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The cold gas component and jet-ISM interplay in nearby low-excitation radio galaxies

Ilaria Ruffa

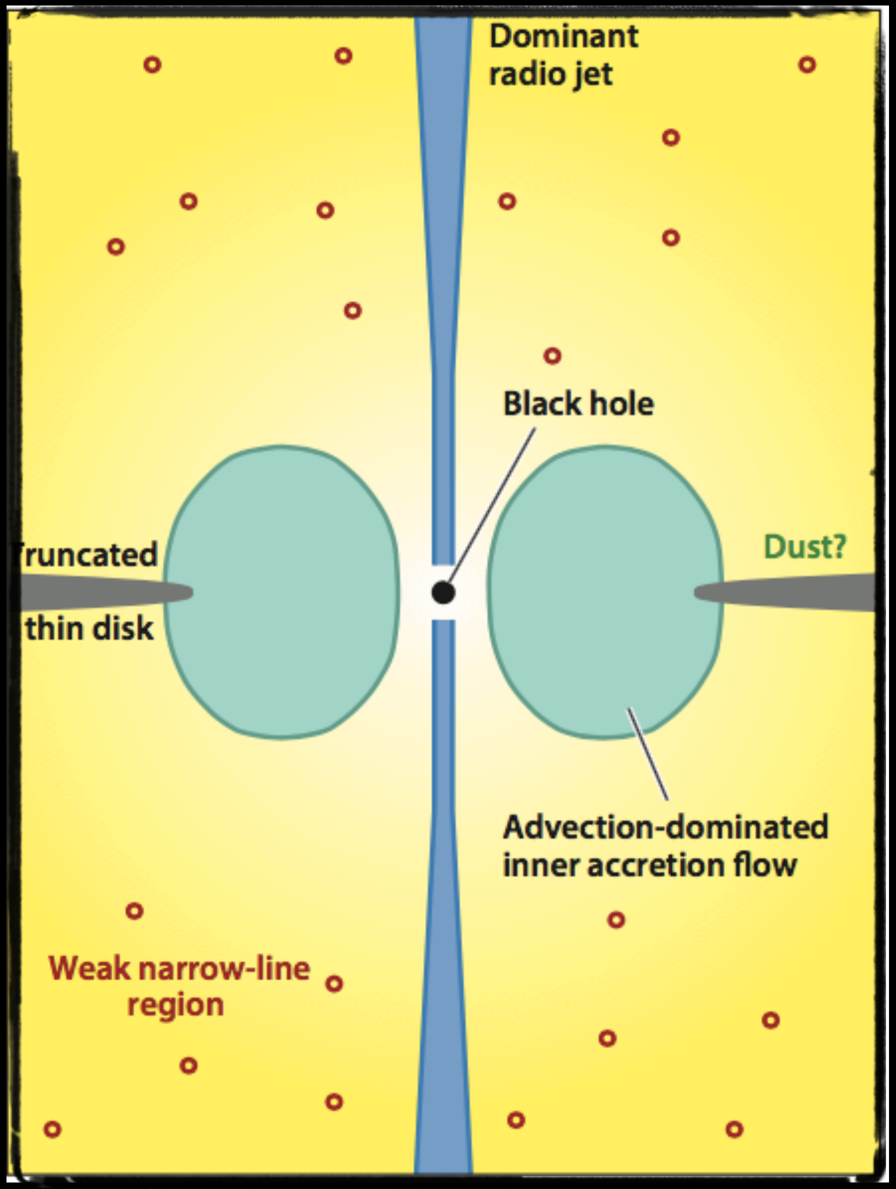
(Cardiff University/INAF-IRA)

In collaboration with: Isabella Prandoni (INAF-IRA) , Robert A. Laing (SKAO), Timothy A. Davis (Cardiff University), Paola Parma (INAF-IRA), Hans de Ruiter (INAF-IRA), Rosita Paladino (INAF-IRA), Viviana Casasola (INAF-IRA), Joshua Warren (Oxford University), Martin Bureau (Oxford University), Filippo Maccagni (INAF-OAC), and many others

The Italian Route to the SKAO Revolution, 7 October 2021

Low excitation radio galaxies

In the local Universe jet-mode AGN associated to low excitation radio galaxies



(Heckman & Best 2014)

Low excitation radio galaxies

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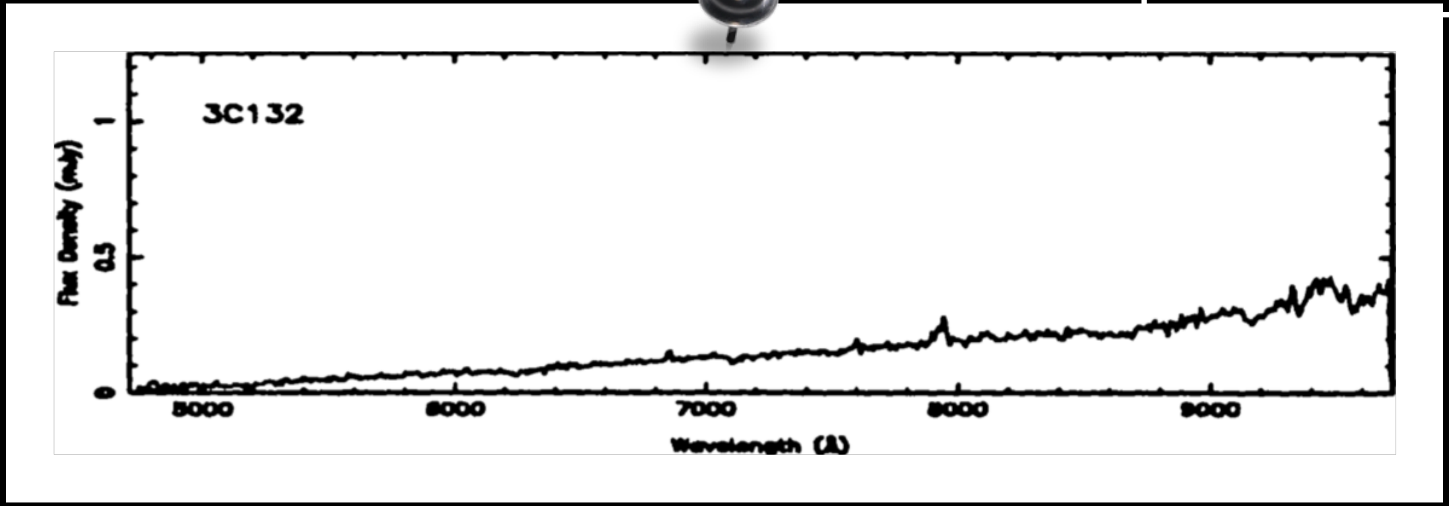
- Weak (or absent) **low-ionization** narrow **emission lines** (LINER-like optical spectra)



(Laing et al. 1994)

Low excitation radio galaxies

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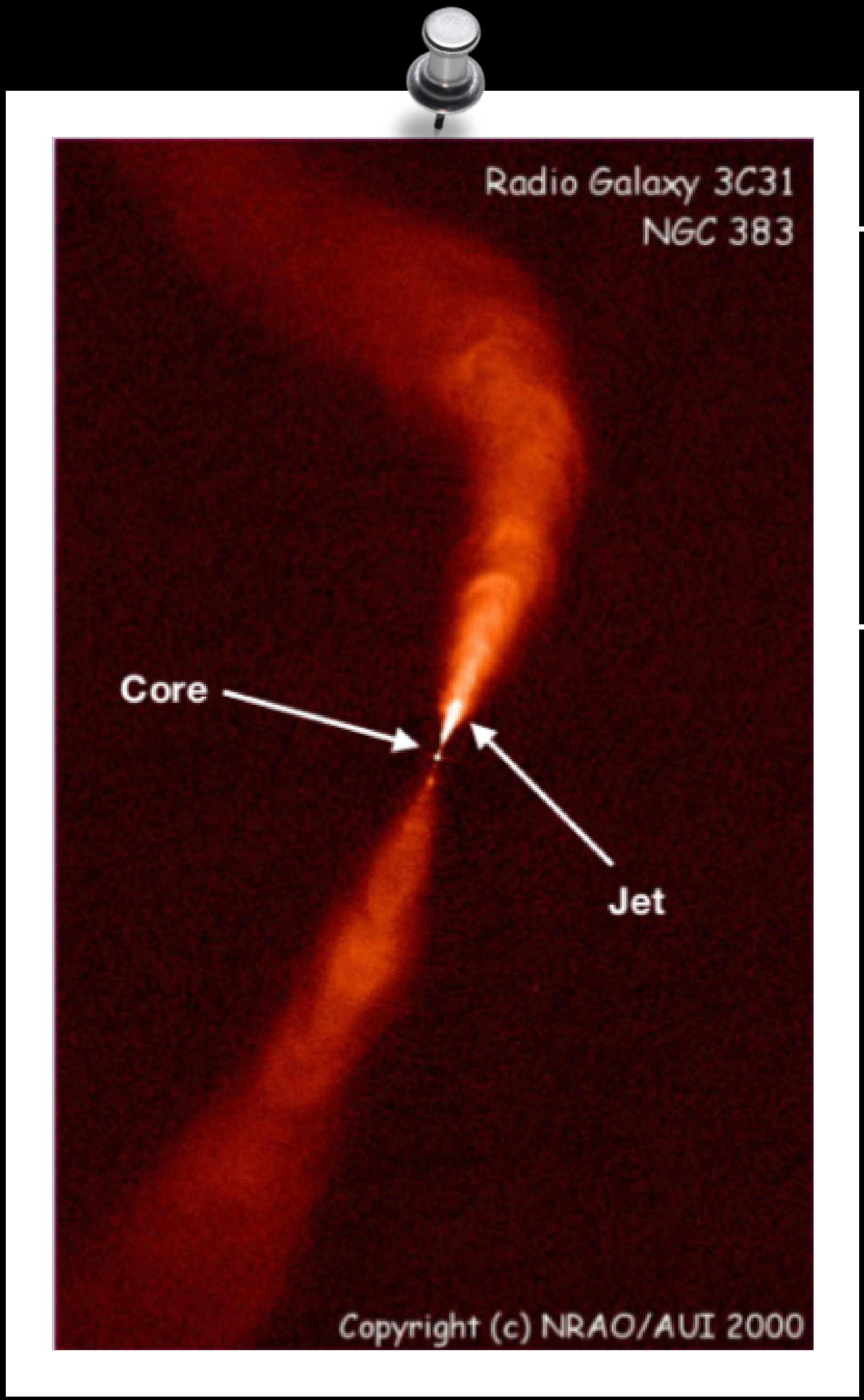

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Mostly FRI (some FRII) radio morphology

Low excitation radio galaxies

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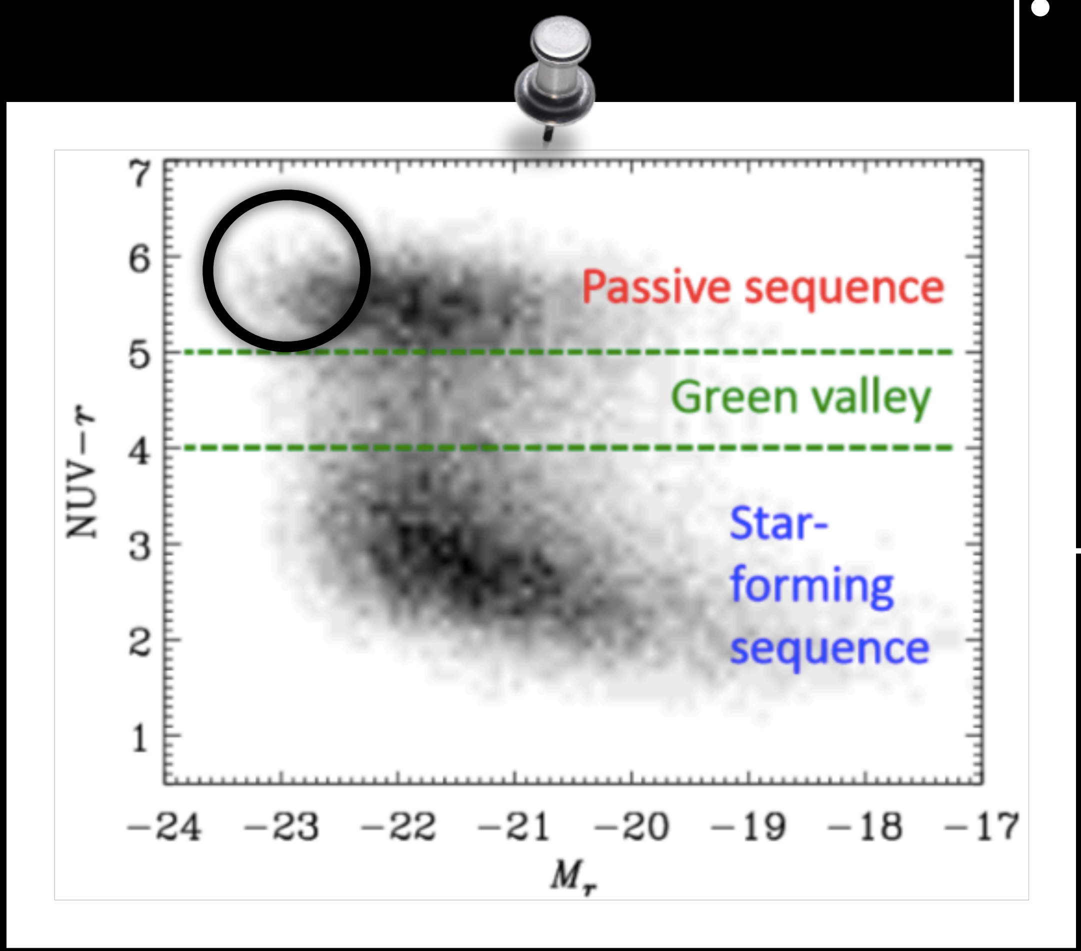
- **Moderate** radio luminosity ($L_{1.4GHz}$<10^{25} W/Hz)
- **Mostly FRI** (some FRII) radio morphology
- Hosted by **very massive** ETGs ($M_K \leq -24$, $M_* \geq 10^{11}$ $M_\odot$)
- **Old** stellar population (red sequence galaxies)



(Salim et al. 2007)

Low excitation radio galaxies

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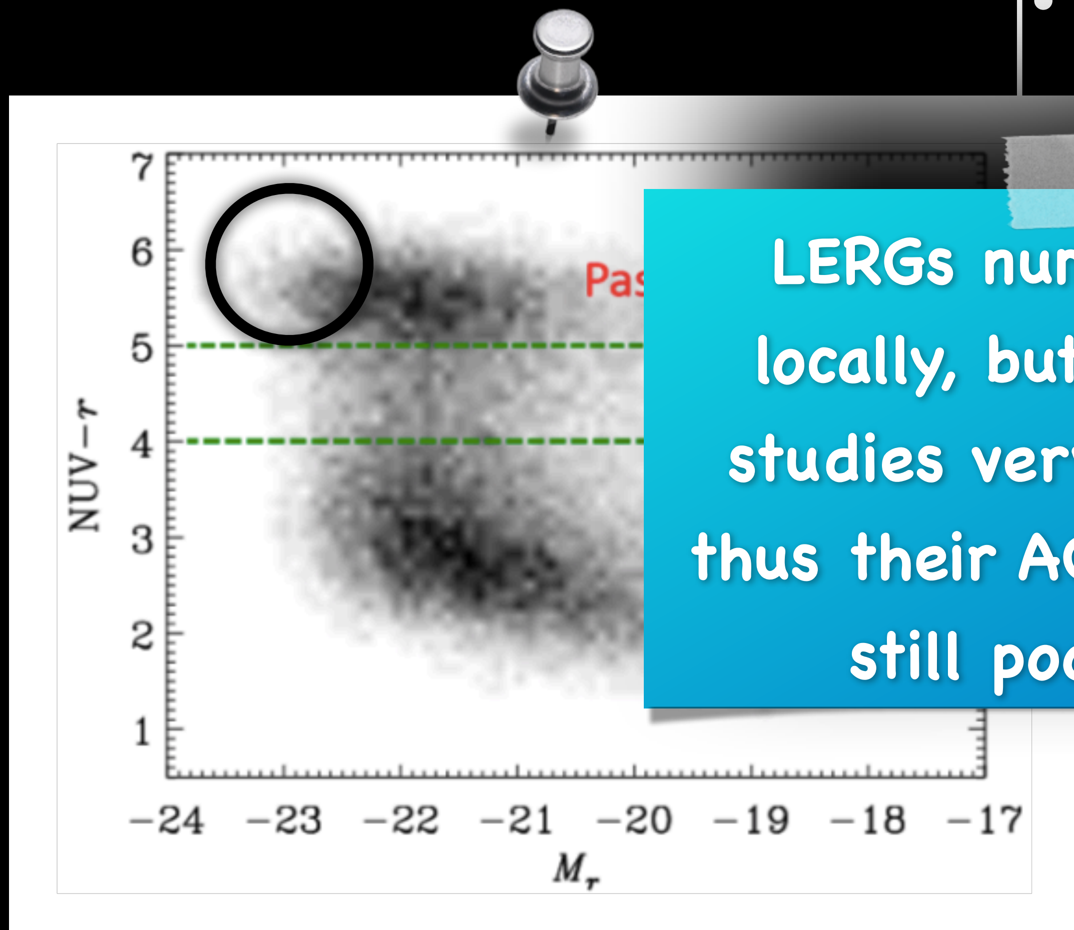


(Salim et al. 2007)

LERGs numerically dominant locally, but spatially-resolved studies very sparse so far and thus their AGN feeding/feedback still poorly understood

The Southern Sample project

First systematic study of a volume-limited (z<0.03) sample of **eleven LERGs** selected from the Ekers et al. (1989) sub-sample of the Southern Parkes 2.7 GHz Survey

Radio source (1)	Host galaxy (2)	z (3)	$S_{1.4}$ (Jy) (4)	Log $P_{1.4}$ (W Hz^{-1}) (5)	Jet (6)	FR class (7)
PKS 0007−325	IC 1531	0.0256	0.5	23.9	1	I
PKS 0131−31	NGC 612	0.0298	5.6	25.1	2	I/II
PKS 0320−37	NGC 1316	0.0058	150	25.1	2	I
PKS 0336−35	NGC 1399	0.0047	2.2	23.0	2	I
PKS 0718−34	–	0.0284	2.1	24.6	2	II
PKS 0958−314	NGC 3100	0.0088	0.5	23.0	2	I
PKS 1107−372	NGC 3557	0.0103	0.8	23.3	2	I
PKS 1258−321	ESO 443-G 024	0.0170	1.2	23.9	2	I
PKS 1333−33	IC 4296	0.0125	4.5	24.2	2	I
PKS 2128−388	NGC 7075	0.0185	0.9	23.8	2	I
PKS 2254−367	IC 1459	0.0060	1.2	23.9	2[a]	I[a]

AGN feeding/feedback loop in LERGs
mapping different galaxy components
(stars, hot/warm/cold gas, dust, jets)

The dataset

VLT/VIMOS + MUSE IFU spectroscopy (Warren et al. in prep.)

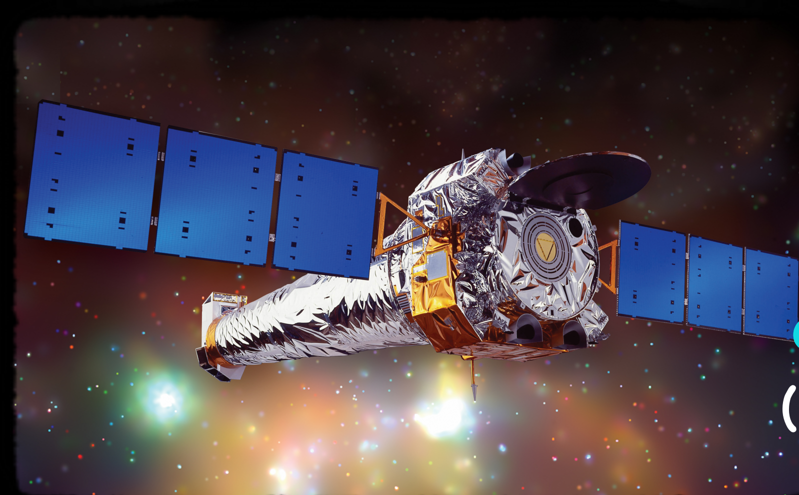
APEX CO (2-1) integrated spectra (Prandoni et al. 2010, Laing et al. in prep.)

ALMA Cycle 3 CO (2-1) observations (Ruffa et al. 2019a,b)

ATCA HI observations (Maccagni et al. in prep., Ruffa et al. in prep)

Archival HST data (or from ground-based telescopes; Ruffa et al. 2019a, Ruffa et al. 2021)

Archival plus proprietary VLA high-res. imaging (Ruffa et al. 2019a,2020)



Chandra X-ray data (Ruffa et al. in prep)

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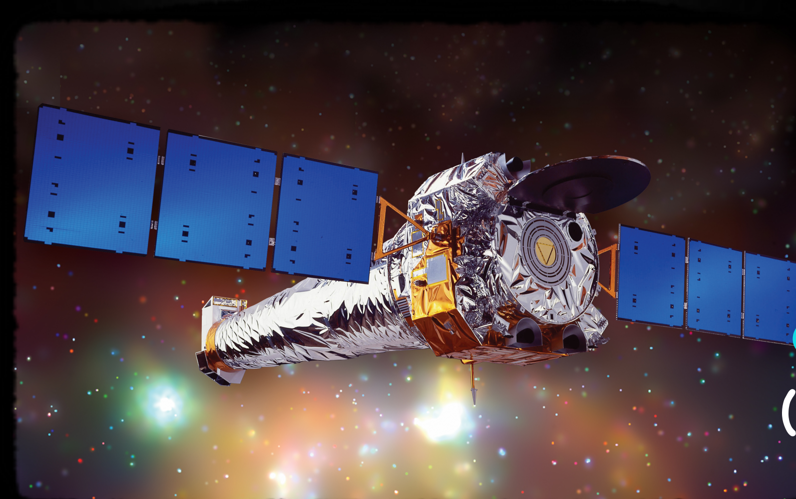
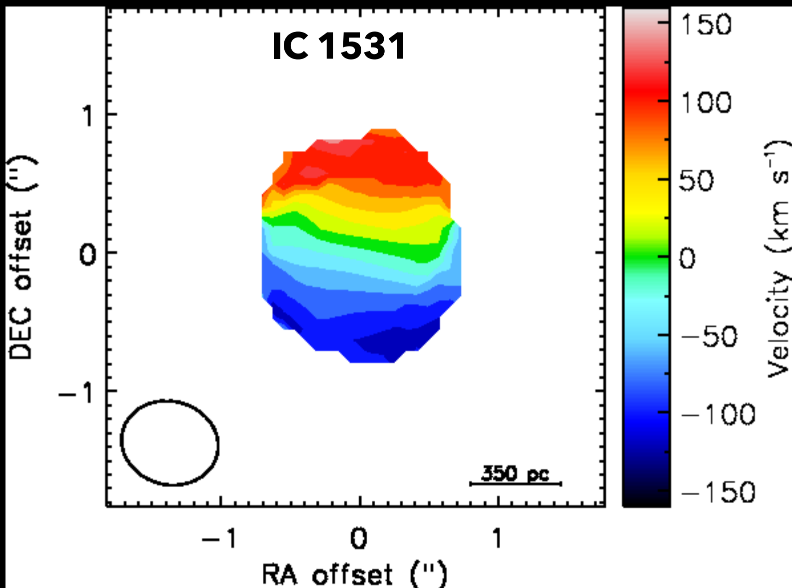


Chandra X-ray data (Ruffa et al. in prep)

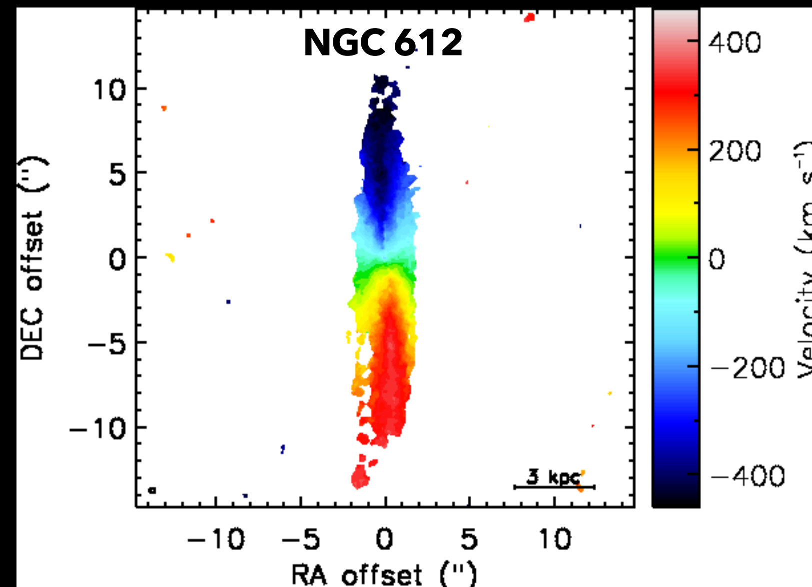
Properties of the molecular gas (Ruffa et al. 2019a,b)

Molecular gas content

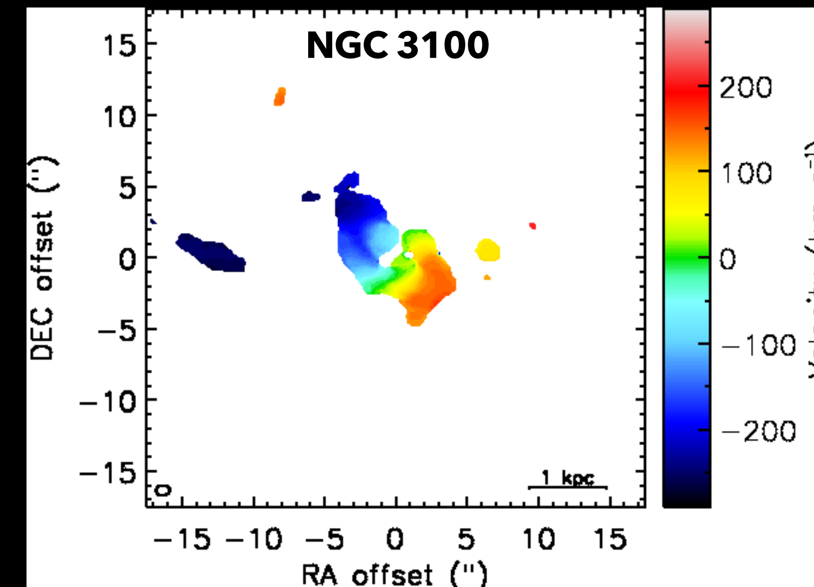
Cycle 3 CO(2-1) ALMA observations of 9 targets → **6 CO detections**



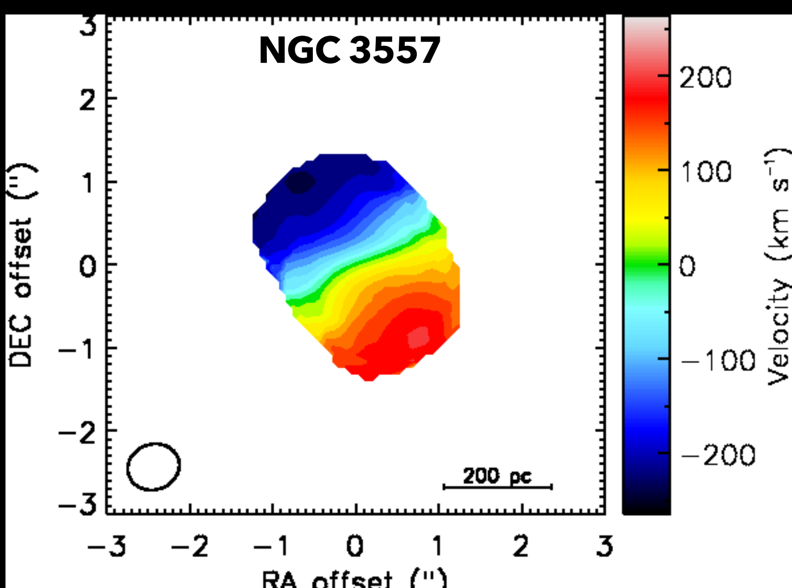
Size = 250 pc
$M_{H2} = 1.1 \times 10^8 M_\odot$



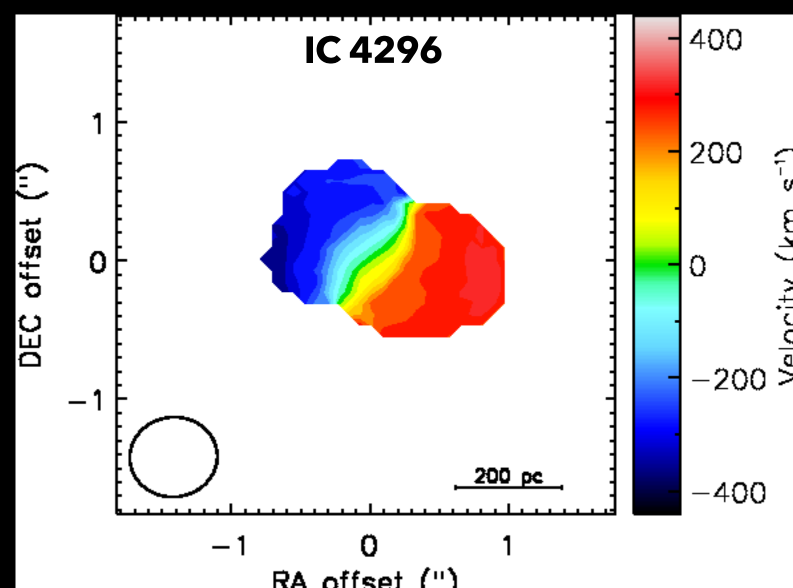
Size = 9.6 kpc
$M_{H2} = 2.0 \times 10^{10} M_\odot$



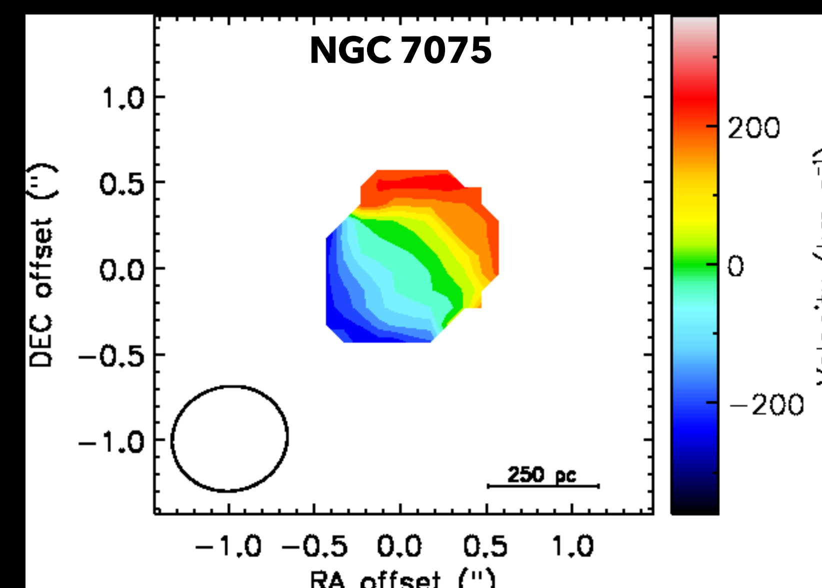
Size= 1.6 kpc
$M_{H2} = 1.2 \times 10^8 M_\odot$



Size = 300 pc
$M_{H2} = 6.2 \times 10^7 M_\odot$



Size = 200 pc
$M_{H2} = 2.0 \times 10^7 M_\odot$



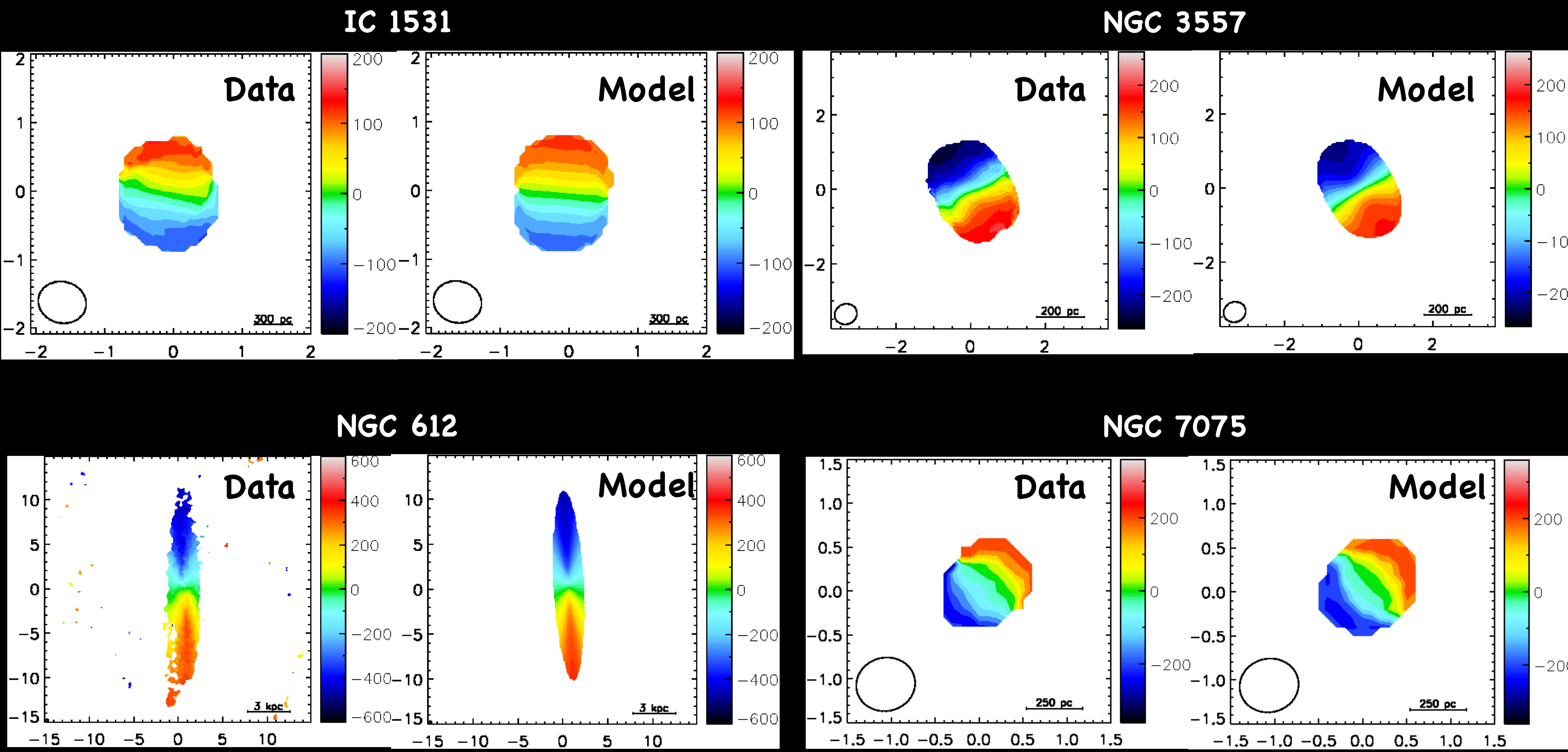
Size < 200 pc
$M_{H2} = 2.9 \times 10^7 M_\odot$

Rotating CO discs are very common in LERGs → **considerable amounts of cold gas in the inner (sub-)kpc scales**

Ruffa et al. 2019a

CO kinematics

Detailed **modelling** of the **CO kinematics** using the KinMS tool (Davis et al. 2013)

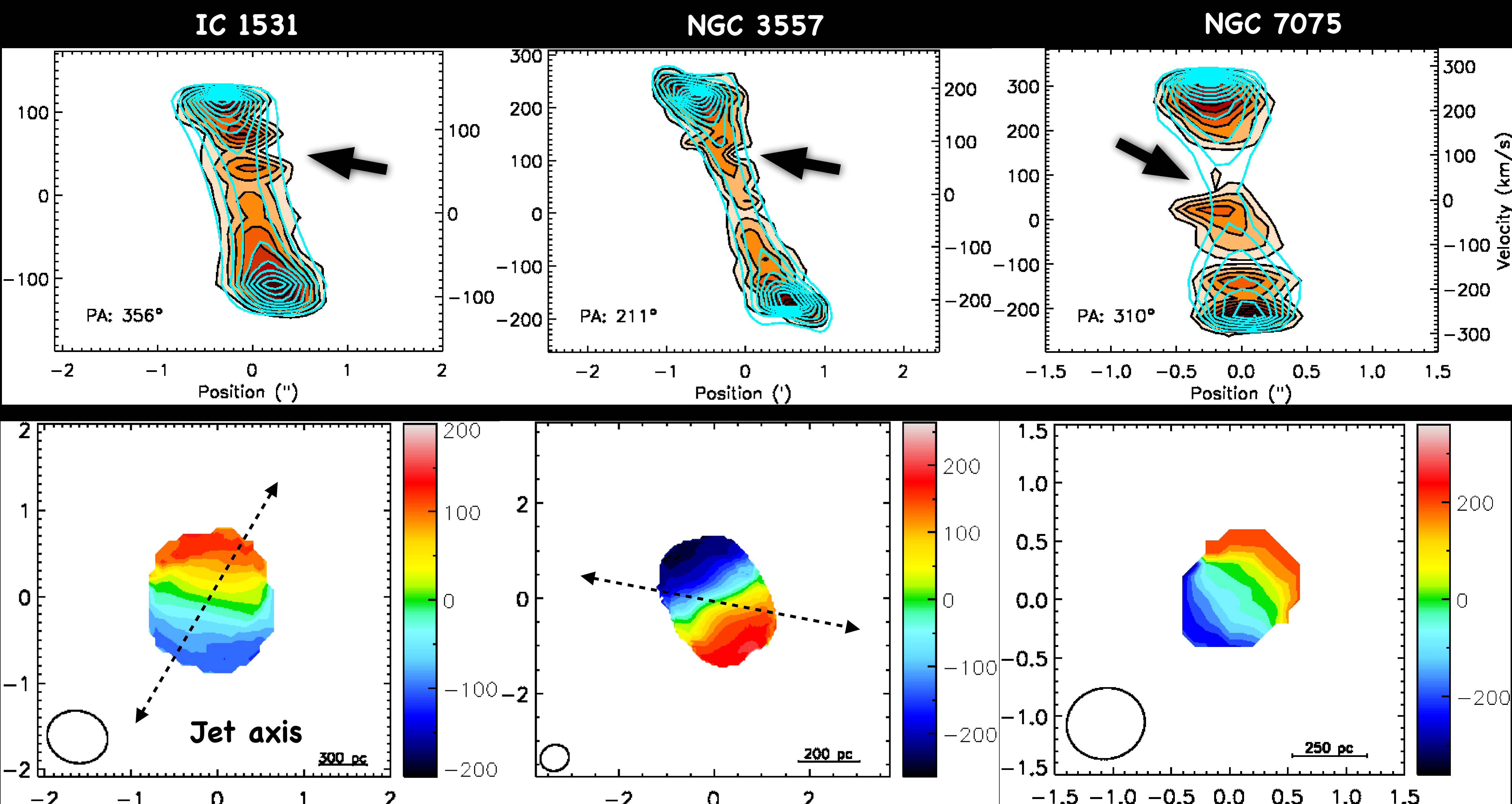


Gas kinematics well reproduced by **axysimmetric models** assuming purely circular motions → Bulk of the gas in **ordered rotation. Possible link with low-accretion rates in LERGs**

Ruffa et al. 2019b

CO kinematics

Signs of **asymmetries** and/or **perturbations** are ubiquitous



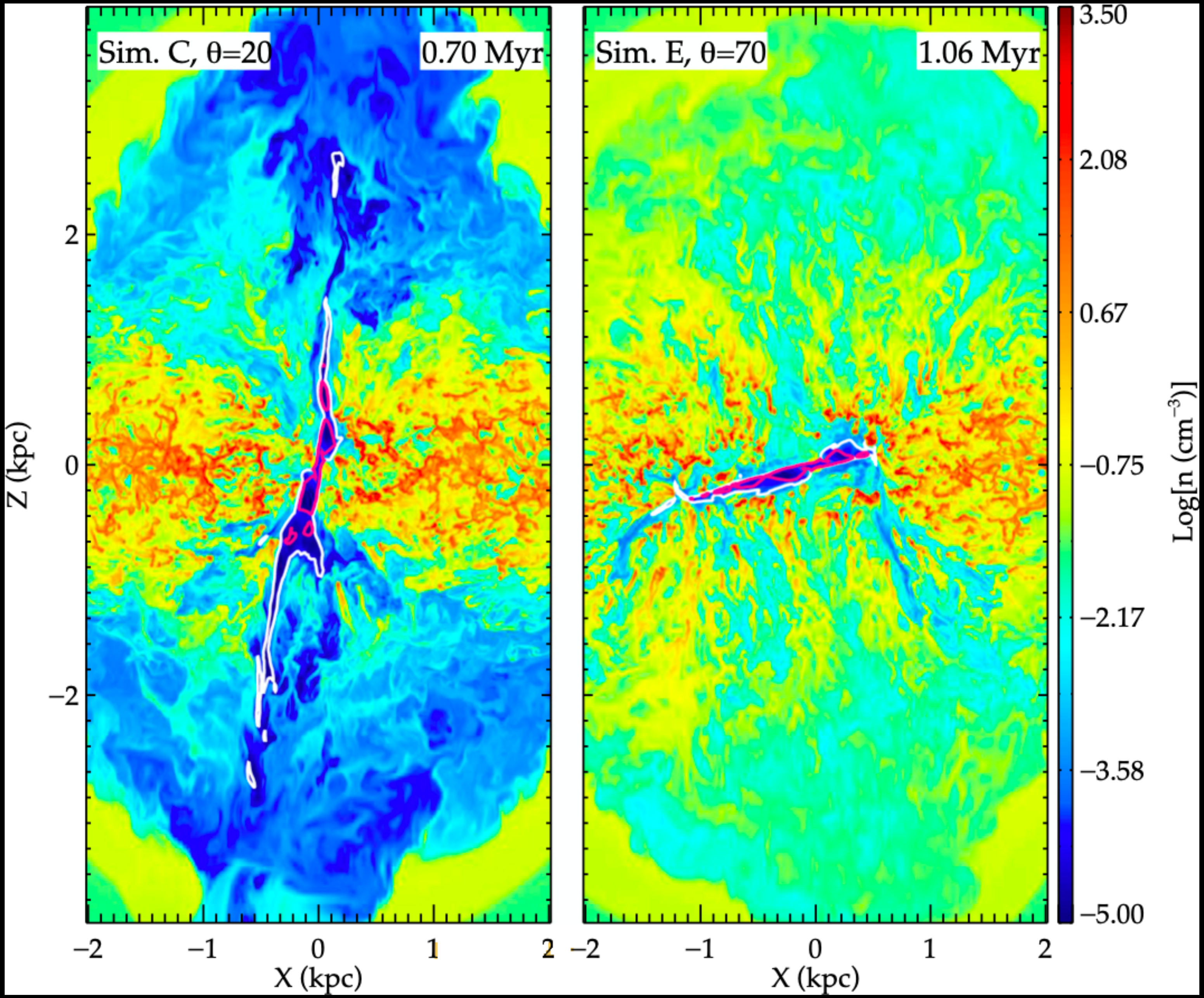
Possible cases of **jet/gas interactions** (claimed in NGC 3557 also by Vila Vilaro et al. 2019)

Ruffa et al. 2019b

Jets and molecular gas (Ruffa et al. 2020)

Jet-ISM interactions

Jet-ISM interaction processes sensitive to jet-disc **relative orientation** ➜ **stronger for $\vartheta_{dj} \geq 45$ deg**



(Mukherjee et al. 2018b)

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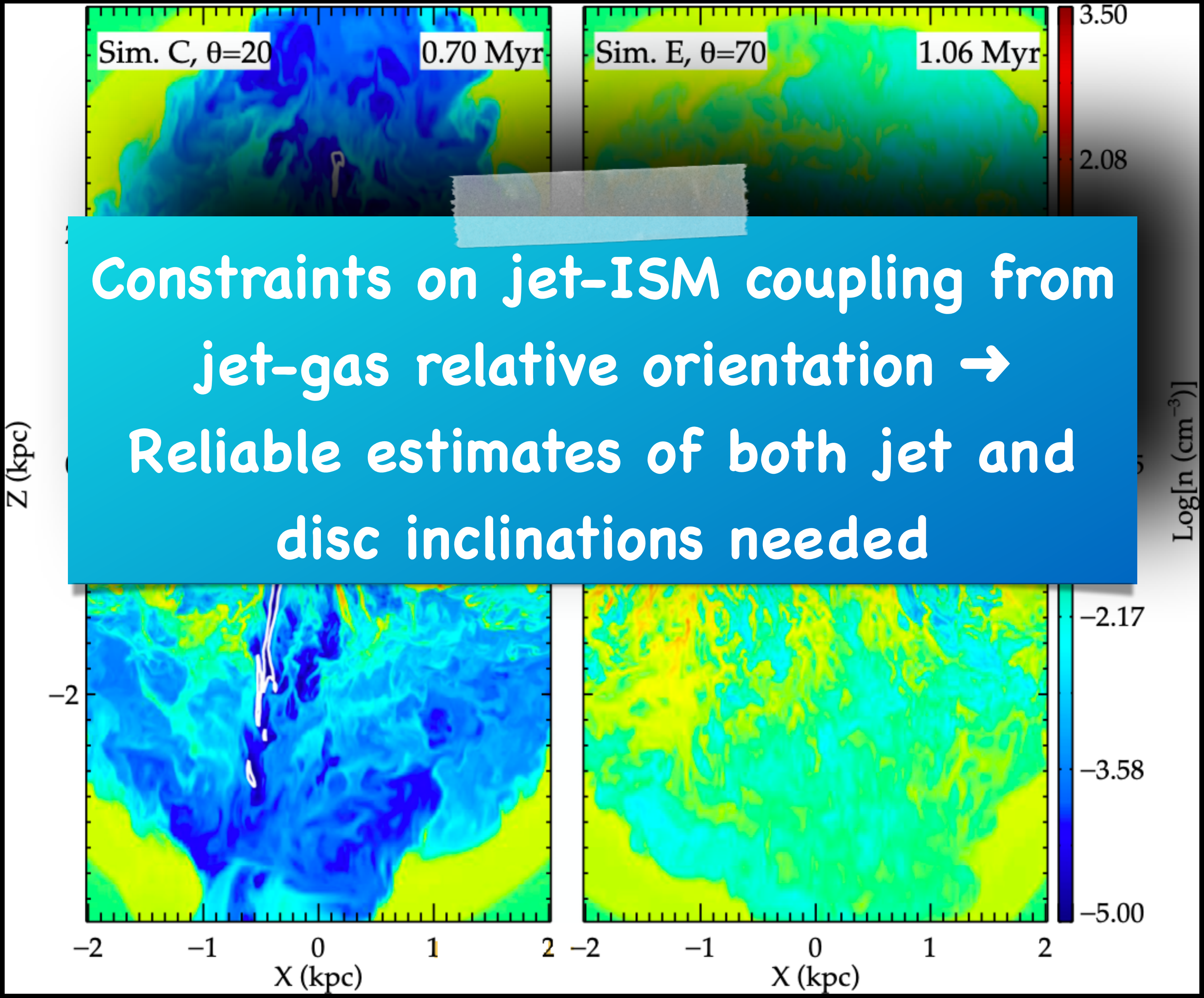


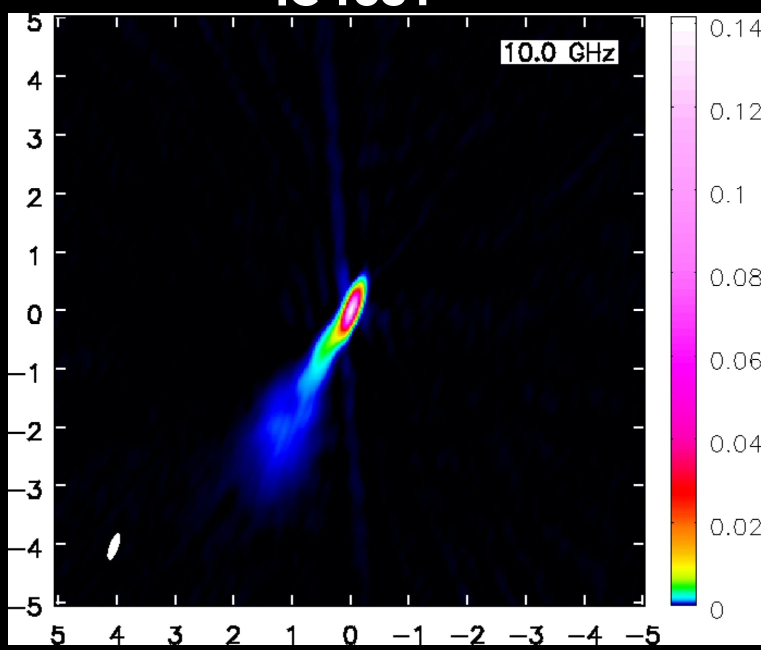
Constraints on jet-ISM coupling from jet-gas relative orientation ➜ Reliable estimates of both jet and disc inclinations needed

(Mukherjee et al. 2018b)

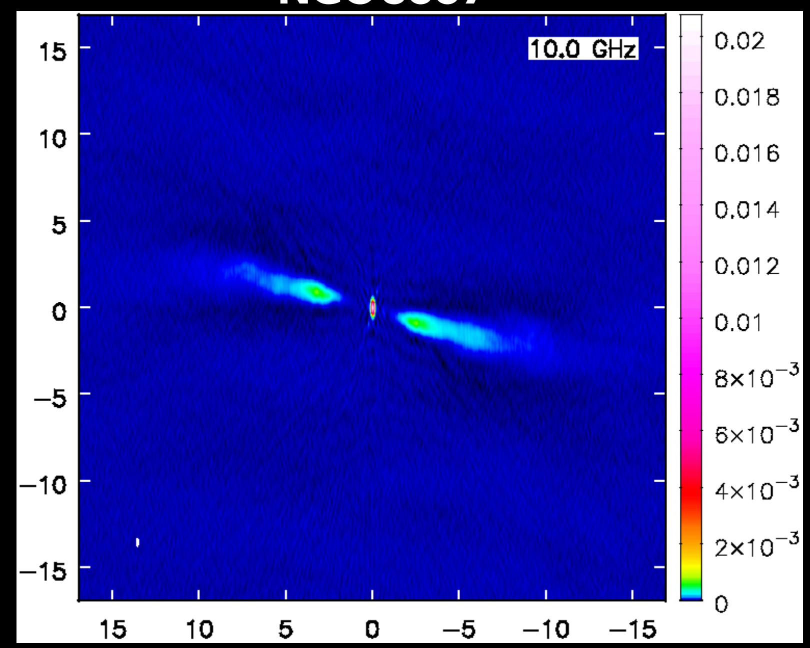
JVLA observations

- CO inclinations from **kinematic modelling**
- Jet inclination from **high-resolution** JVLA data at 10 GHz for **five CO-detected** sources

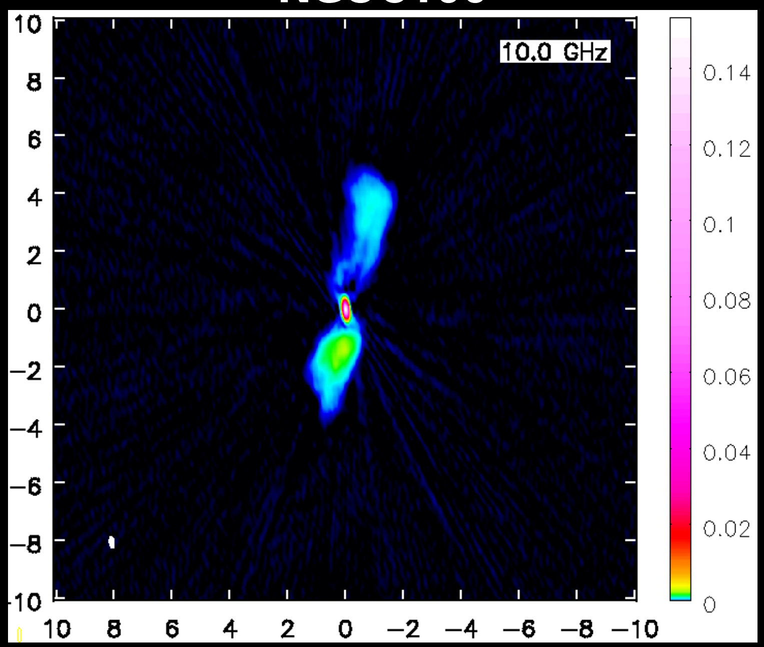
IC 1531



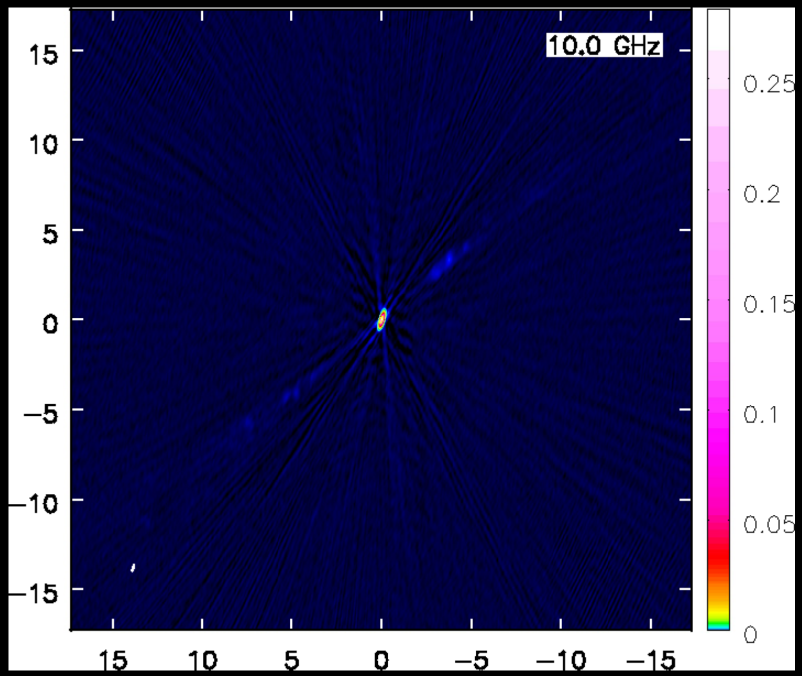
NGC 3557



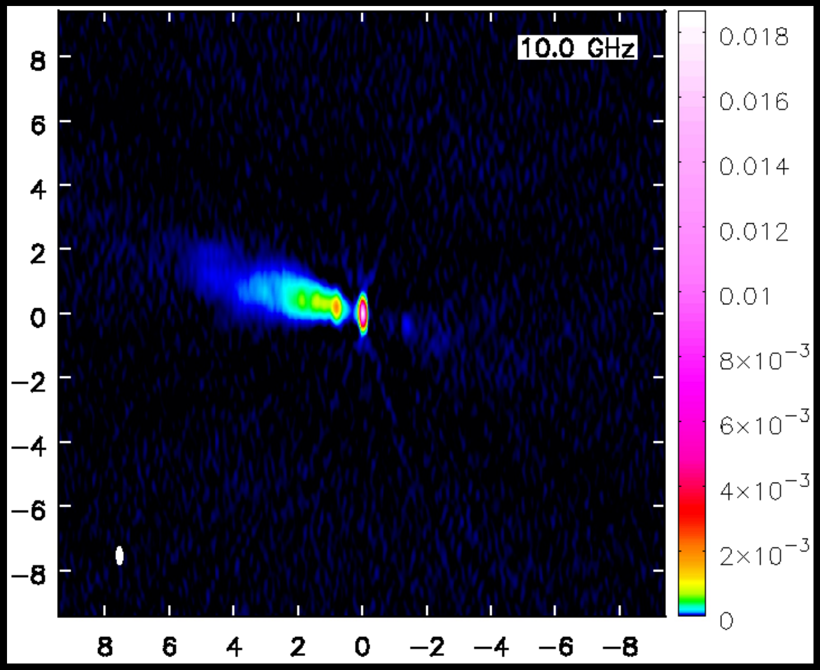
NGC 3100



IC 4296



NGC 7075



Resolution: 0.37″ – 0.46″ (≤ 200 pc)

Ruffa et al. 2020

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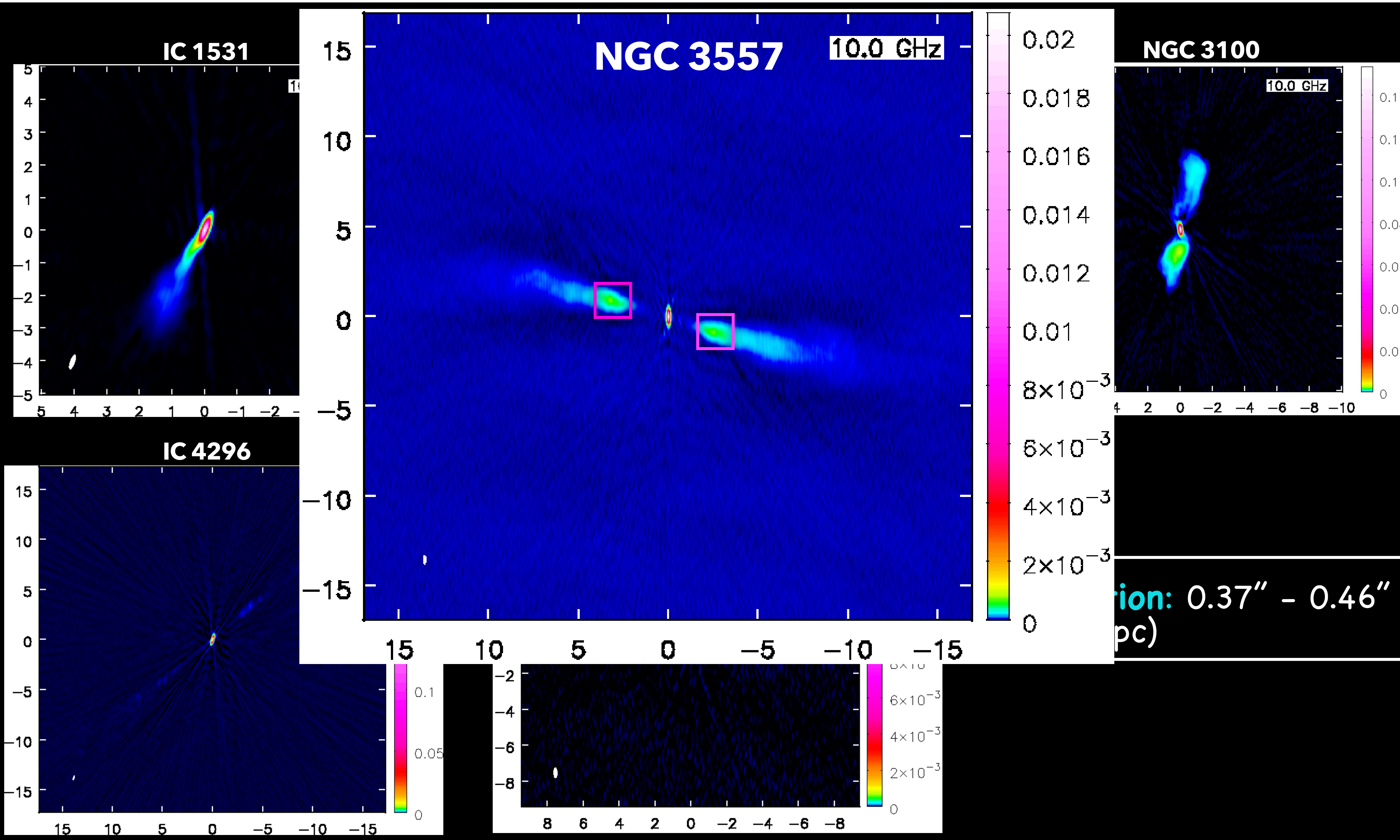
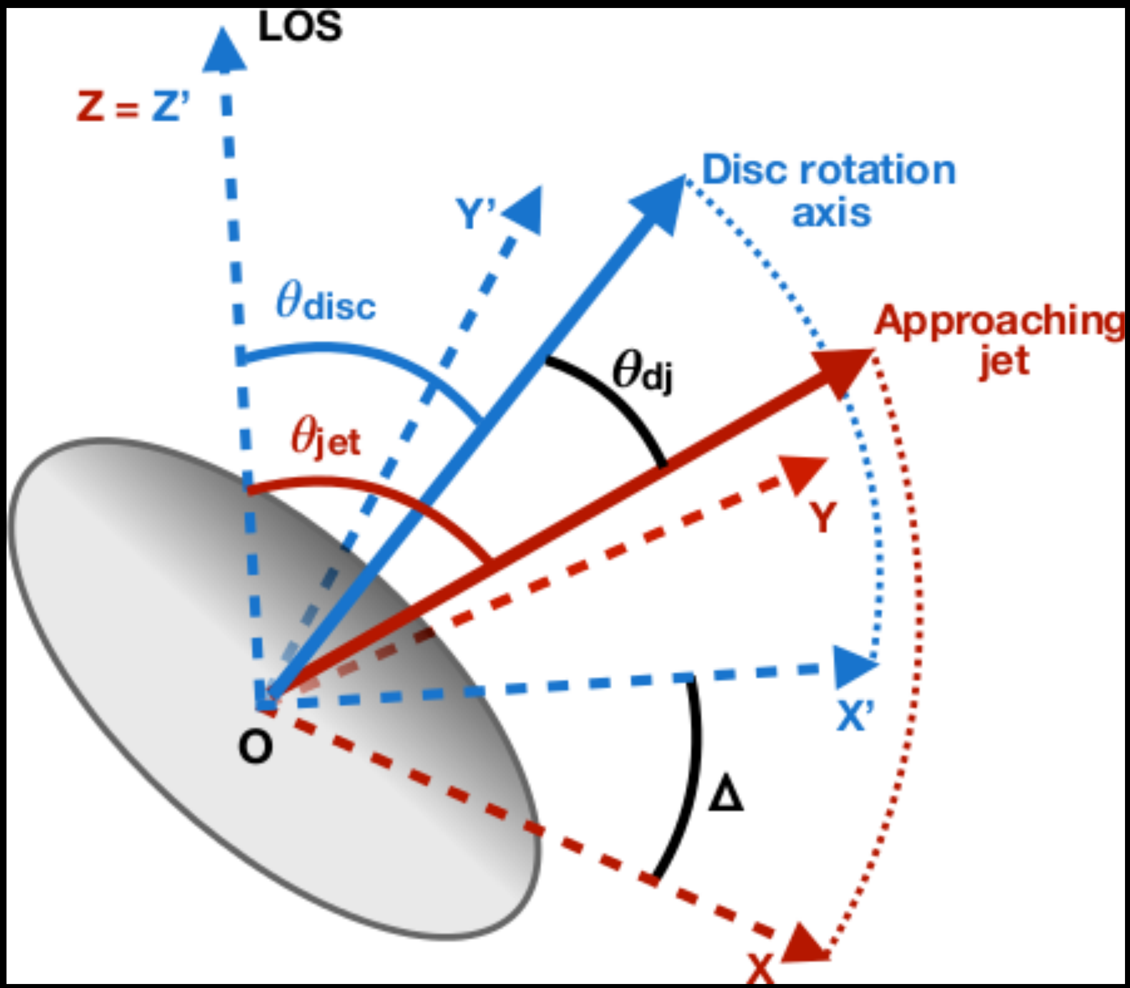
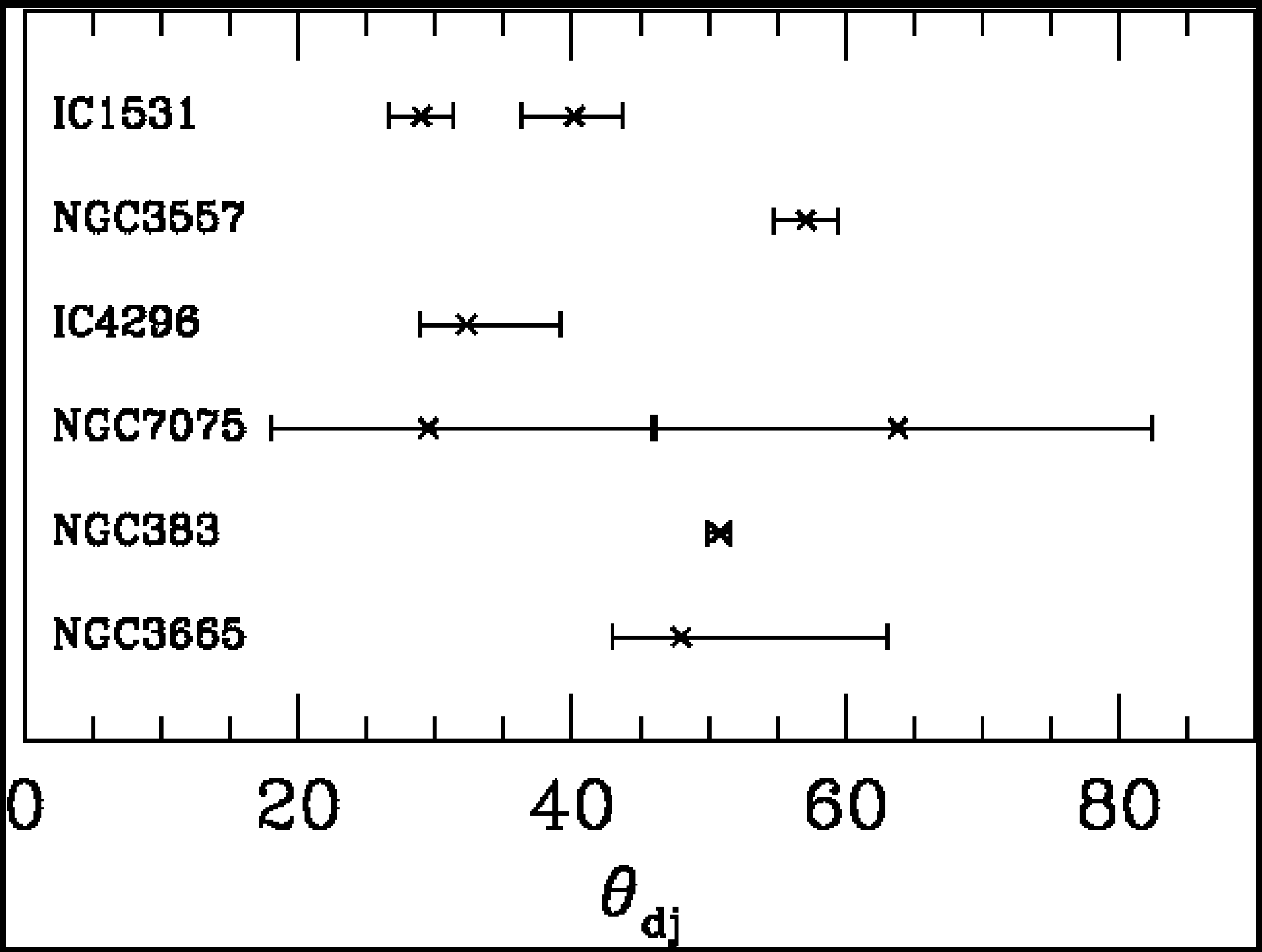


Ruffa et al. 2020

Jet/disc relative inclination

Once a **3D jet/disc geometry** is assumed ➜ **intrinsic relative inclination** angles





- **Wide range** of angles but marginal **preference** around **45deg:** consistence with the statistical analysis of Verdoes Kleijn & de Zeeuw (2005) but **for the first time in 3D**
- **No simple relation** between the gas rotation and radio jet axes (defined by the axis of the inner accretion disc and/or the spin of the black hole)

Ruffa et al. 2020

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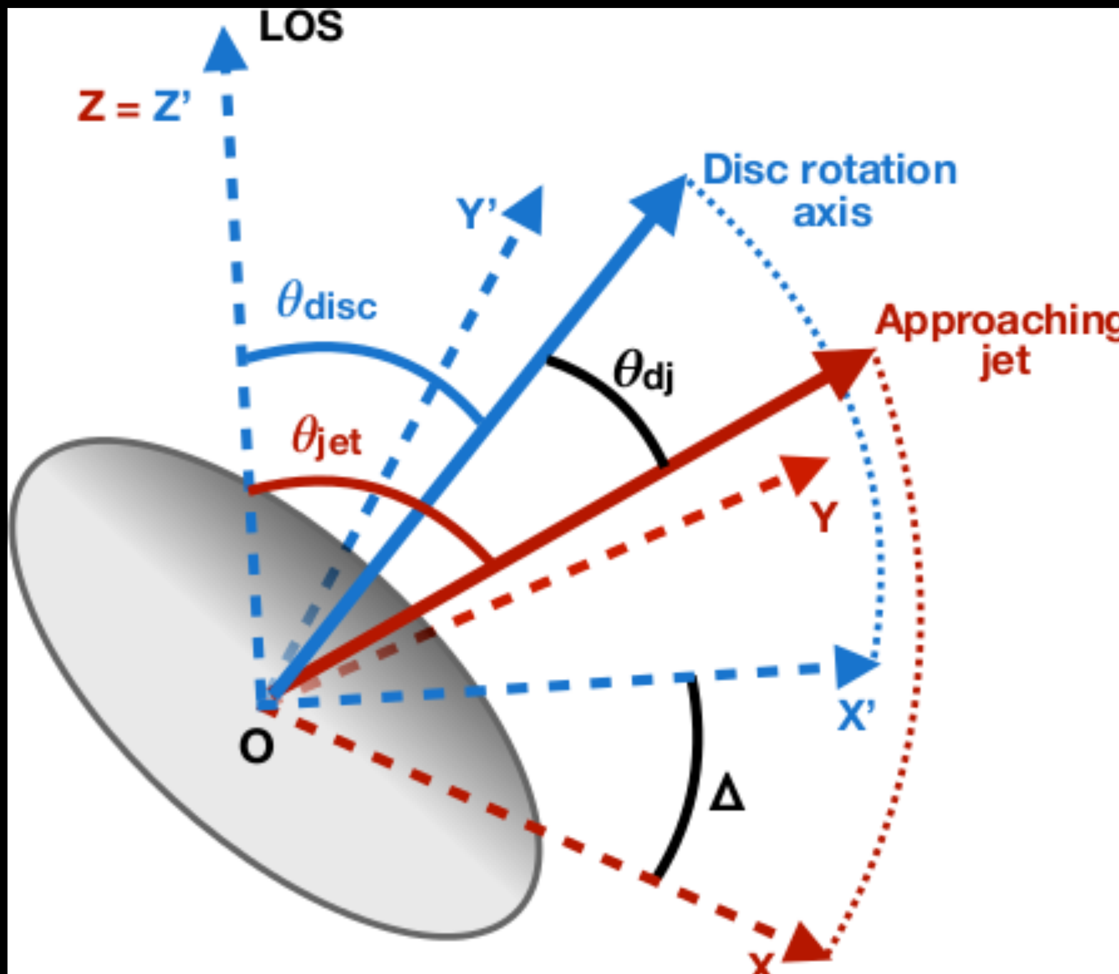

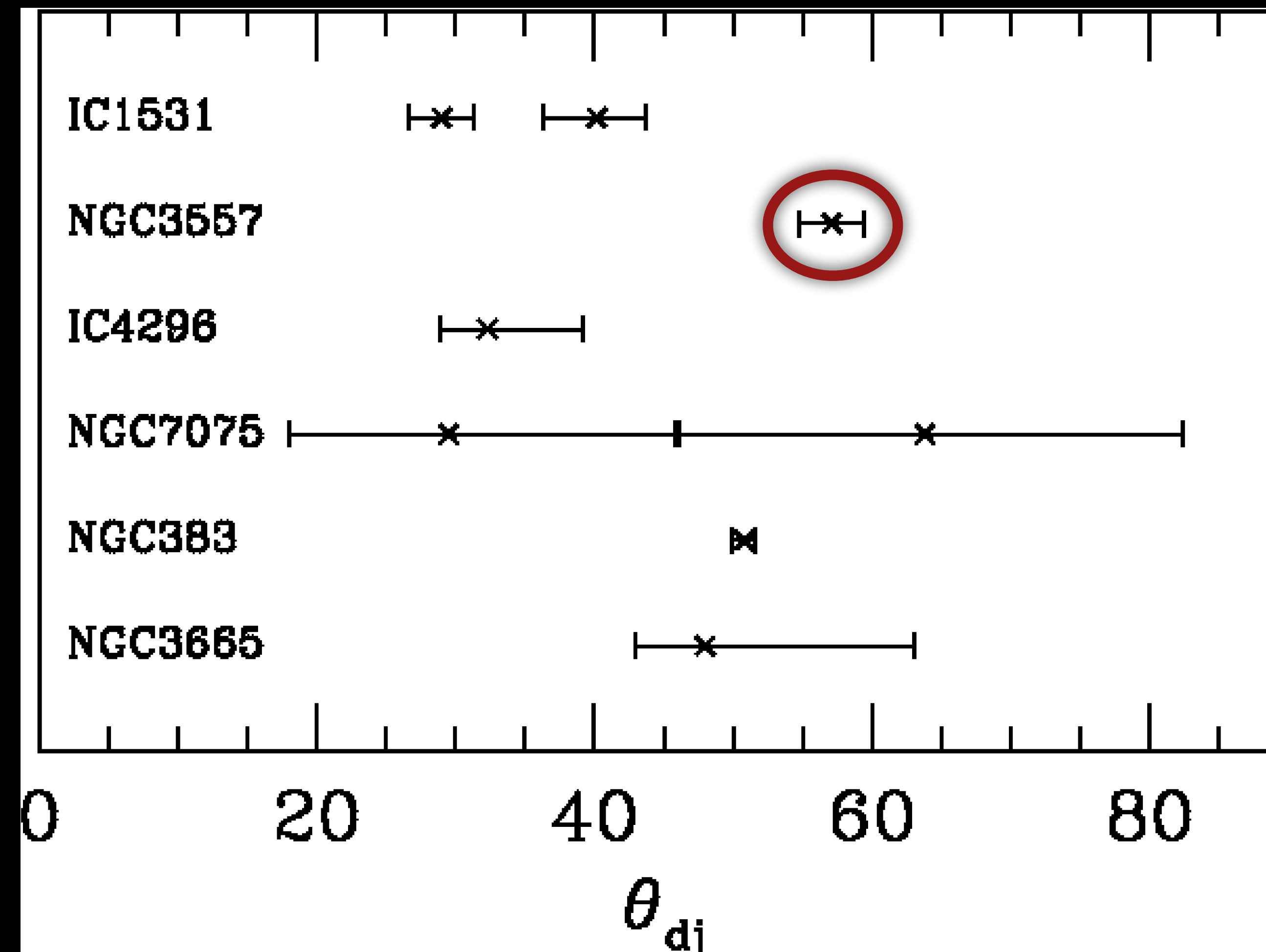

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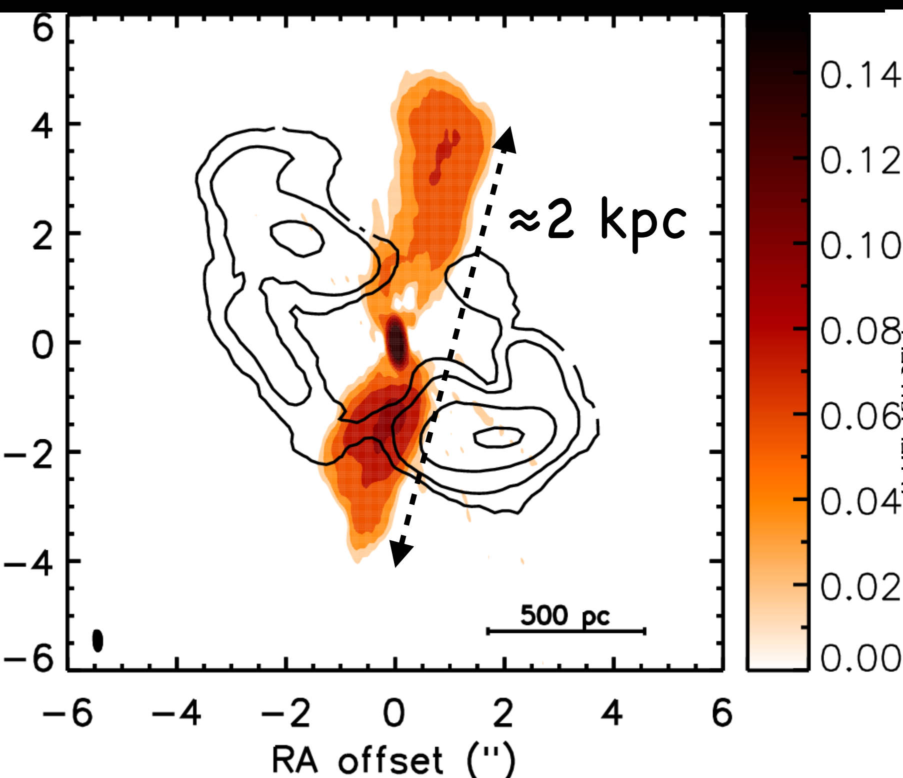
- **No simple relation** between the gas rotation and radio jet axes (defined by the axis of the inner accretion disc and/or the spin of the black hole)
- Support for **jet-ISM coupling** in **NGC 3557**

Ruffa et al. 2020

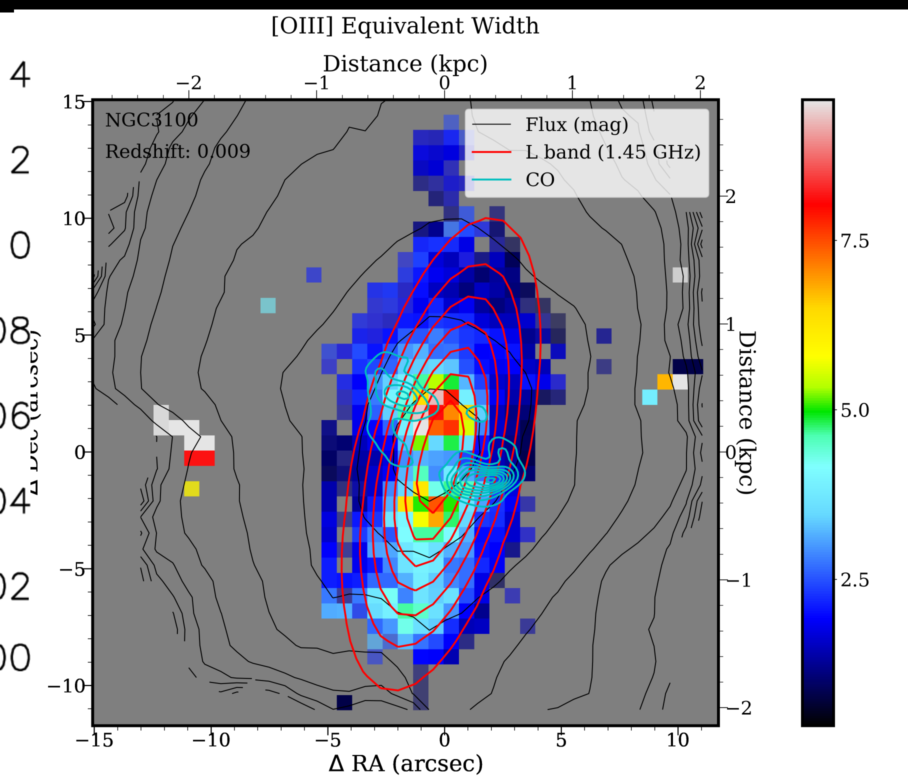
The special case of NGC 3100

CO(2-1) mom0 over 10GHz continuum



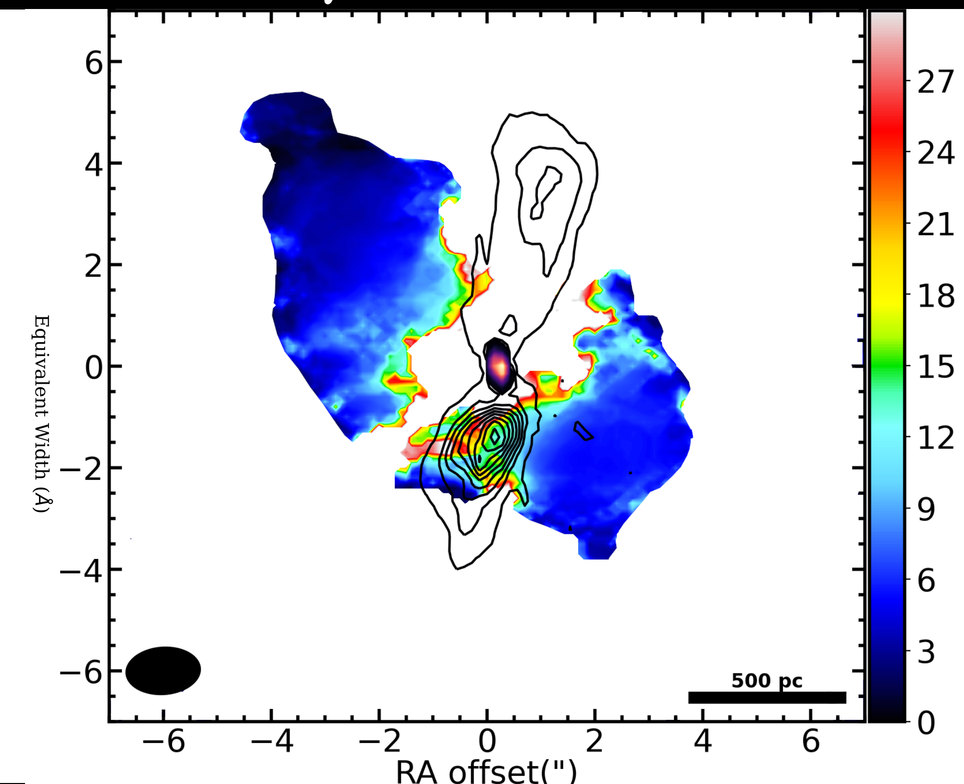
(Ruffa et al. 2020)

[OIII] EW



(Warren et al. 2021, in prep.)

CO(3-2)/CO(1-0) flux density ratio + 10GHz cont



(Ruffa et al. 2021, submitted)

- Disc **disruption** in the direction of the **northern jet**
- Jet **morphological and surface brightness** asymmetries
- **[OIII] EW enhancement** along the jet axis
- **Enhanced** line ratios along the path of the jet ➜ **higher gas excitation** ($T_{ex} \gg 50$ K)

Origin of
the molecular gas
(Ruffa et al.
2019a,b,2021)

Internal vs external accretion

- Detection of **significant amount** of cold gas in **gas poor** ETGs ➜ recent **regeneration**
- **Origin** of the cold gas **still debated**: either **internal** (stellar mass loss, hot halo cooling) or **external** (interactions or minor mergers)
- Hot halo cooling (either smooth or chaotic) **most likely** mechanisms for LERGs at the centre of groups and clusters
- Incidence of hot halo cooling in more isolated LERGs not clear: galaxy-galaxy interactions may have a major role (e.g. Sabater et al. 2013)

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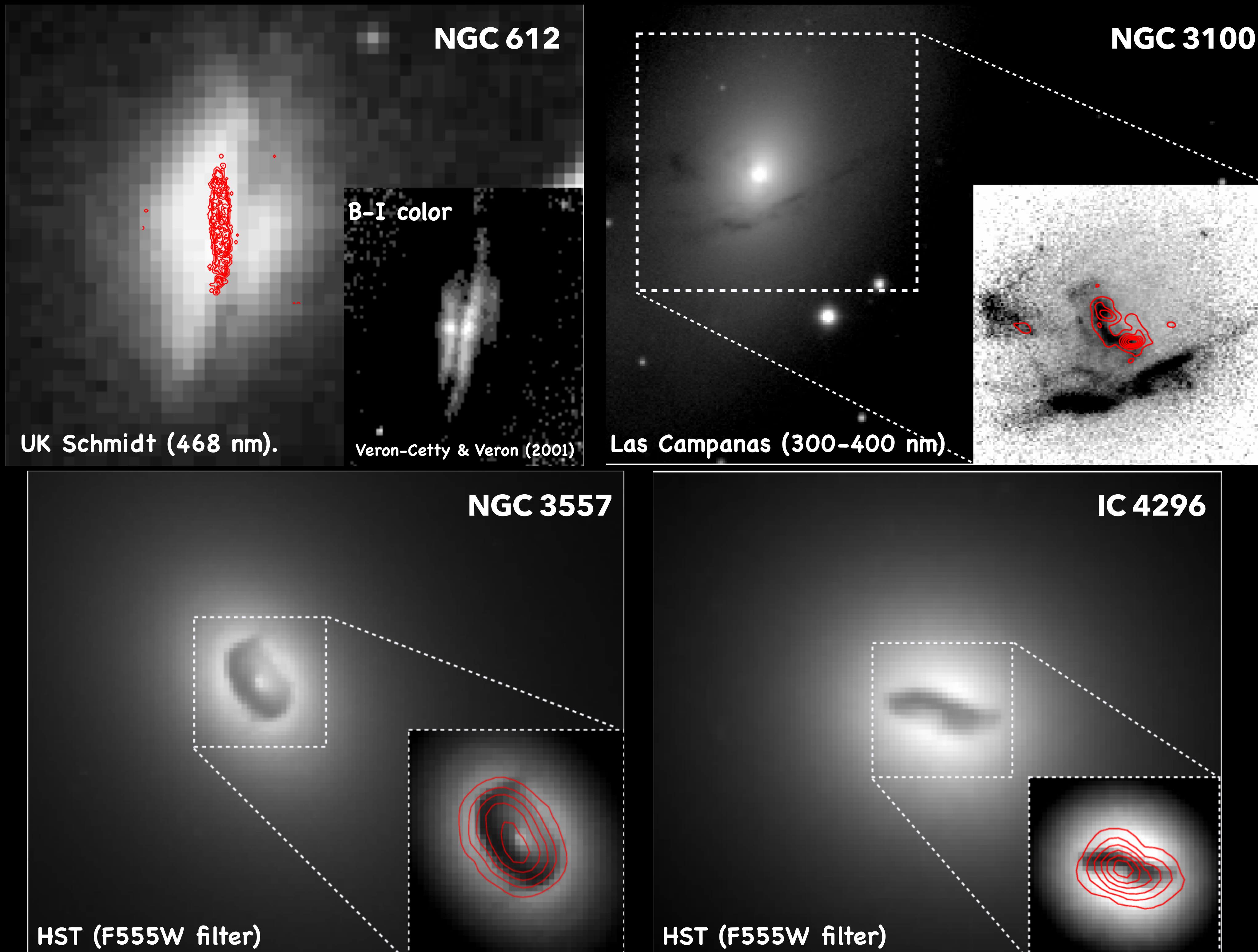
Five out of six CO-detected sources are in low-density environments

Target name	Environment
IC 1531	isolated
NGC 612	pair/companion
NGC 3100	pair/companion
NGC 3557	poor group
IC 4296	cluster/companion
NGC 7075	pair/companion

Dust and molecular gas

Molecular gas tightly **co-spatial** with dust ➜ **same** ISM component



Gas **cooling** from hot haloes **expected** (e.g. Valentini & Brighenti 2015) and **observed** (e.g. Tremblay et al. 2018, Temi et al. 2018) **essentially dustless** ($D/G \approx 10^{-5}$)

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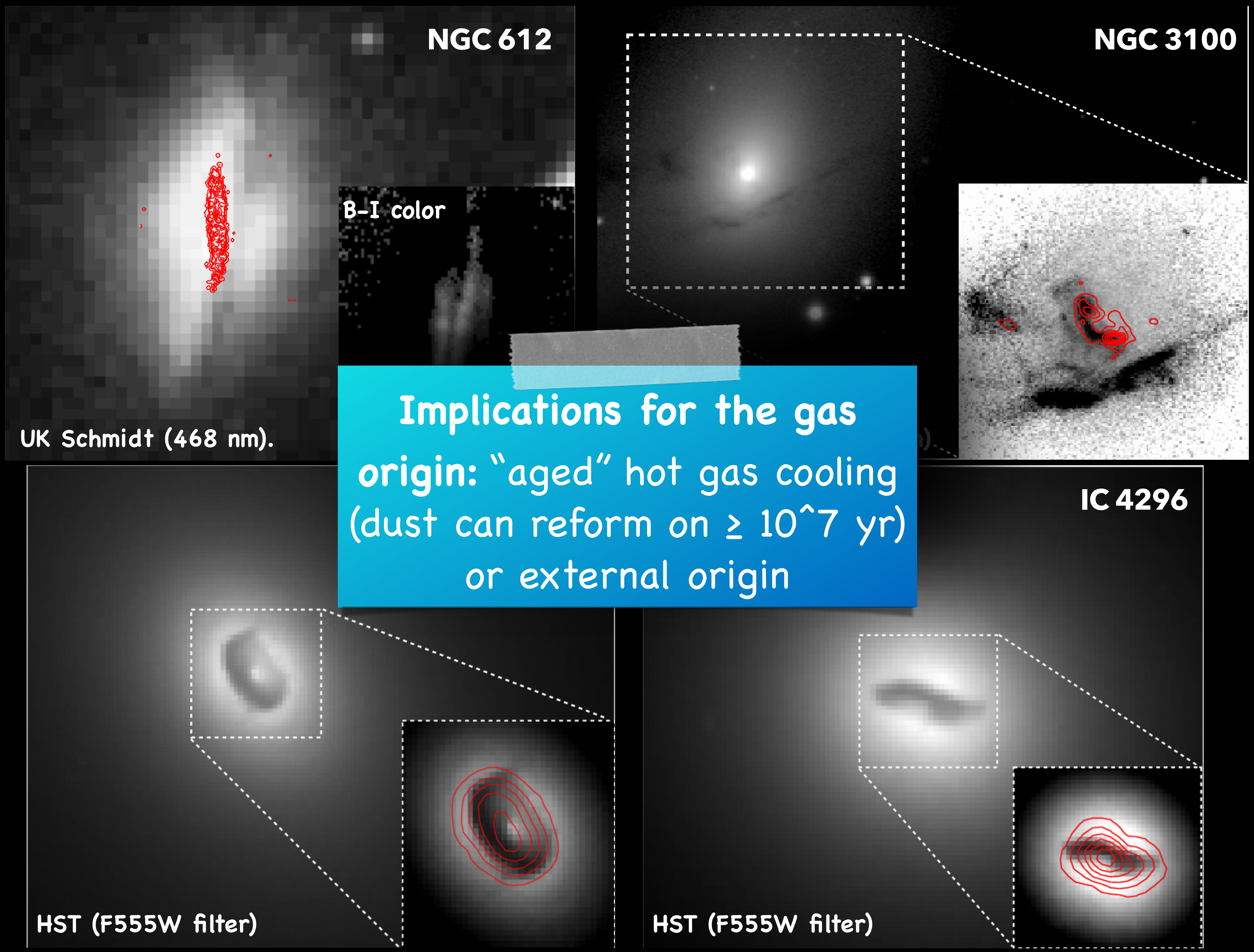

Implications for the gas origin: "aged" hot gas cooling (dust can reform on ≥ 10^7 yr) or external origin

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Internal vs external accretion

Multi-wavelength indicators (e.g. molecular gas/stars kinematic misalignments, sub-solar metallicities) ➜ **external origin strongly favored in at least two cases**

Important insights from the large-scale cold gas component ➜ **ATCA HI observations** recently acquired

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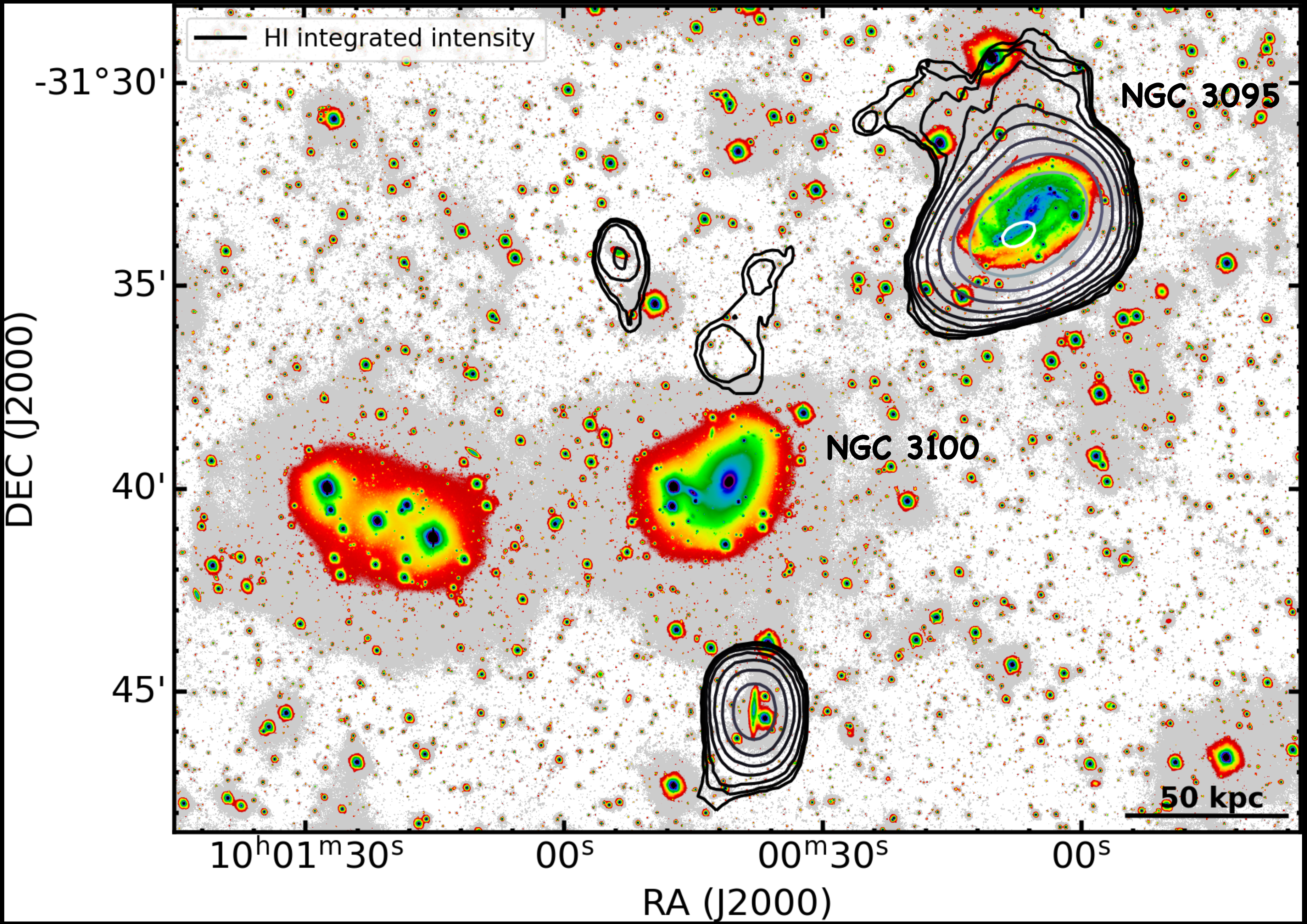

Hint of **HI bridge** connecting NGC 3100 with the companion NGC 3095 (Maccagni et al., in prep.)

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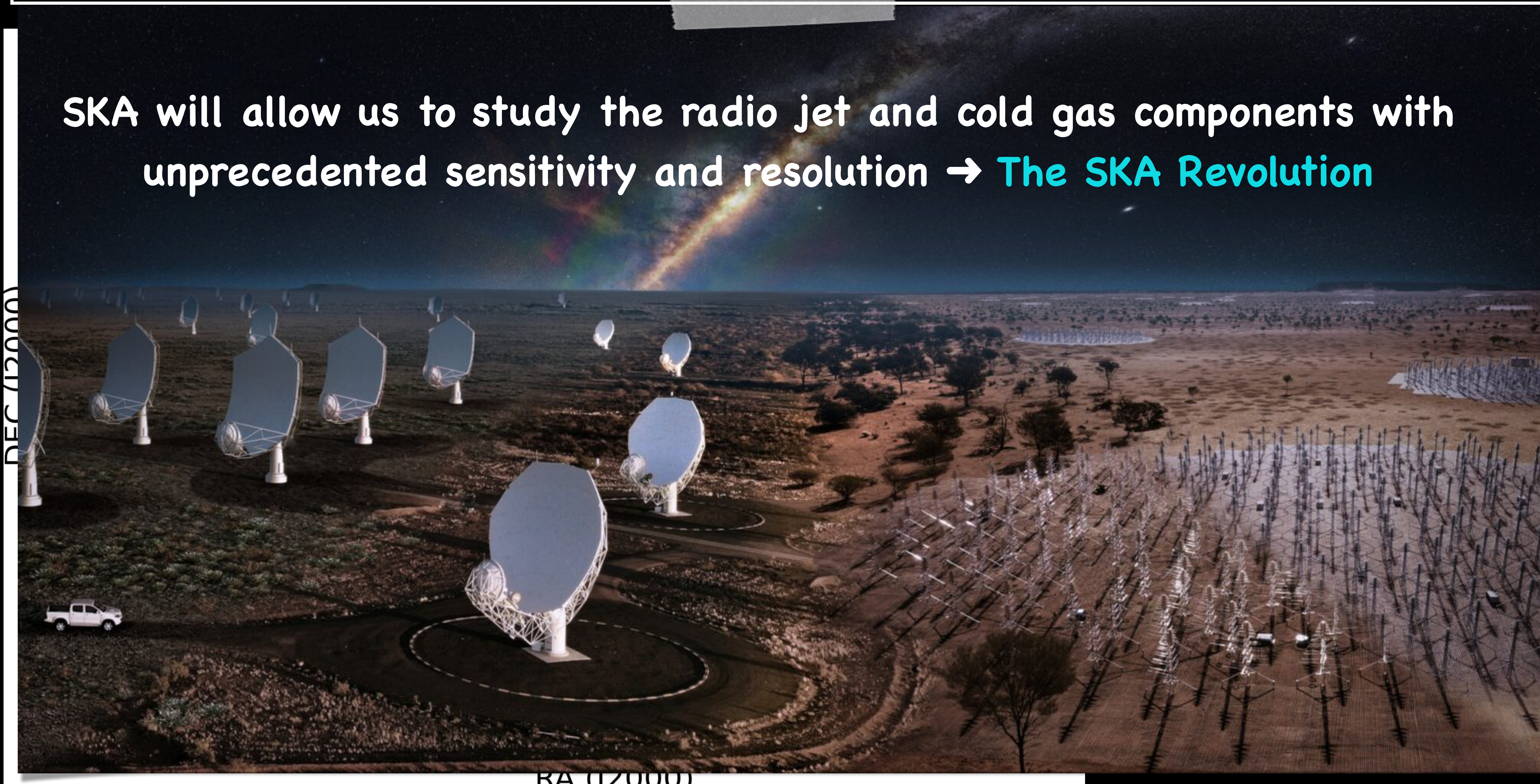


Concluding remarks

MOLECULAR GAS CONTENT

- Rotating CO discs are very common in LERGs ➜ **considerable amounts of cold gas confined in the inner (sub-)kpc scales**

MOLECULAR GAS KINEMATICS

- Bulk of the gas in ordered rotation (at least at the current spatial resolution) ➜ **this may be consistent with low-accretion rates in LERGs**
- Asymmetries, perturbations and/or non-circular motions are ubiquitous ➜ **the observed discs may be an essential link in the fueling/feedback of LERGs**

JETS AND MOLECULAR GAS

- Wide range of jet/disc relative orientation angles but marginal preference around 45deg ➜ **no simple axi-symmetry between black hole and inner/outer disc**
- NGC 3557 object with the largest ϑ_{dj} ➜ **support for jet-ISM coupling**
- NGC 3100 most interesting case ➜ **evidence of both gas inflow and jet-ISM interaction**

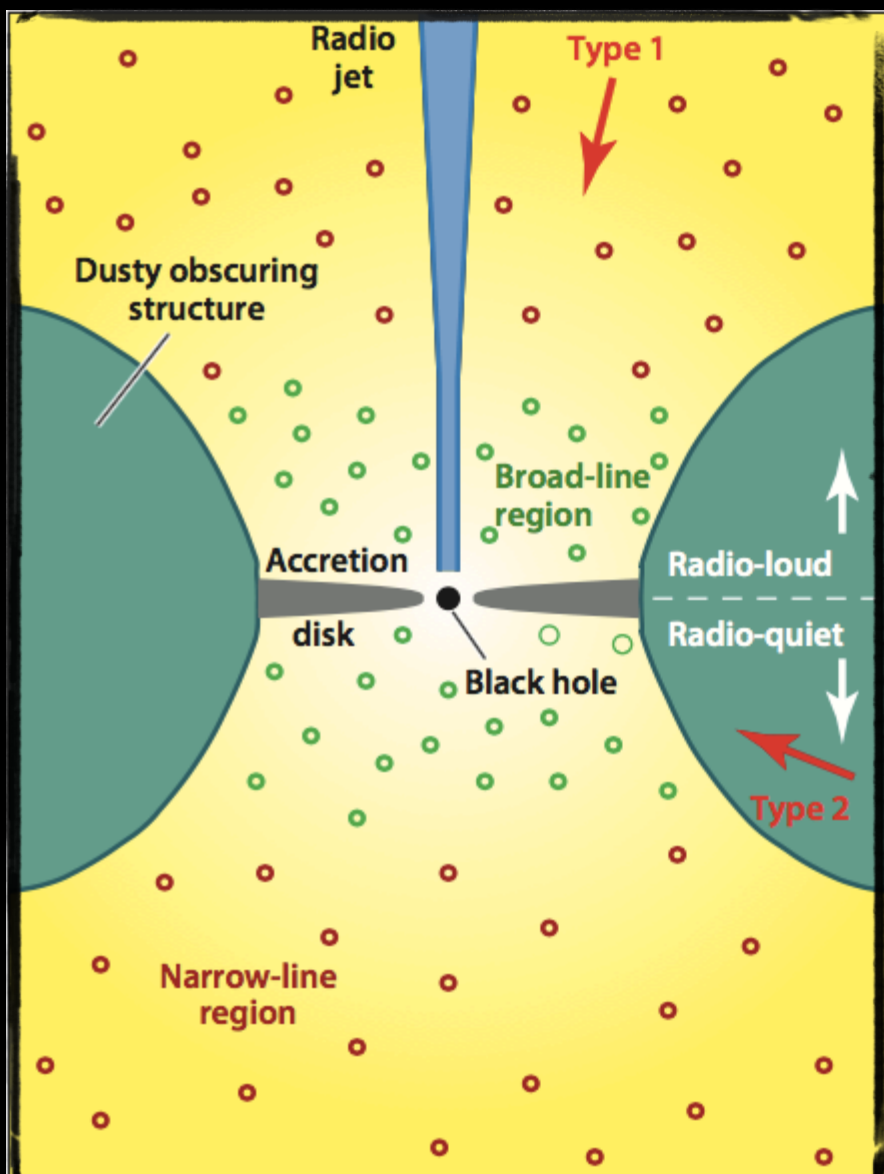
ORIGIN OF THE MOLECULAR GAS

- Dust/molecular gas co-spatiality ➜ **difficult to reconcile with hot gas cooling**
- External origin strongly favoured in sources with companions ➜ **support for galaxy-galaxy interaction having a major role for LERGs in low-density environments**

Local AGN population

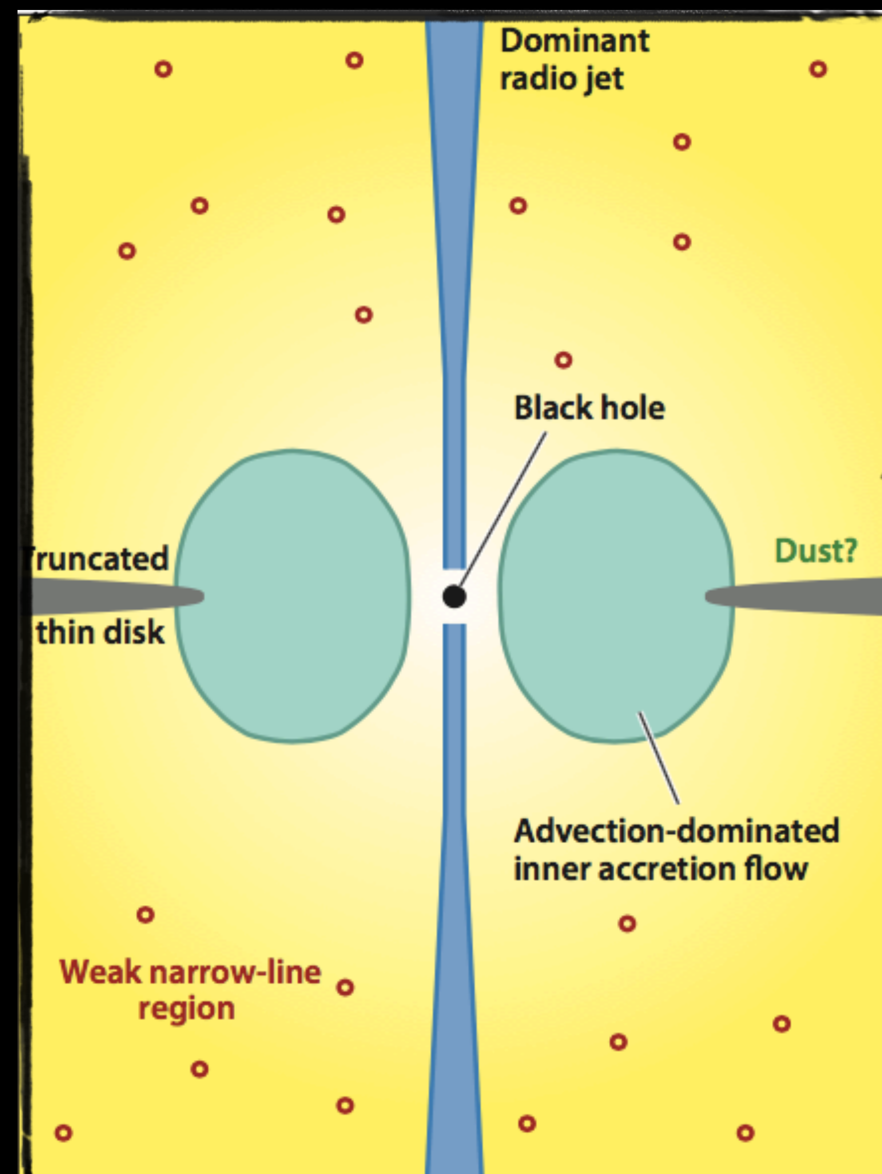
Two main AGN modes in the **low-redshift** ($z<0.1$) Universe ➜ different **dominant type** of feedback

Radiative-mode AGN



High accretion rates ($\dot{M} \gtrsim 0.01\dot{M}_{edd}$)

Jet-mode AGN



Low accretion rates ($\dot{M} \ll 0.01\dot{M}_{edd}$)

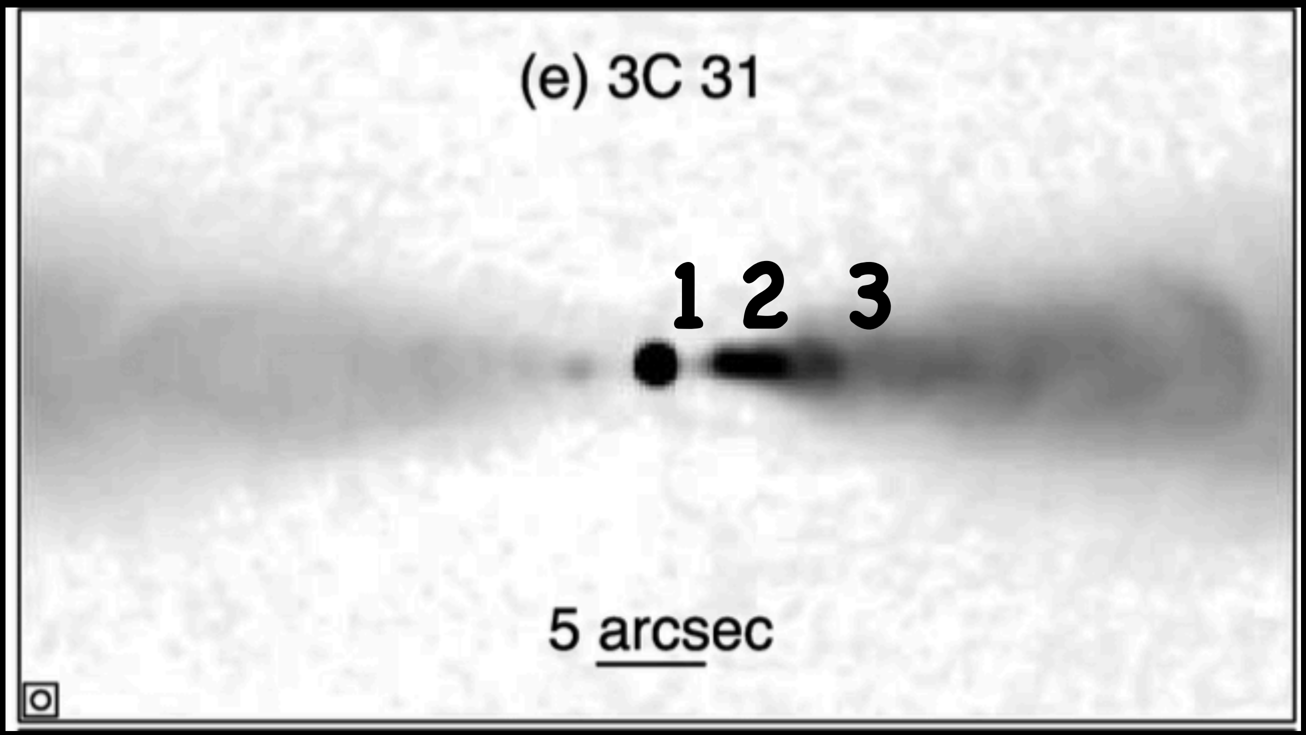
(Heckman & Best 2014)

Jet inclination

FRI jets are **intrinsically identical, axisymmetric** flows of particles initially relativistic and decelerating on kpc-scales

Three inner (within 1 kpc) features:

1. **Inner region** of well-collimated flow, typically observed as **a gap**
2. Brightness **flaring point** at increasing distance from the core
3. **Flaring region** where they decelerate and the apparent opening angle increase



(Laing & Bridle 2014)

Apparent differences due to **relativistic aberration** ➜ the brightness difference between the jet/counter jet (i.e. **sidedness ratio**) give information on the jet inclination

Sidedness ratio

$$R = \frac{I_{\rm j}}{I_{\rm cj}} = \left(\frac{1+\beta cos\theta}{1-\beta cos\theta}\right)^{2+\alpha}$$

β = 0.75; α = 0.6 ($S \propto \nu^{-\alpha}$) ➜

Jet inclination

$$\theta = \arccos\left(\frac{1}{\beta}\frac{R^{\frac{1}{2+\alpha}}-1}{R^{\frac{1}{2+\alpha}}+1}\right)$$

Jets and CO discs

Assumption: Jets are intrinsically symmetrical, relativistic flows → **sidedness ratio**

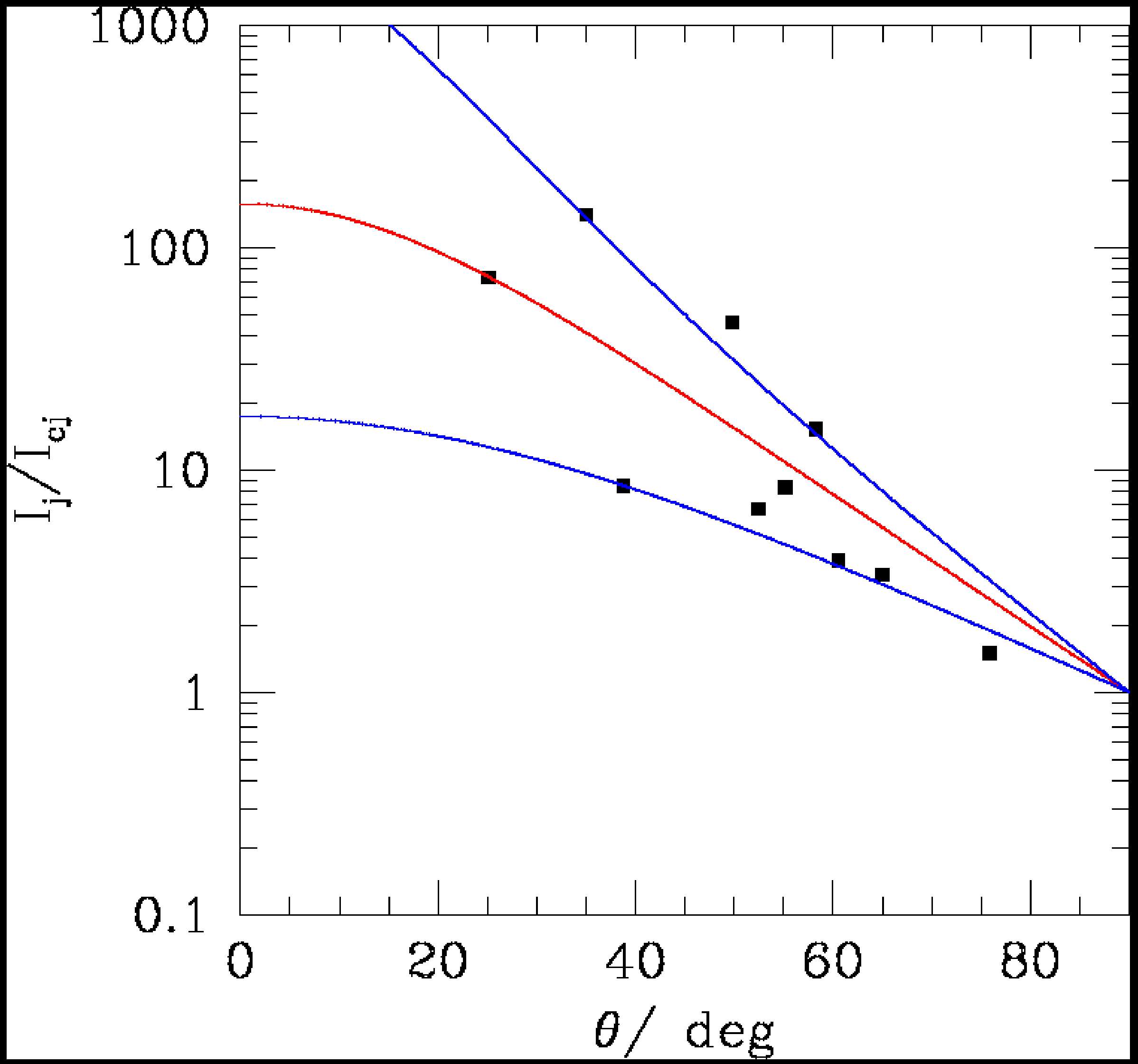
$$R = \frac{I_{\rm j}}{I_{\rm cj}} = \left(\frac{1+\beta cos\theta}{1-\beta cos\theta}\right)^{2+\alpha}$$

- θ ($0 \leq \theta \leq \pi/2$): angle to the l.o.s.
- β = v/c (v = flow velocity)
- α: jet spectral index

β and θ cannot be derived independently → Laing & Bridle (2014) provide a calibration of the relation between R and θ

$$\theta = \arccos\left(\frac{1}{\beta}\frac{R^{\frac{1}{2+\alpha}}-1}{R^{\frac{1}{2+\alpha}}+1}\right)$$

- β = 0.75 (best-fit); α = 0.6 ($S \propto \nu^{-\alpha}$)



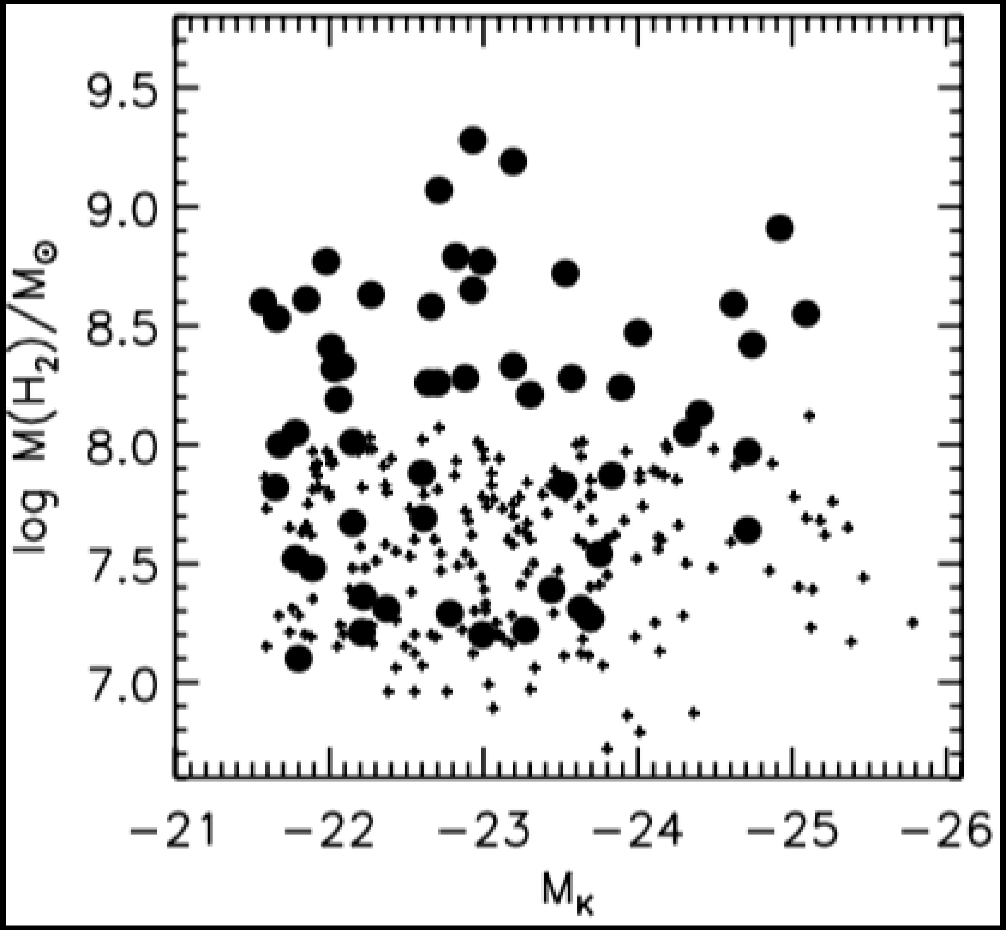
Ruffa et al. 2020

Internal processes

Stellar mass loss

Always present. Correlation expected between molecular and stellar masses if dominant mechanism

No correlation found in both radio-loud and radio-quiet ETGs

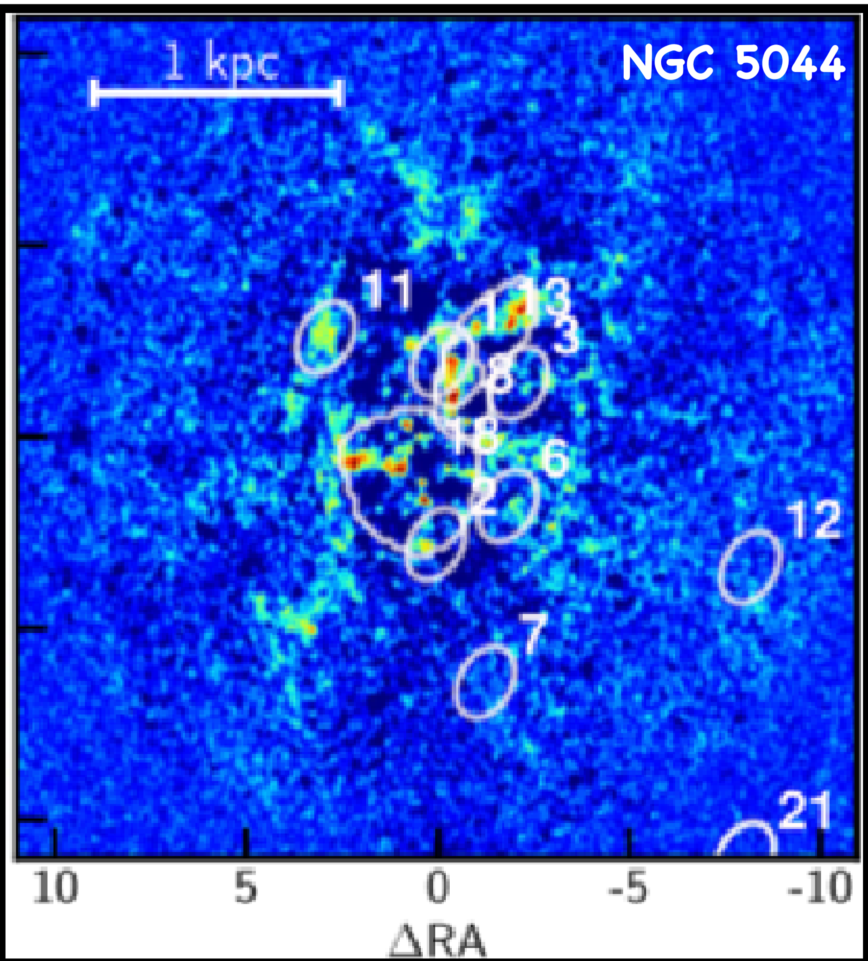


(Young et al. 2011)

Hot halo cooling

Either smooth (e.g. Lagos et al. 2015) or chaotic (as in CCA; e.g. Gaspari et al. 2015)

Filaments or blobs reminiscent of chaotic cooling observed in LERGs at the centre of groups/clusters



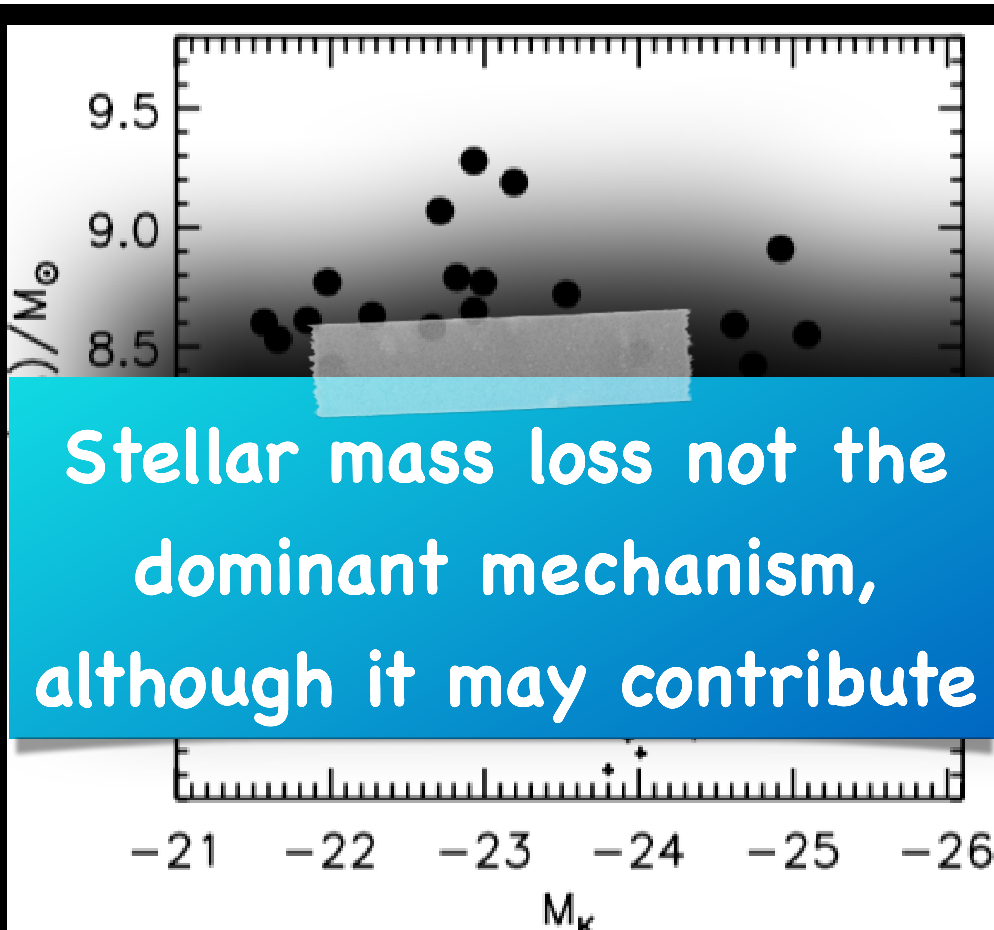
(David et al. 2014; Temi et al. 2018)

Internal processes

Stellar mass loss

Always present. Correlation expected between molecular and stellar masses if dominant mechanism

No correlation found in both radio-loud and radio-quiet ETGs



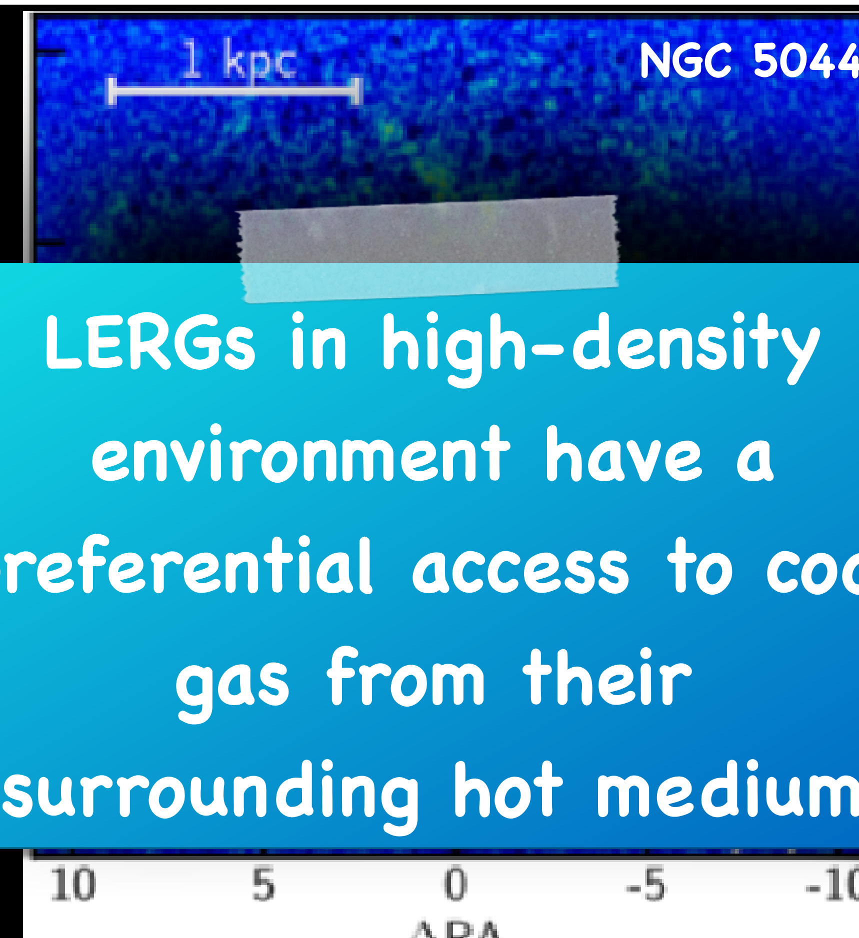
Stellar mass loss not the dominant mechanism, although it may contribute

(Young et al. 2011)

Hot halo cooling

Either smooth (e.g. Lagos et al. 2015) or chaotic (as in CCA; e.g. Gaspari et al. 2015)

Filaments or blobs reminiscent of chaotic cooling observed in LERGs at the centre of groups/clusters



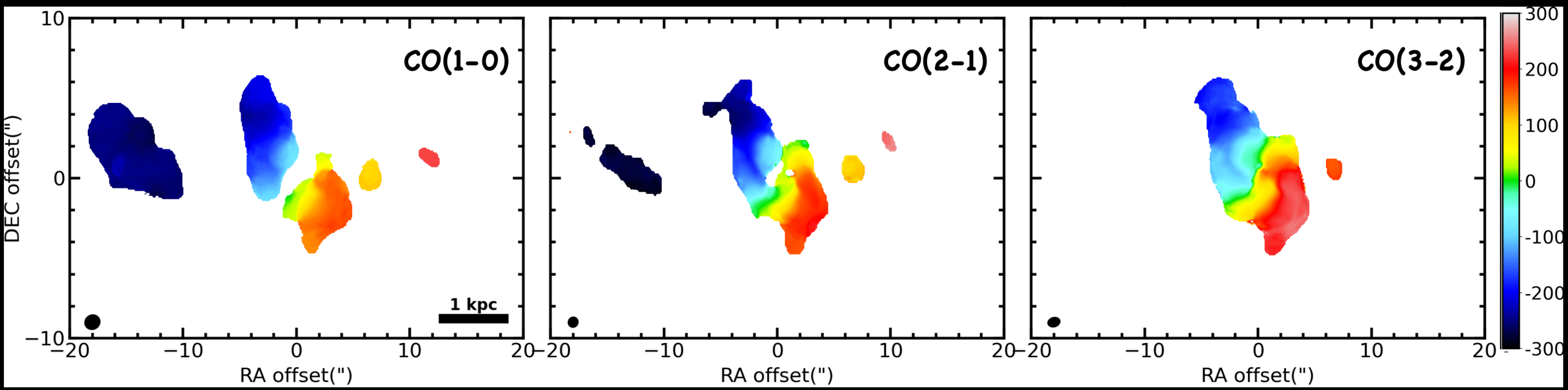
LERGs in high-density environment have a preferential access to cool gas from their surrounding hot medium

(David et al. 2014; Temi et al. 2018)

The special case of NGC 3100

Cycle 6 follow-up **ALMA observations** of NGC 3100 targeting **different** molecular transitions: CO(1-0), CO(3-2), SiO, HNCO, HCO^+ (Ruffa et al. 2021, submitted)

CO(1-0), CO(2-1) and CO(3-2) observed velocity field



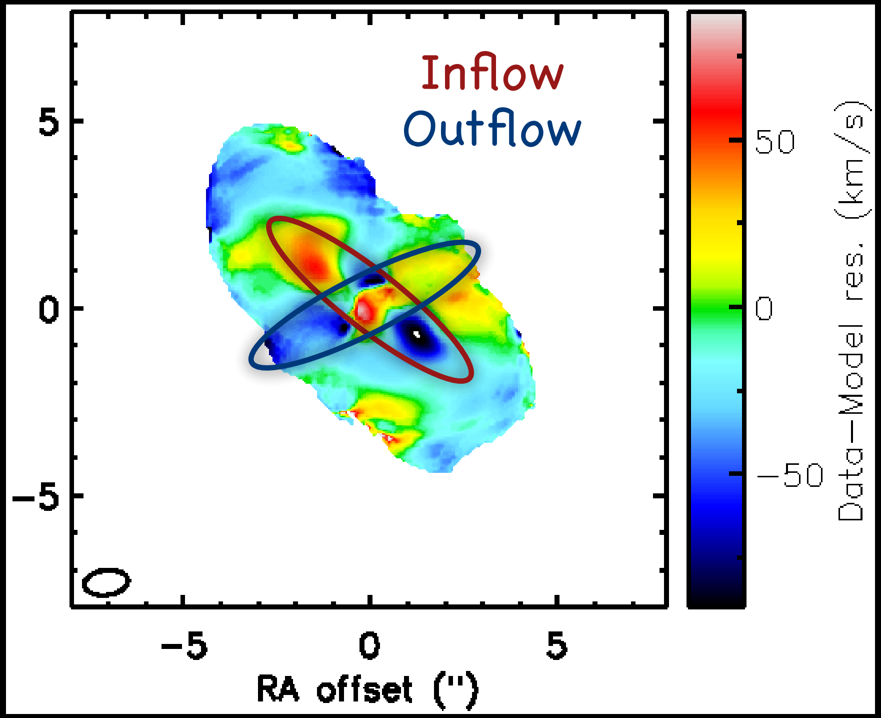
- **Substantial differences** in the distribution of the three lines ➜ **higher gas excitation** in the central regions

Ruffa et al. 2021, submitted

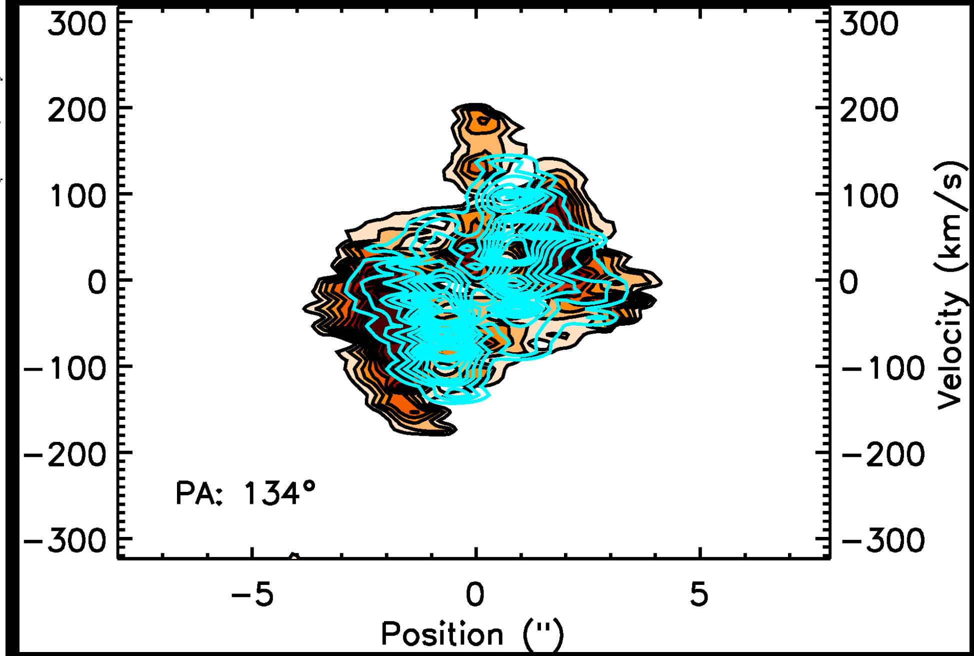
The special case of NGC 3100

Cycle 6 follow-up **ALMA observations** of NGC 3100 targeting **different** molecular transitions: CO(1-0), CO(3-2), SiO, HNCO, HCO^+ (Ruffa et al. 2021, submitted)

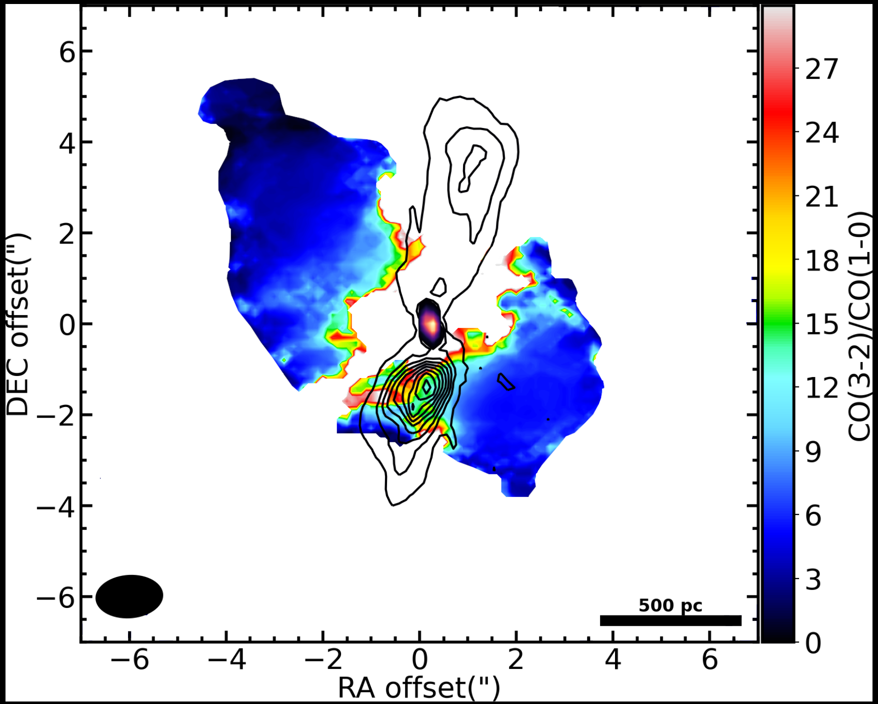
Residual CO(3-2) velocity field



Minor axis CO(3-2) PVD + model (cyan)



CO(3-2)/CO(1-0) ratio + 10GHz cont



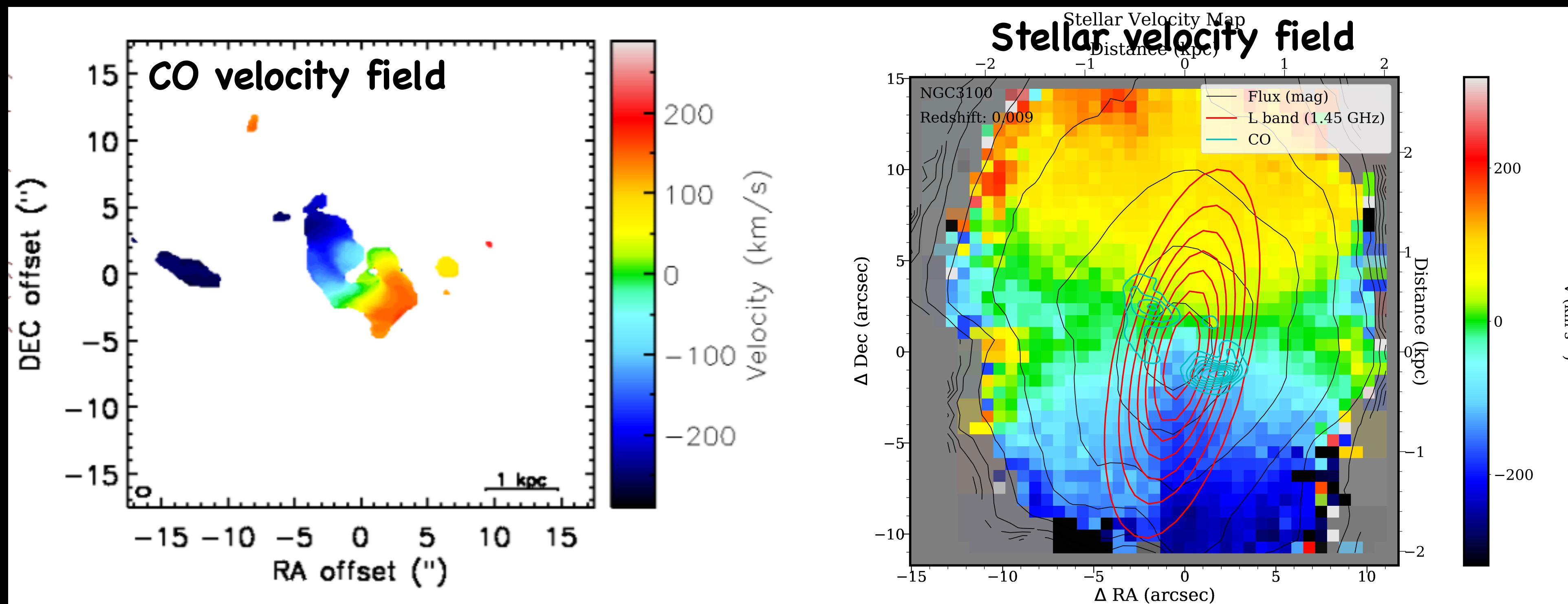
- **Substantial differences** in the distribution of the three lines ➜ **higher gas excitation** in the central regions
- Hints of **inflow/outflow motions** from velocity residuals and PVDs
- **Enhanced** line ratios along the path of the jet ($T_{ex} \gg 50$ K)

Ruffa et al. 2021, submitted

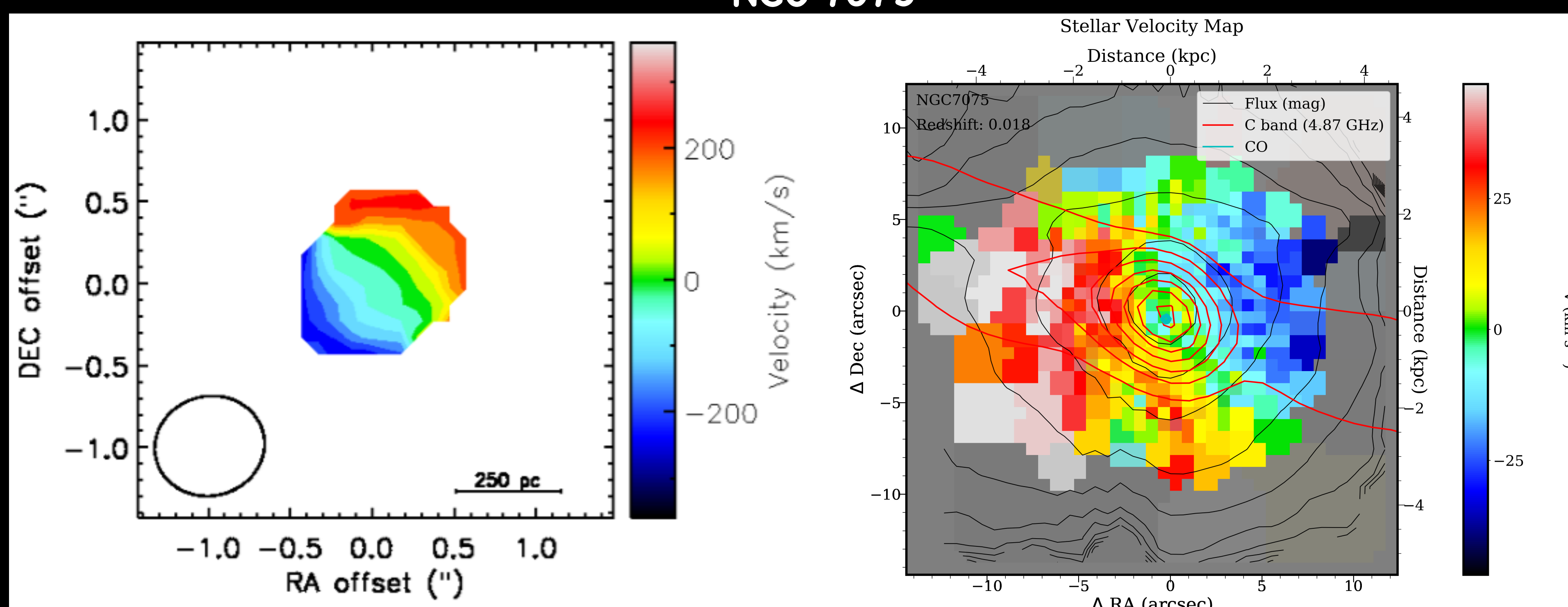
Internal vs external accretion

Internally generated cold gas is mostly expected to **co-rotate** with stars

NGC 3100



NGC 7075

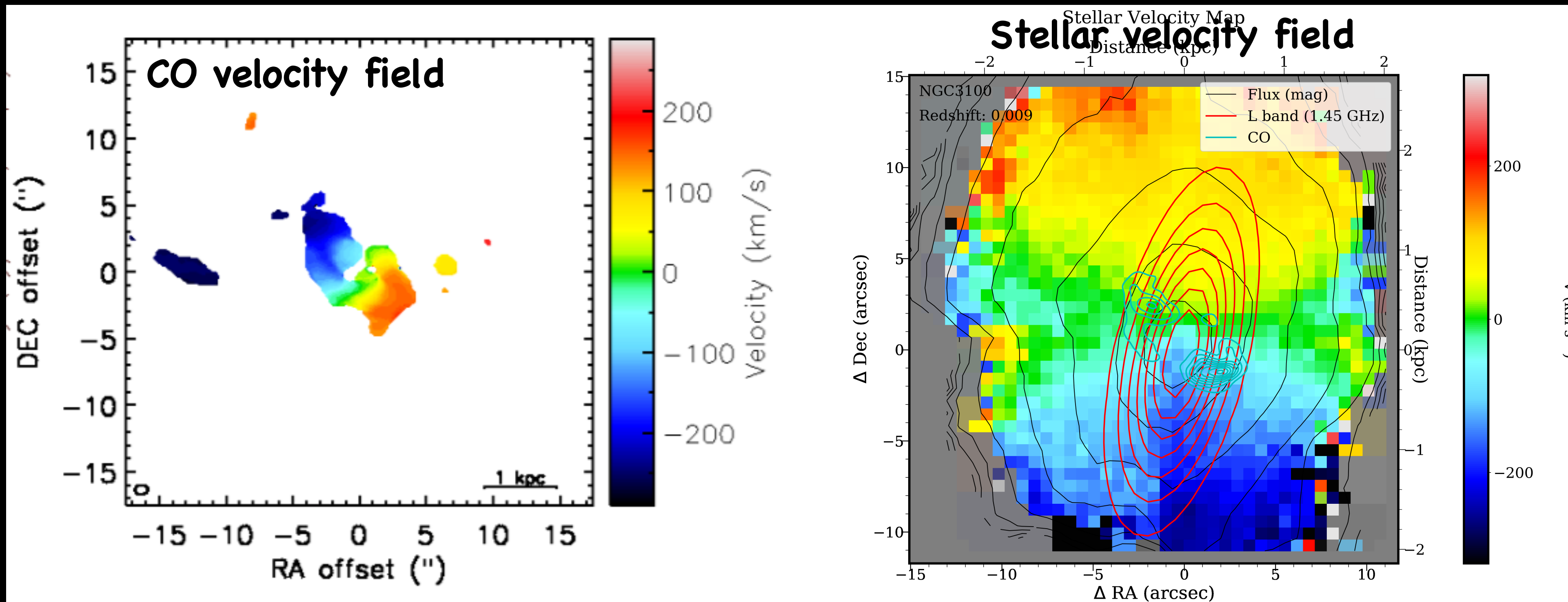


Such **significant discrepancies** consistent with an **external gas origin** (e.g. Davis et al. 2011)

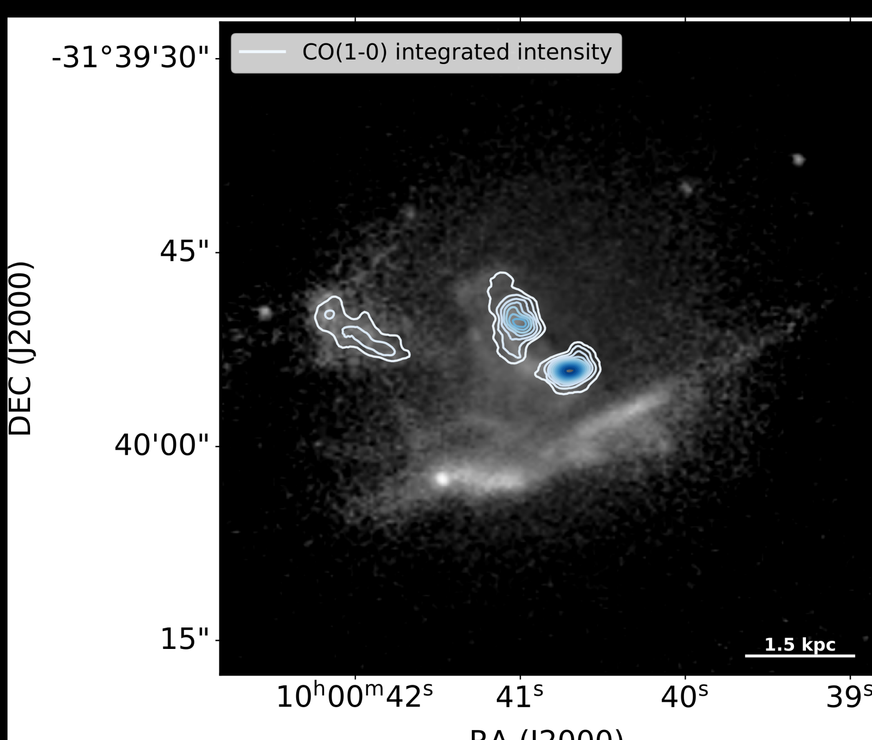
Internal vs external accretion

Internally generated cold gas is mostly expected to **co-rotate** with stars

NGC 3100



Internally generated cold gas in ETGs expected to have high metal enrichments



$$12 + log_{10}(O/H) = 12 + \log_{10}\left(\frac{4.57088 \times 10^{-2}}{M_{\rm gas}/M_{\rm dust}}\right)$$

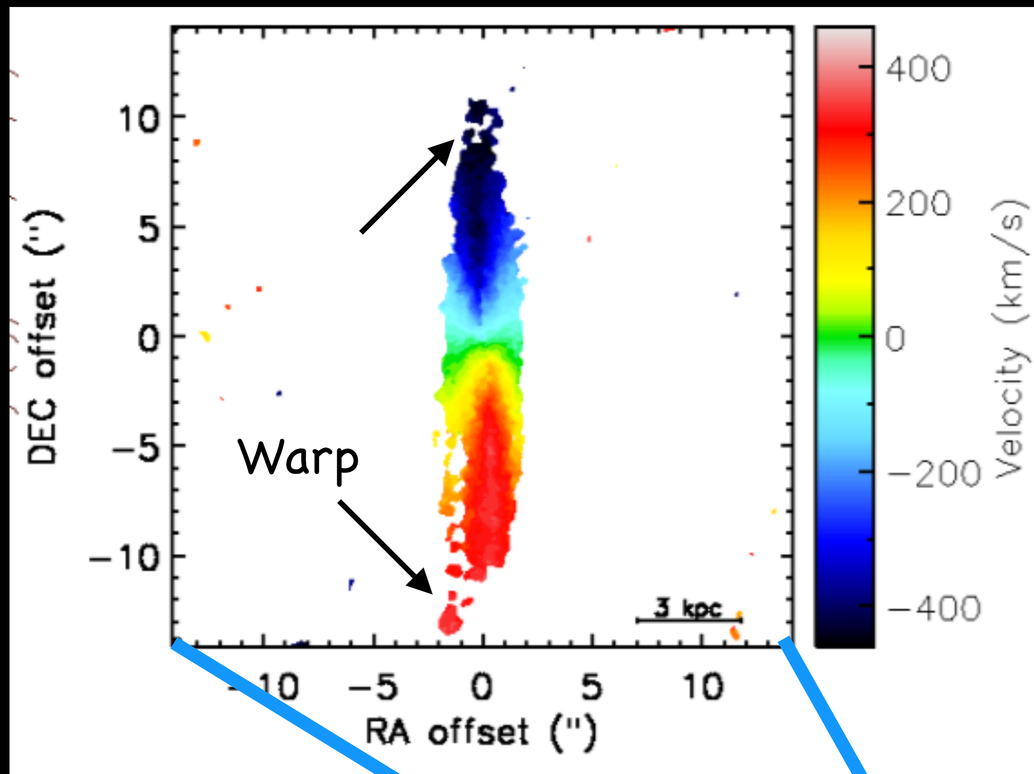
(Davis et al. 2015)

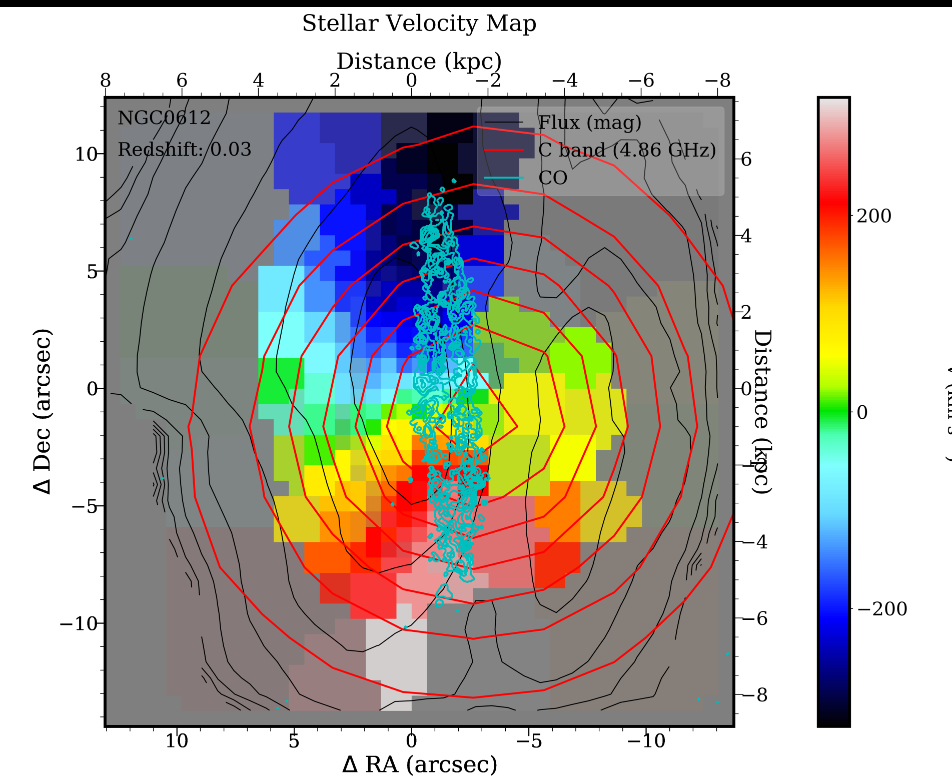
Gas-phase metallicities significantly **sub-solar** (<7.9) in NGC 3100

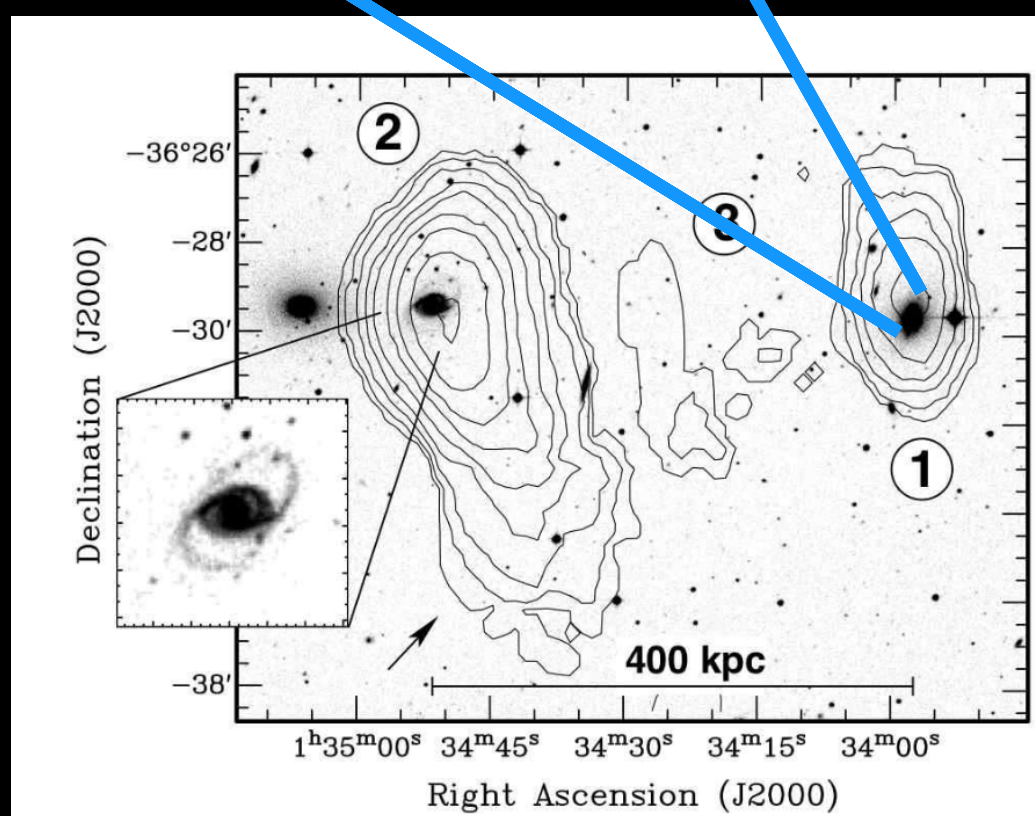
Internal vs external accretion

Even when gas and stars **co-rotate** an external origin **cannot be excluded**

NGC 612

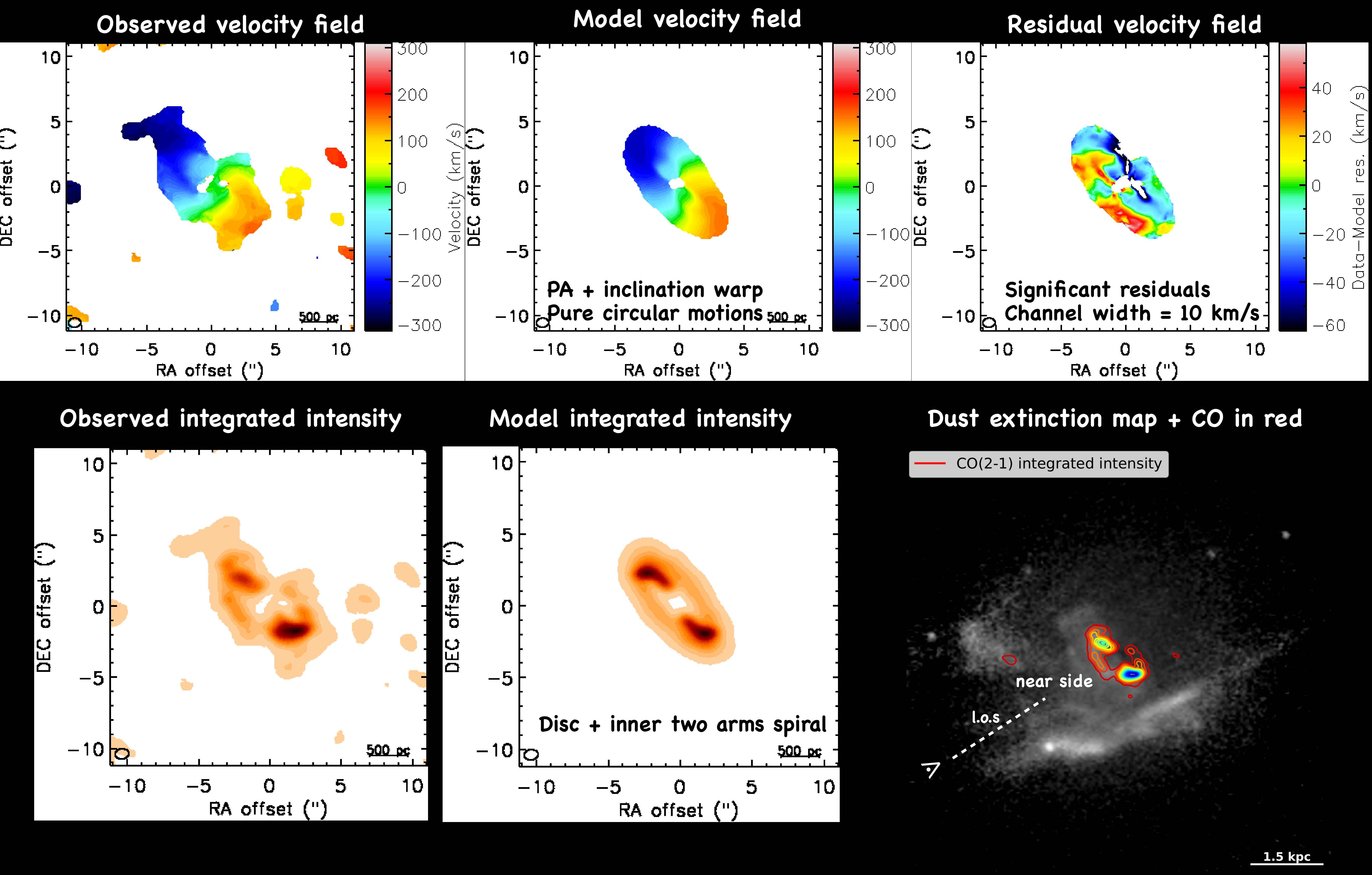






CO **at the center** of the HI disc and **bridge connecting** NGC 612 with the companion NGC 619

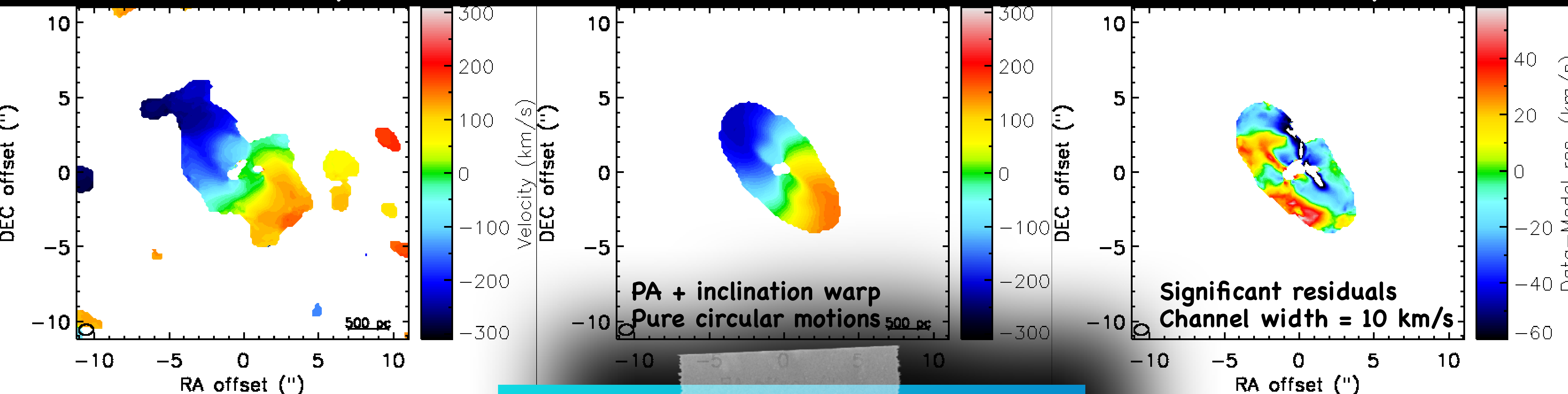
The special case of NGC 3100



Ruffa et al. 2019b

The special case of NGC 3100

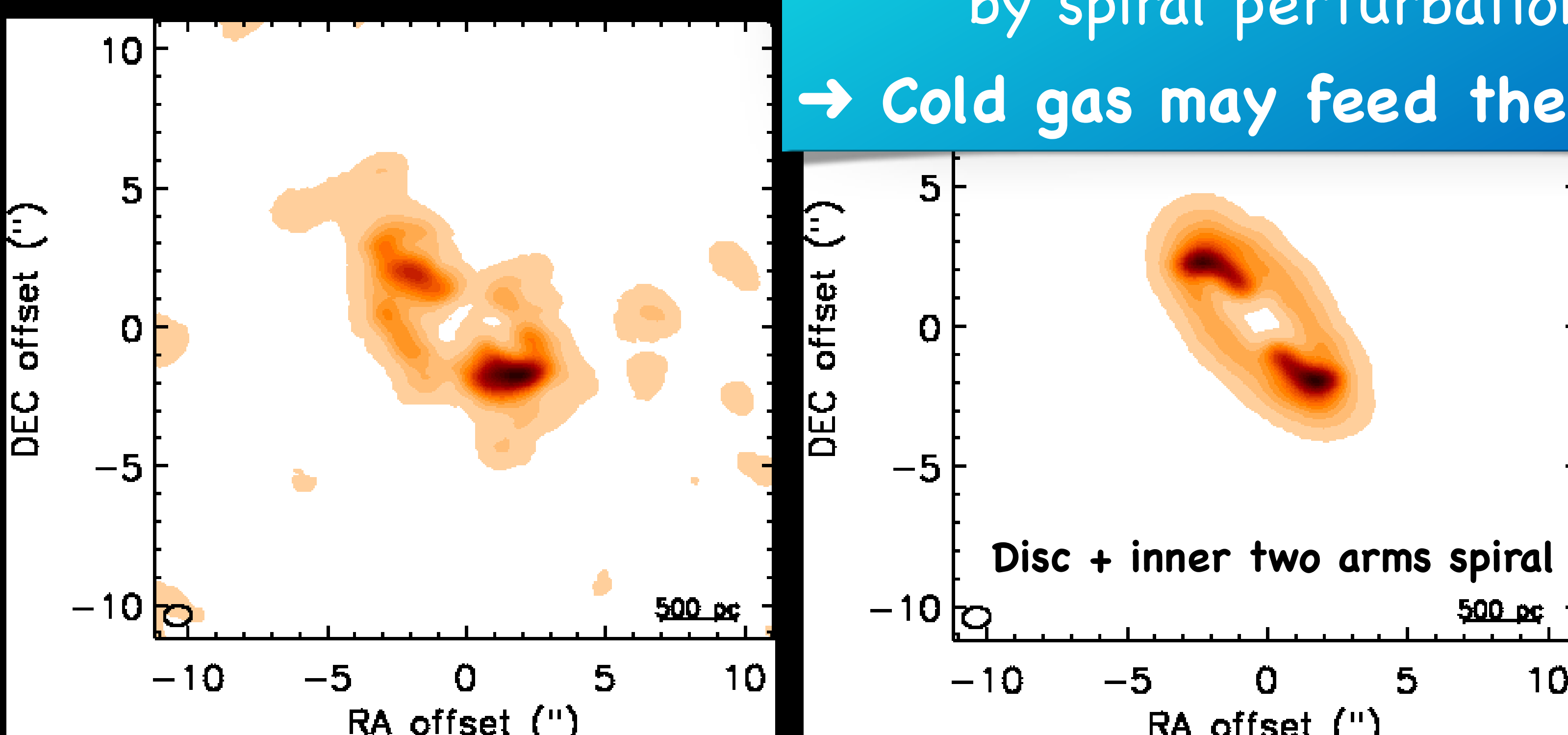
Observed velocity field / Model velocity field / Residual velocity field



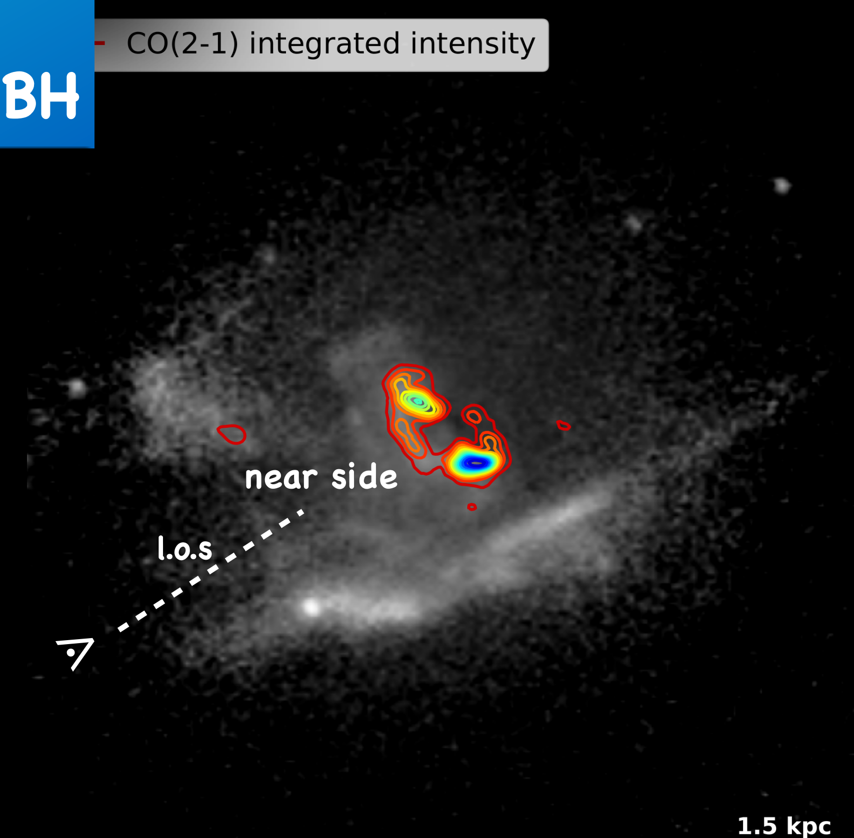
Inflow streaming motions induced by spiral perturbation

→ Cold gas may feed the SMBH

Observed integrated intensity



Dust extinction map + CO in red

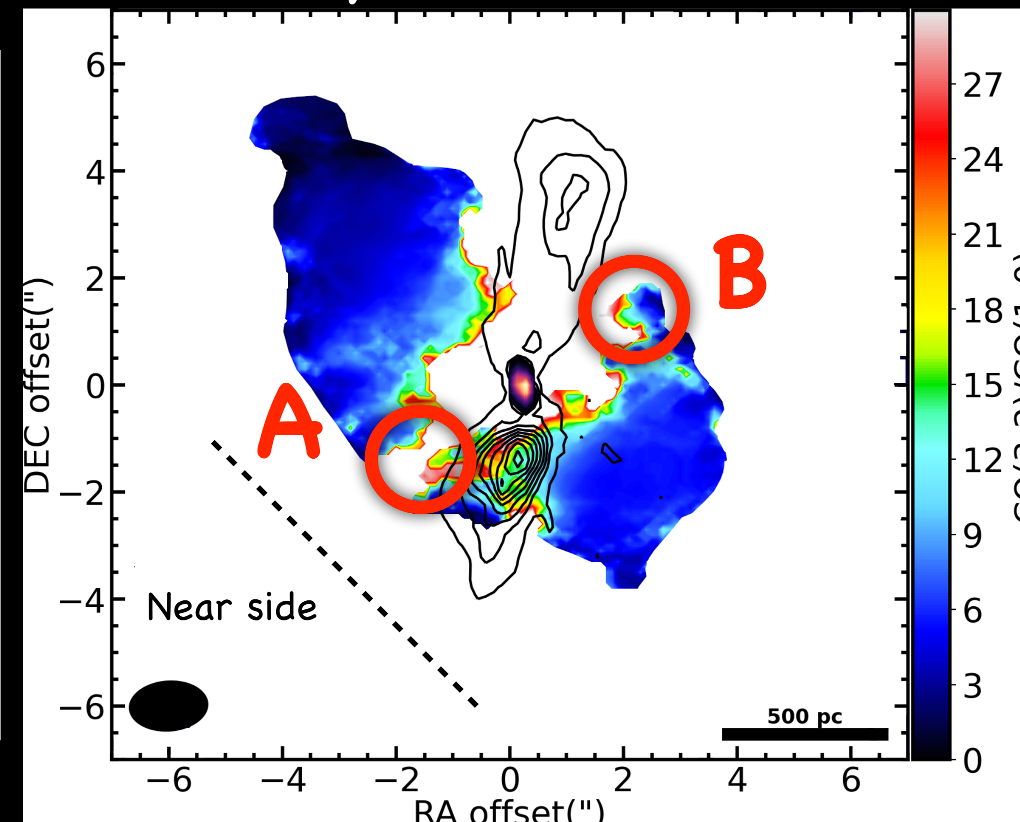


Ruffa et al. 2019b

The special case of NGC 3100

- High velocity kinematic components in addition to the main rotational one ➜ **outflow with v ≤ 200 km/s**
- Far less extreme than known cases of jet-induced sub-kpc scale outflows ➜ **negligible impact on the host galaxy**
- **Implications for interactions involving low-power radio jets**

CO(3-2)/CO(1-0) flux density ratio + 10GHz cont



(Ruffa et al. 2021, submitted)