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

The feeding/feedback cycle in LERGs

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Focus of the talk

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

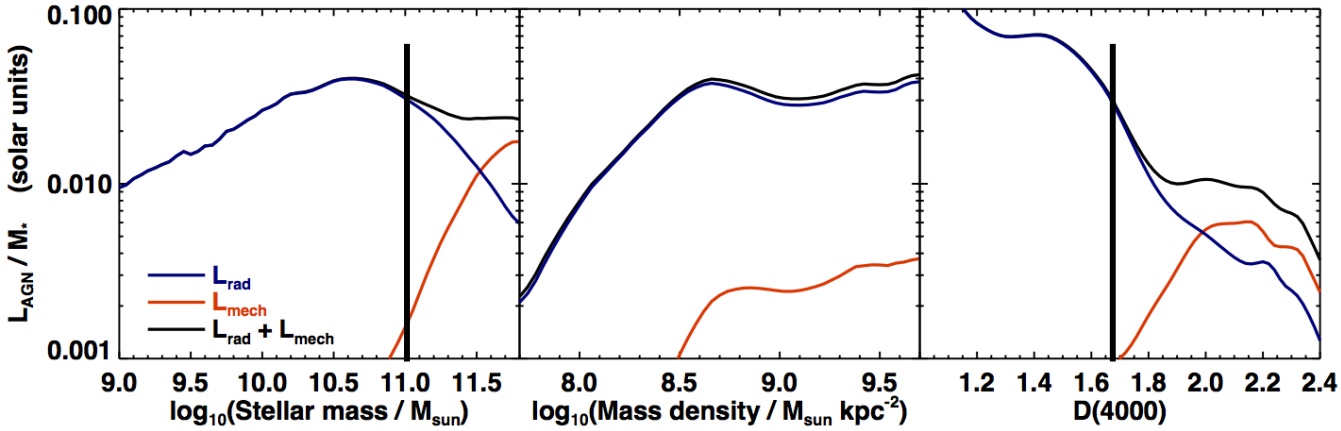
- moderate radio power
- mostly FRI
- **LERG**
- Hosted by very massive ($M > 10^{11}$ M_{sun}) ETG
- little SF

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)

Local Universe - Heckmann & Best 2014



Focus of the talk

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

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

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

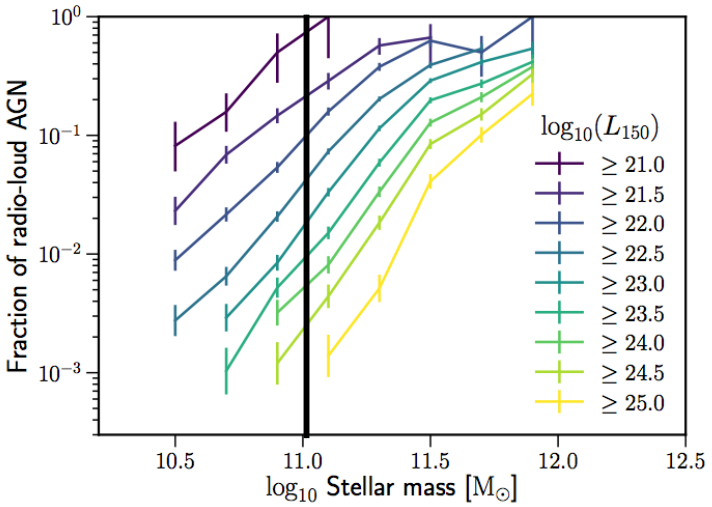
Dominant RL-AGN population: L/L_{Edd} ~10^{-5}

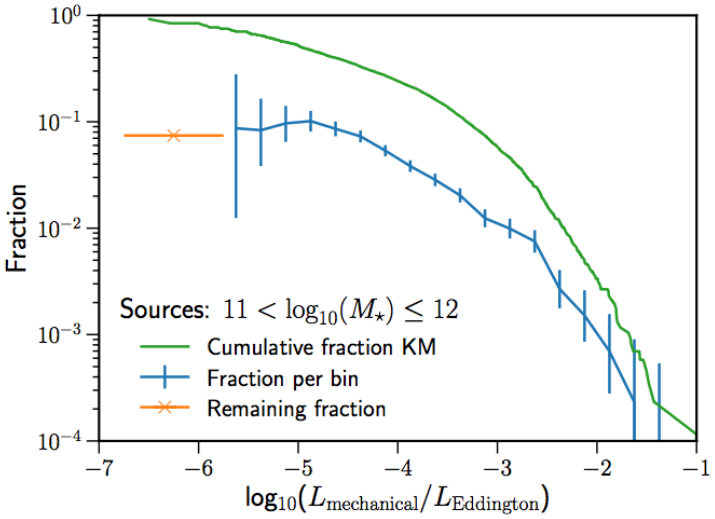
AGN Fueling: hot gas
(from the X-ray halo)

AGN feedback:
mostly kinetic (radio jets)

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

Sabater et al. 2018 - **0.01<z<0.3**





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)

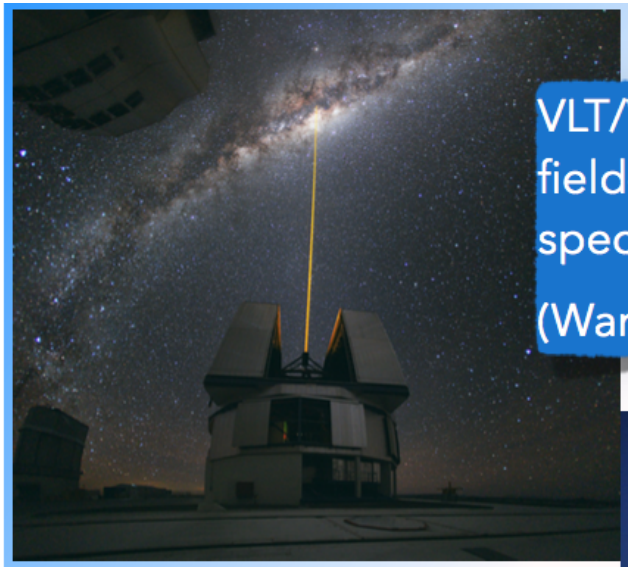
A PILOT SOUTHERN RG SAMPLE

Radio source	Host galaxy	z	Log $P_{1.4GHz}$ (W Hz^{-1})	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° < Decl. < -40°]
- All LERG
- Diverse environs

* *sub-arcsec scale*

The Multi-wavelength dataset



VLT/VIMOS integral-field-unit (IFU) spectroscopy **+ MUSE**

(Warren et al. in prep.)

ALMA Cycle 3 CO (2-1) observations (Ruffa et al. in prep.)

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

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

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

Adapted from I. Ruffa

The Multi-wavelength dataset

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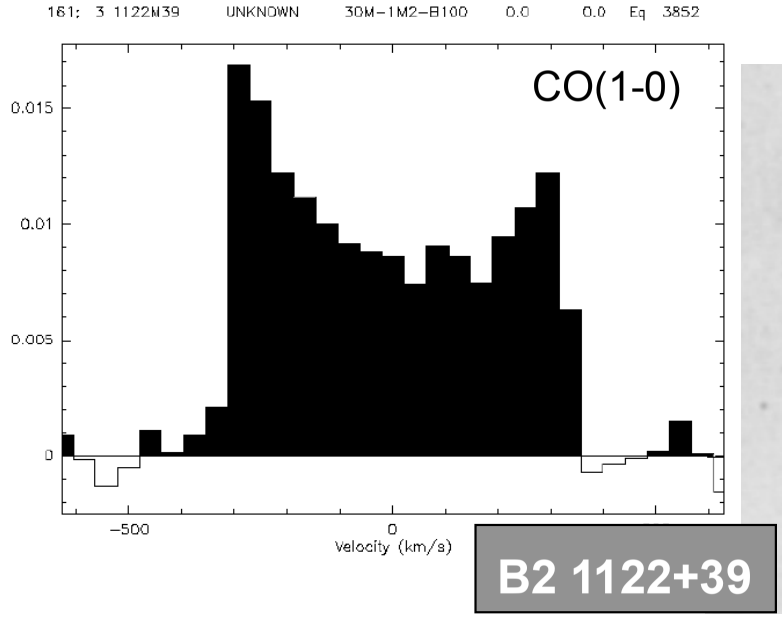
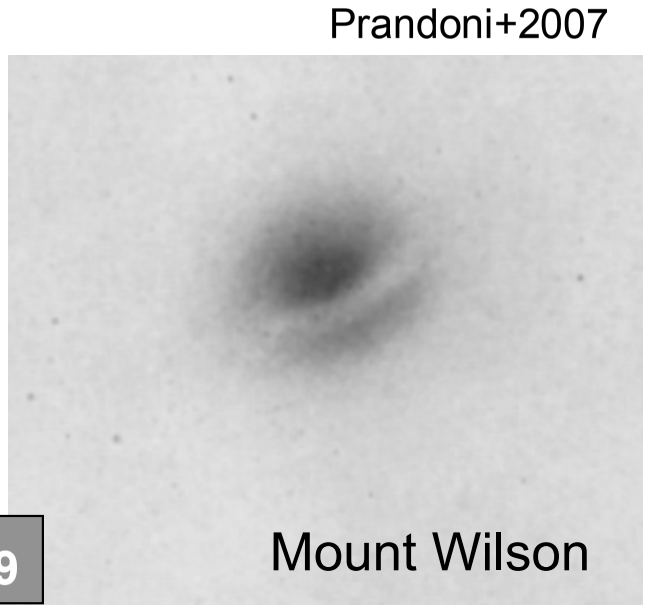
The Role of Molecular Gas in LERGs - I

- H_2 / 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_2 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-Flaquer+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-Flaquer +2010] *no uniform selection criteria*

+ Southern Sample**: 11 objetcs with z<0.03**

➔ 76 distinct Radio Galaxies

Comparison Sample – ATLAS^{3D}

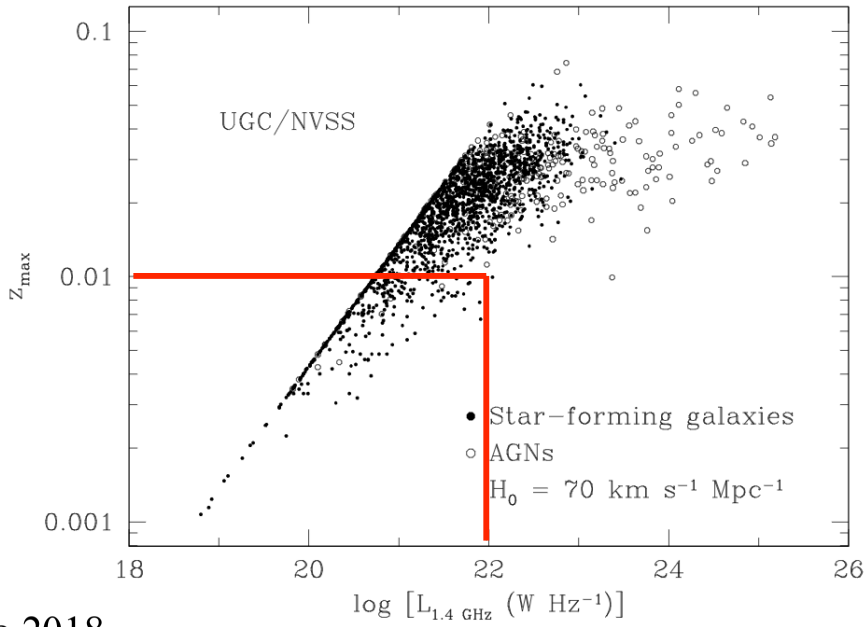
- 260 early-type galaxies (E/S0) with D<42 Mpc (z<0.01) [Cappellari+11]
- extracted from parent sample with -6° < Decl. < 64° and M_K < -21.5
- SAURON @ WHT

- 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

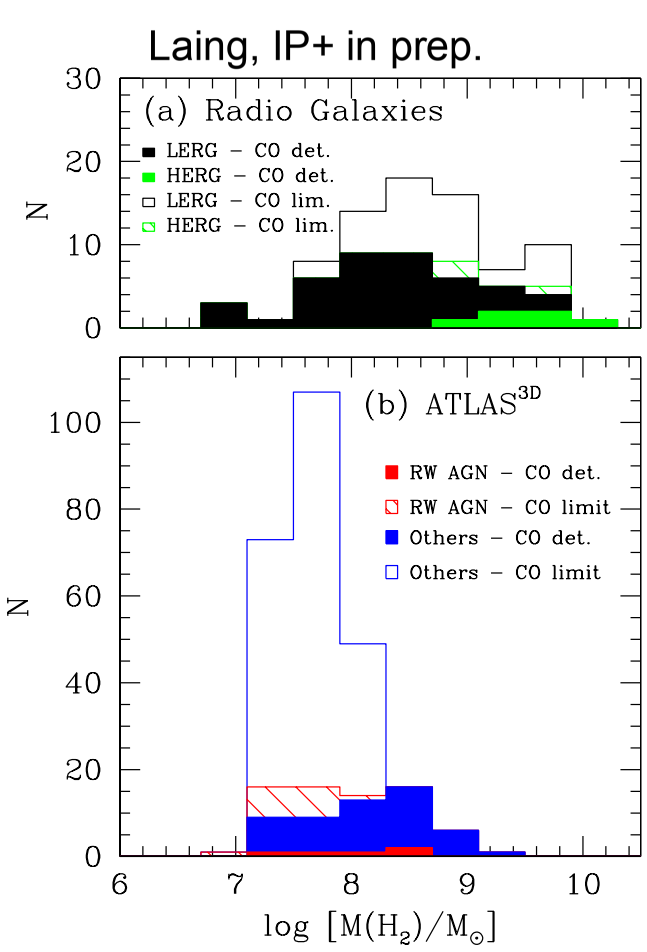
- no large scale jets
- P<10^22 W/Hz

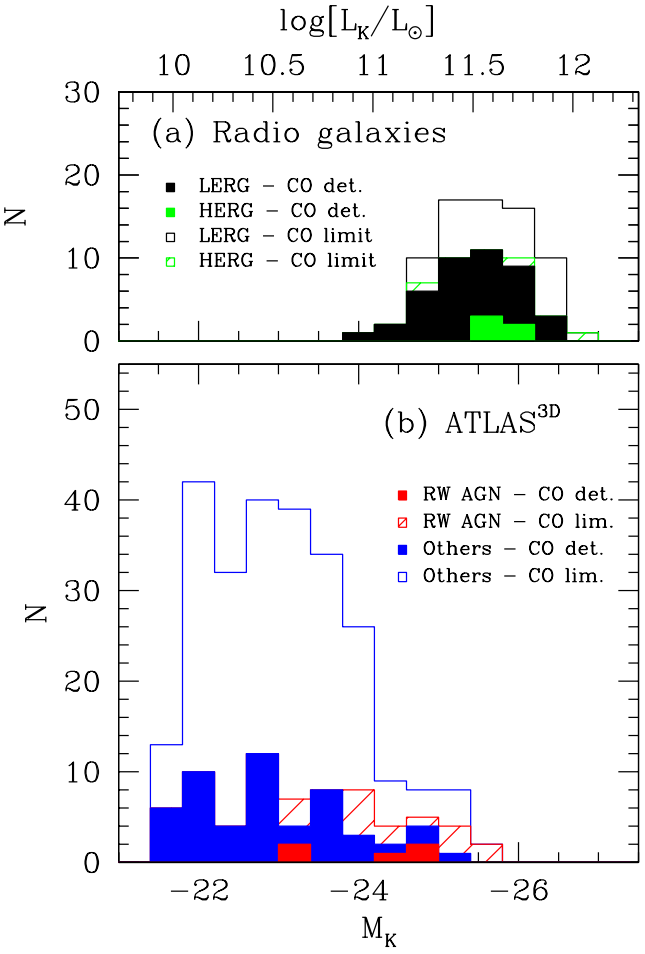
Condon+2002

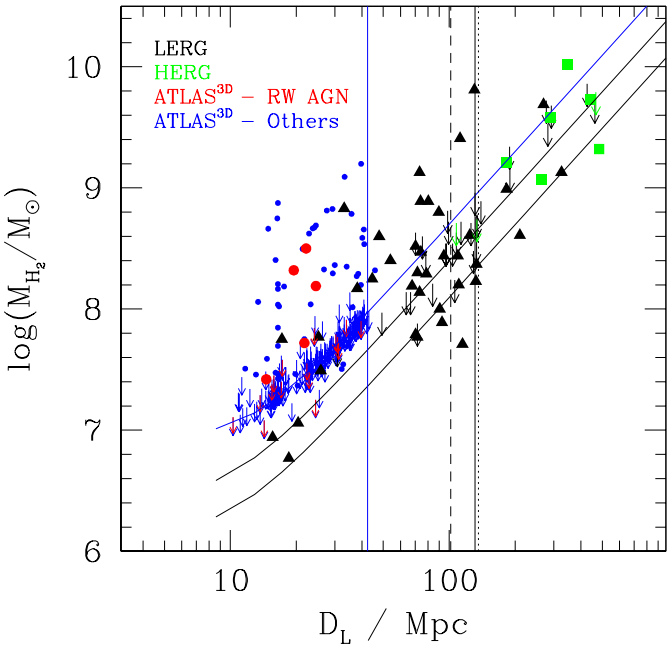


The Role of Molecular Gas in LERGs - I

➔ Is H_2 more abundant in LERGs wrt RQ ETG and/ore Radio weak AGN?



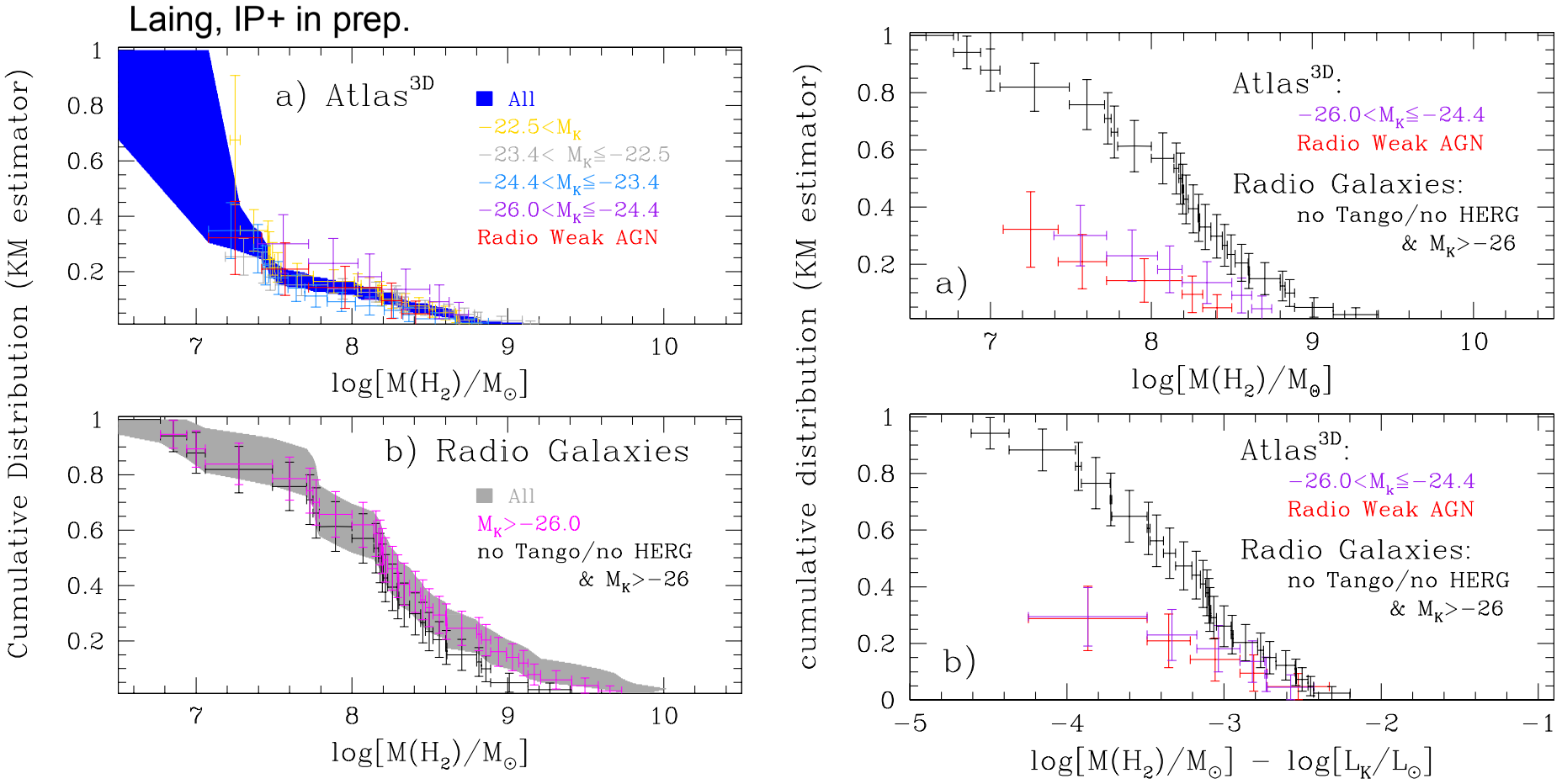




Caveat: ATLAS^{3D} galaxies less distant and less massive

The Role of Molecular Gas in LERGs - I

➔ Is H_2 more abundant in LERGs wrt RQ ETG and/ore Radio weak AGN?



The Role of Molecular Gas in LERGs - I

➔ Is H_2 more abundant in LERGs wrt RQ ETG and/ore Radio weak AGN?

- *H_2 seems to be more abundant in LERG than in RQ ETG*
- *LERG mostly have log M(H2)~7.5 – 8 M_{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_2 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 $^{12}CO(2\text{-}1)$ integrated parameters.

Ruffa, IP+ in prep.

Env.	Target (1)	Line FWHM (km s^{-1}) (2)	Line FWZI (km s^{-1}) (3)	$S_{CO}\Delta v$ (Jy km s^{-1}) (4)	M_{H2} ($M_\odot$) (5)
I	IC 1531	260	280	2.0±0.2	$(6.4 \pm 0.6) \times 10^8$
P	NGC 612	780	840	273±27	$(1.2 \pm 0.2) \times 10^{11}$
I	PKS 0718-34	334[1]	480[1]	< 0.1	$< 3.9 \times 10^7$
G/P	NGC 3100	345	470	18±1.8	$(6.8 \pm 0.8) \times 10^8$
G	NGC 3557	440	484	7.0±0.7	$(3.6 \pm 0.4) \times 10^8$
C	ESO 443-G 024	786[1]	1000[1]	< 0.1	$< 2.1 \times 10^7$
C	IC 4296[2]	680	880	1.6±0.1	$(1.2 \pm 0.8) \times 10^8$
	NGC 7075	560	640	1.0±0.1	$(1.7 \pm 0.2) \times 10^8$
G	IC 1459	492[1]	640[1]	< 0.4	$< 6.3 \times 10^6$

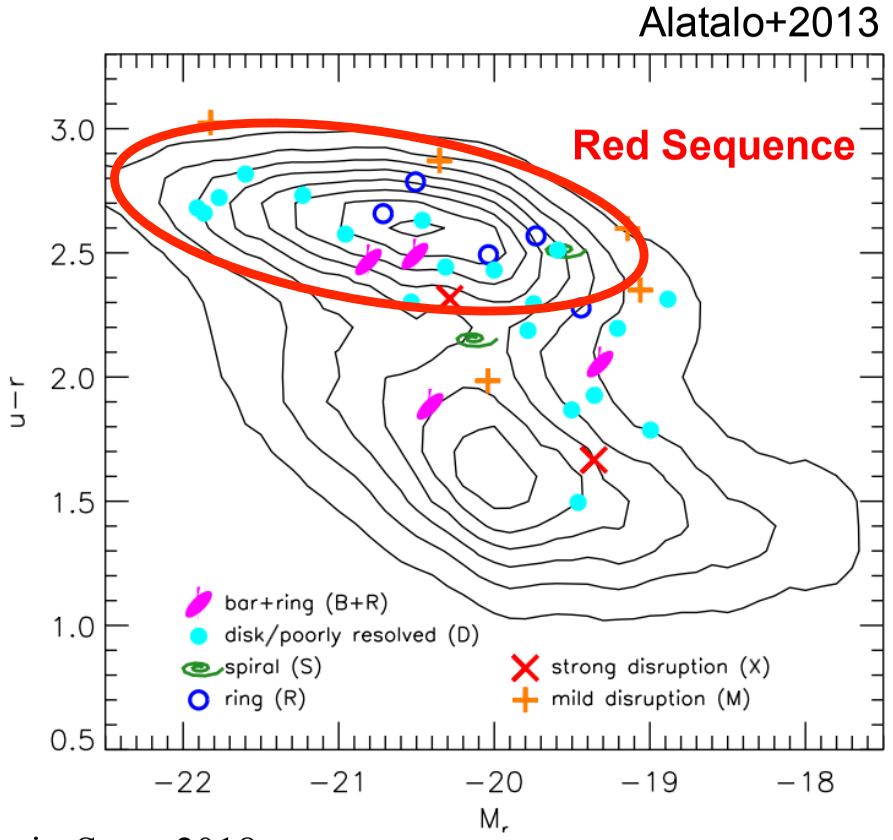
The Role of Molecular Gas in LERGs - II

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

ATLAS^{3D} 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



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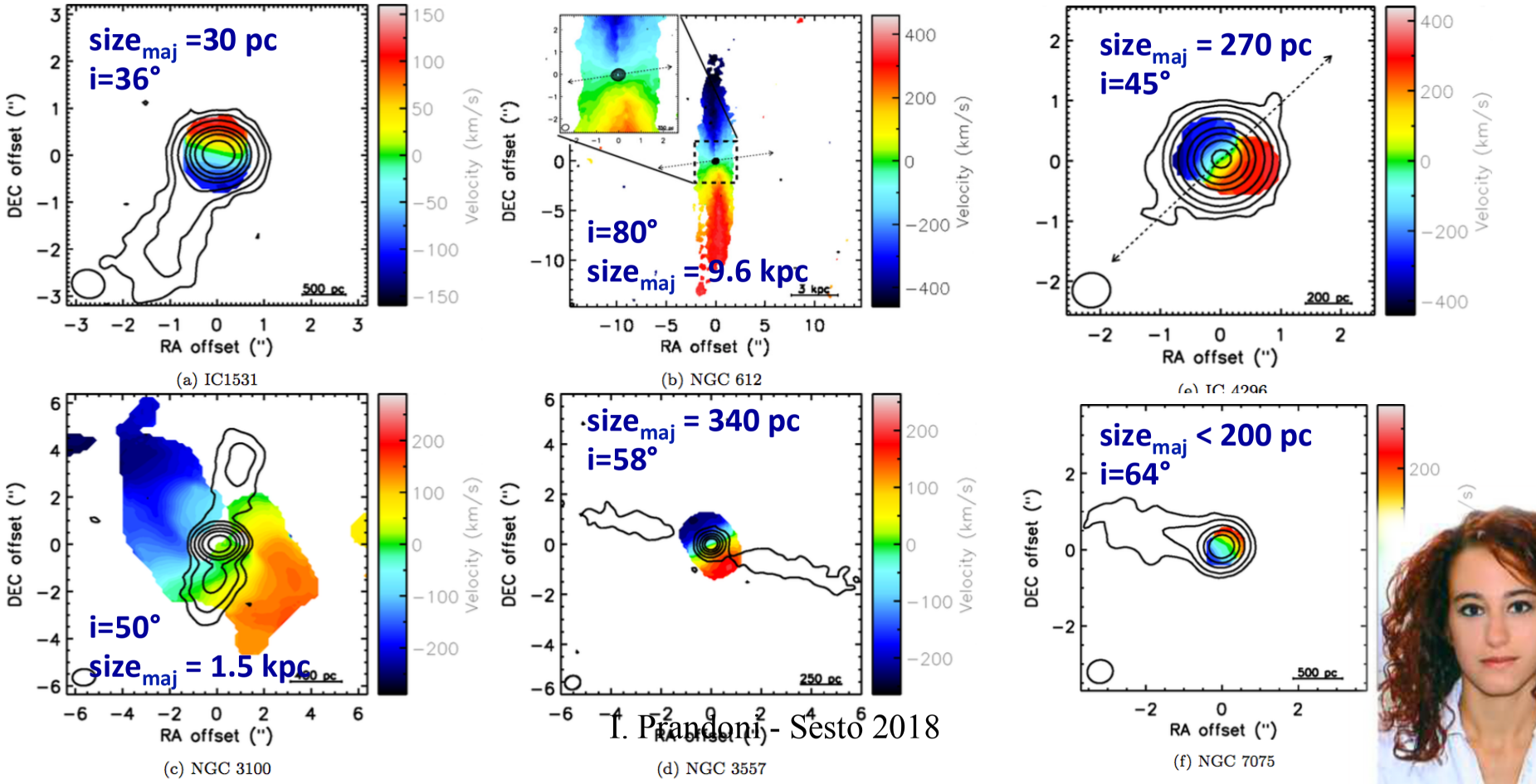

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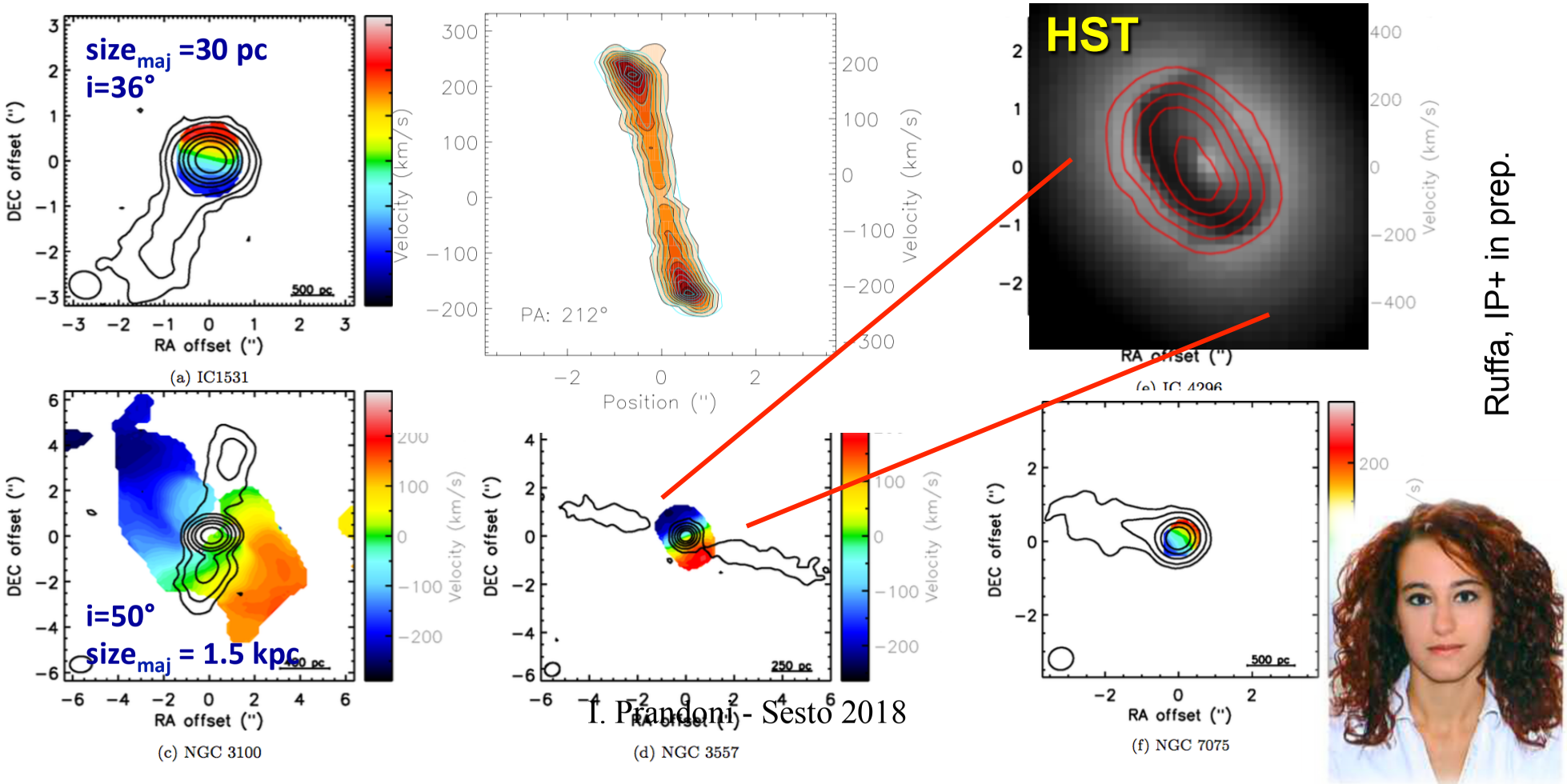

The Role of Molecular Gas in LERGs - II

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

ATLAS^{3D}

50% disks (D)
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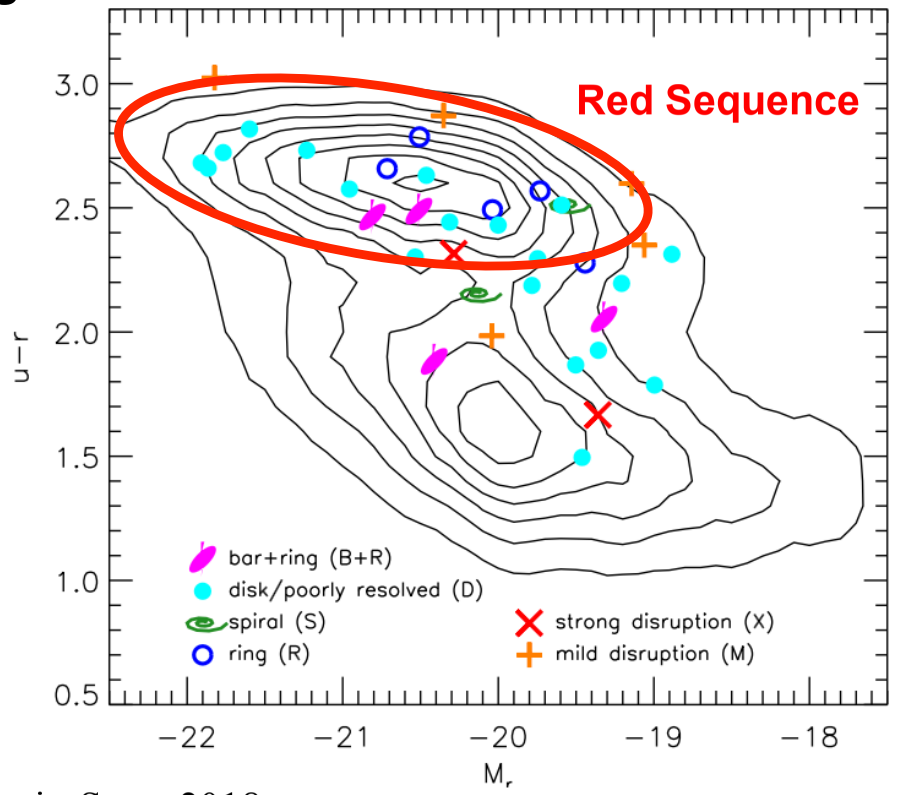
Most massive → disks
Rings → red sequence

6 LERGs

4 ~ 67%
1 ~ 17%

1 ~ 17%?

Alatalo+2013

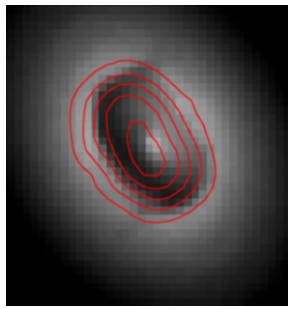


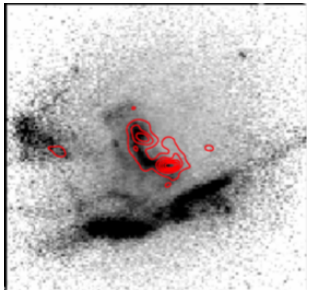
The Role of Molecular Gas in LERGs - II

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

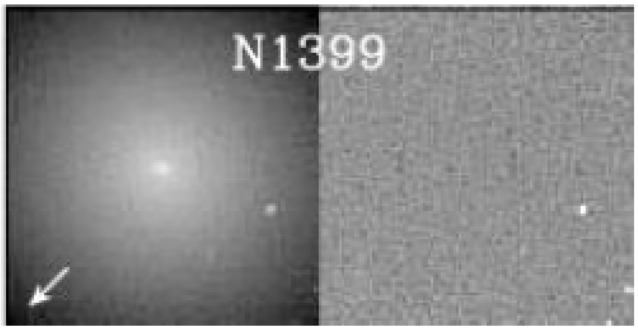
➔ No evidence so far... but comparis**d towards gas-rich galaxies** and compact CO structures**.**

Preliminary

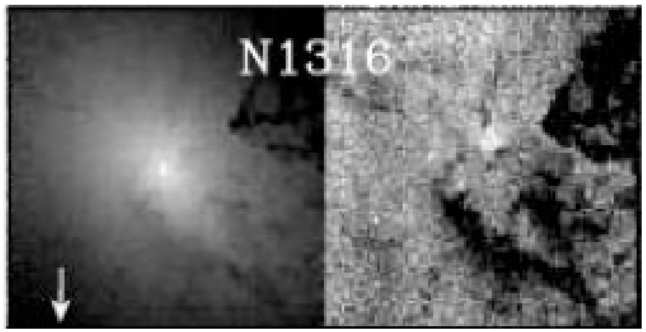




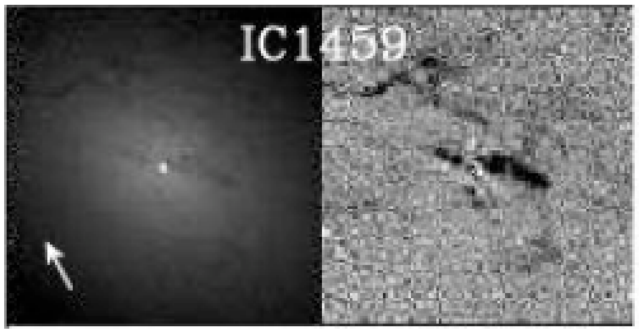
PKS 0336-35



PKS 0320-37



PKS 2254-367



The Role of Molecular Gas in LERGs - III

➔ Is the H_2 of internal or external origin?

- 13 (33%) of **ATLAS^{3D}** CO-rich sub-sample show significant (>30°) kinematic major axis misalignment between stellar and gas components → external origin

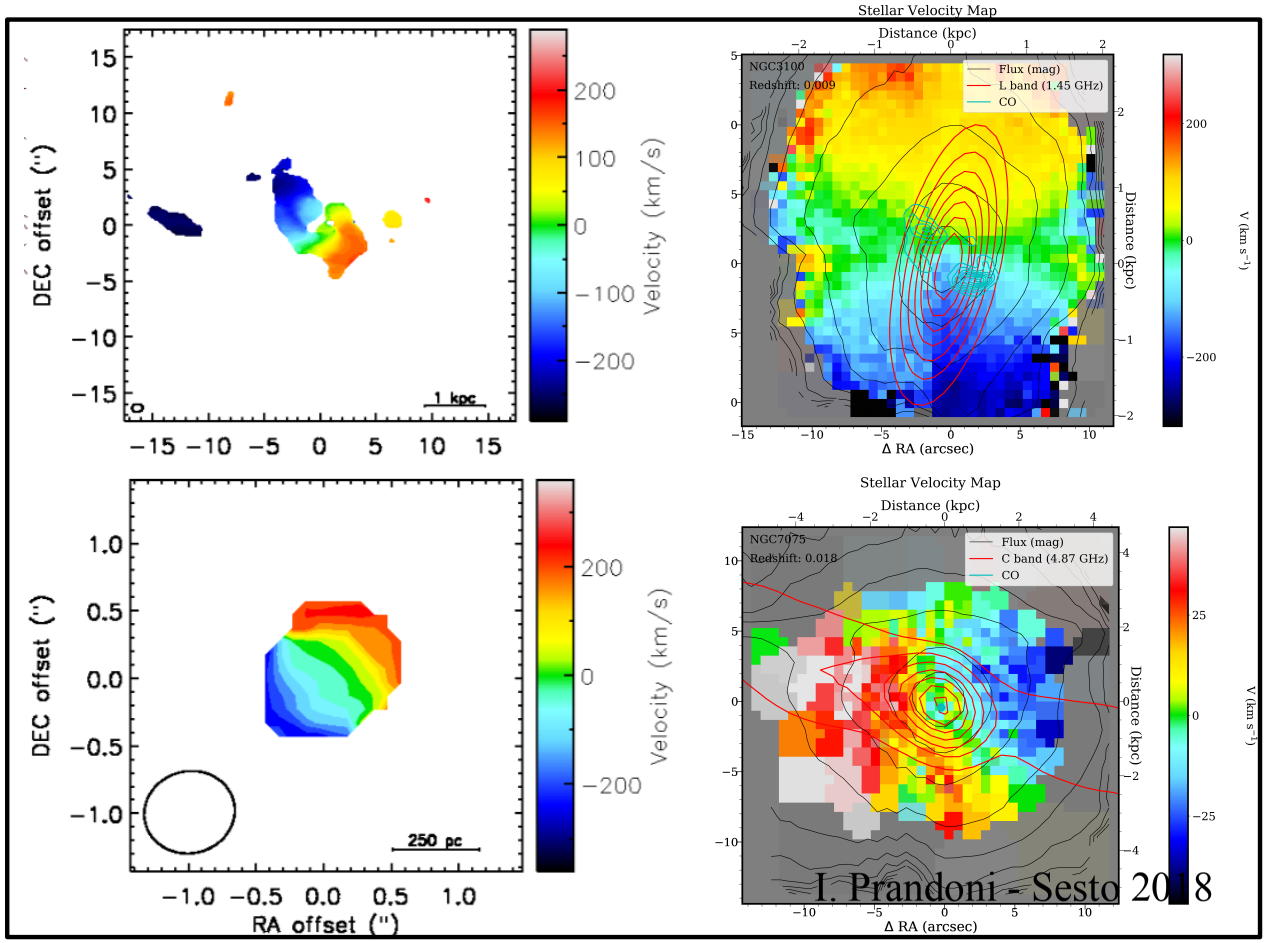
- 2 with other signs of external origin

➔ **38% external** [Alatalo+13]

The Role of Molecular Gas in LERGs - III

➔ Is the H_2 of internal or external origin?

2 (33%) with kinematic axis misalignments

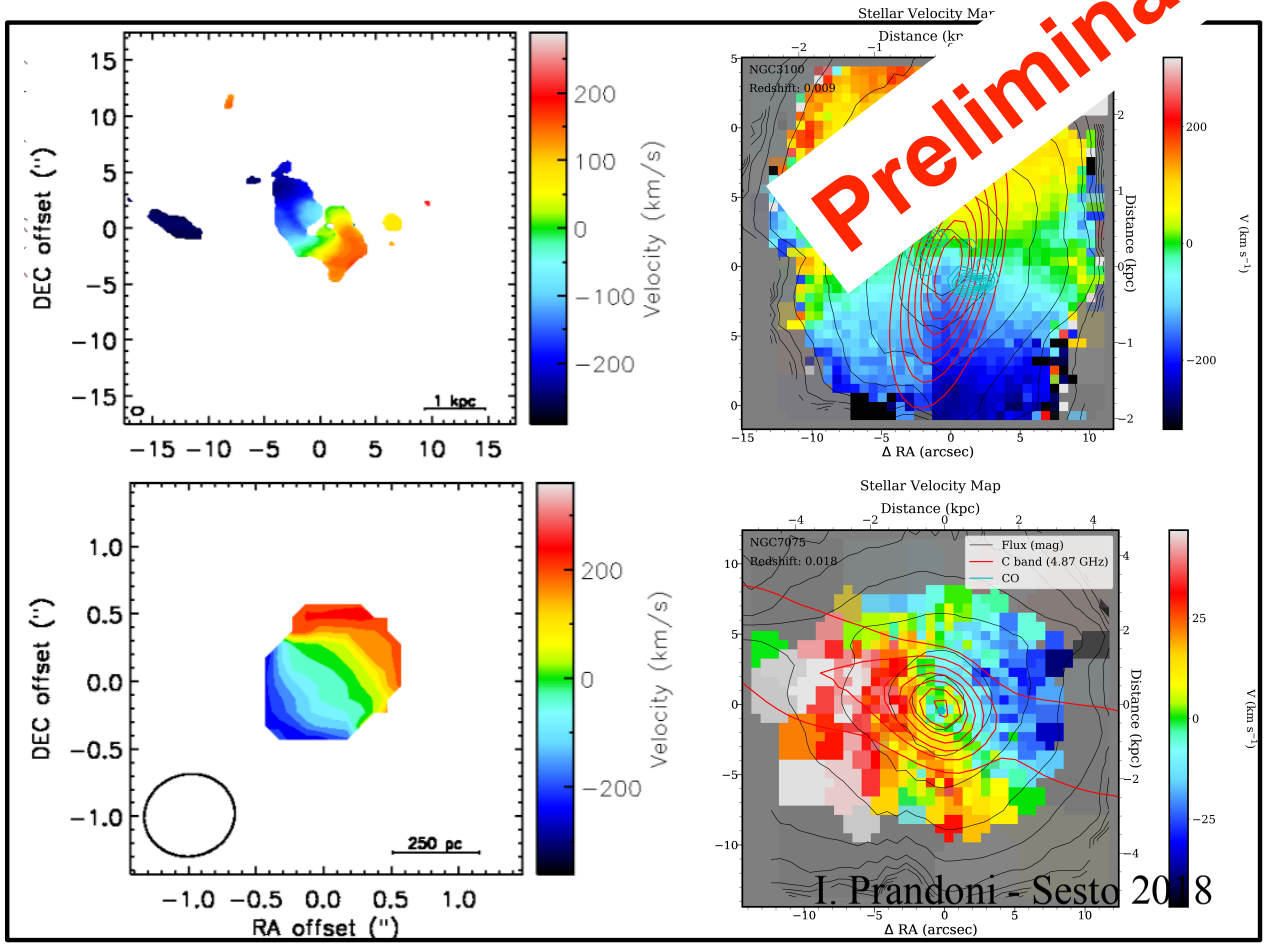


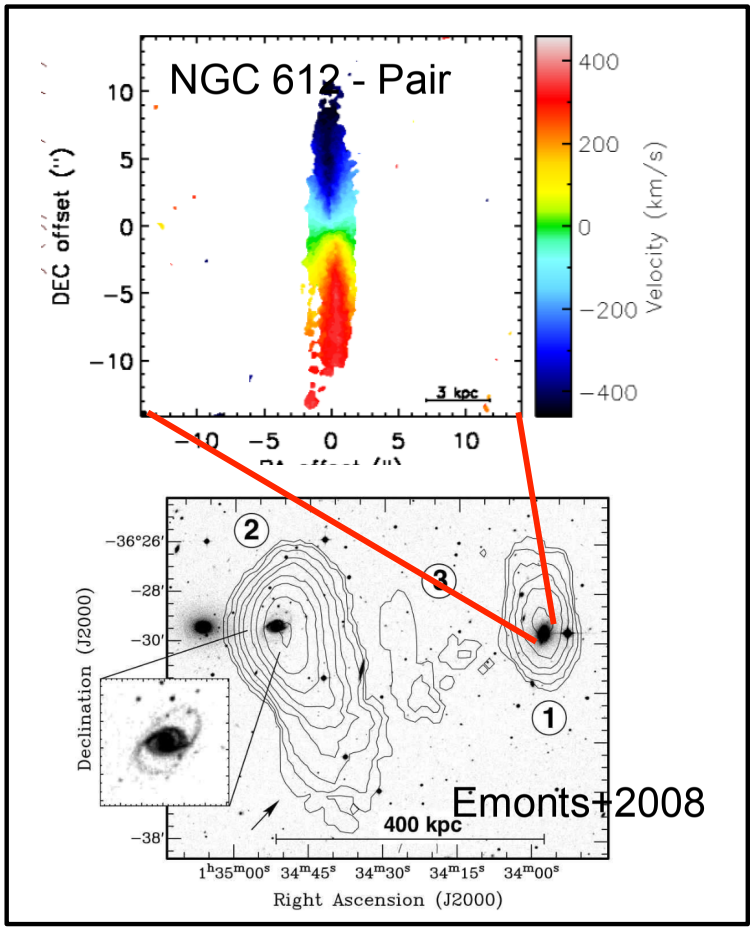
Warren+in prep.

The Role of Molecular Gas in LERGs - III

➔ Is the H_2 of internal or external origin?

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



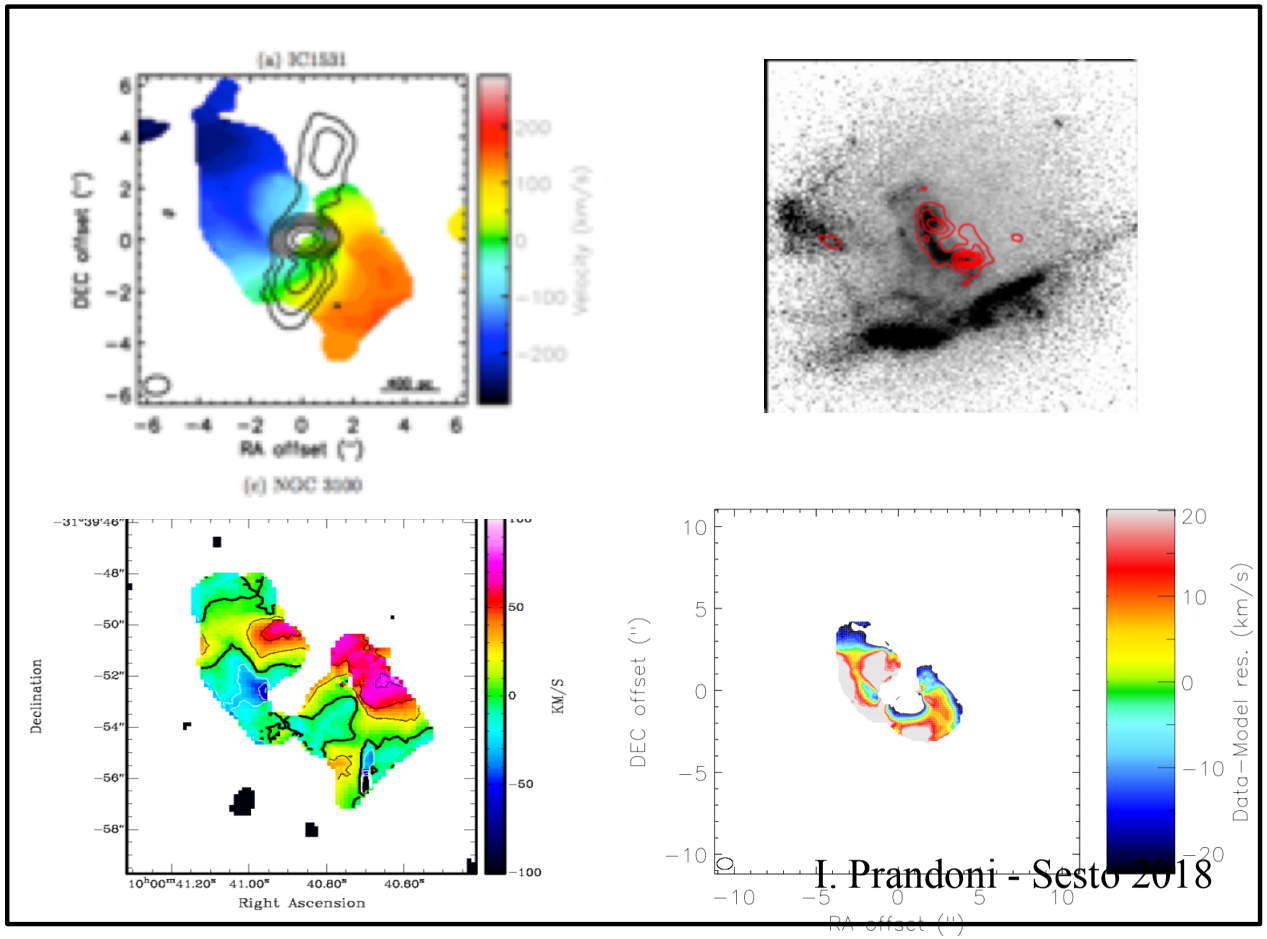


Preview: The case of NGC 3100

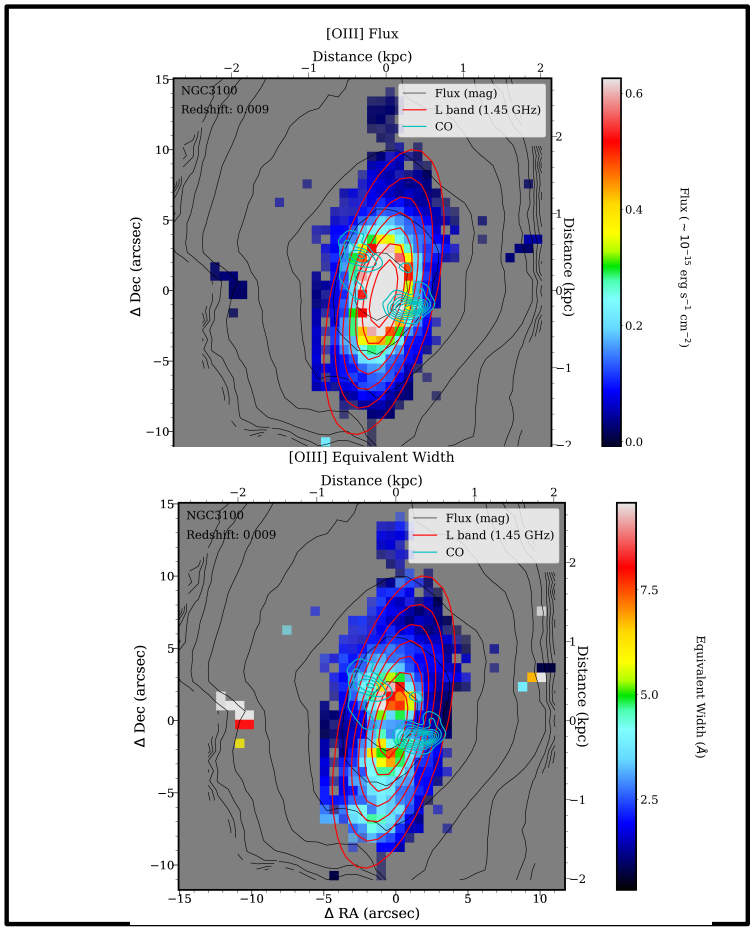
➔ *Evidence of feeding/feedback?*

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

Ruffa, Davis+ in prep.



Warren+in prep.



Summary

- H_2 is more abundant in LERG than in RQ ETG
- H_2 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_2 morphology and kinematics similar in LERG and gas-rich RQ ETGs
- H_2 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_2 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_2 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?*