Exploiting the synergy of Herschel and ALMA for nearby galaxies

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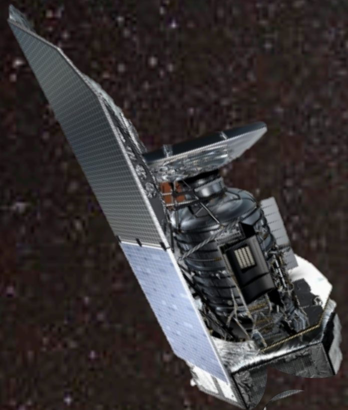
Herschel and ALMA, a ‘lethal’ synergy

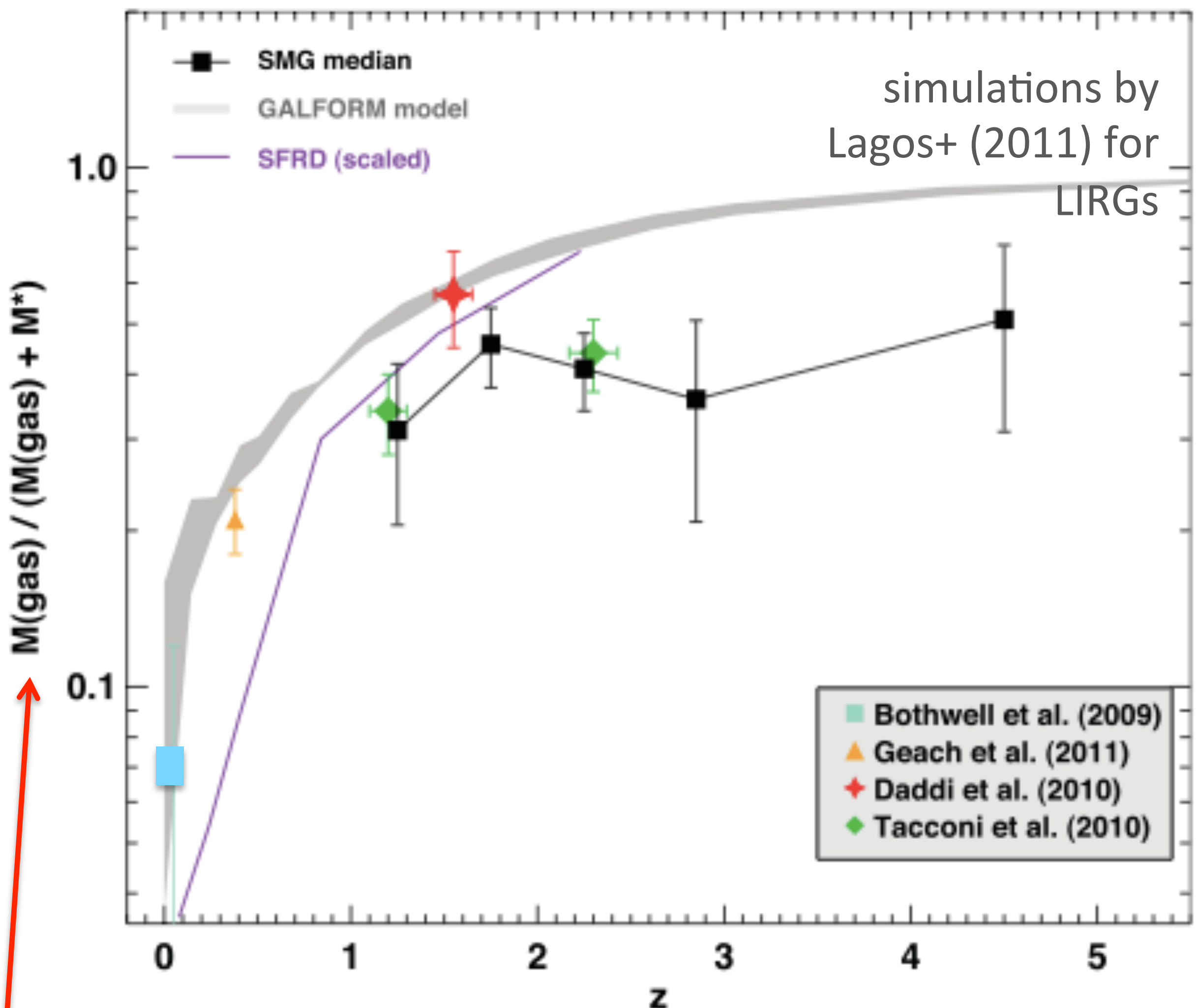


The combination of *Herschel* data with ALMA observations is a powerful tool for characterizing the physical conditions of the interstellar medium (ISM) in galaxies. Since a large part of galaxy evolution is driven by the evolution of the ISM and identifying mechanisms for getting dust and gas into and out of galaxies (i.e., infall/accretion and feedback), this combination is potentially very fruitful.

Science cases:

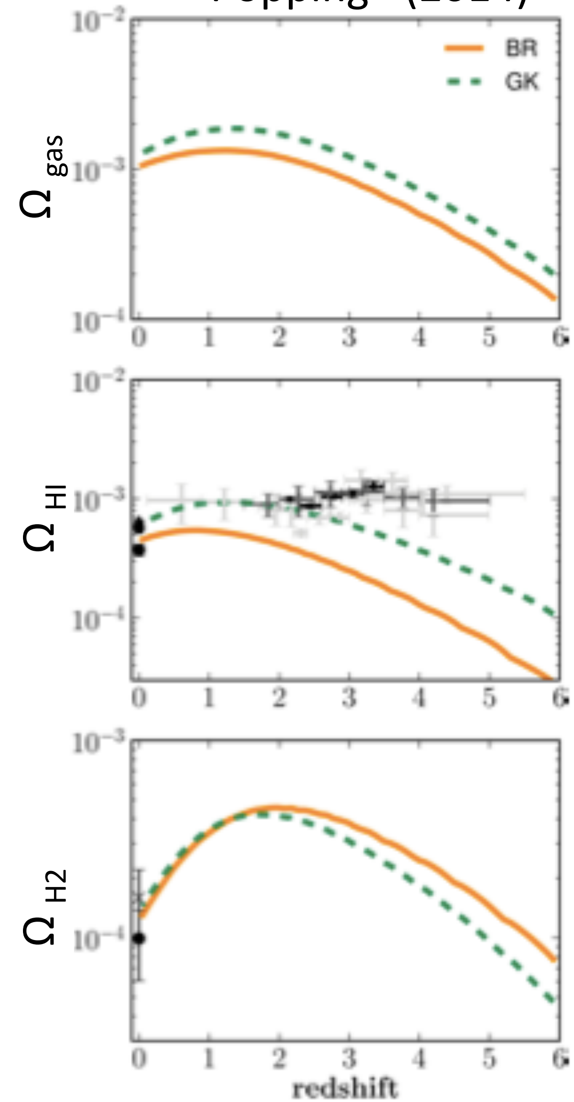
- ✓ galaxy dust content and properties
- ✓ excitation conditions of molecular gas
- ✓ feedback as traced by FIR molecular transitions
- ✓ how studies of nearby galaxies serve as benchmarks for interpreting observations at high redshift.

gas mass fractions increase with redshift



Bothwell+ (2013) H_2 only

simulations by Popping+ (2014)



gas mass fractions increase with redshift

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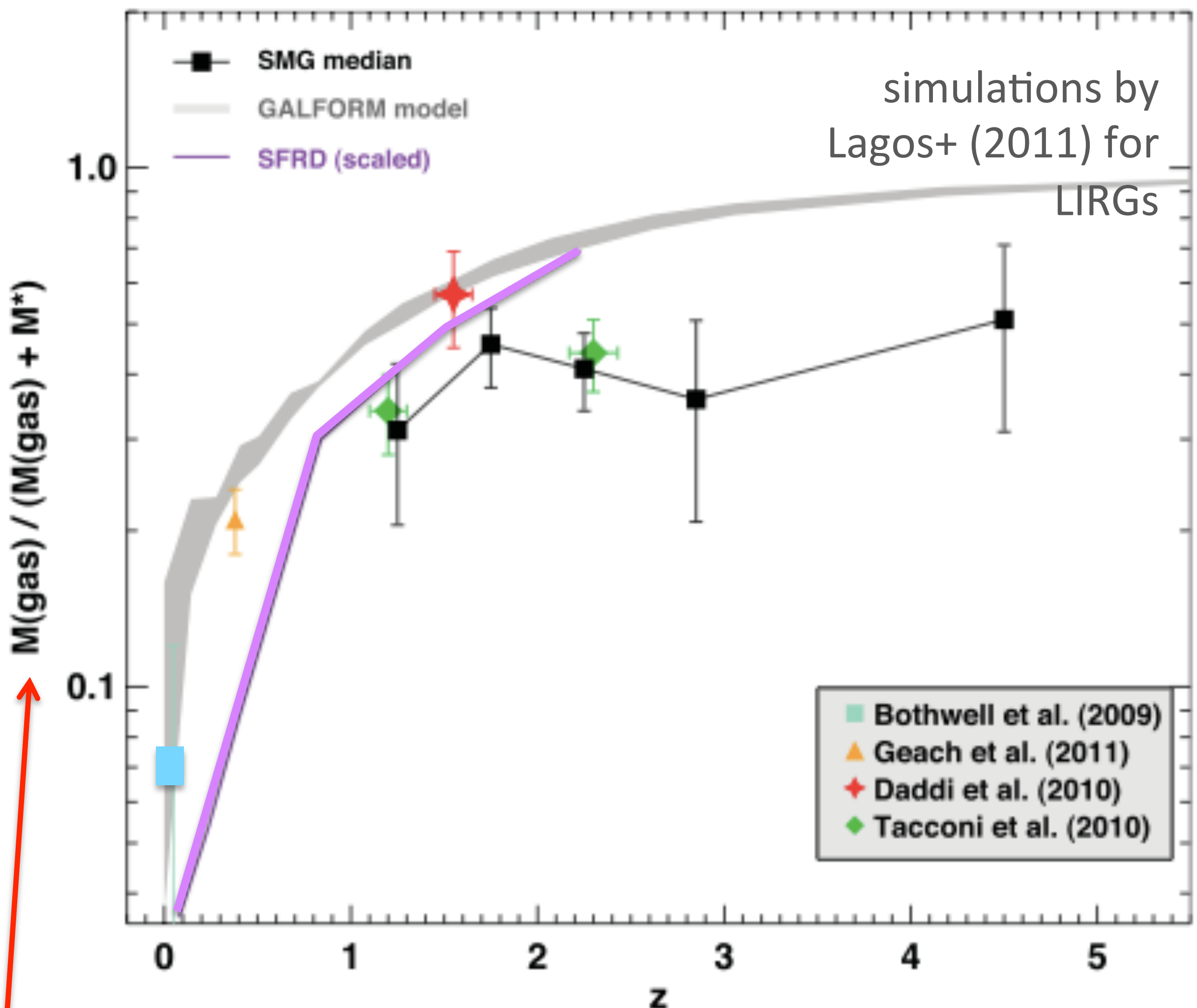
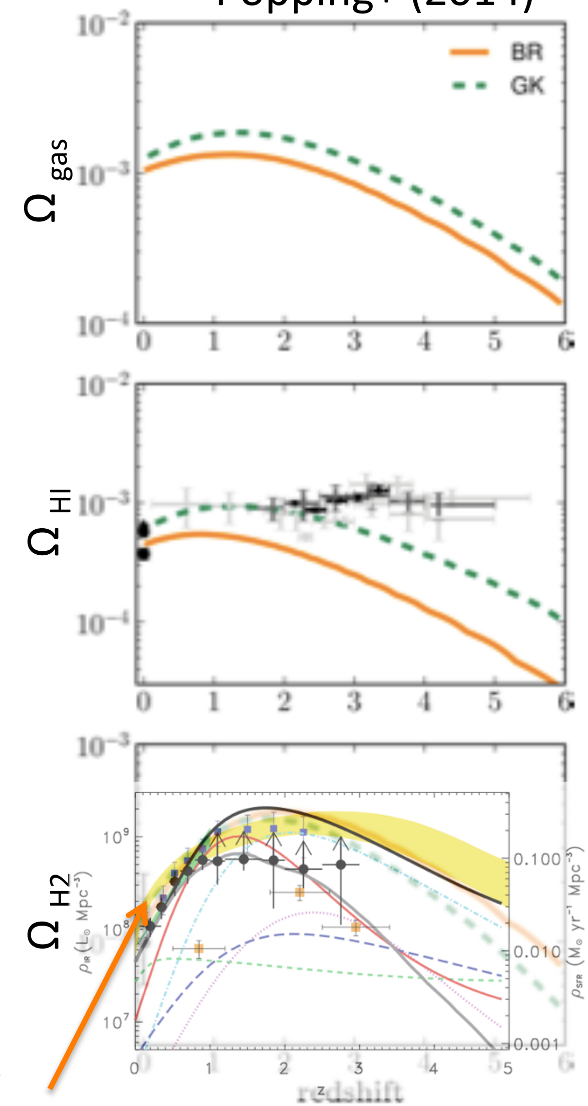




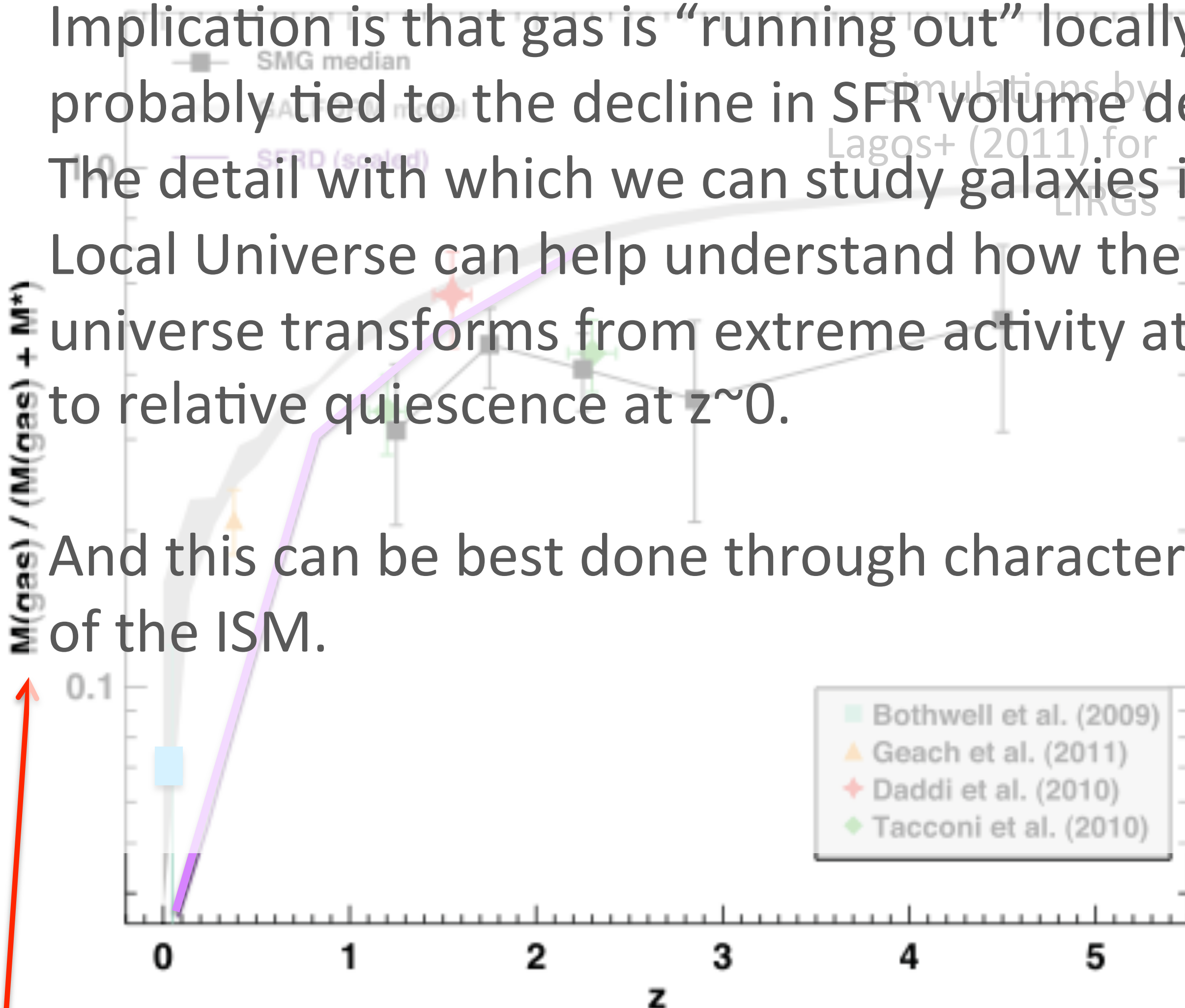
Bothwell+ (2013) H_2 only

H_2 evolution resembles SFR volume
density evolution (e.g. Gruppioni+ 2010)

gas mass fractions increase with redshift

Implication is that gas is "running out" locally and probably tied to the decline in SFR volume density. The detail with which we can study galaxies in the Local Universe can help understand how the universe transforms from extreme activity at z~2-3 to relative quiescence at z~0.

And this can be best done through characterization of the ISM.



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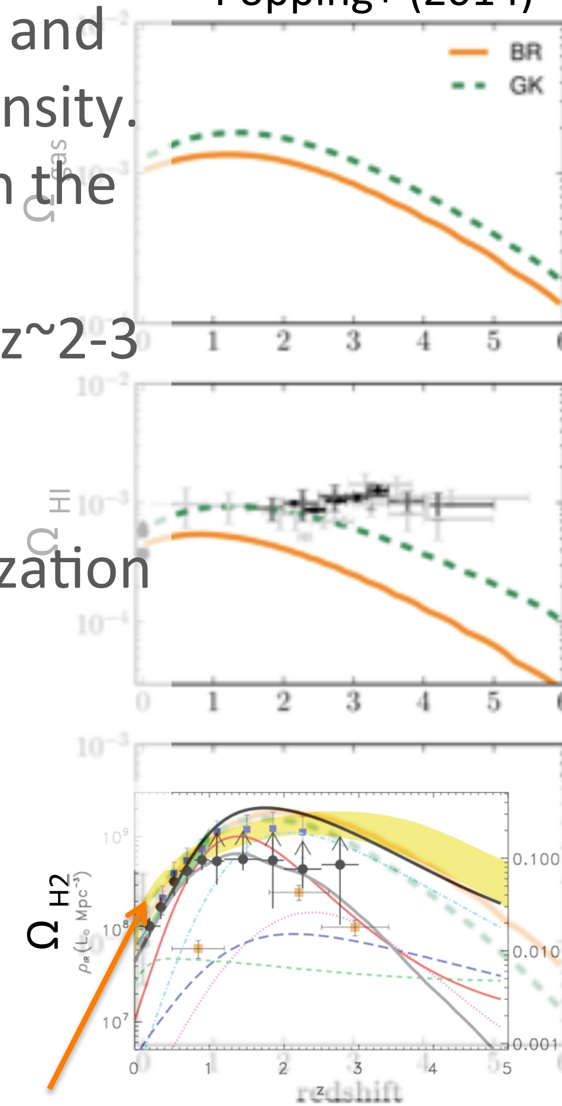
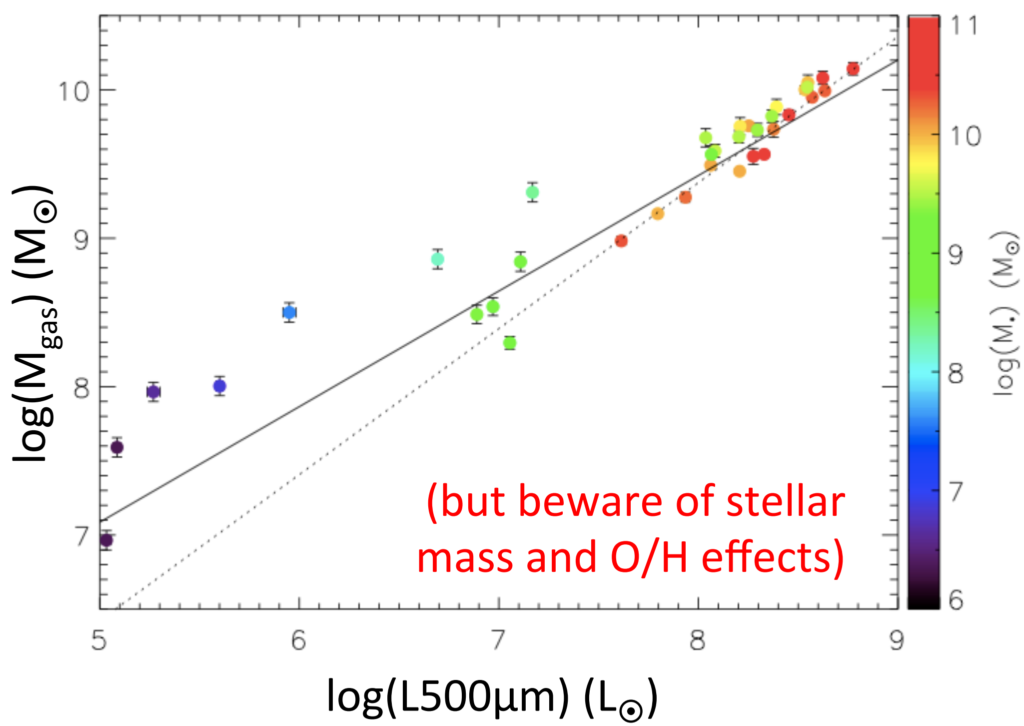


H_2 evolution resembles SFR volume density evolution (e.g. Gruppioni+ 2010)

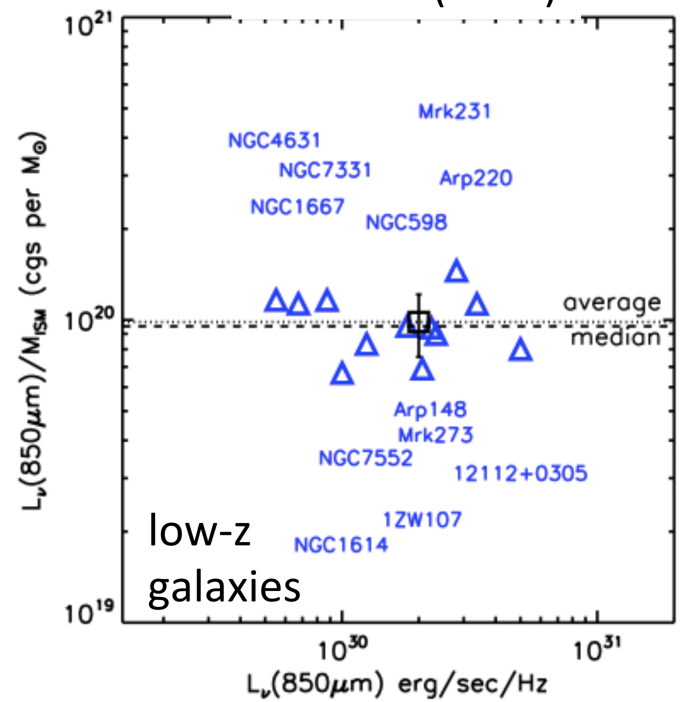
dust continuum

long-wavelength dust emission as a proxy for ISM mass

Groves+ (2015) KINGFISH galaxies



Scoville+ (2014)

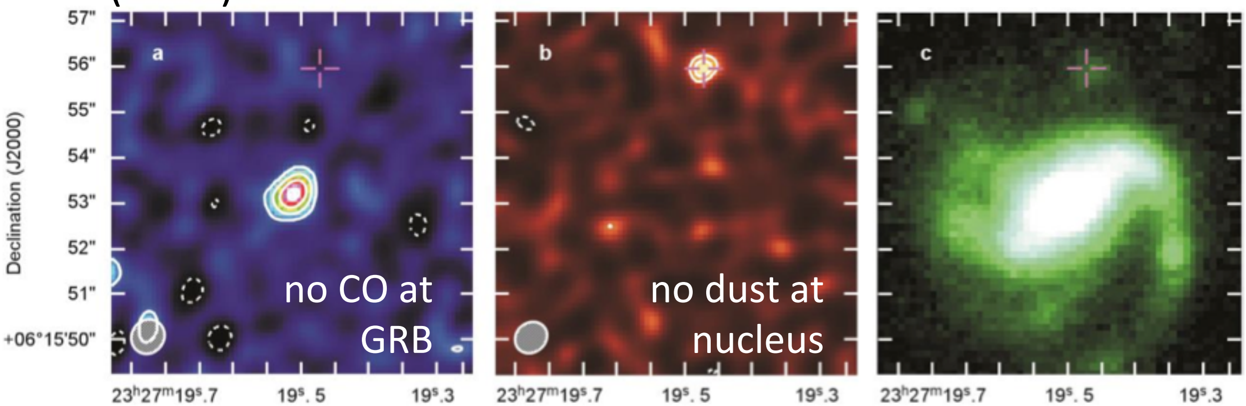


Herschel has shown that as long the emission is sampling the Rayleigh-Jeans portion of the dust spectral energy distribution (SED), then dust monochromatic luminosity (assumed to be optically thin) is a good proxy for total ISM mass (gas+dust). This means that ALMA Band 7 surveys (or Bands 8-10 for high redshift galaxies) are efficient (~10 times faster than CO) tools for measuring ISM mass and its evolution with redshift (Scoville+ 2014).

better dust-mass estimates for GRB host galaxies

ALMA Hatsukade+ (2014)

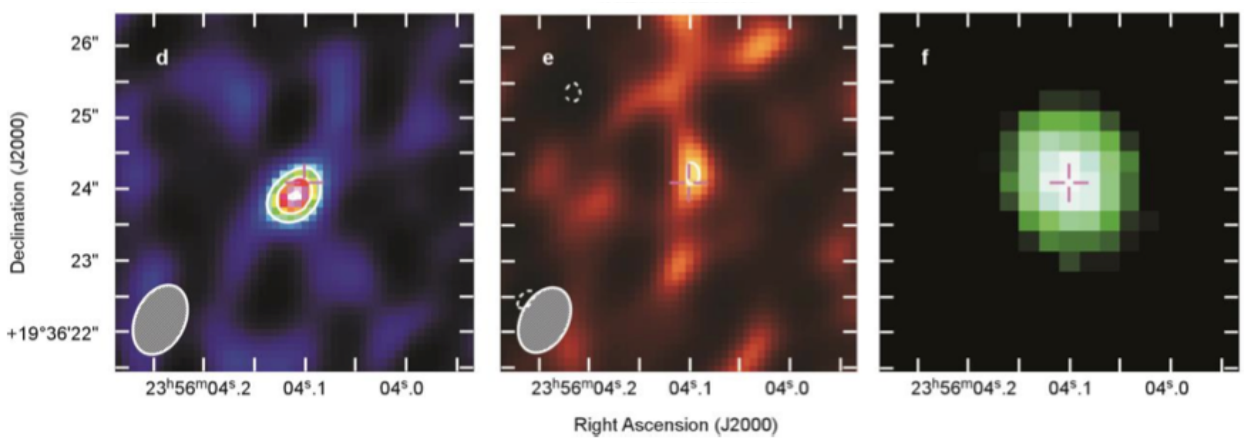
dark GRB host 020819B, z=0.41



CO(3-2) velocity-CO(4-3) integrated

dust continuum

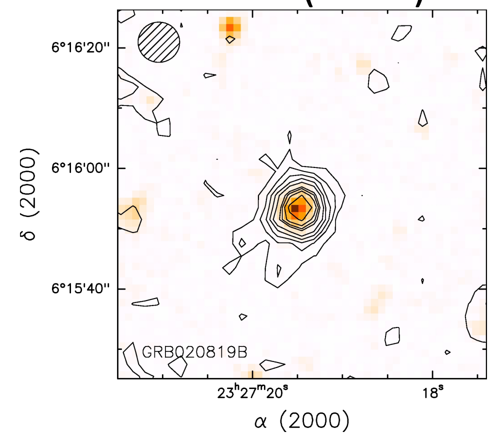
optical



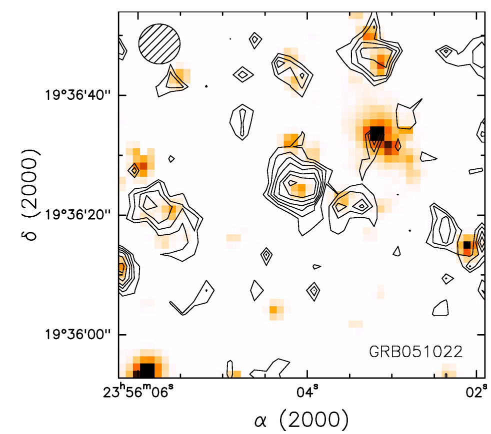
dark GRB host 051022, z=0.81

Herschel PACS

Hunt+ (2014)



PACS 100μm overlaid on 3.6μm



better dust-mass estimates for GRB host galaxies

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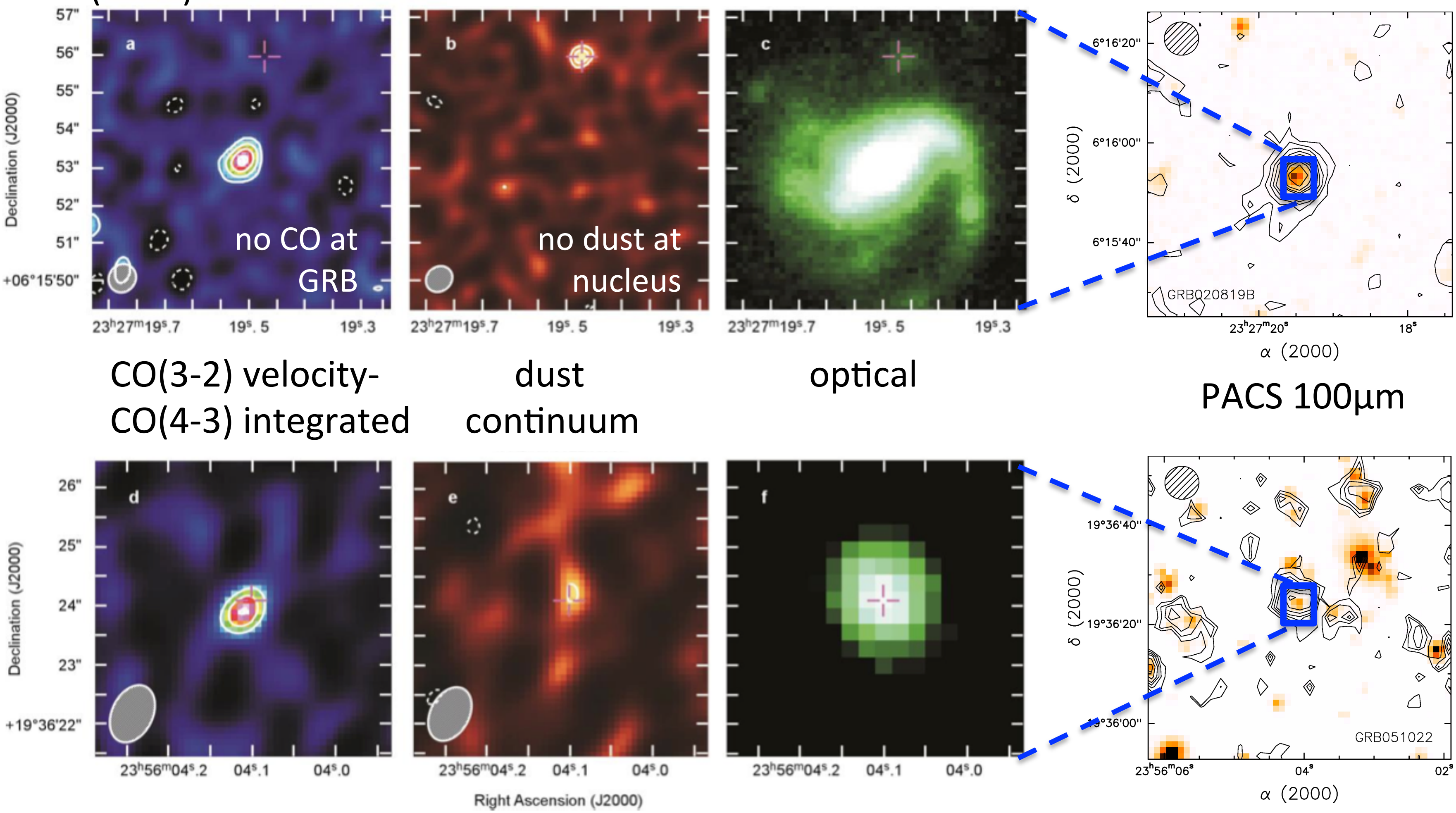
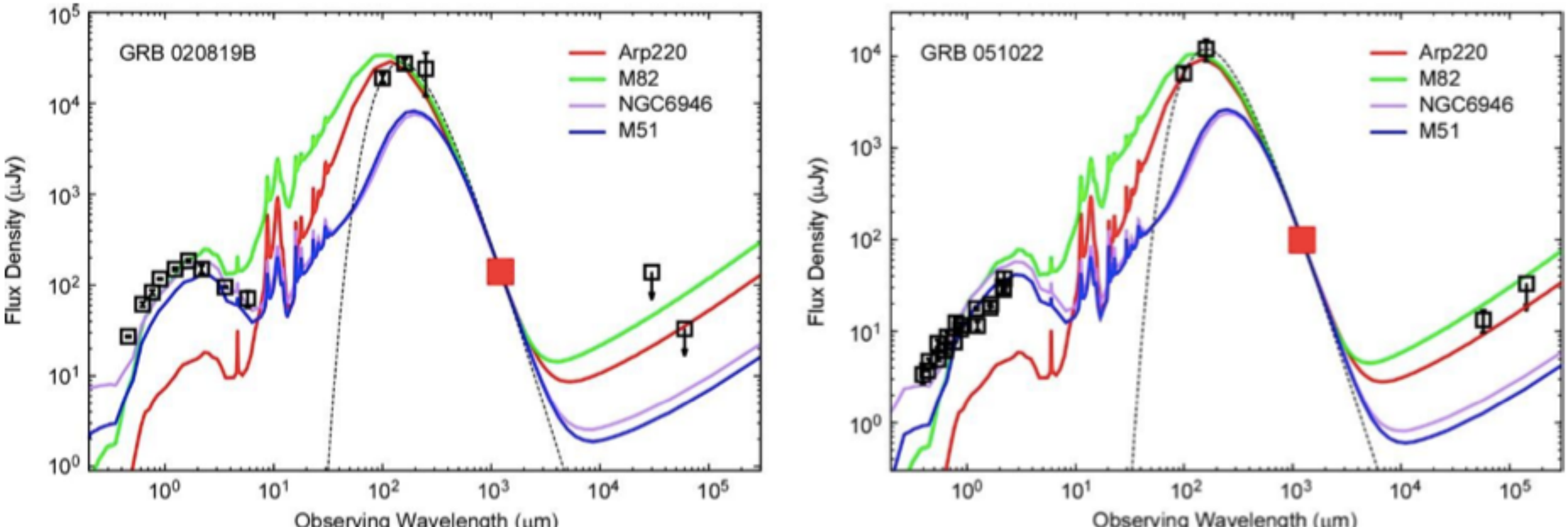
Herschel Hunt+ (2014)



dark GRB host 051022, z=0.81

better dust-mass estimates for GRB host galaxies

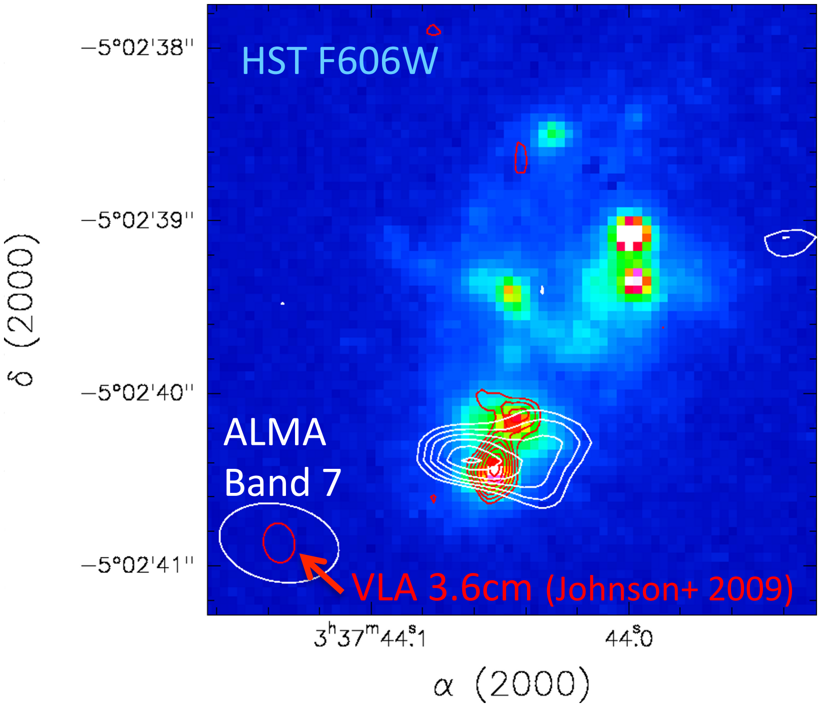


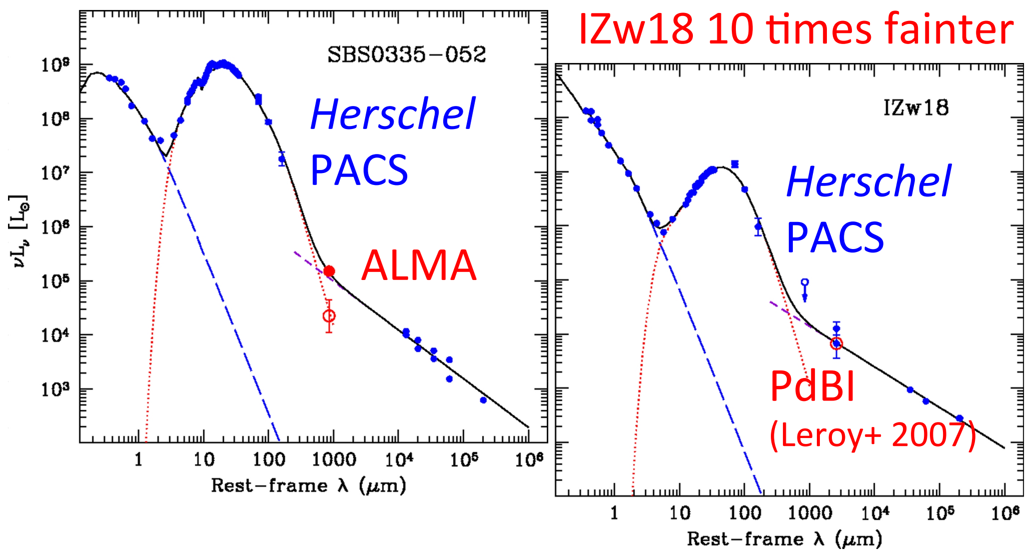
SEDs from Hatsukade+ (2014)

The GRB occurred in dusty regions (both hosts are for dark GRBs) but the molecular gas content at the GRB site (in 020819B) is low, evidently having been dissipated by massive stars before the burst. Important caveat: *Herschel* beam encompasses the entire galaxy, not only the GRB. How does this affect estimates of dust mass?

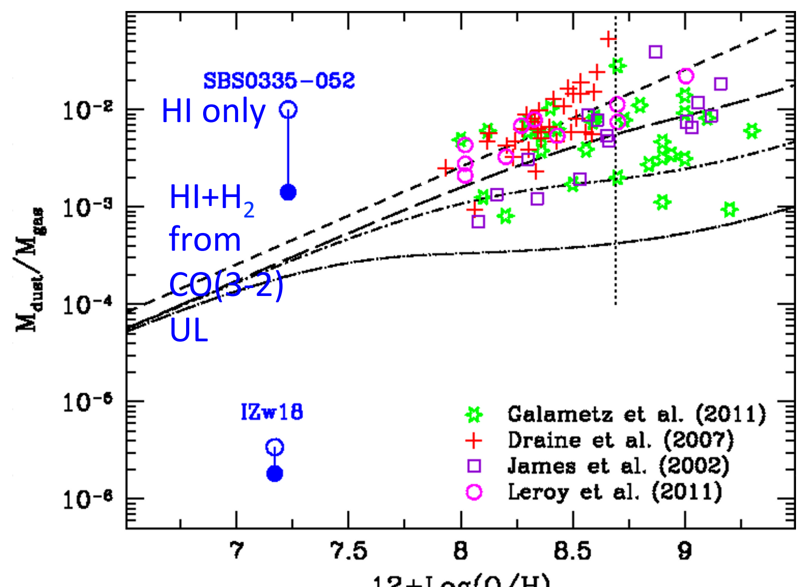
See talks by Galametz (sub-mm excesses) and Michalowski (the nearest GRB host galaxy).

better dust-mass estimates at low metallicity





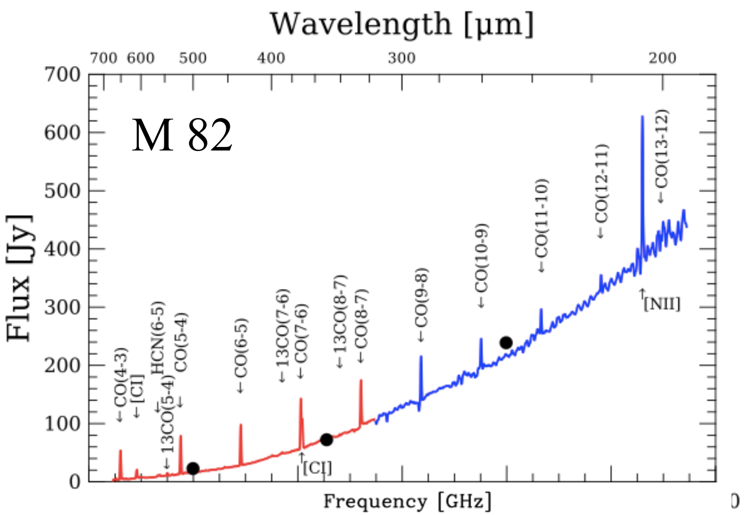
Two metal-poor starburst galaxies, SBS0335-052 and IZw18, both at ~3% solar metallicity, differ in dust-to-gas ratios by more than a factor of 1000 (Hunt+ 2014). This can be explained through the higher ISM density in SBS0335-052 that enhances grain formation (Schneider+ 2015). (Free-free emission at 870µm = 87% of observed flux!).



excitation of molecular gas

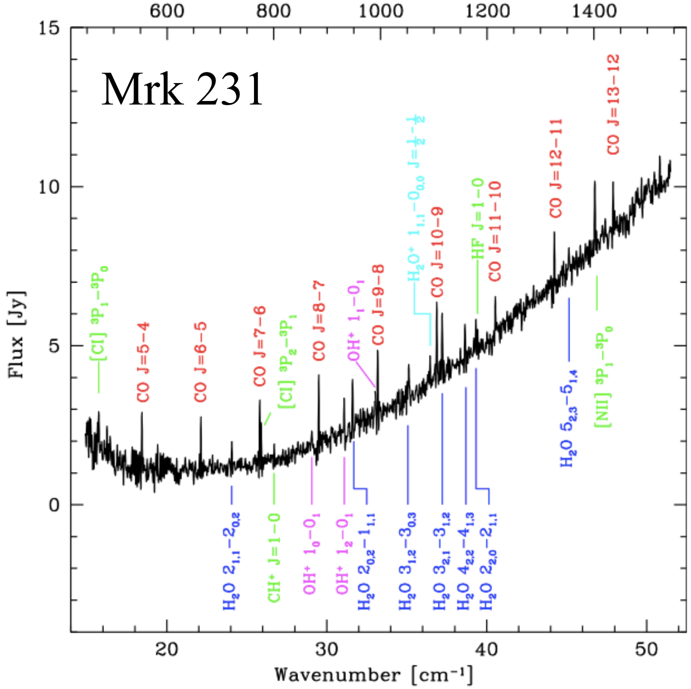
CO cooling curves with Herschel SPIRE-FTS

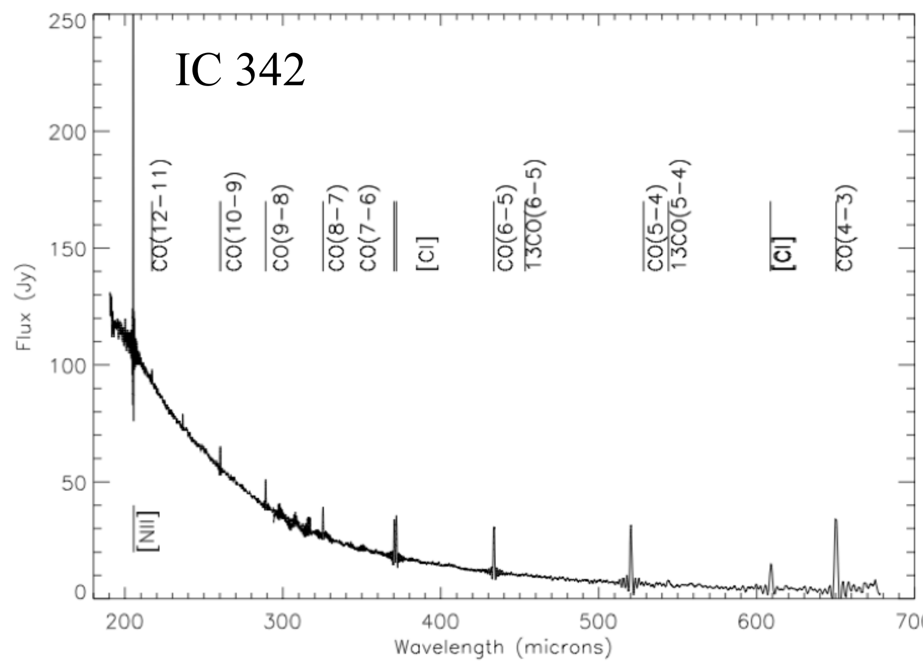
Panuzzo+ (2010)



Already with early science, SPIRE-FTS was giving spectacular spectra from 200 to 600μm of starbursts (M82, Panuzzo+ 2010), ULIRGs/ quasars (Mrk 231, van der Werf+ 2010), and normal spirals (IC 342, Rigopoulou+ 2013). (see also many other examples, e.g., Rosenberg+ 2013: NGC 253).

van der Werf+ (2010)



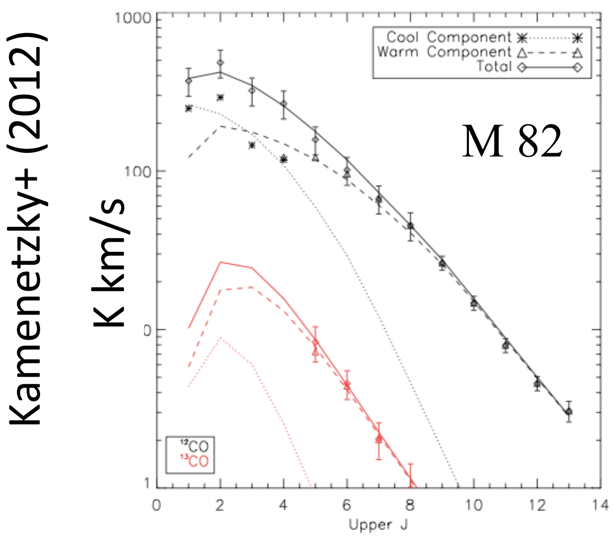


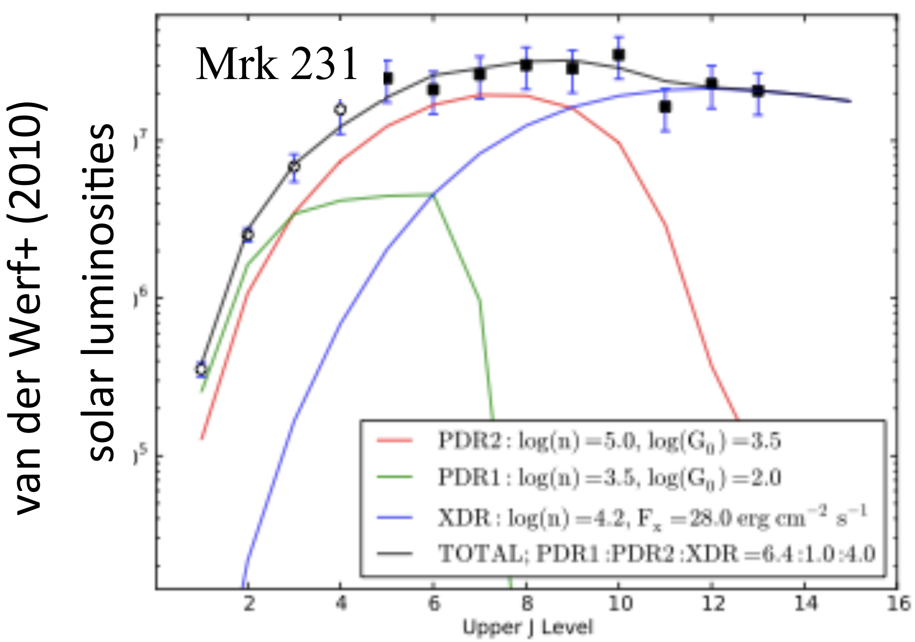
Rigopoulou+ (2013)

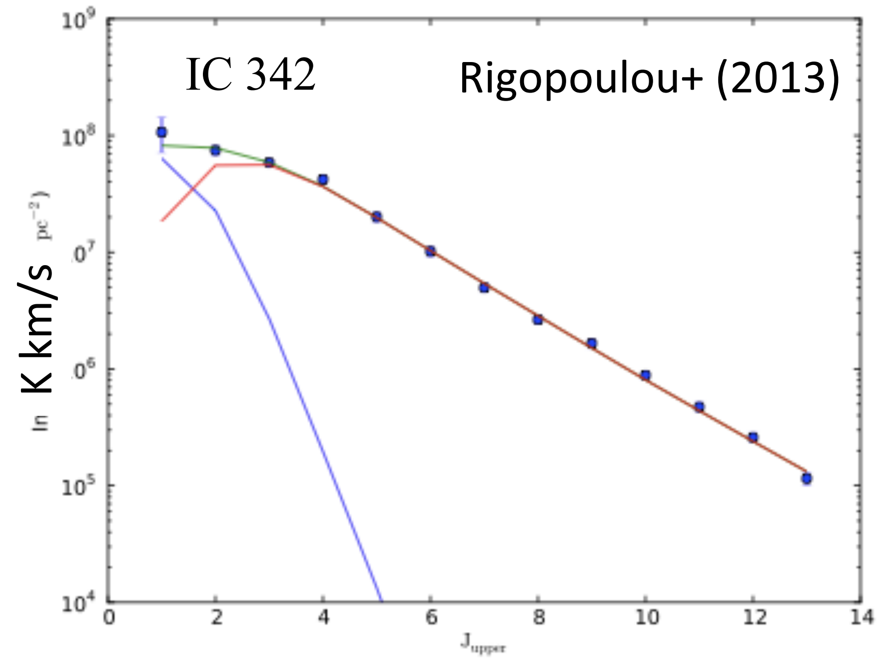
CO cooling curves with Herschel SPIRE-FTS

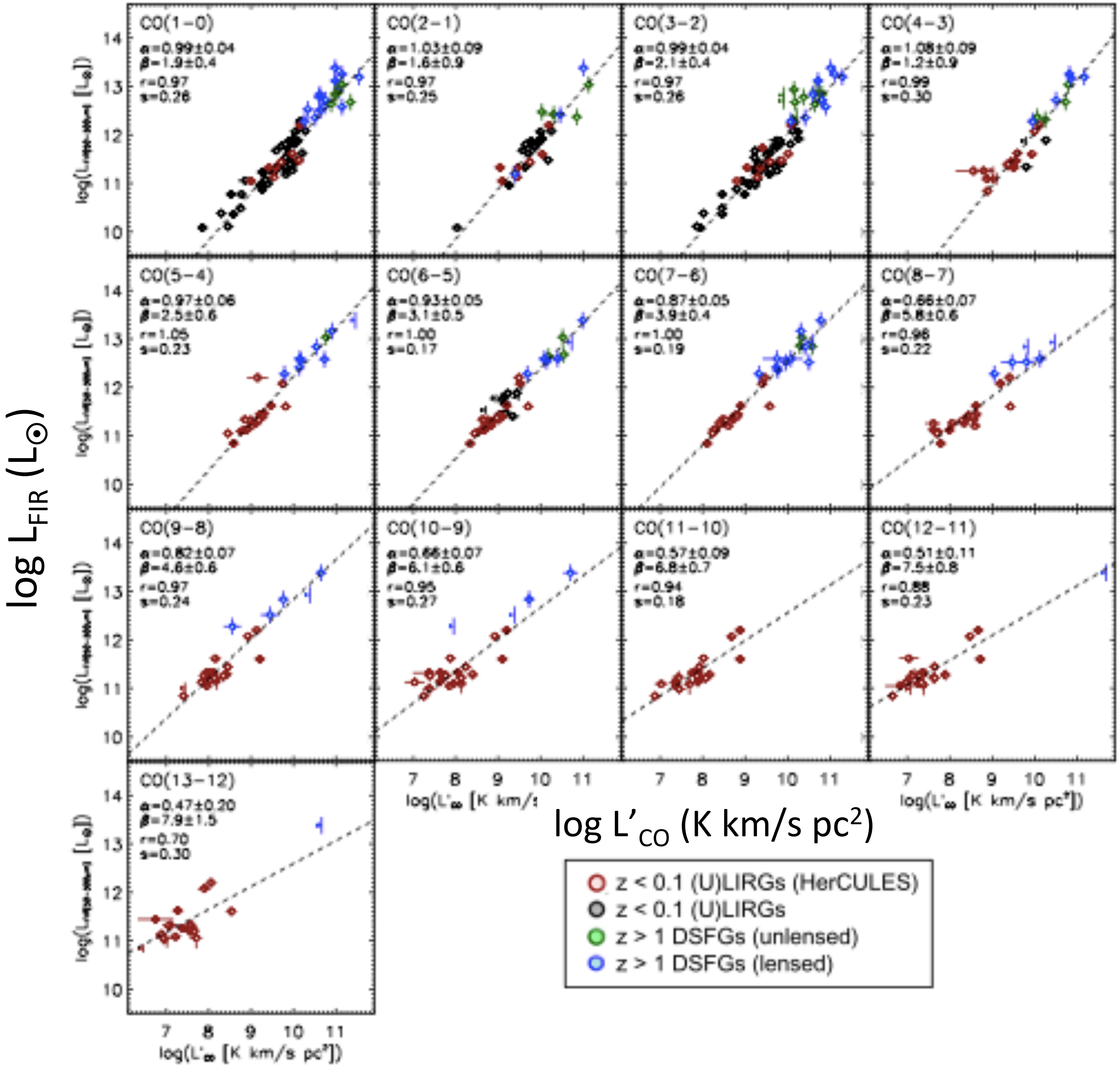
The addition of high-J CO lines makes it possible to determine quite accurately molecular gas excitation mechanisms.

While warm+cool PDR models can fit the quiescent spiral IC342 (Rigopoulou+ 2013), mechanical heating (turbulence, shocks) is required for the starburst M82 (Kamenetzky+ 2012). For the AGN-dominated ULIRG, Mrk231, in addition to PDRs, XDRs are needed (van der Werf+ 2010).

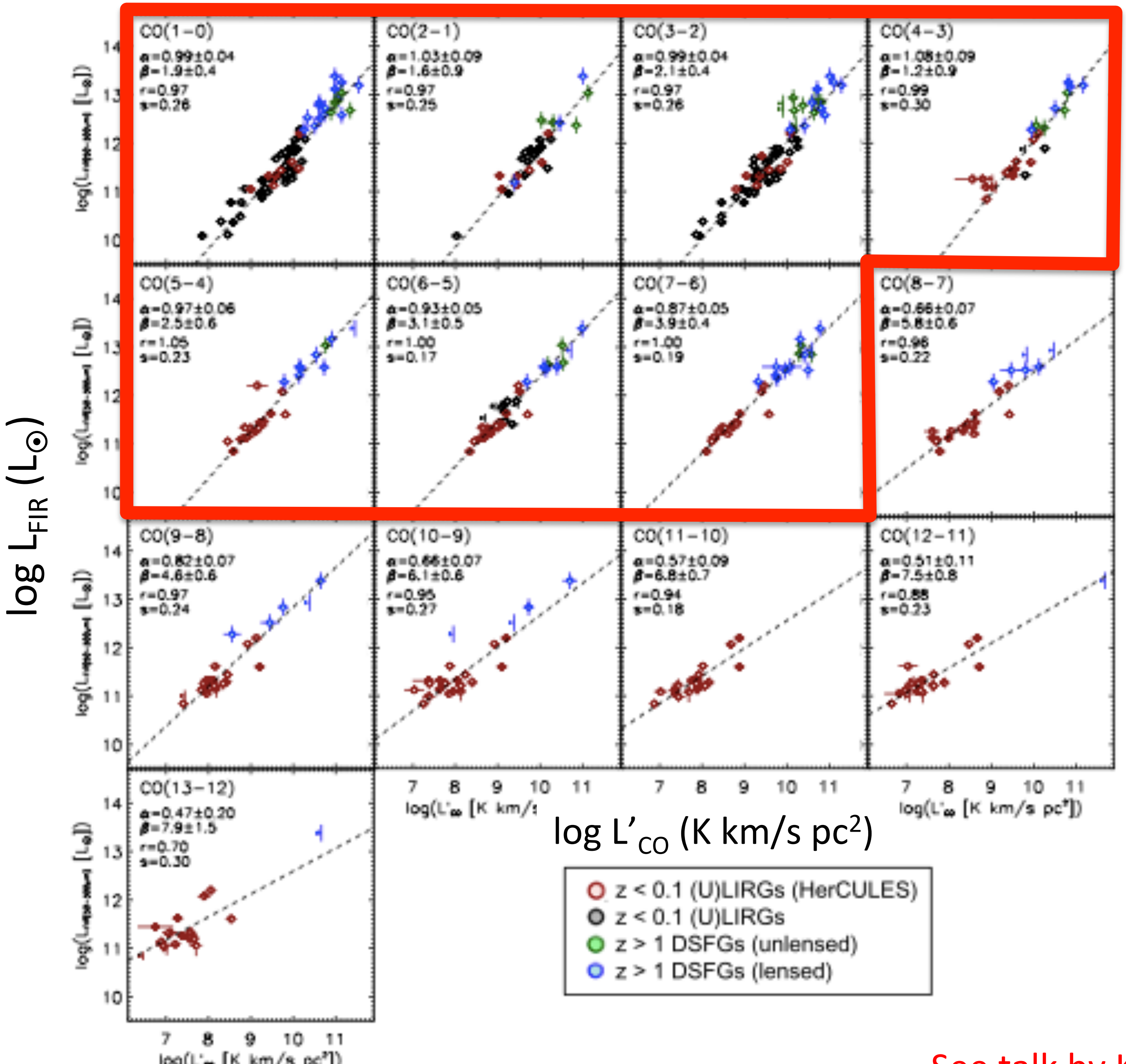








More generally, in luminous IR galaxies from CO(6-5) and higher J_{upper}, sub-linear slopes and increasing normalizations of CO luminosity and L_{FIR} imply that the warm dense gas cannot be merely heated by UV photons in a PDR, but rather that mechanical heating is required (Greve+ 2014).



Use ALMA to constrain low-J lines

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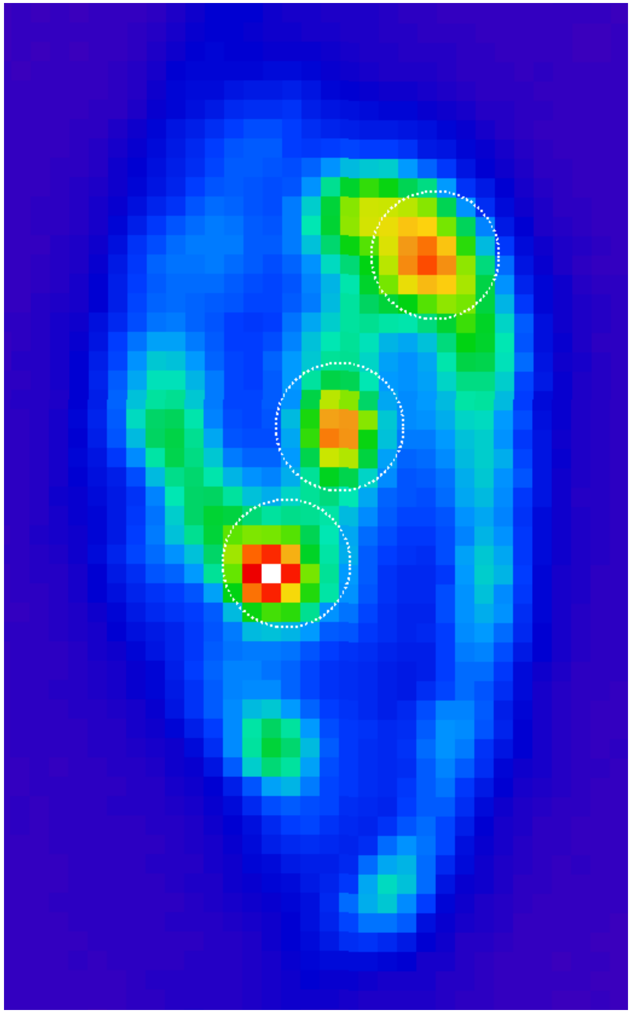
See talk by Kamanetzky (high-J CO).

resolved CO cooling curves with Herschel SPIRE-FTS

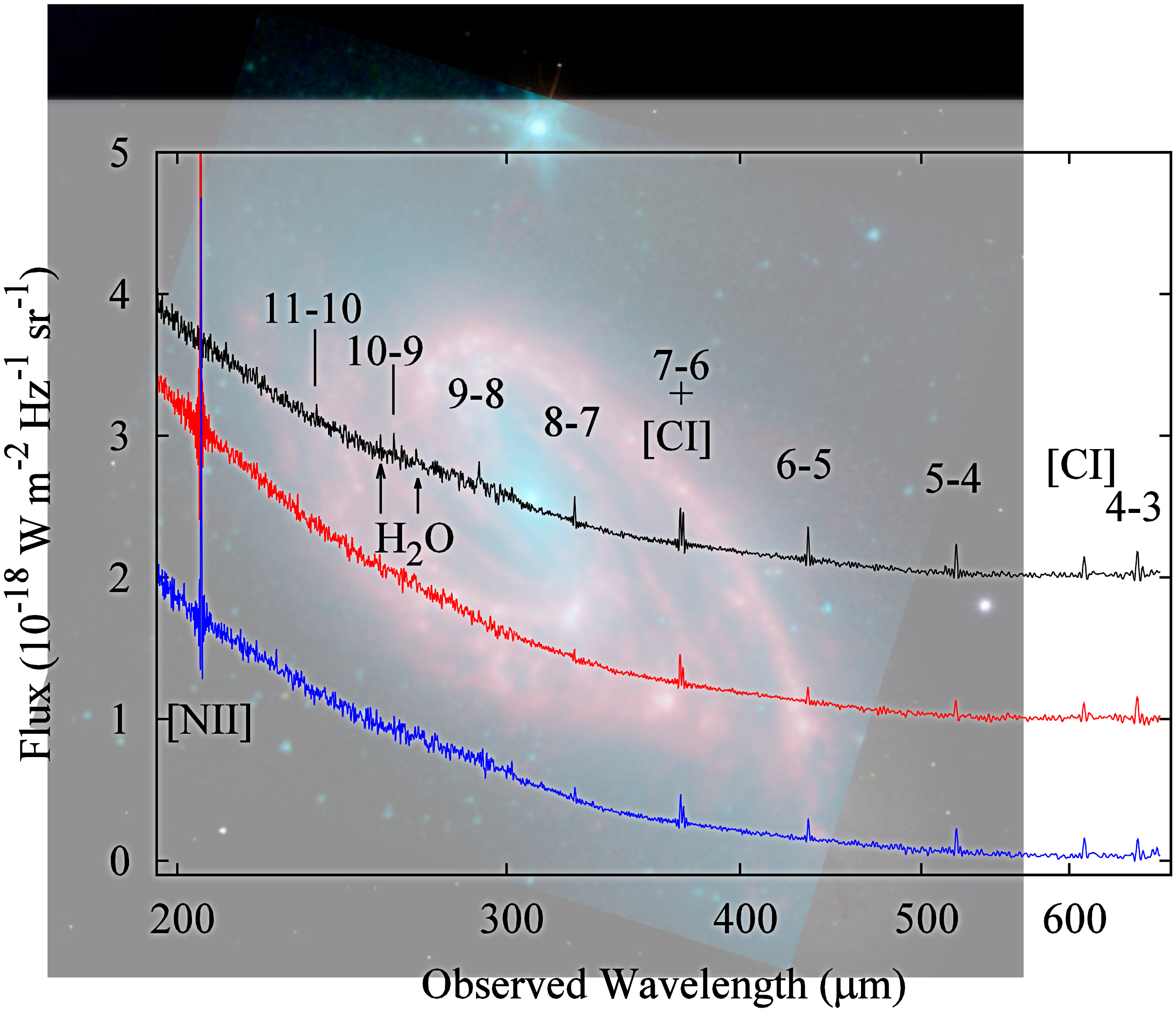
NGC 3627, a late-type barred interacting galaxy

SPIRE image

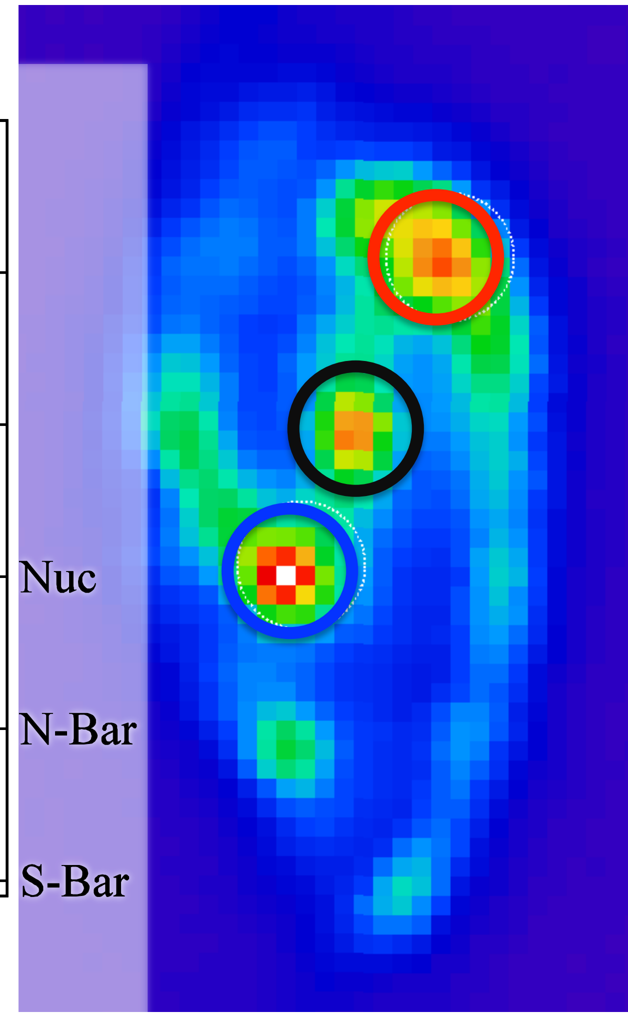


Herschel SPIRE-FTS OT2 Large Project, Beyond the Peak *(JD Smith et al.)*

NGC 3627, a late-type barred interacting galaxy



SPIRE image



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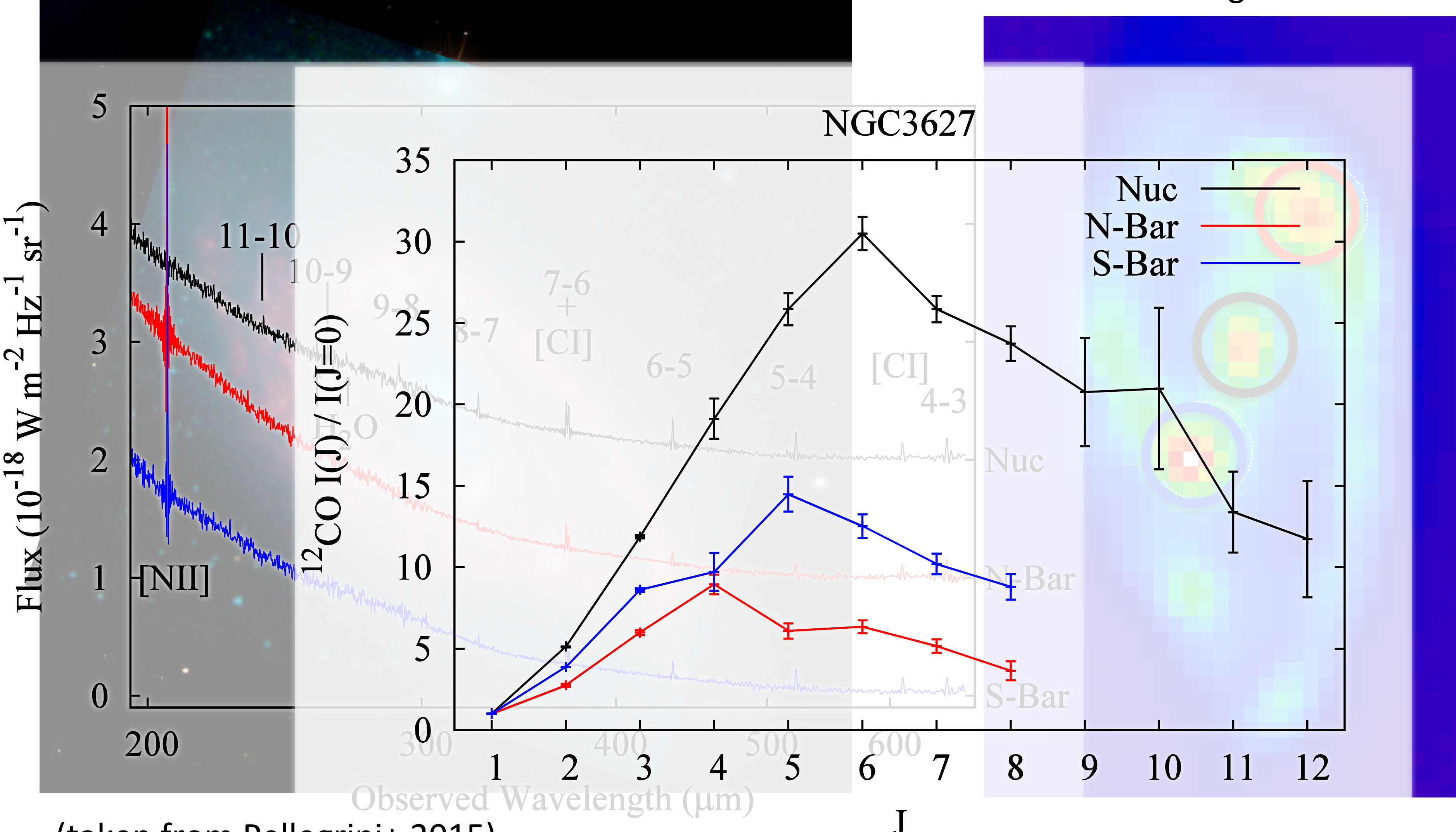
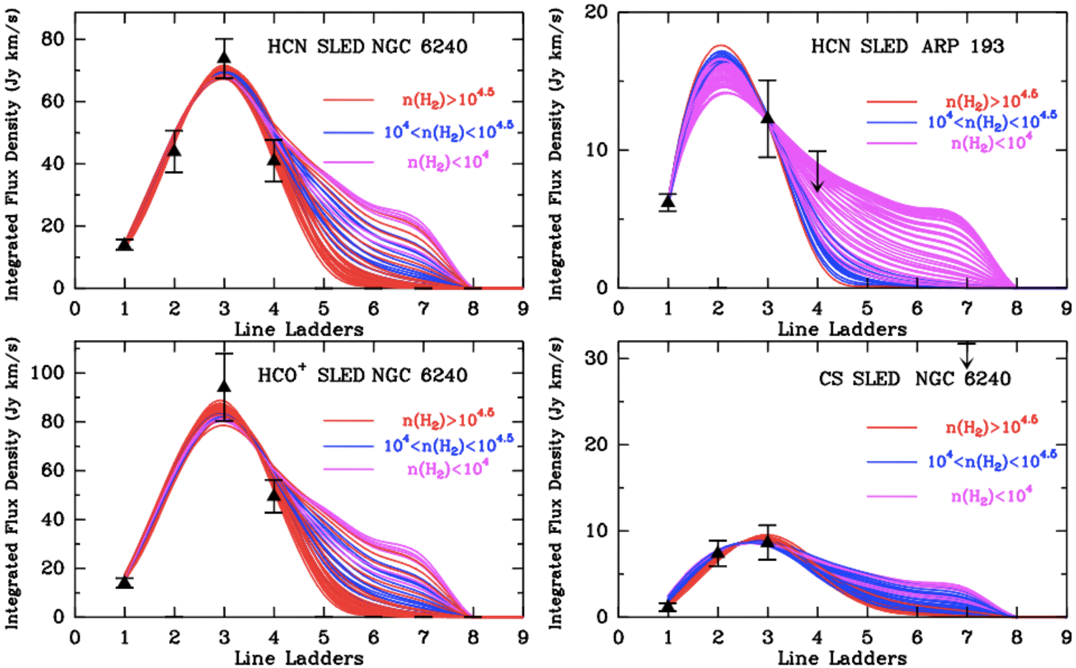
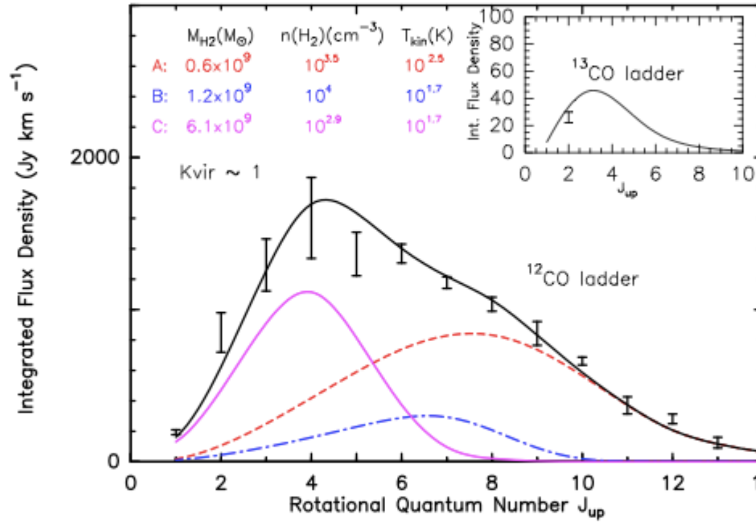


(taken from Pellegrini+ 2015)

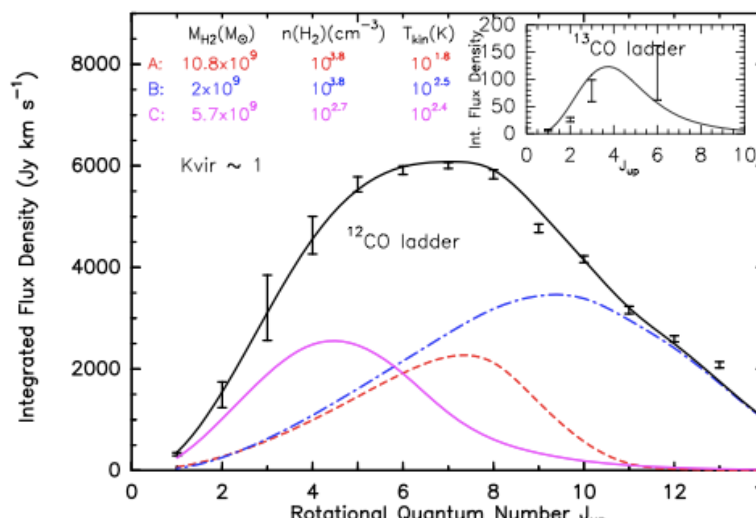
molecular excitation constraints from HCN, HCO+, CS



Arp 193



NGC 6240

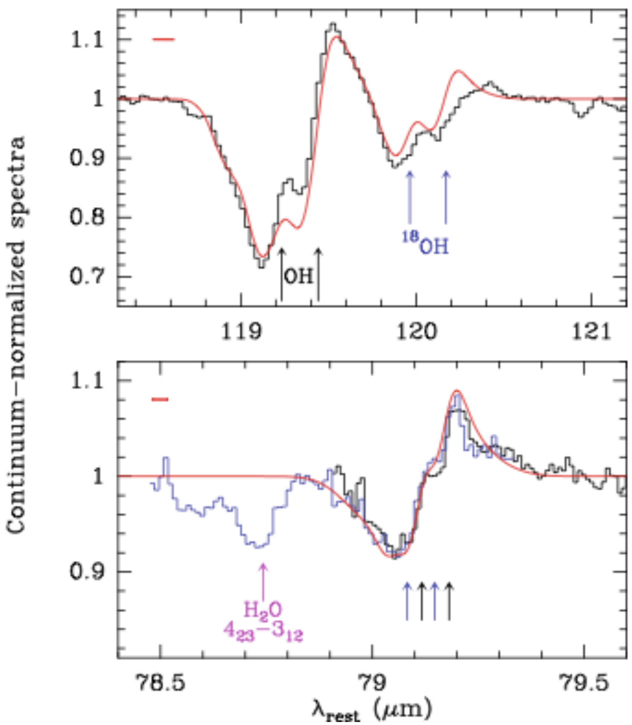


Papadopoulos+ (2014) use ground-based dense-gas tracers (APEX) to constrain the high-J CO lines observed by SPIRE-FTS. They find that 5-15% of the gas is dense ($n_{H2} > 10^4$ cm^{-3}) in Arp 193 (LIRG), while most (60-70%) of the gas is dense in NGC 6240 (ULIRG). The dense component cannot be heated by FUV photons in a PDR.

AGN and stellar feedback

AGN-driven outflows identified by PACS, followed up by PdBI

OH (79µm, 119 µm) P-Cygni absorption feature

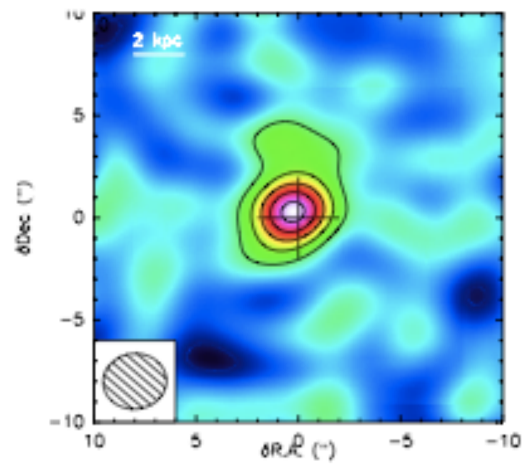


Fischer+ (2010): Herschel highlights)

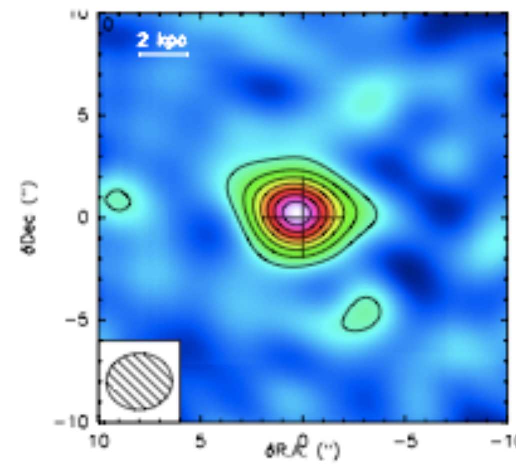
Peaks of both broad CO components spatially coincident, implying outflow mainly along line of sight, consistent with OH.

Mrk 231, a quasar-dominated ULIRG

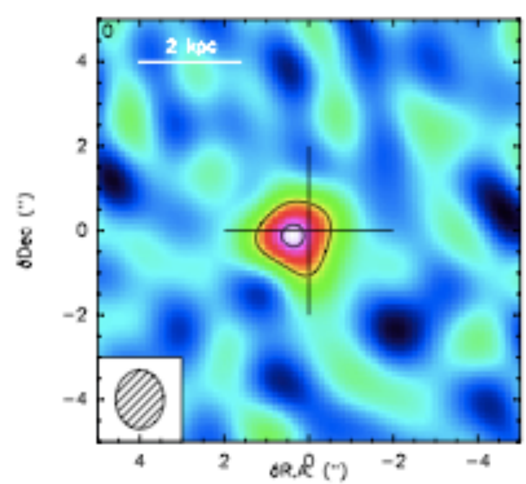
PdBI CO(1-0) blue



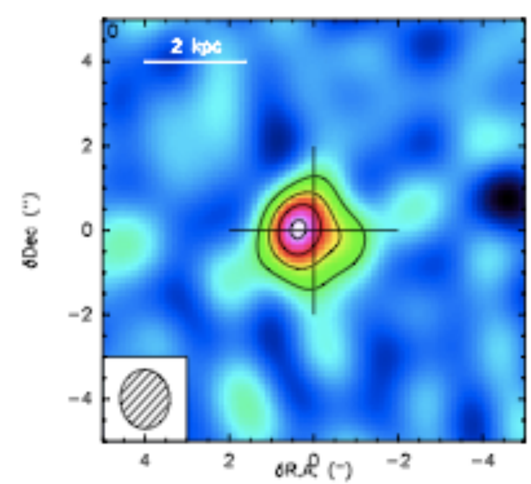
red broad wings



PdBI CO(2-1) blue

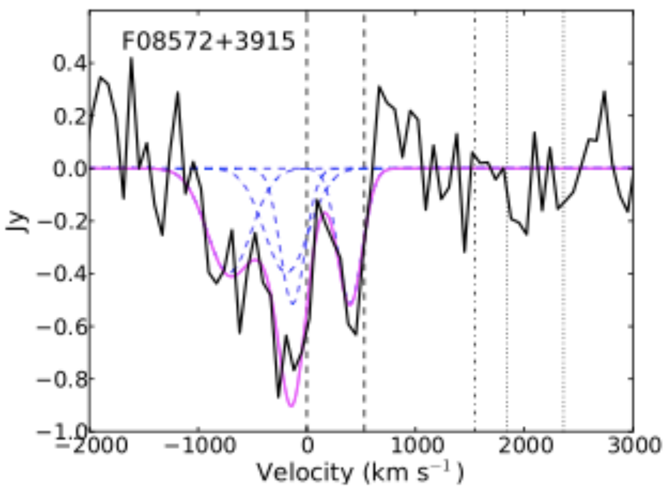


red broad wings

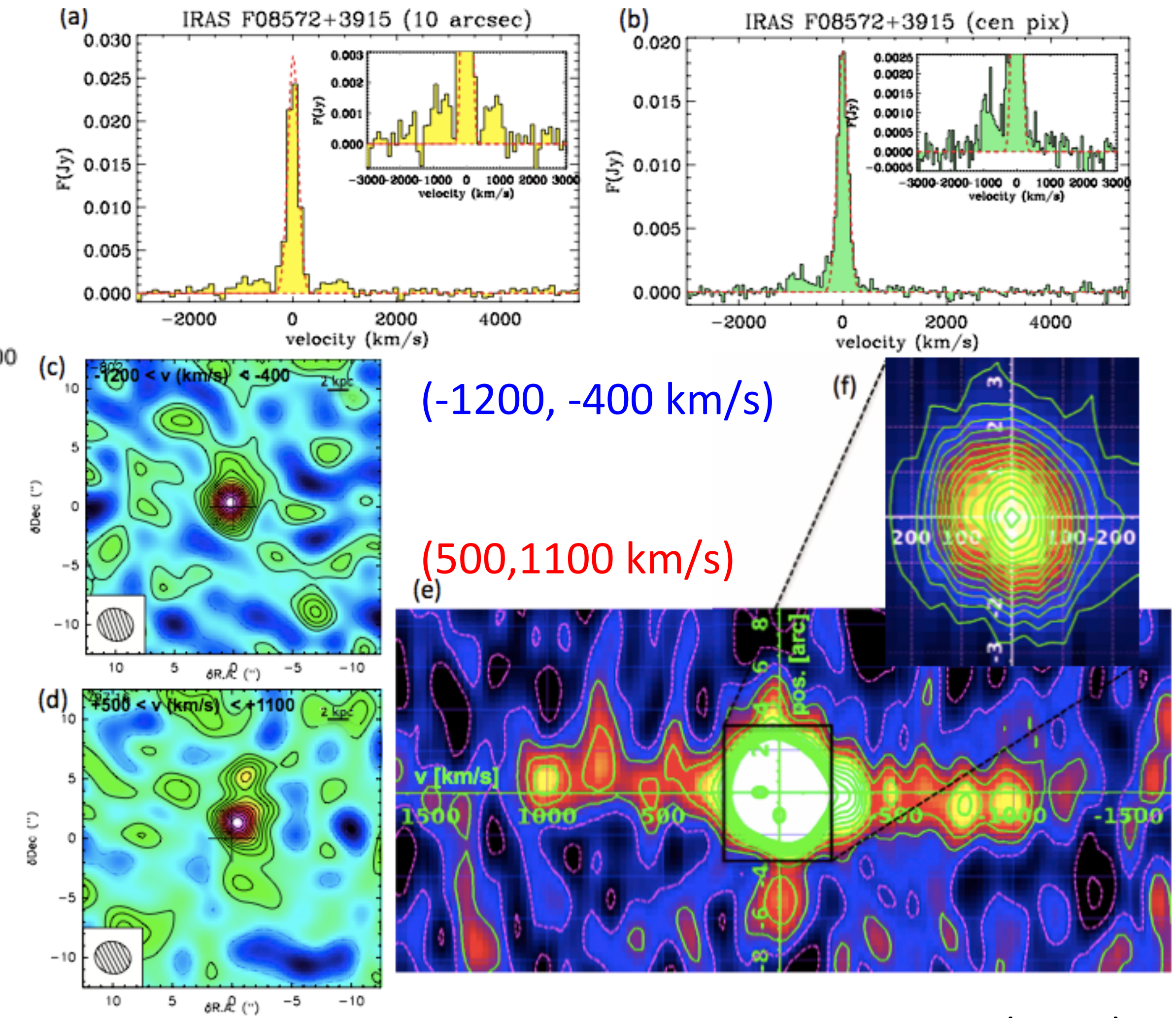


(± 400-1000 km/s) Cicone+ (2012), Feruglio+ (2010)

AGN-driven outflows identified by PACS, followed up by PdBI



F08572+3915, a dust-embedded ULIRG



(-1200, -400 km/s)

(500,1100 km/s)

Sturm+ (2011), Veilleux+ (2012) strong OH (here 119μm) P-Cygni absorption feature

~1200 $M_{\odot}$ yr^{-1} molecular outflow, most powerful in the Cicone+ (2014) sample, potentially quenching future star formation by eliminating gas supply.

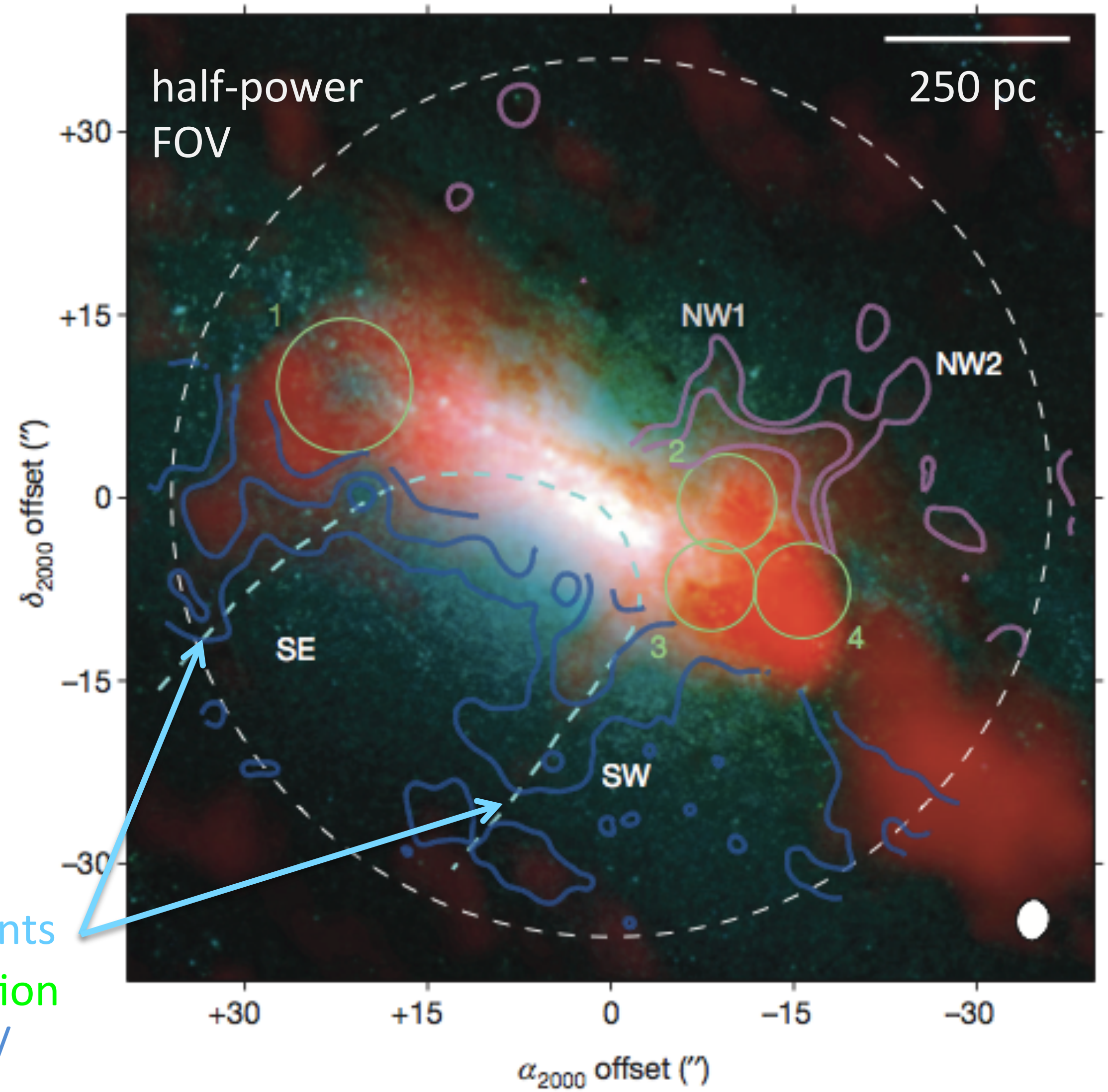
ALMA next step (for southern sources).

Cicone+ (2014)

ALMA quantifies the cool molecular wind in NGC 253

Bolatto+ (2013) use ALMA to image $^{12}CO(1\text{-}0)$ in a nearby prototypical starburst, NGC 253.

NGC 253 also shows absorption features in OH lines with PACS, and the outflow mass in the wind measured from OH (1.6 -6.4 $M_\odot$ yr^{-1}, Sturm+ 2011) agrees roughly with the values of 3-9 $M_\odot$ yr^{-1} found by Bolatto+ (2013), comparable to or larger than the SFR of 2-3 $M_\odot$ yr^{-1}. Mass loading and velocities in stellar-driven outflows smaller than in AGN.



Bright Hα outflow filaments

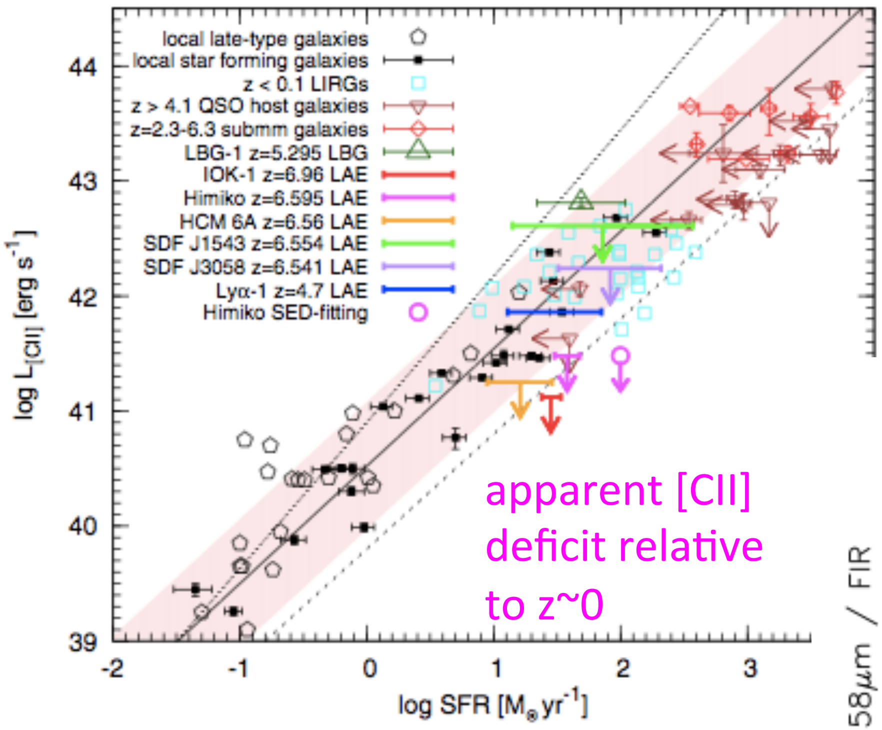
Green circles indicate size and location of expanding molecular shells; blue/ magenta contours show approaching (73-273 km/s) and receding (208-356 km/s) outflow lobes.

Background image HST J band (blue), H band (green), integrated CO emission (red)

extrapolating to the high-redshift universe

[CII] as a tracer of SFR at epoch of reionization

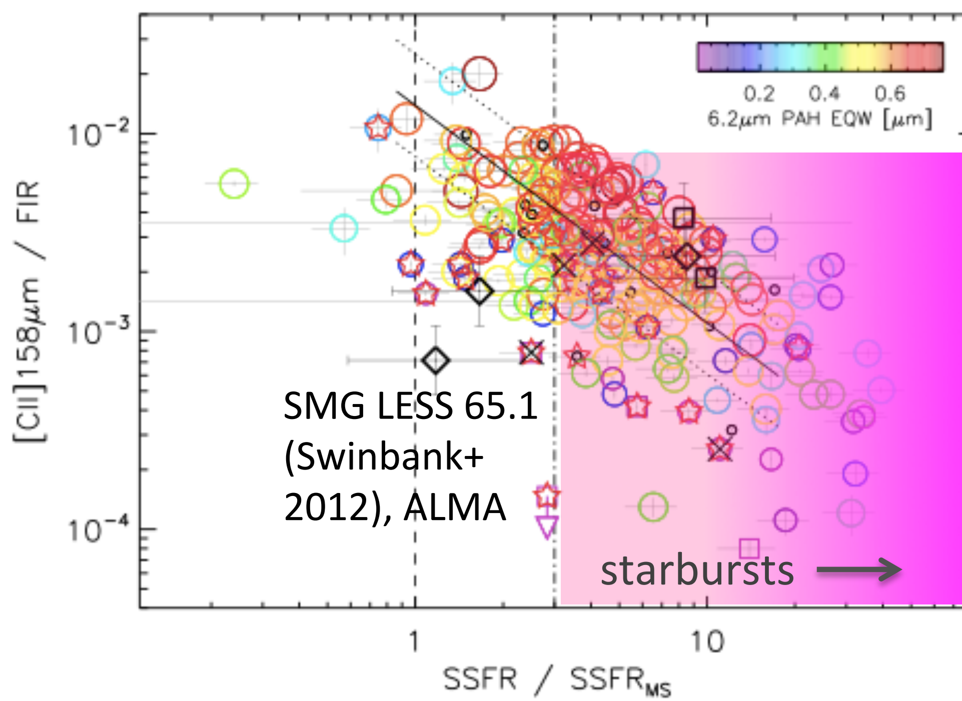
Ota+ (2014) [CII] luminosity vs. SFR



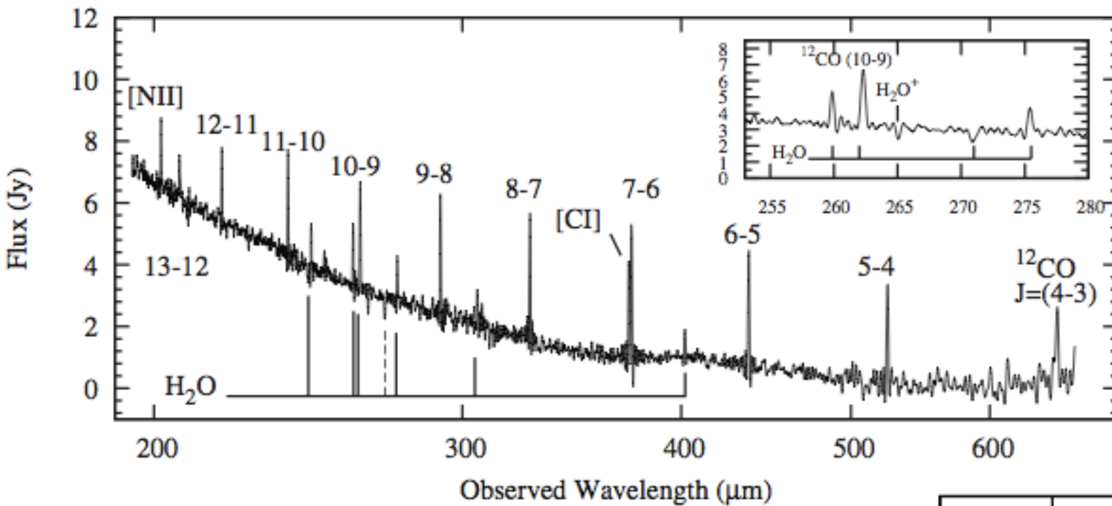
Calibrate locally with *Herschel*/PACS: e.g., GOALS (Diaz-Santos+ 2013) who find that L[CII]/FIR inversely correlated with SSFR (normalized to "main sequence" at that redshift).

"Cottage industry" searches with ALMA (and PdBI) for [CII] in galaxies at z>~7 (e.g., Ouchi+ 2013, Kanekar+ 2013, Ota+ 2014, Gonzalez-Lopez+ 2014, Schaerer+ 2015, and more). No detections yet!

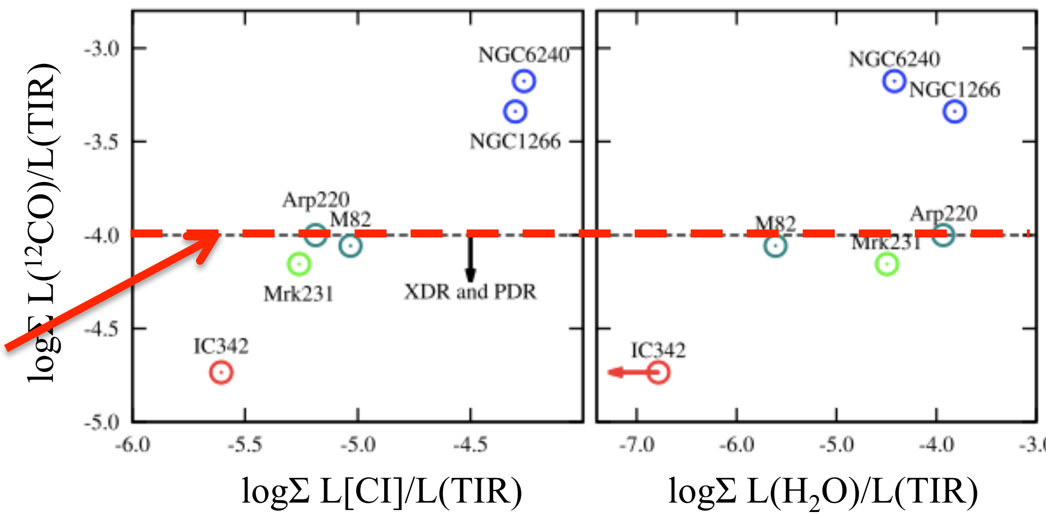
GOALS LIRGs [CII]/FIR vs. SSFR/SSFR(MS)



H_2O with Herschel at z~0, higher z with ALMA



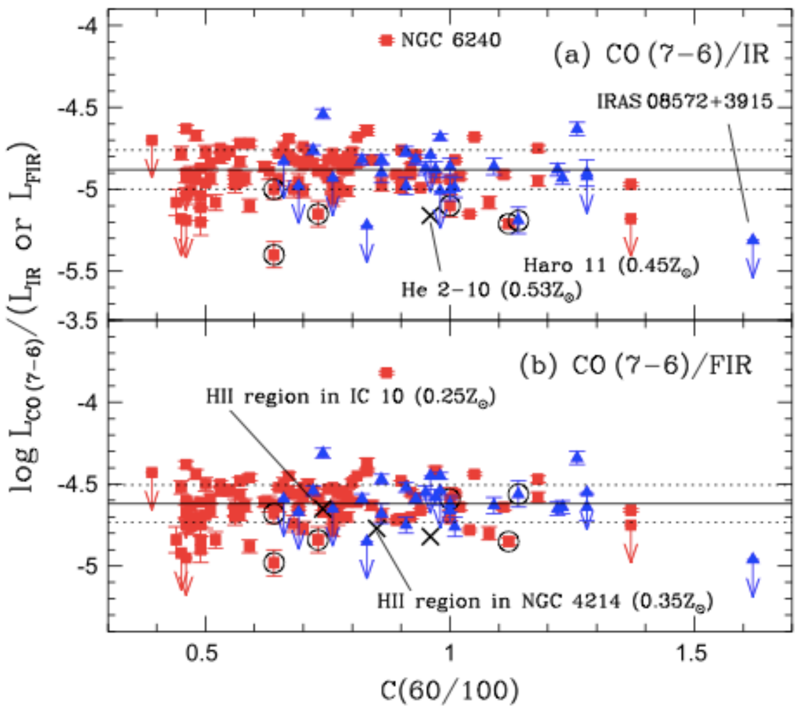
NGC 1266, an S0 galaxy with a massive molecular outflow (Alatolo+ 2011, 2015) shows strong evidence from SPIRE-FTS for shock-excited water emission (Pellegrini+ 2013).

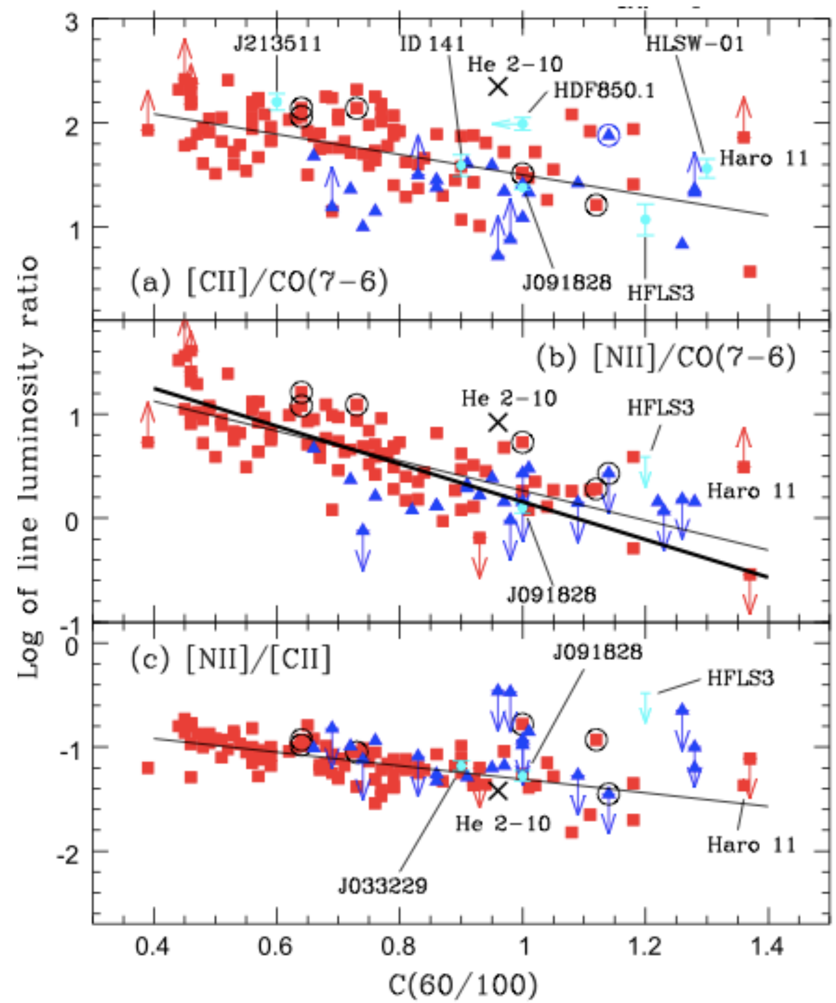


upper limit of L(CO)/L(FIR) for PDRs and XDRs

(see also Weiss+ 2010: M82; Gonzalez-Alfonso+ 2010: Mrk231; Gonzalez-Alfonso+ 2012: NGC4418; Rangwala+ 2012: Arp220; Spinoglio+ 2012: NGC1068, Meijerink+ 2013: NGC6240; Appleton+ 2013: Stephan's Quintet)

[NII] 205μm, CO(7-6) as tracers of SFR

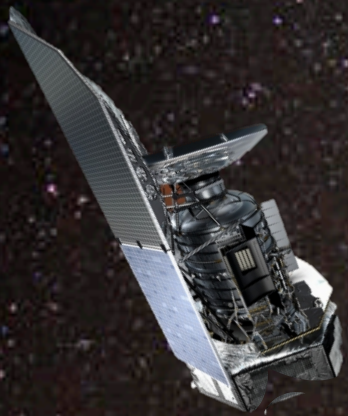




Lu+ (2015) argue that to characterize SFR, also need color temperature (e.g., C60/100, and thus interstellar radiation field intensity, the surface brightness, etc.). Using ratio [NII] 205μm/CO(7-6) 372μm to infer color temperature and CO(7-6) to trace SFR, apply *Herschel*-calibrated local relation to high-z.

(for other SFR/ionized gas tracers see talks by Gruppioni and Bendo)

Conclusions



- ✓ *Herschel* has given (and will continue to provide) unique results for dust continuum emission unobservable from the ground at z~0, but ALMA can better constrain dust masses at long wavelengths

- ✓ PACS and SPIRE-FTS spectroscopy, through observations of H_2O, high-J CO, , HCN, and other lines, constrains the mechanisms that heat the molecular gas, but the addition of low-J lines with ALMA (up to CO(7-6) for z~0) gives the overall normalization, especially since most of the molecular mass lies in the low-J lines

- ✓ PACS spectroscopy identifies unambiguous signatures of massive AGN (and starburst-driven) outflows in the Local Universe, while ALMA can probe deeply into the outflows resolving them spatially and kinematically defining their mass loading

- ✓ *Everything that Herschel observes from space at z~0 can be observed by ALMA at higher redshift: Local calibration for the high-z young universe.*