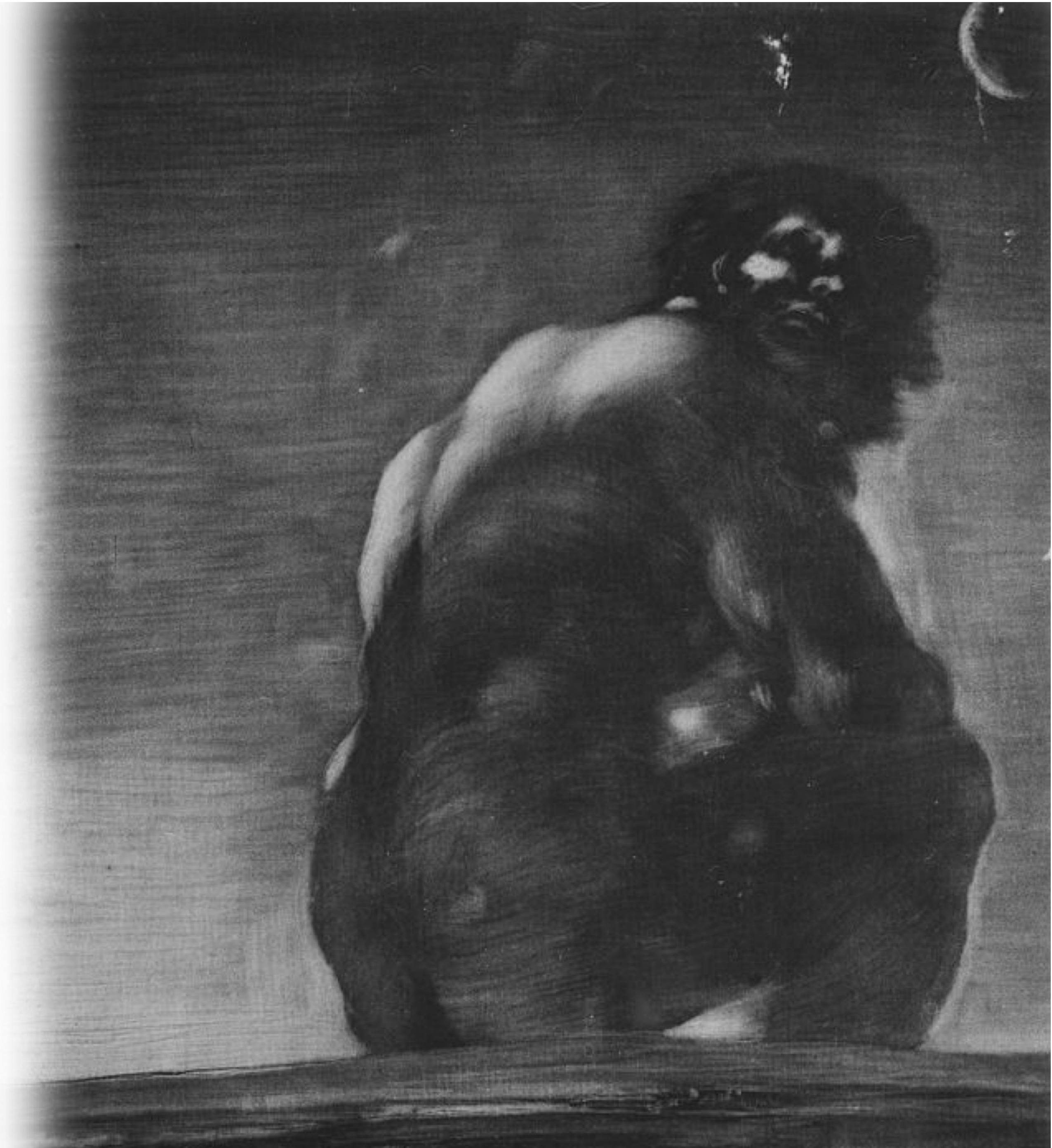
The story of an ALMA survey

Francesco Valentino

Cosmic Dawn Center – NBI
University of Copenhagen

DAWN
COSMIC DAWN CENTER

GRAD @
CARLSBERG FOUNDATION



A giant seated in a landscape, Francisco Goya, 1818

Galaxies: Rise And Death

Francesco Valentino

Cosmic Dawn Center – NBI
University of Copenhagen

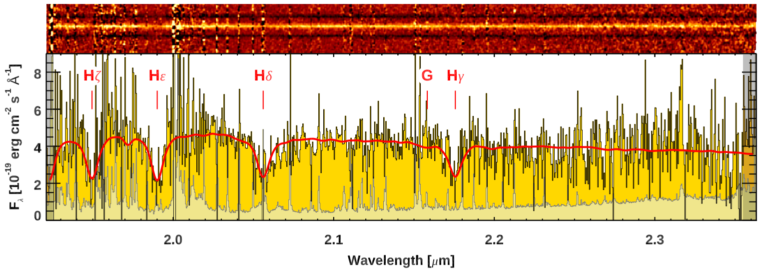
DAWN COSMIC DAWN CENTER

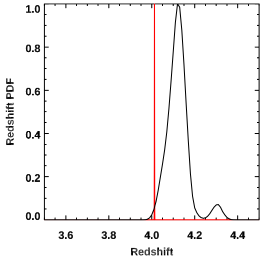
GRAD @ CARLSBERG FOUNDATION

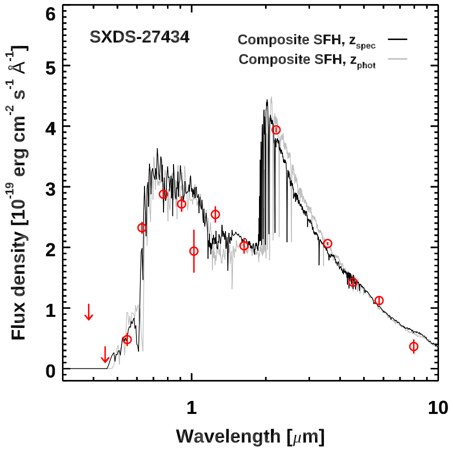
A giant seated in a landscape, Francisco Goya, 1818

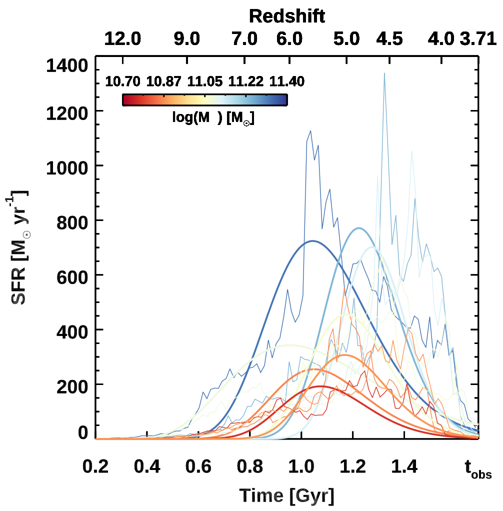
The death of massive galaxies

...could be the subject for another talk!









Happy to discuss it in person or via email

Valentino, Tanaka, Davidzon+2020a, 889, 93
Tanaka, Valentino, Toft+2019, ApJL, 885, 34
Valentino, Hirschmann+in prep.

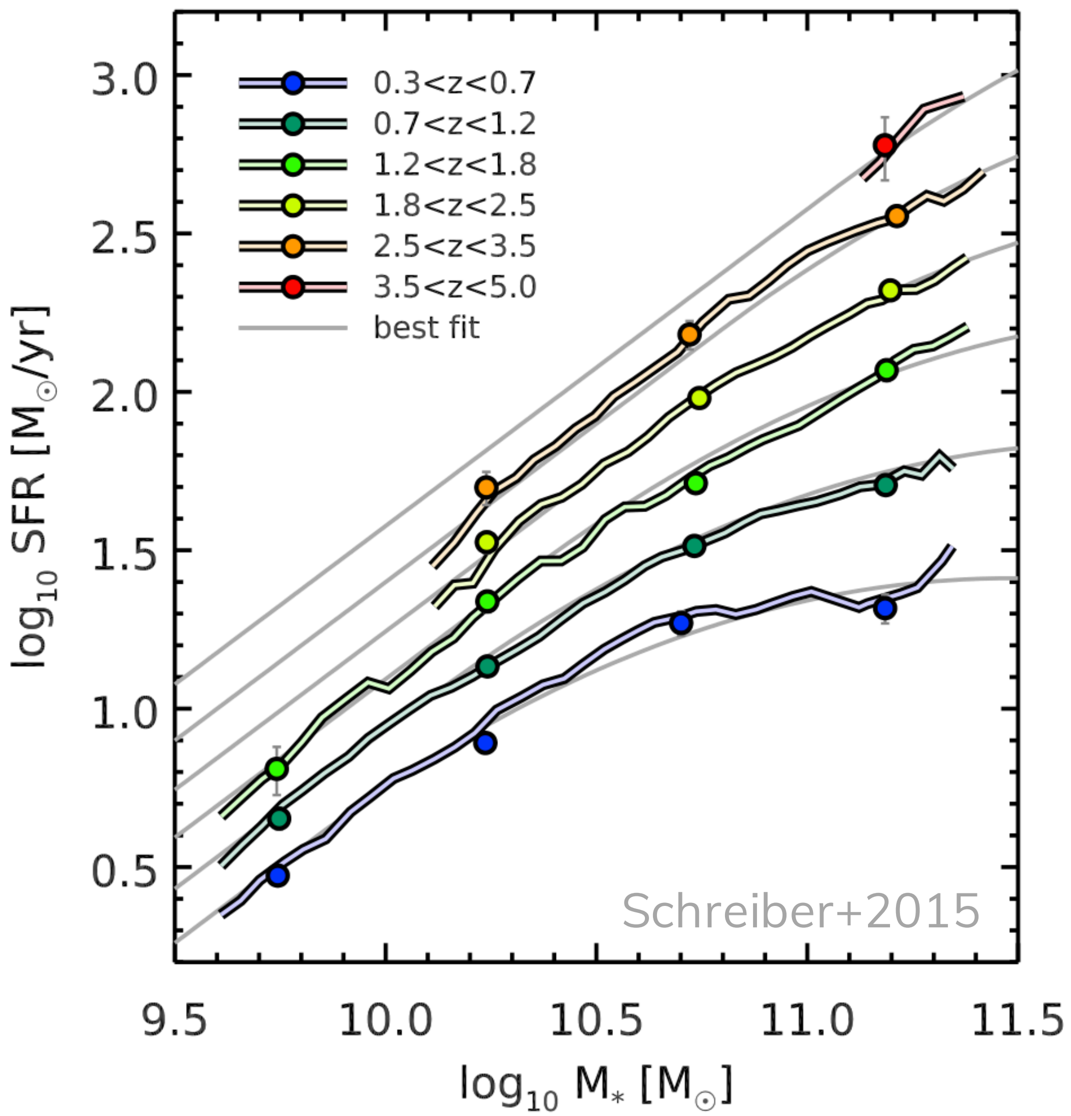
Spectroscopic confirmation of z=3-4 quiescent galaxies
Stellar velocity dispersion: remarkably “mature”
Progenitors (not extreme starbursts only)
Comparison with simulations

Magdis, Gobat, Valentino+2021, A&A, 647, 33
Gobat, Magdis, d’Eugenio, Valentino+2020, A&A, 644, L7

ISM in quiescent galaxies across time

The rise of massive galaxies

Two growing modes?



The vast majority of galaxies follows a stellar mass – SFR correlation (scatter 0.2 dex)

> "Normal"

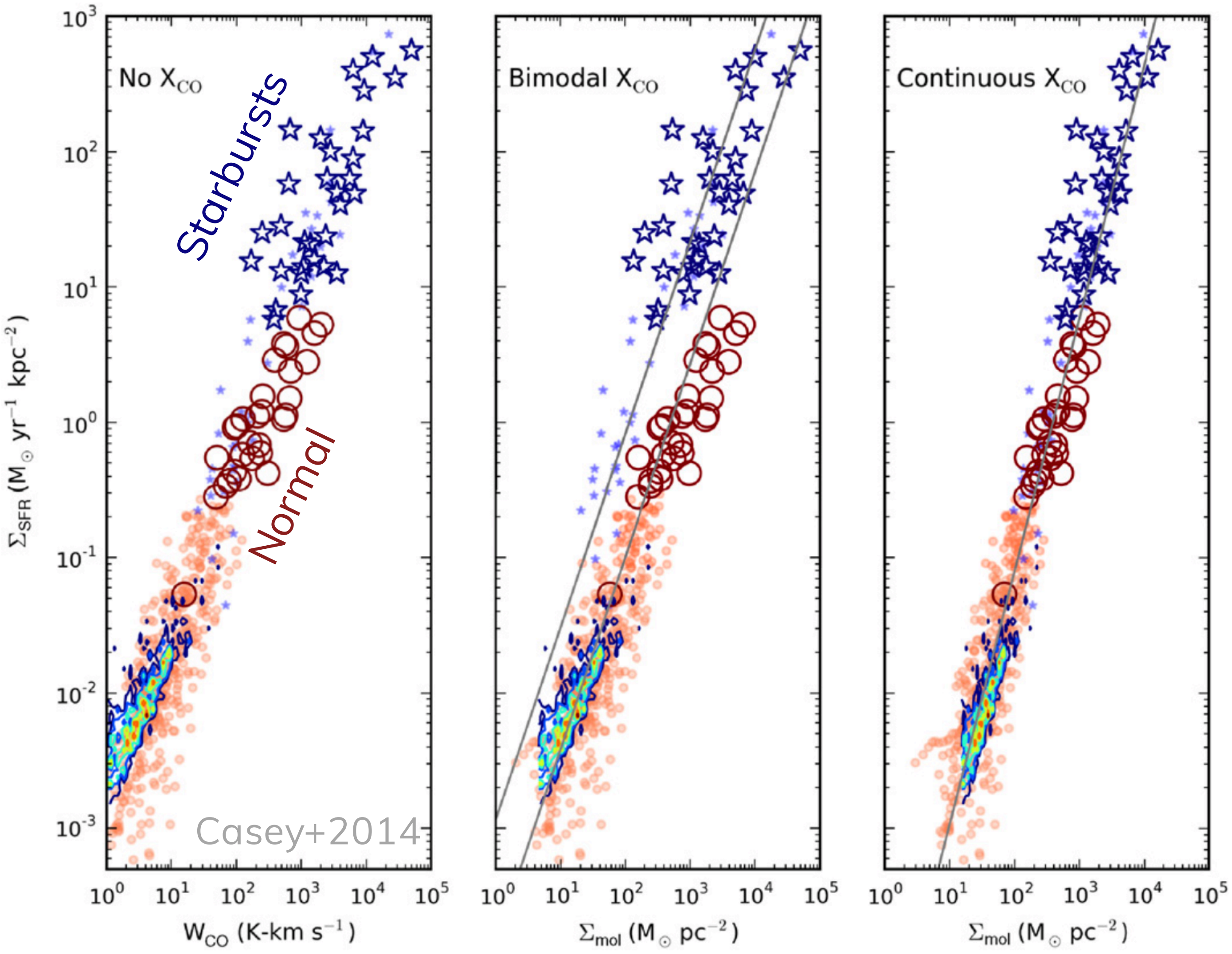
(associated with steady and secular growth regulated by gas accretion, disk formation)

A small fraction strongly deviates from the sequence showing SFR >> SFR(MS, $M_\star$)

> "Starbursts"

(associated with stochastic events, gas rich mergers, violent dynamical variations)

Two growing modes?



Starbursts appear to be more efficient than normal galaxies in converting gas into stars:

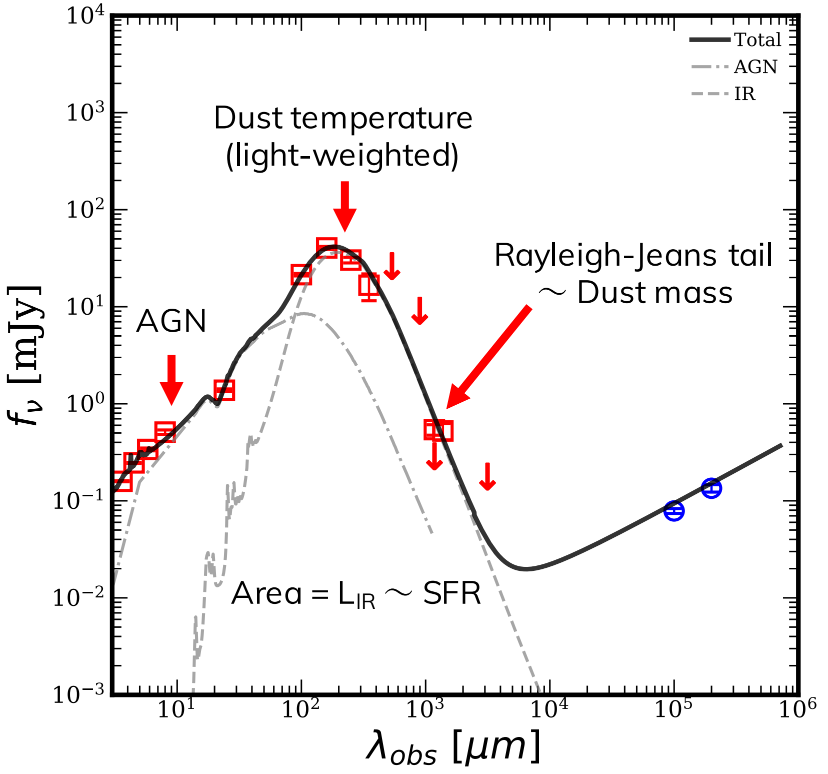
"Efficiency" = SFR / Mgas

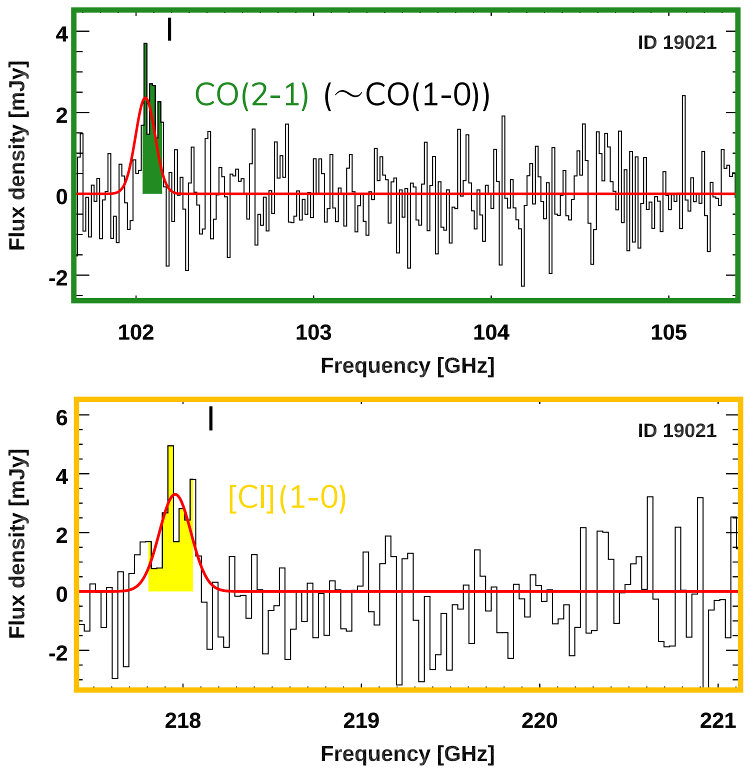
Classically:

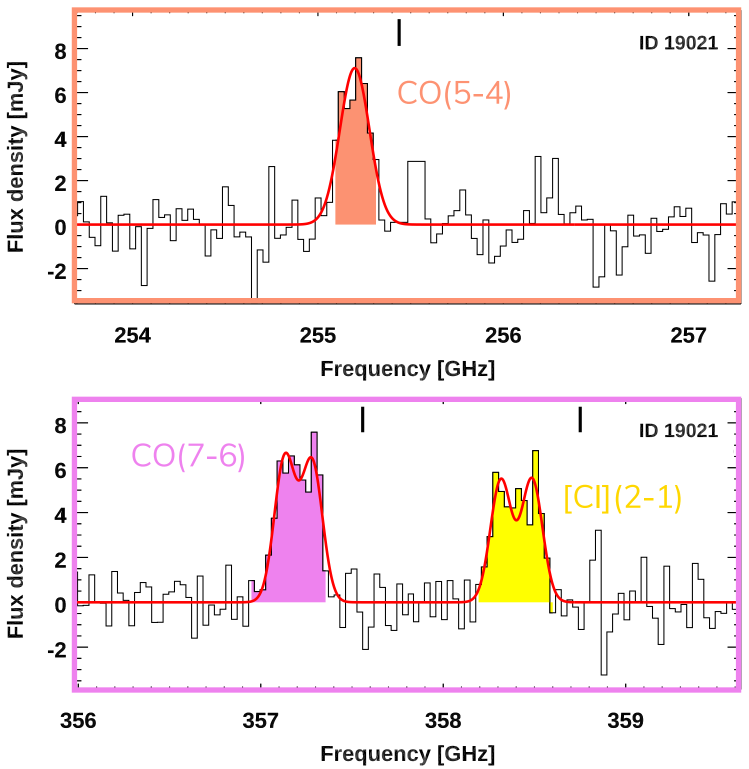
SFR $\sim$ UV, recombination/forbidden lines, FIR continuum, radio
(relatively well constrained)

Mgas $\sim$ carbon monoxide low-*J* (CO), optically thin dust emission
(here's where the problems begin)
+
Neutral atomic ([CI]) and ionized carbon ([CII], Zanella+2018, Madden+2020), Polycyclic Aromatic Hydrocarbons (PAH, Cortzen+2019)

What’s the problem, then?







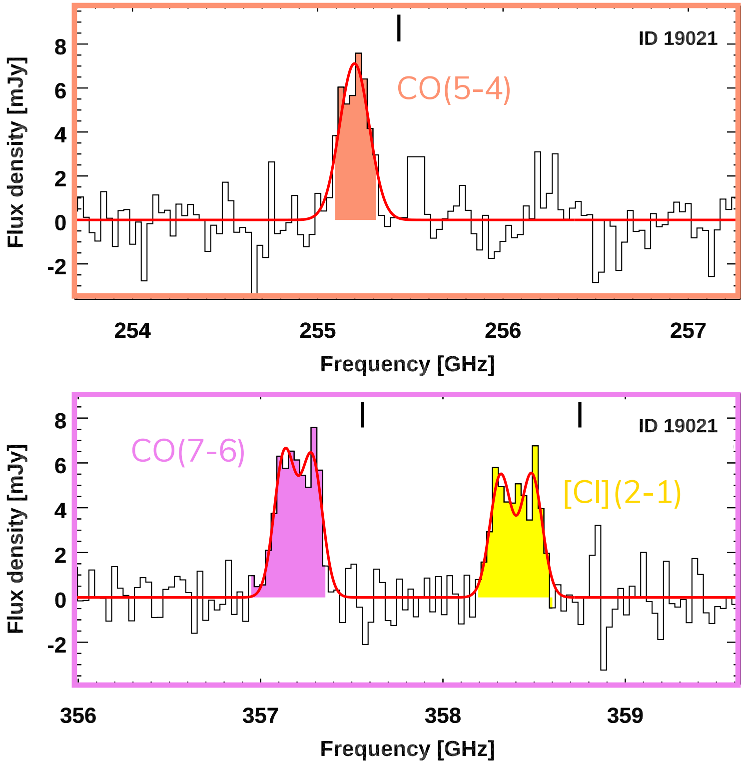
Dust continuum method
(and the infamous gas-to-dust ratio, Magdis+12, Groves+15, Scoville+16 and many others)
Kokorev+2021

Low-J CO emission
(and the infamous α(CO) e.g. Bolatto+13)

High-J CO emission? SFR?

Neutral atomic carbon
(potentially a better tracer of Mgas, Papadopoulos+04, Madden+20, Heintz+20)
Abundance?

What’s the problem, then?



Dust continuum method
(and the infamous gas-to-dust ratio, Magdis+12, Groves+15, Scoville+16 and many others)
Kokorev+2021

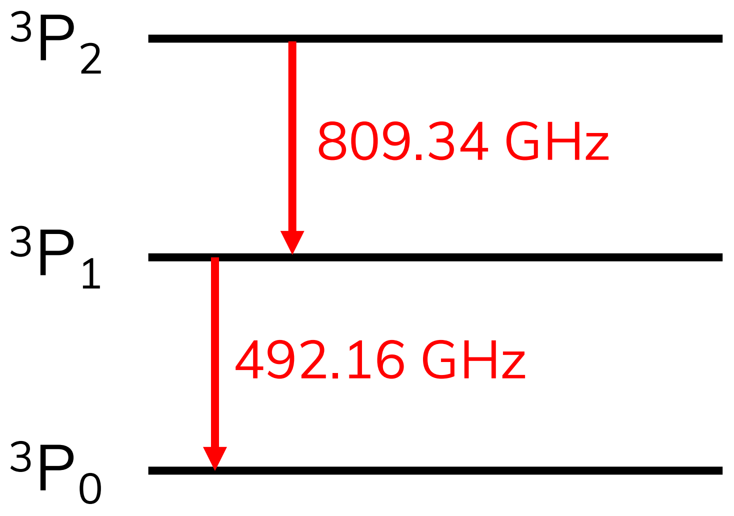
Low-J CO emission
(and the infamous α(CO) e.g. Bolatto+13)

High-J CO emission? SFR?

Neutral atomic carbon
(potentially a better tracer of Mgas, Papadopoulos+04, Madden+20, Heintz+20)
Abundance?

Neutral atomic carbon [CI]

Two optically thin transitions at 492.16 – 809.34 GHz rest-frame
Their ratio depends only on the temperature under LTE (Weiss+03, but see Papadopoulos+21 about this assumption!)
No strong excitation bias as high-J CO transitions



Neutral atomic carbon [CI]

Two optically thin transitions at 492.16 – 809.34 GHz rest-frame
Their ratio depends only on the temperature under LTE (Weiss+03, but see Papadopoulos+21 about this assumption!)
No strong excitation bias as high-J CO transitions
Tight correlation with the total gas mass independently of the intensity of the radiation field and density over several order of magnitudes (Madden+2020)

Neutral atomic carbon [CI]

Two optically thin transitions at 492.16 – 809.34 GHz rest-frame

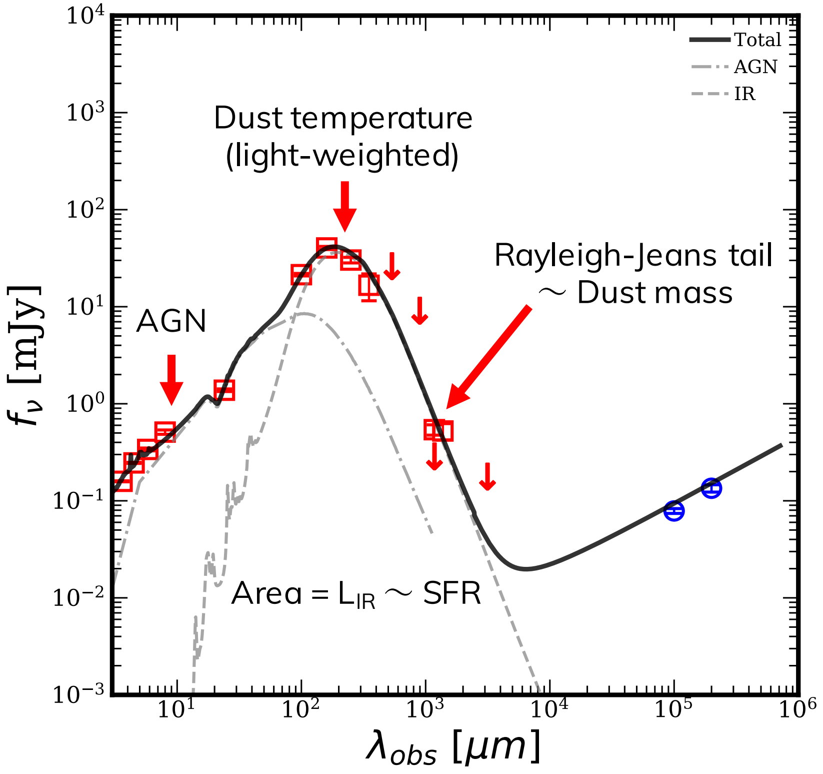
Their ratio depends only on the temperature under LTE (Weiss+03, but see Papadopoulos+21 about this assumption!)

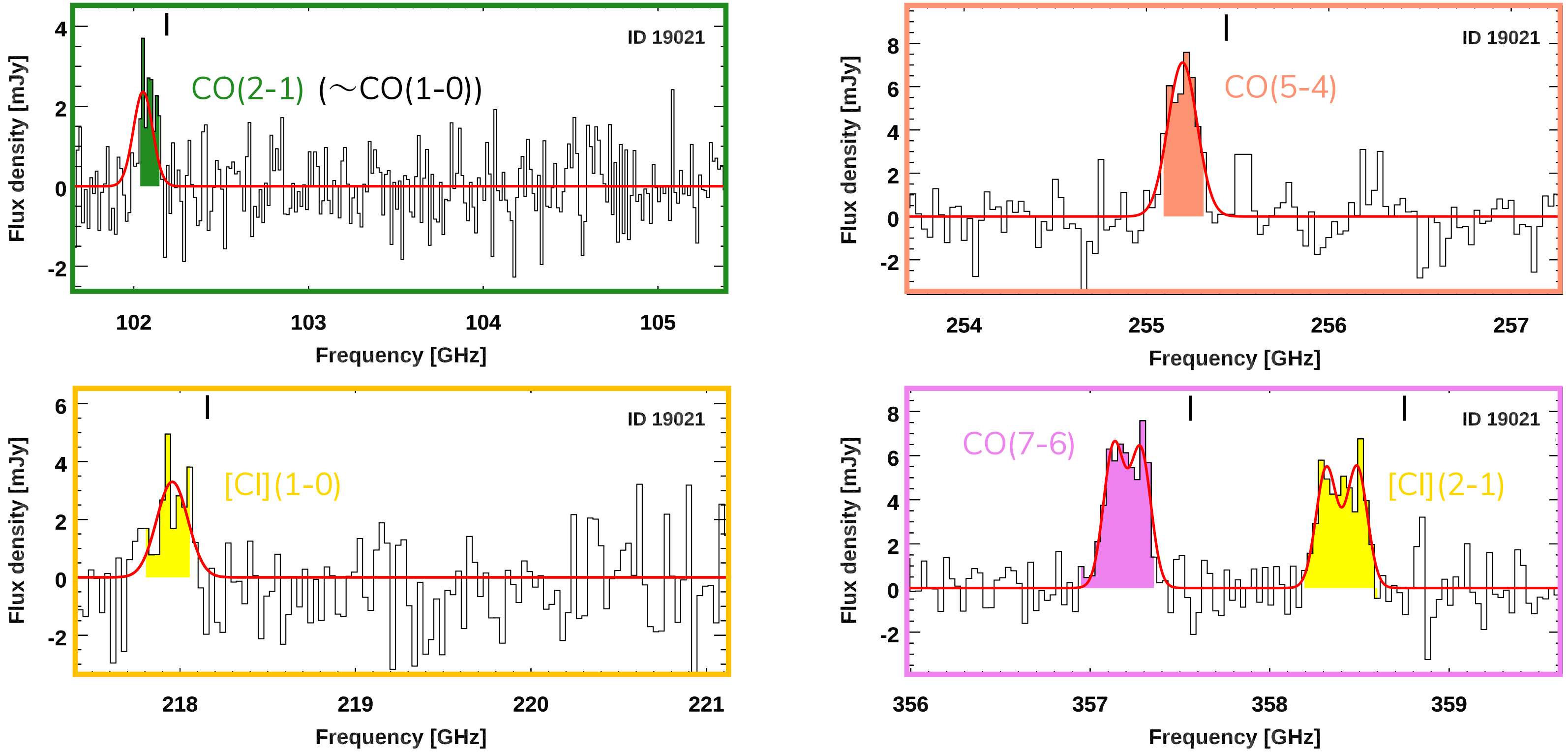
No strong excitation bias as high-J CO transitions

Tight correlation with the total gas mass independently of the intensity of the radiation field and density over several order of magnitudes

Better tracer than CO in presence of high cosmic ray rates (Papadopoulos+2004, +2018, Bisbas+2015, +2017), expected at high surface SFR densities - typical of distant galaxies

What’s the problem, then?

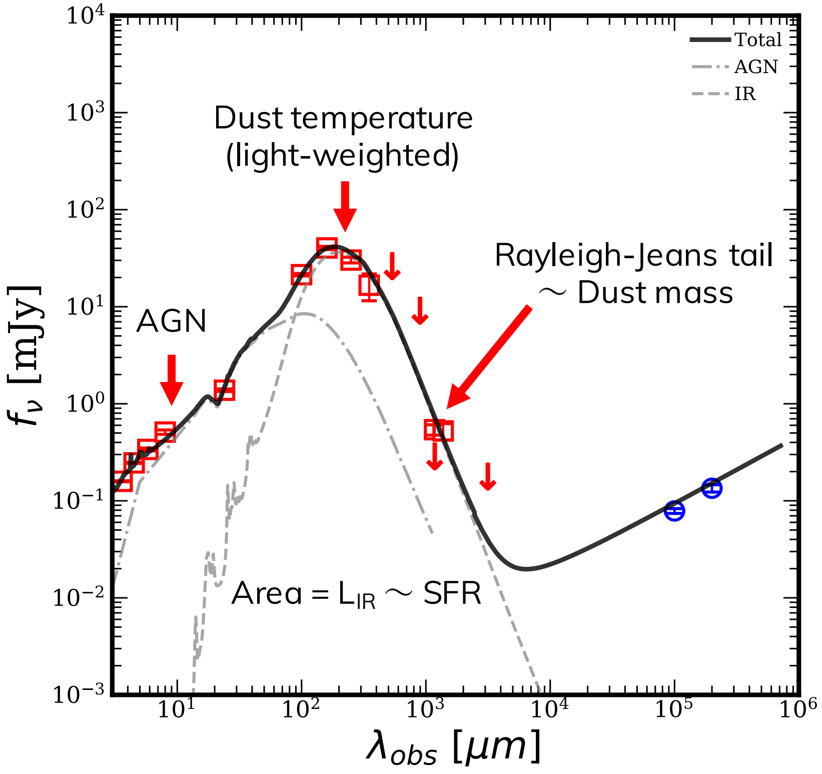


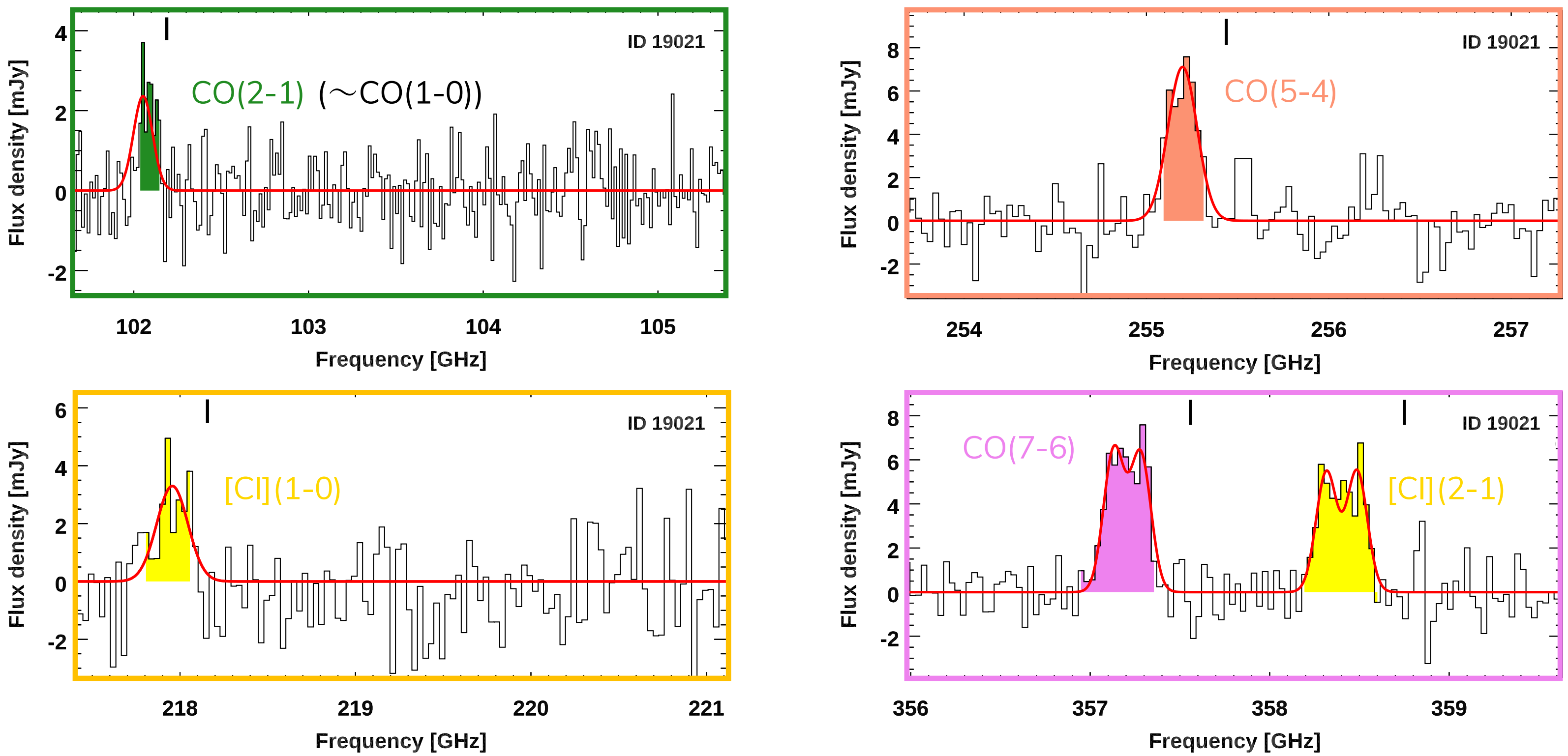


All this is “routine” for local or distant bright galaxies, aka starbursts, lenses, sub-mm galaxies, quasars
(reviews by Carilli & Walter+13, Casey+14, Tacconi+20, Hodge & da Cunha+20)

Many great spectroscopic surveys of distant bright galaxies over the years
SPT, (A)LESS, H-ATLAS, Planck, AS2UDS/COSMOS, zGAL, and others in no particular order

What's the problem, then?



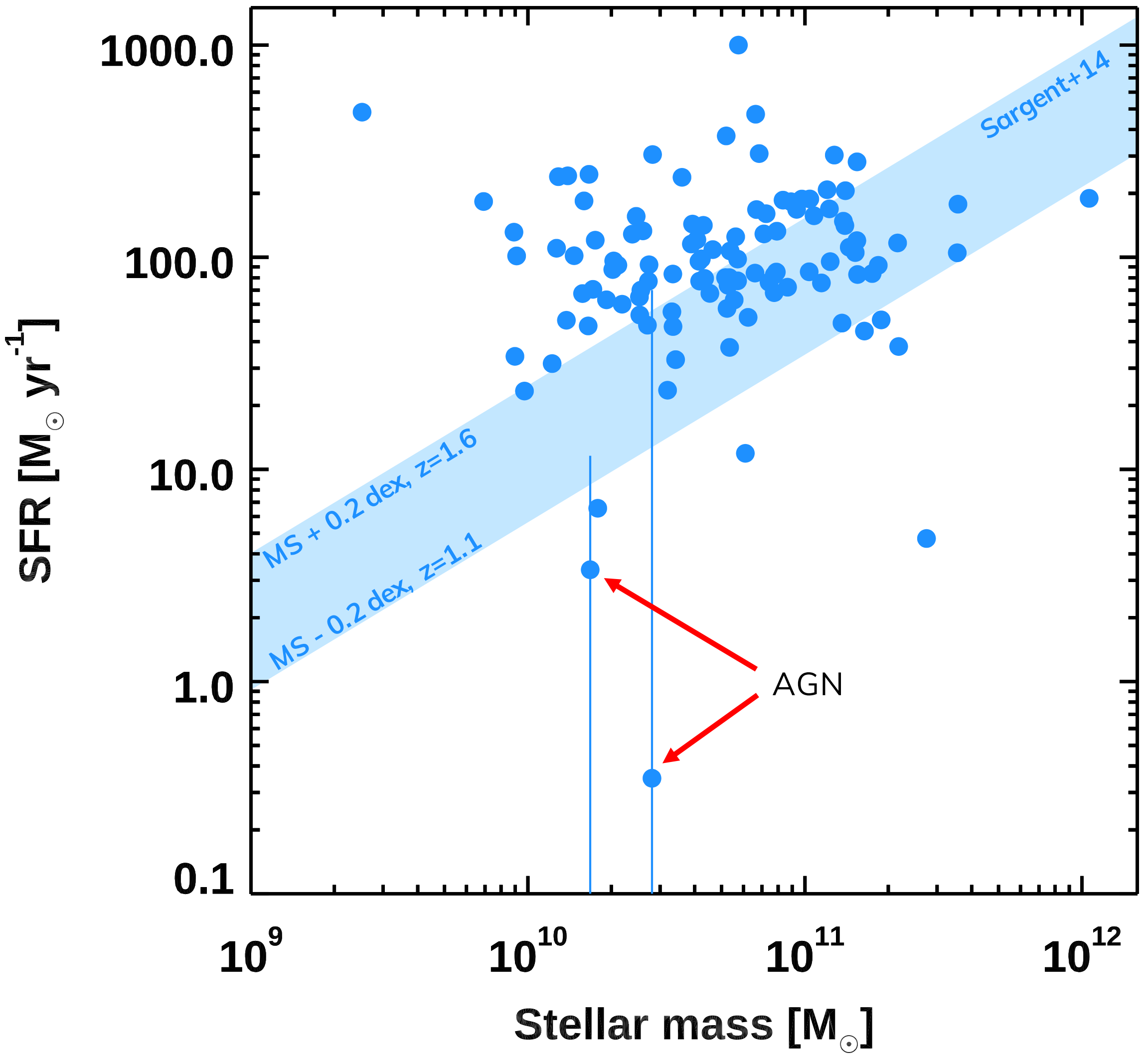


All this is "routine" for local or distant bright galaxies, aka starbursts, lenses, sub-mm galaxies, quasars
(reviews by Carilli & Walter+13, Casey+14, Tacconi+20, Hodge & da Cunha+20)

We entered an epoch where all this information is finally available for normal main-sequence galaxies

A survey of main sequence galaxies

A survey of main sequence galaxies



Main sequence and starburst roughly equally represented

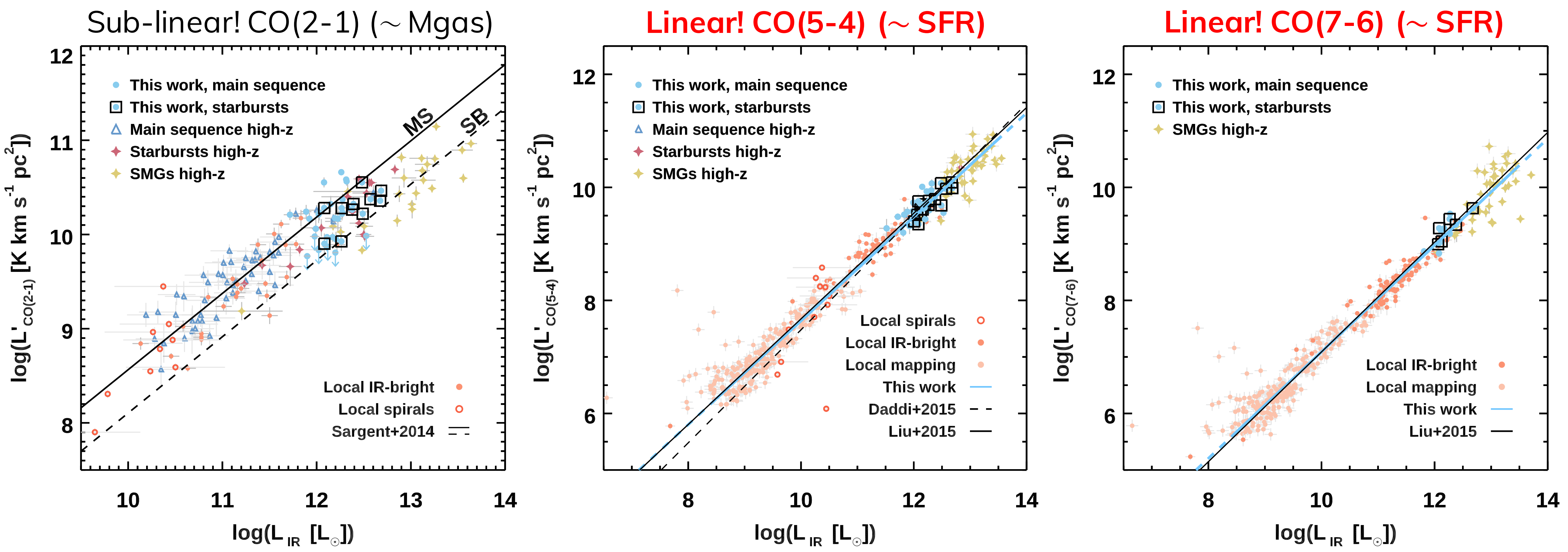
L_{IR} (~SFR) cut, z = 1.1-1.7, $M_\star$ available

ALMA coverage:

CO(5-4) / CO(2-1) (Cycle 3-4, PI: E. Daddi): 123 / 75 galaxies

CO(4-3), CO(7-6), [CI](1-0), [CI](2-1), (Cycle 4, 6, and 7, PI: Valentino): a subsample of ~15 galaxies.

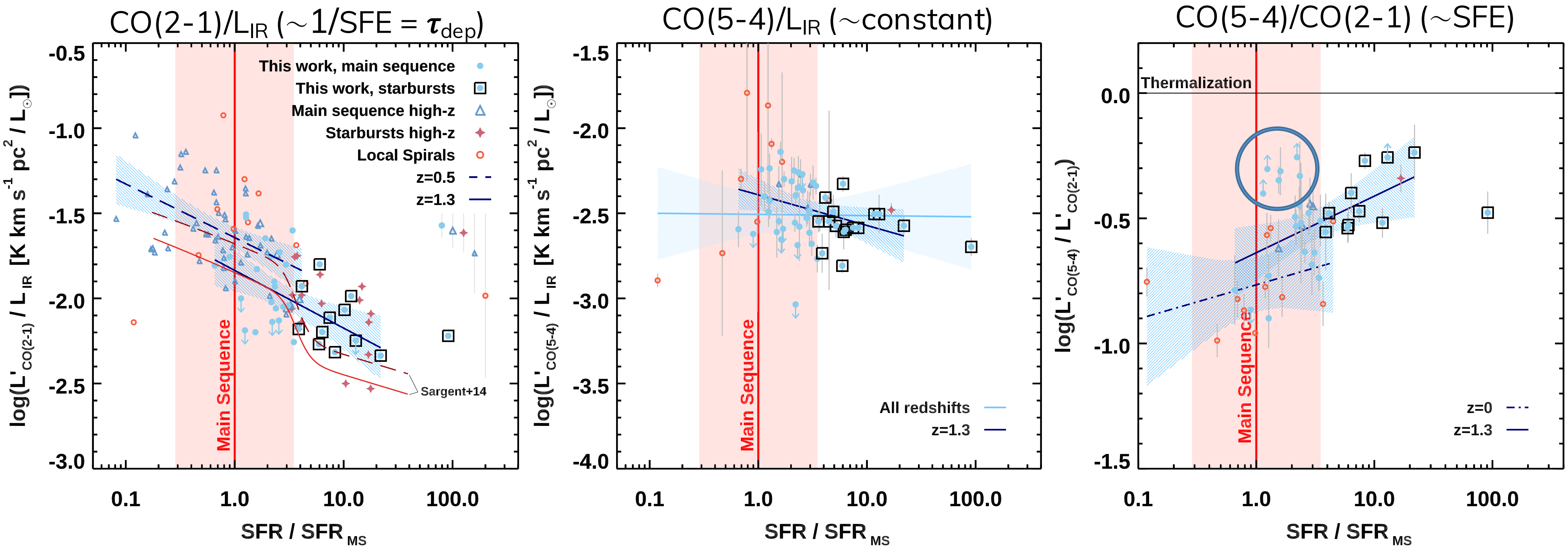
Some basics: CO, [CI], and L_{IR}



$L_{IR} \sim SFR$

Valentino+2020c

Some basics: CO, [CI], and L_{IR}

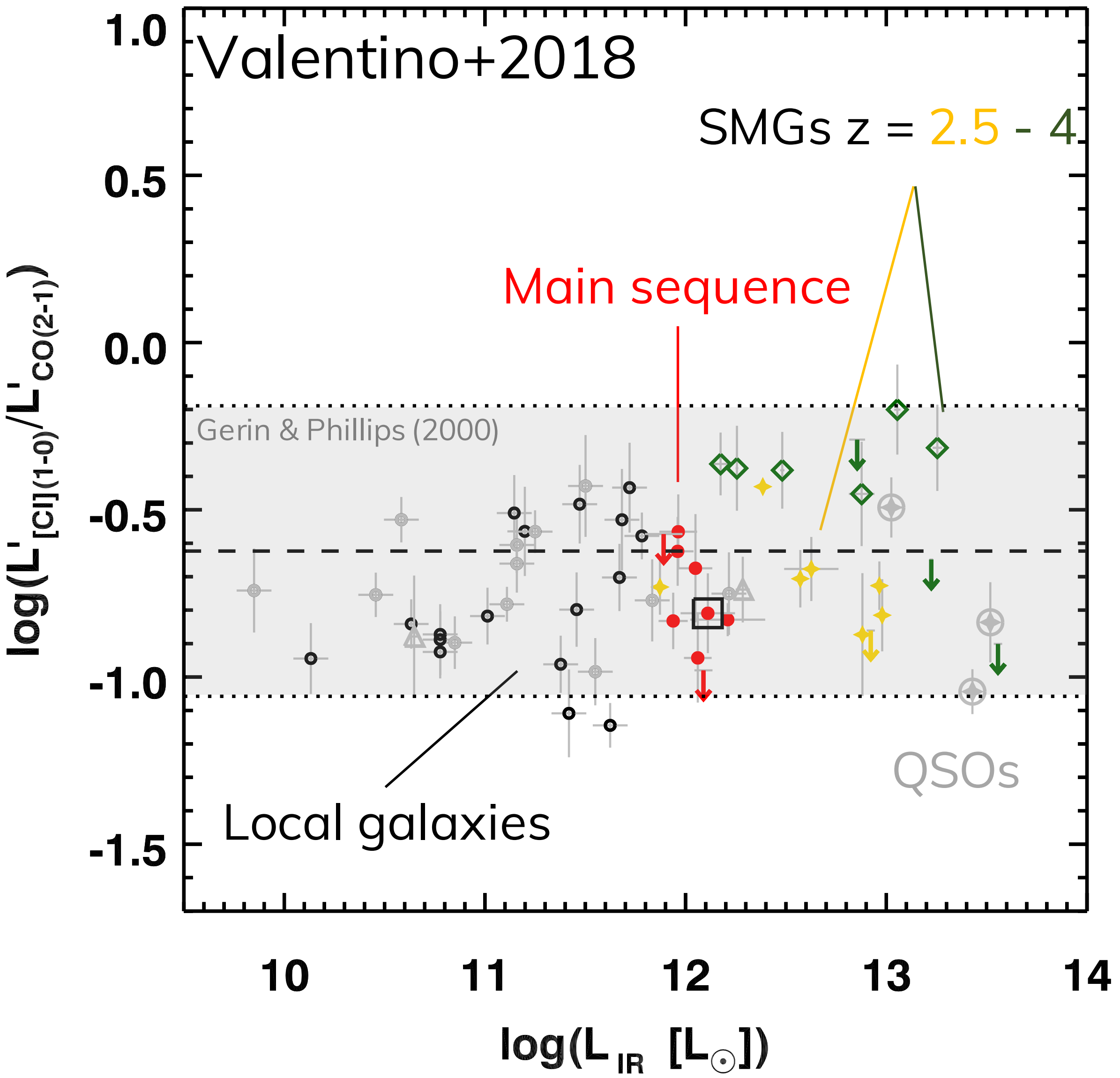


Smooth decrease from main sequence to starbursts
Decreasing normalization

CO(5-4) ~ SFR irrespectively of the distance from the main sequence

A population of **starburst-like main sequence galaxies** (Puglisi+2019, +2021)

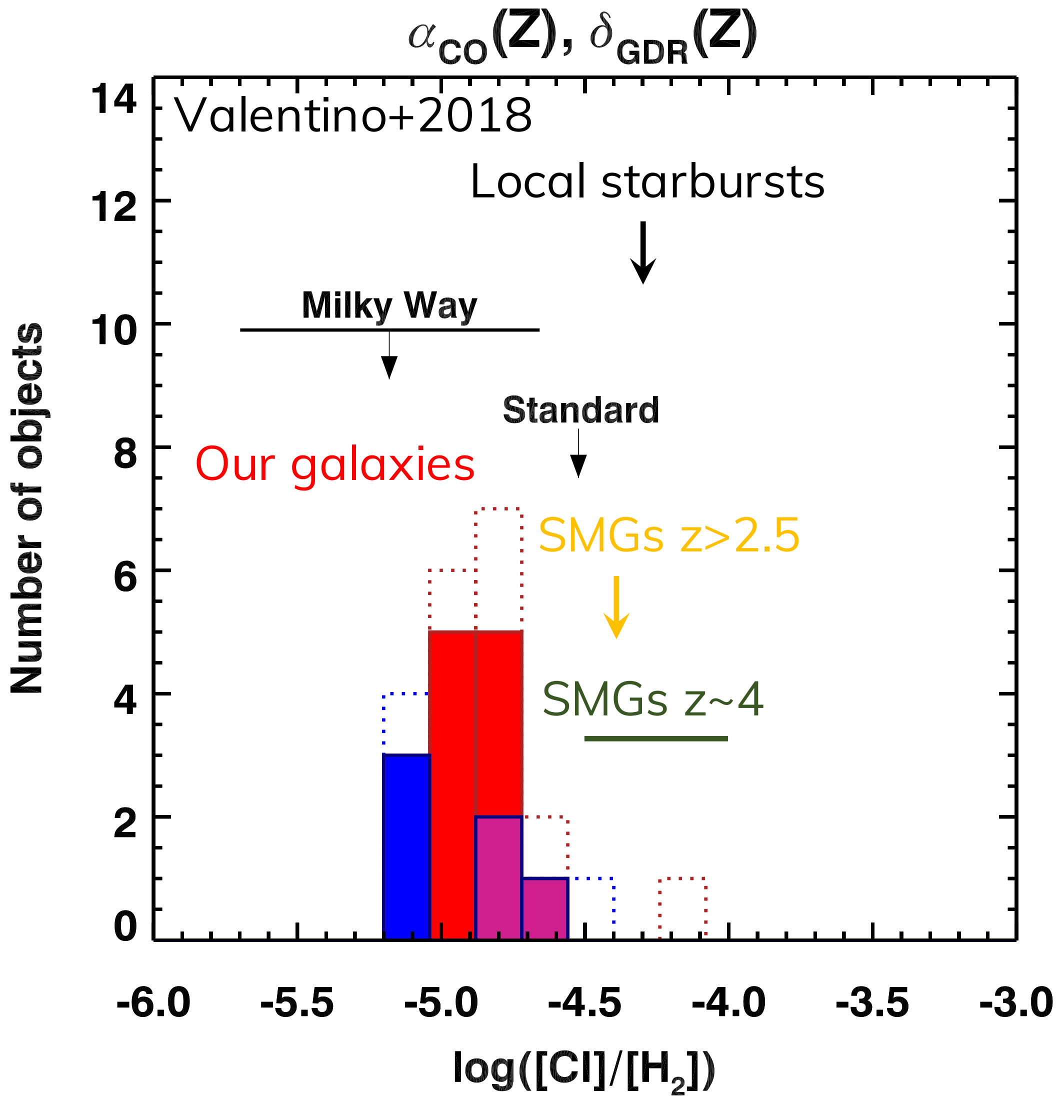
[C I] and low-*J* CO talk to each other



Constant [CI](1-0) / low-*J* CO
([CI](1-0) / dust continuum)

➔Abundance?

Calibration or physics?



$$[\mathrm{C\,I}]/[\mathrm{H_2}] = M_{[\mathrm{C\,I}]}/(6\,M_{\mathrm{H_2}})$$

From L’[CI](1-0) ✔

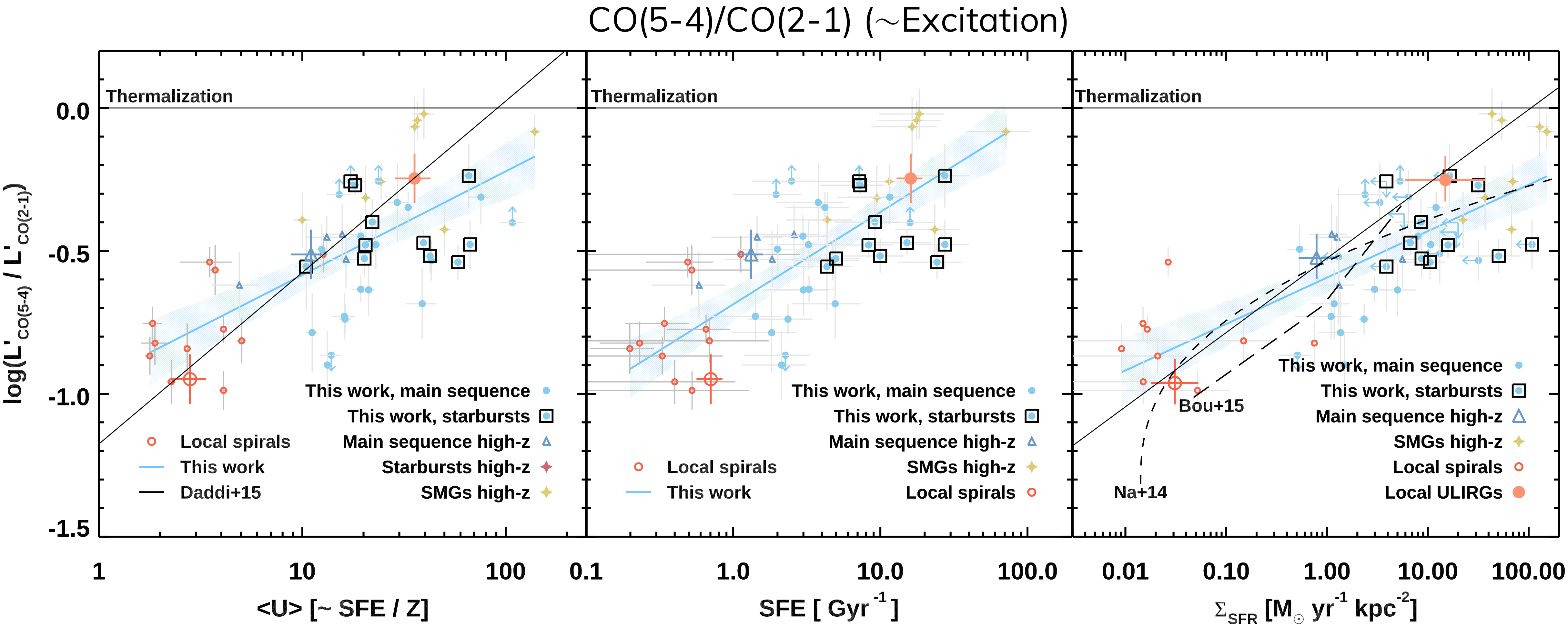
From low-J CO or dust ✔

Lower [CI] abundance in main sequence galaxies than SB/SMGs?

(Crocker+19, Heintz+20, Madden+20, Jiao+21, Dunne+21)

Molecular gas excitation

Gas excitation! What are its drivers?

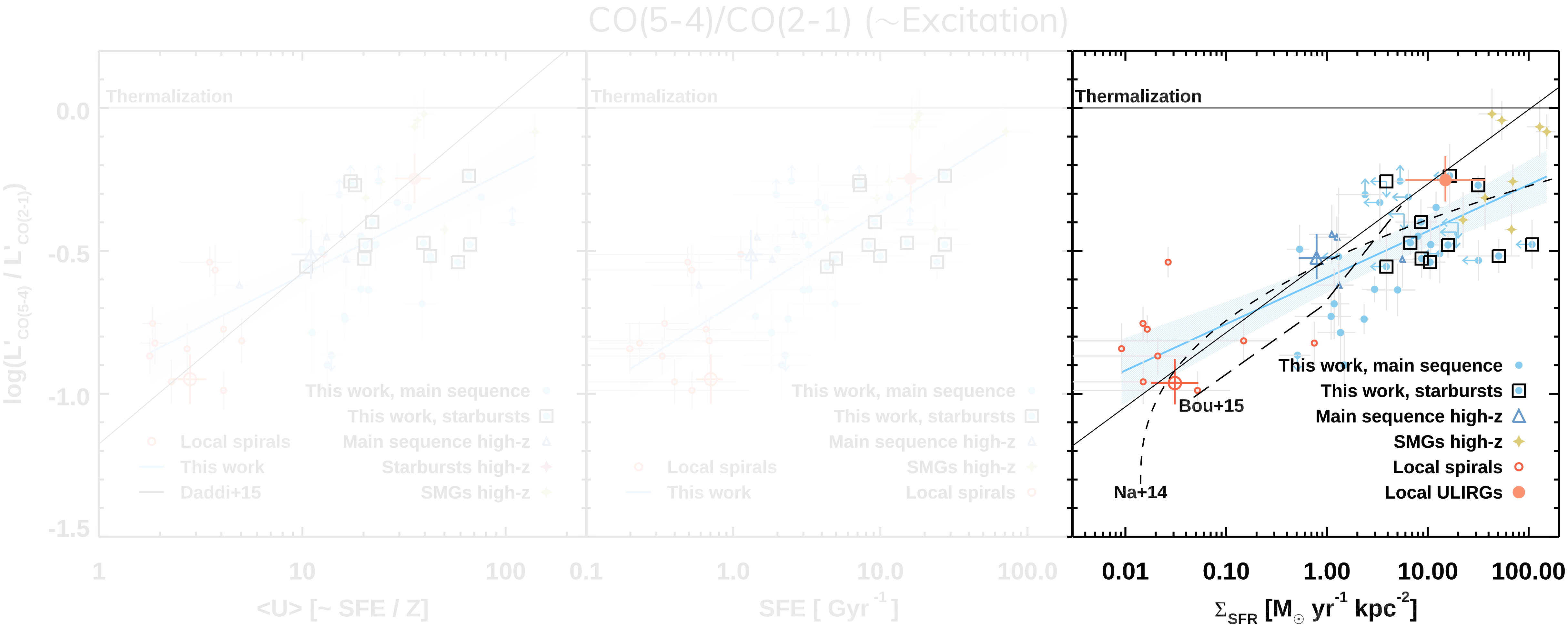


Intensity of the interstellar radiation field (~Temperature)

Star formation efficiency SFR / Mgas

SFR surface density

Gas excitation! What are its drivers?

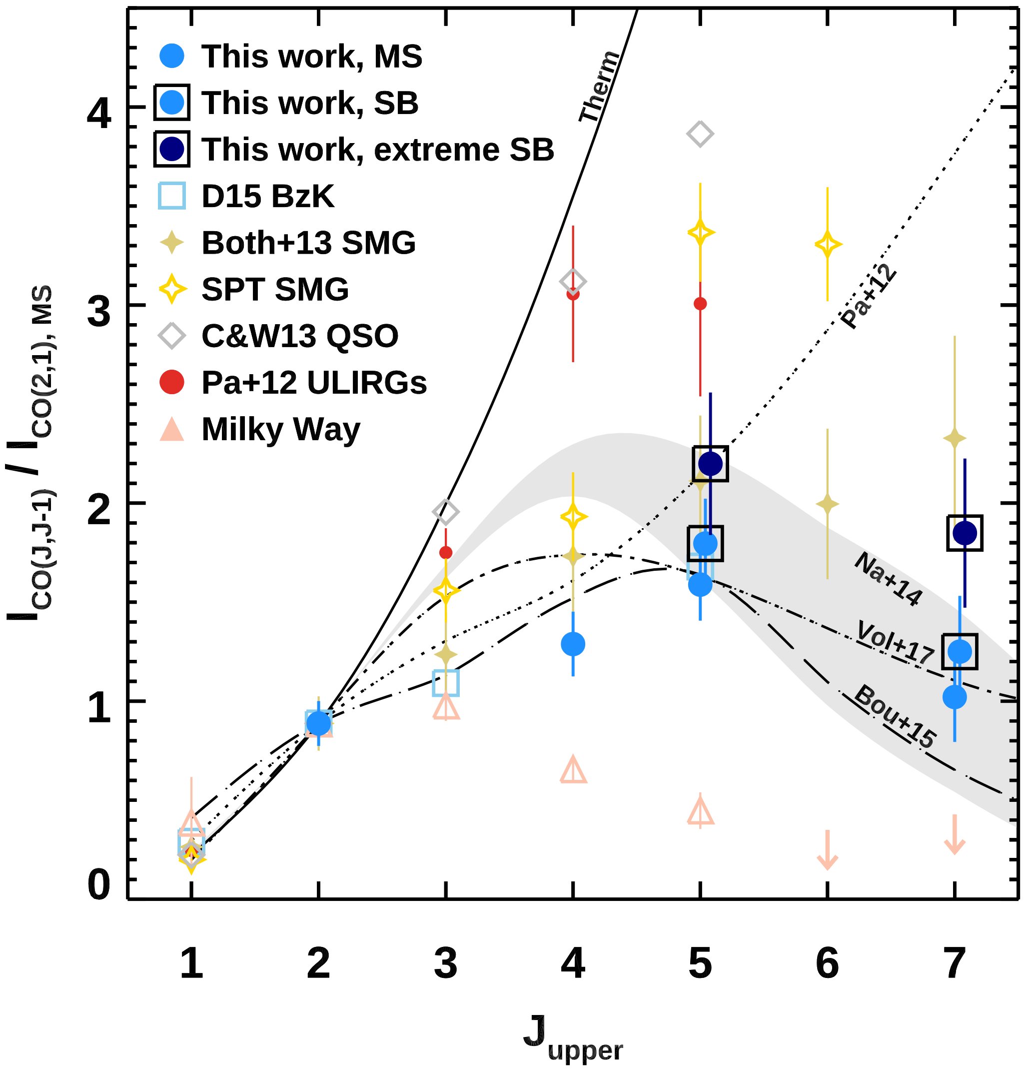


Intensity of the interstellar radiation field (~Temperature)

Star formation efficiency SFR / Mgas

SFR surface density

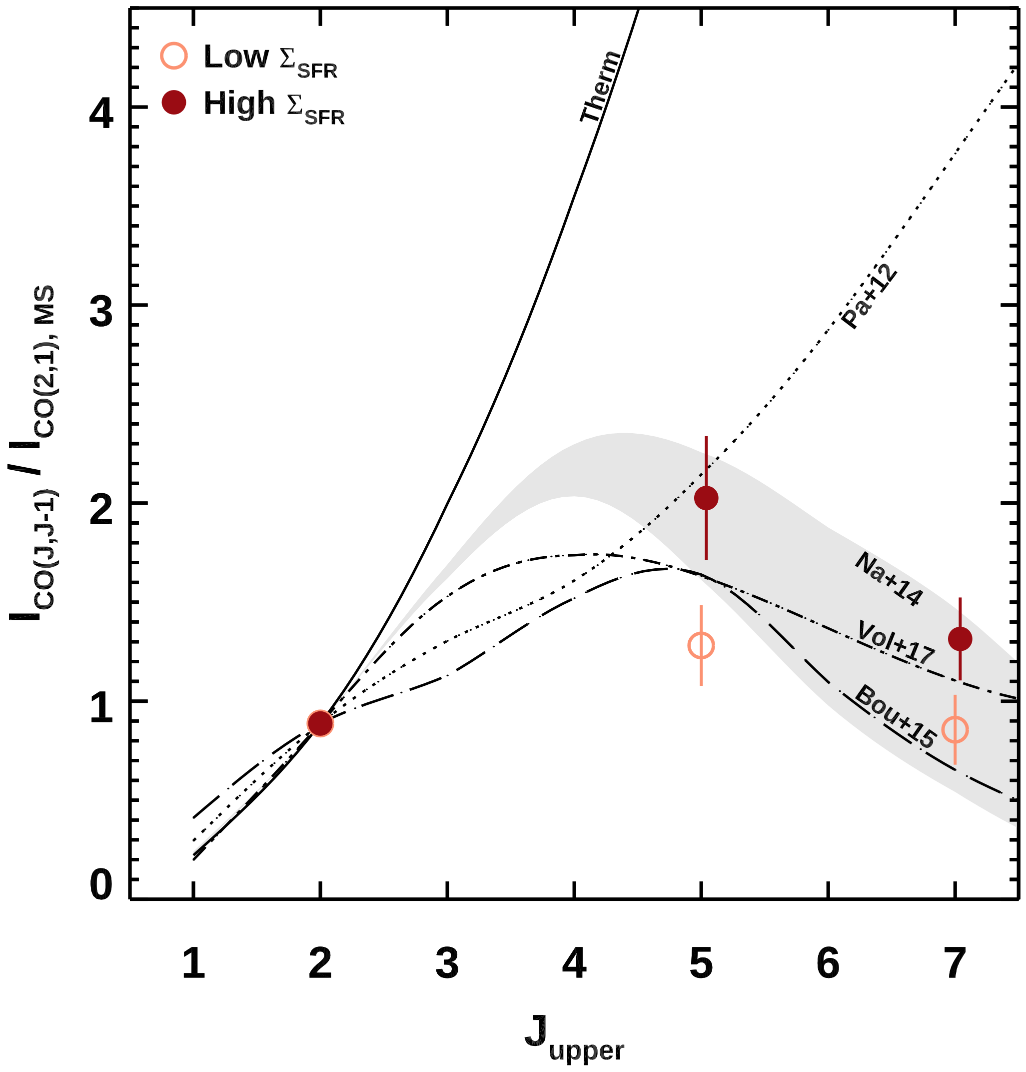
Spectral Line Energy Distribution (SLED)



Main sequence galaxies are more excited than the inner disk of the Milky Way (Fixsen+1999)

Increasing excitation with the distance from the main sequence, but with a wide variety of shapes and an outlying population of compact starburst-like galaxies (Elbaz+18, Puglisi+19,+21, Gómez-Guijarro+19,+21 and others)

Spectral Line Energy Distribution (SLED)



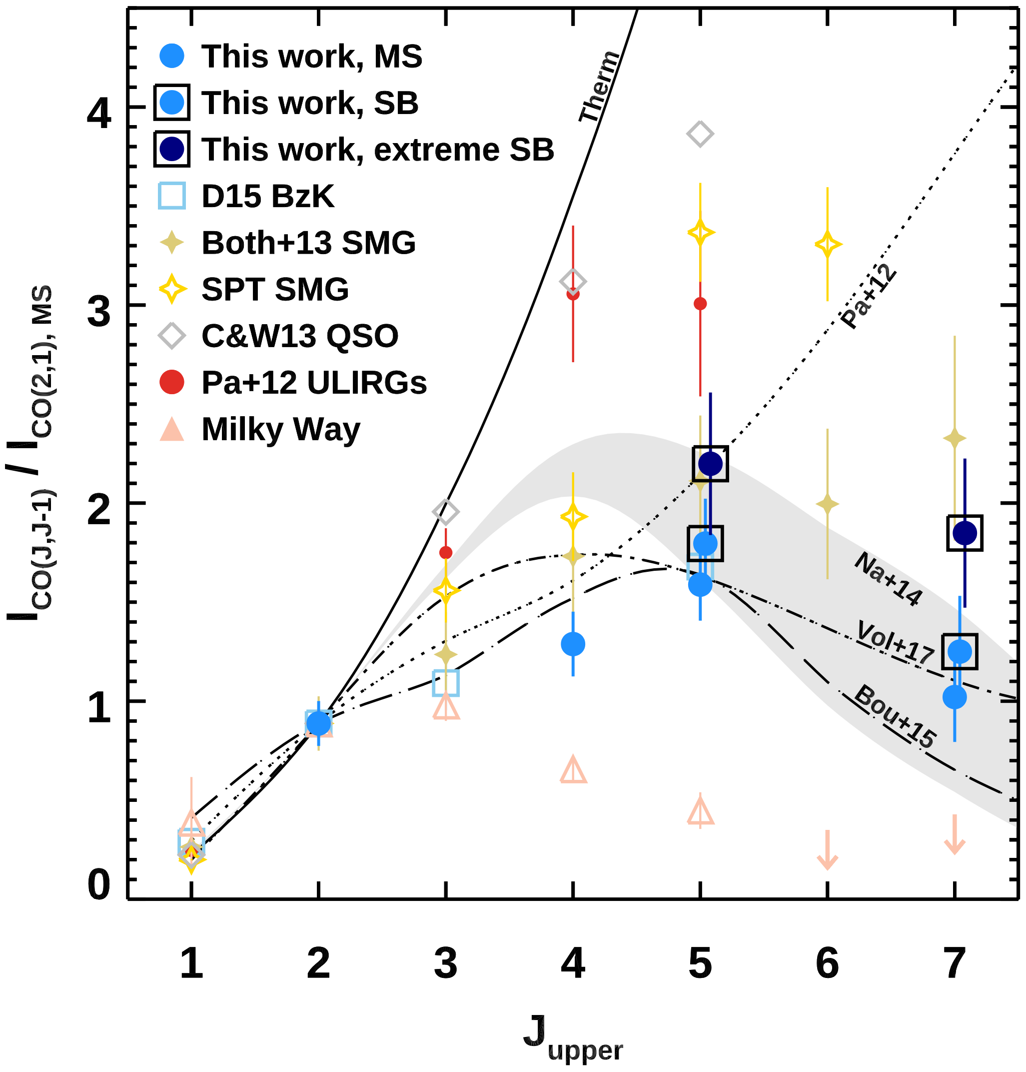
Main sequence galaxies are more excited than the inner disk of the Milky Way (Fixsen+1999)

Increasing excitation with the distance from the main sequence, but with a wide variety of shapes and an outlying population of compact starburst-like galaxies (Elbaz+18, Puglisi+19,+21, Gómez-Guijarro+19,+21 and others)

Splitting the sample according to Σ_{SFR} appears to better separate the two populations (see also Boogaard+2021 from ASPECS)

An advantageous definition of starbursts (Jimenez-Andrade+18, Tacconi+20)?

Spectral Line Energy Distribution (SLED)



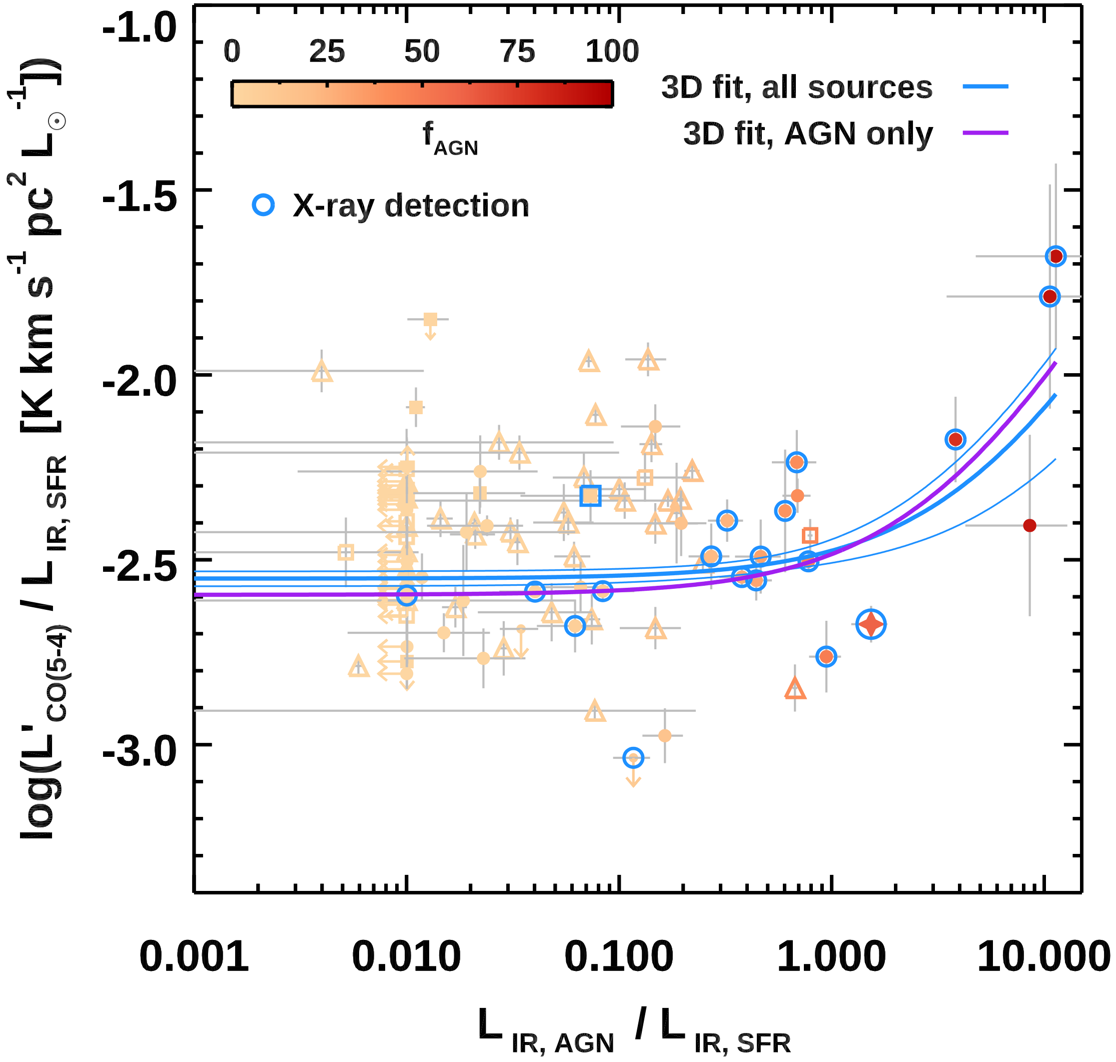
Main sequence galaxies are more excited than the inner disk of the Milky Way (Fixsen+1999)

Increasing excitation with the distance from the main sequence, but with a wide variety of shapes and an outlying population of compact starburst-like galaxies (Elbaz+18, Puglisi+19,+21, Gómez-Guijarro+19,+21 and others)

Peak at J=4-5 and smooth decrease beyond it

Qualitative and rough agreement with models (Narayanan+14, Bournaud+15, Vollmer+17)

A minor role of AGN



Mid-IR and X-ray detected AGN in the sample show similar properties to the rest of the star-forming galaxies.

Hint of a boosted CO(5-4) in extreme situations with dominating AGN

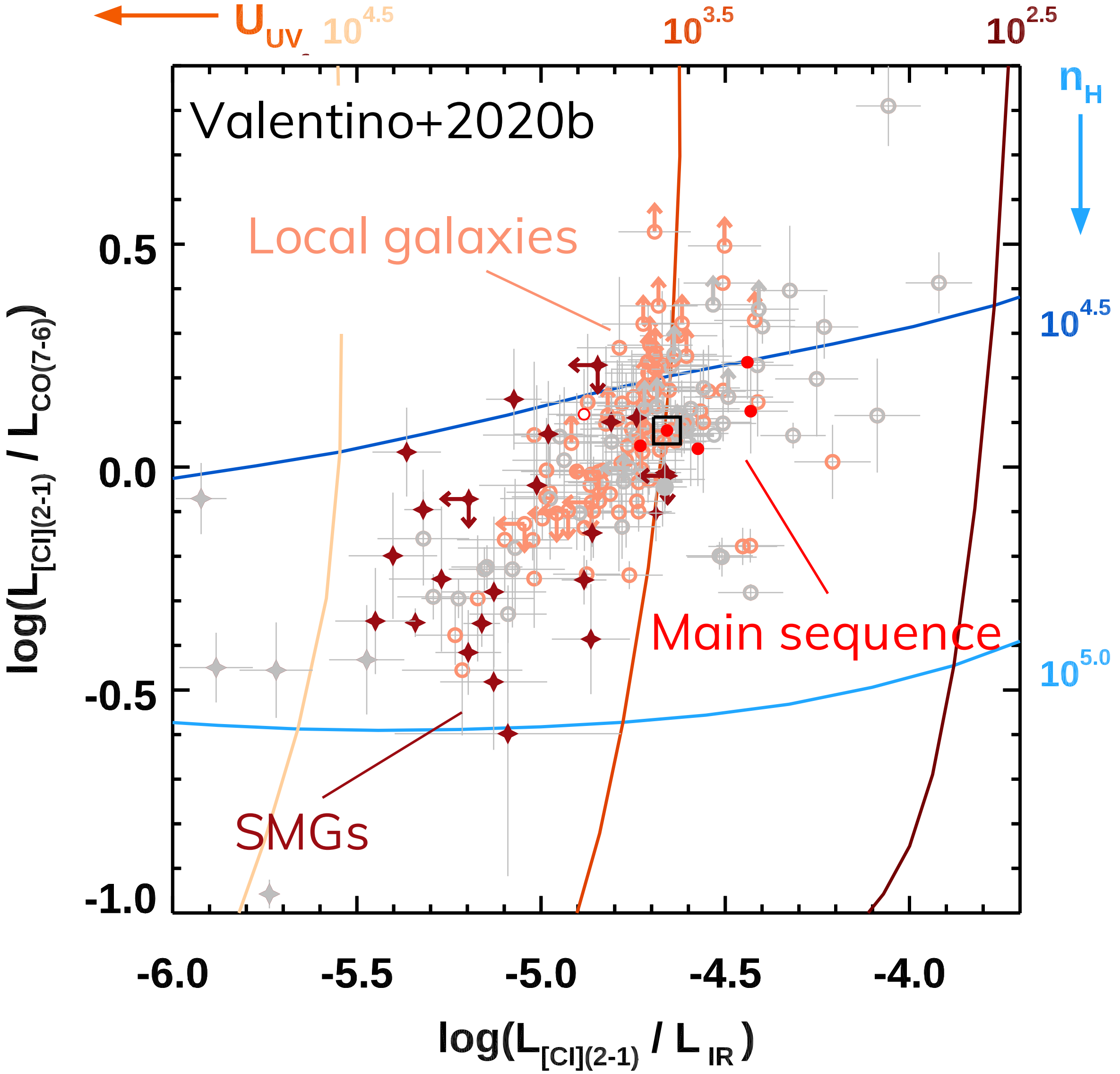
XDR are expected to excite high-J CO transitions!

Future development to cover the strongest AGN (with enough mid-/far-IR photometric coverage)

Valentino+2021

A benchmark for modeling

A baseline to model the ISM excitation

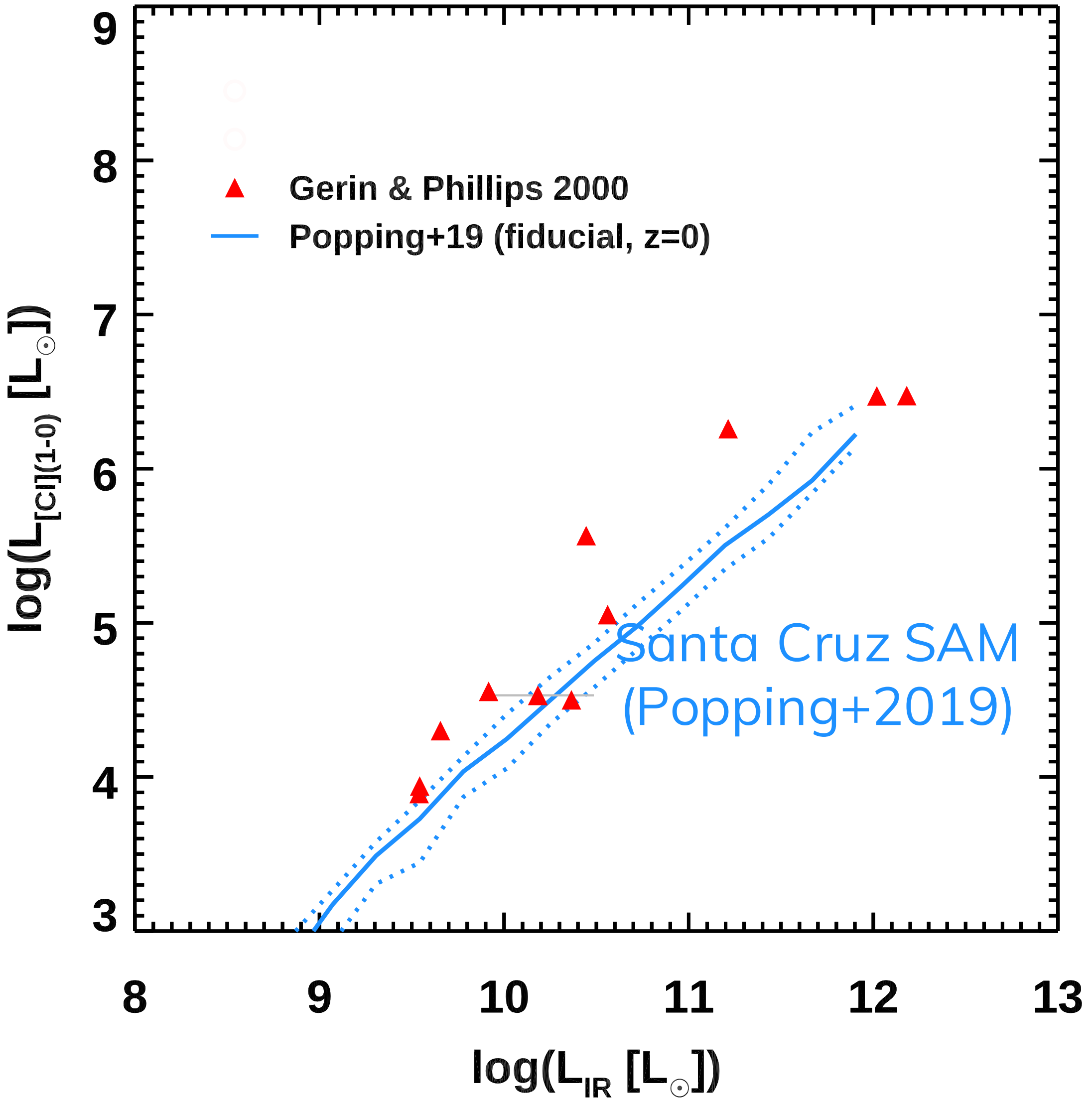


Systematic variations of [CI] / high-J CO

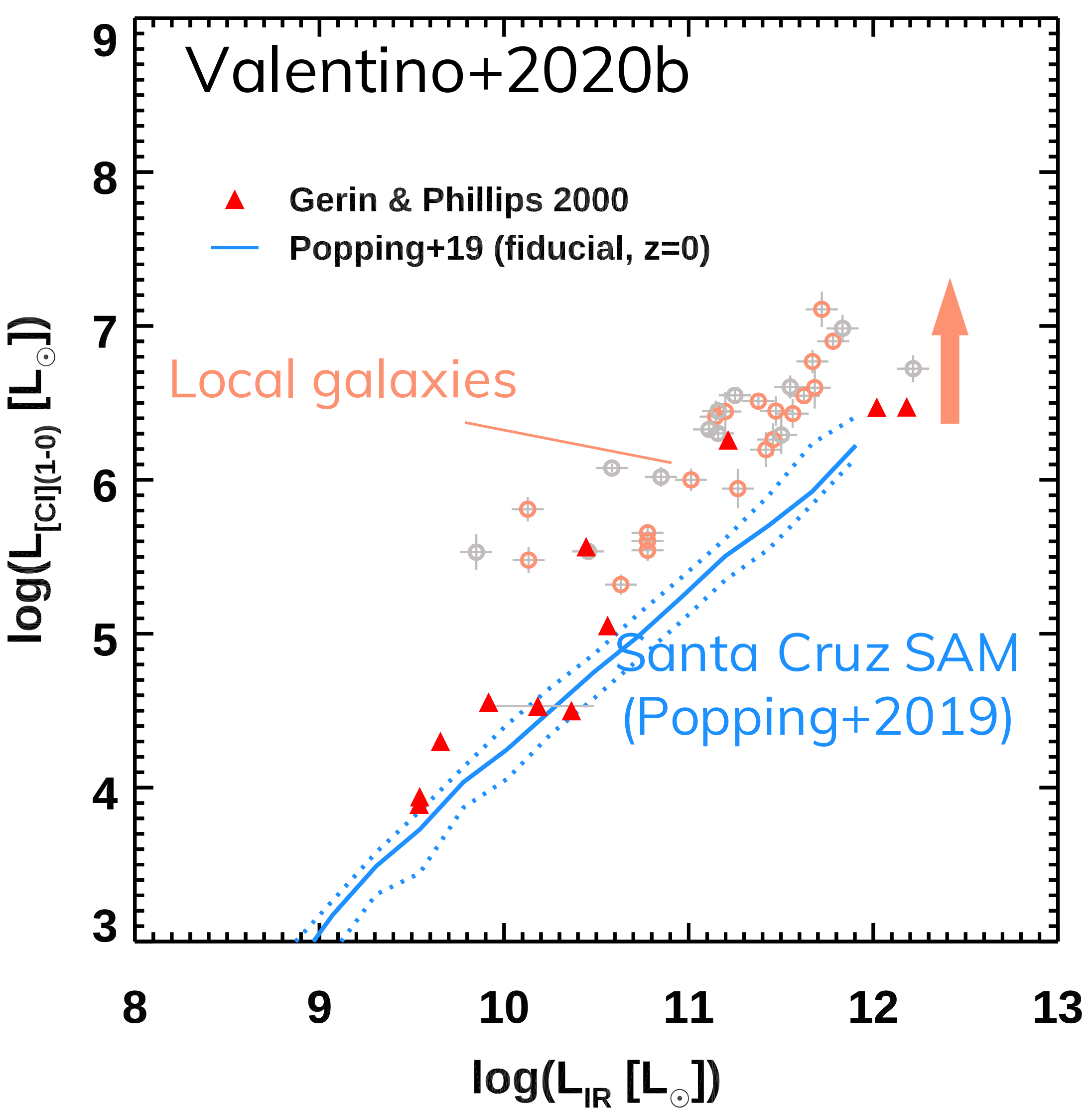
Door open for modeling (PDR, LVG, semi-analytical)

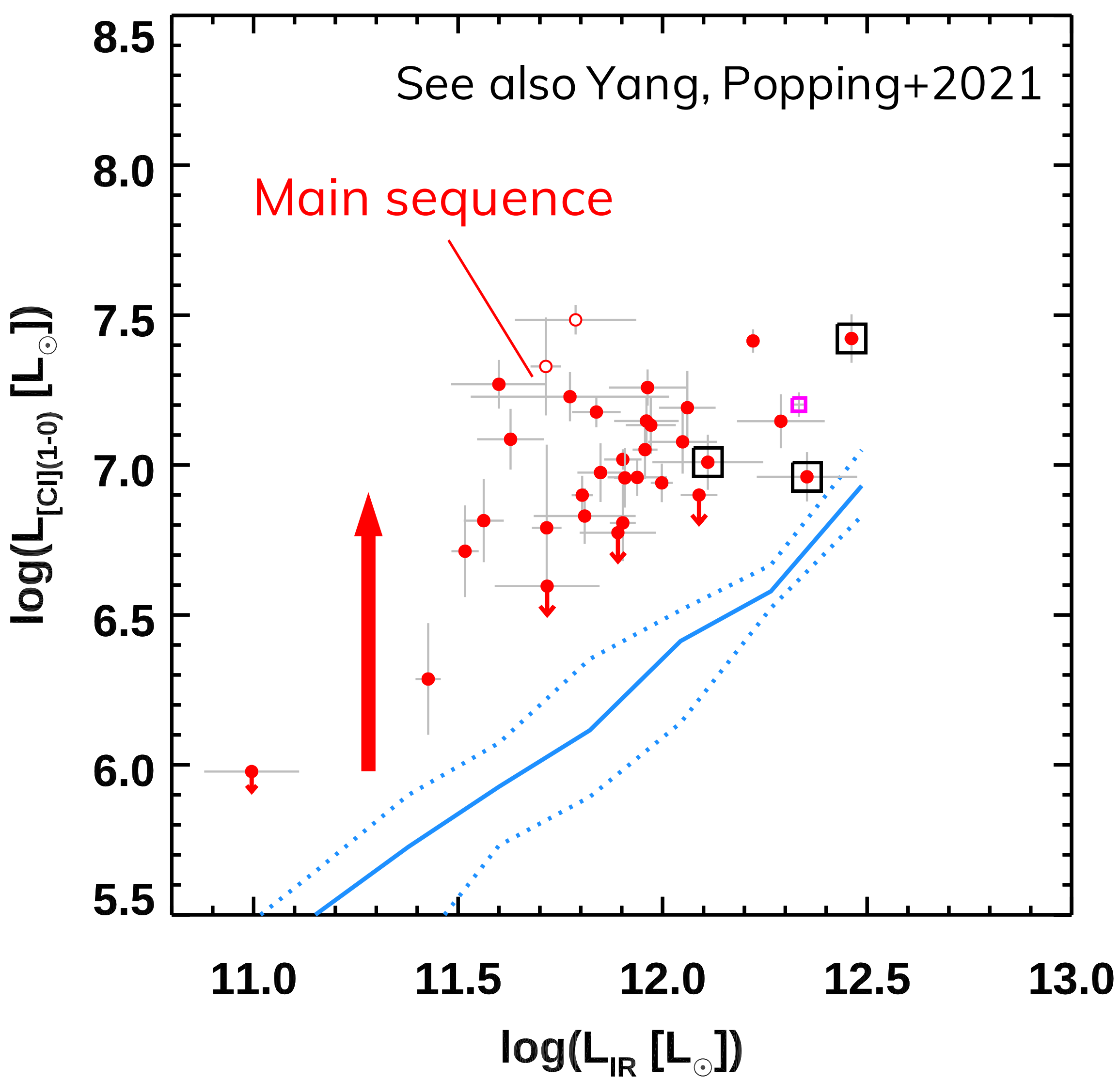
Denser gas / stronger radiation field in SB/SMGs than main sequence
(very crude and failing in many aspects!)

[C I] in a cosmological context



[C I] in a cosmological context





Summary

ALMA can detect [CI] and CO in main sequence objects at $z \approx 1.5$ in few minutes: normal galaxies are accessible!

All the measurements and catalogs are publicly available
(including most of the literature compilation)!

Suggestions or enquiries:
francesco.valentino@nbi.ku.dk

Summary

ALMA can detect [CI] and CO in main sequence objects at $z \approx 1.5$ in few minutes: normal galaxies are accessible!

The CO excitation conditions suggest the existence of different growing modes and depend on the star formation efficiencies, intensity of the radiation fields, SFR surface densities Σ_{SFR} . The latter appears to be an advantageous property to characterize the CO excitation and define a starburst (compact, highly excited, high SFE, <U>, T_{dust}, FUV, n_{gas}, cosmic ray rates, coupling).

A wide variety of SLEDs and excitation conditions even in homogeneously selected normal galaxies suggests the utmost caution when deriving gas masses from $J>2$ CO transitions. Modest effect of AGN on dust, CO $J<7$, and [CI] emission at this stage.

[CI], CO, and dust are well correlated with the total molecular gas mass. The empirical estimate of the [CI] abundance suggests different level of enrichment for normal and starburst galaxies (but look out for degeneracies!).

Models roughly capture the CO SLEDs, while the [CI] emission is still hard to reconcile with the observations – both for SAM and PDR models. These kind of data can help us!