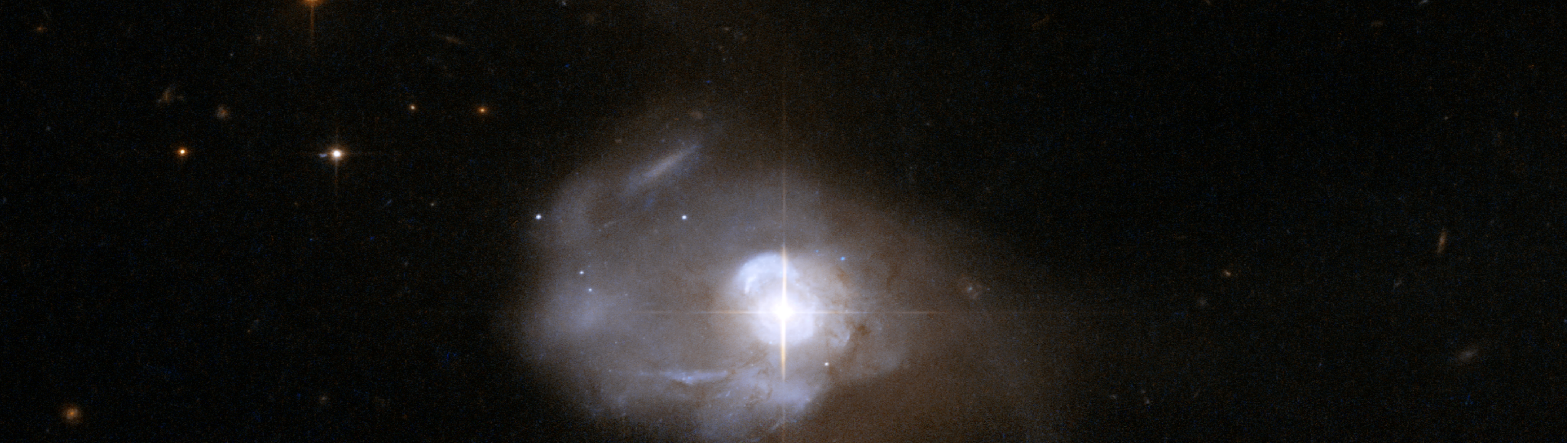
The state and mass of H_2 in starbursts: a new view in the age of Herschel and ALMA



Padelis P. Papadopoulos (School of Physics and Astronomy, Univ. of Cardiff)

Paul van der Werf (Leiden Observatory)

Zhang Zhi-Yu (ESO, ROE)

Axel Weiss (MPIfR, Germany)

Kate Isaak (ESA/ESTEC, The Netherlands)

Yu Gao (Purple Mountain Observatory, China)

Manolis Xilouris, Ioanna Leonidaki (National Observatory of Athens, Greece)

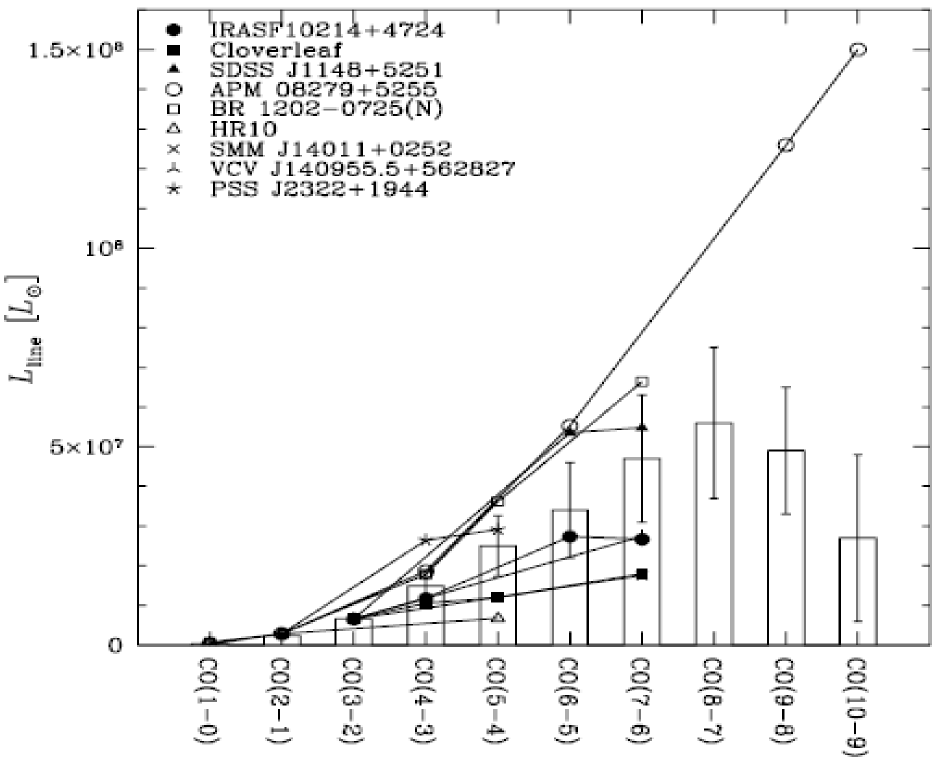
Thomas R. Greve (University College London, UK)

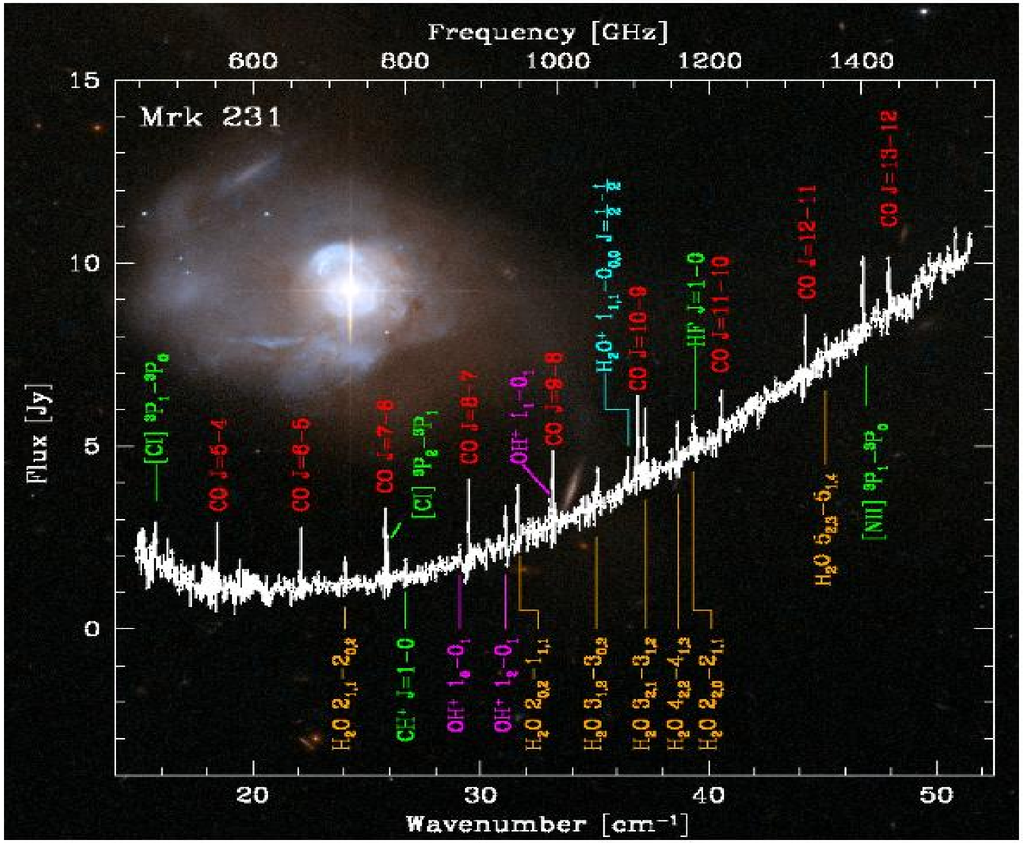
Two fundamental questions

- **What powers the molecular lines in the ISM?** (especially high-J CO, HCN, HCO^+ lines from the dense gas) (Related issues: SF initial conditions, turbulence dissipation and injection mechanisms).
- **How do we measure molecular gas mass in galaxies?** (Related issues: SF efficiency, gas consumption timescales in galaxies).

Short answers: far-UV/optical photons, CO 1-0

Mrk 231: multi-J CO, HCN line modeling



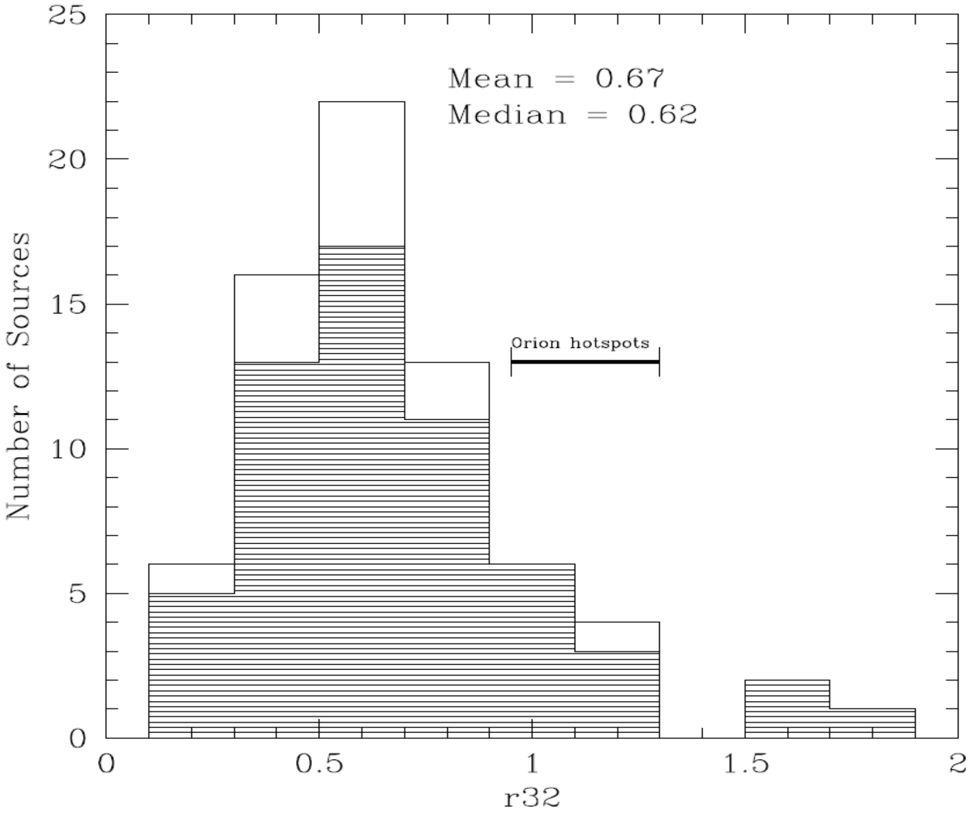


(Papadopoulos et al. 2007, van der Werf et al. 2010, Panuzzo et al. 2010 for M82, Rangwala et al. 2011 for Arp 220....**something is amiss**...)

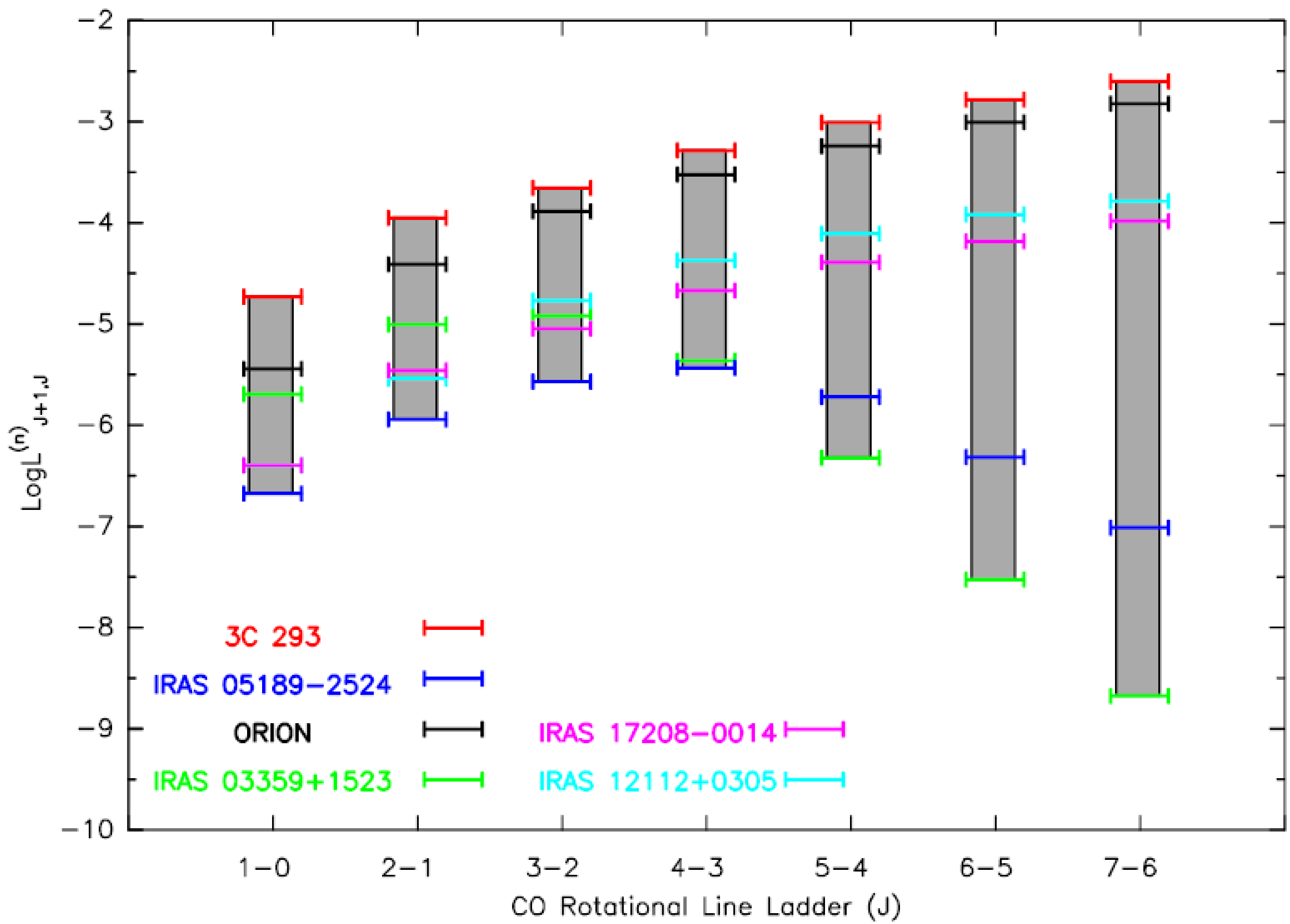
A CO and HCN multi-J line survey

- Luminous Infrared Galaxies (LIRGs), $L_{IR} \geq 10^{11} L_{\odot}$ from the *IRAS,* BGS survey with CO 1-0 line data (Sanders et al. 1991, Solomon et al. 1997). (N=36 LIRGs)
- All at $z \leq 0.1$ (CO 3-2 accessible to JCMT).
- All with sizes $\theta_s \leq 8''$ (beam of JCMT at 690GHz).
- CO 1-0, 2-1, 3-2, 4-3, 6-5 (^{13}CO 1-0, 2-1), and HCN 1-0, 3-2, and 4-3 (JCMT+IRAM 30m).
- **CO J=4-3 up to J=13-12** with Herschel Space Observatory (HerCULES Key Project, PI: van der Werf)

Some surprises.....

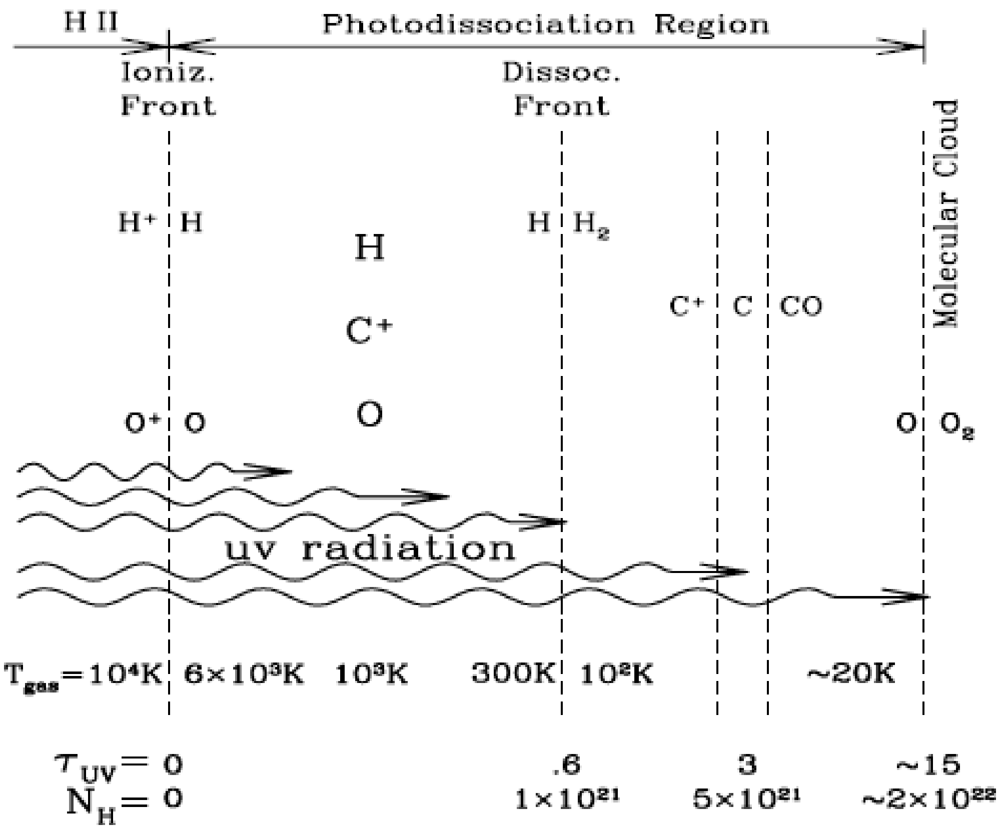


- ULIRGs out-exciting Orion hot SF spots!
- Large amounts: (1-5)x10^9 $M_{\odot}$ of warm (100K) **and** dense ($>10^4$ cm^{-3}) gas: $T_{kin}>T_{dust}$
- Diverging high-J CO and HCN SLEDs in mergers.



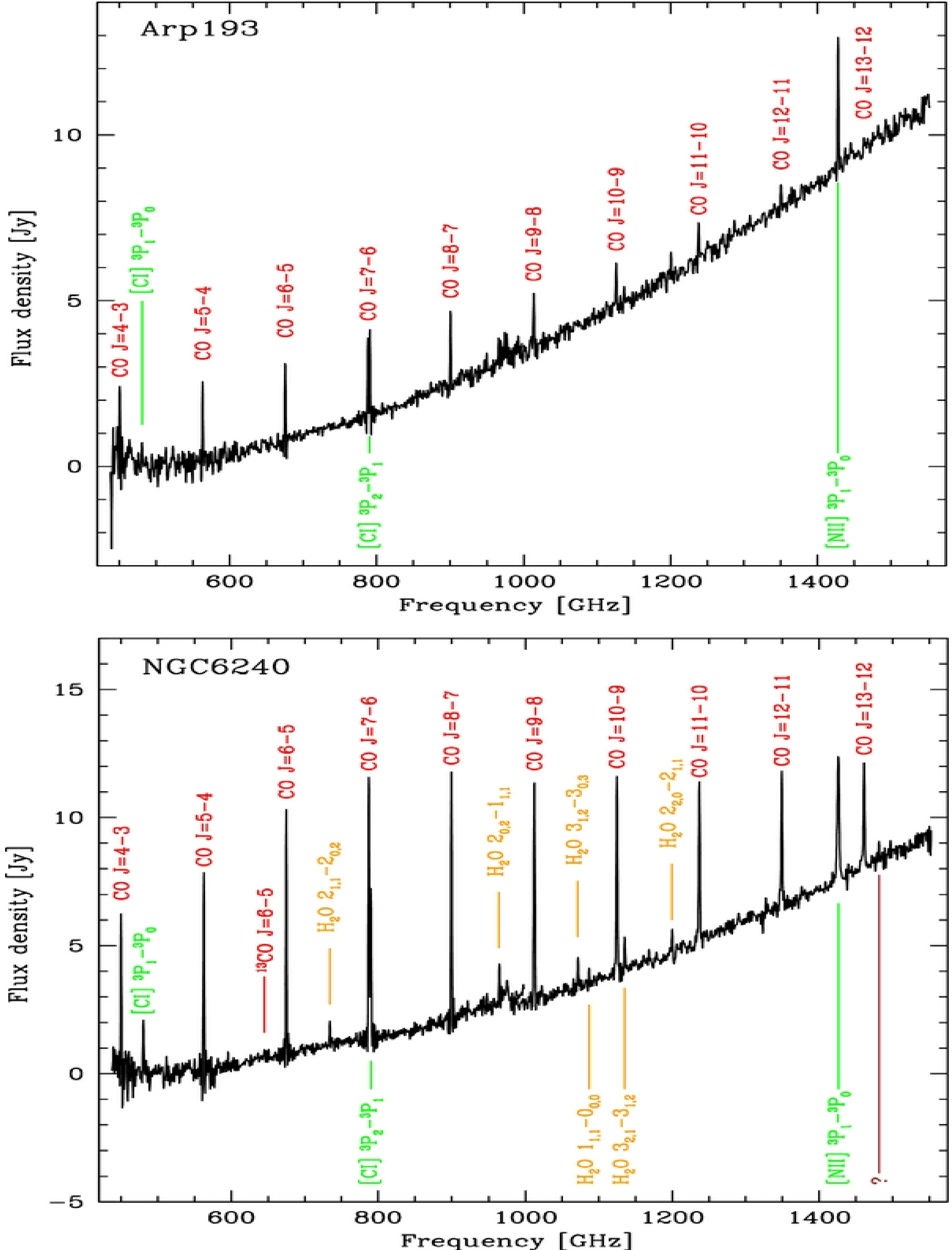
(Papadopoulos et al. 2012)

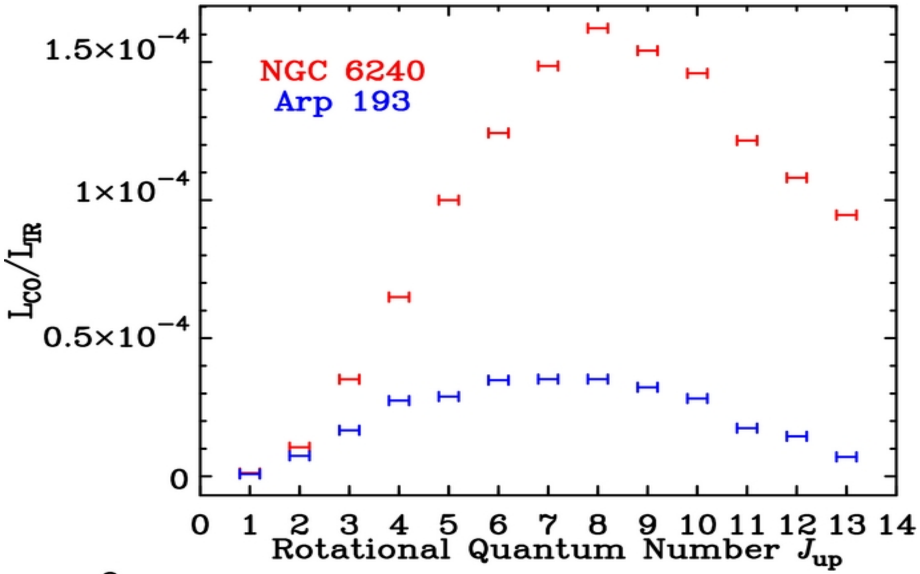
...most H_2 gas in Photon Dominated Regions (PDRs)?

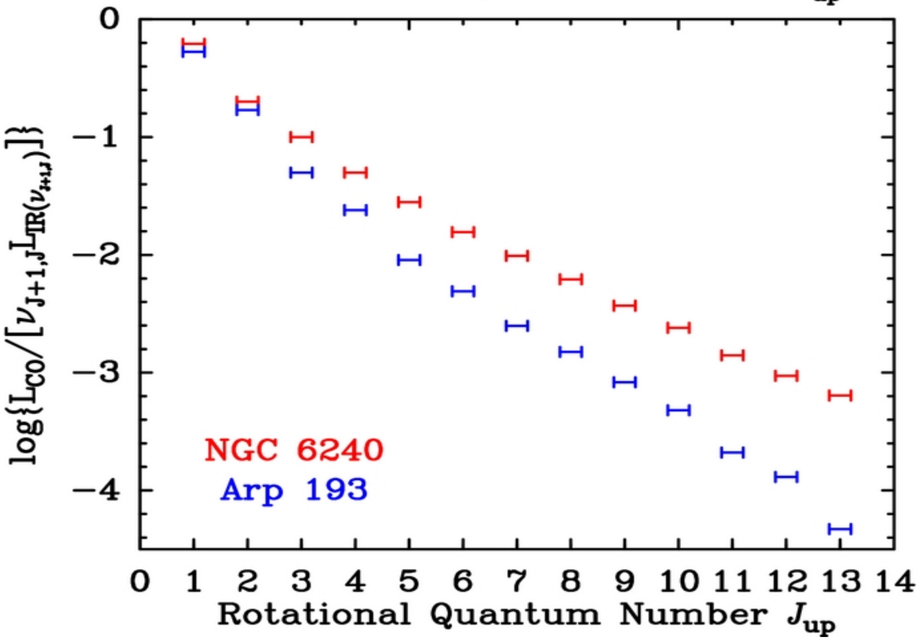


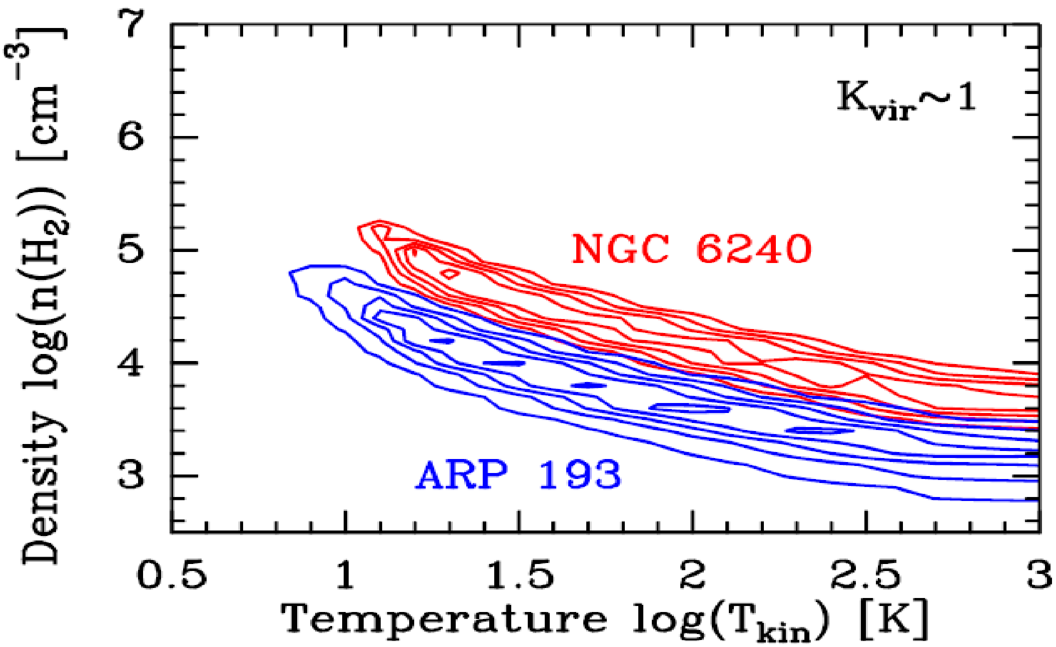
- Gas-dust temperatures well coupled (except near the surface).
- Only few% of warm gas (100K+) per PDR where $T_{kIn} >> T_{dust}$.
- Only few% of mass in cold (10K) CR-dominated regions (CRDR) per GMC where more complex molecules (HCN, HCO^+) can survive.

GMCs=(Massive PDRs)+ (few% mass CRDRs)


Arp193
Flux density [Jy]
Frequency [GHz]
CO J=4-3
[CI] 3P1-3P0
CO J=5-4
CO J=6-5
CO J=7-6
[CI] 3P2-3P1
CO J=8-7
CO J=9-8
CO J=10-9
CO J=11-10
CO J=12-11
CO J=13-12
[NII] 3P1-3P0
NGC6240
13CO J=6-5
H2O 2_{1,1}-2_{0,2}
H2O 2_{0,2}-1_{1,1}
H2O 3_{1,2}-3_{0,3}
H2O 2_{2,0}-2_{1,1}
H2O 1_{1,1}-0_{0,0}
H2O 3_{2,1}-3_{1,2}
?





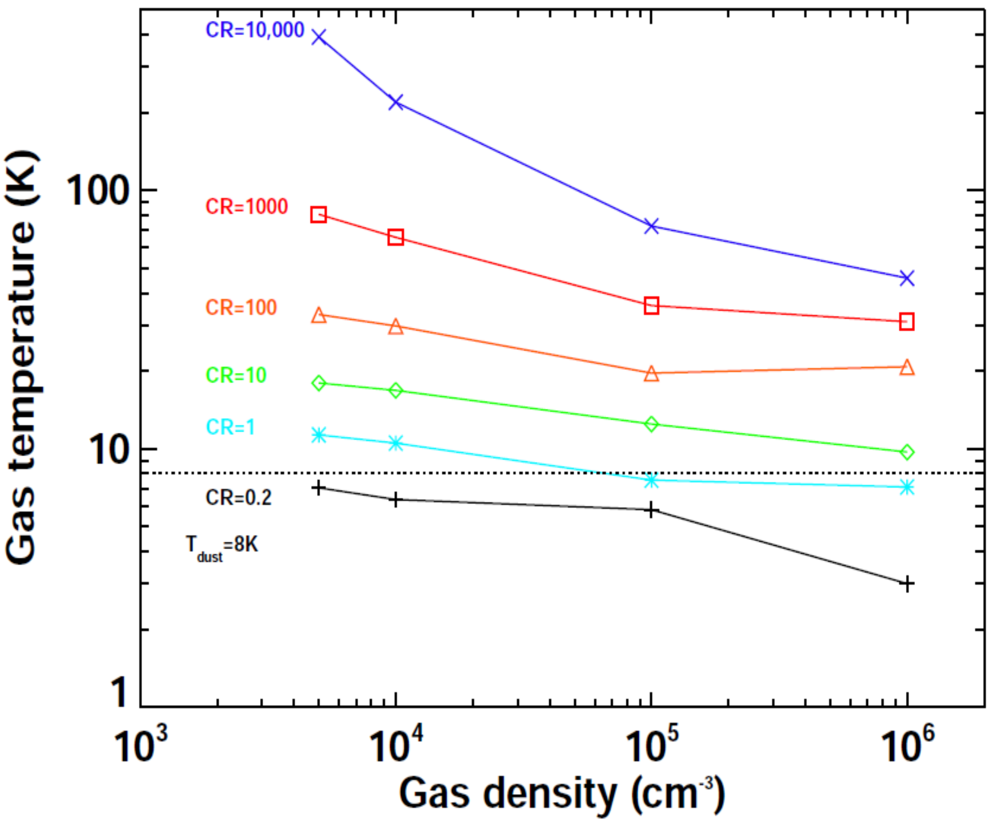


(Papadopoulos, Zhang, Weiss, et al. 2013)

The dense gas in merger/starbursts:

- Dominates their molecular gas mass budget.
- It can be in an extraordinary thermal state with T_{kin}~(100-200)K, concomitant with cooler dust.
- HCN/CS-bright gas **can account for much of the high-J CO lines** (non-dissociative heating).
- Often has large dV/dR (often with K_{vir}>1).
- $\Gamma_{pe} < \Lambda_{CO} + \Lambda_{g-d} + \Lambda_{OI} + \Lambda_{H2} + \Lambda_{CII}$

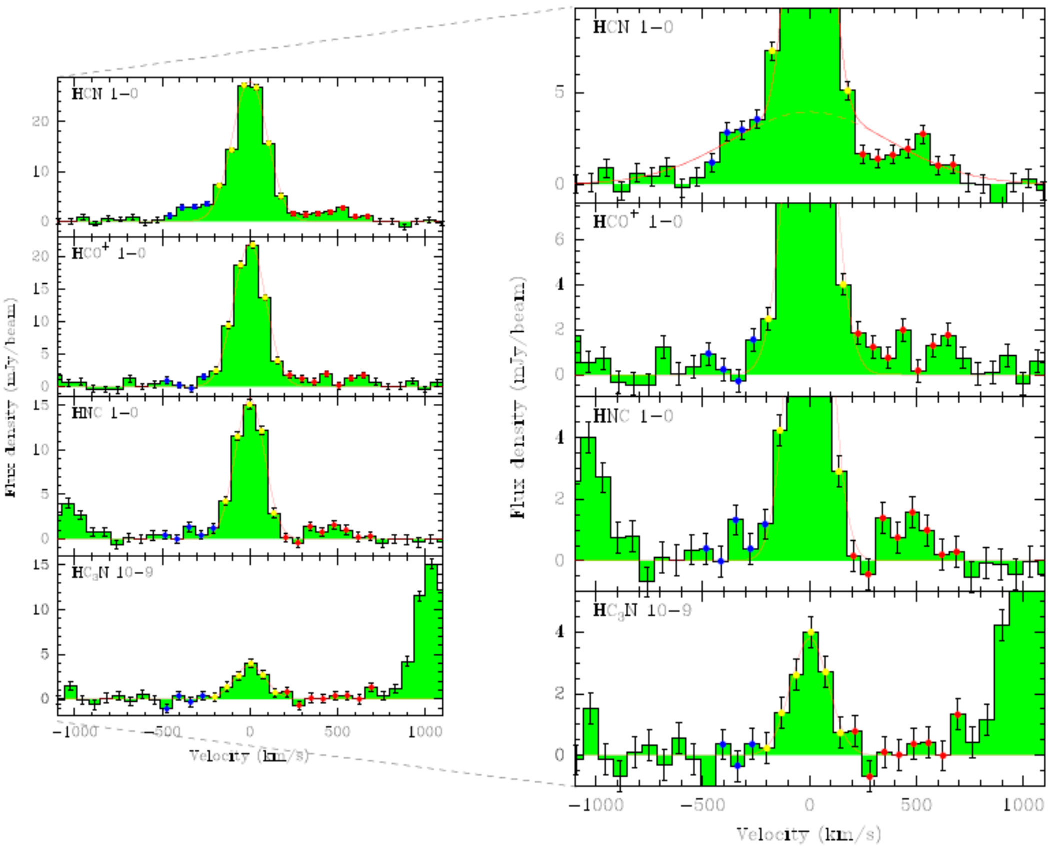
Most of the dense H_2 in merger/starbursts is NOT in PDRs

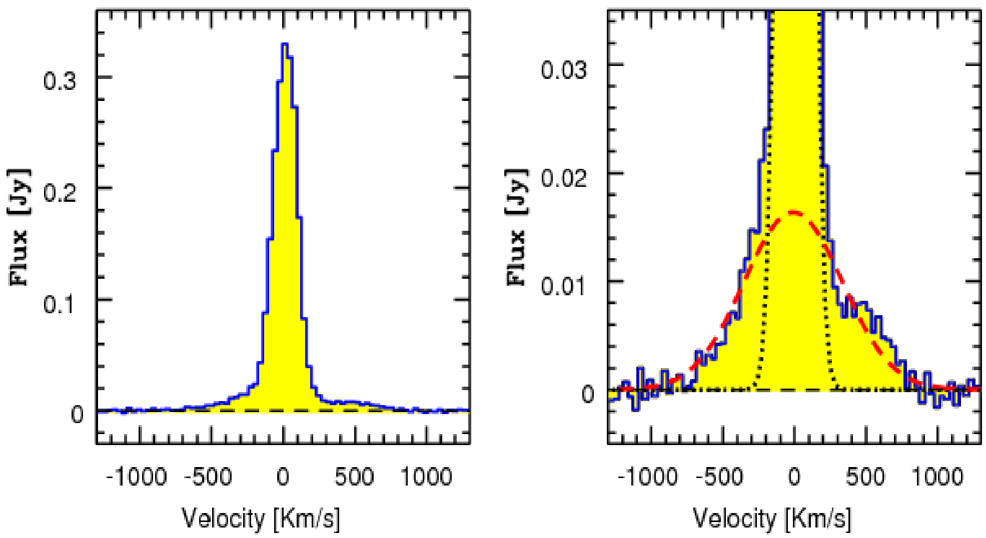


- It is in CRDRs and/or turbulently-heated regions (THRs).
- With large, volumetric, heating rates.
- Leaving the dust colder.
- THRs may extend way beyond the galaxy...

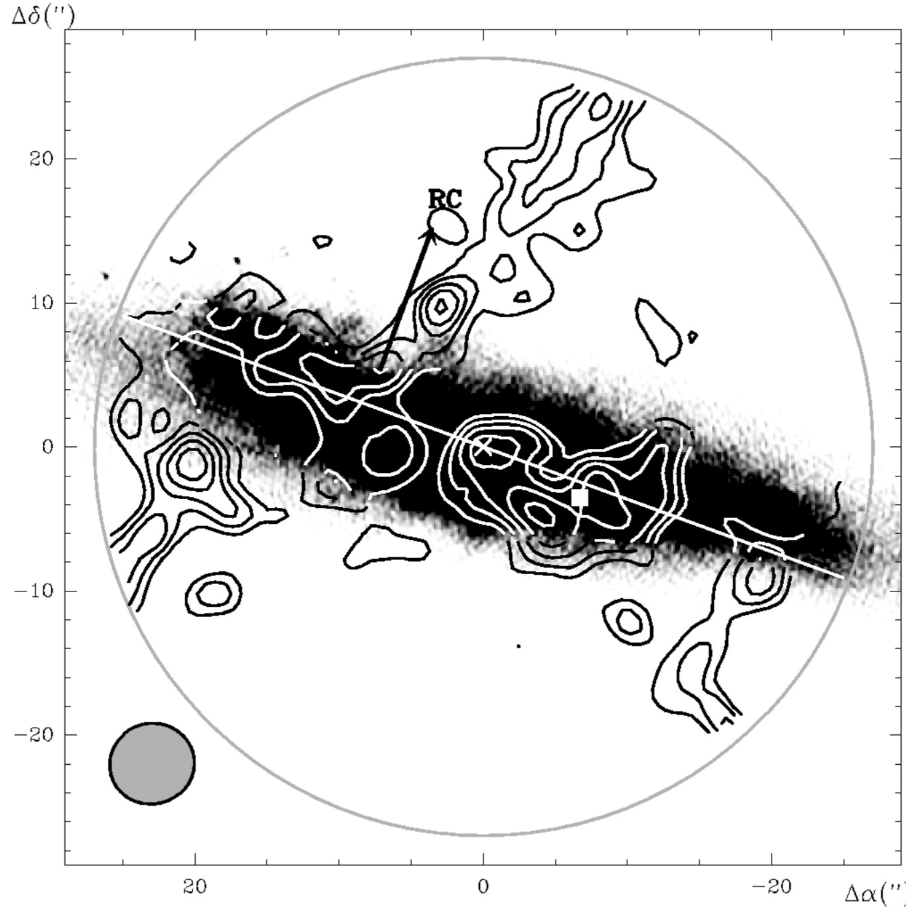
Powerful molecular outflows!

(Feruglio et al. 2010, Aalto et al. 2012)





....driven by star formation?



SiO (v=0,J=2-1) emission in M82 (Burillo et al. 2001), gas pushed out by SNRs...,

Other examples of (non-photon)-driven heating

- The Galactic Center (Bradford et al. 2005, Ao et al 2012).
- NGC 253(Bradford et al. 2003, Hailey-Dunsheath et al. 2008).
- M82 with SPIRE/FTS (Panuzzo et al. 2010).
- Arp 220 with SPIRE/FTS (Rangwala et al. 2011)
- ULIRGs (Papadopoulos et al. 2012).

Why H_2 gas heating in mergers/starbursts cannot be photon-driven

$$A_v^{(tr)} = 1.086\xi_{FUV}^{-1} \ln\left[1 + \frac{G_\circ k_\circ}{nR_f}\Phi\right]$$

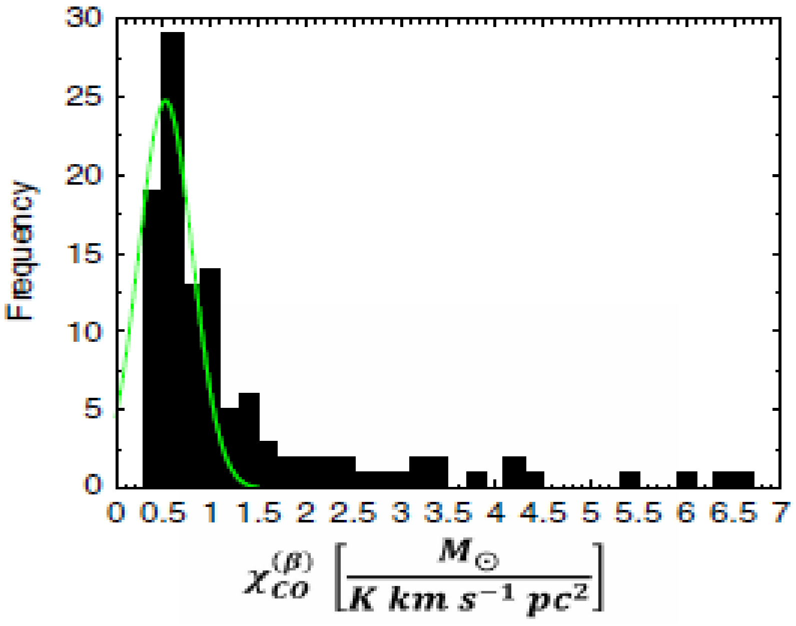
$$f_{PDR} \sim 2 \times \left[1 - \left(1 - \frac{4A_v^{(tr)}}{3\langle A_v \rangle}\right)^3\right]$$

$$\langle A_v \rangle \sim 0.22\,Z \left(\frac{n_\circ}{100\,\mathrm{cm}^{-3}}\right)\left(\frac{P_e/k_B}{10^4\mathrm{cm}^{-3}\mathrm{K}}\right)^{1/2}$$

Molecular gas mass estimates

$$X_{CO} = 2.65 \frac{\sqrt{n(H_2)}}{T_{b,1-0}} K_{vir}^{-1} \left(\frac{M_\odot}{\mathrm{K\ km\ s^{-1}\ pc^2}} \right).$$

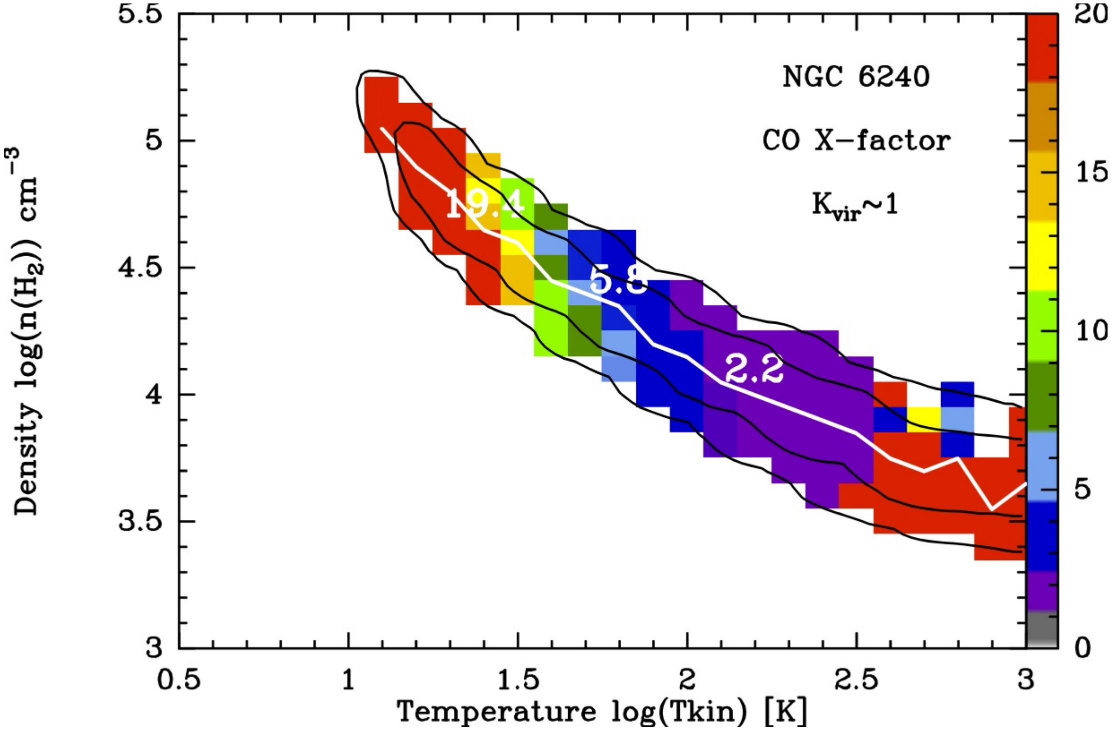
$$K_{vir} = \frac{(dV/dR)}{(dV/dR)_{virial}} \sim 1.54 \frac{[CO/H_2]}{\sqrt{\alpha \Lambda_{co}}} \left(\frac{n(H_2)}{10^3\ \mathrm{cm^{-3}}} \right)^{-1/2}$$

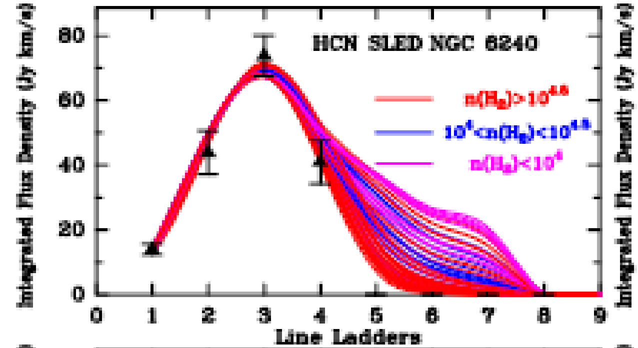


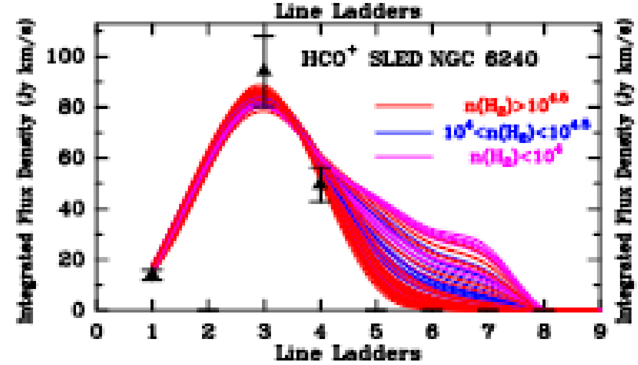
1) It matters what the conditions of the gas are.

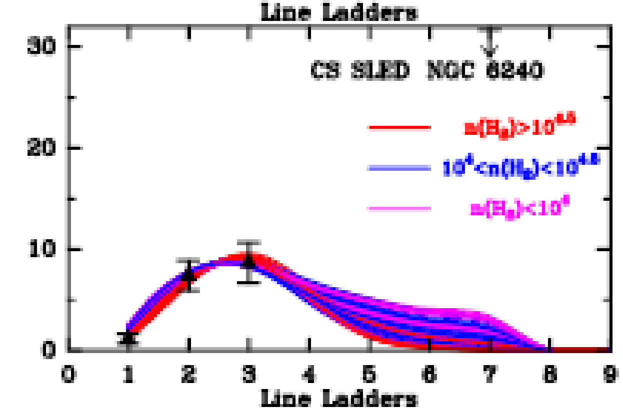
2) Even a single GMC is multi-phase... (X_{CO} works for ensemble averages).

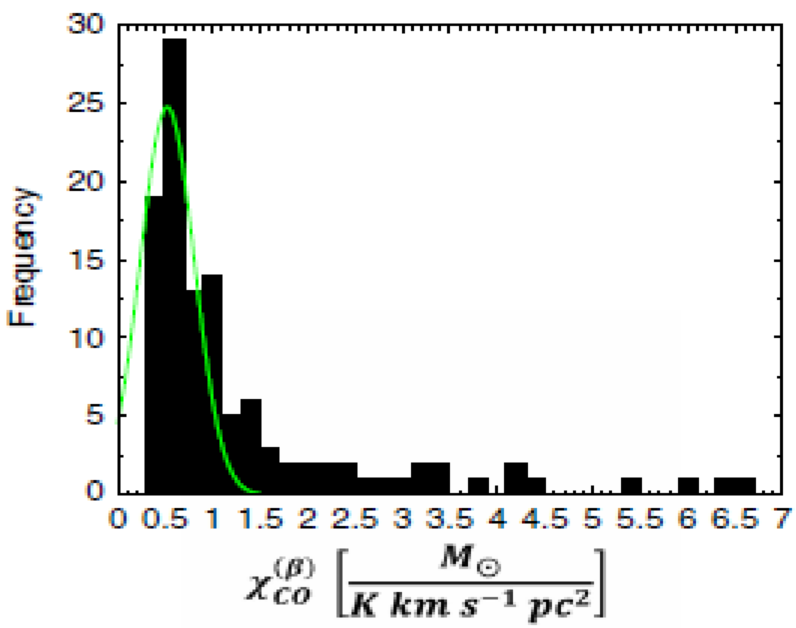
3) The kinematic state of the gas is particularly important (see Downes & Solomon 1998).





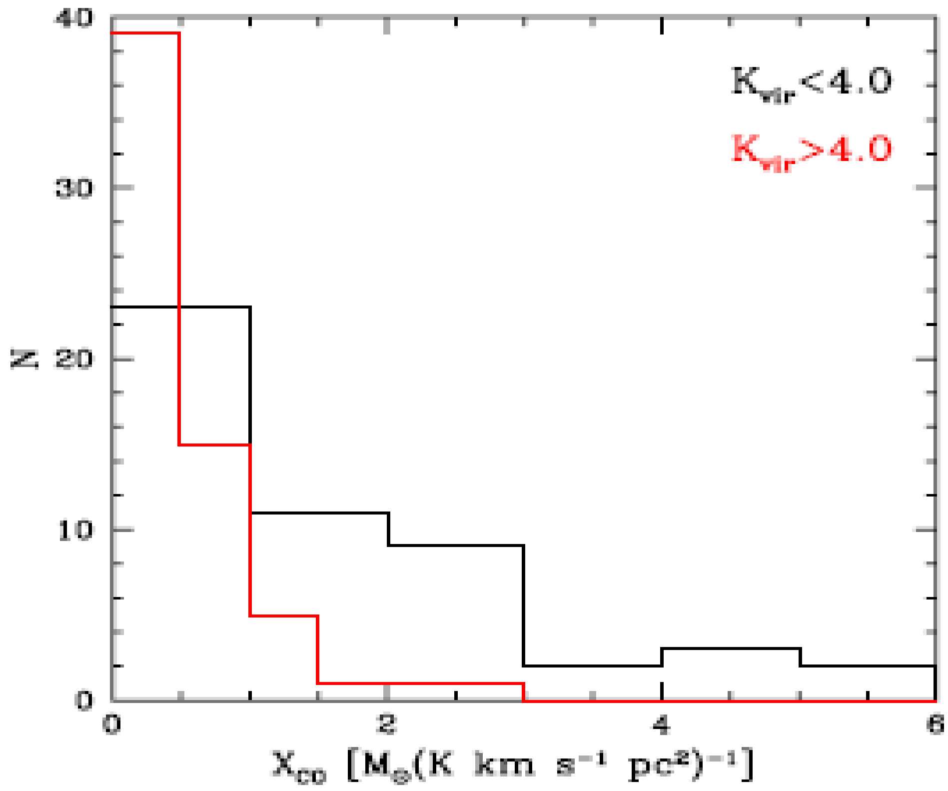


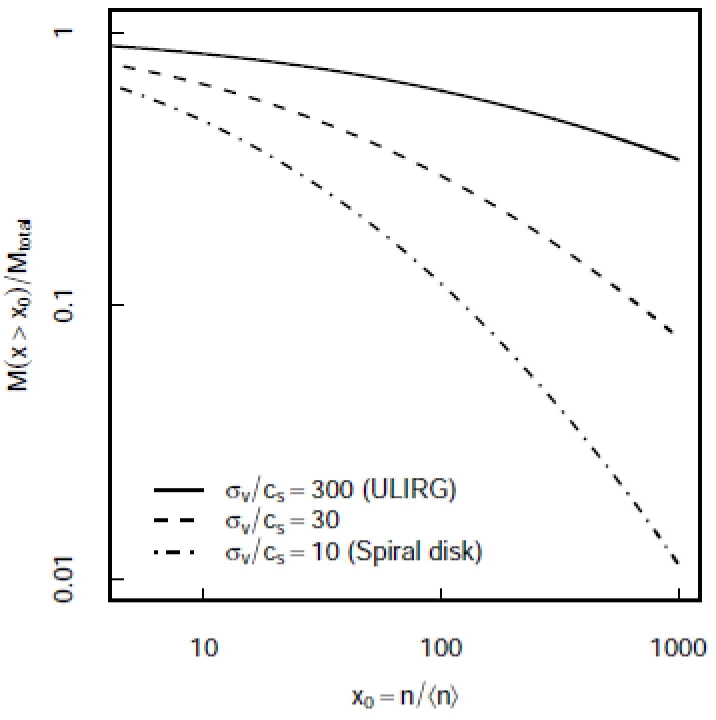




Dense gas matters!

The effects of the gas kinematic state on X_{CO}





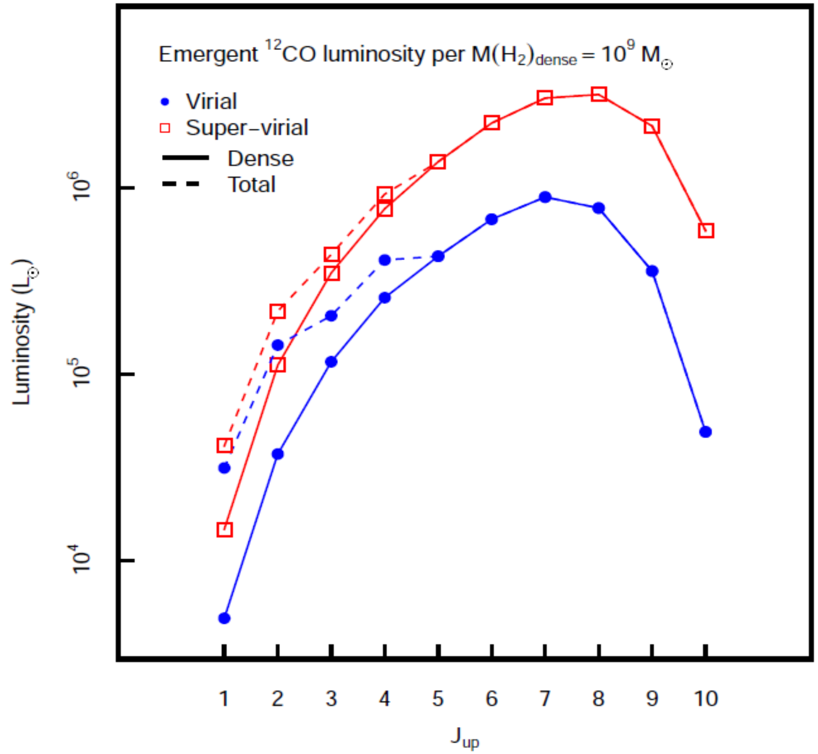
The Xco factor in mergers/starbursts

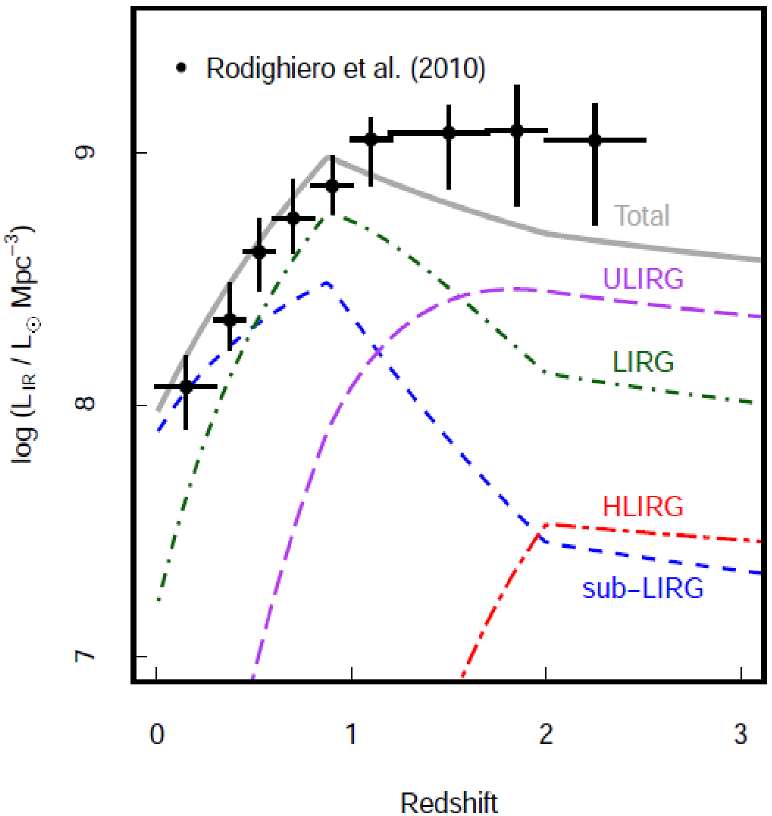
- **It can be Galactic** (low-J CO lines can mislead, as they can be dominated by a marginal gas phase).
- The average kinematic state of the dense gas is important.
- CO, HCN, HCO^+, CS multi-J imaging is necessary for probing the thermal/dynamical state of the dense gas.
- **Realistic (non-isothermal) supersonic turbulent cloud simulations must enter this game...**. (with ALMA providing the multi-line dataset needed)

Molecular and atomic line surveys of Galaxies: the dense star-forming phase as a beacon

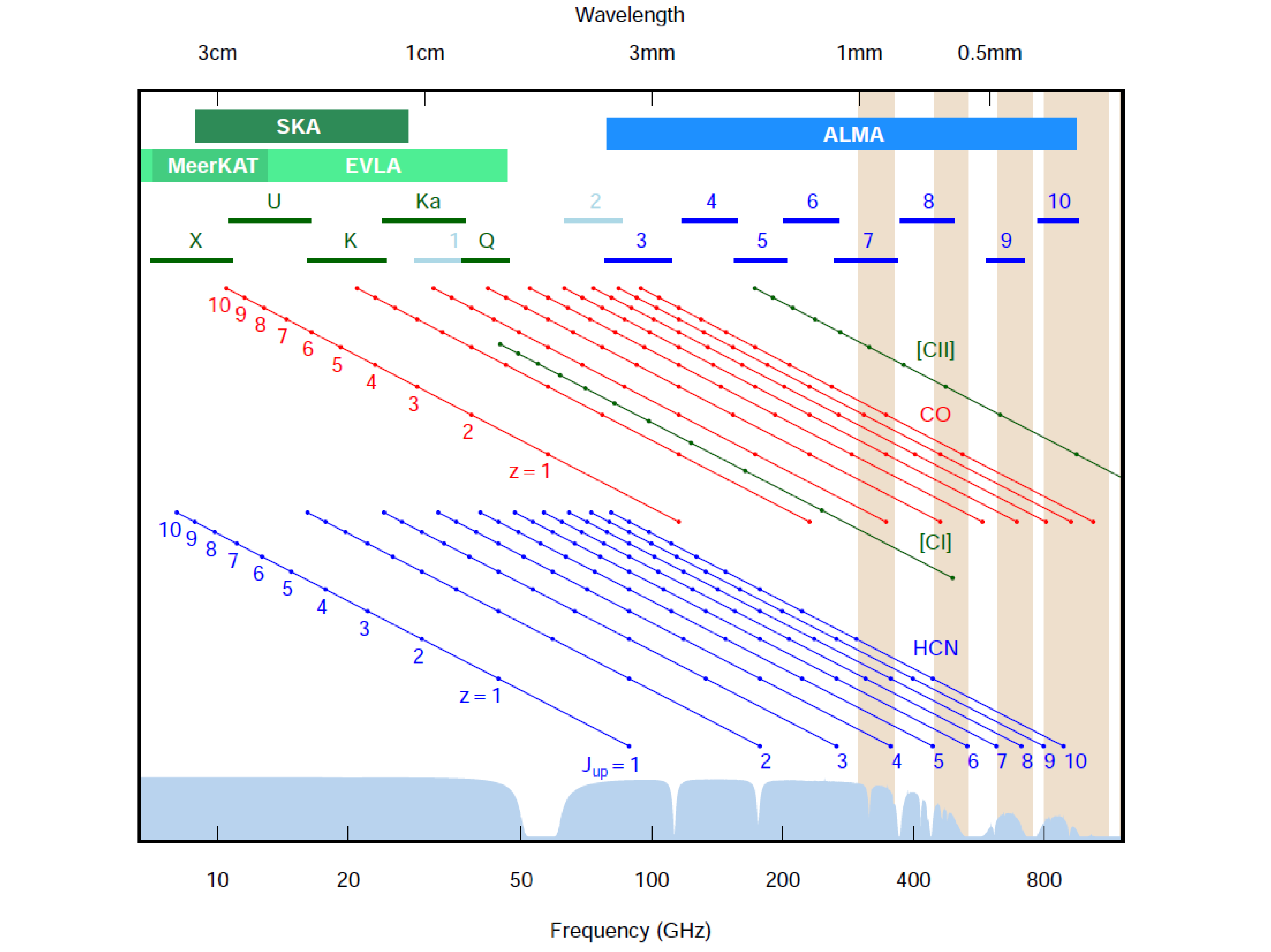
- It will be there as long as star-formation is.
- The $L_{IR}/M_{dense}(H_2)$ [~SFR/$M_{dense}(H_2)$] 'normalization' is now fixed (Scoville 2004, Thompson 2009).
- Minimal emergent CO, CI, SLEDs of dense gas can now be confidently estimated from local molecular line extragalactic surveys.
- Diffuse and/or cold non-SF molecular gas will only add line luminosities (low-J CO and CI).

[Minimal SLED]+[SFR-normalization]+[galaxy evolution] = [minimal galaxy counts] (Geach & Papadopoulos 2012)



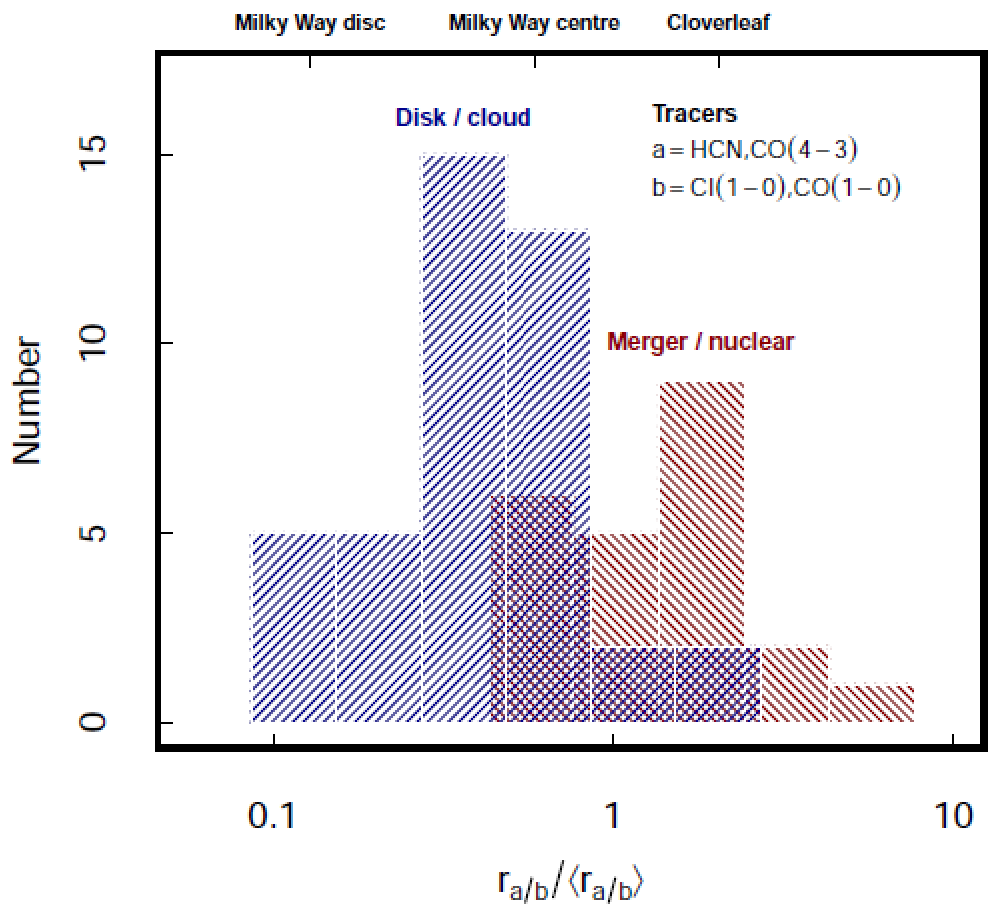


(see also pioneering early work by Combes et al. 1999, Blain et al. 2000, Carilli & Blain 2000)



Wavelength
3cm
1cm
3mm
1mm
0.5mm
SKA
ALMA
MeerKAT
EVLA
U
Ka
2
4
6
8
10
X
K
1
Q
3
5
7
9
[CII]
CO
[CI]
HCN
z = 1
$J_{up} = 1$
2
3
4
5
6
7
8
9
10
10
20
50
100
200
400
800
Frequency (GHz)

The SF mode in galaxies

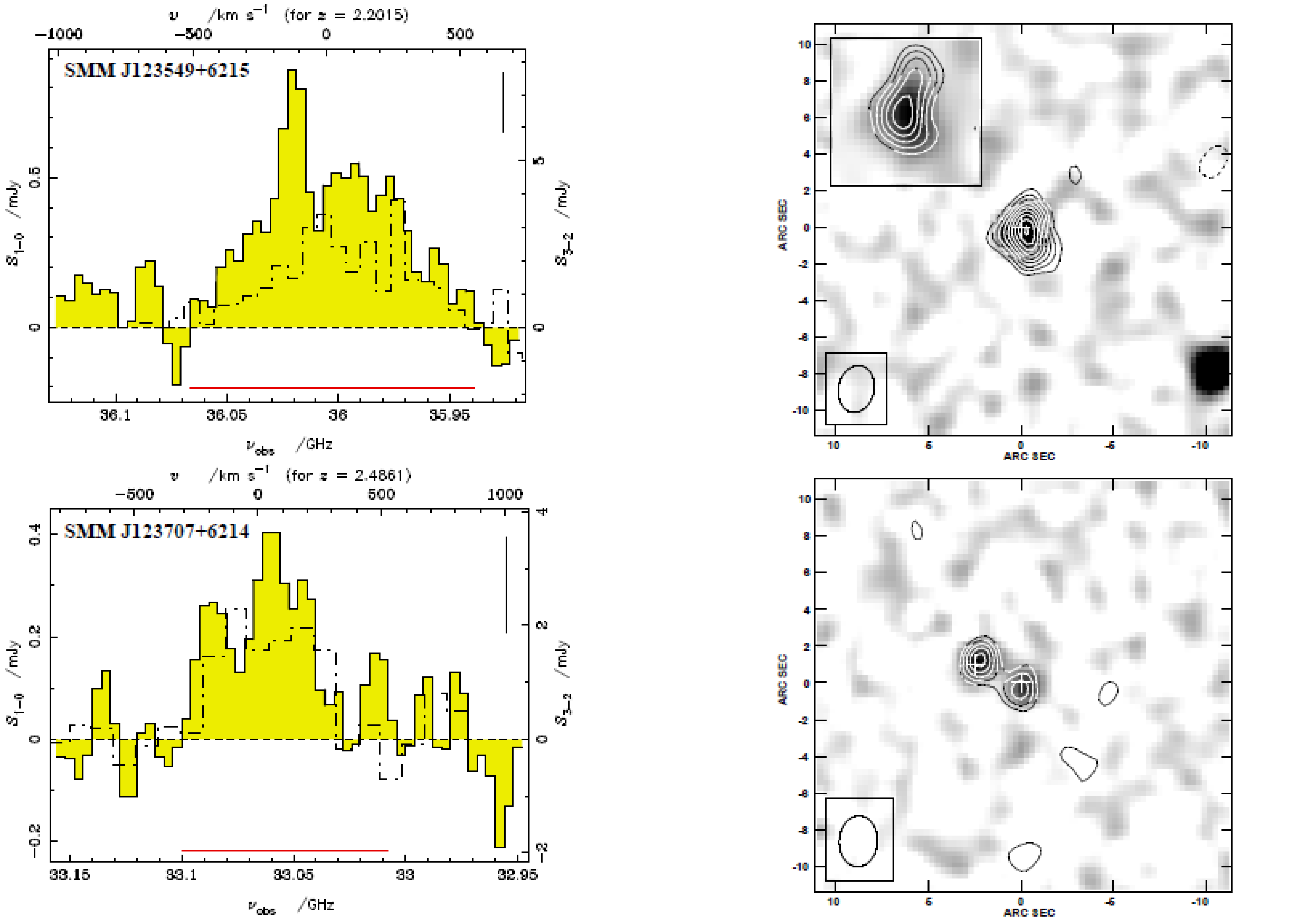


The best parameter is: $f_{dense}=M(n>10^4 cm^{-3})/M_{tot}$,

(low-J CO SLEDs, Xco values not reliable)

(ApJ 757, 157, 2012)

ALMA ,and synergies with the JVLA
(CO J=1-0 imaging of distant SMGs, Ivison et al. 2011)

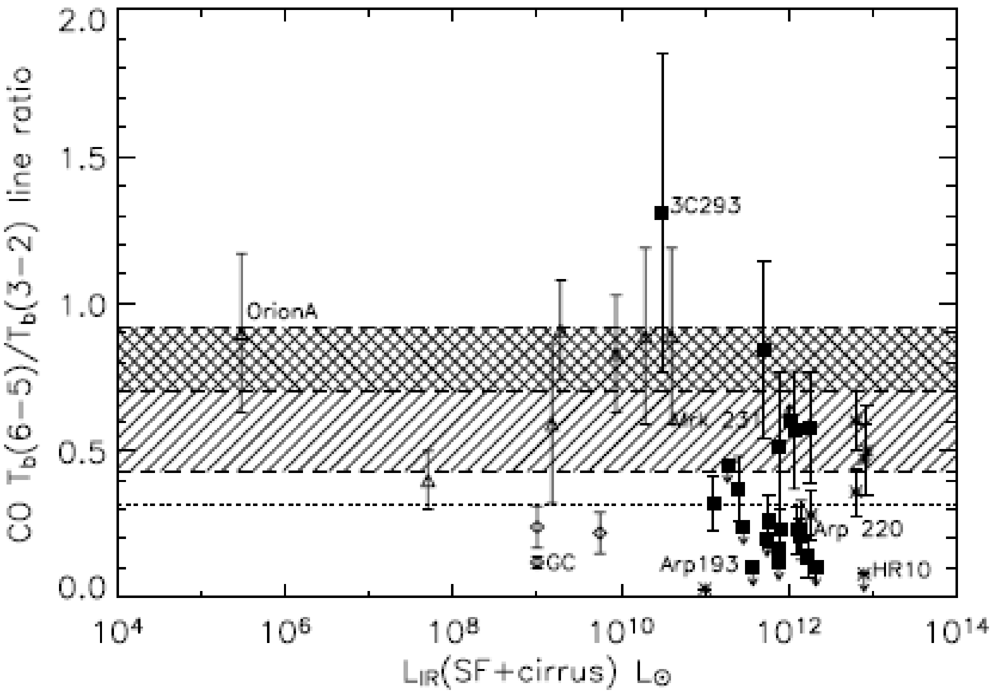


Conclusions, and the way forward in the age of ALMA and the JVLA

- PDRs do not power the molecular lines in the dense gas of ULIRGs, CRs and turbulence do (**molecular line diagnostics to separate them**).
- Xco factor can be Galactic in ULIRGs $M_{gas}/M_{dyn}\sim 1$ for their compact starbursts (**high-resolution imaging of high-μ molecules**).
- SF initial conditions, SF-relation gas-rich outliers, the IMF in dust-obscured regions!

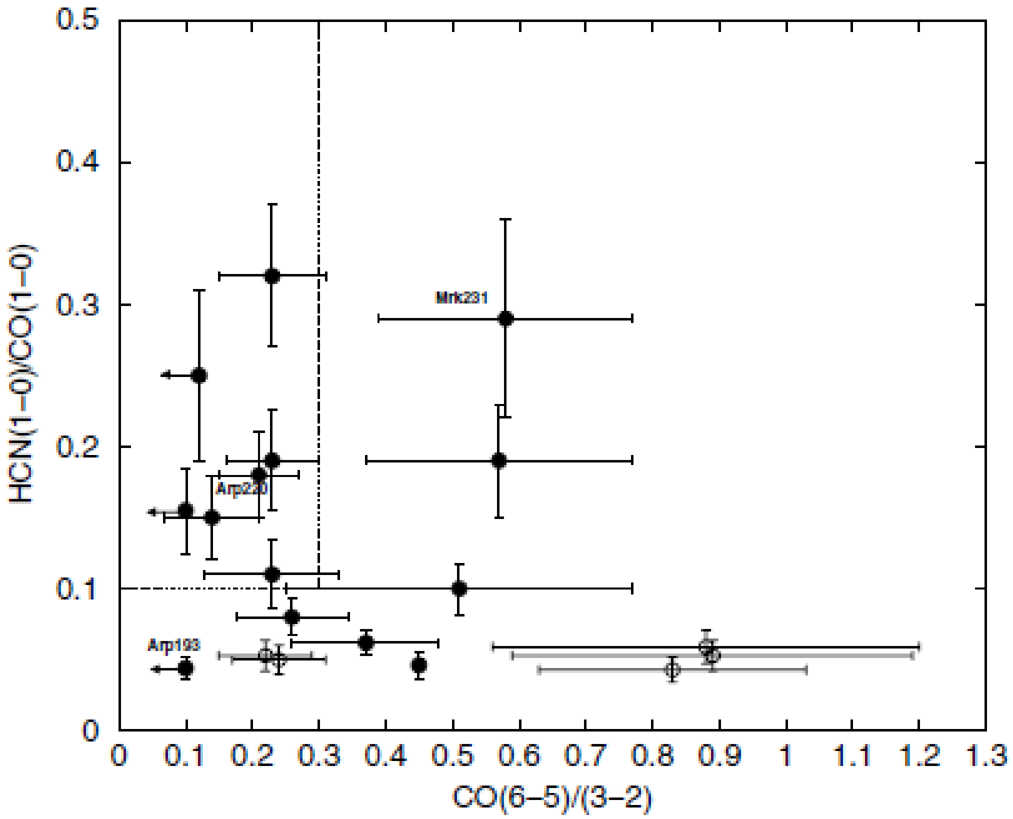
Exciting decades ahead for all of you....

Comparing the ISM in low and high redshift systems (at last...)

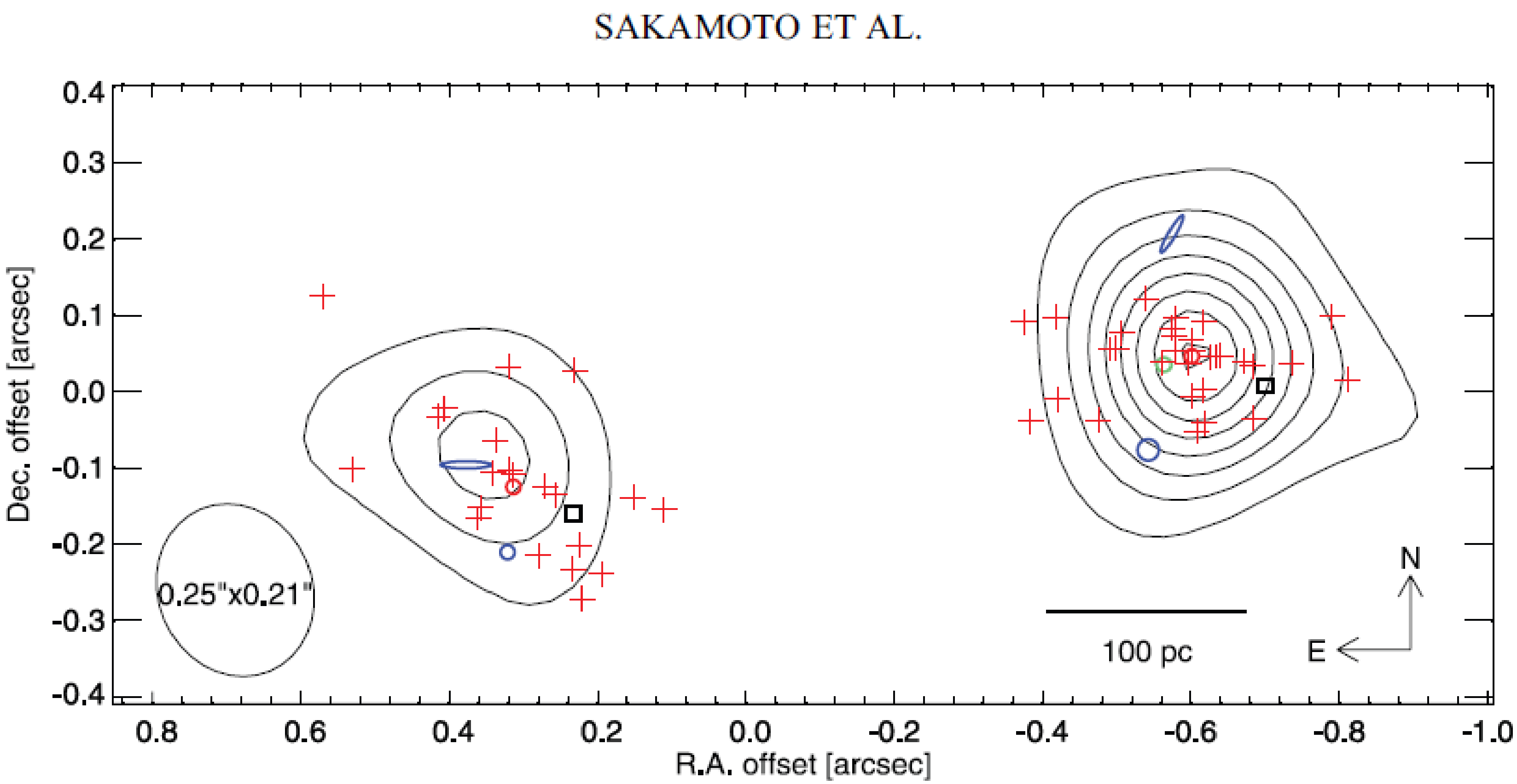


...significant optical depths at short submm wavelengths (see Sakamoto et al. 2008 for Arp220)

(Papadopoulos et al. 2010)



...yes for the likes of Arp 220.

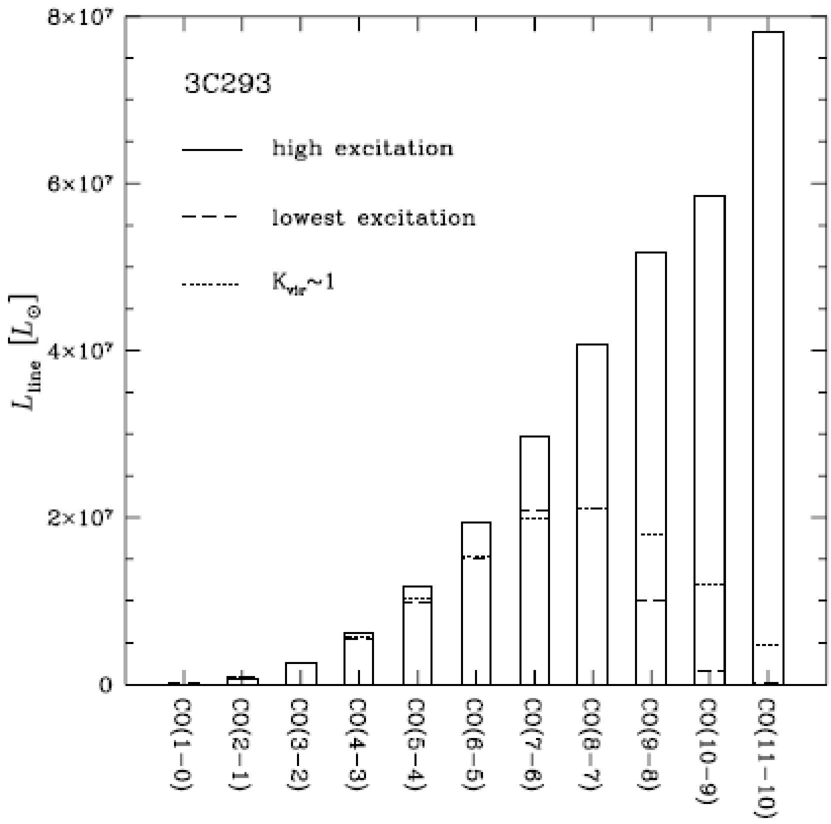


$$\tau_d(\lambda) \sim 1.66 \left(\frac{\lambda}{400\ \mu\mathrm{m}}\right)^{-2} \left[\frac{h\langle n(\mathrm{H_2})\rangle(\cos\theta)^{-1}}{10^{25}\ \mathrm{cm^{-2}}}\right]$$

$$\sim (2.05\text{–}30.7) \times \left(\frac{\lambda}{400\ \mu\mathrm{m}}\right)^{-2} (\cos\theta)^{-1},$$

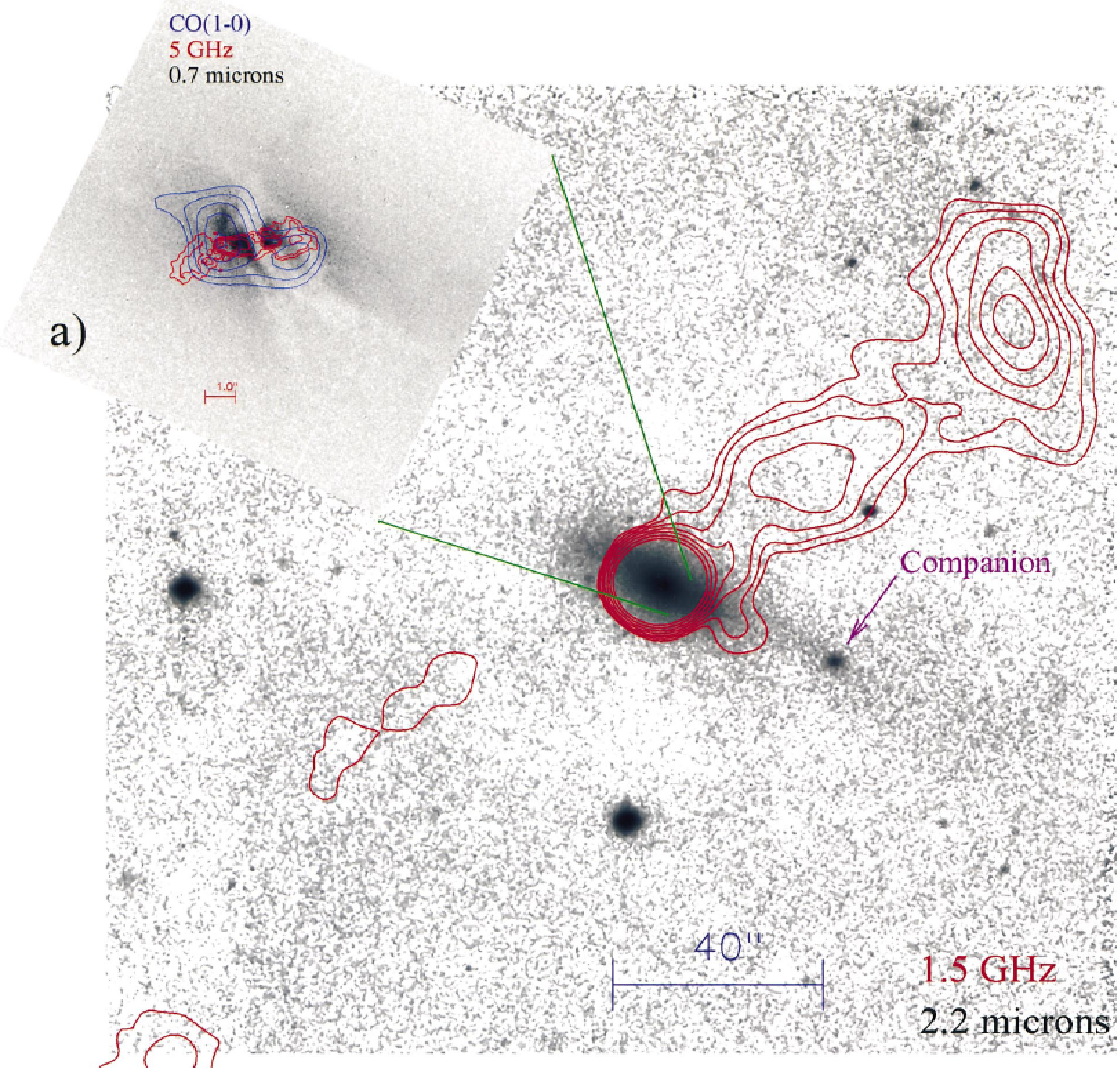
The over-excited ones (1)

(Papadopoulos et al. 2008, Nesvadba et al. 2010)



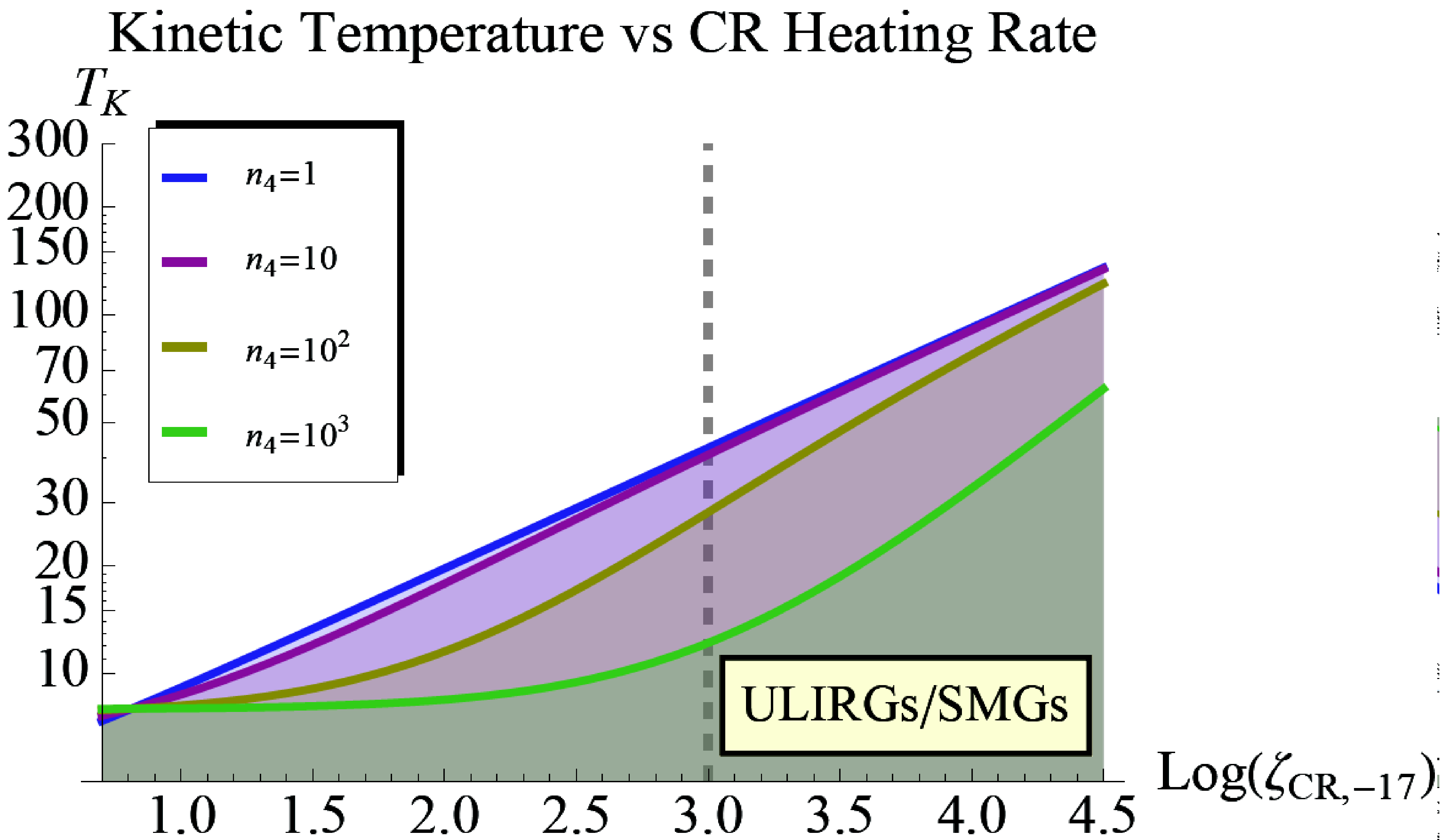
- 3C 293, a powerful FRII radio galaxy.
- Strongest jet-ISM interaction known (Emonts et al. 2005).
- Milky-Way level SFR.
- "Hot" CO 6-5, 4-3 lines!! with $T_{kin} >> T_{dust}$.
- Imagine that "firing" at high redshifts.....

Evans et al. 1999
(CO 1-0: 7'' → 6 kpc)



The over-excited ones (2) (van der Werf et al. 2010)

CRs versus far-UV photons: a drastic reseting of the SF initial conditions in compact starbursts? (Papadopoulos 2010, ApJ, 720, 226)



ALMA ,and synergies with the JVLA
CO J=1-0 imaging of distant SMGs, (Ivison et al. 2011)