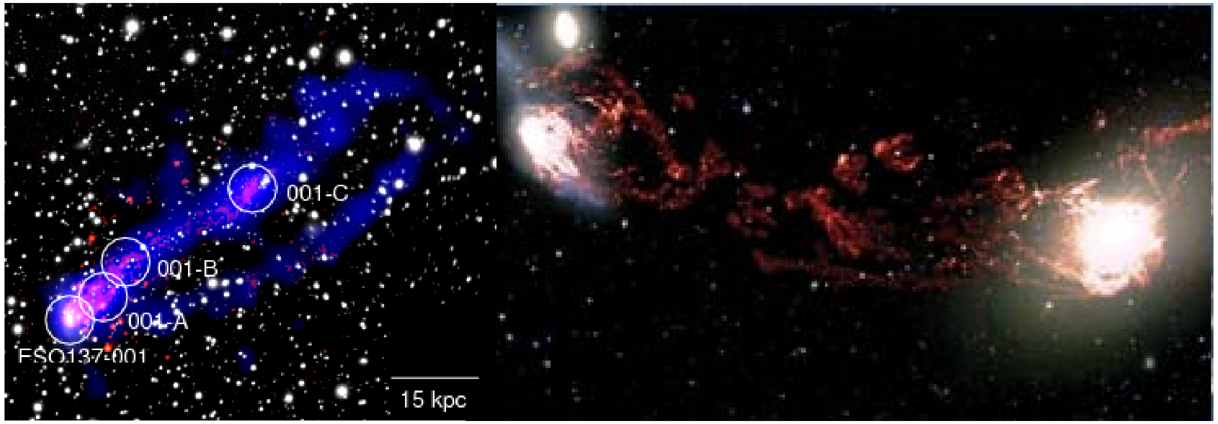
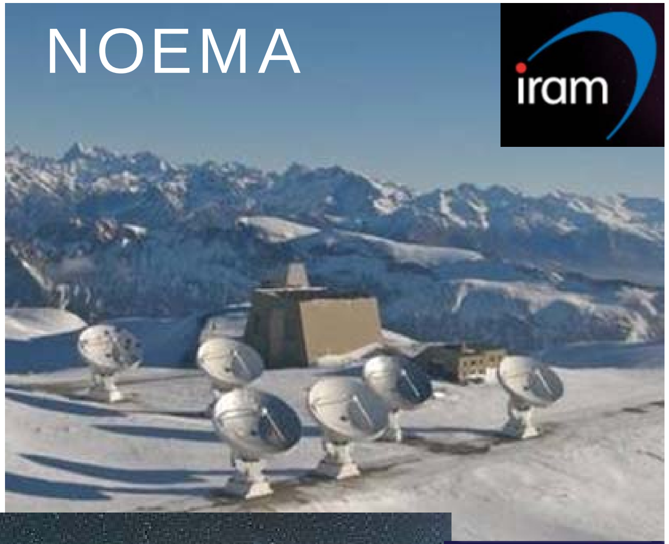
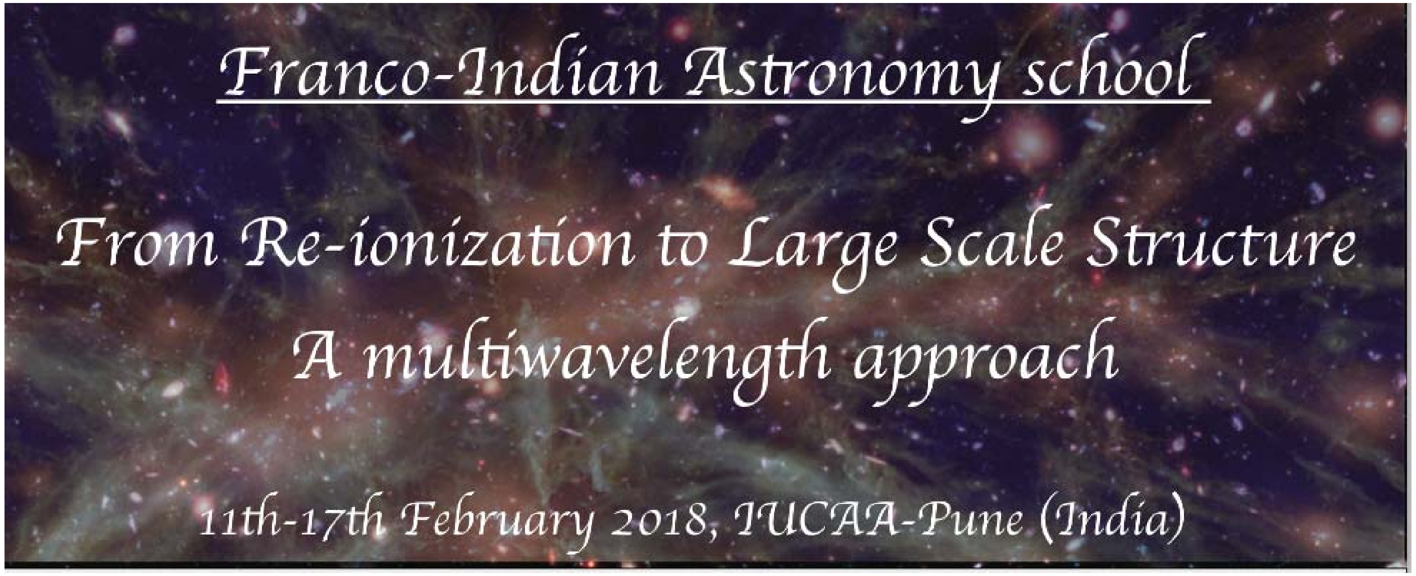




ALMA: Molecular gas across cosmic times and environments



Franco-Indian Astronomy school

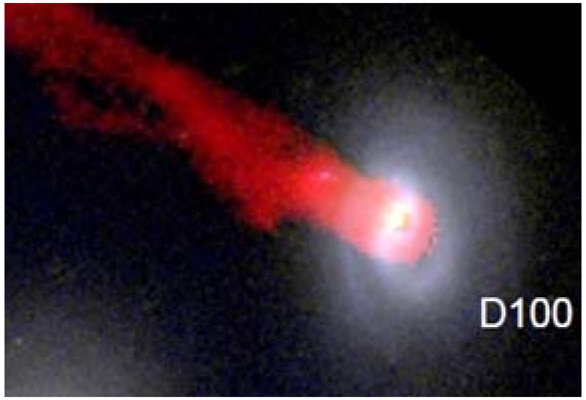
From Re-ionization to Large Scale Structure

A multiwavelength approach

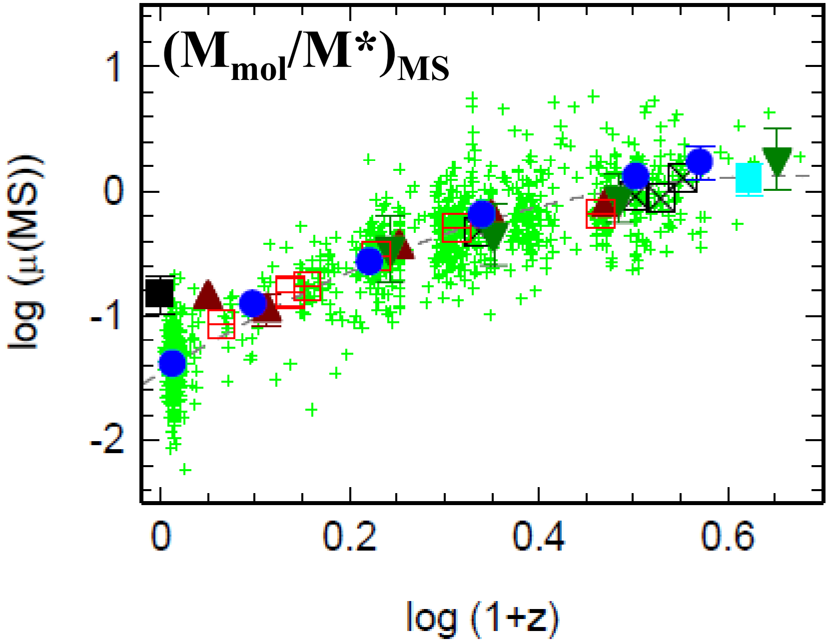
11th-17th February 2018, IUCAA-Pune (India)

Françoise Combes
Observatoire de Paris

15 February 2018



Outline



1- Cosmic evolution of gas content

2- Evolution of Star Formation Efficiency

3- Physical processes of quenching

4- Environmental effects

1-Census of cold gas in galaxies

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

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

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)*

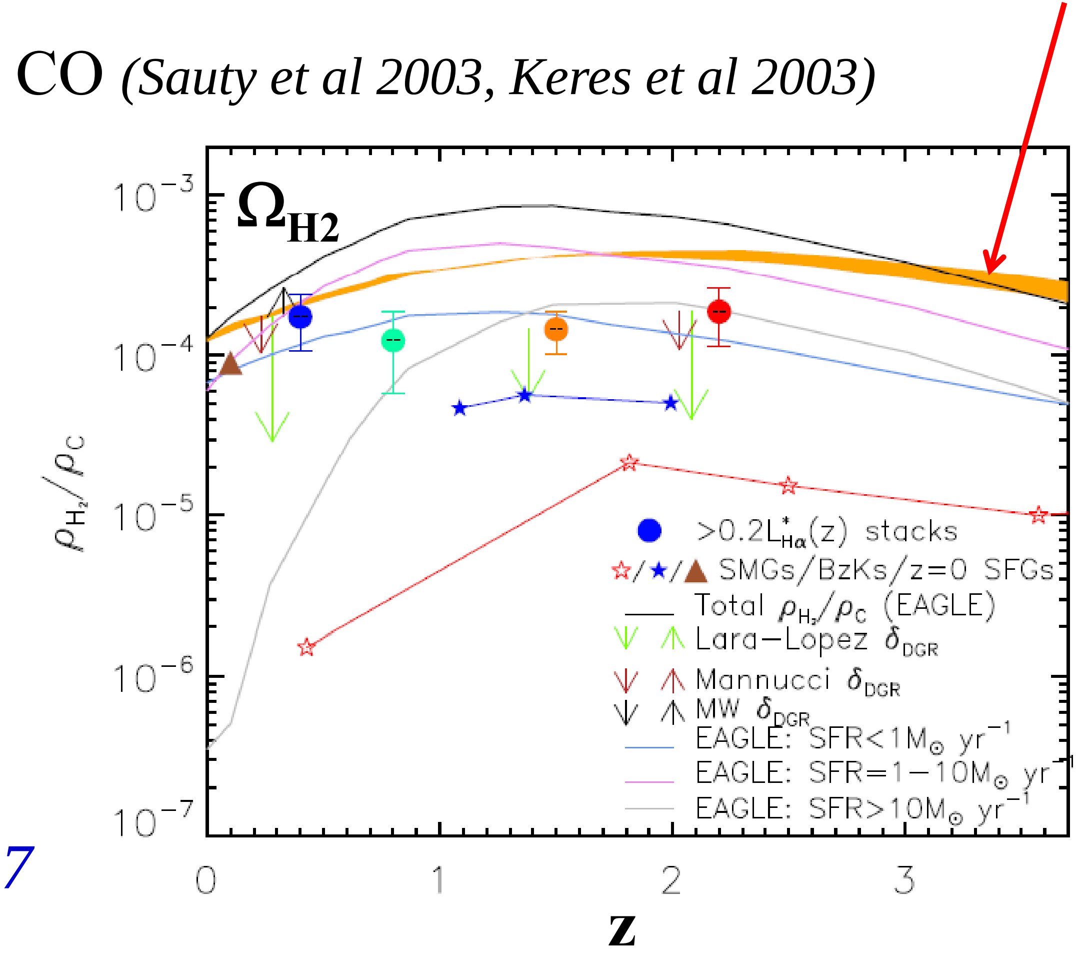
$\Omega_{H2} \sim 1.2\ 10^{-4}$

The molecular fraction is expected to increase with z:

Galaxy size ~ 1/(1+z),
+ Fgas higher:
➔Denser gas HI → H_2

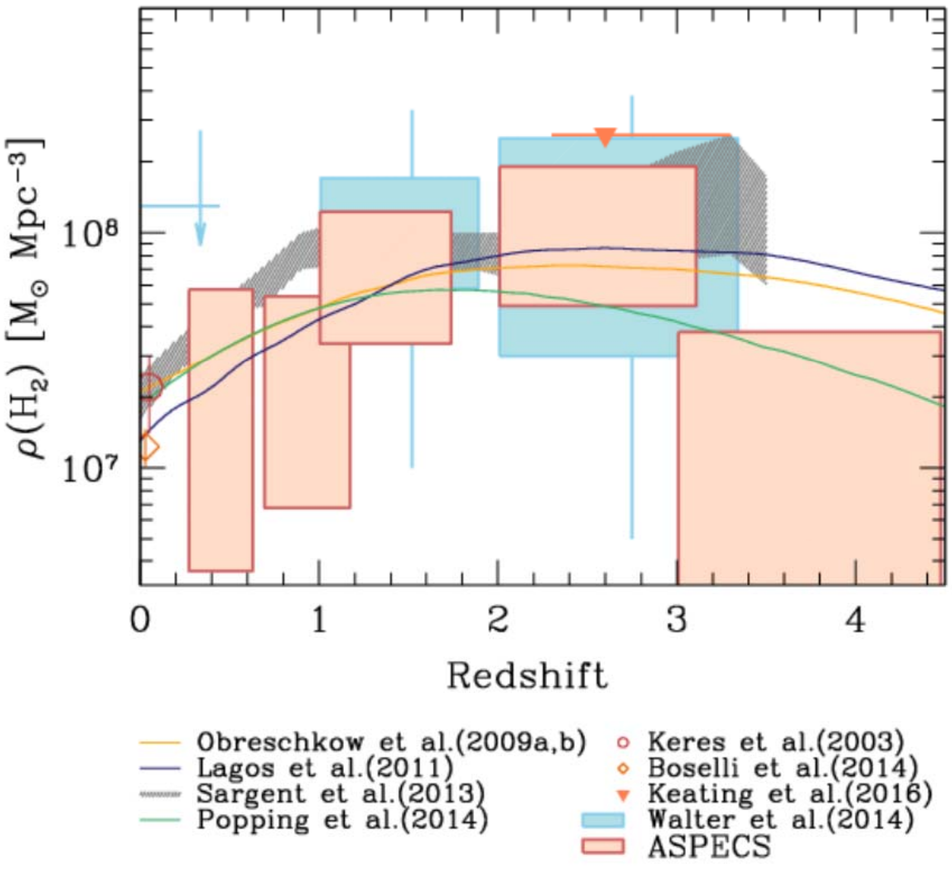
HIZELS, Thomson et al 2017

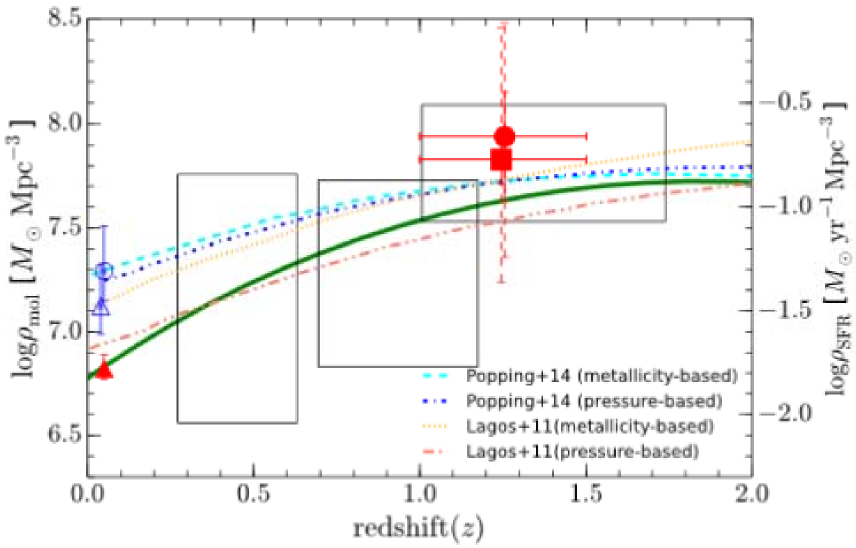
Popping



Cosmic evolution of H_2

Walter et al, *Decarli et al 2014:* Deep PdBI obs of the HDF-N, 3mm
Decarli et al 2016: ASPECS, ALMA of UDF in Bands 3 & 6
Evolution more contrasted then in models, factor 3-10

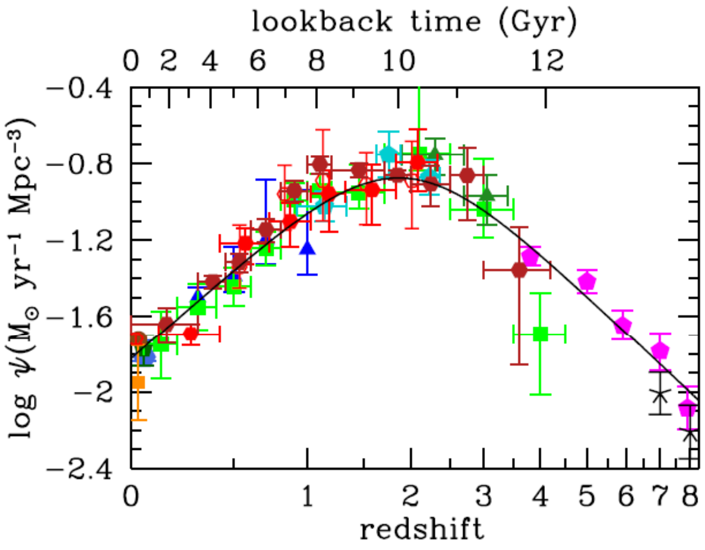




from M* function and fgas
Maeda et al 2017

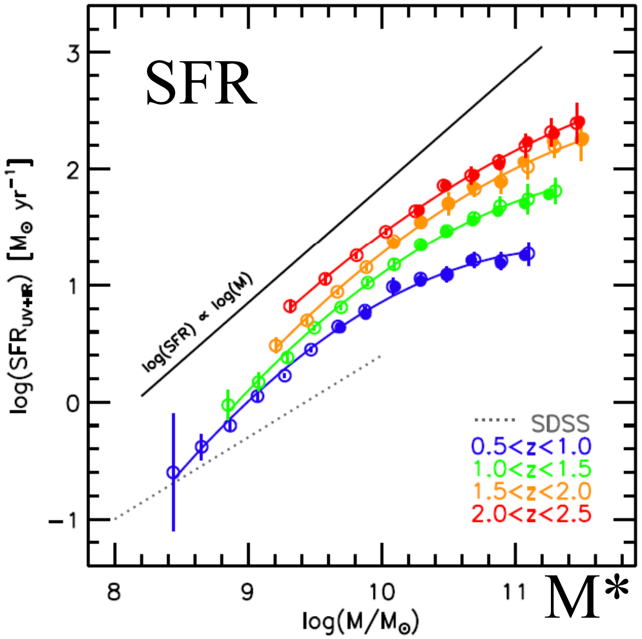
$$\rho_{\rm mol} = \int_{M_{\rm min}}^{M_{\rm max}} f_{\rm mol} M_{\rm star} \Phi(M_{\rm star}) dM_{\rm star}$$

Why does SFR(z) increases?



Madau & Dickinson 2014

The main sequence



Whitaker et al 2014

➔**Gas fraction**

➔Star formation efficiency

Frequent mergers

Shorter dynamical times

Higher gas density

➔Quenching since z=1.7

Environment

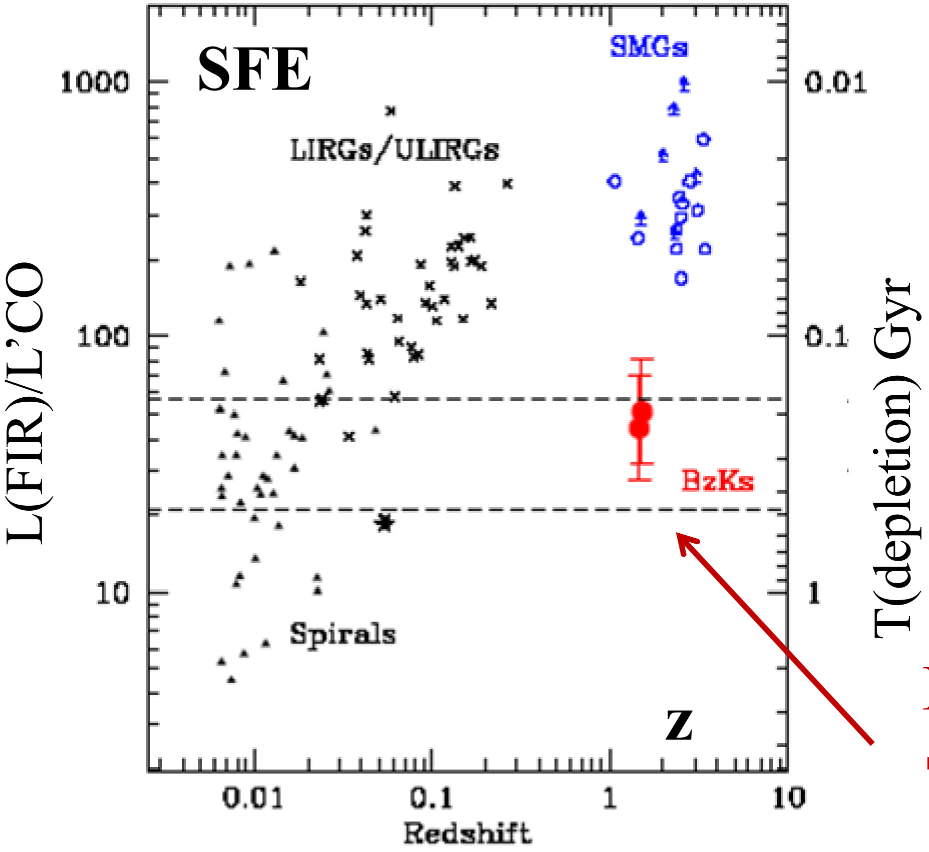
Morphology

Mass

2-Large range of SF efficiency at high-z

In SMGs, starbursts **t_{dep} = 1/SFE** ~10-100 Myr
Massive BzK galaxies, CO sizes ~10kpc? L(FIR) ~10^{12} Lo
« Normal » SFR, M(H2) ~ 2 10^{10} Mo **t_{dep}** ~2 Gyr

Greve et al 2005. Daddi et al 2008

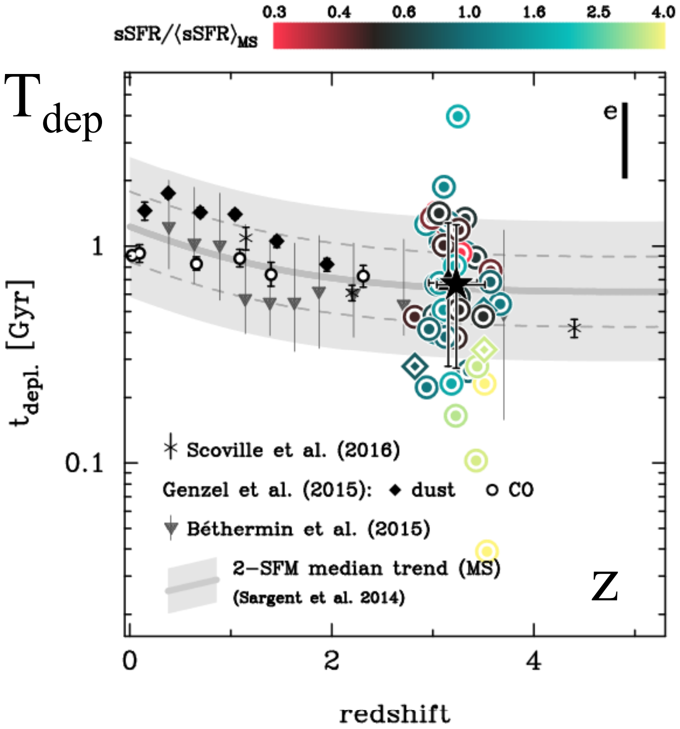


Starburst when gas concentrated in the center (nuclear SB)

Caveat: XCO conversion ratio
Requires high-J CO lines
HCN, HCO+,,
Dust emission, etc..

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

High SFE (starbursts) at z=1.4-3.2



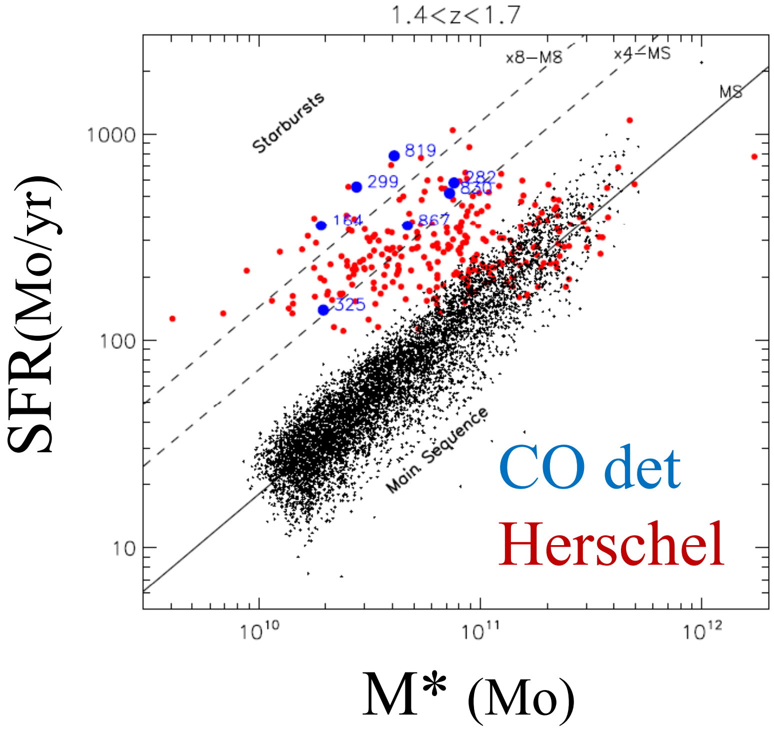
SFG, z=3.2 (COSMOS)

Schinnerer et al 2017

Herschel detected starbursts

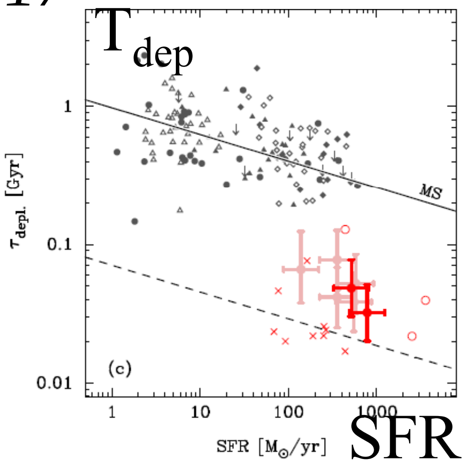
Galaxies from COSMOS,

300-800 Mo/yr, f_{gas} 30-50%

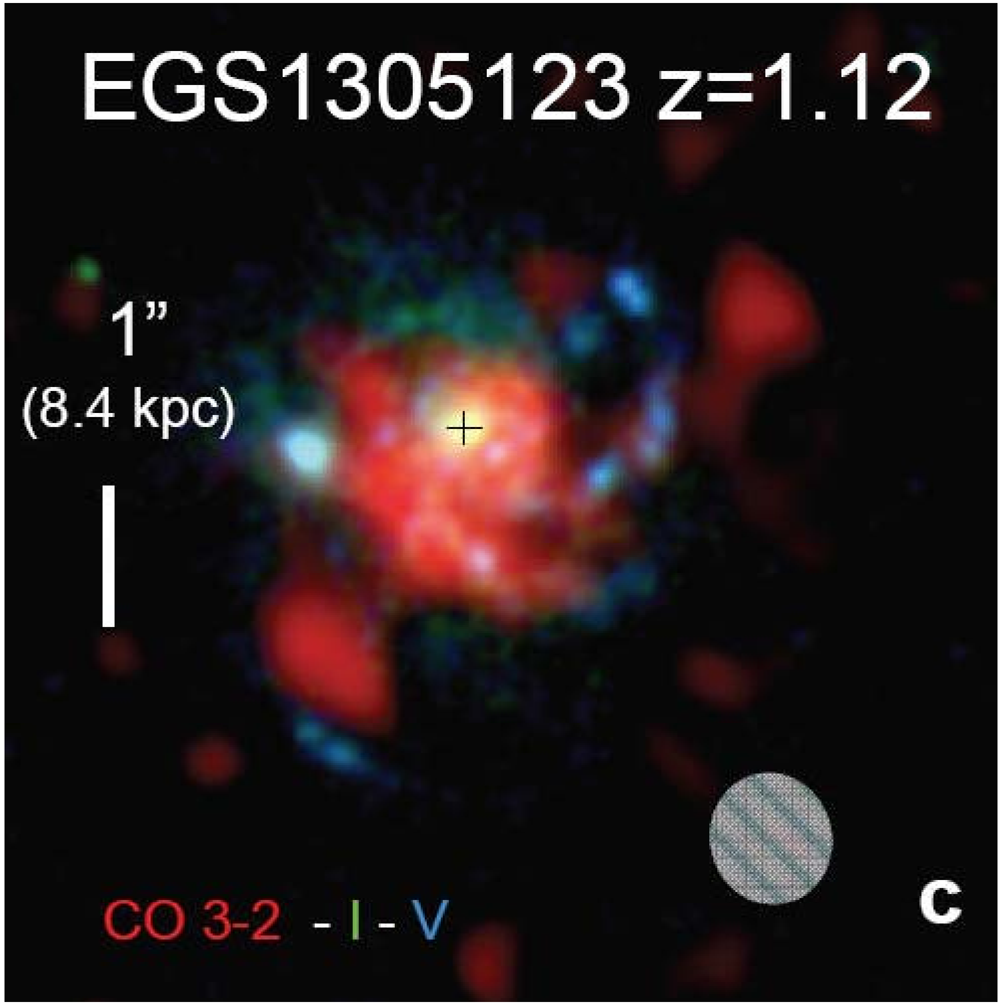


Starburst

SFR= 10x MS

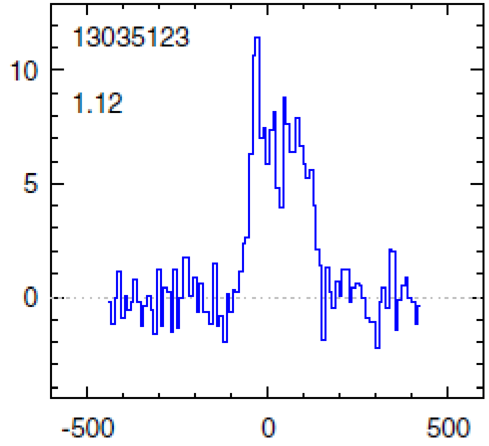


Silverman et al 2015

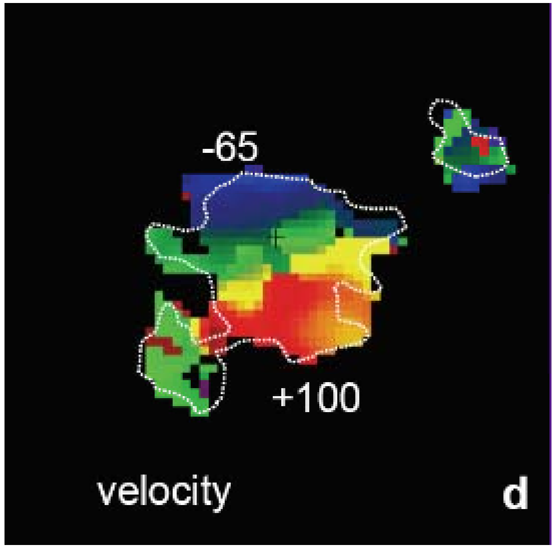


PHIBSS-1 Project

with L. Tacconi, R. Genzel,
S. Garcia-Burillo, R. Neri, et al



~50 galaxies
at z~2.3 and z~1.2

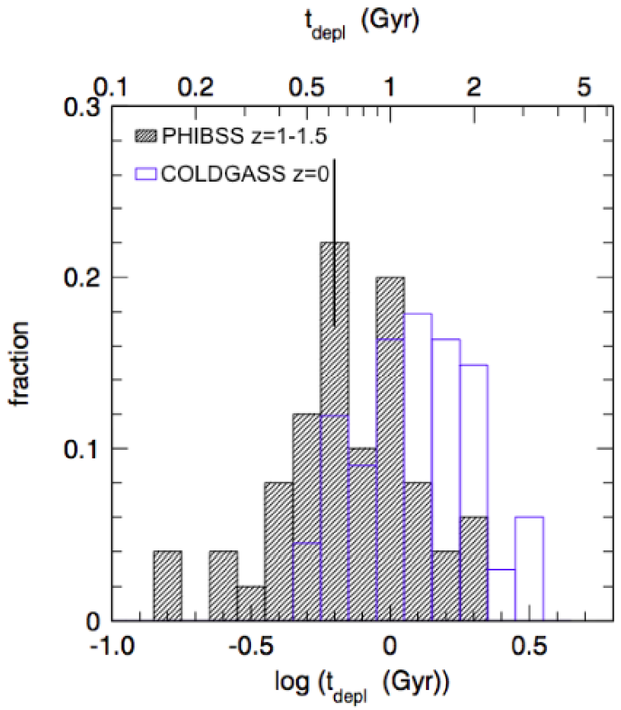


High detection rate >85%, in these « normal »
massive Star Forming Galaxies (SFG)
Gas content **~34% and 44% in average**
at z=1.2 and 2.3 resp.

Tacconi et al 2010, 2013

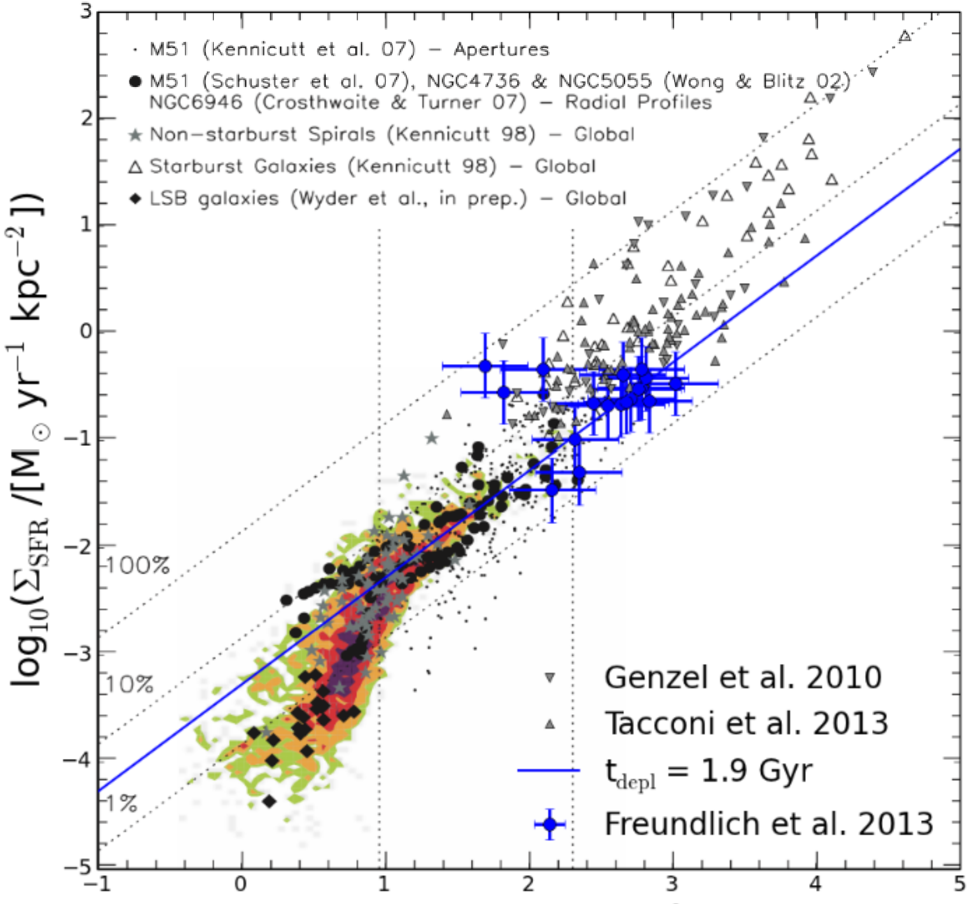
Resolved Kennicutt-Schmidt diagram

Depletion time
smaller than for z=0



Freundlich et al 2013

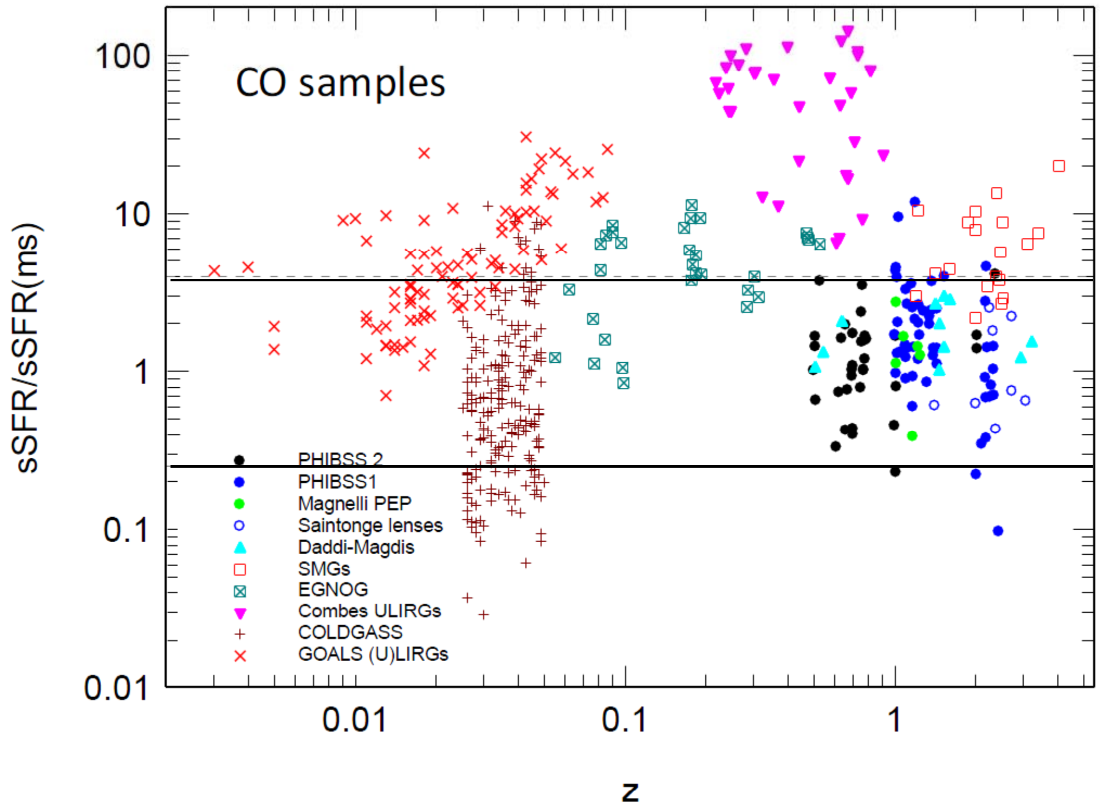
ΣSFR

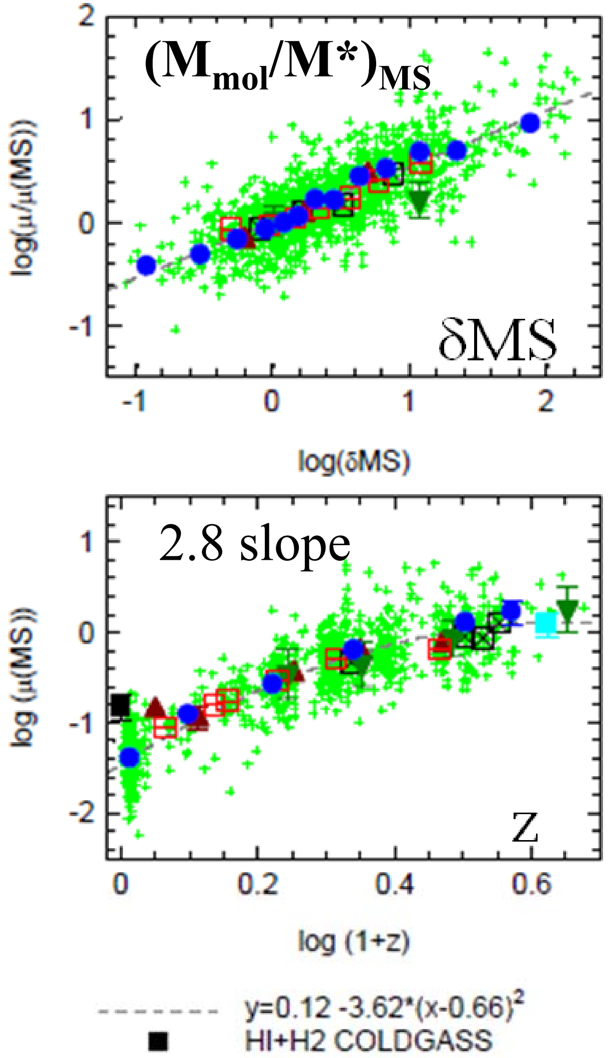


Σgas

Scaling relations, several samples

Gas fraction increases regularly with z on the MS





log(M*/Mo)=9.-11.8, δMS=SFR/SFR(MS)

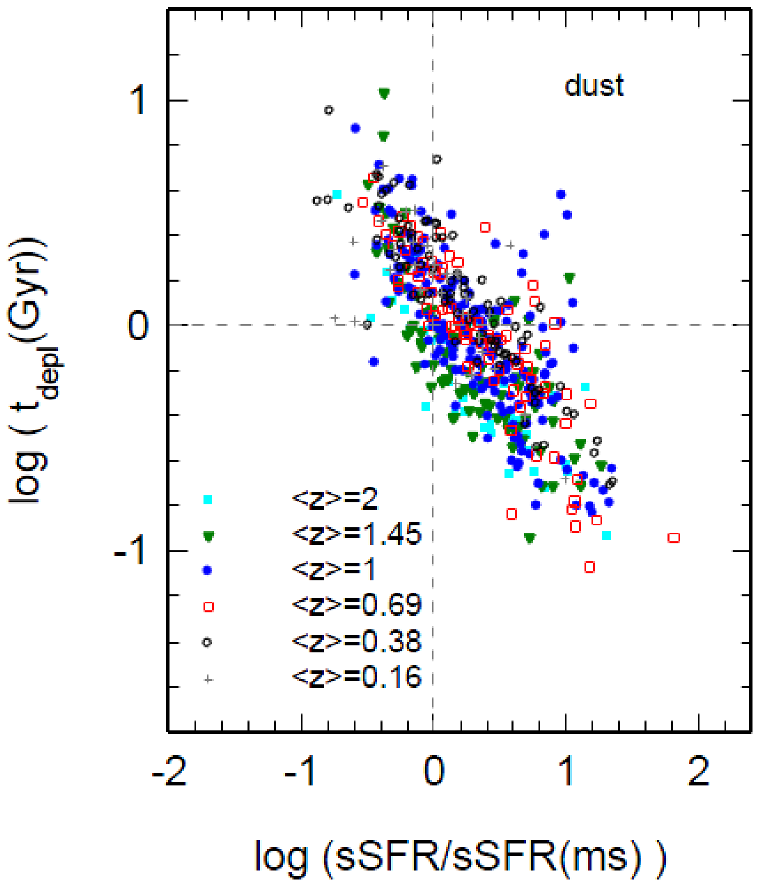
tdep ~ $(1+z)^{-0.57}$ $(\delta MS)^{-0.44}$

$\mu = M_{mol}/M^* \sim (1+z)^{2.8} (\delta MS)^{0.54} (M^*)^{-0.34}$

Tacconi et al 2017

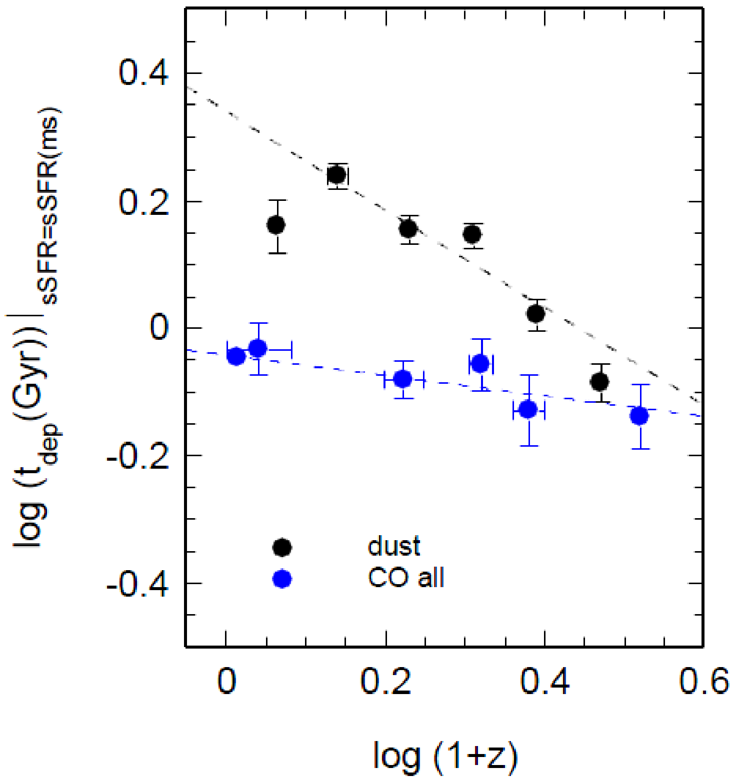
Depletion time, CO or dust tracers

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



dust: $\log t_{dep}|_{ms} = 0.34(0.05) - 0.77\ (\pm 0.19) \times \log(1+z)$

CO: $\log t_{dep}|_{ms} = -0.04\ (0.01) - 0.16\ (\pm 0.04) \times \log(1+z)$



Genzel et al 2015

Compilation between z=0 and 4

758 galaxies, different samples, normalised to the Main sequence (MS)

PHIBSS2, COLD-GASS *(Saintonge et al 2016-17)*
ALMA *(Decarli et al 2016)*
Herschel dust *(Magnelli e tal 2014, Bethermin et al 2015)*
normalised to minimise the zero points of calibration (M*, CO masses..)

log(M*/Mo)=9.-11.8, δMS=SFR/SFR(MS)= $10^{-1.3}$ to $10^{2.2}$

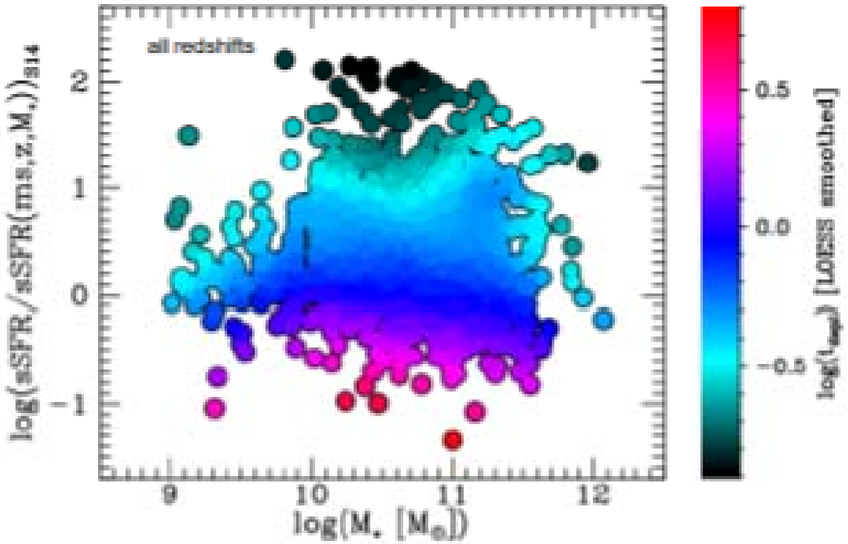
tdepl $\sim (1+z)^{-0.57} \; (\delta MS)^{-0.44}$

$\mu = M_{mol} / M^* \sim (1+z)^{2.8} \; (\delta MS)^{0.54} \; (M^*)^{-0.34}$

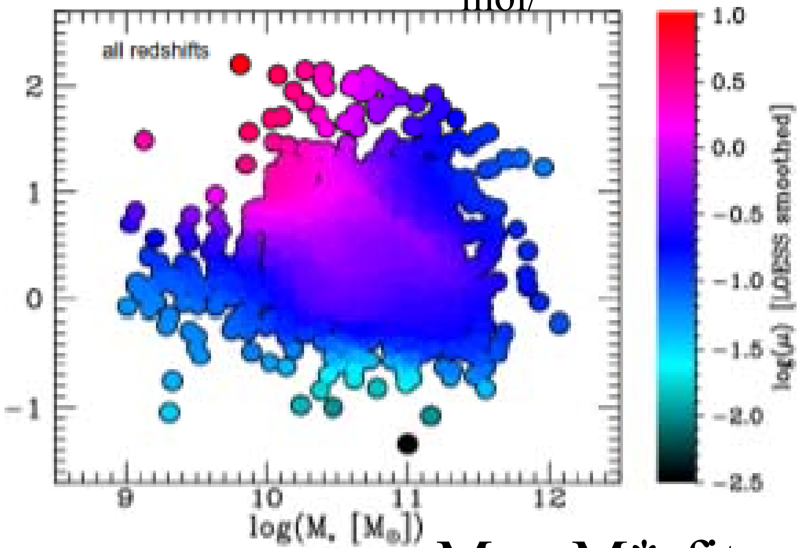
Tacconi et al 2017

Normalisation, after z-dependency removed

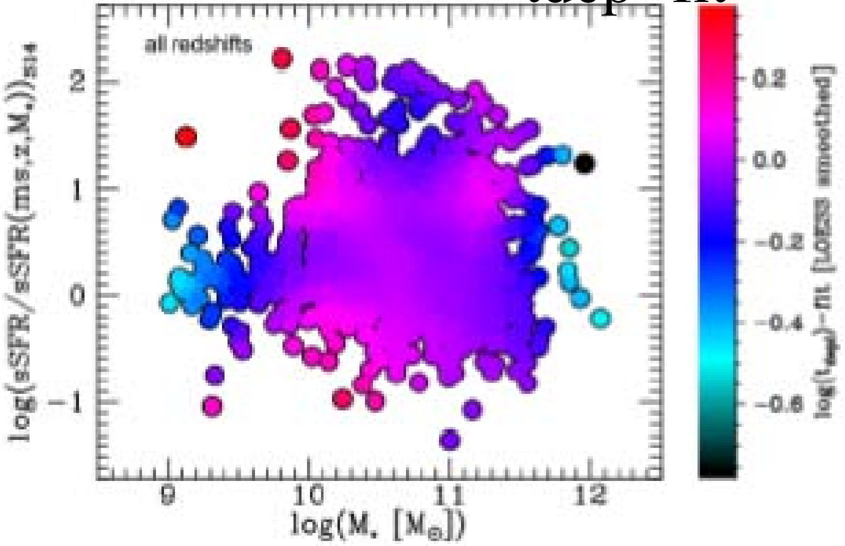
tdep



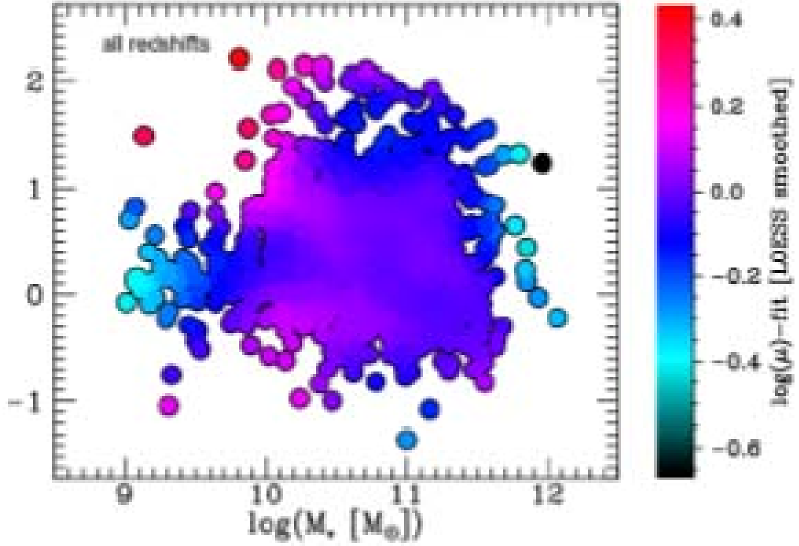
$M_{mol/}M*$



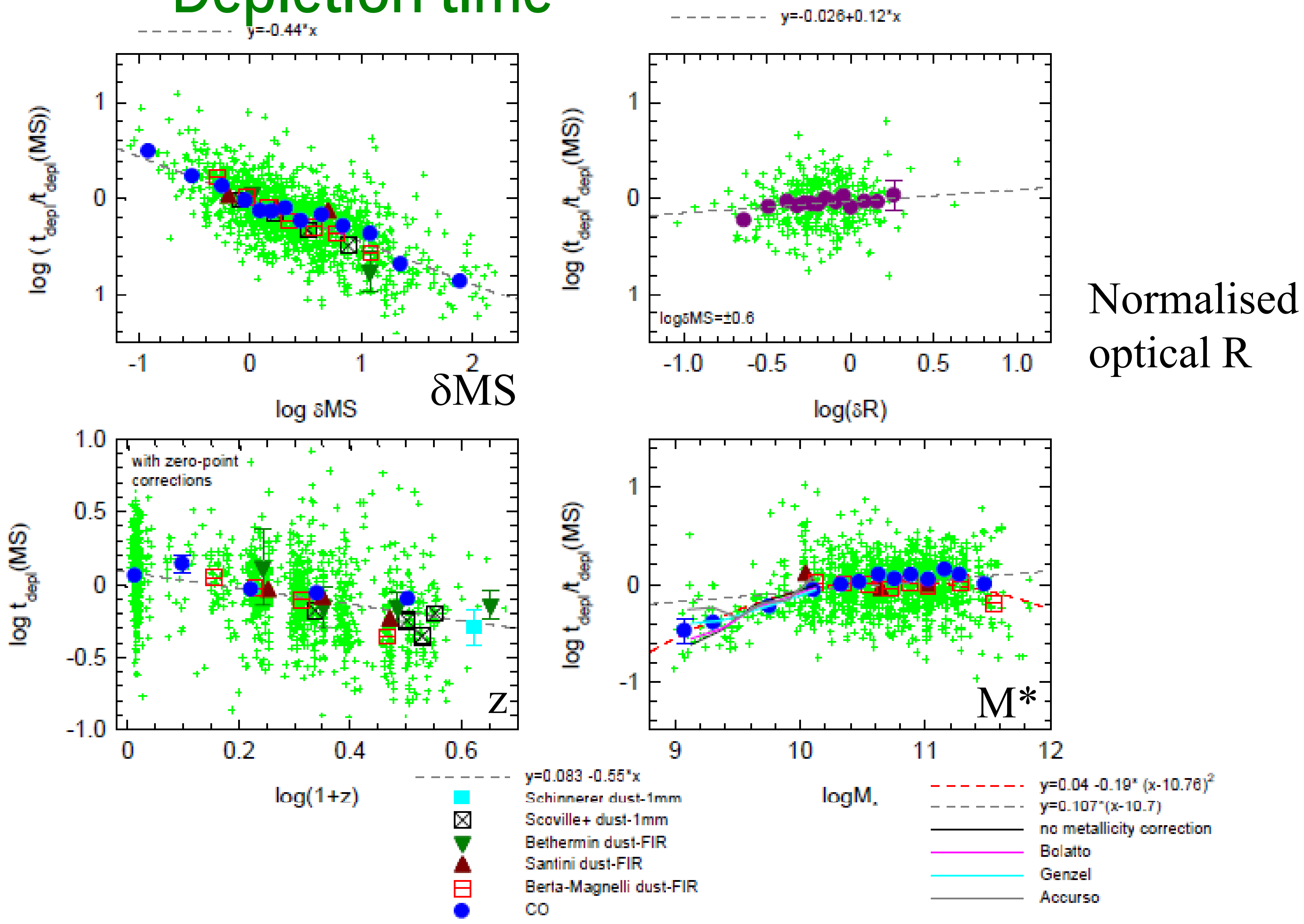
tdep -fit



$M_{mol/}M*$-fit

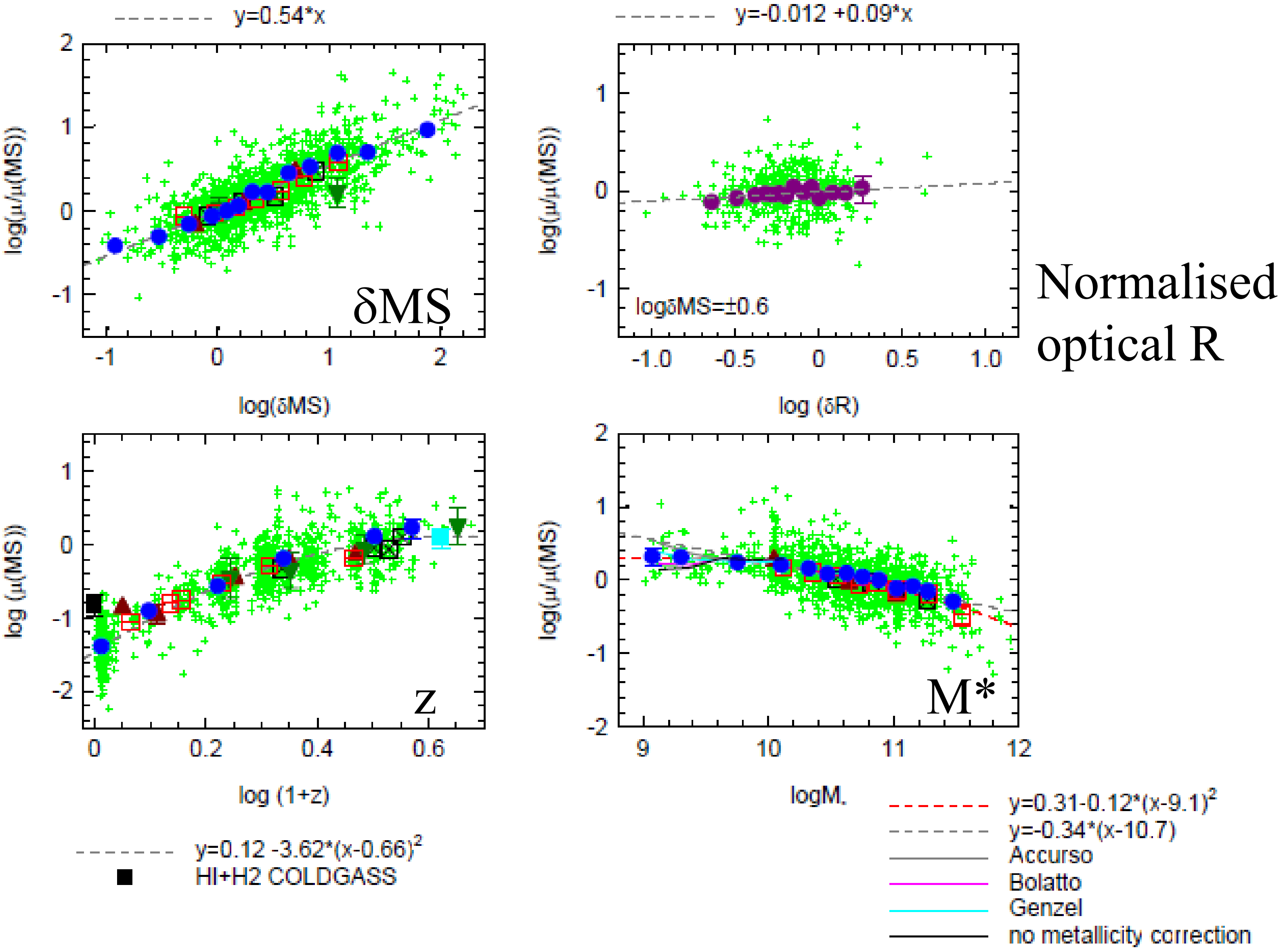


Depletion time



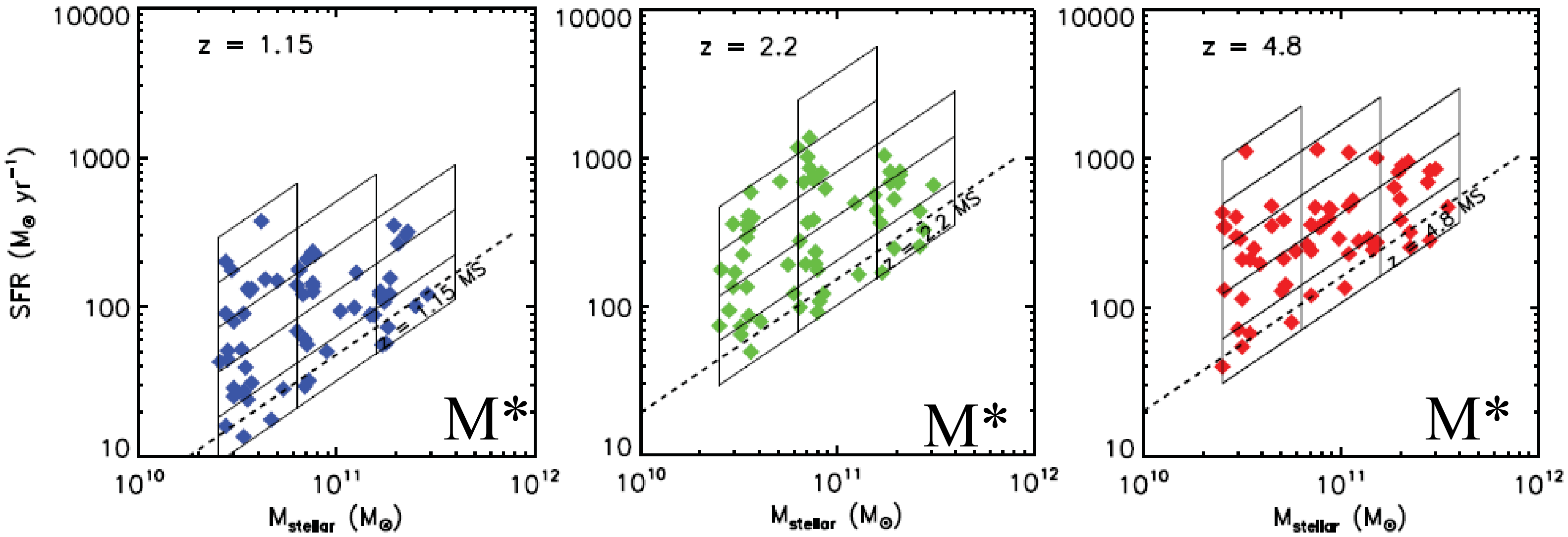
Normalised optical R

Gas fraction $\mu = M_{mol} / M^*$

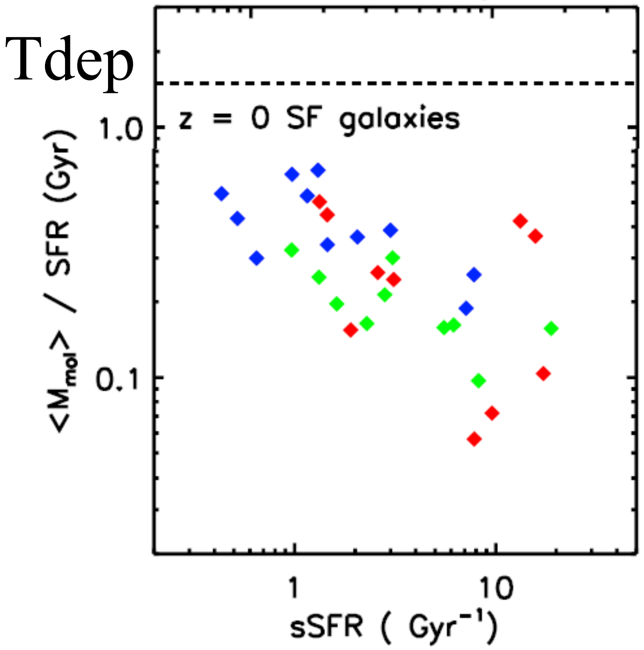


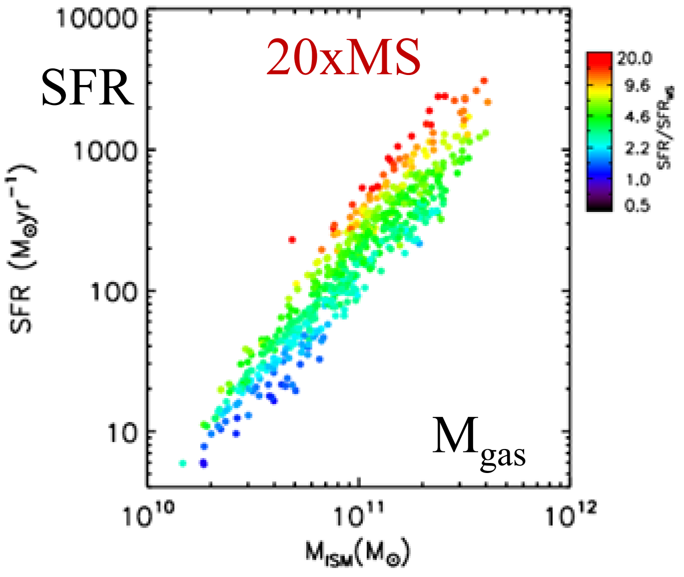
Normalised optical R

SFE and depletion times with continuum



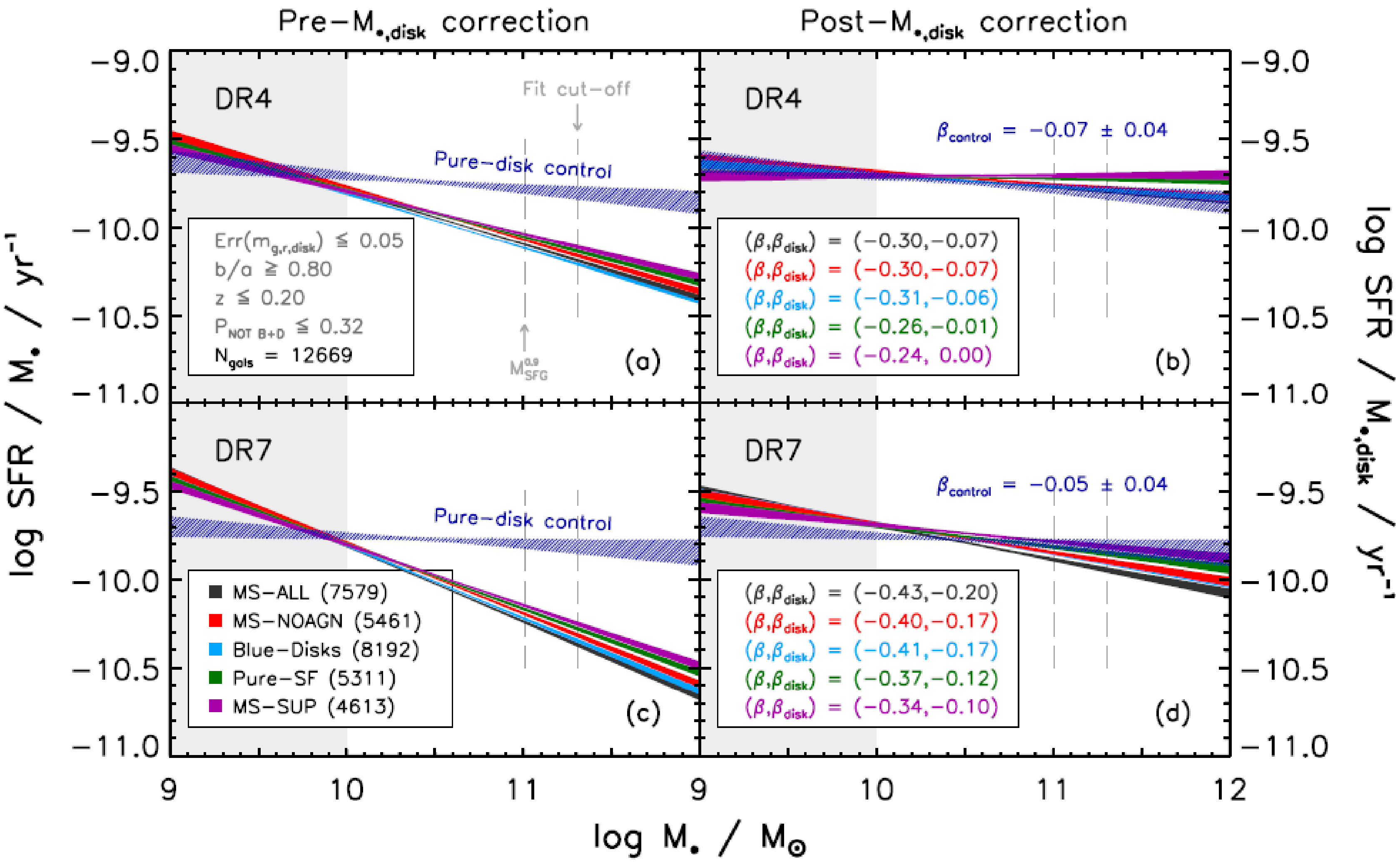
Scoville et al 2016





Scoville et al 2017

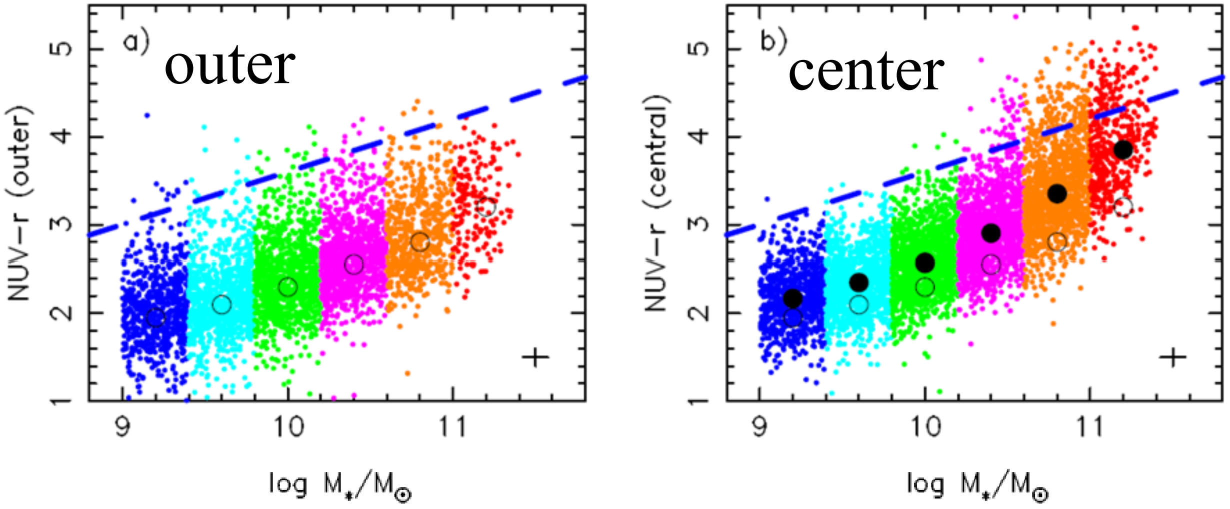
sSFR of disks?, slope ~0



Abramson et al 2014

DR4 different SFR estimation
Overestimate in QG

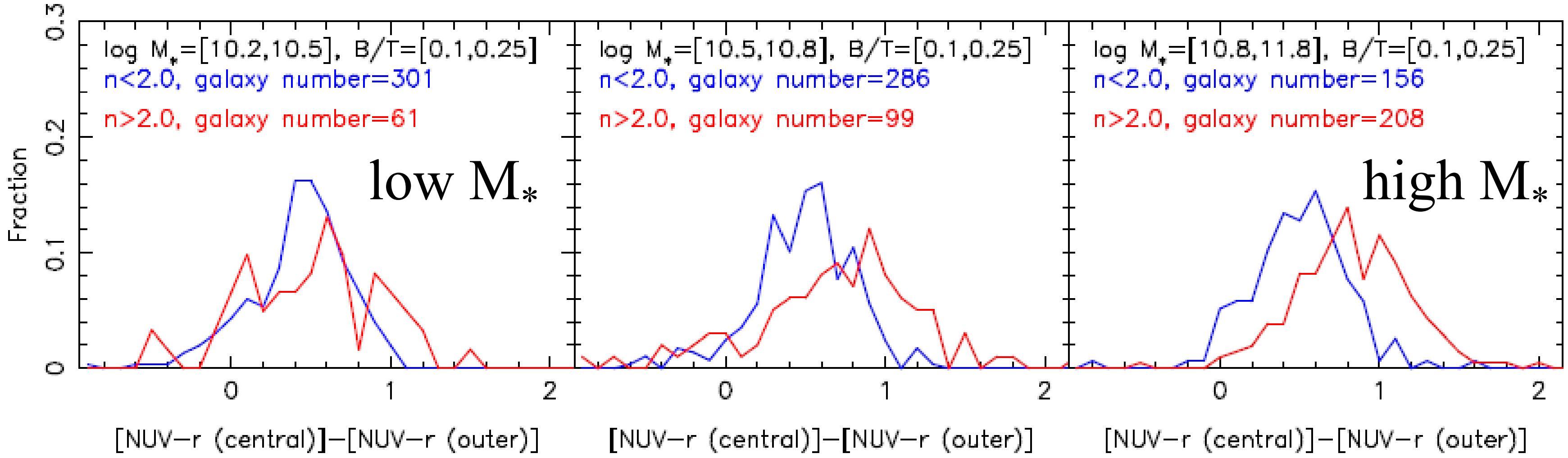
More than B/T, the concentration (Sersic n)



The reason of sSFR/M_* slope different from 0

➔High-M galaxies have a much redder bulge

Not for pseudo-bulges!

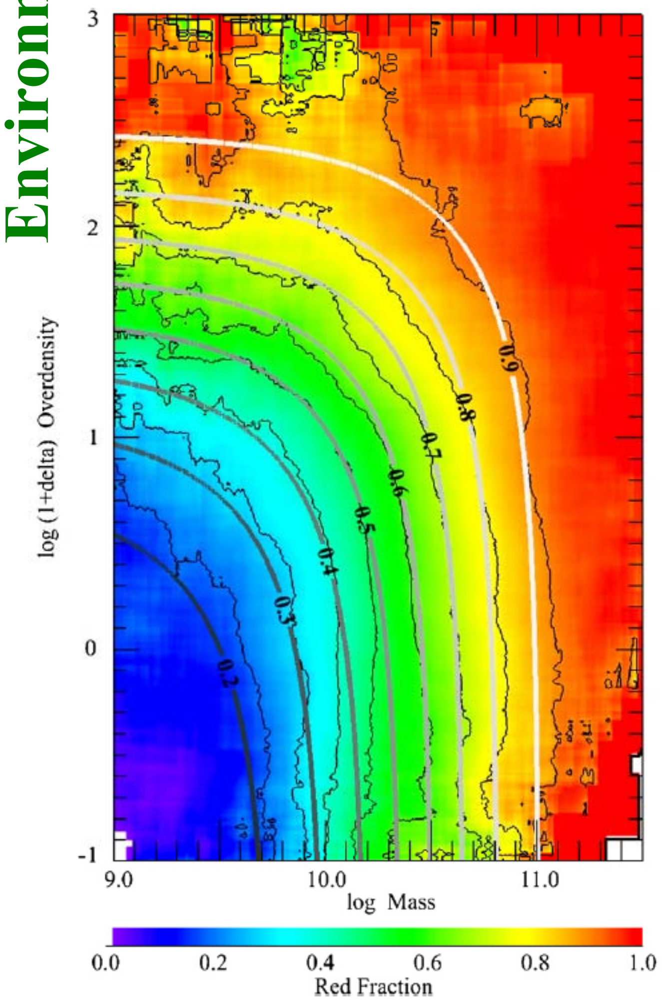


Color(center) –Color(outer)

Z. Pan et al 2016

3- Quenching processes

Environment



Mass

FAST (<~0.1 Gyr)

➔Heating the gas (transient)

Turbulence by interactions, SF feedback

Gas will dissipate, and SF come back

➔Ejecting the gas present (transient)

SN and AGN winds, radio jets

SLOW (2-4 Gyr)

➔Stabilising the gas:

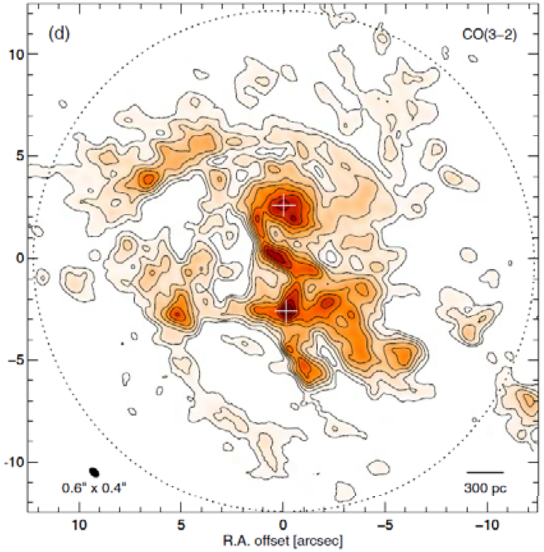
Morphological quenching, bulge formation

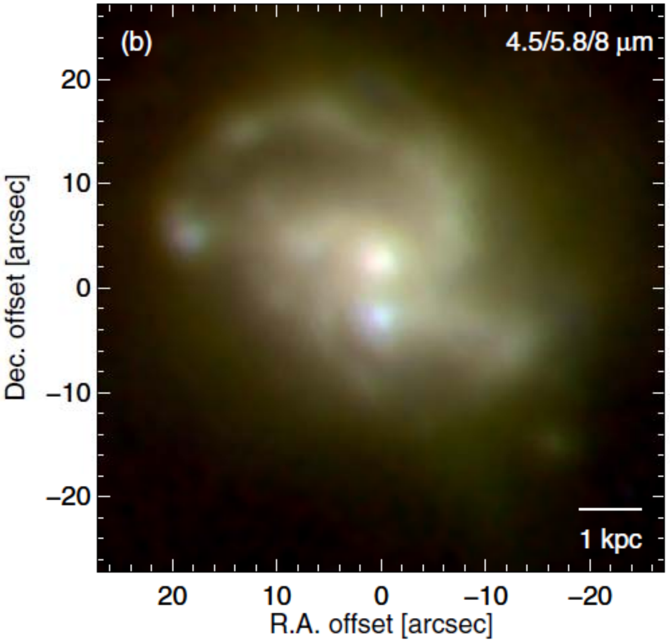
➔Cutting the gas refueling:

Gravity/halo quenching, Environment (harassment, strangulation, ram-pressure or tidal stripping..)

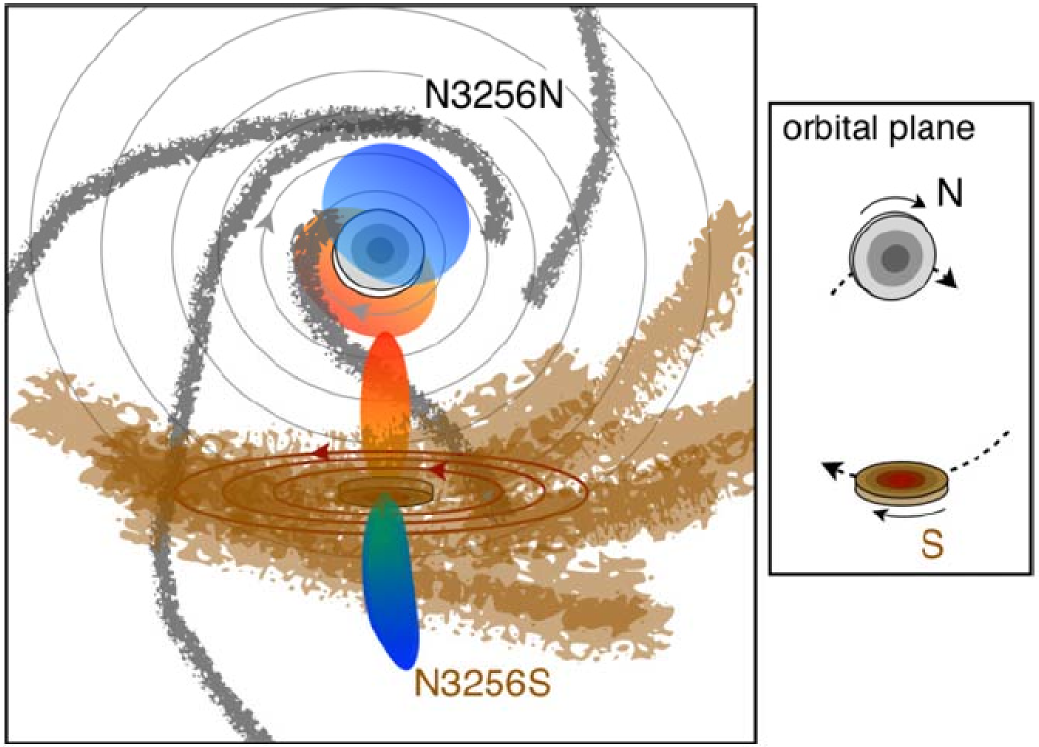
Peng et al 2010

Galactic wind quenching





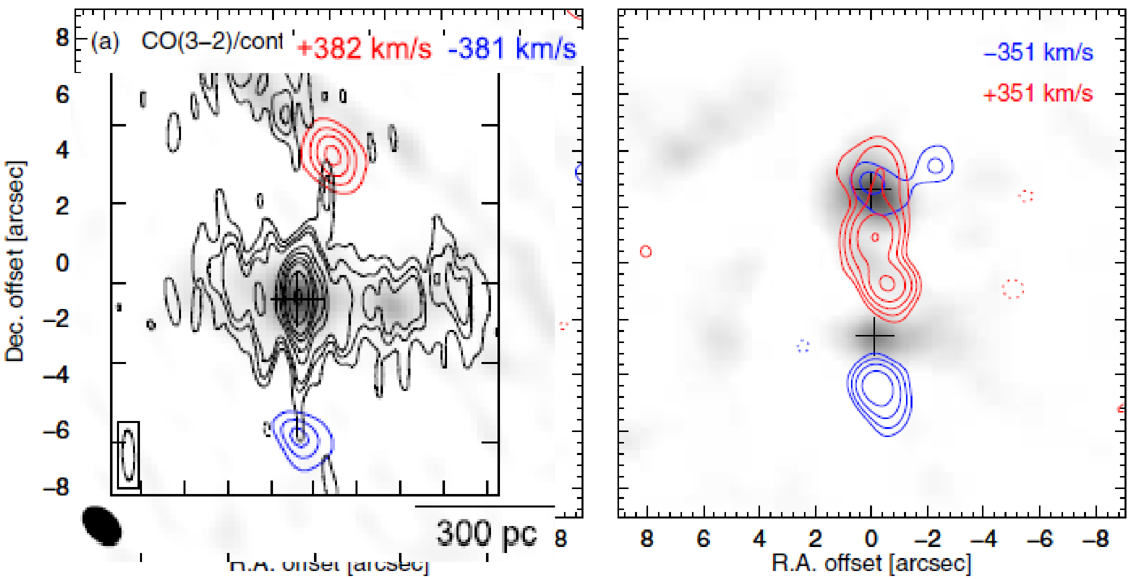
ALMA obs CO(3-2)
Merger-induced
Starburst: N3256
ULIRG z=0.01



High-velocity wings
in both nuclei!
One nearly edge-on, the other
face-on

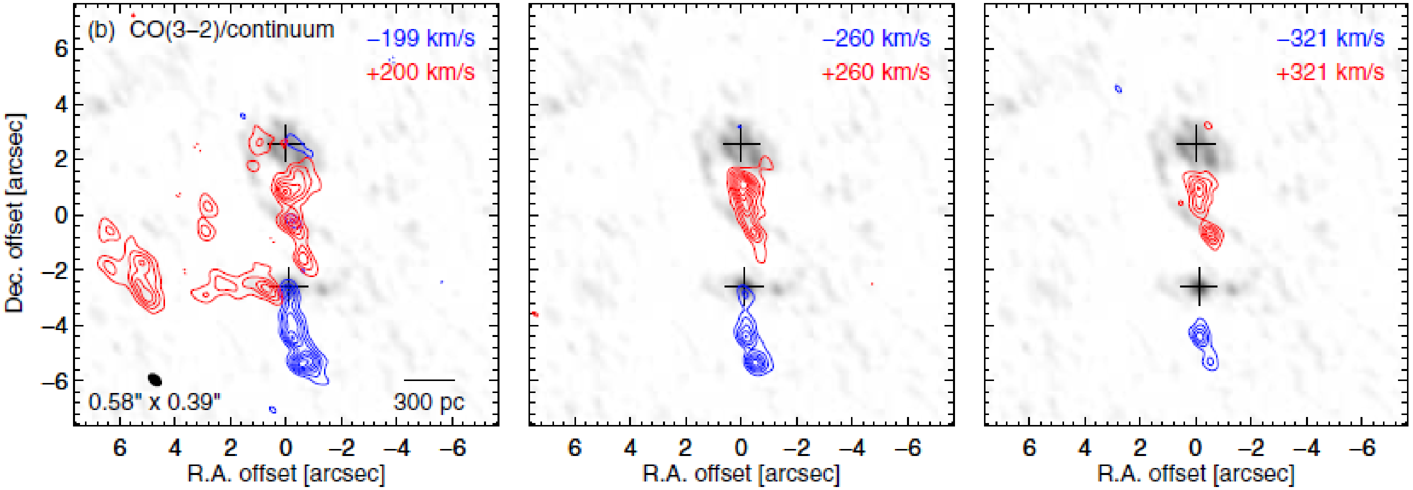
Sakamoto et al 2014

Two bipolar flows, $\tau \sim 1$ Myr



Northern outflow: SF
V > 750km/s, 60 Mo/yr
Wide angle

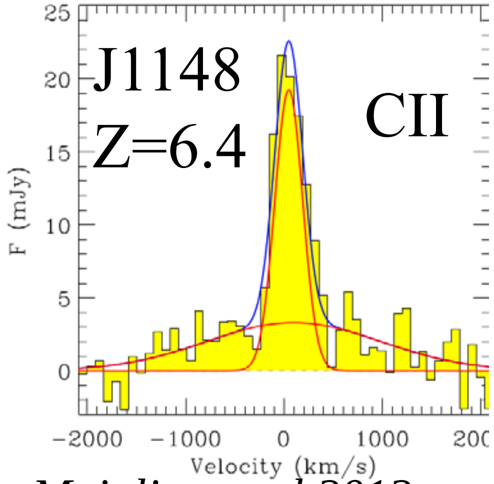
Southern outflow: AGN
V ~2000km/s out to 300pc
➢50 Mo/yr
➢Highly collimated



Rate comparable to SFR
➔efficient quenching?

Sakamoto et al 2014

Molecular outflows



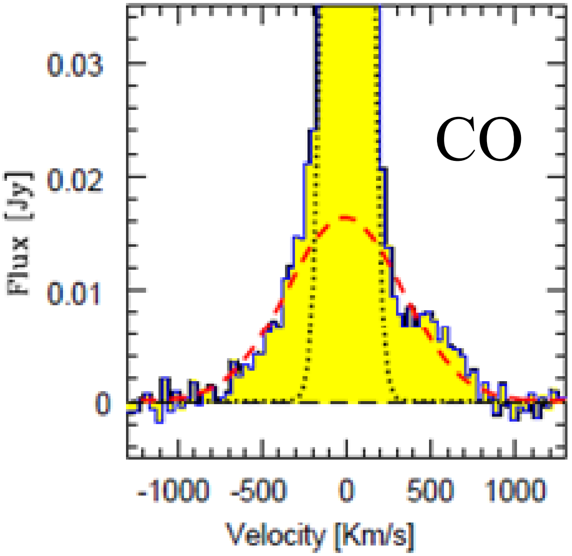
Maiolino et al 2012

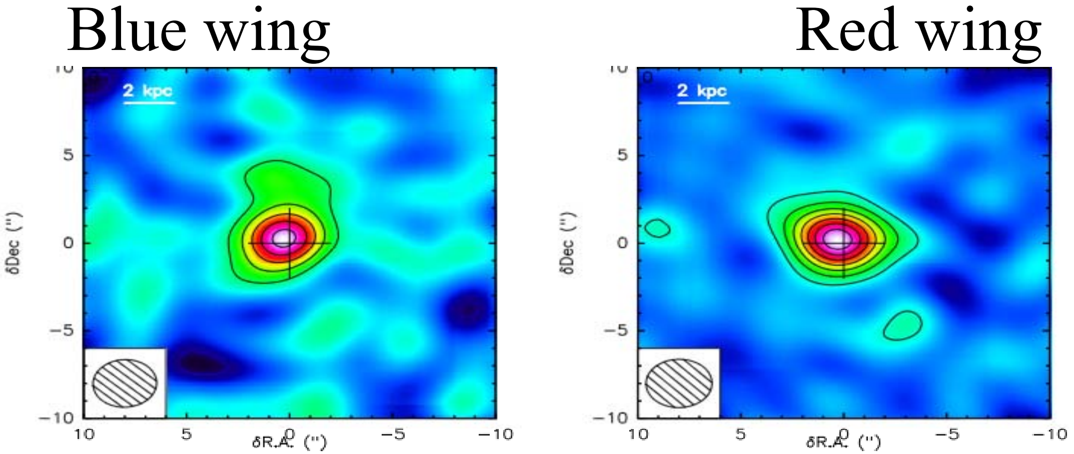
Mrk 231

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

On kpc scales, ➔
affects the galaxy, quenches SF?

IRAM *Ferruglio et al 2010*




Blue wing

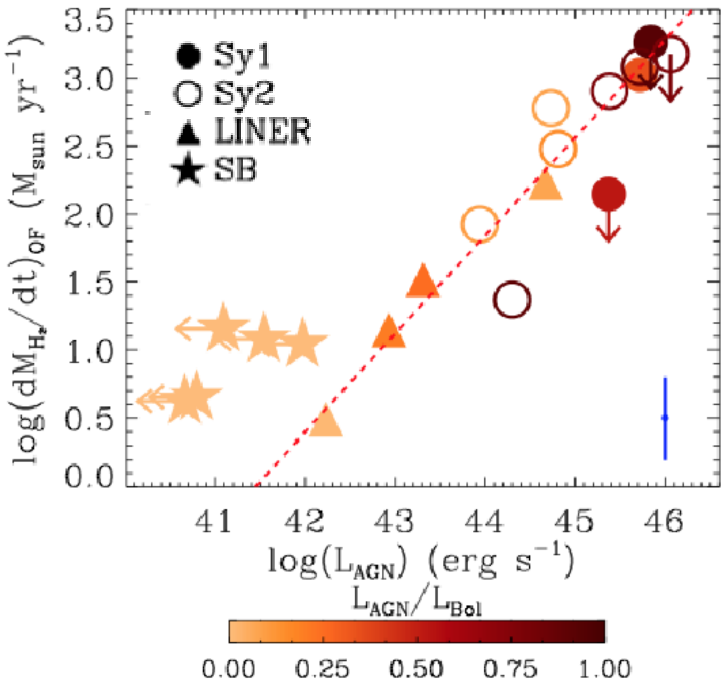
Red wing

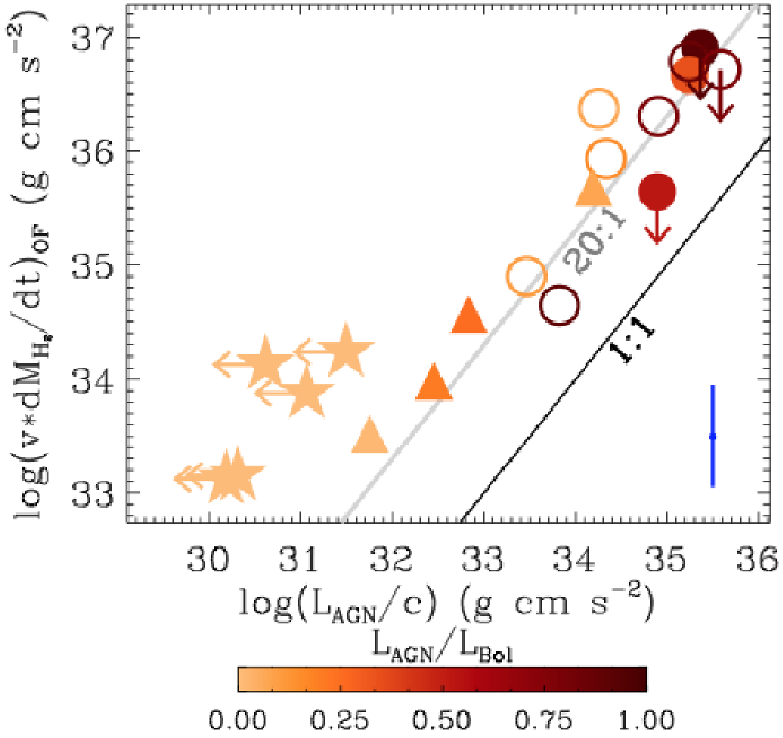
Cicone et al 2012

dM/dt = 3v M_{OF}/R_{OF} ~1000 Mo/yr, (5xSFR)
Kinetic power ~2 10^{44} erg/s ➔ AGN

High density, HCN, HCO+, *Aalto et al 2012*

Relations outflows with AGN





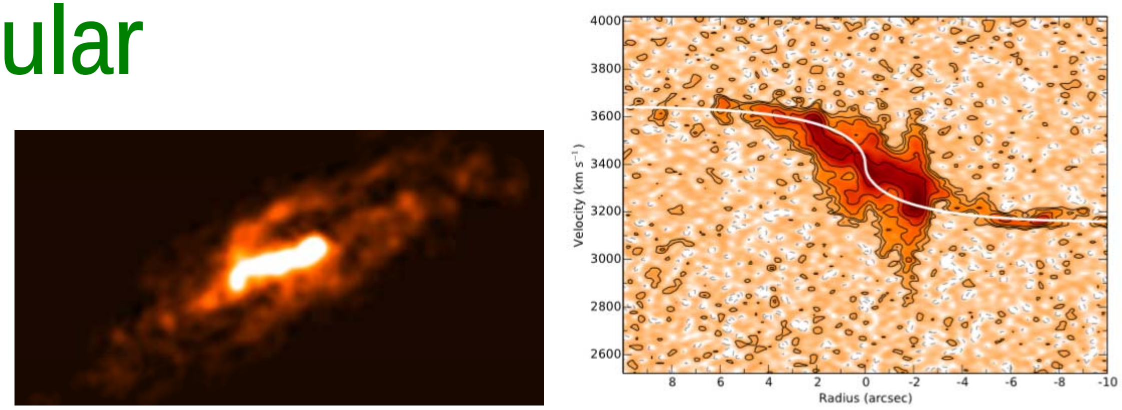
For AGN-hosts, the outflow rate
Correlates with the AGN power

Cicone et al 2014

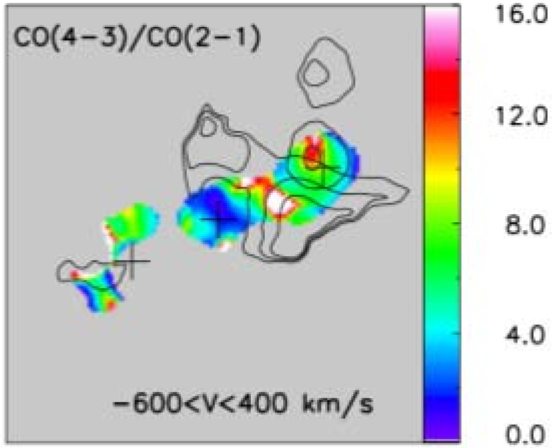
$dM/dt\ v \sim 20\ L_{AGN}/c$

Can be explained by
energy-driven outflows
(Zubovas & King 2012)

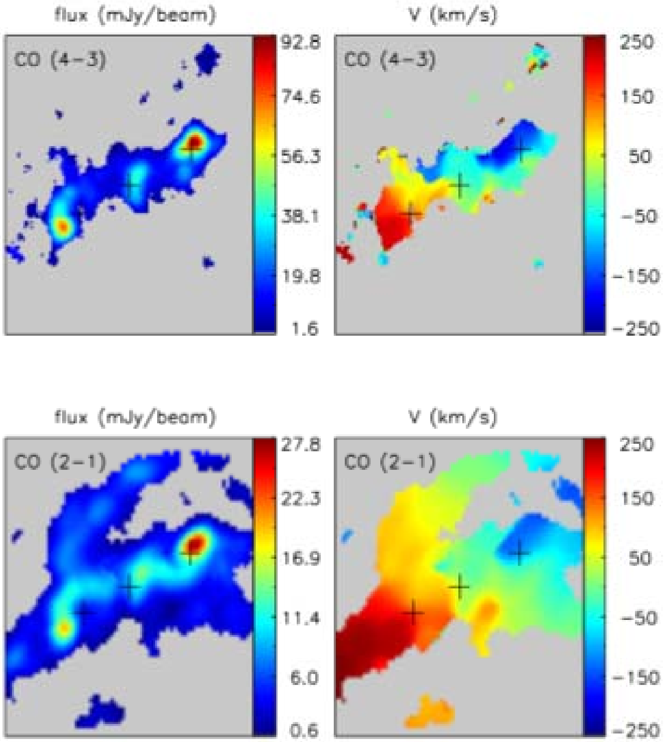
Radio mode: molecular flow IC5063

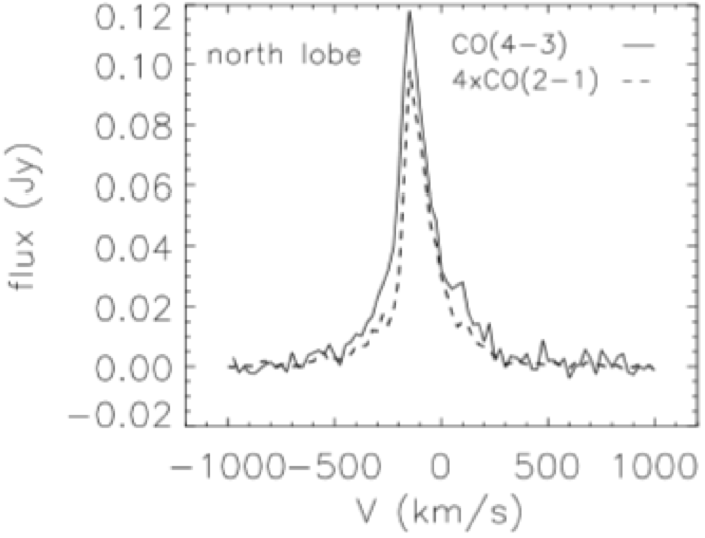


Morganti et al 2015



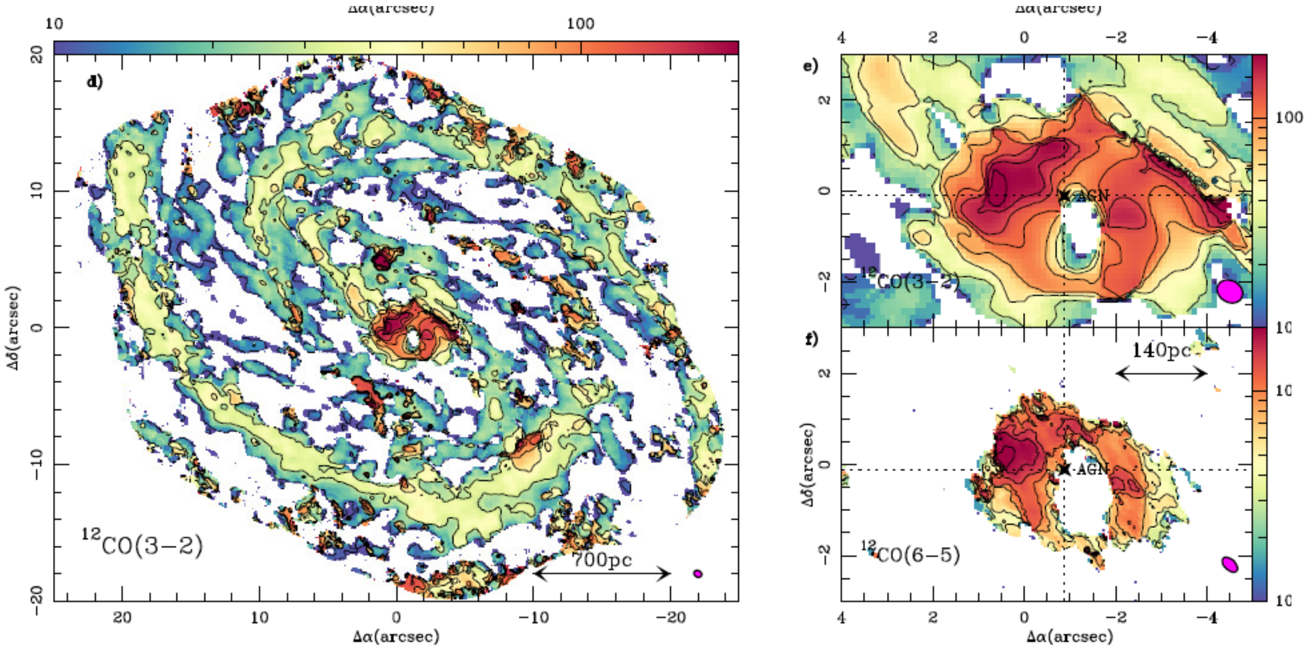
Some of the gas optically thin in the flow?



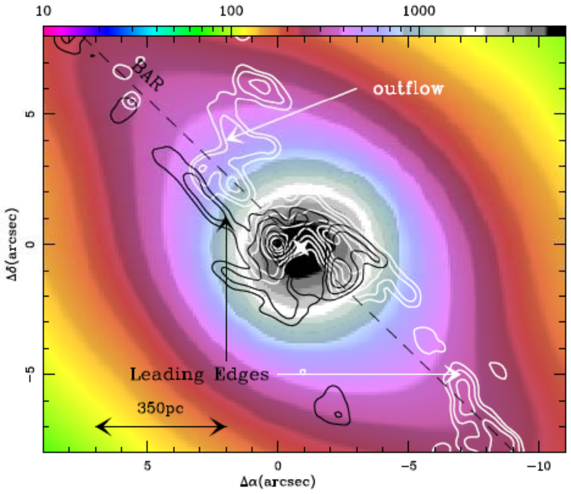


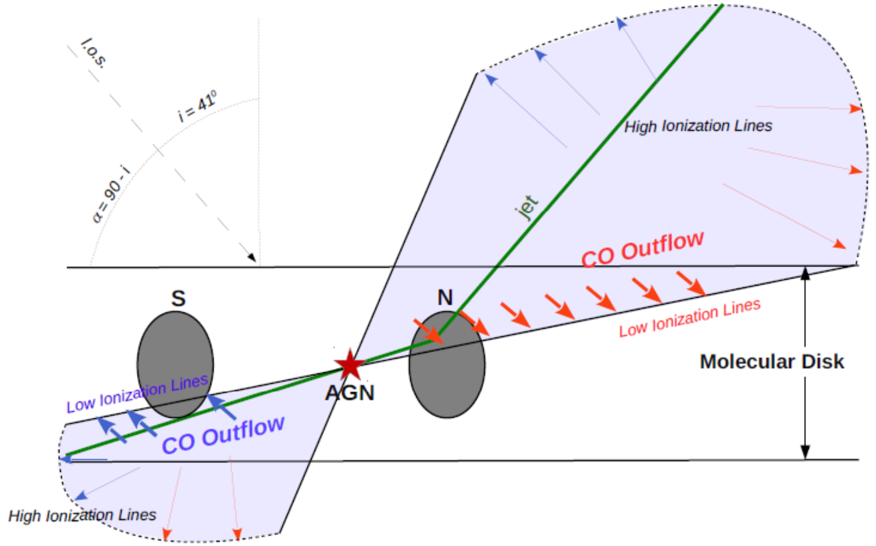
Dasyra et al 2016

AGN jet in the plane of N1068



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

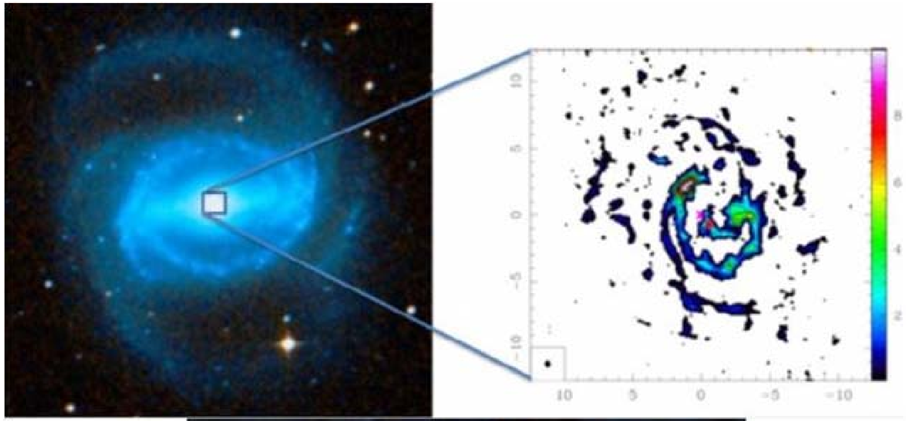




Outflow of 63Mo/yr
About 10 times the SFR in this CMD region

Garcia-Burillo et al 2014

Fueling BH and feedback in low-lum AGN

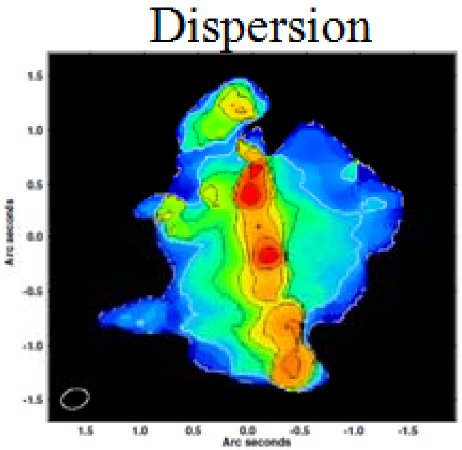


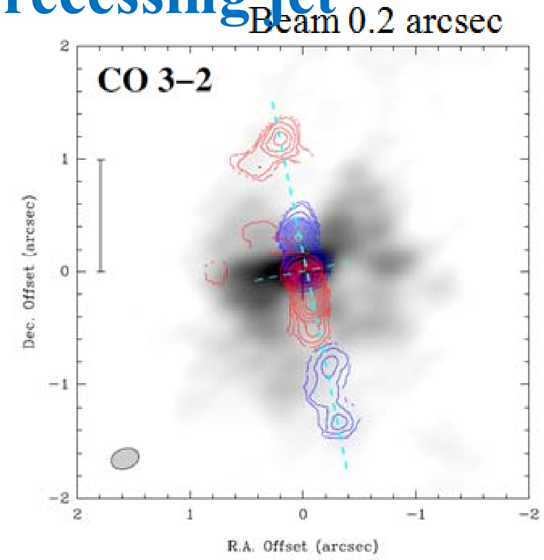
The smallest outflow detected
AGN feedback
V=100km/s, 7% of the mass
$M_{BH} = 4\ 10^6 Mo$
Flow momentum $=10\ L_{AGN}/c$

Combes et al 2013

N1433
CO(3-2)
ALMA
On HST

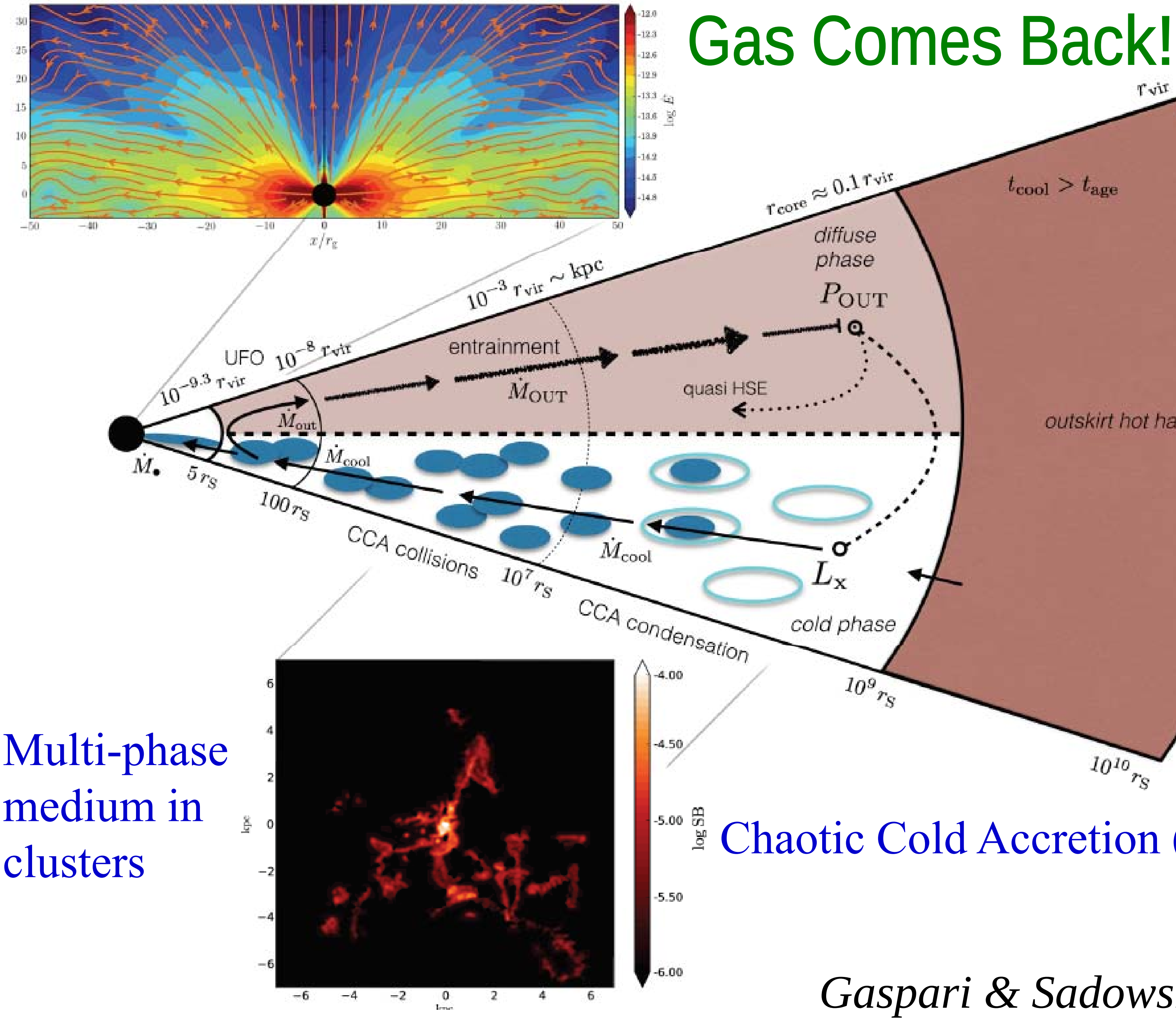
N1377 precessing jet





Aalto et al 2015

Gas Comes Back!



Multi-phase medium in clusters

Chaotic Cold Accretion (CCA)

Gaspari & Sadowski 2017

Cold gas in filaments

Inflow and outflow coexist

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

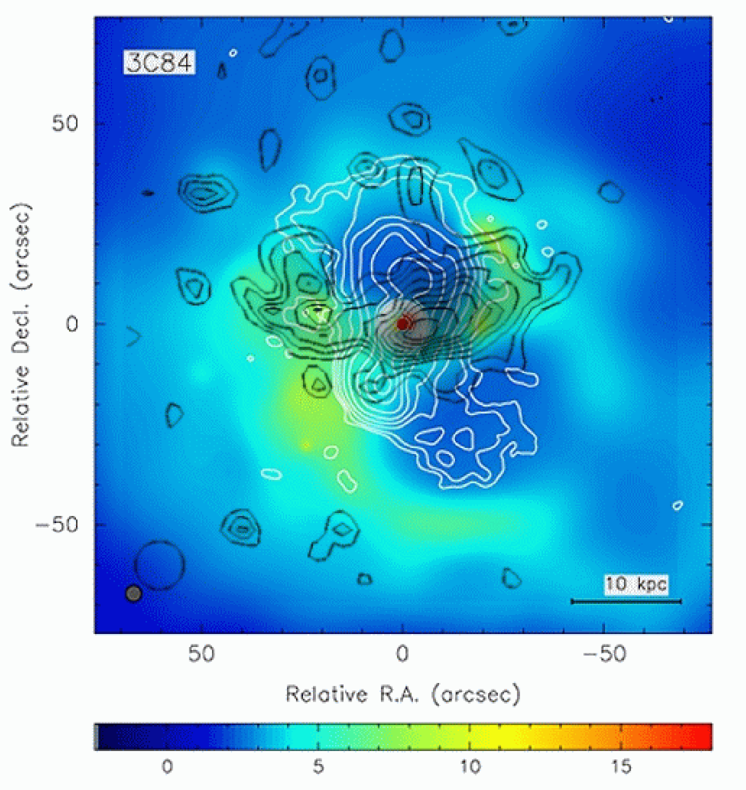
The bubbles create inhomogeneities and further cooling
At R~20kpc, tc/tff ~10
➔thermal instability *(McCourt et al 12)*

The cooled gas fuels the AGN

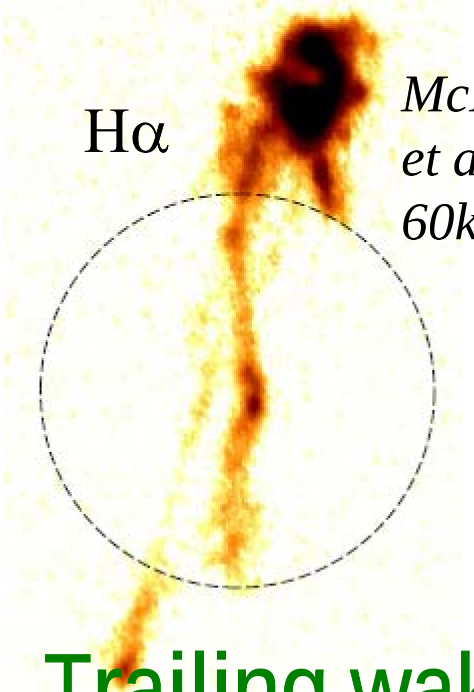
Velocity much lower than free-fall
Salome et al 2008, 2011


X-ray Perseus A , *Fabian et al 2003*

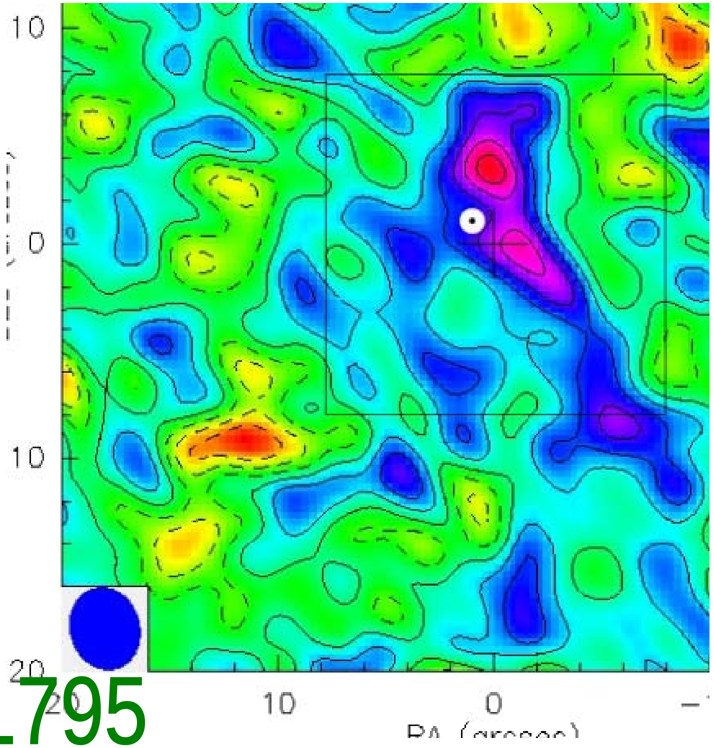
Salomé et al 2006

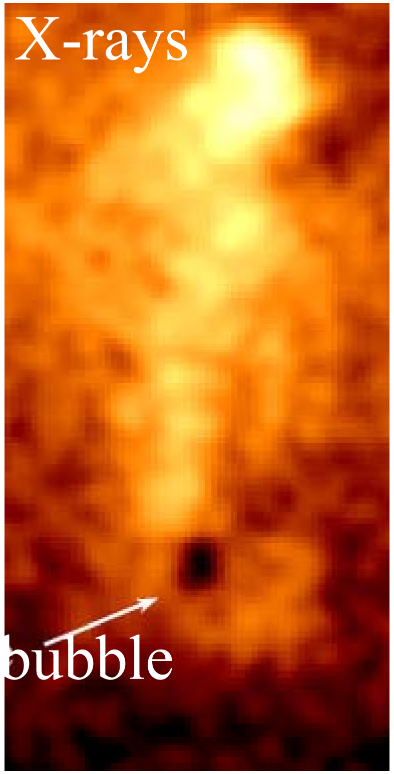


Trailing wake A1795

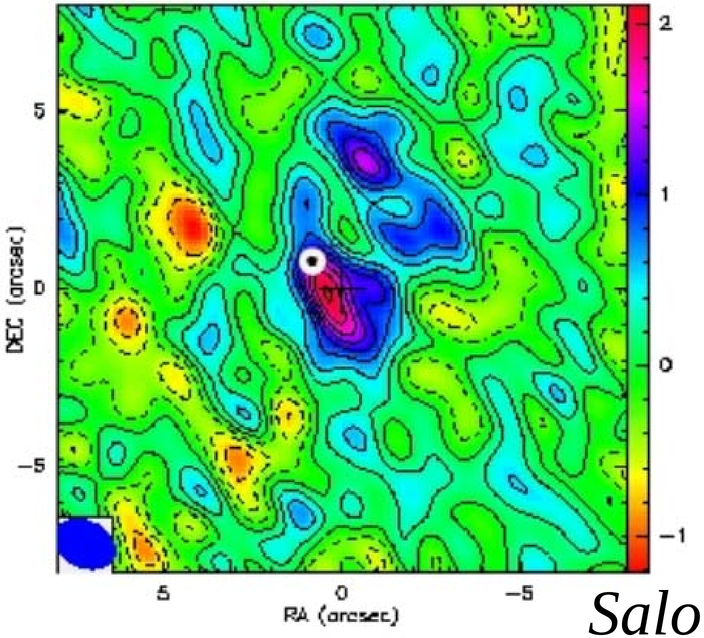


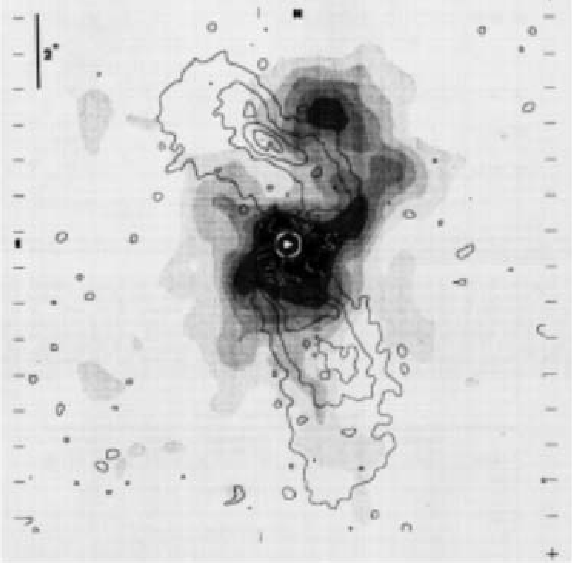
McDonald et al 2009
60kpc tail



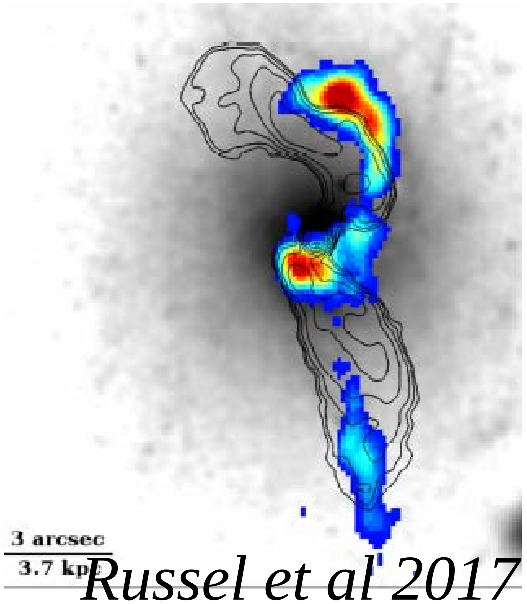


tcool= 300Myr= tdyn



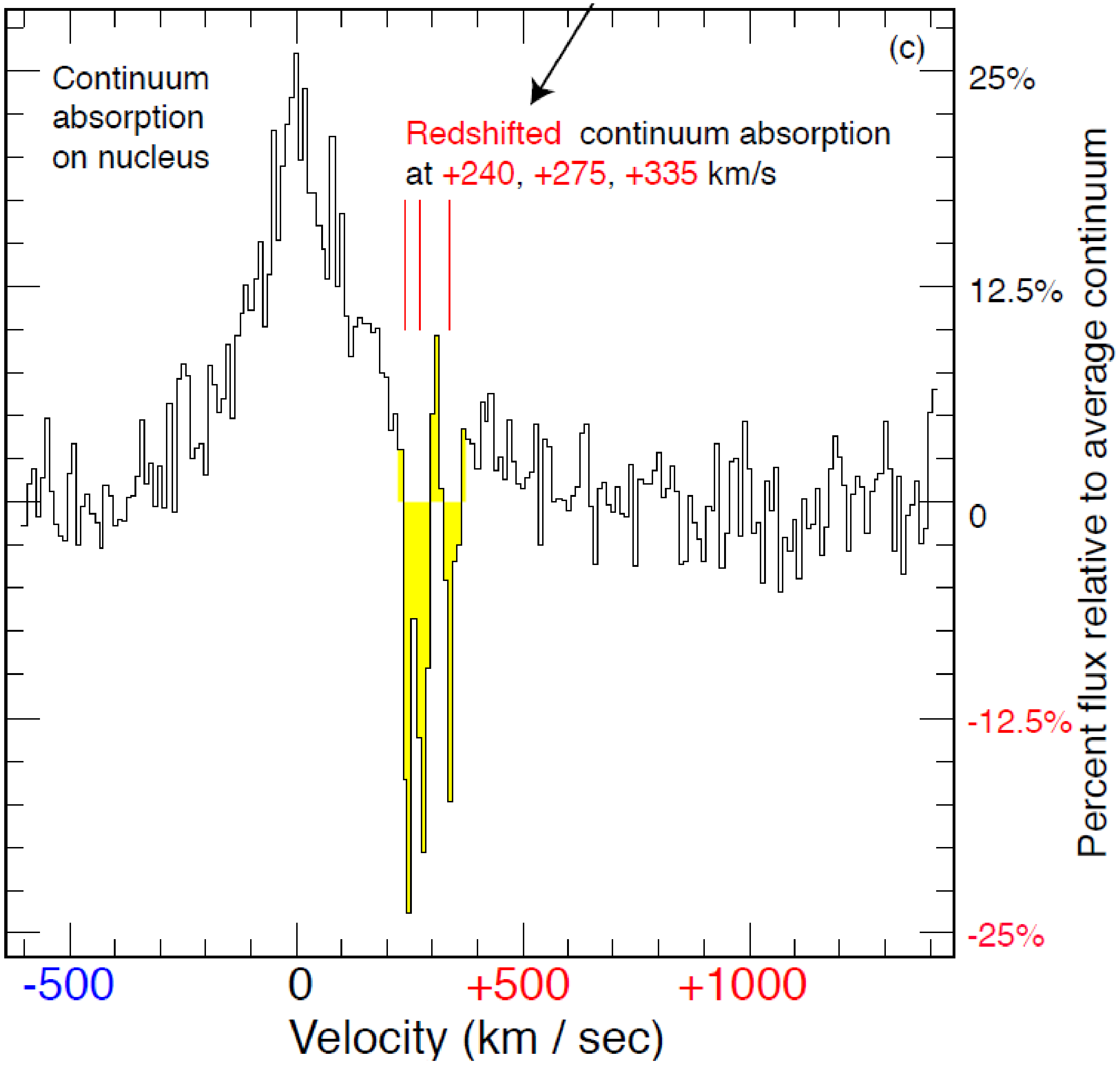


Salome & Combes 2004



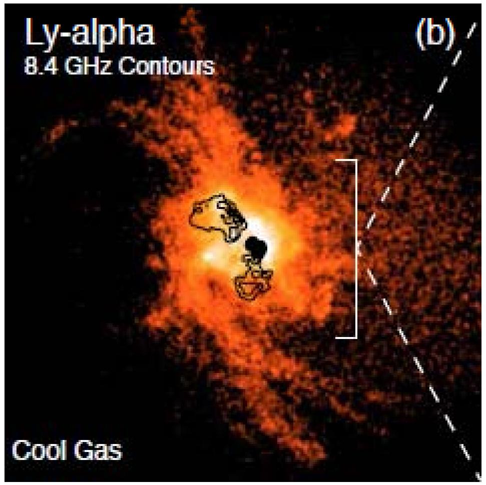
Russel et al 2017

ALMA: cold gas in cool core clusters



Abell 2597 ALMA
CO(2-1) absorption
in front of the
AGN synchrotron

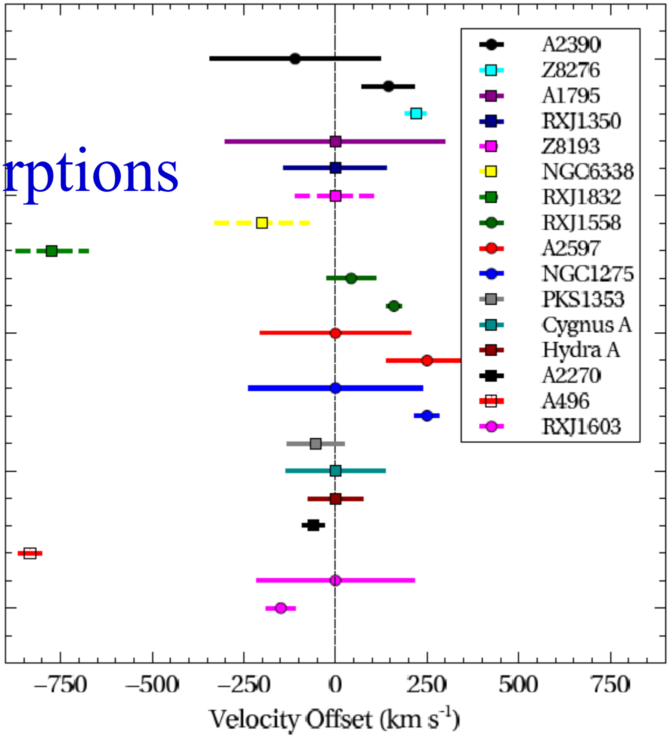
Red-shifted only
Dense clouds
fueling the AGN



Tremblay et al 2016

CO absorptions

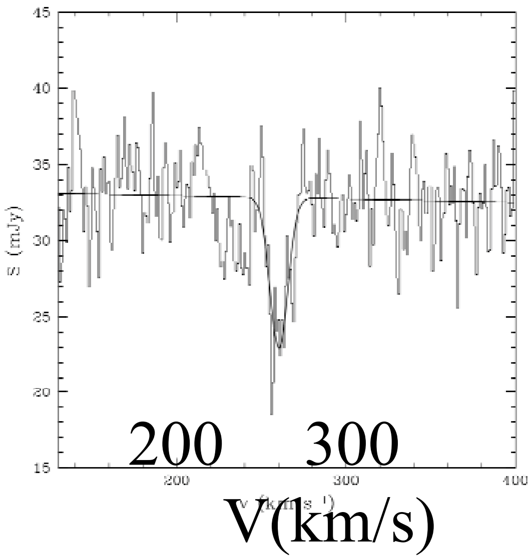
HI absorptions



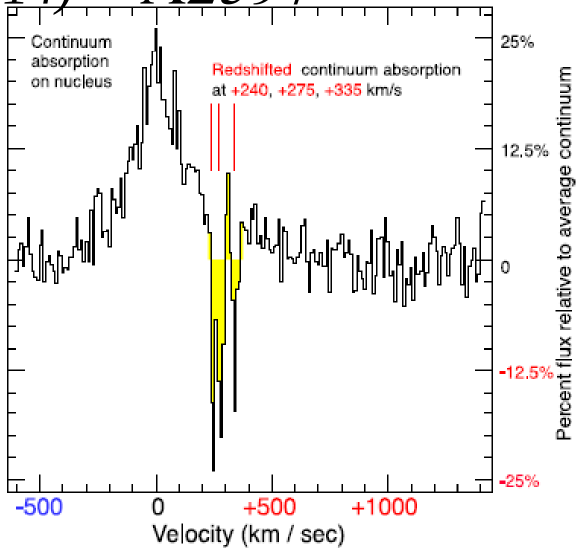
10^{21}-10^{23} cm^{-2} cold (< 40K) gas present within 30kpc of the BCG

Only inflowing in CO
Also outflowing in HI

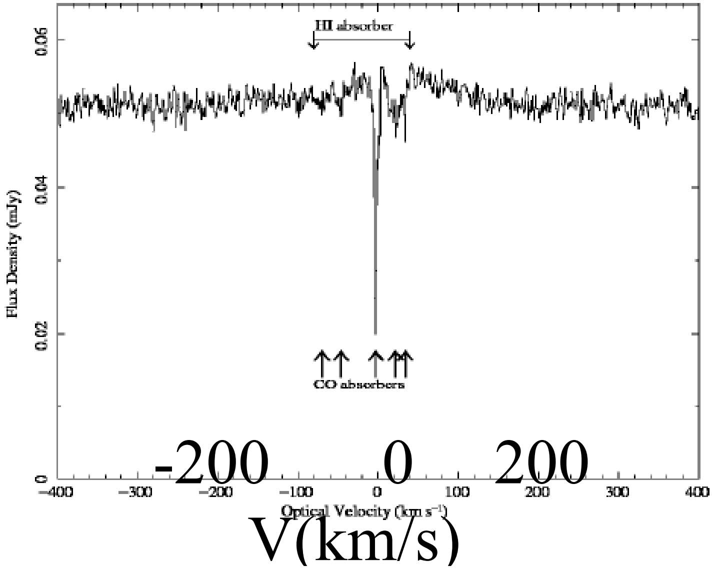
N5044 *(David et al 2014)*



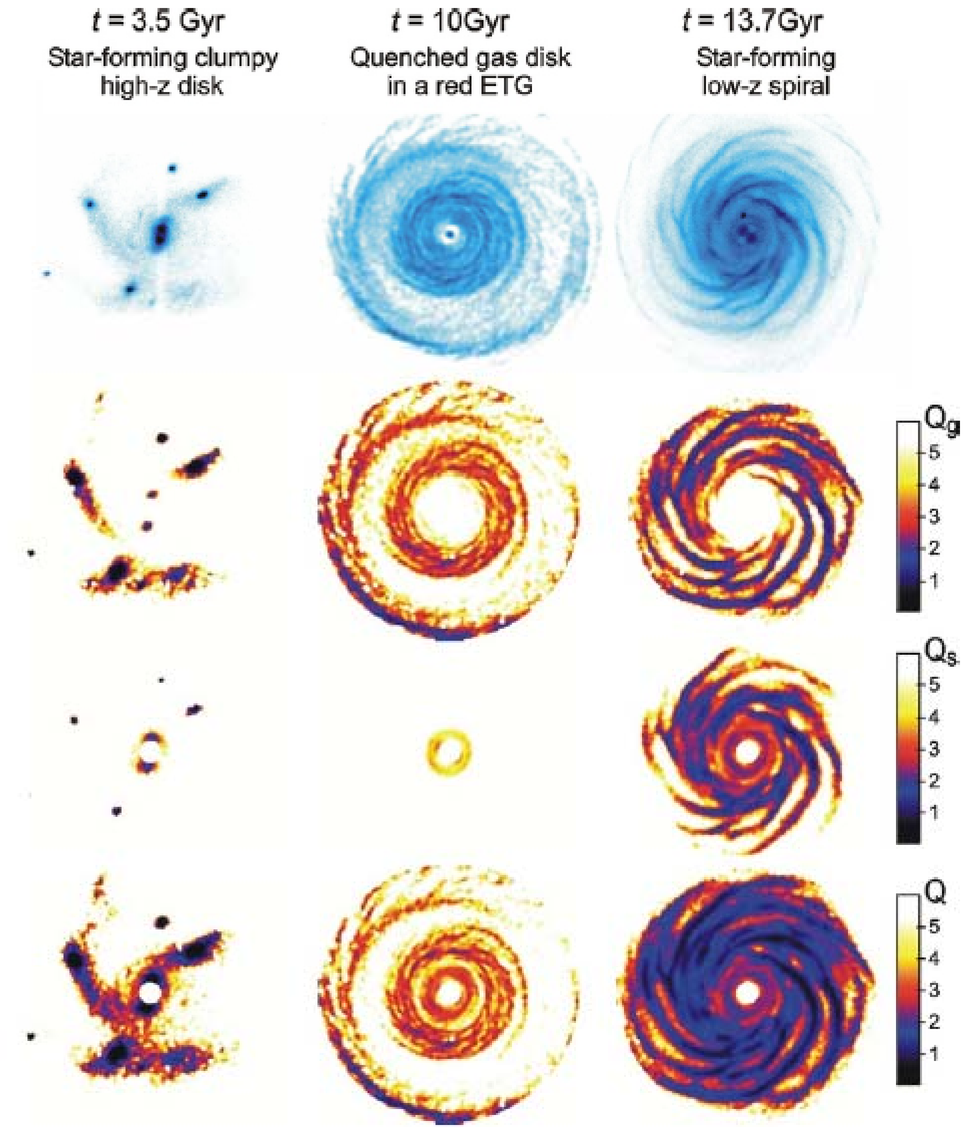
A2597



Hydra A *(Edge et al)*



Morphological Quenching (~5 Gyr)



Disks only are more unstable

Bulges and central condensations stabilise disks

Toomre parameter Q= σ/σcrit

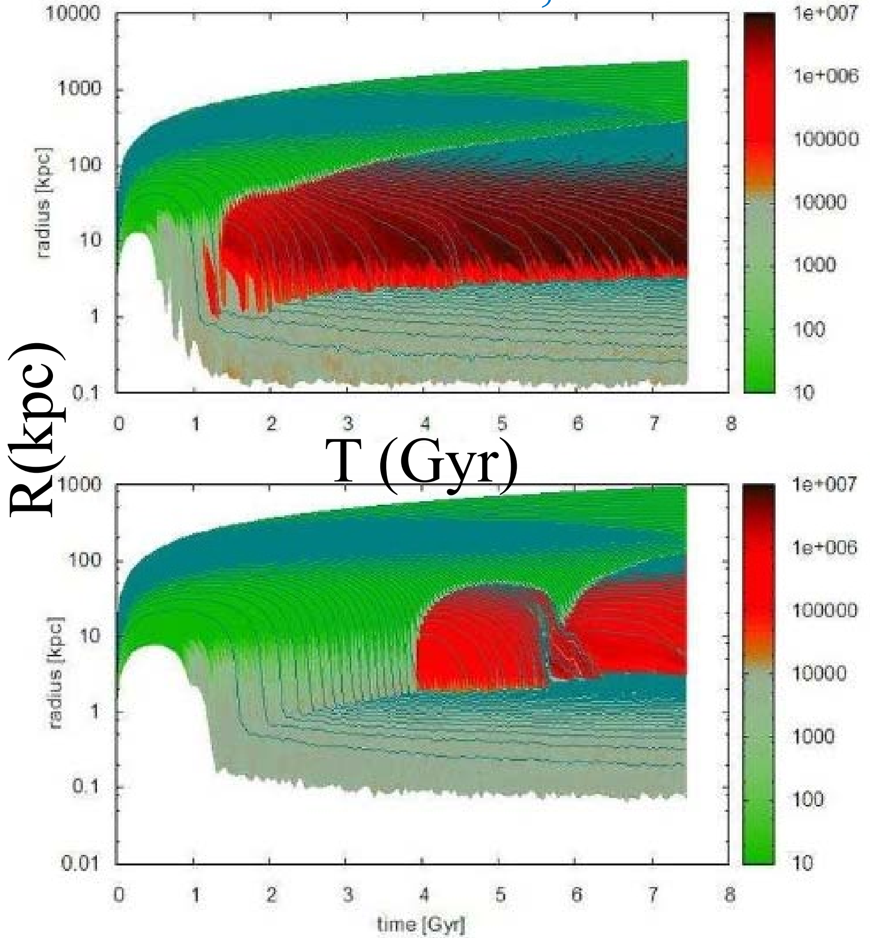
σcrit= 3.36 GΣ /κ

Bulge increases κ, and Q
If σ and Σ remains constant
➔ Inside out quenching

Martig et al 2009

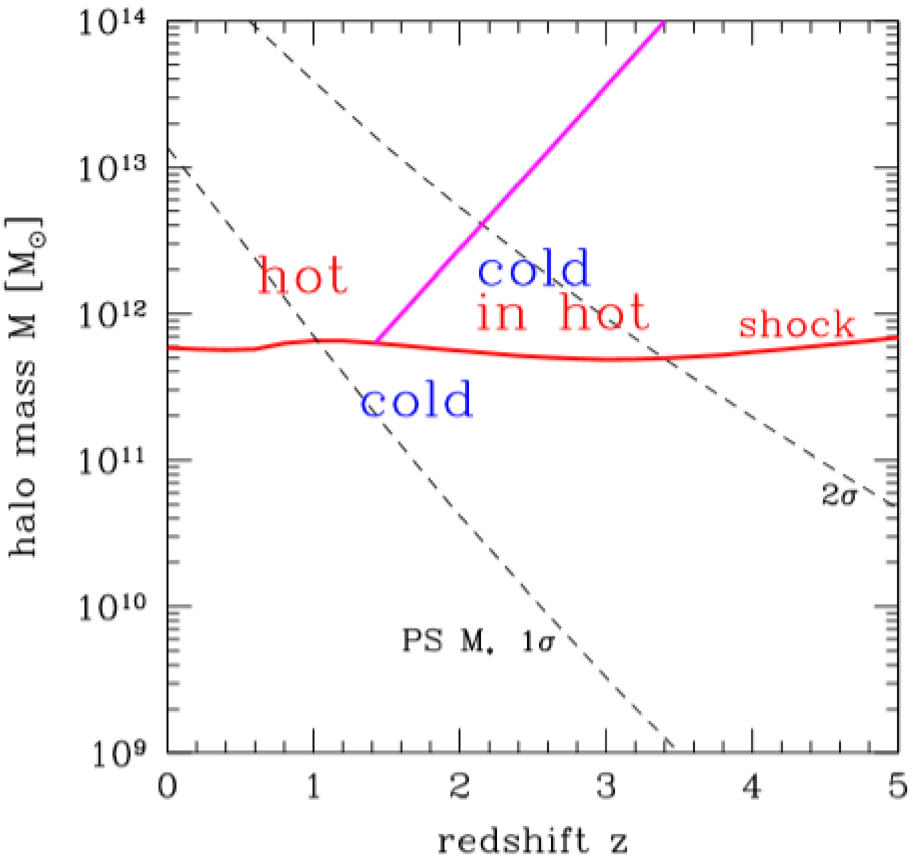
Gravity quenching

Mh>10^{12}Mo, shocks



Mh<10^{12}Mo

Dekel & Birnboim 2005

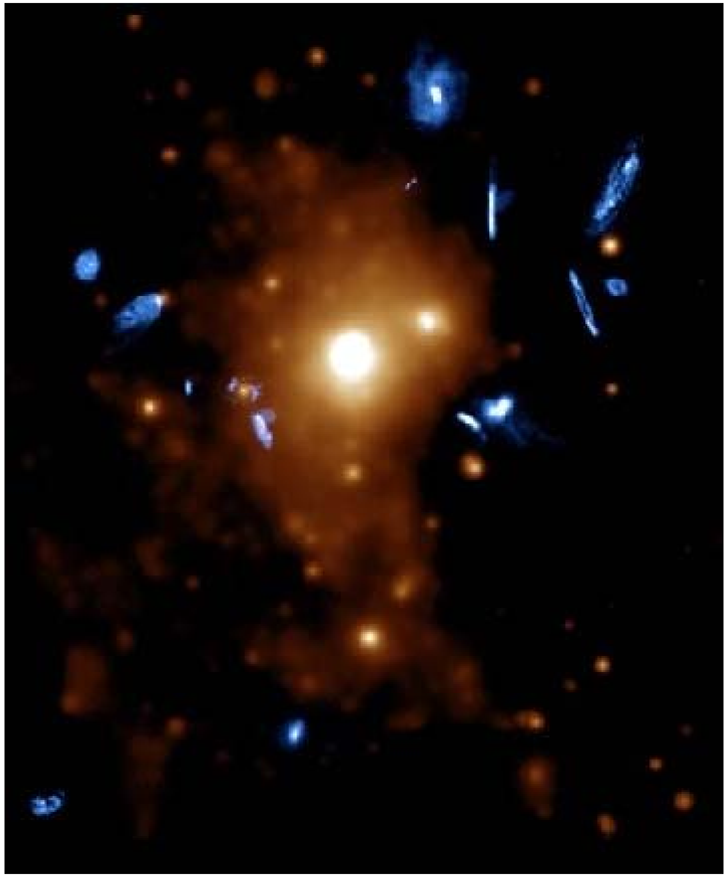


Depends on halo mass (not galaxy)
May stop the gas supply
already in groups ➔ red and dead

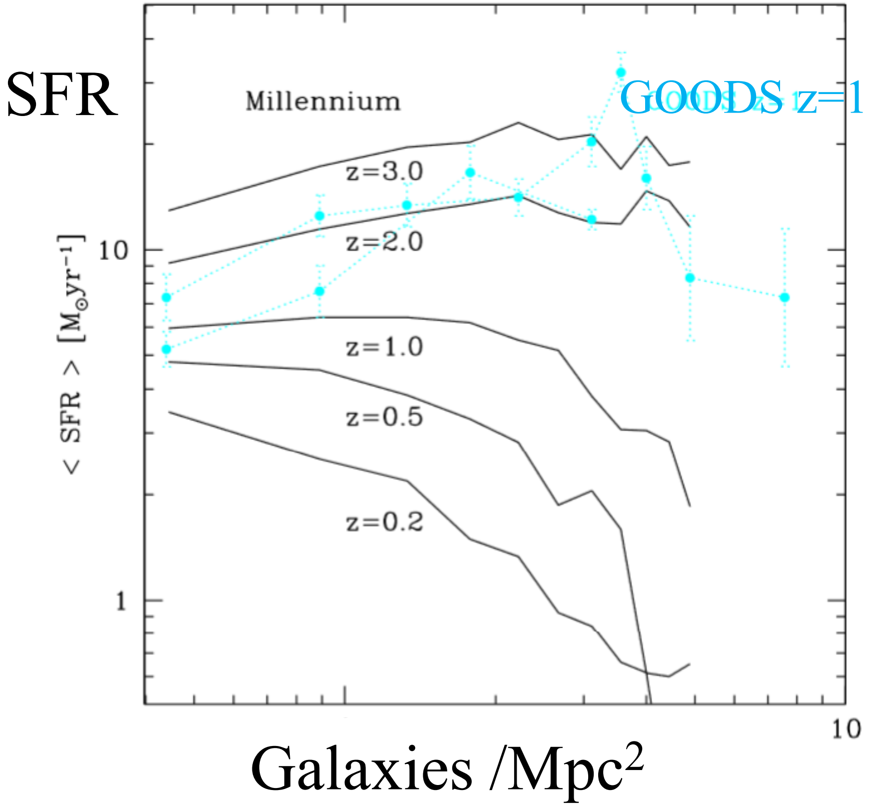
4- Environmental effects

- ➔ Gas stripped in clusters at z=0
- ➔ A reversal is expected at z~1

Chung et al, VIVA with VLA



Elbaz et al 2007

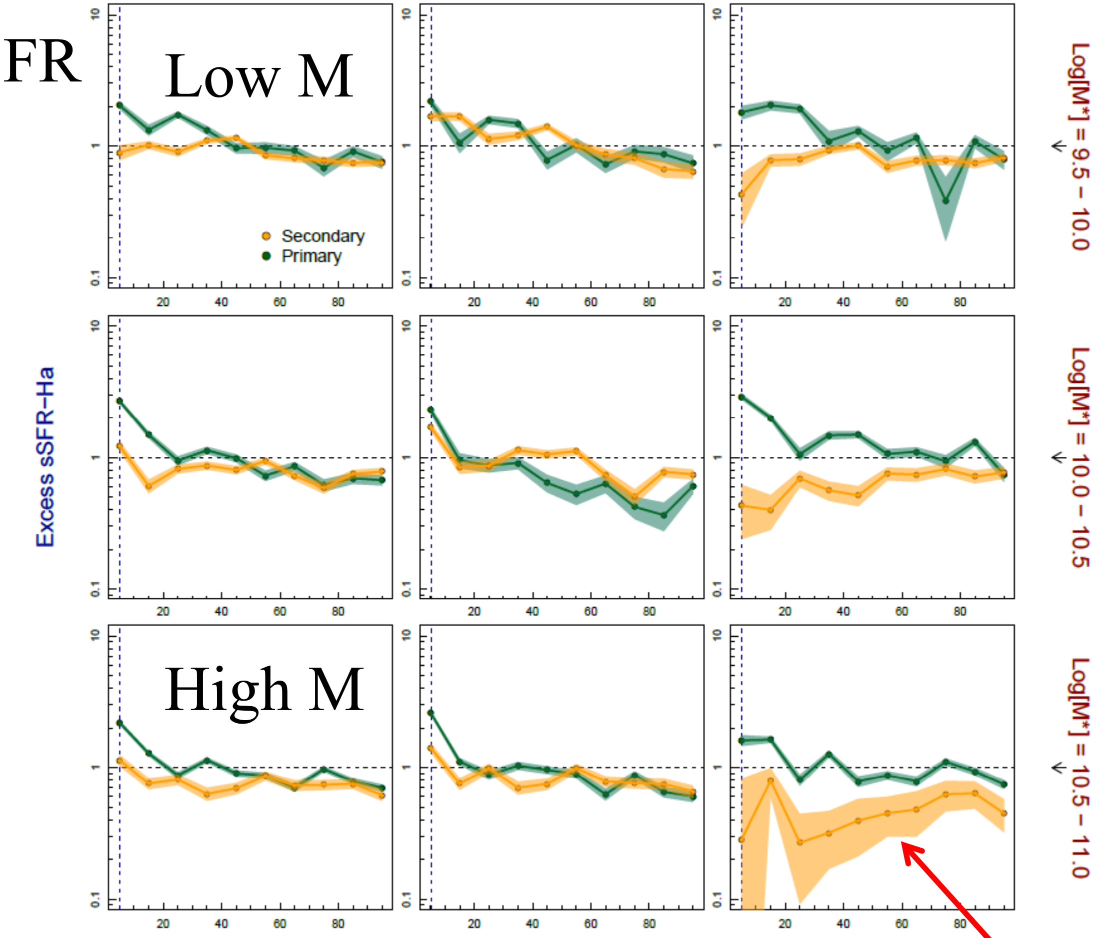


The reversal of the star formation-density relation?

Effects of mergers (major or minor)

All Major minor

SFR



Low M

High M

Pair separation

secondary

SF in general enhanced in major mergers

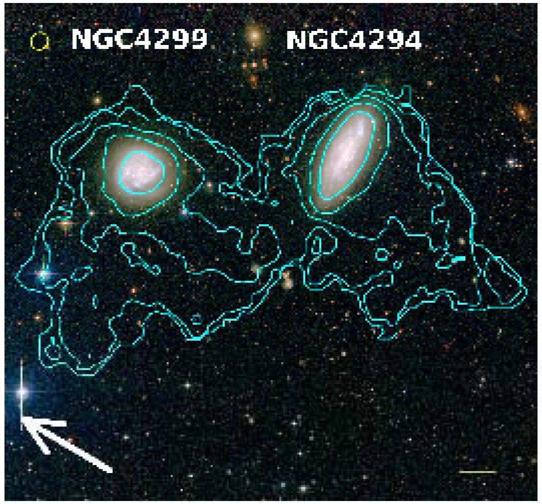
However, suppressed in minor mergers, for the smallest companion

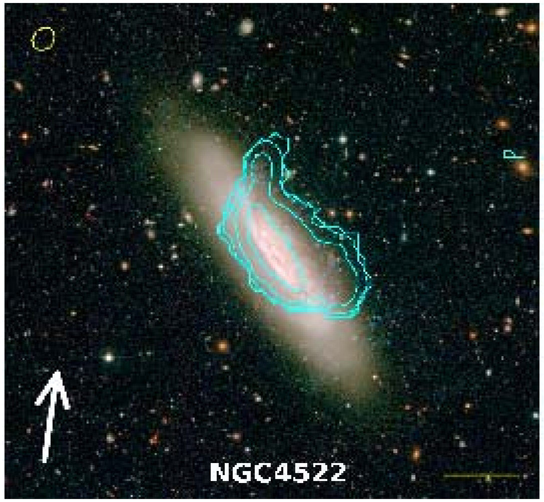
➔Gas heating, stripping at the benefit of the primary

Davies et al 2015 (GAMA) 300 000 galaxies, 20 000 pairs

Tides and ram-pressure

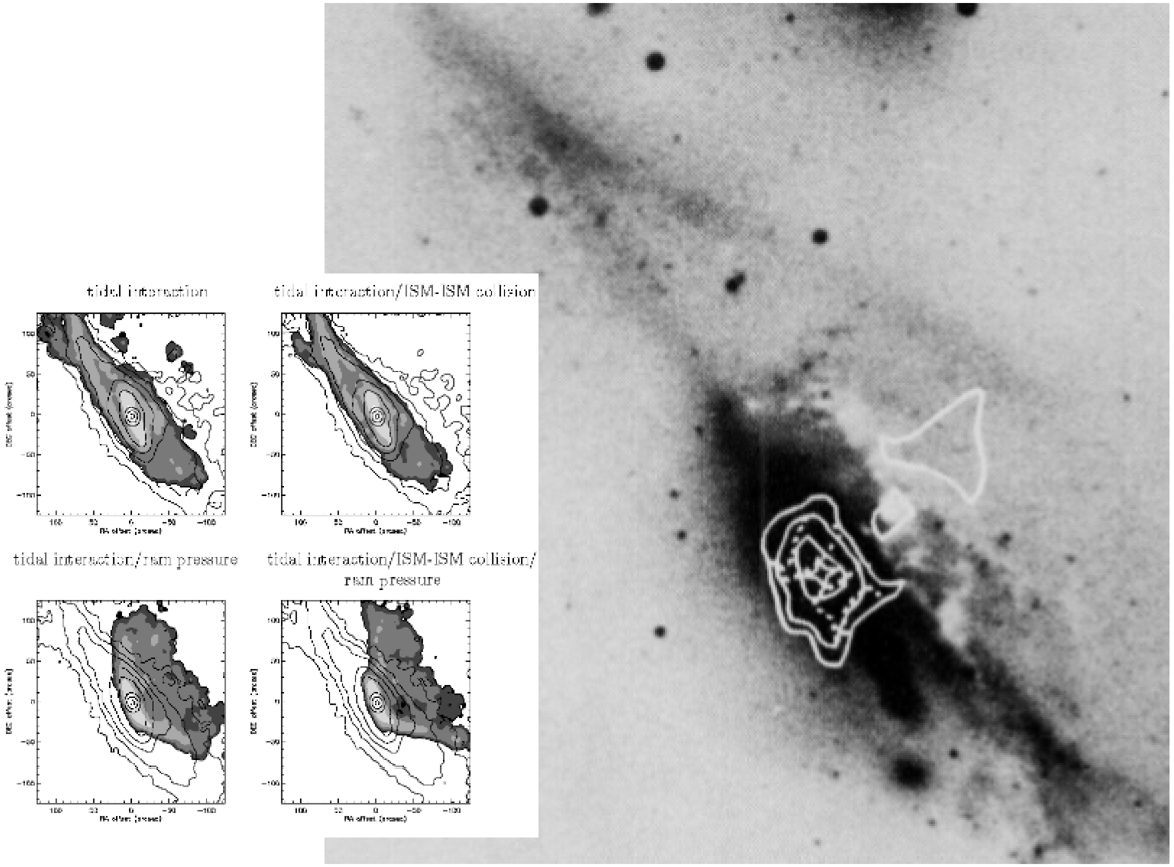
Both physical processes are acting, difficult to disentangle





NGC 4438 & 4435 in Virgo

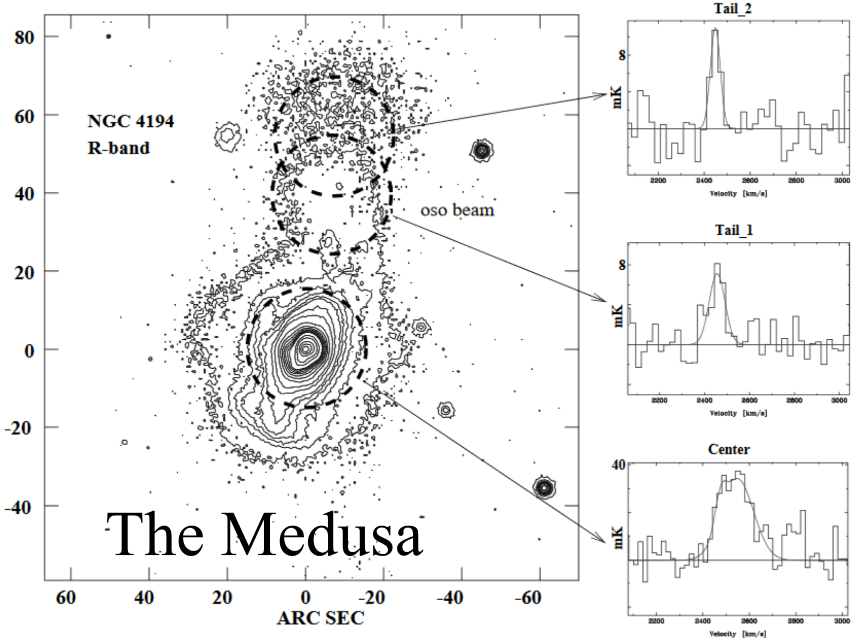
First CO detections outside galaxy disks



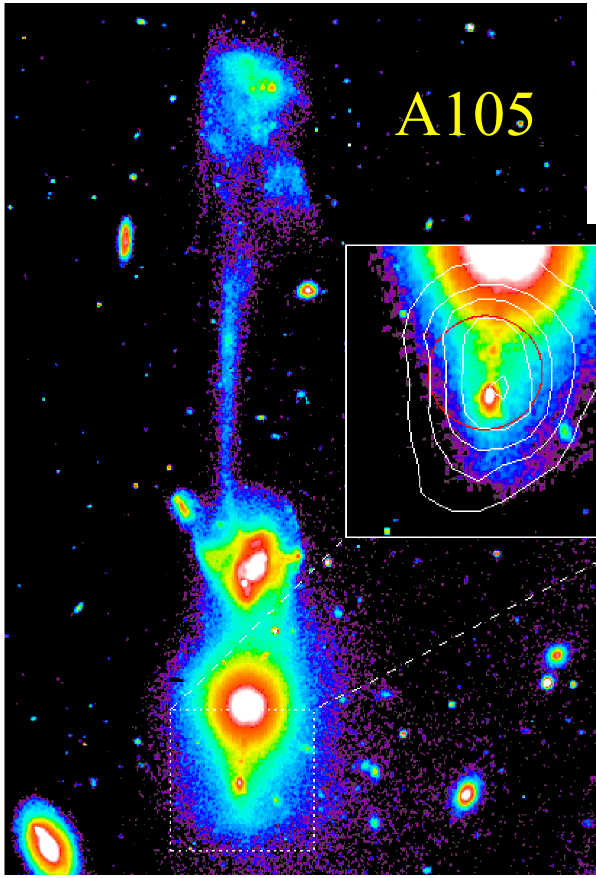
Vollmer et al 2005 *Combes et al 1988*

CO detection in tidal dwarfs and tails

Time-scales of
the tail formation
a few 100 Myr



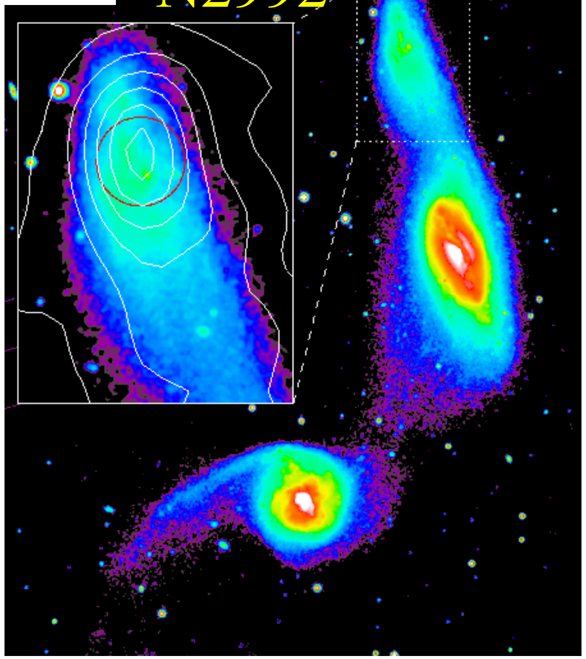
Time-scale of
the bridge
50-100 Myr



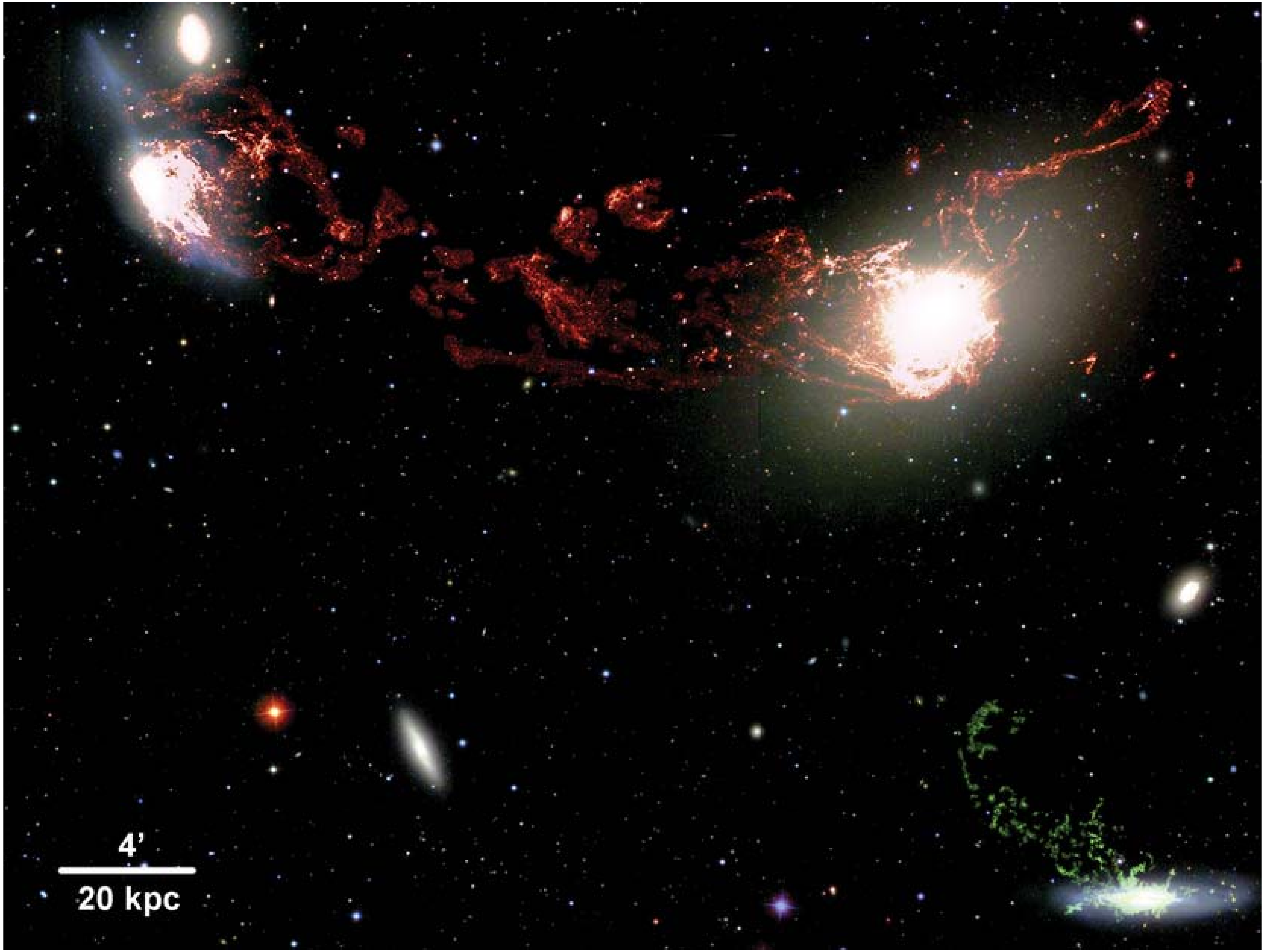
Aalto et al 2001

Time to form H_2 clouds
and new stars few 10Myr

Braine et al 2000

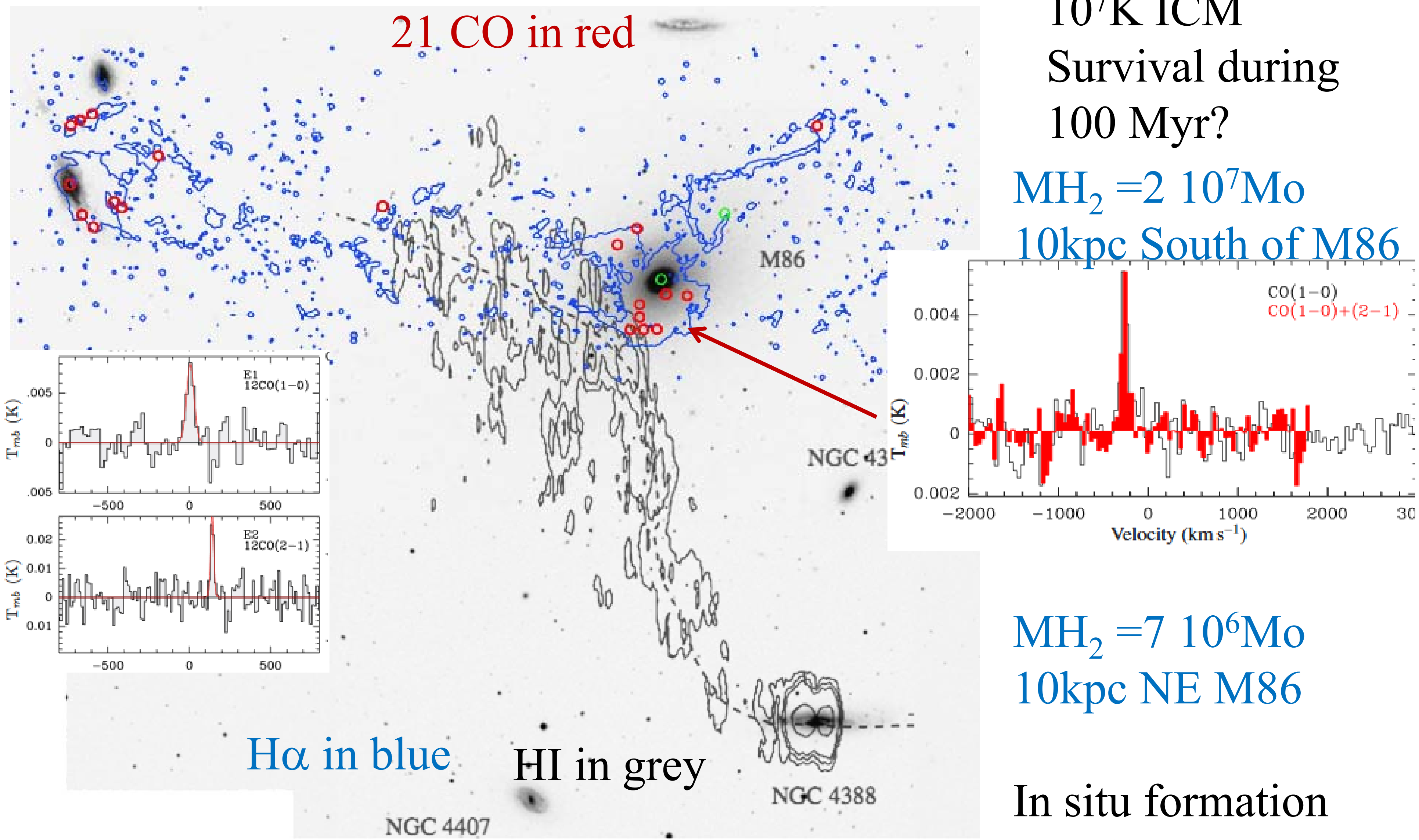


Giant Hα tail in Virgo



Kenney+ 2008

Tail around M86 : H2 gas in hostile environment



21 CO in red

Hα in blue

HI in grey

10^7K ICM
Survival during
100 Myr?

$M_{H_2} = 2\ 10^7 M_o$
10kpc South of M86

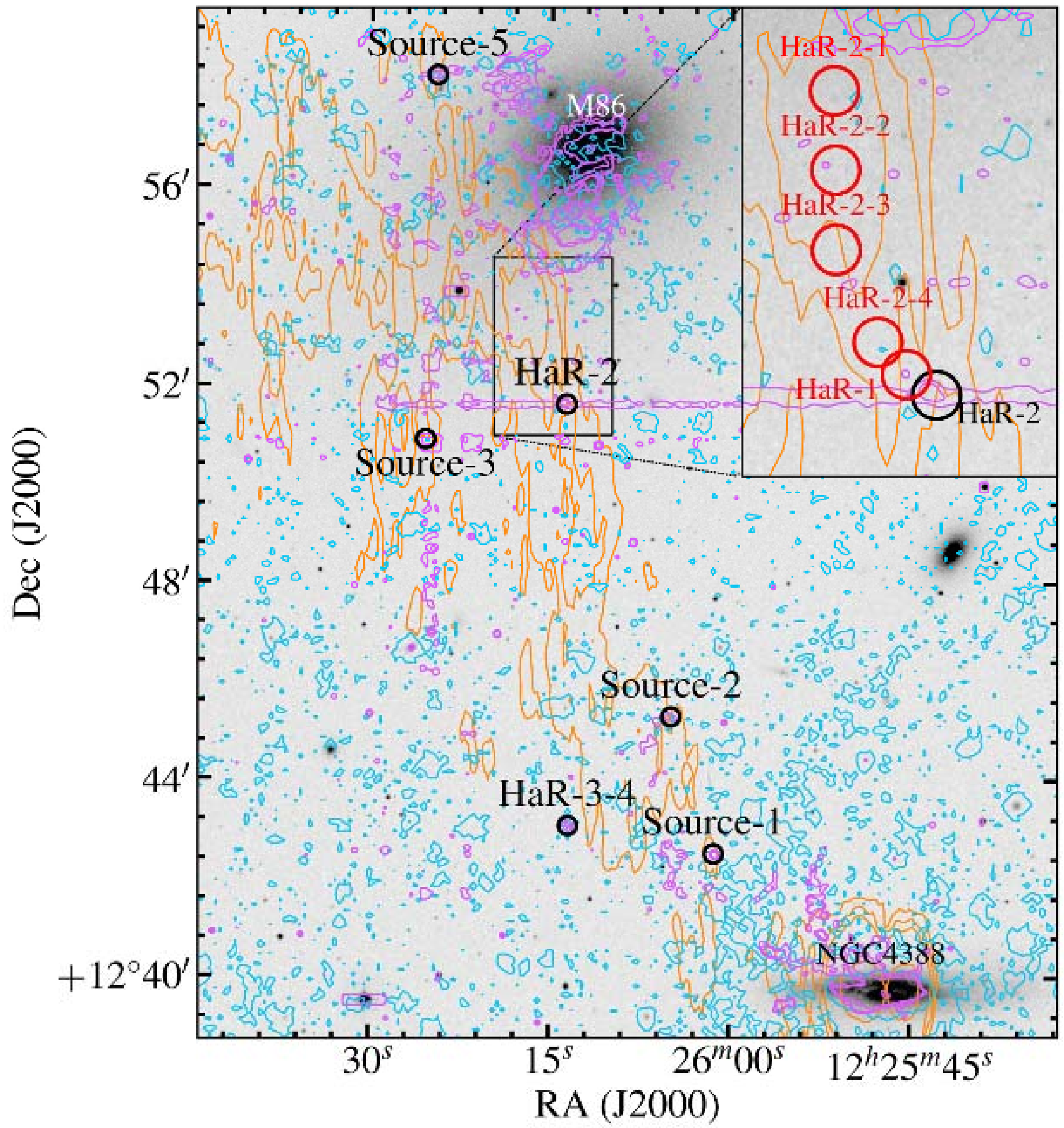
$M_{H_2} = 7\ 10^6 M_o$
10kpc NE M86

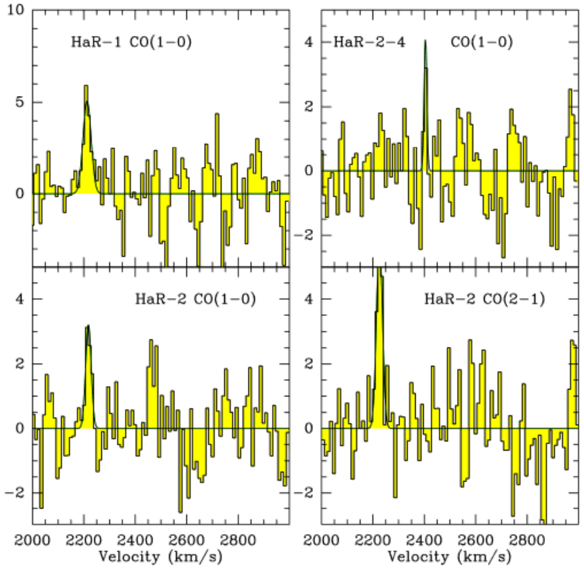
In situ formation
Or tail from N4438

Dasyra et al 2012

Tidal tail N4388 – M86

At 100kpc distance, 2 10^6Mo of H_2





➔Formation in situ of H_2

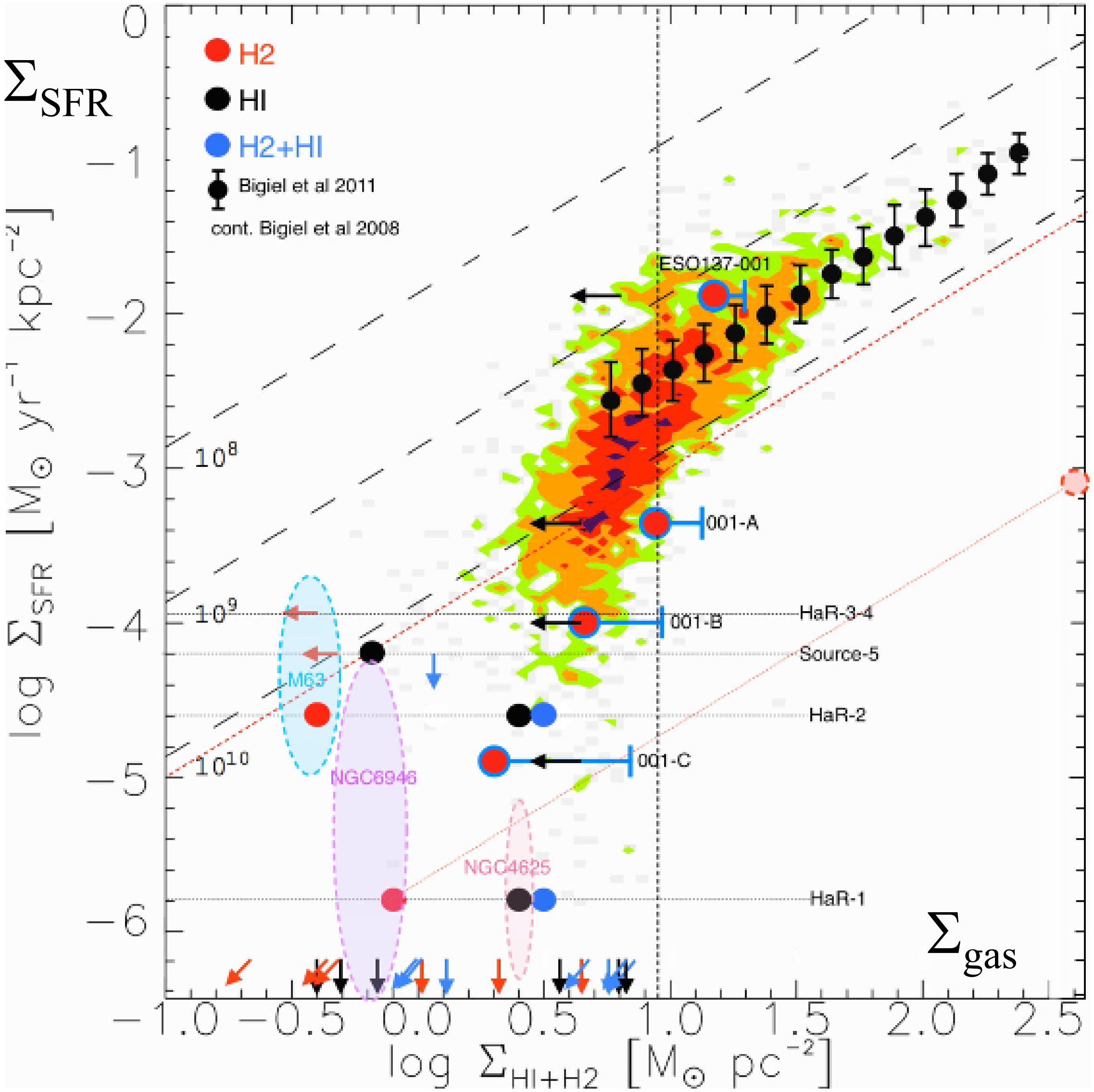
Star formation enrich the ICM

Low SFE, tdep ~500Gyr

Verdugo et al 2015

Star formation efficiency

Comparison with XUV disks



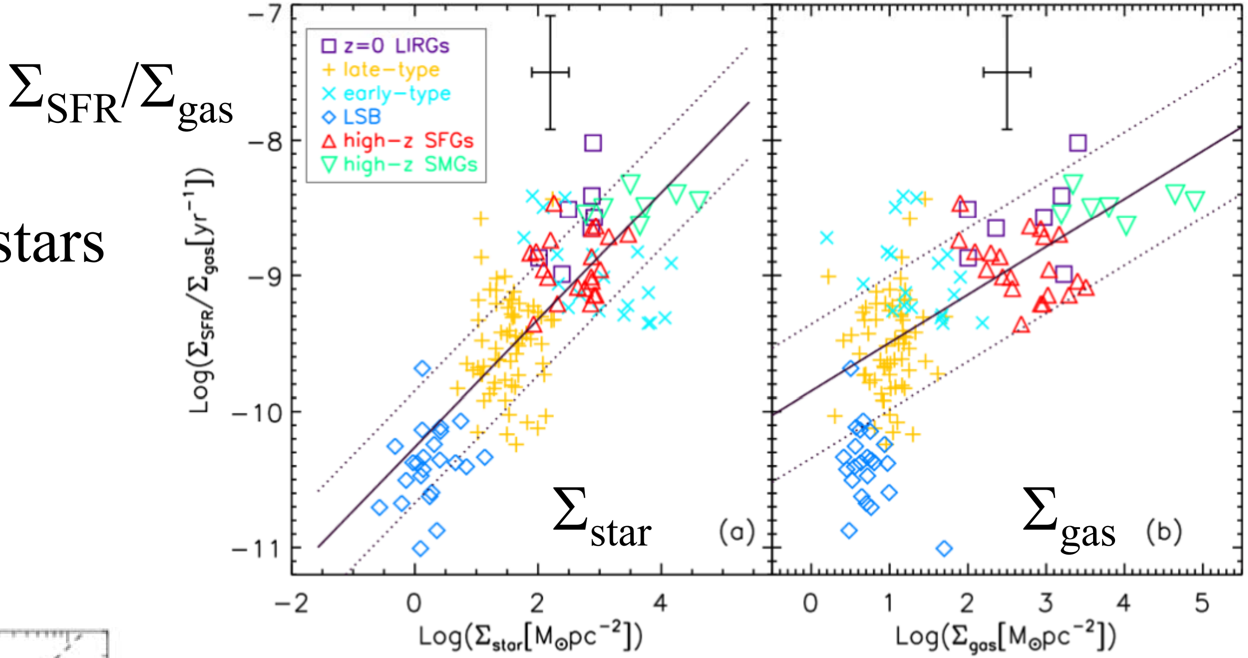
Gas in tails, and far from disks have not enough pressure from stars

And the gas surface density is not enough for fast HI to H_2 transition

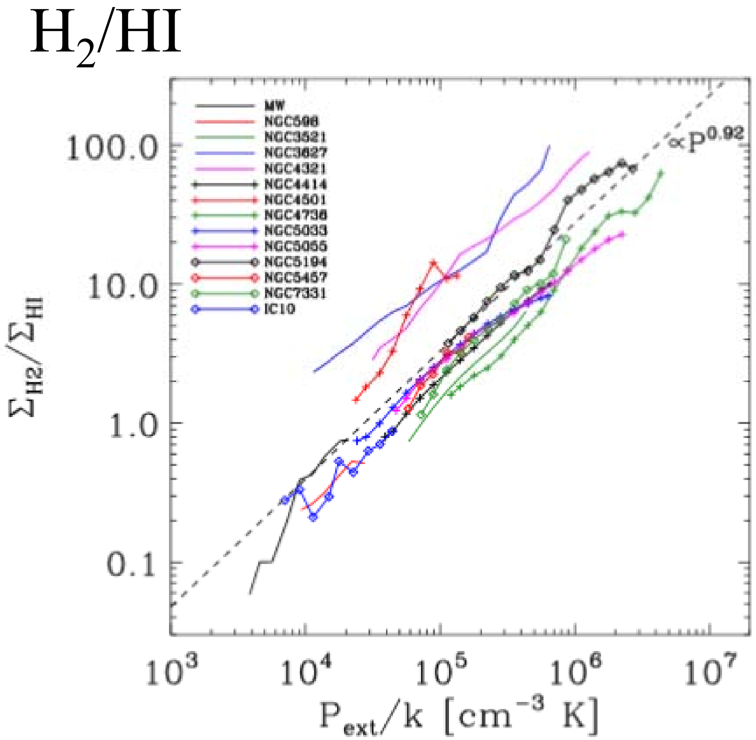
Verdugo et al 2015

Importance of pressure

The surface density of stars
is very important for
the SF efficiency



Shi, Helou et al 2011



The HI to H_2 transituon
is favored by external pressure

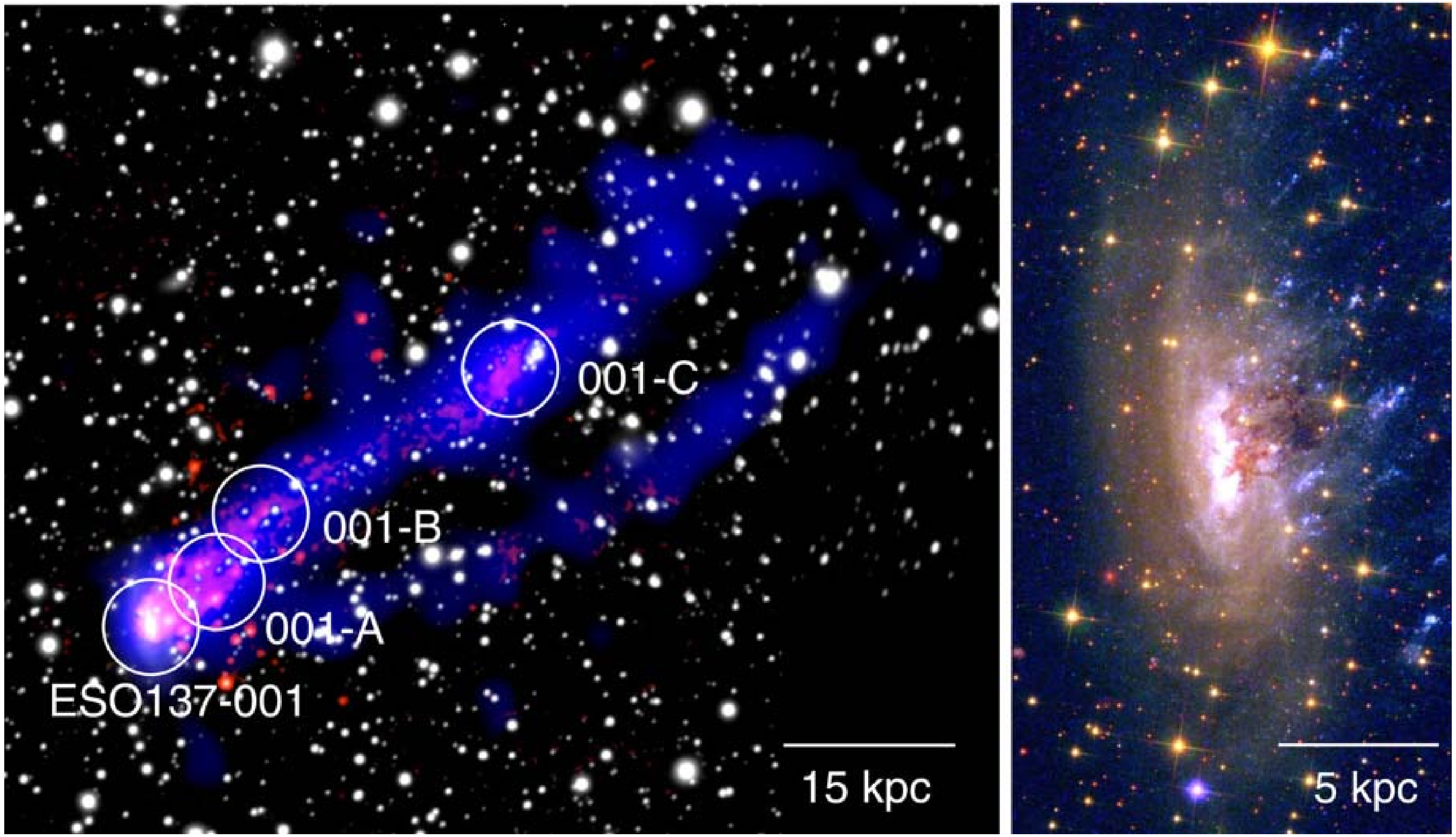
Blitz & Rosolowsky 2006

Ram-pressure in Norma cluster

Ram pressure in clusters: **in general slow**:

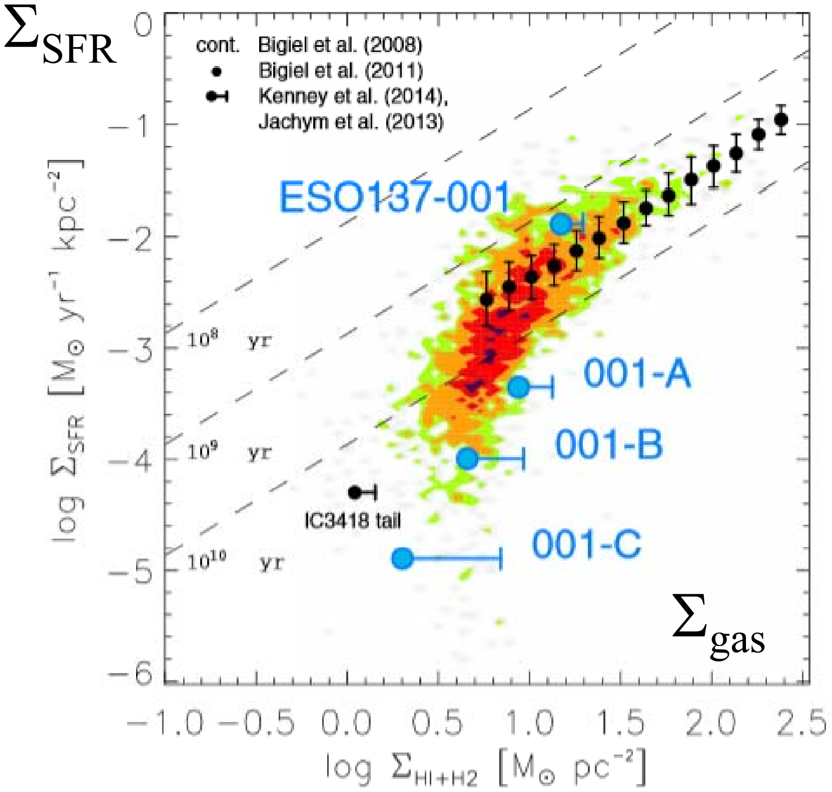
In Virgo, HI deficient, but not H_2 (Kenney & Young 1989)

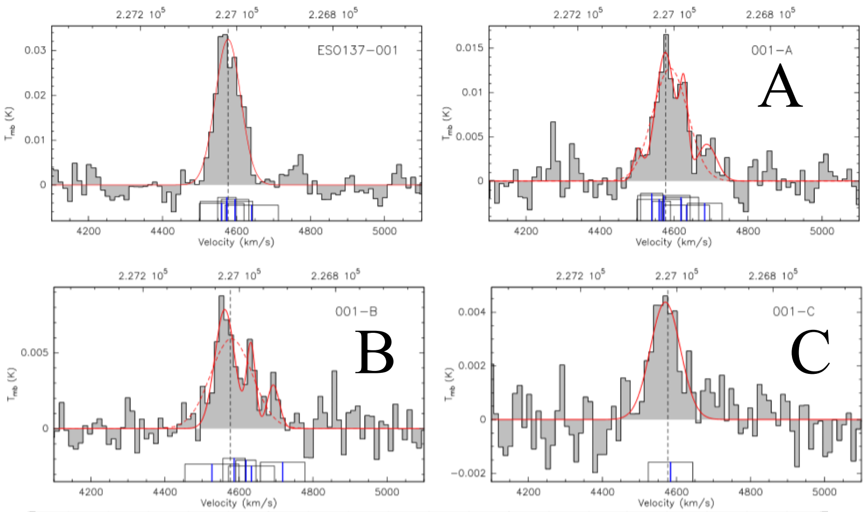
but **can be fast** in exceptional cases: ESO137-001

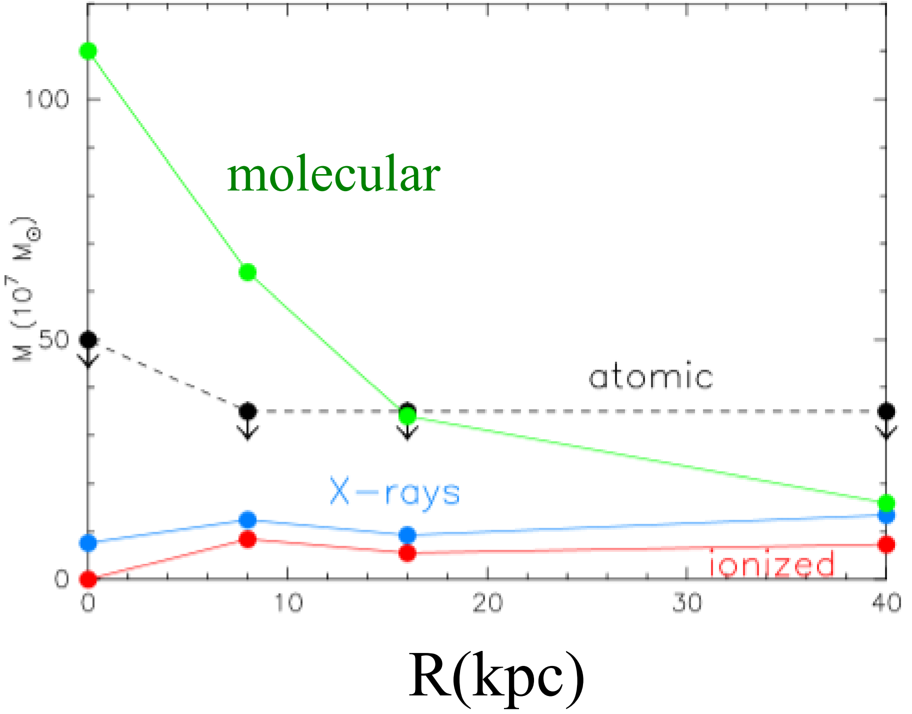


Jachym et al 2014

Ram-pressure quenching



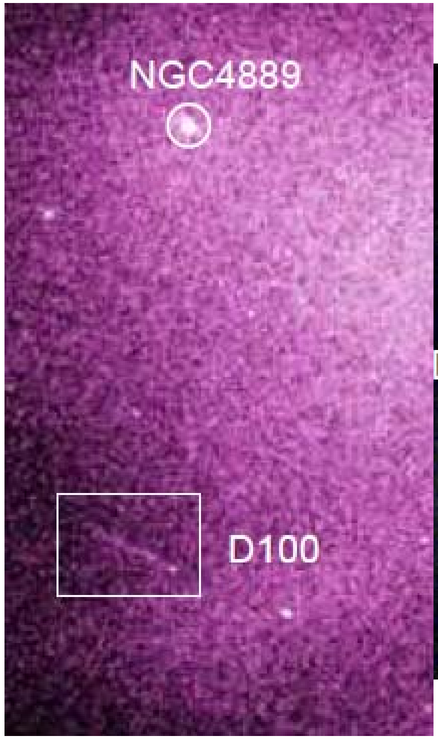


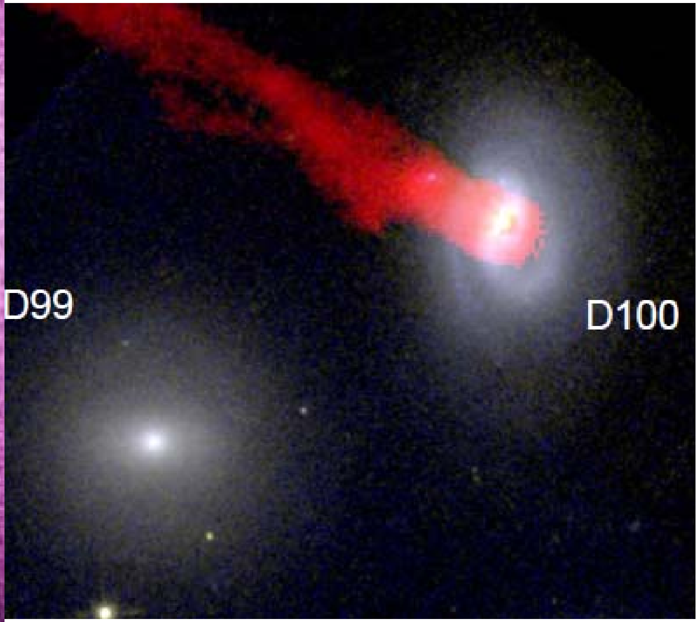


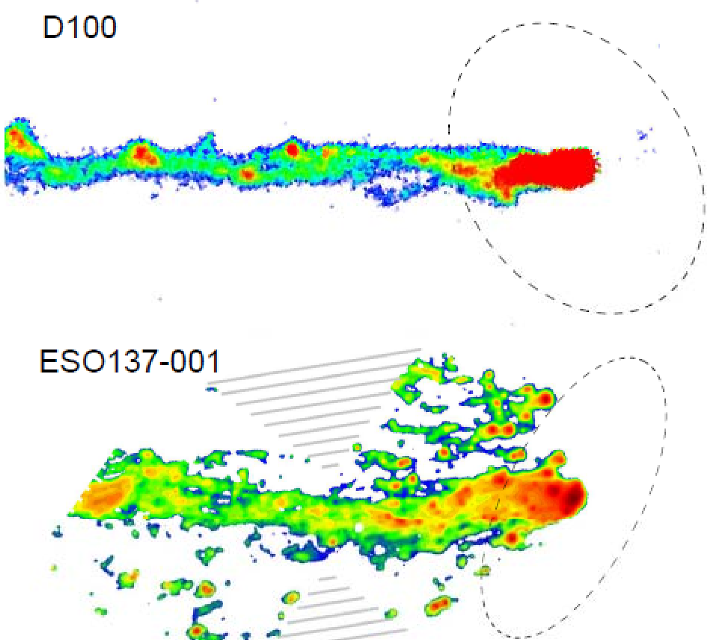
Tail of 80kpc in X-ray gas,
40kpc in CO
M(H_2) in C =1.5 10^8Mo

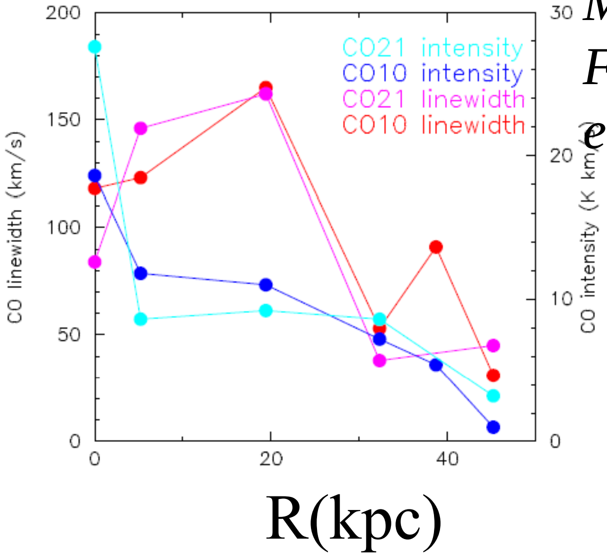
Jachym et al 2014

Ram-pressure in Coma





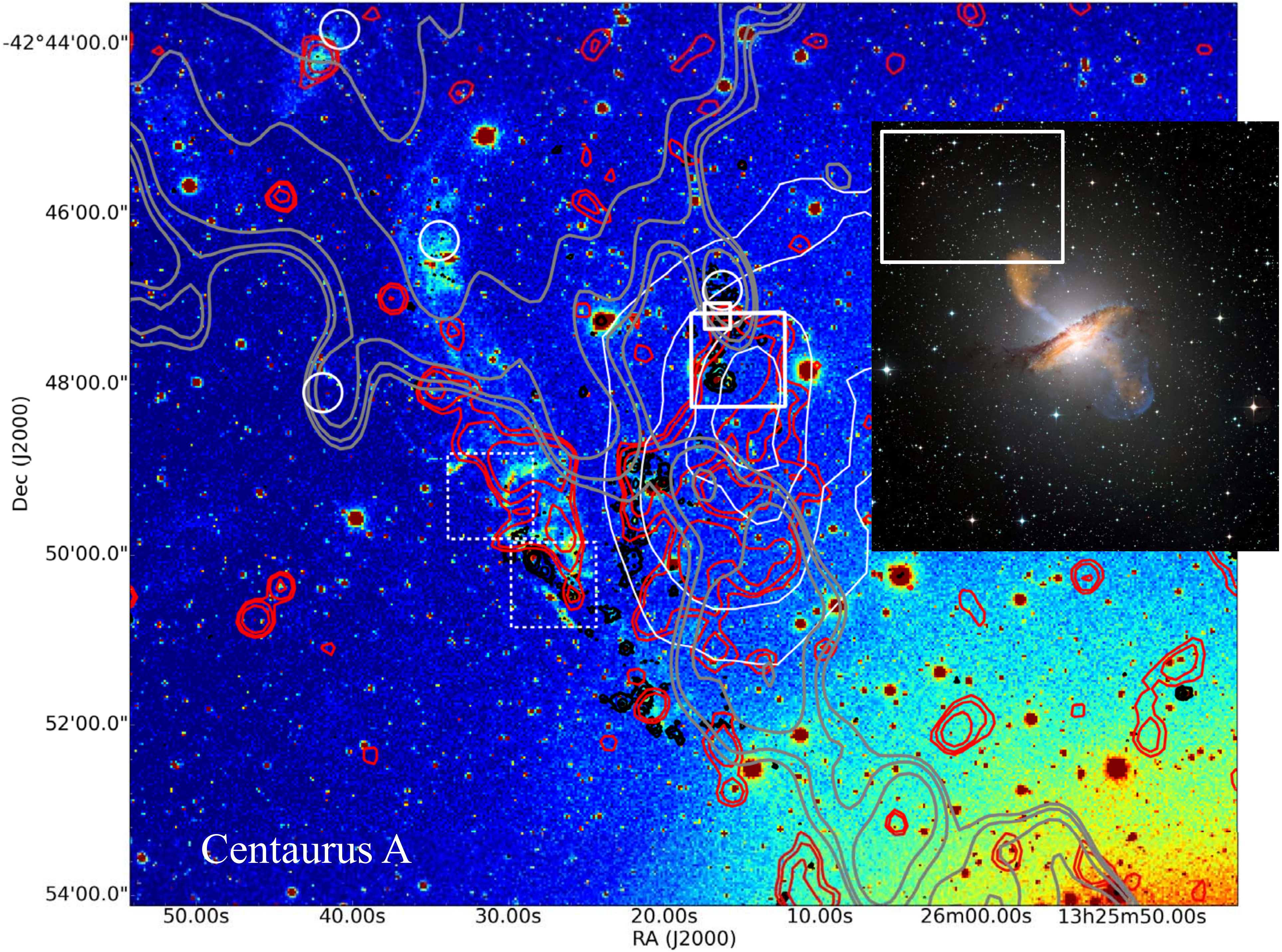




MUSE Fumagalli et al 2014

D100 tail: thinner
Last stage of stripping
CO detected along, until 45kpc

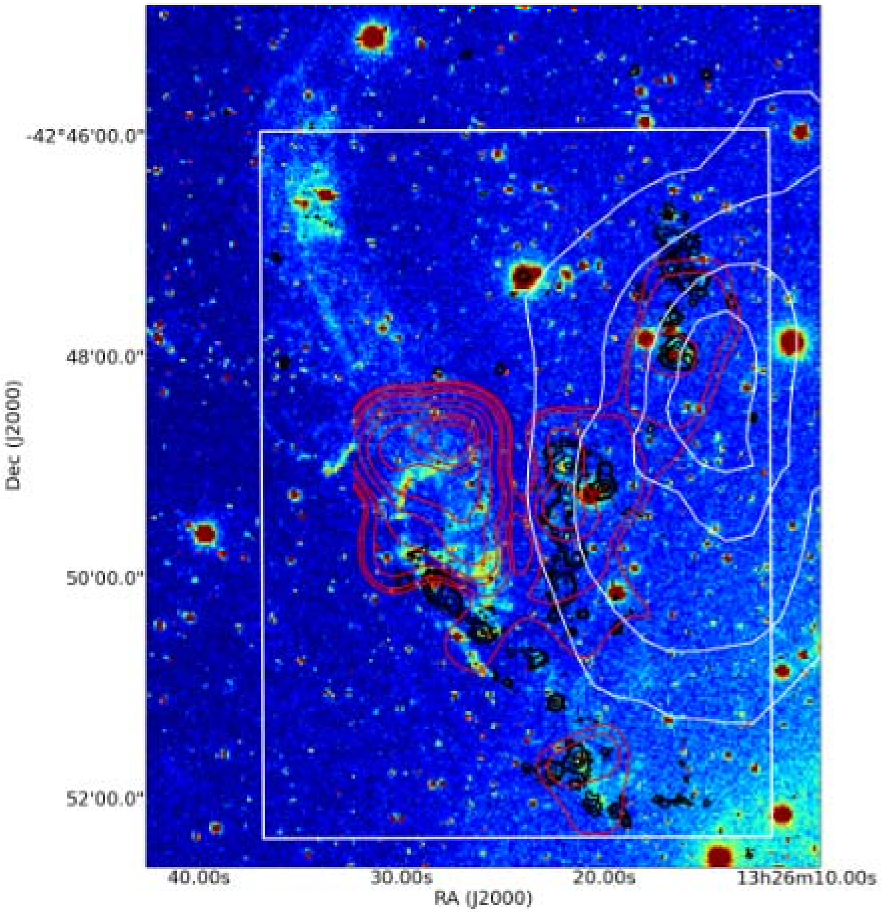
Jachym et al 2016


-42°44'00.0"
46'00.0"
48'00.0"
50'00.0"
52'00.0"
54'00.0"
Dec (J2000)
50.00s
40.00s
30.00s
20.00s
10.00s
26m00.00s
13h25m50.00s
RA (J2000)
Centaurus A

Molecular gas in the shell

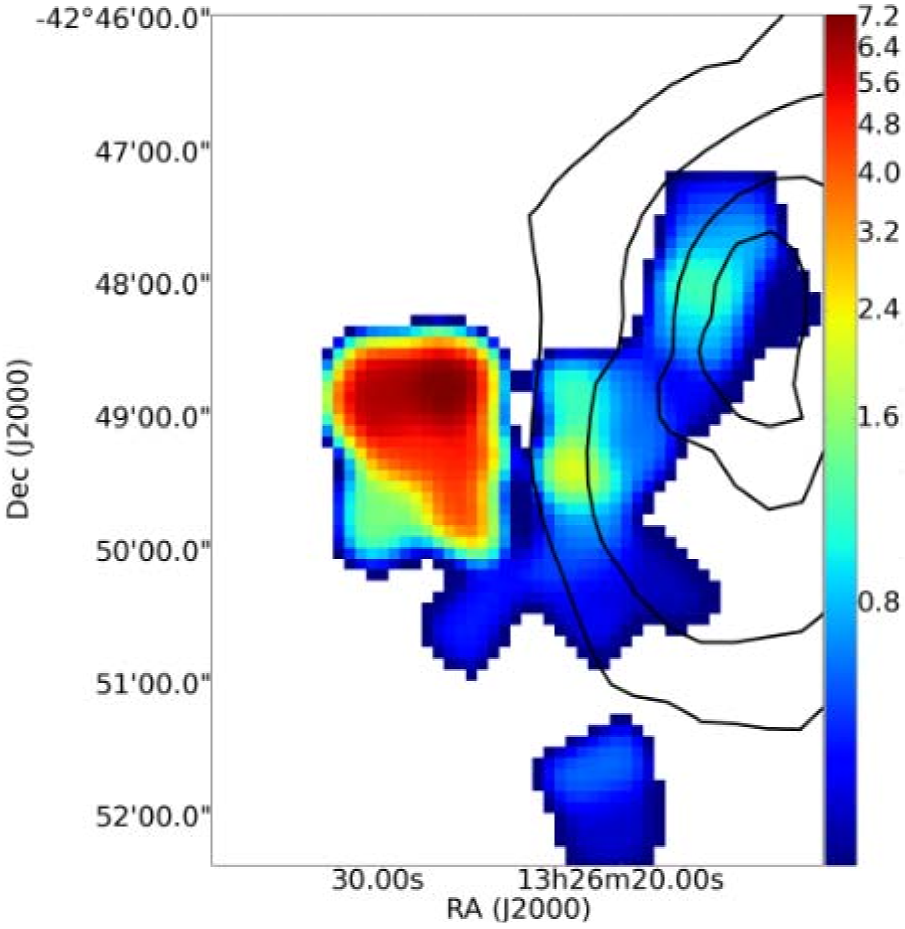
H_2 dominant at E, while HI at W

Hα map



Red: CO, White: HI, **FUV-Galex: black**

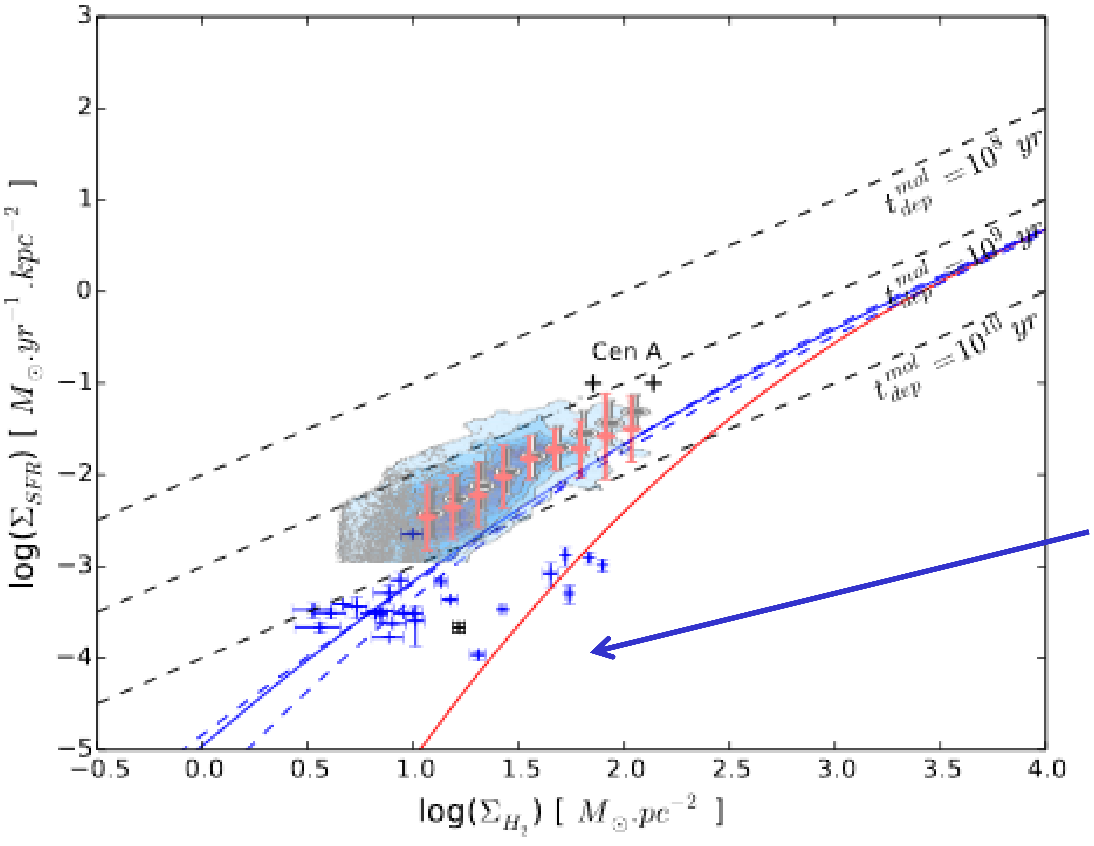
Salome et al 2016



CO21, HI contours

Star formation triggering

The radio jet effectively triggers star formation in the shell along the jet ➔ positive AGN feedback



However, the SF efficiency is lower than in disks

➔Not enough pressure

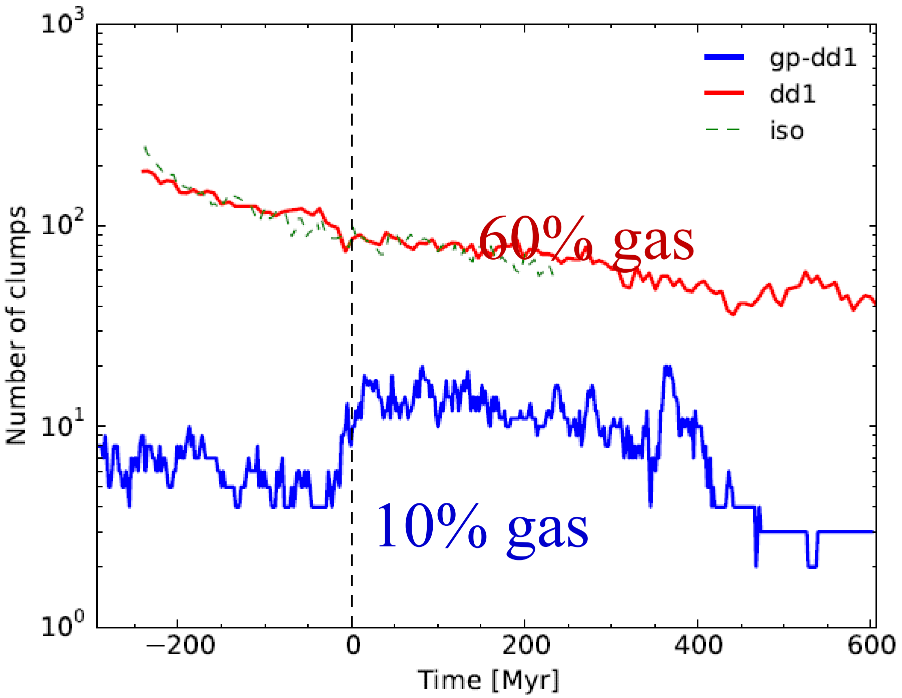
➔Tdep larger than a Hubble time

Salome et al 2016

Role of mergers in starbursts

At low z, mergers trigger starbursts – The most energetic ULIRGs with highest SFE are all mergers *(Sanders & Mirabel 1996)*

Mergers increase $\sim(1+z)^4$ *(Lefevre et al, 2000, Lotz et al 2011)*
➔ How SFE varies with z?



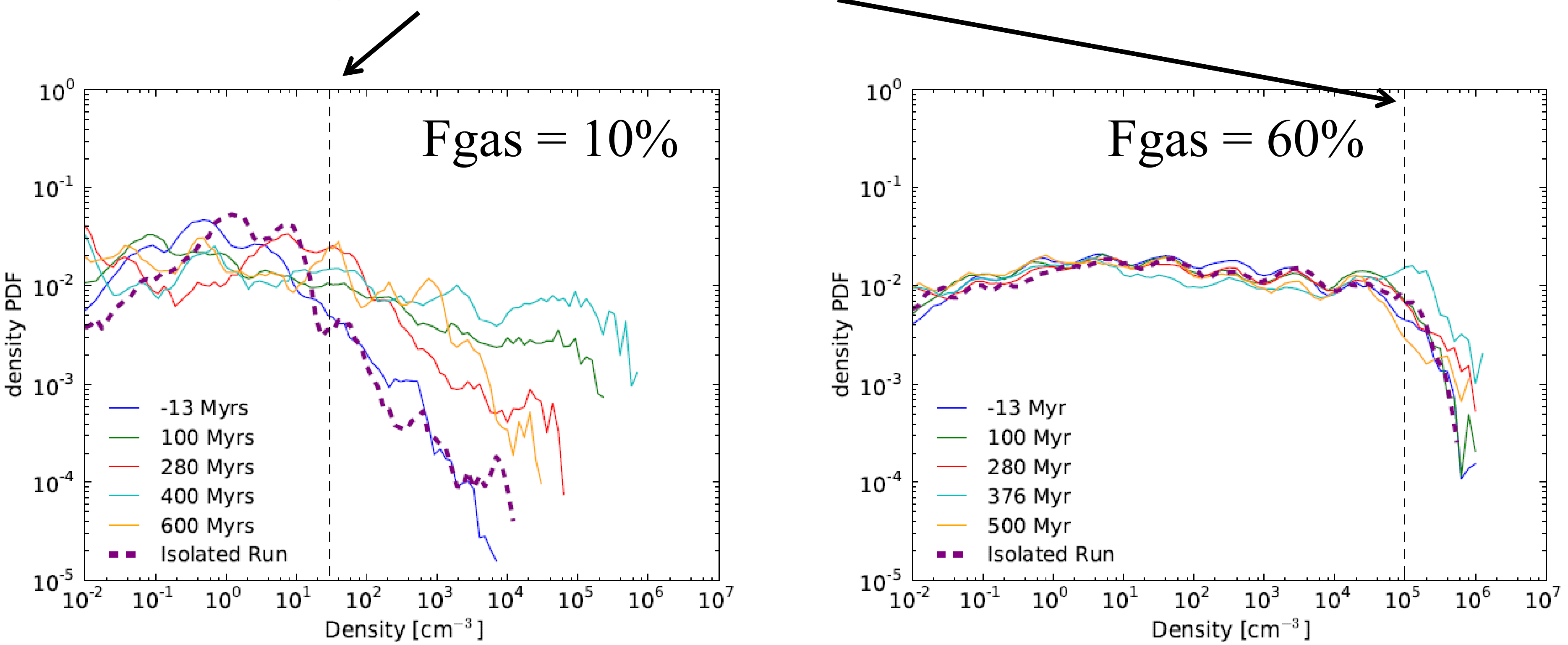
Due to high gas fraction, the number of clumps, violent instabilities, is already large in isolated galaxies at high z

Fensch et al 2017

Gas density PDF

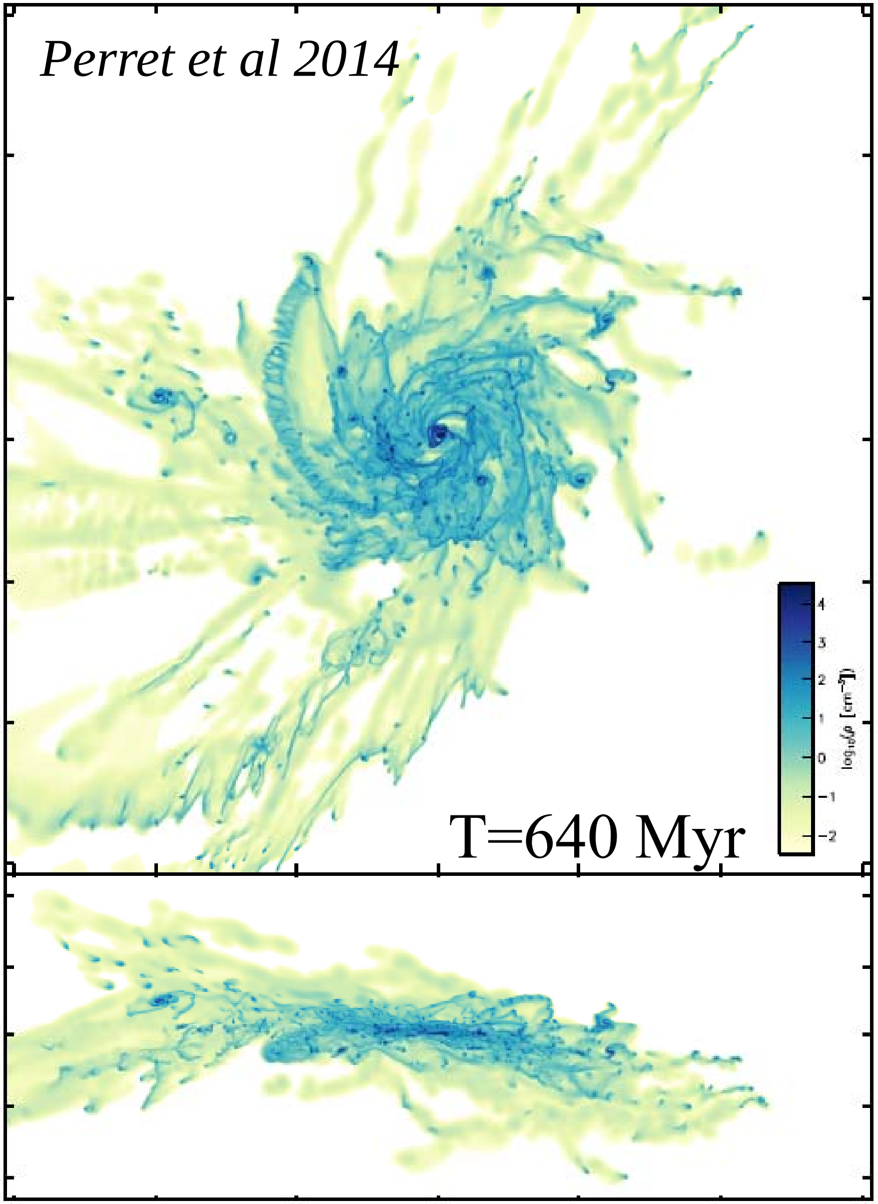
No difference in the PDF for high gas fraction
for isolated or interacting galaxies *(Fensch et al 2017)*

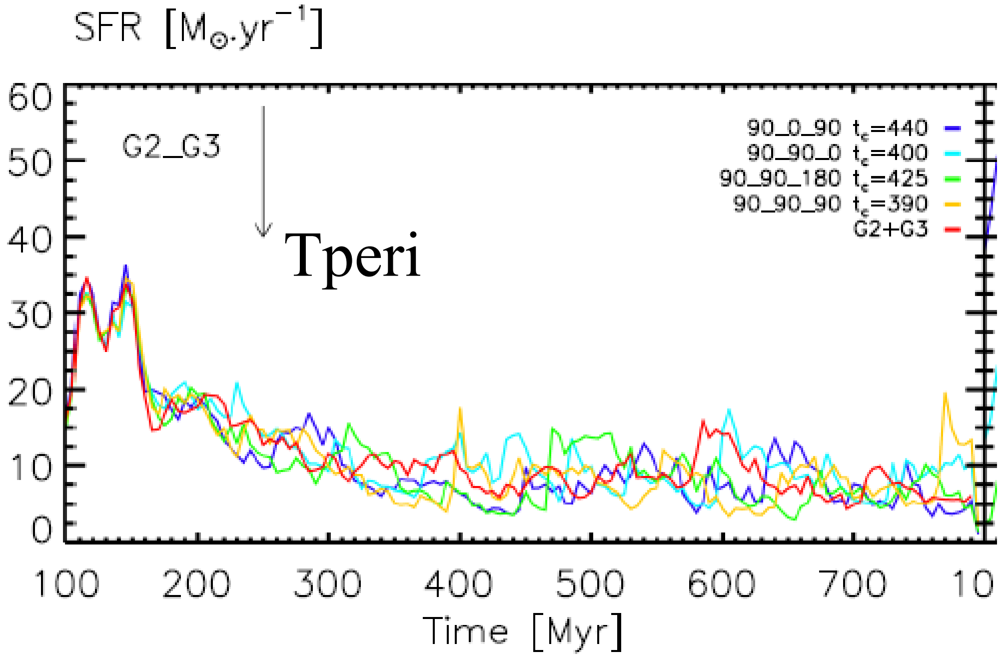
Density threshold for star formation: 30 and 10^5 cm^{-3}



to have SFR = 1Mo/yr and 60Mo/yr for isolated galaxies

Galaxy mergers with high gas content

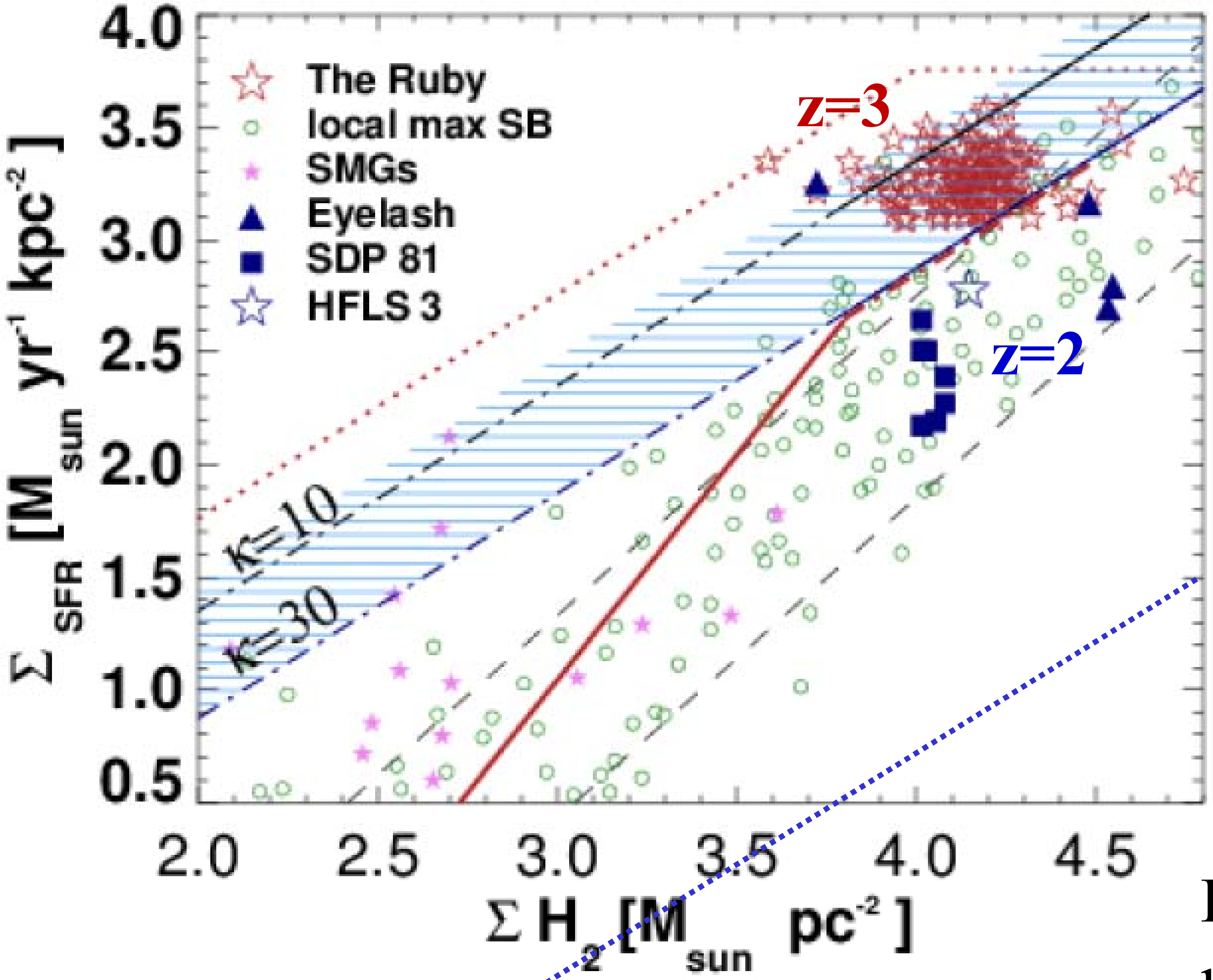




No SFR difference with isolated case

However: numerical effects?
(temperature floor, depends on density)

Starbursts at high redshift z~ 2-3



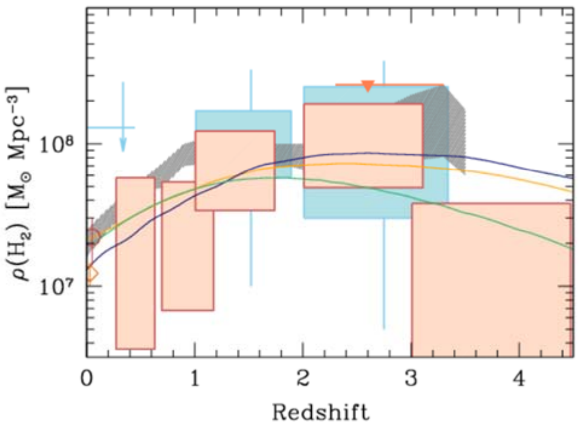
Eddington limit
t_{dep}=20Myr

MS, z=0 (t_{dep}=2Gyr)

Dust opacities
κ=10, 30 cm^2/g
Andrews & Thompson 2011

Canameras et al 2016

Conclusion



➔Galaxies at high z have a larger gas fraction

Whatever their position, on the MS or not

➔SFE vs z, small evolution on MS, larger for SB

Depletion time 2 or 10 times smaller

The starburst is triggered when the gas is concentrated (merger?)

Diagnostics with CO excitation, Dense gas tracers (HCN, HCO+)..

➔Simulations show SF saturation at high z

No influence of galaxy interactions,
contrary to observations