EVIDENCES OF RAM PRESSURE STRIPPING IN CLUSTER GALAXIES

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+ THE VESTIGE TEAM

INTRODUCTION

Major environmental mechanisms:

1) **Gravitational** (tidal interactions, **harassment**..)

2) **Interactions with the ICM** (**ram pressure**, thermal evaporation, viscous stripping, **starvation**…)

3) **Pre-processing**

The identification of the dominant process in different environments and at different epochs is crucial for tuning cosmological and semi-analytic models of galaxy evolution.

IDENTIFICATION OF THE DOMINANT PROCESS ON RESOLVED GALAXIES

Harassment:

- Tidal tails of gas and stars
- Increase of the nuclear SF activity
- Truncated stellar discs, asymmetries, bars…

Starvation:

- Homogeneous fading of the SFR
- Possible important contribution of nuclear feedback

Ram pressure:

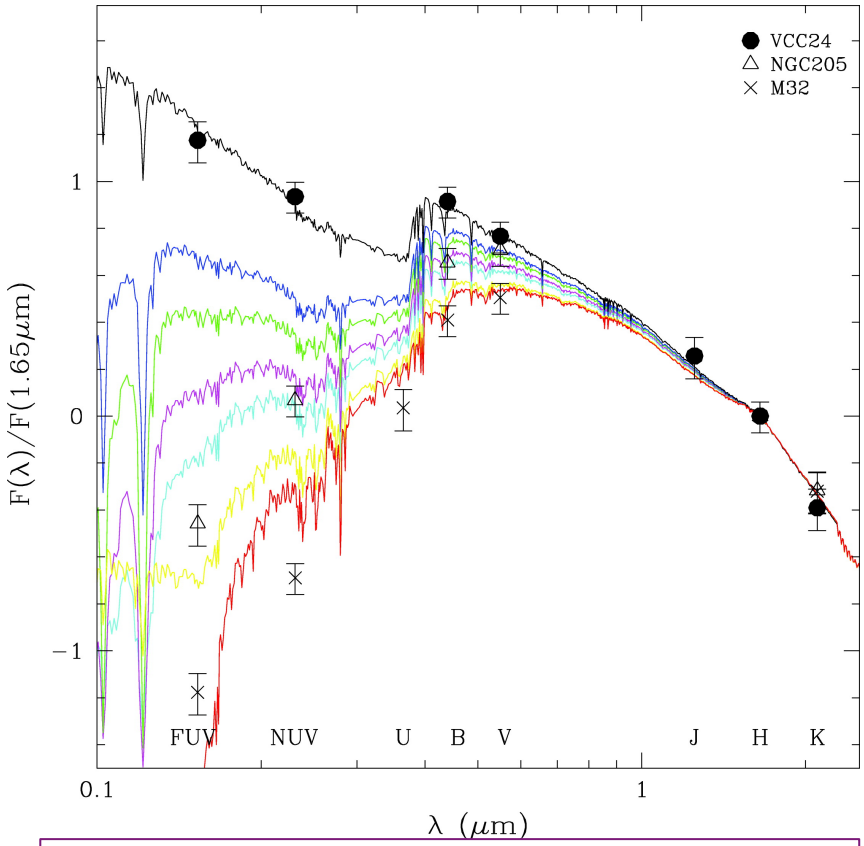
- Long cometary tails of gas with no stars
- Radially truncated gas and SFR discs

IDENTIFICATION OF THE DOMINANT PROCESS IN STATISTICAL SAMPLES

	Timescales	Environment
Harassment :	t >= 5 Gyr	$R < R_{200}$ (R_{vir})
Starvation :	t >= 5 Gyr	$R <= 3\text{-}4\ R_{200}$
Ram pressure :	t< 1.5 Gyr	$R \sim R_{200}$
	Stellar populations	Galaxy distribution

IDENTIFICATION OF THE DOMINANT PROCESS

A rapid truncation of the SFH leaves an imprint in the stellar continuum + emission and absorption lines

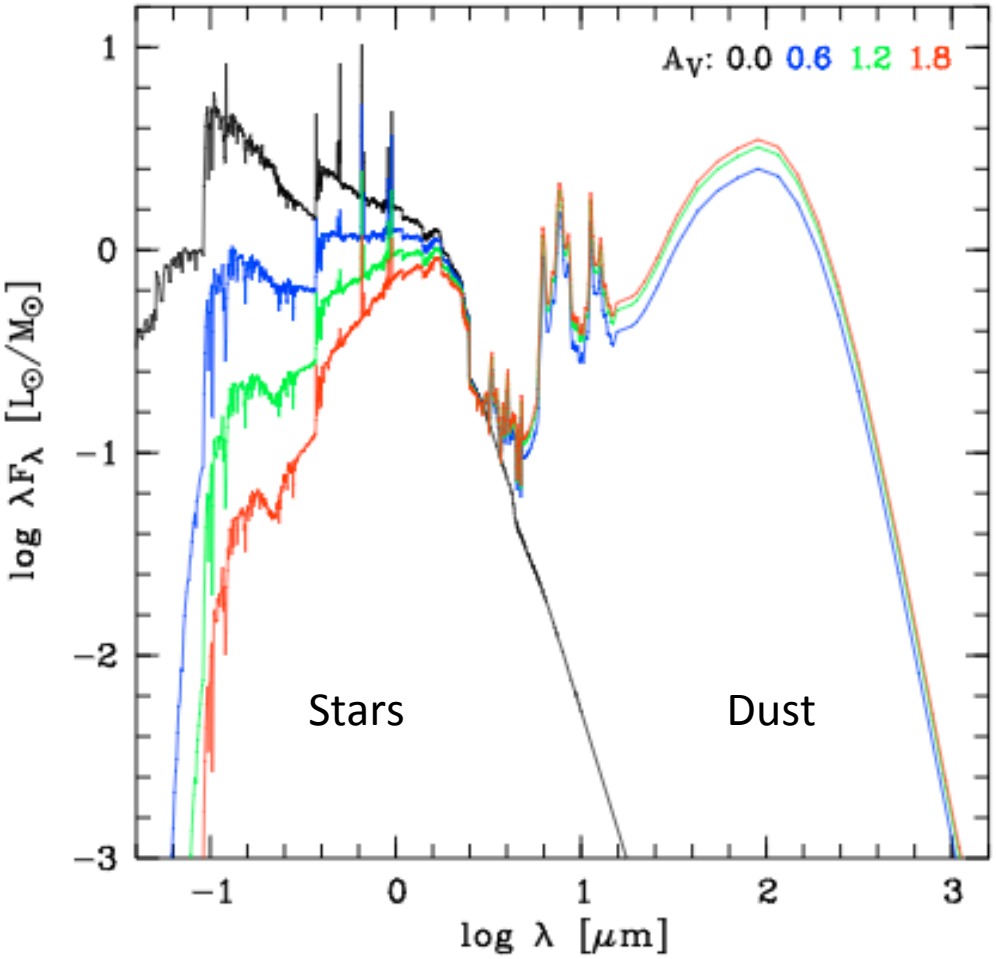


Continuum Black=unperturbed Blue:t=0
green:t=100 magenta:t=300 cyan:t=500
yellow:t=1300 red t=2 crossings

Boselli et al 2008

DEGENERACY DUE TO DUST ATTENUATION

The degeneracy due to dust attenuation can be removed using a SED fitting code: CIGALE



Noll et al 2009

THE HERSCHEL REFERENCE SURVEY

Volume-limited (15<Dist<25 Mpc) K-band-selected (10^8 < M_{star}<10^{11} Mo) sample of galaxies of all morphological type (E-S0-Sa-Sd-Im-BCD) including Virgo cluster and field objects (Boselli et al. 2010).

323 galaxies

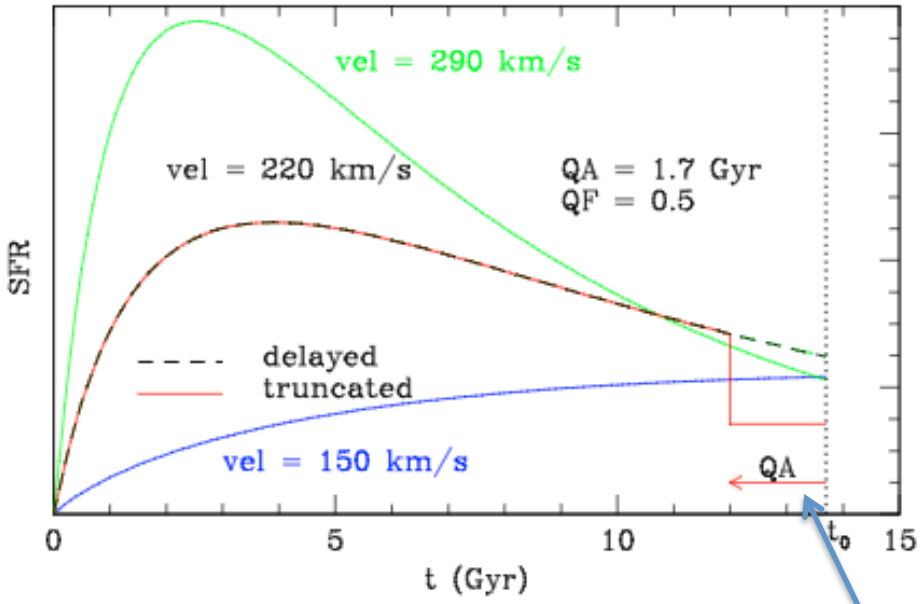
20 photometric bands (from FUV to 500 mic)

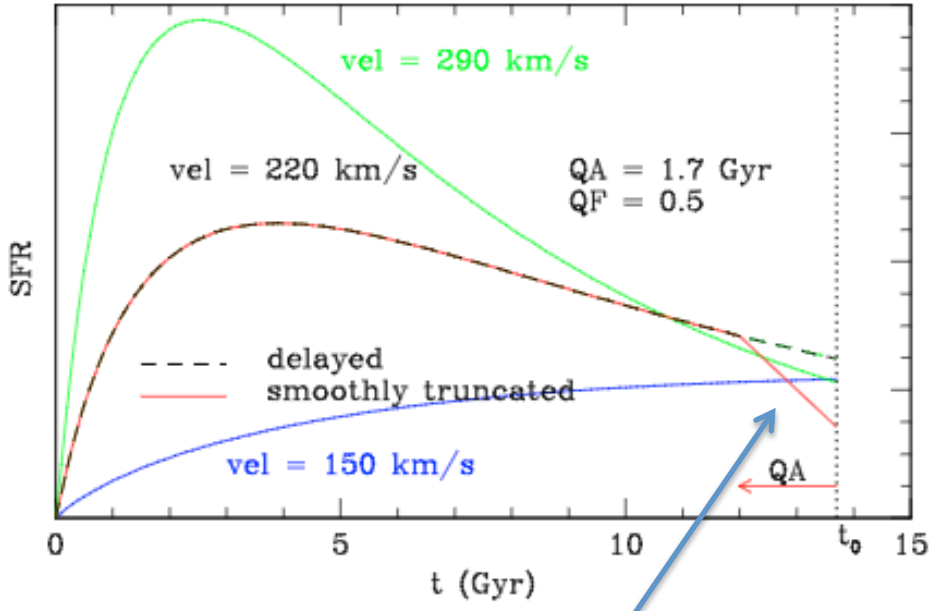
Integrated spectra (drift scan mode) -> Balmer absorption lines

Halpha narrow band imaging

STAR FORMATION HISTORY

Two **truncated star formation histories** with 2 free parameters: QA quenching age and QF quenching factor (secular evolution = f(vel))





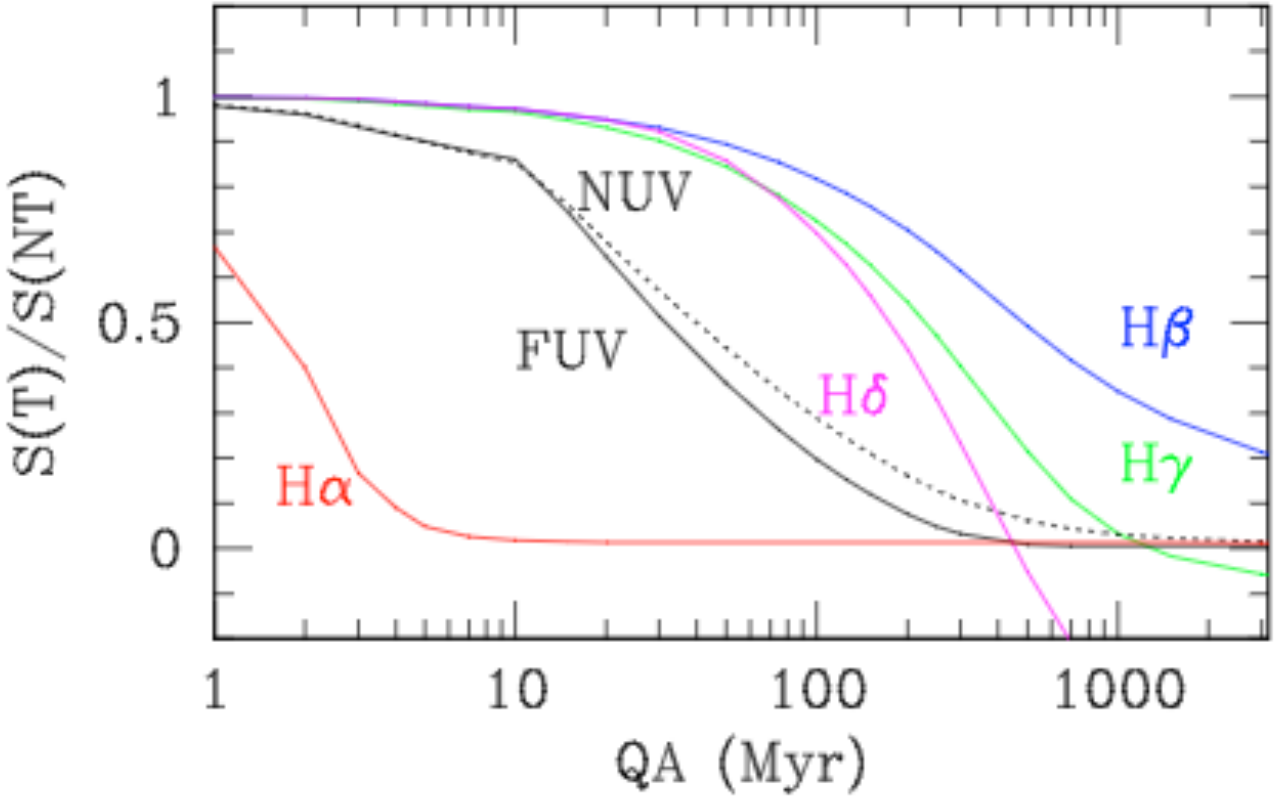
Abrupt truncation

Smooth truncation

Boselli et al 2016b

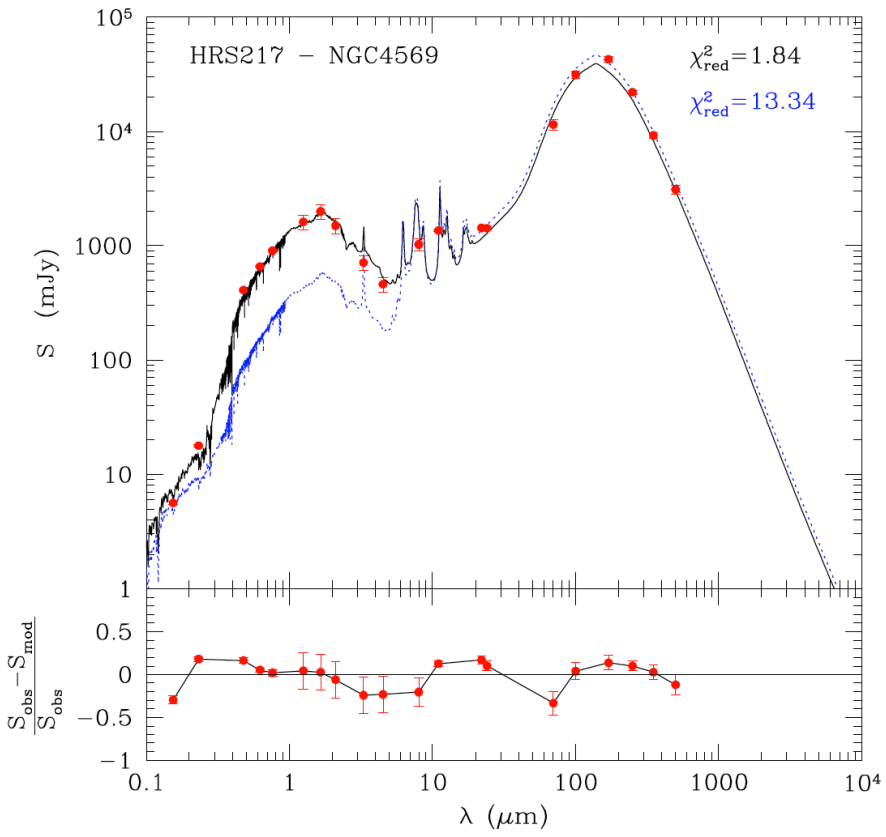
SED FITTING USING SPECTRAL LINE INDICES

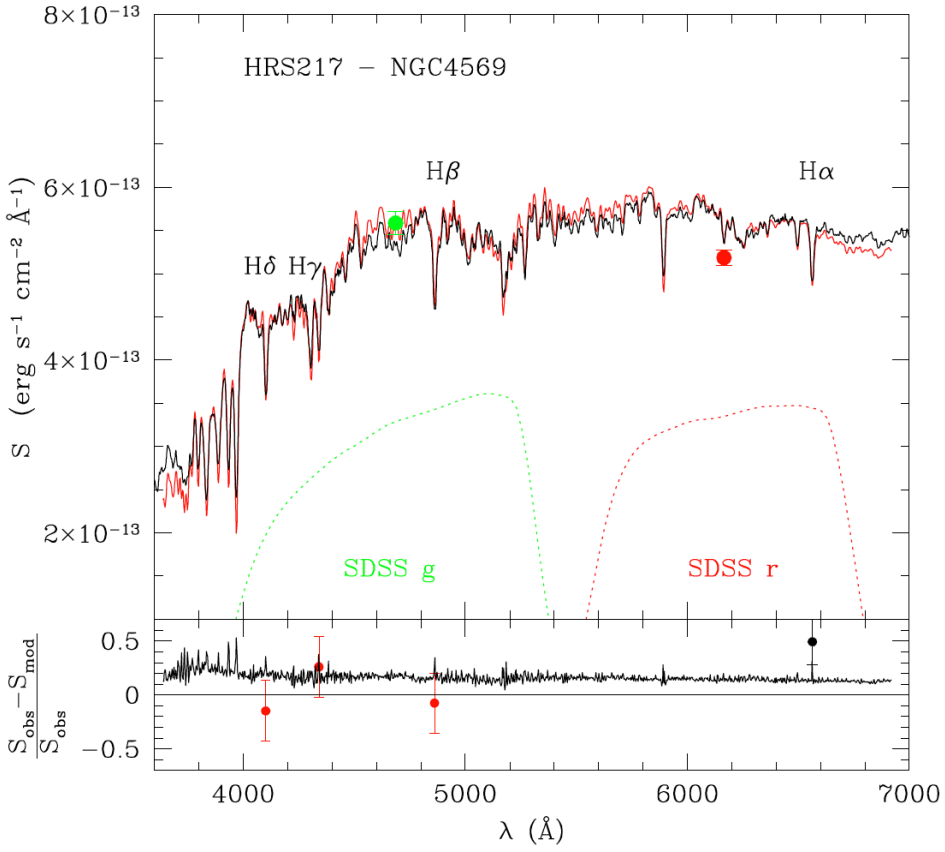
Important to use photometric bands and spectral indices sensitive to the youngest stellar populations



Boselli et al 2016b

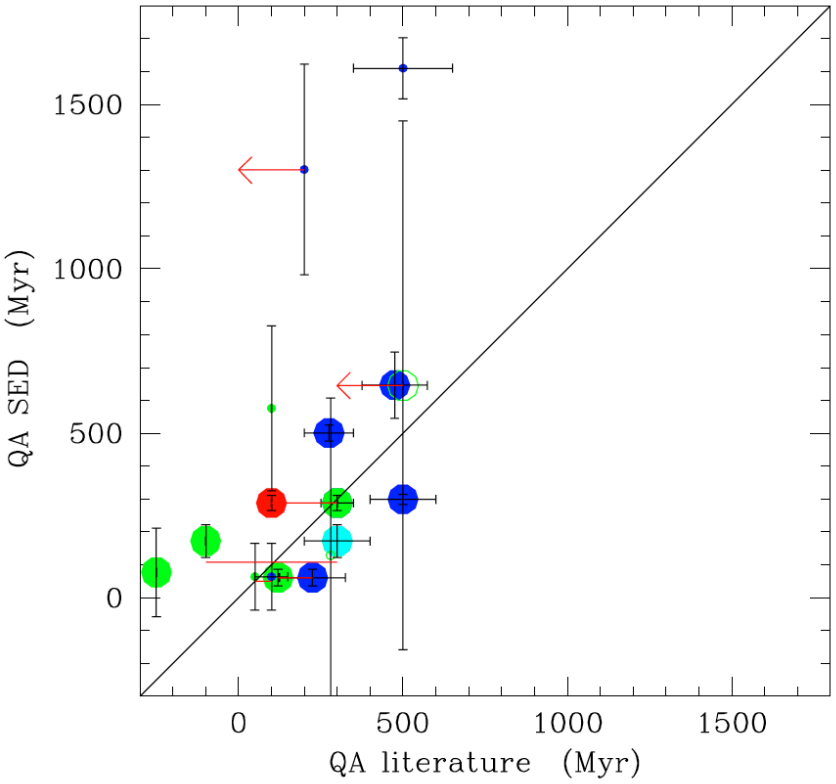
USE OF CIGALE ON NGC 4569

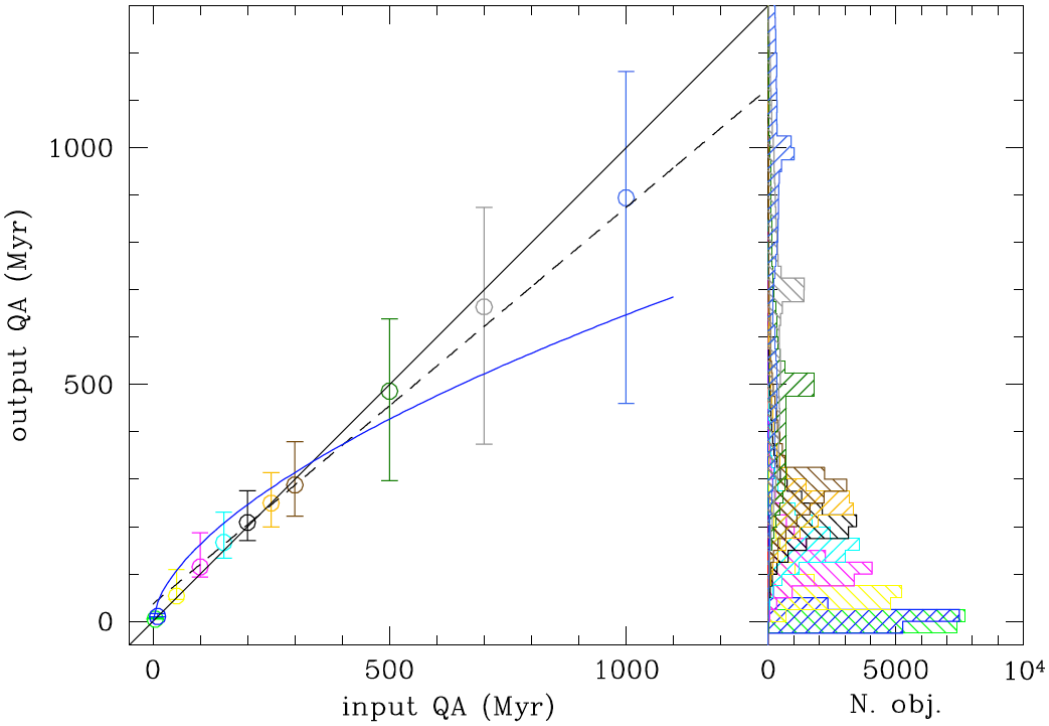




The truncated SFH (black) better fits the observed SED than the untruncated one (blue)

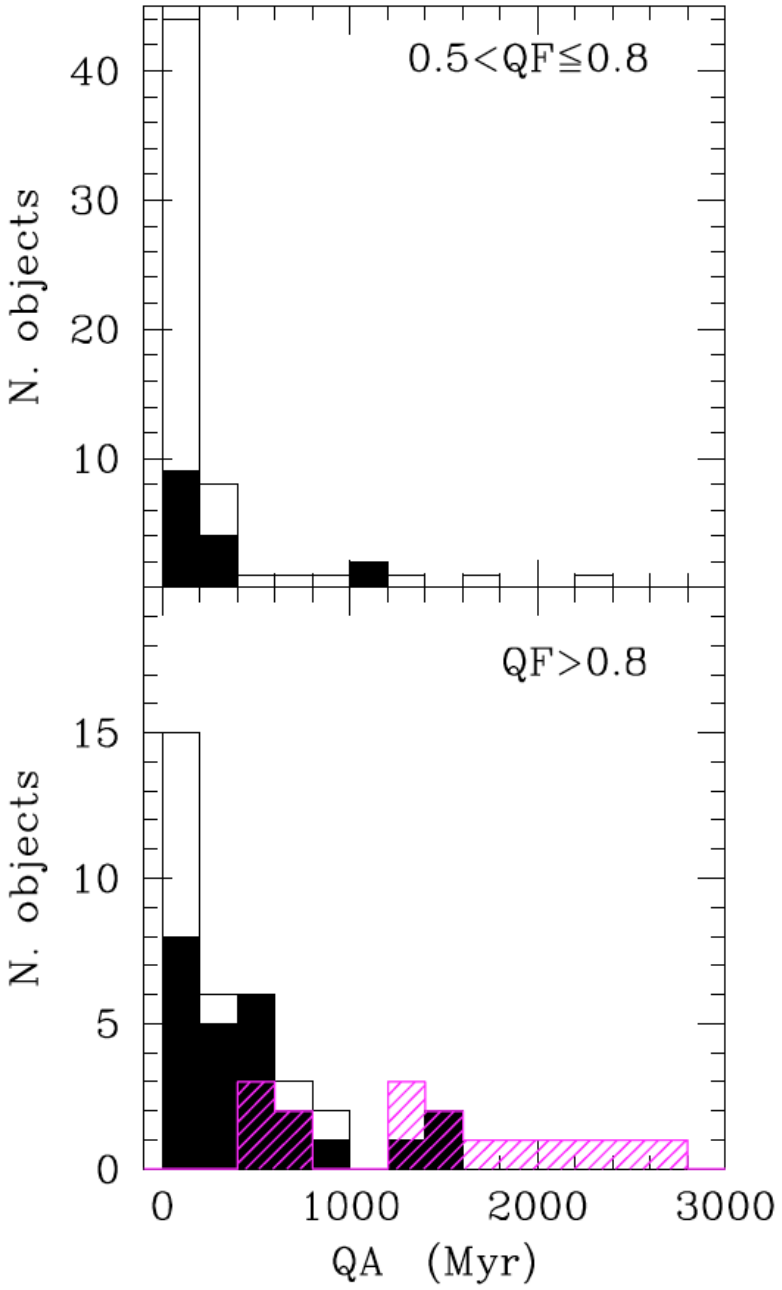
DETERMINATION OF THE QUENCHING TIMESCALE WITH CIGALE





The comparison with known galaxies or tests with mock catalogues show that QA are reliable for QF>0.8 (QF>0.5)

DETERMINATION OF THE QUENCHING TIMESCALE WITH CIGALE



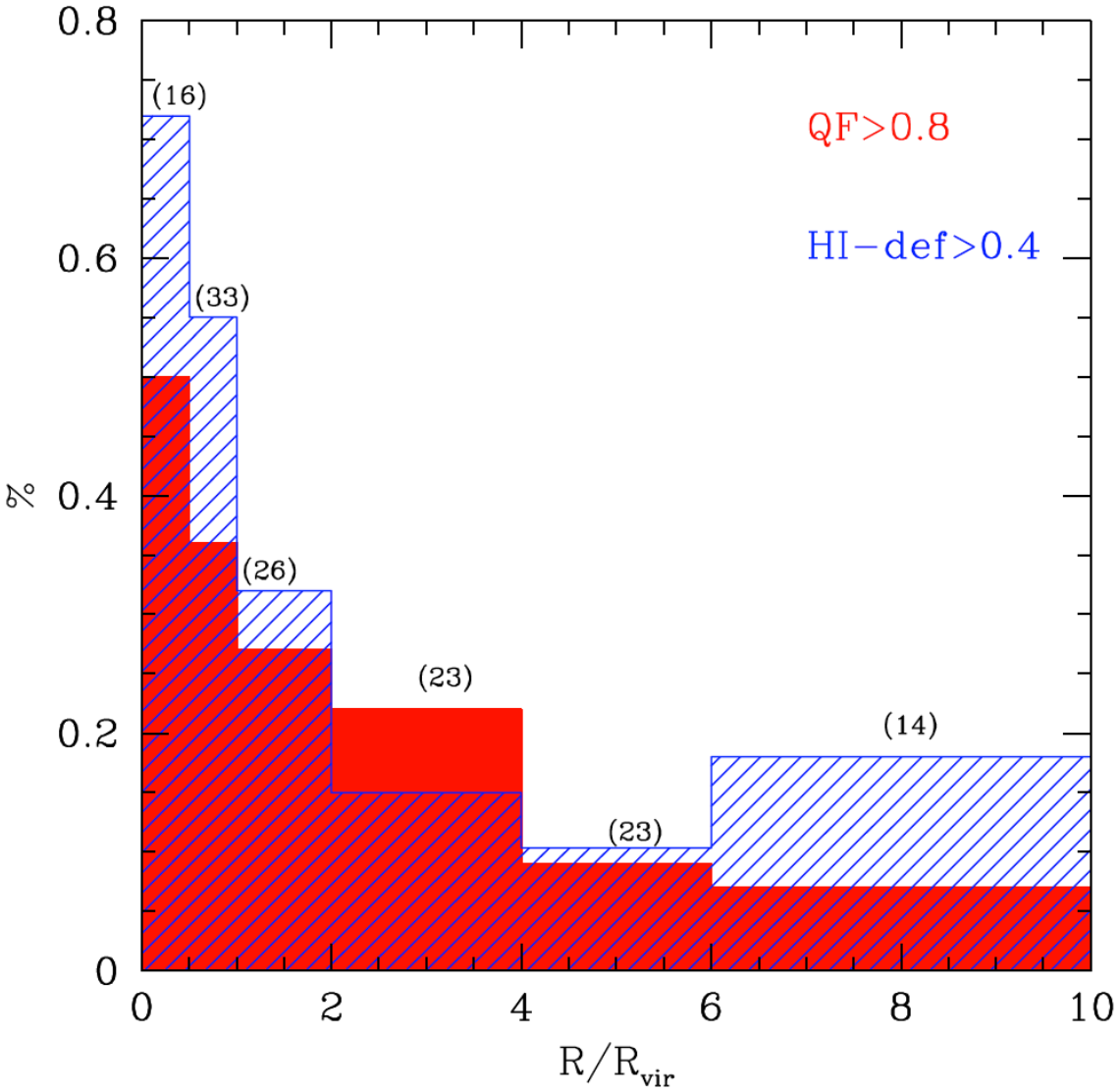
The median quenching age of Virgo cluster galaxies is:

135 Myr for late-type with 0.5<QF<0.8

250 Myr for late-type with QF>0.8

1.3 Gyr for early-type (QF=1)

RELATIONSHIP BETWEEN QUENCHING PROCESS AND RADIAL DISTANCE FROM THE CLUSTER CORE

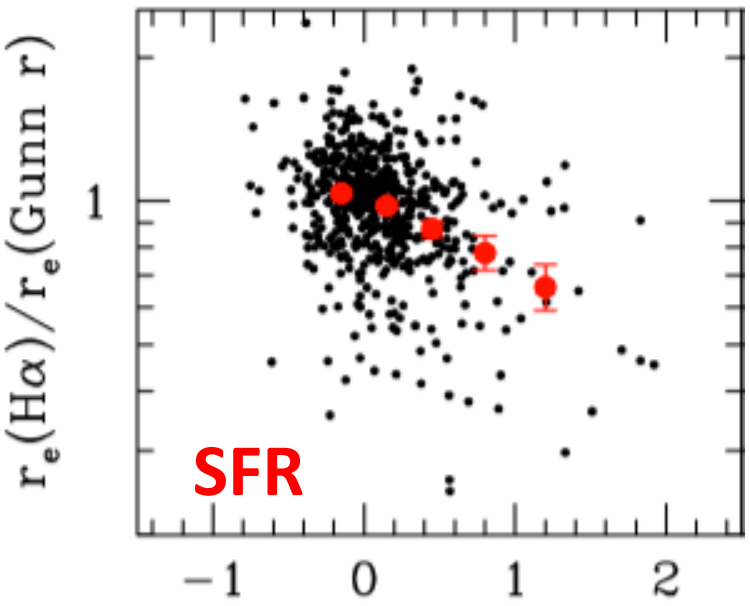


The fraction of quenched galaxies scales radially as the fraction of HI-deficient objects

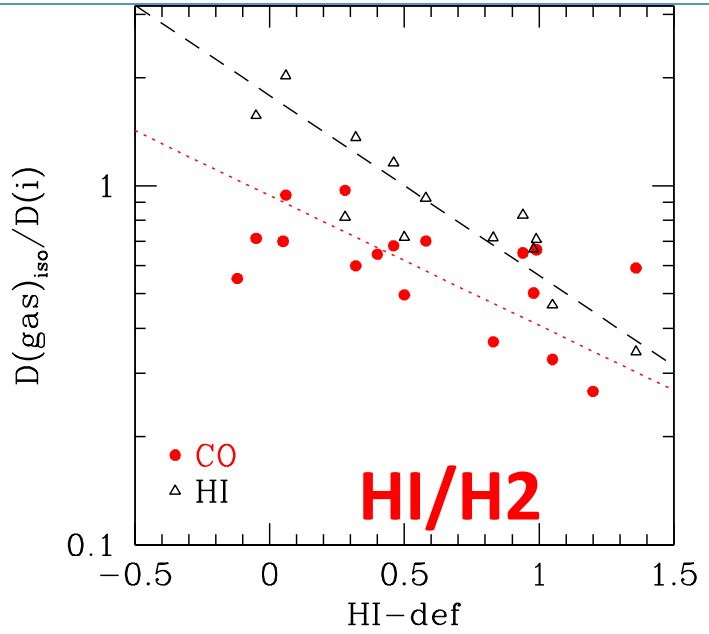
Boselli et al 2016b

DISC TRUNCATION

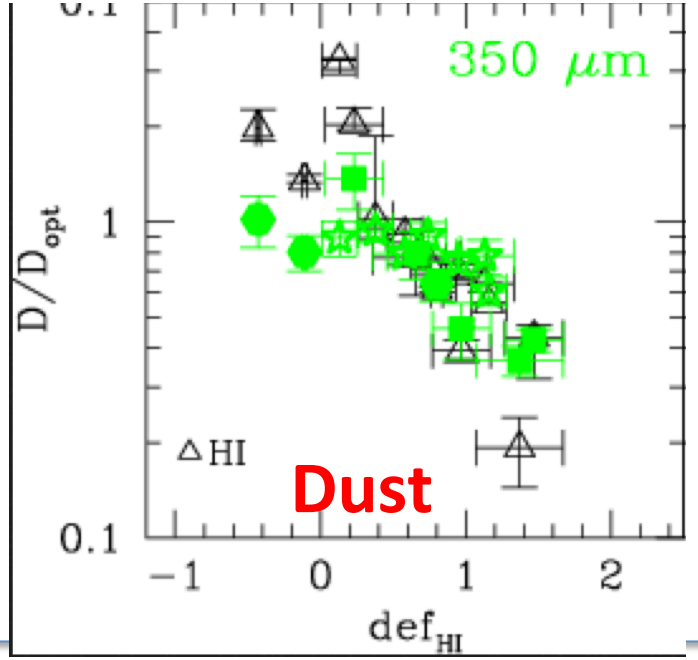
Fossati et al 2013



HI-def



Boselli et al. 2014



Cortese et al. 2010

HI: Warmels 1986; Cayatte et al 1990,94

SFR: Koopmann & Kenney 2004ab, Boselli & Gavazzi 2006

Dust: Cortese et al 2010, 2012

H_2: Fumagalli et al 2009

VESTIGE

A Virgo Environmental Survey Tracing Ionised Gas Emission

A CFHT Large Program 2017-2019

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VESTIGE

A Virgo Environmental Survey Tracing Ionised Gas Emission

A CFHT Large Program 2017-2019

- 50 allocated night with MegaCam (1^ox1^o) to cover the Virgo cluster within 1 virial radius (~ 104^{o2})

- Integration time: 2 h in the Hα filter (λ = 6563 Å, Δλ = 106 Å; T = 93%), 12 min in *r* (for the stellar continuum subtraction)

- Sensitivity:
  $f(H\alpha)$ ~ $2\text{x}10^{-17}$ erg sec^{-1} cm^{-2} (5σ) for point sources
  $\Sigma(H\alpha)$ ~ $2\text{x}10^{-18}$ erg sec^{-1} cm^{-2} $arcsec^{-2}$ (2σ) for extended sources

- Image quality : median seeing 0.65 arcsec in the narrow-band filter

NGC 4569 – RAM PRESSURE STRIPPING

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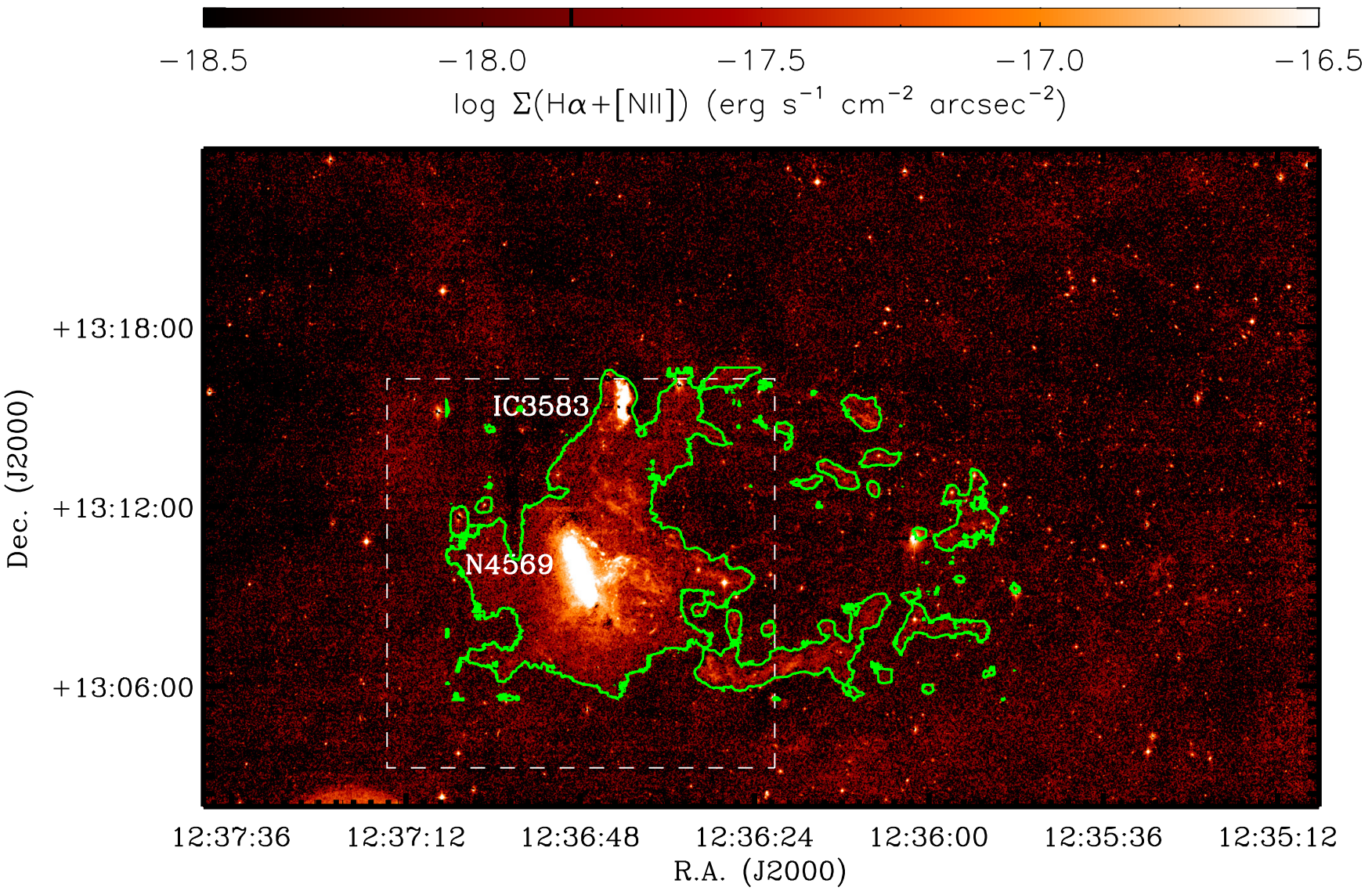
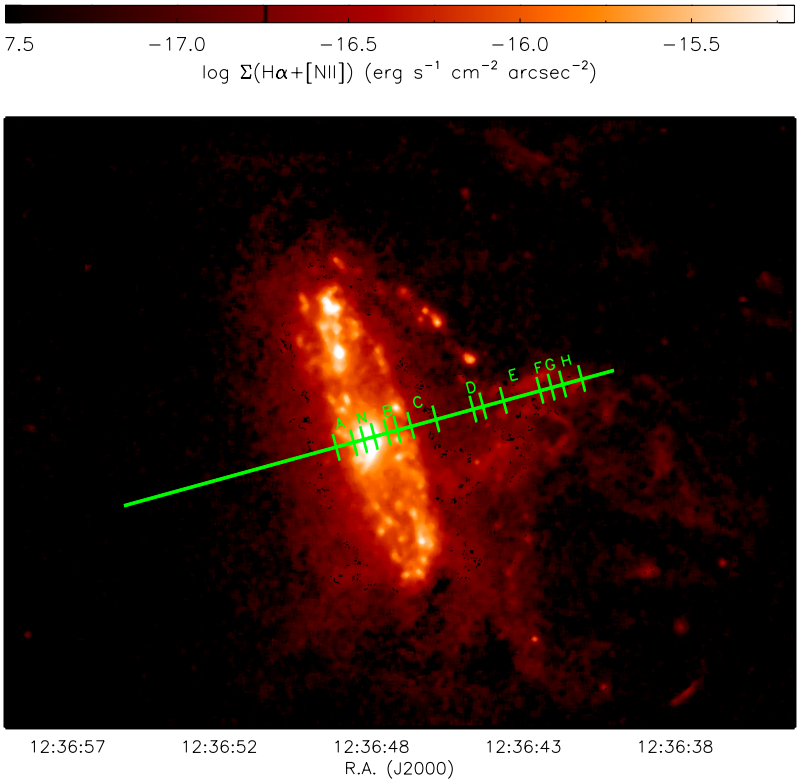
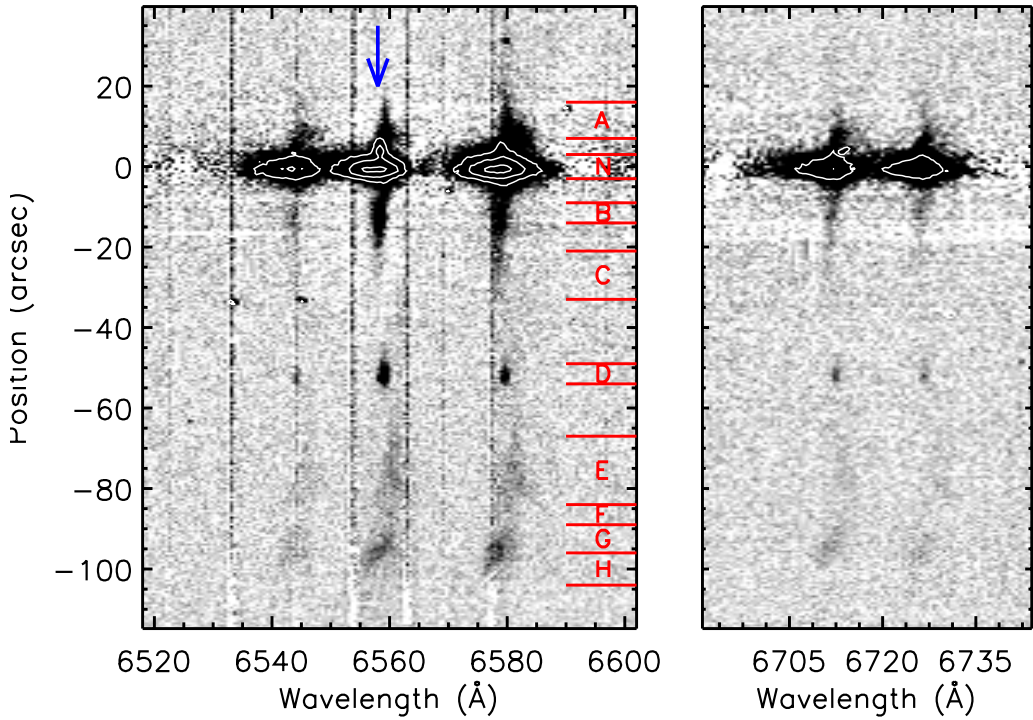


Contours : $\Sigma(H\alpha) = 10^{-18}$ erg sec^{-1} cm^{-2} arcsec^{-2}

Boselli et al 2016

NGC 4569 – RAM PRESSURE STRIPPING



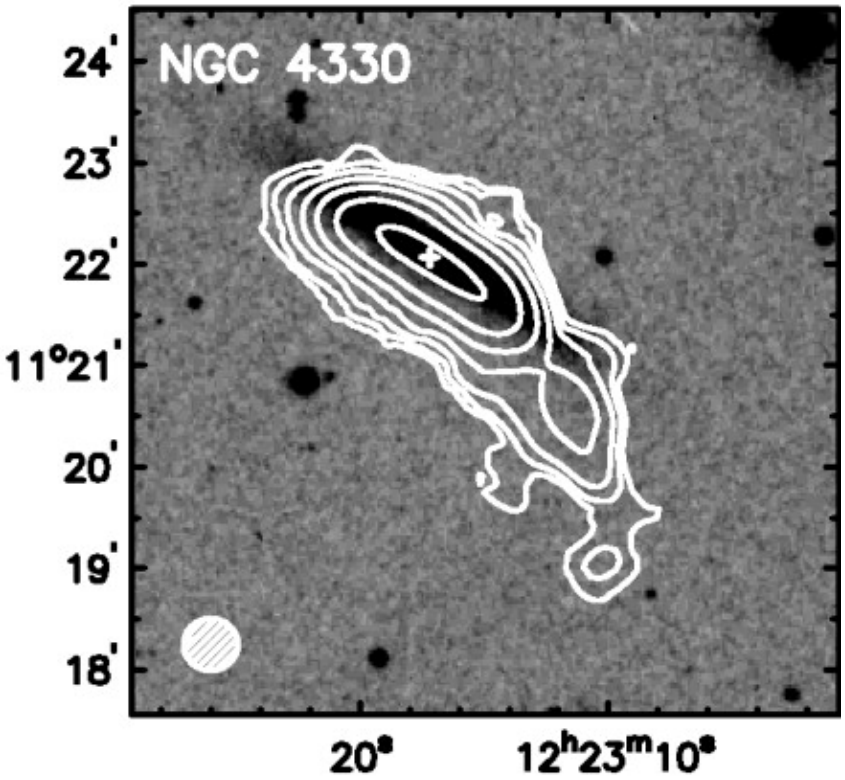


- The mass of the ionised gas in the tail is a large fraction of the stripped HI
- The gas is ionised in the tail by other processes than star formation
- The mass of the gas expelled by the nuclear outflow is only ~ 1% than that removed by ram pressure

Boselli et al 2016

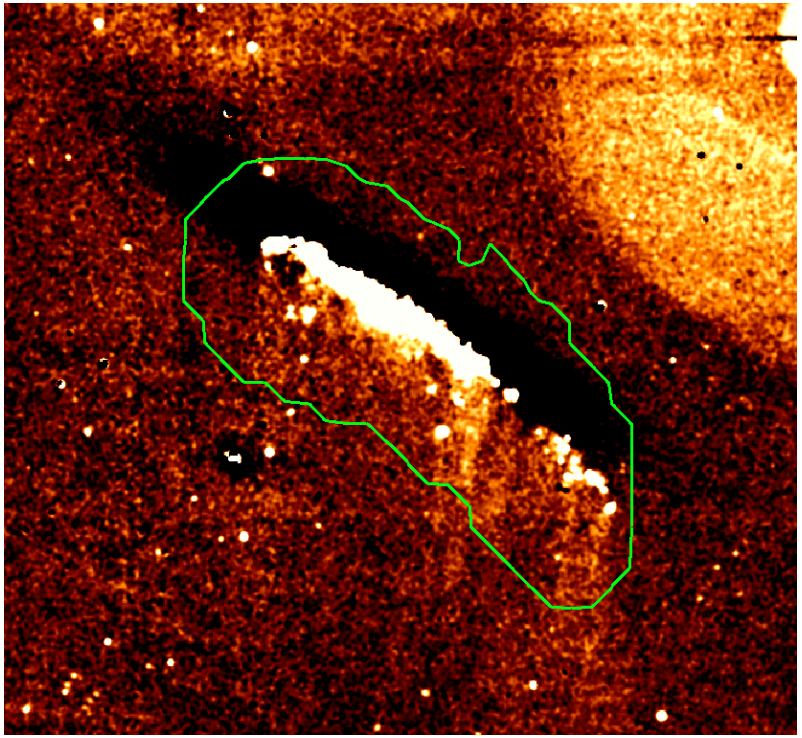
NGC 4330 – RAM PRESSURE

HI VLA



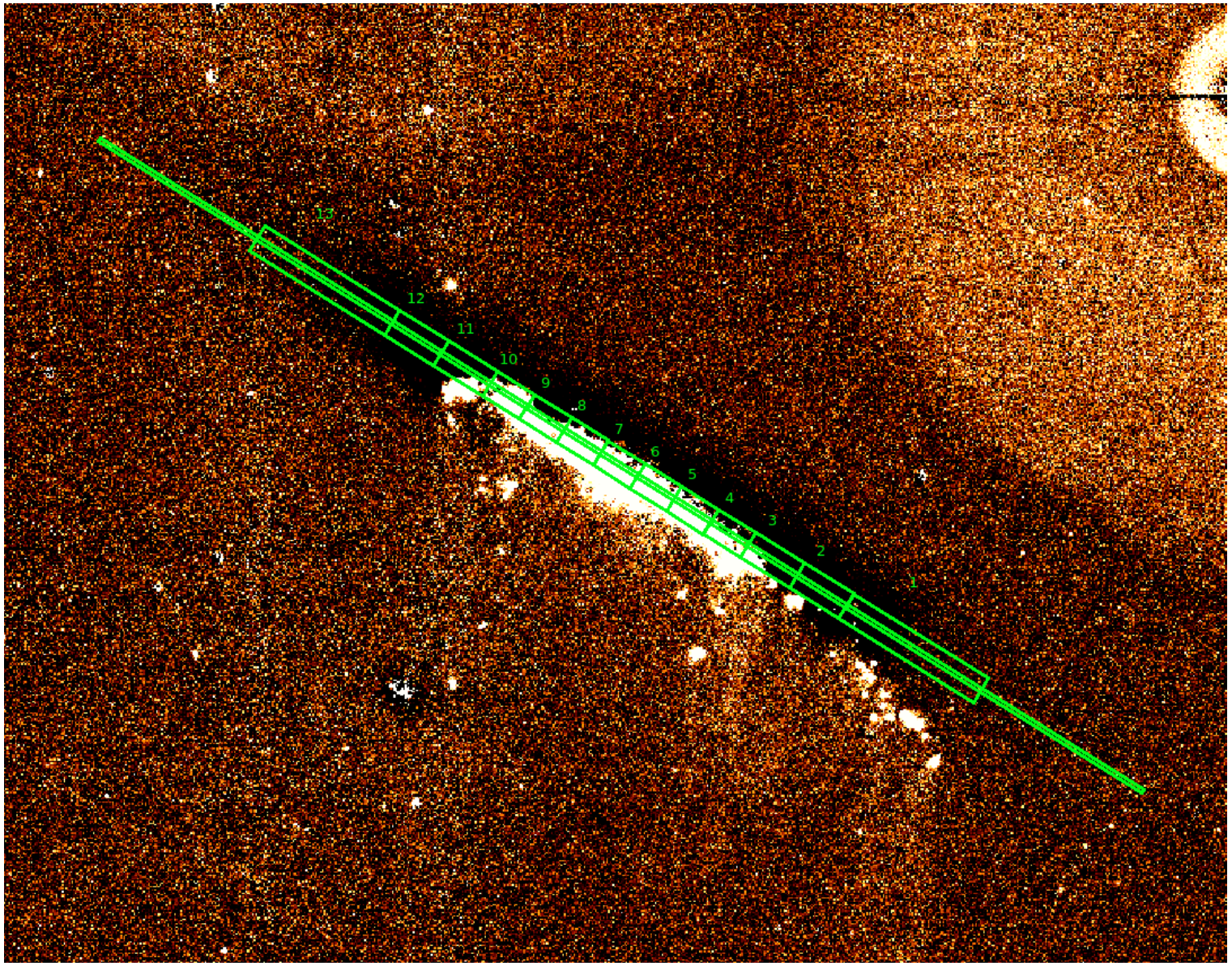
Chung et al 2007

HI contour over Hα



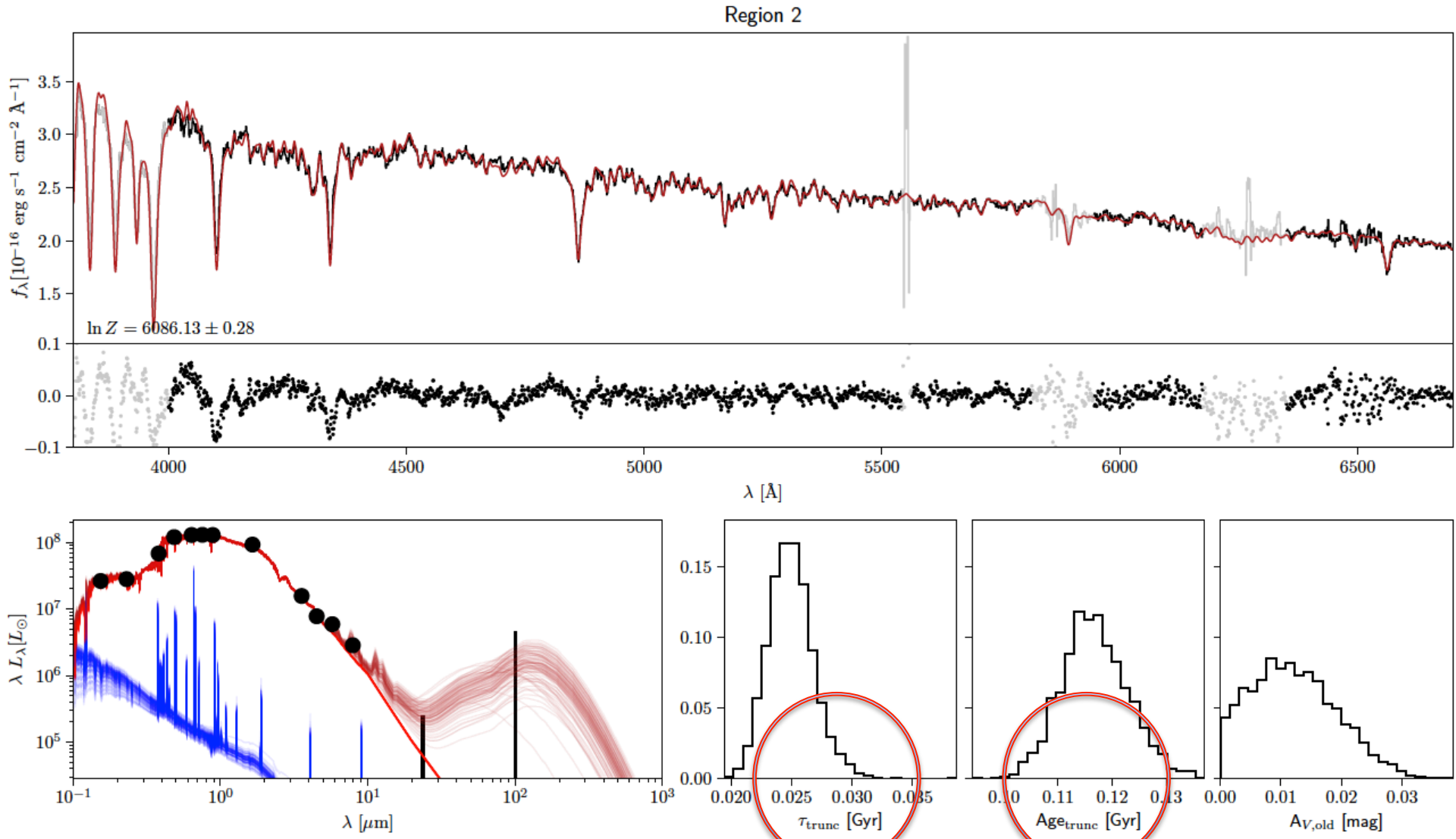
Fossati et al 2017

NGC 4330 – RAM PRESSURE



Fossati et al 2017

NGC 4330 – RAM PRESSURE



Fossati et al 2017

CONCLUSIONS

- The quenching process in clusters like Virgo (~ 10^{14} Mo; σ = 800 km s^{-1}) is rapid and efficient within R_{200}

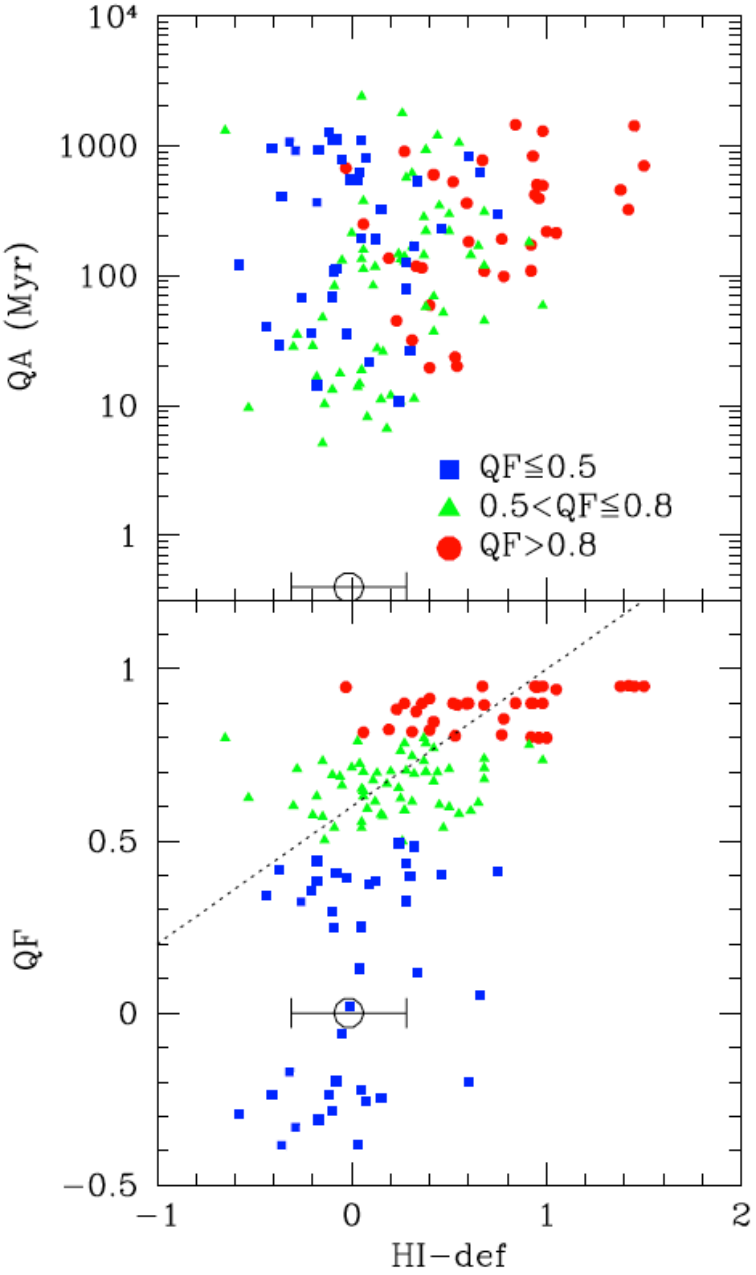
- Spiral galaxies in Virgo have truncated HI, H_2, dust, and SF discs

- There are several examples of galaxies in Virgo with tails of HI or ionised gas

↓

ram pressure stripping is the dominant process

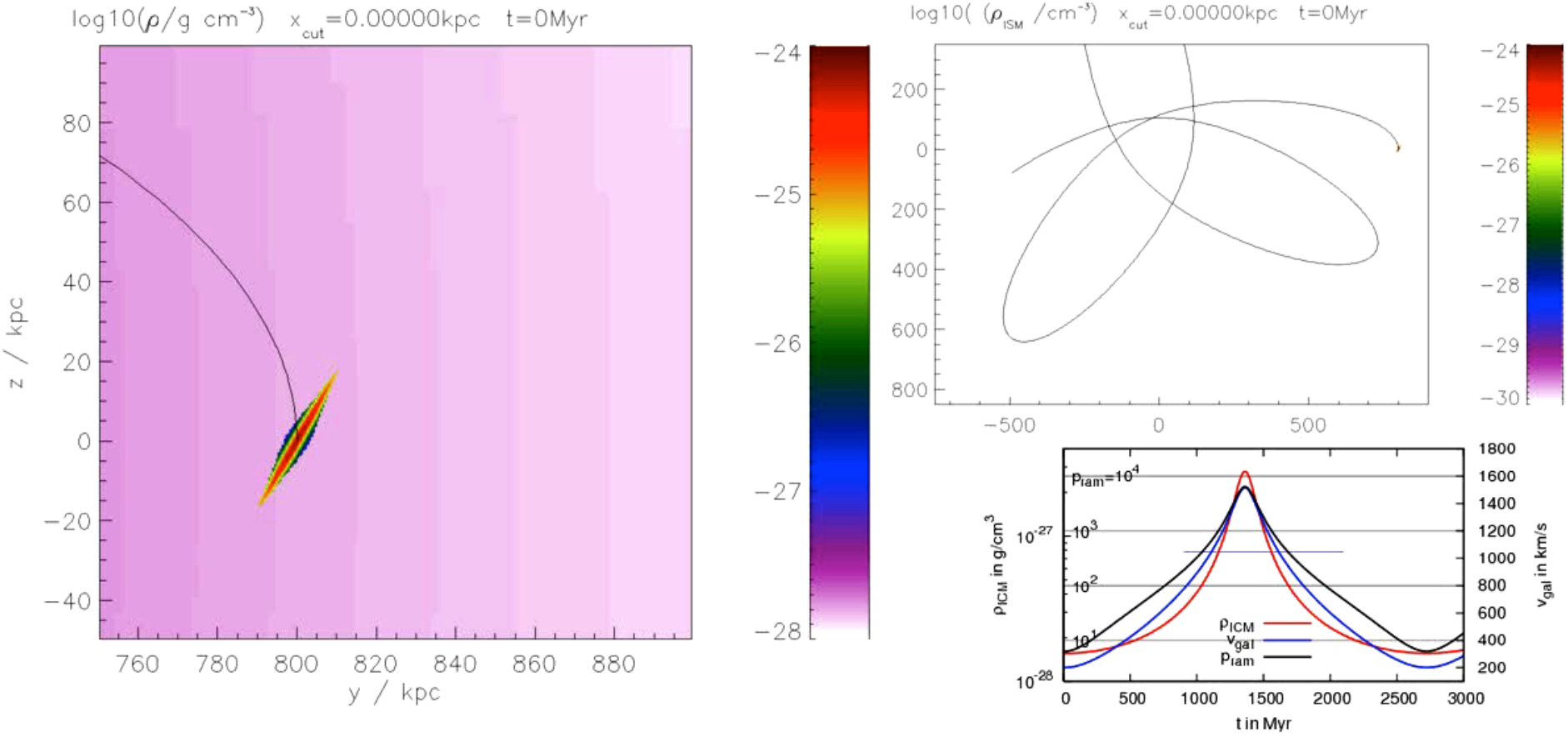
RELATIONSHIP BETWEEN QUENCHING PROCESS AND GAS CONTENT



The quenching age and the quenching factor are related to the total gas content of galaxies

Boselli et al 2016b

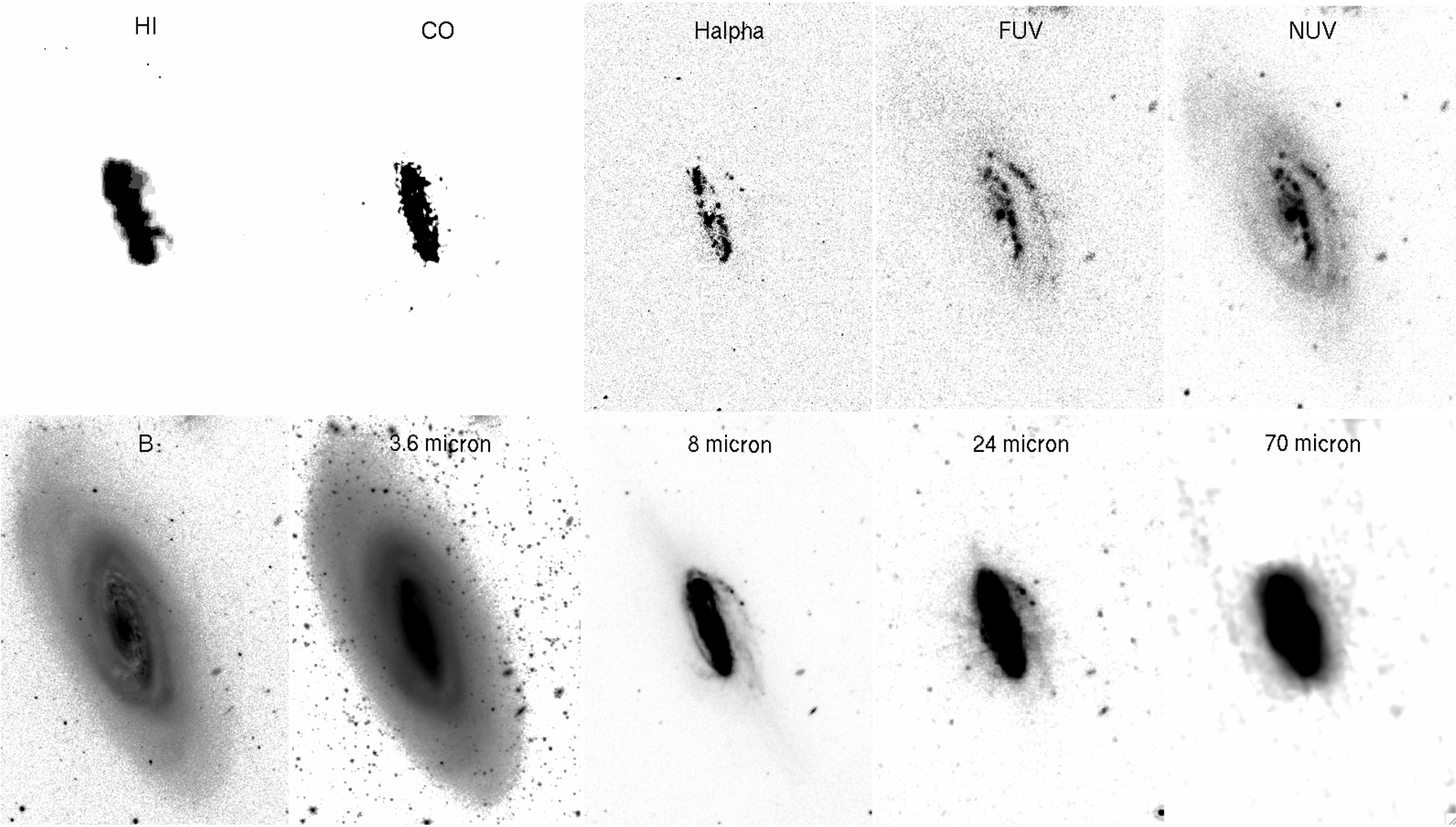
RAM PRESSURE



Roediger et al 05, 06, 07, 12, 13; Tonnesen et al 07, 09, 10, 11, 12, 14; Smith et al 12, 13; Bekki 09, 11, 14; Kronberger et al 08; Kapferer et al 08; Kawata 08; McCarthy et al 08

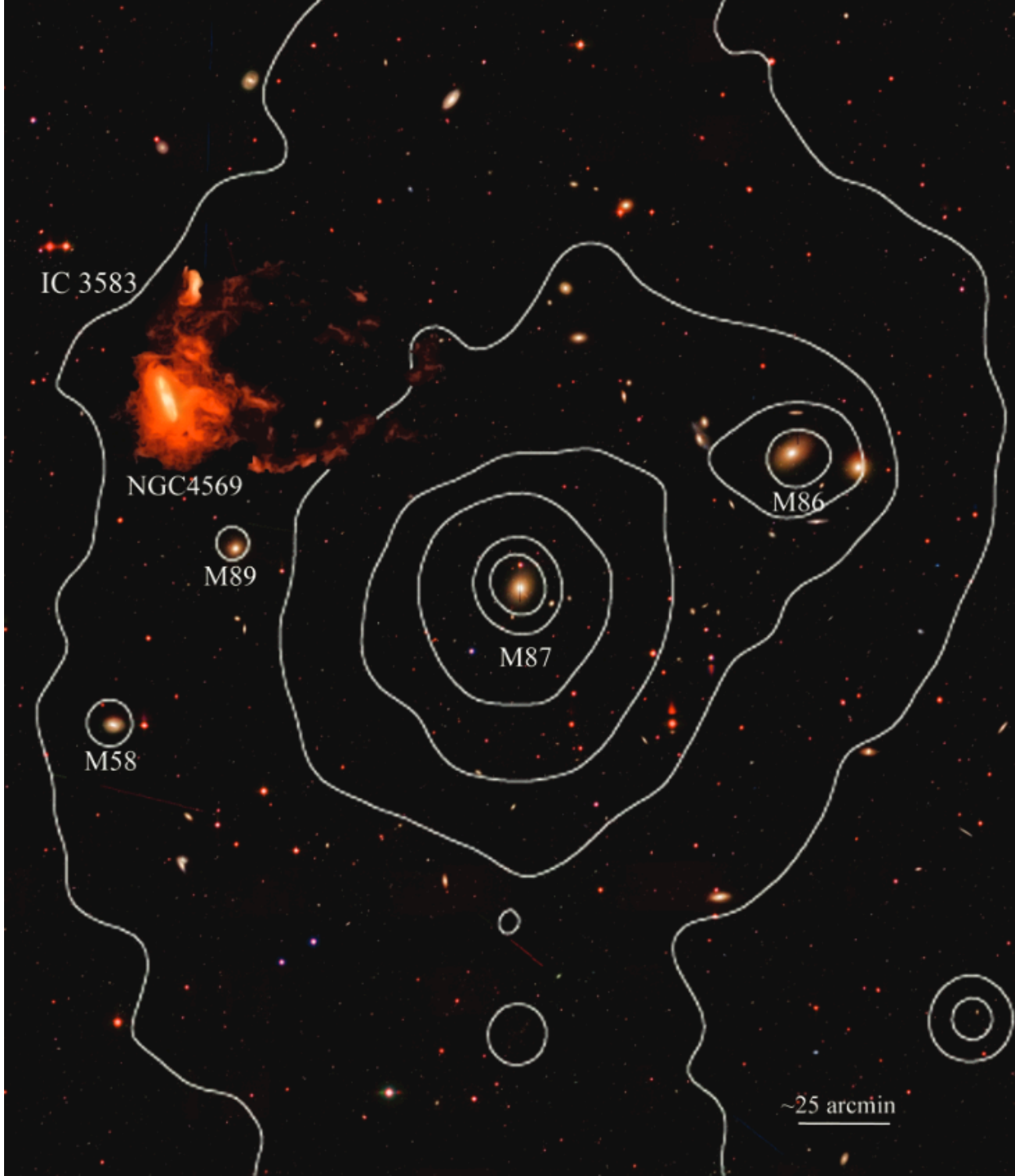
COSMOLOGICAL SIMULATIONS

FIRST TEST: NGC 4569



Boselli et al 2006

NGC 4569 (Halpha)



Boselli et al 2016

SDSS, GALEX, GAMA + SIMULATIONS STATISTICAL SAMPLES

Slow (a few Gyrs) quenching process → starvation (McGee et al 09, Wolf et al 09, von der Linden et al 2010, de Lucia et al 12, Wheeler et al 14, Taranu et al 14, Haines et al 15, Paccagnella et al 16).

Bimodal evolution, first slow then rapid → pre-processing

(Wetzel et al 12,13, Muzzin et al 12, Wijesinghe et al 12).

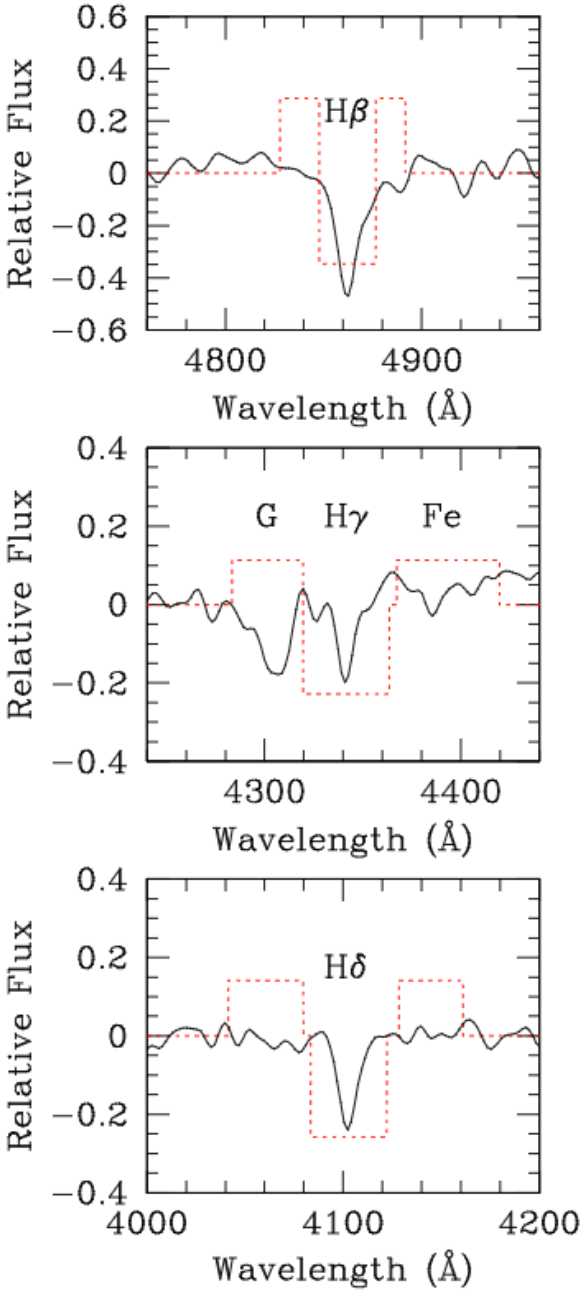
Rapid → ram pressure

(Oman & Hudson 2016)

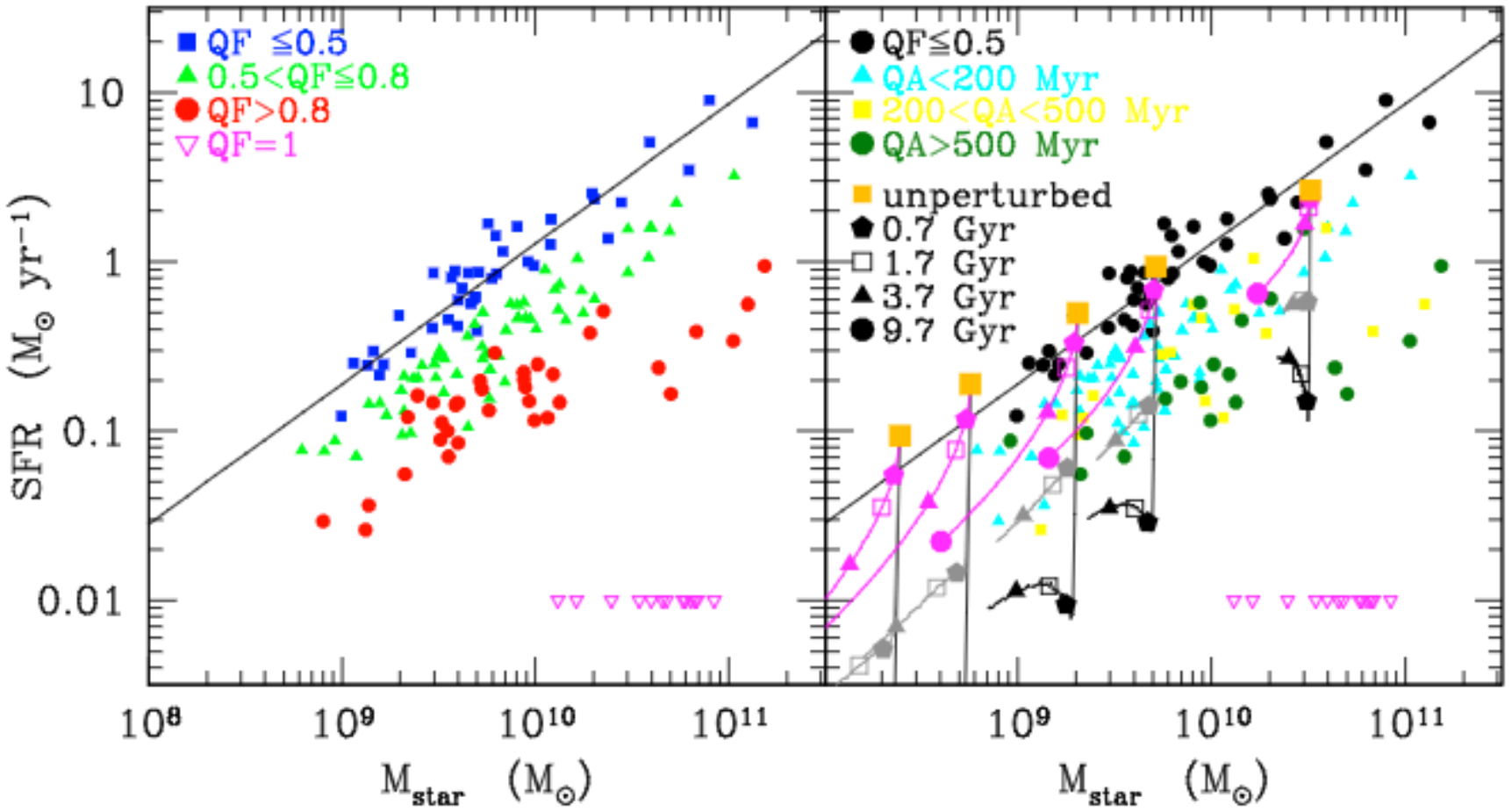
SED FITTING USING SPECTRAL LINE INDICES

Halpha emission line -> N ionising photons (by integrating the SED < 912 A)

Balmer absorption lines : measured using ad-hoc pseudofilters (Lick definitions)



RELATIONSHIP BETWEEN QUENCHING PROCESS AND DISPERSION IN THE MAIN SEQUENCE



The dispersion observed in the MS in dense environments is due to the quenching process