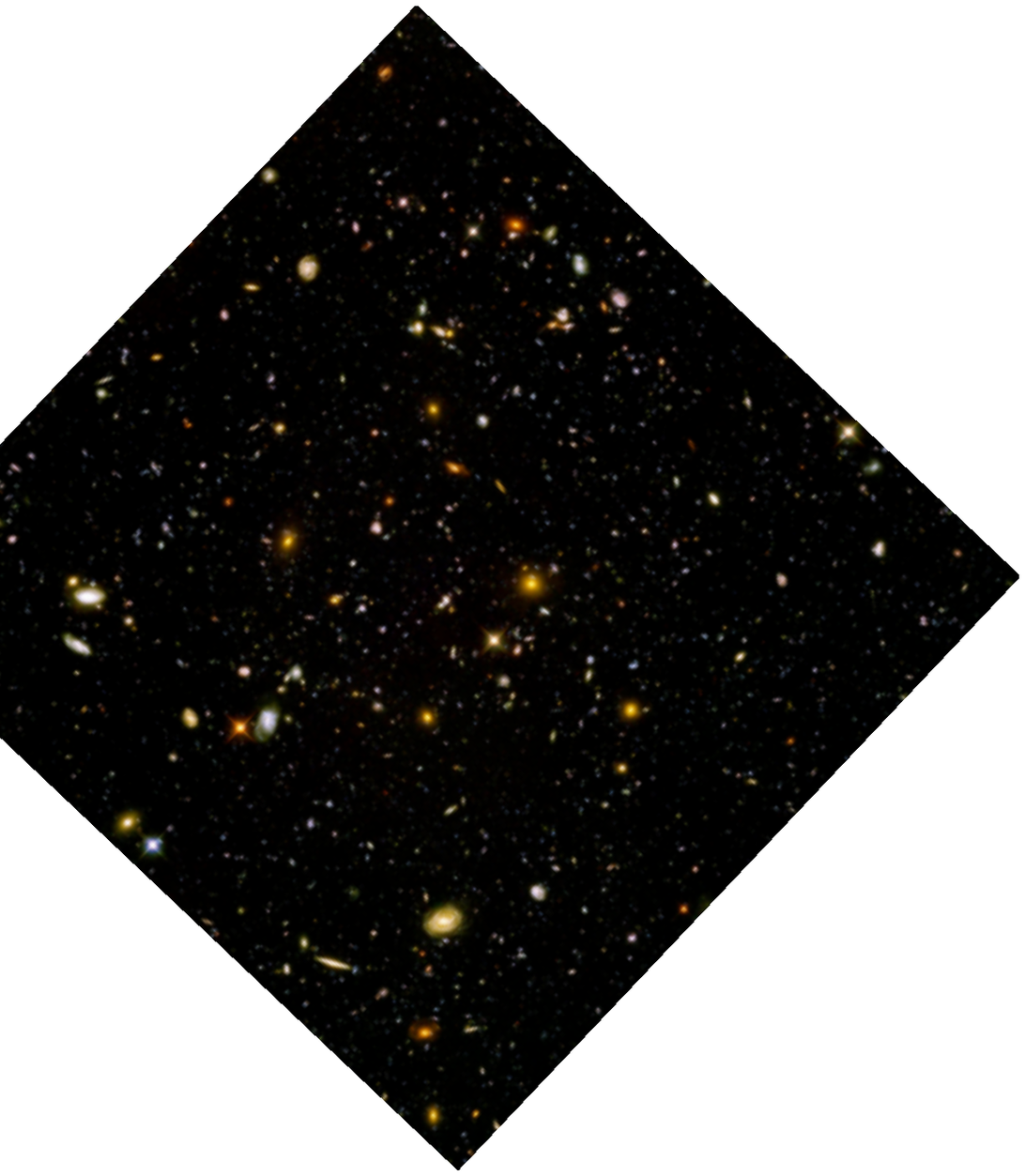
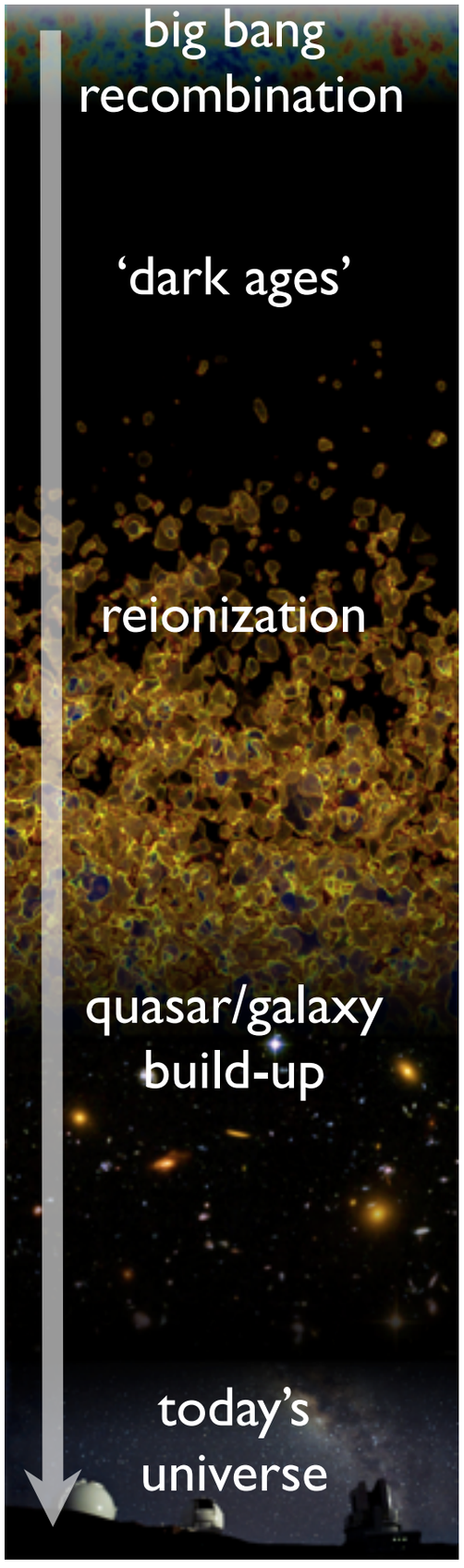


Molecular Deep Fields

Fabian Walter
(MPIA Heidelberg, Germany)

F. Bertoldi, **C. Carilli**, P. Cox, E. da Cunha, E. Daddi, **R. Decarli**,
D. Downes, M. Dickinson, R. Ellis, R. Maiolino, K. Menten, R. Neri,
D. Riechers, H.-W. Rix, M. Sargent, D. Stark, B. Weiner, A. Weiss

history of the universe



z~1000
0.0003 Gyr

z~15-1000
0.0003-0.3 Gyr

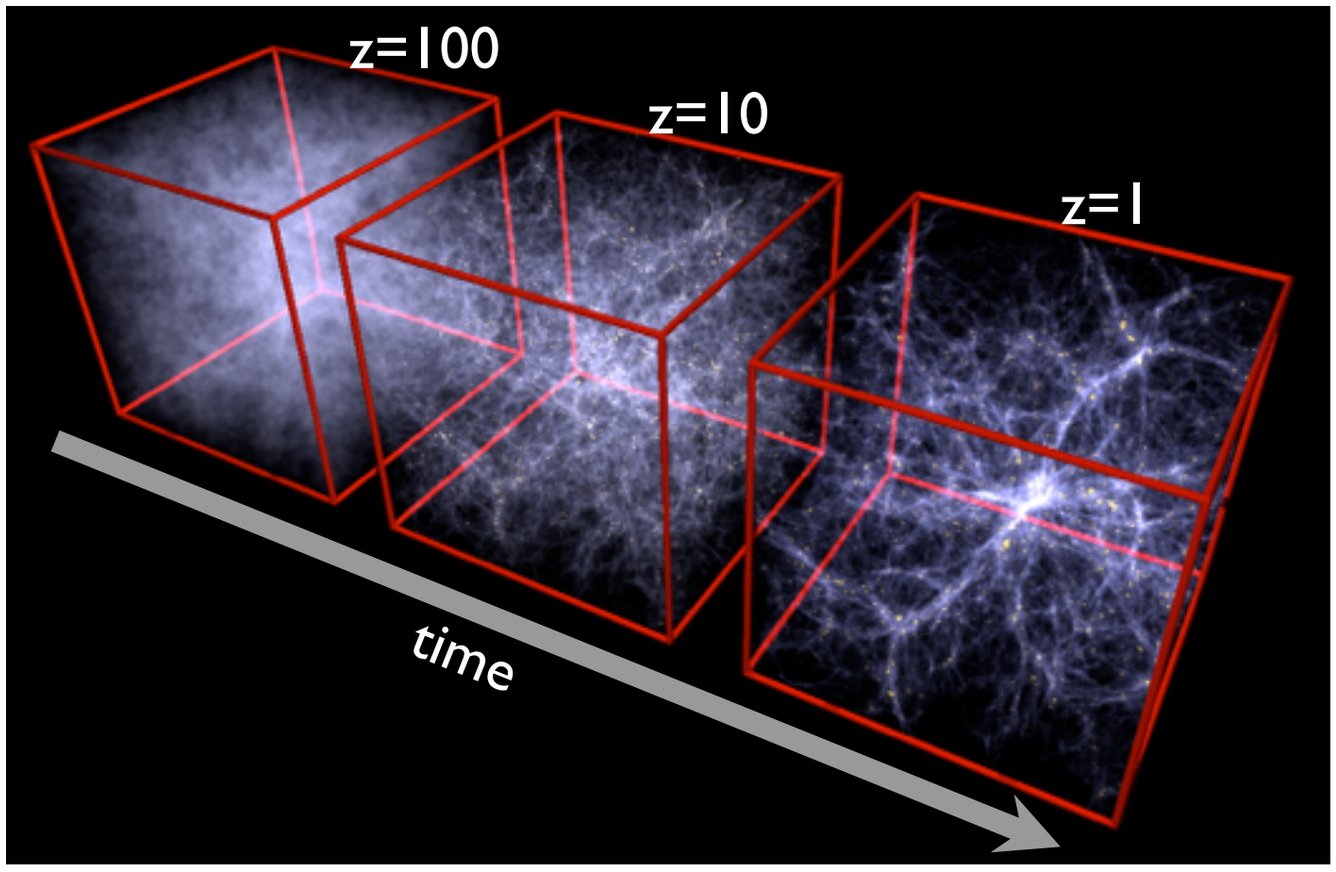
z~8-15
0.3-1 Gyr

z<~8
>1 Gyr

z~0
14.3 Gyr

theoretical framework

hydrodyn. simulations of cosmic structure formation



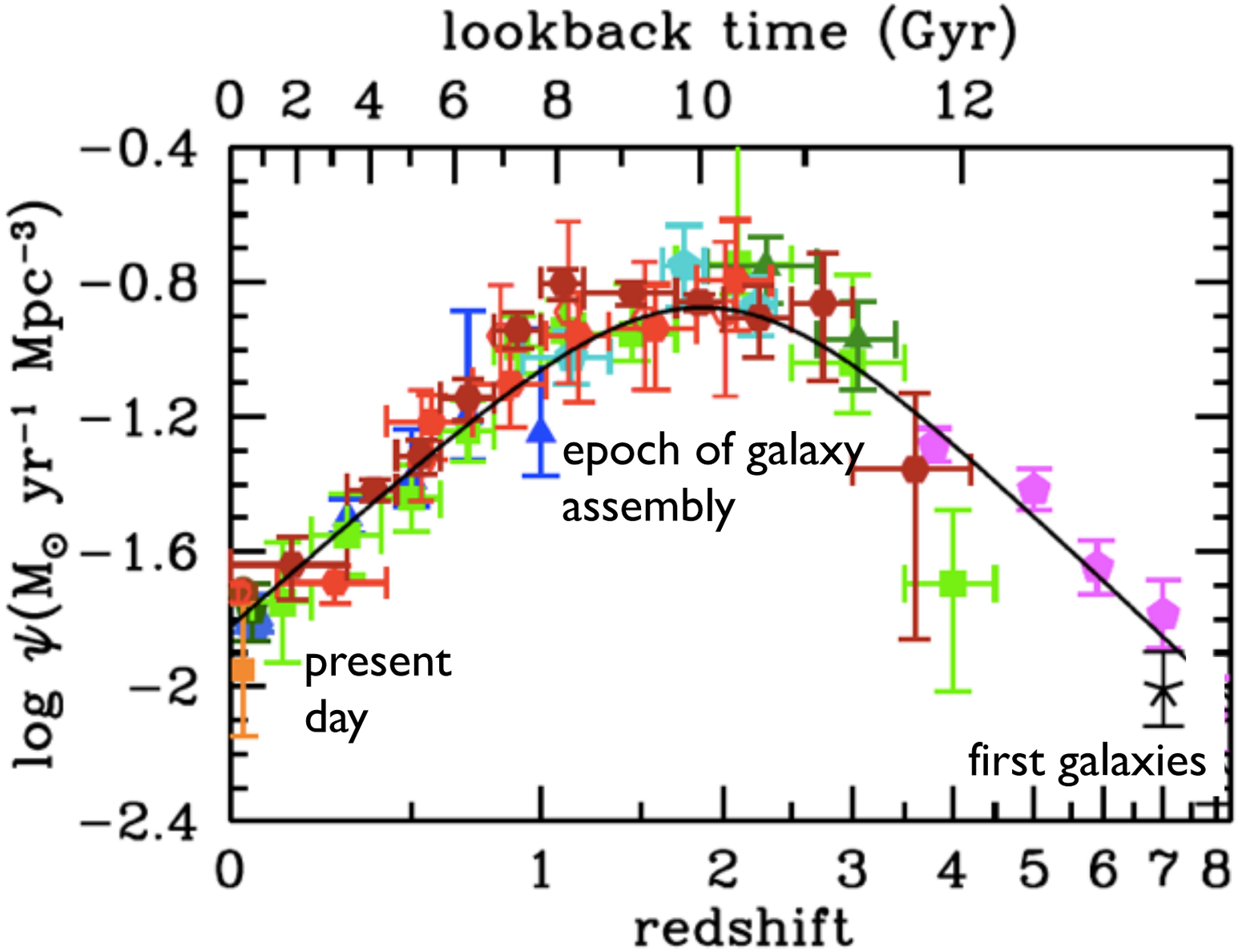
e.g. GADGET, AREPO, Springel et al.

Galaxy growth through gas accretion...

...but this gas supply is currently largely unconstrained observationally

cosmic star formation

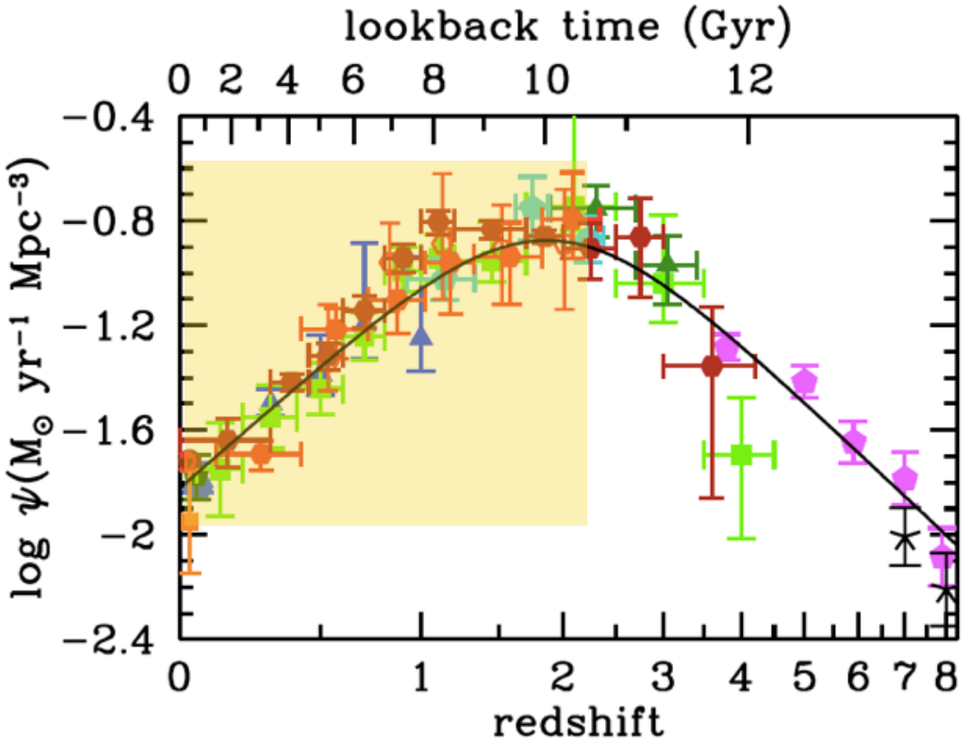
Volume density of star formation in galaxies as f(cosmic time)

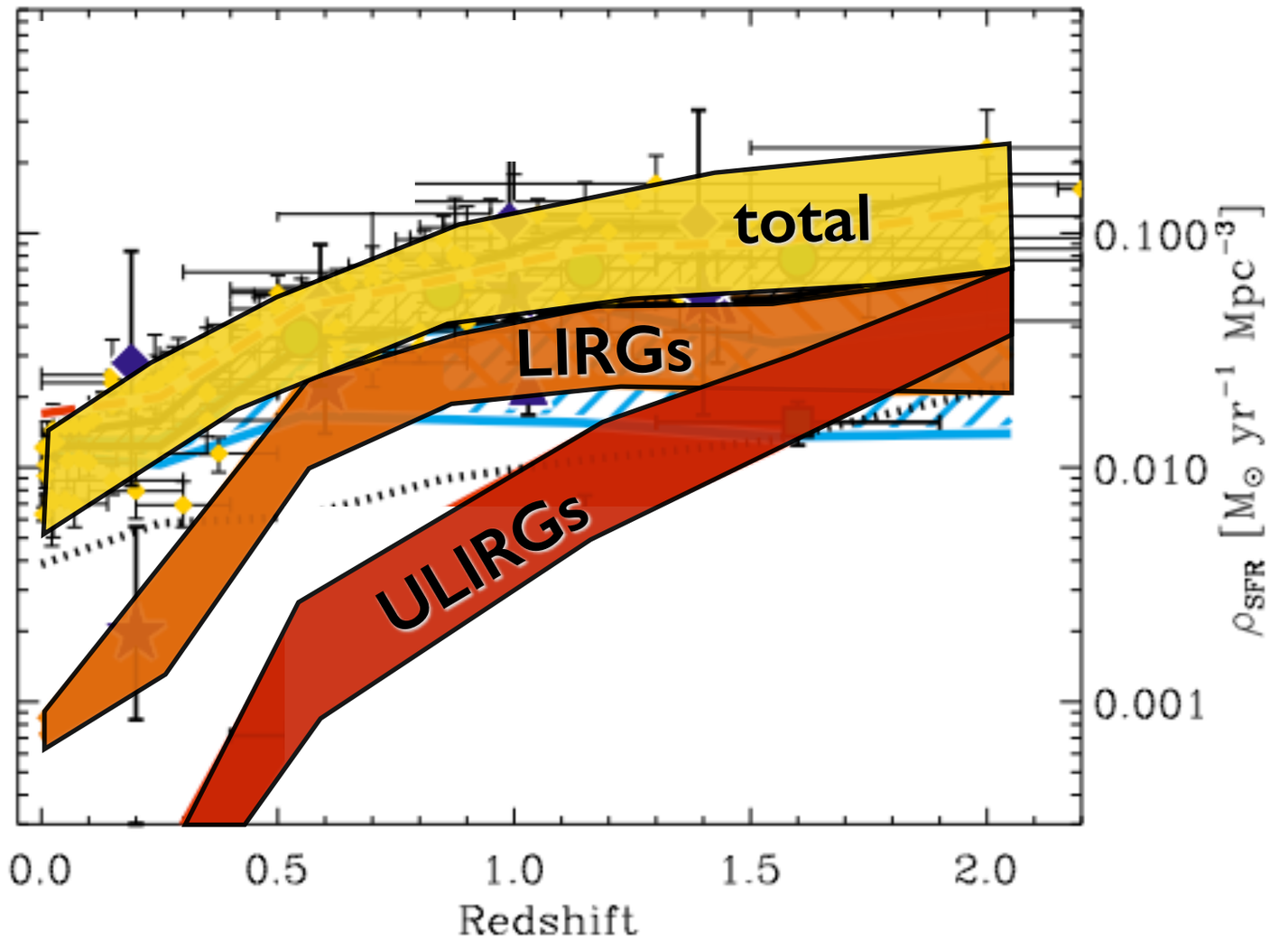


Madau & Dickinson, ARA&A 2014

cosmic star formation

Contributors to cosmic star formation density



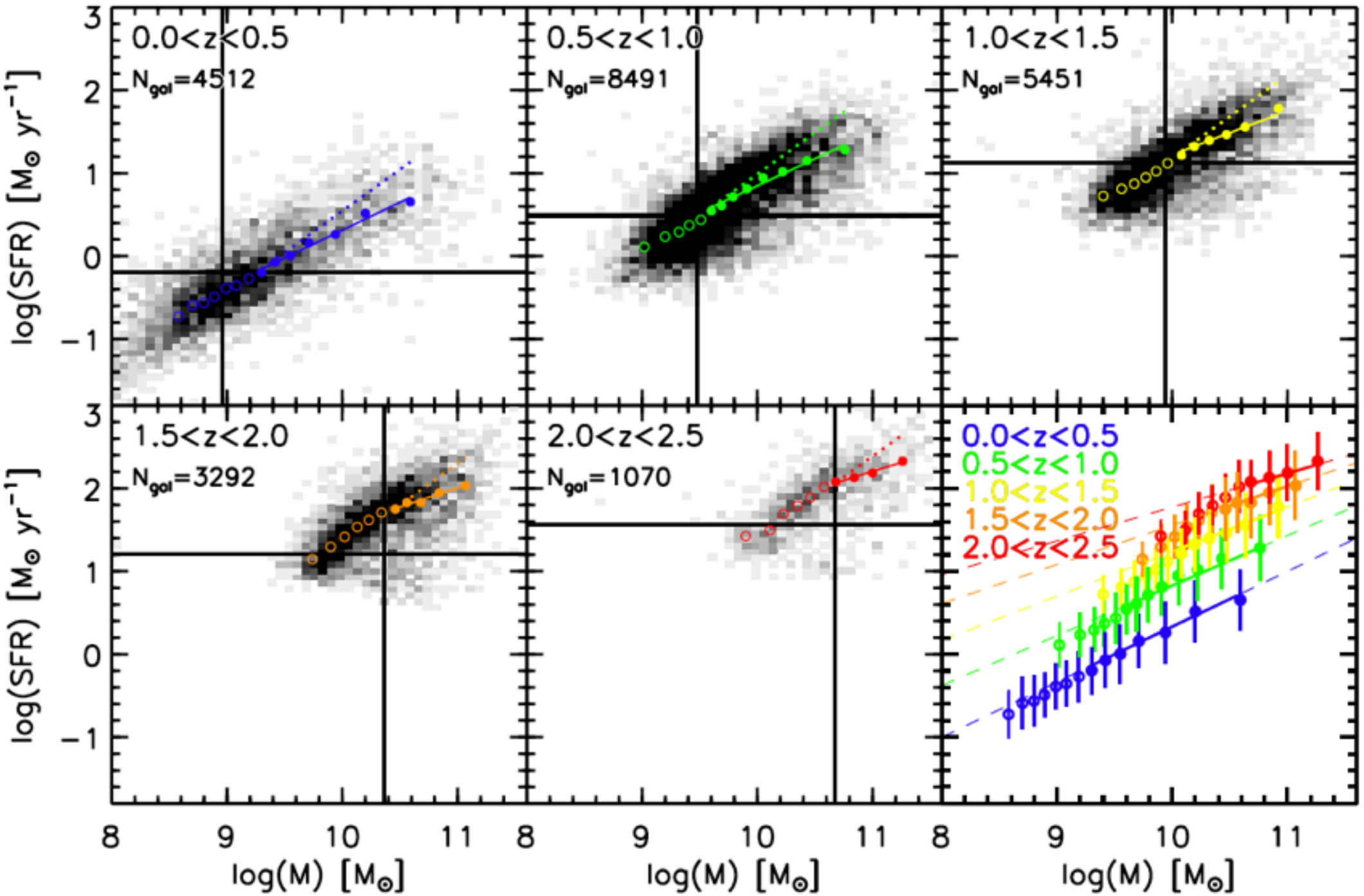


adapted from Magnelli et al. 2013

ULIRGs (i.e. $L_{IR}>10^{12}$ L_{sun}): **negligible contributor at z=0.**

main contributor at z=2.

the galaxy ‘main sequence’



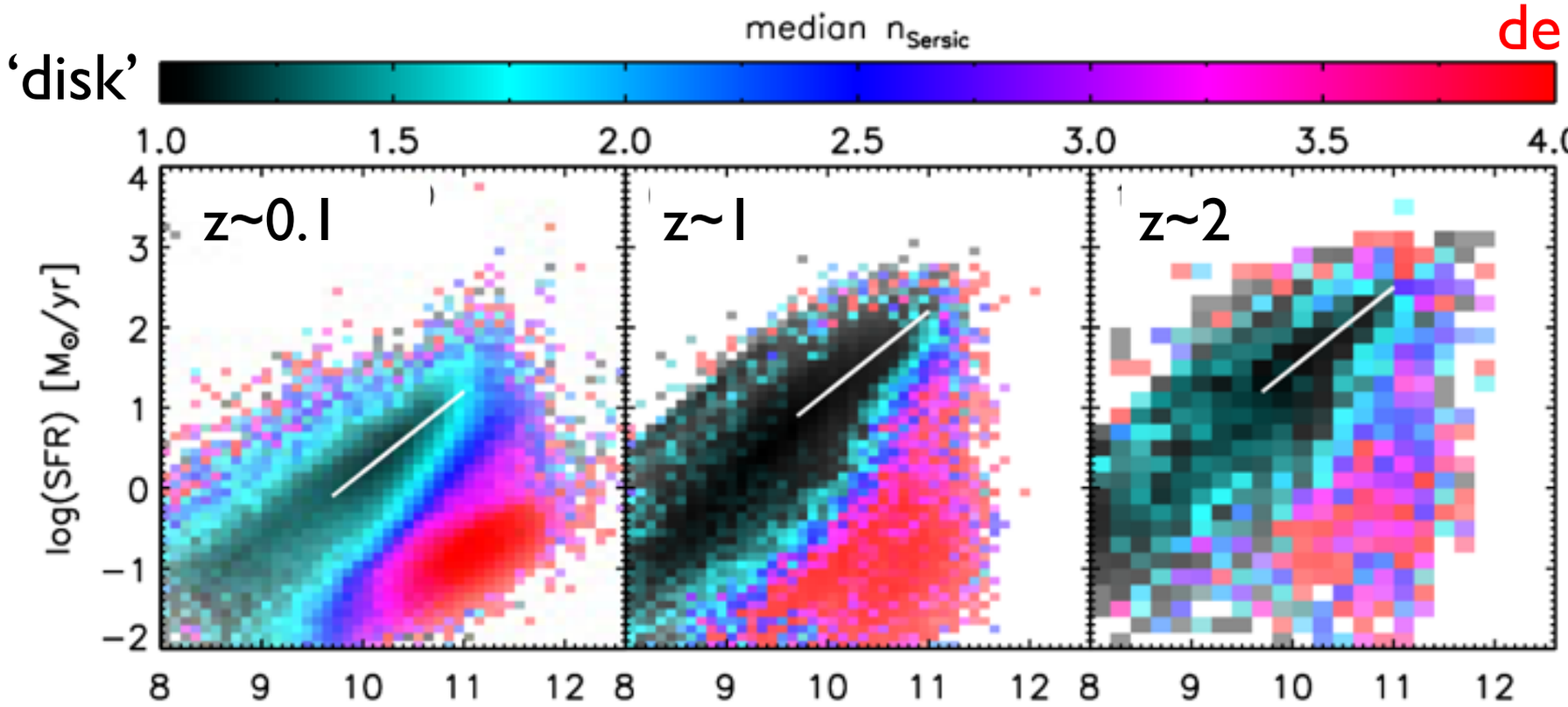
higher z: more SFR per M_{star}, flatter slope? (cf. Karim)

Whitaker et al. 2012, 2014

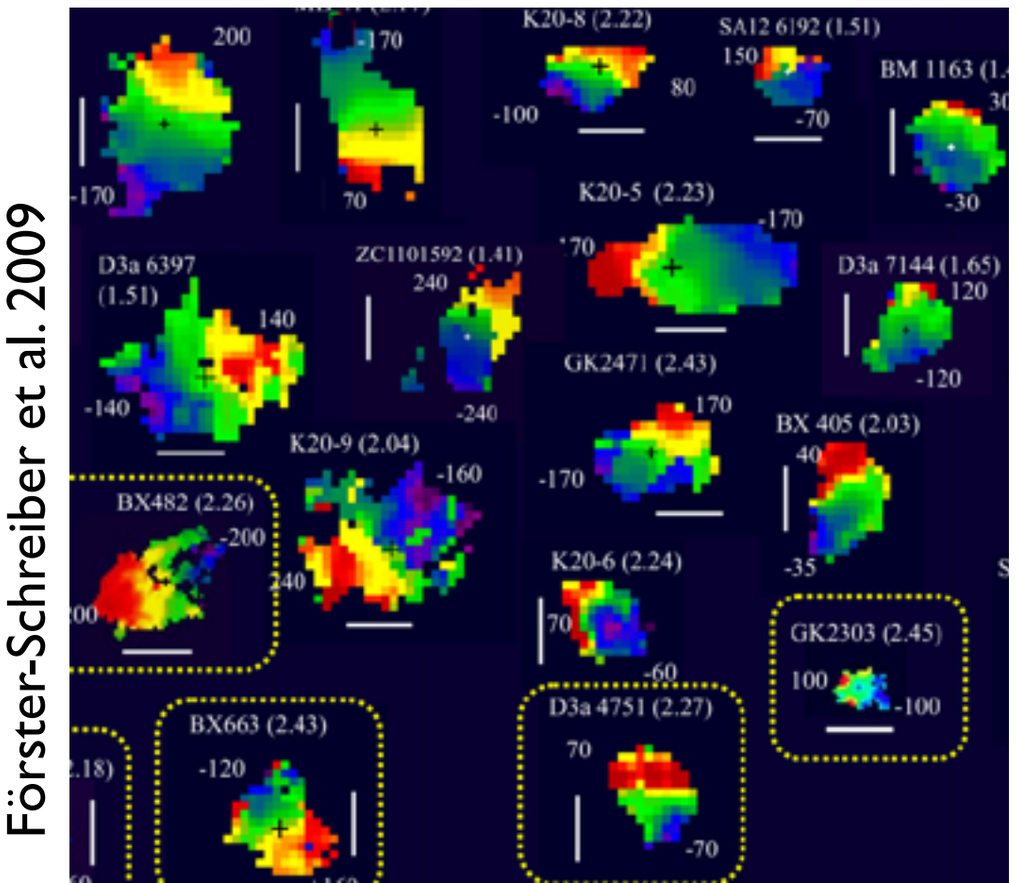
see also: Sargent et al. 2012, Rodighiero et al. 2011

structure/dynamics of main sequence galaxies

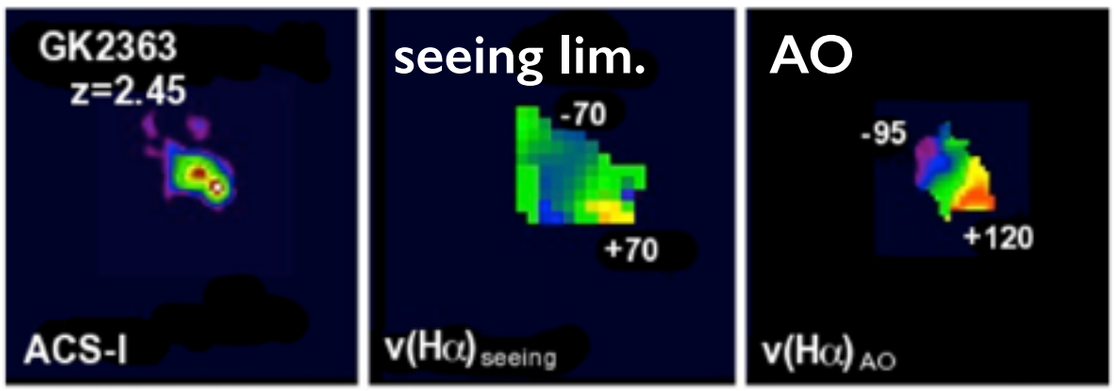
HST imaging



Wuyts et al. 2011



Förster-Schreiber et al. 2009



Newman et al. 2013

at least 50% of MS galaxies are in rotating disks, not mergers

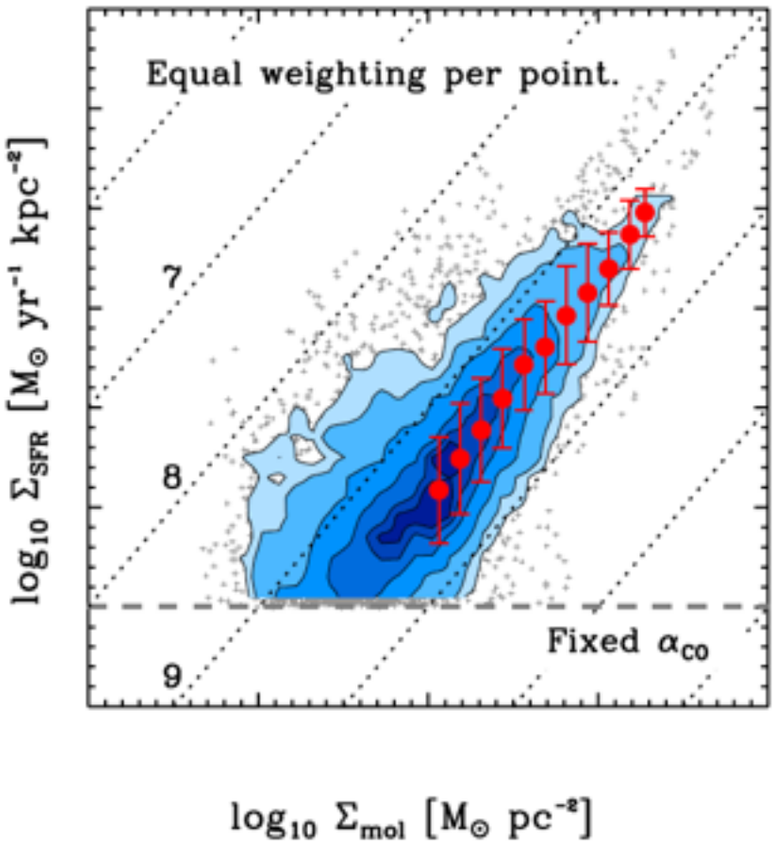
the question

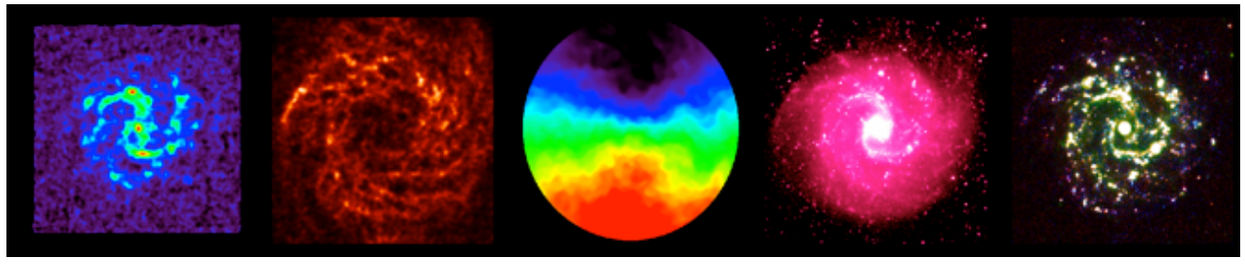
high-z MS galaxies: **not** mergers, **but** disk-like galaxies with ULIRG-like SFR

why high SFRs?

- extremely efficient SF process?
- very gas rich systems?

Need to look at the **cause for SF**: the molecular gas component





based on THINGS and HERACLES
PI: Walter & Leroy

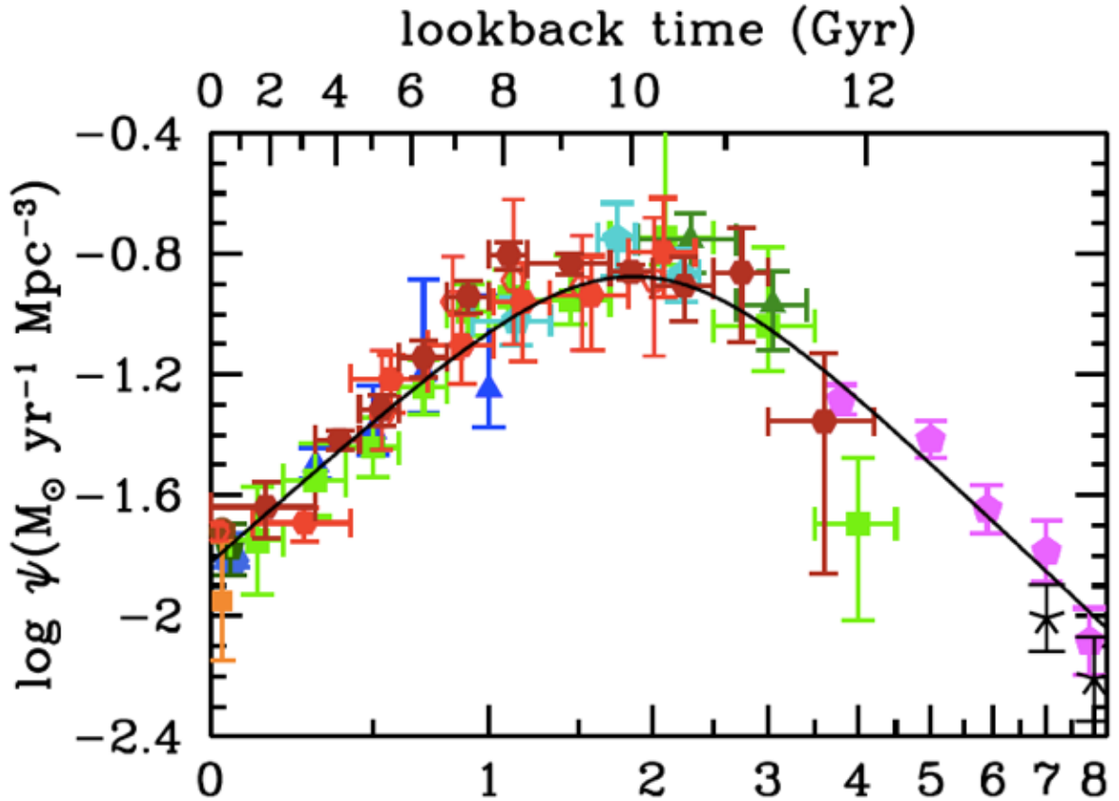
50.000 measurements (1kpc)
in ~40 nearby galaxies.

the 'molecular SF law'

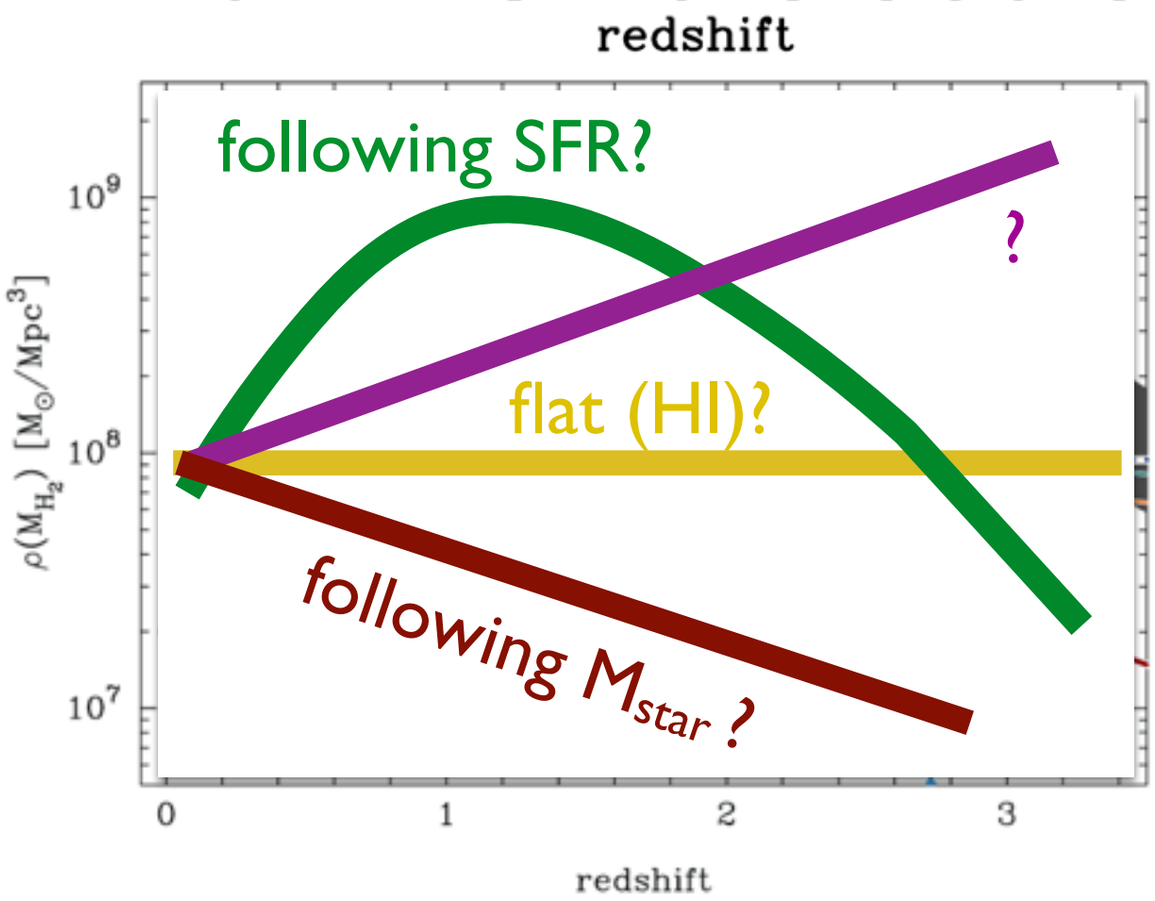
Leroy, Walter, et al. 2013

the question, posed differently

so far:
Omega (SFR)
the result of SF



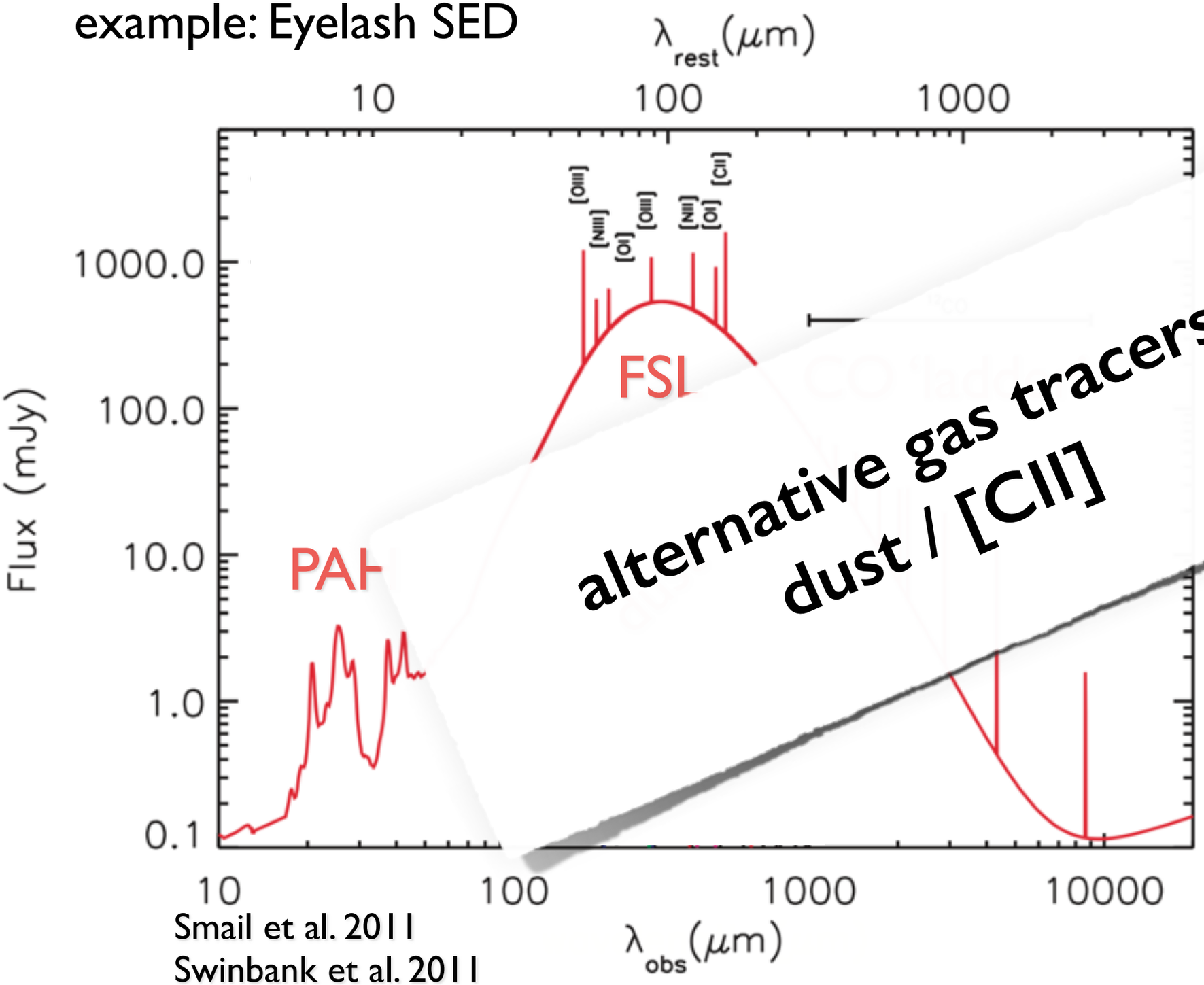
the more fundamental plot:
Omega (H2)
the underlying cause



how do we get here?

need to trace molecular component

example: Eyelash SED



Smail et al. 2011
Swinbank et al. 2011

alternative gas tracers:
dust / [CII]

molecular gas:

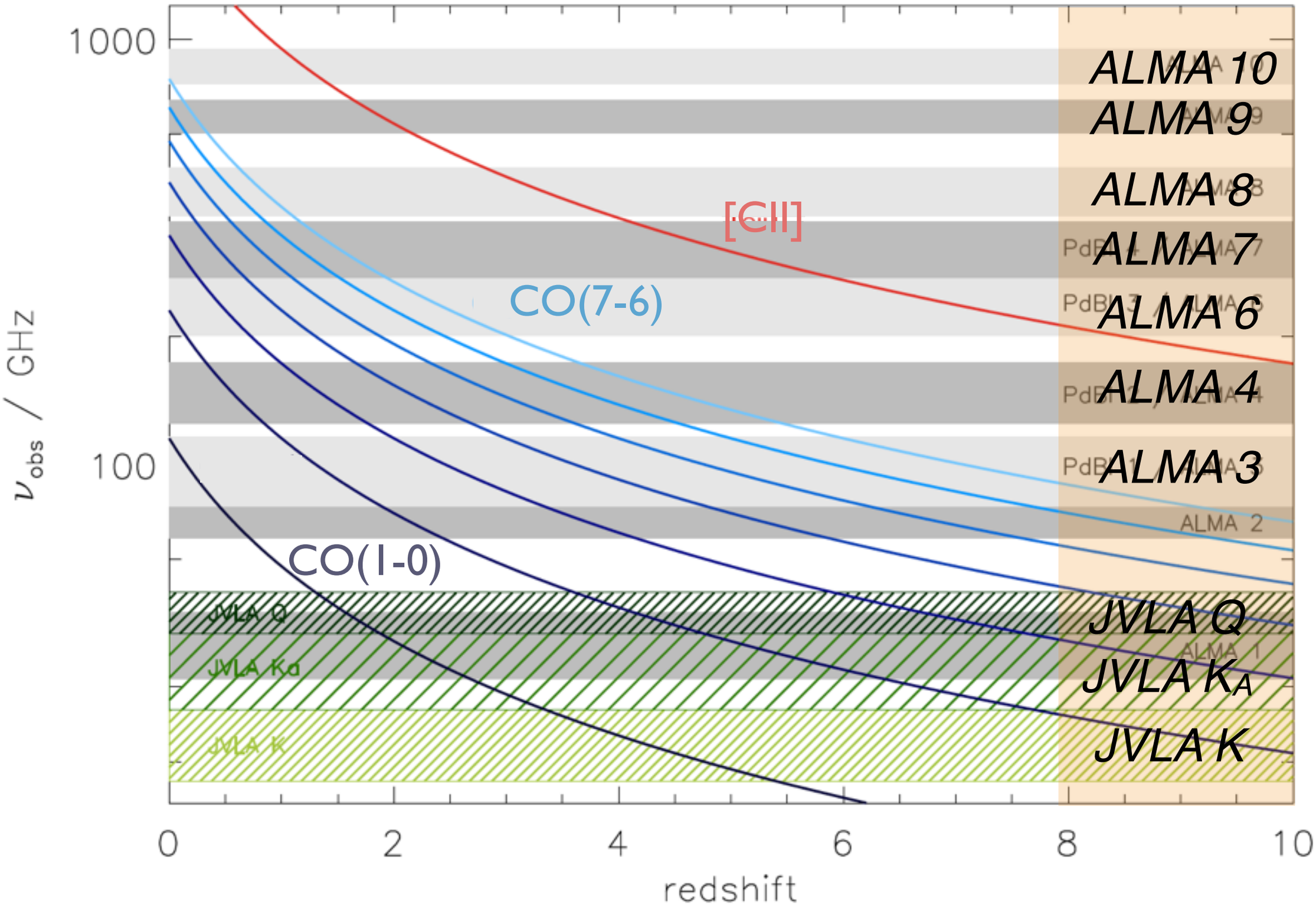
CO ladder

reasonable tracer: CO

M_{H2}, size, M_{dyn}, T_{mb}

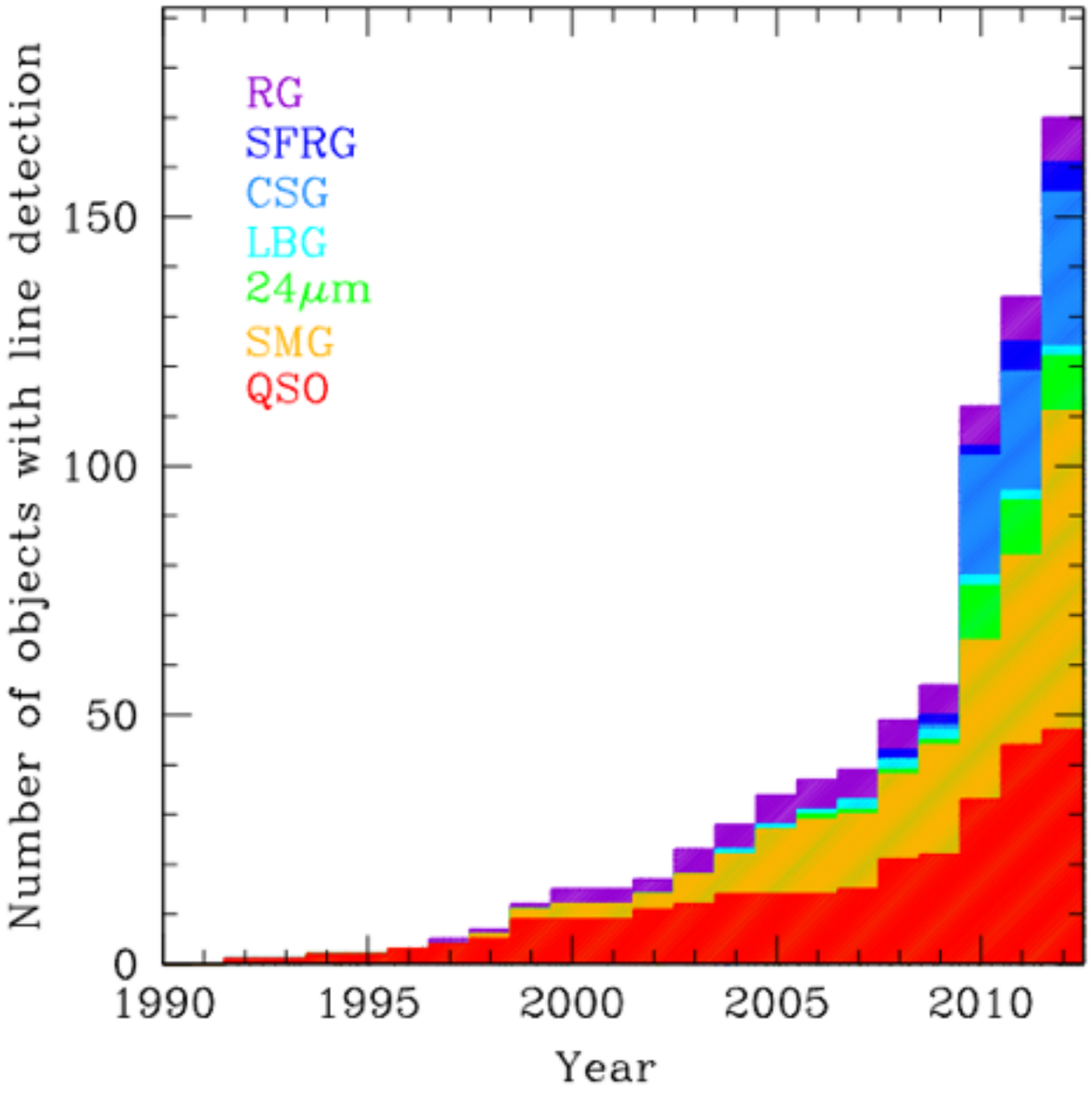
problems: - X_{CO}
- excitation

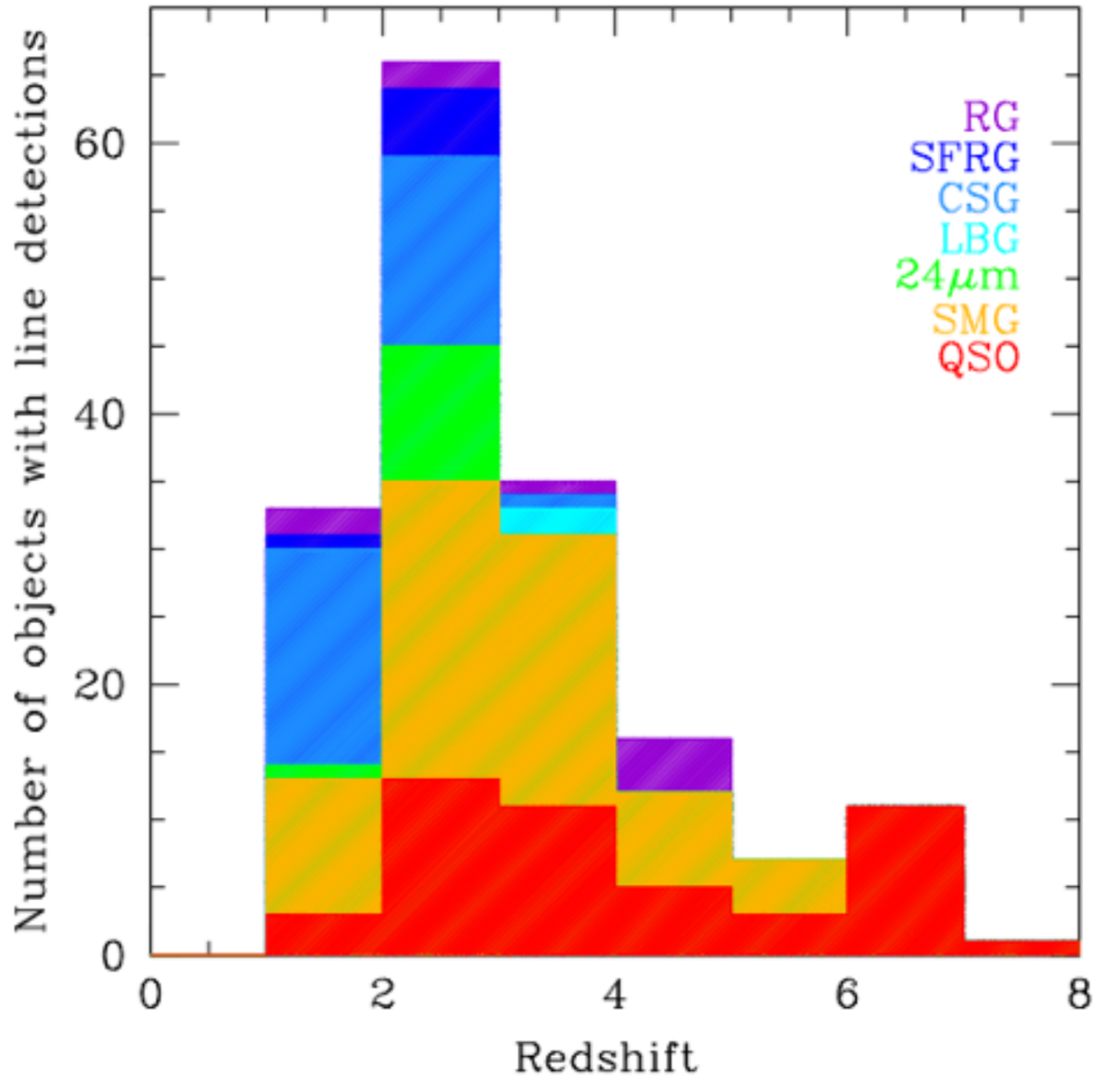
need to trace molecular component



CO: excitation disadvantage also has advantage: many transitions!

high-z galaxies detected in CO so far





Dramatic (~10x) increase in number of detections in the past decade

- Many different populations

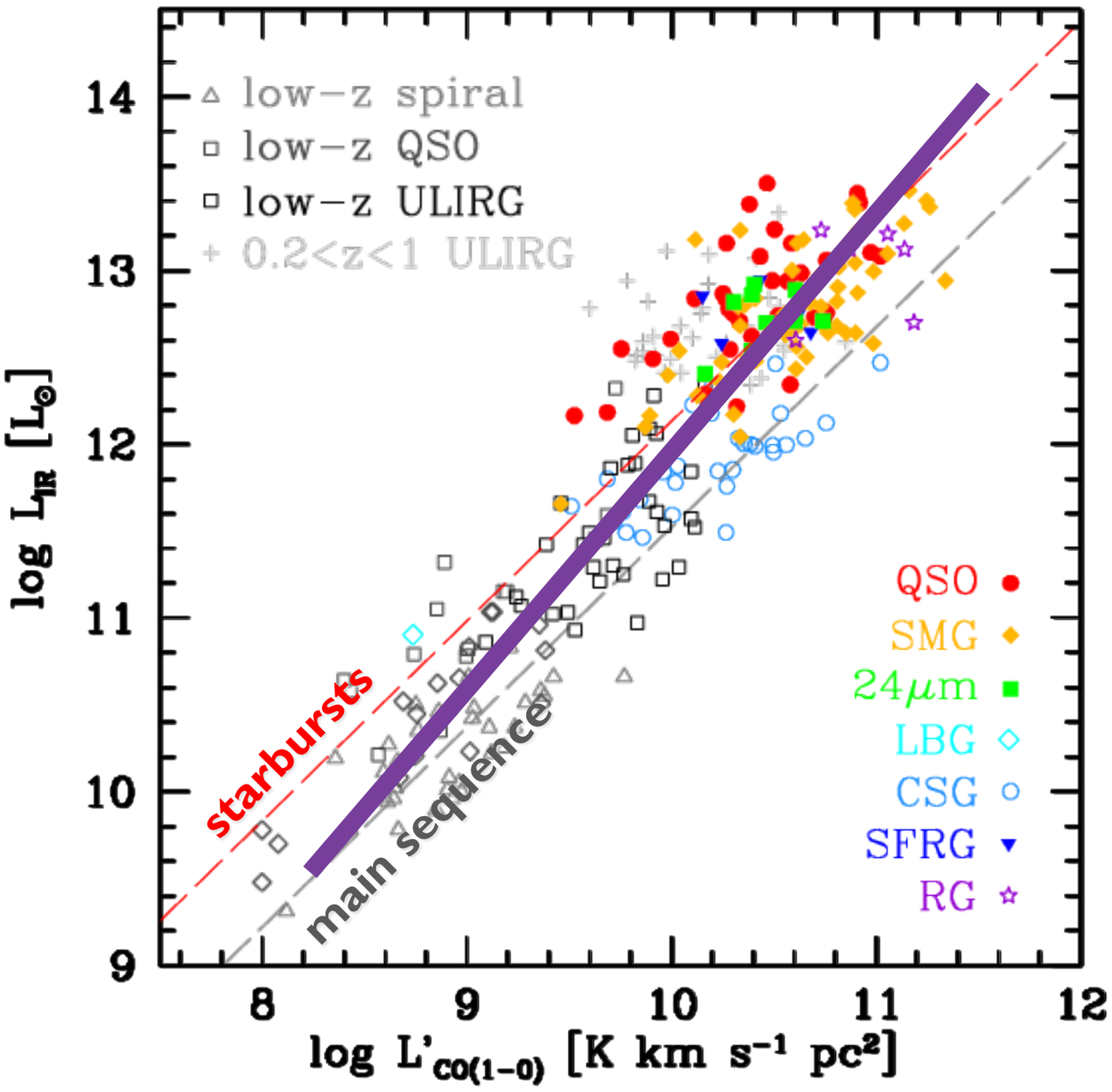
- Most detections in CO, some in [CII]

- **all observations targeted — i.e. pre-selection by SF**

Carilli & Walter 2013 ARAA

the ‘star formation law’

L_{IR} vs L'_{CO} proxy for SFR vs. $M(H_2)$



or: one super-linear relation?
(slope: ~1.4)

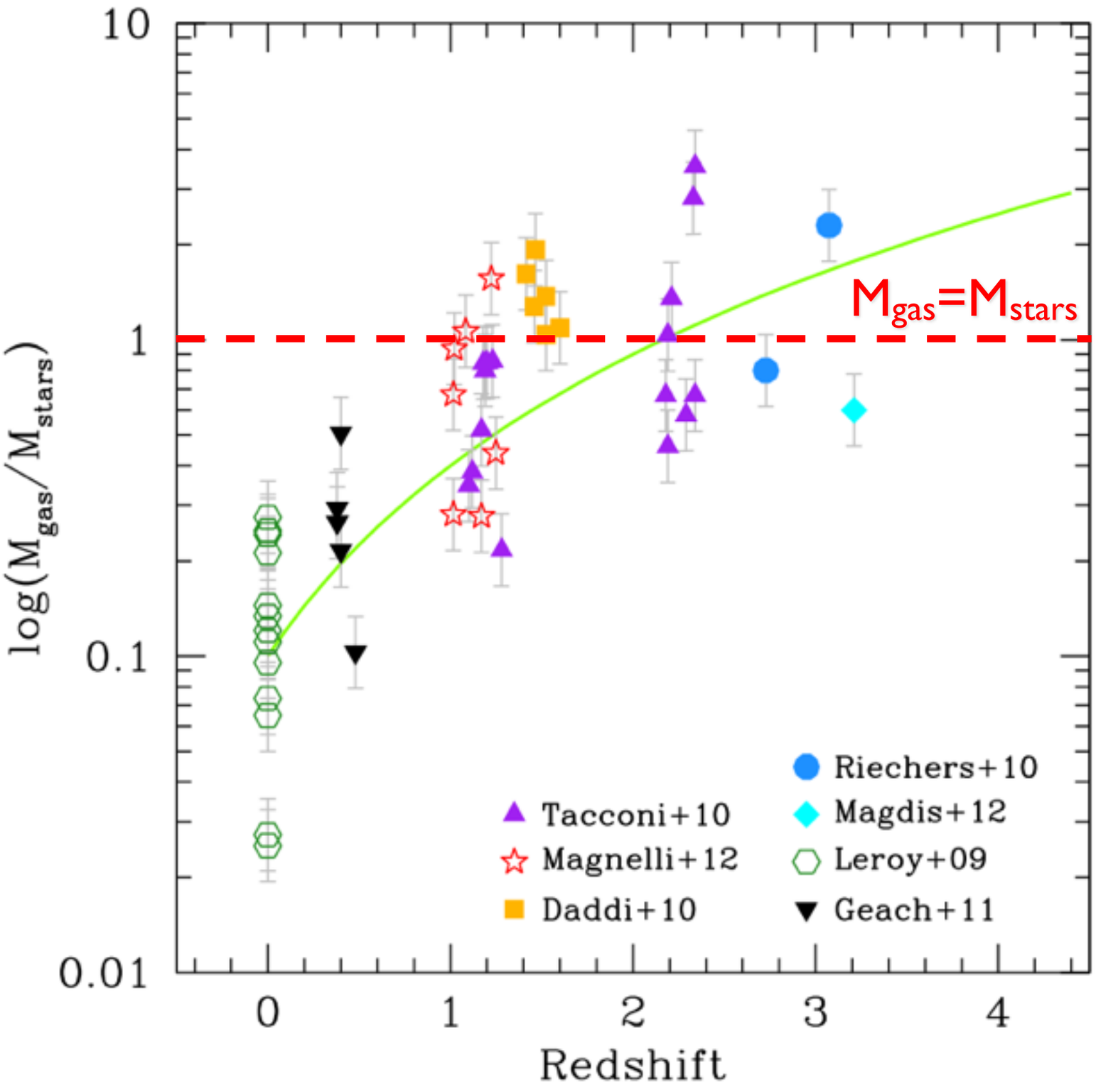
alternatives:

- 2 sequences (MS/starburst) with 1Gyr and 0.1 Gyr depletion times
- Bimodal or running conversion factor

…many subtleties…

Carilli & Walter 2013 ARAA, after Daddi et al. 2010, Genzel et al. 2010

gas fractions (M_{gas} / M_{stars})



MS galaxies only:

same X_{CO}, same stellar masses

gas fraction increases by an order of magnitude to z=2

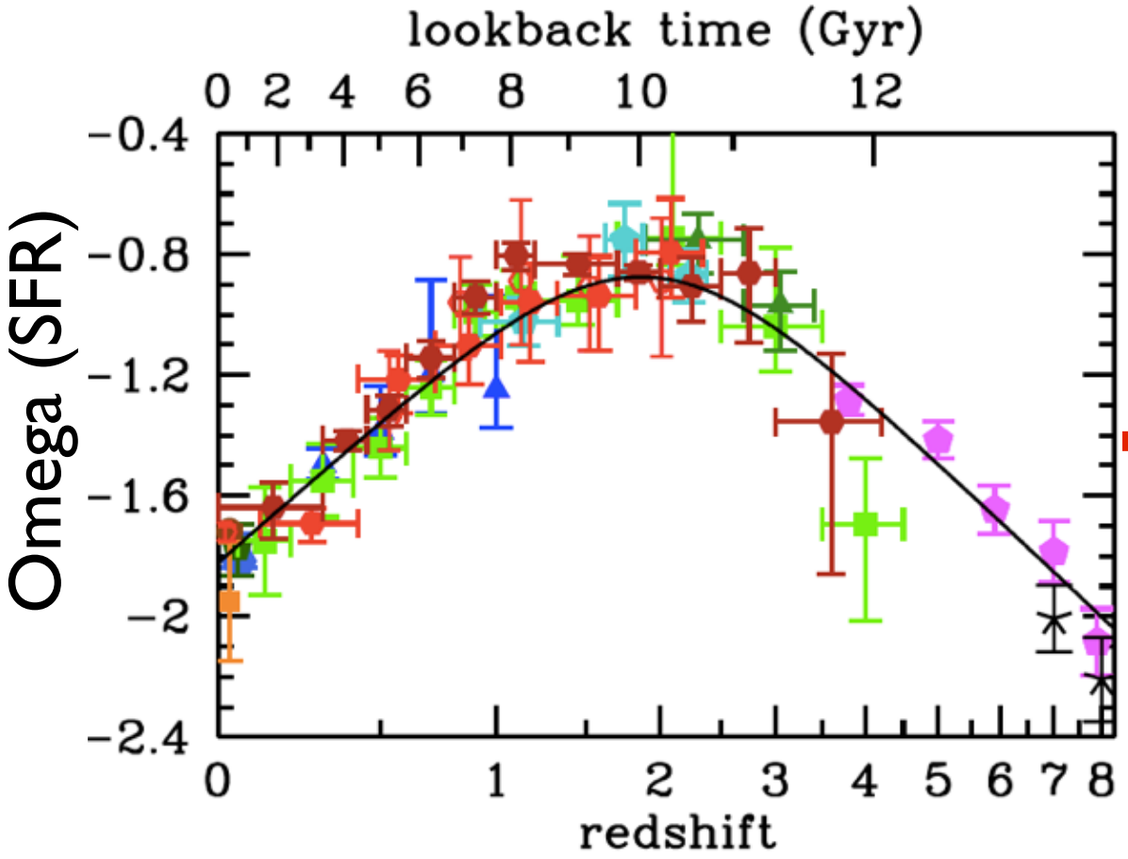
note: same increase as in

— star formation rate density

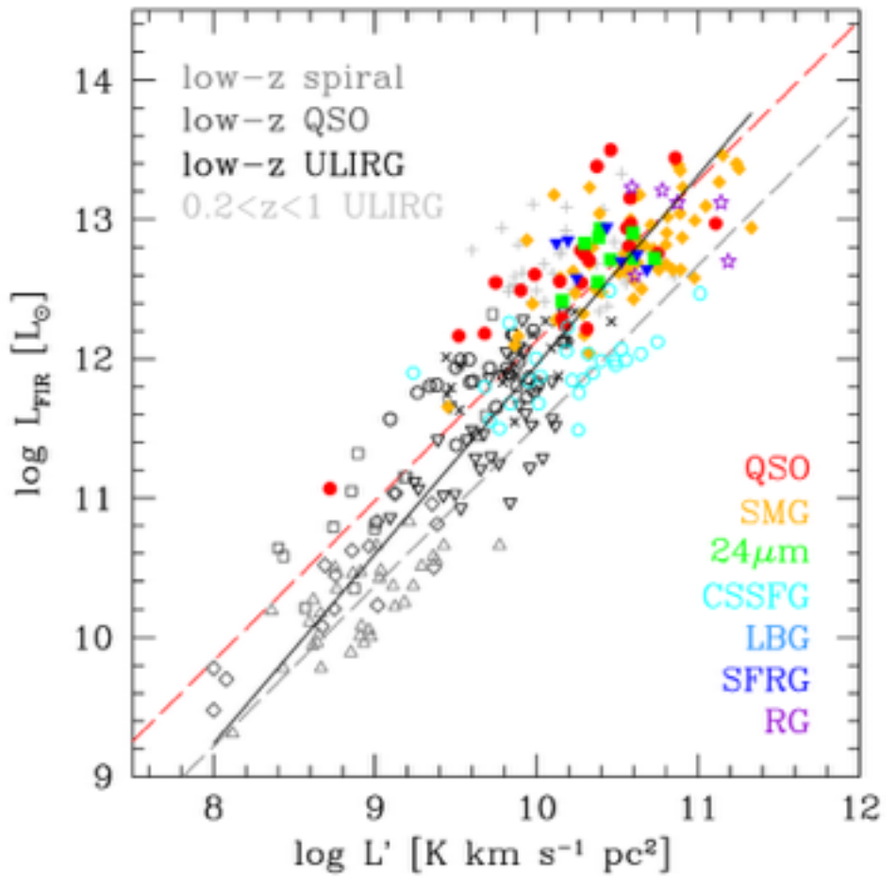
— specific star formation rate

Carilli & Walter 2013 ARAA; after Magdis et al. 2012 see also Saintonge et al 2013

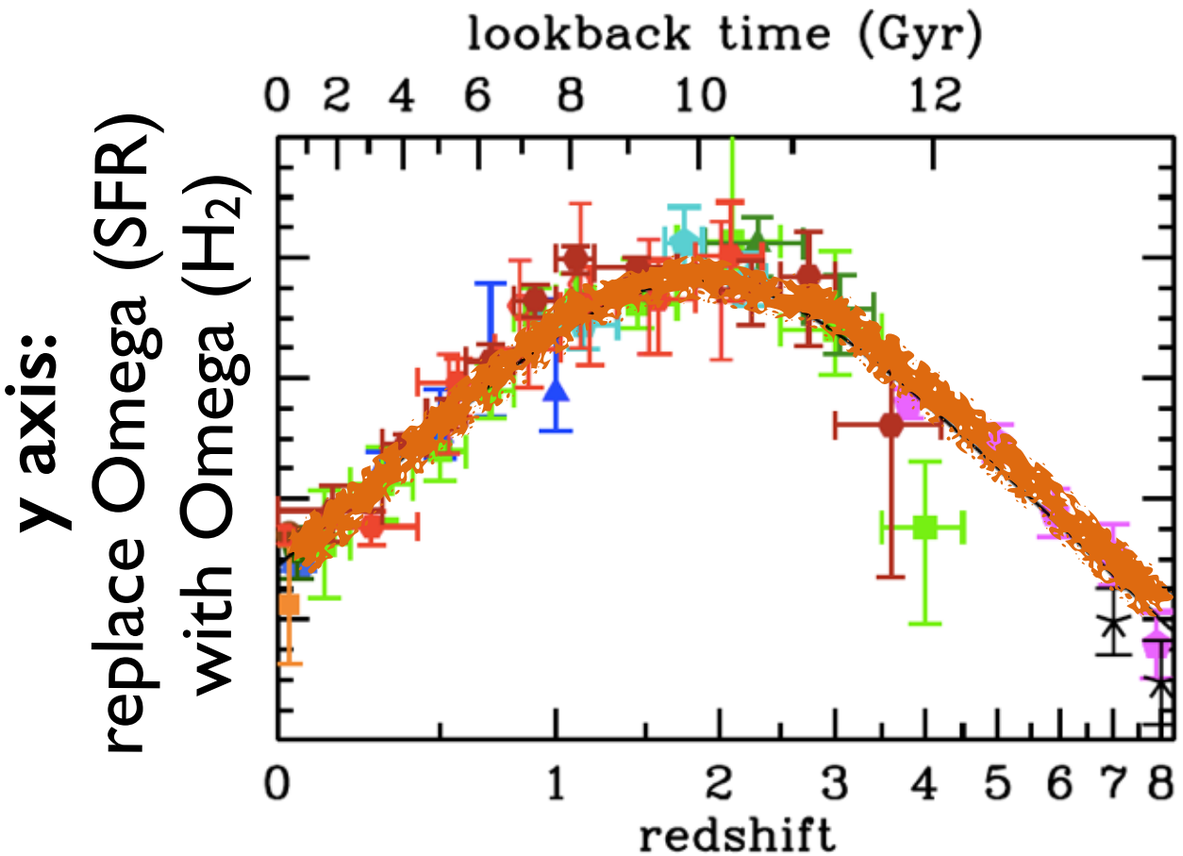
inversion of the SF law?



+



=



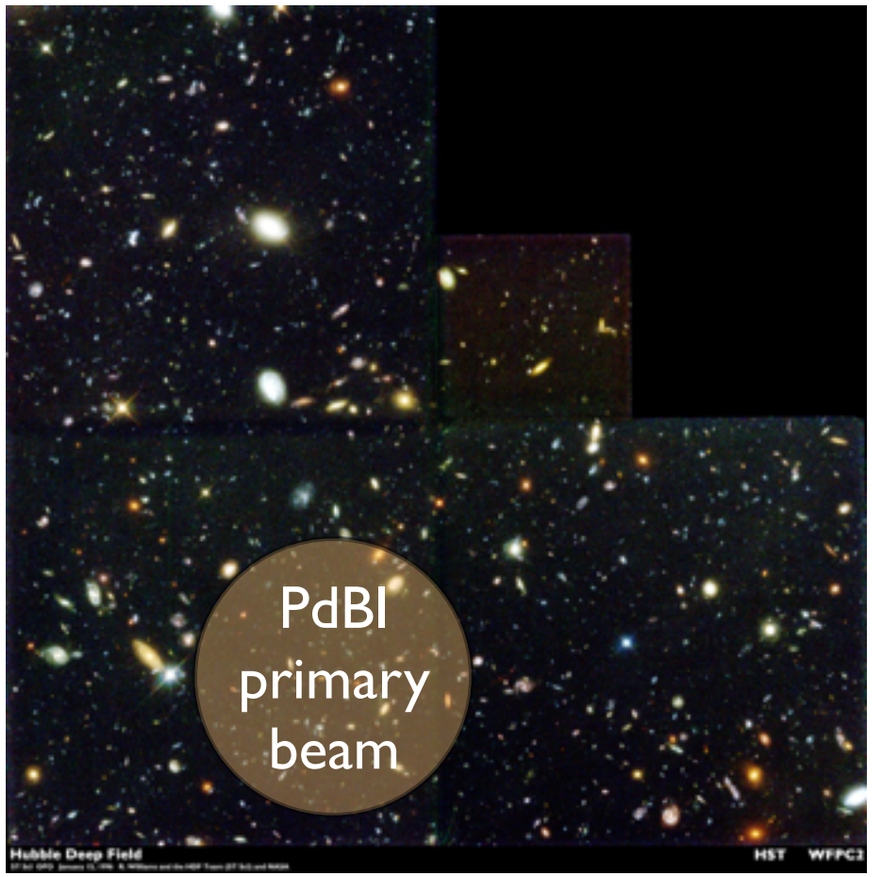
is this the answer?

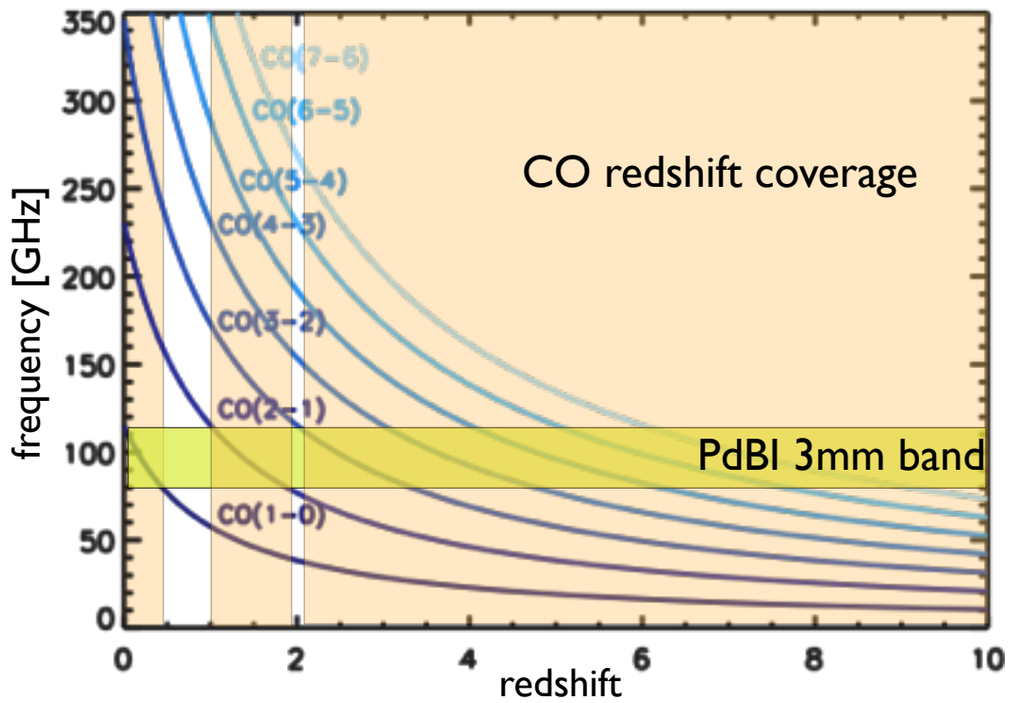
need unbiased census of molecular gas

first molecular deep field (HDF)

covered full 3mm band in 10 frequency settings

[3mm band: low-J coverage, highest fractional BW, largest PB]



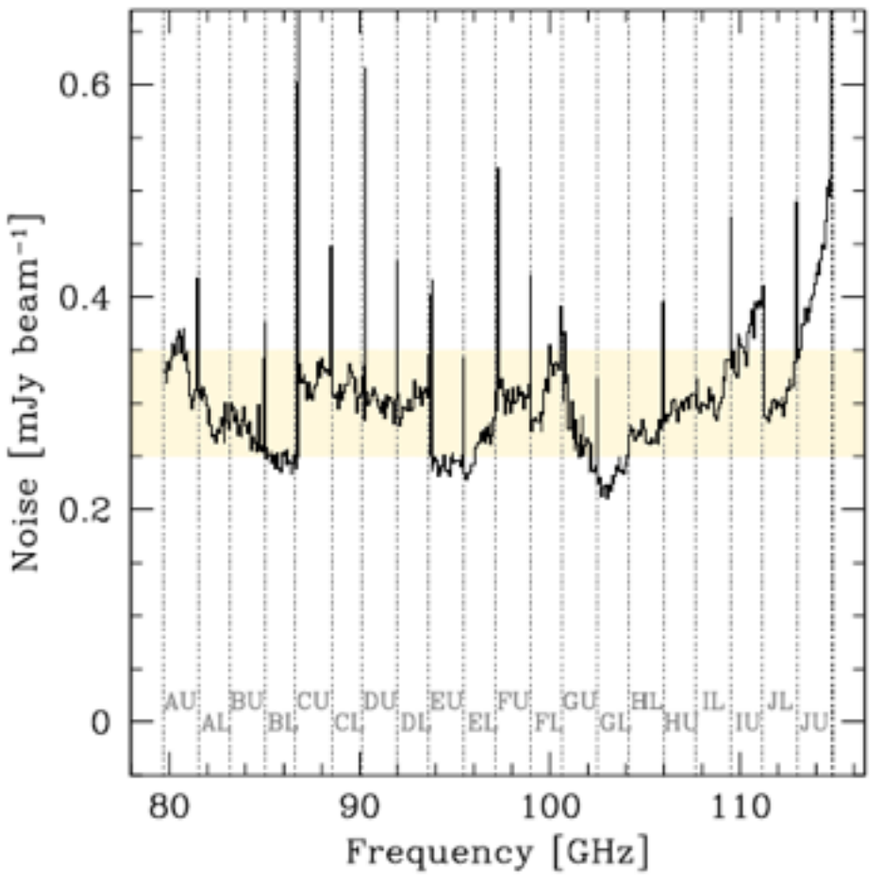


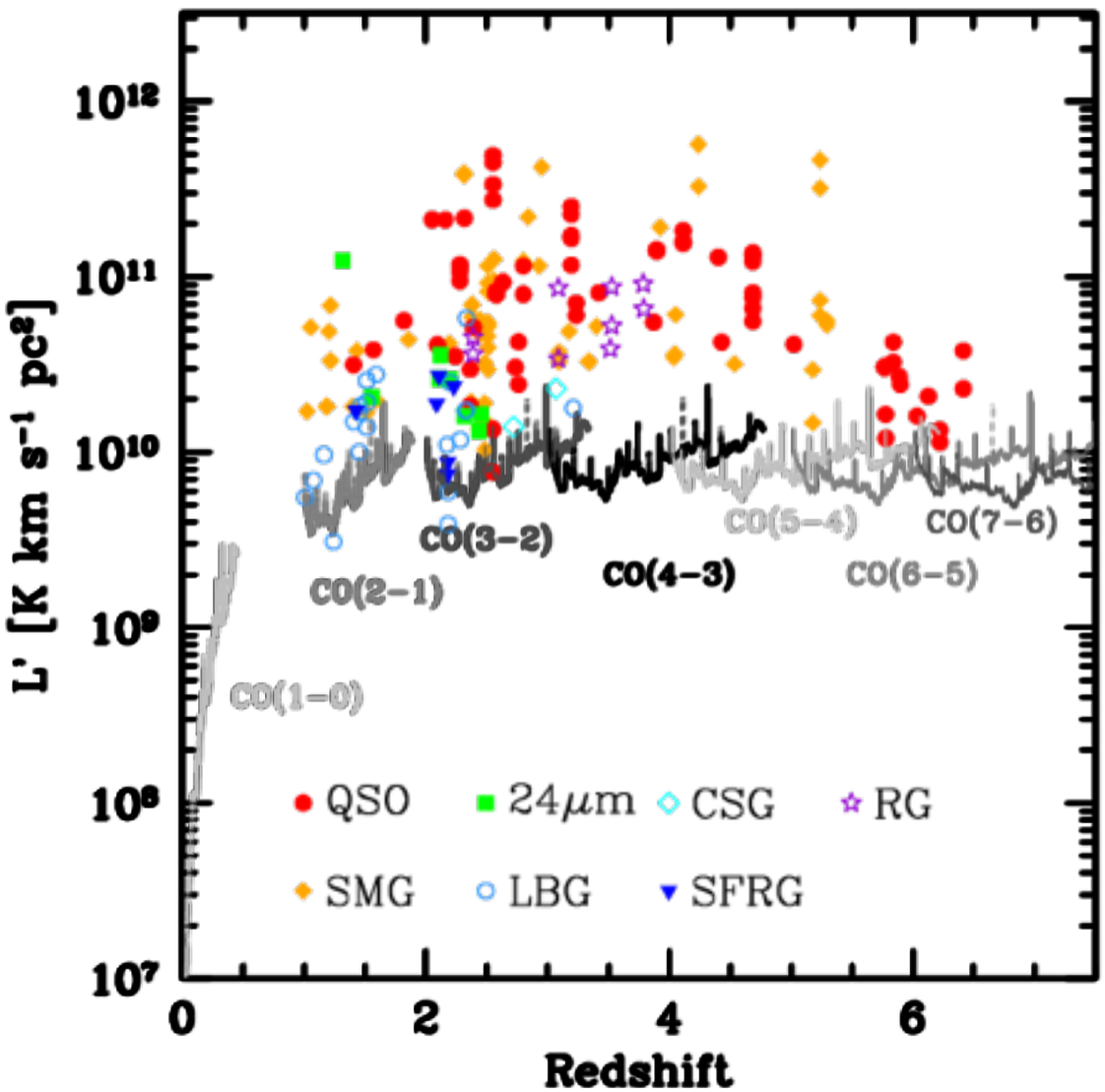
almost complete redshift coverage

line	z_{min}	z_{max}	$< z >^a$	Volume^b Mpc^3
CO(1–0)	0.0041	0.446	0.338	91.66
CO(2–1)	1.01	1.89	1.52	1442
CO(3–2)	2.01	3.34	2.75	2437
CO(4–3)	3.02	4.78	3.98	2966
CO(5–4)	4.02	6.23	5.21	3249

molecular deep field: survey setup

PdBI ~100 hr on-source
10 freq. setups, ~const σ



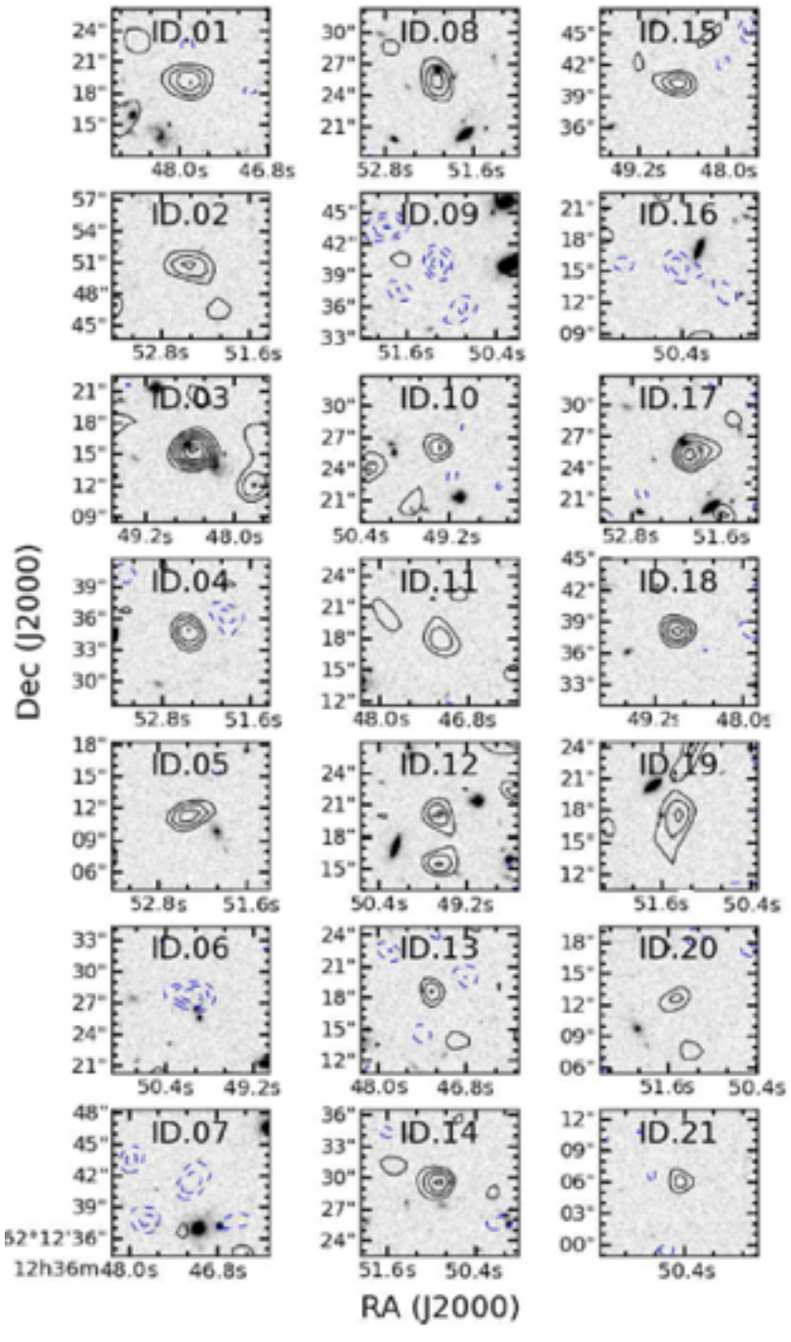


sensitivity such that all previously detected high-z sources would be detected.

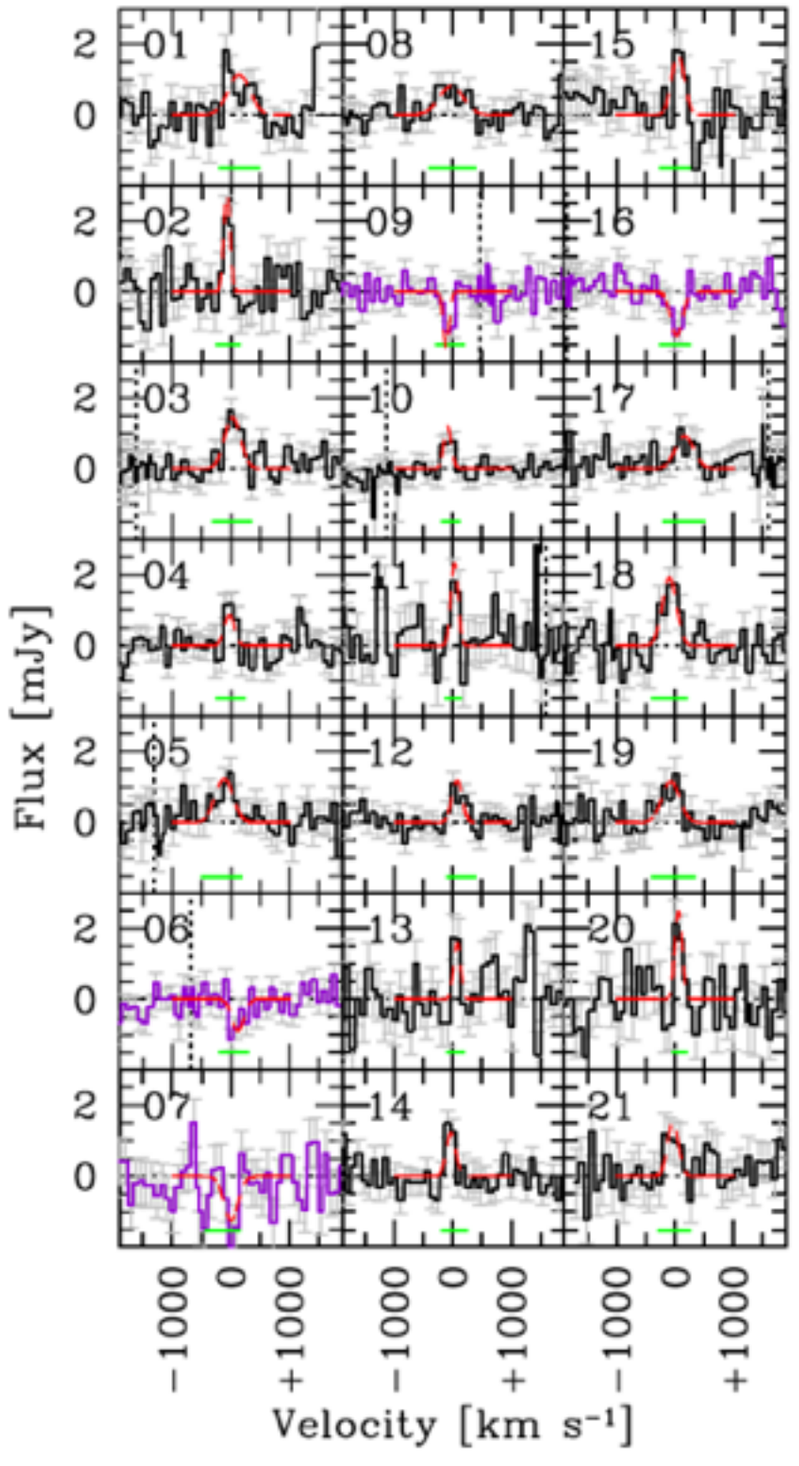
Decarli et al. 2014

molecular deep field: line candidates

Maps



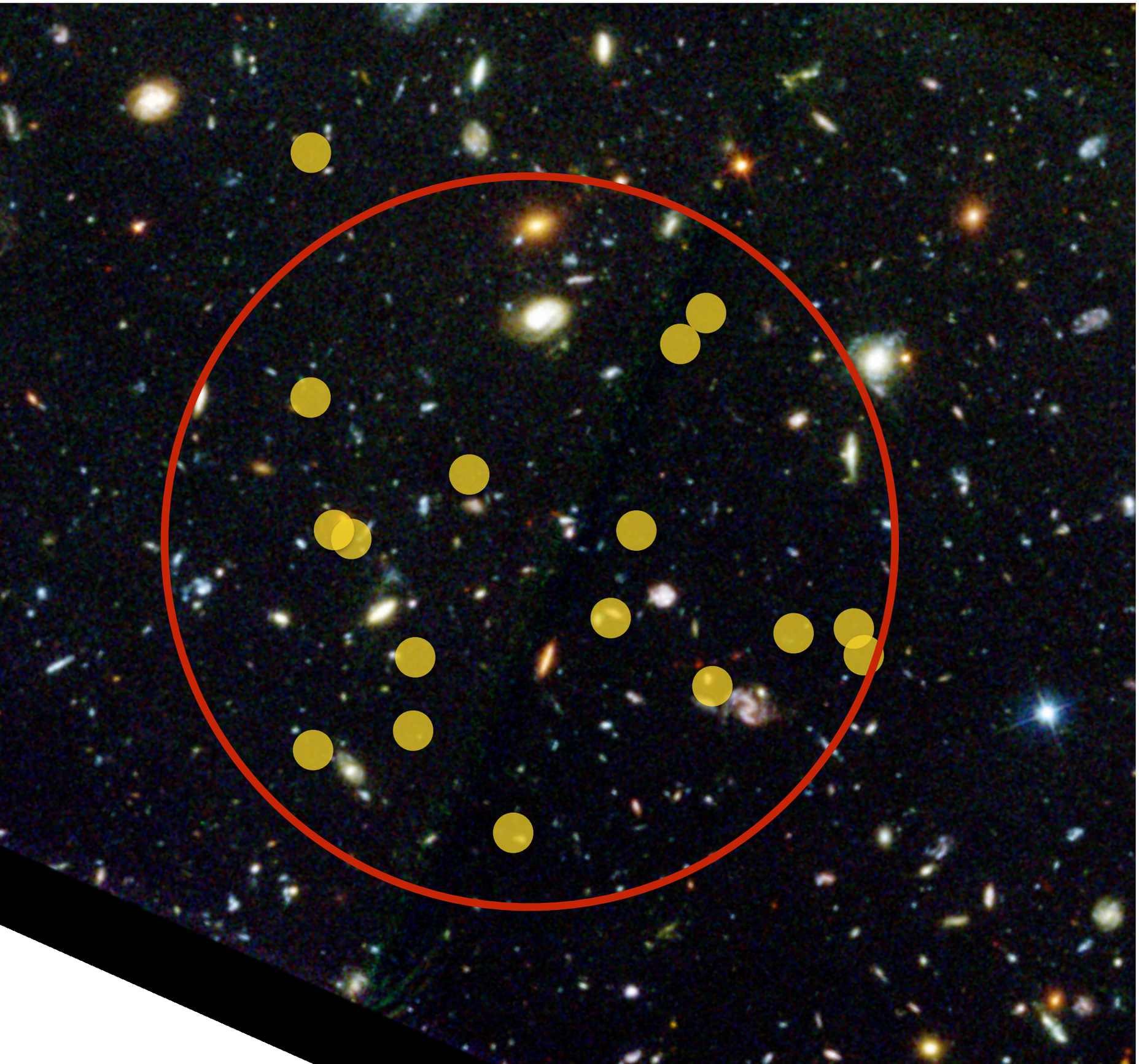
Spectra



total of 21 IDs,
4 ‘negative’

Decarli et al. 2014

molecular deep field: location of line candidates

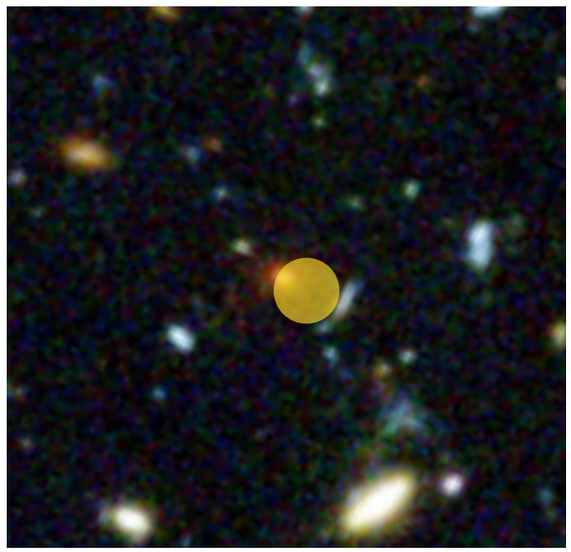


position of CO line candidates

Decarli et al. 2014

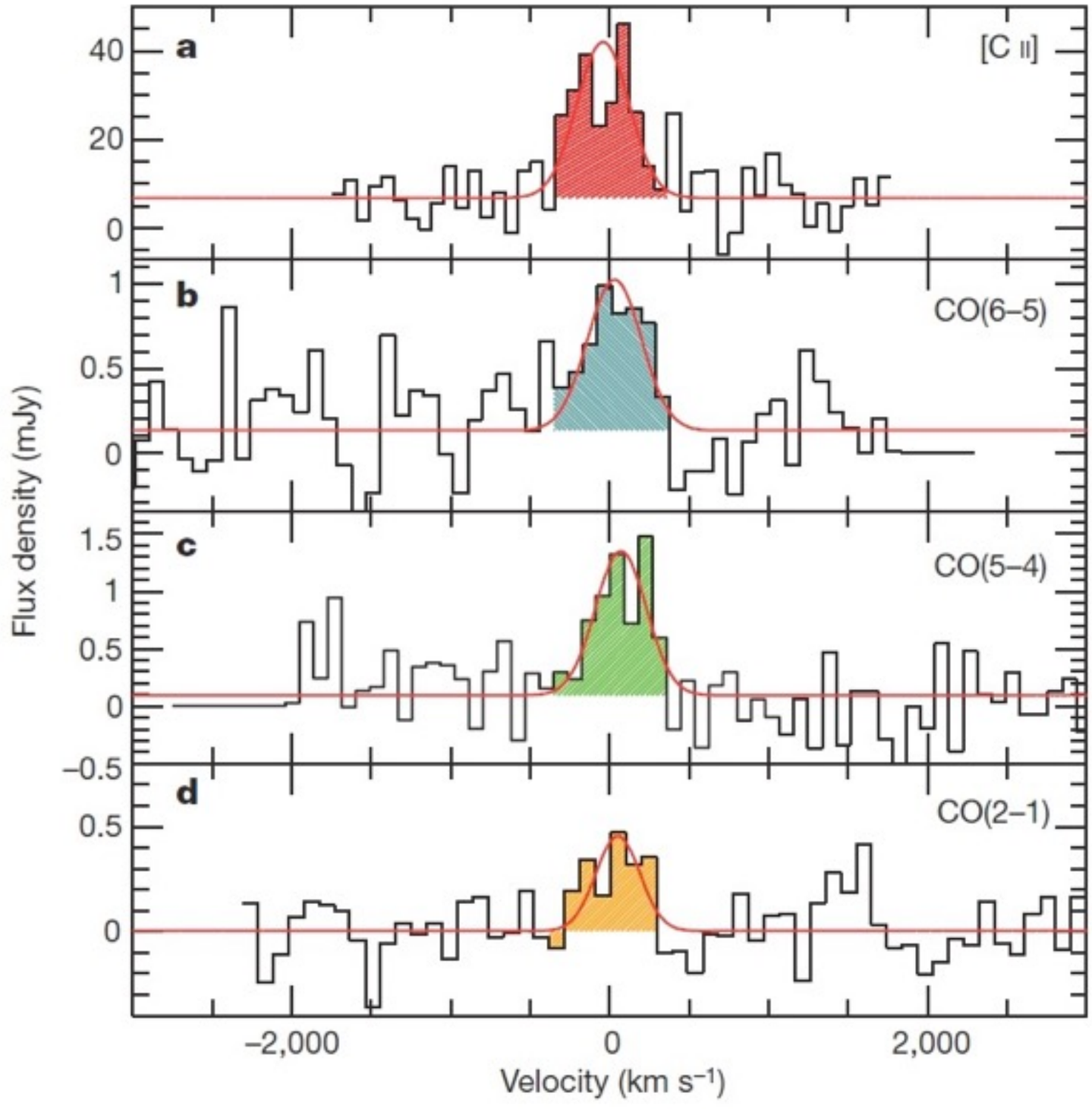
molecular deep field: blind detections

ID.08 & ID.17



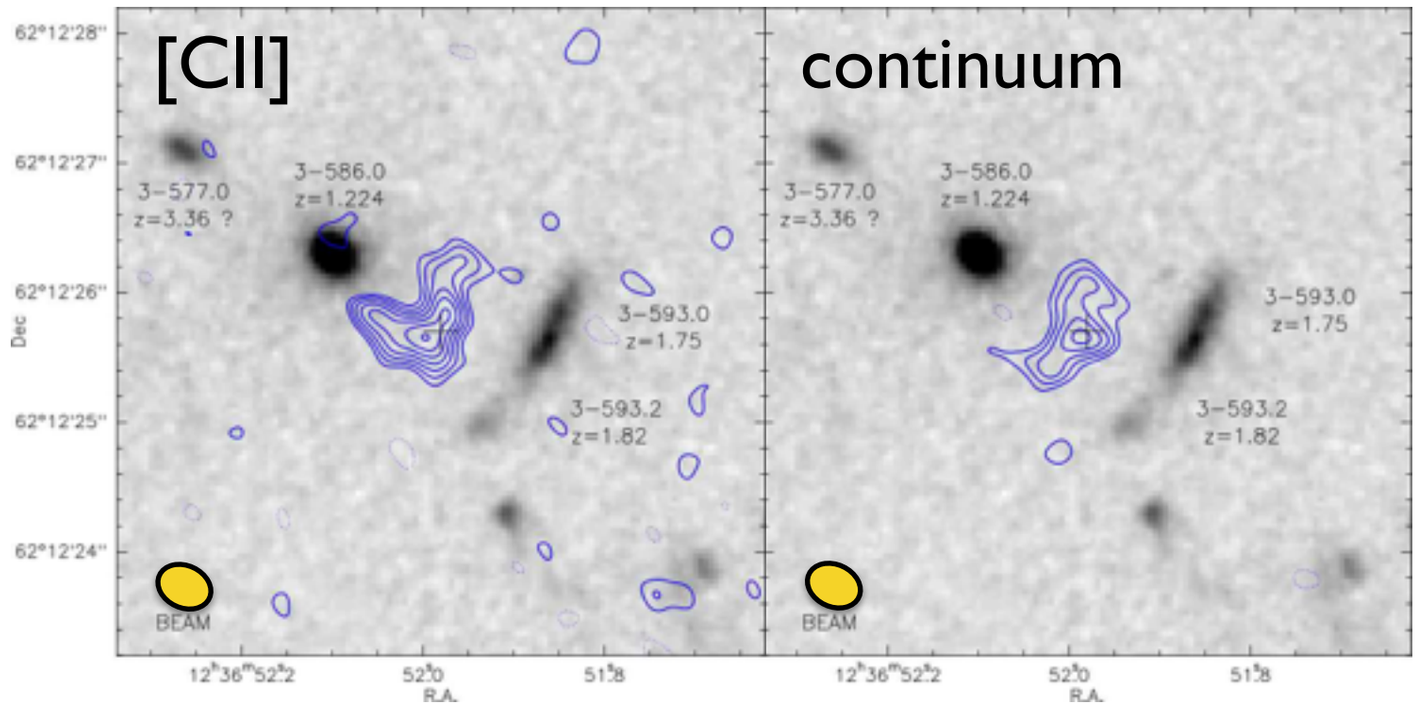
spatially coincident IDs

this corresponds to HDF850.1 — z=5.183



Walter et al. (2012)

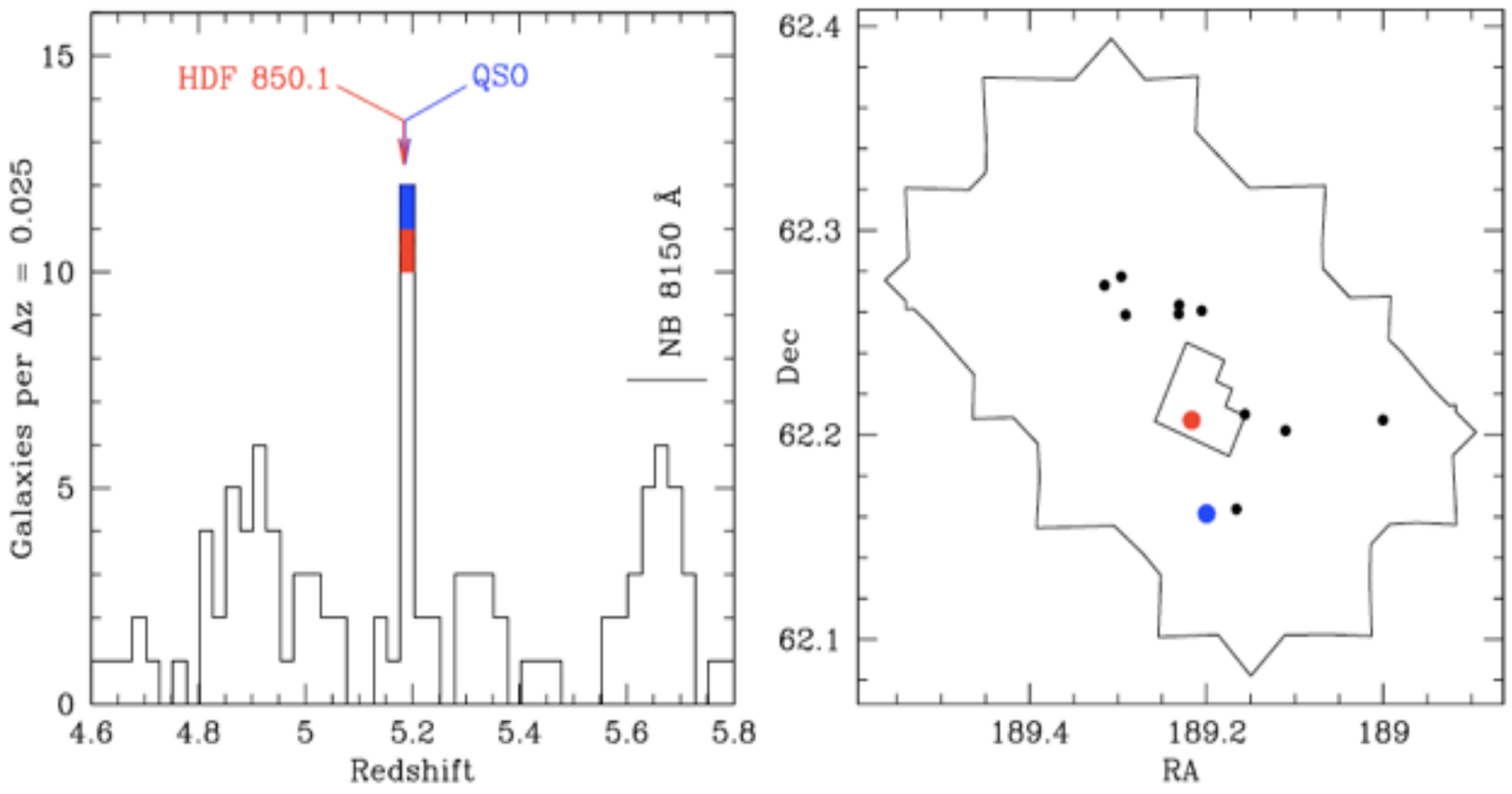
HDF850.1: precise location and environment



precise location and redshift: **no counterpart** identifiable in HST.

dynamics at 0.3" (1.8kpc) consistent with merger

Neri et al. (2014)



source is located in galaxy **overdensity** at z=5.2, including one quasar

Walter et al. (2012)

molecular deep field: blind detections

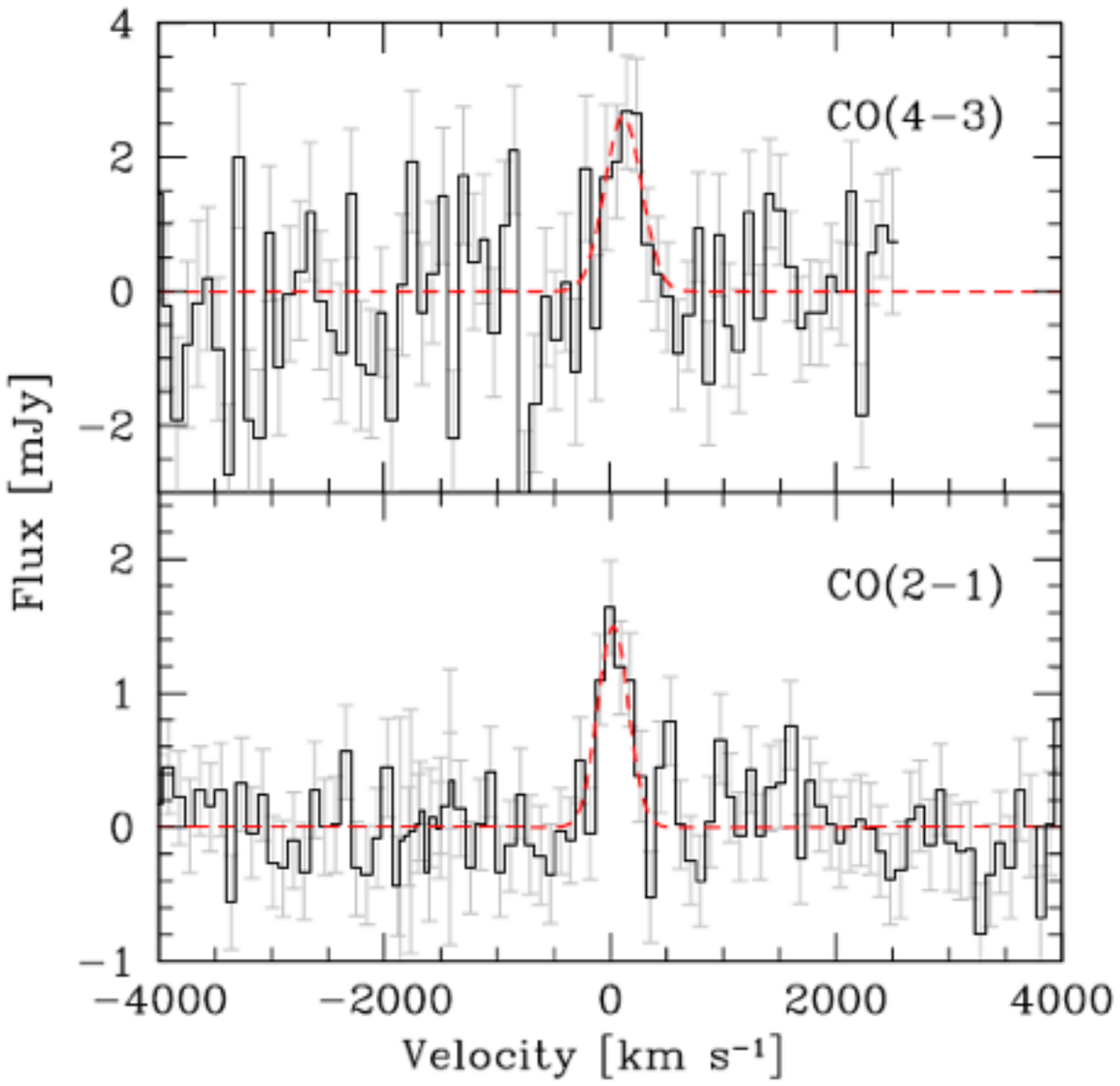
ID.03

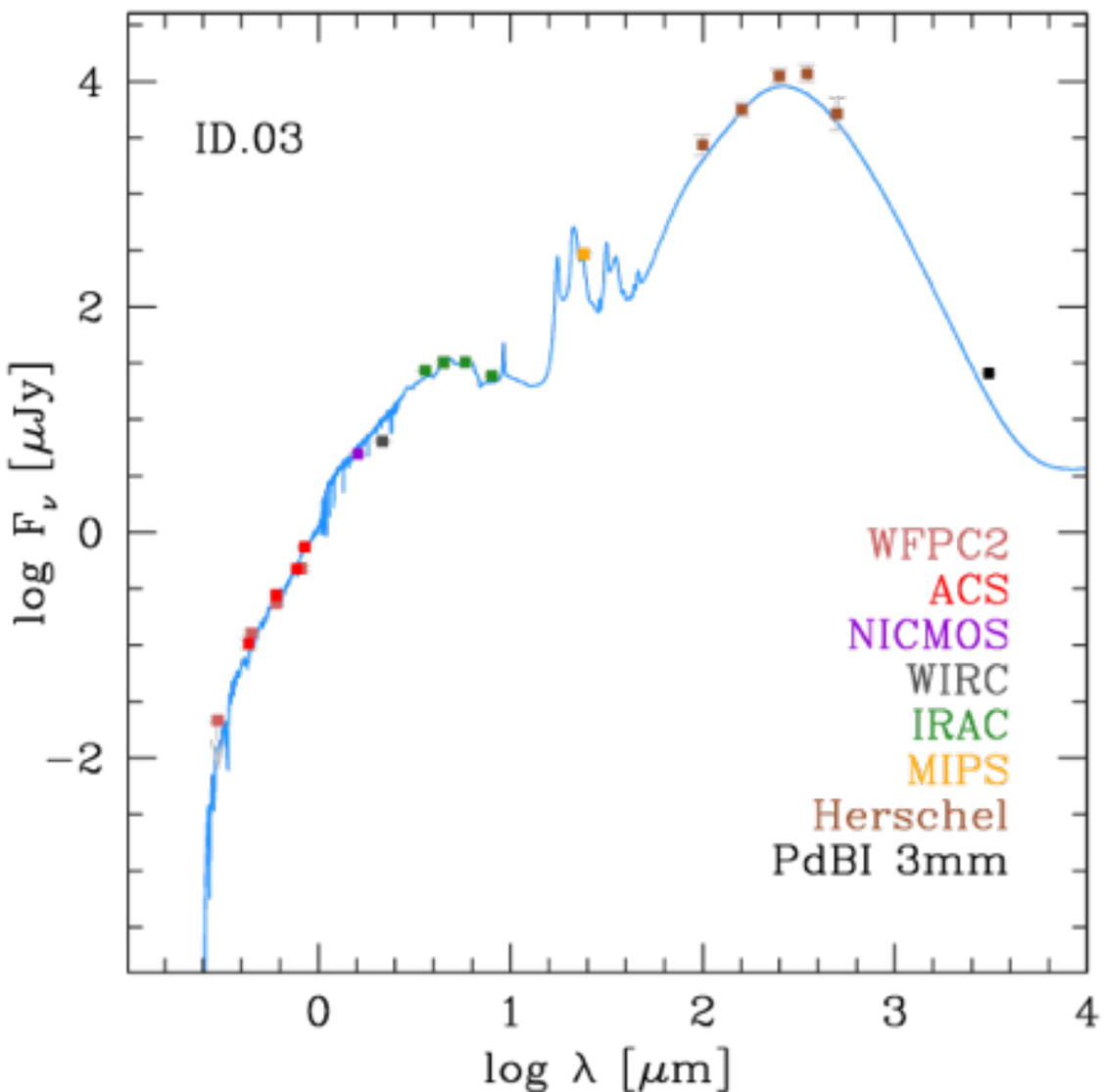
most secure line in scan, 'BzK' galaxy

z=1.784 SMG-like excitation

M_{H2}=9 10^{10} M_{sun} sSFR=0.15 Gyr^{-1}

SFR=38 M_{sun} yr^{-1} M_{star}=2.5 10^{11} M_{sun}





molecular deep field: blind detections

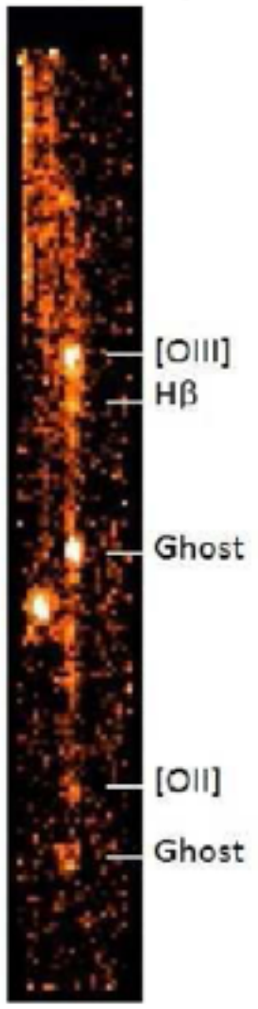
ID.19

only one CO line, but HST grim spectroscopy nails z=2.047

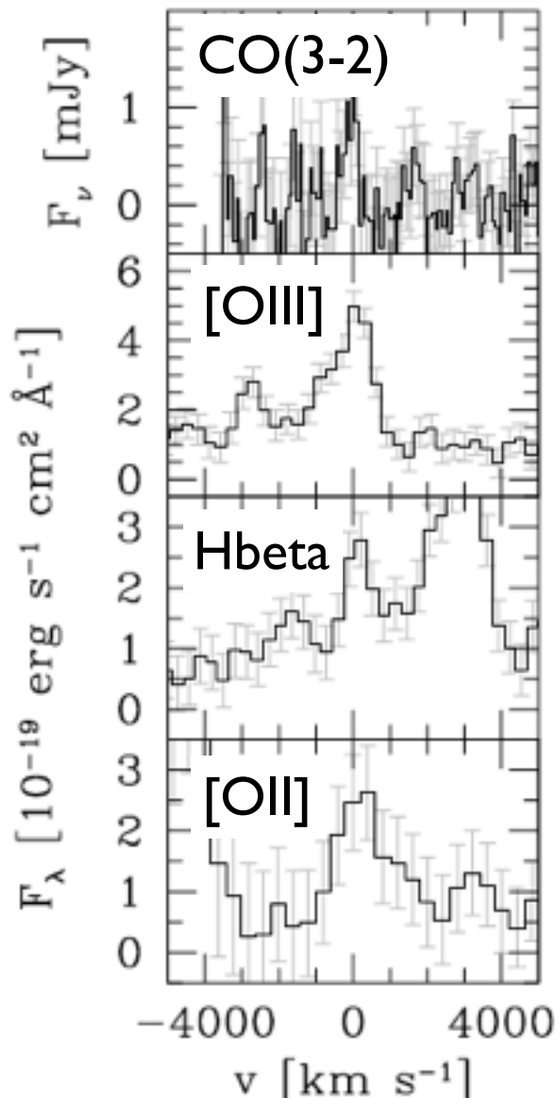
M_{H2}=1.3 10^{11} M_{sun} sSFR=0.4 Gyr^{-1}

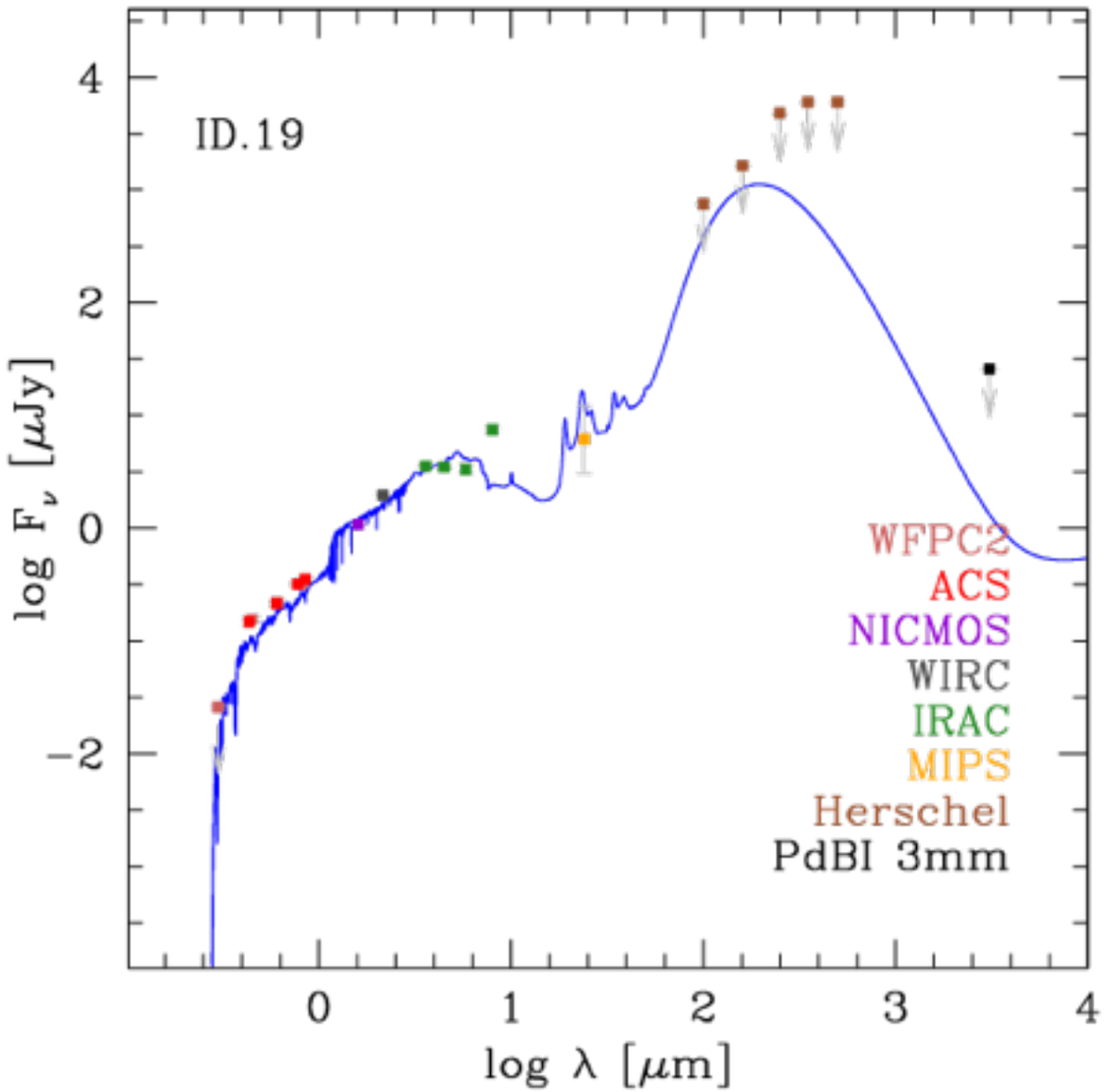
SFR=8 M_{sun} yr^{-1} M_{star}=1.9 10^{10} M_{sun}

HST GRISM

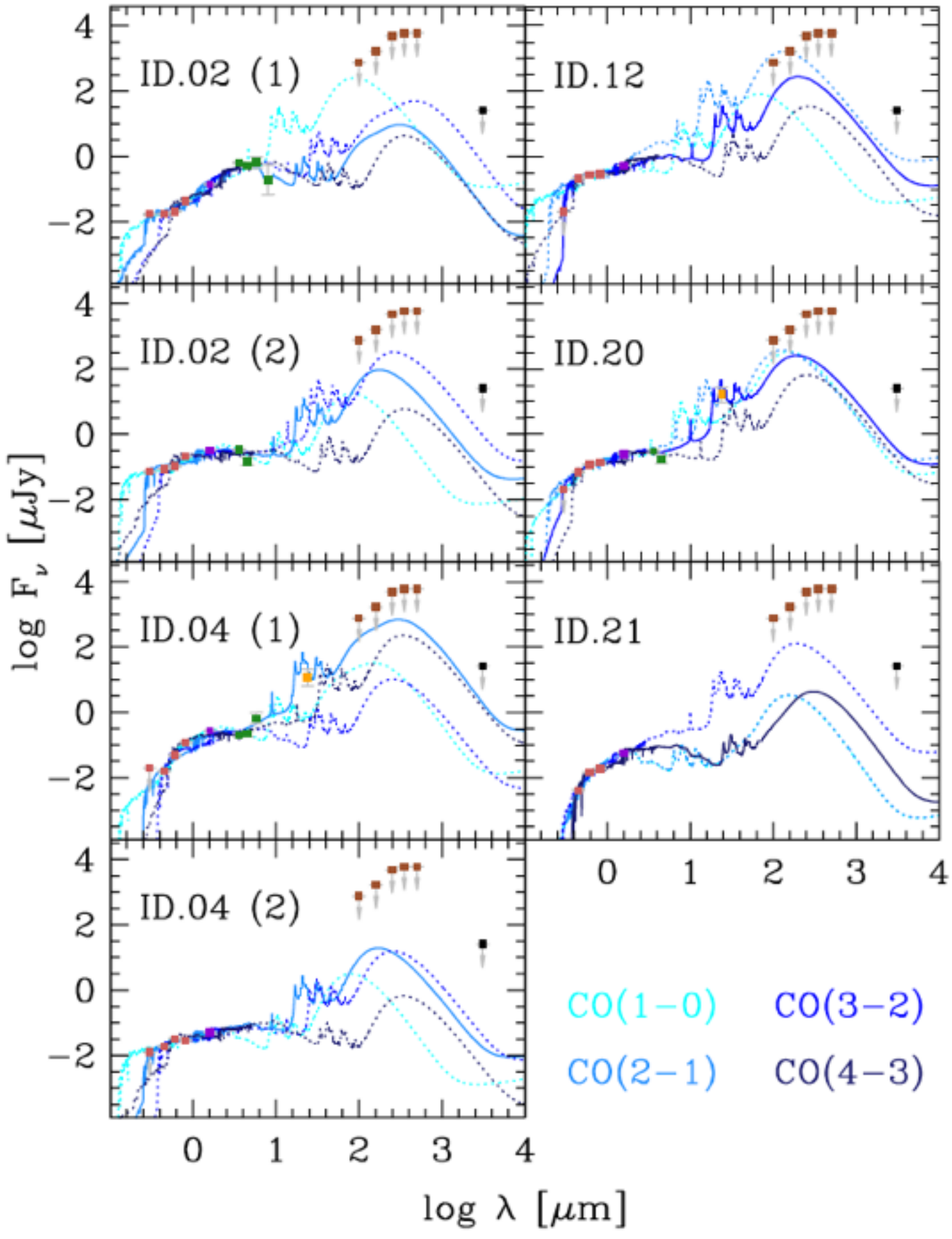


Weiner et al. in prep





molecular deep field: other blind detections

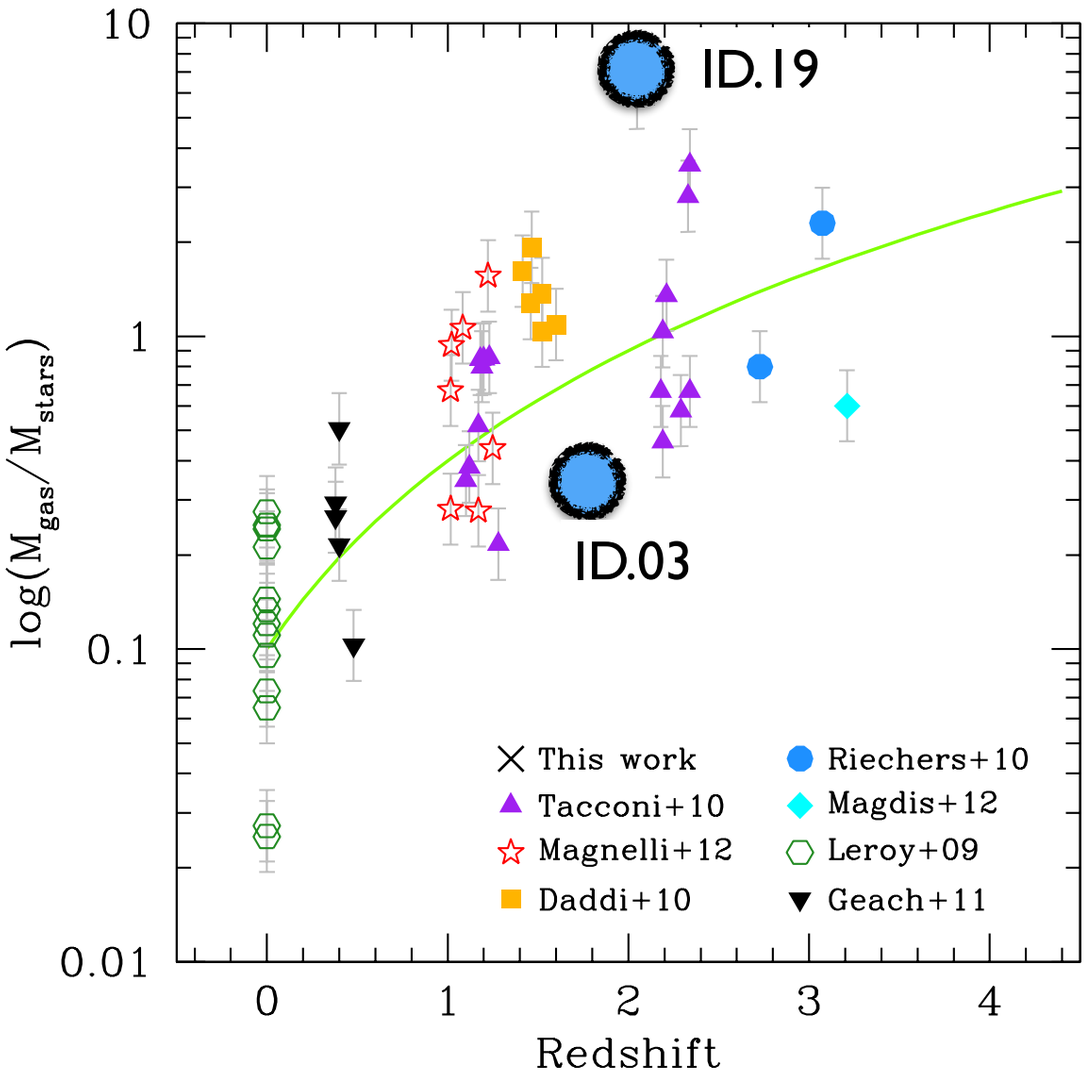


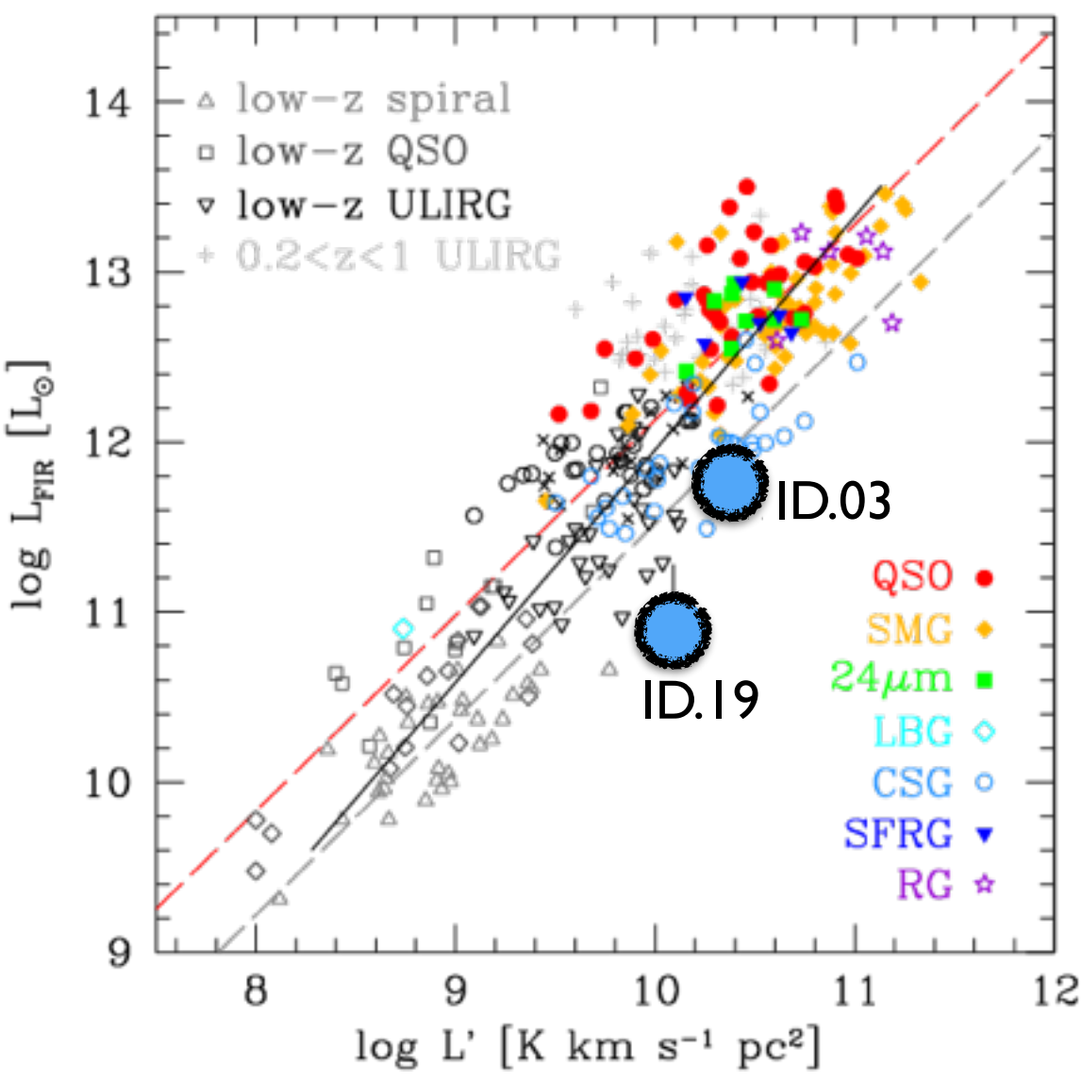
in case we only have one CO line:

assigned 'most likely z' for other candidates based on SED

follow-up scheduled

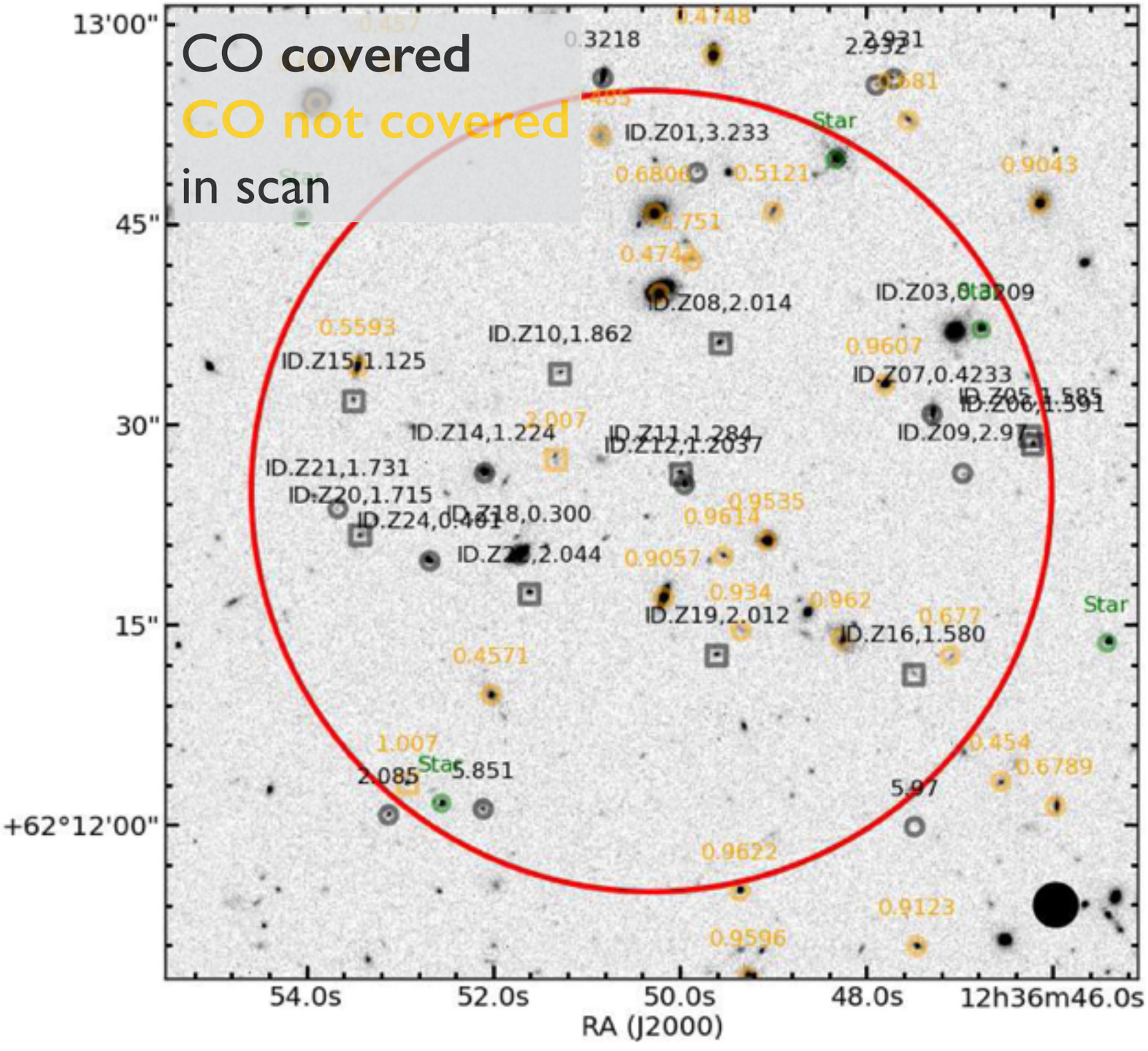
blind detections: gas fractions and location on ‘sf law’





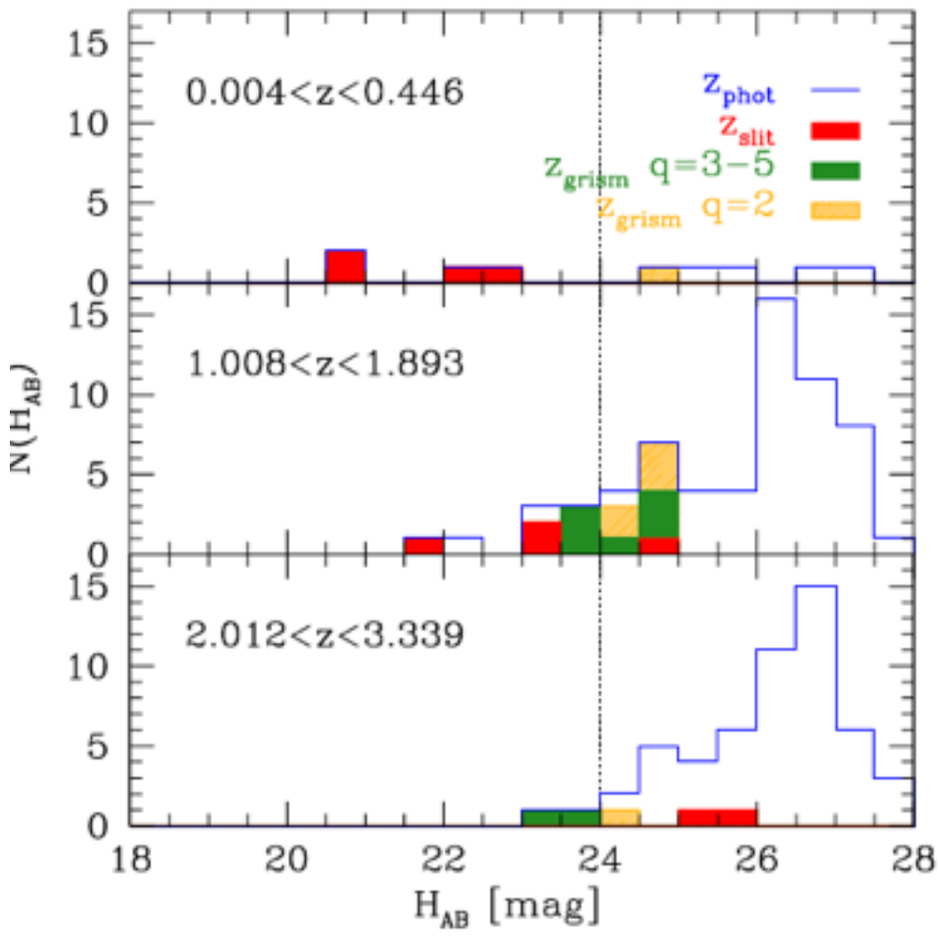
= new blind detections from HDF

CO stacking of galaxies with good z



○ Longslit spec

□ Grism spec

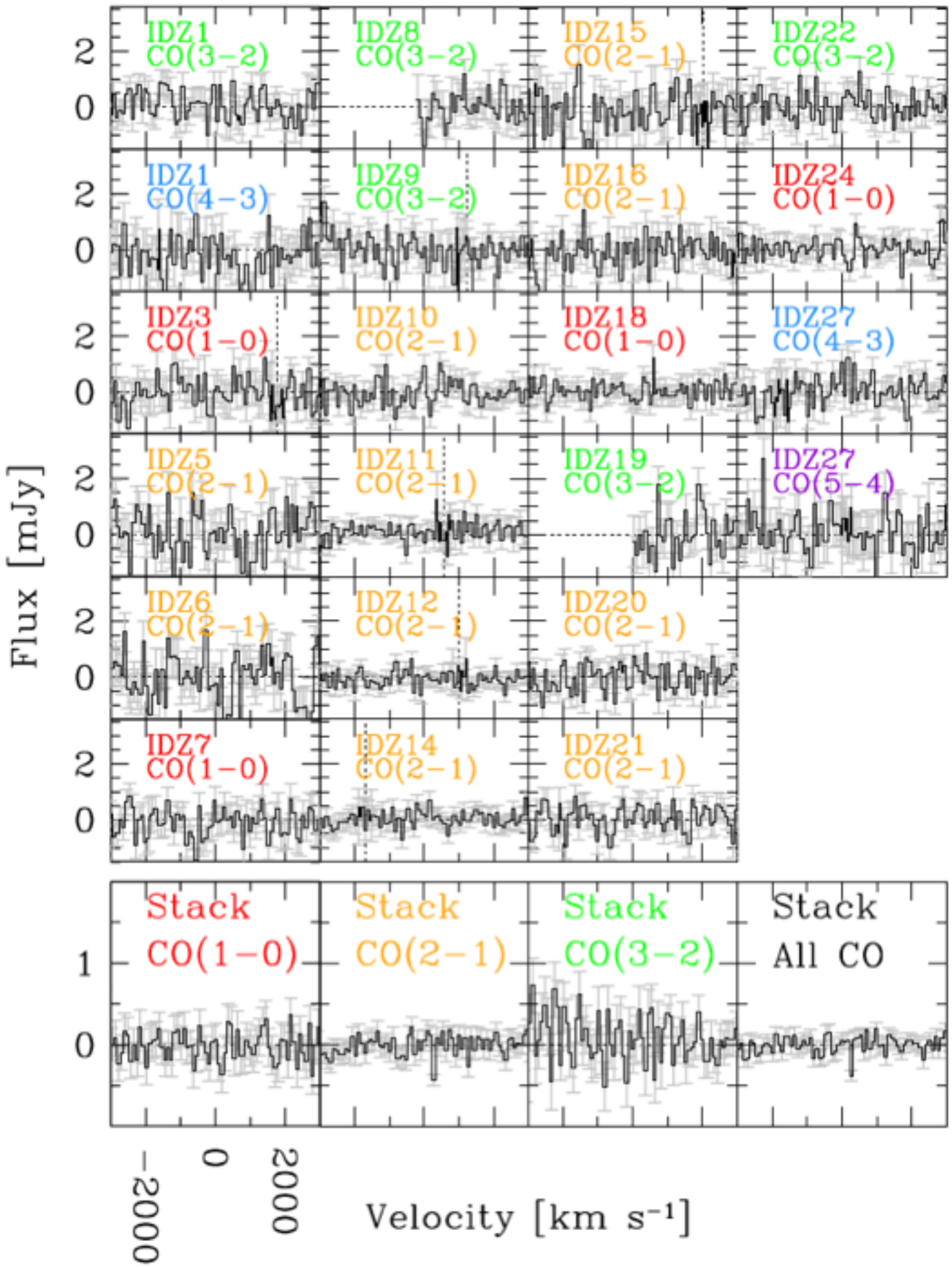


Very complete at m_H<24 mag

M_*~5 10^7 M_{sun}, 3 10^9 M_{sun}, 10^{10} M_{sun}

Walter et al. 2014

CO stacking of galaxies with good z

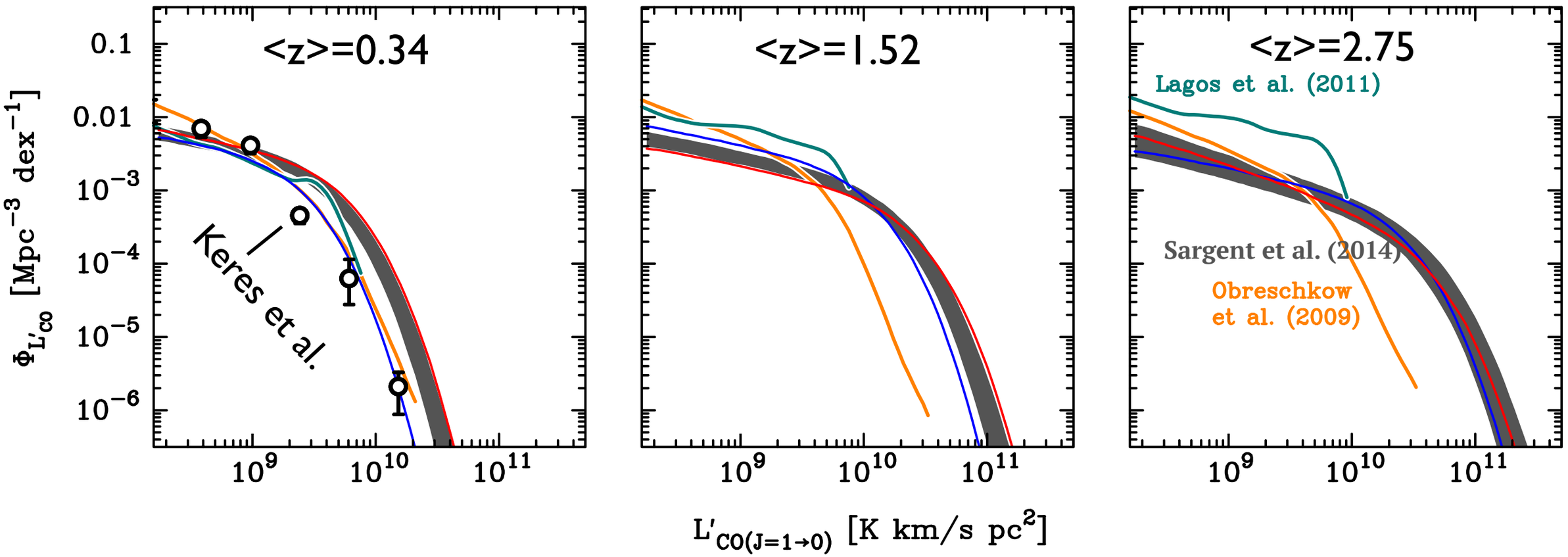


no additional detections towards galaxies w/ spectroscopic redshifts.

CO stack: also non-detection.

Walter et al. 2014

blind constraints: CO luminosity functions



Sargent et al. 2014: empirical predictions

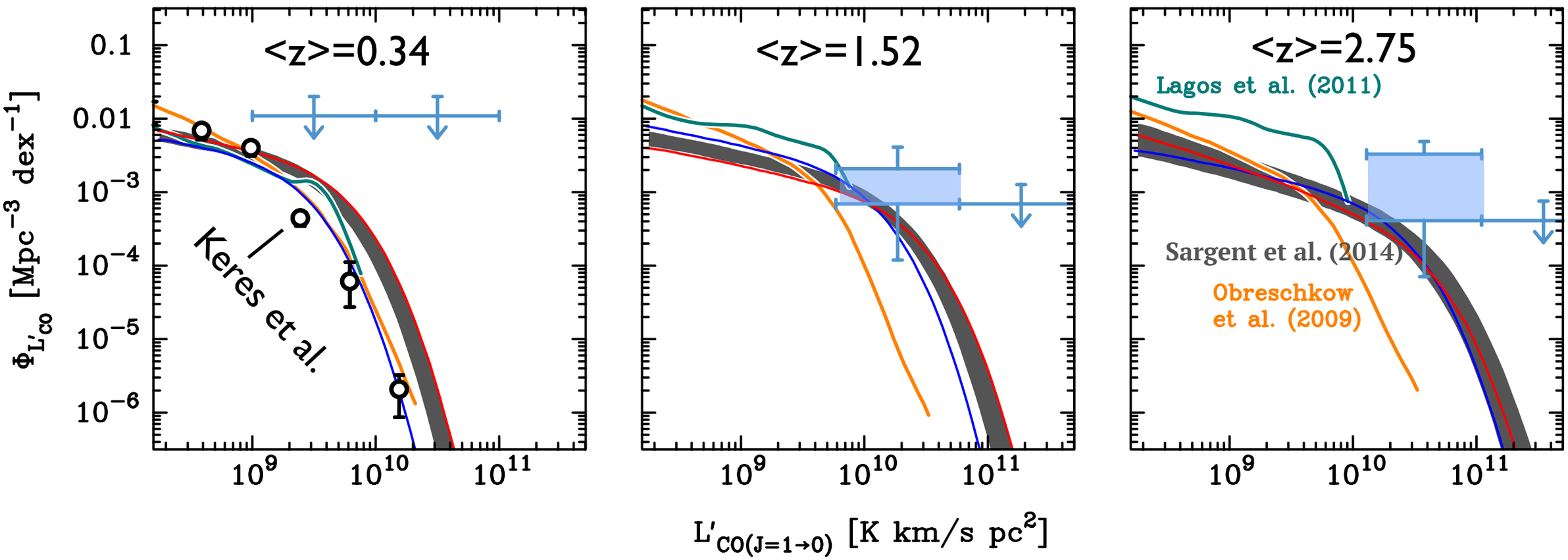
Lagos et al. 2011

Obreschkow et al. 2009

: based on semi-analytical cosmological models + 'recipes'

blind constraints: CO luminosity functions

limits from blind detections in HDF



Sargent et al. 2014

Lagos et al. 2011

Obreschkow et al. 2009

measurements: higher than the predictions

caveats: small number statistics

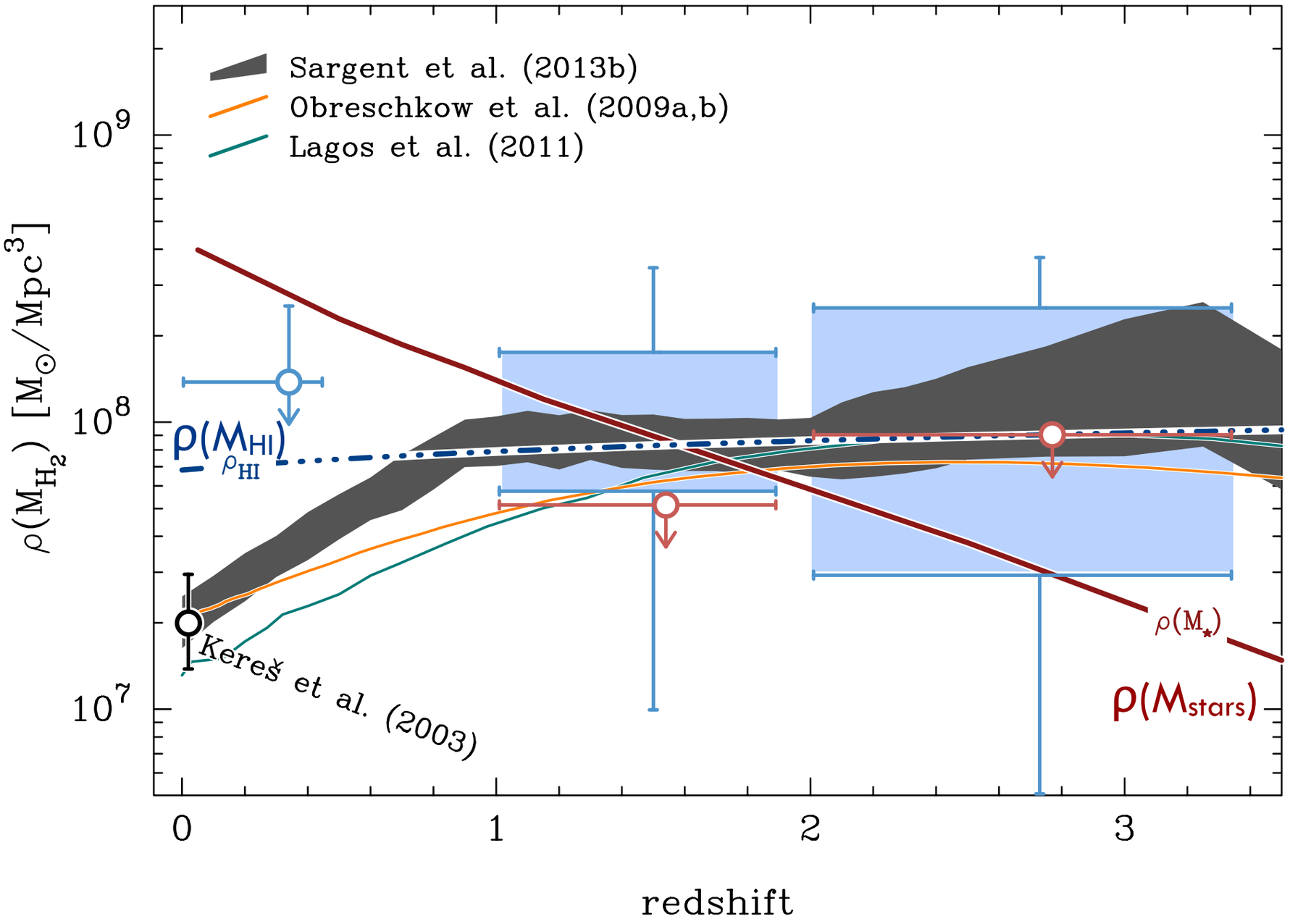
small volume covered

Walter et al. 2014

blind constraints: cosmic H2 density

limits from blind detections in HDF

limits from stack



Walter et al. 2014

our measurements are high compared to SAMs/hydros, though no extrapolation of lum. function

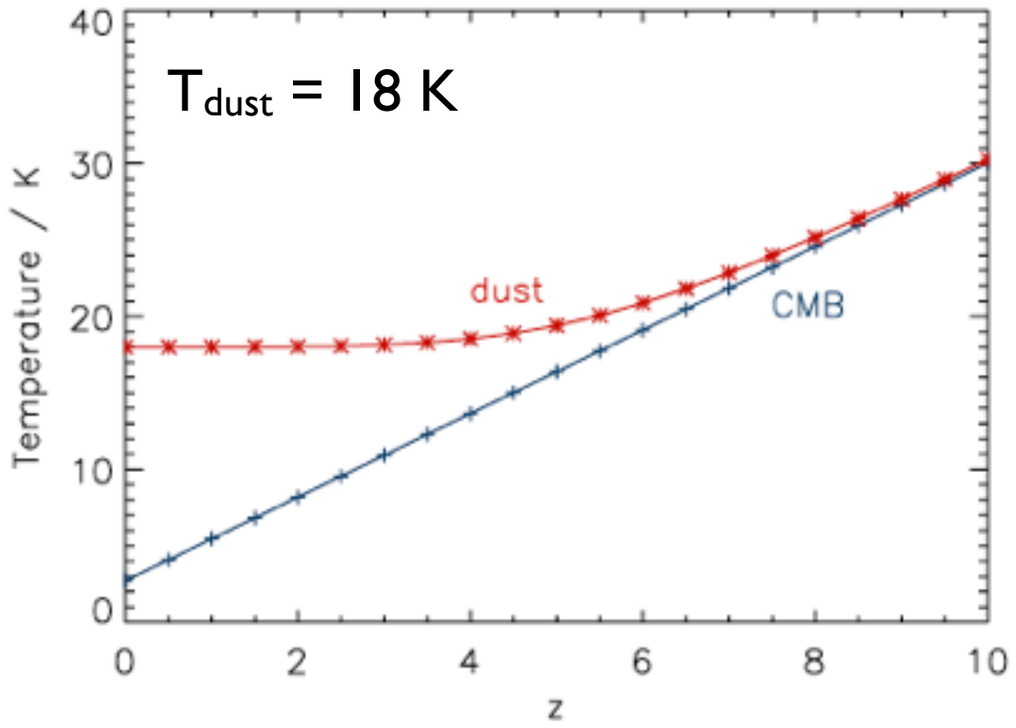
detecting dust & CO at higher z: CMB issue

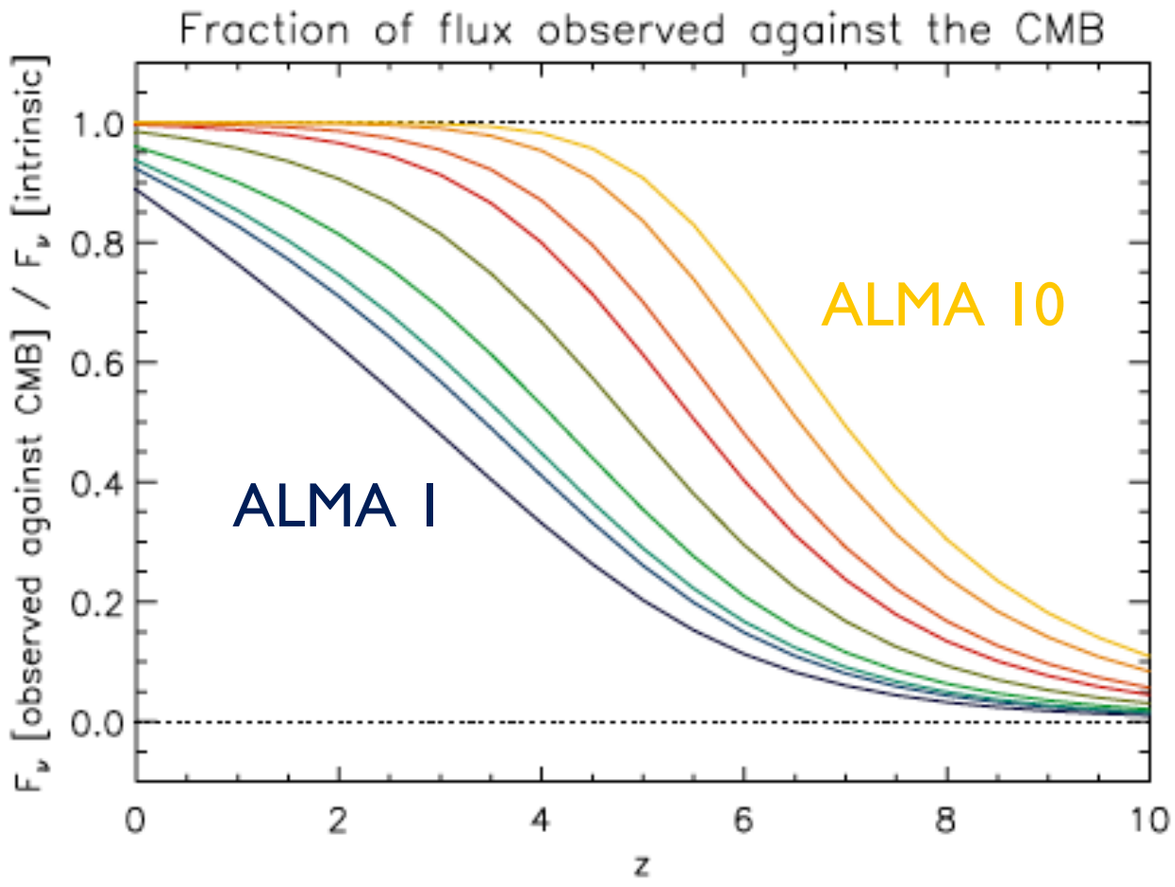
will we loose CO as our main tracer?

problem I: conversion factor too high at low metallicities?

problem II: the CMB works against us

consider dust at 18K (MW)

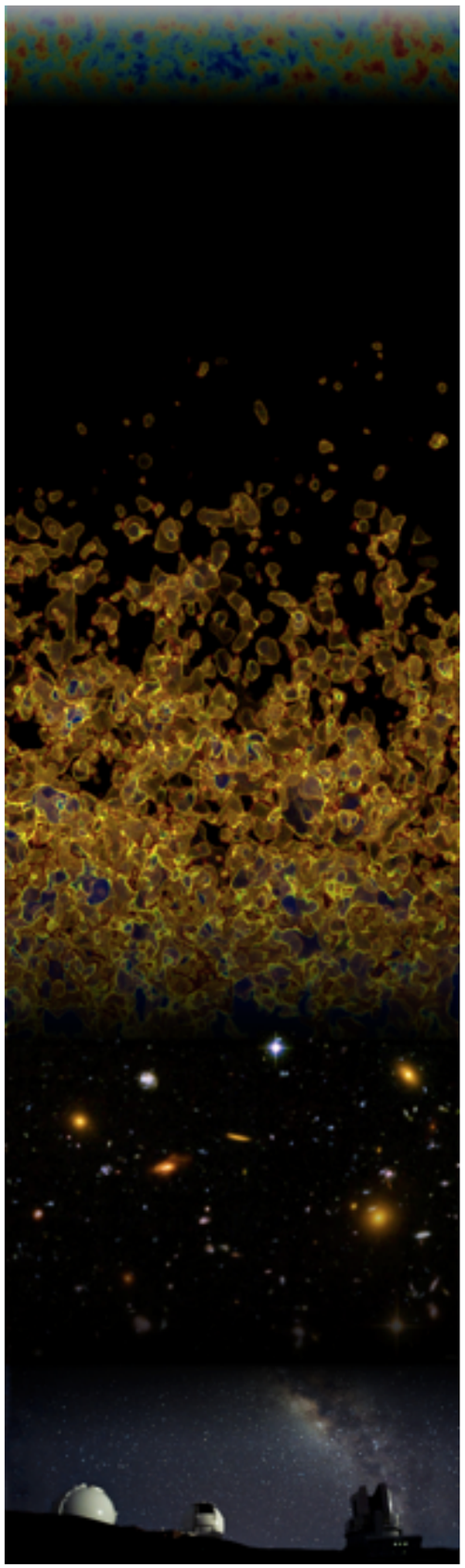




CMB provides additional heating, but emission can only be measured wrt CMB. Net effect: decreased flux density

da Cunha et al. 2012

Summary



- tremendous progress in past decade
  studying high-z molecular gas reservoirs

- number of CO-detected galaxies still limited
  (most are SF pre-selected)

- MS galaxies: high SFR because of high M_{gas}

- ultimate goal: constraints on $\Omega_{H2}(z)$: needs molecular deep fields and ALMA

- but: CO will fail as a tracer for normal galaxies at z>5