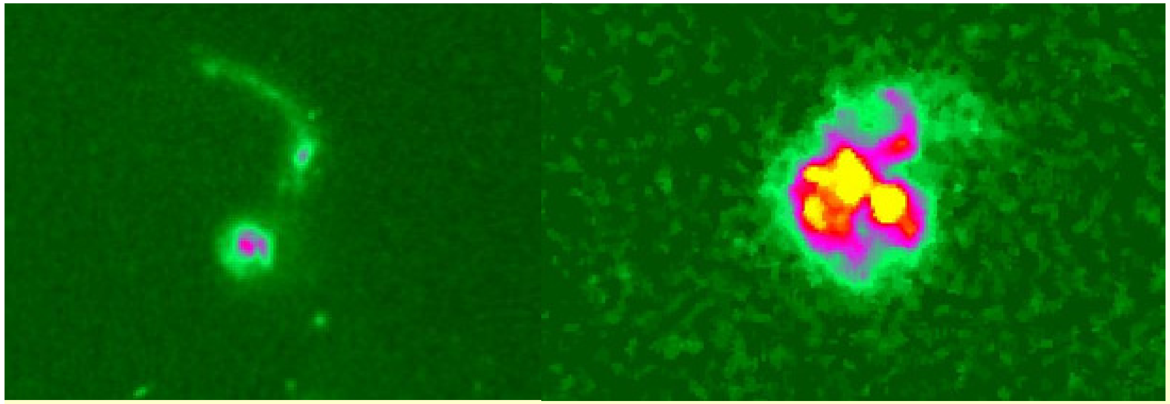
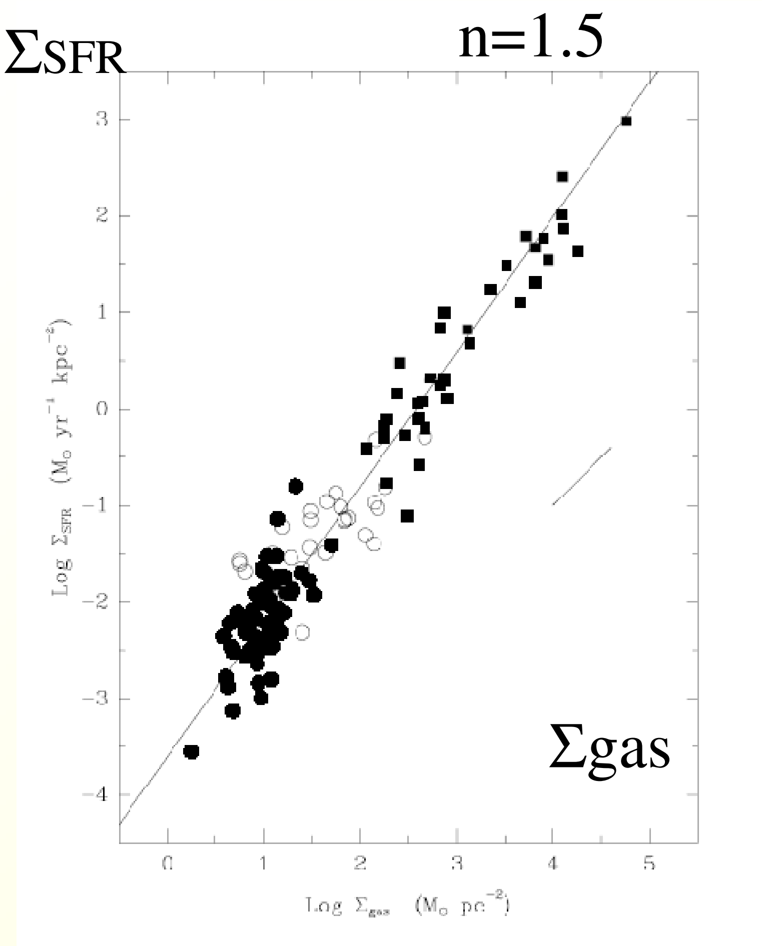


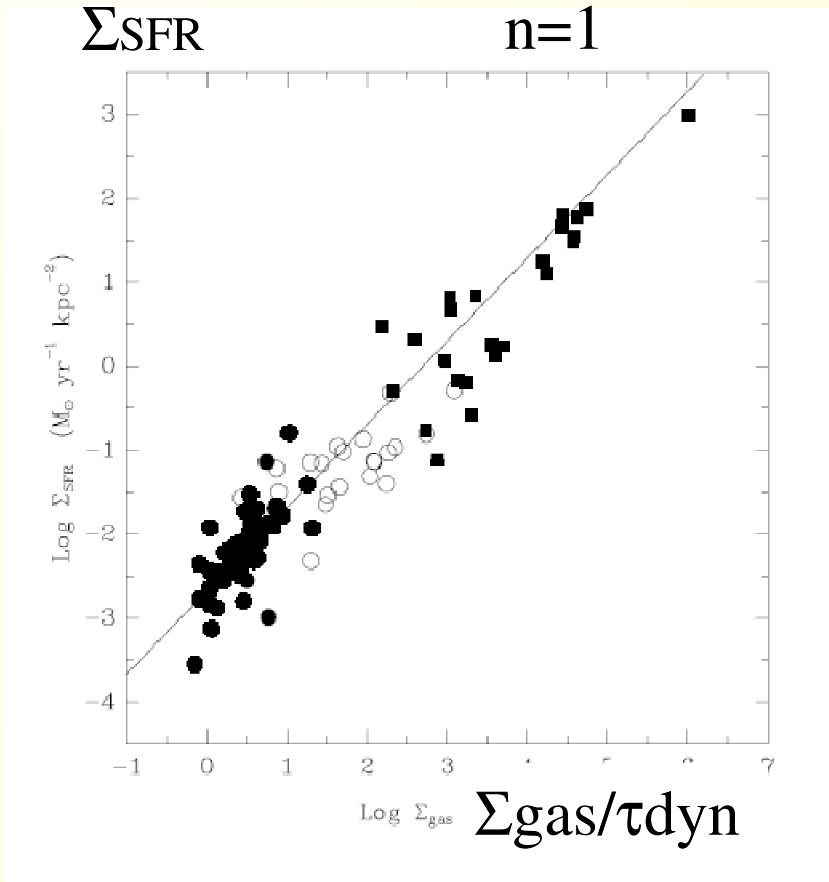
How star formation is triggered and regulated in galaxies: future progress with ALMA

Françoise Combes
Observatoire de Paris

5 September 2012

Global Schmidt law





Kennicutt 1998

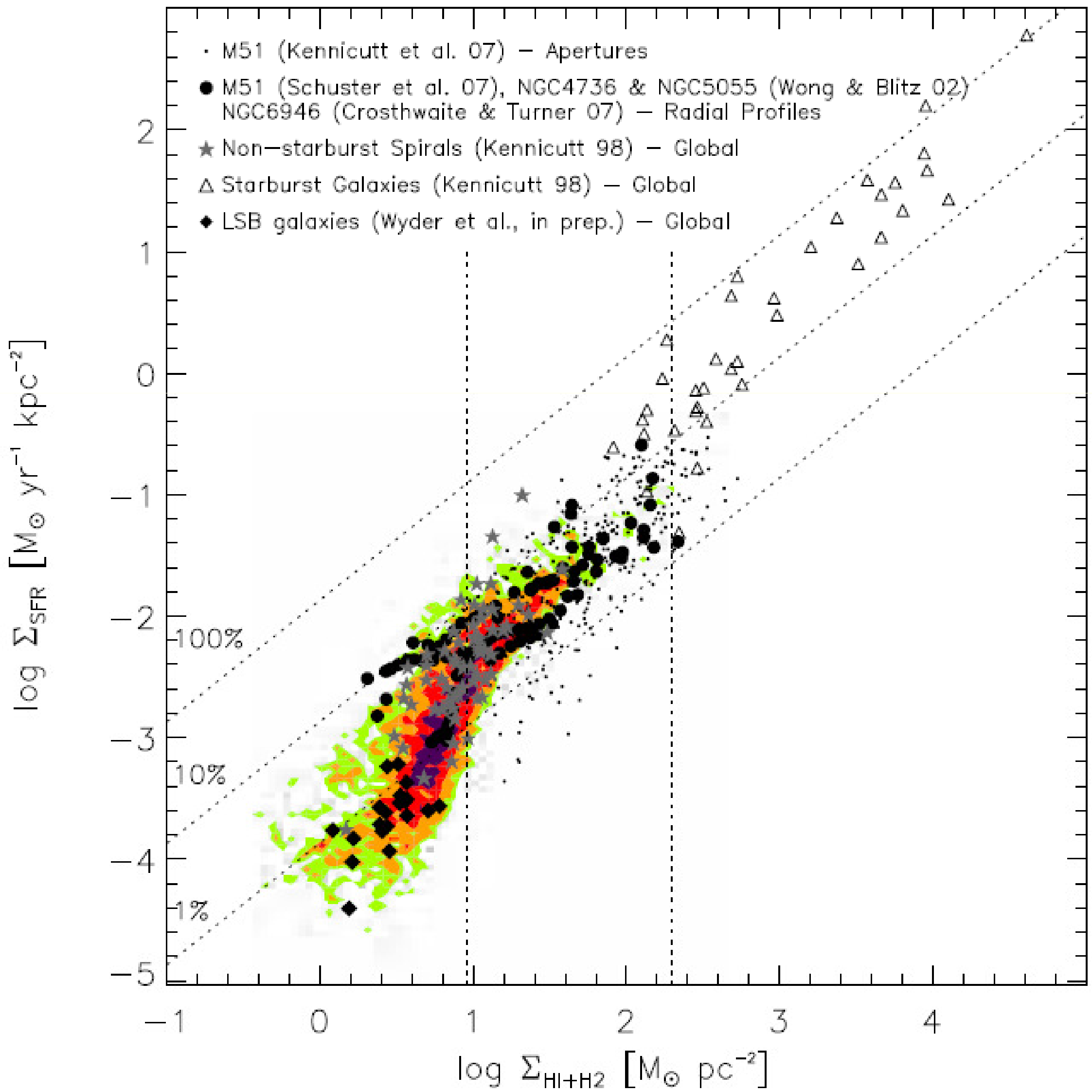
Star formation law in galaxies

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

Time-scale for SF
2 10^9 yrs
At sub-kpc scale

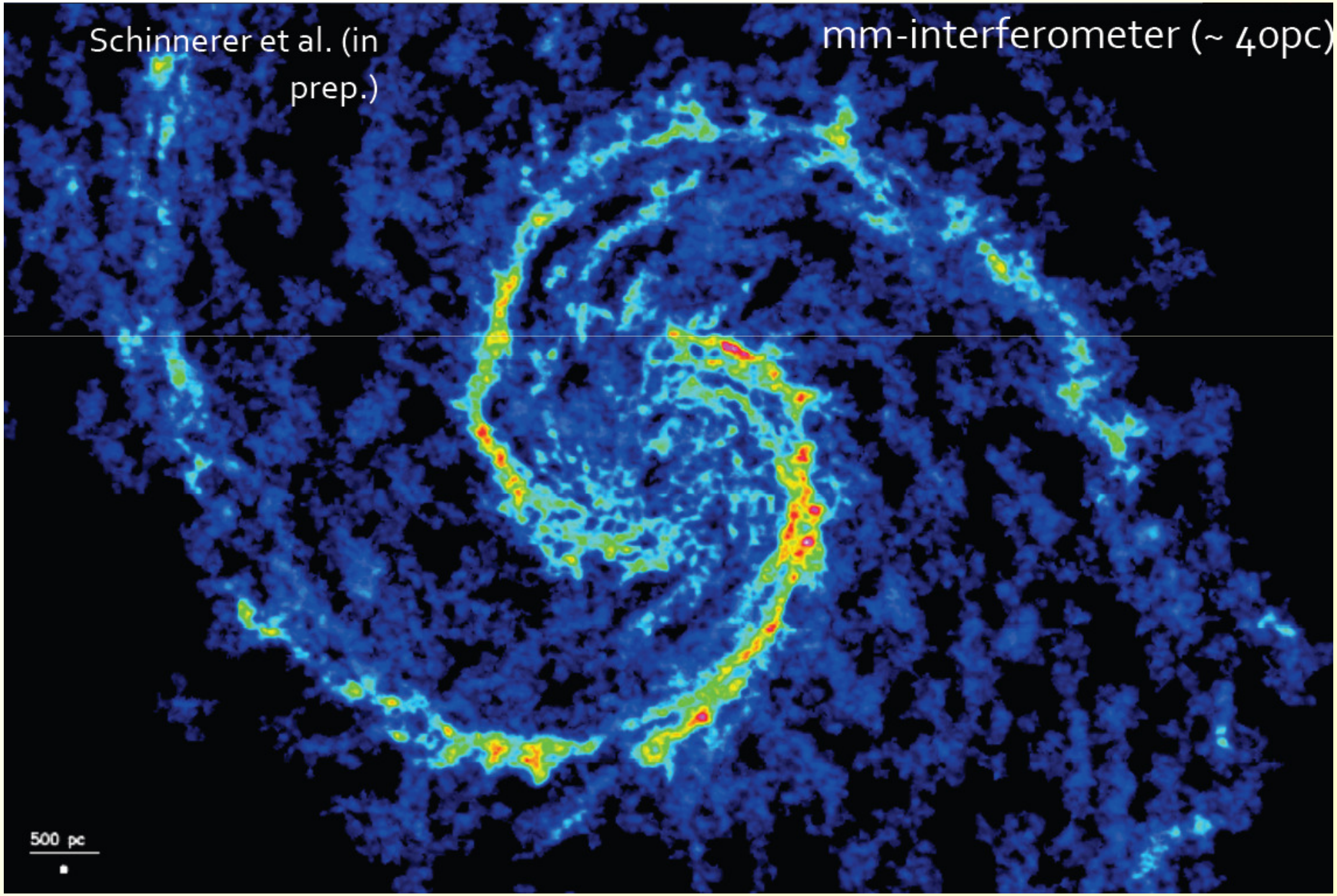
SFR not strongly
Correlated with HI

H_2 when > 9 Mopc^{-2}

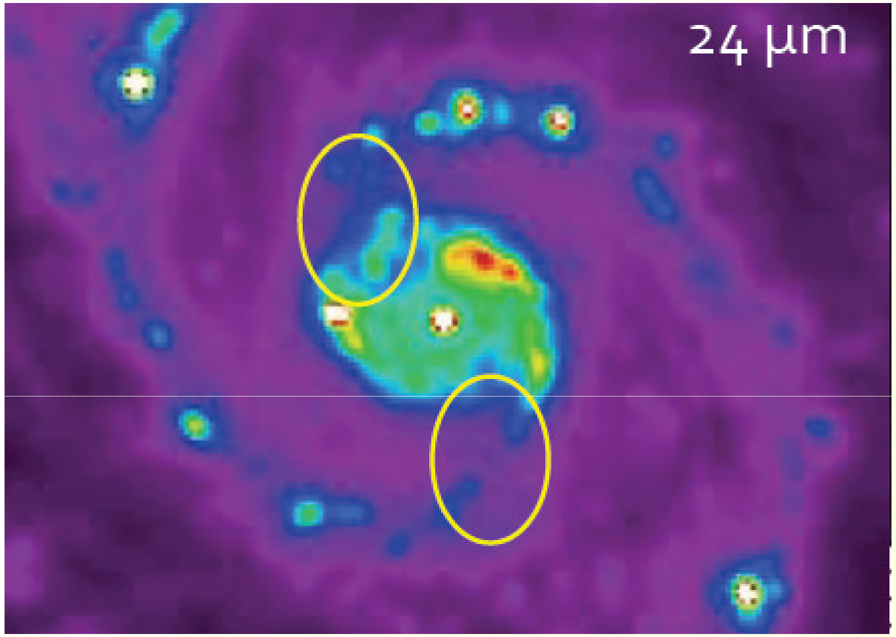


High-resolution CO clouds in M51

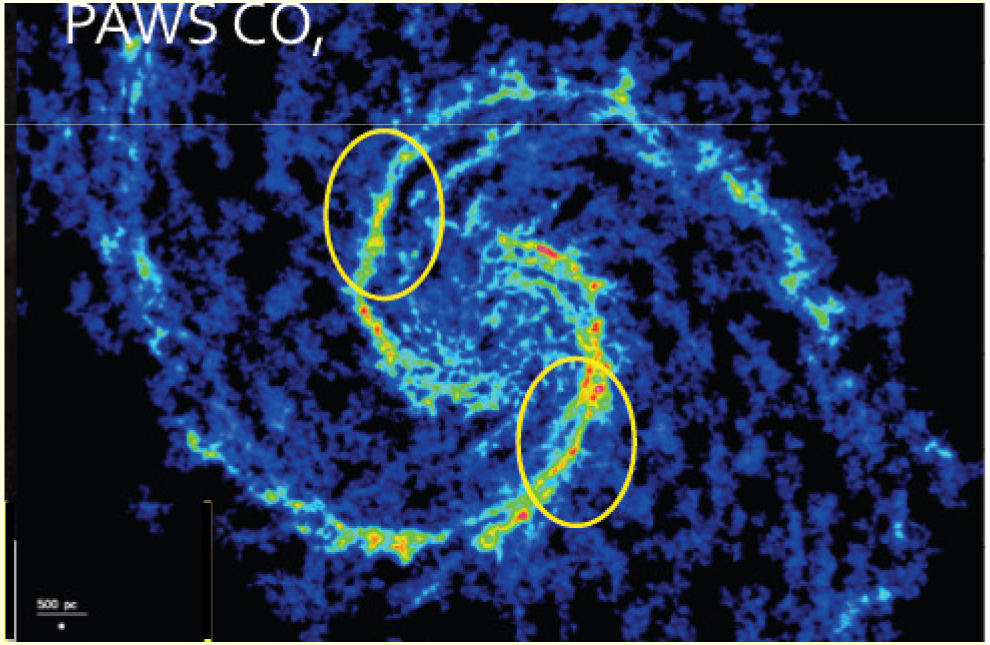
PdBI Arcsecond Whirlpool Survey



Influence of density waves



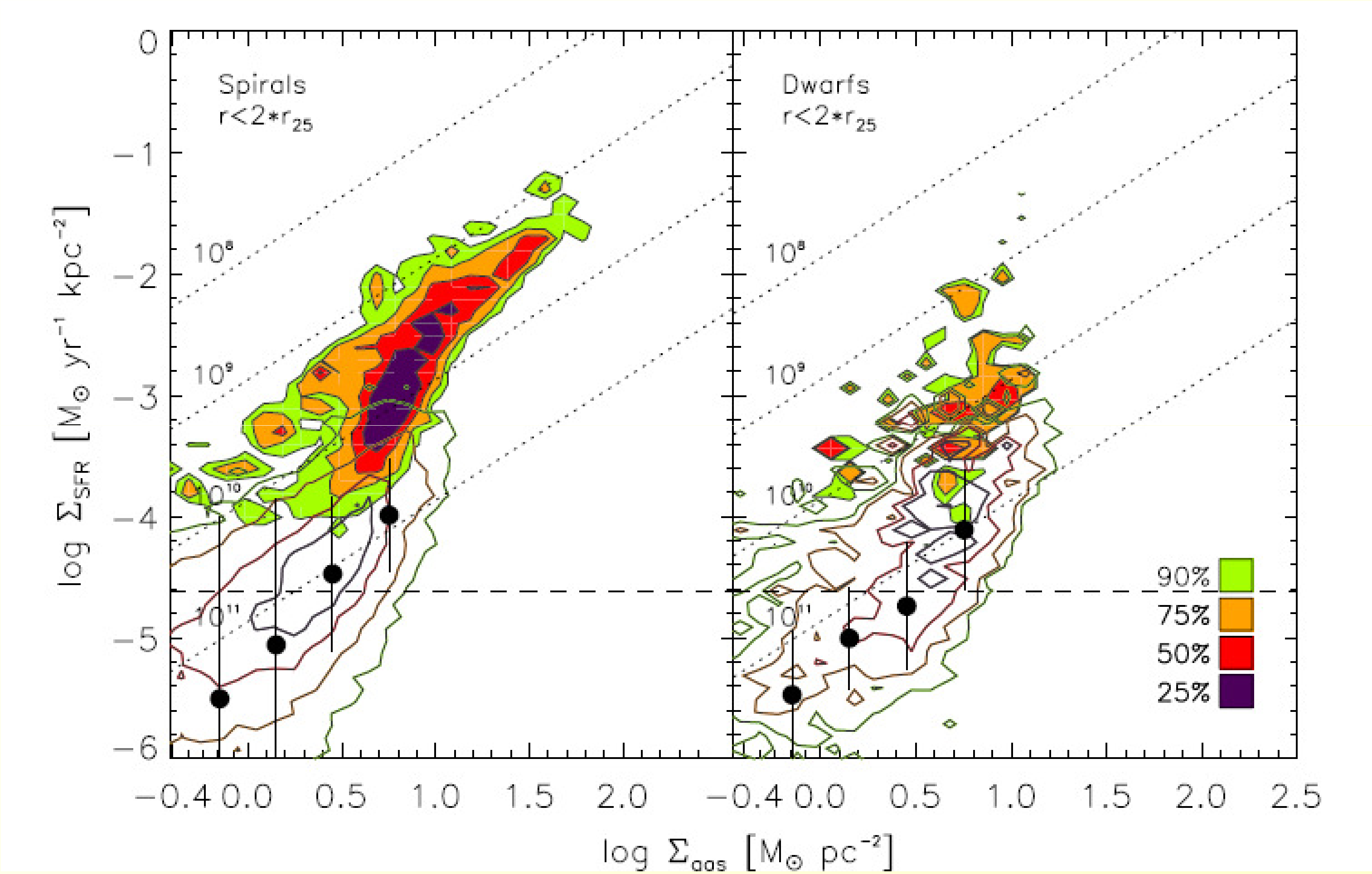
Meidt et al (2012)



The efficiency of SF is not constant over arms and rings

Also found in barred galaxies (Reynaud & Downes 1999)

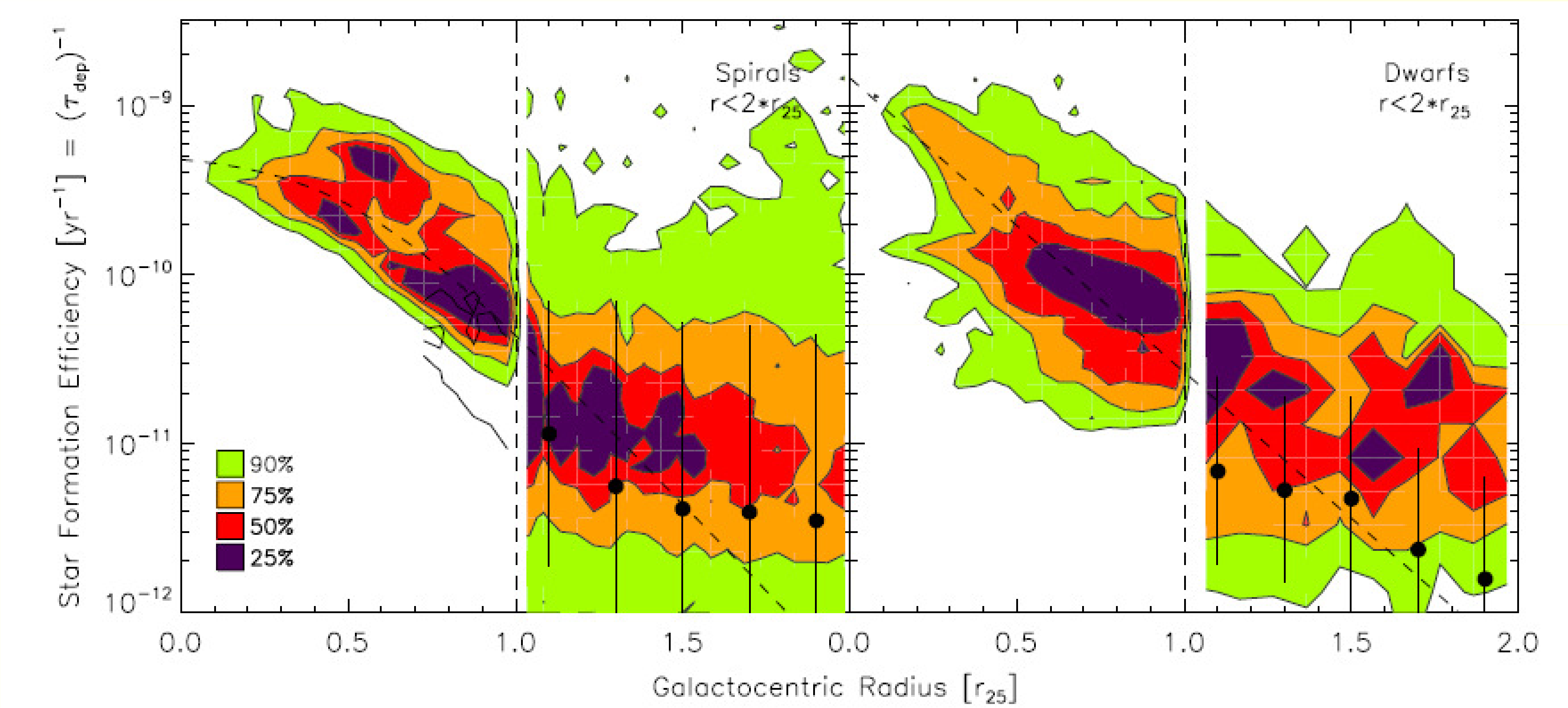
Lower SF rate in outer parts of galaxies



2 factors: --volume density (flaring)
-- metallicity: H2 formation

Bigiel et al 2010

SF efficiency in outer parts



But essentially HI, H2 is difficult to observe there

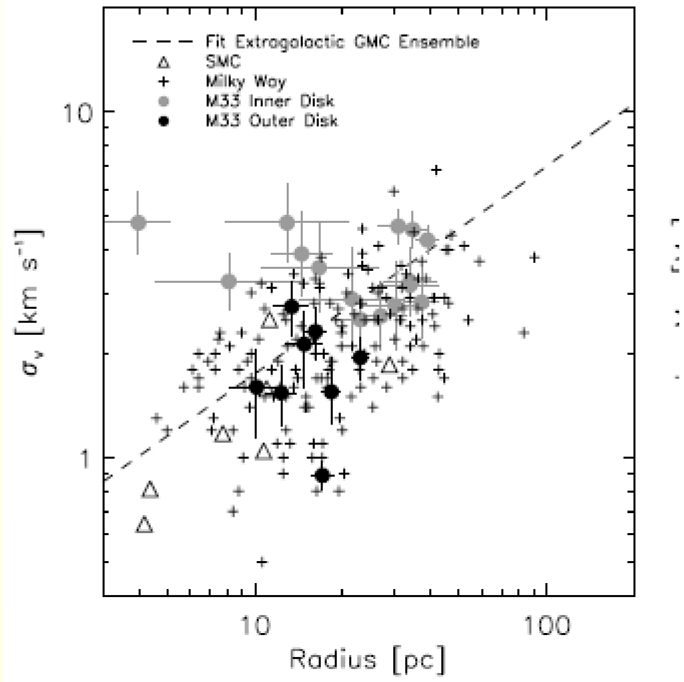
Bigiel et al 2010

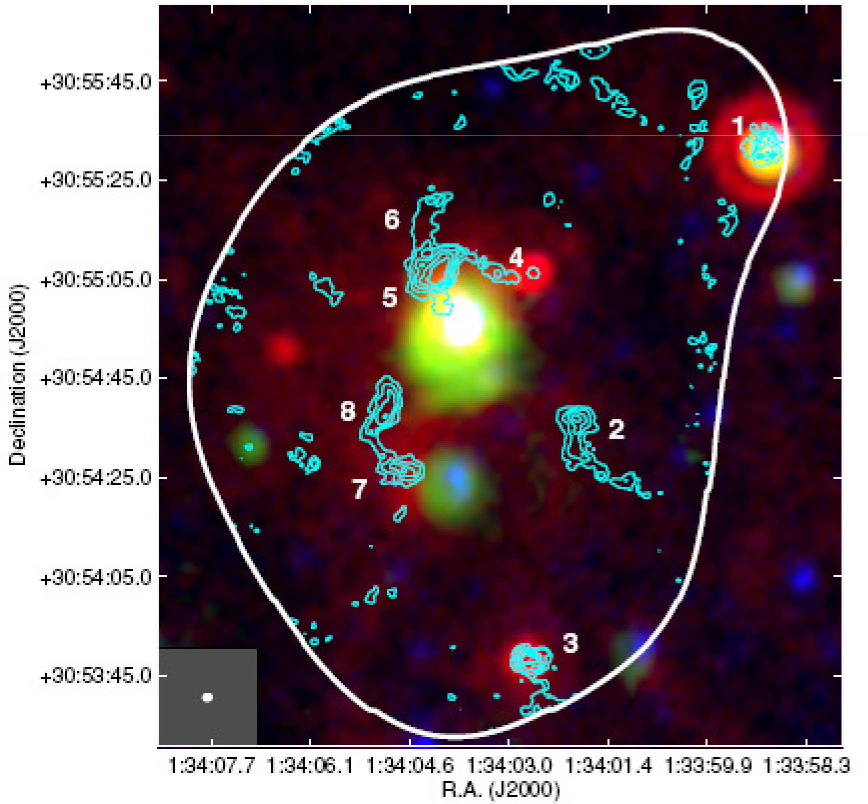
M33: outer molecular complexes

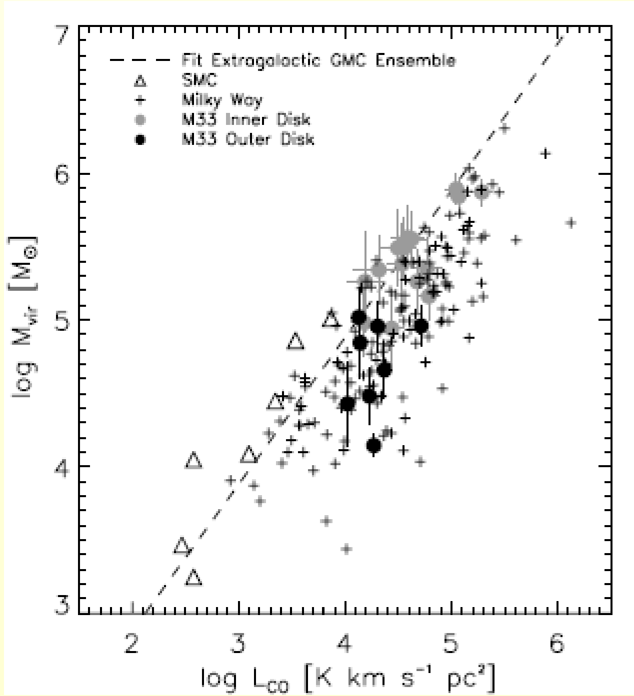
Bigiel et al 2010: CARMA

Exceptionally bright CO clouds

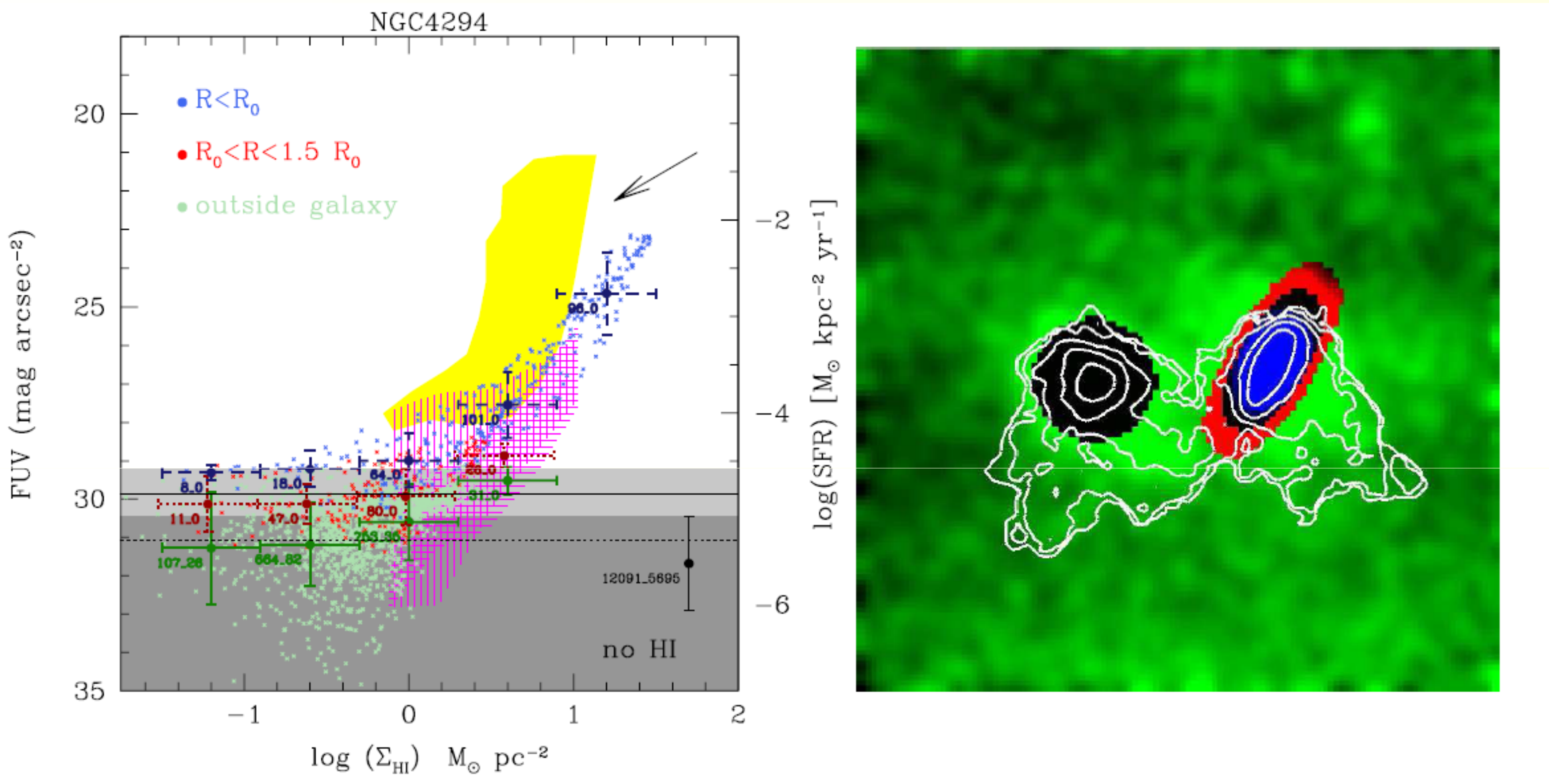
Lower X-factor than inner ones ?





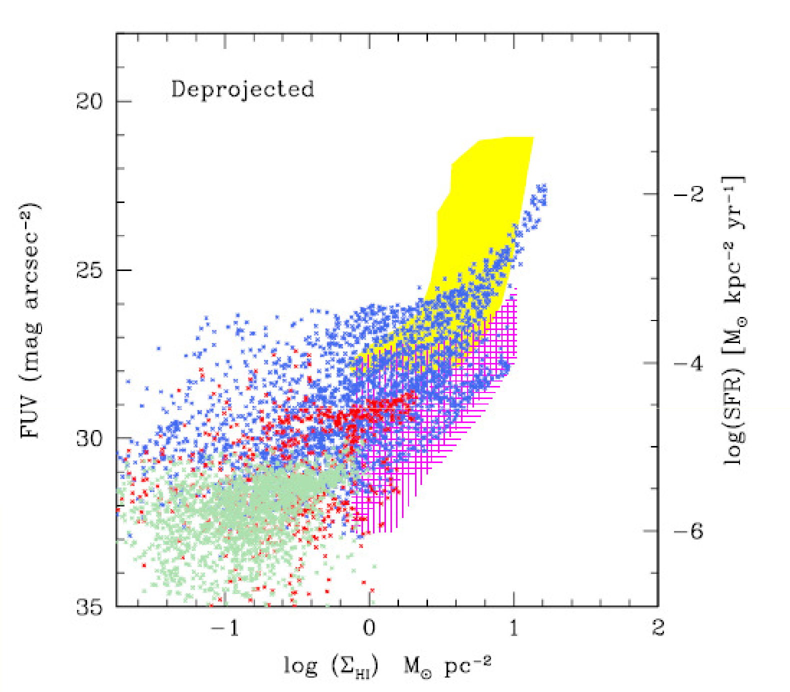


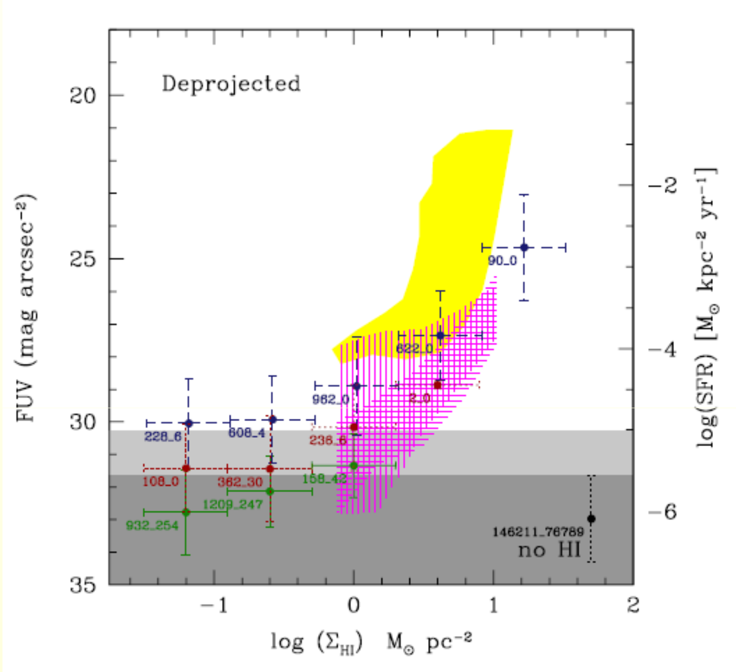
SF efficiency in stripped gas



Galaxies in with GALEX and HI
Different regions according to distance from center
Boissier et al 2012

Lower SFE in tails and outer gas



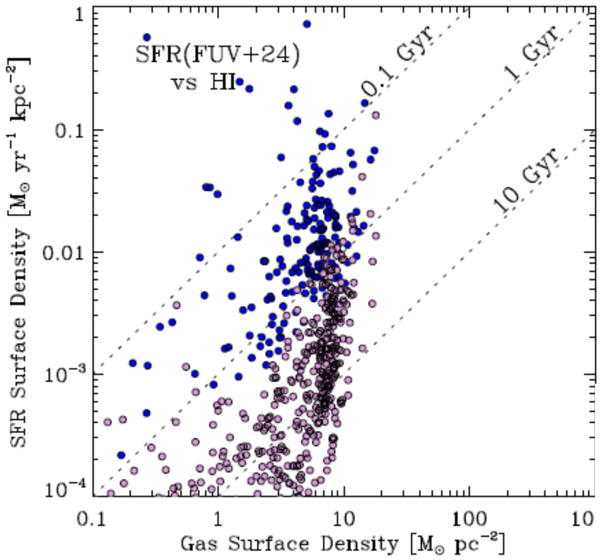


Virgo survey: GALEX and HI

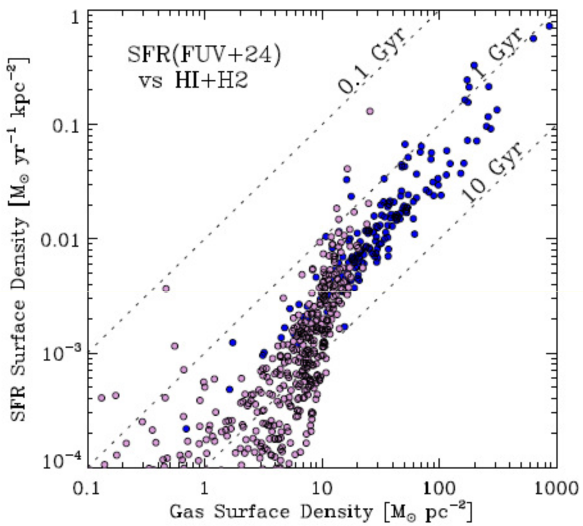
Ram-pressure stripped gas

Boissier et al 2012

ΣSFR and Σgas



HI

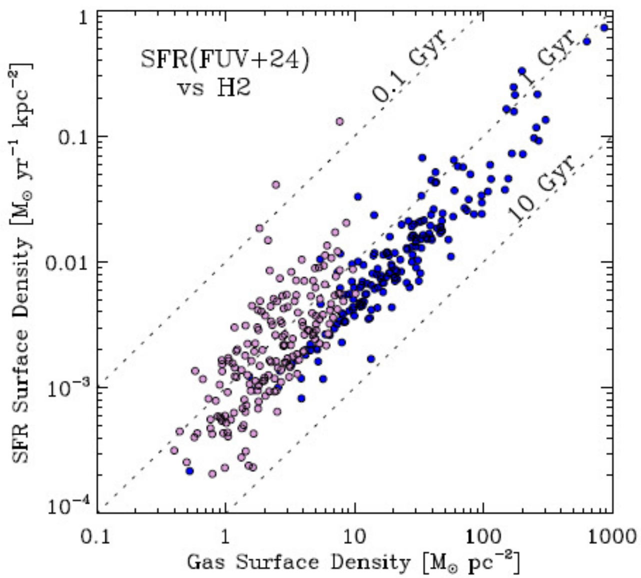


HI +H2

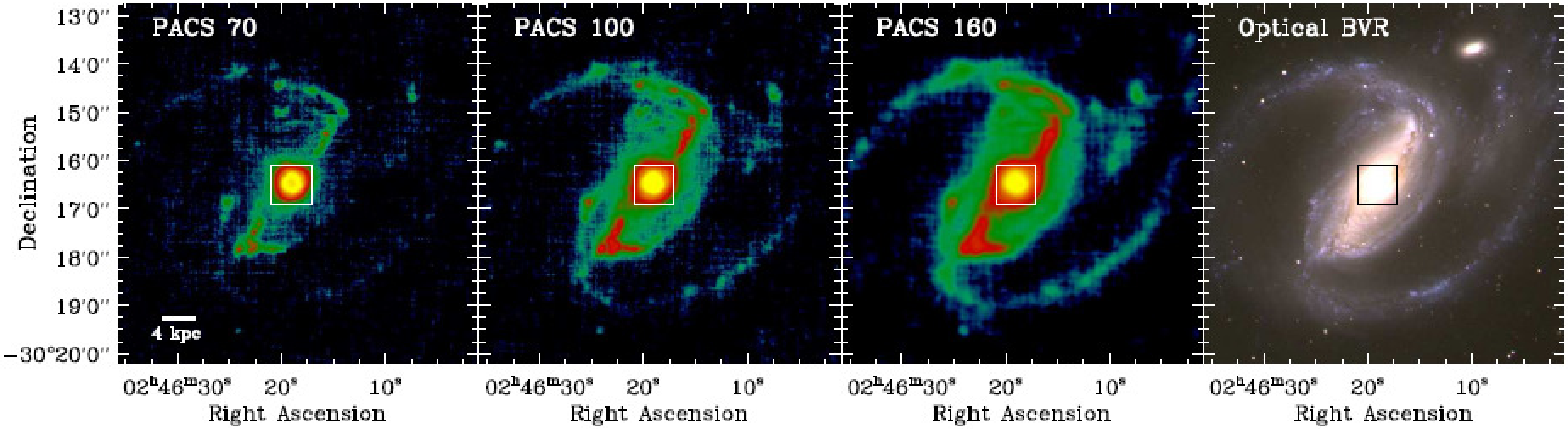
HI seems unrelated to SFR
Only H2 is a good tracer, and linear

Schruba et al 2011

H2

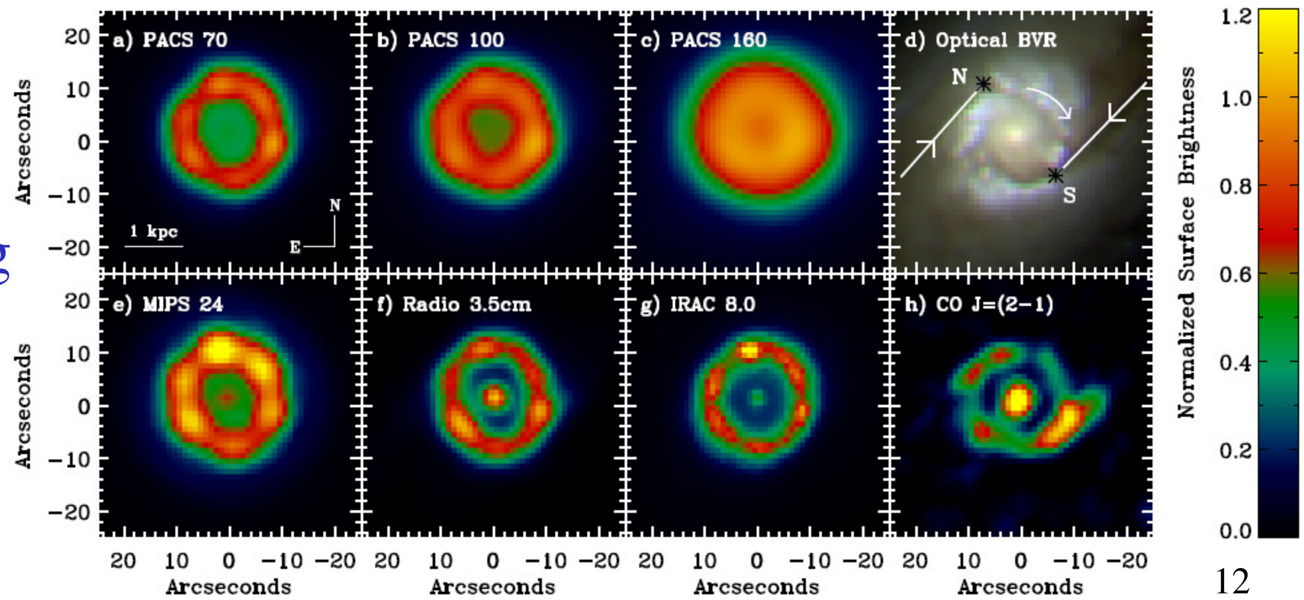


Dynamical triggers: starburst in rings



N1097

Uniformisation
of the dust heating
in the ring
ISRF or smoothing

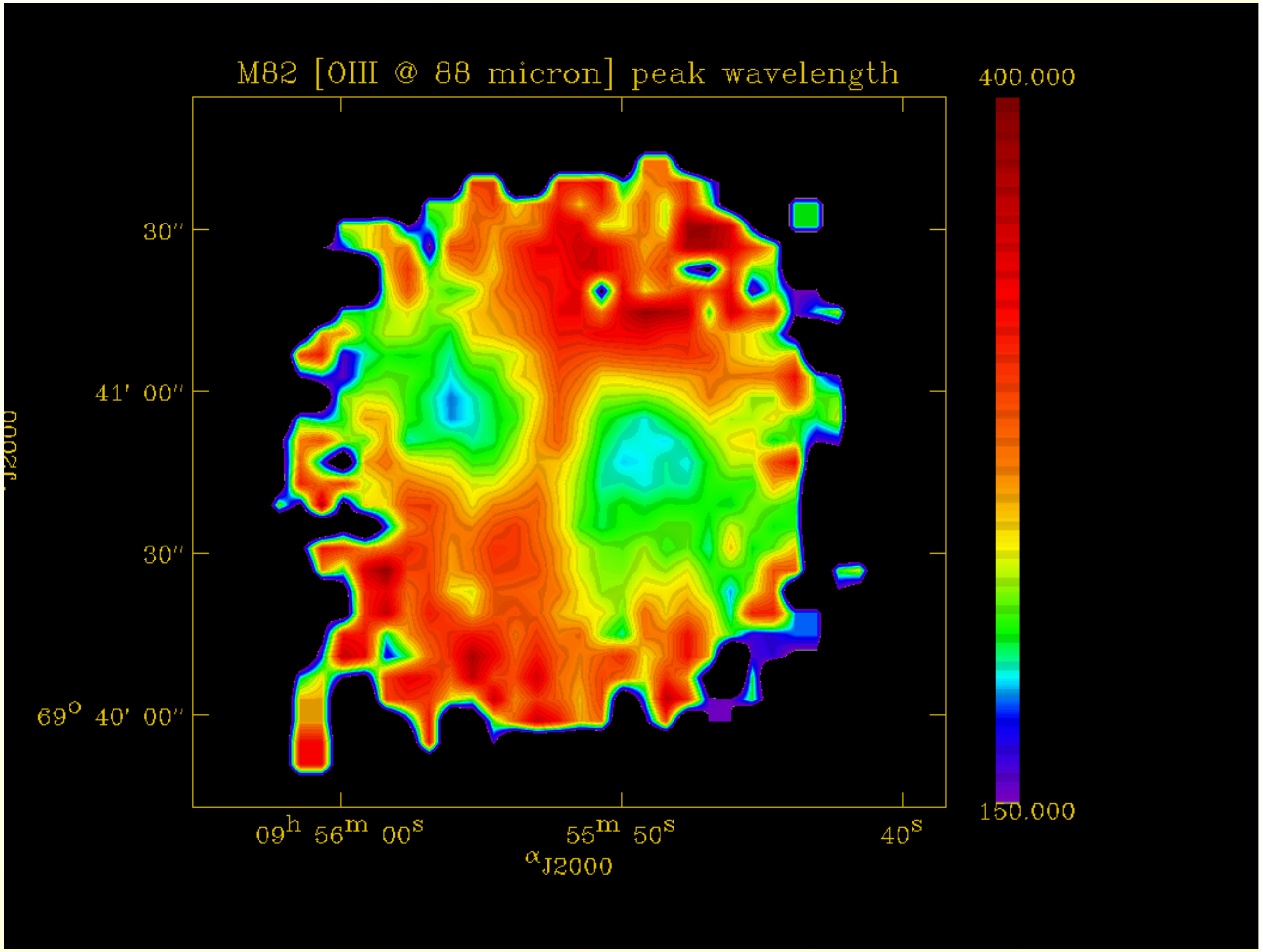


Sandstrom et al 2010

SF feedback regulation: outflows

NW expand in a free flow.
SW still in a bow shock phase

SF outflow in dwarf galaxies like M82

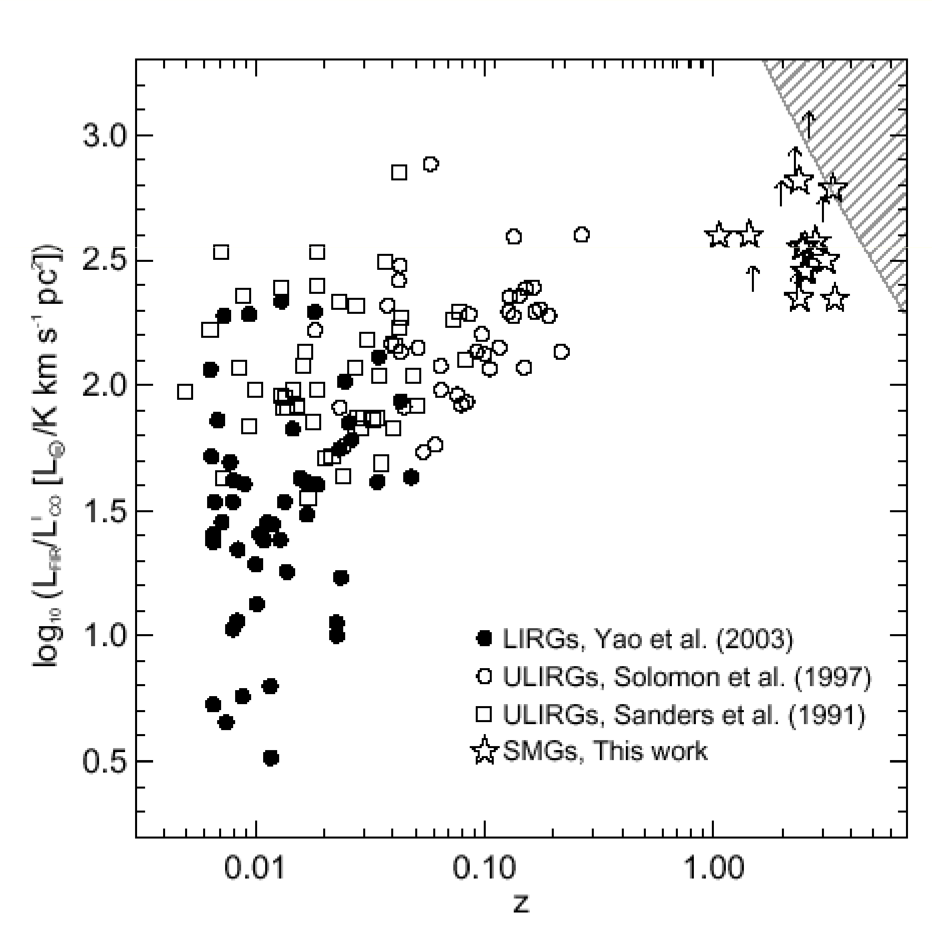


Contursi et al 2010

OIII 88μ, DV

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

Greve et al 2005



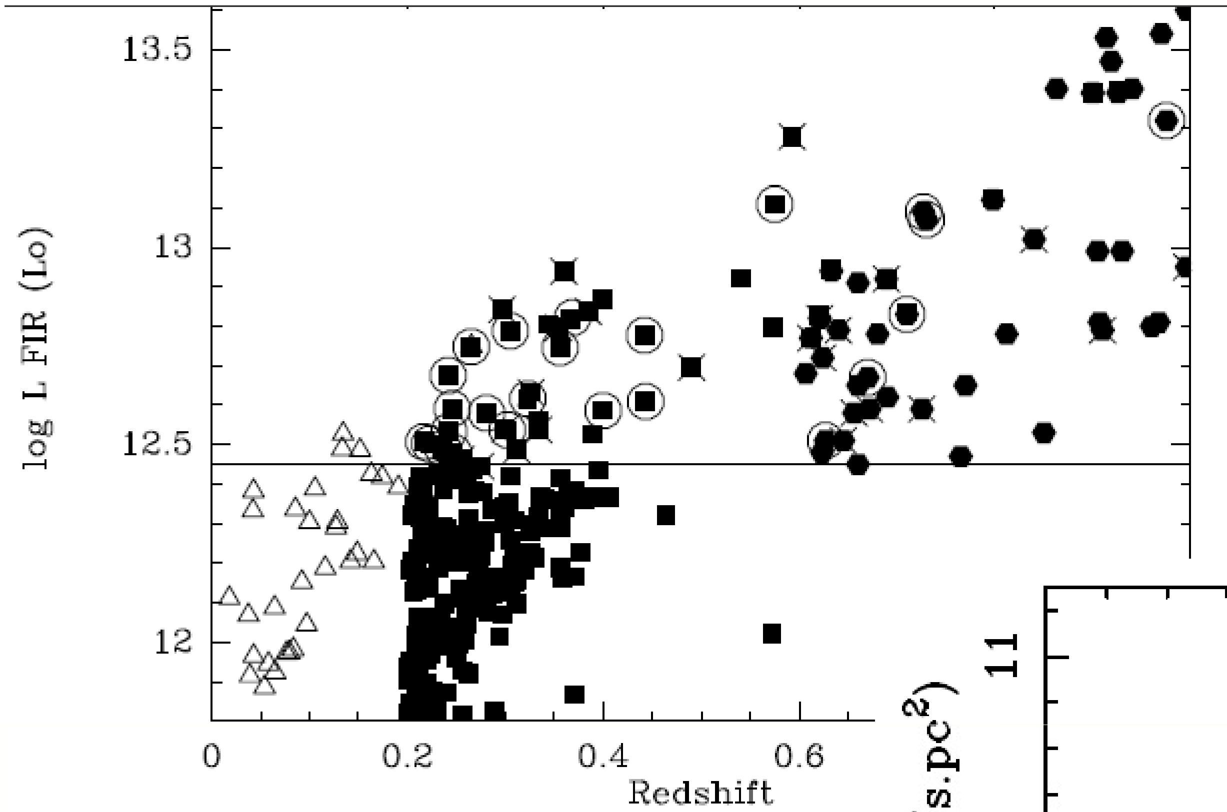
6 SMGs not detected in CO

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

Mergers without bulges?

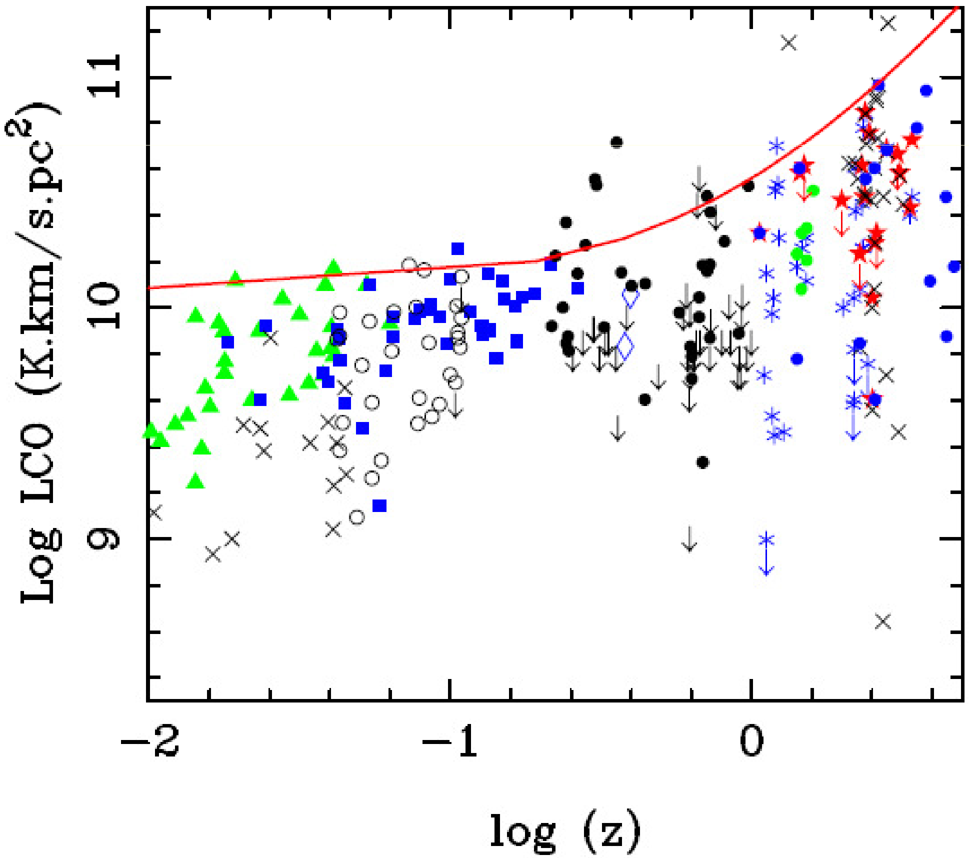
Total masses ~0.6 M_*

ULIRGs at intermediate z



Gas content increases with z

H_2/HI



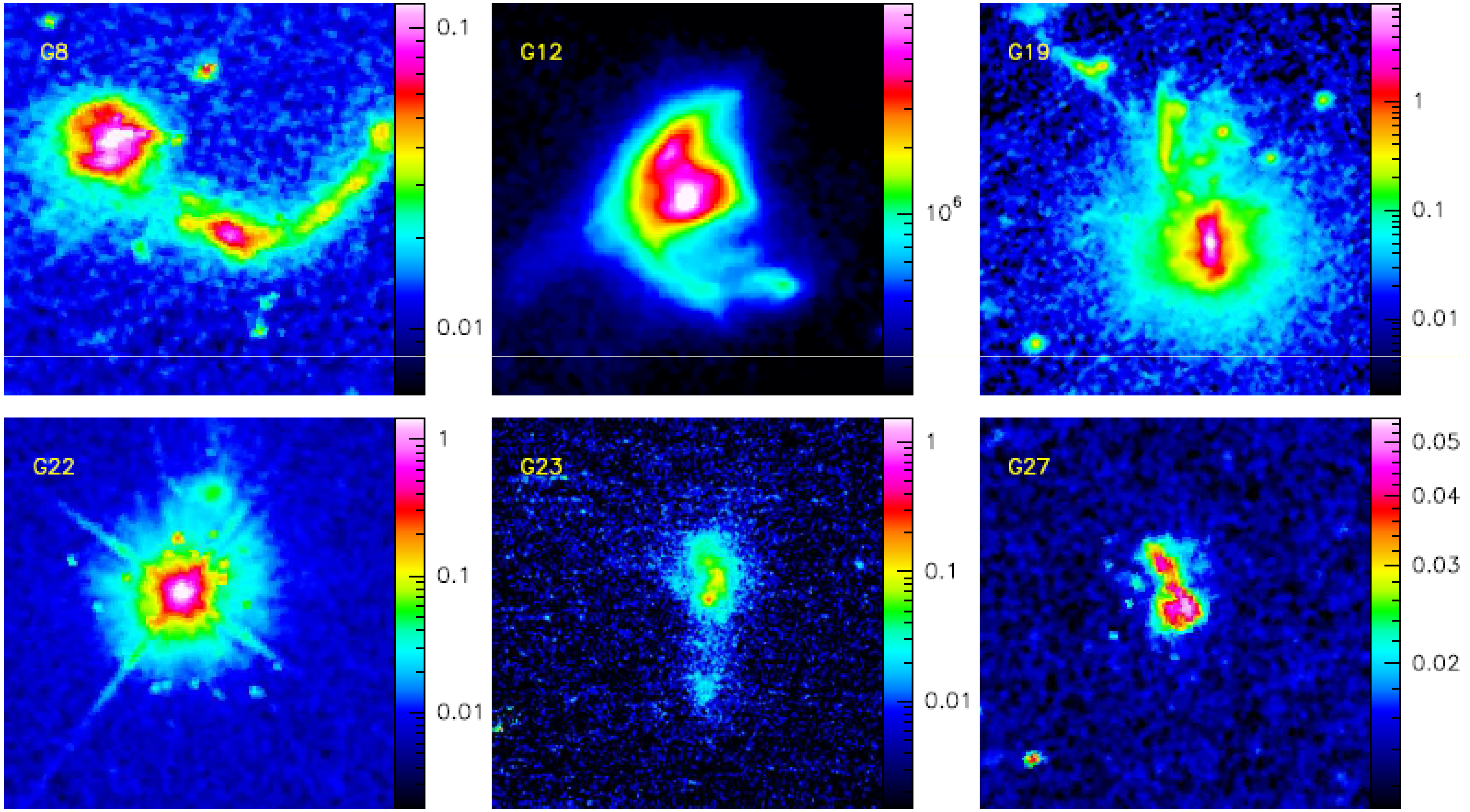
Selection of the brightest ULIRGs: 70 galaxies

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

Combes et al 2011

ULIRGs are perturbed systems

All galaxies are detected in CO

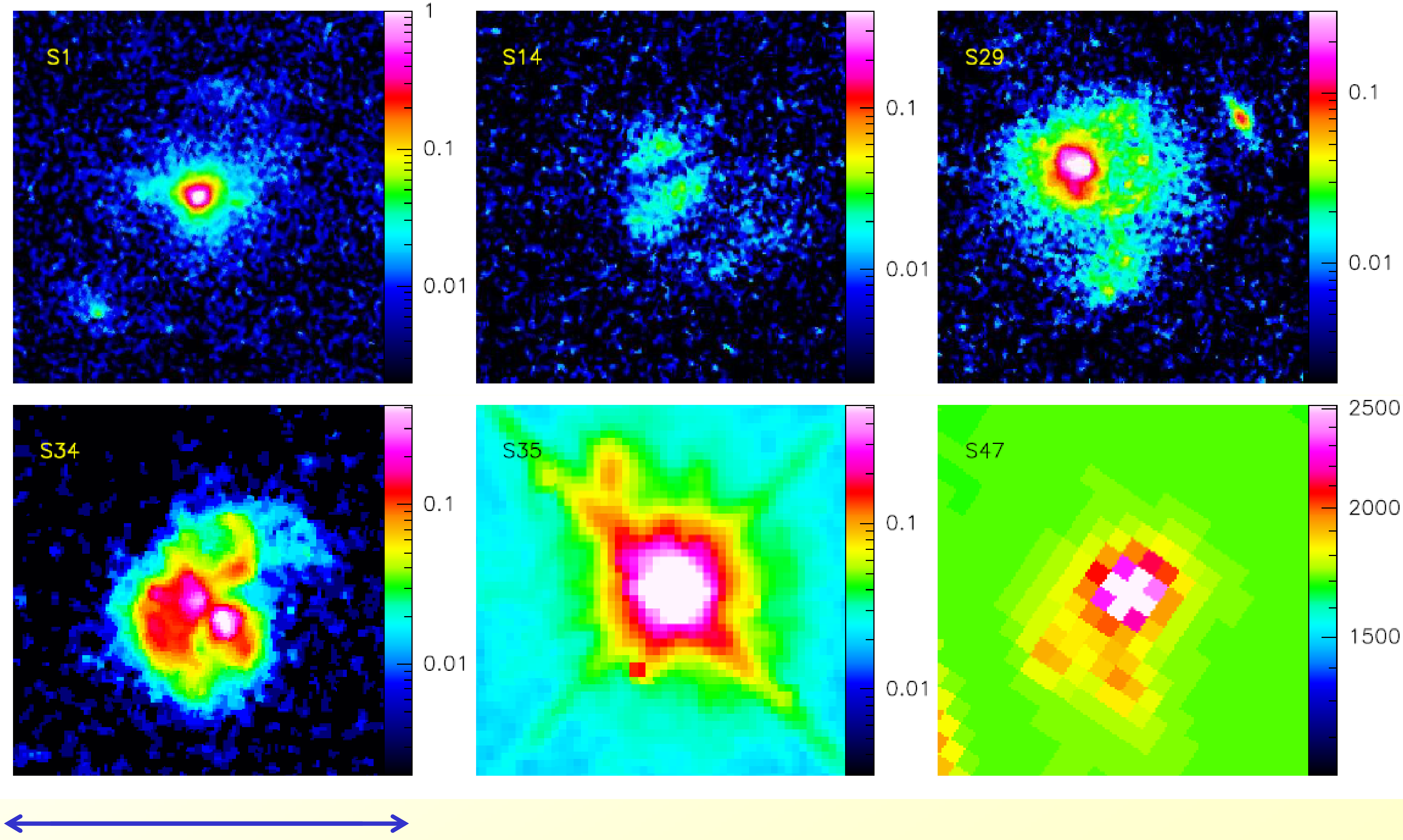


10 arcsec

0.2 < z < 0.6

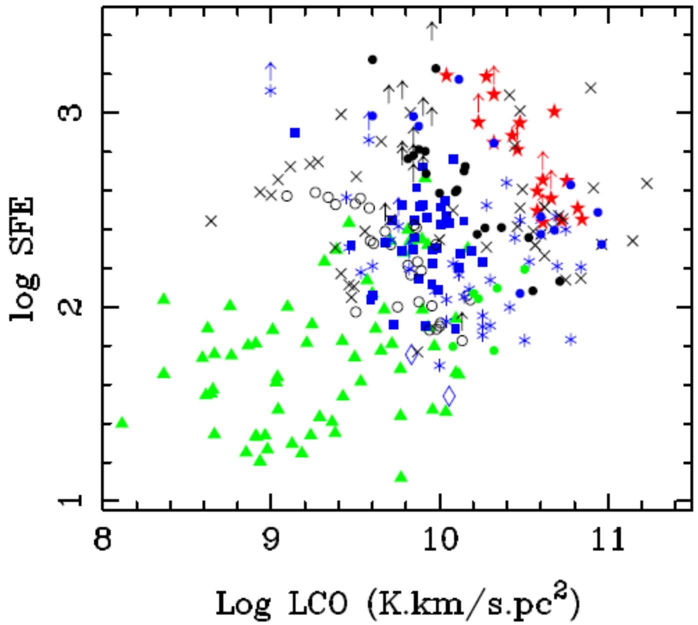
Combes et al 2011, 2012

All galaxies CO detected



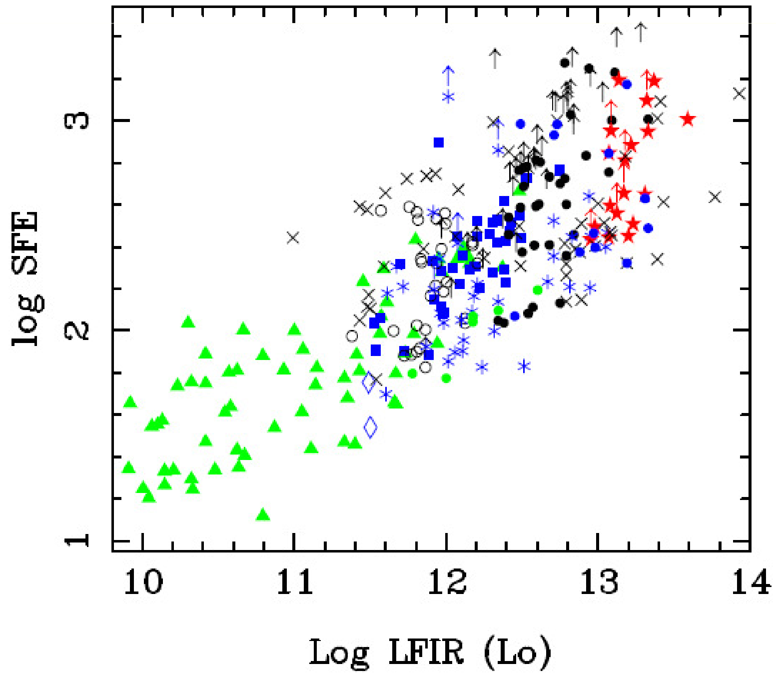
0.6 < z < 1

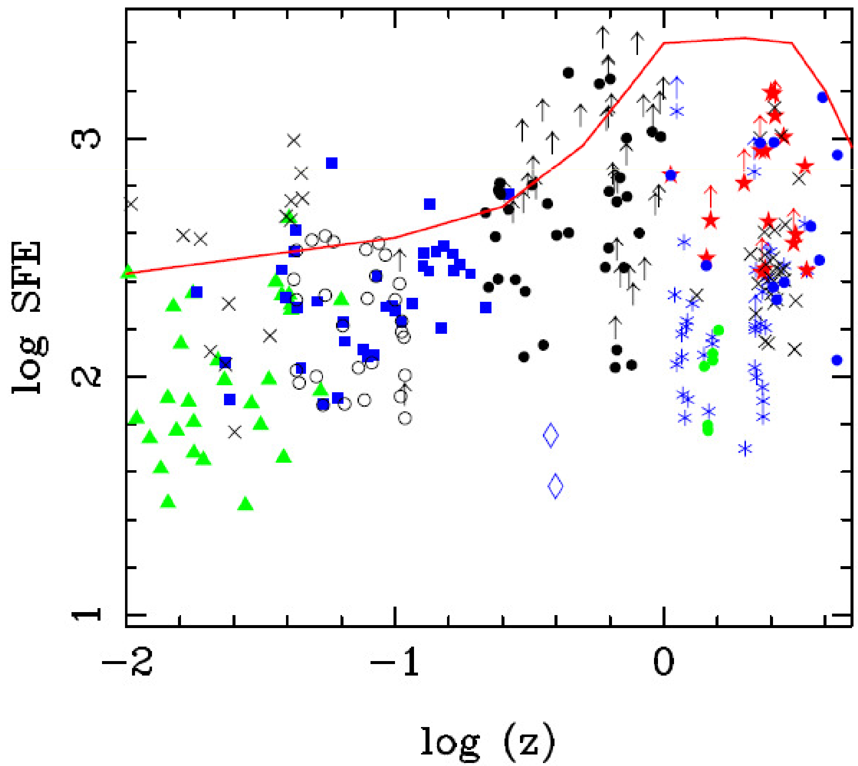
SFE versus z



Follows the SF history in relative magnitude

Hopkins & Beacom (2006),



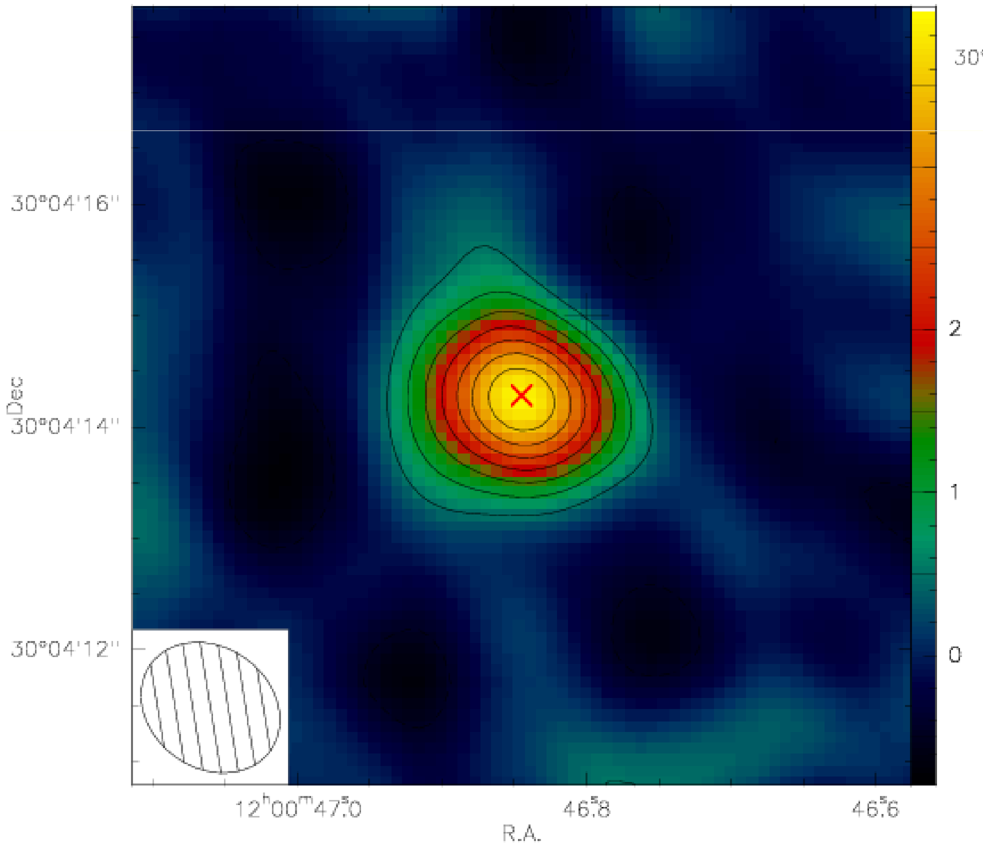


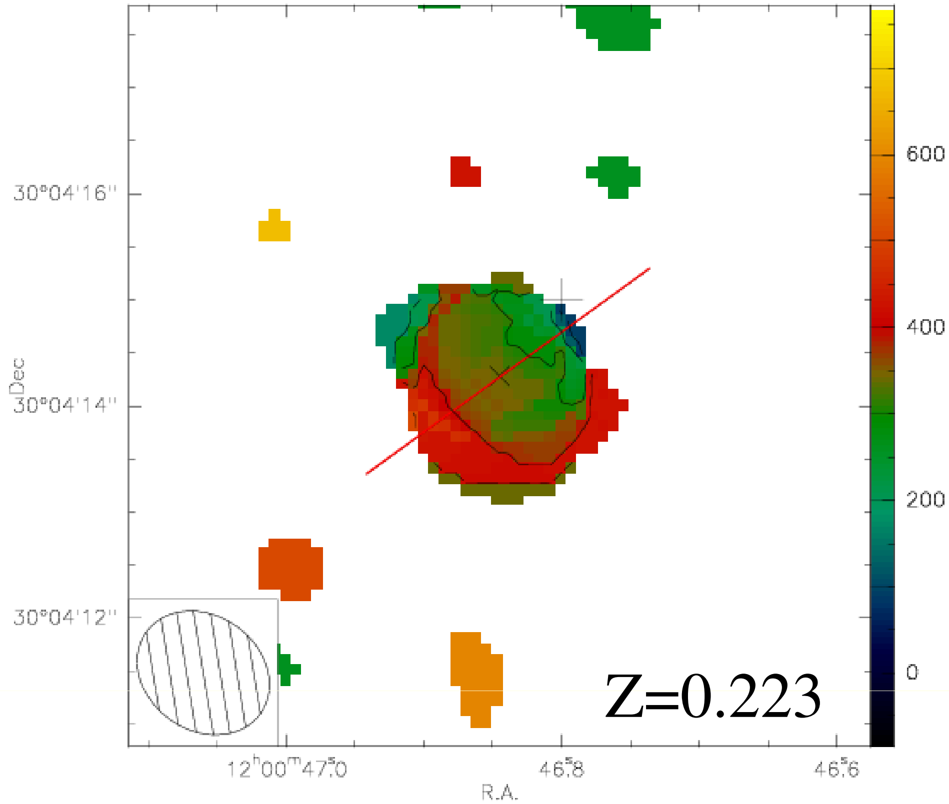
Combes et al 2011

Same XCO assumed: α=0.8 (MW α=4.6)

IRAS 11582+3020

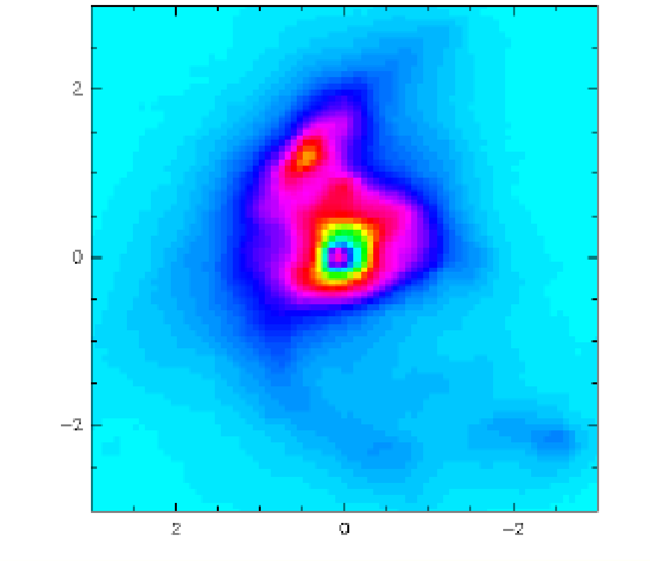
1.2 10^{10} Mo with 30m
6 10^{9} Mo with PdB
Half of the flux lost
➔Extended structure
At 7-15" ~ 35 kpc





2 components
1.5kpc radius nuclear disk
➔ nuclear starburst
+ extended disk up to 20-30kpc diameter, would correspond to the merger optically

G12 with high resolution: PdBI

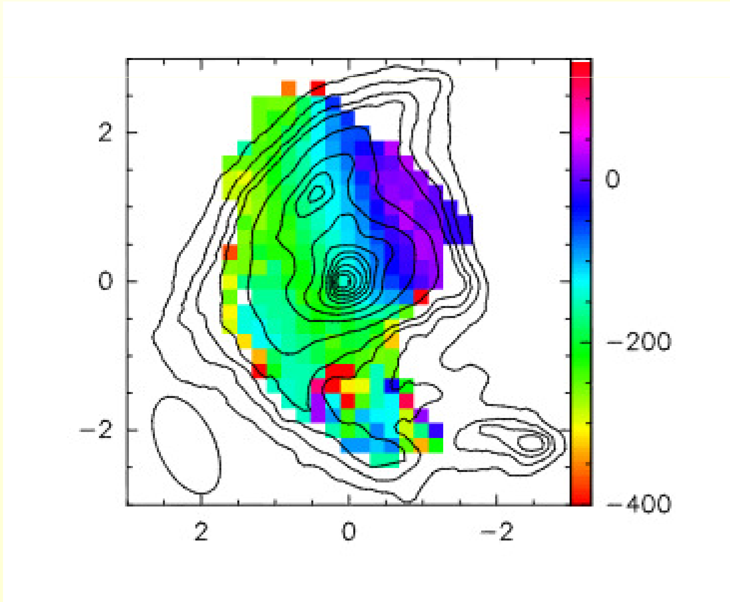


G12: HST-NICMOS image
Z=0.2417
1"~3.7kpc

Extended ~20kpc
➔Some of these objects could have a large XCO

Excitation: some of the objects have a low H2 density

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



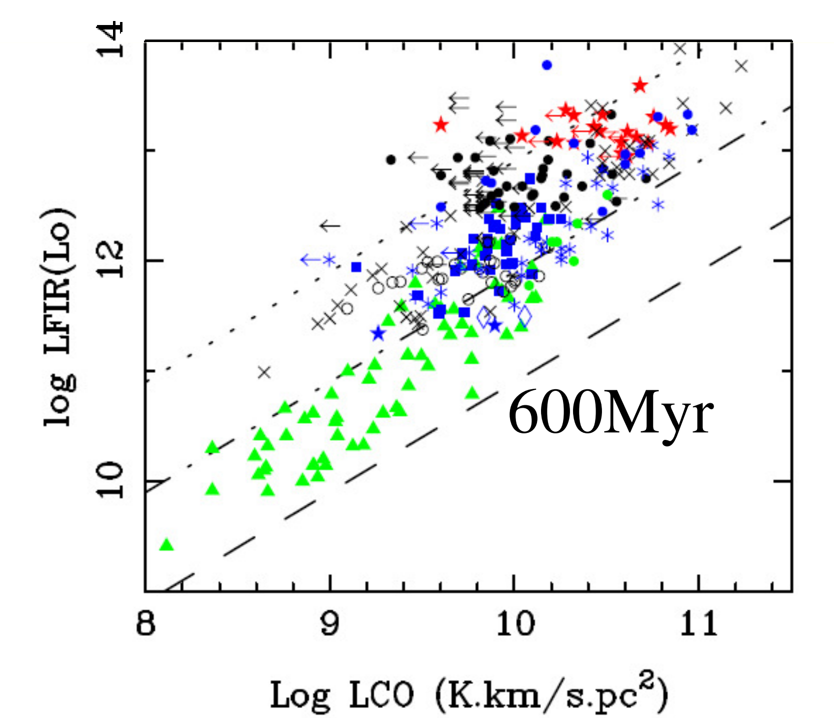
Velocity gradient resolved

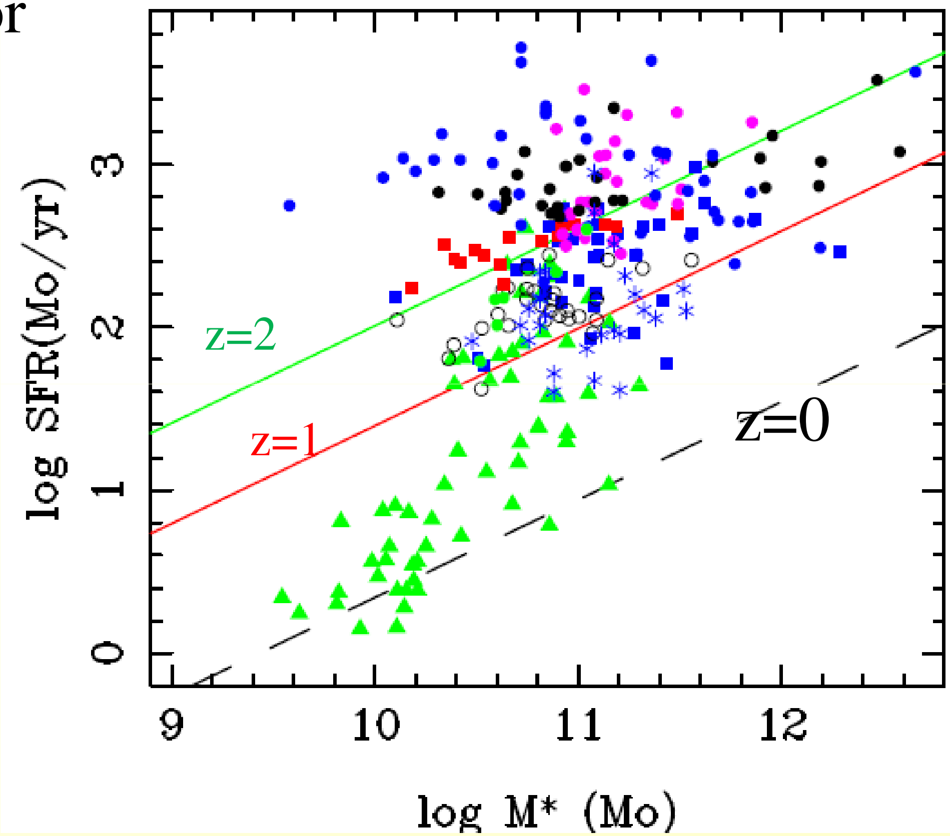
Combes et al 2012

Depletion time, stellar mass

Assuming ULIRG conversion factor
MH2= 0.8 L'CO

3curves t_{dep}= 6, 60, 600 Myr

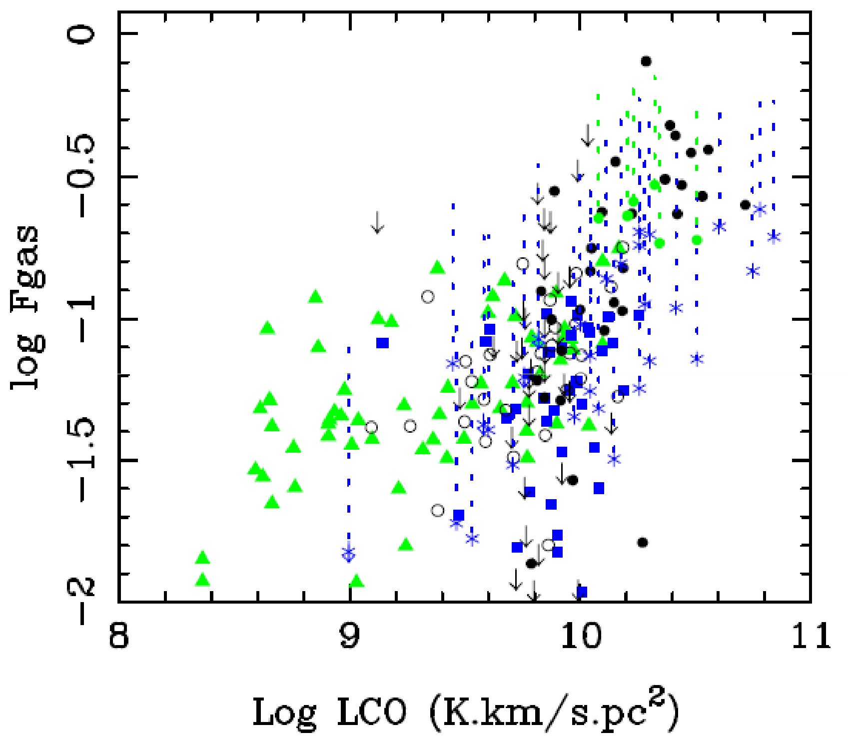




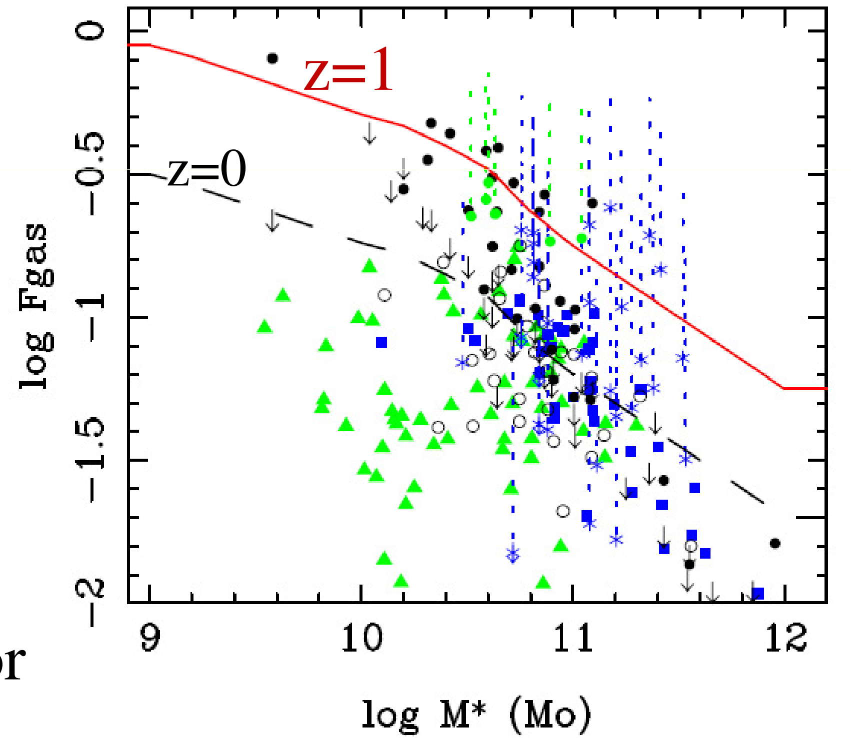
Stellar mass obtained by SED fitting
SDSS ugriz, 2MASS JHK, IRAC 3-4μm

Gas fraction vs LCO, and vs Ms

Fgas= MH2/(MH2+Ms)

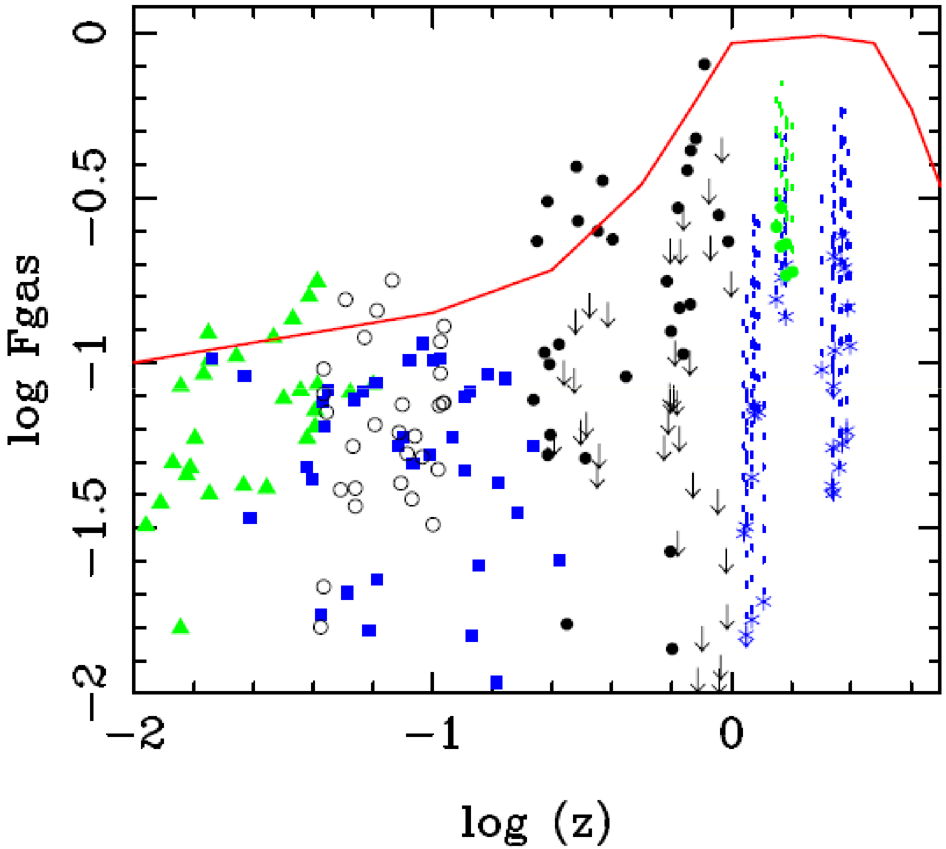


Curves expected from numerical simulations (Dave et al 2011)



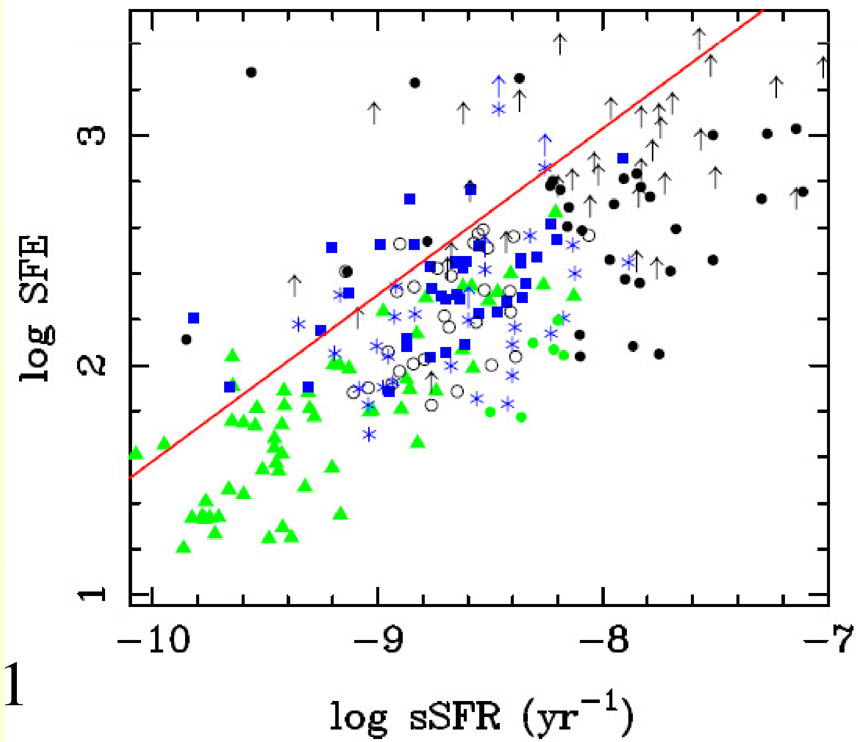
Assuming the same conversion factor
MH2= α L'CO, α=0.8
If α=4.6, dotted lines (MW standard)

Gas fraction vs z: sharper evolution than SFE



Fgas= MH2/(MH2+Ms)

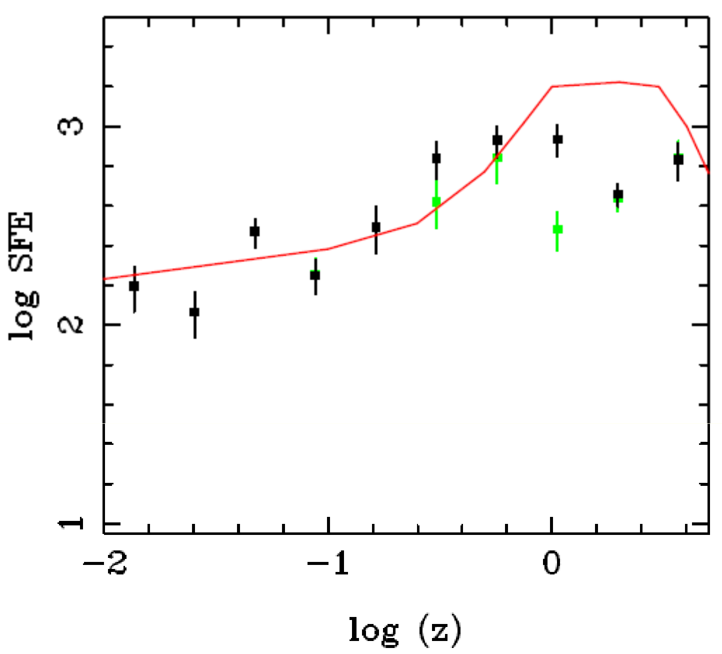
May be the main factor behind the strong evolution of SFRD

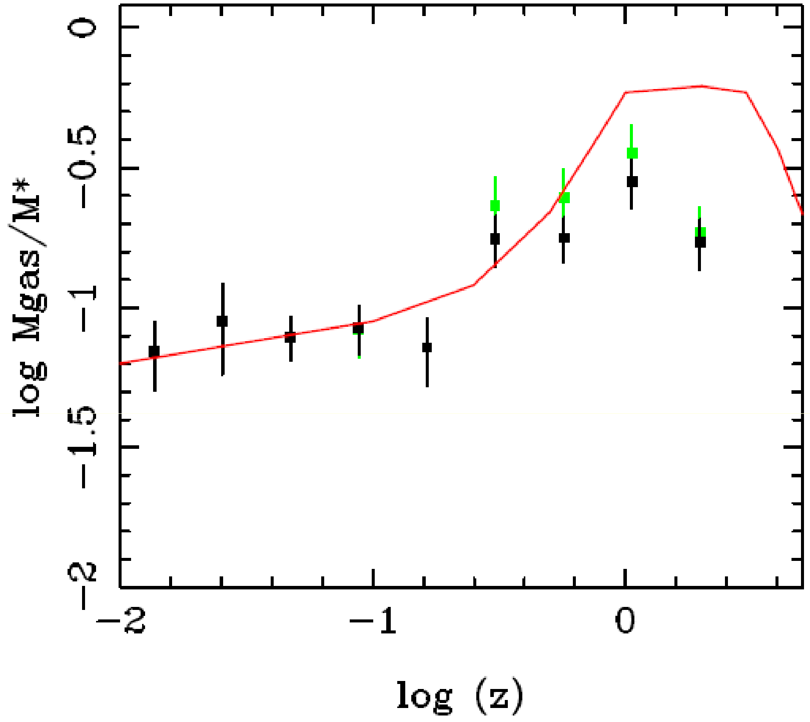


SFE versus sSFR

Red line: Saintonge et al 2011

Key factors to explain SFRD



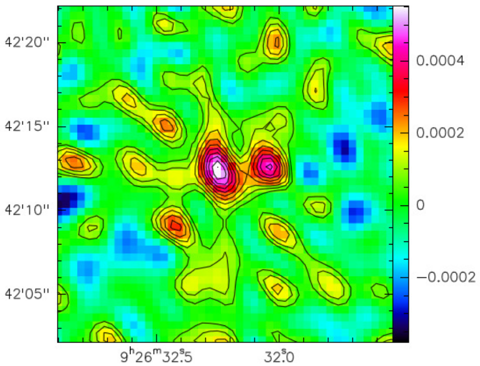


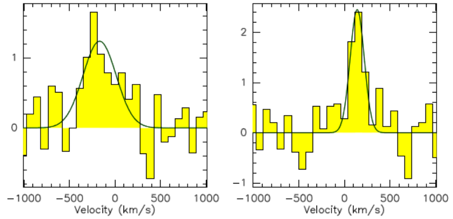
Star formation efficiency and gas fraction

Both contribute, may be the gas fraction is dominant

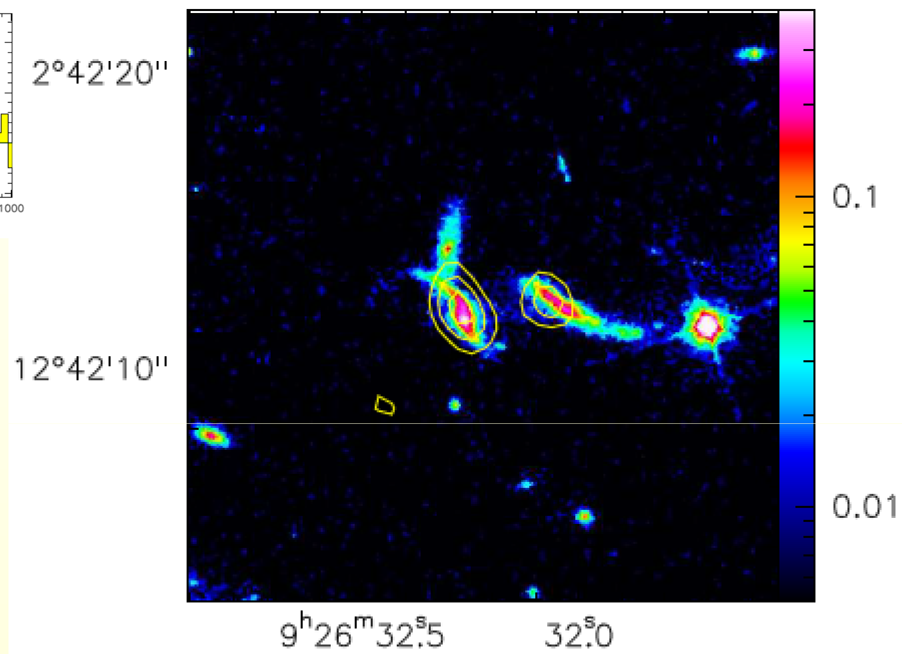
But the SFE should also be increased due to more violent dynamics

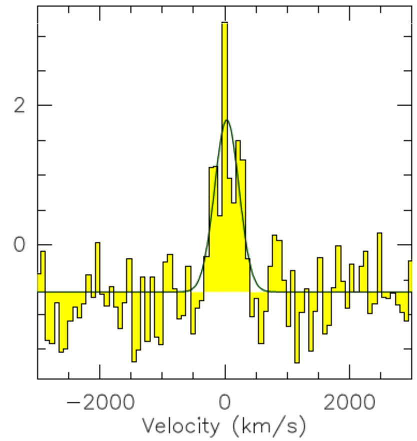
Intermediate z galaxy clusters

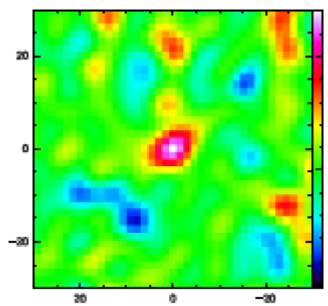




CL0926+1242
Z=0.489







CL1416+4446
Z=0.4

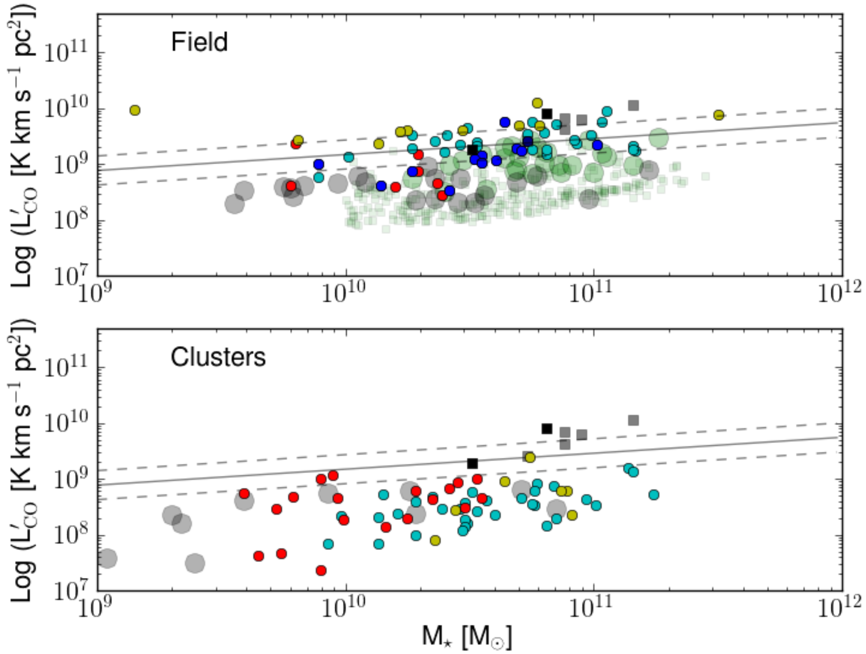
Three galaxies detected in CO
in the heart of the clusters
(previously only in the outer parts
(Geach et al 2009, 2011)

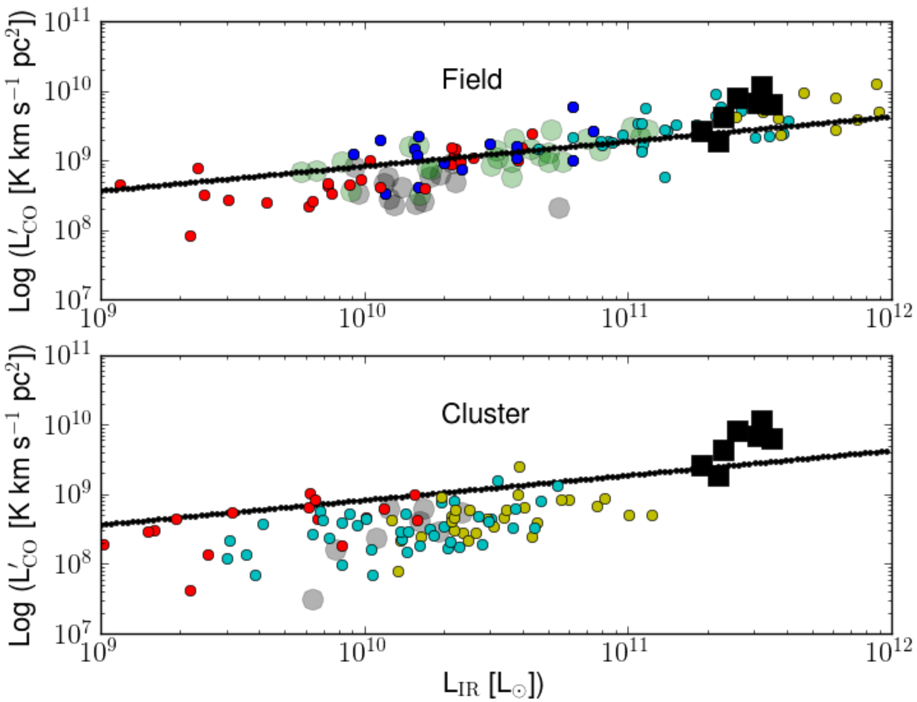
Jablonka, Combes et al 2012

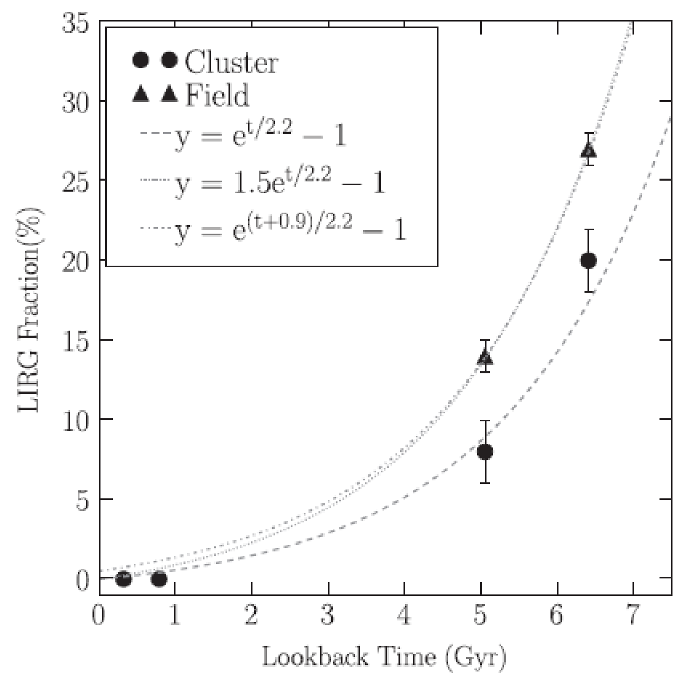
Field-Cluster comparison

The LIRG fraction falls exponentially (Finn et al 2010)

At some z, galaxies are not yet quenched



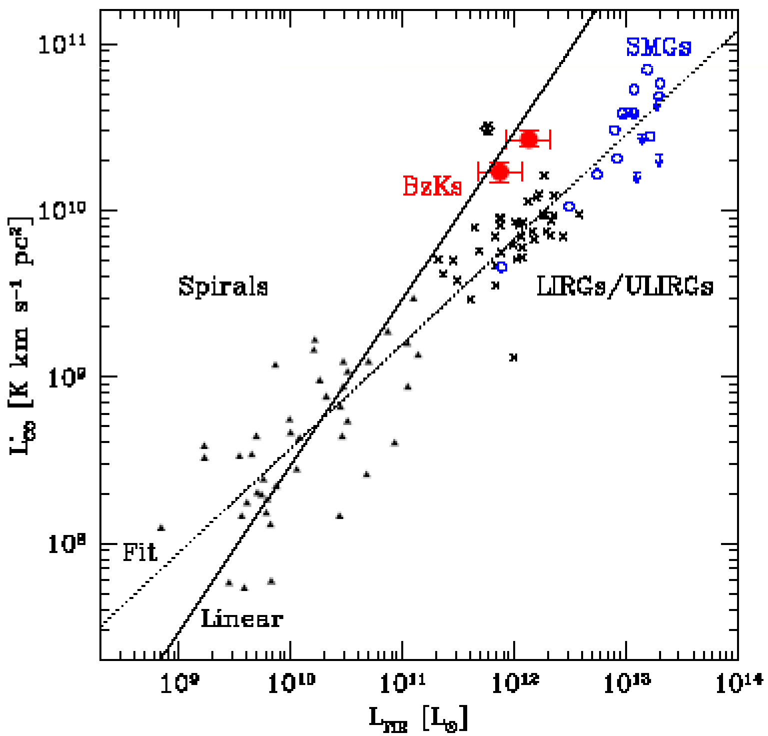


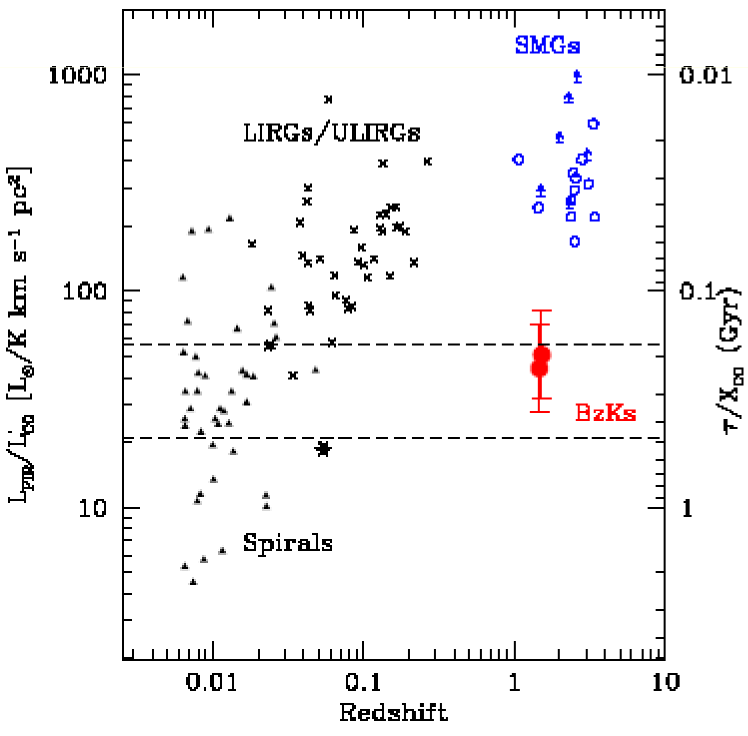


Low efficiency of star formation

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

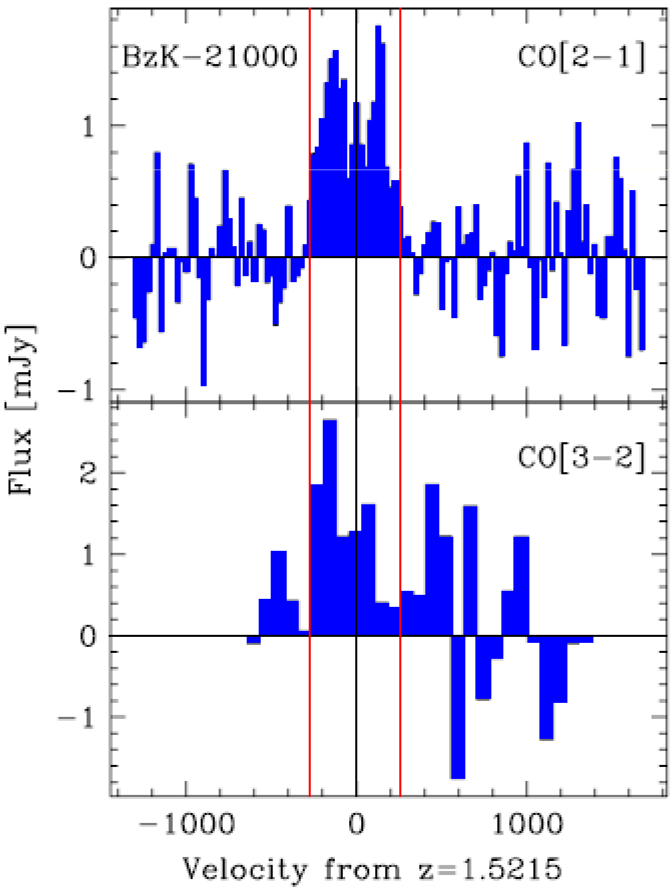


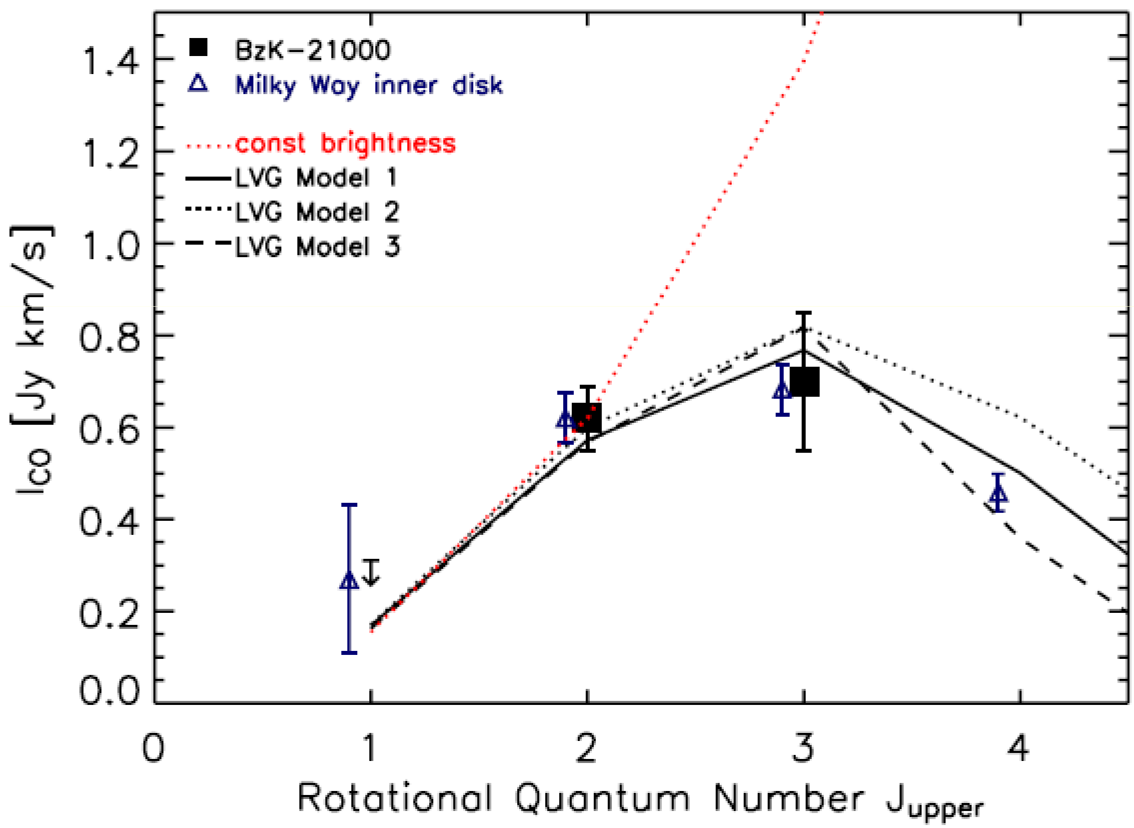


Low excitation, MW-like

In BzK-21000, z=1.52, weak CO(3-2)

➔ CO conversion factor 4.5 x that of ULIRGS (MH2/LCO)

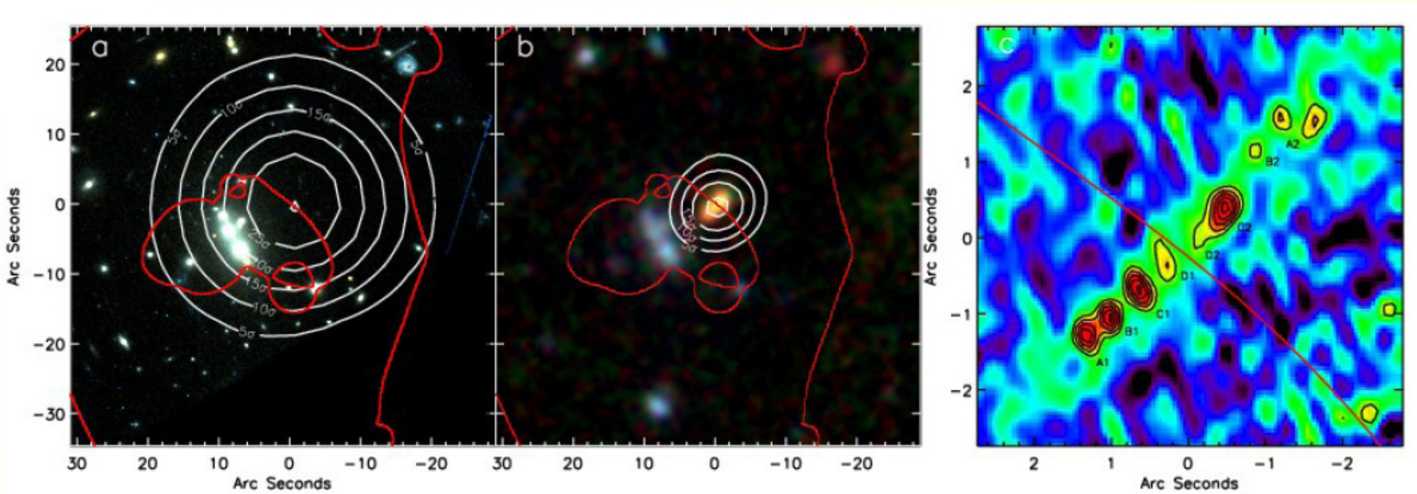




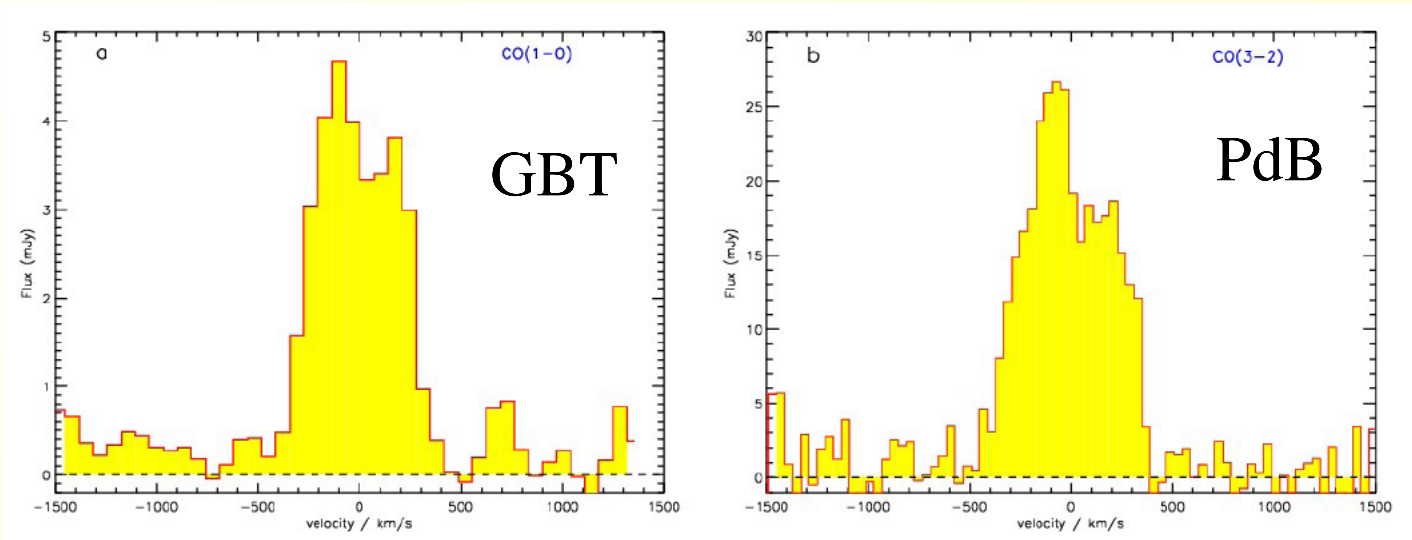
Dannerbauer et al 2009

Lensed SF galaxy z=2.33

z=2.326
Critical curves



APEX 850μ onHST, 350μ on IRAC SMA



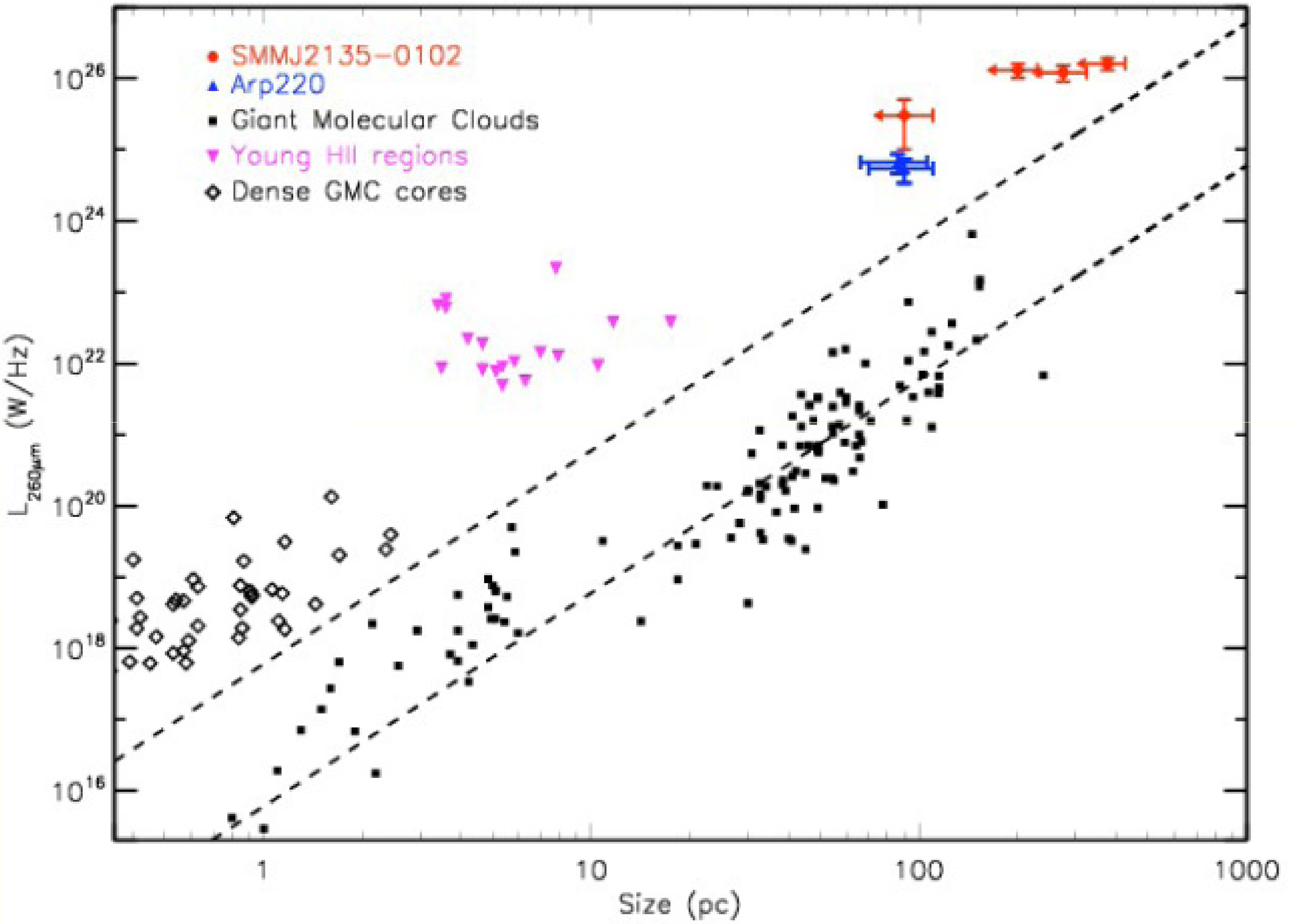
Swinbank et al 2010

Resolving GMC at z=2.33 ?

Size of SF regions

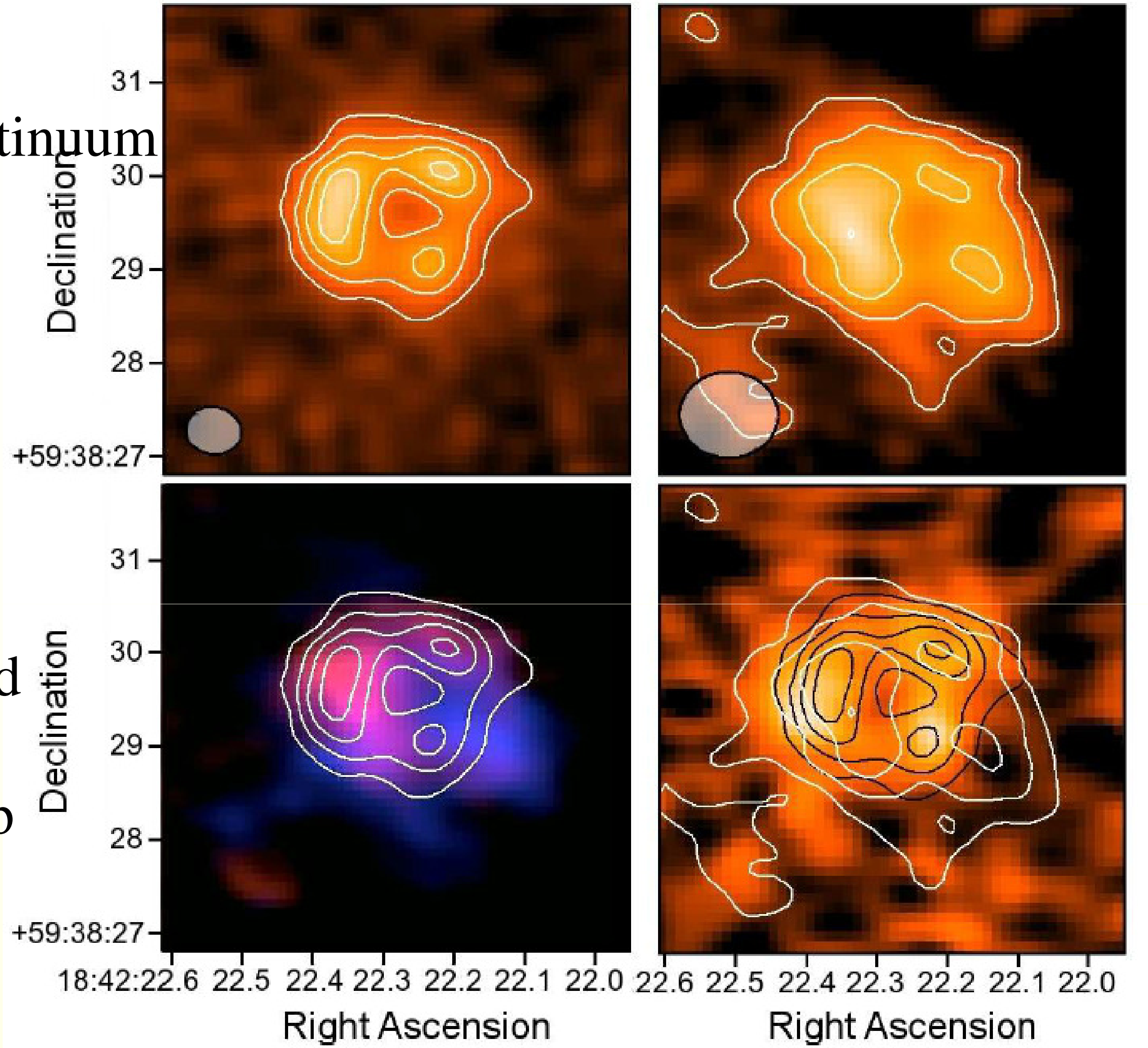
100 times more luminous at a given size than MW GMC

Magn=32



Swinbank et al 2010

Continuum



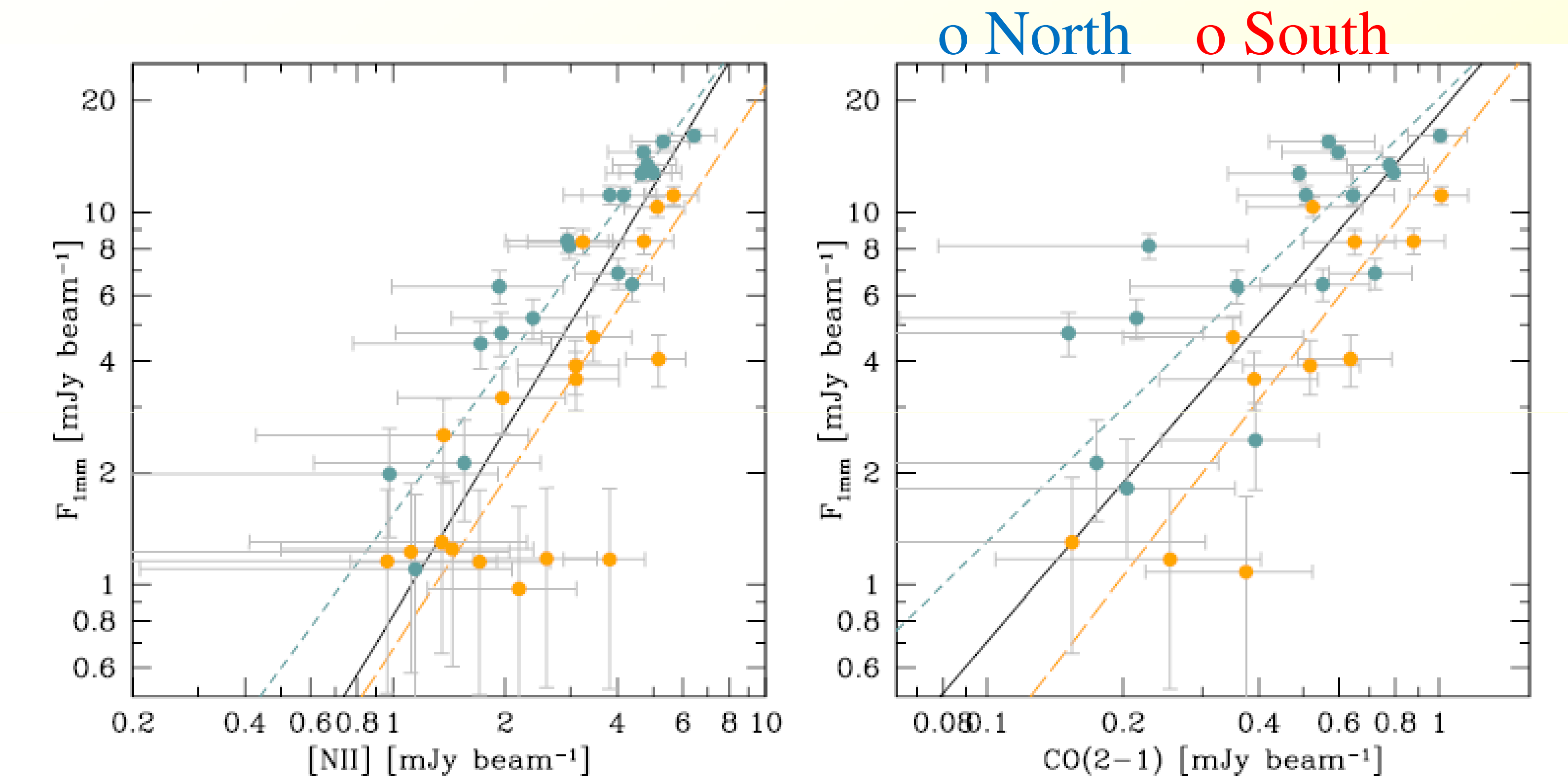
[NII]205μ

Red and
Blue
V-comp

[NII], CO
continuum

MM18423+5938 Decarli et al 2012

Resolved Kennicutt-Schmidt law

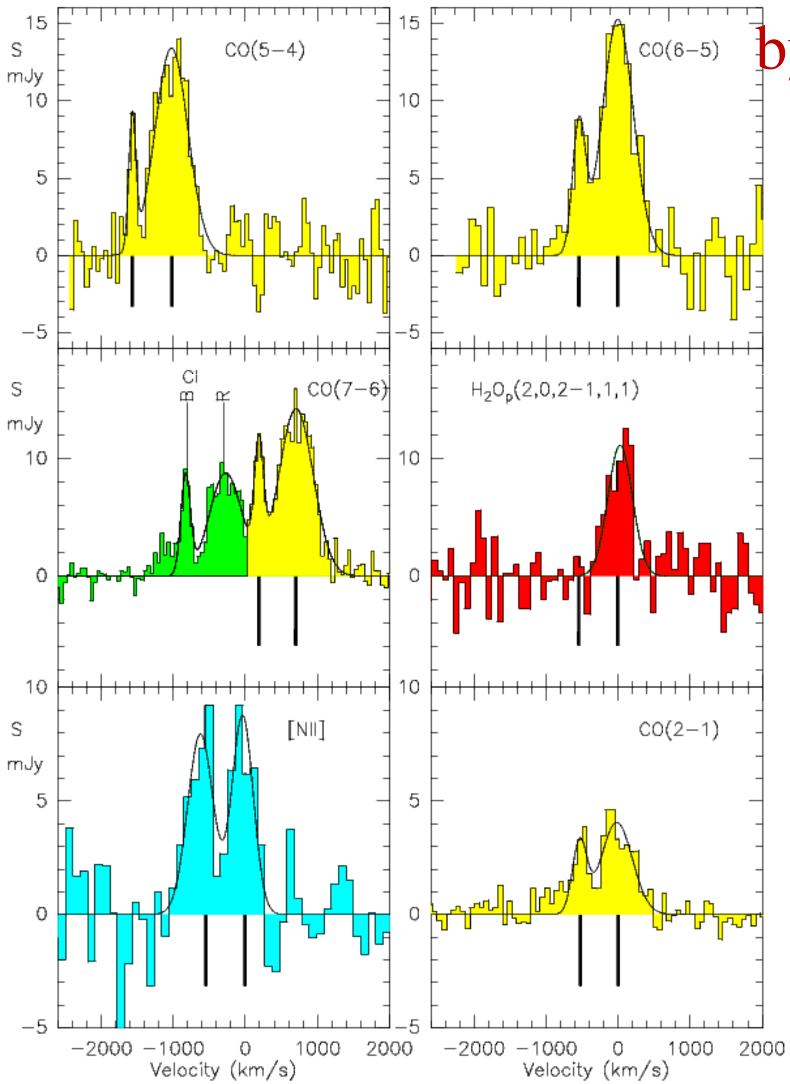


Ionised gas correlated to 1mm continuum (Star Formation proxy)

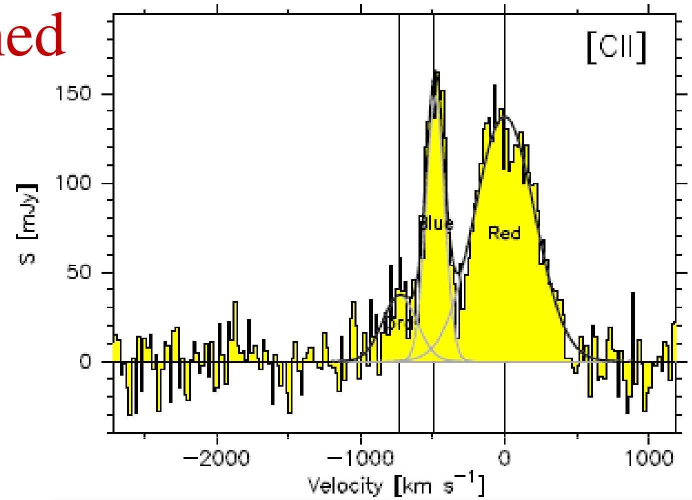
MM18423+5938

Decarli et al 2012

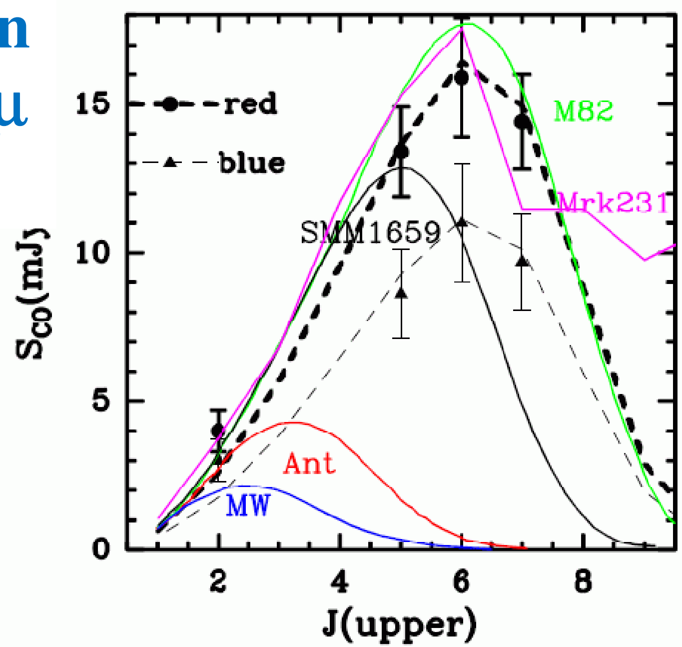
Discovery of high-z galaxies with Herschel (z=5.243)



Redshift determined by CO lines



1st detection of [NII]205μ at high z

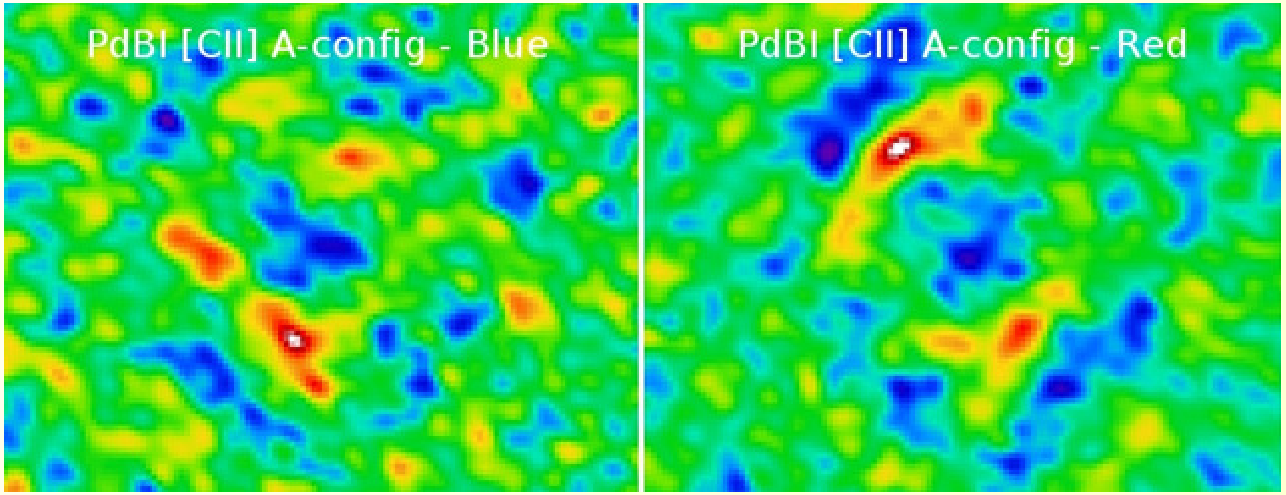


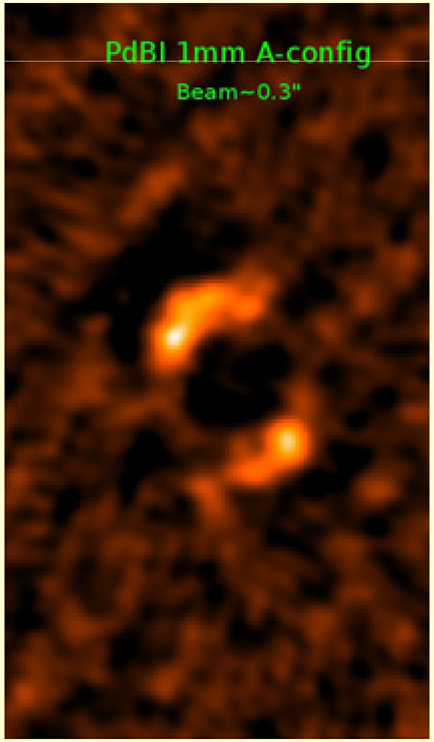
An amplification by a factor ~11

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

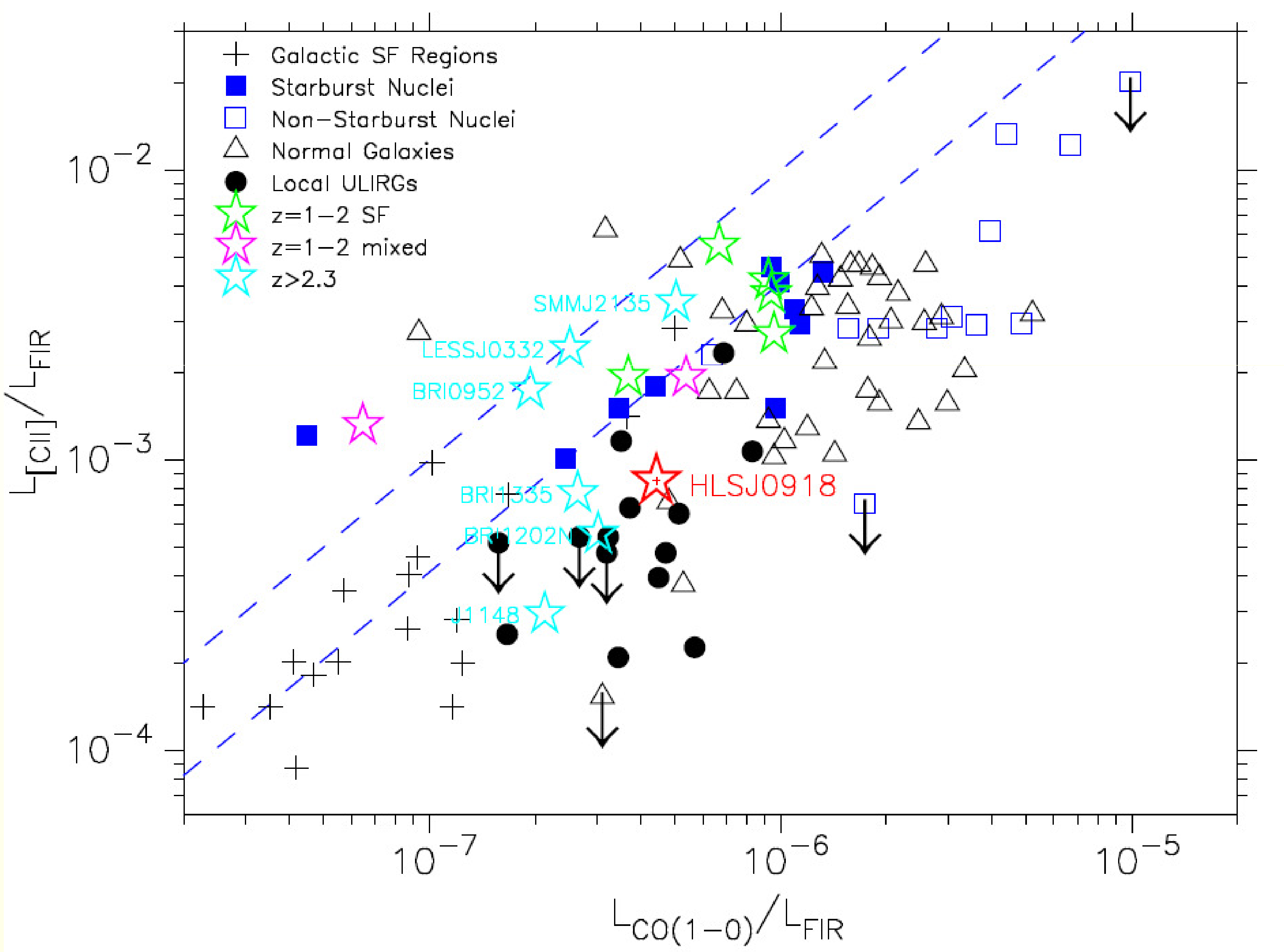
Continuum at 300GHz ~1mm, or 160µ in the rest-frame, with SMA and PdBI (IRAM) ➔ Einstein ring

Blue V-component Red V-component





Neutral and Ionised gas



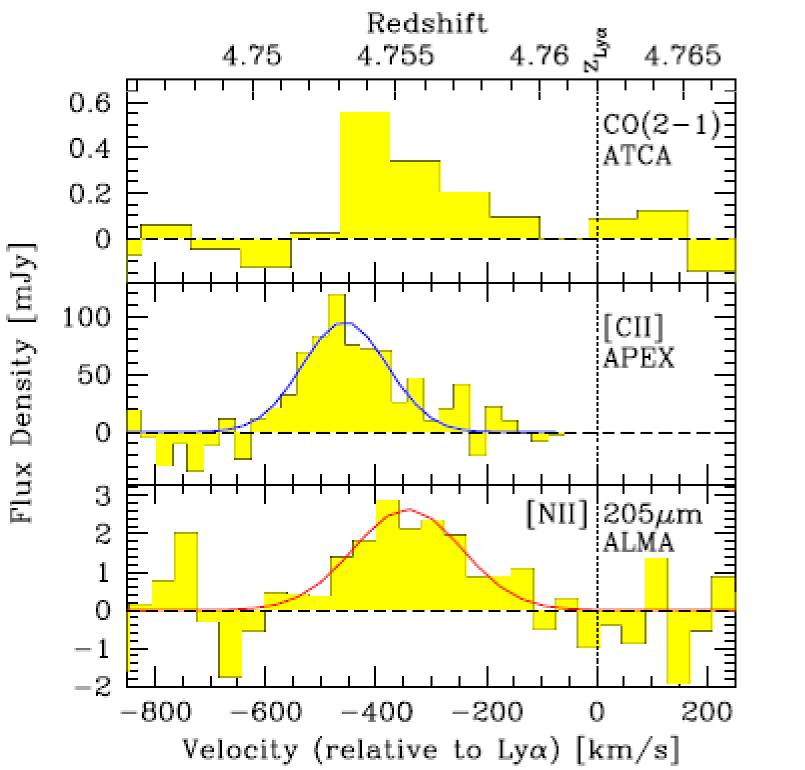
Rawle et al 2012

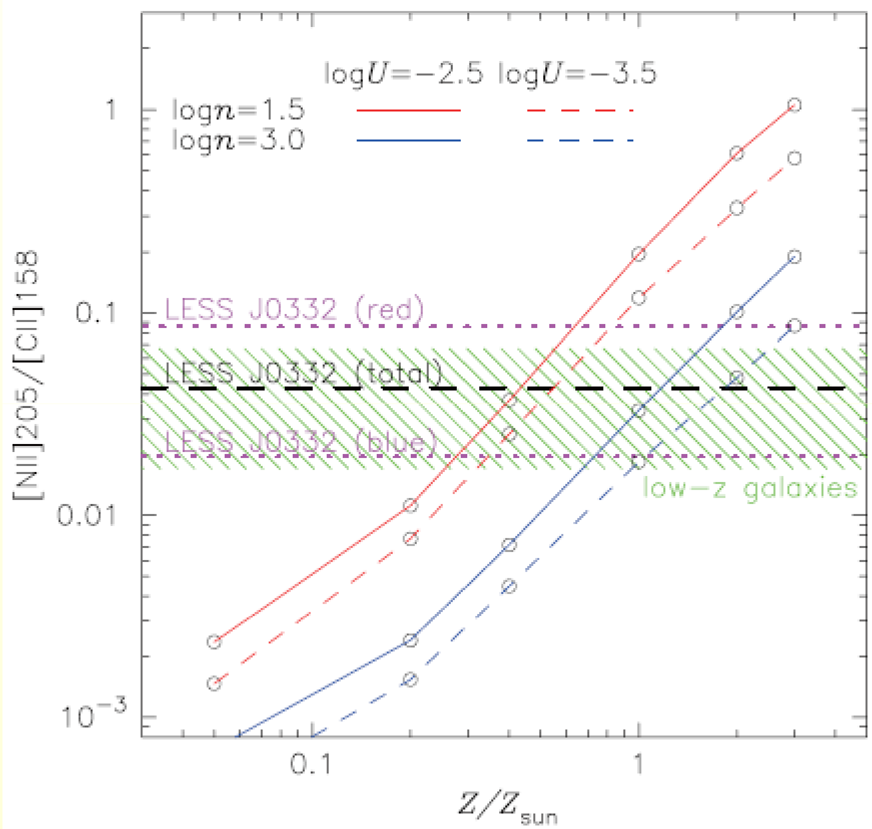
[NII]/[CII] metallicity diagnostic

LESS J033229.4–275619

Z=4.76

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





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

Nagao et al 2012

ALMA papers

➔Herrera et al 2012 A&A: The Antennae (Science Verification)
ALMA CO and VLT/SINFONI H_2 observations of the Antennae overlap region: mass and energy dissipation

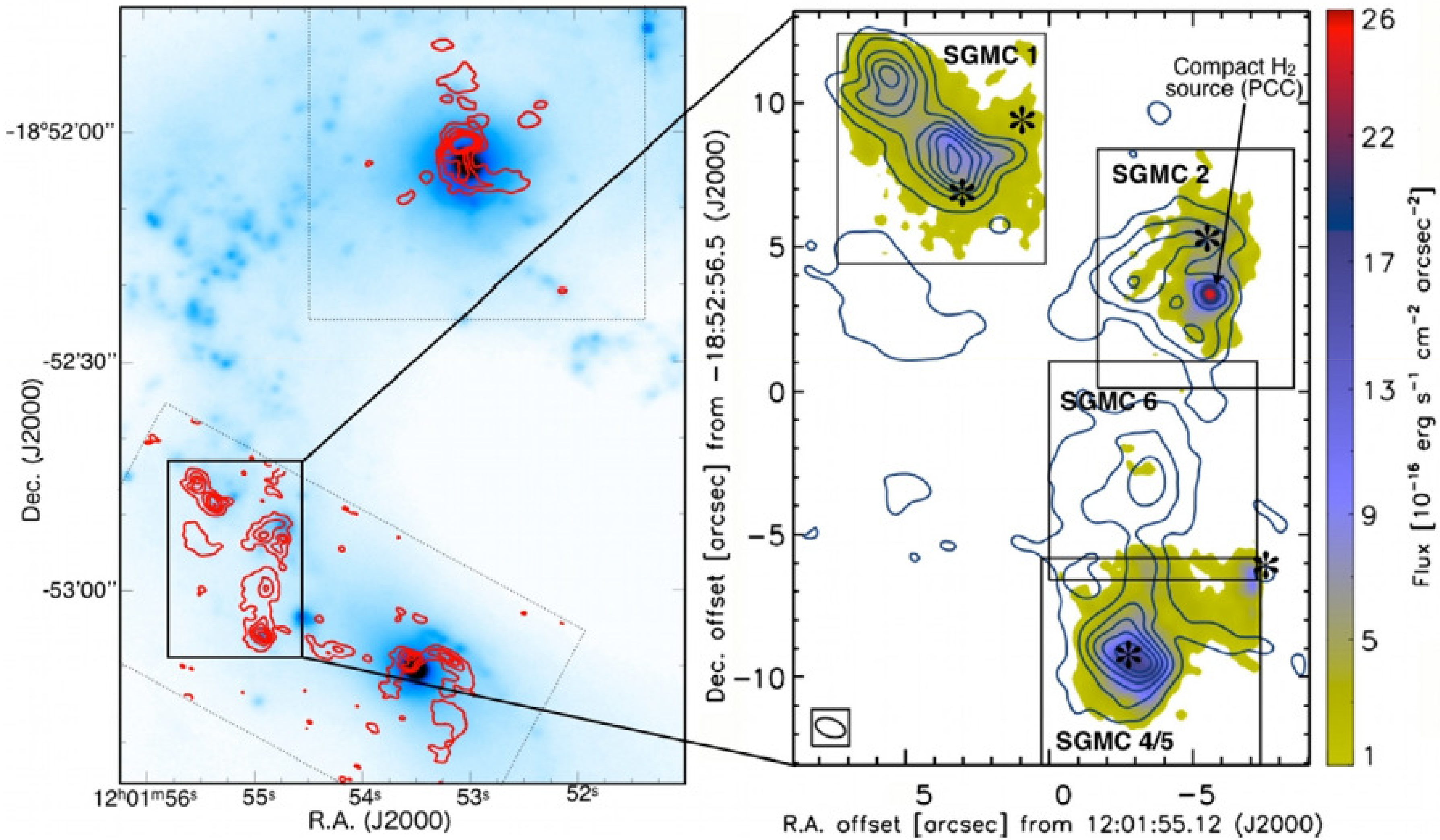
➔Nagao et al 2012 A&A : [NII]/[CII] ratio z=4.76
Diagnostic of metallicity, in dust-enshrouded starburst galaxies

➔Wagg et al 2012 ApJ: (SVerif) [C II] Line Emission in Massive Star-forming Galaxies at z = 4.7: BR1202-0725, a QSO/SMG pair

CO(3-2) contours from ALMA, on H2 1-0 S(1) from SINFONI

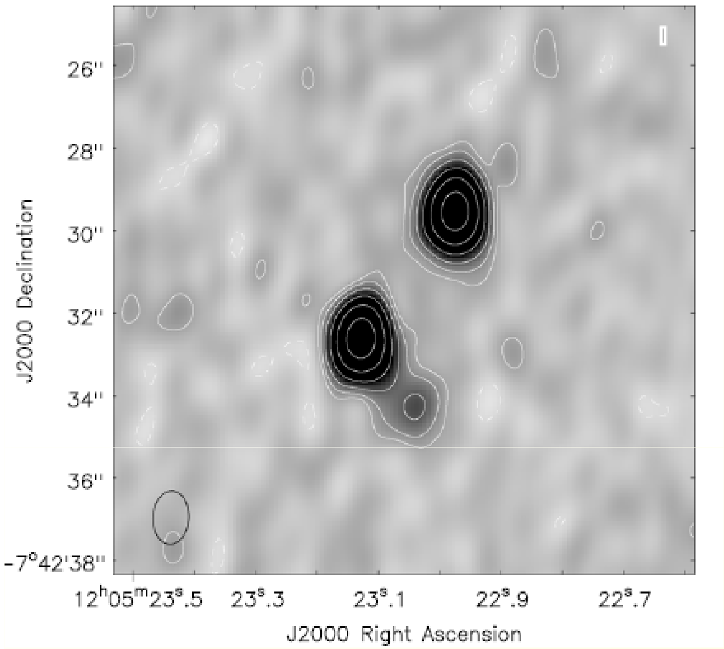
The Antennae overlap regions (0.9 ” and 0.7 ”=60pc)

H2/CO varies by more than 10



Herrera et al 2012

BR1202-0725, a QSO/SMG pair at z=4.7

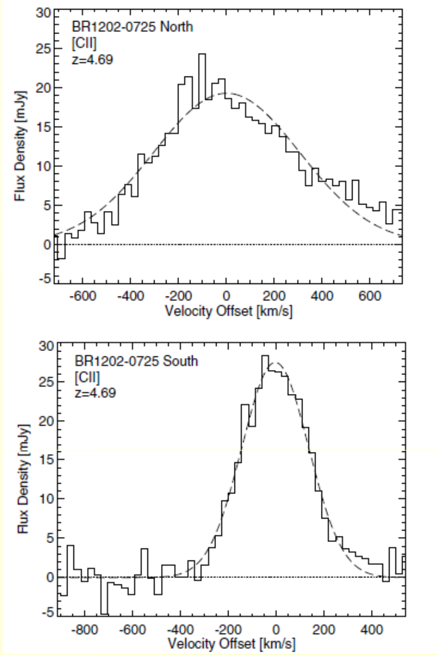


340 GHz cont 1.3x 0.86"

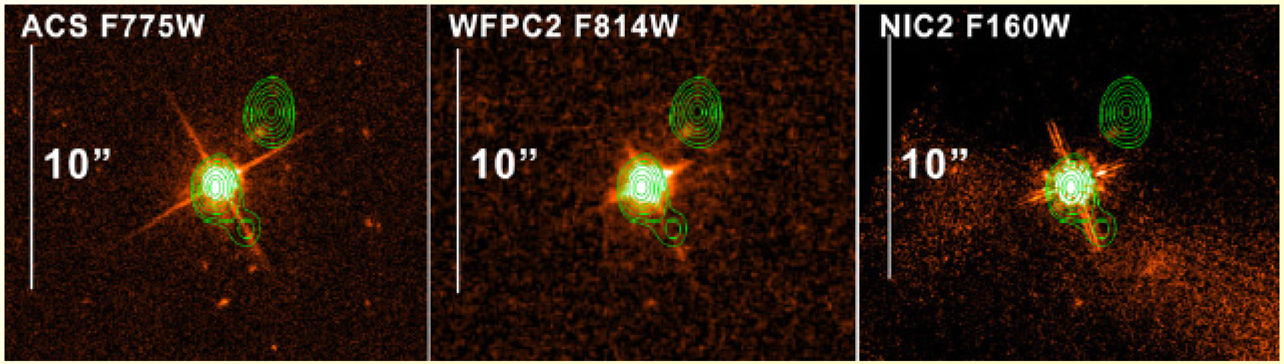
$L \sim 10^{13} L_o$

CII/FIR same ratio as previous ULIRGs *(lower in QSO)*

Wagg et al 2012



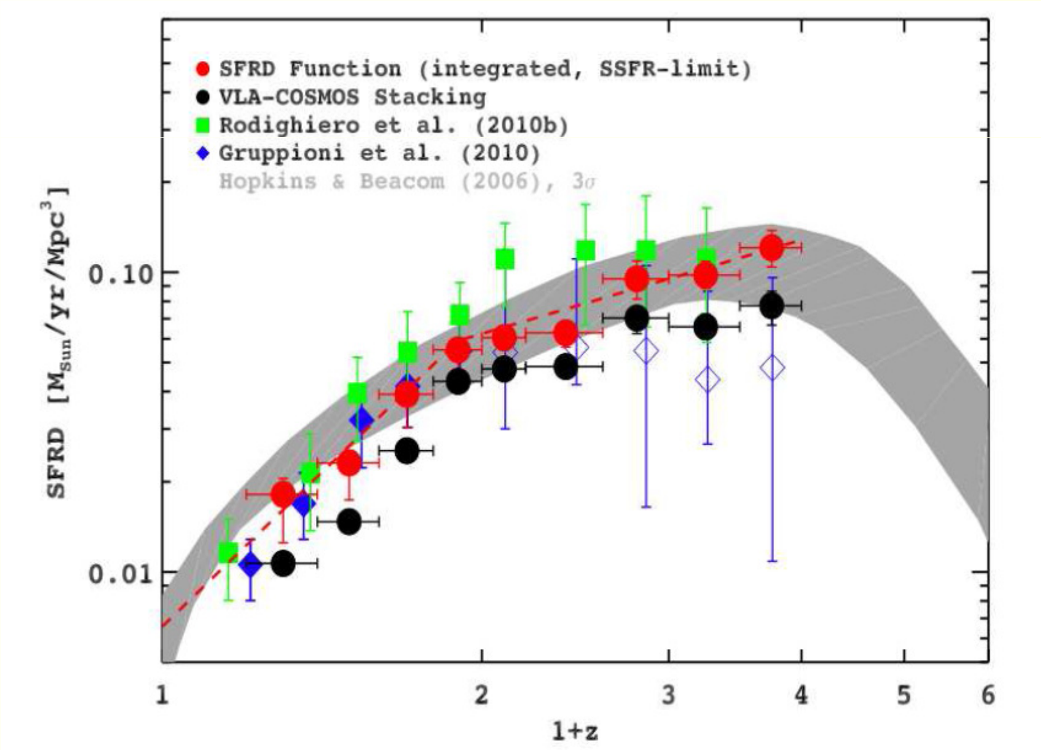
CII line
At 333 GHz



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



➔ SFH + MH2 ➔ SFE

Karim et al 2011