# "The Evolution of the Progenitors of Today's Ultra-Massive Galaxies Over the Last 12 Gyr"

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Gabe Brammer (STScI), **Cemile Marsan (Tufts)**, **Nick Martis (Tufts)**,
Adam Muzzin (York), Mauro Stefanon (Leiden), Benedetta Vulcani (Melbourne)

**Marchesini, et al., 2010, ApJ, 725, 1277**
**Marchesini, et al., 2014, ApJ, 794, 65**
**Marsan, Marchesini, et al., 2015, ApJ, 801, 133**
**Vulcani, Marchesini, et al., 2016, ApJ, 816, 86**
**Martis, Marchesini, et al. 2016, ApJL, 827, 25**
**Marsan, Marchesini, et al., 2016, ApJ submitted [arXiv:1606.05350]**

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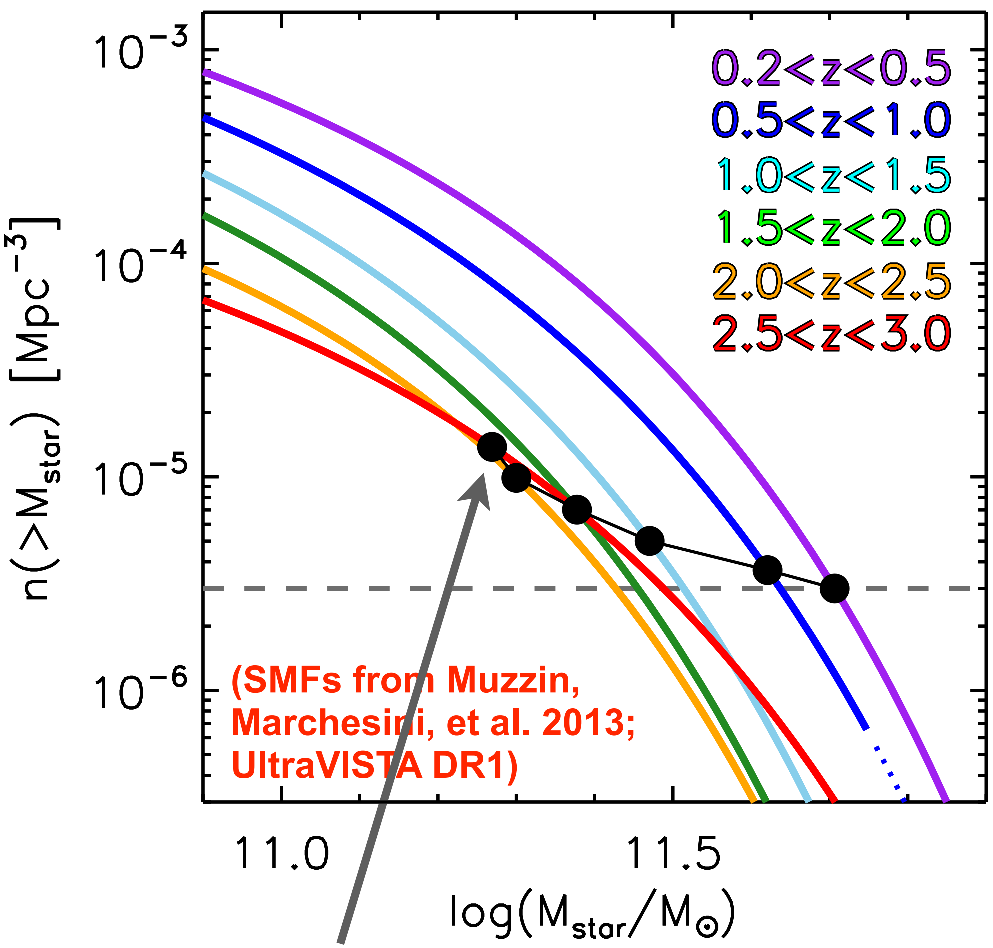
Panoramas of the Evolving Cosmos: Nov 28 - Dec 2, 2016 - Hiroshima (Japan)

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

(Marchesini, Muzzin, et al. 2014)




- Abundance matching (accounting for galaxy-galaxy mergers)
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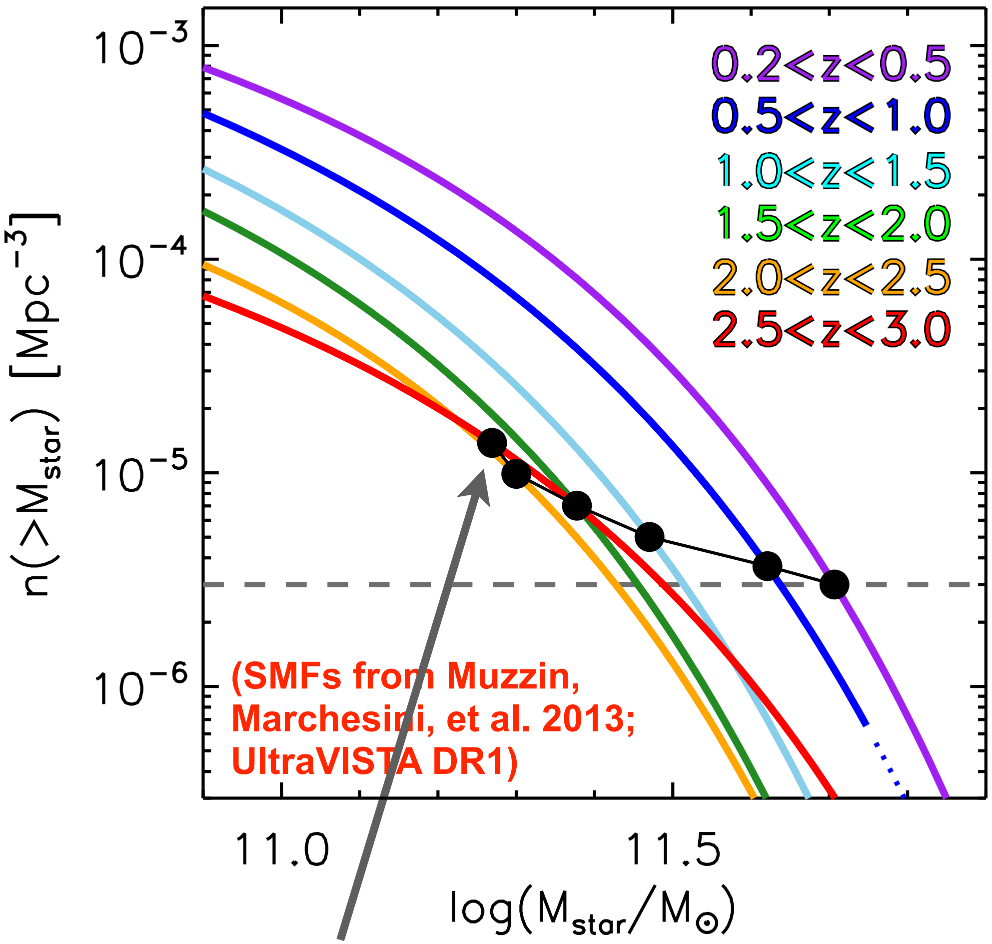


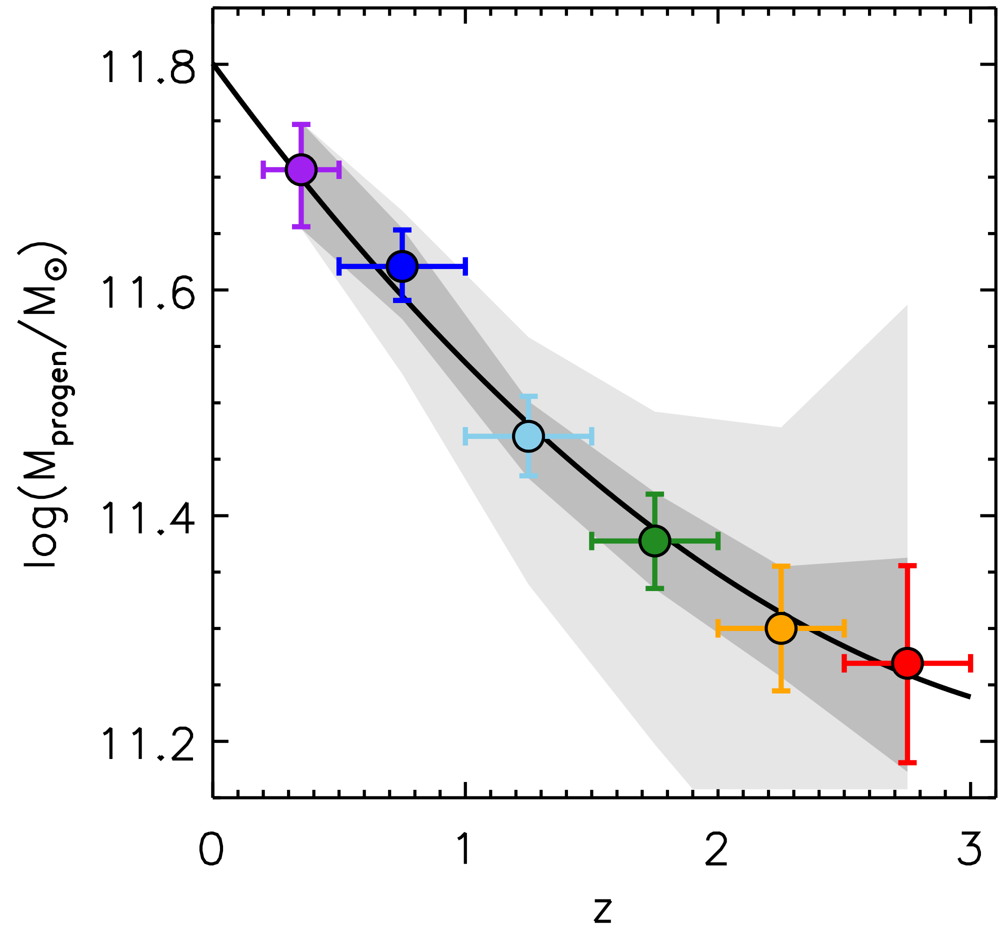


● Abundance matching (accounting for galaxy-galaxy mergers)
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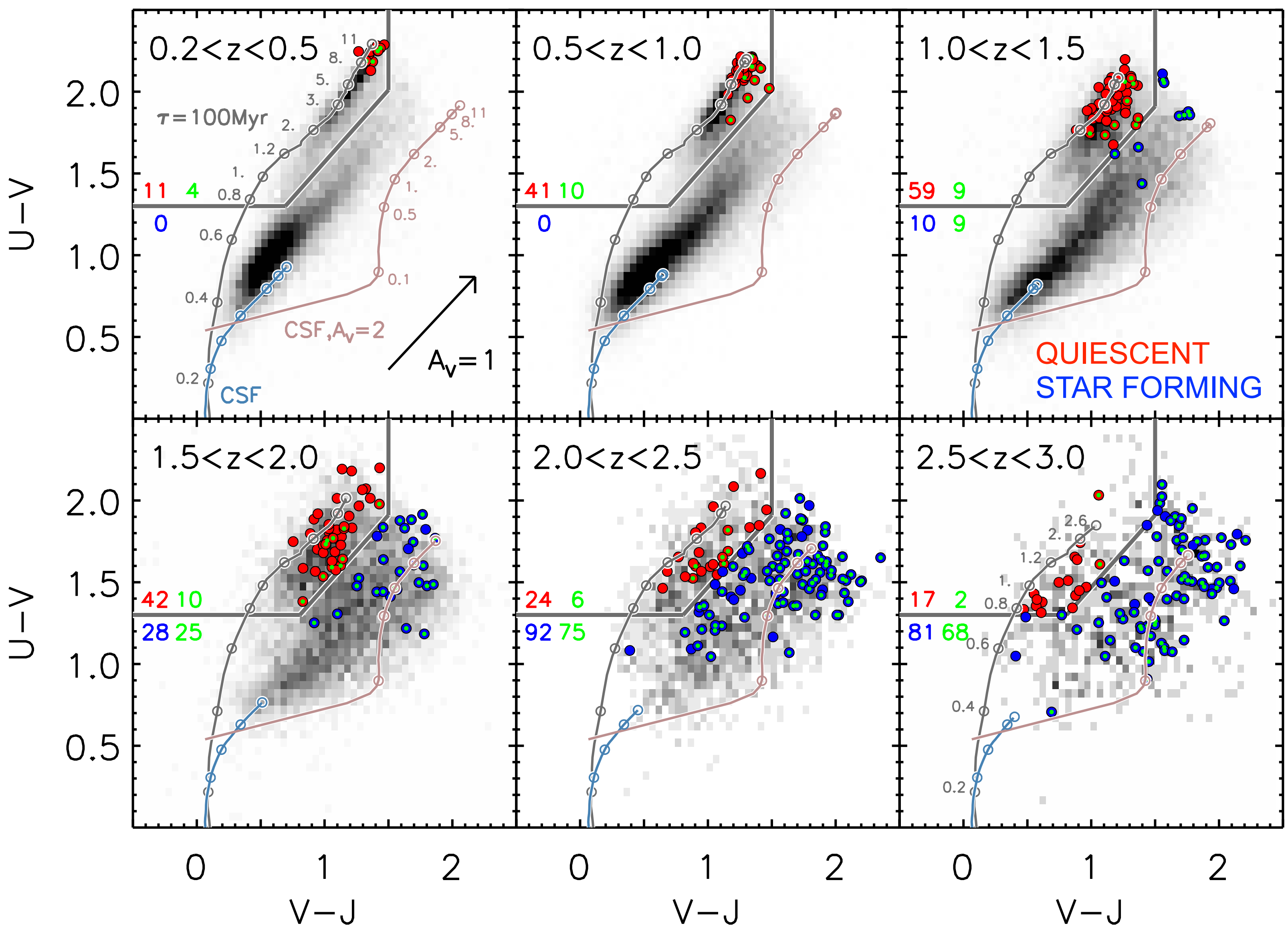
- **z~0 UMGs** defined as galaxies with $M_{star}=6x10^{11}$ Msun, i.e., **$log(M_{star}/M_{Sun})=11.8$** (Kroupa)
- **Mass growth is** a factor of **~3.6 from z=3 to z=0** using **abundance matching** techniques

# Evolution of Progenitors in the UVJ diagram

(Marchesini et al. 2014)



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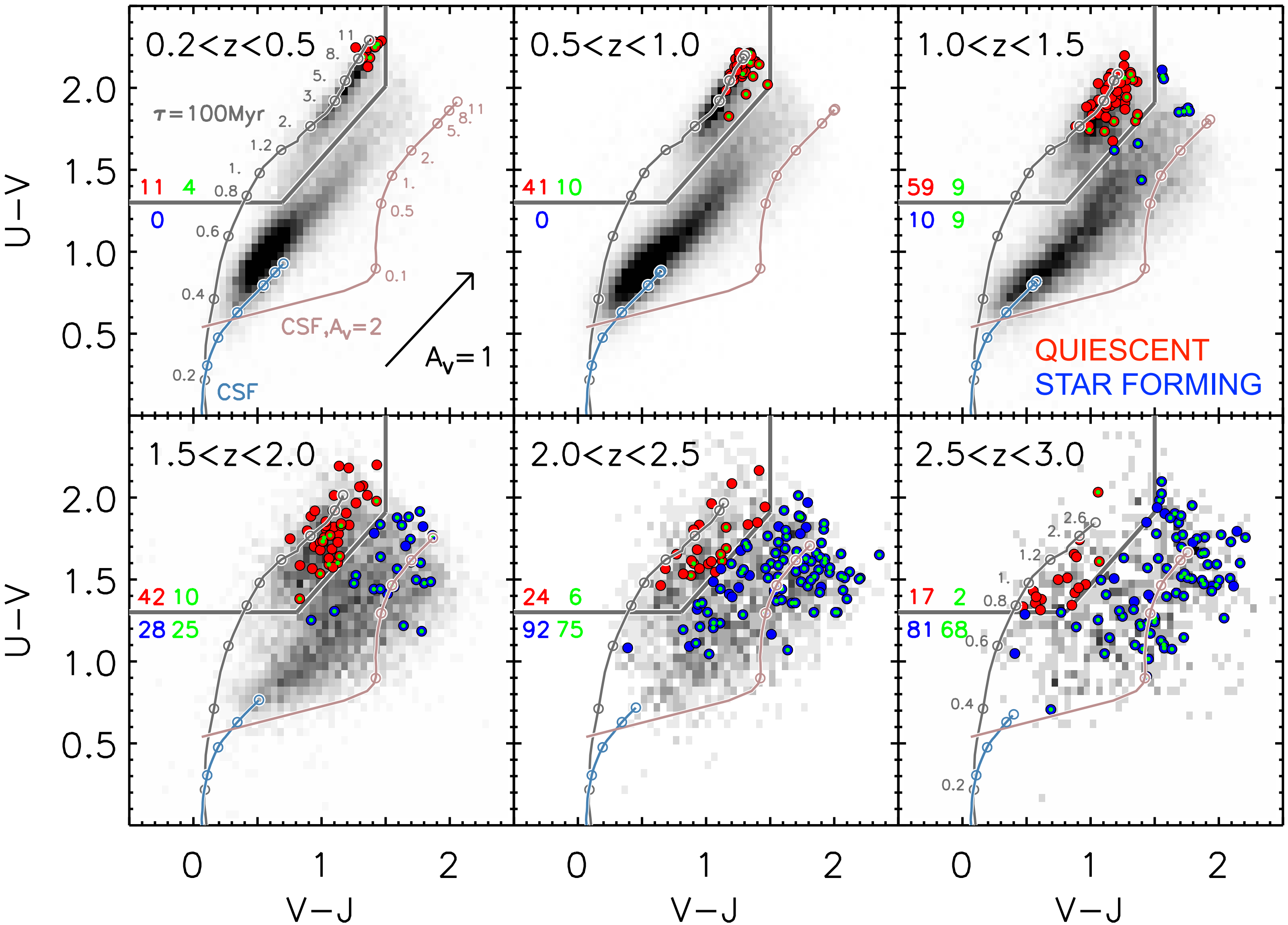


- **At z<1, all progenitors are quiescent**, and constitute a very homogeneous population. At high-z, the contribution from star-forming galaxies progressively increases, with the **progenitors' population dominated by star-forming galaxies at 2<z<3**.

# Evolution of Progenitors in the UVJ diagram

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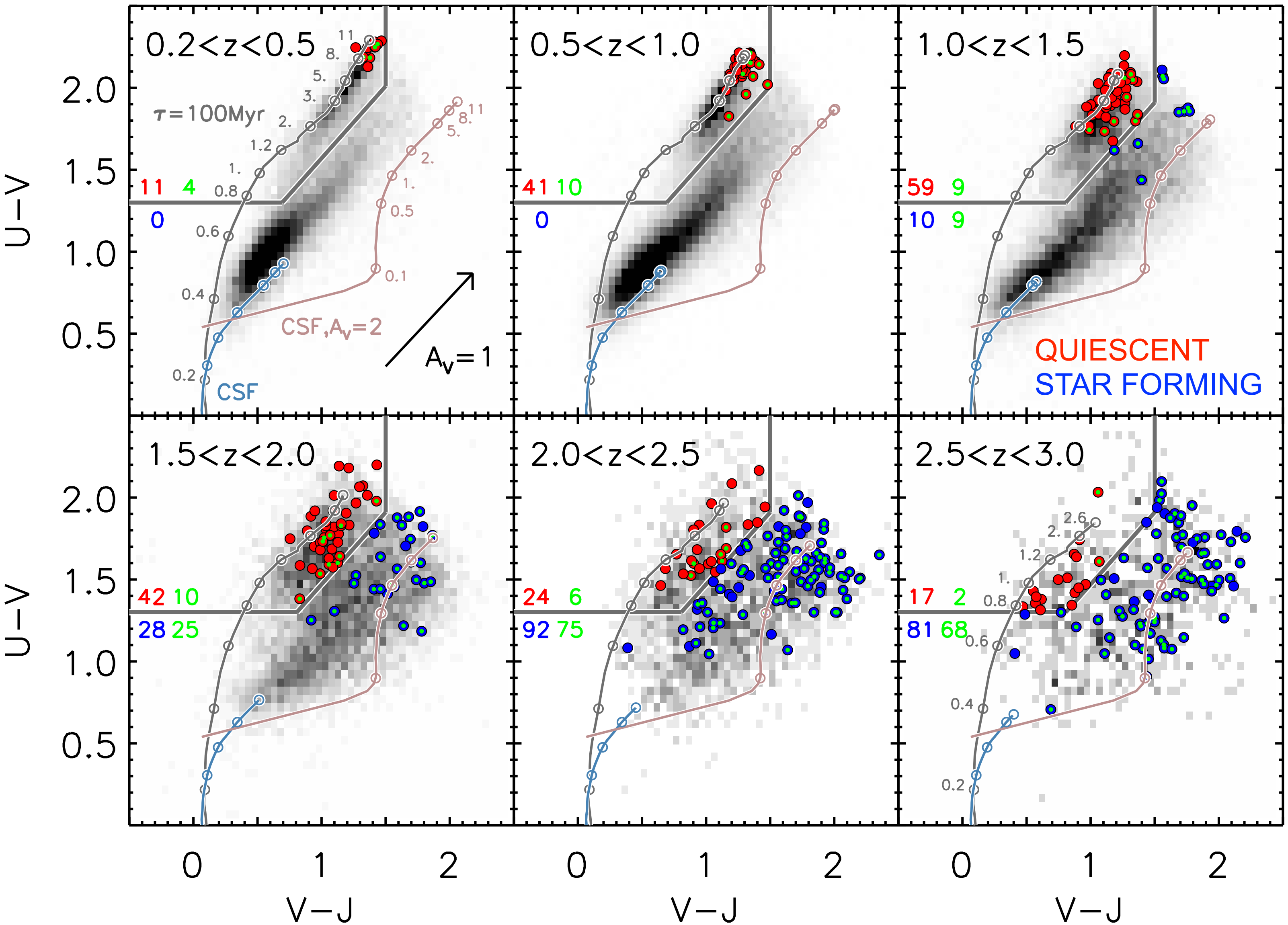


- **Aging of the quiescent population** clearly detected.

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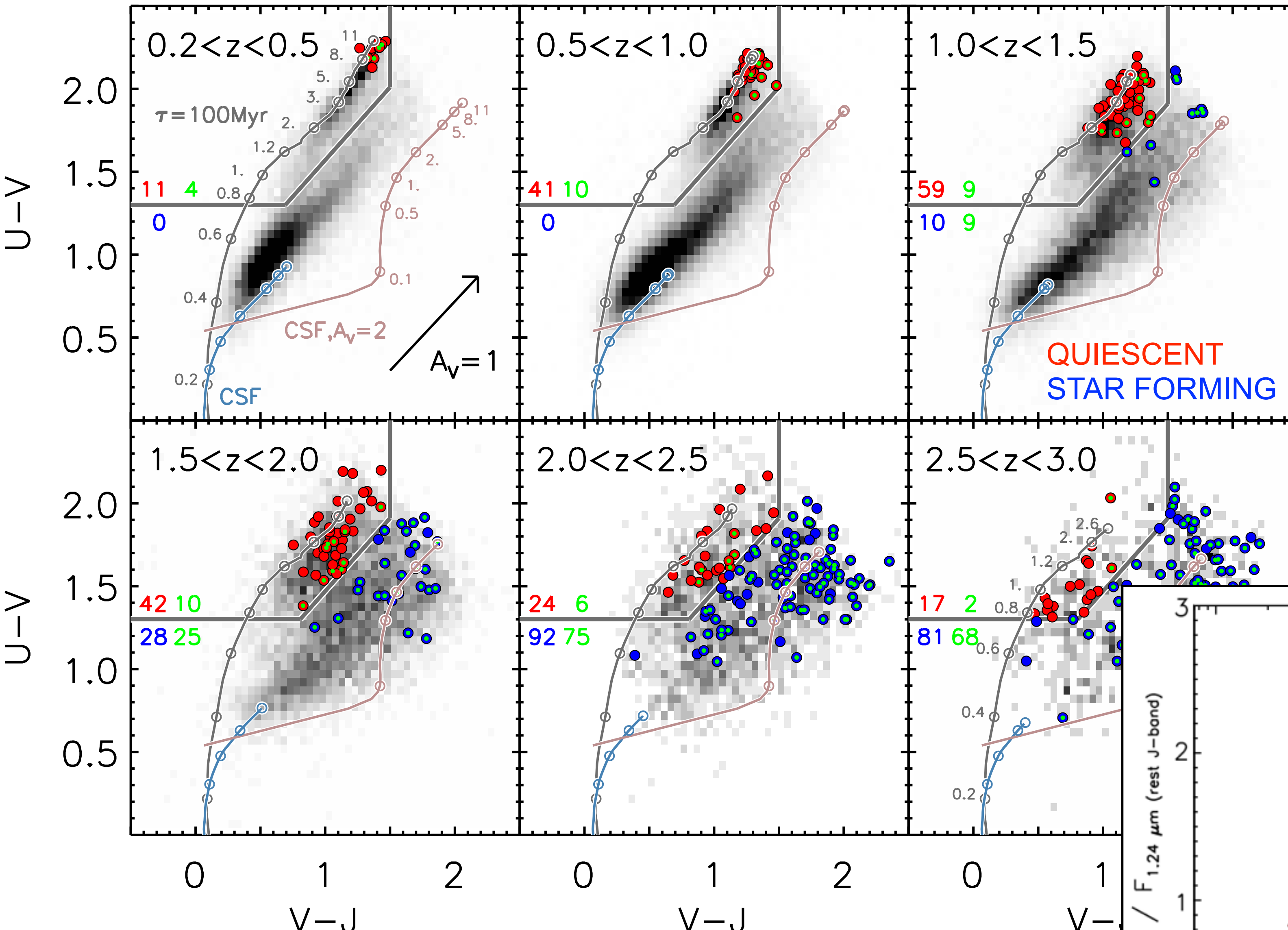


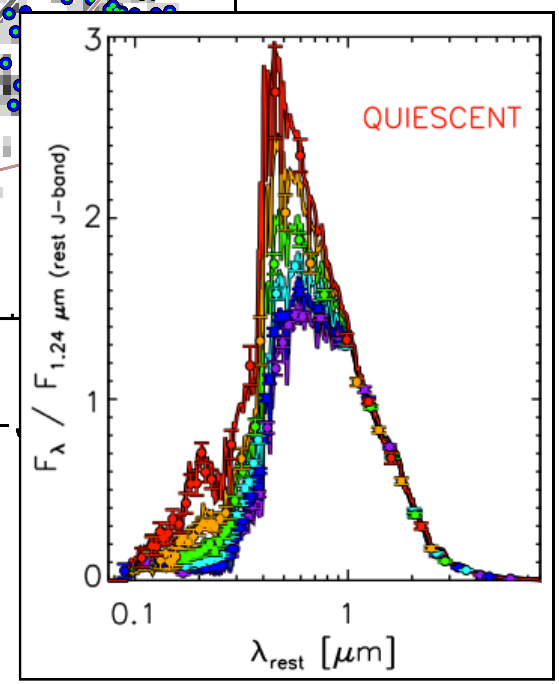


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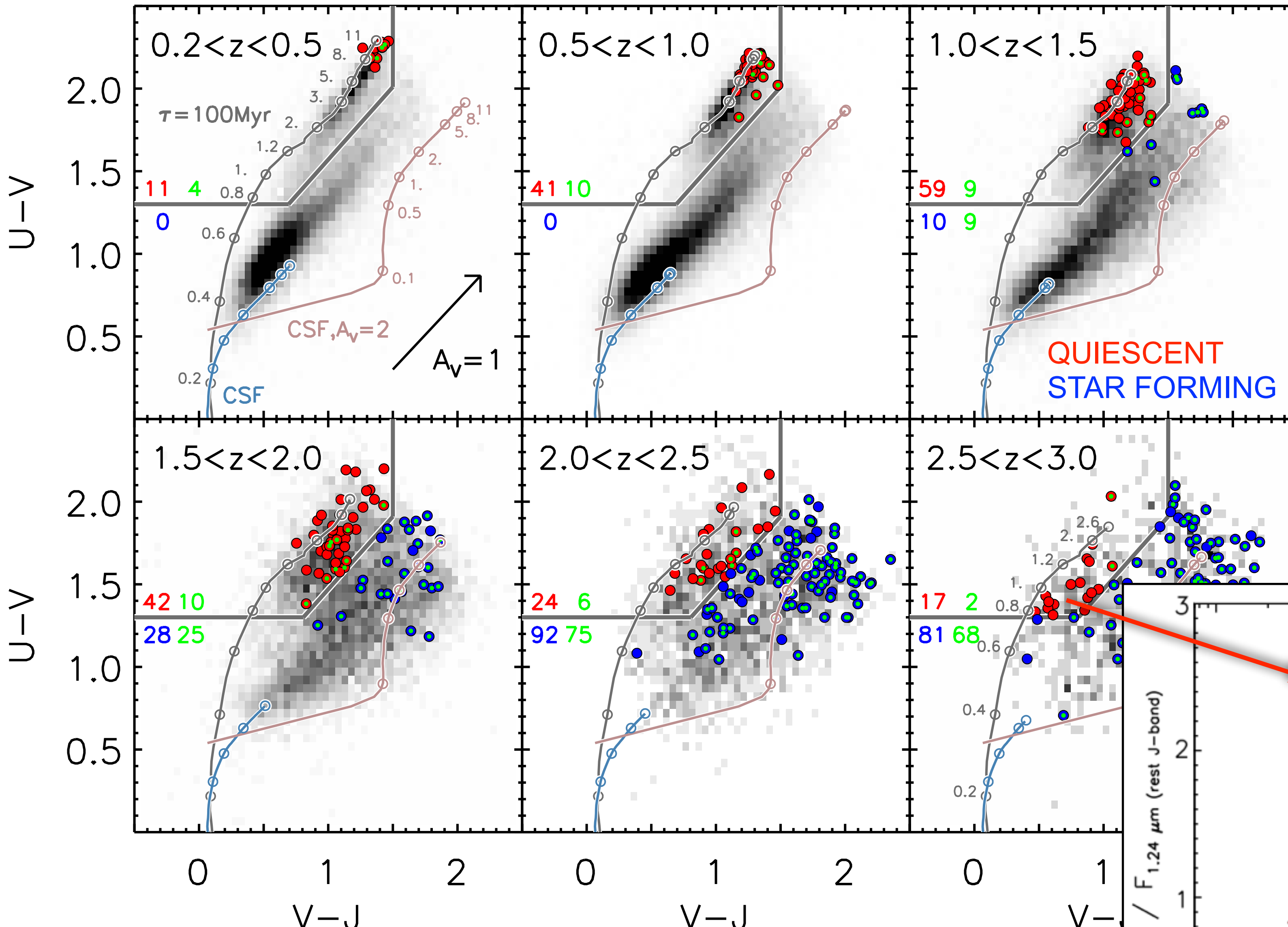


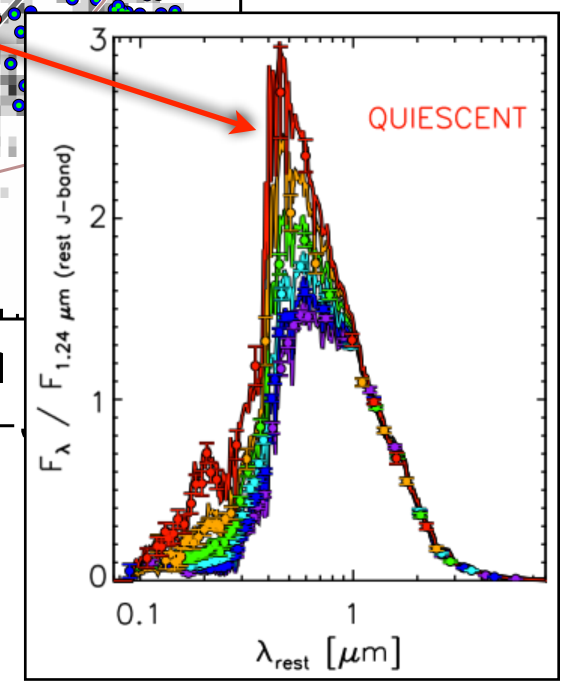


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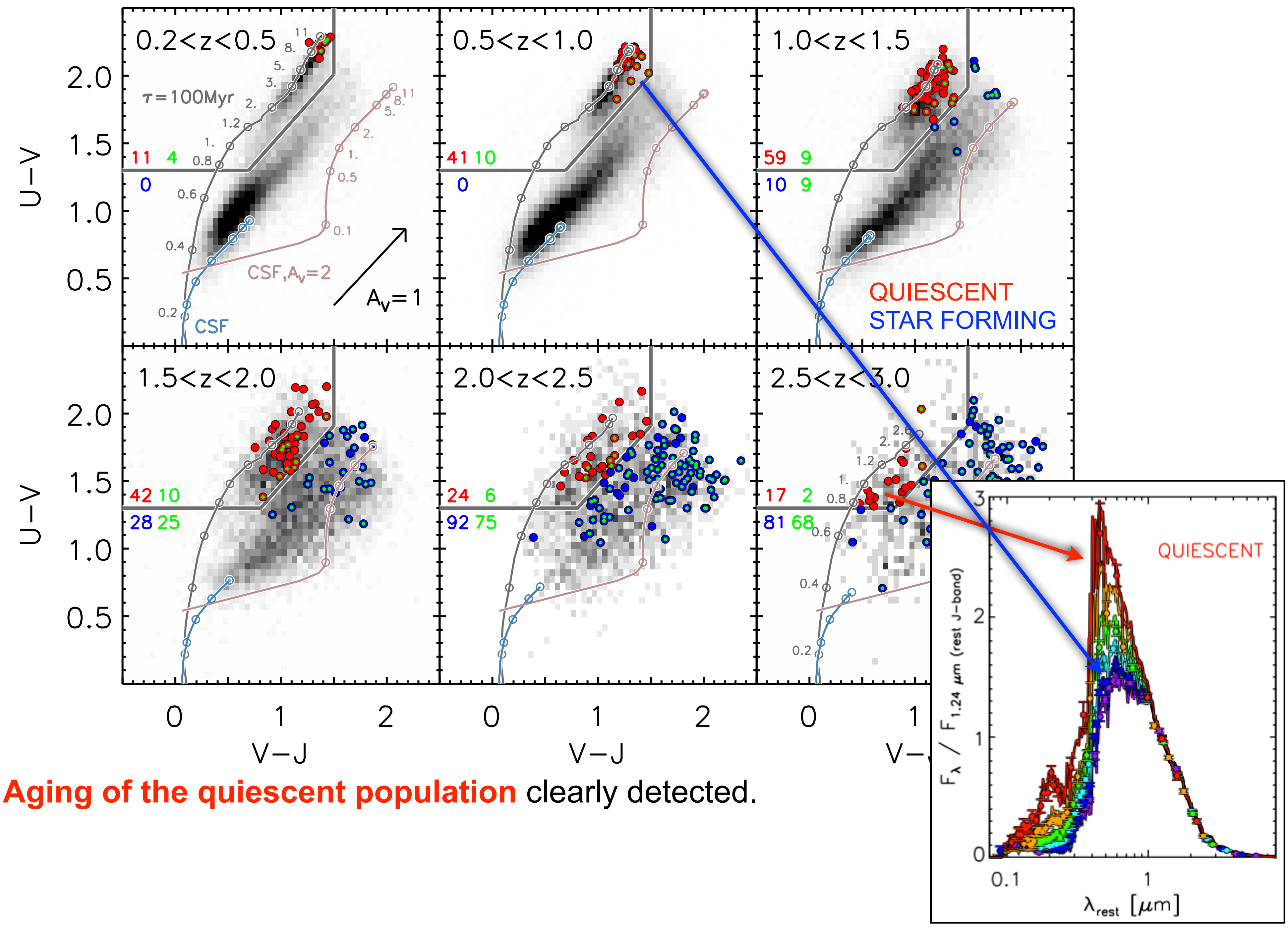


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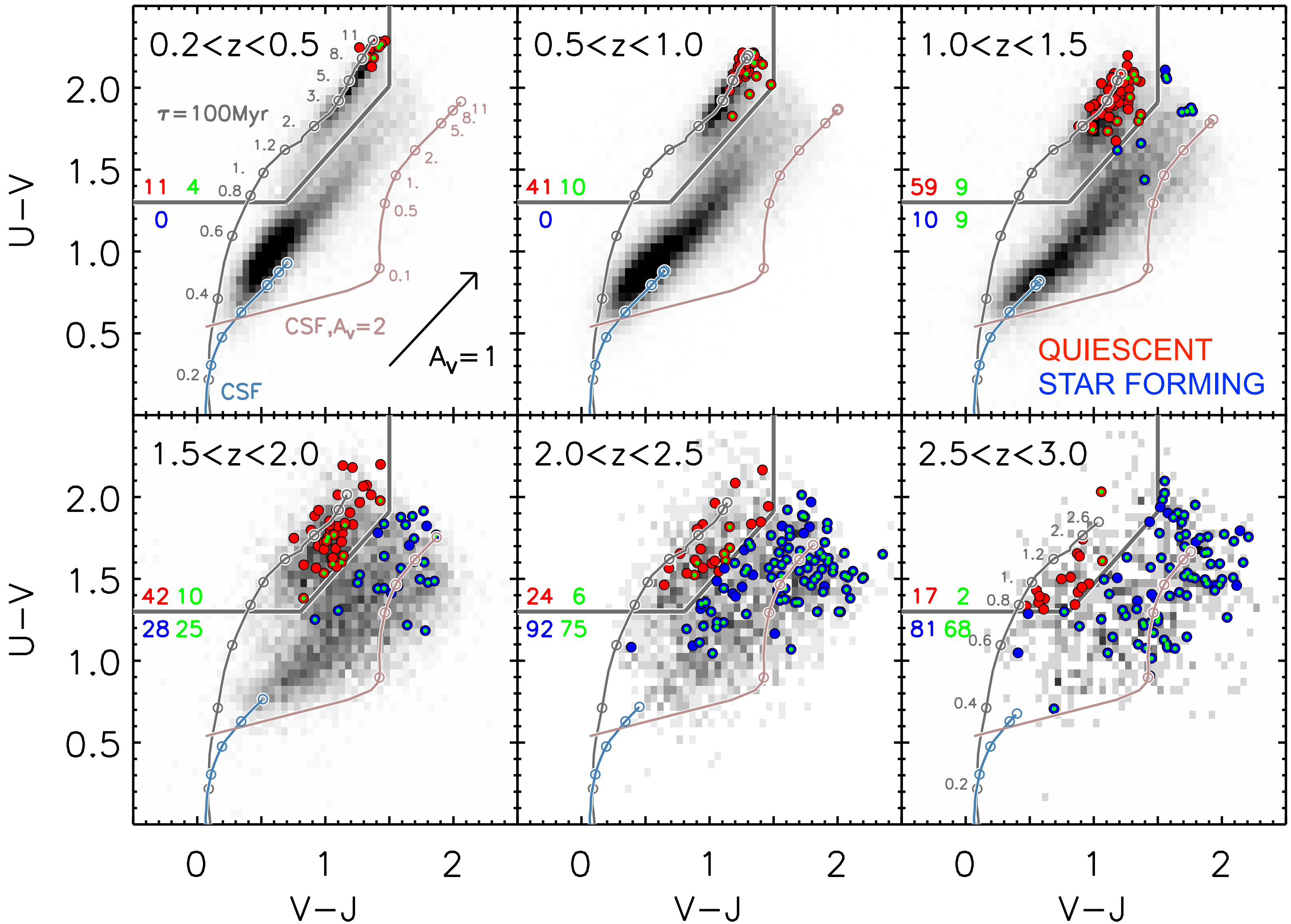


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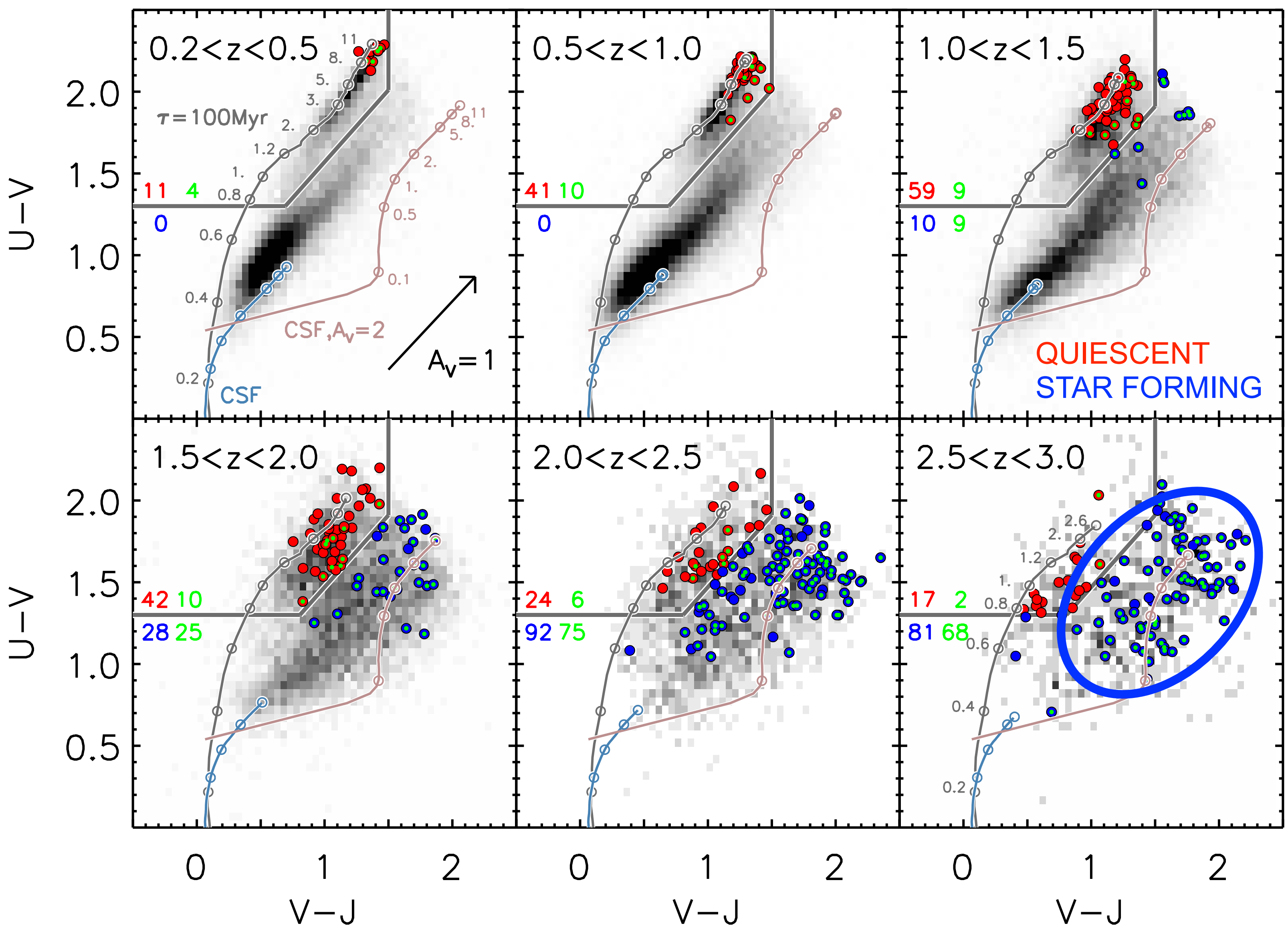


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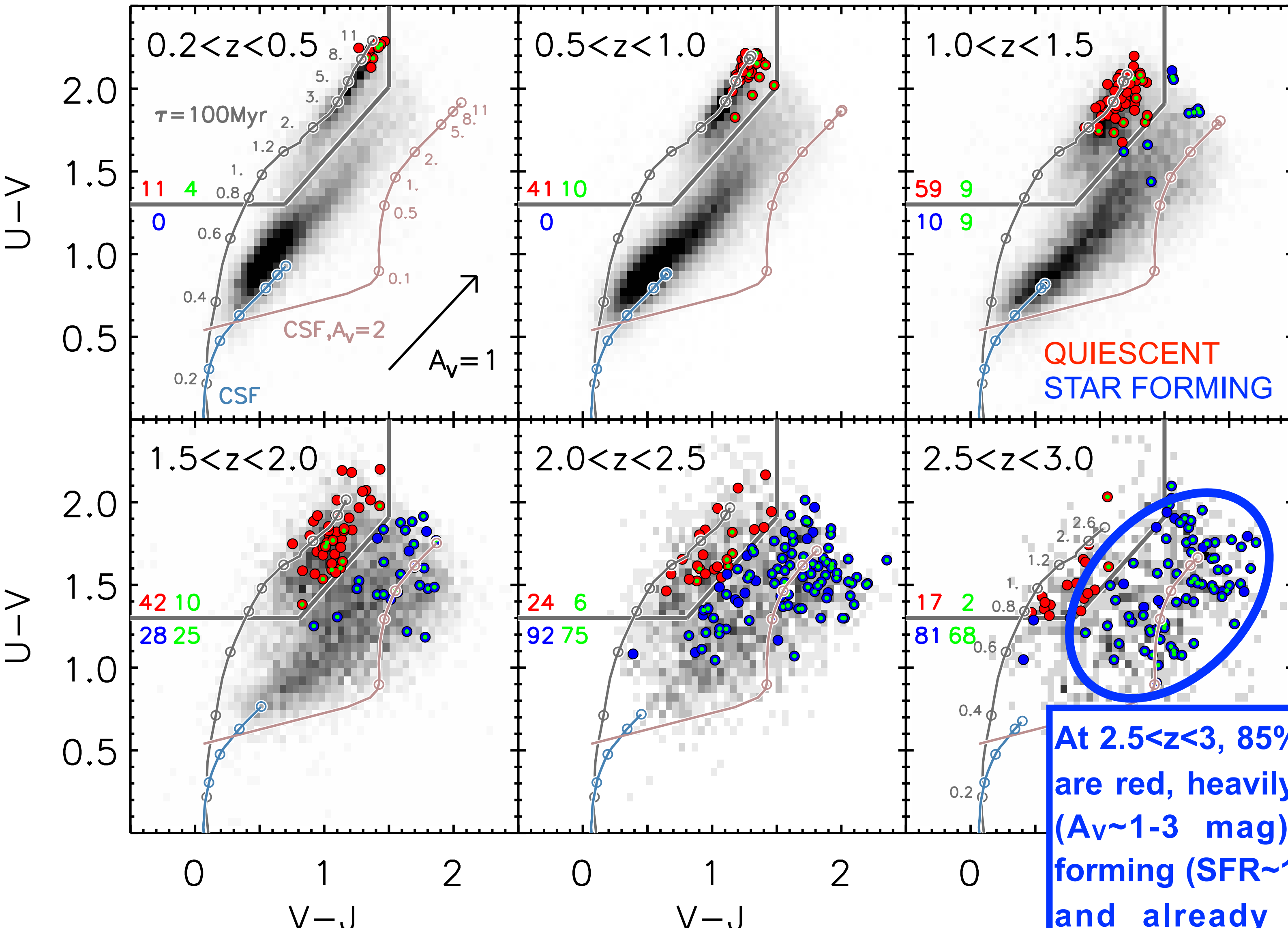


At 2.5<z<3, 85% of progenitors are red, heavily dust-obscured ($A_V$~1-3 mag), highly star-forming (SFR~100-400 $M_{sun}$/yr), and already very massive ($\lg(M_{star}/M_{sun})$~$2\times10^{11}$) galaxies.

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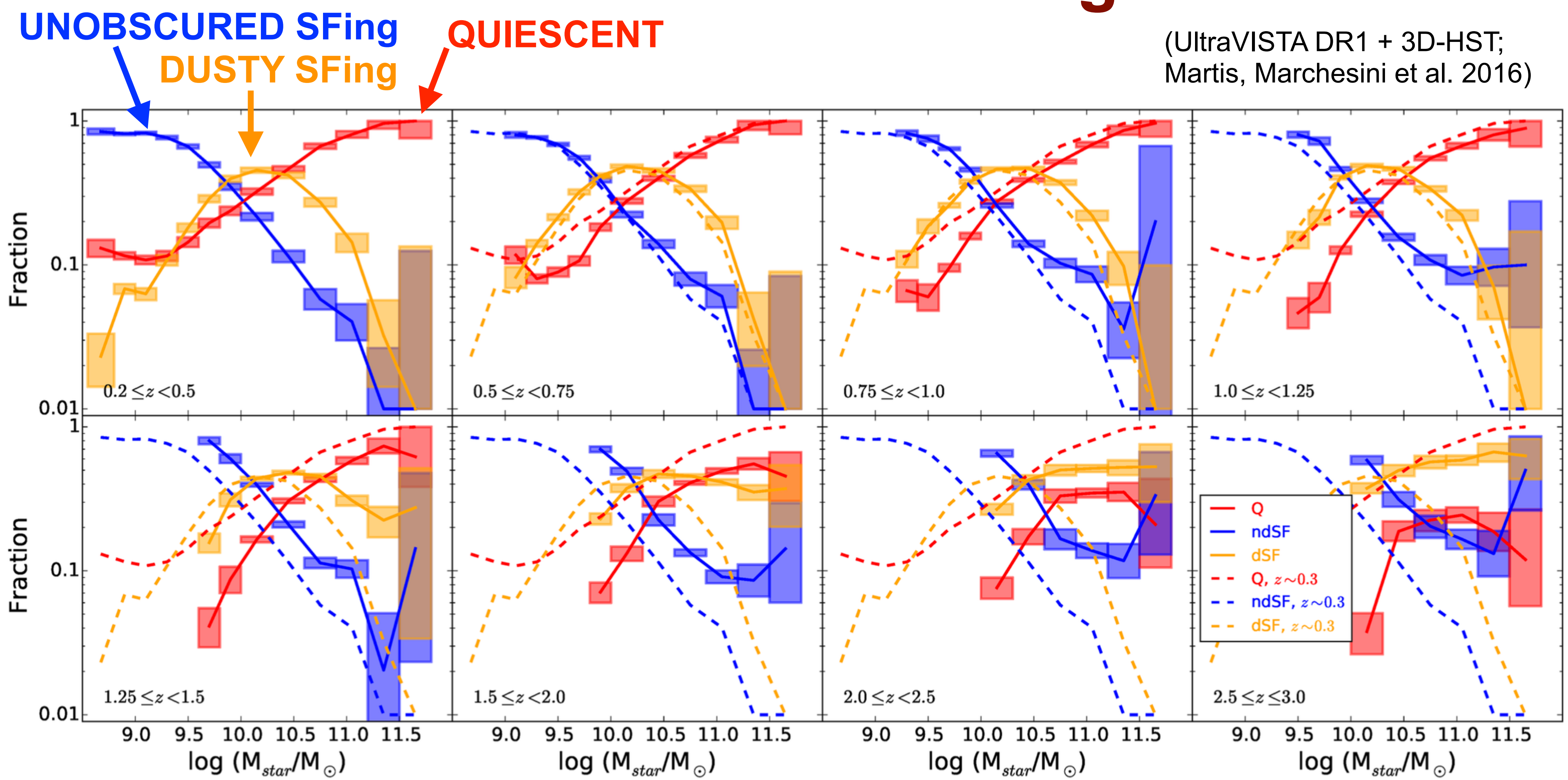
# Evolution of the Fractions of Quiescent, Dusty and Unobscured Star-forming Galaxies

(UltraVISTA DR1 + 3D-HST; Martis, Marchesini et al. 2016)



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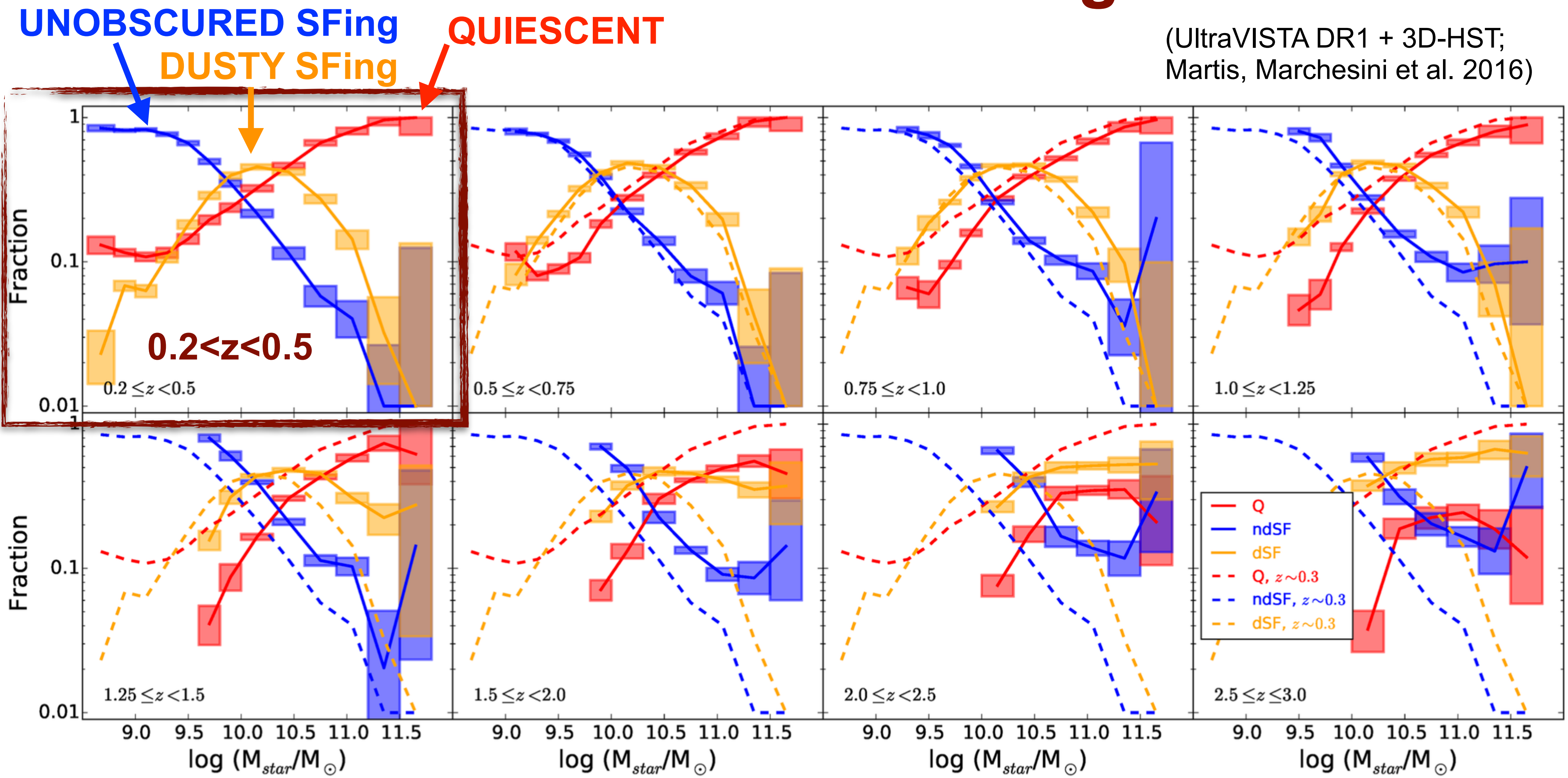

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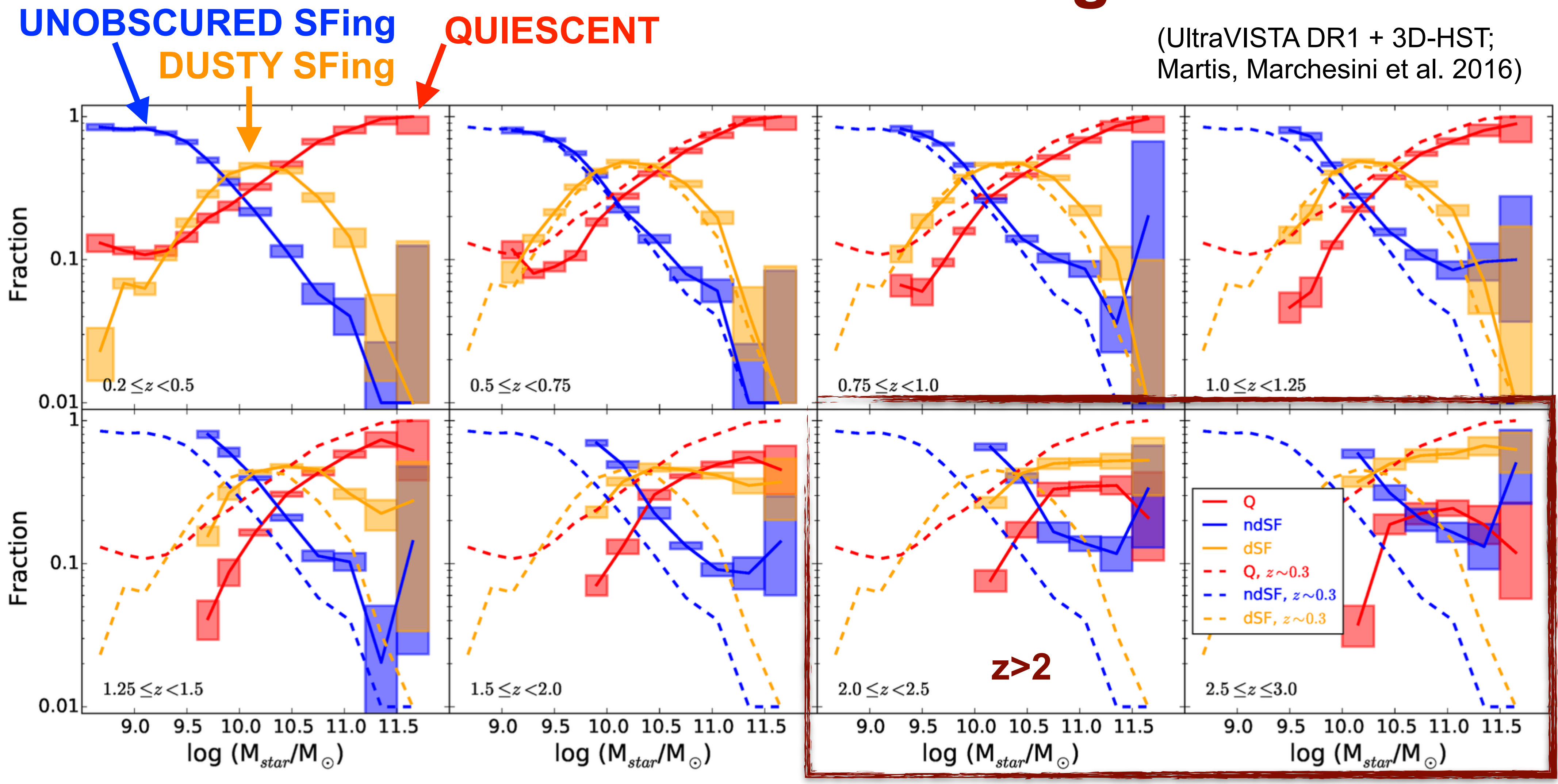


- At low z, **dSF** important only at log($M_{star}/M_{Sun}$)=10-10.5; **at z>2**, they **represent 50-60% of the massive galaxies population** (log($M_{star}/M_{Sun}$)>10.5)

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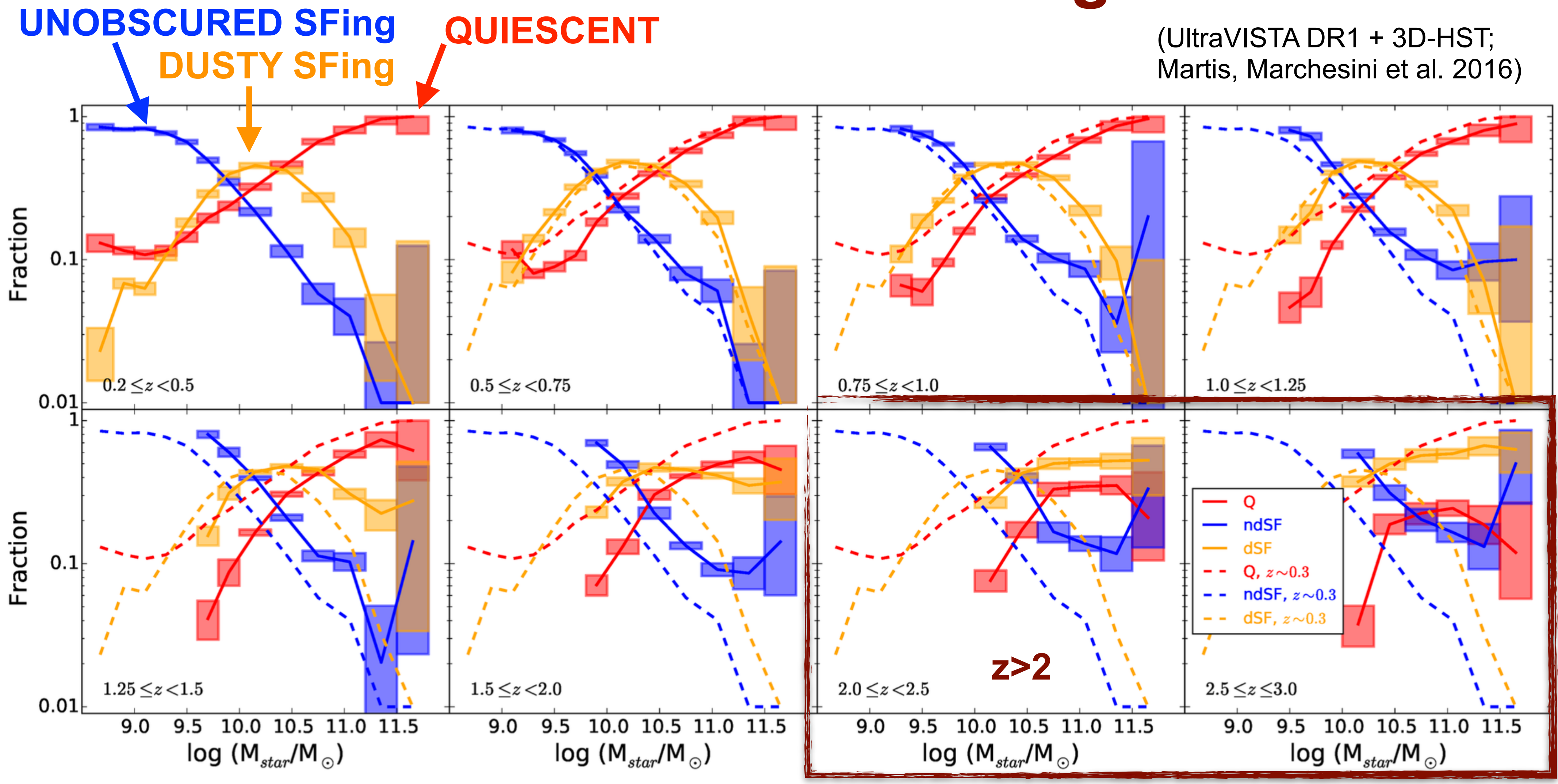


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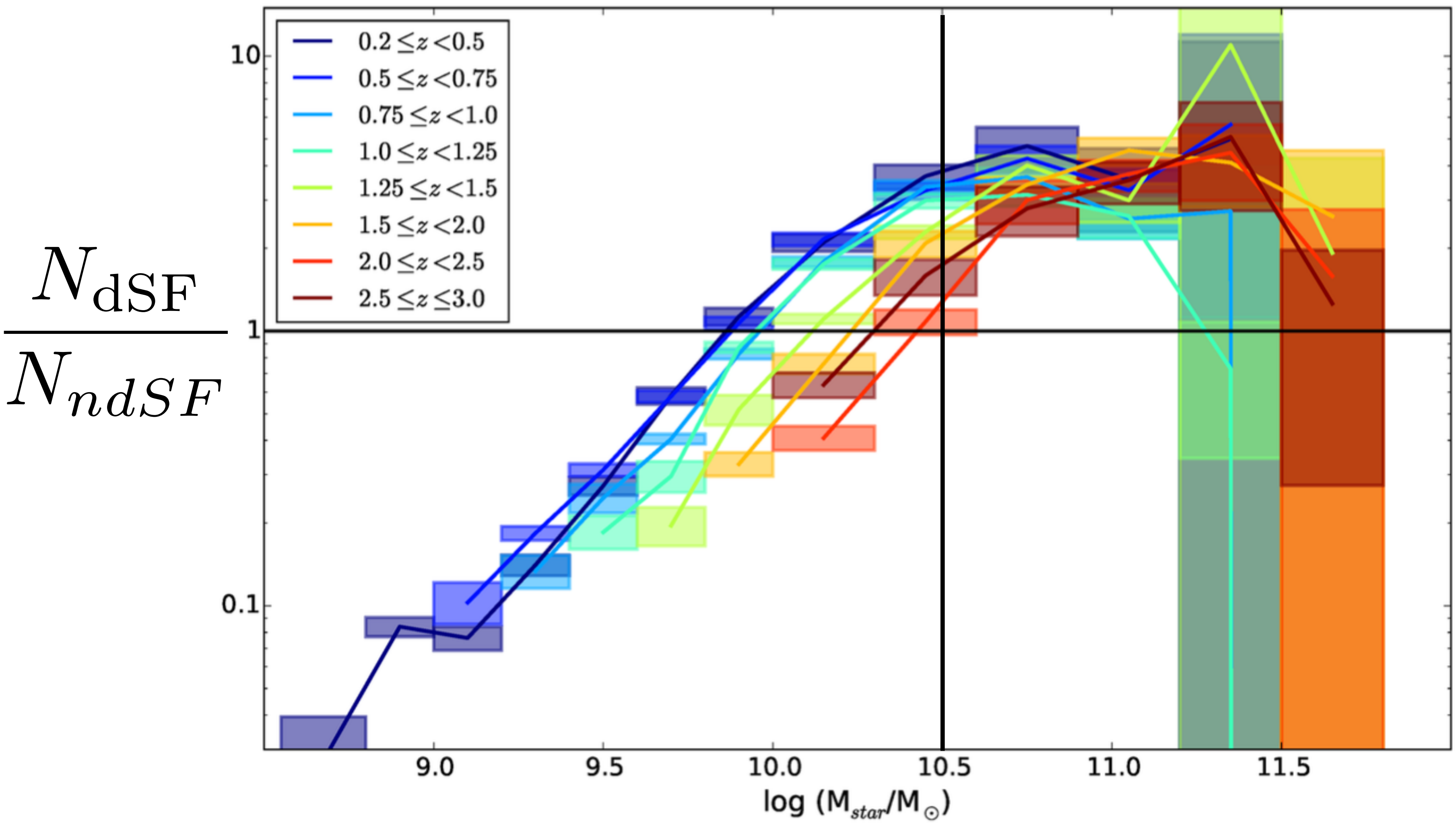
- **high-mass end always dominated by red galaxies**, either because **quiescent (at z<1.5) or dusty star-forming (in the early universe, z>1.5)**

# Relative Importance of Dusty and Unobscured SF-ing Galaxies

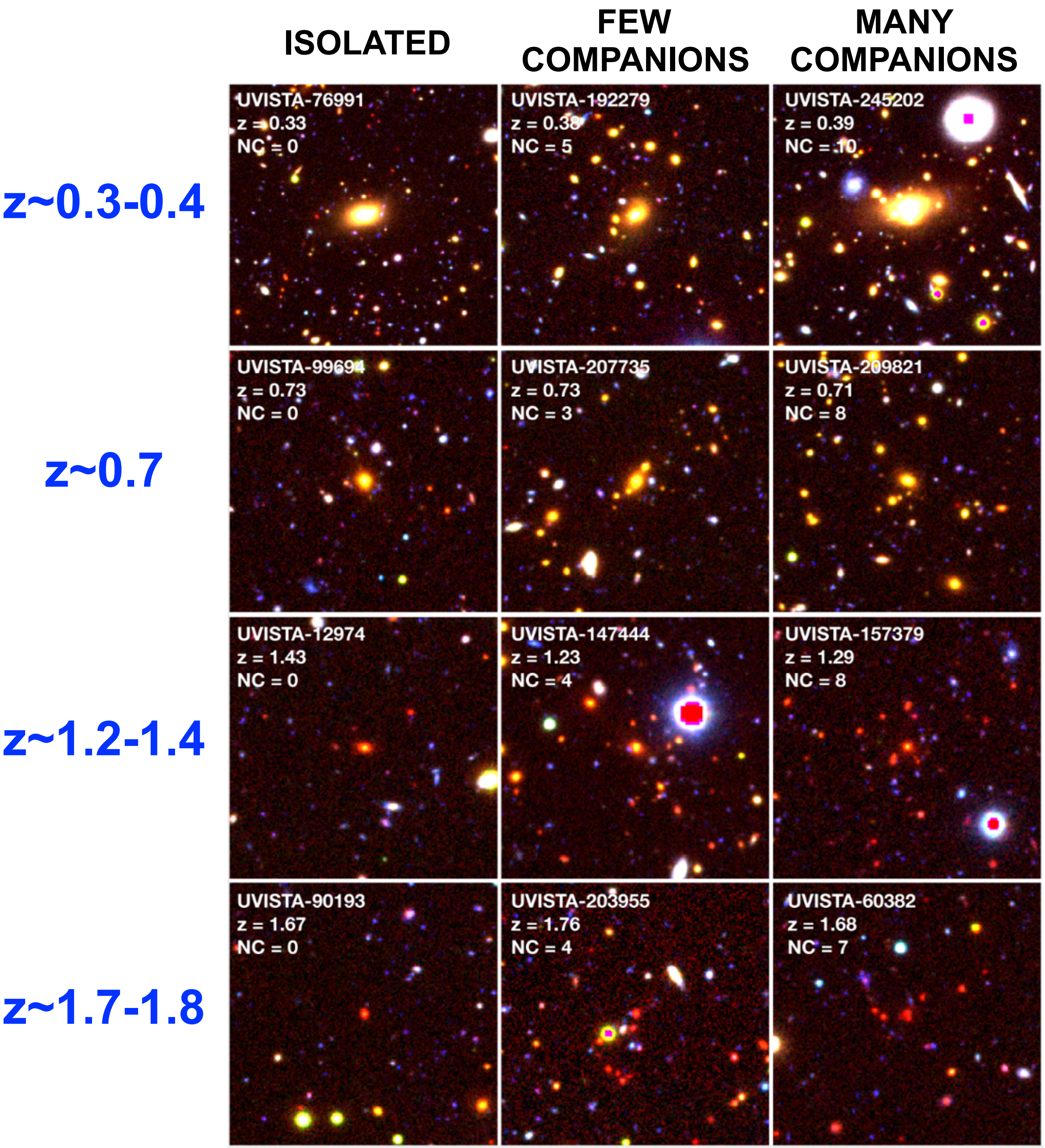
(UltraVISTA DR1 + 3D-HST; Martis, Marchesini et al. 2016)




- **At all z<3, dusty SF-ing galaxies are a factor of ~3-5x more important than unobscured SF-ing galaxies at the high-mass end (i.e., log($M_{star}/M_{Sun}$)>10.5).**

# Environment of Progenitors of Today's UMGs

(Vulcani, Marchesini, et al. 2016)




**BzK color image**
**FoV~500 kpc on a side**

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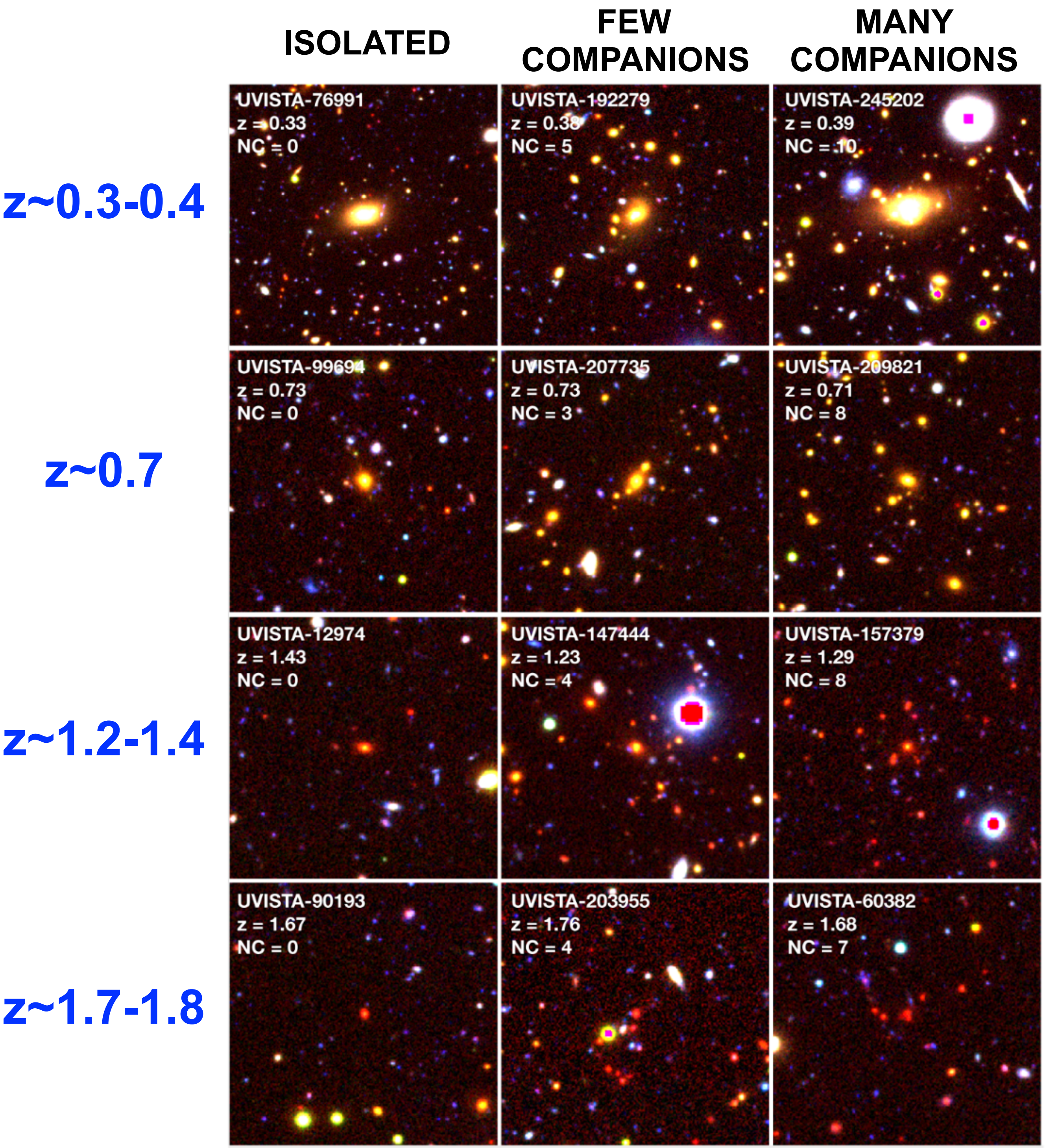



- ☑ The **progenitors** of today's UMGs **reside in a variety of environments**.

**BzK color image**
**FoV~500 kpc on a side**

# Environment of Progenitors of Today's UMGs

(Vulcani, Marchesini, et al. 2016)

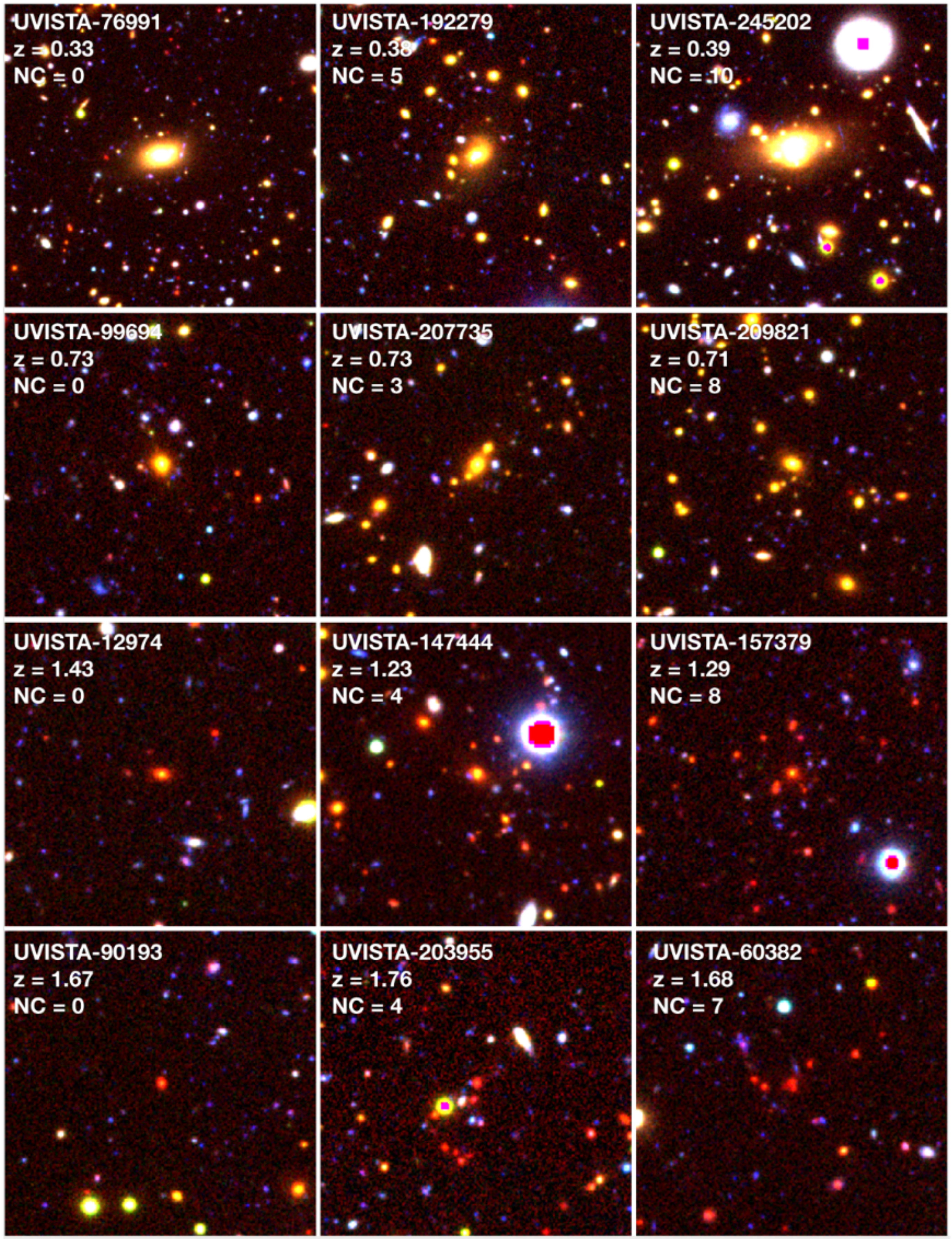
ISOLATED | FEW COMPANIONS | MANY COMPANIONS

z~0.3-0.4

z~0.7

z~1.2-1.4

z~1.7-1.8

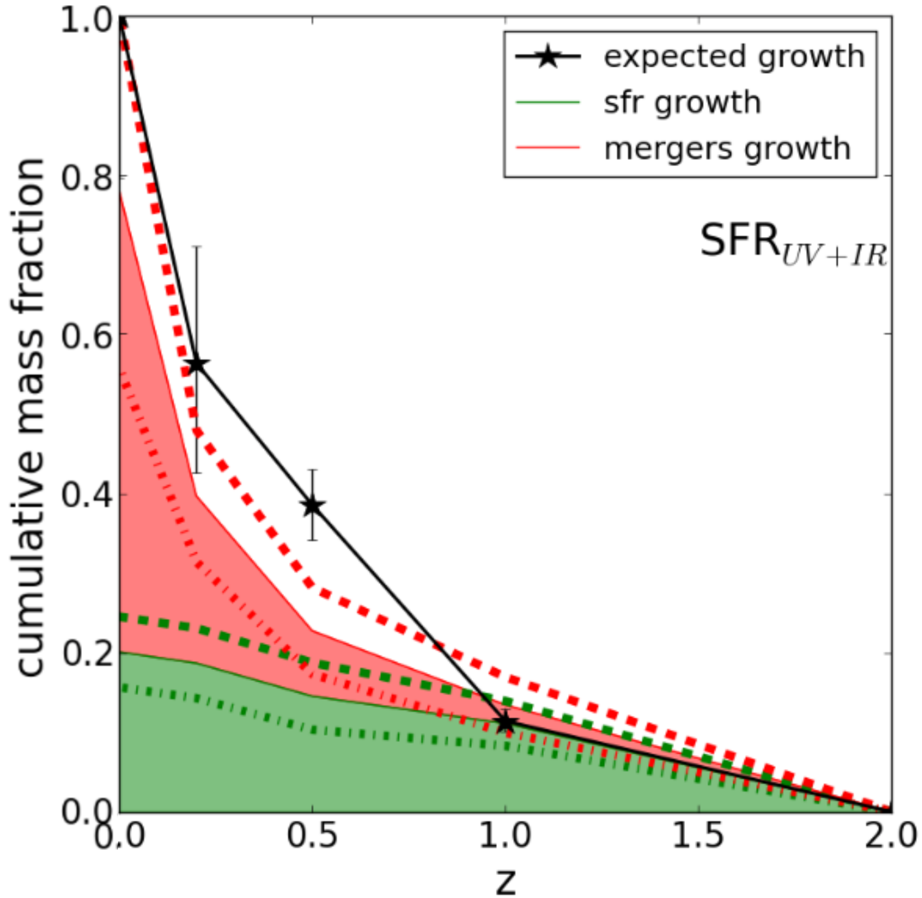



- ☑ The **progenitors** of today's UMGs **reside in a variety of environments**.
- ☑ The **environment** around progenitors **is seen to get richer with cosmic time**.
- ☑ The number of companions is seen to drop as a function of distance from the progenitor: **progenitors are centrals**

**BzK color image**
**FoV~500 kpc on a side**

# What drives the progenitors' mass growth?

(Vulcani, Marchesini, et al. 2016)



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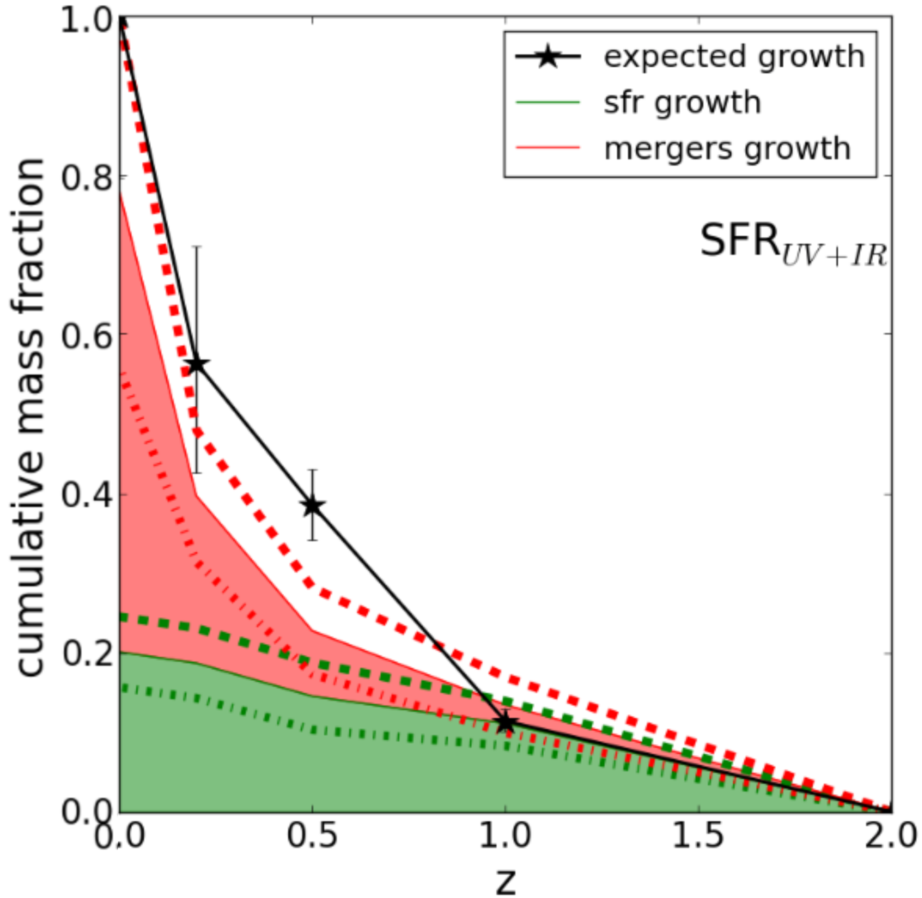


☑ Growth of **star-formation (from UV+IR) and merging can account for most of the observed growth in stellar mass of the progenitors** inferred from the abundance matching approach (only marginally consistent if SFRs derived from SED modeling).

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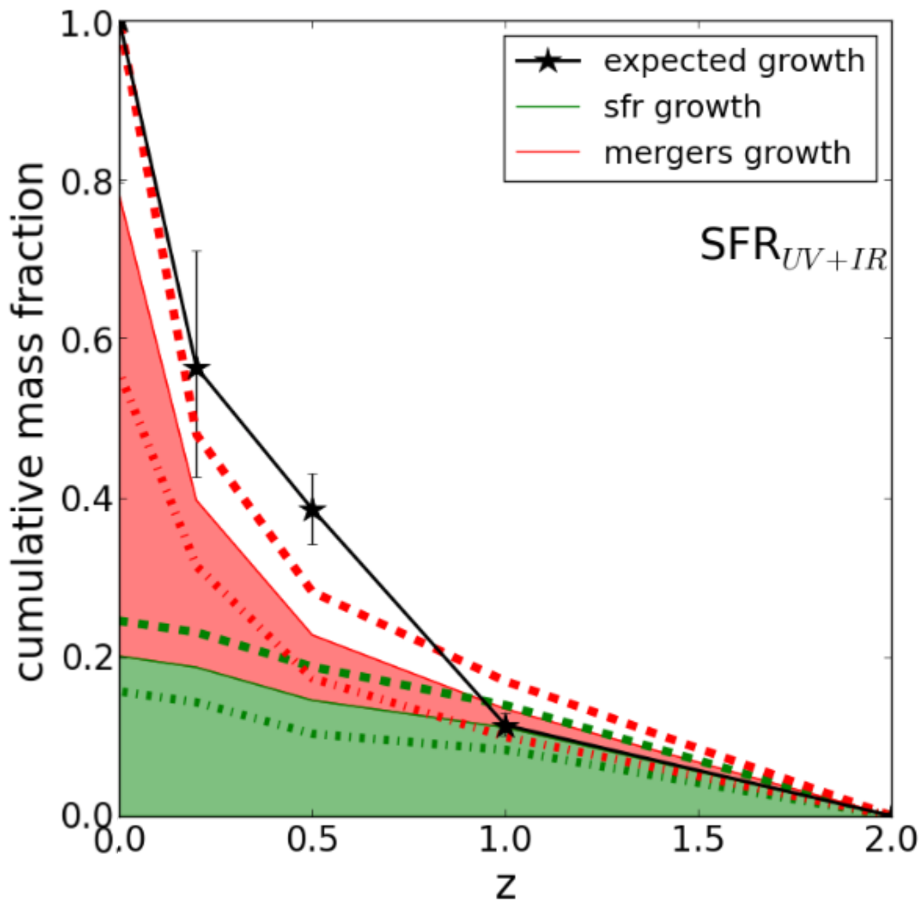
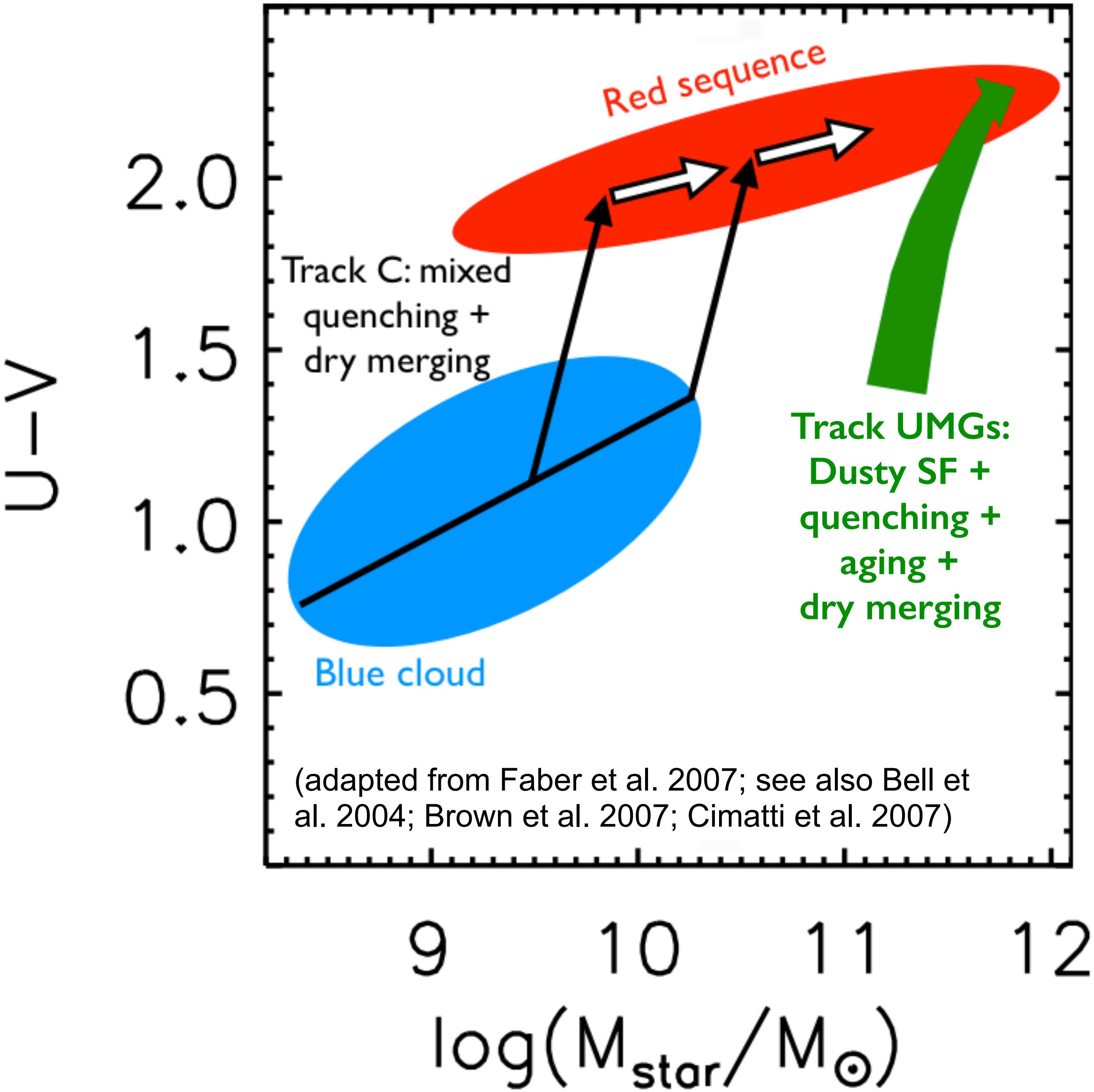



- Growth of **star-formation (from UV+IR) and merging can account for most of the observed growth in stellar mass of the progenitors** inferred from the abundance matching approach (only marginally consistent if SFRs derived from SED modeling).

- 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>1.5**.

# Refined evolutionary path for the evolution of today's UMGs since z=3



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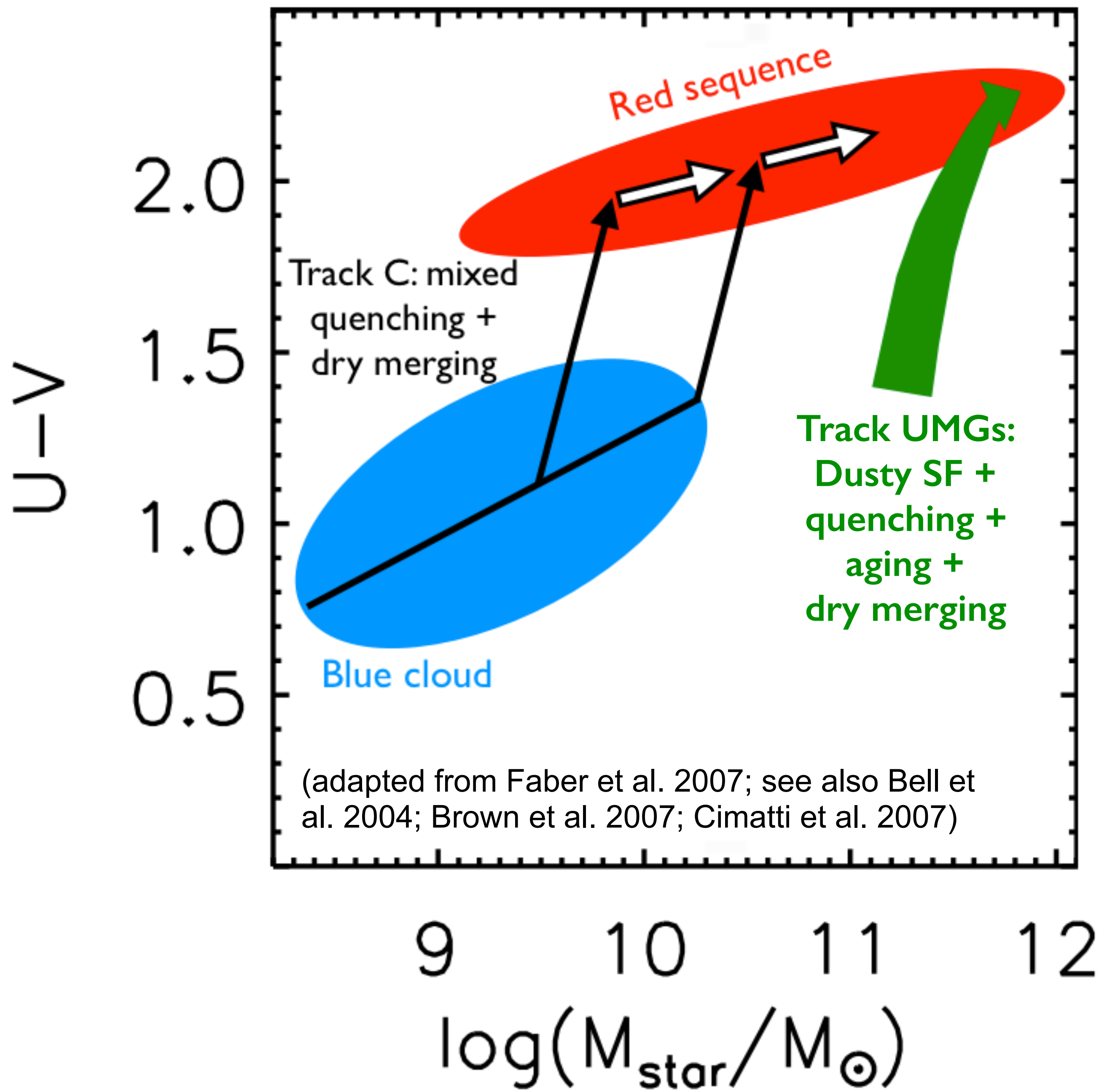


- ☑ **Early mass assembly** and stellar growth in an intense dusty burst of star formation - **progenitors as red, heavily dust-obscured, star-forming galaxies**.
- ☑ After quenching, **progenitors redden due to aging**.
- ☑ **At $z<1$,** the **growth in stellar mass** is **dominated by merging**, while **at $z>1$** the relative **contribution from star-formation increases with redshift** and **dominates at $z>1.5$**.

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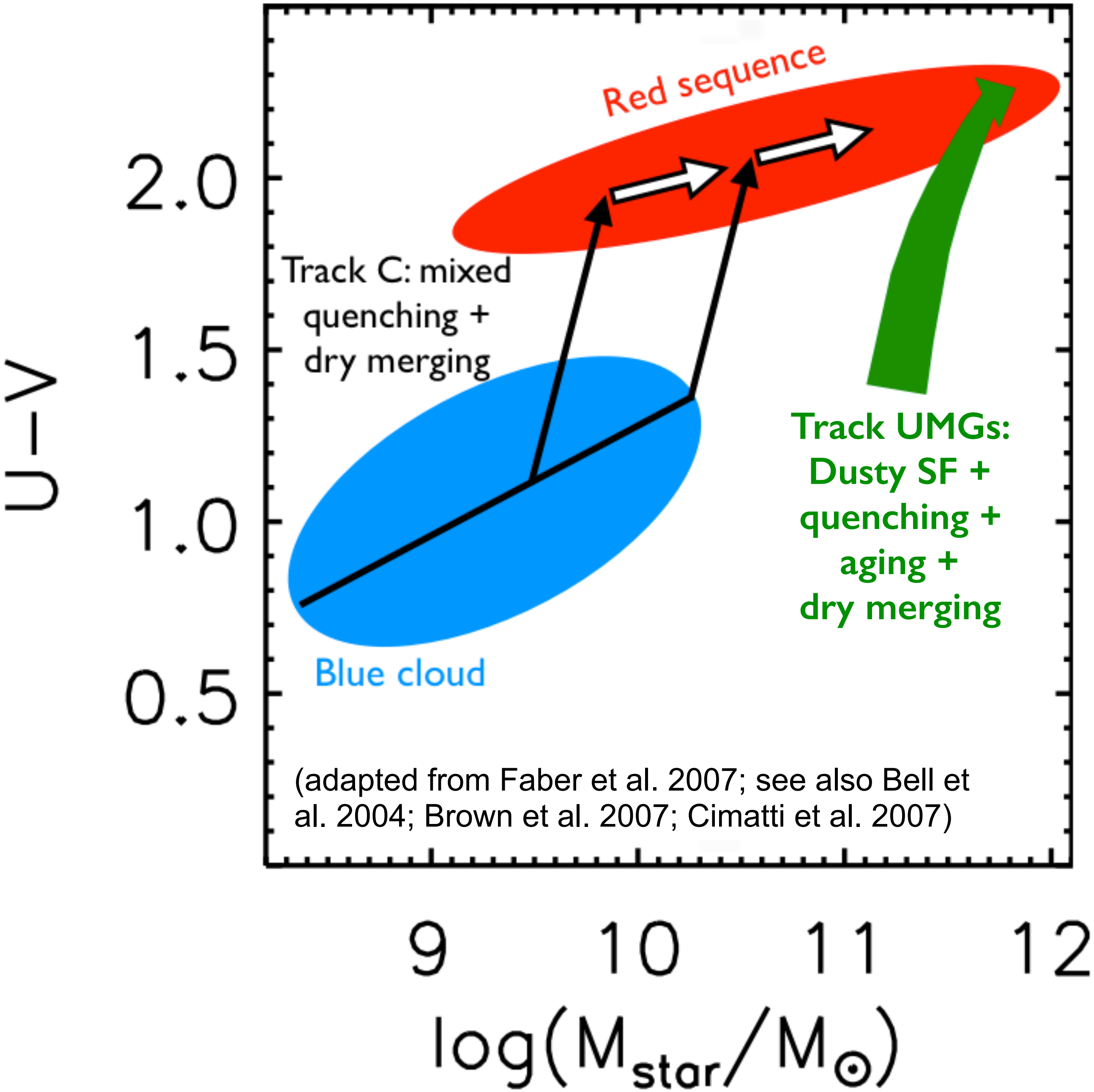


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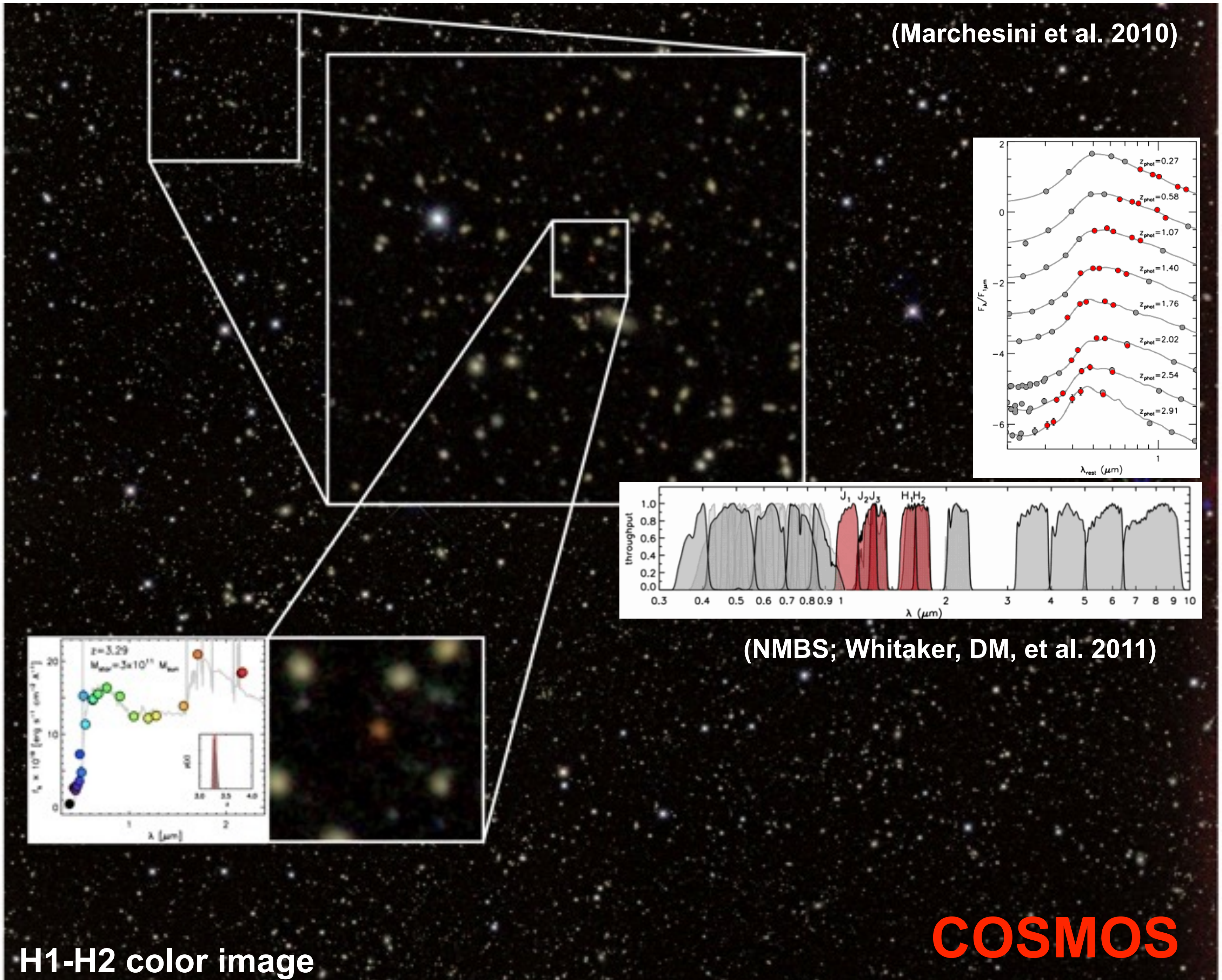
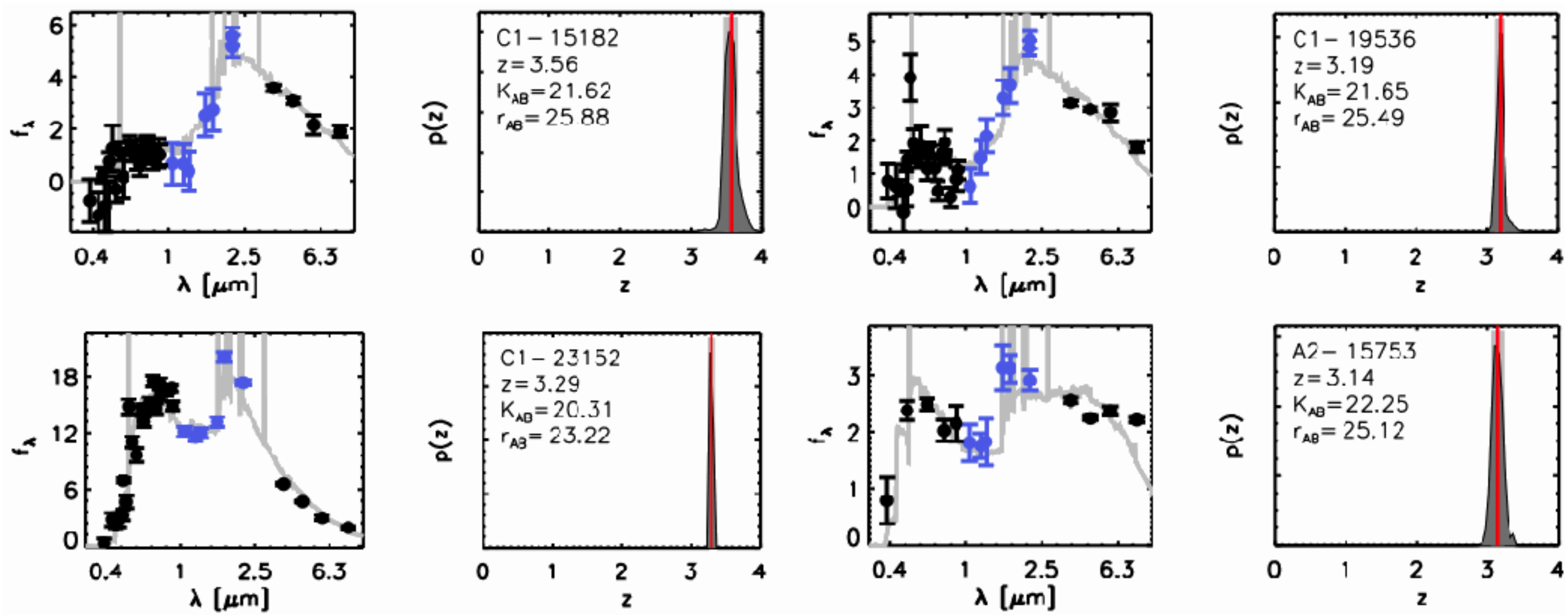
**What about the progenitors at z>3?**

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



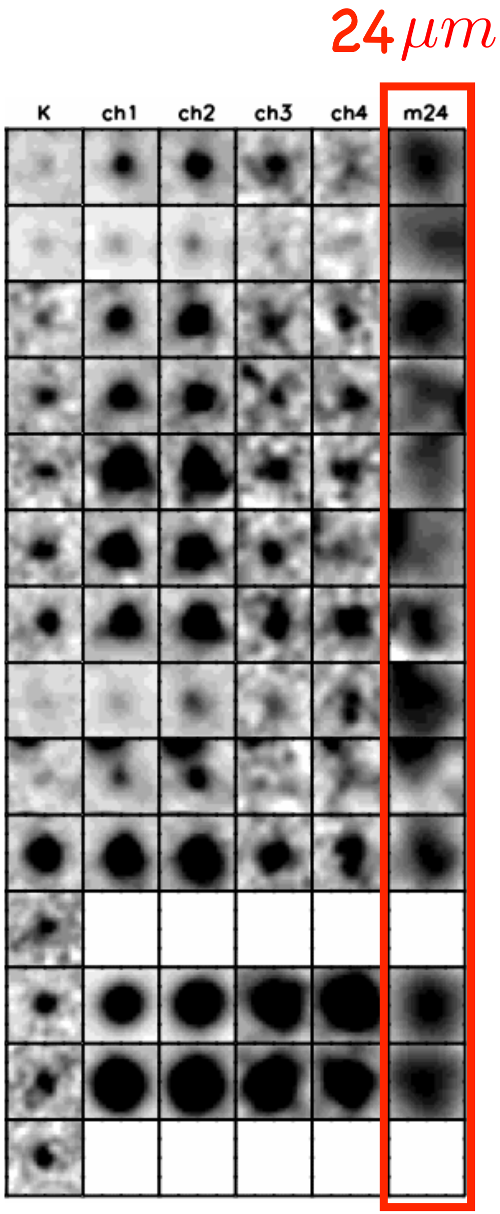
# Stellar Mass-complete Sample of Galaxies at 3<z<4 from the NMBS

(Marchesini et al. 2010)




- **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
- **Robust evidence** of **existence of very massive galaxies at z>3** and of **large diversity in properties within this population**.

# Massive galaxies at z>3 are very luminous IR sources



(Marchesini et al. 2010)

- ☐ 80% have MIPS 24 $\mu m$ fluxes significant at >3 sigma.
- ☐ $L_{IR}$=0.5-4x$10^{13}$ $L_{Sun}$, 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

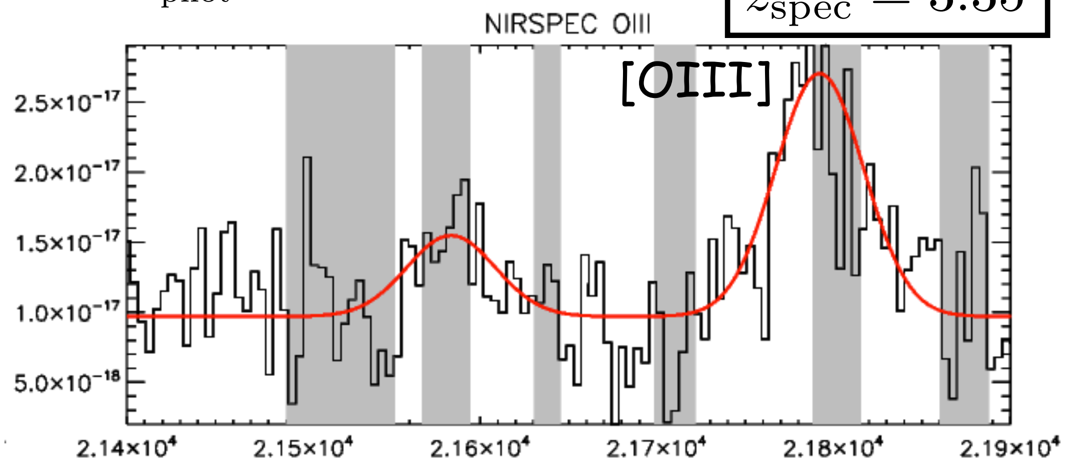
  **Duty cycle of duration of intense dusty star-bursting phase ~$60^{+140}_{-50}$ Myr**

- ☑ $SFR_{24}$=600-4300 $M_{Sun}$/yr (a few 100x$SFR_{SED}$), implying mass-doubling times ~ 0.5-7x$10^8$ 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 $\mu m$ corresponds to ~5.5 $\mu m$ rest-frame, where hot dust dominates the MIR emission

# Spectroscopy of 3<z<4 Massive Galaxies

$z_{\rm phot} = 3.29 \pm 0.06$

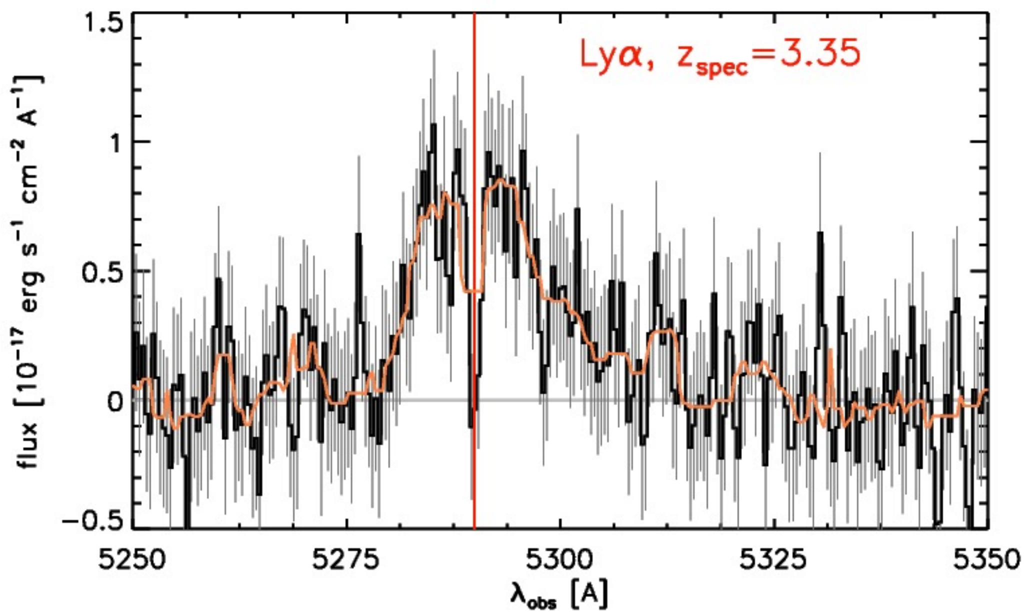
$z_{\rm spec} = 3.35$




(Marsan, Marchesini, et al., 2015,2016)

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

(tentative CIV in emission also detected)



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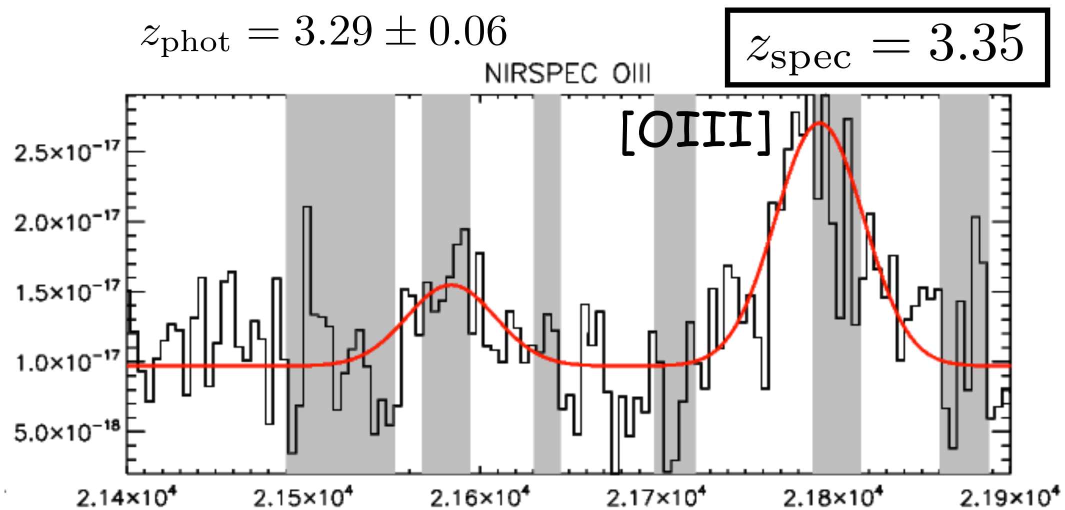


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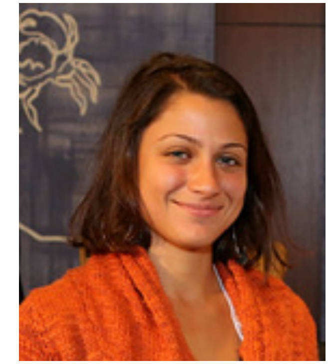

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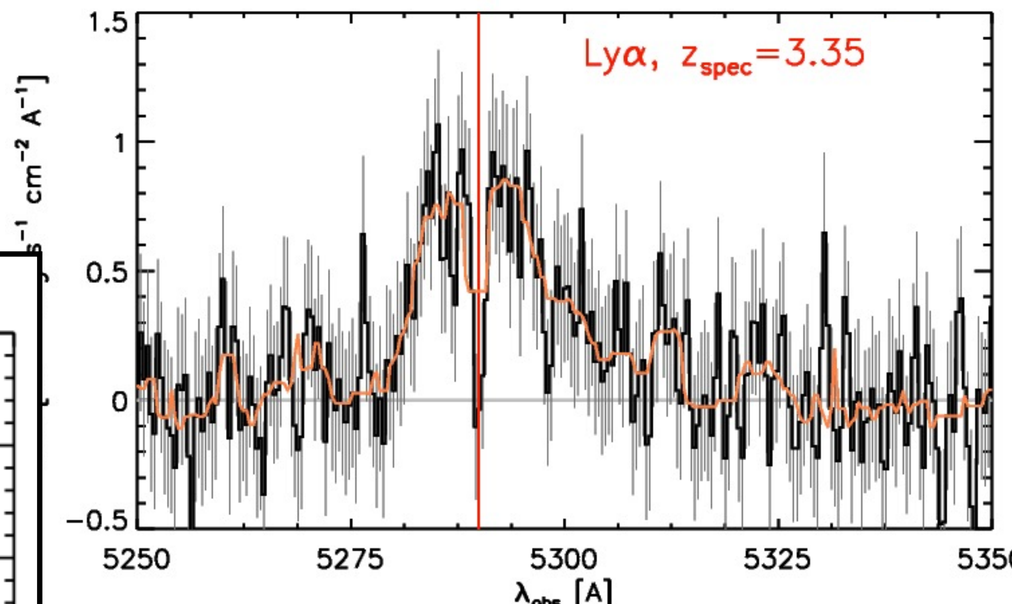
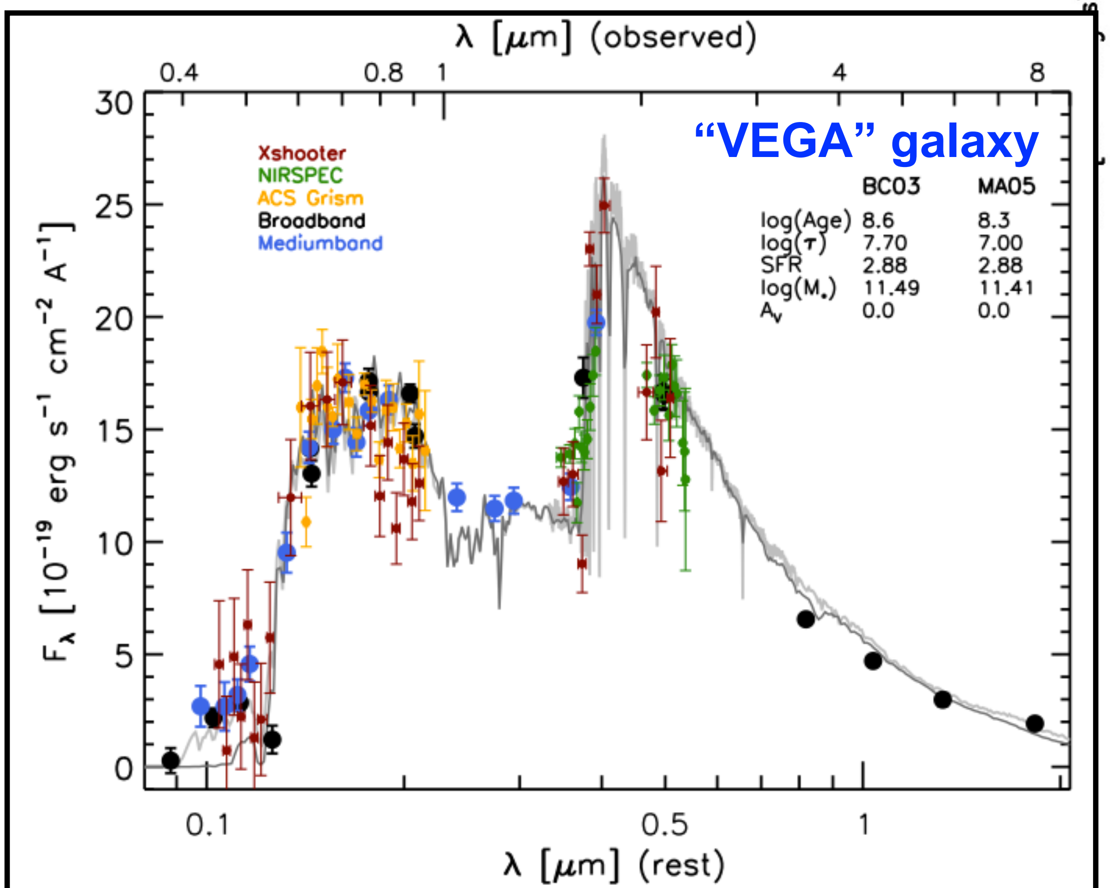



**$M_{star} = 3x10^{11}$ $M_{sun}$** (Kroupa IMF)

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

**$A_V$=0**

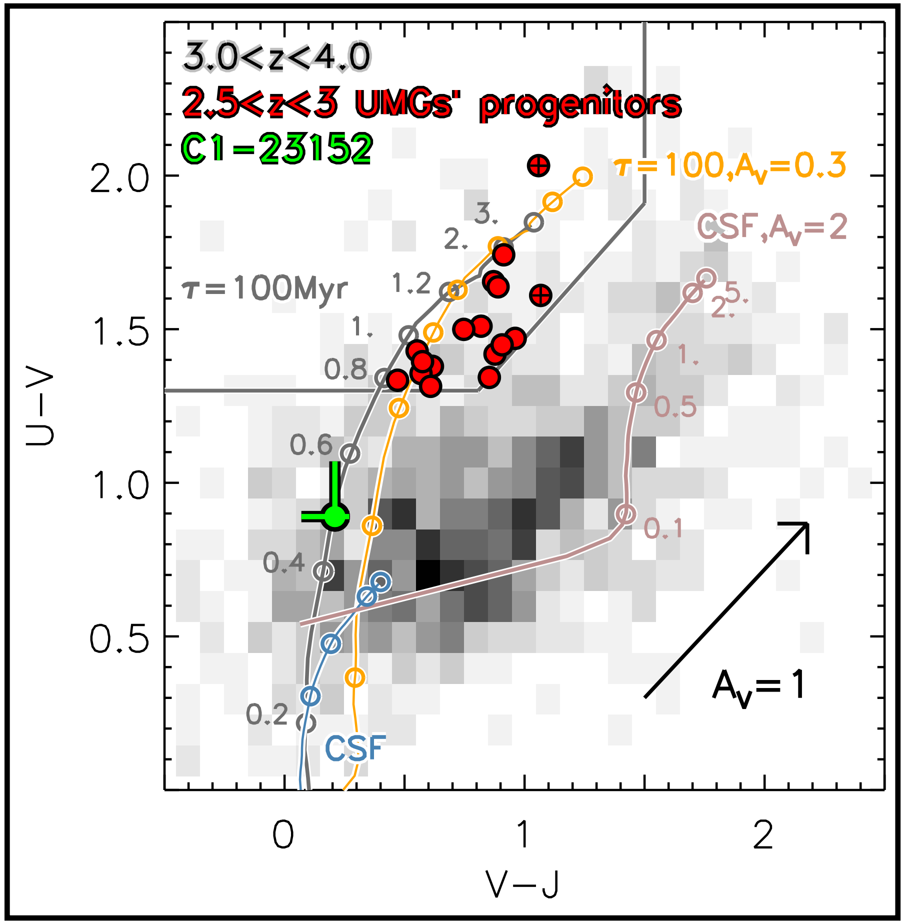
**log(sSFR $yr^{-1}$) ~ -11**

**age~400 Myr**

**tau ~ 50 Myr**

# Spectroscopy of 3<z<4 Massive Galaxies

(Marsan, Marchesini, et al., 2015,2016)



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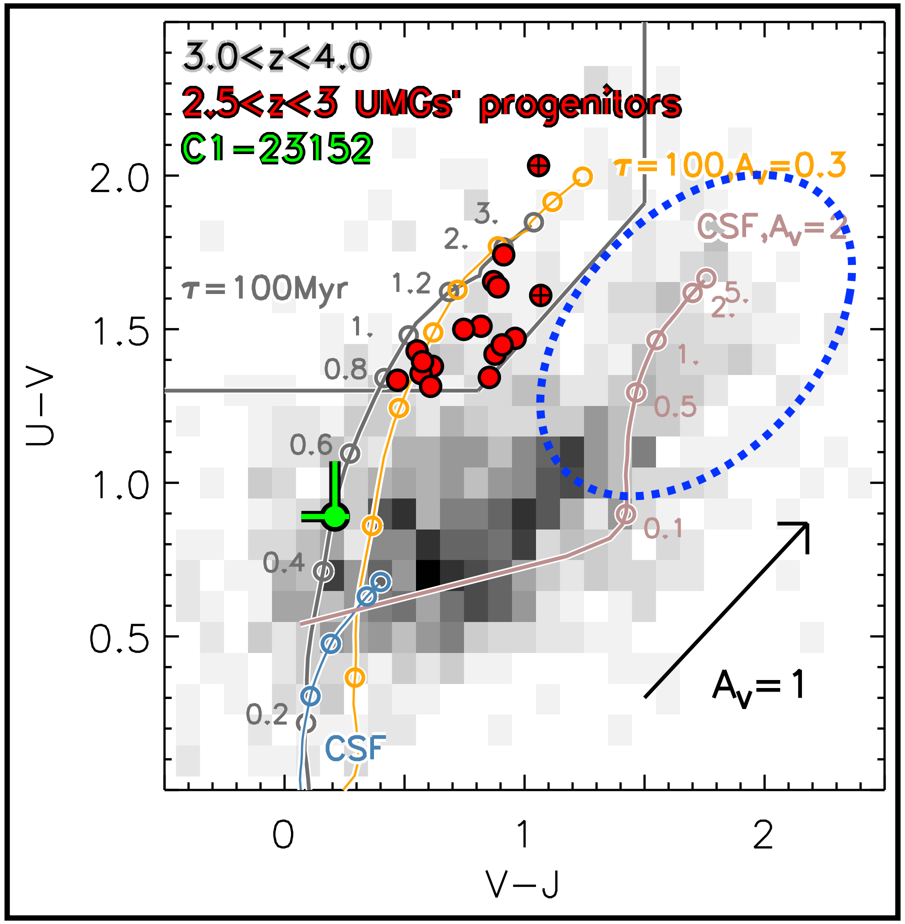


2.5<z<3 dusty SF progenitors

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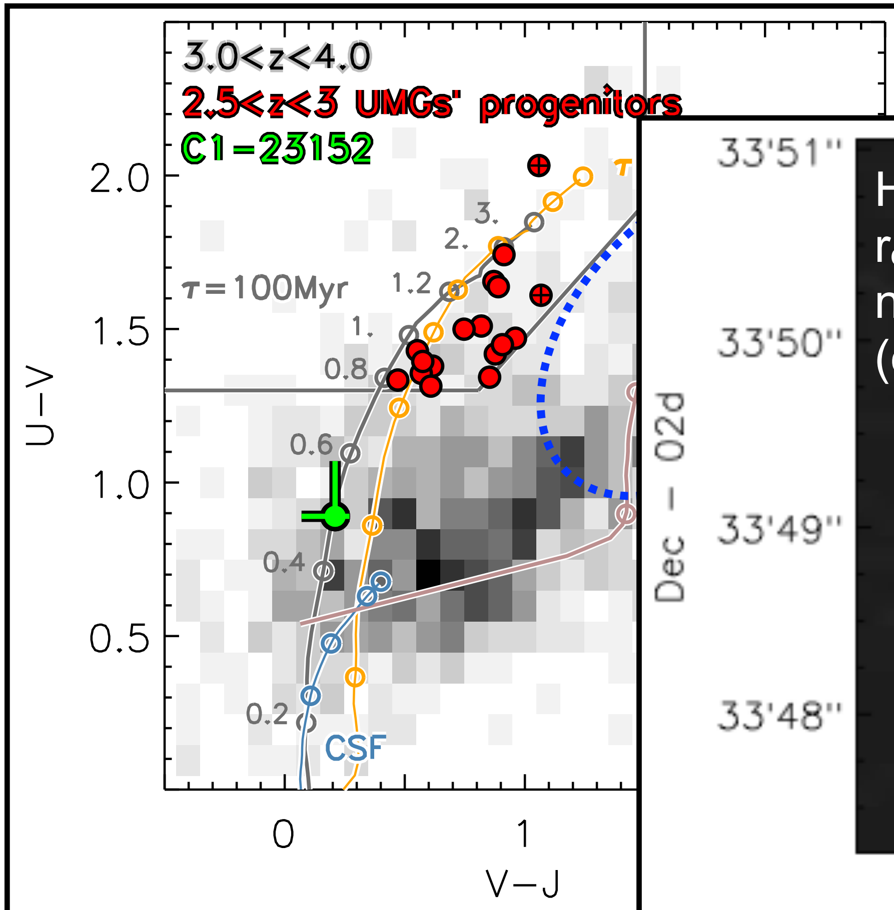


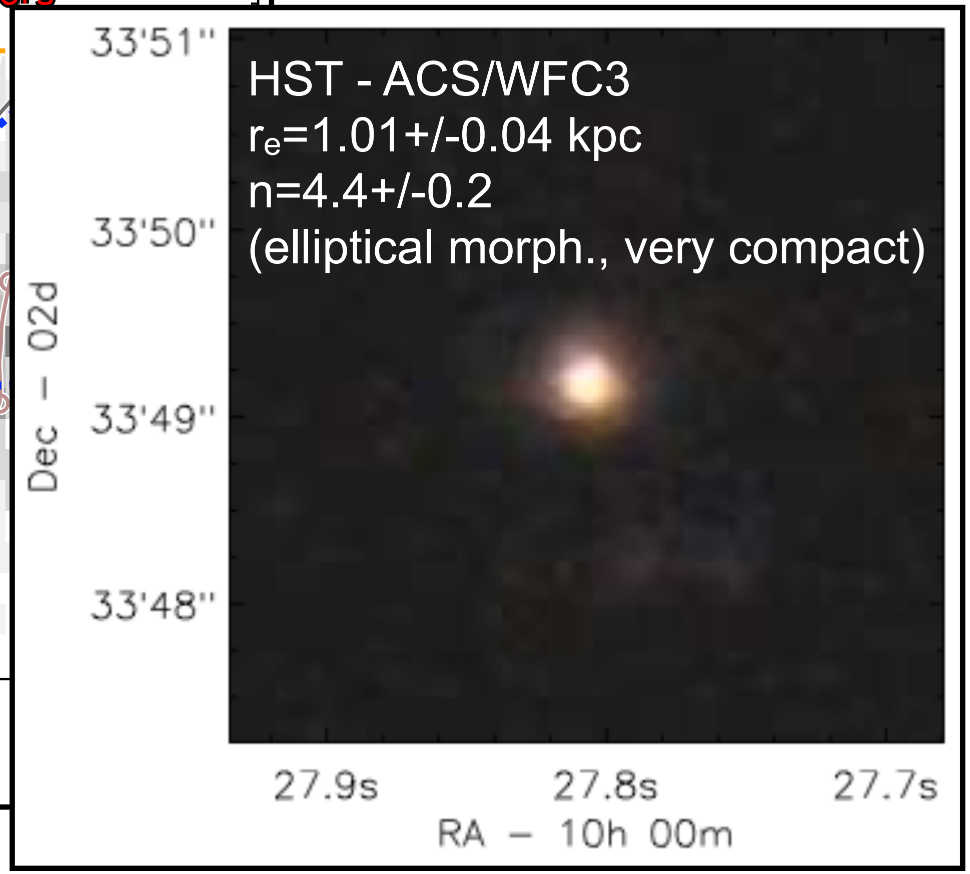

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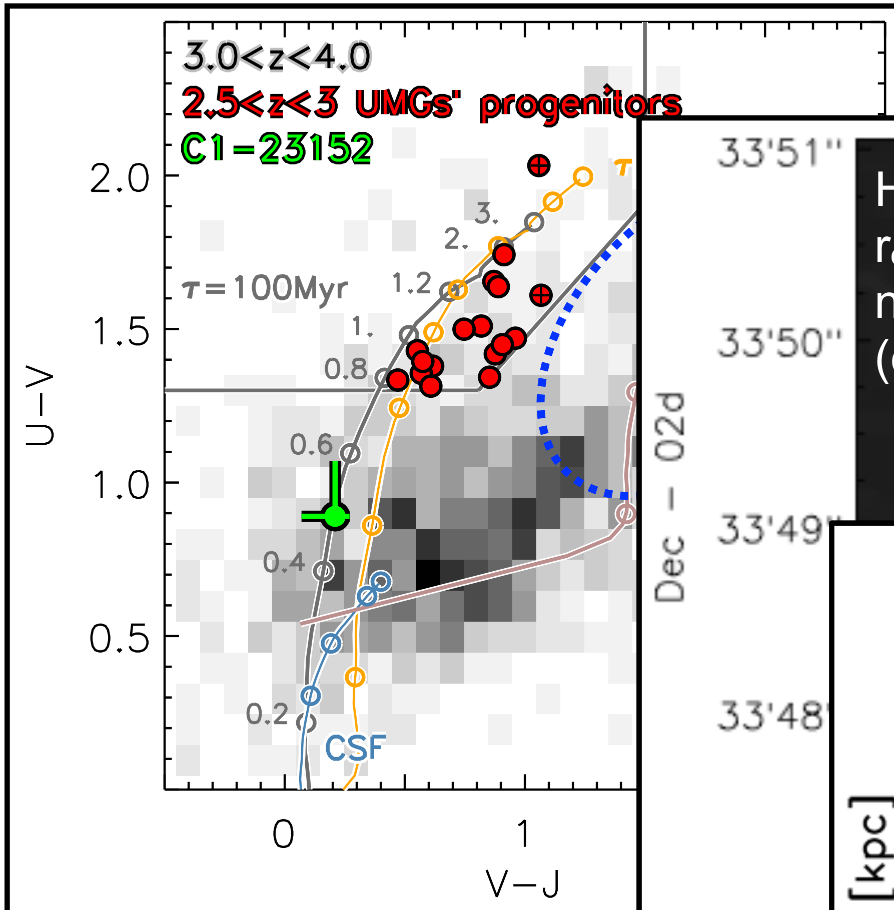


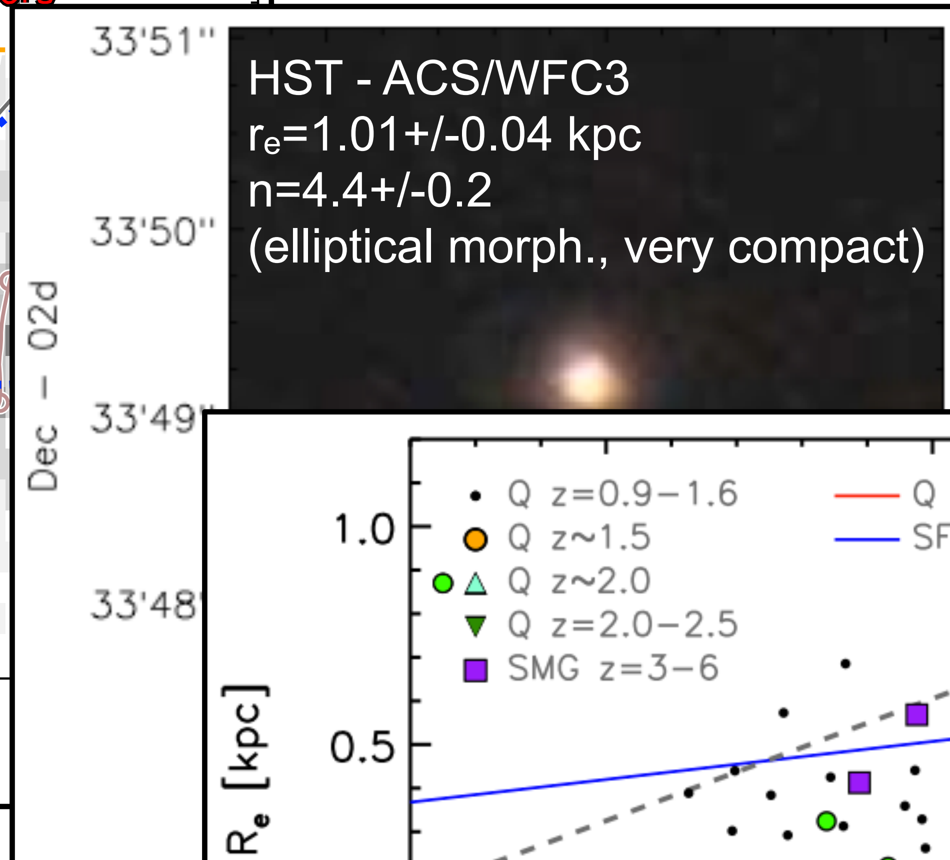


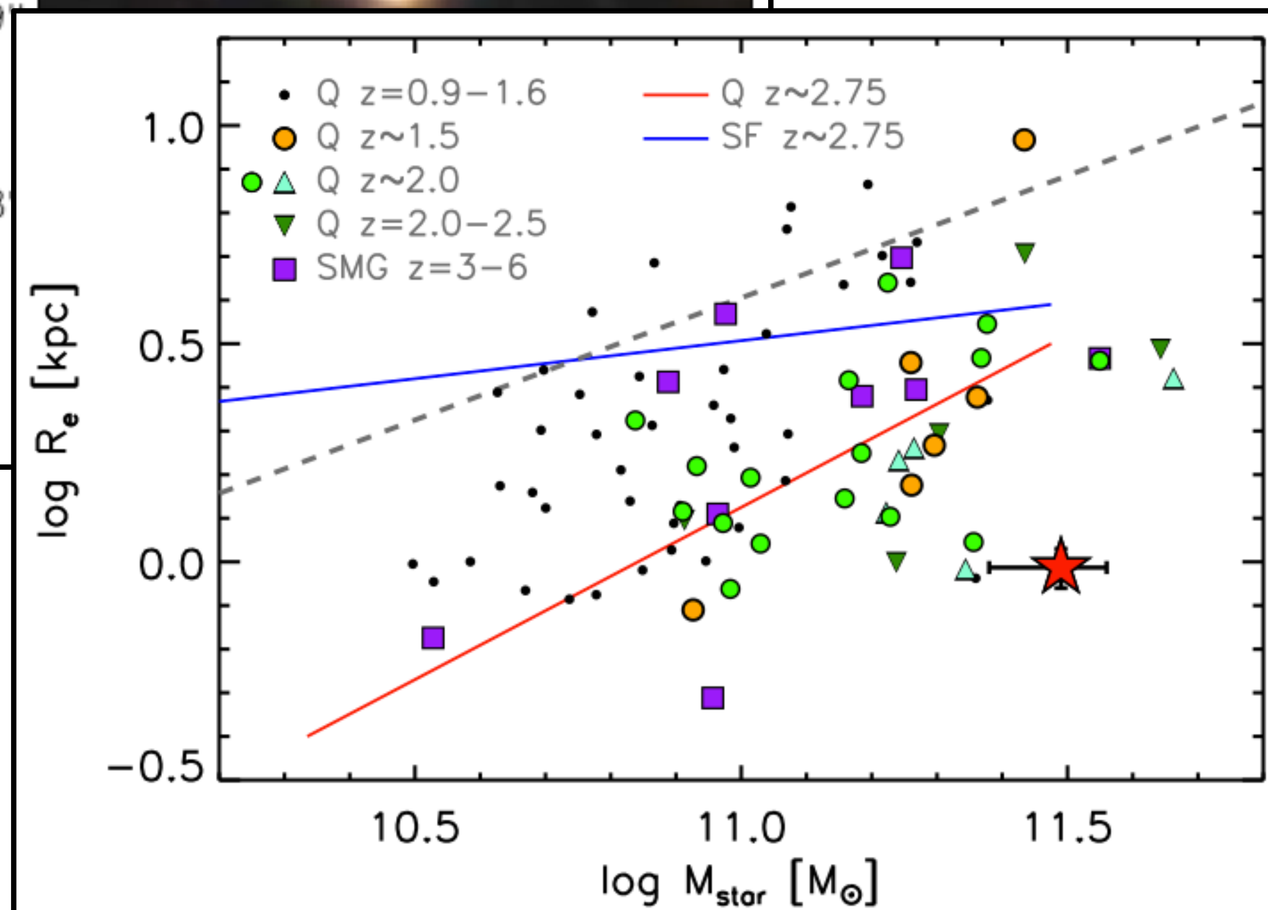

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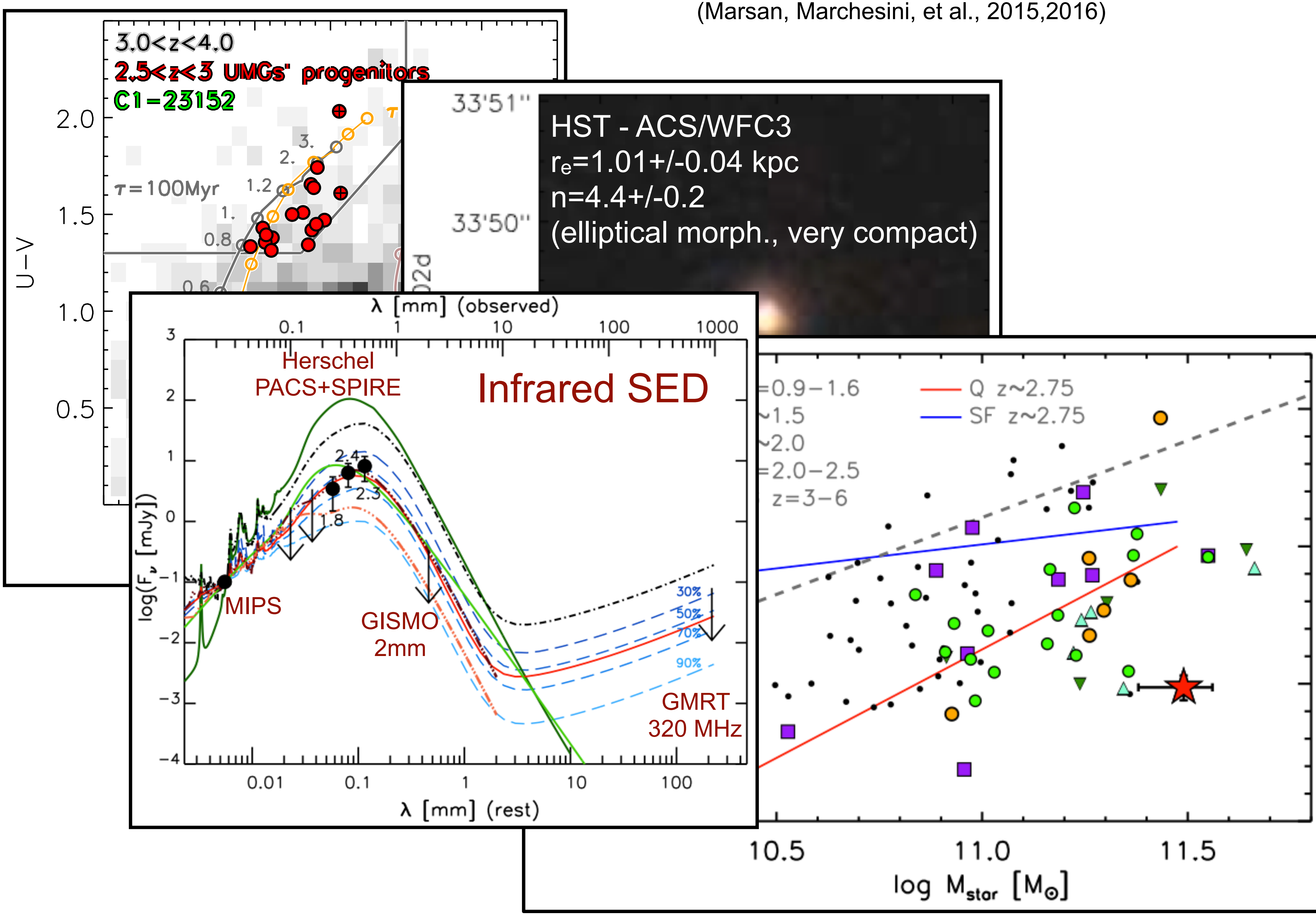

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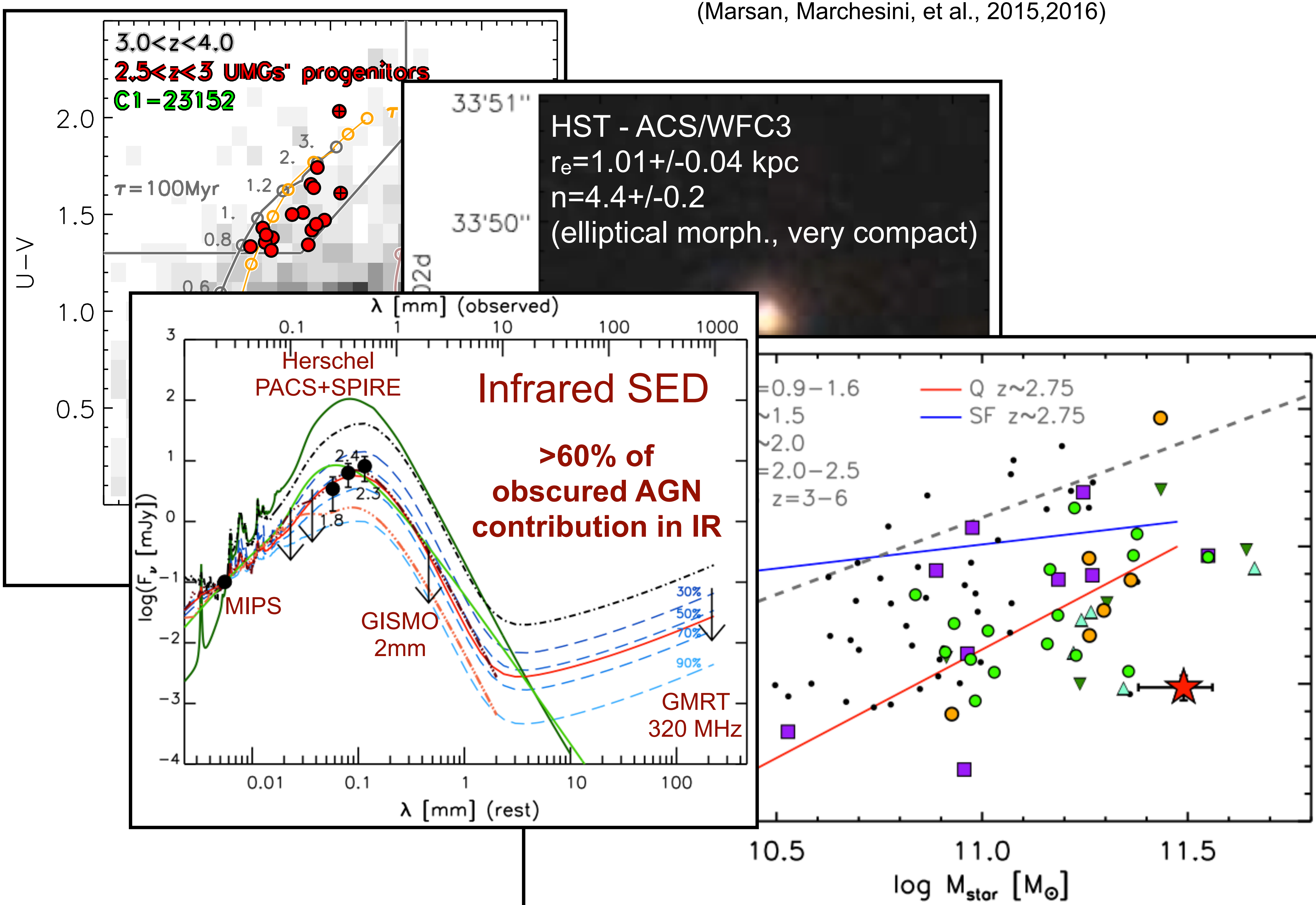

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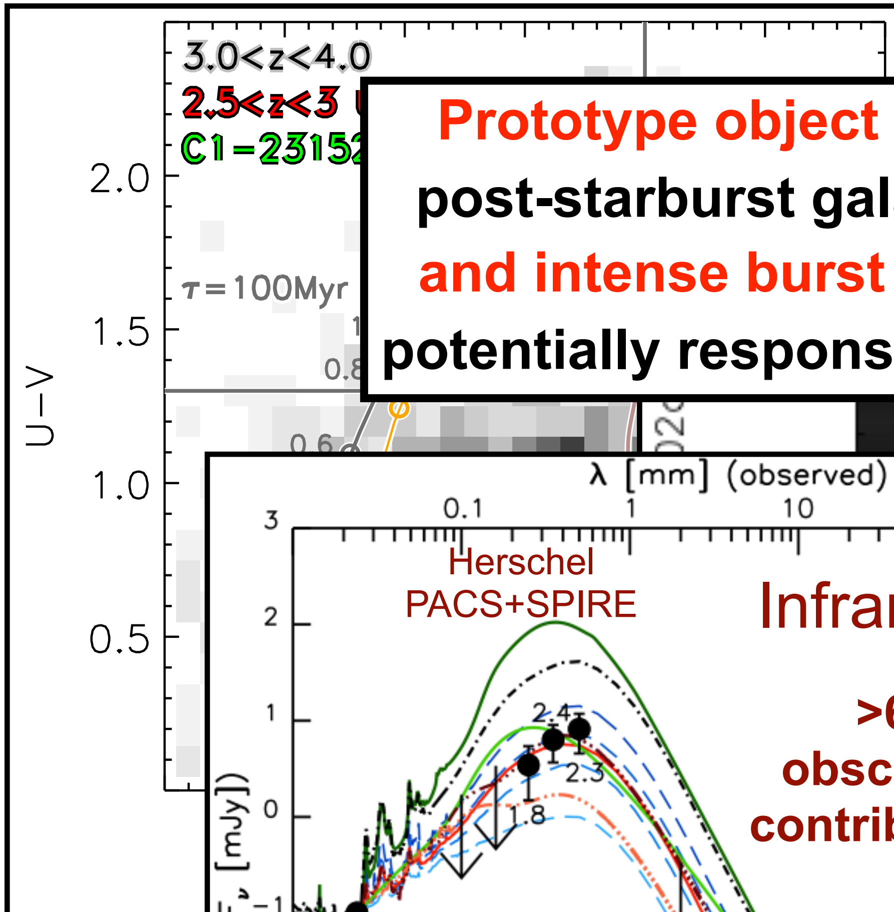
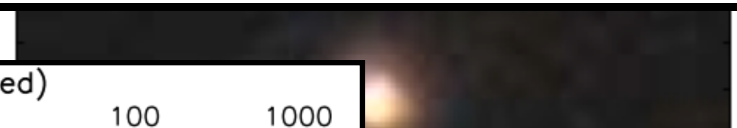
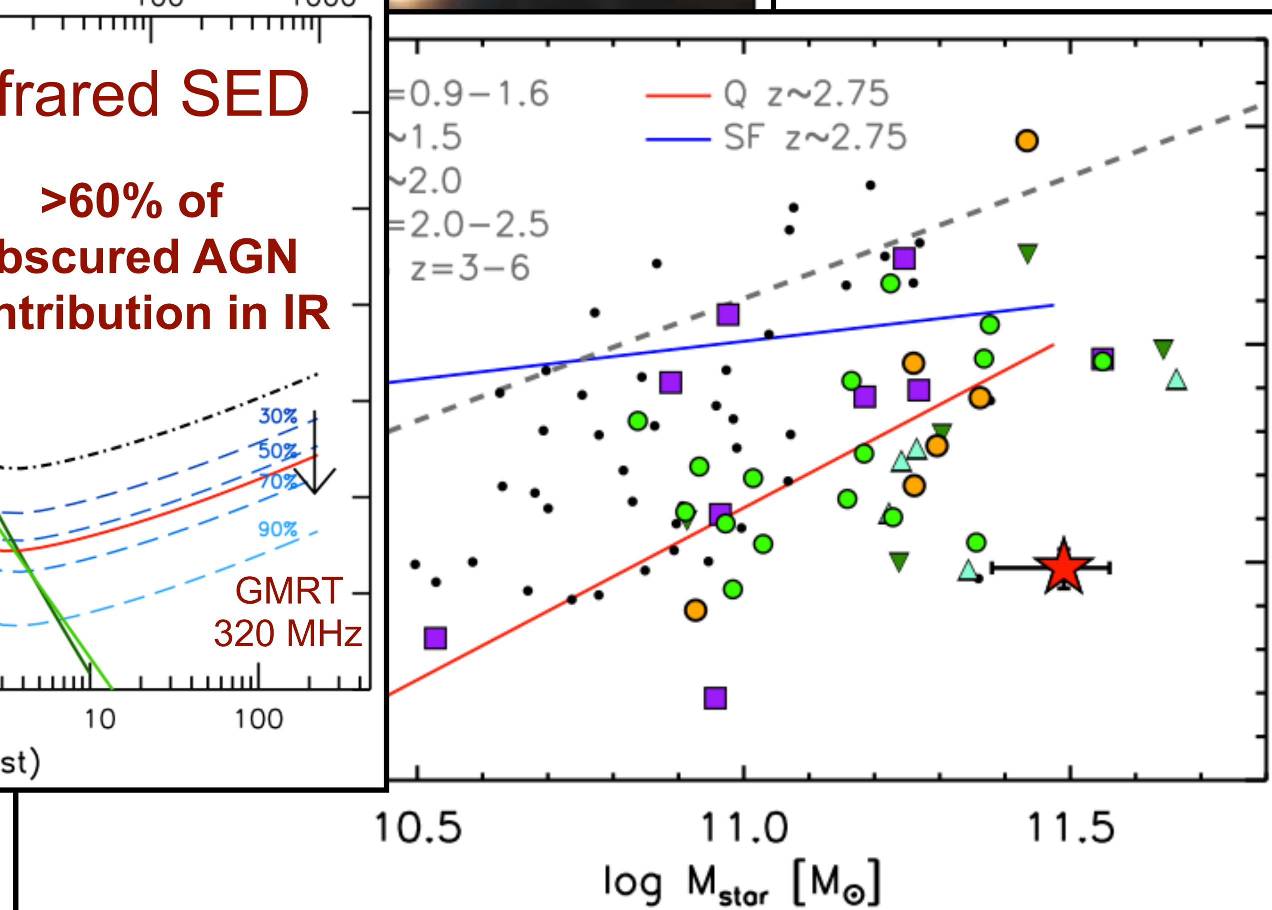
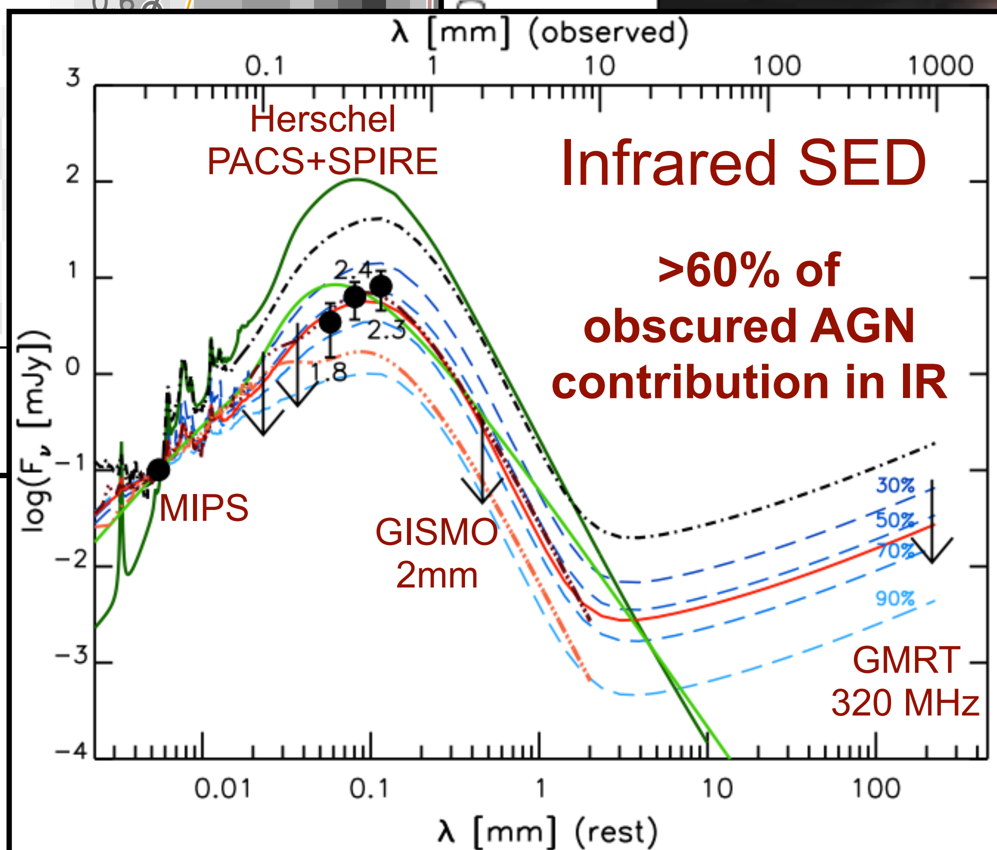
(Marsan, Marchesini, et al., 2015,2016)

**Prototype object of a very massive, very compact, (almost) post-starburst galaxy that formed most of its stars in a short and intense burst at $z_{form}$~4.1 and hosting an obscured AGN, potentially responsible for the quenching of the star-formation.**





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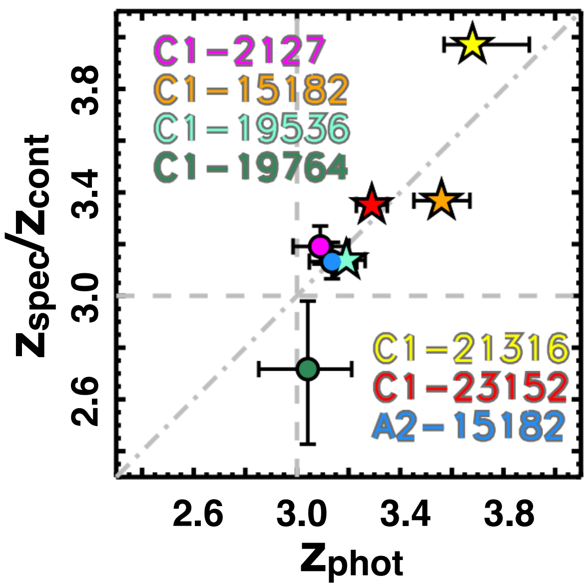
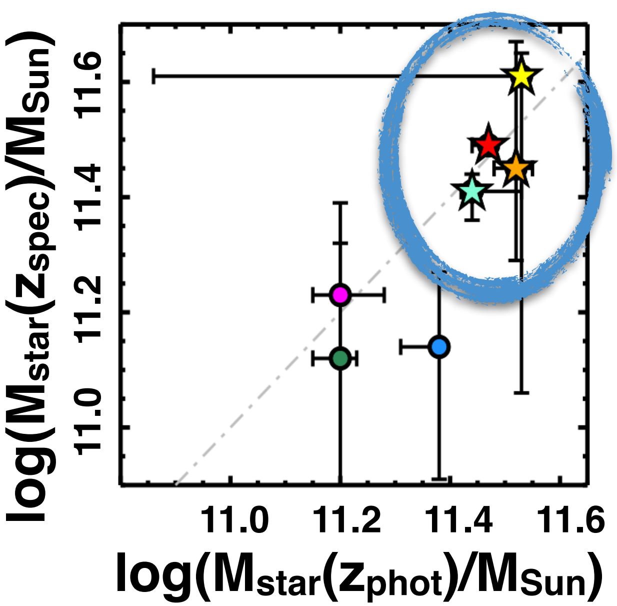
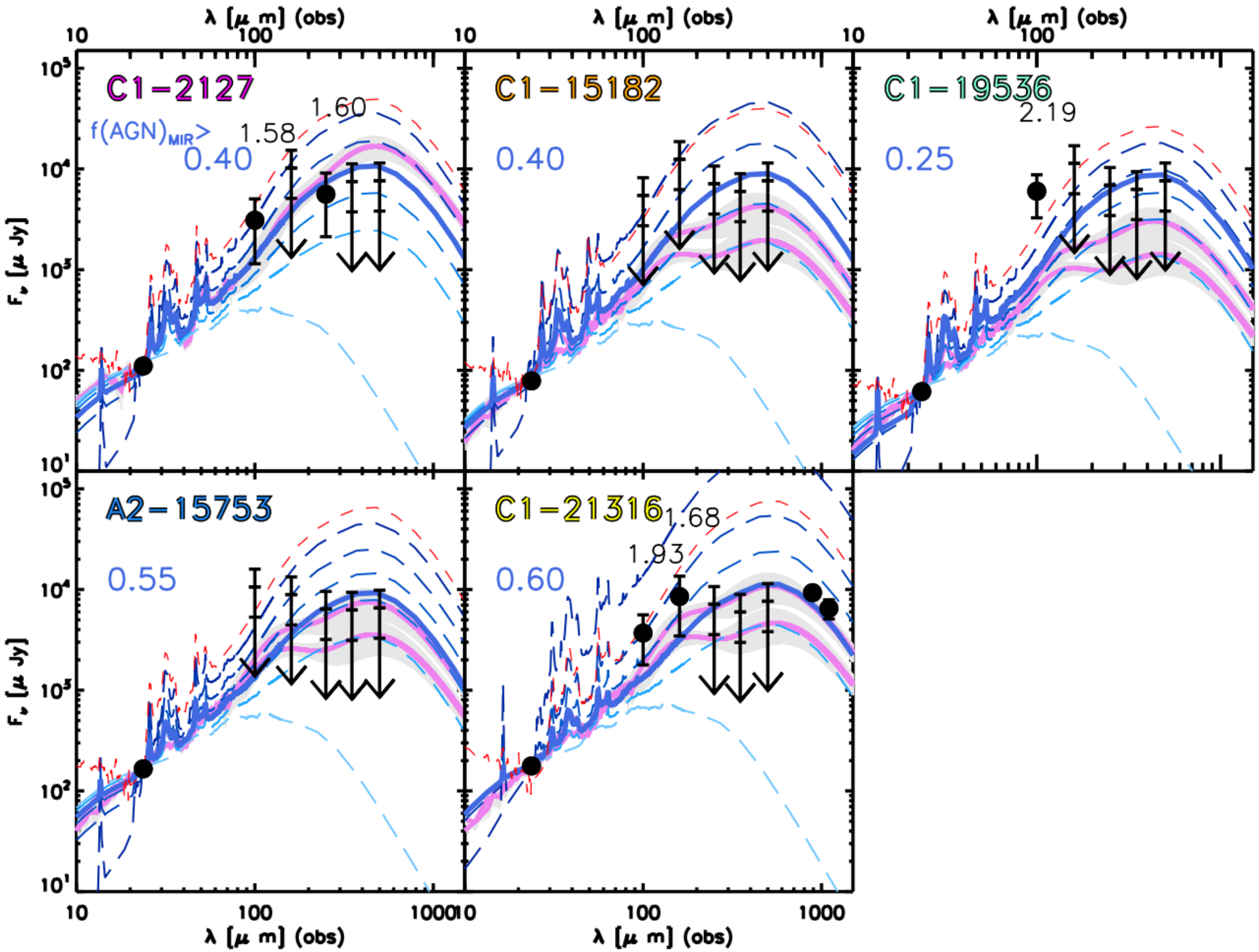


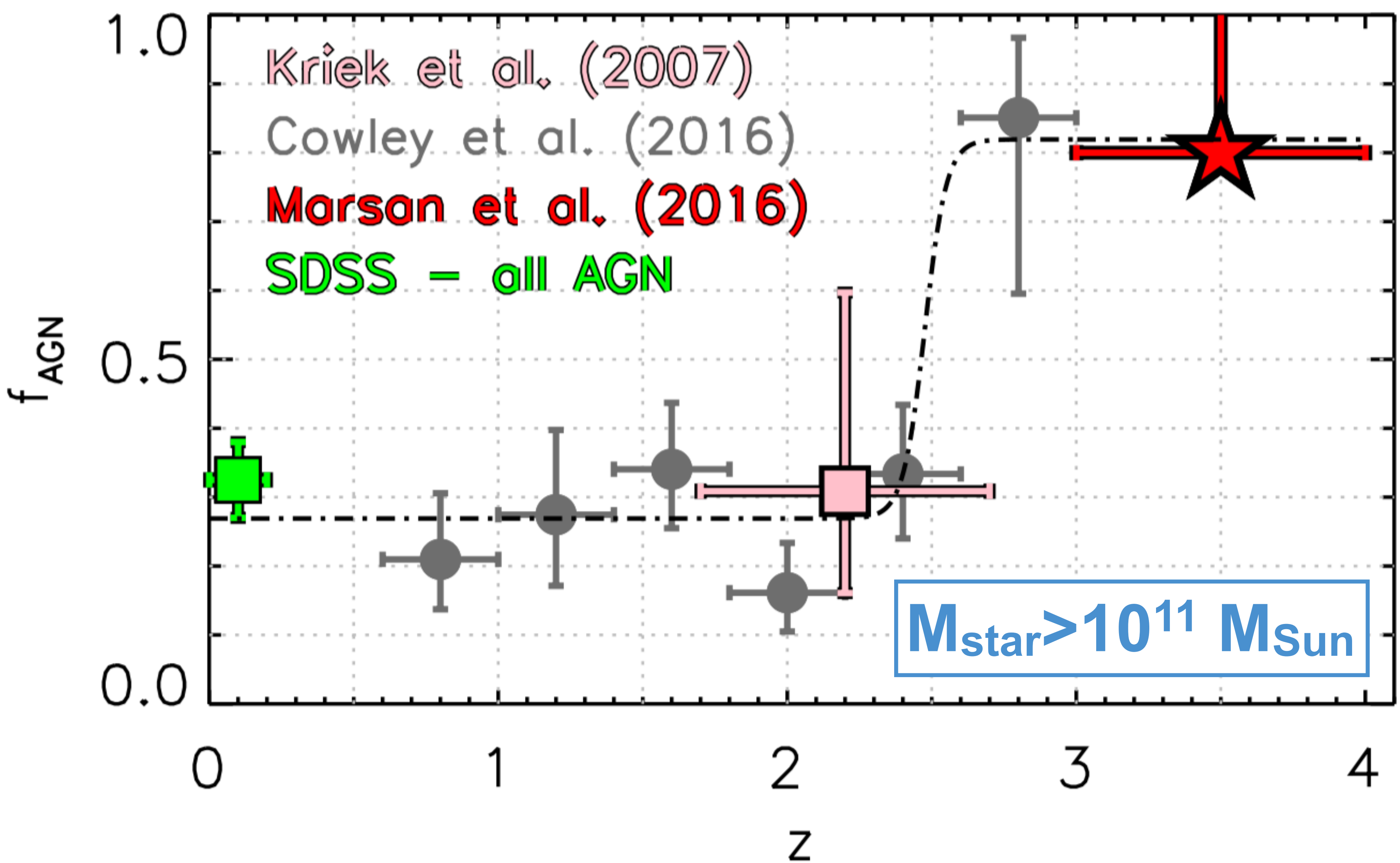



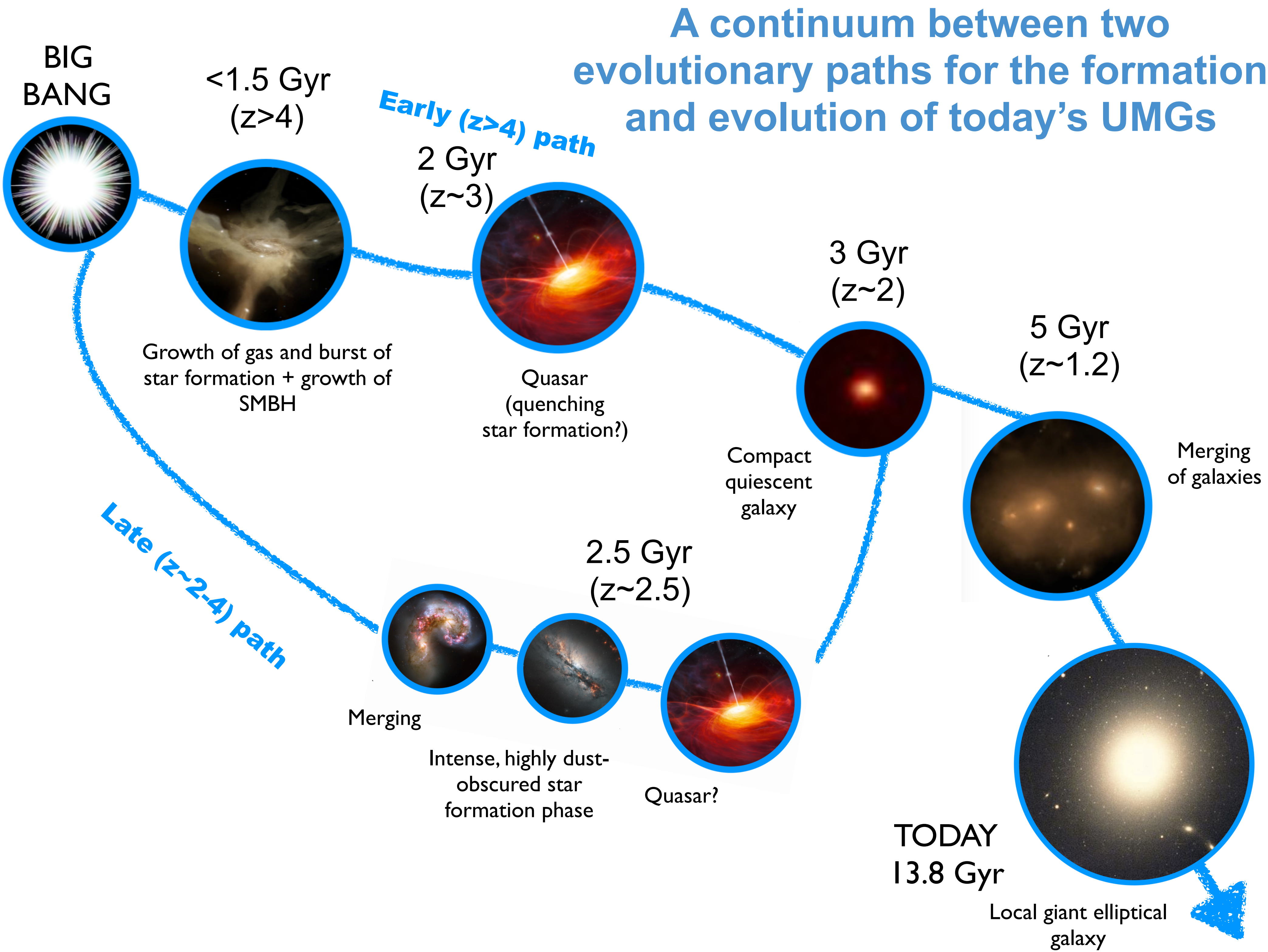

(Marsan, Marchesini, et al., 2016)

☑ **Confirmed existence of numerous z>3 massive galaxies** ($M_{star}$=1.5-4x$10^{11}$ $M_{Sun}$); diverse range of age, SFR, $A_V$; **>80% hosting AGN** ($L_{bol}$~$10^{44-46}$ erg $s^{-1}$); **MIPS largely contaminated by AGN** ($SFR_{corr}$<300-600 $M_{Sun}$ $yr^{-1}$).

# AGN Fraction in Massive Galaxies

(Marsan, Marchesini, et al., 2016)

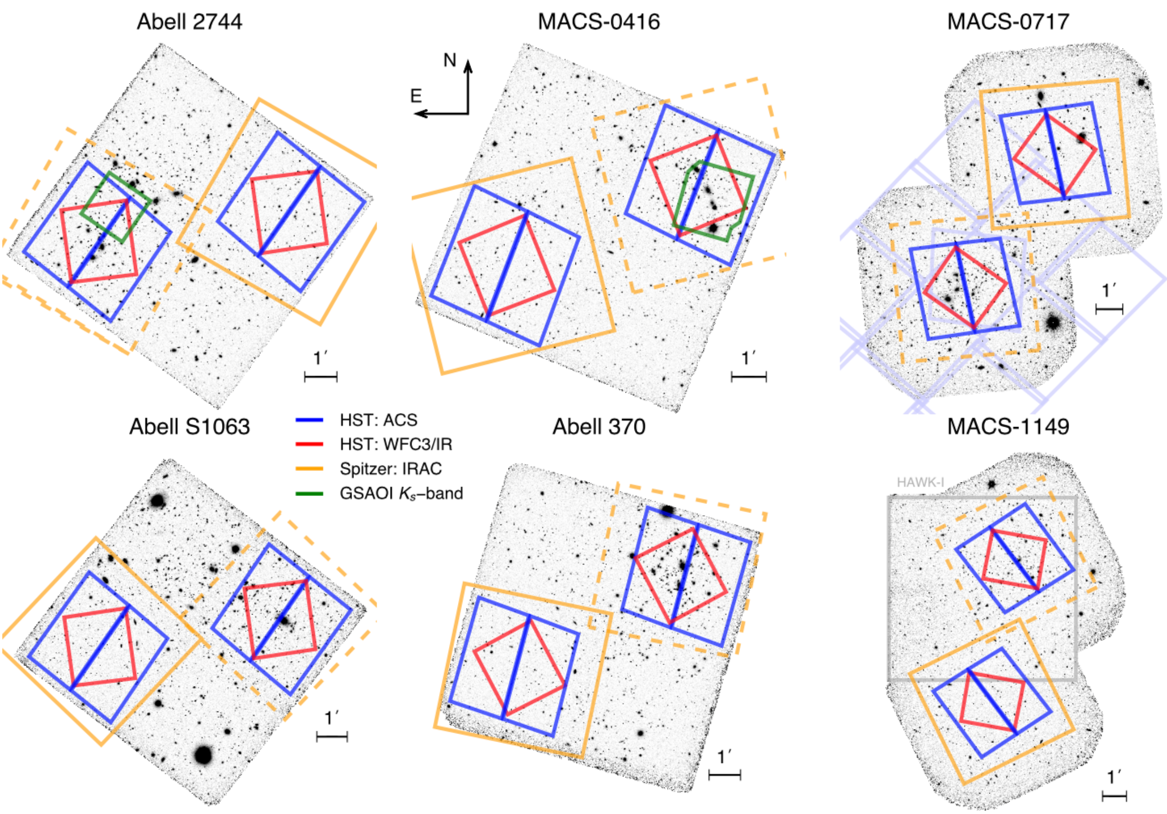


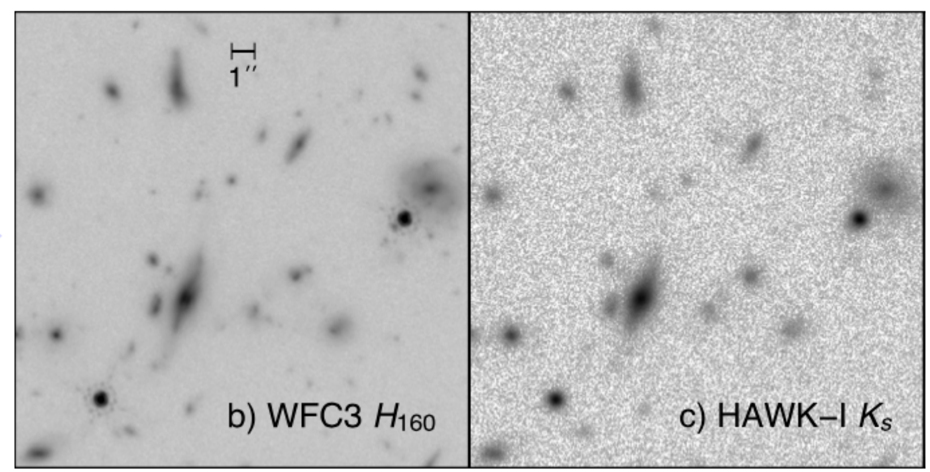

A continuum between two evolutionary paths for the formation and evolution of today's UMGs
BIG BANG
<1.5 Gyr (z>4)
Growth of gas and burst of star formation + growth of SMBH
Early (z>4) path
2 Gyr (z~3)
Quasar (quenching star formation?)
3 Gyr (z~2)
Compact quiescent galaxy
5 Gyr (z~1.2)
Merging of galaxies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

KIFF

*$K_s$-band Imaging of the Frontier Fields*

(co-PIs: Brammer; Marchesini)




http://cosmos.phy.tufts.edu/~danilo/HFF

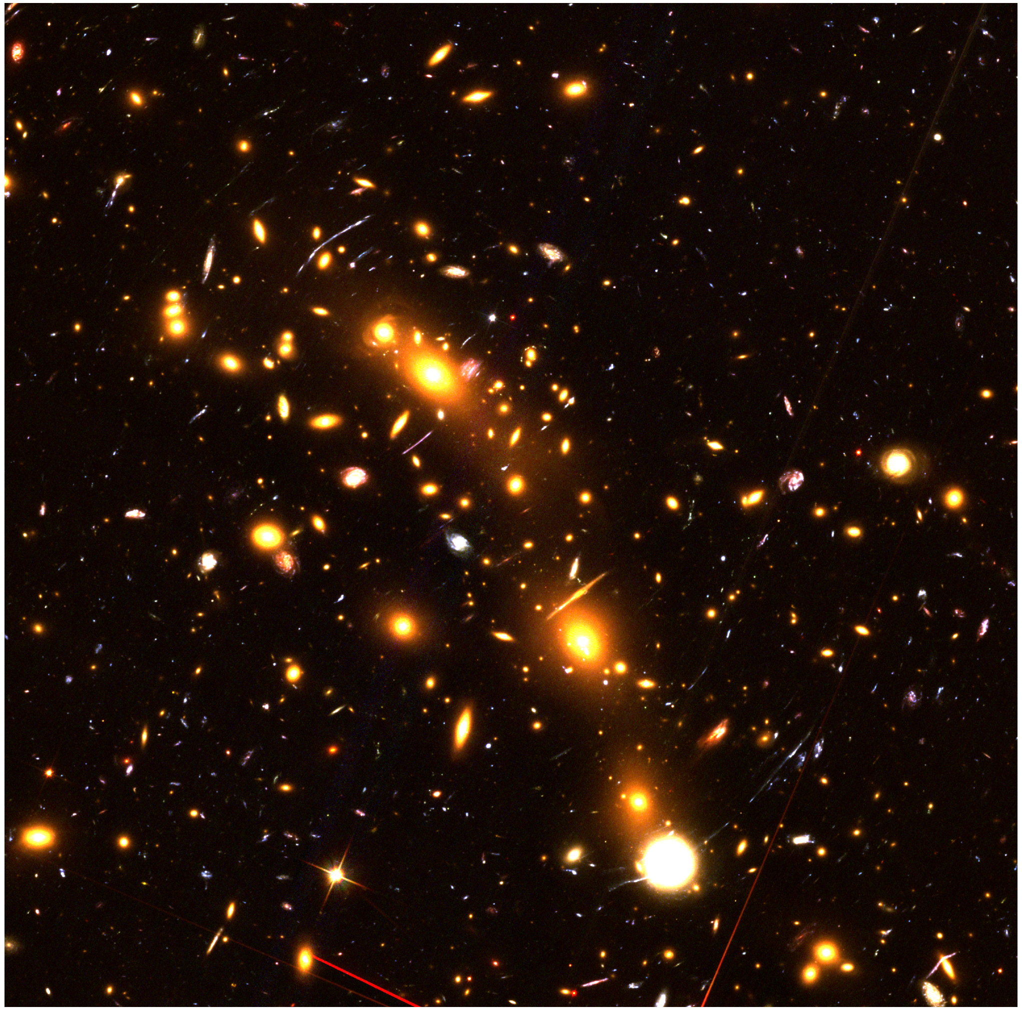
(Brammer, Marchesini, et al. 2016)

# HFF-DeepSpace
# (catalogs of the Hubble Frontier Fields)

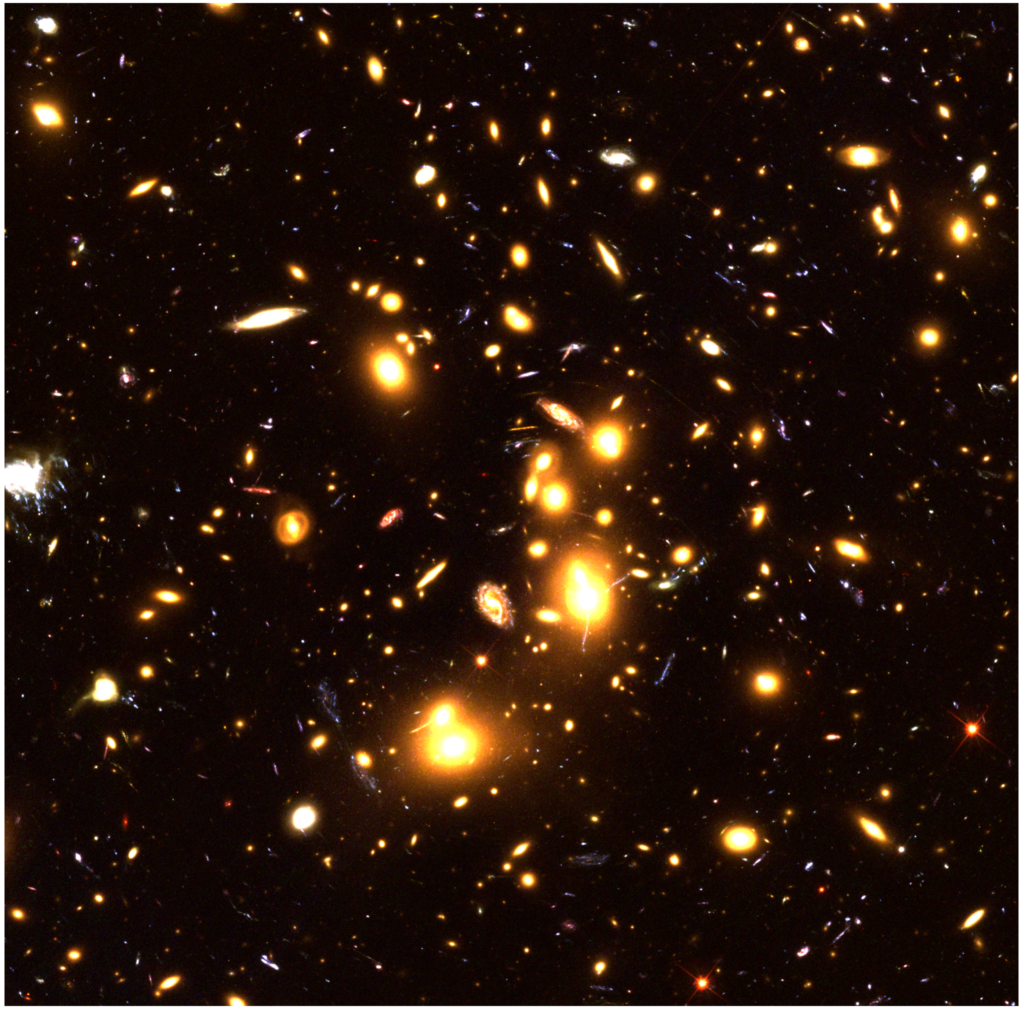
http://cosmos.phy.tufts.edu/~danilo/HFF

Catalogs public release schedule in January 2017

**MACS-0416**



**ABELL-2744**



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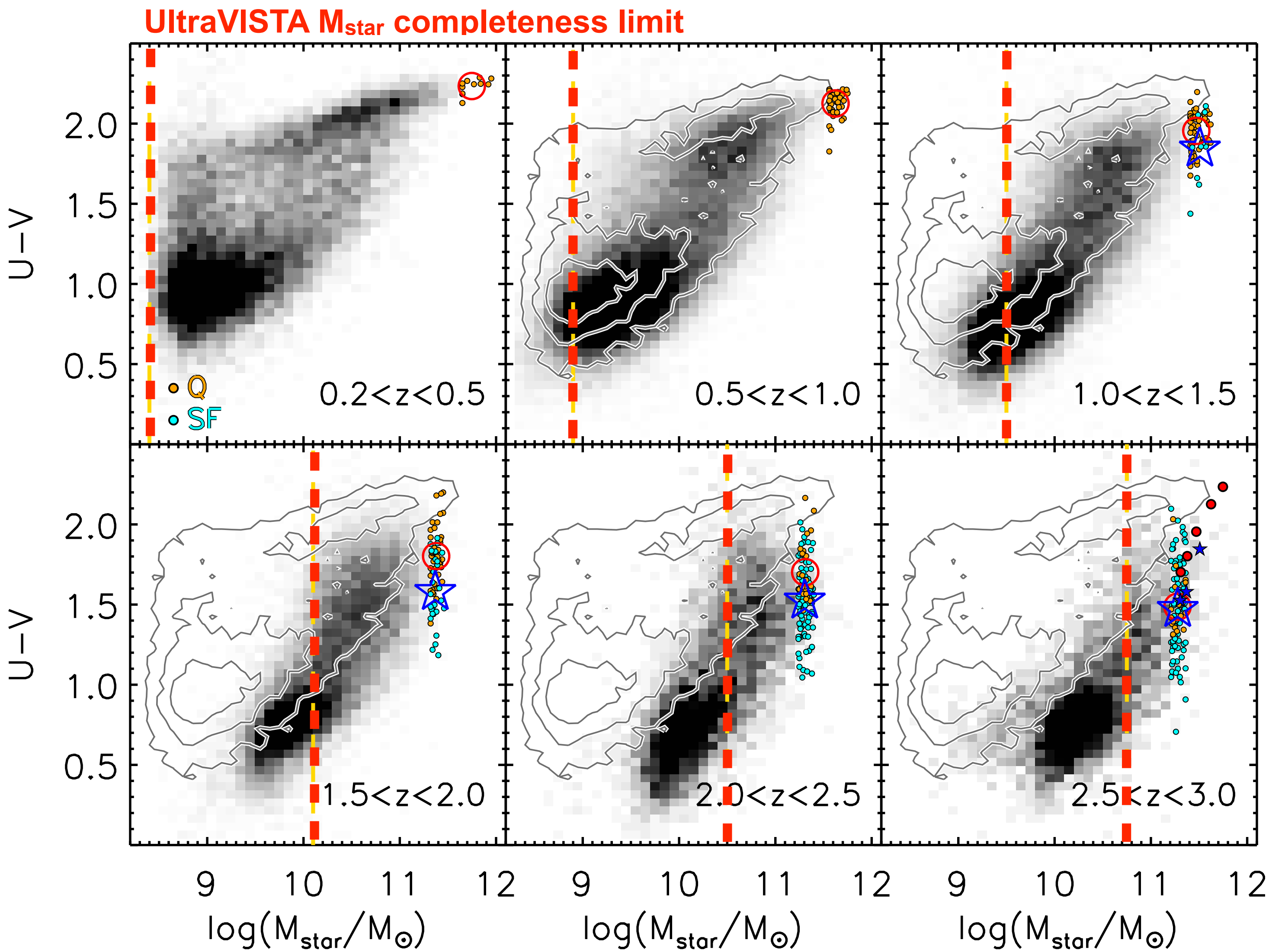
# Summary

- **The evolution of the progenitors of local UMGs was 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 a factor of ~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 (~2x$10^{11}$ $M_{Sun}$), 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 fossil records**.
- **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 $M_{star}$=3x$10^{11}$ $M_{Sun}$, 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.
- **Highlighted result from the whole spectroscopic campaign of very massive z>3 galaxies** (Marsan et al. 2016)
- Presented **the evolution of the fraction of quiescent, dusty star-forming and unobscured star-forming galaxies since z=3** (Martis et al. 2016) - **the high-mass end has always been mostly populated by red galaxies** (quiescent at low-z, dusty star-forming at high-z).
- **Advertised KIFF and HFF-DeepSpace**

# Color versus Stellar Mass Diagram

(Marchesini et al. 2014)




- 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.

- **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).