Antennae

Arp 220

The effect of Galaxy Dynamics on Star formation

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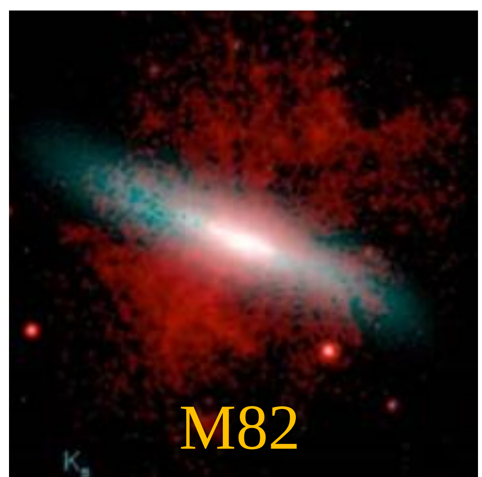
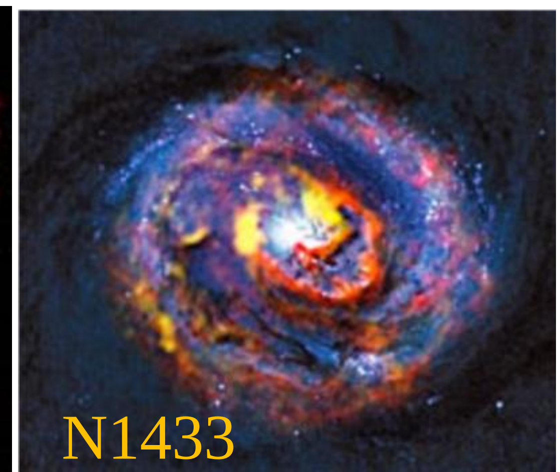
Observatoire de Paris
Stockholm, 23 August 2016

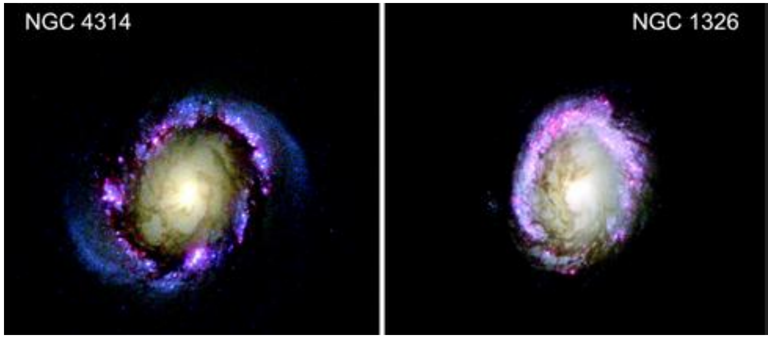


M82



N1433

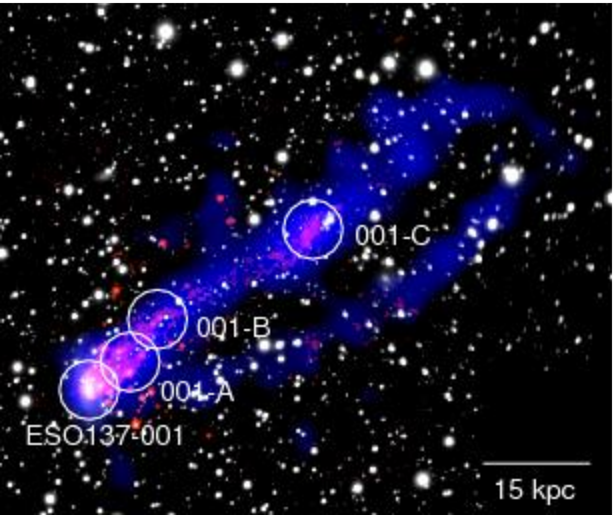
Outline



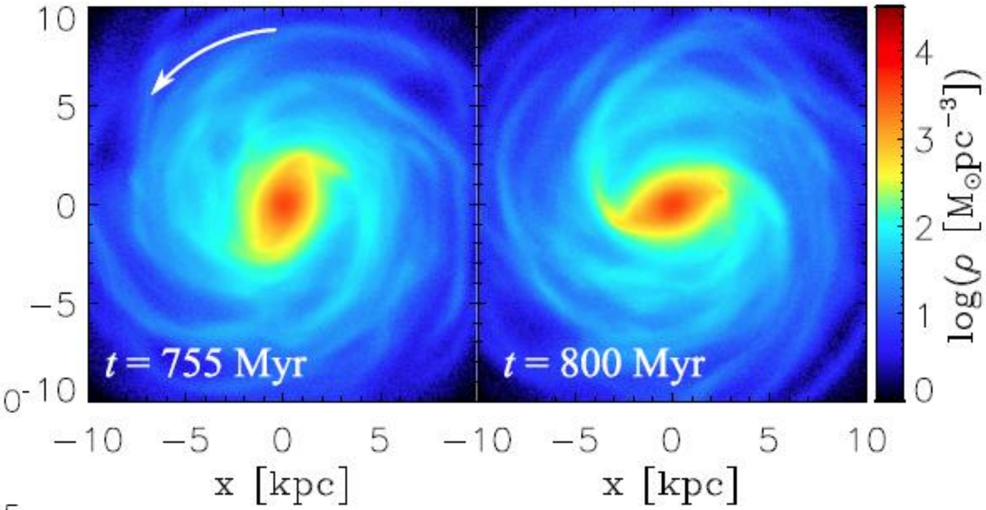
1- Dynamical action of bars
in enhancing star formation: where?

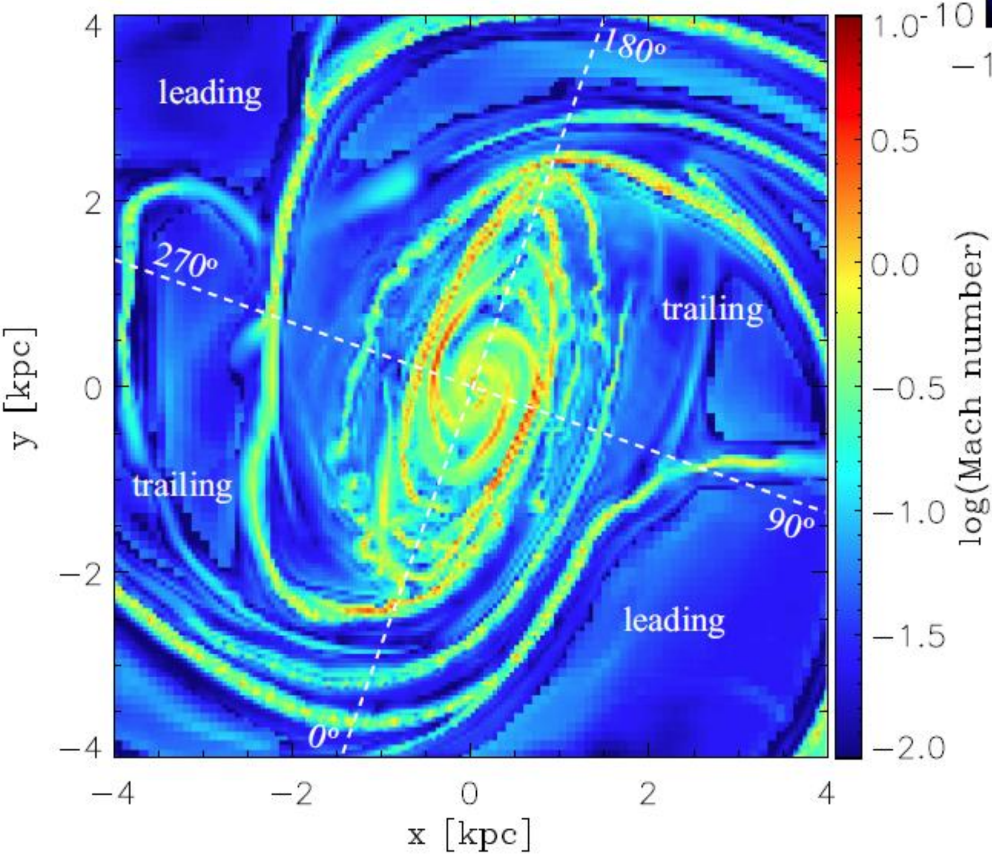
2- Interactions of galaxies: how efficient in triggering star formation? Starburst & mergers

3- Environment dynamics:
SF enhanced or quenched
in groups and clusters



1- Role of bars, non-axisymmetries





Compression of the gas on the leading edge (where the dust lanes are conspicuous)

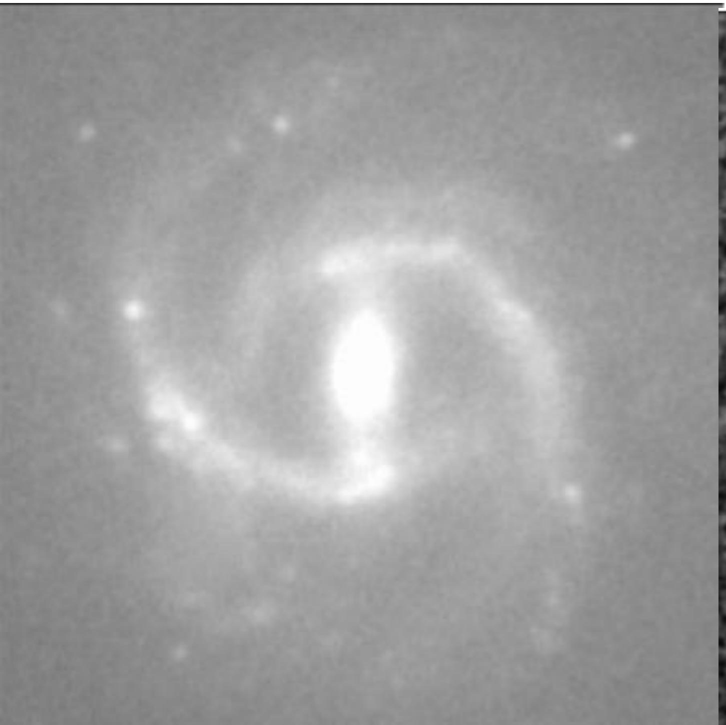
No compressive turbulence (only in the interarms) but solenoidal

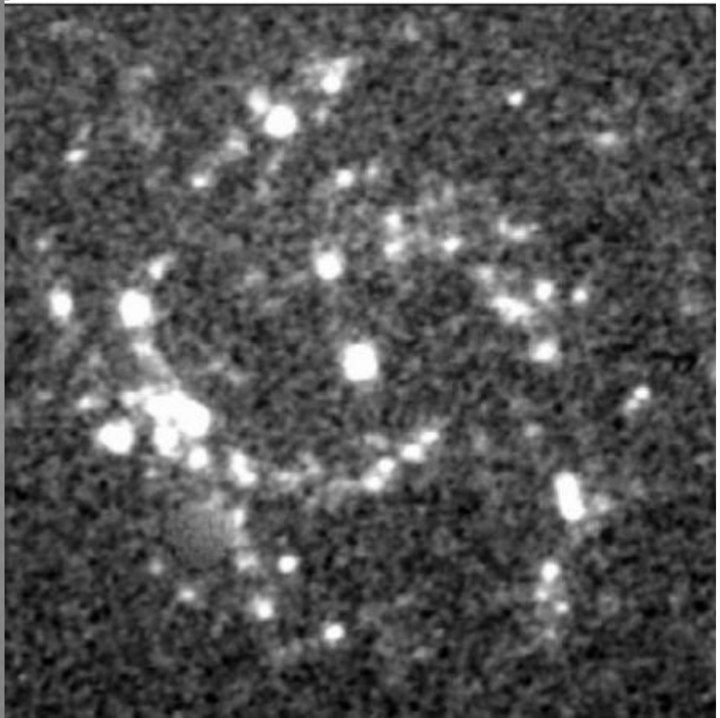
Mach number at the 24pc scale

Renaud et al 2015

No star formation in the bar, but in a ring or extremities of the bar

The orbits along the bar are too rapid, but then the gas accumulates at the end of the bar ➔ crowding

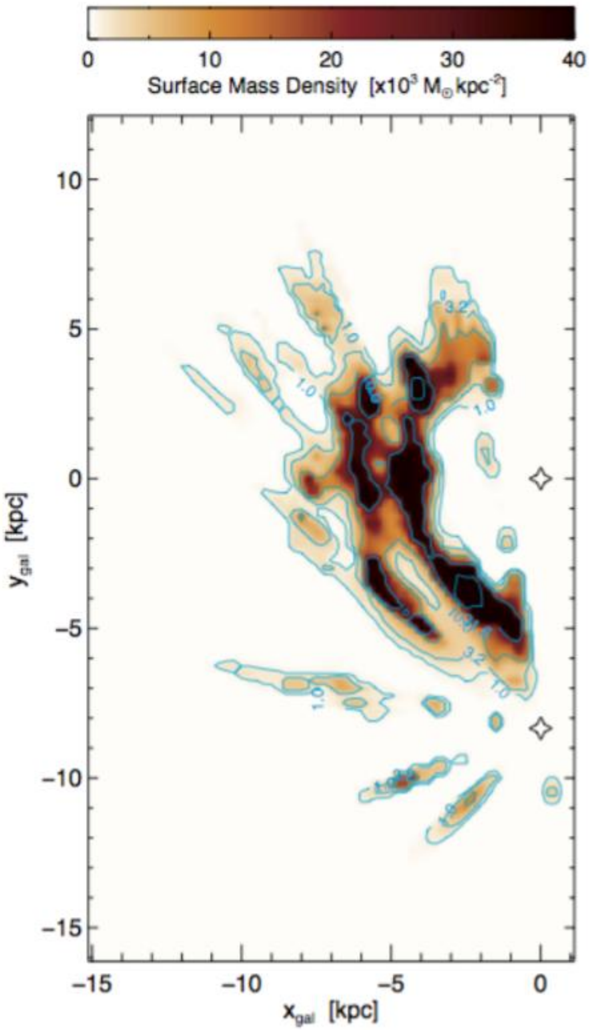


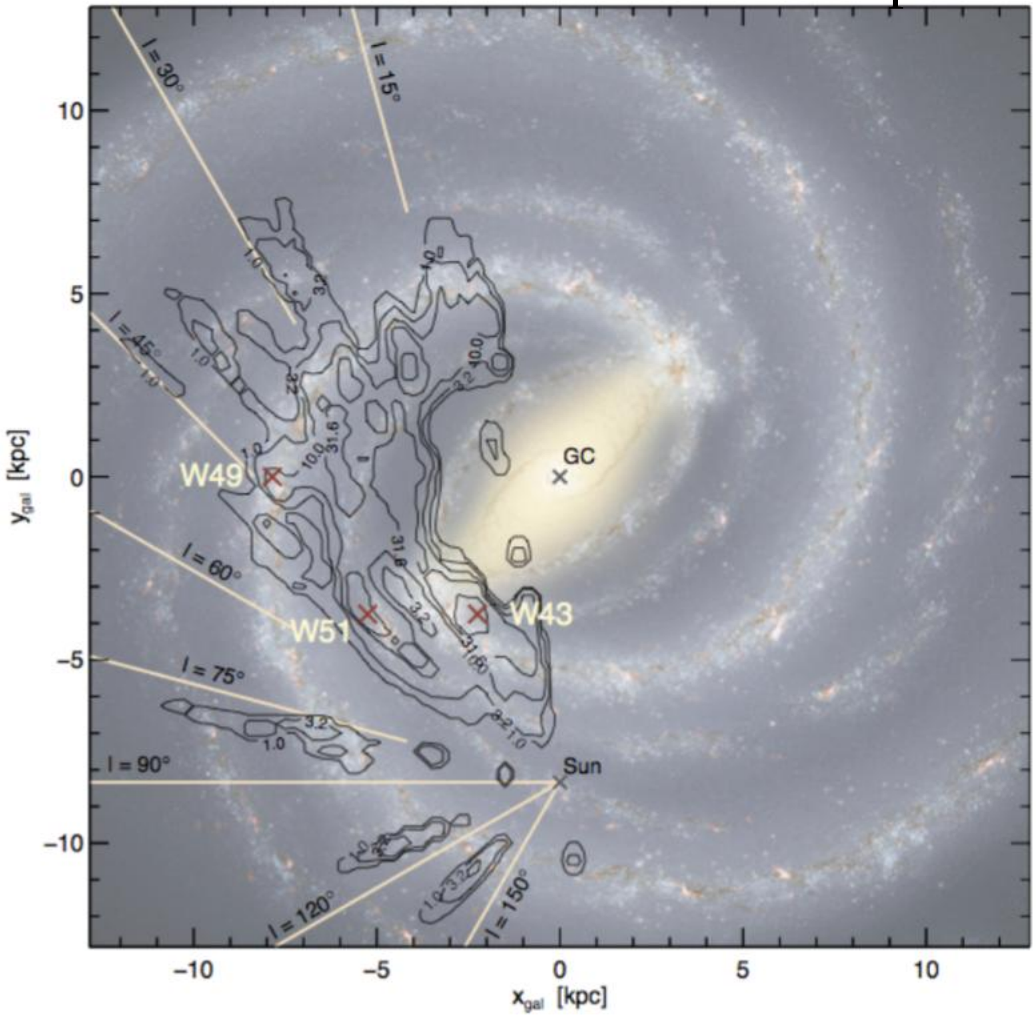


Verley et al 2007

Star formation at the end of the bar in the MW

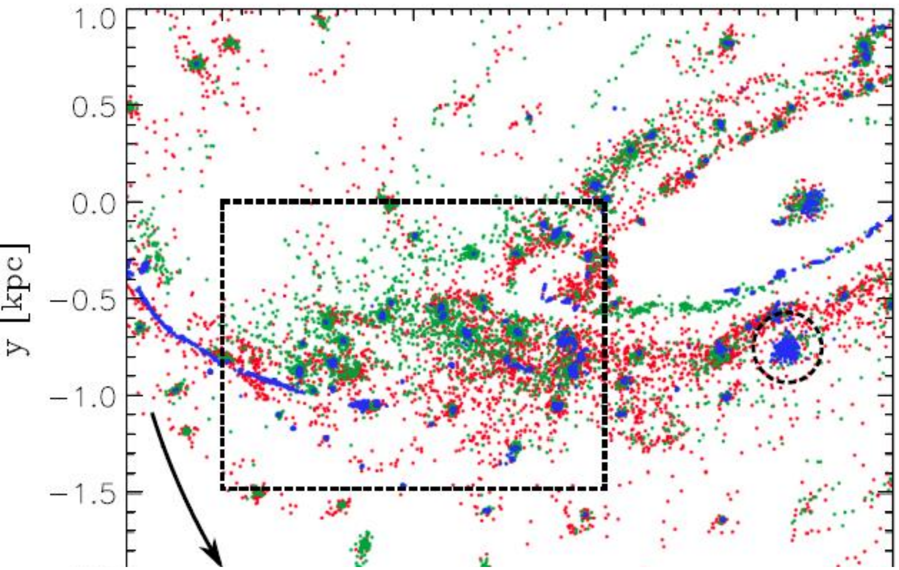
R Hurt from Spitzer NIR



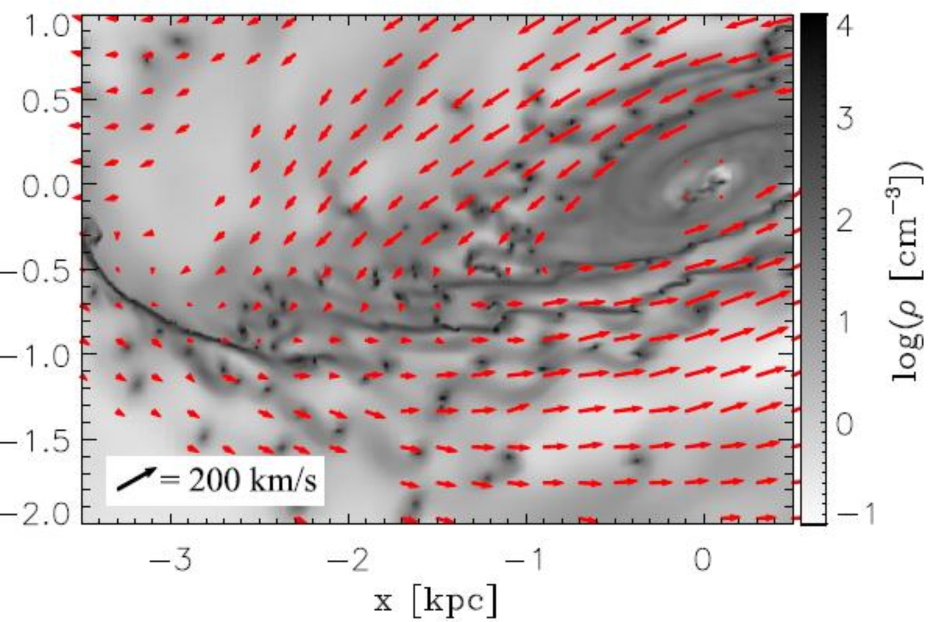


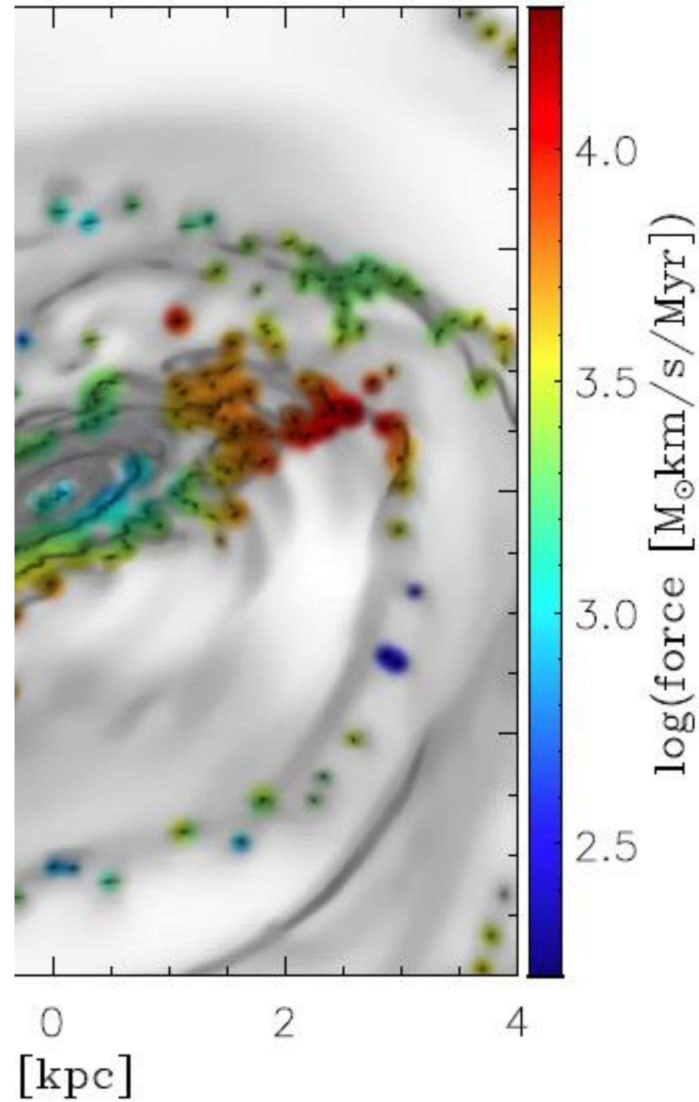
W43 complex, from the agglomeration of clouds, *(Motte et al 2014, Nguyen-Luong et al 2011)*

Young stars form at the tip of the bar



Blue < 20Myr
Green 20-40 Myr
Red > 40 Myr





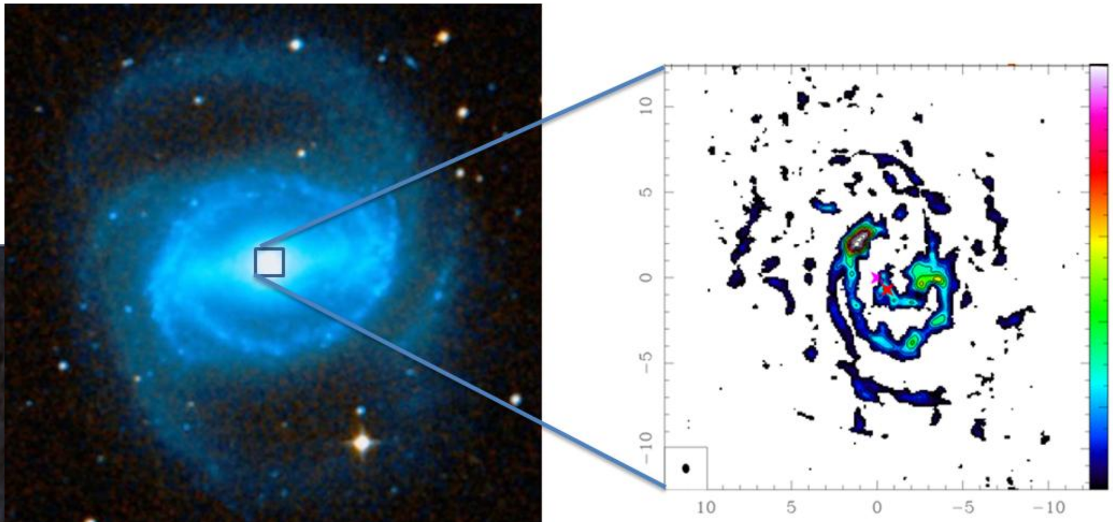
Force separating gas and stars

Renaud et al 2015

Star formation in nuclear rings

NGC 1433: Sy 2 barred spiral, the « Lord of the Rings »

Nuclear starburst +
AGN-driven outflow

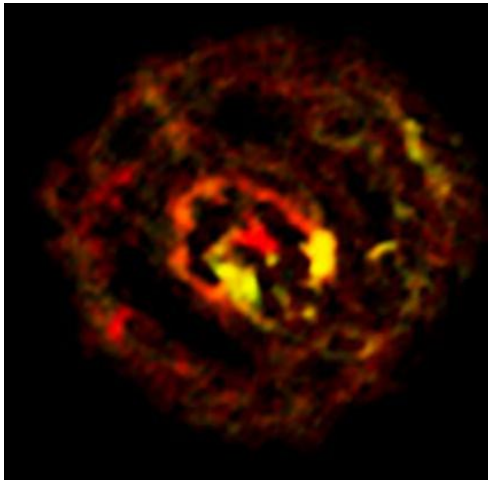


CO(3-2) with ALMA

Beam = 0.5’’ = 24pc

A second ring inside the first at ILR

Combes et al 13, 14



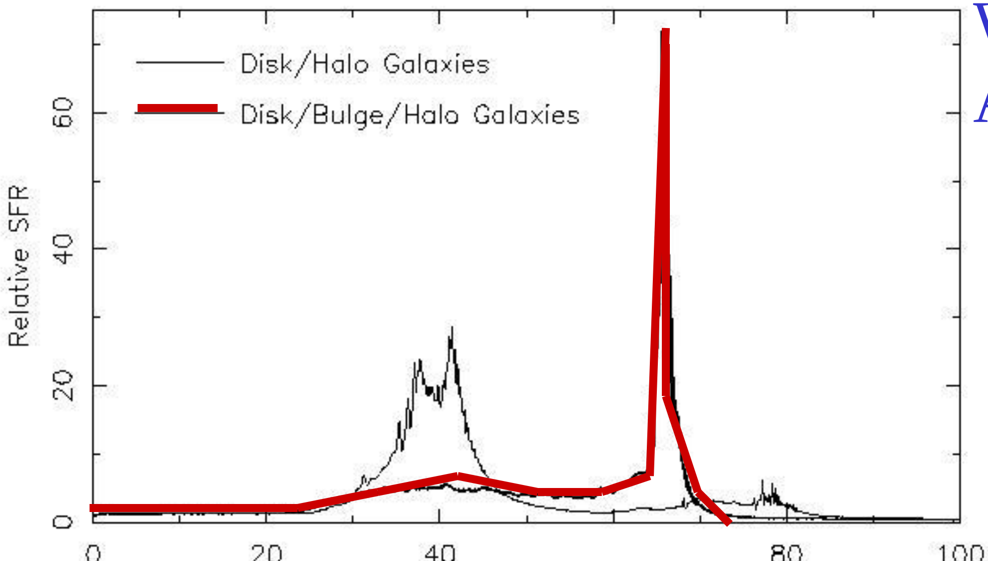
2- Impact of interactions on SFR

Very high impact, according to some simulations!

Numerical simulations use recipes, for the sub-grid physics
Katz (1992), Mihos & Hernquist (1994, 96)
Schmidt law with threshold, with **exponent n=1.5**

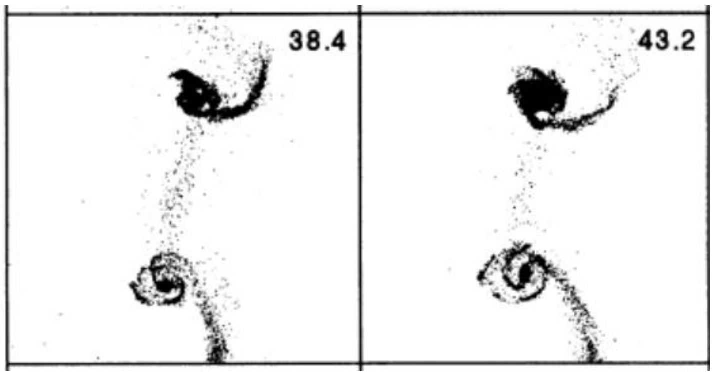
Results depends on disk stability

Relative SFR



Time

Without bulge, disk more unstable
At the end, the same SFR



Evidence of dynamical triggering

Interacting galaxies have more SF
Larson & Tinsley (1978)
Colors of interacting galaxies show evidence of recent bursts

ULIRGs are all mergers of galaxies
(e.g. Sanders & Mirabel 1996)

♣ Interacting galaxies don't show intense starbursts
(Bergvall et al 03), or **only in their centers**
Interactions: necessary condition, but not sufficient

Radial gas flows due to bars, or spirals (+DW triggering)
Molecular gas concentrations, and circumnuclear starbursts
(e.g. Sakamoto et al 1999, Buta & Combes 96, Knapen 2004)

Mechanisms

Tidal forces ➔Spiral and bars: torques ➔ radial gas flows

Interacting galaxies appear to have more H_2 content by 4-5
And more concentrated (e.g. Braine & Combes 1993)

The condition of starburst: **accumulating gas in a time short enough that feedback mechanisms have no time to regulate**

Compressive tidal forces

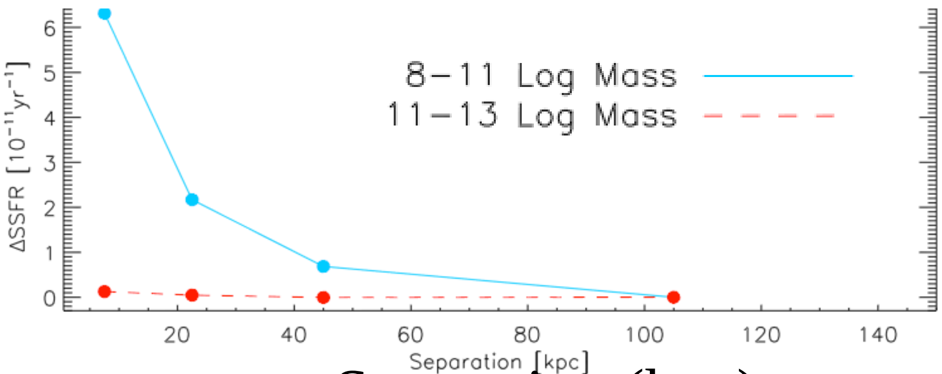
For a spherical density profile in a power-law $\rho(r) \sim r^{-\alpha}$, then the acceleration is in $r^{1-\alpha}$, so the attraction can increase with distance, if $0 < \alpha < 1$

➔ the tidal force is compressive Ftid ~ $(1-\alpha)\, r^{-\alpha}$

In particular, for a core density (rotation curve V is in $r^{1-\alpha/2}$)

Interactions: observations

ΔSSFR



Separation (kpc)

Scott & Kaviraj 2014

More SSFR in close pairs
5.3 increase in SSFR for low mass (10^8-10^{11}Mo) **and a factor of~2.1** for high mass (10^{11}-10^{13} Mo)
Less in cluster environment

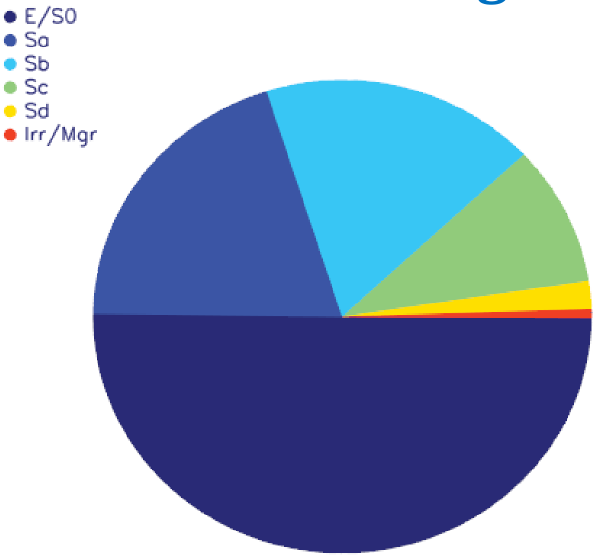
As seen in SDSS pairs by
Ellison et al 2008, *Patton et al 2013*
Until 150kpc separation

Also SF triggering by interaction at higher z : $0.1 < z < 0.6$
accompanied by asymmetries *Patton et al 2005*

At z=1.2 (COSMOS) more triggered SF in low-mass galaxies
(Ideue, Taniguchi et al 2012)

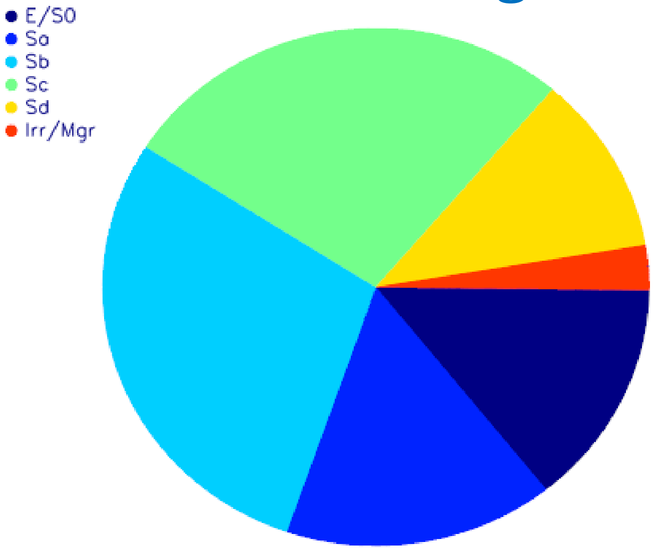
Minor mergers are important in global SF

Mass budget



In ETG: 14% of the SFR today
LTG (Sb/Sc) 53%
ETG: SF due to minor mergers
➔ 24% of SF in LTG is due to minor mergers

SFR budget

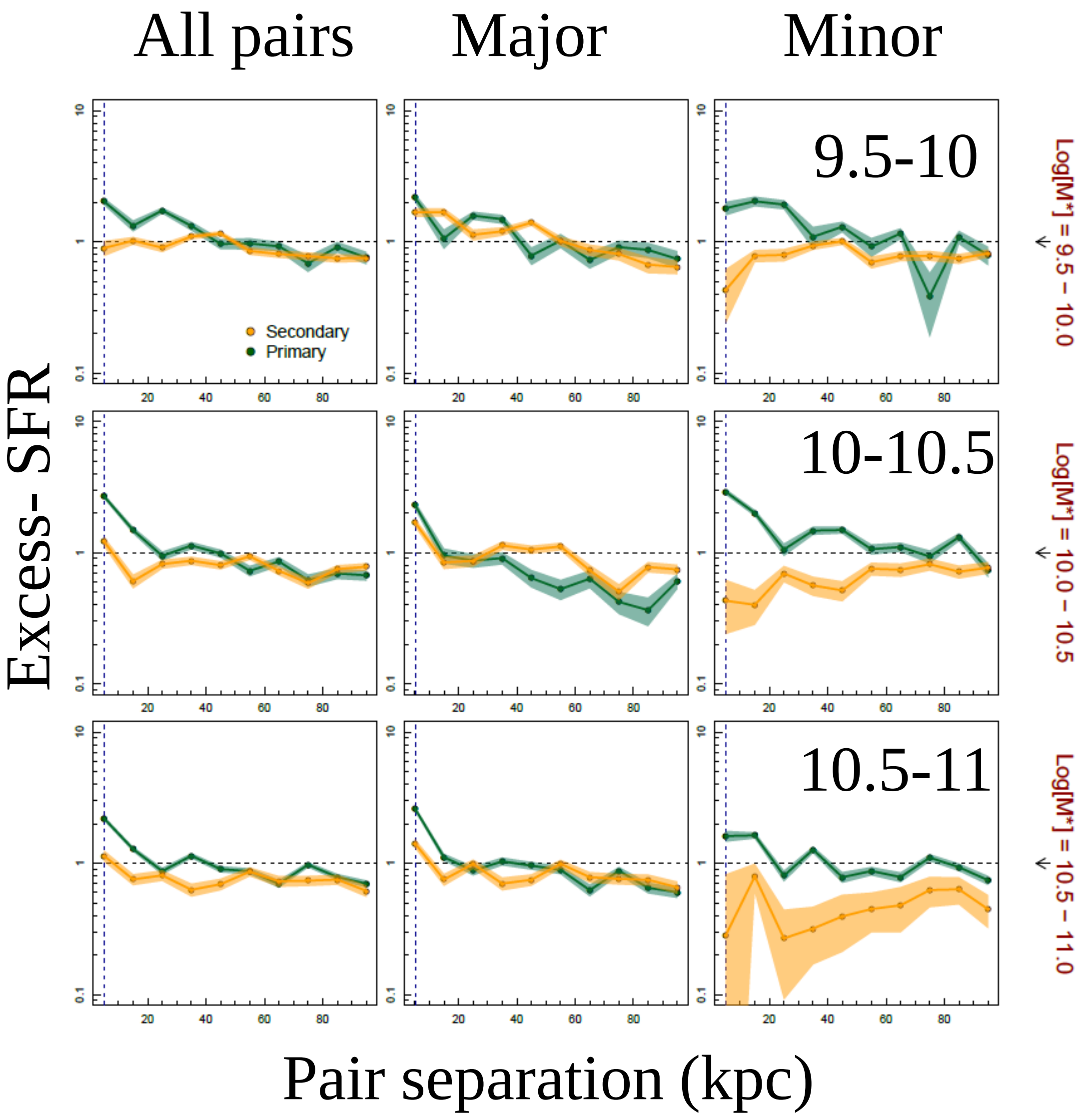


Fraction of the cosmic SF induced by minor mergers = 35%

Origin of the bulge and BH growth?

Kaviraj 2014, SDSS catalog z<0.07

Effects of mergers (major or minor)



SF in general enhanced in major mergers

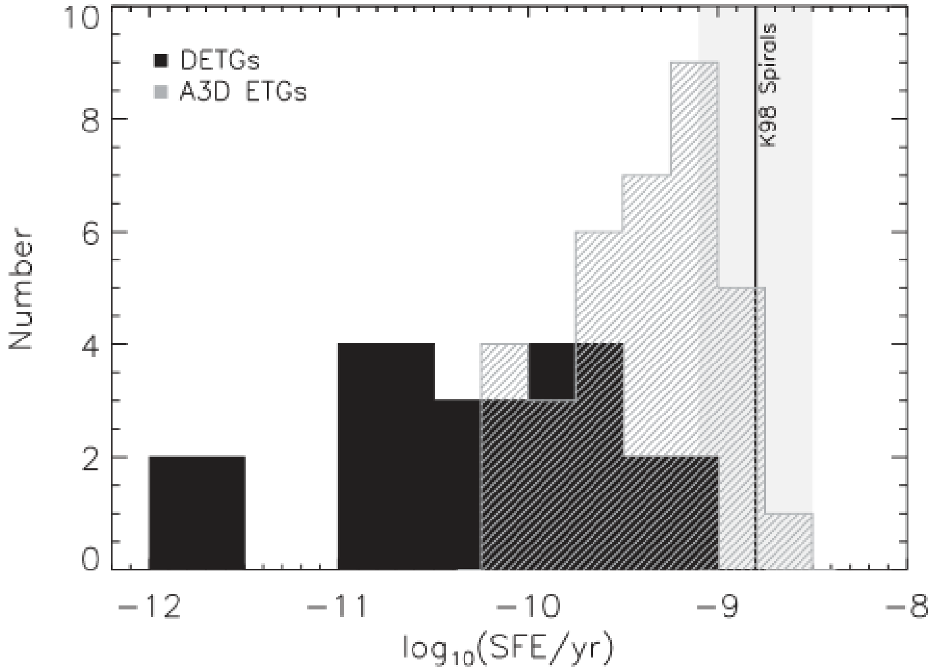
However, suppressed in minor mergers, for the smallest companion

➔Gas heating, stripping at the benefit of the primary

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

Minor mergers in ETG: low SFE

Davis et al 2015



Morphological quenching

+ something

Hot halo gas?

15 objects

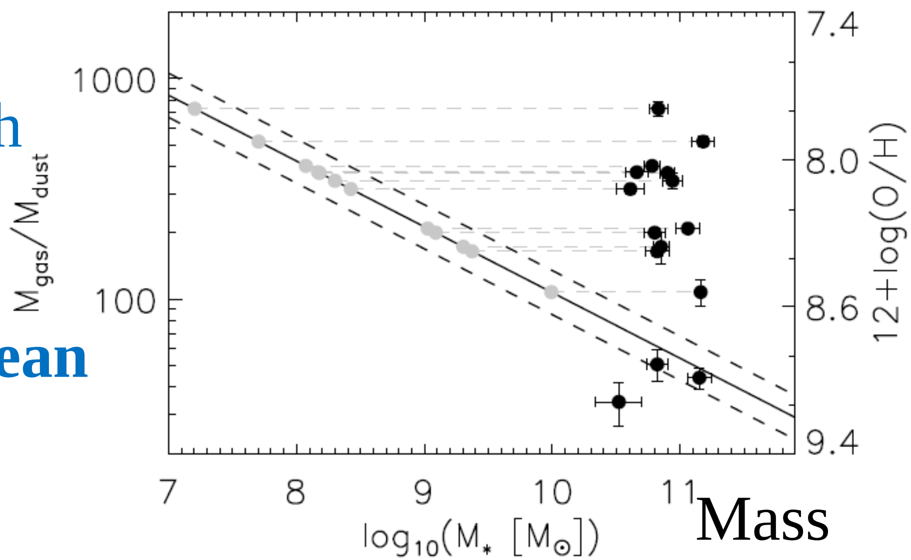
detected in CO

Accreted gas with

low metallicity

CO-rich, and mean

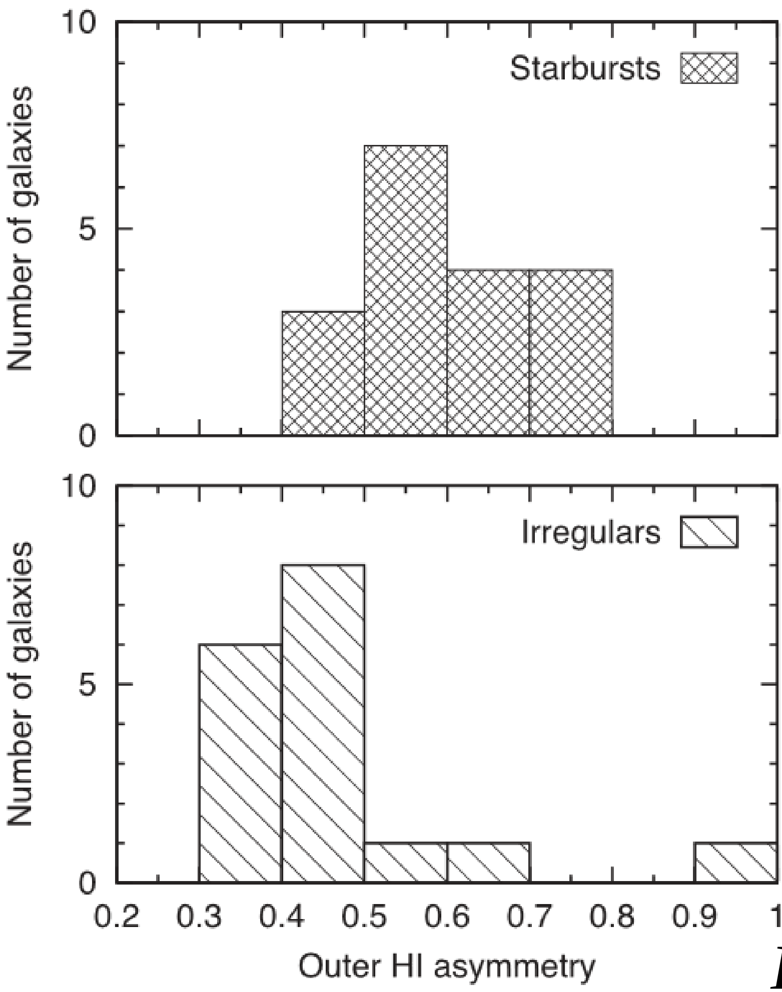
t_{dep} ~6.5 Gyr

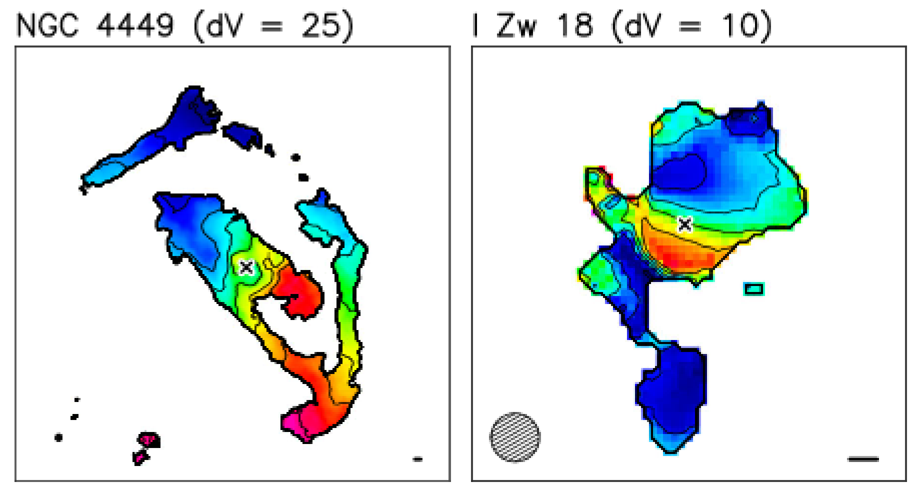


Mass

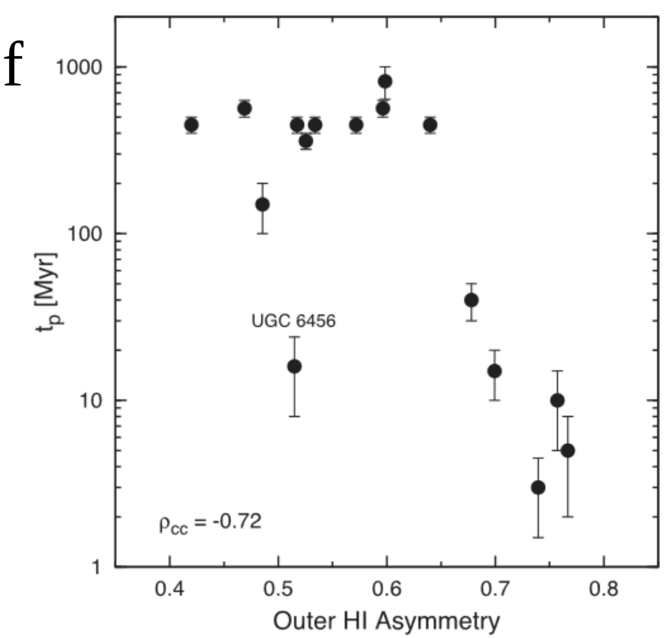
Starbursts in dwarfs: due to external interaction

HI in 18 dwarfs





Age of stars

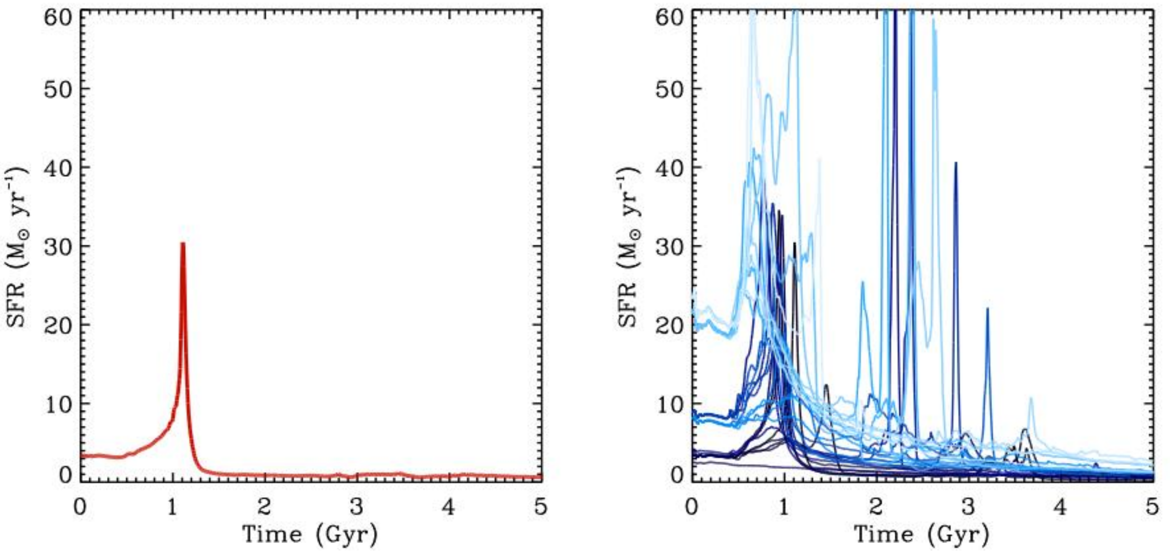


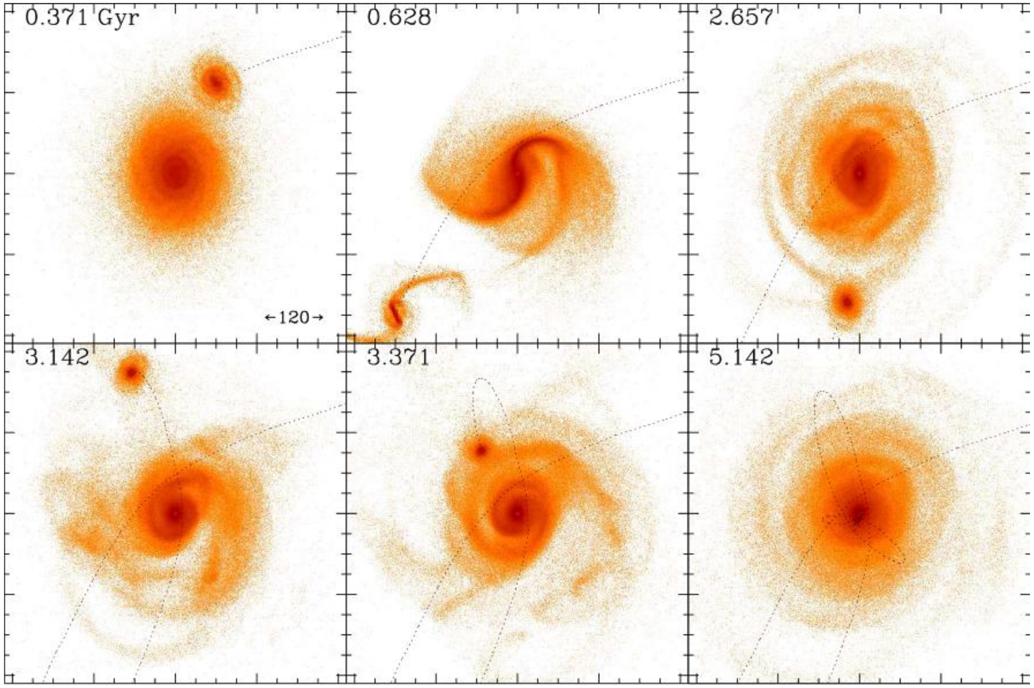
HI asymmetry

Lelli et al 2015

Influence of minor mergers

Can have a significant
Impact on SF
Depending on many
parameters





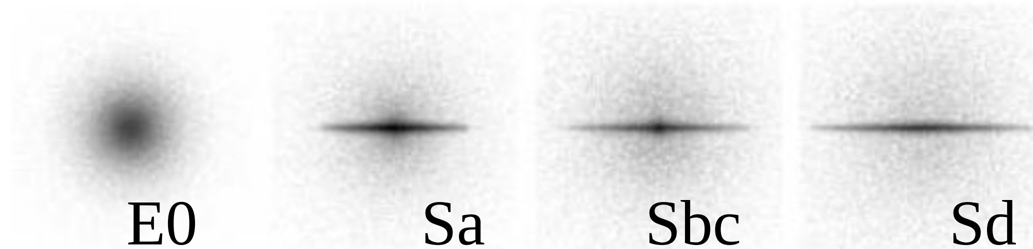
Heating of the old stellar disk

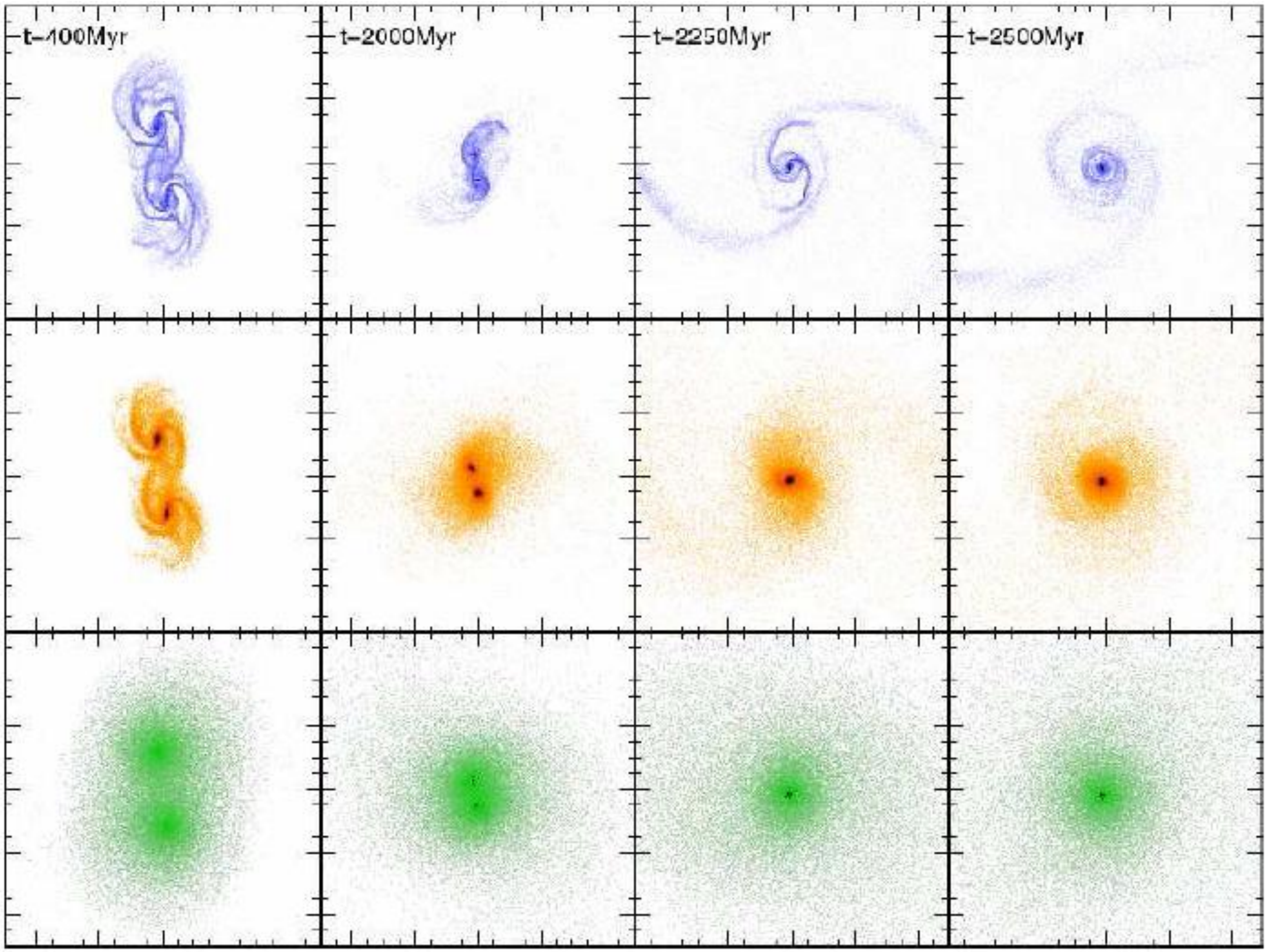
Remnant can rebuilt
a cold disk, if gas-rich
satellite

Cox 2009

Direct orbit merger gSb gSb

Gas flows through bars
in galaxy interactions



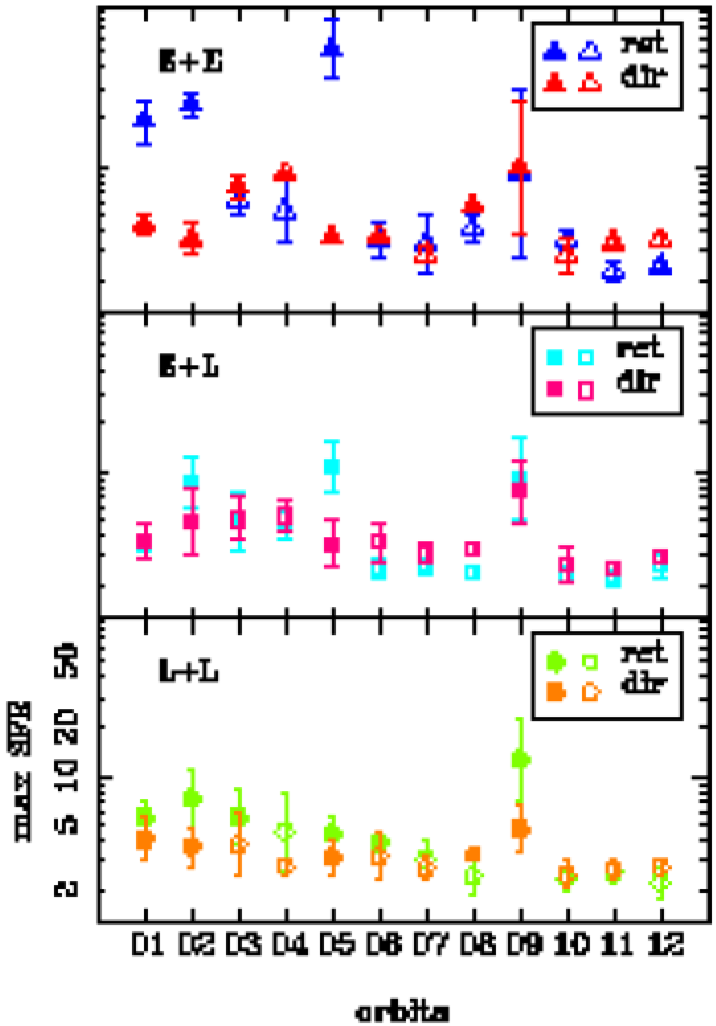


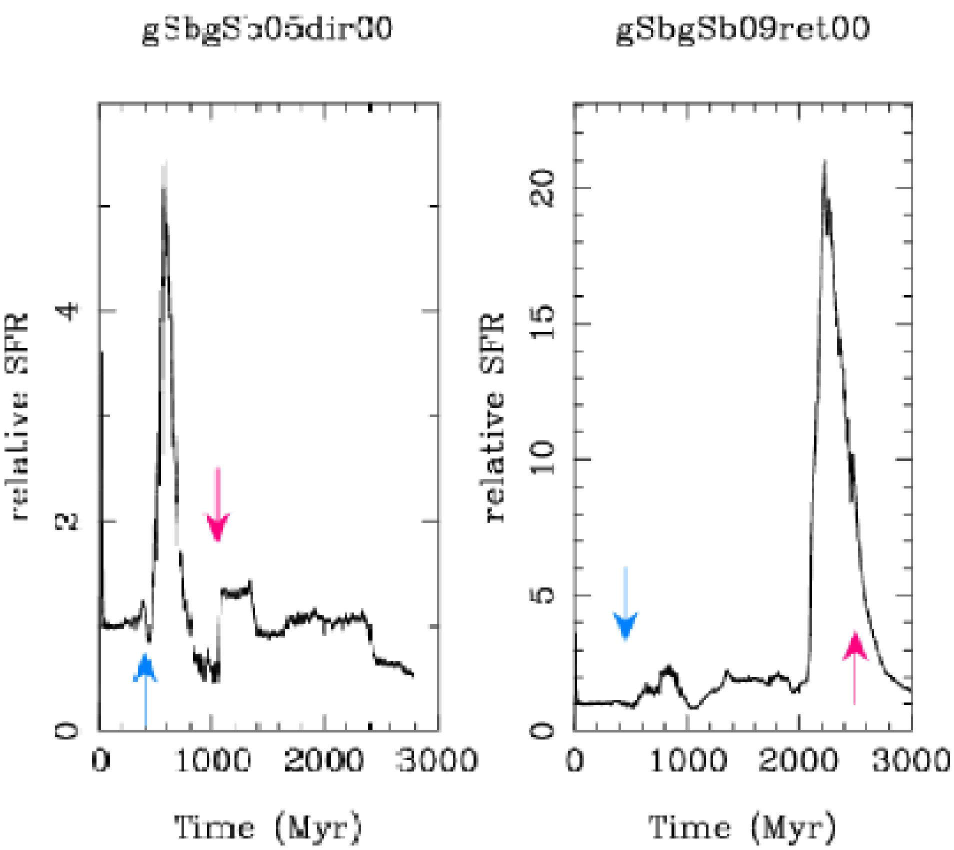
GALMER
Di Matteo et al 07

A high trigger
In mergers is rare

<10% SF in z=0.6
major mergers
For Massive Gal
Robaina et al 2009

Gas flows produce starbursts

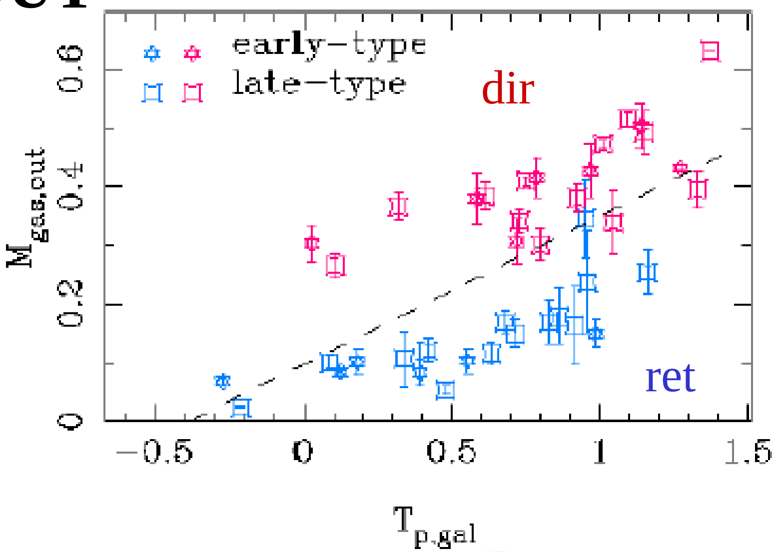




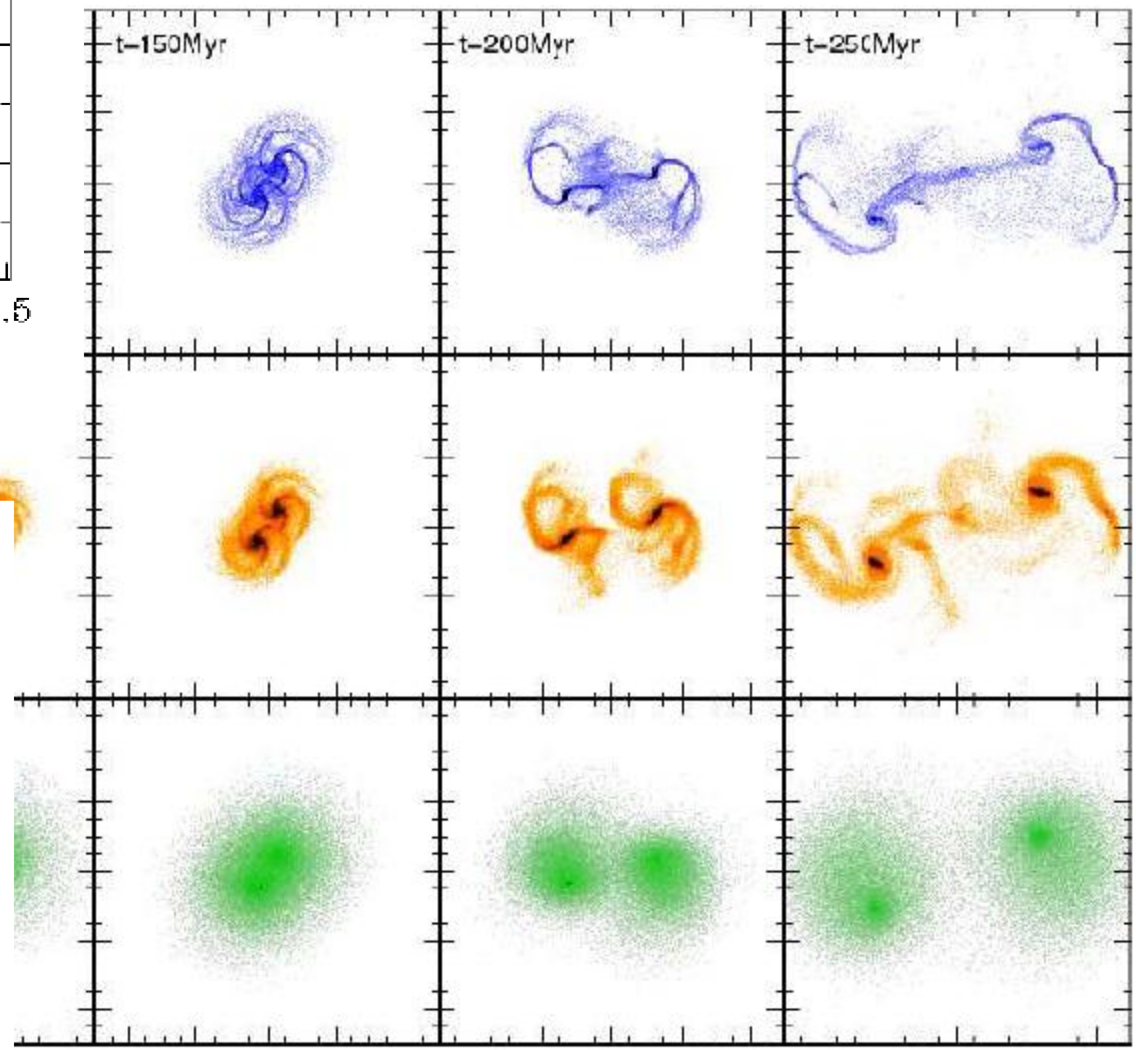
Retrograde orbits produce more starbursts

Gas flows IN and OUT

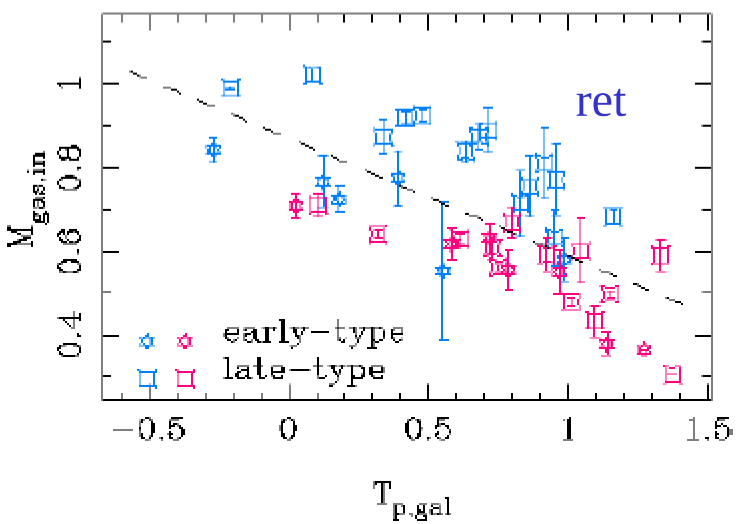
OUT



direct orbit flyby gSa gSa

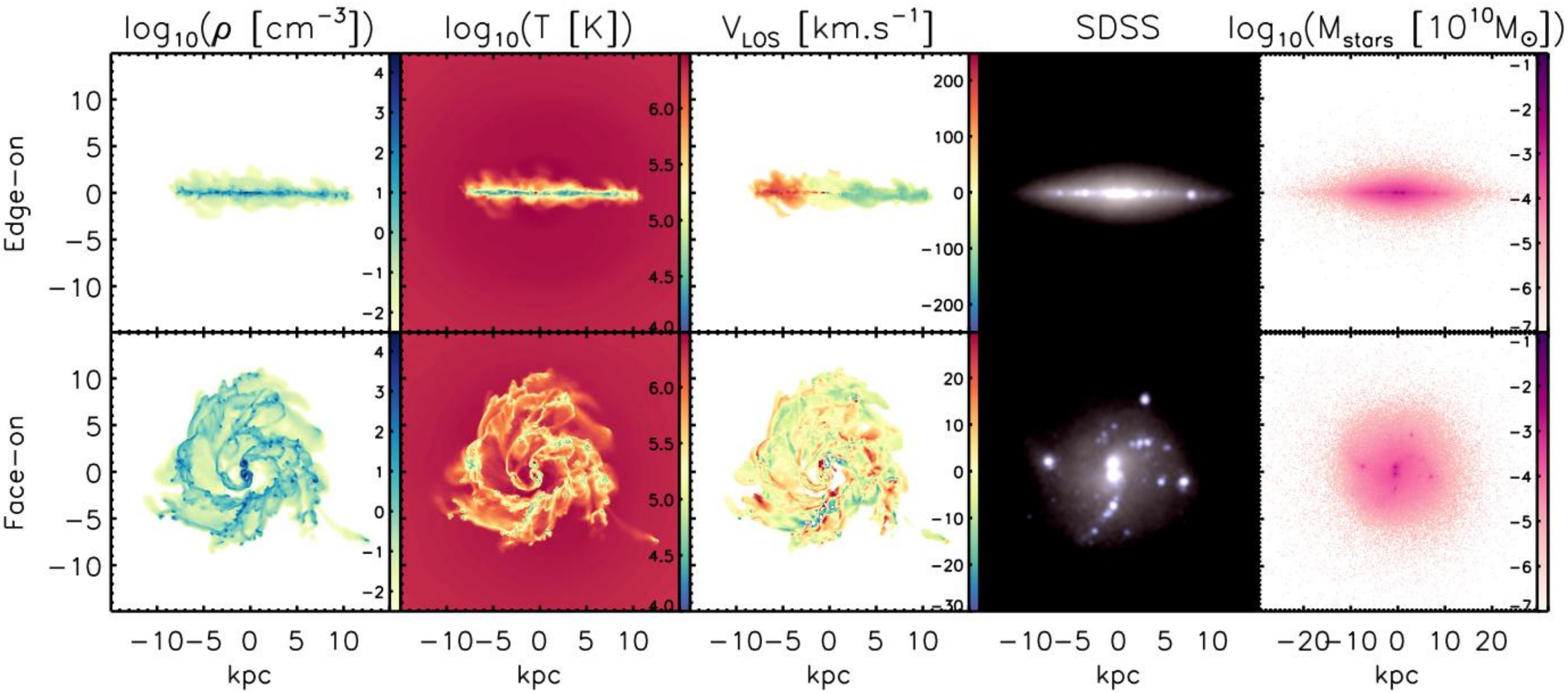


IN



100kpc size

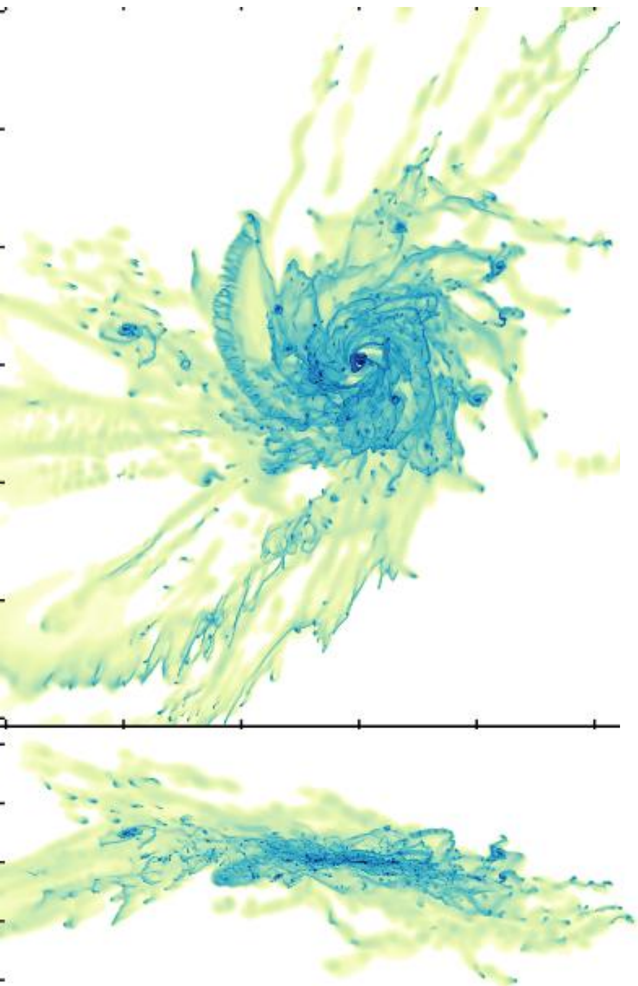
Gas-rich galaxies, high resolution

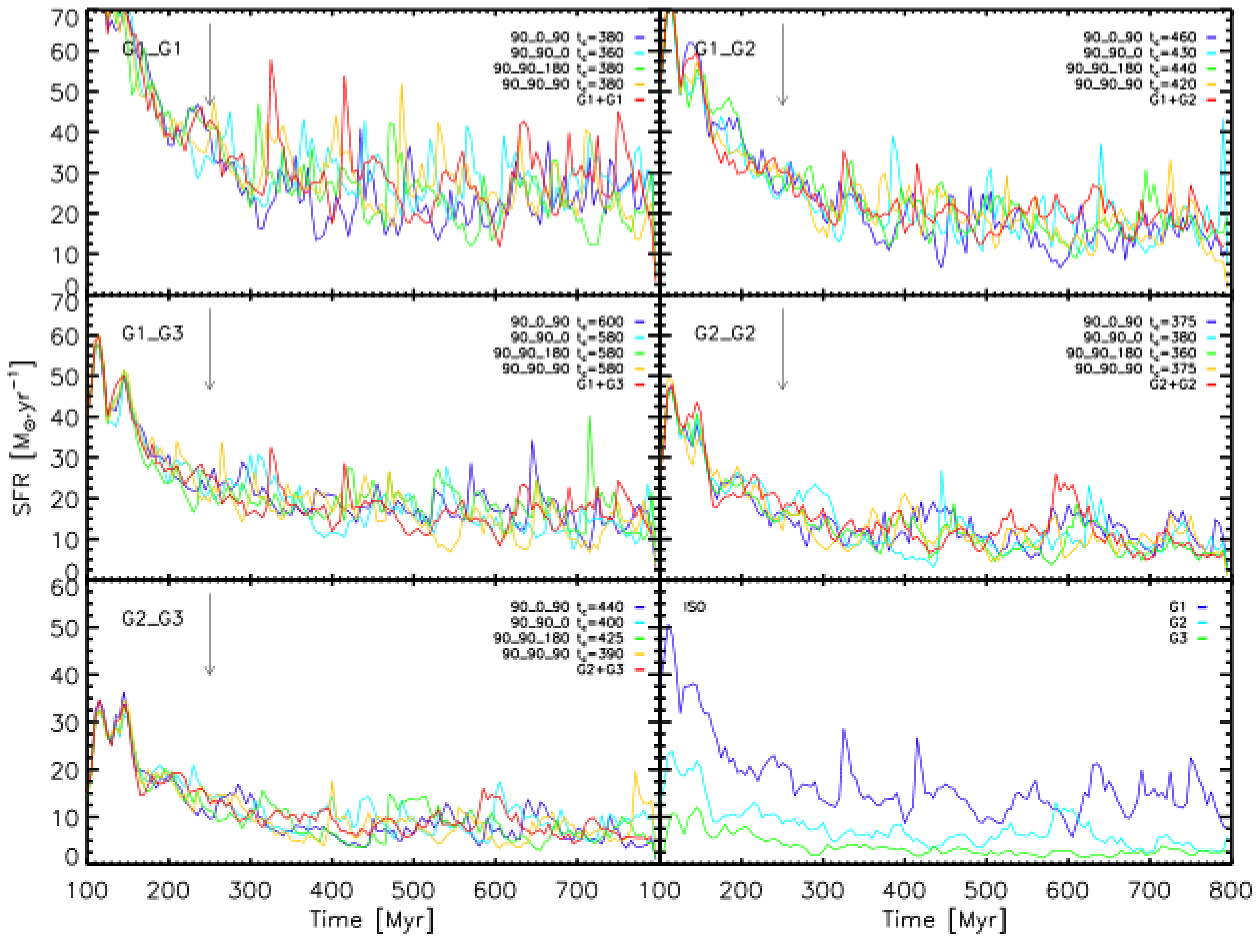


Intermediate mass, 65% of gas

Evolution during 400 Myr *Perret, Renaud et al 2014*

Influence of interaction/merger





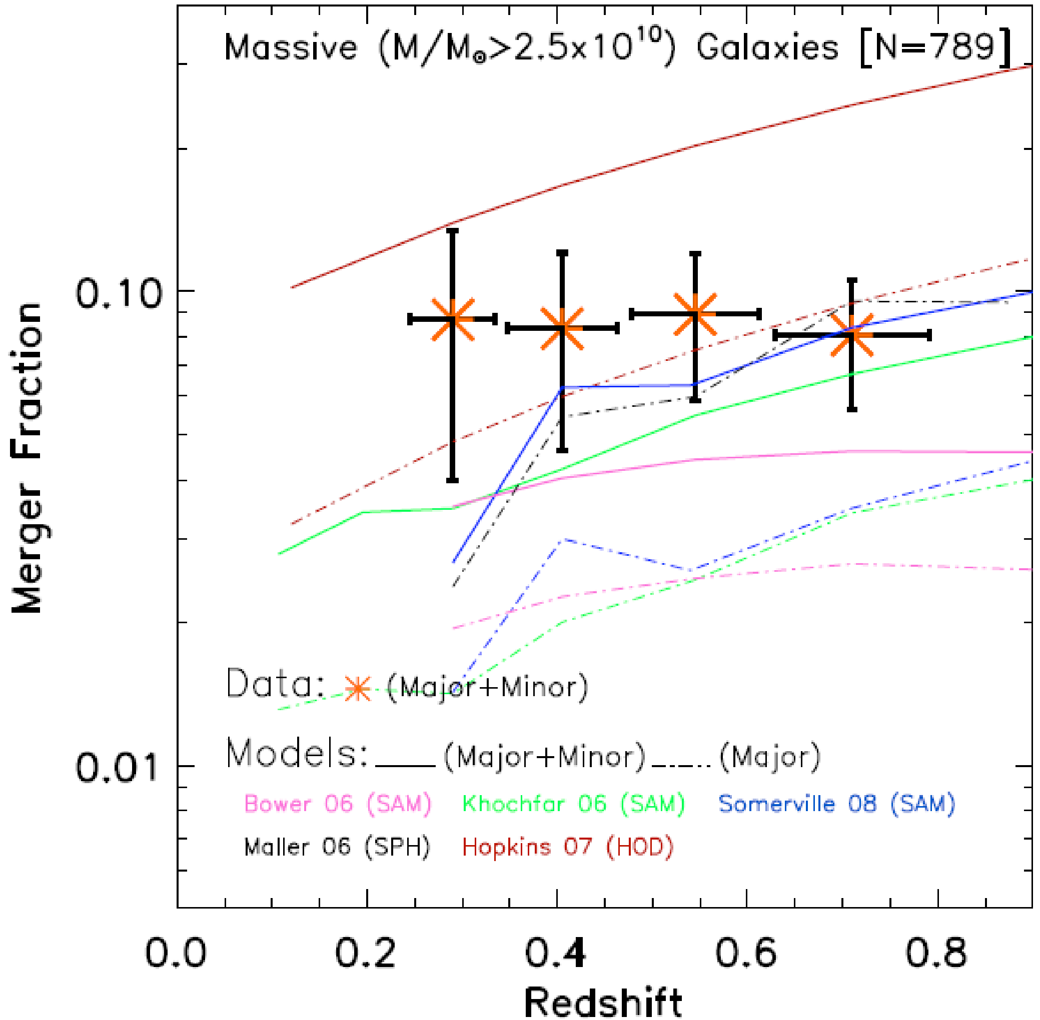
No impact at all

Same SFR for isolated galaxies

Temperature floor?, EoS? **High-z Saturation?**

Perret, Renaud et al 2014

Star formation modes: main sequence, starburst ?



Jogee et al 2009

< 10% of SF in z=0.6 massive galaxies is triggered by major interactions
Robaina et al 2009

Starburst mode at z=2
Only 10% of the SF
Rodighiero et al 2011
Herschel-GOODS

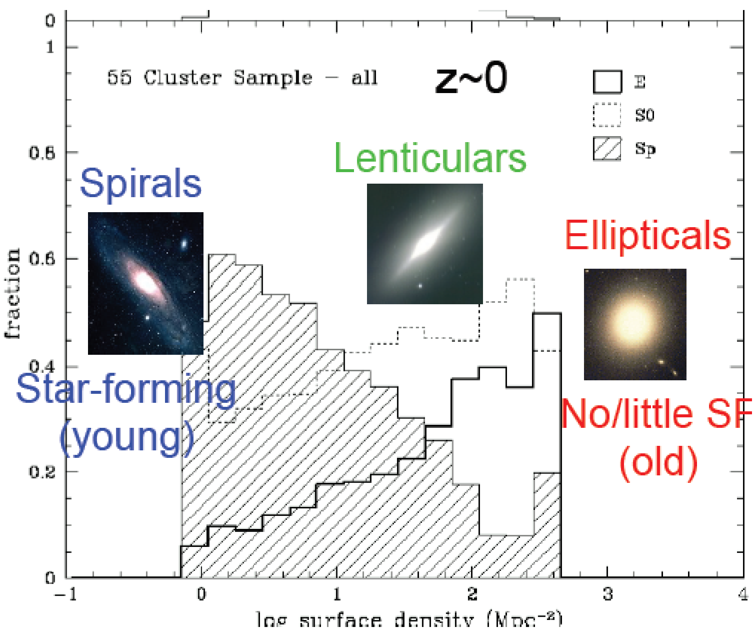
➔Compatible with the **GALMER simulations**
Di Matteo et al 2007

3- Environmental effects

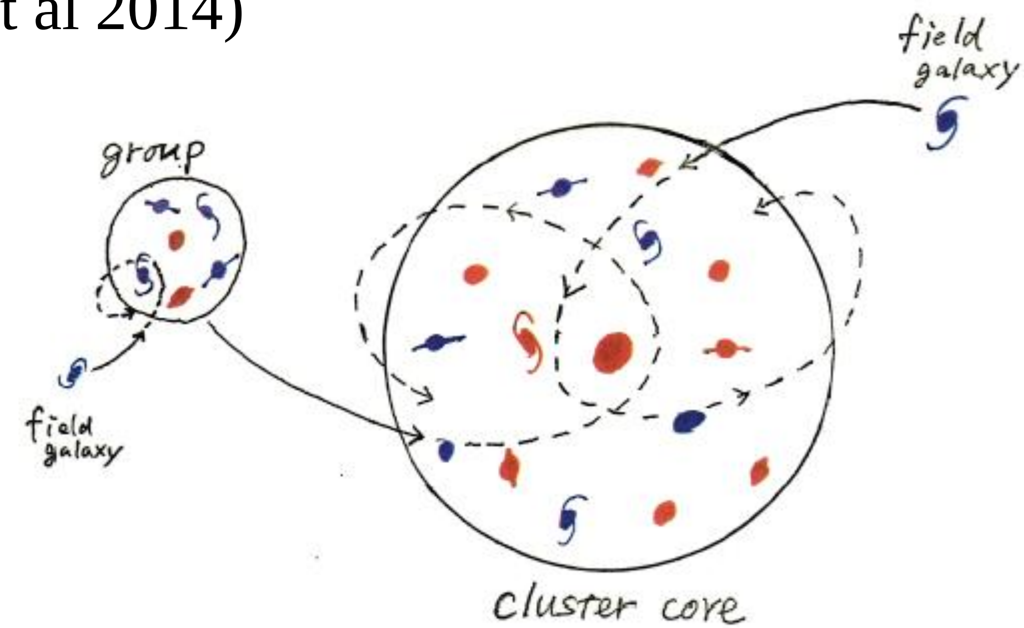
➔ Spheroids favored at high density, SF quenched

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

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



log surface density (Mpc^{-2})



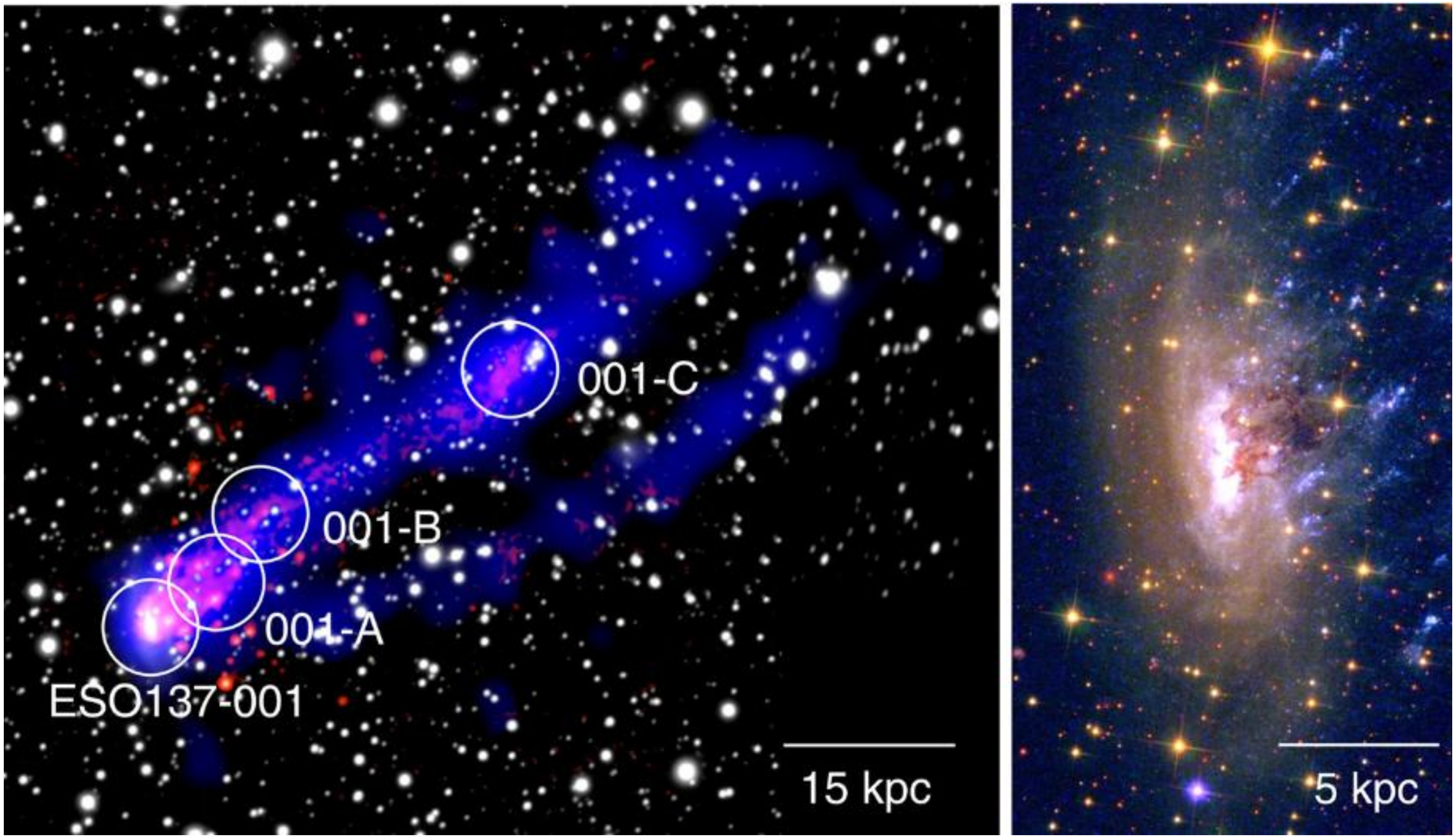
Mergers in small groups

Then group merge in clusters,

➔ ram-pressure, harassment

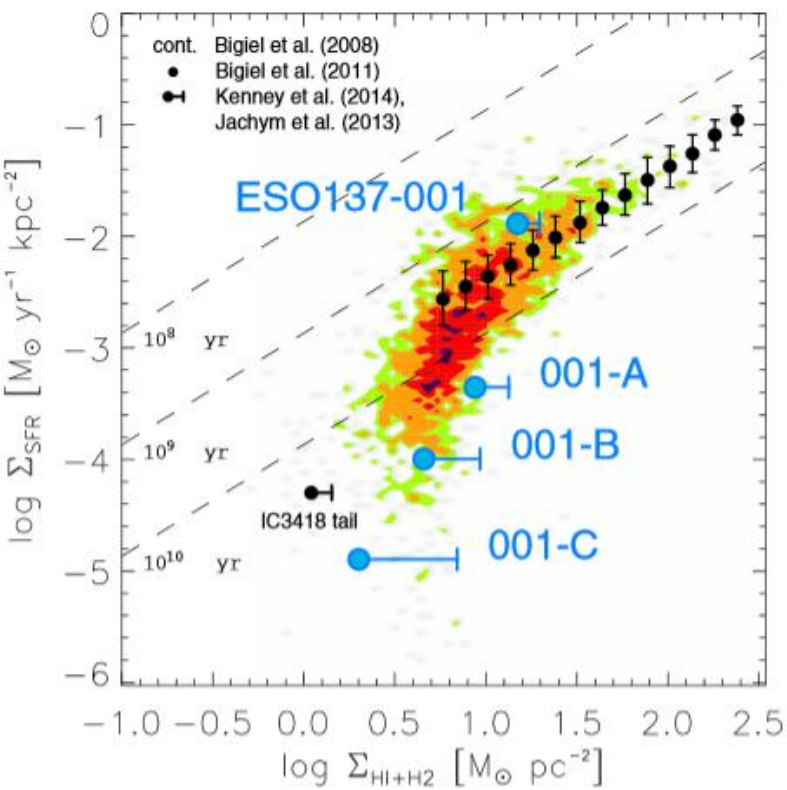
Environmental quenching

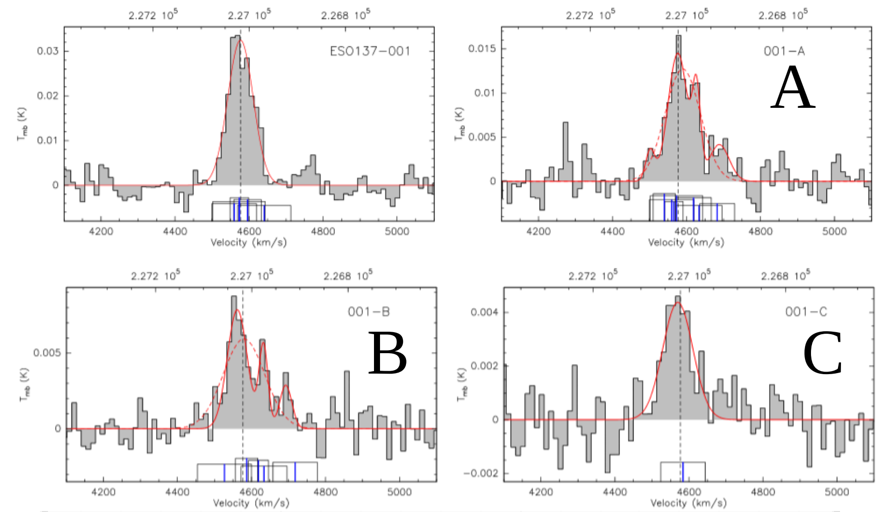
Ram pressure in clusters: **in general slow**:
In Virgo, HI deficient, but not H_2 (Kenney & Young 1989)
but **can be fast** in exceptional cases: ESO137-001

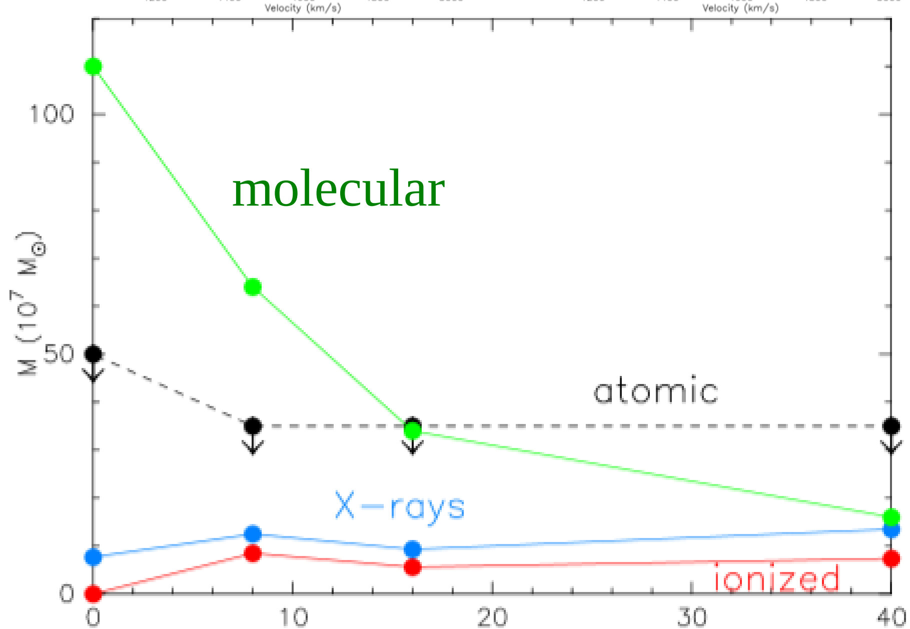


Jachym et al 2014

Ram-pressure quenching







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

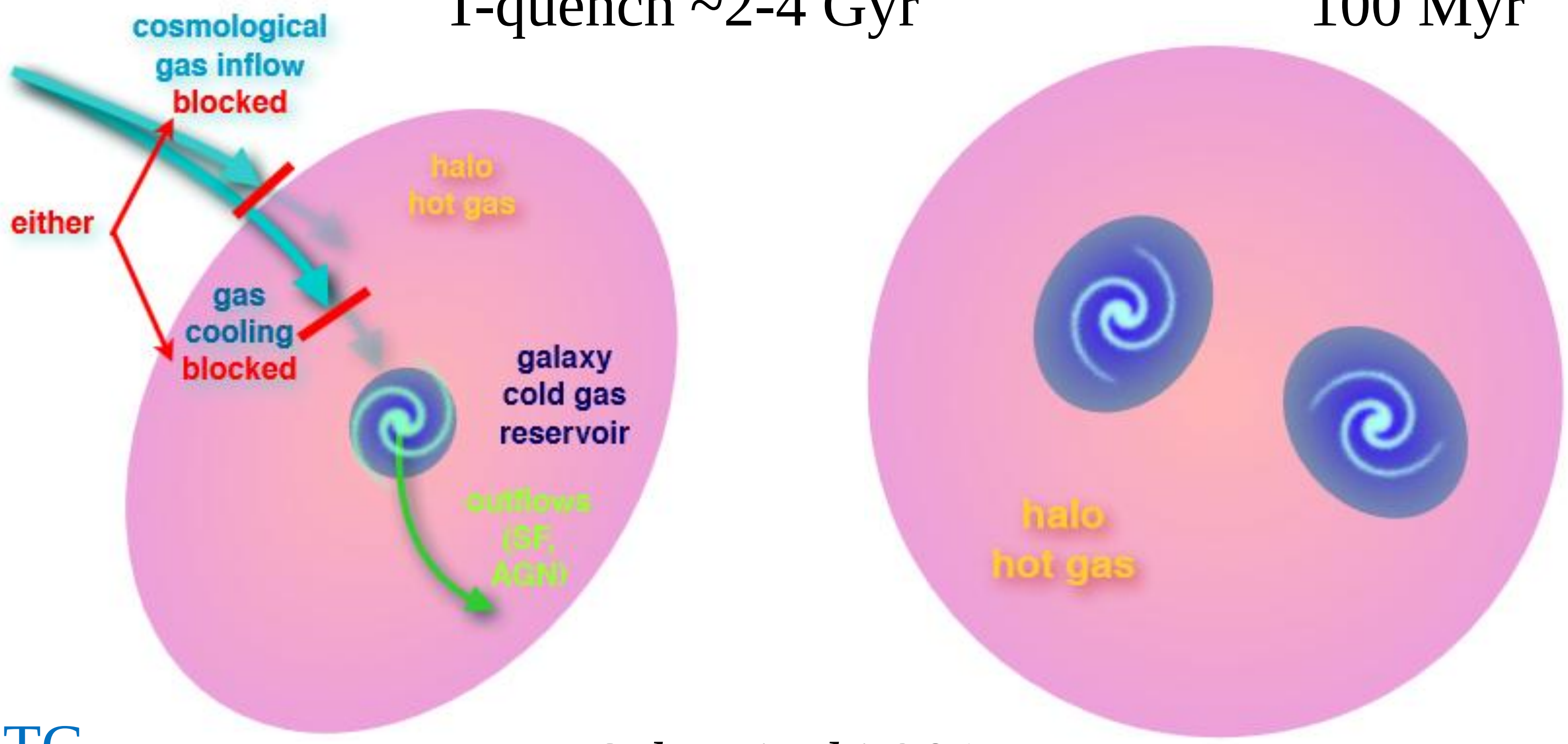
Jachym et al 2014

Slow and fast passage through 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

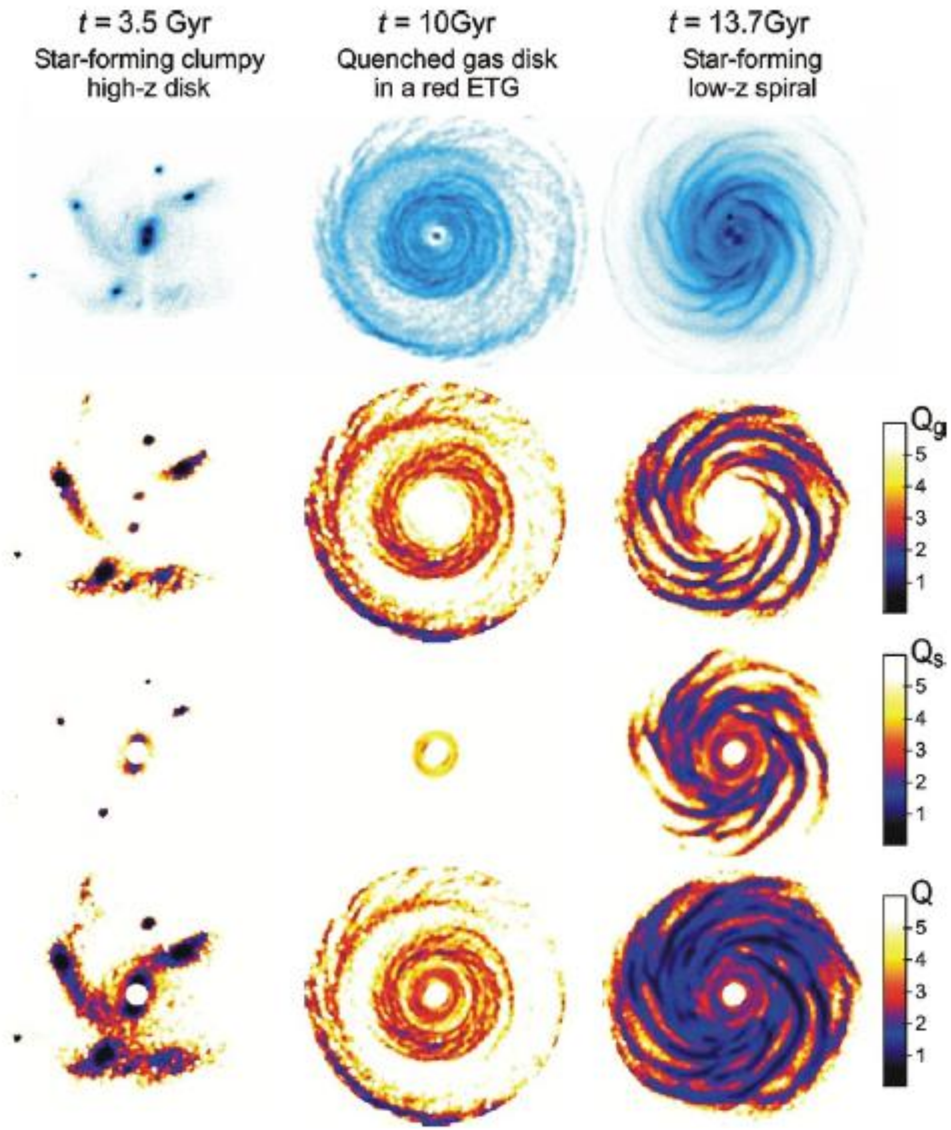


ETG

LTG

Schawinski 2014

Morphological Quenching (~5 Gyr)



Disks only are more unstable

Bulges and central condensations stabilise disks

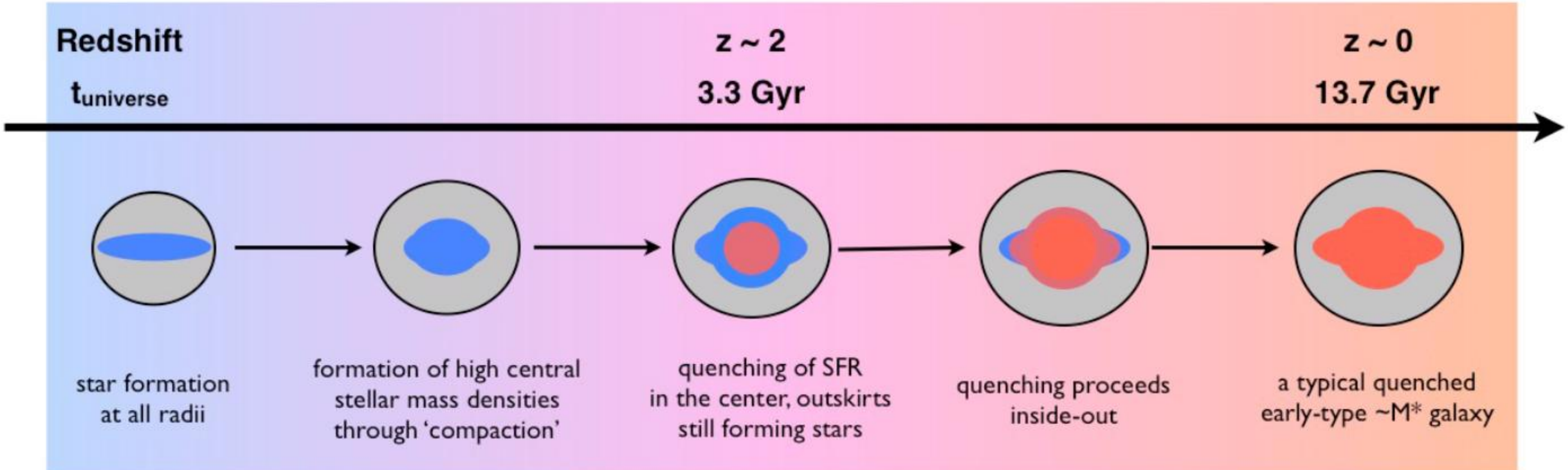
Toomre parameter Q= σ/σcrit

σcrit= 3.36 GΣ /κ

Bulge increases κ, and Q
If σ and Σ remains constant

Martig et al 2009

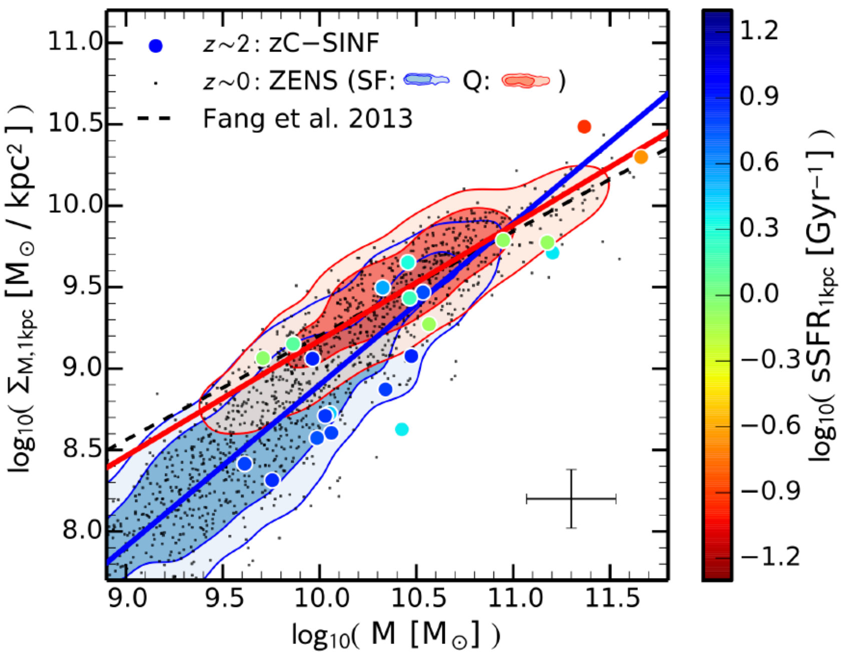
Inside out Quenching



➔ Morphological quenching?

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

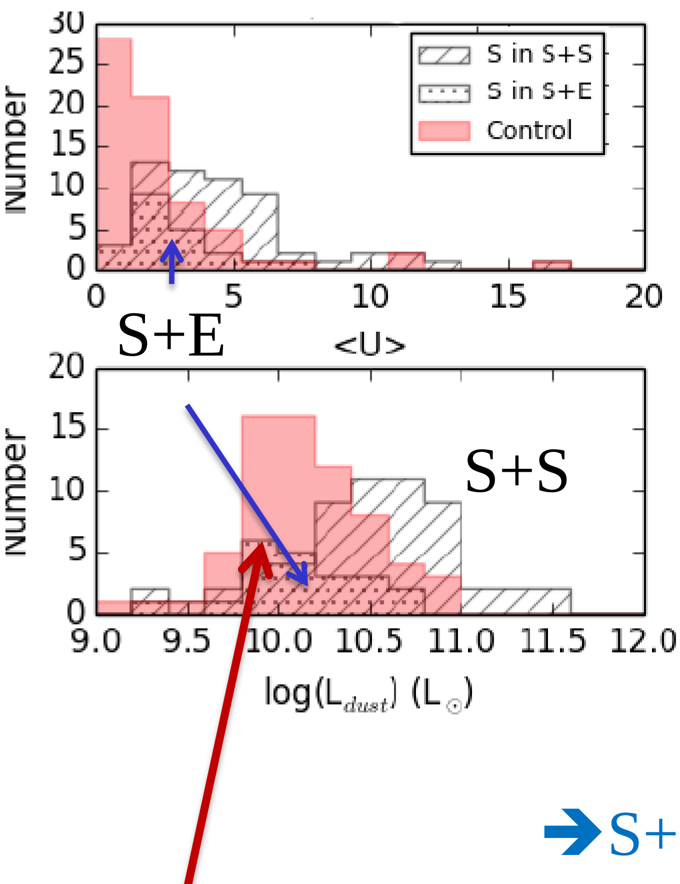
Guo et al 2011

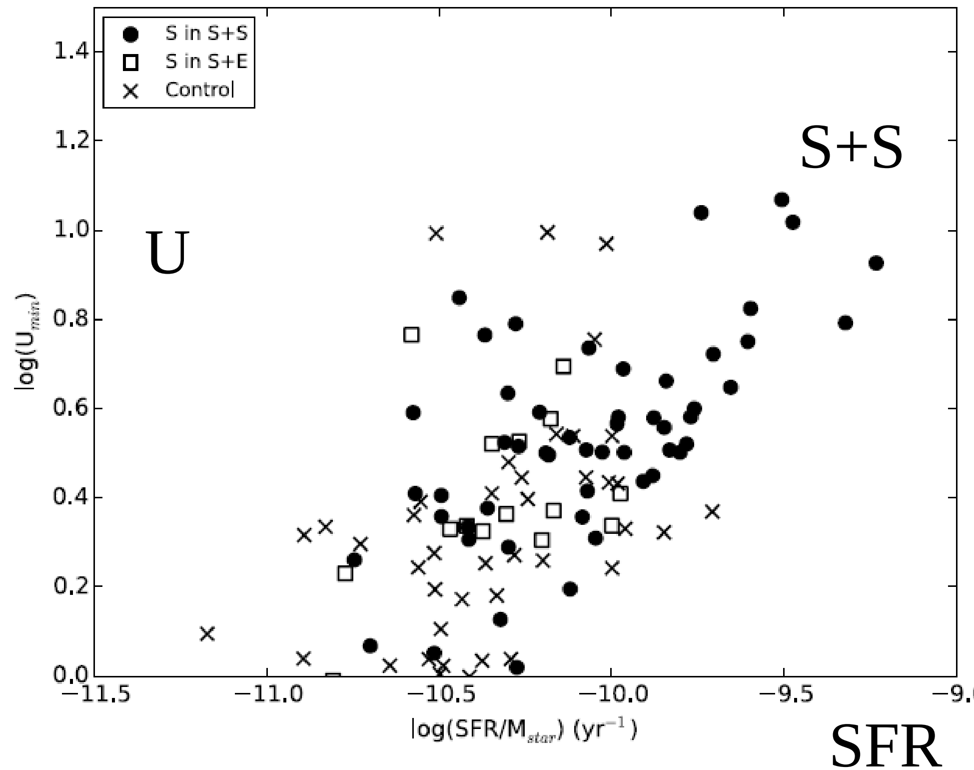


Tacchella et al 2015

Environment and morphology

Mergers of spirals (S+S) show a much larger SFR enhancement than S+E





Control

➔S+S: Twice more gas + collision, not only torques

No hot inter-galactic gas

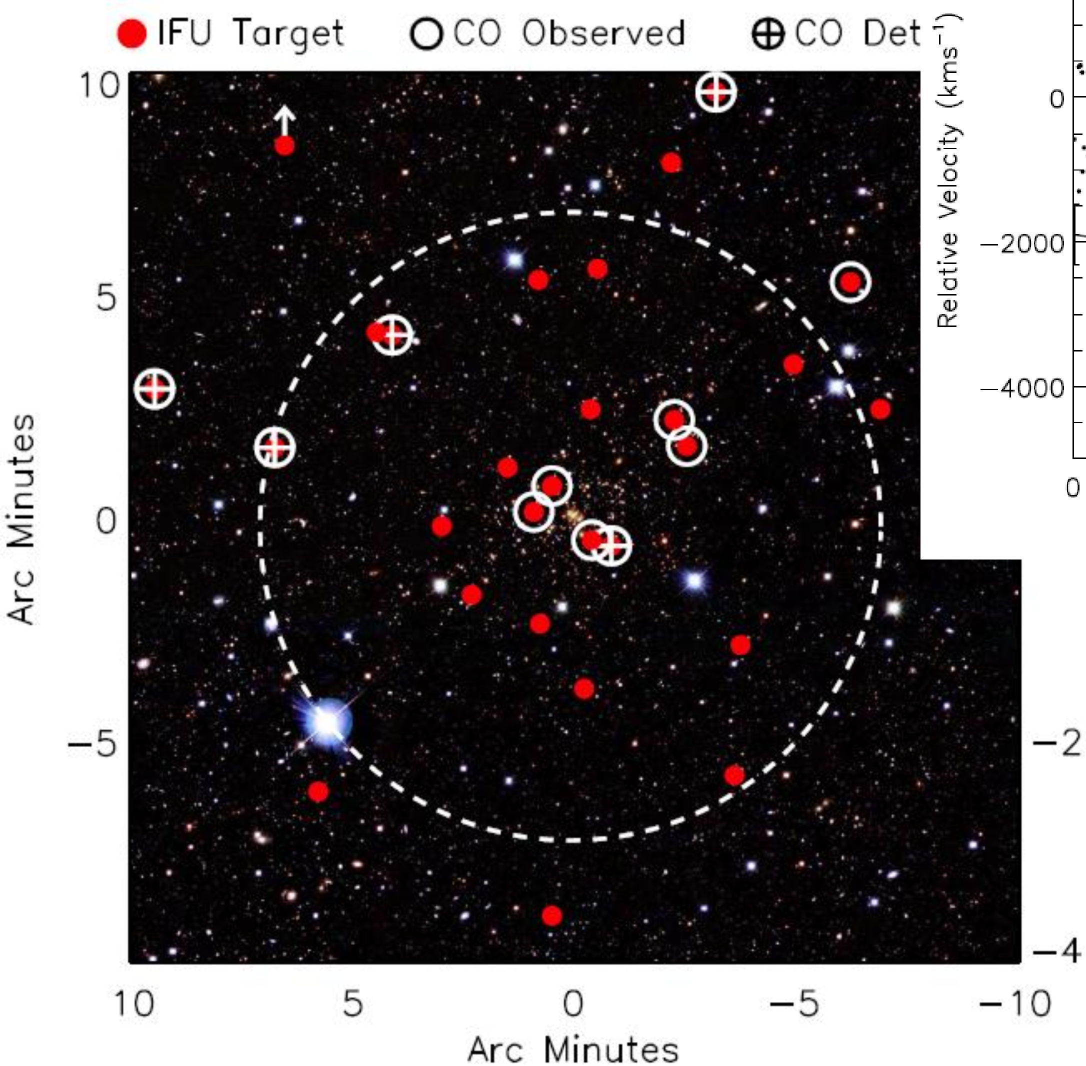
Domingue et al 2016

Star formation enhanced in clusters

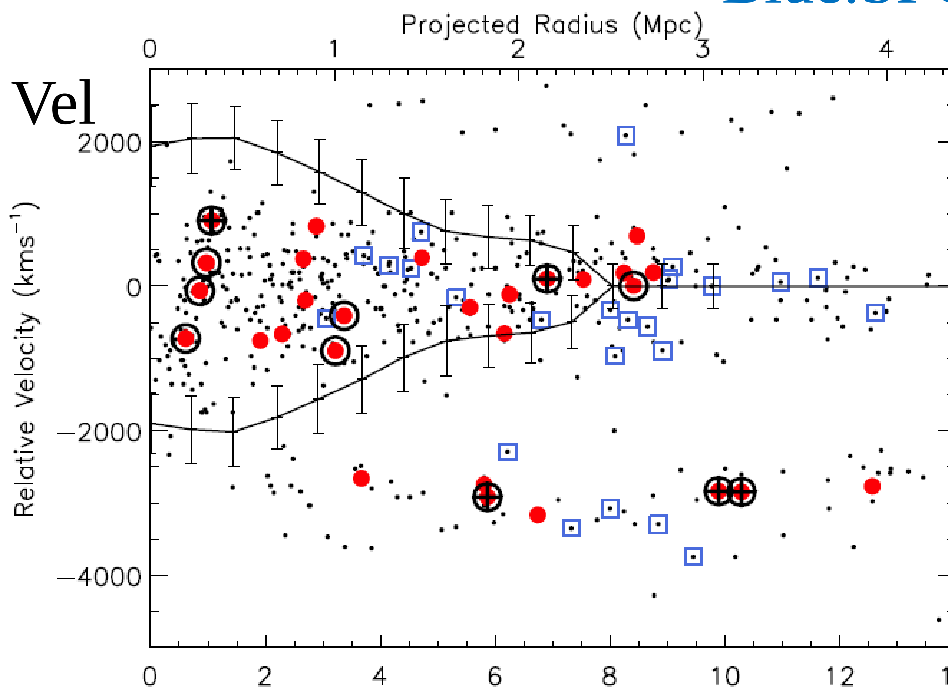
Reversal at high z?

Blue:SFG

CL0024+17 z=0.395



Vel



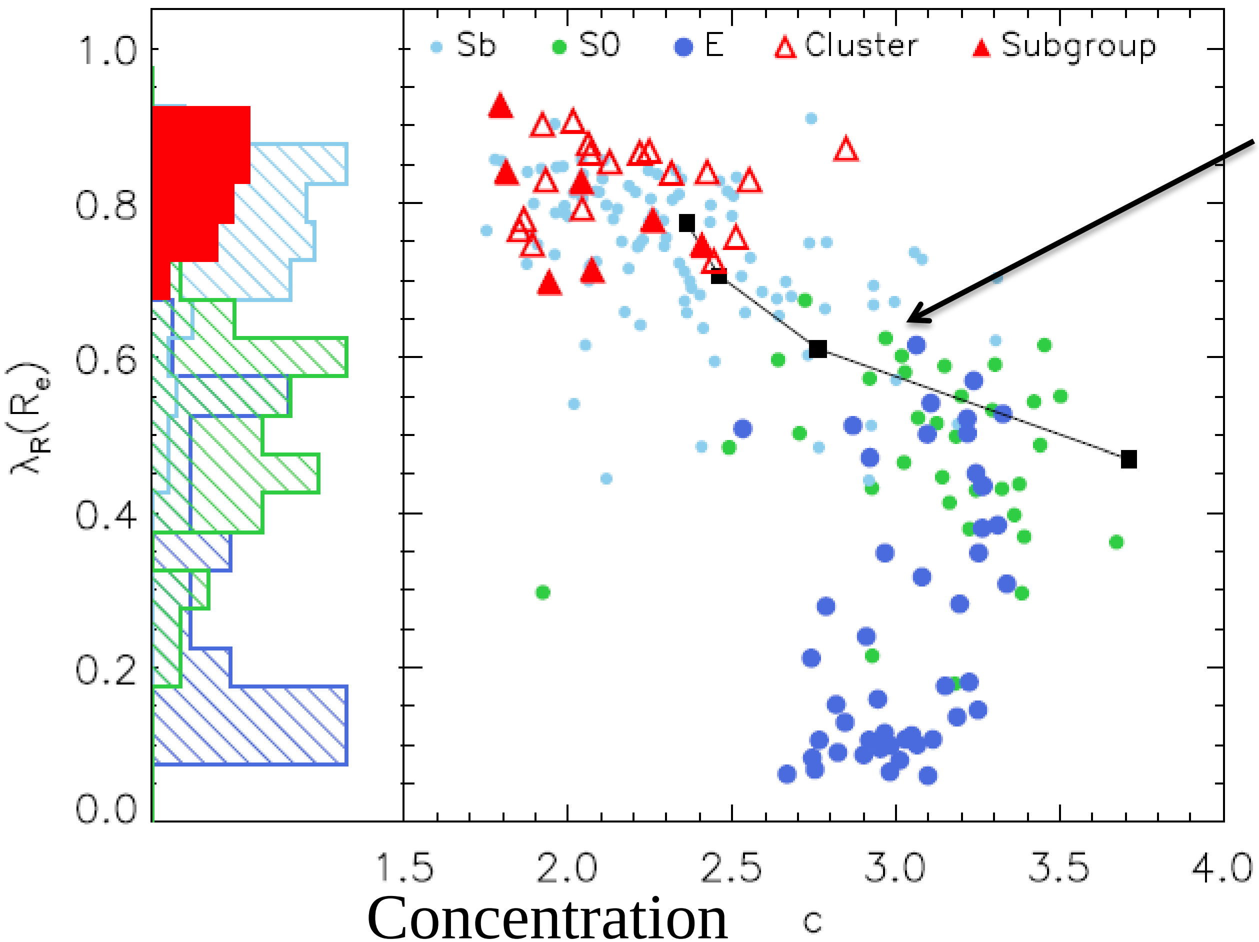
Projected radius (arcmin)

Substructure at V=-3000km/s
Pre-processing?

H.L. Johnson et al 2016

Star formation and transformation of galaxies into S0

Spin



Concentration

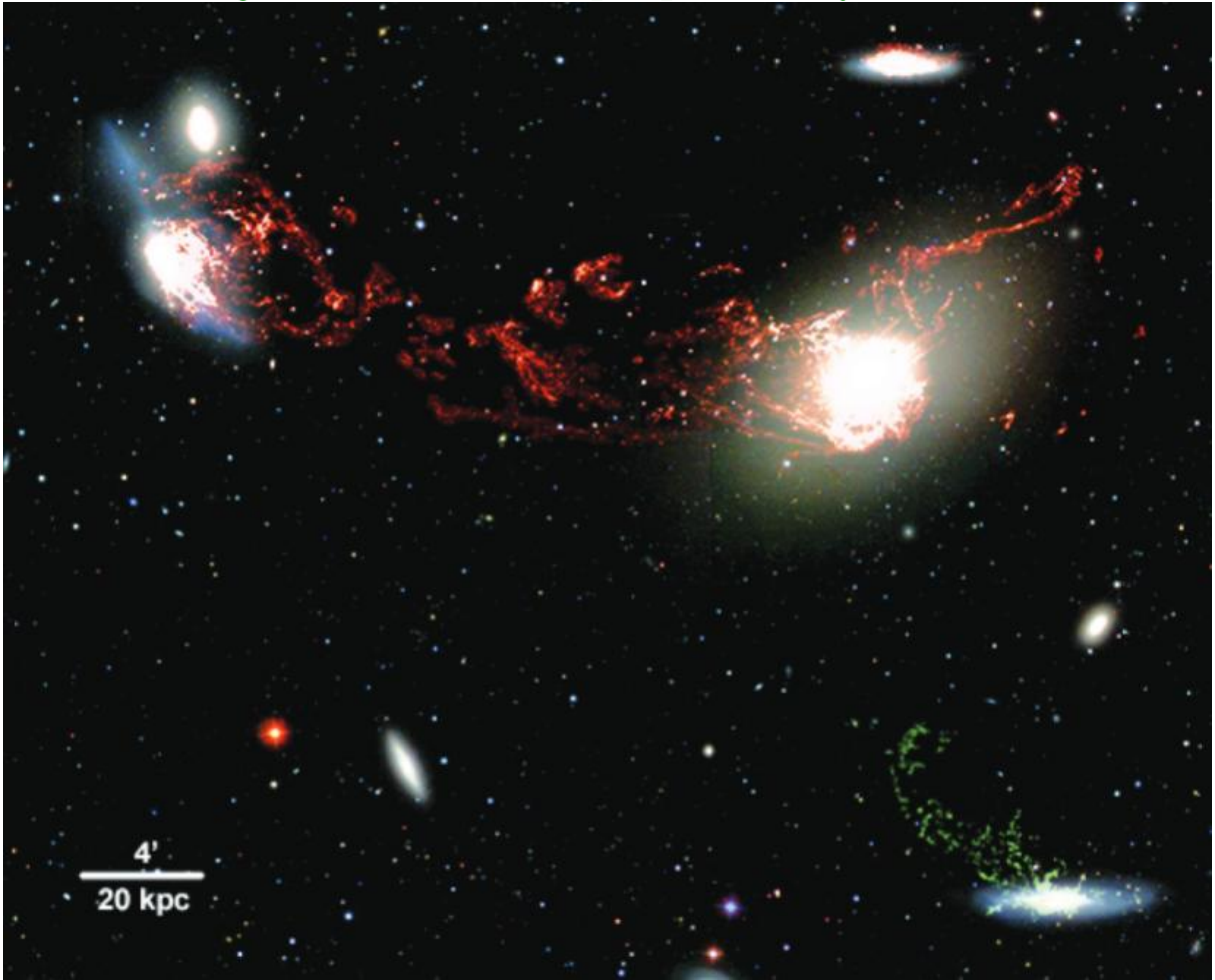
Prediction of models
(Bekki & Couch 2011)

Tidal interactions
Or ram-pressure?

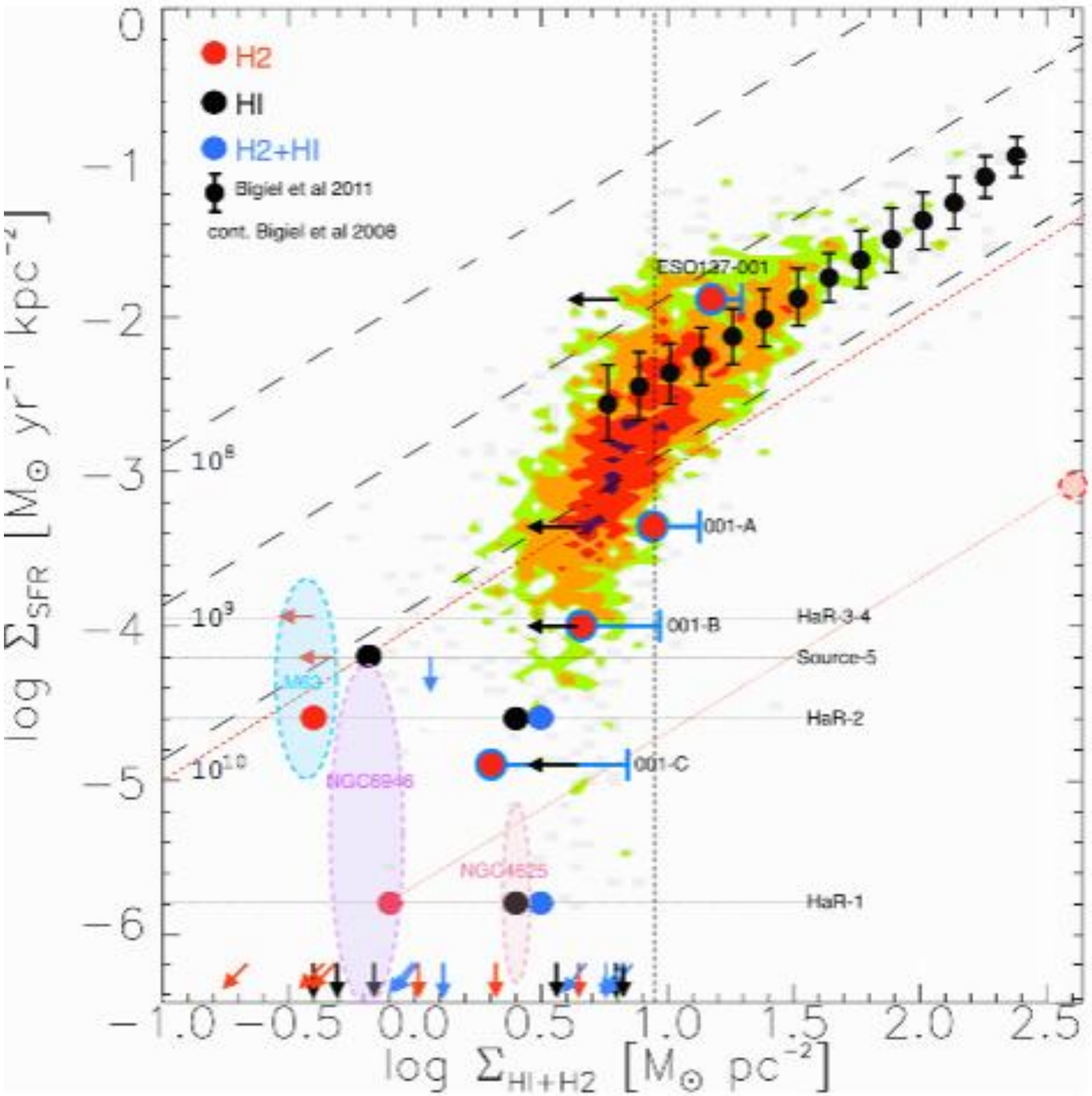
It appears that bursting galaxies are undisturbed
➔Disks in rotation

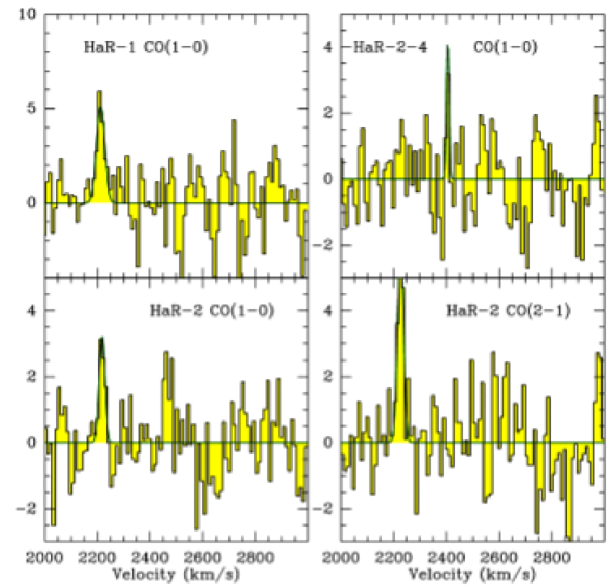
Johnson et al 2016

Virgo cluster: Hα + [NII], Kenney et al 2008



Tidal streams in clusters: Virgo

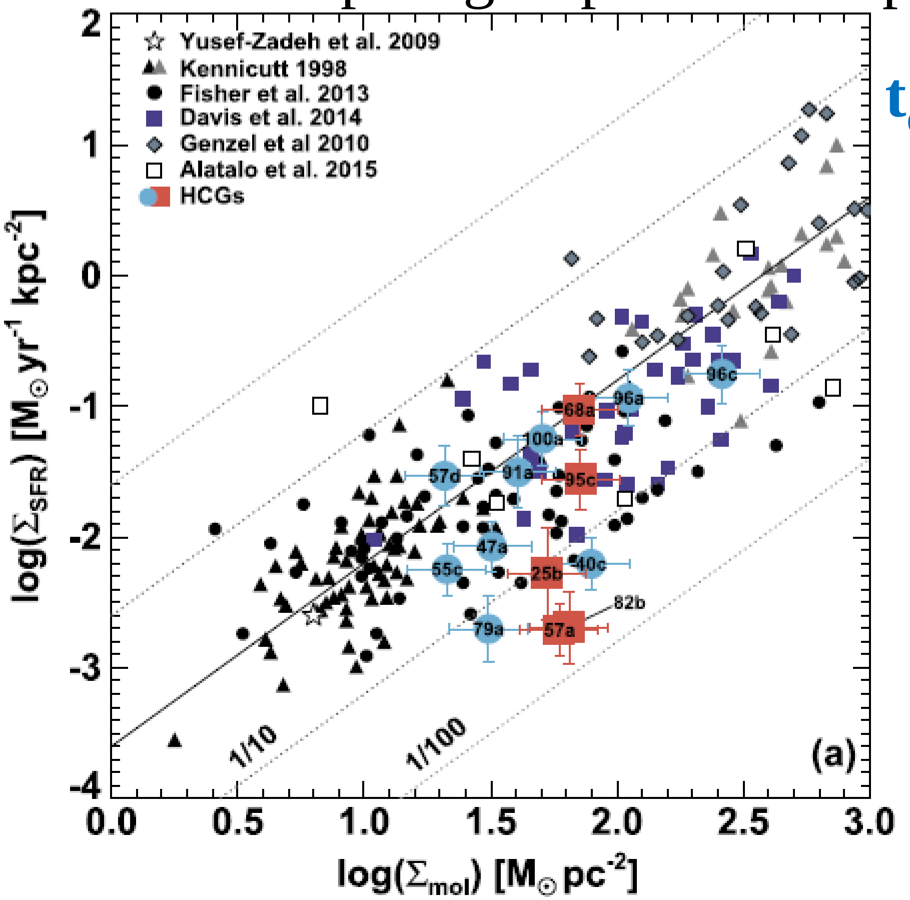




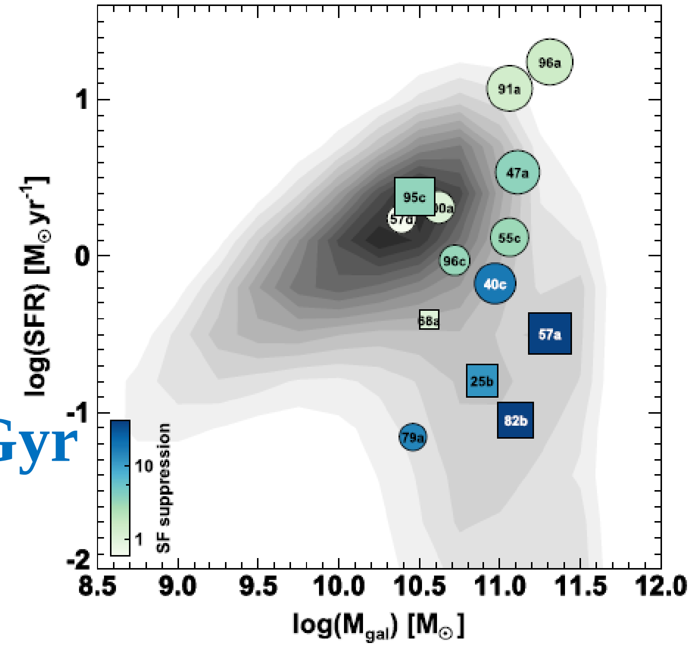
Verdugo et al 2015

Shocks and turbulence quenching

Hickson compact groups ➔ SF suppression

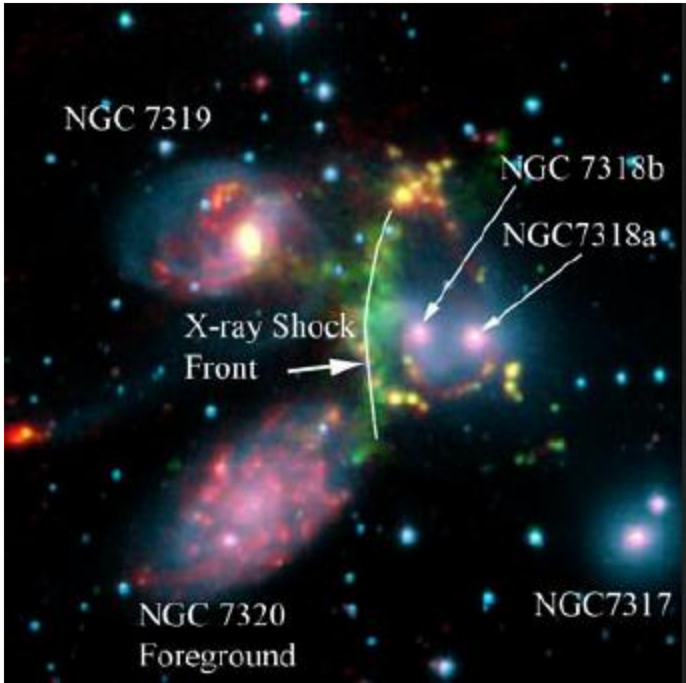


t_{dep} > 10Gyr



Shocks ➔ H_2 emission

Gas/Dust normal



➔Quenching before gas consumption

Alatalo et al 2015

CONCLUSION

➔ Main sequence: SFE=cst, above Σ_{gas} = 9 $M_{\odot}/pc^2$
(tdep ~2Gyr)

➔ Density waves, bars and spirals, gas compression, starbursts in nuclear rings

➔ Starbursts triggered by galaxy interactions and mergers,
tdep ~100 Myr

➔ Role of environment: trigger by interactions, mergers, but quenching by strangulation, harassment, cluster-wide interactions
tdep >10 Gyr