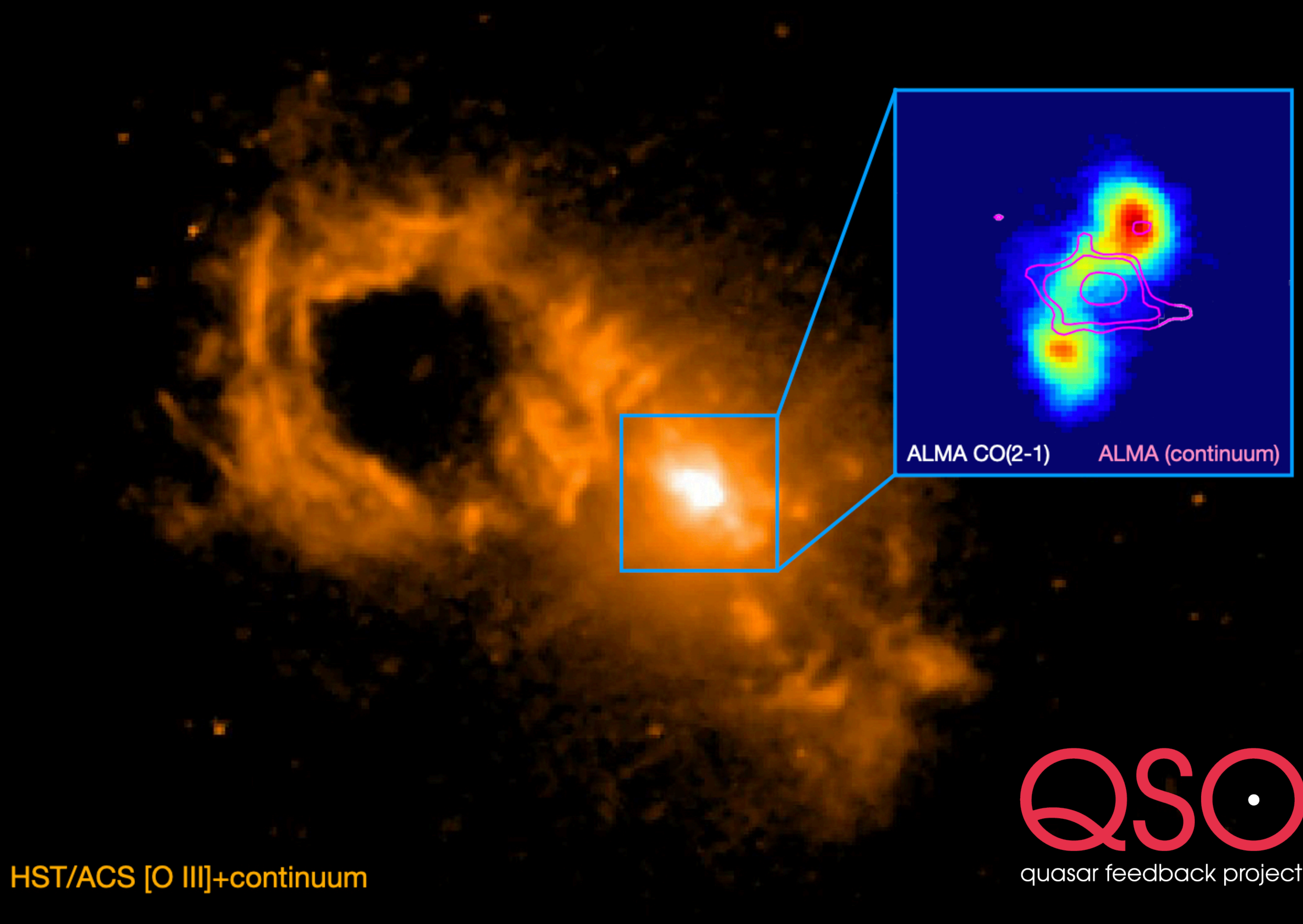
A multi-phase investigation of AGN feedback - 2018.1.00870.S



QSOFEED quasar feedback project

Cristina Ramos Almeida
& the QSOFEED team

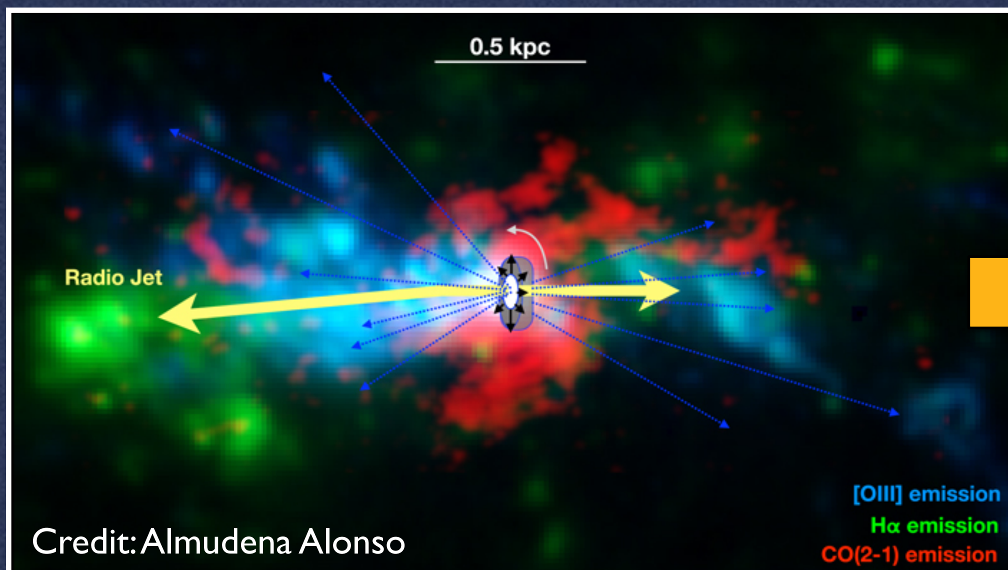
Instituto de Astrofísica de Canarias · IAC

BiD4BEST Big Data applications for Black hole Evolution Studies

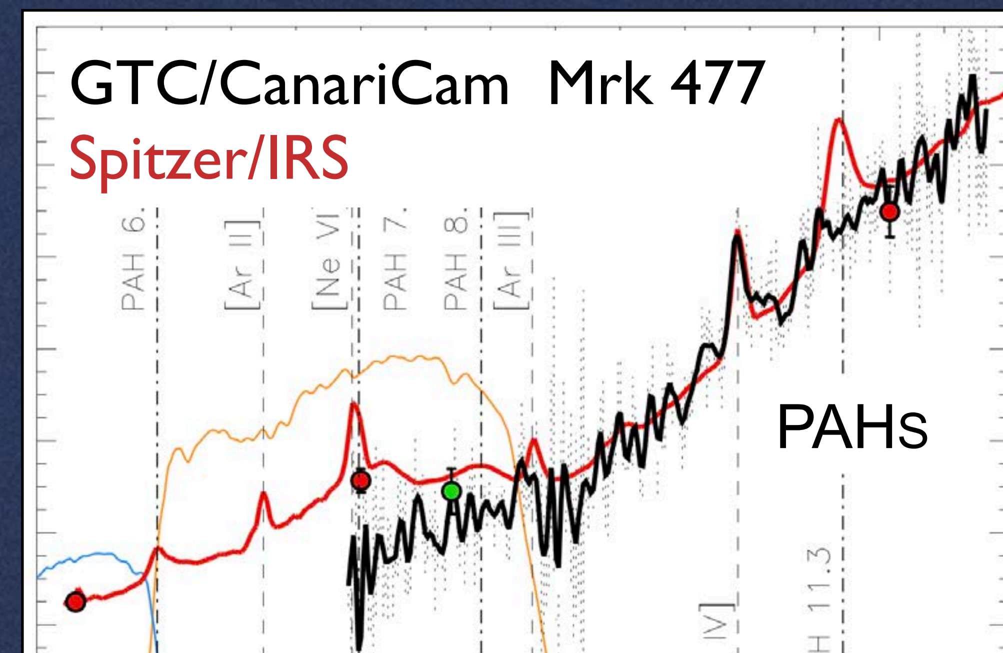
EXCELENCIA SEVERO OCHOA

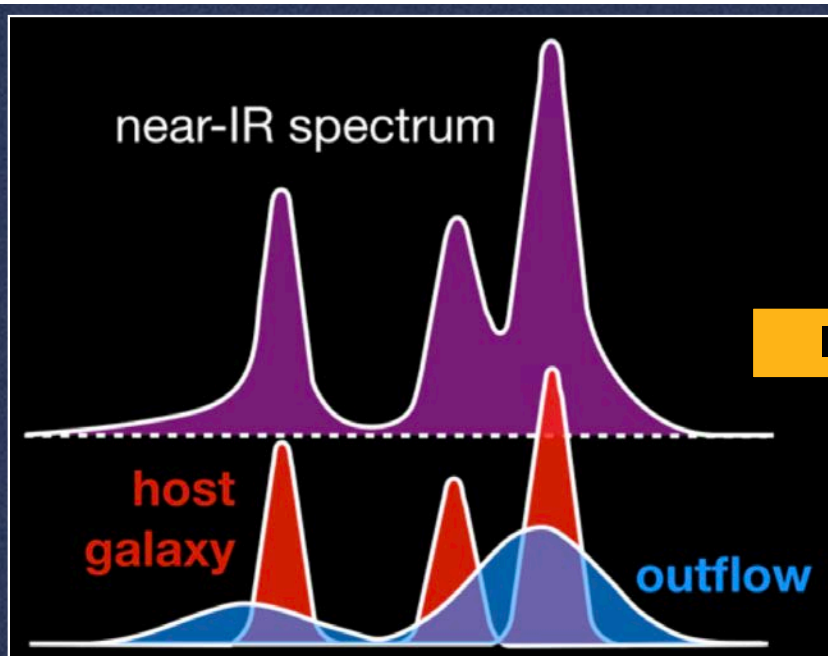
QSOFEED: Assessing the impact of quasar-driven outflows on galaxy properties with same dynamical timescales

Ramos Almeida+23

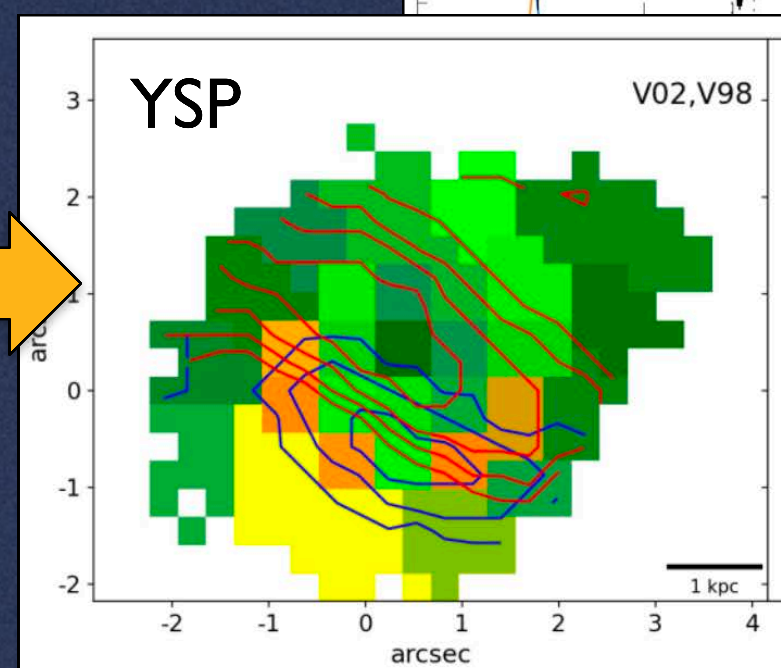


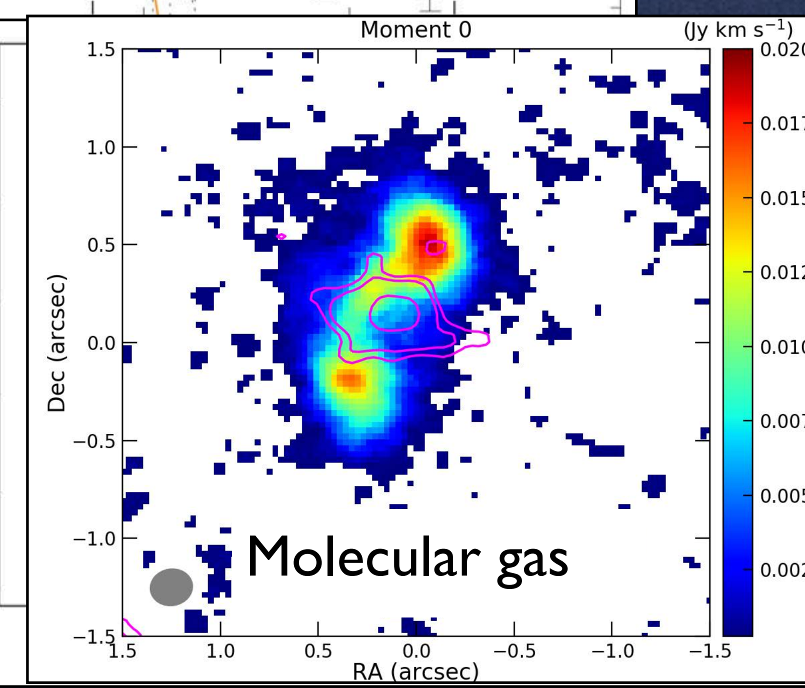
IMPACT





IMPACT





Ramos Almeida+19; Speranza+22, 24
Hervella-Seoane+23

Bessiere & Ramos Almeida 22
Bessiere+24

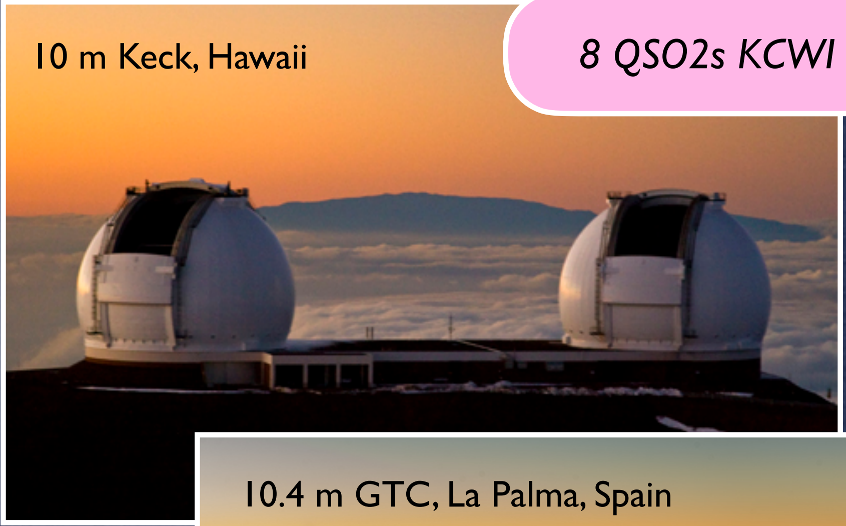
Ramos Almeida+22
Audibert+23
Zanchettin+25

QSO FEED quasar feedback project

All brightest ($L_{[OIII]} > 10^{8.5}\,L_\odot \sim L_{bol} > 10^{45}$ erg/s) and most nearby ($z<0.14 \approx D<650$ Mpc) sources in Reyes+2008 = 48 QSO2s.

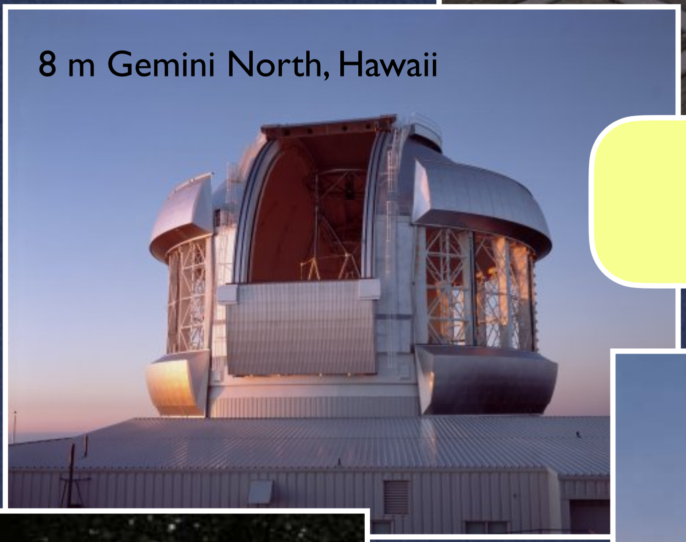
- High luminosity AGN → good S/N & high probability of powerful outflows.
- Nearby → resolve outflows and host galaxy properties.
- Type-2 AGN → BLR lines & AGN continuum obscured by dust.

QSOFEED
quasar feedback project

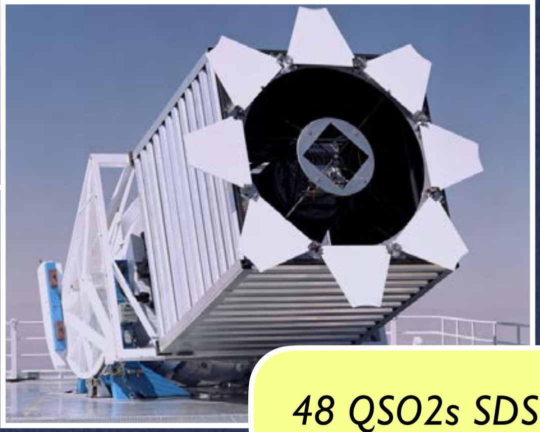


8 QSO2s KCWI

44 QSO2s EMIR
12 QSO2s MEGARA



7 QSO2s VLT/SINFONI
2 QSO2s Gemini/NIFS



48 QSO2s SDSS

12 QSO2s STIS & ACS

7 QSO2s Cycle 6 ALMA

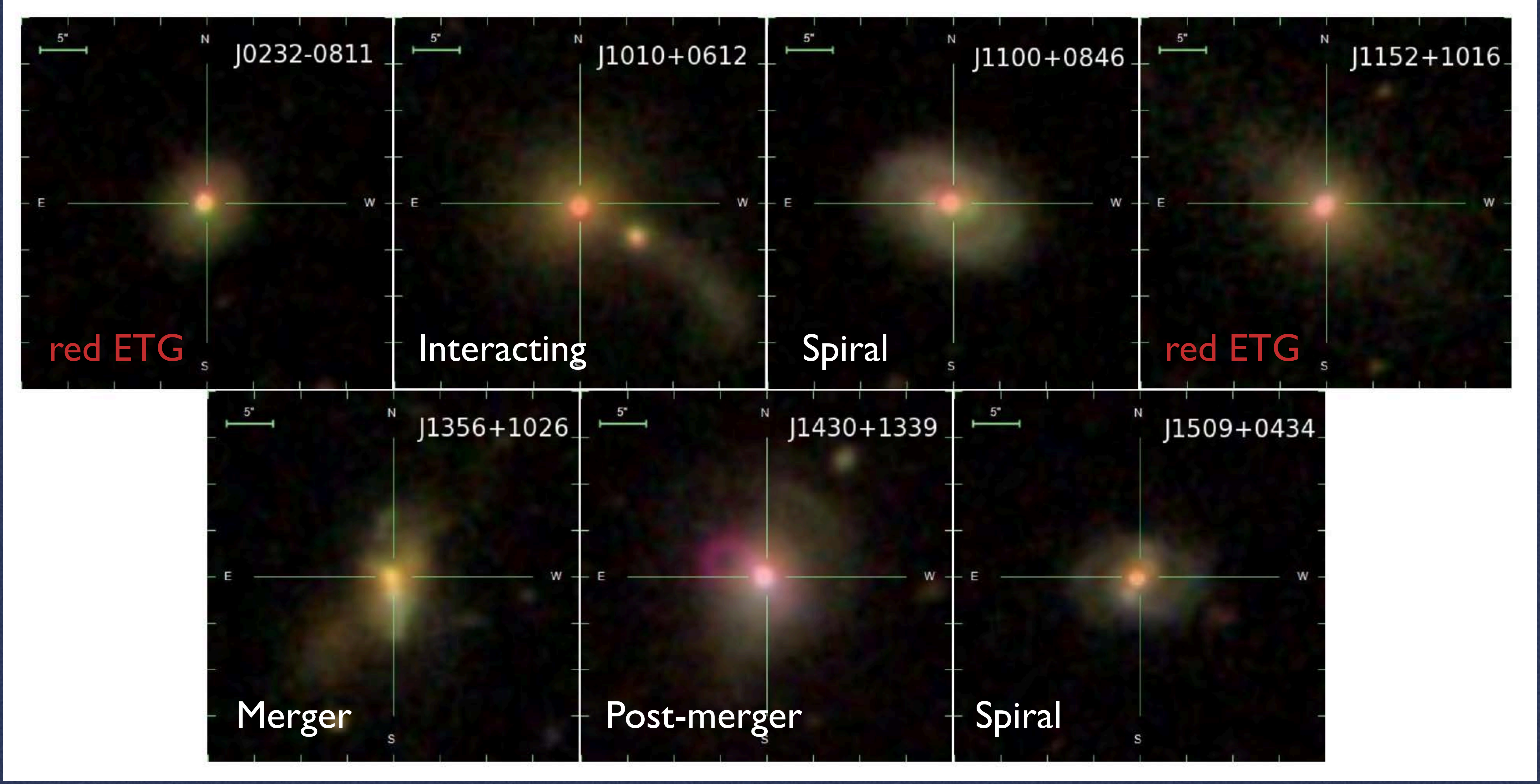
48 QSO2s INT/WFC

30 h Cycle 2 GO MIRI/MRS

ALMA observations

- ALMA subset of 7 QSO2s in CO(2-1) at ~0.2 arcsec resolution ≃ 370 pc.

- $L_{[OIII]} > 10^{8.5} L_\odot \sim L_{bol} > 10^{45.6}$ erg/s and z~0.1 -- QSOFEED sample (48 QSO2s from Reyes+2008).



ALMA observations

C-1

A multiphase investigation of AGN feedback — 2018.1.00870.S

ABSTRACT

The broad scientific objective of this project is to advance in our understanding of AGN feedback and its connection with the galaxies molecular gas reservoirs. We propose to perform the first multiphase characterization of outflow properties (size, geometry, kinematics and mass) in a sample of nearby and luminous type-2 quasars (QSO2s). By combining the requested ALMA observations with available VLT/SINFONI data we will study the properties of the line-emitting gas in the ionized, hot and cold molecular phases for a pilot sample of 7 QSO2s. These AGN are drawn from a larger sample and are representative of the luminous QSO2 population in terms of bolometric and radio luminosity, morphology and SFR. We will also investigate for quasar circum-nuclear disks (CNDs) of molecular gas, characterize them and study their connection with the host galaxy via outflows. We ultimately wish to answer the important questions of whether quasars with luminous outflows differ in terms of the molecular gas reservoirs from those without outflows and/or whether there is a dependency with the outflow properties.

PI NAME:	Cristina Ramos Almeida			**SCIENCE CATEGORY:**	Galaxies and Galactic Nuclei
ESTIMATED 12M TIME:	9.5 h	**ESTIMATED ACA TIME:**	0.0 h	**ESTIMATED NON-STANDARD MODE TIME (12-M):**	0.0 h
CO-PI NAME(S): (Large & VLBI Proposals only)					
CO-INVESTIGATOR NAME(S):	Almudena Alonso-Herrero; Claudia Cicone; Santiago Garcia-Burillo; Héctor Vives-Arias; Clive Tadhunter				
DUPLICATE OBSERVATION JUSTIFICATION:					

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)

SCIENCE GOAL	POSITION	BAND	ANG.RES.(")	LAS.(")	ACA?	NON-STANDARD MODE
J0232-0811	ICRS 02:32:24.2500, -08:11:40.230	5	0.150	3.000	N	N
J1010+0612	ICRS 10:10:43.3615, 06:12:01.287	5	0.150	3.000	N	N
J1100+0846	ICRS 11:00:12.3837, 08:46:16.316	5	0.150	3.000	N	N
J1152+1016	ICRS 11:52:45.6620, 10:16:23.870	6	0.150	3.000	N	N
J1356+1026	ICRS 13:56:46.1060, 10:26:09.090	5	0.150	3.000	N	N
J1430+1339	ICRS 14:30:29.8680, 13:39:11.790	6	0.150	3.000	N	N
J1509+0434	ICRS 15:09:04.2199, 04:34:41.800	5	0.150	3.000	N	N
Total # Science Goals : 7						

SCHEDULING TIME CONSTRAINTS	NONE	**TIME ESTIMATES OVERRIDDEN ?**	No

ALMA observations

<u>Observations Requested.</u> Our targets have redshifts between 0.07 and 0.14, which enables to observe $^{12}CO(2-1)$ in band 5 with ALMA (band 6 for J1152 and J1430). We chose the CO(2–1) line because it is a good tracer of the total molecular gas content and it is expected to be enhanced with respect to CO(1–0) in the nuclear region of AGN (GB2014). We request an angular resolution of 0.15" (<325 pc for our targets) to resolve compact outflow sizes (≤1-2 kpc; e.g. Fischer et al. 2018) and the CNDs (~0.5-2 kpc; Downes & Solomon 1998; Wilson et al. 2008; Sun et al. 2014). **The proposed angular resolution is crucial to spatially resolve the CNDs and the nuclear outflows.**

Considering an average total $M_{gas}\sim10^9\,M_\odot$ for our targets, estimated from the SFRs reported in Table 1 and consistent with the values reported in the literature for QSO2s (Krips et al. 2012; Villar-Martín et al. 2013), we expect an outflow gas mass of $\sim10^7\,M_\odot$ (a conservative 1% of total M_{gas}). We can test this prediction in one of our targets, J1356+1026, for which lower angular resolution ALMA Cycle 1 CO(1-0) and CO(3-2) observations are available (Sun et al. 2014). For this source, total M_{gas} $\sim9\times10^8\,M_\odot$ and the outflow mass is $\sim7\times10^7\,M_\odot$, consistent with our estimates. In addition, from our NIR H_2 data we derived a total $M_{gas} = (7\pm2)\times10^9\,M_\odot$ in the CND of the Teacup (RA2017).

Our sensitivity estimates are driven by our more demanding goal, which is detecting and imaging the CO(2-1) line from the molecular outflow component. We assume a conservative MW-like CO-to-H_2 conversion factor of 4.6, a CO(2-1)/CO(1-0)~0.7, and total line-width for the CO outflow ~600 km/s, which corresponds to $v_{outflow}\sim300$ km/s. Our rms goals imply that we will image with a SNR=5 (per channel) the emission from any $M_{H2}\sim10^7\,M_\odot$ outflow component present in the system. The predicted SNR for the velocity-integrated CO(2-1) line in the outflow will be > 17-20.

ALMA observations

2018.1.00870.S

SG : 3 of 7 J1100+0846 Band 5

Search for the CDN and characterization of the cold molecular outflow in J1100+0846.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.1500"	3.0"	400 µJy, 495.2 mK	25 km/s, 17.5 MHz	230.538000 GHz	19.4 µJy, 24 mK	7.386 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-6)	t_total(C43-3)	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
1.6 h	0.7 h	0.2 h	9.3 "	1	offset	27.8 "	2479.6 s	9.4 GB	2.0 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Spectral Line

BB	Center Freq Rest GHz	spw name	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Res.	Res. El. per FWHM
1	230.538000	CO v=0 2-1	3840	1875.00 MHz	7812.500 kHz	2683.1 km/s	11.180 km/s	27
2	228.600000	Continuum-1	128	1875.00 MHz	31.250 MHz	2705.8 km/s	45.097 km/s	7
3	217.550000	SiO+H2CO	3840	1875.00 MHz	7812.500 kHz	2843.3 km/s	11.847 km/s	25
4	215.400000	Continuum-2	128	1875.00 MHz	31.250 MHz	2871.6 km/s	47.861 km/s	6

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-SDSS_J110012....	11:00:12, 08:46:16	27352.93 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	2.00 mJy	10.0	300 k...	199.45 µJy, 246...	12.00	0.0%	0.0
Continuum	1.00 mJy	51.5				0.0%	0.0

Dynamic range (cont flux/line rms): 2.5

1 Tuning

Tuning	Target	Rep. Freq. Sky GHz	RMS (Rep. Freq.)	RMS Achieved
1	1	209.503817	398.9 µJy, 493.9 mK	398.90 uJy - 471.45 uJy

ALMA observations

SG-3

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity ca...

Sensitivity estimates are driven by our highest priority and likely more demanding goal, which aims at detecting and imaging the CO(2-1) line from any putative molecular outflow component of mass M(H2)~1e07 Msun or above this very conservative threshold. To quantify the expected S/N ratio we assume that the dimensions (diameter, D) and molecular gas mass (MH2) of the putative outflow of the QSO will be D~2 kpc and MH2~1e07 Msun. We assume a conservative MW-like CO-to-H2 conversion factor= 4.6, a CO21-to-CO10 line ratio ~0.7 and total line-width for the CO outflow ~600 km/s, which corresponds to v-outflow~300 km/s. In this scenario our rms goal of 0.4 mJy per channel of 25 km/s implies that we will image with a SNR of 5 (per 25 km/s-channel) the emission from any MH2~1e07 Msun outflow component present in the system. The predicted S/N ratio for the velocity-integrated CO(2-1) line in the outflow will be > 20.

We can expect signals of more than 2 mJy at the 0.15'' resolution in CO(2-1) in the outflow, assuming that any 1-2 kpc-size outflow will be partly resolved by our beam due to the likely expected velocity structure/gradient of this component.

The CO(2-1) line emission stemming from a M(H2)~1e08-1e09 Msun circumnuclear disk will be comfortably imaged at SNR >> 20. We need to spend about 1.5hour to take into account calibrations. Furthermore, a 1.5 hour integration time will allow for a correct sampling of the UV plane.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

We want to reach 0.15'' beam ~300 pc to be able to image a possible molecular outflow of 1-2 kpc-diameter. At a given velocity, the largest scale in the circumnuclear disk (CND) of the QSO host will not likely exceed 3 arcsec (~5.5 kpc), which fits the LAS requirements for the proposed observations. This estimate is based on the CND size measured by SINFONI for the hot molecular gas phase and also on pre-ALMA interferometric observations of low-J CO lines of ULIRGs hosting QSOs (e.g. Downes & Solomon 1998; Wilson et al. 2008).

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line ...

The wide bandwidths of the ALMA correlator will also be used to map the continuum emission of the sources in two dedicated sub-bands. Besides the spectral window covering the CO(2-1) line (the main goal of this proposal) we will also tune a spectral window to the SiO(v=0, J=5-4) line to be able to detect the higher density component from the shocked gas. The latter is a mostly secondary goal that does not constrain in any way the time estimate. For the lines, we can smooth to 25 km/s channels, enough to resolve the emission from any putative molecular outflow component of v-out=+-300 km/s (FWHM=600 km/s).

Proposal accepted

Your ALMA Cycle 6 Proposal 2018.1.00870.S ALMA/Cycle6 ×

ph1m_noreply@alma.cl mié, 25 jul 2018, 17:24

para cra

From the Joint ALMA Observatory on behalf of the ****European ALMA Regional Center of ESO*****.

PROPOSAL CODE: 2018.1.00870.S
PROPOSAL TITLE: A multiphase investigation of AGN feedback

Dear Dr. Ramos Almeida,

I am pleased to inform you that your ALMA proposal 2018.1.00870.S has been accepted with a priority grade of B* and will be added to the Cycle 6 observing queue.

ALMA proposals were peer-reviewed using a Panel-based system as described in the ALMA Cycle 6 Proposer's Guide. The Joint ALMA Observatory (JAO) created an observing queue that considers the scientific ranking from the review panels, the array configuration schedule, historical weather patterns, and the time available for each region. The ALMA Director and representatives from Chile, East Asia, Europe, and North America conducted a final review of the results.

Your proposal was ranked in the top quartile of the proposals in your Panel. Comments from the Panel reviewers are presented below,

QSO2s observed with ALMA

ALMA C43-3 and C46-6 antenna configurations (compact and extended) to target CO(2–1) emission line and underlying continuum during Cycle 6.

Angular resolution ~0.2′′ (370 pc at z~0.1) while recovering emission from the whole galaxies.

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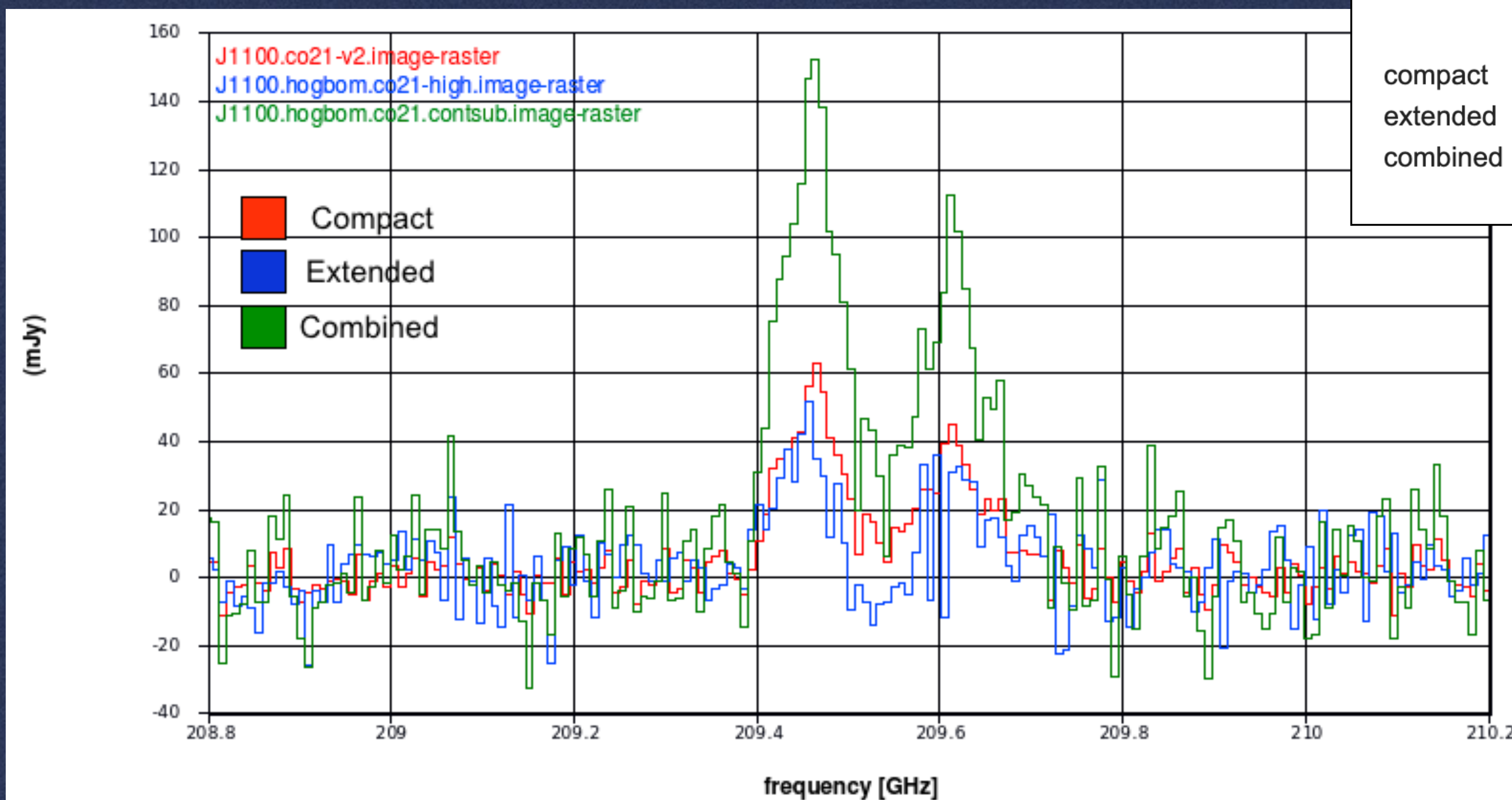
		Band	1	3	4	5	6	7	8	9	10
Config.	**L_{max}**	**Freq. (GHz)**	**40**	**100**	**150**	**185**	**230**	**345**	**460**	**650**	**870**
	L_{min}										
7-m	**45 m**	θ_{res} (arcsec)	31.5	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	9 m	θ_{MRS} (arcsec)	167	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C-1	**161 m**	θ_{res} (arcsec)	8.45	3.38	2.25	1.83	1.47	0.98	0.74	0.52	0.39
	15 m	θ_{MRS} (arcsec)	71.2	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C-2	**314 m**	θ_{res} (arcsec)	5.75	2.30	1.53	1.24	1.00	0.67	0.50	0.35	0.26
	15 m	θ_{MRS} (arcsec)	56.5	22.6	15.0	12.2	9.81	6.54	4.90	3.47	2.59
C-3	**500 m**	θ_{res} (arcsec)	3.55	1.42	0.94	0.77	0.62	0.41	0.31	0.22	0.16
	15 m	θ_{MRS} (arcsec)	40.5	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C-4	**784 m**	θ_{res} (arcsec)	2.30	0.92	0.61	0.50	0.40	0.27	0.20	0.14	0.11
	15 m	θ_{MRS} (arcsec)	28.0	11.2	7.50	6.08	4.89	3.26	2.44	1.73	1.29
C-5	**1.4 km**	θ_{res} (arcsec)	1.38	0.55	0.36	0.30	0.24	0.16	0.12	0.084	0.063
	15 m	θ_{MRS} (arcsec)	16.8	6.70	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C-6	**2.5 km**	θ_{res} (arcsec)	0.78	0.31	0.20	0.17	0.13	0.089	0.067	0.047	0.035
	15 m	θ_{MRS} (arcsec)	10.3	4.11	2.74	2.22	1.78	1.19	0.89	0.63	0.47

QSO2s observed with ALMA

ALMA C43-3 and C46-6 antenna configurations (compact and extended) to target CO(2–1) emission line and underlying continuum during Cycle 6.

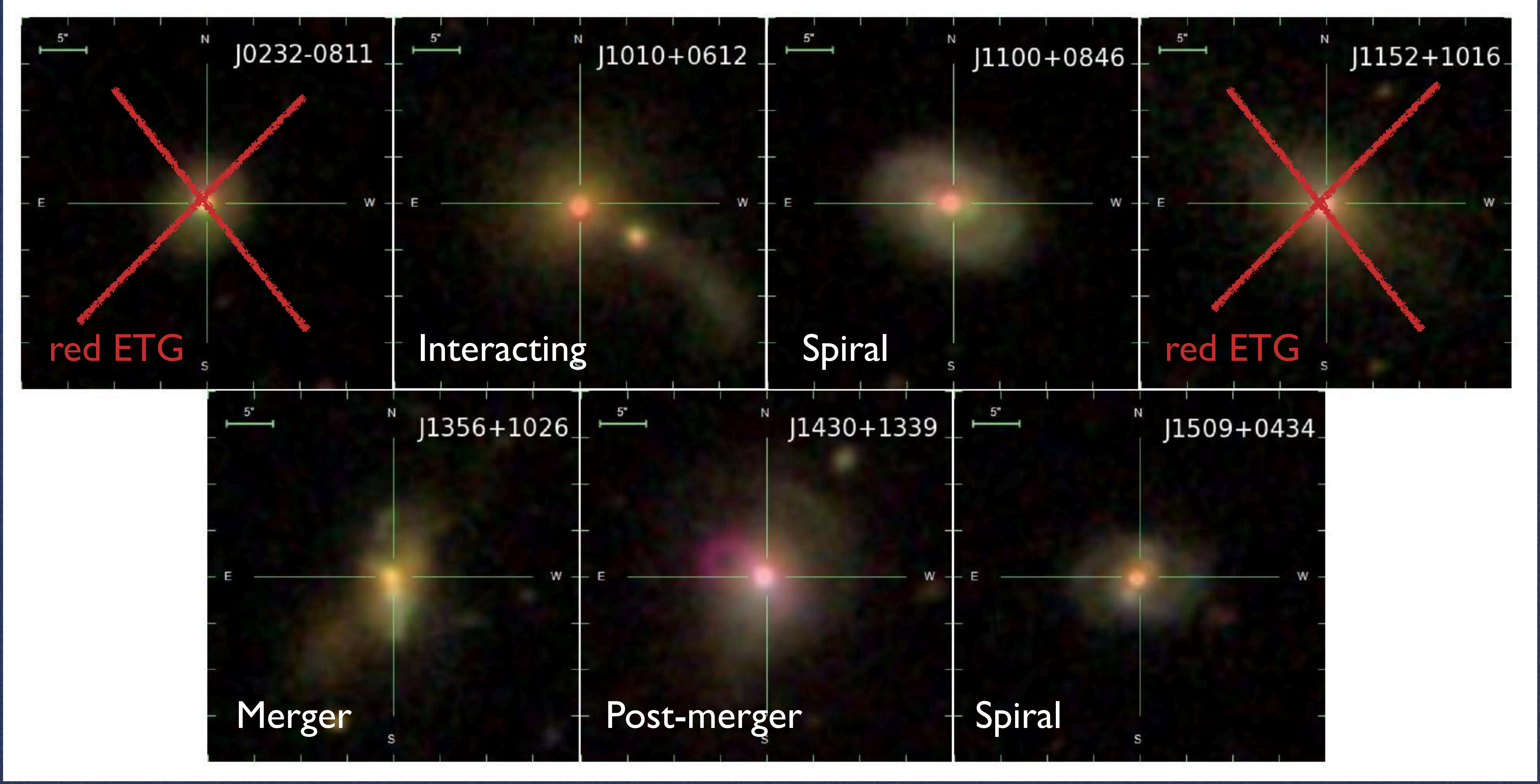
Angular resolution ~0.2′′ (370 pc at z~0.1) while recovering emission from the whole galaxies.



	beam[arcsec]
compact	0.75x0.67
extended	0.18x0.13
combined	0.23x0.20

QSO2s observed with ALMA

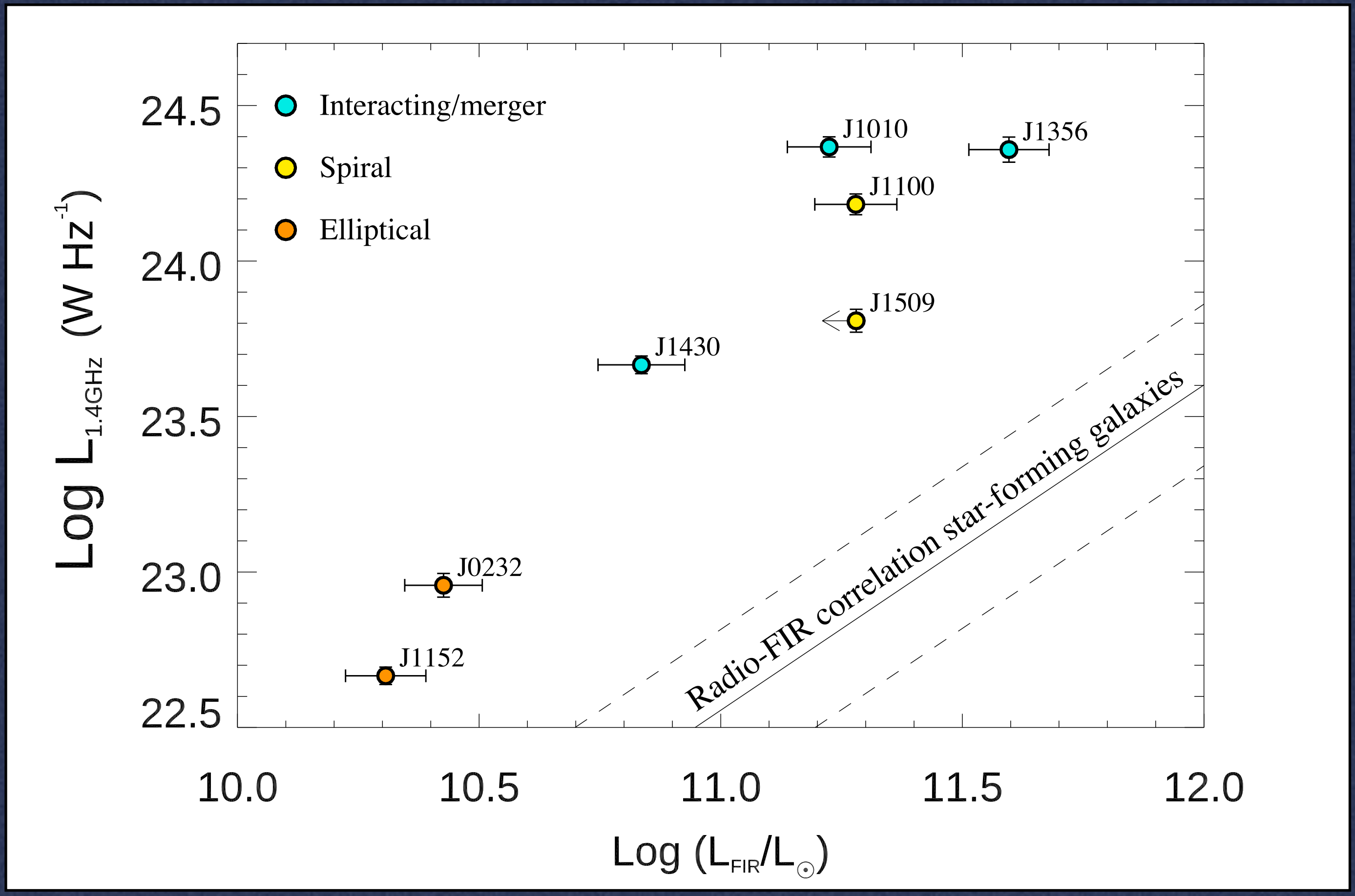
A wide range of cold molecular gas masses/fractions driven by galaxy morphology (Husemann+2017) and radio-power/outflow properties.



ALMA observations

•ALMA pilot sample of 7 QSO2s in CO(2-1) at ~0.2 arcsec resolution ≃ 370 pc.

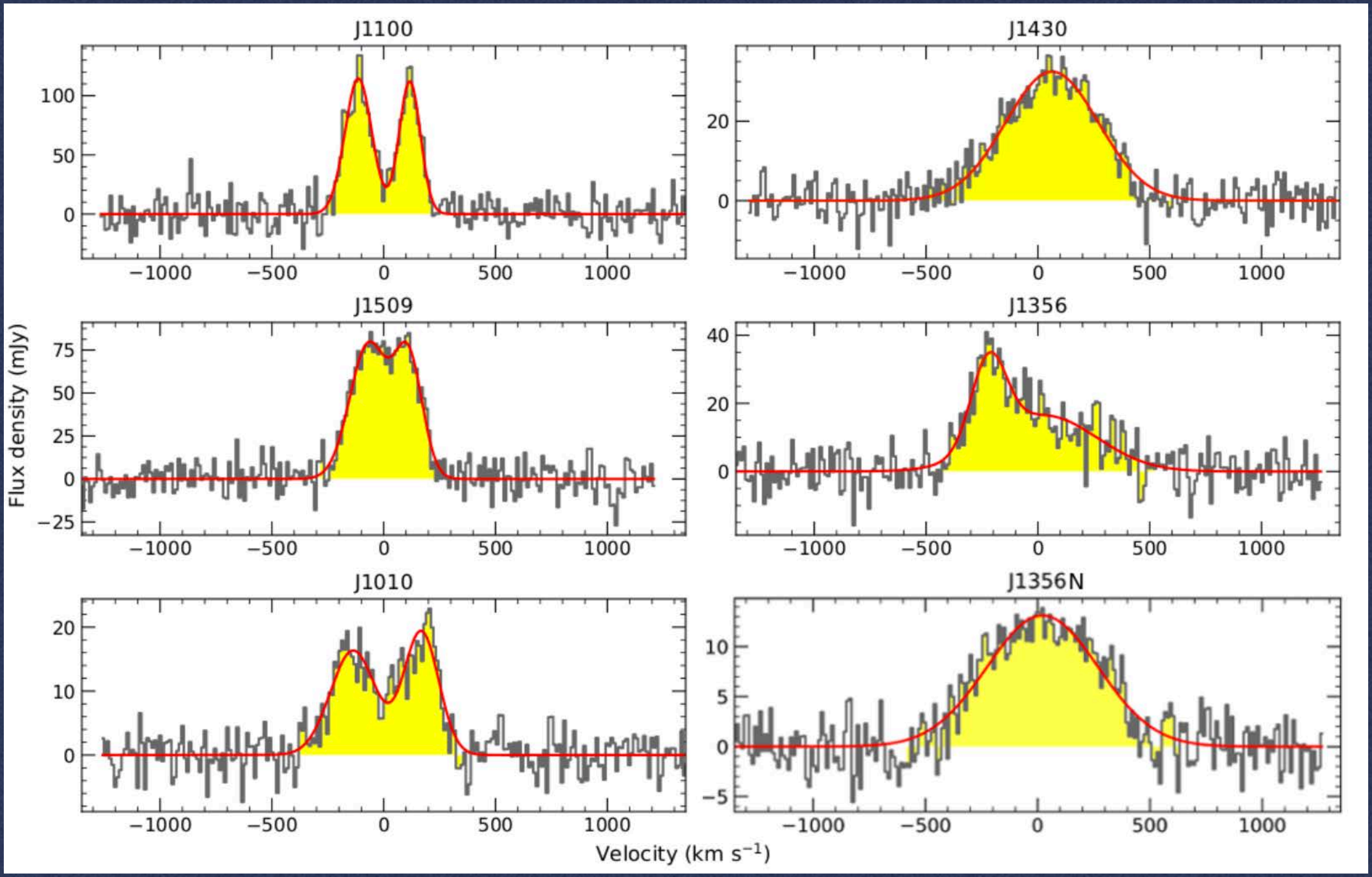
•$L_{[OIII]} > 10^{8.5} L_{\odot} \sim L_{bol} > 10^{45.6}$ erg/s and z~0.1 -- QSOFEED sample (48 QSO2s from Reyes+2008).



•Pilot sample of 7 optically selected QSO2s: radio-quiet but all showing a radio excess unrelated to star formation (see Jarvis+2019).

QSO2s observed with ALMA

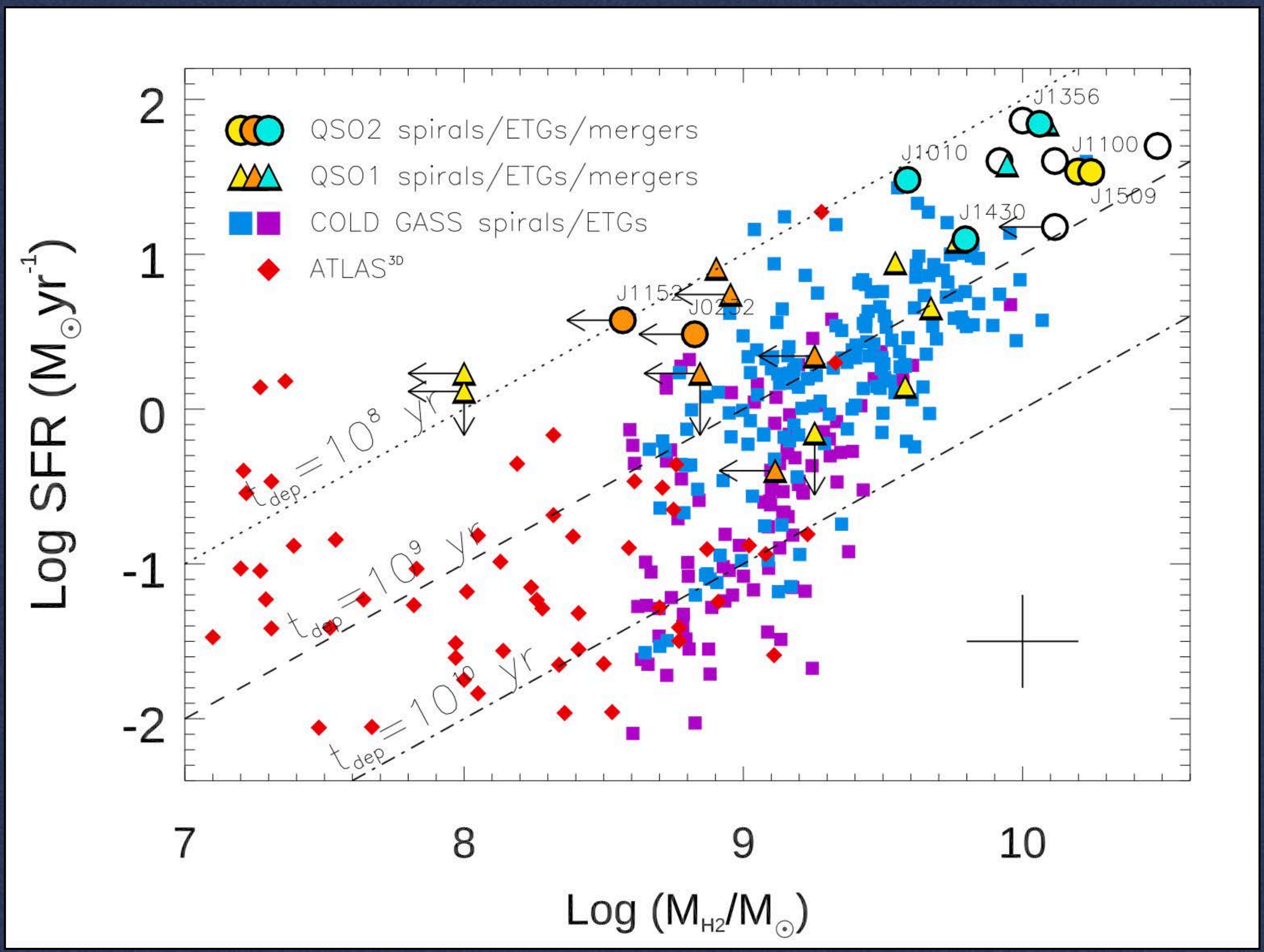
A wide range of cold molecular gas masses/fractions mainly driven by galaxy morphology (Husemann+2017). Not all QSO2s are in gas-rich galaxies!

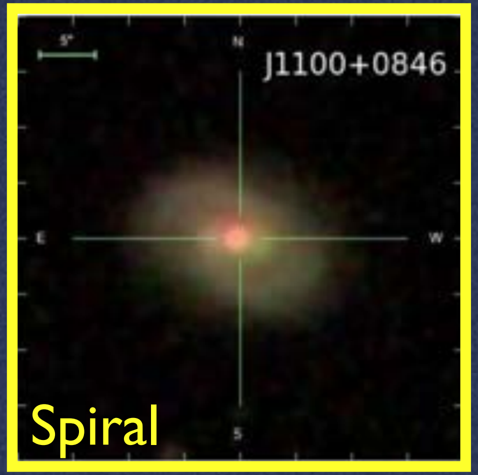


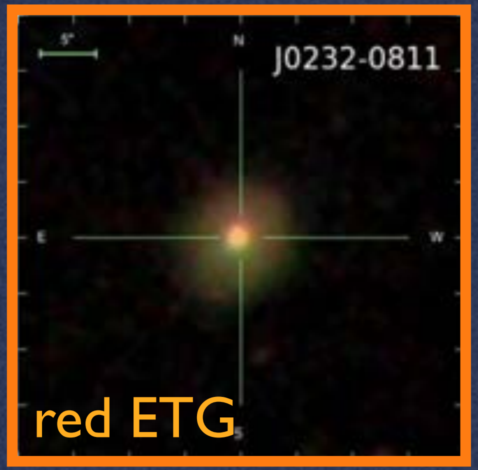
Ramos Almeida+22

Molecular gas reservoirs

A wide range of cold molecular gas masses/fractions mainly driven by galaxy morphology (Husemann+2017). Not all QSO2s are in gas-rich galaxies!



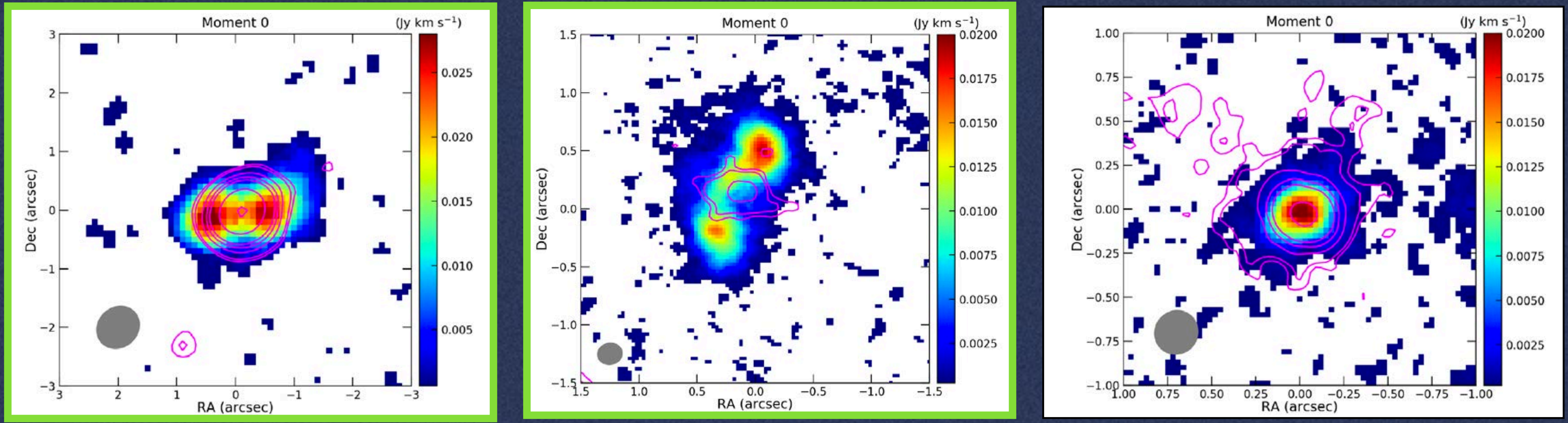




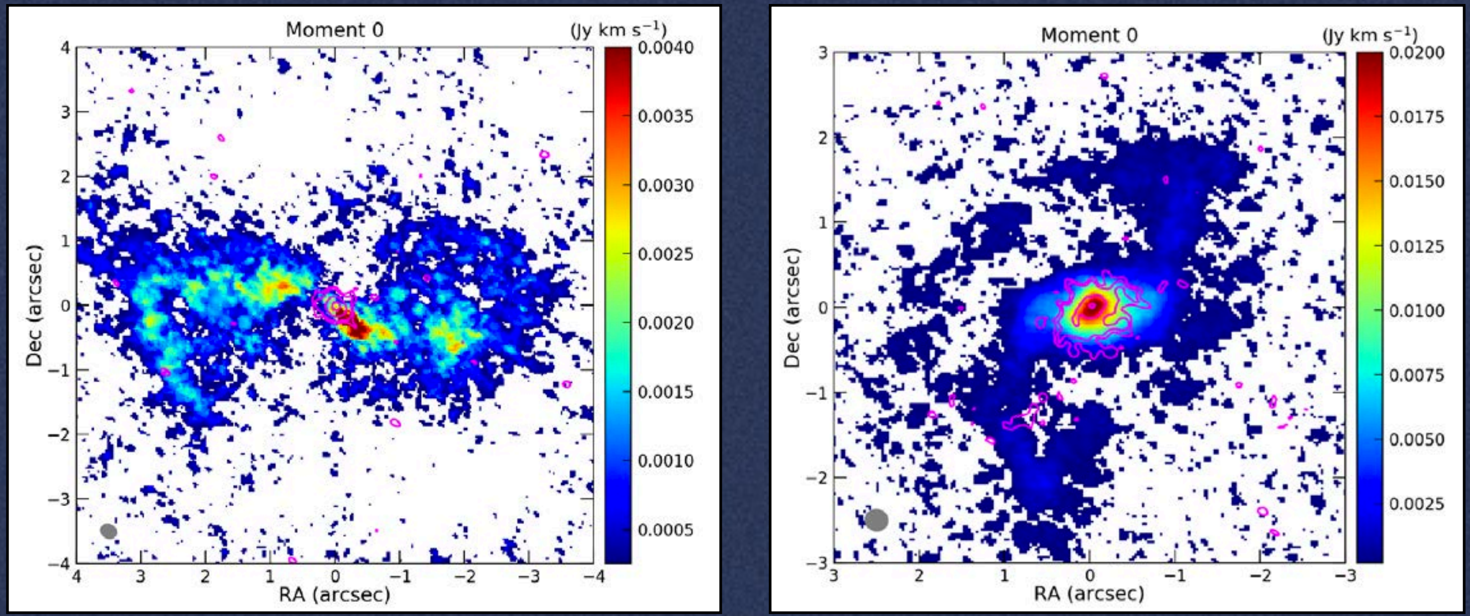
Molecular gas morphologies

- CO masses ranging from 4–18×10^9 $M_\odot$ (spirals & interacting) to <4-7×10^8 $M_\odot$ (red ETGs).
- Central kpc contains ~5–12% of total molecular gas in spirals, and 18-25% in the interacting systems.

INTERACTING



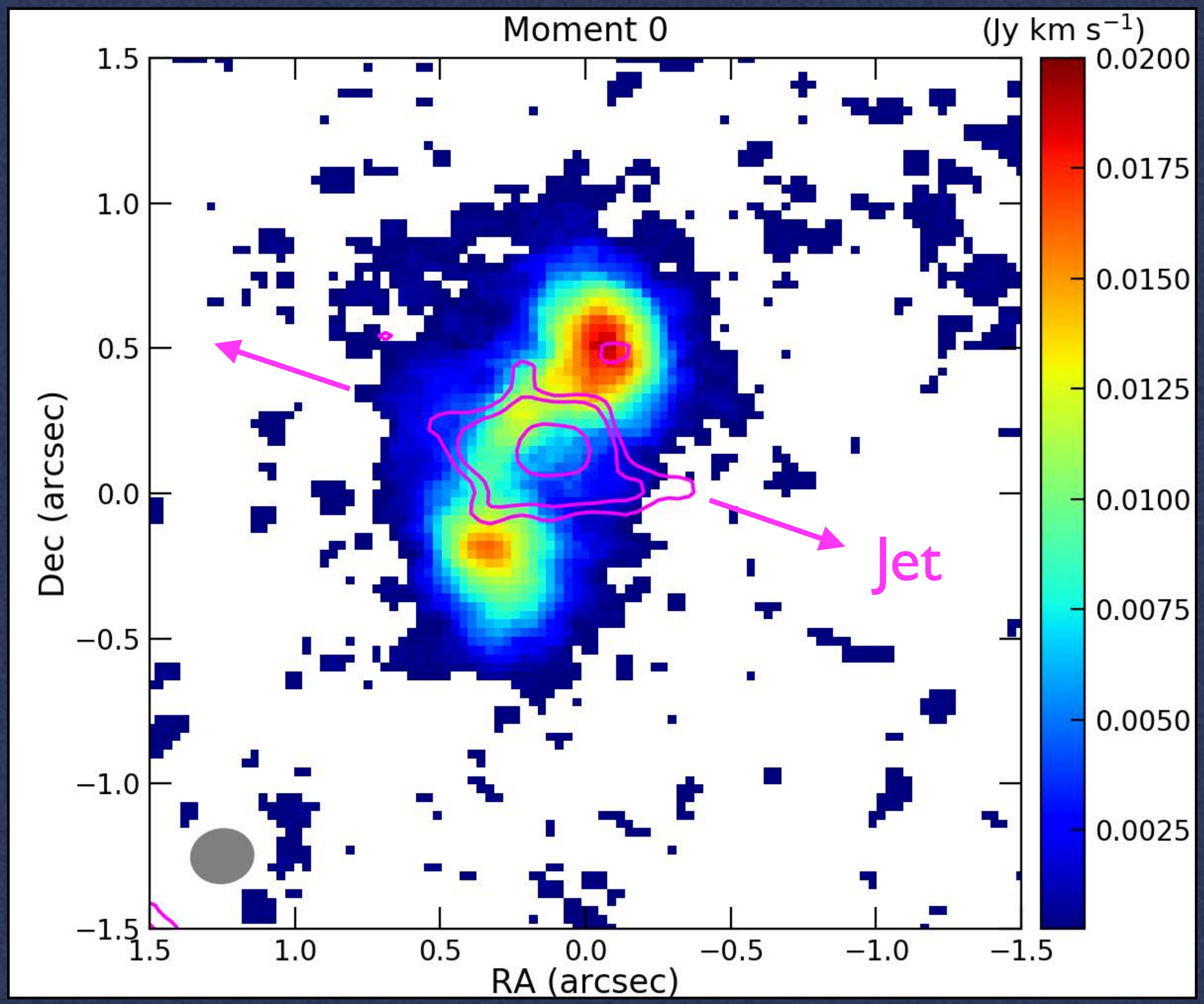
SPIRALS

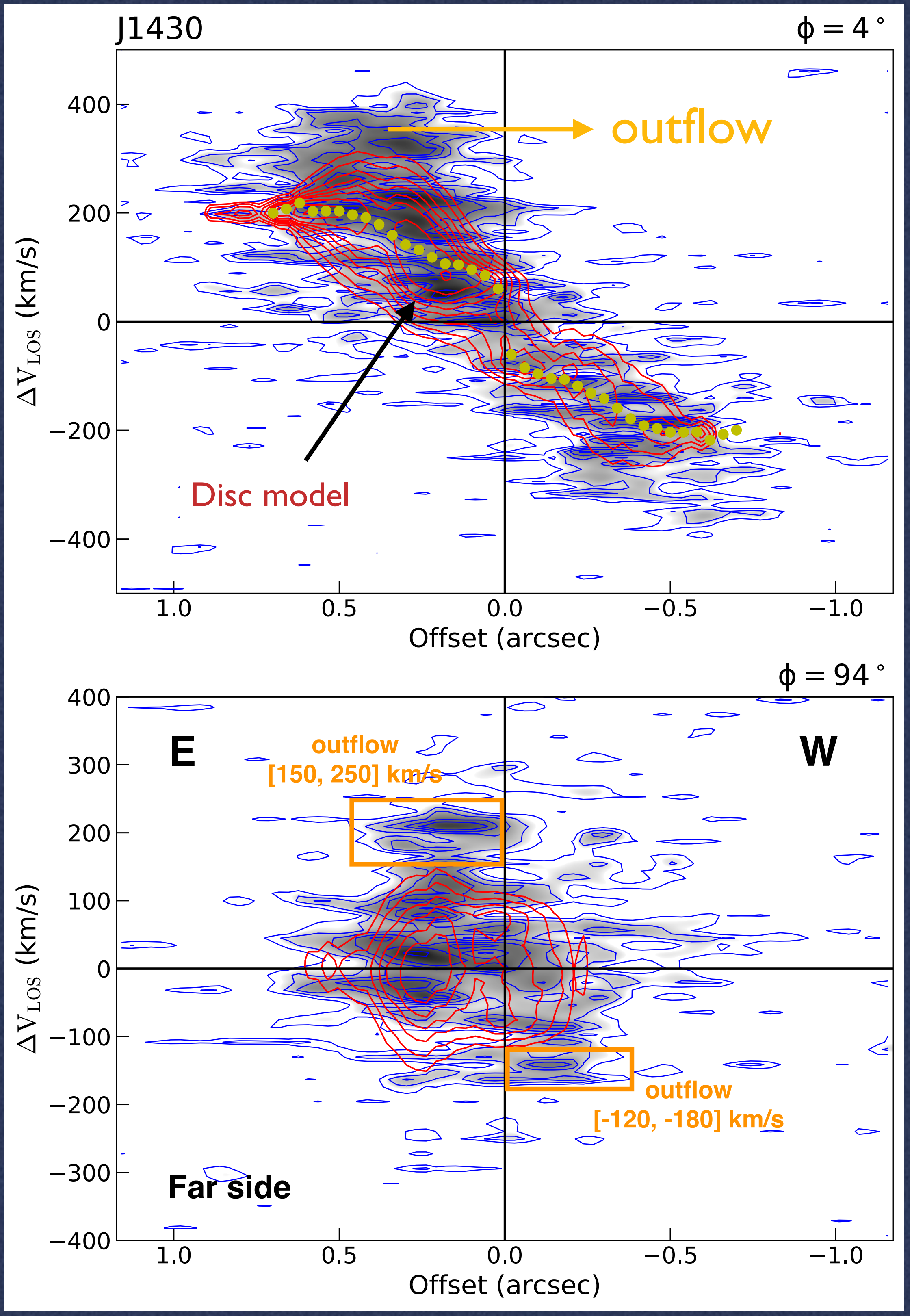


1.3 mm continuum
CO(2-1)

Ramos Almeida+22

Molecular gas kinematics

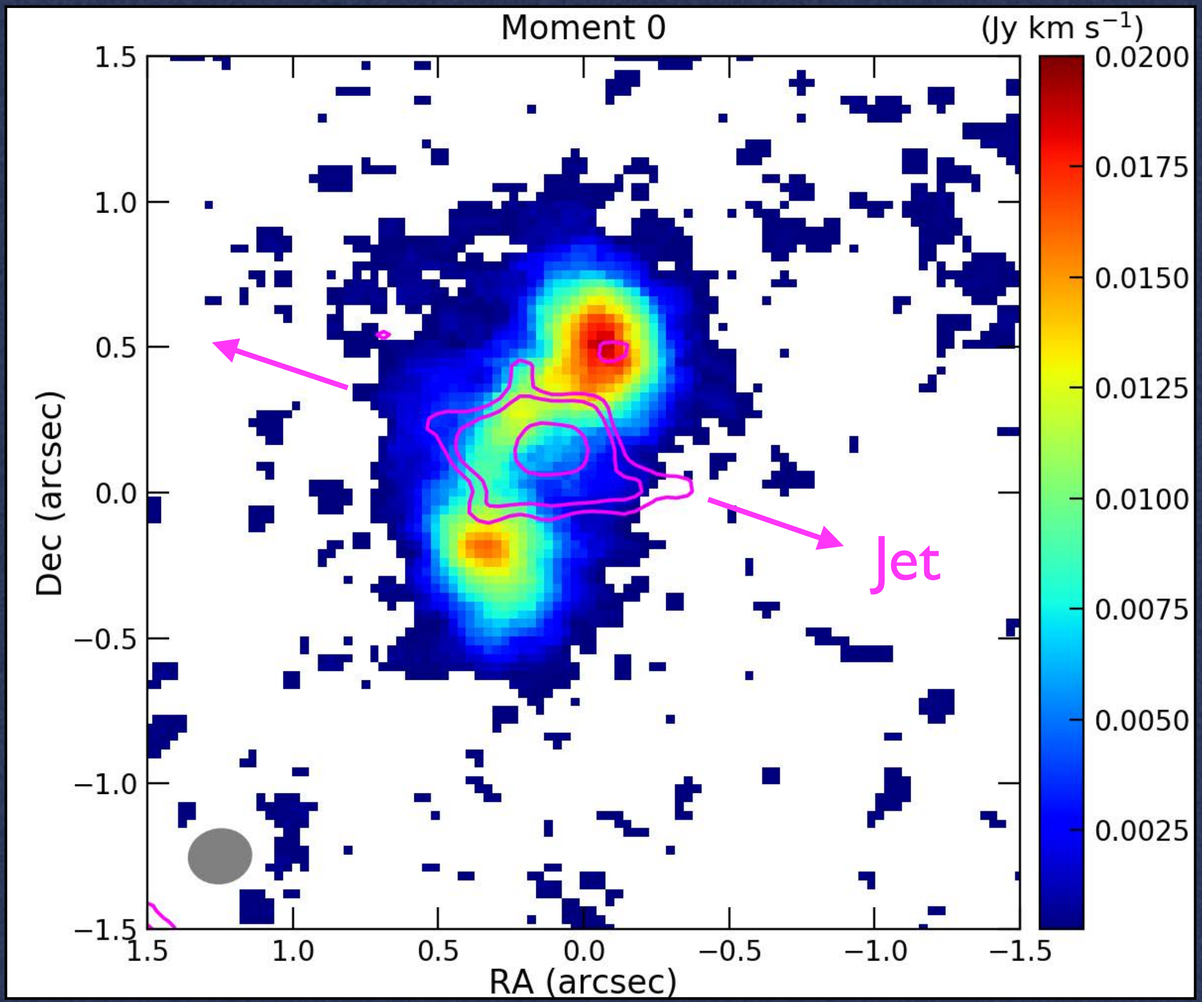


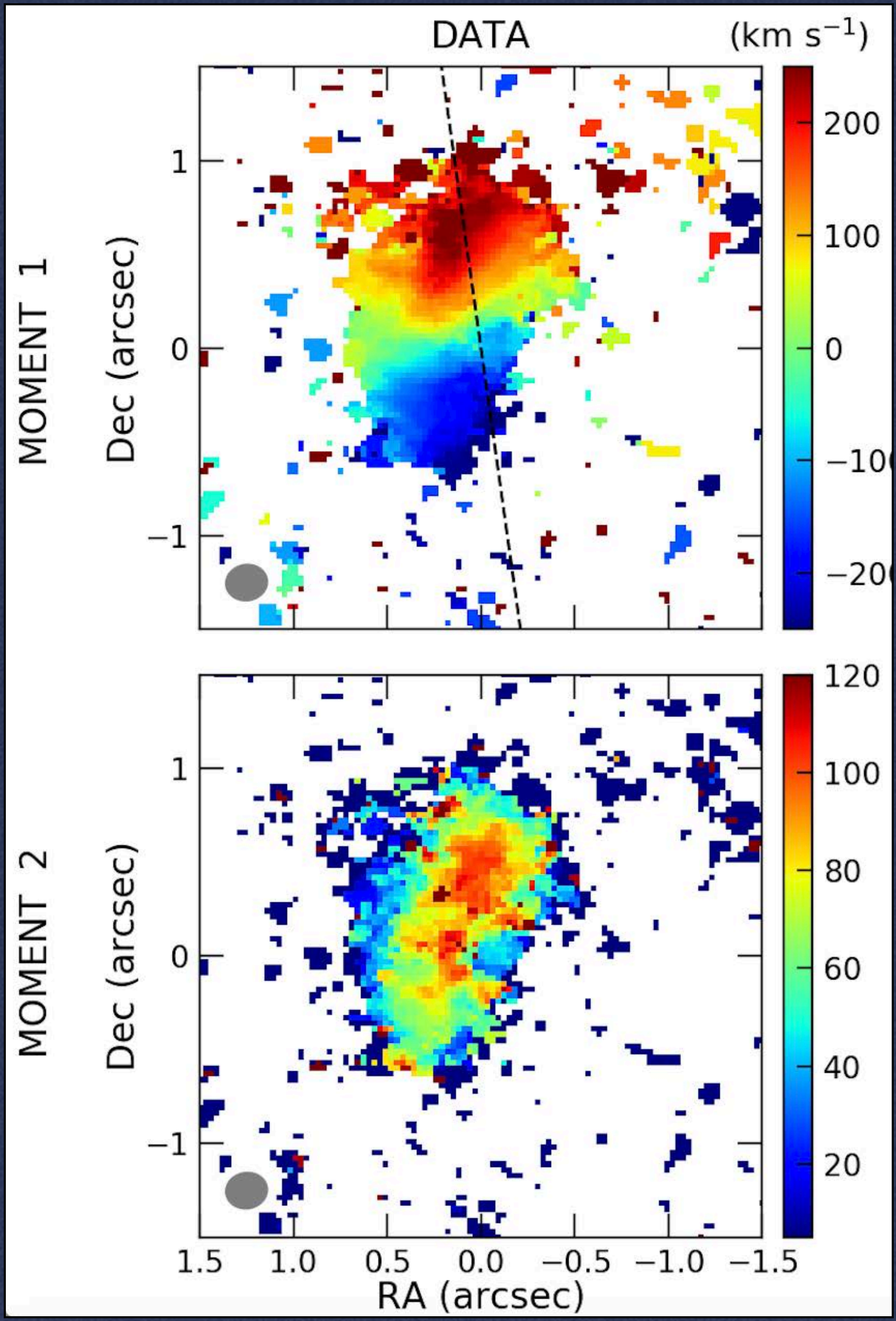


Position-velocity diagrams show non-circular motions of ~ ±350 km/s consistent with outflowing gas.

Ramos Almeida+22

Molecular gas kinematics



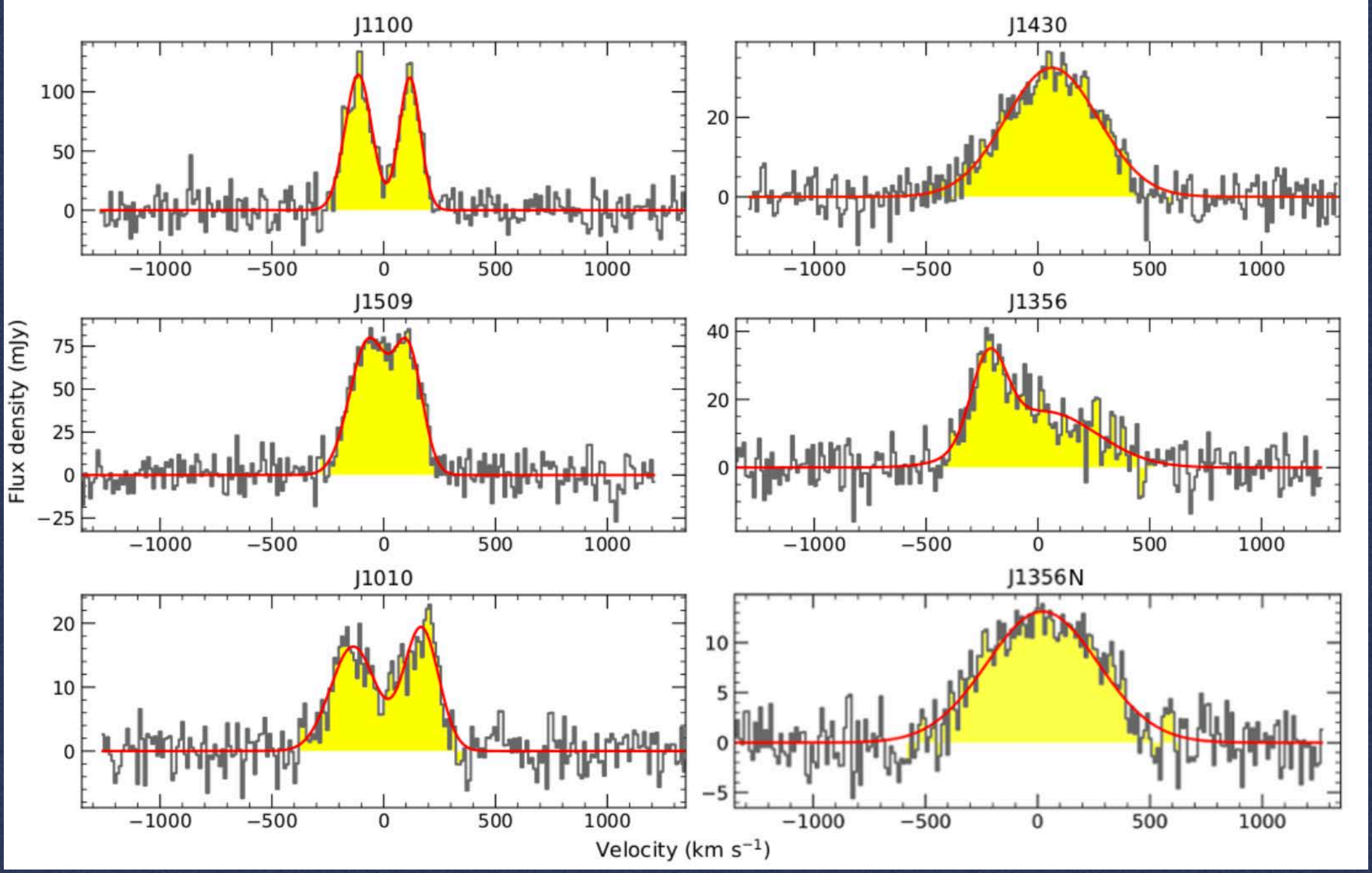


Combined action of AGN-driven wind + jet pushing molecular gas outwards and producing double-peaked morphology.

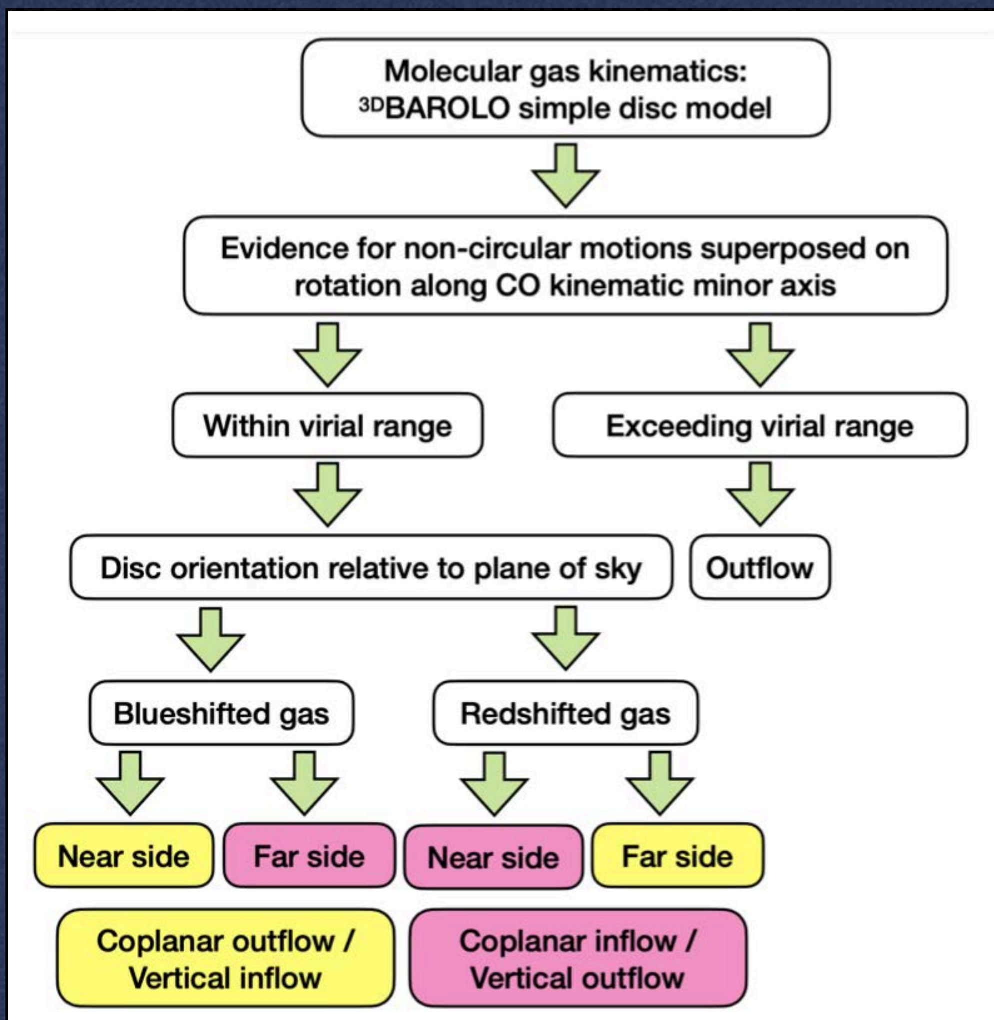
Ramos Almeida+22

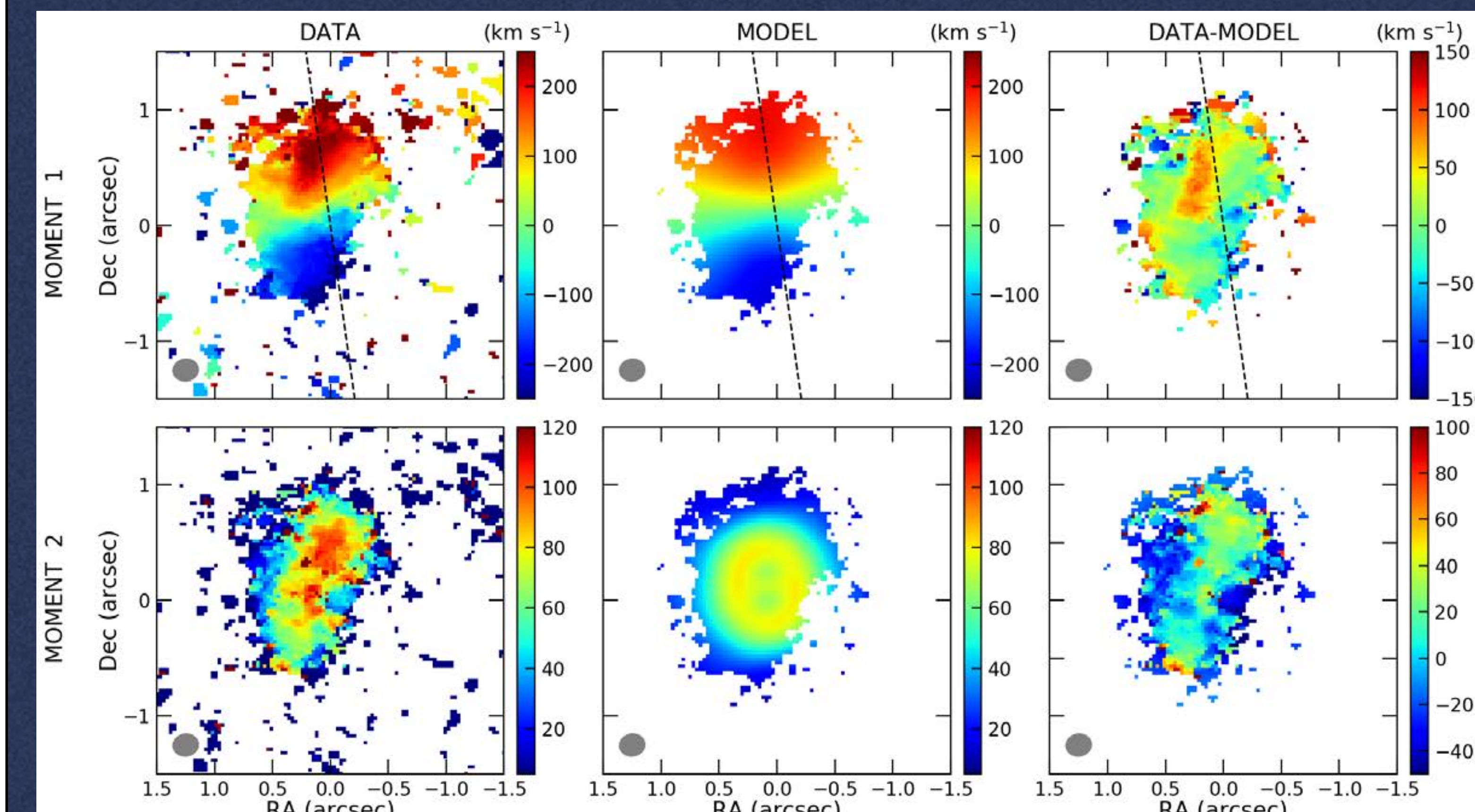
Molecular gas kinematics

No high-velocity wings detected in the CO line profiles.



Molecular gas kinematics





J1100
J1356
J1430
J1509

J1010

Molecular outflows

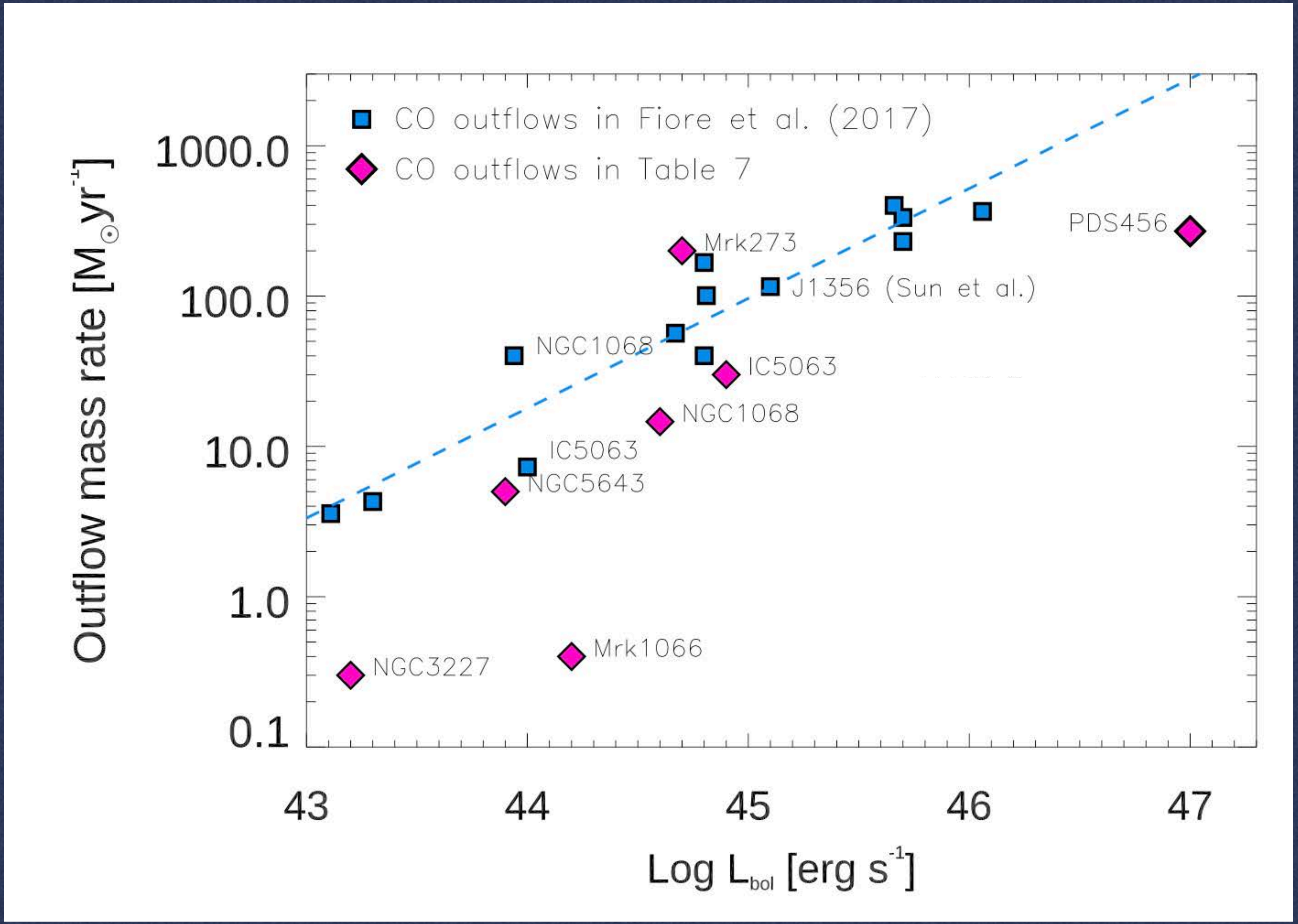
- Molecular outflows represent 0.2–0.7% of total molecular gas mass, max velocities of 200–350 km s^{-1}, radii from 0.4 to 1.3 kpc and outflow mass rates of 8–16 $M_\odot$ yr^{-1}.

- Outflow properties intermediate between mild molecular outflows of Seyfert galaxies and fast & energetic outflows of ULIRGs.

ID	Disc model		Cold molecular outflow								
	PA	i	r_{out}		v_{out}	$S\Delta\nu_{CO}$	M_{out}	$\dot{M}_{out}$	t^{out}_{dyn}	t^{out}_{dep}	η
	(deg)	(deg)	($''$)	(kpc)	(km s^{-1})	(Jy km s^{-1})	(10^7 $M_\odot$)	($M_\odot$ yr^{-1})	(Myr)	(Gyr)	
J1100	69	38	0.7±0.3	1.3±0.5	115±95	1.11±0.13	10.5±7.8	12.2±9.0	11.0	1.3	0.3
J1356	-70	52	0.20±0.05	0.4±0.2	310±40	0.10±0.02	1.4±1.2	7.8±6.9	1.4	0.8	0.1
J1430	4	38	0.3±0.1	0.5±0.2	185±65	0.46±0.07	3.1±2.4	15.8±12.2	2.5	0.4	1.3
J1509	82	43	≤1.50	≤3.00	≥45	≥0.58	≥6.8	≥1.1	≤66	≤16	≥0.03

Molecular outflows

- Outflow mass rate does not depend only on L_{bol}, other factors as jet power, jet/ionized outflow orientation, amount & geometry of dense gas key to produce massive molecular outflows.



Molecular outflows

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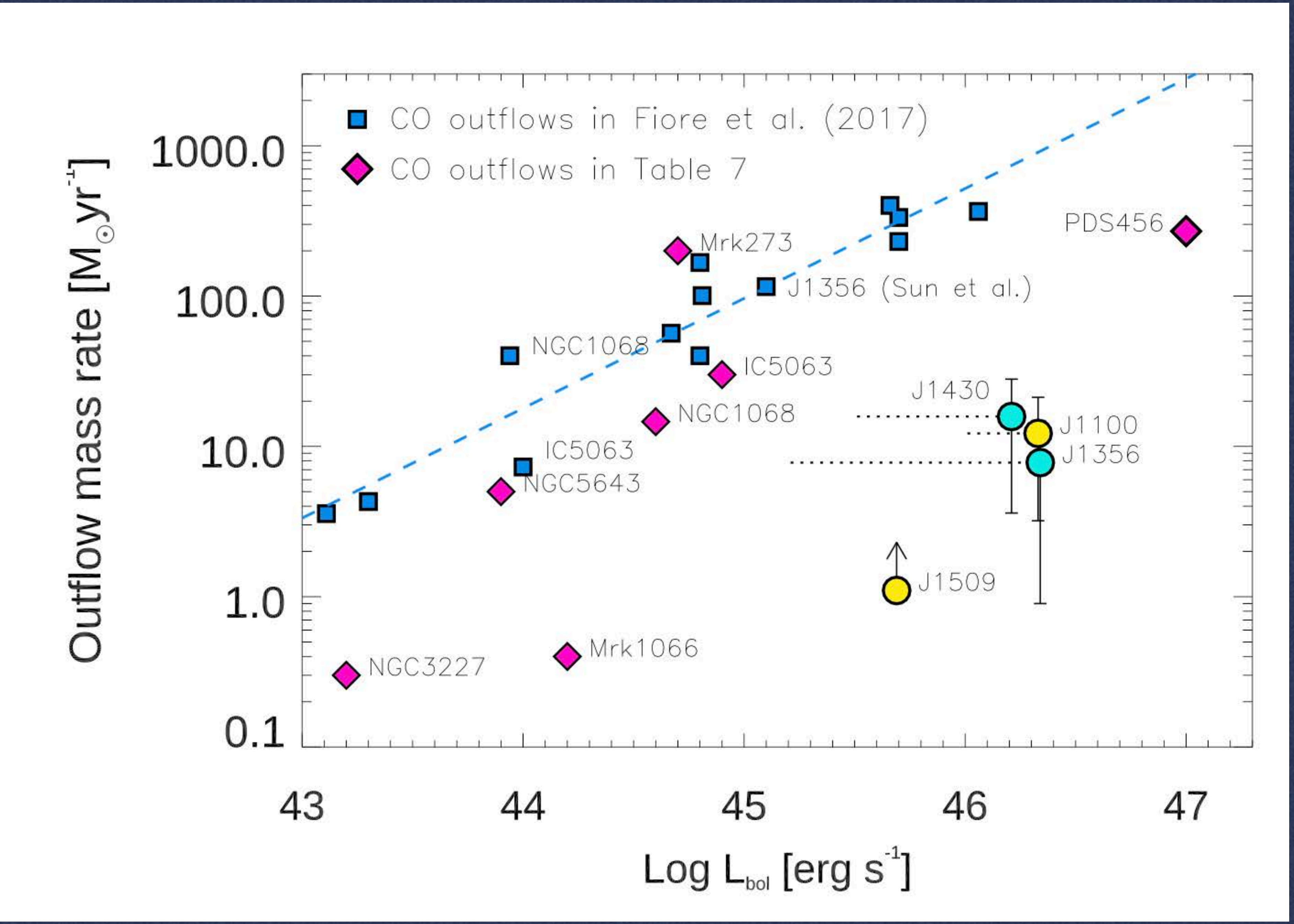

Molecular outflows

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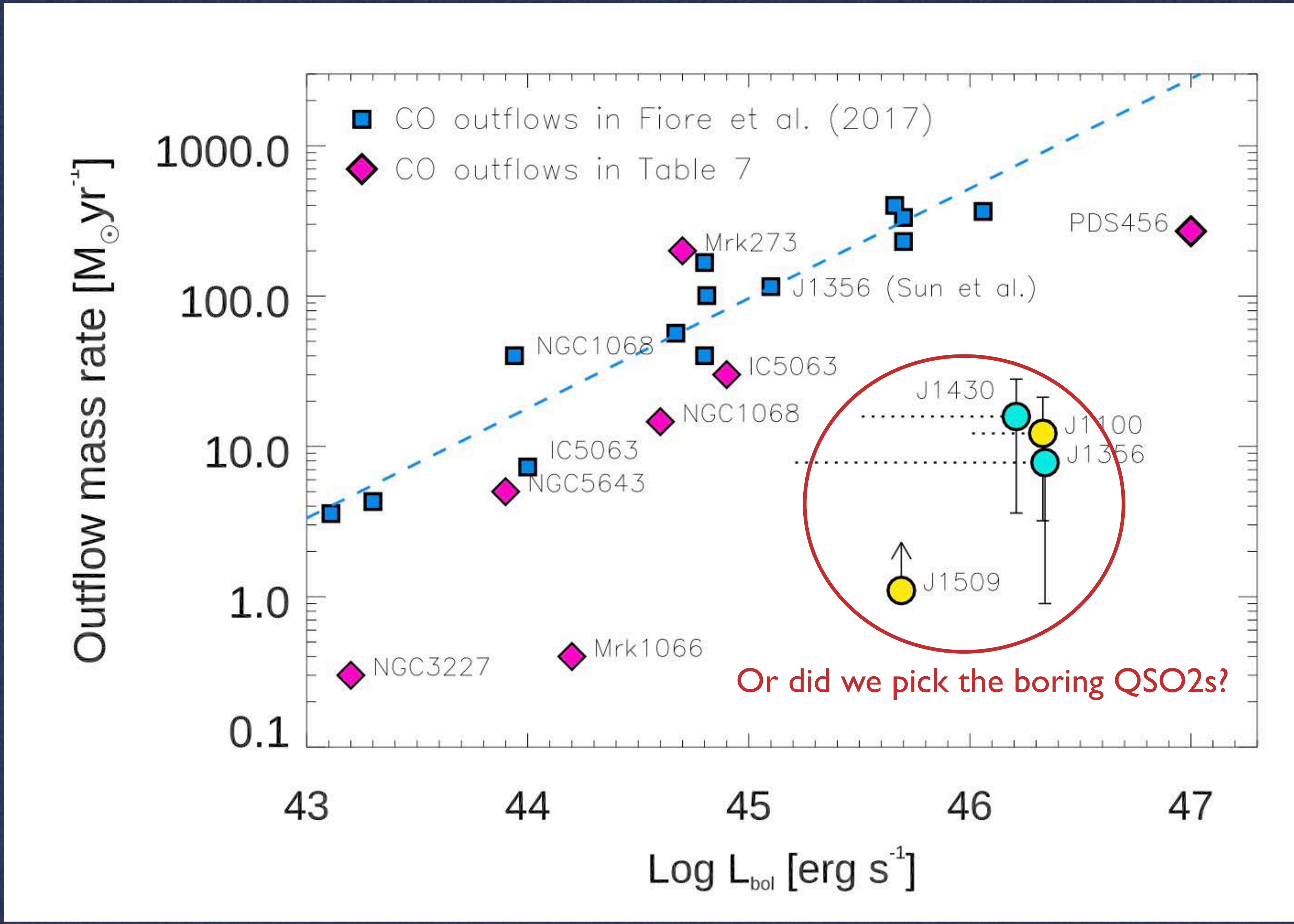

QSO FEED
quasar feedback project

Conclusions

- Be conservative with your assumptions when it comes to calculating exposure time.
- Make sure about the angular resolution you need, but also about the maximum recoverable scale! combining configurations is usually the best choice depending on your science goals.
- Be explicit in the proposal about all your assumptions, sensitivity calculations, angular resolution needed, etc.
- Sometimes observations do not look as you expected, but still useful for your science goal or another! Sometimes you need to dig into the data to get what you were looking for.

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Science conclusions

- Quasars of the same bolometric luminosity and hosted in galaxies of similar stellar masses (log $M_* = 10.9–11.3\ M_\odot$) have CO masses ranging from $4–18\times10^9\ M_\odot$ to $<4-7\times10^8\ M_\odot$

- Outflow mass rate does not depend only on L_{bol}, other factors as jet power, jet/ionized outflow orientation (coupling) key to launch massive molecular outflows.

- AGN feedback shapes the circumnuclear (<1 kpc) environment of AGN (Rosario+2019; García-Burillo+2019,2021; García-Bernete+2021; Ramos Almeida+2022).

- No significant impact of molecular outflows/AGN feedback on total molecular gas reservoirs/SFR, BUT feedback modifying the molecular gas distribution in central kpc of galaxies.

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