Quenching in galaxy clusters during the last 10 Gyrs: the role of secular evolution, galaxy mass, cluster mass, and environment.

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Recent results appeared on:

Raichoor & Andreon 2012, A&A 543, A19
Raichoor & Andreon 2012, A&A 537, A88
Raichoor & Andreon 2012, A&A , in preparation

Quenching == cessation of star formation

Taken an observational approach, faced with difficulties

a) statistical :

- Complex observational set-up, not case vs control set-up (i.e. two samples differing by just one physical parameter switched on or off), both at galaxy and cluster level.
- Parameter collinearities (two parameters have similar effects on quenching e.g. galaxy mass & clustercentric distance). Need to control as many parameters as possible.
- Lack of knowledge (and control) of all explanatory variables (those having a potential effect). It is safe to fix as many of them as possible (e.g. cluster mass)

i.e. a challenging statistical analysis, where "systematics" dominate.

b) Astronomical difficulties

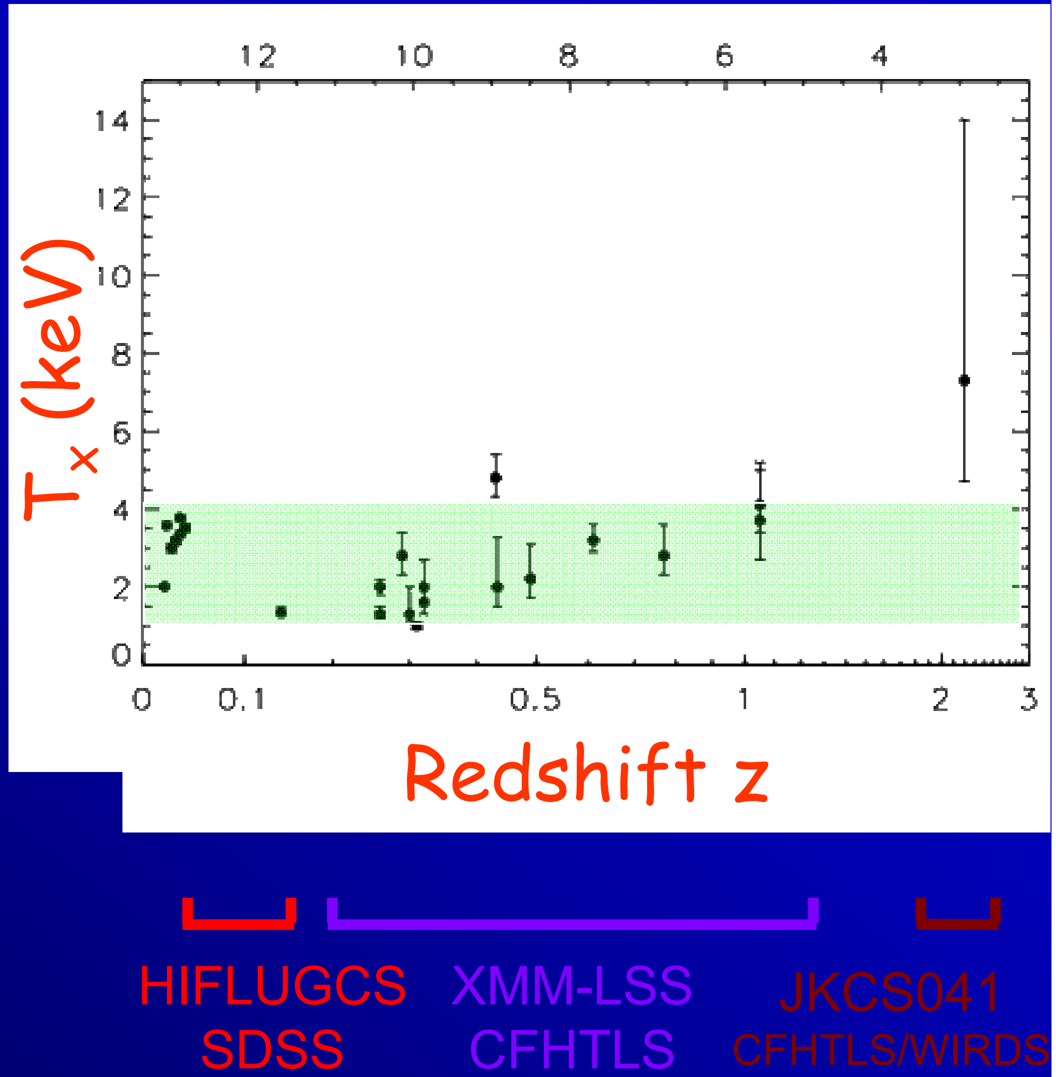
- Cluster selection matters! A) If you select high-redshift clusters using galaxy colors (or SED), no surprise if hi-z clusters have biased galaxy populations! (SA '06) B) If you study normal clusters at low z and peculiar/very massive ones at high-z, you are comparing unripe apples to ripe oranges in order to understand how fruits ripe! (SA & Ettori '99) . Close control on cluster selection is important!
- Precise definition of mass matters! If you select galaxies of a fixed absolute luminosity L, or an evolving L*+c value, or even at a fixed mass, you introduces a bias, because you are not selecting the same population at different redshifts: galaxies of different SFR (and thus color) don't keep a fixed mass and have different luminosity evolutions. Select instead at a fixed-today (i.e. evolving) mass (SA et al. '06, SA '06, also Patel et al. '12).
- Precise definition of red or star forming matters! If you are interested in cluster issues, taking a fixed sSFR threshold, or a fixed distance from the red sequence would discover that in the high-redshift universe star formation is higher (SA et a. 2006, also Penn et al. 2011). Interested in cluster?

If you relax control to get a large sample,
systematics (may) kill you

Cluster sample

- **X-ray selected**
  → do not use galaxy populations, i.e. unbiased about galaxy population composition (with one exception, the z=2.2 cluster)
  → robust size estimation (r_{200})

- **Similar mass**
  → neutralize possible dependence of f_{blue} on cluster mass

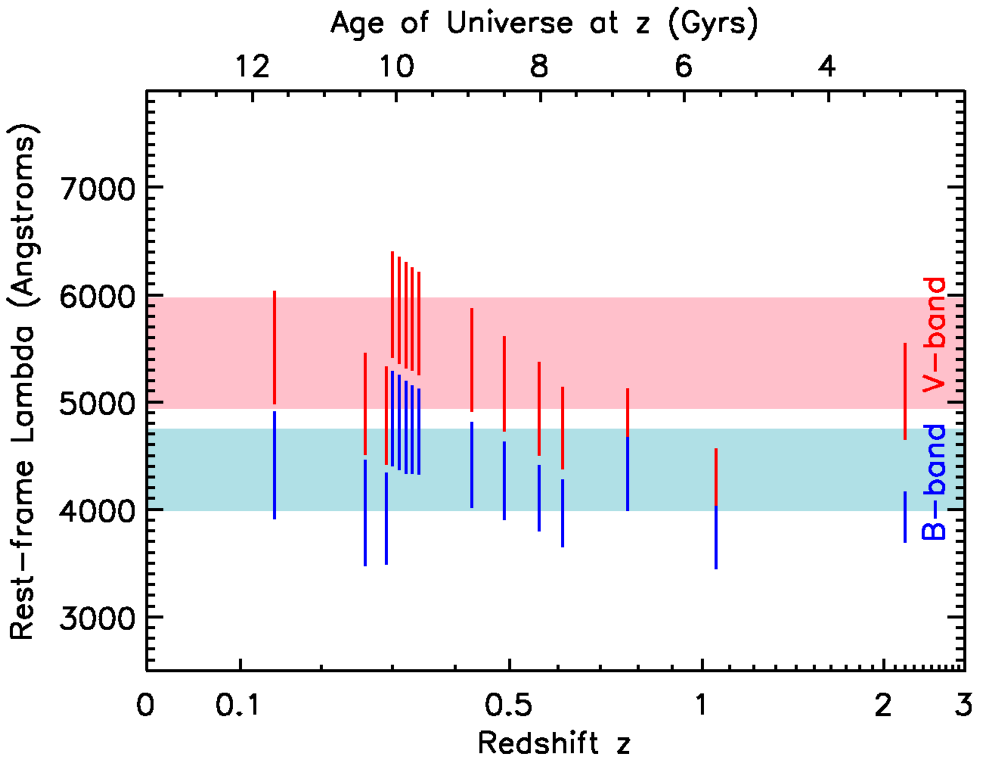


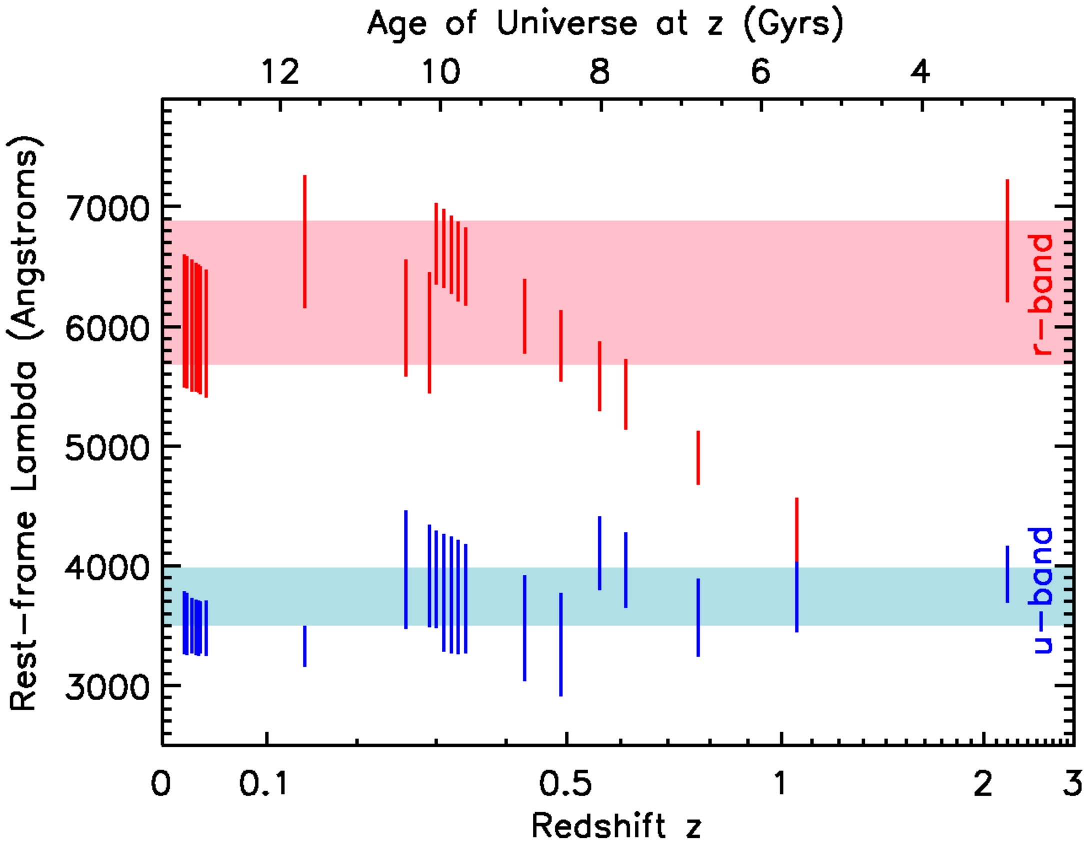
→ a unique sample of
26 clusters with 0<z<2.2
with well-controlled properties

	HIFLUGCS	XMM-LSS	JKCS041
Redshift	0.02<z<0.04	0.14<z<1.05	~2.2
Data	SDSS *ugriz*	CFHTLS W1 *ugriz*	CFHTLS/WIRS D1 *ugrizJHK*
Spectro	SDSS Main Sample (~30,000)	VVDS (~1,500)	VVDS (~2,500)

- Homogeneous photometry & analysis
- Very conservative background treatment:
  Minimal removal of obvious non-member (photo-z, EAZY)
  statistical subtraction for the remaining objects.

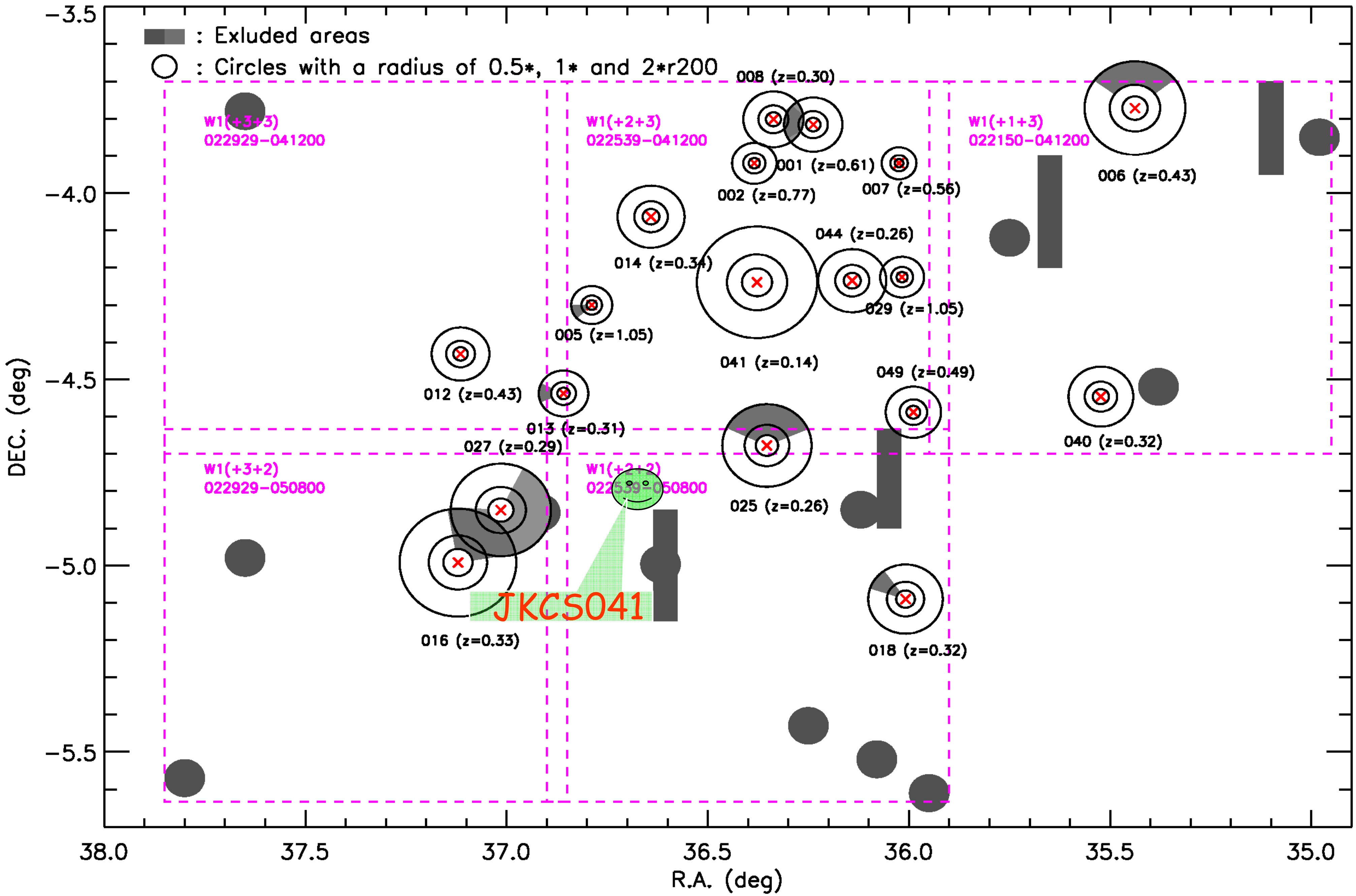
Our sampling of the 4000 A break





Very good compared to other works

XMM-LSS clusters

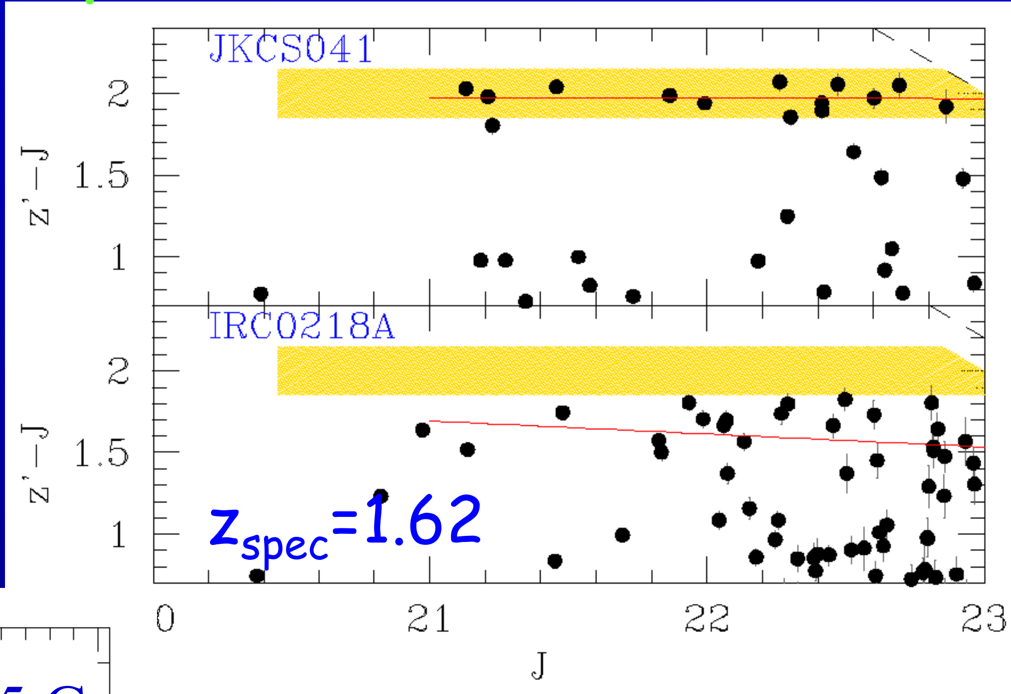


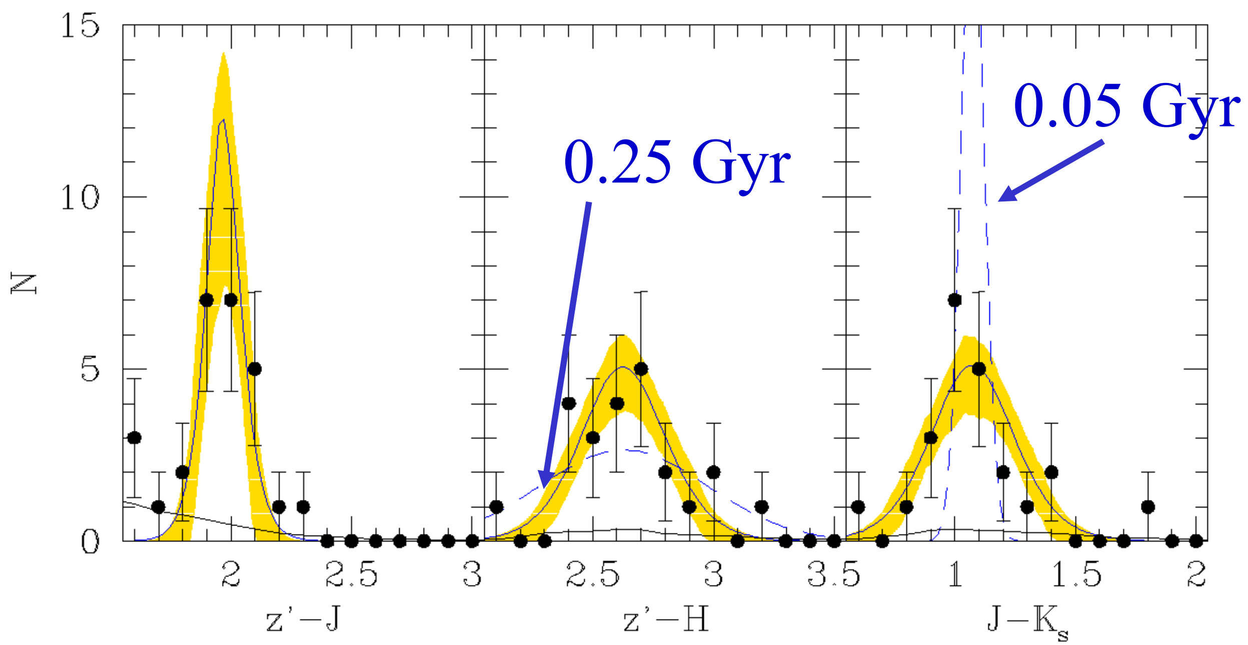
JI
MI

The single exception to our rules: JKCS041, tight red sequence

Only useful cluster at z>1.5, i.e. with X-ray Temperature, or core radius. No choice left to us!

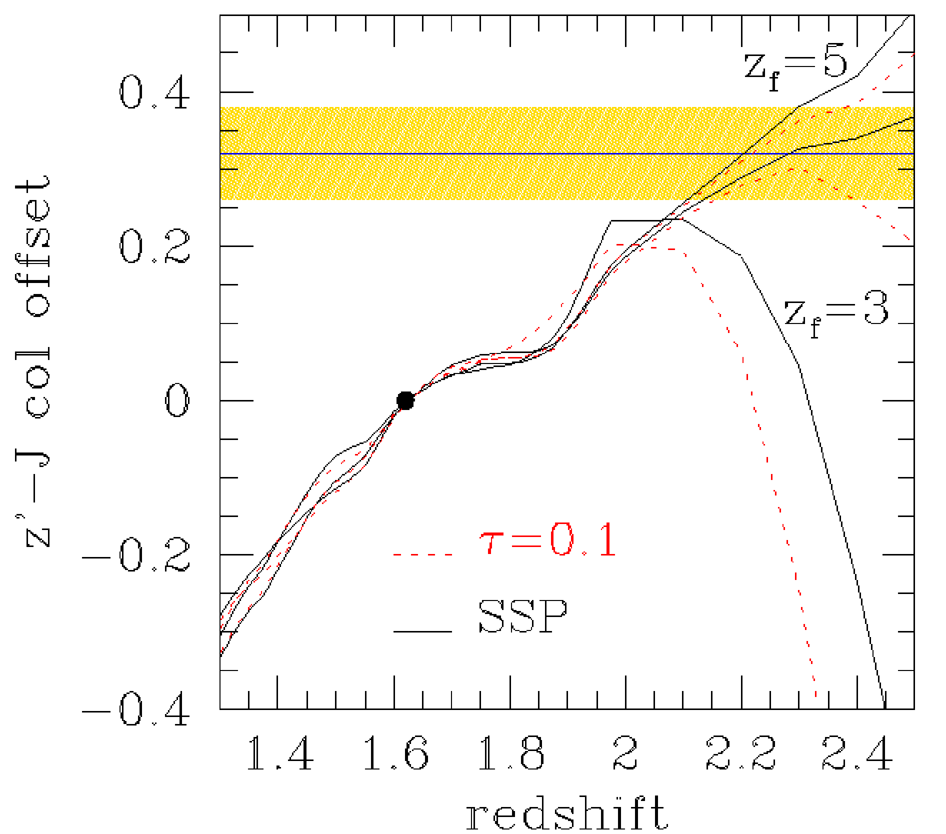
Redshift » 1.62 (SA & Huertas-Company, '11)





Small scatter in color implies a synchronicity in t_form of 0.16±0.03 Gyr of red-sequence galaxies (SA '11) under the usual assumptions

JKCS041, photo-z



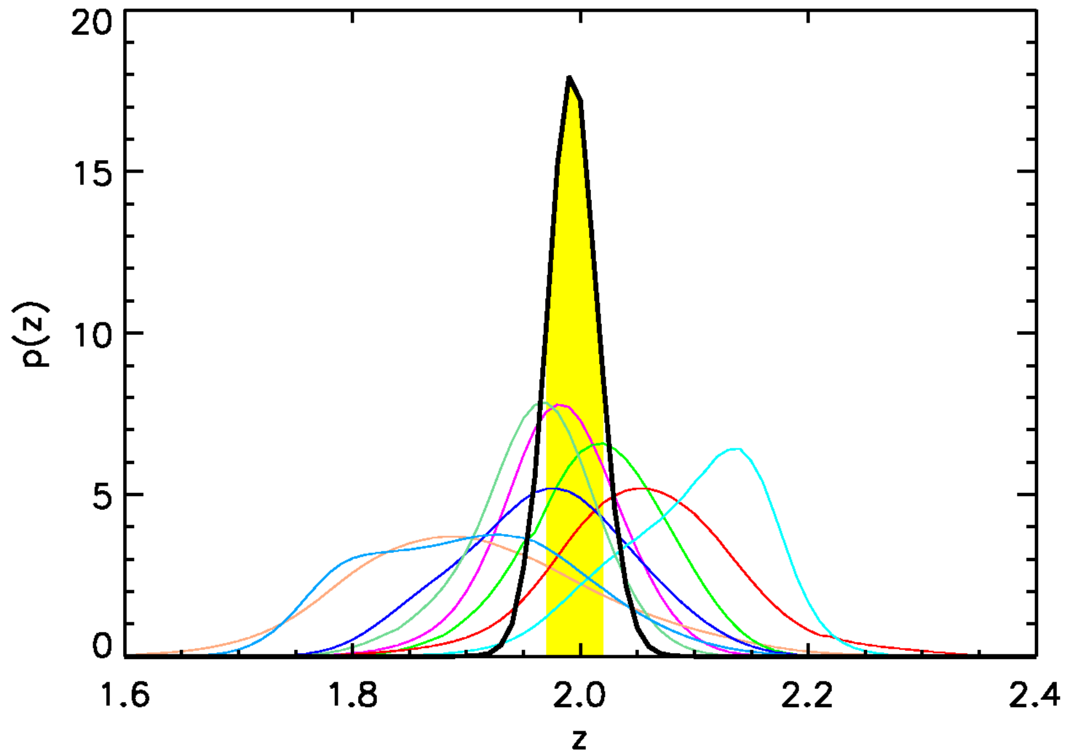


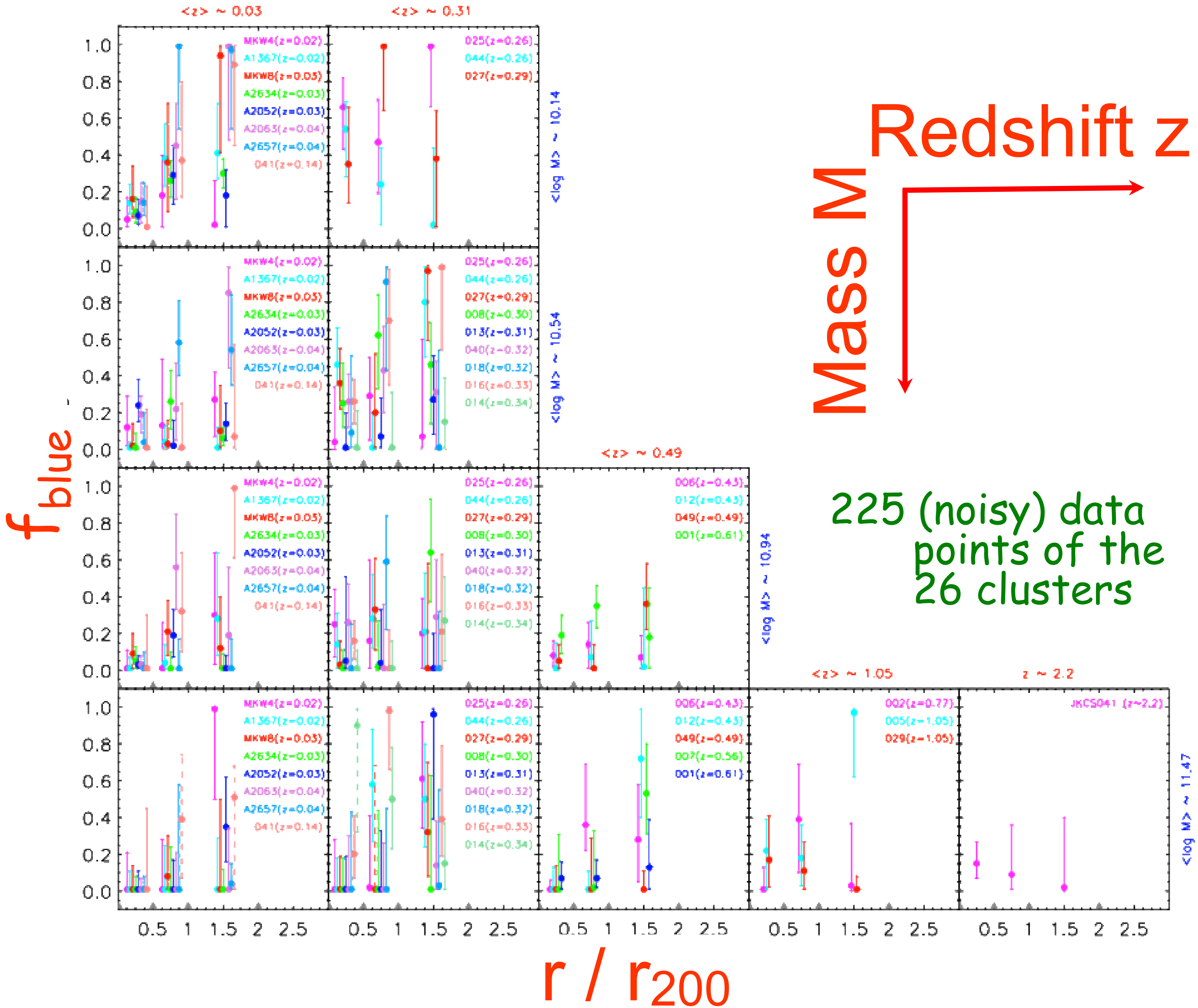
Photo-z, 8 bands, Raichoor & SA '11 :

z-phot=2.00± 0.03

Red sequence color, SA& Huertas-Company '11:

z-phot=2.2 ± 0.1

Old 12 bands photo-z: [1.84-2.12] at 68 % confidence (SA et al. '09)


Redshift z
Mass M
225 (noisy) data points of the 26 clusters
f_blue
r / r200
<z> ~ 0.03
<z> ~ 0.31
<z> ~ 0.49
<z> ~ 1.05
z ~ 2.2
<log M> ~ 10.14
<log M> ~ 10.54
<log M> ~ 10.94
<log M> ~ 11.47

Extracting info by fitting a model:

$$f_{blue}(r/r_{200}, M, z) = ilogit\Big[A_0 +$$

Environmental quenching $\quad \alpha \cdot \log(r/r_{200}) +$

mass quenching $\quad \beta \cdot \log(M) +$

Strengths

evolution of massive galaxies beyond secular $\quad \gamma \cdot z +$

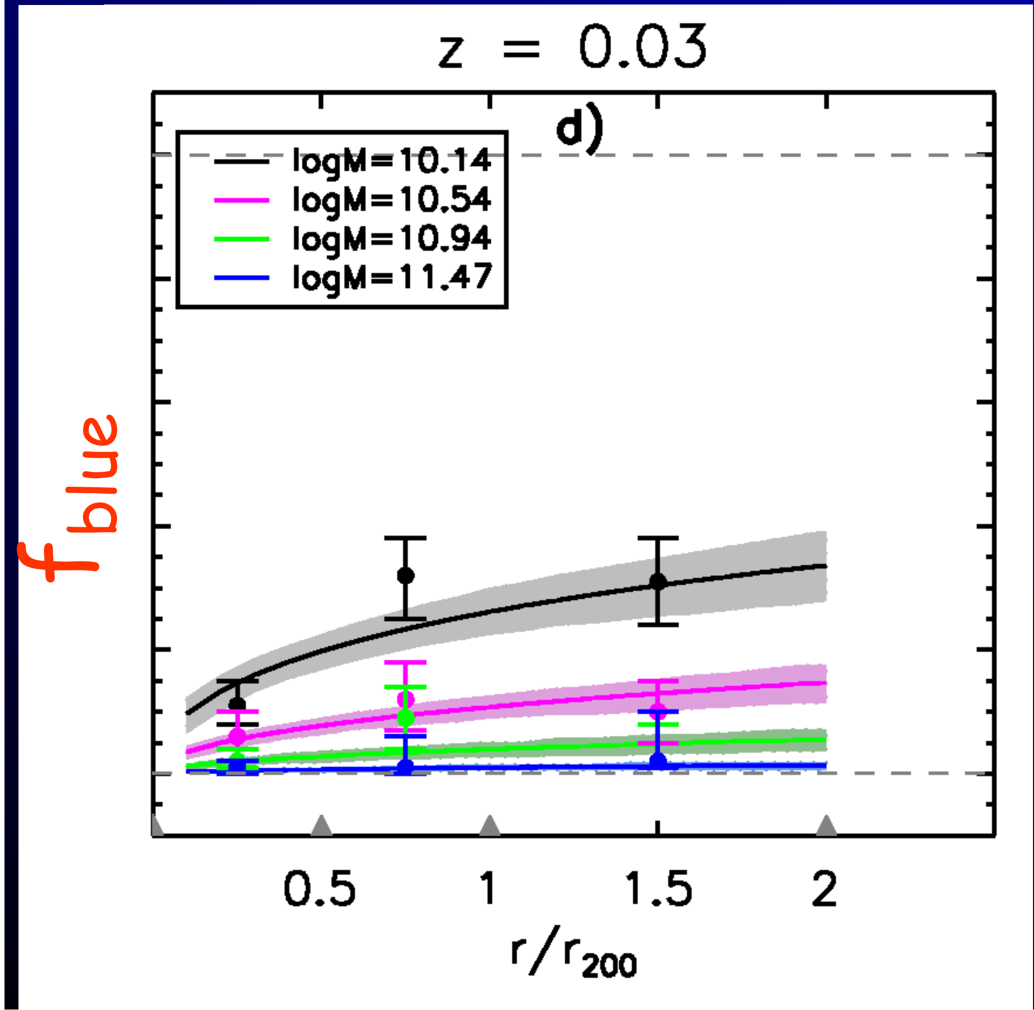
Differential evolution of mass quenching $\quad \zeta \cdot \log(M) \cdot z \Big]$

$\mathrm{ilogit}(x) = (1+\exp(-x))^{-1} \rightarrow 0 \leq f_{blue} \leq 1$

Environmental quenching

At a given mass and redshift, galaxies in denser environments tend to be quiescent

Trivial, but not always found in other works using "cluster stacks"

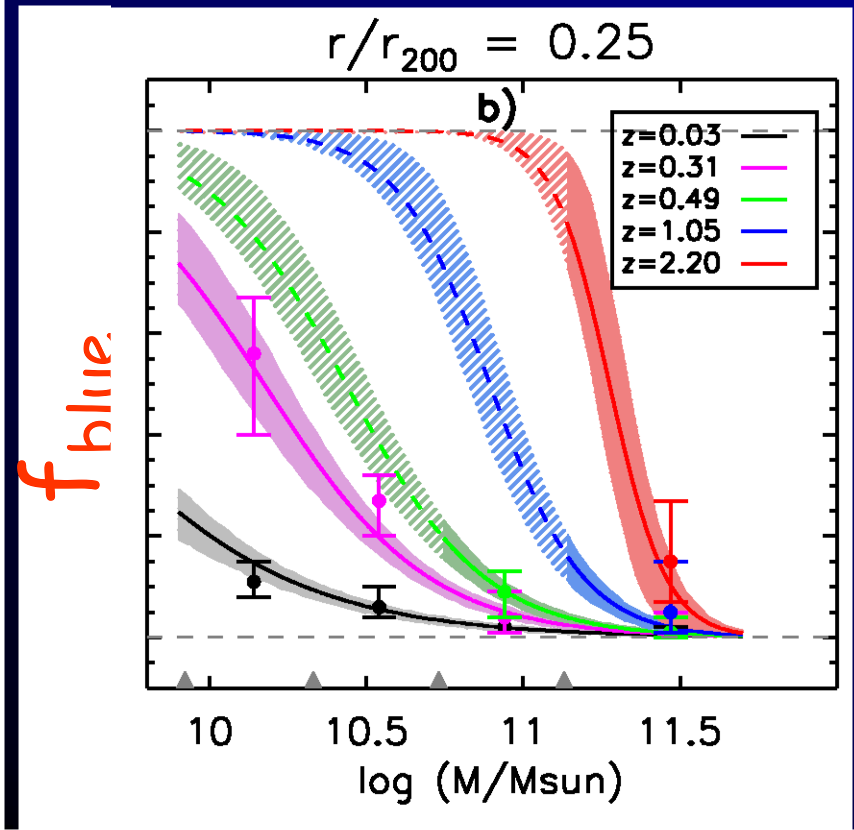


Plotted 30 % of the data, to avoid crowding

$$
\begin{aligned}
f_{blue}(r/r_{200}, M, z) = \quad & ilogit\Big[-3.1^{+0.2}_{-0.4} & + \\
& 1.2^{+0.6}_{-0.5} \cdot \log(r/r_{200}) & + \\
& -3.8^{+0.6}_{-0.5} \cdot \log(M) & + \\
& 3.3^{+0.7}_{-0.6} \cdot z & + \\
& -3.9^{+0.9}_{-1.1} \cdot \log(M) \cdot z \Big]
\end{aligned}
$$

Mass quenching

massive galaxies are more likely quenched (and in all environments and up to z=0.5 at least)



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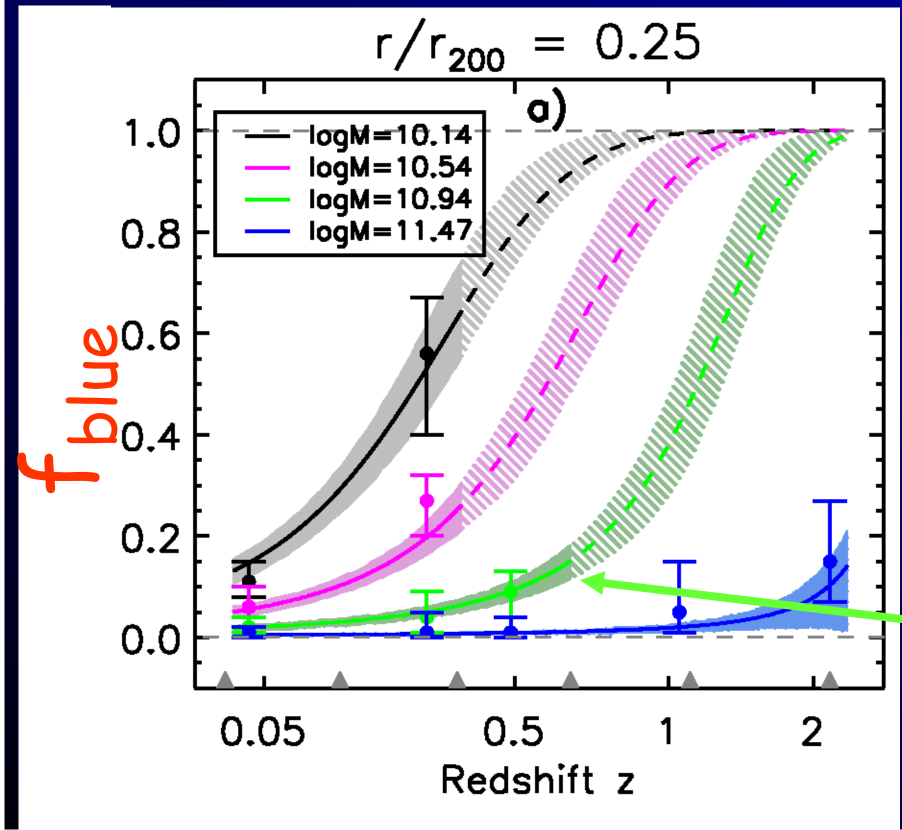
& 3.3^{+0.7}_{-0.6}\cdot z & + \\
& -3.9^{+0.9}_{-1.1}\cdot \log(M)\cdot z\Big] &
\end{aligned}
$$

Evolution (beyond secular)

At earlier times galaxies tend to be more starforming than τ models (f_{blue} it's not constant!)

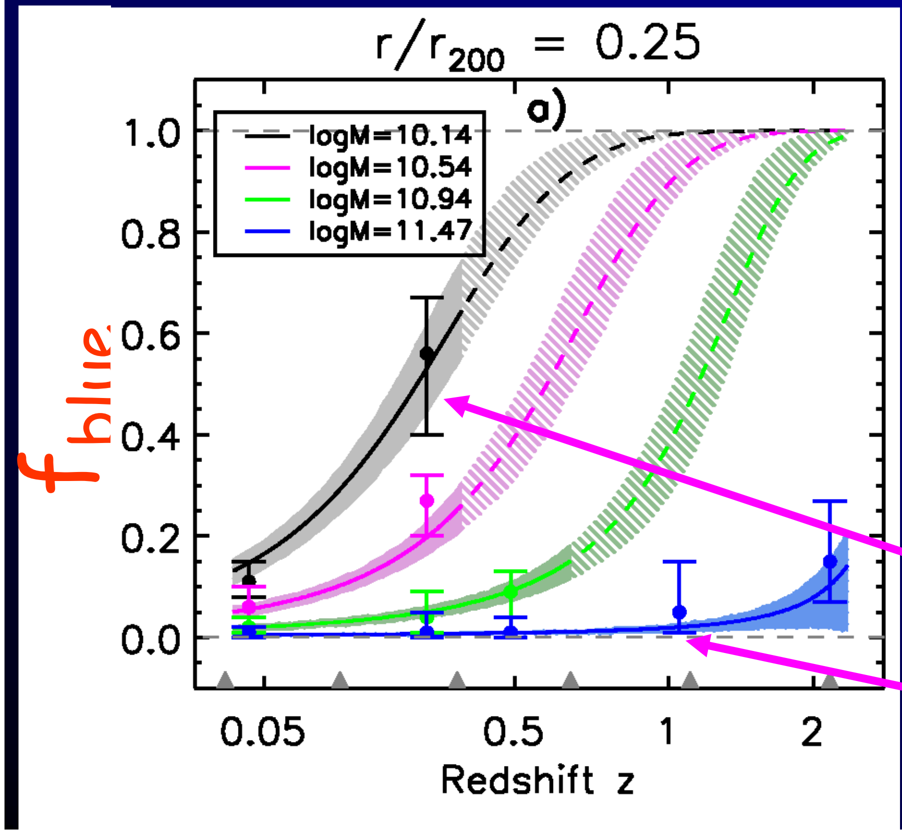
Plotted 30 % of the data, to avoid crowding



$$
\begin{aligned}
f_{blue}(r/r_{200}, M, z) = \quad & ilogit\Big[-3.1^{+0.2}_{-0.4} && + \\
& 1.2^{+0.6}_{-0.5} \cdot \log(r/r_{200}) && + \\
& -3.8^{+0.6}_{-0.5} \cdot \log(M) && + \\
& 3.3^{+0.7}_{-0.6} \cdot z && + \\
& -3.9^{+0.9}_{-1.1} \cdot \log(M) \cdot z \Big]
\end{aligned}
$$

Differential evolution of mass quenching

More massive galaxies evolve more rapidly/earlier (all the remaining kept fixed)



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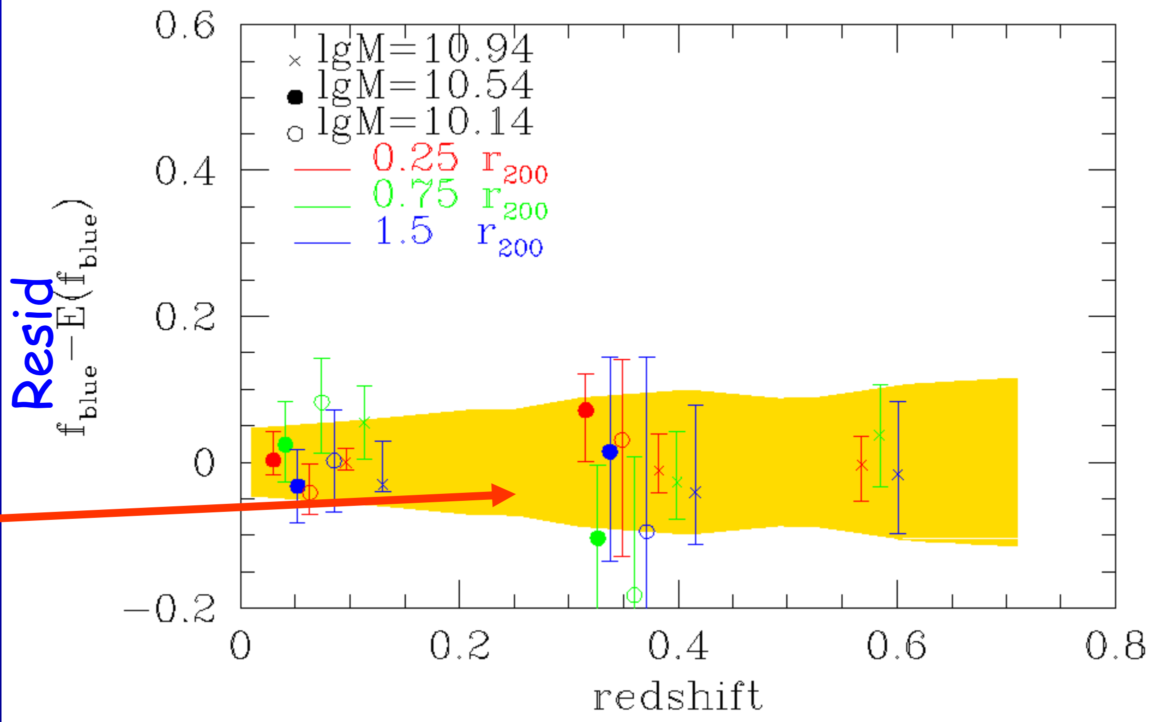
$$
\begin{aligned}
f_{blue}(r/r_{200}, M, z) = \quad & ilogit\big[-3.1^{+0.2}_{-0.4} \quad + \\
& 1.2^{+0.6}_{-0.5} \cdot \log(r/r_{200}) \quad + \\
& -3.8^{+0.6}_{-0.5} \cdot \log(M) \quad + \\
& 3.3^{+0.7}_{-0.6} \cdot z \quad + \\
& -3.9^{+0.9}_{-1.1} \cdot \log(M) \cdot z \,\big]
\end{aligned}
$$

Illustration of the un-necessity of a more complex model.

Current 4-param model



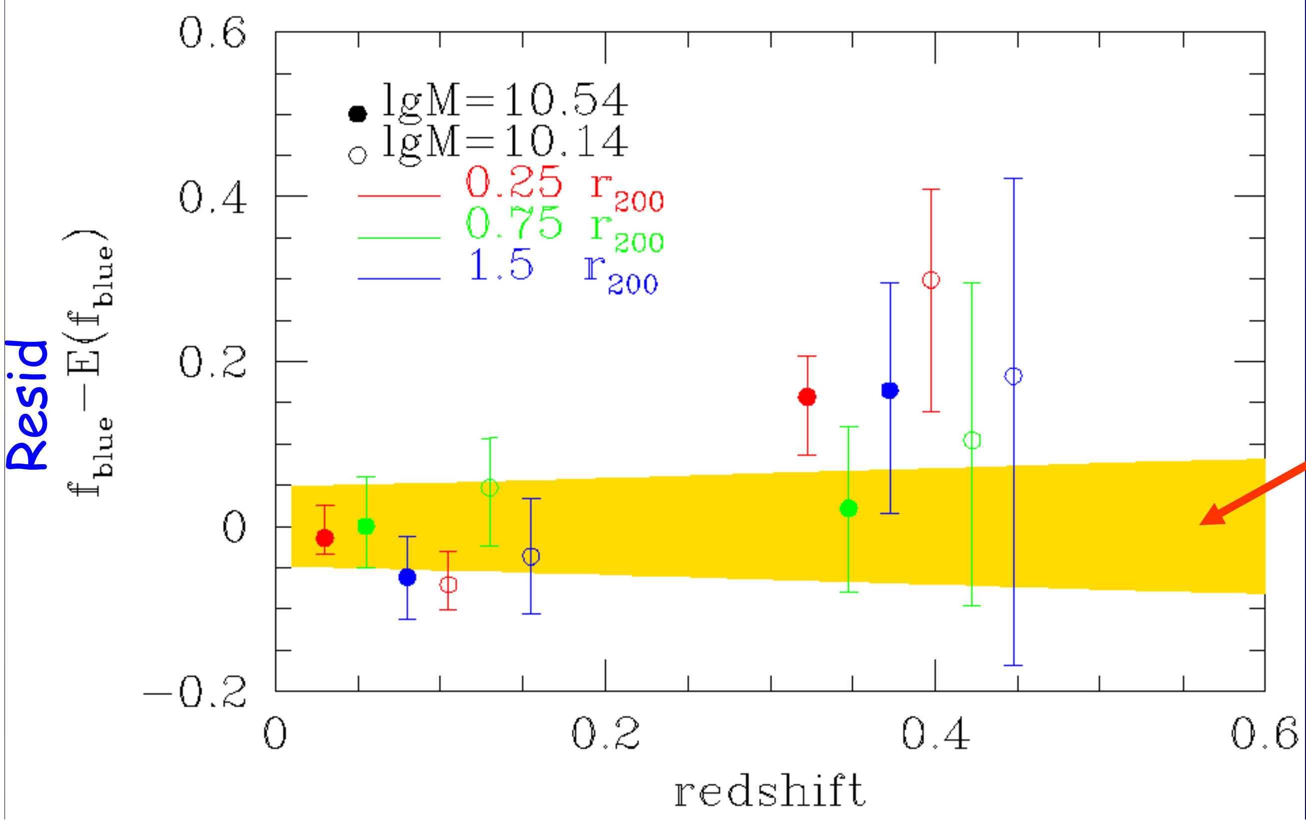
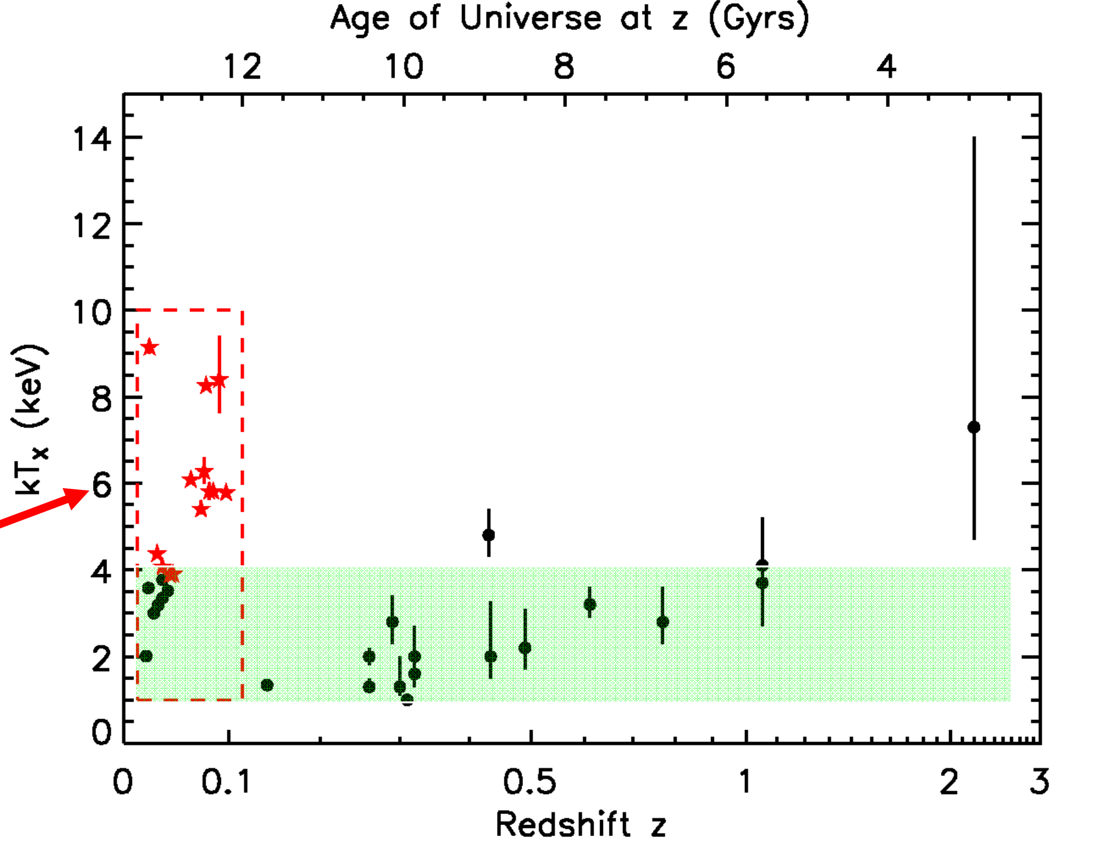


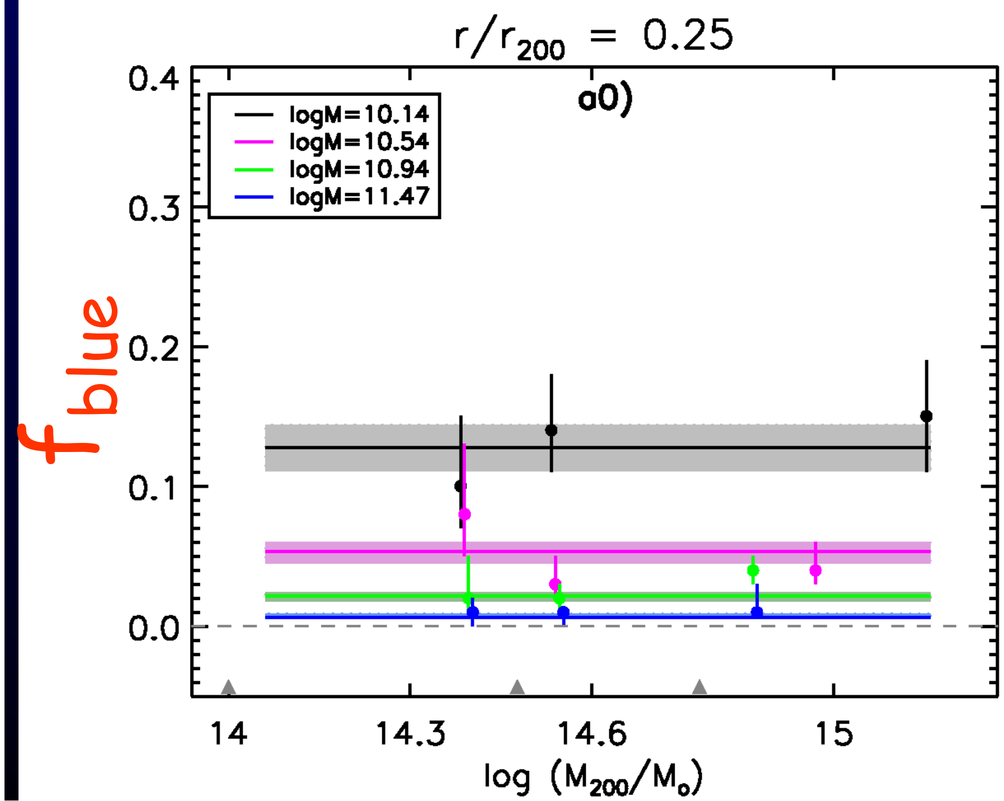
Illustration of the need of a mass-dependent evolving term.

The model without it

Is controlling for cluster mass necessary?

Tested with 12 additional clusters, much more massive





Cluster mass plays no appreciable role (once r/r200 is used) in the local Universe.

Plotted 30 % of the data, to avoid crowding

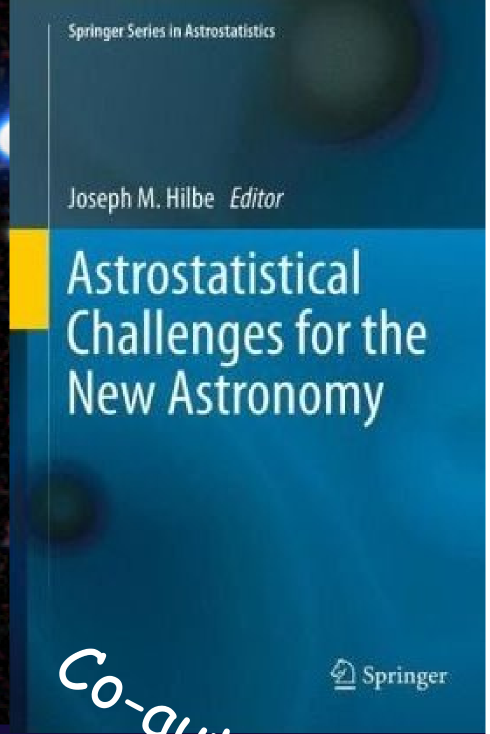
Conclusions

- Quenching depends on galaxy mass, epoch, and environment. They have similar effects, therefore you need to control all them. Need of controlling also cluster selection, pay attention to the precise mass definition and remember (if you are interested in cluster-related effects) that star formation changed in the last 10 Gyrs when defining blue, or passive.

- The minimal model describing the data has four parameters: mass-quenching, environmental-quenching, evolution beyond secular and a cross-term between mass and epoch. The strength of the four parameters is now know at 10-50 % level. No other cross-terms are needed, and cluster mass does not play a major role (can be ignored, at least at z=0), for clusters with lgM>14.


Thank you
JKCS041@z=2.2

Co-author of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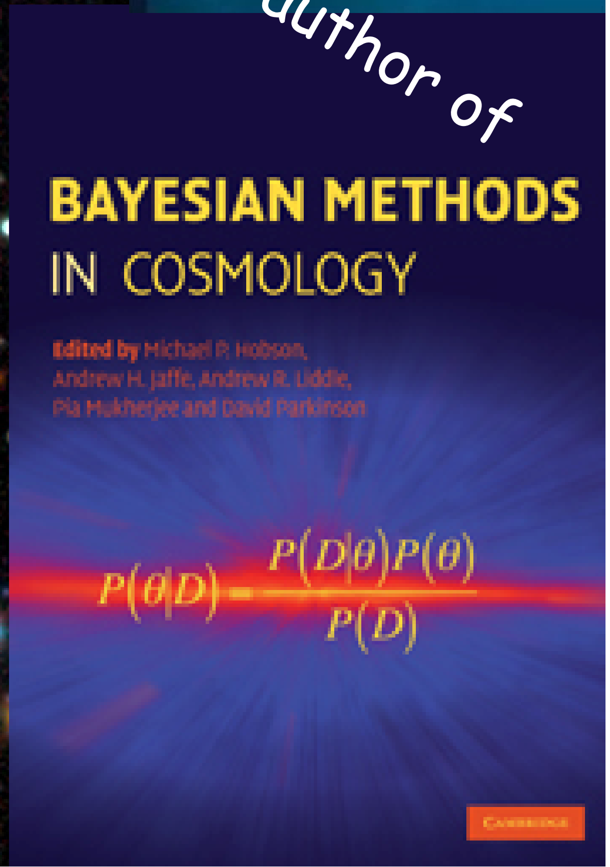
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