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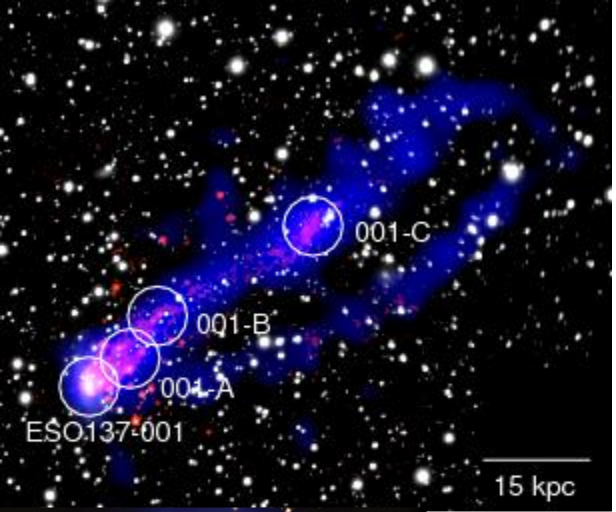
1 September, 2015

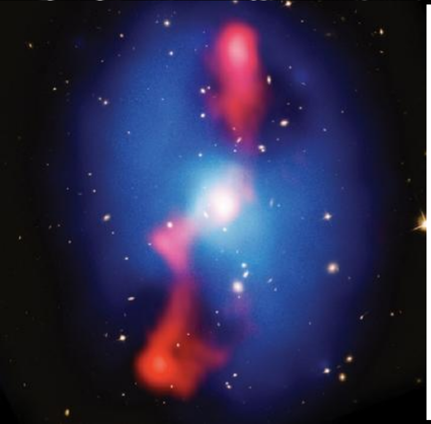
l'Observatoire de Paris

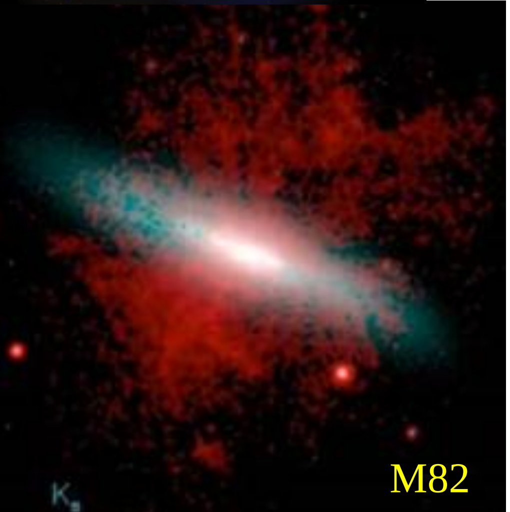
LERMA

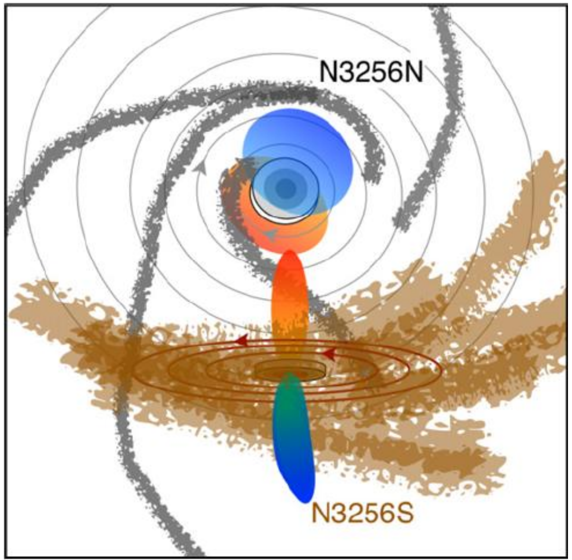
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

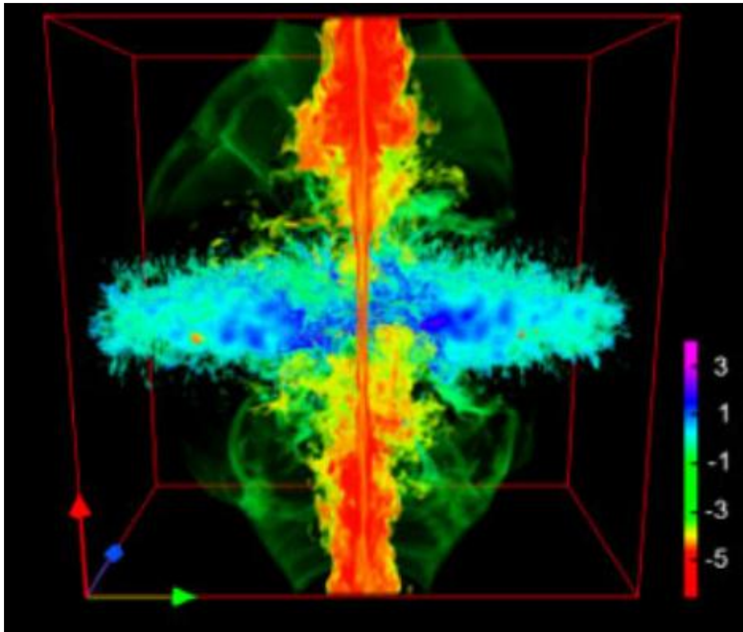
Quenching or the cessation of star formation



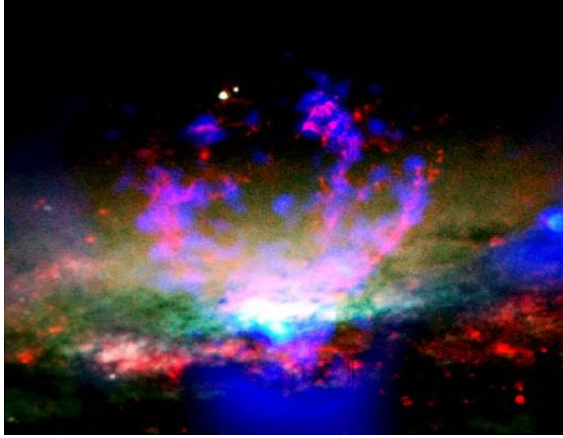








Outline



1- Blue and red components (disks and spheroids)

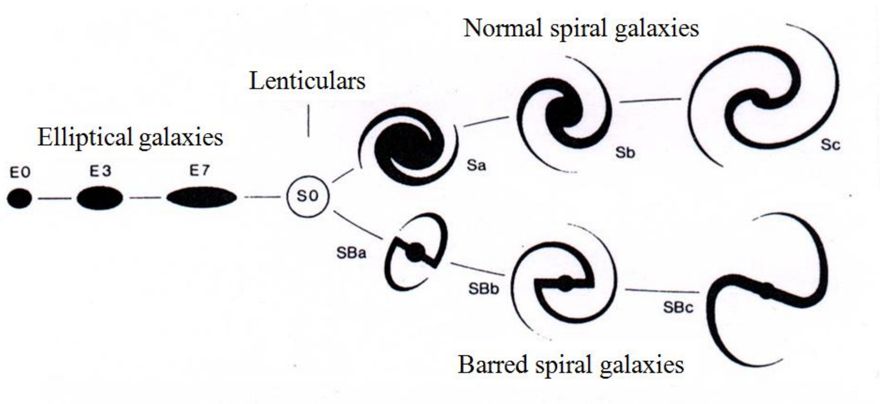
2- Empirical laws of quenching

3- Physical processes of quenching

4- Observational clues of what is dominant

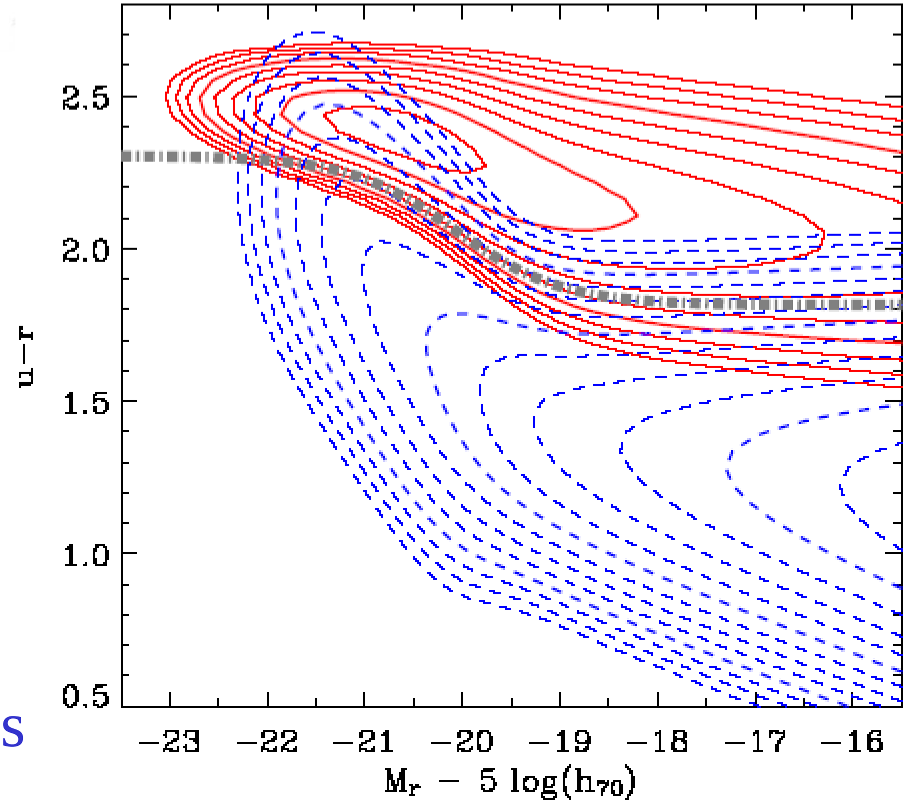
5- Quenching: a necessity

1- From the « Hubble » to the « Red » sequence



A paradigm shift!

Baldry et al 2004



Color-Magnitude diagrams (CMD)
150 000 galaxies in the SDSS

➔Parameter: essentially SFR
But SFH, dust, age, metallicity..

➔2 different formation mechanisms
Separating stellar mass 3 10^{10}Mo

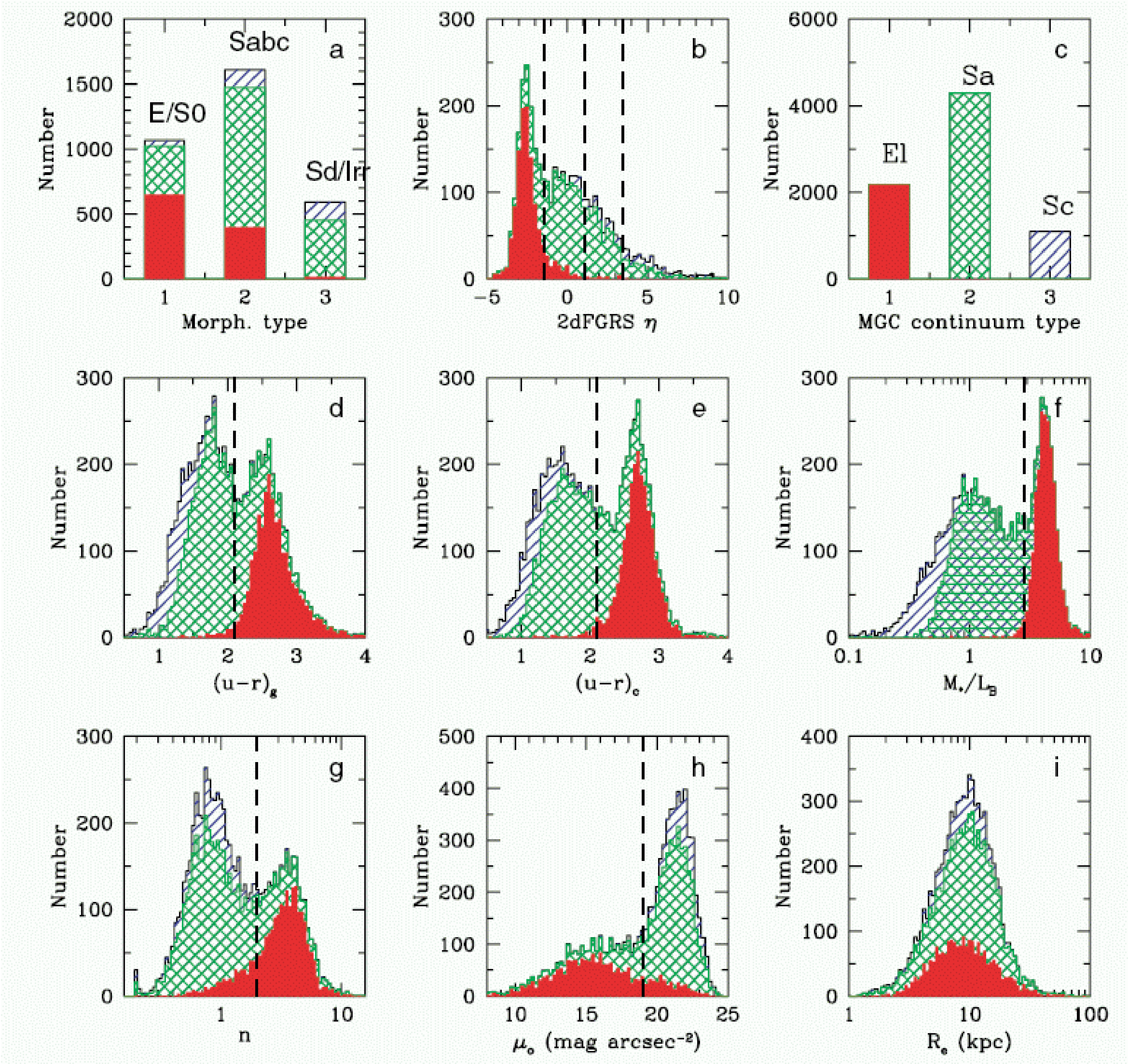
From large surveys: SDSS, 2dF, MGC..

Bimodality: 2 components
Red, old, no-SF, high-C
Blue, young, SF, low-C

Downsizing
Early-type galaxies:
« Red and dead » galaxies
Do not evolve much,
only as passive evolution

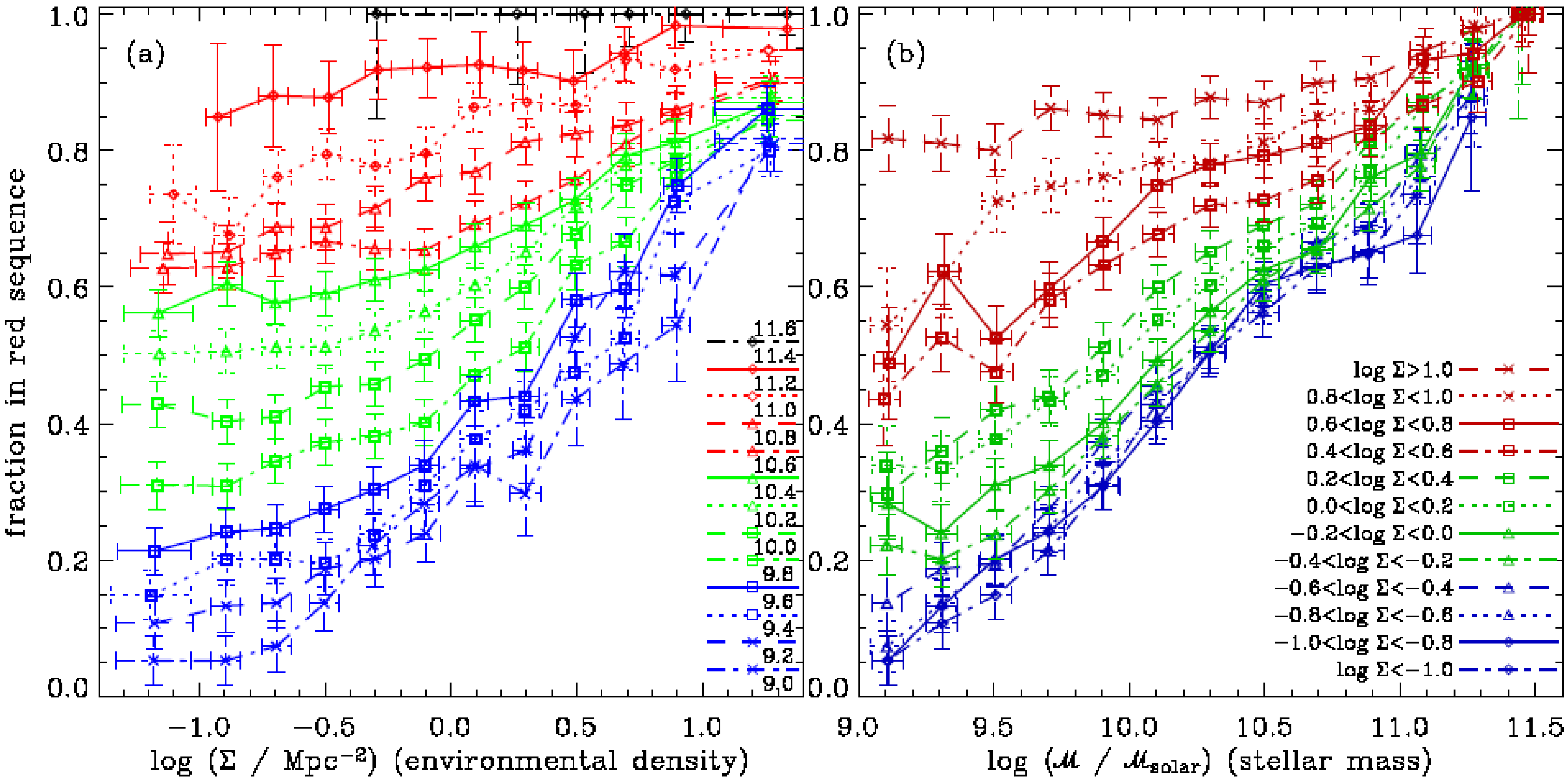
While star formation is
going on now in smaller
spirals and dwarfs

S. Driver et al 2006



Fraction in red sequence increases with mass and environment

Baldry et al 2006



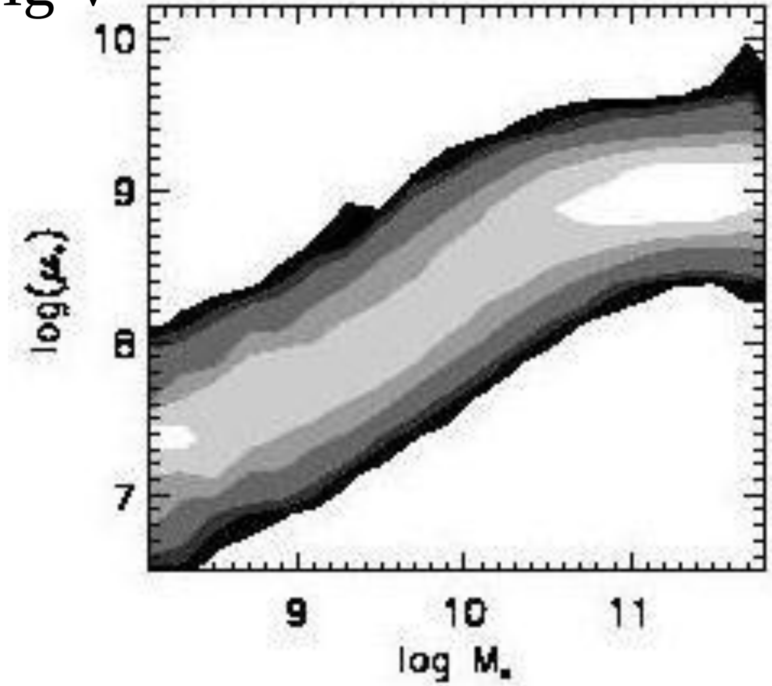
SF History depends on surface density

LSB/dwarfs, high gas content, high and young star formation
HSB high mass, concentrated, old population

Transition at $M_*=3\ 10^{10}$ Mo, $3\ 10^{8}$ Mo/kpc^2
SFH depends more on surface density than on mass

$E_{SN} \sim \varepsilon\ \nu\ dM_*/dt\ \ t_{rad}$ $\varepsilon = 10^{51}$erg ν =1 for 100 Mo stars formed
this energy disperses the gas, when = 1/2 Mg V^2

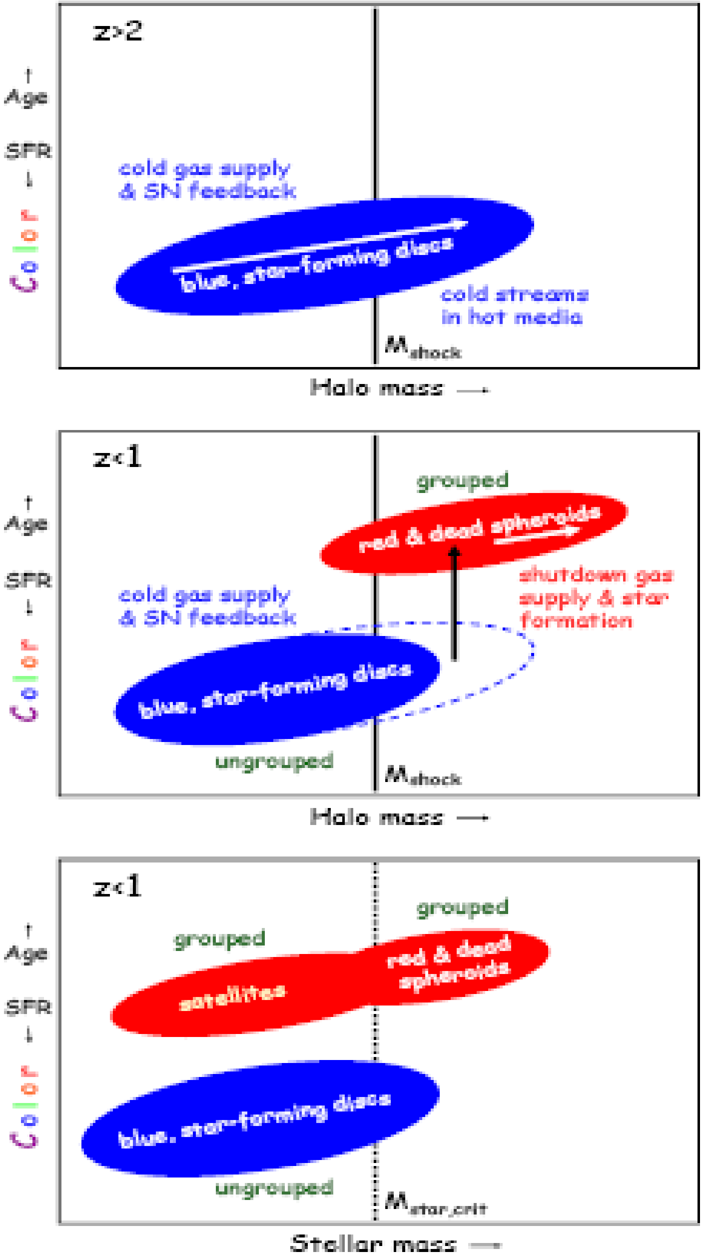
there is a transition where the gas
begins to outflow, at the
V_{SN} velocity ~100km/s



Kauffmann et al 2003

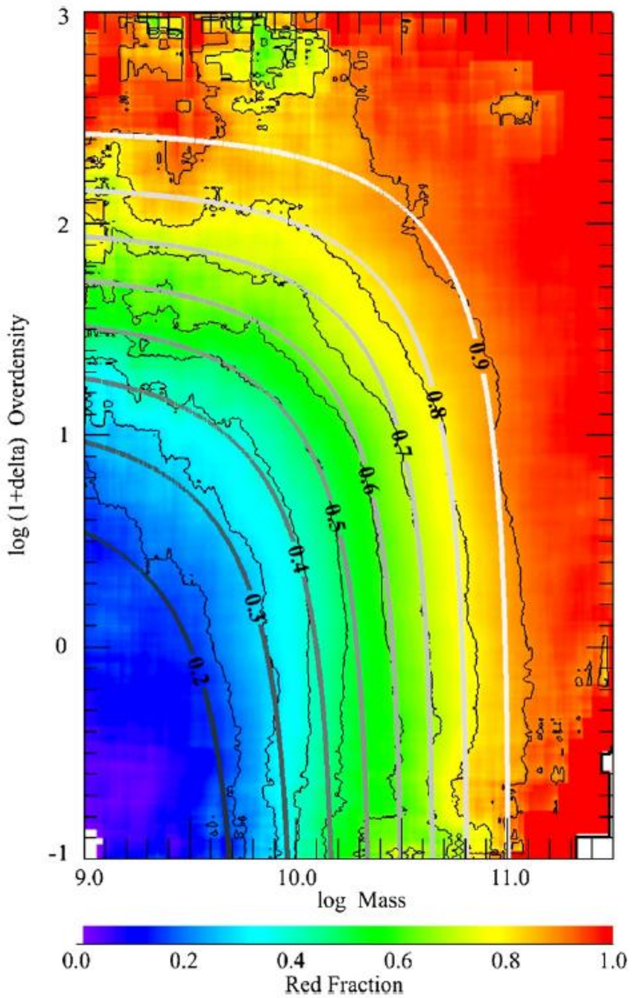
Origin of the bimodality

➔Above a halo mass =3 10^{11} M_o, the gas is not accreted cold, but is heated in shocks and has no time to cool (or AGN feedback)
Dekel & Birnboim 2006
Keres et al 2005

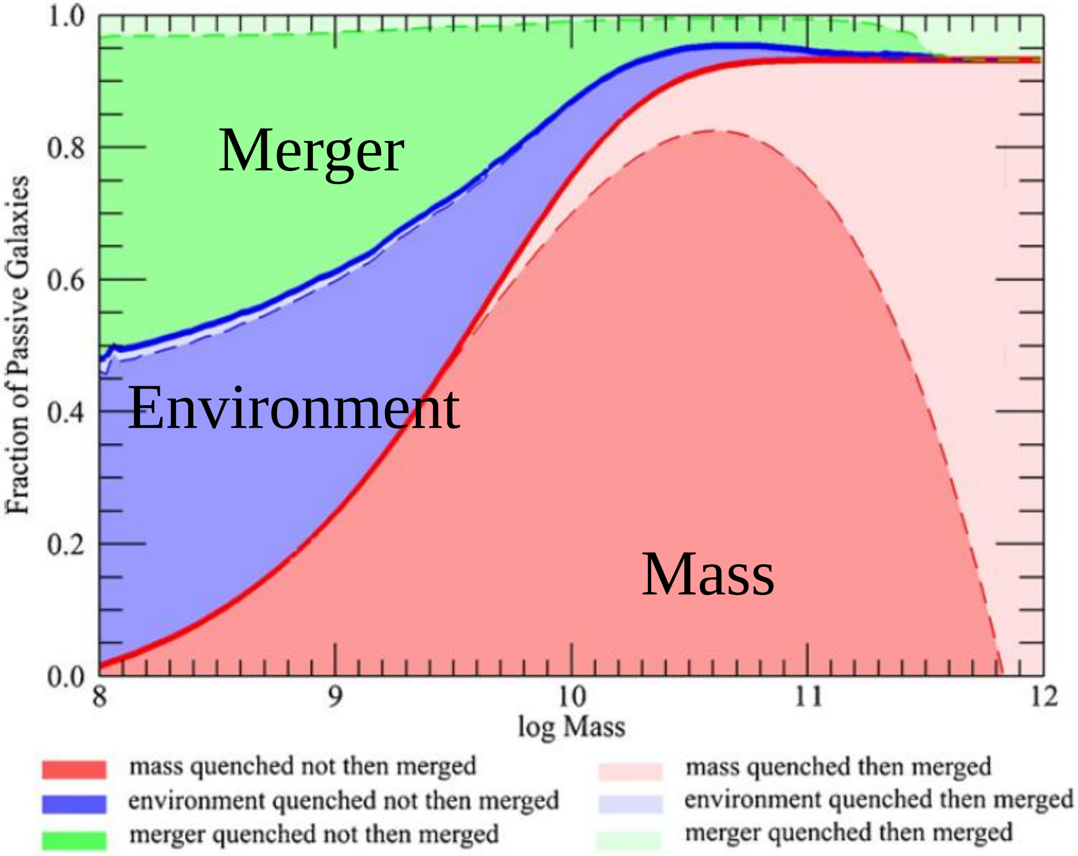


➔Or above a certain surface density of stars (3 $10^8 M_o/kpc^2$), the gas is quickly transformed into stars, and the time spent in the « blue » regime is short.
Kauffmann et al

2- Mass & Environment Quenching



History of z=0 passive galaxies



Post-quenching merger

Separability of the two factors

Mass quenching and environment quenching

Peng et al 2010

Empirical laws of quenching

Environment quenching must be sudden, and once for all

Mass quenching, on the contrary, is continuous in time
Related to bulge mass accumulation, may be also AGN?

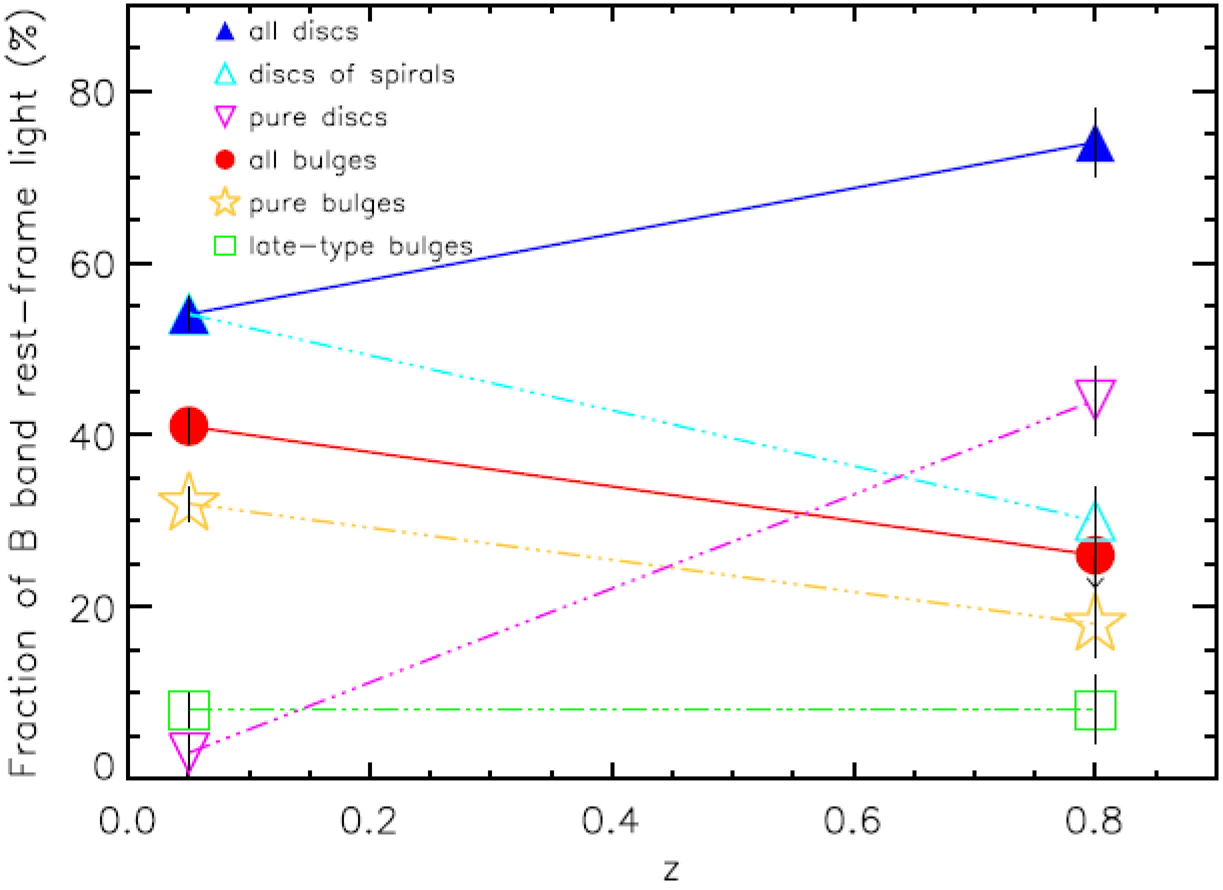
sSFR is almost constant with M_* (and halo mass), just depends on redshift: increases with lookback time by a factor 20

The Schechter function is invariant (z): compensation of the slope of sSFR with M_* and mergers?

Downsizing is related to environment quenching: overdensities evolve faster. Passive satellite are younger than passive centrals

Peng et al 2010

Bulge and disk fraction



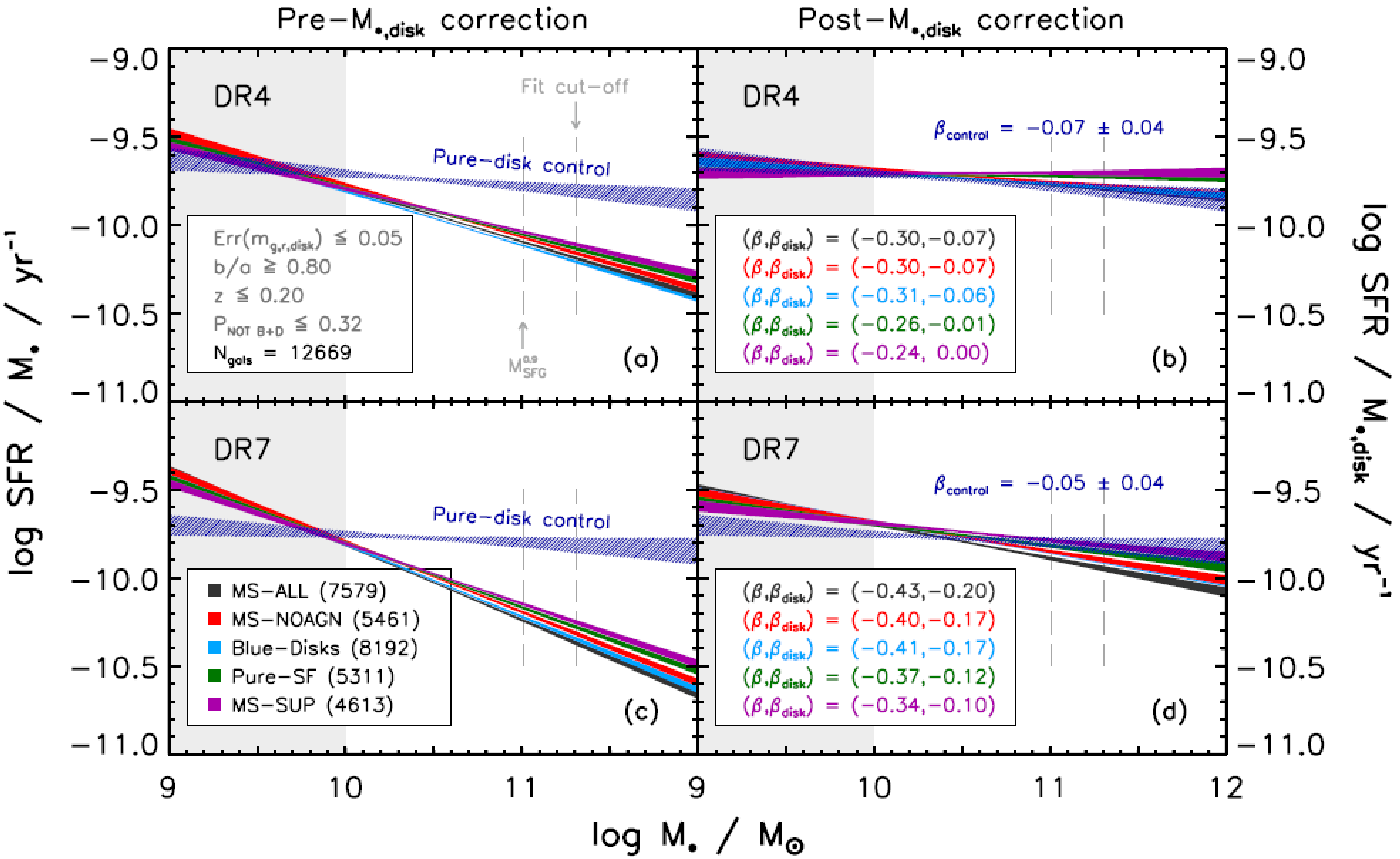
At z=0.8, luminosity
26% in bulges
74% in disks

These evolve by
30% at z=0 to

54% in bulges
46% in disks

Tasca et al 2014

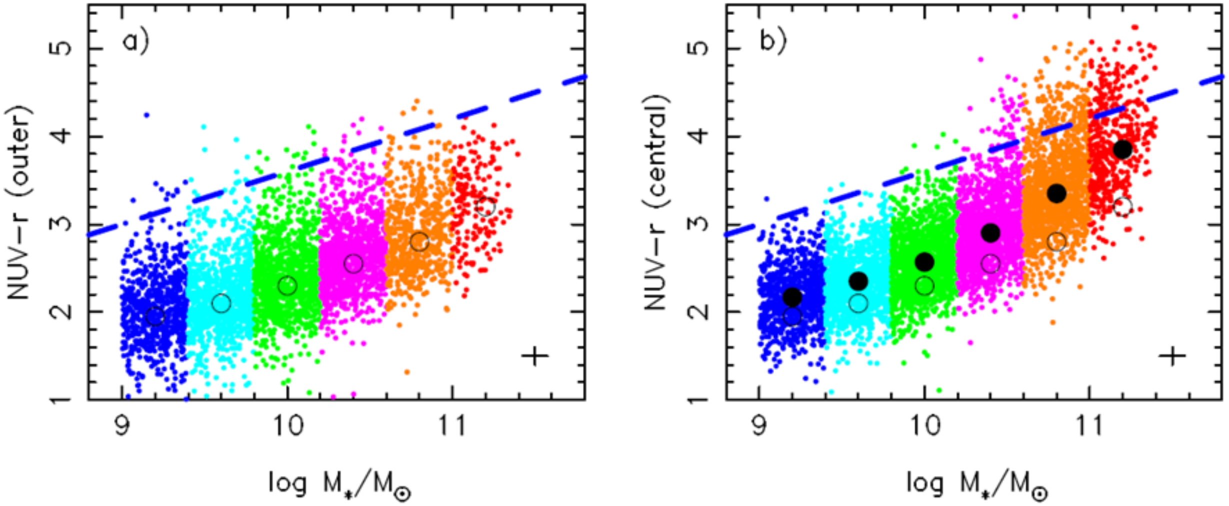
sSFR of disks?, slope ~0



Abramson et al 2014

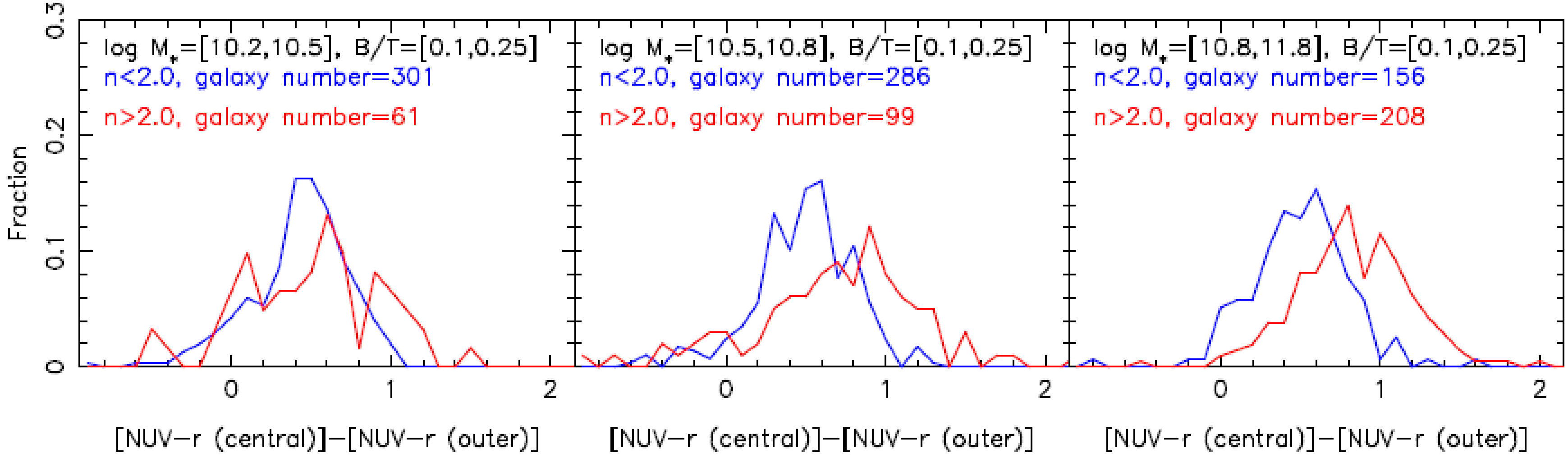
DR4 different SFR estimation
Overestimate in QG

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



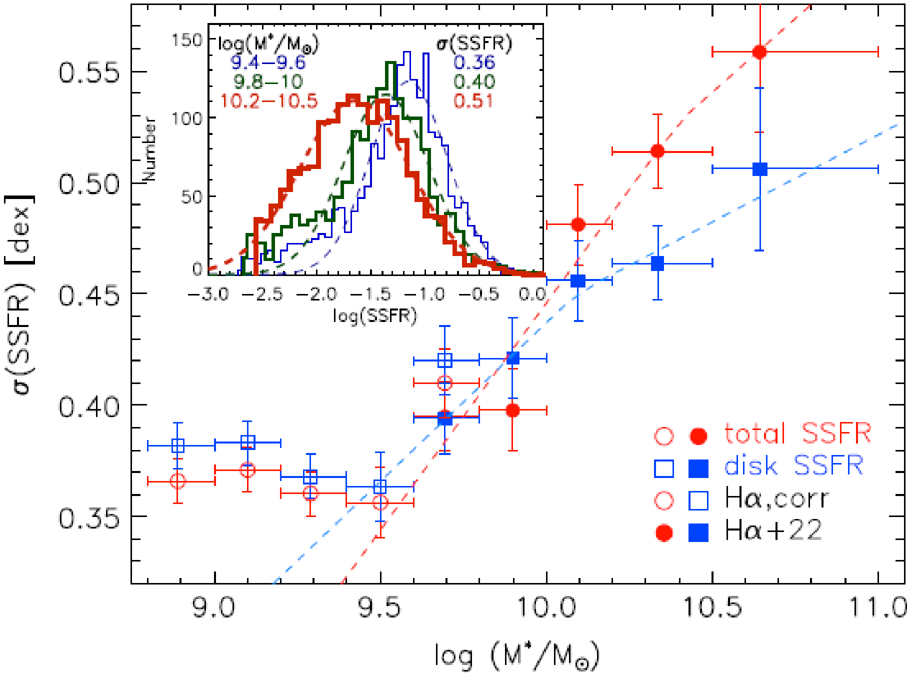
The reason of sSFR/M_* slope different from 0
➔ concentration of the mass towards the center

Not the pseudo-bulge!



Pan et al 2015

Dispersion of sSFR



The dispersion in sSFR increases with mass

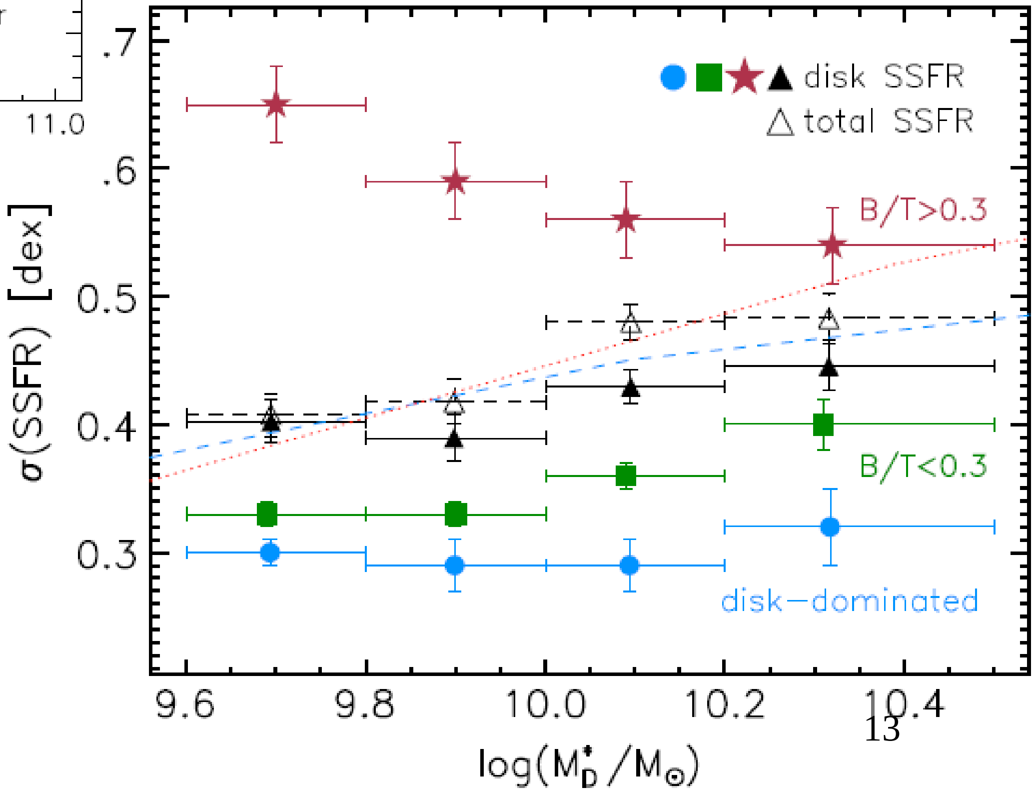
Bursty SF at high mass

➔Bulge effect, quenching?

➔SFH diversity: stochastic starbursts, secular evolution bars, etc..

Independent of halo mass, of total M*

Not favorable to SF feedback



Guo et al 2015

3- Physical processes of quenching

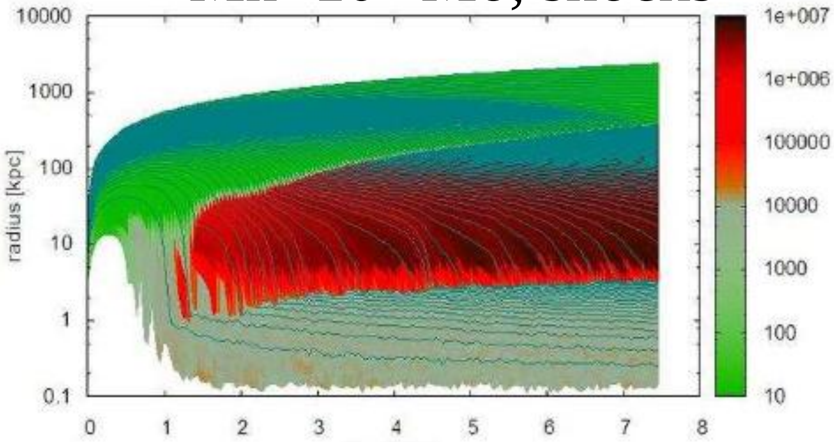
Stopping star formation could be through

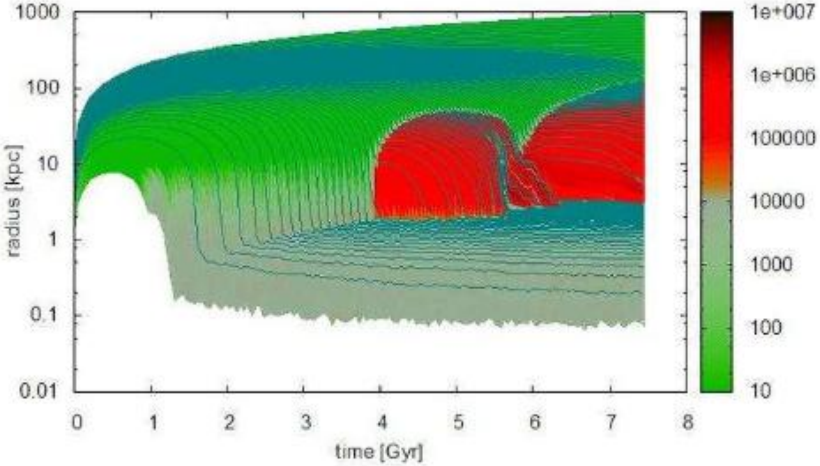
➔Cutting the gas refueling: **SLOW (2-4 Gyr)**
Gravity/halo quenching, Environmental quenching
(harassment, strangulation, ram-pressure or tidal stripping..)
➔Ejecting the gas present: **FAST (<~0.1 Gyr)**
SF feedback, galactic winds, AGN winds, radio jets..

➔Heating the gas (transient) **FAST**
Turbulence by galaxy interactions, star formation feedback
Gas will dissipate, and SF come back
➔Stabilising the gas: **SLOW**
Morphological quenching, bulge formation

Gravity quenching

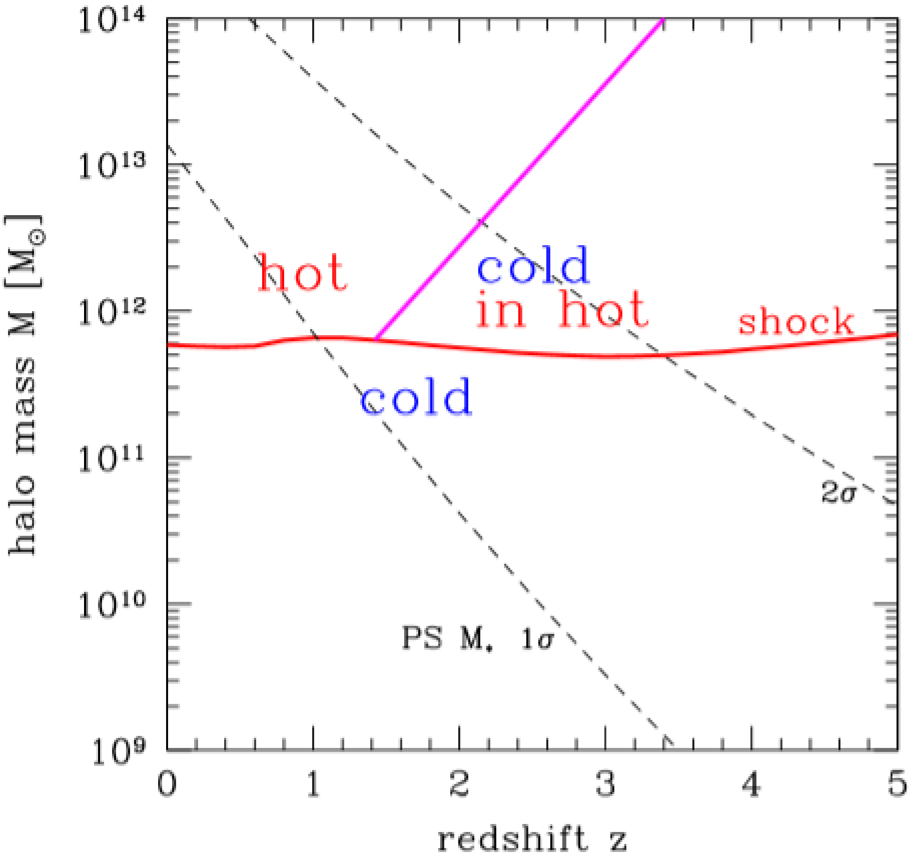
Mh>10^{12}Mo, shocks





Mh<10^{12}Mo

Dekel & Birnboim 2005



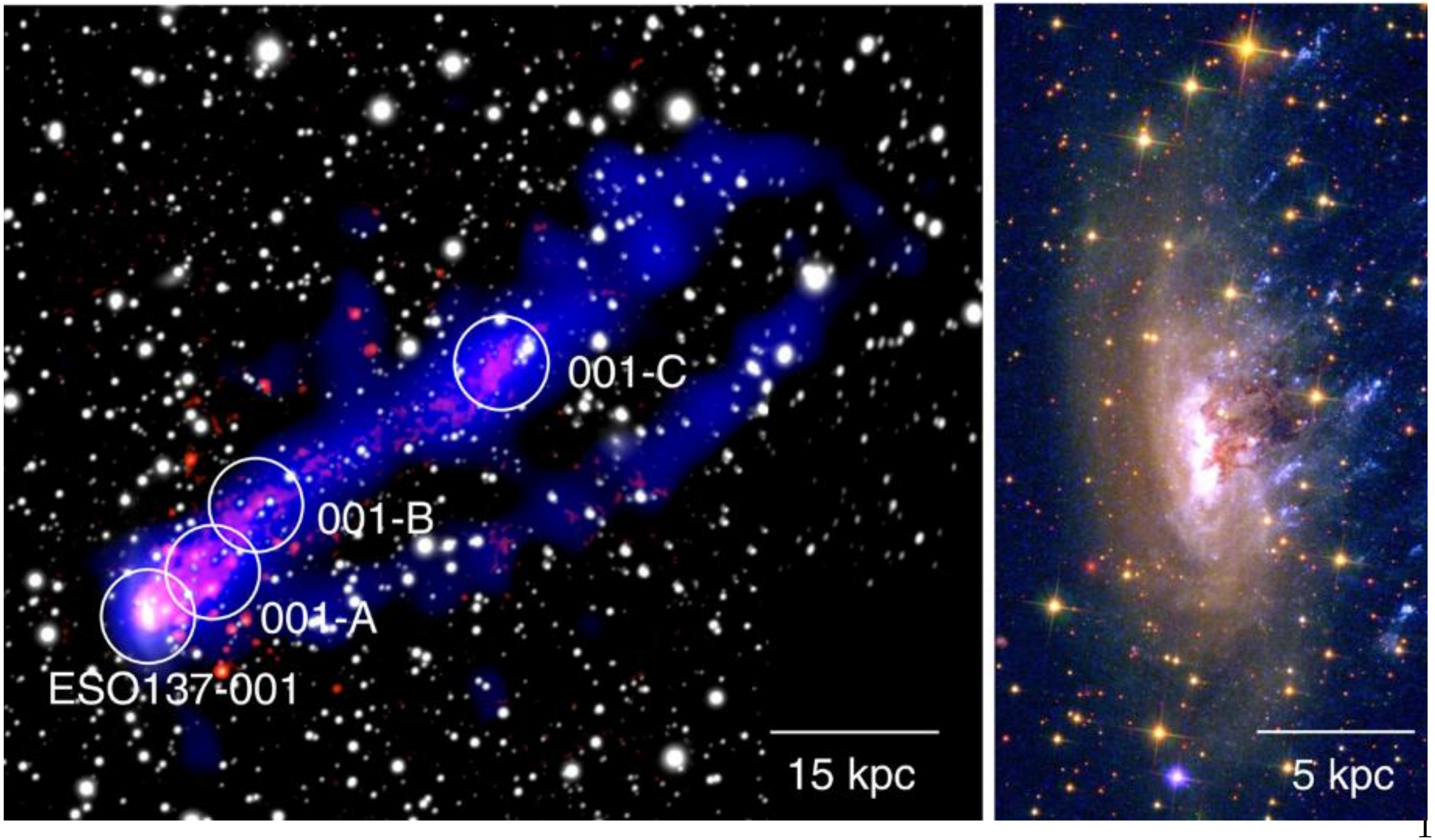
Depends on halo mass (not galaxy)
May stop the gas supply
already in groups ➔ red and dead

Environmental quenching

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

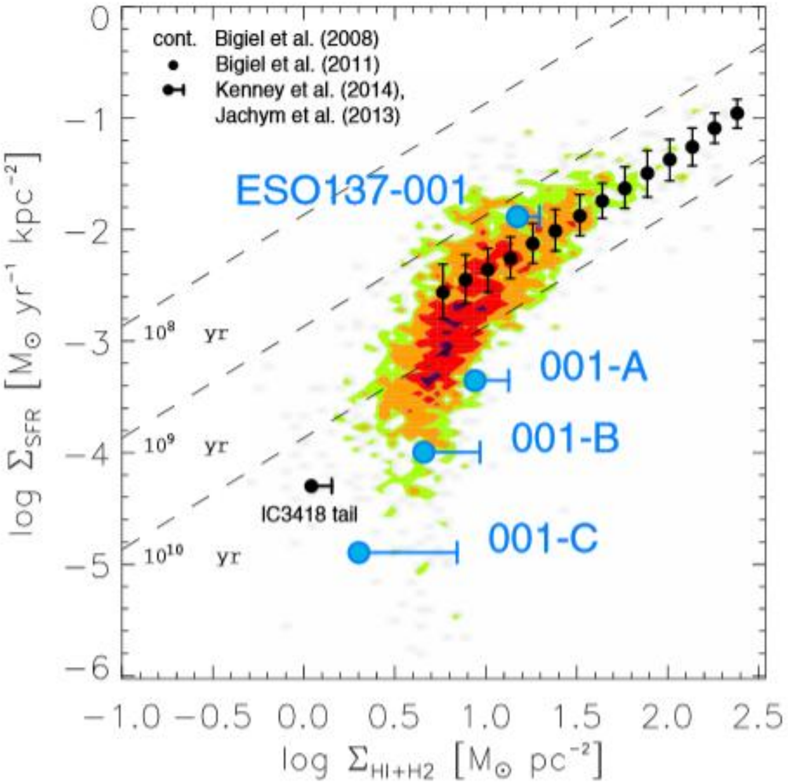
In Virgo, HI deficient, but not H_2 (Kenney & Young 1989)

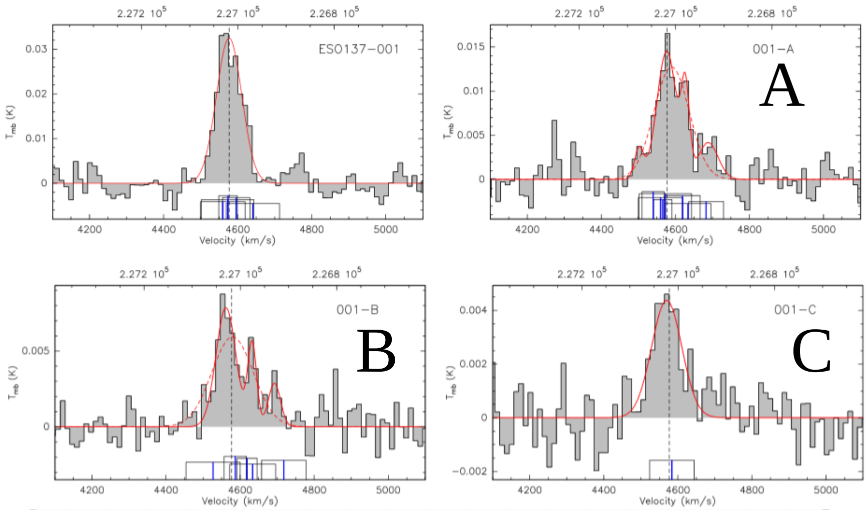
but **can be fast** in exceptional cases: ESO137-001

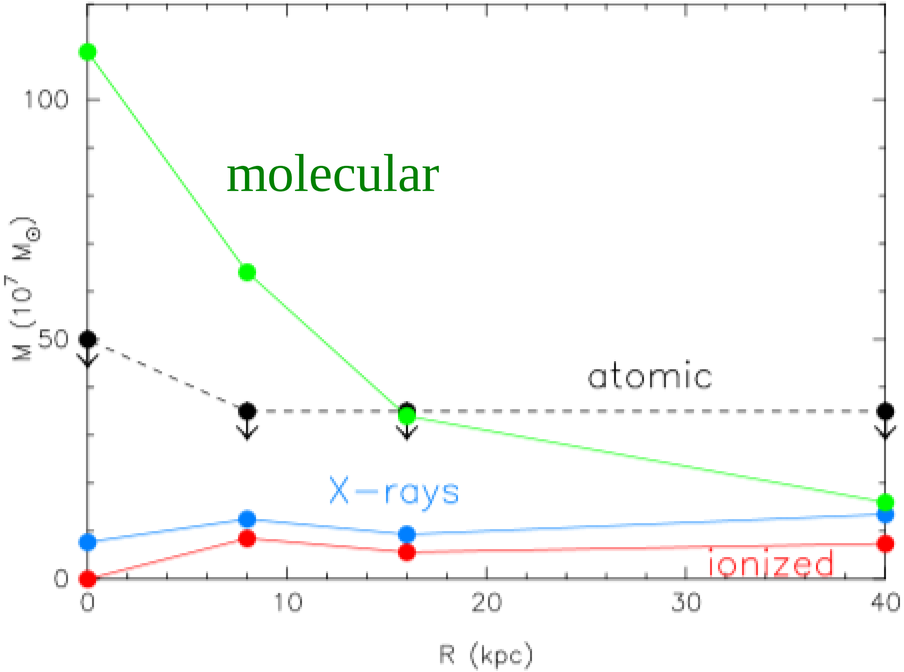


Jachym et al 2014

Ram-pressure quenching



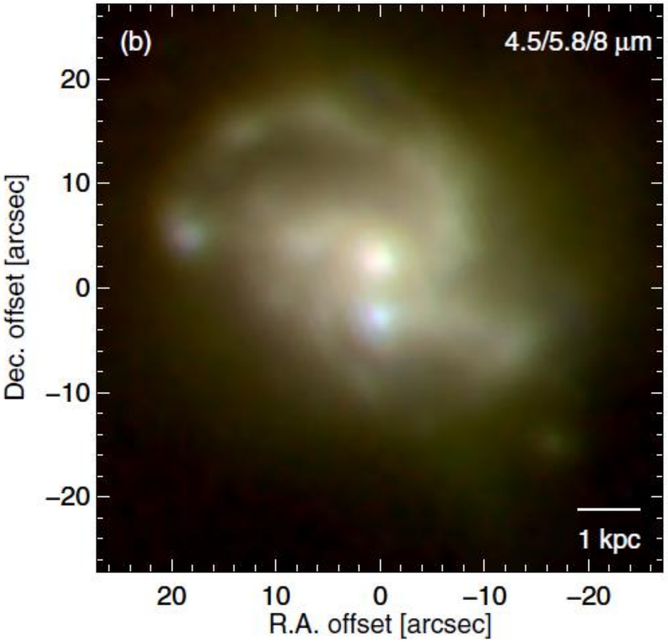




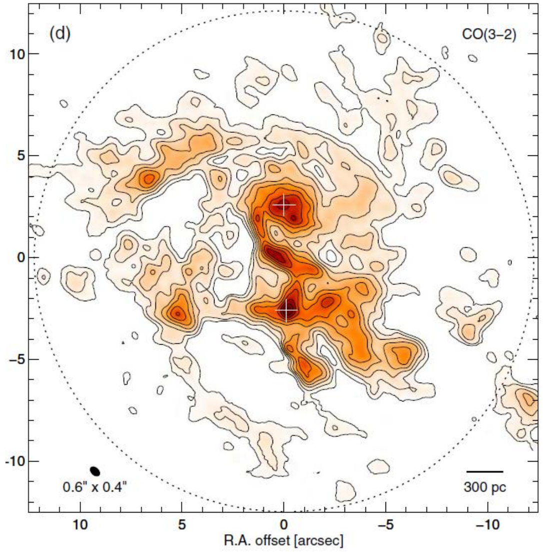
Tail of 80kpc in X-ray gas,
40kpc in CO
M(H_2) in C =1.5 10^8Mo

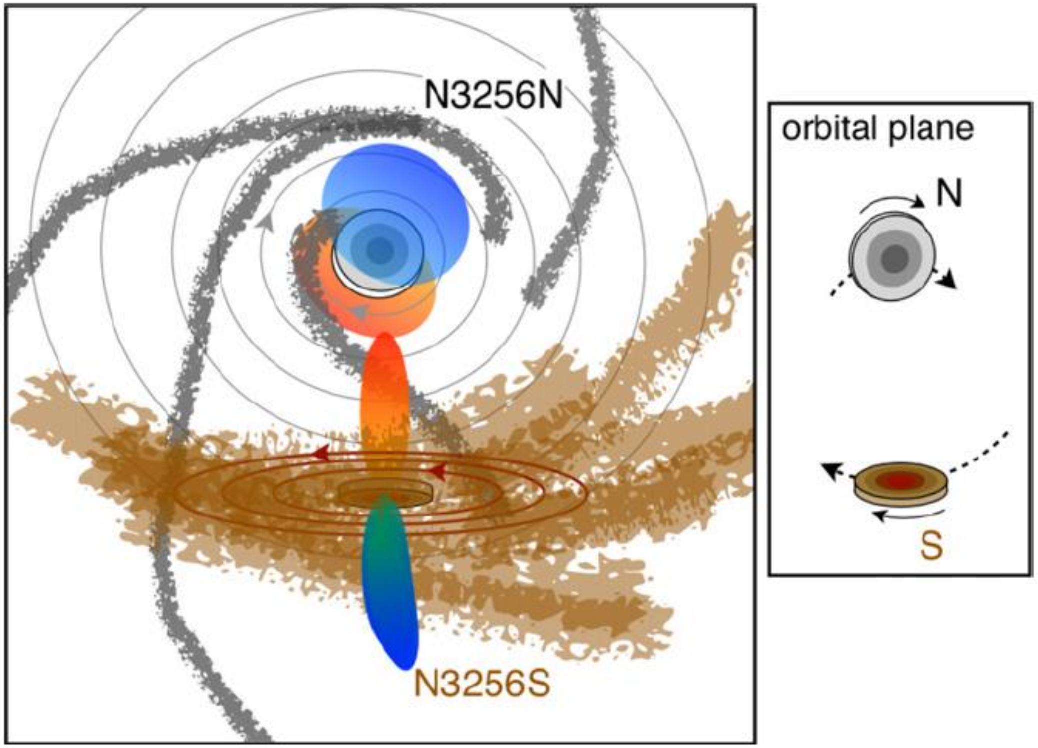
Jachym et al 2014

Galactic wind quenching



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

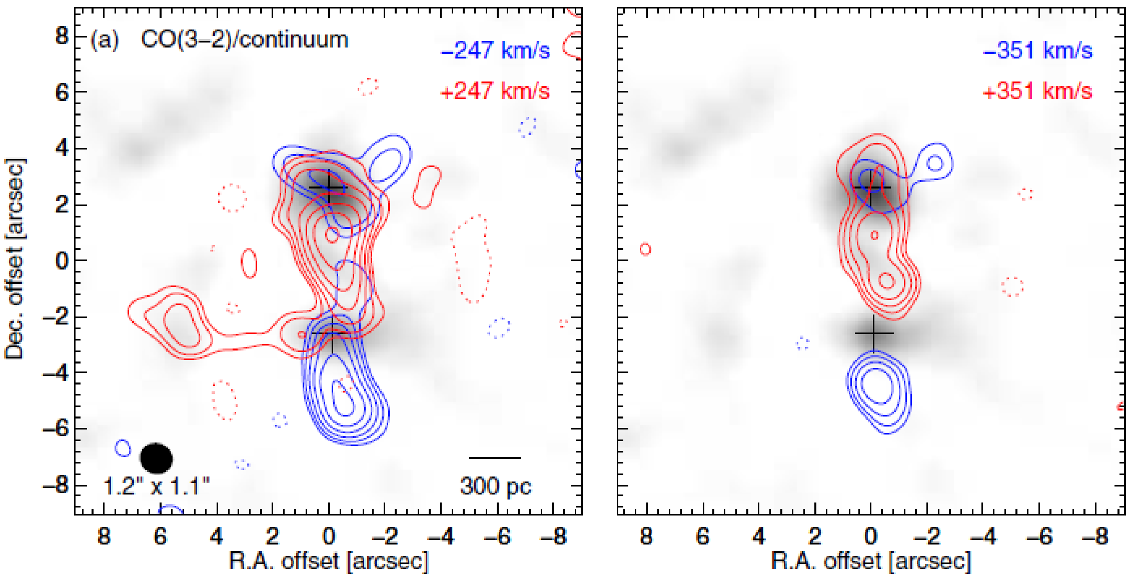




High-velocity wings
in both nuclei!
One nearly edge-on, the other
face-on

Sakamoto et al 2014

Two bipolar flows, τ~ 1 Myr



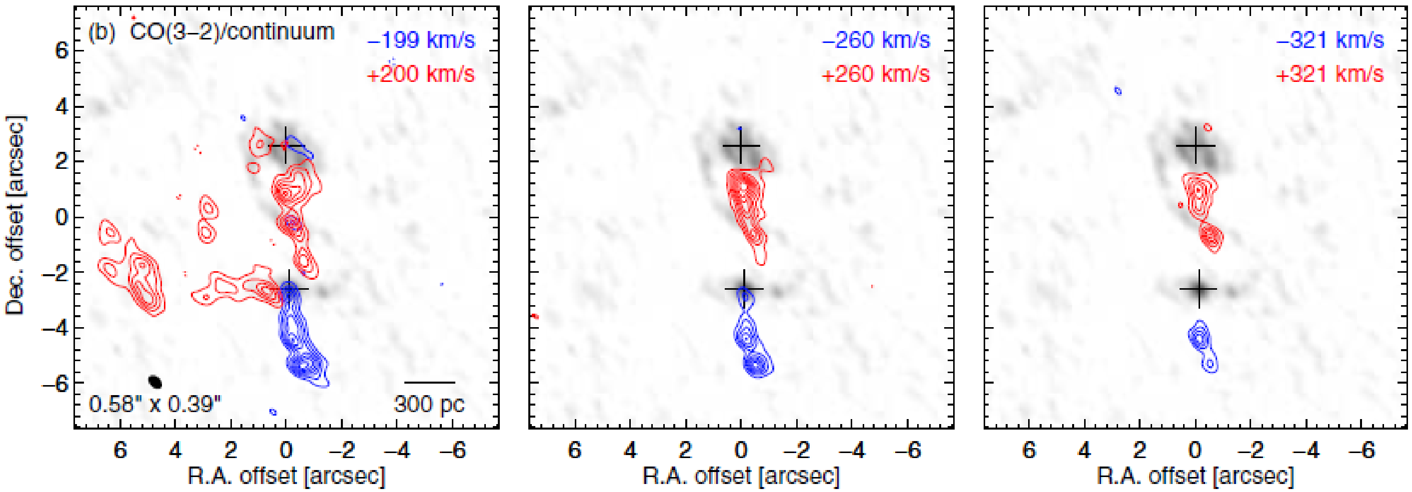
Northern outflow

V > 750km/s, 60 Mo/yr

Southern outflow

V ~2000km/s out to 300pc

- ➢50 Mo/yr
- ➢Highly collimated

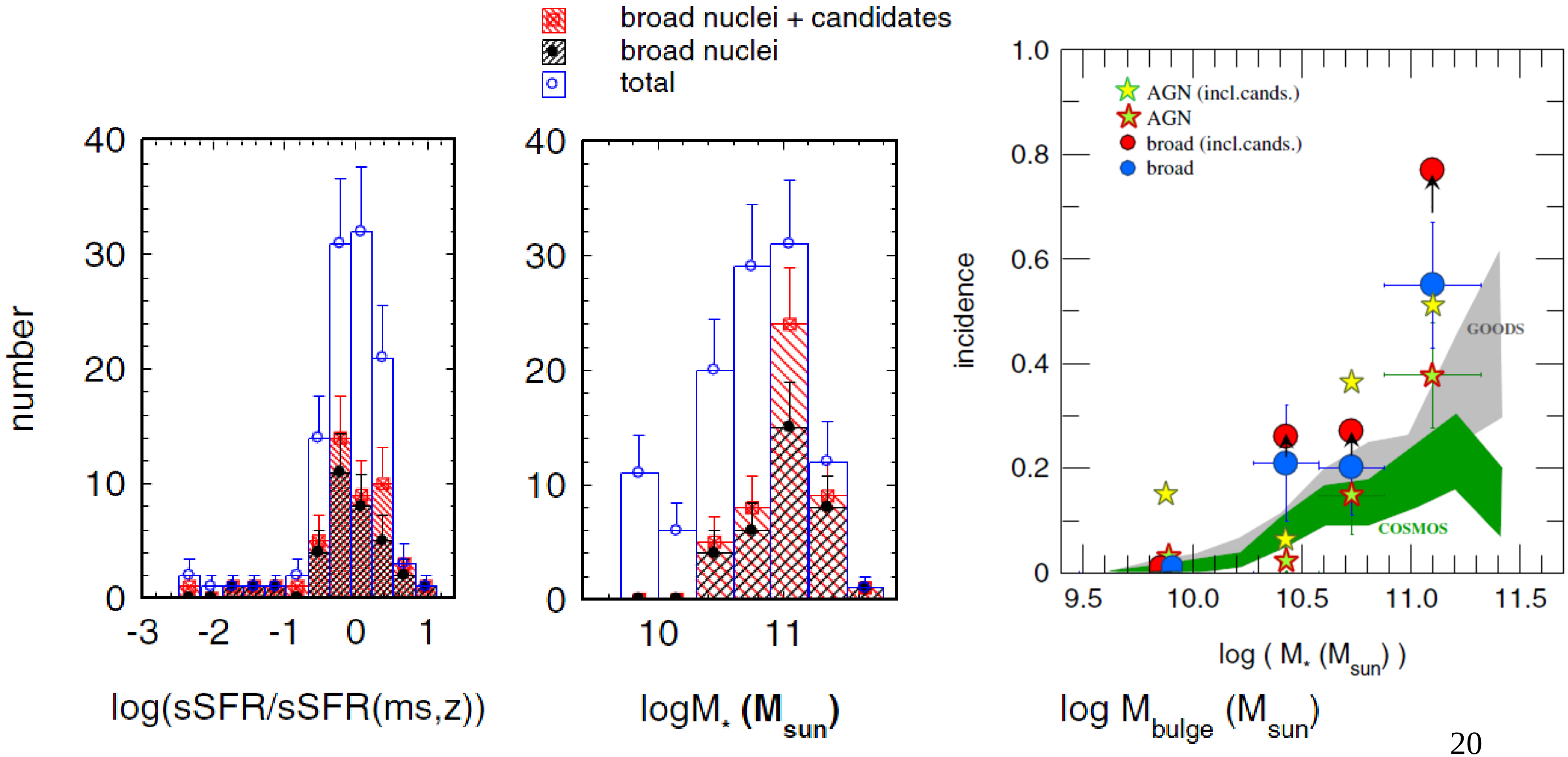


Comparable to SFR ➔efficient quenching?

Sakamoto et al 2014

Wide-spread AGN-driven outflows in massive z=1-2 SFG

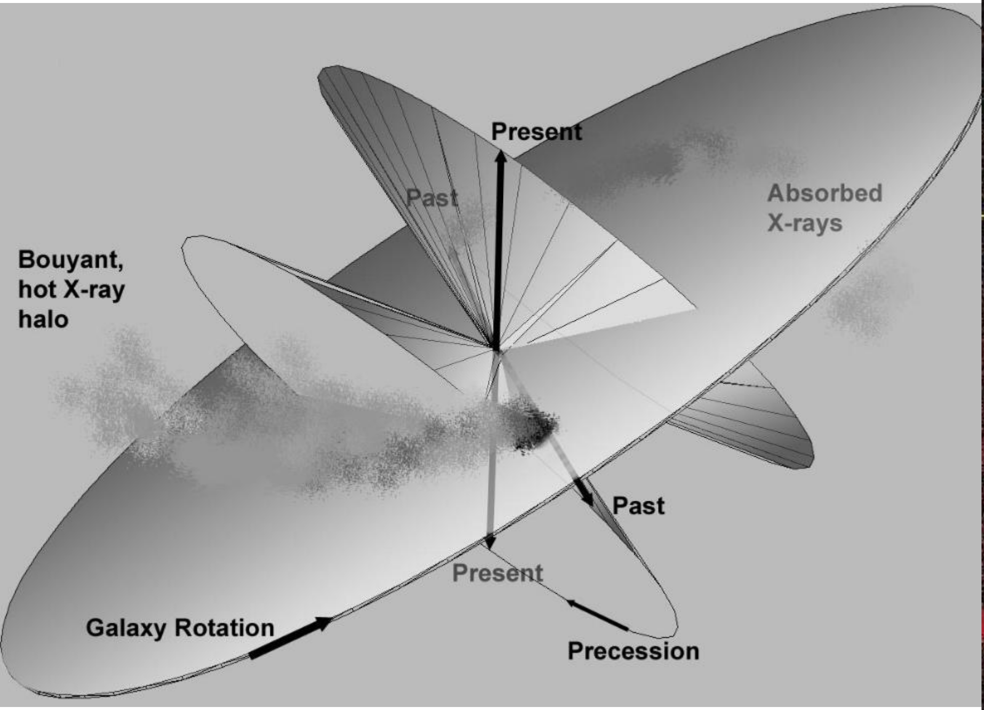
M> $10^{10.9}$ Mo

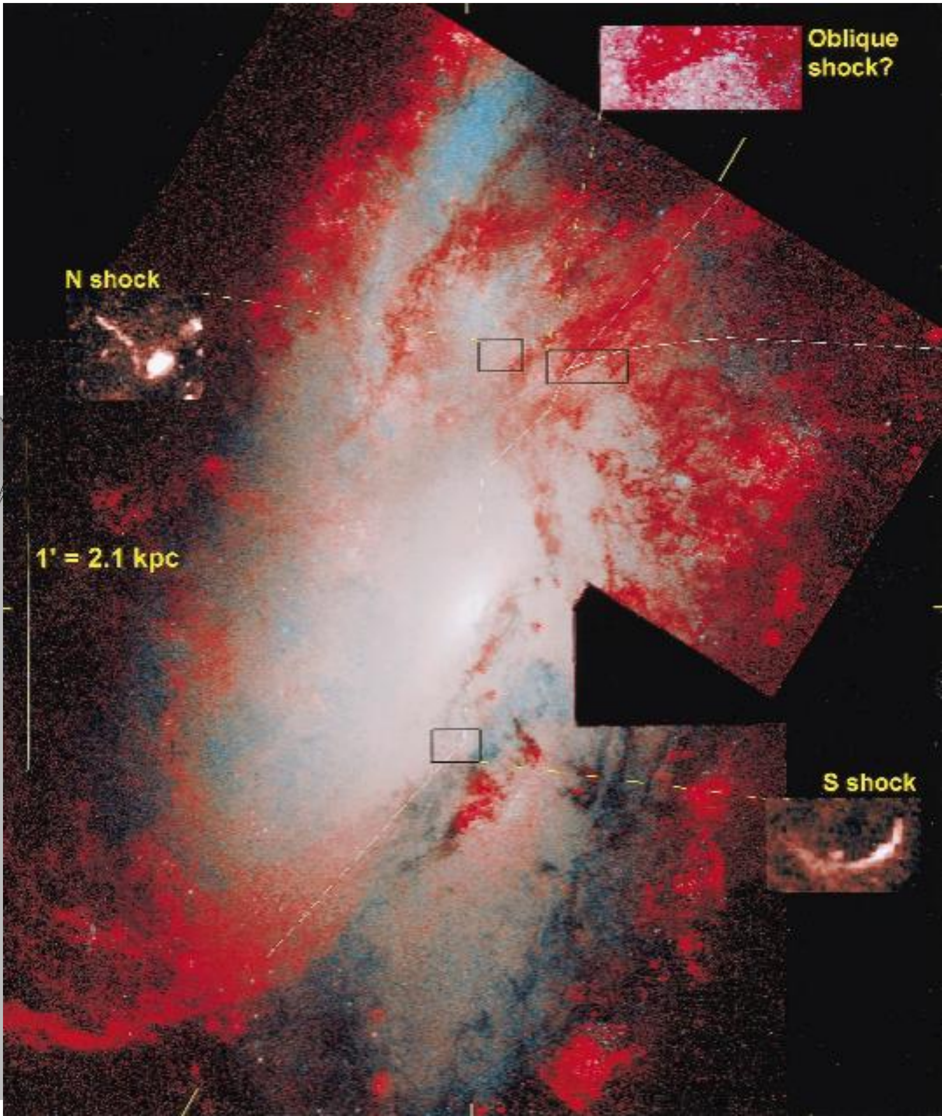


Genzel et al 2014

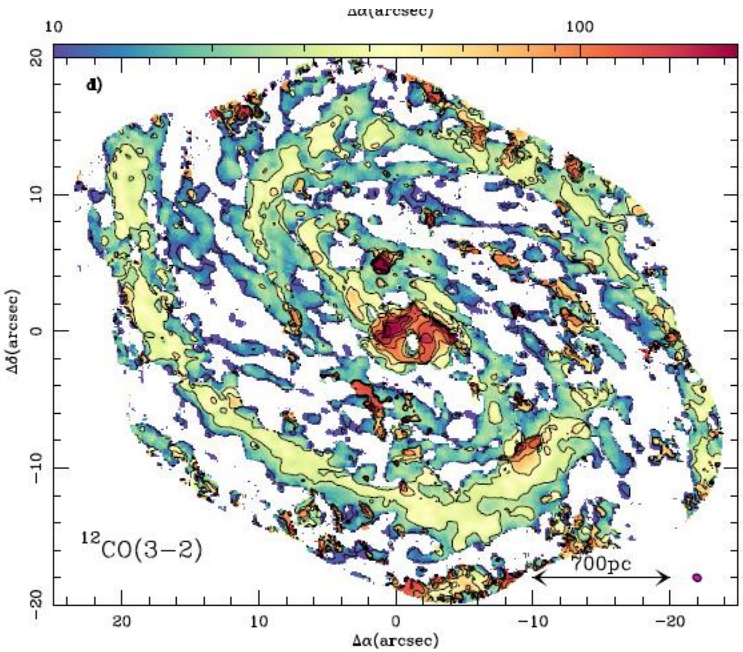
Jet in the disk plane

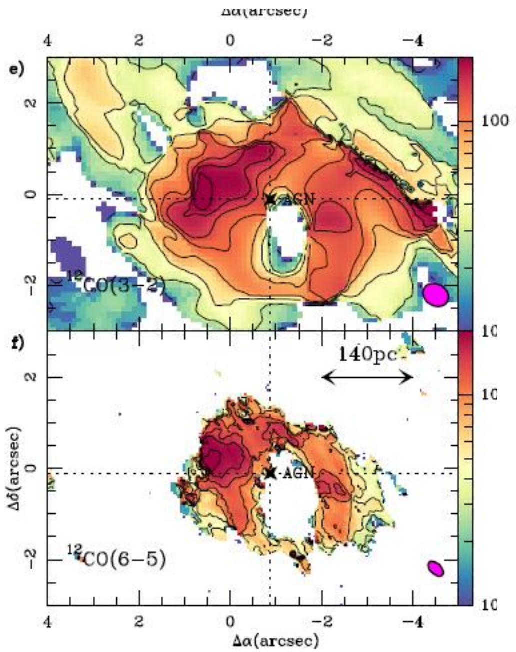
NGC 4258 Cecil et al 2000



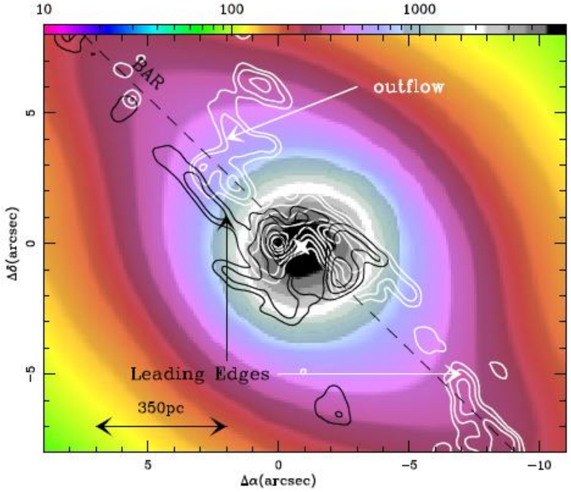


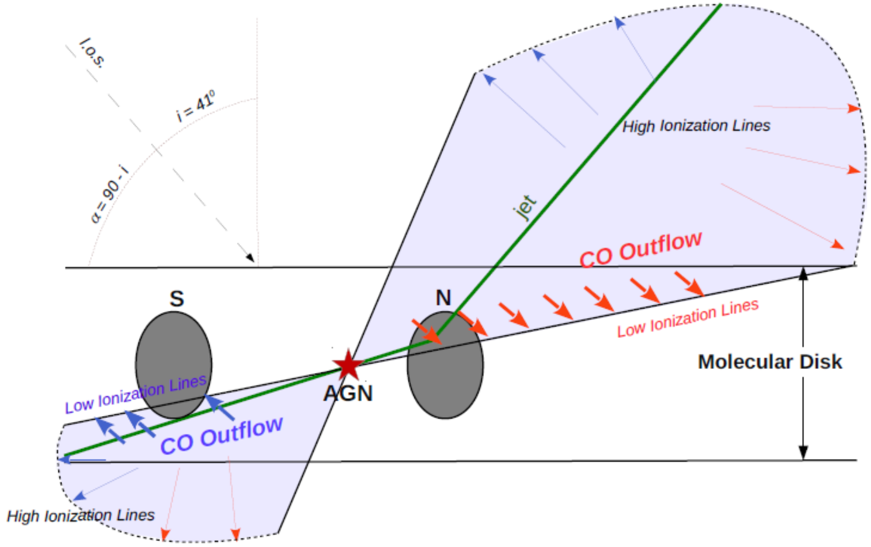
Off-center AGN and outflow in N1068





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

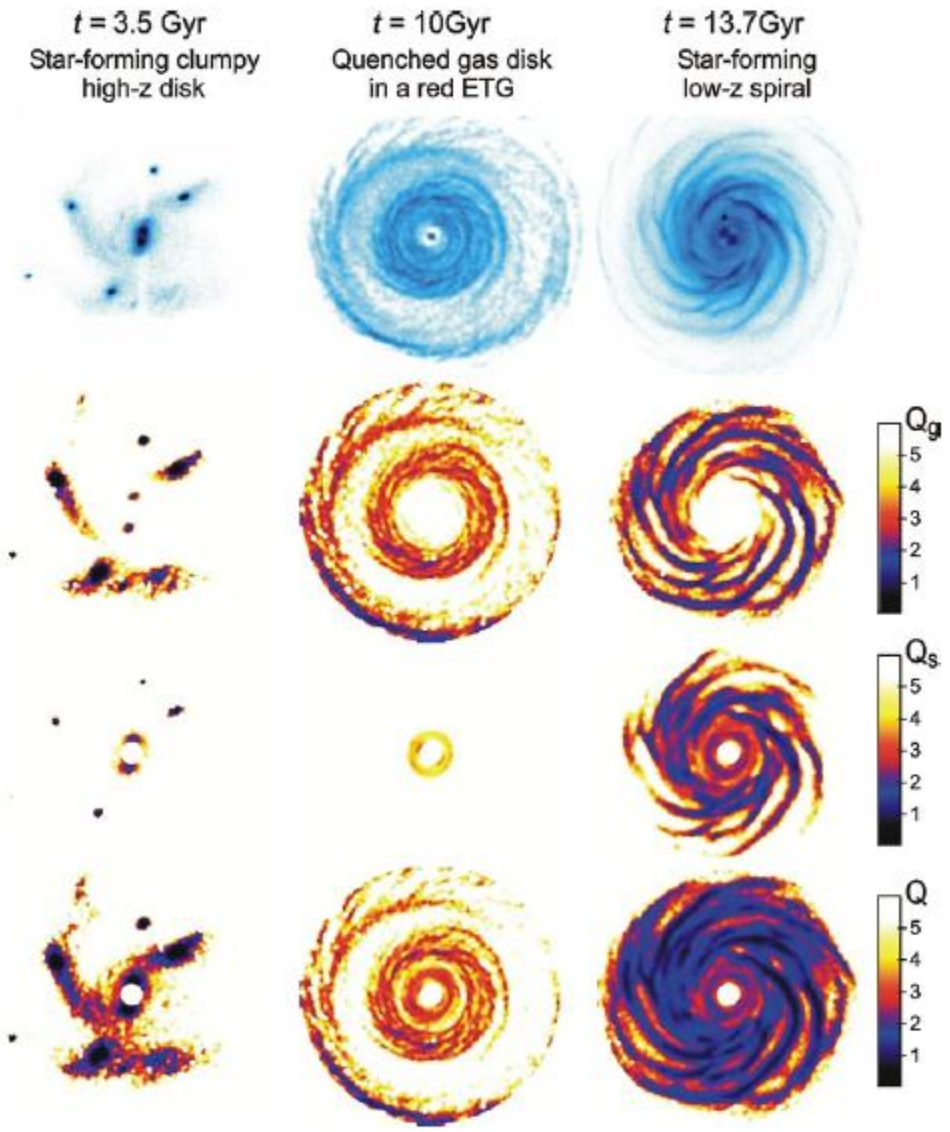




Outflow of 63Mo/yr
About 10 times the SFR in this CMD region

Garcia-Burillo et al 2014

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

Martig et al 2009

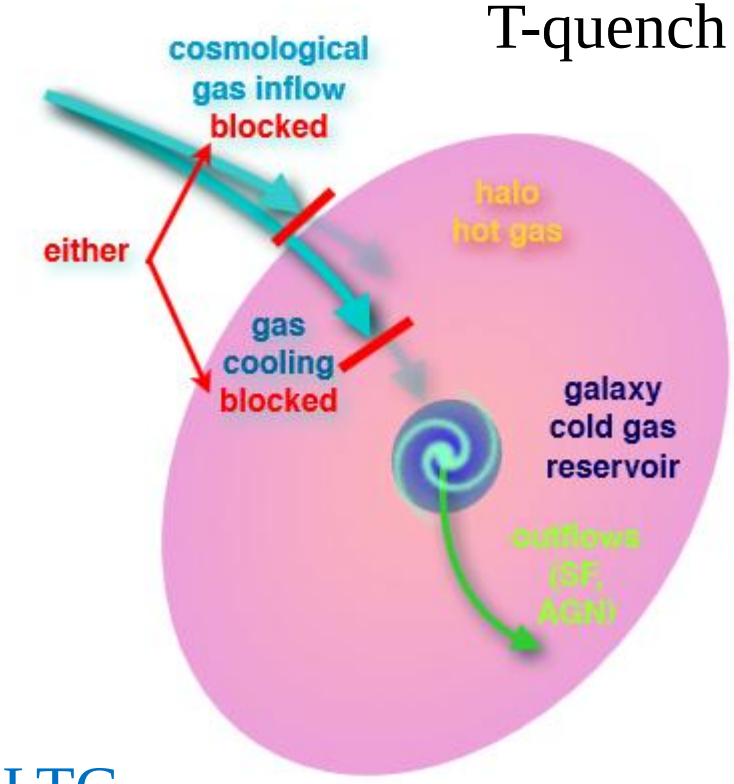
How to populate the green valley

➔ Late-type galaxies slowly run into the green valley, losing their gas reservoirs (t > 1Gyr)

➔ Early-type galaxies are rapidly quenched (mergers), and cross quickly the green valley (t < 0.2 Gyr)

T-quench ~2-4 Gyr

100 Myr



ETG

LTG

Schawinski 2014

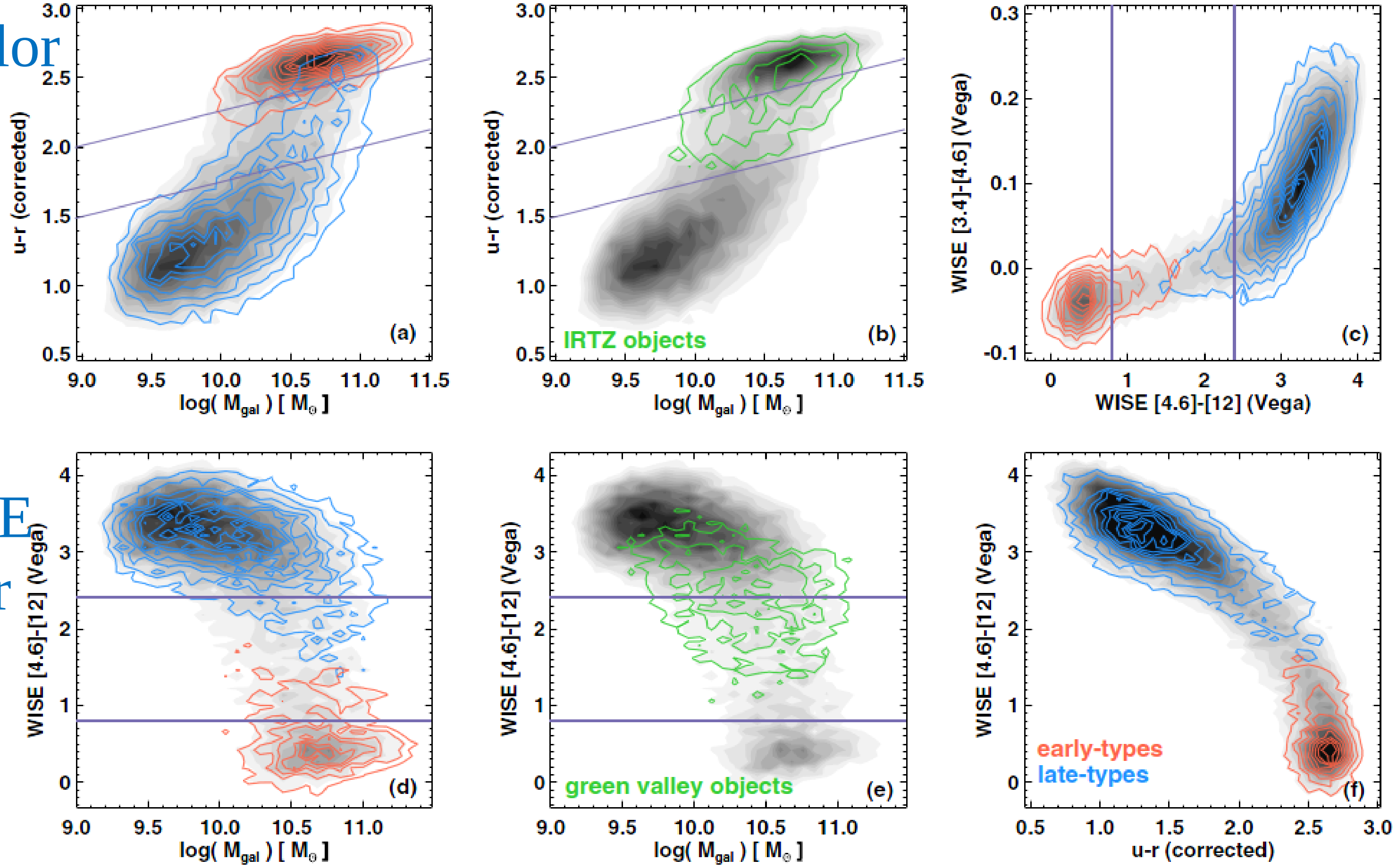
Quenched galaxies, or returning to MS?

SPOGs: Shocked Poststarburst Galaxy Survey, Hβ abs, *Alatalo et al 2014*

IRTZ: Intrared Transition Zone, in WISE (0.02 < z < 0.2)

Color

WISE color

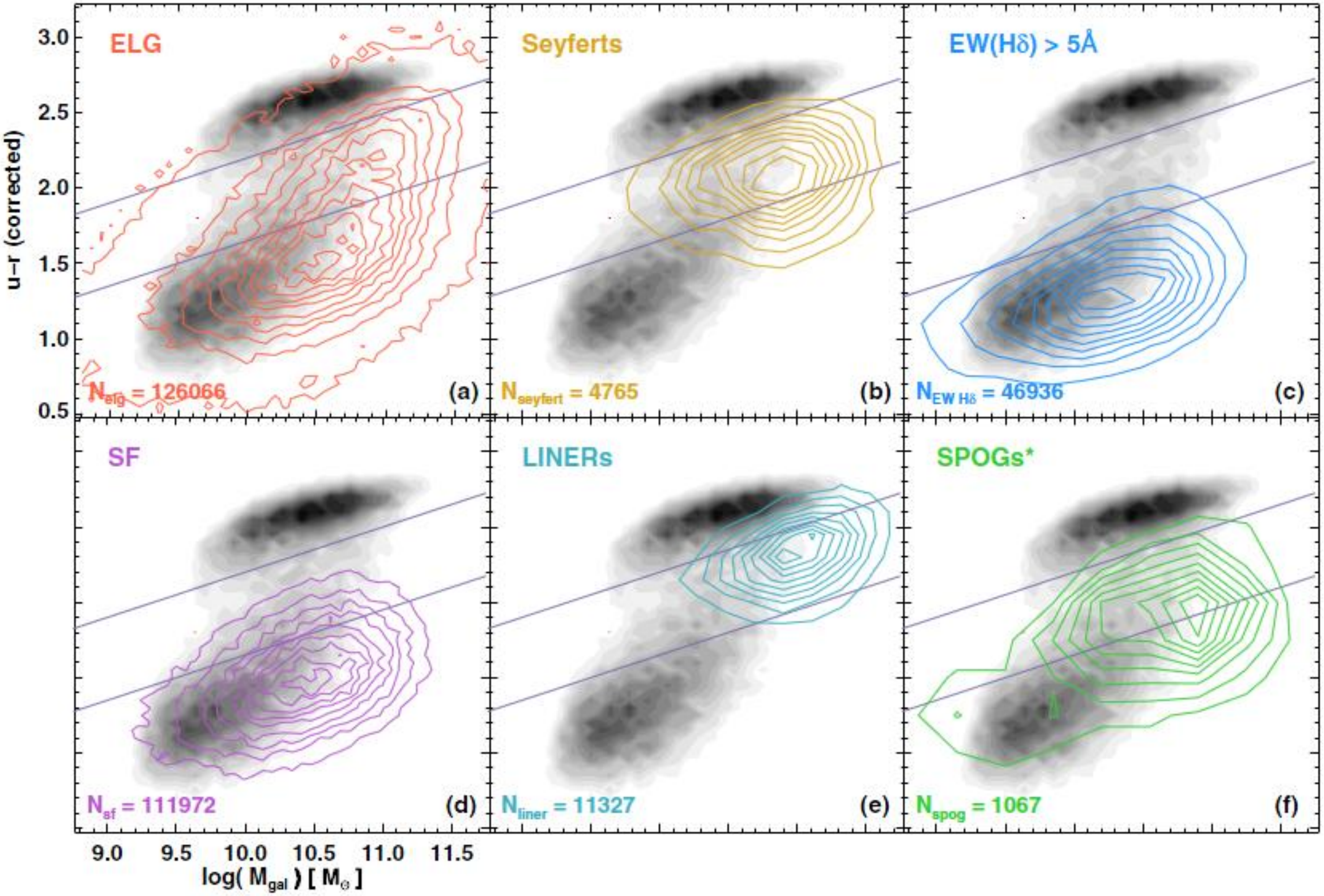


Mass

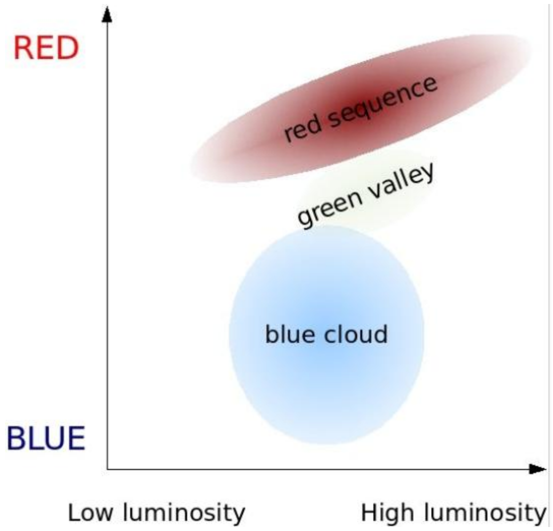
AGN, SF and SPOGS

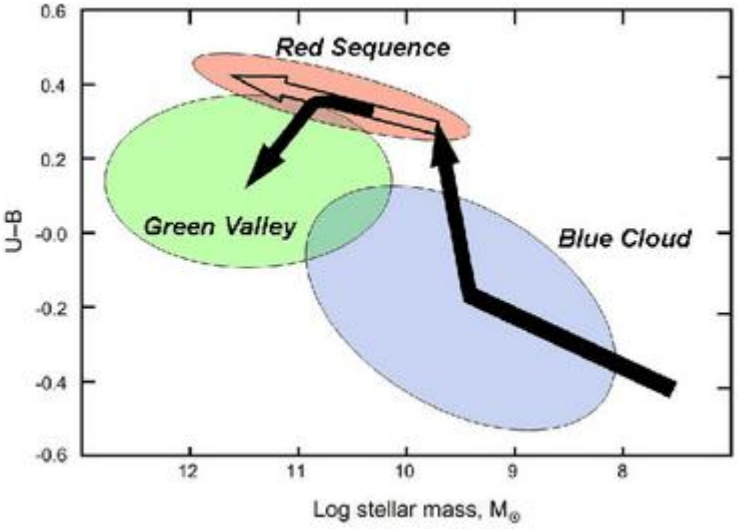
SPOGS: the best transition objects? *(Alatalo et al 14)*

Colors are not strongly affected by AGN



Return to the blue cloud, or green valley?





After an increase in mass

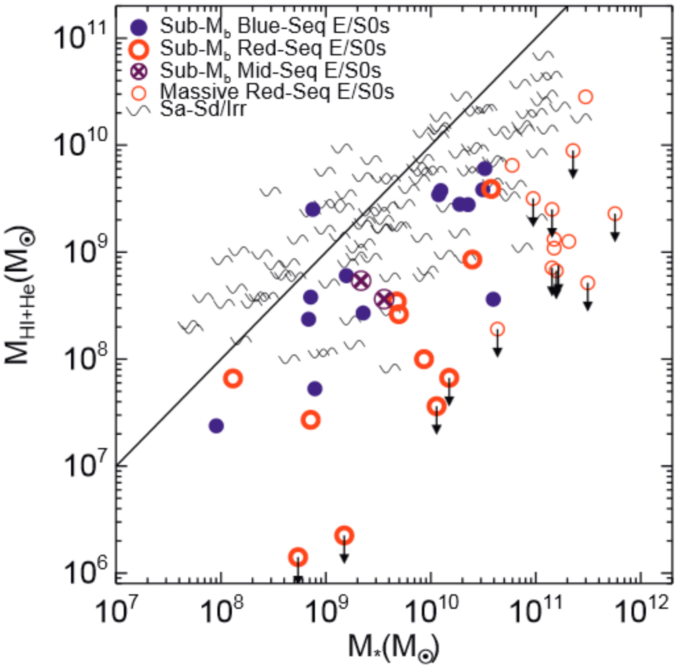
Gas accretion to **regrow a disk**

In most galaxies, existence of a thick disk, like in the MW (Comeron et al 2011, 12)

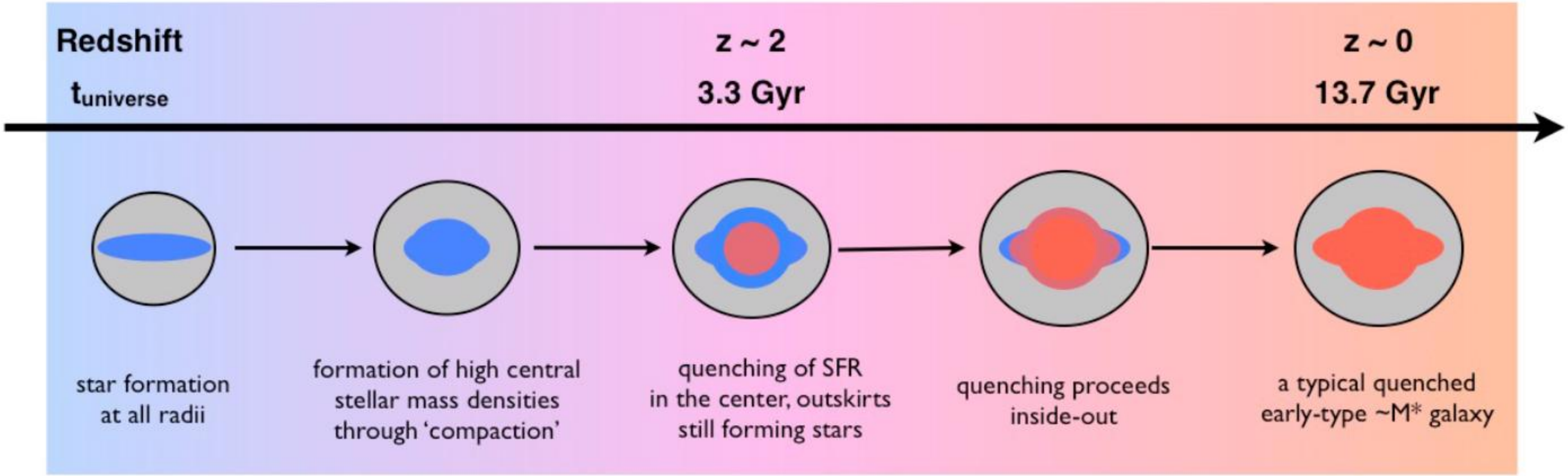
Thin and thick disks: equal masses

E/S0 galaxies in the blue cloud: disk regrowth

Wei et al 2010



4- Clue-1: Inside out Quenching



Redshift

t_{universe}

z ~ 2

3.3 Gyr

z ~ 0

13.7 Gyr

star formation at all radii

formation of high central stellar mass densities through 'compaction'

quenching of SFR in the center, outskirts still forming stars

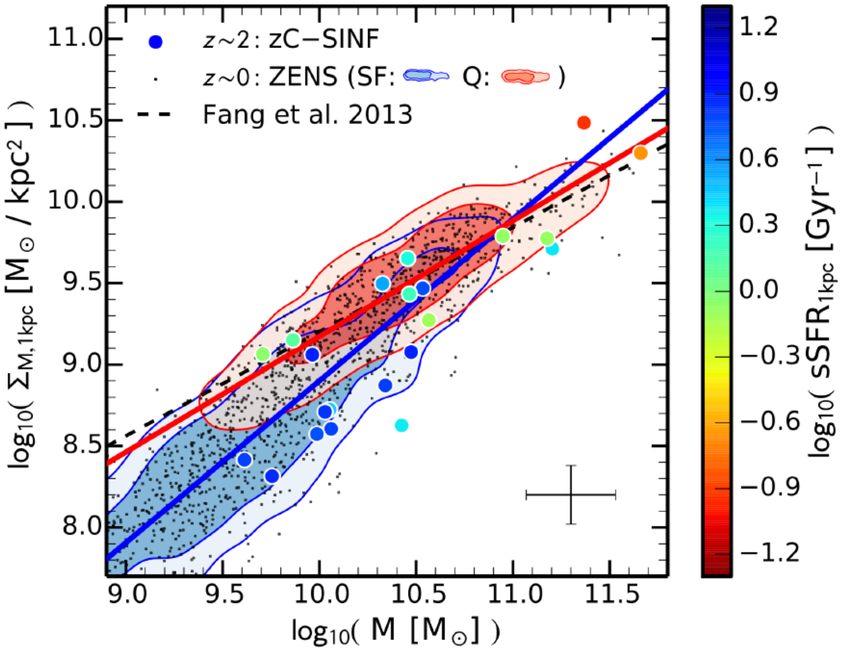
quenching proceeds inside-out

a typical quenched early-type ~M* galaxy

➔ Morphological quenching?

At z=2, inner regions of quiescent galaxies are redder than their outer parts

Guo et al 2011



Tacchella et al 2015

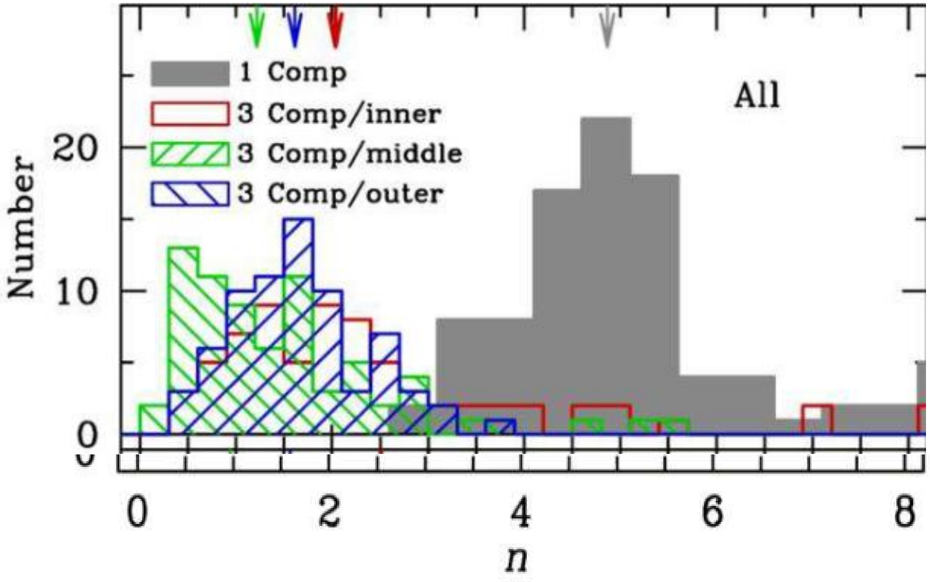
Inside out formation

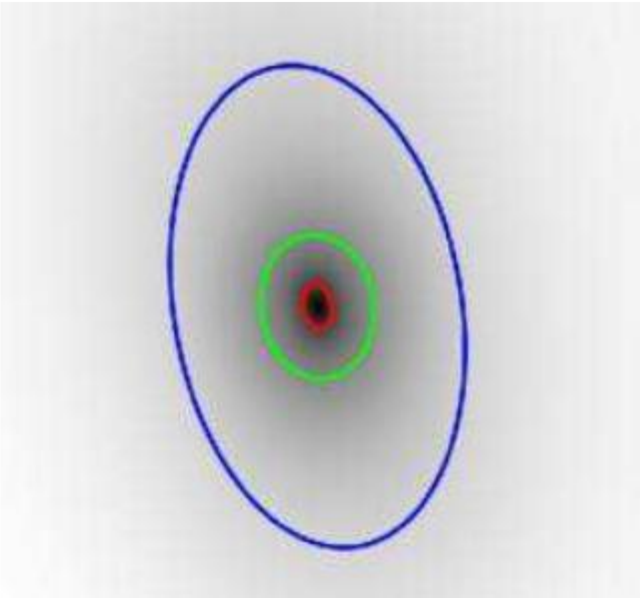
Decomposition into several components of the ETG

(not reducible to only one Sersic index, as commonly thought)

3 components, implied in galaxy formation (Huang, S et al 2013)

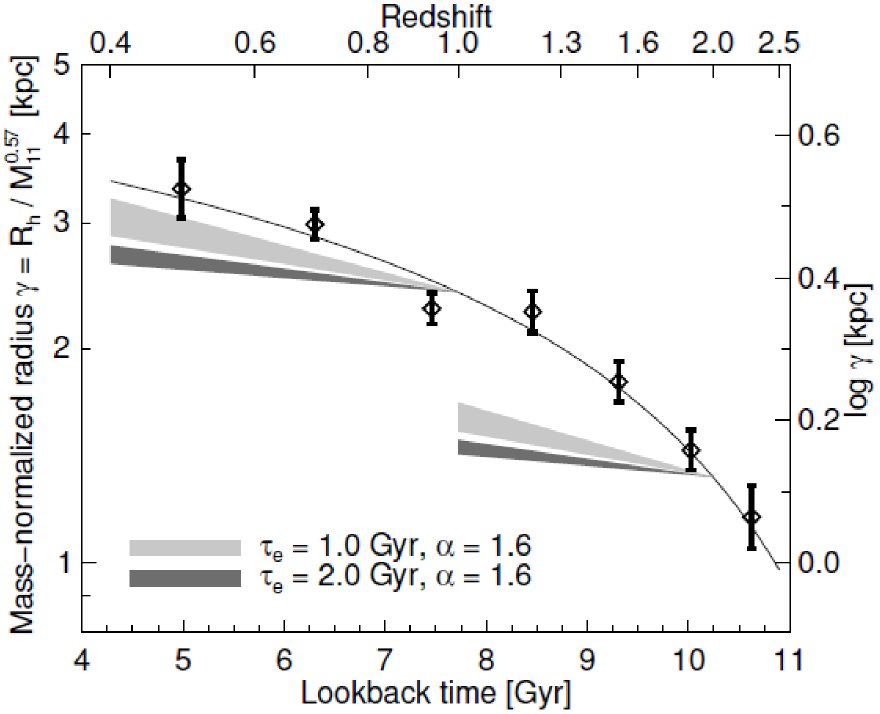
Red nugget at the center, intermediate radii,
outer parts, coming from dry mergers?
Different Sersic index





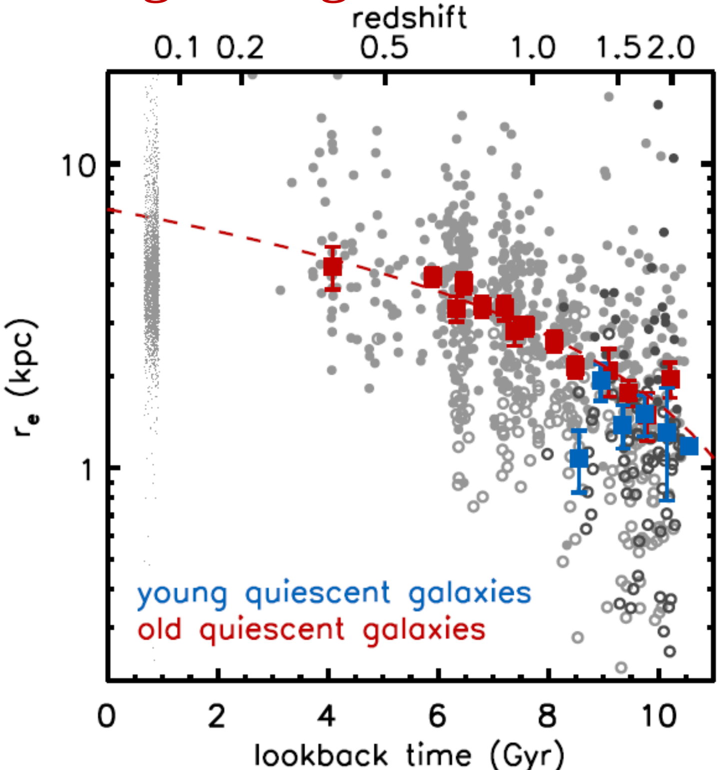
Galaxy size evolution

Could be due to minor mergers at z=1, but has to come from another population shift at z=2 (Newman et al 2012)



Young quiescent galaxies at z>1 are more compact than the old ones

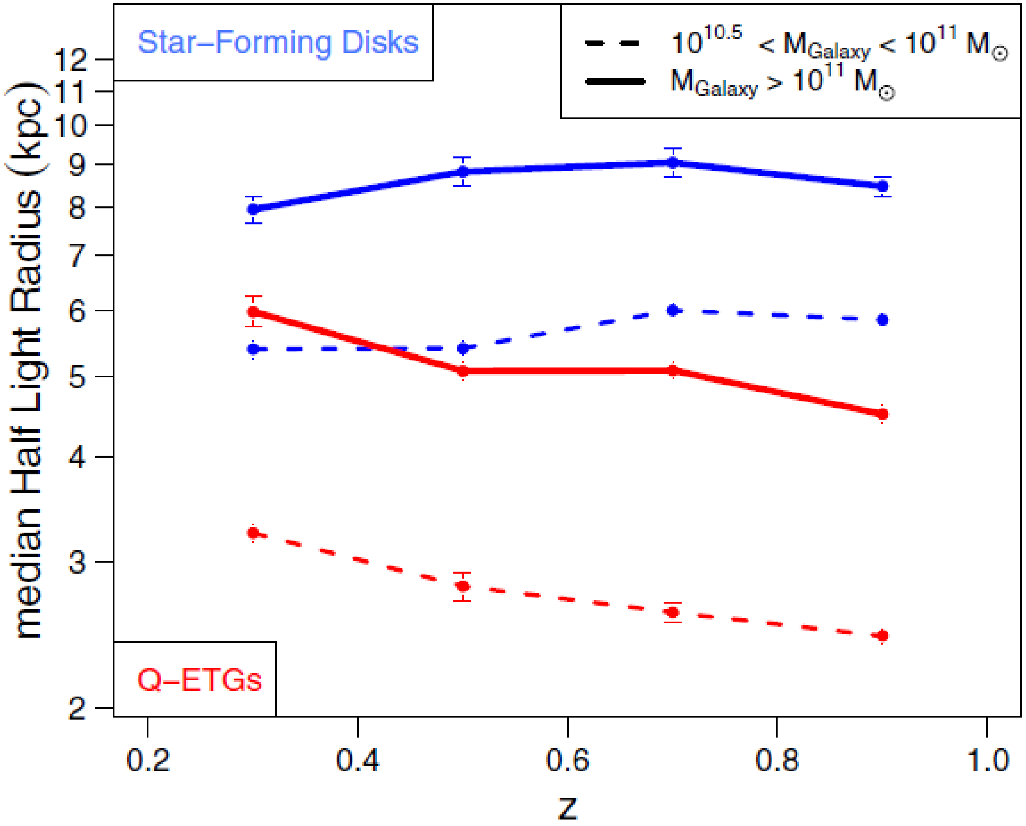
The old passive galaxies must grow in size through mergers



➔The quenching mechanism is associated to compaction

Whitaker et al 2012

Fading of the disk?

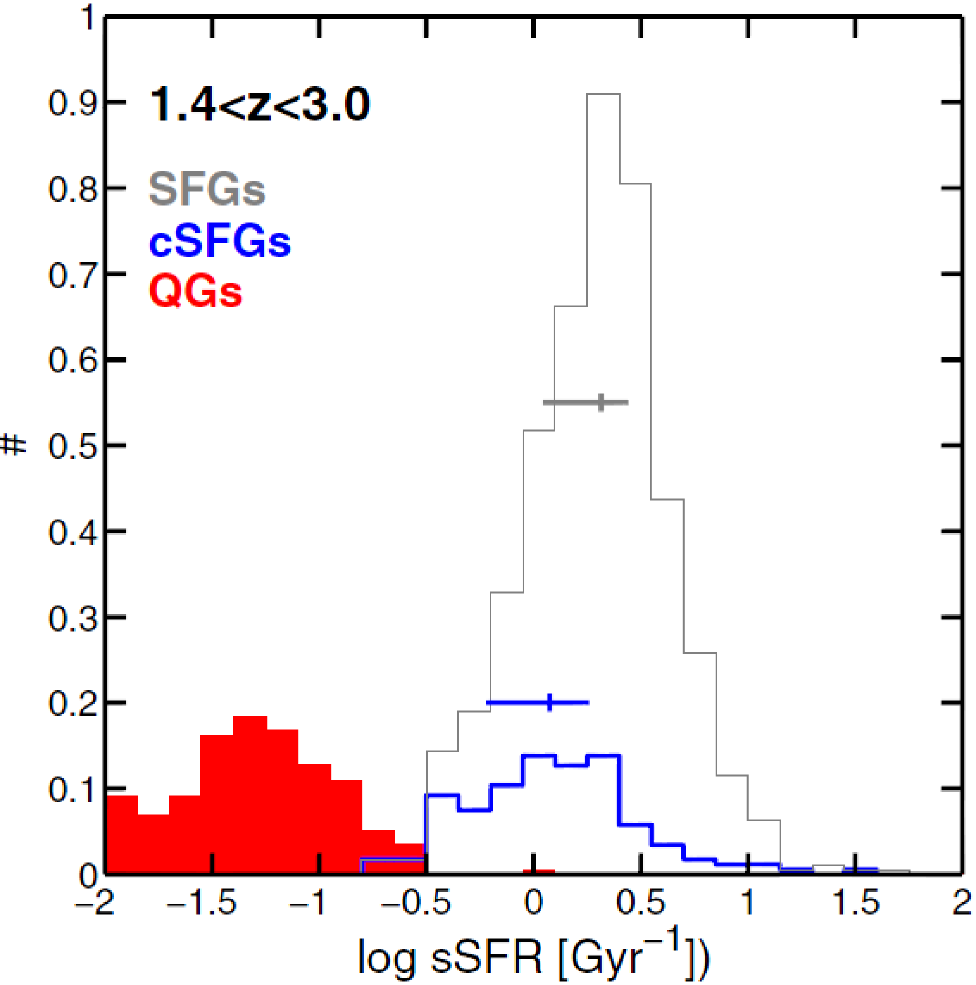


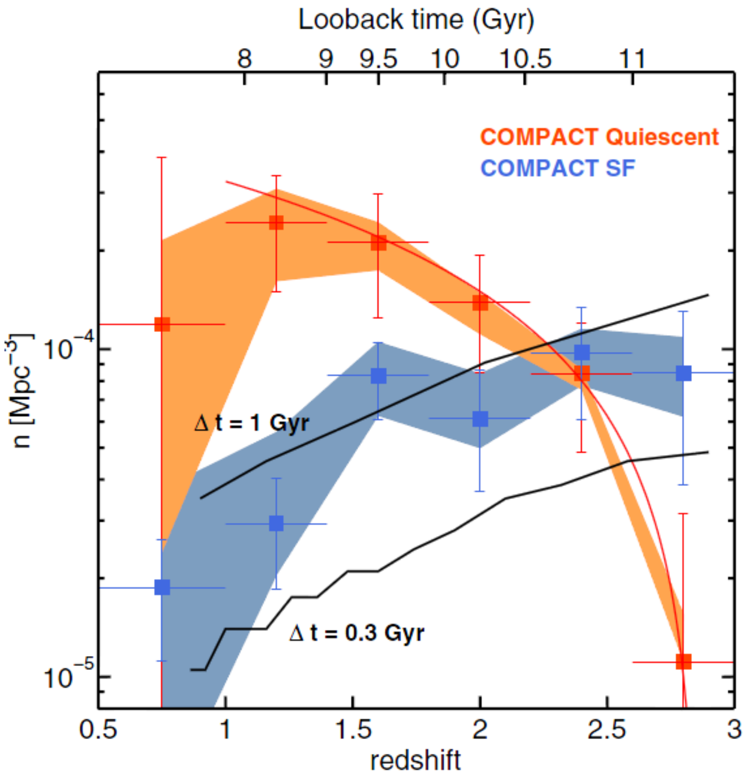
Contrary results found by Carollo et al 2013 larger Q-ETGs have average rest-frame colors bluer and then are younger

Size evolution= Addition of larger and diffuse ETG

Compact red and blue galaxies

M > 10^{10}Mo



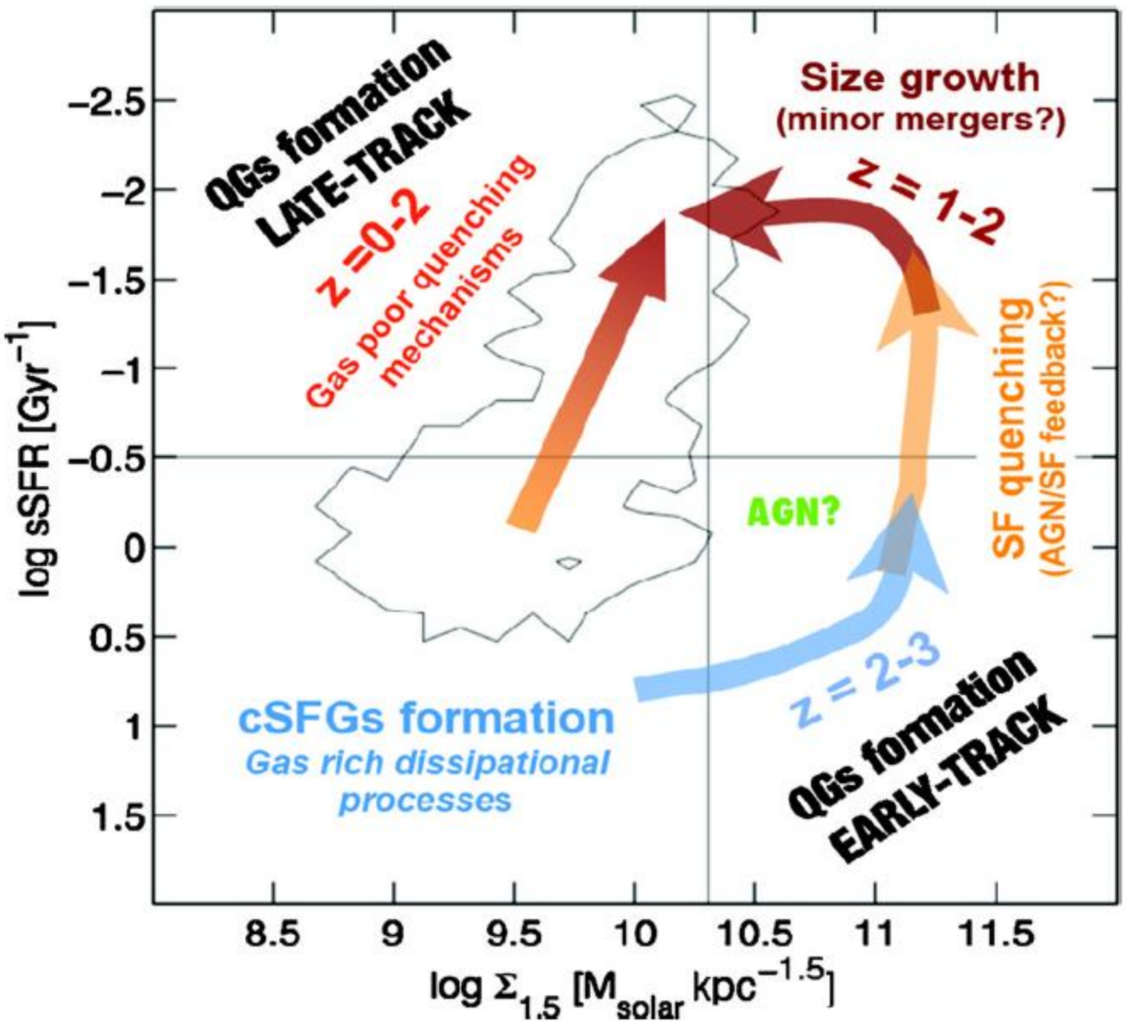


Black lines: density of cSFG required to explain the red nugget t_{burst}=0.3-1 Gyr

Barro et al 2013

CANDELS

Possible scenarios



$\Sigma_{1.5} \equiv M/r^{1.5}$

Two evolutionary tracks of QG formation:

(1) early (z>2), formation path of rapidly quenched cSFGs fading into cQGs that later enlarge,

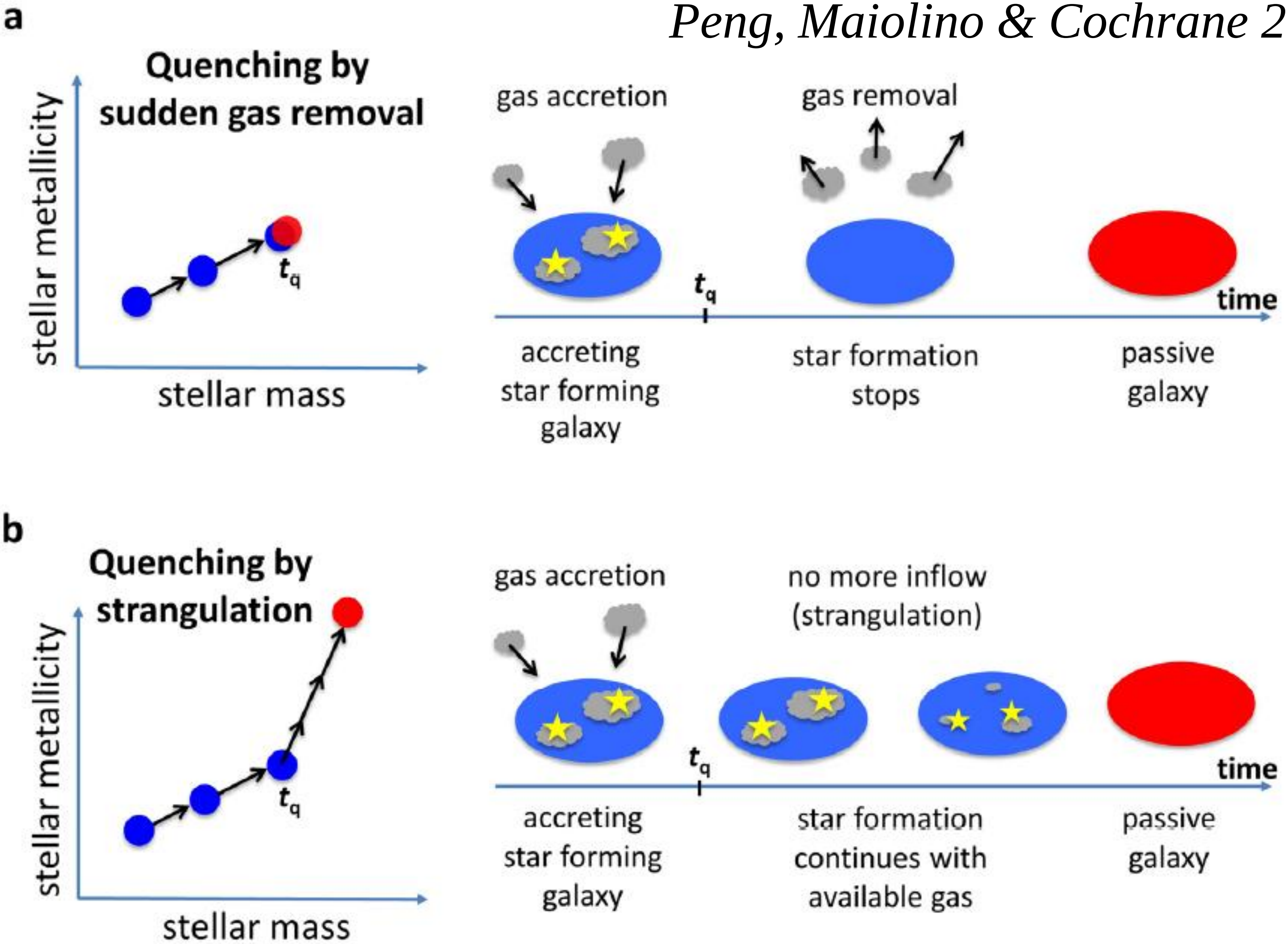
(2) late-arrival (z<2) path in which larger SFGs form extended QGs without passing through a compact state

Barro et al 2013

Clue-2: metallicity

Strangulation or outflow/ram pressure

Peng, Maiolino & Cochrane 2015



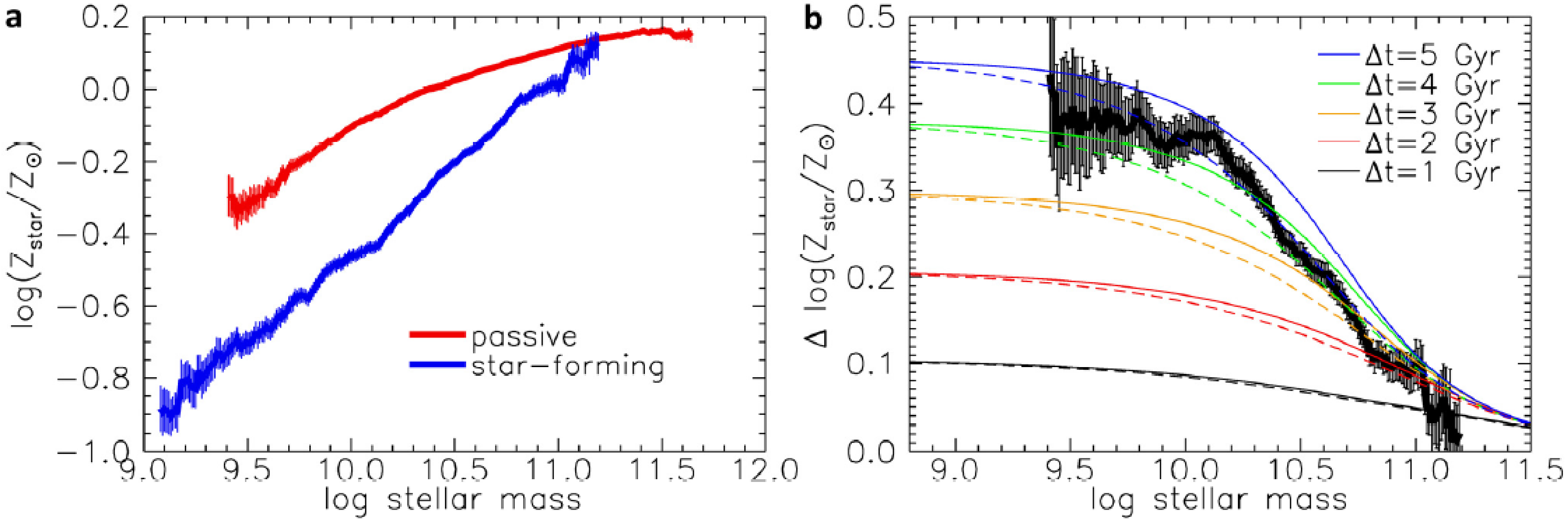
Strangulation dominant

If the gas is removed quickly, the stellar metallicity will be less than in the case of strangulation, where star formation and enrichment continue

➔Strangulation appears dominant for 26 000 SDSS galaxies

Quenching time-scale 4 Gyr, Local galaxies $M < 10^{11}$ Mo

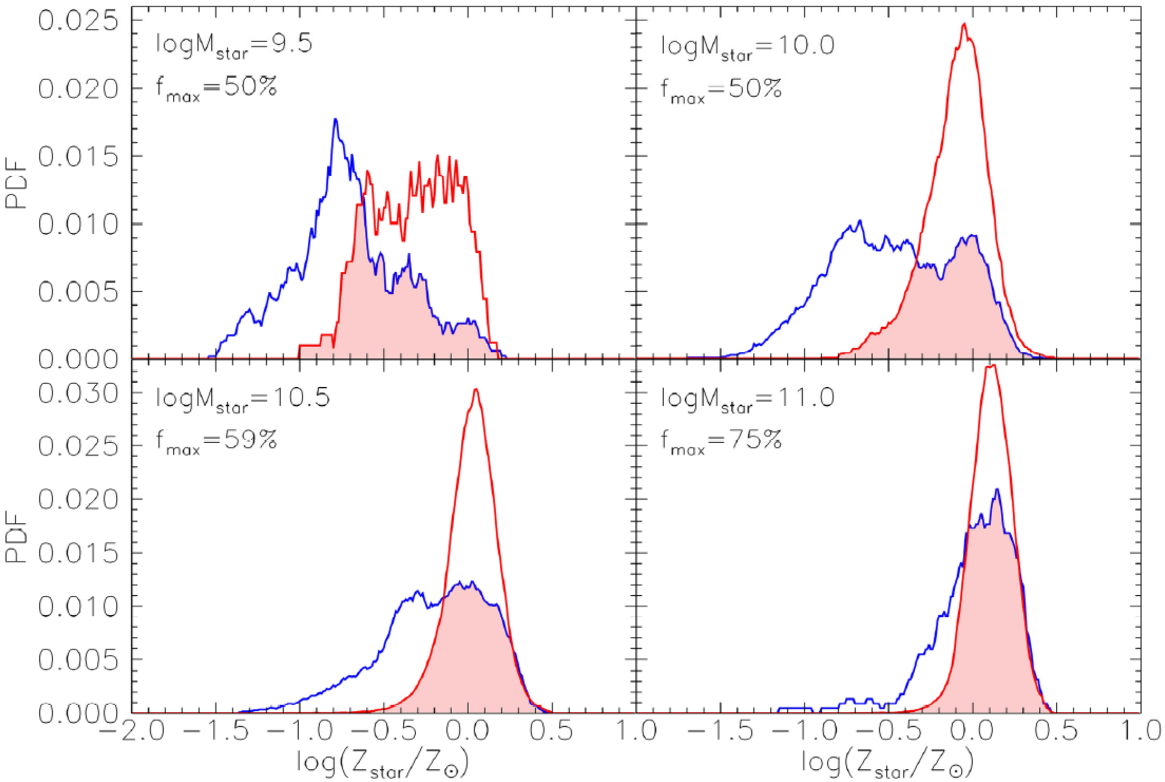
Supported by stellar age difference of 4 Gyr quiecent/SFG

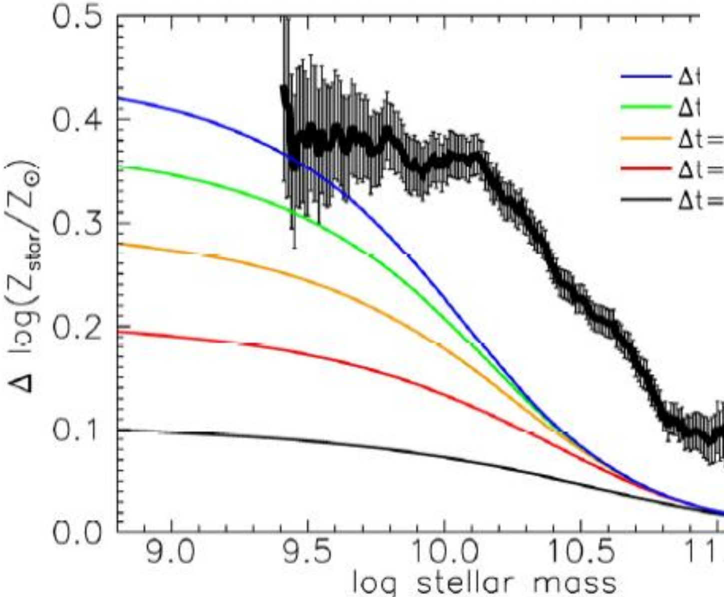


Peng, Maiolino & Cochrane 2015

Rapid quenching possible

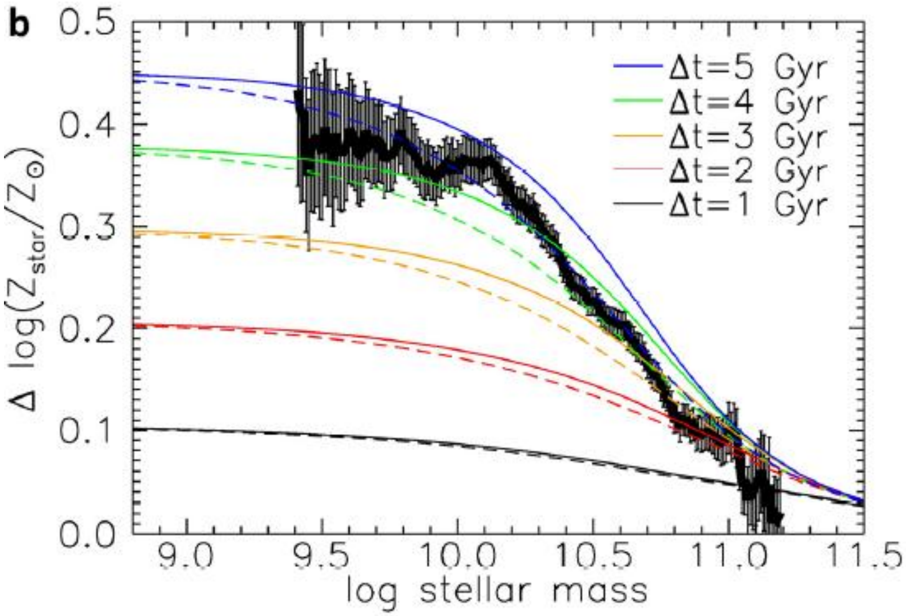
It is still possible
that some galaxies are
quenched by outflow
or ram-pressure



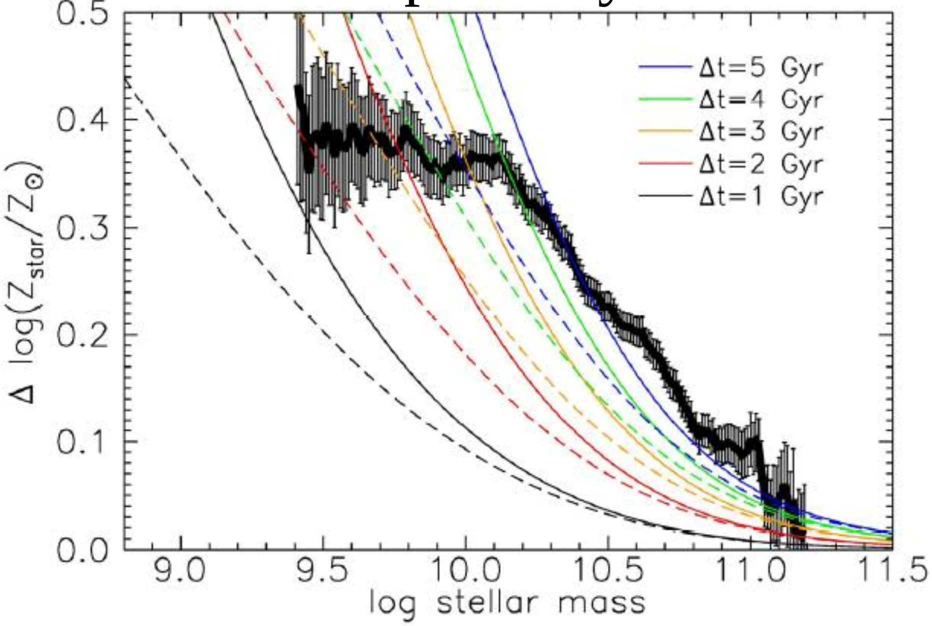


Loading factor η =1
dM/dt = η SFR
Assumed escaping gas

Effect of SFE since strangulation



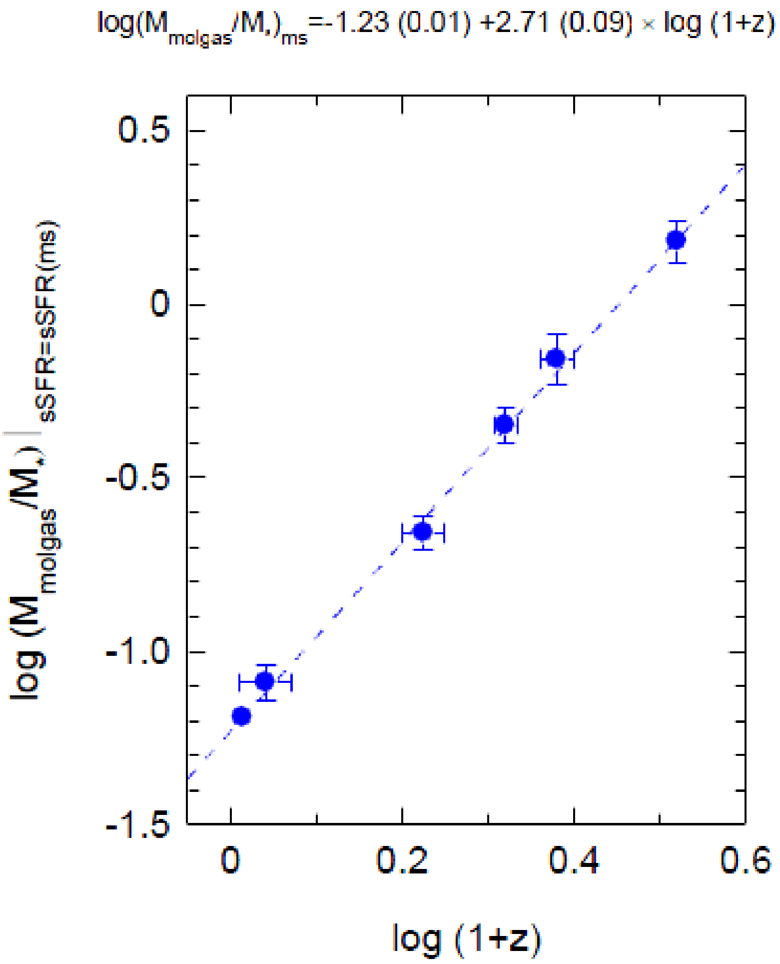
tdep = 2 Gyr = cst



SFE ~ $M_*^{3/4}$

Or tdep = 100 Gyr for $M_*= 10^8$Mo
tdep = 100 Myr for $M_* = 10^{12}$Mo
(3Gyr for $M_* = 10^{10}$Mo)

Clue-3: Gas content of SF Galaxies

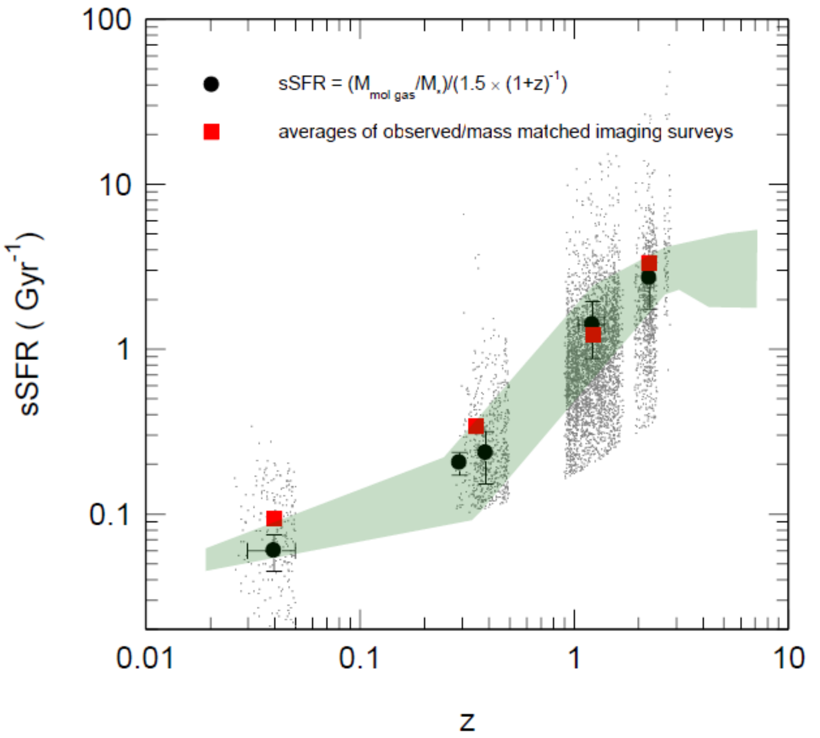


Genzel et al 2014

On the MS, $M_{gas}/M_* \sim (1+z)^{2.7}$

tdep=1.5/(1+z) Gyr

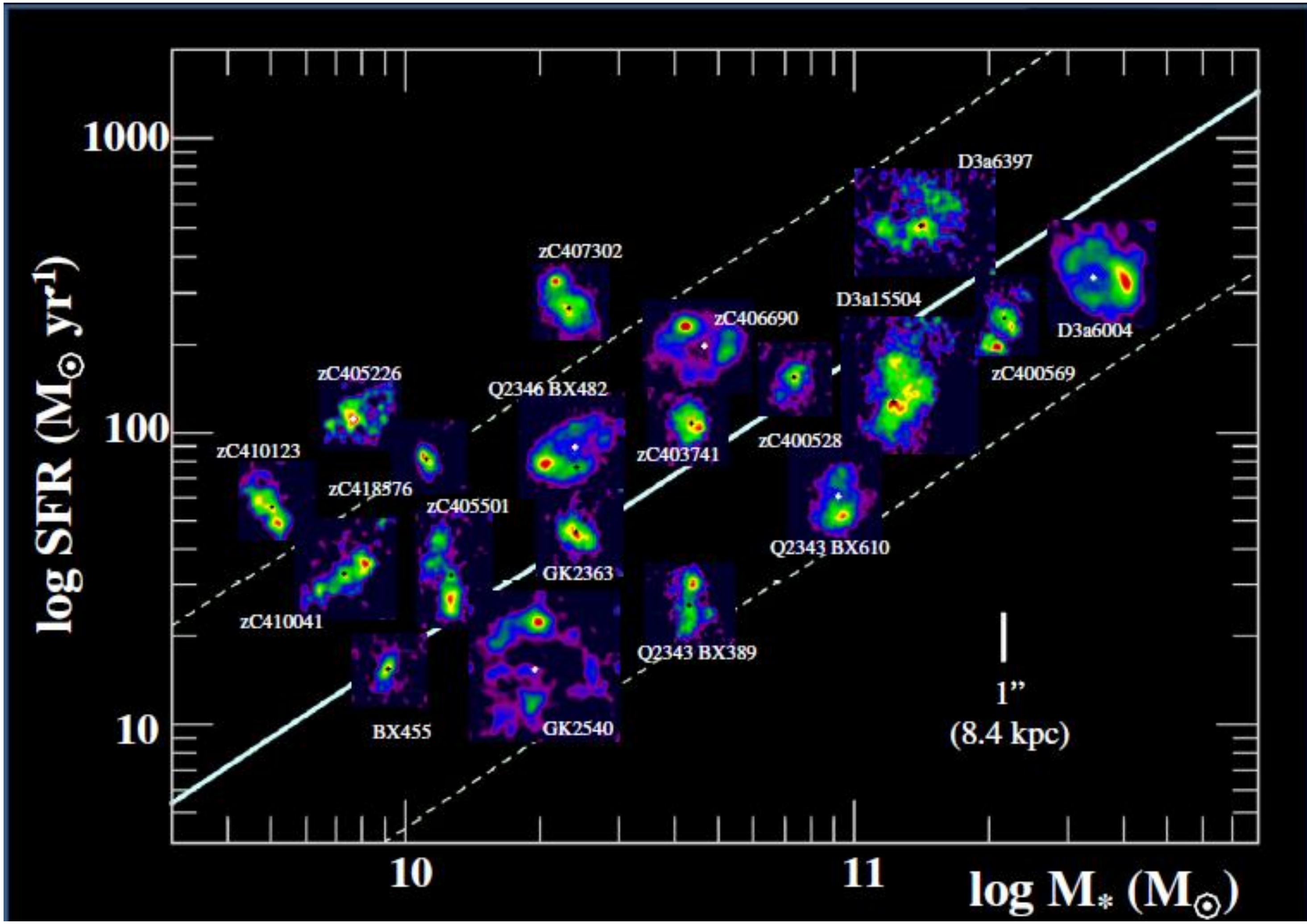
➔ SFE increasing with z



Tacconi et al 2013

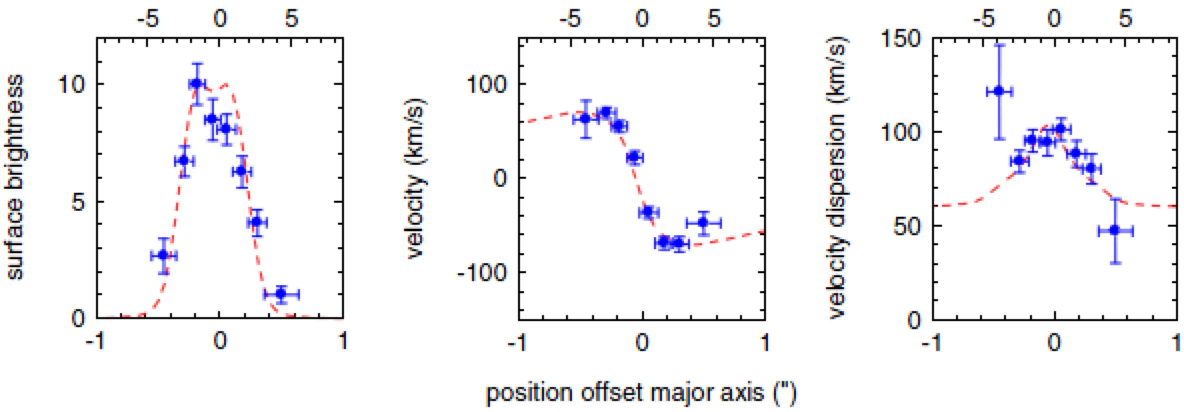
Evidence of quenching

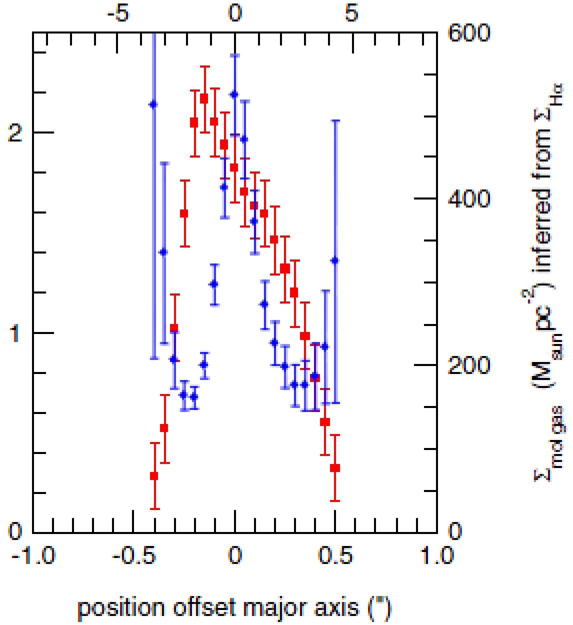
19 over 35
Selected with
Regular rotation
(no major
mergers)

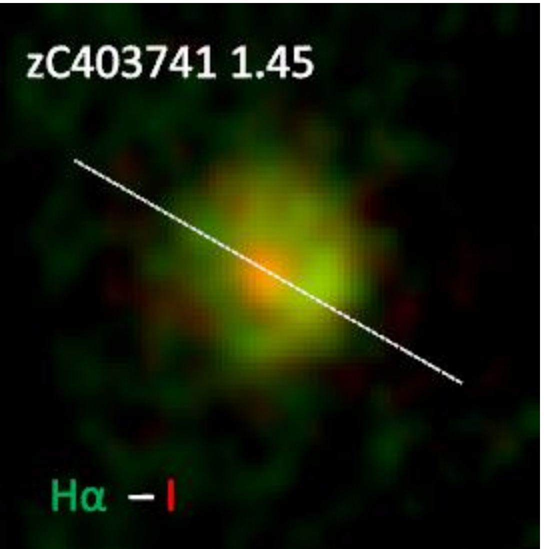


Genzel et al 2014

Computation of disk stability: Q







Gas deduced from the inversion of KS law

Q in blue

Molecular gas in red

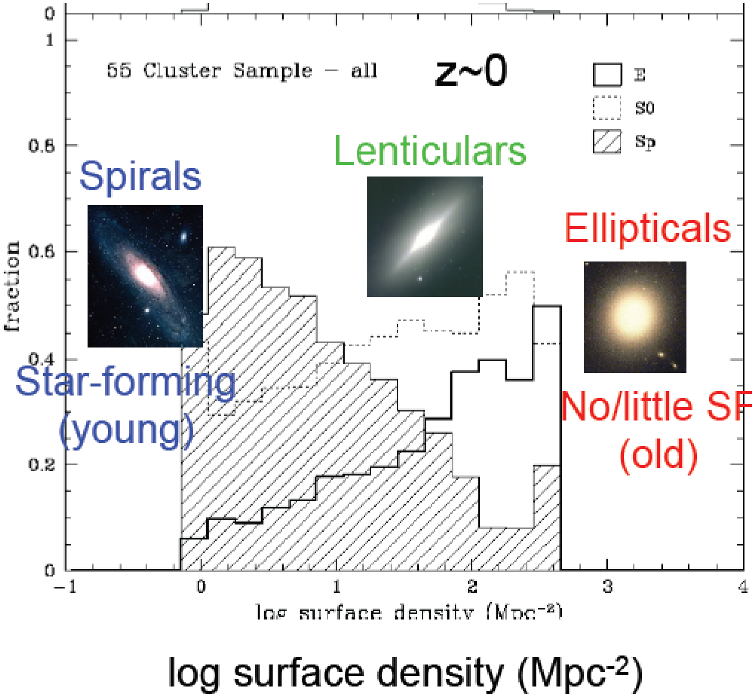
➔Morphological quenching?

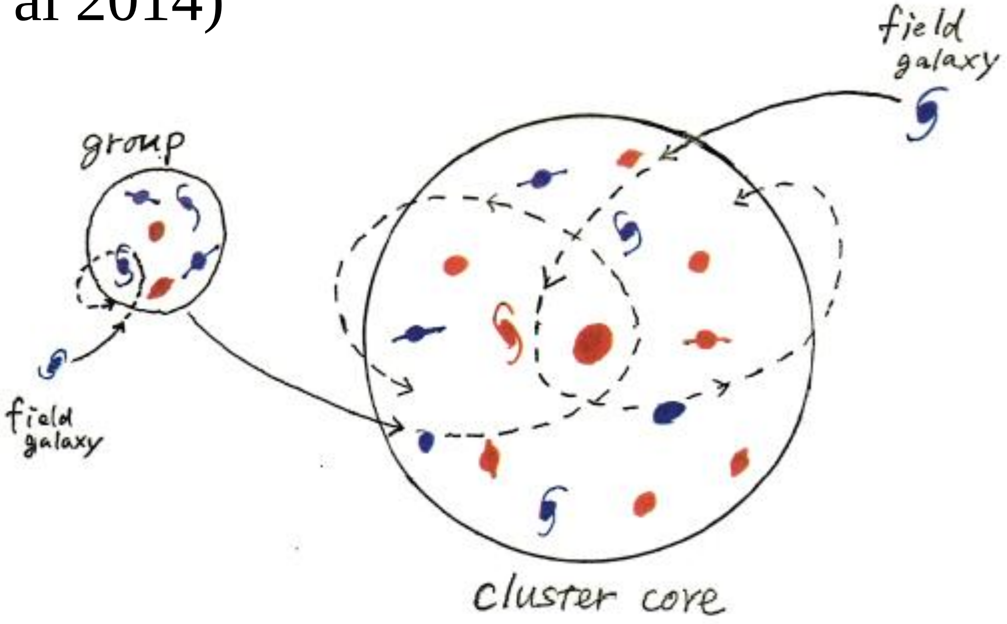
Clue-4: Environmental effects

➔ Spheroids favored at high density

➔ LBG z=3, morphology-density relation already there at z =3 (Cooke et al 2014)

Morphology- (SFR-) density relation
(Dressler 1980)



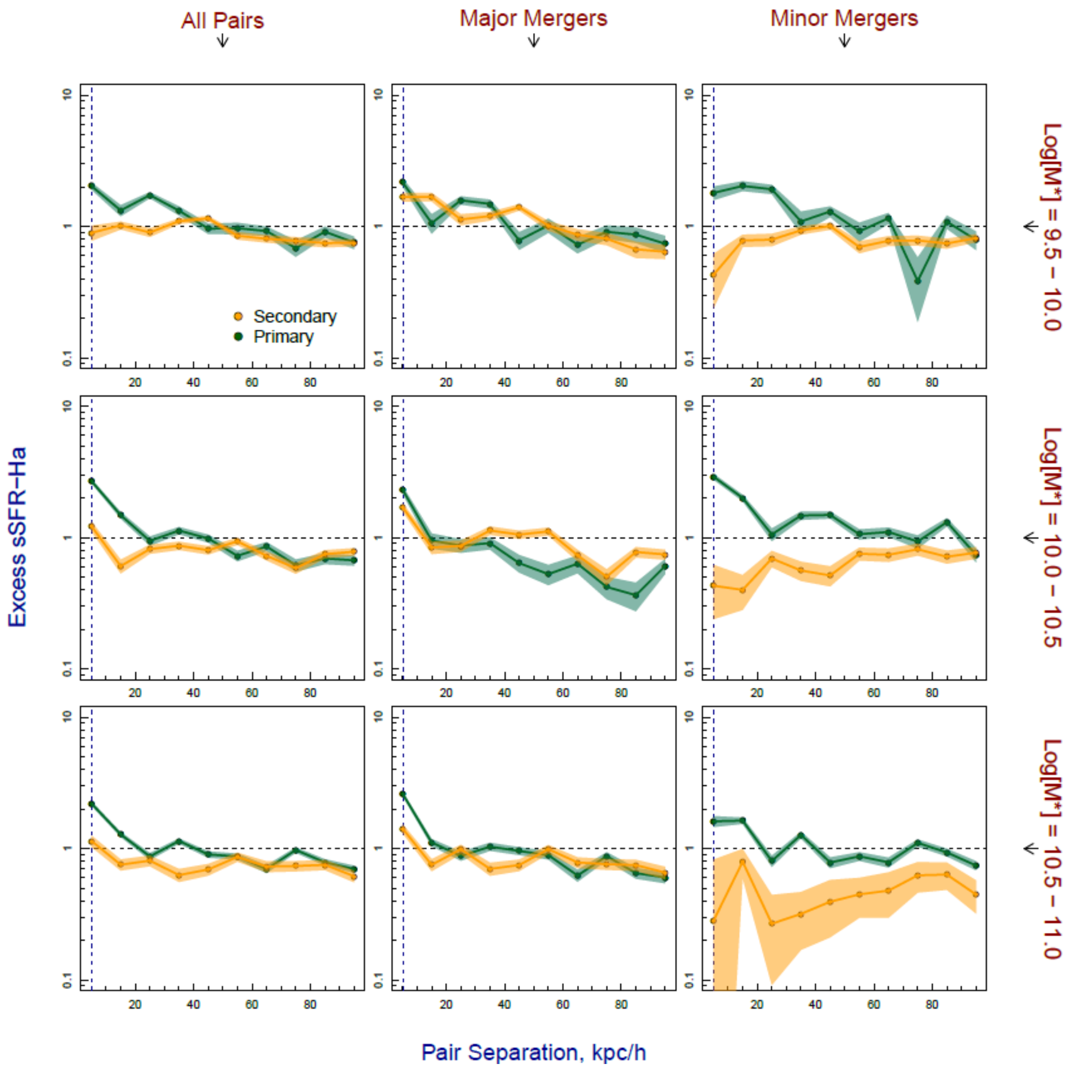


Mergers in small groups

Then group merge in clusters,

➔ ram-pressure, harassment

Effects of mergers (major or minor)



SF in general enhanced in major mergers

However, suppressed in minor mergers, for the smallest companion

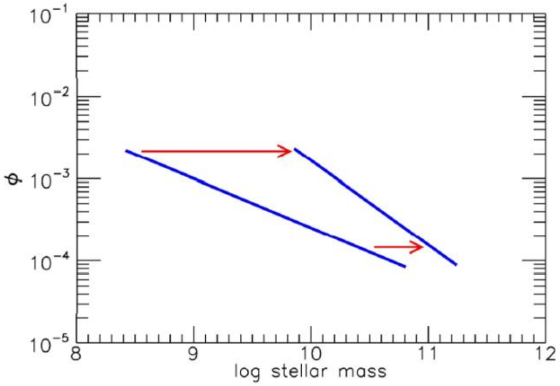
➔Gas heating, stripping at the benefit of the primary

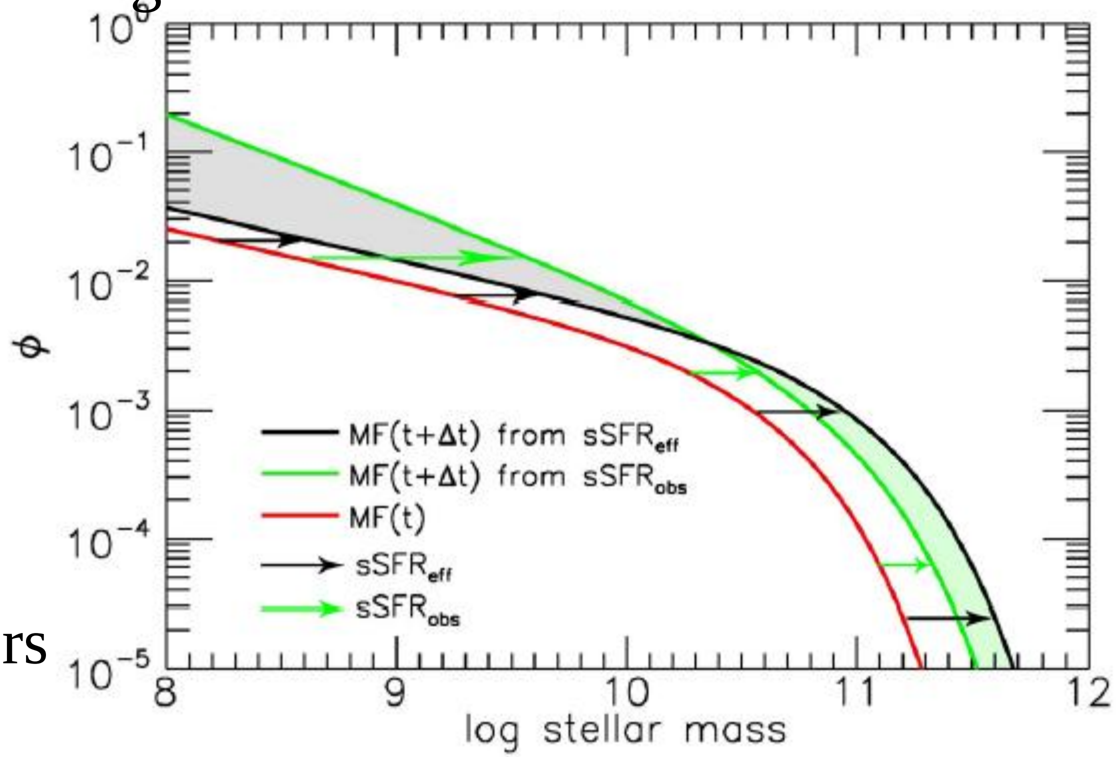
Davies et al 2015 (GAMA) 300 000 galaxies, 20 000 pairs

Rate of mergers

Slope of the Schechter function: constant with z

While sSFR versus M* slope is negative





This is compensated by mergers

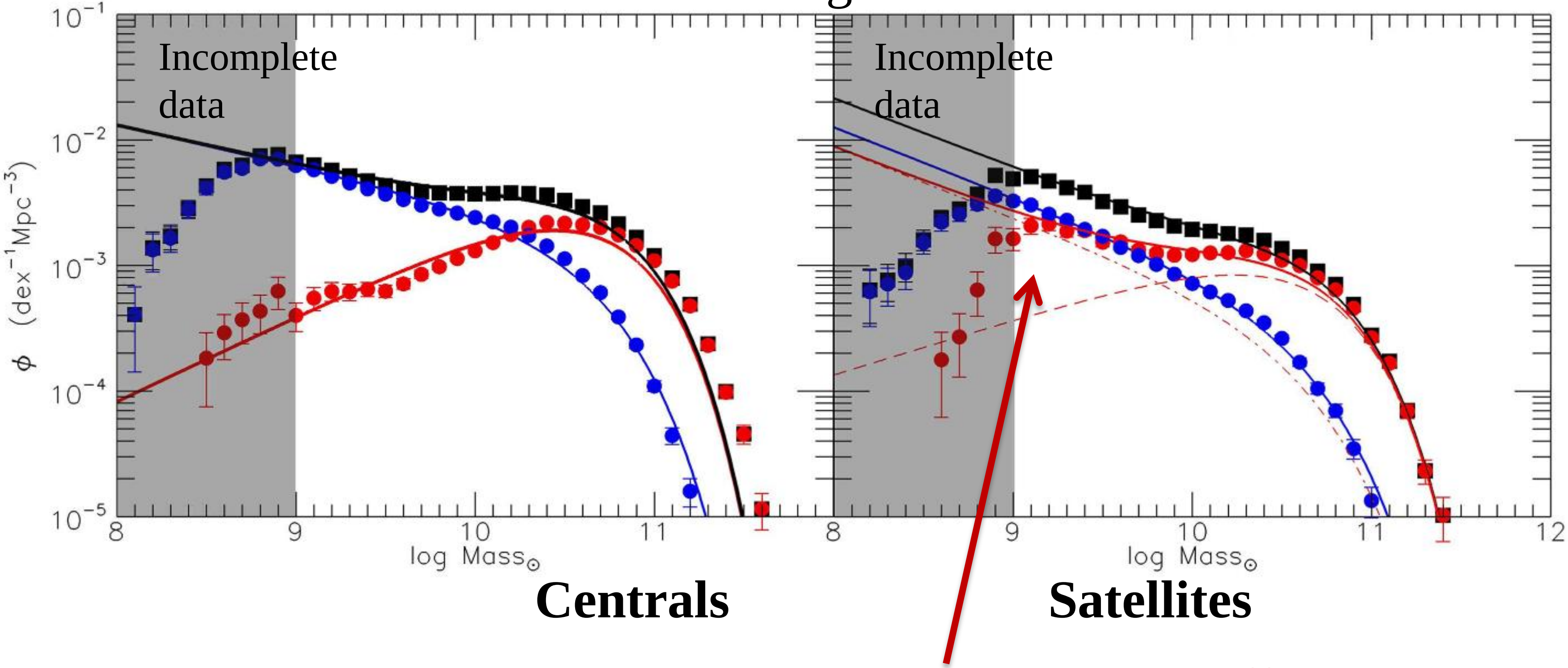
➔Can give a constraint on the rate of mergers with mass

Peng et al 2014

Environment quenching affect satellites

Fraction of red centrals depend only on mass, while for satellites it depends also on environment

The environmental effect depend only on the over-density not on M* or Mh of the satellite galaxies



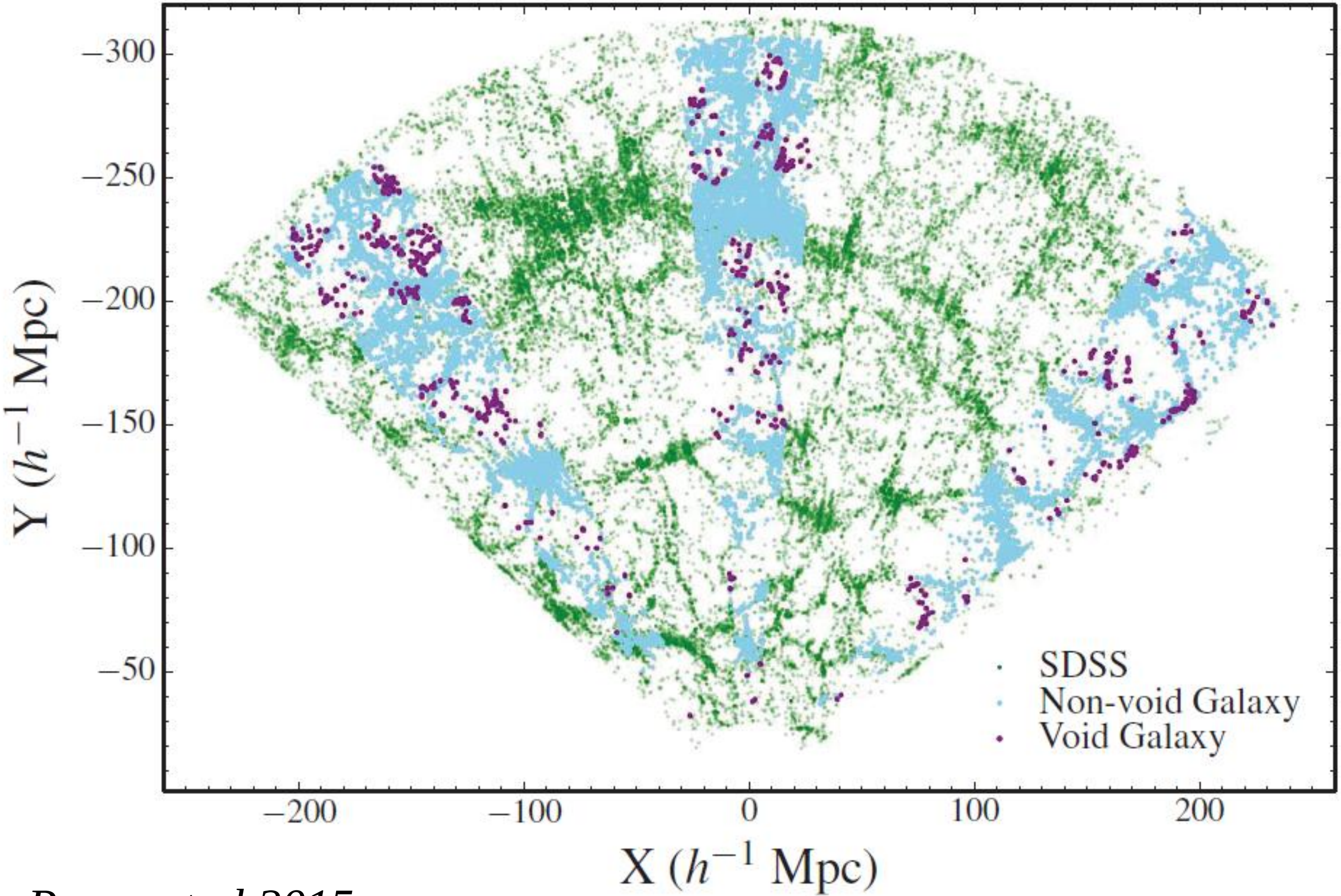
Centrals

Satellites

Environmental effect

Peng et al 2012

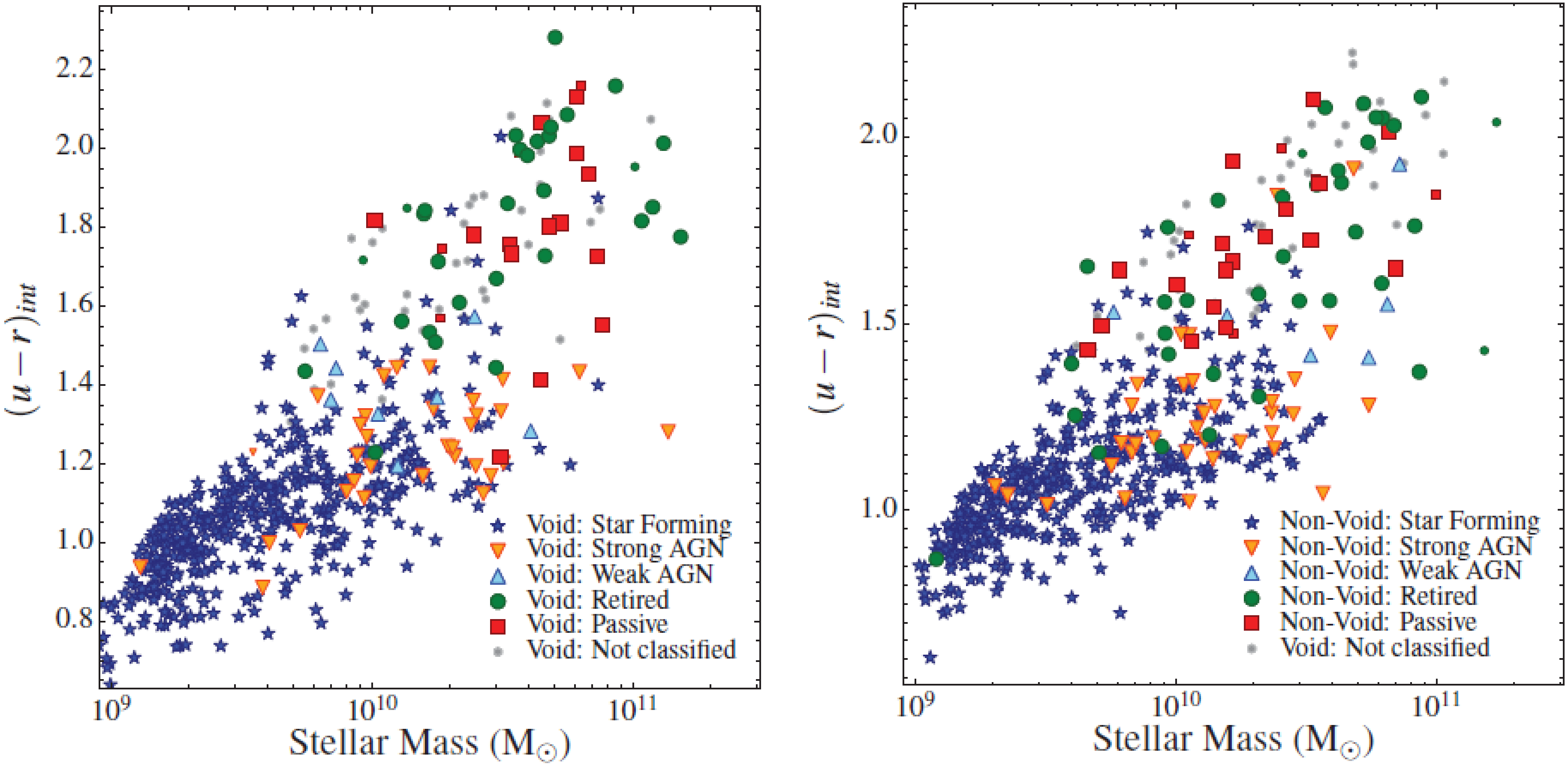
Galaxies in voids



Penny et al 2015

Same mass quenching in voids

Retired and passive galaxies on the red sequence



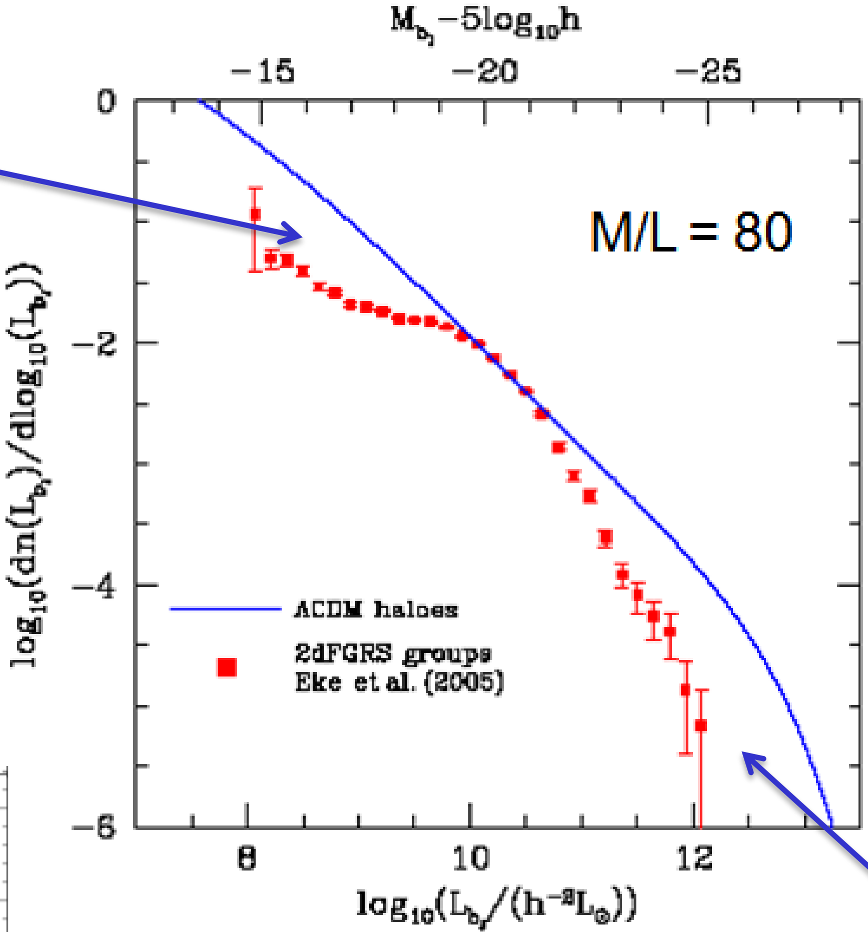
At large masses M > 10^{10} Mo, internally driven processes are dominant

In voids, the massive are more discy

Penny et al 2015

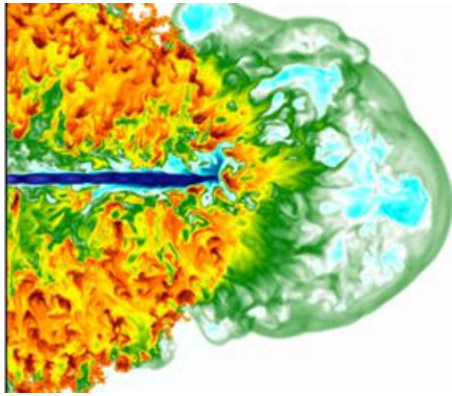
5- Necessity of quenching

Star formation
SN, stellar winds

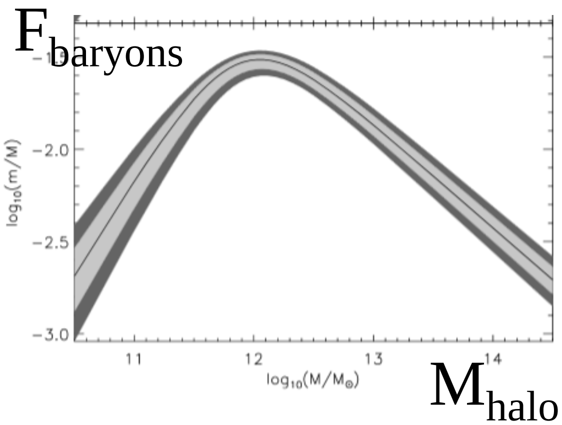


More than 80%
of baryons are
outside galaxies

AGN feedback
Radio jets



Moster et al 2010



Baugh 2006, Eke et al 2006, Jenkins et al 2001

Efficiency of AGN feedback (models)

Feedbak reproduces the M-σ relation, both thermal and kinetic

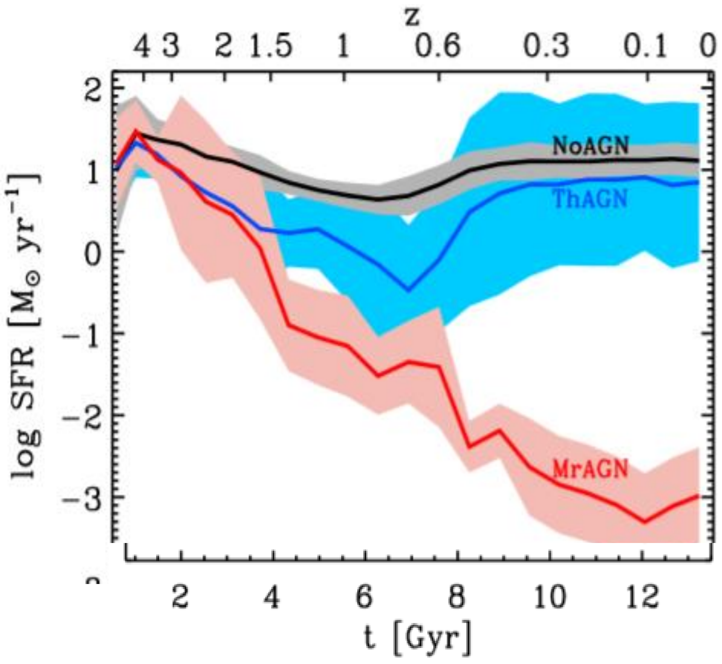
Factor 2 less baryons in stars

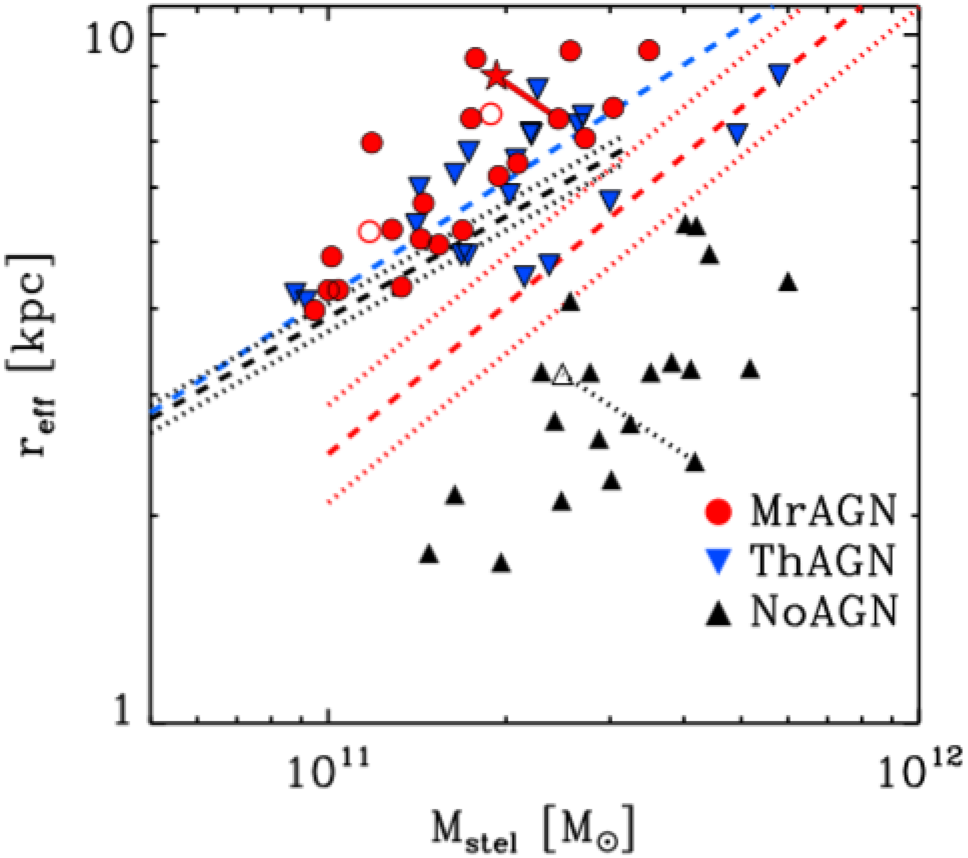
Mechanical/radiation feedback

is more efficient to reduce

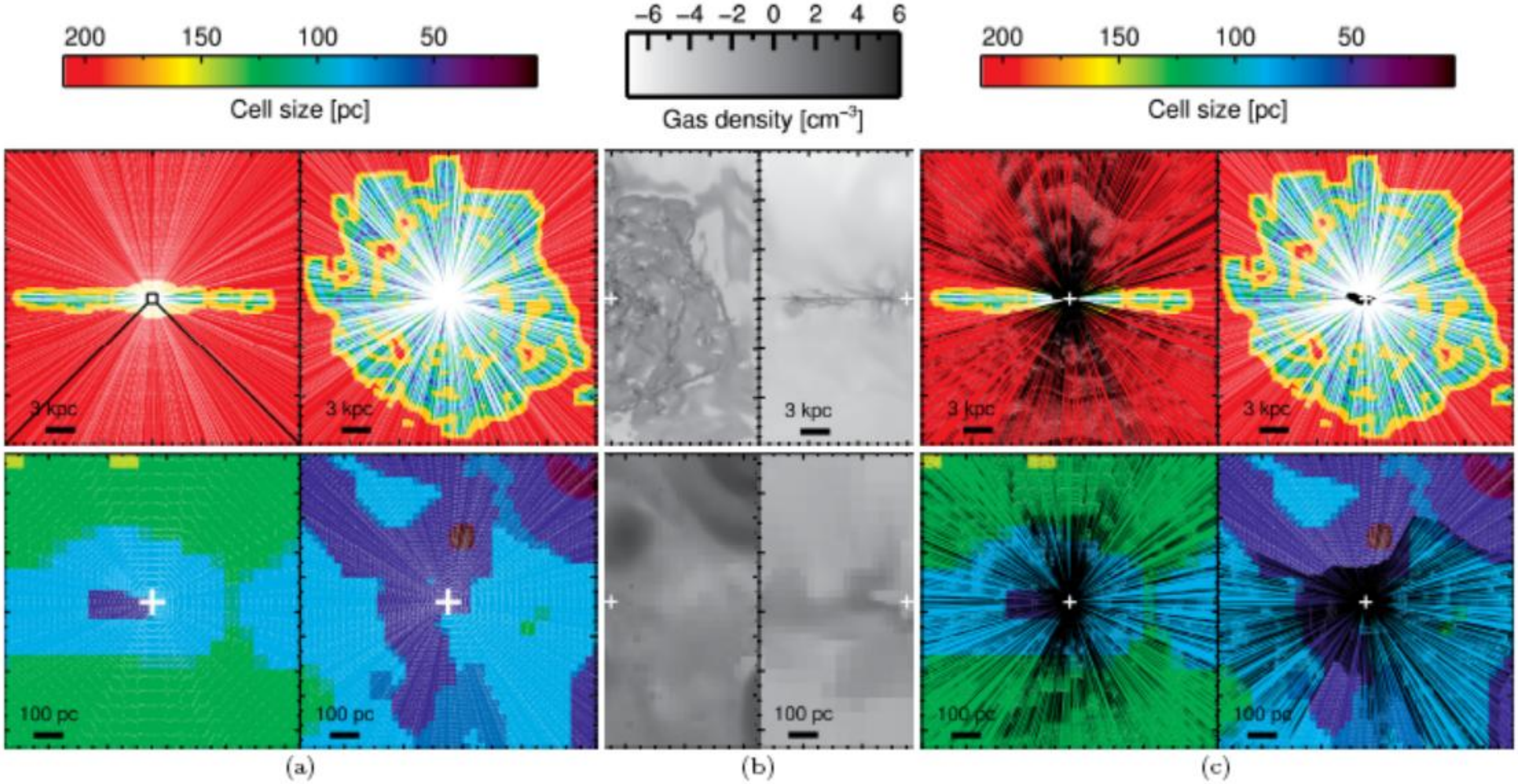
AGN luminosity and SF

Choi et al 2015



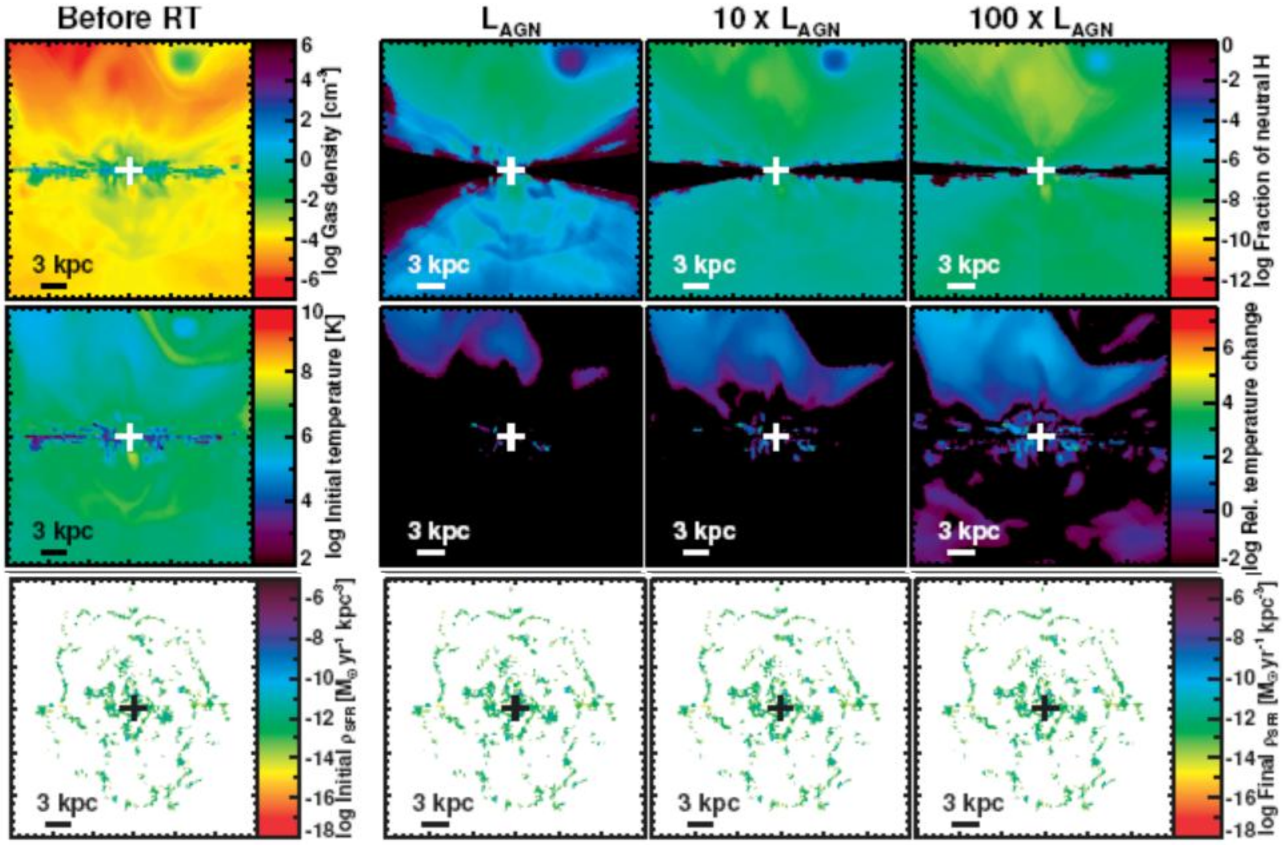


… or inefficiency (models)



Post-processing AGN feedback, dealing with ionisation RT with CLOUDY LOP *Roos et al 2015*

Negligible effect on SFR



Ionisation and heating of the diffuse phase

Dense clouds little affected

Although outflows with loading factors 3-10

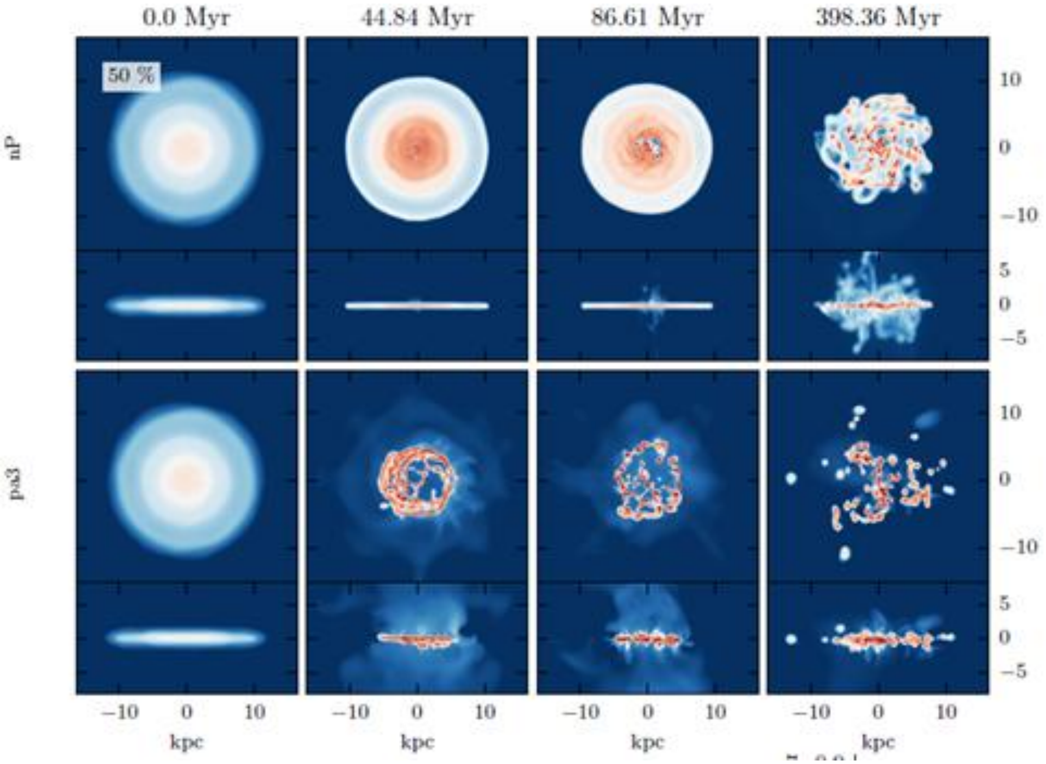
Negligible SF quenching $L_{AGN} = 10^{44.5}$ erg/s

Only r<40pc are affected, and only diffuse clouds

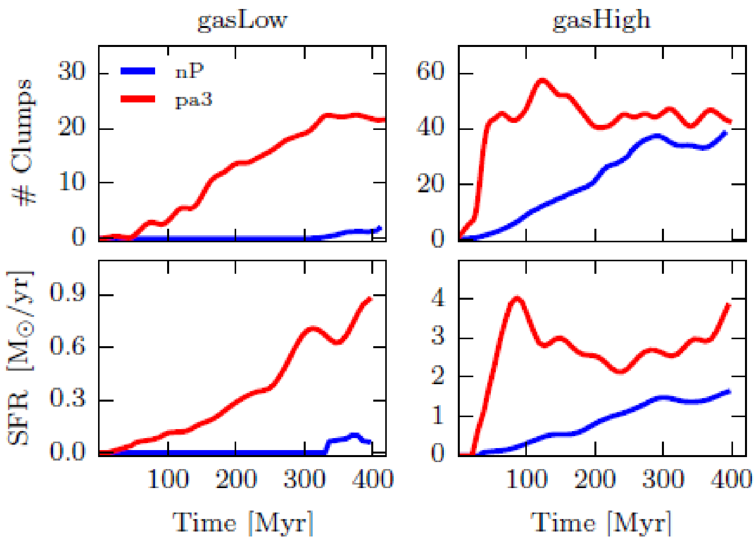
Roos et al 2015, and also Vogelsberger et al 2013, 2014, Illustris

Rosdahl et al 2013, RAMSES-RT

AGN-triggered star formation



The AGN provides an extra-pressure forming more clumps in the molecular gas

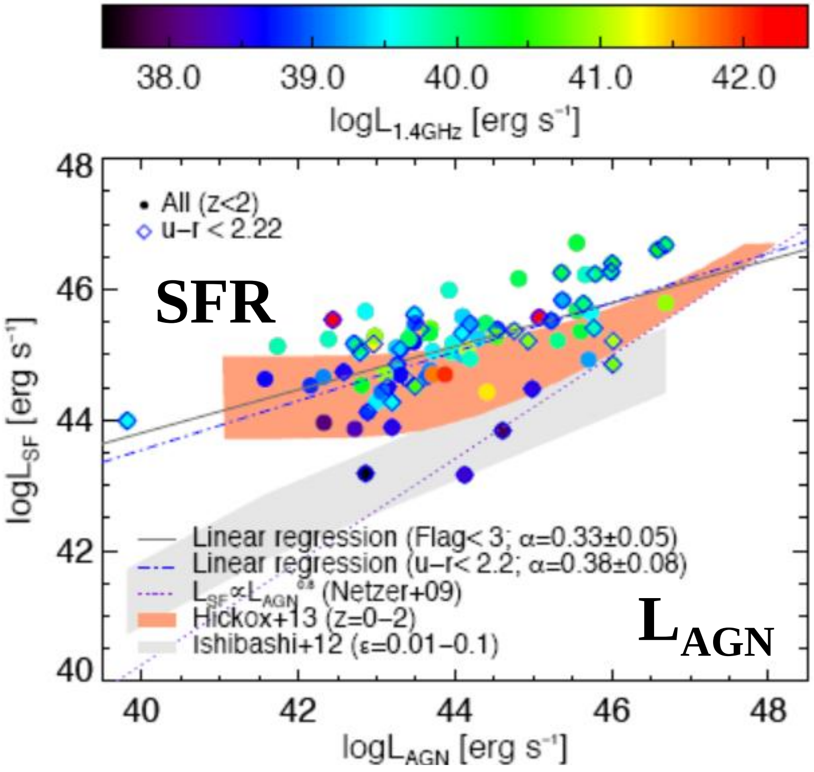


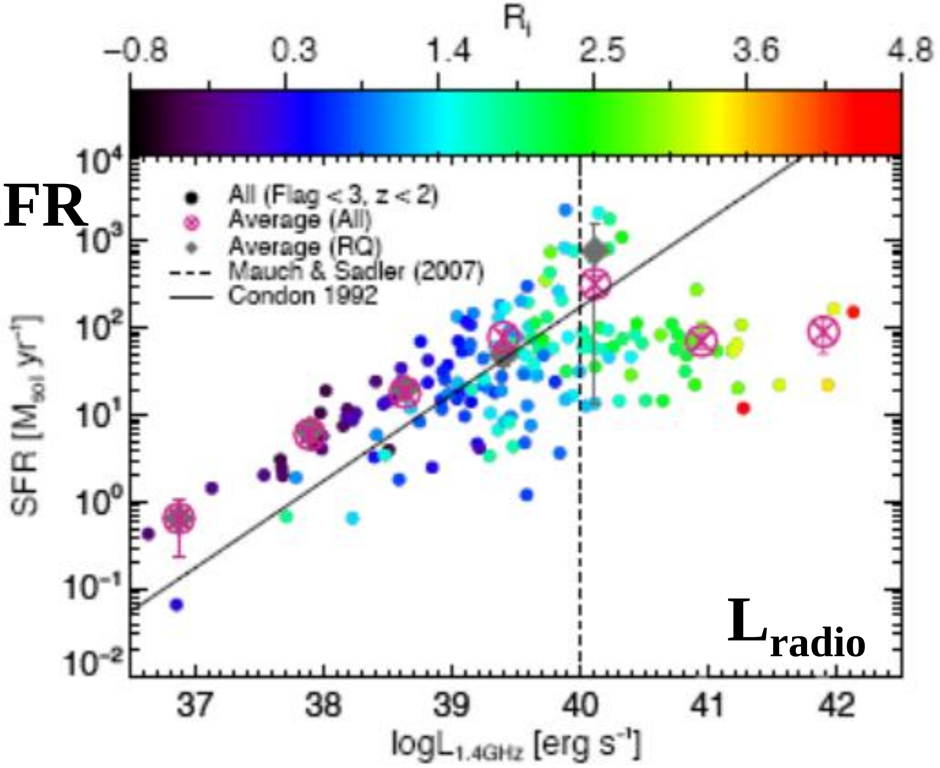
Bieri et al 2015

AGN feedback: observational evidence

Good correlation between AGN luminosity and SFR, but there is a decrease in SFR when Radio Luminosity increases

➔Radio mode feedback of the jets ?

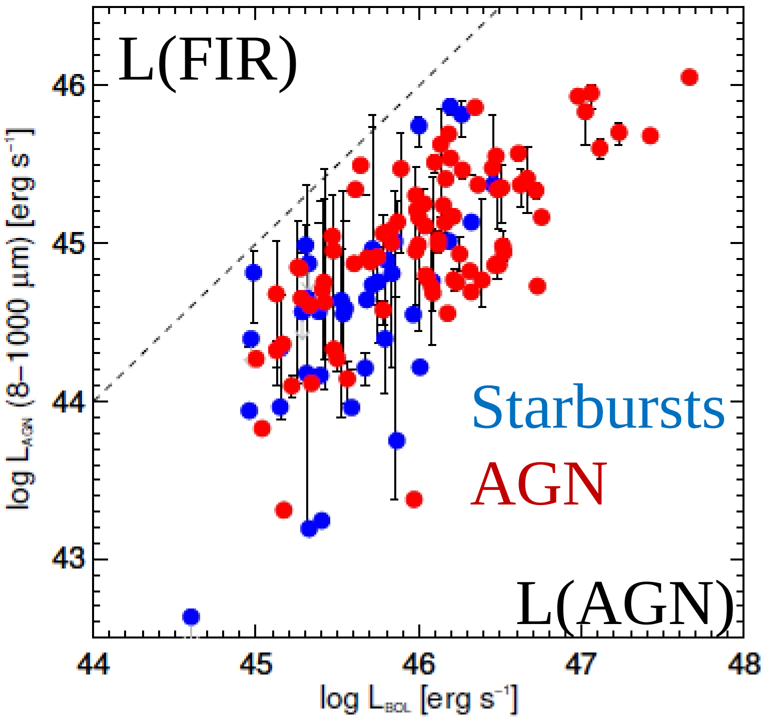




Two-sided feedback process, Reduction of SF, **but no quenching**

Karouzos et al 2014

Inefficient AGN feedback (obs)

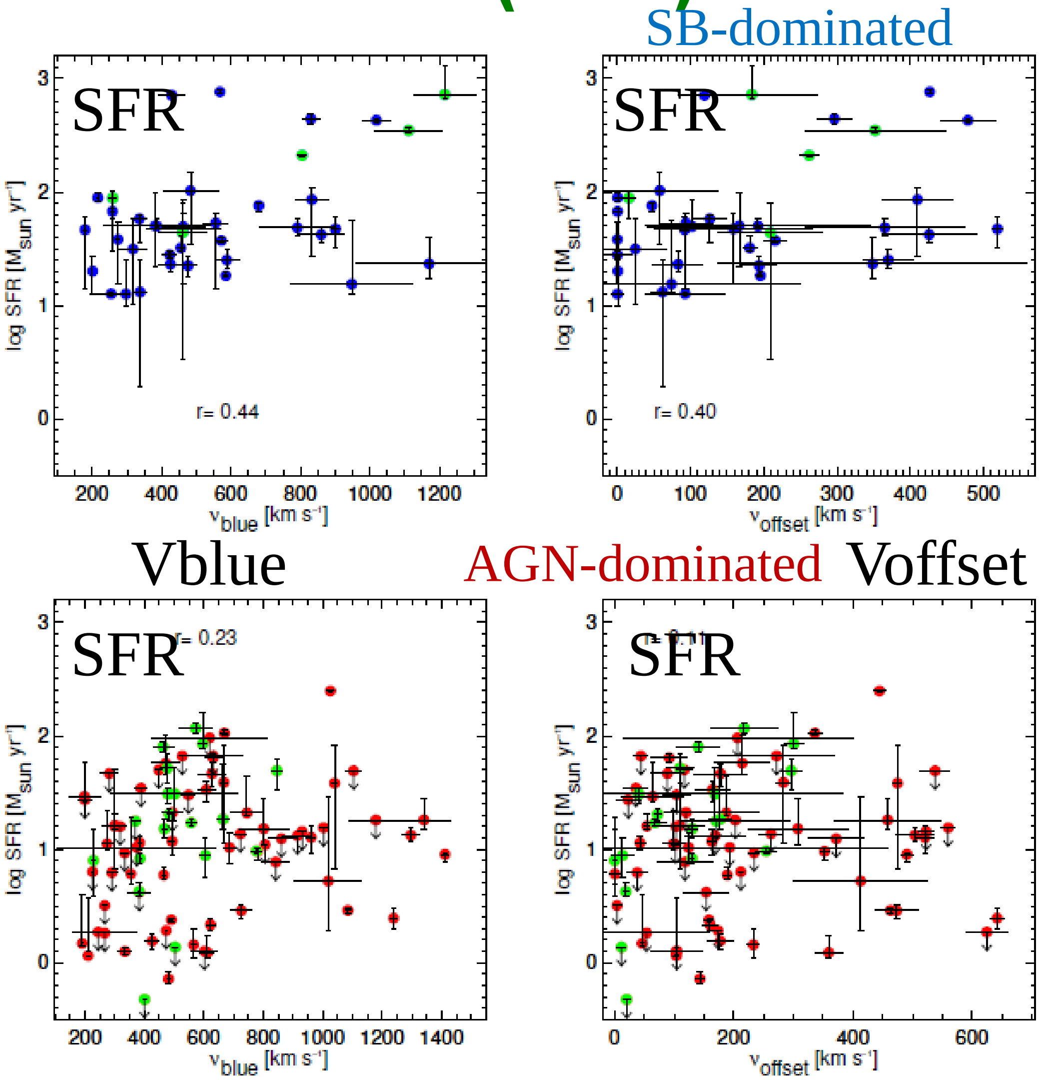


L(FIR)

Starbursts

AGN

L(AGN)



SB-dominated

SFR

Vblue

AGN-dominated

Voffset

224 quasars z<1 No relation between SFR and $V_{outflow}$

AGN feedback not obvious

➔Either delayed time-scales

Or positive feedback also

Balmaverde et al 2015, also

Mullaney et al 2003

Zakmaska & Greene 2014, Stanley et al 2015

SUMMARY

➔ Empirical laws of quenching: Mass and environment

➔ Physical processes: **rapid:** SF/AGN, mergers; **slow:** morphological, Gravity (halo), strangulation (environment)

➔ Clues: increasing size from red nuggets by dry merging, inside out quenching

➔ Metallicity clue favors strangulation

➔ At high z, galaxies have higher gas fraction and SFE

➔ Environment effects important for satellites, in voids massive galaxies are disky