IRAM 30-meter millimeter follow-up of deep OSIRIS / 10.4 meter GTC optical surveys

Two stories on the search for molecular gas in star-forming galaxies from the GLACE and Lockman-SpReSO surveys

Miguel Sánchez Portal & Ángel Bongiovanni
IRAM-ES

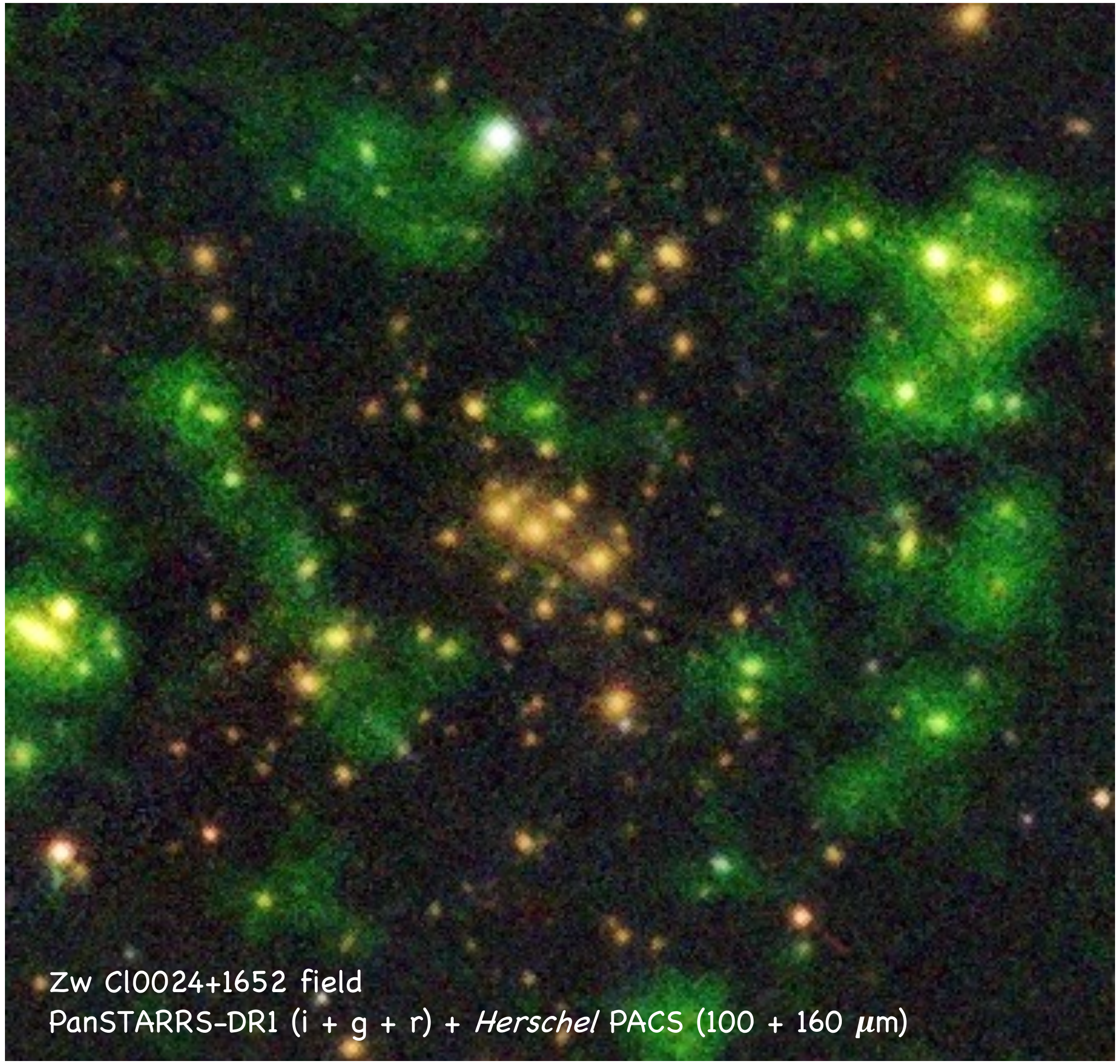
Collaborators: Zeleke Beyoro-Amado, Simón Bonnal, Manuel Castillo, Bernabé Cedrés, Jordi Cepa, Irene Cruz-González, Mauro González-Otero, J. de Jesús González, J. Ignacio González Serrano, Brisa Mancillas, Alenka Negrete, Carmen P. Padilla-Torres, Ana M. Pérez García, Ricardo Pérez-Martínez, Irene Pintos-Castro, Mirjana Pović and Mónica Rodríguez

GaLAxy Cluster Evolution (GLACE) in a nutshell

- Aims at studying the population of emission-line galaxies (ELG) in several clusters in three atmospheric windows at z ~ 0.4, 0.63 and 0.86
- Carried out at the 10.4m GTC telescope using the OSIRIS **tunable-filter tomography technique** for an initial (blind) screening and then the multi-objet spectroscopy mode to obtain **high-quality spectra in strong optical lines** (typically Hα, [NII], [OIII], Hβ and [OII]).
- Aimed at producing a comprehensive picture of the evolution of ELGs in intermediate-redshift clusters, in particular: (I) star formation phenomena, (II) the role of AGN and (III) gas metallicity gradients (Sánchez Portal+2015).

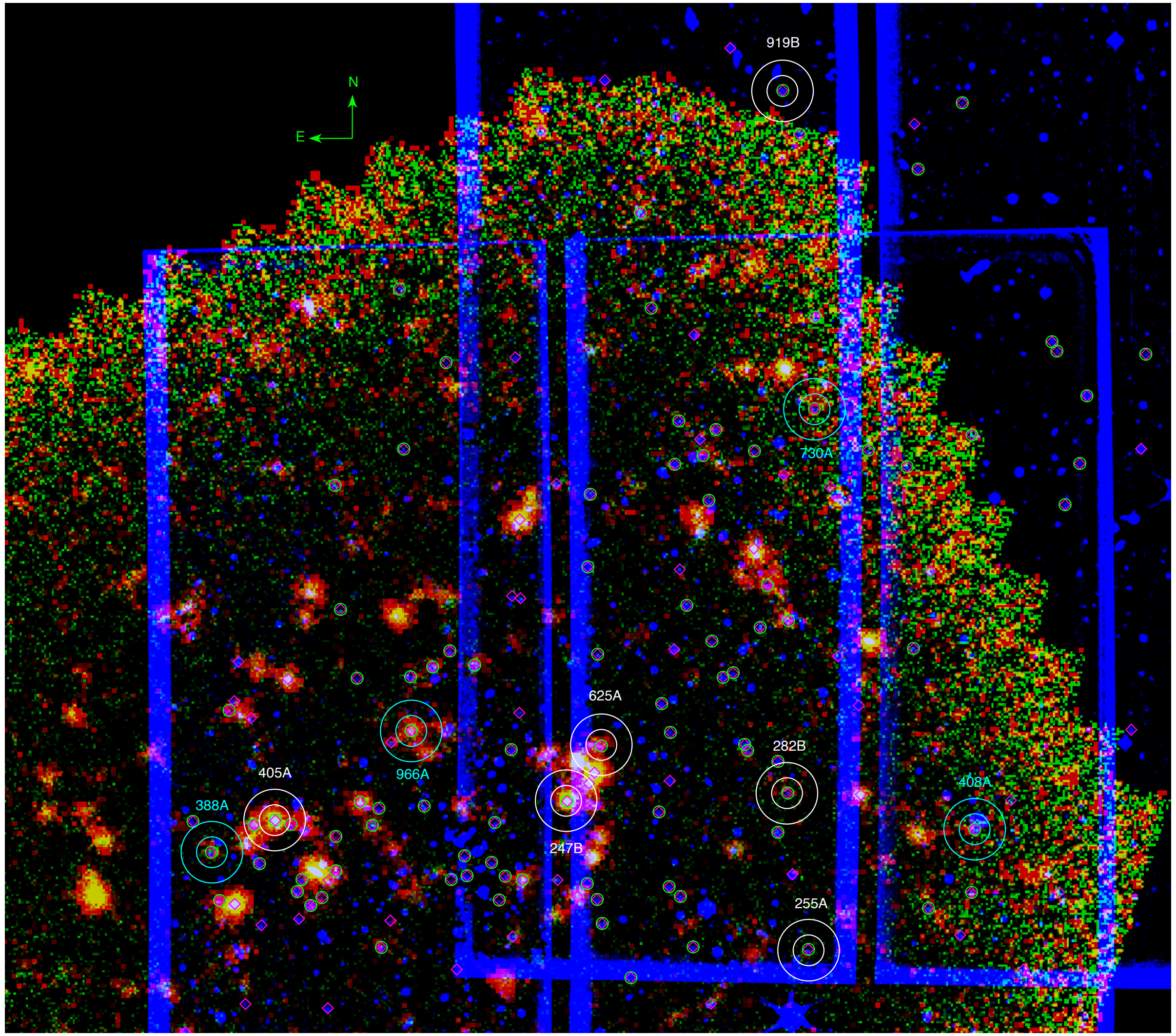
Based on the results of the first cluster explored, **Zw Cl0024+1652** at z=0.395, we aimed at mapping how the **molecular gas contents** and **SF efficiency** behave as as function of the **local environment** in the cluster, from the inner regions to the outskirts, also targeting the **low stellar mass regime for the first time**.

Motivation



- **Local universe cluster galaxies** have, on average, a lower molecular gas content (e.g. Virgo cluster: Boselli+2014) than **similar objects in the field**, or even in **voids** (☞ *CO-CAVITY presentation this afternoon*), likely due to environmental causes.
- Molecular gas is currently well studied in field galaxies (e.g. **xCOLDGASS**, **PHIBSS/PHIBSS2, CO-CAVITY**).
- Scarce studies in cluster galaxies, specially at higher redshifts.
- Only a handful of cluster galaxies at z ~ 0.4 had been studied (Geach+2011, Jablonka+2013) at the time we proposed this study.
- However this situation is being mitigated progressively (e.g. Castignani+2020, Spérone-Longin+ 2021a,b: **SEEDisCS**).

Cl0024+1652: Sample selection & observations



Zw Cl0024+1652 field as seen by GLACE
RGB: Herschel PACS (100 + 160 μm) + GLACE red-TF deep image (Sánchez-Portal+2015)

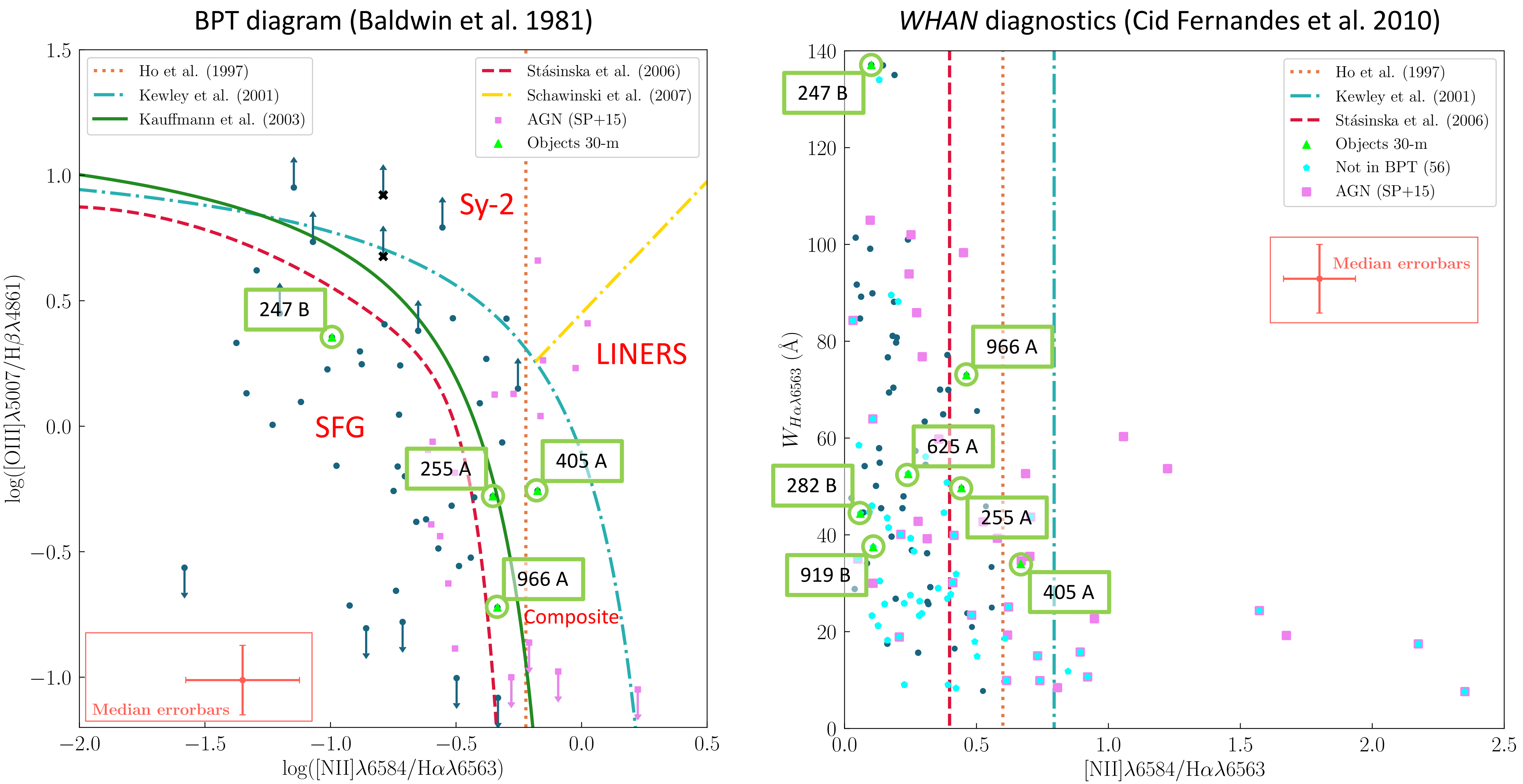
Main goal: mapping how the molecular gas contents, from EMIR receiver observations of low ^{12}CO transitions, and SF efficiency behave as a function of the local environment in the cluster, from the inner regions to the outskirts, **also targeting the low stellar mass regime.**

Sample: We selected the 7 most promising GLACE/Cl0024+1652 **SF galaxies** according to the estimated 12CO(1-0) flux density. They are represented on the RGB (PEP-160 μm, PEP-100 μm, GLACE-Hα-deep) map at left.

Time: A total requested time of **85.5 h** (Summer average conditions, pwv = 7 mm) with EMIR/30m telescope were awarded as an OT program.

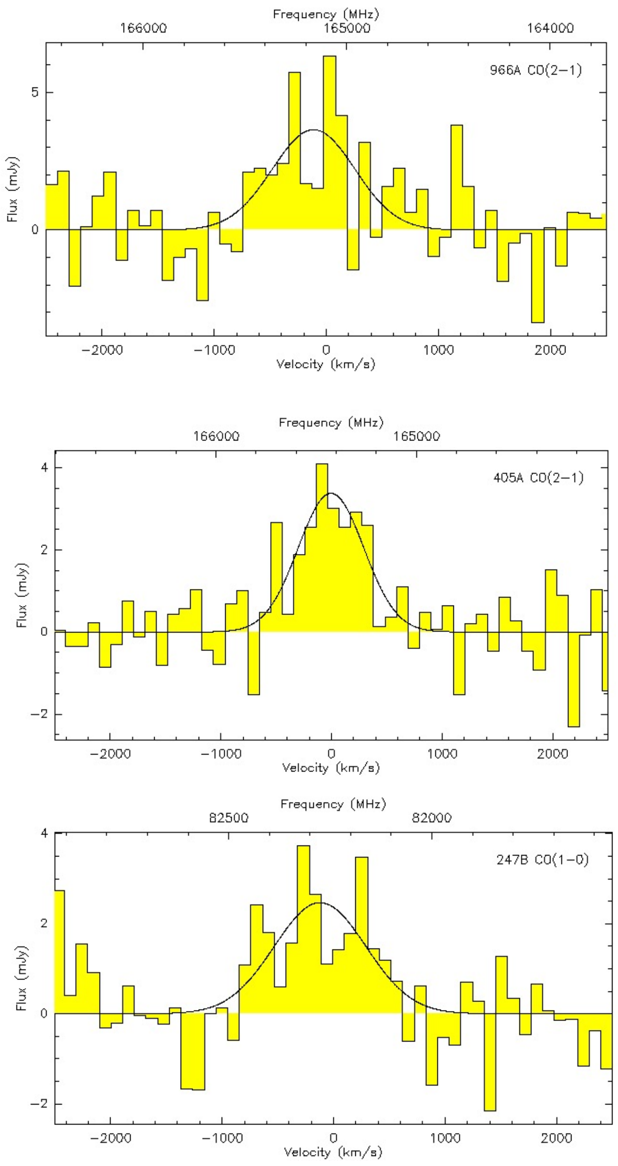
Observations: were carried out between October and November 2020 under the EMIR-30m telescope proposal 073-20 by Alenka Negrete, Ignacio González, Miguel Sánchez and Angel Bongiovanni.

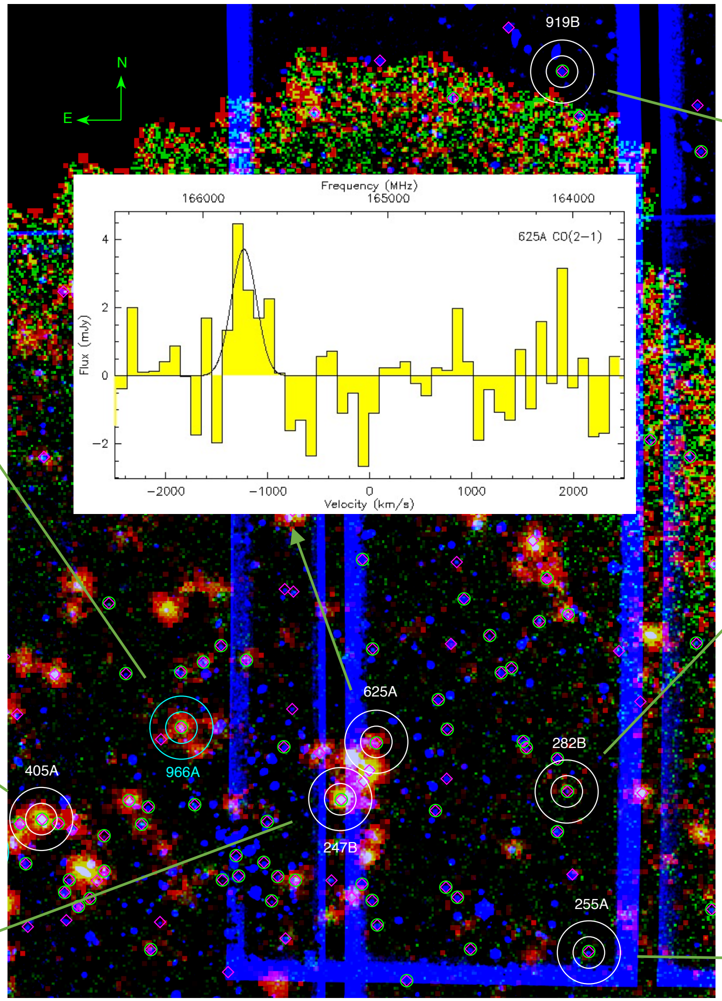
The Cl0024+1652 sample in the SF/AGN diagnostic diagrams

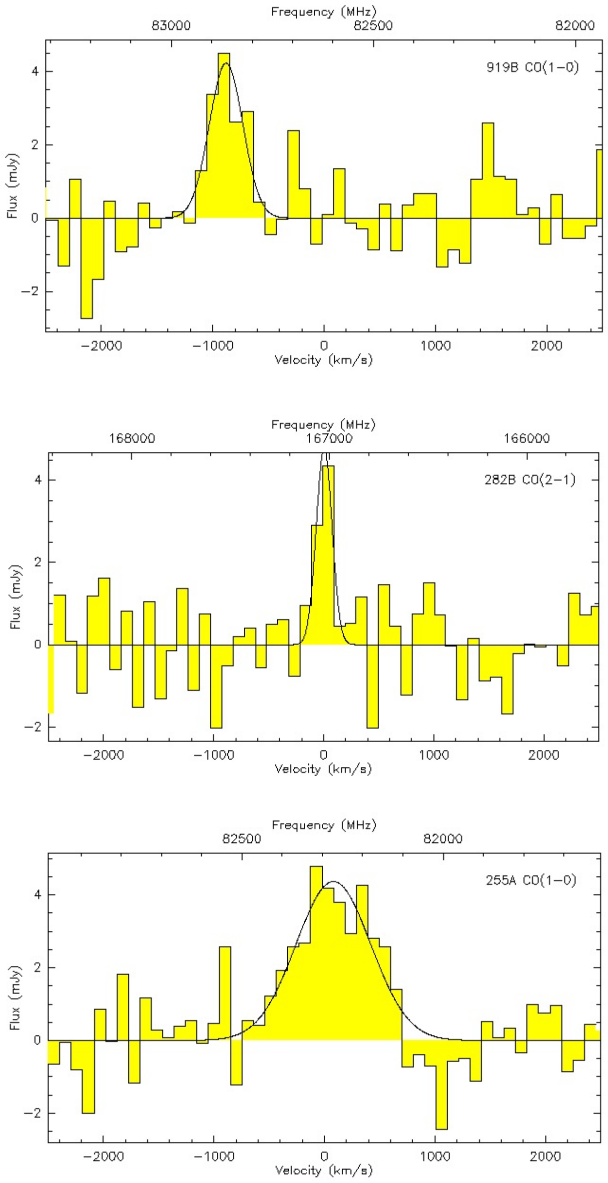


From Bonnal (2023)

Cl0024+1652: Sample selection & observations



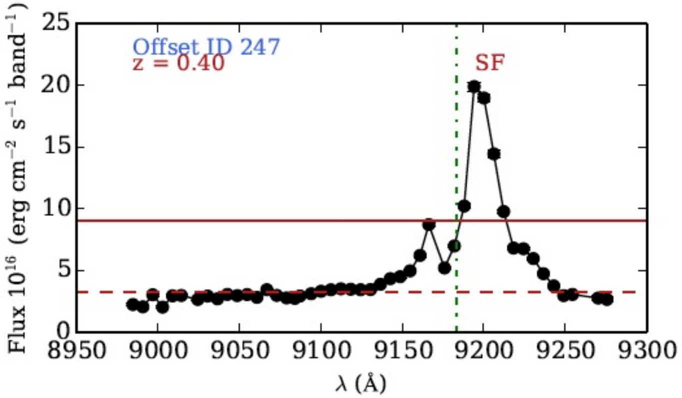




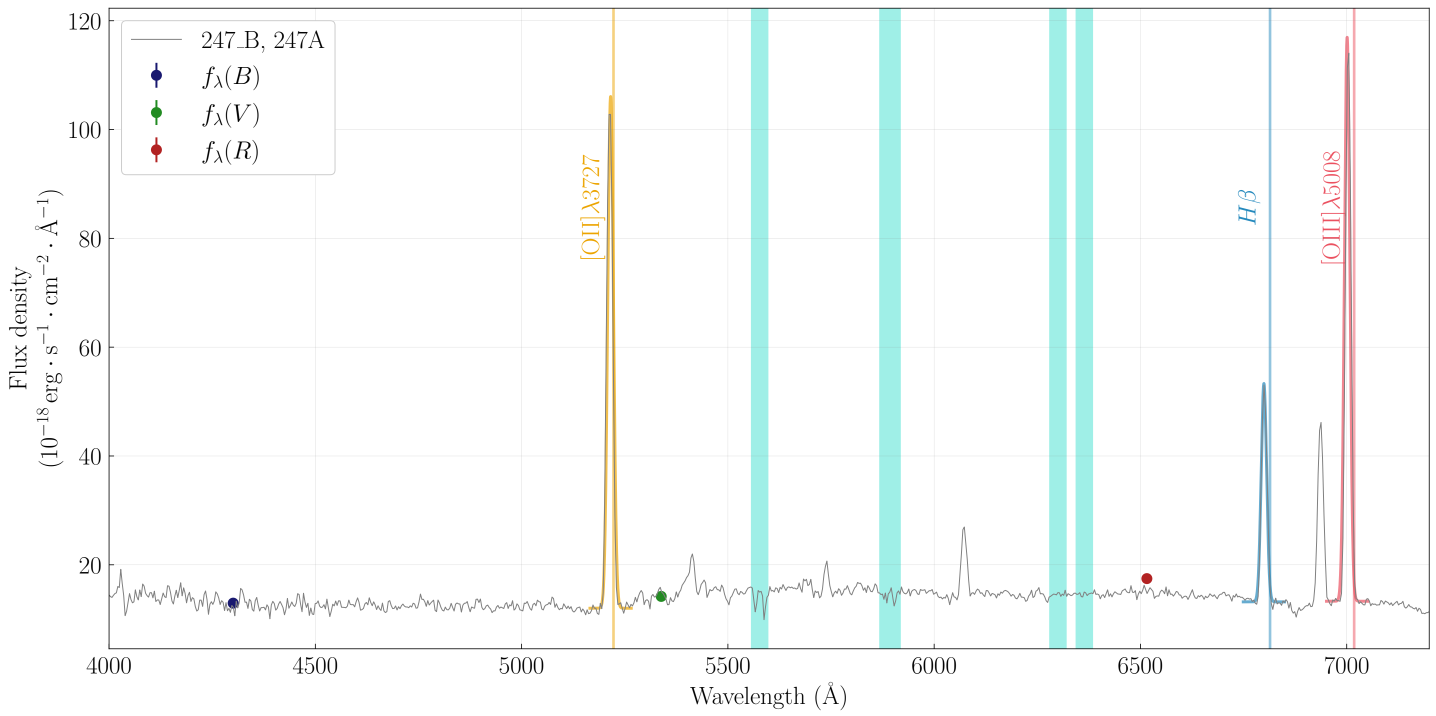
Zw Cl0024+1652 field as seen by GLACE
RGB: Herschel PACS (100 + 160 μm) + GLACE red-TF deep image (Sánchez-Portal+2015)

Source example: 247B

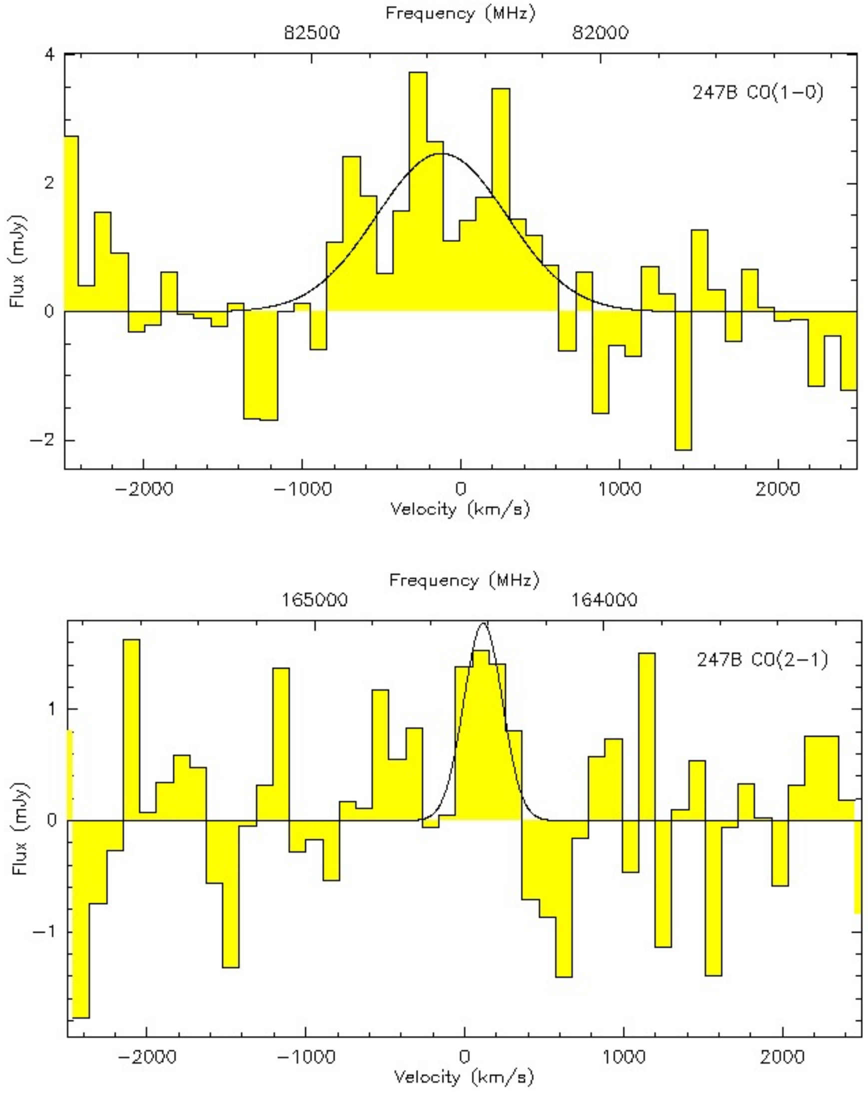
Pseudo-spectrum from Sánchez-Portal+2015



data from
+ first GLACE
catalogue

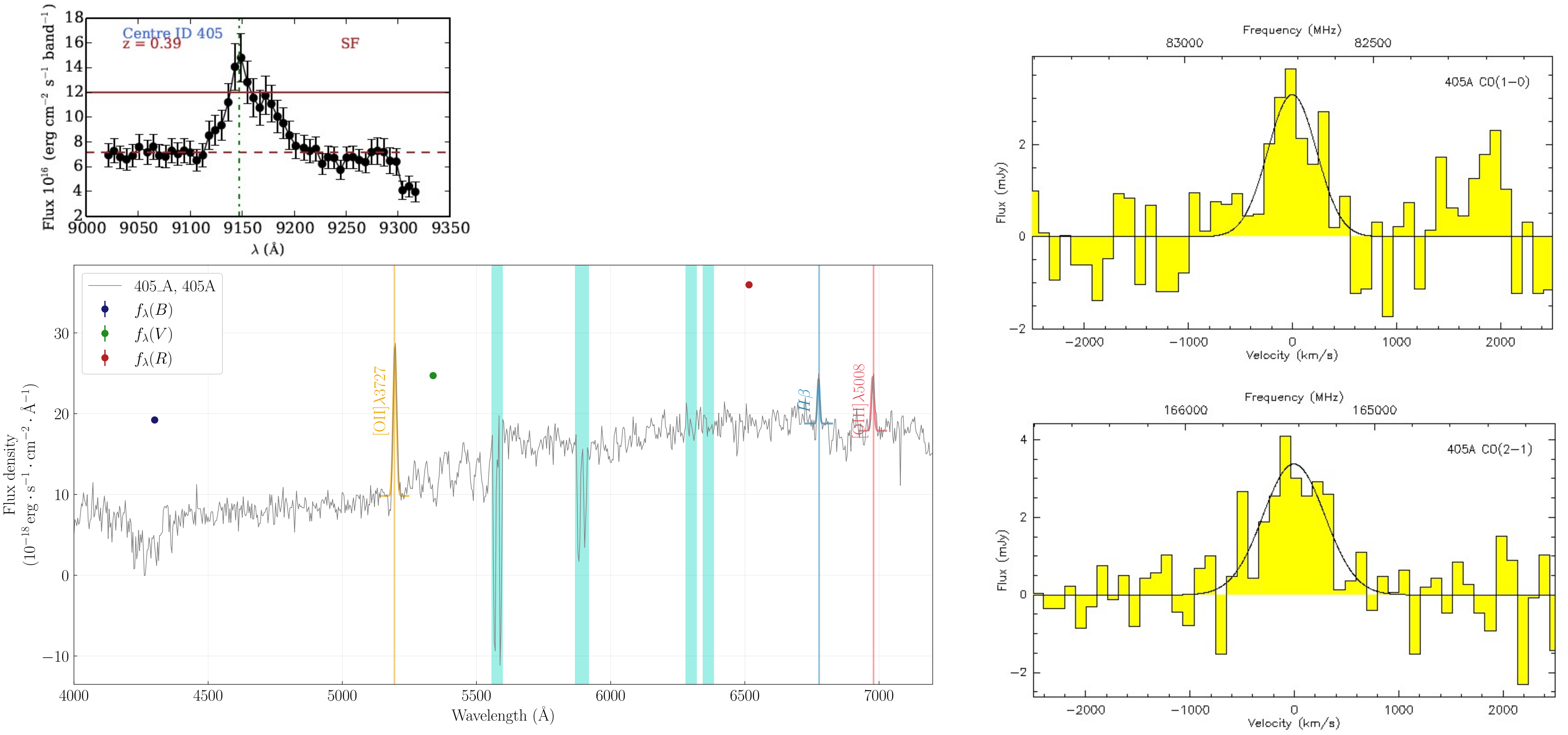


MOS spectrum from the Atlas of Simon Bonnal

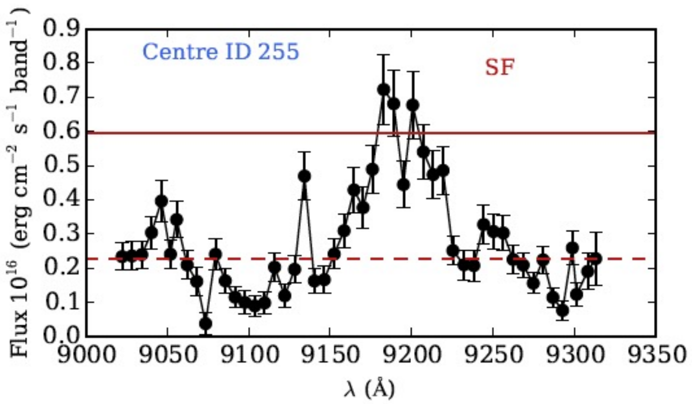


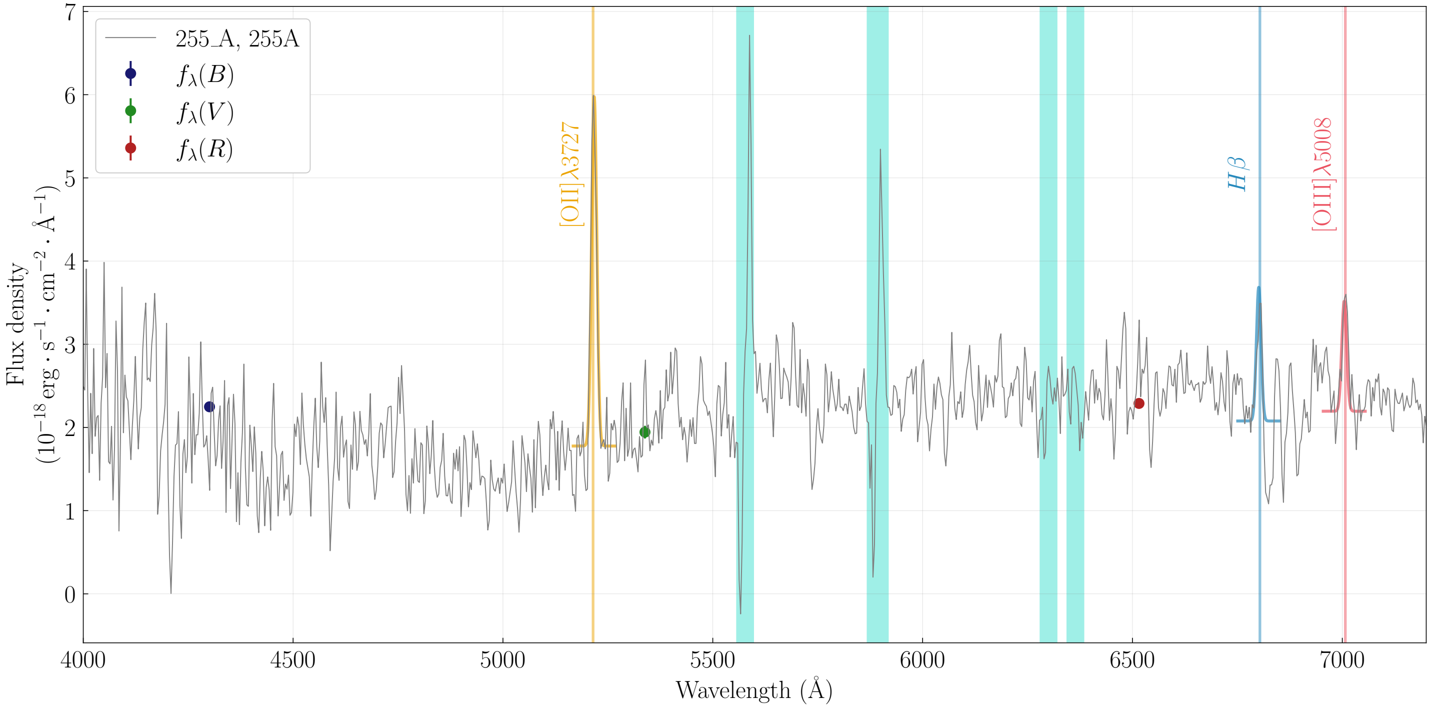
^{12}CO data from EMIR@30m

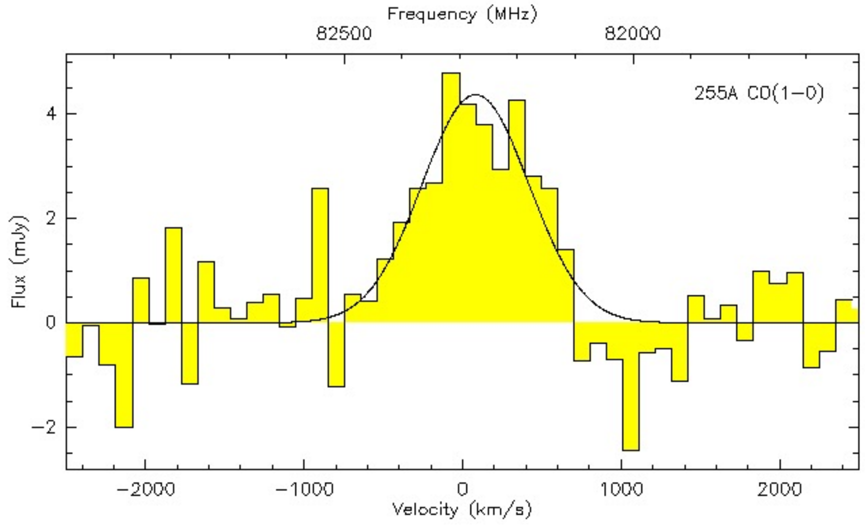
Source example: 405A

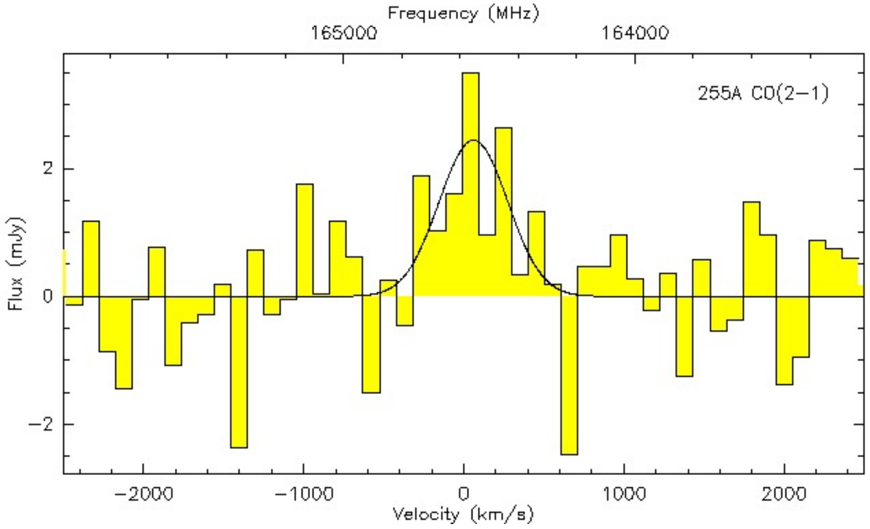


Source example: 255A

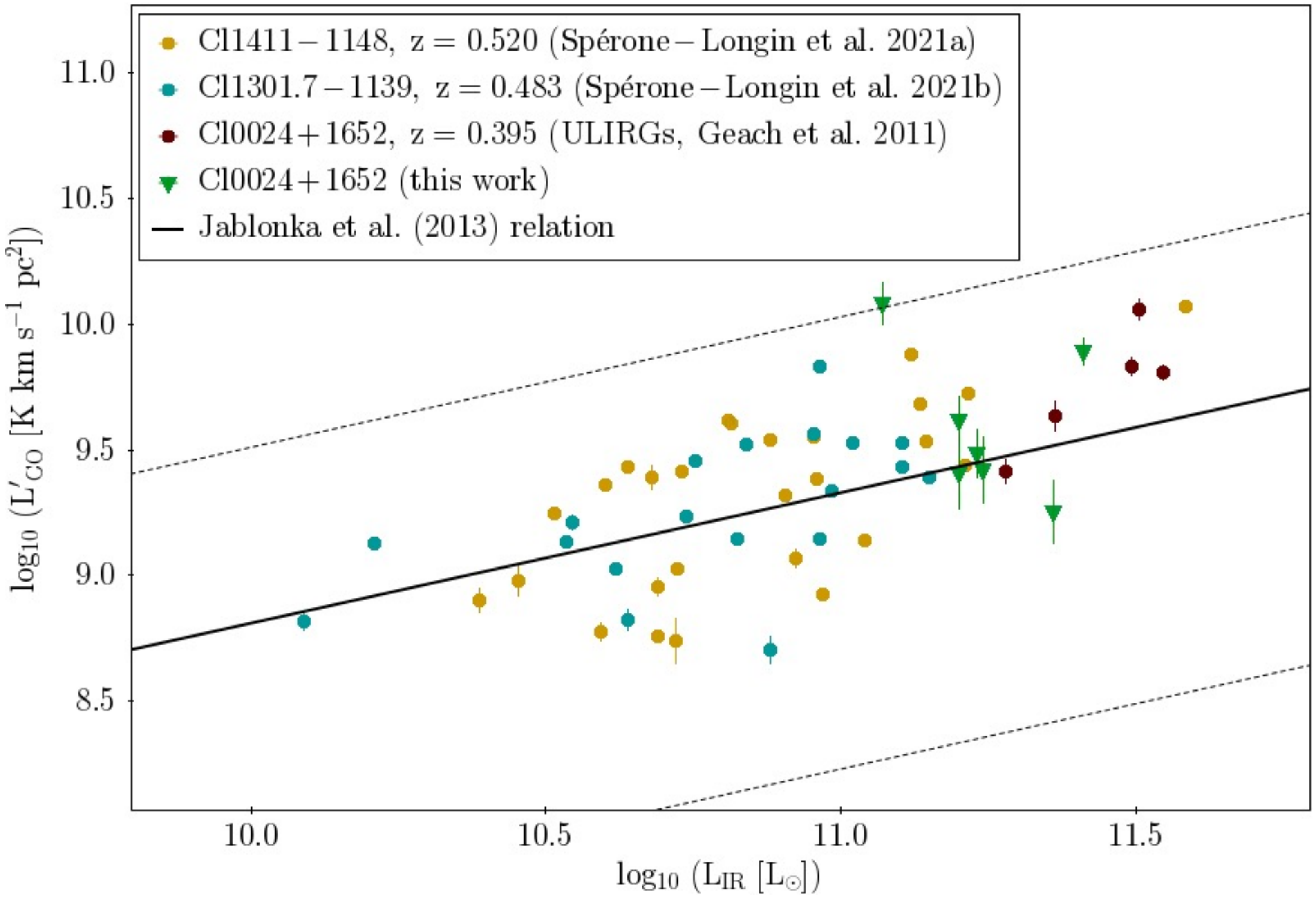








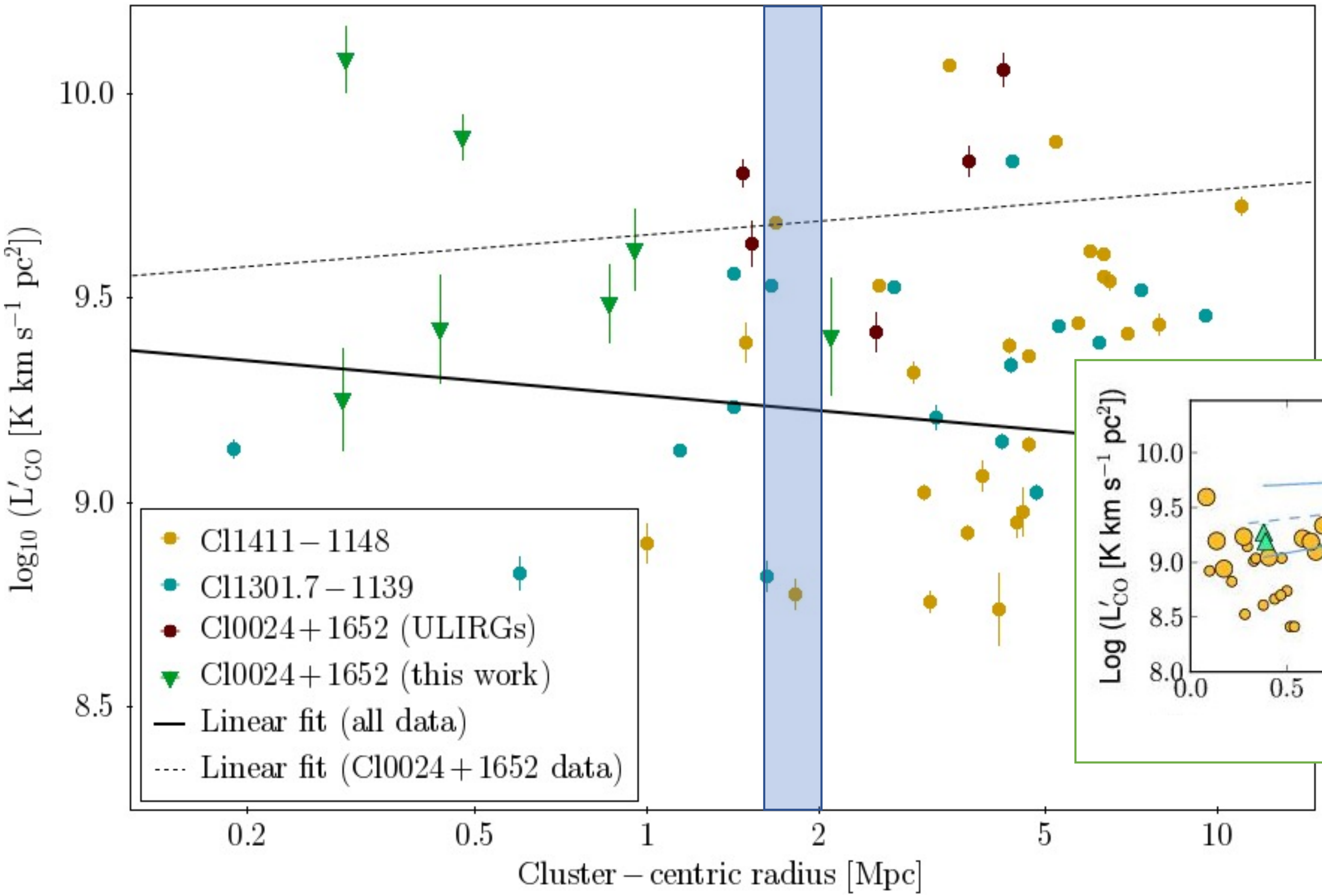
Results: L'_{CO} – $L_{IR(SED)}$ relation



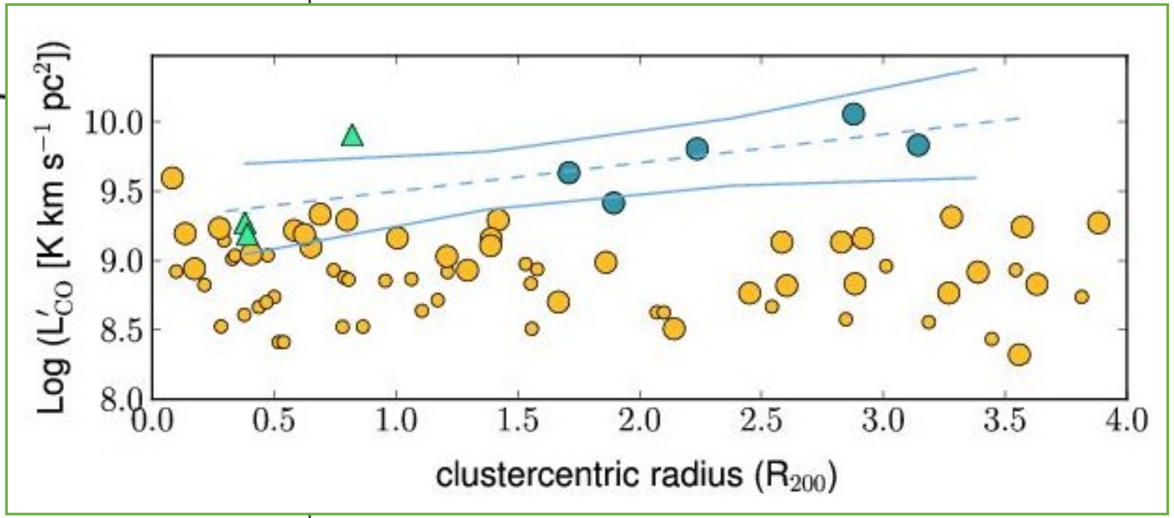
Apart from the ^{12}CO data for 3 galaxies reported in Jablonka+2013, this plot shows **the current census of molecular gas in intermediate-redshift cluster galaxies** different from BCGs (e.g. Castignani+2020).

L'_{CO} estimations for this work come from $^{12}CO(2\text{-}1)$ transition, unless data from the (1-0) one have a higher line-SNR. In this case, we adopted R_{21} = 0.61 (Leroy+2022). In the case of Spérone-Longin+2021a,b data, R_{31} = 0.29 was assumed (idem).

L'_{CO} – cluster-centric radius

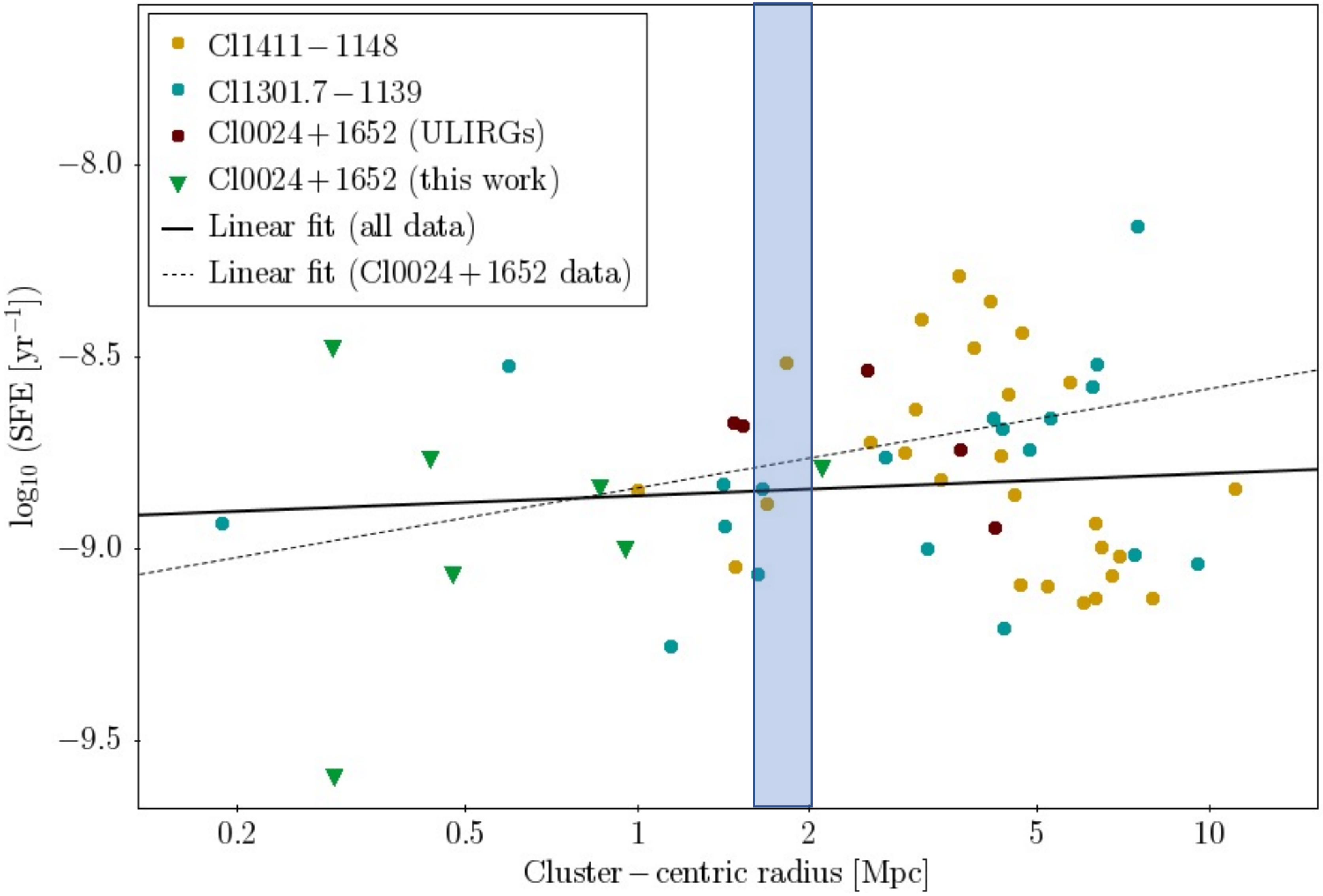


Consistent with Geach+2011 (and also Jablonka+2013), we found that molecular gas increases towards the outskirts of Cl0024+16 by sampling the inner virial radius, in contrast with the SEEdiSC clusters explored until date.



From Jablonka+2013

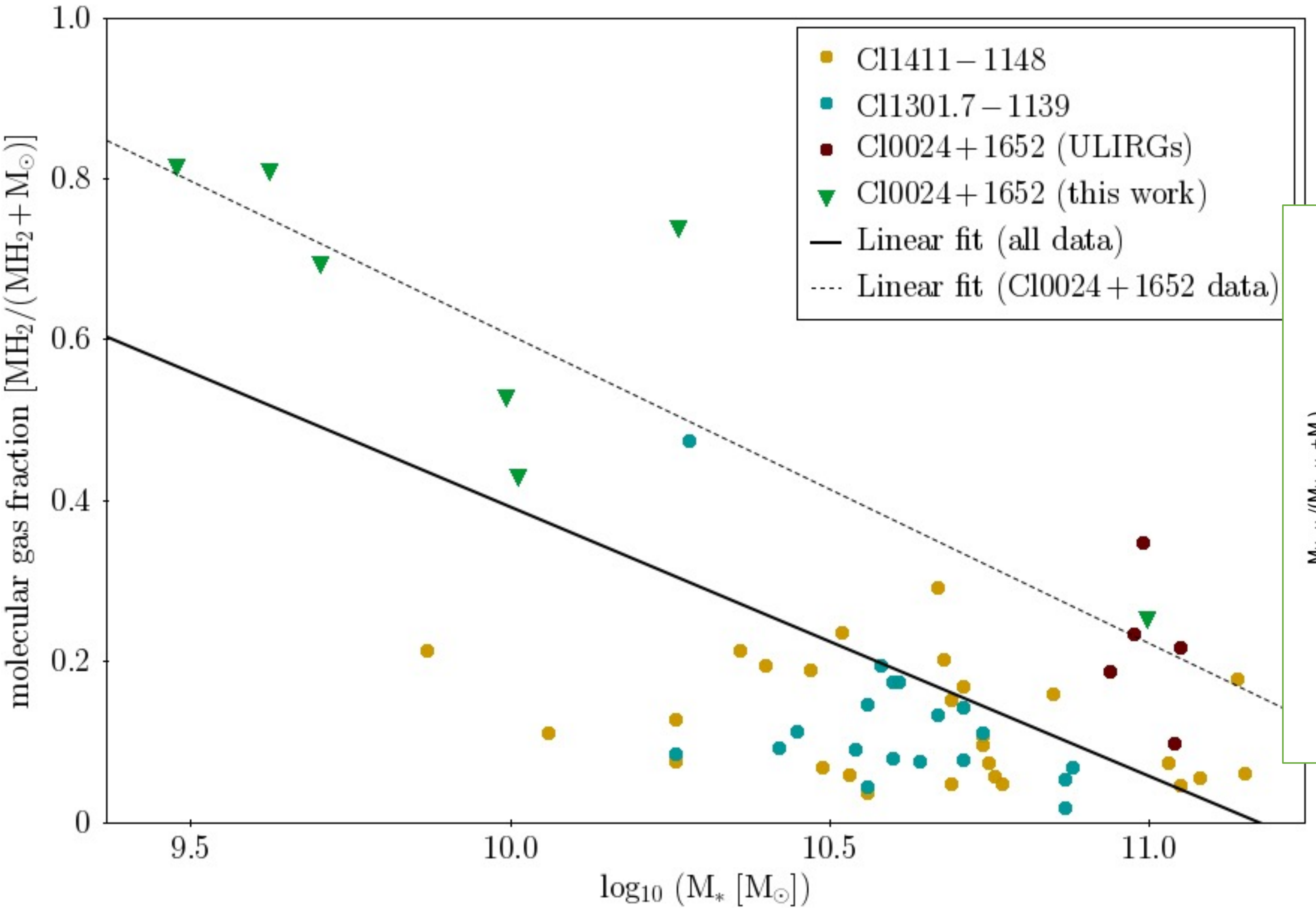
SFE [SFR_{IR}/MH_2] – cluster-centric radius

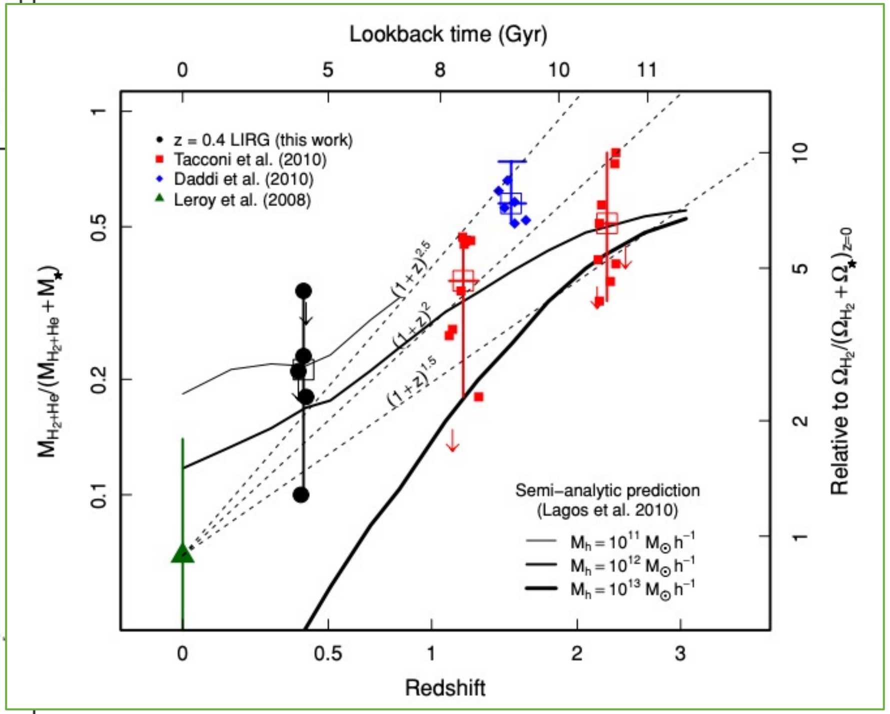


For the MH_2 [$M_{\odot}$] estimated for this work we adopted the $^{12}CO(1\text{-}0)$ luminosity to molecular gas-mass conversion factor $\boldsymbol{\alpha}_{CO}$ = 4.36 ± 0.9 $M_{\odot}$/(K km s^{-1} pc^2) from Carleton+2017 (and references therein), good for normal SFGs.

We find *prima-facie* evidence about a mild increasing of the star formation efficiency in Cl0024+16 at cluster-centric radii $R \lesssim R_{200}$.

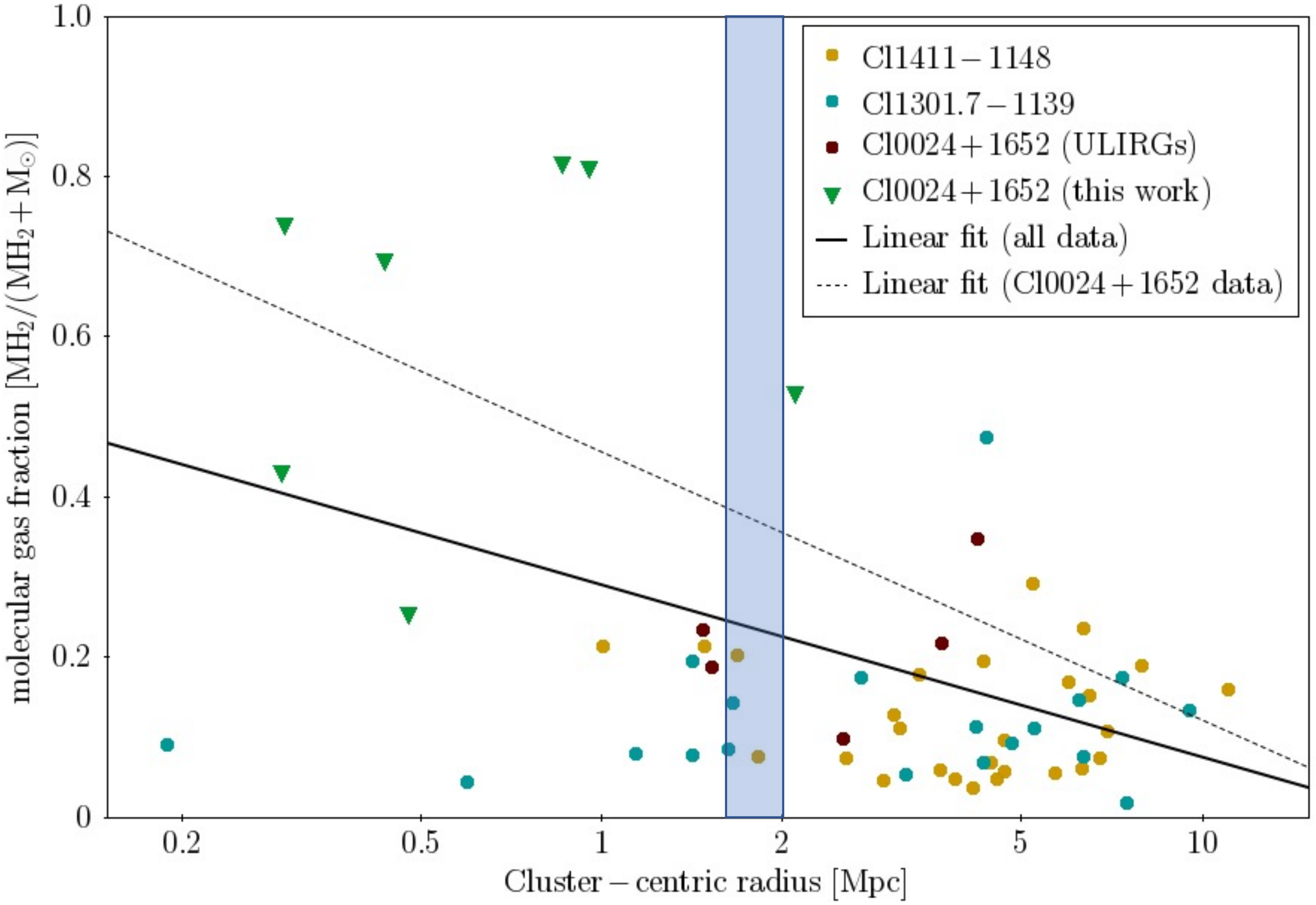
Molecular gas fraction – M_*





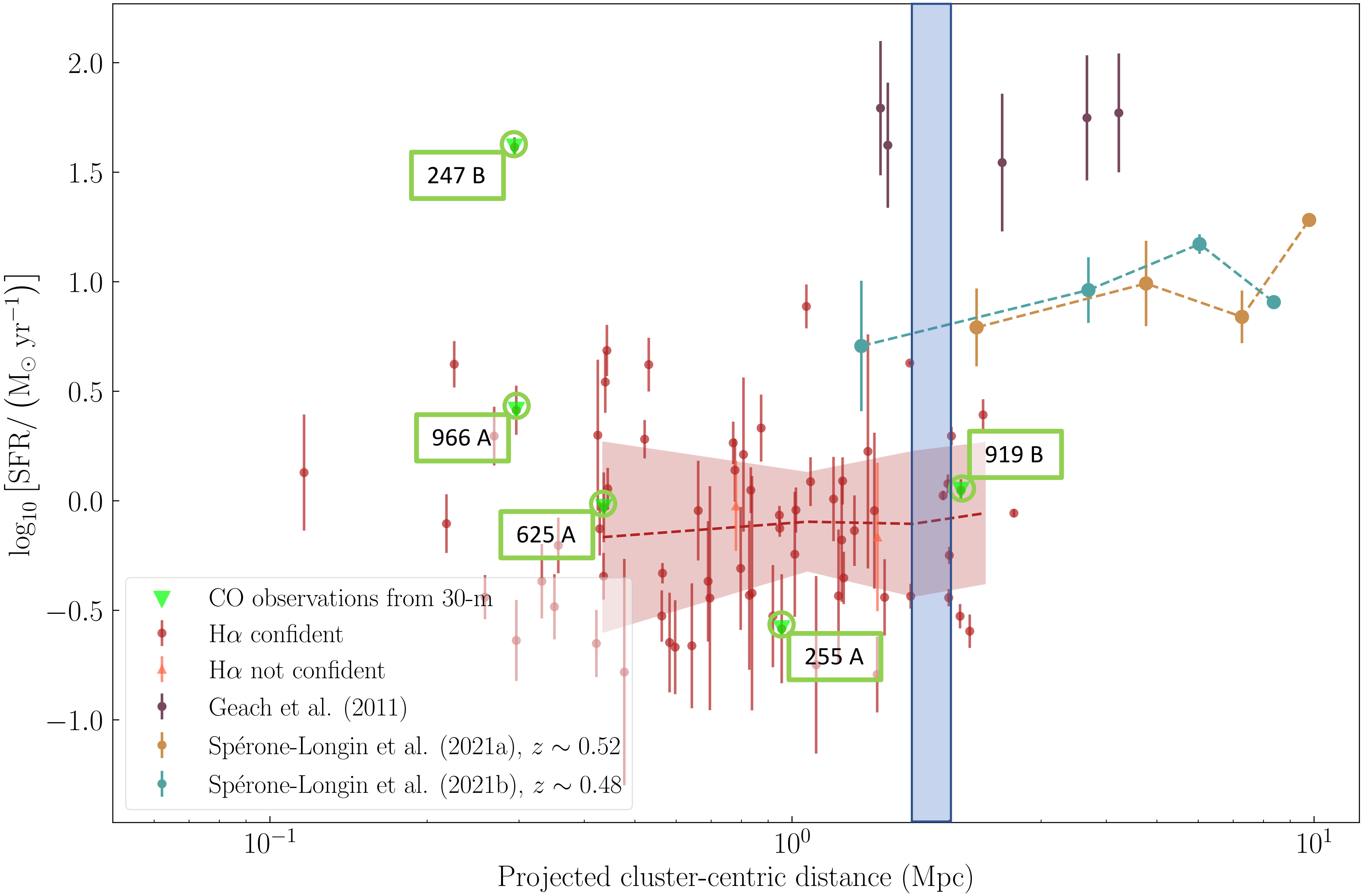
From Geach+2011

Molecular gas fraction – cluster-centric radius



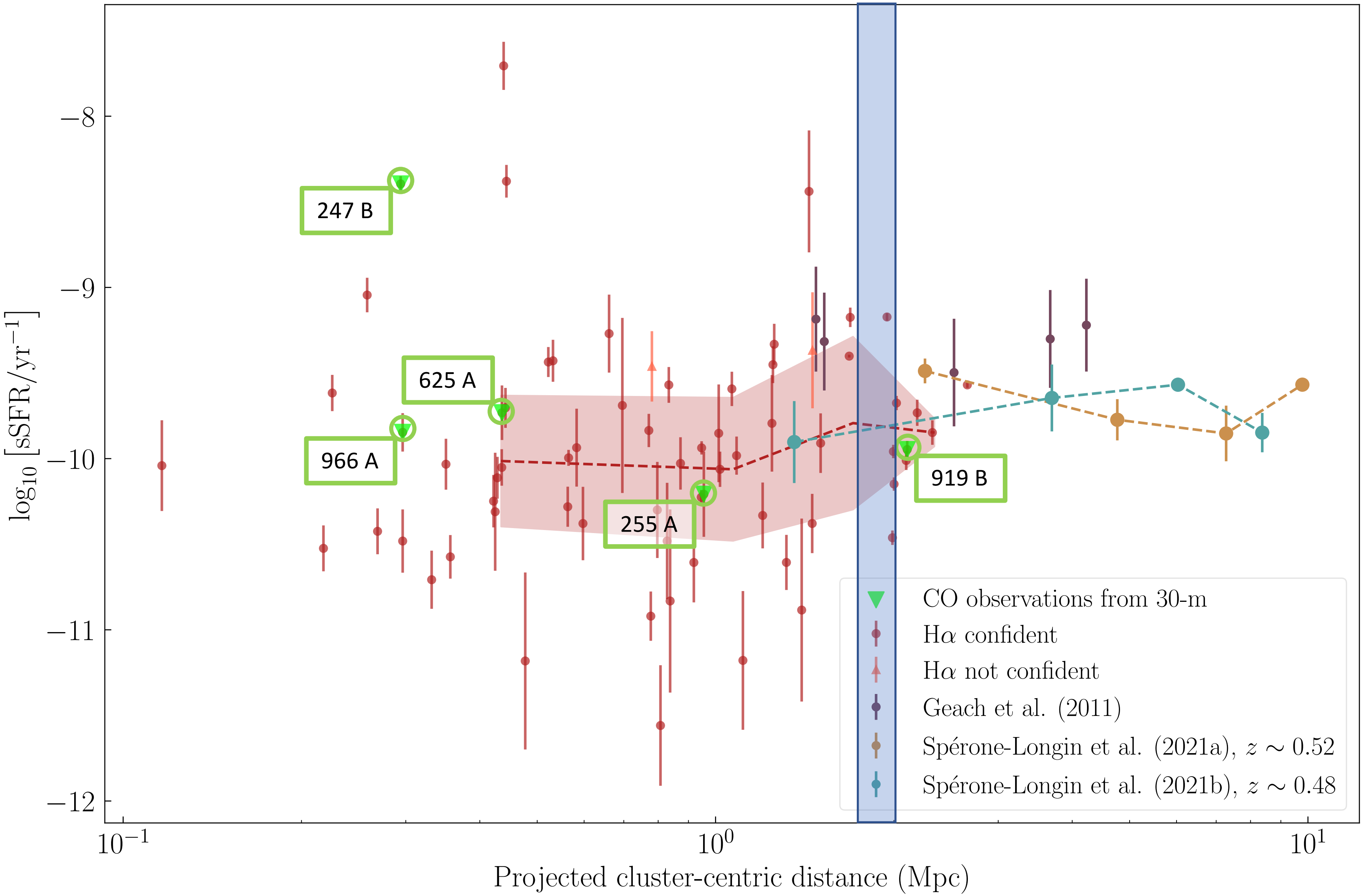
$SFR_{H\alpha}$ – cluster-centric radius

From Bonnal (2023)



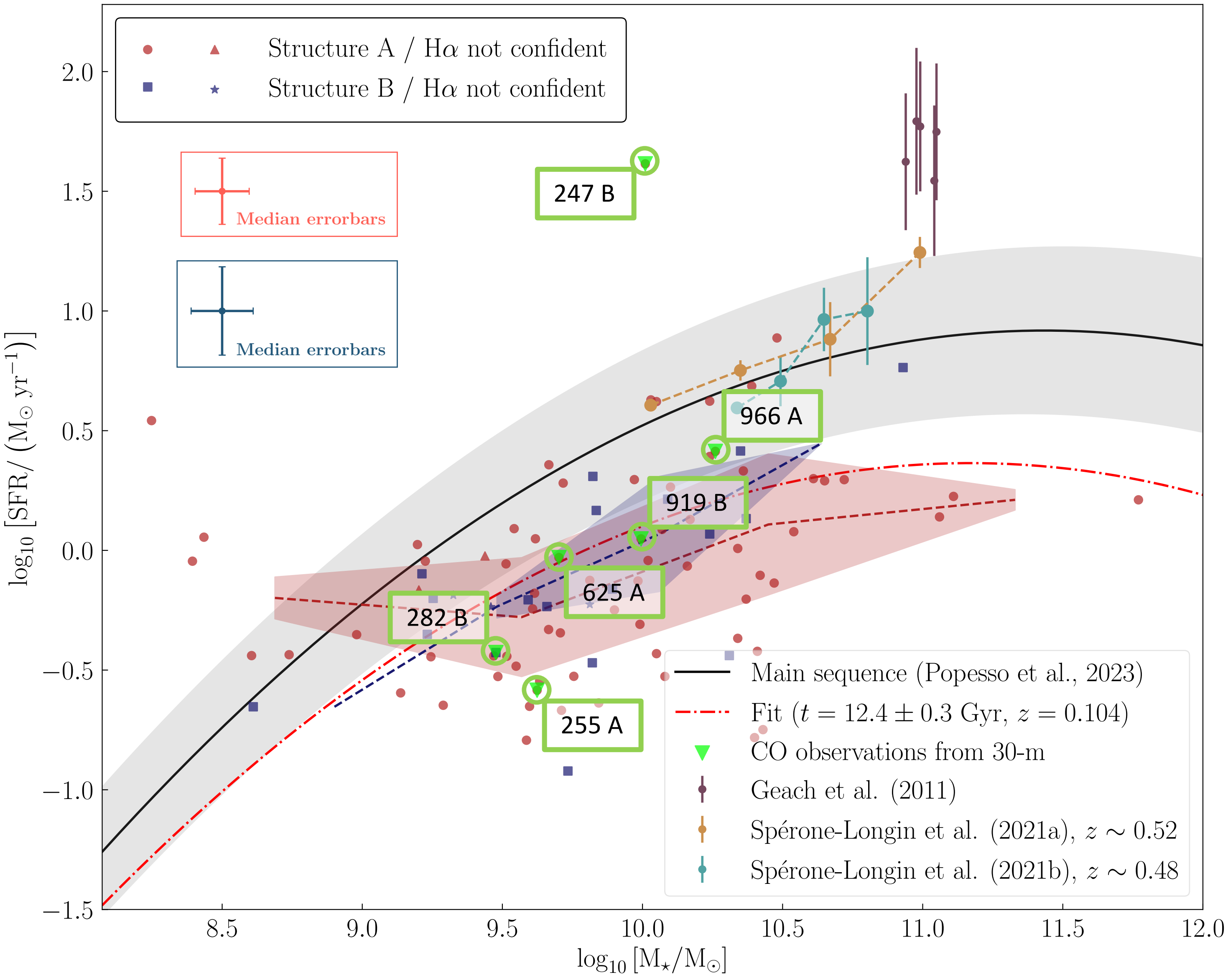
$sSFR_{H\alpha}$– cluster-centric radius

From Bonnal (2023)



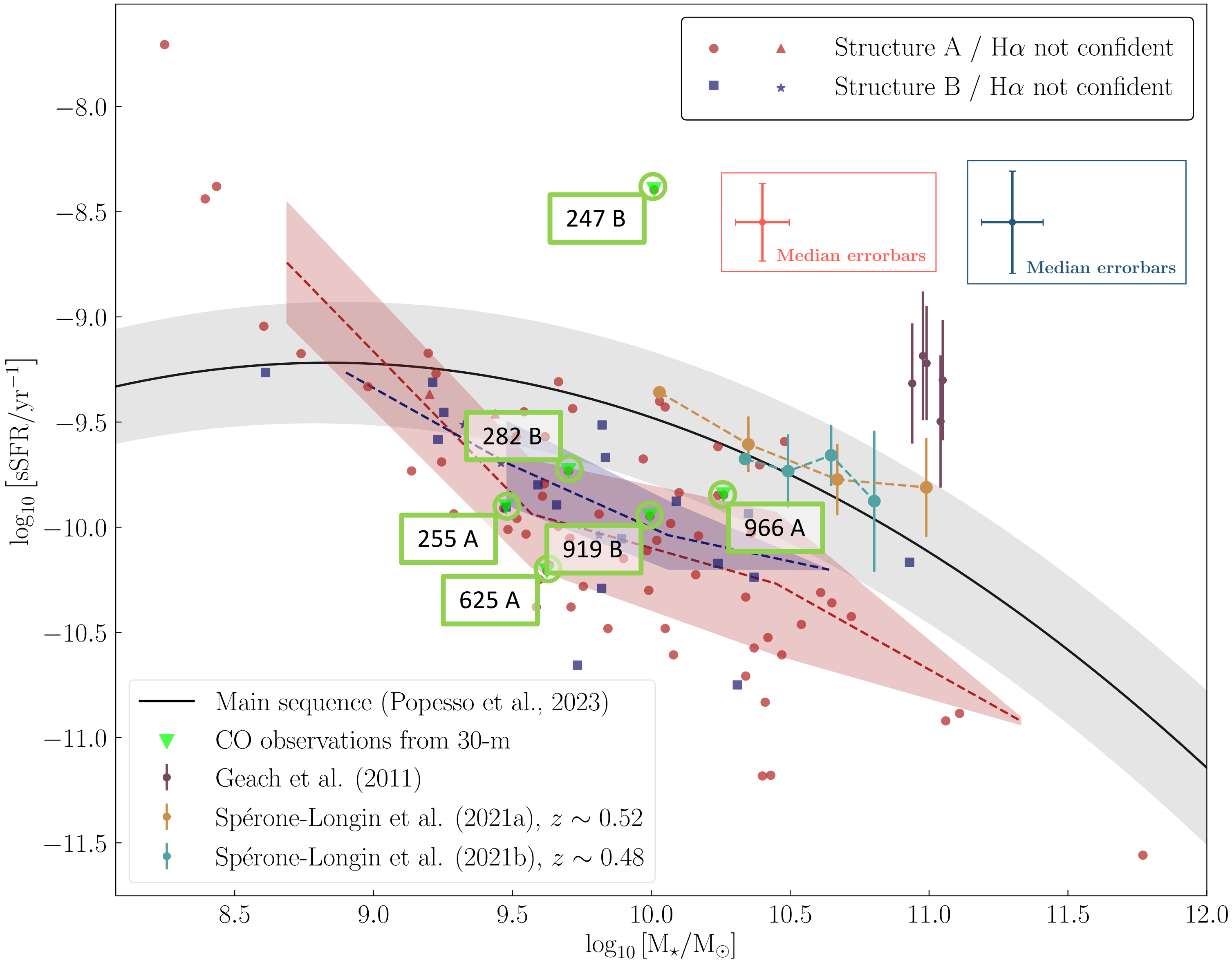
$SFR_{H\alpha}$ – M_* relation

From Bonnal (2023)



$sSFR_{H\alpha} - M_*$ relation

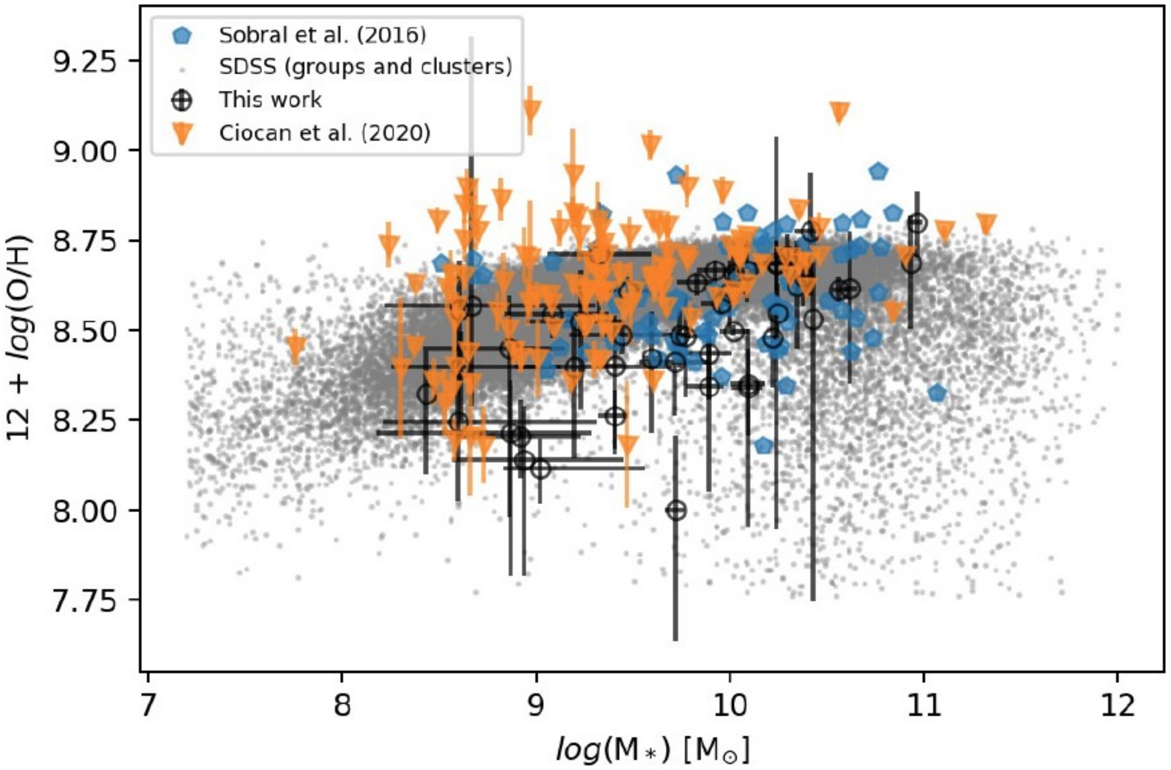
From Bonnal (2023)

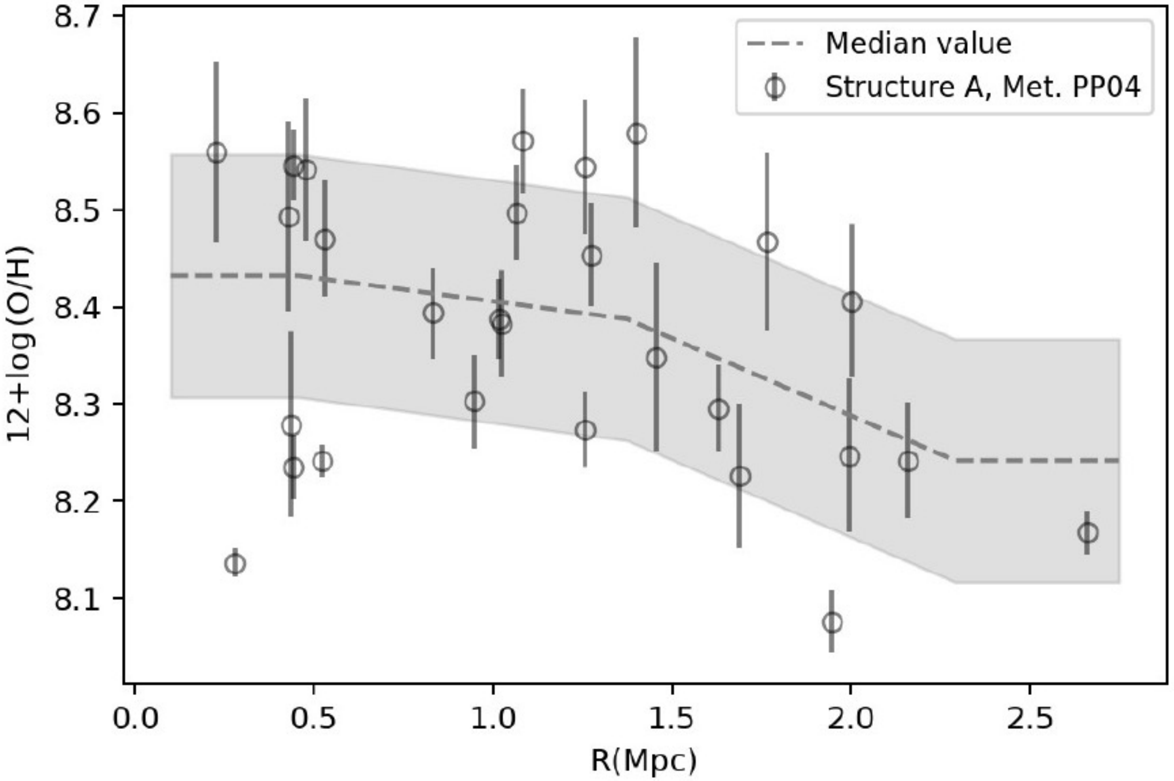


Additional work in progress: gas metallicity relations

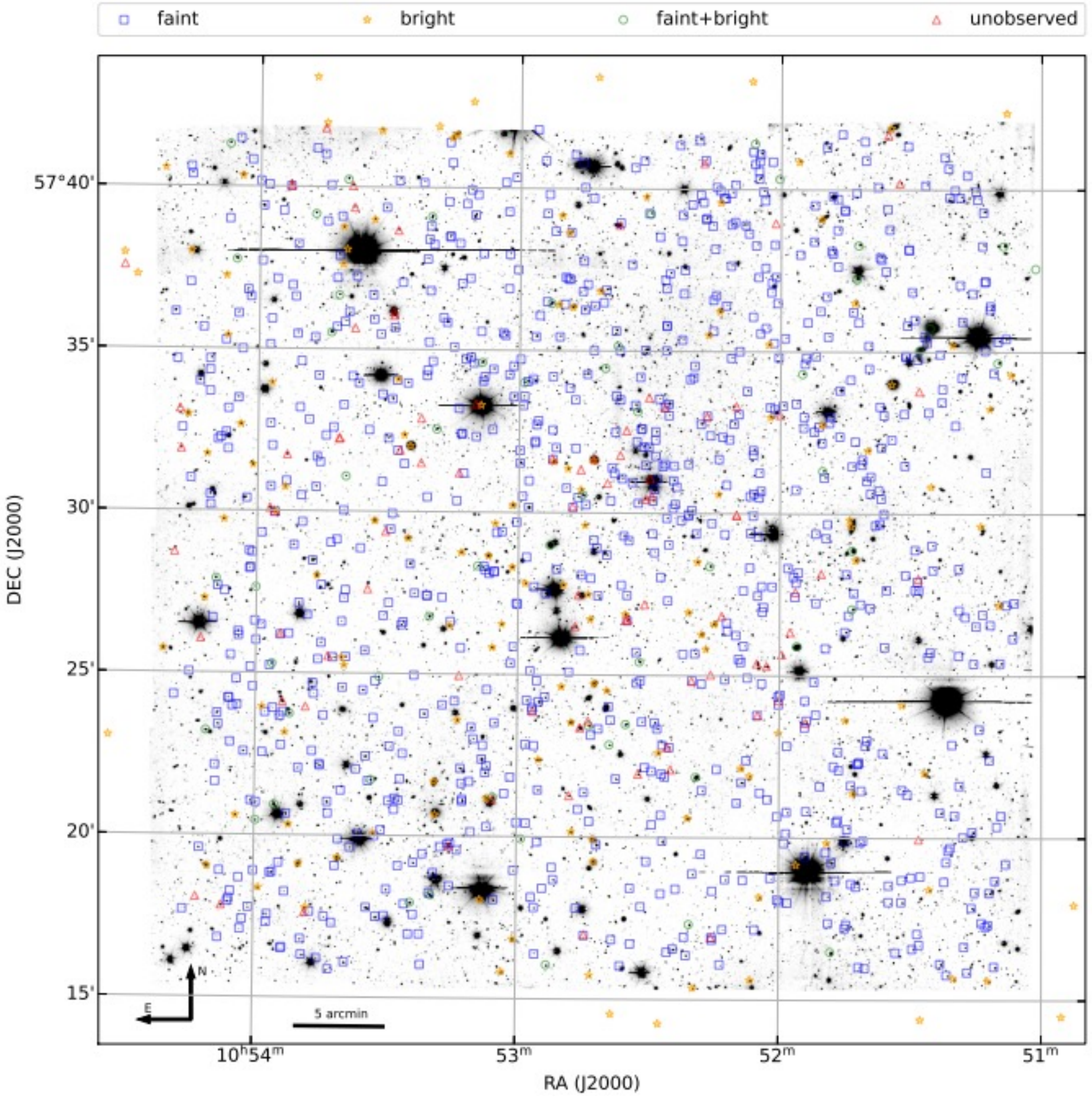
N2 & O3N2 indicators

From Cedrés+2023 (in preparation)





Lockman-SpReSO in a nutshell



From González-Otero+2023

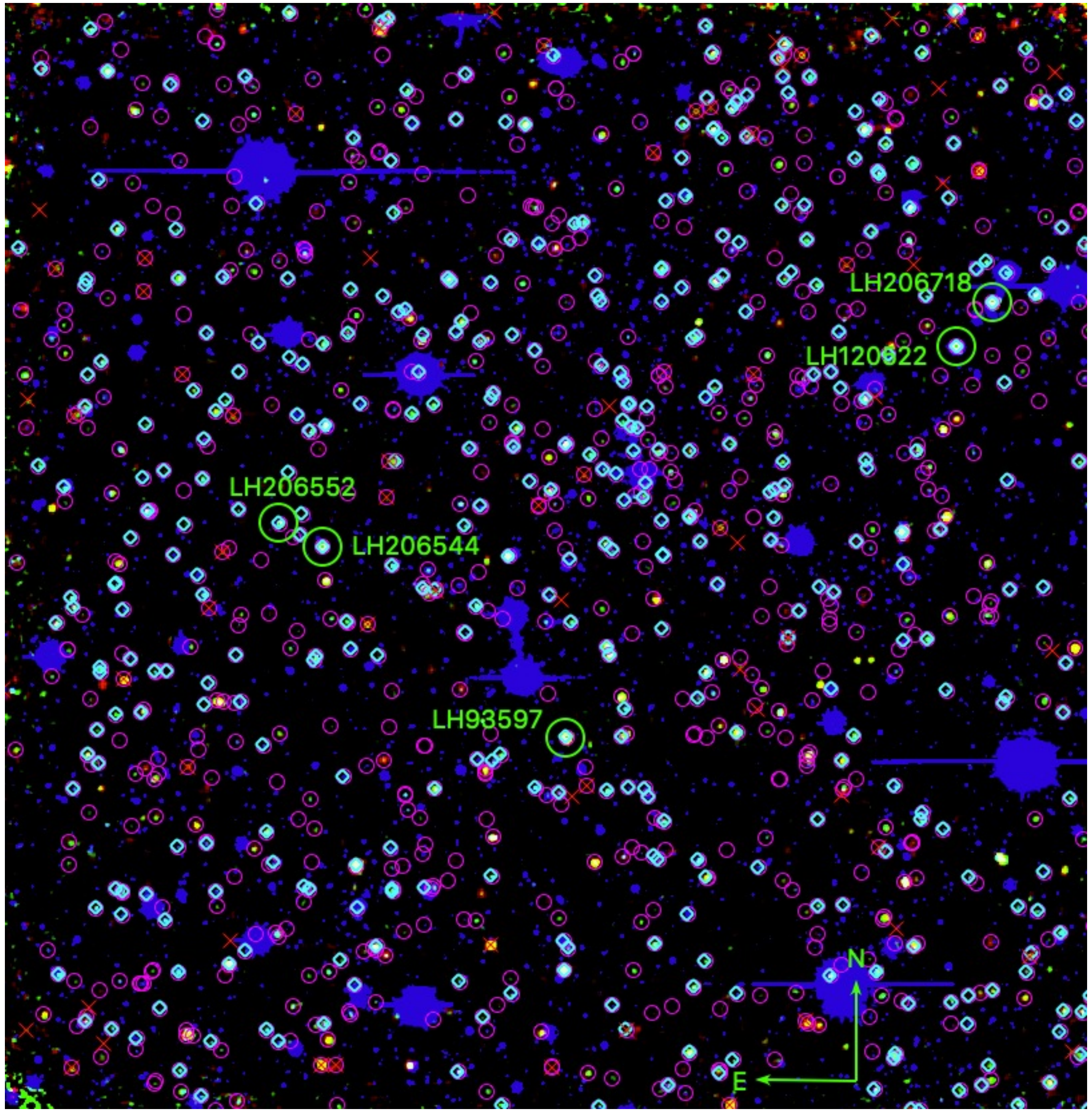
- The **Lockman Sp**ectroscopic **Re**dshift **S**urvey using **O**SIRIS (Lockman-SpReSO) is a complete (R < 24 mag) **optical spectroscopic follow-up** of the far-infrared (FIR) sources detected by the Herschel Space Observatory in the **Lockman Hole (LH) field**.

- Input catalogue of 1144 sources. Secured redshifts for 456 objects.

- Lockman-SpReSO aims at provide spectroscopic redshifts, SFR from strong emission lines and gas of the FIR-selected galaxies (González-Otero+2023).

- In 2022, we started **a mm-wavelength follow-up** of the most promising sources of Lockman-SpReSO with the IRAM-30m telescope, based on the crude ^{12}CO flux estimations from one of the most used $L'_{CO} - L_{IR(SED)}$ scaling relations (Jablonka+2013) as a feasibility test, with similar science goals of GLACE's cold gas scouting, but in significantly less dense environments.

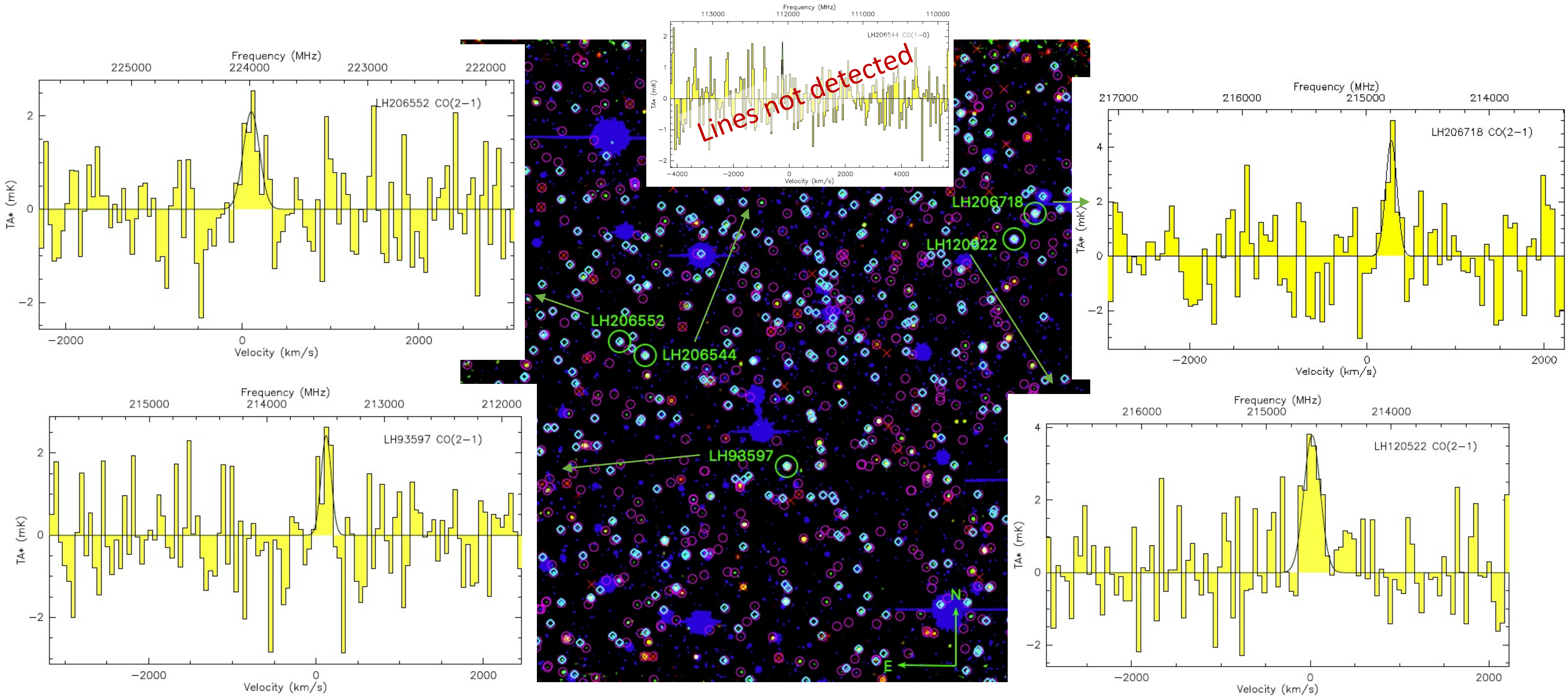
Lockman-SpReSO: Sample selection & observations



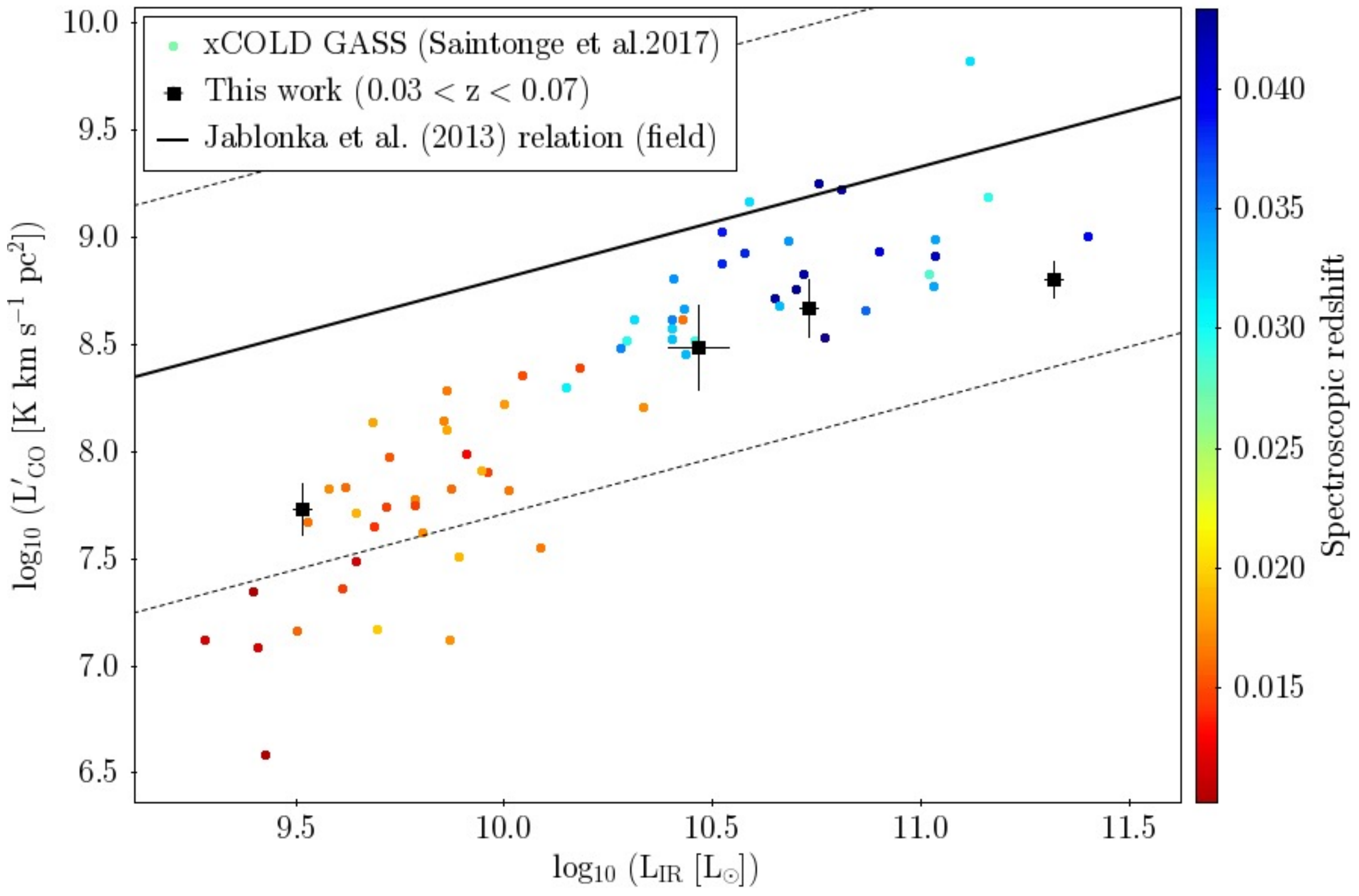
- **Main goal**: Try to constrain observing times with EMIR receiver at the 30m telescope to observe 12CO low transitions, according to the nature of the galaxies in the sample.
- **Sample**: We selected the 5 most promising LH-SpReSO sources according to the estimated 12CO(1-0) flux density. They are represented on the RGB (PEP-160 um, PEP-100 um, OSIRIS-r') map at right.
- **Time**: A total requested time of **15 hours** with EMIR/30m telescope were awarded as a DDT program.
- **Observations**: Were carried out in pooled mode in Summer 2022. Additional data are provided after the upgrading of the IRAM-30m telescope (proposal 043-23).

ID	RA [hms]	Dec [dms]	z_spec	$\nu_{12CO(1-0)}$ [GHz]	$S_{CO(1-0)}$ peak [mJy]	rms Ta* [mK]	Exp. time [h]
LH120522	10:51:34.43	+57:33:59.5	0.0740	107.33	41.01	2.30	0.4
LH206552	10:53:33.04	+57:29:42.8	0.0289	112.03	31.59	1.76	0.8
LH206544	10:53:25.40	+57:29:10.9	0.0294	111.98	28.23	1.57	1.0
LH93597	10:52:42.38	+57:24:44.9	0.0794	106.79	12.79	0.72	3.5
LH206718	10:51:28.07	+57:35:02.5	0.0723	107.50	9.24	0.52	7.0

Lockman-SpReSO: Sample selection & observations



Preliminary results: $L'_{CO} - L_{IR(SED)}$ relation



L'_{CO} estimations for this work, as well as the xCOLD GASS data, come from the observation of the $^{12}CO(2\text{-}1)$ transition. We adopted $R_{21} = 0.61$ (Leroy+2022).

Contrary to what could be argued, the relationship between the L'_{CO} and the L_{IR} is far from being universal for local field galaxies compared to their counterparts at higher redshifts (higher SFE?)

Closing remarks

Methodological issues:

- The obvious one: it is difficult to map moderate SFR (few $M_\odot$/yr) at z = 0.4!
- Comparisons are dangerous if datasets are not uniform, e.g. different SFR derivation methods, different CO transitions (e.g. higher order CO transitions may trace denser gas, more directly connected to SF)
- The conversion of L_{co} to M_{H2} is always an issue (e.g. metallicity dependency)
- Need a large dataset gathered with similar means and processed with uniform methods!

Hints from data (must be taken with caution):

- Increase of L_{CO} with increase of cluster-centric radius (or smaller local density)
- Mild increase of SFE with cluster-centric radius
- The behaviour of the molecular gas fraction can be biased by the fact that we are targeting typically low-stellar mass galaxies
- Our SFR data show a clear distinct (faster) evolution of cluster galaxies with respect to field as given by the position of the MS
- We observe hints of gradients of metallicity with cluster-centric distance (lower metallicity at larger distance).
- The L_{CO} – L_{IR} relation doesn't seem to be as universal as initially thought (at least from our data).