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A sensitive CO and atomic carbon APEX & ALMA/ACA survey of local (U)LIRGs

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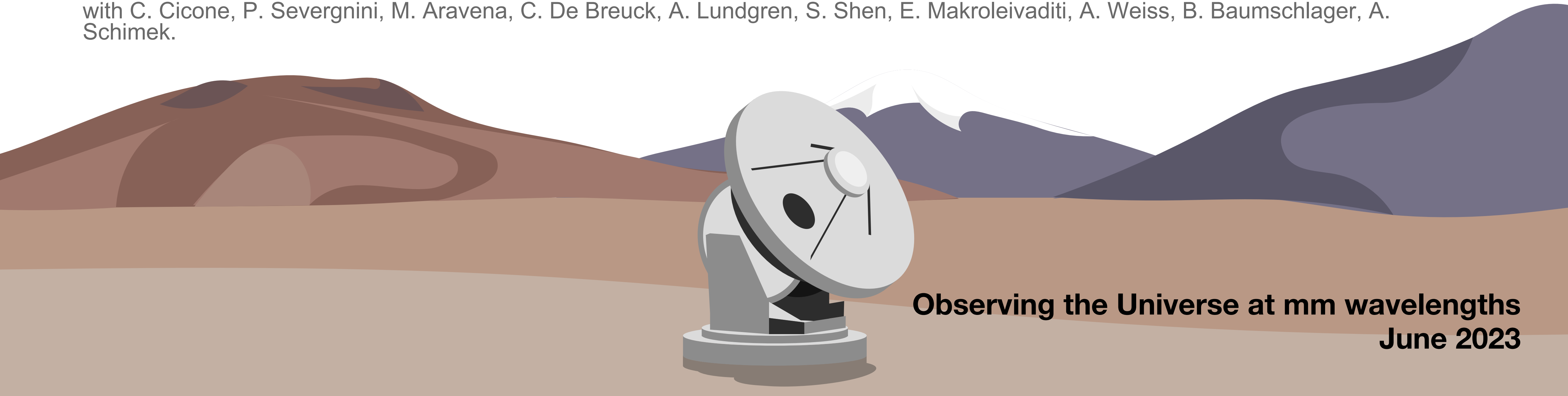
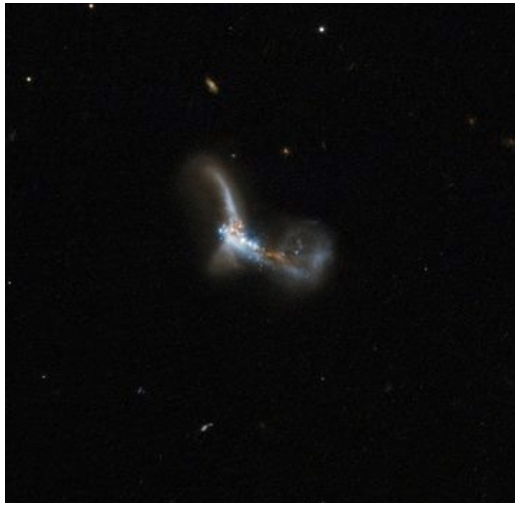


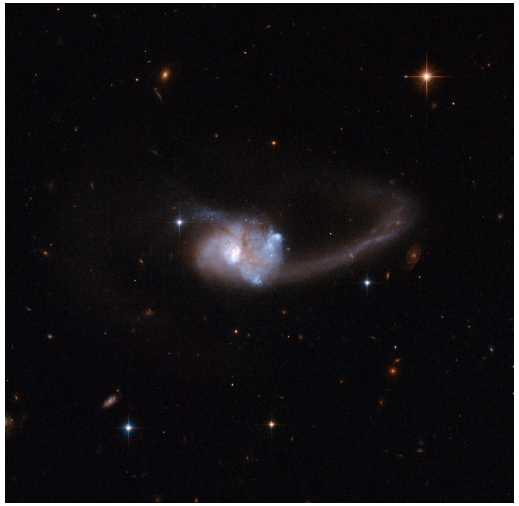
Observing the Universe at mm wavelengths
June 2023

Motivation



IRAS F22491-1808

IRAS F20551-4250



Local (U)LIRGs L_{IR}(8-1000μm) >10^{11} $L_{\odot}$:

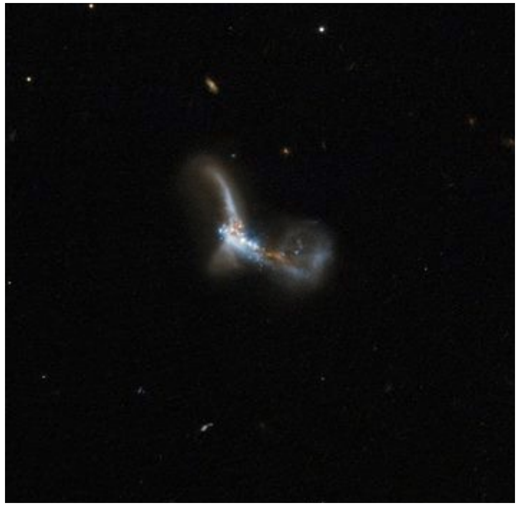
- Powered by SF and AGN
- Dusty and gas-rich
- Most local L_{IR}>$10^{11.5}$ $L_{\odot}$ are galaxy mergers
- Molecular (H_2) gas strongly affected by gravity and feedback
- H_2 gas found in: rotating disks, inflows, outflows, tidal tails

Still many misteries:

- What are the physical properties (M_{H2}, T_{kin}, n_{H2}, extent) and energetics of molecular outflows?
- ISM 'extreme' throughout or just in some components (e.g. outflows)?
- What is the real extent of the H_2 reservoirs?
- Low α_{CO} or large M_{H2}? CO-dark gas due to FUV and CR irradiation?
- Self-gravitating GMCs or diffuse turbulent 'envelope' phase?

Images taken from https://hubblesite.org/

Motivation



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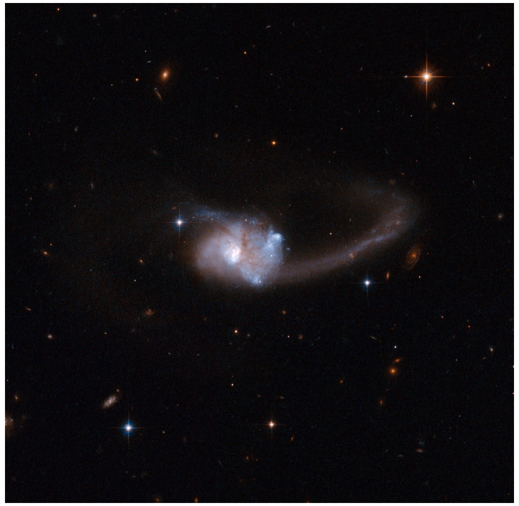


Excitation conditions (and α_{CO}) **of outflowing and non-outflowing H_2 may be different** but we need statistics to confirm (Cicone+18; Dasyra+16, Oosterloo+17 for IC5063; Cicone+12, Cicone+20 and Aalto+15 for Mrk231).

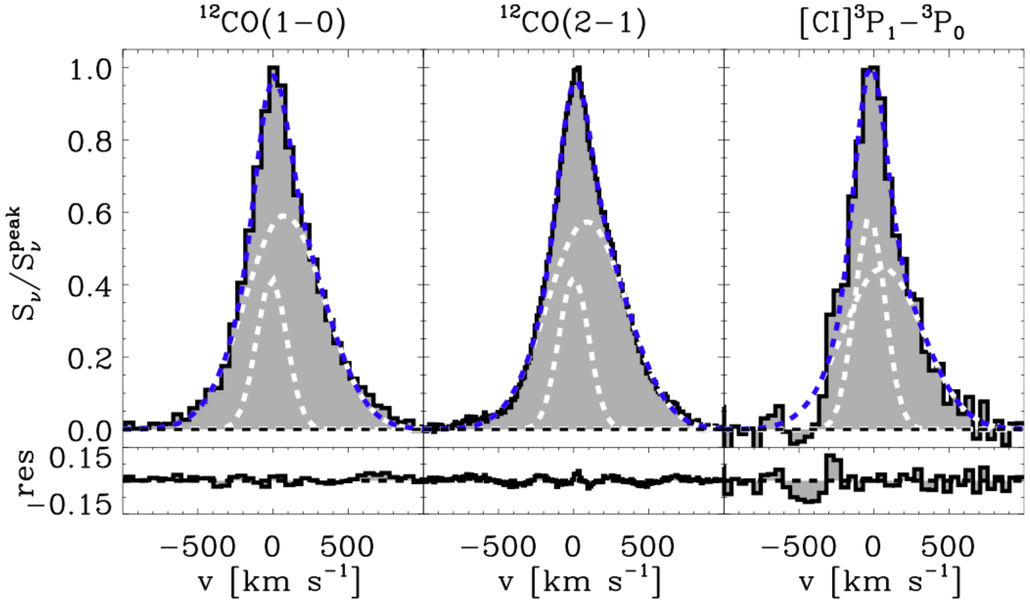
Previous studies focus on few sources, and/or heterogeneous datasets, with different analyses and paying little attention to aperture-matching and capturing large scale flux.

We want to tackle a statistically significant sample of 40 local (U)LIRGs focusing on extended and diffuse emission.

Images taken from https://hubblesite.org/

Motivation

Cicone+18

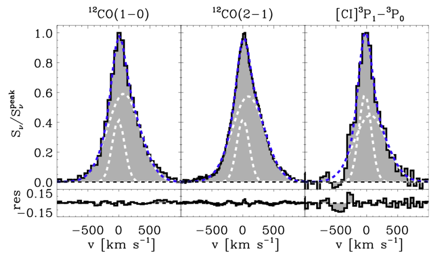


From study of NGC6240's molecular outflow:

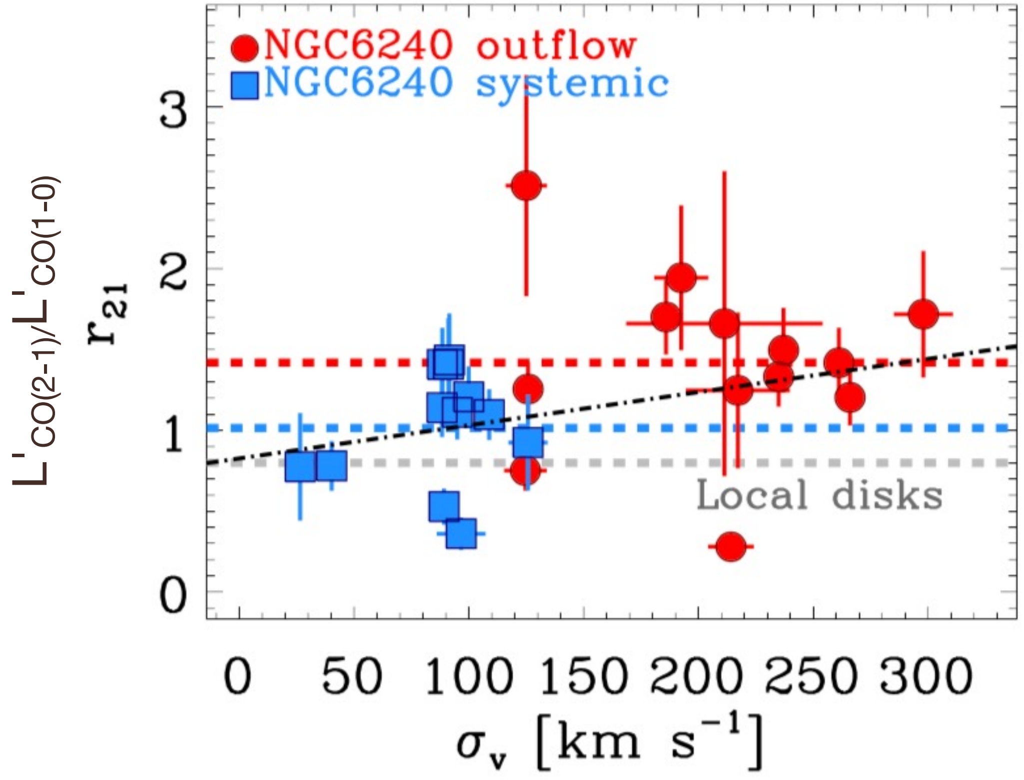
- Combining [CI] and CO info: **different α_{CO} and r_{21} ratio for the quiescent and outflowing gas.**
- $r_{21}(OF) > r_{21}$ (non OF) with a tentative trend of r_{21} increasing with σ_v of the gas.

Do outflows embed warmer optically-thin CO phase?

Motivation



Cicone+18



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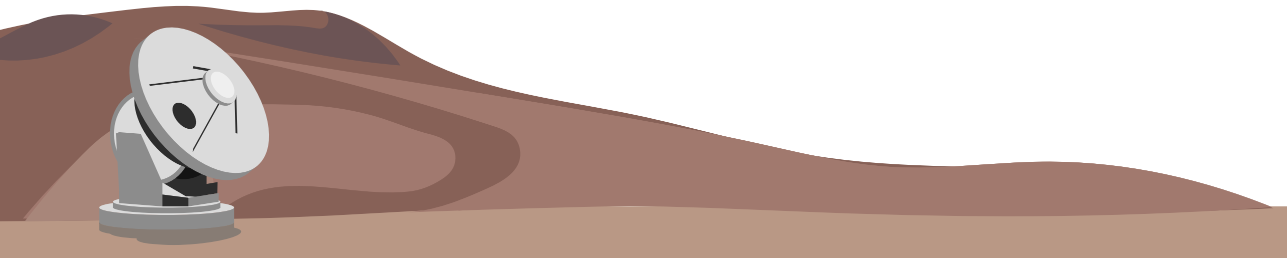
  Do outflows embed warmer optically-thin CO phase?

- A simple simultaneous spectral decomposition (broad/narrow components) of integrated spectra yields results consistent with proper outflow/non outflow spatial decomposition

→ *We applied same spectral decomposition method to a large sample of (U)LIRGs observed with APEX in multiple CO and [CI] lines + ancilliary ALMA/ACA archival data.*

→ *Is NGC6240 is an exception or not?*



Sample selection

Selection criteria:

- Prior Herschel OH119 μm coverage (Veilleux+13, Spoon+13)
- $\delta < 15$ deg to ***maximize overlap with APEX and ACA/ALMA public archives***

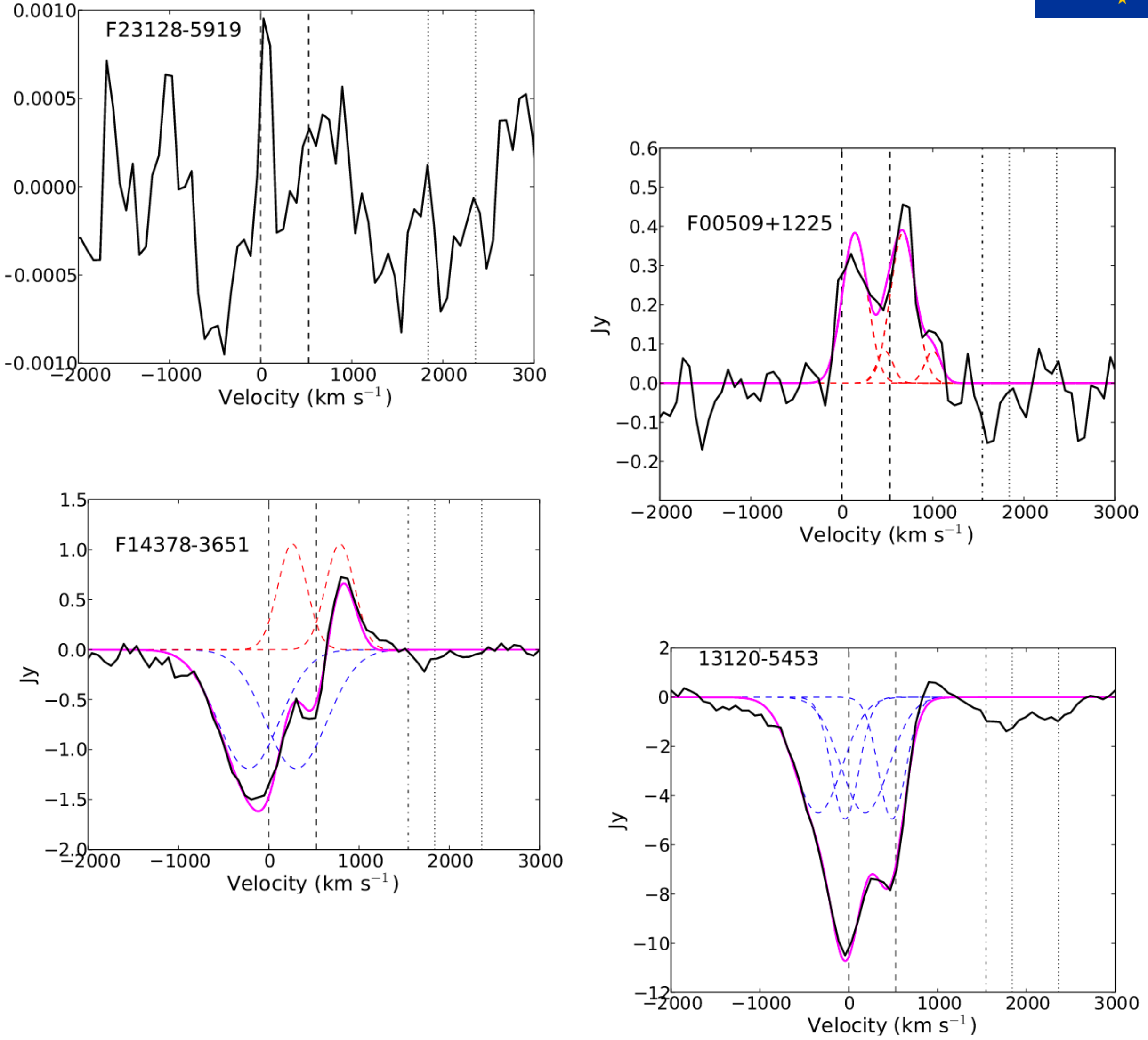
Sample: **40 sources (36 ULIRGs + 4 LIRGs)**.

Properties:

$z < 0.2$

$0.0 < \alpha_{AGN} < 0.92$

$3 < \mathrm{SFR} < \sim 300\ M_{\odot}\mathrm{yr}^{-1}$



Herschel/PACS OH119 μm spectra from Veilleux+13

Observing strategy

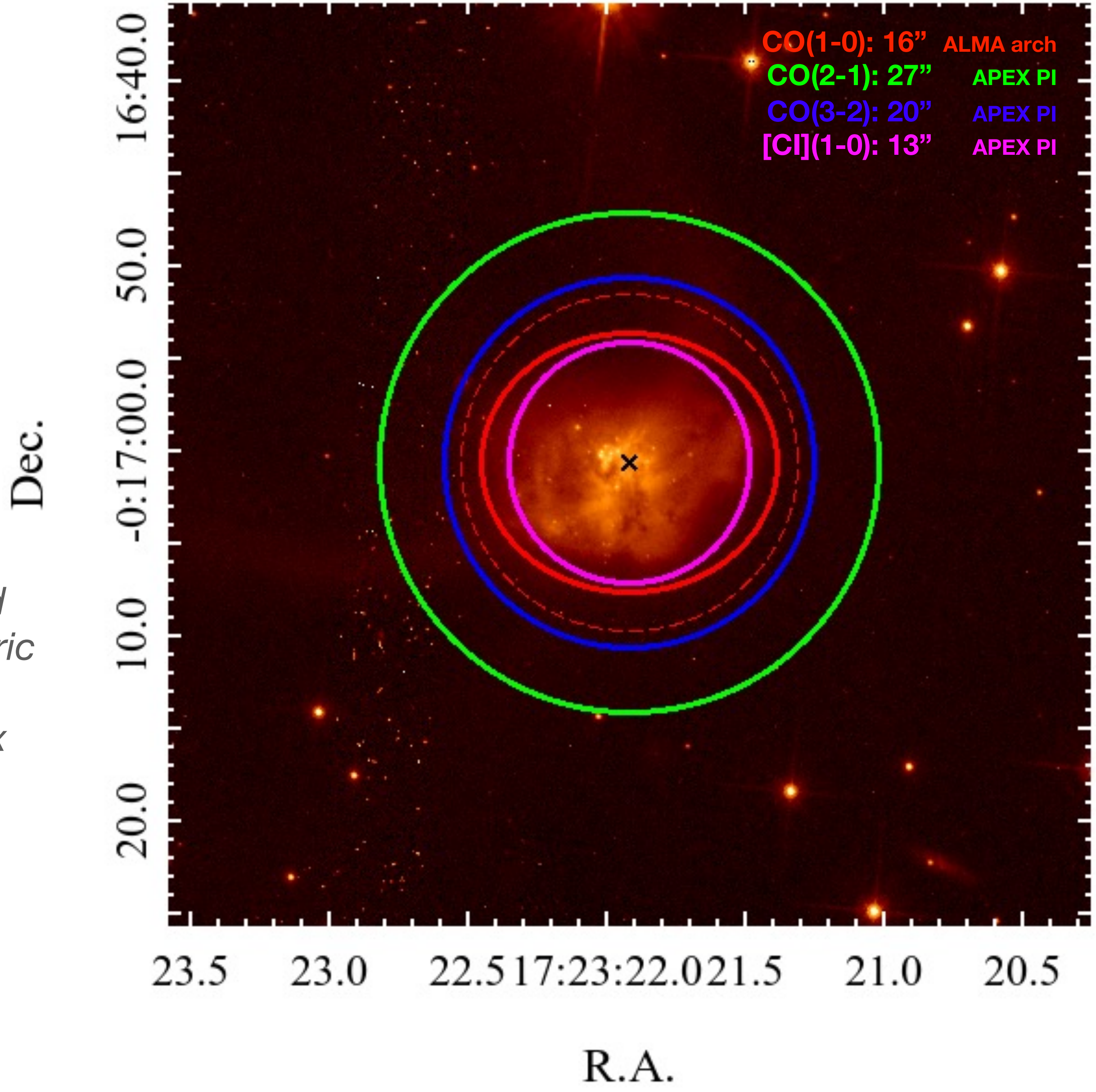
Recall: we are targeting the **extended and diffuse gas**.
We prioritize observations with higher sensitivity to large-scale structures, e.g. single-dish and low-res observations:

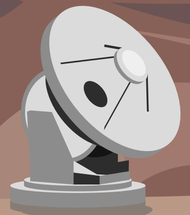
1. APEX data
2. ACA data
3. ALMA data

Final data coverage:
CO(1-0): 22 sources
CO(2-1): 40 sources
CO(3-2): 31 sources
[CI](1-0): 16 sources

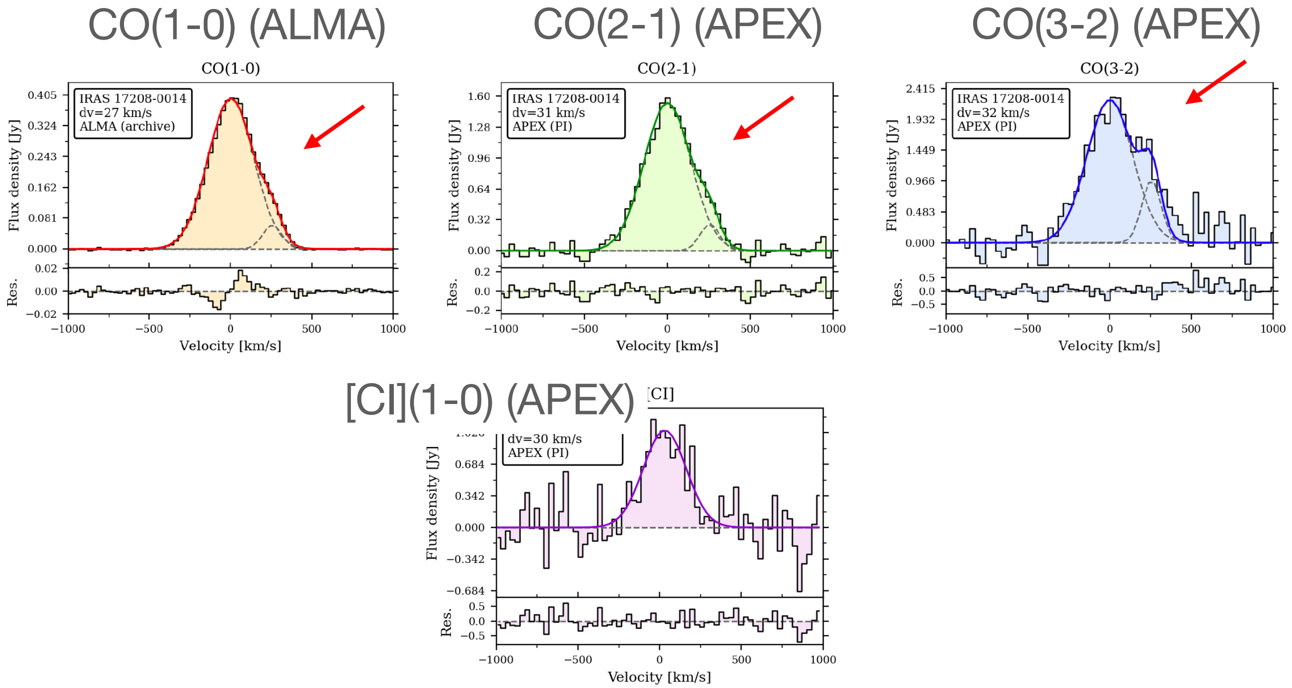
All data consistently re-reduced and re-analysed, for interferometric data spectra extracted from apertures that maximise the flux

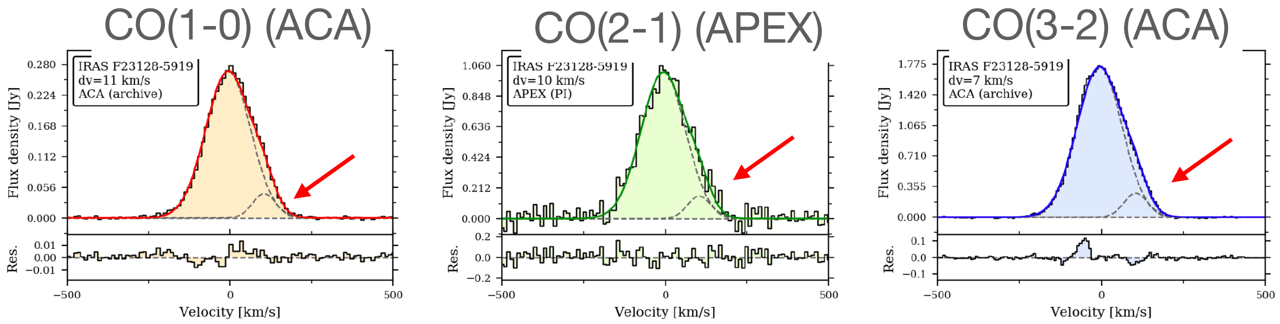
Galaxy IRAS 17208-0014 (*HST* in the background).

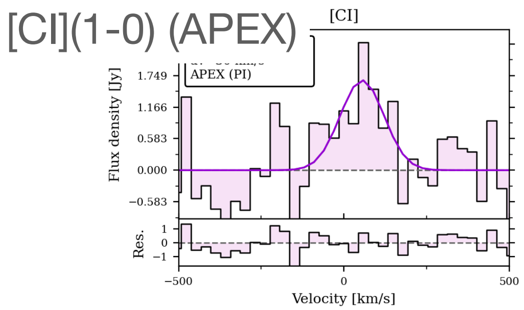




Spectral fitting







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Simultaneous fit with multiple Gaussians (max 3)

CO lines:

- CO transitions tied to be fitted with same components (same σ_v and v_{cen}, different flux)
- Working hypothesis is that the high-σ_v and/or high-v_{cen} components tend to be more dominated by outflowing gas (tested on NGC6240, see Cicone+18)

This enables us to investigate any **statistical trends between CO line ratios and v_{cen} and/or σ_v of spectral components**

[CI] line fitted separately from CO due to lower S/N → enables **investigation of any differences between CO and [CI] kinematics**

[CI]-based α_{CO} estimate

Use the [CI](1-0) line to estimate α_{CO}. Assumptions:

- **[CI] is a tracer of bulk of H_2 as good as CO** (supported by tight ~linear relation between [CI] and CO line luminosity, see e.g. Jiao+17), and potentially superior because capturing **CO-*dark* gas**

- **Optically thin** (see e.g. Israel+15)

- **Main uncertainties come from X_{CI}** (species abundance) and Q_{10} (excitation factor): we use $X_{CI} = (3 \pm 1.5)\, 10^{-5}$ (Weiss+05, Papadopoulos+04, Walter+11) and Q_{10} **= 0.48** following Papadopoulos+22.

$$M_{mol}^{[CI]-based}[M_{\odot}] = 1.293\times10^{-4}(X_{CI}Q_{10})^{-1}L'_{[CI](1-0)}$$

$$\alpha_{CO} = M_{mol}[M_{\odot}]/L'_{CO(1-0)}$$

e.g. Dunne+21

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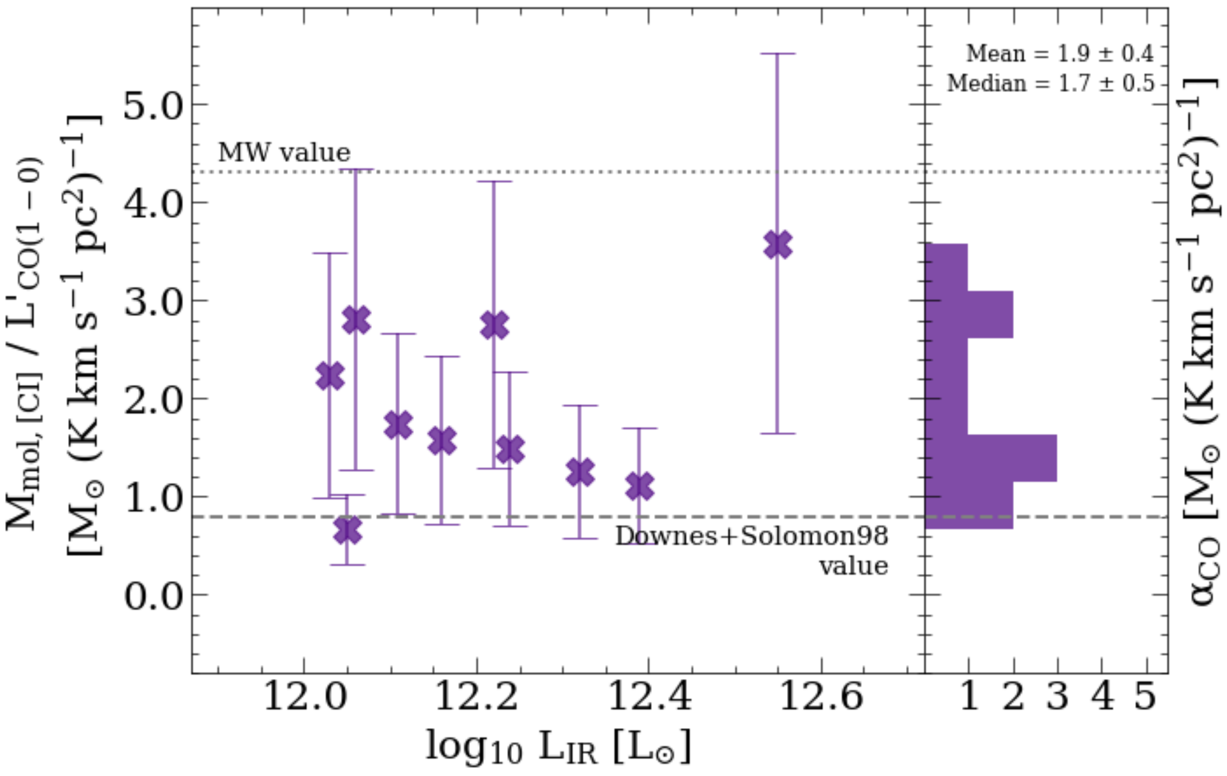

$$\langle\alpha_{CO}\rangle^{median} = 1.7 \pm 0.5 \quad M_{\odot}(\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$$

Consistent with dust-based estimate for GOALS LIRGs by Herrero-Illana+19

Global CO line ratios

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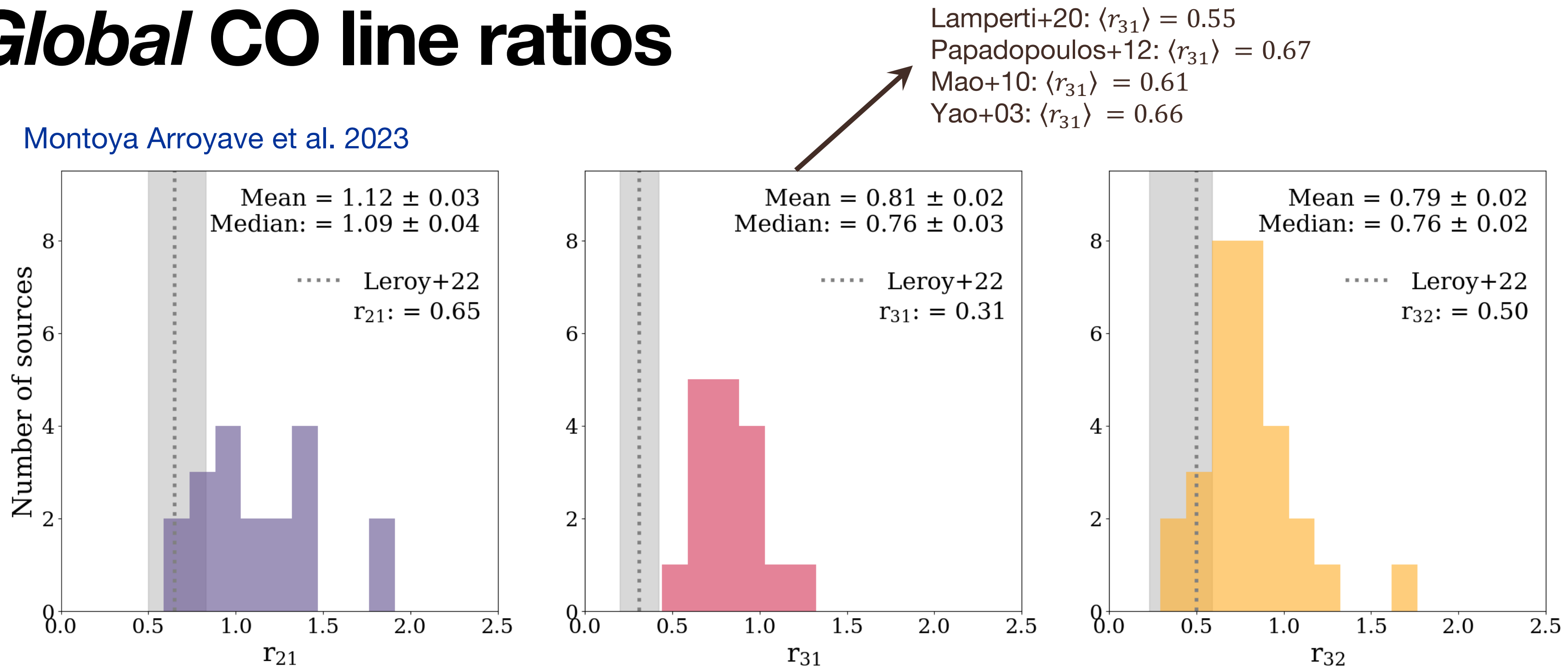


Extremely high galaxy-integrated CO line ratios, suggesting high excitation rates for (U)LIRGs. **Offset from global galaxy population** is even more extreme for higher-*J* lines.

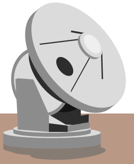
Global ratios > 1 values are extremely rare in local Universe, yet **r_{21} > 1 are predominant in our sample of ULIRGs** (*higher excitation + optical depth effects*)

Absence of significant correlations between global r_{21} and r_{32} line ratios and Galaxy properties.

Only r_{31} correlates with L_{IR} and SFR but not with L_{AGN}.

The whole **molecular ISM is extreme** in these sources.

Global low-*J* CO line ratios are generally **poor tracers of CO excitation** in (U)LIRGs.



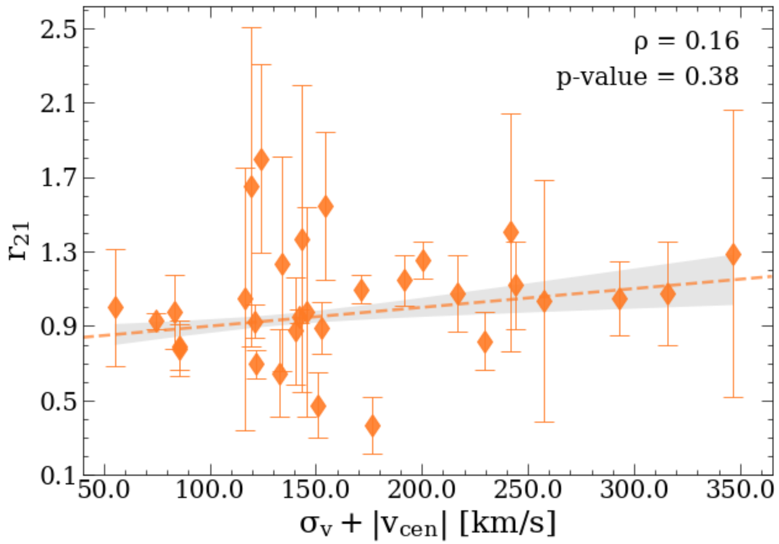
Effects of high-v/σ gas on CO line ratios

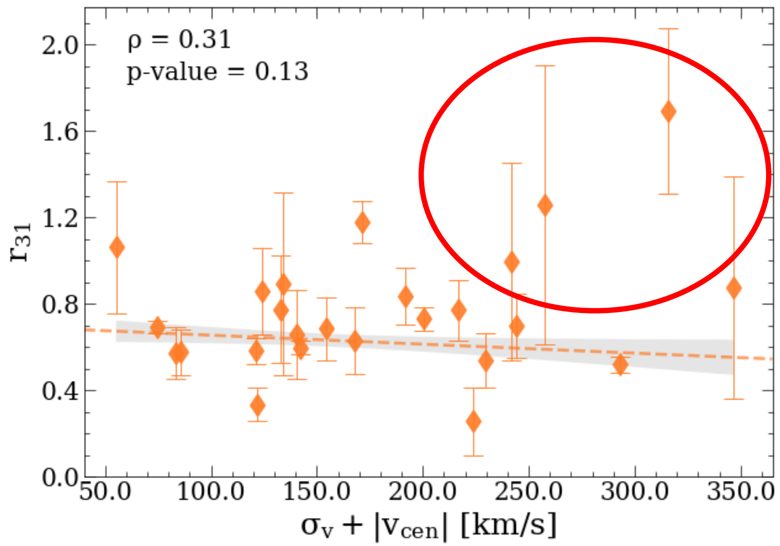
For some sources, higher excitation is already visible in these low-*J* CO lines.

The trend found for r_{21} is **most likely due to optical depth effects**, as no similar trend is found for higher ratios, which would be more sensitive to excitation effects.

Even though there are hints of higher excitation for components with higher σ_v and/or $|v_{cen}|$, **it may not be the rule of thumb for all (U)LIRGs**, and may be present only for very extreme cases, such as NGC6240.

Higher-*J* CO lines (with high sensitivity to large scale structures) are needed for a clearer view on the physical state of the gas.





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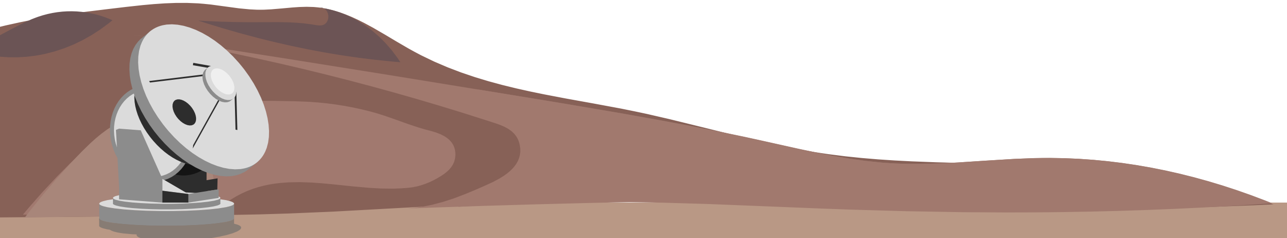

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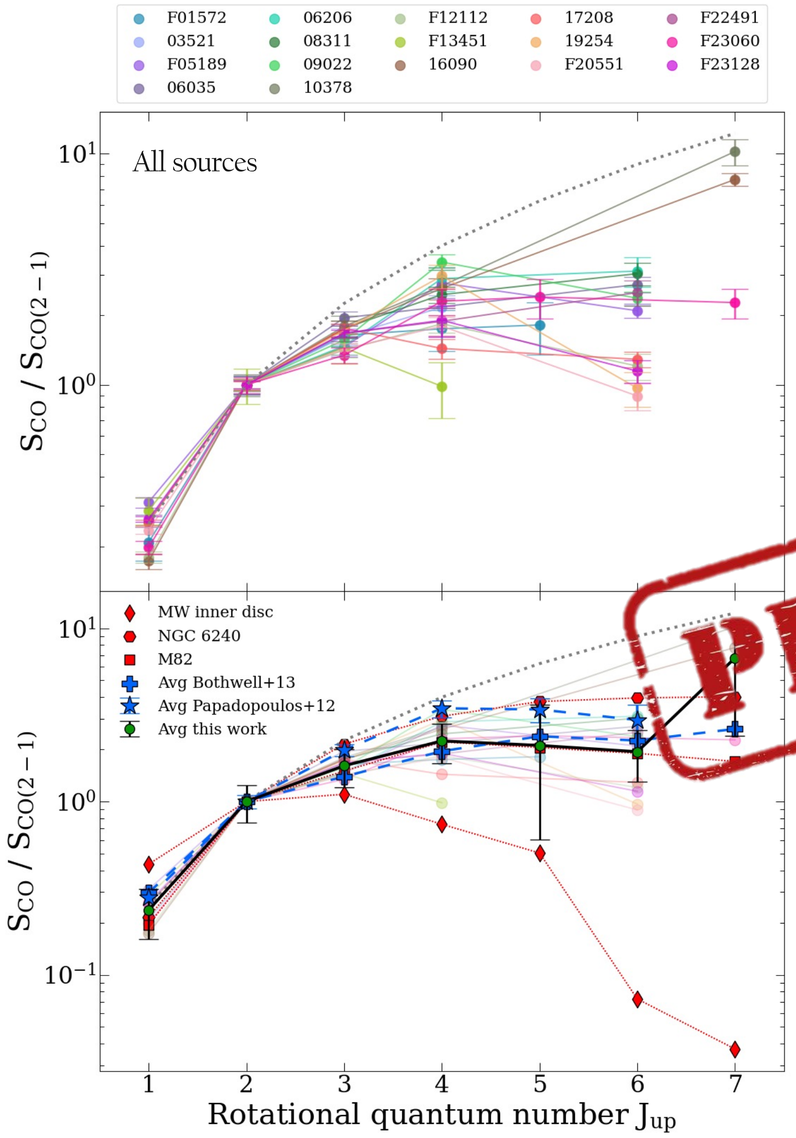

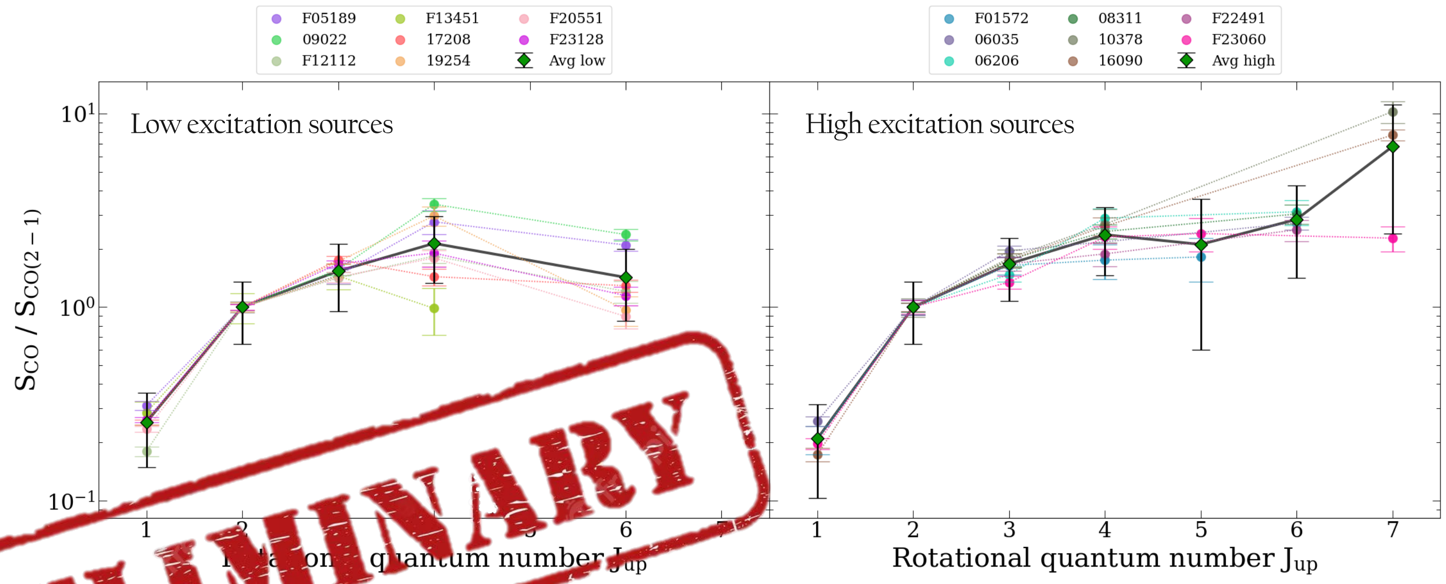

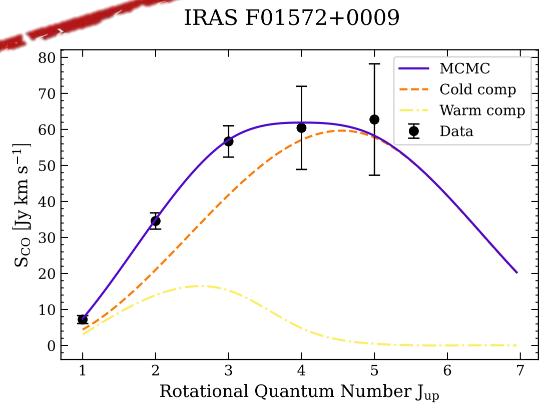

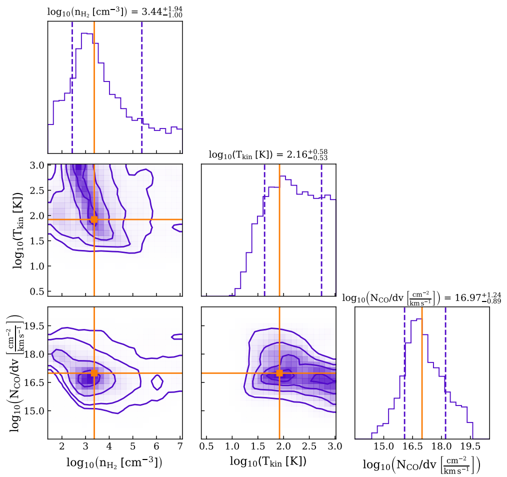

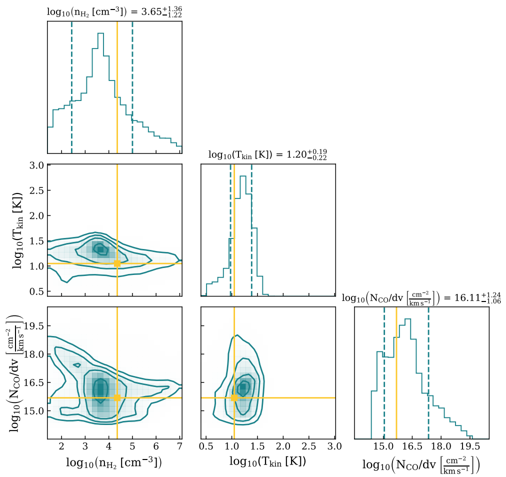

Global r_{CICO} line ratio

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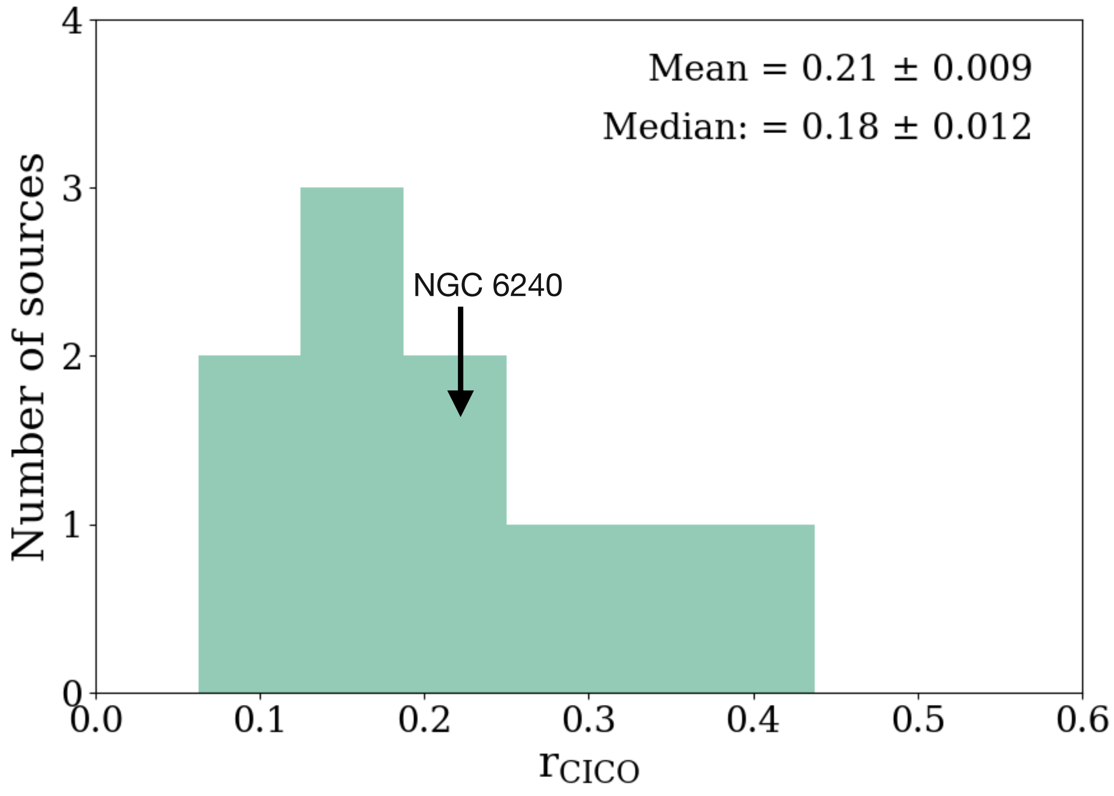


$L'_{[CI](1-0)}/L'_{CO(1-0)}$

We measure $\langle r_{CICO}\rangle^{\text{median}}$ = 0.18.
Higher than previous studies [CI](1-0)/CO(1-0) studies.

Jiao+19 (Herschel+Nobeyama, 15 nearby galaxies):

$$\langle r_{CICO}\rangle^{\text{median}} = 0.11$$

Michiyama+21 (25 local ULIRGs, [CI] from ACA and CO(1-0) from literature):

$$\langle r_{CICO}\rangle^{\text{median}} = 0.13 \pm 0.07$$

- Very few previous works with uniform [CI] *and* low-*J* CO coverage
- **We have 7 sources in common with Michiyama+21, but for 5 of them we used our own APEX PI [CI] data because of higher quality compared to their ACA [CI] data (30-40% [CI] flux loss in their ACA data)**

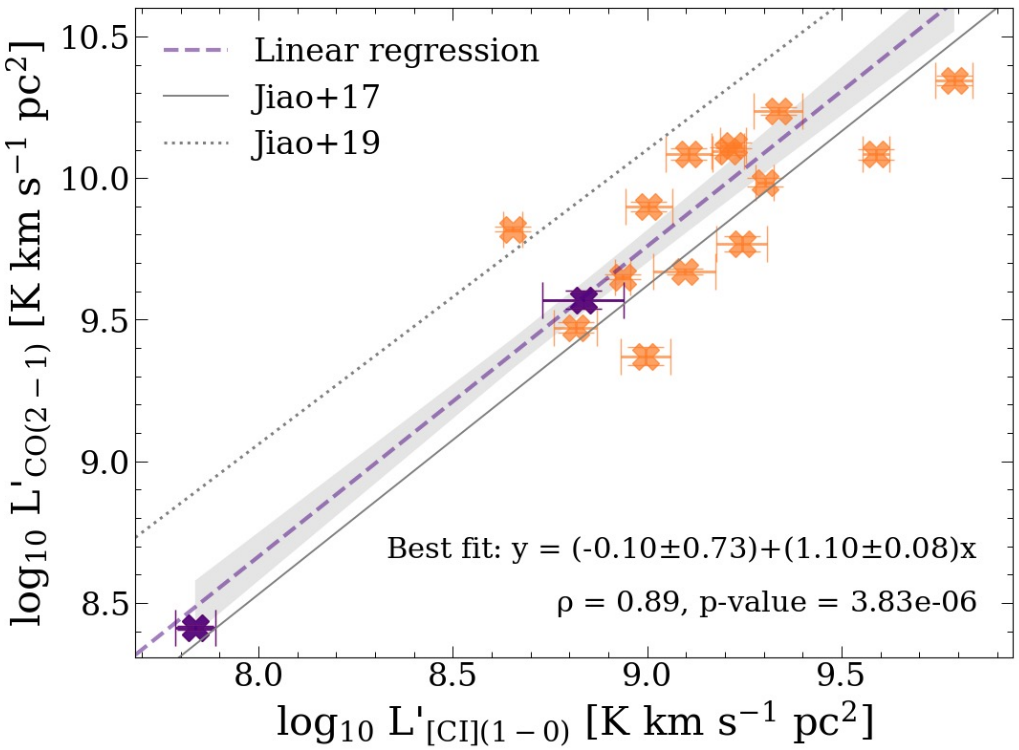
We measure **significantly higher [CI]/CO ratios in ULIRGs** and **our study highlights the limitations of previous works** that lack low-*J* CO coverage and miss significant [CI] flux.

CO and [CI] as independent tracers

How accurate is the assumption of CO and [CI] to be **concomitant** with H_2?

Tight -almost linear- correlation between both species luminosities for our sample of (U)LIRGs (similar to results by Jiao+17, Jiao+19).

Suggesting CO and [CI] arise from similar regions, at least when **averaged over galactic scales.**



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CO and [CI] as independent tracers

What about kinematics?

In <u>our sample</u>, [CI] lines are *on average* **narrower** than the CO lines, especially in **high-σ_v sources**.

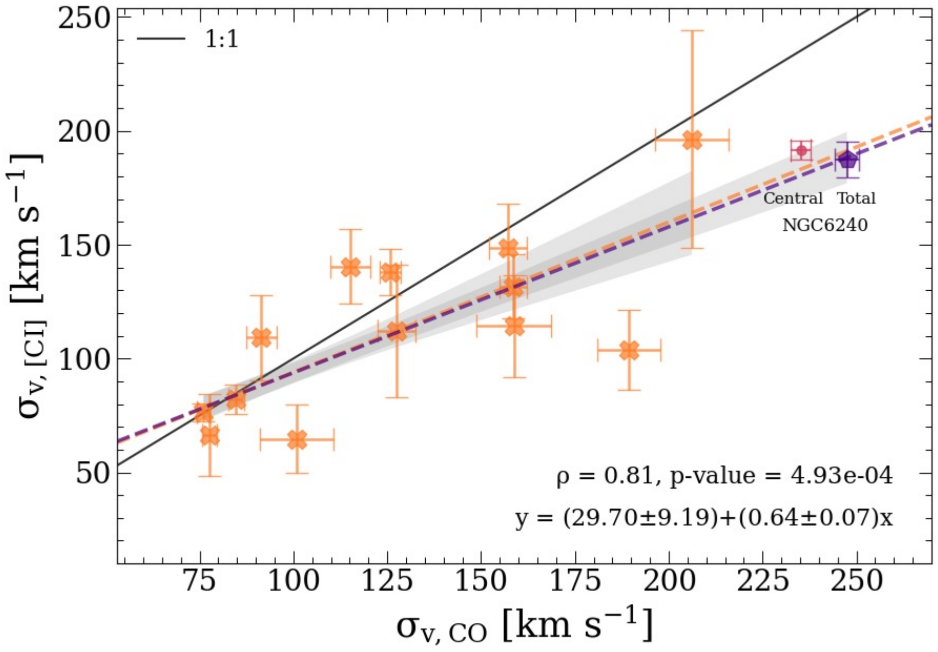
Still a <u>marginal result</u>, larger statistics needed.

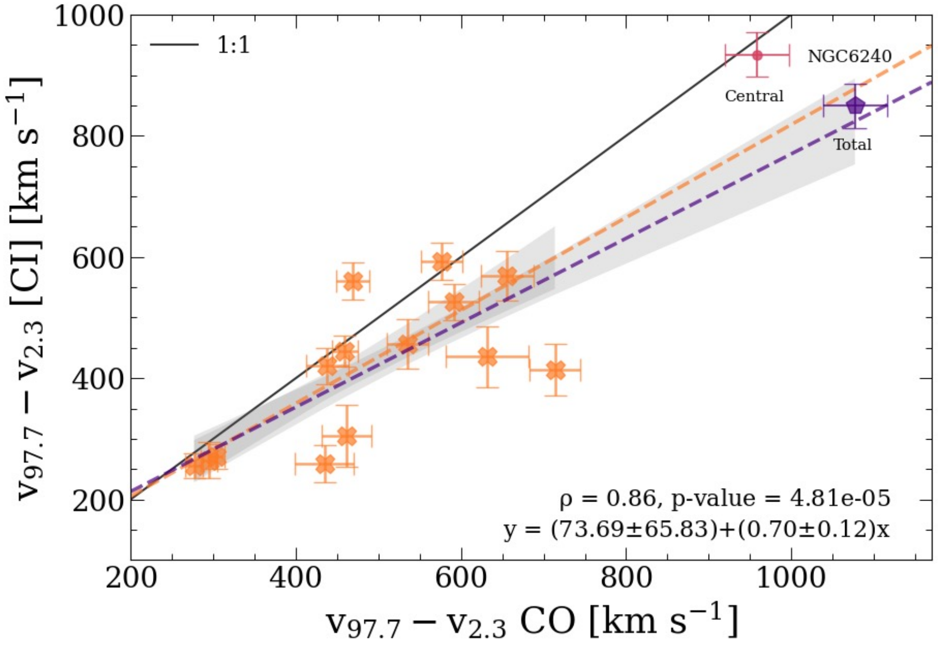
The [CI] vs CO line width best fit relation predicts very nicely the NGC6240 value (not included in the fit). On average: $\boldsymbol{\sigma_v^{[CI]}/\sigma_v^{CO} = 0.91 \pm 0.4}$

Discrepancy becomes larger if consider wings of the lines (probed by v97-v2.3 and v99-v01):

Possible causes:

- Depletion of Carbon in line wings (but would be at odds with theoretical predictions of CO-dark gas in outflows)?
- Optical depth effects (little mass in high-v components: optically thin [CI] is faint, while optically thick CO is bright)?





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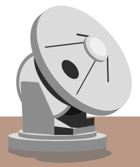
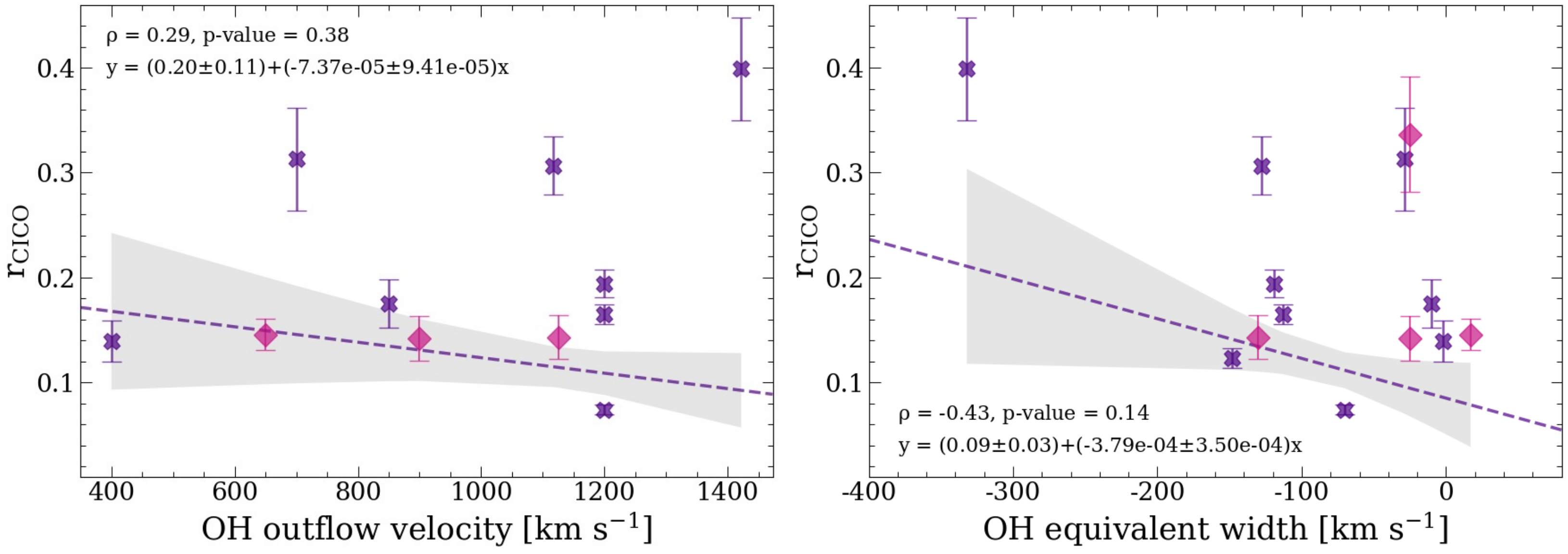
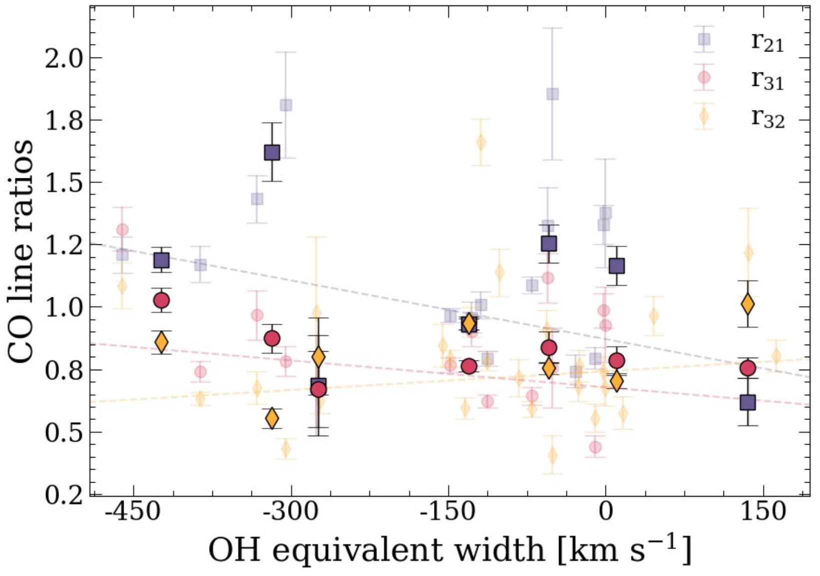


Impact of molecular outflows on *global* line ratios?

[CI](1-0)/CO(1-0) ratio vs OH outflow strengths



CO line ratios vs OH outflows



- **No statistically significant trends** observed between line ratios (r_{21}, r_{31}, or r_{CICO}) and OH outflow velocity or OH equivalent width
- **Possibly any effects are washed out on global scales**, see e.g. Arp220 where $r_{CICO} = 0.9 \pm 0.3$ in molecular outflow, while the galaxy-averaged value is $\langle r_{CICO} \rangle = 0.22 \pm 0.04$ (Ueda+22)
- **Lack of dynamic range in outflow and galaxy properties** also a potential issue -> but not so easy to solve, *getting [CI] and high-J CO for "normal" galaxies is challenging*

Conclusions

We use CO and [CI] as independent molecular gas tracers and derive an α_{CO} factor of $1.7 \pm 0.4 \quad M_{\odot}(\mathrm{K\ km\ s^{-1}\ pc^{2}})^{-1}$ for our sample of local (U)LIRGs.

Our sample probes very extreme and narrow regimes in galaxy properties, such as L_{IR}, SFR, L_{AGN}, and is difficult to retrieve scaling relations seen in MS galaxies.

Global CO line ratios are remarkably high when compared to normal disc galaxies; such high values suggest optical depth effects. Supported by kinematical analysis.

Only r_{31} shows correlation with SFR and L_{IR} . Low-J CO lines are inadequate tracers of heating or density effects and so of the H_2 gas excitation.

Different linewidths between CO and [CI]. Could they be tracing different kinematics and/or gas environments?

Some sources show higher CO line ratios and/or higher r_{CICO} values in outflow components, but such trends are not statistically significant in the sample (washed out)