Warm Molecular Gas in Luminous Infrared Galaxies: Views from *Herschel* and ALMA

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Observation Programs

- ***Herschel*** SPIRE/FTS spectroscopic survey of a flux-limited sample of 125 LIRGs (93 done by us; PI: N. Lu) selected from the **Great Observatieries All-sky LIRG Survey (GOALS)** (see Lu et al. 2014a, ApJ, 787, 23)
- Follow-up **ALMA** high-angular resolution imaging in **CO (6-5)**:
  - Cycle-0 progarm (PI: C. K. Xu): **NGC 34** (Xu et al. 2014a, ApJ, 787, 48)
    NGC 1614 (Xu et al. 2014b, arXiv 1411.1111)
    - ~0.25" (~100 pc) resolution
  - On-going cycle-2 progarm (PI: N. Lu) of 4 more galaxies: **CGCG 049-057, IC 5179, NGC 5135, & NGC 7130**
    - CO(6-5) and dust maps of ~0.1" (< 50 pc, GMC scale) resolution
- ***Herschel*** SPIRE/PACS imaging photometry of the complete GOALS sample (PI: D. Sanders) ~~(see D. Sanders's talk)~~ (Here we used the 70 μm image to estimate the spatial extent of the warm/dense molecular gas.)

The GOALS *Herschel*-ALMA team:

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V. Charmandaris (U. of Crete, Greece)
A. Evans (U. Virginia & NRAO, US)
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K. Issak (ESTEC, Netherlands)
K. Iwasawa (U. Barcelona, Spain)
J. Leech (U. Oxford, UK)
A. Petric (Gemini, US)
D. Sanders (U. Hawaii, US)
P. Van der Werf (Leiden Obs, Netherlands)
+ More

Outline

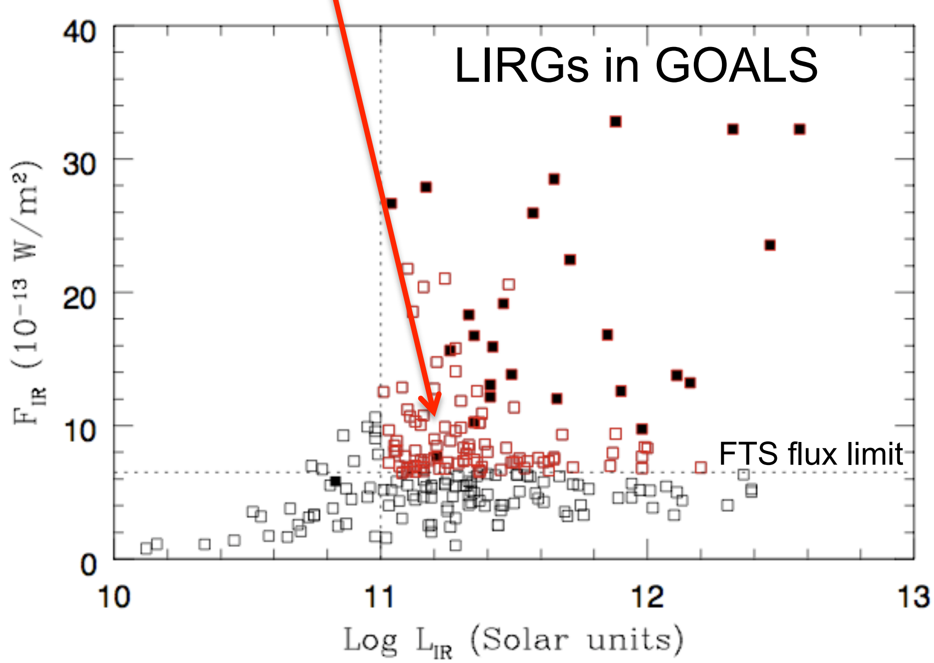
- *Herschel* SPIRE/FTS spectroscopic survey of the GOALS (U)LIRGs and ALMA high-resolution imaging in CO (6-5)
- The CO spectral line energy distributions (SLEDs)
- Cold, warm and hot molecular gas components, on-going star formation rate and gas heating sources

If time allows, also

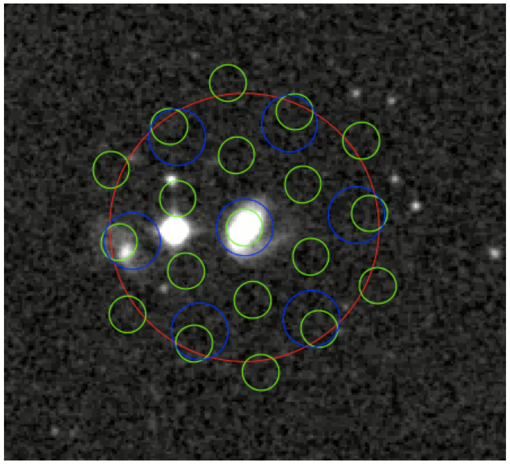
- The CO(7-6) line luminosity as a SFR tracer up to z ~ 6-7
- The [NII] 205 μm to CO(7-6) ratio and the SFR surface density in galaxies at high z

Largest SPIRE/FTS Program on (U)LIRGs

- *Herschel* SPIRE FTS spectroscopy of 93 (u)LIRGs over wavelengths 194 – 671 um in the staring mode.
- These, plus 32 additional (u)LIRGs with FTS spectra from *Herschel* archive, form a flux–limited [F_{IR}(8-1000μm)> 6.5 x 10^{-13} W/m^2] subset from the *Great Observatories All–Sky LIRG Survey (GOALS) sample* (Armus et al. 2009).
- Sampling typical LIRGs in the local universe.



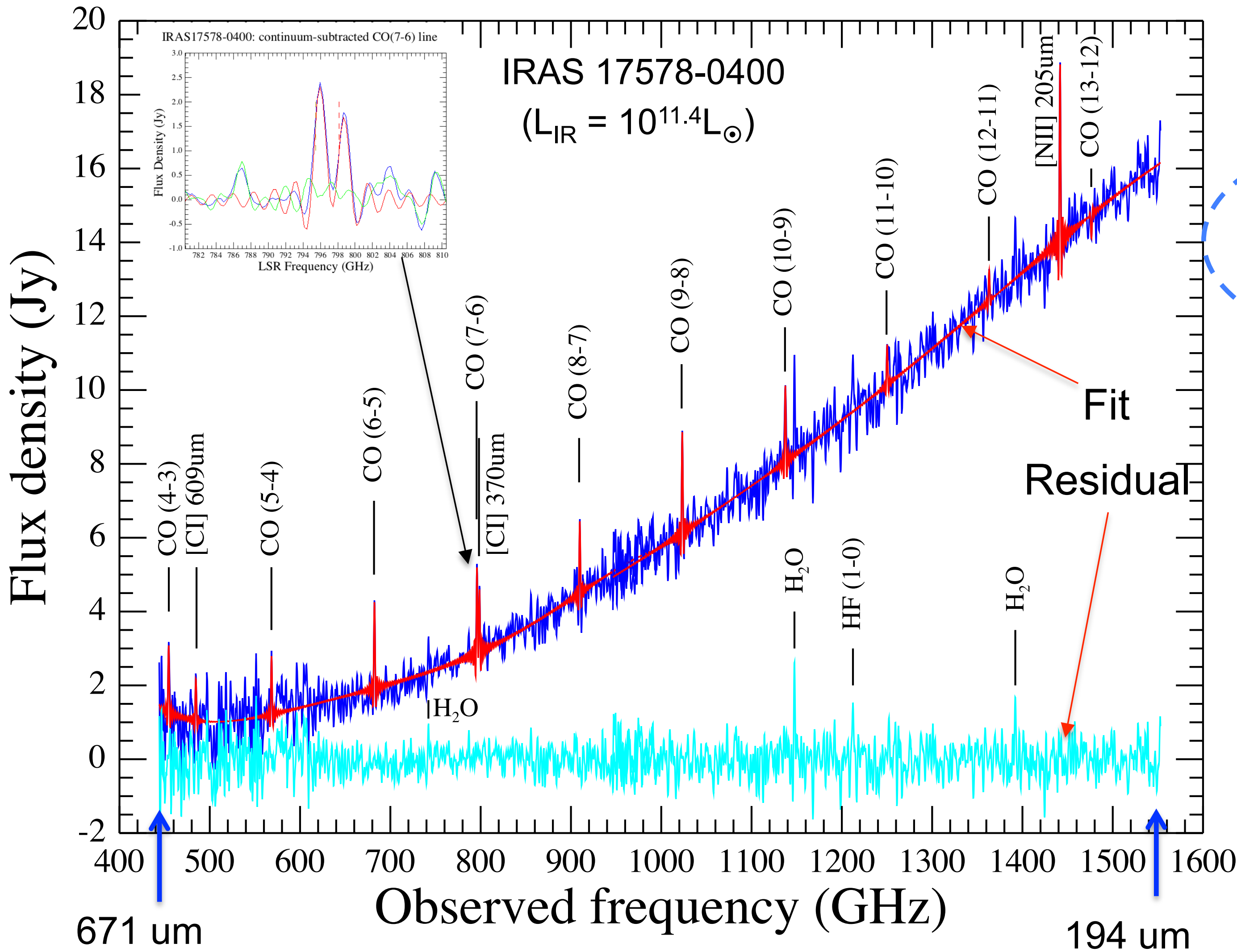
SPIRE/FTS detectors



Green: SSW bolometer detectors (194-313 um; Beam=17”-21”)

Blue: SLW bolometer detectors (303-671 um; Beam=29”-42”)

SPIRE/FTS Spectra

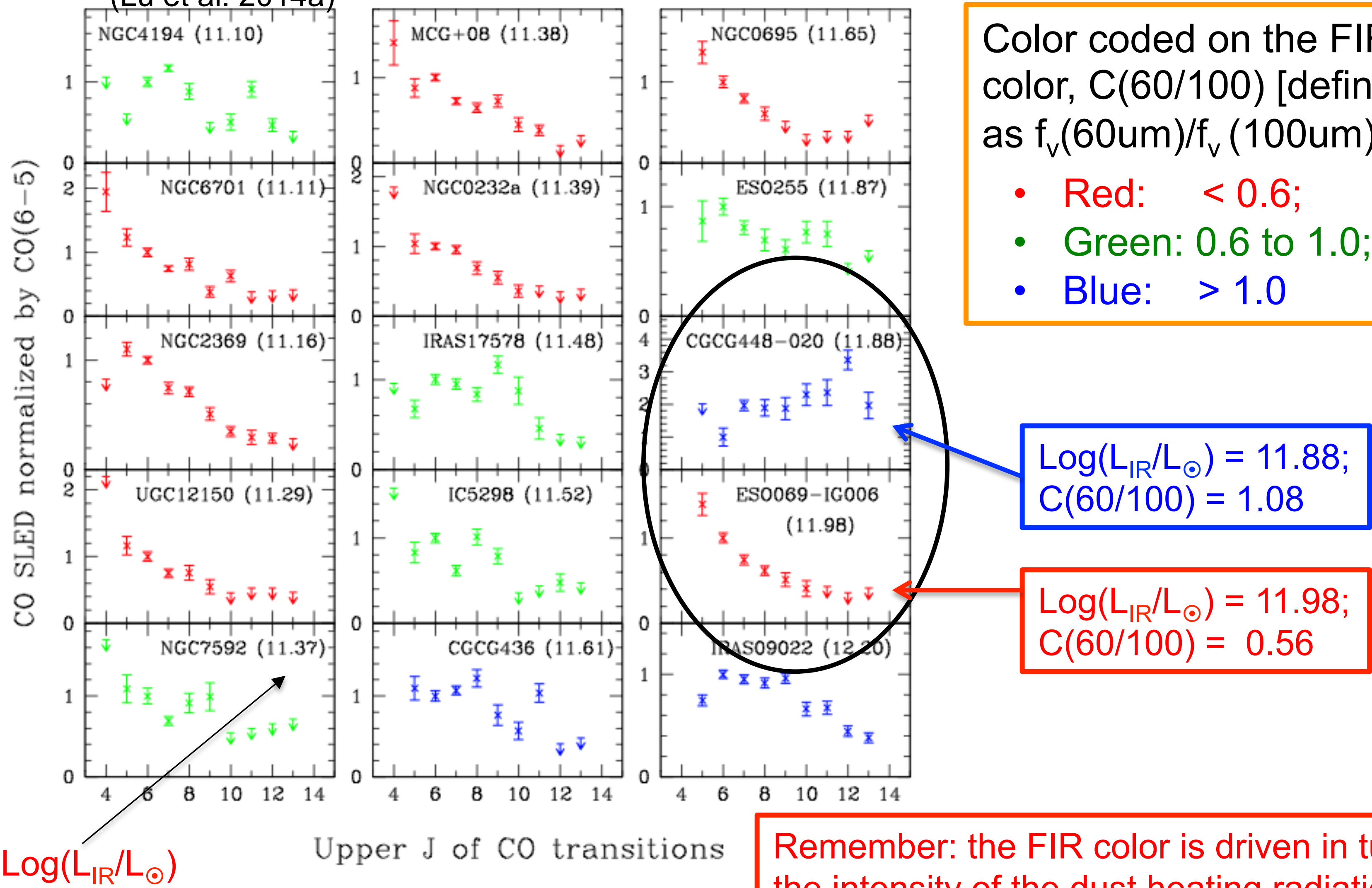


Lines detected:

- CO SLED (mainly mid-J, i.e., 5 <= J <= 10) (Lu et al.2 014a)
- [NII] 205um (Zhao et al 2013)
- [CI] 370um
- [CI] 609um
- H_2O
- HF(1-0)

The FIR Color, not L_{IR}, Drives the Shape of a CO SLED

(Lu et al. 2014a)

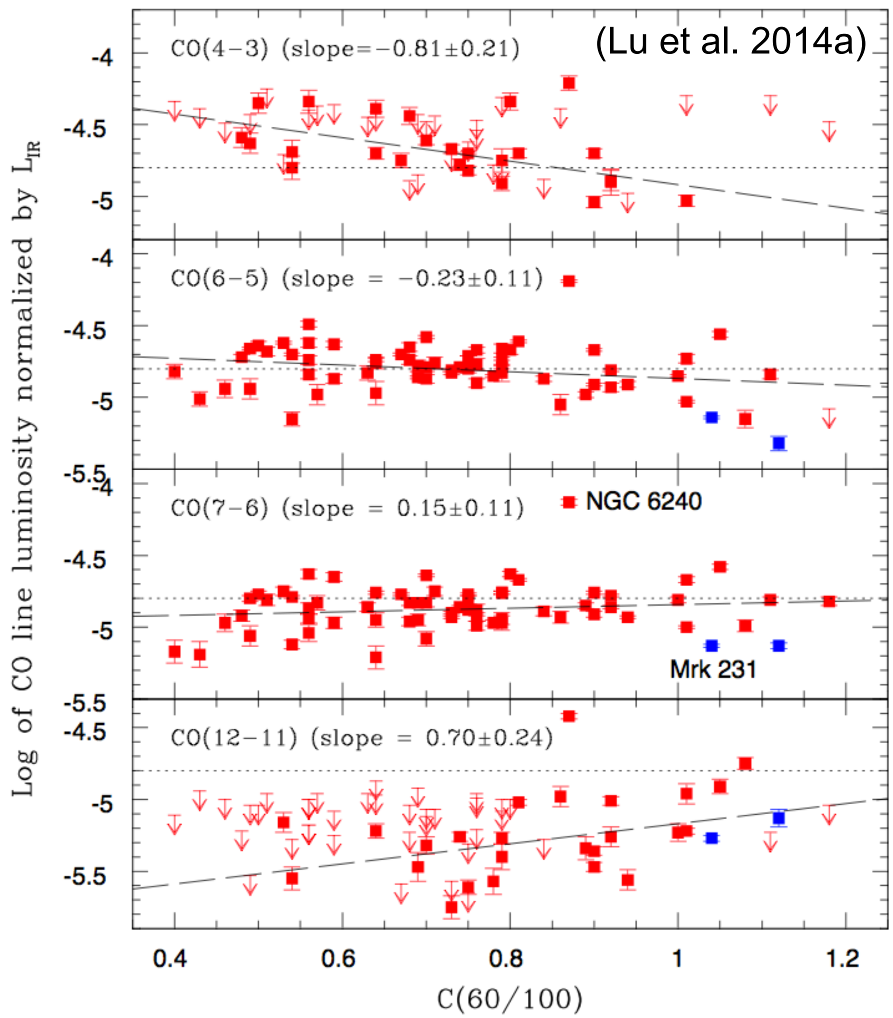


Color coded on the FIR color, C(60/100) [defined as $f_\nu(60um)/f_\nu(100um)$]:

- Red: < 0.6;
- Green: 0.6 to 1.0;
- Blue: > 1.0

Remember: the FIR color is driven in turn by the intensity of the dust heating radiation field

Need (at least) Two Molecular Gas Phases



As the FIR color increases,

- The CO gas becomes warmer overall.
- More significantly, the CO line to IR ratios show the smallest varaition and least dependence on the FIR color at J ~ 7

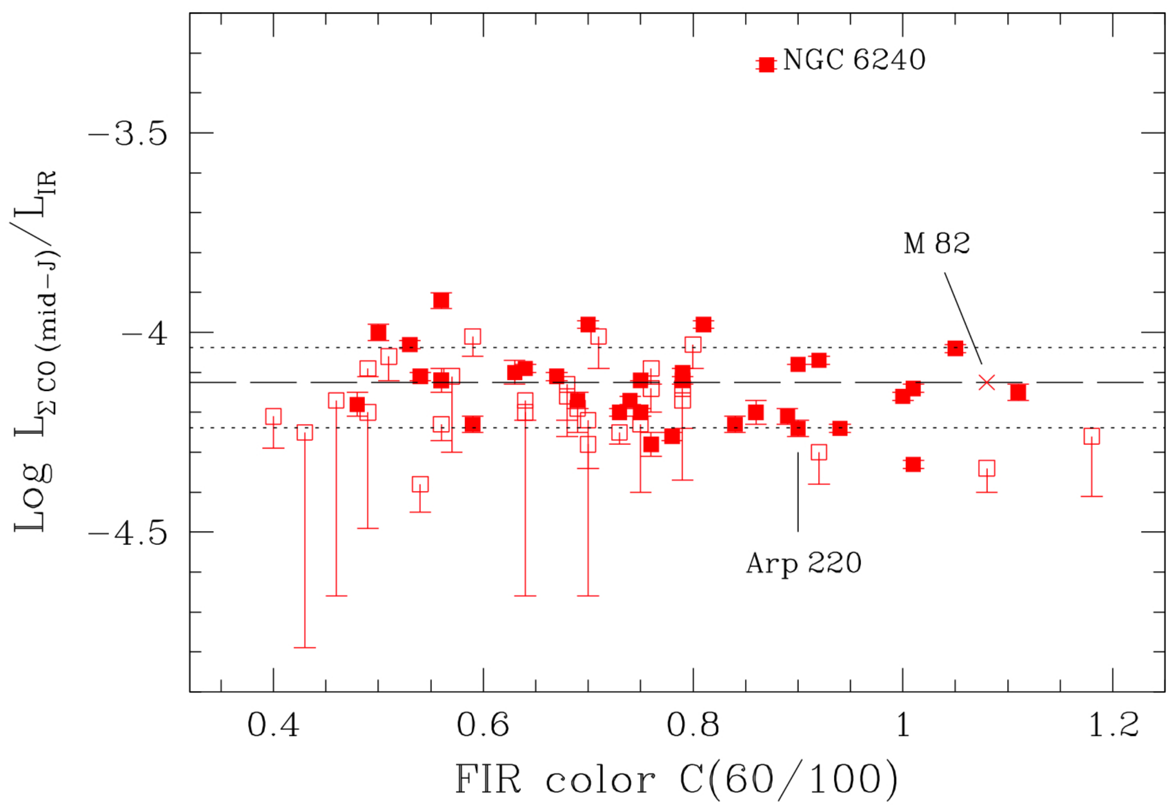
Inferences:

- Single CO gas component can be ruled out. **Need at least 2 gas components:**
  - A "cold" componet mainly at J < 4 or so, not directly related to SF
  - A "warm" one in mid-J (4 < J < 10), peaking around J ~ 7, heated by some processe(s) related to the current SF.

Blue: AGN significant systems with f_{AGN} > 40% L_{bol} (average from mid-IR diagnostics; Armus et al 2007);
Red: Starburst systems with f_{AGN} < 40%.

Dust and Molecular Gas Heating in Starburst Galaxies

$L_{\Sigma CO\ (mid\text{-}J)}$ = CO(5-4)+(6-5)+(7-6)+(8-7)+(10-9)



- When summed over the mid-J CO lines, the resulting CO/IR luminosity ratios show little dependence on C(60/100) for starburst galaxies.
- The sample std. dev. is only of ~0.1 dex.
- So there is a well-defined characteristic mean ratio for starburst galaxies:

  $\langle L_{\Sigma CO\ (mid\text{-}J)} / L_{IR} \rangle \sim 7.4 \times 10^{-5}$

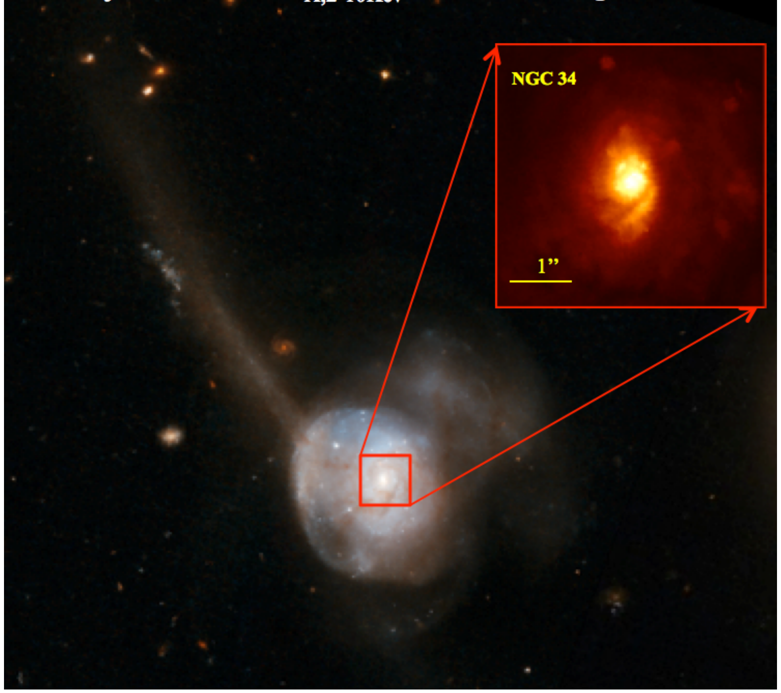
- NGC 6240 is the only clear exception here

Red squares: dust heating dominated by starburst, based on the mid-IR diagnostics

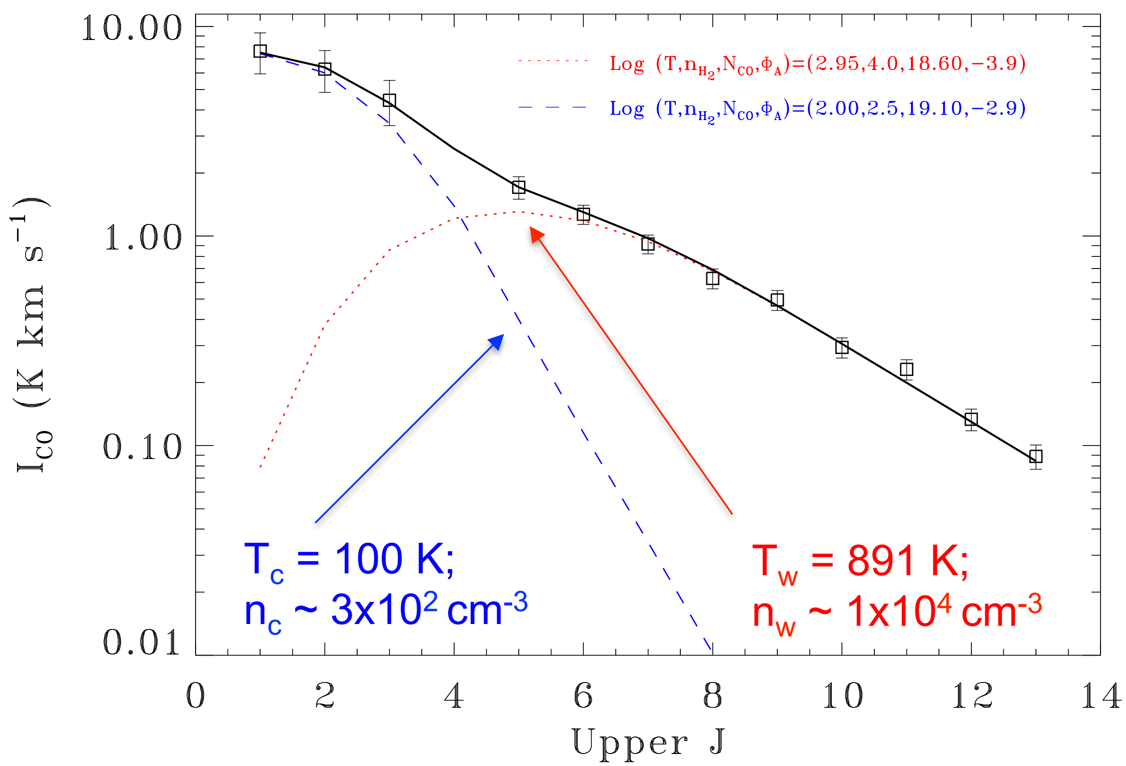
Warm vs. Cold Molecular Gas: Case Study -- NGC 34

NGC 34: major merger, starburst & AGN

- $L_{IR} = 10^{11.49} L_{\odot}$,
- D = 84 Mpc (0".25 ~ 100 pc)
- Major-merger (m/M~1/2 -1/3), coalesced
- Sy2 nucleus: $L_{X,2\text{-}10Kev} = 1.4\times10^{42}$ ergs/s



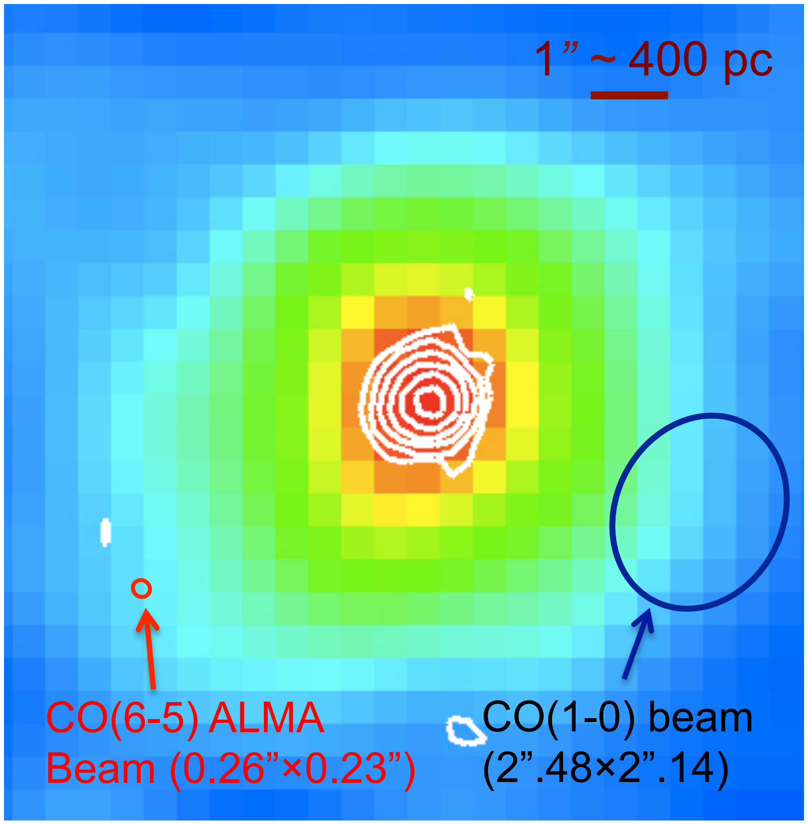
Warm and cold CO components (Zhao et al. 2014, in prep.)



[From running the non-LTE code RADEX code (van der Tak et al. 2007)]

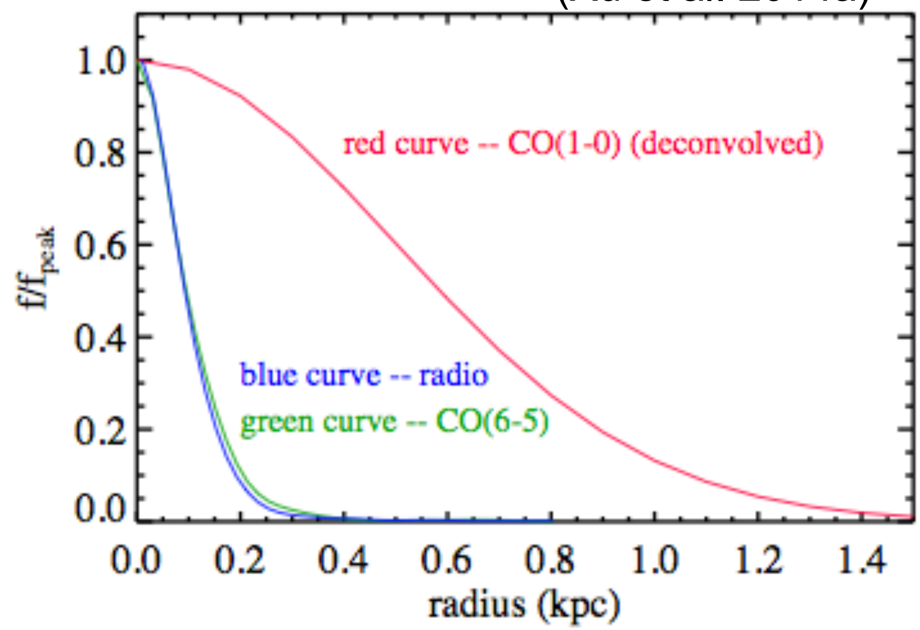
Warm vs. Cold Molecular Gas: Case Study -- NGC 34

White contour: ALMA CO(6-5) – a smooth rotating circumnuclear disk of d ~ 200 pc;
Image: CARMA CO(1-0) (Fernandez et al 2014)



(Xu et al. 2014a)

(Xu et al. 2014a)

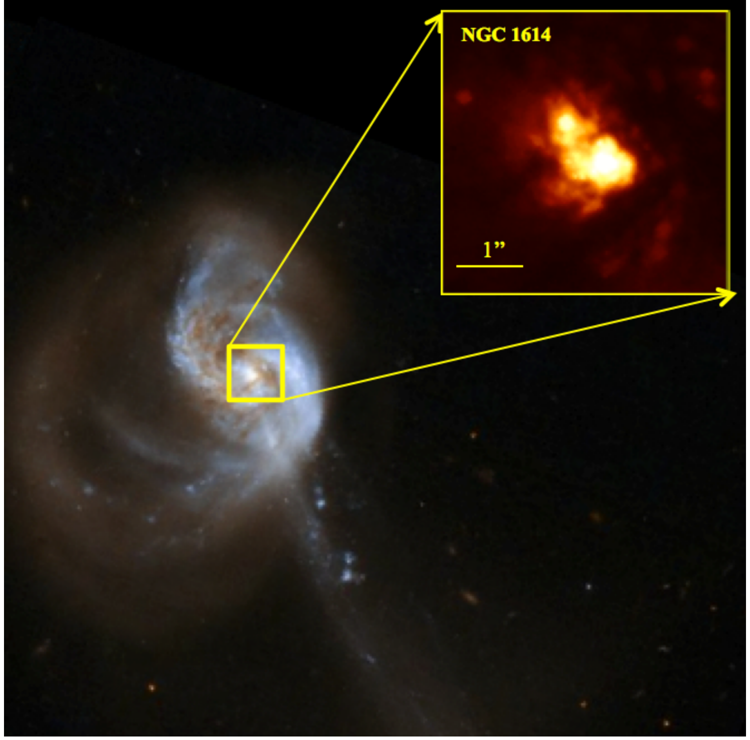


- Green curve & contours: ALMA CO(6-5) at ~100 pc resolution
- Blue curve: radio continuum @ 8.44 GHz (at ~122 pc resolution)

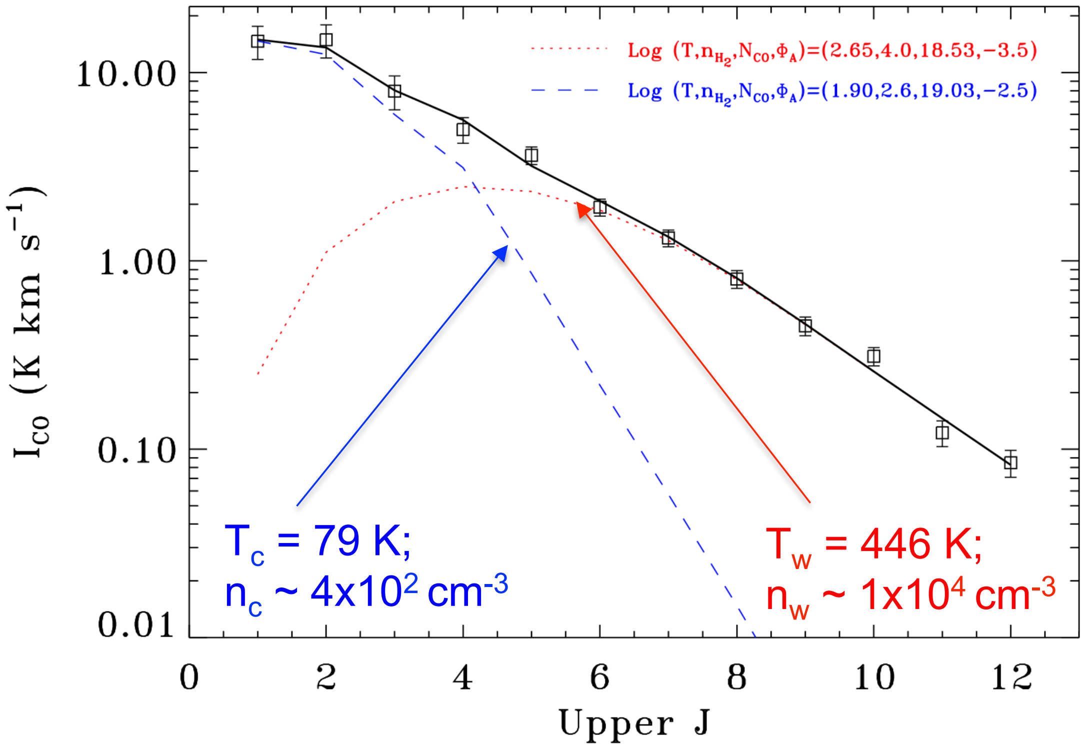
Warm vs. Cold Molecular Gas: Case Study – NGC 1614

NGC 1614: minor merger, starburst

- $L_{IR} = 10^{11.65} L_{\odot}$
- D = 67.8 Mpc (0".25 ~ 80 pc)
- Minor merger (m/M ~ 1/5)
- No AGN?



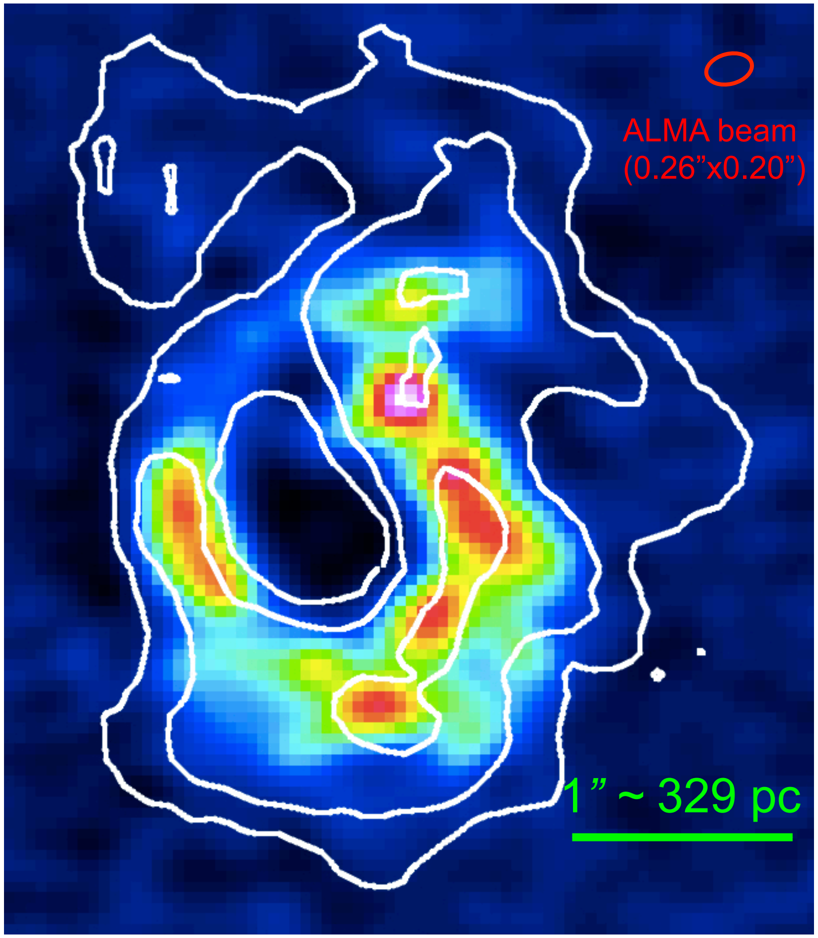
Warm and cold CO components (Zhao et al. 2014, in prep.)



[from running the non-LTE code RADEX code (van der Tak et al. 2007)]

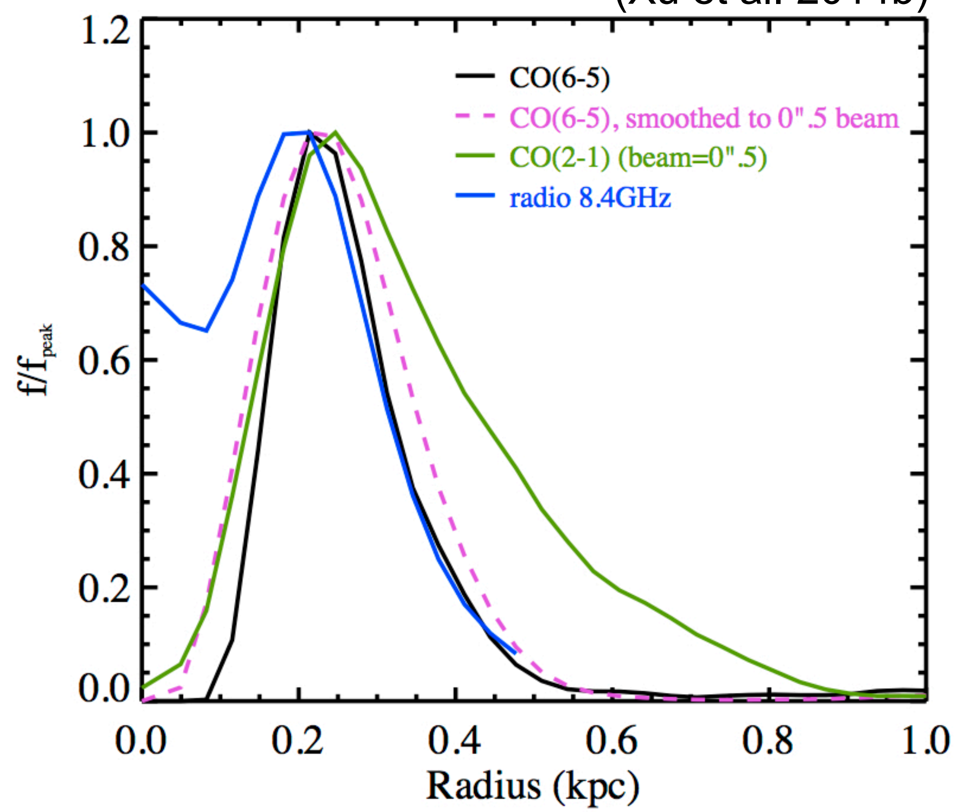
Warm vs. Cold Molecular Gas: Case Study – NGC 1614

Image: ALMA CO(6-5) – a rotating ring of r = 100-350 pc, with molecular clumps;
White contours: CO (2-1), beam ~0.5” (König et al 2013)



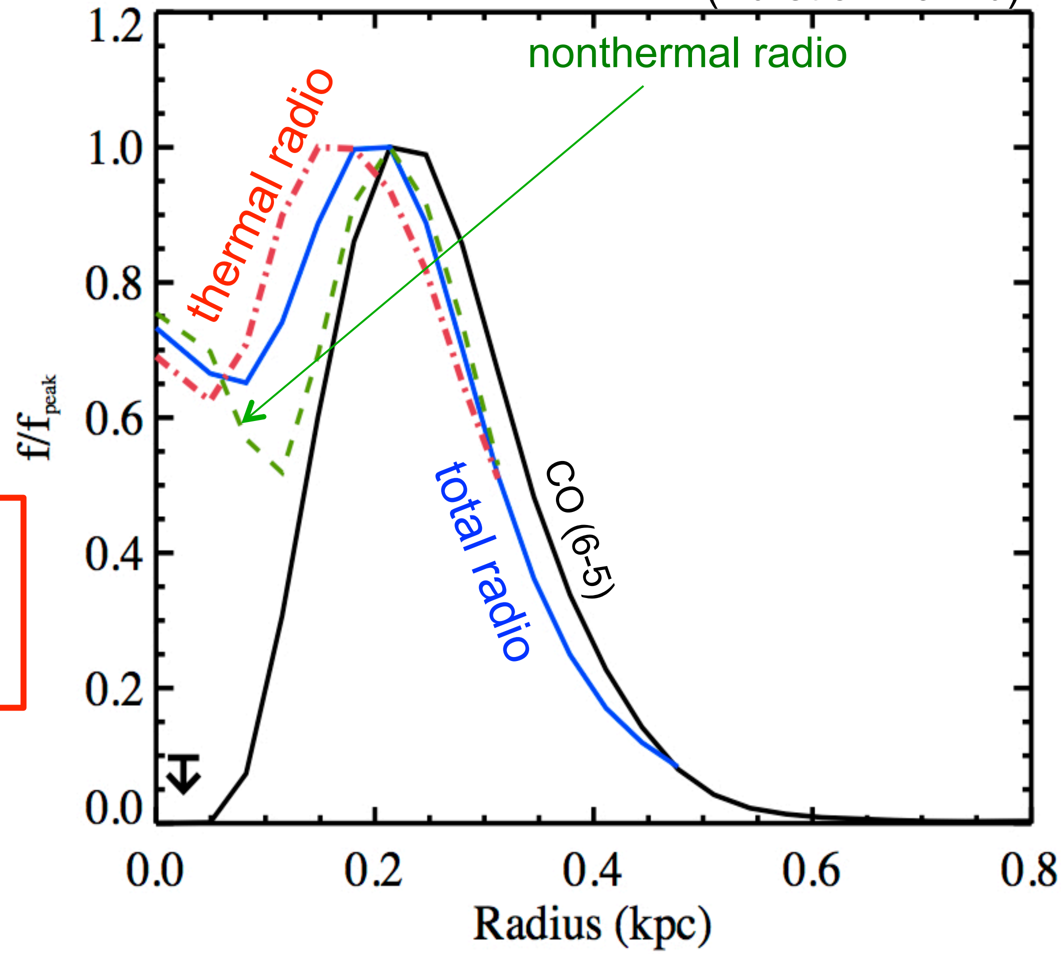
(Xu et al. 2014b)

(Xu et al. 2014b)



Warm vs. Cold Molecular Gas: Case Study – NGC 1614

(Xu et al. 2014b)



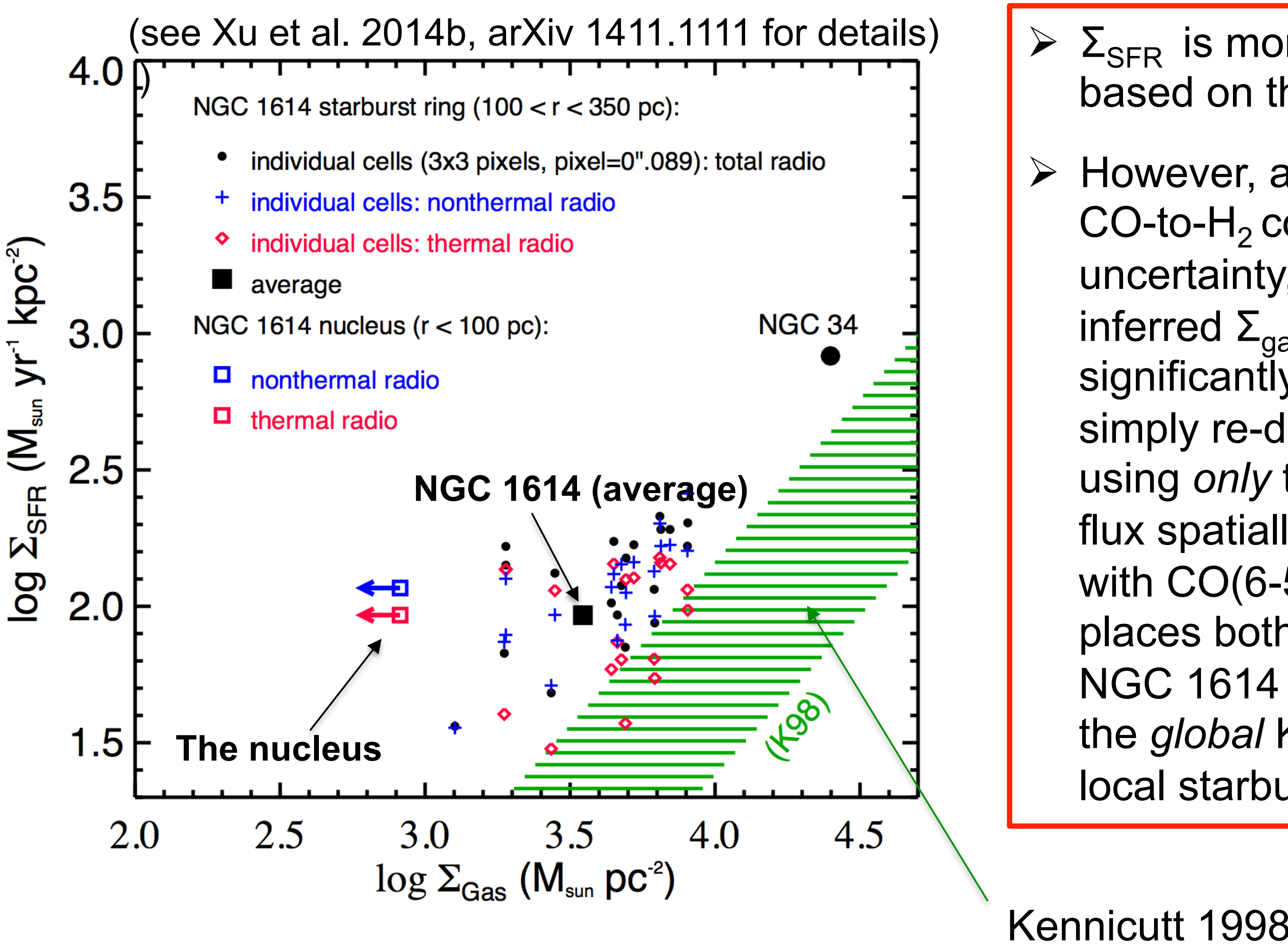
Little gas <100pc!
but on-going SF:

SF feedback?

* thermal radio from Pa-α after extinction

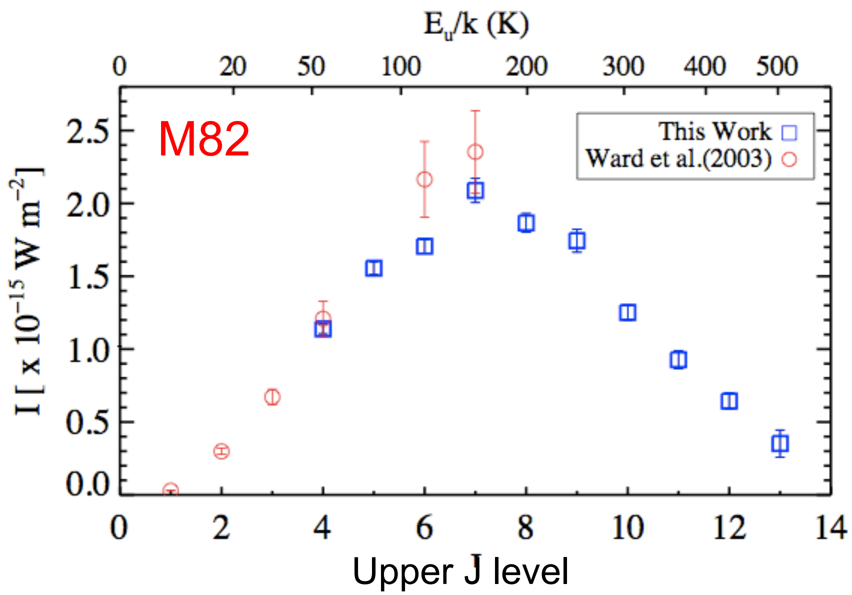
CO (6-5) corresponds best to the non-thermal radio emission

Help Understanding the Bimodal SF Relation

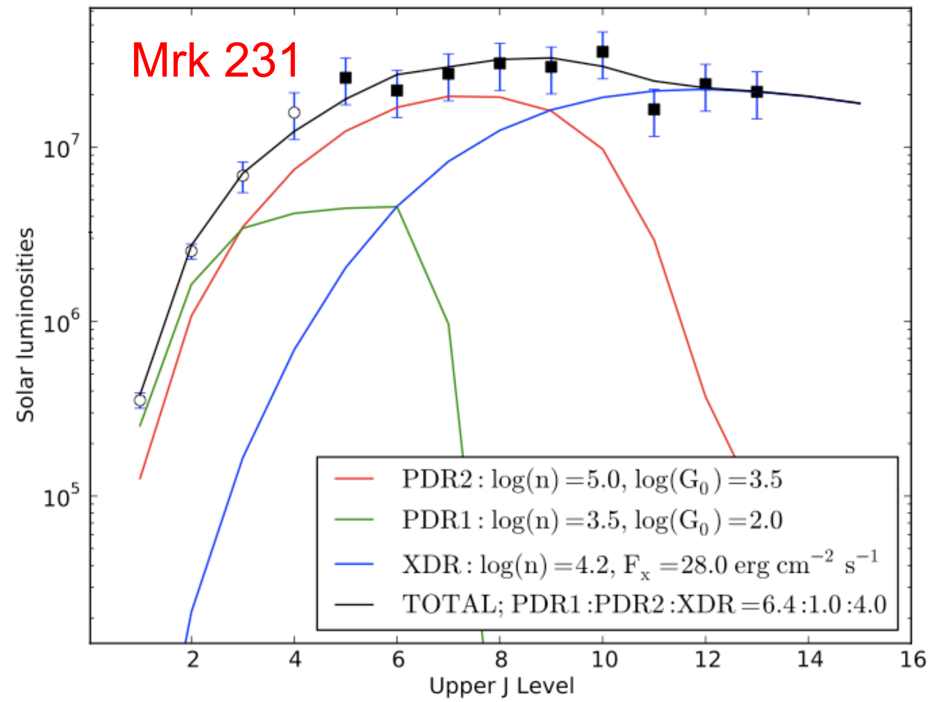


- Σ_{SFR} is more or less fixed, based on the radio data.
- However, aside from the CO-to-H_2 conversion uncertainty, the CO(1-0)-inferred Σ_{gas} could be significantly reduced if one simply re-derives Σ_{gas} by using *only* the CO(1-0) flux spatially coinciding with CO(6-5). Doing so places both NGC 34 & NGC 1614 to the left of the *global* K-S law for the local starbursts

CO SLED Difference: Starburst vs. AGN Gas Heating



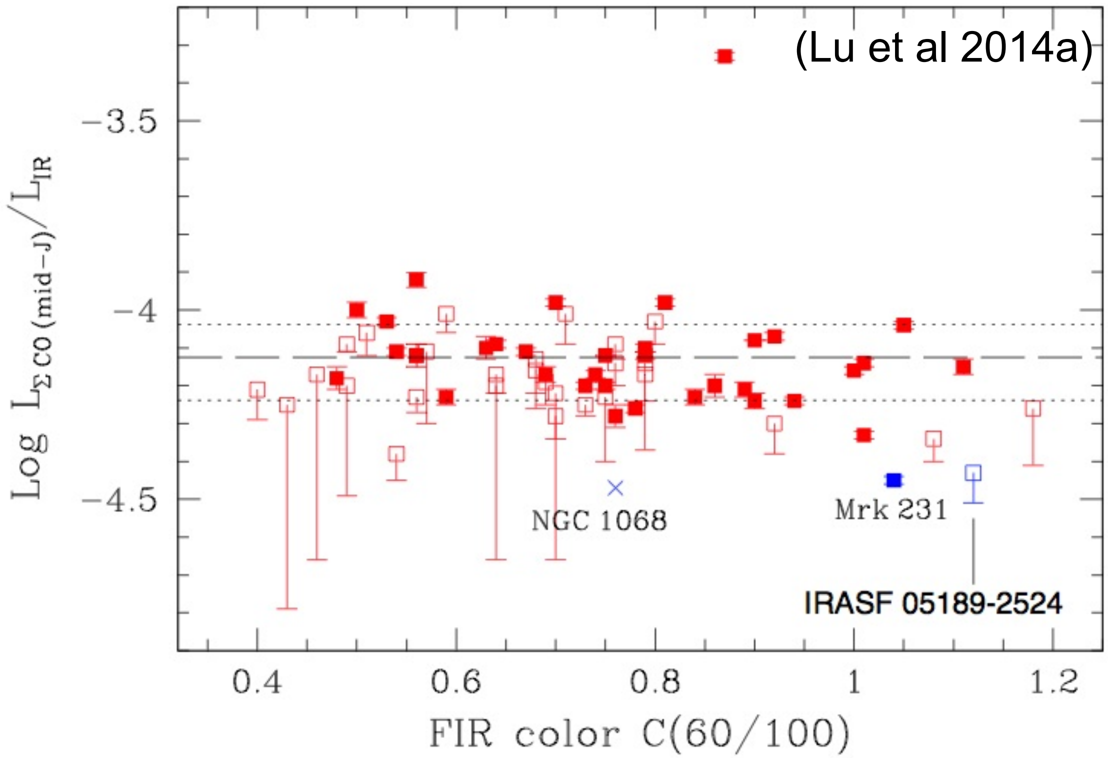
(Panuzzo et al 2010)



(Van der Werf et al 2010)

AGN and Hot Molecular Gas

(NGC 1068 data from Spinoglio et al. 2012)

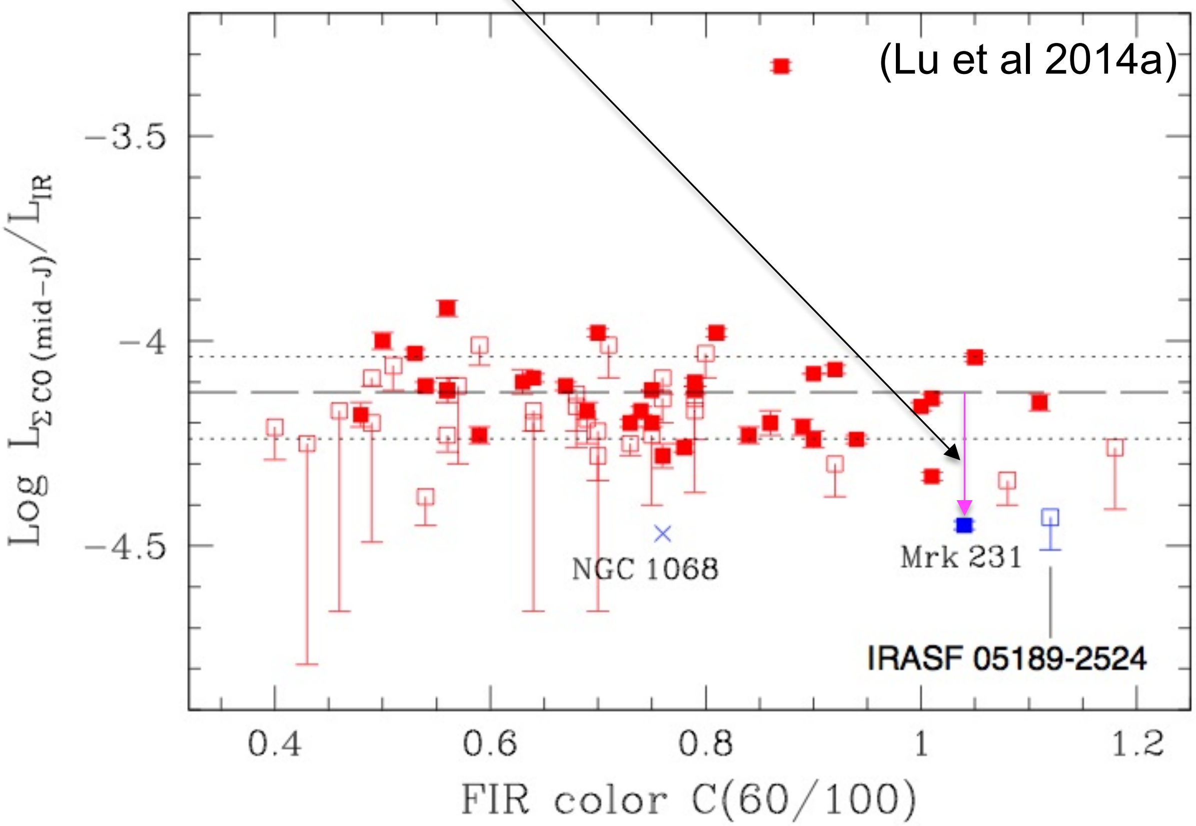


- Galaxies with a significant AGN tend to have a lower CO/IR ratio.
- X-ray photon heating leads to CO emission peaking at J > 10 (Spaans & Meijerink 2008).
- Both NGC 1068 & Mrk 231 known to have strong CO lines at J > 10 (Hailey-Dunsheath et al. 2012; Fischer et al. 2013).
- ➢ Observed lower mid-J CO/IR ratios because we missed the CO cooling of the hot gas component associated with the AGN.

Red: Starbursts (f_{AGN} < 40%)
Blue: With significan AGN (f_{AGN} ~ 56% for Mrk231; ~ 41% for IRASF 05189-2524; and ~ 50% for NGC 1068)

AGN and Hot Molecular Gas

Vertical displacement = log [1 – (L_{AGN}/L_{IR})]



Directly measure the fractional dust heating from the AGN:

- For Mrk 231:

  L_{AGN}/L_{IR} ~ 52 (+/-10%), in good agreement with f_{AGN} = 56% from our mid-IR diadonostics.

- For NGC 1068:

  L_{AGN}/L_{IR} ~ 54%, also in agreement with earlier estimate of ~ 50% (e.g., Telesco & Decher 1988).

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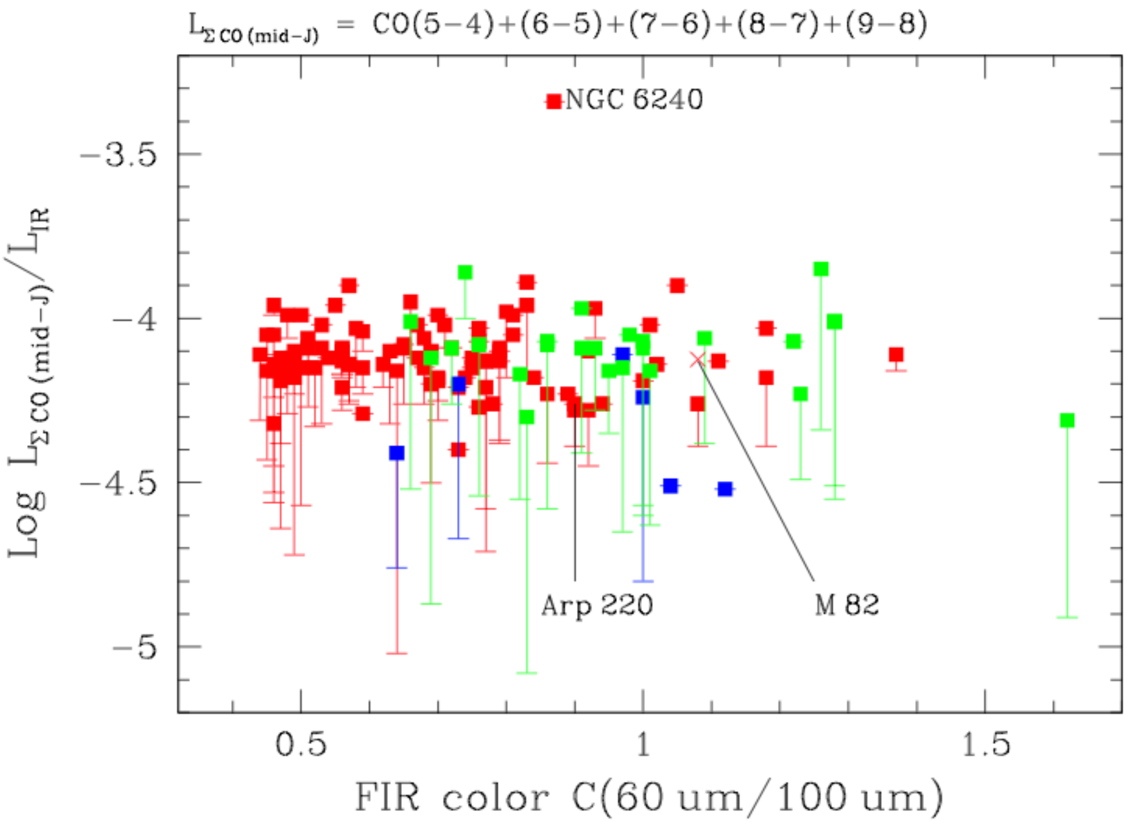
Blue: AGN;
Red: non AGN.

NGC 6240 is Truly Remarkable



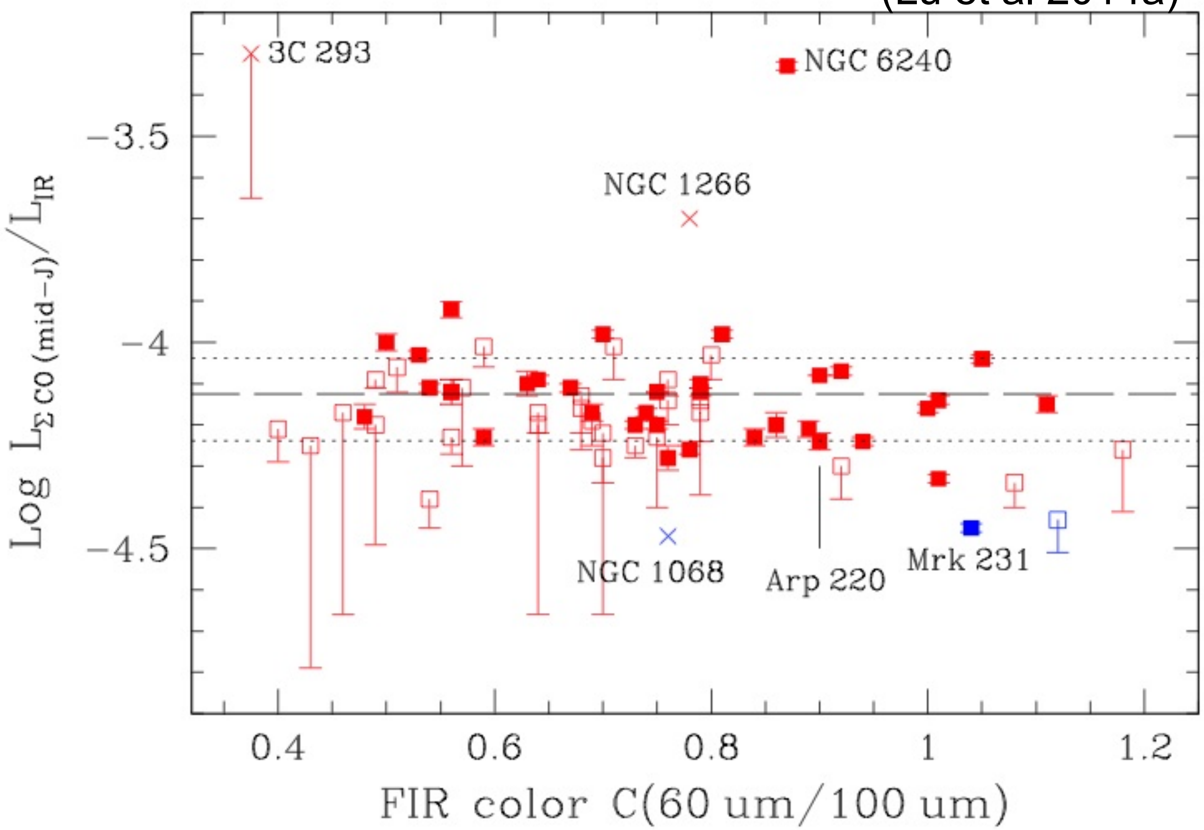
- NGC 6240 has exceptionally strong steller super winds. However, this is unlikely the explanation:
  - Dust heating of the far-UV photon counterpart of the super stellar winds should result in a more normal CO/IR ratio.
  - Other superwind galaxies (e.g., Arp 220, M82) do show normal CO/IR ratios.

- Red: 97 starbusrts in our GOALS/FTS sample
- Blue: 6 AGNs (with f_{AGN} > 40%) in our GOALS/FTS sample
- Green: 25 additional local ULIRGs from the Herschel archive

Note: Only galaxies that are spatially unresolved by SPIRE/FTS are plotted.

Or Maybe not that Remarkable?
Possible Gas Heating by Shocks Not Derived from Current SF

(Lu et al 2014a)



Non-SF triggered shocks can easily enhance the warm CO/IR ratio:

- NGC 1266: Possible shocks associated with AGN-driven molecular outflows (Alatalo et al. 2011).
- 3C 293: Possible radio-jet driven shocks (Ogle et al. 2010).

Blue: AGN;
Red: non AGN.

- 3C 293: Archival FTS data (PI: P. Papadopoulos)
- NGC 1266 (Pellergrini et al. 2013)

Summary

- The observed CO SLEDs of the (U)LIRGs change on average from one peaking at J ≤ 4 to a broad distribution peaking around J = 6 or 7 as the intensity of the dust heating radiation field increases.
- A simple but adequate picture that can describe molecular CO gas in most LIRGs involves 2 gas components: (a) a "cold," less dense gas, which emits CO lines primarily at J < 4, is not directly related to current SF, and (b) a warm component, which emits CO lines mainly in the mid-J regime (5 ≤ J ≤10).
- For the vast majority of the starburst (U)LIRGs, the ratios of the total luminosity of the warm CO line emission (5 ≤ J ≤10) to L_{IR} show a well defined characteristic value, R_{SF}, suggesting strogly that current SF is the power source for both the warm CO and IR dust emissions. This is confirmed by our high-resolution ALMA maping in CO (6-5).
- For galaxies with an energetic AGN, a 3rd, hot gas component could become significant, which emits CO lines primarily at J > 10.
- We showed rare galaxy examples where energetic shocks unrelated to the current SF may enhance the warm CO line emission relative to the IR dust emission.