Radiative and mechanical feedback in the molecular gas in (Ultra)Luminous Infrared Galaxies

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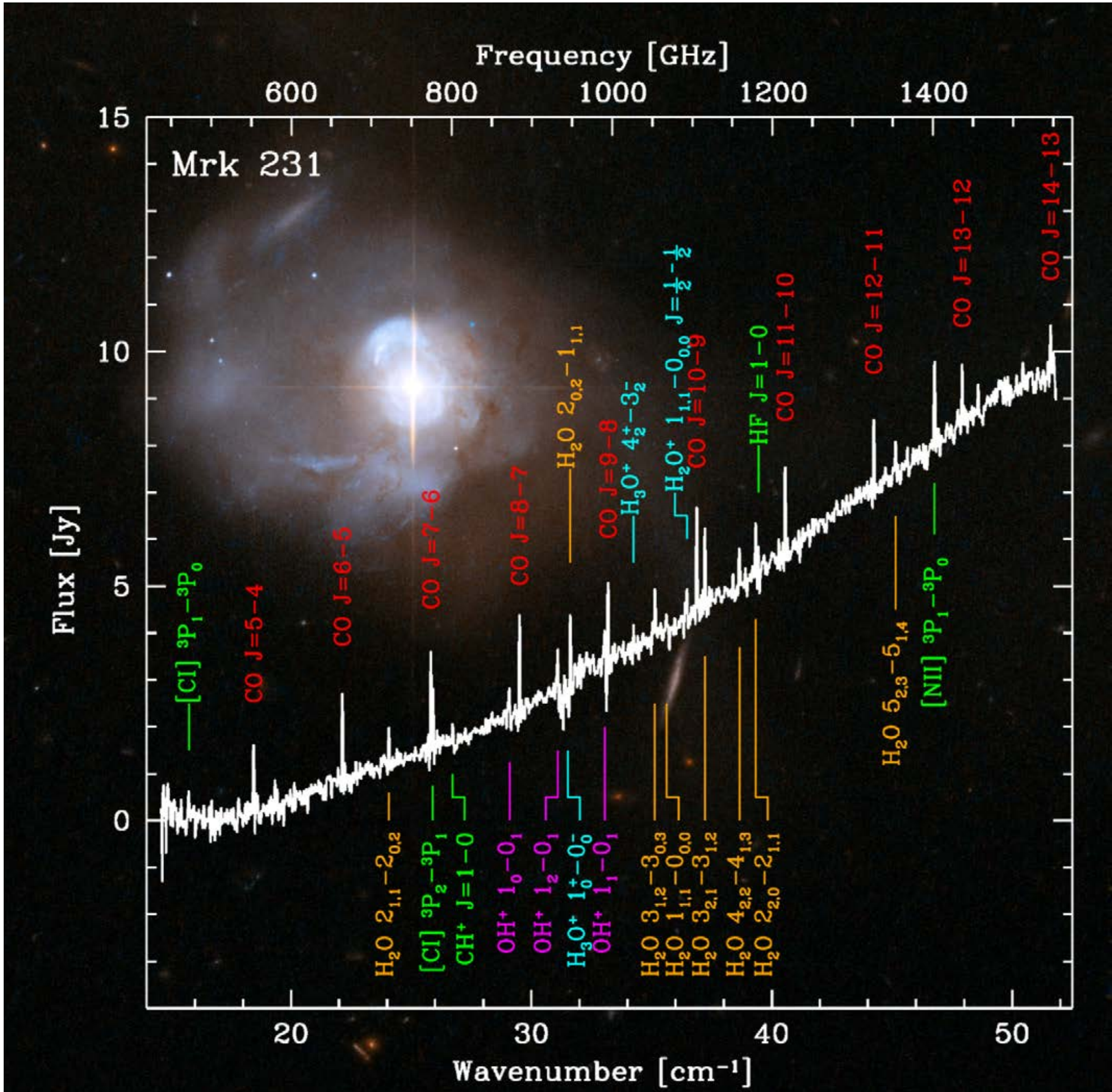
+ the HerCULES team

Outline

- Review of early SPIRE/FTS results
- CO as a probe of what?
- Tracing molecular gas mass

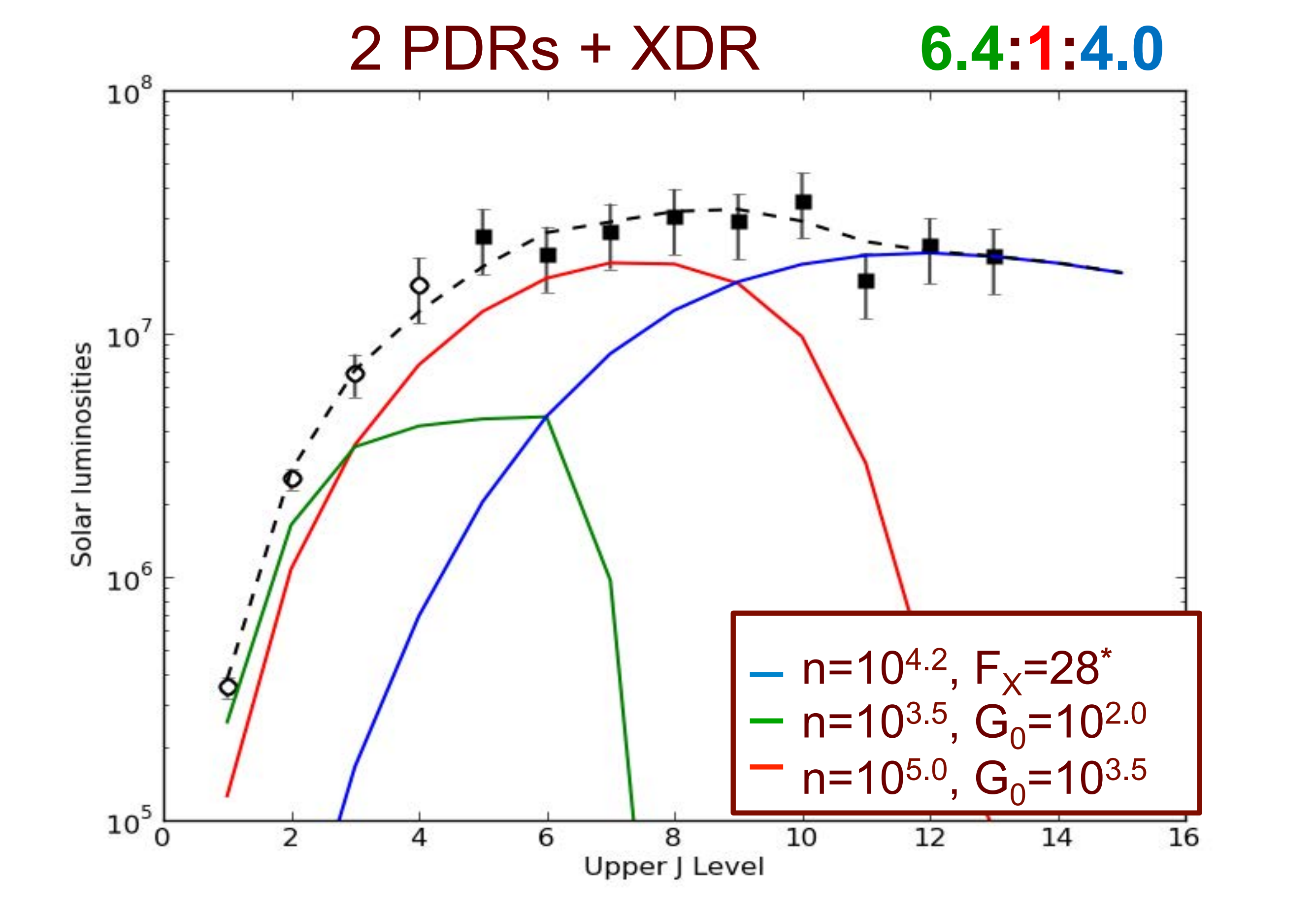


(Van der Werf *et al.*, 2010)

Mrk231 SPIRE FTS

- At z=0.042, one of the closest QSOs (D_L=192 Mpc)
- With $L_{IR} = 4\cdot10^{12}\,L_\odot$, the most luminous ULIRG in the IRAS Revised bright Galaxy Sample
- “Warm” infrared colours
- Star-forming disk (~500 pc radius) + absorbed X-ray nucleus
- Face-on molecular disk, $M_{H_2} \sim 5\cdot10^9\,M_\odot$

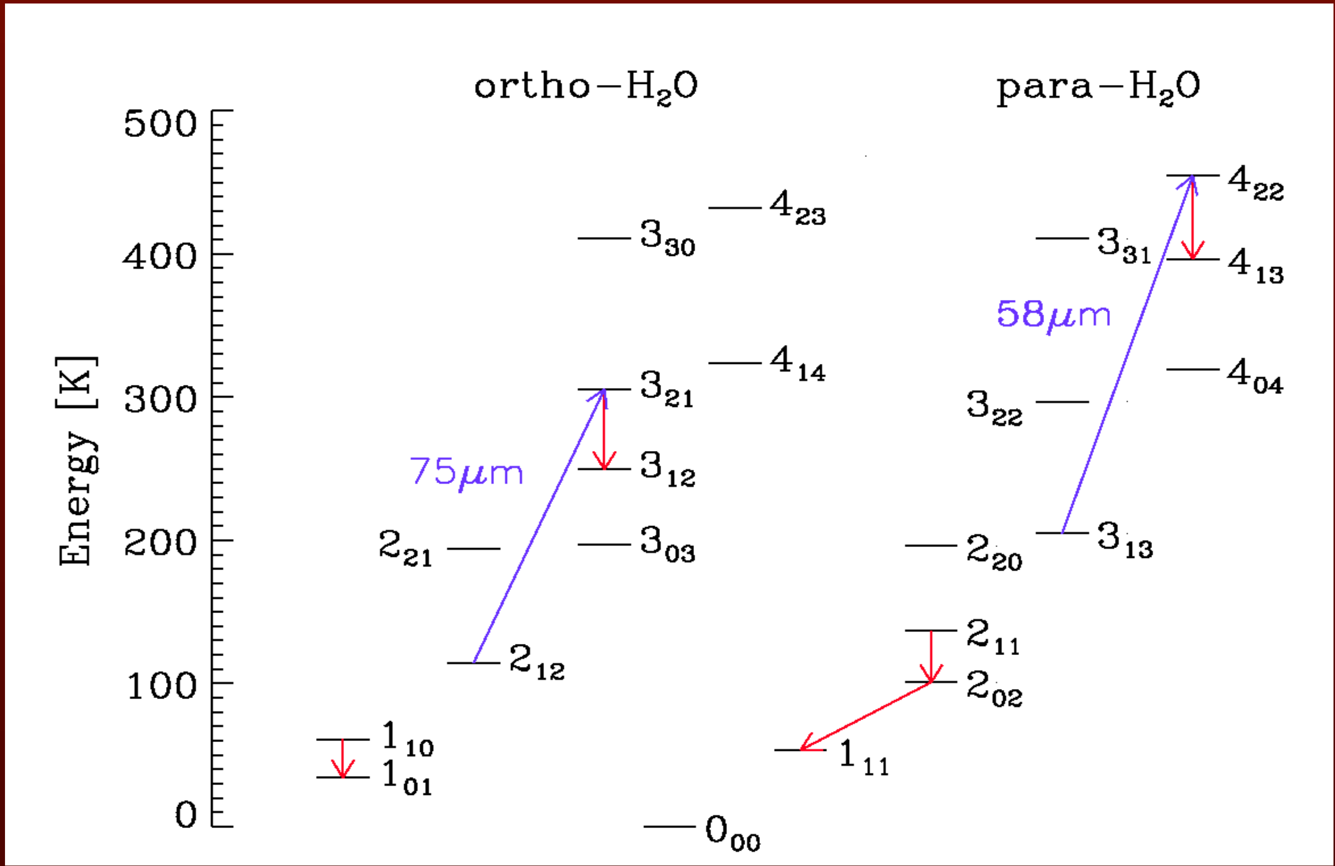
CO excitation in Mrk231



* 28 erg cm^{-2} s^{-1} → $G_0=10^{4.2}$

- High-*J* lines require XDR
- Low-*J* lines powered by star formation.

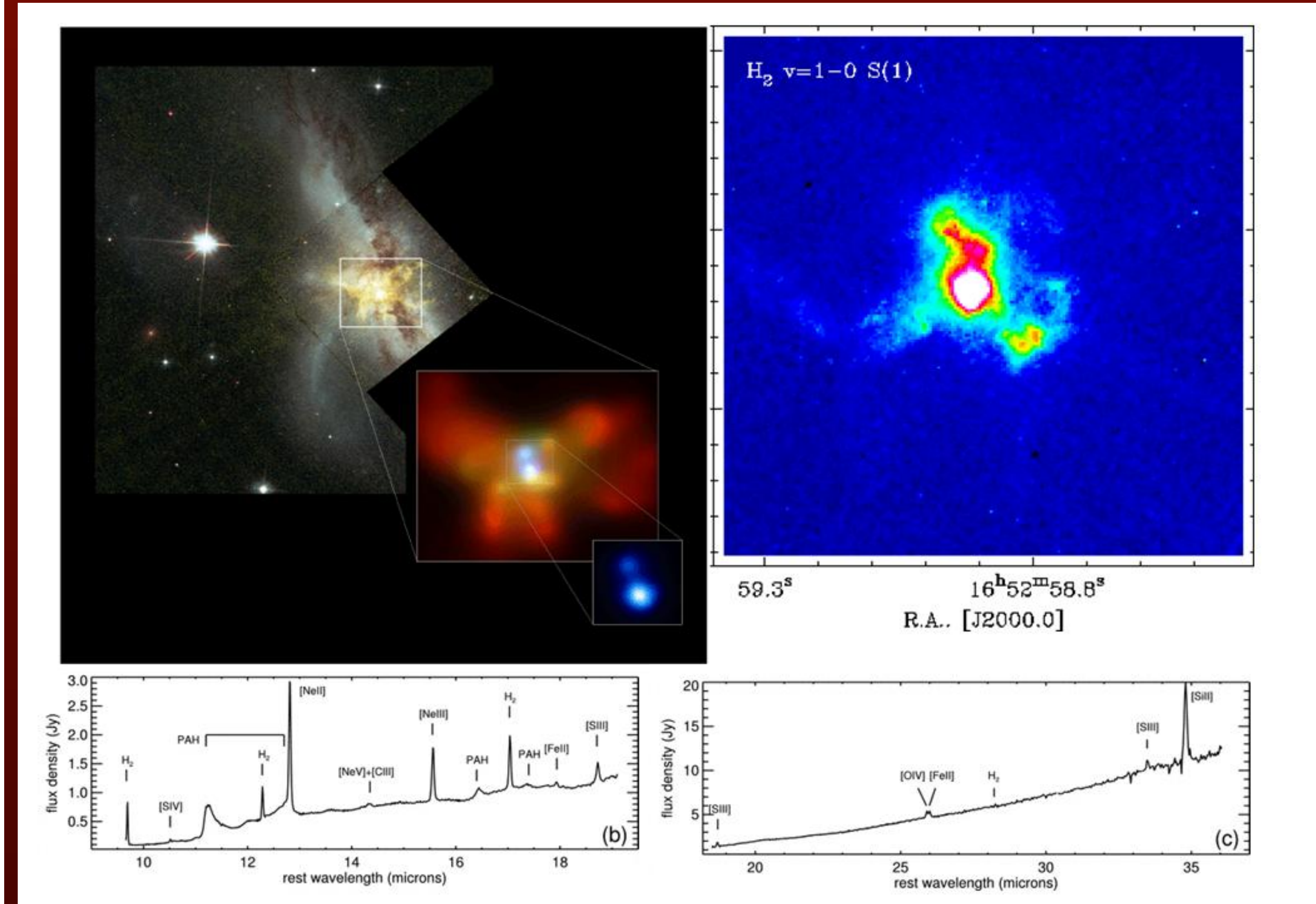
H_2O excitation in Mrk231



- Radiative pumping dominates
- H_2O probes the temperature and intensity of the local IR radiation field

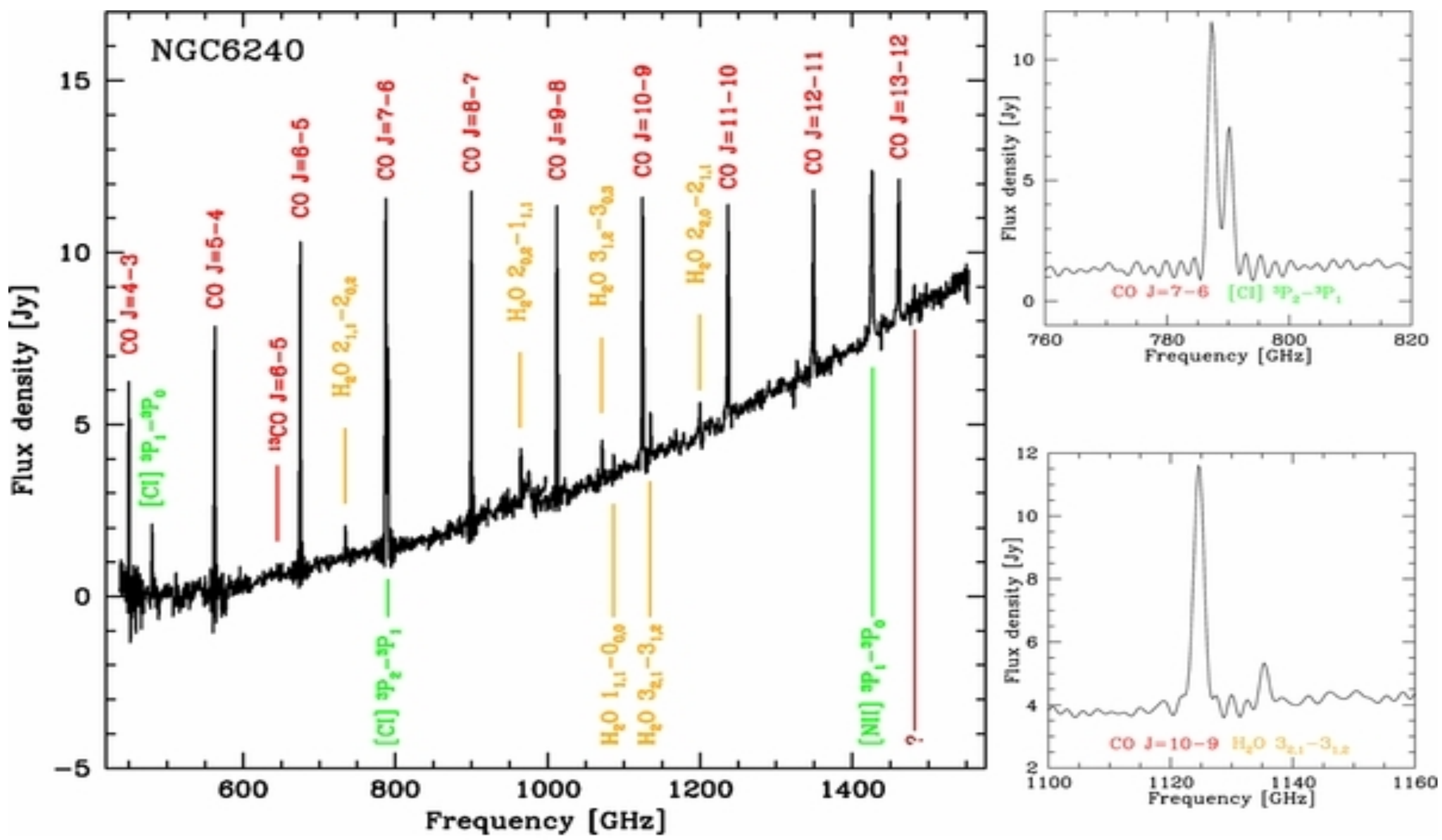
(González-Alfonso *et al.*, 2010)

NGC6240 – shocked gas



- LIRG, merger, 2 nuclei separated by 1.8″
- Molecular gas concentrated between the nuclei
- Gas excitation mostly by shocks/ dissipation of mechanical energy
- Bright H_2 emission confirms this

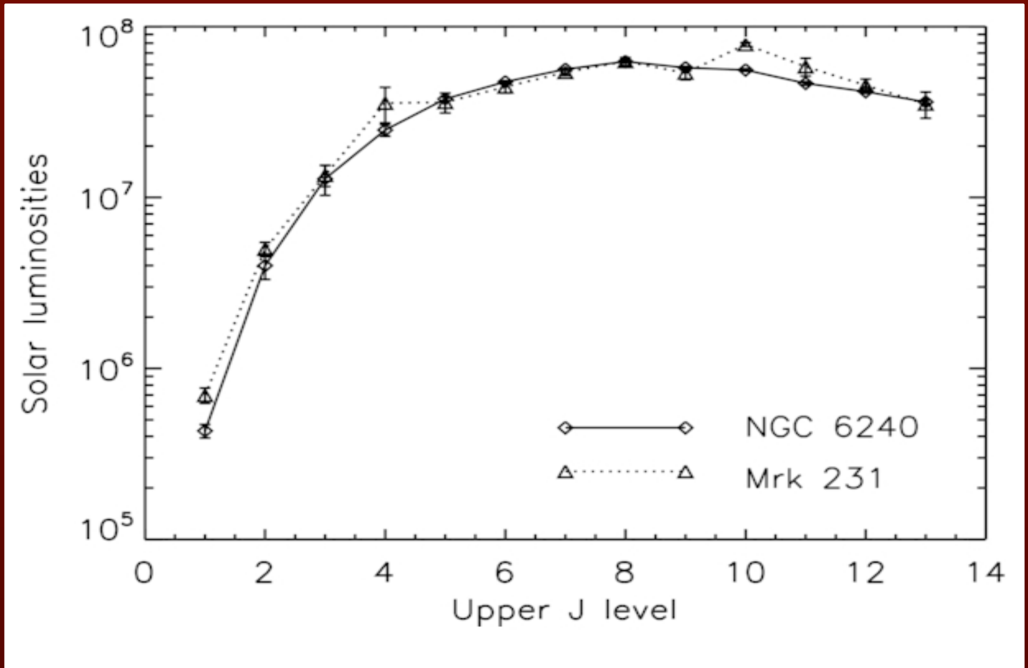
CO lines in NGC6240



- High excitation CO ladder
- Very high Line/Cont ratio
- Shock excitation dominates

(Meijerink *et al.* 2013)

CO ladders: excited or shocked?

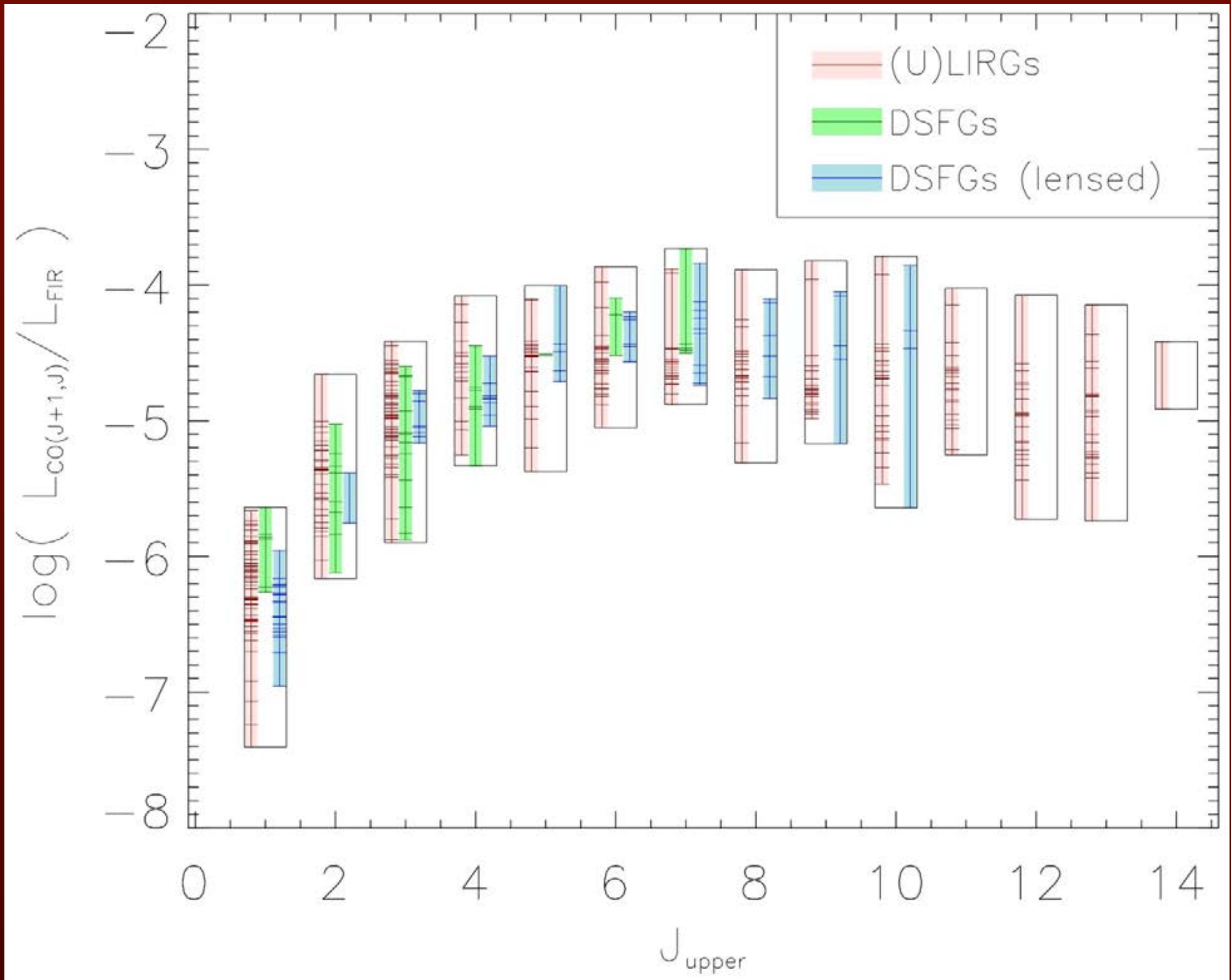


- CO ladders of Mrk231 (X-ray excited) and NGC6240 (shocked) are very similar

(Meijerink *et al.*, 2013)

Taken by itself, the CO ladder is not a clean probe of physical processes! Addition information is needed (an often available).

CO ladders: general trends



- CO excitation increases with L_{IR} and F_{60}/F_{100} colour: warm gas and warm dust correlate
- Multiple excitation components always present in starburst galaxies/LIRGs/ULIRGs

(see also Lu *et al.* poster)

(see Greve *et al.* poster)

NGC 253

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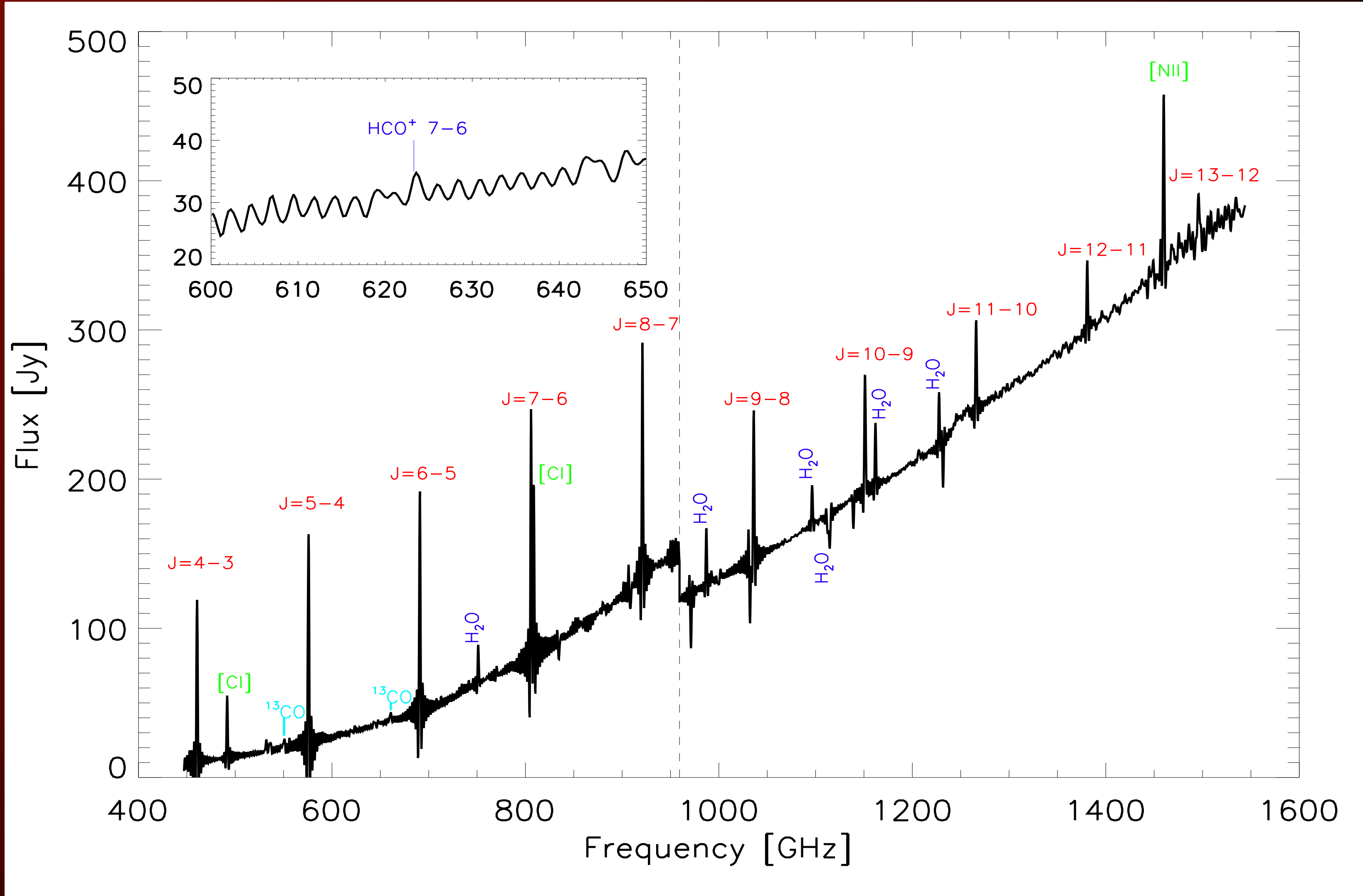
- Nearby starburst
- 2.5 Mpc (1″≈12pc)
- Starburst in inner 200 pc
- $L_{FIR} = 2 \times 10^{10}\, L_{\odot}$

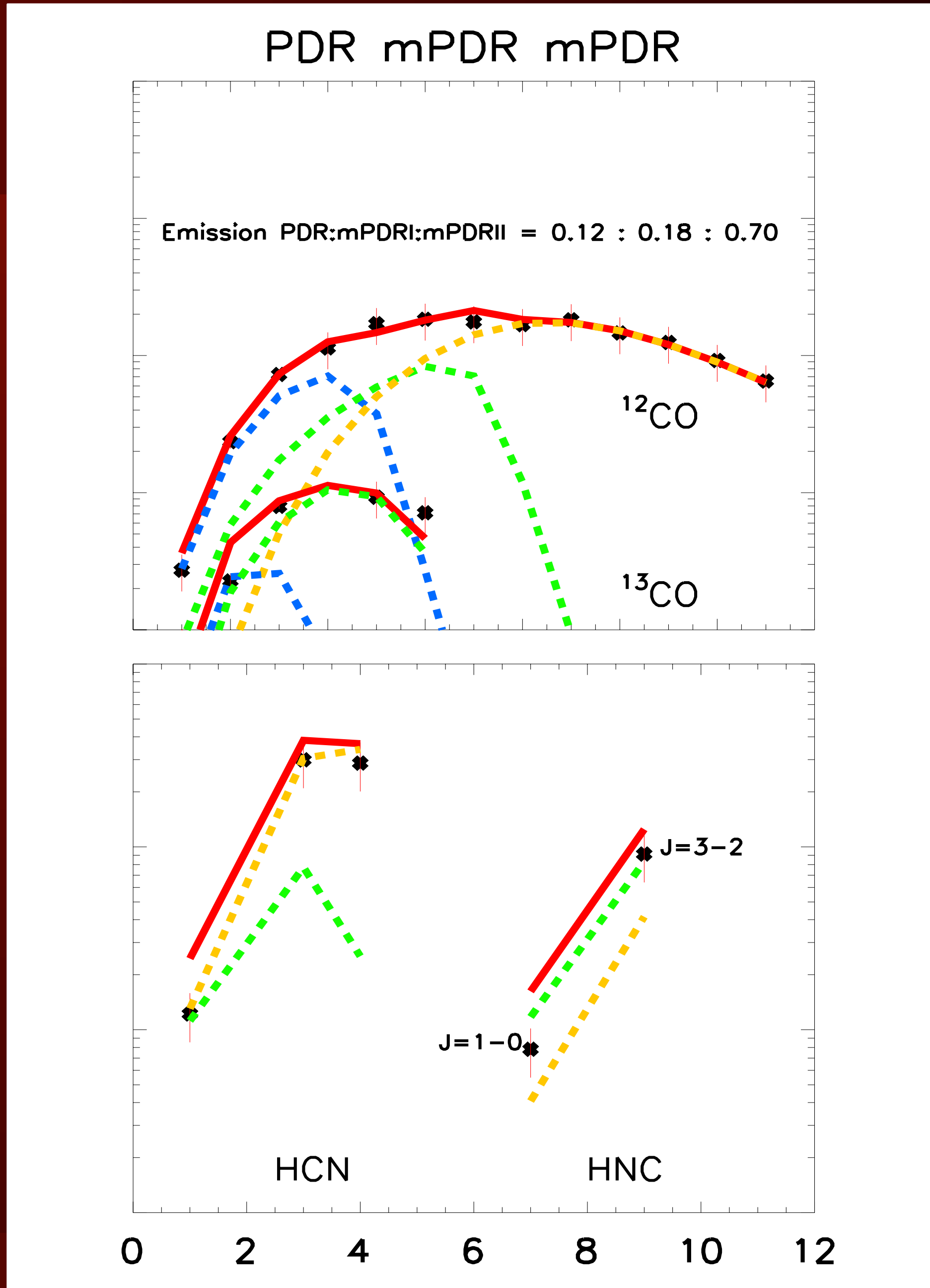
NGC253: SPIRE/FTS



(Rosenberg *et al.*, in prep, and talk at this conference)

NGC253
CO ladder

- Simultaneous fit to ^{12}CO, ^{13}CO, HCN and HNC ladders
- Three excitation components required
- >70% of CO emission from high-excitation component
- Excitation mechanism?



CO excitation in NGC253

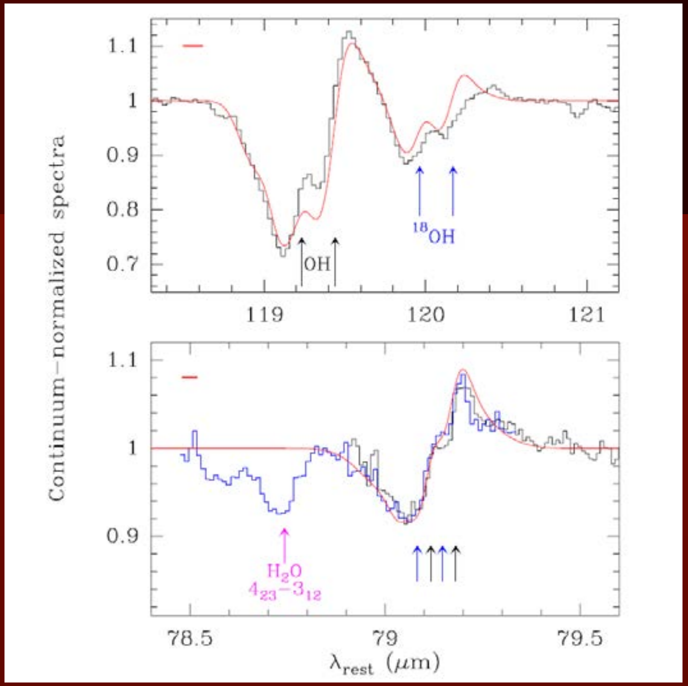
- Photon heating (PDRs) is not sufficient to produce the medium and high excitation gas components in NGC253
- Additional heating: mechanical (dissipation of turbulence) or cosmic rays; cf., Bradford et al. (NGC253), Rangwala et al. (Arp220)
- Chemistry (HCN/HNC) favours mechanical heating
- Mechanical heating is the dominant heating mechanism for the warm gas in NGC253
- The need for additional heating is a general result for starbursts/LIRGs/ULIRGs

Sources of mechanical heating

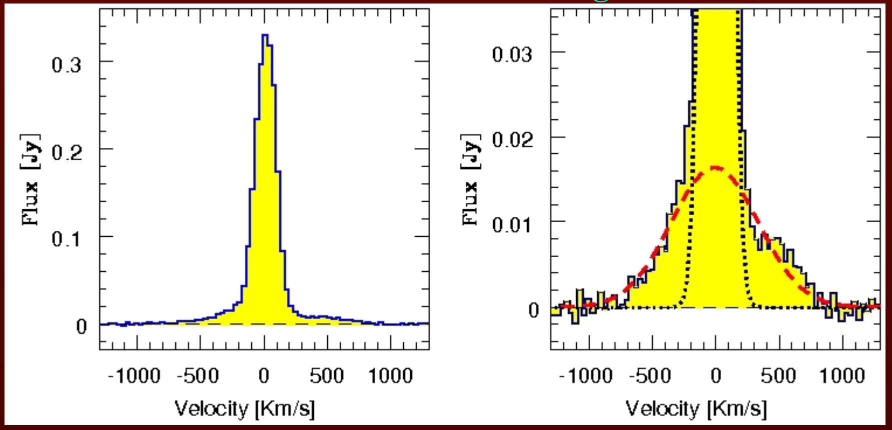
- Supersonic turbulence is very dissipative
- $M_{gas}=10^{11}\ M_\odot$, $\Delta v=400$ km/s, dissipated over a crossing time in a ULIRG:

$$L_{mech} \approx 10^{12}\ L_\odot \approx L_{IR}$$

- What drives this turbulence? Large-scale shocks, outflows, stellar winds, SN explosions, radiation pressure?



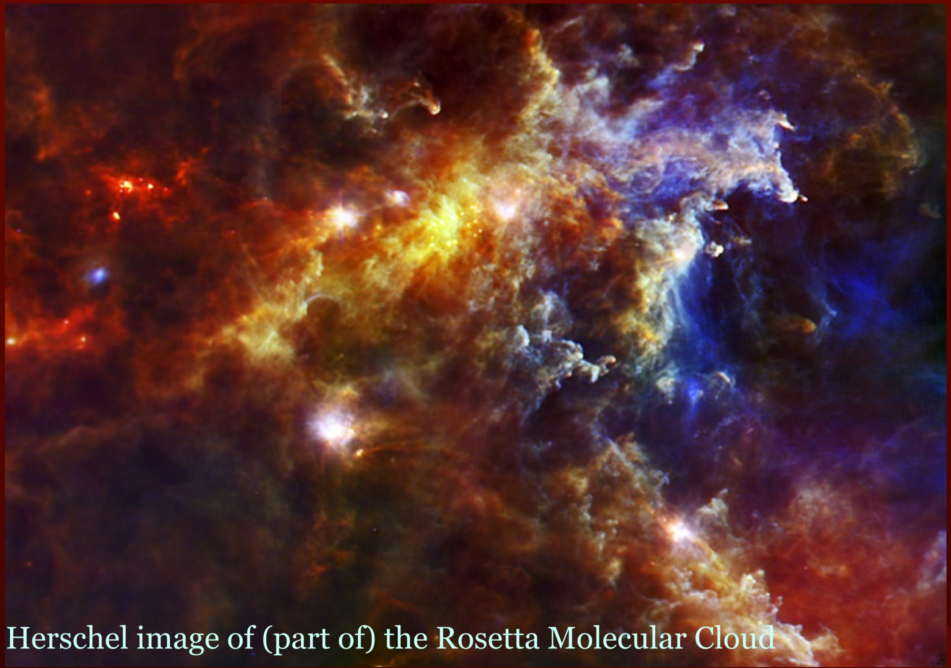
(Fischer *et al.*, 2010)



(Feruglio *et al.*, 2010)

outflows: talks by Sturm, Fischer, poster by Spoon, etc.

Water as a probe



Herschel image of (part of) the Rosetta Molecular Cloud

- Radiative pumping of H_2O lines: derive local FIR flux
- Combine with T_d: implies emission at the blackbody limit
- $\Rightarrow$ Infrared-opaque ($\tau_{100\mu m} \approx 1$) central regions
- Radiation pressure from the strong IR radiation field:

$$P_{rad} \approx \tau_{100} \sigma T_d^4 / c$$

- Can be dominant pressure term and source of local turbulence

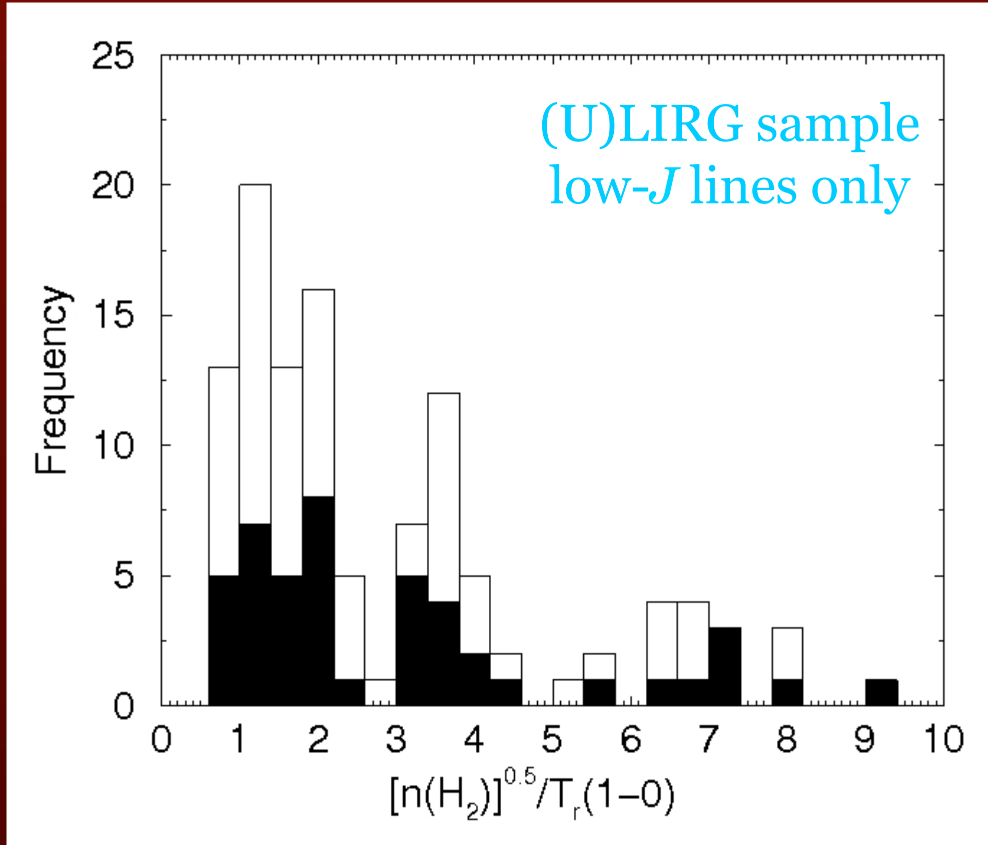
CO and molecular gas mass

- Converting CO flux (luminosity) into H_2 column density (mass):

$$X = \frac{N(\mathrm{H_2})}{I(\mathrm{CO})} = c_1 \left(\frac{n(\mathrm{H_2})}{200\,\mathrm{cm^{-3}}} \right)^{1/2} \left(\frac{T_{\mathrm{line}}}{6K} \right)^{-1}$$

$$\alpha = \frac{M(\mathrm{H_2})}{L'(\mathrm{CO})} = c_2 \left(\frac{n(\mathrm{H_2})}{200\,\mathrm{cm^{-3}}} \right)^{1/2} \left(\frac{T_{\mathrm{line}}}{6K} \right)^{-1}$$

(MW: α=4; ULIRGs: α=0.8)

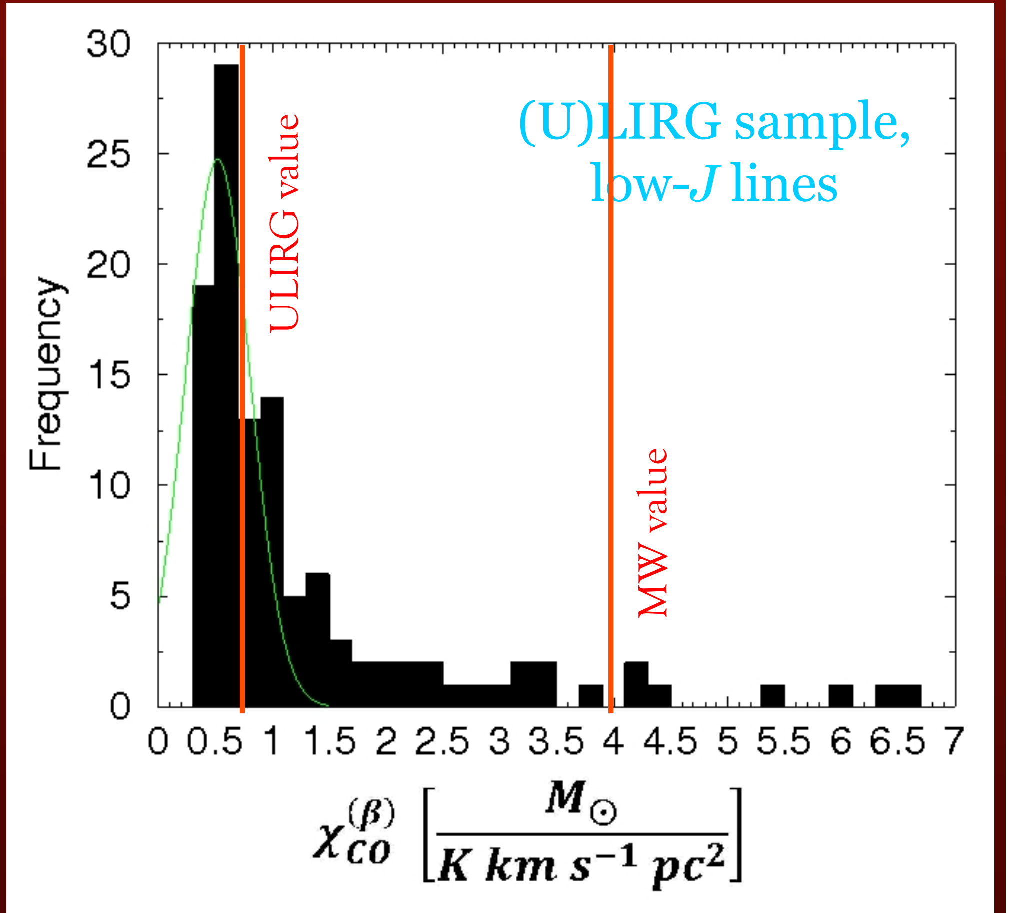


(Papadopoulos, Van der Werf, Isaak & Xilouris, 2012)

X-factors based on low CO lines only

Assumptions:

- One gas component
- Based on low-*J* CO lines only



Results:

- α-values cluster between 0.5 and 1 with tail up to and exceeding Milky Way values

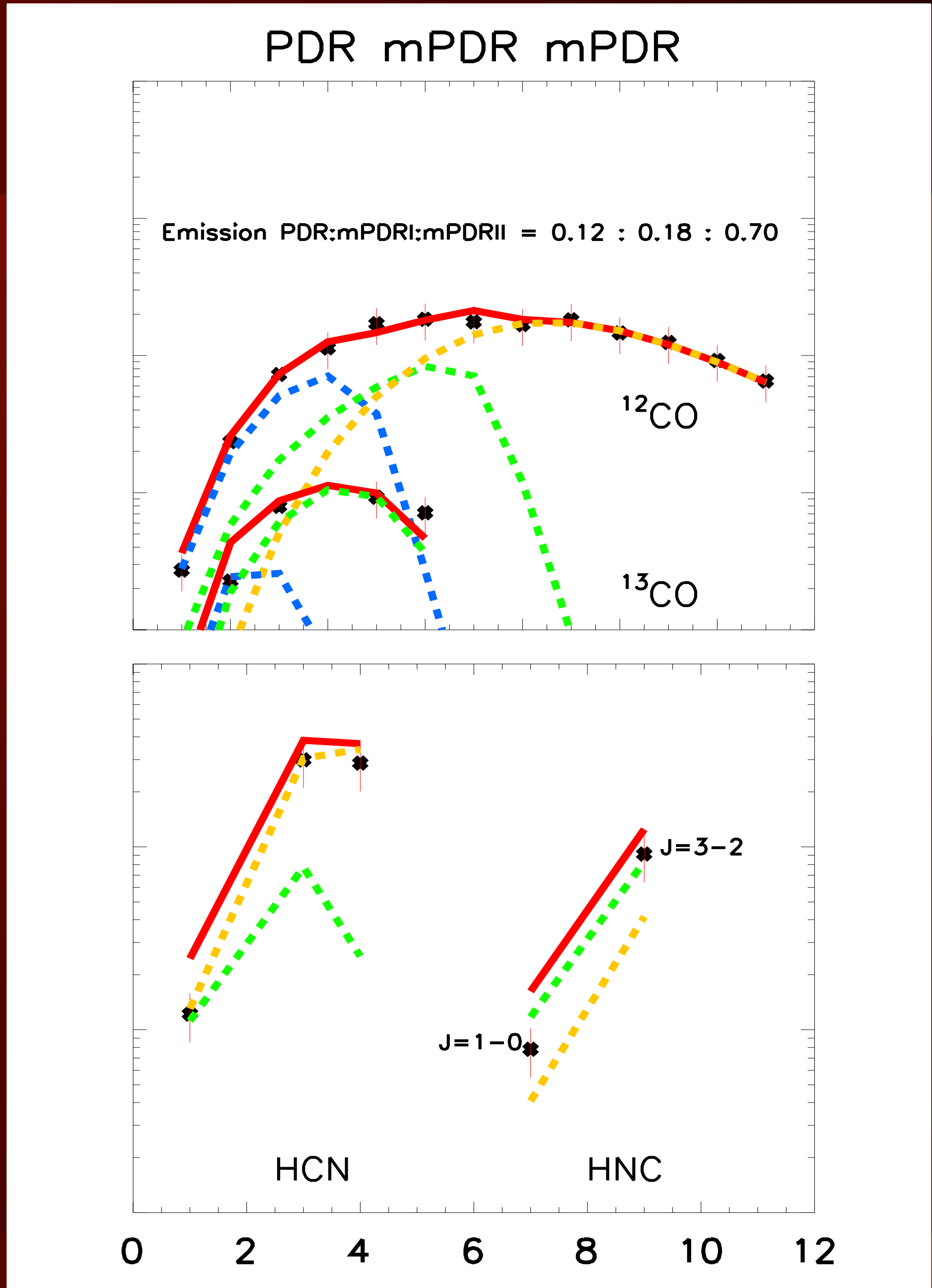
But:

- Higher CO lines and density tracing lines reveal a substantial dense gas component

(Papadopoulos, Van der Werf, Isaak & Xilouris, 2012)

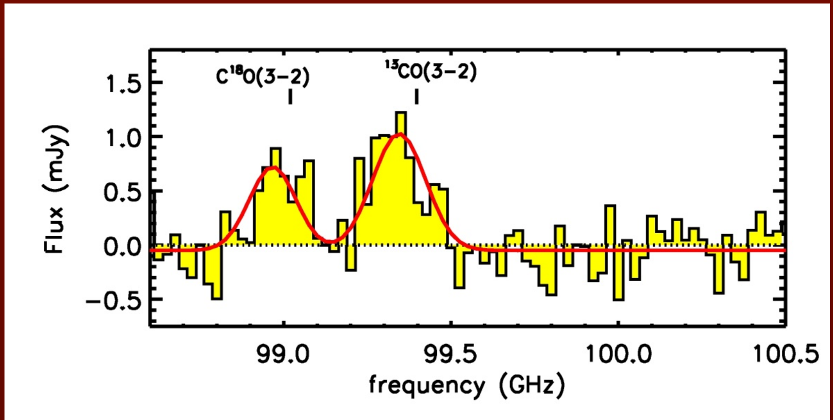
Molecular gas masses in NGC253

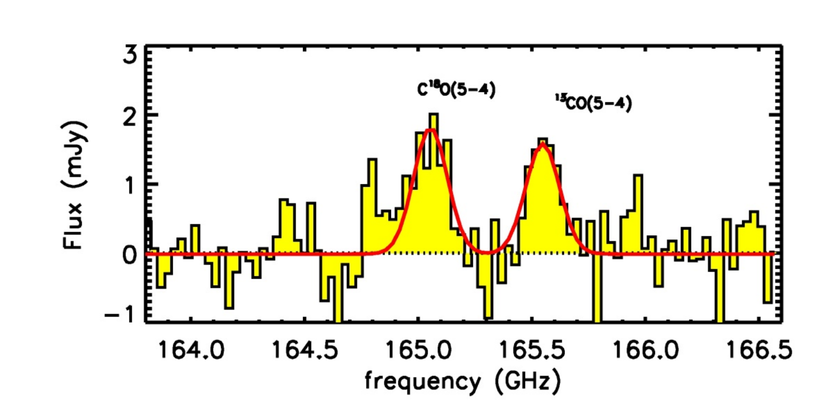
- The three components have comparable H_2 masses!
- Low-*J* CO lines alone miss a significant amount of molecular gas
- In ULIRGs, most mass may be in high-excitation component, not seen in low-*J* lines – to be verified



Tracing molecular gas mass

- Warning: discussions of this have been the death-blow for many conferences.
- CO:
  - Need to deal with CO-dark molecular gas: [CII] – requires abundance and modelling
  - Need multi-line data from 1-0 (2-1) to at least 9-8
  - Need additional information to beat down degeneracies (e.g., HCN)
  - Use of ^{13}CO to get at CO optical depth is problematic due to possibly redshift-dependent abundance ratio
  - Calibration based on CO, [CI], HCN and L_{IR} may be feasible but still needs much work





(Danielson, Swinbank *et al.*, astro-ph/1309.5952)

Can we use dust emission instead?

- To derive M_{gas} from $\mathrm{M}_{\mathrm{dust}}$ a dust/gas ratio is always needed
- A CO molecule is always a CO molecule, but dust grains at low and high redshift likely have different properties
- Need long-wavelength data (ALMA) in order to avoid to probe cool dust and avoid possible optical depth effects near continuum peak
- Need also short-wavelength data to determine T_{d} – but confusion at Herschel resolution (see Swinbank talk)
- Multiple temperature components difficult to disentangle

Summary

- The CO ladder probes the thermal state of the molecular gas, in particular cooling of the warm molecular gas.
- Prominent AGNs produce high-*J* CO lines, but so do shocks
- In star-forming galaxies, photon-heating is typically insufficient to account for the heating of the warm molecular gas; additional (and dominant) heating by cosmic rays or mechanical energy input is needed.
- Mechanical energy input and enhanced cosmic ray fluxes lead to chemical differences which can be separated observationally.
- There can be significant mass in warm CO, which is not traced by low-*J* CO lines.