EVOLVING GALAXIES IN EVOLVING ENVIRONMENTS
15-19th September 2014, Bologna

The influence of the environmental history on quenching star formation

Michaela Hirschmann (IAP-France) with
Gabriella De Lucia (INAF-Trieste), Dave Wilman, Simone Weinmann,
Angela Iovino, Olga Cucciati, Stefano Zibetti, Alvaro Villalobos

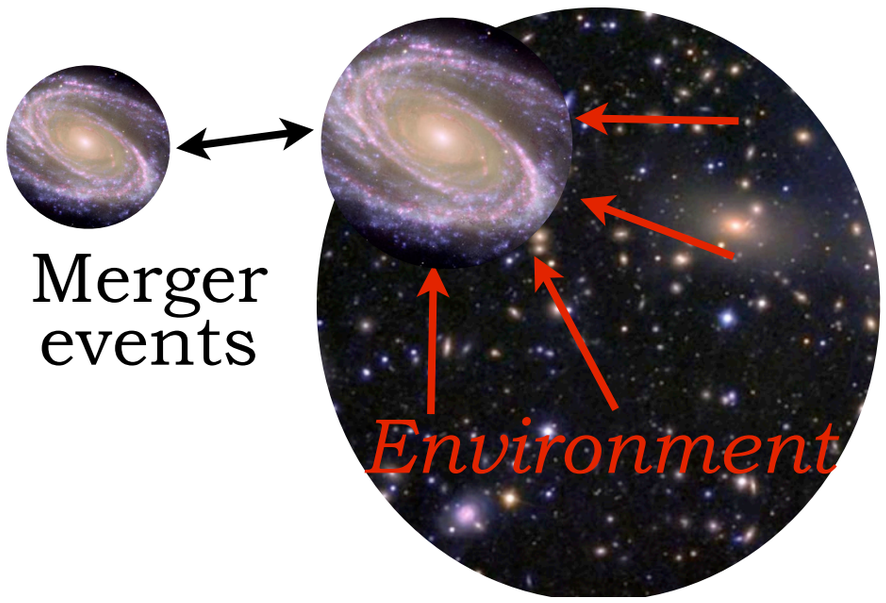
Star formation can get quenched by…

A) Internal processes (***nature***)

Feedback from stars, SN *(e.g. Hirschmann, Naab +13a)* & AGN

best traced by isolated centrals *(see e.g. Hirschmann, DeLucia+13b)*

B) External processes (***nurture***)



How relevant is environment for quenching galaxies?

(e.g. Font+08, vandenBosch+08, Kimm+09, Weinmann +09/ 10, Peng+10, Tinker+11, Woo+12, Cucciati+12, Wetzel+12/ 13, DeLucia+13, Bahe+13, Kovac+13, Mok+14…)

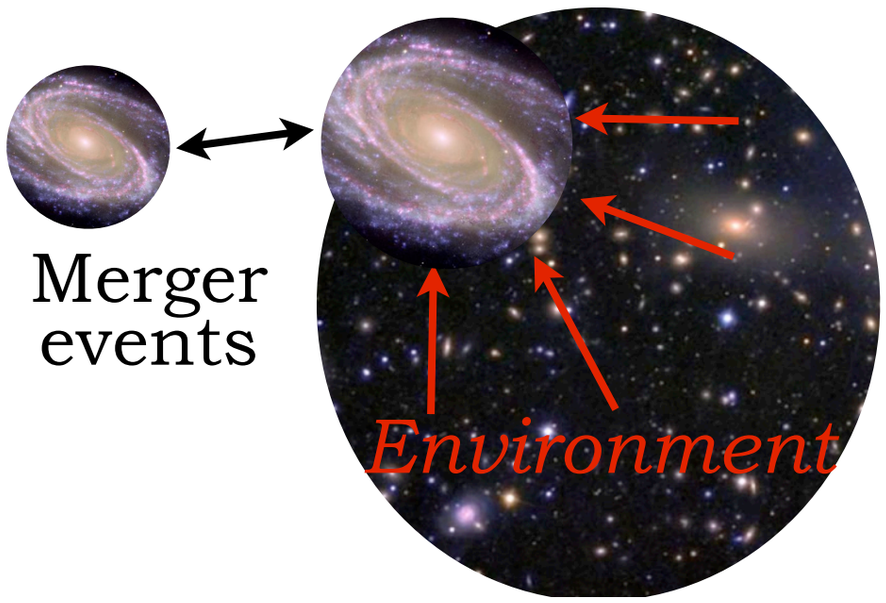
Star formation can get quenched by…

A) Internal processes (***nature***)

Feedback from stars, SN *(e.g. Hirschmann, Naab +13a)* & AGN

best traced by isolated centrals *(see e.g. Hirschmann, DeLucia+13b)*

B) External processes (***nurture***)



How relevant is environment for quenching galaxies?

(e.g. Font+08, vandenBosch+08, Kimm+09, Weinmann +09/ 10, Peng+10, Tinker+11, Woo+12, Cucciati+12, Wetzel+12/ 13, DeLucia+13, Bahe+13, Kovac+13, Mok+14…)

Our approach: analyse the environmental history!

- Environmental effects important for *centrals* (*super-halo scales*)?
- Typical *quenching time-scales* of *satellites*?

Method: Comparing galaxy formation models to observations

Method

Observational data

- *Density catalogue* of *Wilman et al. (2010)* using SDSS (DR8):
  z = 0.015-0.08, M_r<-18,
  Δv = +/-1000km/s + V_{max} correction
- *Cross-correlated* with *Brinchmann et al. (2004)* & *Yang et al. (2007)*:
  Estimates for stellar masses, SFRs (Halpha emission lines), galaxy types

Theoretical models

- *Millennium-Simulation* (*Springel at al. 2005*):
  512^3 particles in a $(500\text{Mpc/h})^3$ box, merger trees & spatial distribution of the halos
- *Semi-analytic model*, *Guo et al., 2011*, assuming a *gradual stripping of the hot halo gas*:
  Populate dark matter halos with galaxies, same selection criteria as in observations

Quiescent galaxies: $$\mathrm{sSFR} \equiv \frac{\mathrm{SFR}}{M_{\mathrm{stellar}}} < \frac{0.3}{t_{\mathrm{Hubble}}}$$ *see Franx+10*

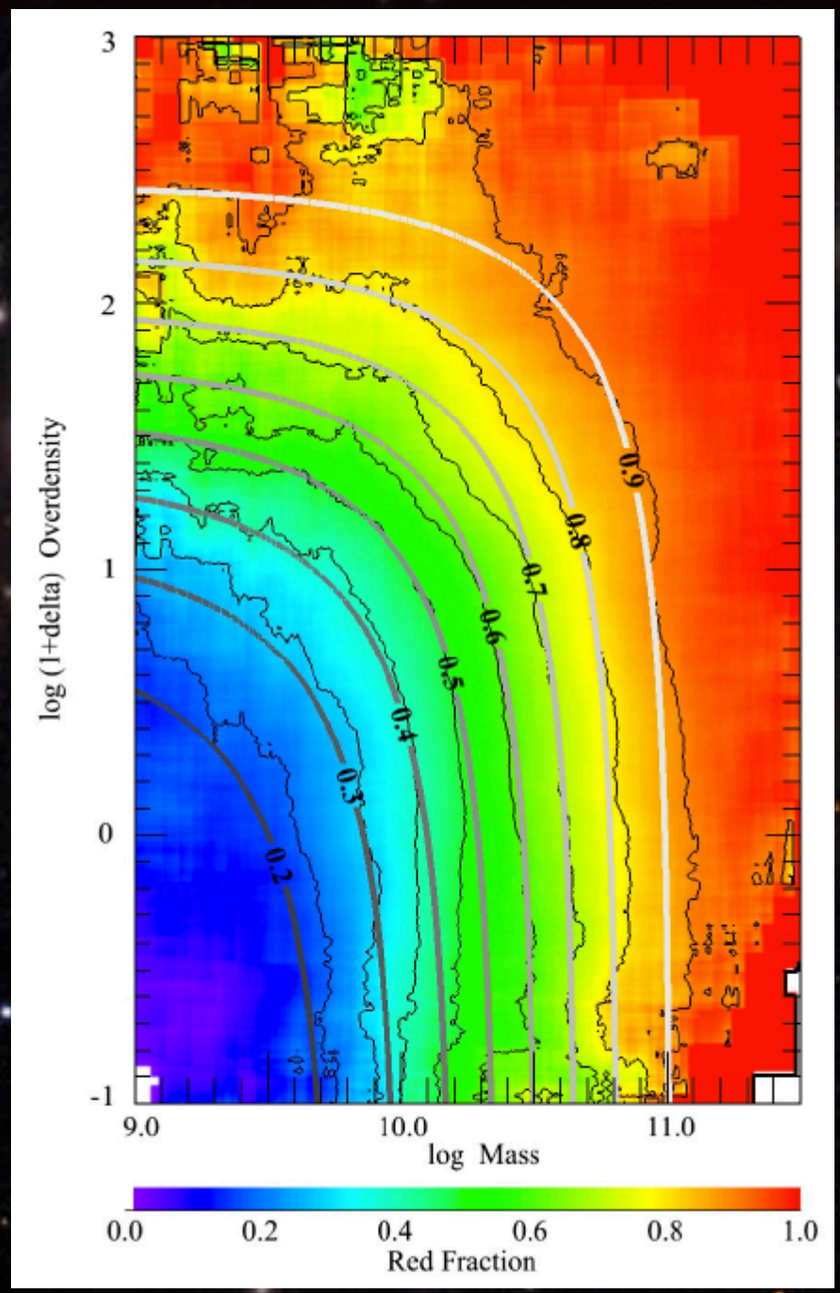
Density estimation: $$\Sigma_{r_i, r_a} = \frac{N_{\mathrm{gal}}}{\pi(r_a^2 - r_i^2)}$$ *see Wilman+10*

with: $r_i = 0$ Mpc, $r_a = 1$ Mpc

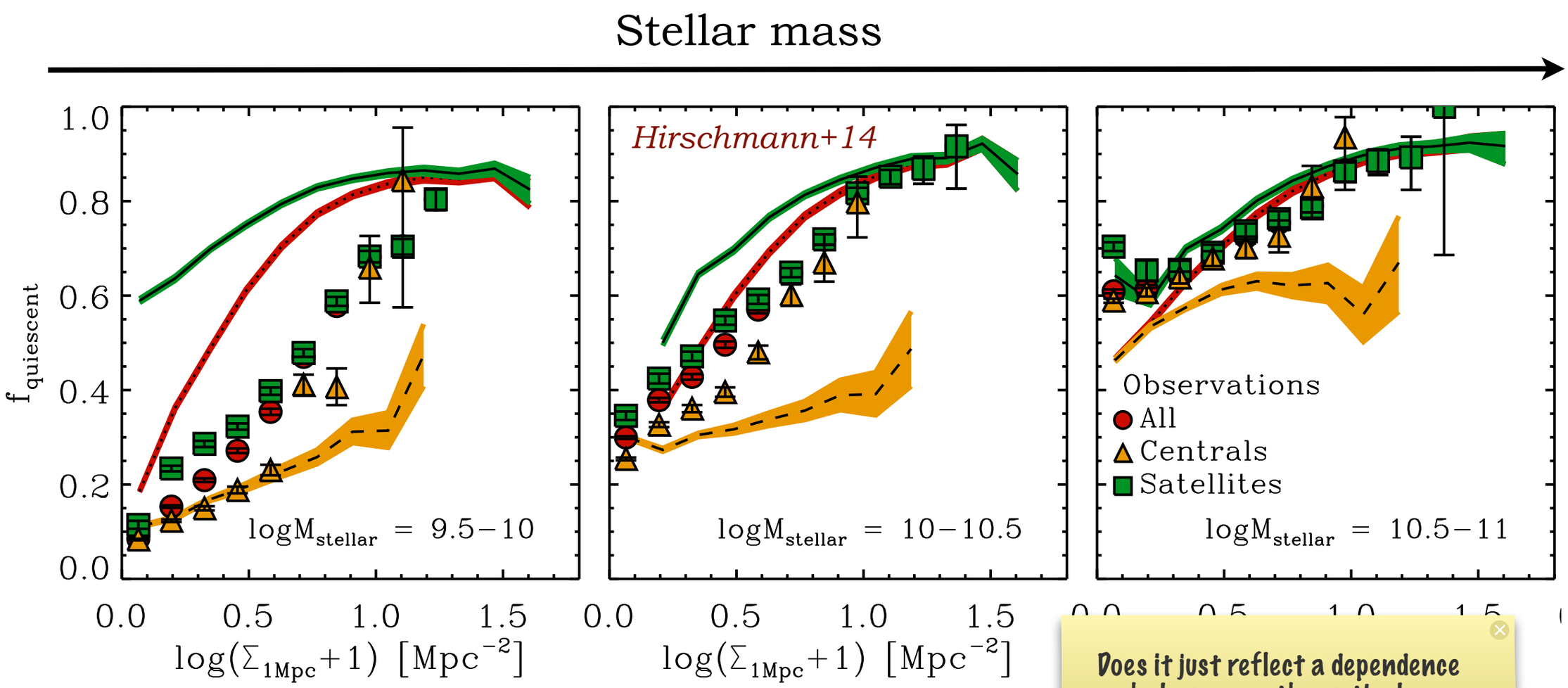
I. How well do current models (Guo) reproduce the observed quiescent fractions?

Quiescent/red fractions are dependent on both stellar mass and density

(e.g. Peng+10)

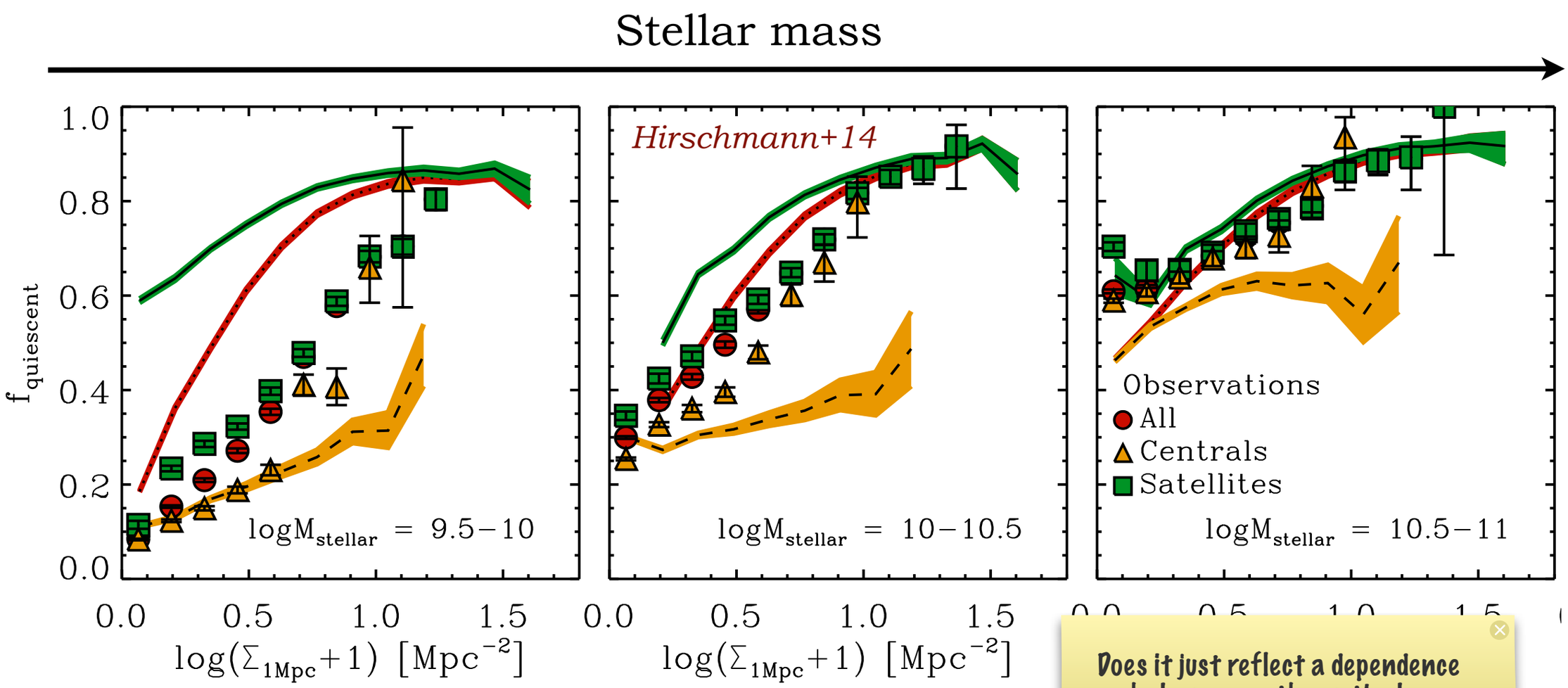


Quiescent galaxy fractions



✦ *Observations*:
overall density dependence mainly driven by satellites (Kovac et al.,2013)
similar behavior of centrals & satellites & strong density dependence

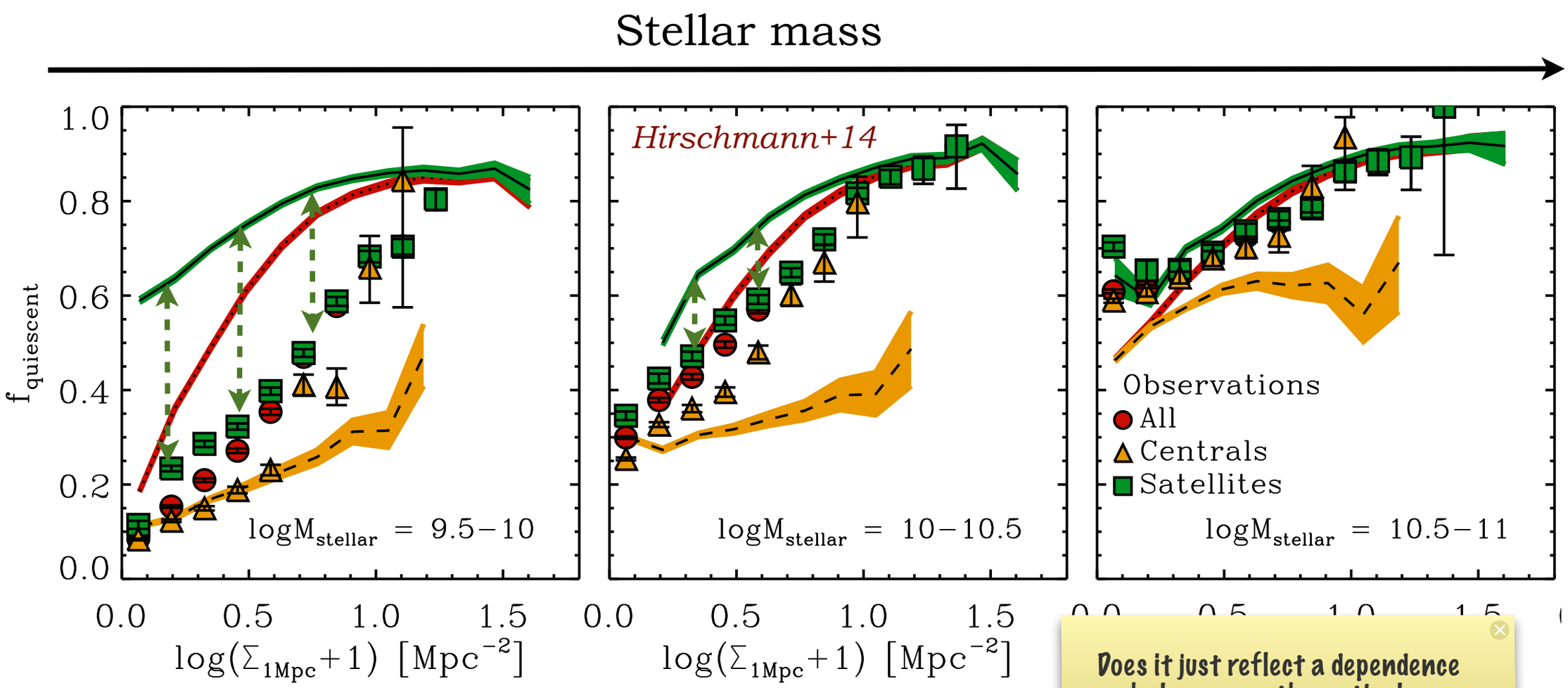
Quiescent galaxy fractions



Does it just reflect a dependence on halo mass, a theoretical measure for environment?

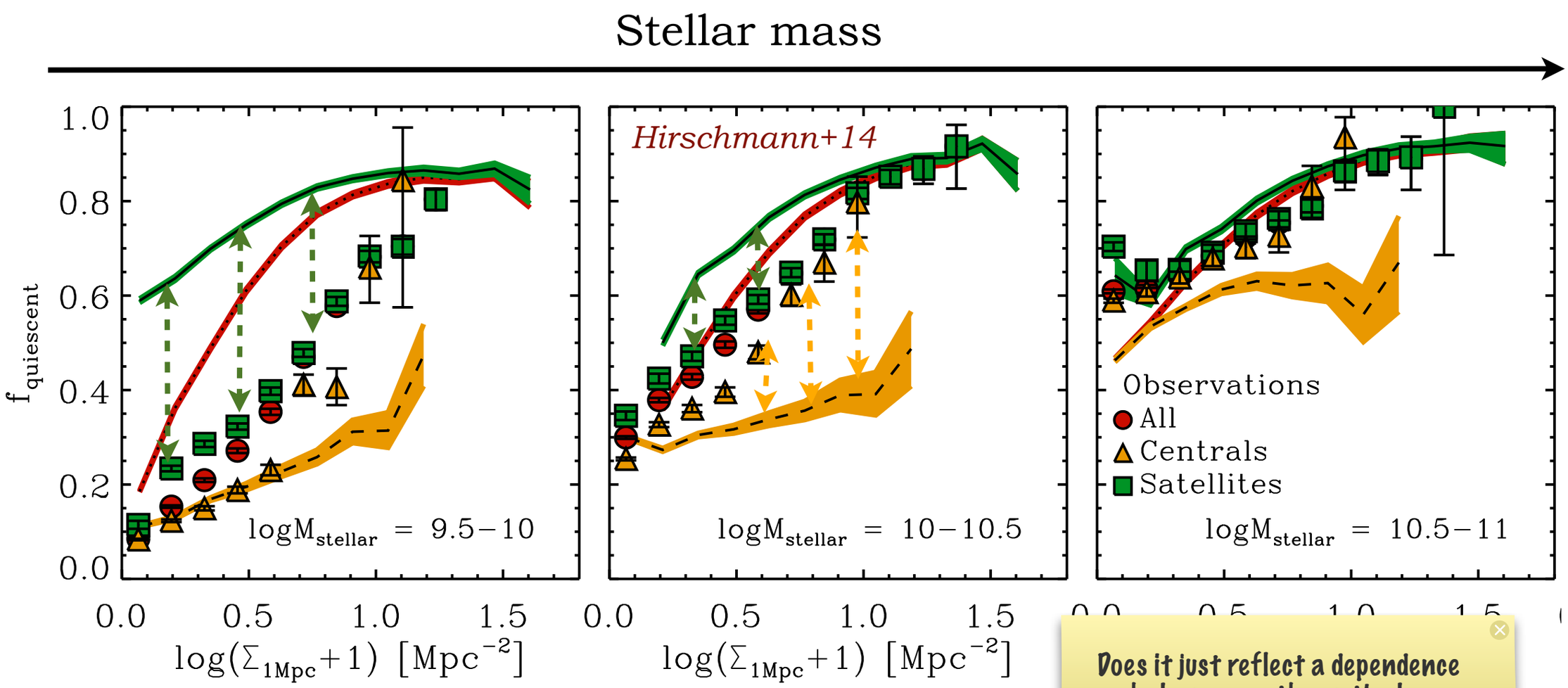
- *Observations*:
  overall density dependence mainly driven by satellites (Kovac et al.,2013)
  similar behavior of centrals & satellites & strong density dependence
- *Models*: *centrals & satellites behave differently & weaker density dependence*

Quiescent galaxy fractions



- *Observations*:
  overall density dependence mainly driven by satellites (Kovac et al.,2013)
  similar behavior of centrals & satellites & strong density dependence
- *Models*: *centrals & satellites behave differently & weaker density dependence*
  ⇨ Over-estimating *quiescent satellites* (e.g. Kimm+09)

Quiescent galaxy fractions



Does it just reflect a dependence on halo mass, a theoretical measure for environment?

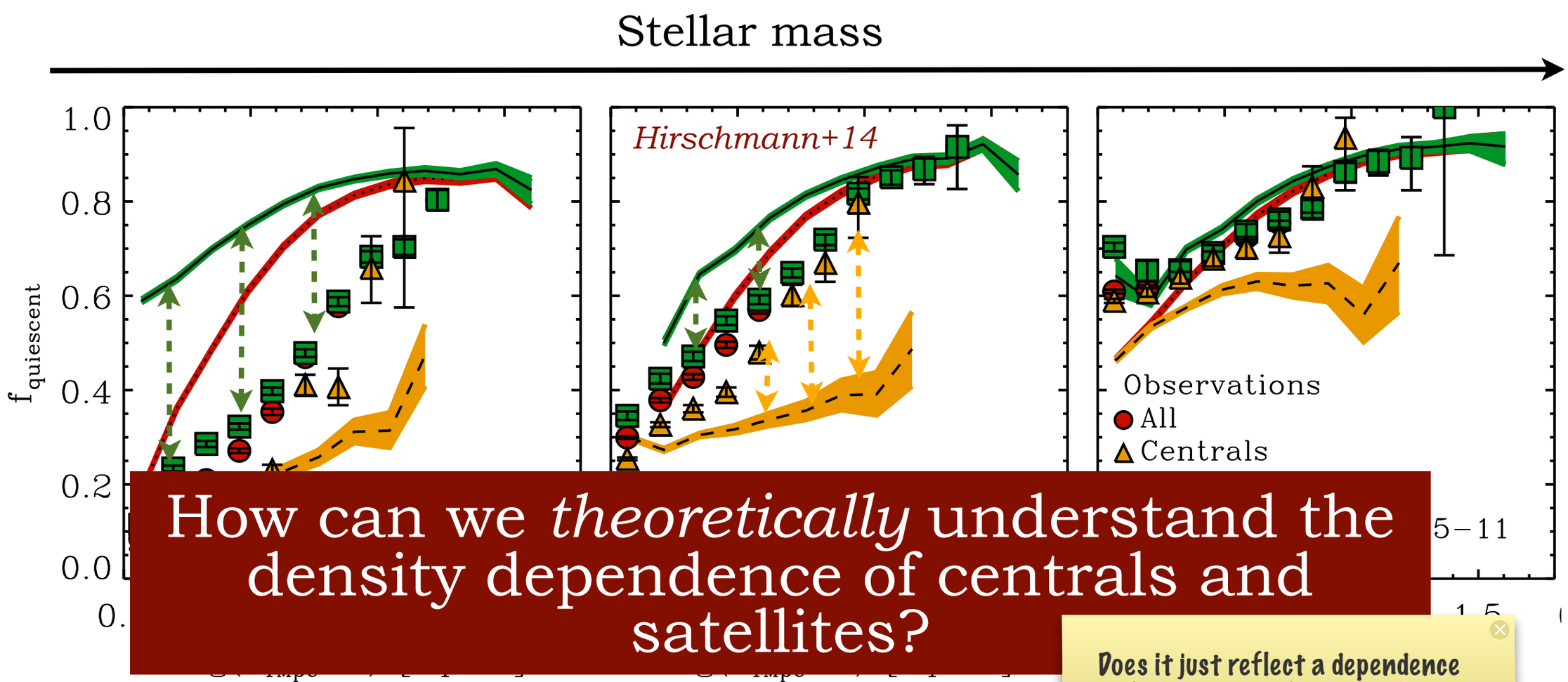
✦ *Observations*:
overall density dependence mainly driven by satellites (Kovac et al.,2013)
similar behavior of centrals & satellites & strong density dependence

✦ *Models*: *centrals & satellites behave differently & weaker density dependence*

⇨ Over-estimating *quiescent satellites* (e.g. Kimm+09)

⇨ Under-estimating *quiescent centrals*

Quiescent galaxy fractions

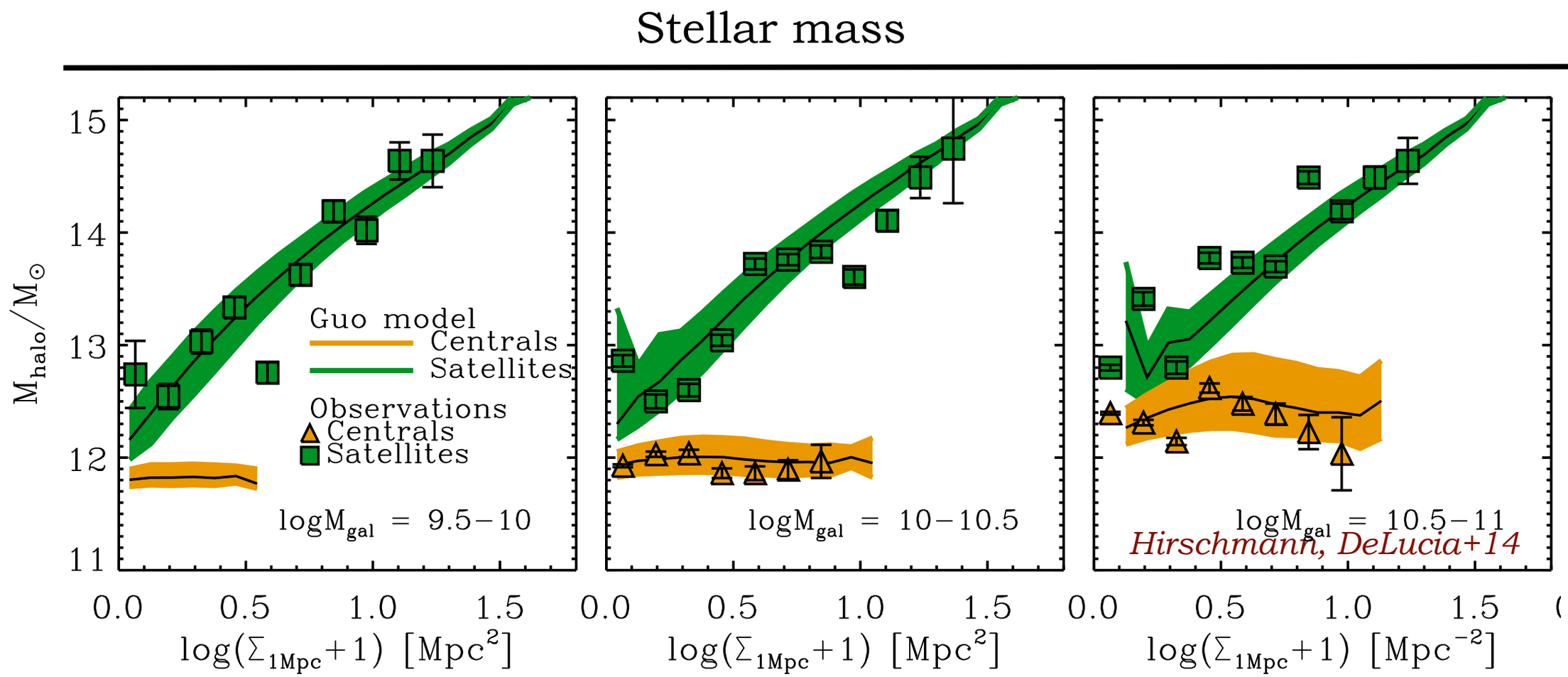


How can we *theoretically* understand the density dependence of centrals and satellites?

Does it just reflect a dependence on halo mass, a theoretical measure for environment?

- *Observations*:
  overall density dependence mainly driven by satellites (Kovac et al.,2013)
  similar behavior of centrals & satellites & strong density dependence
- *Models*: *centrals & satellites behave differently & weaker density dependence*
  - ⇨ Over-estimating *quiescent satellites* (e.g. Kimm+09)
  - ⇨ Under-estimating *quiescent centrals*

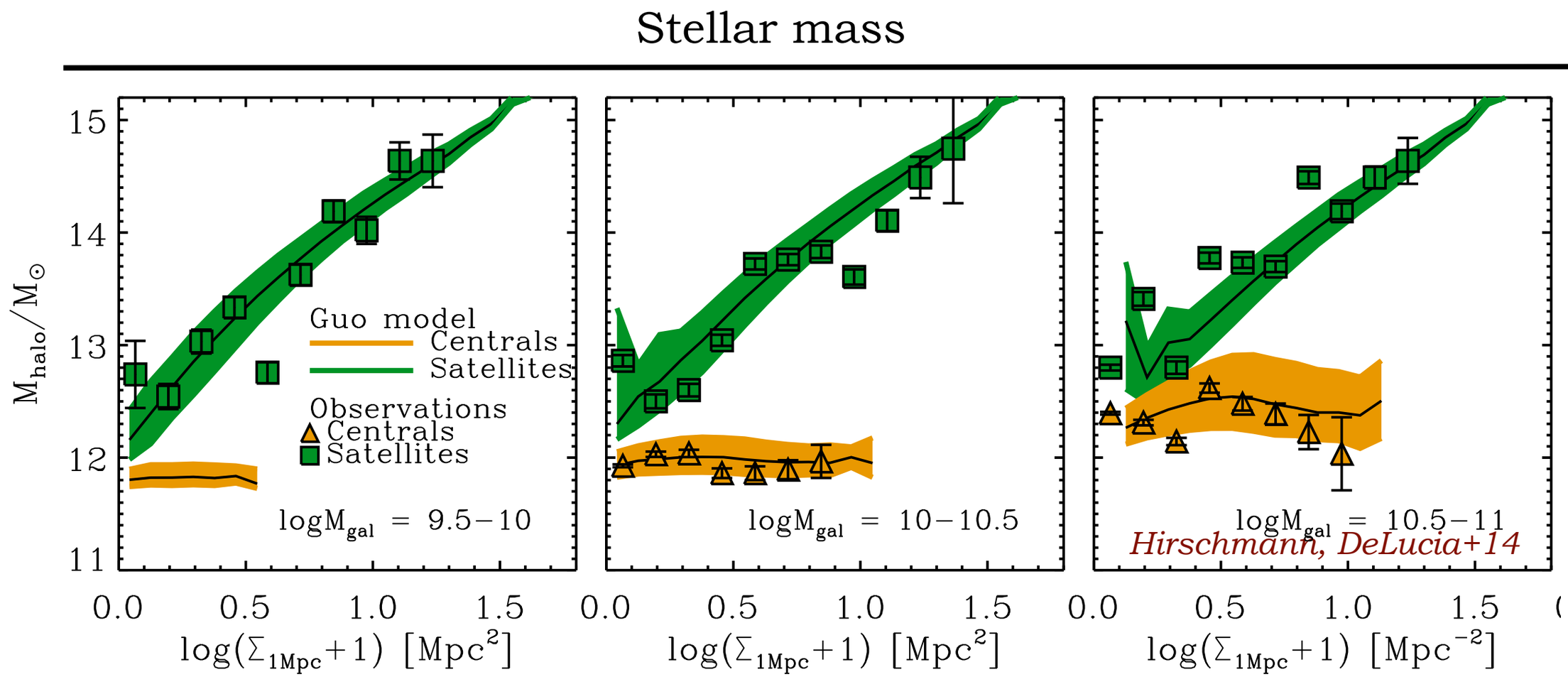
Density-halo mass relation



- *Models and observations agree well*
- ***Satellites:*** Halo mass is related with 1Mpc-density at all stellar masses
- ***Centrals:*** Halo mass is unrelated with 1Mpc-density (except for the most massive galaxies >10^{11} $M_\odot$)

see also Haas+12, Muldrew+12

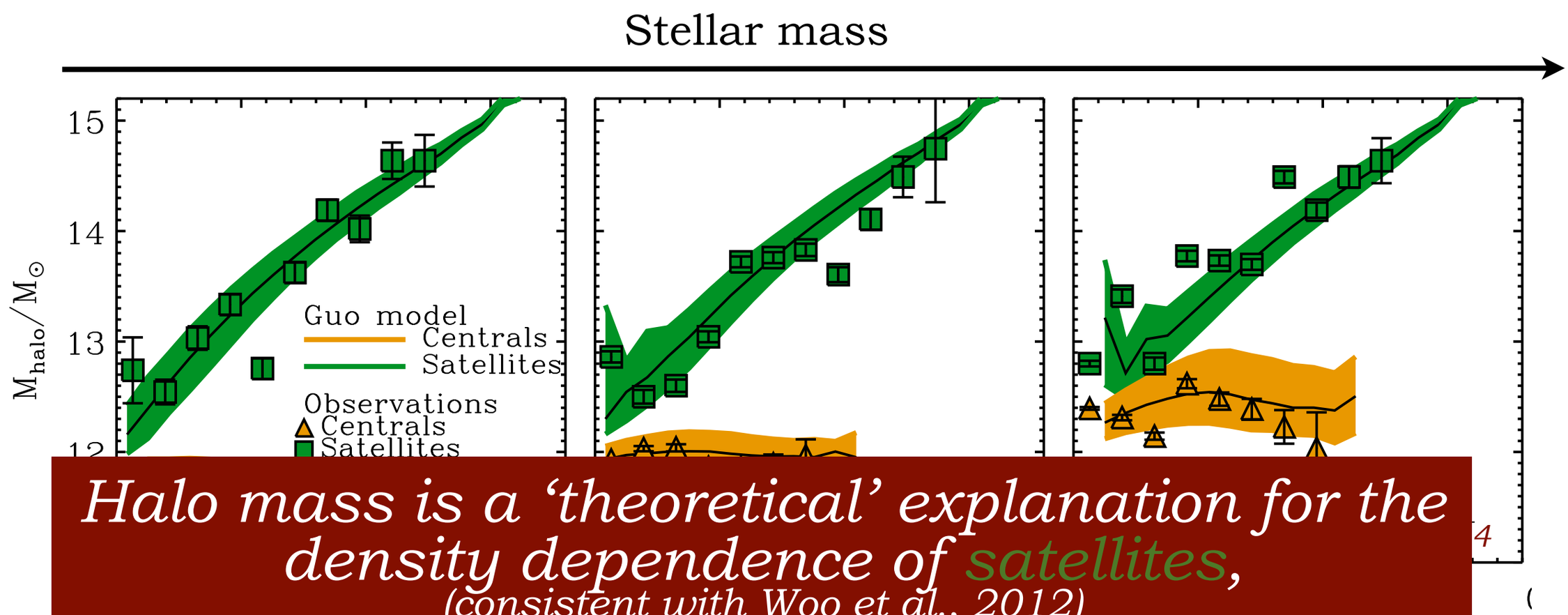
Density-halo mass relation



- *Models and observations agree well*
- ***Satellites:*** Halo mass is related with 1Mpc-density at all stellar masses
- ***Centrals:*** Halo mass is unrelated with 1Mpc-density (except for the most massive galaxies >10^{11} $M_\odot$)

see also Haas+12, Muldrew+12

Density-halo mass relation



Halo mass is a 'theoretical' explanation for the density dependence of satellites,
(consistent with Woo et al., 2012)
*but **not** for the one of centrals!*

- *Models and observations agree well*
- ***Satellites:*** Halo mass is related with 1Mpc-density at all stellar masses
- ***Centrals:*** Halo mass is unrelated with 1Mpc-density (except for the most massive galaxies $>10^{11}$ $M_\odot$)

see also Haas+12, Muldrew+12

II. ***Central*** galaxies

Their density dependence...
... environmental effects on superhalo scales?

(as 1Mpc is larger than the size of 10^{12} $M_\odot$)

(see also Haines+09, von der Linden+10, Wilman +10,Geha et al. 2012, Rasmussen+12)

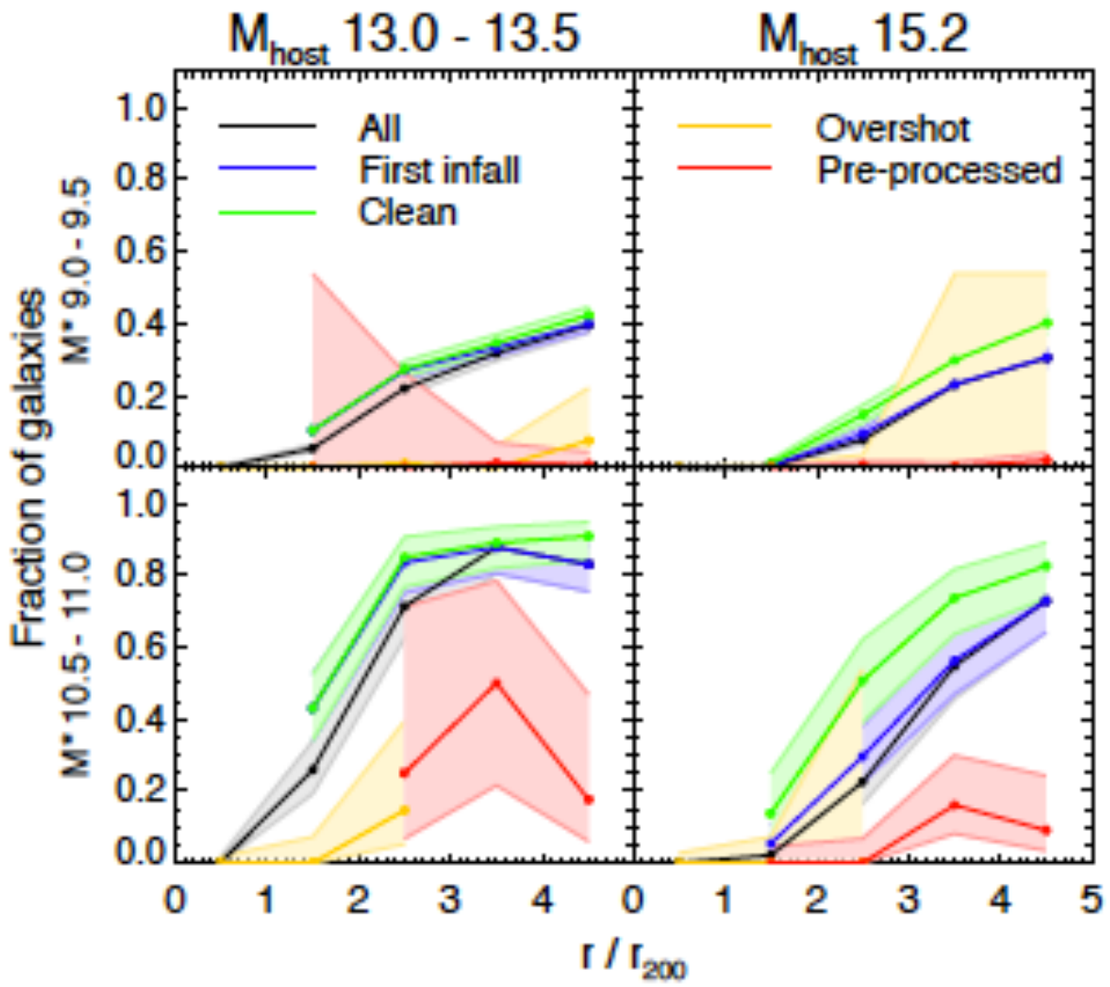
- *Backsplash population of centrals*

(see also Balogh+00, Mamon+04, Ludlow+11, Knebe +11, Wetzel et al. 2014)

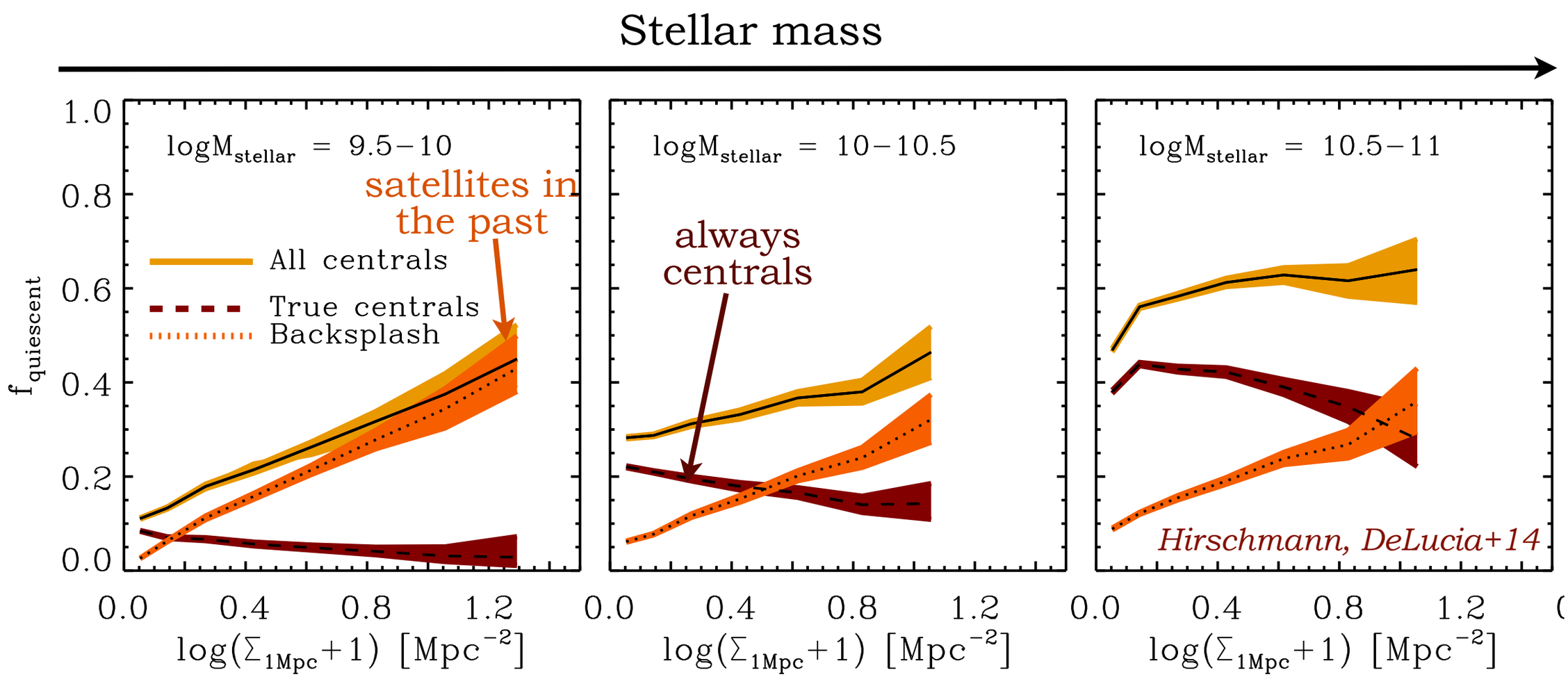
- *Direct interaction with an extended hot halo*

Fraction of galaxies with a hot gas fraction above 0.1

(Bahe+13)



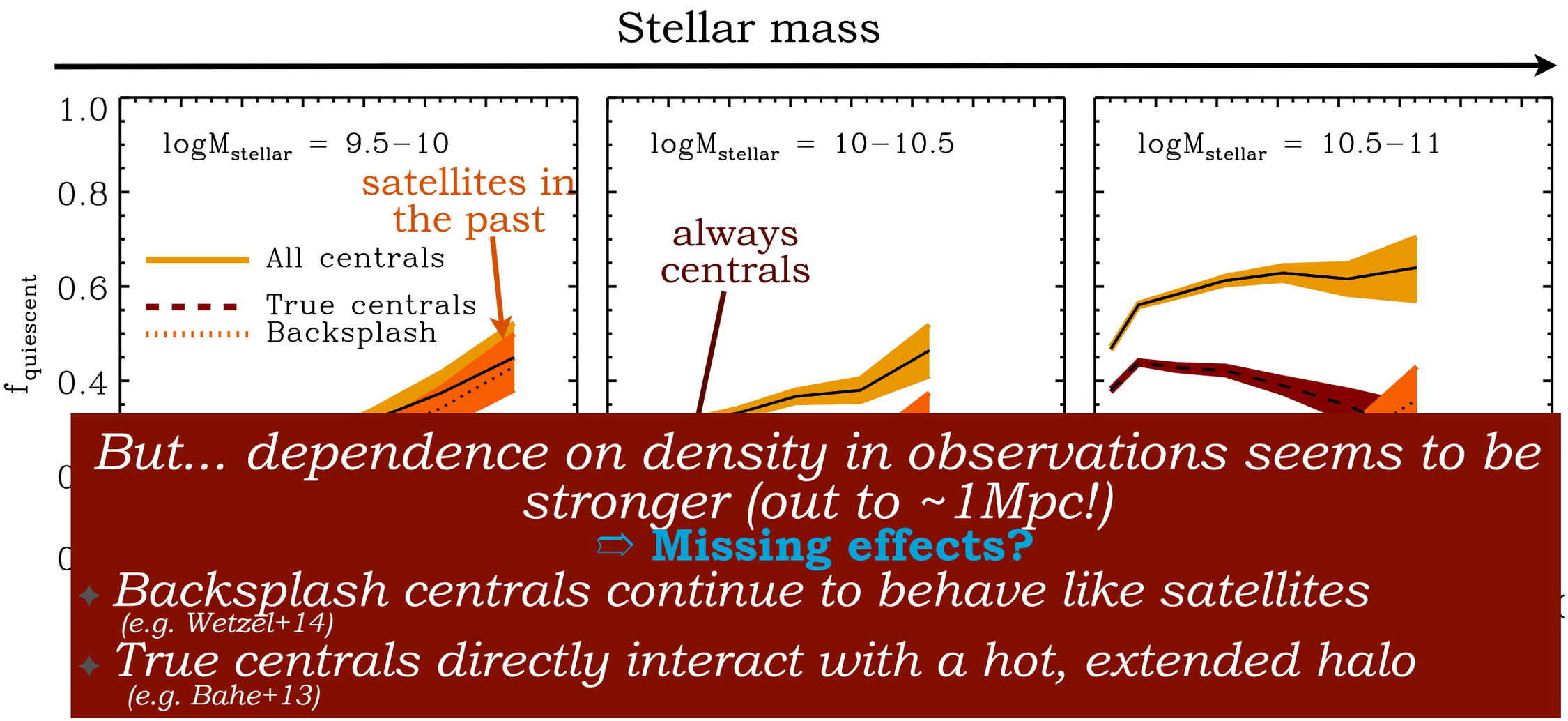
Backsplash population



- ***True centrals:*** *No dependence on density*
- ***Backsplash centrals:*** Responsible for *over-all density dependence ⇨ environment mainly relevant for low mass centrals at high densities*

  Spend on average *1.5-3 Gyrs* at *z=0.5-2* as a satellite (depending on density & mass)

Backsplash population



But… dependence on density in observations seems to be stronger (out to ~1Mpc!)

⇨ **Missing effects?**

- *Backsplash centrals continue to behave like satellites* *(e.g. Wetzel+14)*
- *True centrals directly interact with a hot, extended halo* *(e.g. Bahe+13)*

- ***True centrals:*** *No dependence on density*
- ***Backsplash centrals:*** Responsible for *over-all density dependence* ⇨ *environment mainly relevant for low mass centrals at high densities*

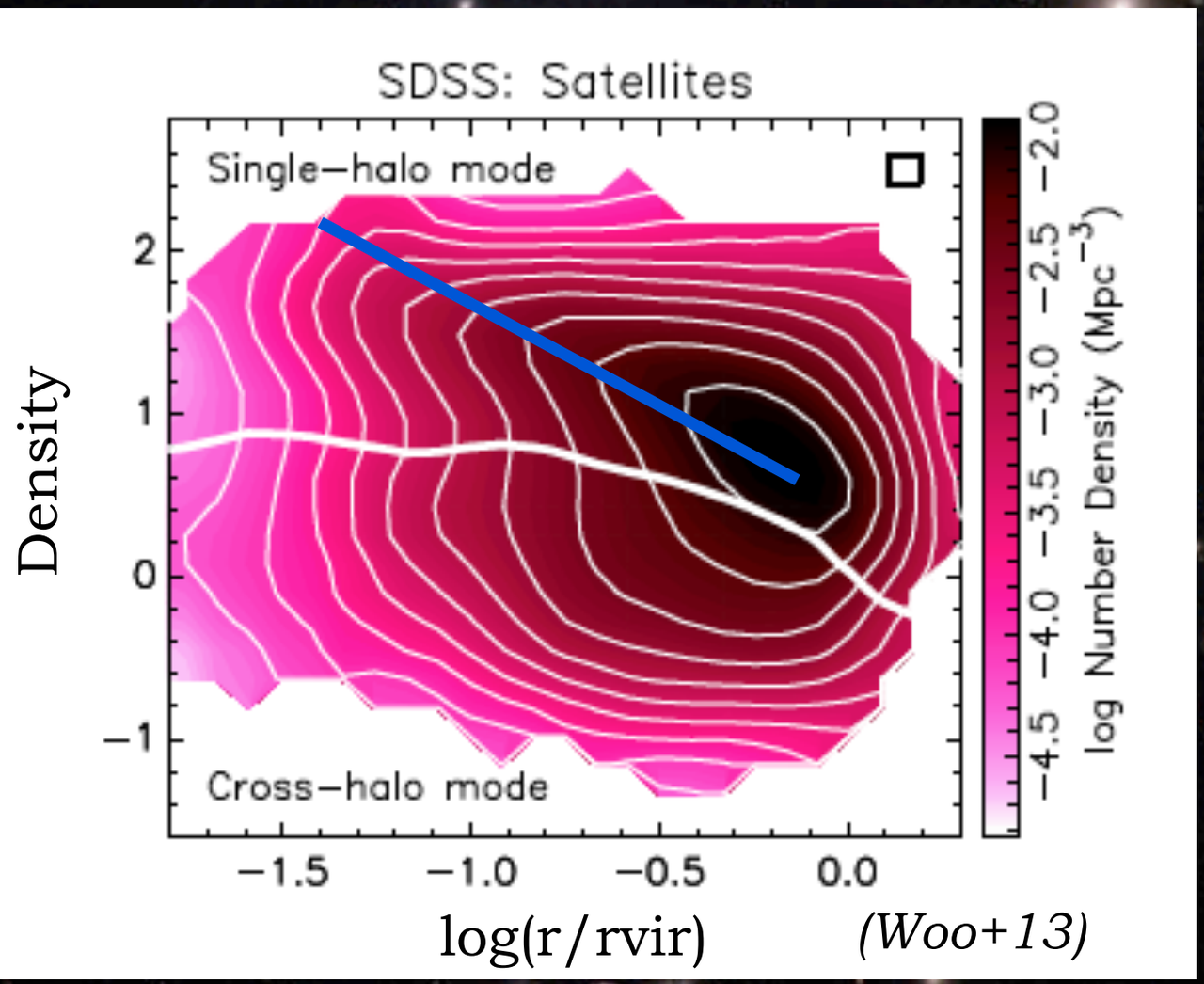
  Spend on average *1.5-3 Gyrs* at *z=0.5-2* as a satellite (depending on density & mass)

III. ***Satellite*** galaxies

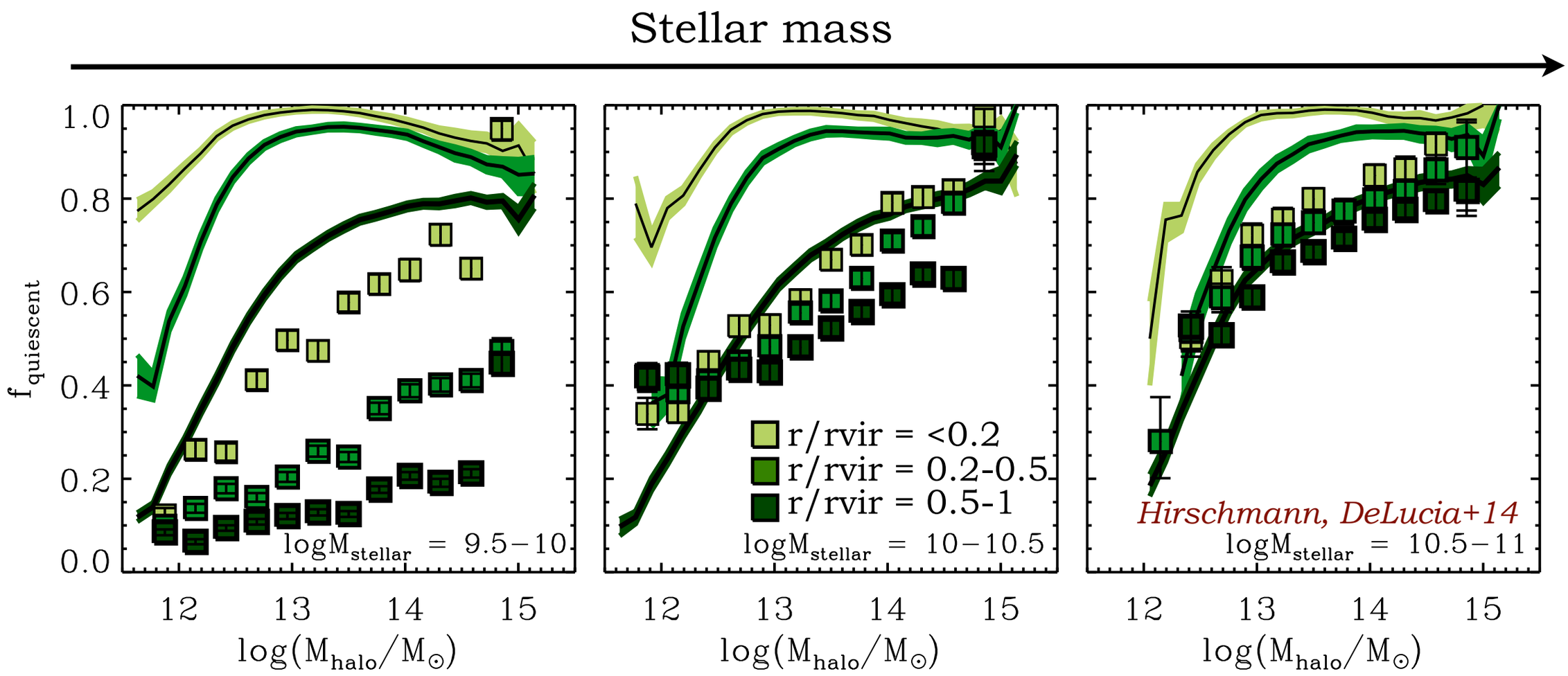
✦ … density correlates with parent halo mass

✦ density also correlates with the radial distance to the parent halo center

⇨ Density dependence is a *superposition of both halo mass & radial distance dependence*



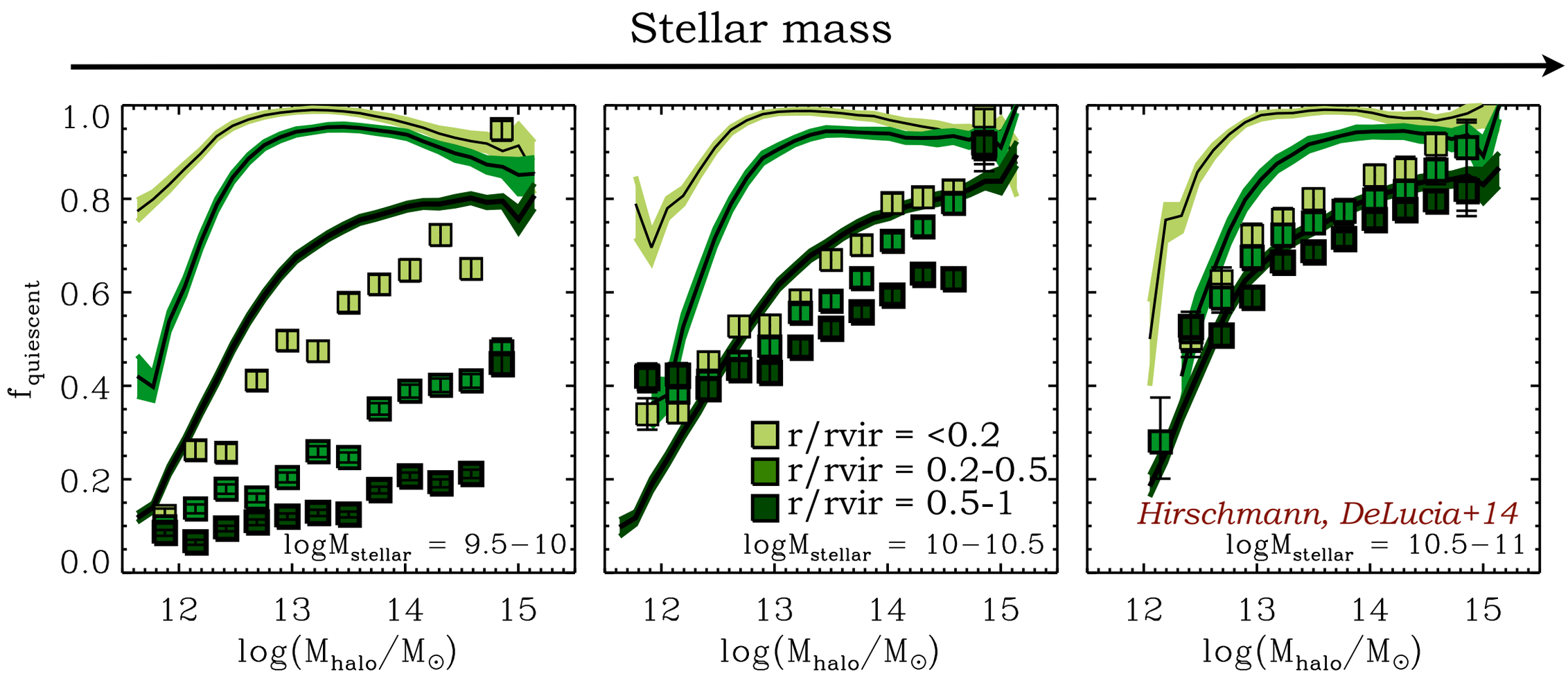
Radial distance to the halo center



Residual effects on the radial distance on top of halo mass

✦ *Observations: Environmental effects* mainly affecting *low-mass satellites in massive halos*

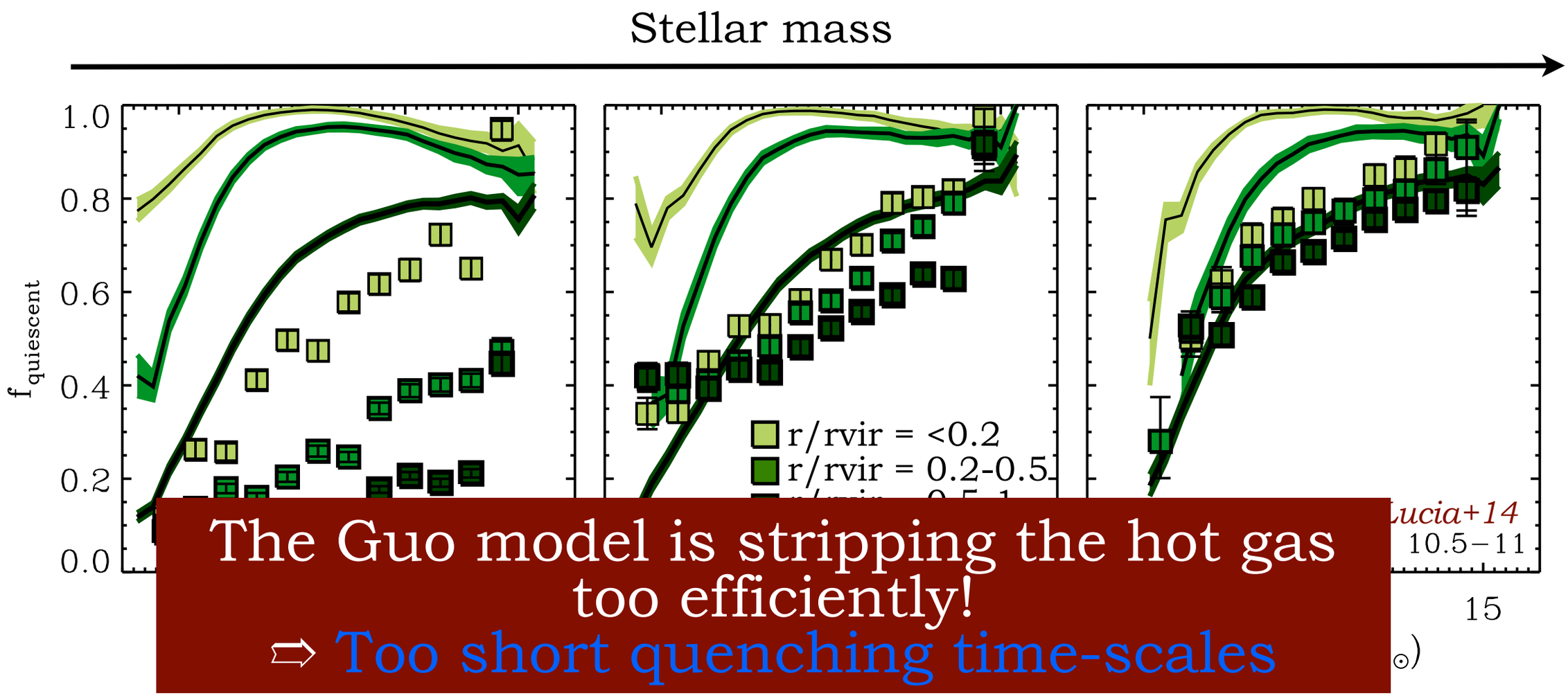
Radial distance to the halo center



Residual effects on the radial distance on top of halo mass

- *Observations: Environmental effects* mainly affecting *low-mass satellites in massive halos*
- *Models*: *Much stronger residual dependence* at all masses
  Quiescent fractions over-estimated, particularly in the innermost regions

Radial distance to the halo center



The Guo model is stripping the hot gas too efficiently!

⇨ Too short quenching time-scales

Residual effects on the radial distance on top of halo mass

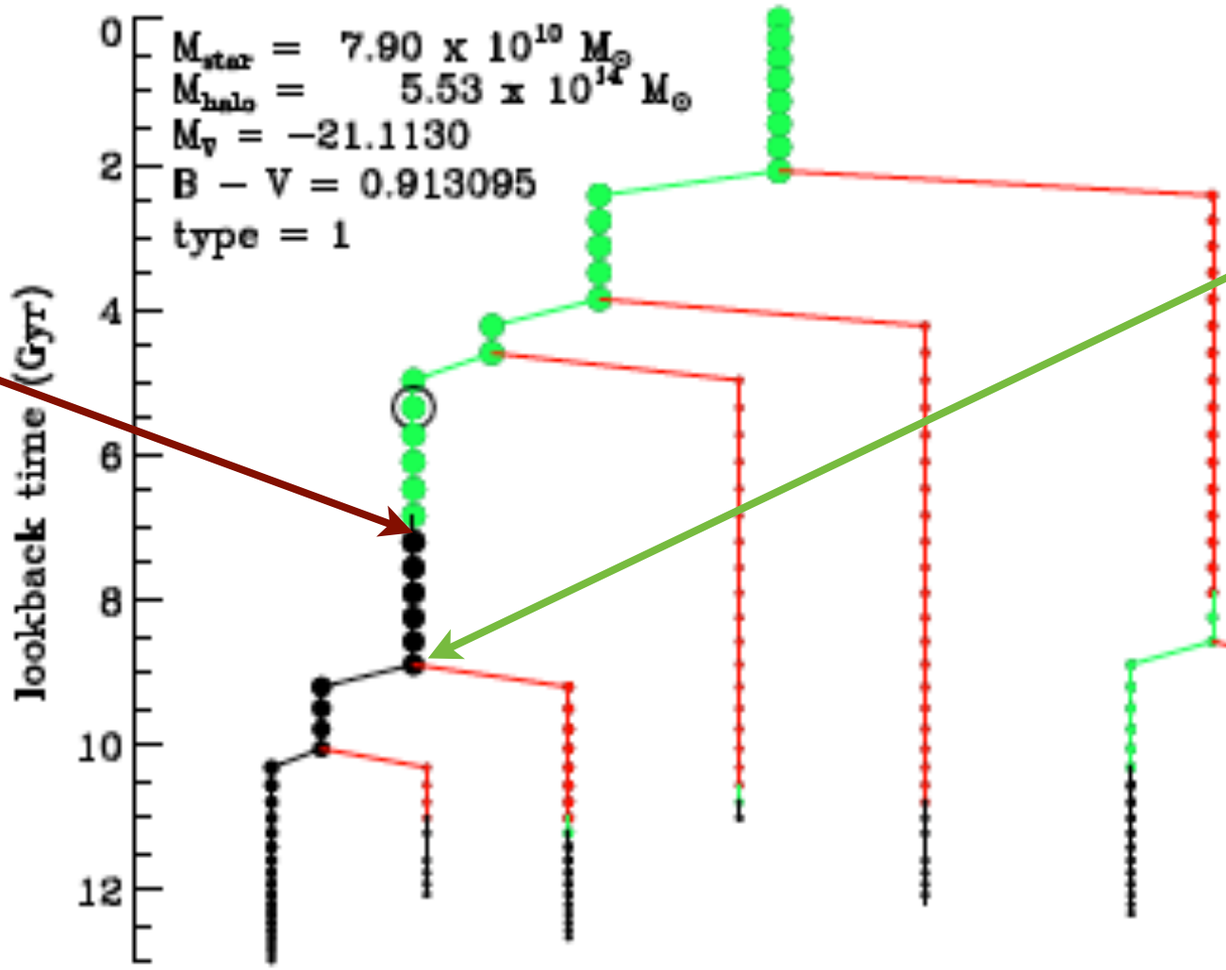
- *Observations: Environmental effects* mainly affecting *low-mass satellites in massive halos*
- *Models*: *Much stronger residual dependence* at all masses *Quiescent fractions over-estimated*, particularly in the innermost regions

Environmental history

Can we gain any information on the *typical time-scale* of *star formation quenching in satellites*?

Investigate the environmental history of galaxies…

galaxy was accreted onto the final parent halo



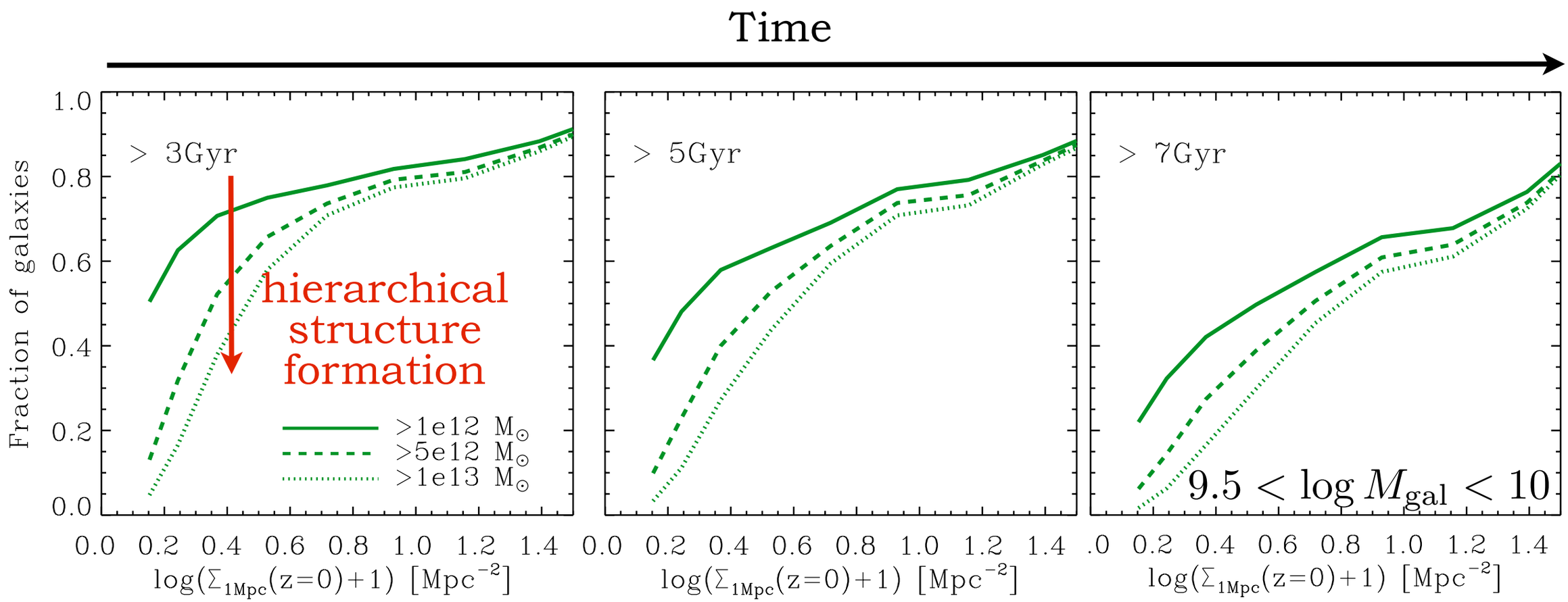
galaxy became the first time a satellite galaxy

- Using galaxy merger trees
- *How long has a satellite galaxy been living in a parent halo of a certain mass?*

Central
Type 1 satellite
Type II satellite

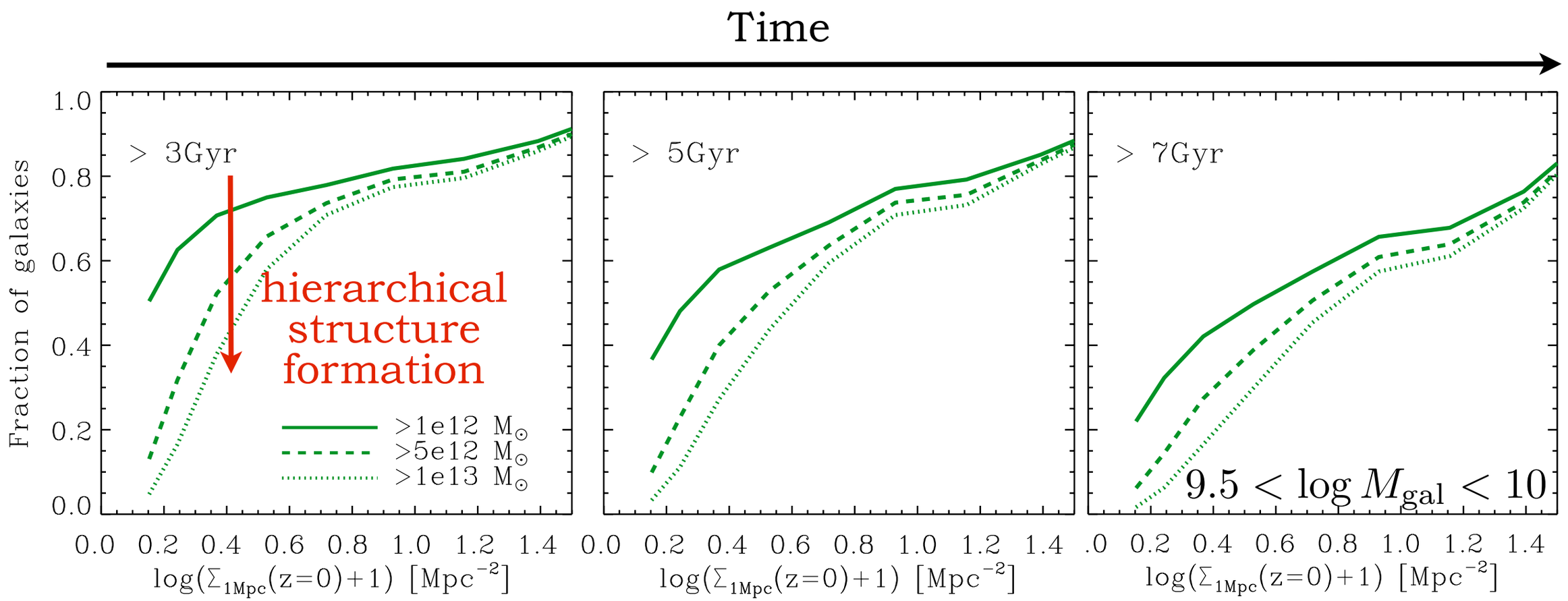
De Lucia+12

Environmental history



Lines: *'Environmental fractions'* vs the z=0 density = fraction of *model satellite galaxies* having been residing in *halos more massive than* 1e12, 5e12 or 1e13 $M_\odot$ *for a longer time than* 3, 5 or 7 Gyr

Environmental history



Lines: *'Environmental fractions'* vs the z=0 density = fraction of *model satellite galaxies* having been residing in *halos more massive than* 1e12, 5e12 or 1e13 $M_\odot$ *for a longer time than* 3, 5 or 7 Gyr

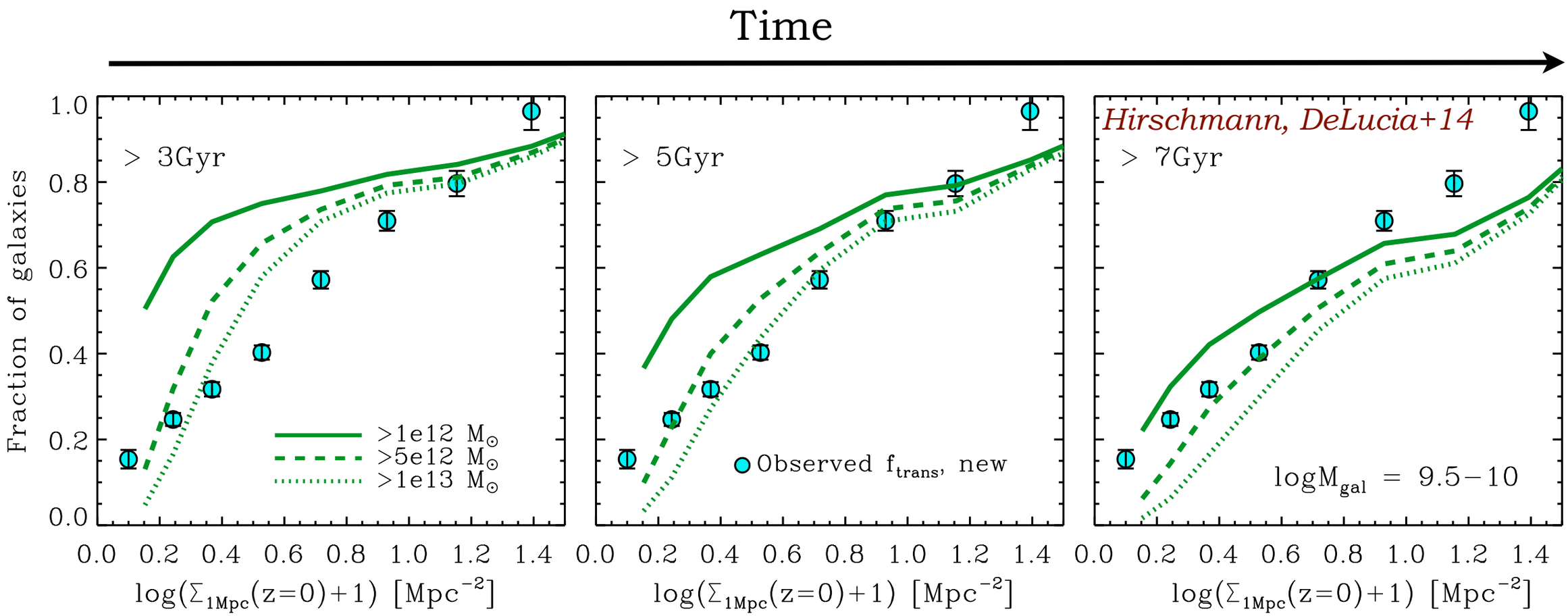
compare with

Observed transition fraction

(*van den Bosch et al., 2008 and Peng et al., 2011*) i.e. *"the probability of satellites getting quenched after being accreted"*:

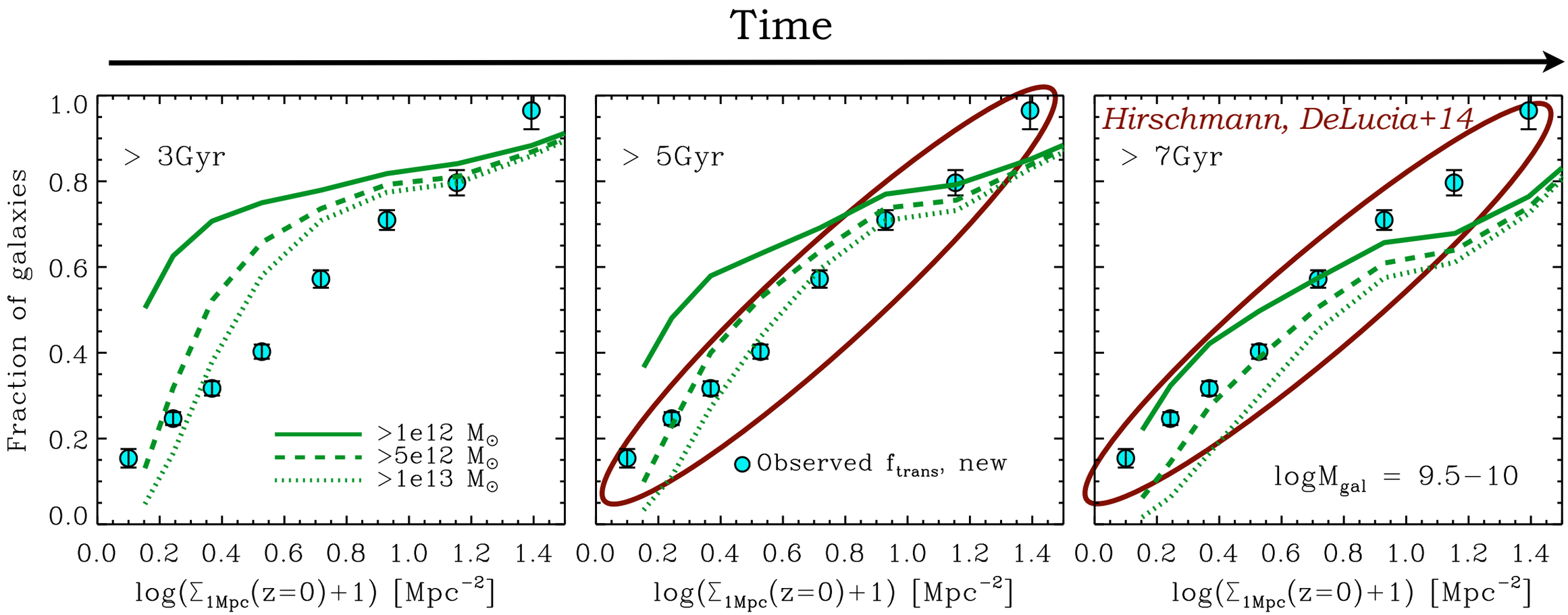
$$f_{\rm trans} = \frac{f_{\rm qu,sat}(z=0) - f_{\rm qu,cent}(t_{\rm inf})}{f_{\rm sf,cent}(t_{\rm inf})}$$

Quenching time-scales



Lines: *'Environmental'* fractions
of *model satellite galaxies*
Symbols: *Transition fractions*
from observations

Quenching time-scales



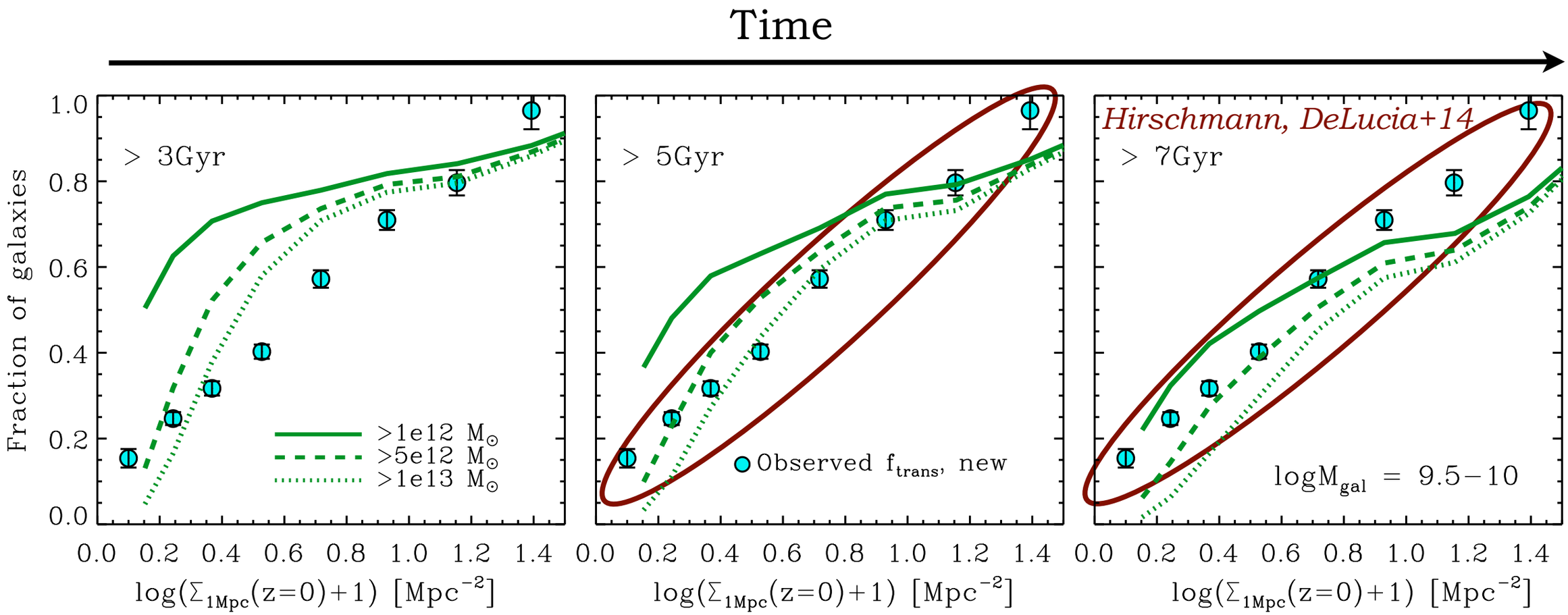
Lines: *'Environmental'* fractions of *model satellite galaxies*

Symbols: *Transition fractions* from observations

Implication:
Long quenching timescales for low-mass satellites: ***5-7 Gyr***

Very gentle mode of strangulation/ stripping

Quenching time-scales



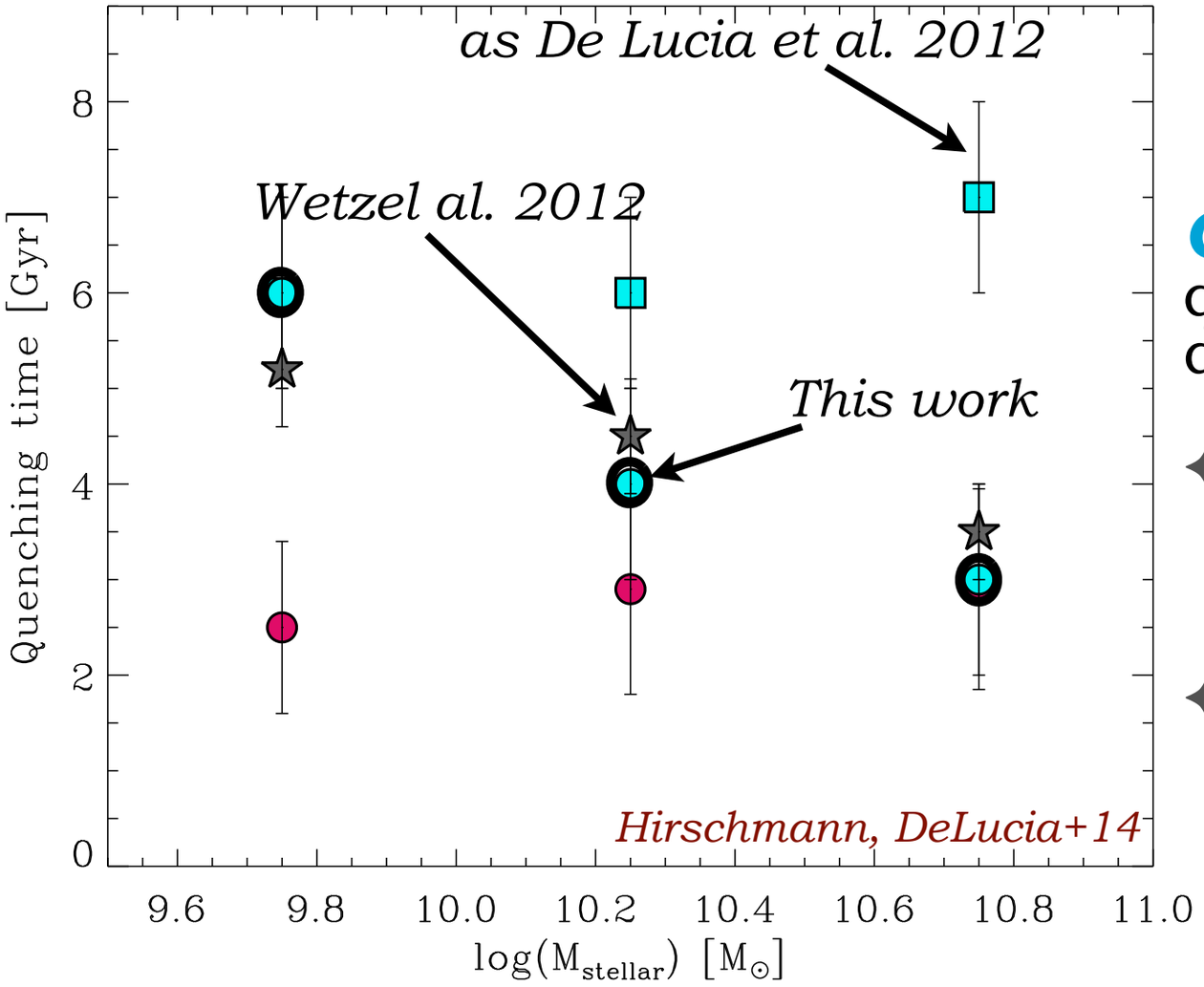
Lines: *'Environmental'* fractions of *model satellite galaxies*

Symbols: *Transition fractions* from observations

Implication:
Long quenching timescales for low-mass satellites: ***5-7 Gyr***

Very gentle mode of strangulation/ stripping

Stellar mass dependence



Circles: Increasing quenching time-scales with decreasing stellar mass

- stronger internal quenching effects for massive satellites
- longer dynamical friction time-scales for less massive satellites

For low mass satellites consistent with De Lucia+12
Fully consistent with Wetzel+12 (HOD)

Conclusion

Challenges:

Current models (with similar prescriptions as the Guo model) *cannot predict observed environmental trends*

*More **continuous transition** between centrals & satellites!*

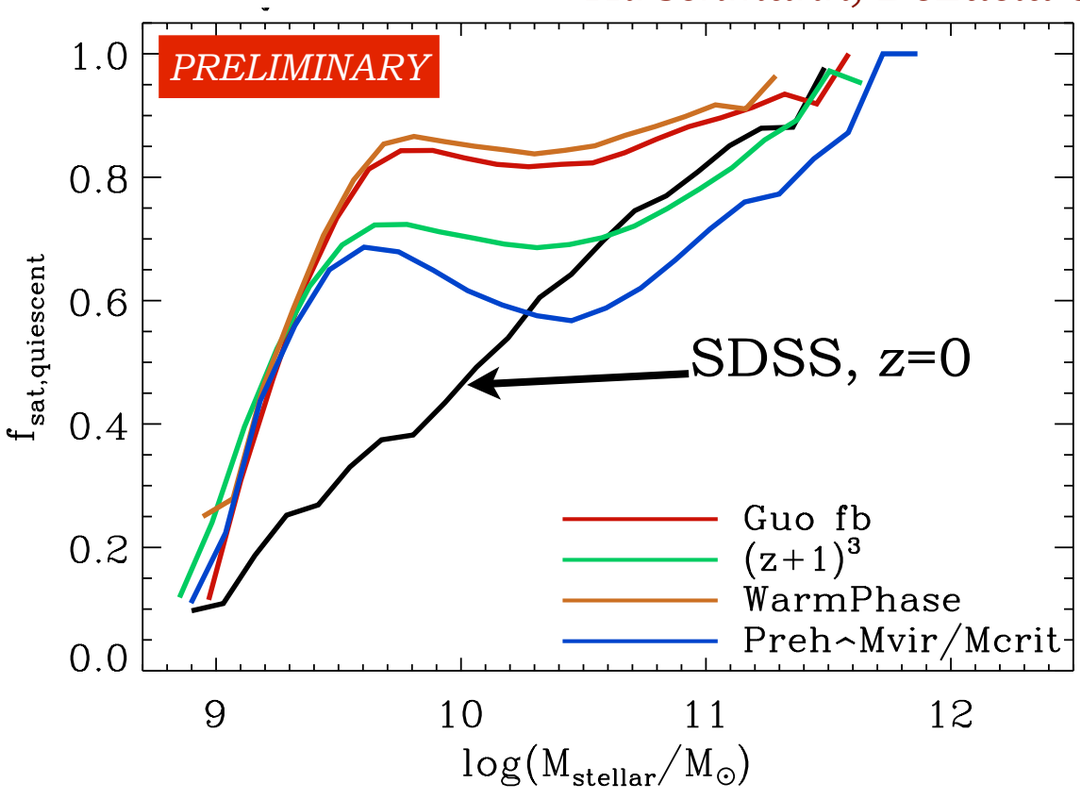
1. *Environmental effects* important for *low mass* ***Centrals*** out to ~1Mpc
   - ⇨ Non-negligible fraction of *backsplash centrals*
   - ⇨ Additional effects in the models?

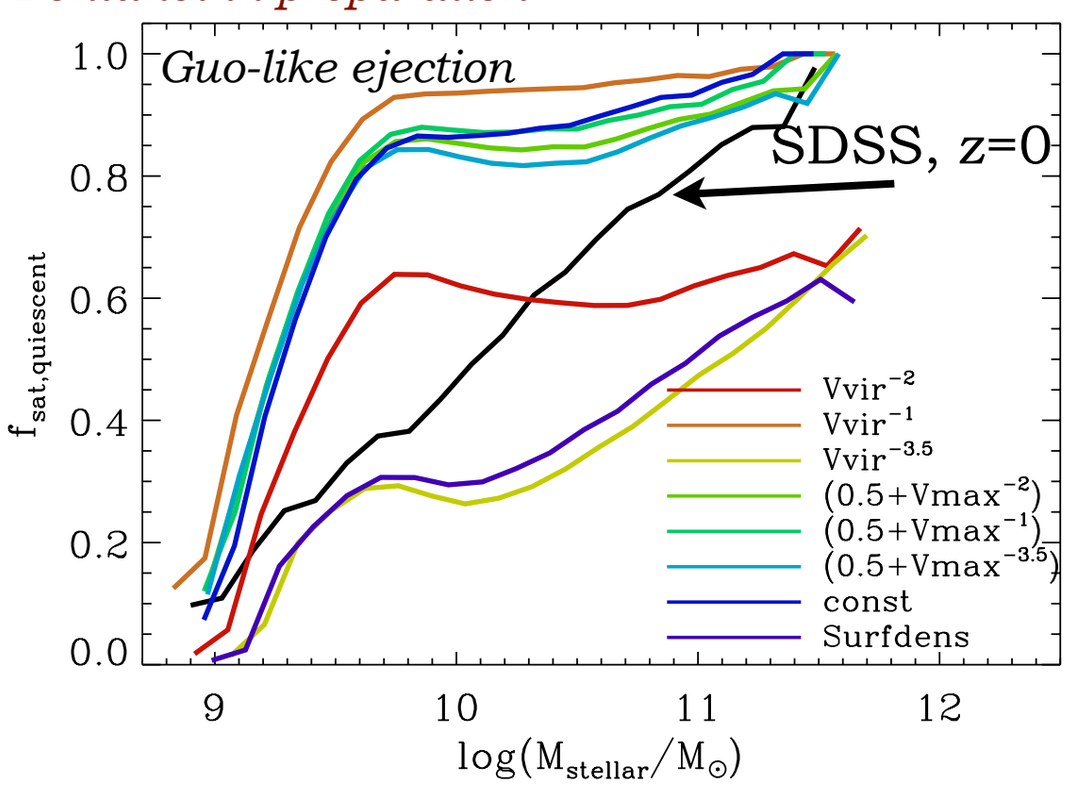
2. ***Satellites:*** *Environmental histories* indicate *long quenching time-scales (5-7Gyrs)* in low-mass sats
   - ⇨ modifying recipes for ***internal*** & environmental processes (dep. on dynamical friction time-scales?)

Outlook…

Effect of stellar feedback

Hirschmann, DeLucia & Fontanot in preparation





- Changing stellar feedback can have a significant *effect on the quiescent satellite fraction*:
  - If star formation is delayed due to fb in low mass galaxies, infalling galaxies are younger and contain more gas
  - Reducing the quiescent satellite fraction!

EVOLVING GALAXIES IN EVOLVING ENVIRONMENTS
15-19th September 2014, Bologna

Thank you