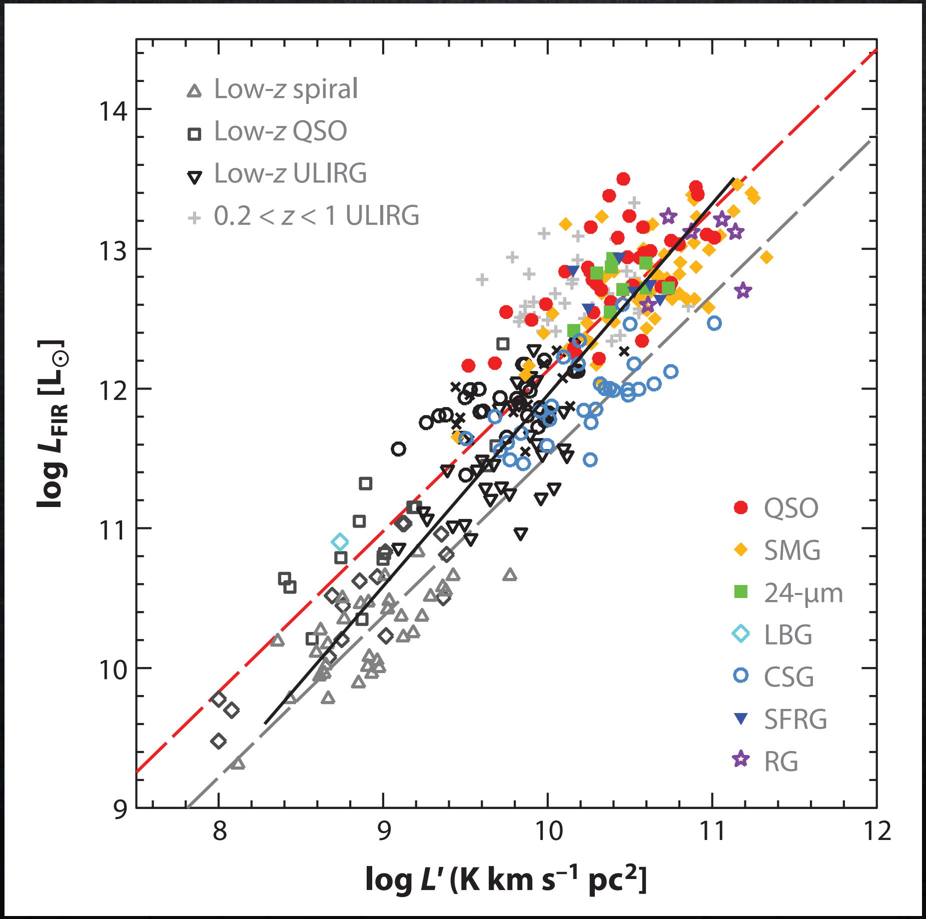
High-J CO Excitation at z~1.5 (~4.2 Gyr) and at Local

Daizhong Liu, Yu Gao (PMO), Emanuele Daddi (CEA),
J. Silverman, G. Magdis, Q. Tan, K. Isaak, C. Yang, N. Lu, P. van der Werf, et al.
May 25th 2015

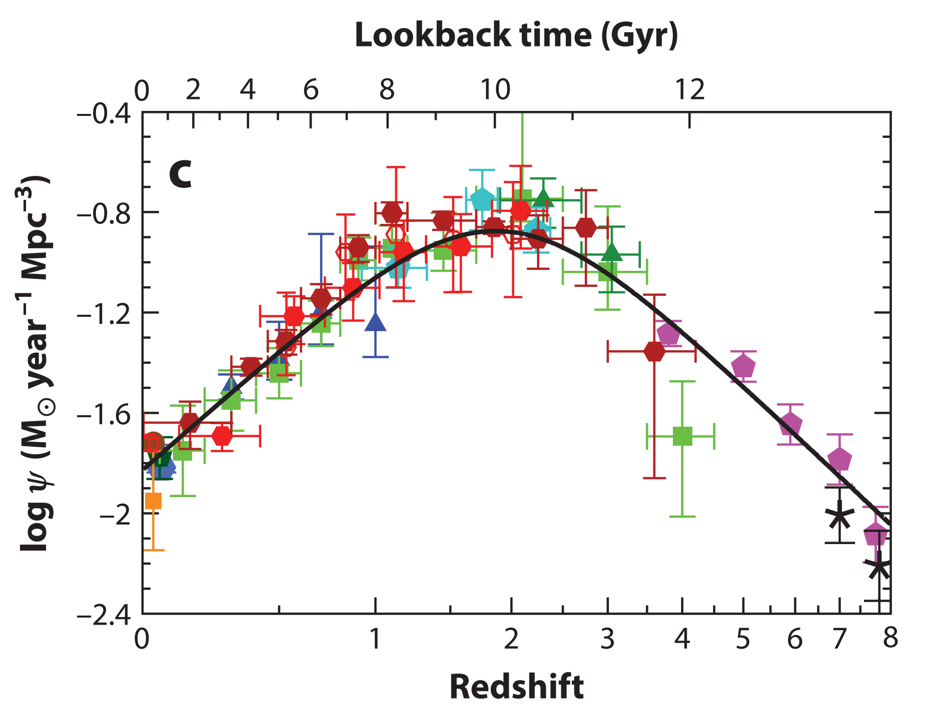
- Importance of CO
  - most abundant molecule other than H_2
  - rotational transitions *J* -> *J*-1 in far-infrared (FIR) to sub-millimeter (SMM)
  - low-*J* (*J*=1,2,3) lines are the most widely used molecular gas tracers
  - linking to star formation (SF)

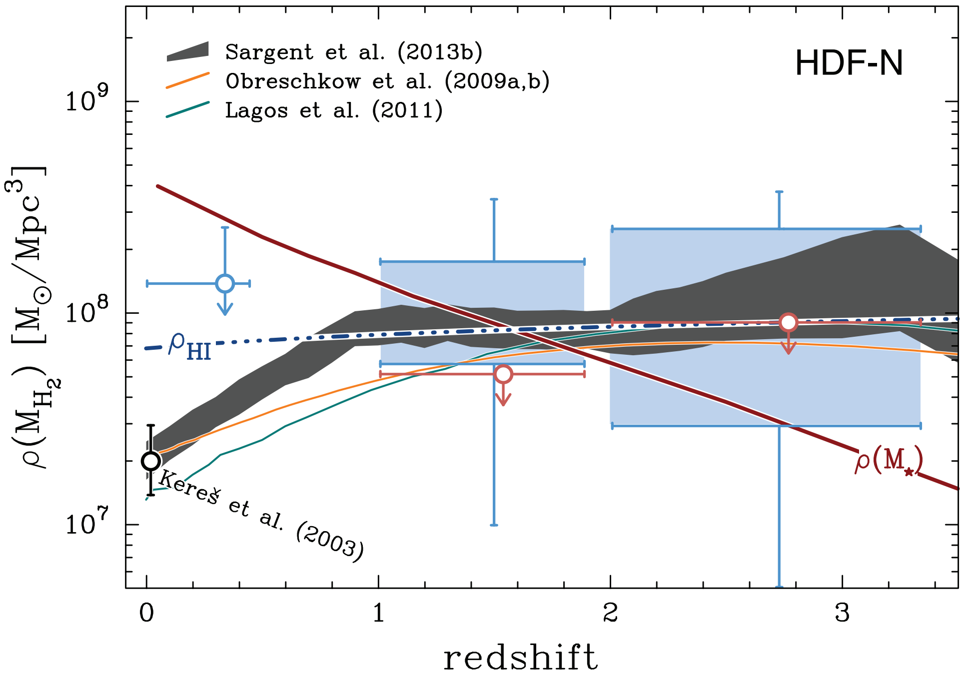


Kennicutt-Schmidit Law
Schmidt (1959)
Kennicutt (1998)
...
Carilli & Walter (2013) (see left figure)
...

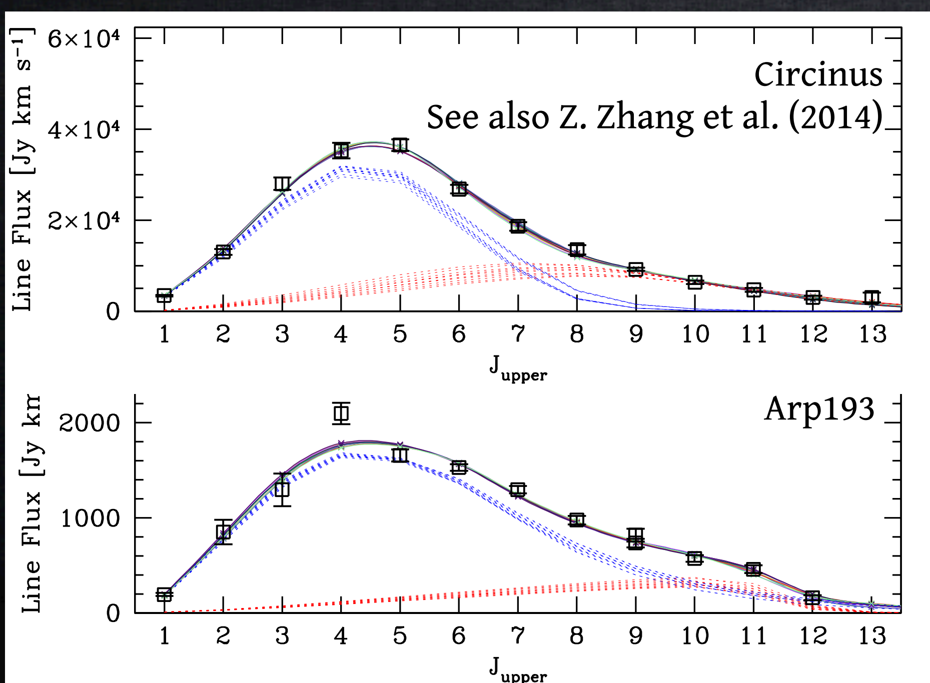
Left:
Star formation rate (SFR) density evolution from deep UV and IR observations
Madau & Dickinson (2014)

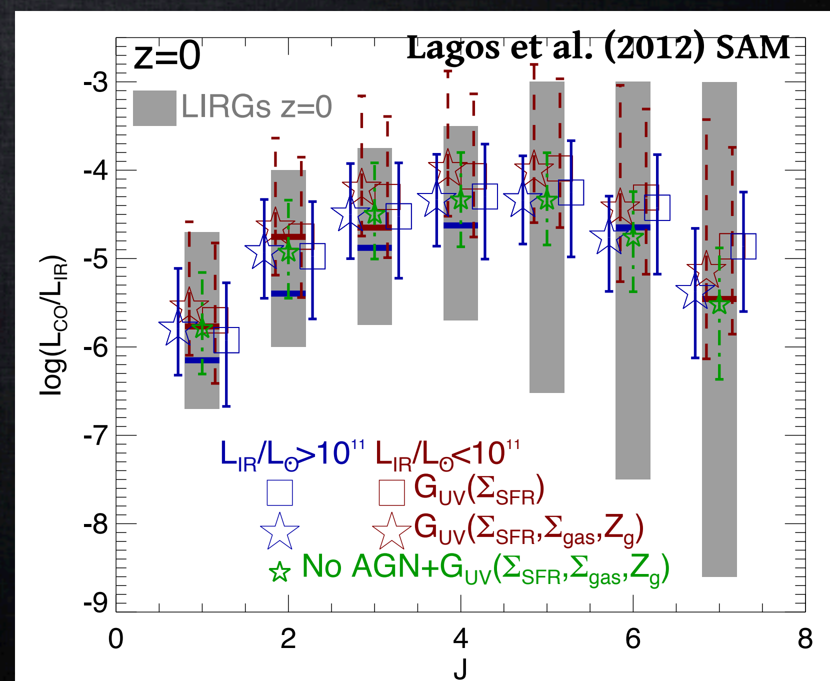
Right:
Total molecular gas mass density evolution
Walter et al. (2014)



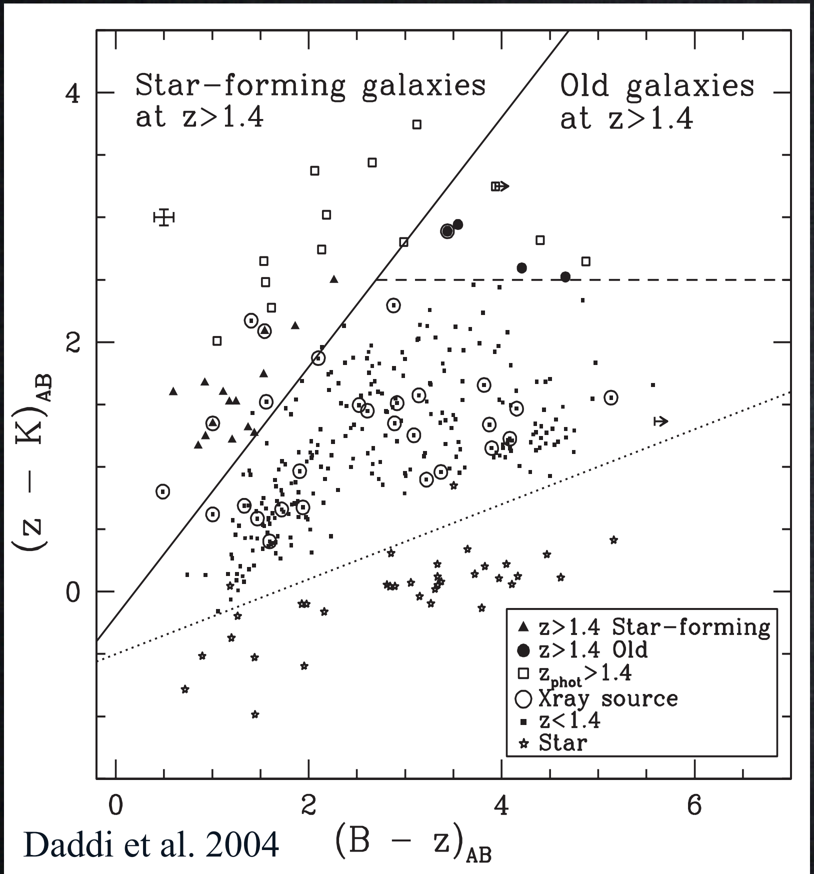


- Importance of high-J CO
  - *J*=5-4 already has a dense and warm condition: n_{crit} > 10^5 cm^{-3}, E_u = 83 K
  - individually provide direct information on the dense and warm molecular gas
  - sites of formation of individual stars *(Kennicutt & Evans 2012; Williams, Blitz & McKee 2000)*
  - low-J + high-J → CO spectral line energy distribution (CO SLED)
  - best diagnostic tool for T_{kin}, n_{H2}, and decomposition (cold + warm) *(Kamenetzky et al. 2014)*
  - new recipes for cosmological simulation *(Lagos et al. 2012)*

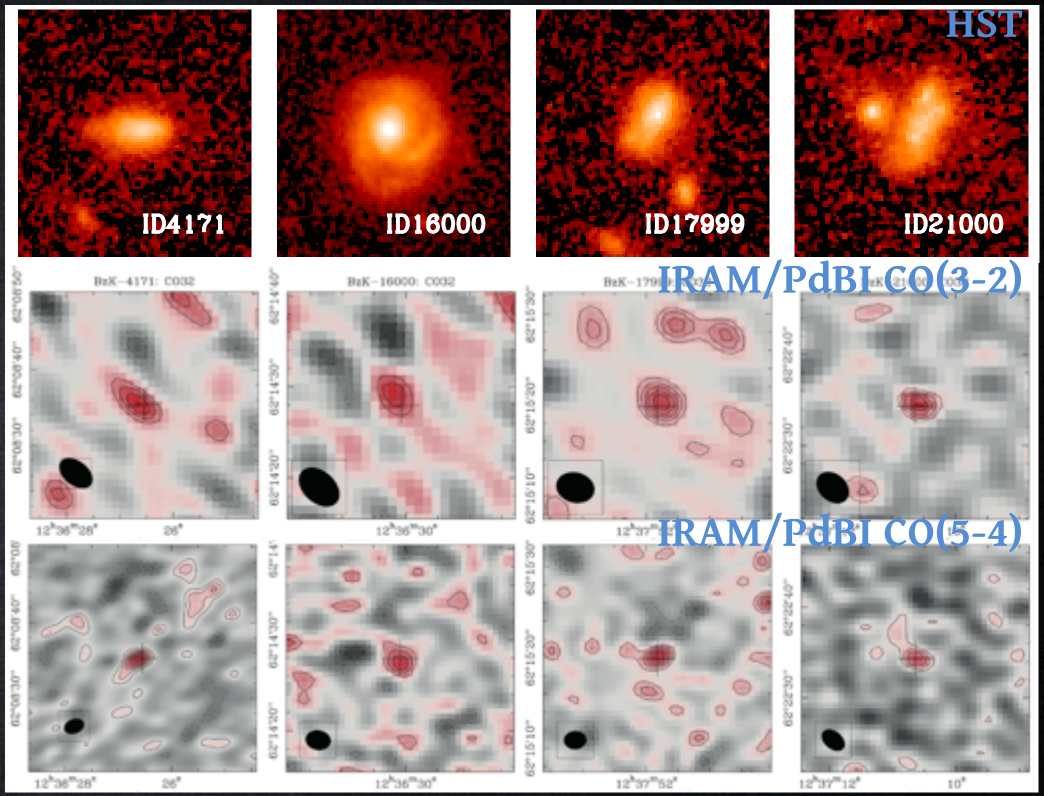




- CO in 4 MS galaxies at z~1.5 (GOODS-N)   *(Daddi, Dannerbauer, Liu et al. 2015)*
- CO in 5 SB galaxies at z~1.5 (COSMOS)
- CO in local galaxies and partially resolved regions (Herschel/SPIRE/FTS)



Effectively selecting "normal" galaxies with SFRs placing them exactly on the main-sequence (MS) at z~1.5!

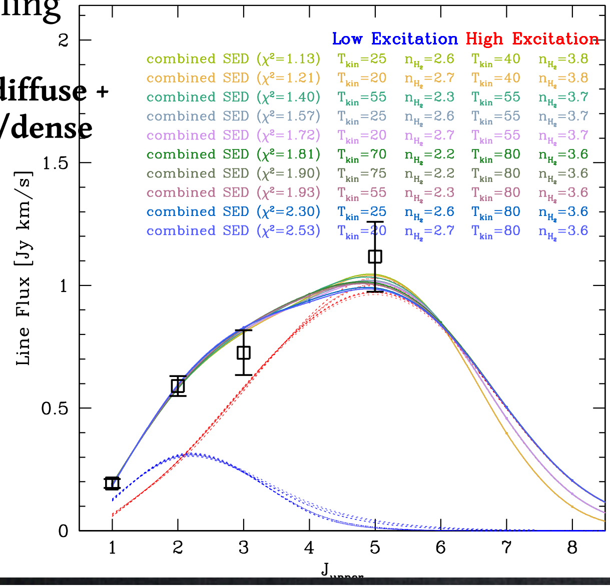


Daddi, Dannerbauer, Liu et al. 2015
A&A, 577, A46

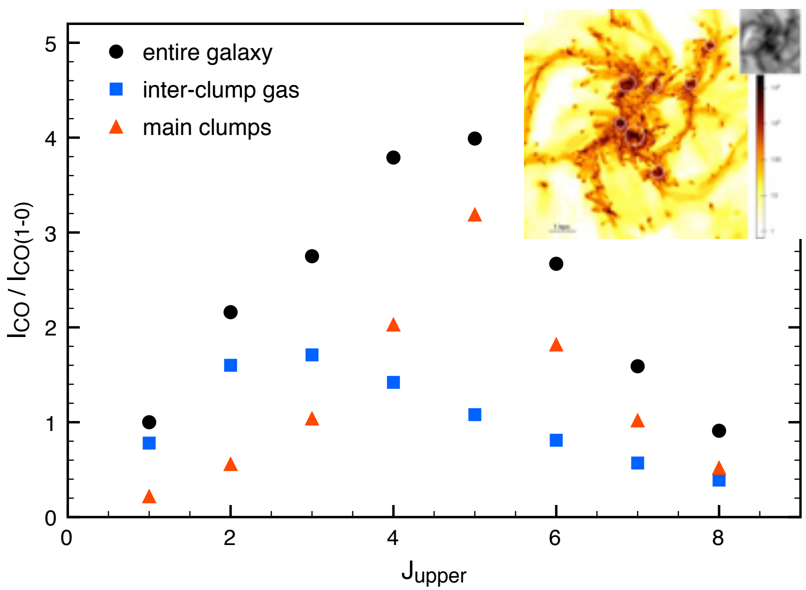
	Main-sequence (MS) galaxies at z~1.5
Sample	NIR BzK-color selected
CO obs	CO(1-0), (2-1), (3-2), (5-4)

CO SLED fitting with Large Velocity Gradient (LVG) modeling

cold/diffuse + warm/dense

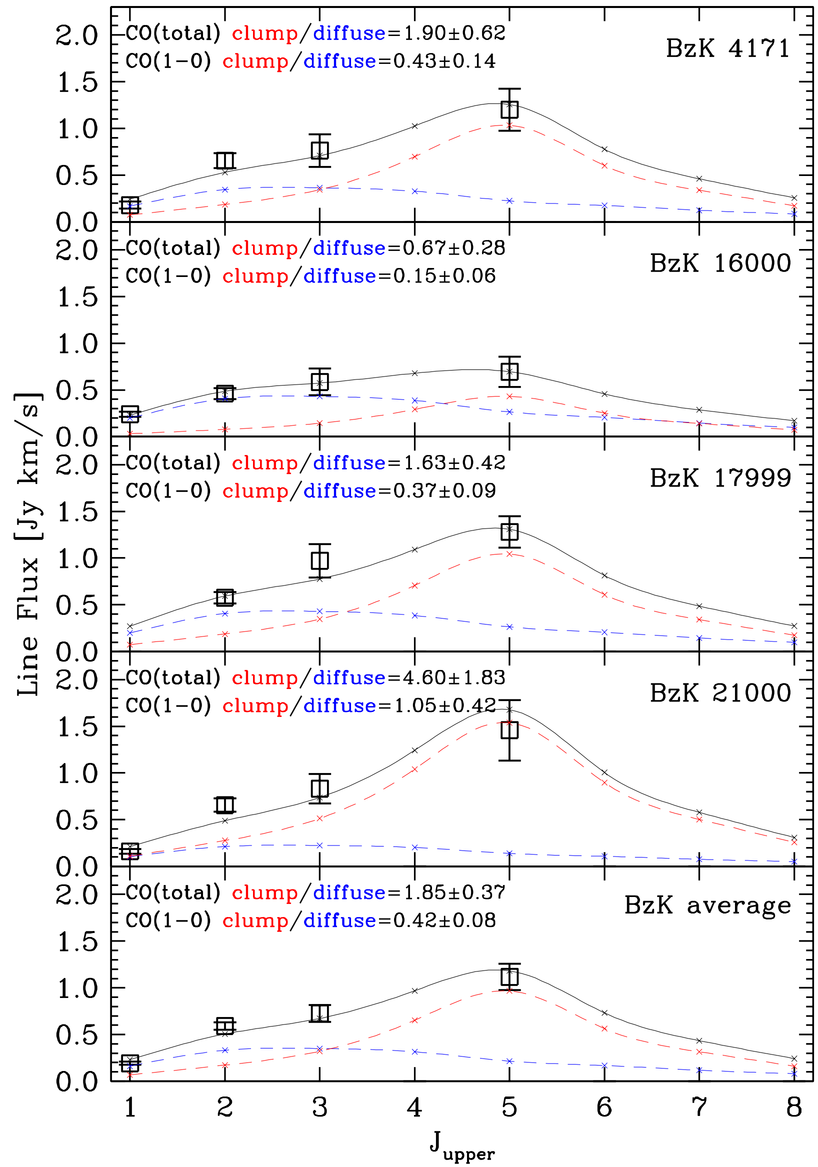


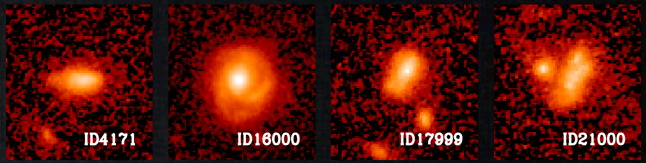
Clumpy SF disk simulation: Bournaud et al. 2015

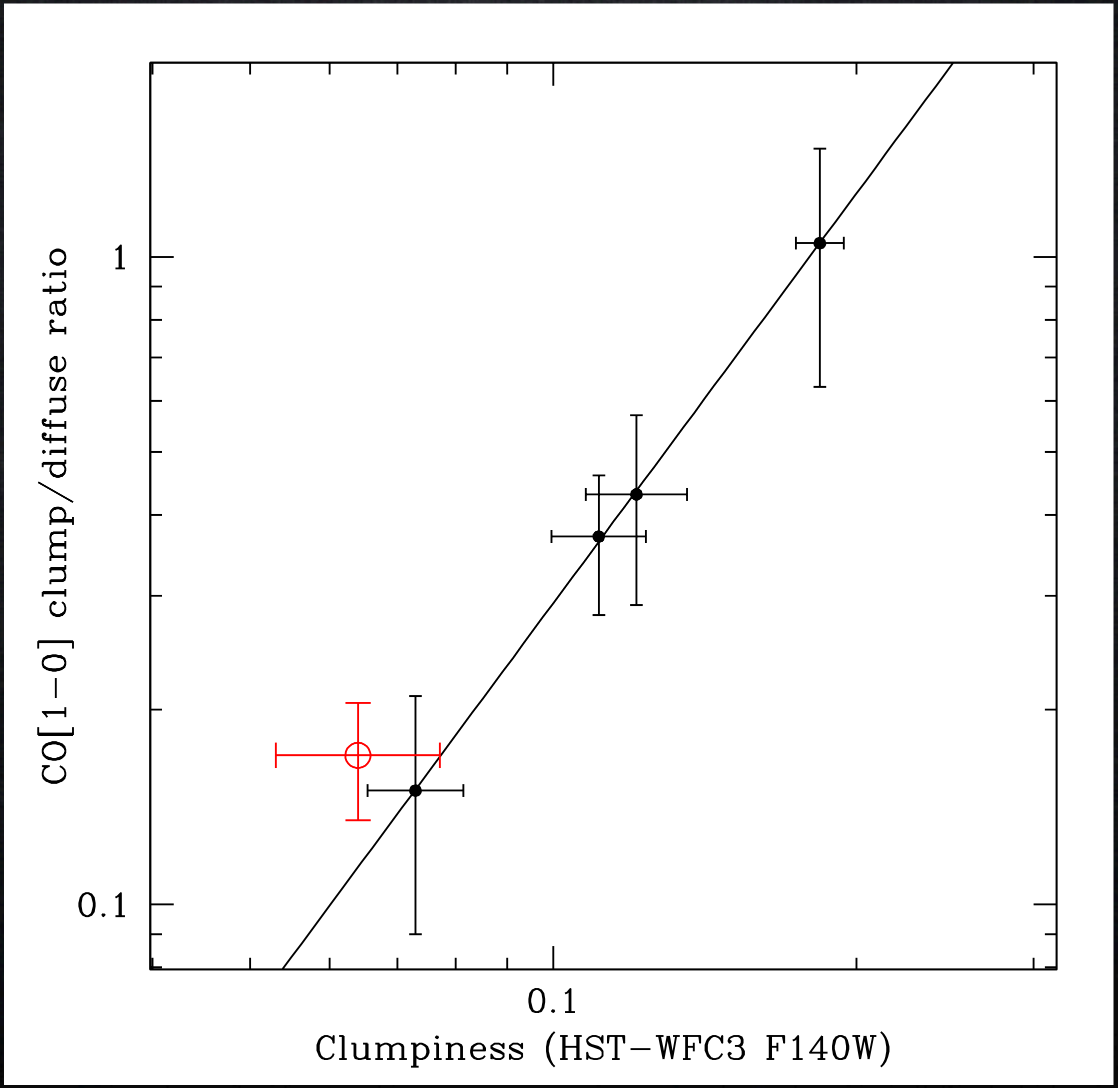


CO SLED fitting with clumpy disk + diffuse gas model

Daddi et al. 2015





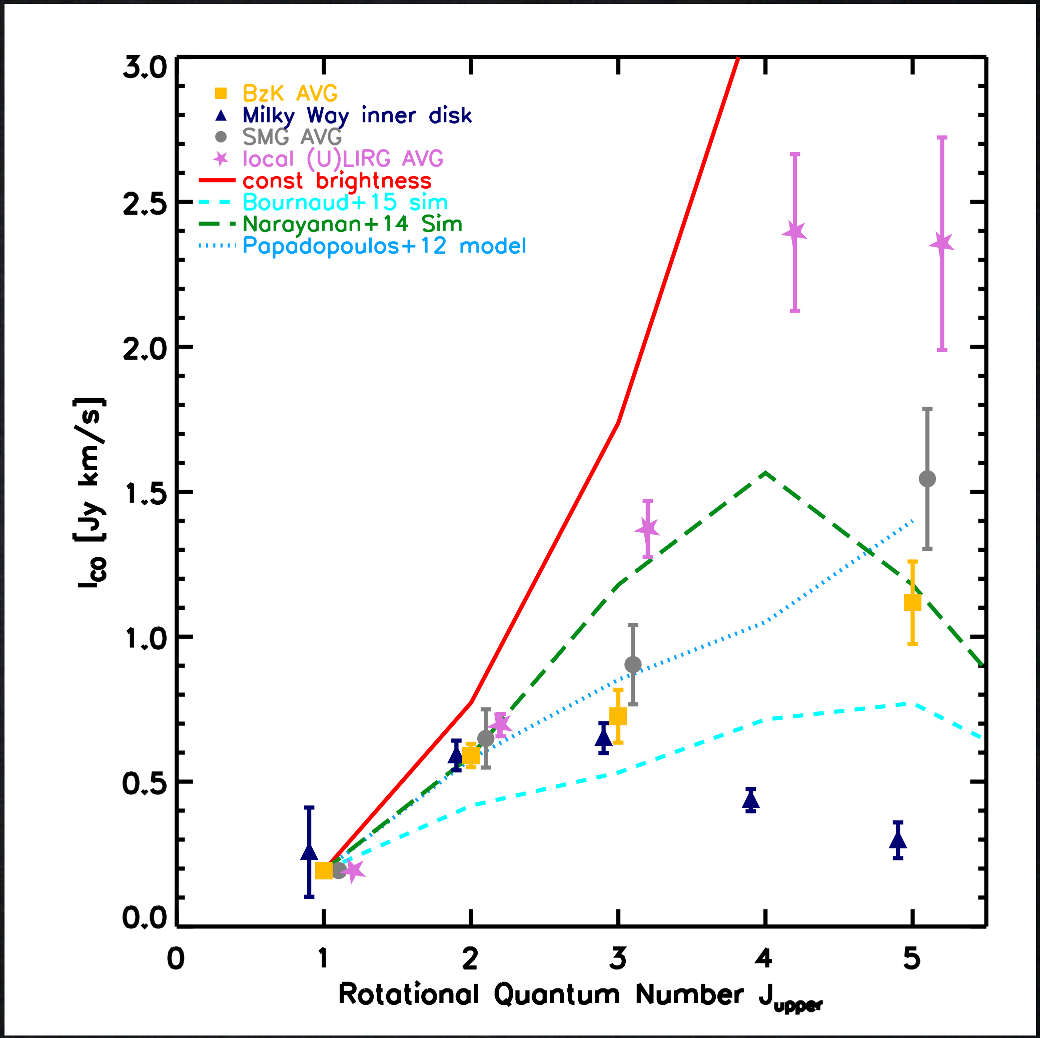


A direct measurement of the "clumpiness" on HST images. (see also Cibinel et al. 2015 arxiv:1503.06220)

The fraction of molecular gas inside clumps are well correlated with the optical morphology!
(see left figure from Daddi et al. 2015)

The plausible physical model encourages more high-z disk observations!

CO Excitation in MS Galaxies at z~1.5



Excitation from high to low:

Local (U)LIRG:

Papadopoulos et al. 2012

SMG:

Bothwell et al. 2013

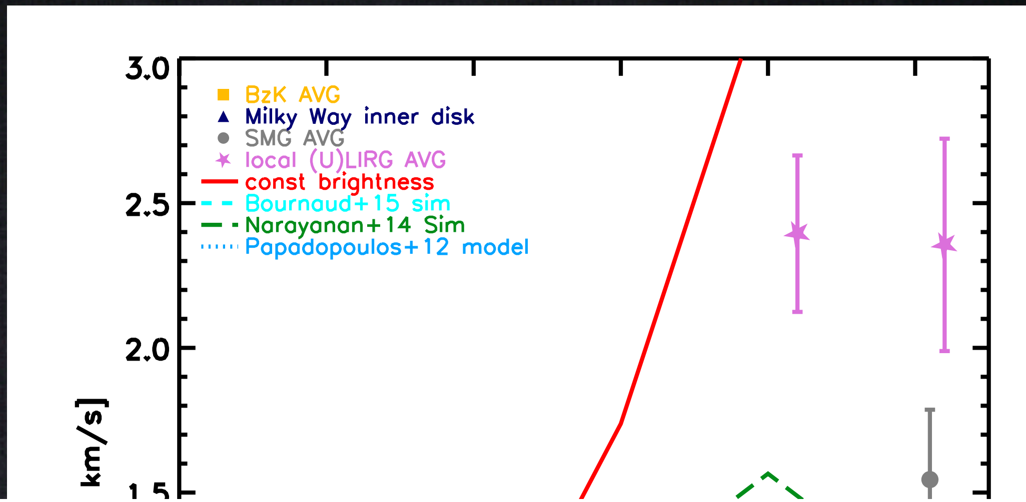
BzK:

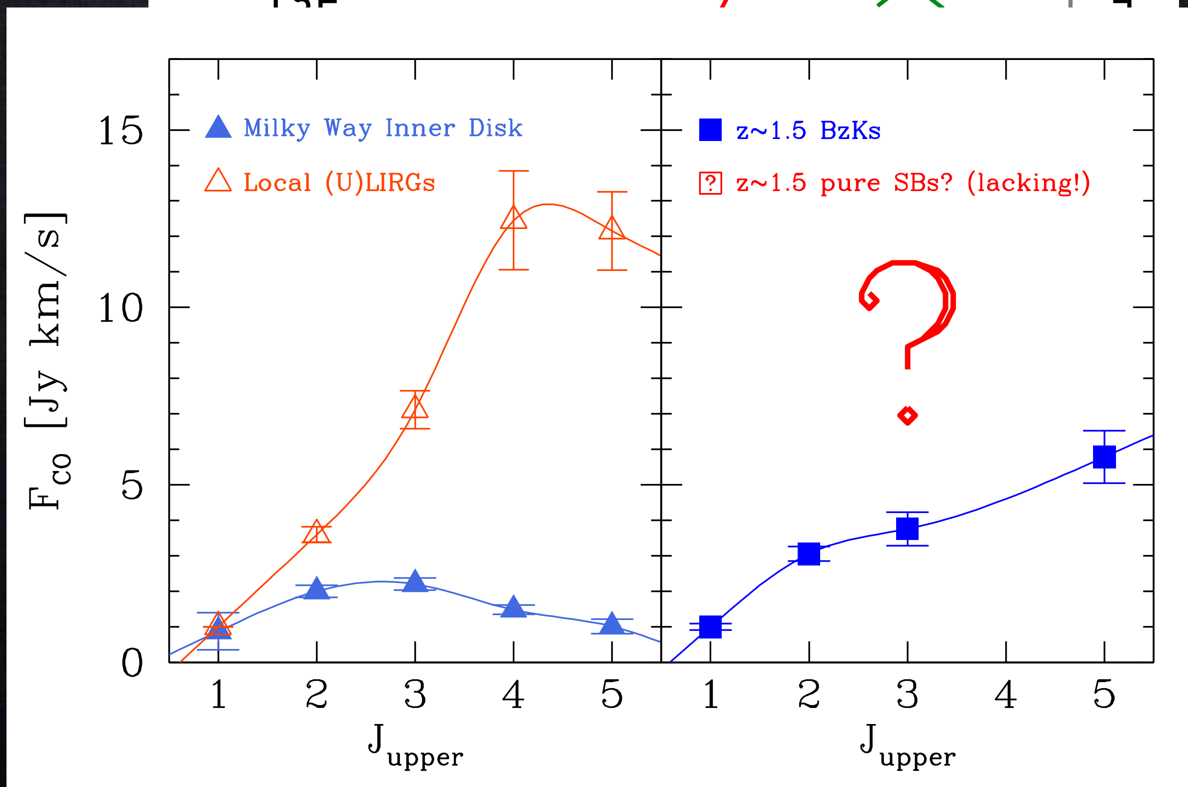
Daddi et al. 2015 (this talk)

Milky Way inner disk:

Fixen et al. 1999

CO Excitation in MS Galaxies at z~1.5





<u>Excitation from high to low:</u>

Local (U)LIRG:

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SMG:

Bothwell et al. 2013

BzK:

Daddi et al. 2015 (this talk)

Milky Way inner disk:

Fixen et al. 1999

Sorting by redshift:

From z=1.5 to local:

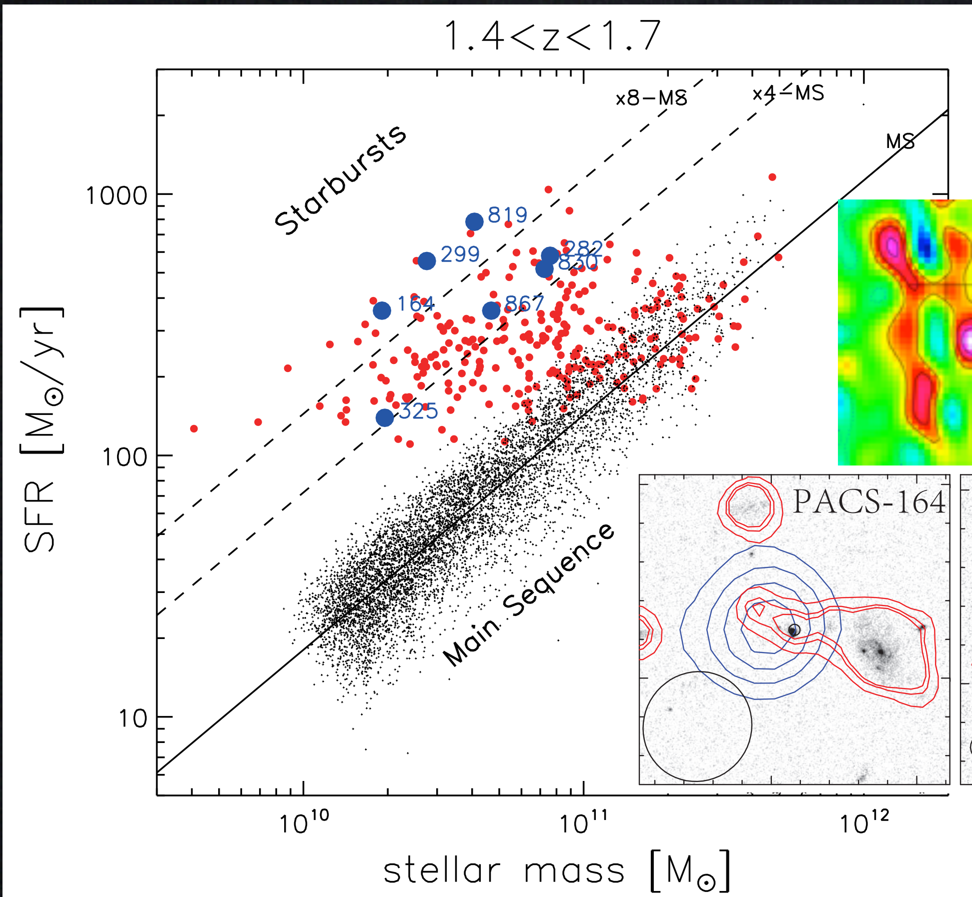
high-z MS v.s. local MS

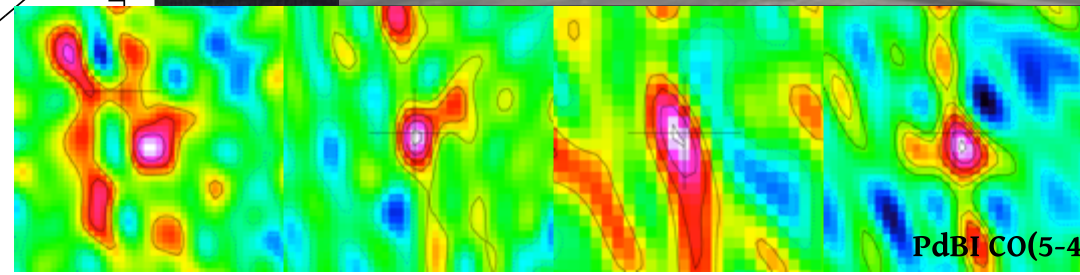
high-z SB v.s. local SB

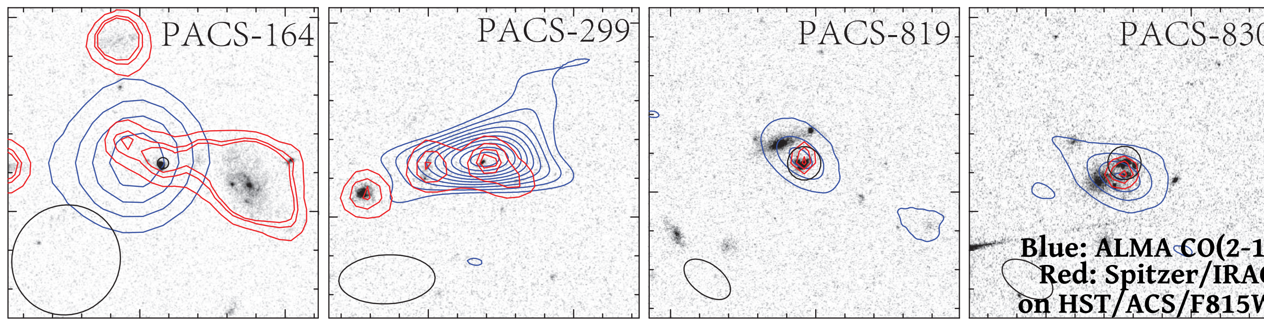
("pure" = a pure sample of strong SB based on star-forming main-sequence)

- CO in 4 MS galaxies at z~1.5 (GOODS-N)
- **CO in 5 SB galaxies at z~1.5 (COSMOS)** ***(Silverman et al. 2015 arxiv: 1505.04977; D. Liu et al. in prep.)***
- CO in local galaxies and partially resolved regions (Herschel/SPIRE/FTS)

CO in SB Galaxies at z~1.5

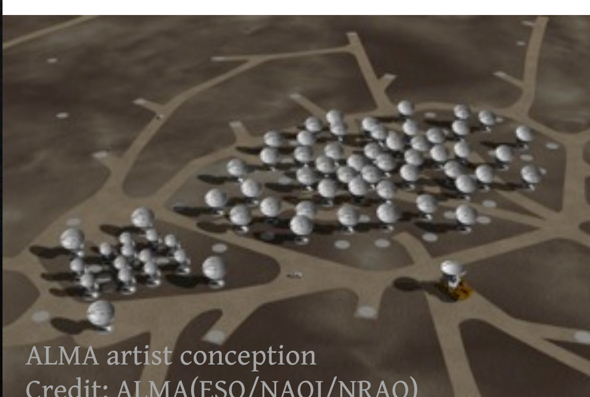


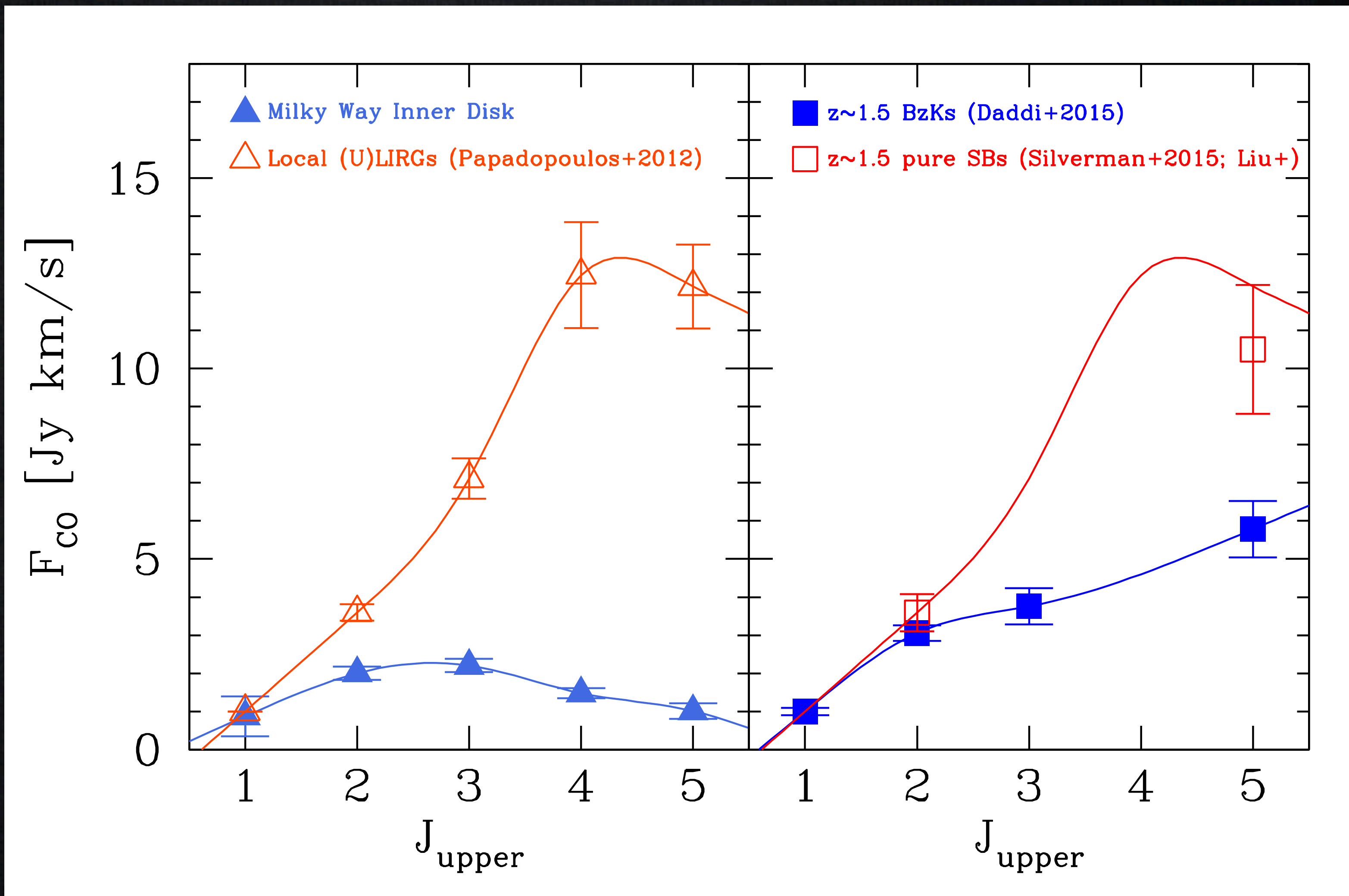




Silverman et al. (incl. D. Liu) (2015)
(arxiv:1505.04977)

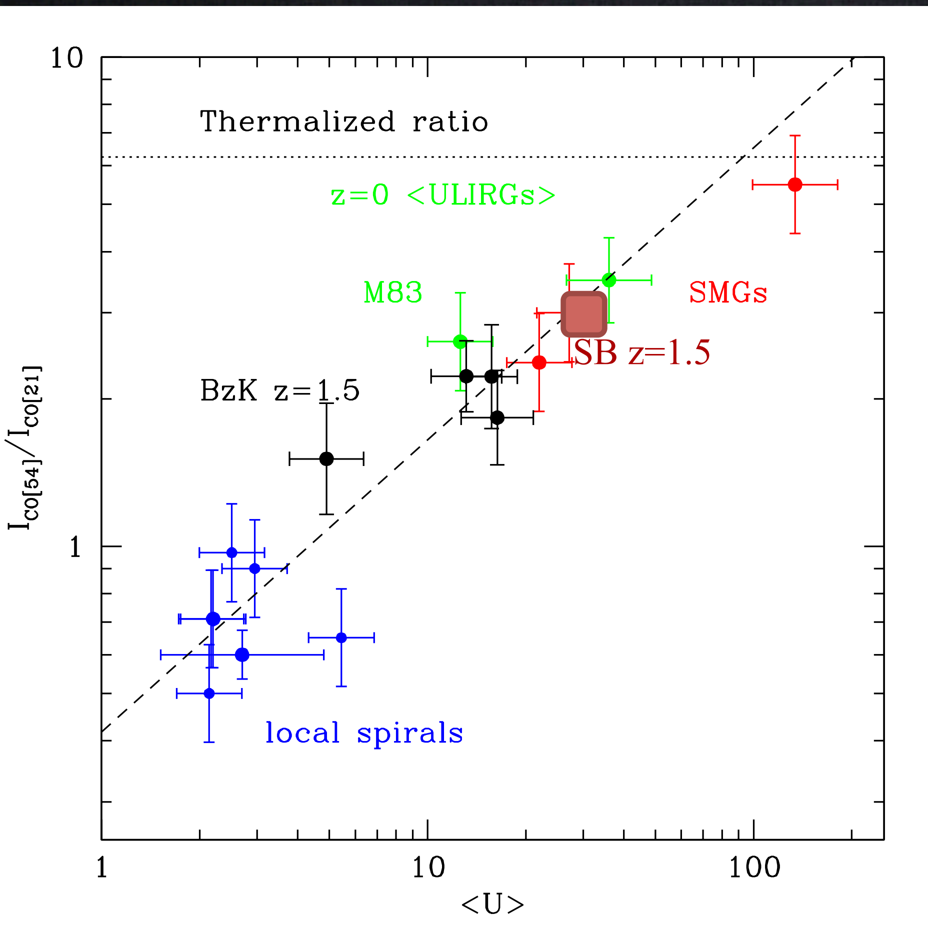
	Starburst (SB) galaxies at z~1.5
Sample	IR SED-based SFR-selected
CO obs	CO(2-1): ALMA (PI: Silverman) + PdBI (PI: Rodighiero) CO(5-4): IRAM/PdBI (PIs: Daddi, Liu)



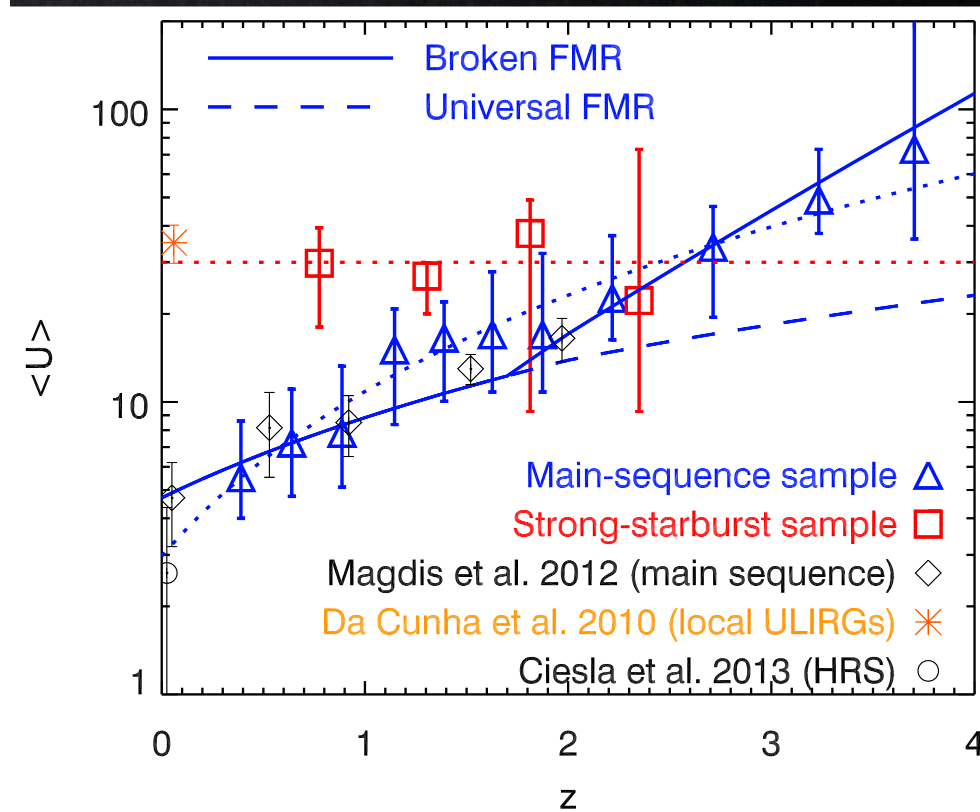


- Surprisingly, z~1.5 “pure” SB sample does not have an average CO SLED highly excited as local (U)LIRGs *(assuming a same R21 = CO(2-1)/CO(1-0) as local (U)LIRGs)*

Daddi et al. 2015



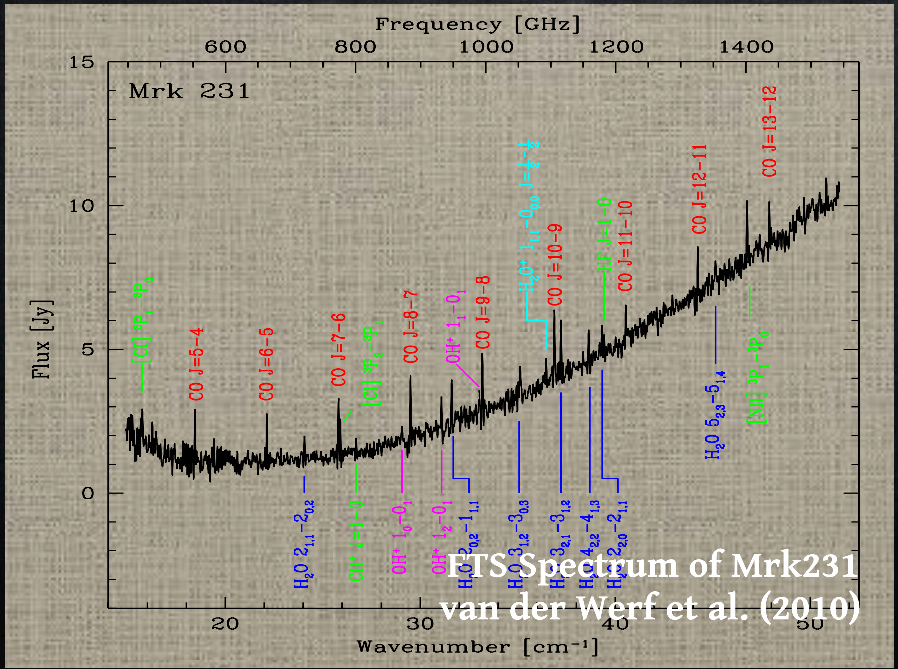
Bethermin et al. 2015
The evolution model of mean dust radiation field <U> from z~4 down to 0.



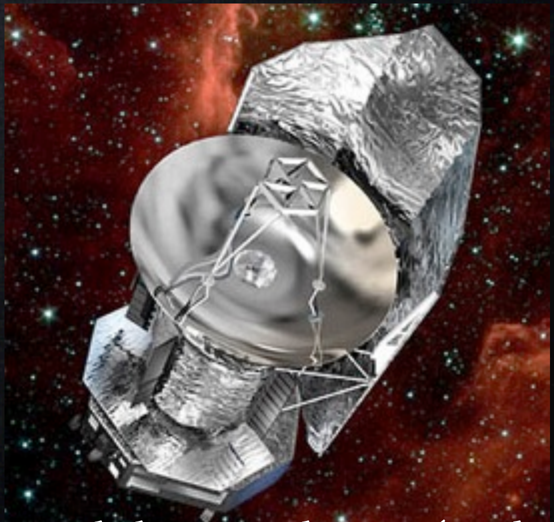
- Suggesting that:
- gas excitation and dust interstellar radiation field <U> (Draine & Li 2007) are strongly coupled.

- CO in 4 MS galaxies at z~1.5 (GOODS-N)
- CO in 5 SB galaxies at z~1.5 (COSMOS)
- **CO in local galaxies and partially resolved regions (Herschel/SPIRE/FTS)**

(D. Liu et al. 2015 CO-IR correlation – arxiv:1504.05897 ApJL submitted & dataset in prep.)



FTS Spectrum of Mrk231
van der Werf et al. (2010)



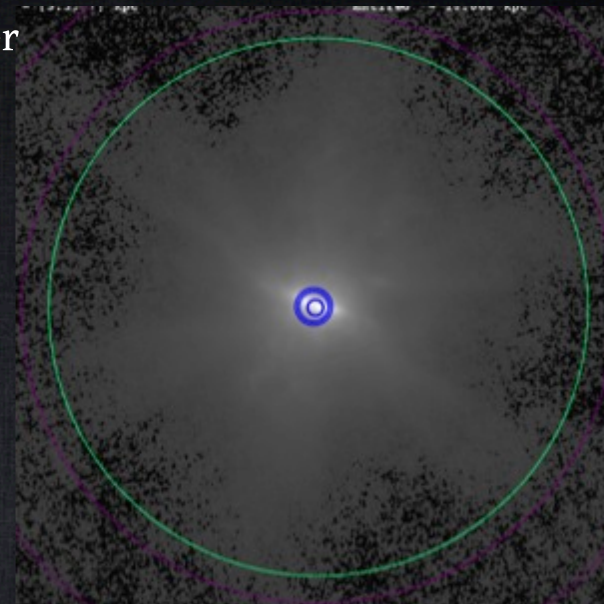
Herschel Space Telescope (Credit: ESA)

FTS = Fourier Transform Spectrometer (Naylor et al. 2010)

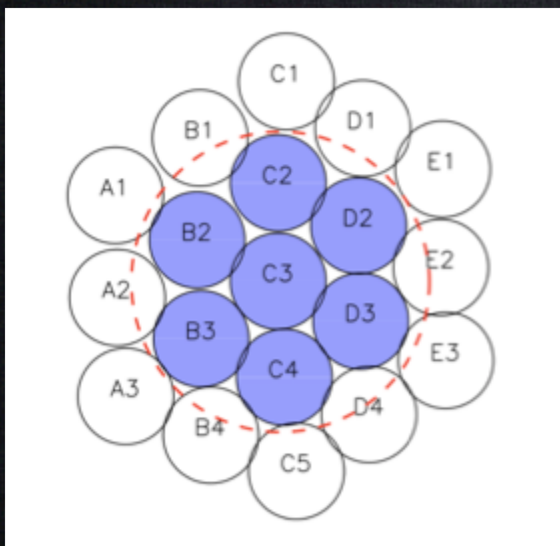
SPIRE (Griffin et al. 2010)

Herschel/FTS CO (4-3) to (13-12) observations in Local Galaxies

FTS central bolometer
pointing to M82

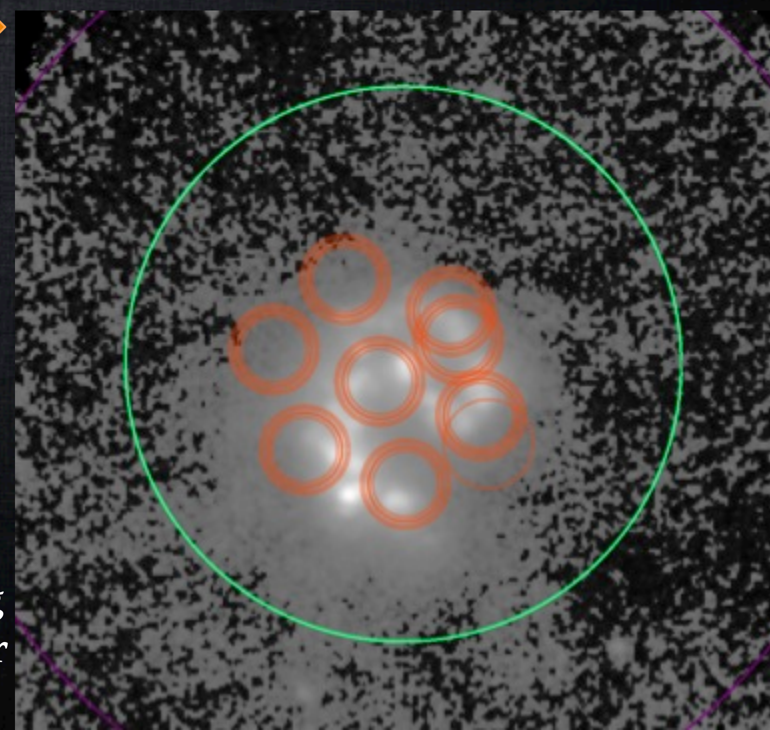


Herschel/SPIRE Spectrometer
(FTS) bolometer array
Covering: CO(4-3) to CO(13-12)



Performed detailed
photometry on
Herschel/PACS

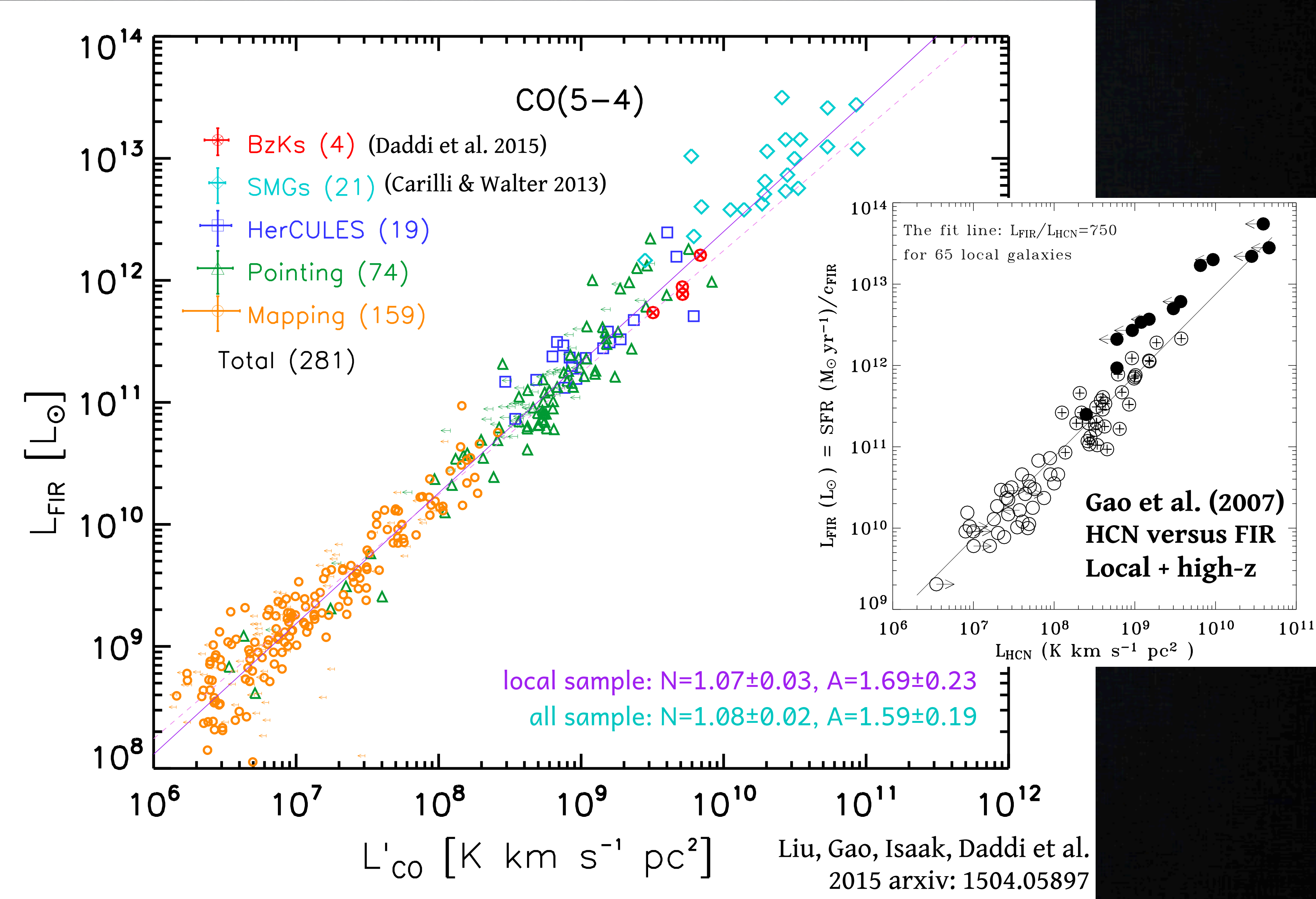
Correlating with
FIR luminosity
with matched beam



Herschel Science Archive (HSA)
FTS Programmes
e.g. HerCULES *(PI: van der Werf)*, GOALS *(PI: Lu)*, KINGFISH *(PI: Smith)*, etc...

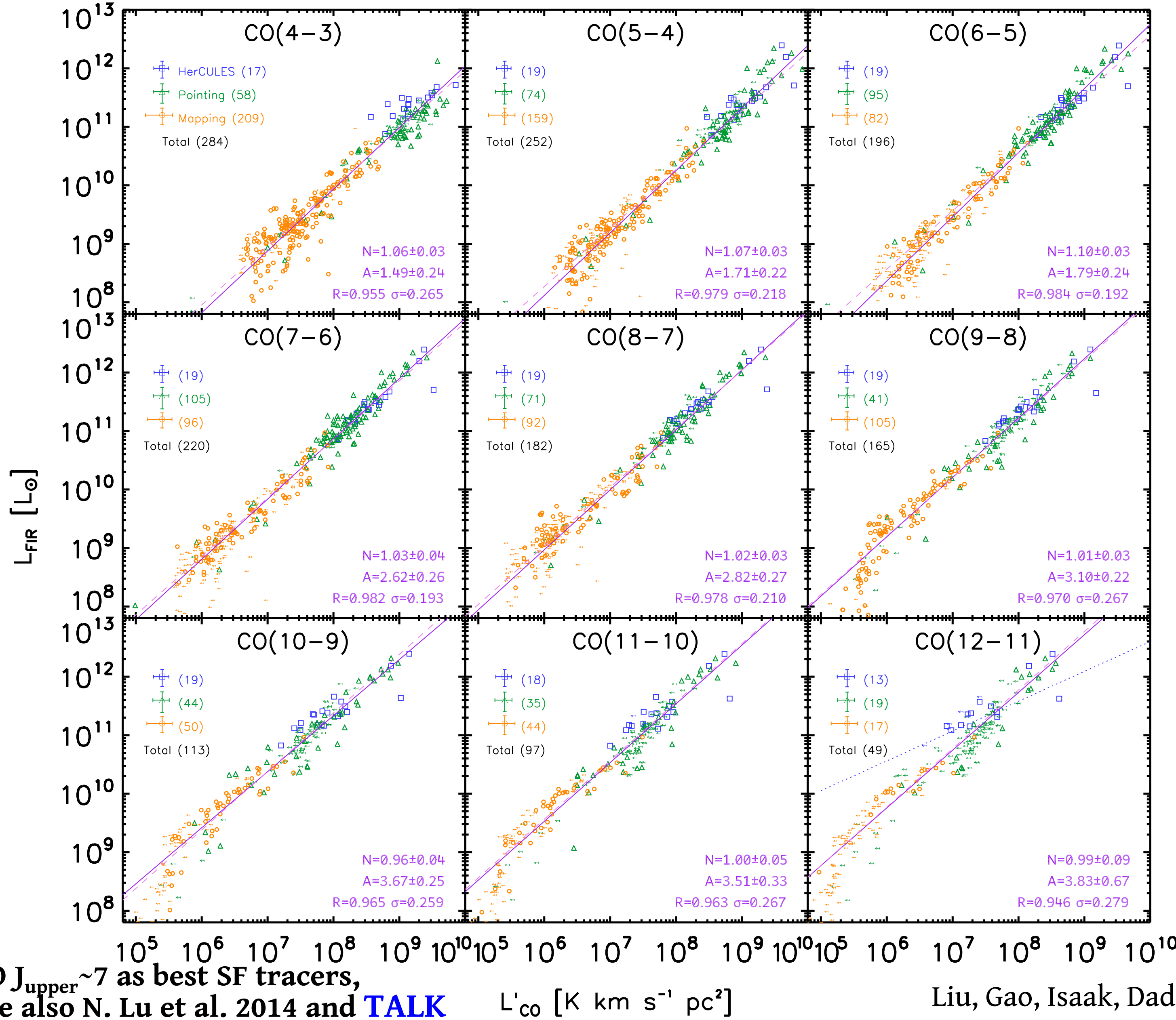
FTS bolometers mapping
the Antennae Galaxy Pair

CO(5-4) in Local Galaxies and High-z Galaxies



Liu, Gao, Isaak, Daddi et al.
2015 arxiv: 1504.05897

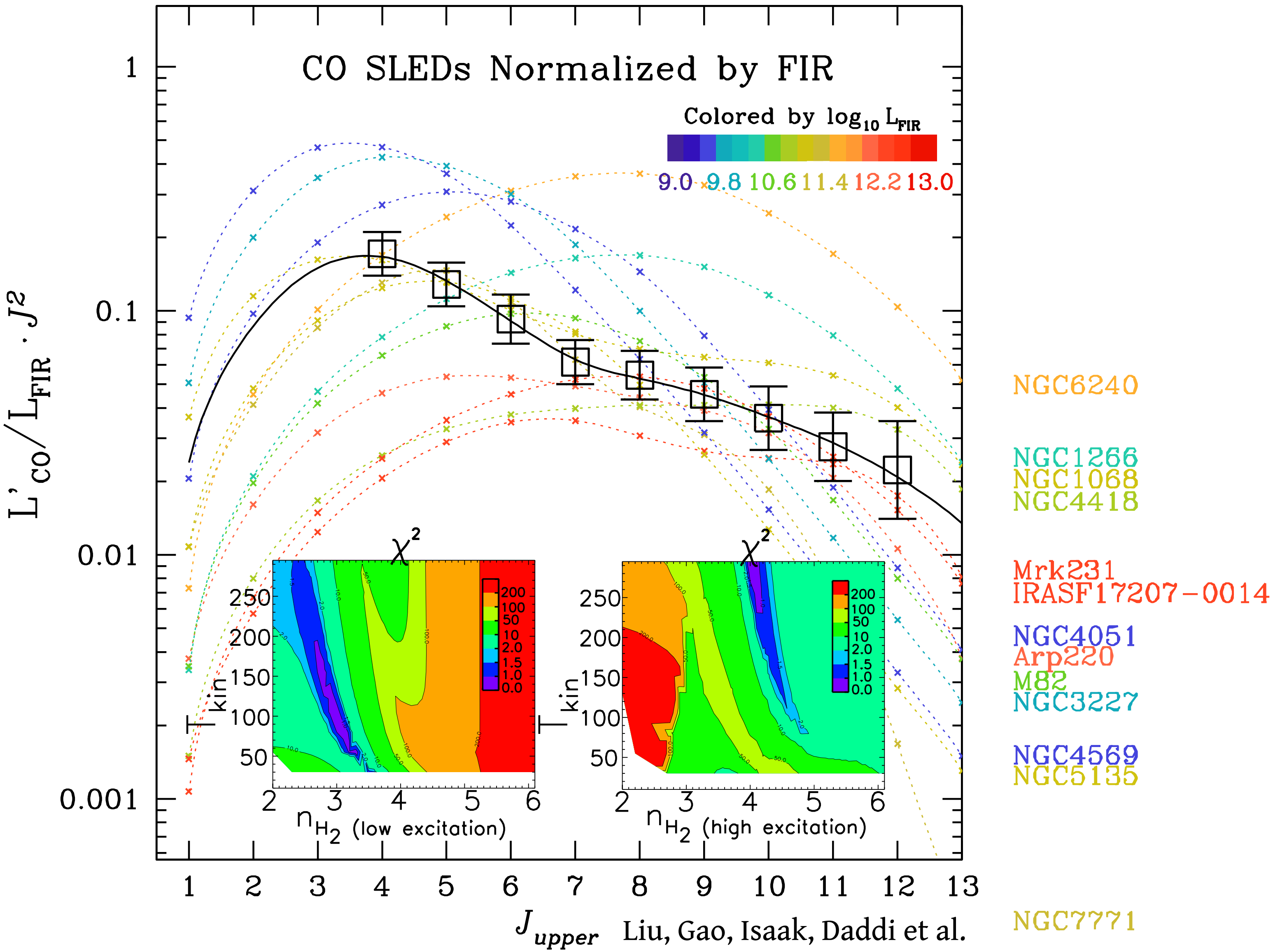
Many thanks to the Herschel/FTS and many public Herschel programs!



CO J_{upper}~7 as best SF tracers,
see also N. Lu et al. 2014 and TALK

Other dense gas tracers: high-J CS, HCN, HCO+ (Z. Zhang et al. 2014 **POSTER**)

Liu, Gao, Isaak, Daddi et al.
2015 arxiv: 1504.05897



Liu, Gao, Isaak, Daddi et al.
2015 arxiv: 1504.05897

Local average CO SLED for our sample:
Two gas components needed (see also Kamenetzky et al. 2014)

SUMMARY

PART 1 & 2

- CO SLED up to J=5-4 --- "normal" MS sample at z~1.5
- CO J=2-1 and J=5-4 --- "pure" SB sample at z~1.5
- Strongly coupled dust <U> and gas excitation evolution
- Physical clumpy/diffuse ISM model and good morphological correlation

PART 3

- CO SLED from J=4-3 to J=12-11 --- local galaxies observed by Herschel/SPIRE/FTS
- Tight & linear dense gas versus far-infrared relations
- A local average CO SLED revealing two gas components
- A local benchmark for high-z CO surveys in the ALMA era!

Thank you!

Thank you!

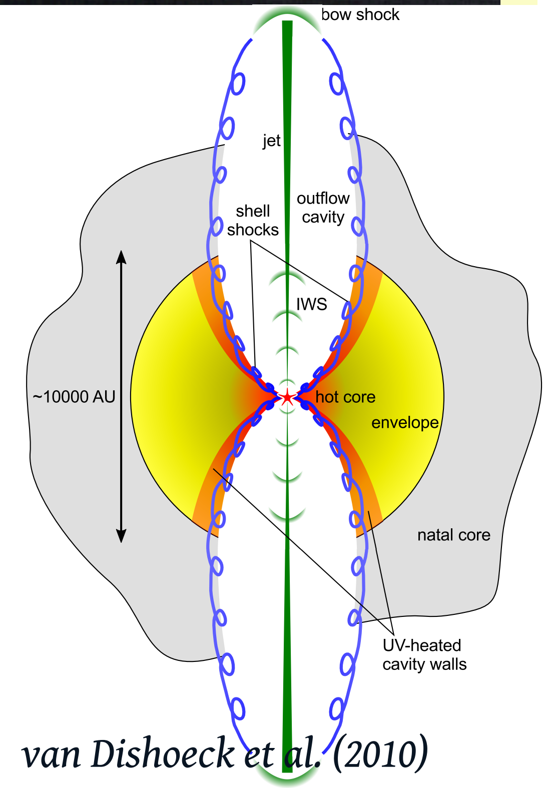
Table of CO rotational transition properties

		Excitation potential (K)	n_{crit} (cm^{-3})
CO	J = 1–0	5.5	2.1×10^3
	J = 2–1	16.6	1.1×10^4
	J = 3–2	33.2	3.6×10^4
	J = 4–3	55.3	8.7×10^4
	J = 5–4	83.0	1.7×10^5
	J = 6–5	116.2	2.9×10^5
	J = 7–6	154.9	4.5×10^5
	J = 8–7	199.1	6.4×10^5
	J = 9–8	248.9	8.7×10^5
	J = 10–9	304.2	1.1×10^6

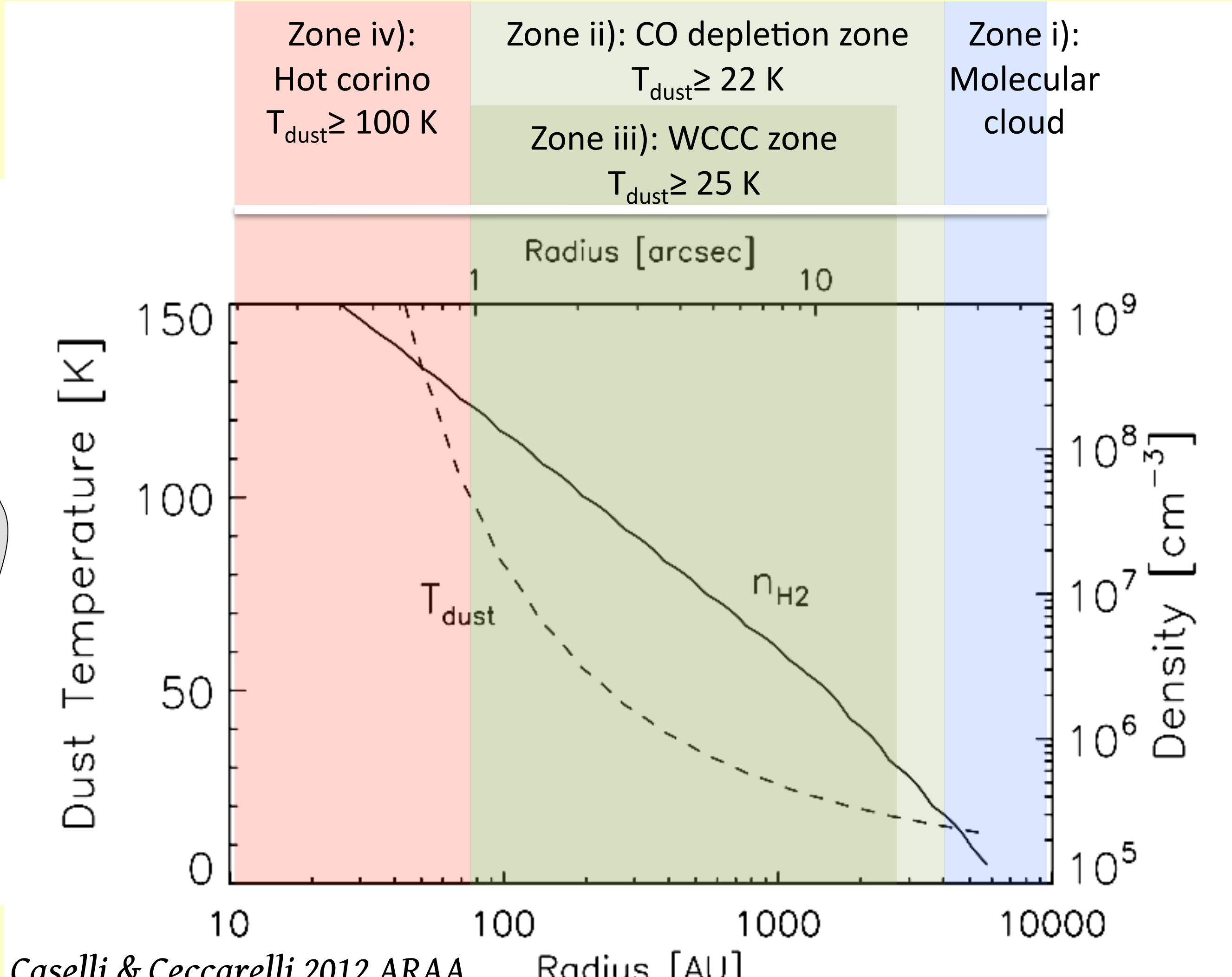
Adopted from Carilli & Walter (2013)

Possible origin of high-J CO emissions

van Kempen et al. 2009:
(iii) quiescent gas heated by UV
(ii) shocked gas in outflow
(i) inner envelope heated by protostar

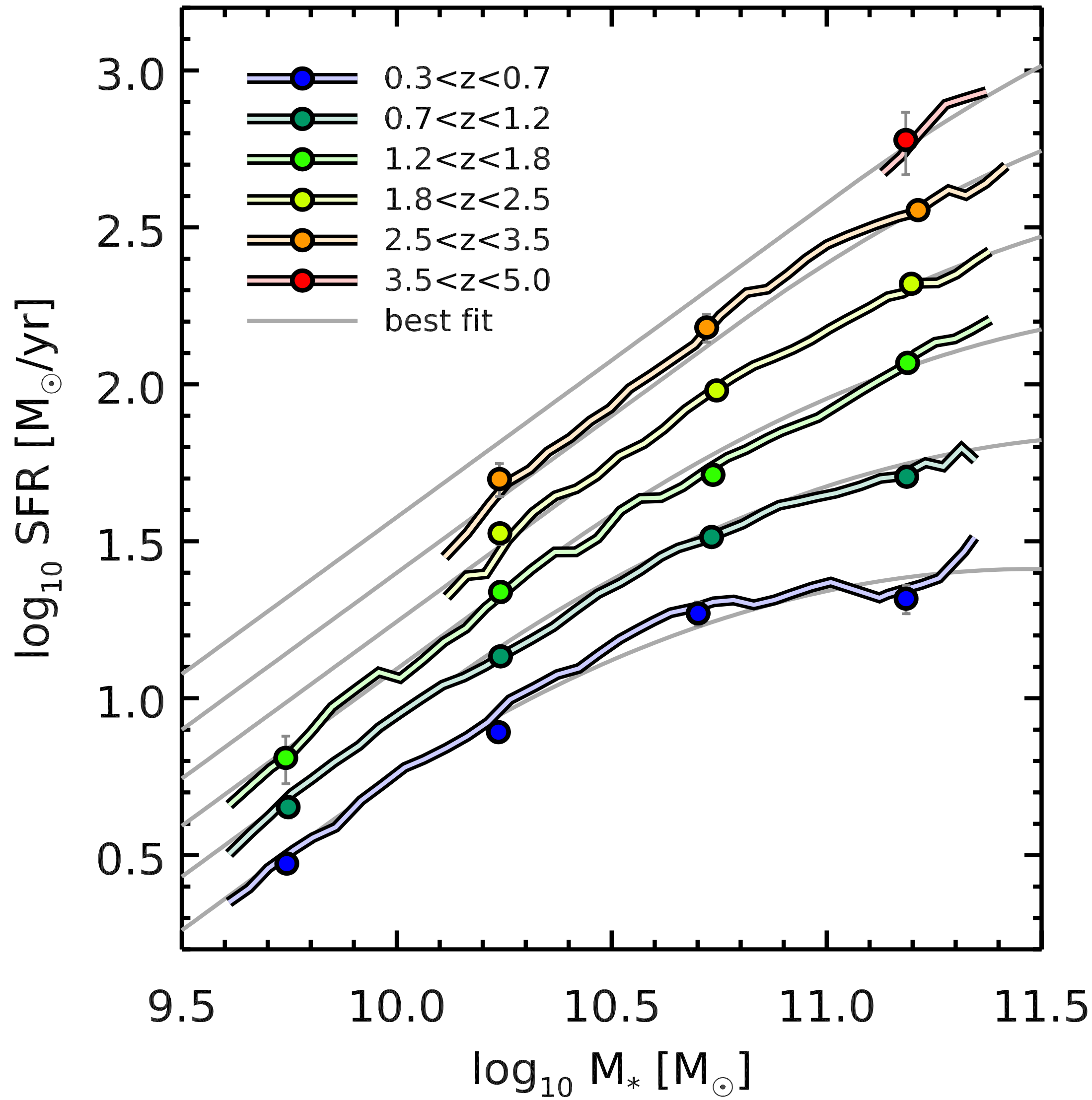


van Dishoeck et al. (2010)



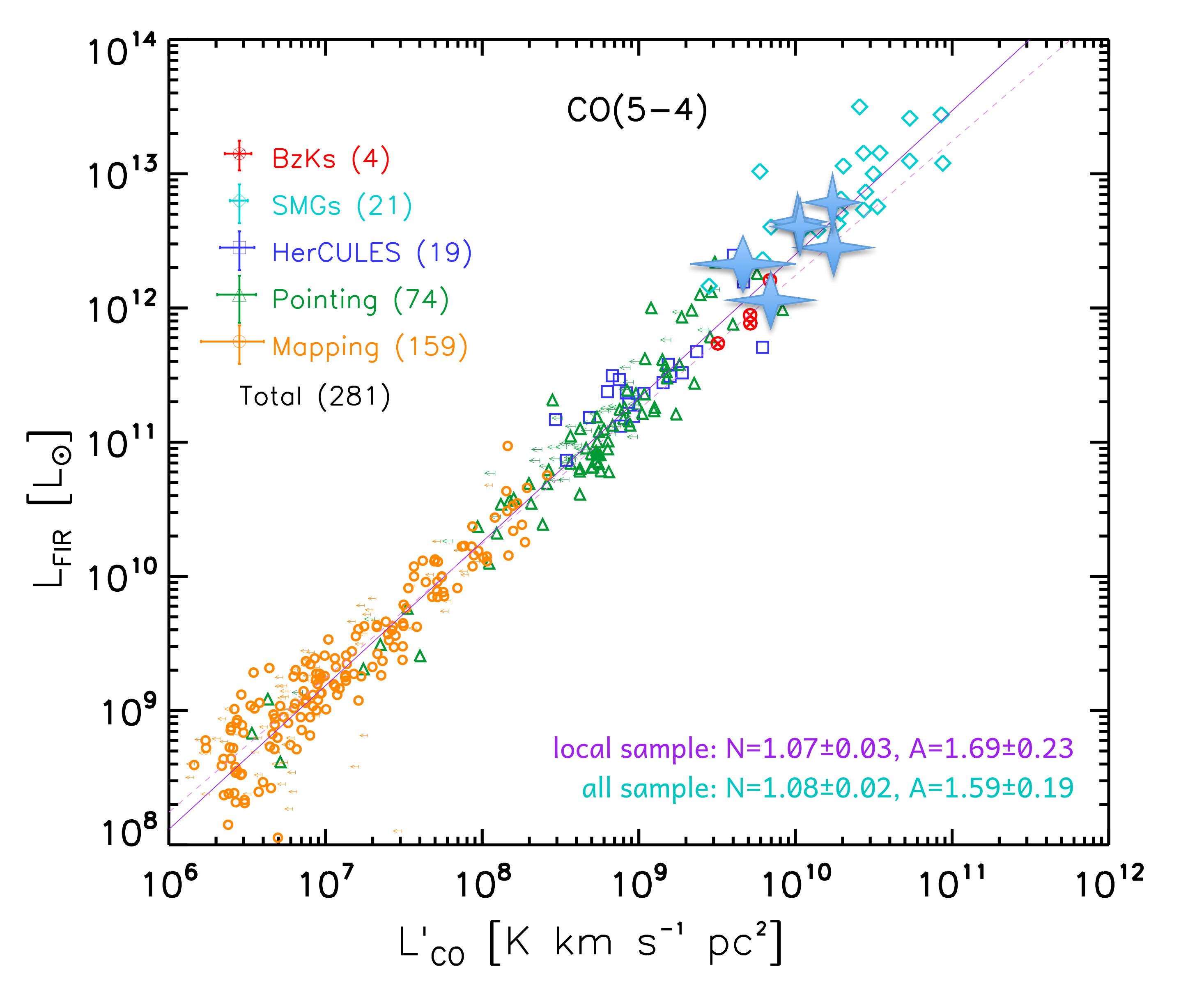
Caselli & Ceccarelli 2012 ARAA

protostellar IRAS16293-2422 radial profile out to 10000 AU (0.05 pc).



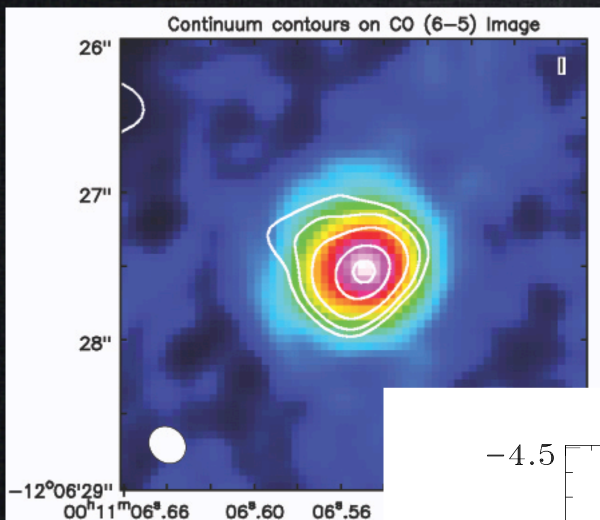
C. Schreiber et al. 2014 star-forming main-sequence across cosmic time with stacking technique
(see also M. Sargent et al. 2014 sSFR evolution)

Do z~1.5 SB and MS galaxies still follow two Kennicutt-Schmidt Law?!

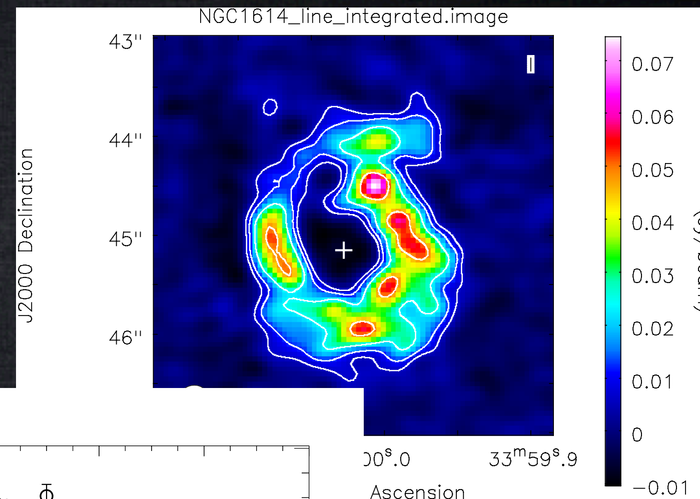


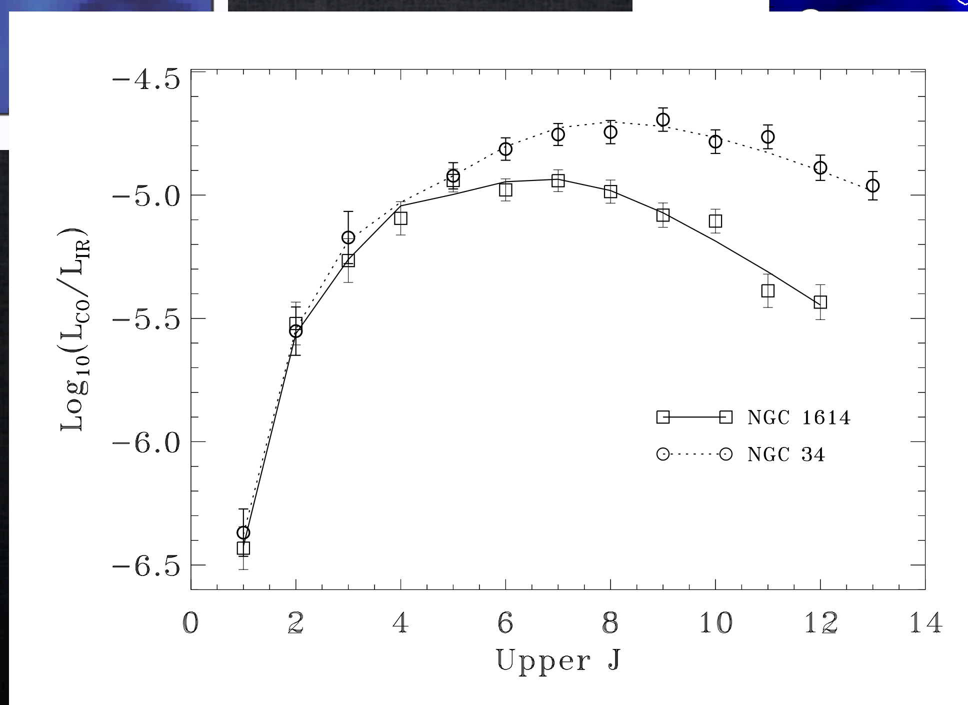
Left: ALMA CO(6-5) in NGC0034 from Xu et al. 2014
NGC0034 unresolved core (central AGN) contributes 28% continuum and 19% CO(6-5).

Left: ALMA CO(6-5) in NGC0034 from Xu et al. 2014
Right: ALMA CO(6-5) in NGC1614 from Xu et al. 2015

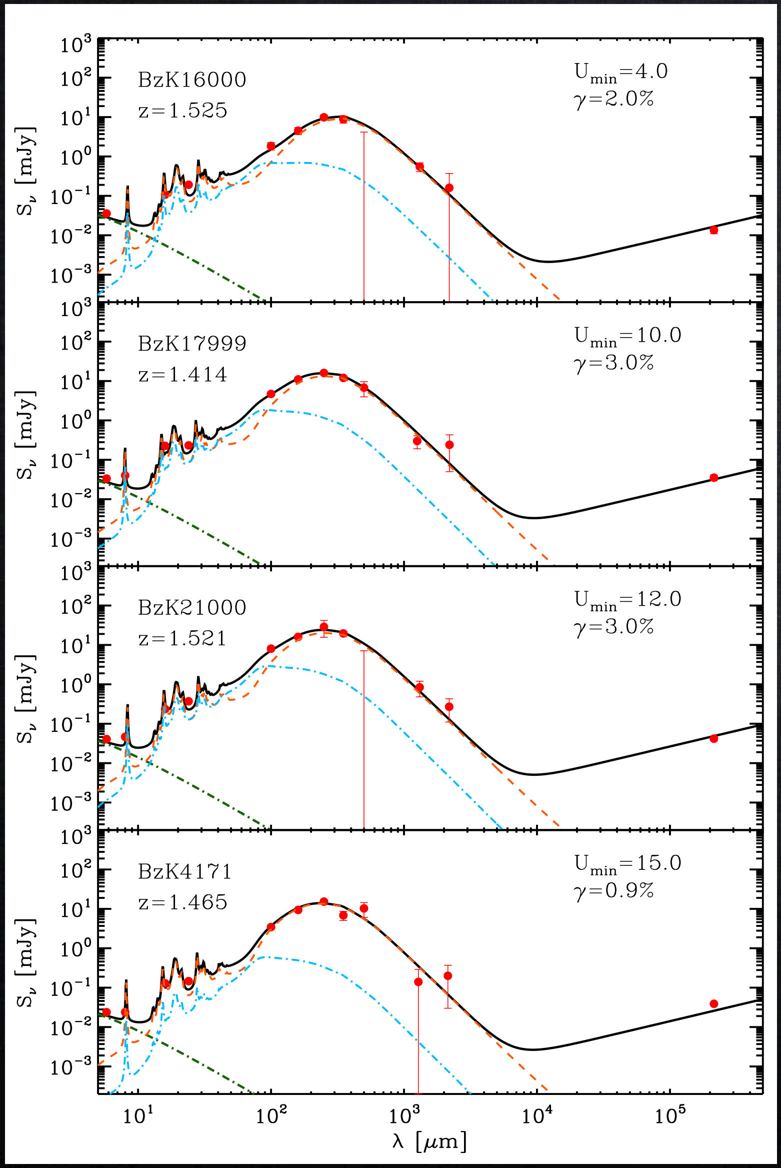


Middle: ALMA+FTS +literature CO SLED from Xu et al. 2015



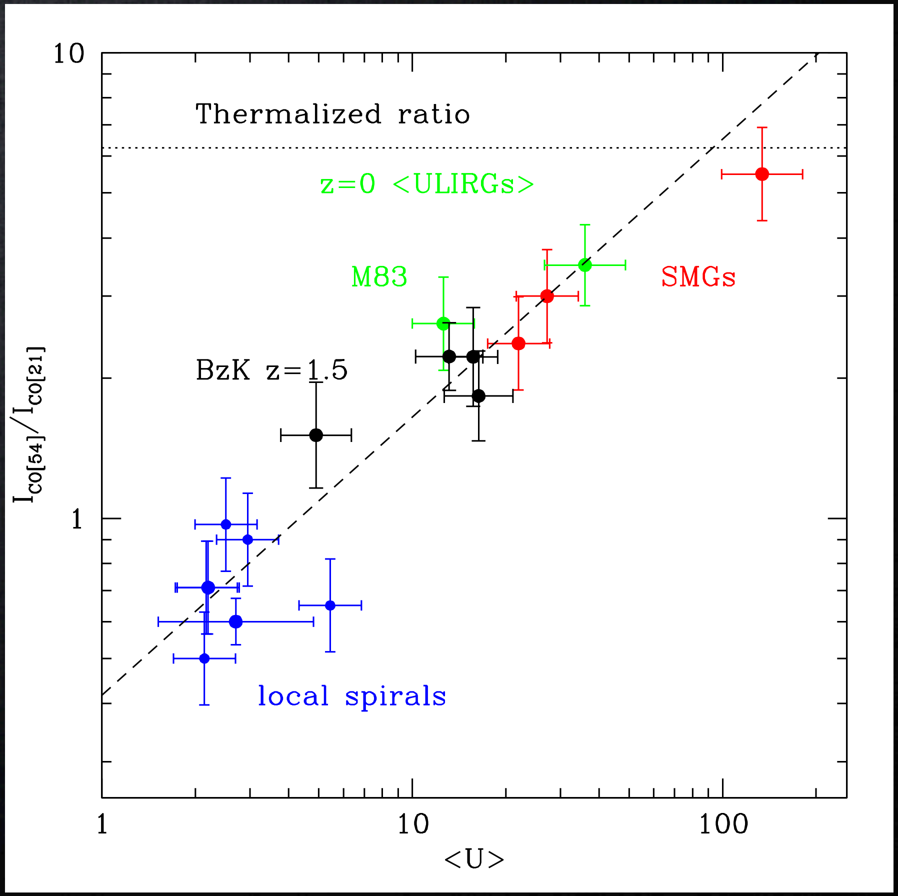


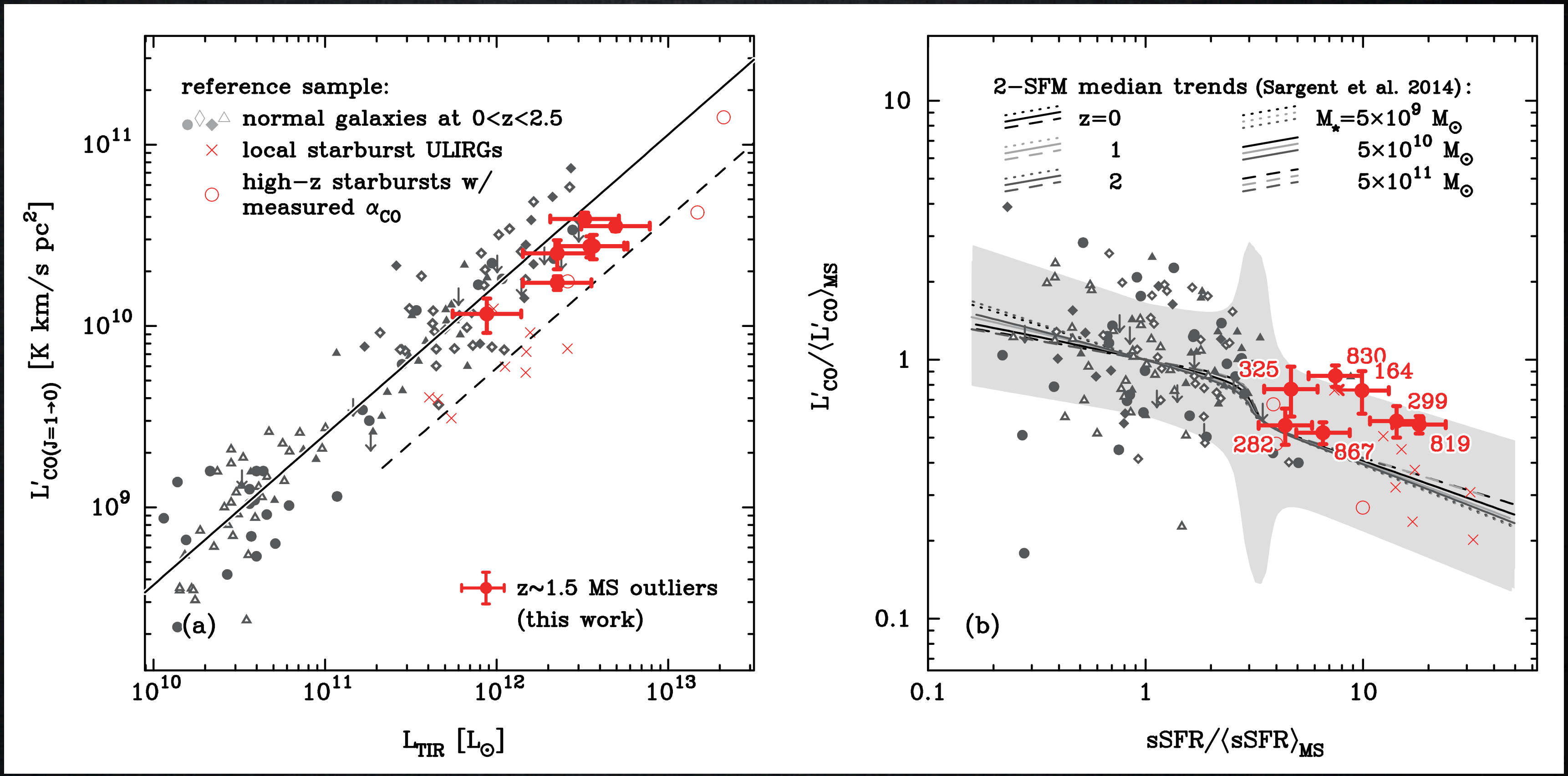
IR SED fitting with two-component dust:
Magdis et al. 2012; Draine & Li 2007



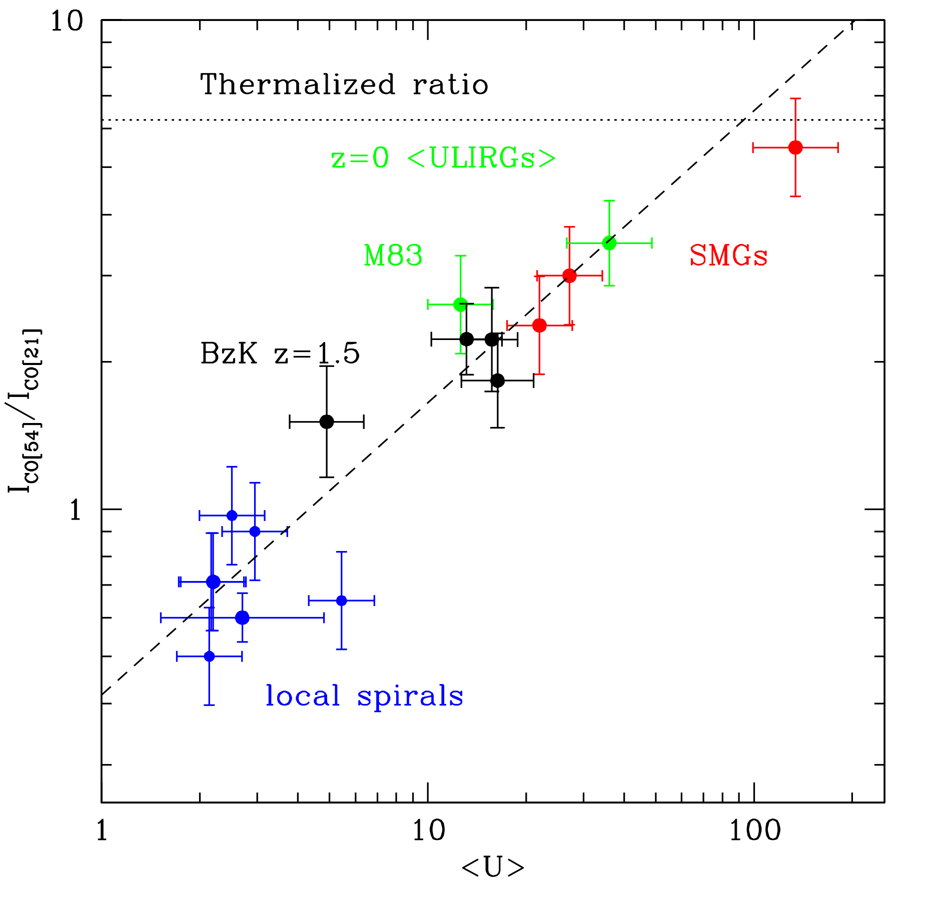
Cold dust: U_{min} (a minimum radiation field)
Warm dust: U_{min}-U_{max} (a powerlaw radiation field)
mean ISRF: <U> ~ dust temperture

Good correlation between R52 and <U>

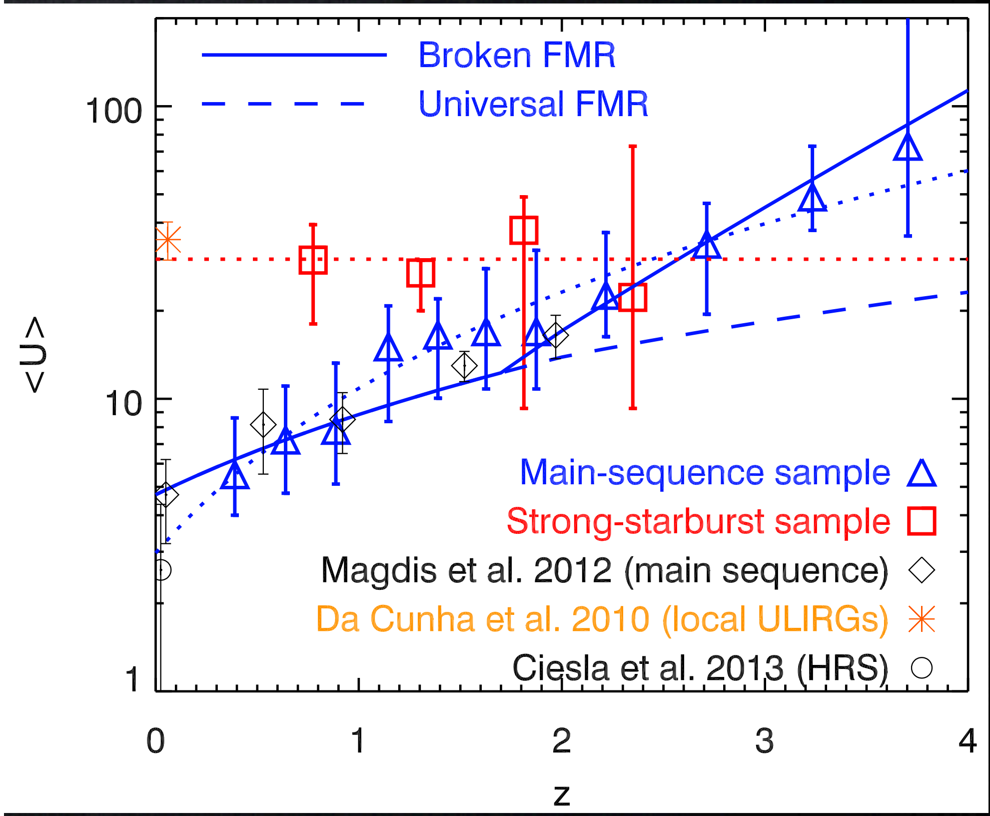



reference sample:
normal galaxies at 0<z<2.5
local starburst ULIRGs
high−z starbursts w/ measured α_{CO}
z~1.5 MS outliers (this work)
(a)
$L'_{CO(J=1\to0)}$ [K km/s pc^2]
L_{TIR} [$L_\odot$]
10^{10}
10^{11}
10^{12}
10^{13}
10^9
2−SFM median trends (Sargent et al. 2014):
z=0
1
2
$M_\star=5\times10^9$ $M_\odot$
5×10^{10} $M_\odot$
5×10^{11} $M_\odot$
325
830
164
299
282
867
819
(b)
$L'_{CO}/\langle L'_{CO}\rangle_{MS}$
sSFR/⟨sSFR⟩$_{MS}$
0.1
1
10

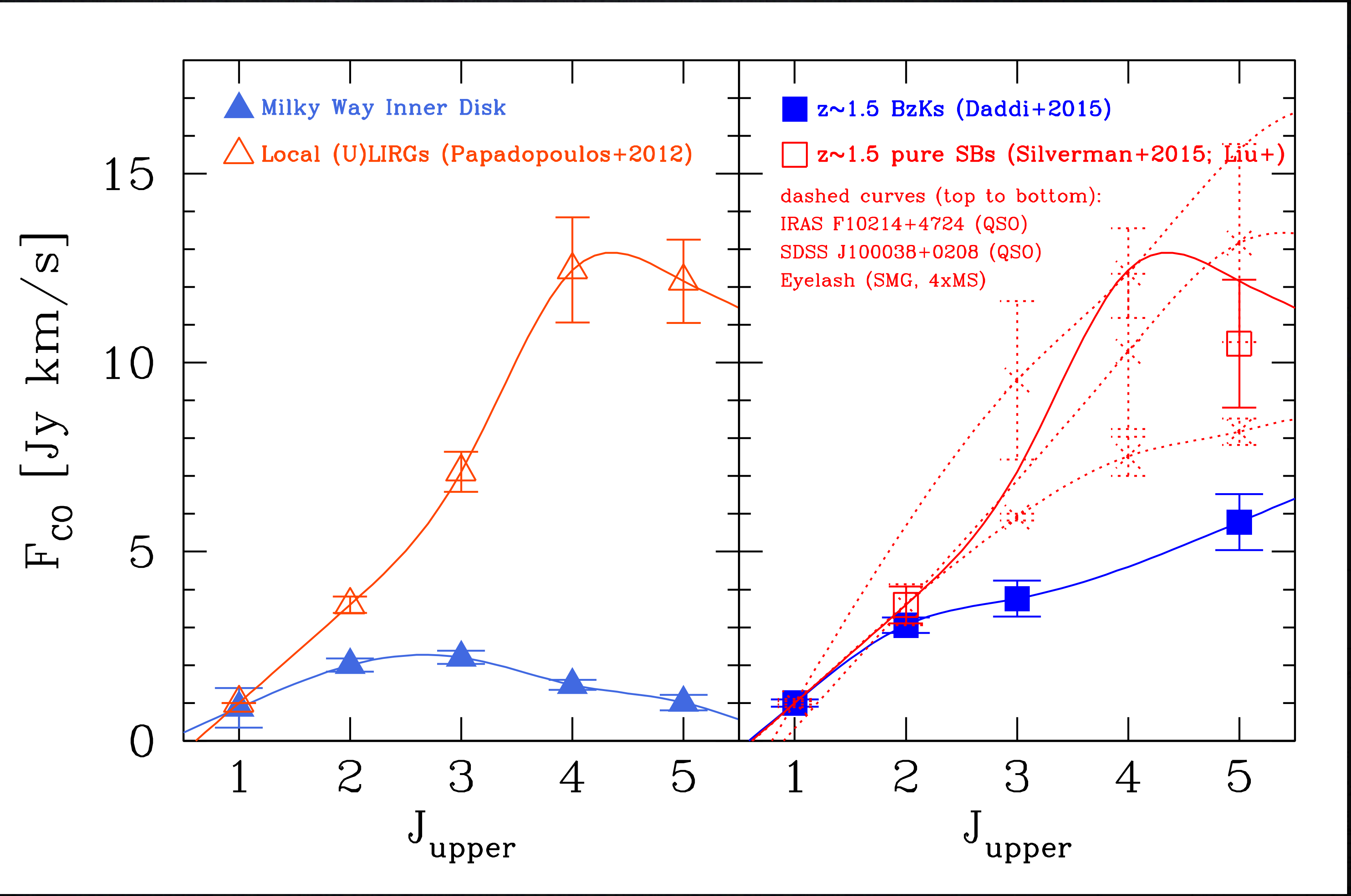
Daddi et al. 2015



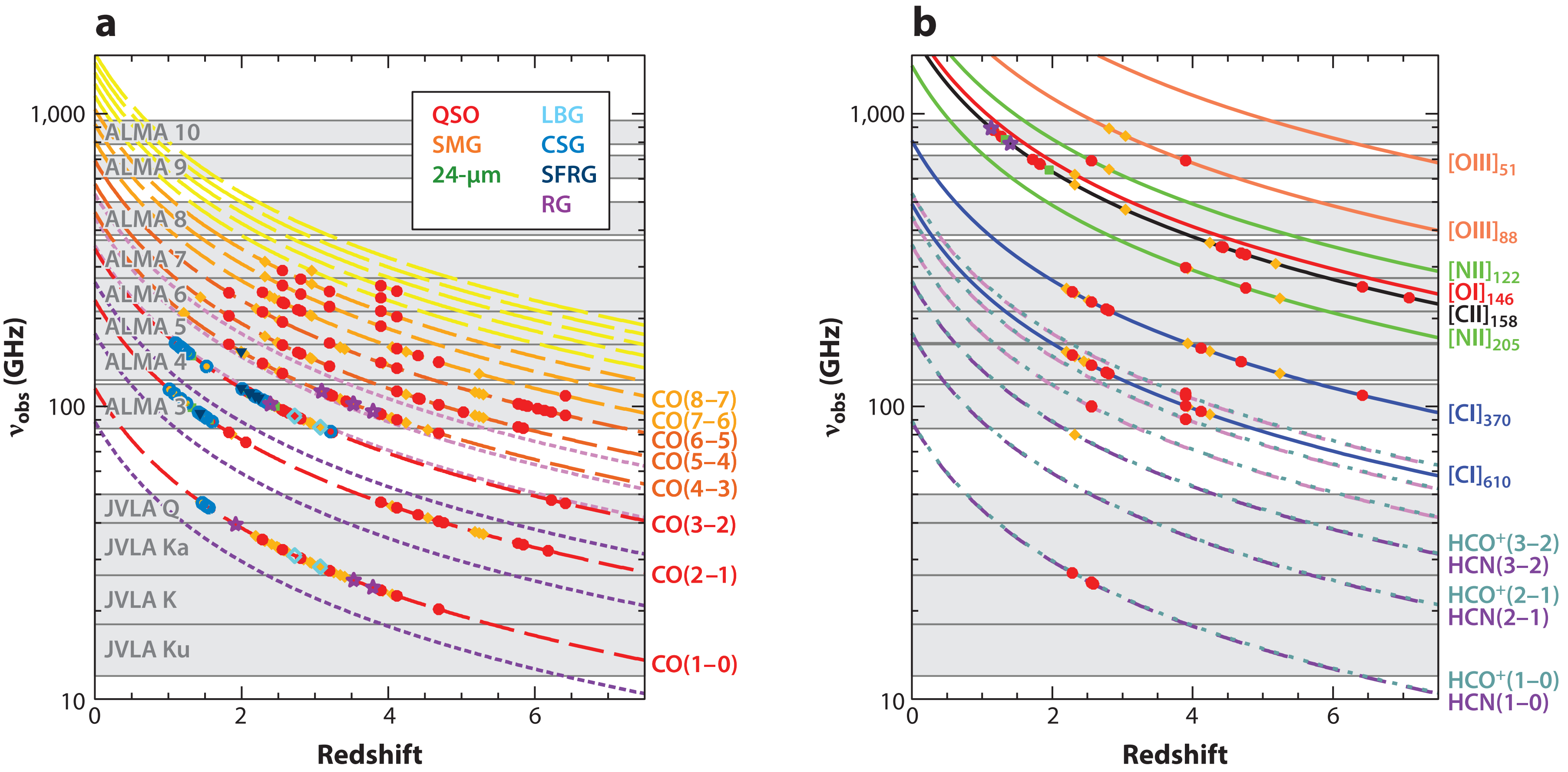
Bethermin et al. 2015



More CO SLEDs at high-z (including QSOs)



This is ALMA era!



Carilli & Walter 2013 ARAA Fig.1 -- high-J CO etc. lines and ALMA/JVLA bands