"THE GROWTH OF TODAY's MOST MASSIVE GALAXIES OVER THE LAST 12.8 Gyr OF COSMIC HISTORY"

DANILO MARCHESINI (Tufts University)

Adam Muzzin (KICC), Benedetta Vulcani (IPMU), Cemile Marsan (Tufts), Mauro Stefanon (Leiden Univ.), the NMBS and UltraVISTA collaborations

Marchesini, et al., 2010, ApJ, 725, 1277
Marchesini, et al., 2014, ApJ, 794, 65
Marsan, Marchesini, et al., 2015, ApJ, 801, 133
Stefanon, Marchesini, et al., 2015, ApJ, 803, 11
Vulcani, Marchesini, et al., 2015, ApJ submitted [arXiv:1509.00486]

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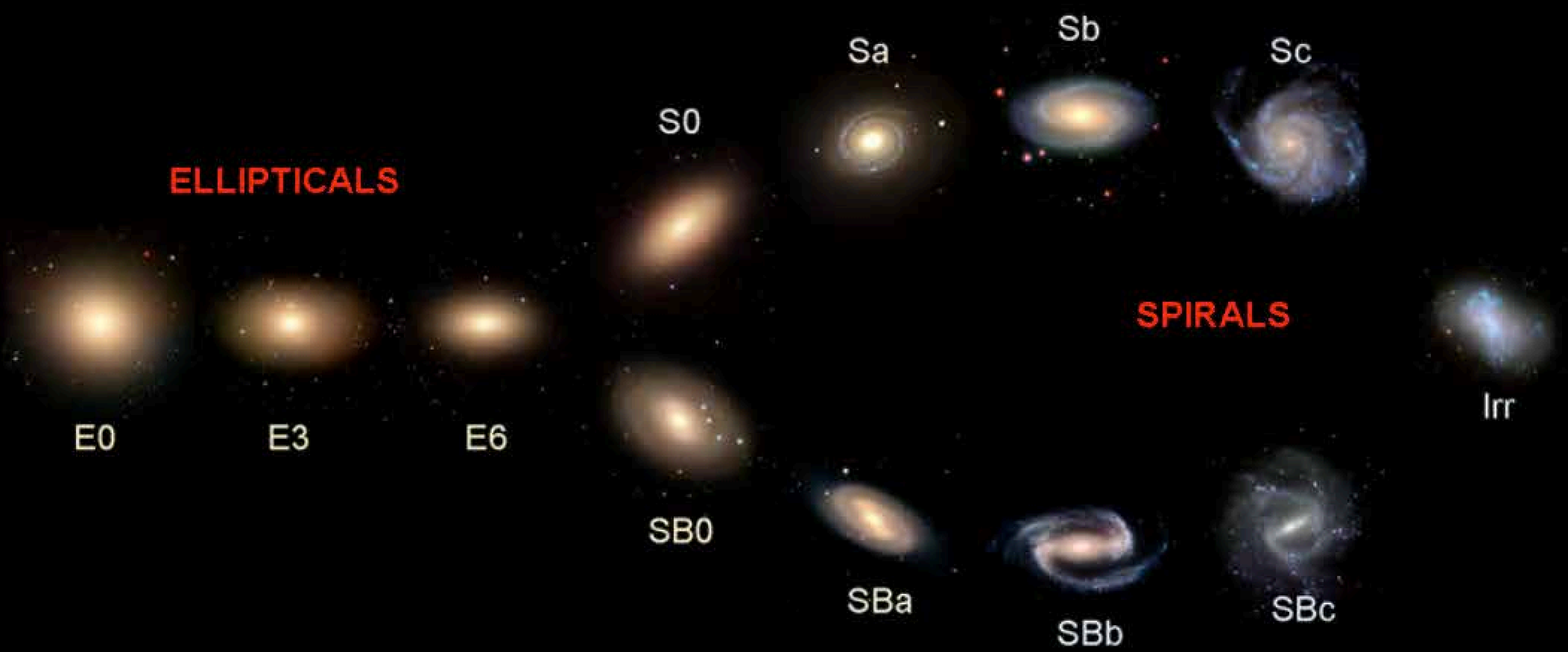
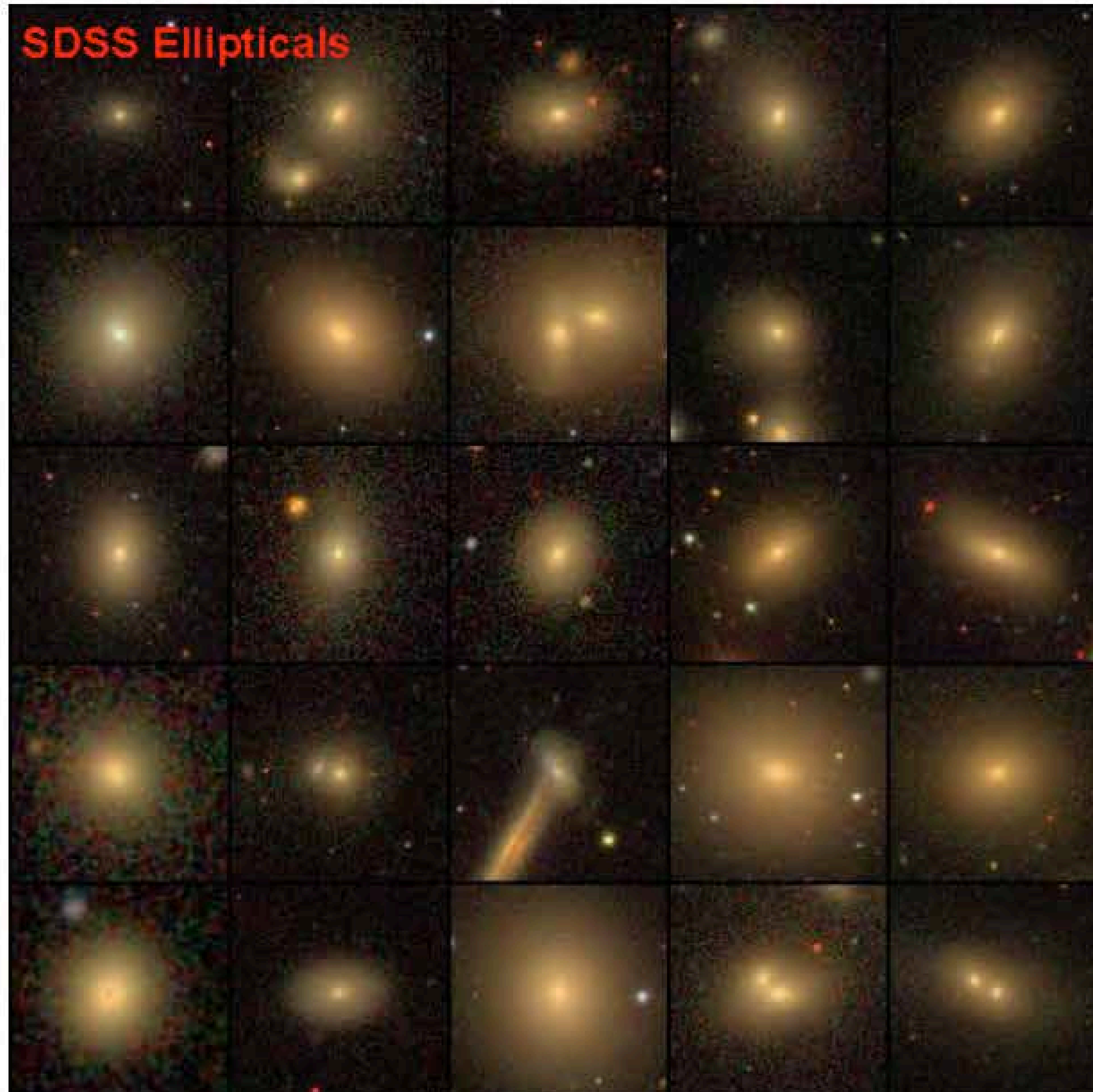
IPMU - October 8th, 2015

Hubble's Galaxy Classification Scheme

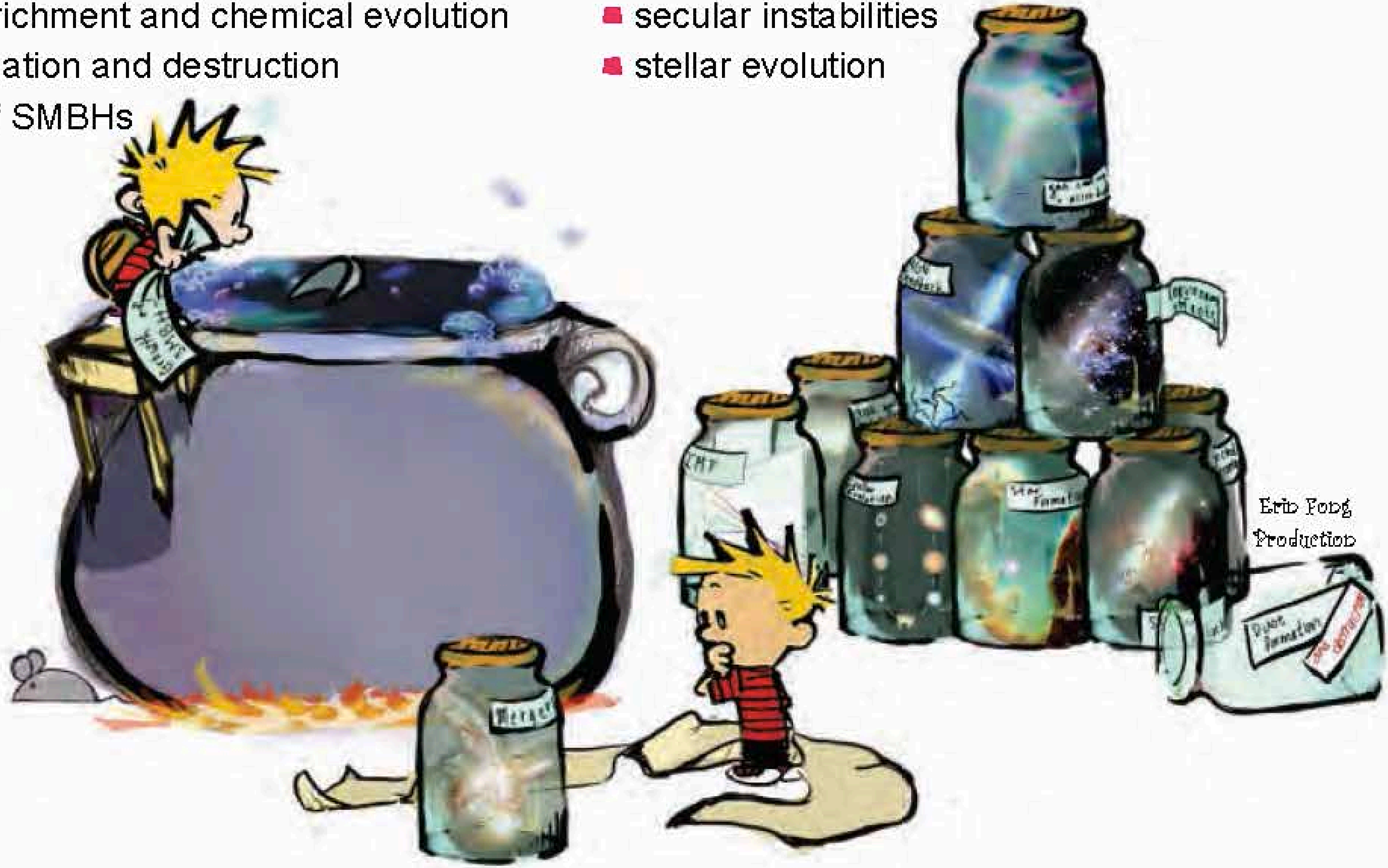


When and how did today's most massive galaxies form?

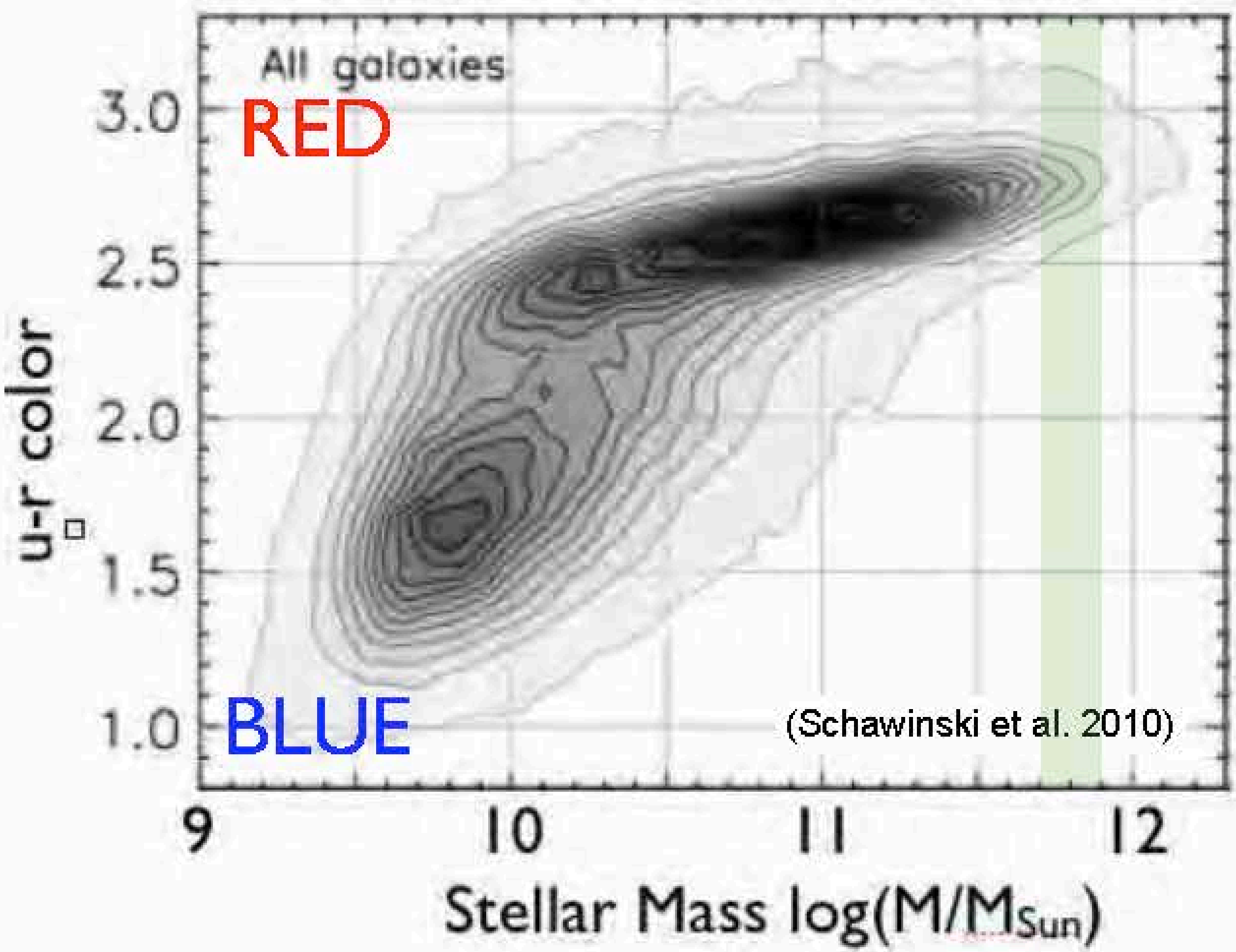


The ultimate goal: the “recipe” for galaxy formation

- gas cooling and accretion
- star formation
- stellar feedback (SNs, winds, evolved stars)
- re-accretion of ejecta
- metal enrichment and chemical evolution
- dust formation and destruction
- growth of SMBHs
- IMF
- AGN feedback (quasar vs. radio modes)
- merging
- environmental effects
- disk and bulge formation
- secular instabilities
- stellar evolution



Properties of today's most massive galaxies



- They populate the extreme massive end of the red sequence, with very homogeneous red colors

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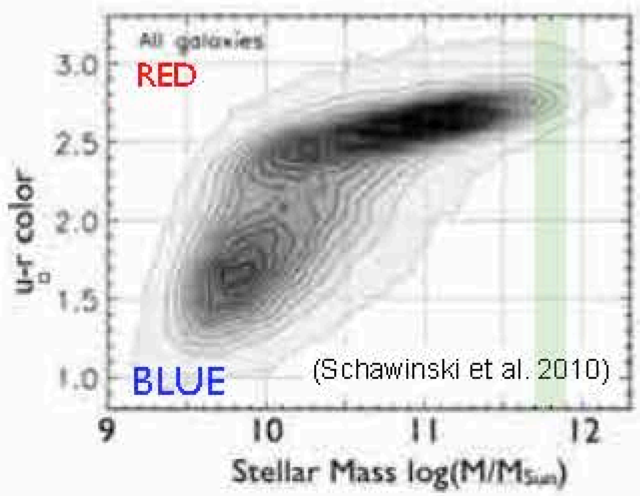

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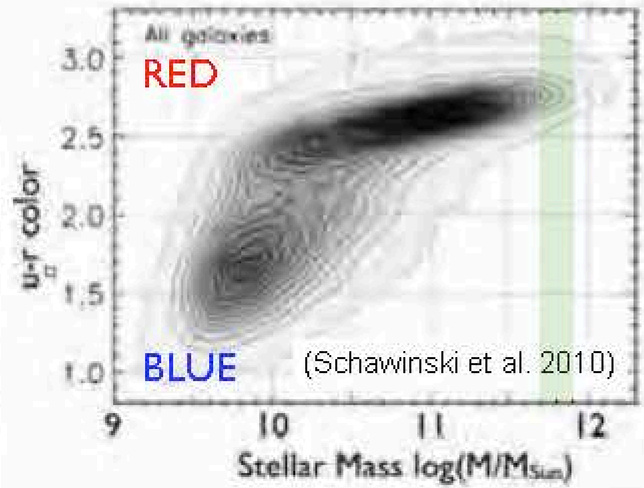

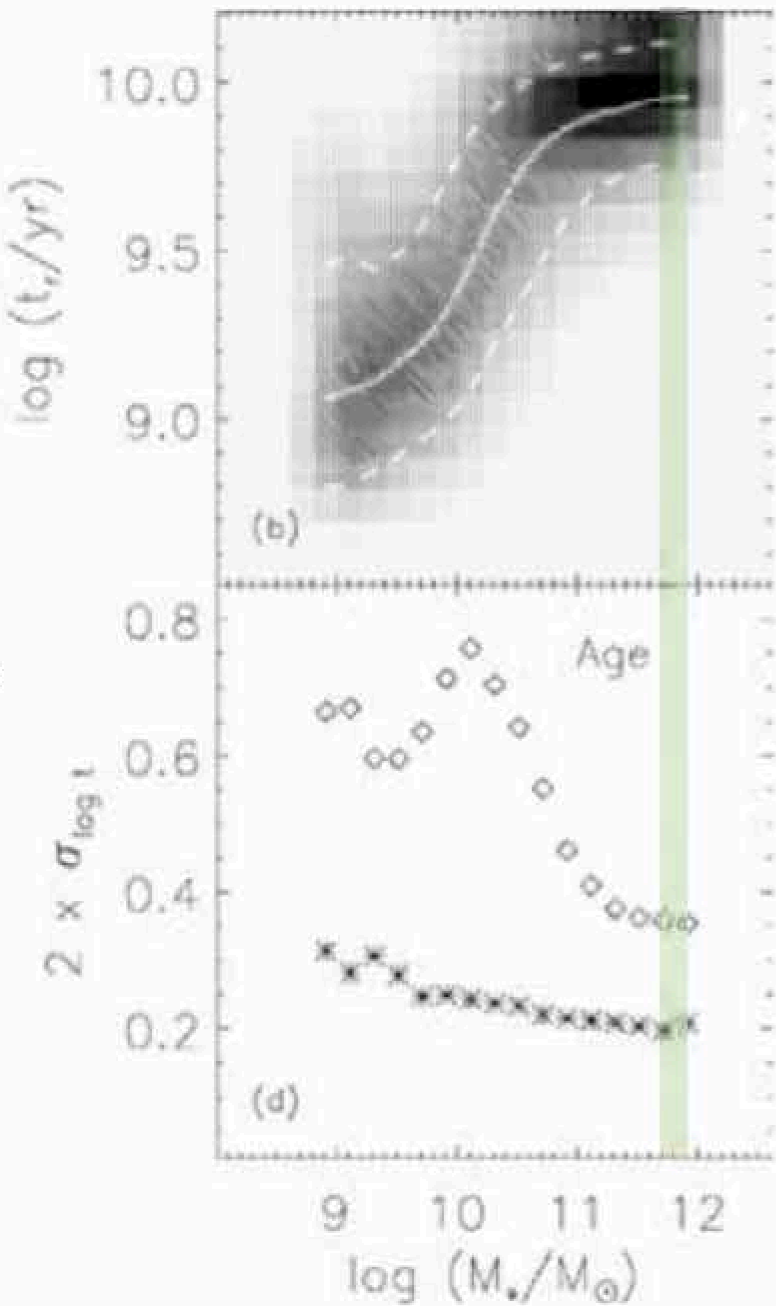

- They are characterized by old ages, with little dispersion in age of ~20%, consistent with having formed most of their stars at $1.1<z_{form}<4.2$

(Gallazzi et al. 2005,2006; Thomas et al. 2005,2010)

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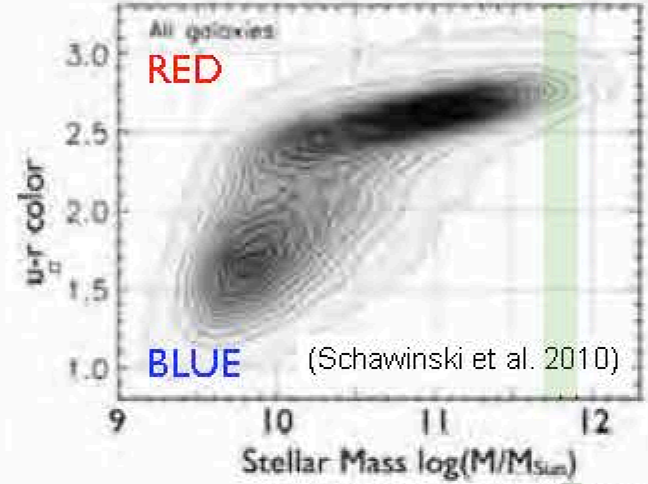

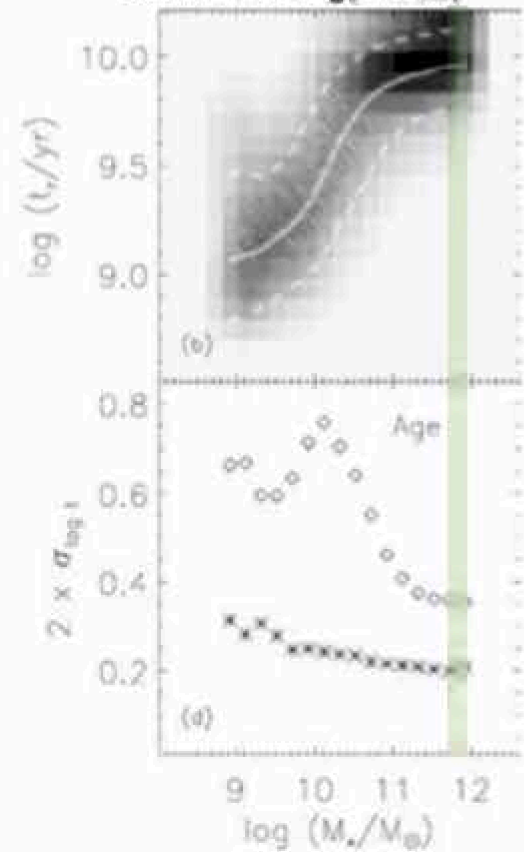

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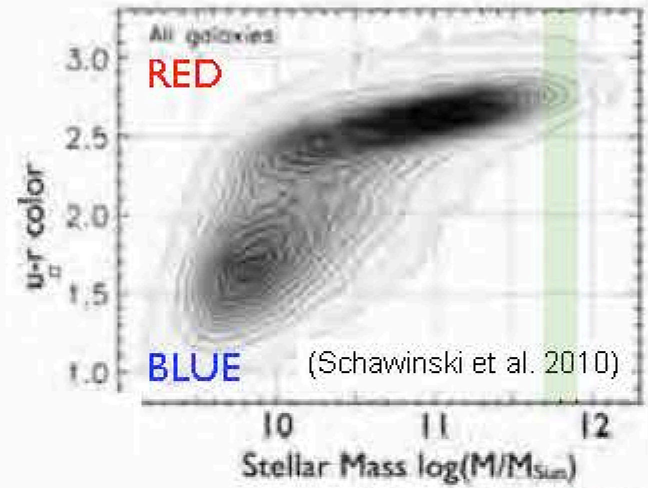

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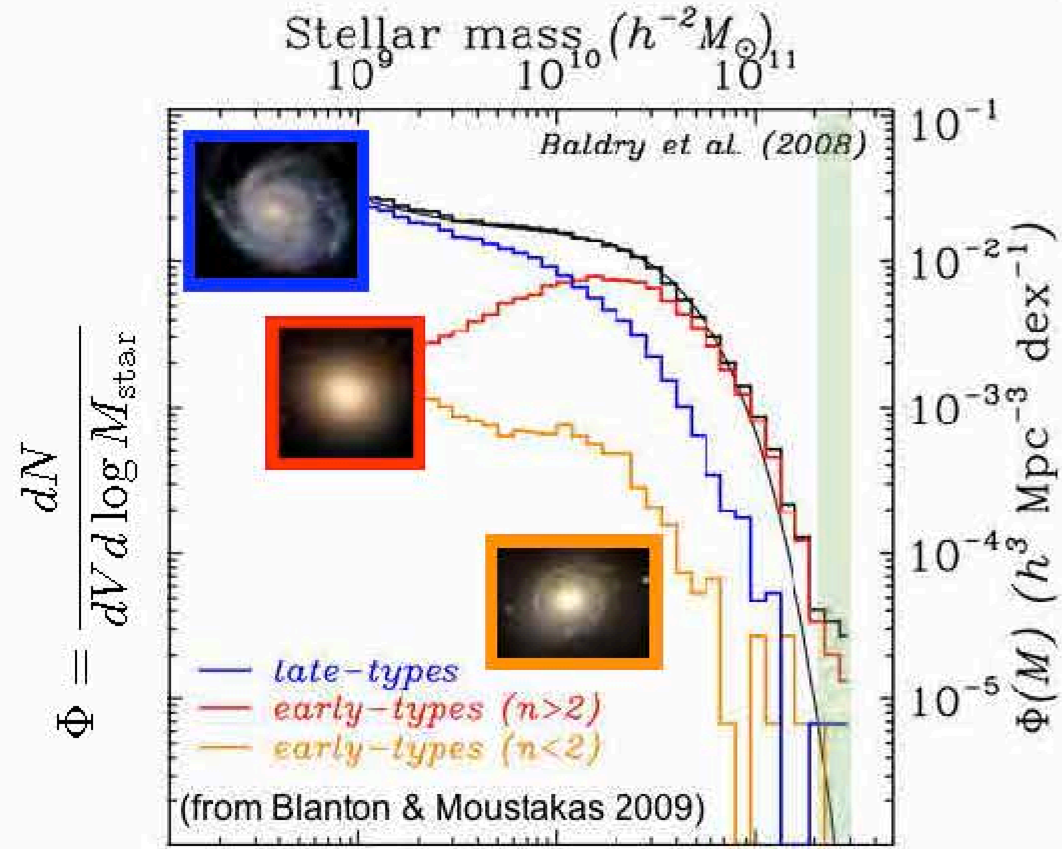

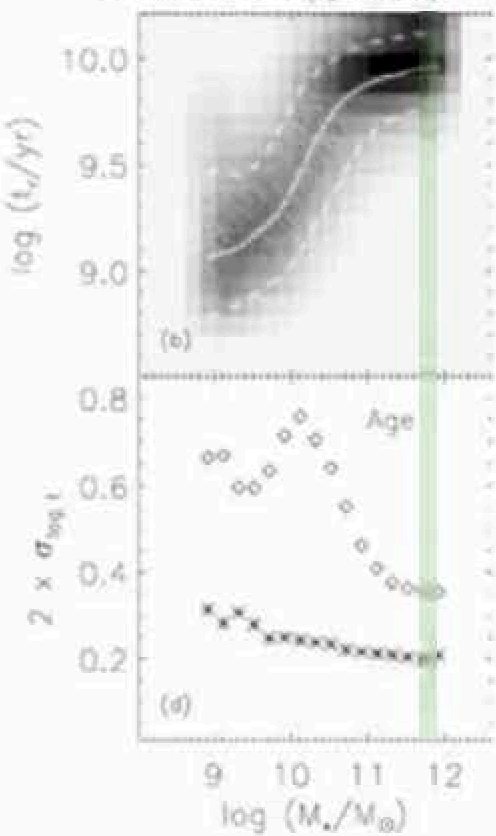

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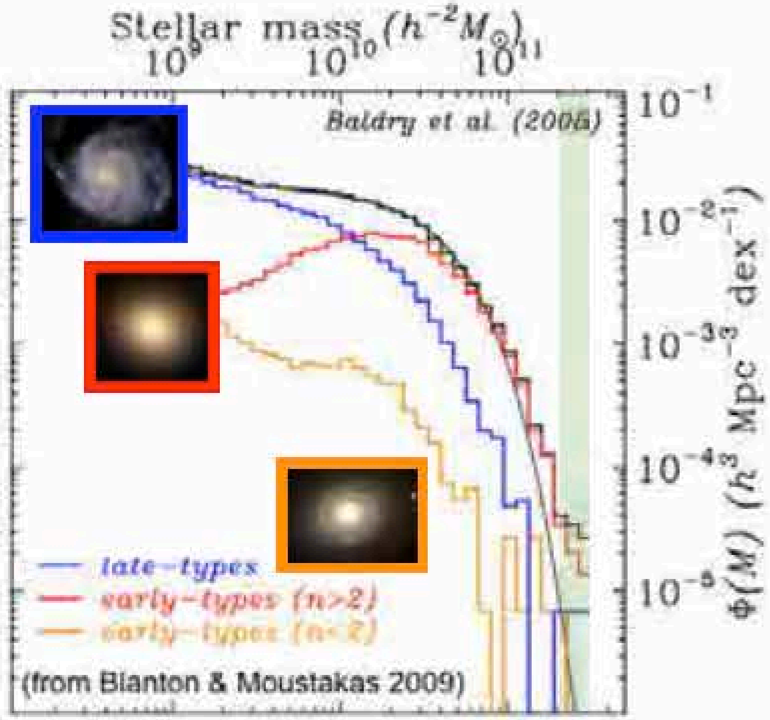

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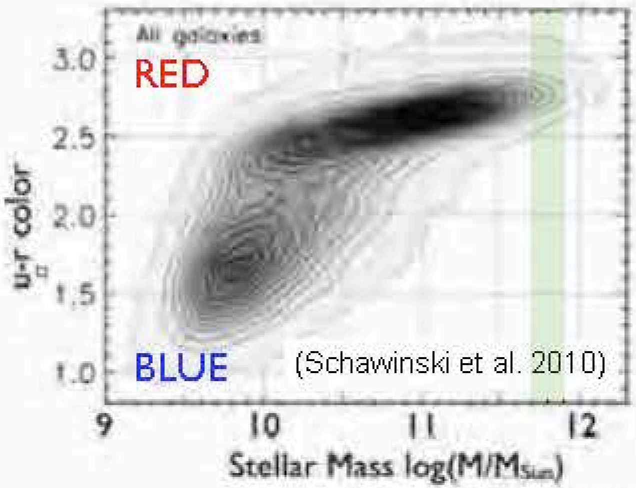

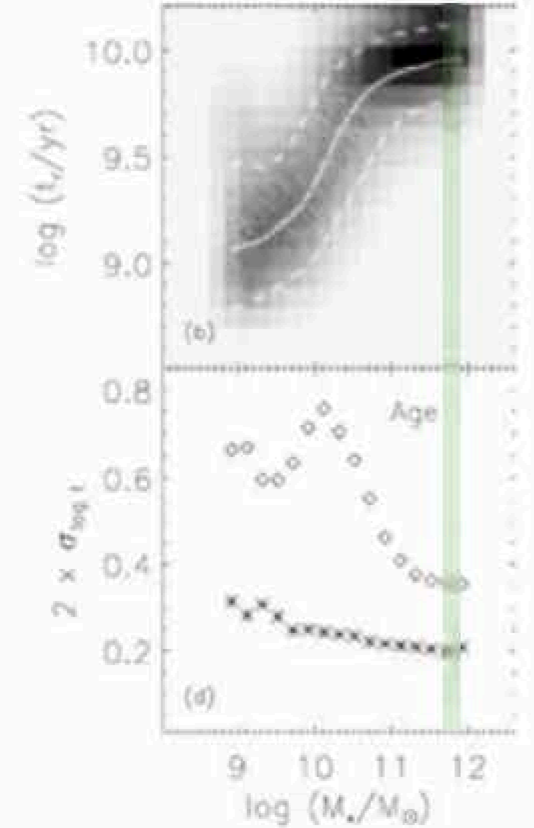

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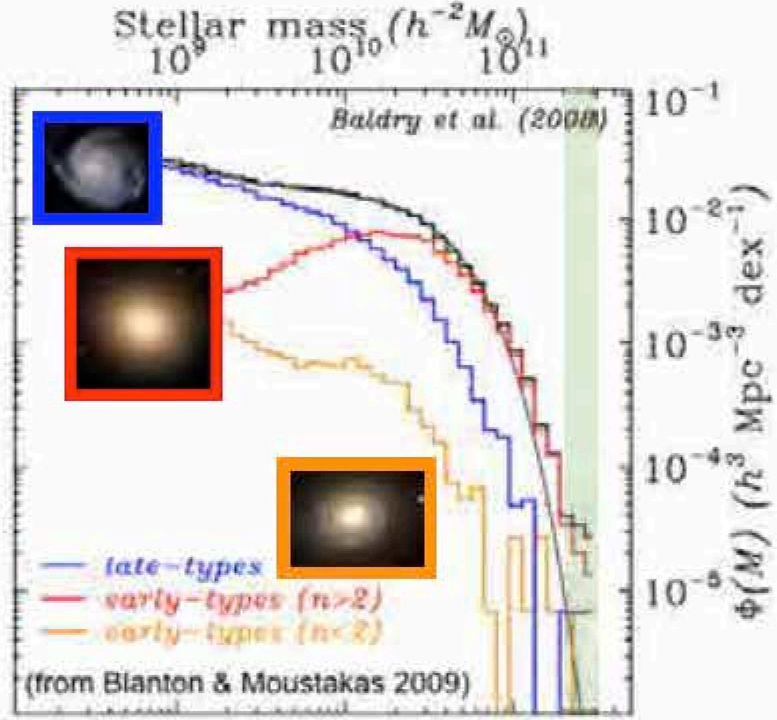
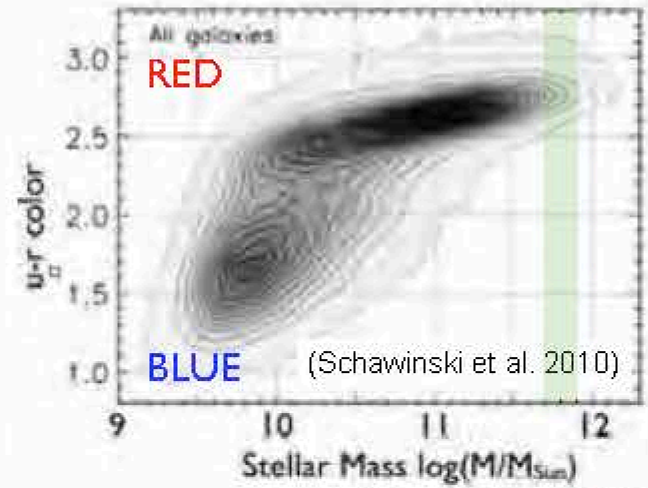
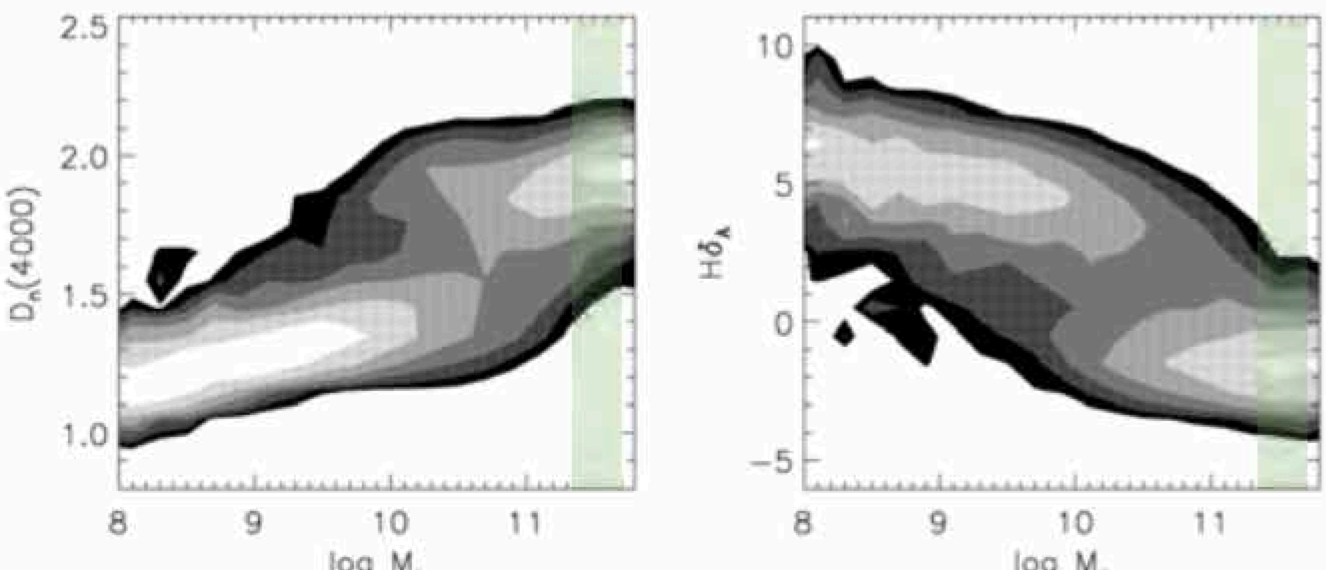
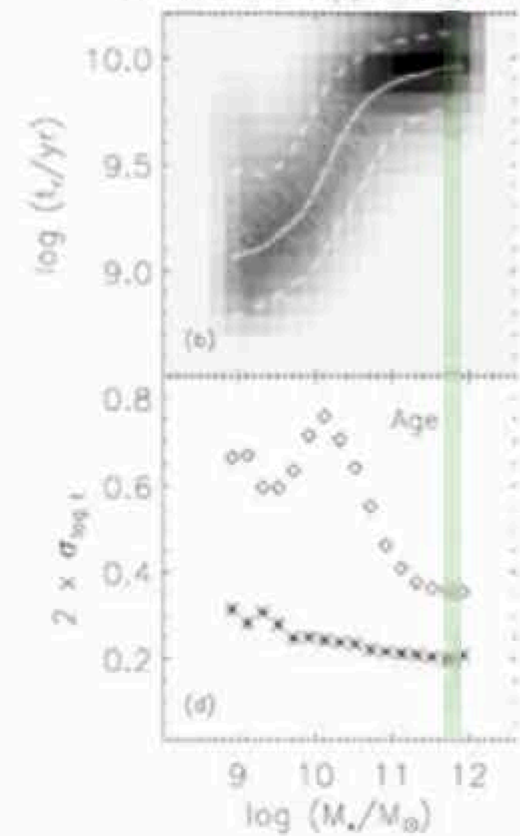


- They are characterized by quiescent stellar populations, with little dust extinction and enhanced alpha/Fe ratios.





(Kauffmann et al. 2003)



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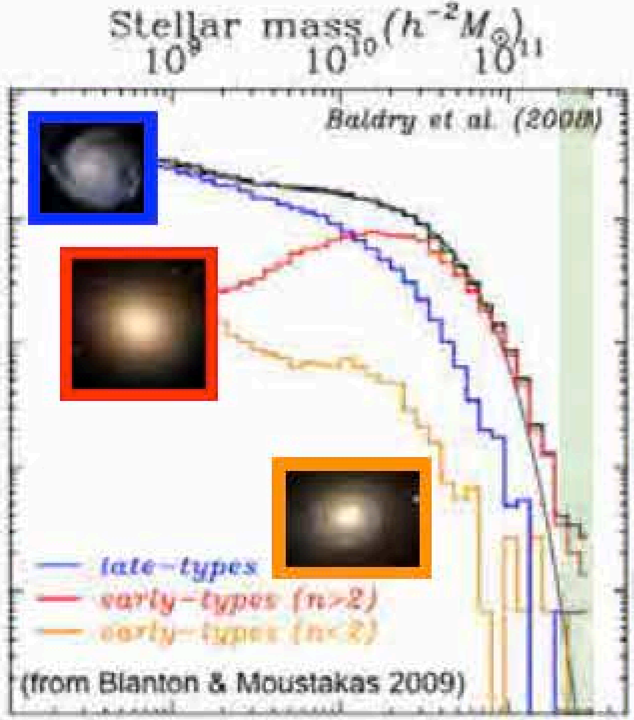
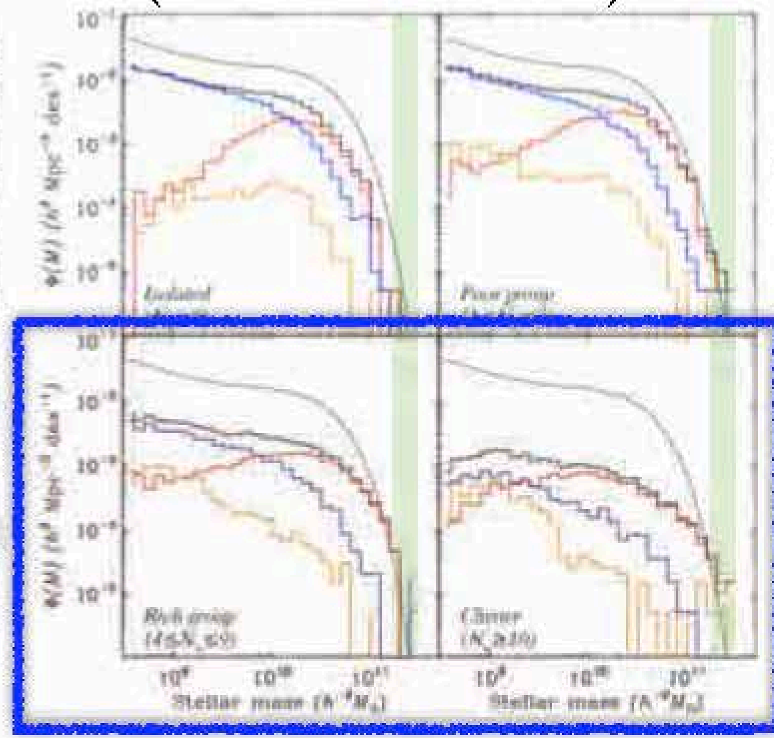
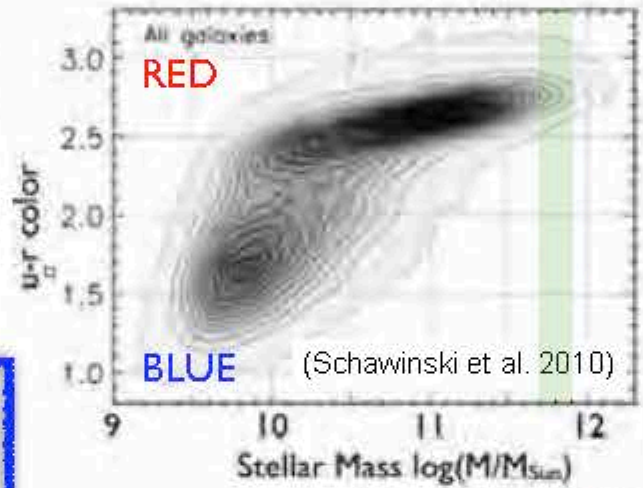
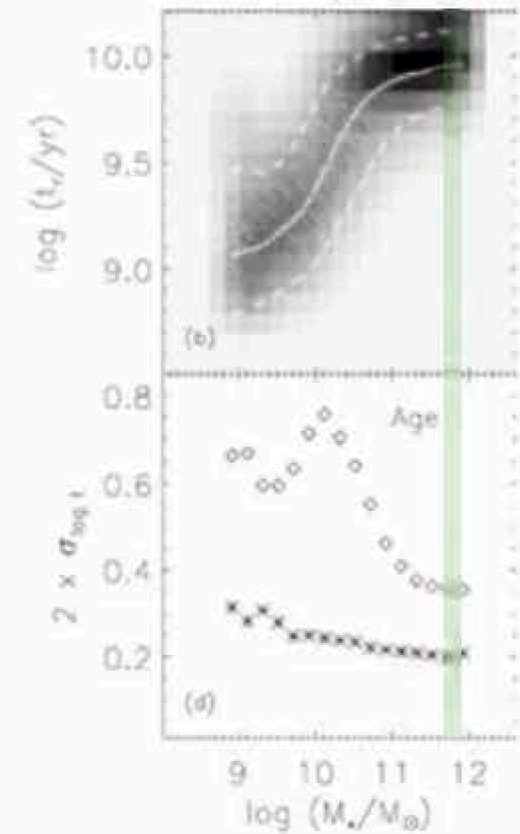


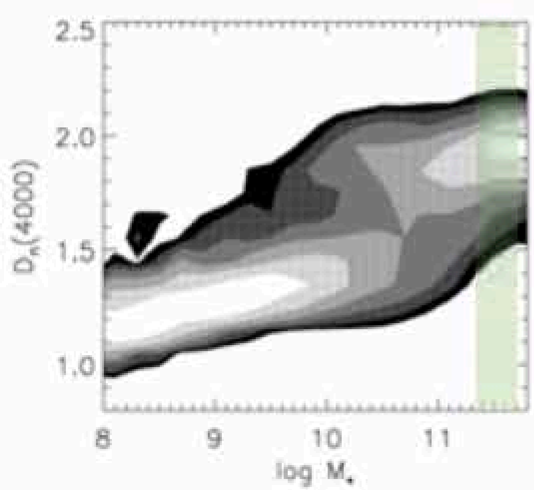
(Blanton & Moustakas 2009)

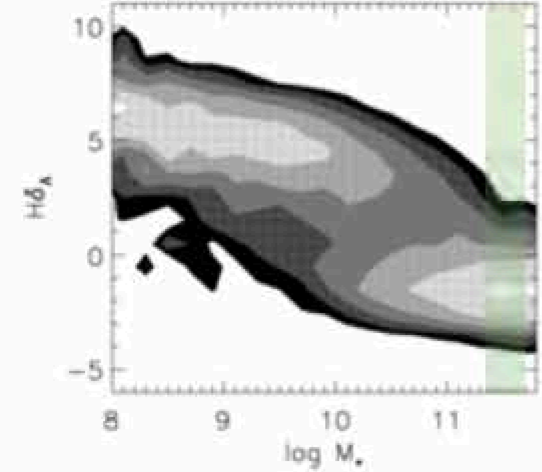






tend to live in high-density environments





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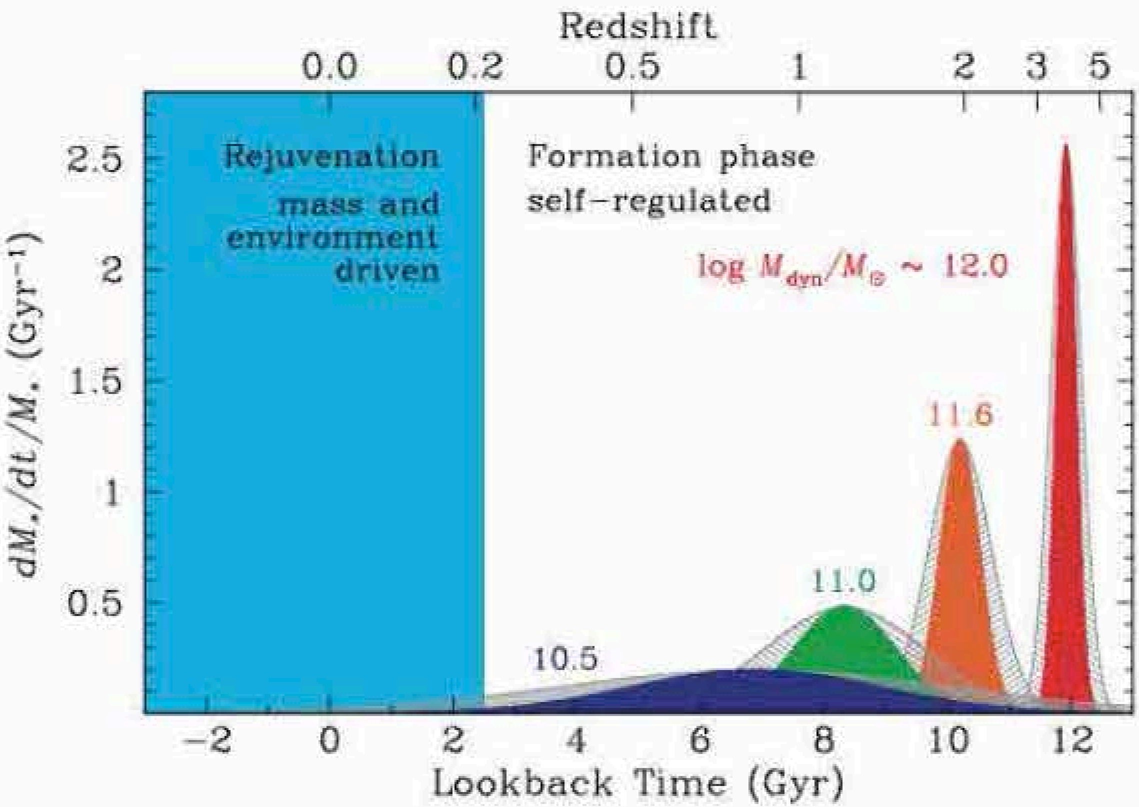

Downsizing:

More massive galaxies must have started forming stars at earlier times with shorter timescales: **most stars in local most massive galaxies must have formed at z>2 (in the first 3 Gyr), through short (<1 Gyr) and intense bursts of star formation**.

(Thomas et al. 2005, 2010; see also van Dokkum & van der Marel 2007)

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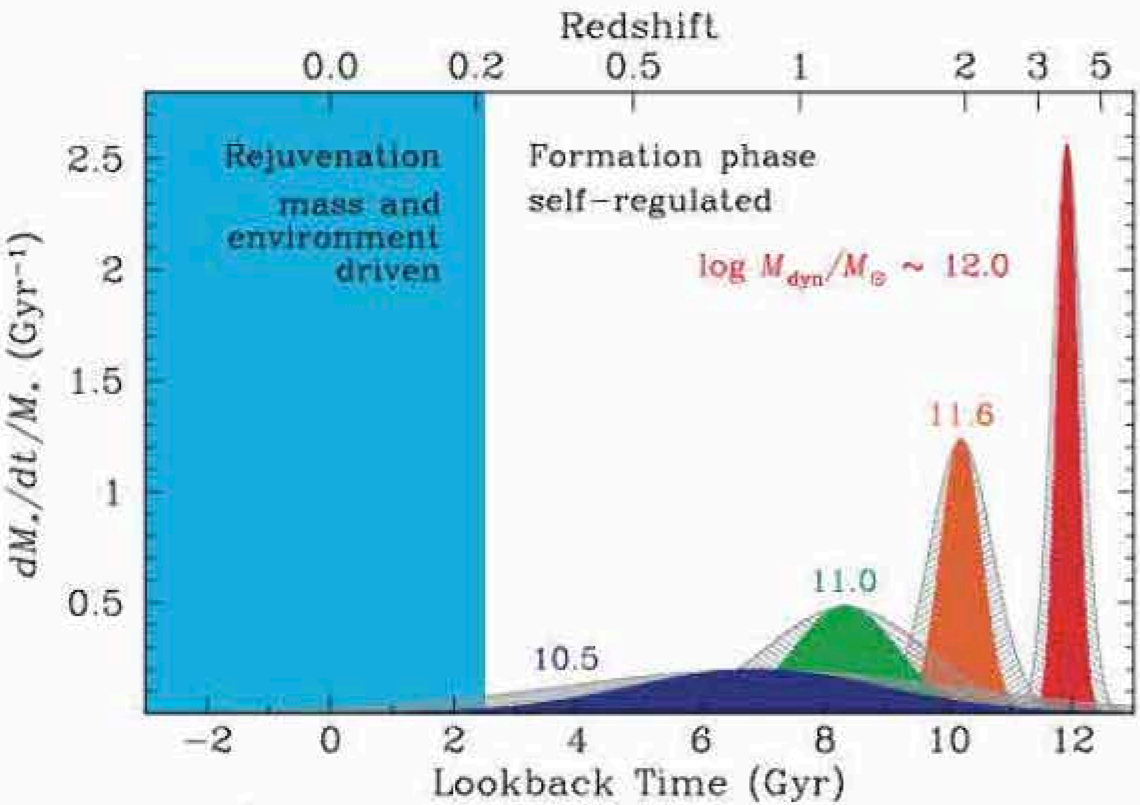

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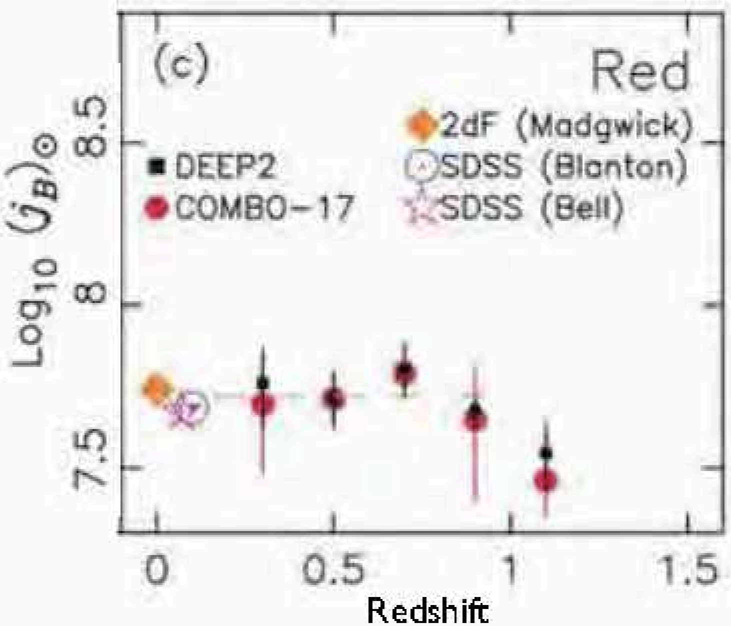
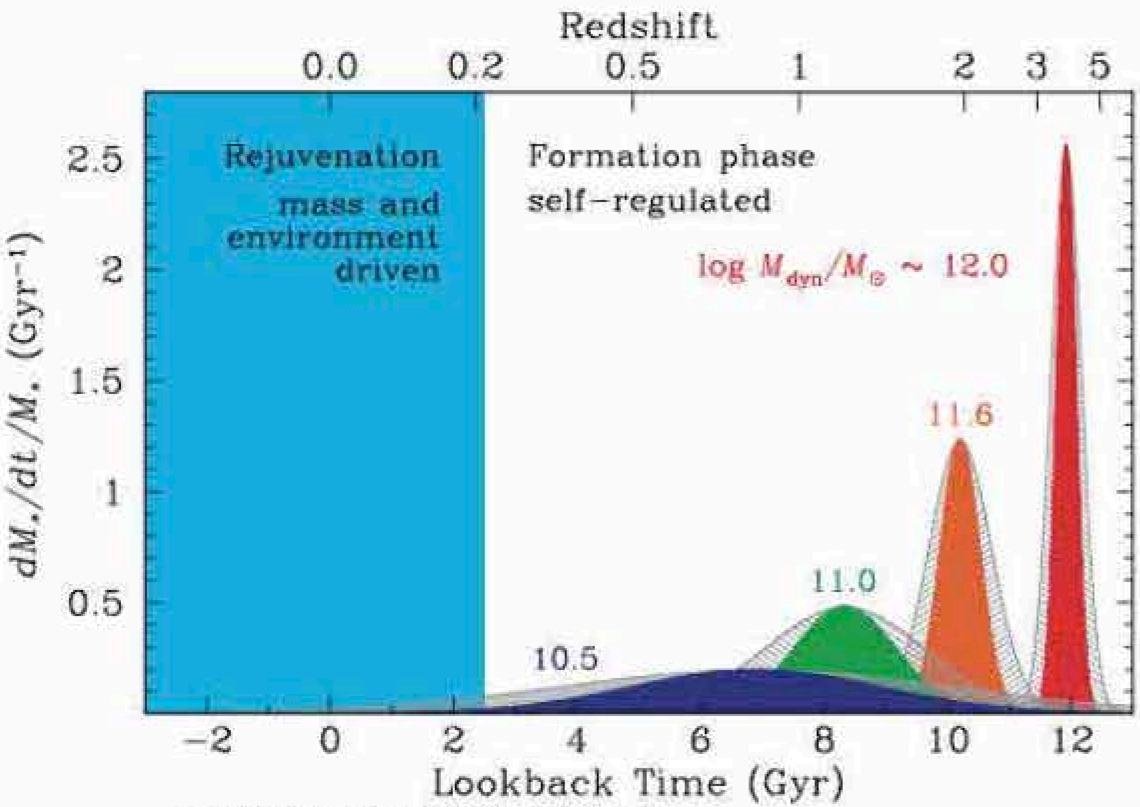


- The stellar mass density in red-sequence galaxies appears to have doubled since z=1 due to quenching of star-forming galaxies.

(Bell et al. 2004; Brown et al. 2007; Faber et al. 2007; see also Cimatti et al. 2007)

Properties of today's most massive galaxies



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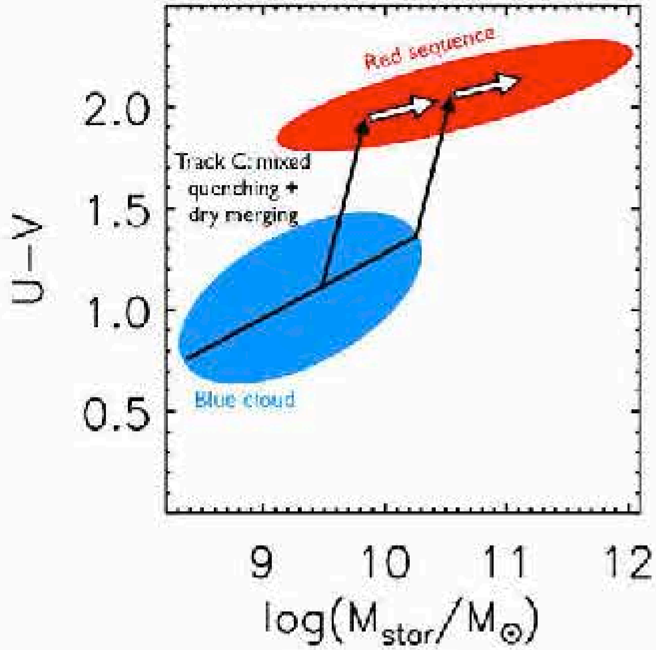

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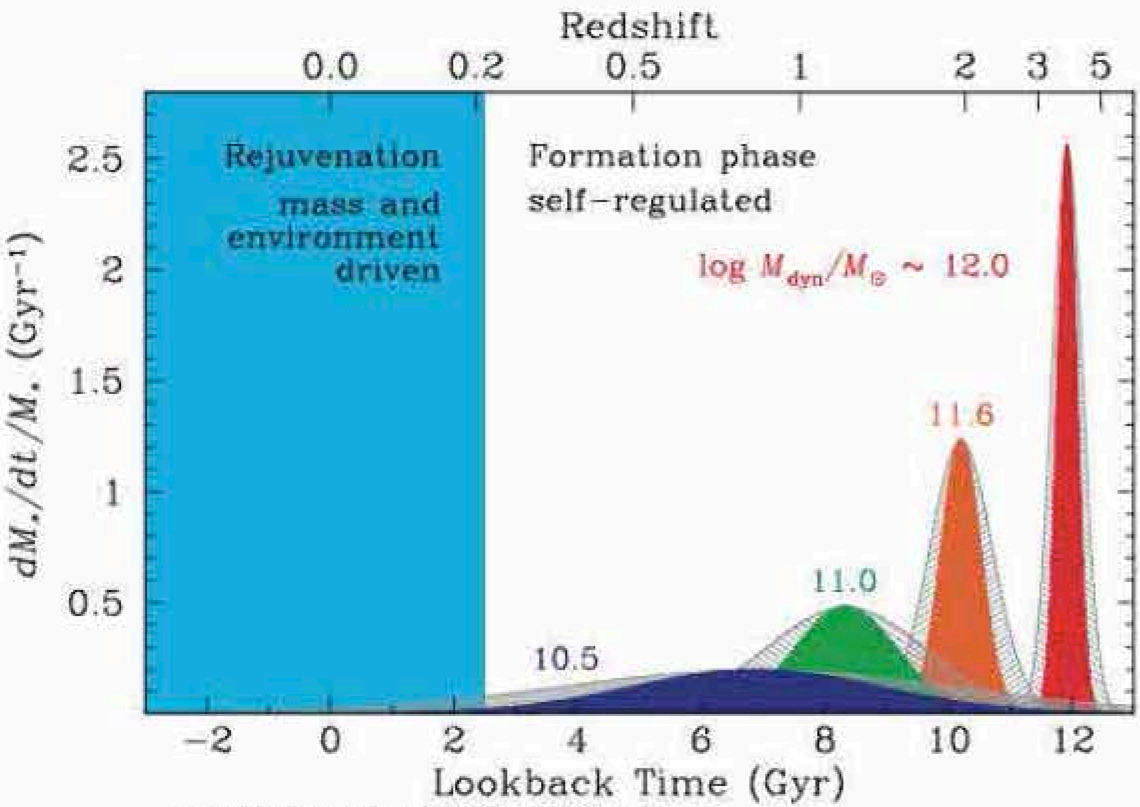

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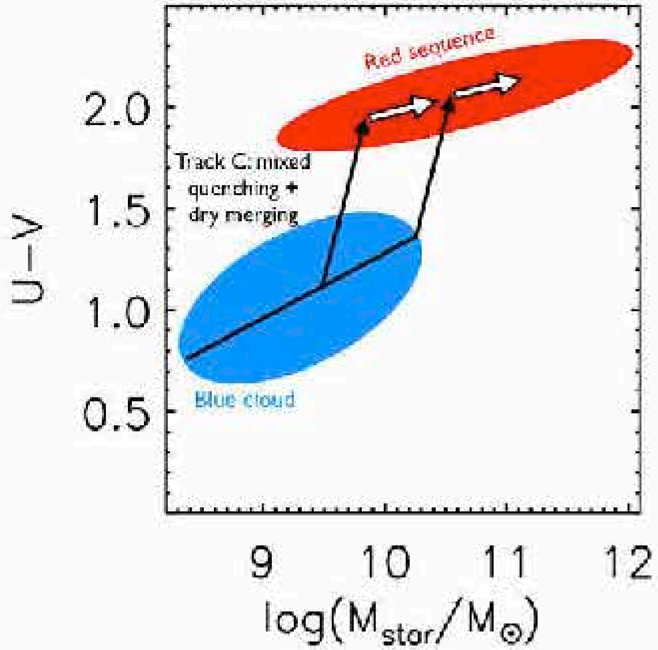

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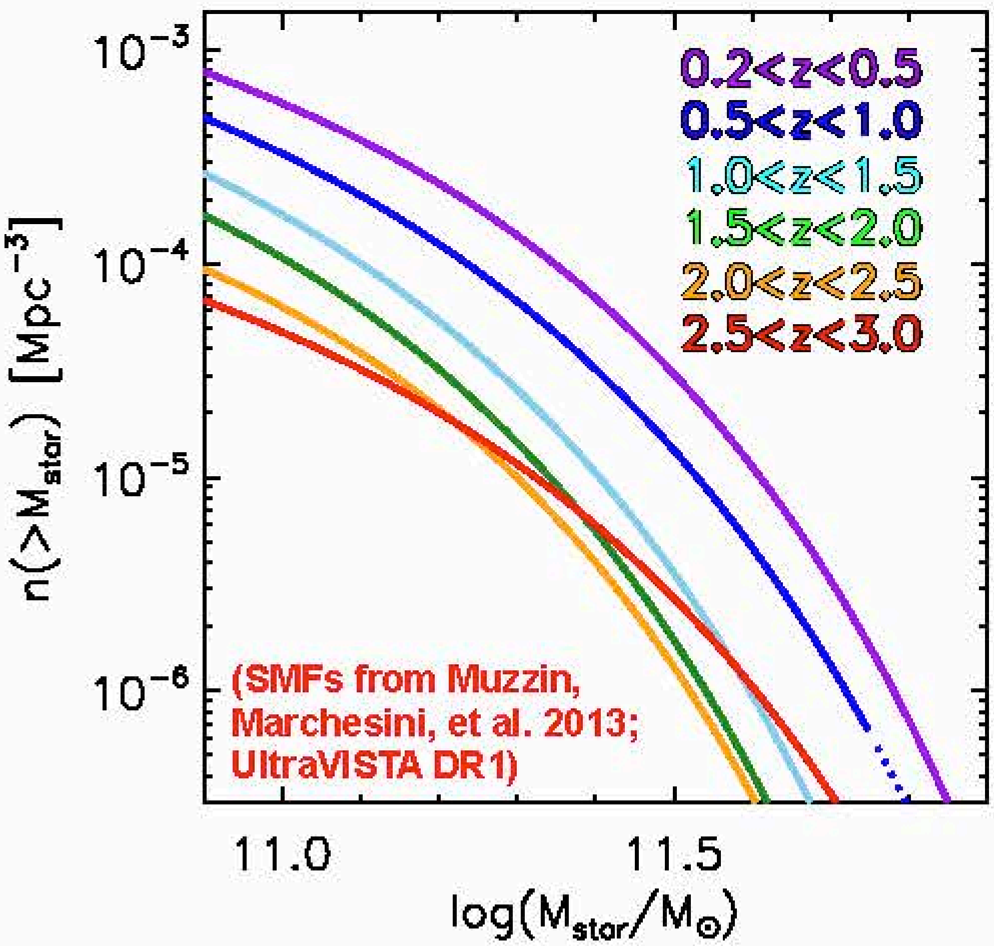
One would like to directly connect local most massive galaxies to their progenitors in the early universe.

Selection of the Progenitors of Local Ultra-Massive Galaxies (UMGs)

(Marchesini et al. 2014)



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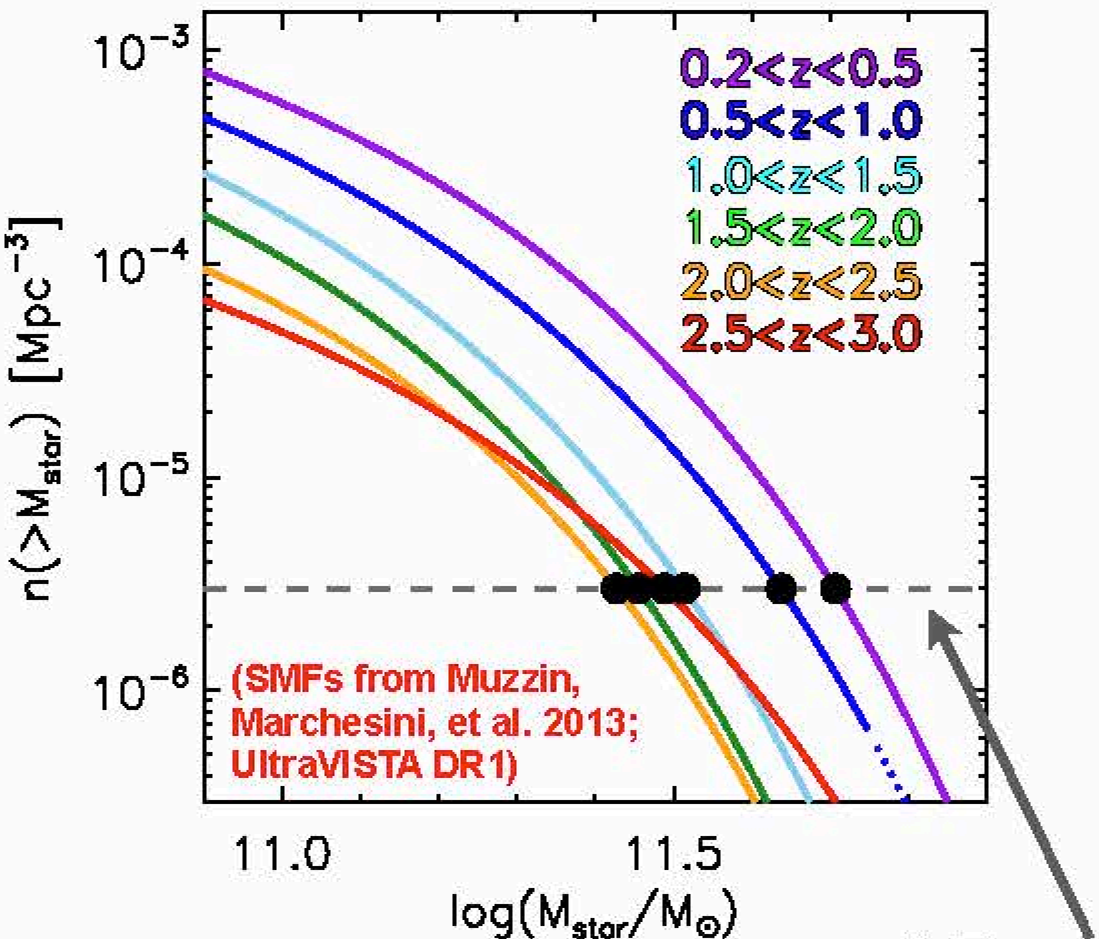

● Fixed cumulative number density

(e.g., Brammer, DM, et al. 2011; Leja et al. 2013)

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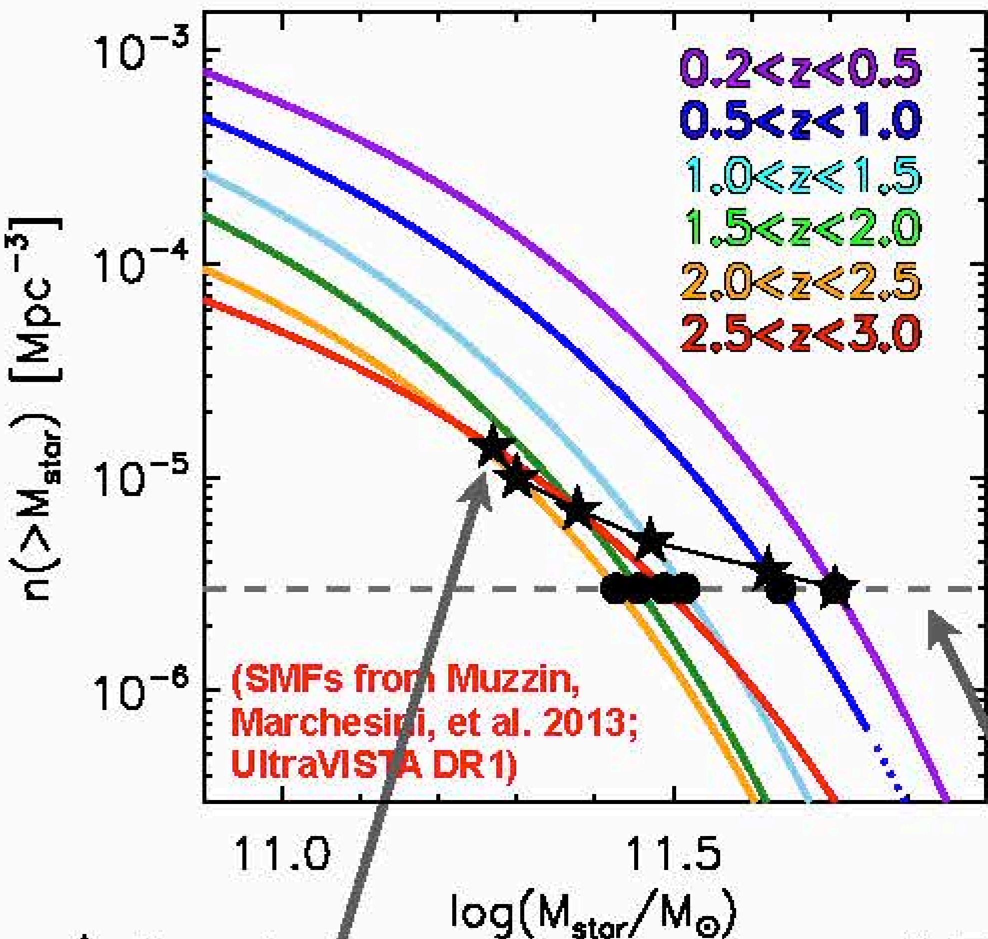

★ Abundance matching
(Behroozi, Marchesini, et al. 2014)

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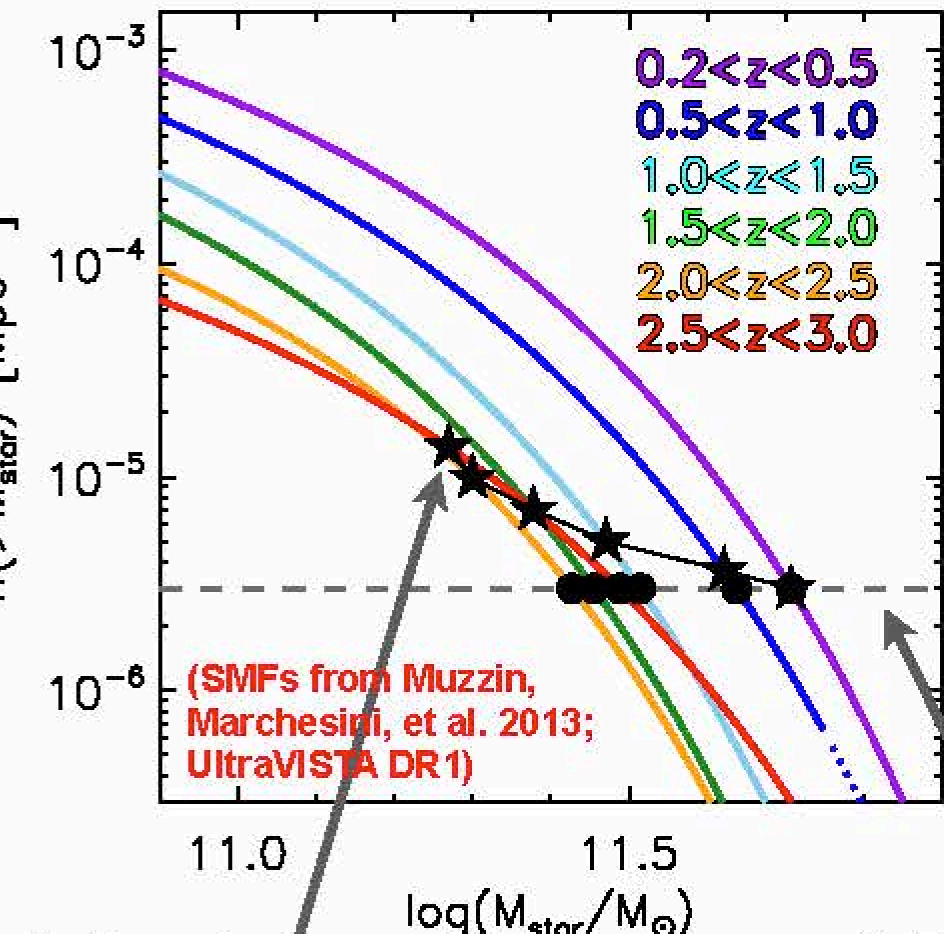

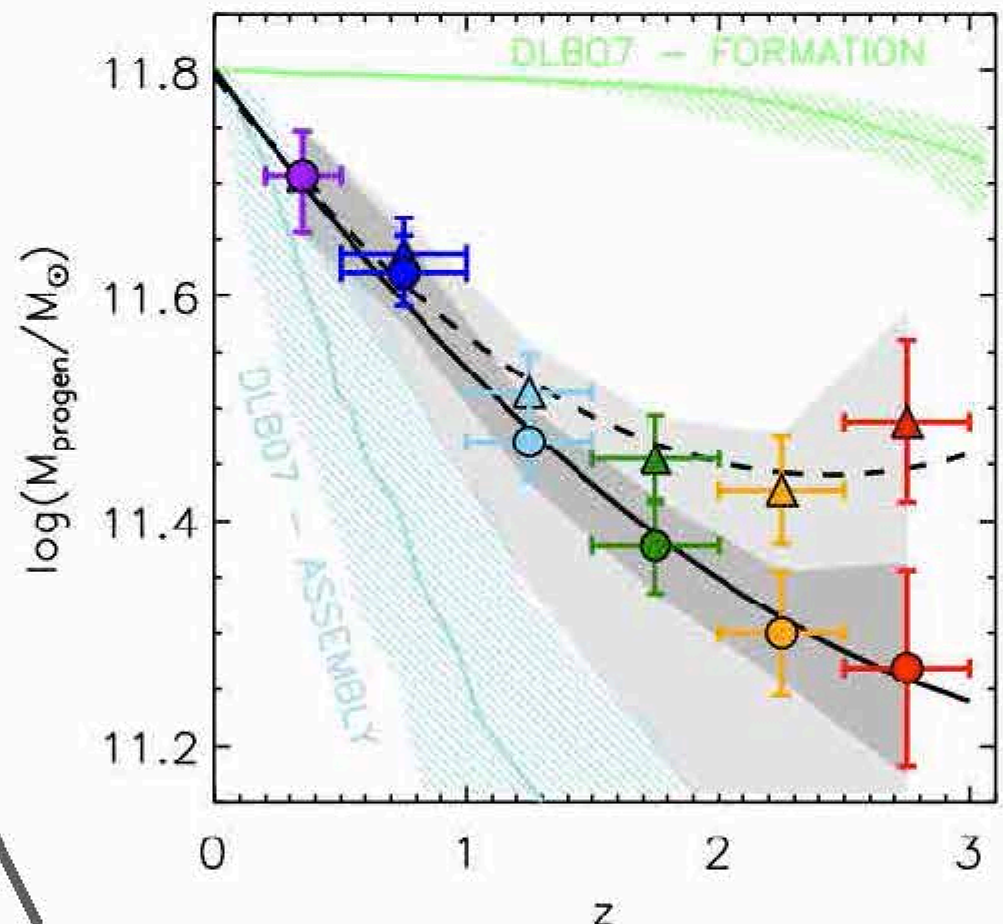

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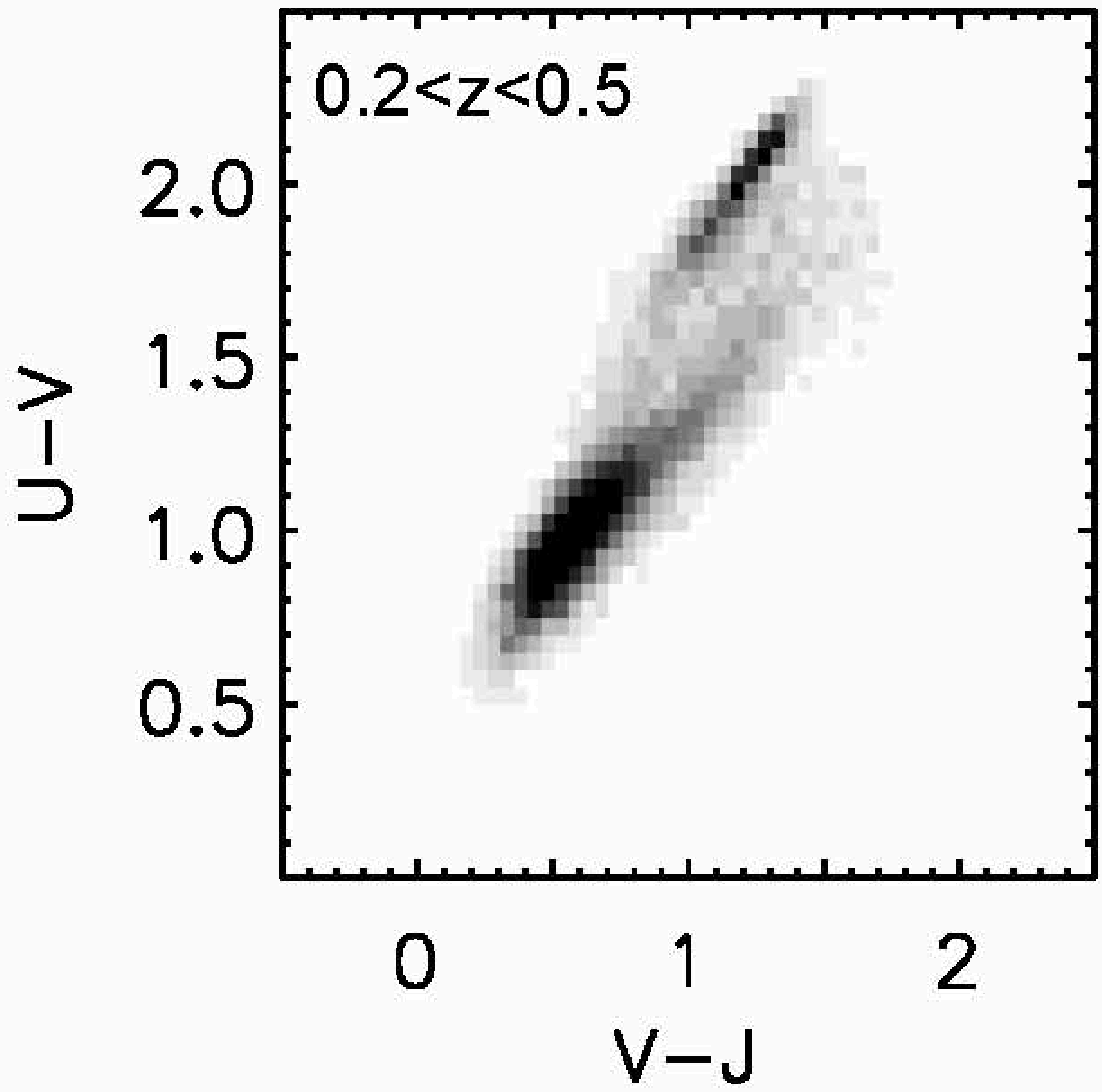
- **z~0 UMGs** defined as galaxies with $M_{star}=6\times10^{11}$ Msun, i.e., **$\log(M_{star}/M_{Sun})=11.8$** (Kroupa)
- Mass growth by a factor of ~2 from z=3 to z=0 using fixed cumulative number density.
- **Mass growth is** a factor of **~3.6 from z=3 to z=0** using **abundance matching** techniques

The UVJ diagram and separation of Quiescent and Star-forming Galaxies



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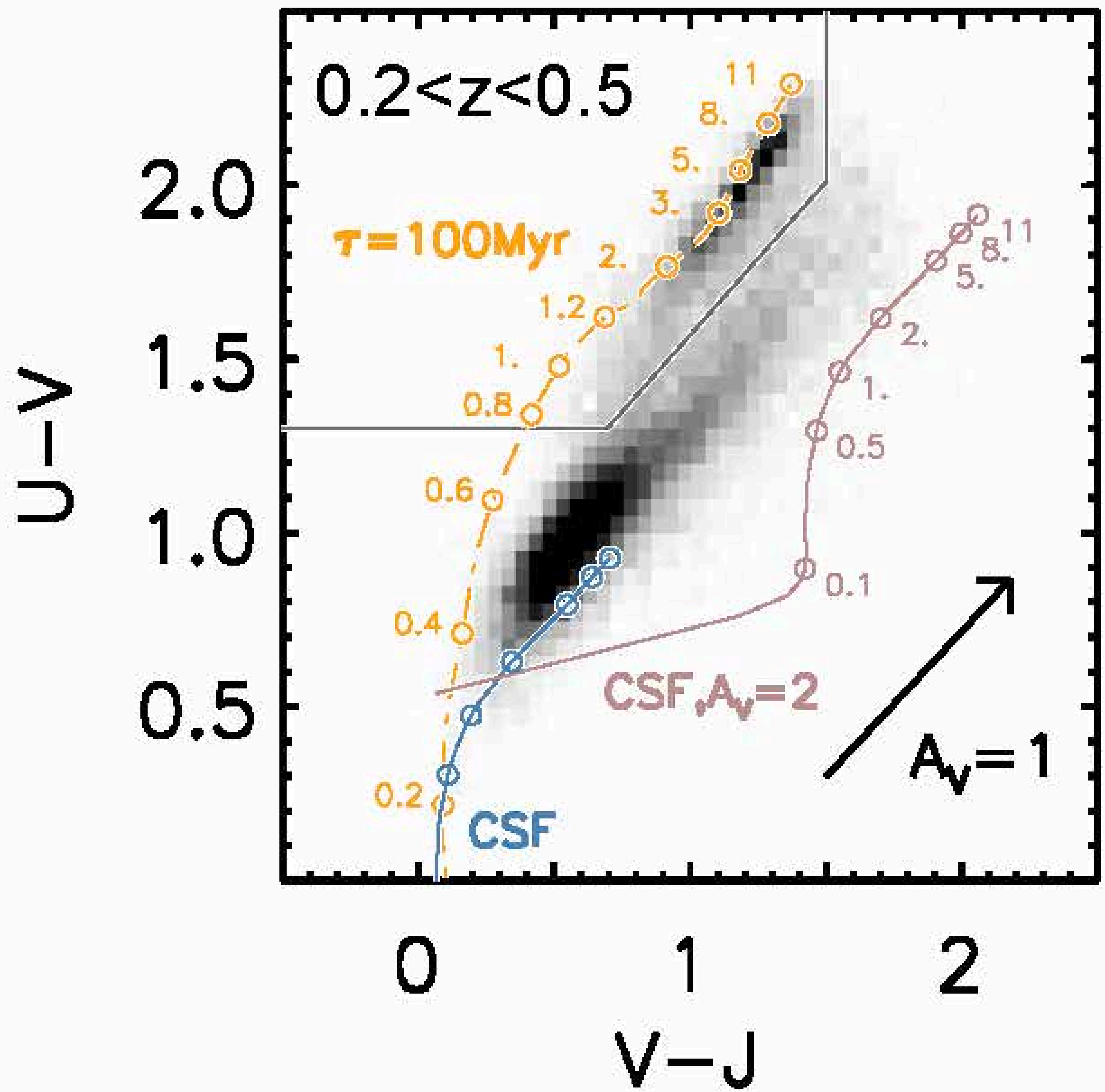

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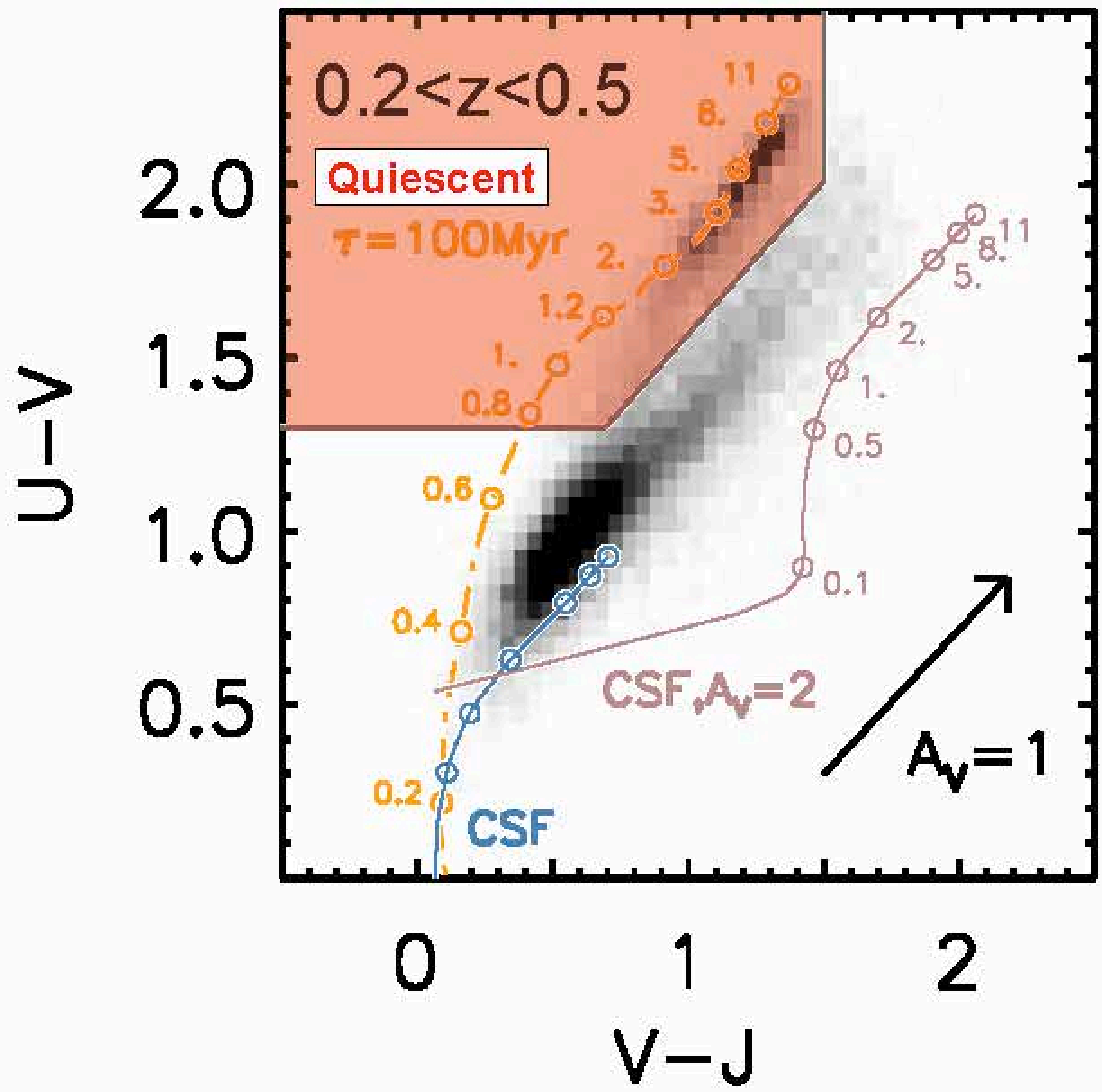

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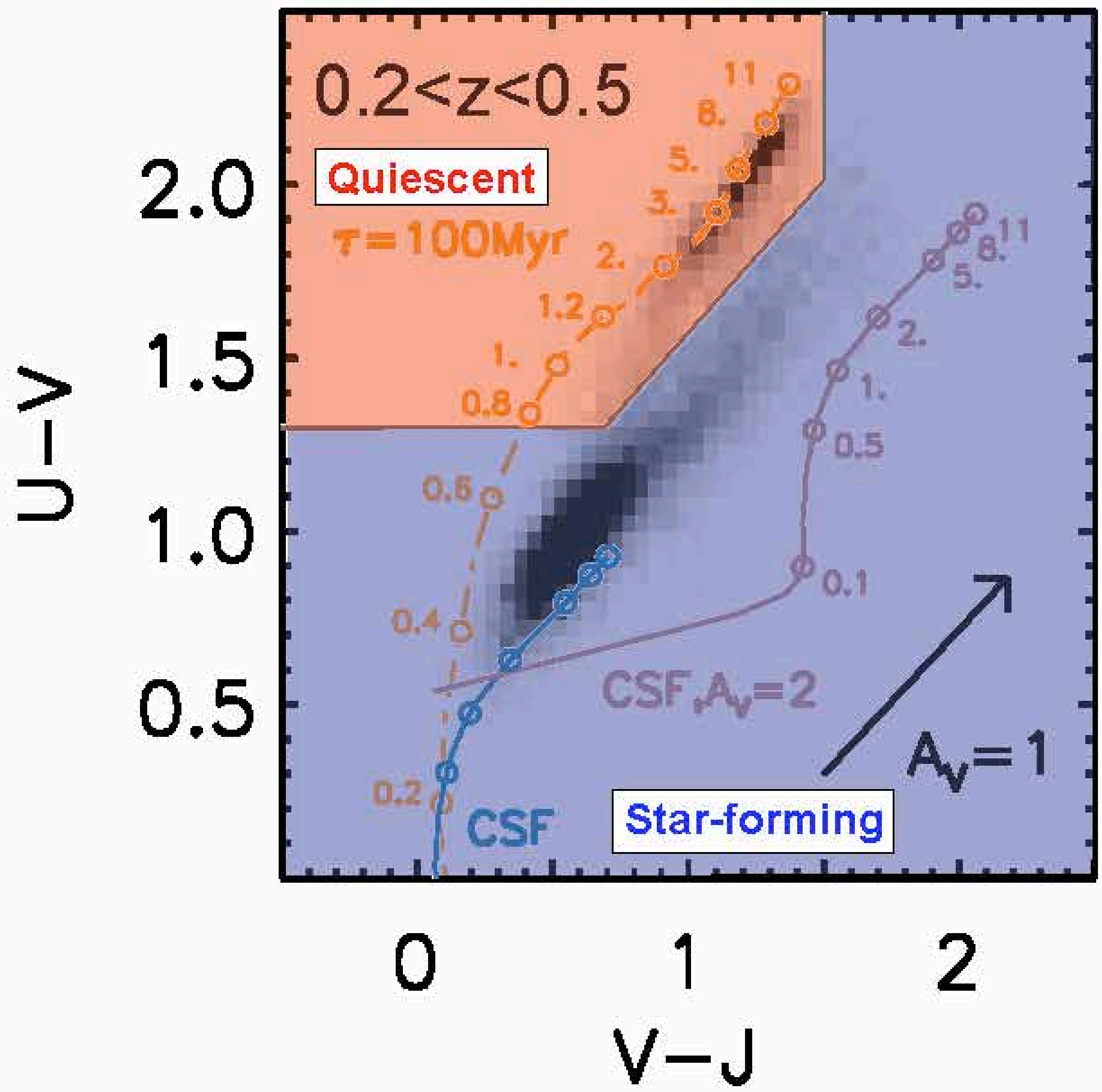
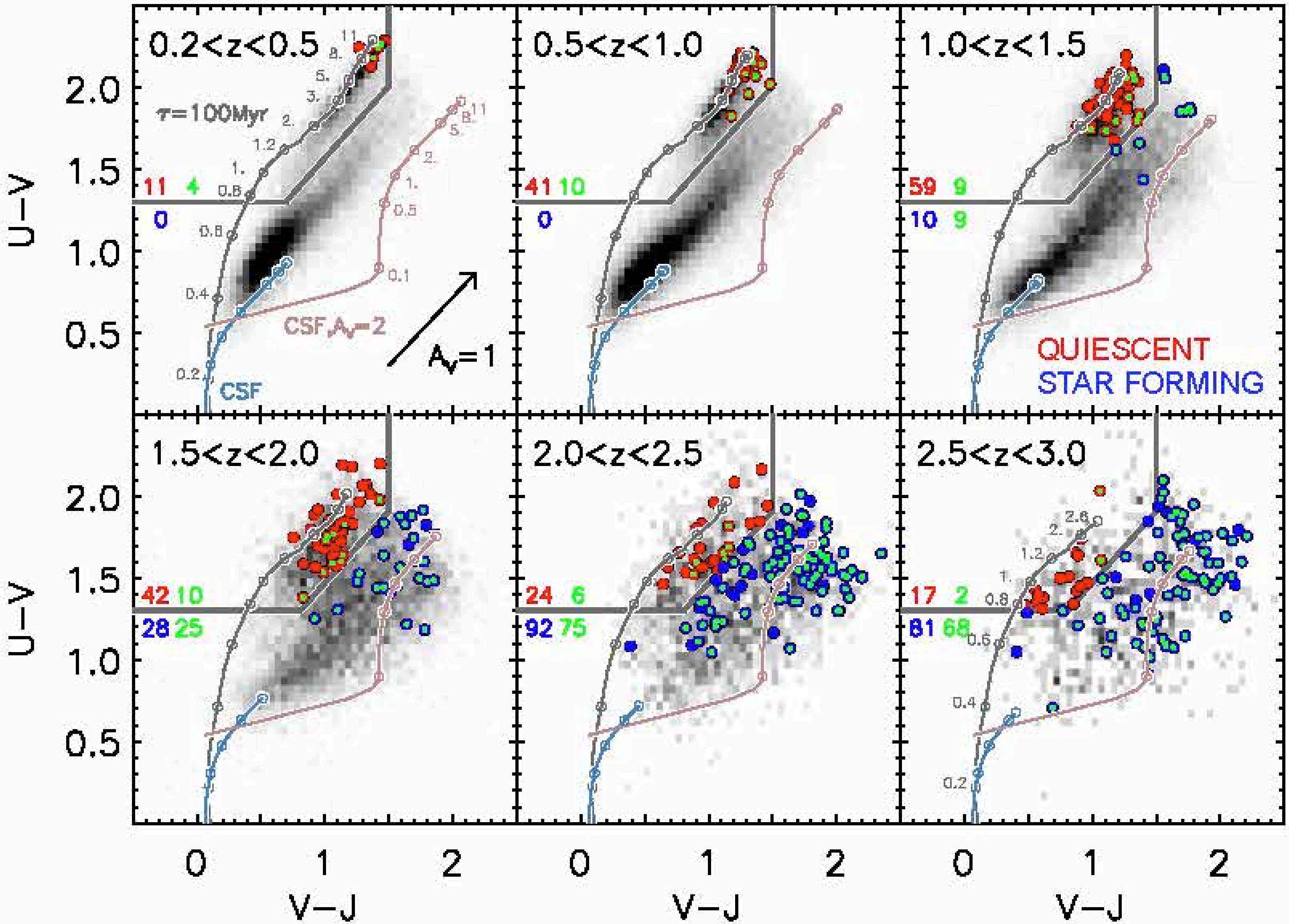


Evolution of Progenitors in the UVJ diagram

(Marchesini et al. 2014)



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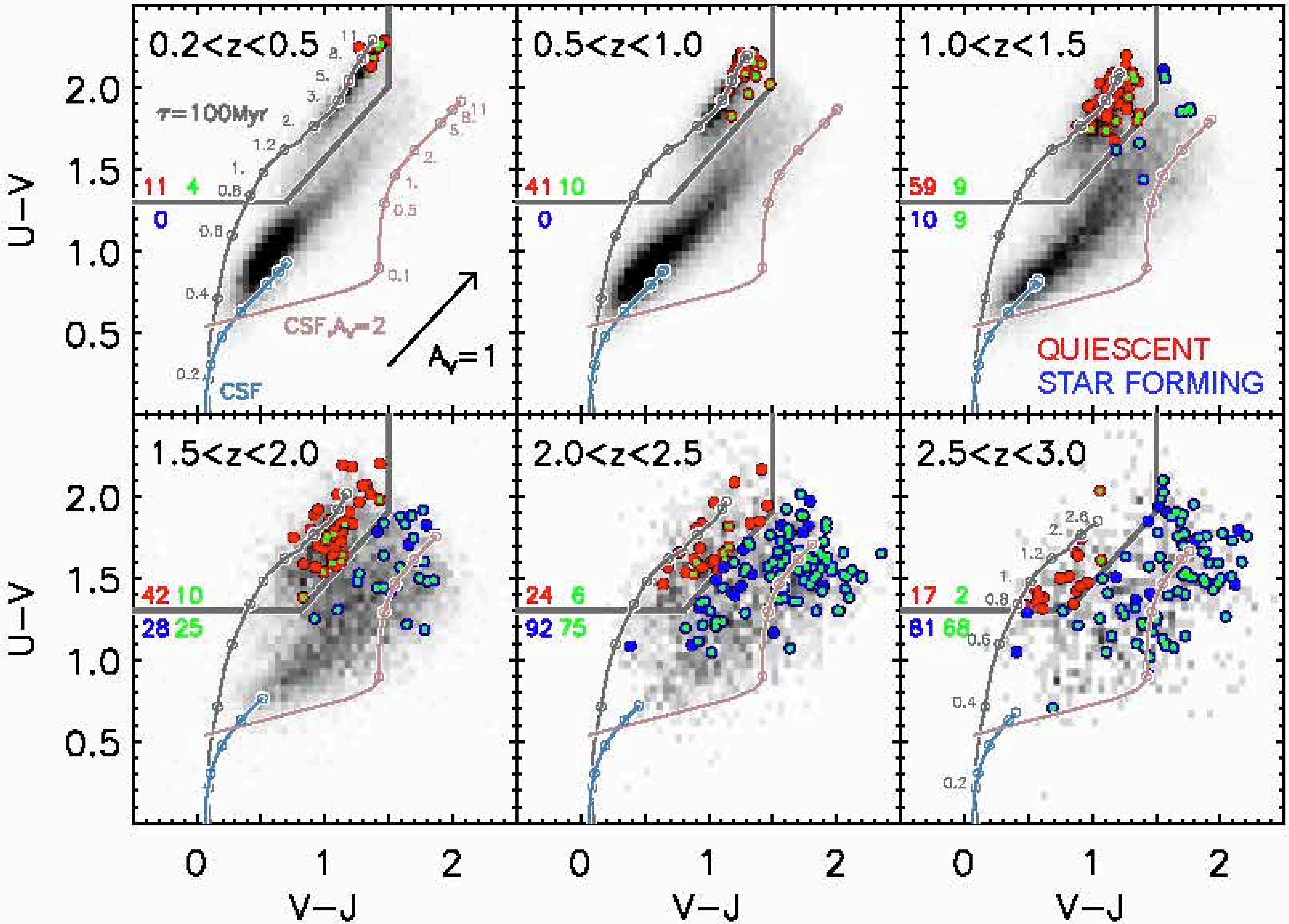

- **At z<1, all progenitors are quiescent**, and constitute a very homogeneous population. At high-z, the contribution from star-forming galaxies progressively increases, with the **progenitors' population dominated by star-forming galaxies at 2<z<3**.

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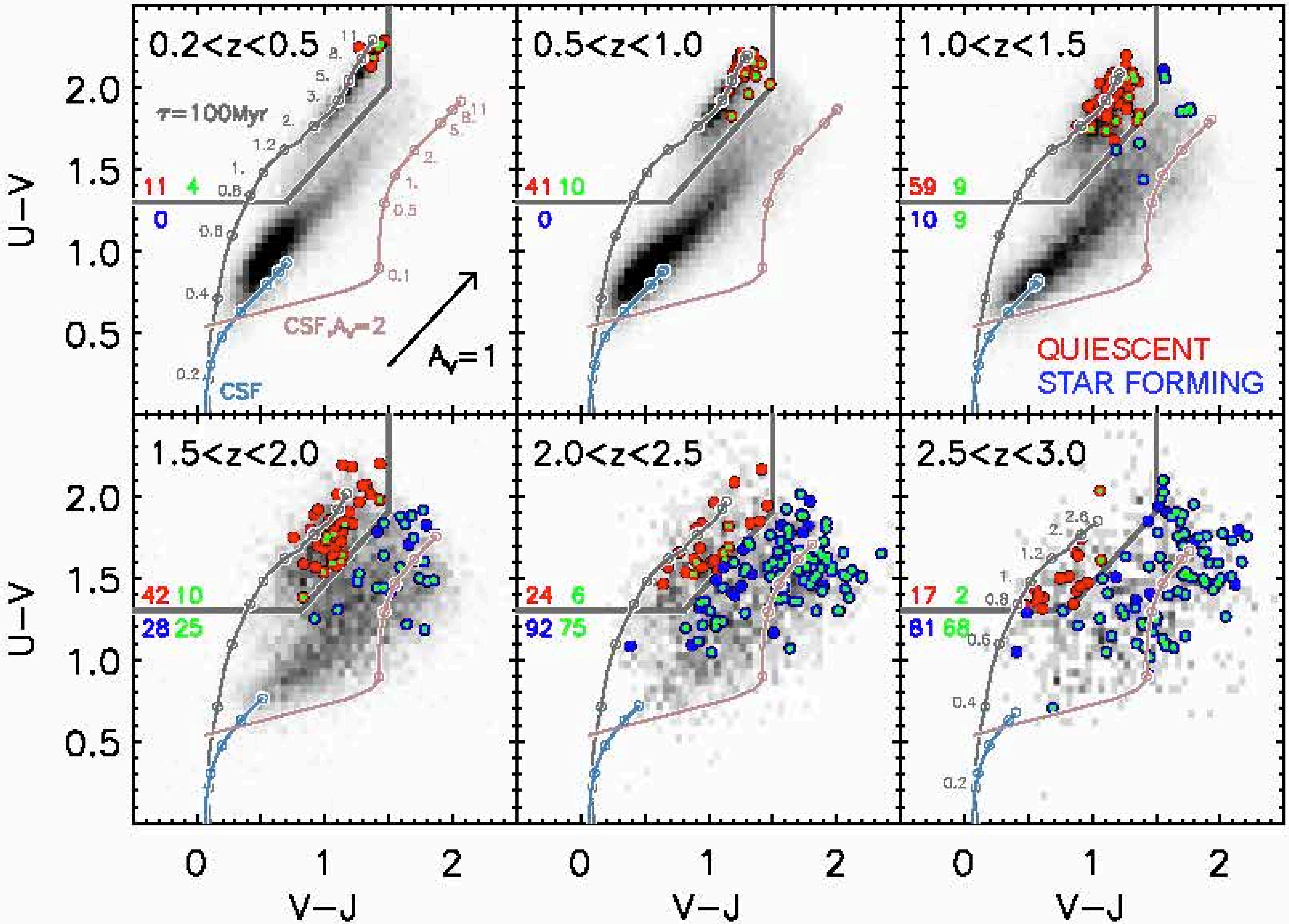

- **Aging of the quiescent population** clearly detected.

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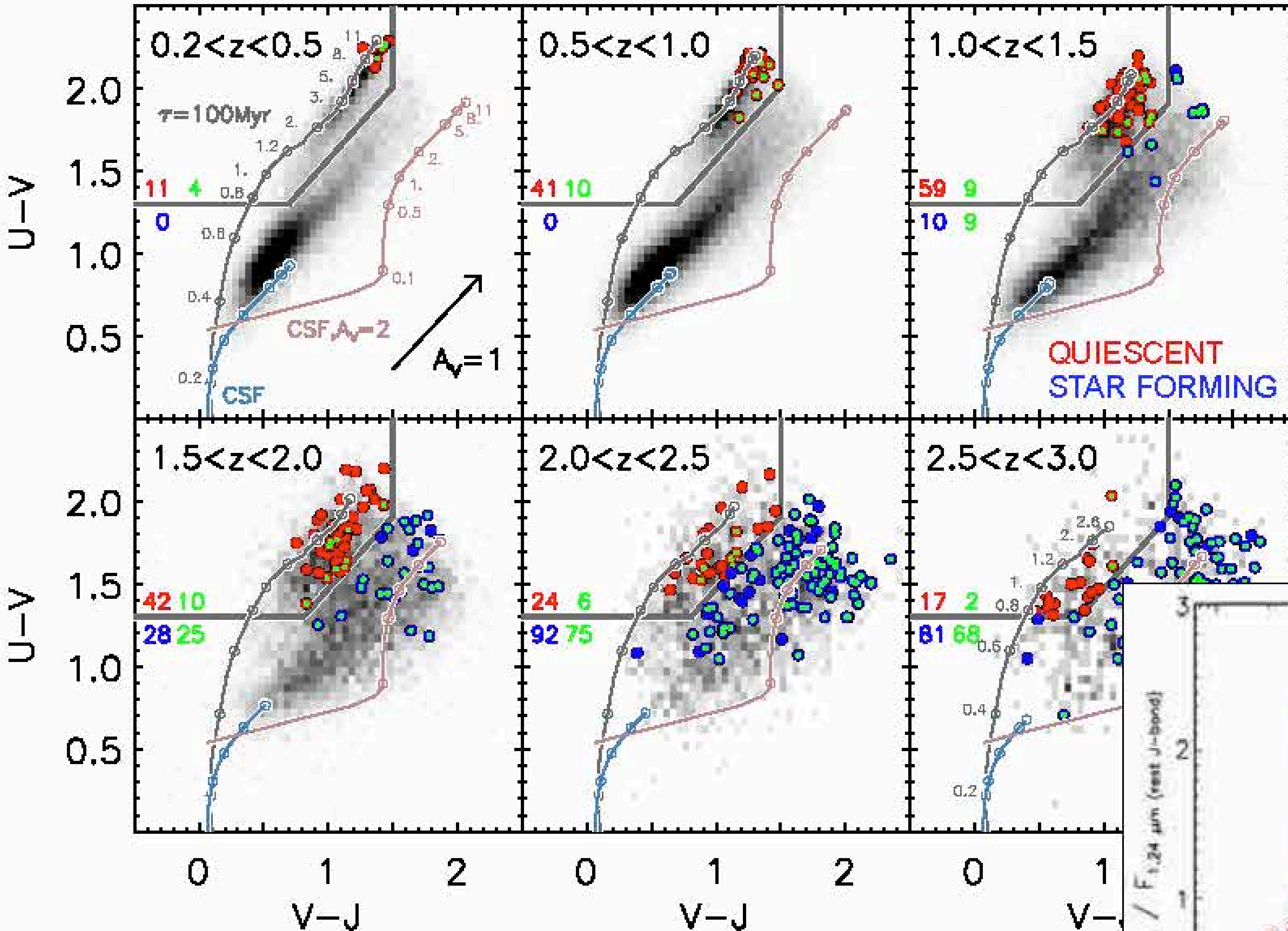

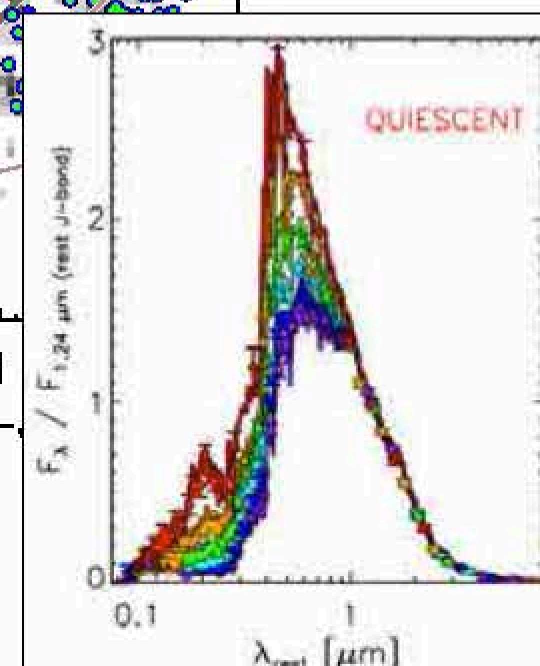

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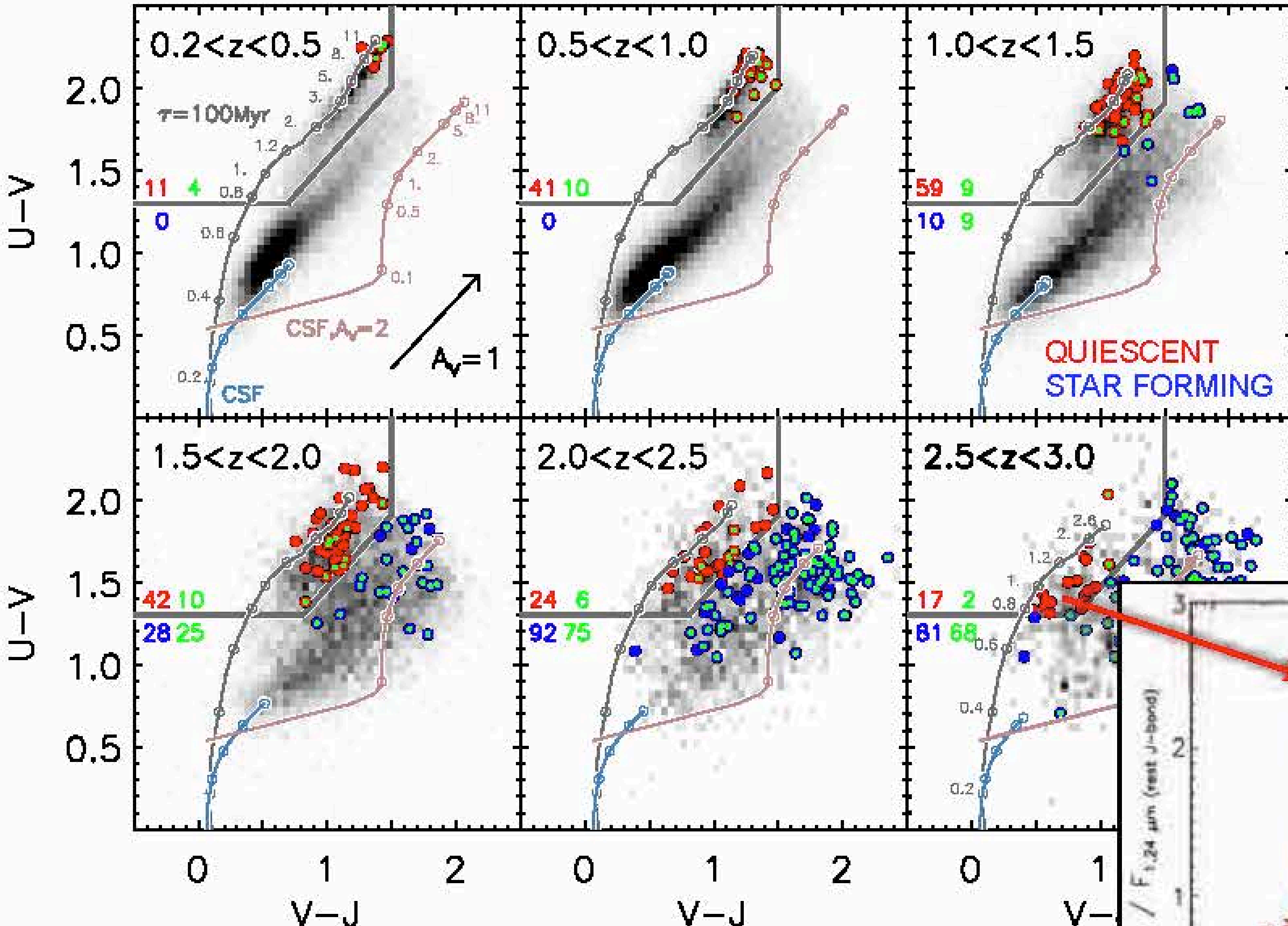

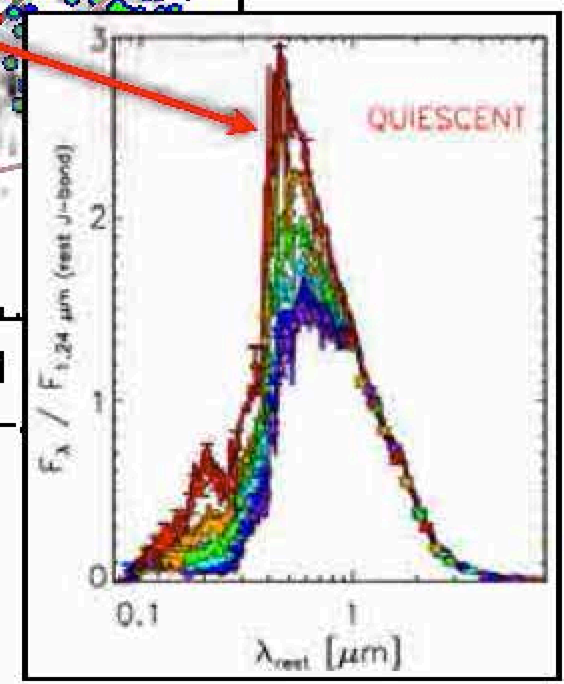

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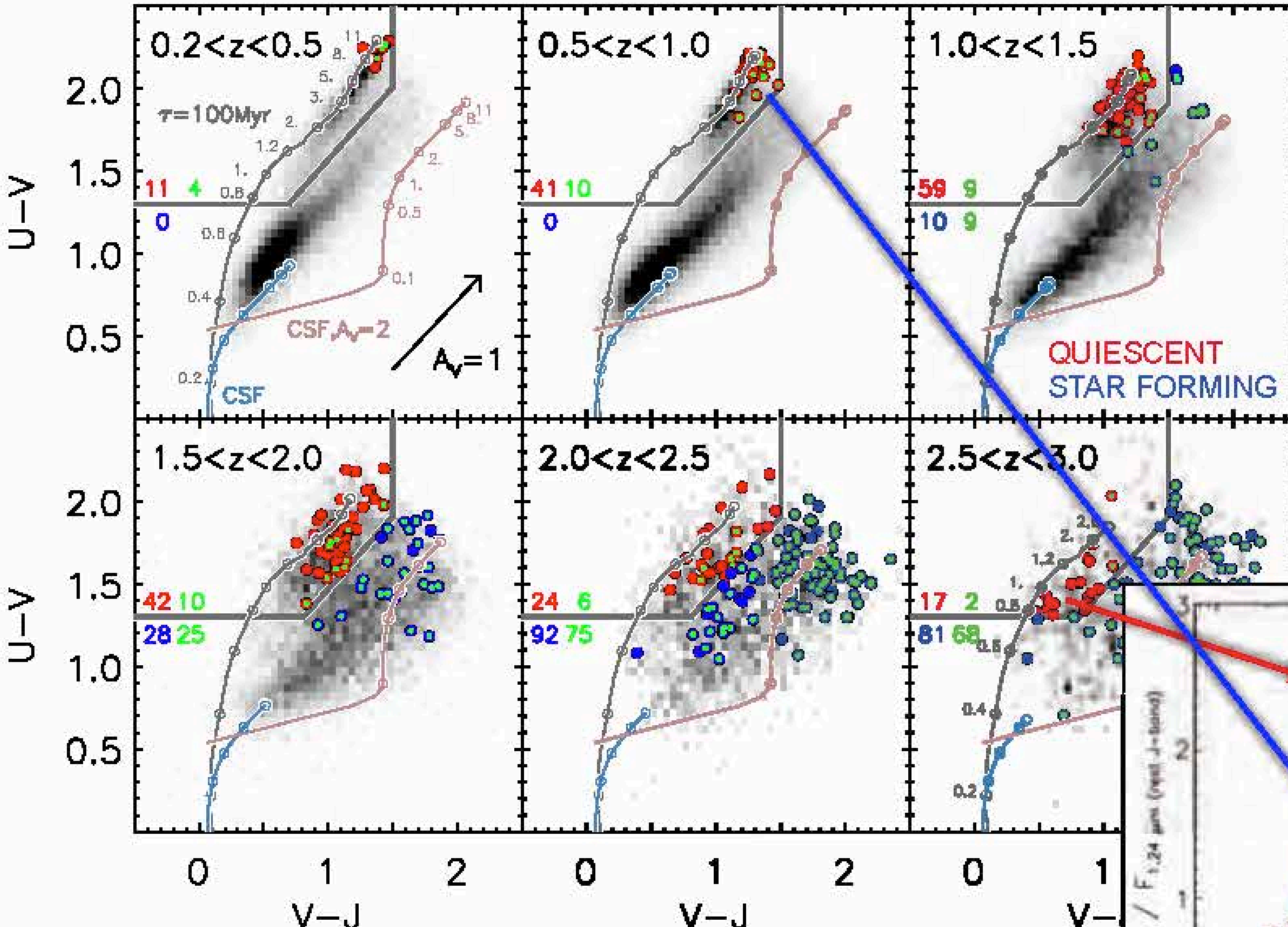

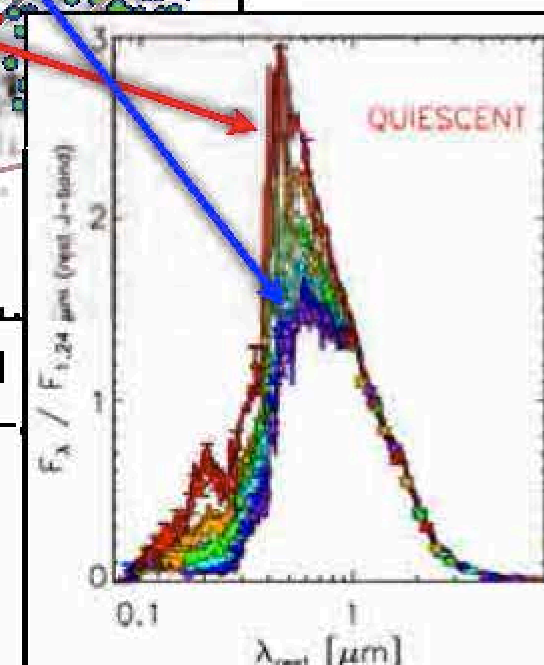

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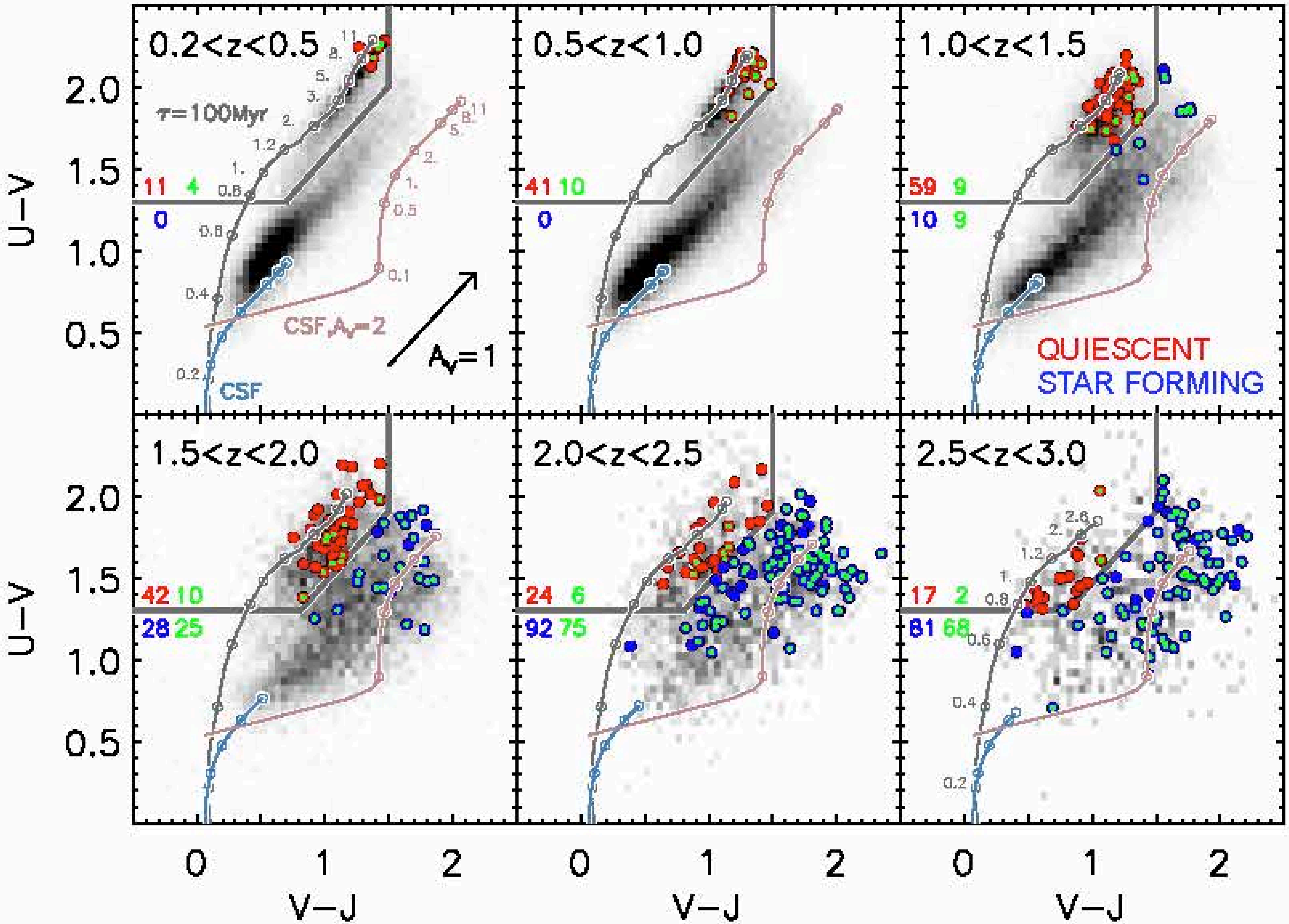

- **Aging of the quiescent population** clearly detected.
- The **star-forming progenitors are very dusty**, confirmed by their ubiquitous detection in the MIPS 24 micron data (green).

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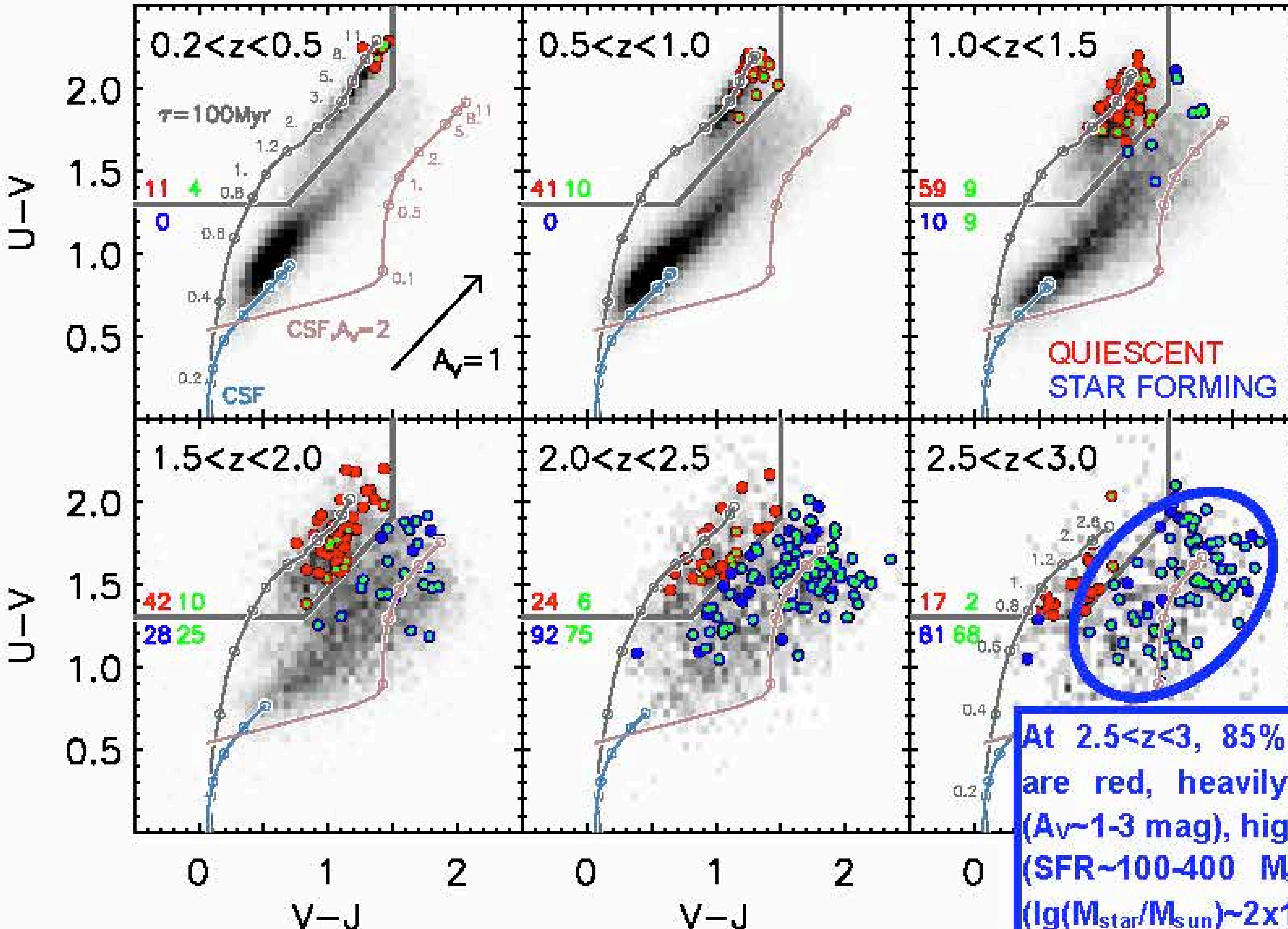

At 2.5<z<3, 85% of progenitors are red, heavily dust-obscured (A_V~1-3 mag), highly star-forming (SFR~100-400 M_{sun}/yr), massive (lg(M_{star}/M_{sun})~2x10^{11}) galaxies.

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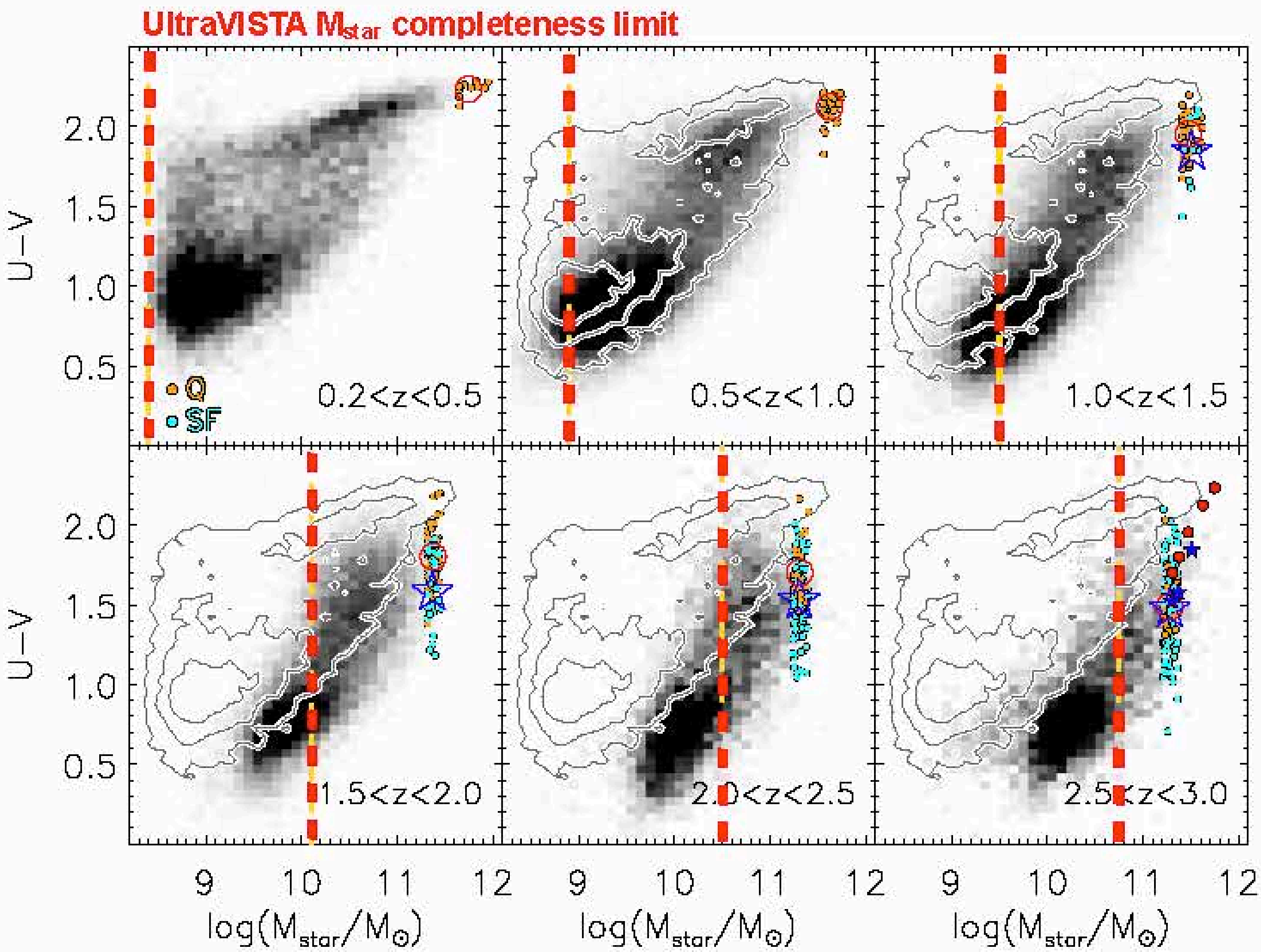
Color versus Stellar Mass Diagram

(Marchesini et al. 2014)



- The **star-forming progenitors** have **never lived on the blue cloud since z=3**.

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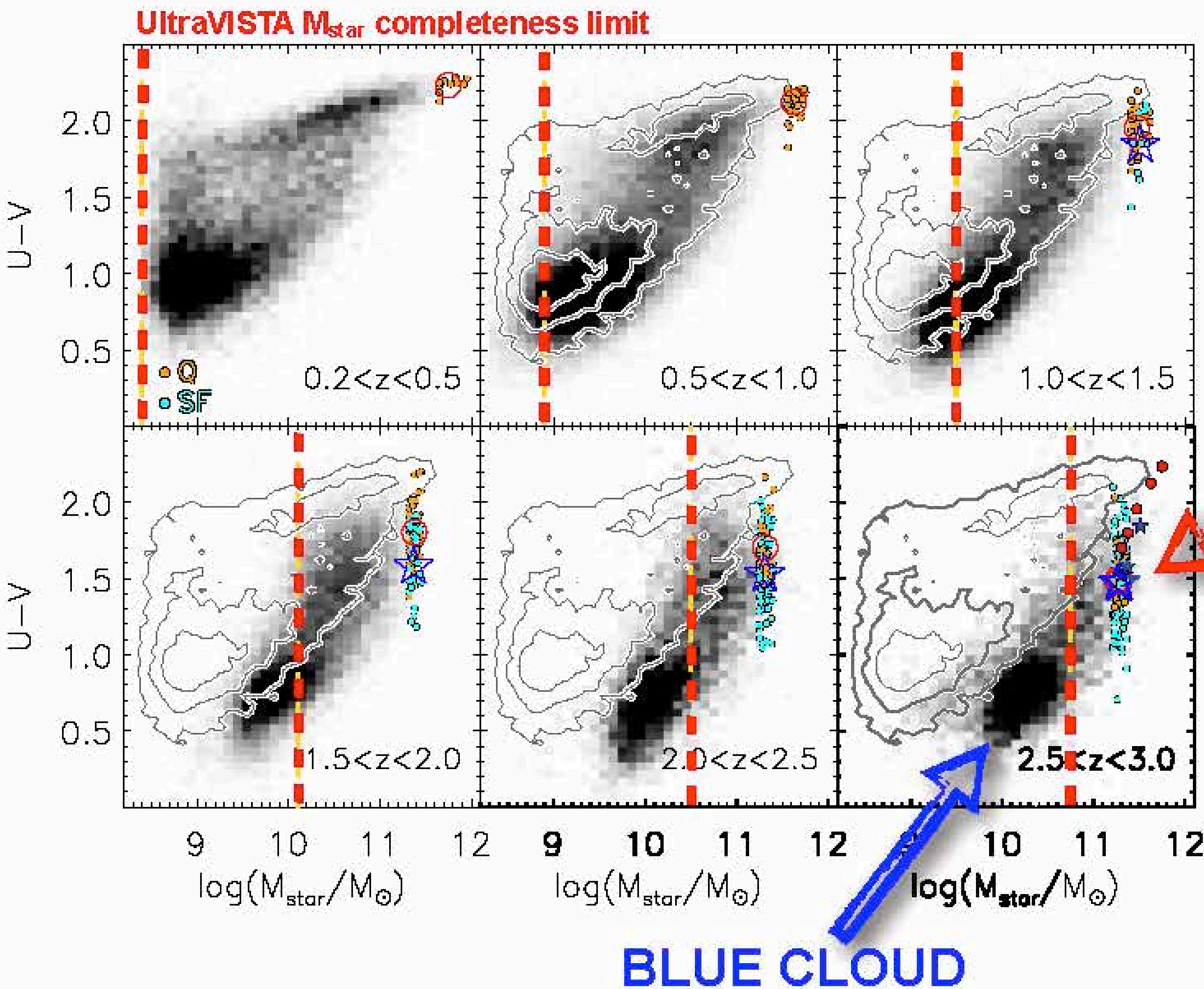

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Quiescent and **star-forming** progenitors have **similar** median rest-frame **U-V colors** at **2.5<z<3**.

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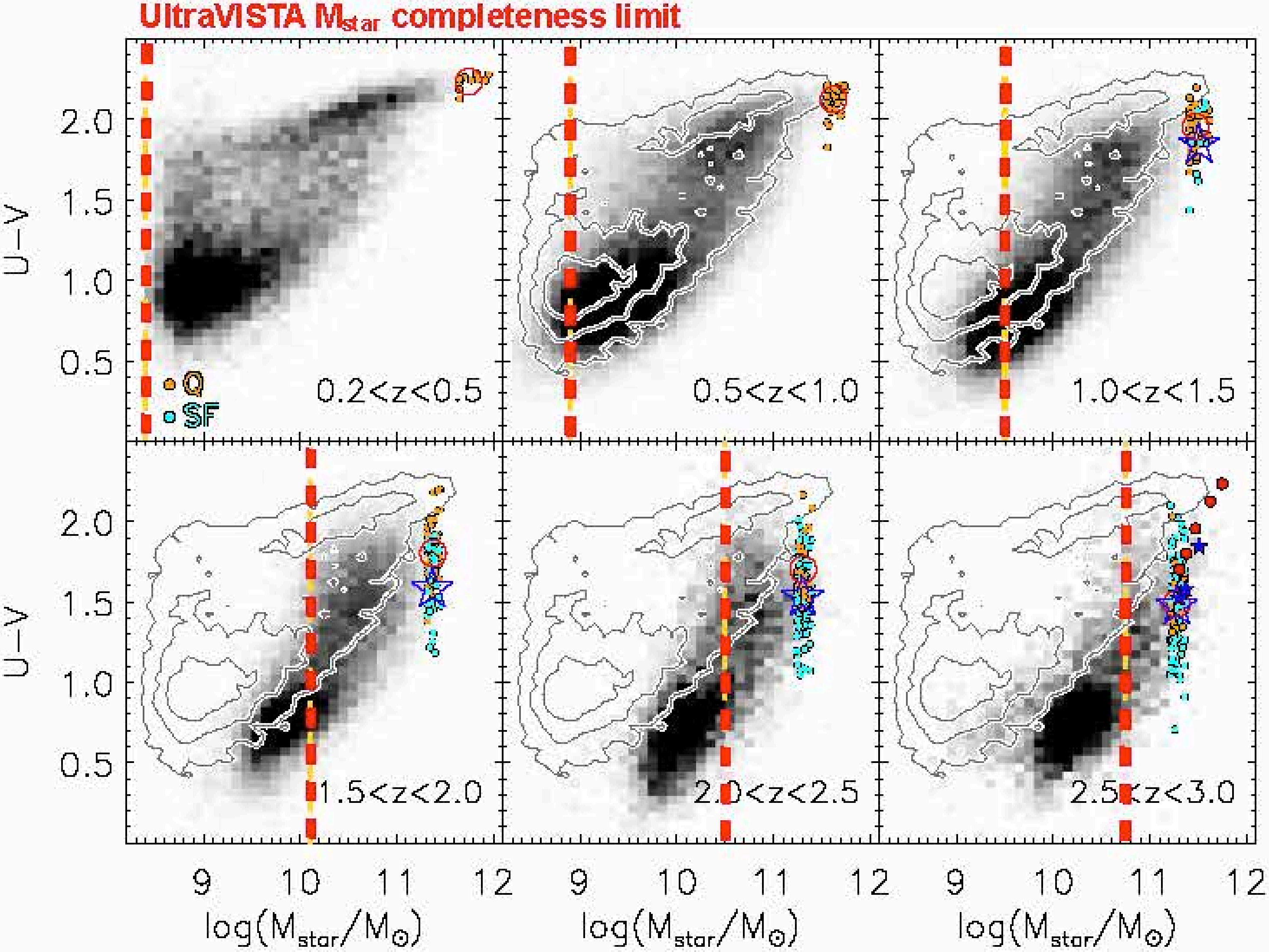
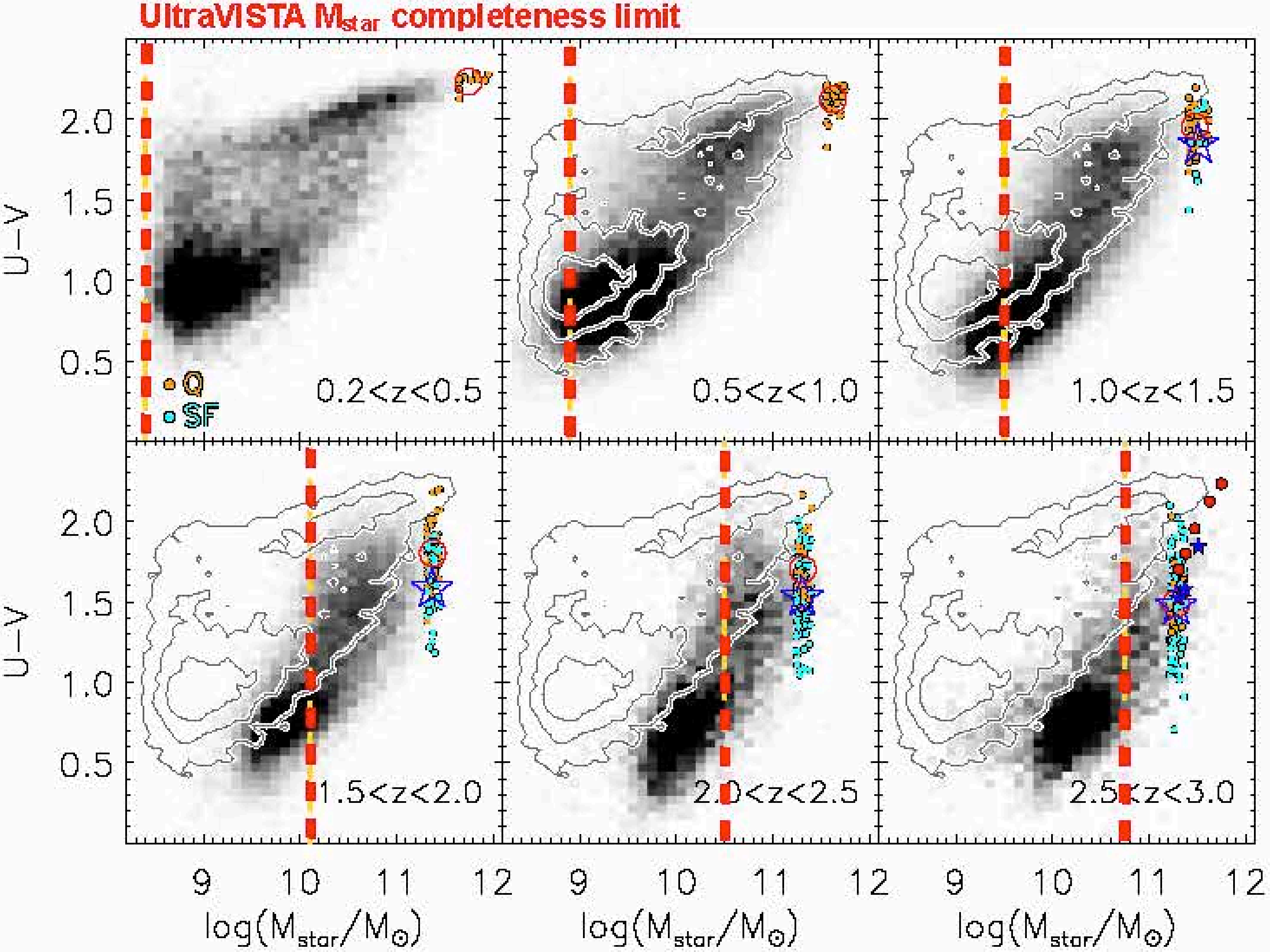


- The **star-forming progenitors** have **never lived on the blue cloud since z=3**.
- The **very massive end of the local red-sequence** is **in the process of assembling between z=3 and z=1**

  Most of the star-forming progenitors quench in the 2.6 Gyr from z=2.75 to z=1.25. By z=1, all star-forming progenitors have quenched.

Color versus Stellar Mass Diagram

(Marchesini et al. 2014)



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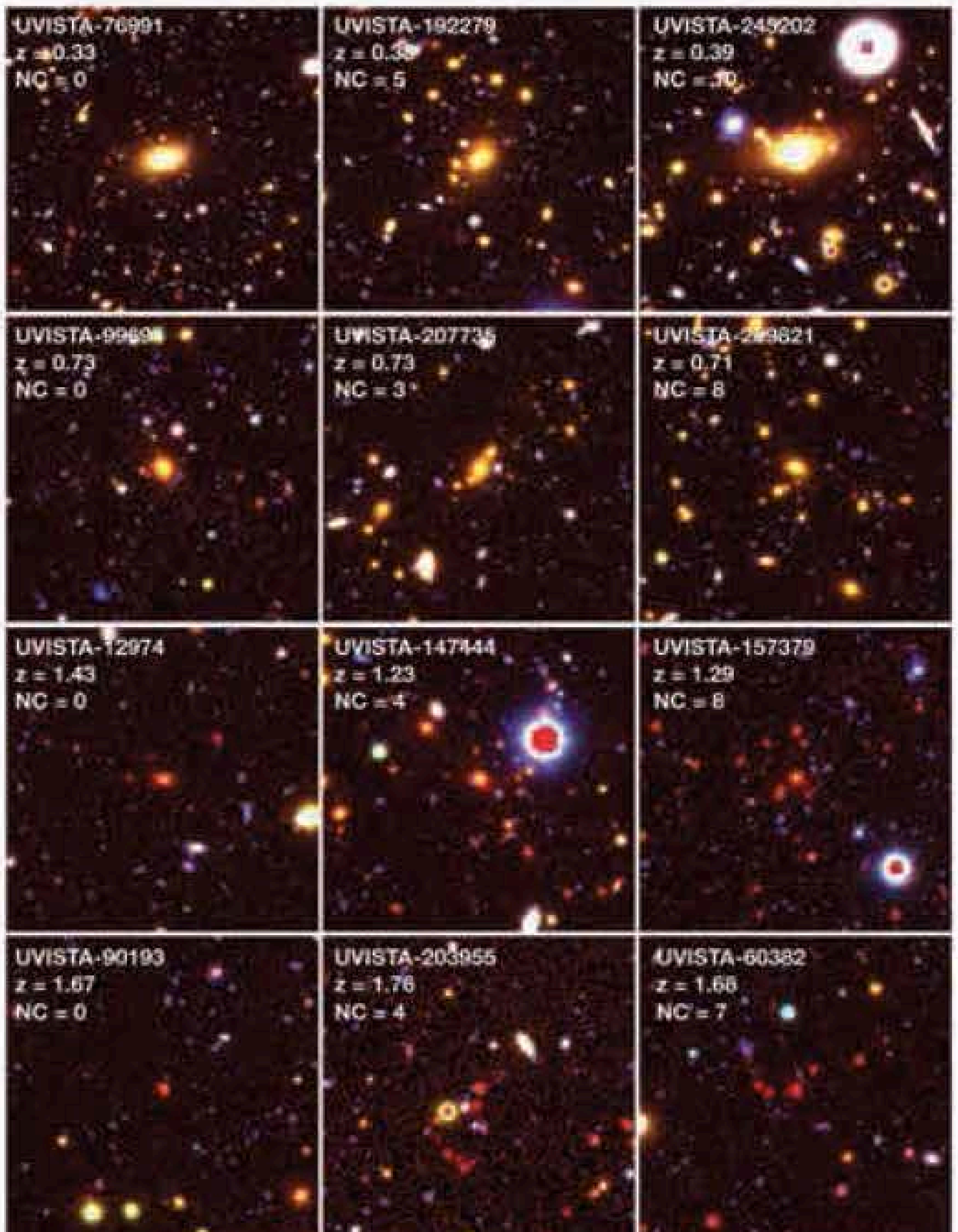
- **First direct proof in the early universe of the results and implications of the archeological studies of local UMGs**, i.e., inferred median z_{form}~1.9 from age of local UMGs, and 1.1<z_{form}<4.2 from the spread in age (~20%, i.e., 1.8-2 Gyr). Our results are in **remarkably good agreement with these fossil records** (Gallazzi et al. 2006).

Environment of Progenitors of Today's UMGs

(Vulcani, Marchesini, et al. 2015)

	ISOLATED	FEW COMPANIONS	MANY COMPANIONS
z~0.3-0.4			
z~0.7			
z~1.2-1.4			
z~1.7-1.8			



BzK color image
FoV~500 kpc on a side

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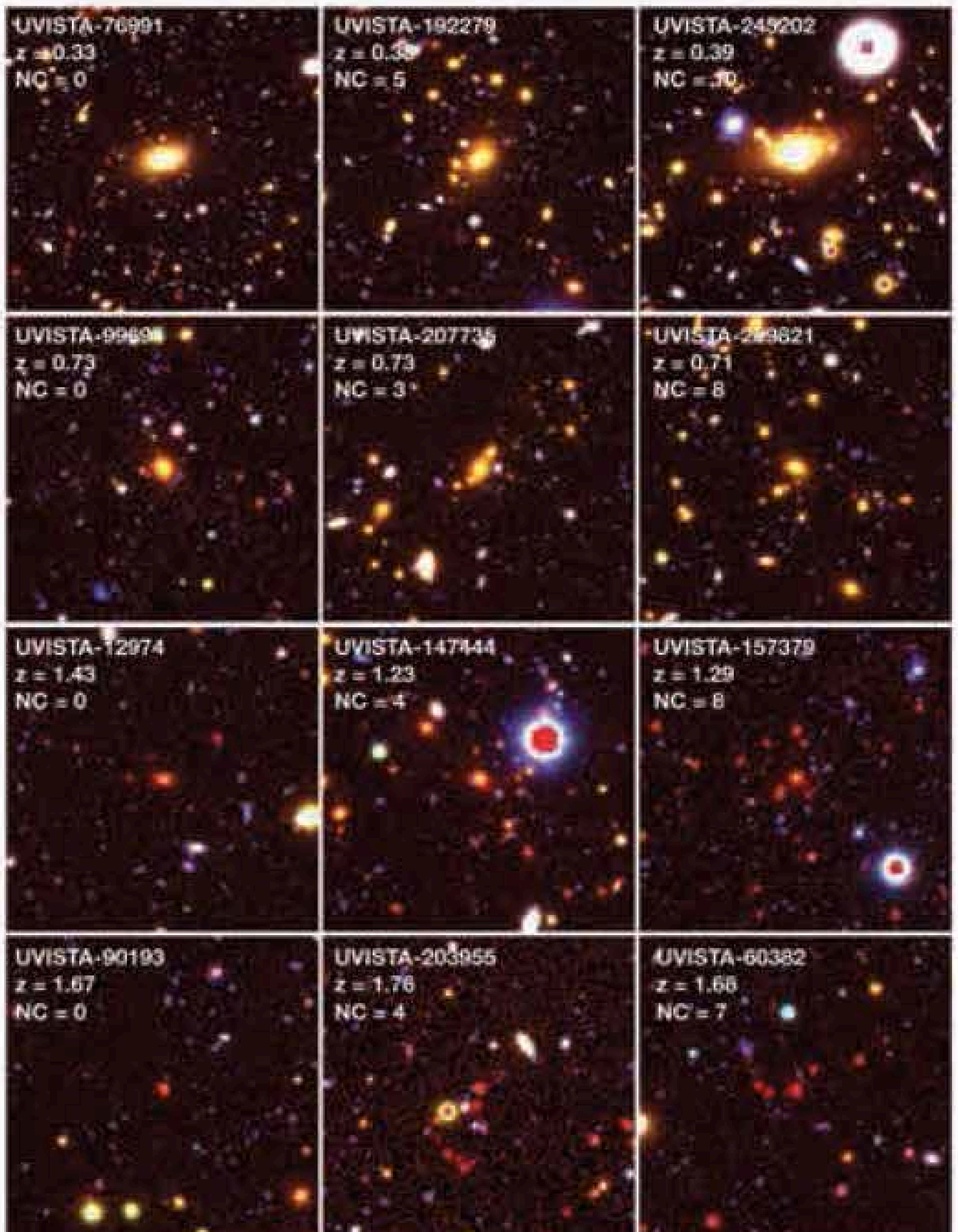

- ☑ The **progenitors** of today's UMGs **reside in a variety of environments**.

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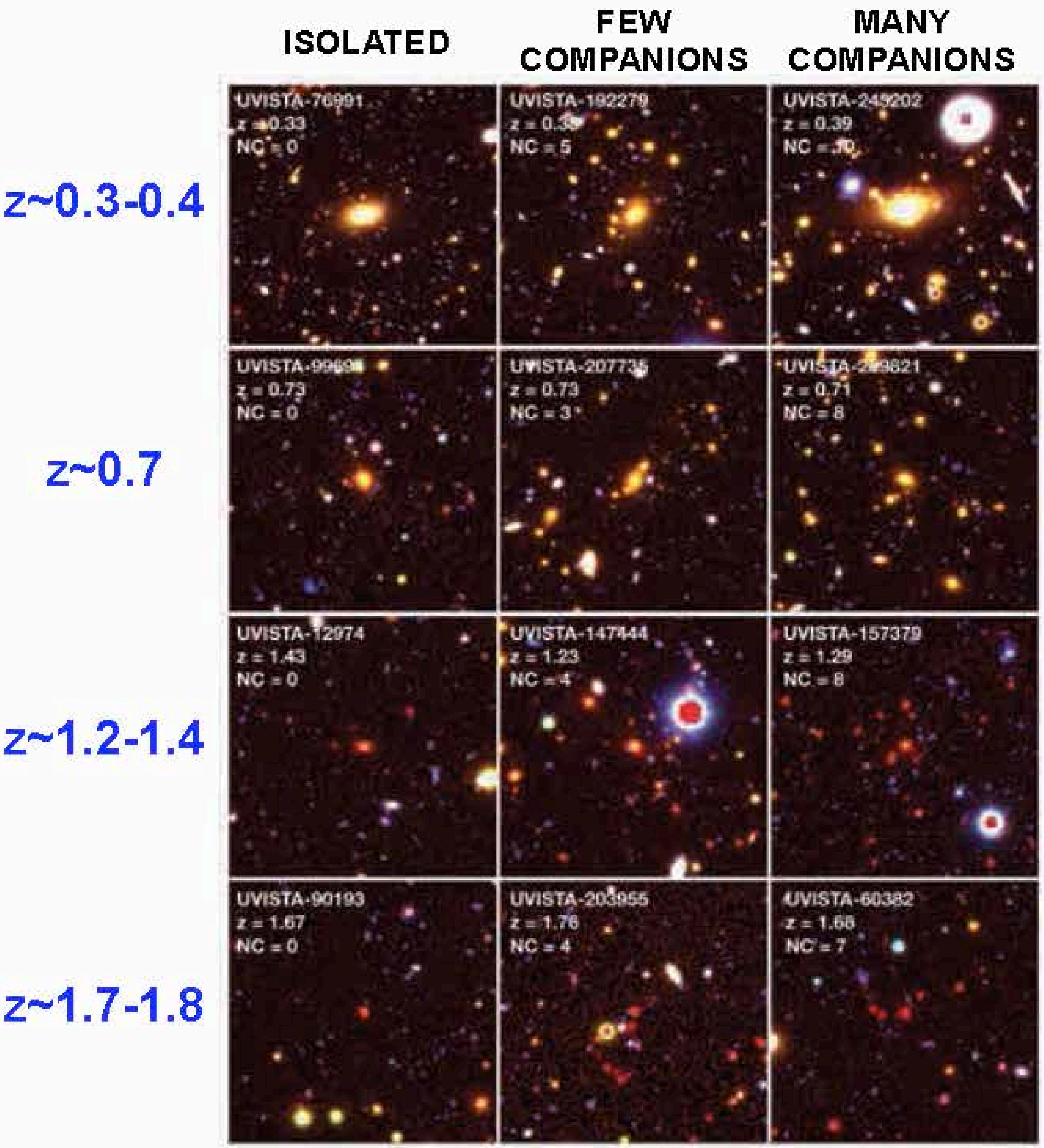

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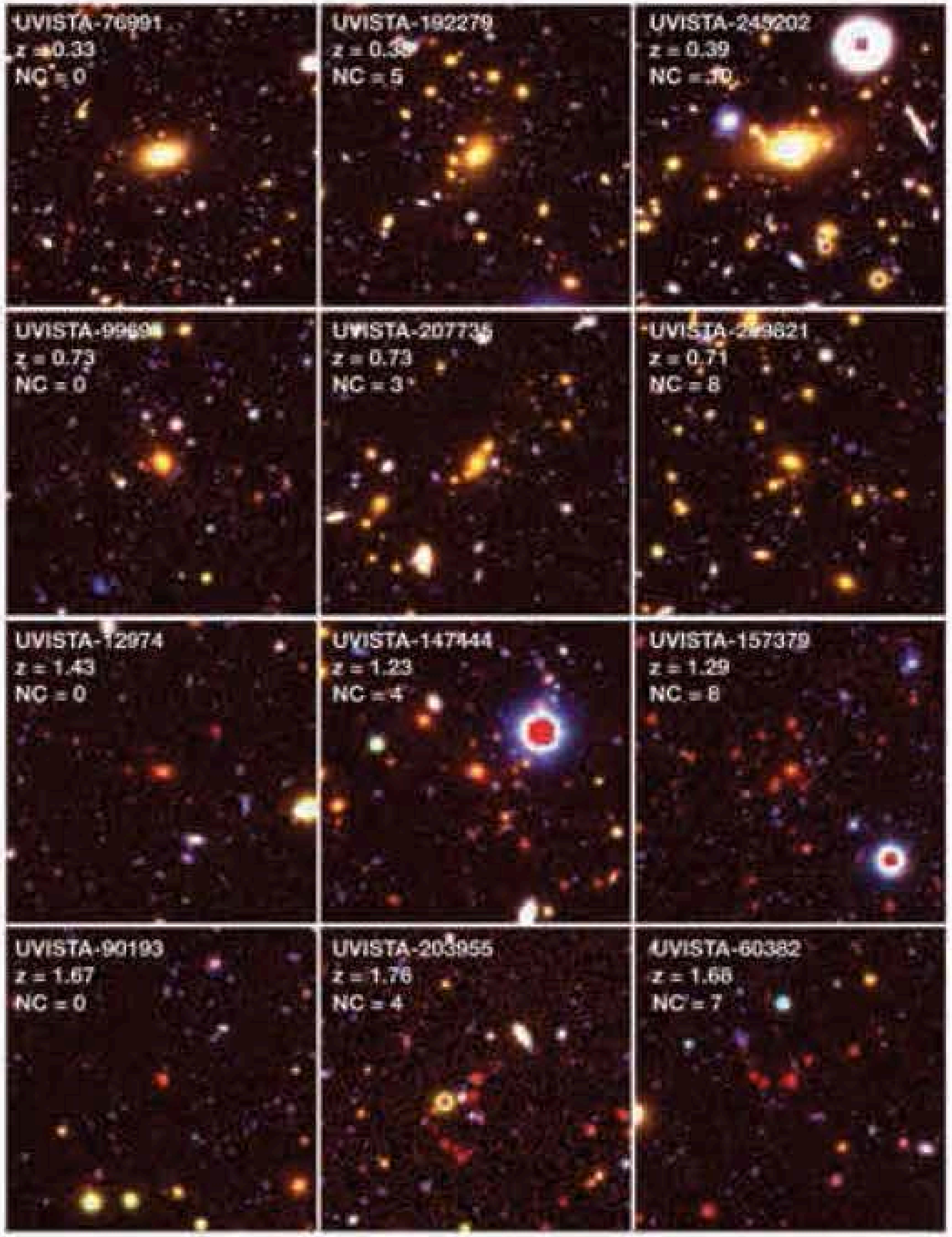

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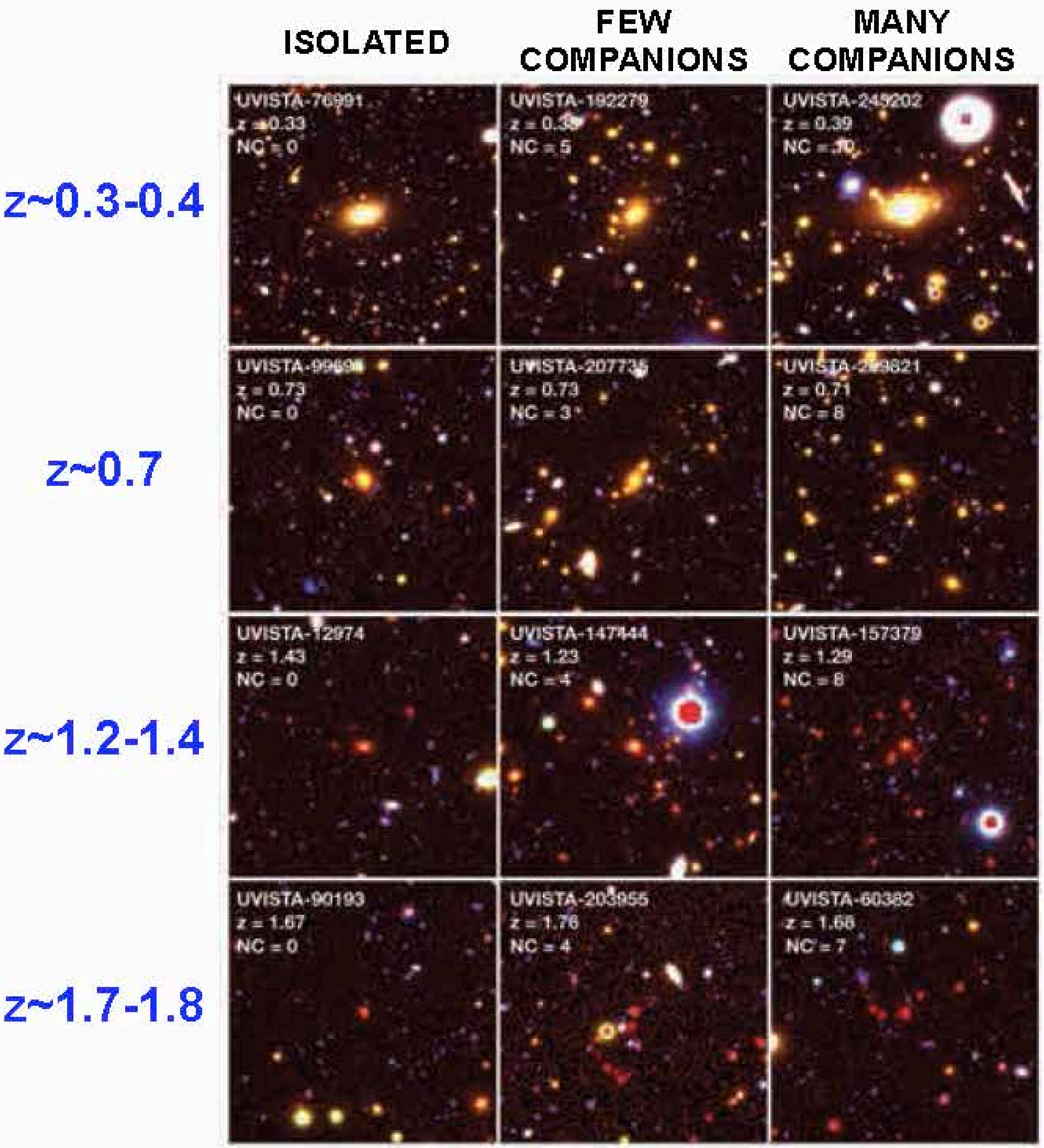

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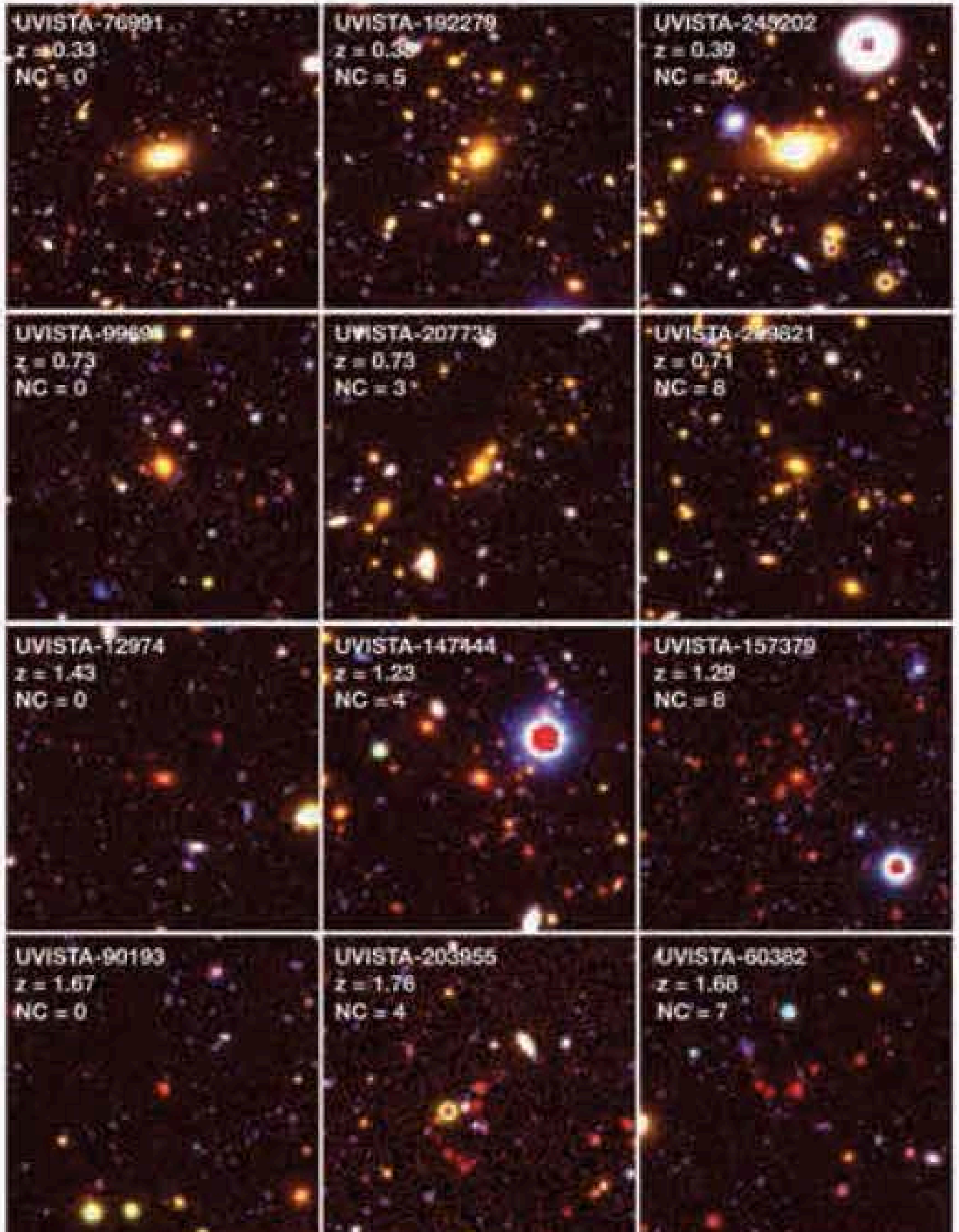

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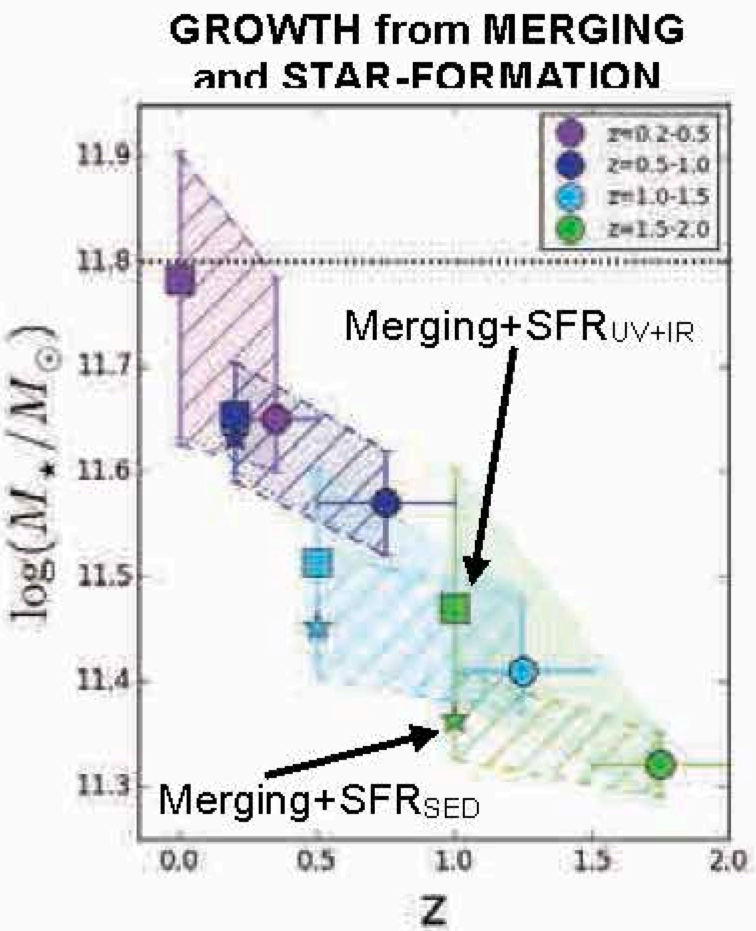
- The **environment** around progenitors **is seen to get richer with cosmic time**.
- The number of companions is seen to drop as a function of distance from the progenitor: **progenitors are centrals**

BzK color image
FoV~500 kpc on a side

What drives the progenitors' mass growth?

(Vulcani, Marchesini, et al. 2015)



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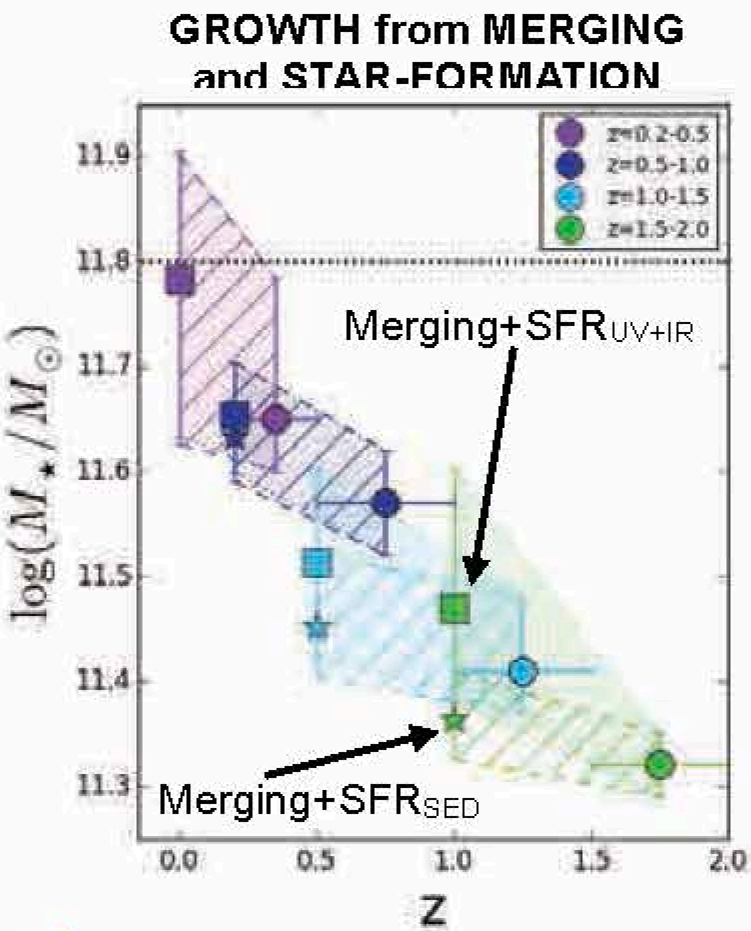

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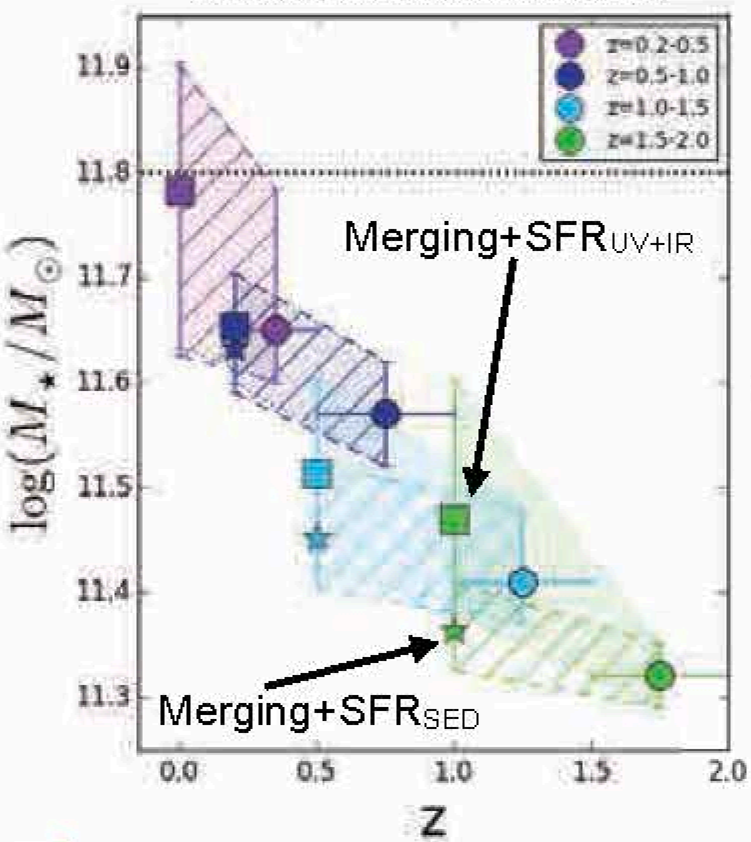
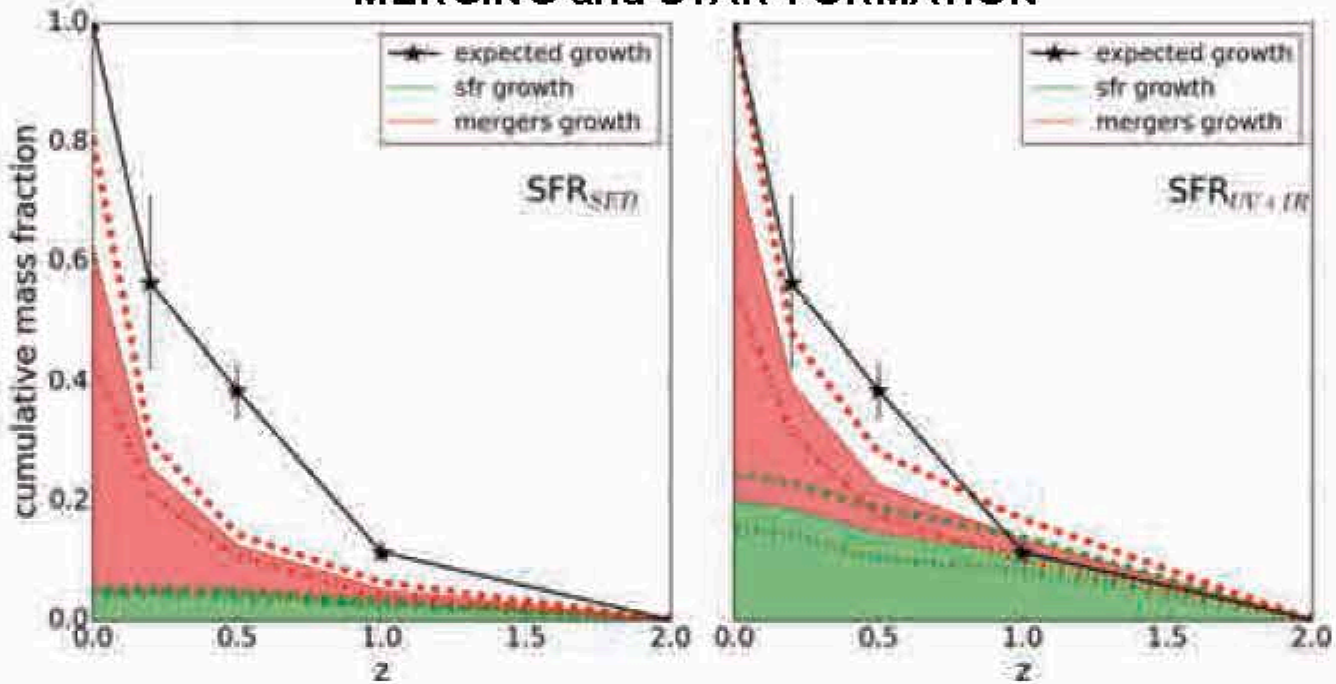
GROWTH from MERGING and STAR-FORMATION



RELATIVE CONTRIBUTION of MERGING and STAR-FORMATION



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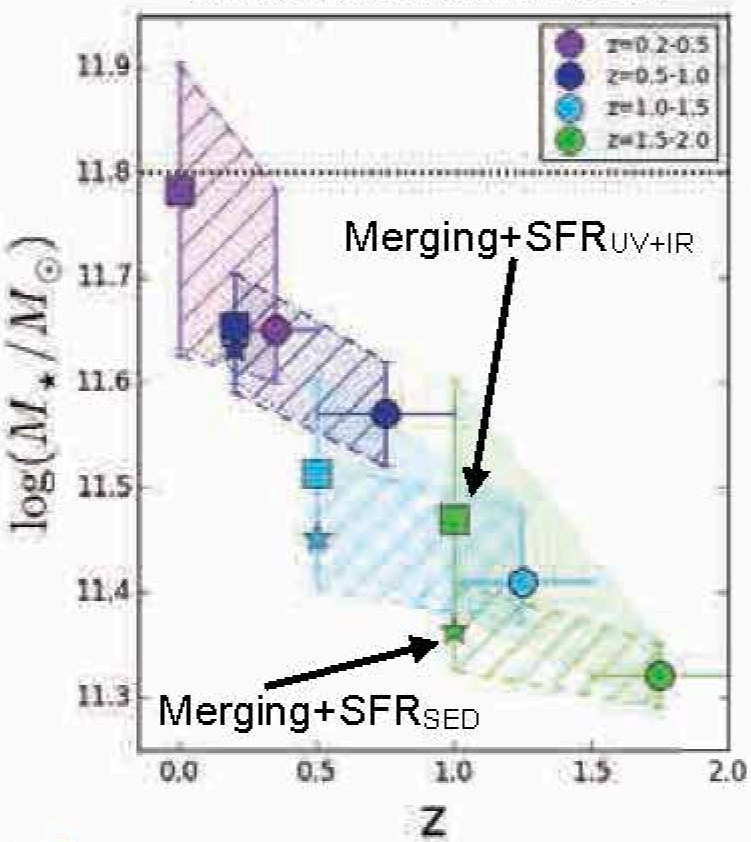

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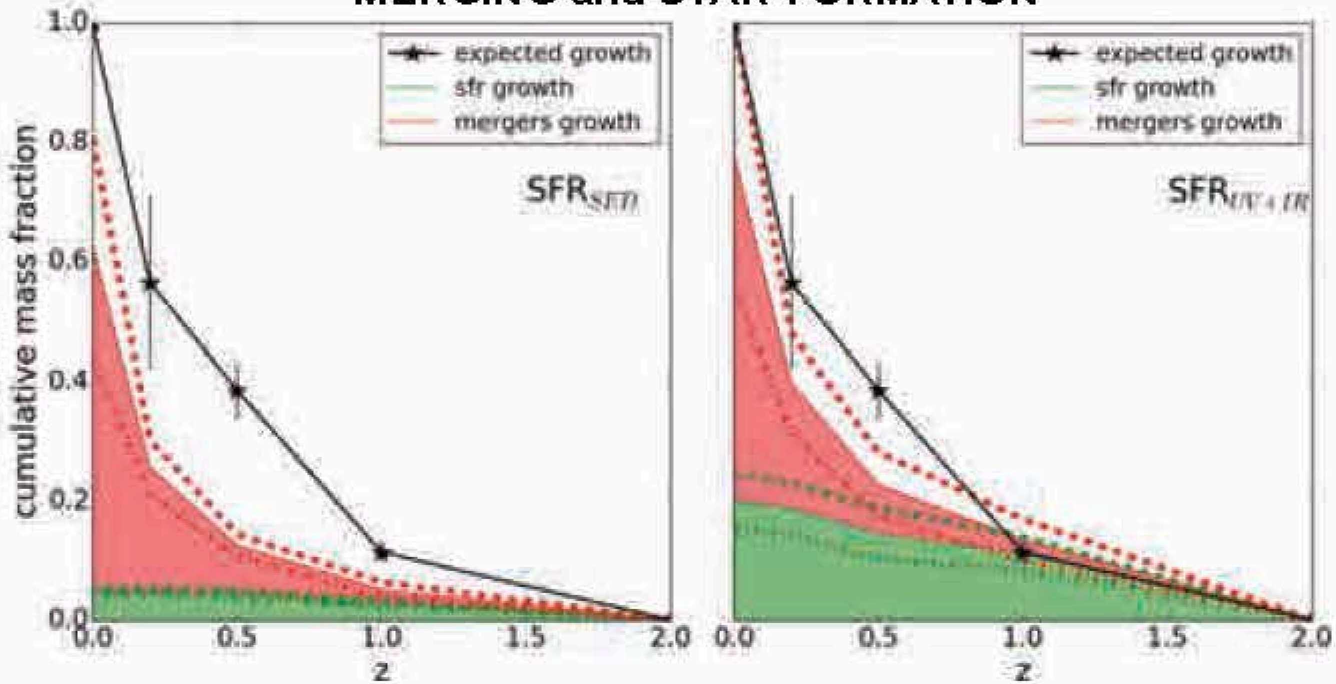

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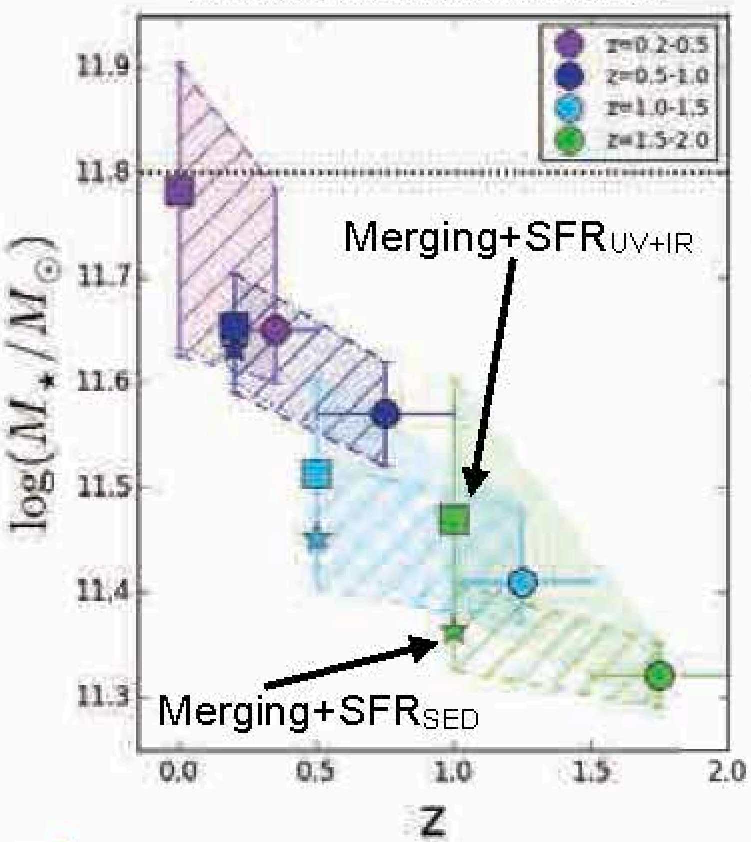

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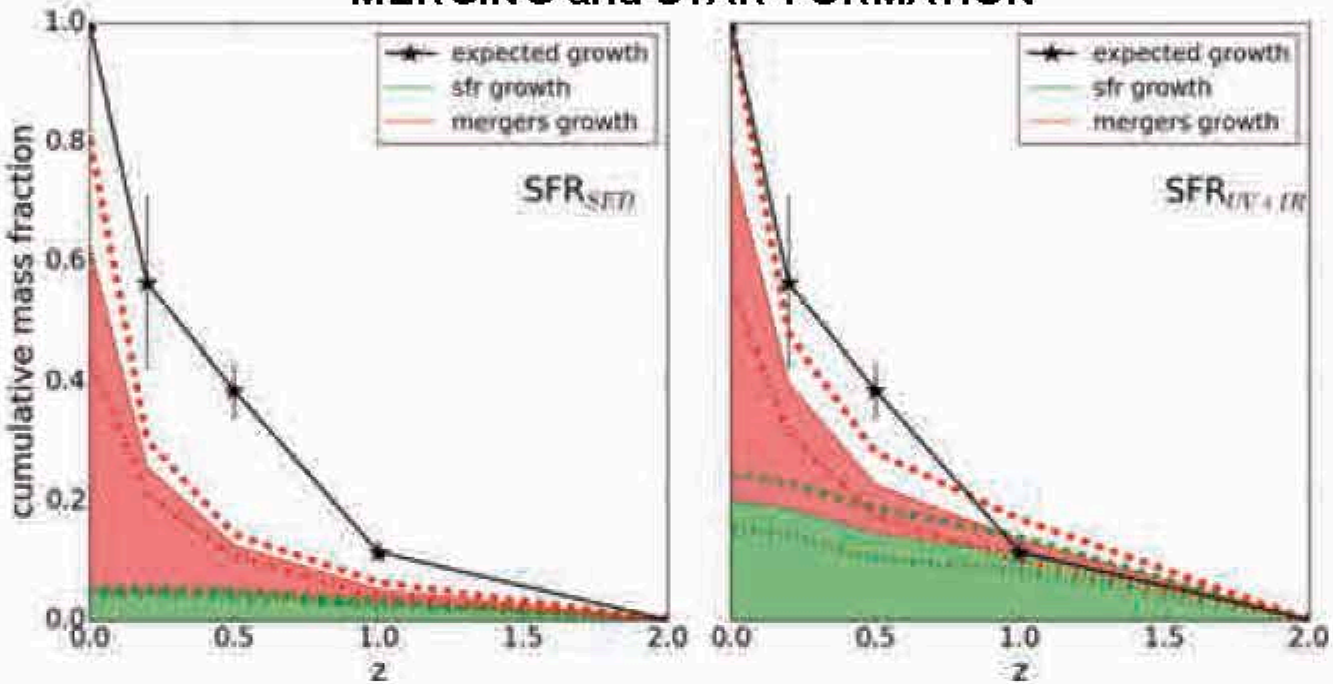

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- The contribution to the **growth from merging increases with cosmic time and dominates at z<1**, while **star-formation** decreases with cosmic time and **dominates at z>1-1.5**.

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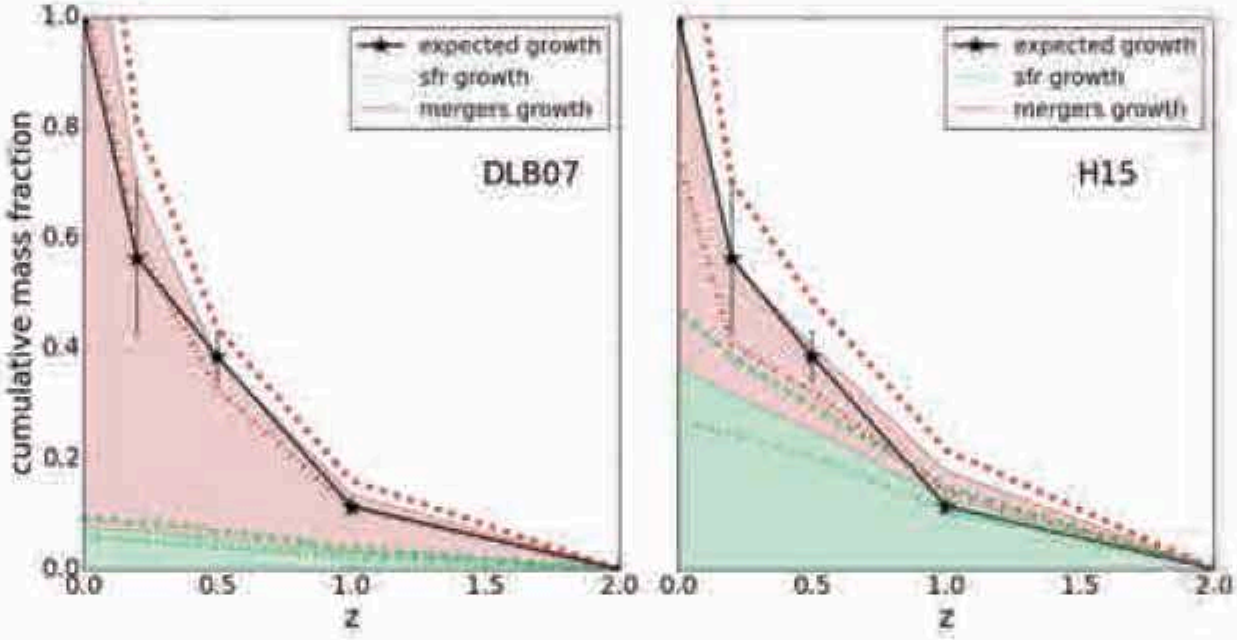

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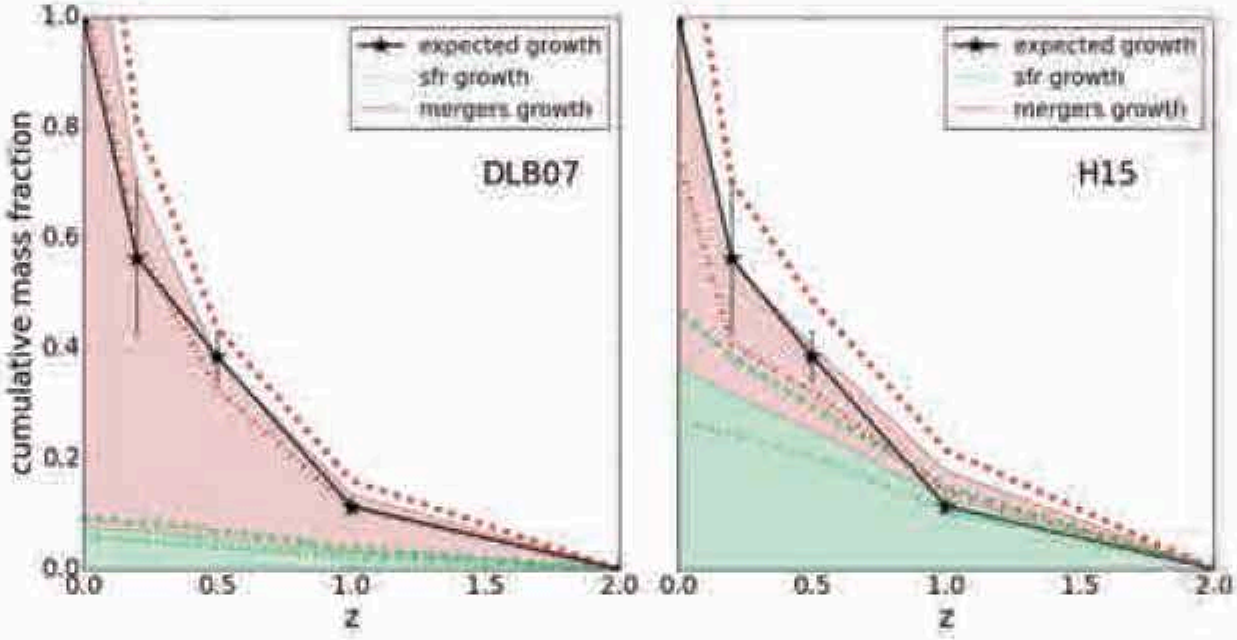

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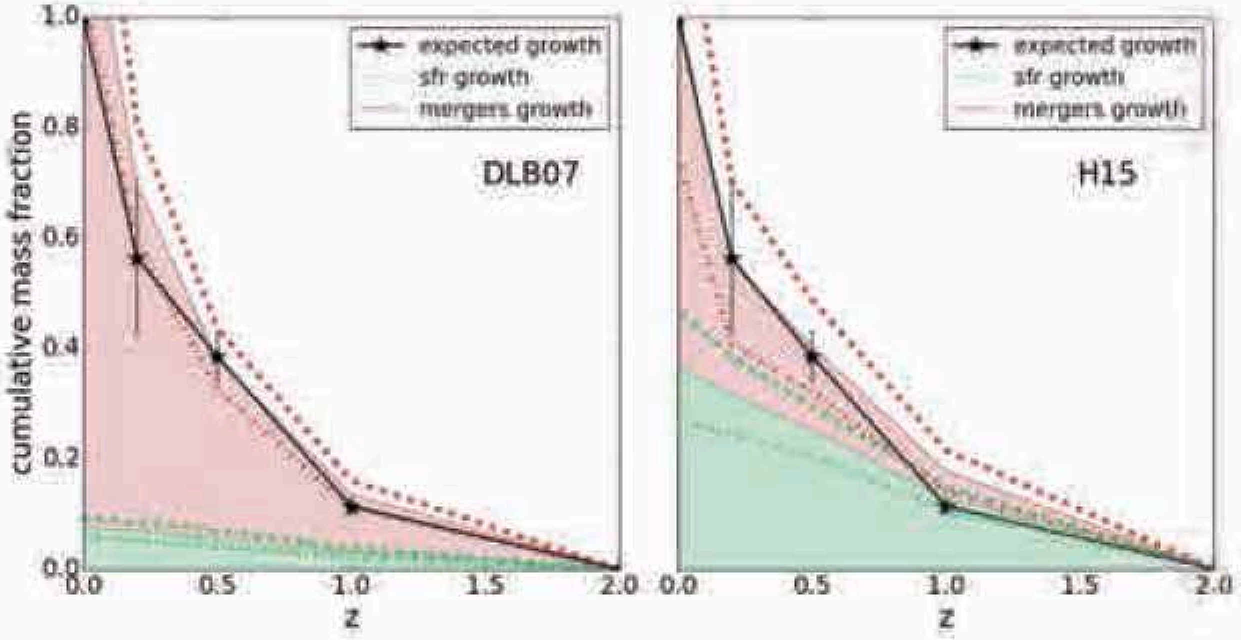

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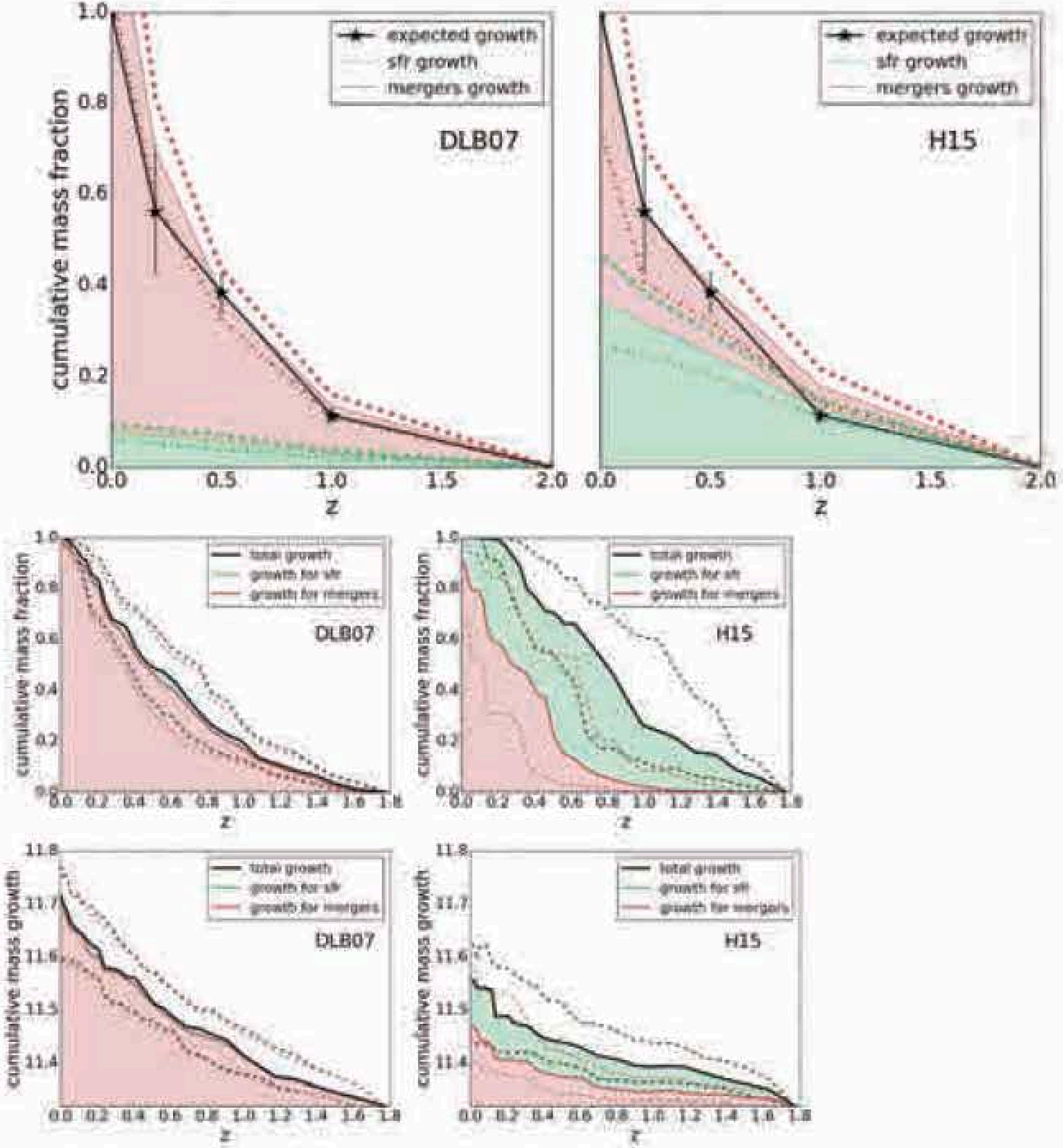

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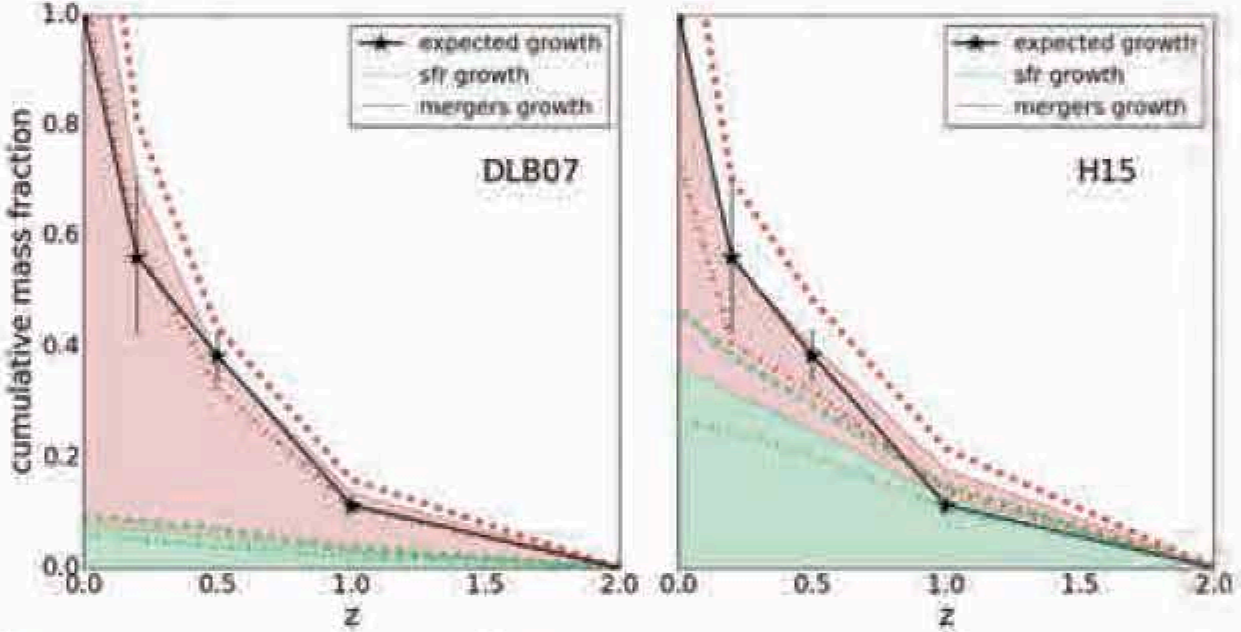

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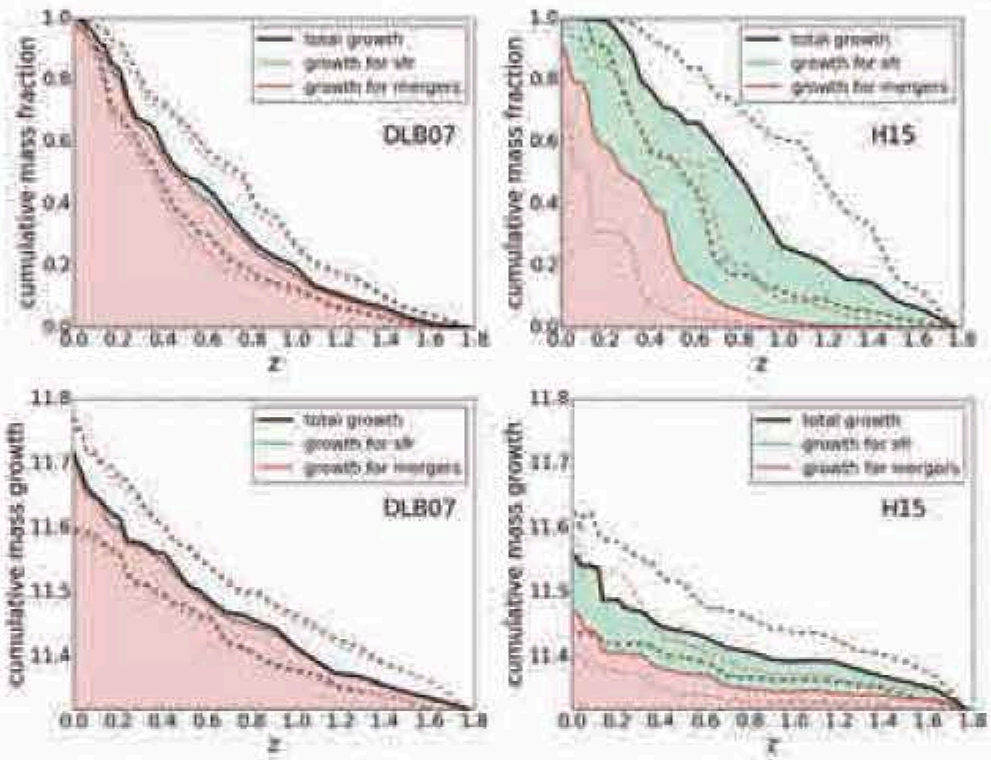
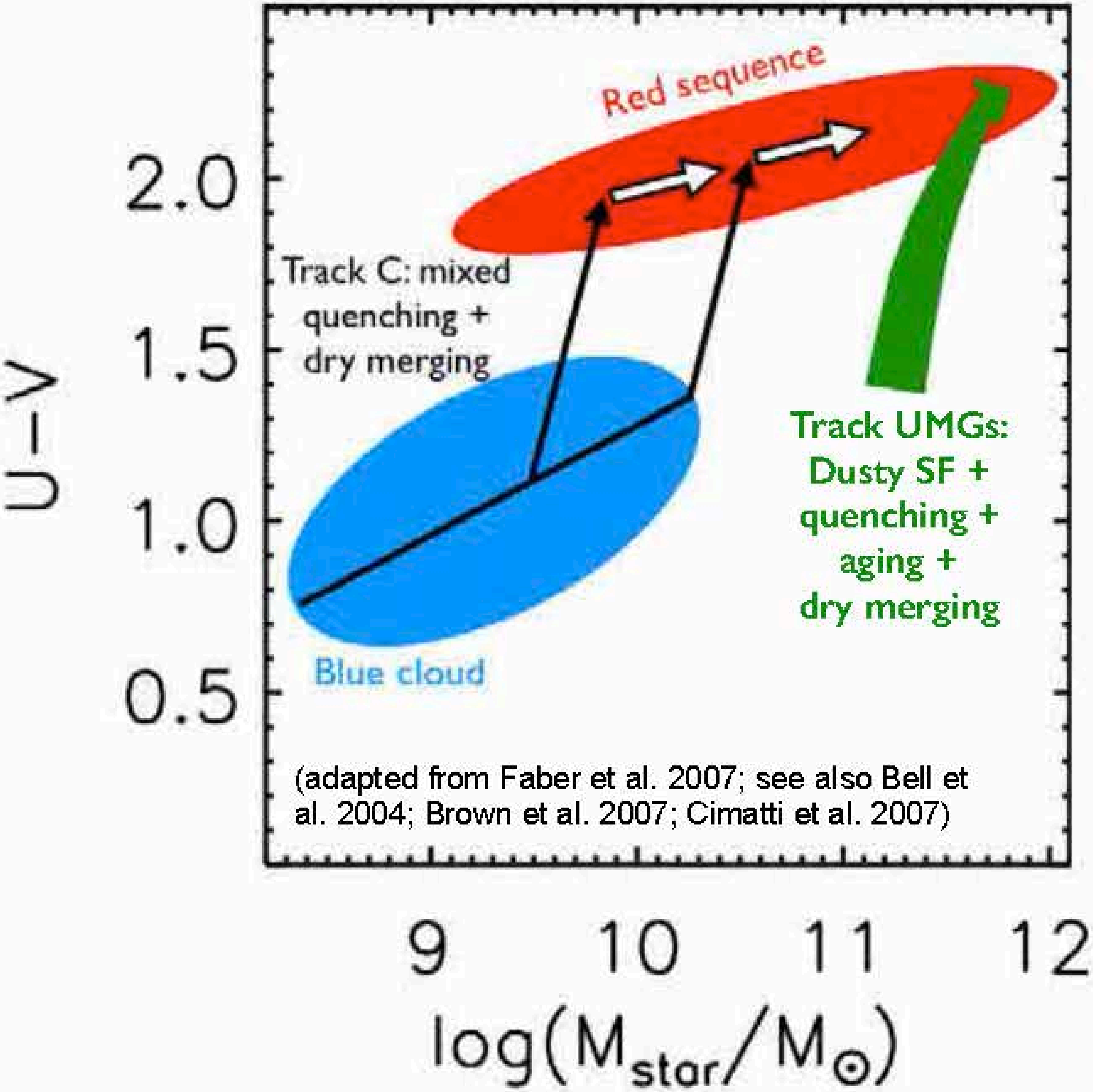


- **Following the actual merger trees**, the absolute predicted growth of the descendants is consistent with observations in the DLB07 SAM, but not in the H15 SAM. Note also very different contribution of star formation

Alternative evolutionary path for the formation of local UMGs



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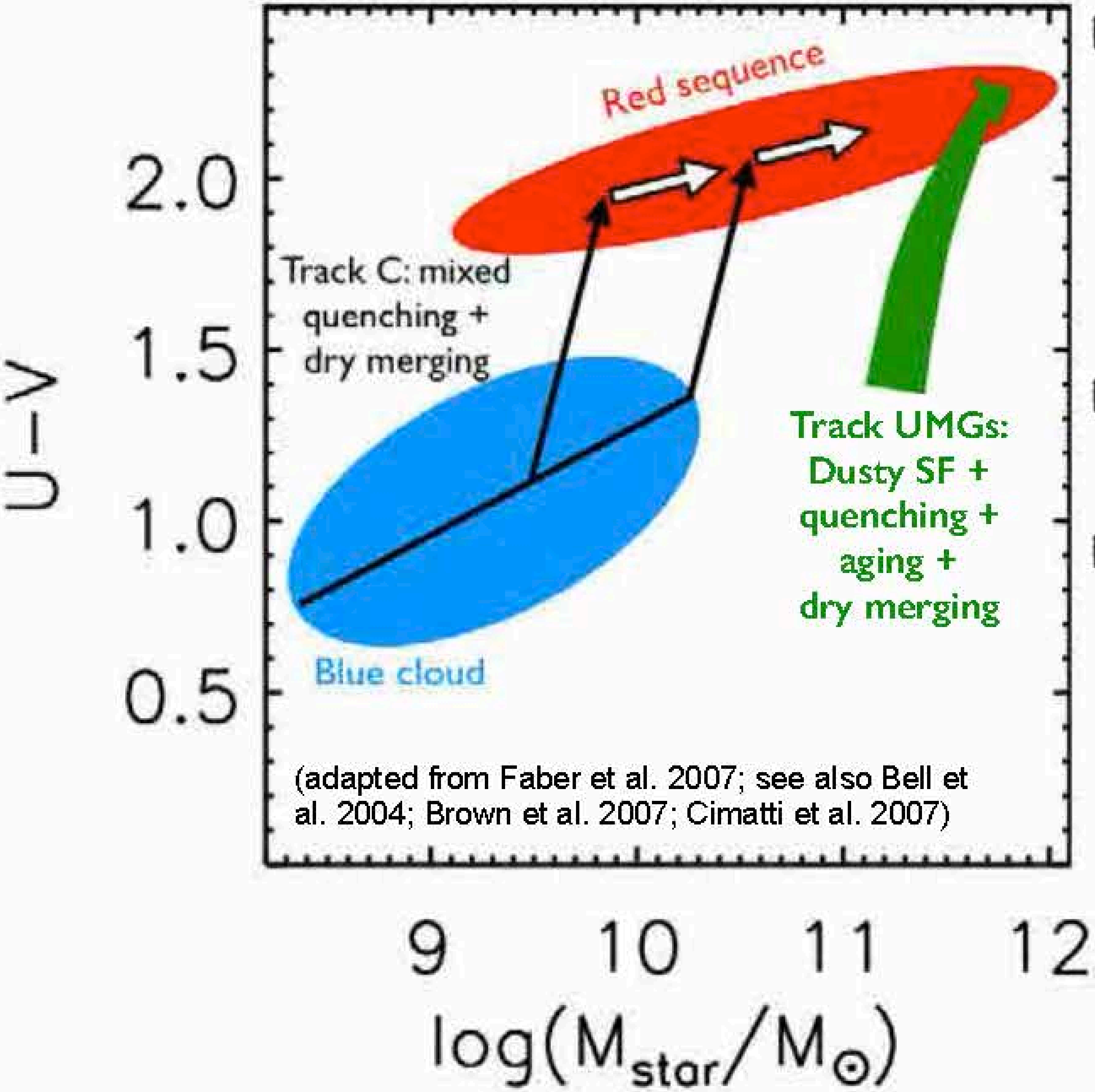

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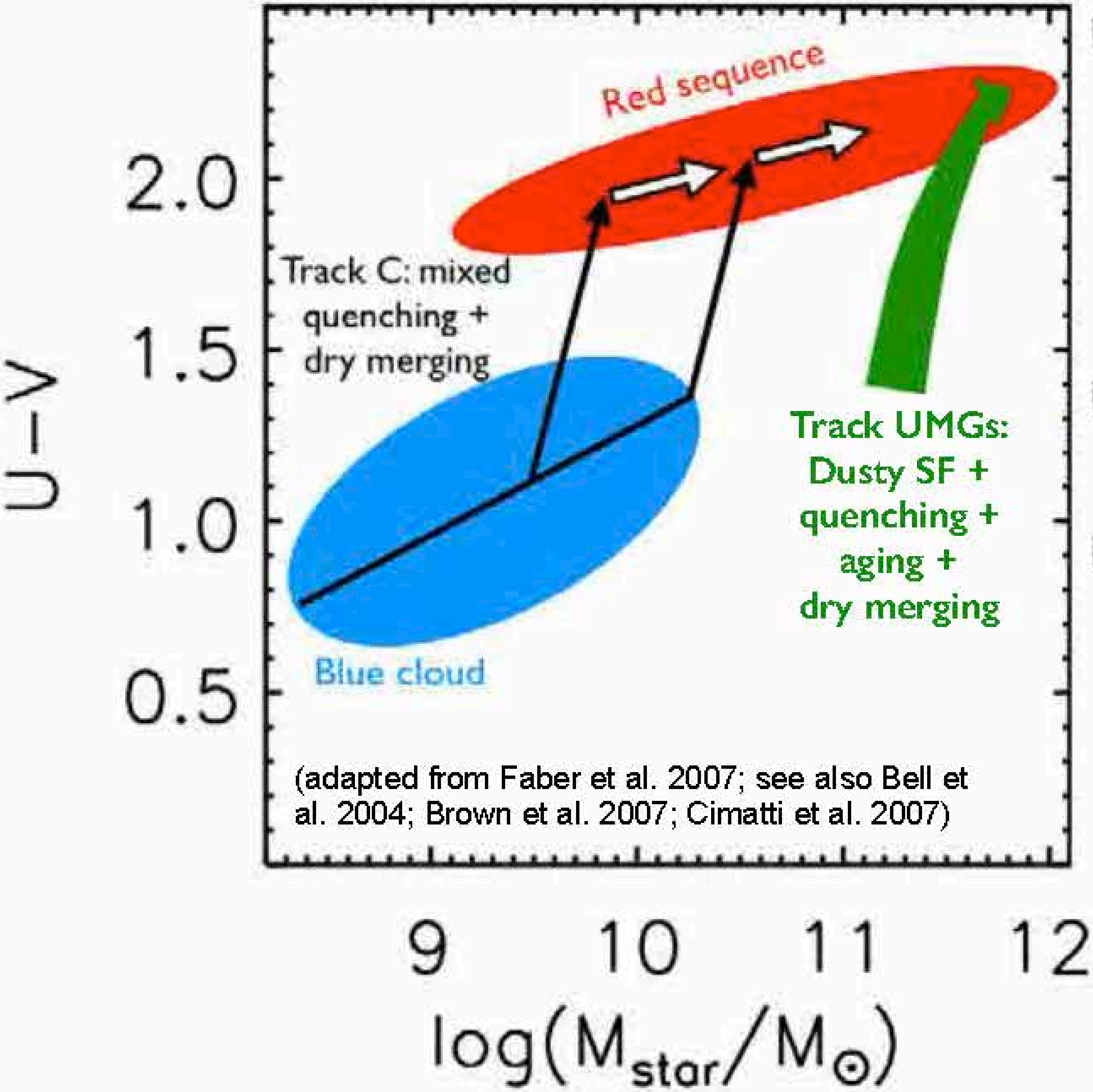

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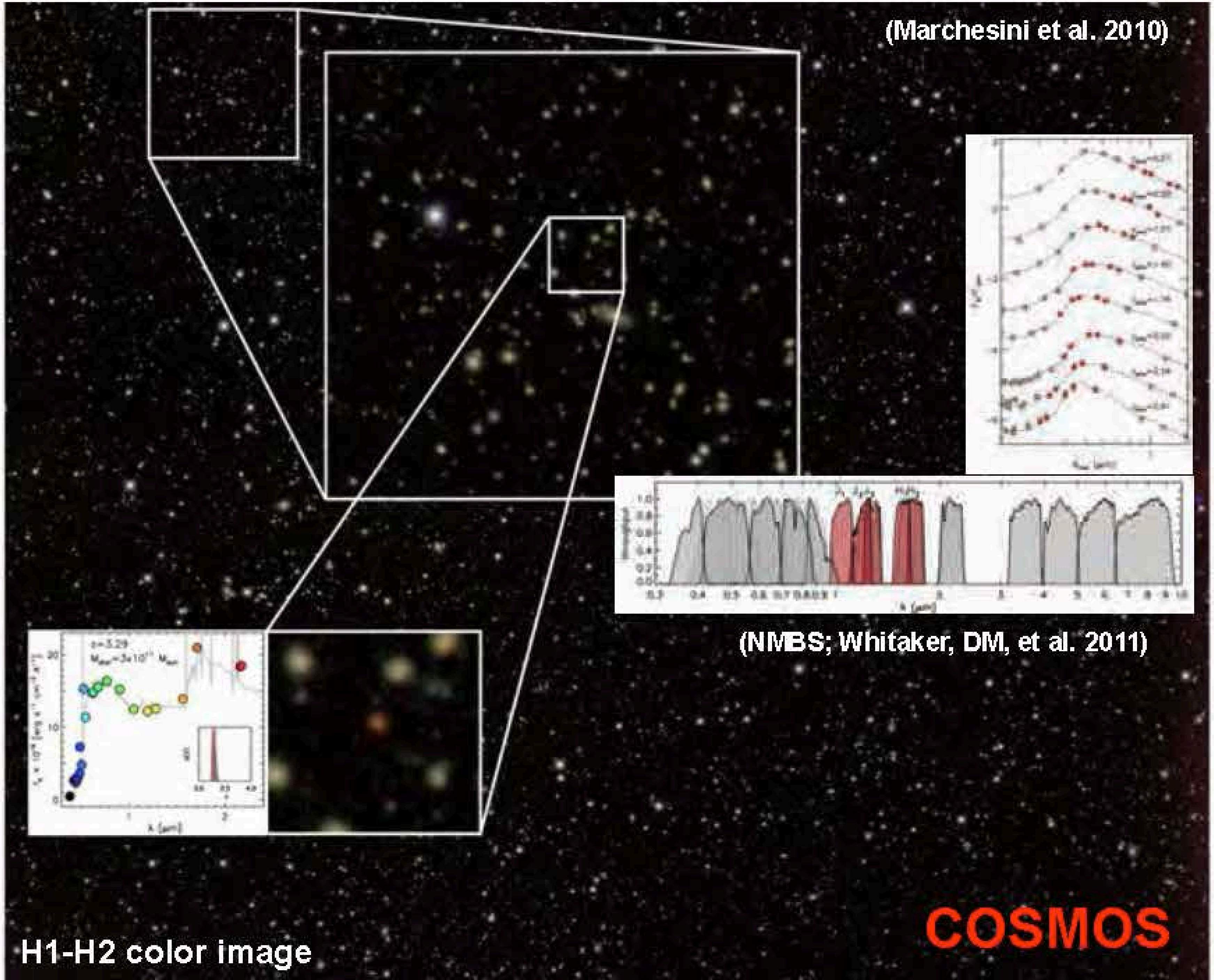
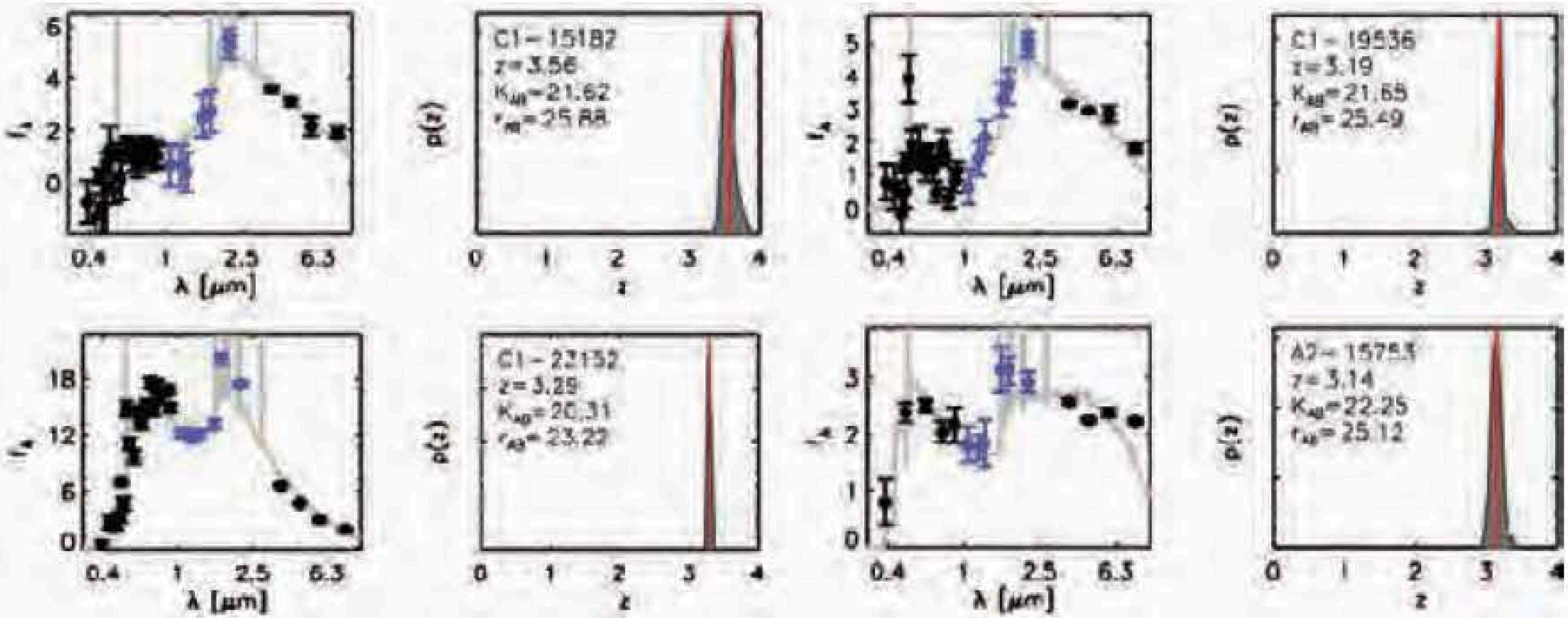
What about the progenitors at $z>3$?

Searching for Very Massive Galaxies at z>3 in the NEWFIRM Medium-Band Survey (NMBS)



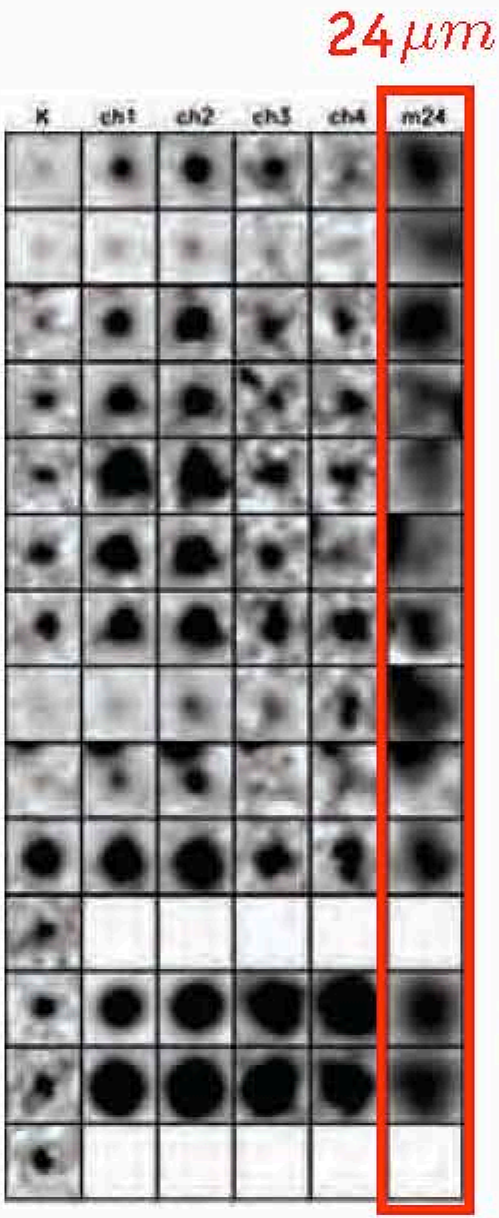
Stellar Mass-complete Sample of Galaxies at 3<z<4 from the NMBS

(Marchesini et al. 2010; confirmed by Spitler et al. 2014)



- **14 galaxies at 3<z<4 with $M_{star}>10^{11.4}$ $M_{sun}=2.5\times10^{11}$ M_{sun}** in COSMOS and AEGIS over an effective area of 0.44 deg^2
- ~50% with ages consistent with age of the universe (~1.6-2.1 Gyr)
- **~30% have SFRs** (from SED modeling) **consistent with no star formation activity; ~30% have large SFRs**, a few hundreds M_{sun}/yr
- **First robust evidence** of **existence of very massive galaxies at z>3** and of **large diversity in properties among this population**.

Massive galaxies at z=3.5 are very luminous IR sources



(Marchesini et al. 2010)

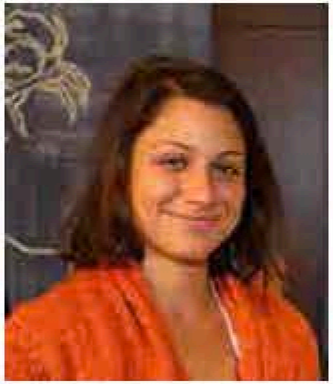
- 80% have MIPS 24 μm fluxes significant at >3 sigma.
- L_{IR}=0.5-4x10^{13} L_{Sun}, with 80% being HLIRGs
- Either very actively star-forming systems and/or large fraction of obscured AGNs
- 1/10 (in COSMOS) is a sub-mm galaxy

  Duty cycle of duration of intense dusty star-bursting phase ~60^{+140}_{-50} Myr

- SFR_{24}=600-4300 M_{Sun}/yr (a few 100xSFR_{SED}), implying mass-doubling times ~ 0.5-7x10^8 yr.
  - This **extreme star-forming activity has to be quickly quenched** to be consistent with the little evolution in the SMF (Marchesini et al. 2009).
- HOWEVER, **likely contamination from obscured AGN**
  - 3 detected in X-rays + 1 RL-AGN
  - 24 μm corresponds to ~5.5 μm rest-frame, where hot dust dominates the MIR emission

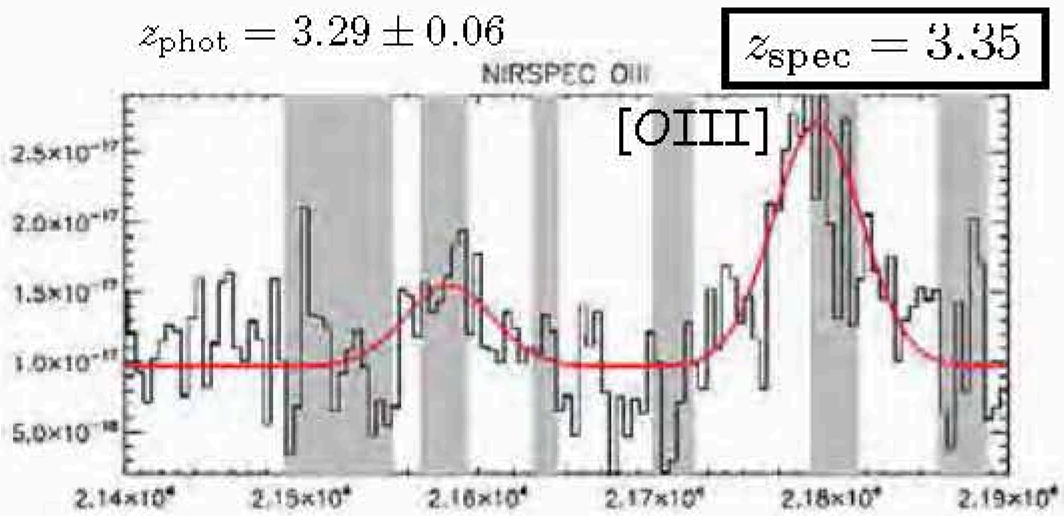
Spectroscopy of $3<z<4$ Massive Galaxies

(PhD Thesis of Tufts student Cemile Marsan)



- Spectroscopic confirmation required to break the ambiguity between massive $3<z<4$ galaxies and massive, OLD AND DUSTY galaxies at $z<3$

Spectroscopy of 3<z<4 Massive Galaxies



(Marsan, Marchesini, et al., 2015)

- NIR spectroscopy w/ Keck-NIRSPEC
- UV-NIR spectr. w/ VLT-Xshooter
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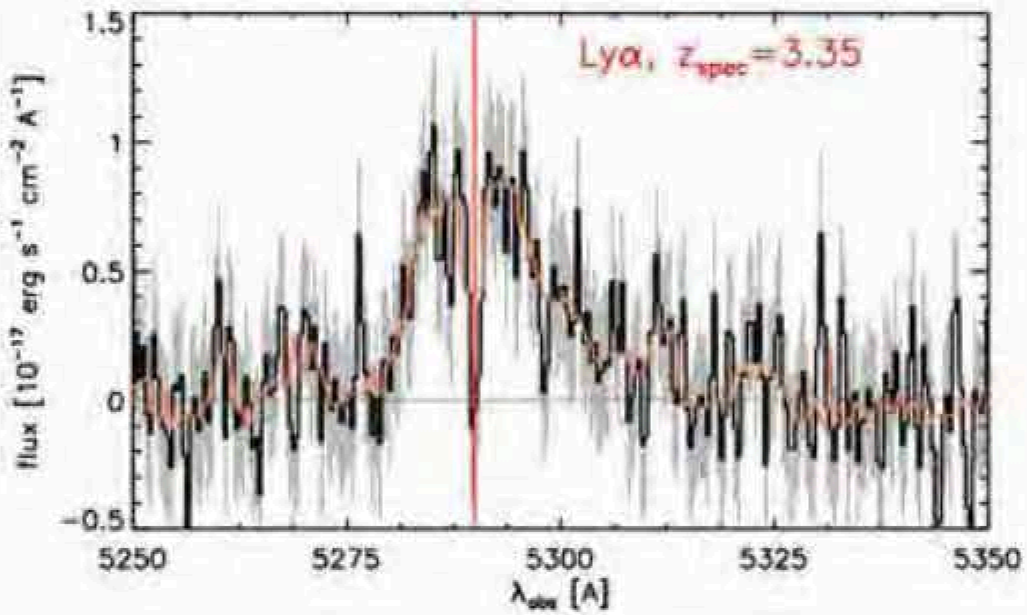
- ACS grism spectroscopy

(tentative CIV in emission also detected)



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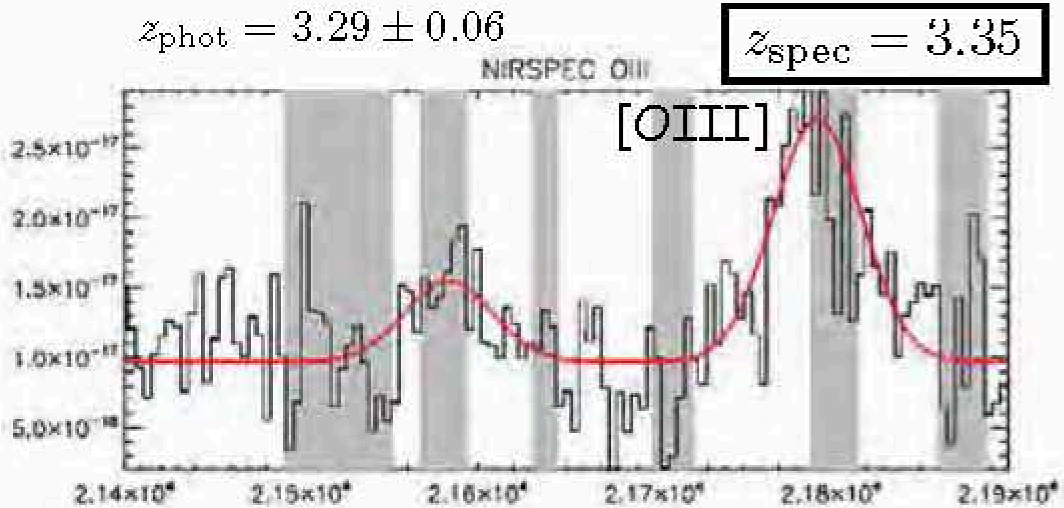

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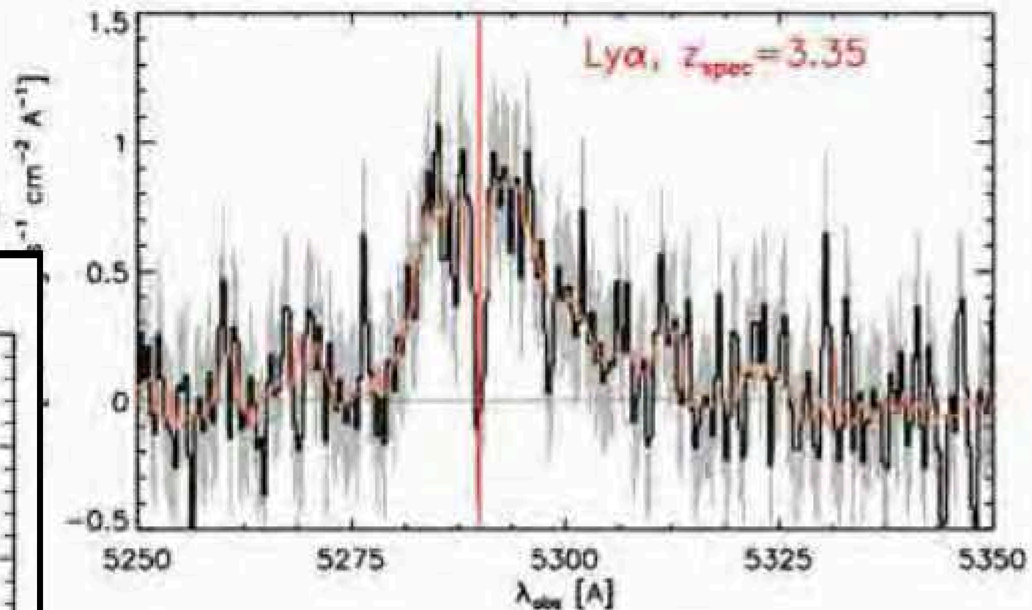
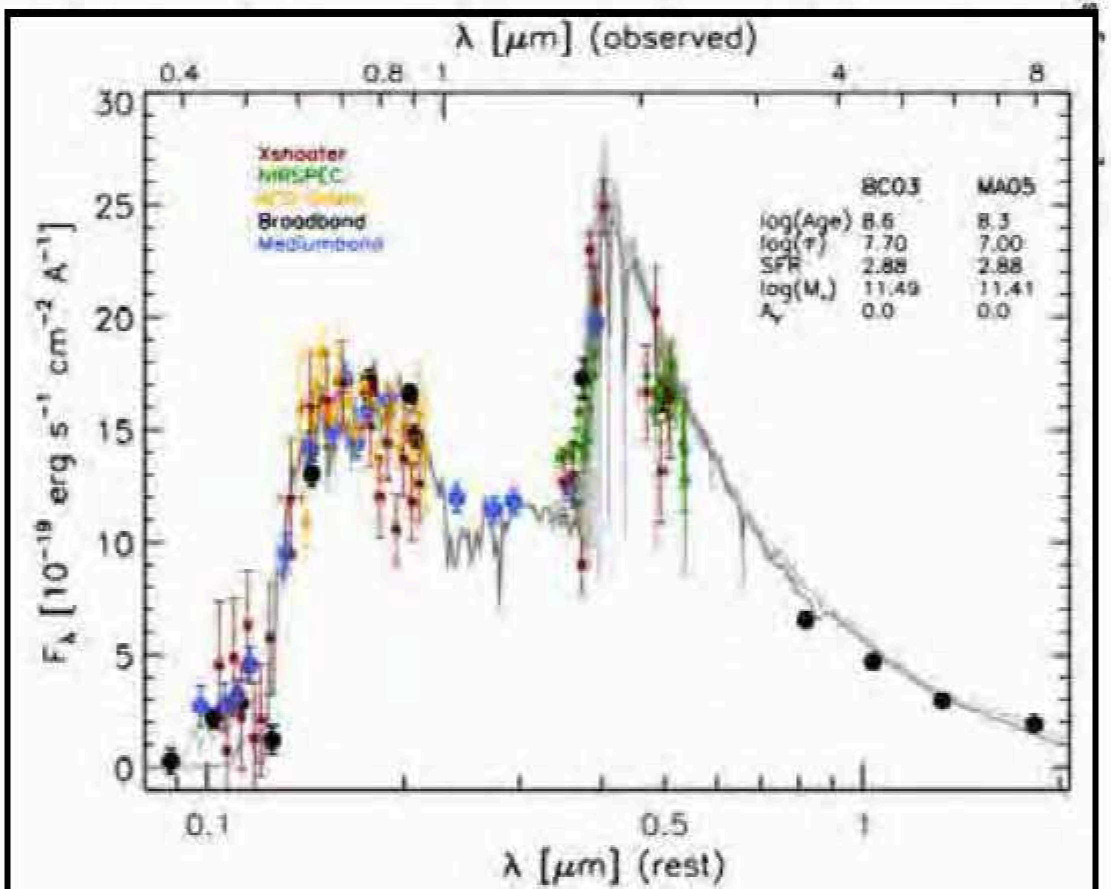




$M_{star} = 3\times10^{11}\ M_{sun}$ (Kroupa IMF)

SFR=3 $M_{sun}\ yr^{-1}$ ($<7\ M_{sun}\ yr^{-1}$)

A_V=0

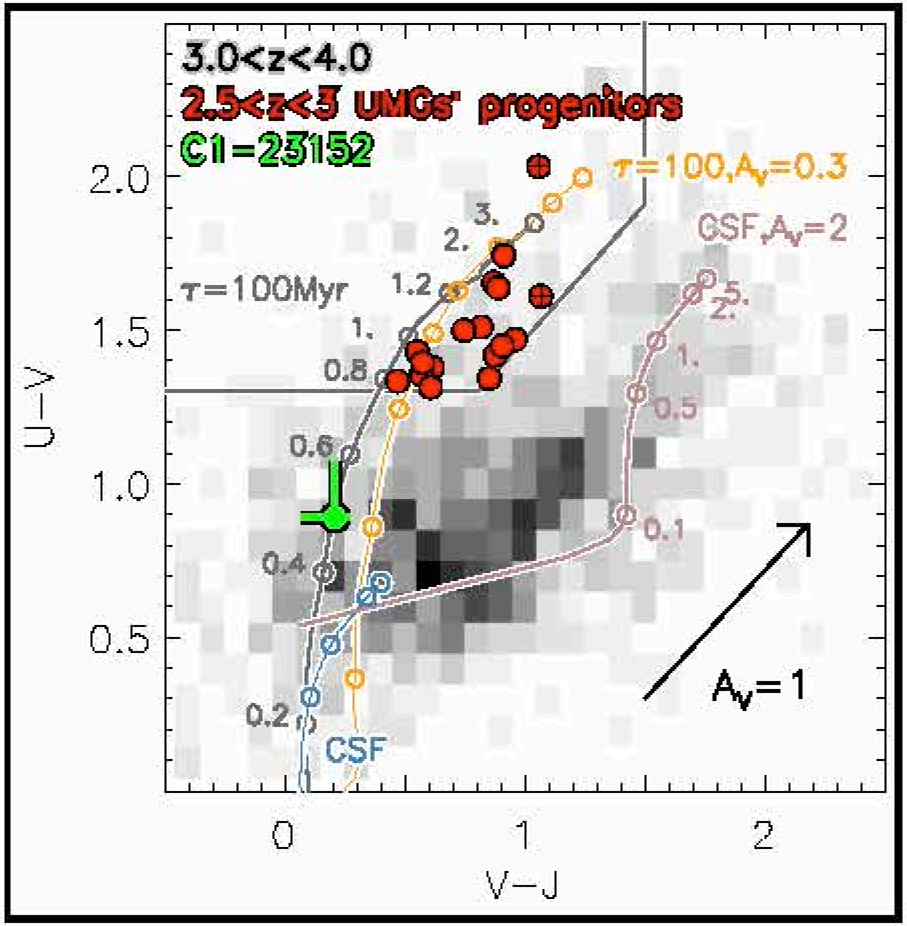
log(sSFR yr^{-1}) ~ -11

age~400 Myr

tau ~ 50 Myr

Spectroscopy of 3<z<4 Massive Galaxies

(Marsan, Marchesini, et al., 2015)



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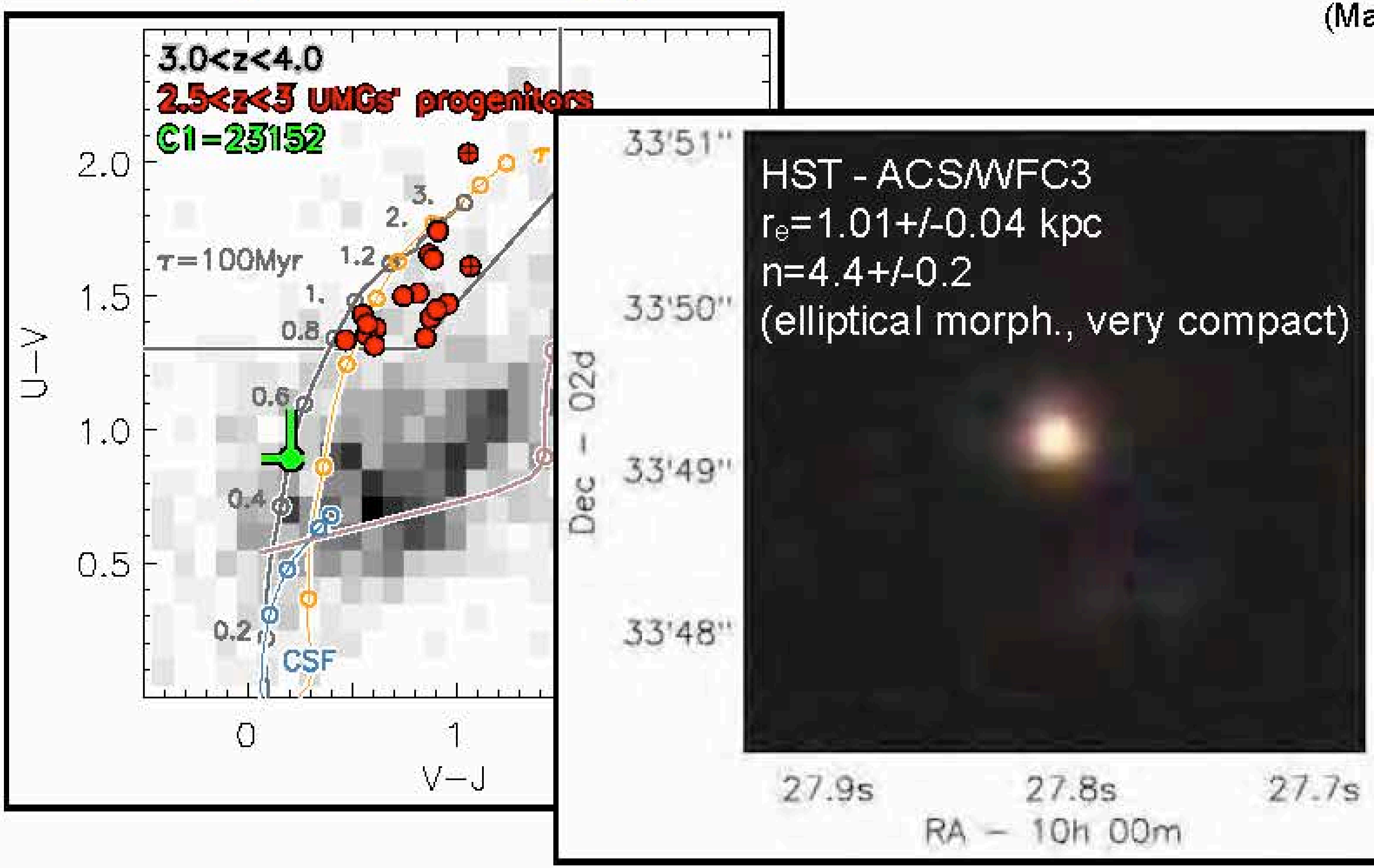

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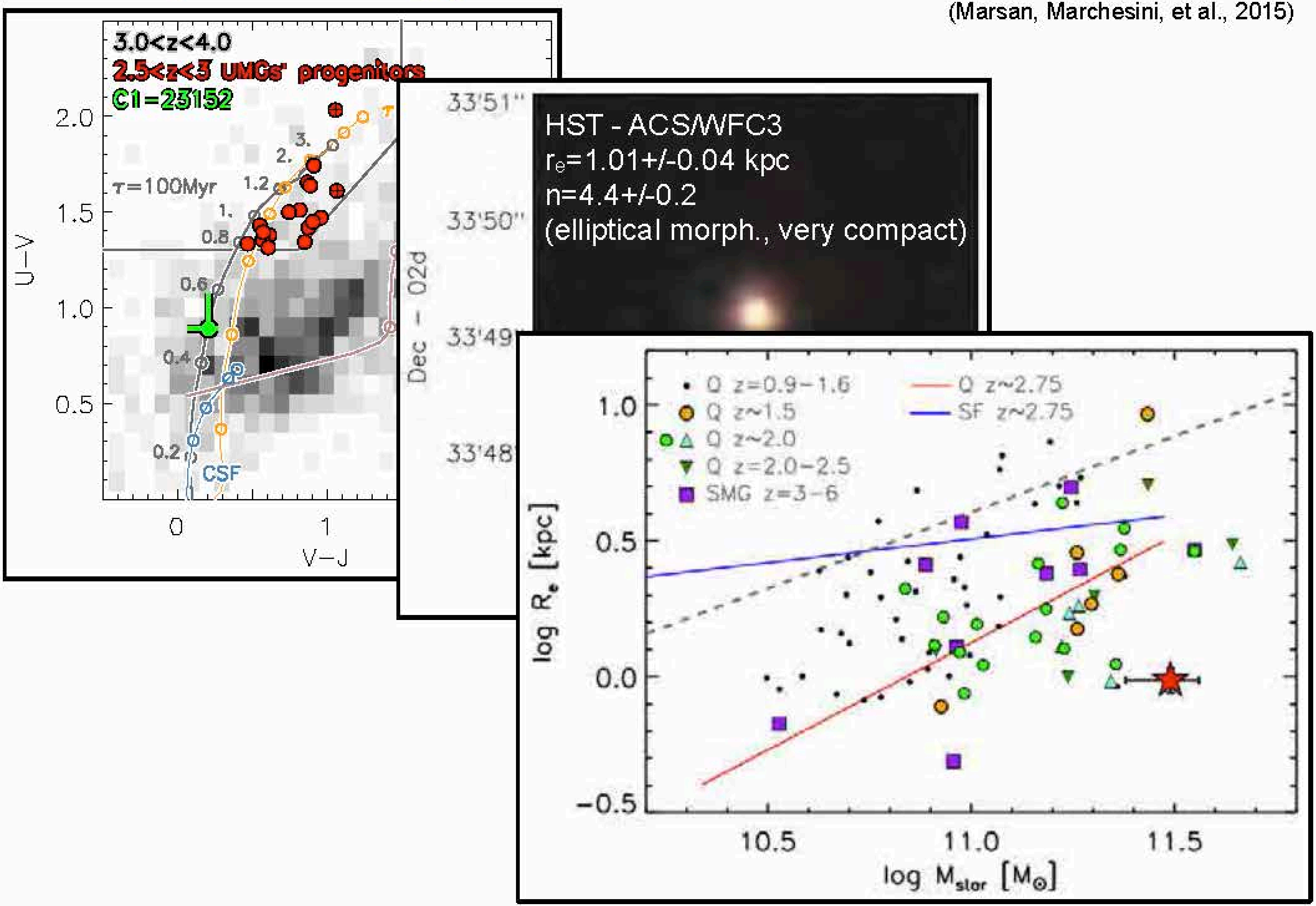

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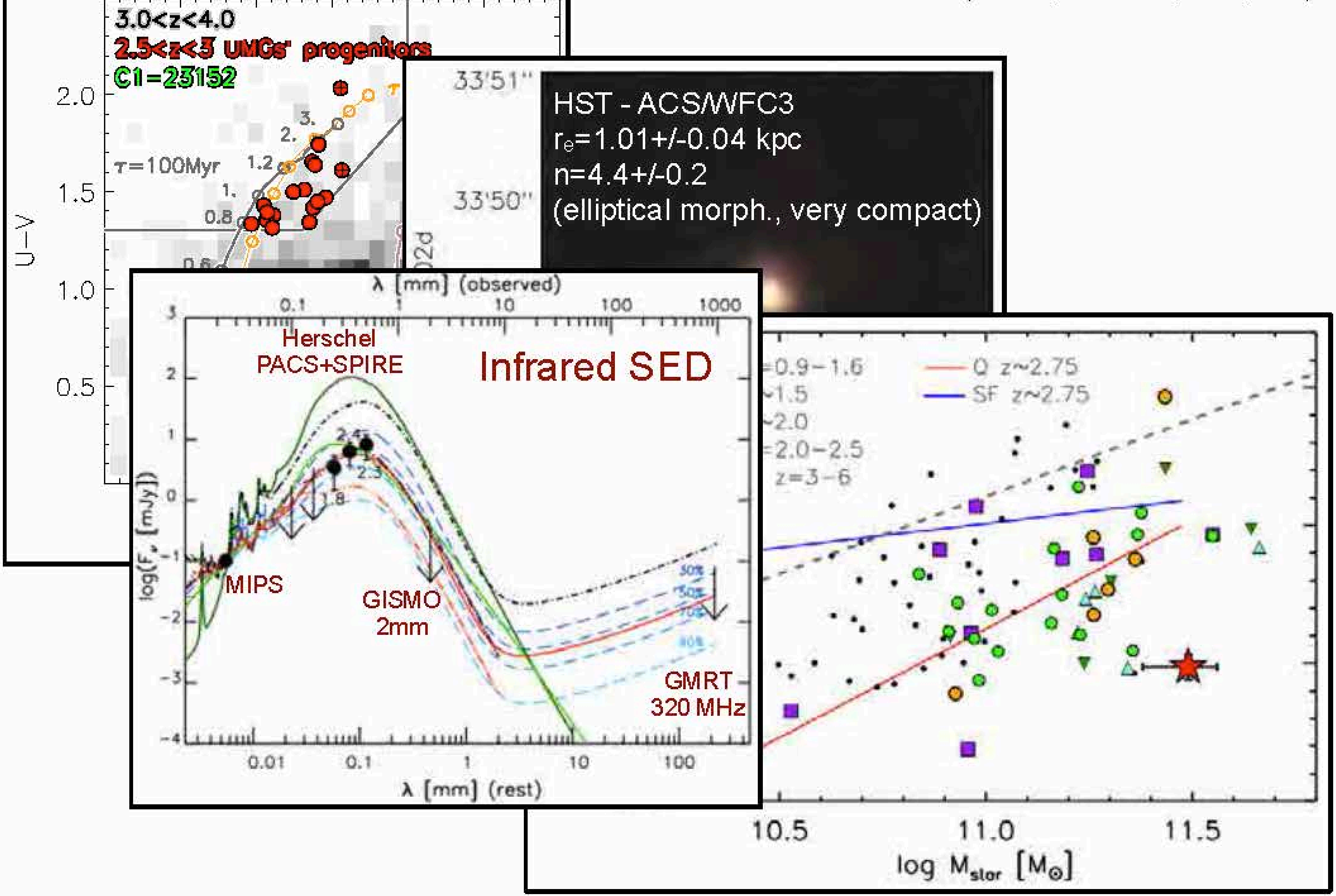

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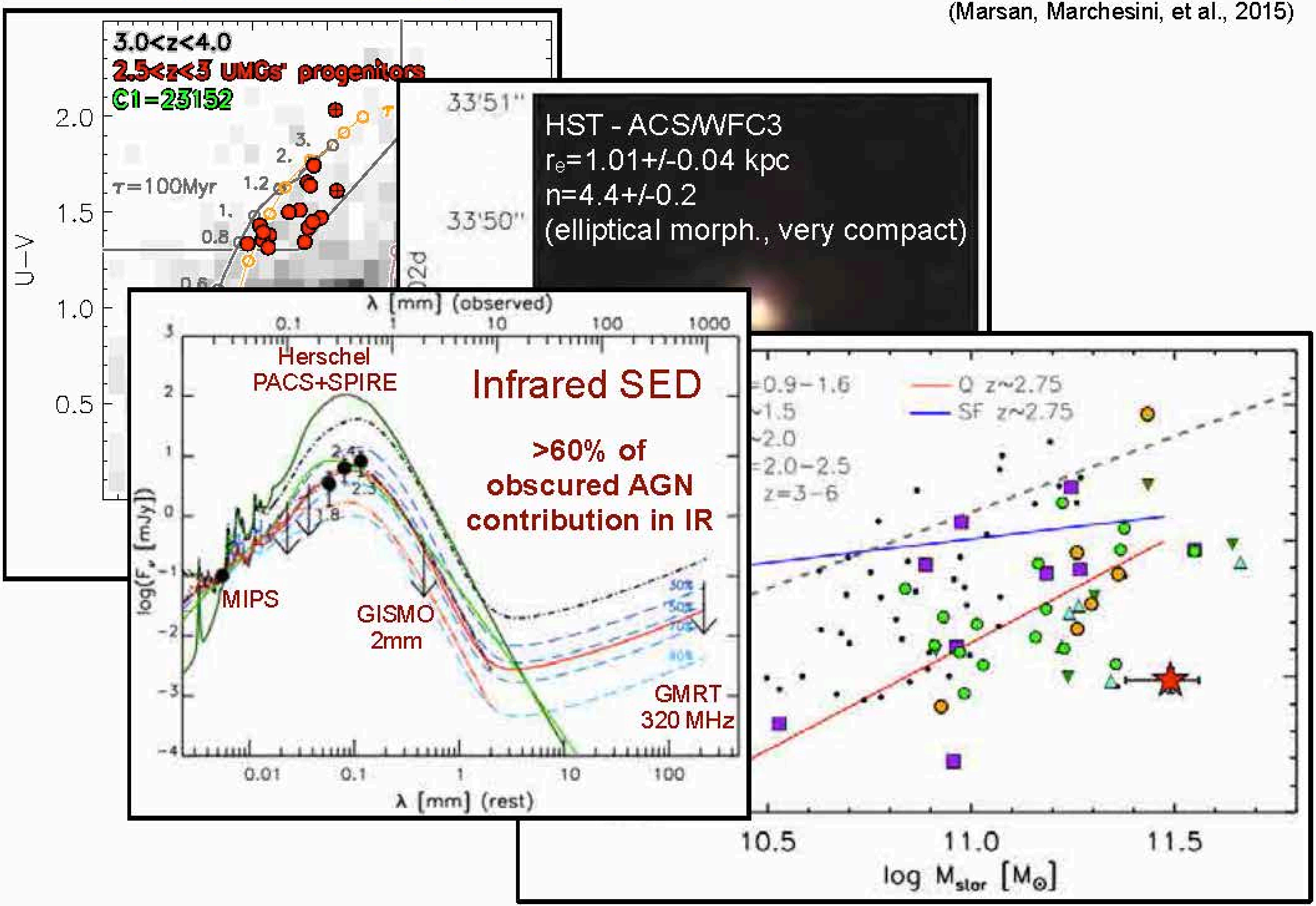

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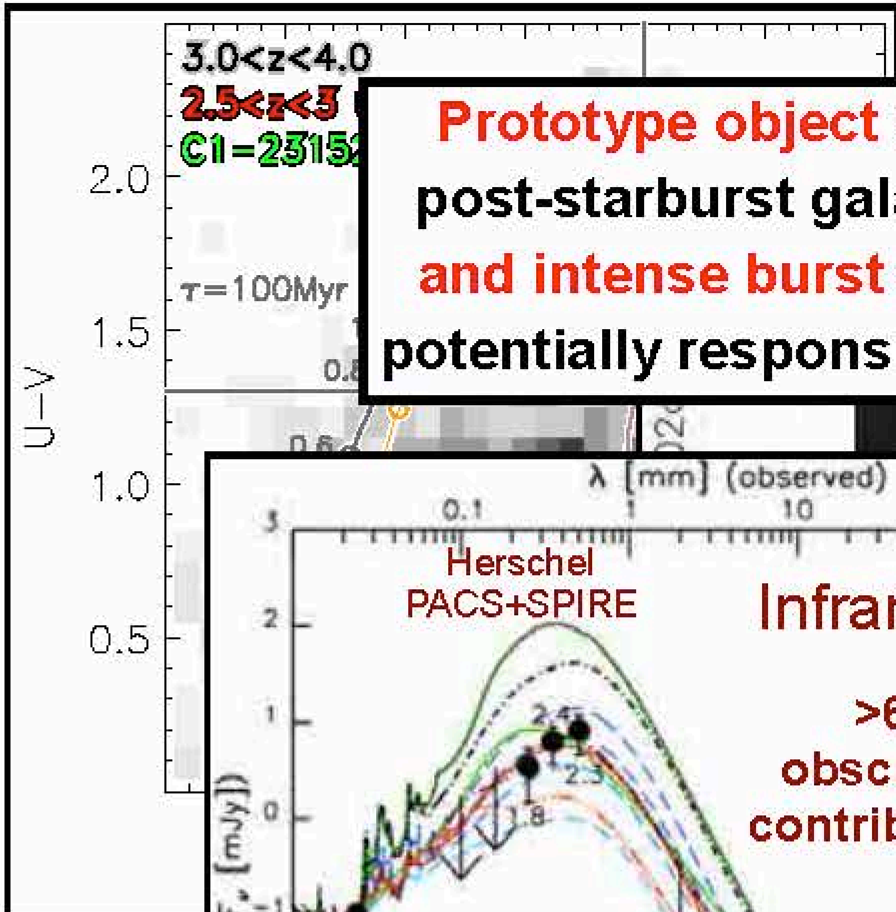

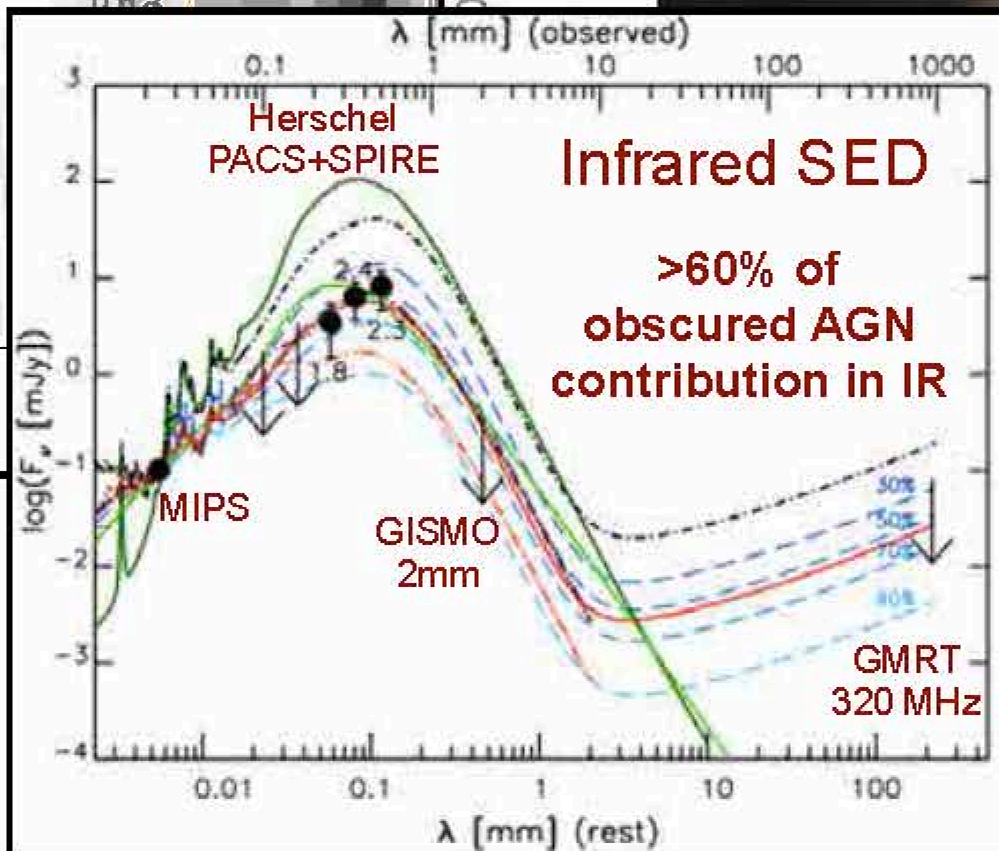

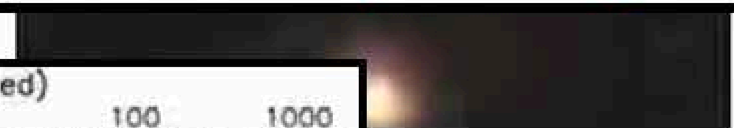

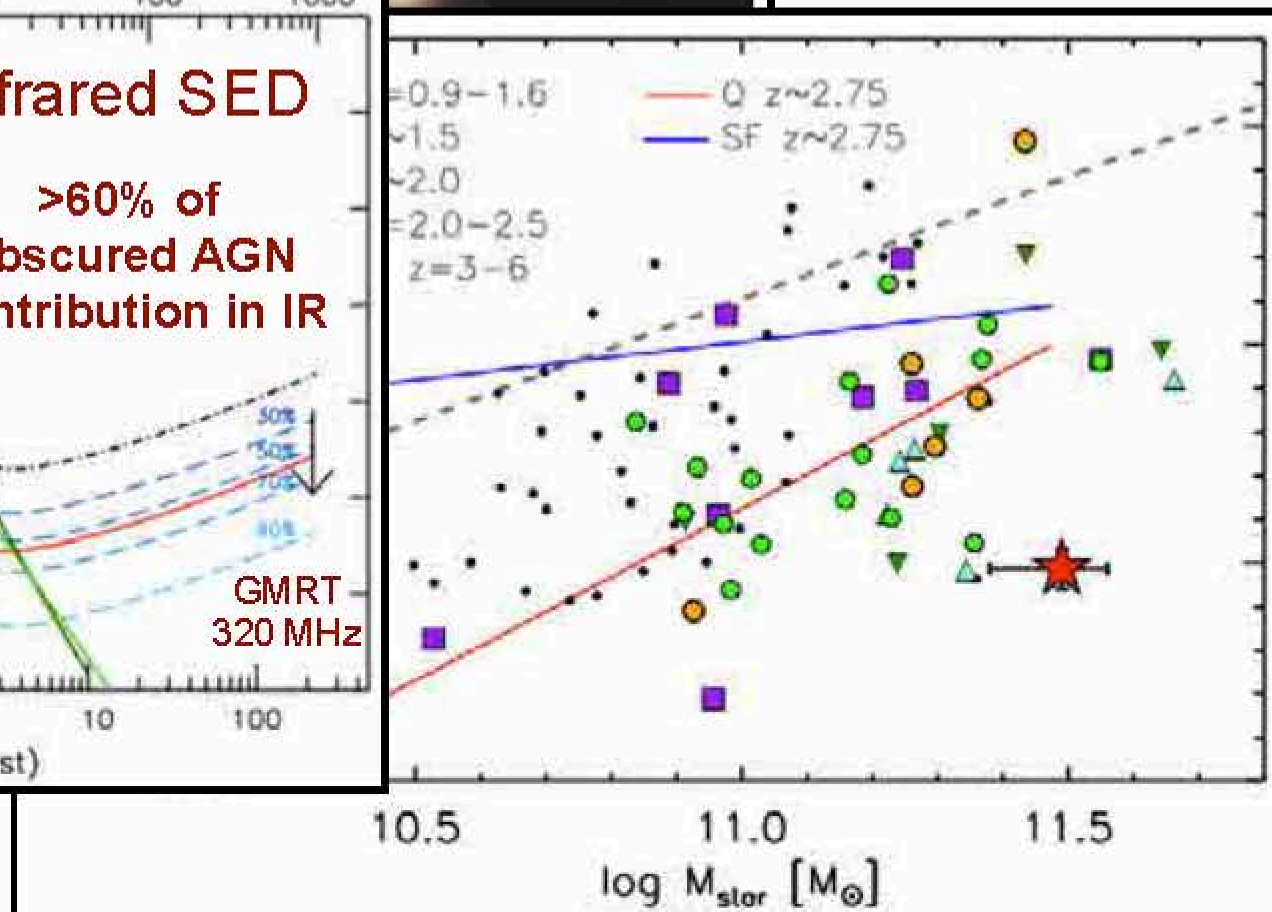

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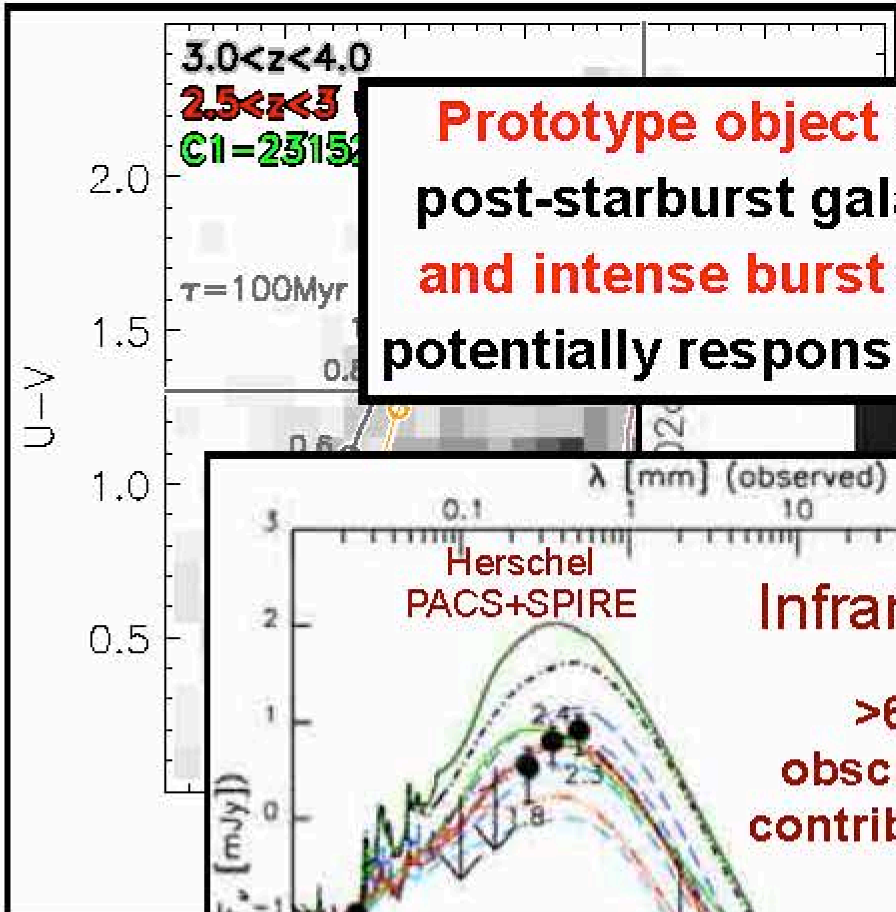

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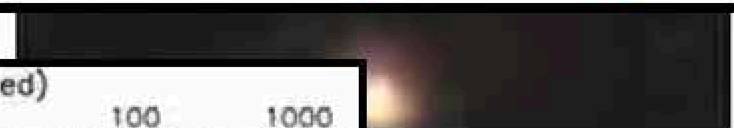
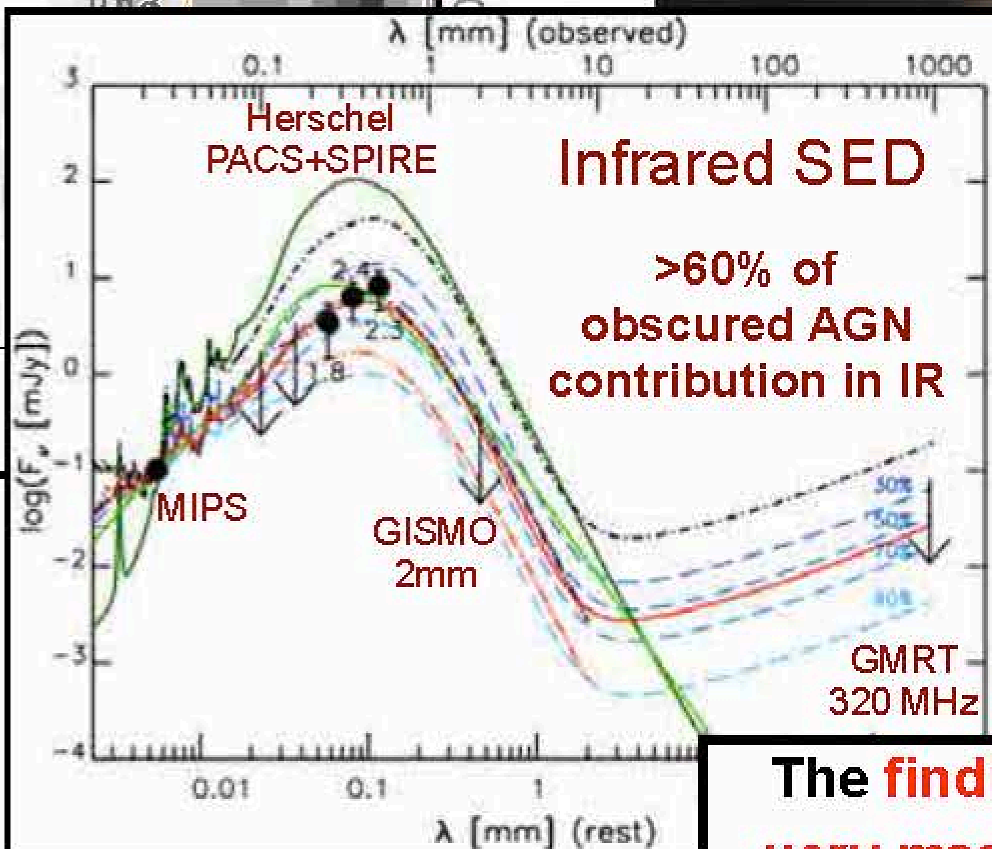
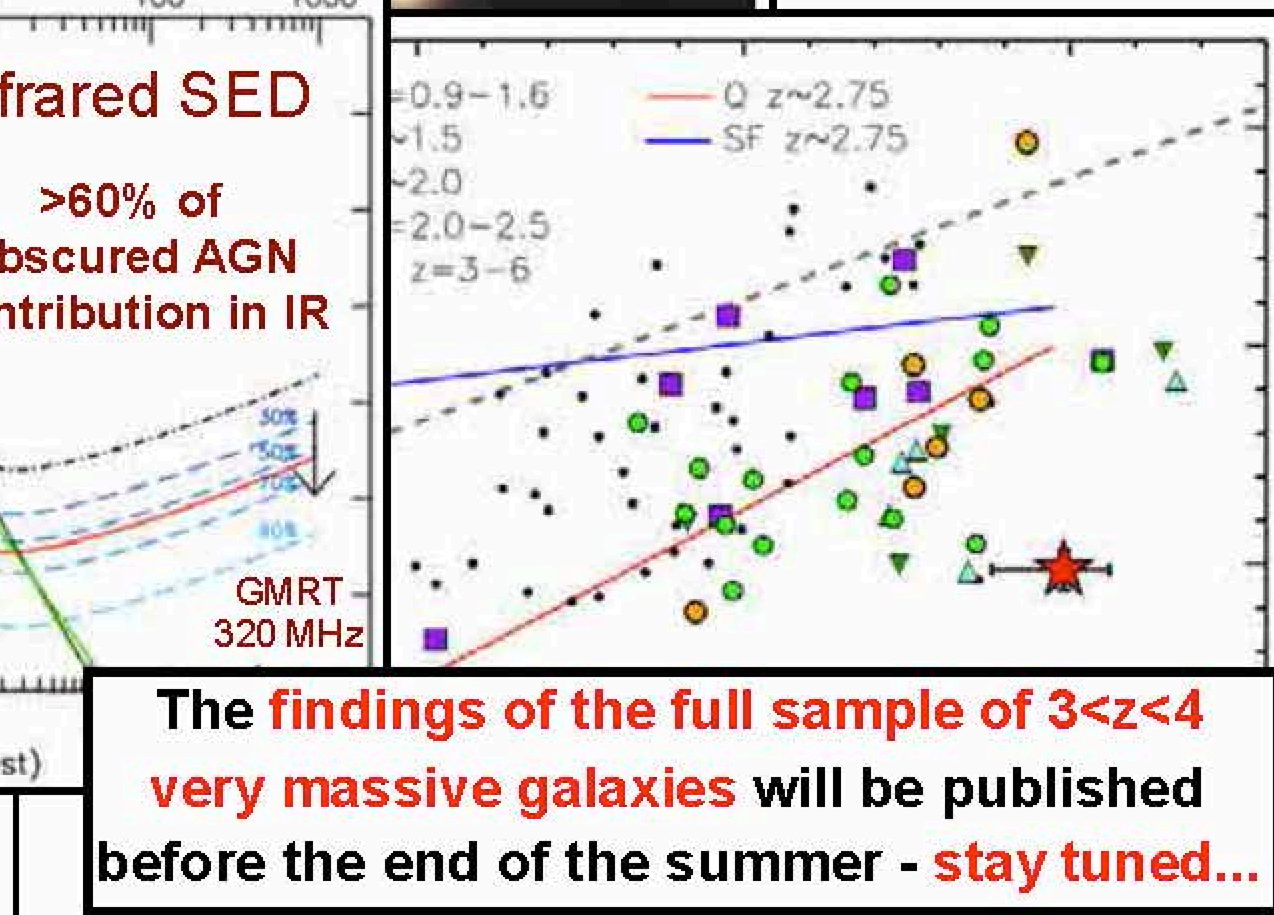
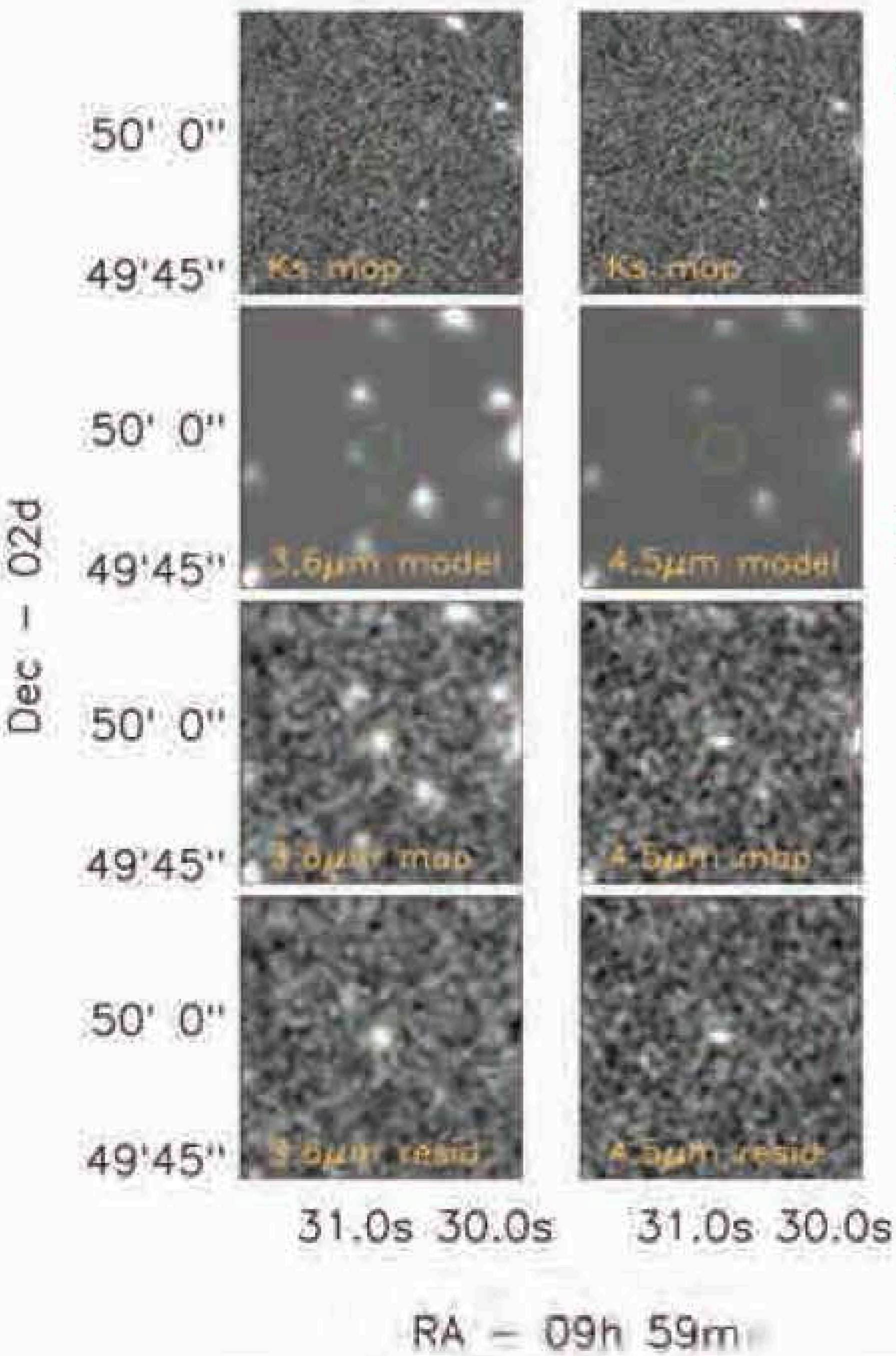






The **findings of the full sample of 3<z<4 very massive galaxies** will be published before the end of the summer - **stay tuned...**

Very Massive Galaxies at 4<z<7 and their Number Density (Stefanon, Marchesini, et al., 2015)

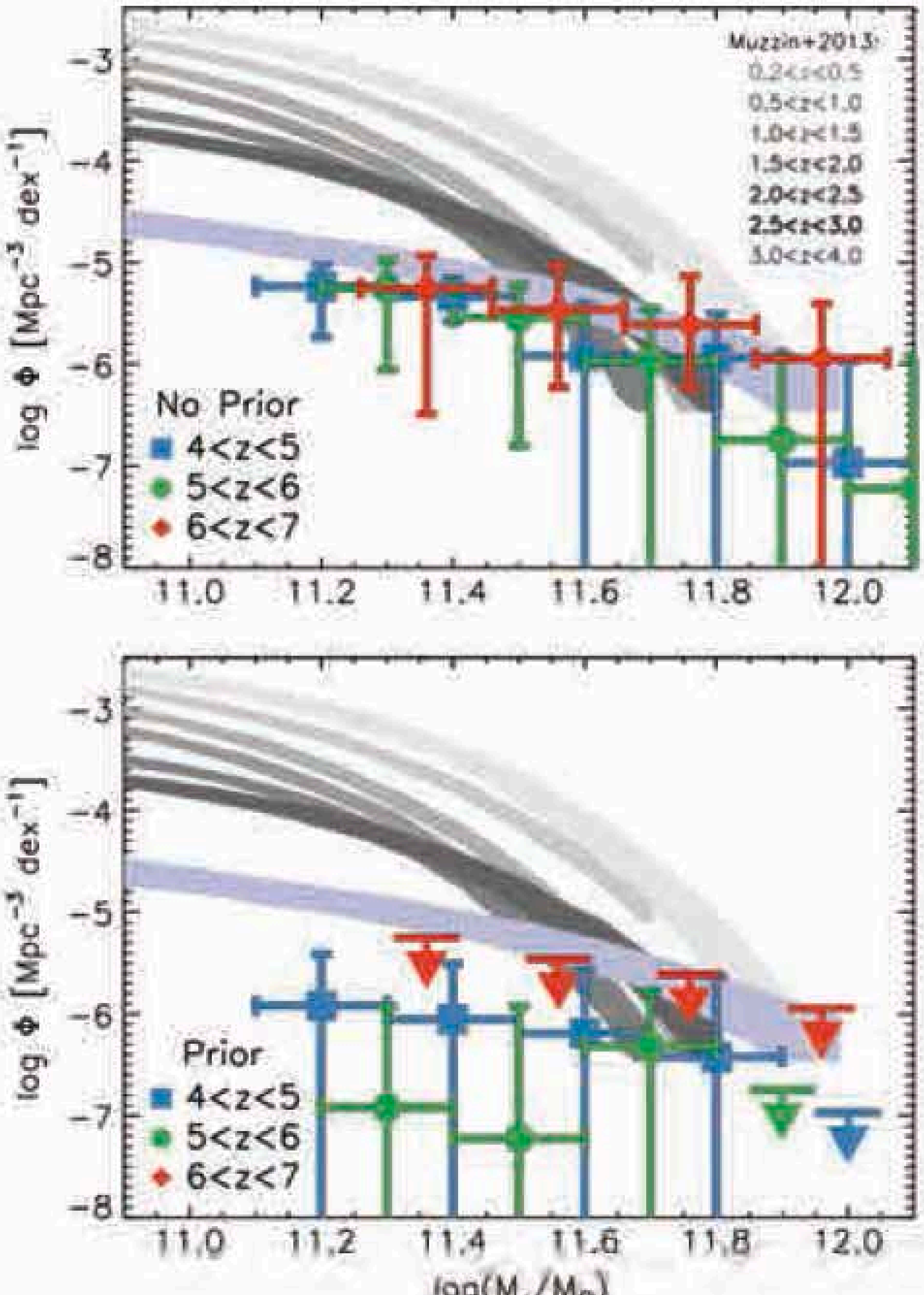


- **Search for massive galaxies at 4<z>7 with log(M_{star}/M_{sun})>11-11.2** in an IRAC-selected sample complementing the UltraVISTA DR1 K-band constructed catalog (Muzzin, Marchesini, et al. 2013a).

- **Systematic effects on photometric redshifts** (from addition of old+dusty template and/or applying a bayesian prior on luminosity) **and on stellar population properties** (from different SFHs and nebular emission lines' contamination) **were investigated**.

Very Massive Galaxies at 4<z<7 and their Number Density

(Stefanon, Marchesini, et al., 2015)



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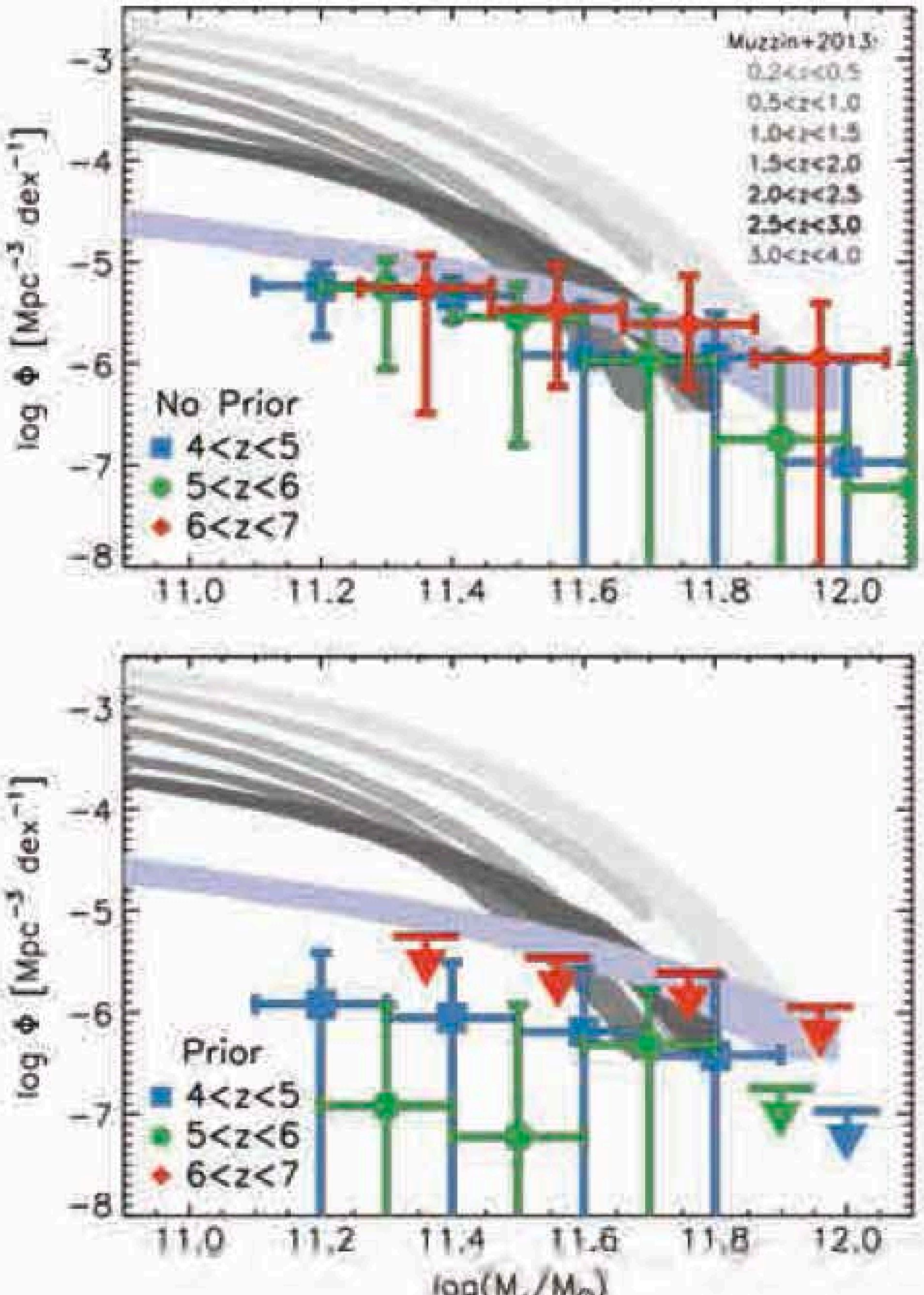

- **The systematics effects**, particularly on the photometric redshifts, **reduce the number of candidates of massive galaxies at z>4 by 83%**.

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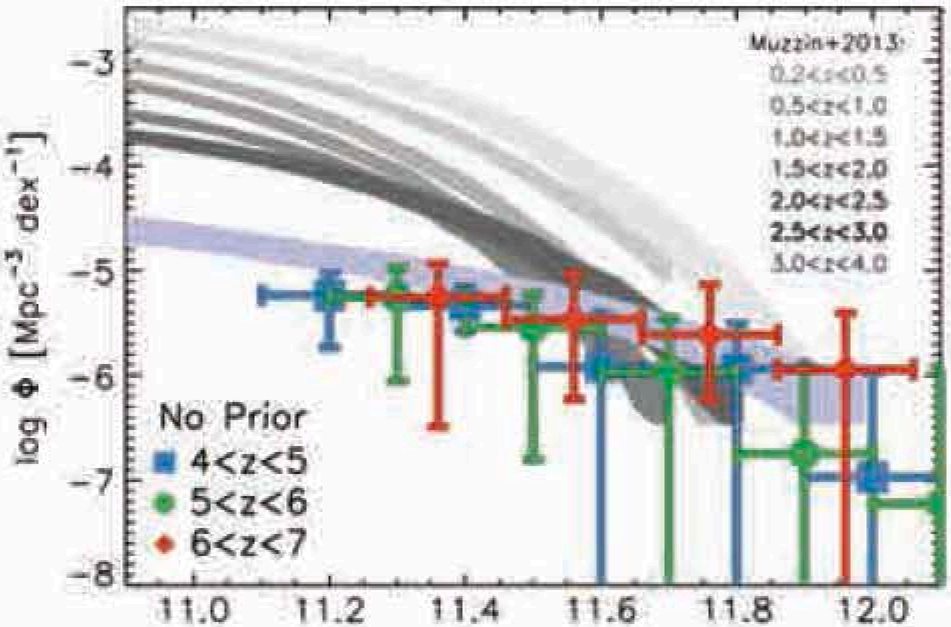

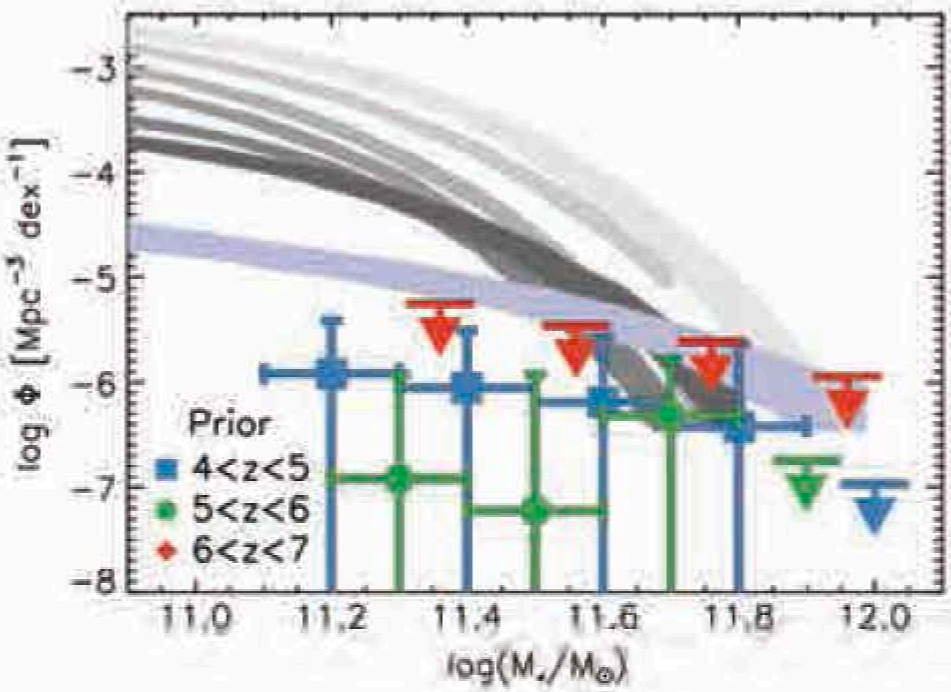

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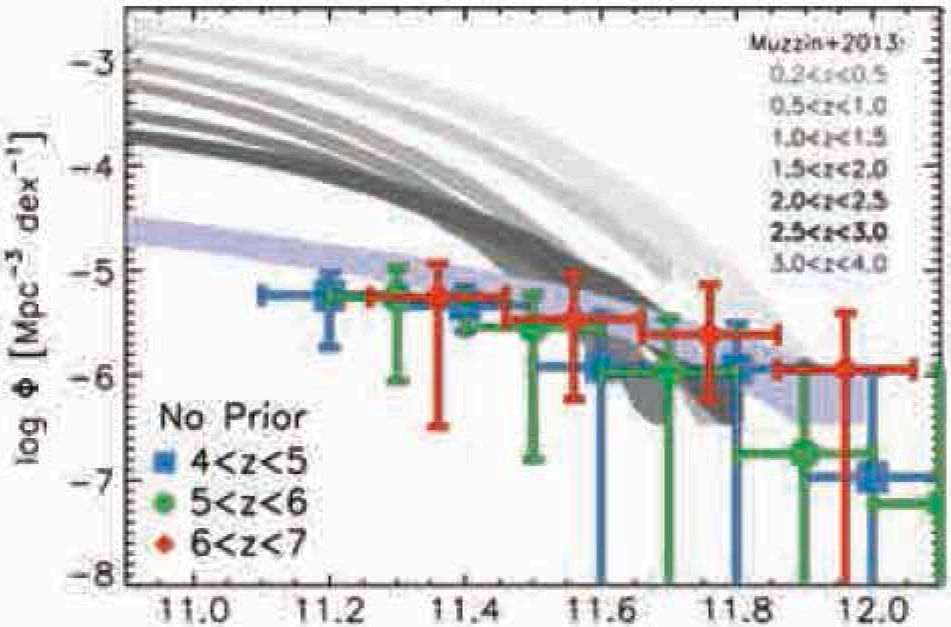
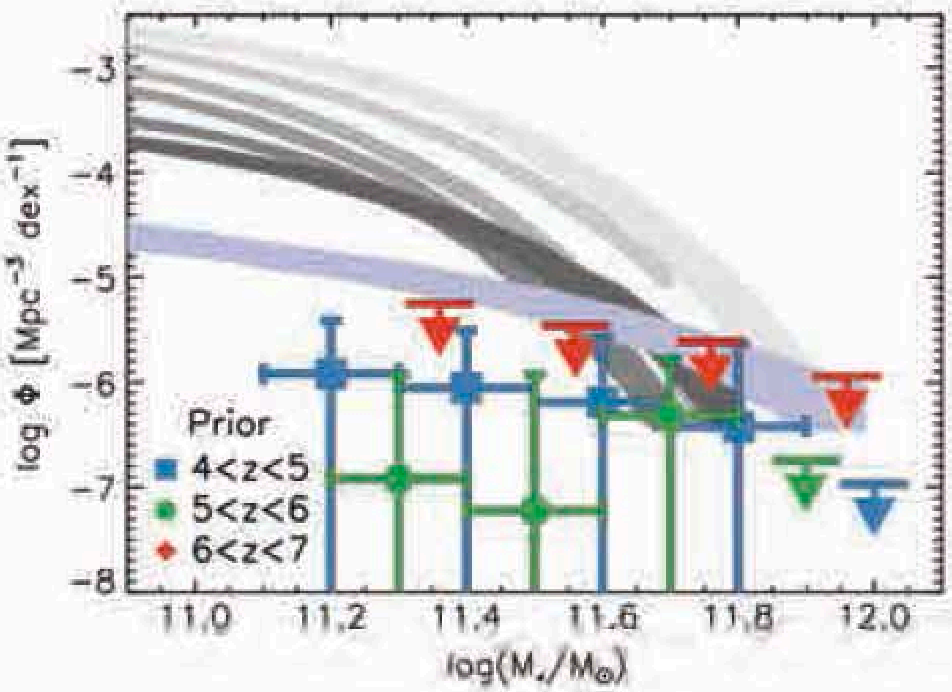
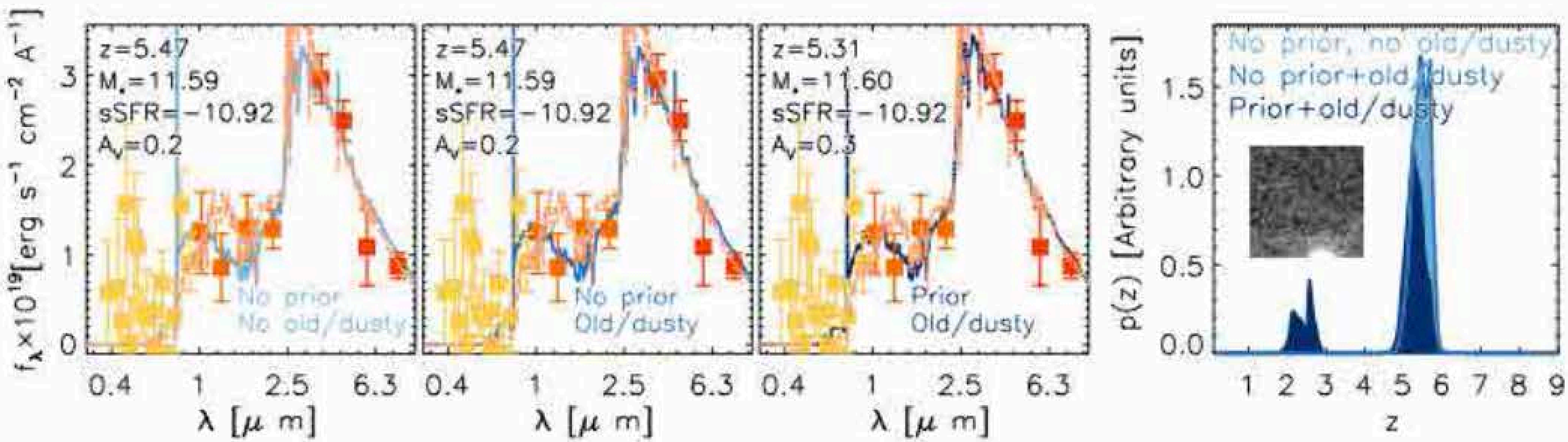
Very Massive Galaxies at 4<z<7 and their Number Density (Stefanon, Marchesini, et al., 2015)



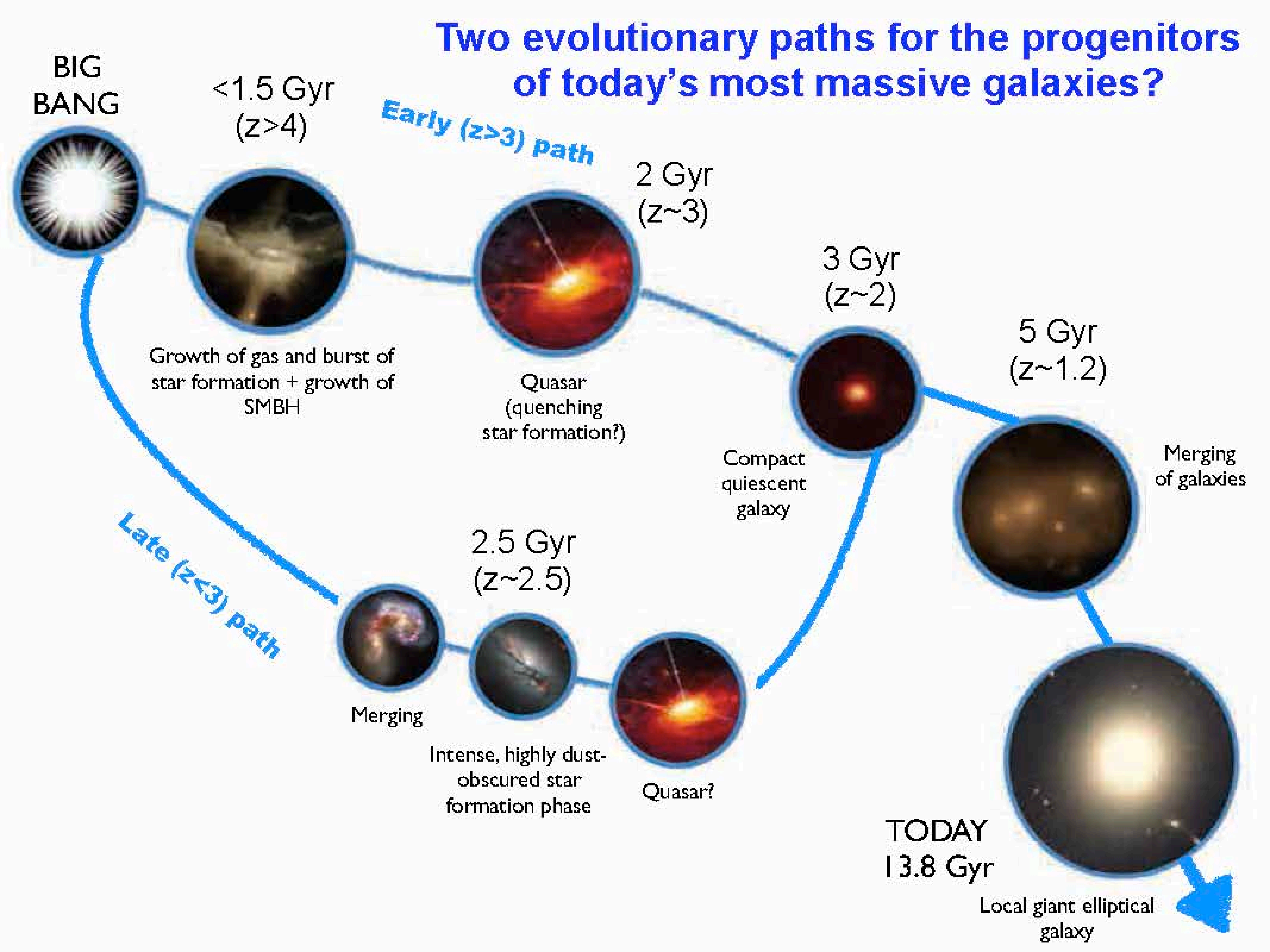


- **The systematics effects**, particularly on the photometric redshifts, **reduce the number of candidates of massive galaxies at z>4 by 83%**.
- Accounting for the systematic effects results in a **rapid growth of massive galaxies in the first 1.5 Gyr of cosmic history down to z=4**.

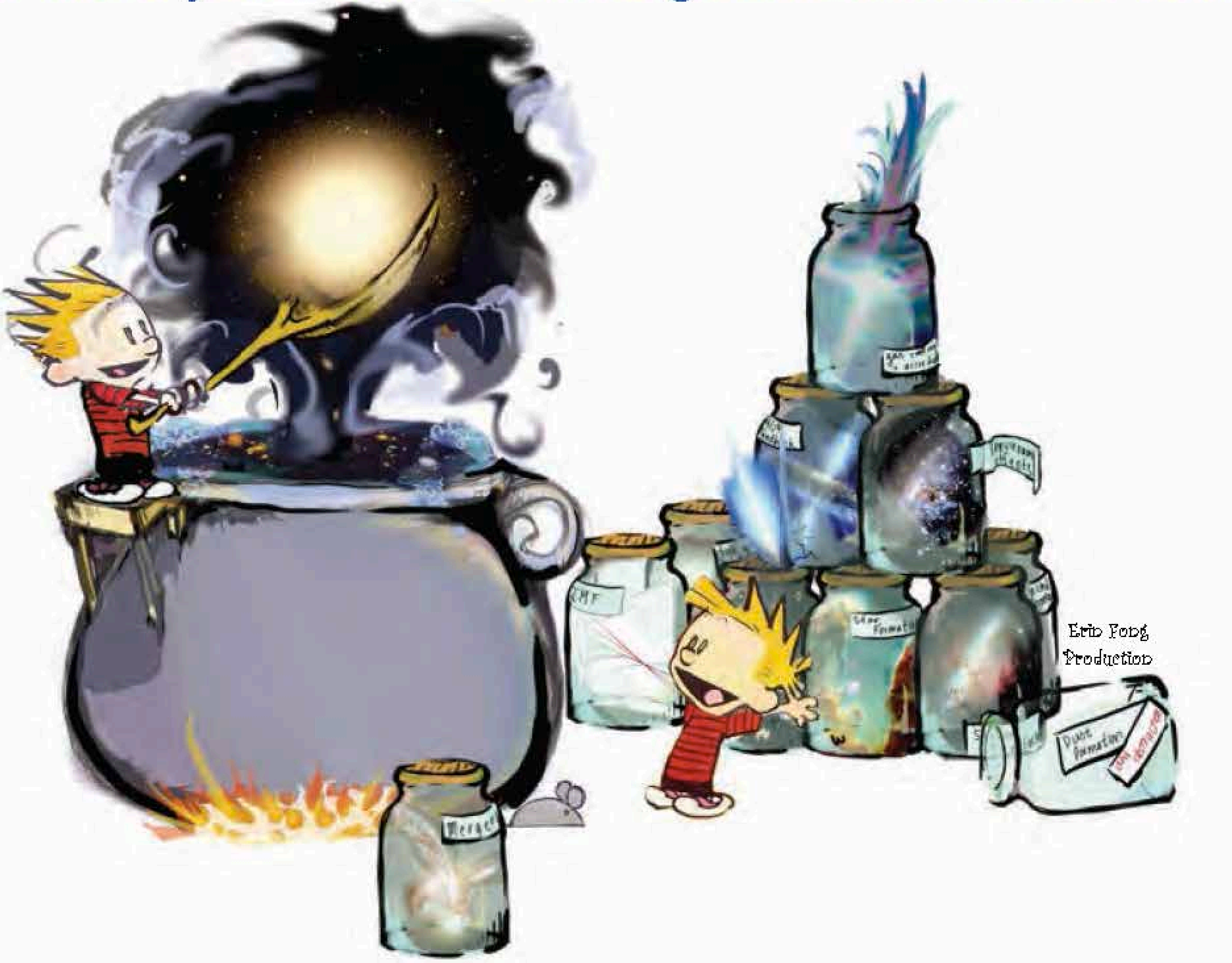
Very Massive Galaxies at 4<z<7 and their Number Density (Stefanon, Marchesini, et al., 2015)



- The stellar-mass complete sample includes one **robust candidate of a very massive ($\log(M_{star}/M_{sun})$~11.5) quiescent galaxy at z~5.4 with MIPS 24 micron detection**, suggesting the **presence of an obscured AGN.**
- This candidate is being **spectroscopically followed-up with VLT/Xshooter** to confirm the redshift and the emission line contamination to the photometry.


Two evolutionary paths for the progenitors of today's most massive galaxies?
BIG BANG
<1.5 Gyr (z>4)
Early (z>3) path
Growth of gas and burst of star formation + growth of SMBH
2 Gyr (z~3)
Quasar (quenching star formation?)
3 Gyr (z~2)
Compact quiescent galaxy
5 Gyr (z~1.2)
Merging of galaxies
Late (z<3) path
2.5 Gyr (z~2.5)
Merging
Intense, highly dust-obscured star formation phase
Quasar?
TODAY 13.8 Gyr
Local giant elliptical galaxy

Not there yet… but we have gotten a lot closer to it!



Summary

- The **evolution of the progenitors of local UMGs** has been **investigated since z=3 with UltraVISTA**, providing a complete and consistent picture of how the most massive galaxies in the local universe have assembled in the last 11.4 Gyr.
- **Local UMGs have grown** by 0.56 dex, 0.45 dex, and 0.27 dex from z=3, z=2, and z=1, respectively, to z=0, growing **by a factor of ~2-3.6 in the last 11.4 Gyr**; growth **dominated by star formation at $z>1.5$ and mergers at $z<1$**.
- **At $z<1$**, the progenitors are **all quiescent**, while **at $z>1$** the contribution from **star-forming galaxies progressively increases**.
- **At $2<z<3$, the progenitors are dominated by massive (~2×10^{11} M_{Sun}), dusty (A_V~1-2.2 mag), star-forming (SFR~100-400 M_{Sun}/yr) galaxies**.
- **At z=2.75, ~15% of the progenitors are quiescent, with properties typical of massive, young, post-starburst galaxies with little dust extinction and strong Balmer breaks and large intrinsic scatter in U-V colors**.
- The very massive end of the local red-sequence population had been mostly assembled between z=3 and z=1, in good agreement with the typical formation redshift and scatter in age from fossil records.
- **The progenitors of z~0 UMGs have never lived on the blue cloud since z=3**, challenging previously proposed pictures for the formation and evolution of local massive spheroids.
- **At $z<2$**, the **progenitors are central** galaxies **and live in a variety of environments**.
- Presented **first spectroscopic confirmation of an ultra-massive galaxy at $z>3$** (z_{spec}=3.351) with $M_{star}=3\times10^{11}$ M_{Sun}, compact (r_e=1 kpc) and n~4.4, hosting a powerful hidden AGN, with z_{form}~4.1: prototype of the progenitors of local most massive ellipticals.
- Investigated the **abundance of massive galaxies at $z>4$** (Stefanon et al. 2014).