Star formation in hostile environments: galaxy clusters and groups

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Summary

- Current topics in galaxy clusters
- Star-formation distribution in the CPPS

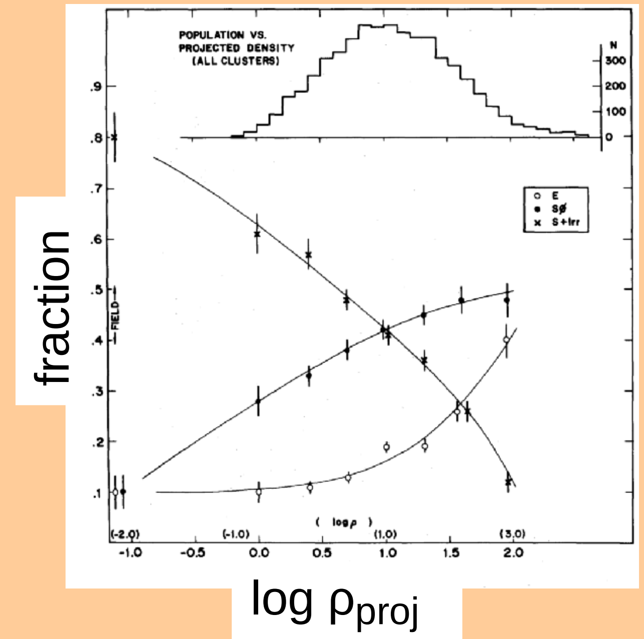
  (Hernández-Fernández et al. 2014)
- Star-forming compact groups

  (current work)

Star formation in hostile environments: galaxy clusters and groups

Dressler 1980: Morphology-density relation T-Σ

"… the more fundamental correlation of galaxy morphology is with galaxy mass, and that the morphology-density relation is basically an expression of the prevalence of more massive galaxies in regions of higher galaxy density" (**Dressler 2011**, see also Weinmann et al. 2006)



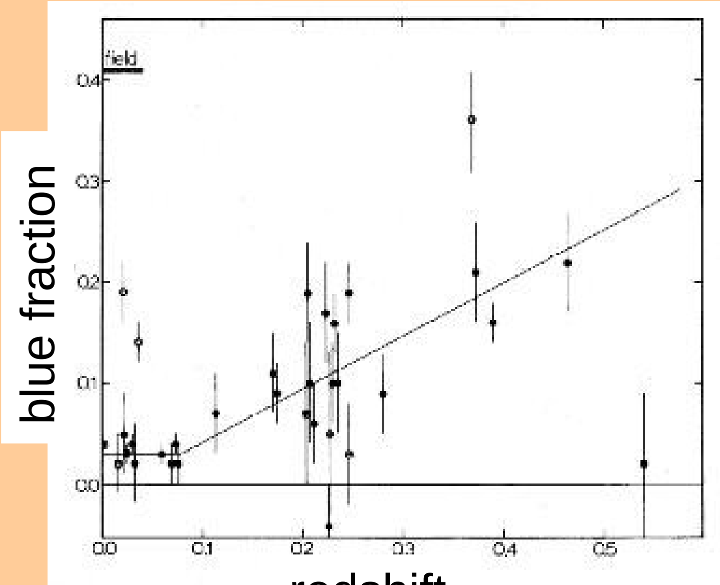


FIG. 3.—Blue galaxy f… filled circles, compact clusters (C ≥ 0.40); open circles, irregular clusters (C < 0.35); dotted circles, intermediate clusters (0.35 ≤ C < 0.40).

Butcher & Oemler 1984: First cosmic star-formation history

Andreon et al. 2006: there is no differential cluster galaxy evolution from z~0.35

Haines et al. 2013: Butcher-Oemler effect including FIR since z~0.3 can be attributed to a combination of:

- ~1.5 × decrease in number density of star-forming cluster galaxies with a
- ~3 × decline in the average SSFRs of them =

= (2/3) steady cosmic decline + (1/3) accelerated decline by cluster environment

Star formation in hostile environments: galaxy clusters and groups

• **Saintonge 2008, Brodwin 2013**

z ~ 1.5 represents a transition redshift for star formation in clusters (Santos+2014)

z >1.5: an active era of cluster star formation at earlier times.

e.g. the fraction of star-forming cluster members increases toward the cluster centers.

• Qualitative differences between

BCG and the rest of cluster galaxies

Central and satellite galaxies

Dynamics, luminosity function, colors, etc.

Peng 2010 and 2012:

- Bright **central galaxies** becomes passive by a **mass-quenching** mechanism
- While **satellite galaxies** are quenched by an **enviroment-quenching** process.

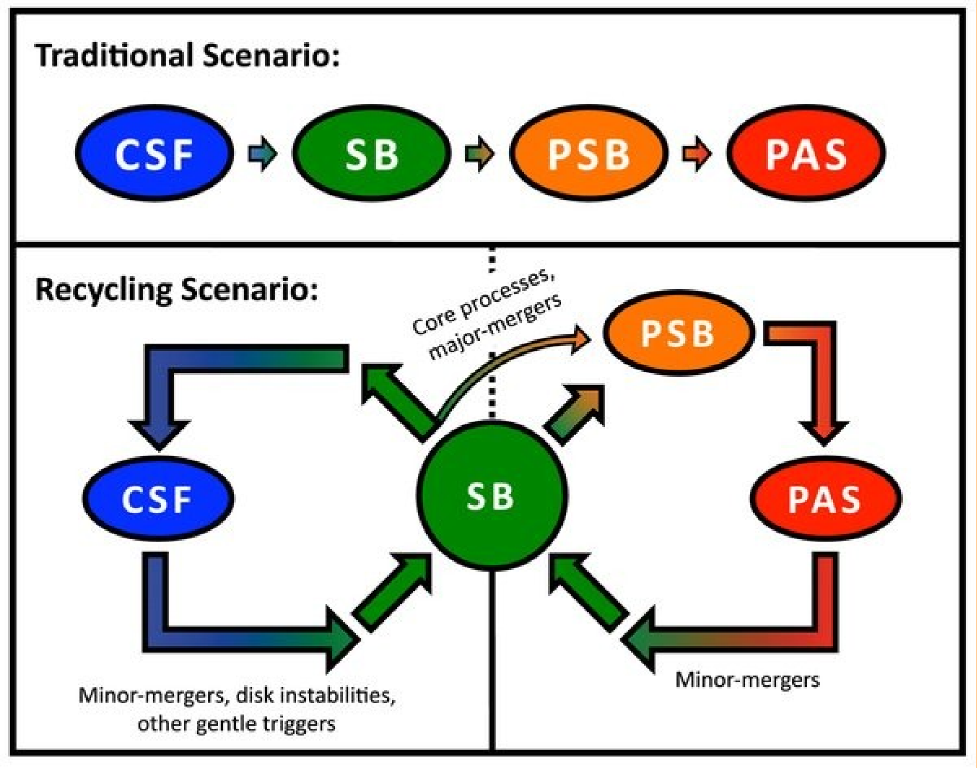
Star formation in hostile environments: galaxy clusters and groups

- **Double cycle scenario**

(Dressler et al 2013)
The most of the starburst population is **not** a previous phase of poststarbursts,
it is requiered a recycling pathway between starburst and normal star-forming galaxies.

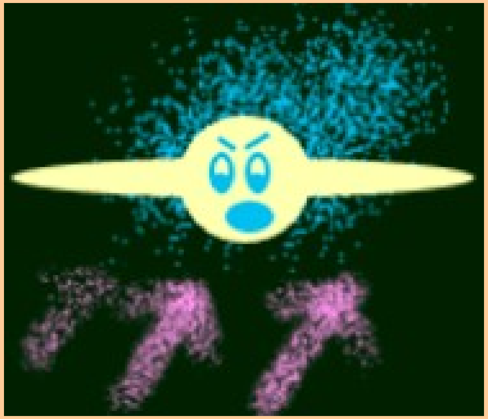
- **Preprocessing scenario**

(e.g. Hou et al. 2014)

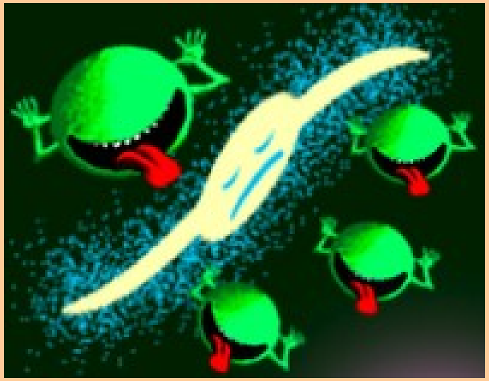


Summary of environmental processes

galaxy gas stripping
(ICM – ISM)
$P_{ram} = \rho_{ICM}(r) \times V^2$
$P_{ram} > \Pi_{gal}$ anchor pressure



galaxy harrassment
(galaxy-galaxy and
galaxy-CDMH
interacitions)



galaxy mergers and strong
galaxy interaction
(galaxy-galaxy interacions)

starvation
strangulation
suffocation
(CDMH –
cold halo gas)

Cartoons by Aeree Chung

Summary of environmental processes

Radial range

- Small radii
  ($r < r_{vir}$)
  - Gas stripping
  - Starvation – Cluster Halo
- Large radii
  ($r > r_{vir}$)
  - Starvation - ICM
  - Harassment

Kinematical conditions

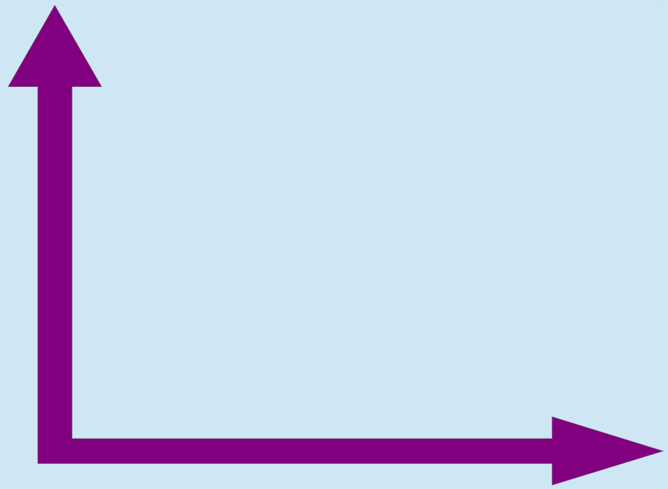
- High velocity
  ($v >\sim 500$ kms^{-1})
  - Gas stripping
  - Harrasment
- Low velocity
  ($v \sim< 500$ kms^{-1})
  - Galaxy mergers

More environmental conditions and galaxy properties determining the intensity of environmental processes in ***Hernández-Fernández et al. 2012a,b***

The CPPS:
Cluster Projected Phase-Space

$s^{\sim} = (c\ \Delta z) / \sigma_c$

is the cluster-frame line-of-sight (l-o-s) velocity $c\Delta z$ normalized by the rest-frame cluster velocity dispersion σ_c,



$r^{\sim} = R_P / r_{200}$

is the cluster-centric projected radius R_P normalized by the virial radius r_{200}

The CPPS contains these two prominent observables, which strongly **determine the intensity of the different environmental processes**.

It is crucial to study the distribution of the different galaxy populations in this phase-space, in order to assess the specific influence of each process in the build-up of different galaxy populations
(e.g. Diaferio et al. 2001)

The cluster sample

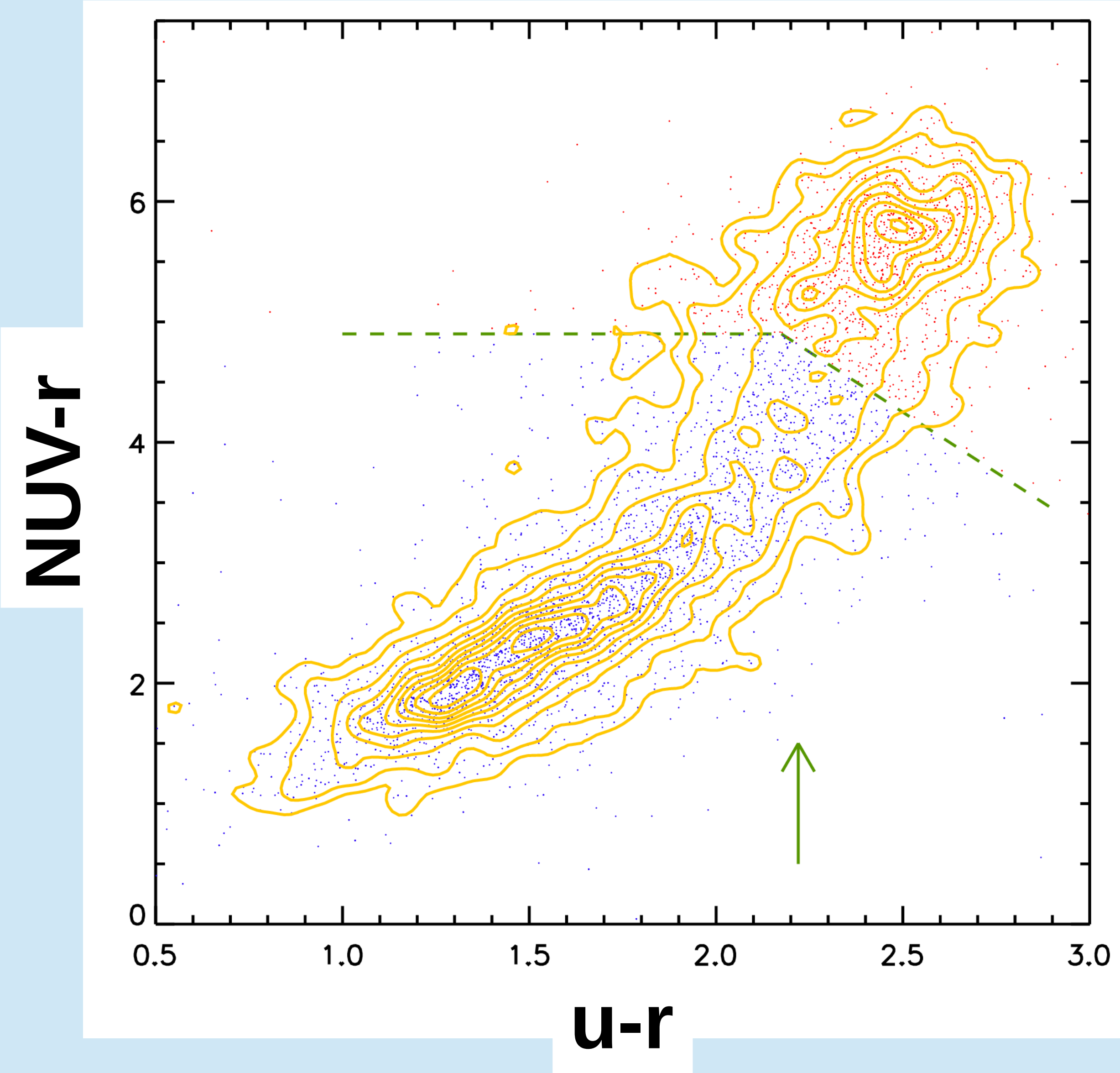
- *The set of galaxy clusters under study in this work is taken from the sample of cluster galaxies extensively described in Hernández-Fernández, Iglesias-Páramo & Vílchez (2012a).*

- *This sample consists of **nine nearby ($z < 0.05$) and massive ($\sigma > 500$ km s^{-1}) clusters**.*

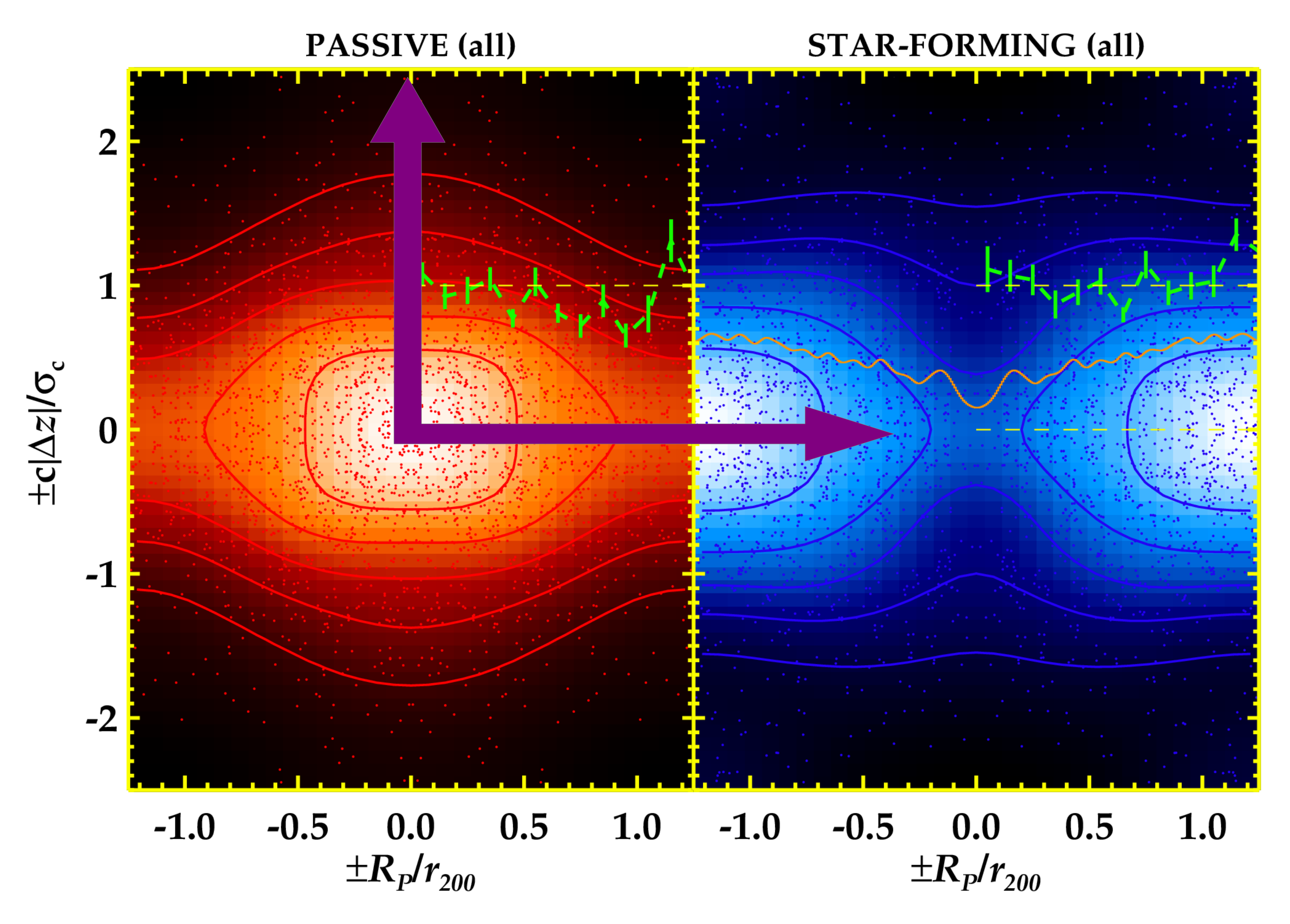
- *The galaxy sample spans an r'-band luminosity range corresponding to $-23 \lesssim Mr' \lesssim -18$ **(no dwarf galaxies)***

- *The selection of this sample was constrained by the condition that it be observed by the Data Release 6 of the MGS of **SDSS** and the AIS (All Imaging Survey) of **GALEX** mission.*

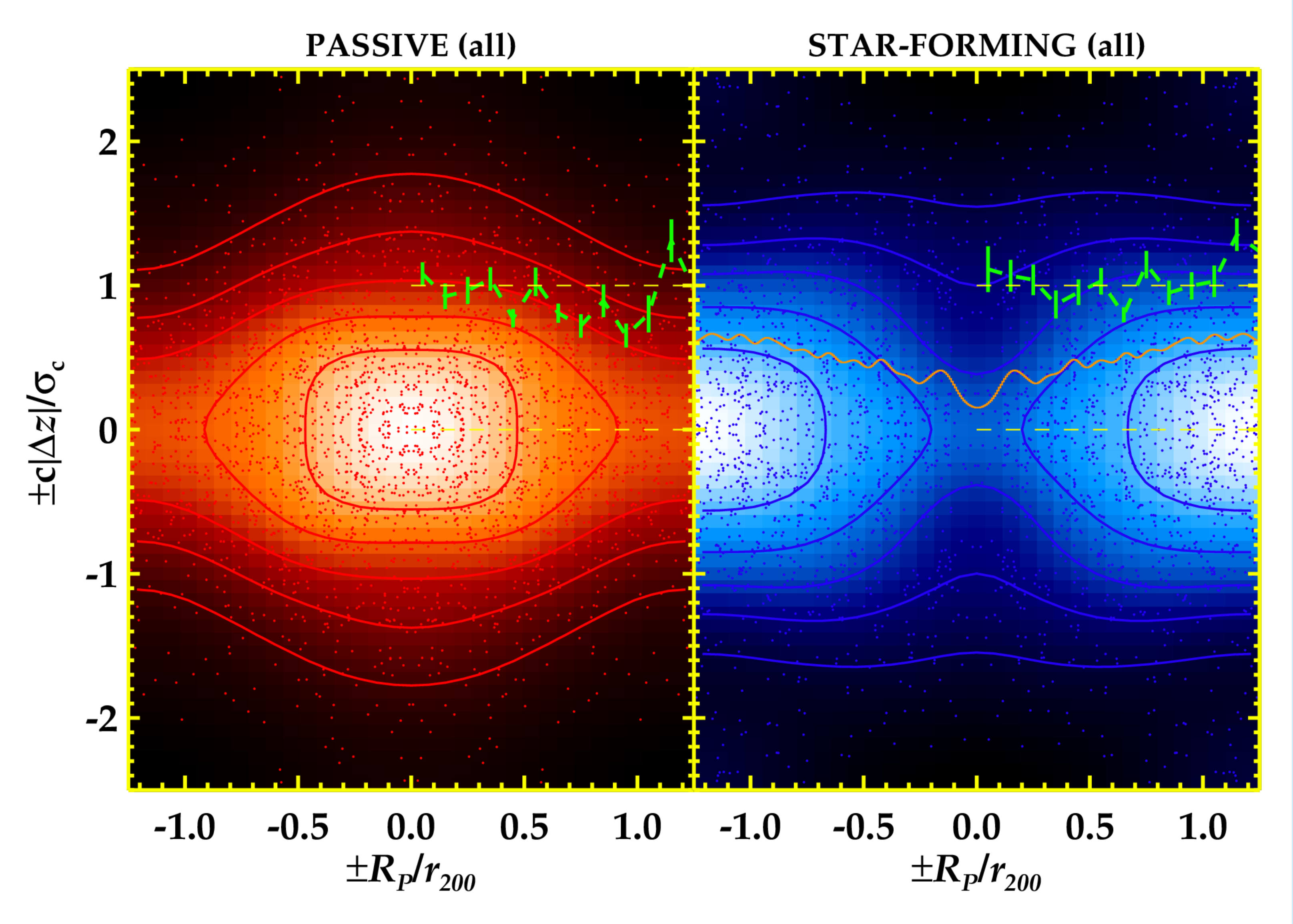
Distribution in the CPPS



Distribution of star-formings and passives in the CPPS

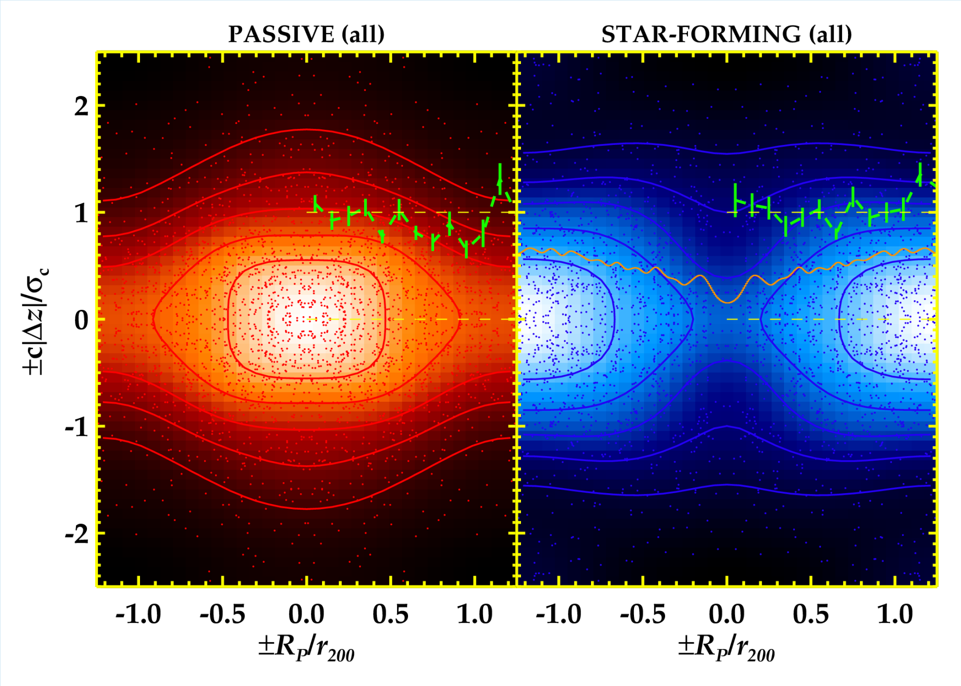


Distribution of star-formings and passives in the CPPS



- The passive population is concentrated around a unique maximum in the CPPS clearly centred at (r,s)~(0,0) as it was found by previous works in the literature.

- The isocontours present a characteristic ‘boxy’ for inner isocontours while intermediate ones show a ‘peanut’ shape
→ centering uncertainty



- The star-forming population presents a maximum around (r~0,s~1) showing an evident preference for environments outside the virial region and with lower l-o-s velocities.

- the non-negligible fraction of star-forming galaxies at the projected centre of clusters are mainly those galaxies with low l-o-s velocities

- the regions of high velocities near to the center are virtually devoid of star forming galaxies → gas stripping ...

Stripping modulation of star-forming distribution

Including the effects of the ram-pressure stripping in the frame of the CPPS ...

Ram-pressure:

$P_{ram} = \rho_{ICM}(r) \times v^2$

King radial profile for ICM density

$$\rho_{ICM}(r) = \rho_0 \left[1 + \left(\frac{r}{R_c}\right)^2\right]^{-(3/2)\beta}$$

$$\sim \rho_0 \left[1 + (c\bar{r})^2\right]^{-(3/2)\beta} = \rho_0\, \bar{K}(\bar{r};\, c, \beta) = \rho_0\, \bar{K}(\bar{r})$$

$$\left.\begin{aligned} P_{ram} = \rho_{ICM} \times v_{gal}^2 \sim \rho_0 \bar{K}(\bar{r}) \times \bar{s}^2 (3\sigma_c^2) \\ \Pi_{gal} \sim \Pi_{MW} \end{aligned}\right\}$$

$$\Longrightarrow \eta = \frac{P_{ram}(\bar{r}, \bar{s})}{\Pi_{MW}}; \quad \bar{s}^2\, \bar{K}(\bar{r}) = \eta \left(\frac{\Pi_{MW}}{3\rho_0 \sigma_c^2}\right)$$

intensity of ram pressure stripping
$\eta = P_{ram} / \Pi_{gal} = \eta\,(r, v)$

… stripping occurs for $\eta \geq 1$

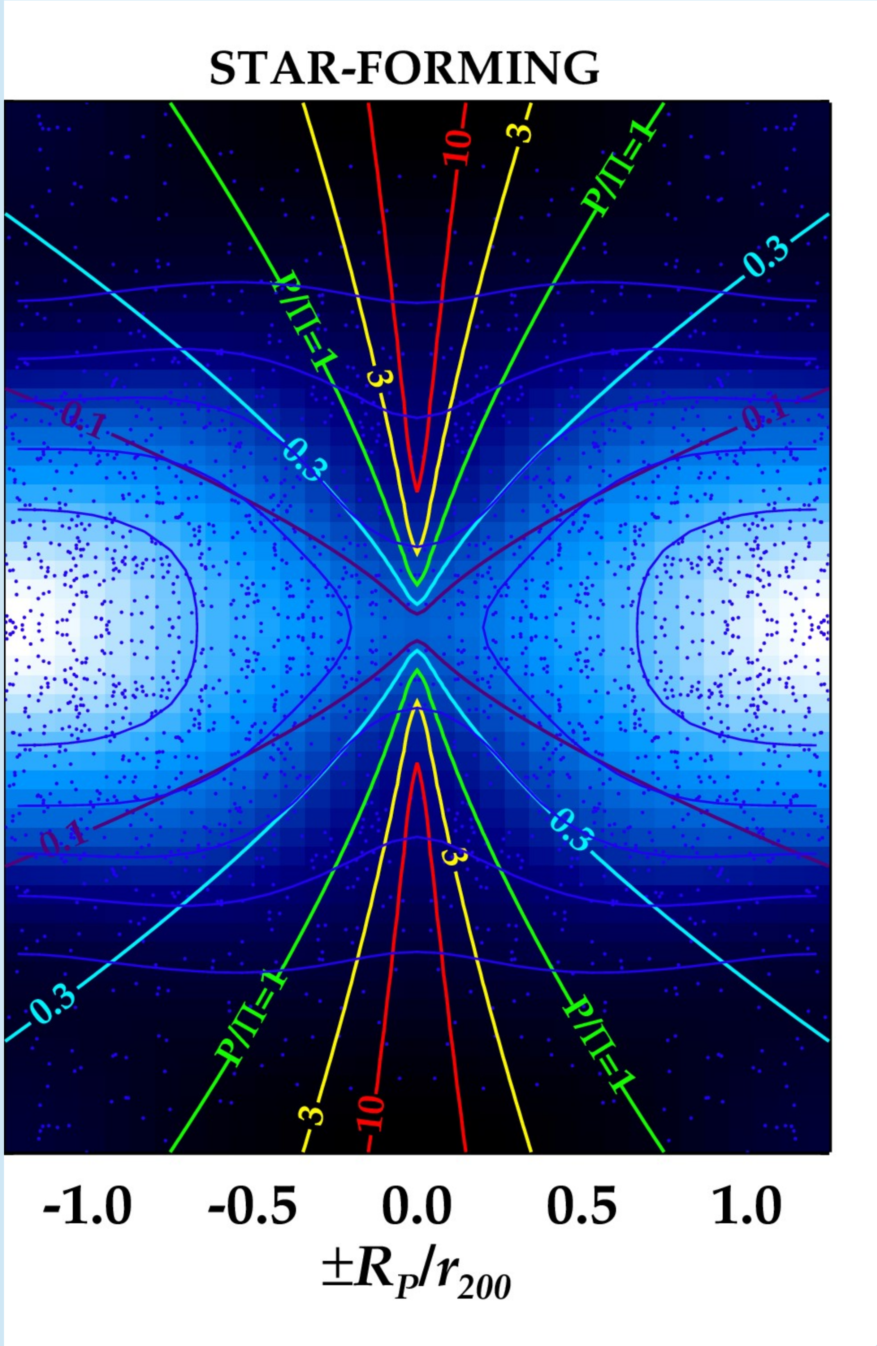
Stripping modulation of star-forming distribution

We must be aware that:

- Projection effects, $r_{3D} \rightarrow R_P$
- We know just one velocity component, v_z
- Clusters with (not very) different velocity dispersions and ICM densities
- Galaxies with different binding pressure
- Ram-pressure stripping is an immediate quenching process

But even with that ...

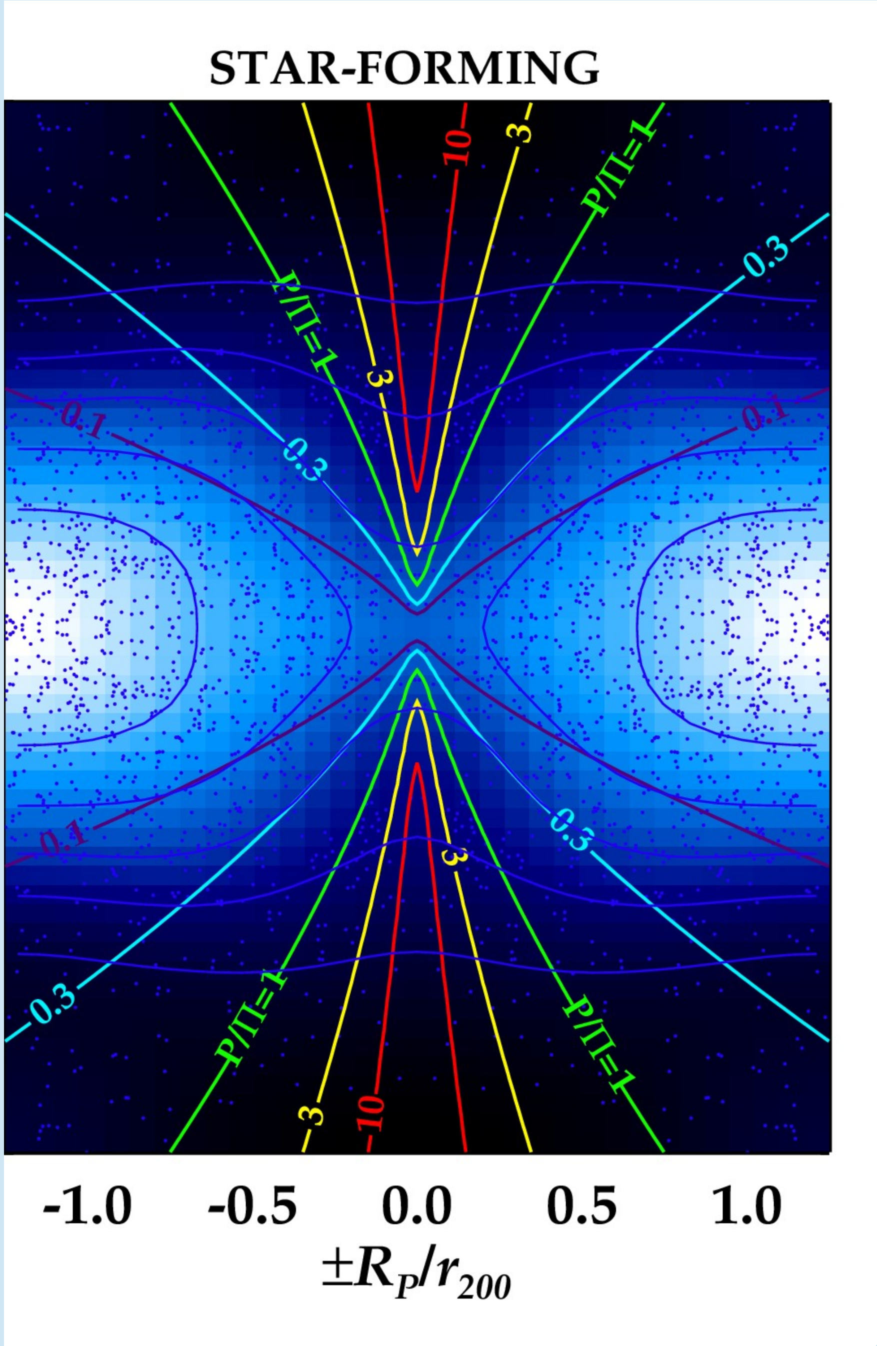
Stripping modulation of star-forming distribution



Stripping modulation of star-forming distribution

- The map of the stripping intensity presents a region of very high intensity for those galaxies close to the projected cluster centre $\tilde{r}\sim 0$ and with relatively high velocities $\tilde{s}>0.5$ (red isocontours)

➔ the paucity of star-forming galaxies in this specific region of the CPPS.



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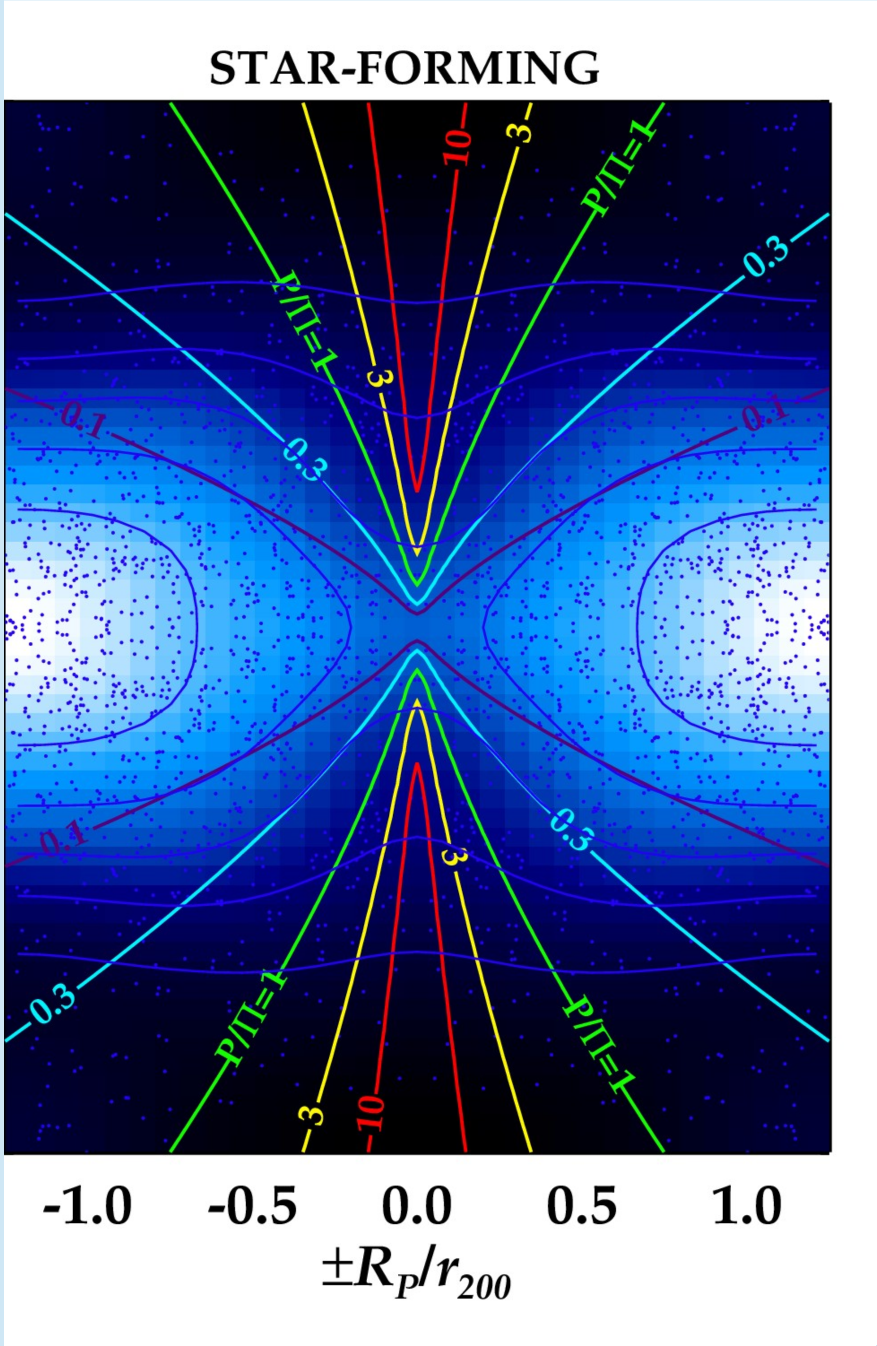
➔ the paucity of star-forming galaxies in this specific region of the CPPS.

- The region of very low stripping intensity (purple isocontours) presents a triangular shape, increasing in separation towards larger radii and connected through a ‘bridge’ around $(\tilde{r}, \tilde{s})\approx(0,0)$

➔ the presence of star-forming galaxies near to the projected cluster centre, but only for those galaxies with relatively lowl-o-s velocities.



Distribution in the CPPS

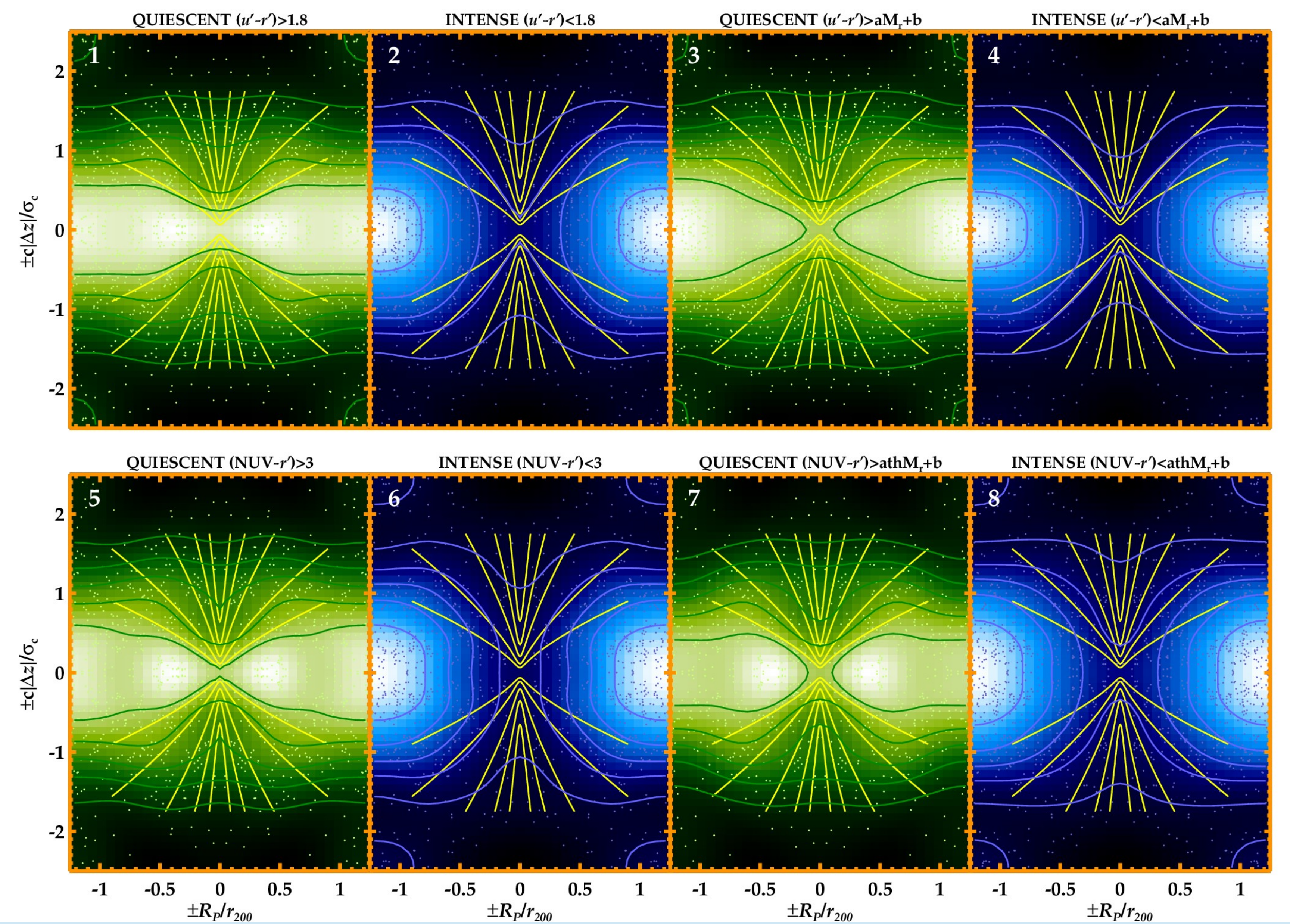
CPPS distribution of "star formation"

Intense star-forming galaxies:
Star-forming galaxies with
high levels of star formation
Bluest colors (optical and ultraviolet)

Quiescent star-forming galaxies:
Star-forming galaxies with
low levels of star formation
Less bluer colors (optical and ultraviolet)

Distribution in the CPPS

CPPS distribution of “star formation”

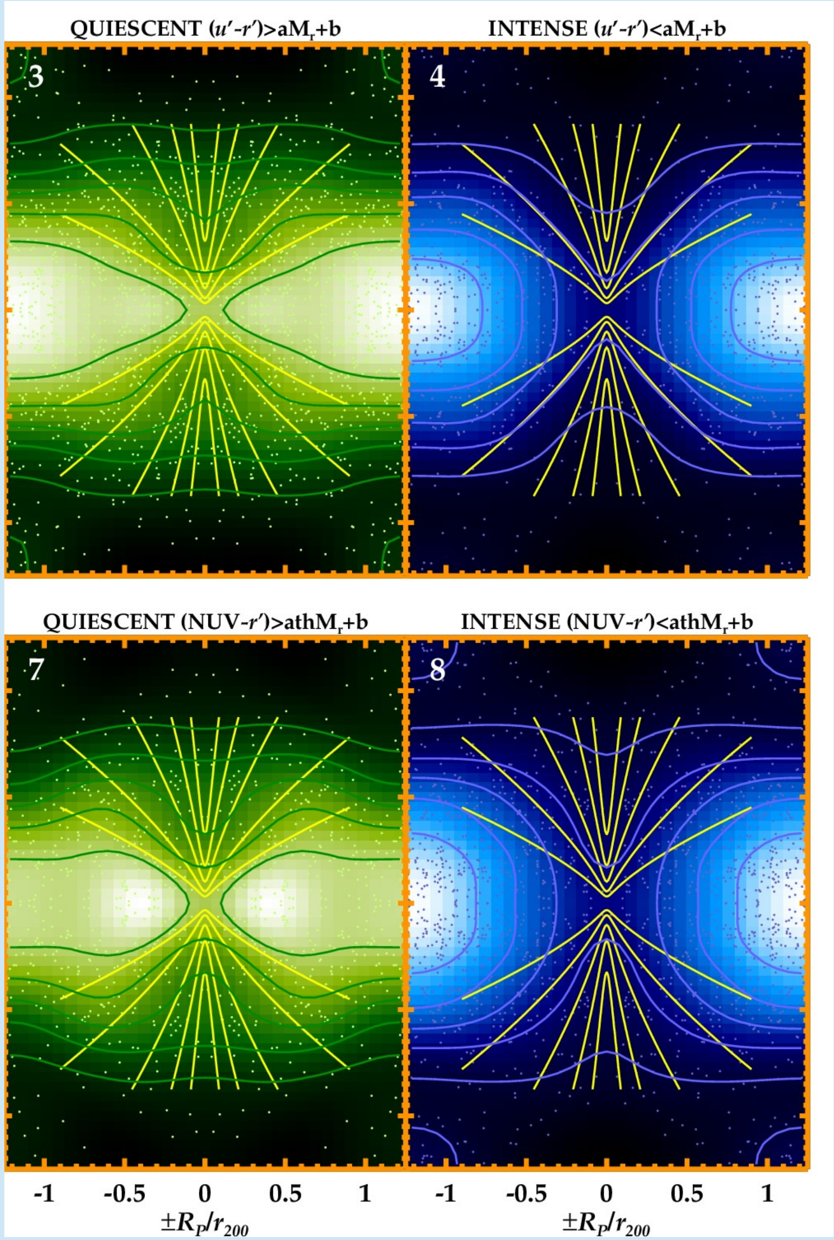


Distribution in the CPPS

CPPS distribution of "star formation"

- The intense star-forming population is mainly located around an unique maximum outside the virial region and with low velocity. This maximum coincides with the outer part of the regions with lowest stripping intensity.

- The quiescent star-forming population is distributed in a more extended range of radii, also occupying the CPPS region of the lowest stripping intensity but as much inside the projected virial radius as outside the projected virial radius.



Distribution in the CPPS

comparison with simulations

For this purpose, cosmic regions centred on ***28 massive clusters*** *($M_{200}>2\times10^{14}$ h^{-1} $M_{\odot}$) were extracted from the Millennium simulation (Springel et al. 2005).*

The 28 clusters were specially selected
(1) to have clean caustics without significant contamination from background structures, and
(2) to have ***velocity dispersions (for galaxies with $R_P<r_{200}$) matching those of our observed cluster sample.***

The galaxy l-o-s velocities and sky positions for the 28 systems were stacked, setting the origin at the average l-o-s velocity czc and at the cluster centre, respectively. Normalization by the velocity dispersion σc and the virial radius r200, respectively, was then performed.

Millennium simulation (Springel et al. 2005)

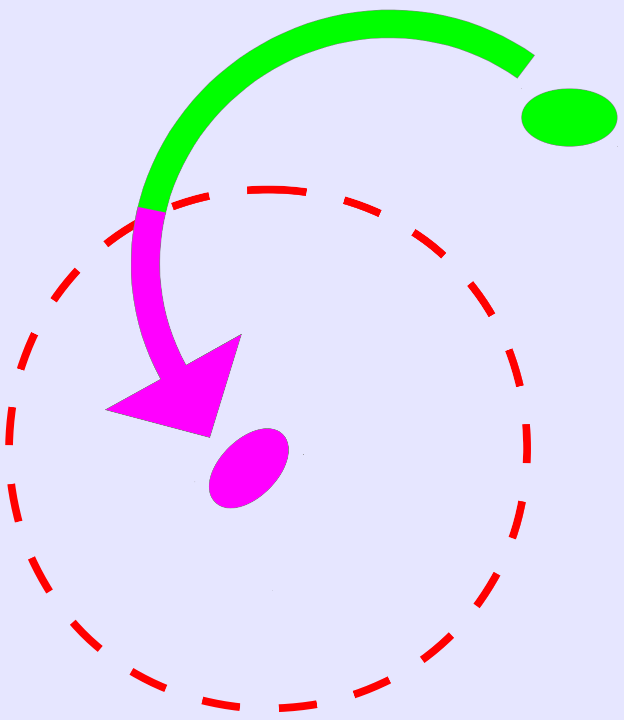
Distribution in the CPPS

comparison with simulations

We consider various cluster accretion epochs and accretion radii, where it is assumed that star formation in galaxies starts to be quenched, in order to segregate the accreted (quenched) population from the non-accreted (non-quenched) population.

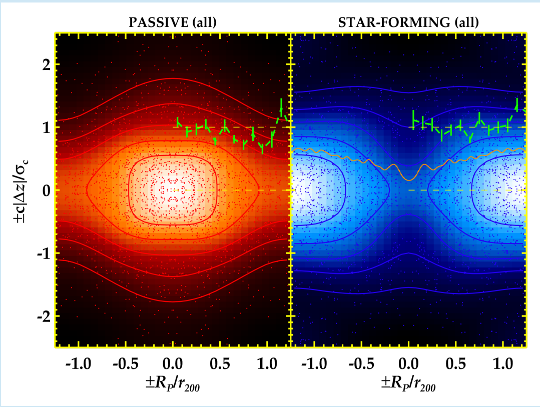
Accreted (quenched) population:
Those all galaxies which pass through a quenching radius after a specific lookback time.

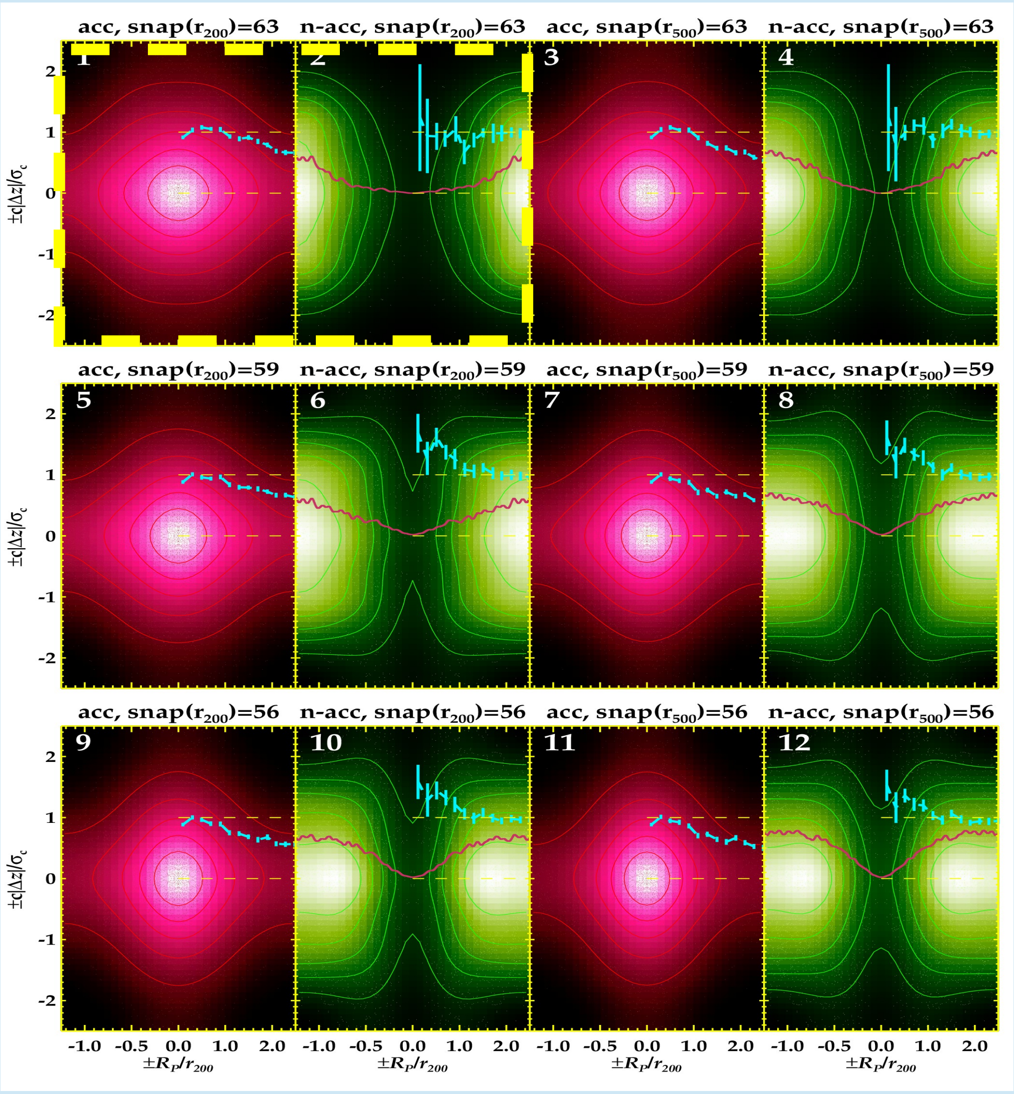
Non-accreted (non-quenched) population:
Those all galaxies which are still outside a quencing radius before a specific lookback time.



Distribution in the CPPS

comparison with simulations





(i) the contribution of the accreted population outside the projected virial radius $R_P > r_{200}$ to the whole accreted population is the largest of the cases shown here and the most similar to the contribution of the passive population outside the projected virial radius $R_P > r_{200}$ to the whole passive population and

(ii) the radial profile of velocity dispersion and the range of l-o-s velocities of non-accreted haloes inside the virial radius $R_P < r_{200}$ are the most similar to those ones of star-forming galaxies.

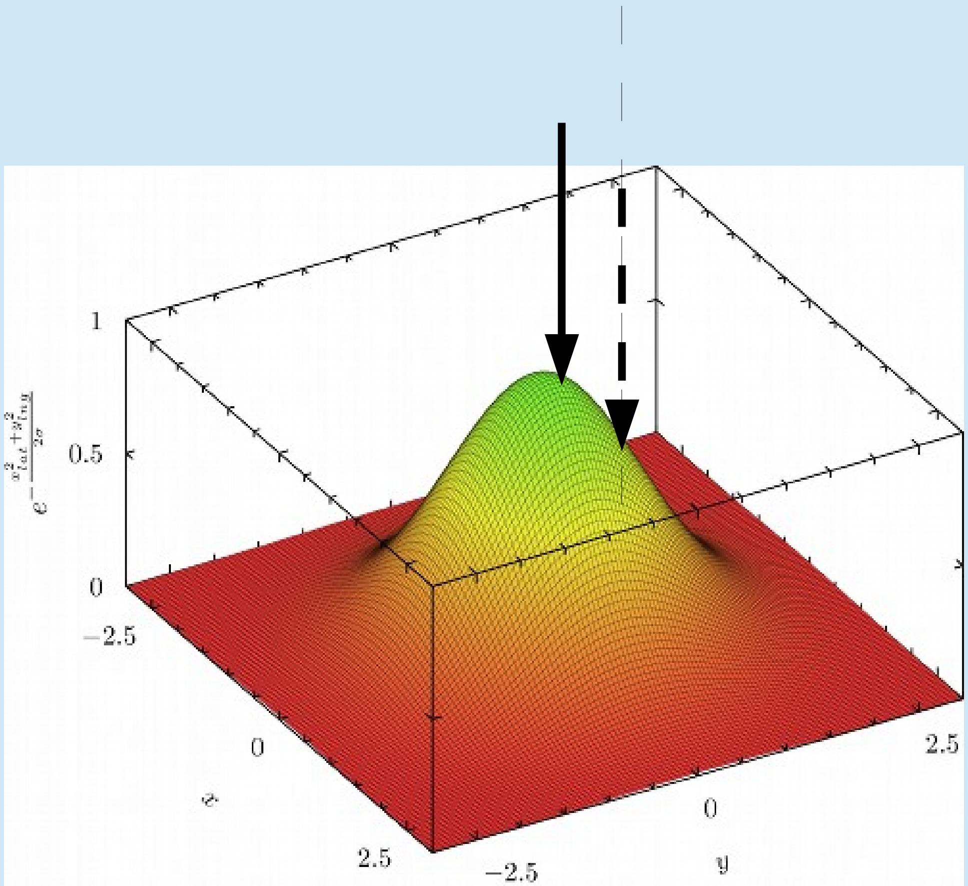
quenching lookback time-scale (0, ~1, ~2 Gyr)

How long does the sf galaxy take to be quenched? ***t<< 1 Gyr***

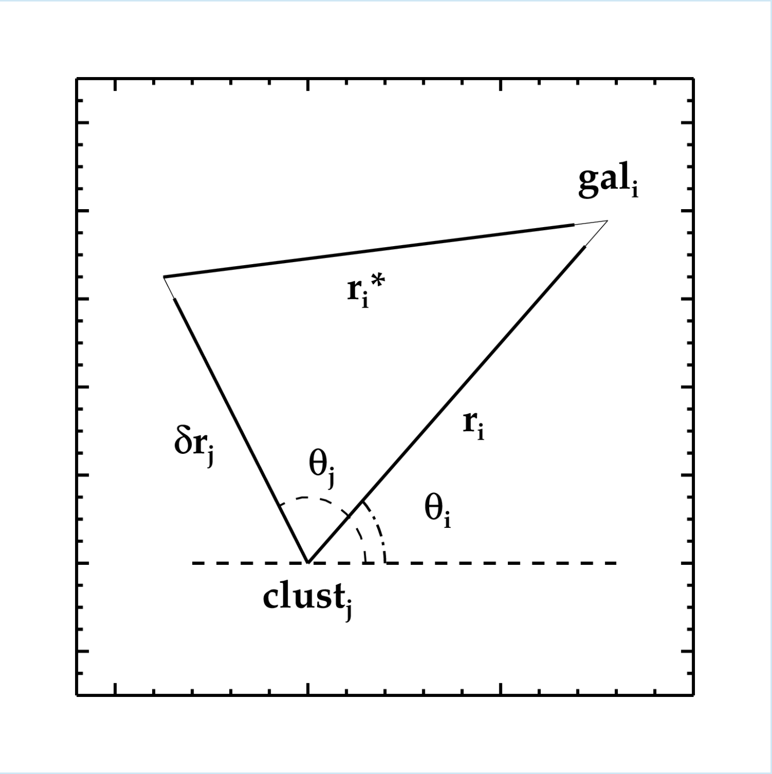
quenching radius (r_{200}, r_{500})

Where does the sf galaxy start to “feel” the cluster environment? ***r200***

Effect of the centering uncertainty



Beers & Toomre 1986

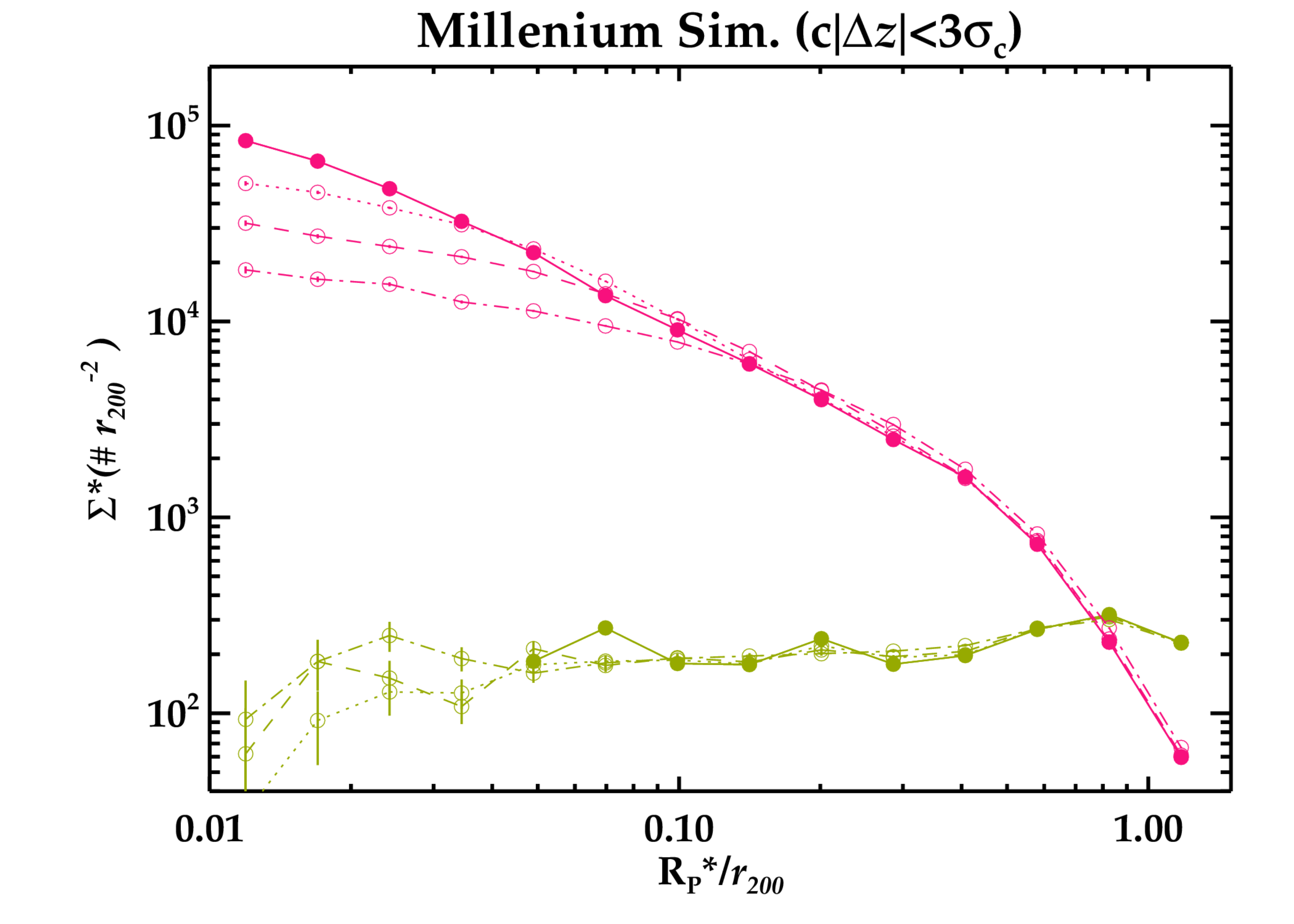


$(r*_i)2 = (r_i)^2 + (\delta r_j)^2 - 2\, r_i\, \delta r_j \cos(\theta_j - \theta_i)$

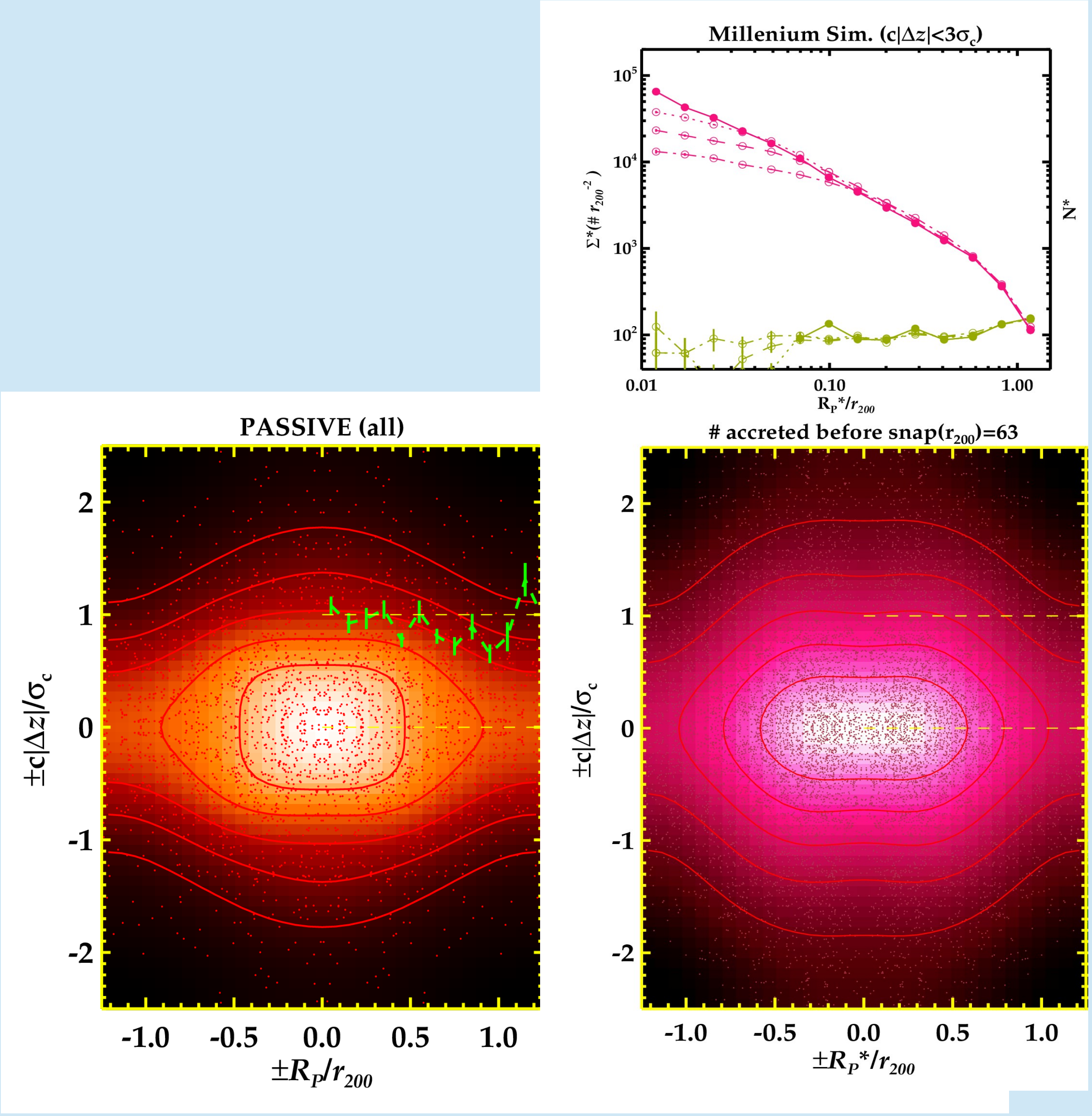
$\theta_j - \theta_i \sim \boldsymbol{U}_j\,[0, 2\pi]$

$\delta r_j \sim \| \boldsymbol{N}(0; \sigma_r\,[r200]) \|$

Radial profile comparison



Effect of the centering uncertainty



The inner logarithmic slope of the radial profile of projected density of accreted population α ∼ −1.19 can be substantially reduced when are considered the uncertainties of cluster centring.

This decrease in the inner slope can be enough to reach the value of the inner slope of the density profile of the passive population
α ∼ −1.

Conclusions

- Just applying the segregation “accreted = quenched” in simulations, we get a qualitative agreement between the CPPS distributions of the passive and the accreted populations and also between the star-forming and the non-accreted populations.

- The uncertainty in cluster centring strongly affects the pronounced cuspy profiles of the projected density and also, it can explain the main difference (i.e. inner slope) between the CPPS distribution of passive and accreted populations.

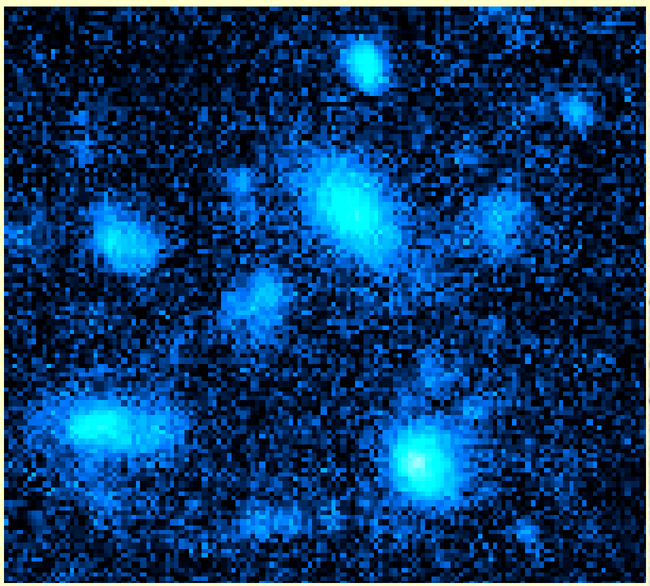
- The CPPS density of star-forming galaxies and the intensity of ram-pressure stripping present an opposite trend throughout the CPPS. This implies that ram-pressure stripping significantly contributes to modulate the observed CPPS distribution of star-forming galaxies in cluster virial regions and their surroundings.

- The non-negligible fraction of star-forming galaxies at the projected centre of clusters are mainly those galaxies with low line-of-sight velocities and they can be mainly identified:
  - as those galaxies with a remaining star formation activity (quiescent star-forming galaxies) inside the physical virial region or, in a lower degree,
  - as galaxy interlopers, i.e. outside the physical virial region.

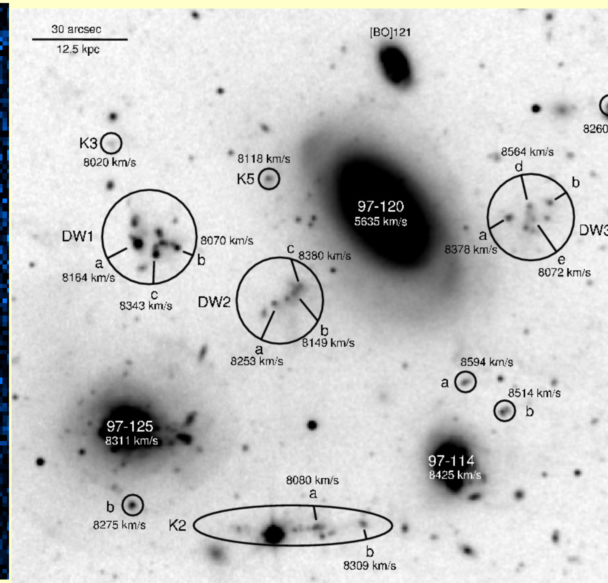
Star-forming compact groups

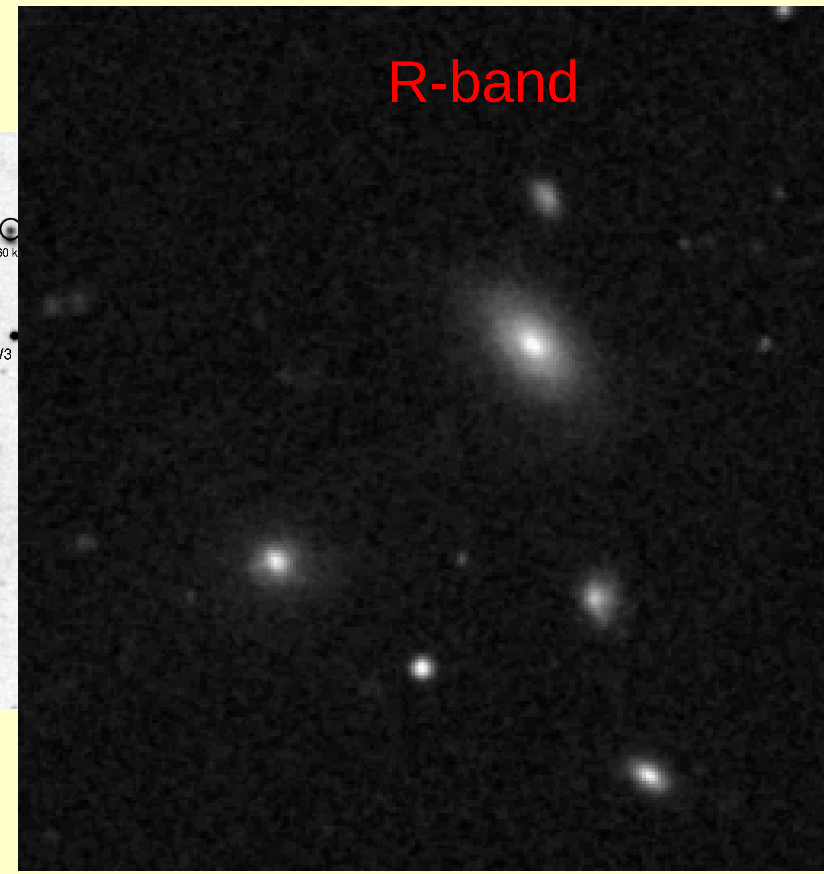
Blue infalling group...

GALEX



Hα





GALEX catalogues are the place to search for this kind of groups...

Star-forming compact groups

We search for similar examples of BIG:

*(1) applying a Friend-of-Friend algorithm in sky coordinates with a **linkinglength of 1.5 arcmin** and*

*(2) with a minimum number of **four members** in a GALEX-AIS catalogue of*

*(3) **bright UV emitting sources***

*(4) in the magnitude range **17<FUV<20.5**.*

Star-forming compact groups

This sample of Star-forming compact Groups of galaxies (SFG)

- 280 groups of UV-emitting galaxies (17<FUV<20.5)

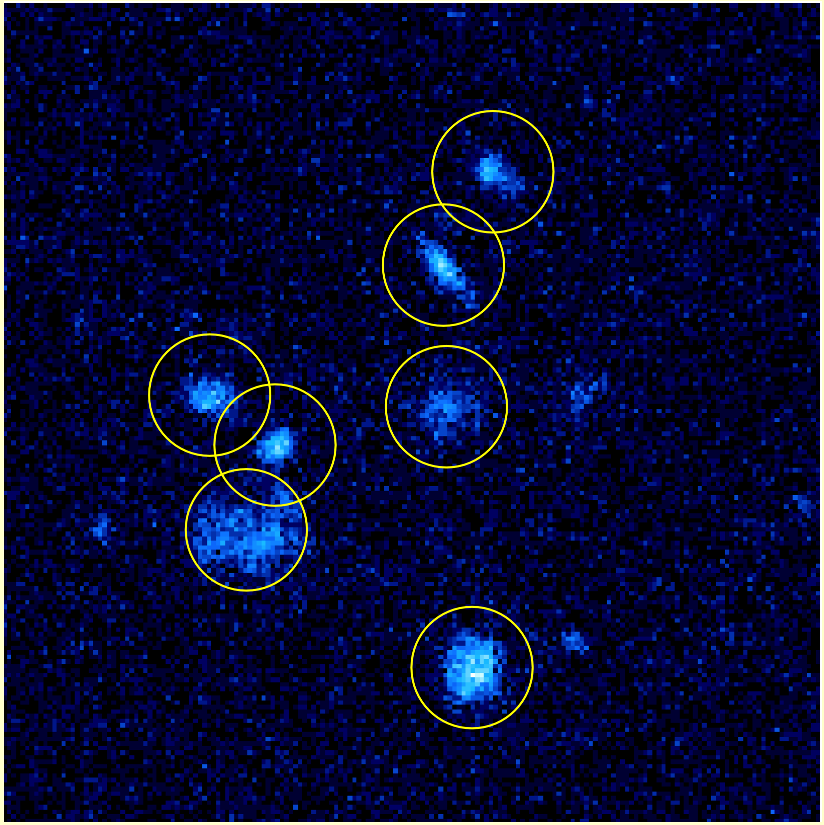
- UV members:
  226 groups with 4 members,
  39 with 5 members,
  11 with 6 members and
  4 with 7 members

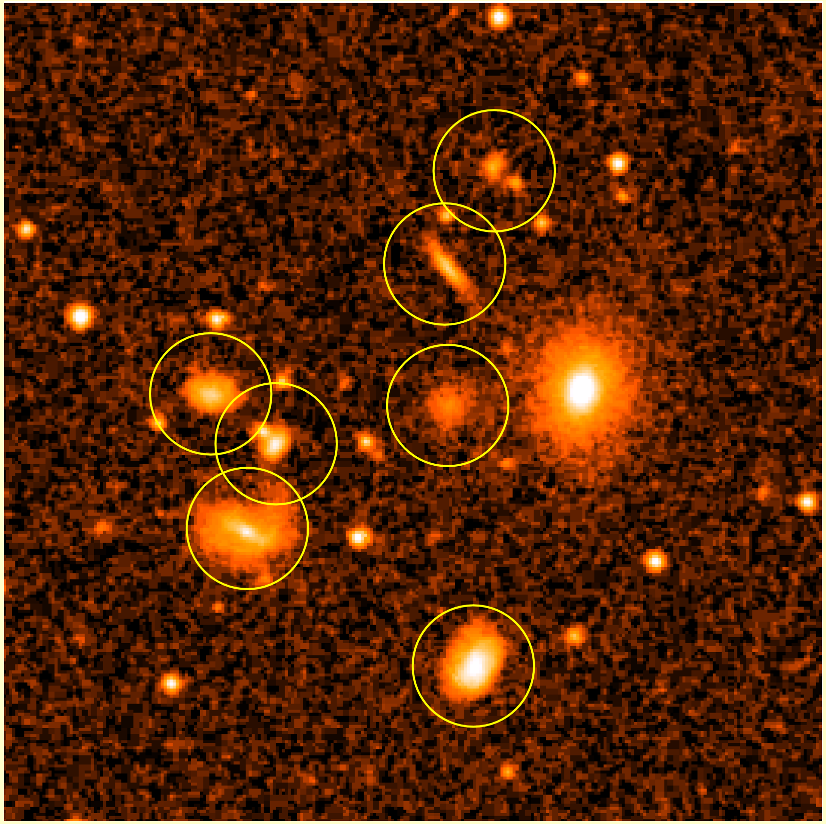
- z-distribution below z~0.2 (local Universe)

- sky projected dispersion below ~1.5 arcmin (compact)

Star-forming compact groups

Just one example of the groups that we found…





Star-forming compact groups

- *The **preprocessing scenario** and the **Blue Infalling Group (BIG)**.*

  The unique case in the local Universe attributes to the preprocessing scenario is the BIG. This view presents some tension with Dressler+(2013) which claim the quenching of star formation is not the main output of a previous starburst.

  SFGs are analogues of the BIG, ideal to assess the significance of the starbursting-to-quenching pathway.

- ***Enviromental evolution of galaxy population** in groups.*

  Galaxies in groups represent the half of the giant galaxy population in the nearby universe.

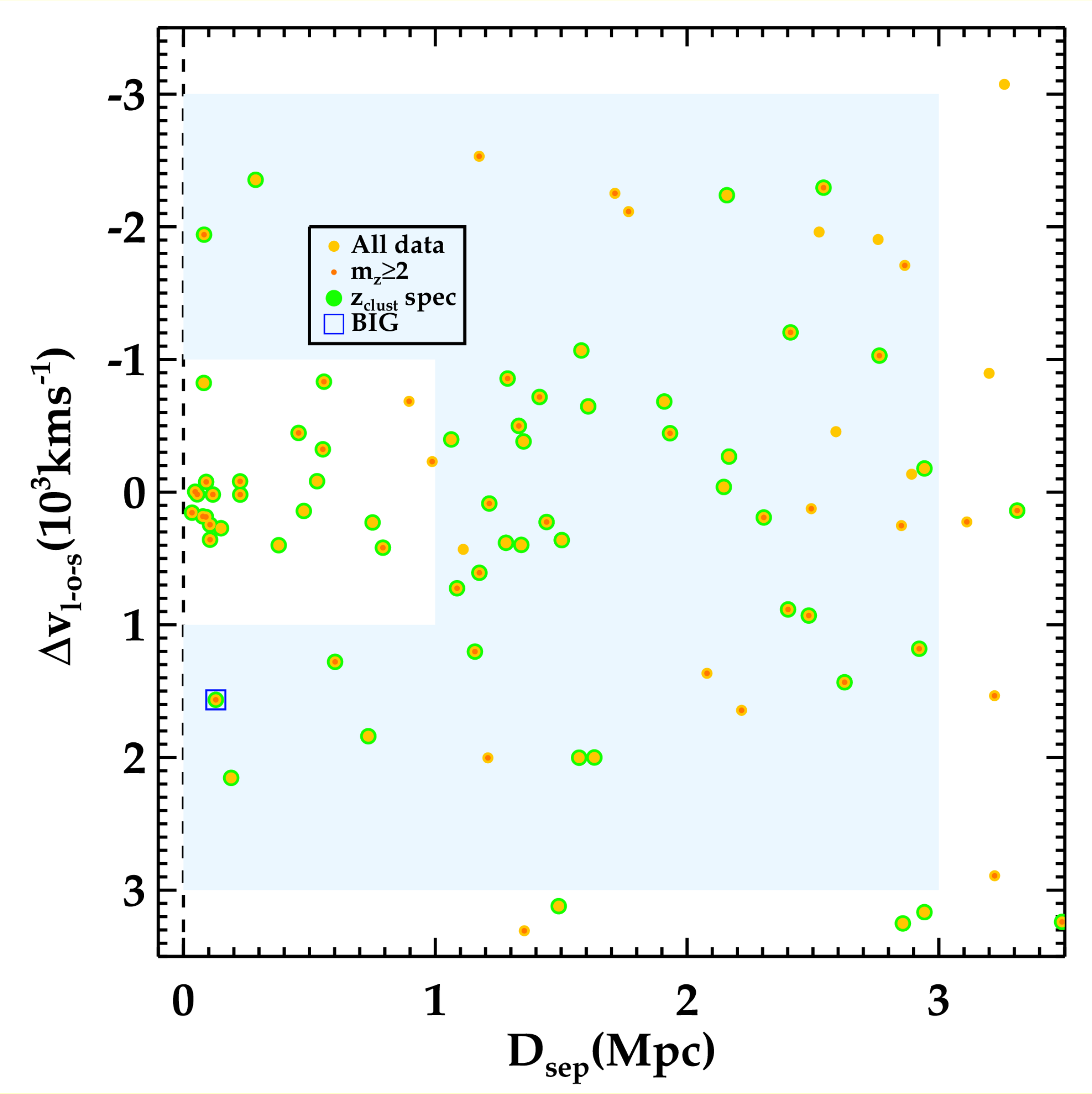
  *Detailed studies of galaxy interactions and environmental processes in their **most frequent environment** in the very moment when they occurs are key to adequately describe the galaxy evolution.*

- *Analogues of the **early stages** of **galaxy clusters / fossil groups / BCG** ?*

Star-forming compact groups

distribution with respect to the nearest cluster

Search for star-forming compact groups infalling to galaxy clusters



Conclusions and future work

- We compile a significant sample of SFGs
- Publish the catalogue …
- Membership confirmation of group galaxies...
- Hα observations of SFG...