Tracing star formation relations across the CO ladder and redshift space

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Abstract:

We present IR – CO luminosity relations (i.e., log L_{FIR} = α log L'_{CO} + β) across the CO rotational ladder (continuously from J = 1 − 0 to J = 13 − 12) for a sample of 87 (Ultra) Luminous Infra-red Galaxies observed either with Herschel SPIRE-FTS and/or with ground-based telescopes. To extent our analysis to high redshifts, we included 76 (sub)-milllimeter selected dusty star forming galaxies from the literature with robust CO observations and well-sampled far-IR/sub-millimetre spectral energy distributions (SEDs). The derived FIR – CO luminosity relations are linear (i.e., slopes, α, consistent with unity) for J=1-0 to J=5-4 (corresponding to gas densities of ~3×10^2 - 4×10^4 cm^{-3}), and become increasingly sub-linear (α < 1) for the higher transitions. The latter is attributed to the higher-J lines becoming sub-thermally excited, as seen in the turn-over at high-J in the CO SLEDs of our sources. We provide a simple theoretical framework with which to understand the observed trends.

Galaxy samples & Data:

Low-z samples:

▸ 70 local (U)LIRGs at *z*<0.1 selected from the IRAS BGS ($f_{60\mu m}$ > 5.24Jy). The IR/submm data for this sample were culled from a number of studies (see Papadopoulos et al. (2012) and references therein). The CO line data consisted of new ground-based, single-dish observations of CO *J*=1-0 to 4-3, and *J*=6-5 for subsets of the full sample, augmented by an exhaustive compilation of literature measurements.

▸ To extend our study to the highest CO transitions, we included data from the Herschel Comprehensive (U)LIRG Emission Survey (HerCULES; van der Werf et al. (2010)) – an open time key program on the ESA Herschel Space Observatory (Pilbratt et al. 2010) which measured CO *J*=4-3 to *J*=13−12 for 29 local (U)LIRGs using the Fourier-transform spectrograph (FTS) of the SPIRE instrument (Griffin et al. 2010).

High-z samples:

▸ Dusty star forming galaxies (DSFGs), selected at (sub)-millimetre wavelengths, are thought to harbour the same extreme ISM and star forming conditions as local (U)LIRGs, and were for that reason chosen as our high-*z* comparison sample. As for the local (U)LIRGs, we carefully sifted through the literature and NED and from that compiled an exhaustive data-base of *all* CO line measurements of DSFGs at *z* > 1, as well as of their optical/UV/near-IR and far-IR/(sub)mm/radio continuum data (see Greve, in prep. for details). A total of 76 DSFGs were found. However, only 49 DSFGs went in to our final analysis, as only these sources had sufficient far-IR/(sub)mm continuum measurements that reliable estimates of the IR luminosities could be made (see below). Of these 49 sources, 25 were strongly lensed DSFGs (e.g., The Eyelash; Swinbank et al. (2010). In total, our analysis is based on 117 CO detections towards 49 DSFGs.

SED fitting and L_{FIR} estimates

▸ The pan-chromatic (from far-UV/optical to radio) spectral energy distributions (SEDs) of our sample galaxies were modeled using CIGALE (Code Investigating GALaxy Emission – Burgarella et al. (2005); Noll et al. (2009)). CIGALE employs dust-attenuated stellar population models to fit the far-UV/optical SED, while at the same time ensuring that the dust-absorbed UV photons are re-emitted in the far-IR, thus ensuring energy-balance between the far-UV and far-IR. The far- IR/submm continuum is modeled using the templates by Dale & Helou (2002) and Chary & Elbaz (2001).

▸ Excellent fits were obtained for all of the local galaxies due to their well-sampled SEDs. For the high-*z* galaxies, only sources with data points longward and shortward of (or near) the expected dust peak were included in the final analysis (49 sources). All SED fits used in this paper can be found at http://demogas.astro.noa.gr. From the SED fits we derived the far-IR (L_{FIR} , from 50 to 300 μm) luminosity. The accuracy of our IR/far-IR luminosity estimates were estimated as the 1-σ dispersion of the distributions obtained through bootstrapping of the photometry errors 1000 times.

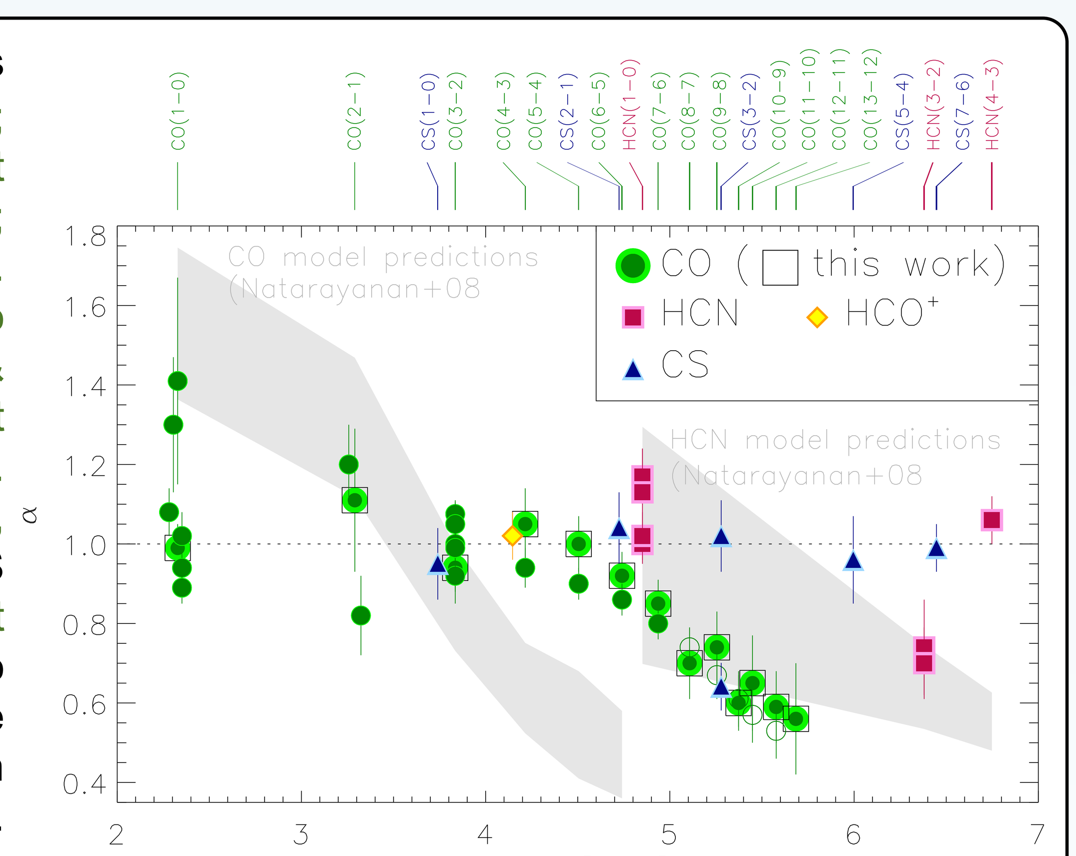

Fig.2: Slope (α) determinations for CO (Yao et al. 2003; Narayanan et al. 2005; Baan et al. 2008; Juneau et al. 2009; Iono et al. 2009; Bayet et al. 2009; Genzel et al. 2010; Mao et al. 2010), HCN (Gao & Solomon 2004b; Bussmann et al. 2008; Gracia-Carpio et al. 2008b; Juneau et al. 2009, Zhang et al., in prep.), and CS (Wu et al. 2005, 2010, Zhang et al., in prep.). For the first two CO transitions, α-estimates are slightly offset horizontally in order to ease the comparison. The grey-shaded regions show the CO and HCN slopes (and the 1-σ scatter) predicted by galaxy radiative transfer models by Narayanan et al. (2008).

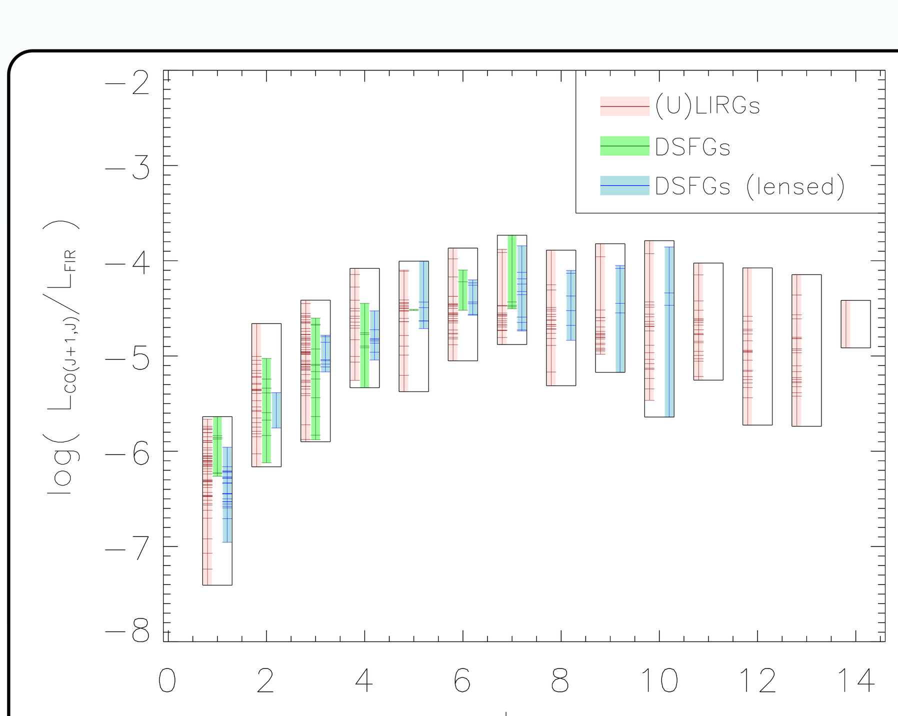

Fig.3: The CO spectral energy distributions – here given as the CO line luminosities in $L_\odot$ units, normalised by the FIR luminosity – for the local (U)LIRG+HerCULES sample (red), the unlensed (green) and strongly lensed (blue) high-z DSFGs. The filled bars indicate the full range of $L_{CO(J+1,J)}$ /L_{FIR} - values, while the tickmarks indicate the values of the individual sources

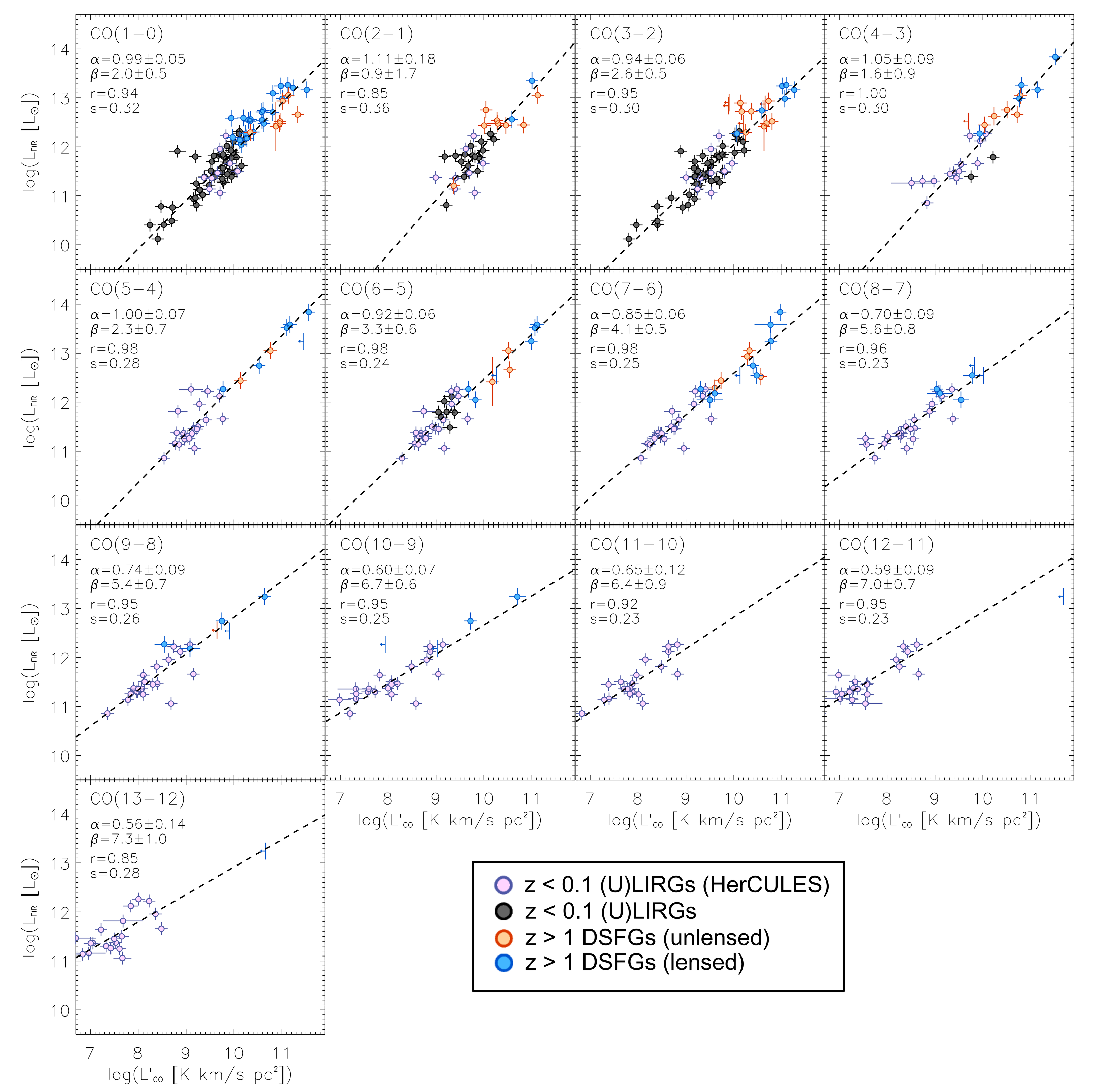

Fig.1: log L_{FIR} vs. log L'_{CO} across the CO rotational ladder (from *J*=1-0 to J=13−12). The low-z (z < 0.1) data include the (U)LIRG sample from Papadopoulos et al. (2012) (dark-grey symbols) with CO observations from *J*=1−0 to *J*=6−5, and (U)LIRGs from HerCULES (van der Werf et al. (2010) (pink symbols). The high-z (z > 1) sources are unlensed, or weakly lensed, DSFGs (yellow symbols) and strongly lensed DSFG (blue symbols) uncovered from various (sub)millimetre surveys. The dashed lines show the best fits of the functional log L_{FIR} = α log L'_{CO} + β to the data, with the optimum parameter (α, β) values and their errors indicated in each panel. The scatter (s) of the data around the best fits along with the correlation coefficient (r) are given in each panel.

Analysis & Discussion

▸ The FIR-CO relations derived here are shown in Fig. 1. This is the first time that FIR-CO relations have been directly inferred from observations up to such high *J*-transitions. Statistically significant correlations are seen across the board and functionals of the form L_{FIR} = α L'_{CO} + β were fitted to the data (dashed lines in Fig.1)

▸For the low- to mid-*J* CO transitions (up to *J*=5-4) we find FIR-CO slopes of unity. This is in agreement with some previous studies, although super-linear slopes have also been found and are in fact predicted by models (Krumholz & Thompson 2007; Narayanan et al. 2008). See Fig. 2. A slope of 1.5 is expected for CO transitions that trace the bulk of the star forming ISM in galaxies, provided that a fixed fraction of the gas mass (M_{gas} ~ ρ) is turned into stars every free-fall time (t_{ff} ~ $\rho^{-0.5}$).

▸ For CO transitions *J*=6-5 and beyond we find statistically significant sub-linear FIR-CO slopes, with the slopes becoming shallower with increasing *J* (Fig. 2). The sub-linear slopes are explained by the fact that the high-*J* CO lines not only require high densities but also high kinetic temperatures to be excited. In fact, from Fig. 3 we see that the lines become significantly sub-thermal, meaning that the lines no longer trace the star forming gas. Although, the models qualitatively agree with these findings, the predicted sub-linearity sets in at much lower transitions (*J*=3-2) than what is observed.

▸ Finally, we note that for the true high density gas tracers like HCN and CS, the observations strongly favour linear slopes (cf. Bussmann et al. 2008; Juneau et al. 2009).

▸ All of the above findings can be explained by a simple theoretical argument, inspired by that of Wong & Blitz (2002). Consider that for a given CO transition, α = dlog(L_{FIR})/ dlog(L'_{CO}) can be expressed as:

$$\alpha = \frac{d\log L_{\rm FIR}}{d\log L'_{\rm HCN}} \times \frac{d\log L'_{\rm HCN}}{d\log L'_{\rm CO}} = \alpha_{\rm dense}\left(1+\frac{d\log f_{\rm dense}}{d\log L'_{\rm CO}}\right)$$

where α_{dense} is the slope of the FIR-HCN(1-0) relation which has been shown to be unity (α_{dense} = 1.00 +/- 0.05; Gao & Solomon 2004). f_{dense} is a measure of the cold, dense gas fraction, i.e. the gas phase that is actively forming stars. There are two cases to consider:

Low- to mid-J CO lines: will trace the bulk of the star forming gas, and we therefore expect f_{dense} to increase or as a minimum stay constant with increasing L'_{CO}, thus rendering α ≥ 1. Since we are considering similar galaxy populations (ULIRGs and DSFGs), with not too dissimilar f_{dense}, the second term in the parenthesis vanishes, and we would thus expect α-values of roughly unity, as observed.

High-J lines: the CO lines no longer trace the star forming gas, but rather hot gas. As L'_{CO} increases we may therefore no longer expect f_{dense} to increase; rather we expect the opposite, i.e. implying a negative log(f_{dense}) - log(L'_{CO}) gradient, and thus α < 1.

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