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# **A Multi-phase study of a Sample of local Radio Galaxies**

## ***The feeding/feedback cycle in LERGs***



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***PhD Students: I. Ruffa (IRA-INAF); J. Warren (Oxford Univ.)***

# Focus of the talk

Jet/Radio Mode:  $L/L_{\text{Edd}} \leq 0.01$

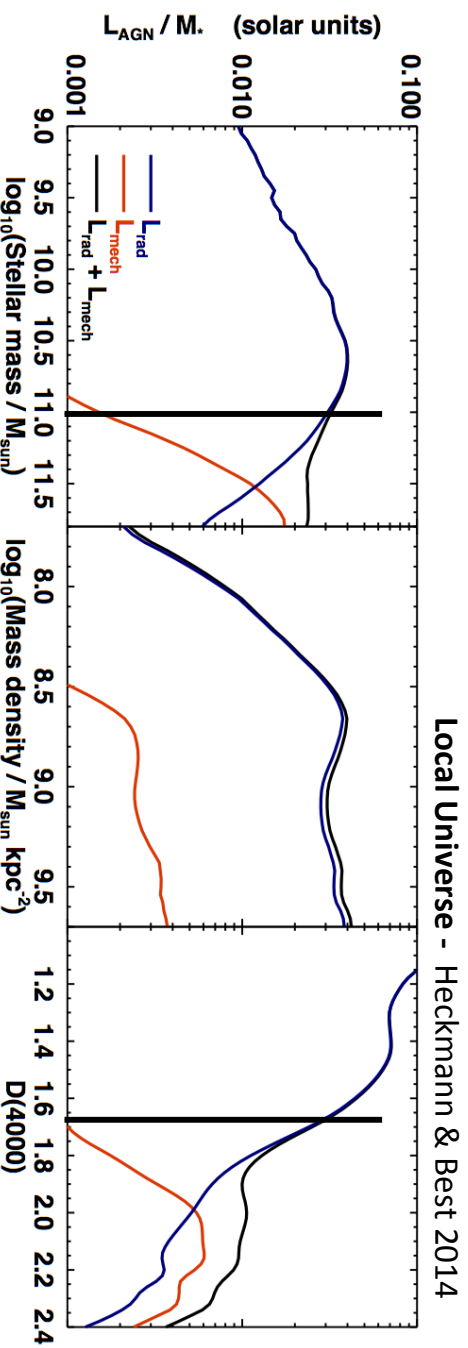
- moderate radio power
- mostly FRI
- **LERG**
- Hosted by very massive ( $M > 10^{11} M_{\text{sun}}$ ) ETG
- little SF

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AGN Fueling: hot gas  
(from the X-ray halo)

AGN feedback:  
mostly kinetic (radio jets)

- radio jets:
- relativistic on pc scales (Giovannini+01)
  - sub-relativistic on 1-10 kpc scales (Laing+99)



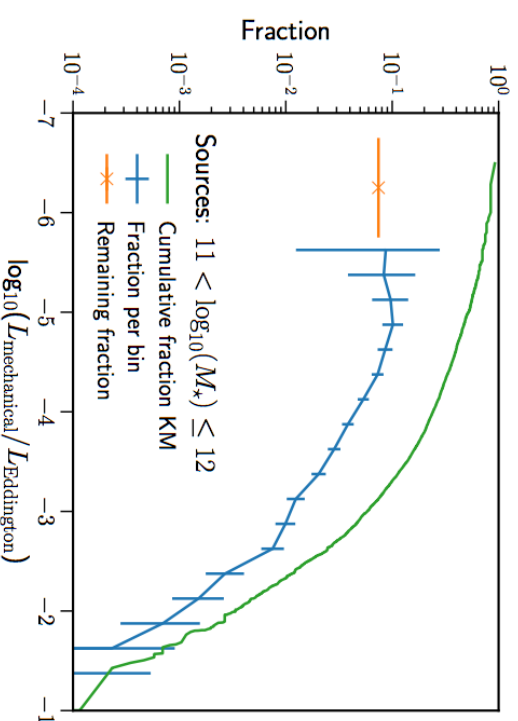
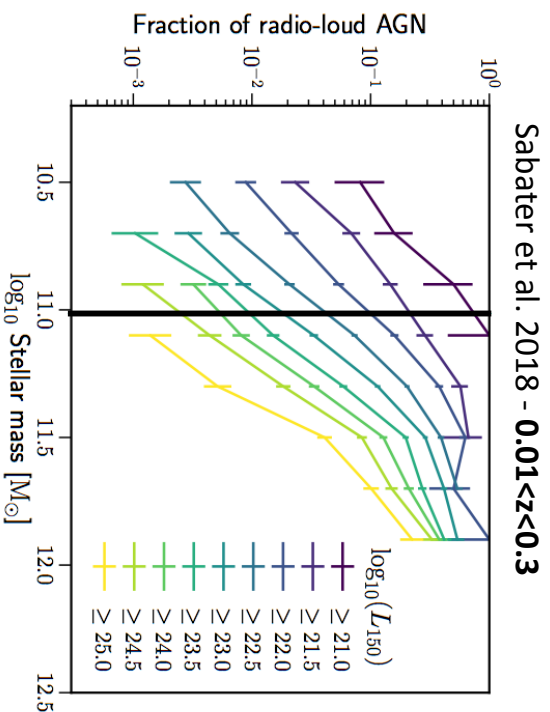
# Focus of the talk

**Jet/Radio Mode:  $L/L_{\text{Edd}} \leq 0.01$**

- moderate radio power
- FRI or FRII
- **LERG**
- Hosted by very massive ( $M > 10^{11} M_{\text{sun}}$ ) ETG

Massive galaxies in local Universe  
 → 100% RL (always switched on)

**Dominant RL-AGN population:  $L/L_{\text{Edd}} \sim 10^{-5}$**



**AGN Fueling: hot gas**  
 (from the X-ray halo)

**AGN feedback:**  
 mostly kinetic (radio jets)

- radio jets:**
- relativistic on pc scales (Giovannini+01)
  - sub-relativistic on 1-10 kpc scales (Lairing+99)

# Our Project

- Better understanding of the feeding/feedback cycle in LERG
- role of LERG in the lifecycle of massive galaxies
- **Statistical approach:** well defined (volume-limited) LERG samples + control samples of RQ early-type galaxies
- **Multi-wavelength (multi-phase) study of LERG (meso scale):**
  - warm ionized gas + stellar component (IFU)
  - molecular gas (single dish and interferometry)
  - detailed radio jet morphology (brightness gradients, deflections, co-spatial heating, outflows)
  - dust (high resolution optical imaging in two bands)

# A PILOT SOUTHERN RG SAMPLE

Radio source	Host galaxy	Z	Log P <sub>1.4GHz</sub> (W Hz <sup>-1</sup> )	FR Type
PKS 0007-325	IC1531	0.025641	23.9	FRI
PKS 0131-31	NGC612	0.029771	25.0	FRI/II
PKS 0320-37	NGC1316	0.005871	22.4	FRI
PKS 0336-35	NGC1399	0.004753	22.5	FRI
PKS 0718-34	—	0.028353	24.6	FRI
PKS 0958-314	NGC3100	0.008813	23.0	FRI
PKS 1107-372	NGC3557	0.010300	23.3	FRI
PKS 1258-321	ESO443-G-024	0.017042	24.0	FRI
PKS 1333-33	IC4296	0.012465	25.4	FRI
PKS 2128-388	NGC7075	0.018479	23.9	FRI
PKS 2254-367	IC1459	0.006011	23.0	FRI *

- 11 objects with  $z < 0.03$  & E/S0 hosts
- extracted from Parkes 2.7 GHz survey (PKS; Ekers et al. 1989)  $[-17^\circ < \text{Decl.} < -40^\circ]$
- ALL LERG
- Diverse environs

\* *sub-arcsec scale*

# The Multi-wavelength dataset



VLTI/VIMOS integral-field-unit (IFU) spectroscopy + MUSE (Warren et al. in prep.)



2-color archival HST data (or from ground telescopes, when useful)



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. in prep.)



Archival + proprietary VLA high res. imaging (Ruffa et al. in prep.)

Adapted from I. Ruffa

# The Multi-wavelength dataset



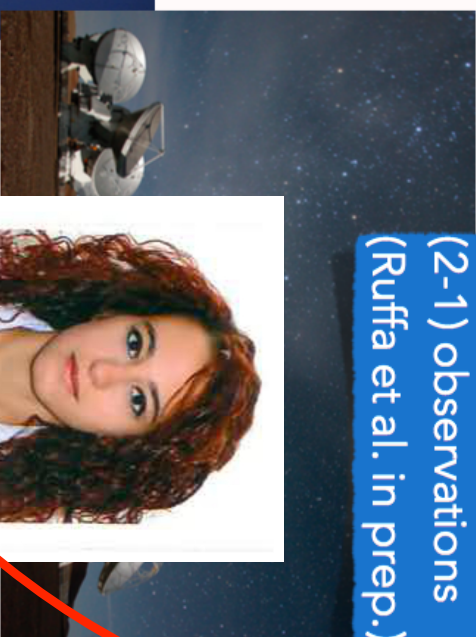
VLT/VIMOS integral-field-unit (IFU) spectroscopy + MUSE  
(Warren et al. in prep.)



2-color archival HST data (or from ground telescopes, when useful)



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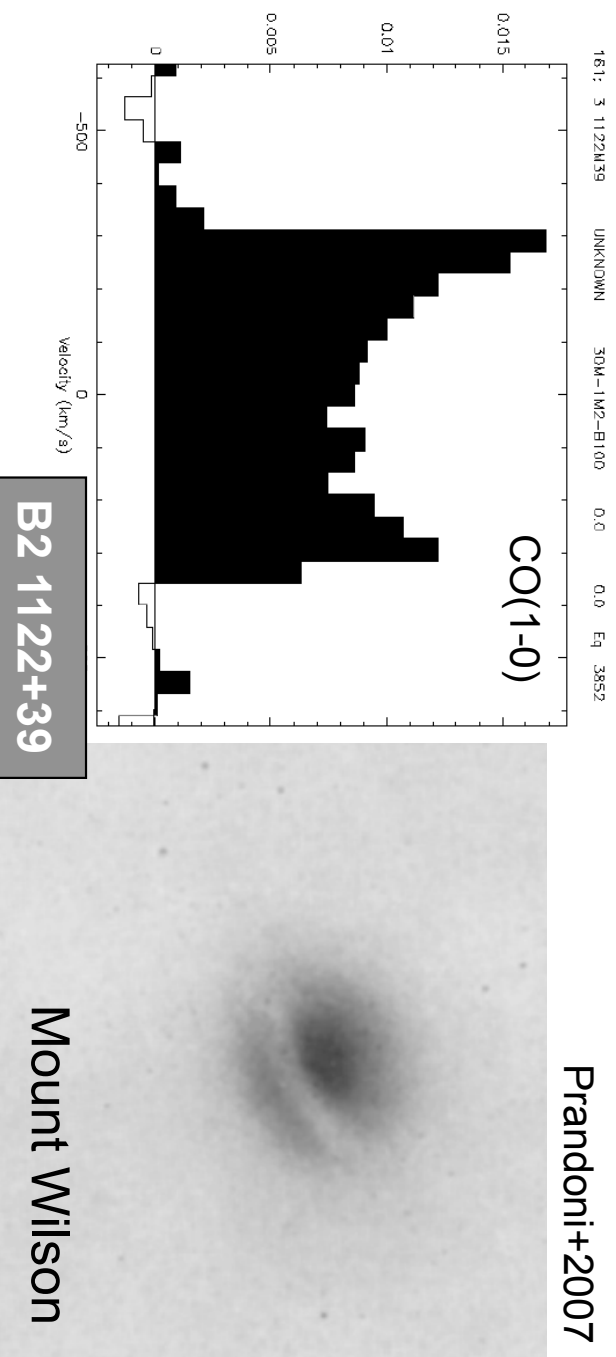
Archival + proprietary VLA high resolution imaging  
(Ruffa et al. in prep.)

Adapted from I. Ruffa

# The Role of Molecular Gas in LERGs - I

- H<sub>2</sub> / dust present in a significant fraction of RQ and RL ETG
- nuclear dust more likely to be found in RL ETG (van Dokkum & Franx 95; de Ruiter *et al.* 2002, Verdoes Kleijn & de Zeeuw 2005)
- Evidence for a relation between CO and dusty disks in ETG cores

→ Is H<sub>2</sub> more abundant in LERG wrt RQ ETG and/or Radio weak AGN?



# Master Radio Galaxy Sample

B2: volume limited sample of **23 objects with  $z < 0.03$** ;  
18 observed in CO [Prandoni+ 2007; Ocana-Flaquero+2010]

3C: volume limited sample of **26 objects with  $z < 0.031$**   
observed in CO [Lim+ 2003]

UGC: All galaxies with radio jets with  $v < 7000$  km/s ( $z < 0.0233$ )  
optical diameter  $> 1$  arcmin  
sample of **18 objects** observed in CO [Leon+ 2003]

TANGO: **20 additional sources with  $0.031 < z < 0.1$**  observed in CO [Ocana-Flaquero  
+2010] *no uniform selection criteria*

+ Southern Sample: **11 objects with  $z < 0.03$**

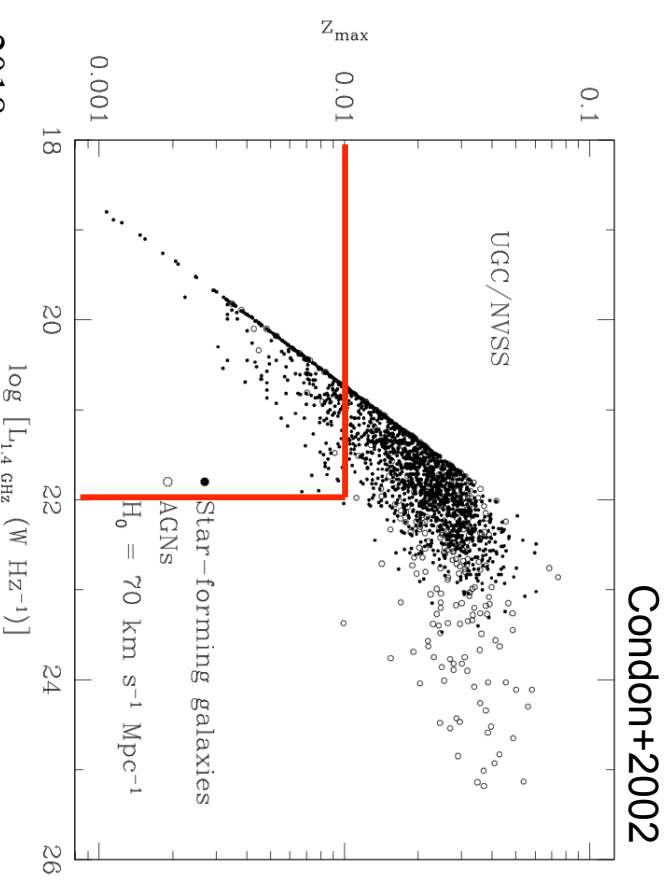
→ **76 distinct Radio Galaxies**

# Comparison Sample – ATLAS<sup>3D</sup>

- 260 early-type galaxies (E/S0) with  $D < 42$  Mpc ( $z < 0.01$ ) [Cappellari+11]
- extracted from parent sample with  $-6^\circ < \text{Decl.} < 64^\circ$  and  $M_K < -21.5$
- SAURON @ WHT
- 259 observed in CO with IRAM [Young+ 2011] → 56 detected

➤ *radio weak AGN* sub-sample:  
 21 radio detected objects with radio emission classified as AGN-powered based on radio/FIR properties

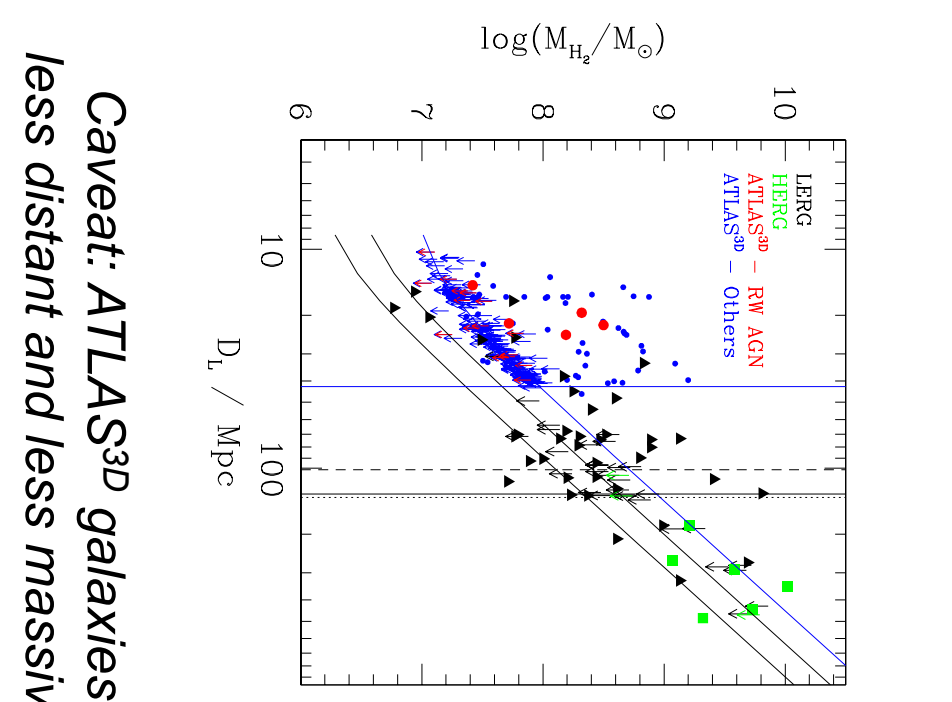
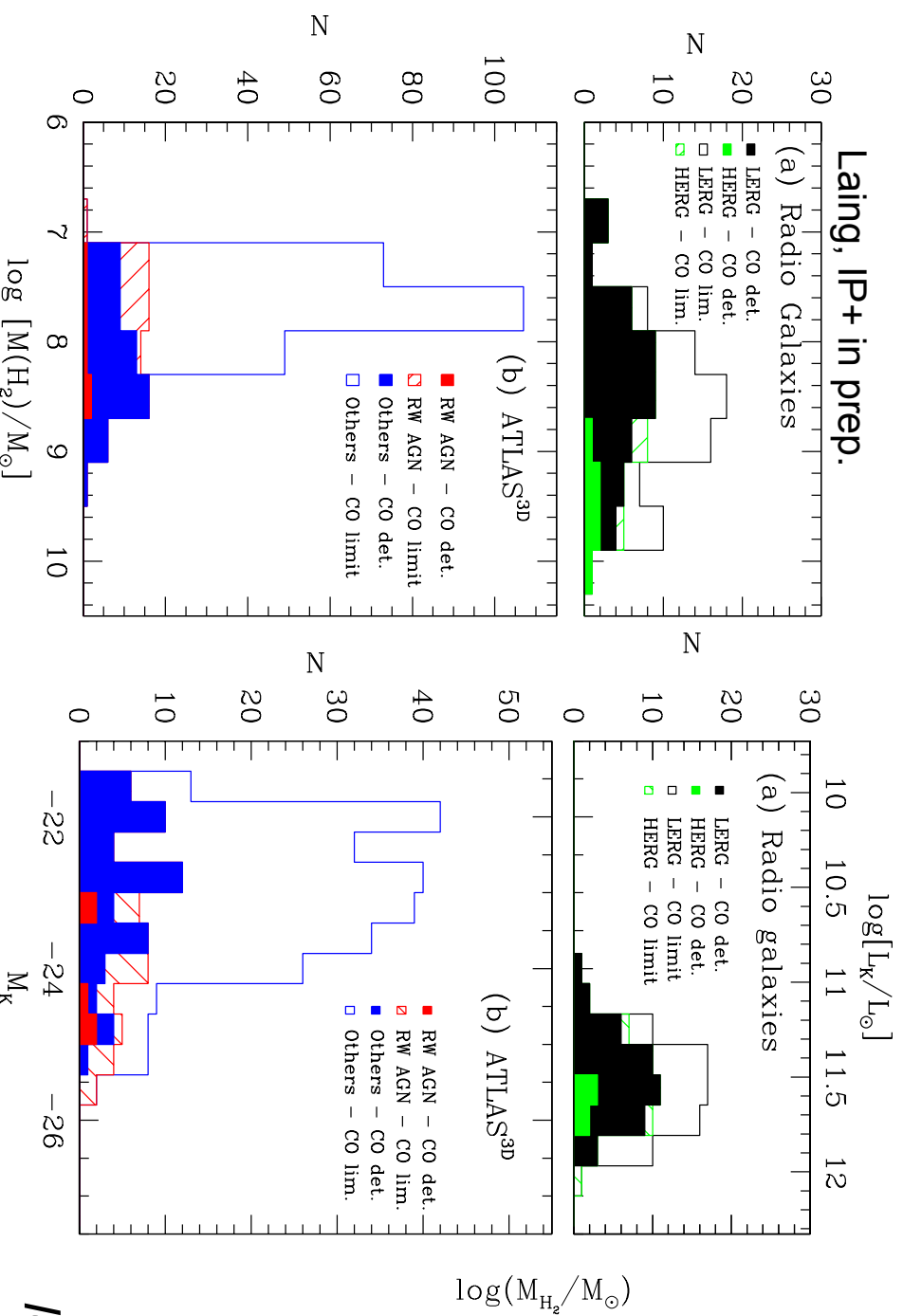
- no large scale jets
- $P < 10^{22}$  W/Hz



# The Role of Molecular Gas in LERGs - I

→ Is  $H_2$  more abundant in LERGs wrt RQ ETG and/or Radio weak AGN?

Laing, IP+ in prep.

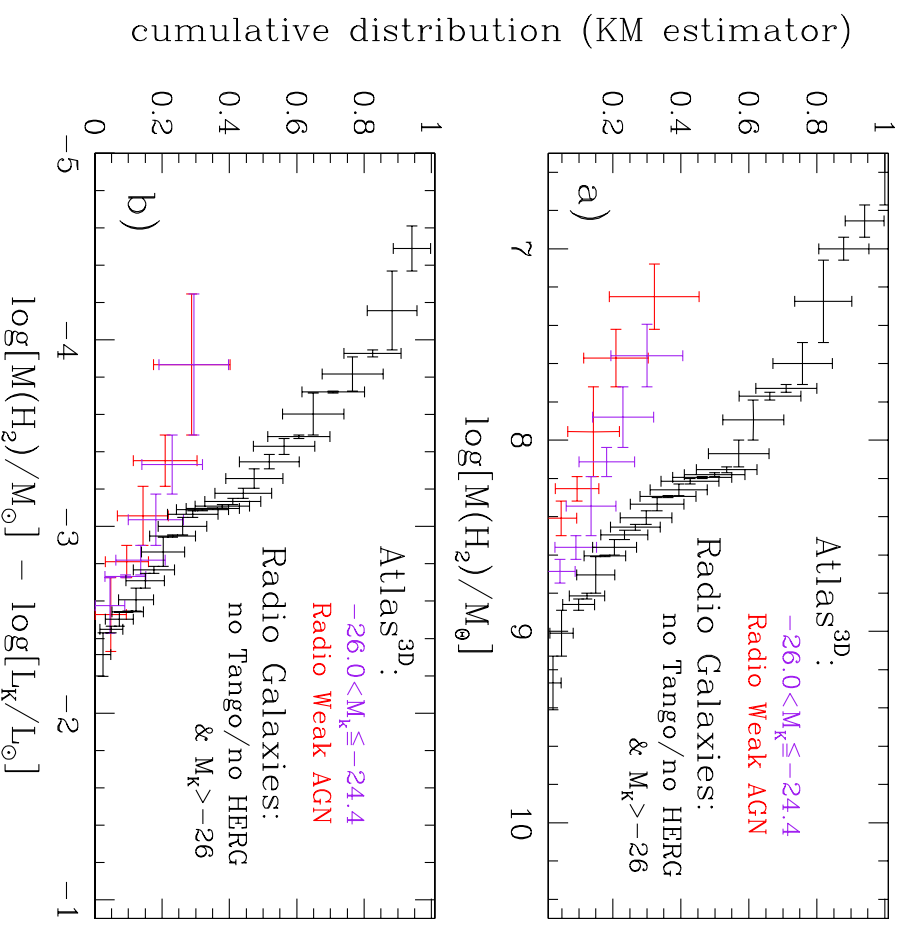
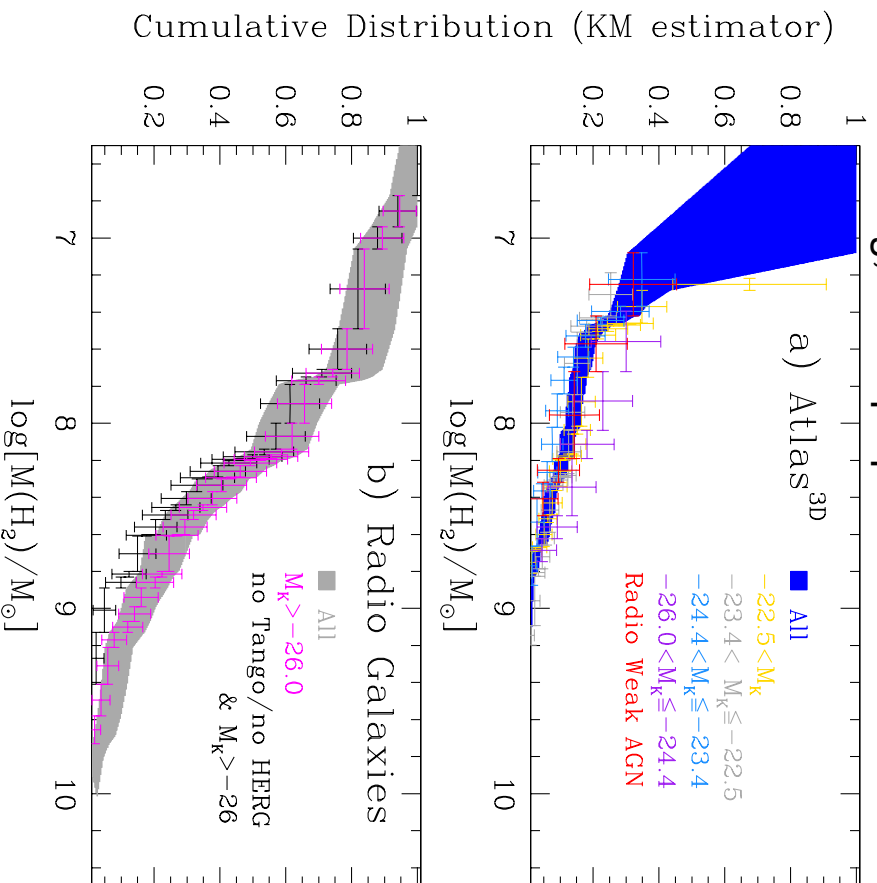


*Caveat: ATLAS<sup>3D</sup> galaxies  
less distant and less massive*

# The Role of Molecular Gas in LERGs - I

→ Is  $H_2$  more abundant in LERGs wrt RQ ETG and/or Radio weak AGN?

Laing, IP+ in prep.



# The Role of Molecular Gas in LERGs - I

→ Is  $H_2$  more abundant in LERGs wrt RQ ETG and/or Radio weak AGN?

- $H_2$  seems to be more abundant in LERG than in RQ ETG
- LERG mostly have  $\log M(H_2) \sim 7.5 - 8 M_{\text{sun}}$
- radio weak AGN have same molecular mass properties as RQ ETG
- this result seems to be robust against scaling relations and distance selection effects
- this result remain consistent with HERG being richer in  $H_2$

# The Role of Molecular Gas in LERGs - II

→ Is the H<sub>2</sub> morphology and kinematics different in RL and RQ ETGs ?

ALMA Cycle 3 Observations for 9 of the 11 RG in the Southern sample:  
[typical resolution of 0.6-0.7 arcsec / ~100-250 pc]

**Table 5.** Main <sup>12</sup>CO(2-1) integrated parameters.

Ruffa, IP+ in prep.

Env.	Target	Line FWHM (km s <sup>-1</sup> )	Line FWHZI (km s <sup>-1</sup> )	SCOΔv (Jy km s <sup>-1</sup> )	M <sub>H2</sub> (M <sub>⊙</sub> )
	(1)	(2)	(3)	(4)	(5)
I	IC 1531	260	280	2.0±0.2	(6.4 ± 0.6) × 10 <sup>8</sup>
P	NGC 612	780	840	273±27	(1.2 ± 0.2) × 10 <sup>11</sup>
I	PKS 0718-34	334 <sup>1</sup>	480 <sup>1</sup>	< 0.1	< 3.9 × 10 <sup>7</sup>
G/P	NGC 3100	345	470	18±1.8	(6.8 ± 0.8) × 10 <sup>8</sup>
G	NGC 3557	440	484	7.0±0.7	(3.6 ± 0.4) × 10 <sup>8</sup>
C	ESO 443-G 024	786 <sup>1</sup>	1000 <sup>1</sup>	< 0.1	< 2.1 × 10 <sup>7</sup>
C	IC 4296 <sup>2</sup>	680	880	1.6±0.1	(1.2 ± 0.8) × 10 <sup>8</sup>
C	NGC 7075	560	640	1.0±0.1	(1.7 ± 0.2) × 10 <sup>8</sup>
G	IC 1459	492 <sup>1</sup>	640 <sup>1</sup>	< 0.4	< 6.3 × 10 <sup>6</sup>



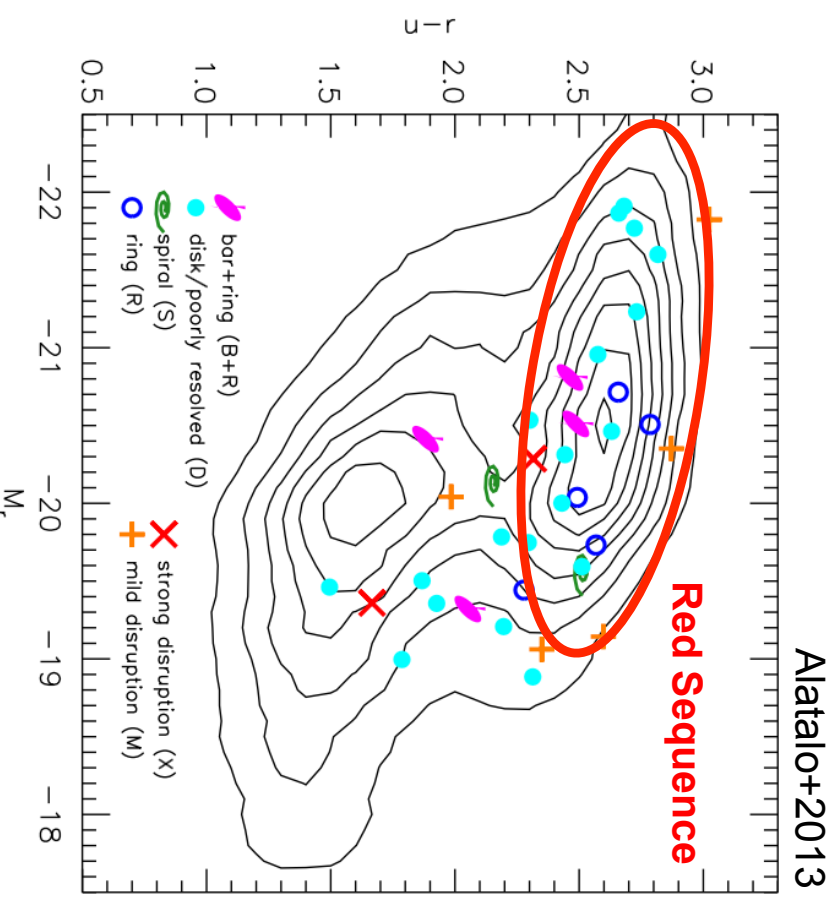
# The Role of Molecular Gas in LERGs - II

→ Is the  $H_2$  morphology and kinematics different in RL and RQ ETGs ?

ATLAS<sup>3D</sup> CO-rich sub-sample (40 objects) observed with CARMA [Alatalo +2013]

- 50% disks (D)
- 15% rings (R)
- 10% bars+rings (B+R)
- 5% spiral arms (S)
- 12.5% mildly disrupted (M)
- 7.5% strongly disrupted (X)

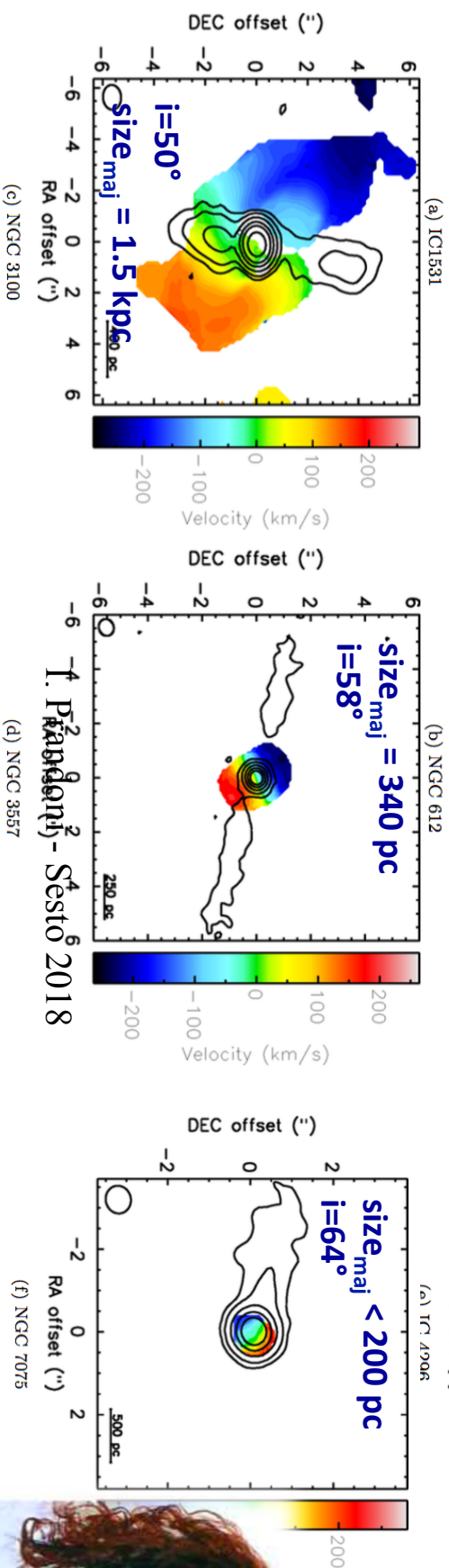
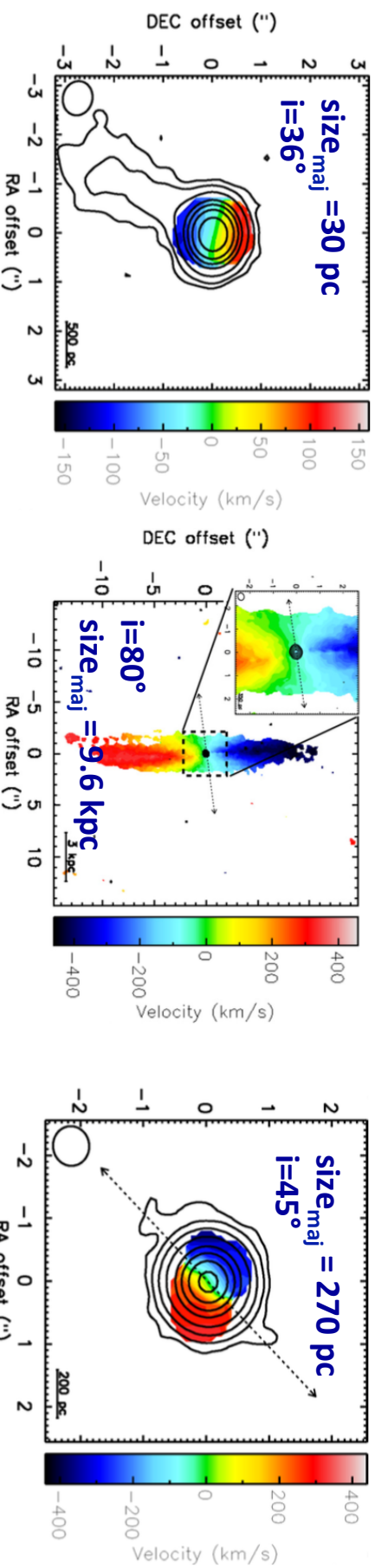
Most massive → disks  
Rings → red sequence



# The Role of Molecular Gas in LERGs - II

→ Is the  $H_2$  morphology and kinematics different in RL and RQ ETGs ?

ALMA Observations for 9 of the 11 RG in the Southern sample:



Ruffa, IP+ in prep.



(c) NGC 3100

(d) NGC 3557

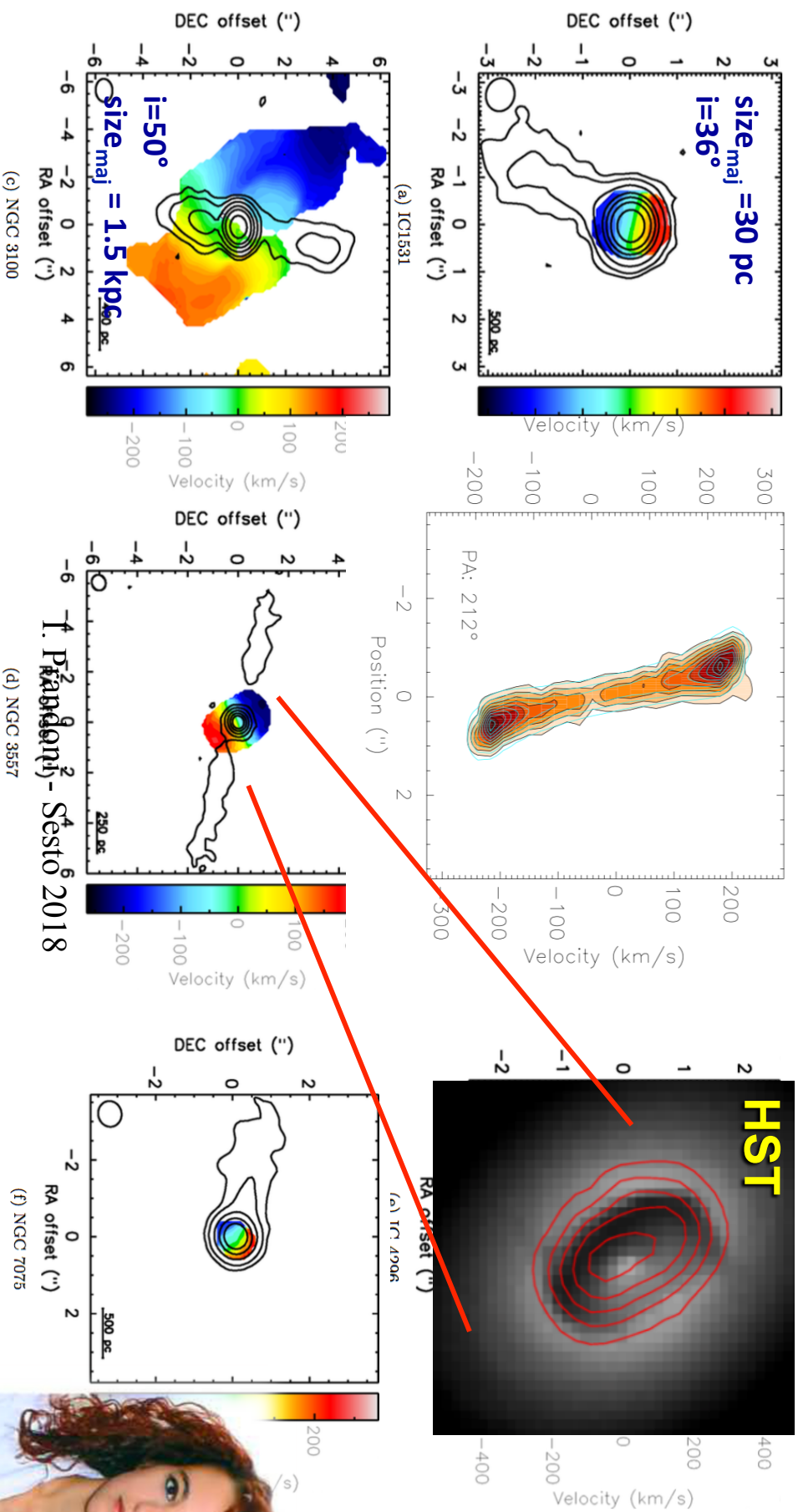
(e) NGC 7075

1. Pandey<sup>2</sup>-Sest<sup>6</sup> 2018

# The Role of Molecular Gas in LERGs - II

→ Is the  $H_2$  morphology and kinematics different in RL and RQ ETGs ?

ALMA Observations for 9 of the 11 RG in the Southern sample:



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(c) NGC 3100

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(f) NGC 7075

# The Role of Molecular Gas in LERGs - II

→ Is the  $H_2$  morphology and kinematics different in RL and RQ ETGs ?

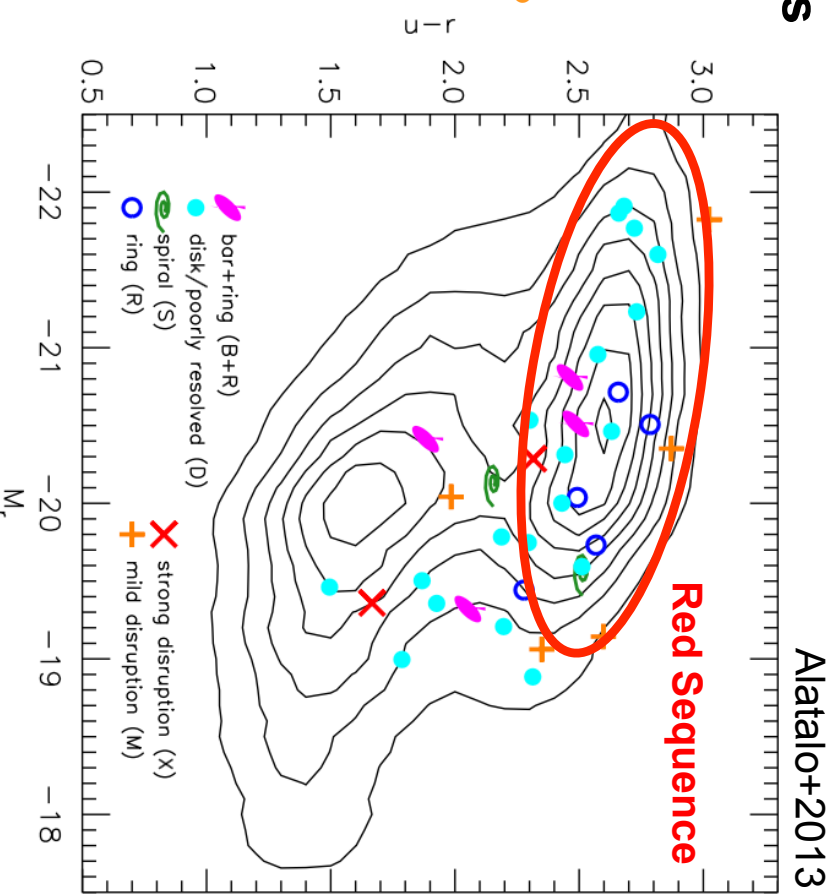
## ATLAS<sup>3D</sup>

- 50% disks (D)
- 15% rings (R)
- 10% bars+rings (B+R)
- 5% spiral arms (S)
- 12.5% mildly disrupted (M)
- 7.5% strongly disrupted (X)

Most massive → disks  
Rings → red sequence

## 6 LERGs

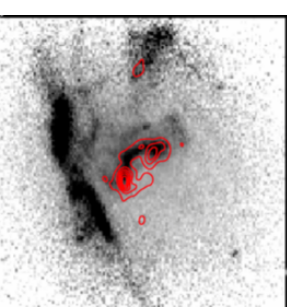
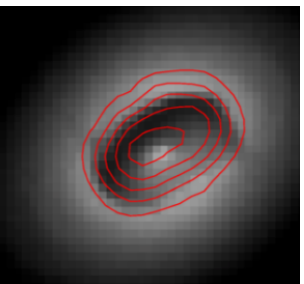
- 4 ~ 67%
- 1 ~ 17%
- 1 ~ 17%?



# The Role of Molecular Gas in LERGs - II

→ Is the  $H_2$  morphology and kinematics different in RL and RQ ETGs ?

→ No evidence so far... but comparison towards gas-rich galaxies and compact CO structures.



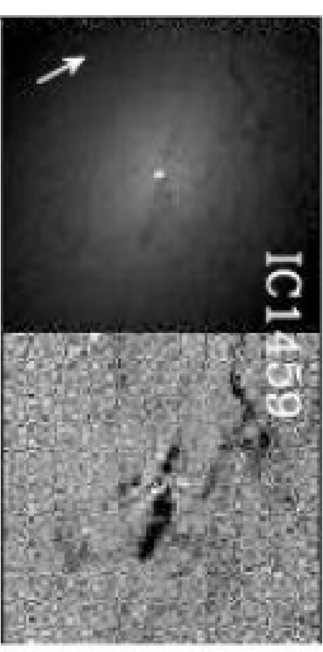
PKS 0336-35



PKS 0320-37



PKS 2254-367



**Preliminary**

# The Role of Molecular Gas in LERGs - III

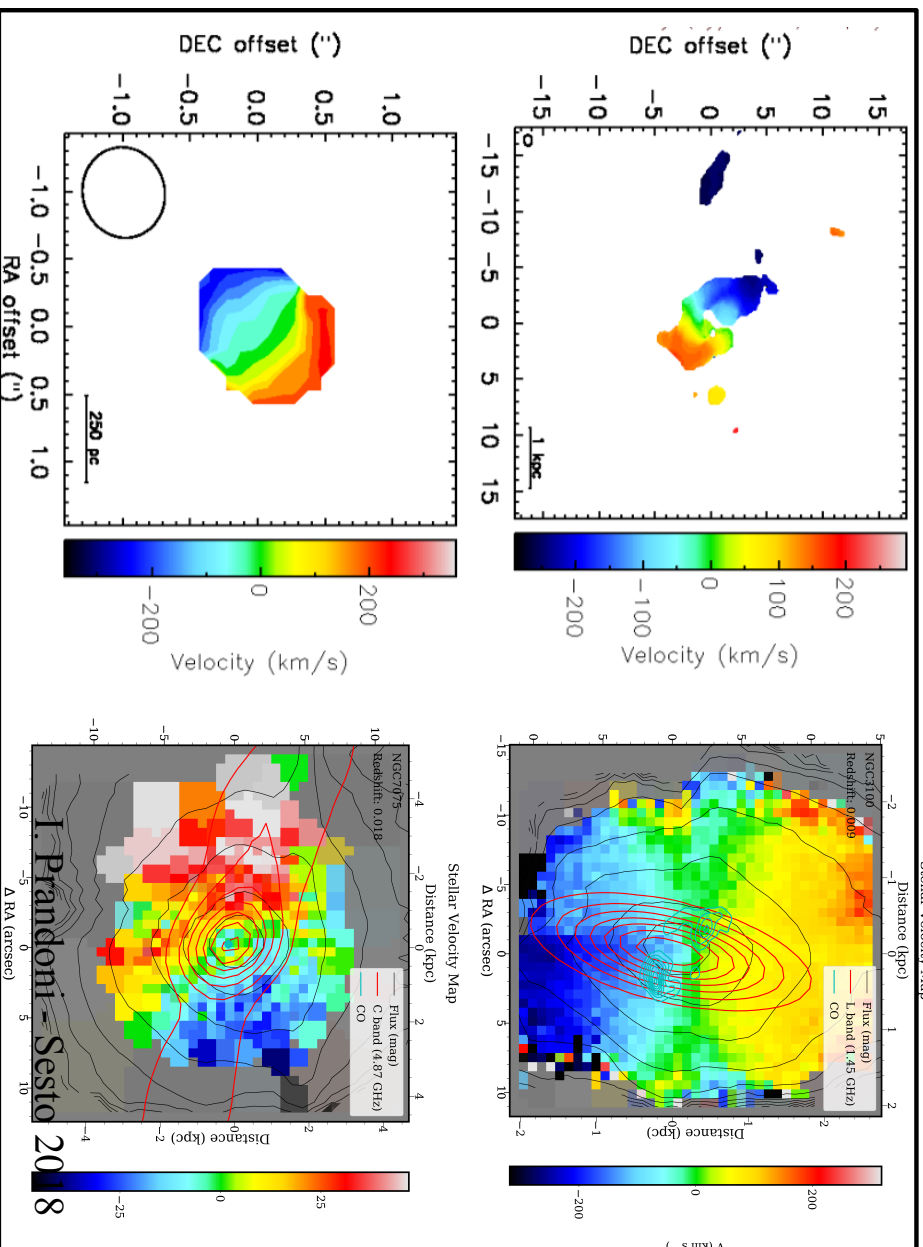
→ Is the H<sub>2</sub> of internal or external origin?

- 13 (33%) of **ATLAS<sup>3D</sup>** CO-rich sub-sample show significant (>30°) kinematic major axis misalignment between stellar and gas components  
→ external origin
  - 2 with other signs of external origin
- **38% external** [Alatalo+13]

# The Role of Molecular Gas in LERGs - III

→ Is the H<sub>2</sub> of internal or external origin?

2 (33%) with kinematic axis misalignments

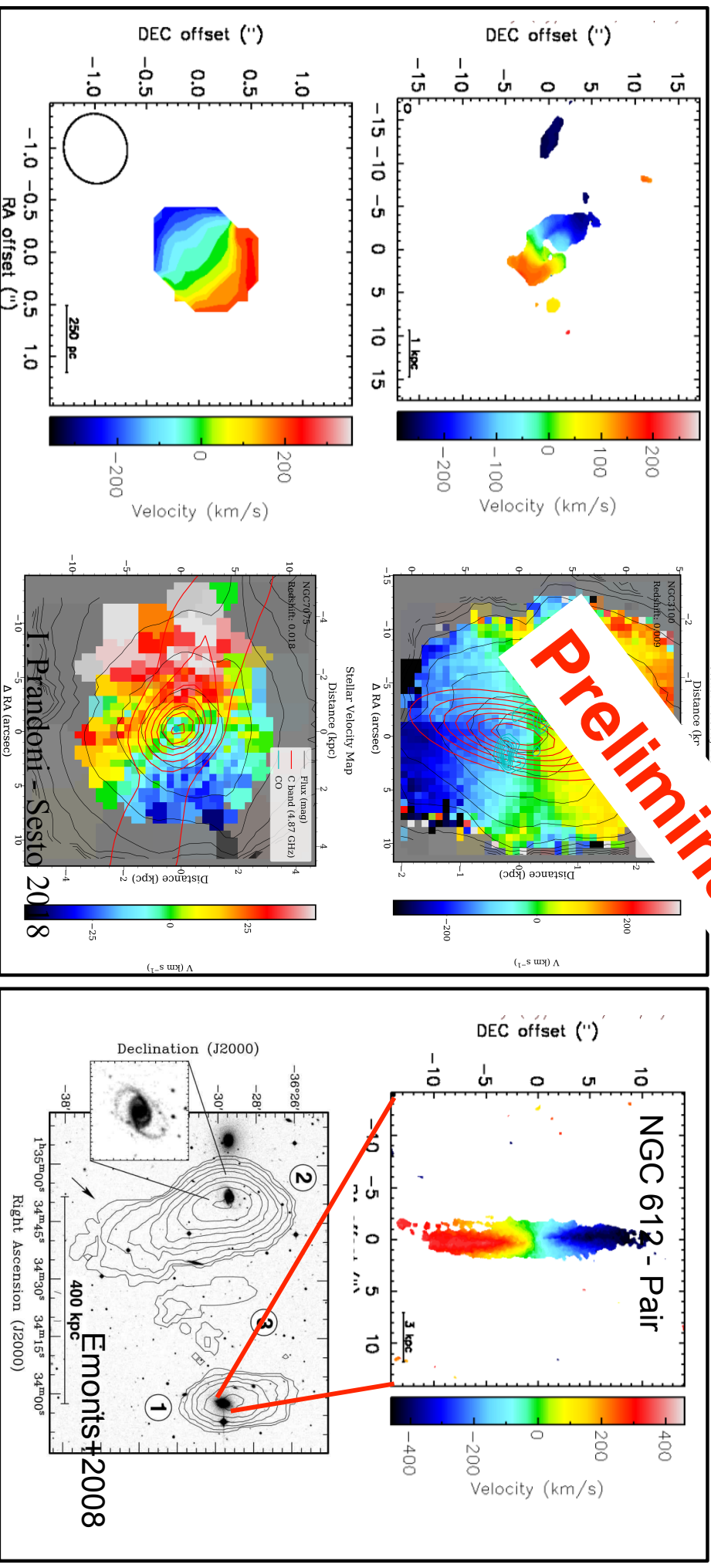


Warren+in prep.

# The Role of Molecular Gas in LERGs - III

→ Is the H<sub>2</sub> of internal or external origin?

2 (33%) with kinematic axis misalignments + NGC 612) → 50%

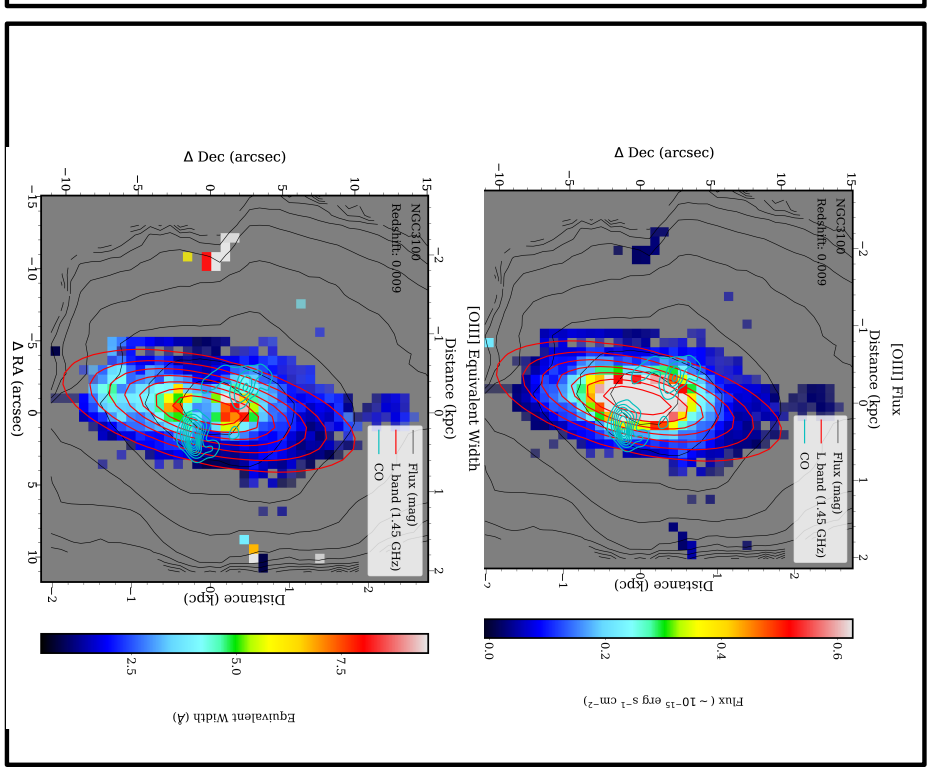
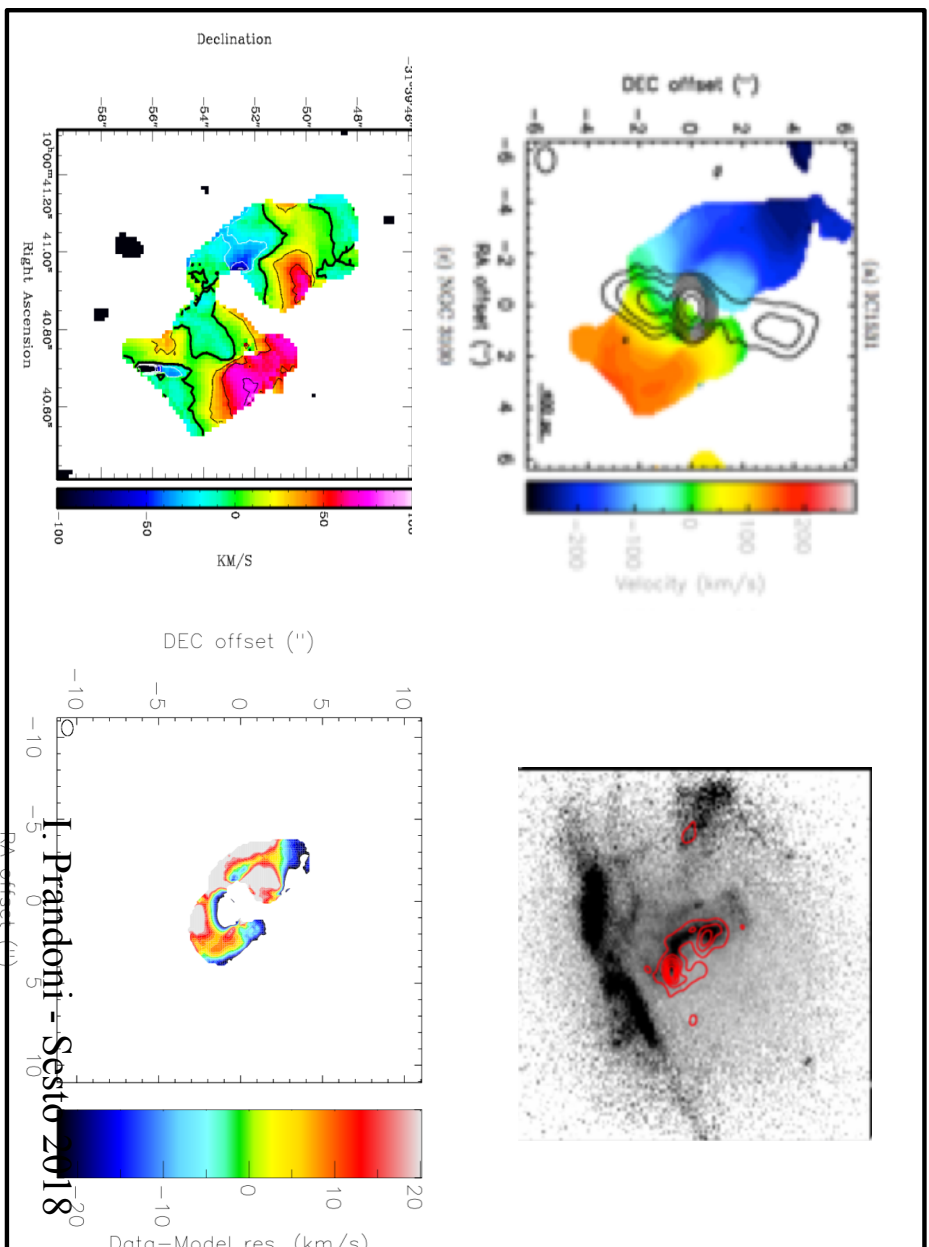


# Preview: The case of NGC 3100

→ Evidence of feeding/feedback?

- Detailed modeling of CO kinematics
- Combined CO/ warm ionized gas analysis

Ruffa, Davis+ in prep.



Warren+in prep.

# Summary

- H<sub>2</sub> is more abundant in LERG than in RQ ETG
- H<sub>2</sub> is more abundant in LERG than in radio weak (no large scale radio jets)

*Based on our ongoing multi-phase study of a pilot LERG sample (11 sources):*

- H<sub>2</sub> morphology and kinematics similar in LERG and gas-rich RQ ETGs
- H<sub>2</sub> disks are very frequent in cores of LERGs (rings also present)
- LERG seem to have smaller disks/rings (sub-kpc) than gas-rich RQ ETGs
- H<sub>2</sub> is of external origin in at least 33-50% of LERG (similar fractions for gas-rich RQ ETGs)
- NGC 3100: detailed kinematic modeling → tentative evidence of H<sub>2</sub> radial inflows (AGN feeding?)
- NGC 3100: link between disrupted CO morphology and presence of OIII emission along radio jet (AGN feedback in action?)

# Open Questions

- *Are the many observed sub-kpc/kpc scale  $H_2$  disks in LERGs in agreement with CCA?*
- *Can the various evolutionary phases of CCA (see Lakhchaura talk) explain what we observe?*
- *Can gas/stars misalignments be explained in CCA?*
- *How the environment fit in?*
- *Are LERG statistically important for galaxy-scale feedback?*