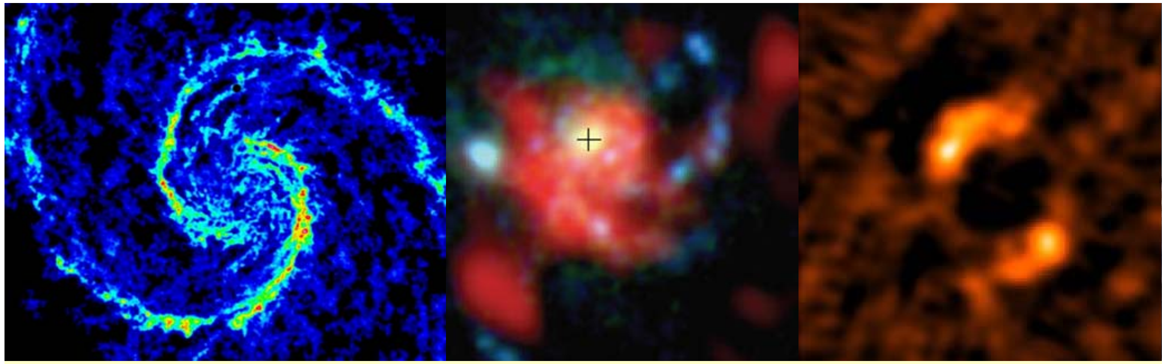


Molecular gas in galaxies across the Hubble time

Françoise Combes
Observatoire de Paris

3 October 2014

Census of cold gas in galaxies

While 6% of baryons are in stars now (Fukugita et al 1998)

$\Omega_* = 3\ 10^{-3}$

the atomic gas HI in galaxies is ~10% (Zwaan et al 2005)

$\Omega_{HI} \sim 3.5\ 10^{-4}$

and the molecular gas, from CO (Sauty et al 2003, Keres et al 2003)

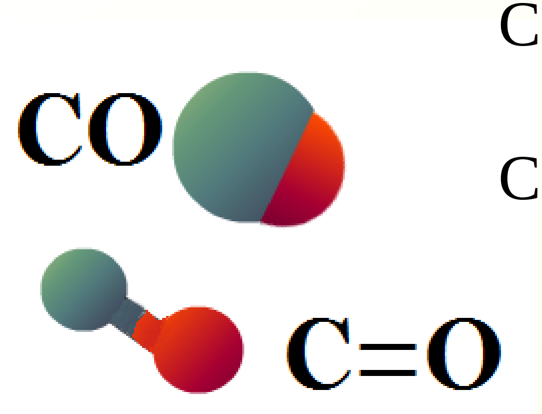
$\Omega_{H2} \sim 1.2\ 10^{-4}$

The molecular fraction is expected to increase at high redshift:

→**Galaxies were smaller in 1/(1+z), and gas fraction higher,**
Denser gas favors the HI → H_2 transition

Either by pressure (Blitz & Rosolowsky 2006), or from balance between formation on grains, UV-photodissociation (Krumholz et al 2009)

Tools to observe molecular gas



Cold H_2 does not radiate

$CO/H_2 \sim 10^{-4}$

Low dipole moment

$n(H_2) \sim 10^3\ cm^{-3}$ critical density
for CO(1-0)

Density tracers, high-J CO, HCN,; HCO+

CO to H_2 conversion factor= XCO

E=52K J=4

CO(4-3) 650μ 460GHz

E=31.2K J=3

CO(3-2) 345GHz

E=15.6K J=2

230GHz

E=5.2K J=1

115GHz

E=0 J=0

2.6mm

Cosmic evolution of the CO-Lum. function

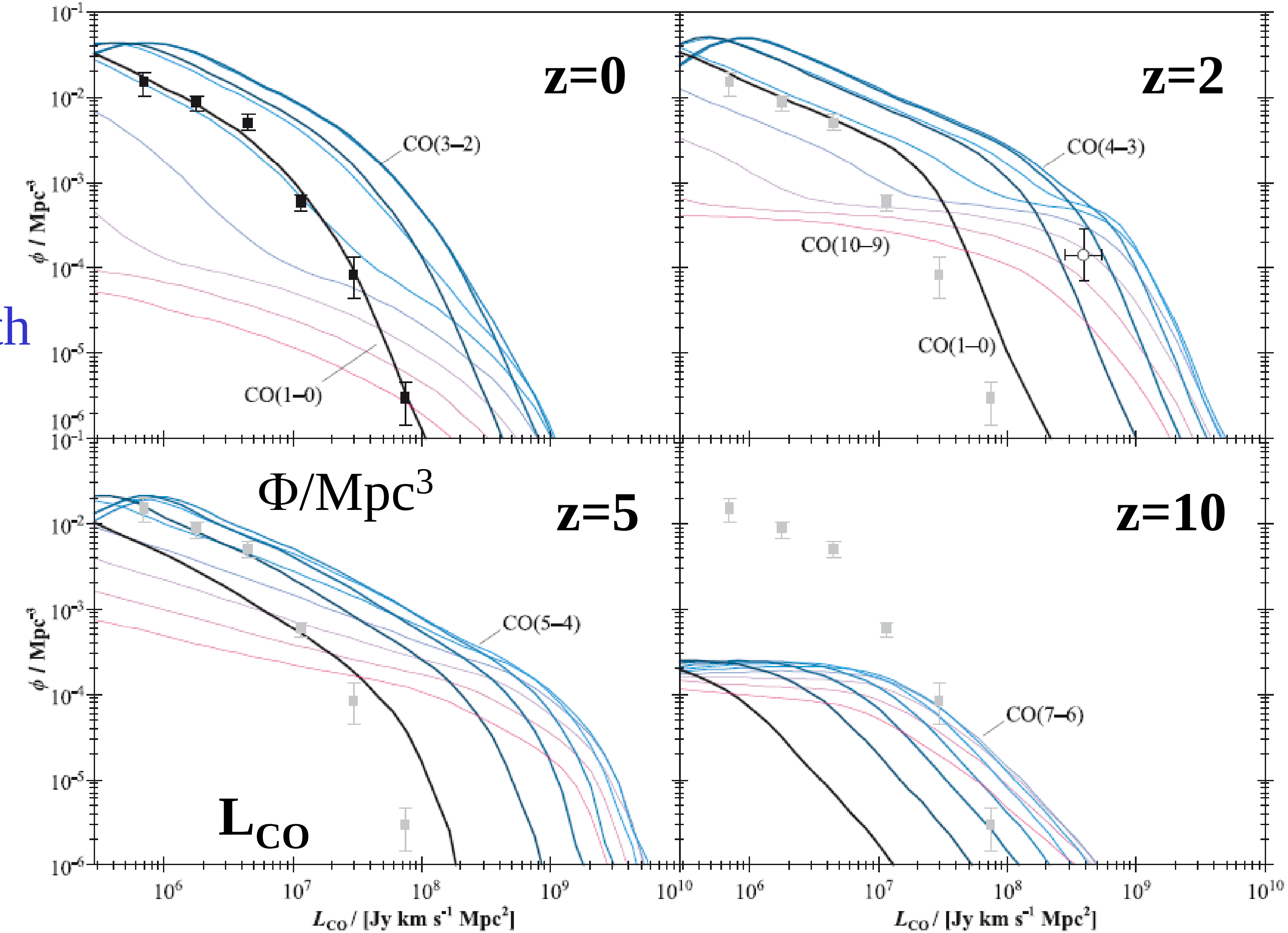
With some hypothesis, about the H_2/HI ratio in galaxies

More H_2, due to more compact and gaseous galaxies

Heating by Starbursts AGN, CMB

Metals, smooth or clumpy

Overlap of clouds, etc..



Obreschkow et al 2009

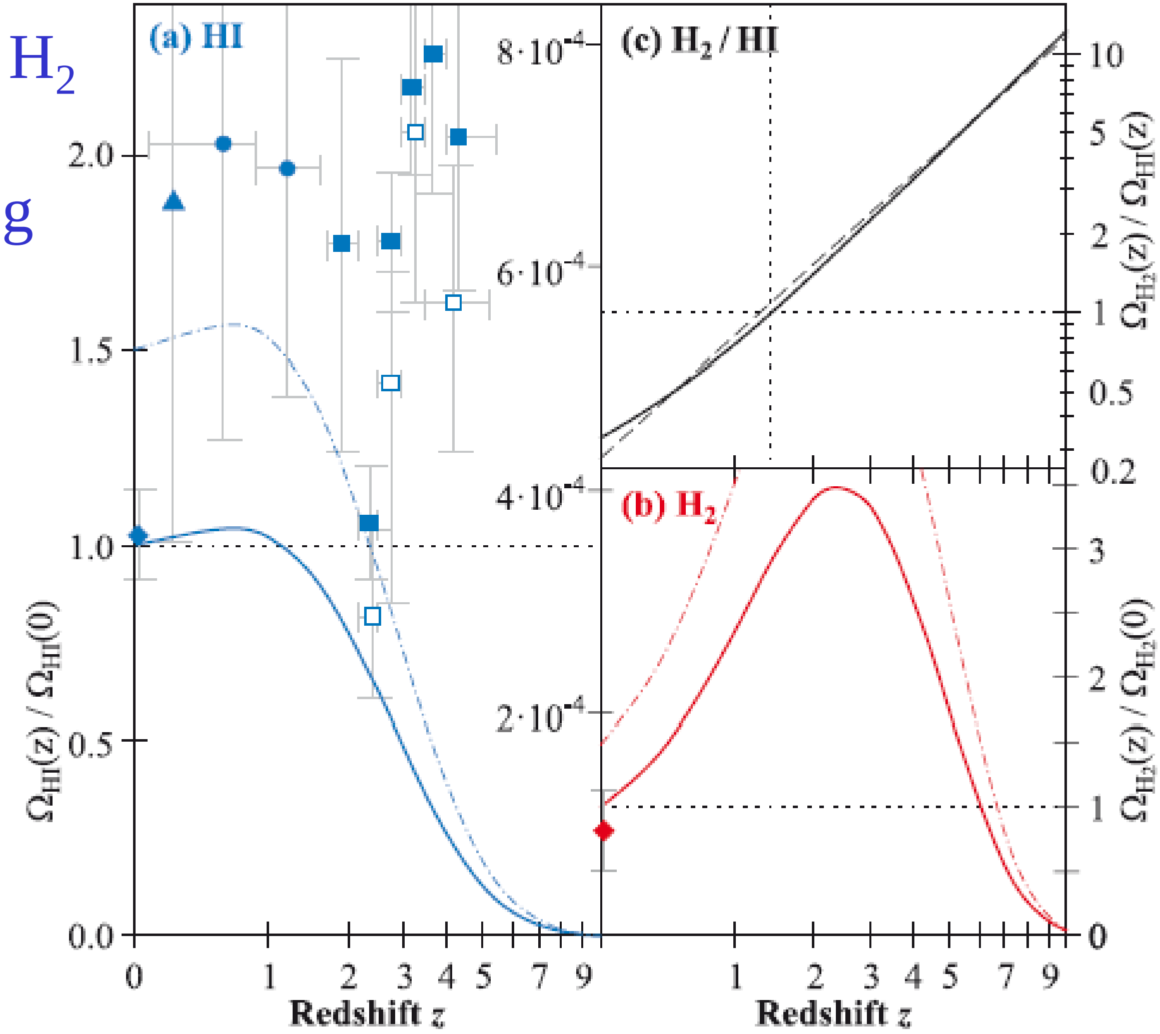
Cosmic evolution of H_2/HI

The HI evolution is taken from DLA absorbants, but could be biased

Pressure-based model for H_2

Simulations from a catalog of Millenium, + SAM

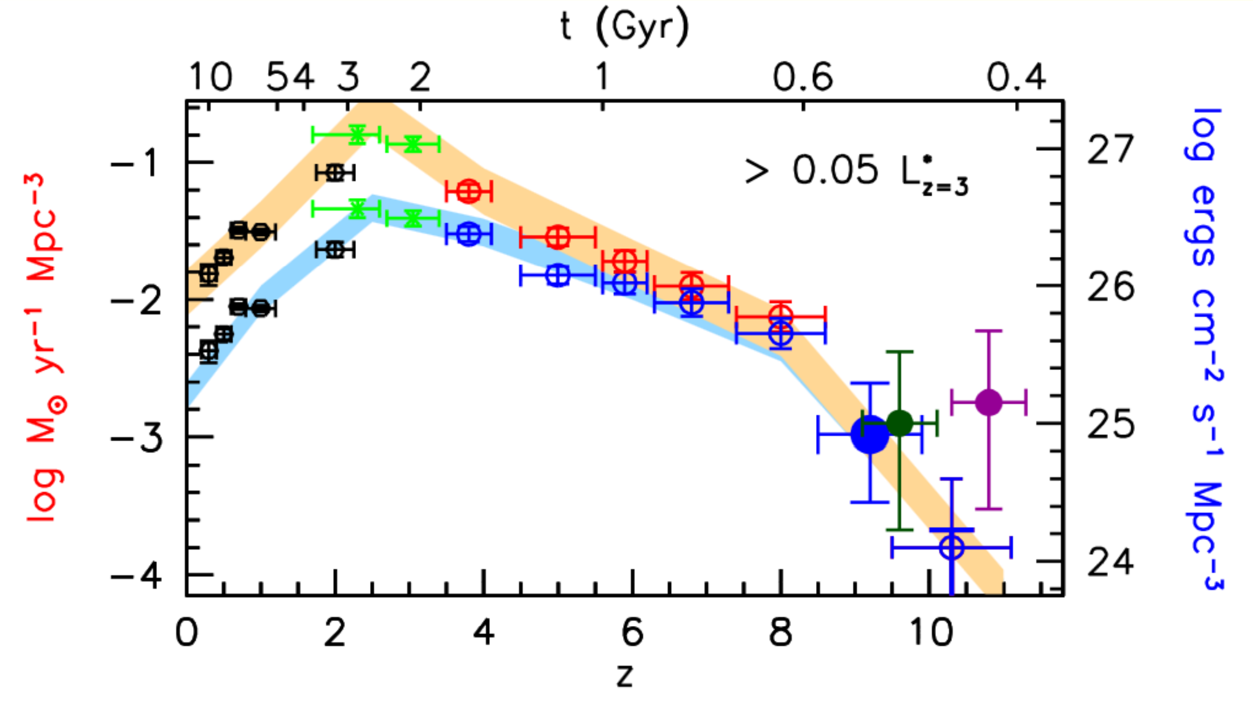
H_2/HI ~$(1+z)^{1.6}$



Obreschkow & Rawlings 2009

Star formation history: main issues

--How gas is accreted, form stars?
--Quenching of star formation (SF)
--Downsizing of starbursts



Red : corrected from dust attenuation

Dust from UV slope at high-z

Bouwens et al (2013)

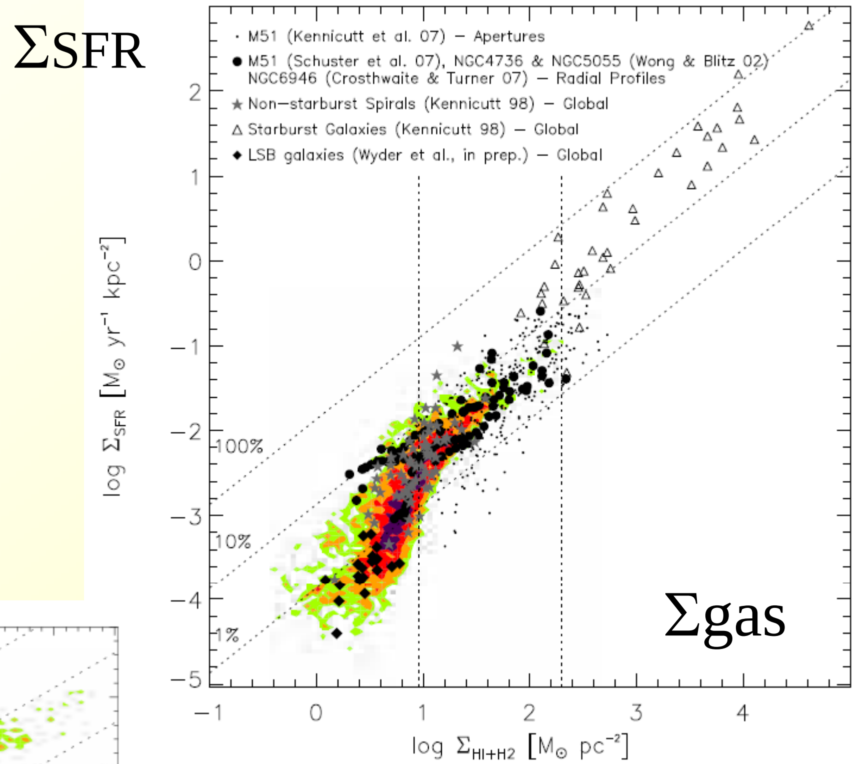
➔ **Higher evolution above z=8**

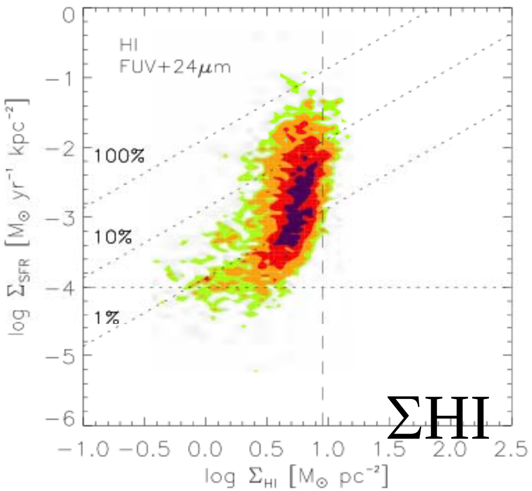
Molecular gas and Star formation z=0

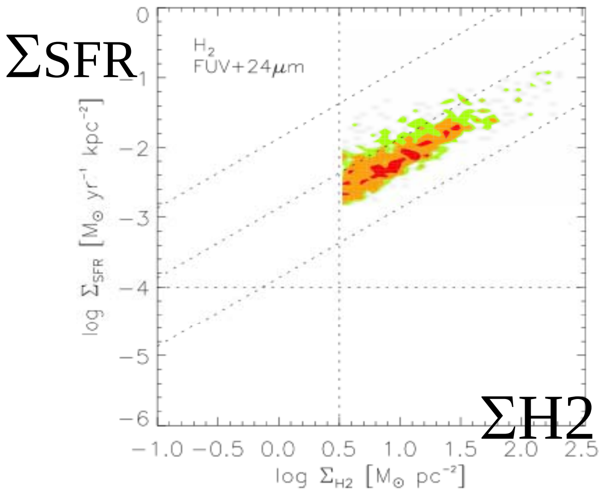
H_2 forms stars at a constant efficiency (n=1)
Bigiel et al 2008, 2009

Depletion time
2 10^9 yrs

SFR not strongly
correlated with HI
But with H2





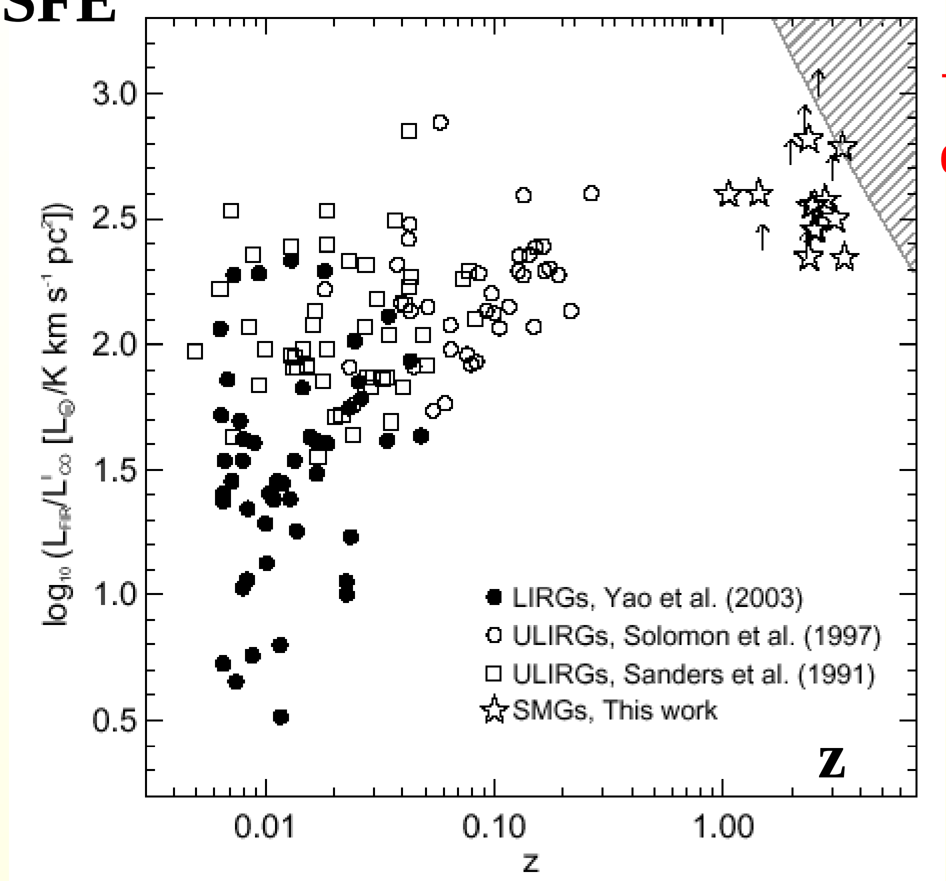


Kennicutt-Schmidt
Relation➔ KS

Star formation efficiency SFE ~L_{IR}/L'_{CO} vs z

Greve et al 2005

SFE



ULIRG: Ultra-luminous > 10^{12} Lo
LIRG Luminous > 10^{11} Lo
SMGs: Submillimeter Galaxies

+6 SMGs not detected in CO

40- 200 Myr SB phase
SFR ~700 Mo/yr
More efficient than ULIRGs

Mergers without bulges?

Total masses ~0.6 M_*

ULIRGs at intermediate z

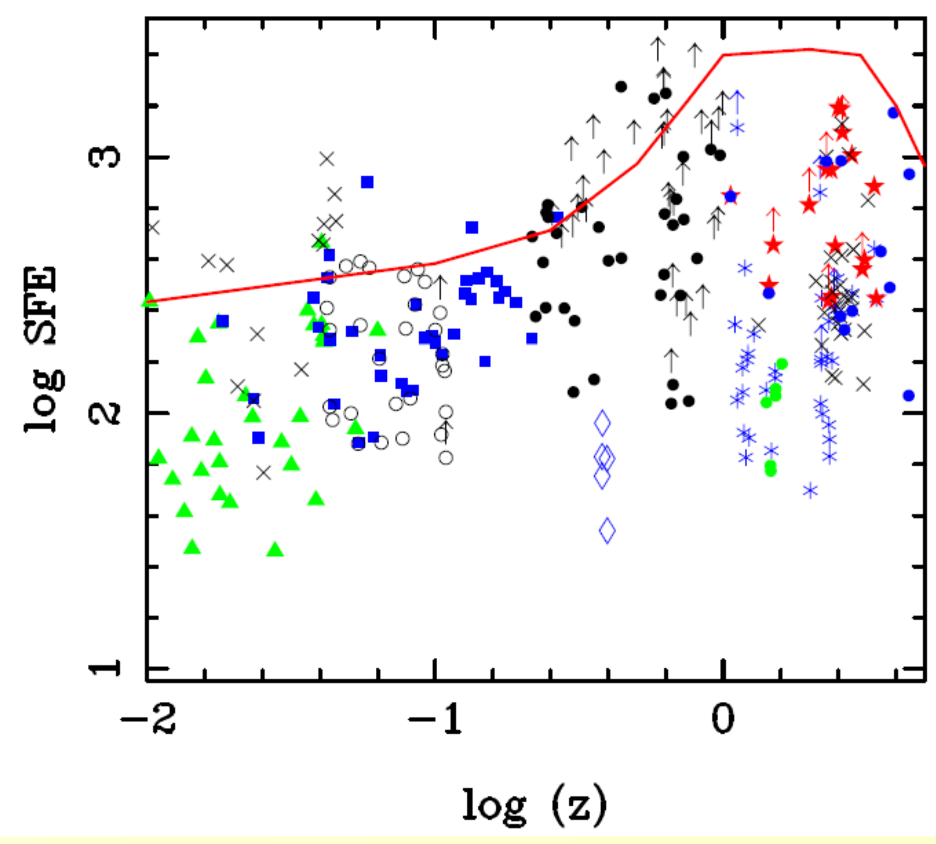
Selection of the brightest ULIRGs: 69 galaxies

1st step 0.2 < z < 0.6
60% CO detected
2^{nd} step 0.6 < z < 1,
37% detected

XCO assumed: α=0.8 (ULIRGs)
(MW α=4.6)

SFE_{max} follows the SF history in relative magnitude

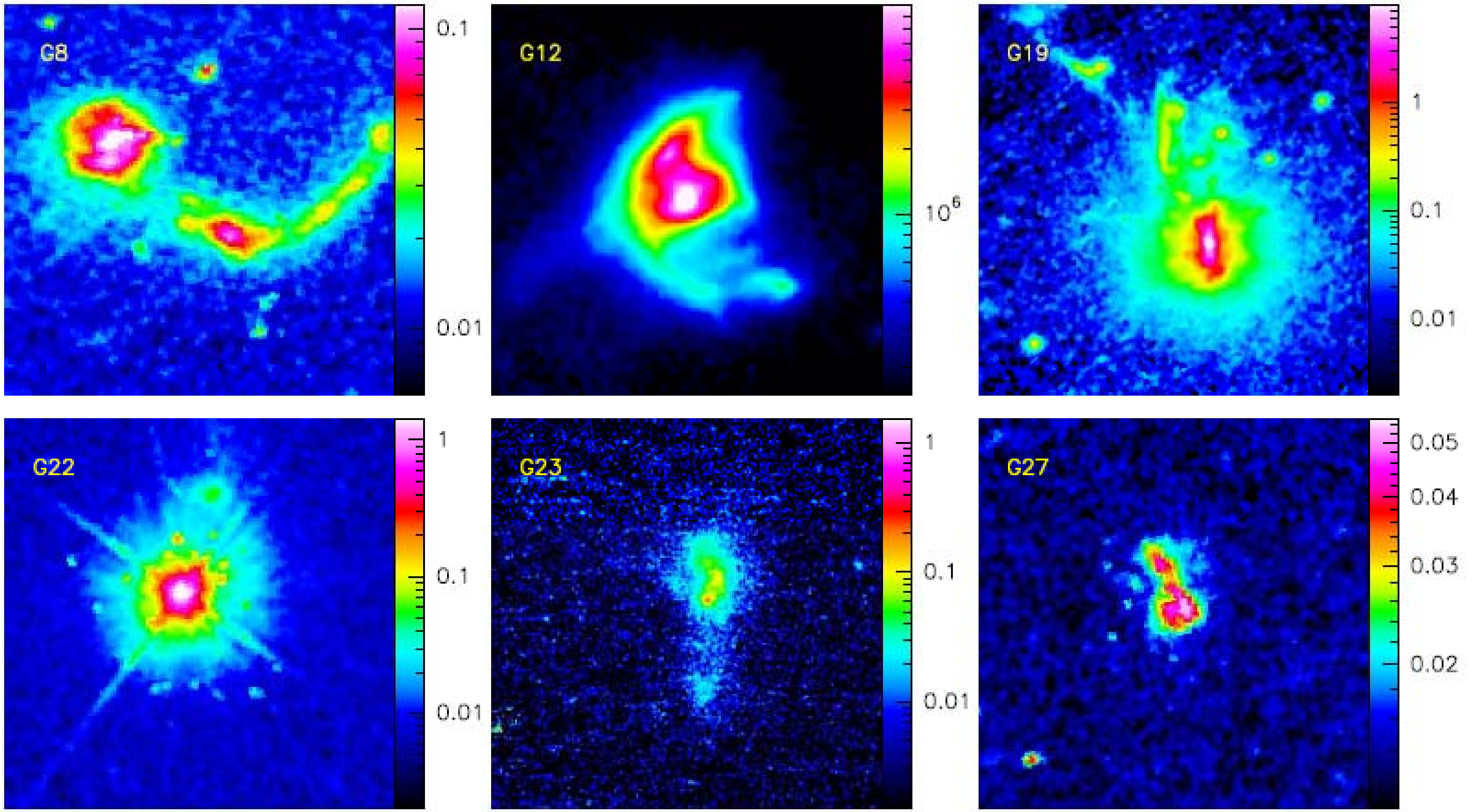
Hopkins & Beacom (2006)



Combes et al 2011, 13

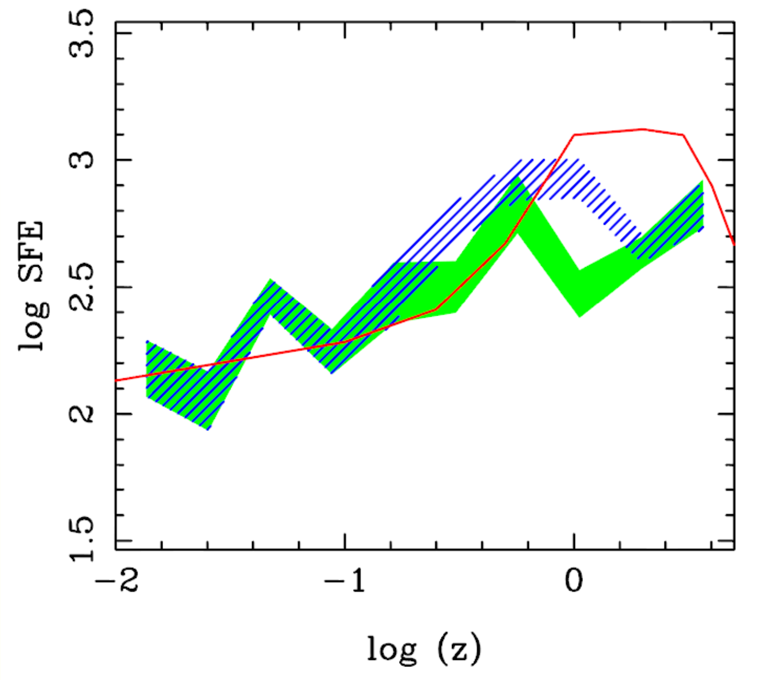
ULIRGs are perturbed systems

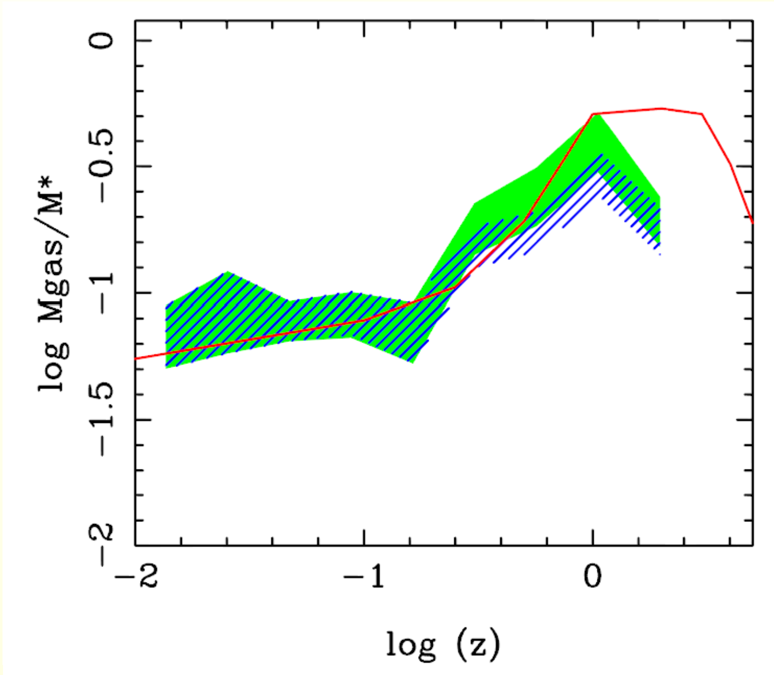
Galaxies 0.2 < z < 0.6 detected in CO



10 arcsec

Key factors to explain SFRD





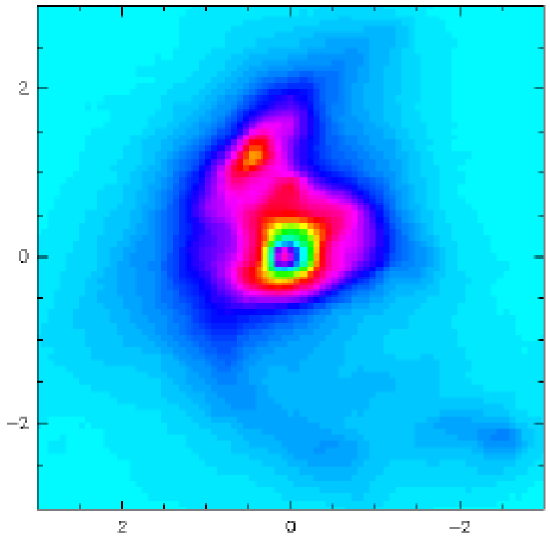
Star formation efficiency **and gas fraction**

<z=1>/<z=0>= 2.1 /3.8 (hatched: with upper limits) 3.2 and 2.5

Both contribute, **factor 3±1 increase between z=0 and 1**

SFE should also be increased due to more violent dynamics

Galaxies with high resolution: PdBI



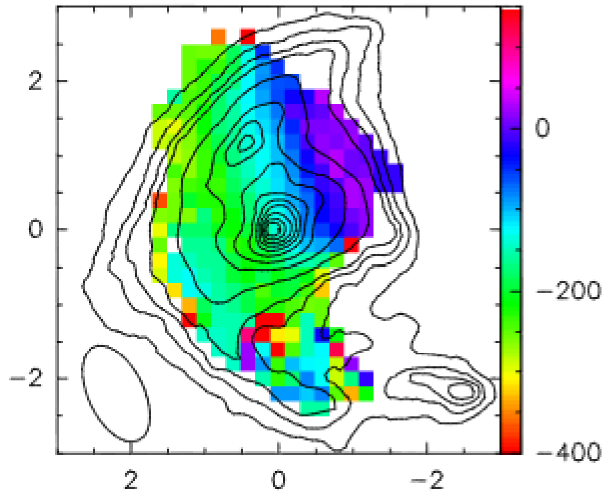
Some of these objects have a dense nuclear disk, and an extended cold disk

Extended flux filtered out by intereferomete

G12: HST-NICMOS image
Z=0.2417
1''~3.7kpc

Extended ~20kpc
➔Some of these objects could have a large CO-H_2 conversion factor

CO(1-0) V-field with HST contours superposed



Velocity gradient resolved

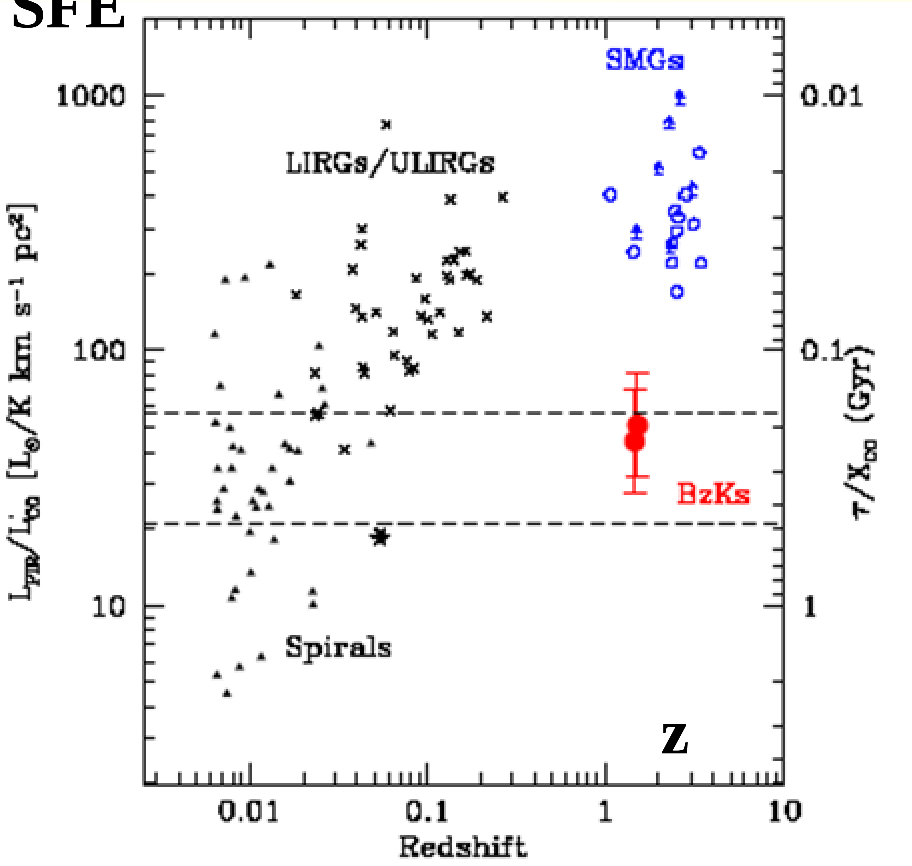
Combes et al 2013

Low efficiency of SF at high-z

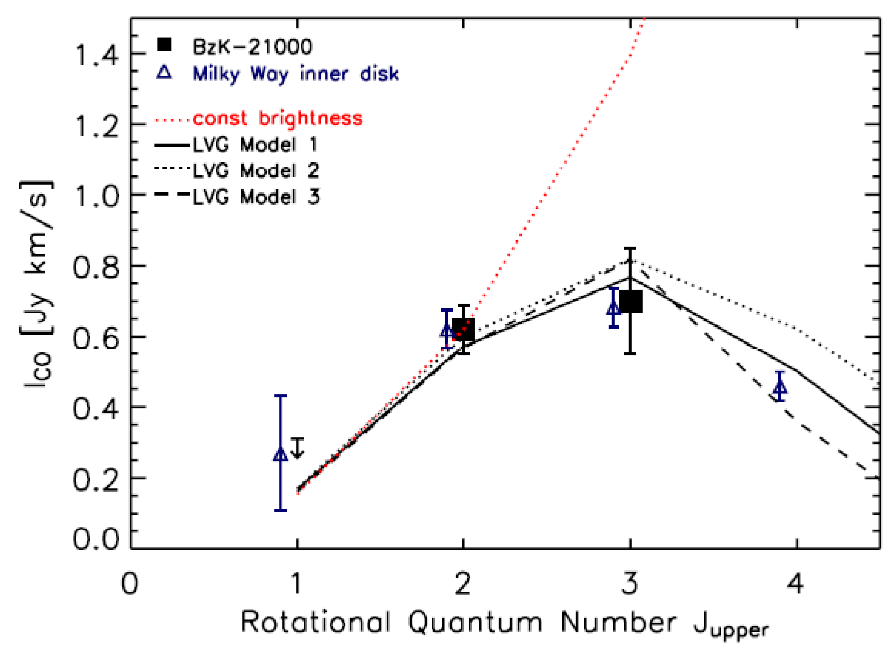
In BzK galaxies, much more CO emission detected than expected
Massive galaxies, CO sizes ~10kpc? L(FIR) ~10^{12} Lo
Normal SFR, M(H2) ~ 2 10^{10} Mo τ ~2 Gyr
➔ Much larger population of gas rich galaxies at high z

Daddi et al 2008

SFE



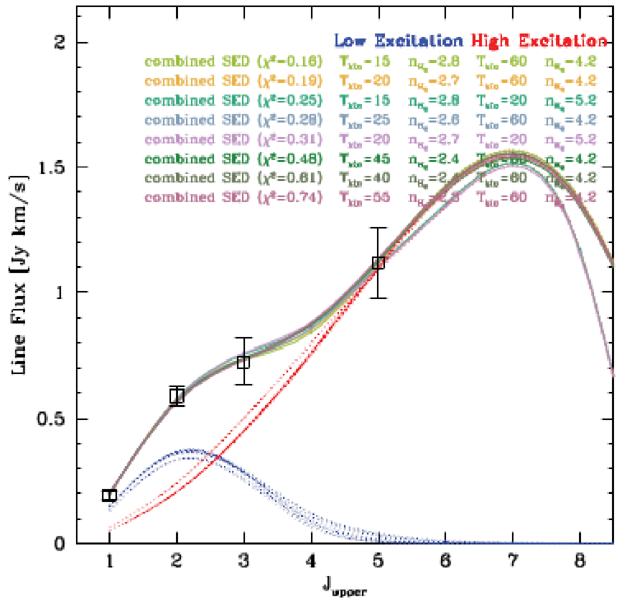
Dannerbauer et al 2009



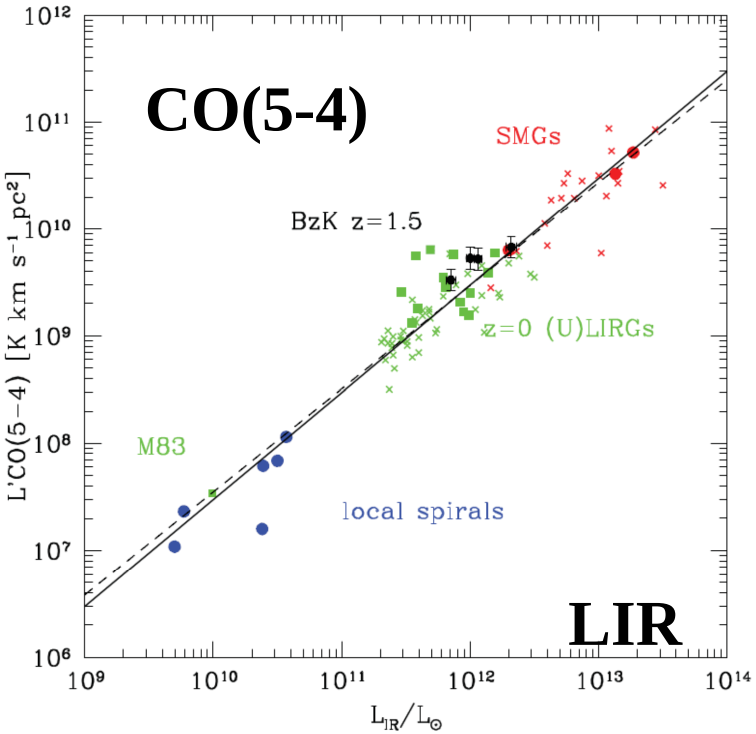
Low excitation, like MW
➔ XCO 4.5 x that of ULIRGS

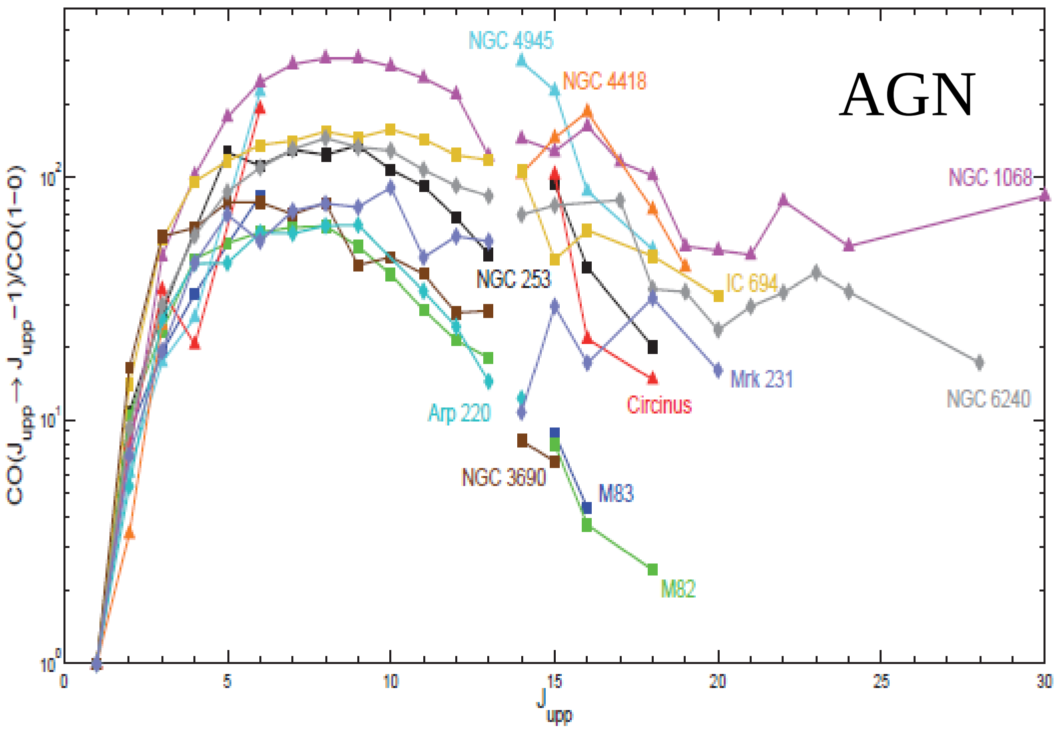
Two gas components: one extended cold, one nuclear hot and dense

When observing higher-J CO lines



Mashian et al 2014



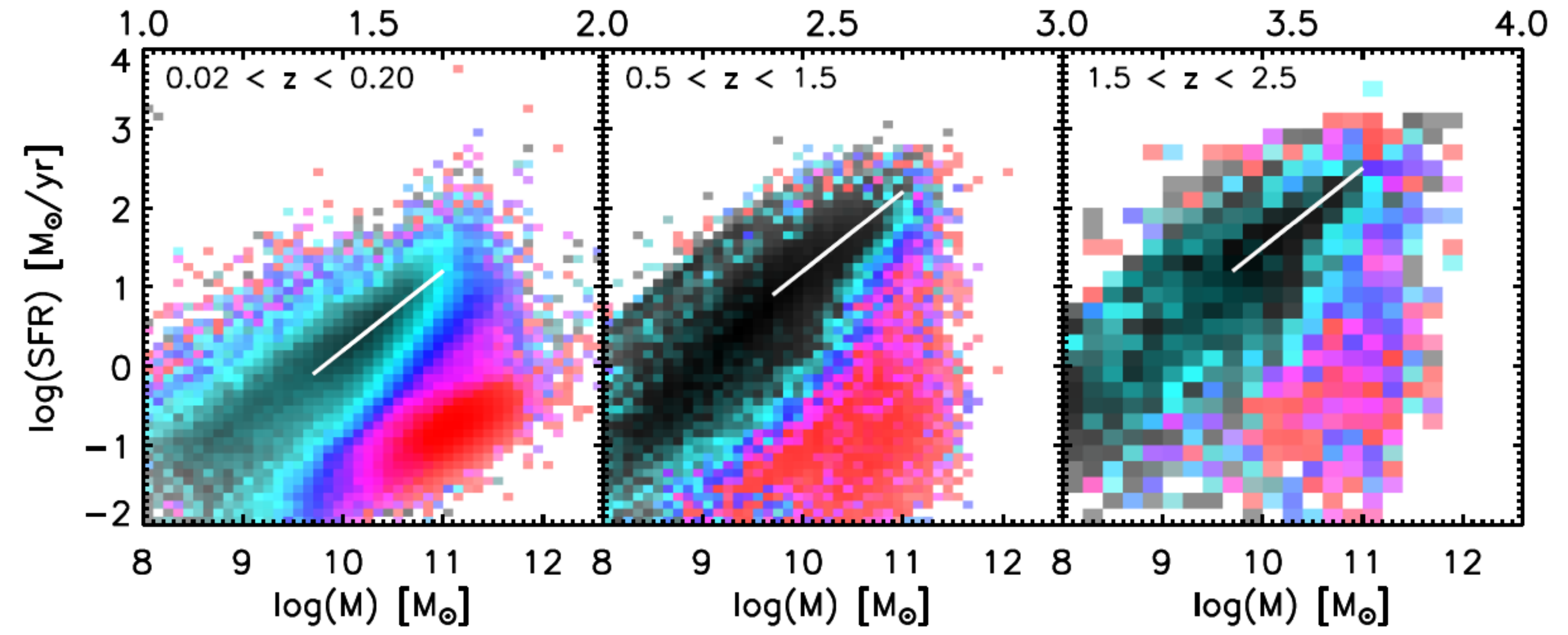


Daddi et al 2014

Main sequence of Star Forming Galaxies

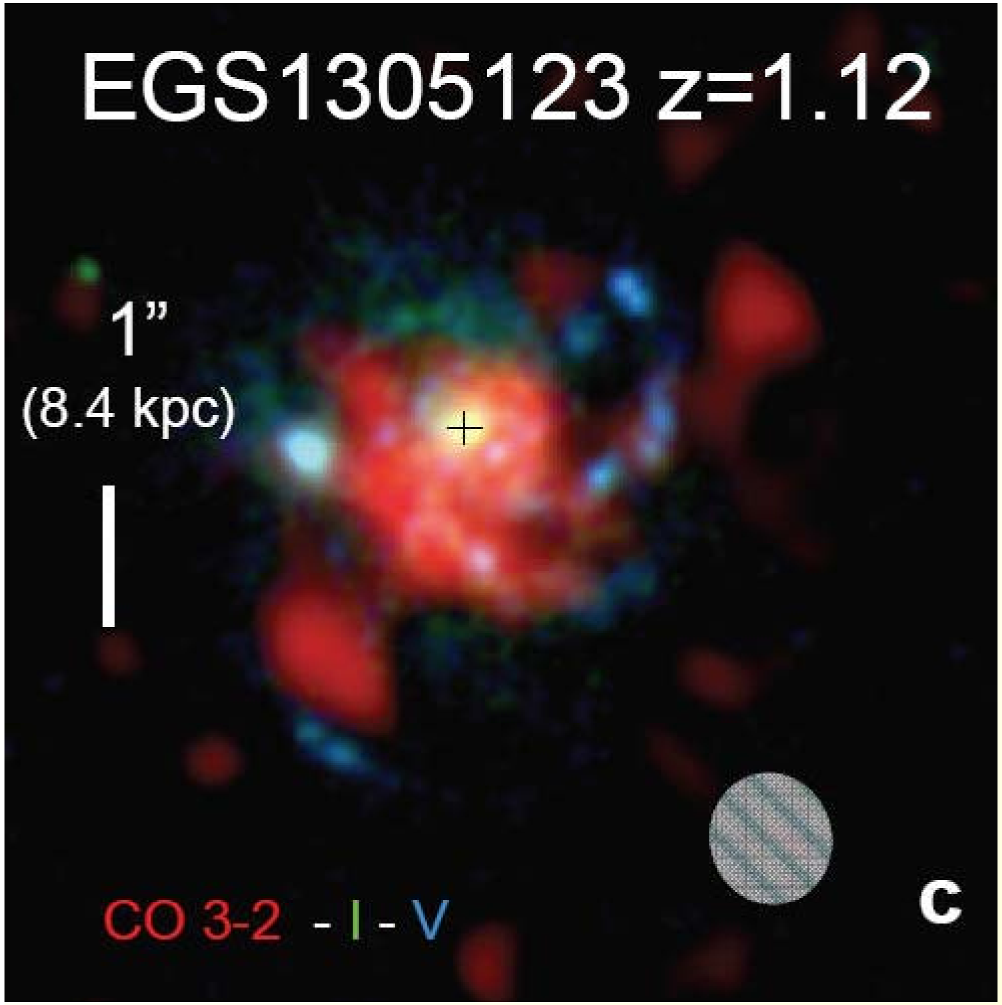
About 800 000 galaxies: correlation between structure and SP since z~2.5, **SF galaxies** on the main sequence are **exp disks**

Quiescent systems are de Vaucouleurs



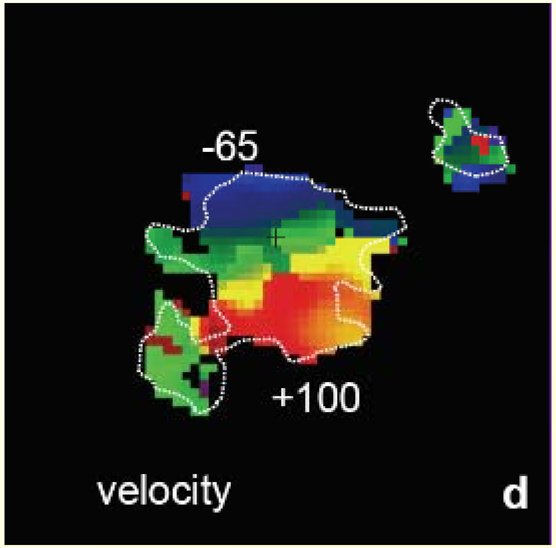
90% of cosmic star formation occurs on the main sequence (slope 0.8)

Wuyts et al 2011



PHIBSS Project

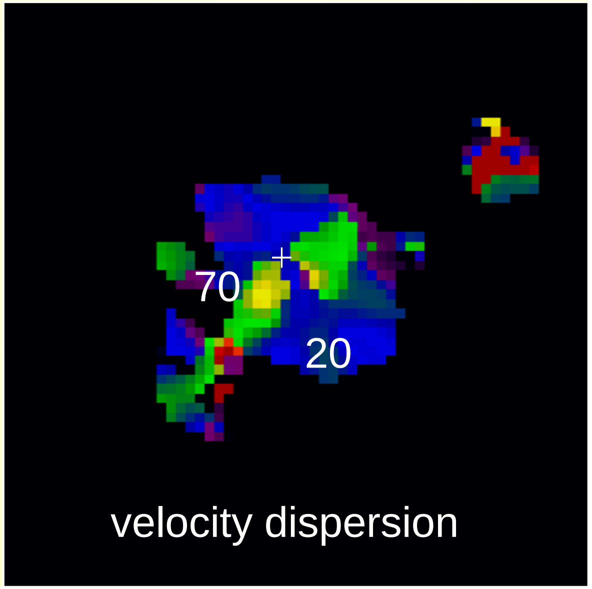
~100 galaxies observed at IRAM,
at z~2.3 and z~1.2



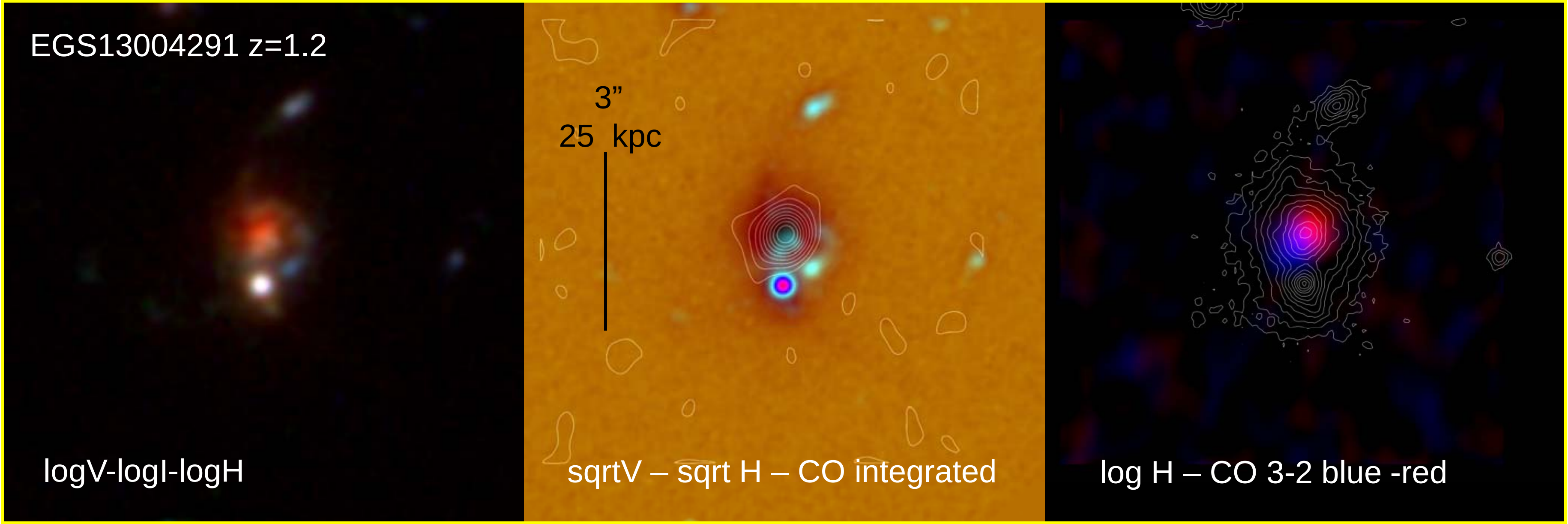
High detection rate >85%, in these « normal » massive Star Forming Galaxies (SFG)

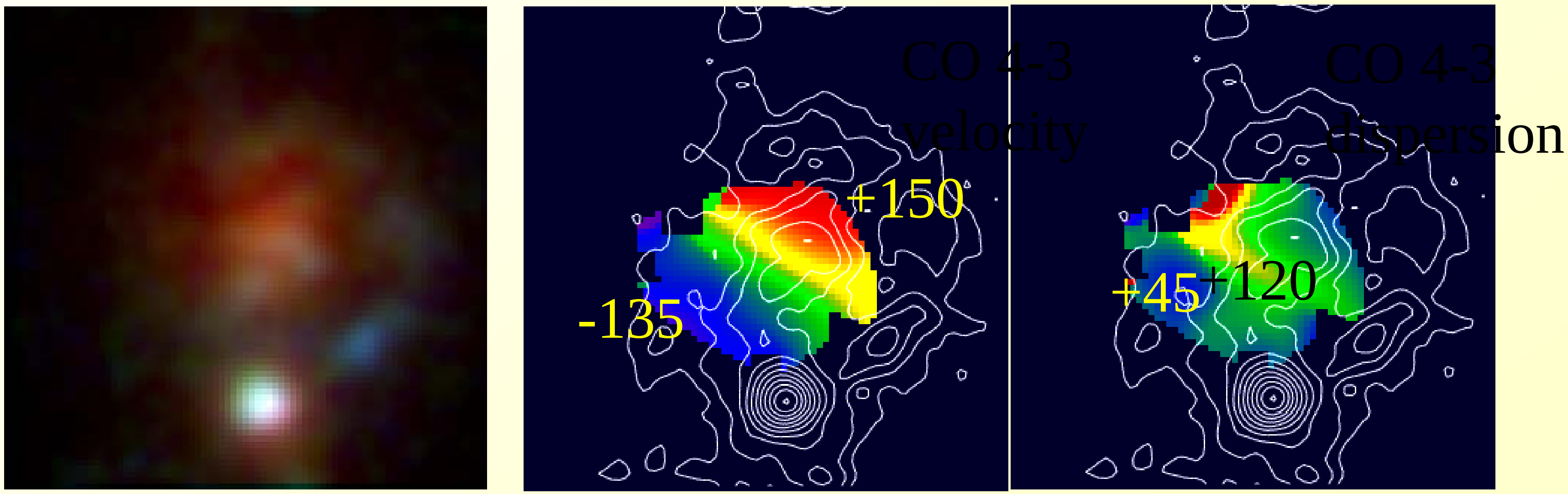
Gas content ~34% and 44% in average at z=1.2 and 2.3 resp.

Tacconi et al 2010, 2013



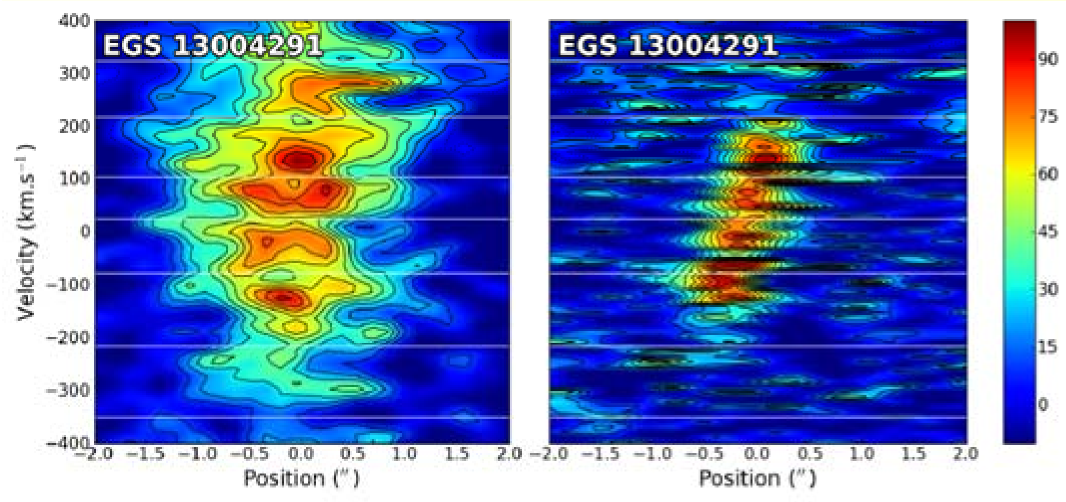
PHIBSS Project: examples of massive SF galaxies



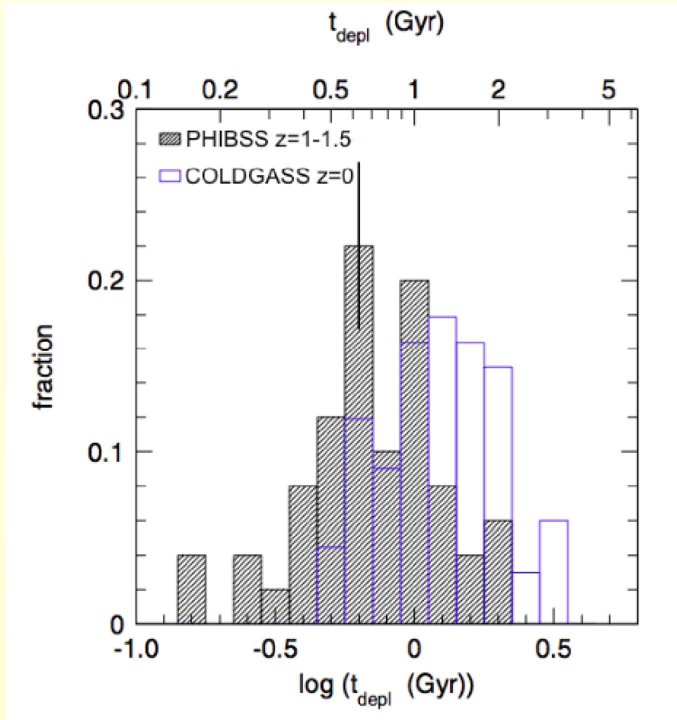


Resolved Kennicutt-Schmidt law?

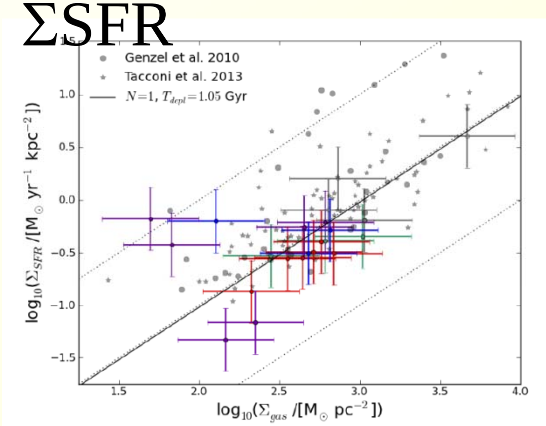
[OII] and CO Position-Velocity diagrams: identification of clumps



Depletion time
smaller than for z=0



ΣSFR

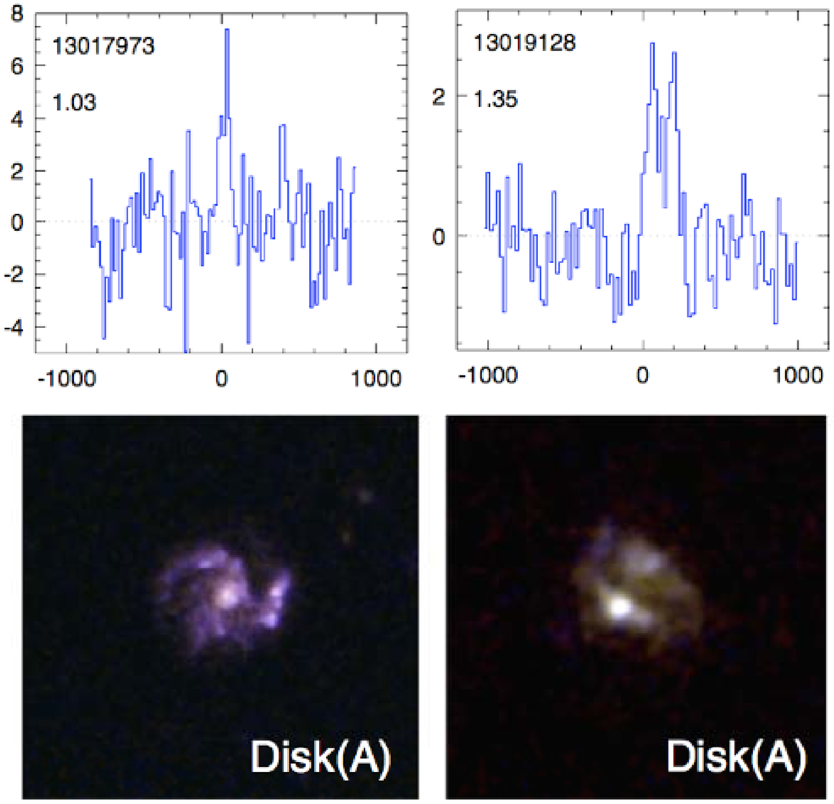


KS diagram

ΣH2

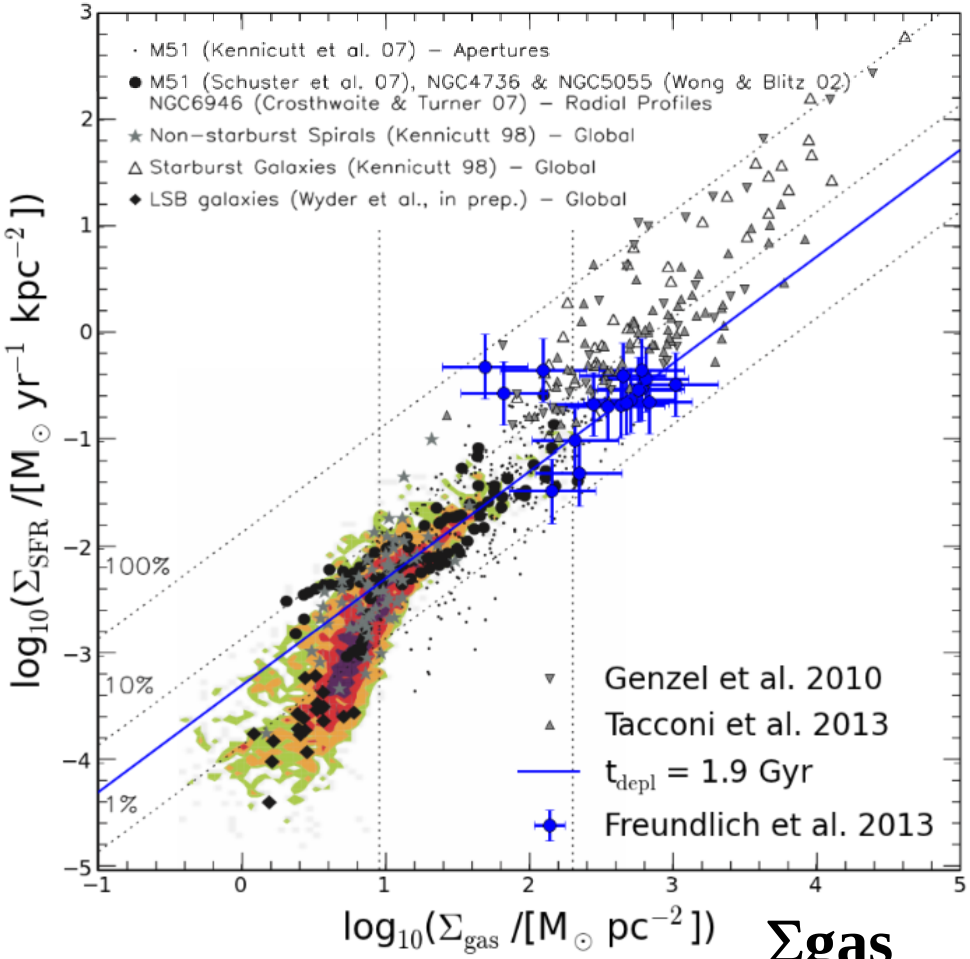
Freundlich et al 2013

High z galaxies on the Kennicutt-Schmidt diagram



Freundlich et al 2013

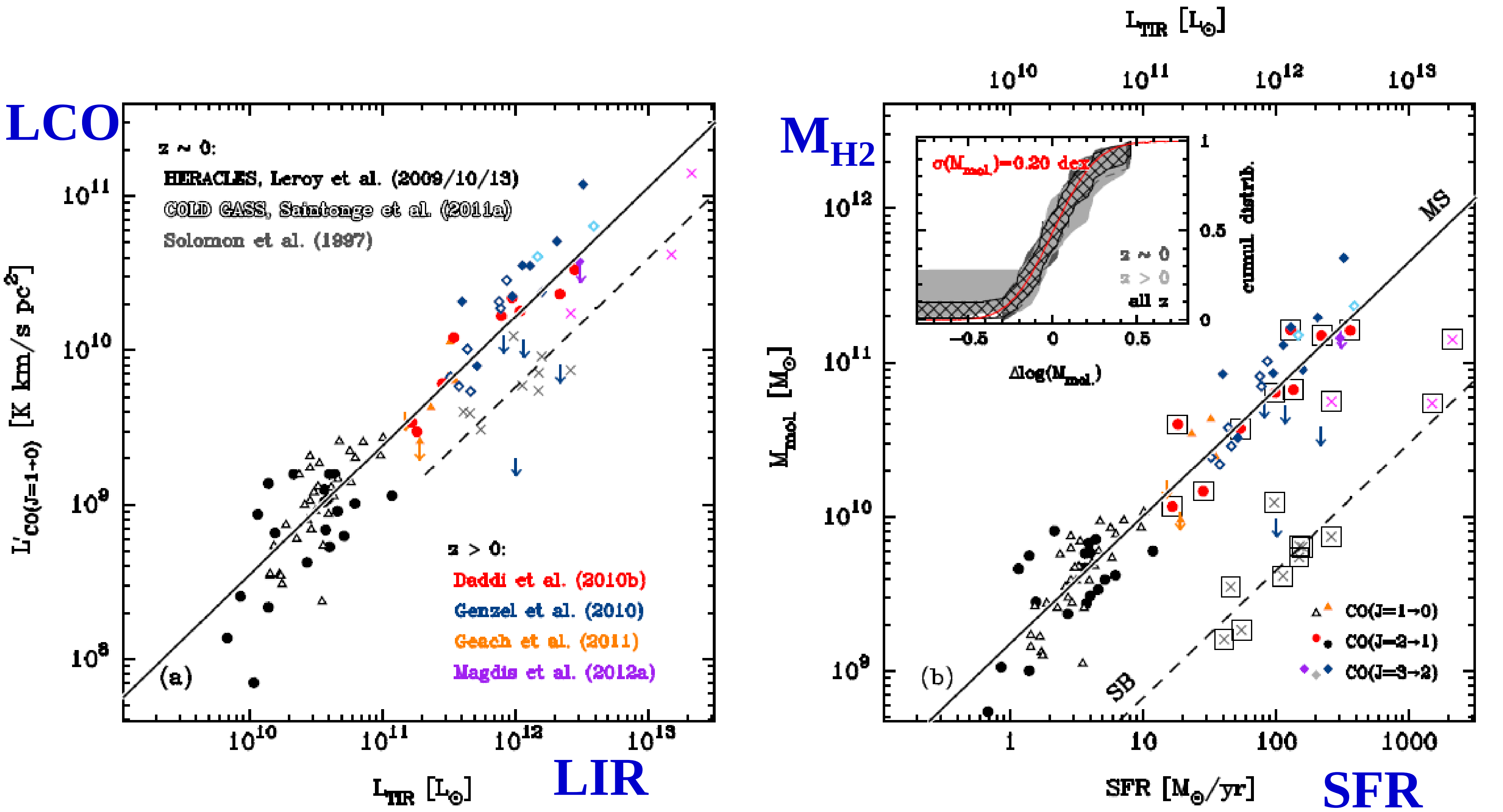
ΣSFR



Σgas

Distinction between MS and SB

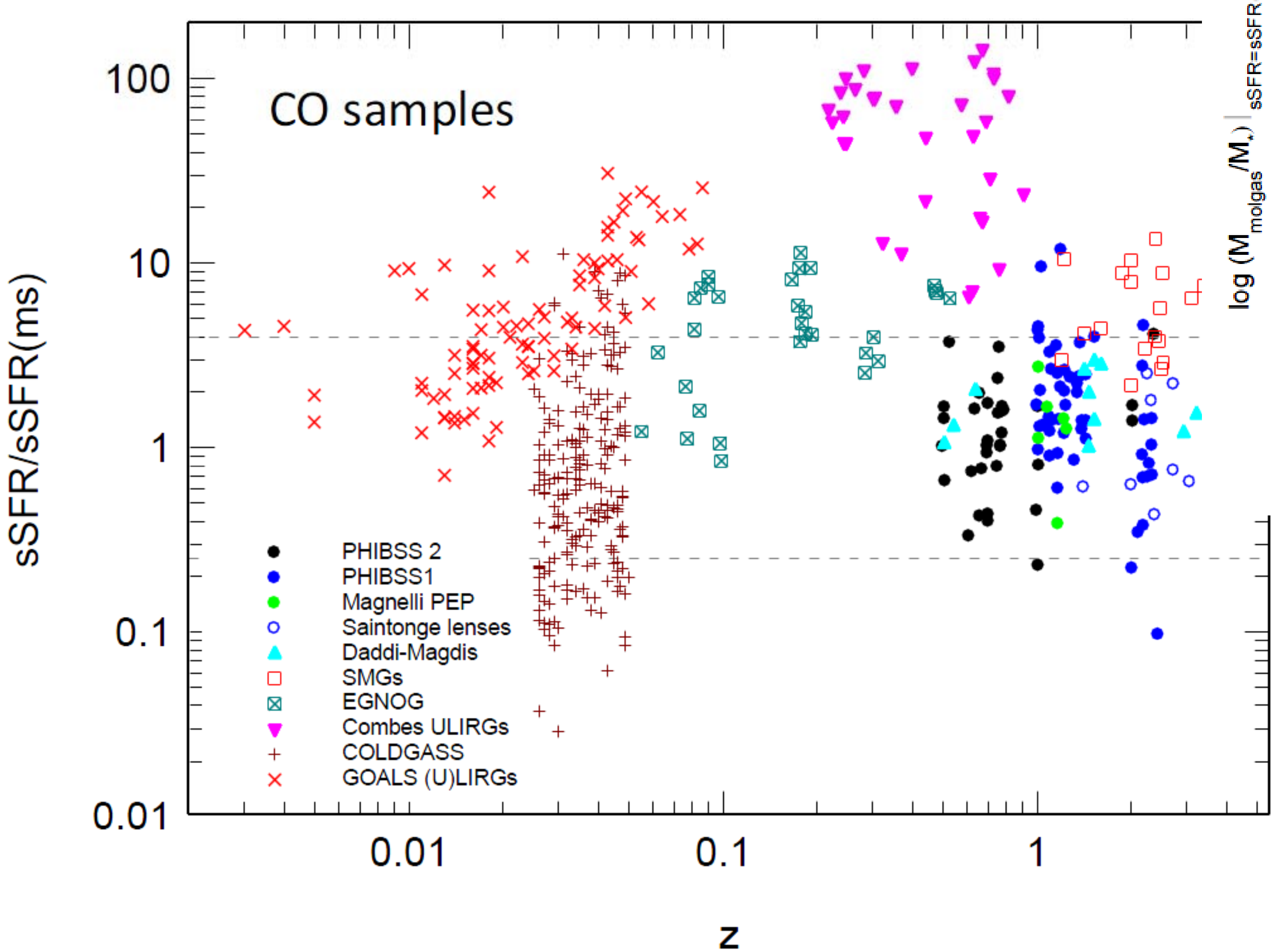
Continuity in L'CO, but discontinuity in MH_2 (due to a bimodal α_{CO})

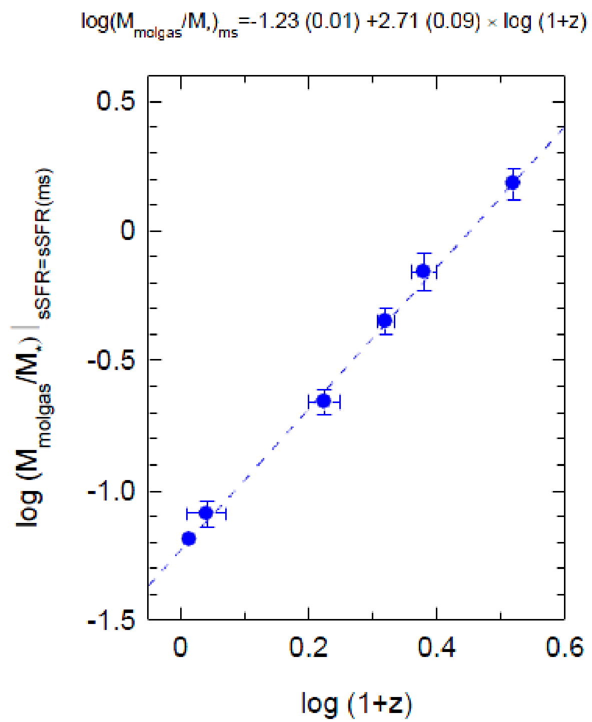


Sargent et al 2013

Scaling relations, several samples

Gas fraction increases regularly with z
on the main sequence

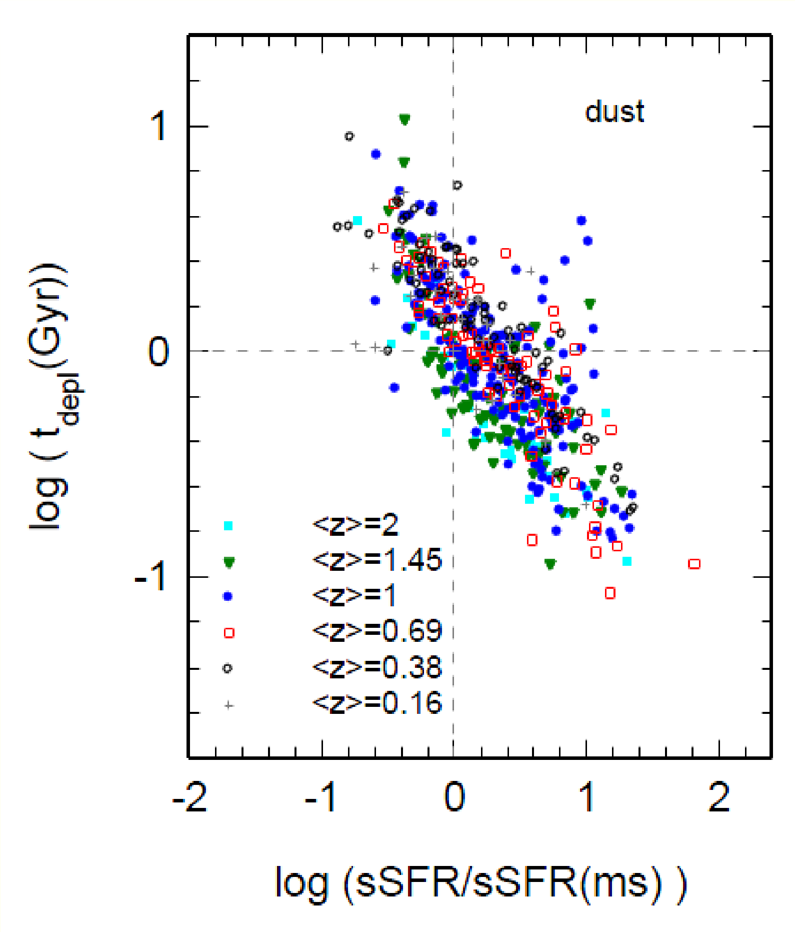


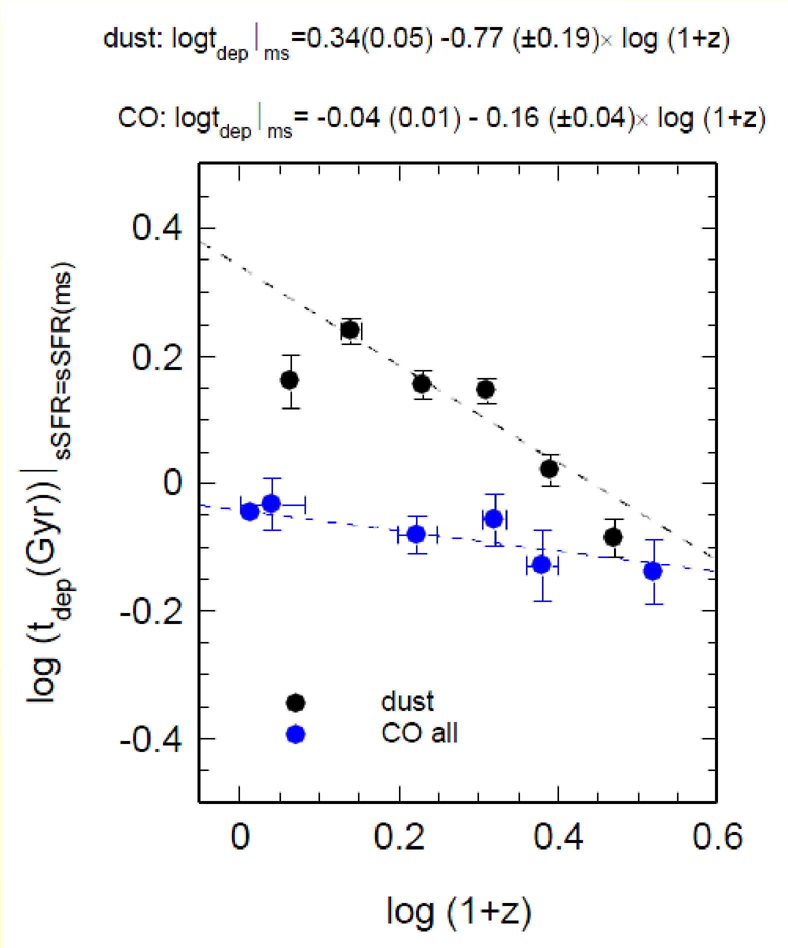


Genzel et al 2014

Depletion time, CO or dust tracers

T_{dep} large variations quiescent-SB
But slow variation on the MS

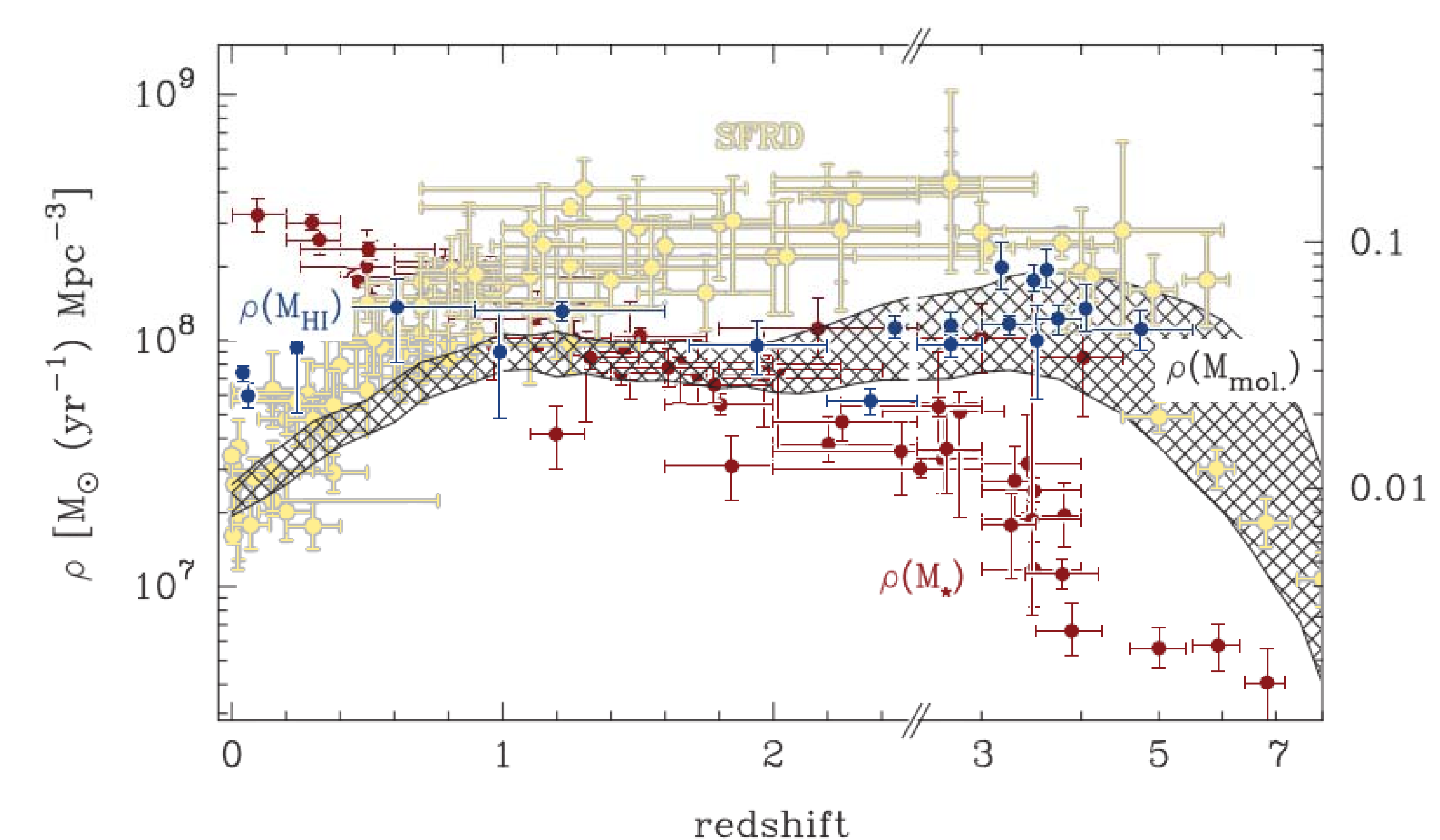




Genzel et al 2014

Cosmic evolutions

ρmol, from H_2 gas mass functions, & extrapolations
Daddi et al 2013



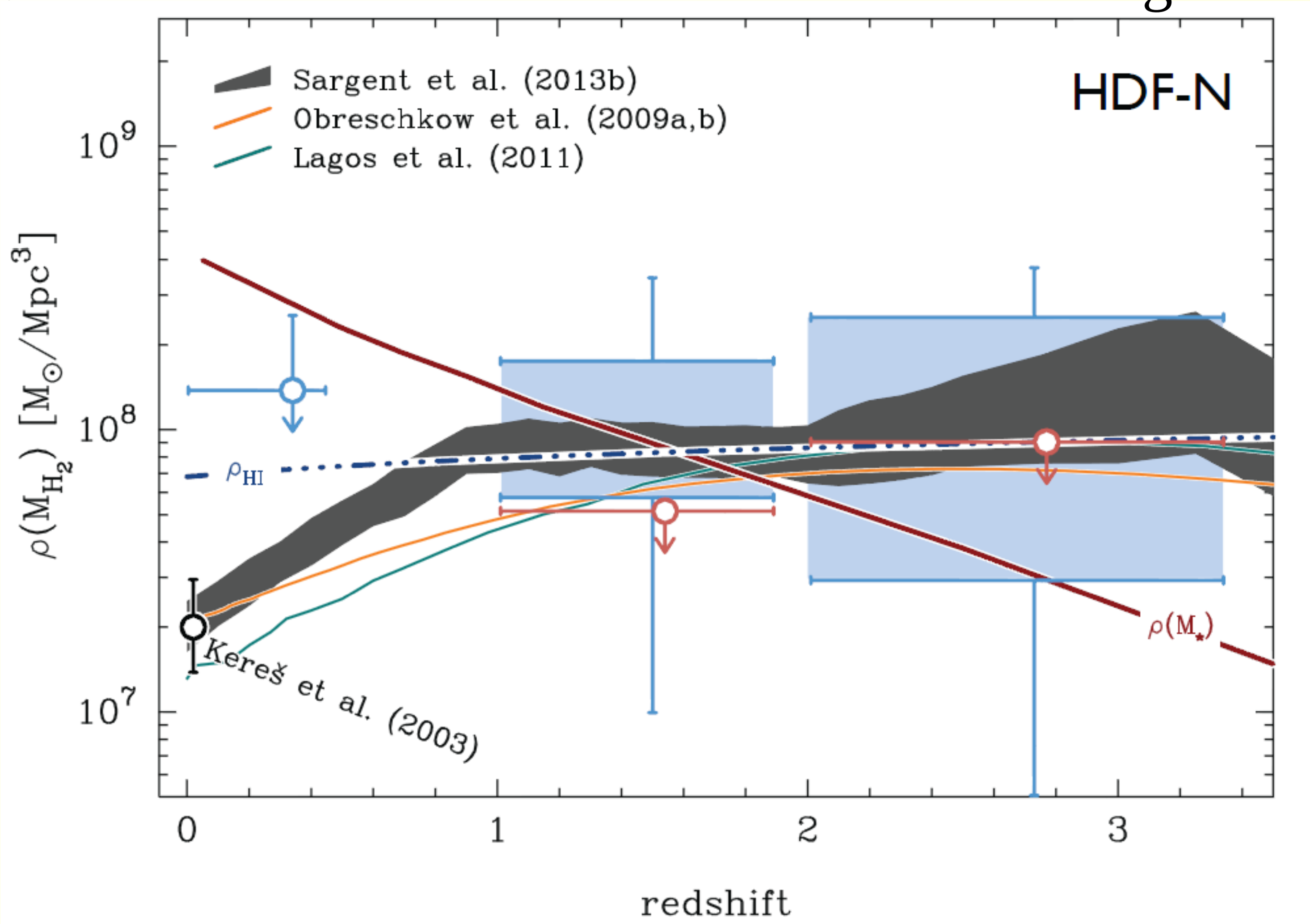
ρ_{HI} from Bauermeister et al 2010
ρ_* Marchesini et al. 2009

Cosmic evolution of H_2

Decarli et al 2014: Deep PdBI observations of the HDF-N, 3mm

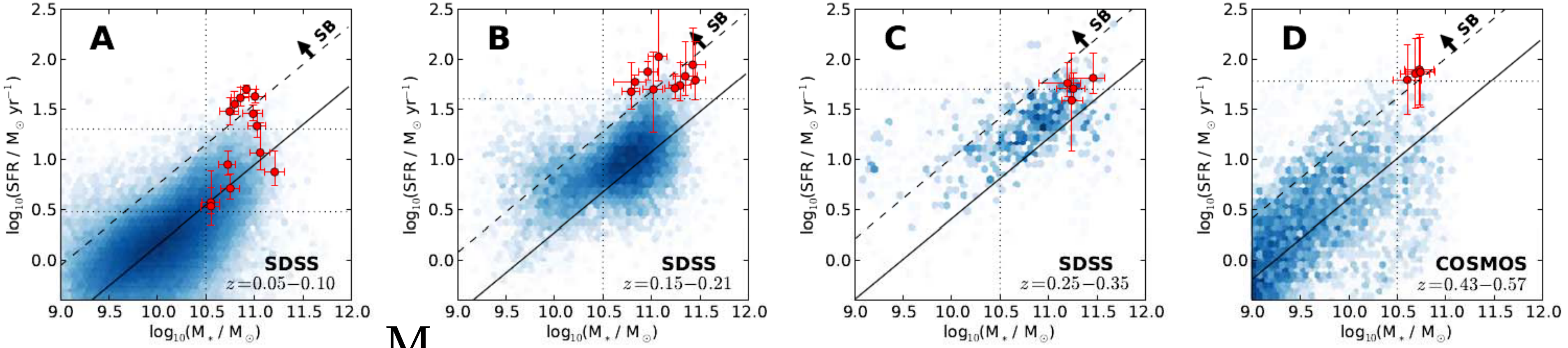
cosmic volume of ~ 7000 Mpc^3, and $z<0.45$, $1.01<z<1.89$ + $z>2$.

Walter et al 2014: 17 1-line detections + stacking



EGNoG: Normal galaxies z<0.5

SFR   z=0.07   z=0.18   z=0.30   z=0.50

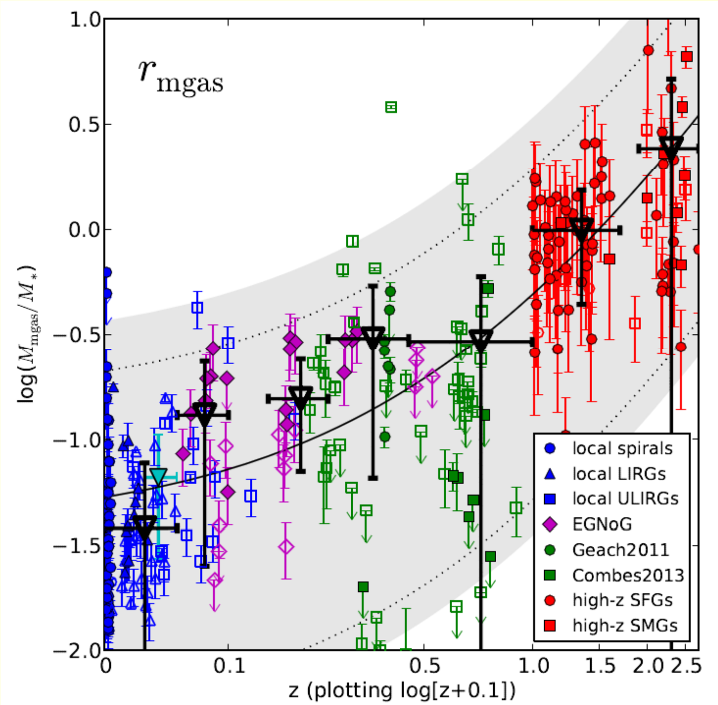


M_*

τ–depletion 0.76 Gyr
for normal galaxies
0.06 Gyr
for starburst galaxies

7-20% gas fraction

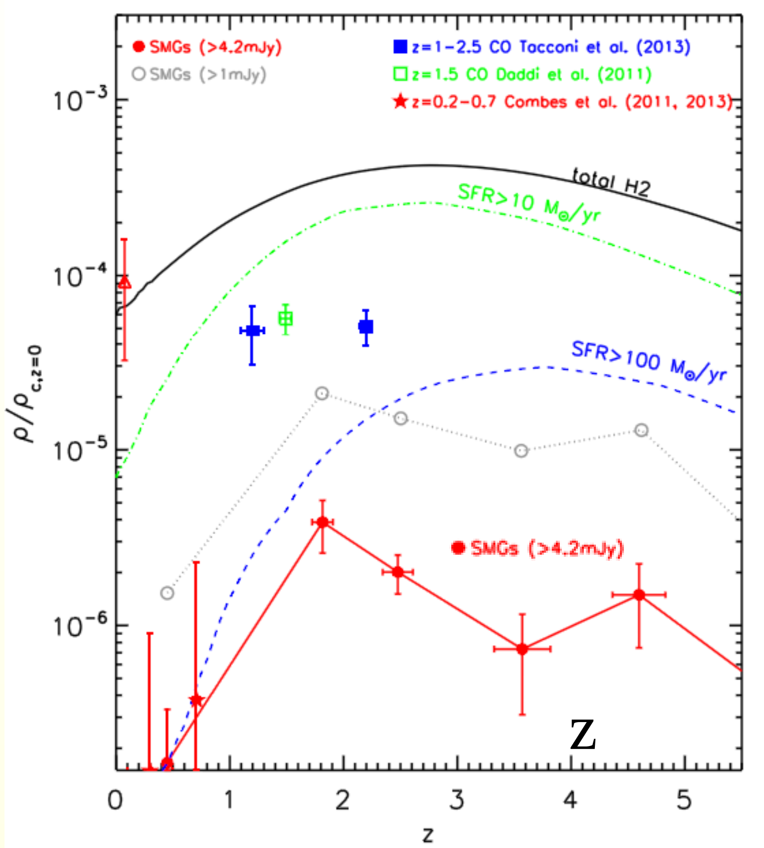
Bauermeister et al 2013



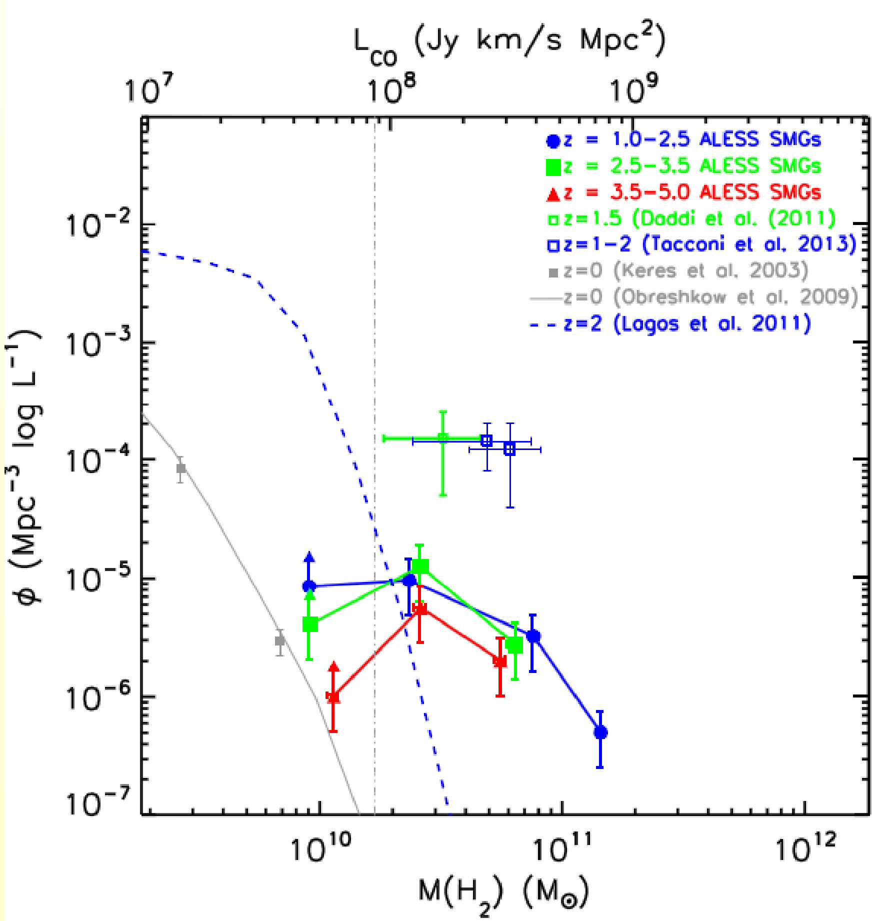
Evolution from dust-emission surveys

ALESS: 870μ Swinbank et al 2014
ALMA obs of 99 SMG, 24μm, radio,
Herschel deblended fluxes
<SFR> = 300 Mo/yr, <Td> = 32K

S_{870}> 4.2mJy, only 1-2% of SFR
S_{870}>1mJy (stacking), 20% SFR



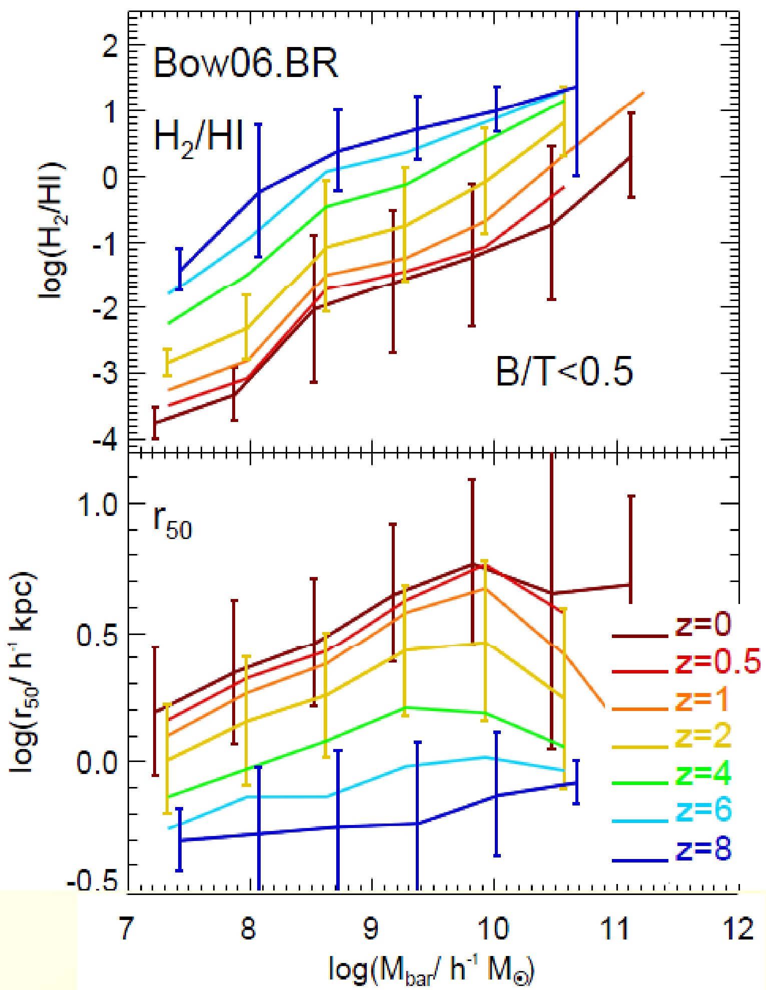
Ω_{H2}



H_2/HI cosmic evolution with SAM

SFR, and H_2 density from pressure (BR-2006)
or H_2 on grains, with UV radiation (KMT-09)

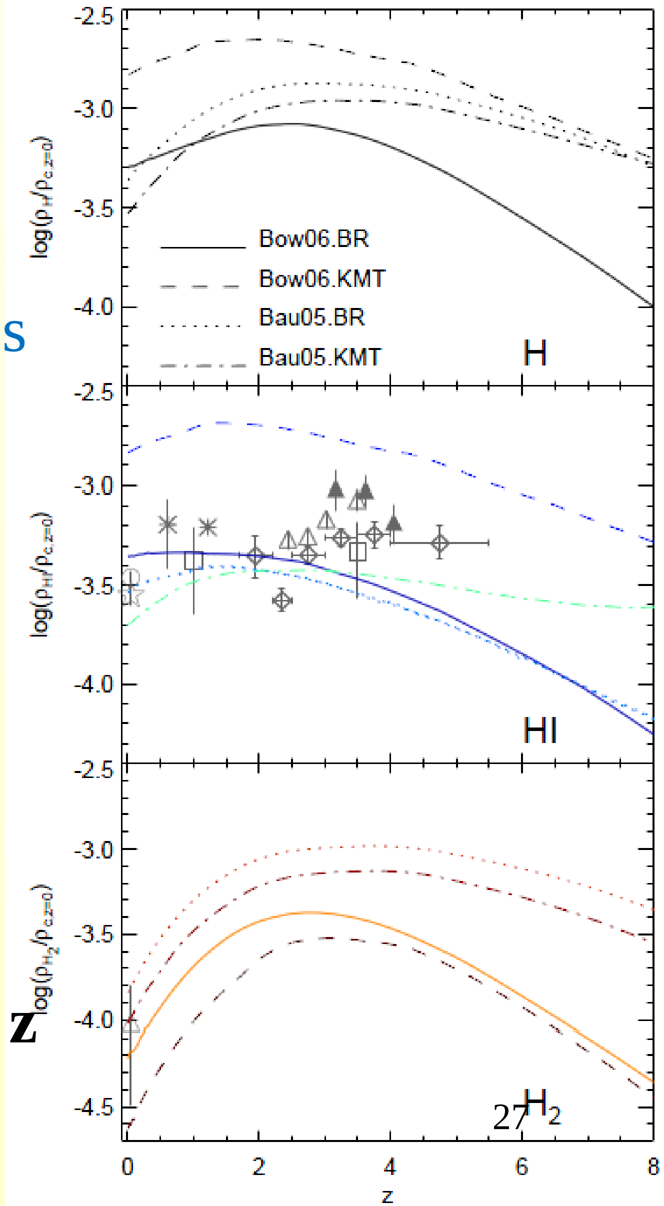
➔BR recipes better (Lagos et al 2011),
KMT best (Fu et al 10, 12)



H_2/HI experiences a peak at z=2-4

More gas, and even more H_2

Galaxies more compact at high z

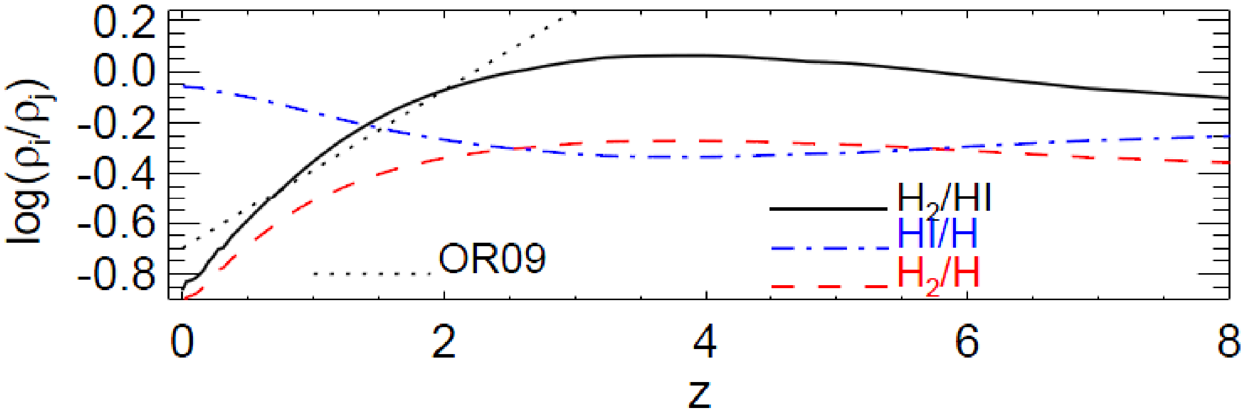


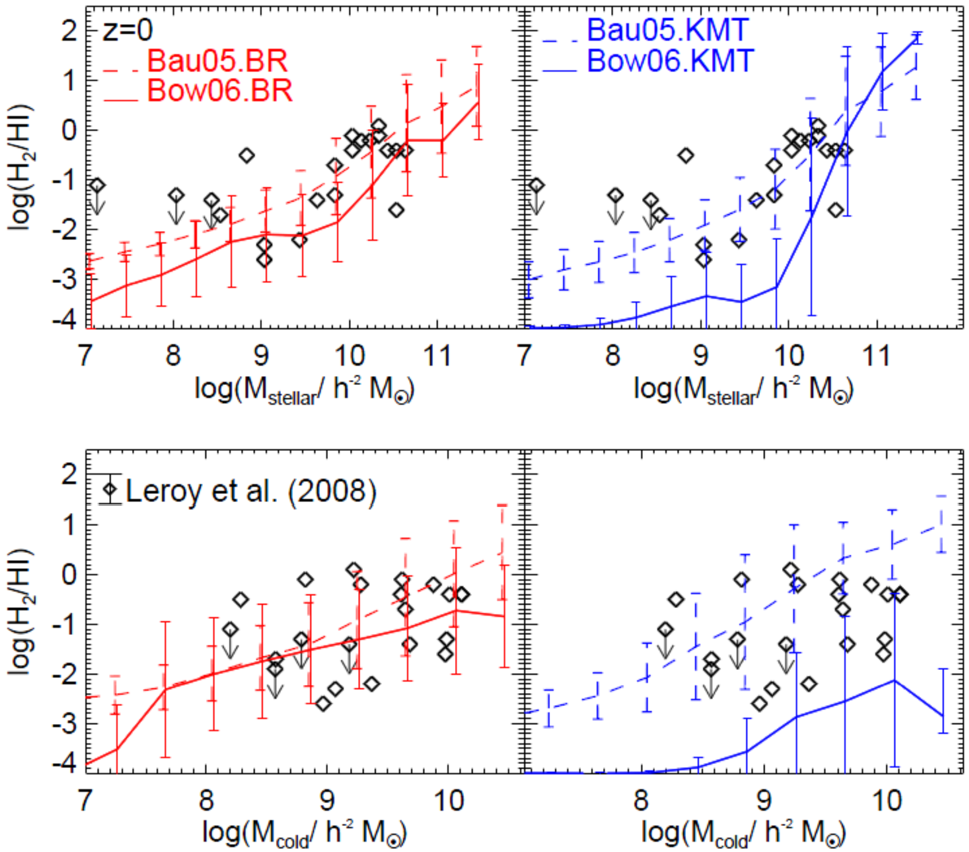
H_2/HI with SAM

Lagos et al 2011

Self-consistent SAM

Different SFE for MS and starbursts



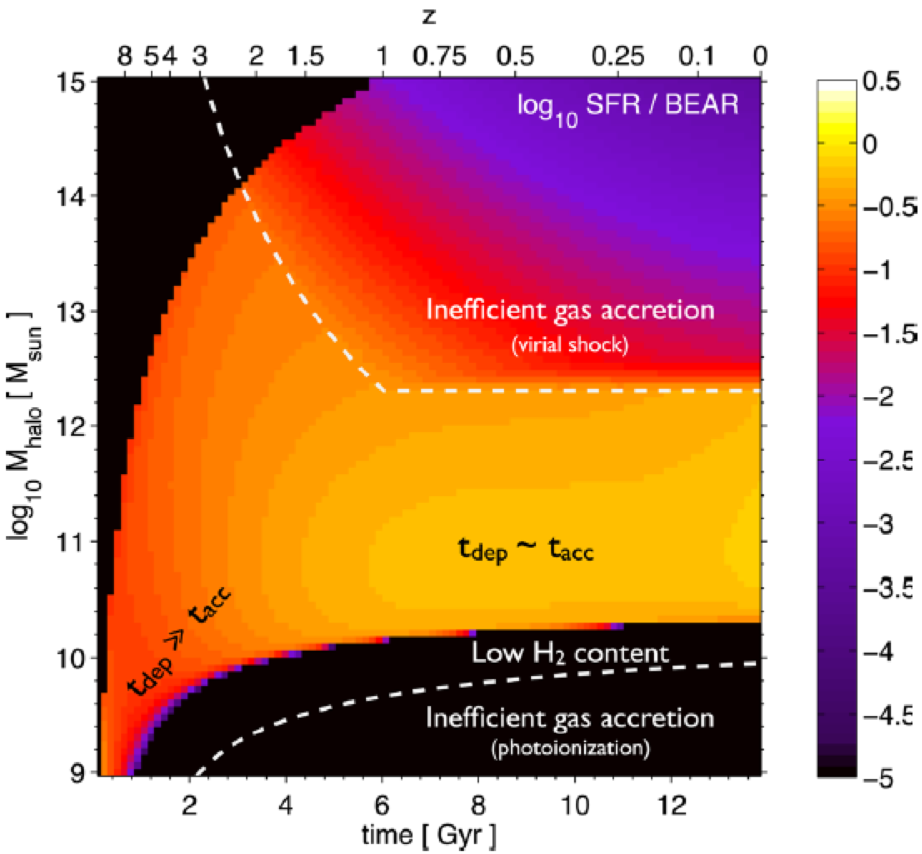


$$\rho_{H_2}/\rho_{HI} \approx 0.13\,(1+z)^{1.7} \quad \text{for} \quad z \lesssim 2$$
$$\approx 0.45\,(1+z)^{0.6} \quad \text{for} \quad 2 \lesssim z \lesssim 4$$
$$\approx 3.7\,(1+z)^{-0.7} \quad \text{for} \quad z \gtrsim 4.$$

Different from OR-09
=post-processed SAM
& lower resolution

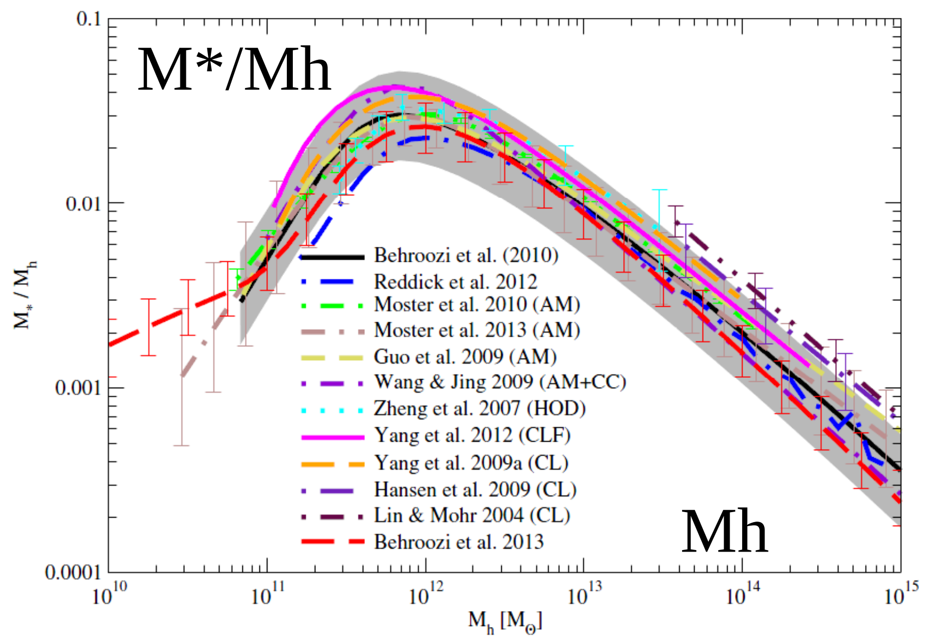
SFRD drops more than gas
➔SFE varies with z

SFR / Gas accretion rate (AR)



At high z, the depletion time larger than the accretion time
➔Galaxies accumulate gas

Then SFR~AR at z < 2, and SF is accretion limited



Feldmann 2013

Behroozi 2013

SFE varies with z, density, ...

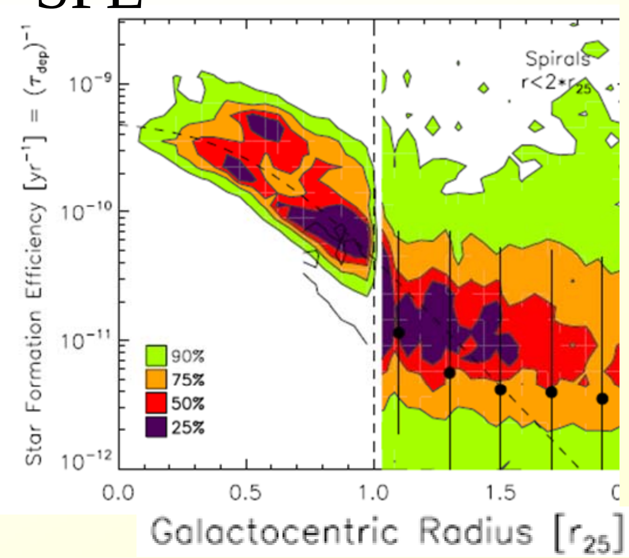
Possible to keep a global linear KS law, but ΣH_2 higher at high z, at equal H_2 mass

For the SAM, Lagos et al (11), Popping et al (14) select an SFE higher for starburst, or for higher density

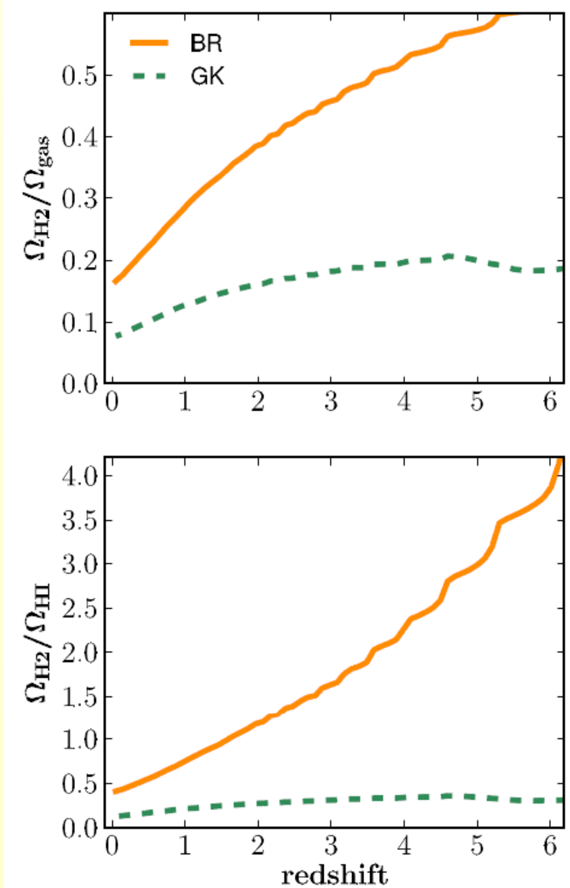
SFE varying with density?

(Bigiel et al 10, Dessauges-Zavadsky et al 14)

SFE

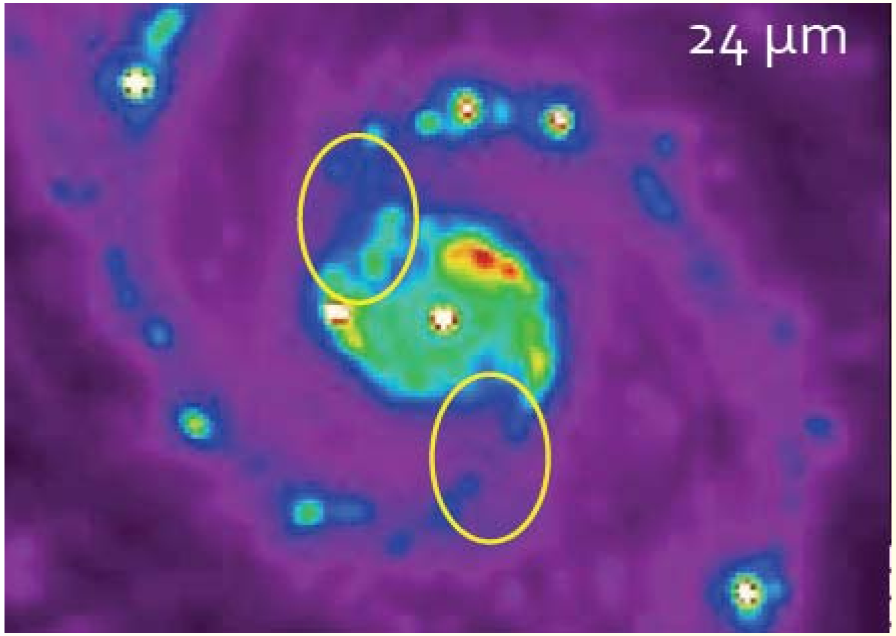


ALMA is needed!

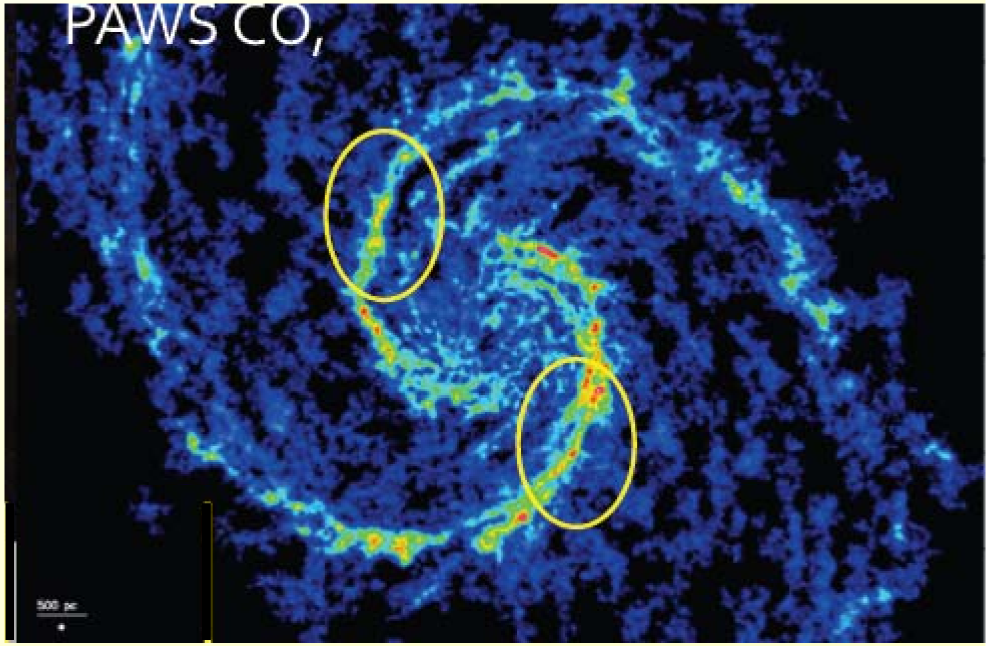


Popping et al 2014

Influence of density waves



Meidt et al (2012)

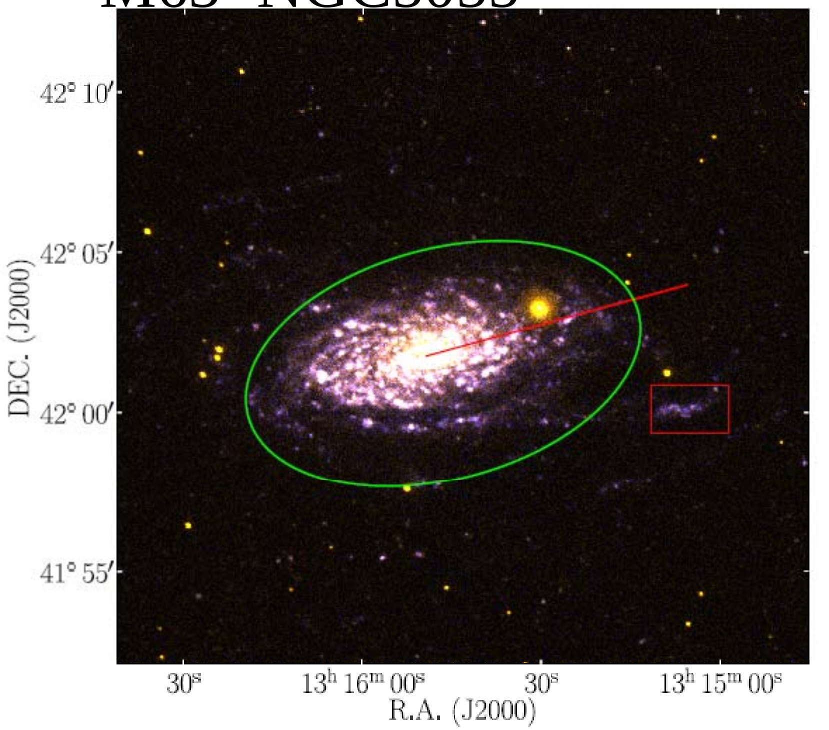


The efficiency of SF is not
constant over arms and rings
A way to find Corotation?

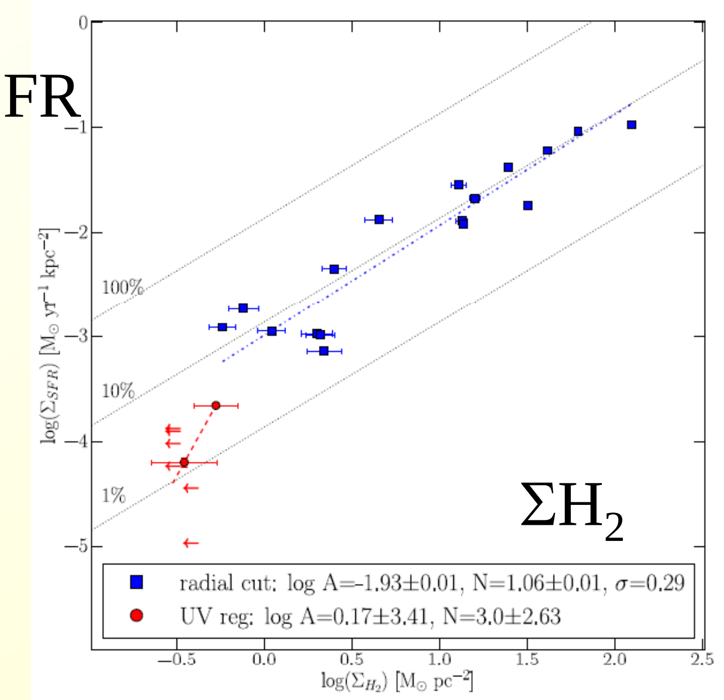
Also found in barred galaxies (Reynaud & Downes 1999)

Molecular gas in XUV disks

M63=NGC5055



ΣSFR



ΣH_2

CO detected very far from the center ➔ **Low SFE**

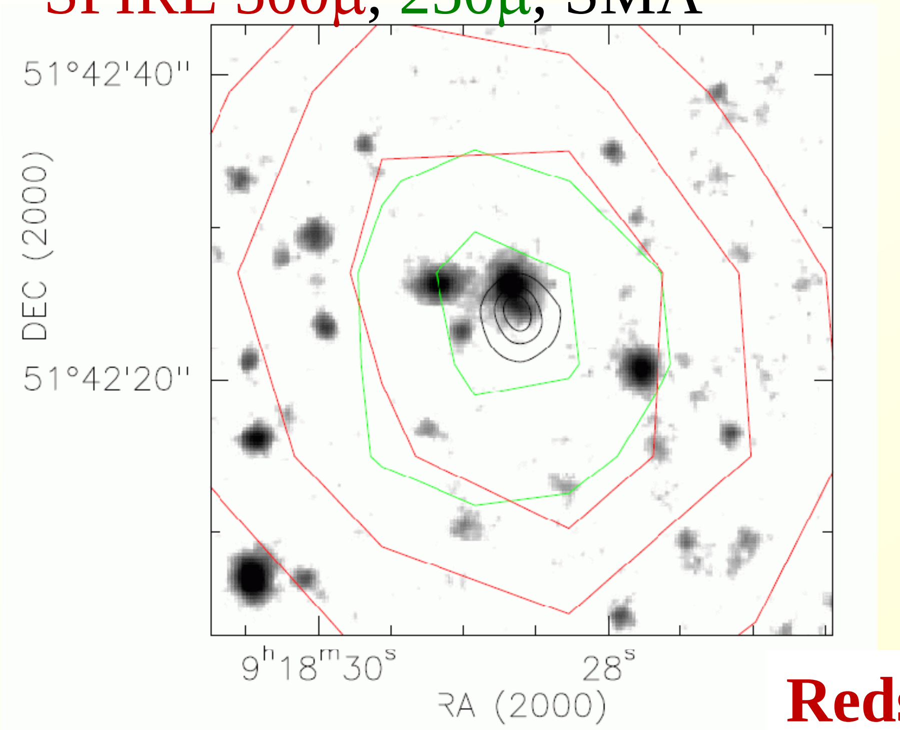
If XCO varies, higher H2 gas, then even lower SFE!

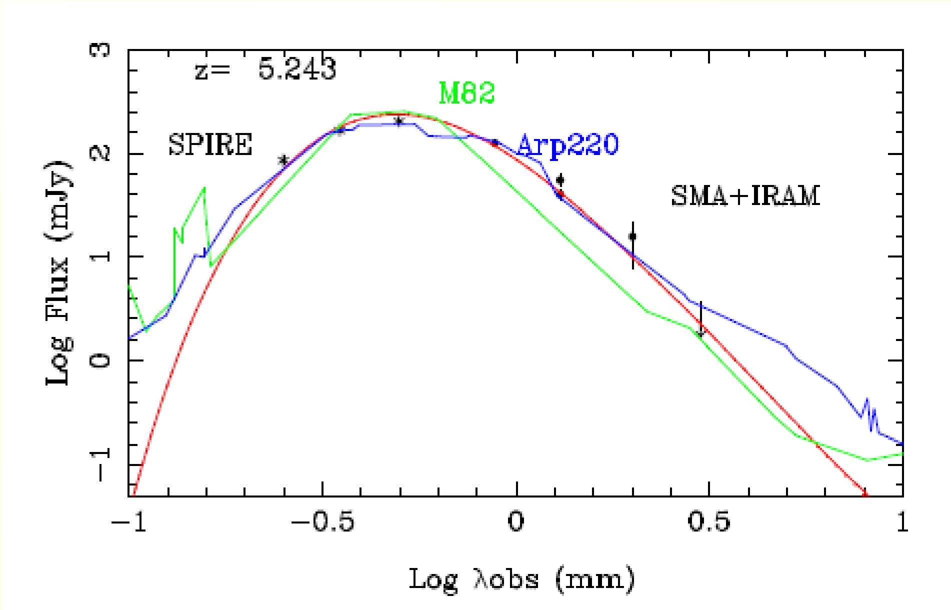
Dessauges-Zavadsky et al 2014

Discovery of high-z galaxies with Herschel

HLS survey of nearby clusters (Egami et al)

SPIRE 500μ, 250μ, SMA



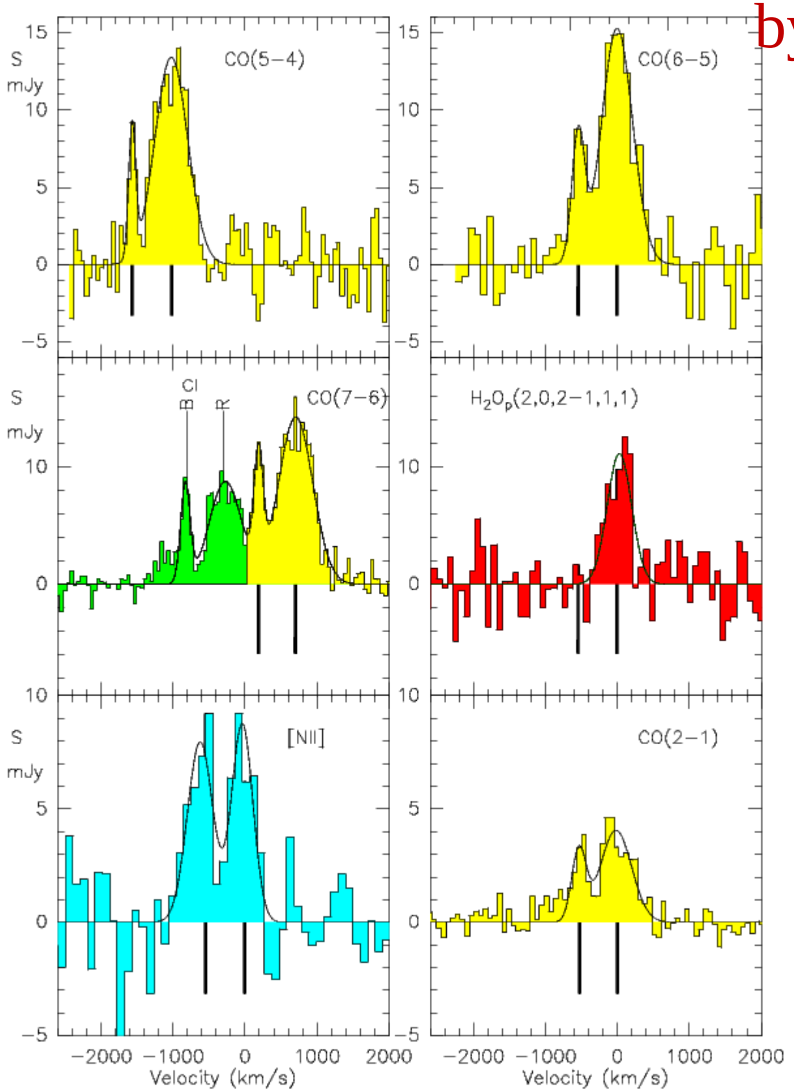


Redshift search with CO at IRAM-30m

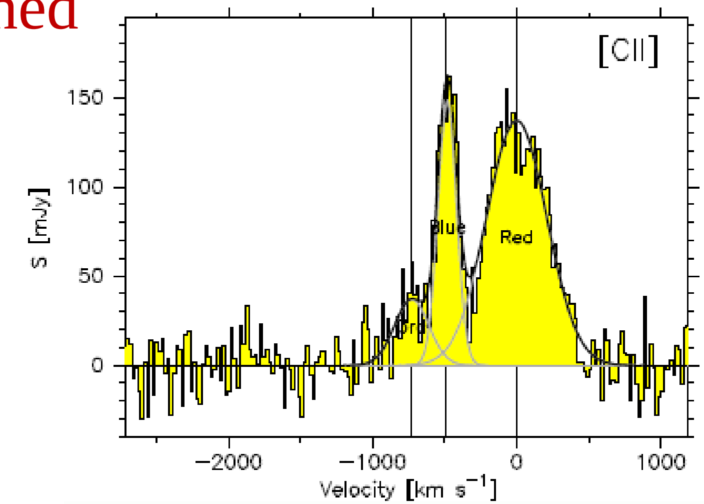
Behind Abell 773 at z=0.22, and an intervening galaxy at z=0.63,
➔Main lens

Combes et al 2012

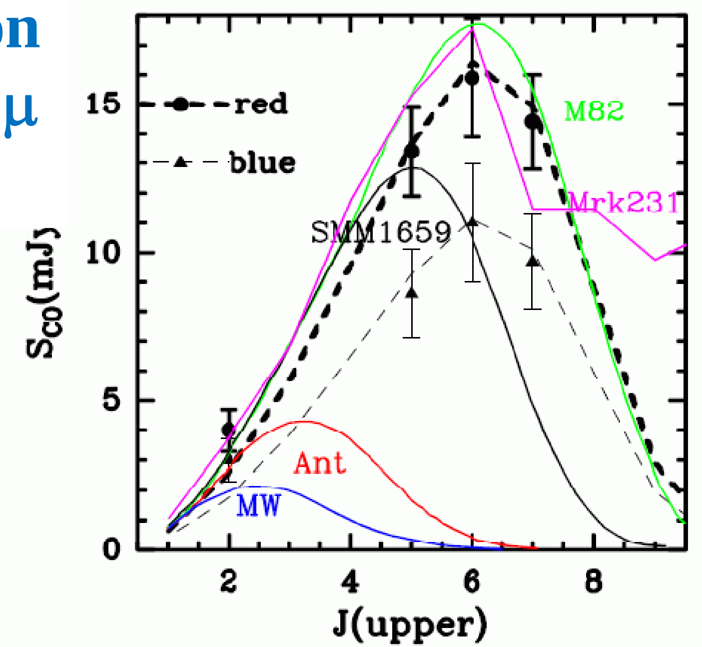
Redshift discovered with IRAM (z=5.243)



Redshift determined by CO lines



1st detection of [NII]205μ at high z

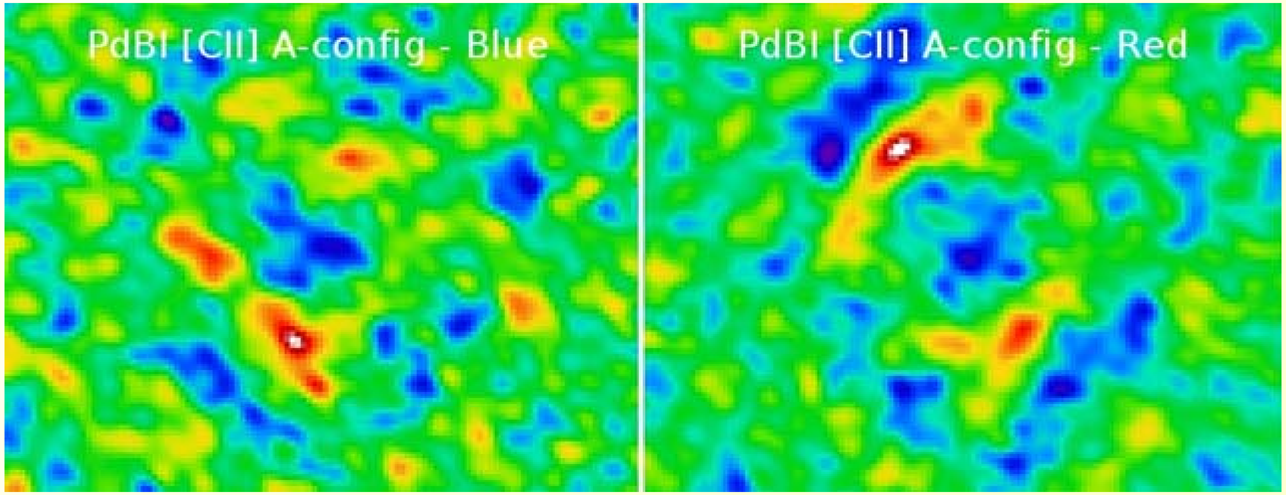


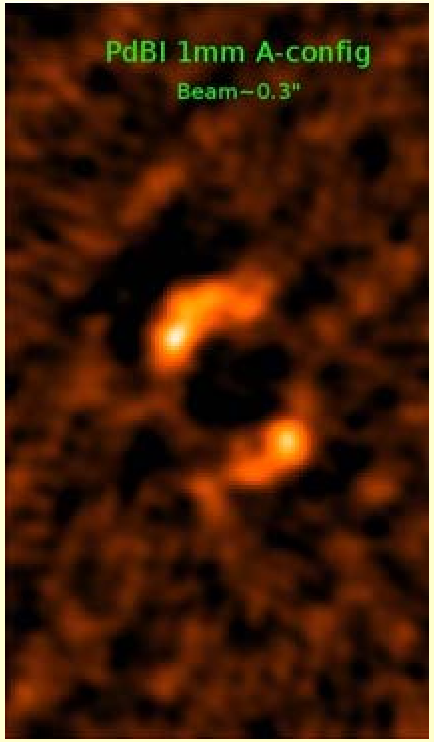
An amplification by a factor ~11

Still an hyperLIRG L ~10^{13} L_o, and M_{H2} ~6 10^{10} M_o, after amplification has been taken into account

Continuum at 300GHz ~1mm, or 160μ in the rest-frame, with SMA and PdBI (IRAM) ➔ Einstein ring

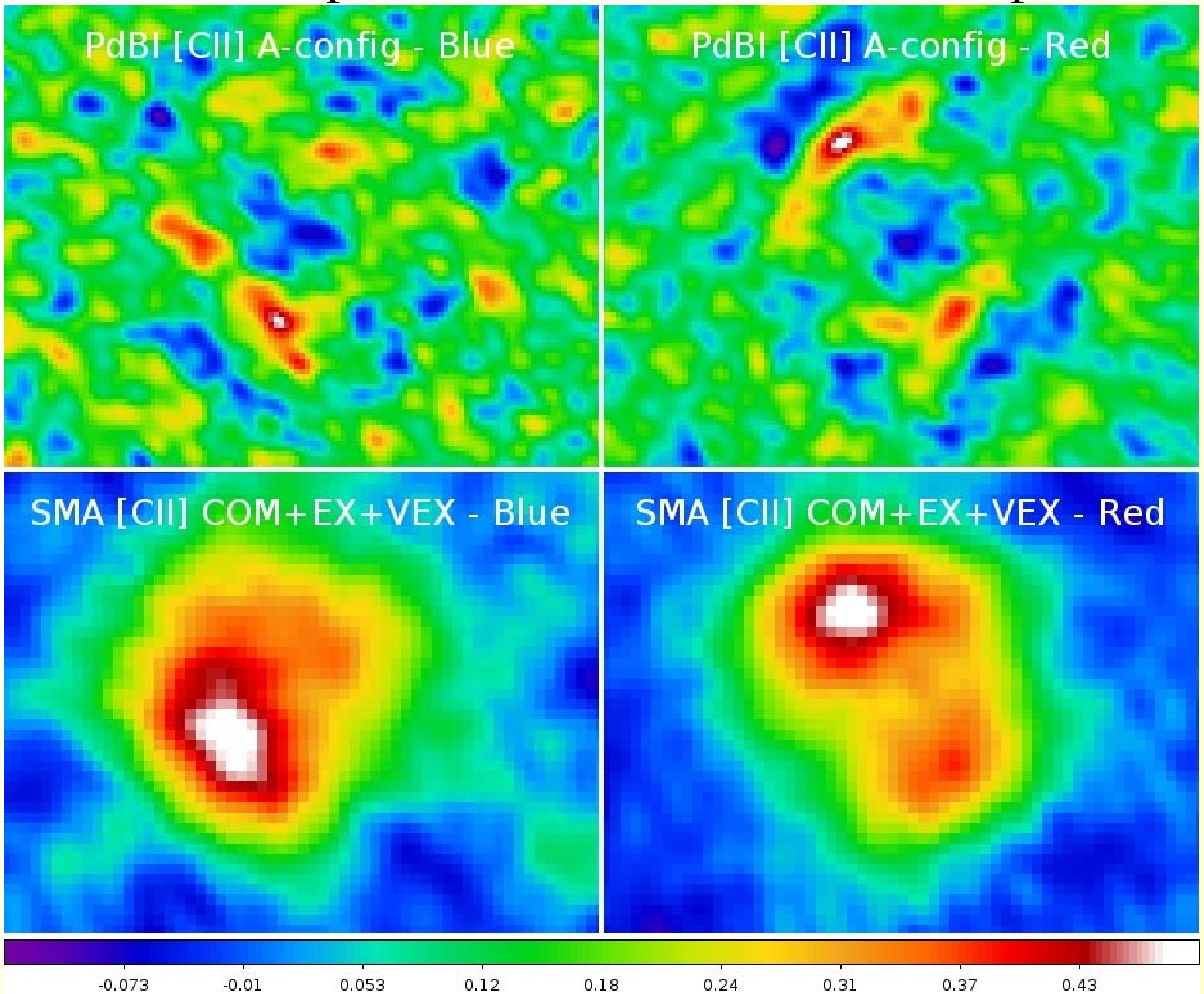
Blue V-component   Red V-component





Plateau de Bure and SMA: CII line

Blue V-component Red V-component

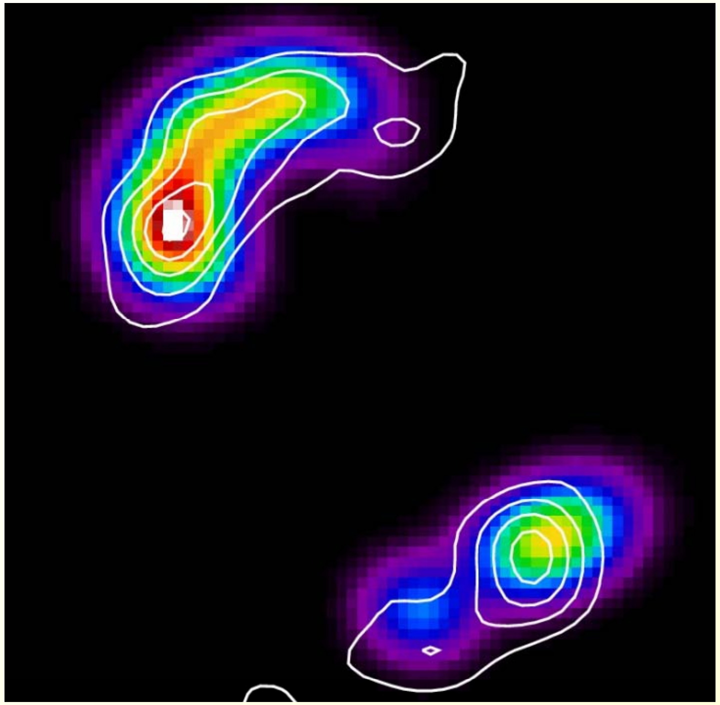


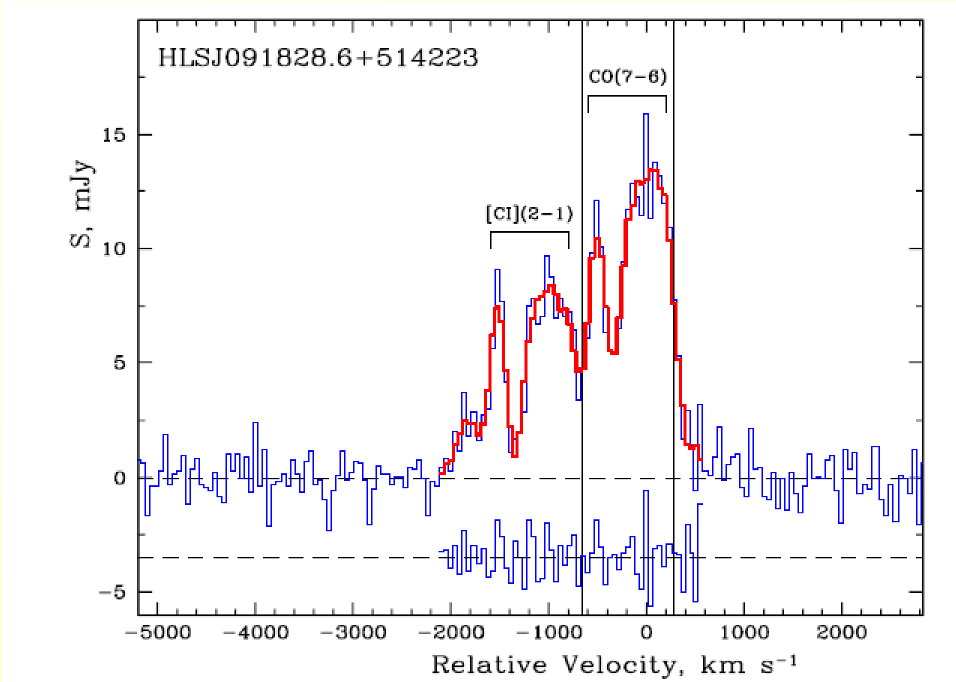
HLSJ091828.6 in Abell 773

Constraints on variation of fundamental constants $\Delta\mu/\mu < 2\ 10^{-5}$

Levshakov, Combes, Boone et al 2012

Lens model, compared to continuum observations





Boone et al 2013

At high-z: gravitational telescope

Lensed MM18423+5938

z=3.93

L= 4.8 10^{14}/m Lo

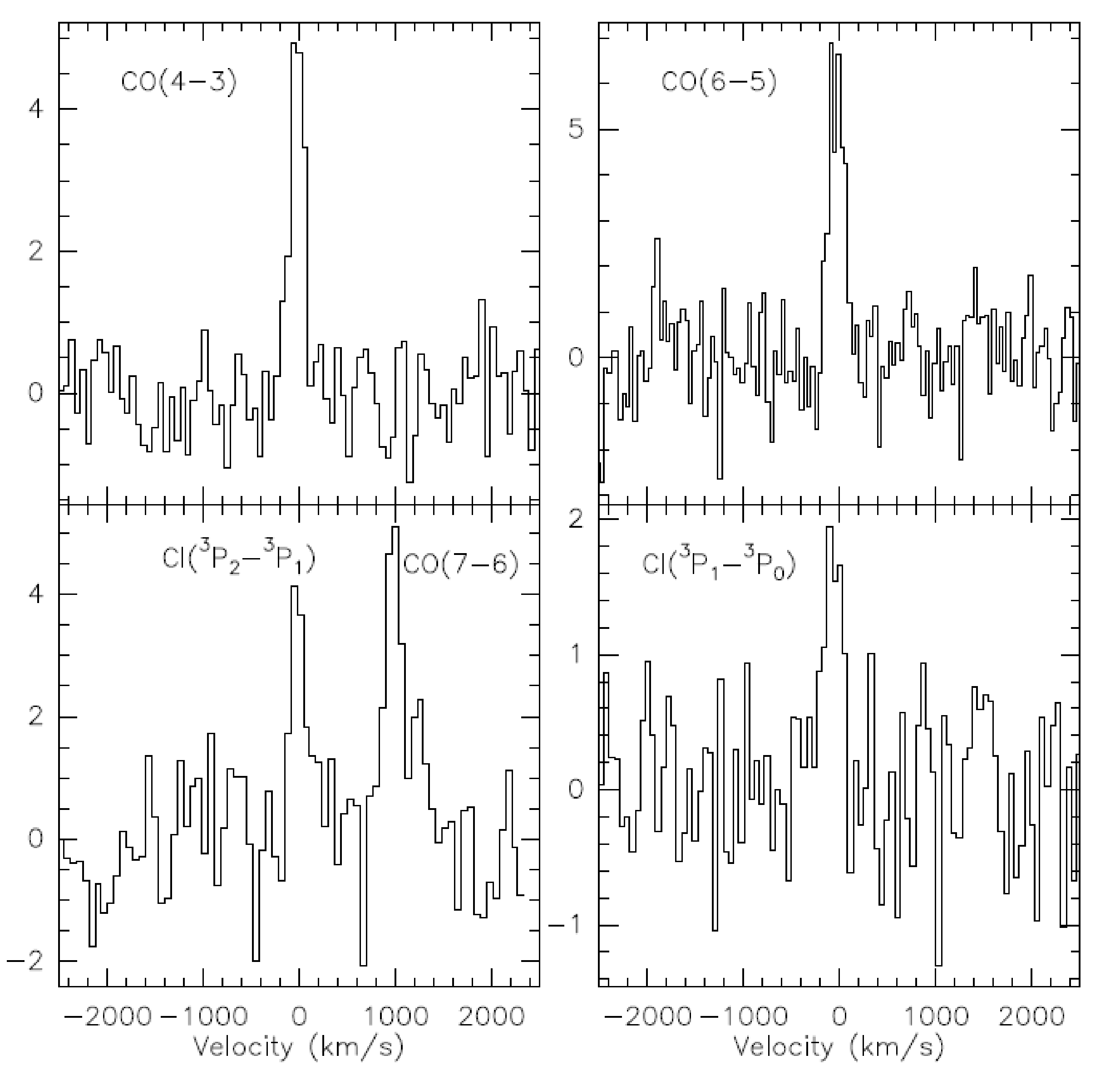
Mdust= 6 10^{9}/m Mo

SFR= 8.3 10^{4}/m Mo/yr

MH_2= 2 10^{11}-10^{12}Mo

CI/H_2 = 1.4-8 10^{-5}

Relatively low CO excitation



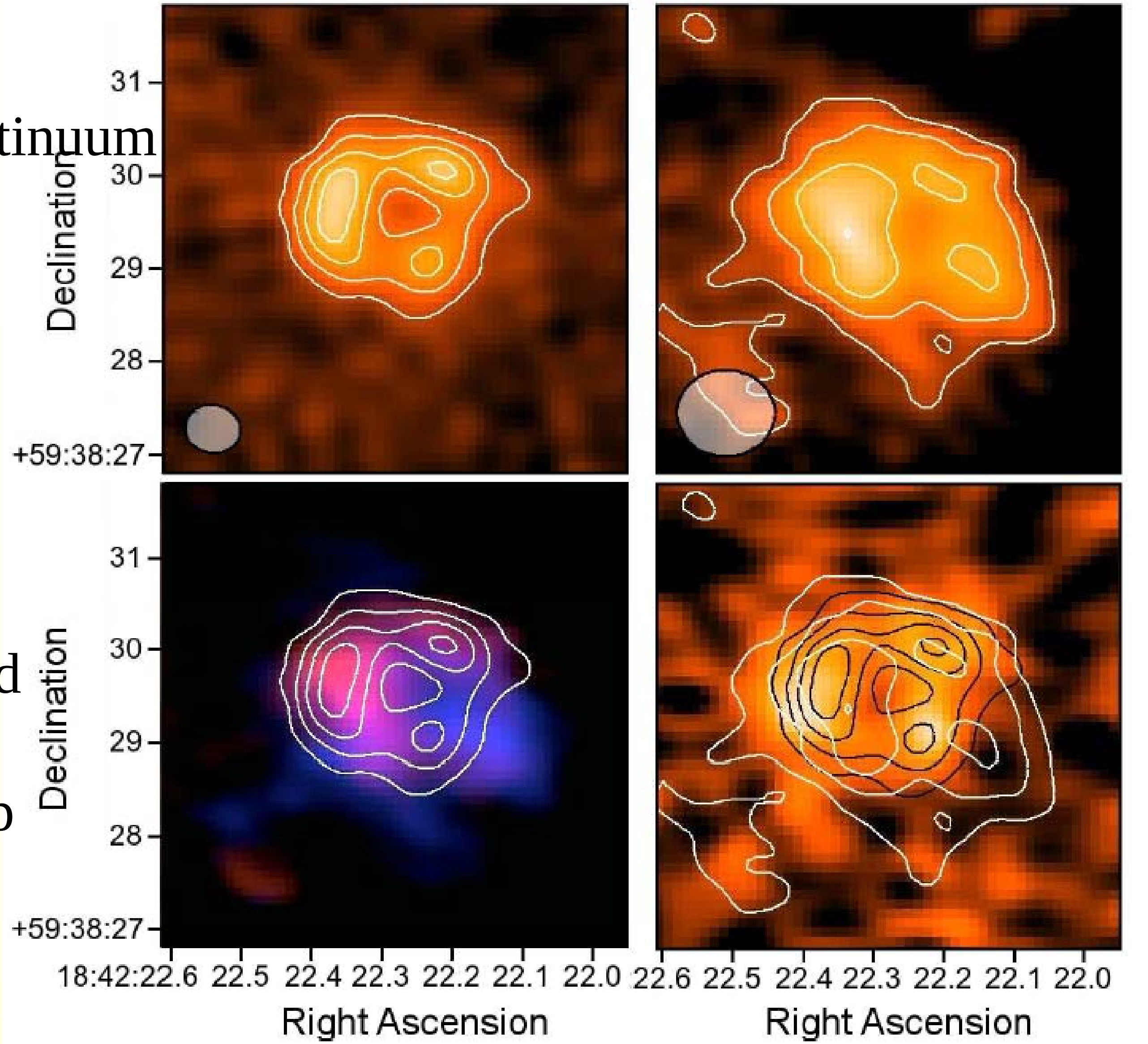
Lestrade, Combes, Salome et al 2010

Continuum

[NII]205μ

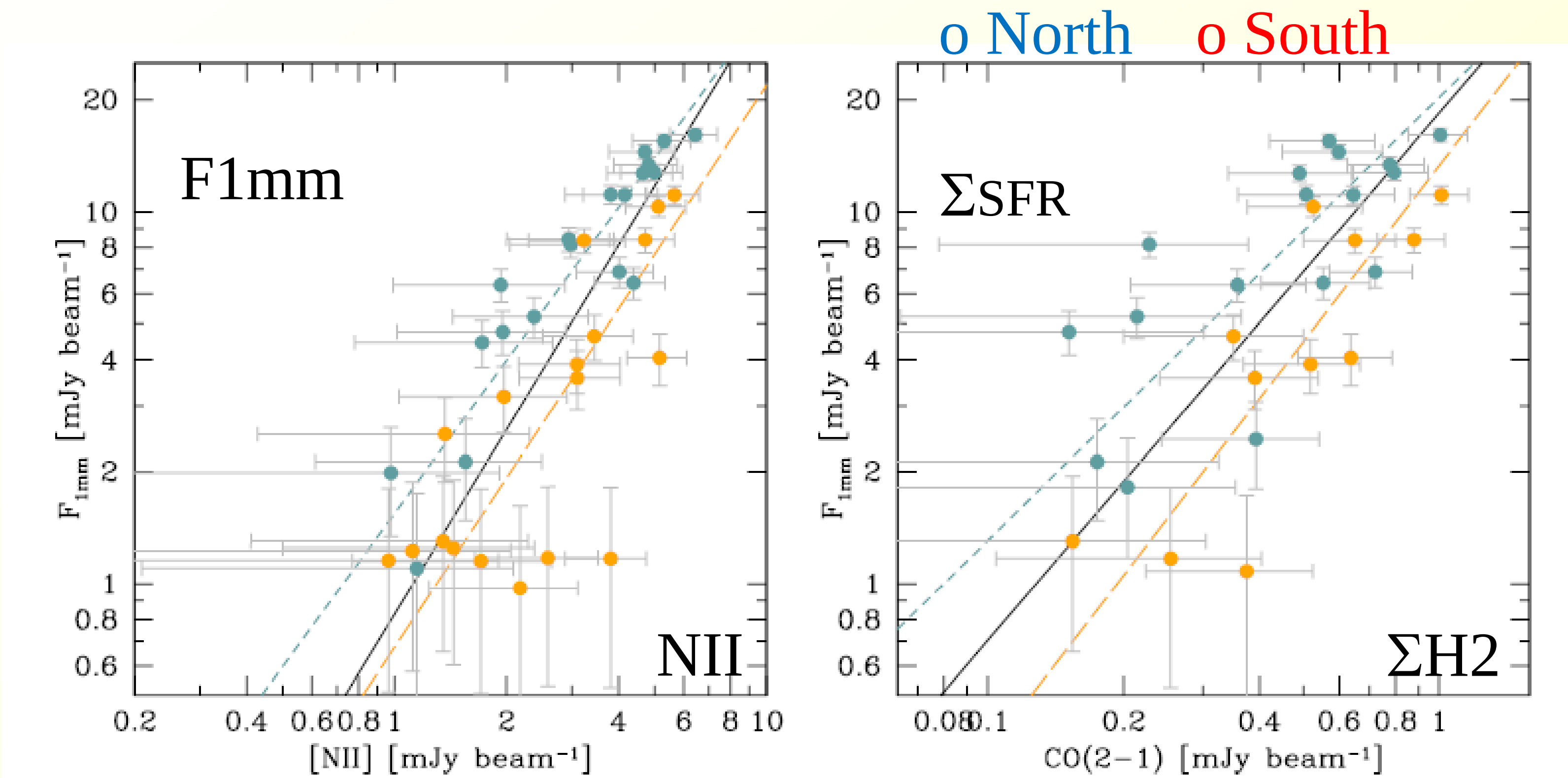
Red and
Blue
V-comp

[NII], CO
continuum



MM18423+5938 Decarli et al 2012

Resolved Kennicutt-Schmidt law



Ionised gas correlated to 1mm continuum (Star Formation proxy)

MM18423+5938

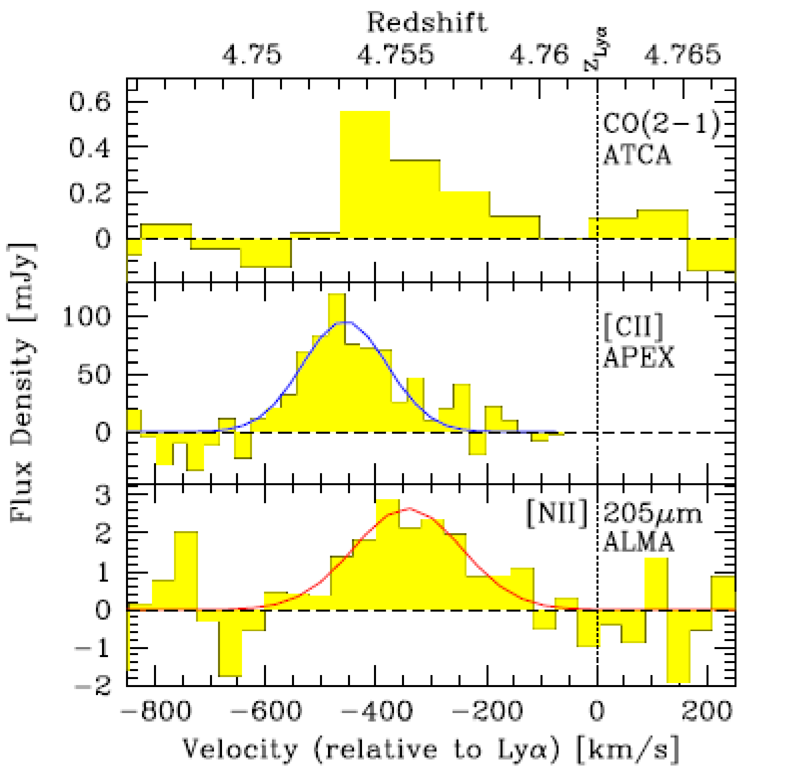
Decarli et al 2012

[NII]/[CII] metallicity diagnostic

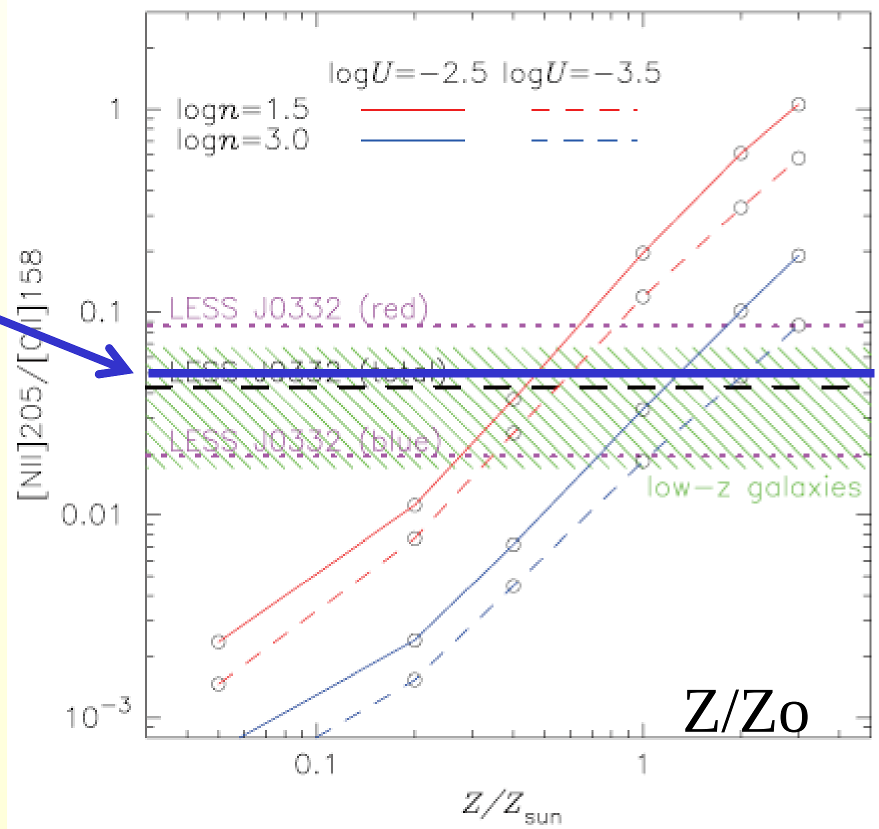
Difficult to have optical diagnostics in dust-enshrouded objects at z>3

LESS J033229.4–275619 z=4.76

HLS J091828.6 z=5.243



NII/CII

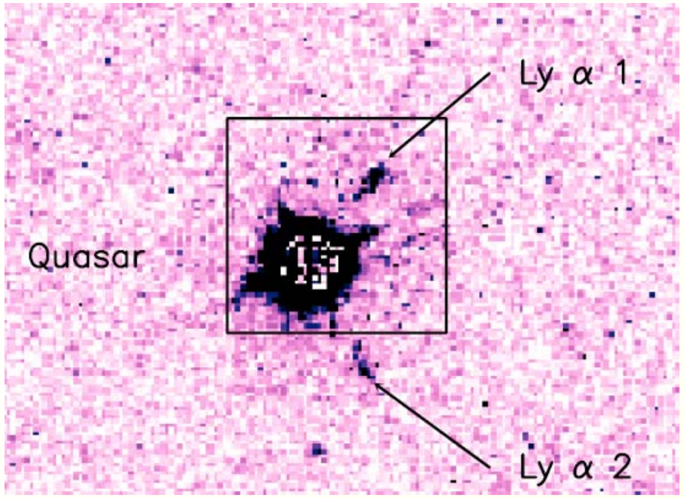


Z/Zo

The [NII]/[CII] ratio is 0.043, similar to nearby objects ➔ Z ~solar

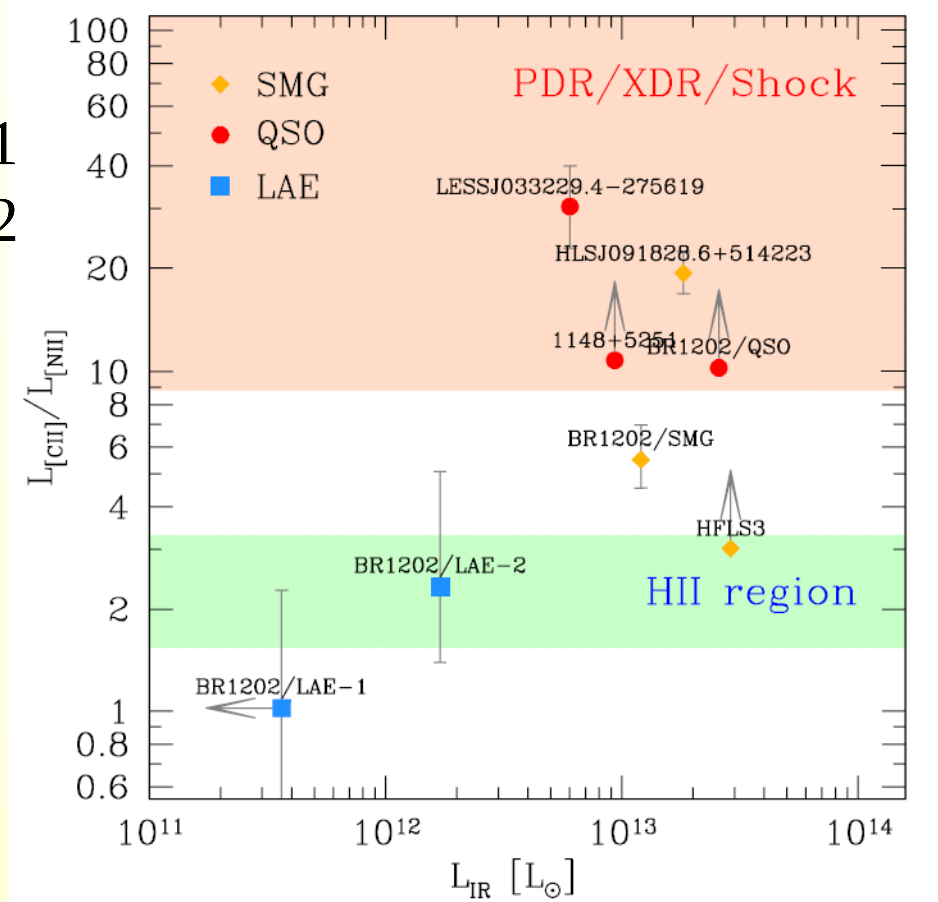
Nagao, Maiolino et al 2012, with ALMA

Merging QSO-SMG at z=4.7: BR1202-0725

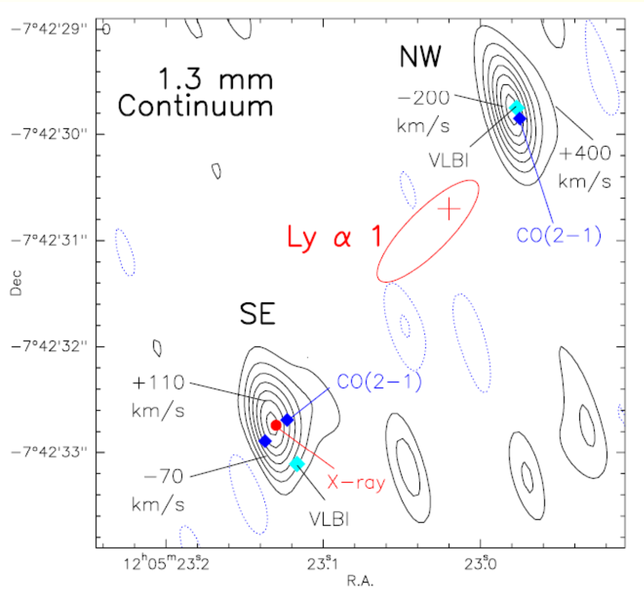


QSO
SMG
LAE1
LAE2

Decarli et al 2014



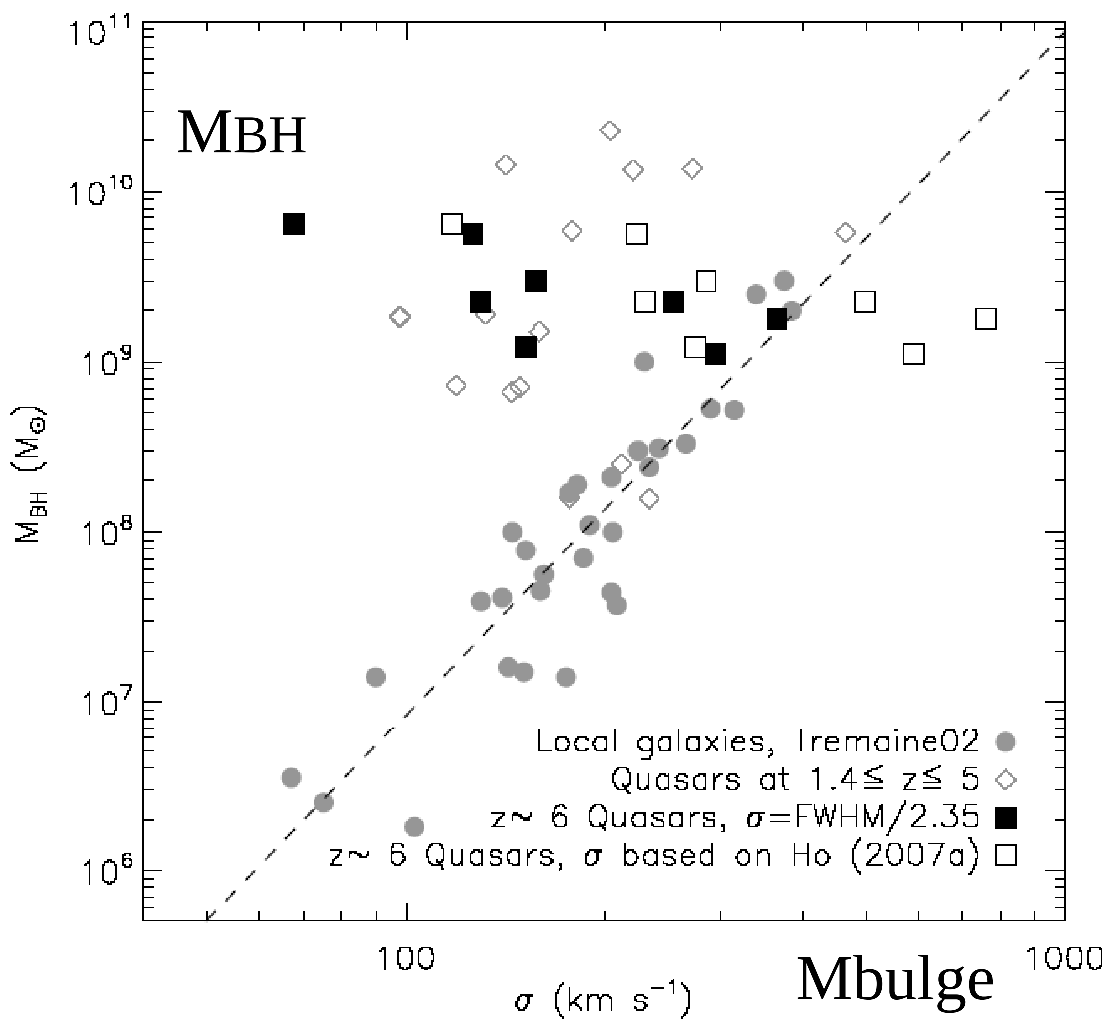
Salome et al 2012



No NII in the QSO, CII/NII ~2 in LAE

➔CII is then associated with HII regions and not PDR, as for QSO & SMG

MBH/Mbulge, Wang et al 2010



QSO at z=6

➔An order of magnitude higher MBH than expected

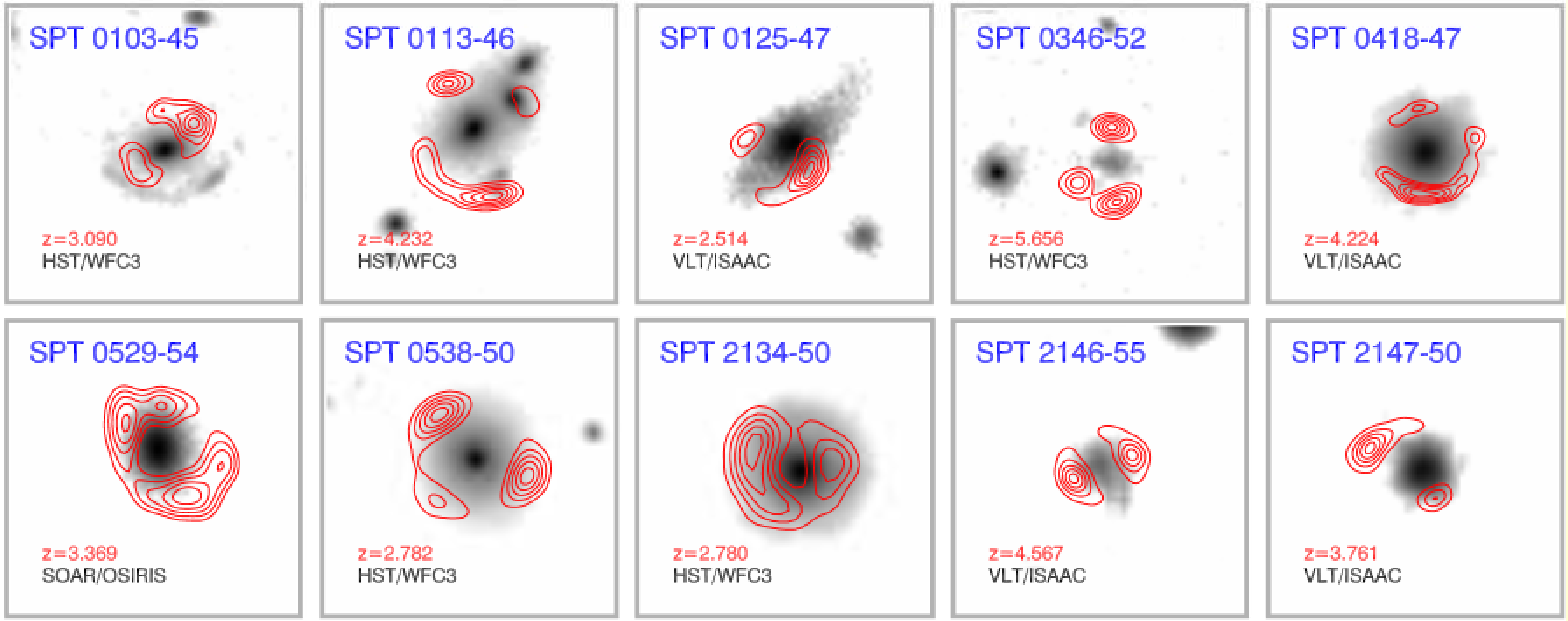
But:
Unknown inclination

Could be a bias in CO width too small due to a detection bias ?

➔ALMA needed to resolve the morphology, and find actual inclinations

First CII obs with ALMA of 6 QSO-hosts (Wang et al 2013)

ALMA high-z searches



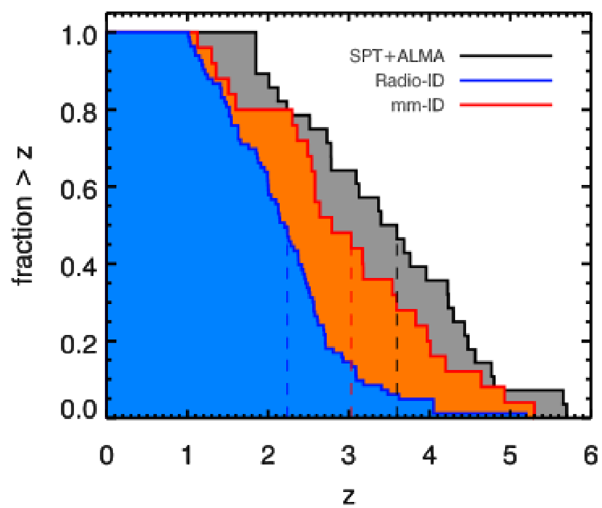
Grey-scale NIR from HST, VLT, SOAR

Vieira et al 2013 (23/26 detected)

10 z > 4

Red=ALMA 870 μm contours, 2min, 0.5''

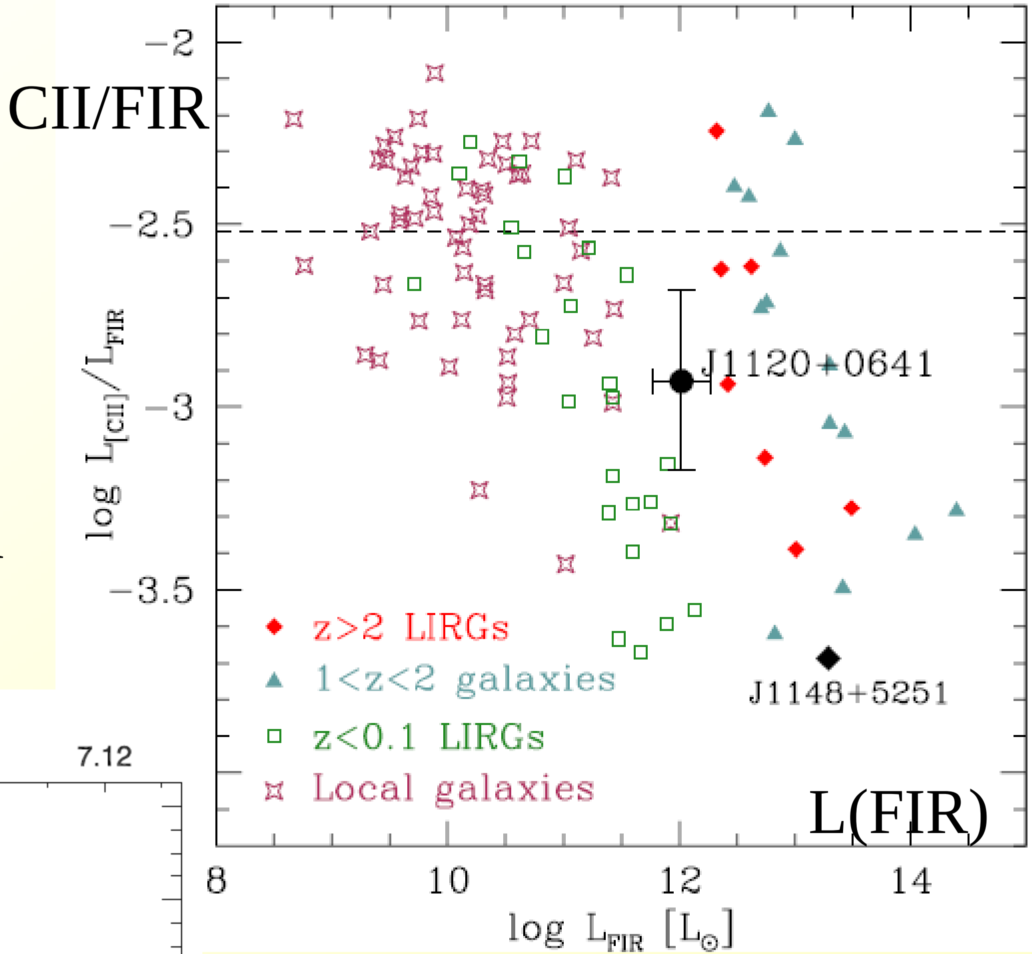
ALMA-obtained spectro redshift

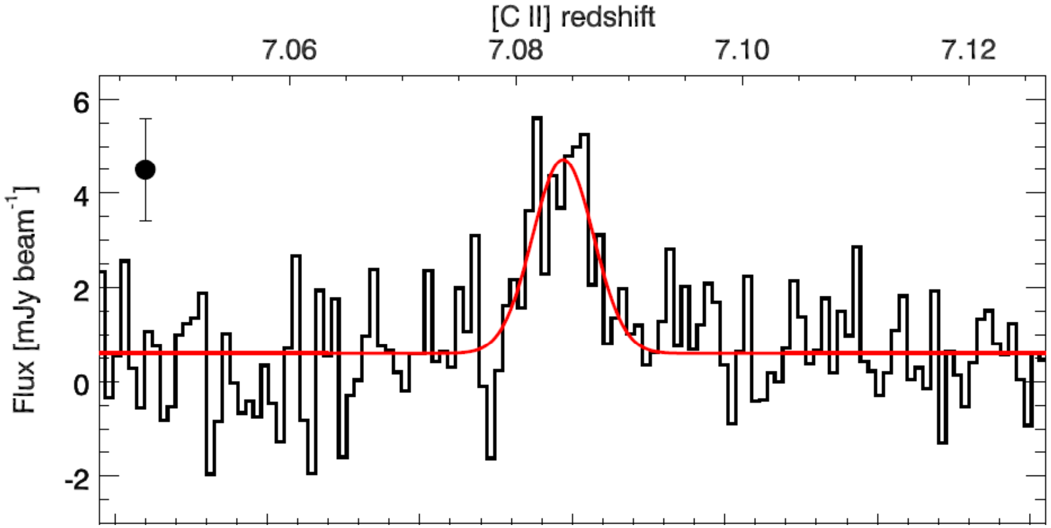


QSO at z=7.1: J1120+0641

Venemans et al 2012
PdB observations,
Unresolved point source

SFR~160-440 Mo/yr
CII line 4 times lower than in J1148+5251





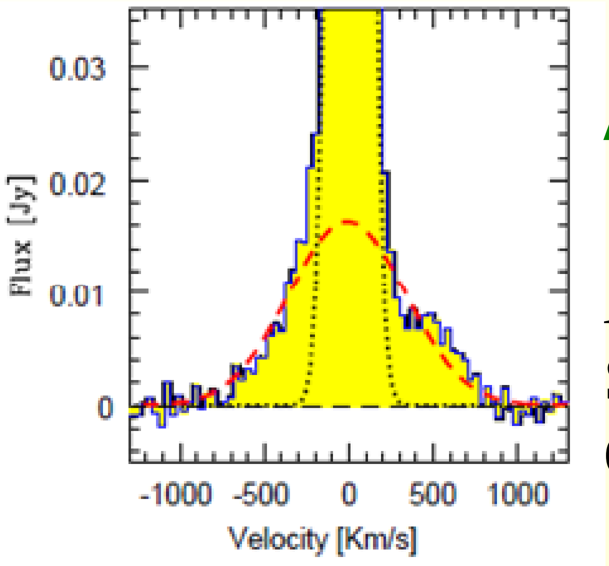
AGN feedback

Salome et al 2008

Cooling flow clusters:
Inflow and outflow coexist

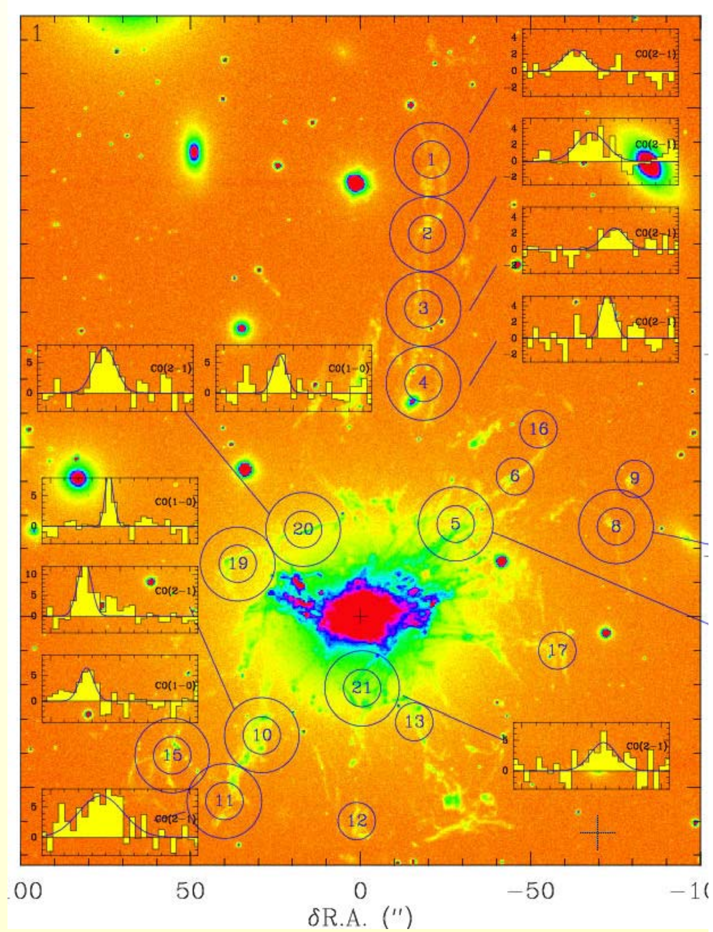
The cooled gas fuels the AGN

The molecular gas coming from previous cooling is dragged out by the AGN feedback



AGN feedback in Mrk 231

AGN and also nuclear Starburst, 10^7-10^8Mo
Outflow 700Mo/yr



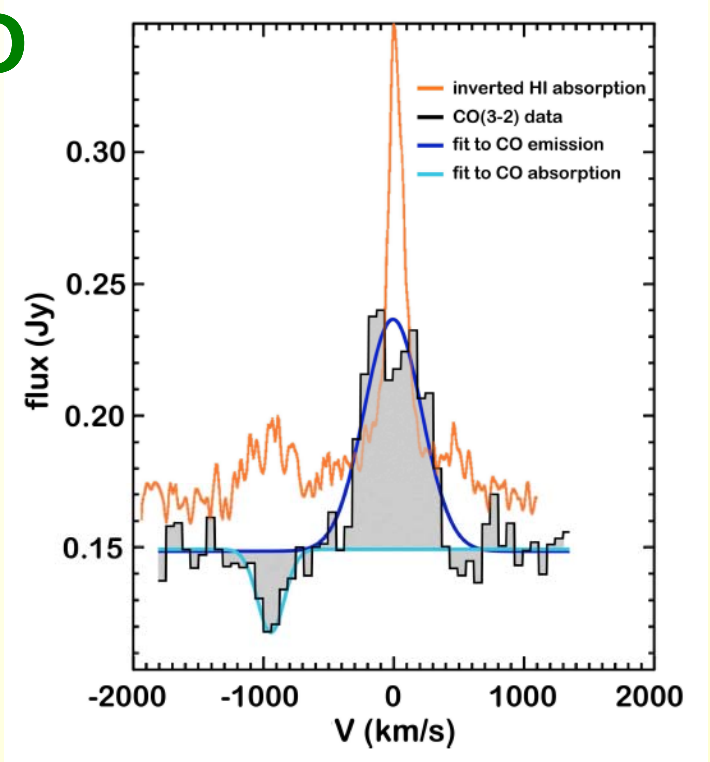
Perseus A

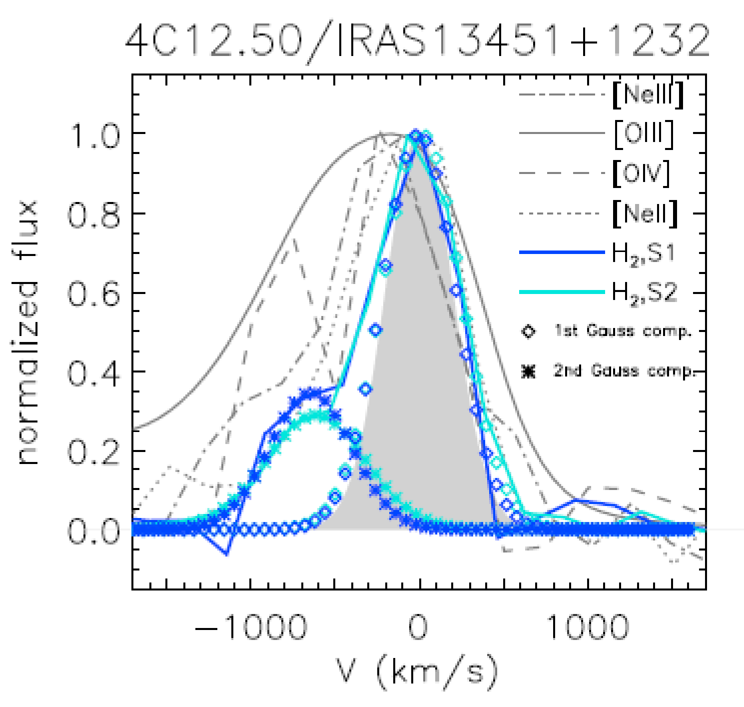
IRAM *Ferruglio et al 2010*

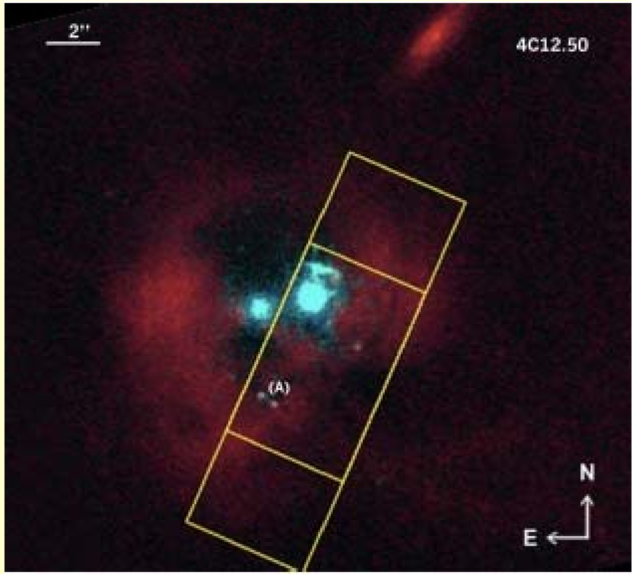
Feedback in nuclei: H2 & CO

6 out of 300 systems searched show H_2 outflows

4C12.50 SFR ~400-1000 Mo/yr
Outflow ~130 Mo/yr



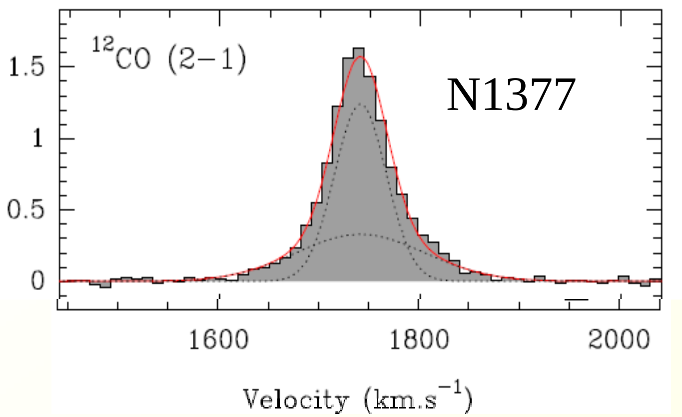




Dasyra & Combes 2011, 2012

Molecular outflows are massive

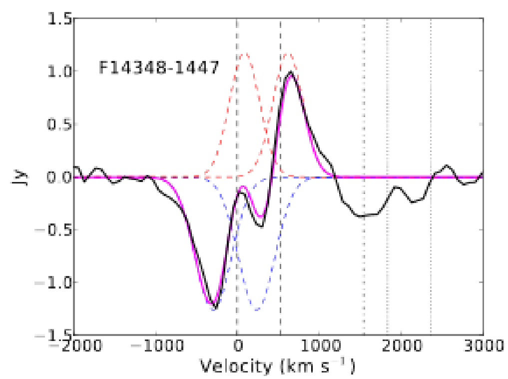
Aalto et al 2012



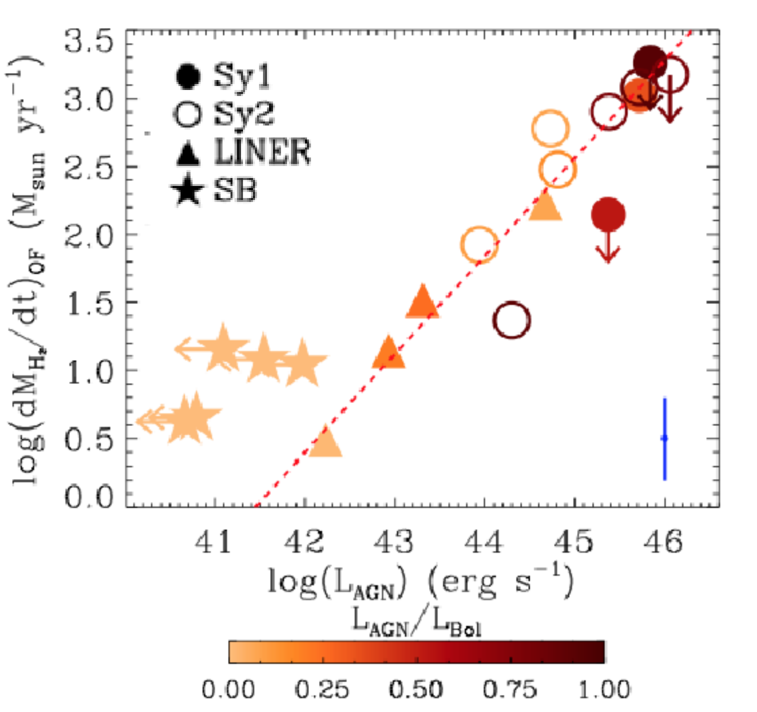
Some outflows are more massive then their dense nuclear disk, e.g. N1377 200pc extent with modest 140km/s
M_{out}= 1-5 $10^7 M_o$, disk mass ~2 10^7 M_o

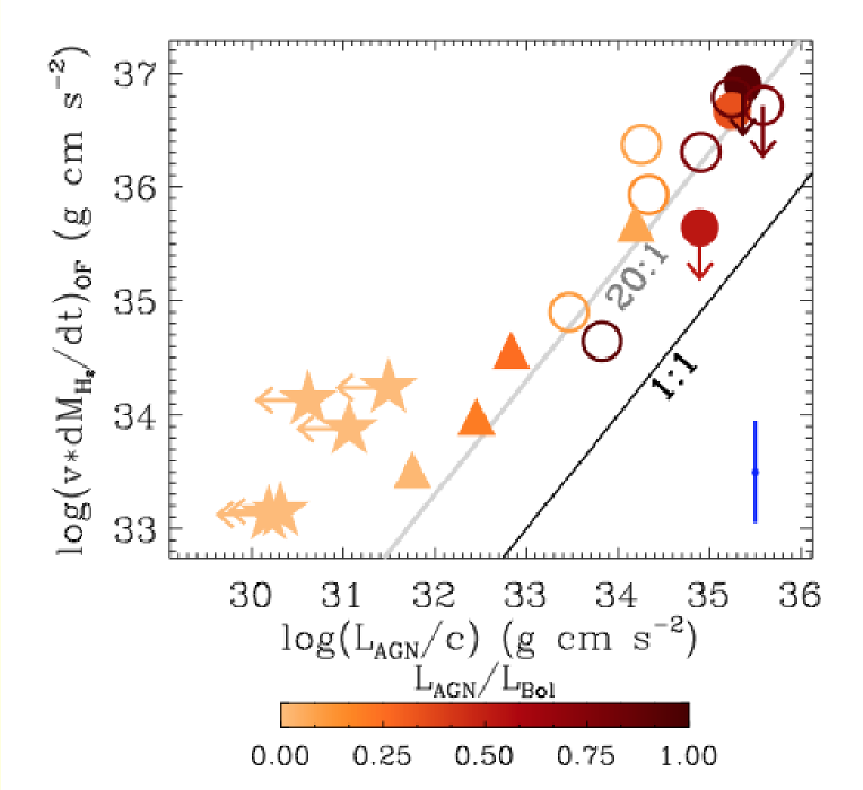
Outflows due to SN: M82, Arp220, Pcygni profiles 100pc,
Mout ~ **$10^8 M_o$** (Sakamoto et al 2009) Load factors 1-3

More violent outflows due to AGN: V> 1000km/s,
up to 1200 Mo/yr OH, H_2O abs Herschel,
Sturm et al (2011), ULIRG+AGN
Spoon et al 2013, Veilleux et al 2013: 70% outflows



Relations outflows with AGN



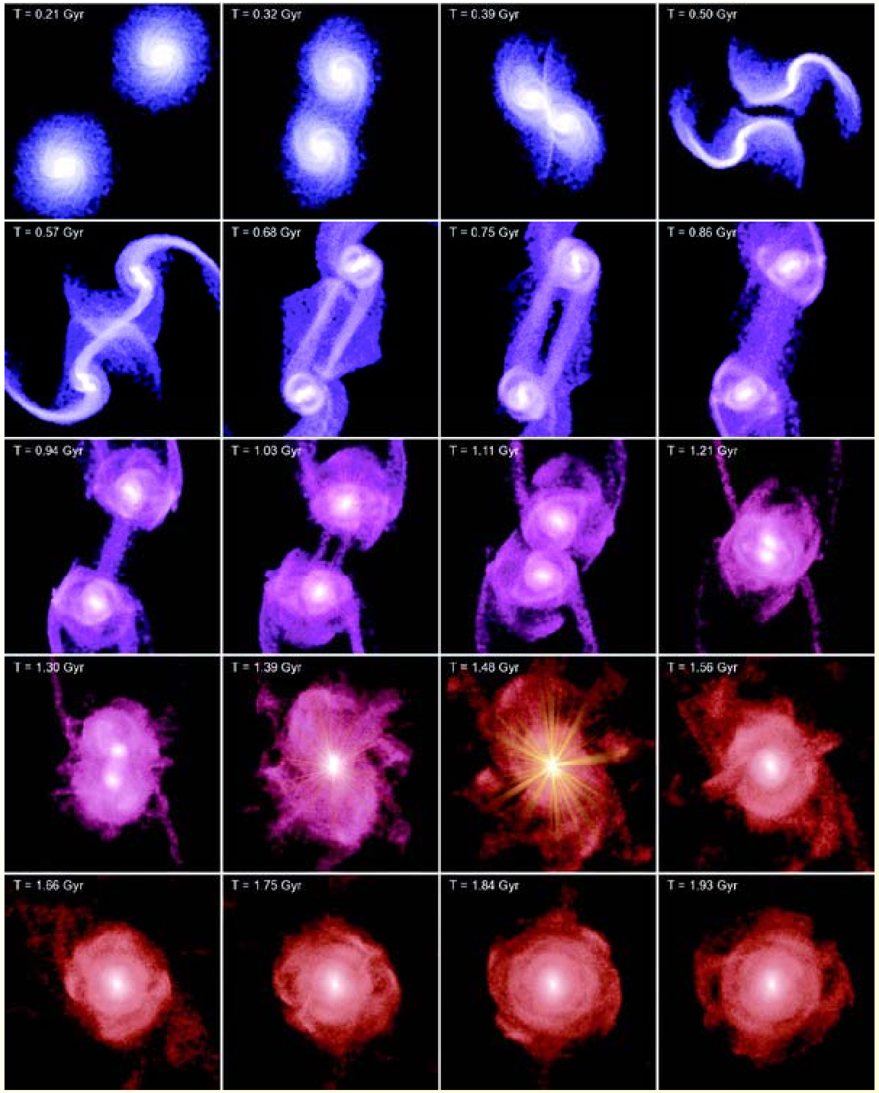


For AGN-hosts, the outflow rate
Correlates with the AGN power

Cicone et al 2014

dM/dt v ~20 L_{AGN}/c
Can be explained by
energy-driven outflows
(Zubovas & King 2012)

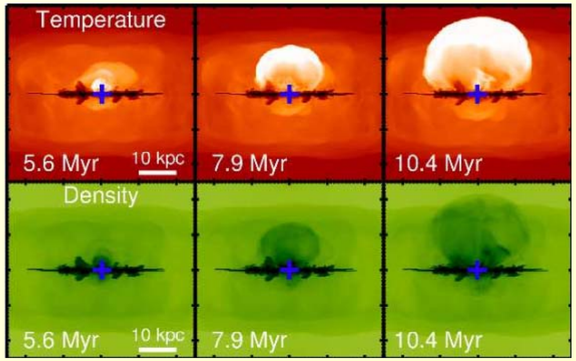
AGN feedback in mergers



Springel et al. (2003-2005),
Hopkins et al. 2006

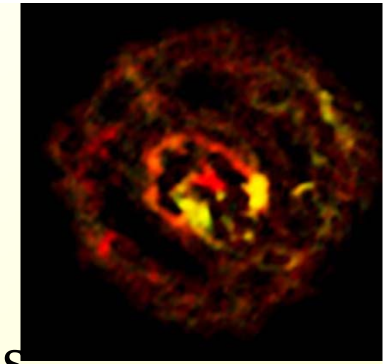
SFR ~ρ^n with n=1, 1.5, 2
SN feedback+
BH growth and associated feedback

Obvious crucial parameter
How much feedback?



Gabor & Bournaud 2014:
No quenching effect

Feedback in low-luminosity AGN



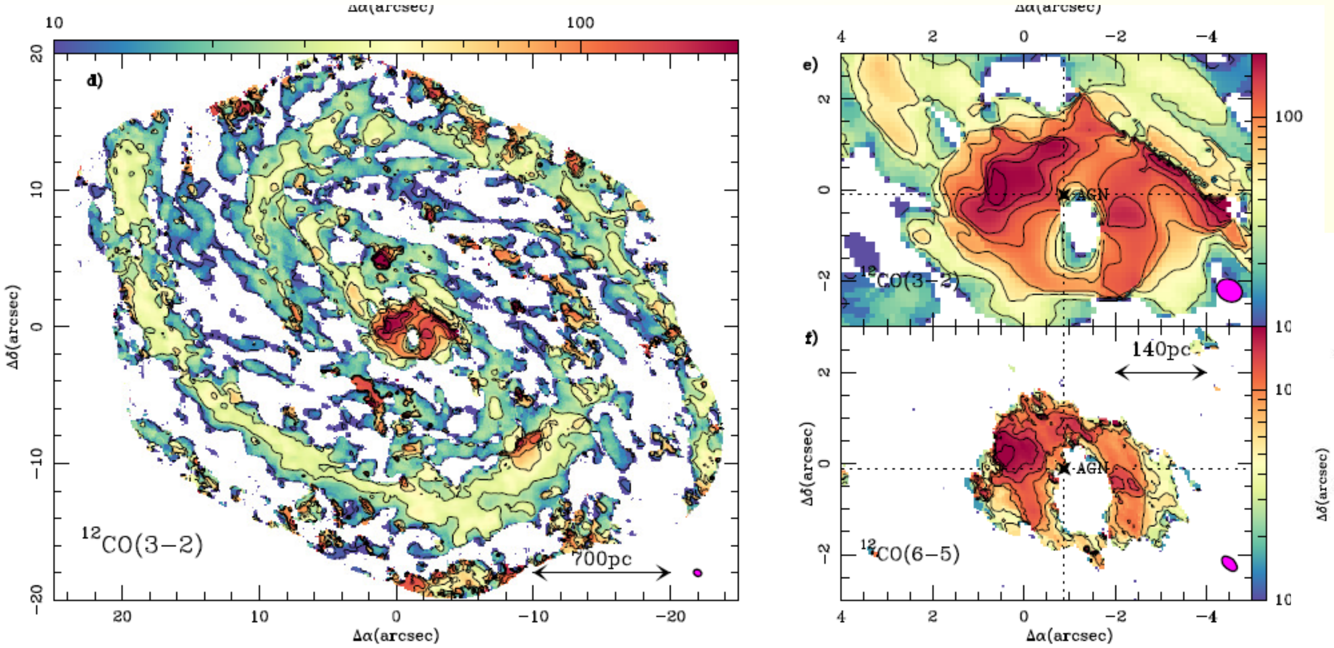
NGC 1433: barred spiral, **CO(3-2) with ALMA**
Molecular gas fueling the AGN, + outflow // the minor axis

M_{H2}= 5.2 10^7 M_o in FOV=18”
100km/s flow
7% of the mass= 3.6 10^6 Mo
Smallest flow detected

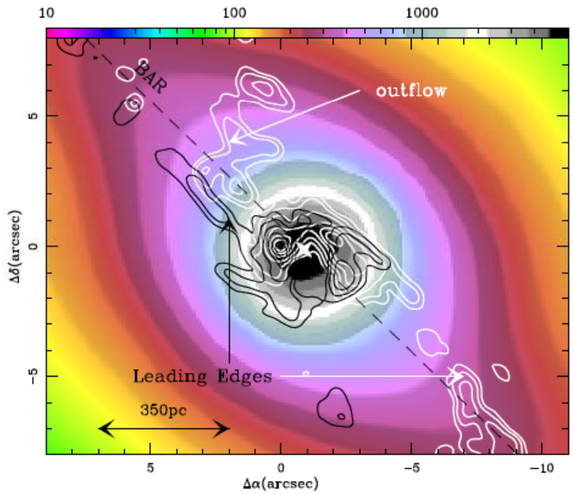
➔ L_{kin}=0.5 dM/dt v^2 ~2.3 10^{40} erg/s
L_{bol} (AGN)= 1.3 10^{43} erg/s
Flow momentum > 10 L_{AGN}/c
Combes et al 2013

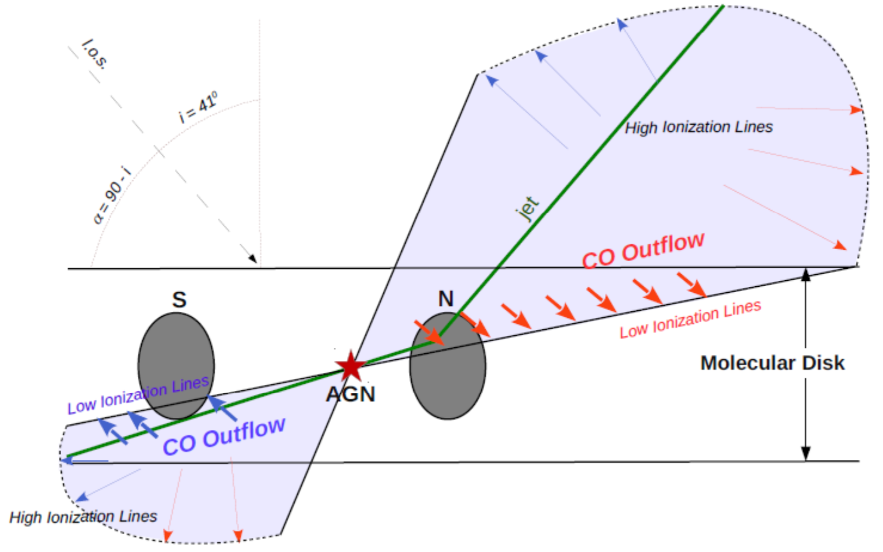
Gravity torques fuel the AGN
Smajic et al 2014

Off-center AGN and outflow in N1068



Black V=-50km/s
White V=50km/s





Outflow of 63Mo/yr
About 10 times the SFR in this CMD region

Garcia-Burillo et al 2014

Why molecular outflows?

Outflowing gas is accelerated by a shock, and heated to 10^6-10^7K

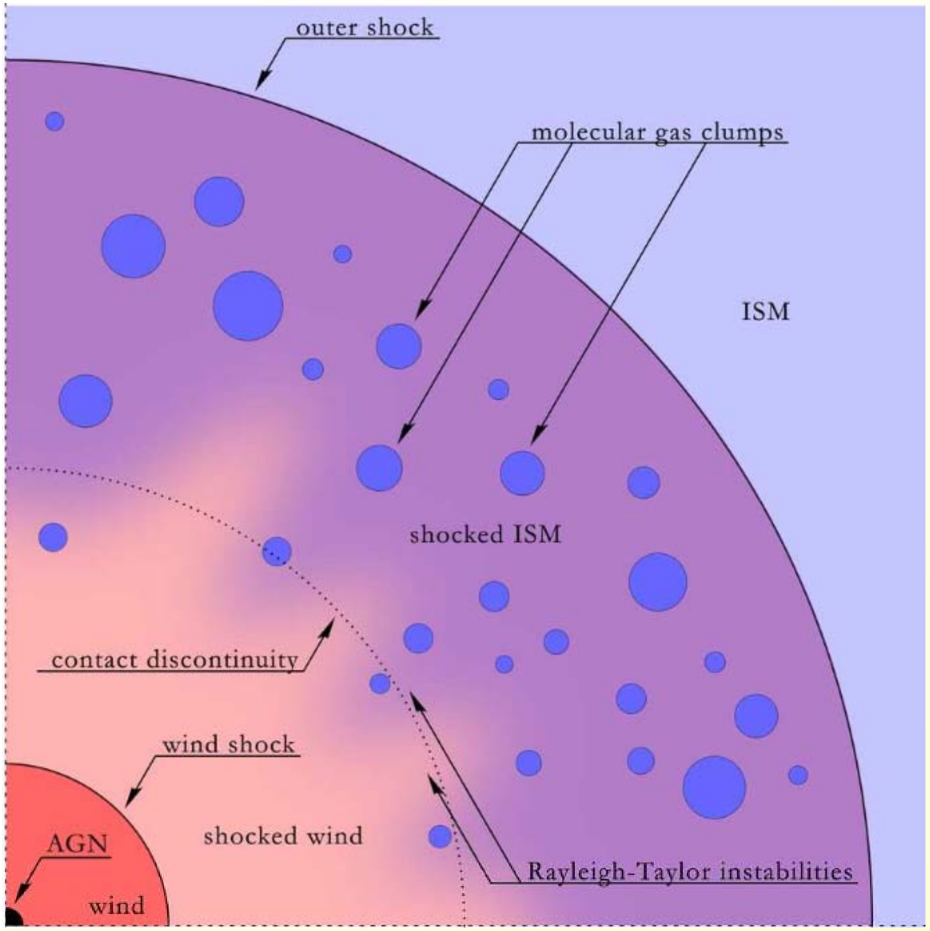
Molecules should be dissociated at such temperatures
Even if cold clumps are carried out in the flow➔ shock signature?

Radiative cooling is quick enough to reform molecules in a large fraction of the outflowing material (Zubovas & King 2014)

With V~1000km/s, and dM/dt ~1000 Mo/yr, efficient cooling produces multi-phase media, with triggered star formation

AGN winds trigger Star Formation ?

Zubovas & King 2014



Cooling efficient (free-free, metals)
Flow unstable, if R=Prad/Pgas<0.5 (Krolik 1981), and
$R \sim 0.07\ M_{BH}/M_{crit}\ f_{EDD} \sim 0.07$
➔Multiphase, with RT instabilities

Time-scale for cooling << 1Myr
At kpc scales, ➔SF induced

The SF results in a Luminosity
Comparable to L_{AGN} 100Mo/yr!

This means that SB or AGN outflows are difficult to disentangle
All could be due to AGN

Energy-conserving outflows?

If the cooling is very efficient, ➔ momentum-conserving outflow

But for very fast winds > 10 000km/s, radiative losses are slow
➔energy-conserving flow (Faucher-Giguère & Quataert 2012)

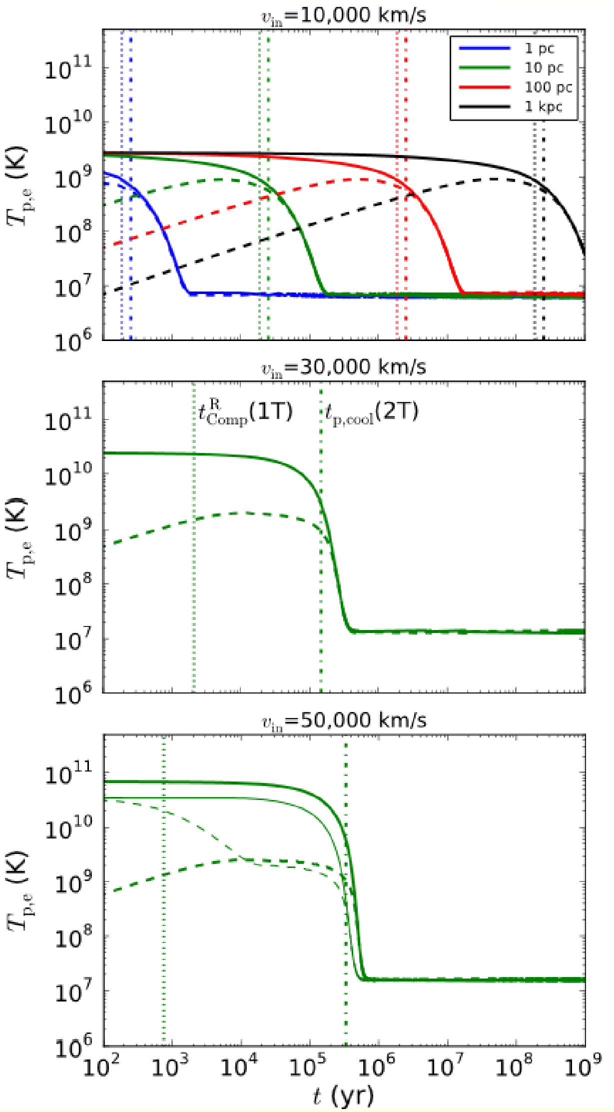
In some cases, even slow winds v_{in} ~1000km/s driven by radiation pressure on dust, could be energy-conserving
Push by the hot post-shock gas, boost the momentum
Vs of the swept-up material

Boost of v_{in} /2 Vs ~50! Explains why momentum flux >> L_{AGN}/c

// Adiabatic phase, or Sedov-Taylor phase in SN remnant

Slow cooling --High momentum fluxes

T behind SW



Full: protons

Dash: electrons

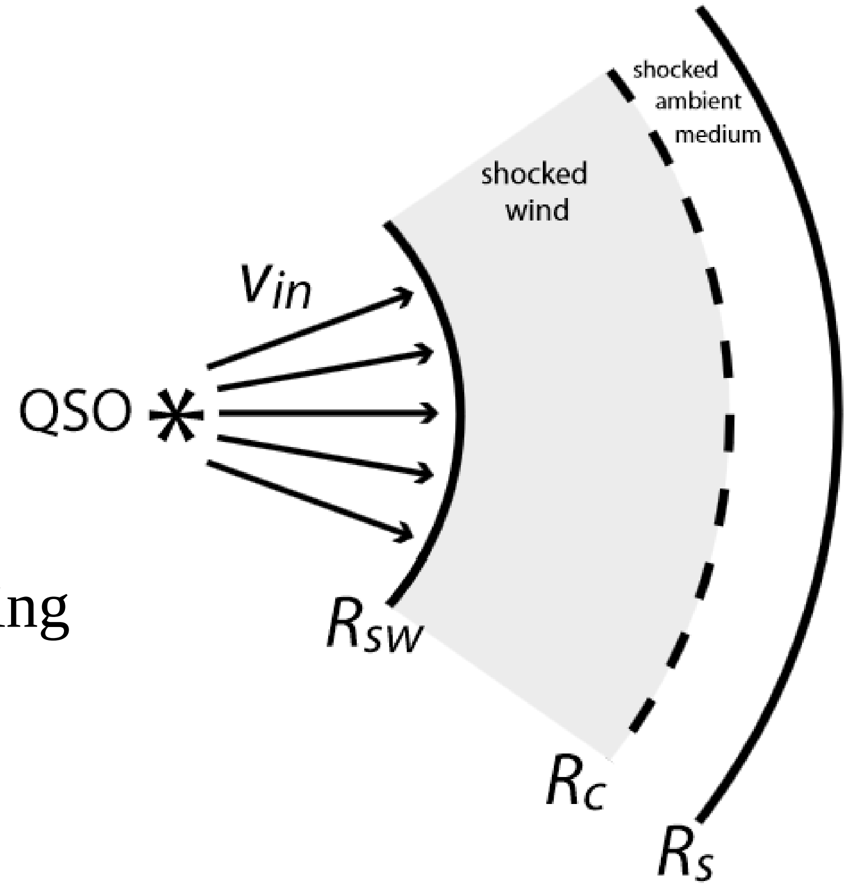
T_{Comp}= 2 10^7K

Minimal e-heating

Te=me/mpTp

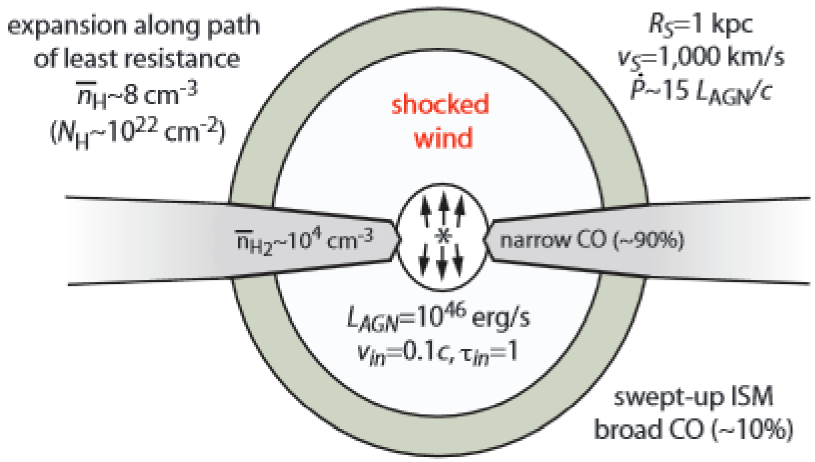
at the shock

2-temp plasma



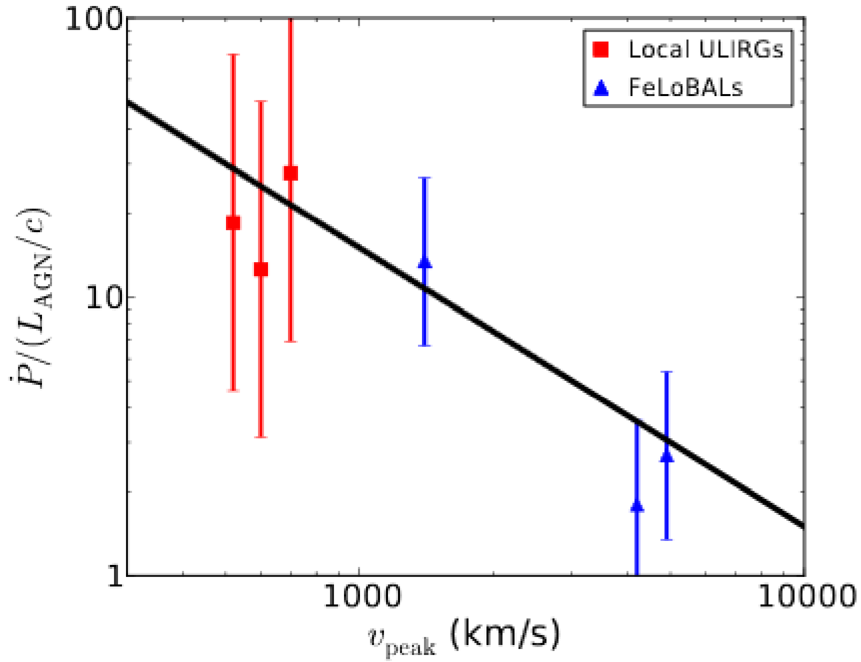
Faucher-Giguère & Quataert 2012

Outflow solutions



Momentum boost

$$\dot{M}_s v_s^2 \approx \frac{1}{2} \dot{M}_{in} v_{in}^2,$$



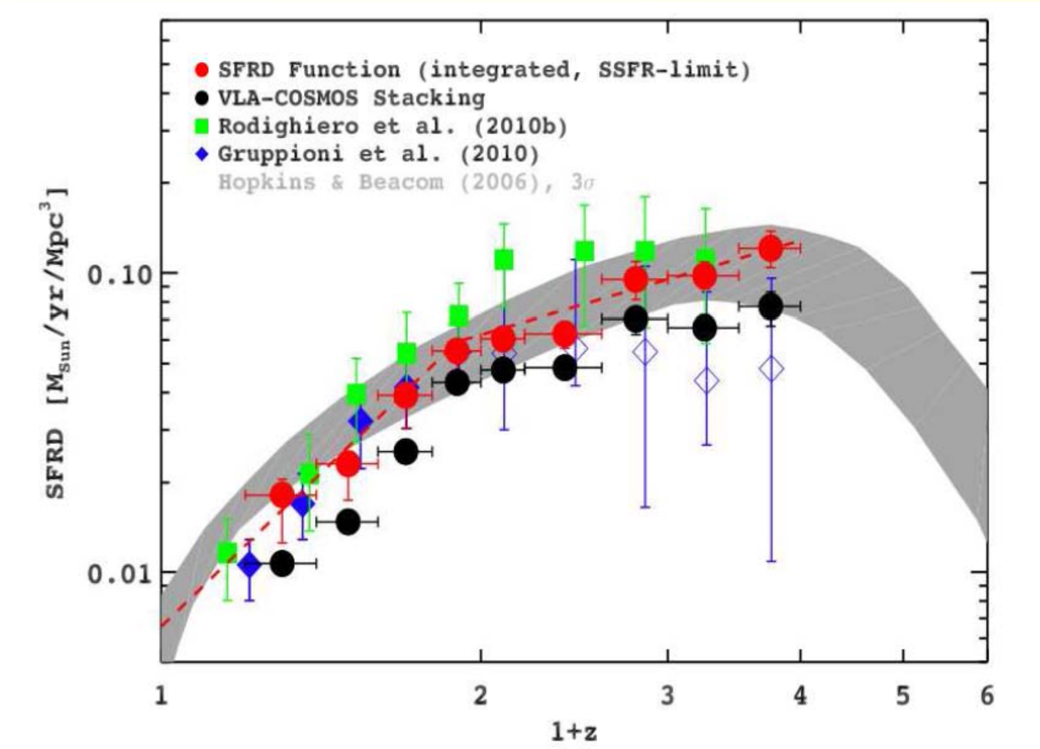
Represent the typical case of Mrk231, face-on, R~3kpc V~1000km/s

Momentum flux =15 L_{AGN}/c

Faucher-Giguère & Quataert 2012

Perspectives with ALMA

The CO lines will be intensively observed at all z with ALMA and determined for **« normal » systems**
➔ efficiency of star formation (z), and the kinematics, Mdyn



Karim et al 2011

➔SFH + MH2 ➔ SFE

sSFR