Constraints on quenching from the galaxy population
and
an update on environmental effects in SDSS and the role of conformity**

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**based on Knobel, SJL, Woo, Kovac 2014 arXiv1408:2553

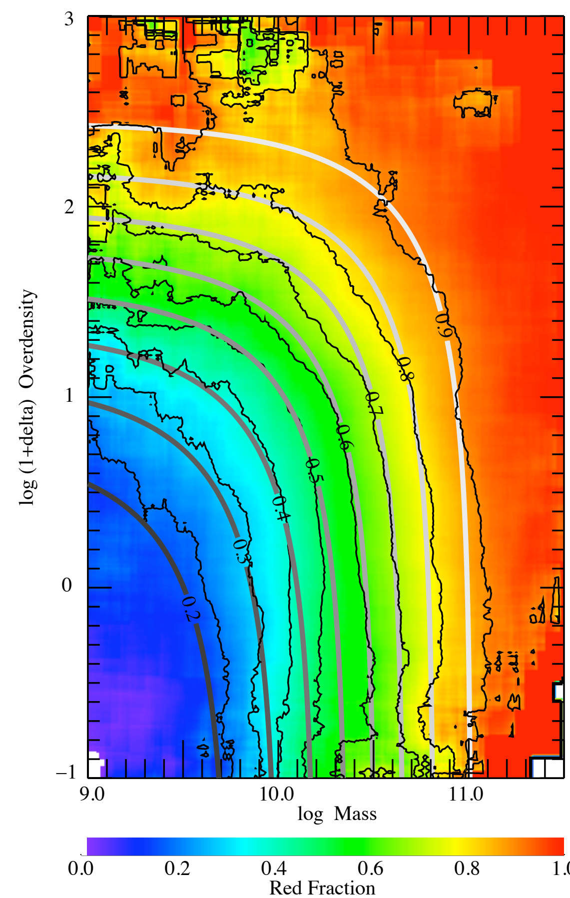
Separability of $f_{red}(m_{star},\rho)$ in m_{star} and ρ (Peng et al 2010)

environment
quenching
(=satellites)

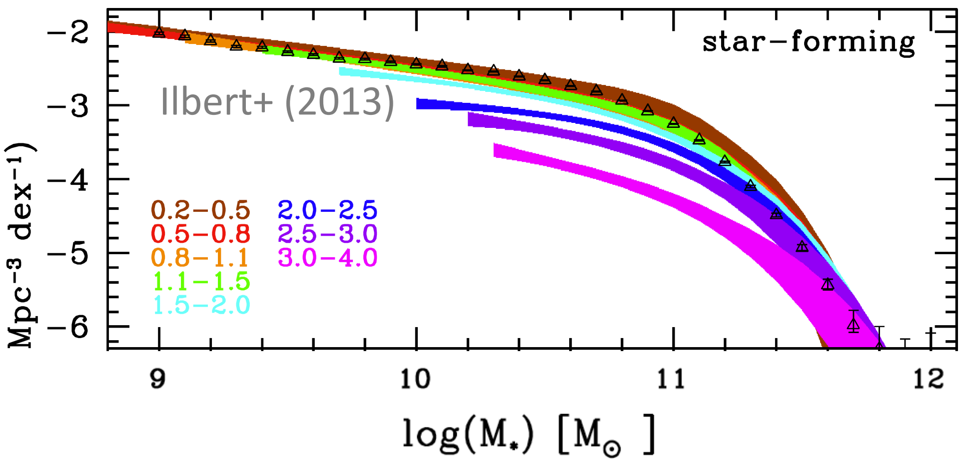
$$\boxed{f_{blue}(m,\rho) = \left(1-\varepsilon_m(m)\right)\times\left(1-\varepsilon_\rho(\rho)\right)}$$

mass quenching

Only mass quenching depends on mass, and therefore it is that process that controls the mass function of the surviving star-forming galaxies



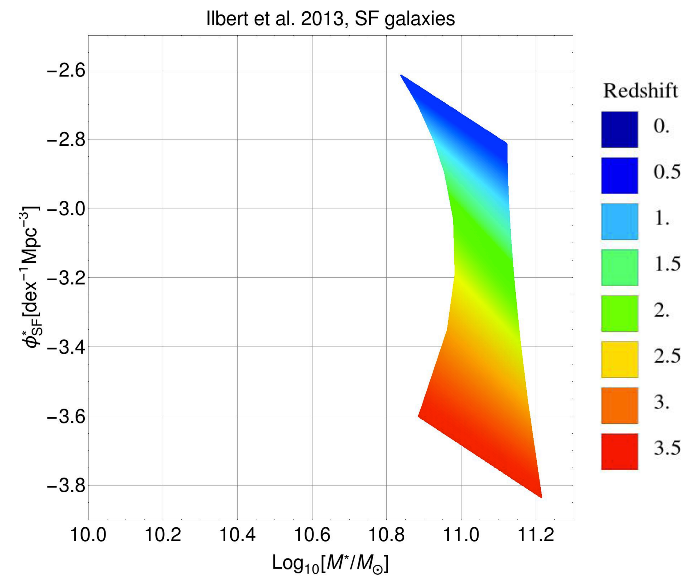
The evolution of $\phi(m)$ of SF galaxies: constant M* (Peng et al 2010, 2012)

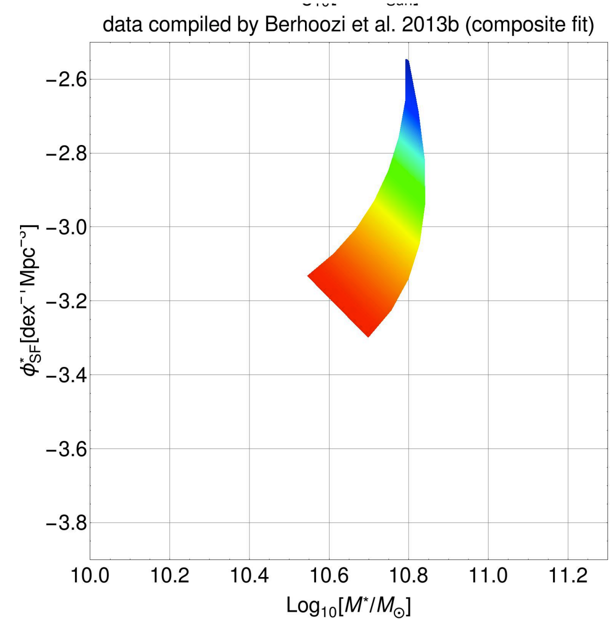


continuity equation gives two terms to quenching rate (Peng et al 2010, 2012)

$$\boxed{\eta = \frac{1}{M^*}\cdot SFR + \varepsilon_{sat}\left(sSFR + \frac{\partial f_{sat}}{\partial t}\right)}$$

Constant M* implies that the mass-scale of (mass) quenching is ~ the same over 0 < z < 4

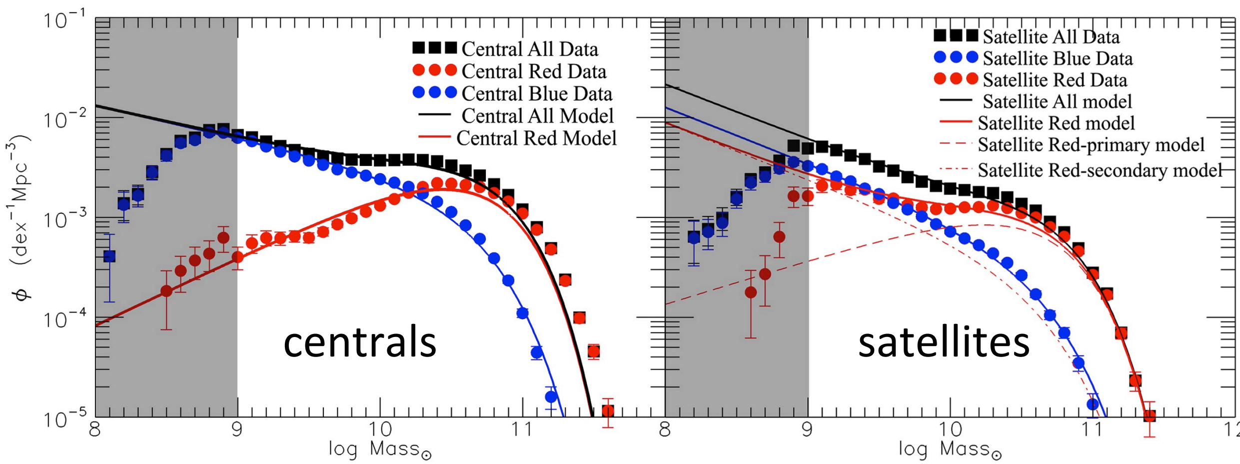




Production of mass functions of passive galaxies (Peng et al 2010, 2012)

SF population with constant M* and α ~ -1.45 (and evolving ϕ*) produces

- "mass-quenching" same M* and α ~ −0.45
- "satellite-quenching" same M* and α ~ −1.45



from Peng et al (2012)

Sample	log (M*/M$_\odot$)	ϕ_1*/10^{-3}Mpc^{-3}	α_1	ϕ_2*/10^{-3}Mpc^{-3}	α_2
Blue central	10.61±0.01	...	...	0.827±0.030	-1.32±0.02
Red central	10.70±0.02	2.23±0.08	-0.33±0.04	...	...
Blue satellite	10.59±0.02	...	...	0.196±0.013	-1.56±0.03
Red satellite	10.61±0.02[a]	0.935±0.07	-0.49±0.08	0.130±0.042	[-1.5][a]

Conclusion: <u>Average</u> increase in the mass of passive central galaxies *during quenching or after they have been quenched* is ≤ 50%

Numbers of "quenching objects" (Peng et al 2010)

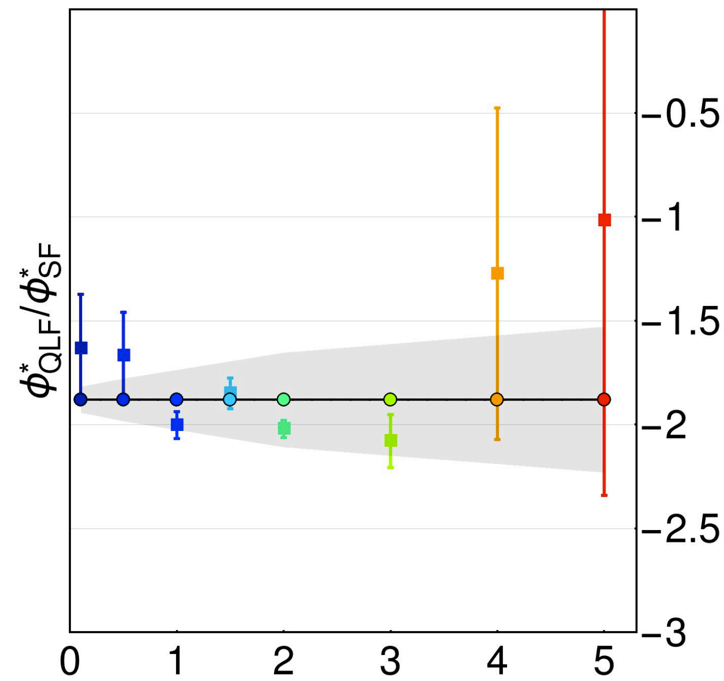
Mass function of objects that are seen in process of (mass) quenching

$$M^* = M^*_{SF} = M^*_{passive}$$

$$\alpha = \alpha_{passive} \approx (\alpha_{SF} - 1)$$

$$\phi^* = \phi^*_{SF} \times (sSFR \times \tau_{vis})$$

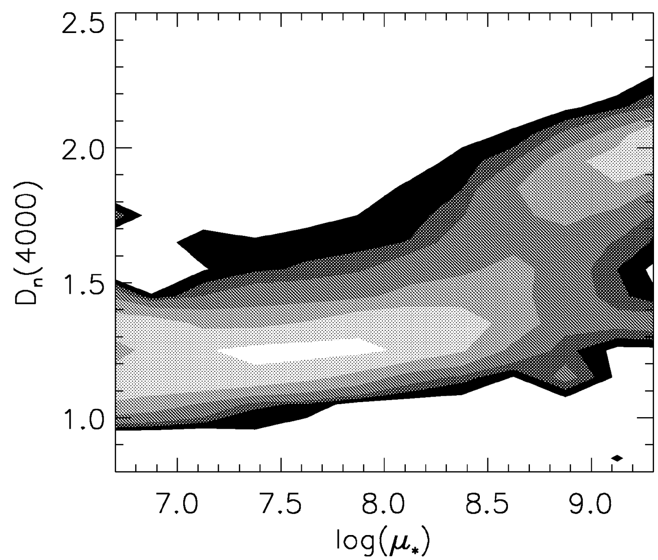
Constant duty cycle: No sign of expected increase with redshift if AGN doing the quenching??
Test should be applied to any quenching candidates



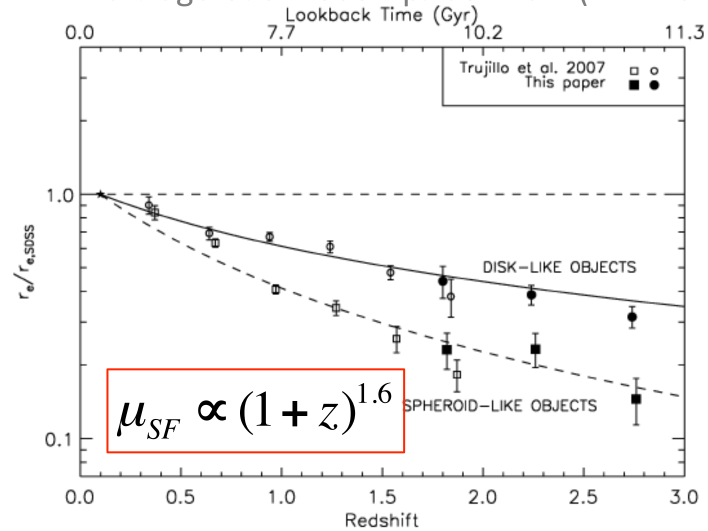
Analysis of Hopkins et al XLF (fit with constant faint-end slope). Constant "duty cycle" Neven Caplar in preparation

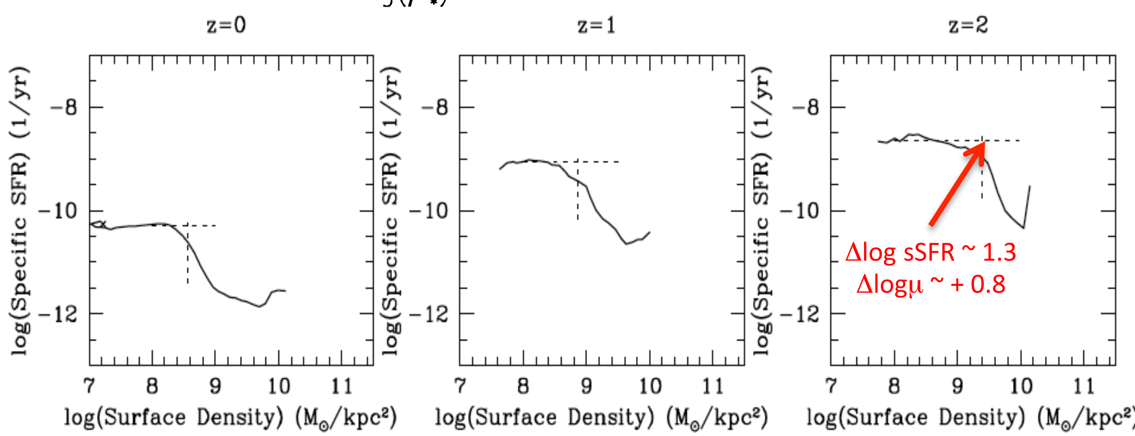
Surface density thresholds for quenching at different redshifts

Kauffmann et al 2003, MNRAS, 341, 54



Buitrago et al 2008 ApJ 687 L61 ($M > 10^{11}$ M_O)





Similar relations hold to z ~ 3, with evolution in sSFR and threshold (from Franx et al, 2008, ApJ, 688, 770)

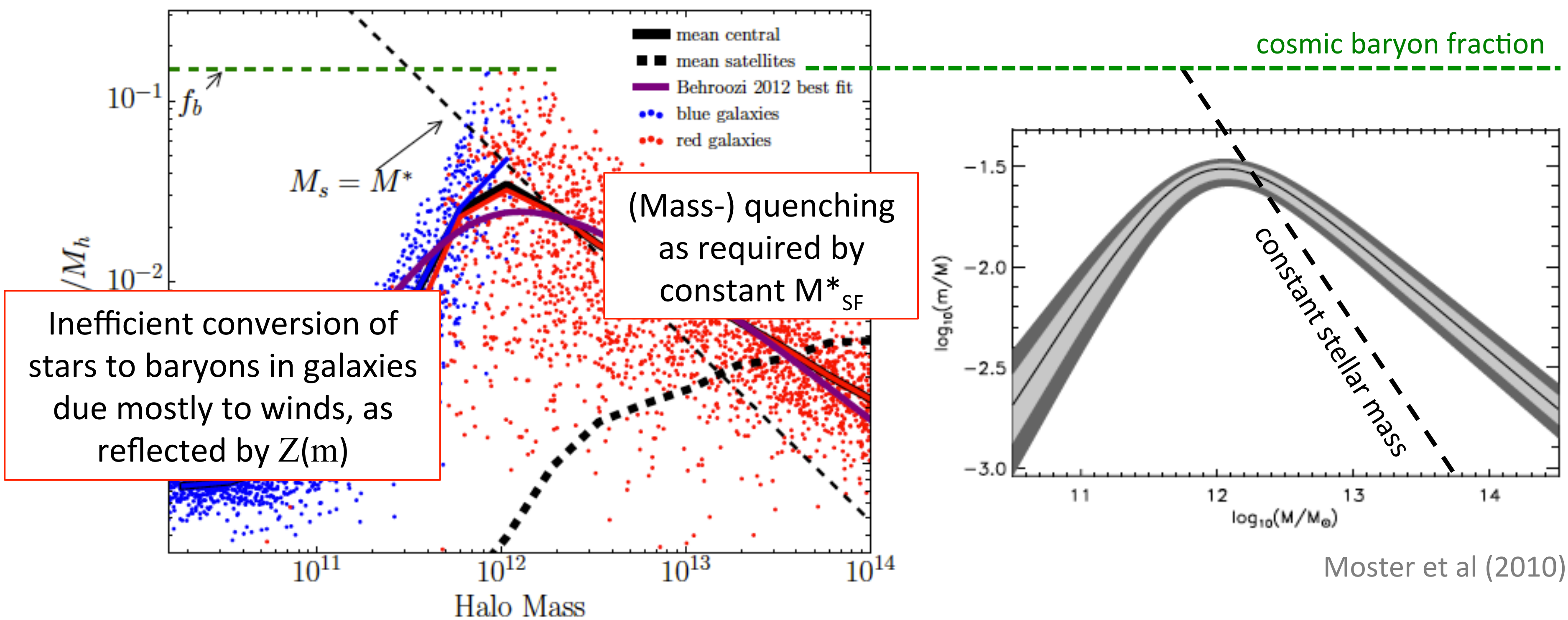
$$\mu_{crit} \propto (1+z)^{1.6}$$

Observed strong change in $\mu_{SF}(z)$:

- $\mu_{crit}(z)$ tracks $\mu_{SF}(z)$
- why quenched will generally have higher μ than still SF
- strong progenitor-bias effects in $r_{0.5}(z)$ of quenched galaxies (Carollo et al 2013)

Last point: the “co-incidence” of quenching? Birrer et al 2014

Birrer et al (2014)



Moster et al (2010)

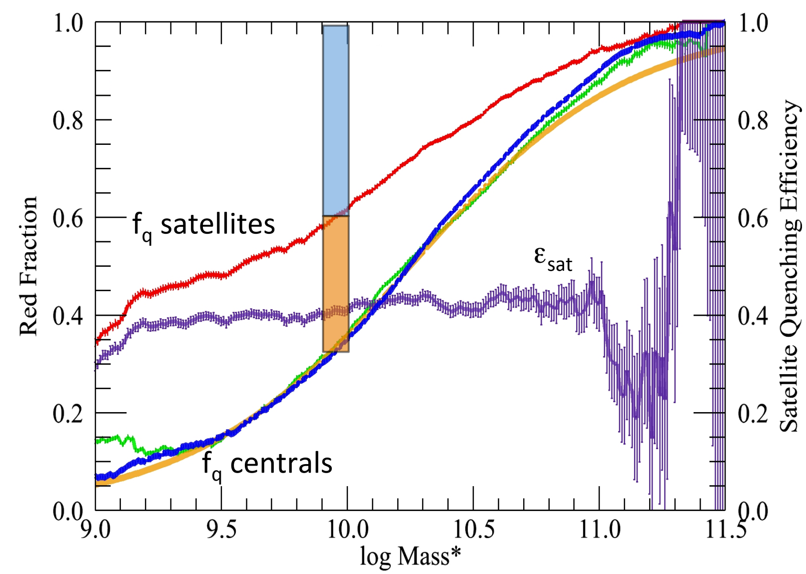
“Quenching” happens just as m_{star}/m_{halo} first approaches to within a factor of a few of the cosmic baryon fraction, when we also start to get “groups” of massive galaxies

Satellite quenching efficiency

(vandenBosch+08, Peng+10,+12 …..)

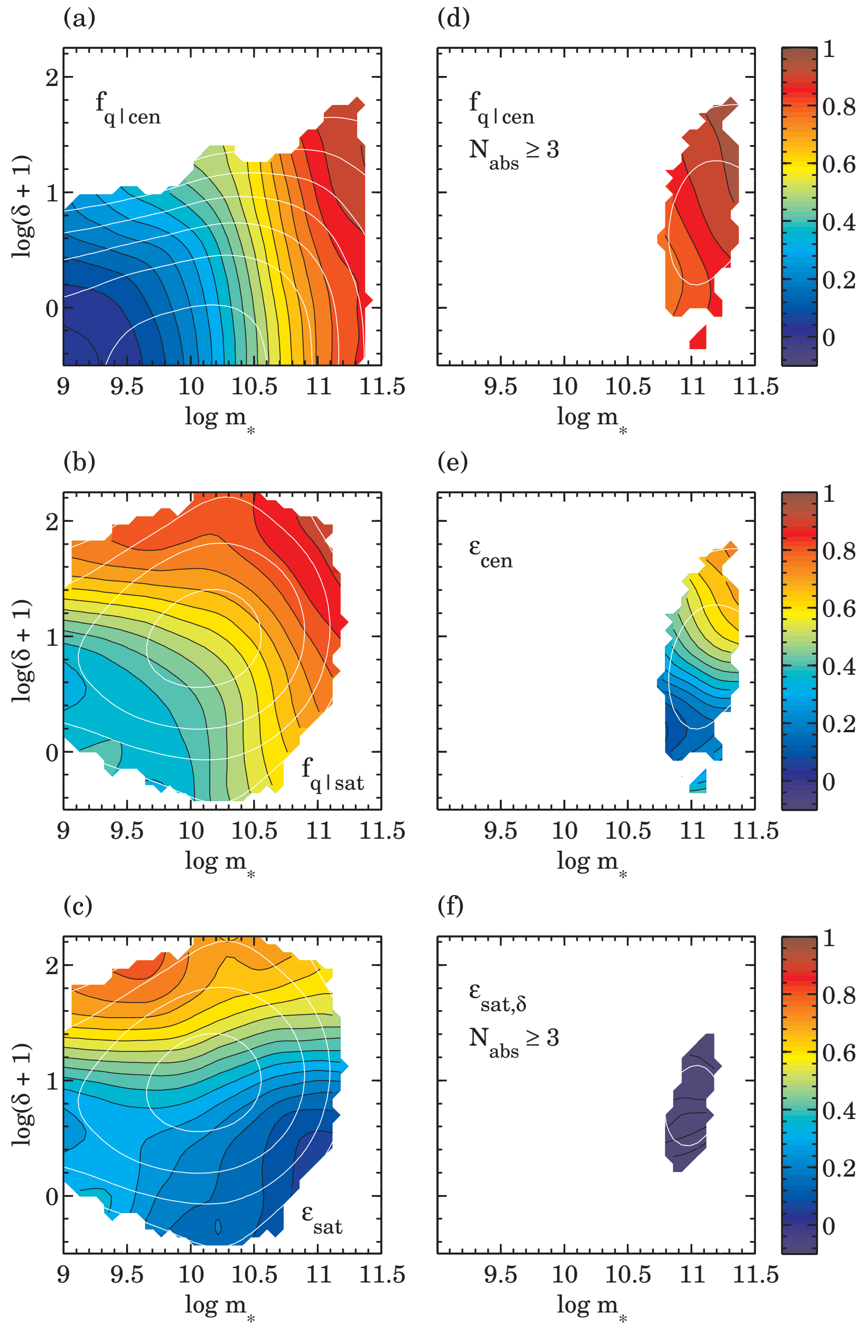
$$\varepsilon_{sat}(m_*, p_1, p_2 \ldots) = \frac{f_{q|sat}(m_*, p_1, p_2 \ldots) - f_{q|cen}(m_*)}{f_{q|cen}(m_*)}$$

- Loosely, ε_{sat} is the probability that a SF central is quenched when it becomes a satellite of something else
- "takes out" the effect of mass (as given by centrals) to isolate effects of environment



New object-by-object estimator $$\varepsilon_{sat}(m_*, \mathbf{p}) = \langle \varepsilon_i \rangle = \left\langle \frac{q_i - f_{q|cen}(m_{*,i})}{1 - f_{q|cen}(m_{*,i})} \right\rangle$$

Re-examining the central-satellite paradigm

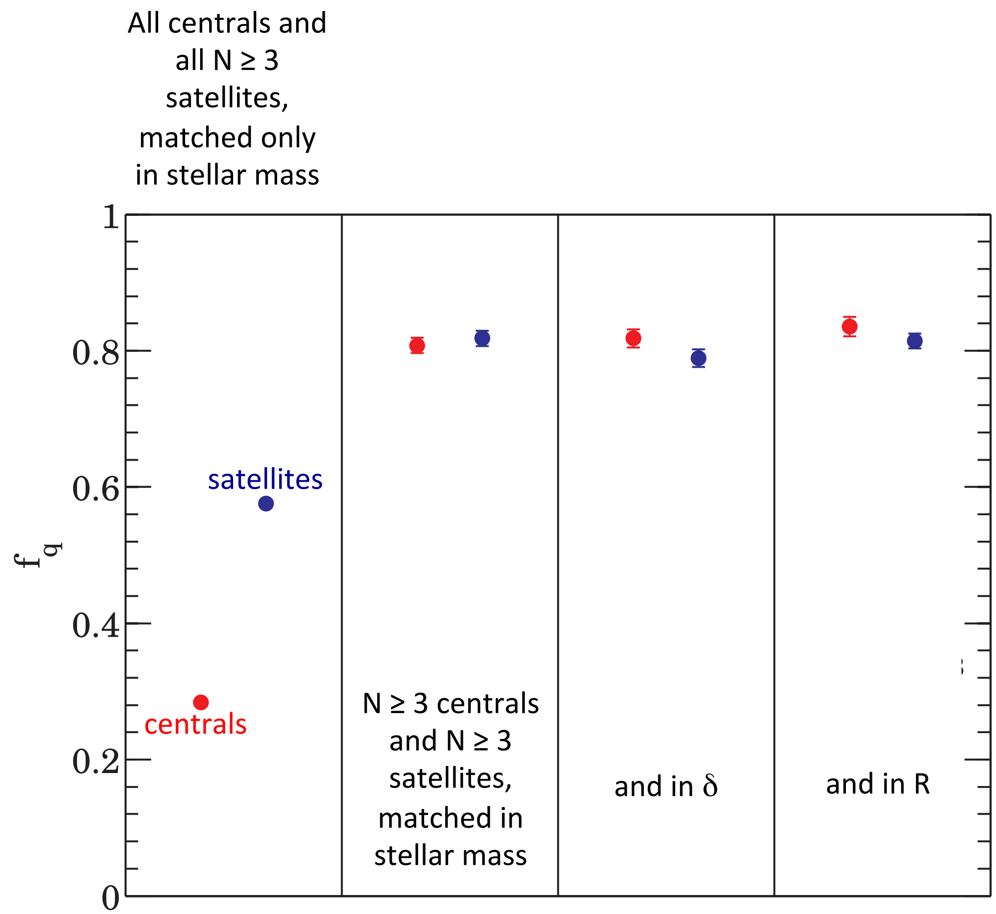


$f_{q|cen}$ just for centrals in N ≥ 3 groups

ε for centrals in N ≥ 3 groups computed as for satellites (i.e. relative to all centrals): same as ε_{sat}

ε_{sat} for satellites computed relative to centrals in N ≥ 3 groups: close to zero

Difference in f_q of centrals and satellites (producing ε_{sat} ~ 0.4 in vandenBosch+08 Peng+12 etc) disappears when we compare satellites with centrals of the same groups (N ≥ 3)

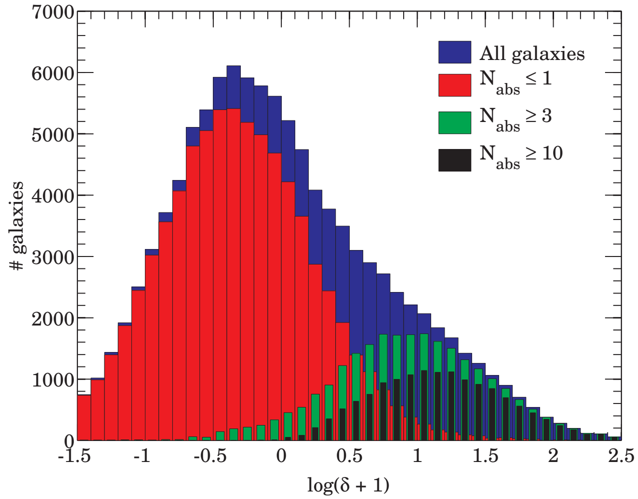


Conclusions so far

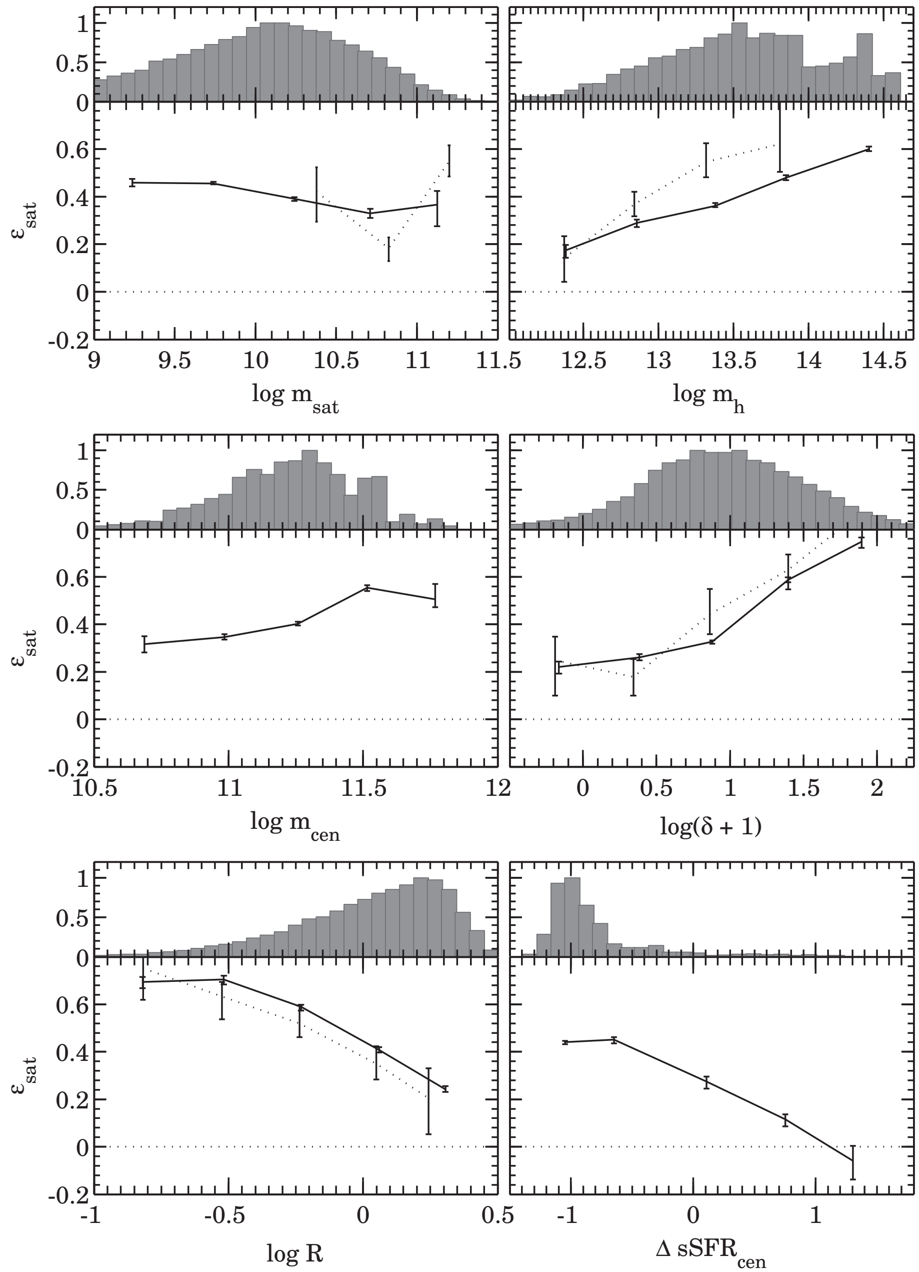
- Centrals of the groups containing the satellites feel the same environmental quenching effects as the satellites relative to field (isolated) centrals (caveat: in the same parameter range)

- It is still true that "satellites dominate the environmental effects in the overall population" because $N_{cen} >> N_{sat} >> N_{cen,groups}$

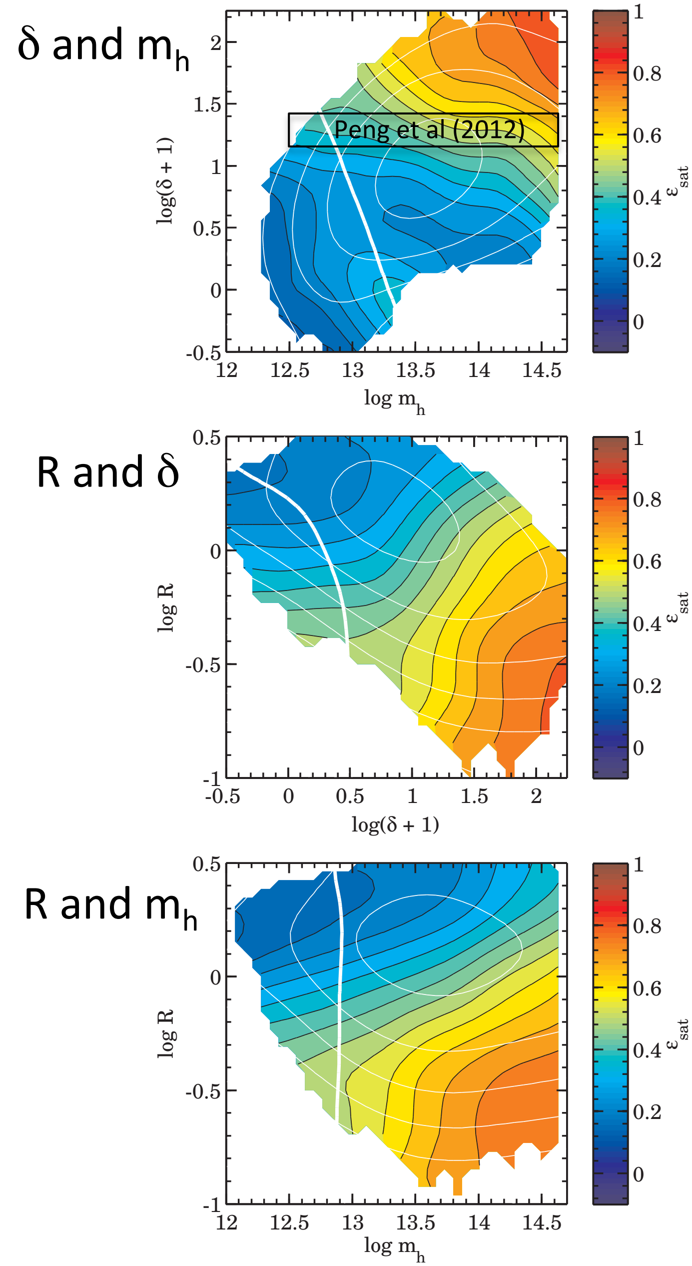
- But we can include centrals as well as satellites in a general concept of "group-quenching" to explain the environment-quenching
  Argument against satellite-only effects like ram-stripping?



Variation of ε_{sat} in 1-d in m_{sat}, m_h, m_{cen}, δ, R and $sSFR_{cen}$



Variation of ε_{sat} in 2-d



Summary of ε_{sat}(....)

- All of R, δ and m_h are playing a role in quenching satellites: m_{sat} (and m_{cen}) do not (as seen before). Different parameters dominate in different regions of parameter space, plus there are observational issues with all three (also in different regions of parameter space). All largely seen before… (Peng+12, Woo+12.. etc)

- Importance of the sSFR of the central (for the few groups with SF centrals). *"Conformity".* Also as in Weinmann et al (2006)

Galaxies as (not) probabilistic systems

Observed fraction of systems quenched ⟷ "probability of quenching"

Galaxies are (probably) not probabilistic systems. The apparent probabilistic aspect of quenching reflects <u>incomplete knowledge</u>, i.e. the presence of "hidden variables" which could be e.g.

- known and measured but not yet considered in the analysis
- not yet astrophysically measurable (shocks etc)
- not measurable e.g. due to the complexity of the system
- unimagined
- residuals from measurement uncertainties

The meaning of conformity

The quenched fraction of satellites is correlated with the quenched state of their central (even when matched in halo mass) Weinmann et al (2006)

A correlation between quenching of satellites and centrals can arise quite trivially if the quenching of centrals and satellites both depend on some parameter which is "shared" between a given central and its satellites (e.g. halo mass but including any correlated parameter).

But it is easy to see that such a correlation will disappear if the quenching of the satellites is studied at a single value of that parameter or, equivalently, if the two samples of satellites (with and without quenched centrals) are carefully matched in that parameter (as Weinmann et al did for m_h), i.e. that parameter is "unhidden" or "exposed"

The meaning of conformity

The quenched fraction of satellites is correlated with the quenched state of their central (even when matched in halo mass) Weinmann et al (2006)

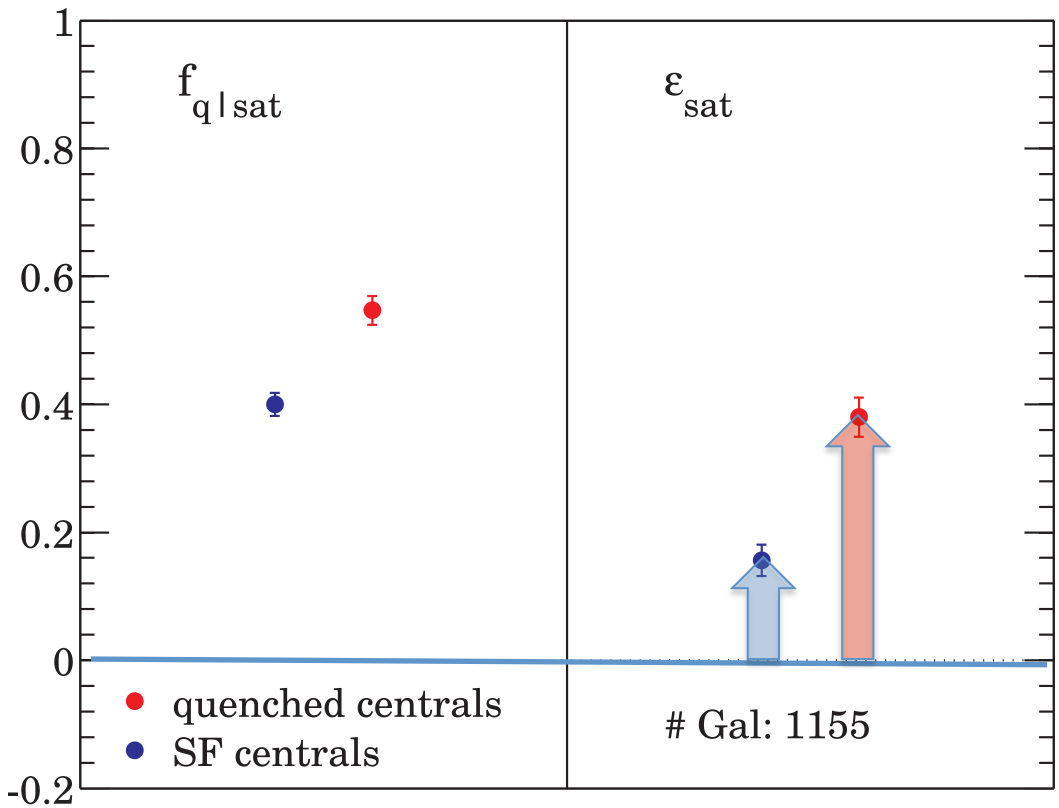
The existence of conformity in a sample tells us that there is still an additional unknown "*hidden common variable*" that is

- effecting the quenching of both satellites and centrals
- shared in some way by the central and satellite
- still hidden (in the sense of "not-matched") so that distributions are in fact different for satellites of SF and quiescent centrals
- "orthogonal" to the currently exposed variables (also measurement errors)

Note: "Conformity" therefore depends on the sample(s) and the analysis

Conformity persists even when matching many variables

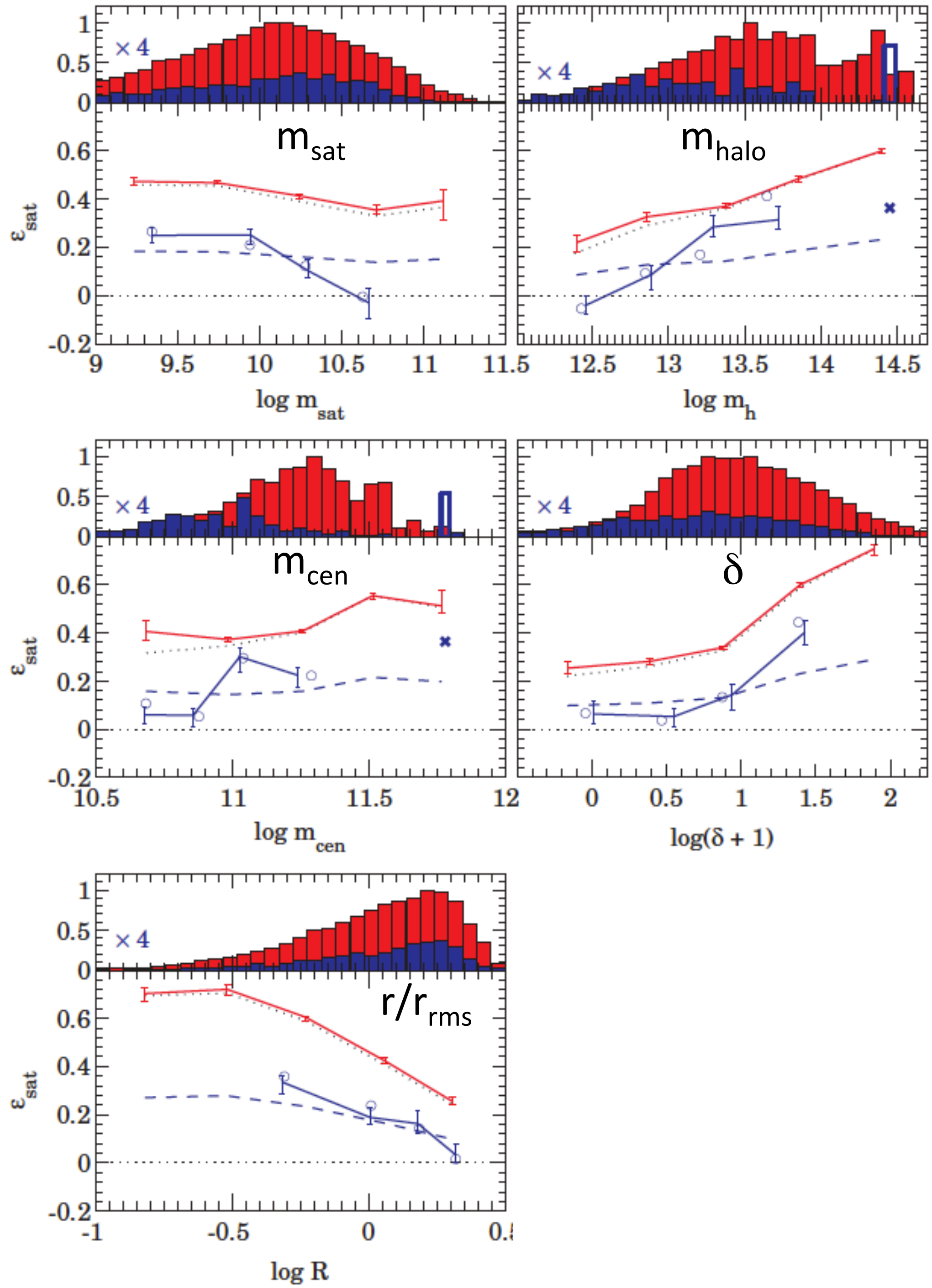
Conformity in satellites that are carefully matched in <u>all five</u> of m_{star}, m_{halo}, δ, R, m_{cen}



For these carefully matched satellites, environmental quenching effects as measured by ε_{sat} are 2.5 times stronger in satellites with quenched centrals than those of SF centrals

1-d dependence of ε_{sat} on 5 parameters for satellites with red and blue centrals

Some degree of conformity seen on all plots over the whole parameter space



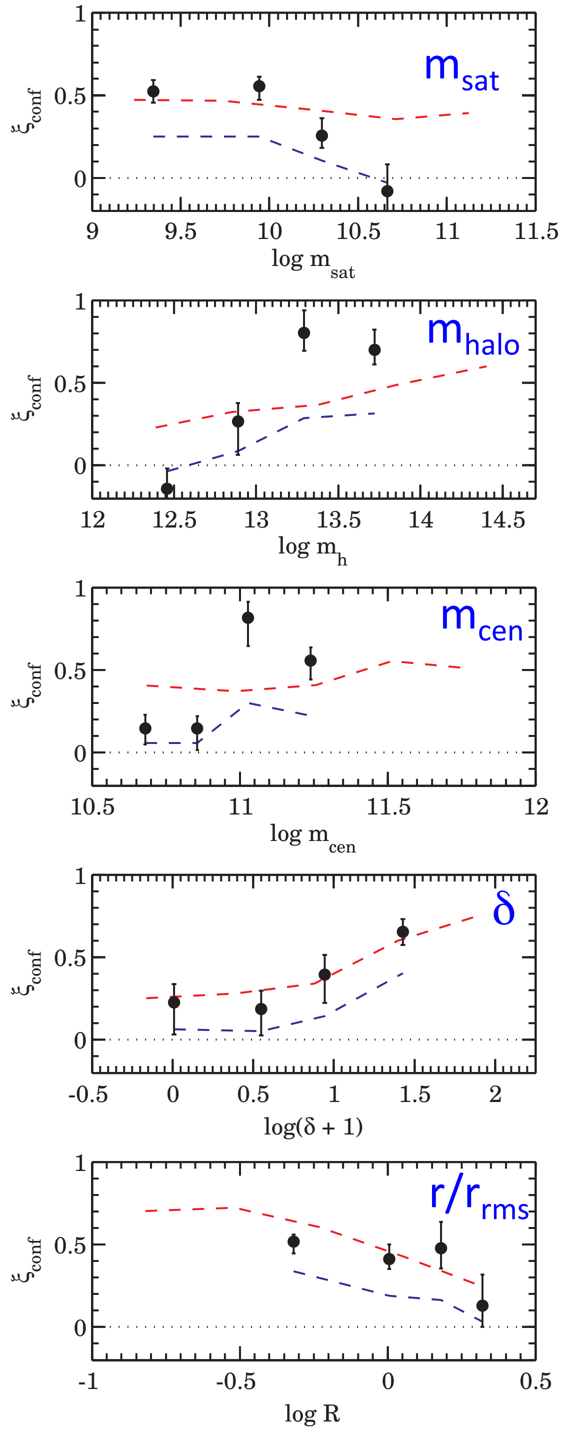
Strength of conformity

$$\xi_{conf} = \frac{\varepsilon_{sat,SF}}{\varepsilon_{sat,q}}$$

$\xi_{conf} = 0$ strong conformity
$\xi_{conf} = 1$ no conformity

Variation of strength of conformity ξ_{conf} with environmental parameters (dots) obtained by ratio of ε_{sat} (dashed lines)

Note: A variation in conformity strength can have different causes: e.g. stochastic regeneration of star-formation in centrals



Points to note:

- large variation in ξ
- conformity is strong for low mass haloes, weak for high mass ones
- strength of conformity appears roughly independent of radius

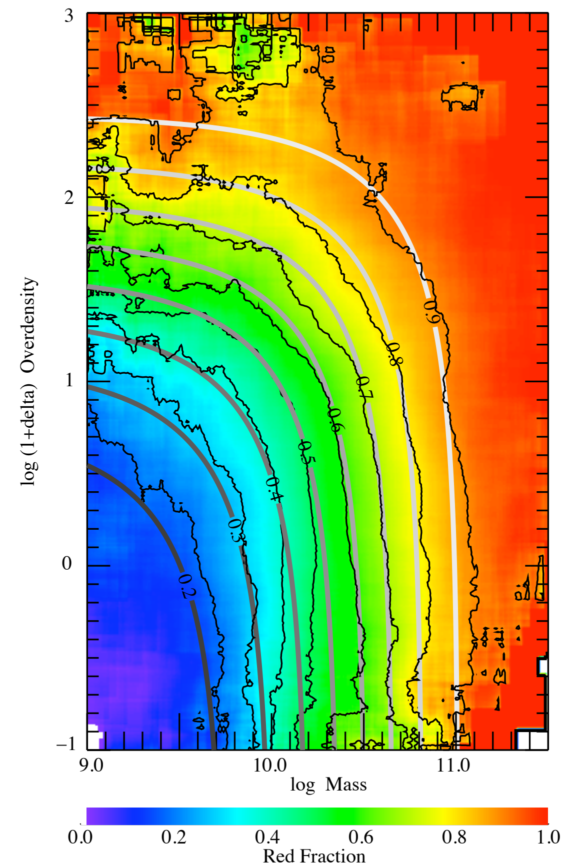
Conclusions from this

- Conformity is a strong effect and persists even when all 5 other parameters are matched. Typically, environmental quenching effects on satellites (ε_{sat}) are 2.5 times larger if the central is quenched.
- The strength of conformity varies over the parameter range, but this could be due to various effects and the variation is hard to interpret.
- Conformity effect is seen at all radii out to ~R_{vir}
- Bottom line: there must be a "hidden common variable" that is playing an important role in linking quenching of centrals and environmental effects in satellites.

Two obvious possibilities

- Environmental-quenching (largely) caused by halo-wide effects consequent to mass-quenching of the central by whatever mechanism.
- Both mass- and environment-quenching are both caused by halo-wide effects shared by centrals and satellites of a given halo (incl. formation history of halo, e.g. Hearin et al 2014). Could mass- and environment-quenching be essentially the same thing?

But don't they have very different dependencies on stellar mass, with environment-quenching independent of mass?

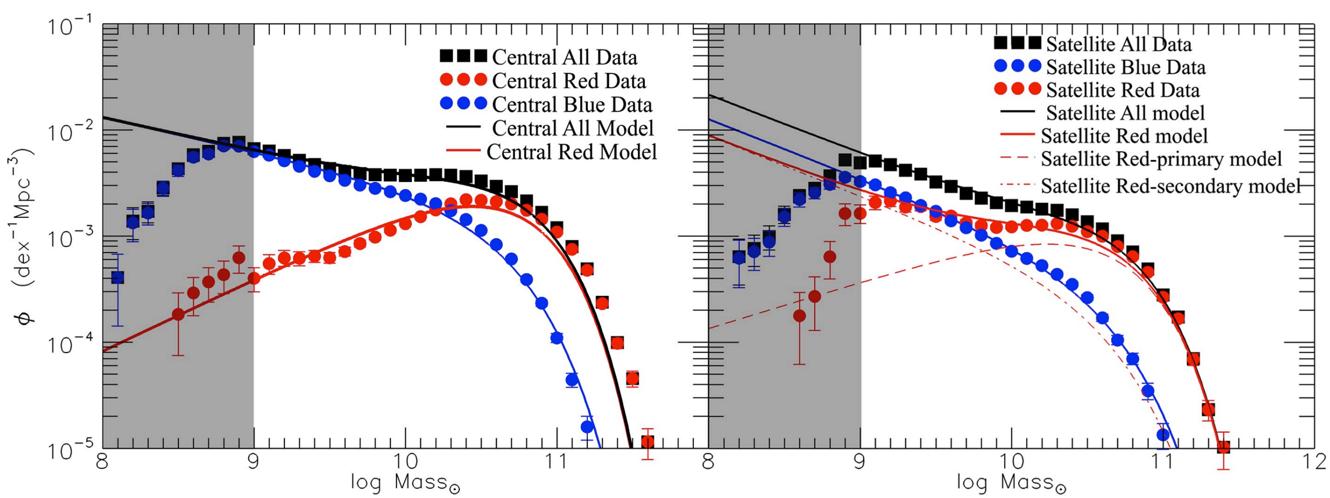


– separability of $f_{\rm red}$?

Peng et al (2010)

– ϕ(m) of centrals and satellites?

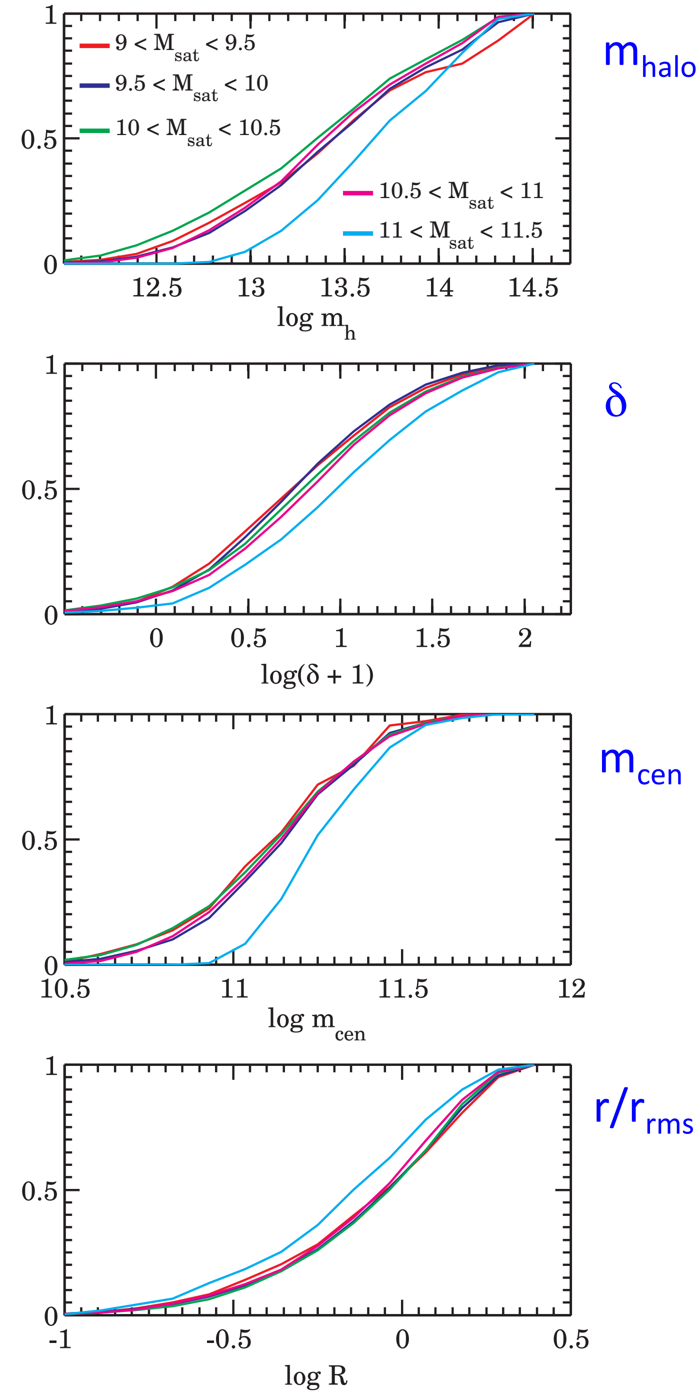
Peng et al (2012)



Expected!!

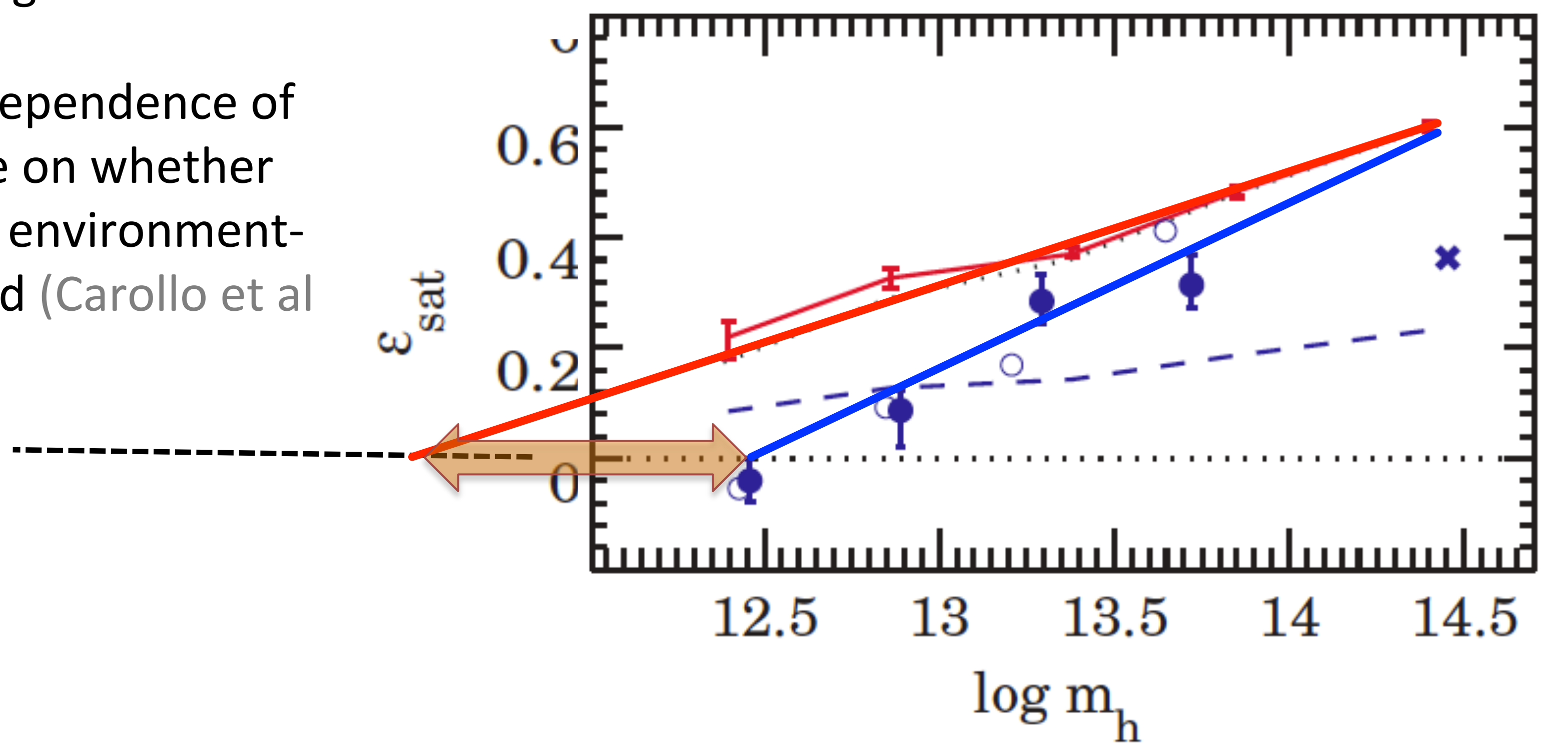
Distribution of most environment variables for satellites is independent of the satellite's mass!

But requires "response" to be independent of mass.



Argument in favour:
Environment-quenching of (reasonably massive) satellites starts to be important at $11.5 < \log m_h < 12.5$. This is the halo mass (of centrals) that is associated with the Schechter stellar M* that is associated with mass-quenching.

Also: independence of structure on whether mass- or environment-quenched (Carollo et al 2014)



Summary

- Reminder: Population gives constraints on quenching outcomes via continuity etc.

- Centrals in groups experience the same environmental quenching effects as their satellites (in the same parameter range). Environmental quenching → satellite quenching →"group quenching"

- Environmental-quenching of satellites depends on all of R, δ and m_h (but not on m_{sat} or m_{cen})

- Some additional "hidden common variable" linking centrals and satellites and with a range out to ~R_{vir} is playing a major role in the quenching of satellites (x2.5 multiplier of environmental effects)
    - Halo-wide consequence of mass-quenching of central, or
    - Halo-wide driving of quenching of both centrals and satellites, i.e. of both mass- and environment-quenching, or of a combined process.

Some arguments in favour of the last?