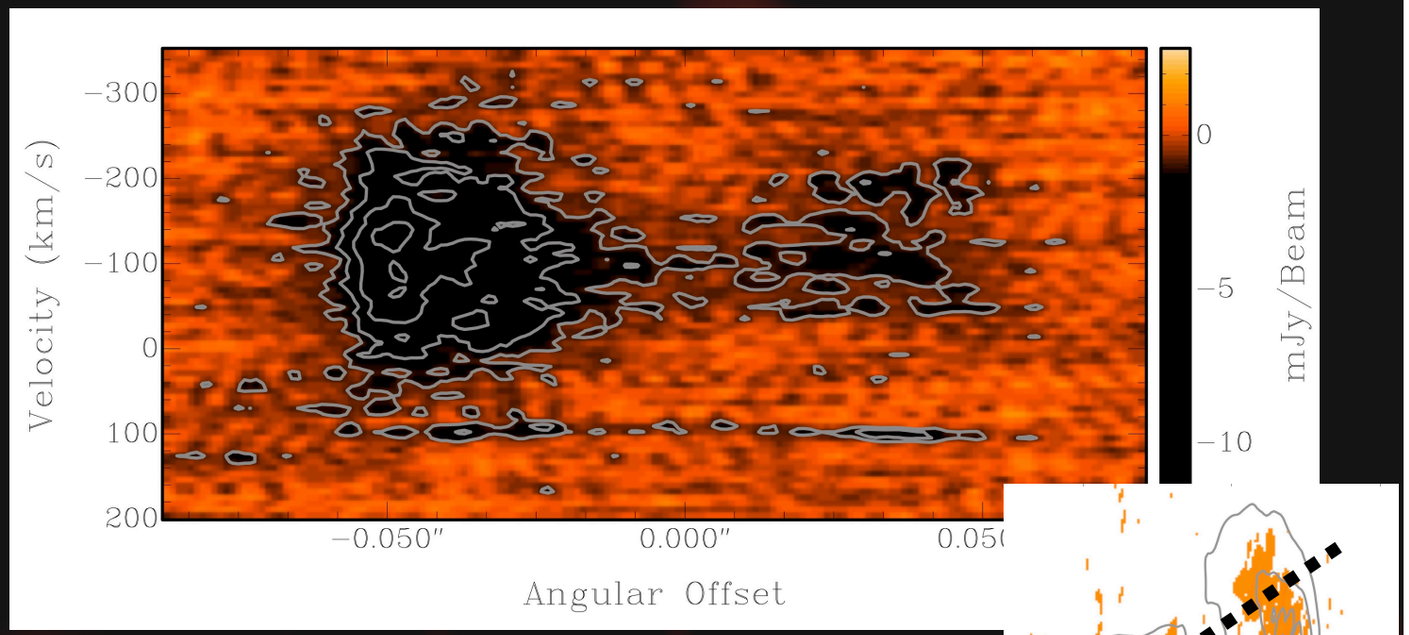
- kpc-scale warped disc
- **sub-kpc scale structure (is it a disc?)**

Murthy et al. in preparation

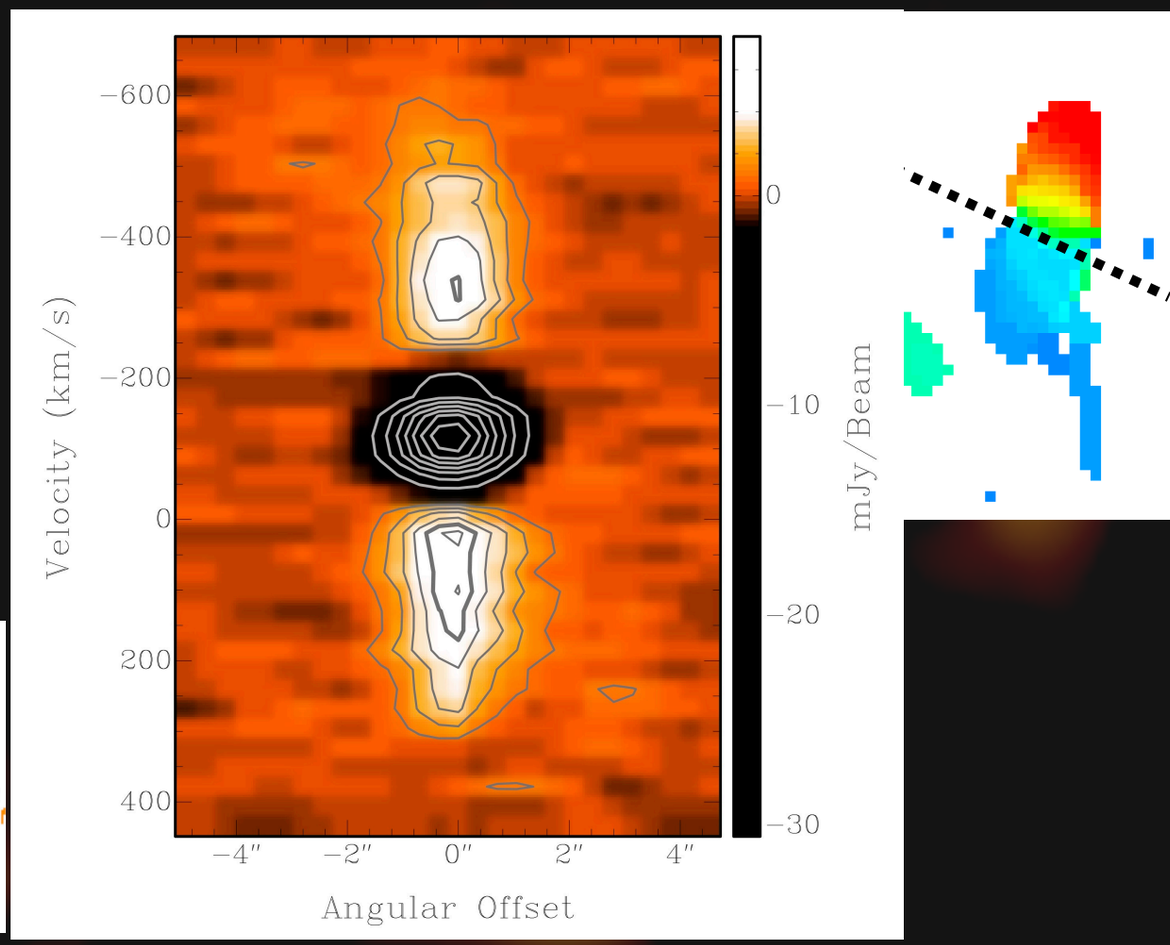
AN EXPANDING SHELL OF COLD GAS?

Driven by radio jets!

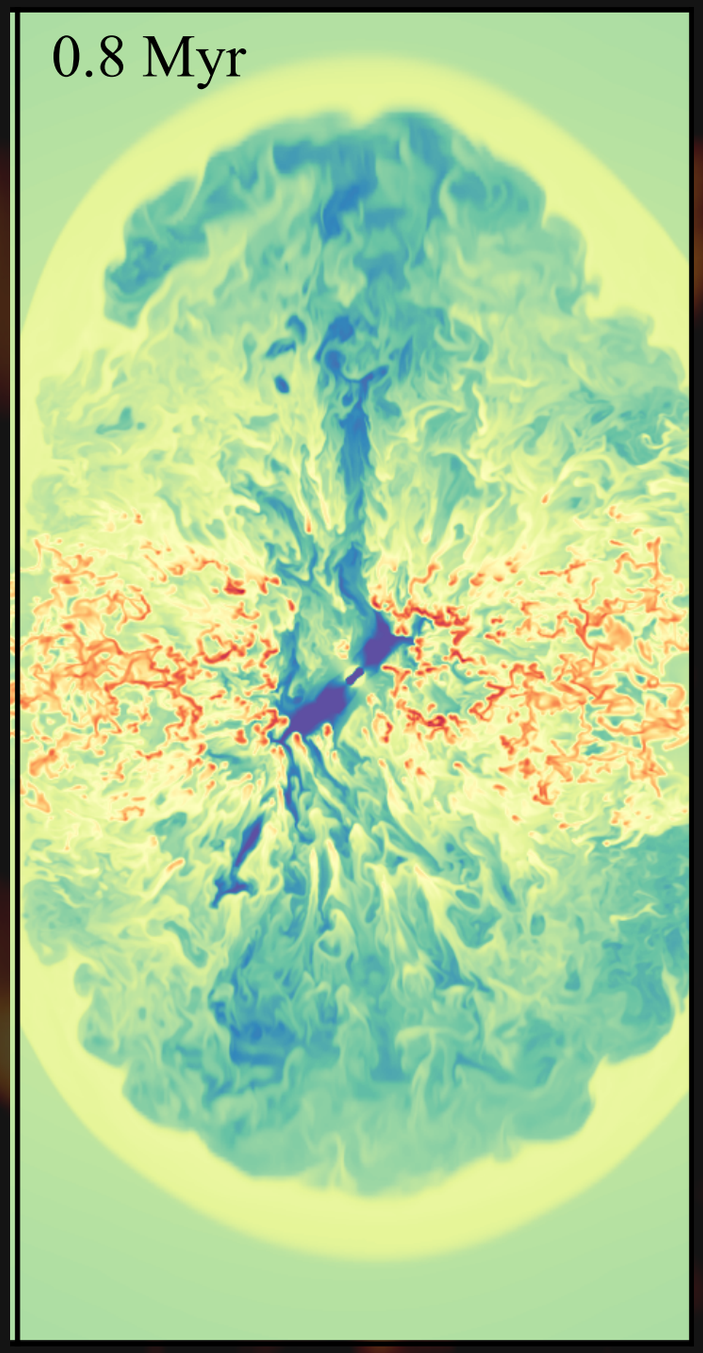
HI (pc scale)



CO (unresolved; sub-kpc)



INPUTS TO MODELS OF JET – ISM INTERACTION

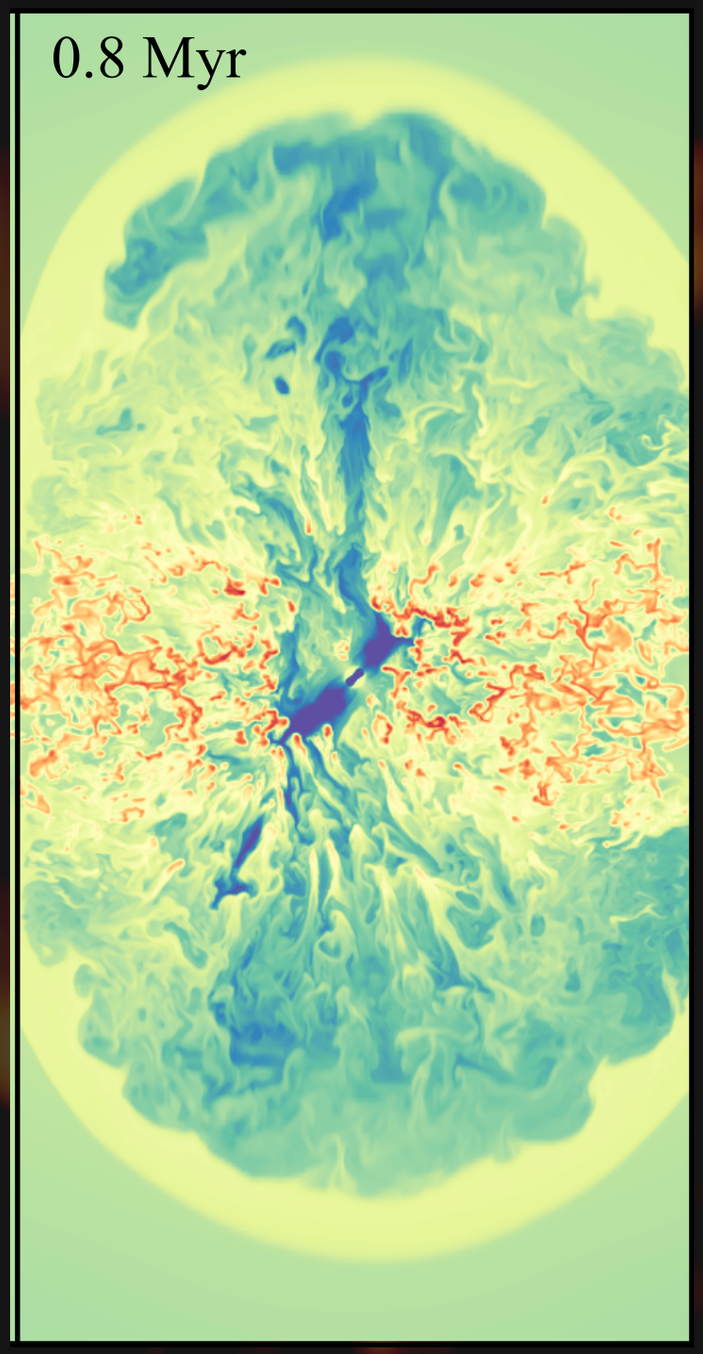


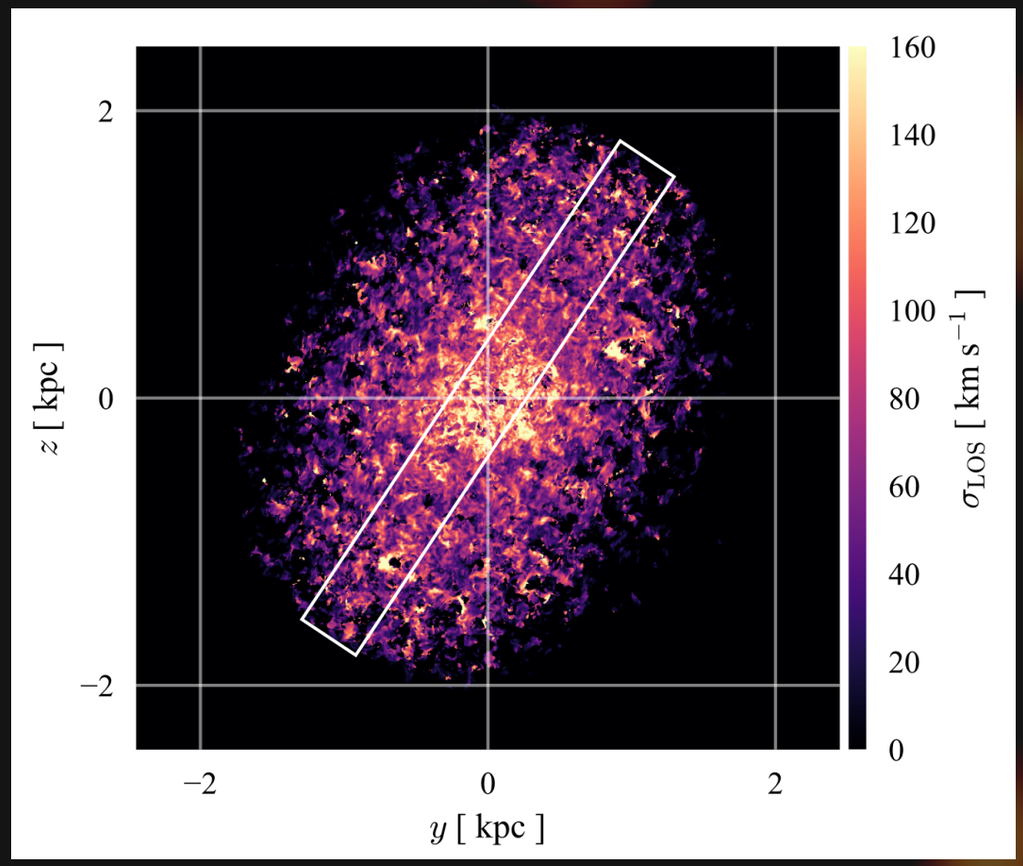
Mukherjee et al. 2018

Observations suggest that this also happens in cold gas!

Murthy et al. 2022b, *Nature Astronomy*

INPUTS TO MODELS OF JET – ISM INTERACTION





Murthy et al. 2022b, *Nature Astronomy*

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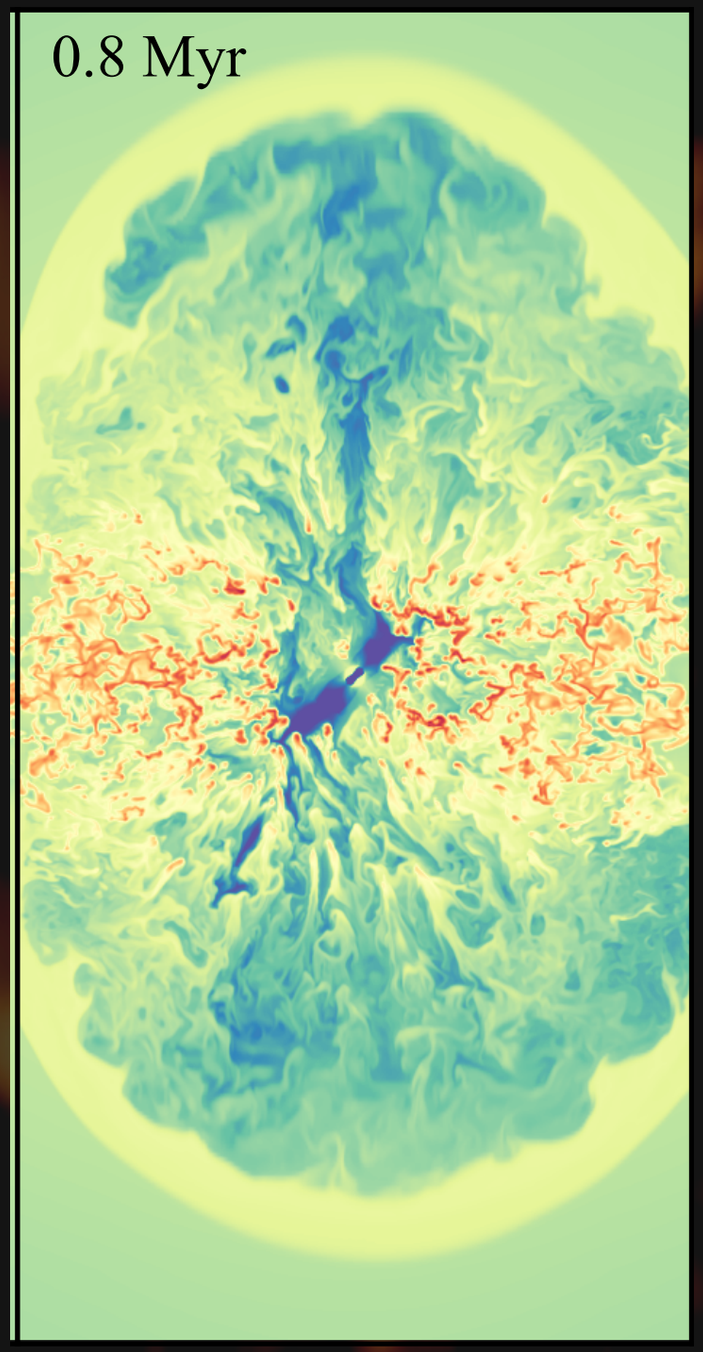
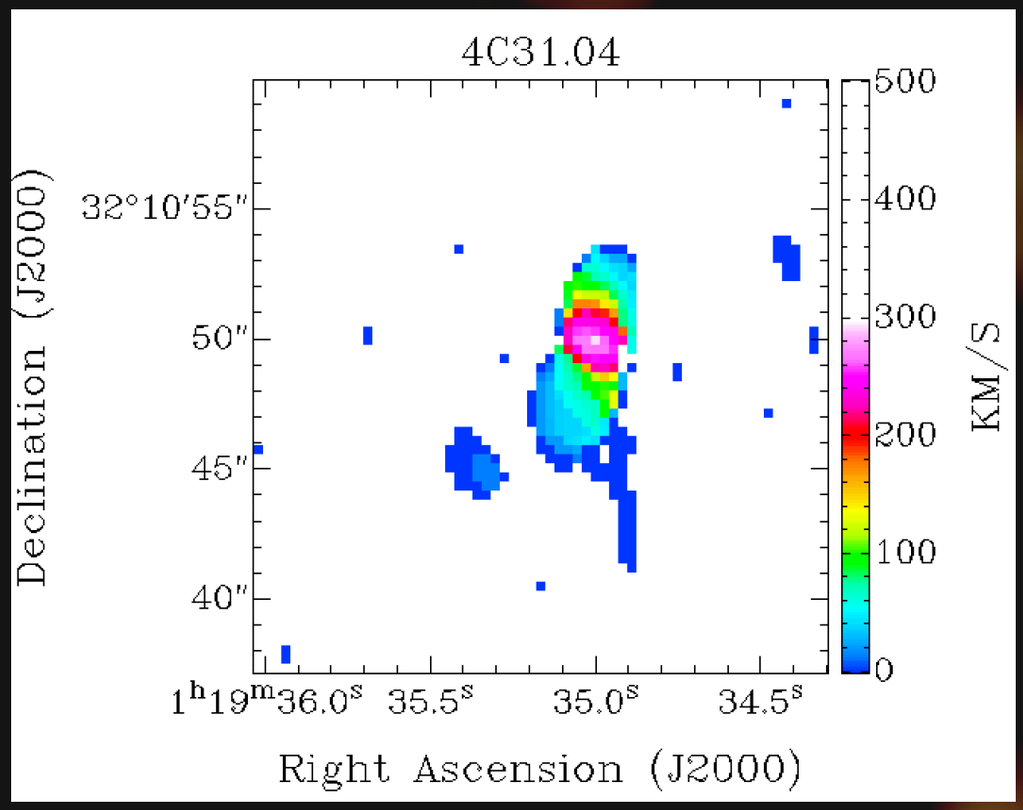
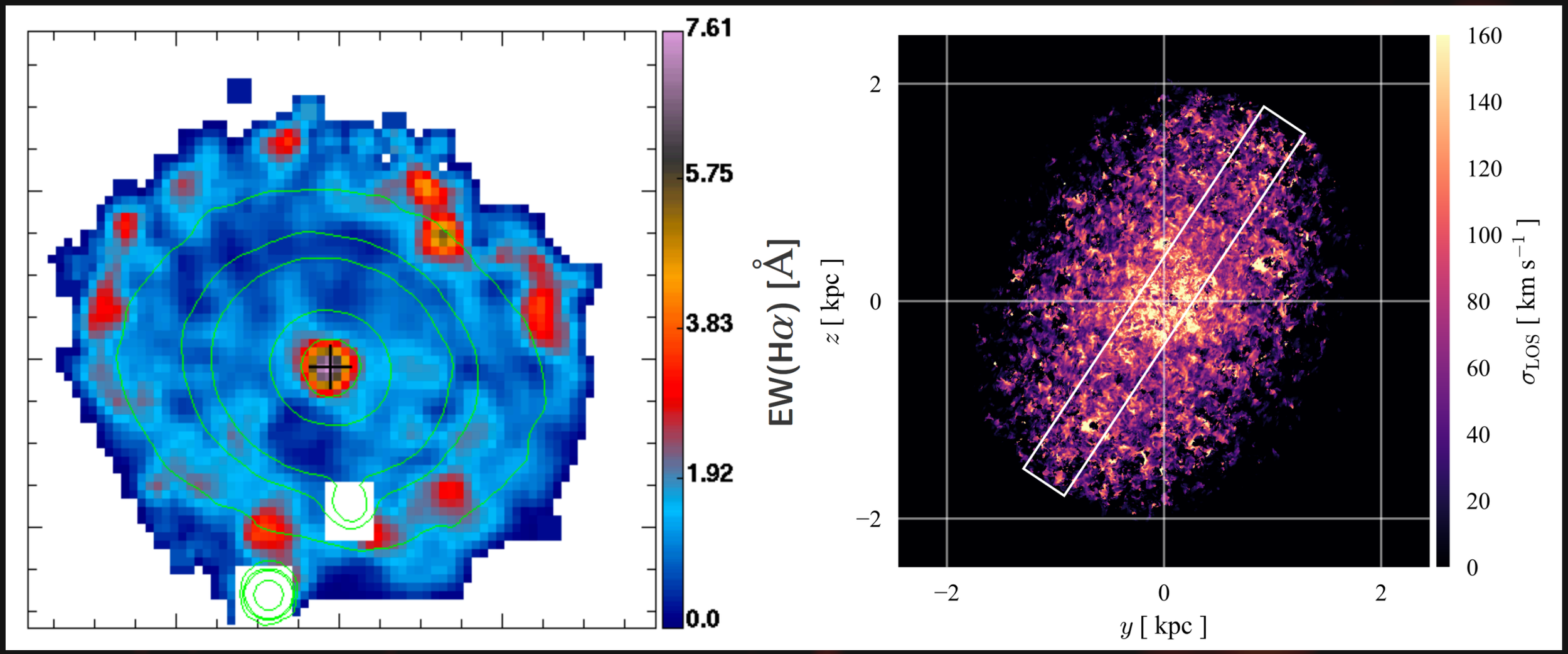




Molecular gas in 4C 31.04 shows high turbulence even at kpc scales!

Murthy et al. 2022b, *Nature Astronomy*

Also seen in other CSS sources: B2 0258+35 (but ionised gas)



Gomes et al. 2016

SIGNIFICANCE FOR FEEDBACK

- Significant feedback by radio jets on cold gas at **(sub) kpc scales**
  - **Even at a very early stage of evolution**
  - Not only direct-impact outflows but also on larger scales relative to the source size

FUTURE:

- Increase the sample size, expand to lower luminosities
- More sophisticated models
- 4C 31.04: Higher spatial resolution CO observations

GALACTIC-SCALE IMPACT OF RADIO SOURCES

- 4C 31.04, z = 0.0602:
- Highly turbulent nuclear gas
- Expanding shell of cold (atomic and molecular gas)
- All driven by radio jets!
- Confirms some of the predictions of models and also provides new insights!

Radio AGN also provide significant feedback to their host galaxies at (sub) kpc scales!