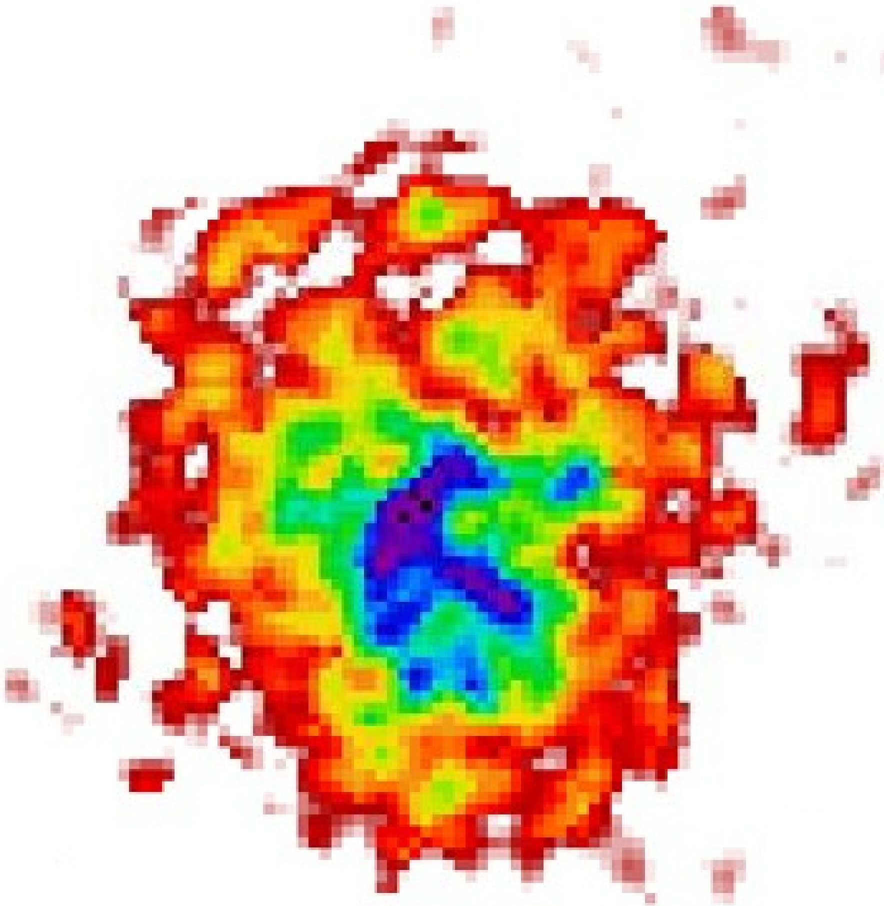
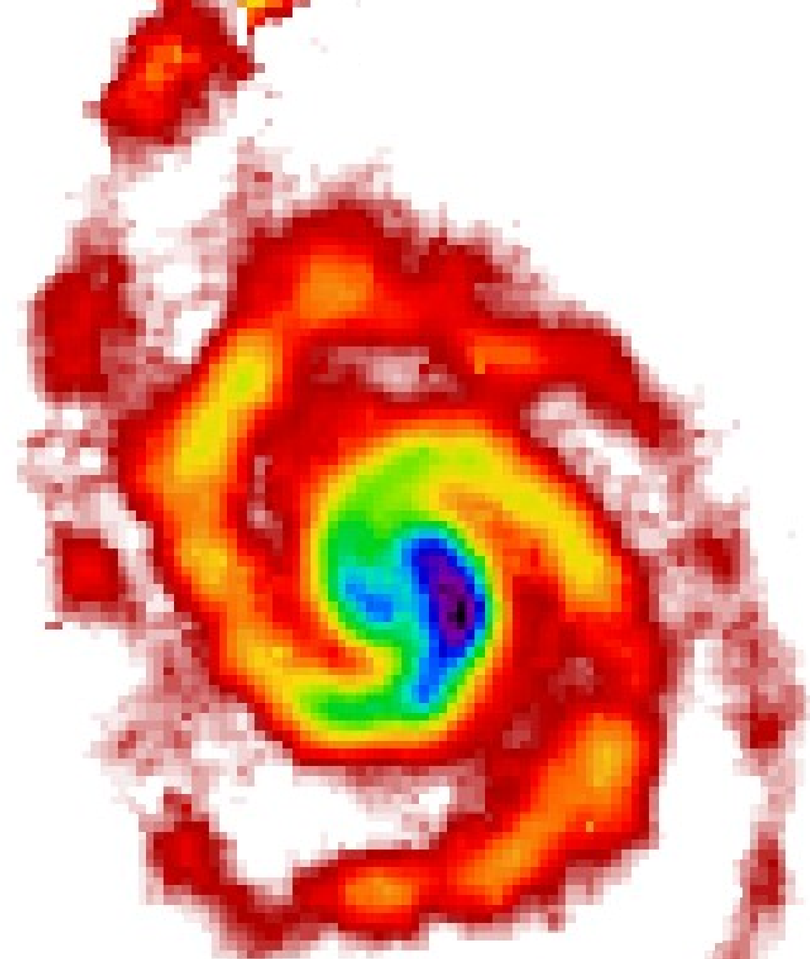




Millimeter astronomy at high redshift

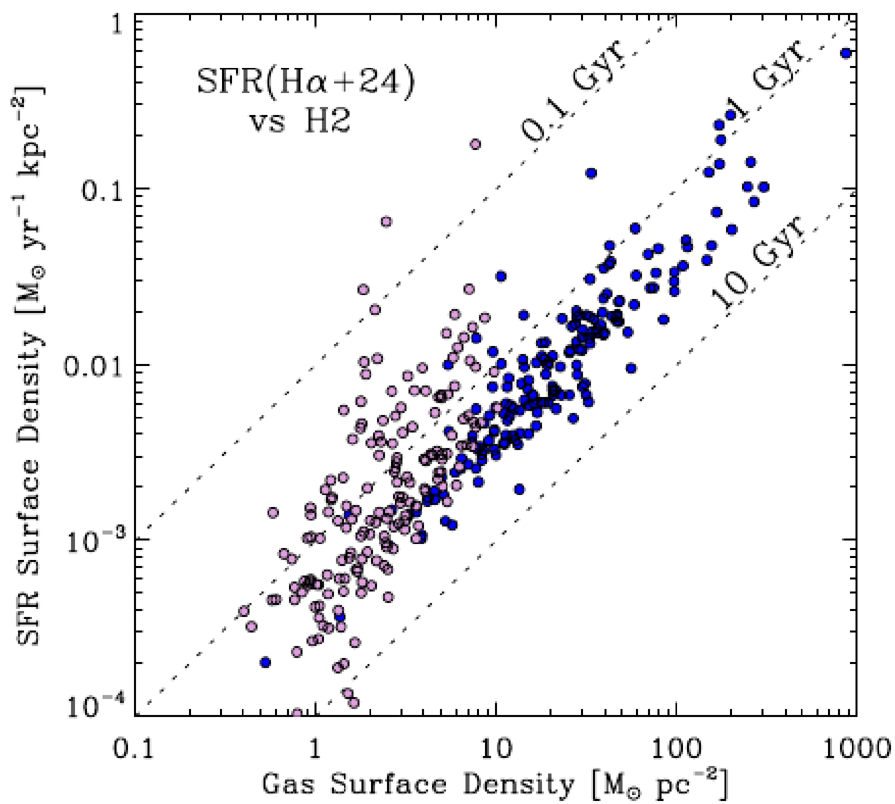
Roberto Decarli

INAF – Osservatorio Astronomico di Bologna

Gas at high redshift: why do we care?

Gas = fuel for star formation

SFR surface density



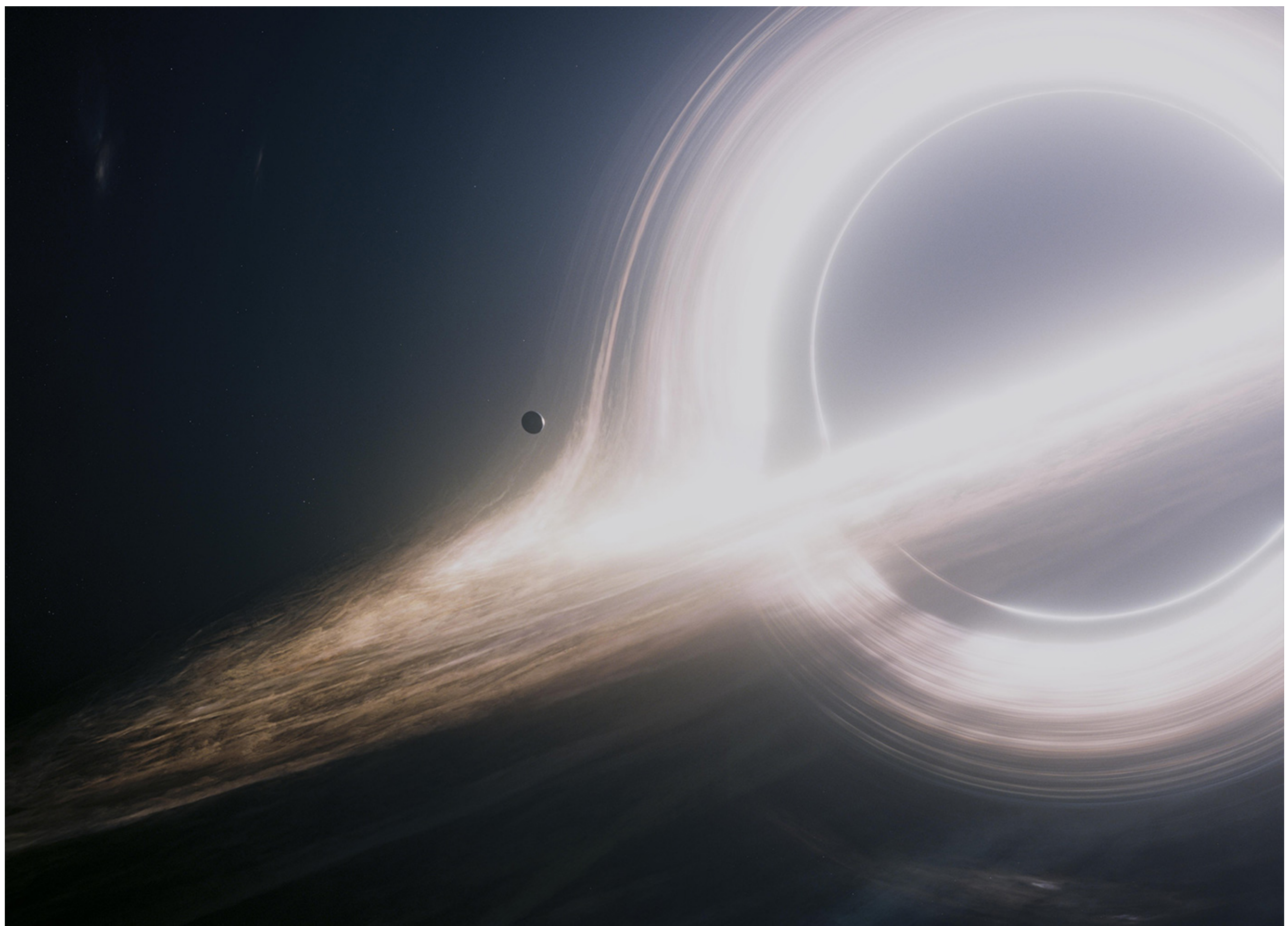
Molecular gas surface density

Schruba+11

Gas = fuel for BH accretion

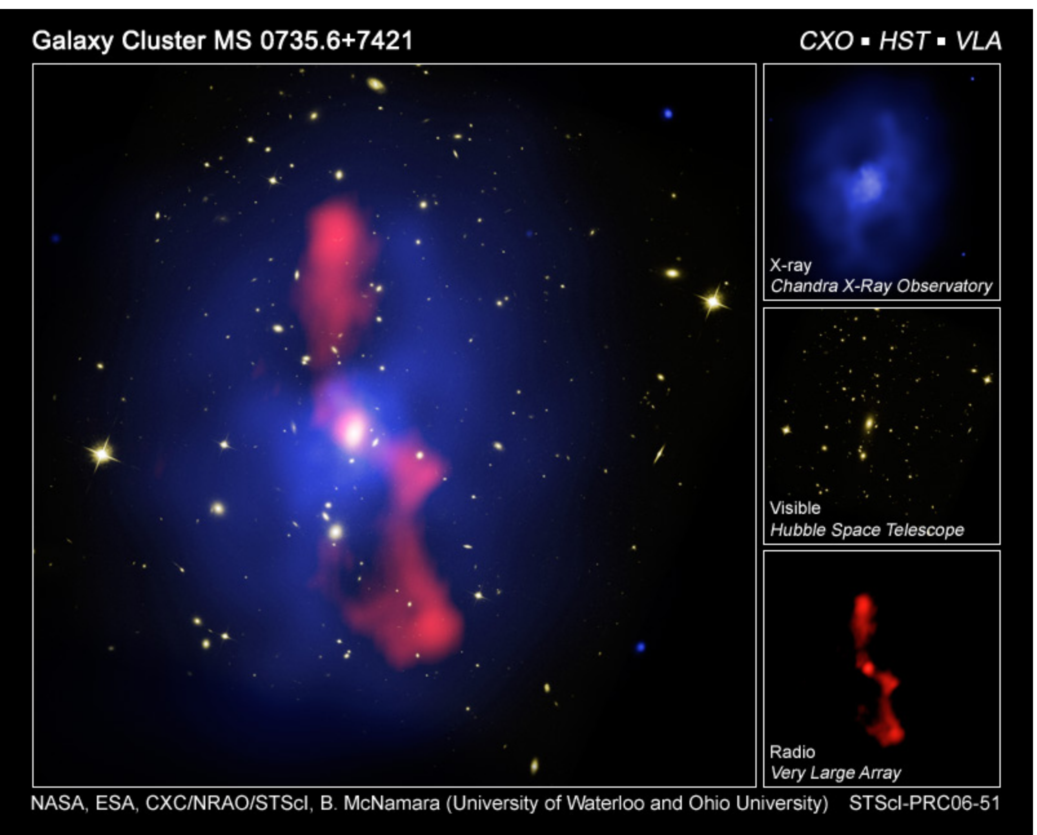
Gas accretion accounts for the majority of local SMBH masses

(e.g., Soltan 1982)



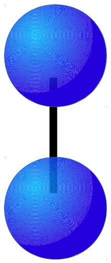
Gas = only vehicle for feedback

SN / AGN feedback only works on gas!



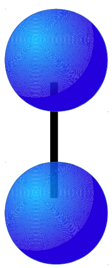
The ISM at high z:
how do we measure it?

Molecular Hydrogen



H_2

Molecular Hydrogen



H_2

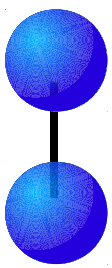
No electric dipole

Very light

→ high energy of vibrational (~mass$^{-1/2}$) and rotational (~mass^{-1}) levels

→ T_{ex}>1000 K

Molecular Hydrogen



H_2

No electric dipole

Very light

→ high energy of vibrational ($\sim mass^{-1/2}$) and rotational ($\sim mass^{-1}$) levels

→ $T_{ex} > 1000$ K

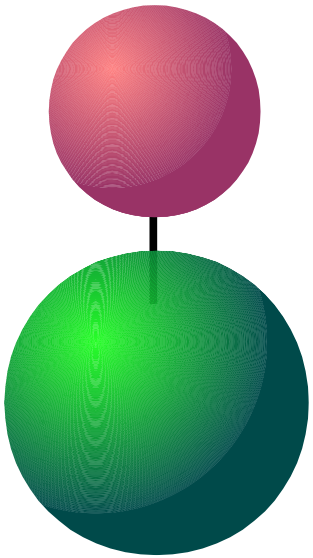
Emission: only in AGN, shocks, etc

Absorption: via UV pumping mechanism

1) H_2 signal is lost in the Lyα forest

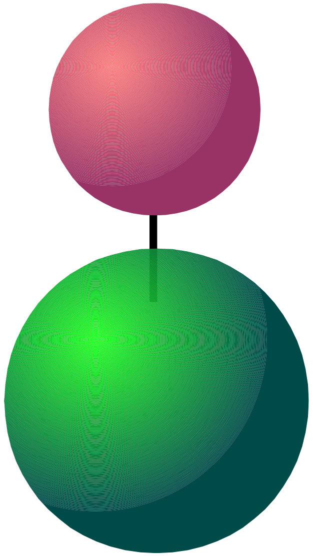
2) small impact parameter

Carbon Monoxide



CO

Carbon Monoxide

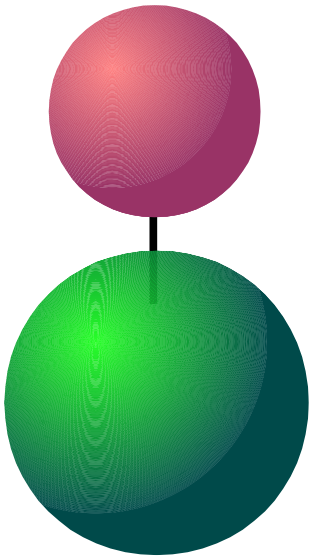


CO

Bright rotational emission lines

First levels have T_{ex}<30 K

Carbon Monoxide



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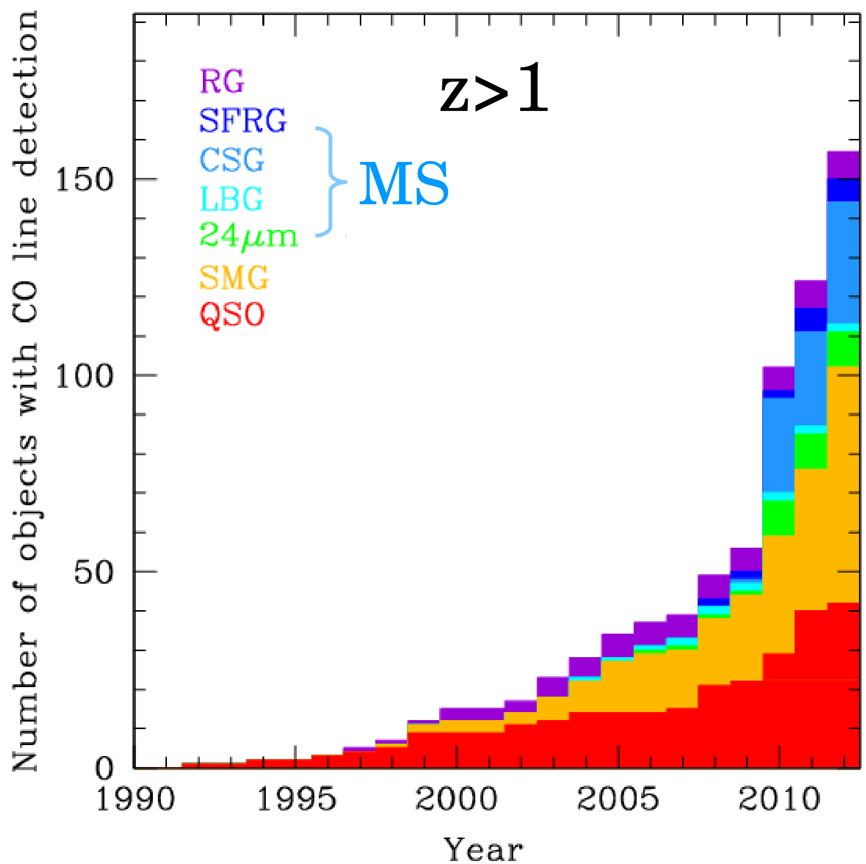
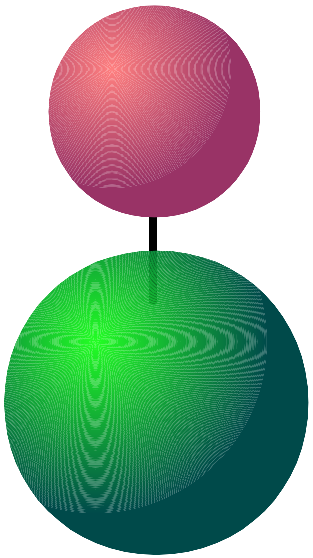
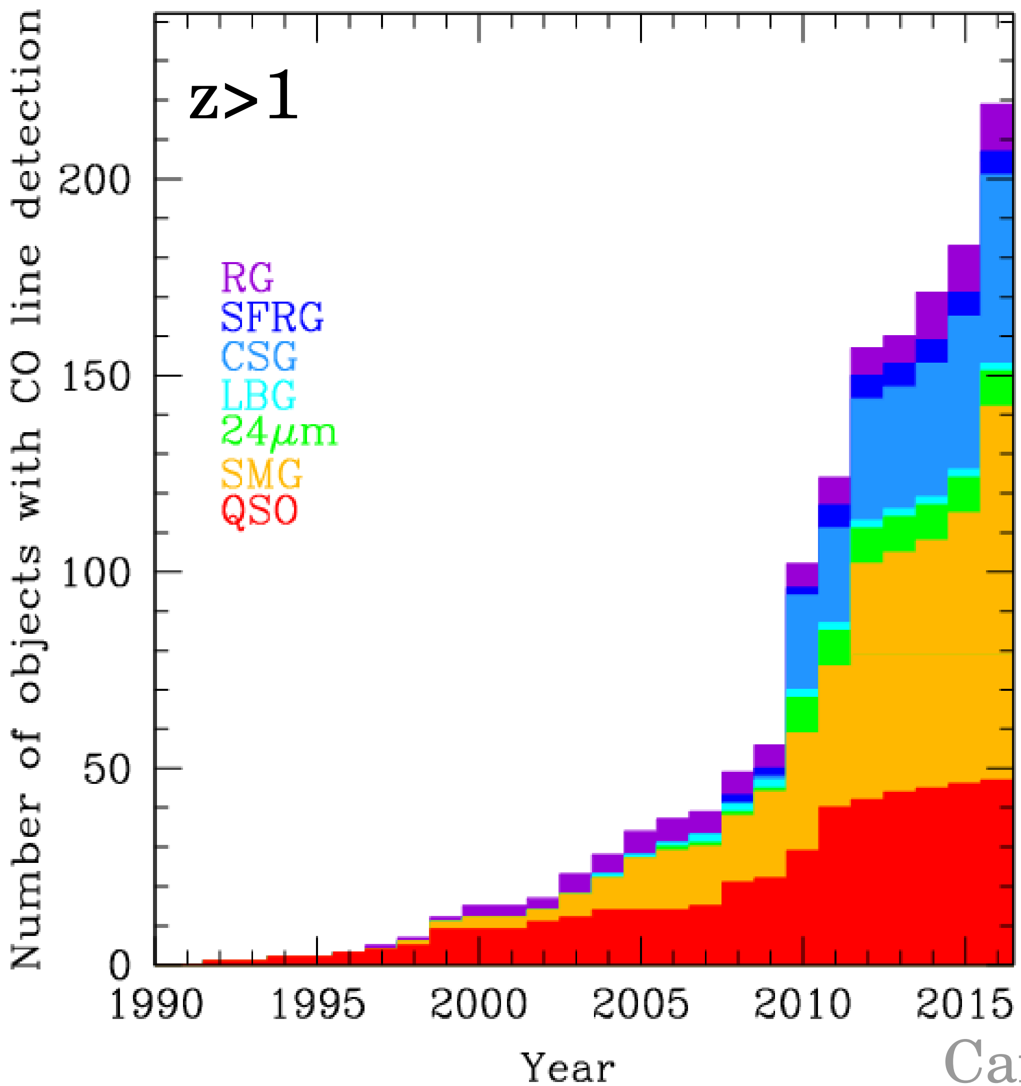


Carilli & Walter 2013

Carbon Monoxide

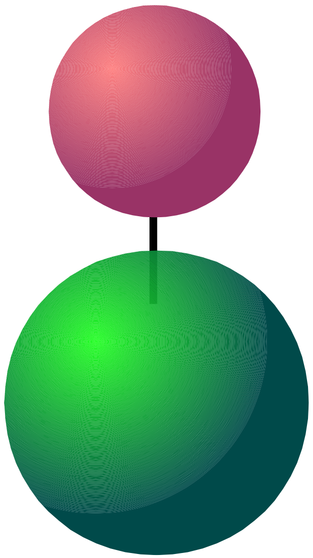


CO

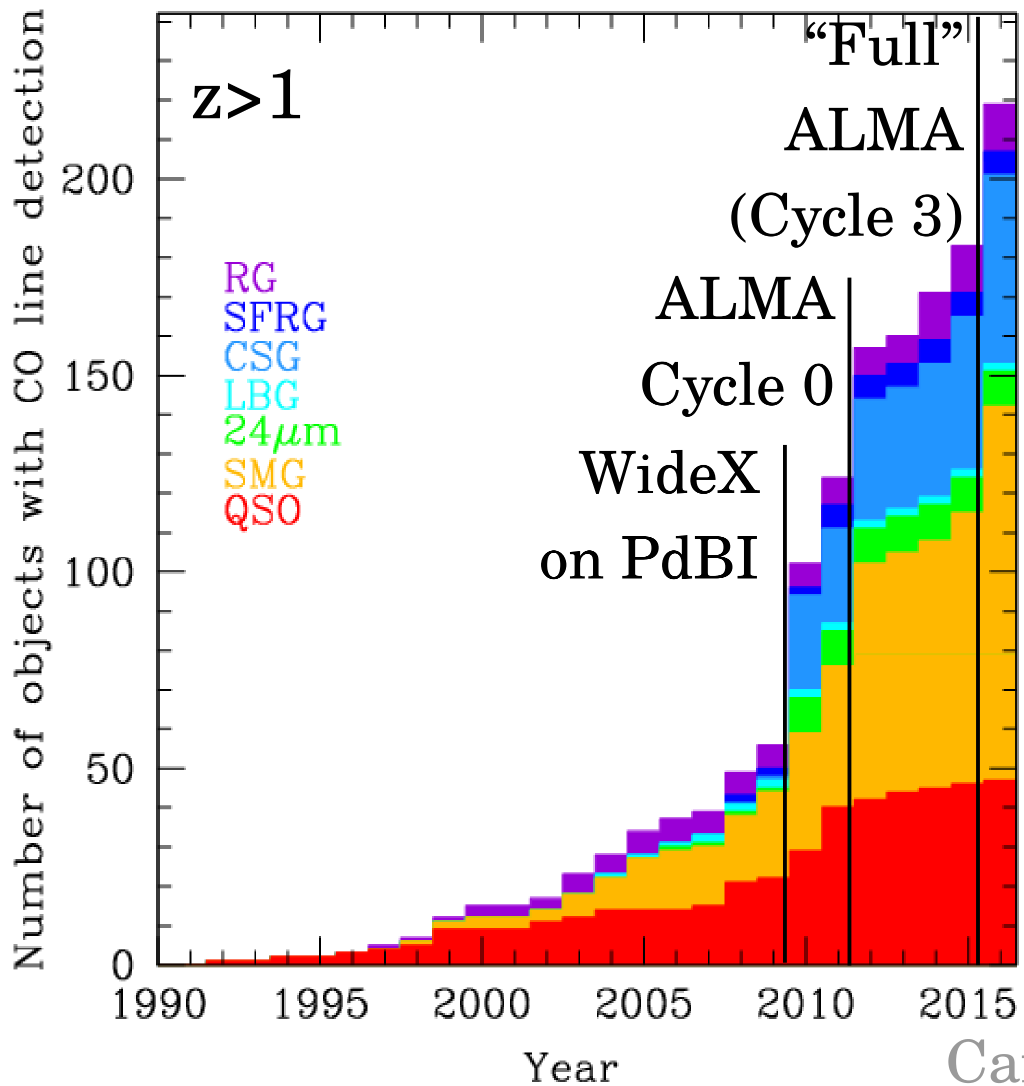


Carilli & Walter 2013

Carbon Monoxide

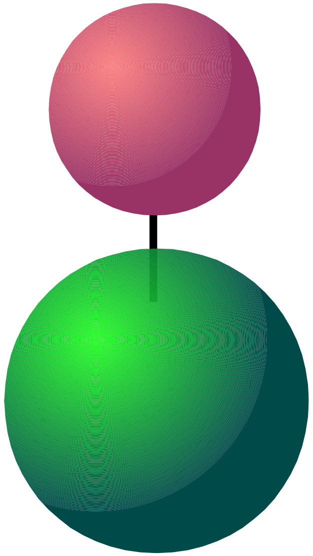


CO

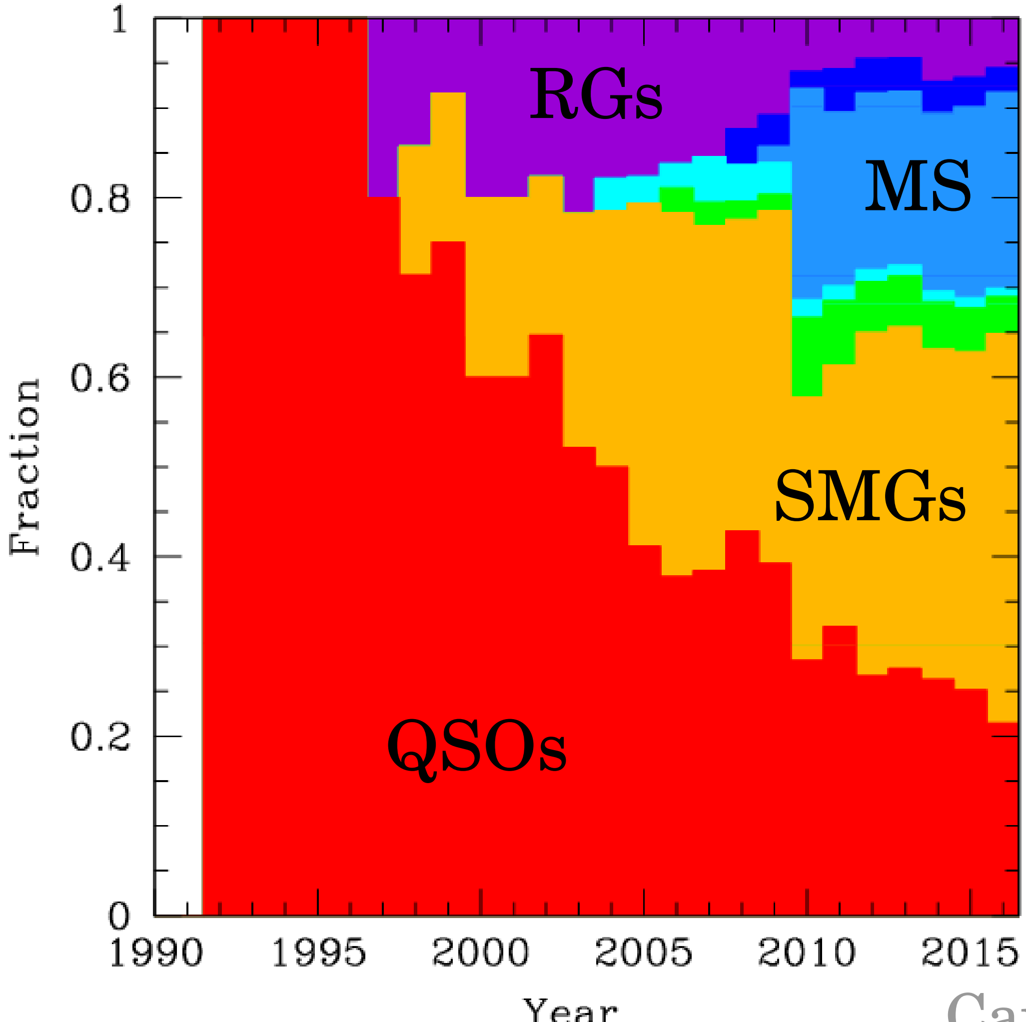


Carilli & Walter 2013

Carbon Monoxide



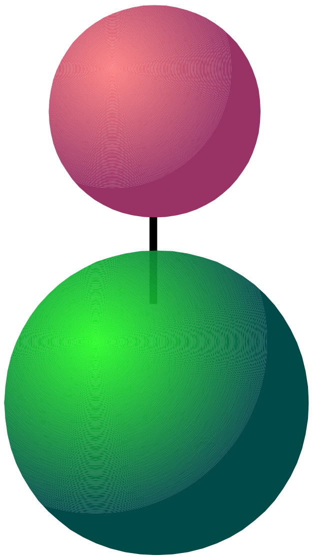
CO



"Beyond the tip of the iceberg"

Carilli & Walter 2013

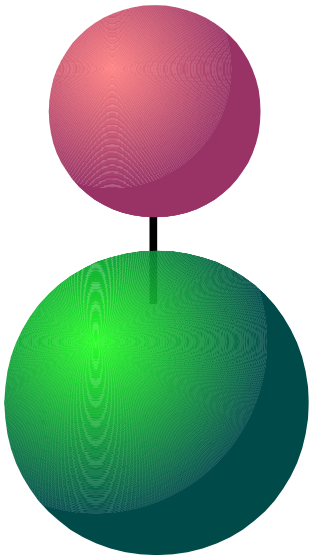
Carbon Monoxide as H_2 mass tracer



CO

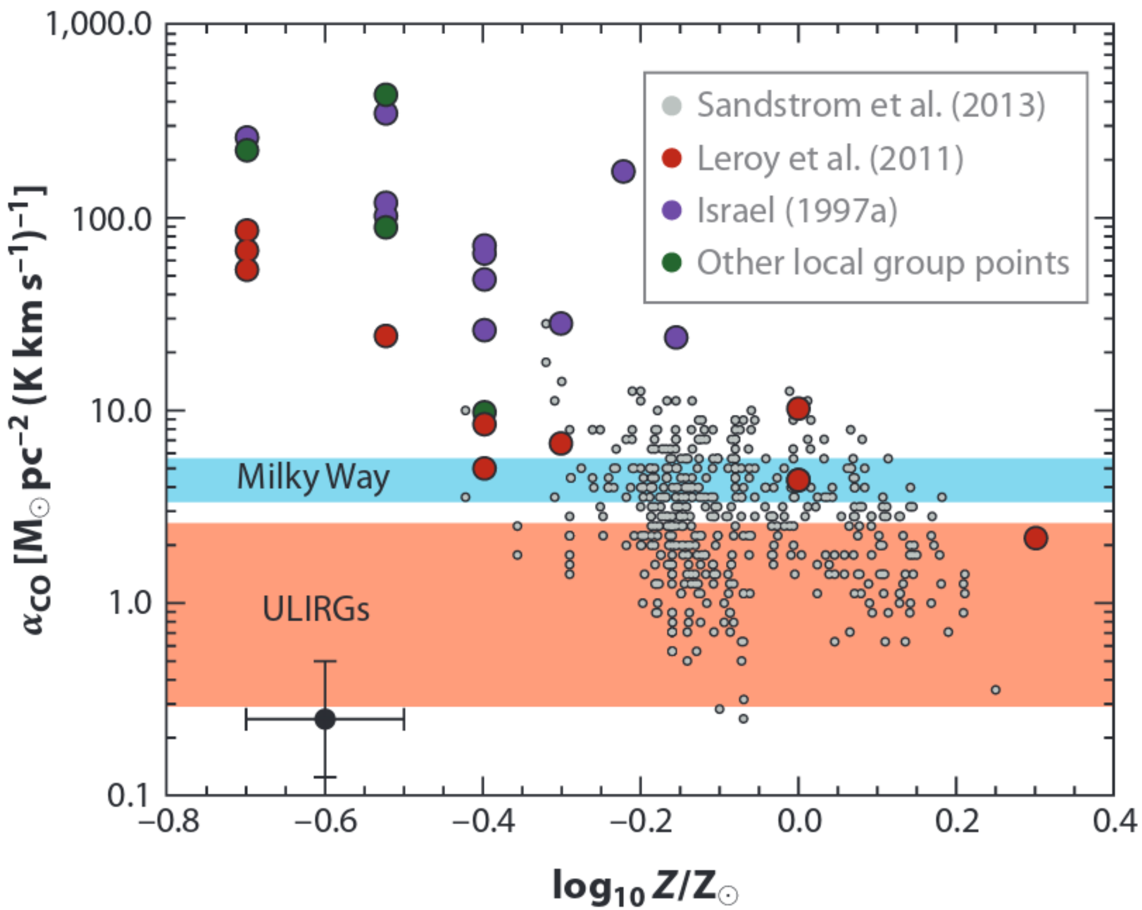
$$M(H_2) = \alpha_{CO} \, L'_{CO(1-0)}$$

Carbon Monoxide as H_2 mass tracer



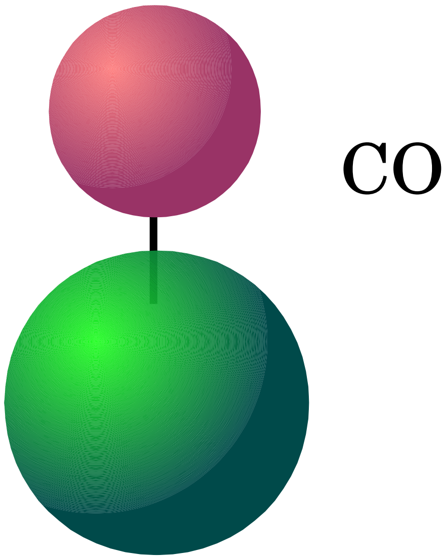
CO

$M(H_2) = \alpha_{CO}\, L'_{CO(1\text{-}0)}$



Bolatto+13

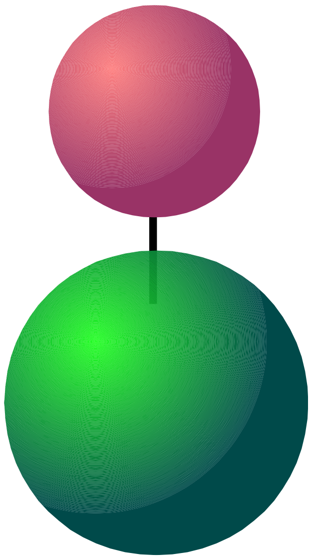
Carbon Monoxide as H_2 mass tracer



$$M(H_2) = \alpha_{CO} \; L'_{CO(1\text{-}0)}$$

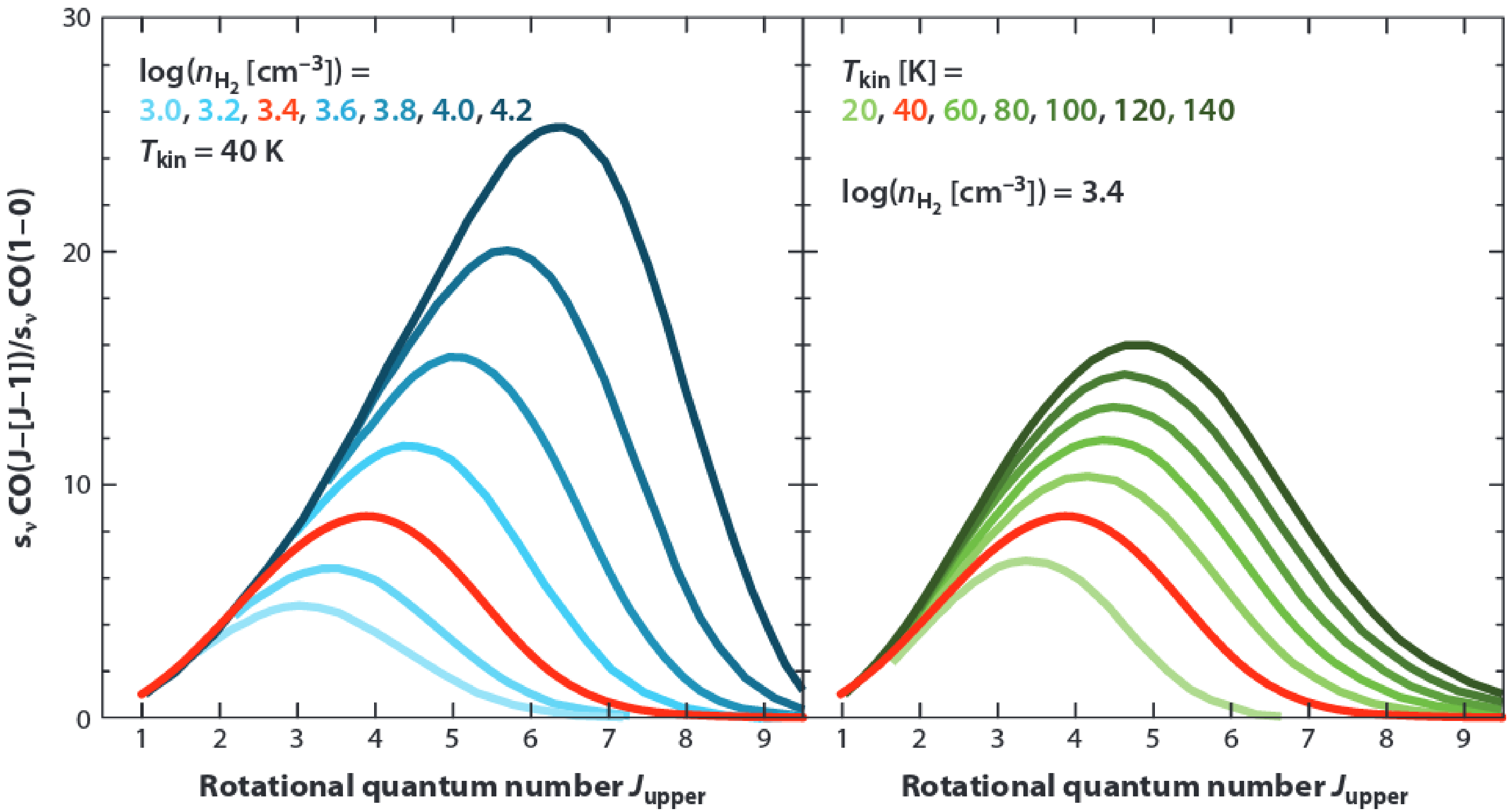
1) Measure α_{CO} (e.g., via dynamics)
2) Know your galaxy! (Z, L_{IR})

CO excitation



CO

$$M(H_2) = \alpha_{CO}\, L'_{CO(1\text{-}0)} = \alpha_{CO}\, R_{J1}^{-1}\, L'_{CO[J\text{-}(J\text{-}1)]}$$



Carilli & Walter 2013

Dense gas tracers

HCN, HCO+, HNC, CN, CS

Dense gas tracers

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Typically ~10-100 times fainter than CO

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Typically ~10-100 times fainter than CO

H_2O

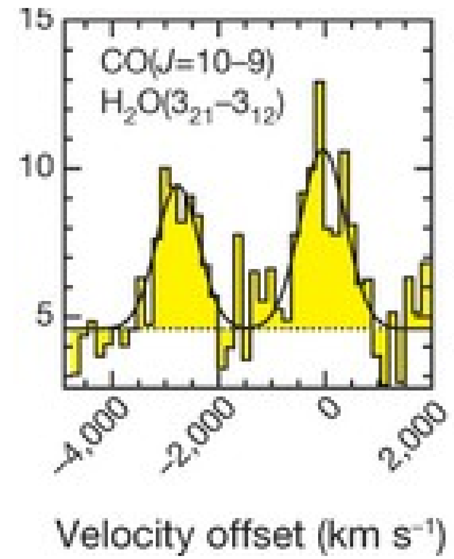
Dense gas tracers

HCN, HCO+, HNC, CN, CS

Typically ~10-100 times fainter than CO

H_2O

Can be brighter than CO

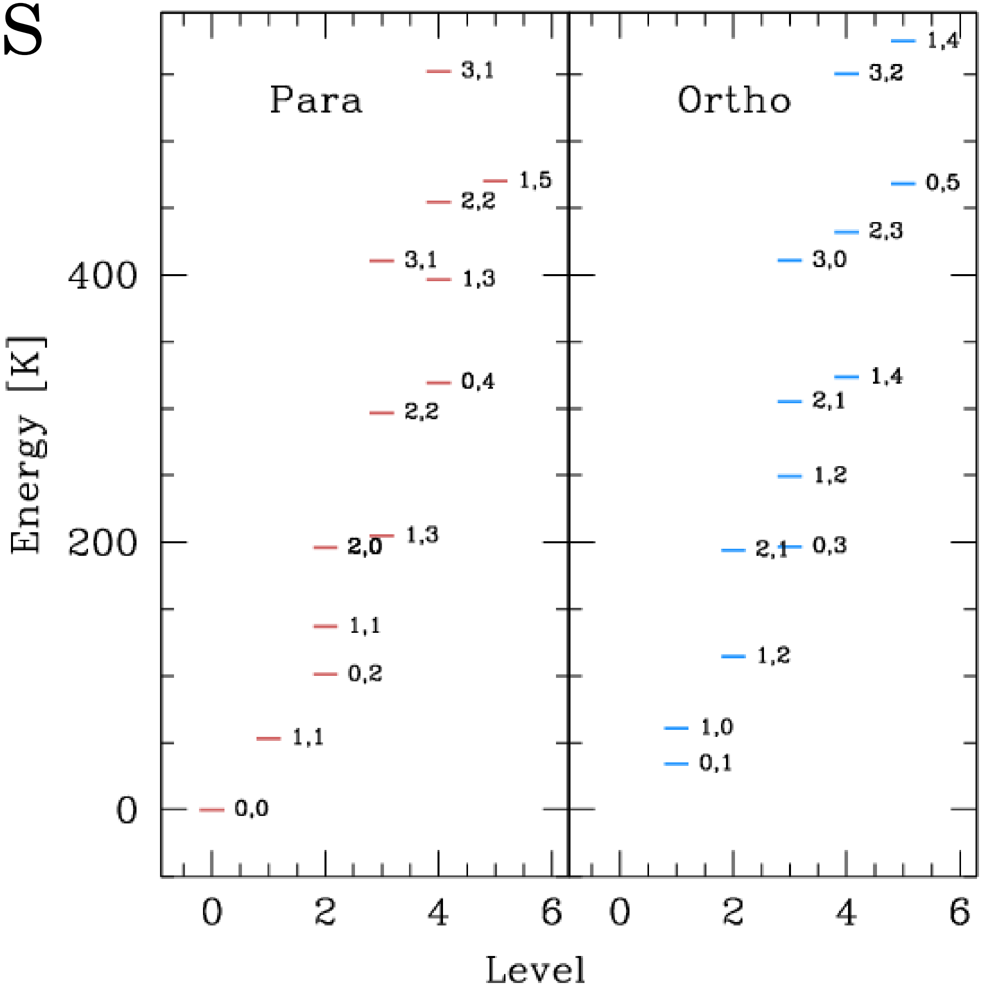


Riechers+13

Dense gas tracers

HCN, HCO+, HNC, CN, CS

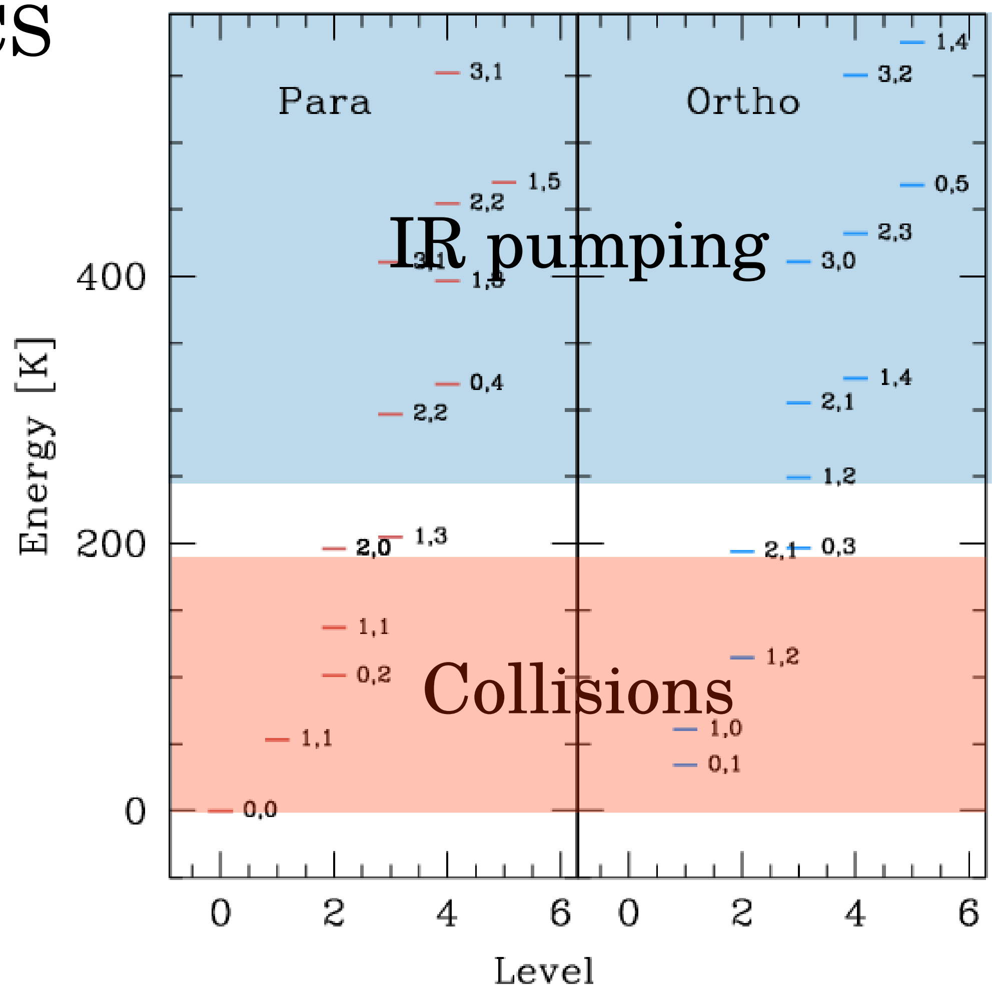
H_2O



Dense gas tracers

HCN, HCO+, HNC, CN, CS

H_2O

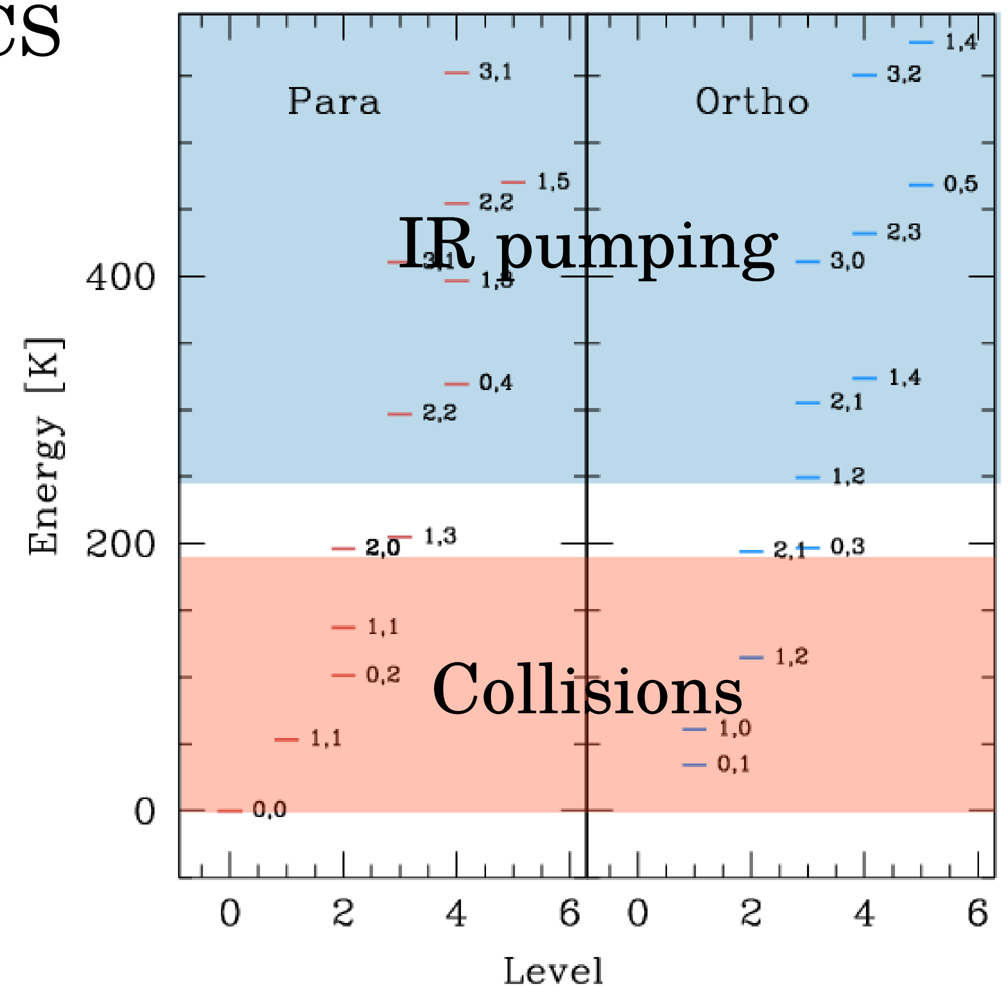


Dense gas tracers

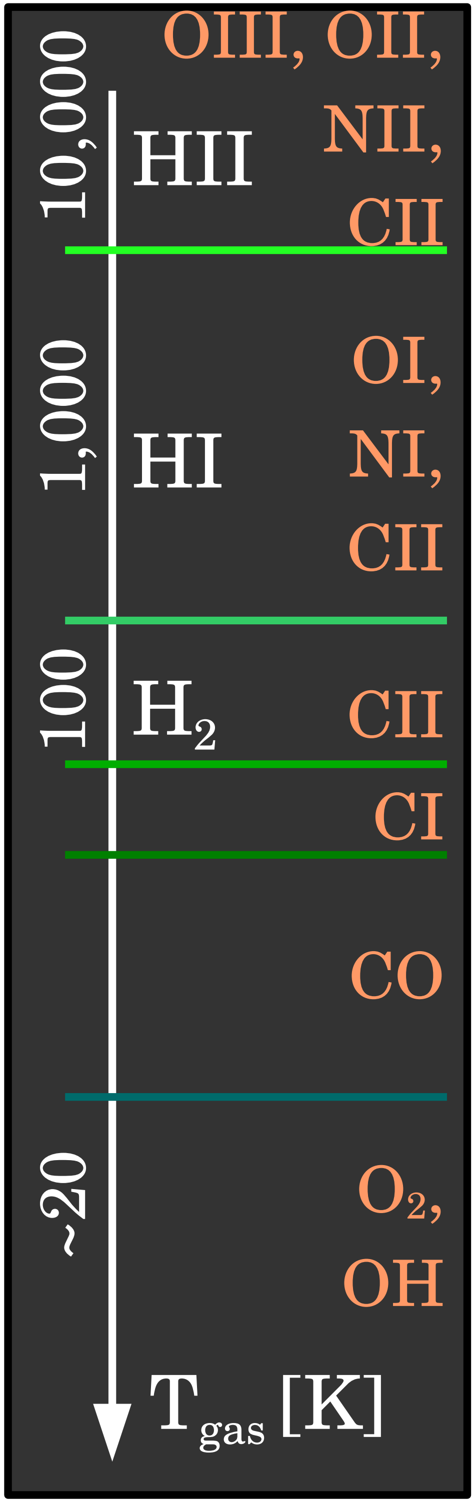
HCN, HCO+, HNC, CN, CS

H_2O

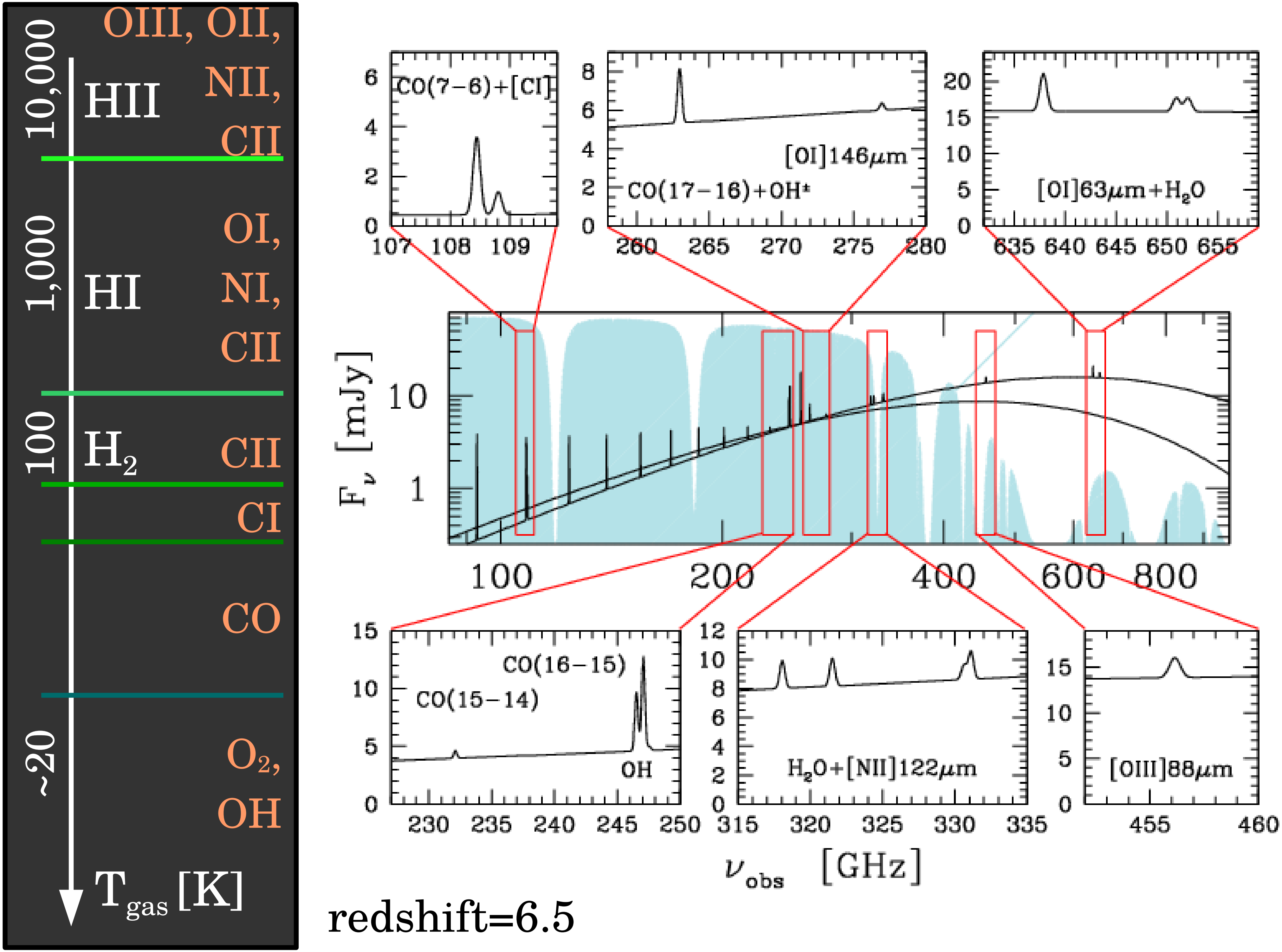
Hard to infer column densities



Beyond CO: Fine structure lines

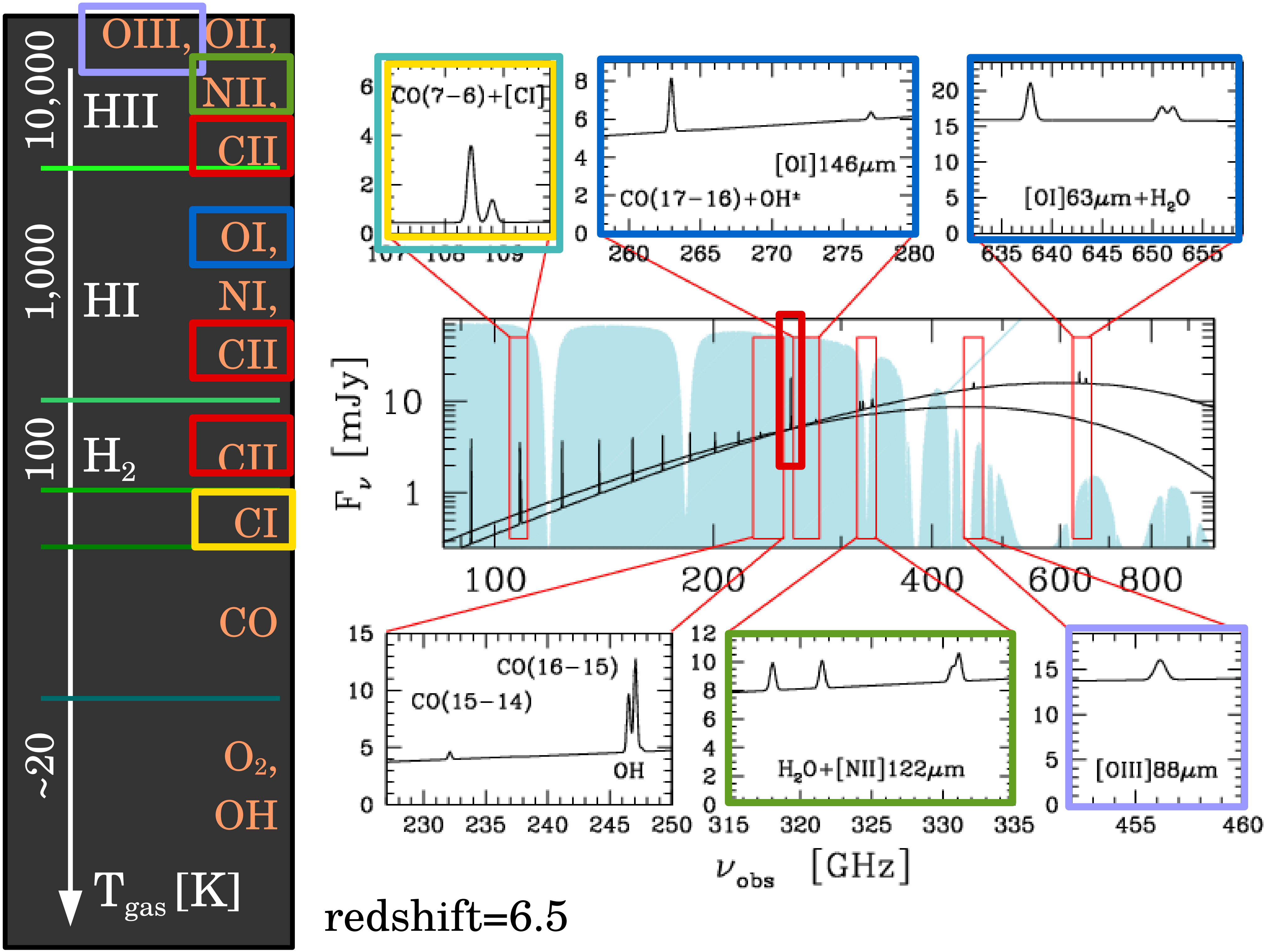


10,000
1,000
100
~20
HII
HI
H_2
OIII, OII,
NII,
CII
OI,
NI,
CII
CII
CI
CO
O_2,
OH
T_{gas} [K]



OIII, OII,
NII,
CII
10,000
HII
OI,
NI,
CII
1,000
HI
100
H_2
CII
CI
CO
~20
O_2,
OH
T_{gas} [K]
CO(7−6)+[CI]
[OI]146μm
CO(17−16)+OH+
[OI]63μm+H_2O
F_ν [mJy]
CO(16−15)
CO(15−14)
OH
H_2O+[NII]122μm
[OIII]88μm
ν_{obs} [GHz]

redshift=6.5


OIII, OII,
NII,
CII
HII
10,000
OI,
NI,
CII
HI
1,000
CII
H_2
100
CI
CO
O_2,
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~20
T_{gas} [K]
CO(7−6)+[CI]
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H_2O+[NII]122μm
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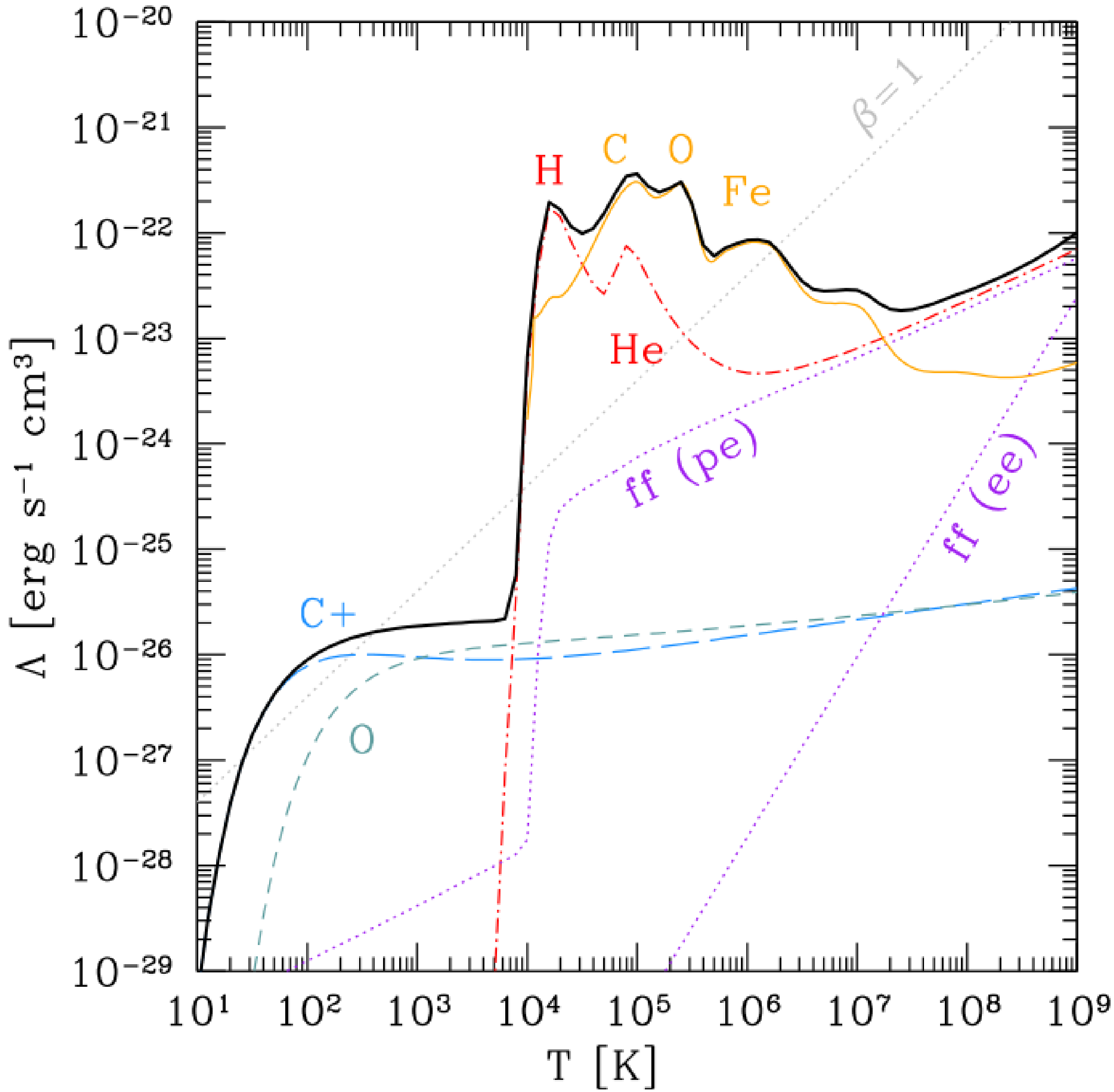
ν_{obs} [GHz]
redshift=6.5

Beyond CO: Fine Structure Lines

[OI] 63 & [CII] 158:
Main coolants of ISM
at 30 K < T < 3000 K



Beyond CO: Fine Structure Lines

[OI] 63 / [CII] 158: Abundance

[OIII] 88 / [OI] 63: Ionization state

[NII] 122 / 205: Electron density (ionized gas)

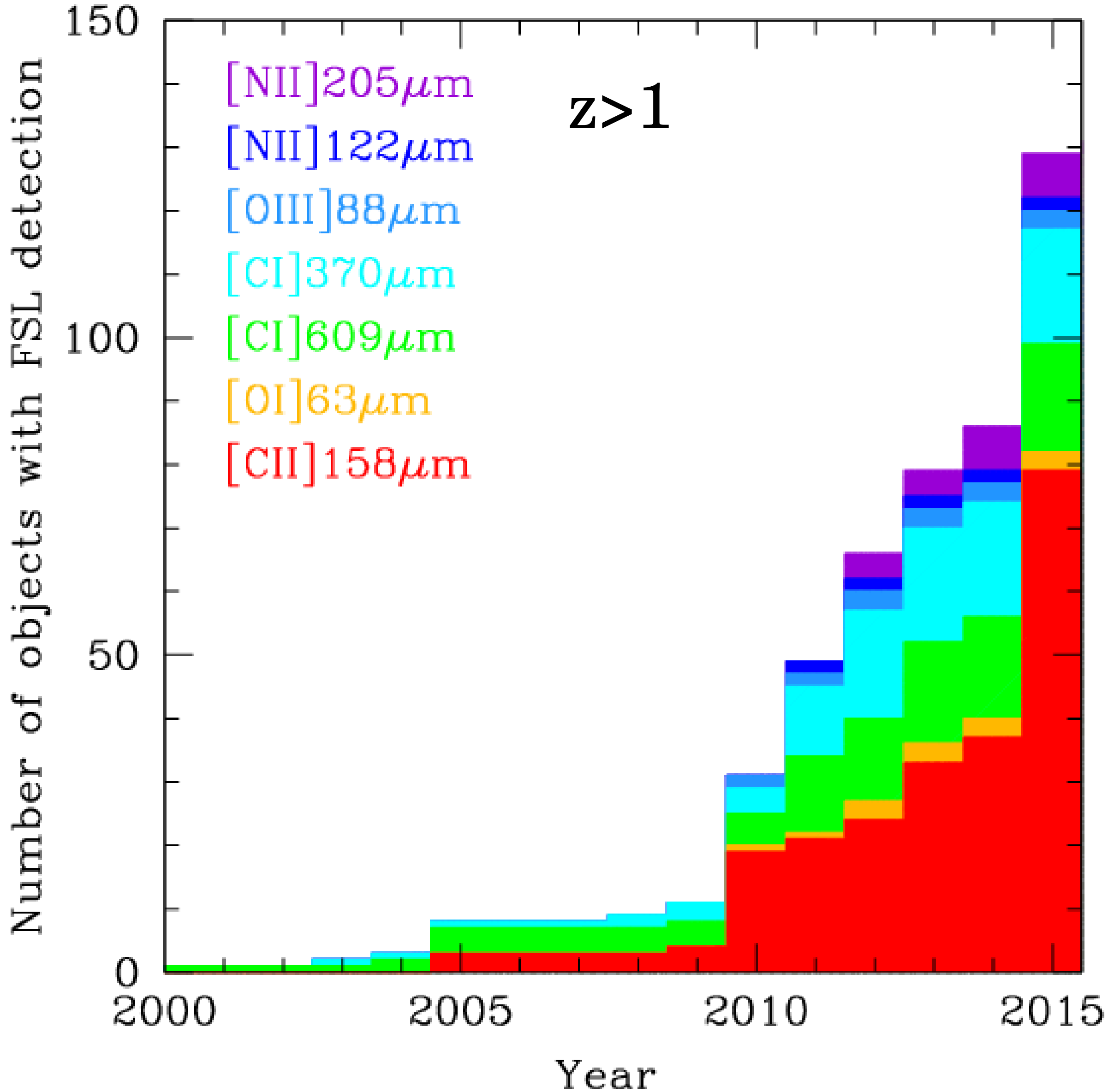
[CI] 609 / 370: Excitation temperature (molecular gas)

[CII] 158 / [NII] 205: Ionized vs neutral ISM / Metallicity

[CII] 158 / [CI] 370: X-ray vs PDR powering / Intensity radiation field

[CII] 158 / CO(7-6): Density (>10,000 cm^{-3})

Beyond CO: Fine Structure Lines



Indirect tracers

Dust is a catalyst
for H_2 formation

Indirect tracers

Dust is a catalyst for H_2 formation → Gas and dust mass are correlated

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M_{dust} is simple to measure

Indirect tracers

Dust is a catalyst for H_2 formation

→ Gas and dust mass are correlated

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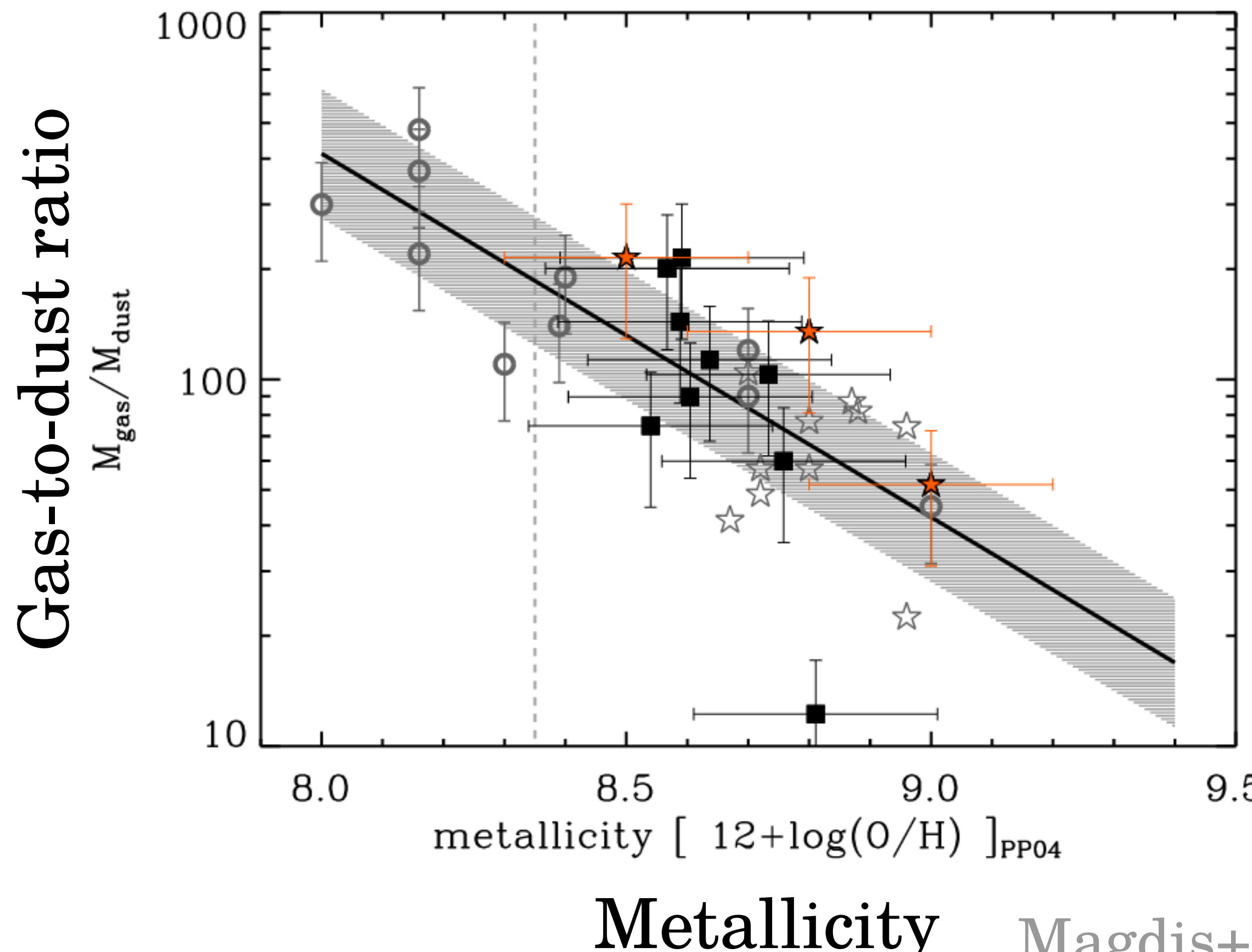
Need to assume a gas-to-dust ratio



Magdis+12

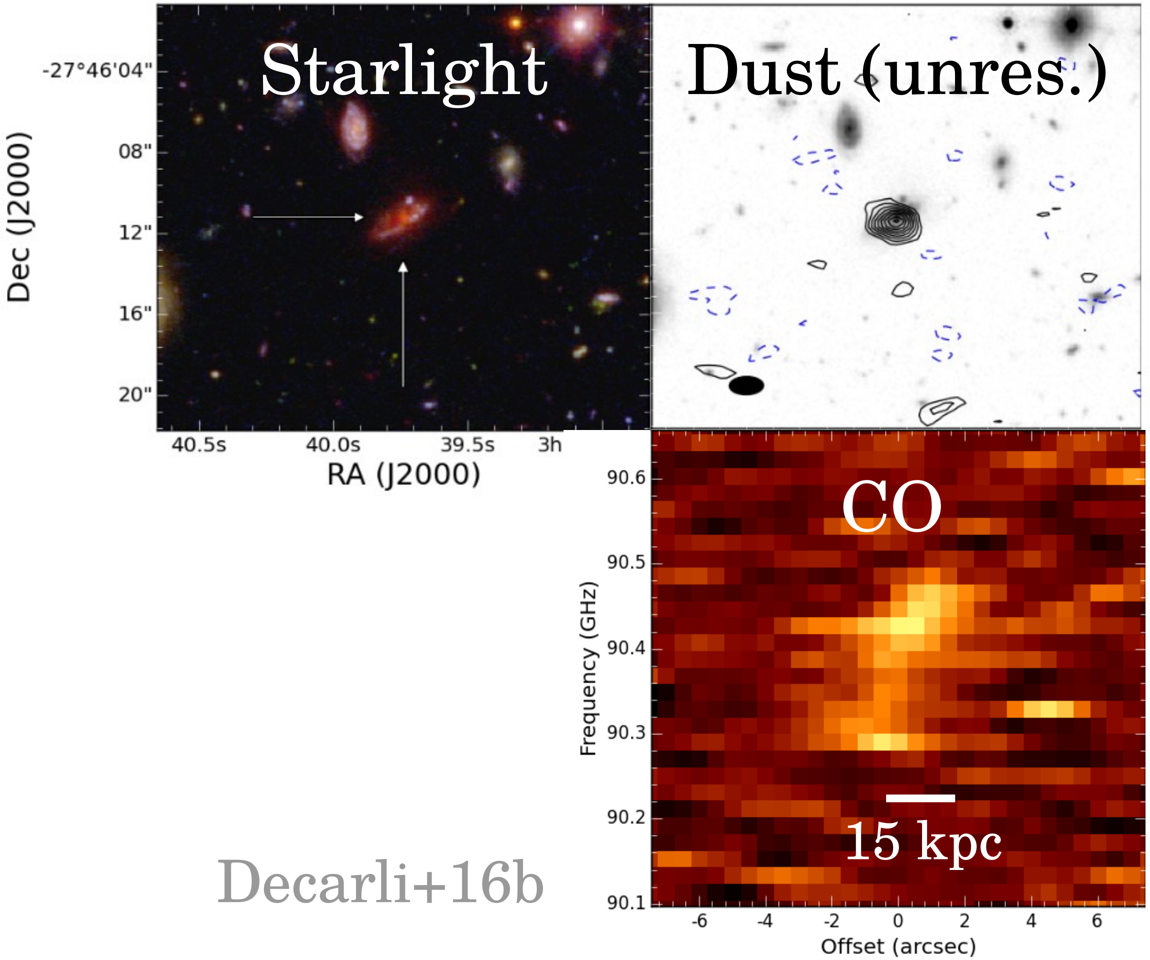
Indirect tracers

Dust is a catalyst for H_2 formation → Gas and dust mass are correlated

M_{dust} is simple to measure

Need to assume a gas-to-dust ratio

Subtleties: same region?



Decarli+16b

ISM observations at $z>1$

Observing “normal” z>1 galaxies

Molecular surveys in (bright) Main Sequence galaxies:

PHIBSS1+2: Tacconi+10,13; Genzel+10,15; etc

Dannerbauer+09, Daddi+10, Aravena+10, ...

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Dannerbauer+09, Daddi+10, Aravena+10, ...

Molecular Deep Fields:

PdBI+HDF-N: Decarli+14, Walter+14

ASPECS: Walter+16, Aravena+16b, Decarli+16ab

COLDz: Lentati+15

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Clusters:

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Seko+16

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COLDz: Lentati+15

Clusters:

Aravena+12

Seko+16

Lenses:

Dessauges-Zavadsky+15

Continuum surveys:

ALESS: Hodge+13, Karim+13, etc

COSMOS: Scoville+14,16

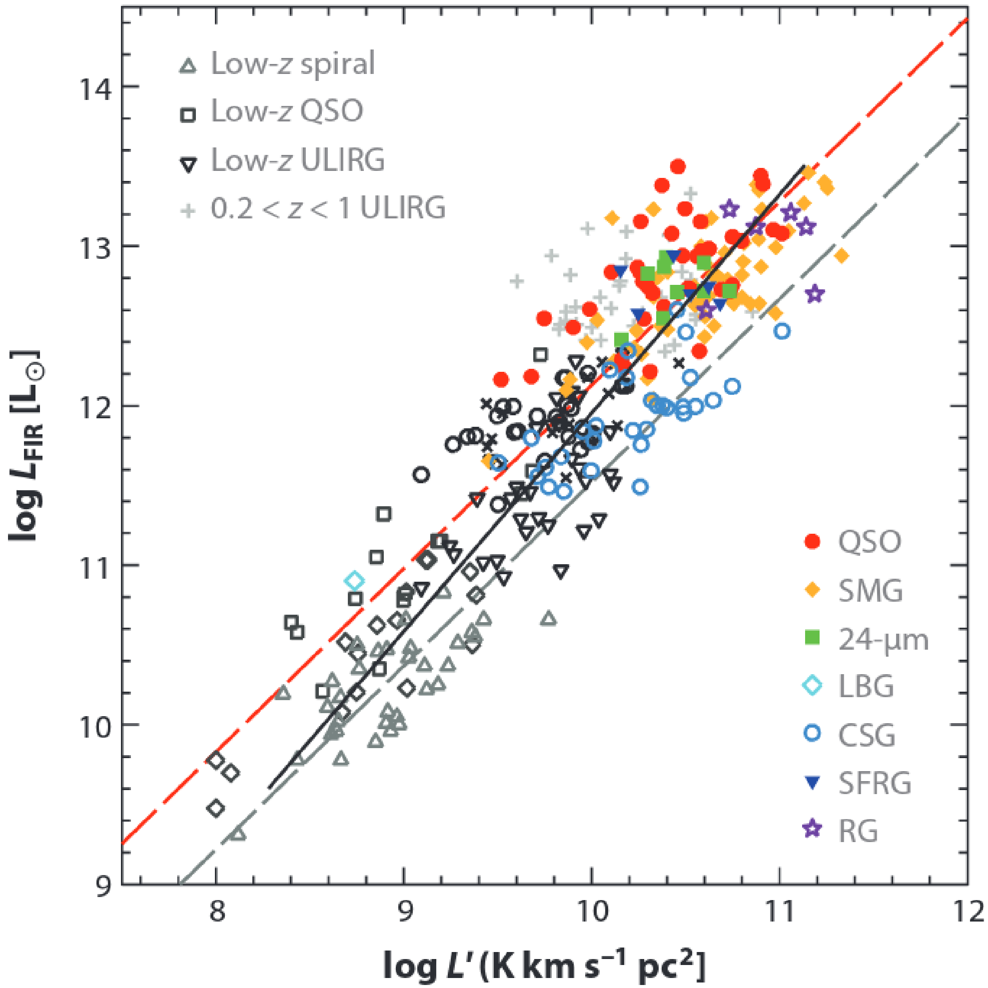
HUDF: Dunlop+16

ASPECS: Aravena+16a, Bouwens+16

Others: Fujimoto+15, …

A few results,
and many open issues

Molecular gas and SFR



~ Molecular gas mass

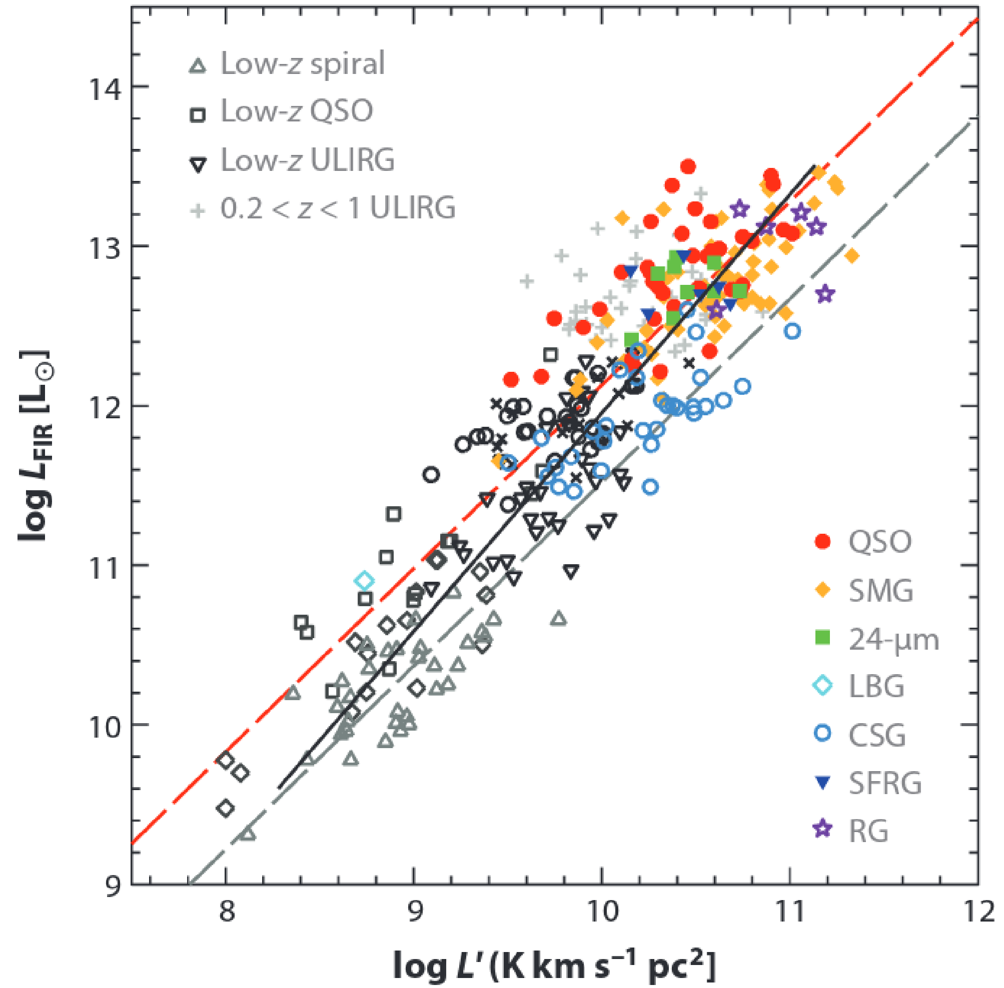
Carilli & Walter 2013

Molecular gas and SFR

One super-linear relation or two linear sequences?

(Genzel+10,15, Daddi+10, Narayanan+10, Krumholtz+12, Federrath+13, Sargent+14, Silverman+15, Usero+15, Liu+15, Salim+15, Escala+15, ...)

~ SFR



~ Molecular gas mass

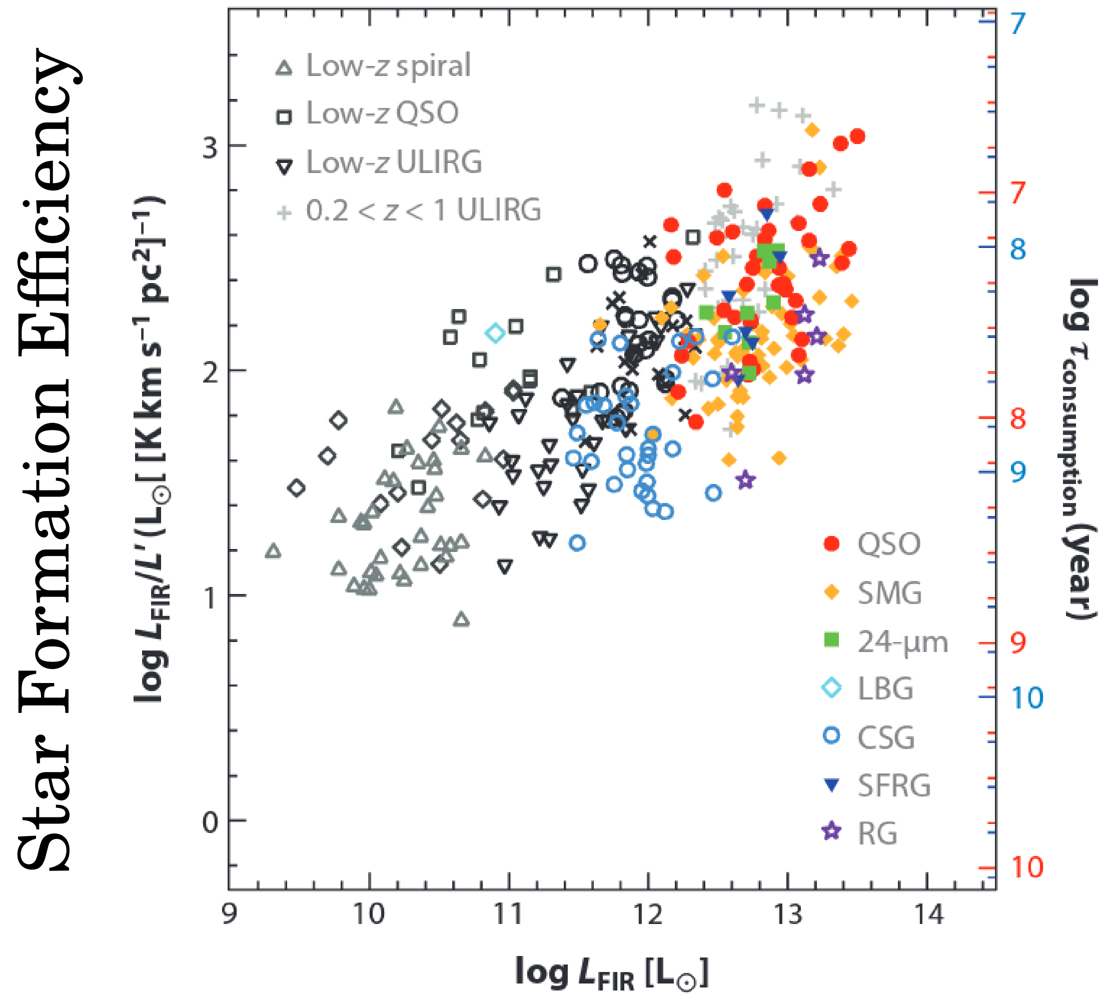
Carilli & Walter 2013

Star Formation Efficiency …

Star Formation Efficiency (SFE):

SFR / M_{gas} = SFE

= $1/t_{depl}$



~ SFR

Carilli & Walter 2013

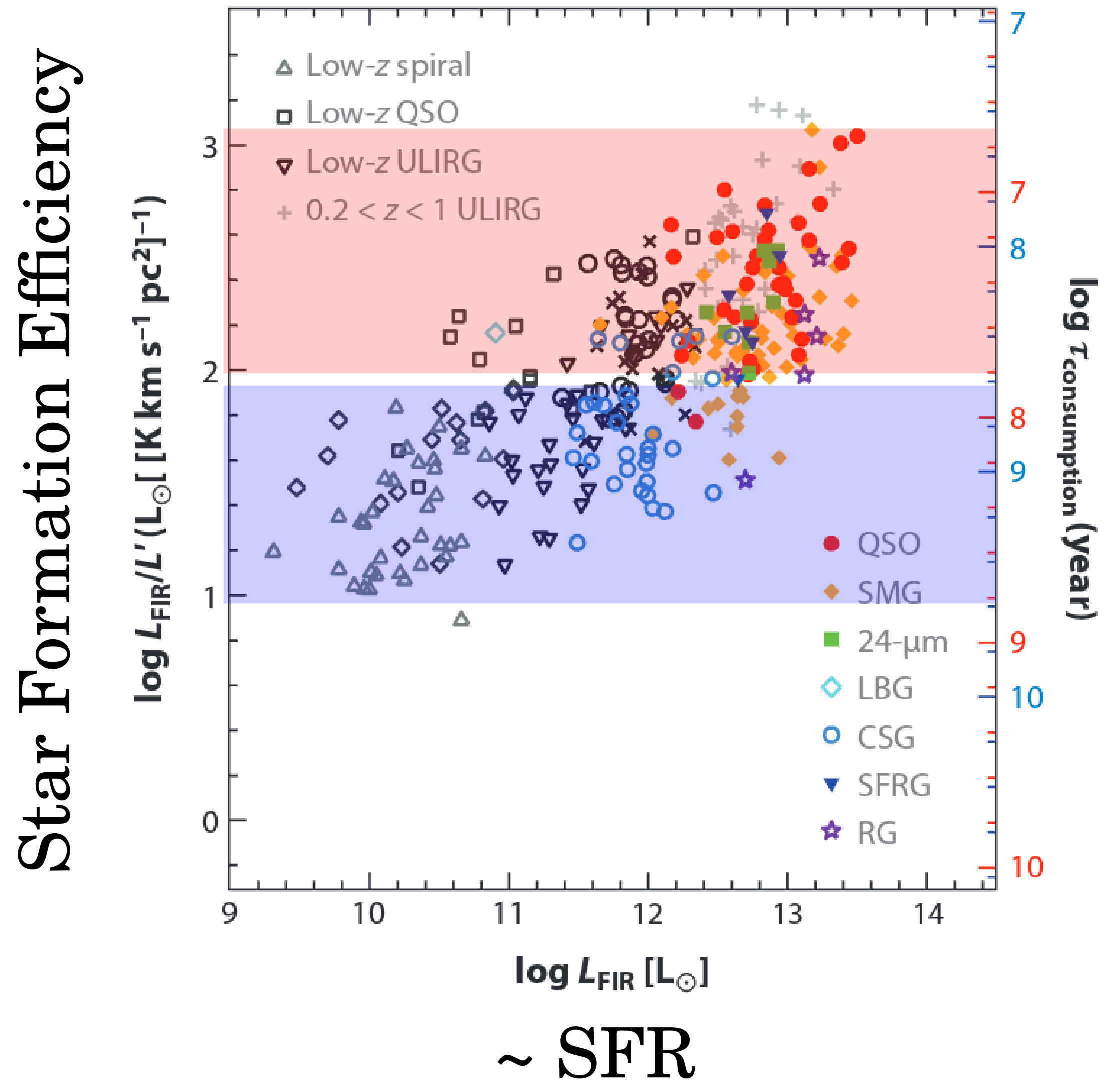
… and depletion time

QSOs, SMGs, starbursts:

$t_{dep} \sim 10^7$-10^8 yr

Main sequence galaxies:

$t_{dep} \sim 10^9$ yr



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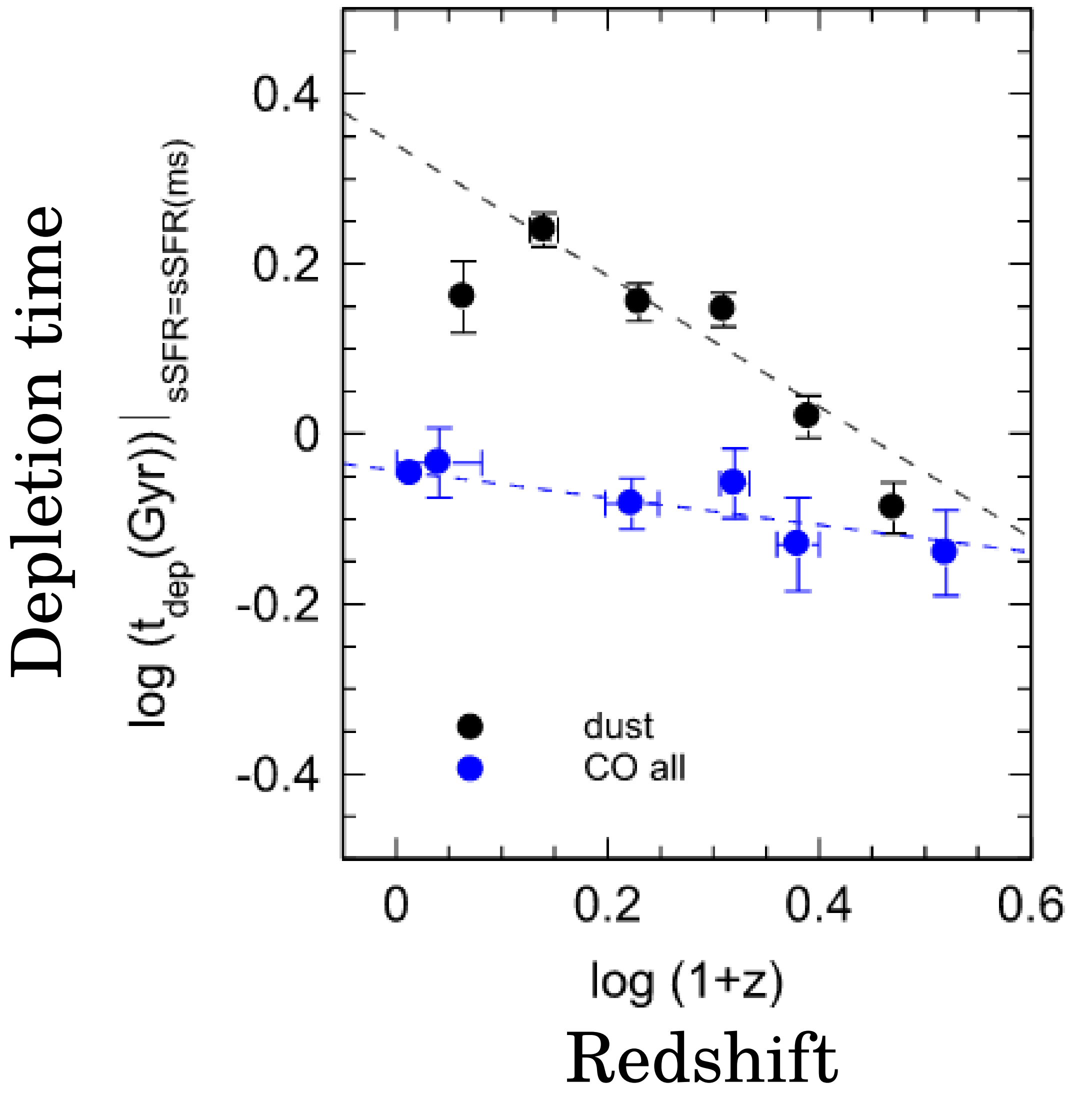
Depletion time

Does t_{dep} evolve?

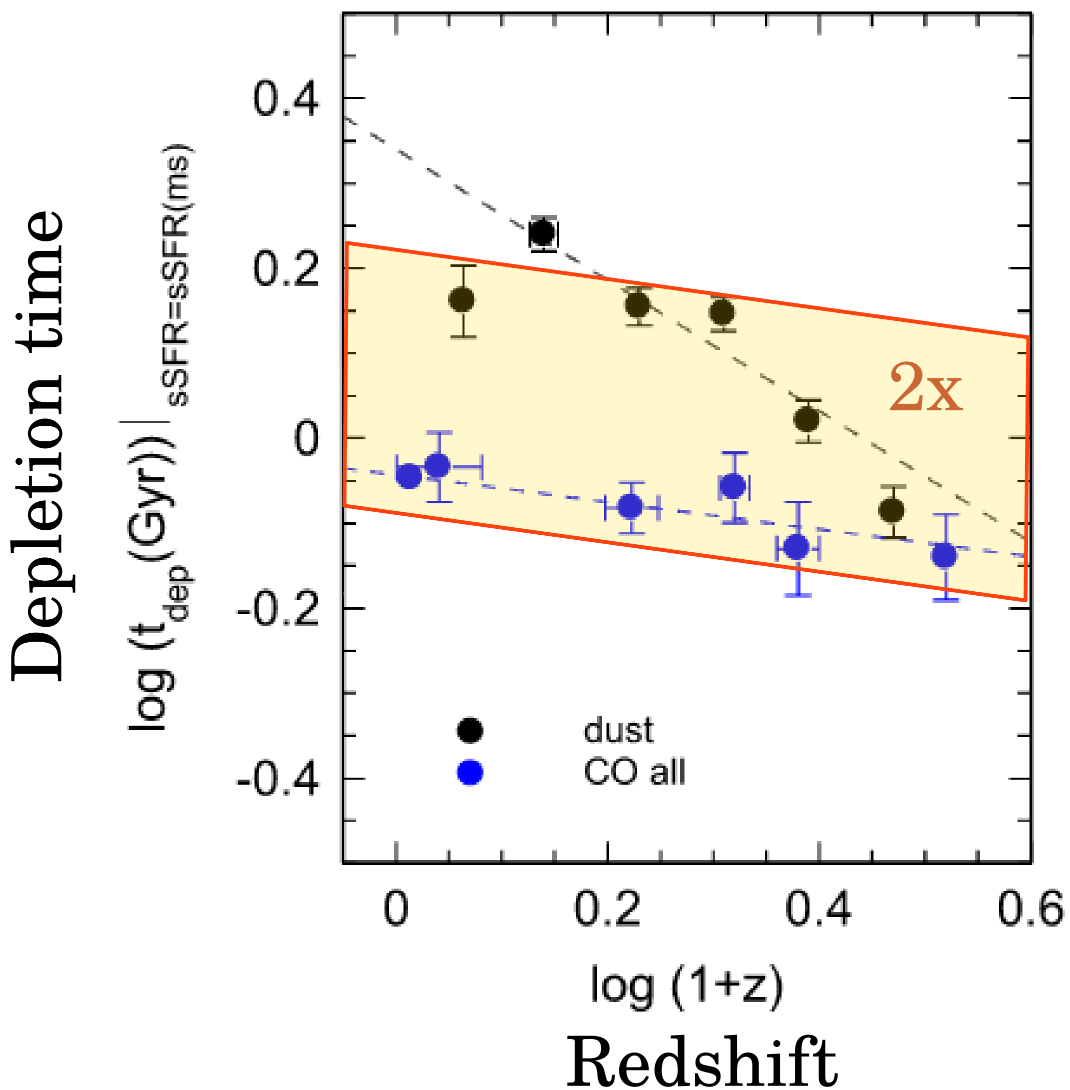


Genzel+15

Depletion time

Does t_{dep} evolve?

Do different tracers tell consistent stories?

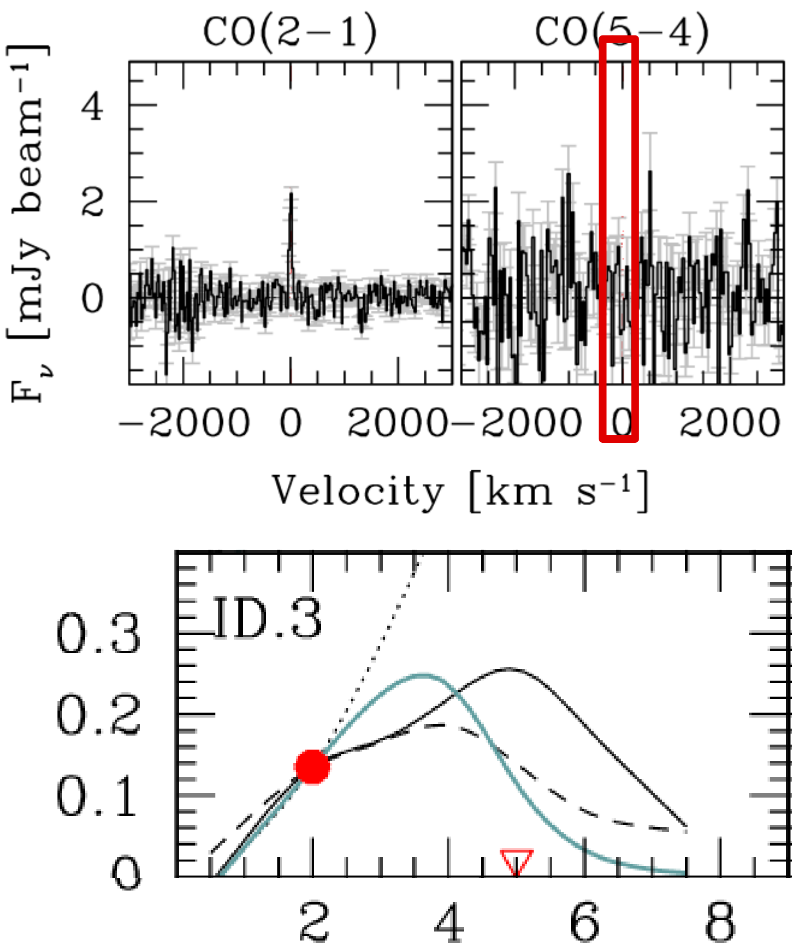


Genzel+15

CO excitation

MS galaxy at z~1.4:

Very low CO excitation



Decarli+16b

QSO host at z~6.4:

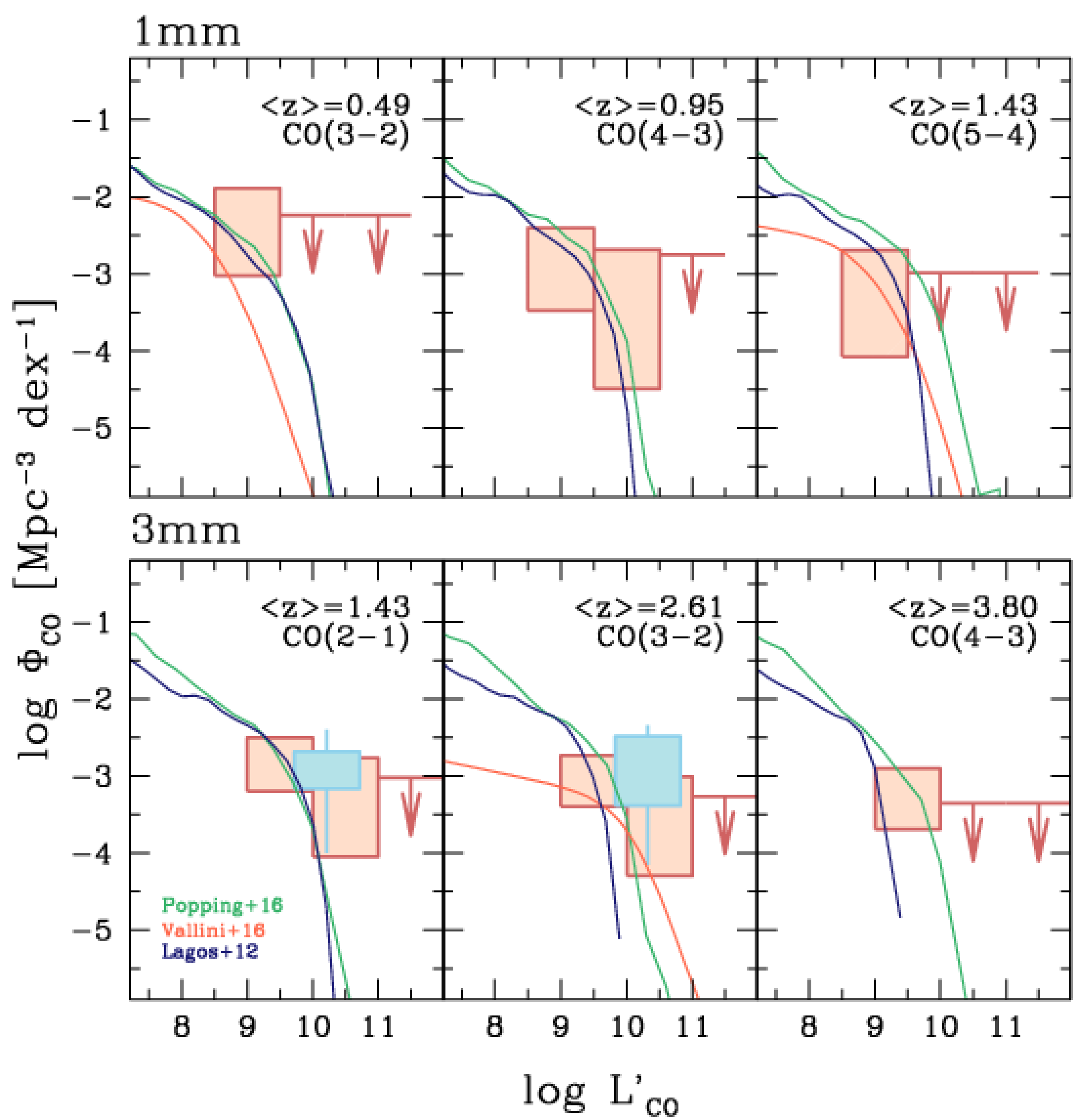
Very high CO excitation

See Simona's talk!

CO luminosity functions

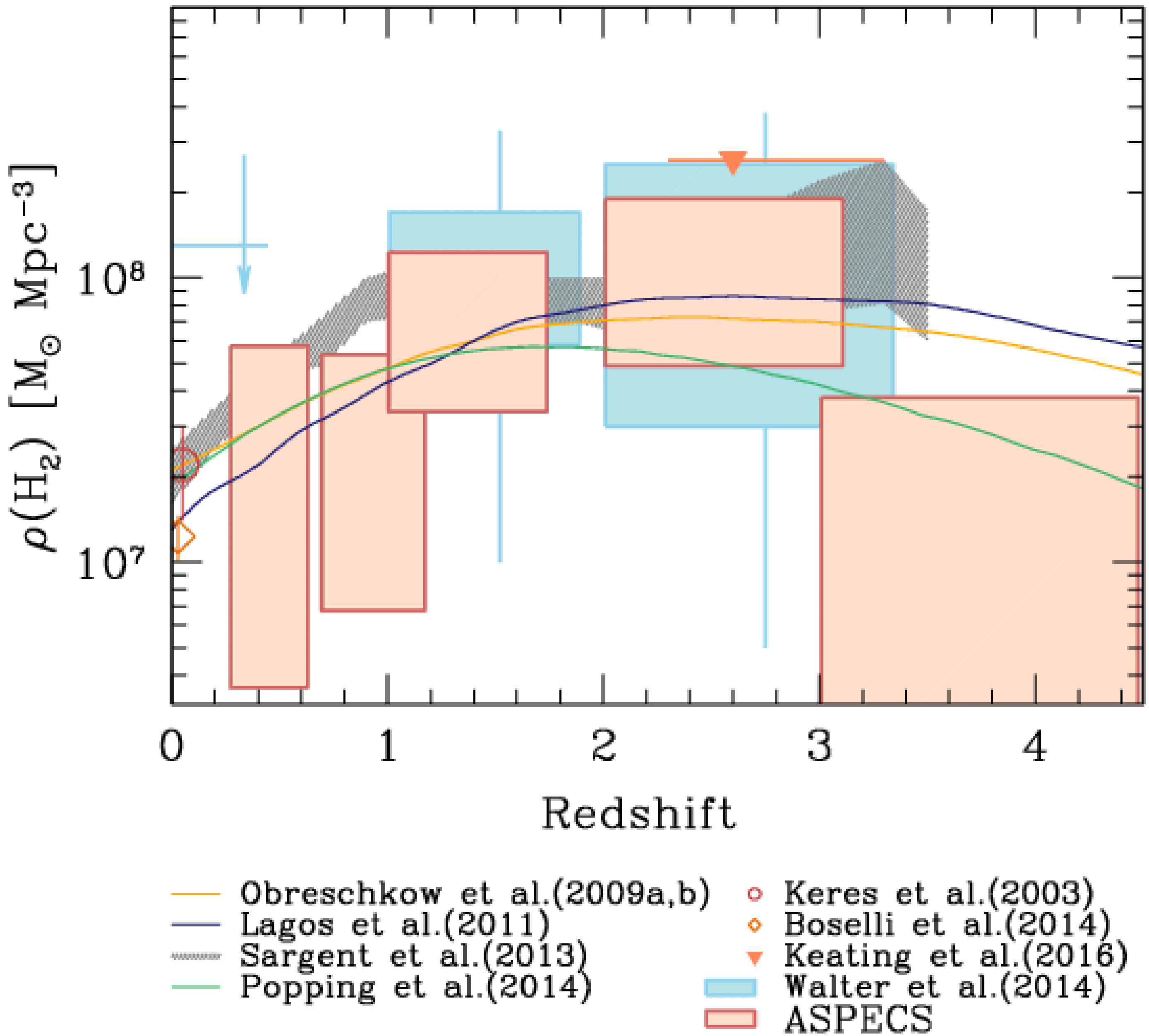
Lines: SAM predictions (Lagos+12, Popping+16)

Boxes: Obs. Constraints (Walter+14, ASPECS)



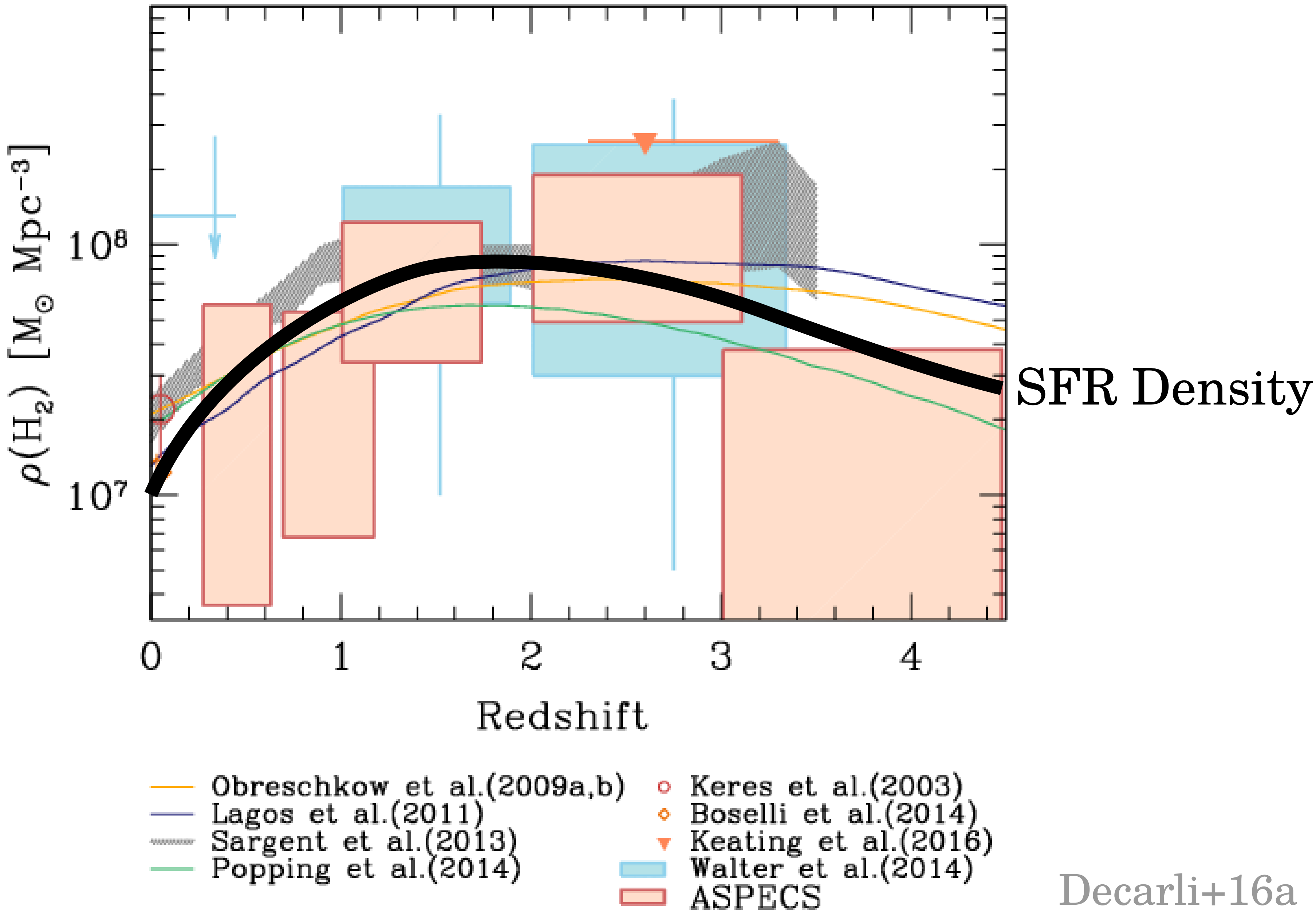
Decarli+16a

Molecular mass budget



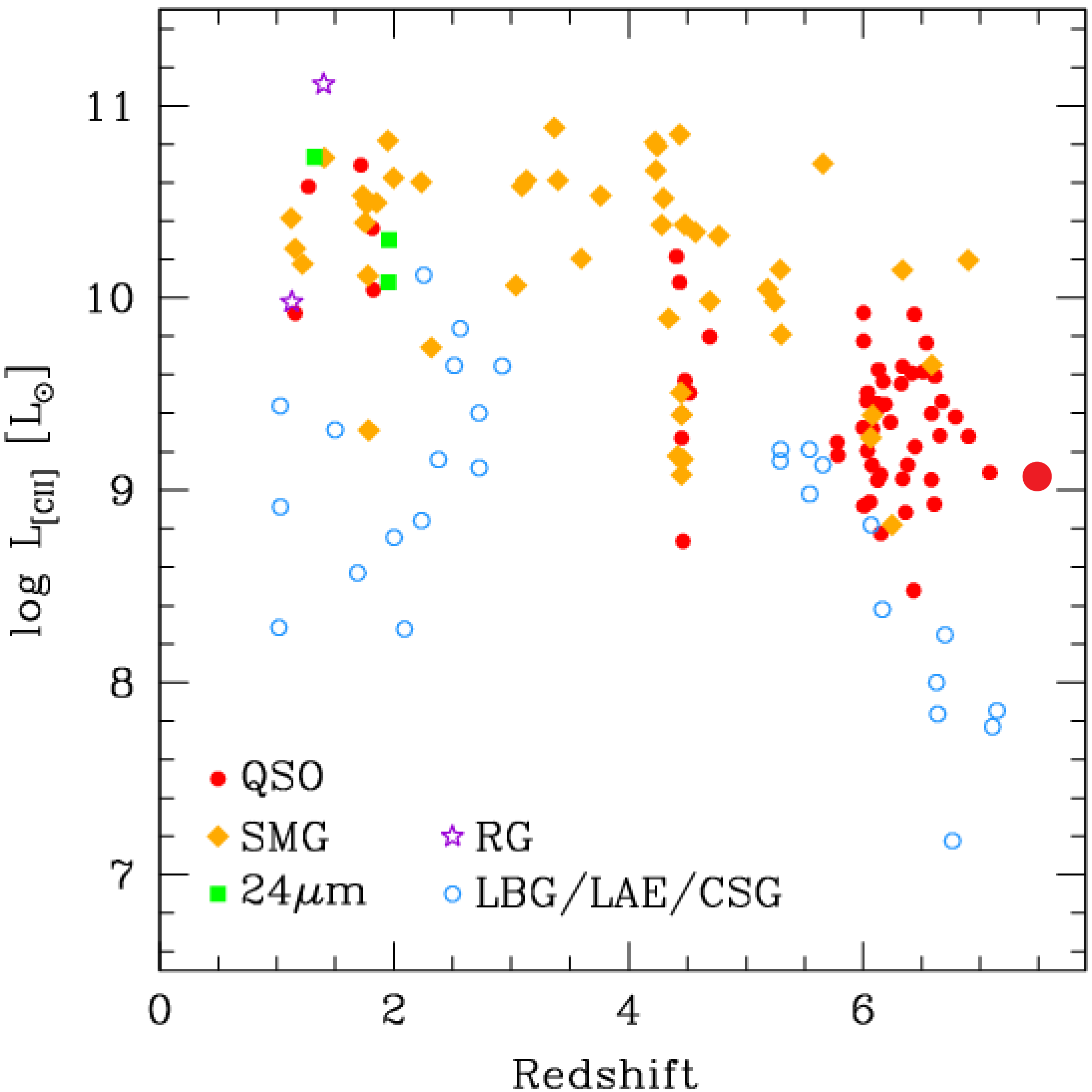
Decarli+16a

Molecular mass budget

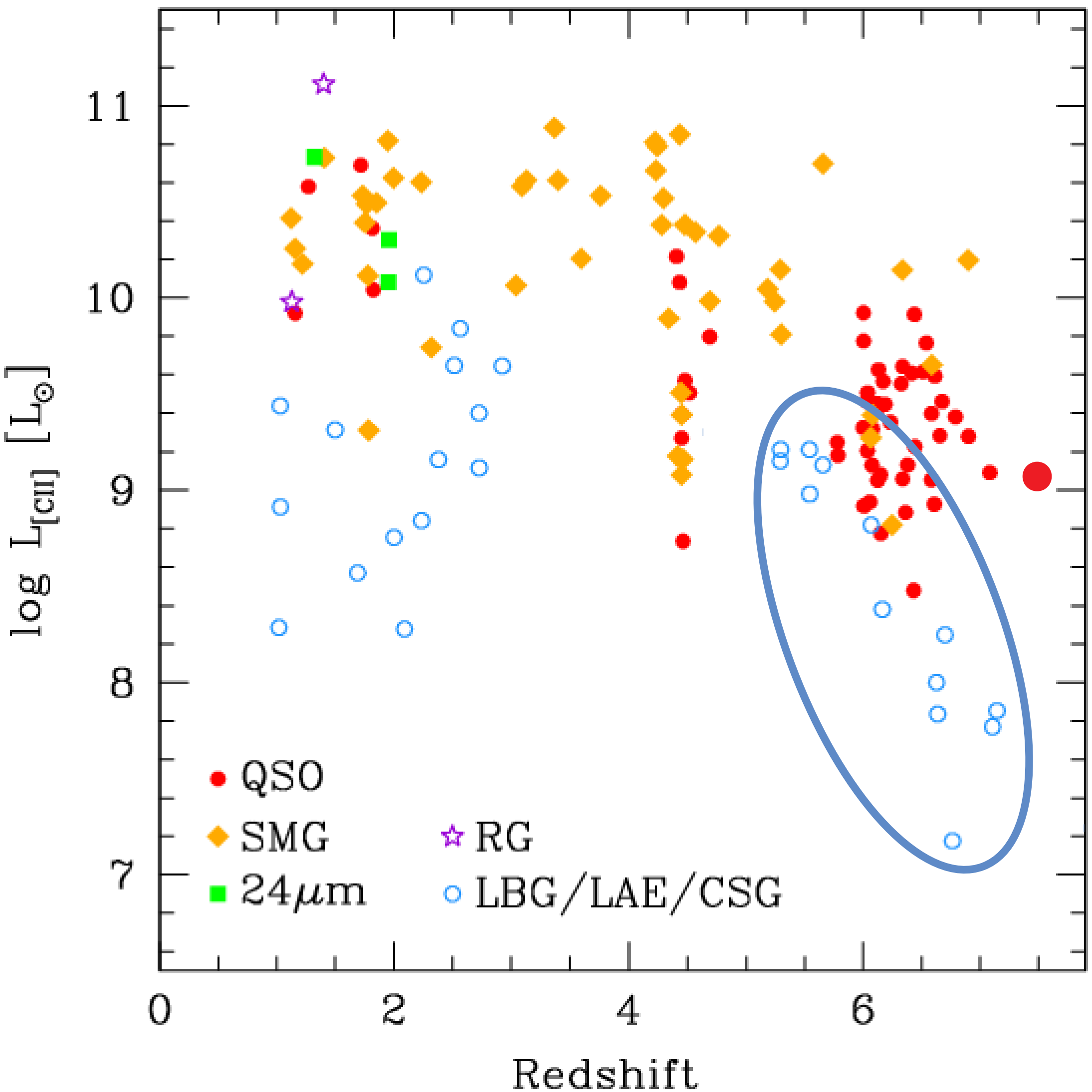


Decarli+16a

The high-z frontier

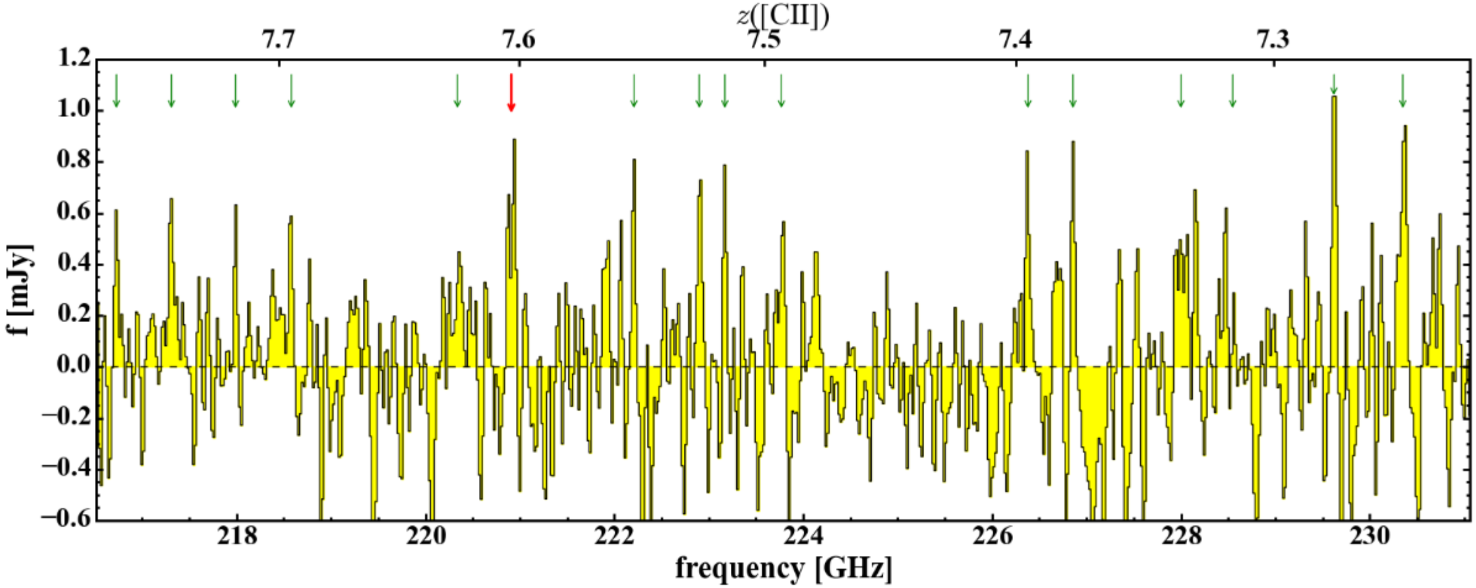


The high-z frontier

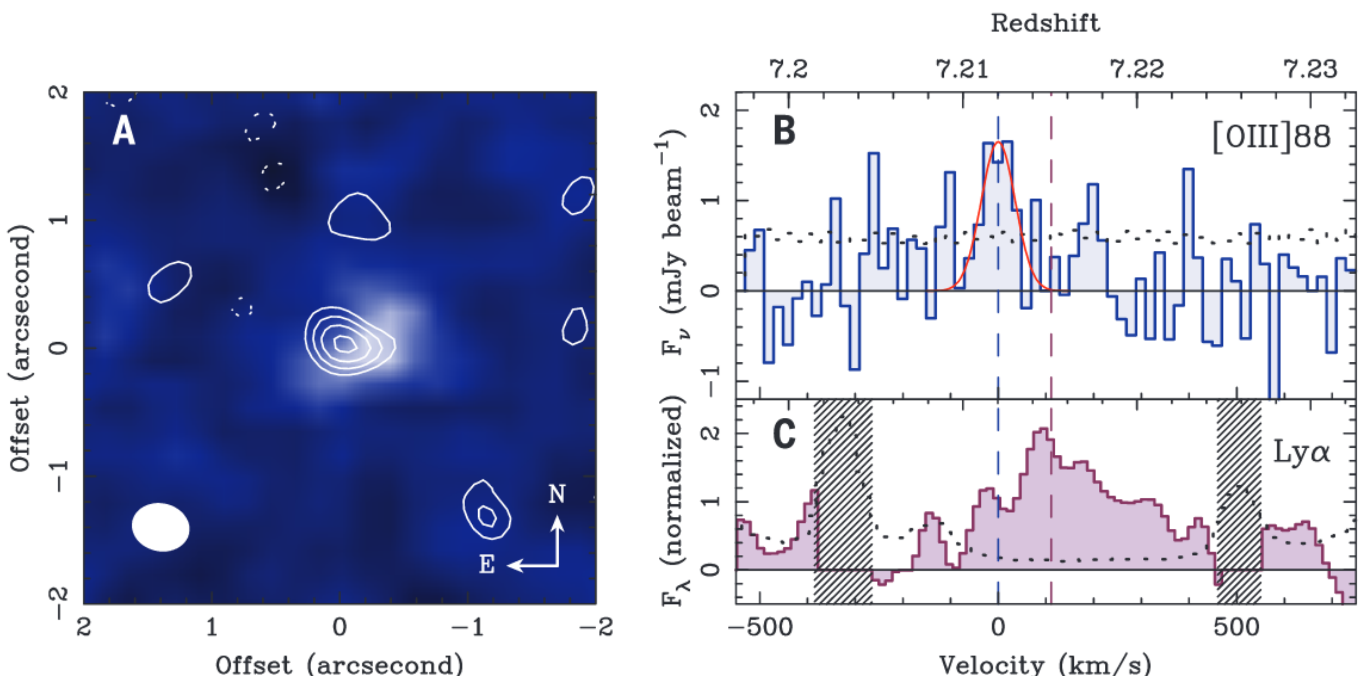


The high-z frontier

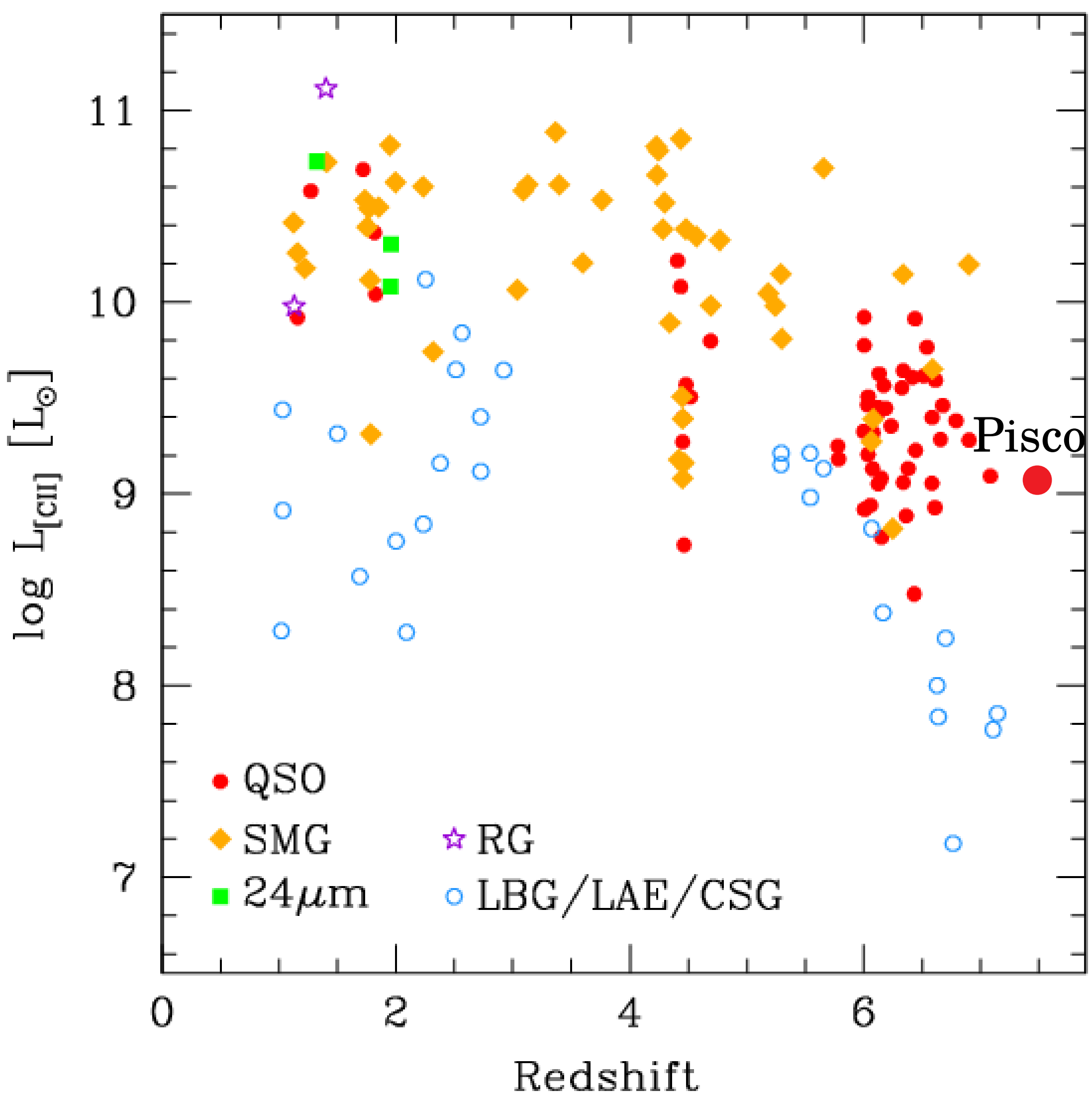
Knudsen+17



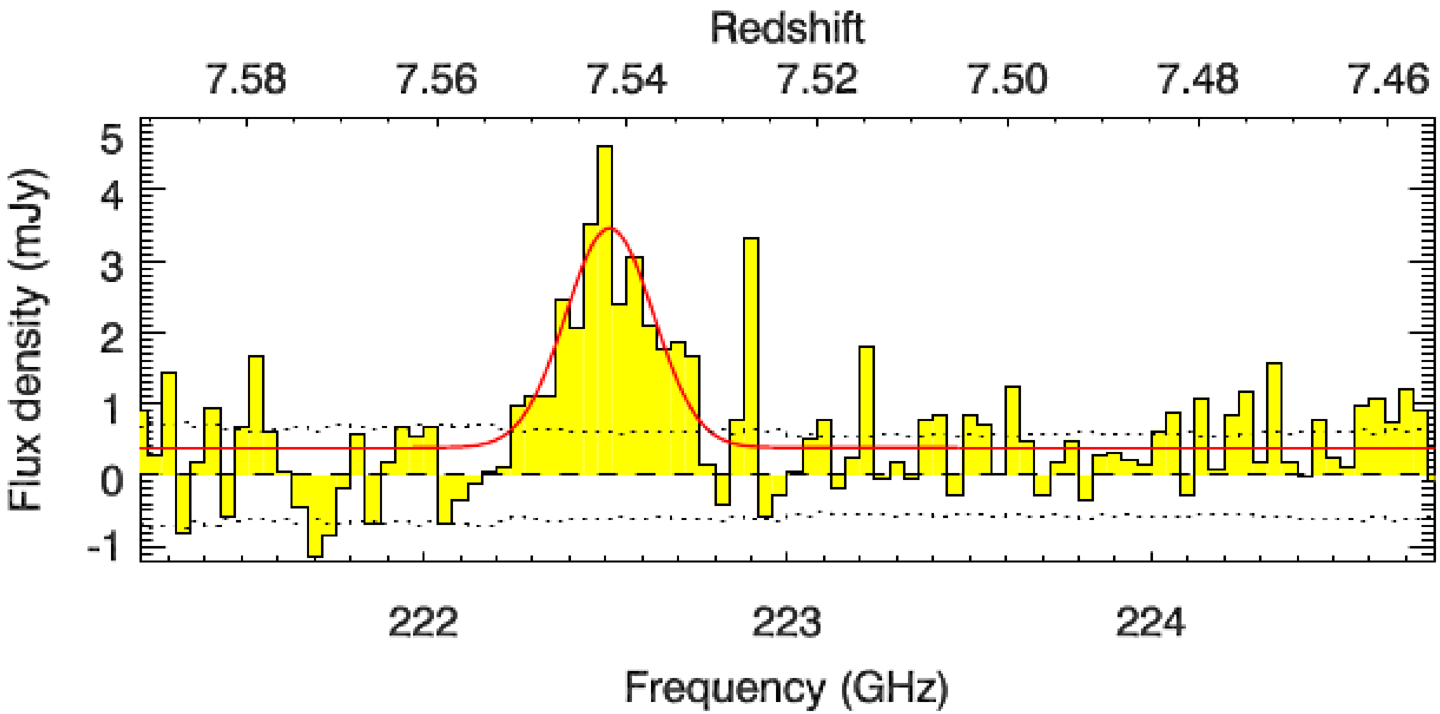
Inoue+16



The high-z frontier



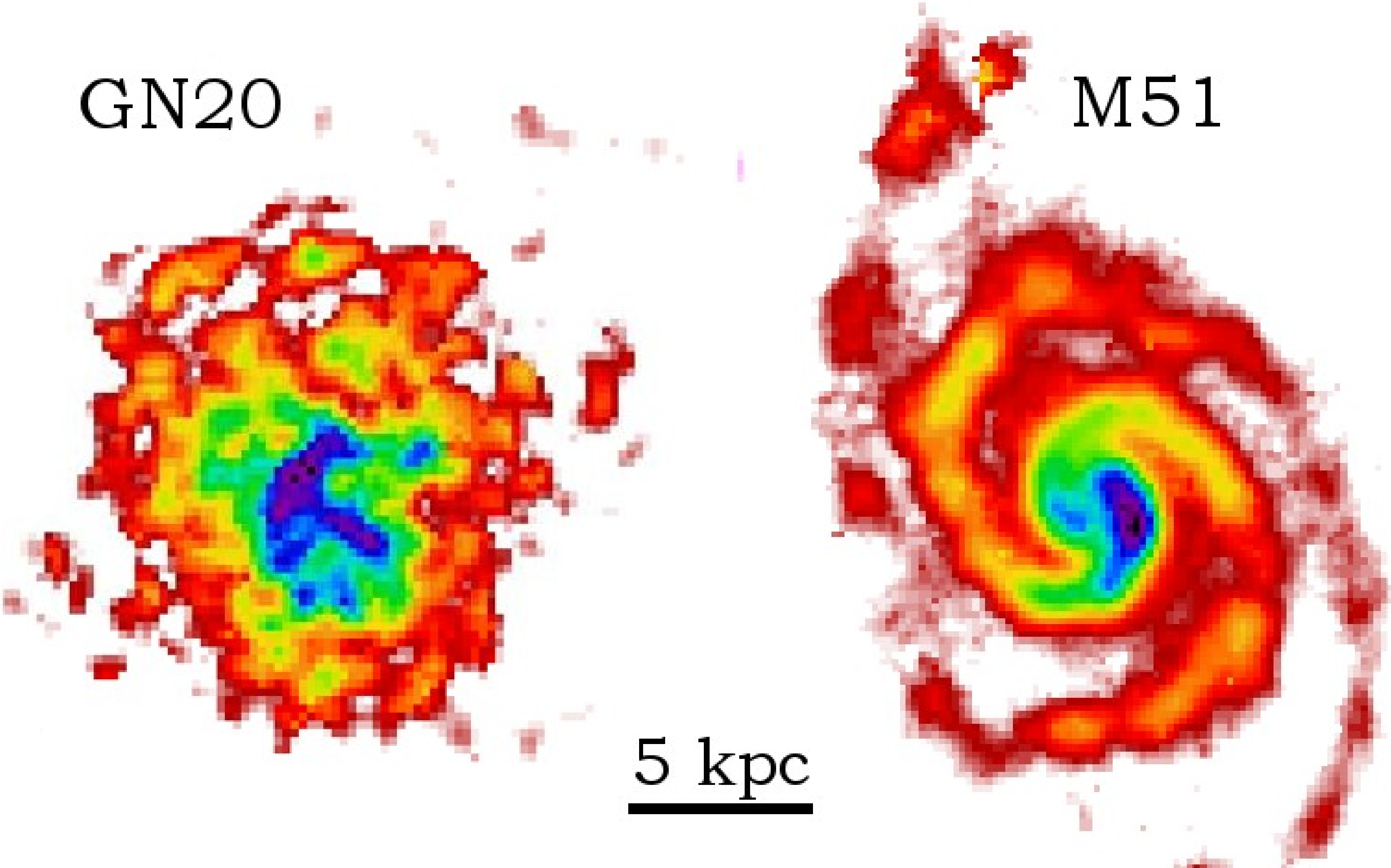
The high-z frontier



Venemans et al. (subm)

What's next?

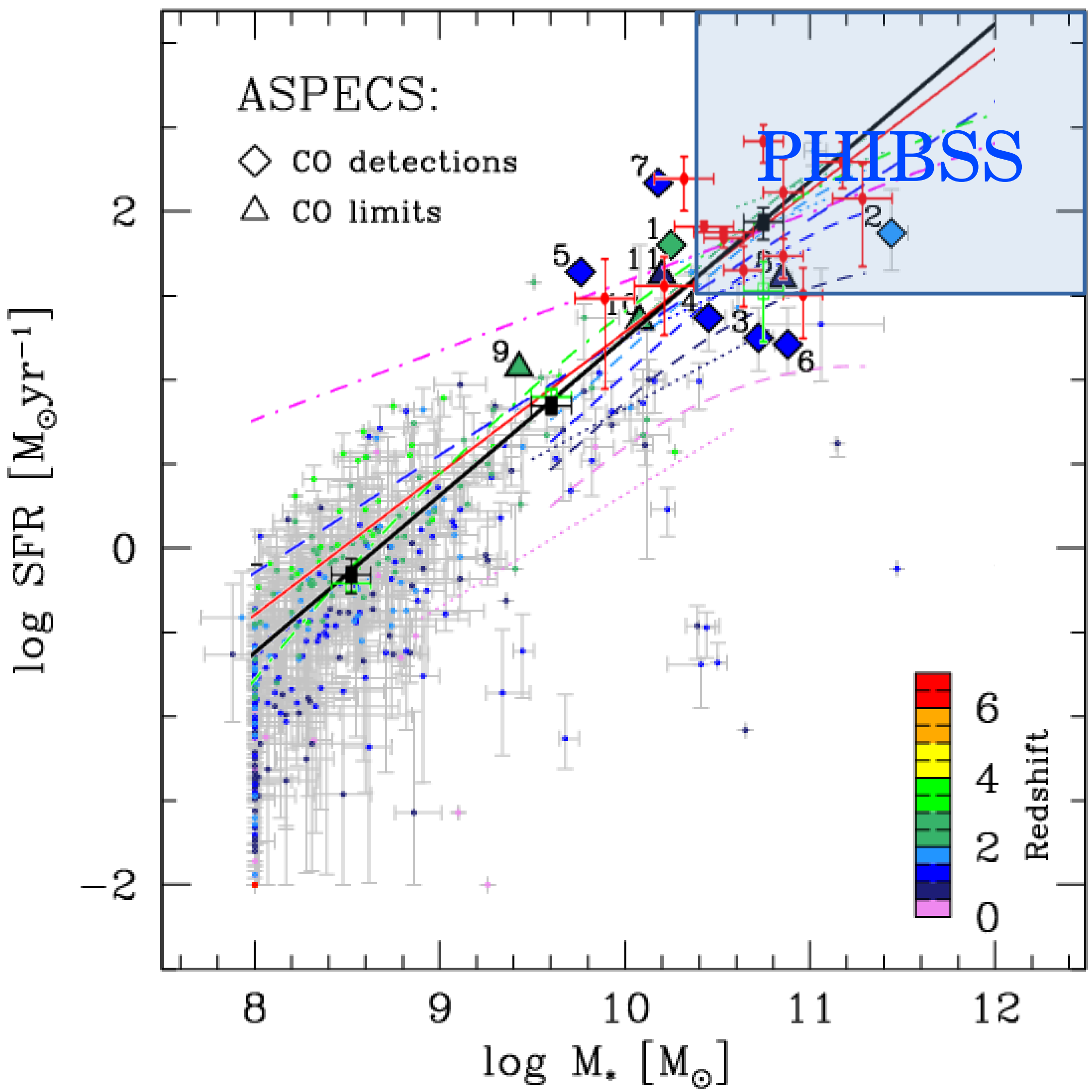
High resolution



Hodge+12

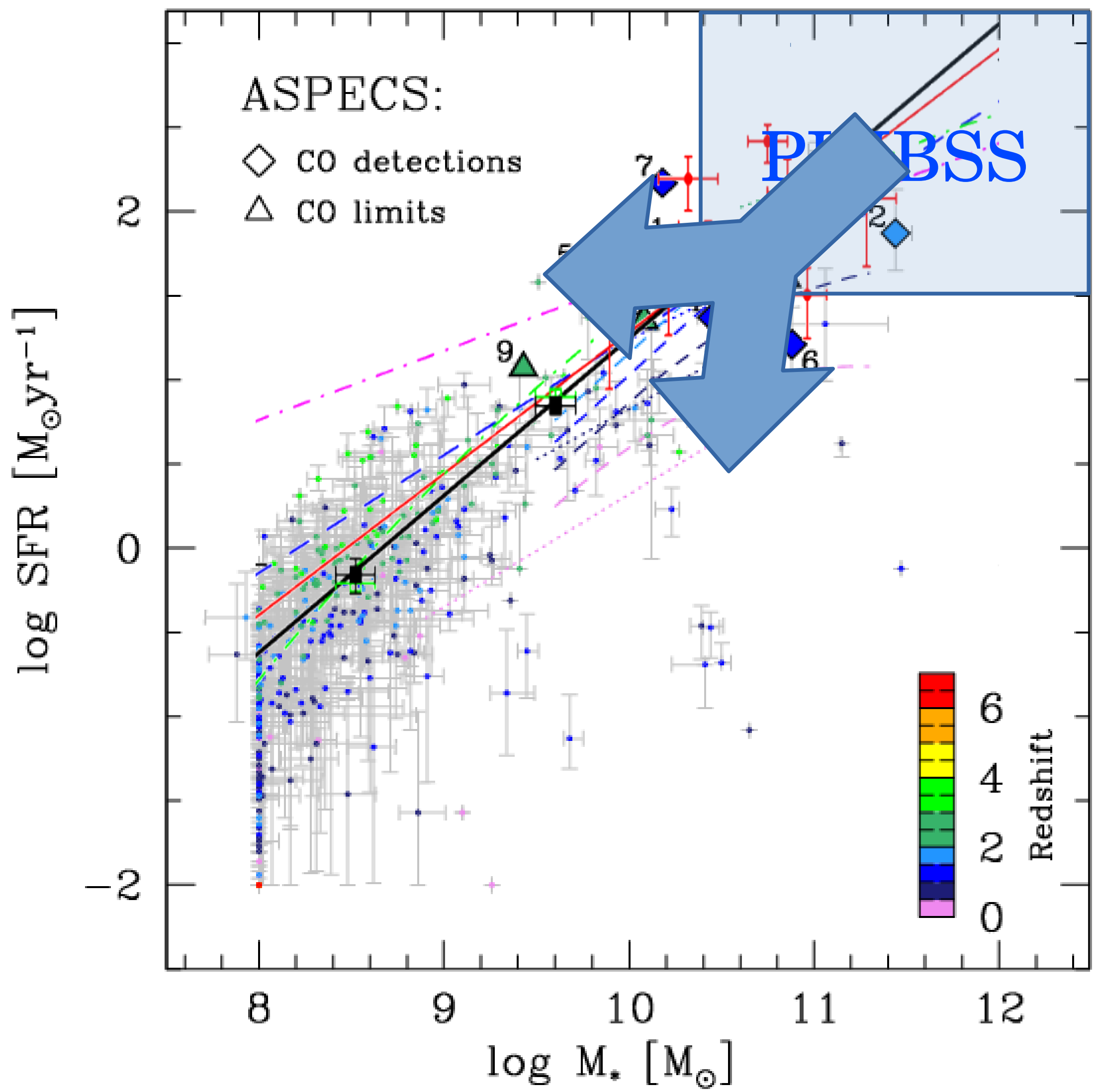
Schuster+07, Schinnerer+13

Expanded parameter space



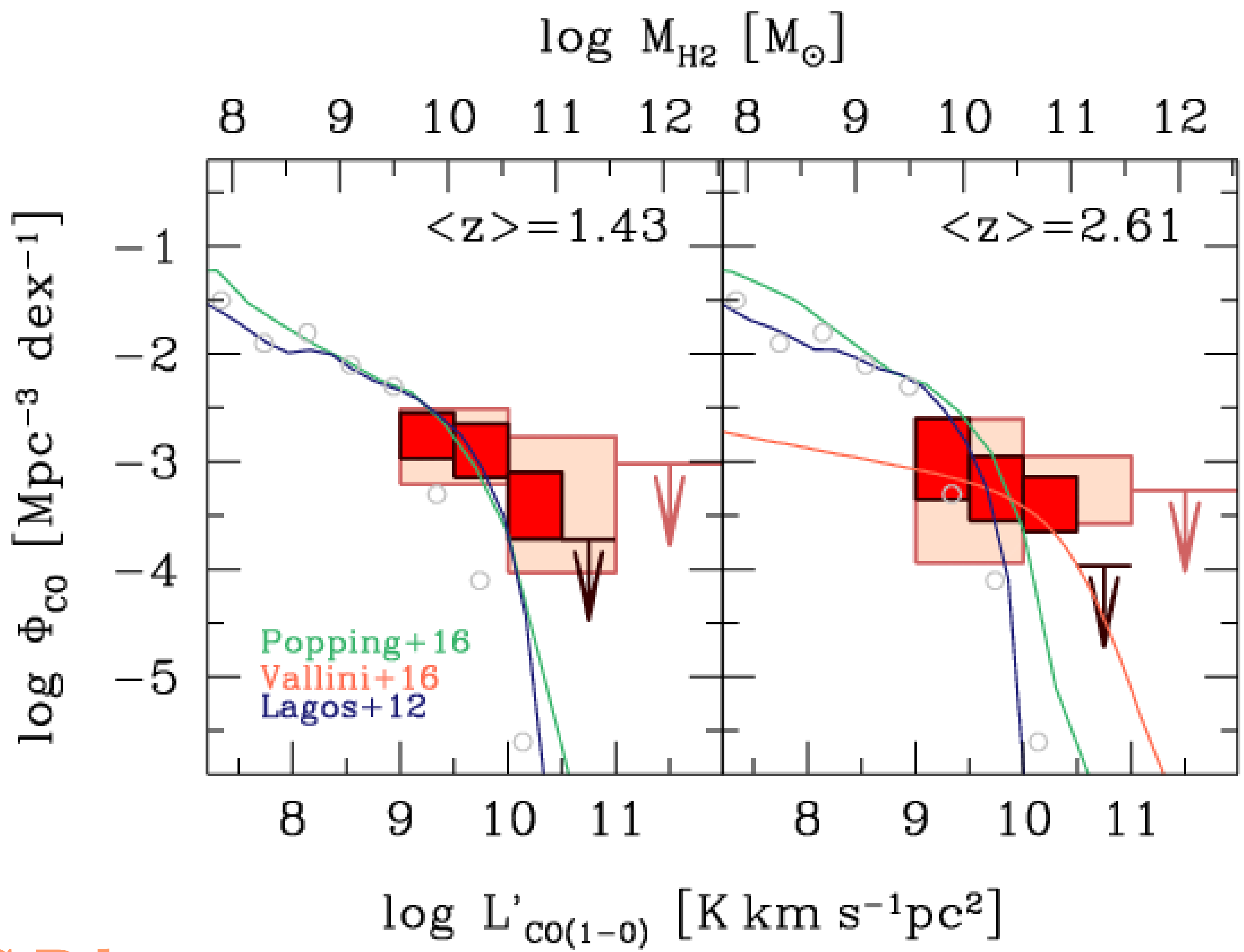
Decarli+16b + Dunlop+16

Expanded parameter space



Decarli+16b + Dunlop+16

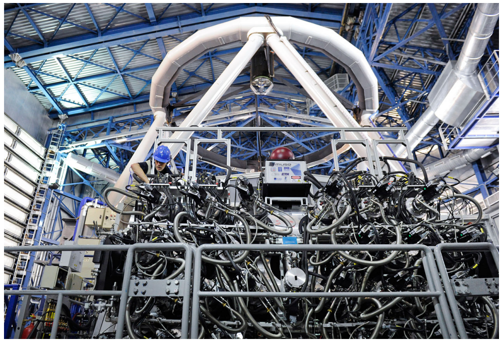
Larger samples



ASPECS Pilot

ASPECS Large Program (expected)

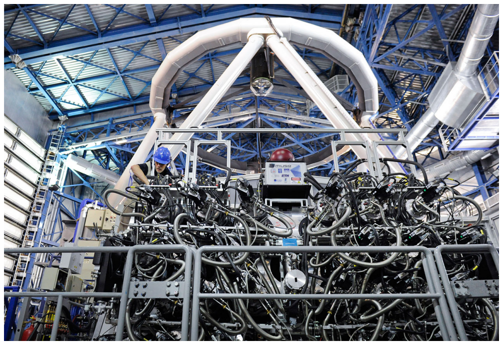
(more) multi-λ synergy



MUSE:

hundreds of redshifts per pointings, UV diagnostics

(more) multi-λ synergy

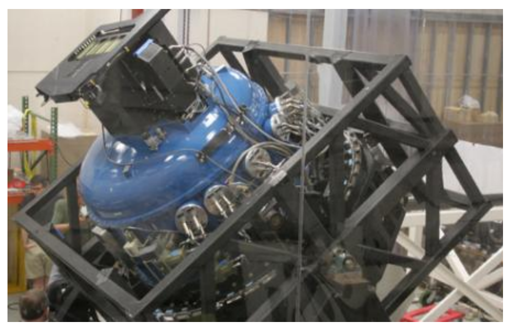


MUSE:

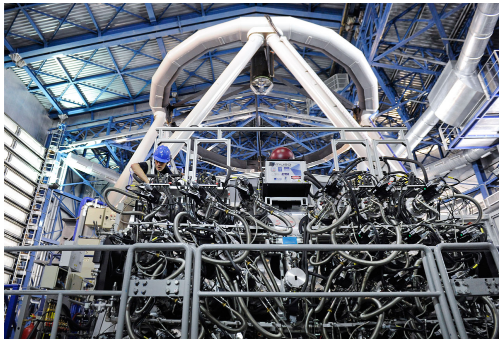
hundreds of redshifts per pointings, UV diagnostics

MOSFIRE, K-MOS:

optical diagnostics, resolved kinematics



(more) multi-λ synergy



MUSE:

hundreds of redshifts per pointings, UV diagnostics

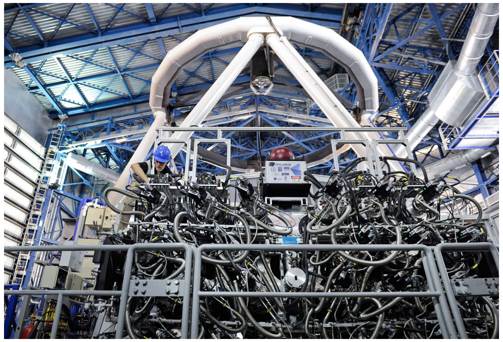
MOSFIRE, K-MOS:

optical diagnostics, resolved kinematics

JWST:

Precise masses, sensitive NIR/MIR spectroscopy

(more) multi-λ synergy



MUSE:

hundreds of redshifts per pointings, UV diagnostics

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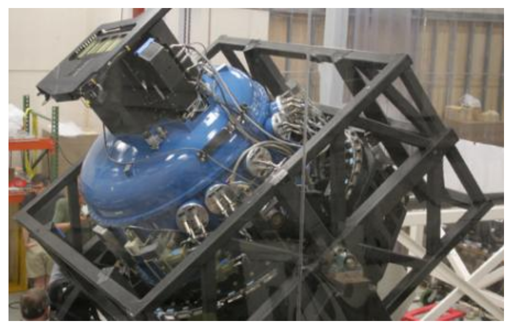


JWST:

Precise masses, sensitive NIR/MIR spectroscopy

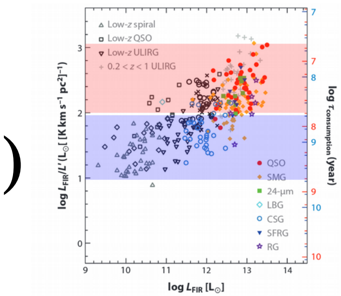
Full ALMA

Upgraded NOEMA

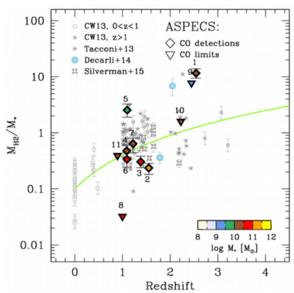
JVLA

Conclusions

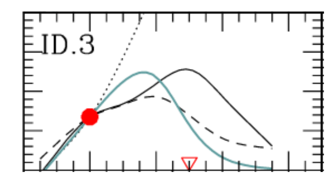
Conclusions



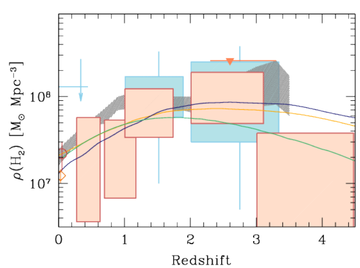
1) Main Sequence galaxies have t_{depl} ~ 1 Gyr (?)



2) Molecular gas fraction is 10x higher at z~2



3) CO excitation is modest in MS galaxies



4) Molecular content evolves as cosmic SFR

5) ISM physics is now accessible even at the highest z

Future: resolved studies, large samples, multi-tracers