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Panchromatic studies of high-z galaxies with deep ALMA programs

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DIPARTIMENTO DI FISICA E ASTRONOMIA "GALILEO GALILEI"

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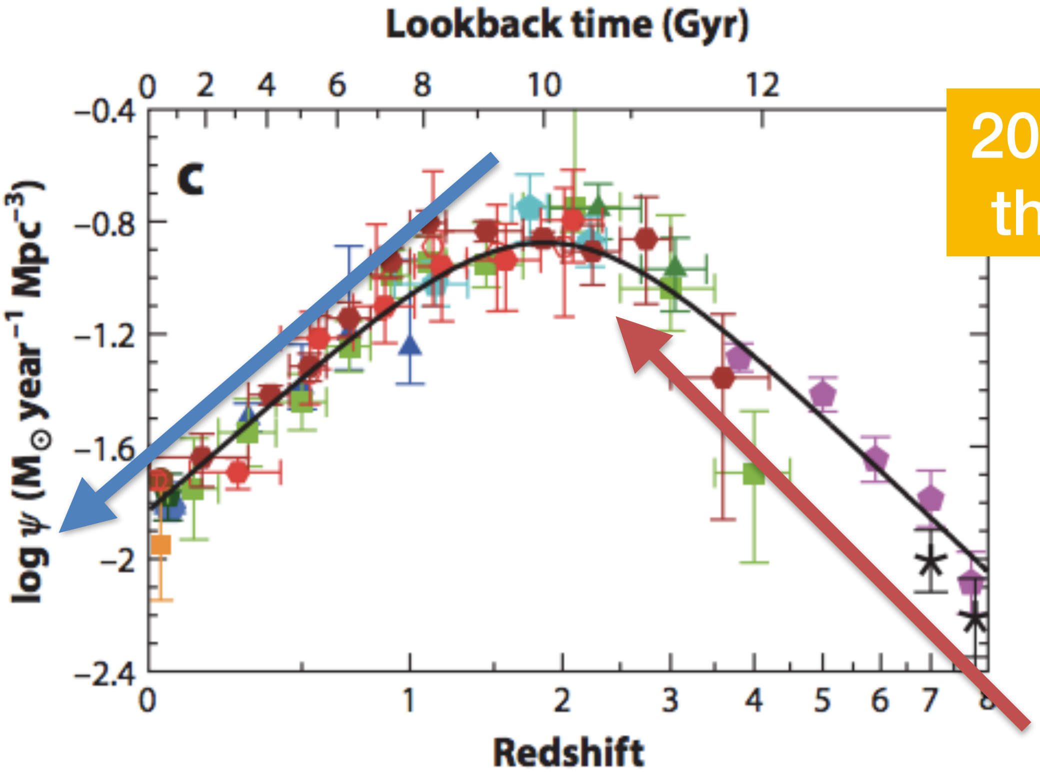
History of star-formation

number of stars born /volume / time

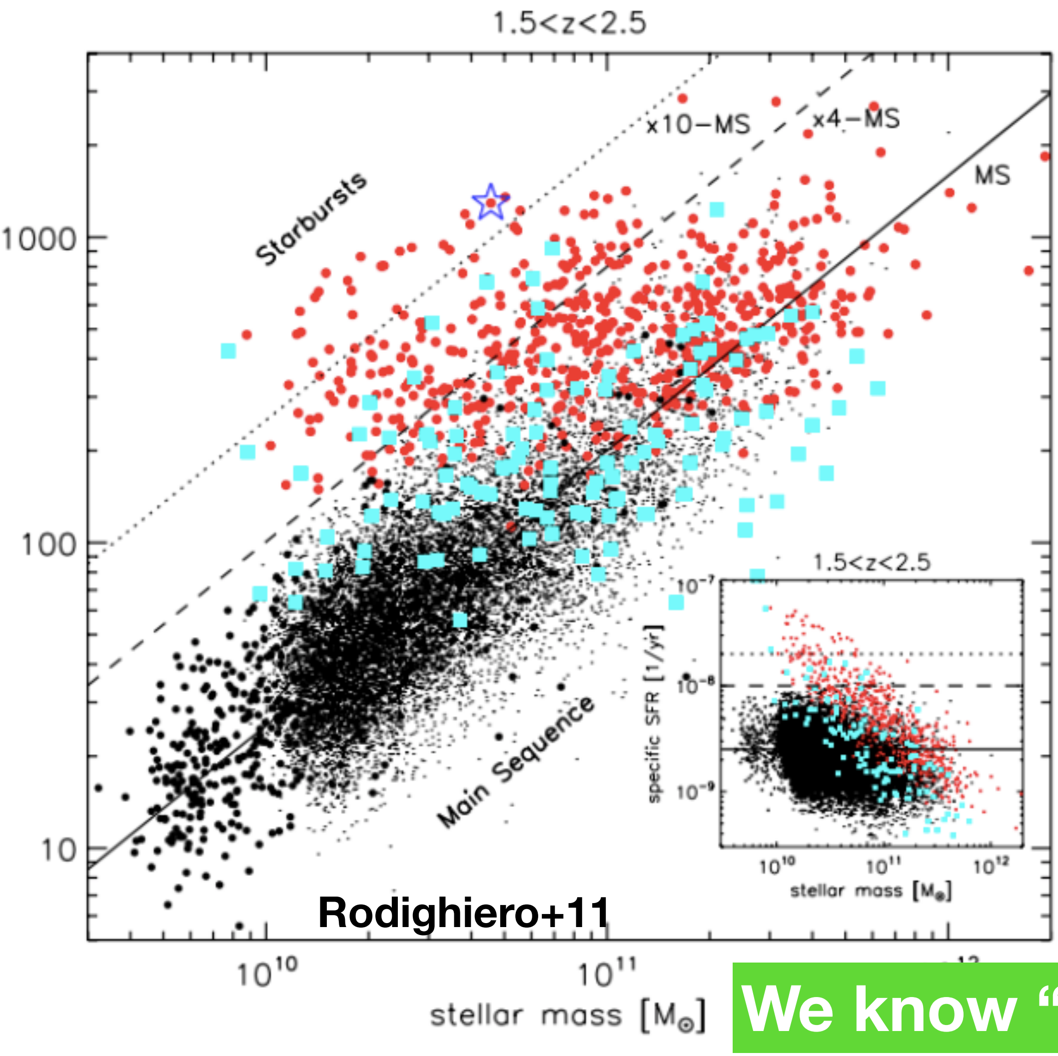


20x increase in the first 3 Gyr

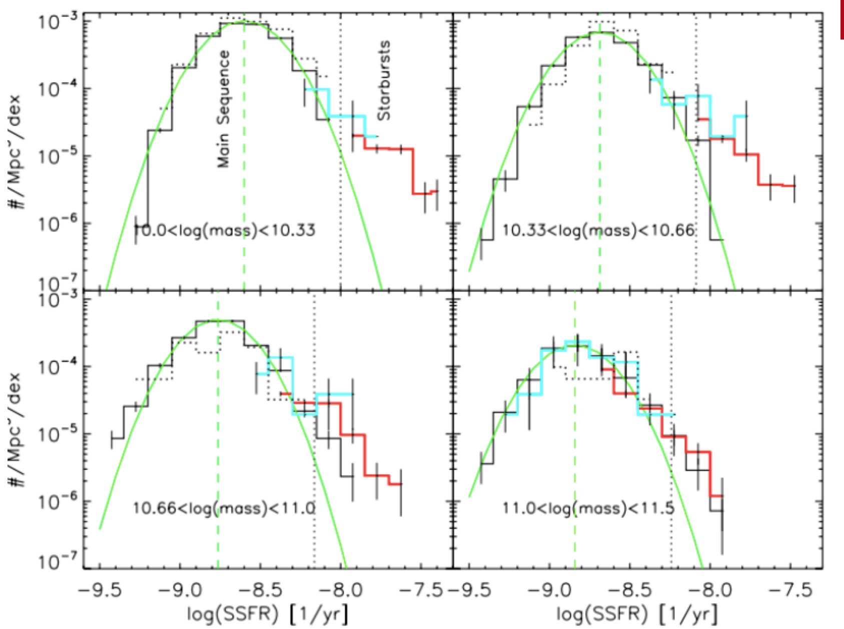
Madau&Dickinson+14

We know “when” the SF occurred

Star-forming main sequence



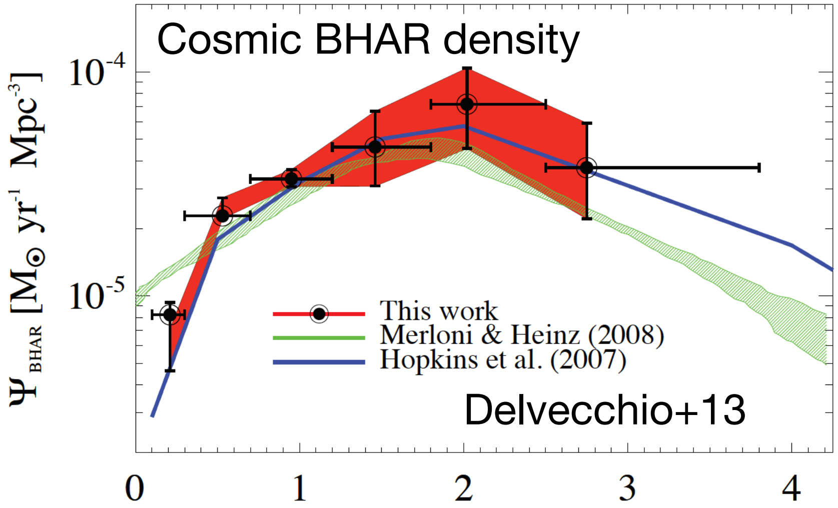
Rodighiero+11

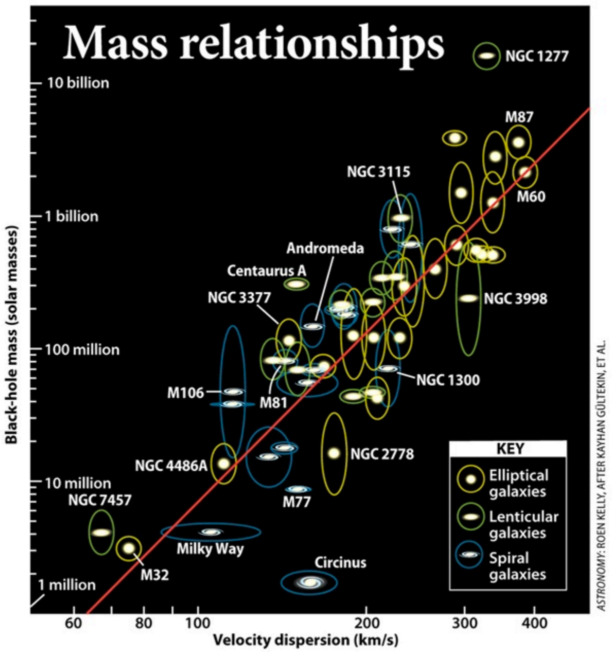


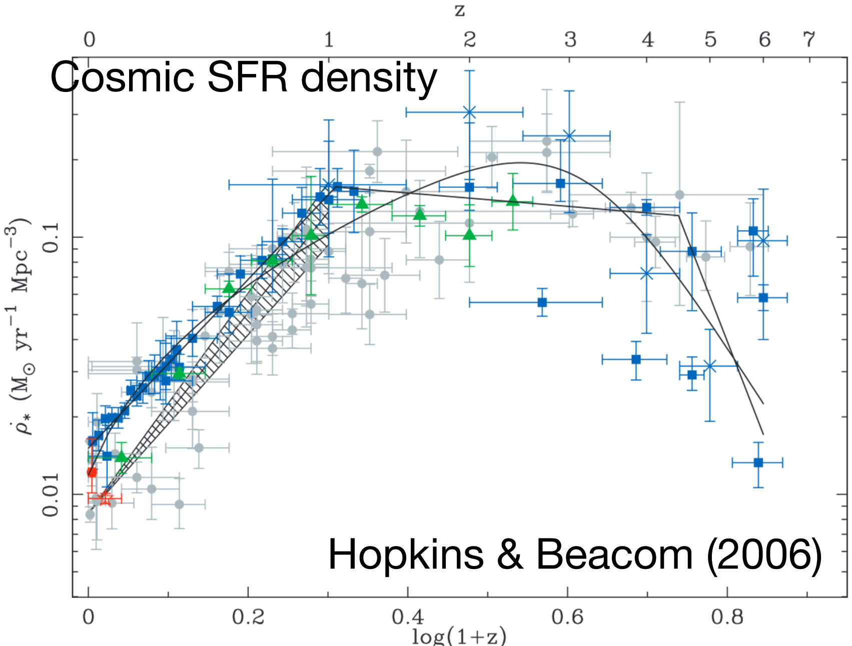
The bulk of the star-formation in the Universe takes place quietly on the star-forming main-sequence

We know "where" the SF occurred

History of Black Hole accretion







Black hole accretion and mass accretion follow a similar cosmic evolution; mass of galaxies and mass of central BH correlate

Black holes and galaxies grow together, influencing each other, feeding from the same cold gas

Open questions

- What is the dominant mode of star formation in Universe?
- What are the processes that regulate galactic scale star formation?
- Is there a universal star formation law?
- What drives the decline of the evolution of the SFRD?

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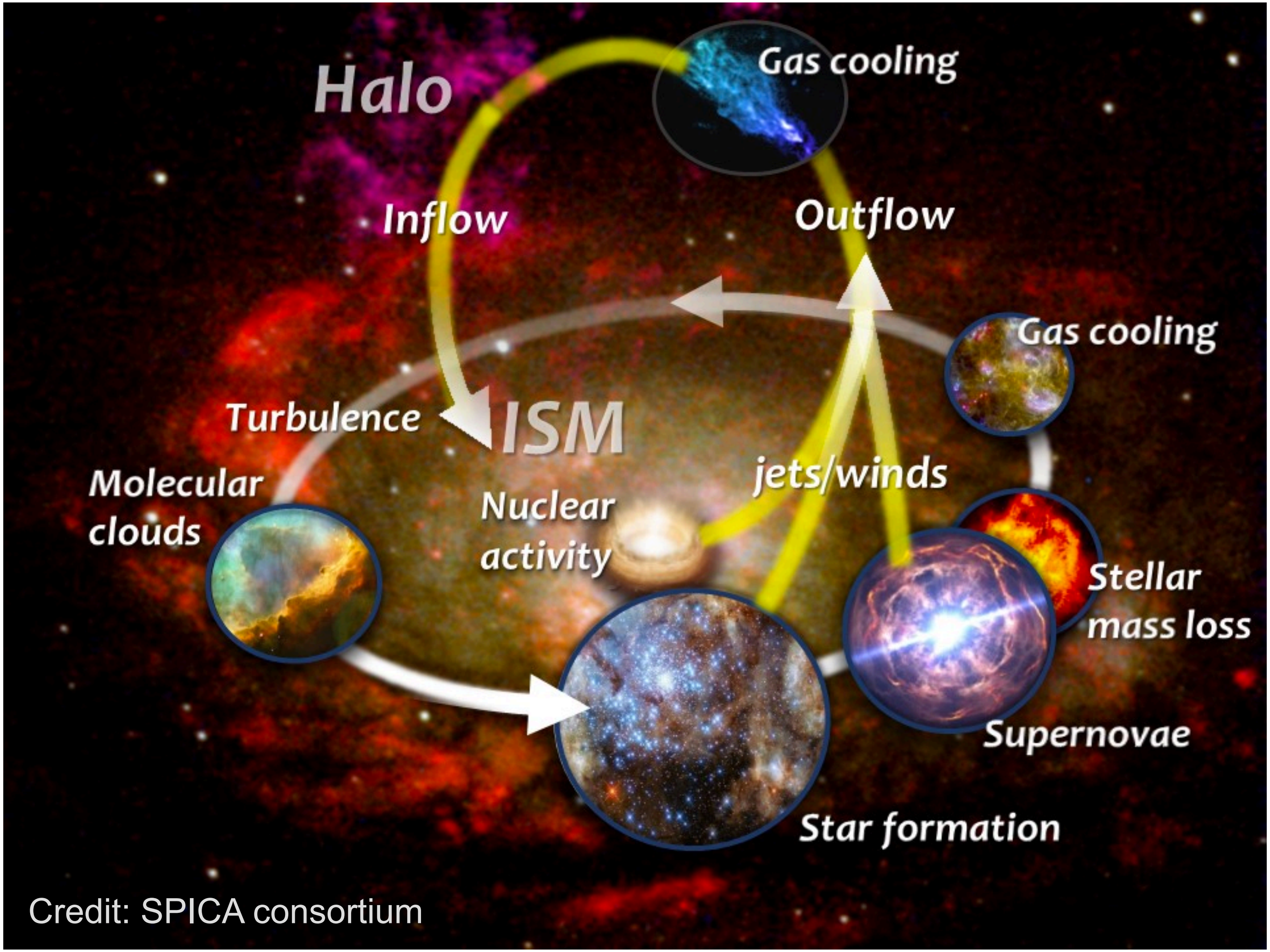
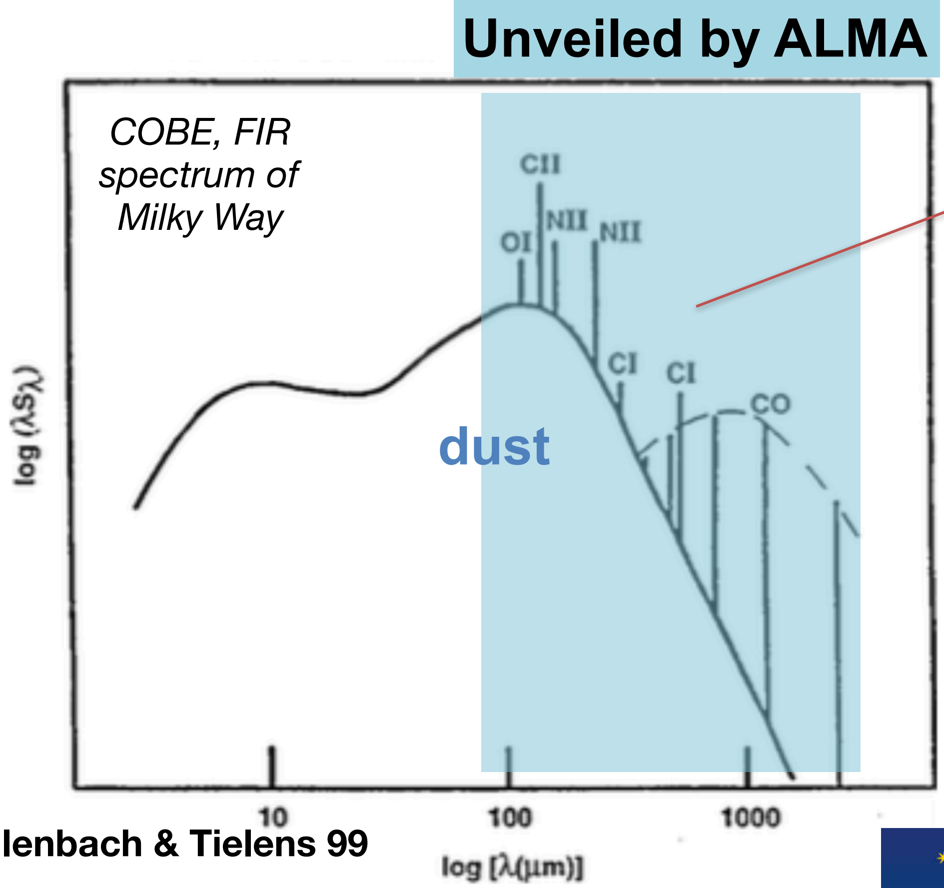
Constraining the gas cycle in galaxies



Credit: SPICA consortium

THE ALMA millimetric REVOLUTION

THE ALMA millimetric REVOLUTION: from statistics to physics of galaxies



COBE, FIR spectrum of Milky Way

Hollenbach & Tielens 99

Spectroscopy:

sub-mm lines

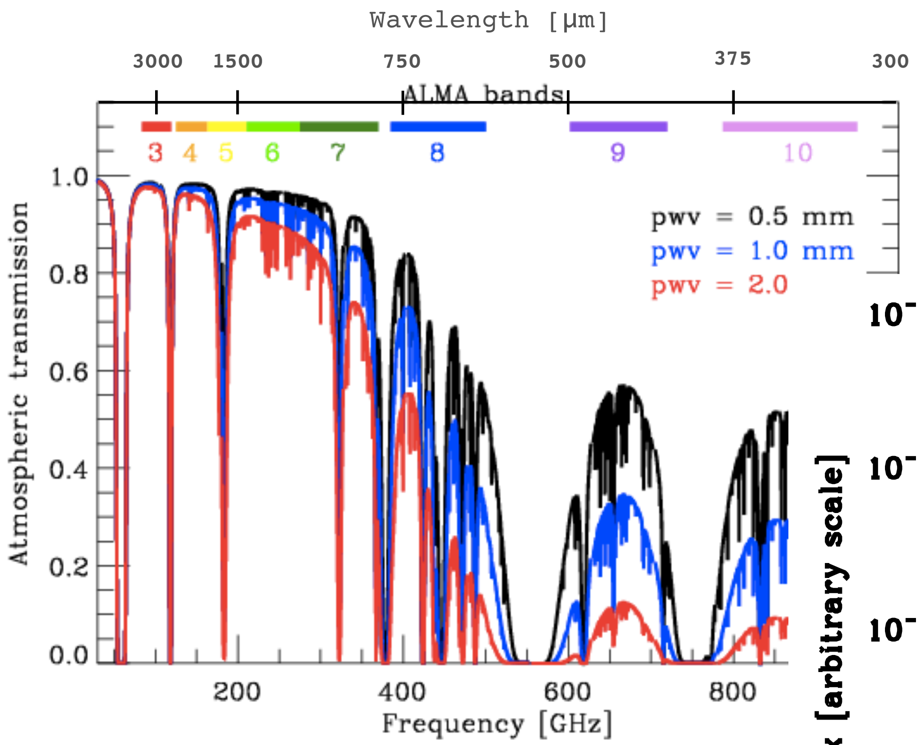
- physical state of the ISM
- star-formation
- gas mass
- gas kinematics

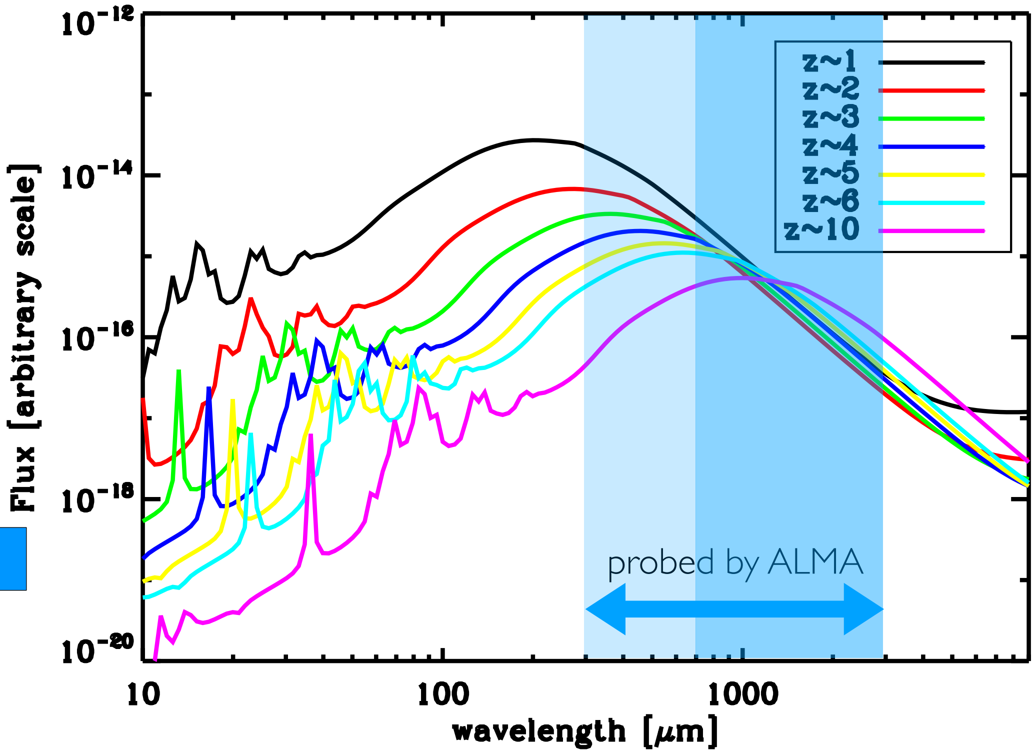
Photometry:

dust emission

- obscured star-formation
- dust/gas content

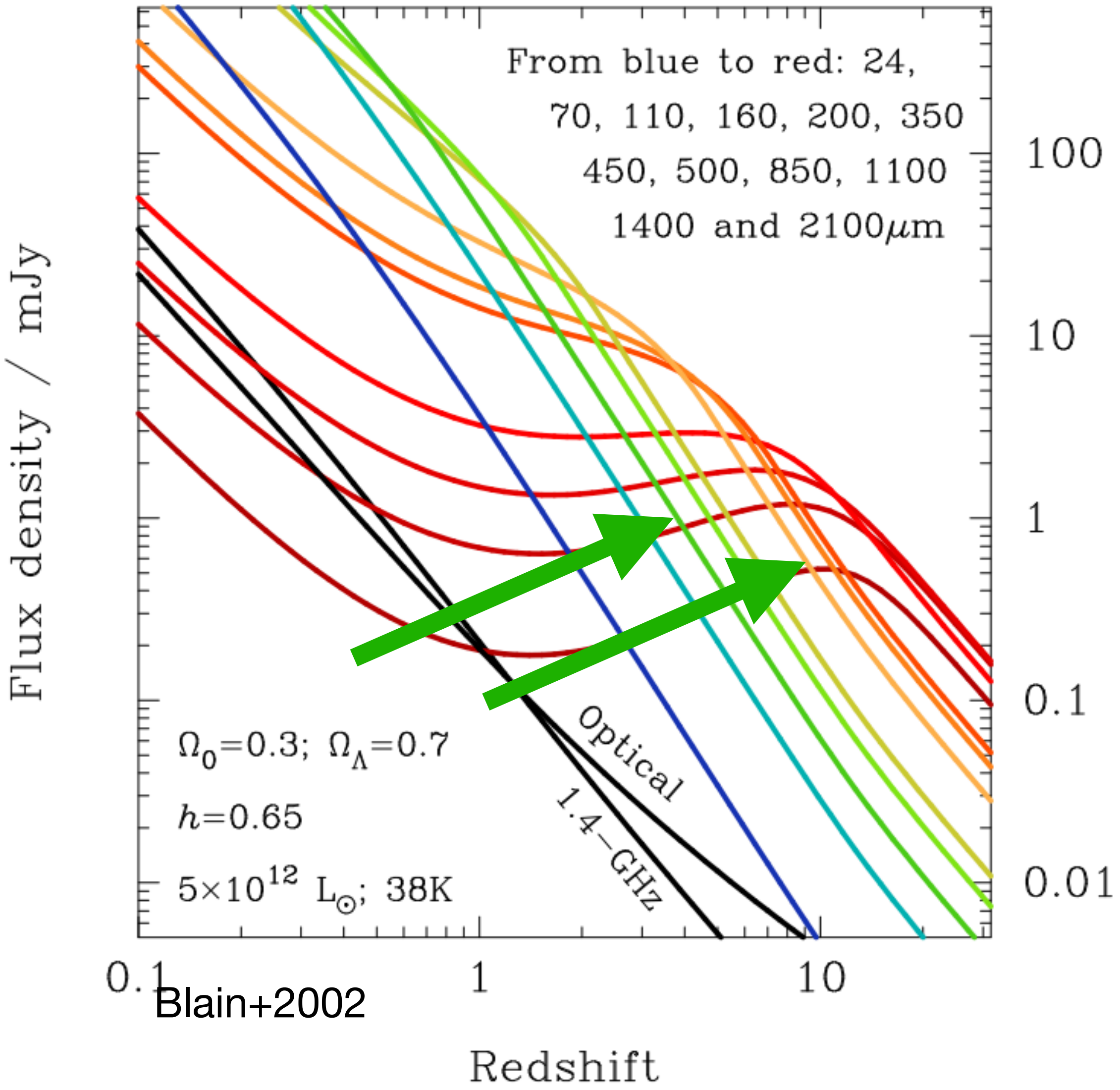
ALMA bands





MS sed vs z

Photometric mode: Dust continuum



Blain+2002

Negative K-correction

Fluxes in the millimetre regime become brighter as redshift increases beyond 2

Easier to find high-z galaxies

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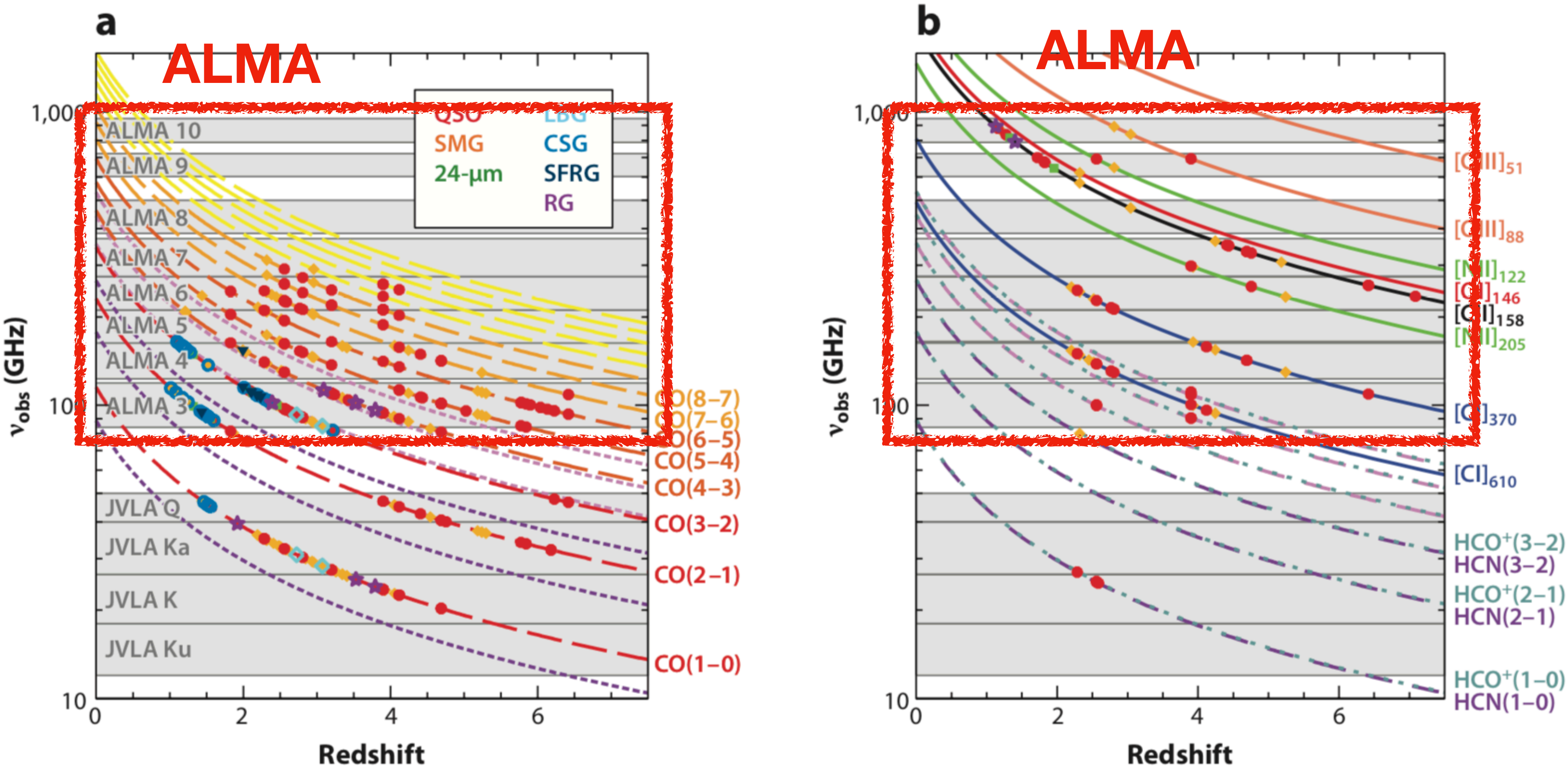
Spectroscopic mode: FIR lines



Carilli&Walter+13

Tracers of molecular gas and tools to constrain the ISM status

Cold gas tracers at high-z

HI	21cm	SKA at z>0.5
H_2	no permanent dipole moment; lowest transitions forbidden; high excitation requirements	not observable
CO	excited through collisions with H_2	**ALMA**
Dust	mixed with gas	**ALMA**

CO as a gas tracer

CO to H_2 conversion

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The CO-to-H_2 Conversion Factor

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Keywords

ISM: general, ISM: molecules, galaxies: ISM, radio lines: ISM

Abstract

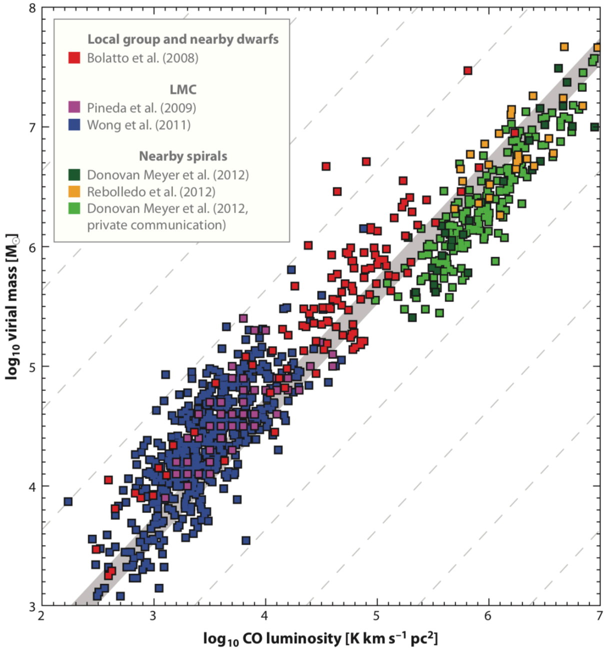
CO line emission represents the most accessible and widely used tracer of the molecular ISM. This renders the translation of observed CO intensity into total H_2 gas mass critical to understanding star formation and the ISM in our Galaxy and beyond. We review the theoretical underpinning, techniques, and results of efforts to estimate this CO-to-H_2 "conversion factor," X_{CO}, in different environments. In the Milky Way disk, we recommend a conversion factor of $X_{CO} = 2 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ with ±30% uncertainty. Studies of other "normal galaxies" return similar values in Milky Way–like disks, but with greater scatter and systematic uncertainty. Departures from this Galactic conversion factor are both observed and expected. Dust-based determinations, theoretical arguments, and scaling relations all suggest that X_{CO} increases with decreasing metallicity, turning up sharply below metallicity ~1/3–1/2 solar in a manner consistent with model predictions that identify shielding as a key parameter. Based on spectral line modeling and dust observations, X_{CO} appears to drop in the central, bright regions of some but not all galaxies, often coincident with regions of bright CO emission and high stellar surface density. This lower X_{CO} is also present in the overwhelmingly molecular ISM of starburst galaxies, where several lines of evidence point to a lower CO-to-H_2 conversion factor. At high redshift, direct evidence regarding the conversion factor remains scarce; we review what is known based on dynamical modeling and other arguments.

Molecular gas mass

CO(1-0) Luminosity

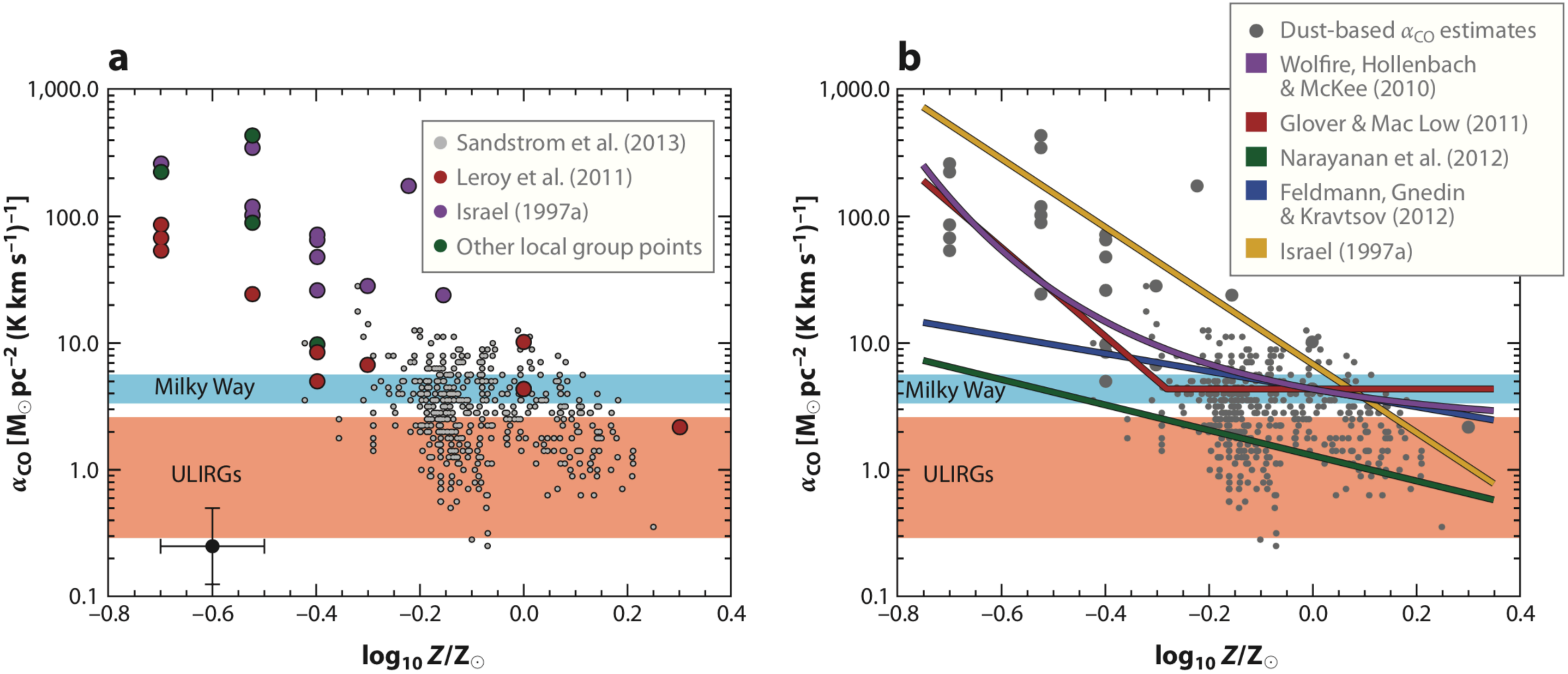
$$M_{mol} = \alpha_{CO} \, L_{CO}$$

α_{CO} conversion factor: how to estimate it?



Dependence of α_{CO} on metallicity, galaxy type

Caveat 1



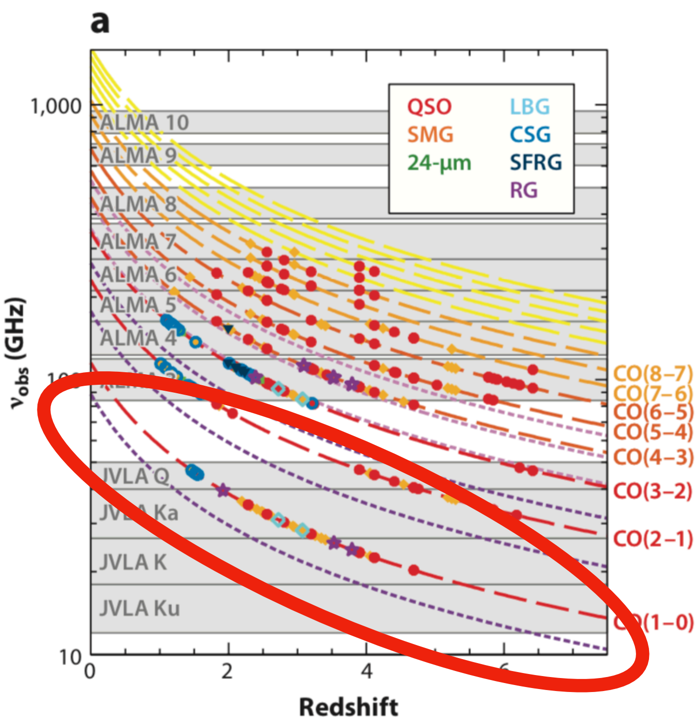
Bolatto+13

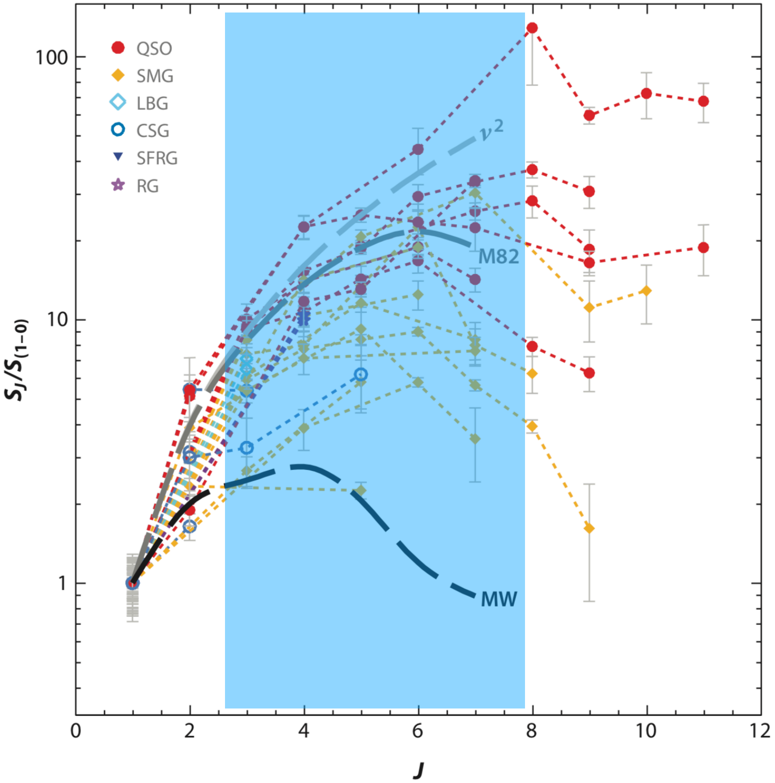
α_{CO} highly uncertain

CO(1-0) at very low frequency at z>0.5

Caveat 2

We have to rely on higher CO transitions, derive the CO SLED slope, and extrapolate down to CO(1-0)





CO(1-0) not observable with ALMA at z>0.5; very faint to be observed with JVLA

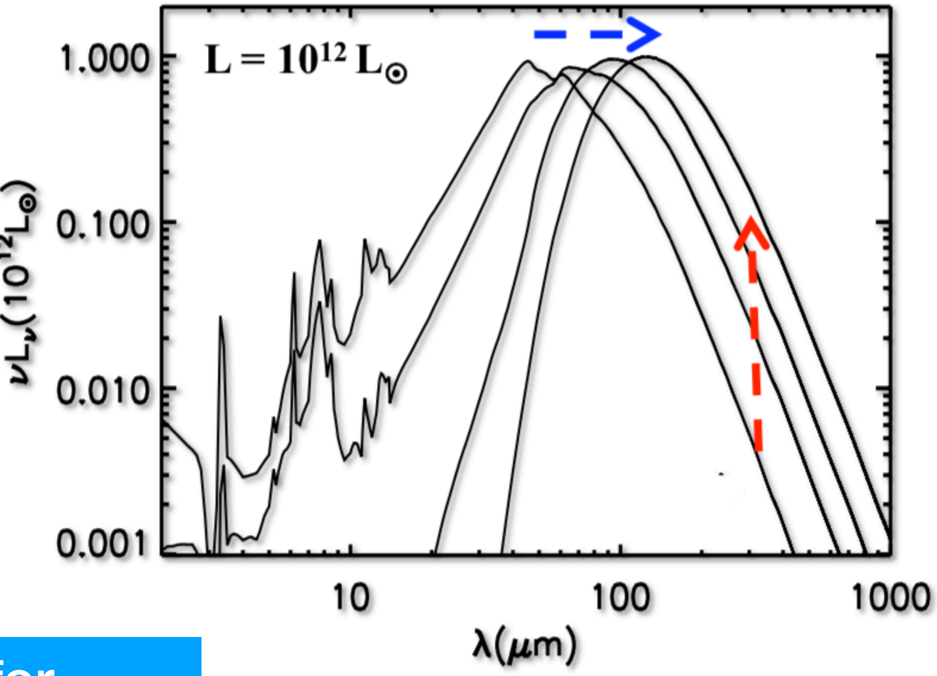
Dust as a molecular gas tracer

In the RJ regime the dust emission is optically thin, therefore

$$S_\nu \propto \kappa_d(\nu) T_d \nu^2 \frac{M_d}{d_l^2}$$

dust opacity per unit mass of dust

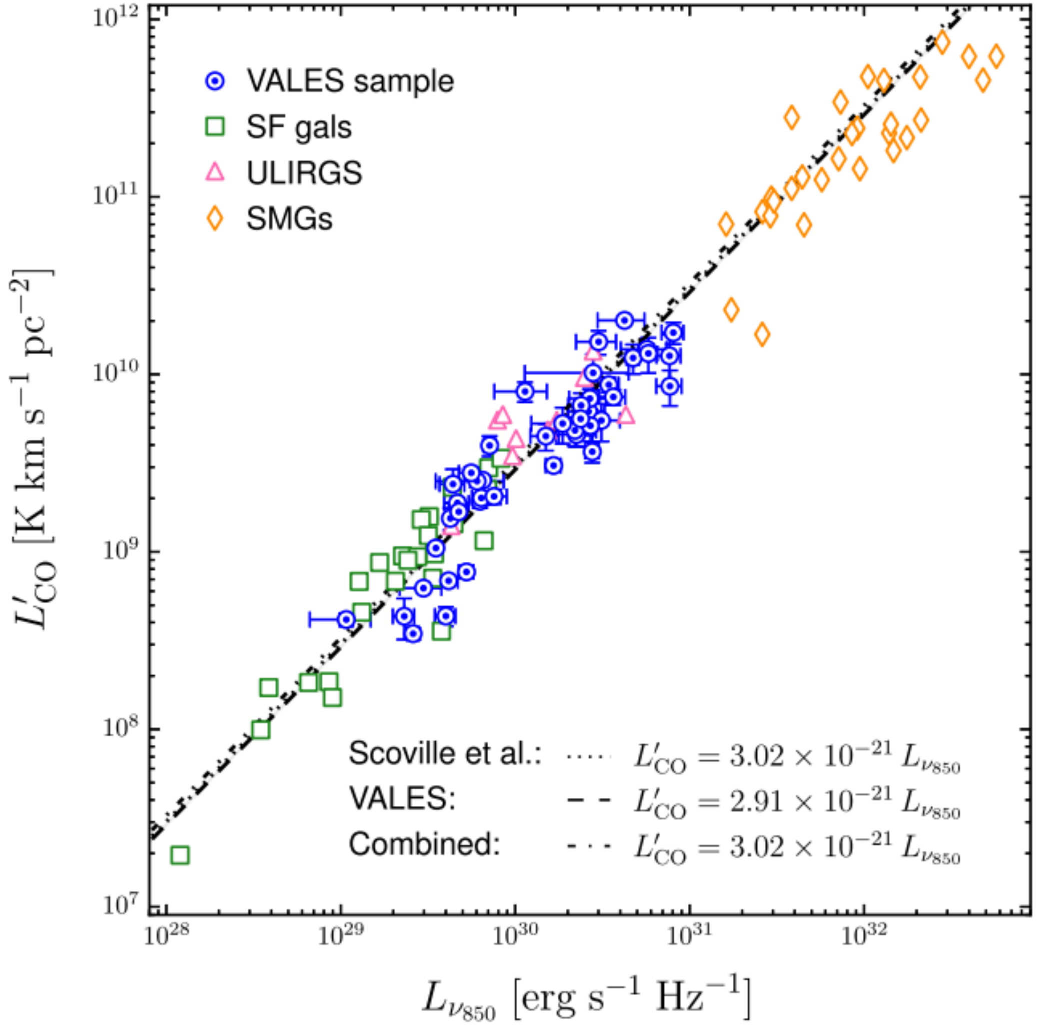
T_d ~ 25-45 °K



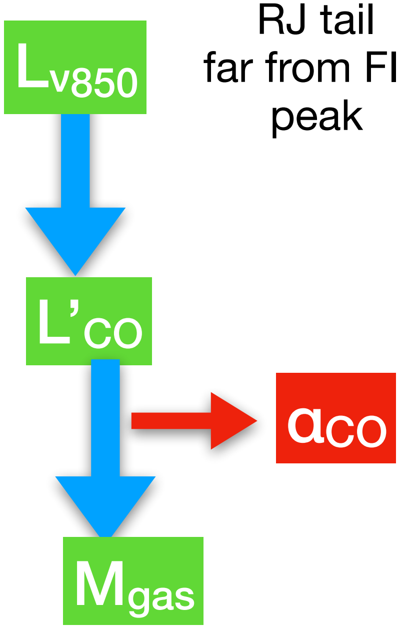
- peak shifts to longer λ for increased τ (or dust mass)
- flux on long λ tail scales linearly with M_{dust}

10^8 - $6 x 10^9$ $M_\odot$

Gas masses from dust emission: empirical calibration



works over ~4 orders of magnitude



$L_{\nu 850}$

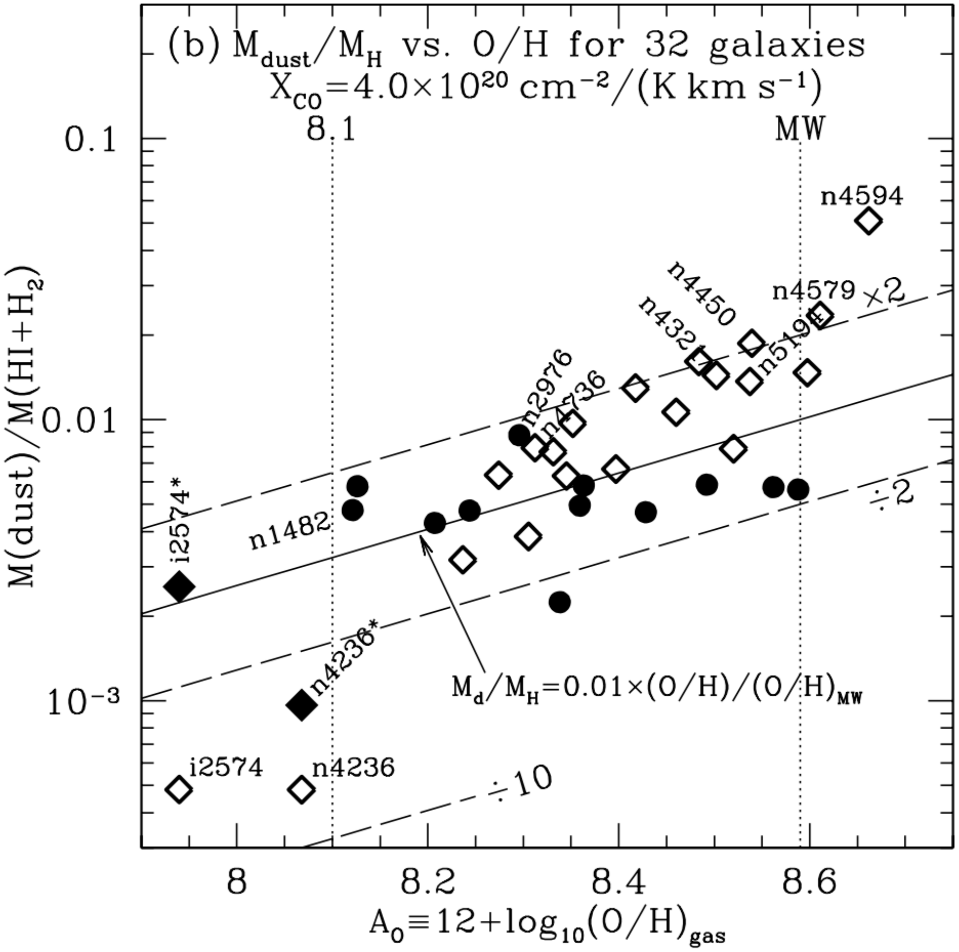
RJ tail
far from FIR
peak

$L'_{\rm CO}$

$\alpha_{\rm CO}$

$M_{\rm gas}$

Gas masses from dust emission: dependence on metallicity



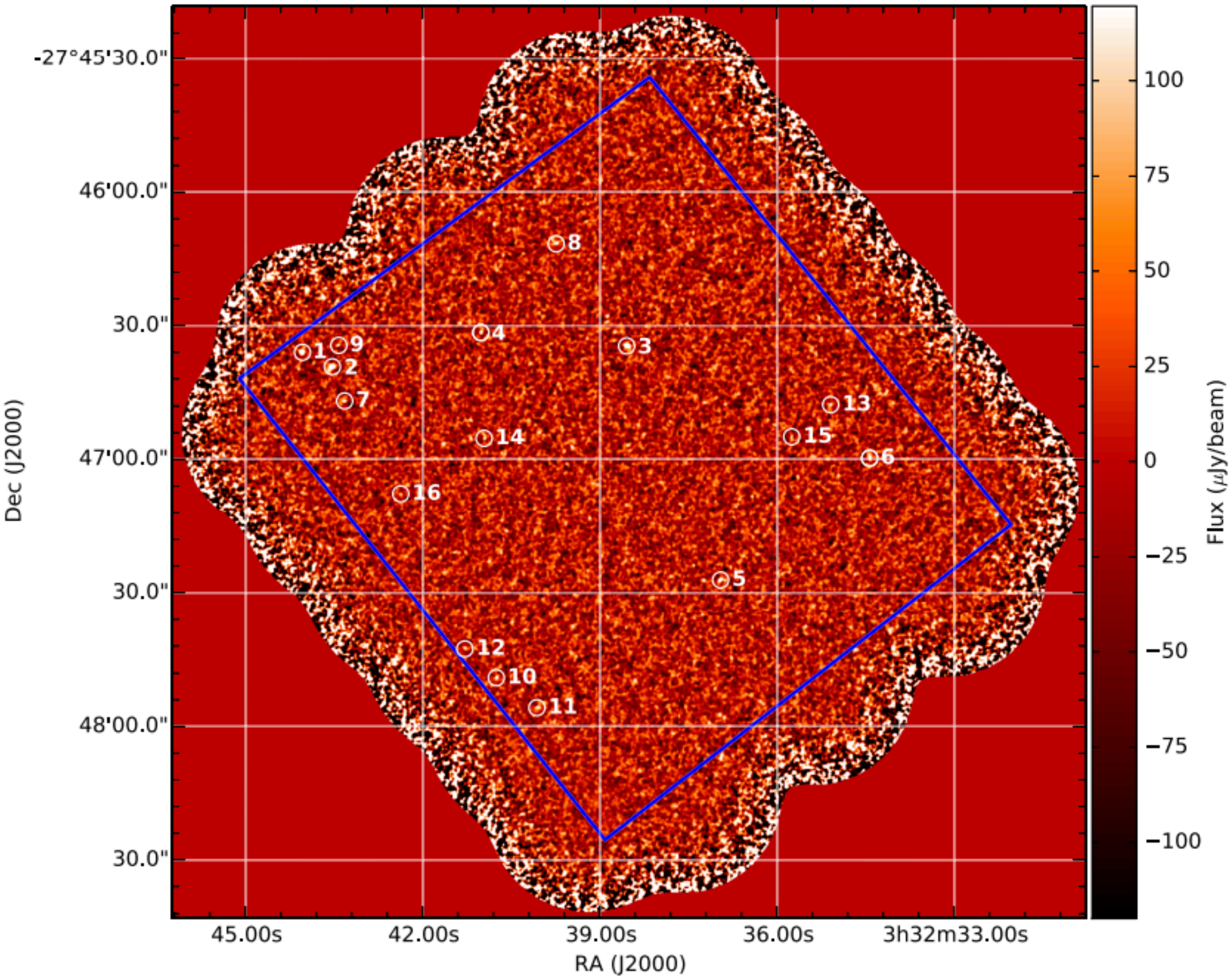
Draine+07

- Slight dependence of dust-to-mass ratio with metallicity
- Lower metallicity, less dust per gas mass
- (Black points: more reliable measurements, flatter dependence?)

How to apply these techniques at high-z?

“Survey” mode

Survey mode: continuum

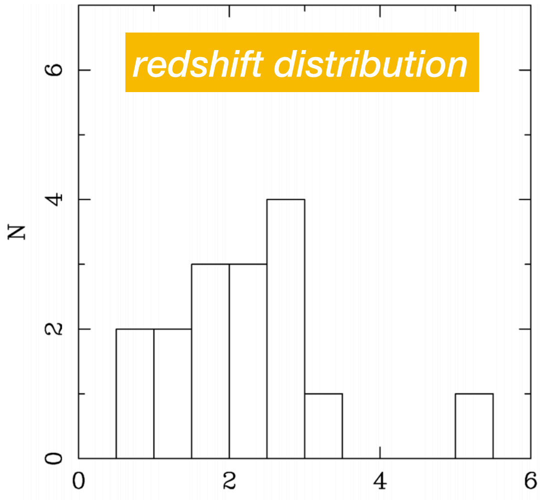


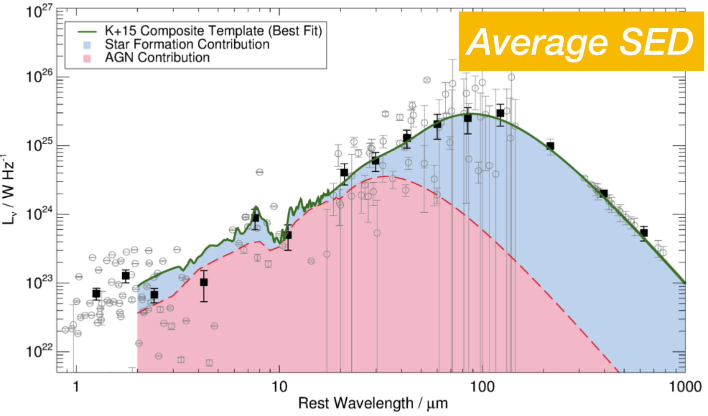
HUDF, Dunlop+17

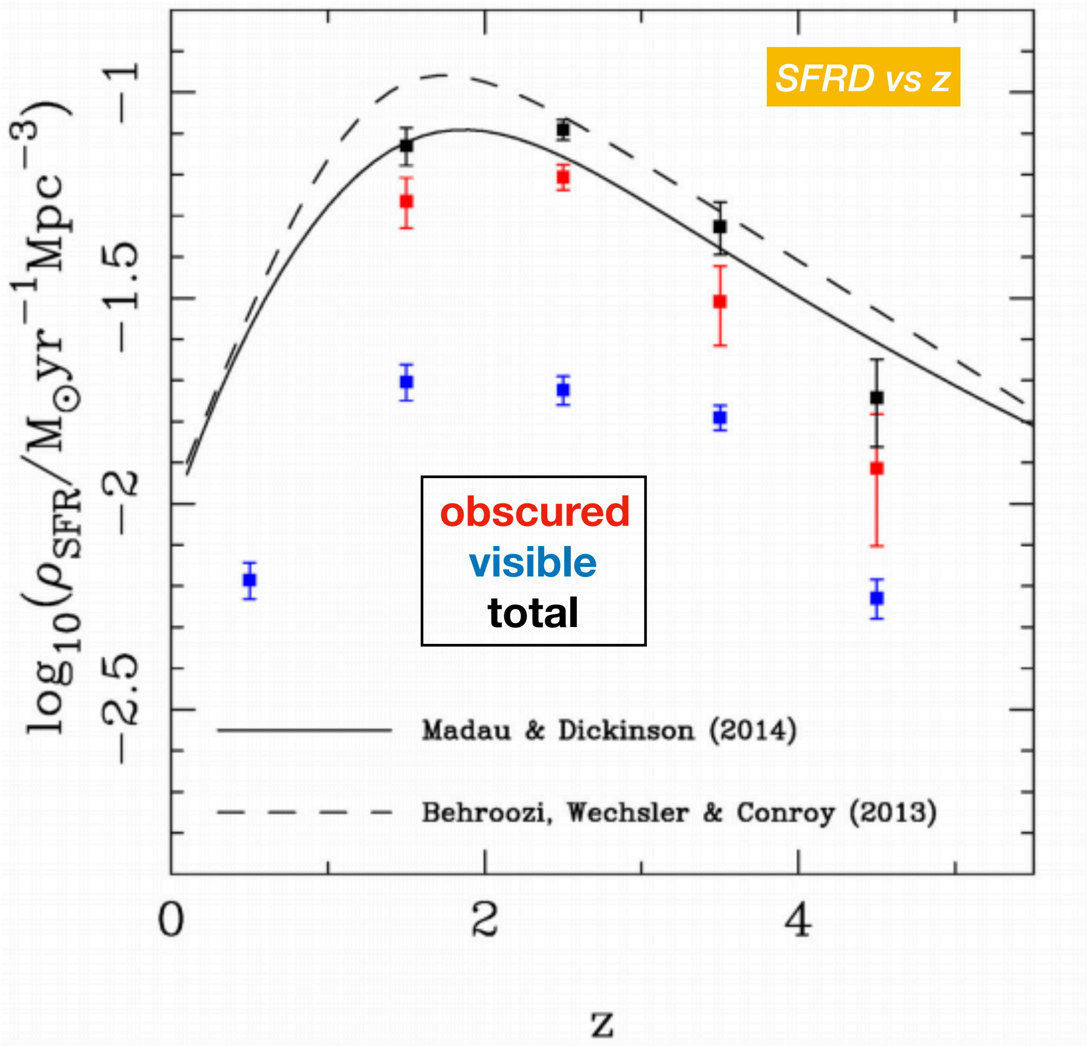
- 4.5 arcmin^2
- 45 ALMA pointings
- 1.3 mm (230 GHz, band 6)
- $\sigma_{1.3mm}$=35μJy
- ~15h on source
- 16 sources S>120μJy
- wealth of ancillary data

Pros:
- Uniform detection limits
- Clean unbiased samples
- Detect both obscured and unobscured objects

Cons:
- Few objects
- Small areas

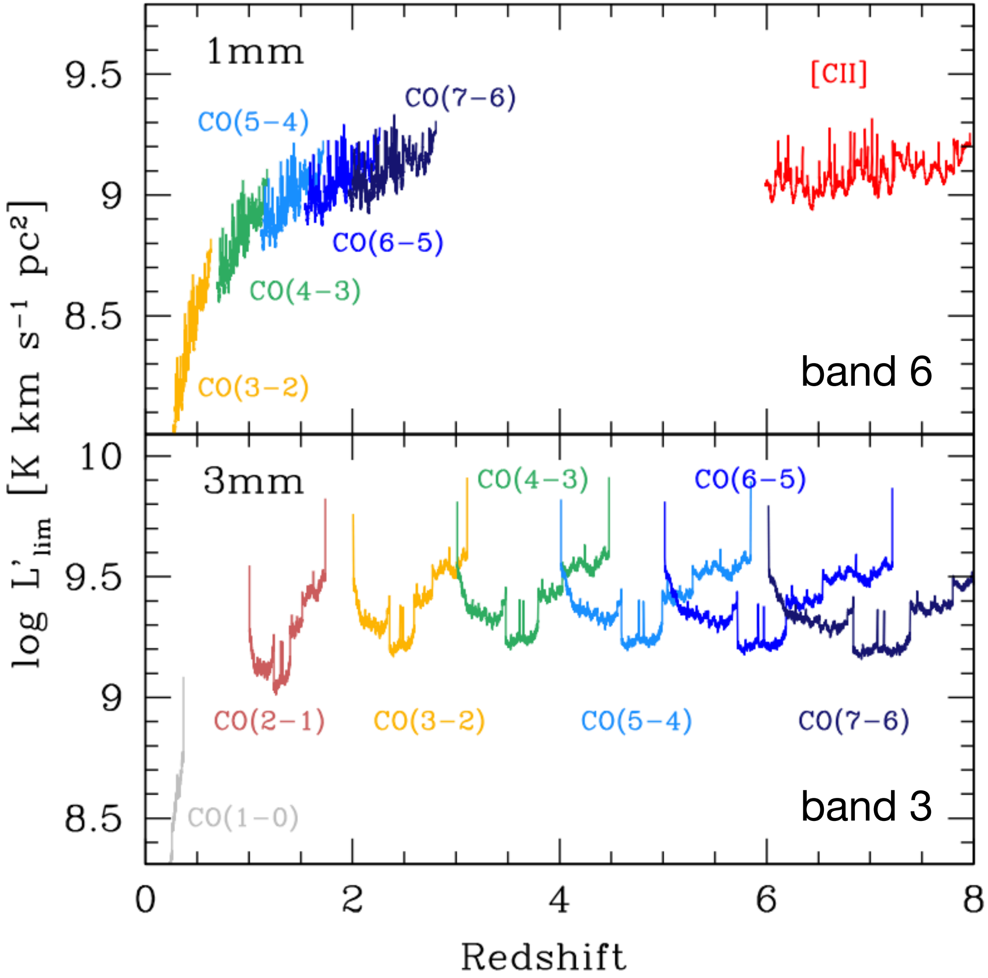

redshift distribution
N
0
2
4
6
0
2
4
6


Average SED
K+15 Composite Template (Best Fit)
Star Formation Contribution
AGN Contribution
L_ν / W Hz^-1
10^27
10^26
10^25
10^24
10^23
10^22
1
10
100
1000
Rest Wavelength / µm


SFRD vs z
log10(ρSFR/M⊙yr^-1Mpc^-3)
−1
−1.5
−2
−2.5
0
2
4
z
obscured
visible
total
Madau & Dickinson (2014)
Behroozi, Wechsler & Conroy (2013)

Dunlop+17

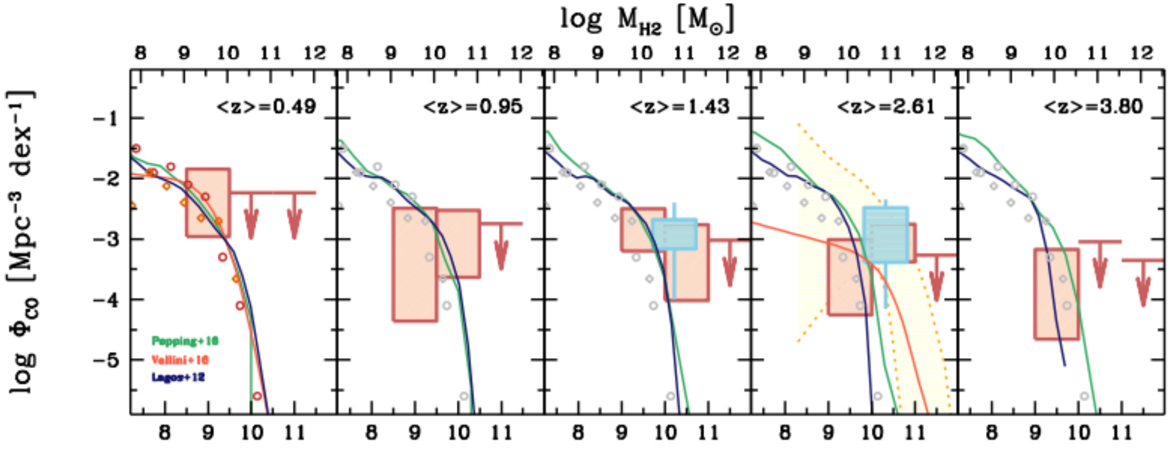
Survey mode: lines



ASPECS, Walter+16; Decarli+16

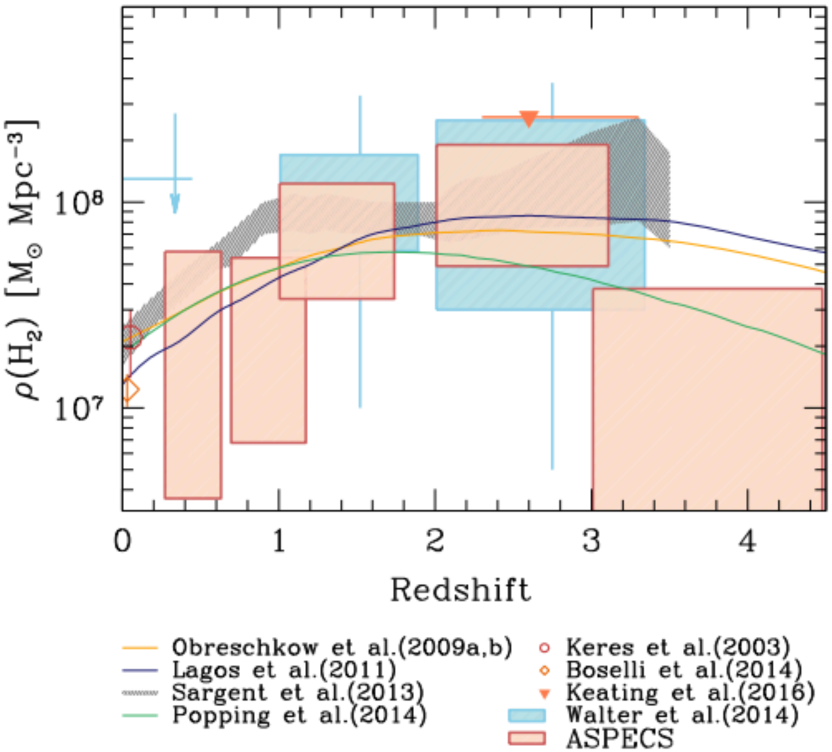
- 40h cycle 2 observations
- scans in band 3 & 6 (84—115&212—272 GHz)
- Uniform line sensitivity: (L'_{CO} ~ 2 × 10^9 K km s^{-1} pc^2)
- **21 line candidates**

CO luminosity functions

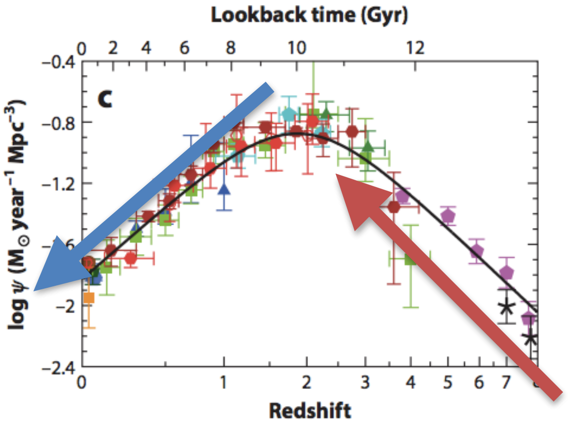


Decarli+16

log L'$_{CO(1-0)}$ [K km s^{-1}pc^2]

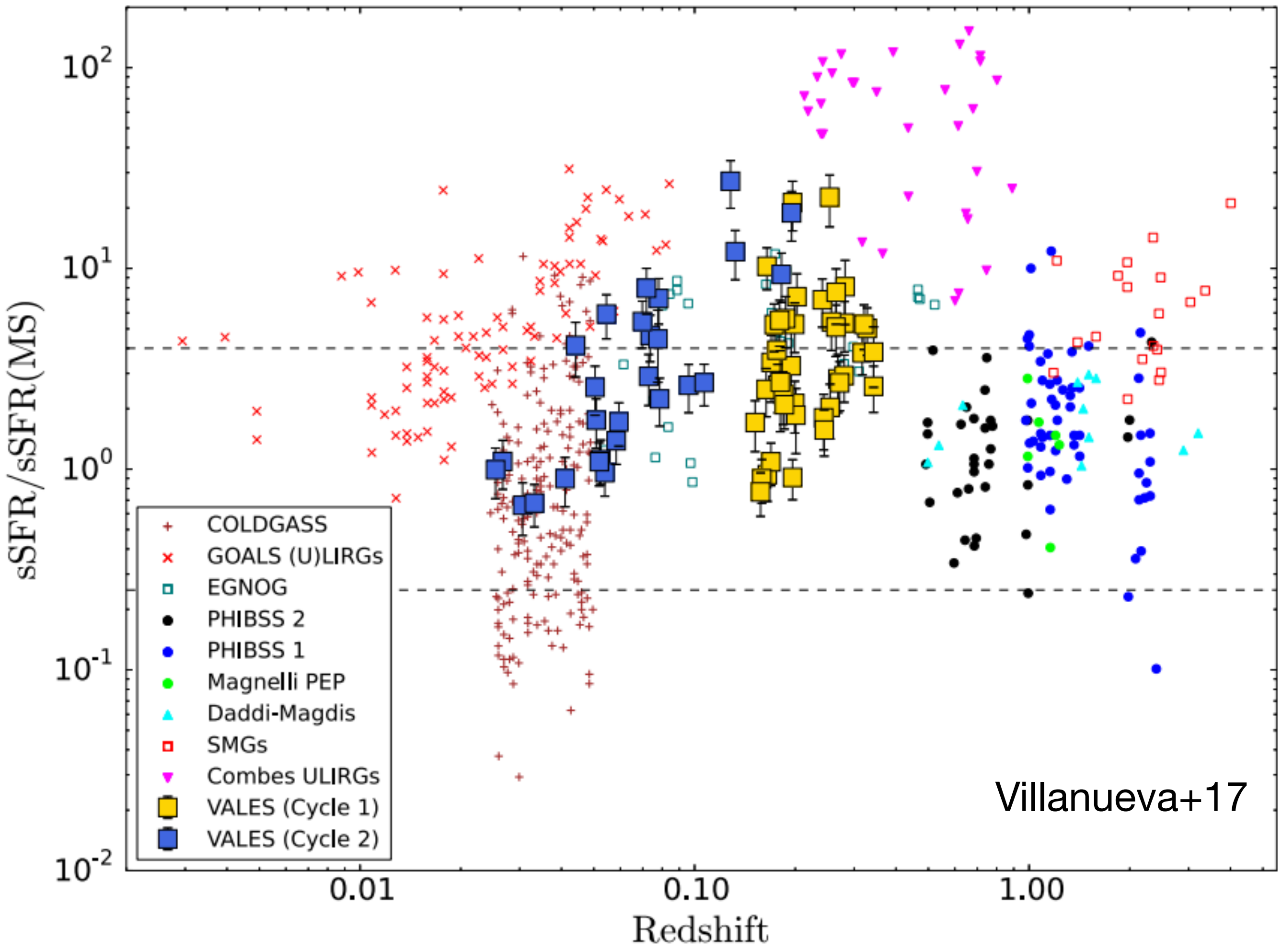


molecular hydrogen space density



Complementary approach: “targeted” mode

CO measurements at 0 < z < 2.5



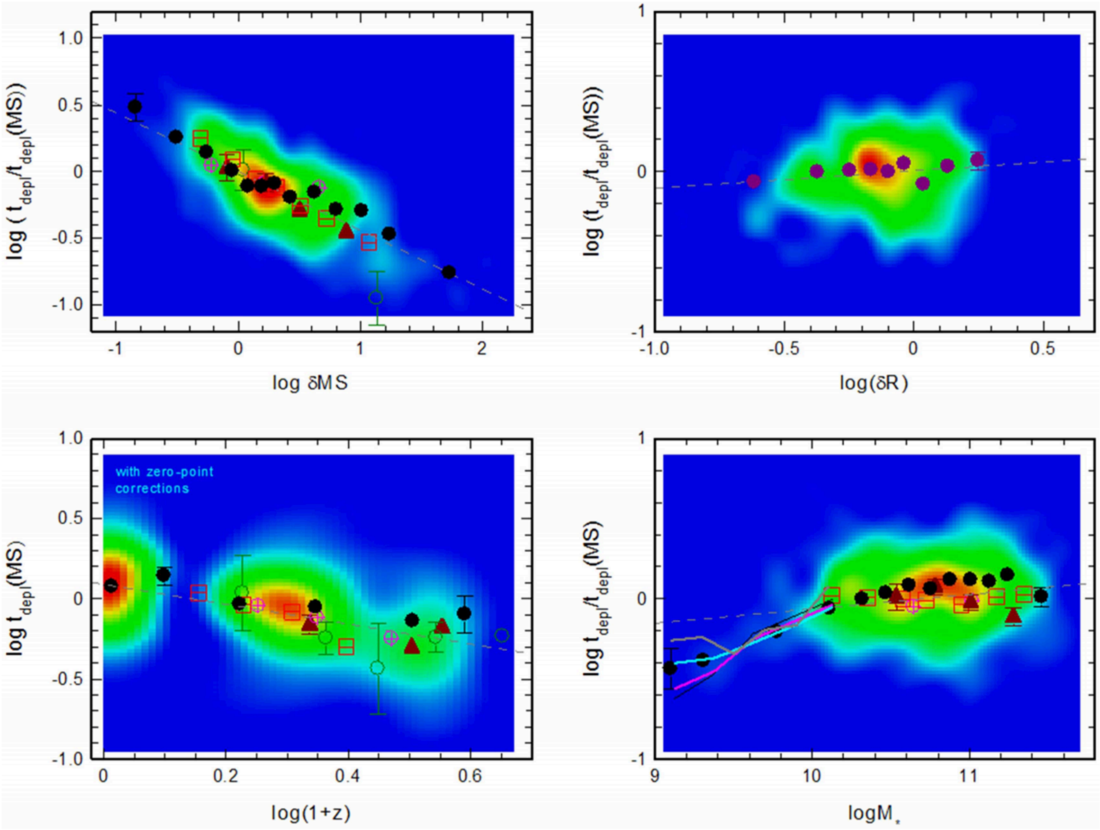
Villanueva+17

- Collection of ALMA, IRAM 30m, CARMA, IRAM PdBI
- ~500 galaxies
- mostly z < 1

Molecular gas mass

Combining CO and dust: scaling relations at $0 < z < 2.5$

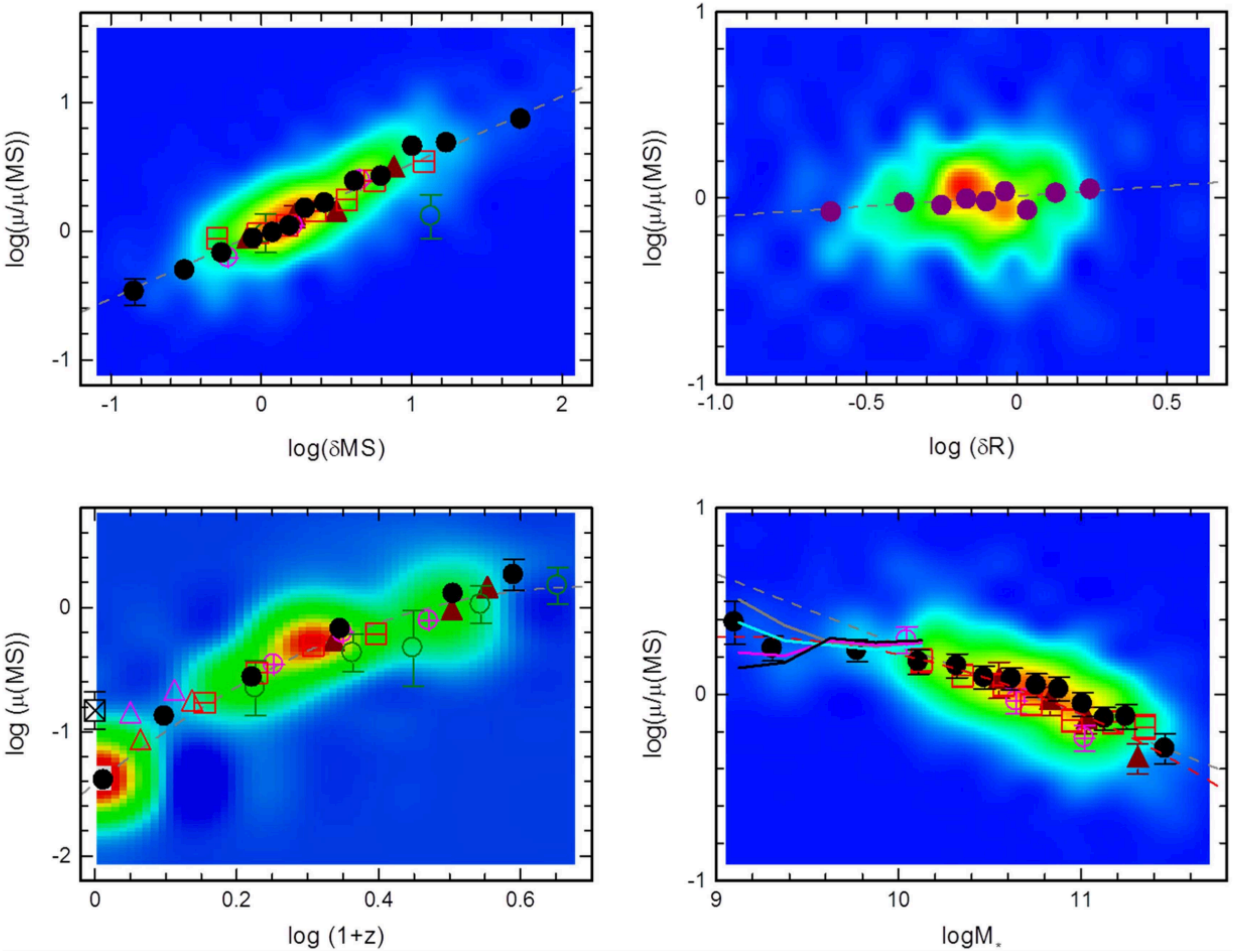
- M^*= stellar mass
- SFR= star formation rate, dM^*/dt
- sSFR=SFR/M_*, specific star formation rate,$1/t_{doubl}$, t_{doubl} time to double the stellar mass
- $\mu_{gas}=M_{gas}/M_*$
- $t_{depl}=M_{gas}/SFR$, time to consume all the gas



- t_{depl} drops relatively slowly with cosmological epoch: ~2 times between z = 0 and 2.5
- t_{depl} does not depend on galaxy size
- t_{depl} drops perpendicularly to the main sequence

Tacconi+18

Similar scaling relations for the gas fractions



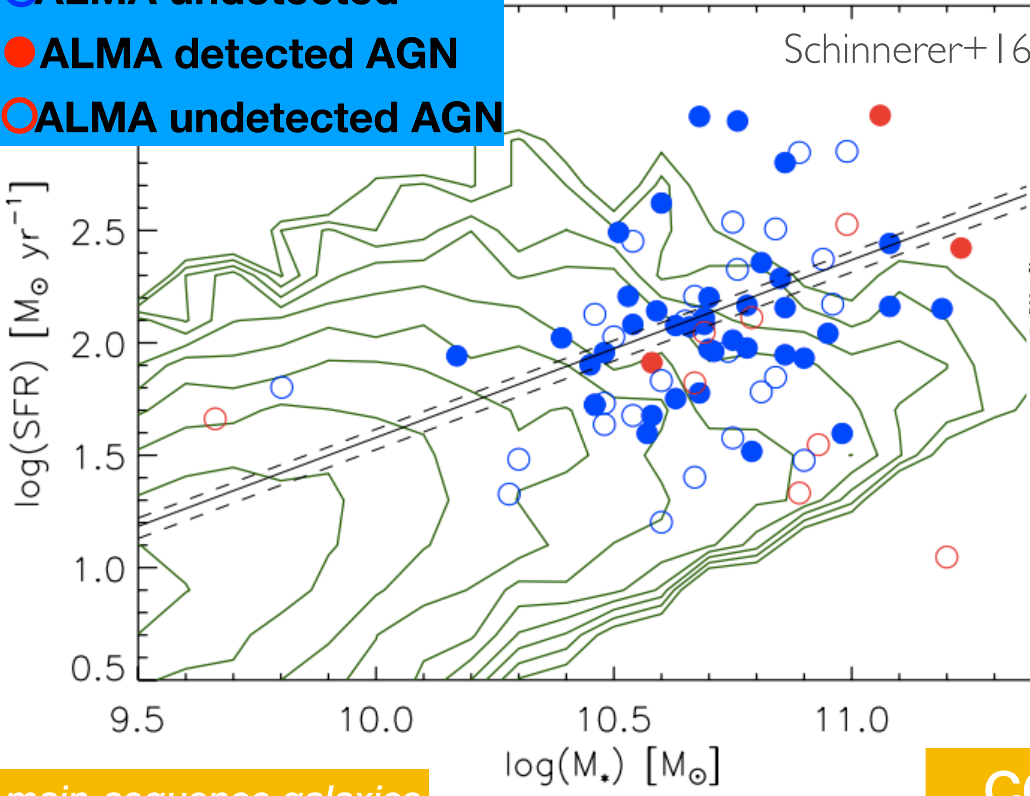
Tacconi+18

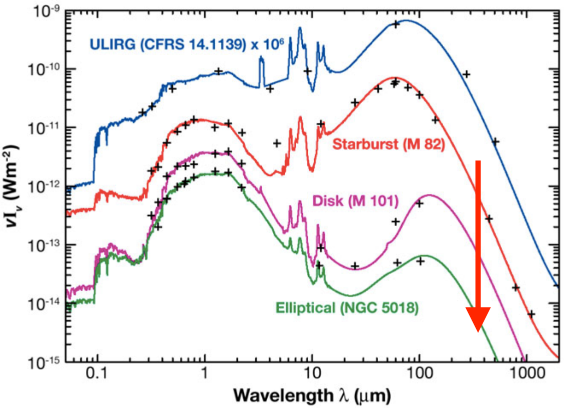
What about $z>3$?

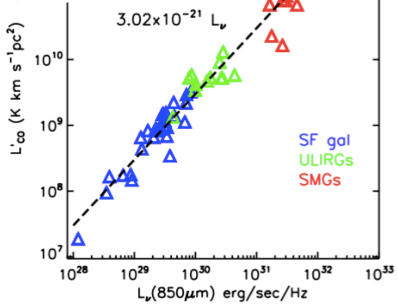
Scaling relations at z > 3: a targeted approach

ALMA Cycle 2
Band 6 ~240GHz
~300 μm rest-frame
86 targets

- ● **ALMA detected**
- ○ **ALMA undetected**
- ● **ALMA detected AGN**
- ○ **ALMA undetected AGN**







main-sequence galaxies

COSMOS-ACS field
z_{spec} from VUDS&zCOSMOS

SFR with magphys, including ALMA: 0.5 dex higher than optical-NIR sed fitting

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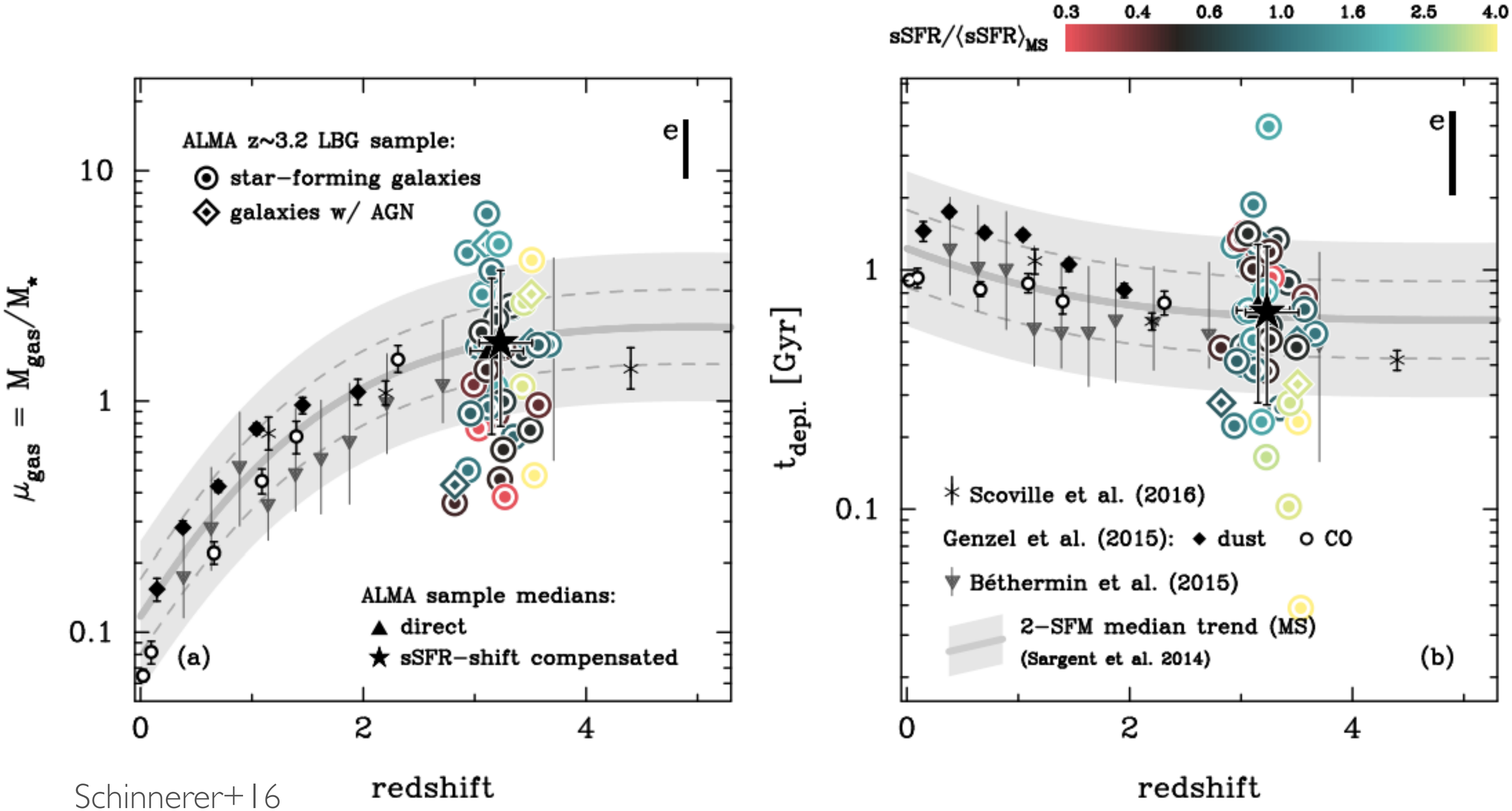
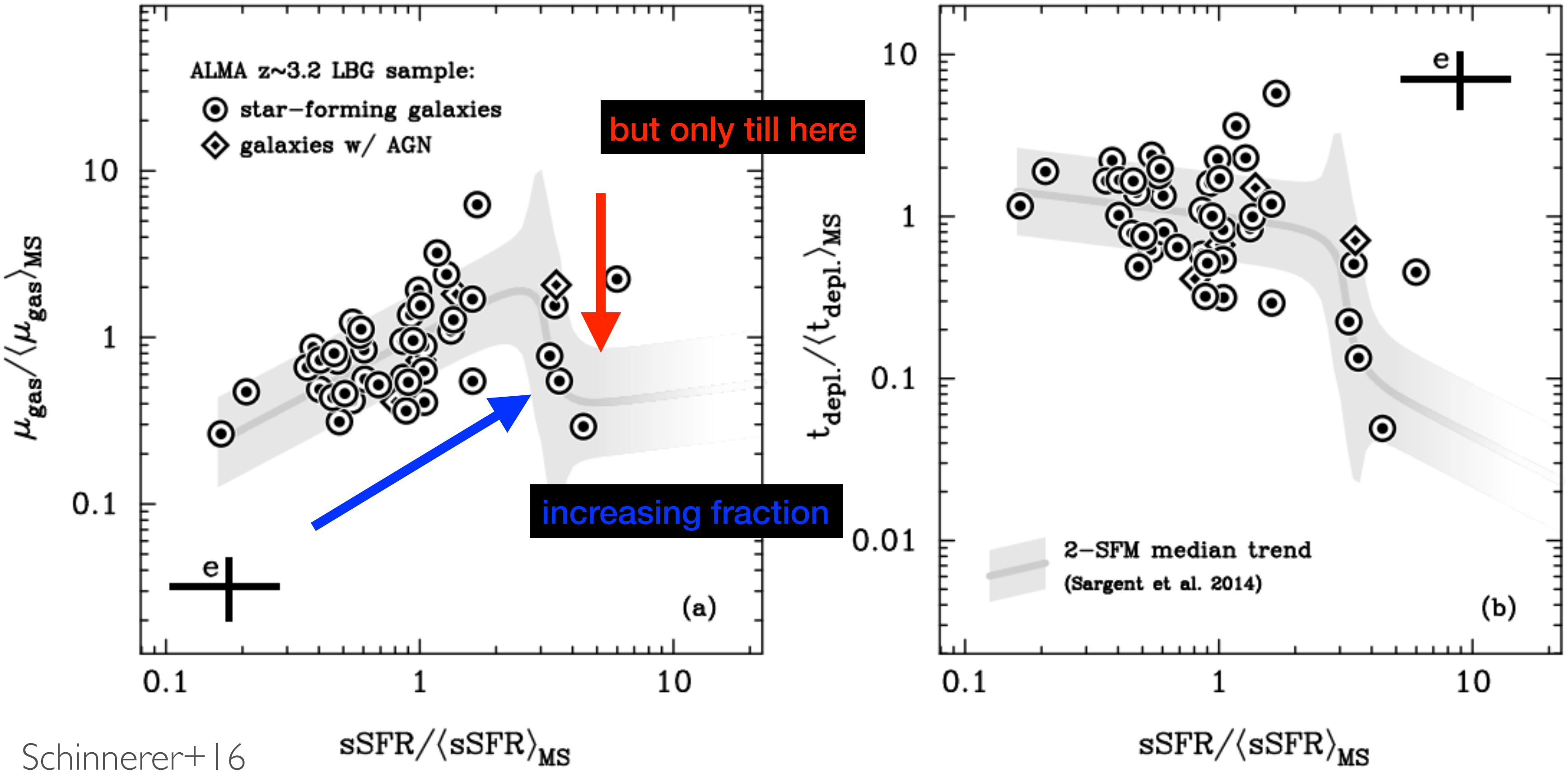
Molecular gas content of 45 MS star-forming galaxies at z~3.2



Schinnerer+16

$t_{depl} = M_{gas}/SFR$

Molecular gas fractions /
Gas depletion timescales vs distance from the SF main-sequence



but only till here

increasing fraction

Schinnerer+16

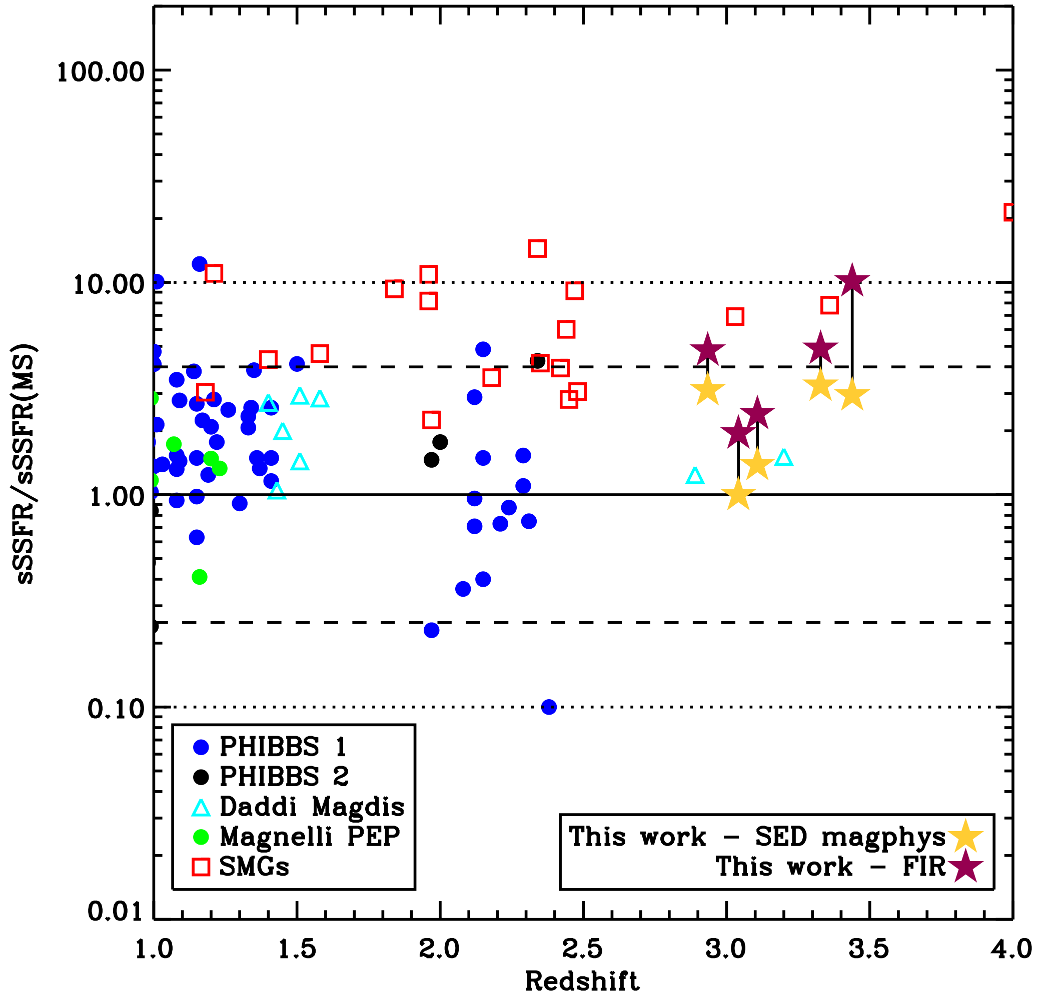
Redshift invariant relations (Sargent+14)

wrap up 1

- **Dust continuum** to estimate gas mass: **extremely fast** to gather large samples, **constrain the general trends**
- flattening of the gas fractions above z~2
- **redshift invariant** relations confirmed
- **gas fractions increase perpendicular to the MS**, but not indefinitely; SB galaxies probably do not have extreme gas fractions

NEXT STEP:

USE CO LINES



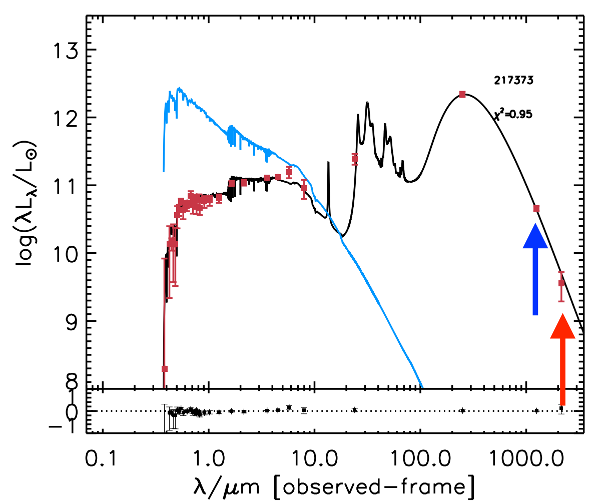
Target selection
5 highest S/N dust continuum
from Schinnerer+16

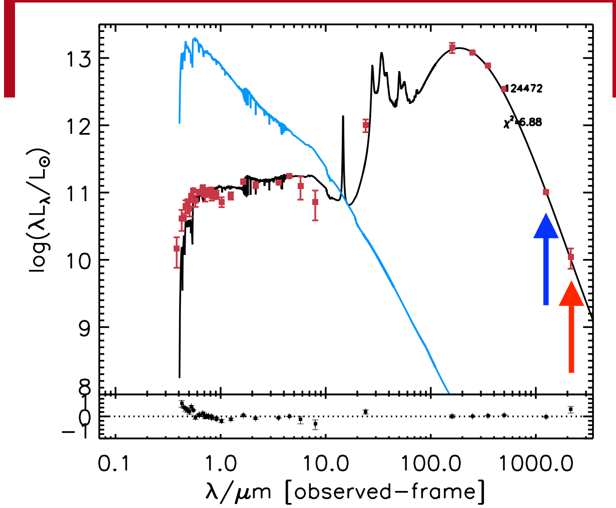
ALMA observations

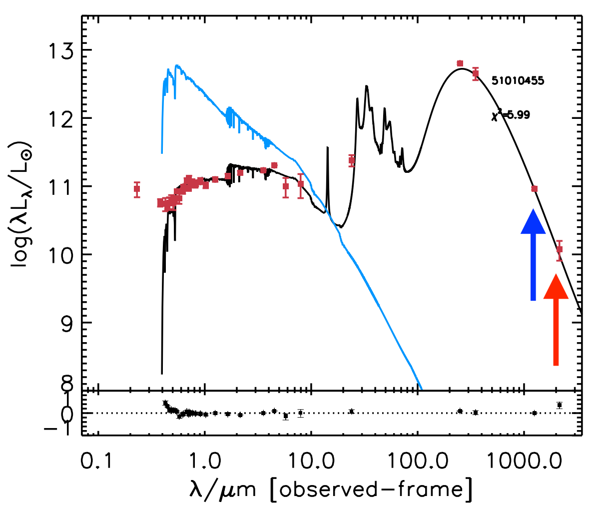
- Cycle3-4, PI: Cassata
- 4.4h total, 2.2h on target
- band3 & band4
- CO(5-4)&CO(4-3) [CO(3-2 for one]
- 0.6” resolution

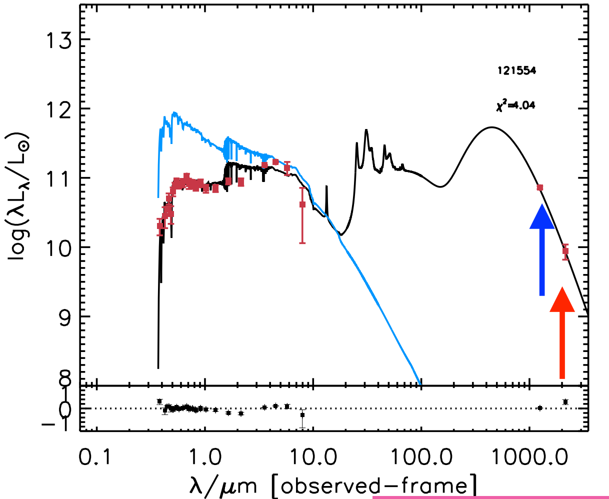
Exploit spectro-z catalogs to target specific sub-mm lines

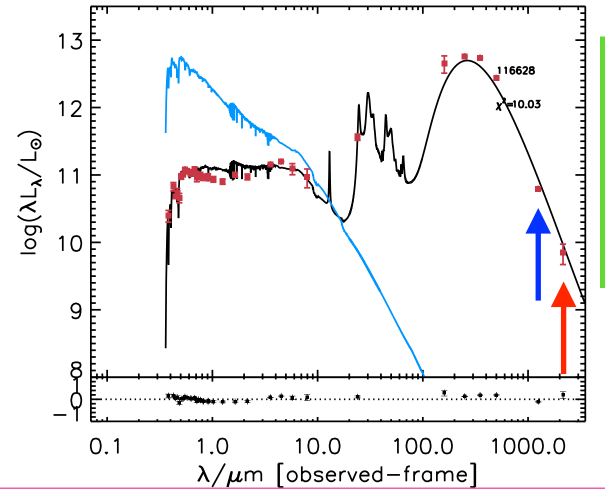
Panchromatic view











band 6: gas mass 10^{11}-$10^{11.2}$ $M_\odot$

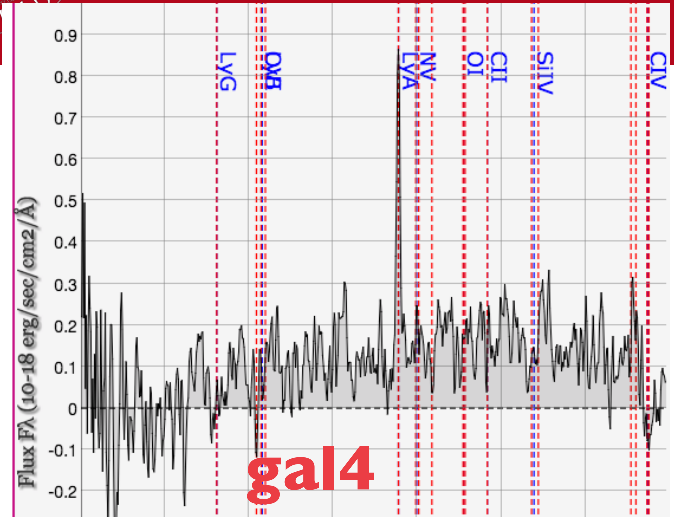
band 4: within ± 20%
band 6

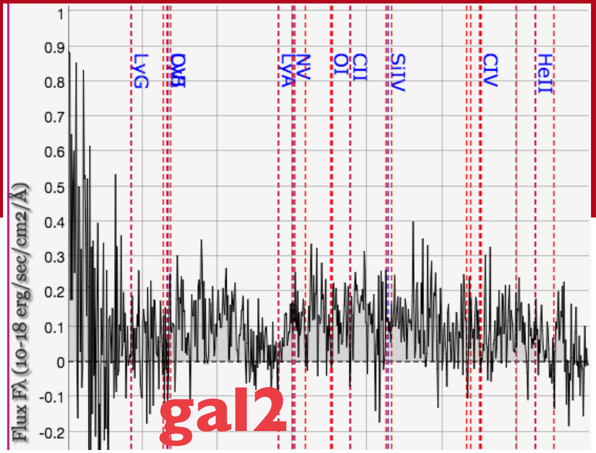
T_{depl} 0.3-2 Gyr

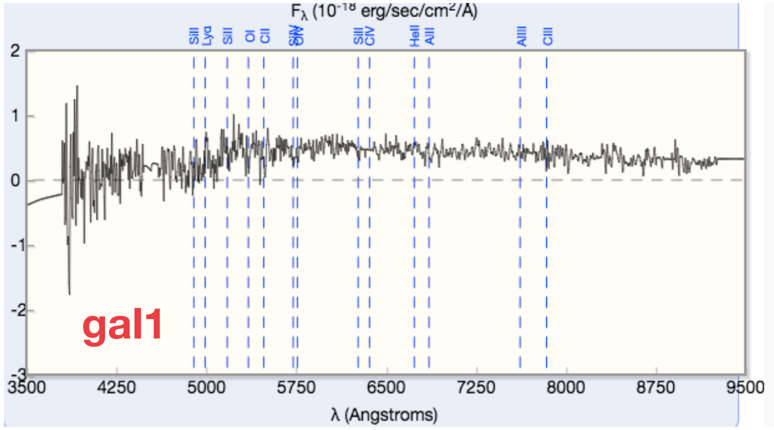
M_{gas}/M_{tot} 65-85%

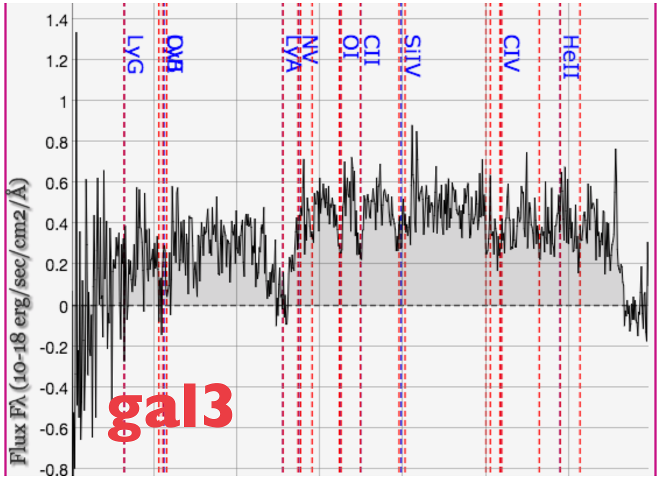
the largest sample of MS galaxies with CO detections at z>3

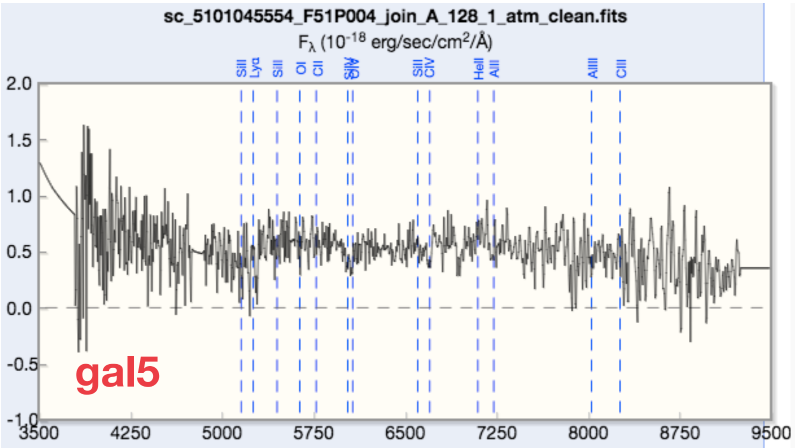
the largest sample of MS galaxies with multiple CO detections at z>2


Flux Fλ (10-18 erg/sec/cm2/Å)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
LyG
OVI
LYA
NV
OI
CII
SiIV
CIV
gal4

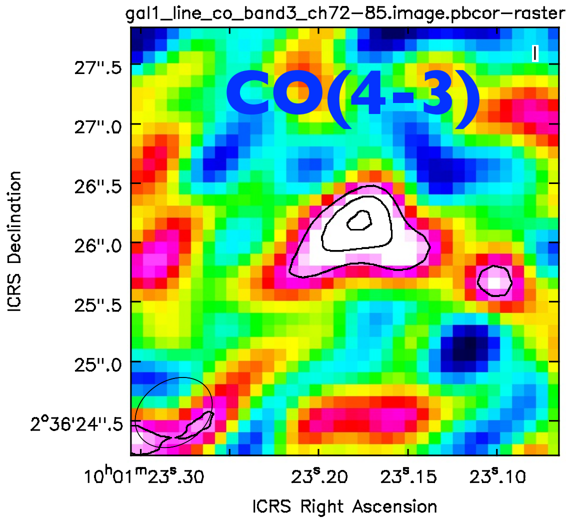

Flux Fλ (10-18 erg/sec/cm2/Å)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
LyG
OVI
LYA
NV
OI
CII
SiIV
CIV
HeII
gal2

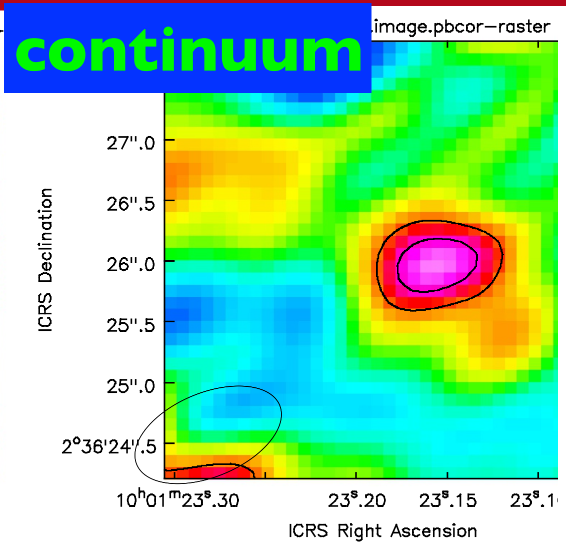

Fλ (10-18 erg/sec/cm²/Å)
SiII
Lyα
SiII
OI
CII
SiIV
SiII
CIV
HeII
AlII
AlIII
CIII
2
1
0
-1
-2
-3
3500
4250
5000
5750
6500
7250
8000
8750
9500
λ (Angstroms)
gal1

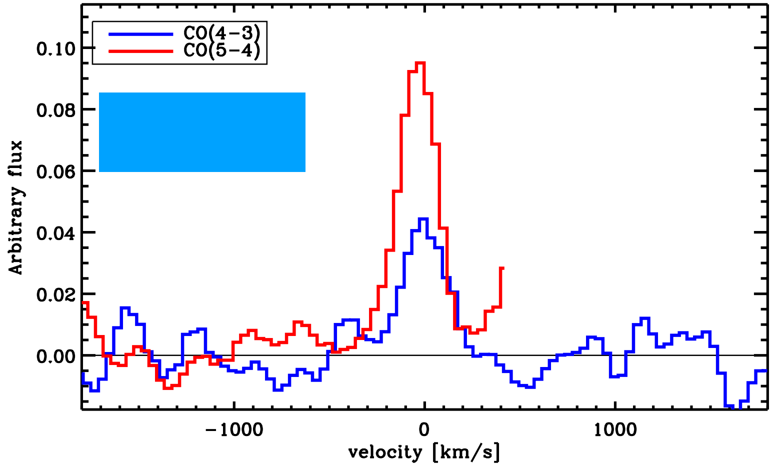

Flux Fλ (10-18 erg/sec/cm2/Å)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
LyG
OVI
LYA
NV
OI
CII
SiIV
CIV
HeII
gal3

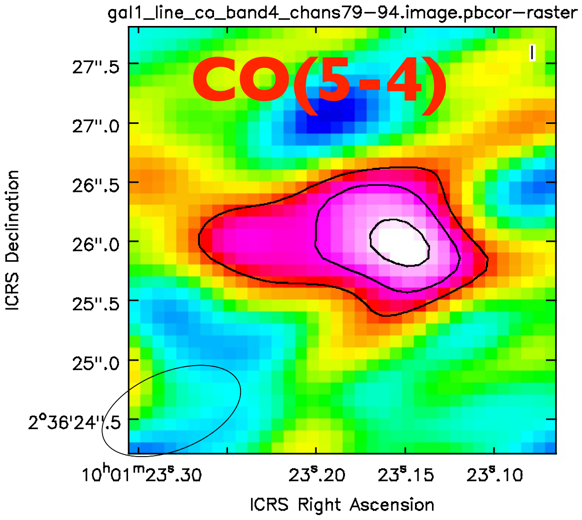

sc_5101045554_F51P004_join_A_128_1_atm_clean.fits
Fλ (10-18 erg/sec/cm²/Å)
SiII
Lyα
SiII
OI
CII
SiIV
SiII
CIV
HeII
AlII
AlIII
CIII
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
3500
4250
5000
5750
6500
7250
8000
8750
9500
gal5

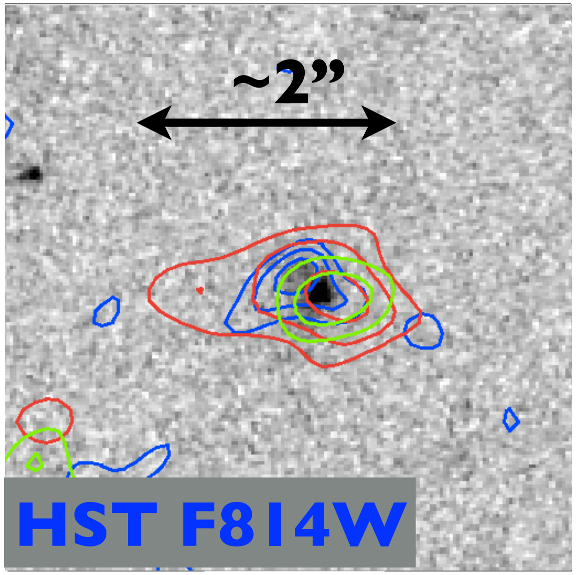
Gal 1

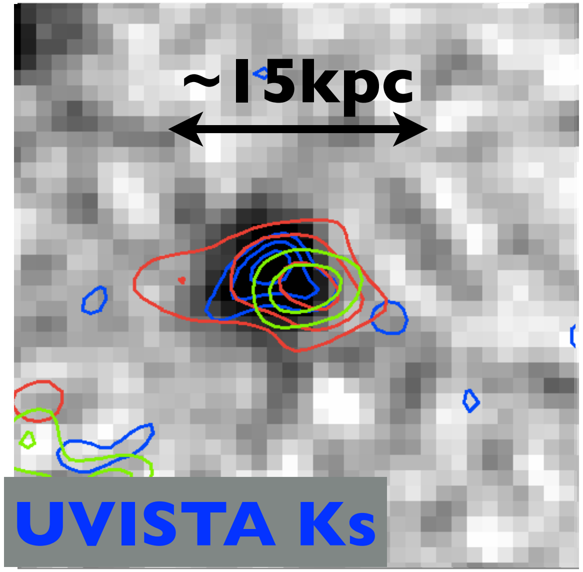

gal1_line_co_band3_ch72–85.image.pbcor–raster
CO(4-3)
27".5
27".0
26".5
26".0
25".5
25".0
2°36'24".5
ICRS Declination
10ʰ01ᵐ23ˢ.30
23ˢ.20
23ˢ.15
23ˢ.10
ICRS Right Ascension


continuum
.image.pbcor–raster
27".0
26".5
26".0
25".5
25".0
2°36'24".5
ICRS Declination
10ʰ01ᵐ23ˢ.30
23ˢ.20
23ˢ.15
23ˢ.1
ICRS Right Ascension

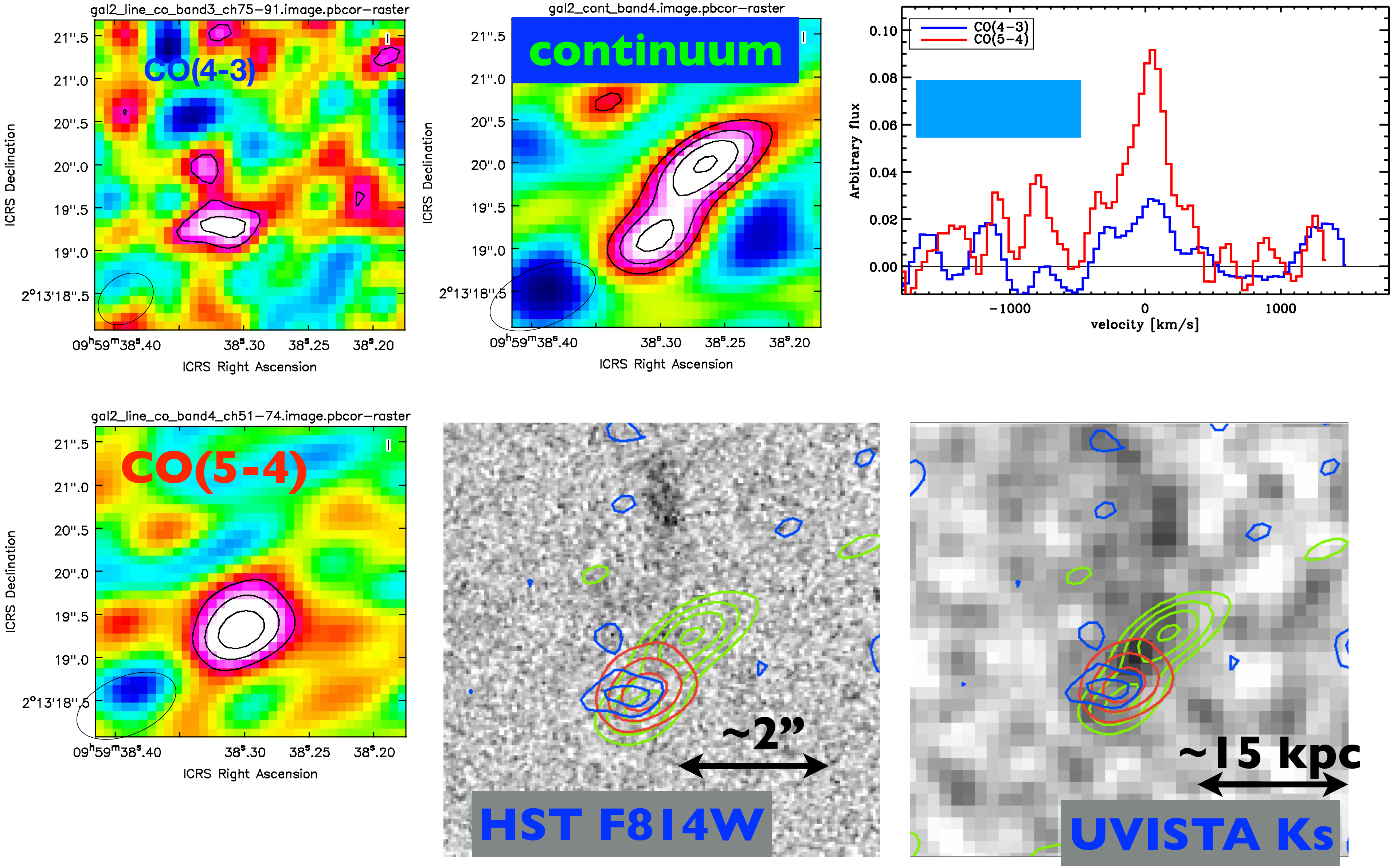

CO(4–3)
CO(5–4)
0.10
0.08
0.06
0.04
0.02
0.00
Arbitrary flux
–1000
0
1000
velocity [km/s]


gal1_line_co_band4_chans79–94.image.pbcor–raster
CO(5-4)
27".5
27".0
26".5
26".0
25".5
25".0
2°36'24".5
ICRS Declination
10ʰ01ᵐ23ˢ.30
23ˢ.20
23ˢ.15
23ˢ.10
ICRS Right Ascension

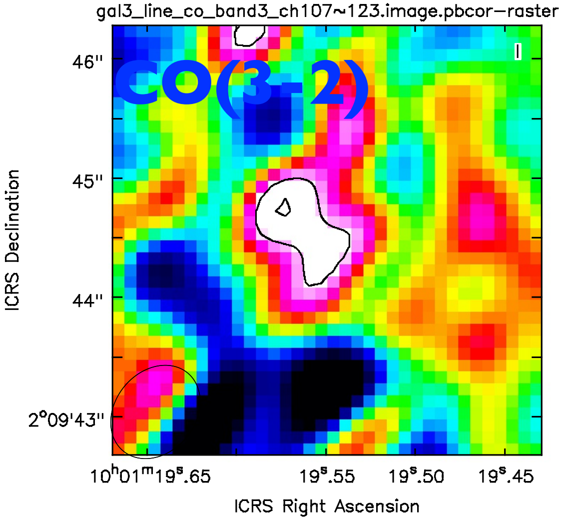

~2"
HST F814W

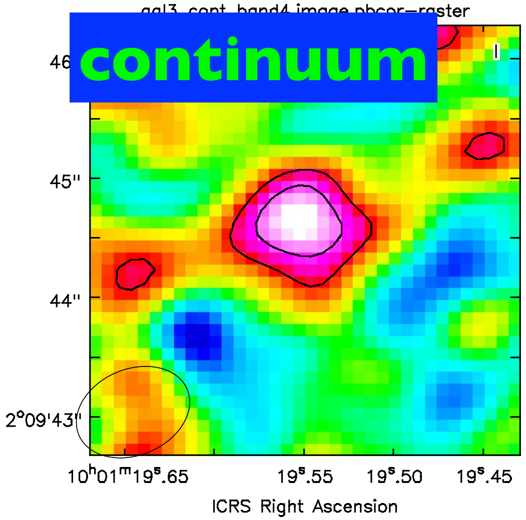

~15kpc
UVISTA Ks

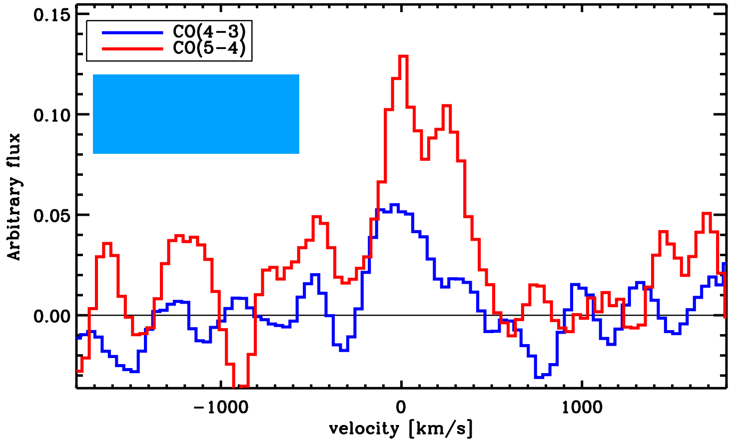
Gal 2

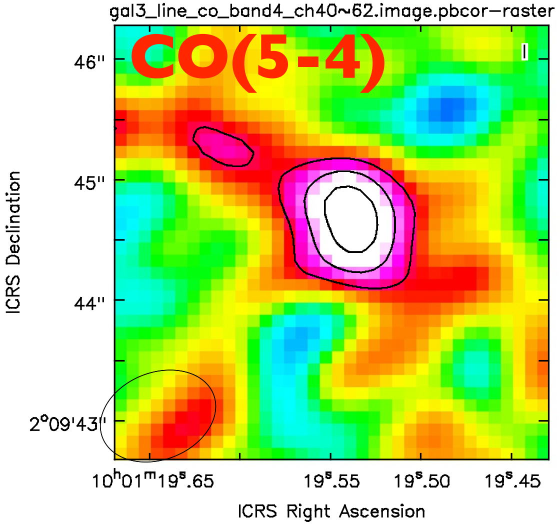

gal2_line_co_band3_ch75–91.image.pbcor–raster
CO(4-3)
21''.5
21''.0
20''.5
20''.0
19''.5
19''.0
2°13'18''.5
ICRS Declination
09h59m38s.40
38s.30
38s.25
38s.20
ICRS Right Ascension
gal2_cont_band4.image.pbcor–raster
continuum
gal2_line_co_band4_ch51–74.image.pbcor–raster
CO(5-4)
CO(4–3)
CO(5–4)
Arbitrary flux
0.10
0.08
0.06
0.04
0.02
0.00
–1000
0
1000
velocity [km/s]
~2''
HST F814W
~15 kpc
UVISTA Ks

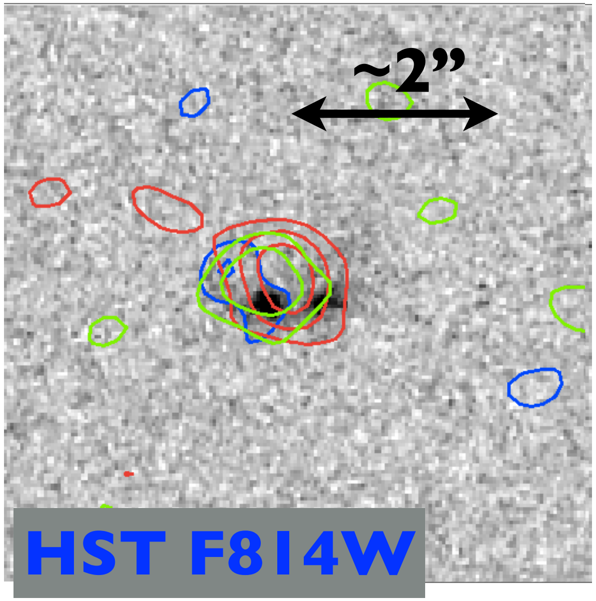
Gal 3

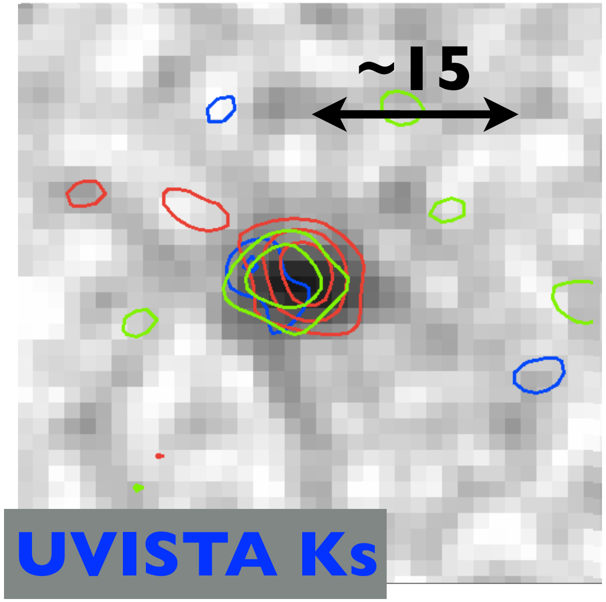

gal3_line_co_band3_ch107~123.image.pbcor–raster
CO(3-2)
46"
45"
44"
2°09'43"
ICRS Declination
10h01m19s.65
19s.55
19s.50
19s.45
ICRS Right Ascension


gal3_cont_band4.image.pbcor–raster
continuum
46"
45"
44"
2°09'43"
10h01m19s.65
19s.55
19s.50
19s.45
ICRS Right Ascension


CO(4–3)
CO(5–4)
0.15
0.10
0.05
0.00
Arbitrary flux
−1000
0
1000
velocity [km/s]


gal3_line_co_band4_ch40~62.image.pbcor–raster
CO(5-4)
46"
45"
44"
2°09'43"
ICRS Declination
10h01m19s.65
19s.55
19s.50
19s.45
ICRS Right Ascension


~2"
HST F814W


~15
UVISTA Ks

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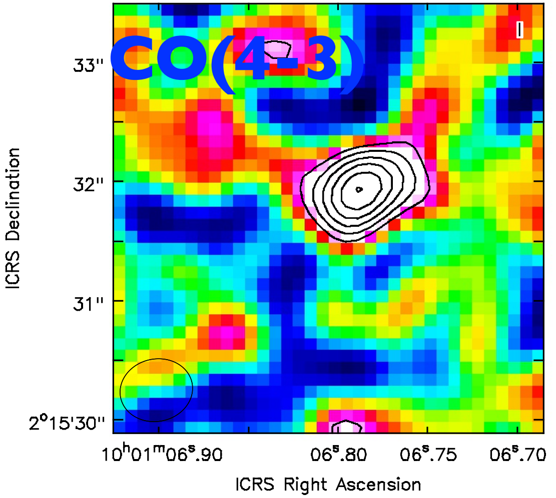
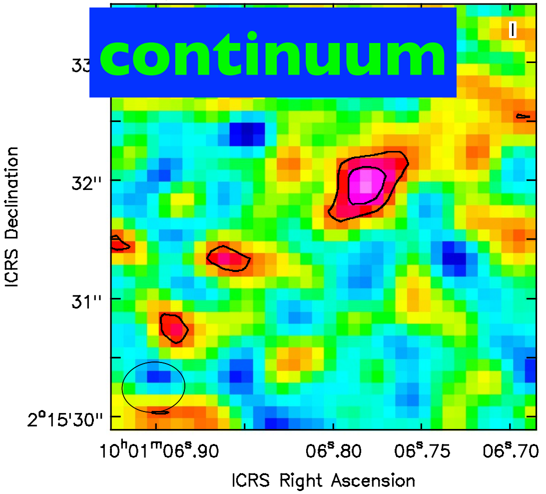
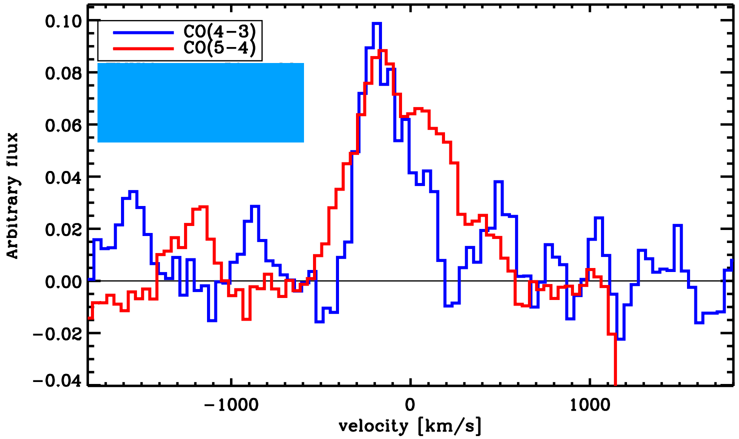
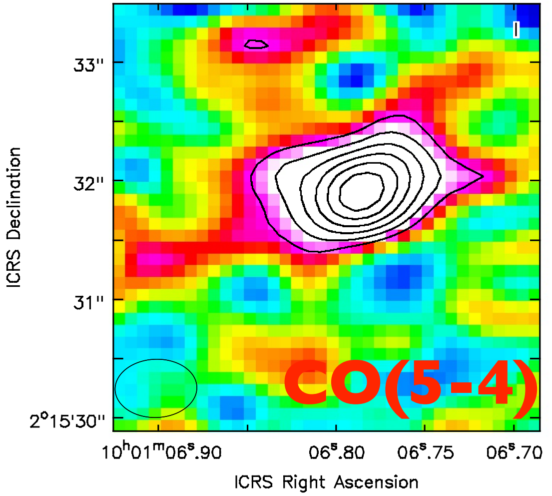
DI PADOVA

Gal 4


gal4_line_co_band3_ch72–87.image.pbcor–raster


gal4_cont_band4.image.pbcor–raster

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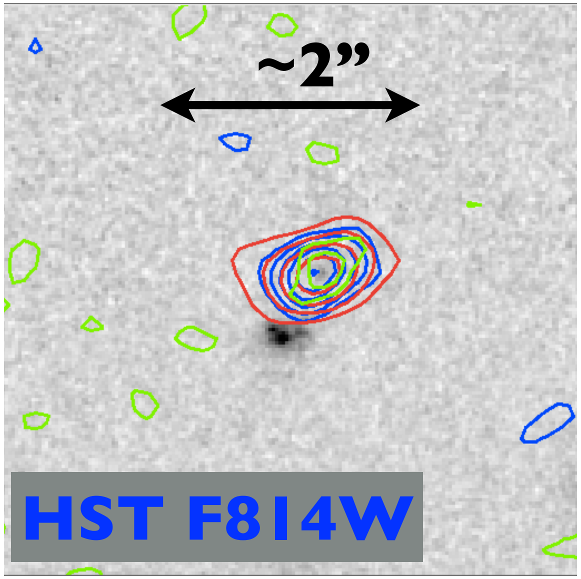
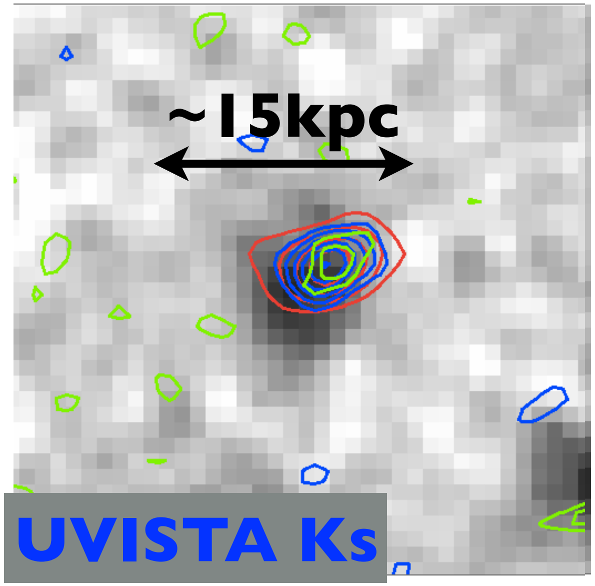
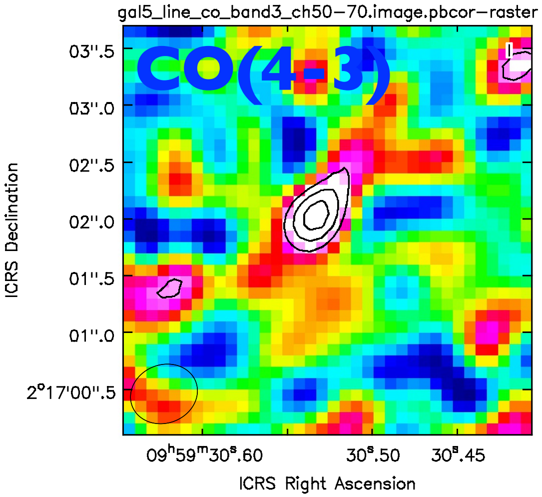
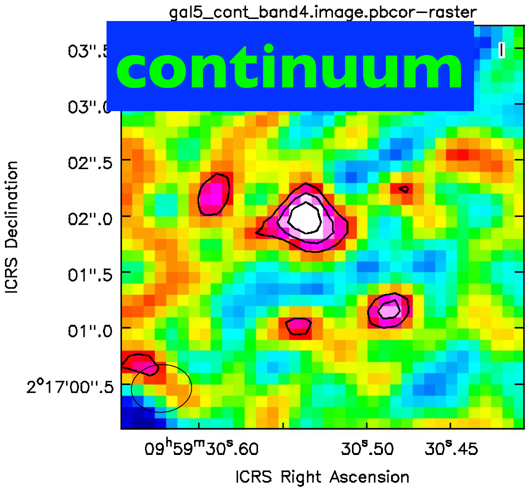
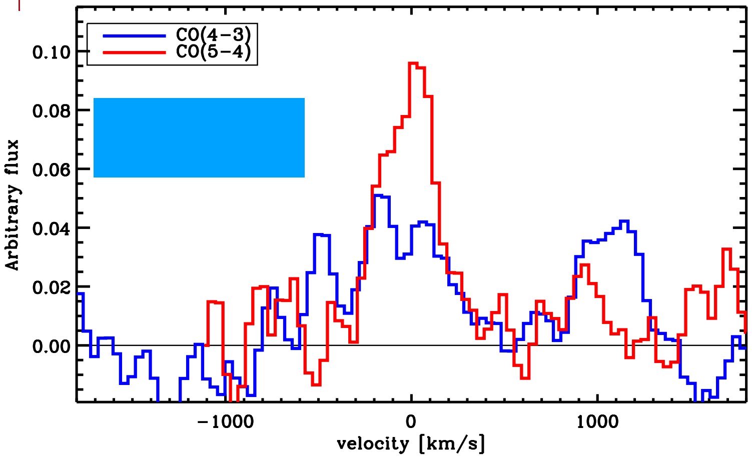


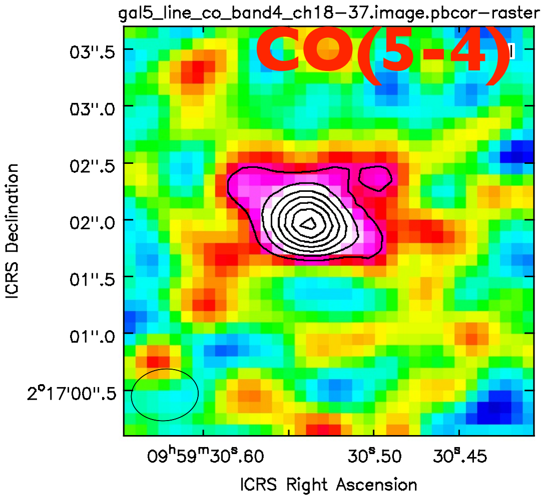


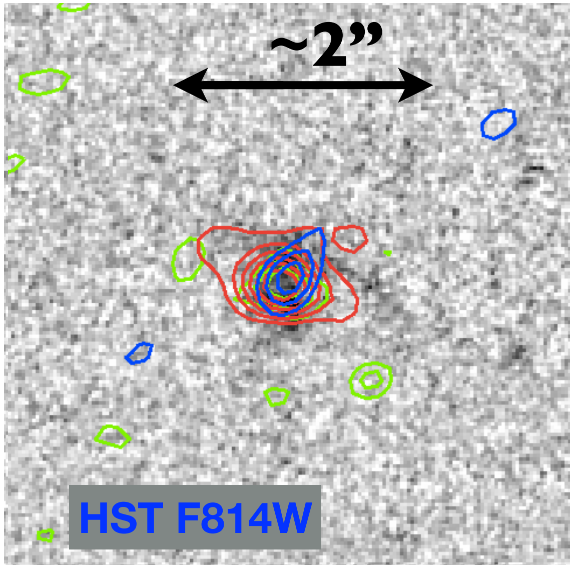
Gal 5

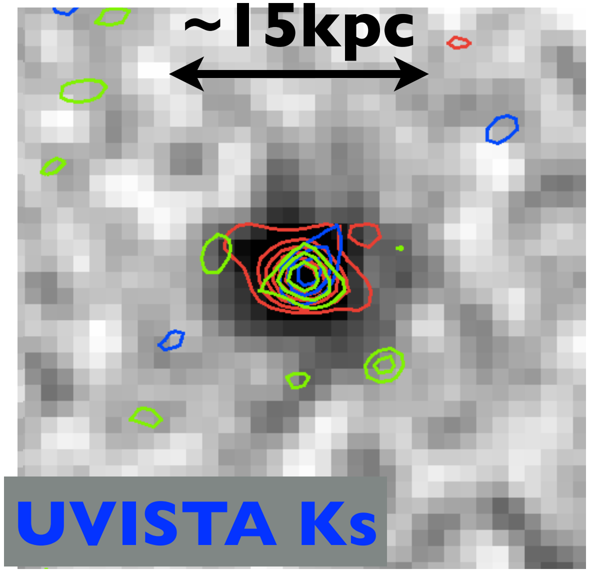

gal5_line_co_band3_ch50–70.image.pbcor–raster
CO(4-3)
03''.5
03''.0
02''.5
02''.0
01''.5
01''.0
2°17'00''.5
ICRS Declination
09h59m30s.60
30s.50
30s.45
ICRS Right Ascension


gal5_cont_band4.image.pbcor–raster
continuum
03''.5
03''.0
02''.5
02''.0
01''.5
01''.0
2°17'00''.5
ICRS Declination
09h59m30s.60
30s.50
30s.45
ICRS Right Ascension


CO(4–3)
CO(5–4)
0.10
0.08
0.06
0.04
0.02
0.00
Arbitrary flux
–1000
0
1000
velocity [km/s]

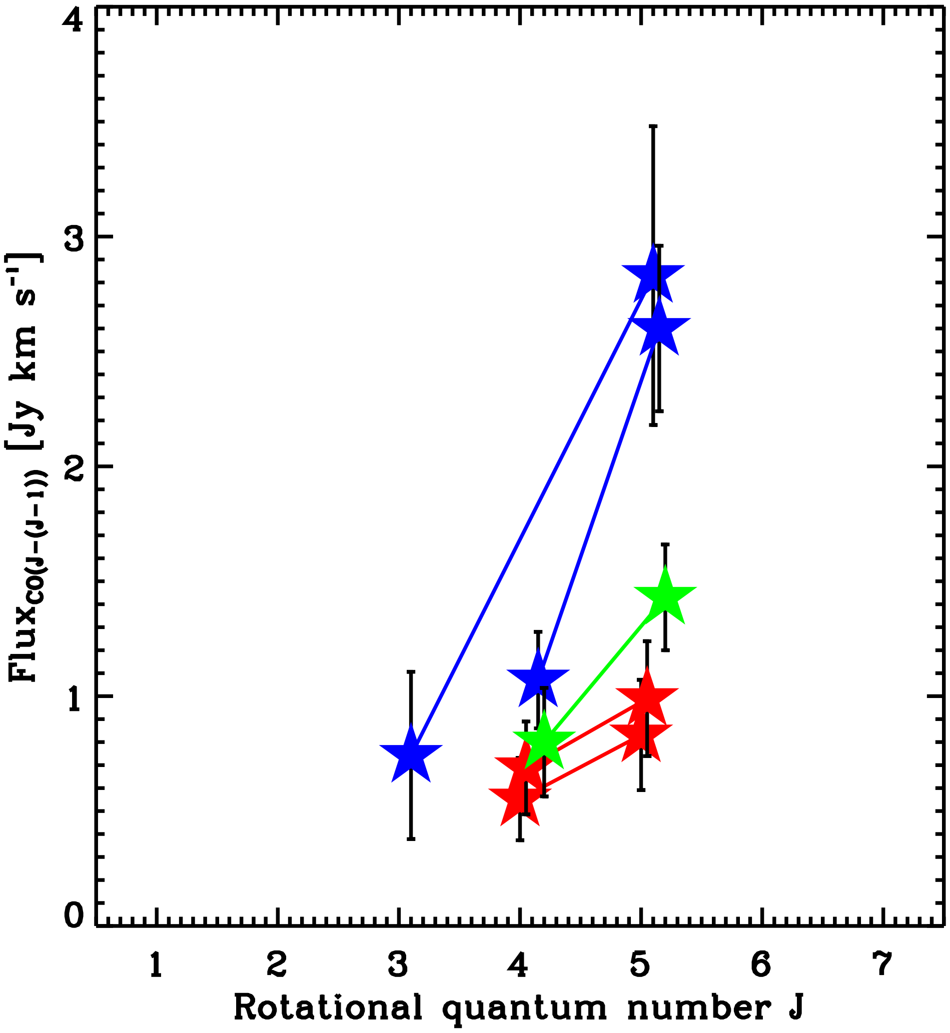

gal5_line_co_band4_ch18–37.image.pbcor–raster
CO(5-4)
03''.5
03''.0
02''.5
02''.0
01''.5
01''.0
2°17'00''.5
ICRS Declination
09h59m30s.60
30s.50
30s.45
ICRS Right Ascension

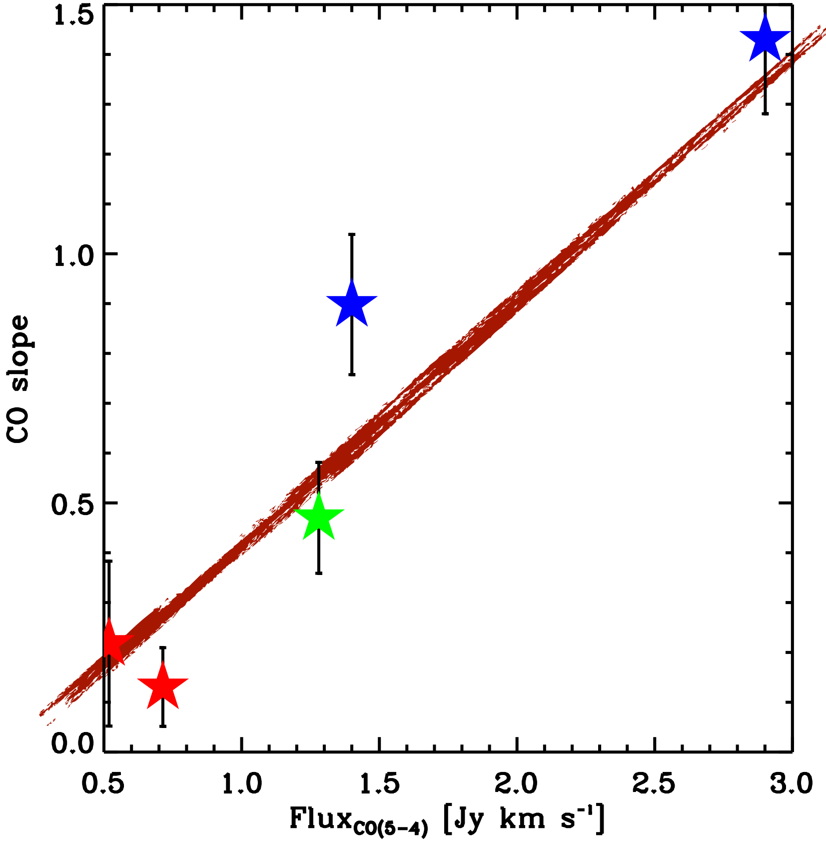

~2"
HST F814W


~15kpc
UVISTA Ks

- **CO(5-4)** detected at **>5σ** for all 5 galaxies
- **CO(4-3) (or CO(3-2))** detected at **>3σ** for all galaxies
- **500μm rest-frame continuum** detected at **>3σ** for all 5 galaxies
- (marginally) **spatially extended**
- **FWHM(lines) ~200-600 km/s**, with tails up to 1000 km/s
- Large **spatial offsets** between ALMA lines, ALMA continuum and optical/NIR
- Offsets also between CO transitions? probing different phases?
- Pair/merger/compact morphology

CO fluxes





CO slopes

the higher CO(5-4) flux, the steeper the slopes

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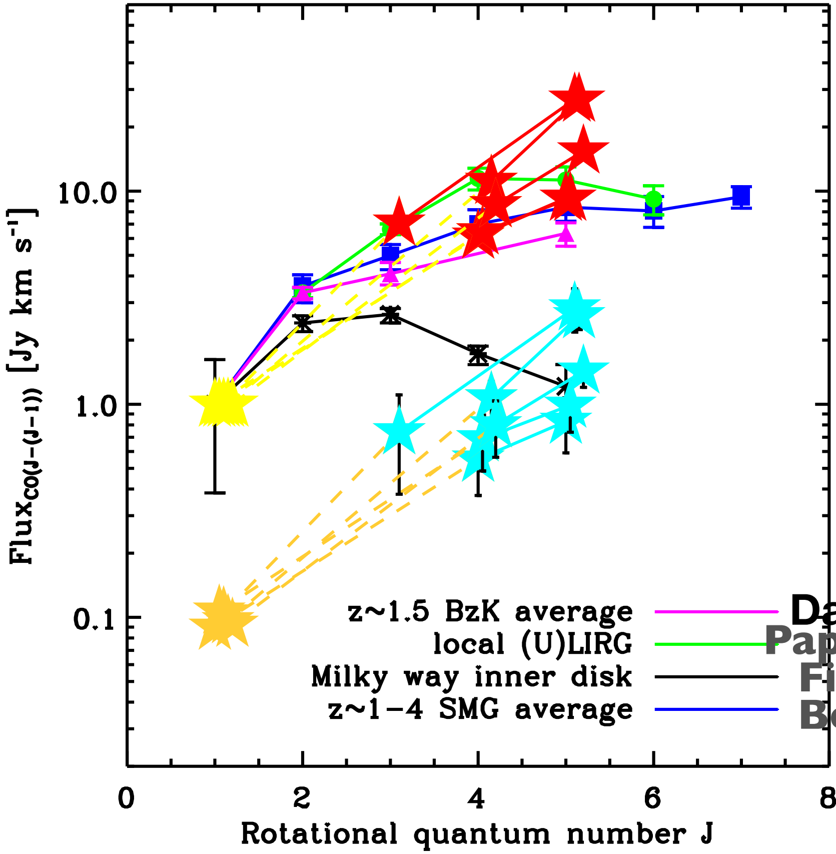
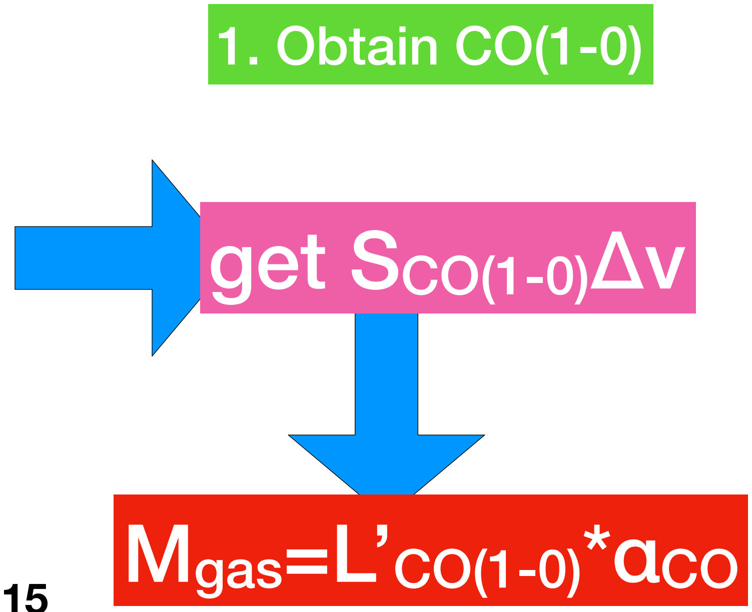
di Padova

CO SLED:
Spectral Line Energy Distribution for CO lines



Daddi+15
Papadopulos+12
Fixsen+99
Bothwell+13



1. Obtain CO(1-0)

get $S_{CO(1-0)}\Delta v$

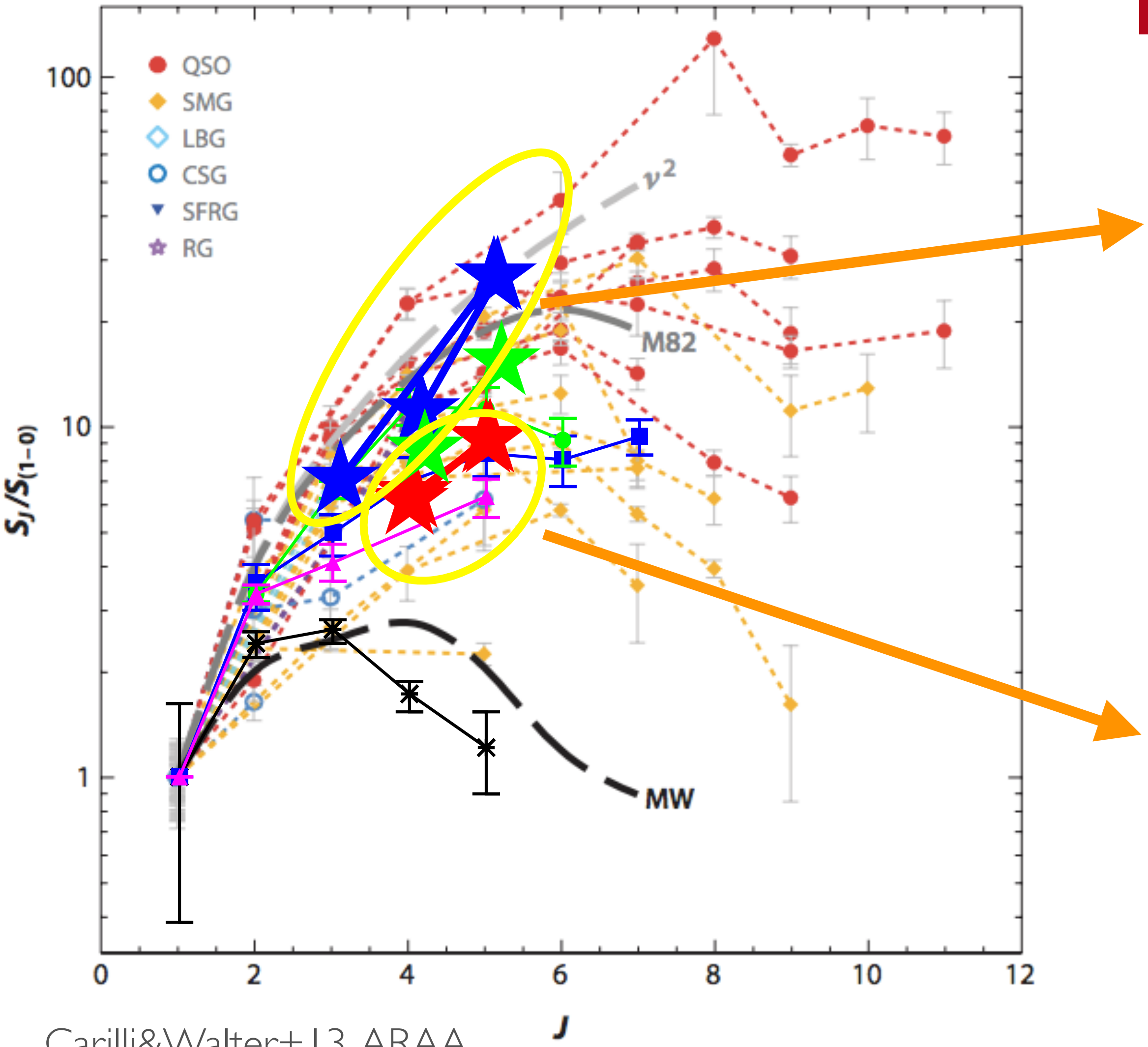
$M_{gas}=L'_{CO(1-0)}{}^{*}\alpha_{CO}$

Carilli&Walter+13, ARAA

α_{CO} =3.7 [Tacconi+18 recipe]

CO SLED

2. Constrain excitation source

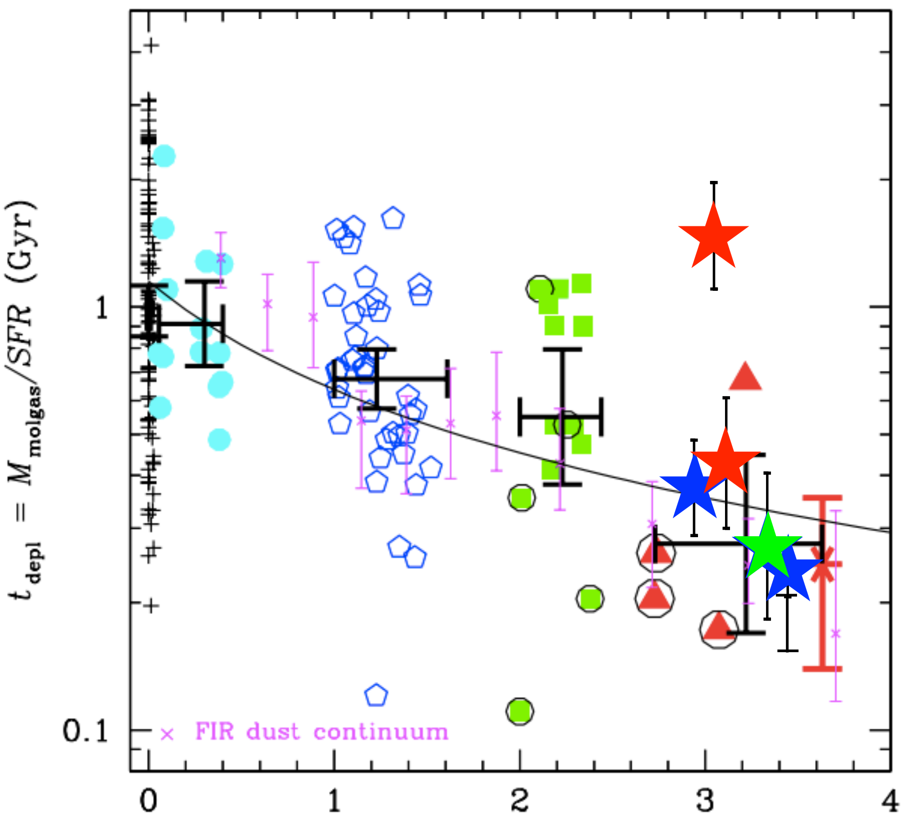


Carilli&Walter+13, ARAA

typical slope of more energetic objects, like QSO, starbursts

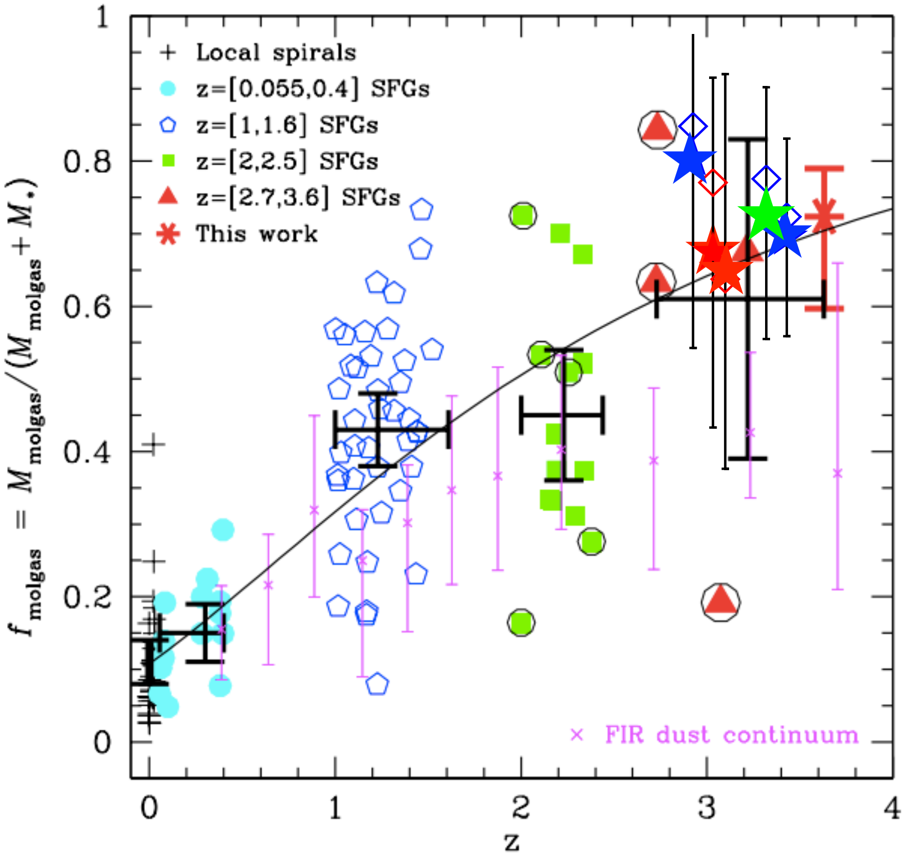
typical slopes of SMG/BzKs

tdepl=Mgas/SFR vs z

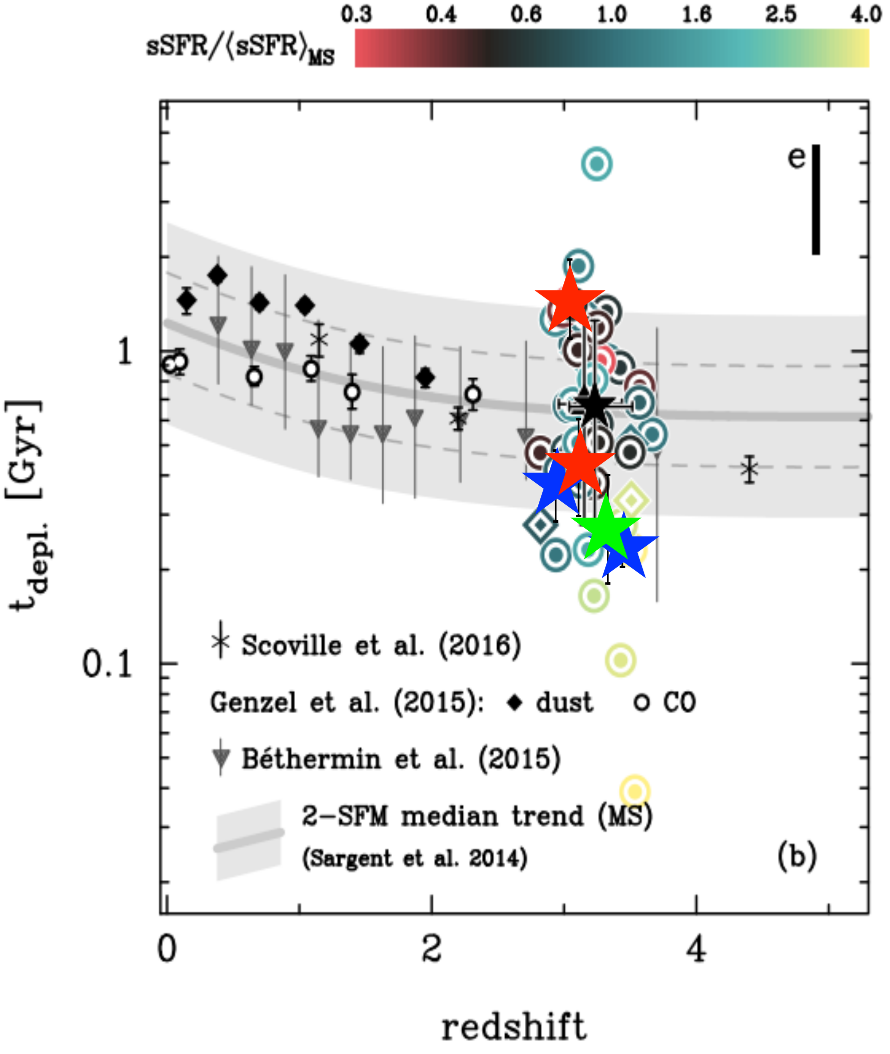


compilation by Dessauges-Zavadsky+17

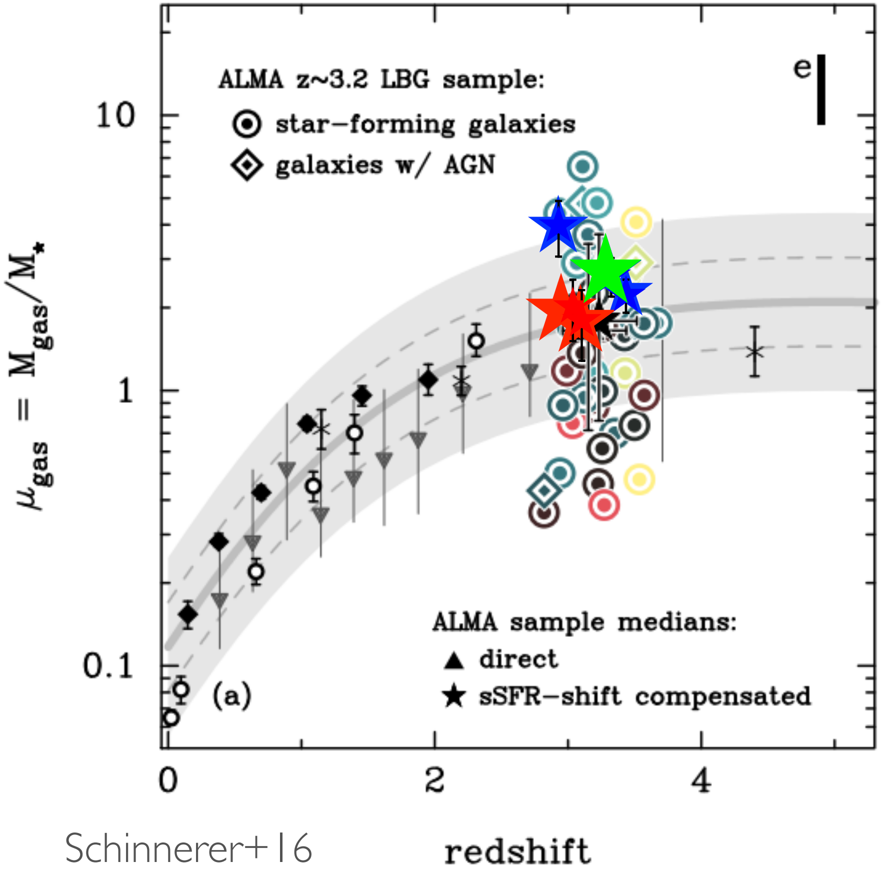
gas fractions vs z



tdepl=Mgas/SFR vs z

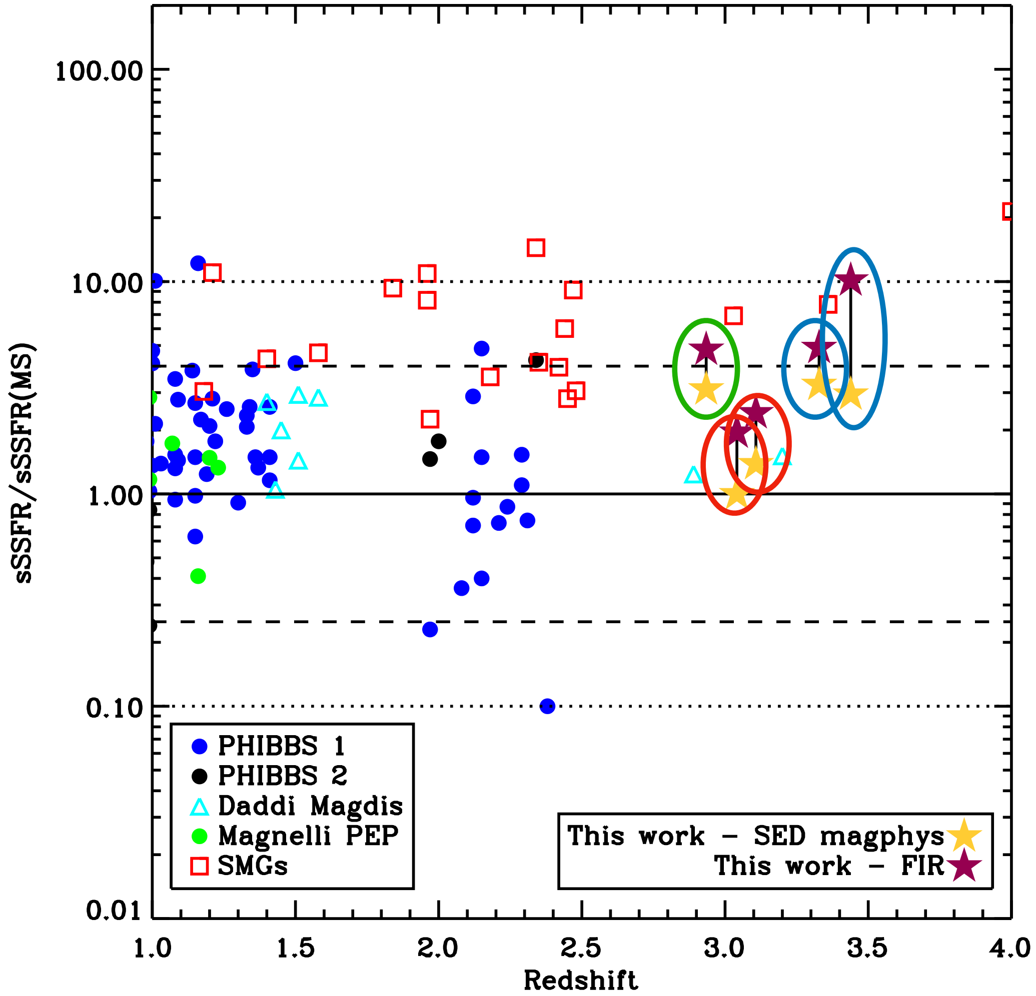


μgas vs z



Schinnerer+16

Back to the main-sequence

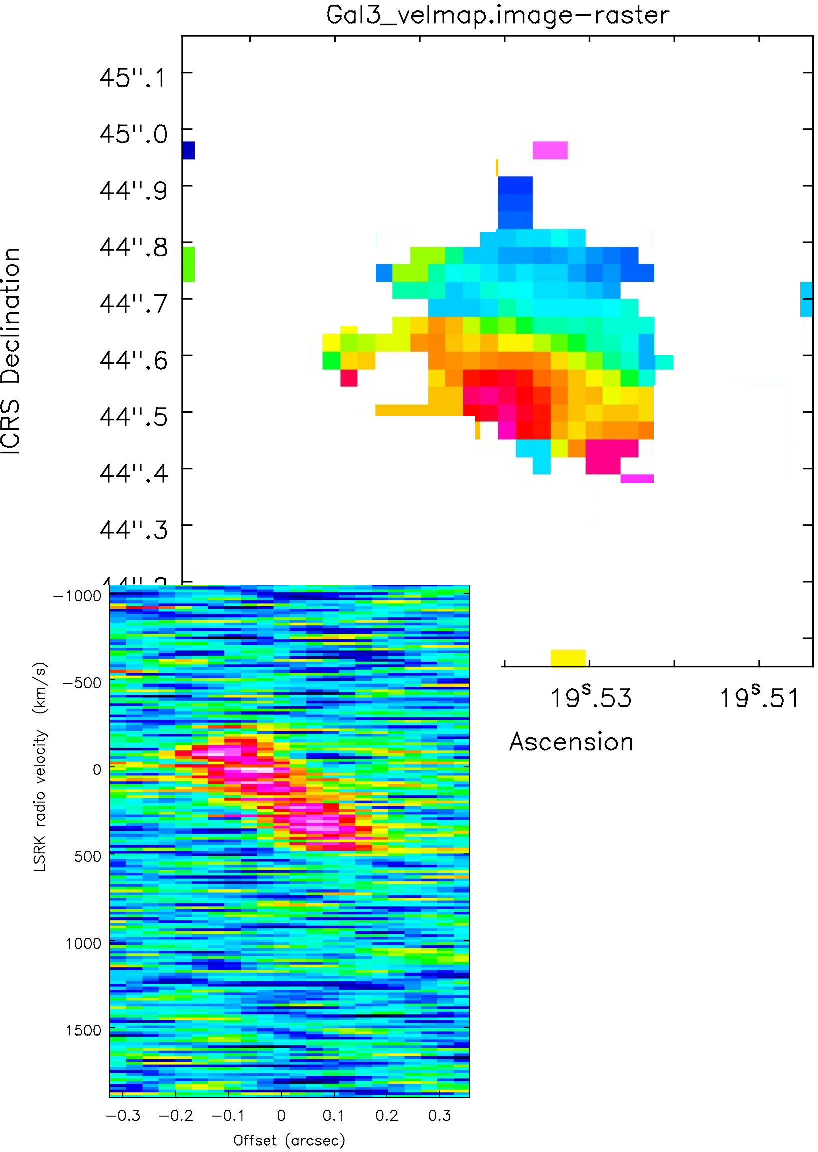


**Flatter SLED
(normal MS galaxies)**

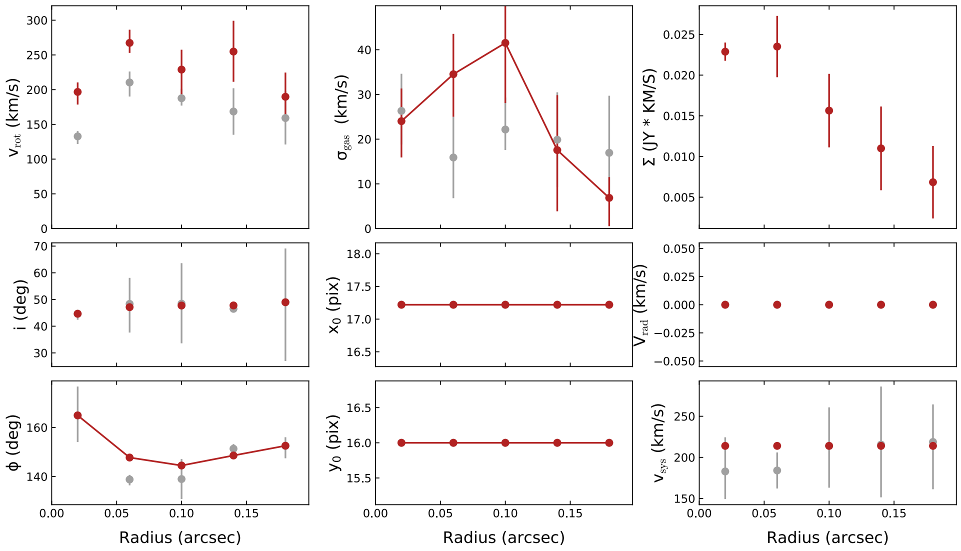
**Steeper SLED
(stronger exciting
source?)**

We have a correlation there: further from MS, steeper SLED, brighter CO(5-4)

Going to higher spatial resolution: resolving the kinematics

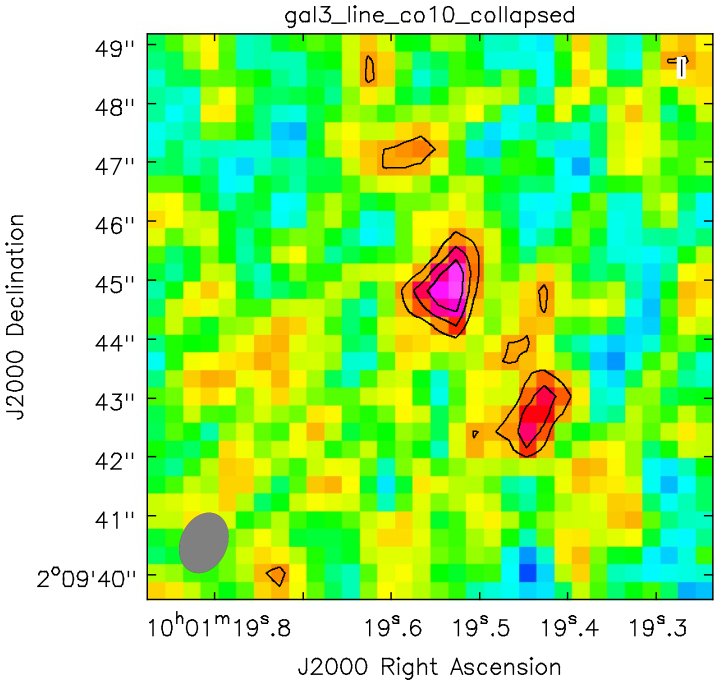


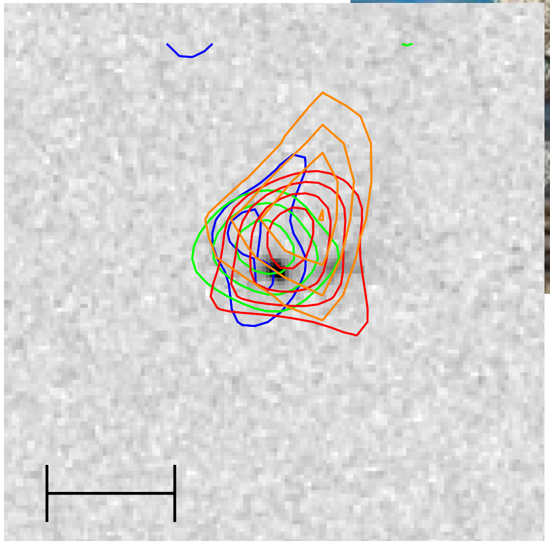
ALMA observations
- Cycle 5, PI: Cassata
- 22.4h total, 16.5h on target
- band4
- CO(5-4)
- C43-6 config: 0.2” resolution



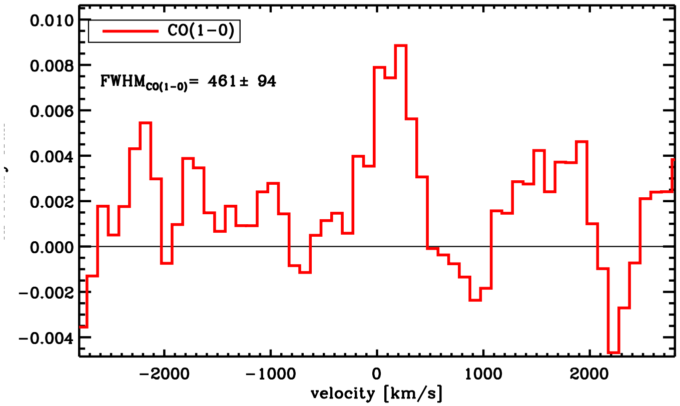
dynamical mass M_{dyn} =~ $1.6 \times 10^{11} M_\odot$

Going to JVLA: getting CO(1-0)





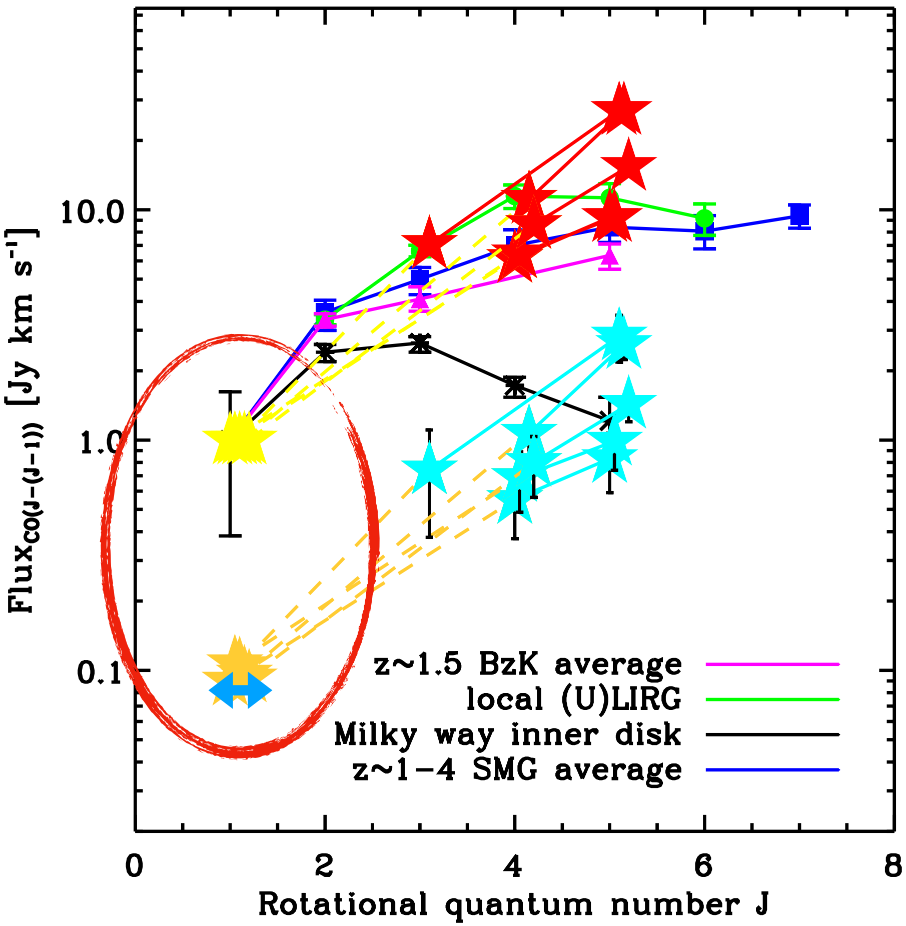
VLA CO(1-0)
ALMA CO(3-2)
ALMA CO(5-4)
ALMA band4 continuum



VLA observations

- 2018B semester
- 35h total, 3h/object on target
- band K/Ka 20-30 GHz
- CO(1-0)
- 1” beam resolution

Mass balance



$S_{CO(1-0)}\Delta v$=0.08 Jy km/s

using α_{CO}=3.7

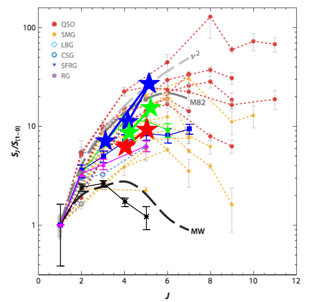
M_{gas}=1.16x10^{11} $M_\odot$

M_{dyn} =~ 1.6x$10^{11}M_\odot$

M_* =~ 3.1x$10^{10}M_\odot$

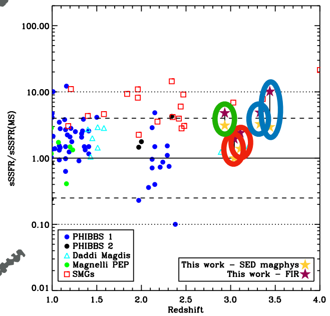
$M_{gas}+M_*$=1.47x$10^{11}M_\odot \approx M_{dyn}$

constraint on α_{CO} at z~3 for a MS galaxy

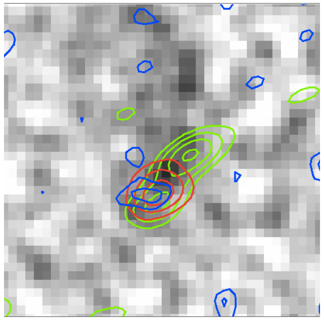


- gas masses from **dust continuum vs CO** in good **agreement**

- **Diversity** of CO **SLEDs**:
  - 2 galaxies seem **normal MS galaxies**; medium-long gas depletion timescale, large gas reservoir
  - 3 other galaxies powered by a more energetic source; possibly obscured **QSO**? **Mergers/Starbursts** on the MS?

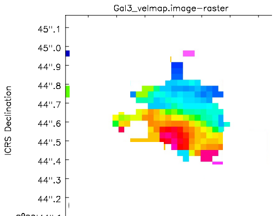


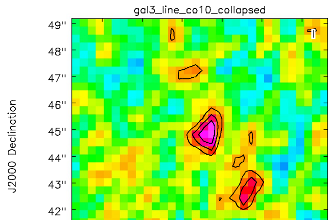
- Objects **more offset** from the main-sequence, **steeper SLED, stronger CO(5-4)**



- **Offsets** between ALMA and optical/NIR, and also between two CO transitions, and between CO and continuum: multiple components?

- $M_{gas}+M_{*}\approx M_{dyn}$: **constraint on α_{CO}**





Going at $z > 4$

A2C2S | ALMA ALPINE [CII] Survey

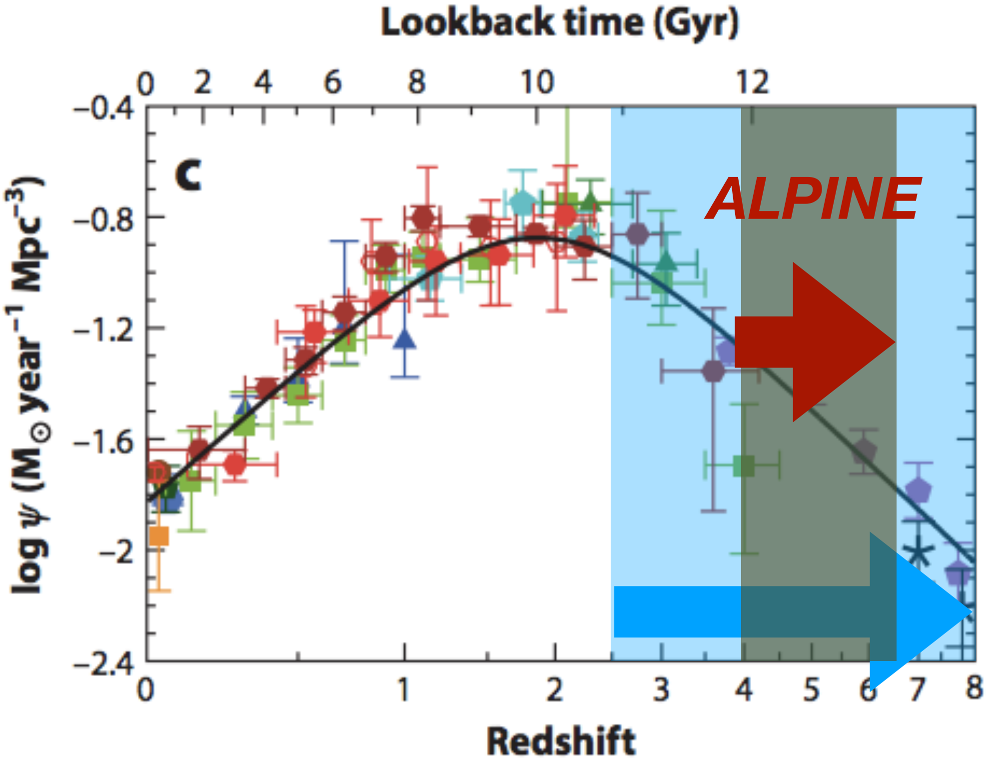
A2C2S: The ALMA ALPINE [CII] Survey

PI: Olivier Le Fèvre
Co-PIs: M. Bethermin, P. Capak, **P. Cassata**,
A. Faisst, D. Schaerer, J. Silverman, L. Yan

Co-Is: Amorin, Bardelli, Boquien, Cimatti, Dessauges-Zavadsky, Dunlop, Giavalisco, Hathi, Hemmati, Hughes, Ibar, Jones, Koekemoer, Lagache, Lemaux, Maiolino, Masters, Nagao, Narayanan, Oesch, Pavesi, Pforr, Pozzi, Riechers, Rujopakarn, Talia, Tasca, Thomas, Toft, Tresse, Vallini, Vergani, Walter, Wei-Hao Wang, Zamorani, Zucca

ALPINE: The ALMA Large Program to INvestigate CII at Early times

Motivation



SFRD(z)

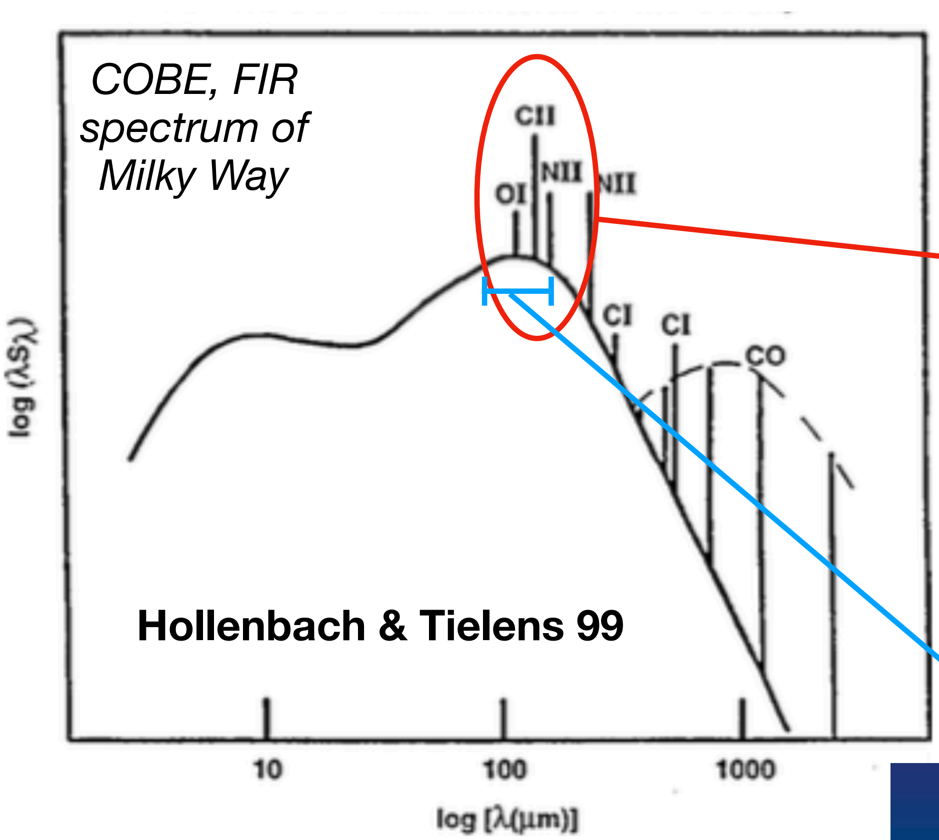
- increased by 10x in the first 3 Gyr after Big Bang
- peak z ~ 2
- decreased by 10x since

Based on UV only

We have a biased view of the Universe at z > 3

What is ALPINE ?

ALMA LP: 70h cycle 5



COBE, FIR spectrum of Milky Way

Hollenbach & Tielens 99

[CII] line:

- one of the main coolants for the ISM
- brightest FIR line: L[CII]/L[FIR]~0.1-0.3%
- can be brighter than Lyα
- in the sub-mm/mm range at 4.5<z<9

Traces SF?

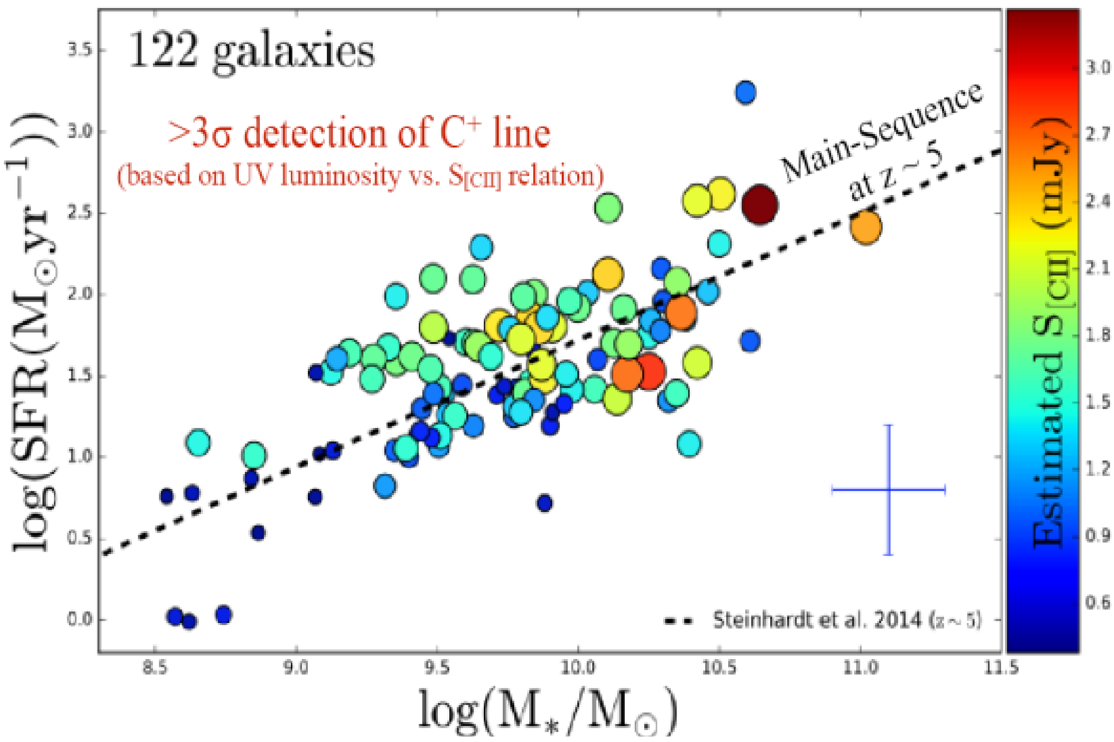
158 μm rest-frame:

- traces the peak of the dust thermal emission
- *not a gas/dust tracer!*

Dust obscured star-formation

What kind of galaxies ?

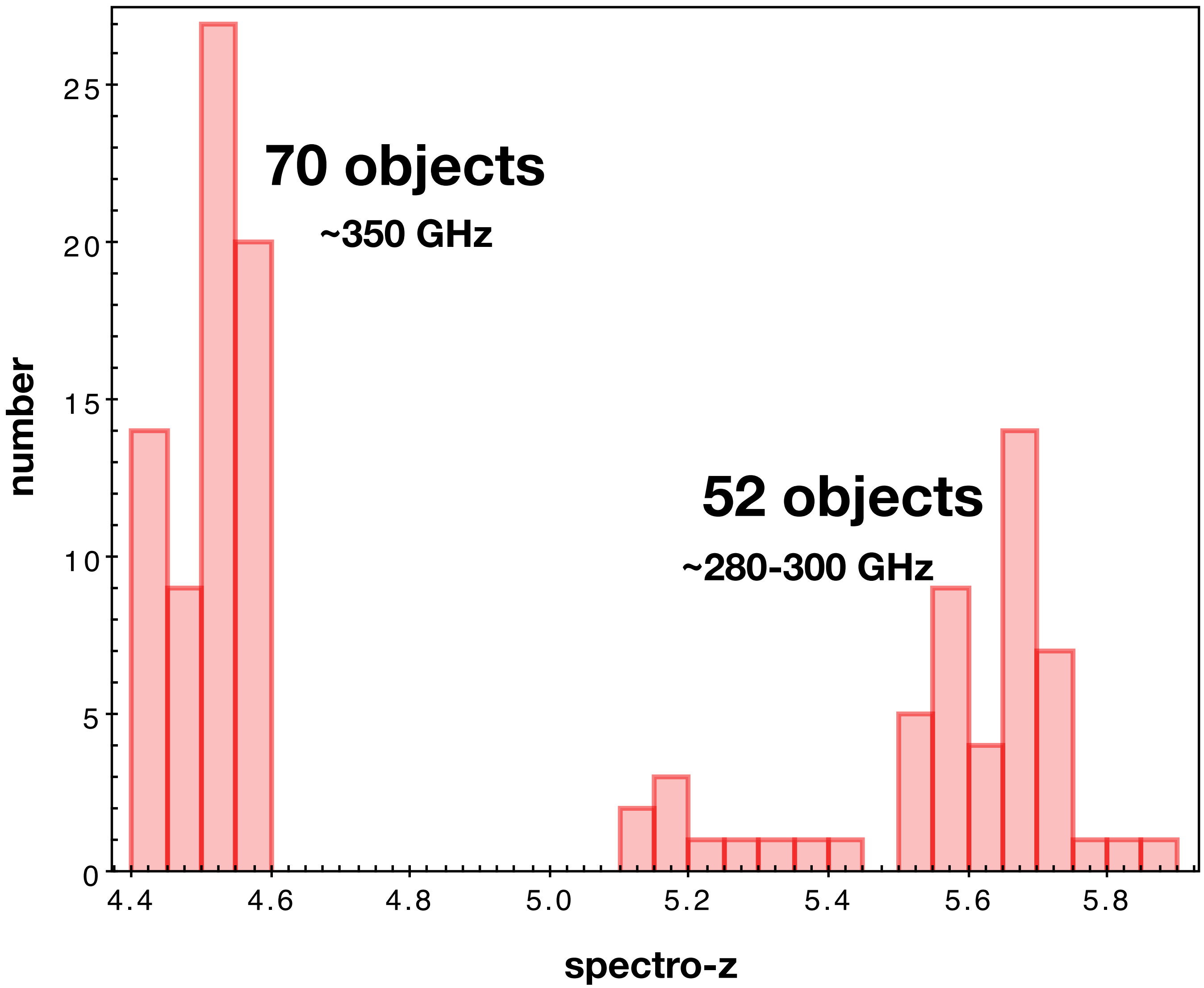
Targeted approach: complementary (and more efficient) than blind surveys



90% of the SFRD in MS galaxies

- 122 main sequence galaxies
- 4 < z < 6: ***primordial Universe***
- ***spectro-z*** from DEIMOS & VIMOS: to set CII in the ALMA band
- COSMOS, ECDFS fields: wealth of ancillary data (including ***CANDELS*** H-band for ~25% of sample)
- ***blind survey*** (~10 arcmin^2) for free

Redshift distribution



70 objects

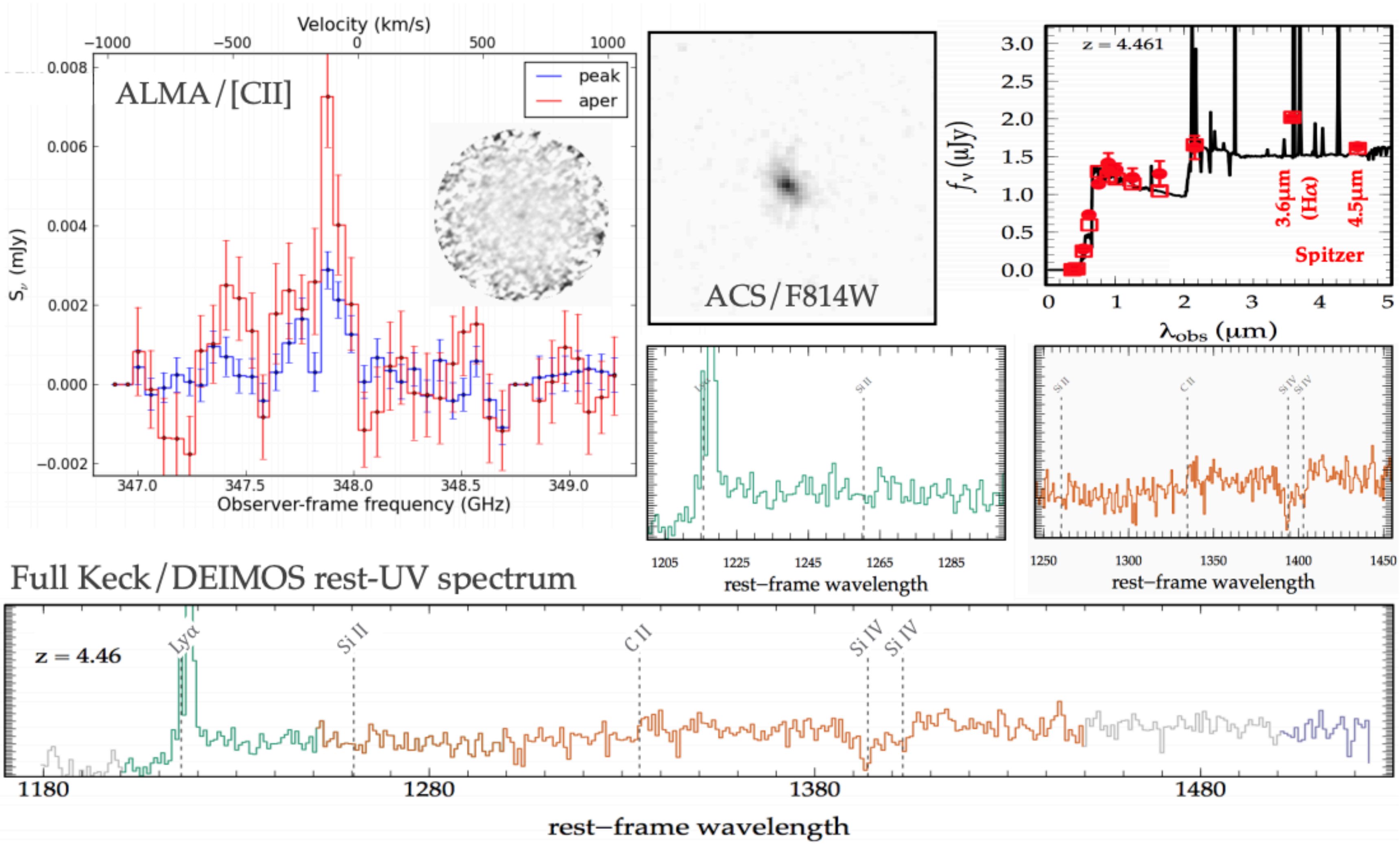
~350 GHz

52 objects

~280-300 GHz

Trends in two bins of redshift

Panchromatic view



Main science goals

- [CII] as a ***SFR indicator***
- A first comprehensive and precise (< 20%) measurement of the ***SFRD at 4 < z < 6*** from UV+FIR continuum and C+ emission
- A first detailed characterization of ***ISM properties*** using LFIR/LUV and C+/FIR diagnostics
- A first measurement of ***dynamical masses*** from spectrally resolved C+, combined with stellar masses and estimates of DM halo masses to measure ***the gas fraction*** and its evolution

Status of the project

- 122 sources observed in cycle 5 & 6
- calibrated and processed automatically with in house pipeline
- detection rate: [CII] ~ 70%; continuum ~ 20% (expected 40%)
- 35 serendipitous line sources, 30 serendipitous continuum
- ***we just started the scientific analysis***

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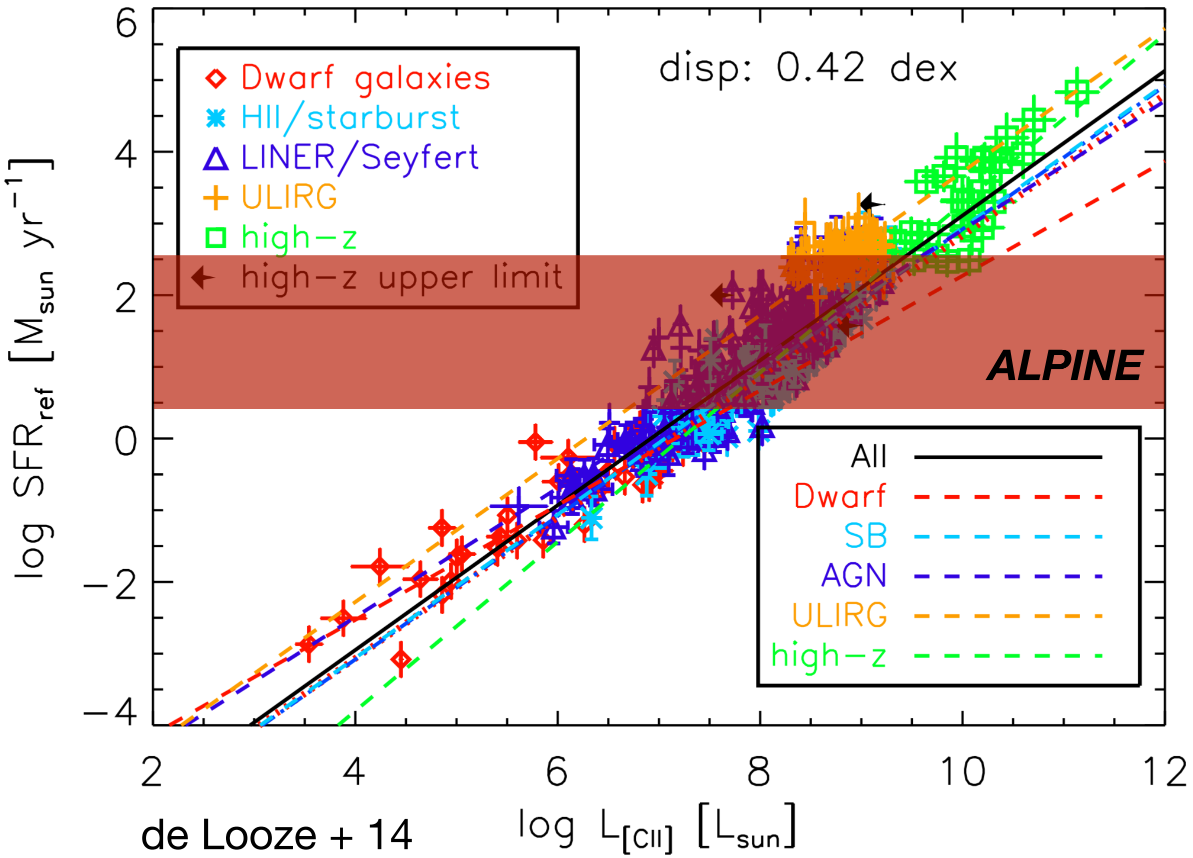
1. [CII] as SFR indicator



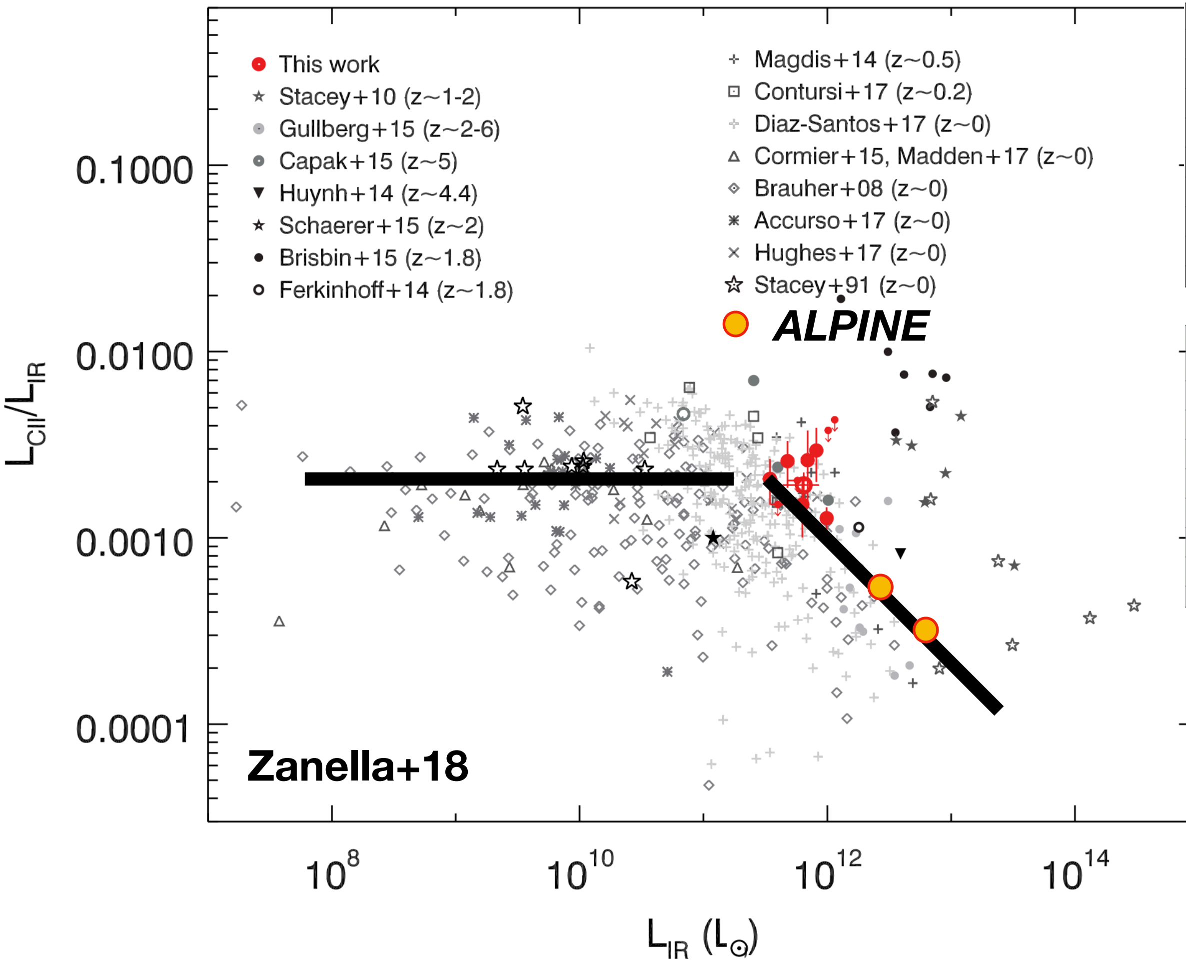
de Looze + 14

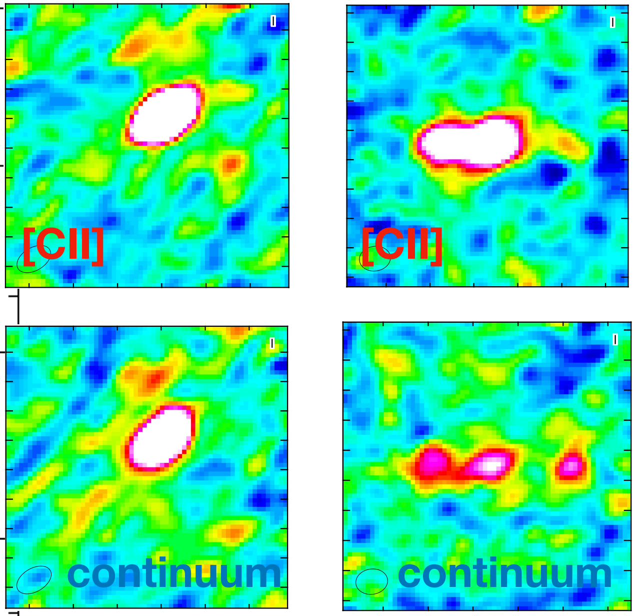
is [CII] a good SFR indicator?

a lot of scatter

Calibration for main-sequence galaxies

…but [CII] deficit

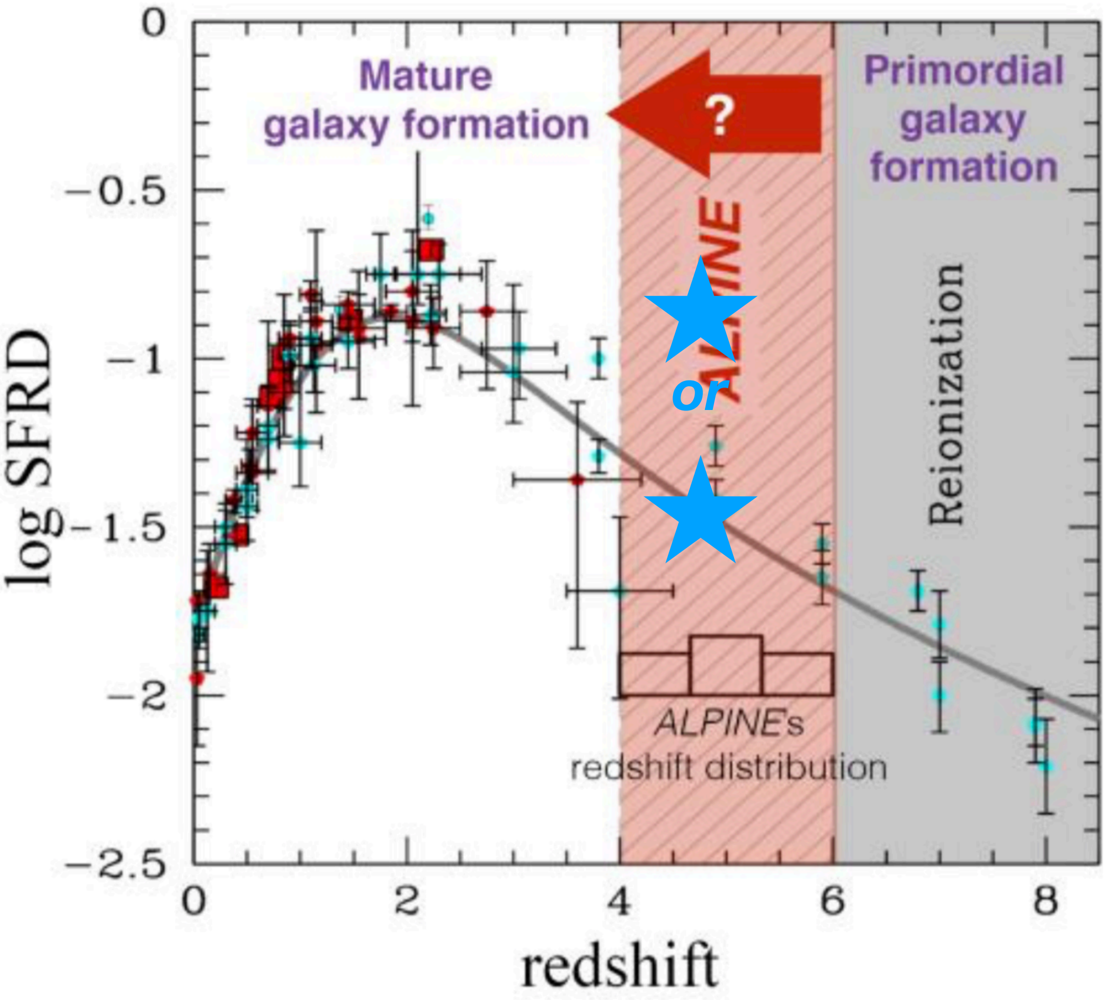




two of the brightest ALPINE [CII] detections

[CII] deficit confirmed at z ~ 5

2. SFRD from [CII], UV+FIR



1. [CII], UV+FIR star-formation for the "UV signposts"

+

**2. blind [CII]
(and continuum) survey:**

10 arcmin^2

expect ~ 40 [CII] serendipitous emitters

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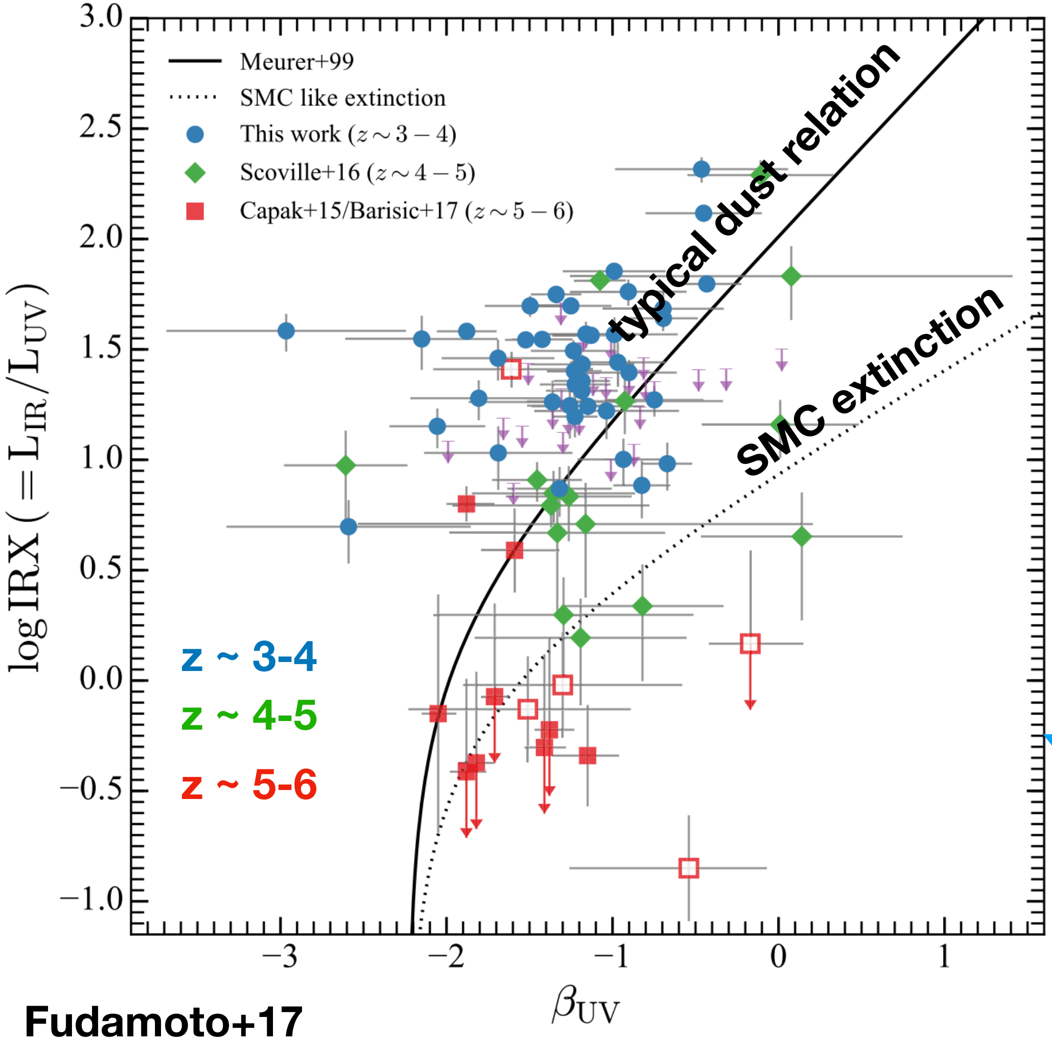
3. ISM properties



Fudamoto+17

Galaxies are moving down at increasing z?

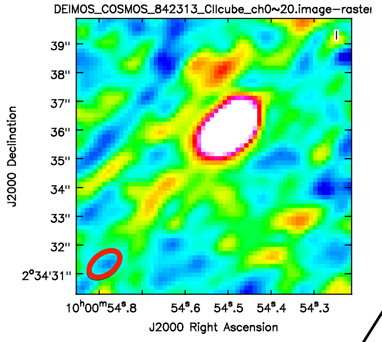
High-z:

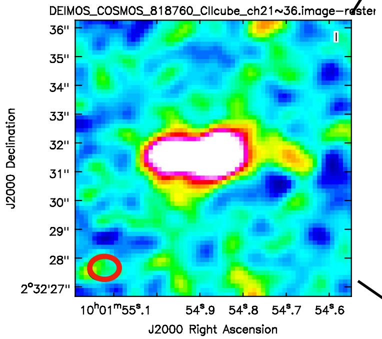
- *more metal poor?*
- *lower optical depth?*

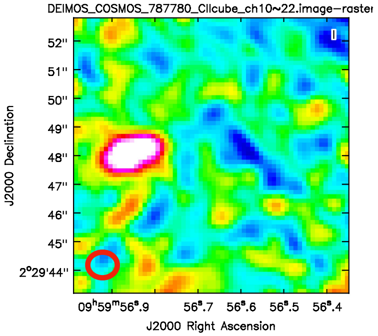
ALPINE adding tens of galaxies at 4.5<z<6

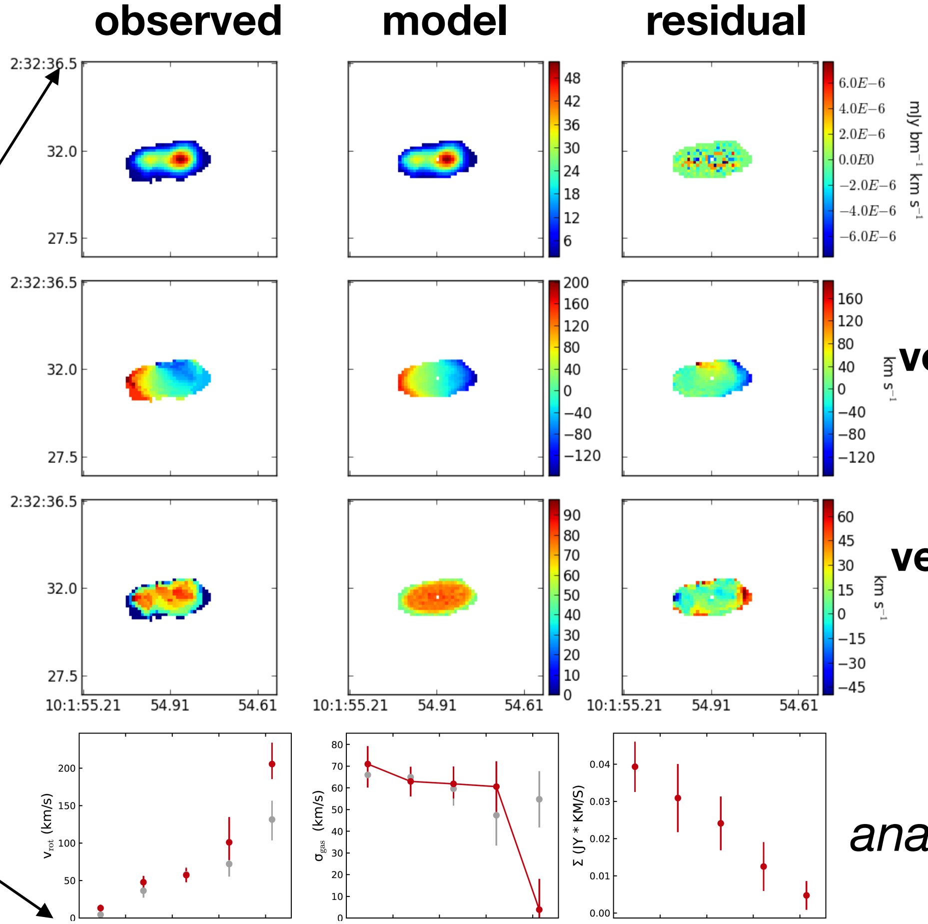
4. dynamics, gas masses

Many resolved sources









[CII] map

velocity map

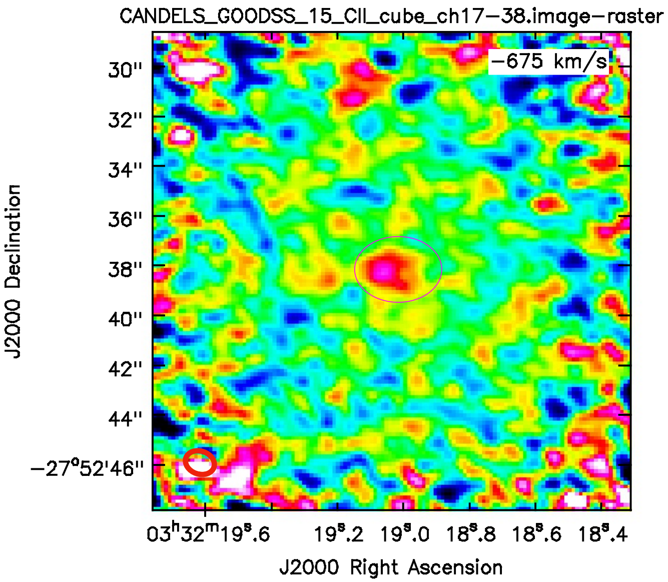
velocity dispersion

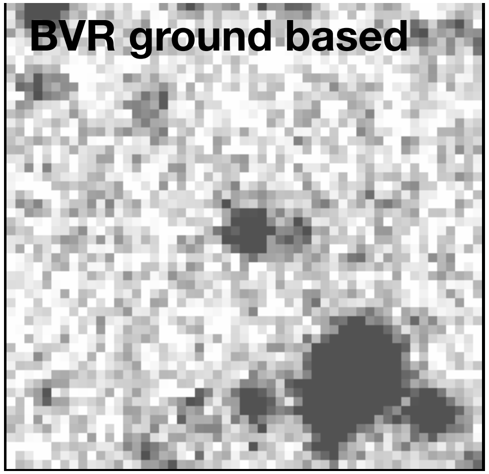
analysis by G. Jones

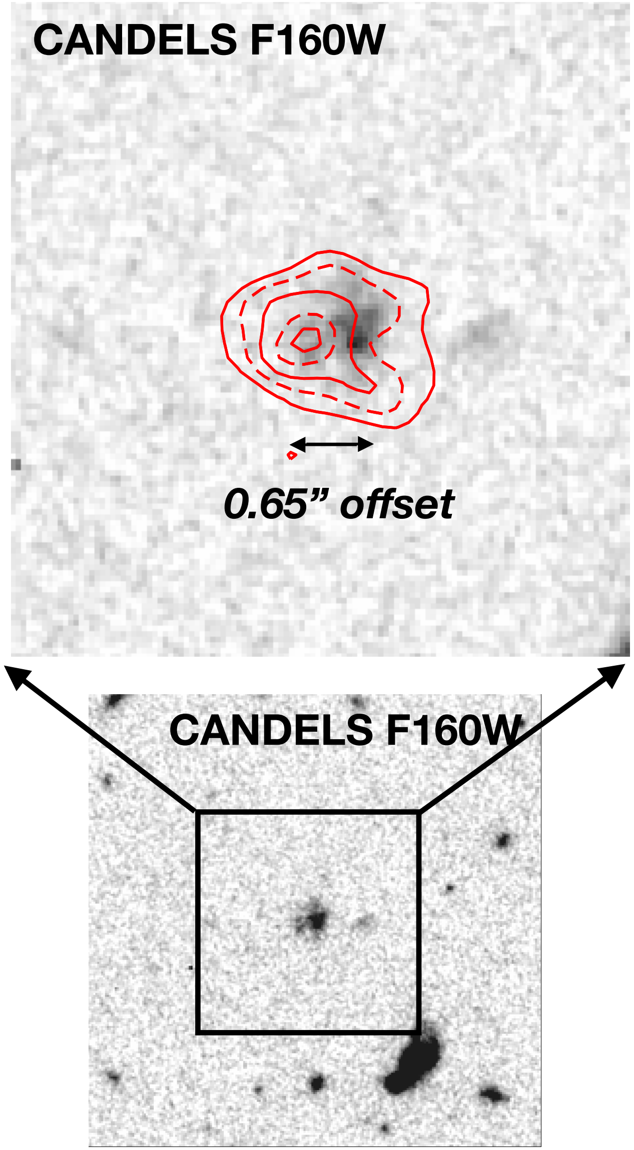
[CII] as tracer of kinematics

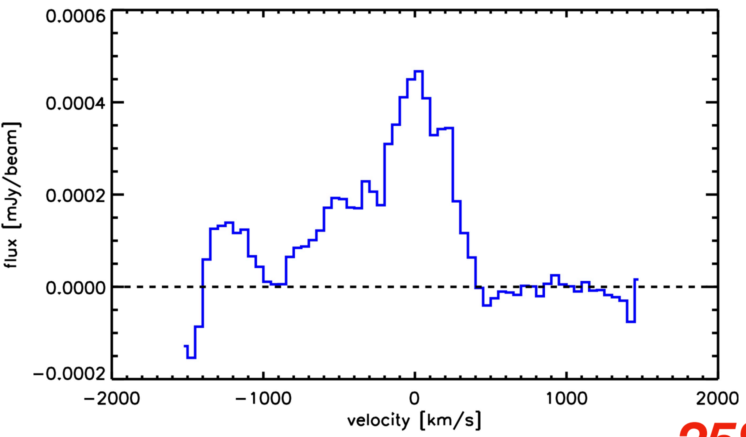
Dynamical mass, gas fractions

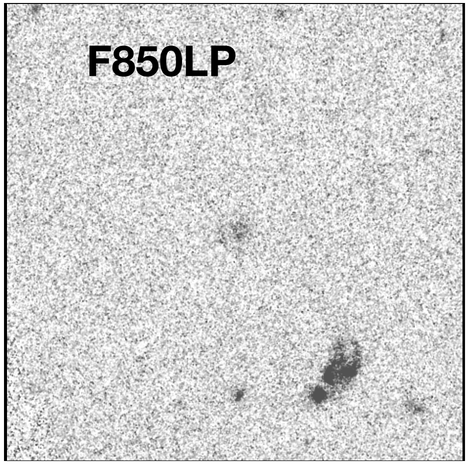
stars vs gas





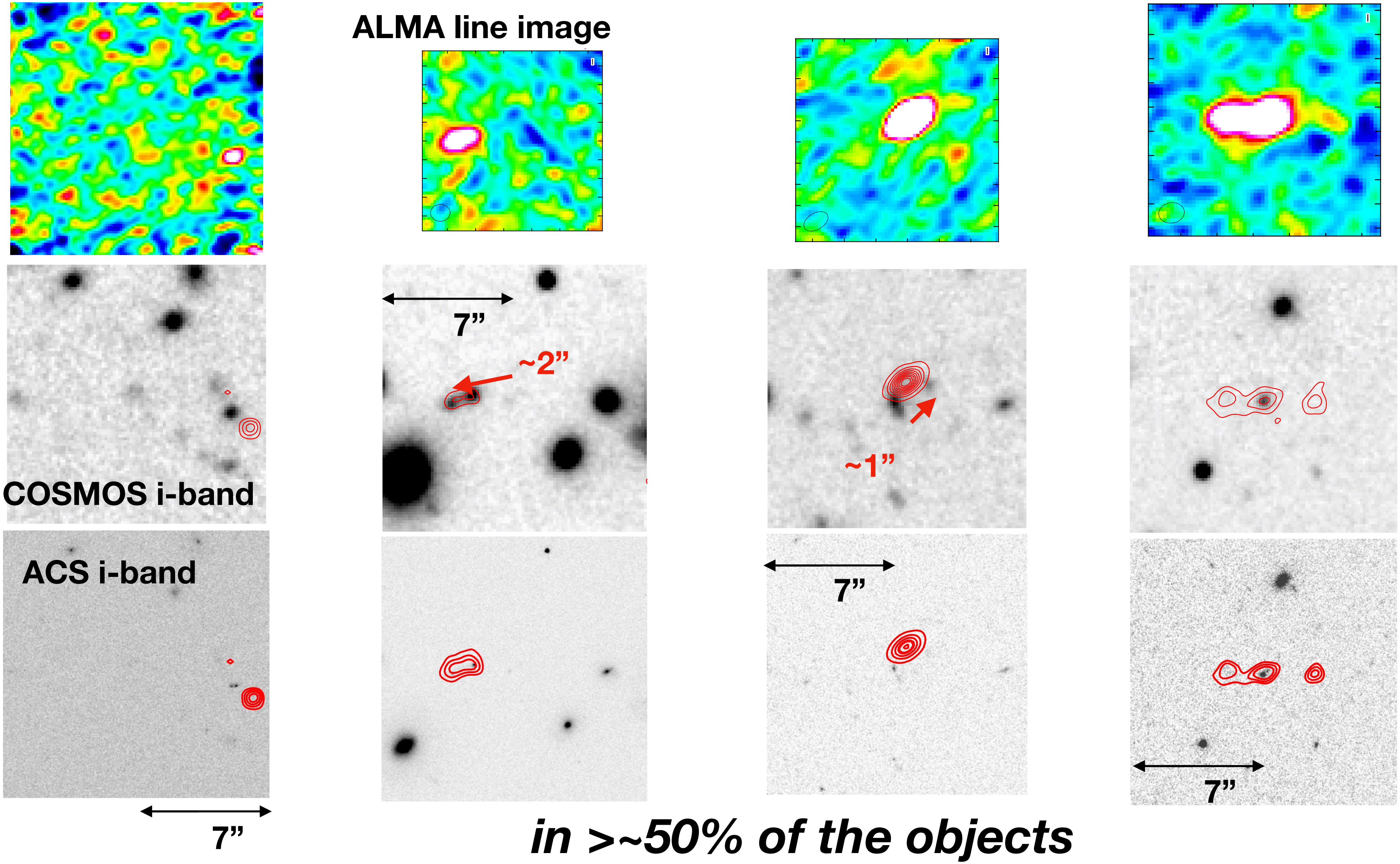






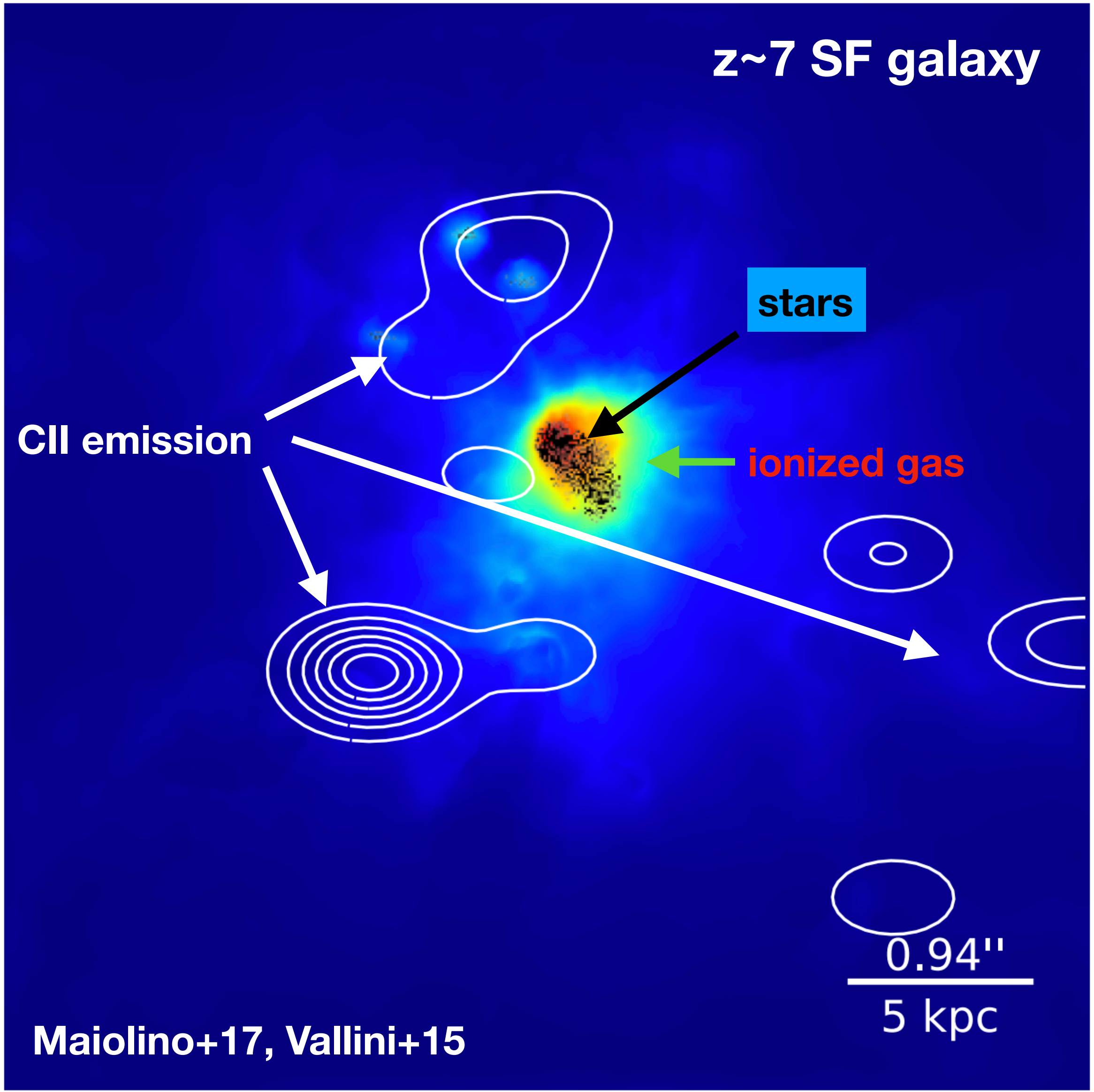
~25% of the sample has CANDELS coverage

many spatially offset [CII] emitters



in >~50% of the objects

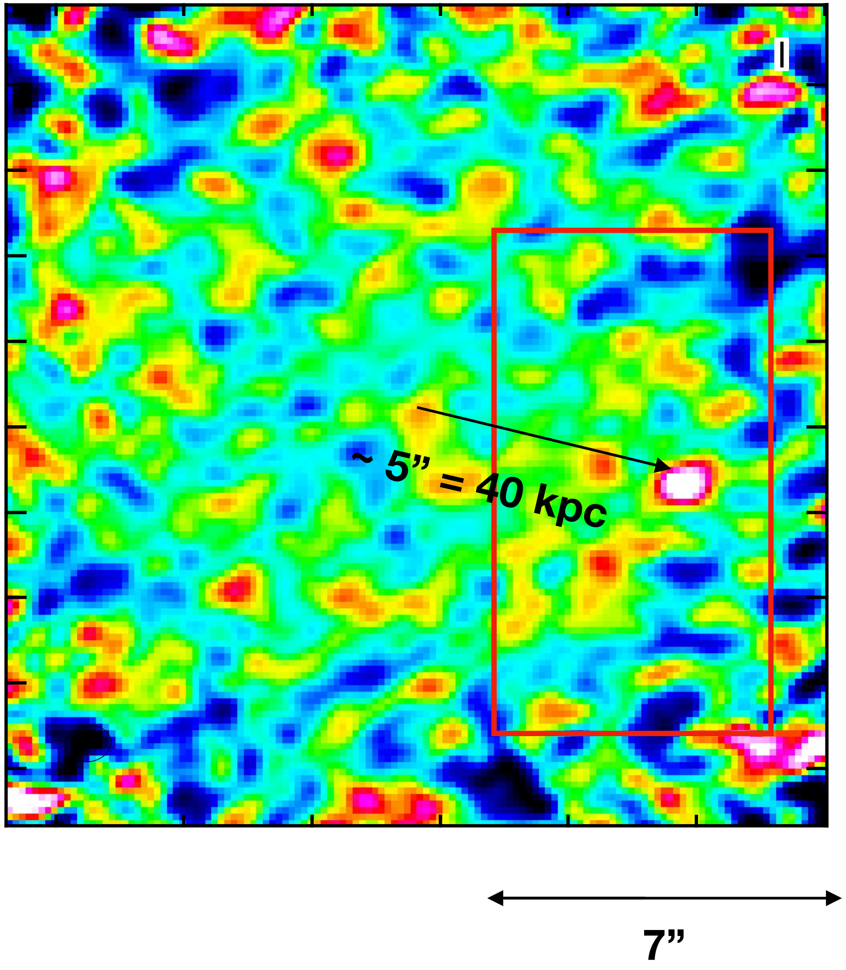
not unexpected: model

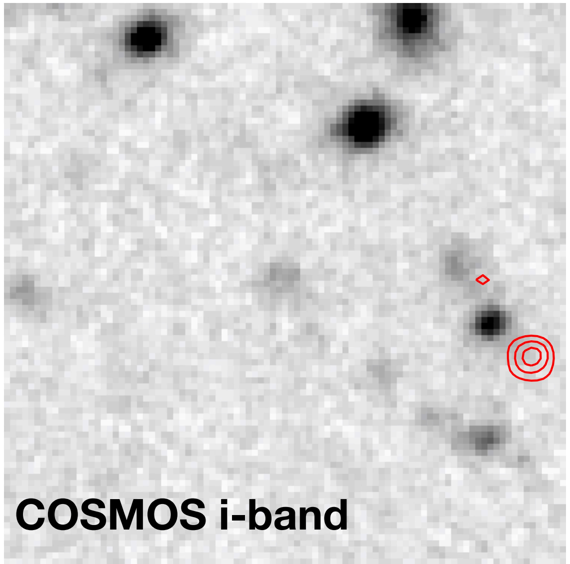


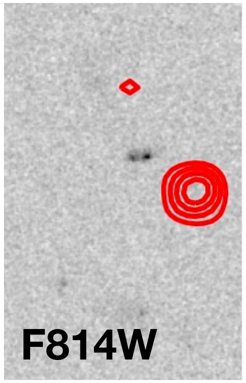
[CII] emission offset by several kpc is expected

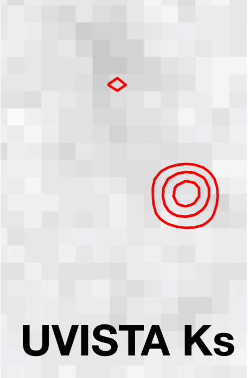
an extreme case

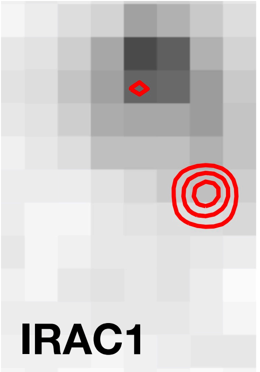
no counterpart with compatible photo-z

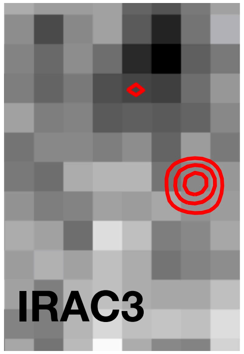


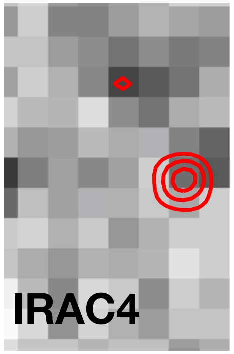




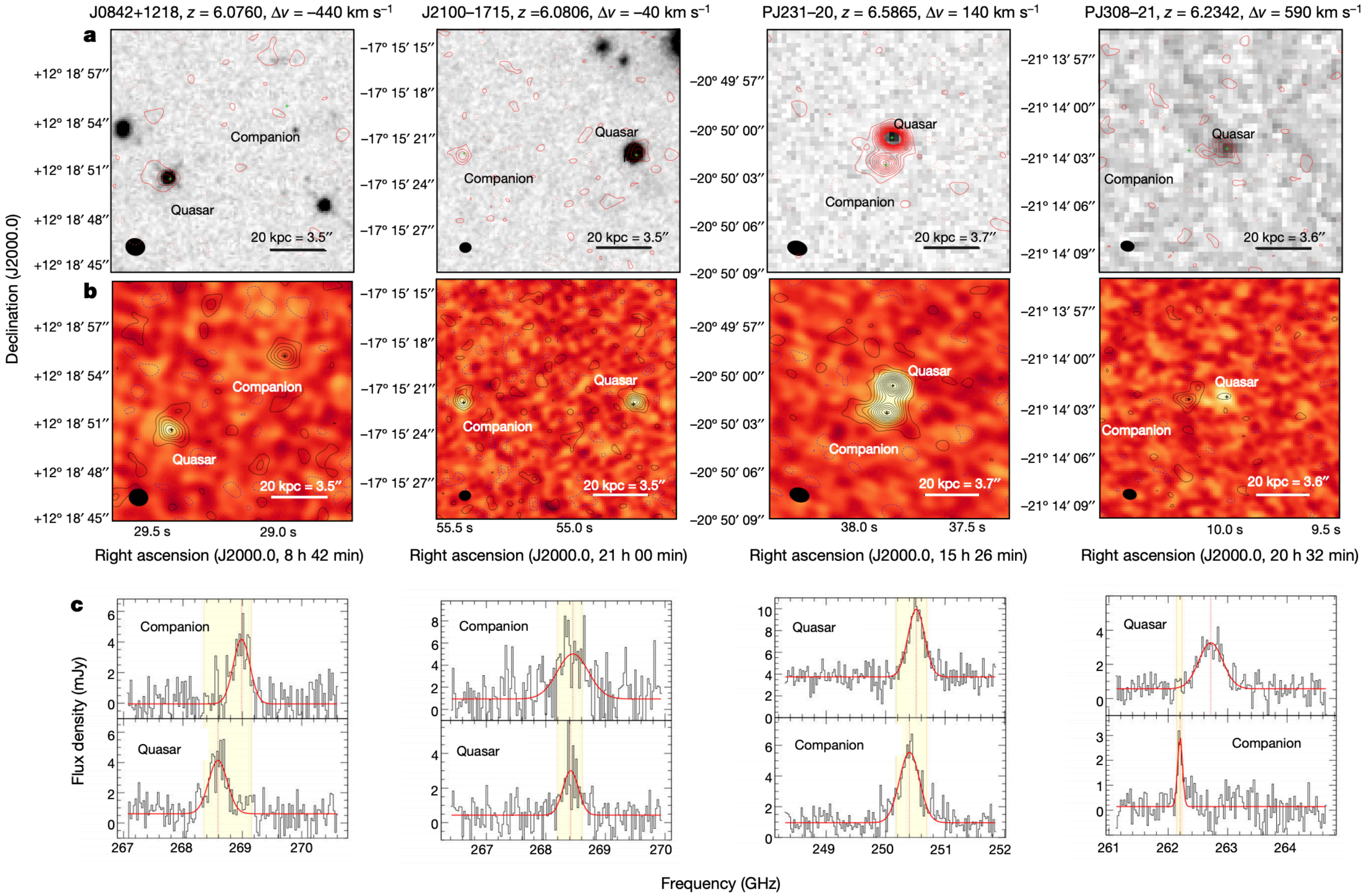






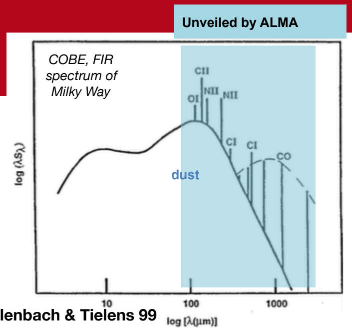


not unusual at z>5-6



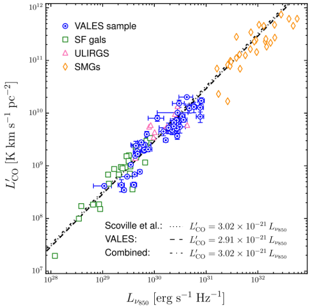
Decarli+17

Conclusions

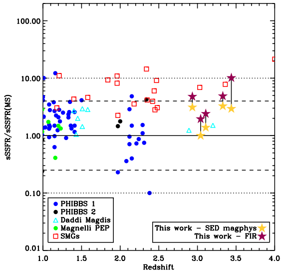


Hollenbach & Tielens 99

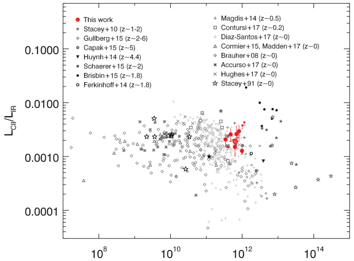
- ALMA is an amazing tool to probe the gas-dust content of galaxies at z>3, and to constrain their ISM properties



- Dust continuum effective tool to probe gas content (with some caveats)



- Still a lot to do at z>3: few MS galaxies with CO detections



- [CII] powerful tool to explore the Early Universe