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Molecular Gas Studies of *Planck-Herschel* Selected Extremely Luminous IR Galaxies at z ~ 1.3-3.3

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Abstract:

Multi-J CO line studies are essential for quantifying the physical properties of the star-forming ISM, yet it is observationally expensive to detect those faint CO emission lines at high redshift. Our eight *Planck-Herschel* selected galaxies, with apparent $L_{IR} > 10^{13-14}\ L_\odot$, serve as the best laboratories to conduct such a CO spectral line energy distribution analysis at high-z. Using our *GBT* and *LMT* (J_{up} = 1-3) measurements, we trace the bulk molecular gas mass, finding relatively large star formation efficiencies (as traced by the L_{IR}-to-$L'_{CO(1-0)}$ ratio) consistent with a starburst mode of activity. With our mid-J (J_{up} = 4-8) CO line measurements, obtained with the IRAM 30m telescope, we find gas excitation conditions ranging from sub-thermal SMGs to highly excited local starbursts out to J_{up} = 5-8.

1. Sample Selection

We cross-matched, within a 150" search radius, the all-sky public Planck Catalog of Compact Sources (350 μm) with archival *Herschel* SPIRE data from the DDT 'Must-Do', HerMES, & Stripe-82 surveys (250, 350, and 500 μm.)

Eight *Planck-Herschel* matches with S_{350} > 100 mJy and no known QSO / low-z counterpart were subsequently followed up (LMT/GBT/IRAM 30m).

L_{IR} vs. z: Our *Planck-Herschel* selected galaxies are amongst the most IR luminous sources in the sky. Ongoing HST Cyc 24 WFC3 observations reveal strong lensing in all cases thus far.

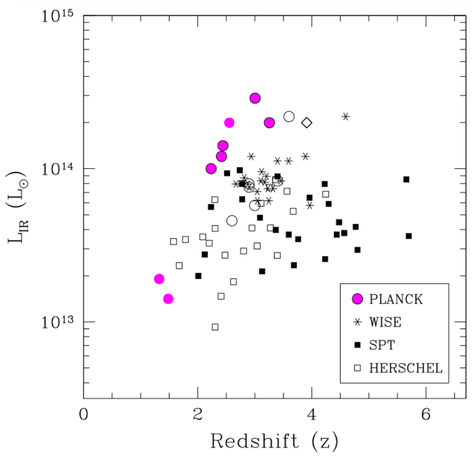
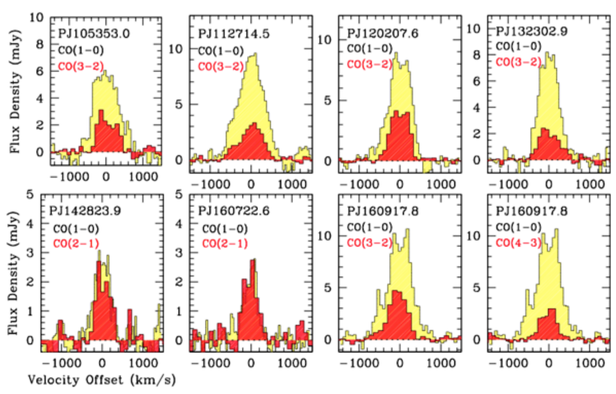


Fig. 1: *Herschel* + AzTEC 1.1mm derived IR luminosity (not corrected for potential lens magnification) vs. z for our *Planck-Herschel* selected galaxies (filled circles) compared with QSOs (diamond- Irwin et al. 1998; stars-Tsai et al 2015); strongly lensed SPT dusty star-forming galaxies (Vieira et al. 2013; Weiß et al. 2013) and *Herschel* selected lensed SMGs (squares - Bussmann et al. 2013; Wardlow et al. 2013).

2. Observations of 8 *Planck-Herschel* Galaxies



With an average of 4 CO lines per galaxy, including CO(1-0), we can systematically and accurately assess their gas excitation conditions.

- CO(1-0) line detection with GBT's VEGAS (Harrington + in prep-A)
- Low-J CO detection with the LMT's RSR (Harrington +16)
- Multiple mid-J CO lines detected with IRAM 30m's EMIR

Fig 2: An example showing the low-J CO spectra from the LMT scaled down by J^2 (red histogram) and overlaid onto GBT CO (1-0) spectra (yellow histogram). The similar line profiles indicate that they are tracing the same volumes of gas, arguing against differential lensing effects.

3. Spectroscopic Results

- z_{CO} = 1.33 – 3.26
- μM_{ISM} = 0.7 - 11 x $10^{12}\ M_\odot$
- L_{IR} / $L'_{CO(1-0)}$ = 60 - 170 $L_\odot$ (K km s^{-1} $pc^2)^{-1}$
- μM_{H2} = 0.09 - 27.4 x 10^{12} (α_{CO}/0.8) $M_\odot$
- FWHM = 300 — 820 km s^{-1}
- $\tau_{depletion}$ = M_{H2} / SFR = 40-130 Myr

L_{IR}-to-$L'_{CO(1-0)}$: This ratio serves as a proxy for star formation efficiency (SFE). The high SFE of our galaxies compared to that of normal SF galaxies suggests a starburst mode of activity.

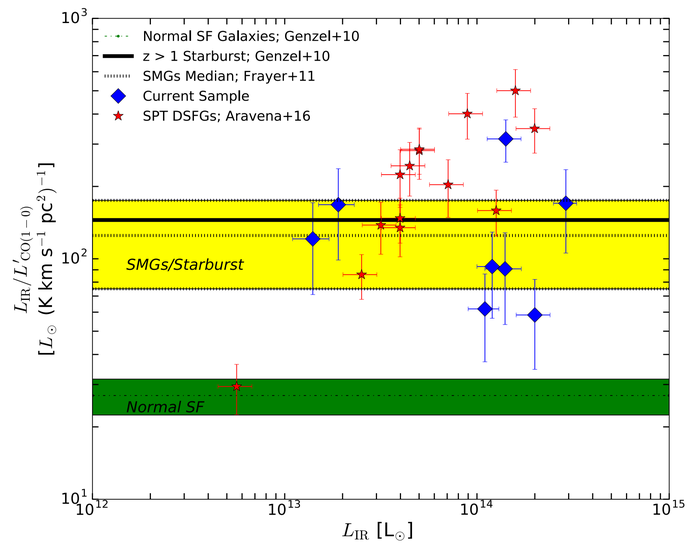


Fig. 3: We compare our sample with known, lensed SPT dusty star-forming galaxies (red stars - Aravena et al. 2016), and the median for SMGs (125 ± 50 L⊙ / K kms^{-1} pc^{-2}), (Frayer et al. 2011 - shaded yellow), and normal SF galaxies (Genzel et al. 2010- green shaded).

$L'_{CO(1-0)}$-to-$L_{850\ \mu m}$: This ratio serves as a proxy for the gas to dust mass ratio. Our galaxies show consistent gas to dust ratios as local solar-metallicity SF galaxies, though with a somewhat higher dispersion.

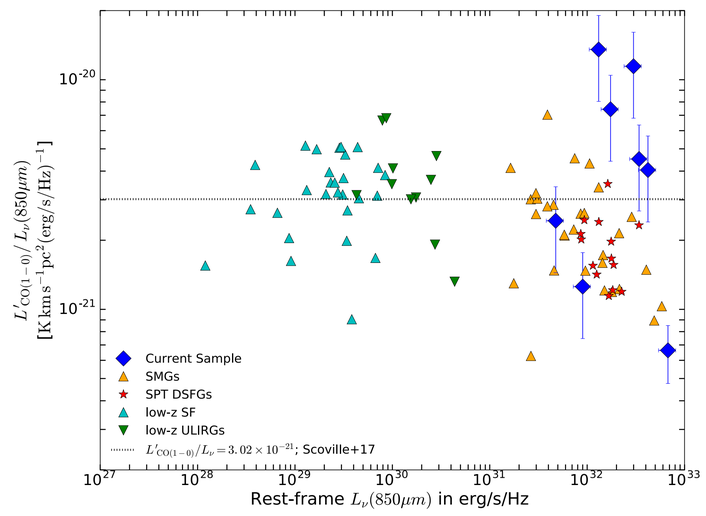


Fig. 4: We compare our sample to low-z SF galaxies, low-z ULIRGs, SMGs (Scoville et al. 2017) and lensed SPT galaxies (Aravena et al. 2016) with comparable photometry as our sample.

CO SLEDs: The CO spectral line energy distributions of 6 out of 8 *Planck-Herschel* selected galaxies show similar excitation to SMGs, while two harbor highly excited gas as seen in QSOs or local ULIRGs .

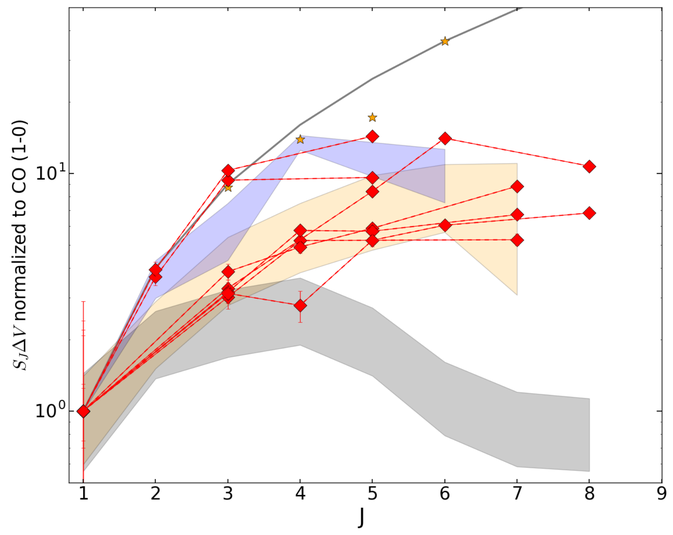


Fig. 5: We normalized the SLEDs of our *Planck-Herschel* selected galaxies to compare to that observed in SMGs (Bothwell et al. 2013 - shaded yellow), average QSOs (Carilli & Walter+13 - stars), average ULIRG population (Papadopoulos +12 -shaded blue), and the sub thermal ISM of our Milky Way (Fixsen+99 - shaded gray).

4. Conclusions

A total of 31 CO lines have now been observed in our 8 *Planck-Herschel* selected SMGs, revealing massive (~ $10^{12}\ M_\odot$) molecular gas reservoirs and short gas depletion times of < 100 Myr. Their excitation conditions and large SFEs indicate that we are witness to a short-lived starburst episode. Ongoing non-LTE radiative transfer modeling will enable us to investigate the range of ISM properties in more detail, such as number densities, thermal dust and kinetic gas temperatures, etc.

References: Aravena M., et al., 2016, MNRAS, 457, 4406, Bothwell M. S., et al., 2013, MNRAS, 429, 3047, Carilli C. L., Walter F., 2013, ARA&A, 51, 105 Efstathiou A. et. al 2000, MNRAS, 313, 734 , Fixsen D. J. et al. 1999, ApJ, 526, 207, Frayer D. T., et al., 2011, ApJ, 726, L22, Genzel R., et al., 2010, MNRAS, 407, 2091 , Papadopoulos et al., 2012, MNRAS, 426, 2601, Planck Collaboration XXVIII 2014, A&A, 571, A28, Scoville N., et al., 2017, ApJ, 837, 150, Vieira J. D., et al., 2013, Nature, 495, 344, Wardlow J. L., et al., 2013, ApJ, 762, 59, Weiß A., et al., 2013, ApJ, 767, 88