"NEW INSIGHTS INTO THE FORMATION AND EVOLUTION OF THE MOST MASSIVE GALAXIES"

DANILO MARCHESINI (Tufts University)

Dr. Adam Muzzin (Leiden Univ.), Dr. Mauro Stefanon (Univ. of Missouri), Cemile Marsan (Tufts Univ., PhD student), and the NMBS, NMBS-II, and UltraVISTA collaborations

Tufts UNIVERSITY

NASA

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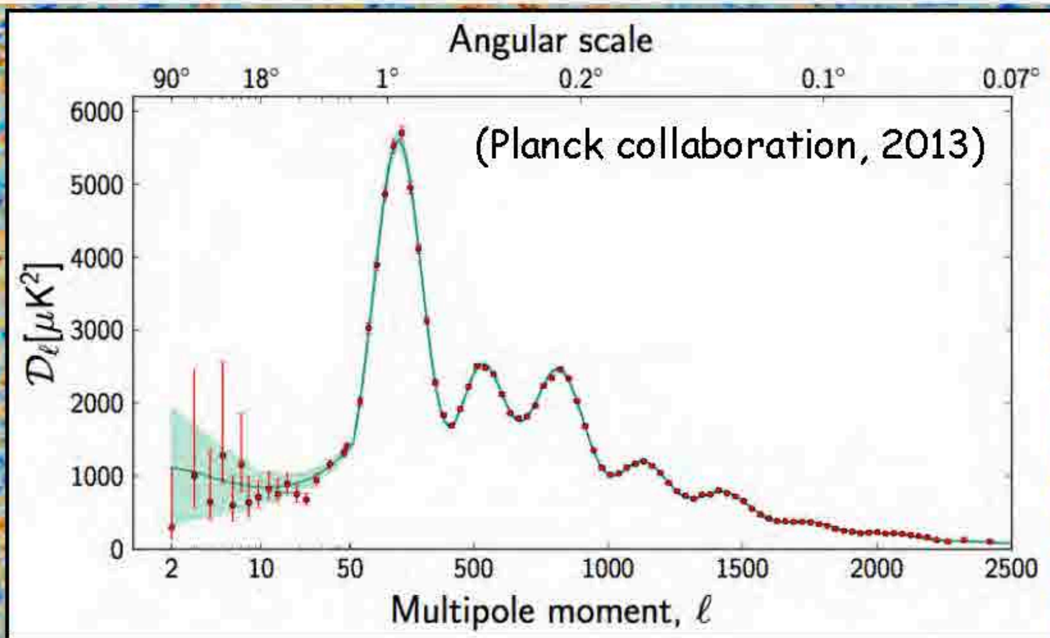
Cottrell Scholar Award
RESEARCH CORPORATION *for* SCIENCE ADVANCEMENT

KAVLI IPMU / November 27th, 2013

The Concordance LCDM Cosmology



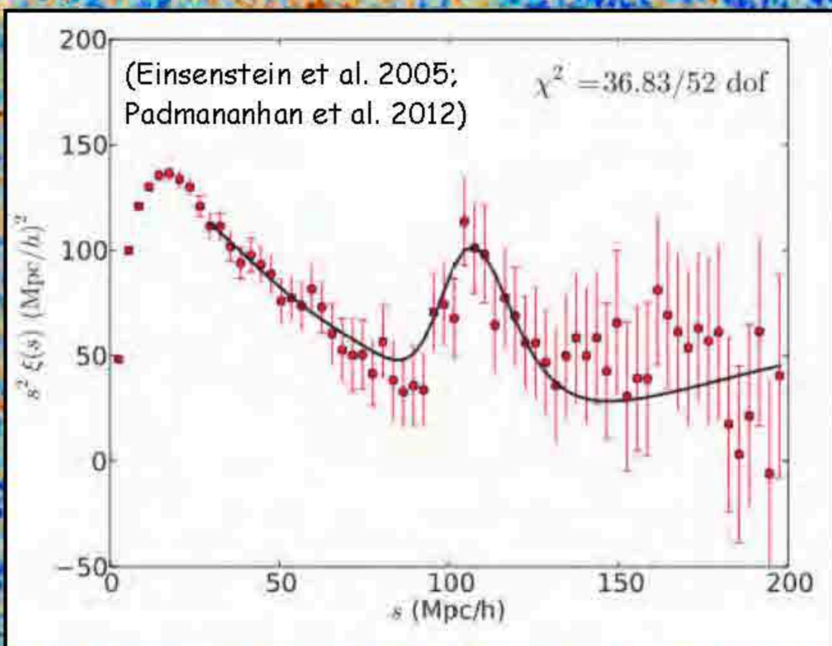
$$\Omega_m = \Omega_{DM} + \Omega_b = 0.31$$

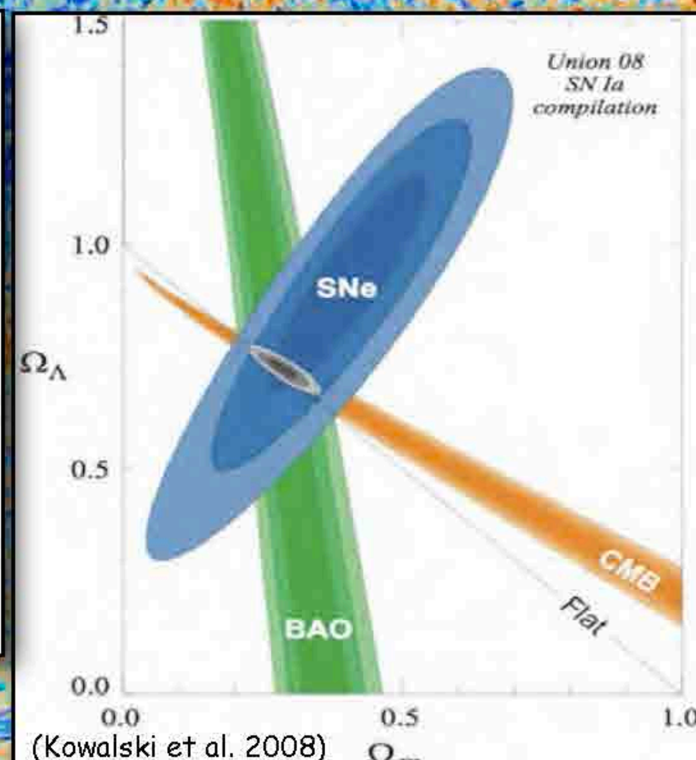
$$\Omega_\Lambda = 0.69 \quad \Omega_b = 0.048$$

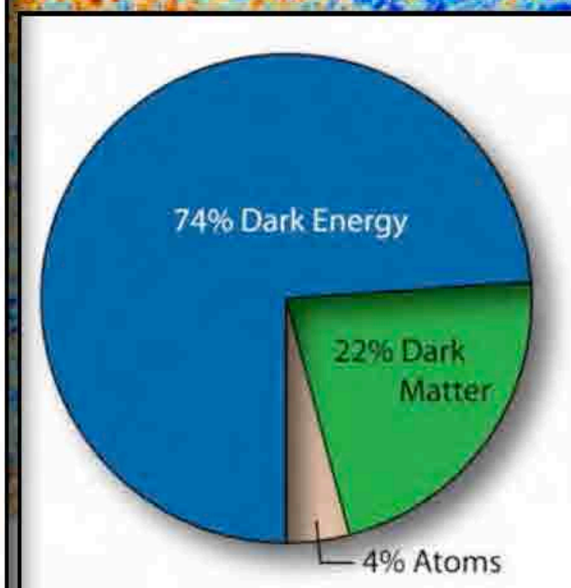
$$H_0 = 67.8 \pm 0.8$$

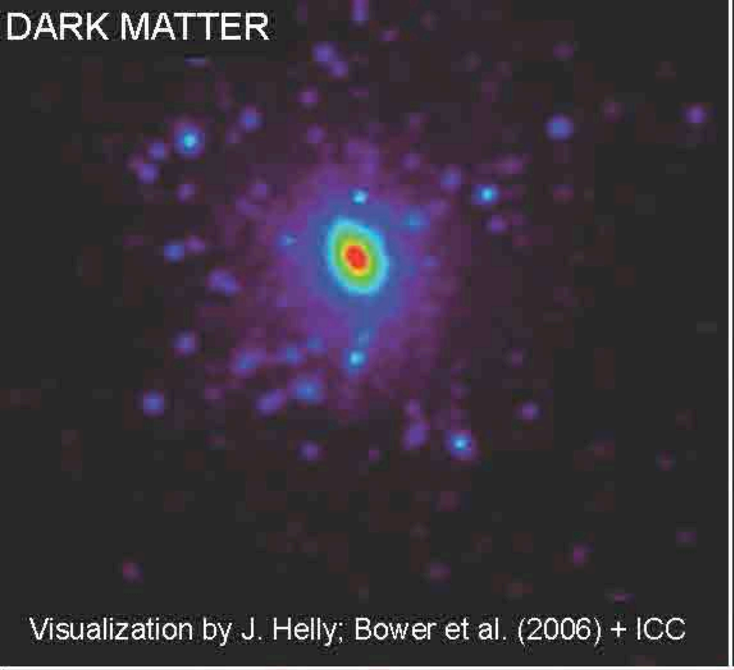
$$Age = 13.8 \text{ Gyr}$$

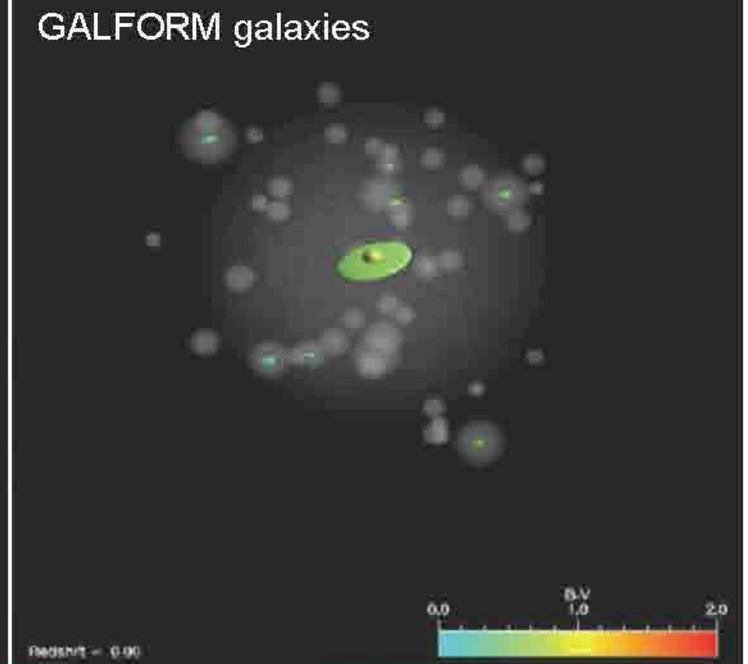
$$w = -1.13^{+0.13}_{-0.10}$$



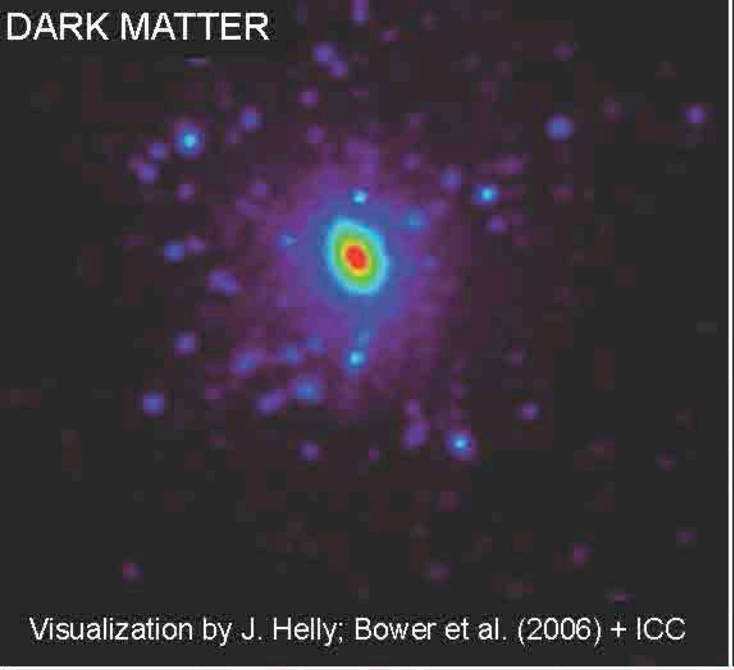


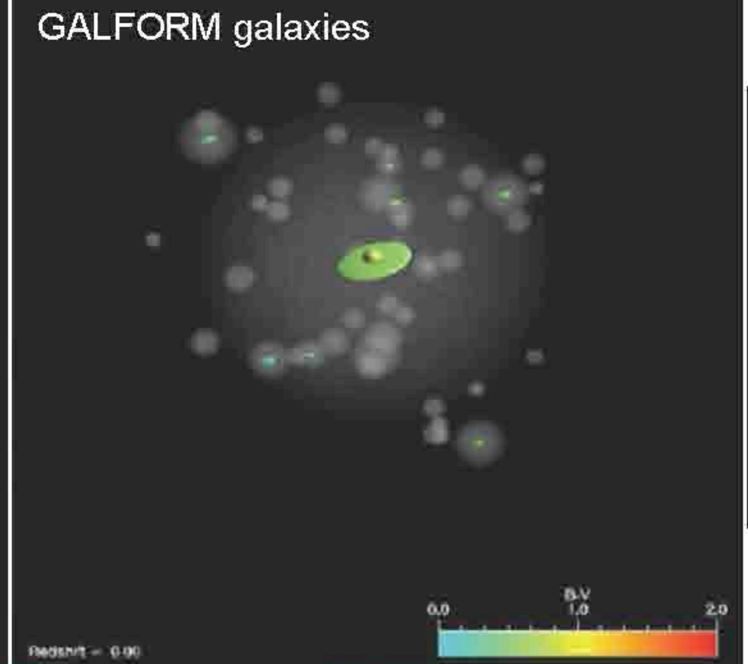


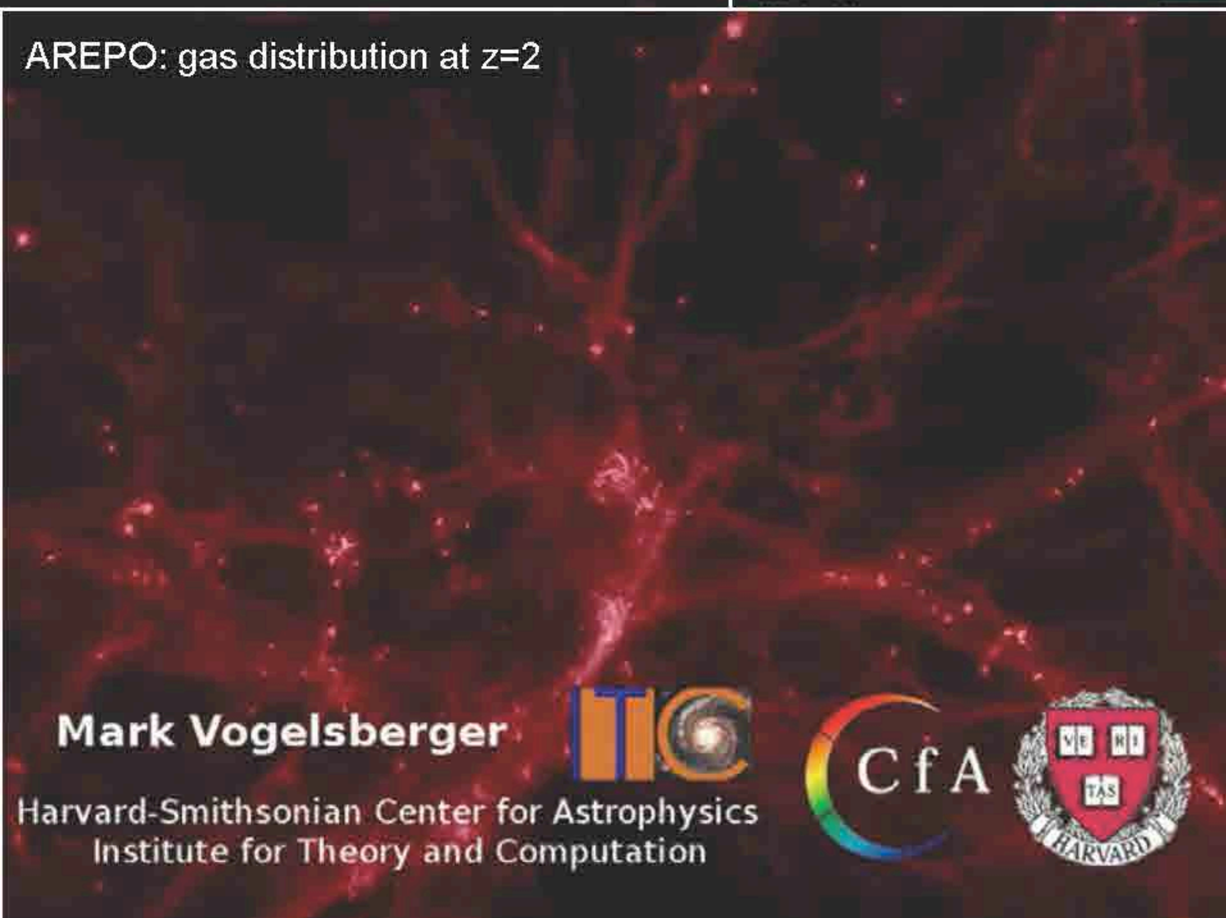




- Gas cooling
- Star formation
- Merging
- Stellar feedback
- Feedback from AGN







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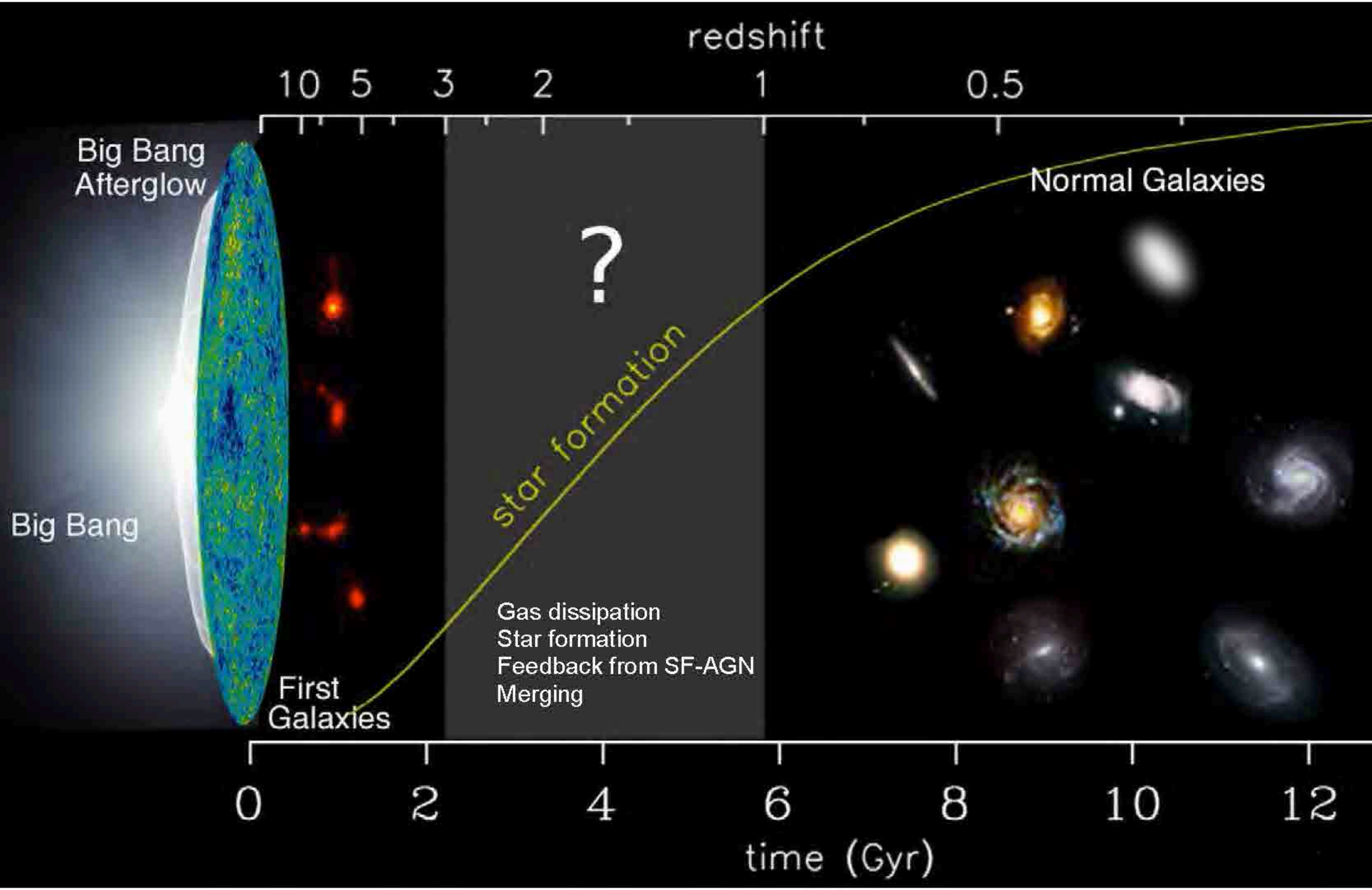
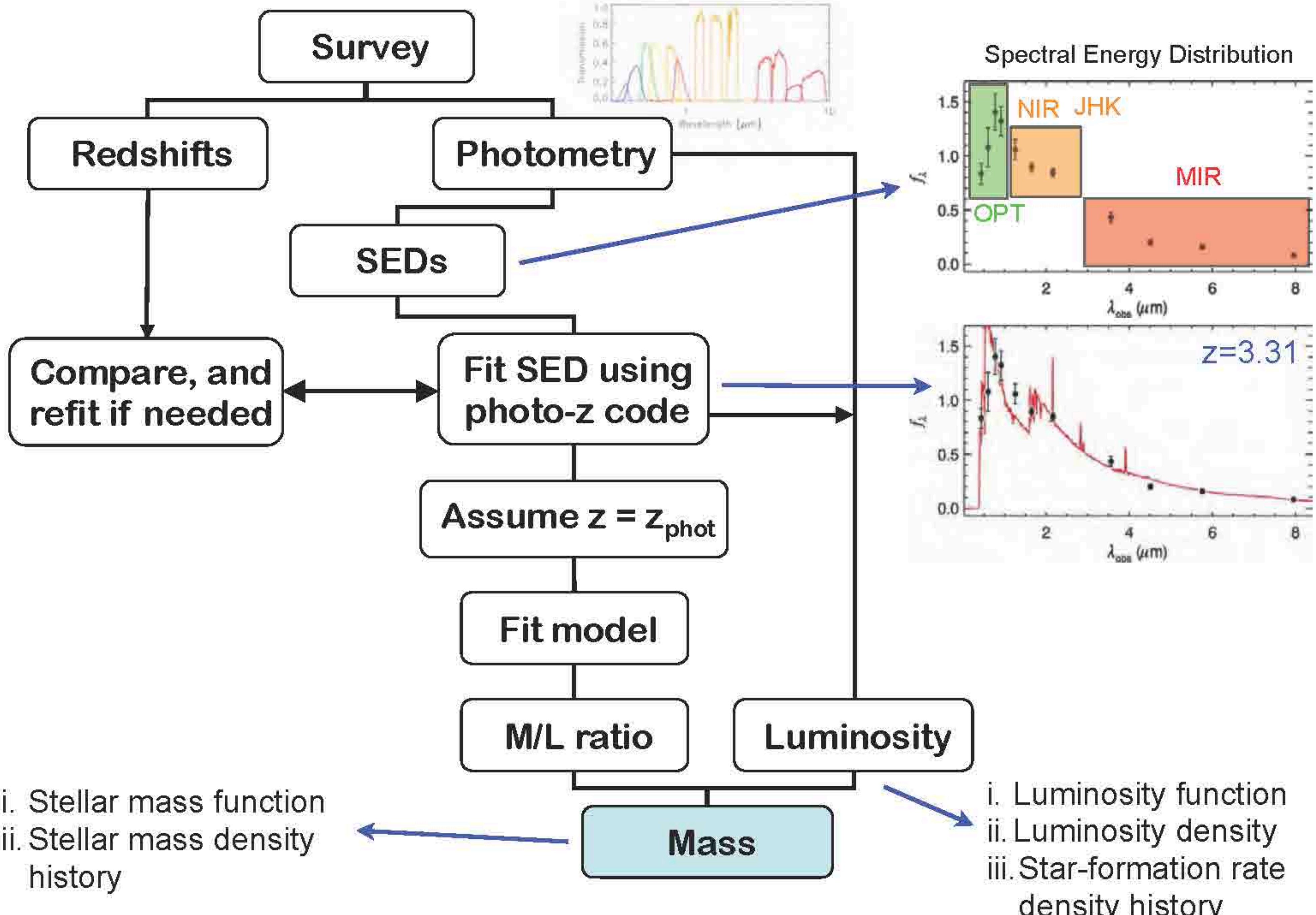


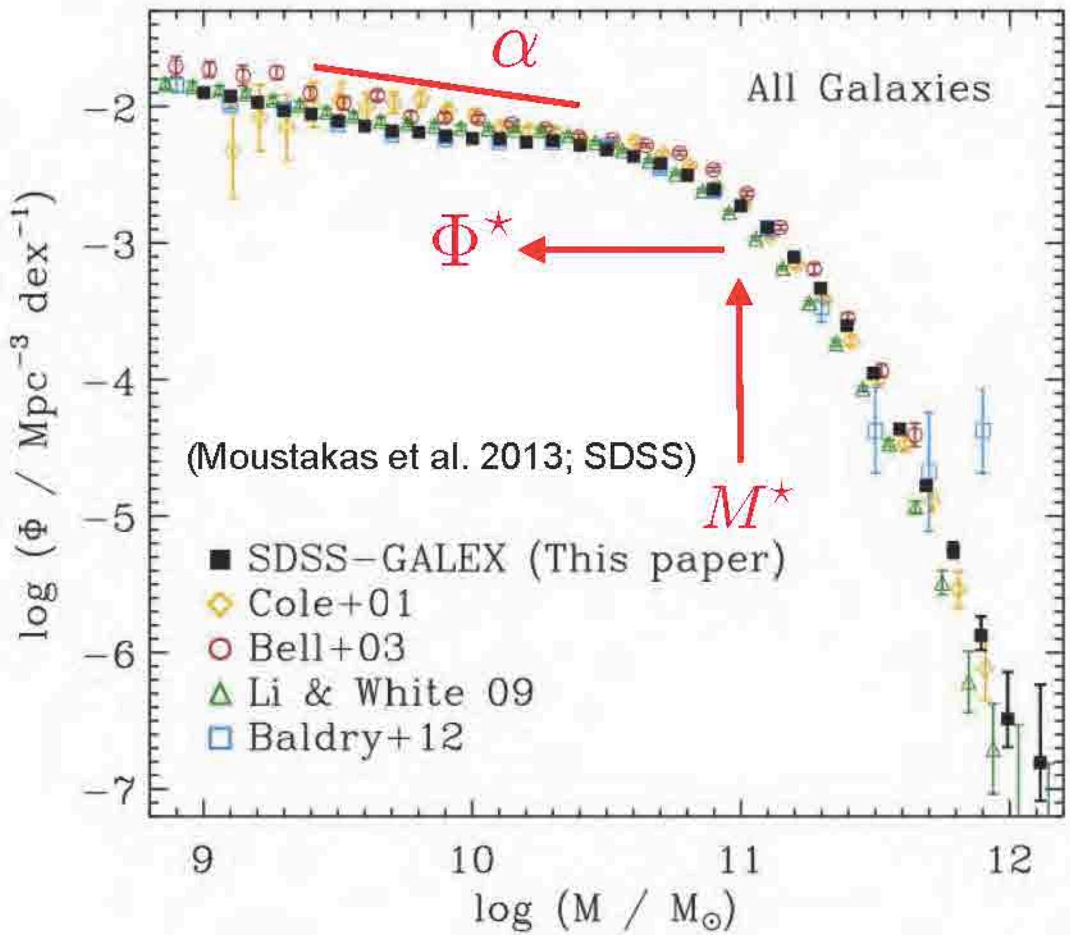
redshift
10
5
3
2
1
0.5
Big Bang
Afterglow
Big Bang
First
Galaxies
?
star formation
Gas dissipation
Star formation
Feedback from SF-AGN
Merging
Normal Galaxies
0
2
4
6
8
10
12
time (Gyr)

Constructing Representative Samples of Galaxies



The Stellar Mass Function (SMF) of Galaxies in the Local Universe

- The SMF is one of the most fundamental observable in the study of galaxy evolution (the shape retains imprint of physical processes)
- It is best fit with an exponential+power law known as the "Schechter Function"
- In the local universe, a "Double Schechter Function" is needed to properly model the detected upturn at the low-mass end.



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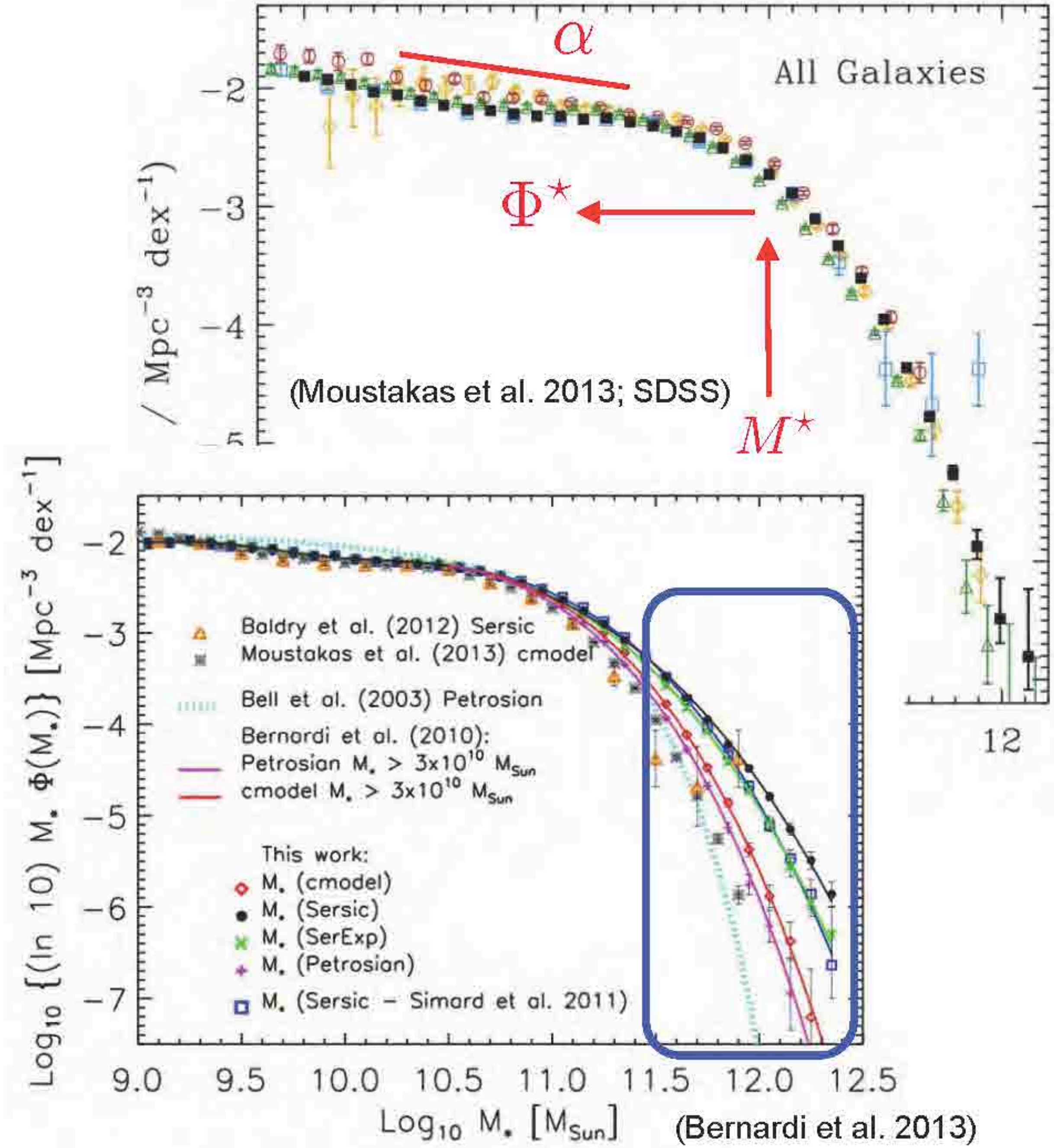
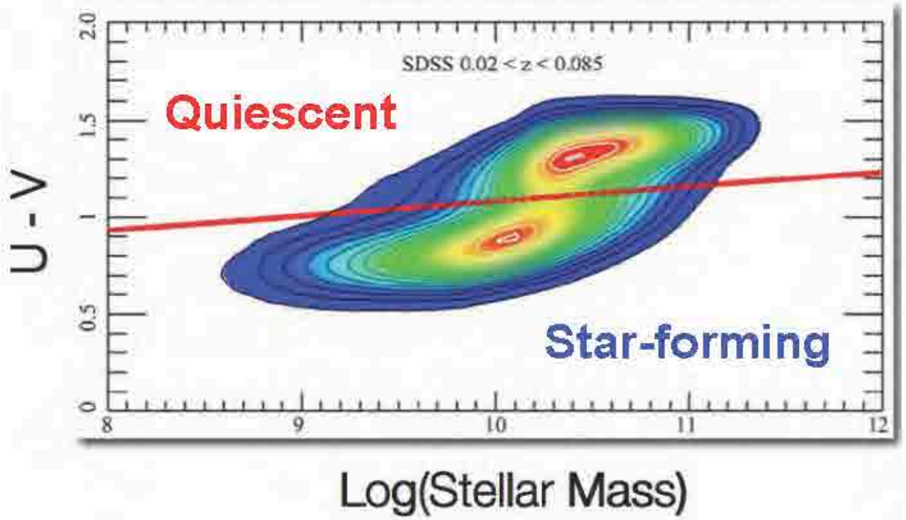
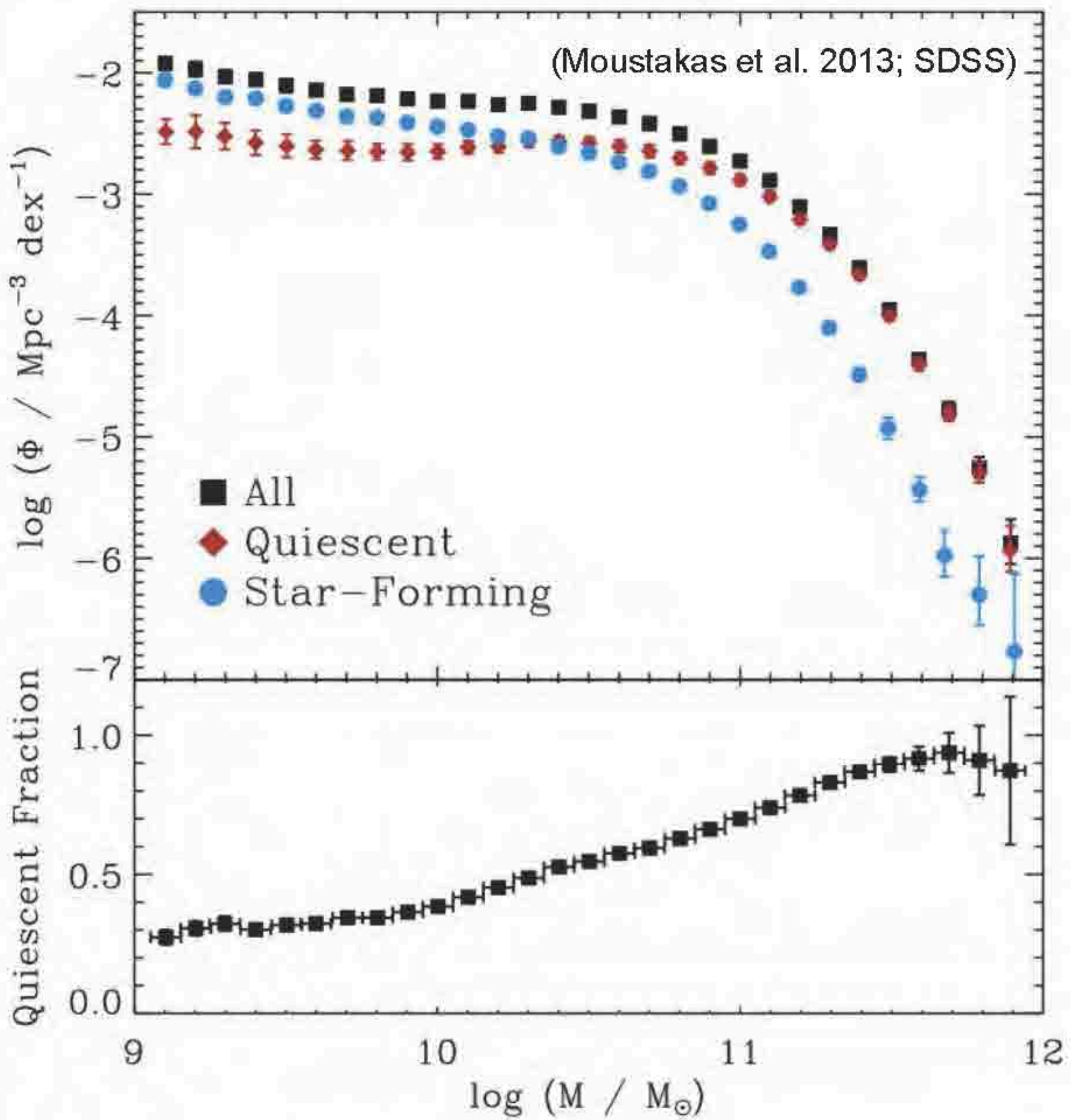


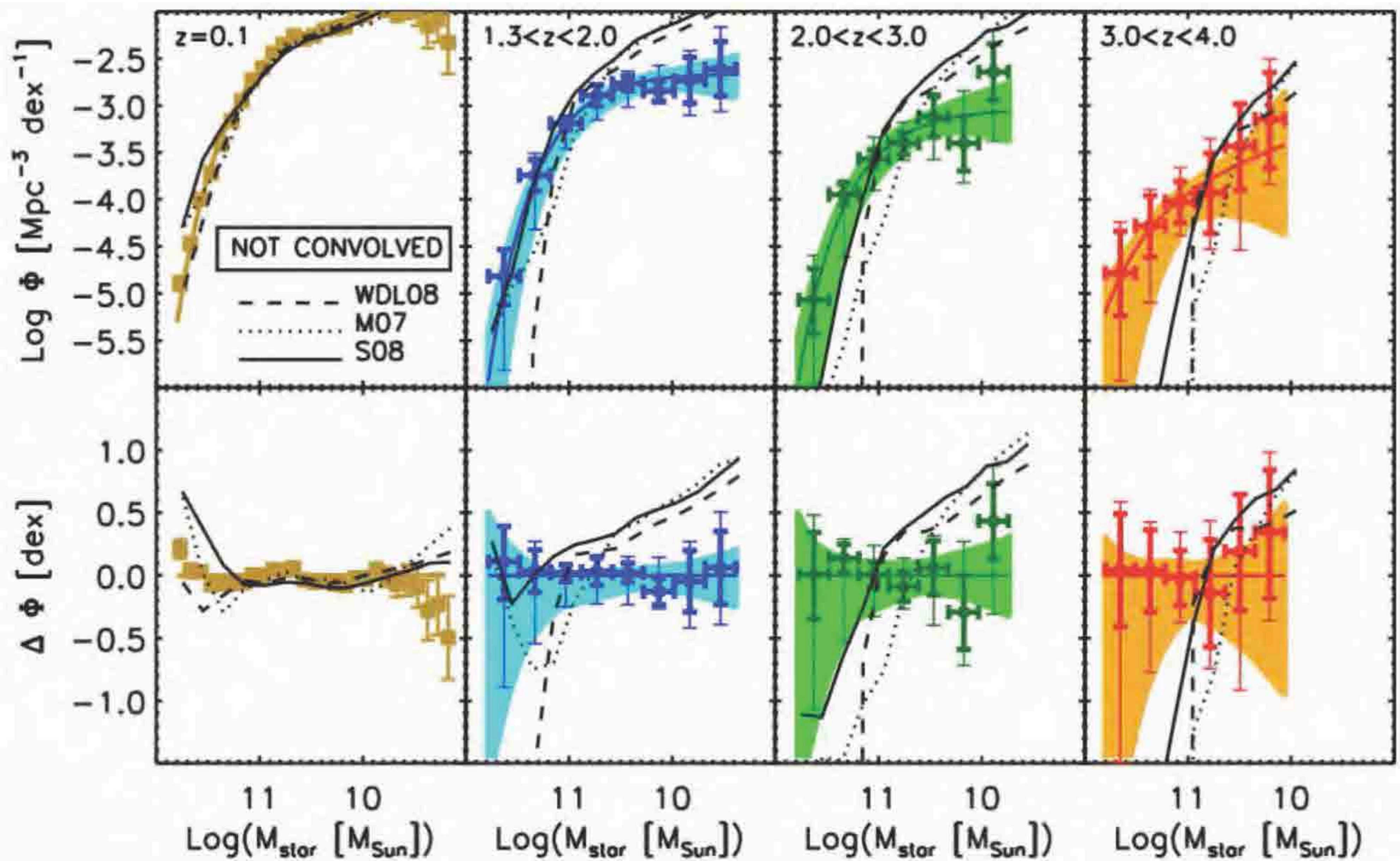
The Stellar Mass Function (SMF) of Galaxies in the Local Universe: Quiescent vs Star-forming





- Clear bi-modality of quiescent and star-forming galaxies.
- Different SMFs of quiescent and star-forming galaxies
- Quiescent galaxies dominate at the high-mass end, star-forming galaxies dominate at low masses.

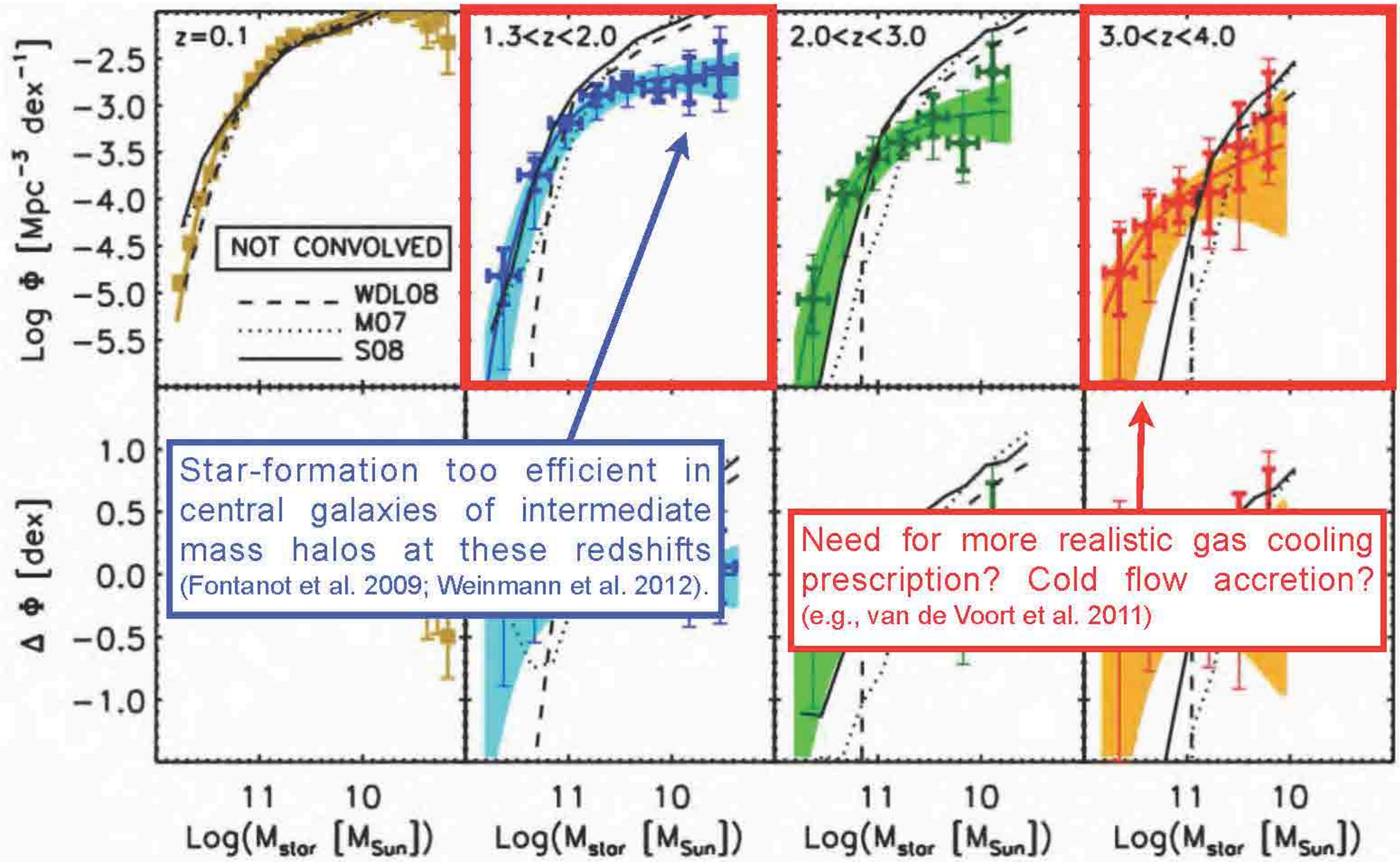
Redshift Evolution of the SMFs



Models from: MILLENNIUM (Wang, De Lucia, et al. 2008)
MORGANA (Monaco et al. 2007)
Somerville et al. (2008)

(Marchesini et al., 2009;
see also Perez-Gonzalez et al. 2008; Kajisawa et al. 2009; Bundy et al. 2005/2006; and many others)

Evolution of the SMFs: Comparison with Models

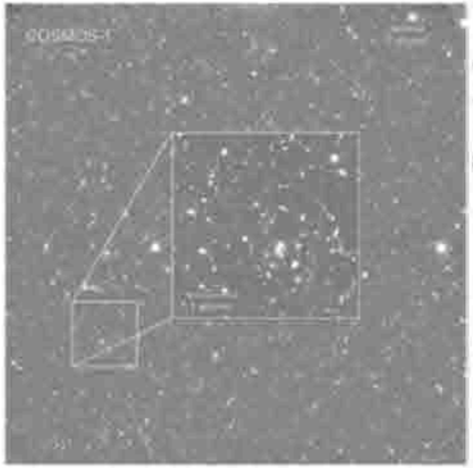


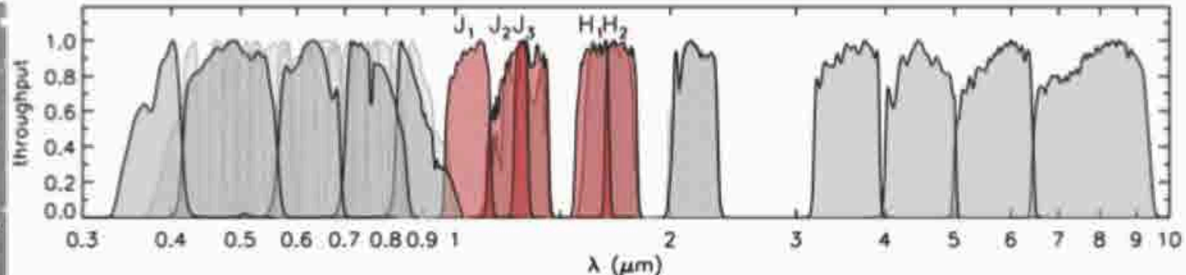
(Marchesini et al., 2009)

NEWFIRM Medium-Band Survey

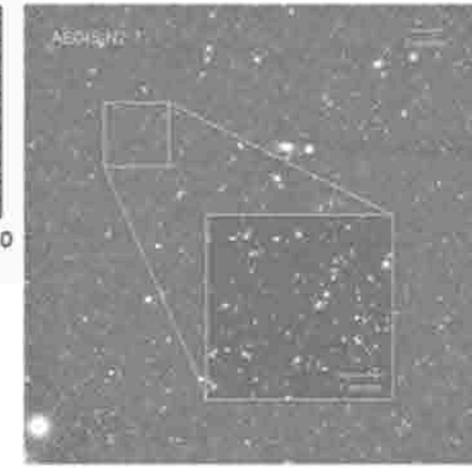
PI: van Dokkum; Marchesini, Labbe', Quadri, Brammer, Whitaker, Kriek, Franx, Muzzin, Rudnick, Illingworth, Lee, Wake, Lundgren

COSMOS

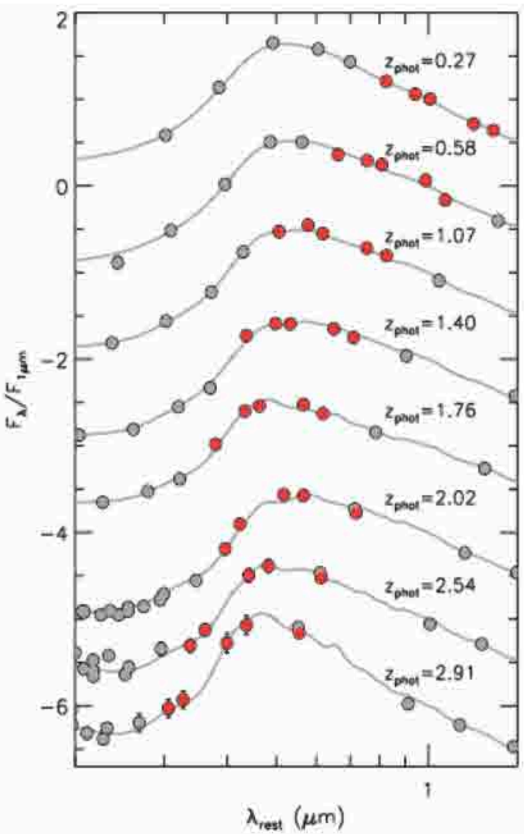


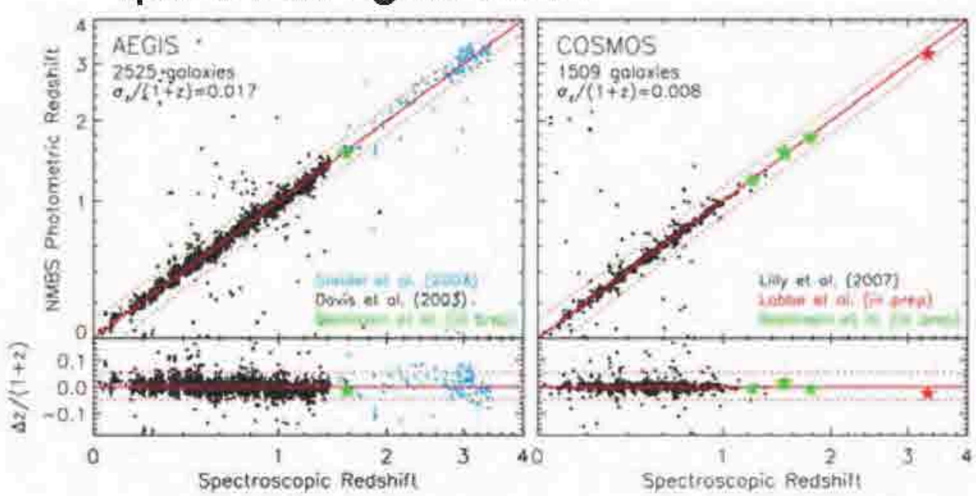


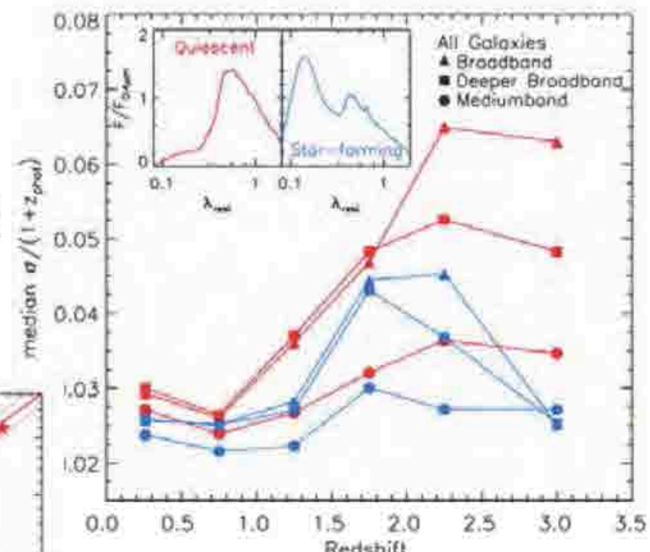
AEGIS



- Two 30'x30' fields: COSMOS and AEGIS
- Completeness $K_{90\%}$=22.5 (AB)
- 13000 galaxies at z>1.5 with accurate z_{phot} (better than 2%)
- Photometric redshifts a factor of ~2-3 better than with broad-band photometry, especially for quiescent galaxies.



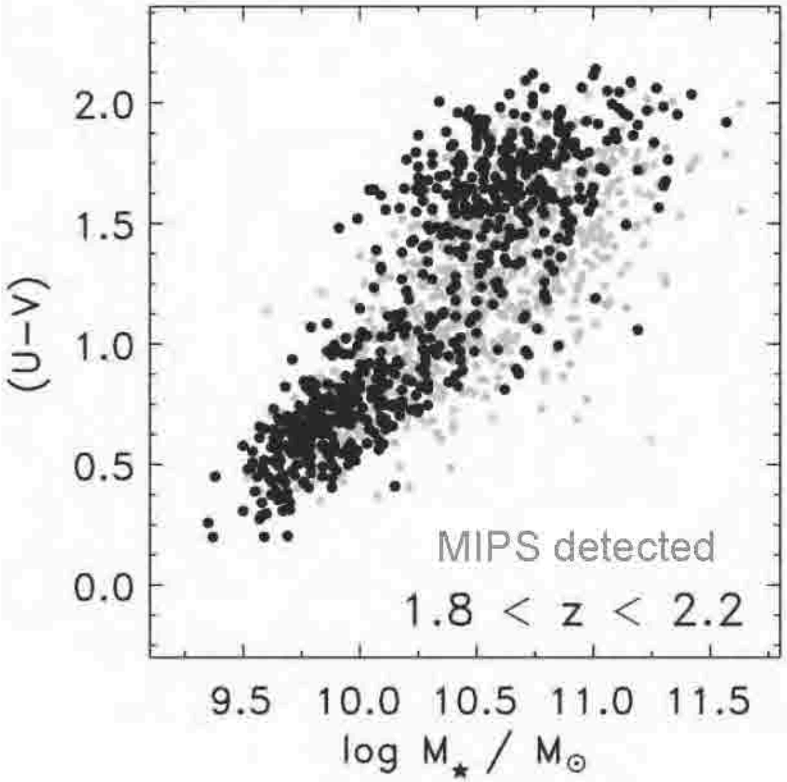




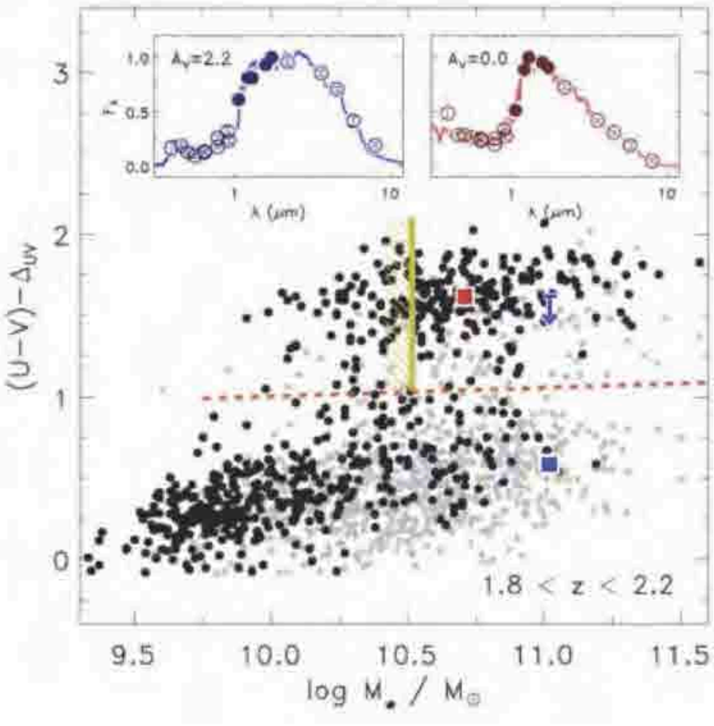
(Whitaker, DM, et al. 2011)

Bi-modality in Place Already at z=2.5

(Brammer, DM, et al. 2009)



Extinction corrected



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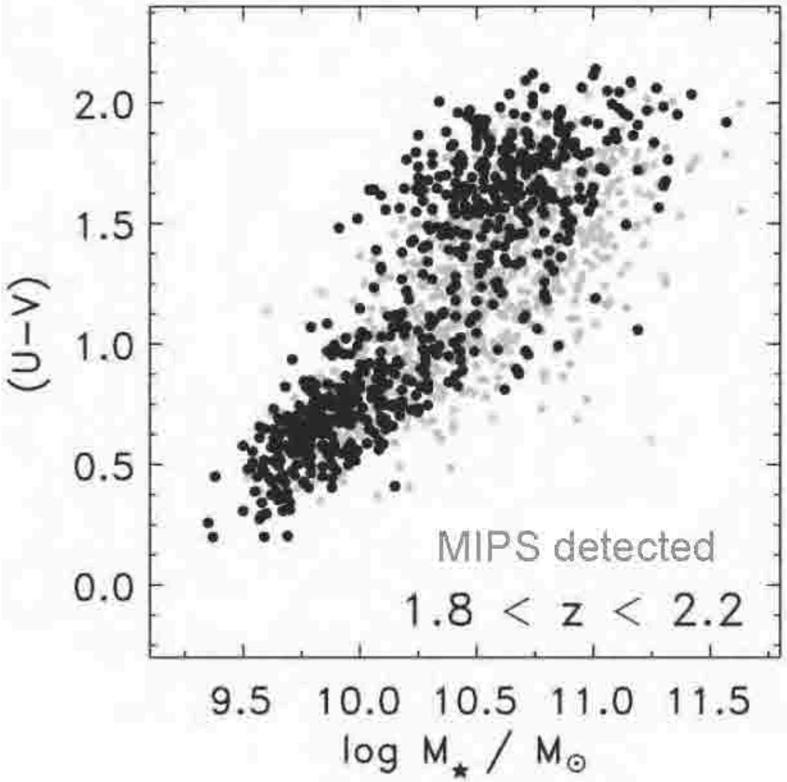
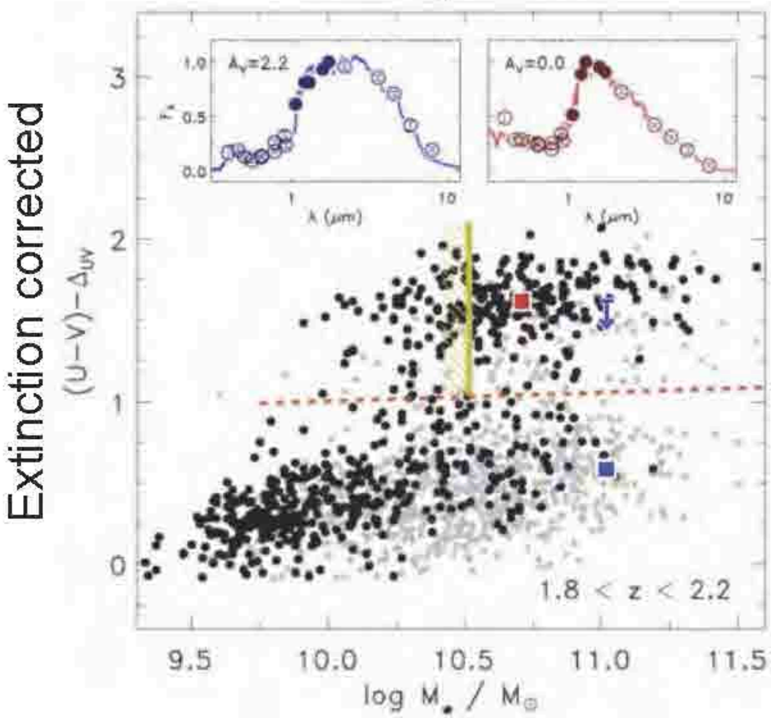
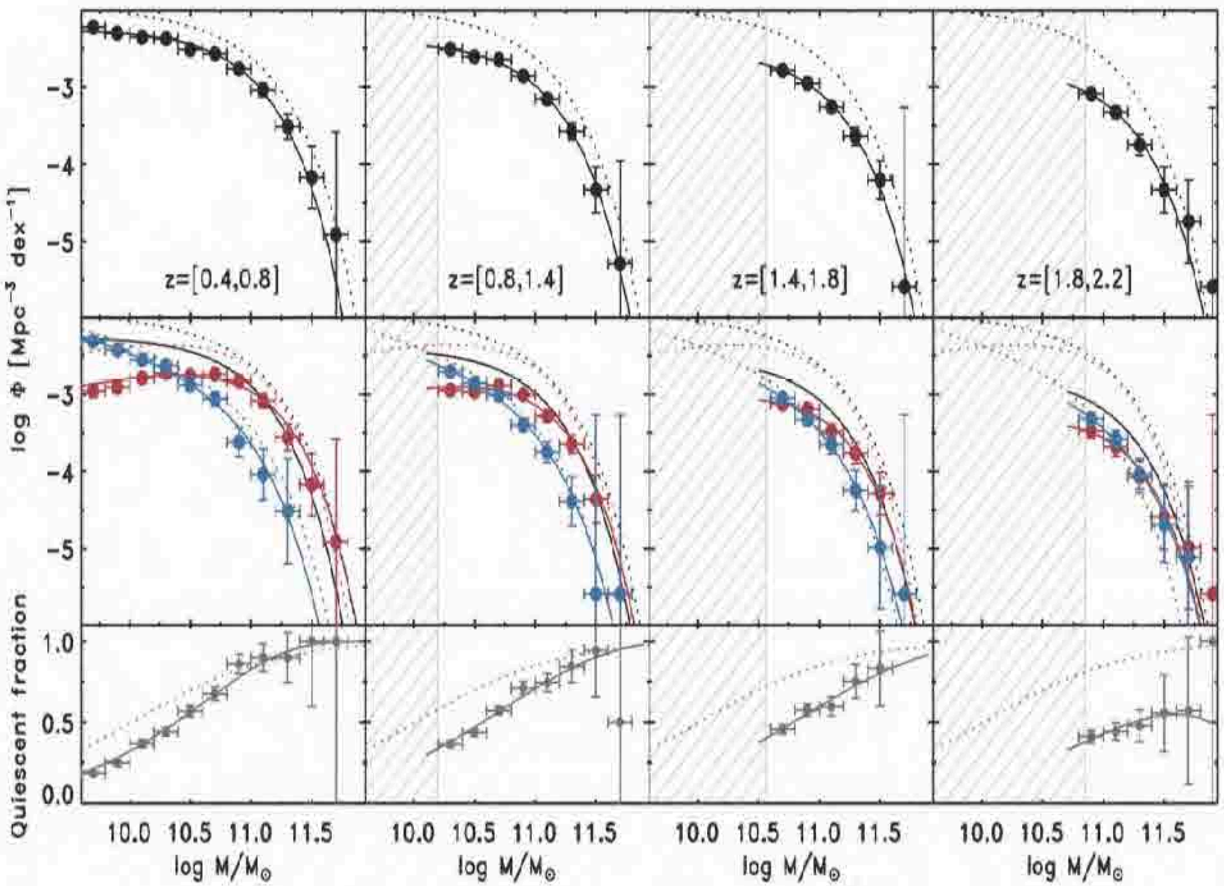
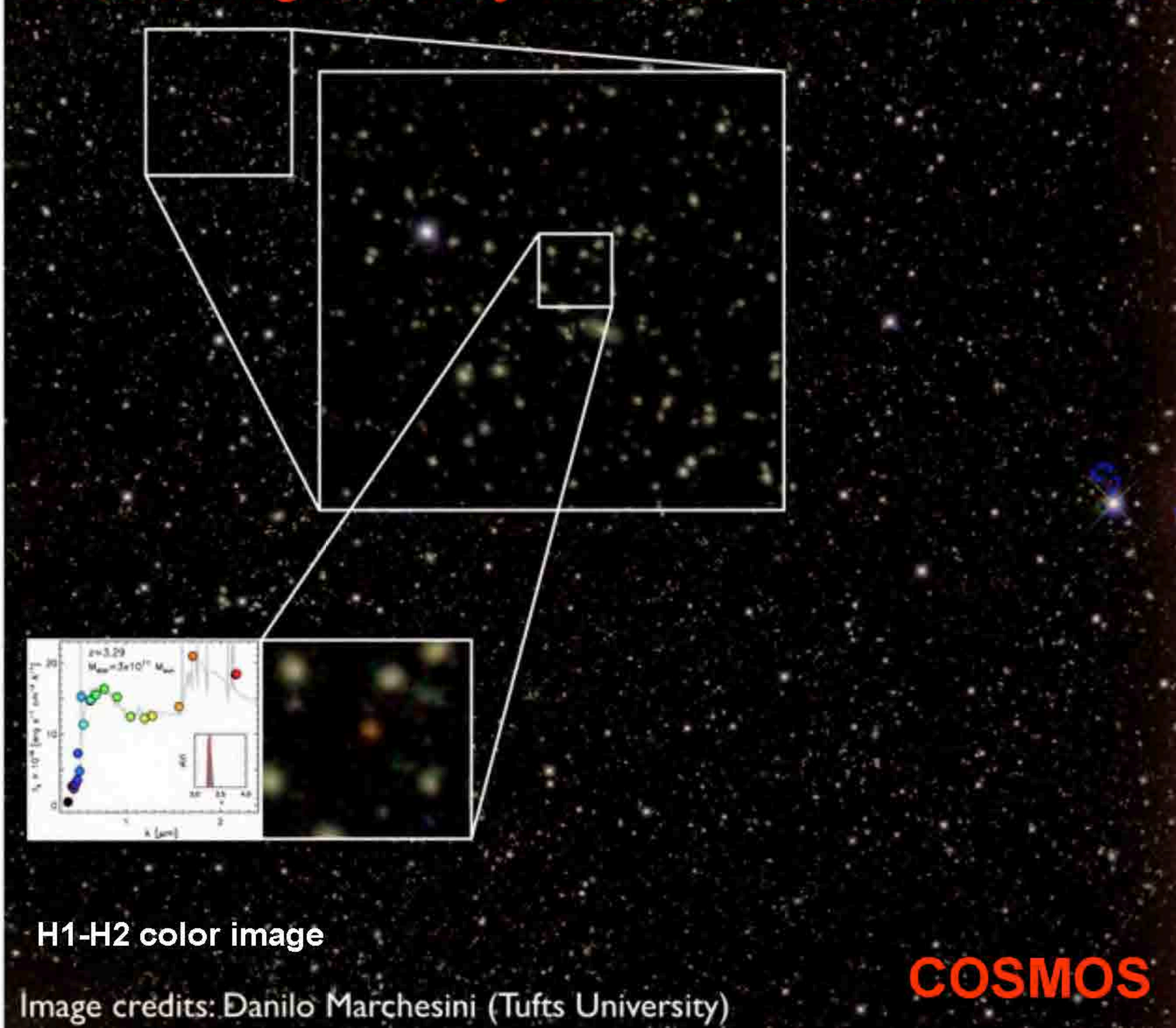




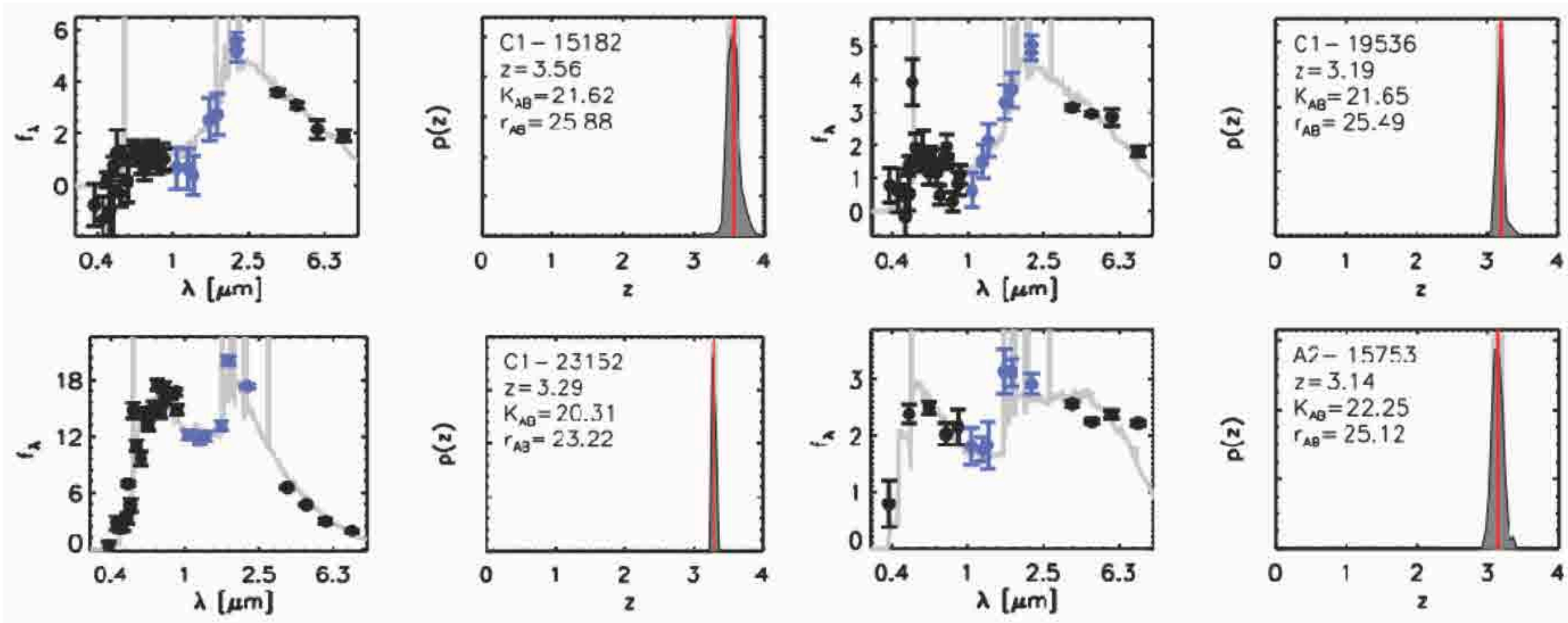


(Brammer, DM, et al. 2011)

Searching for Very Massive Galaxies at z>3



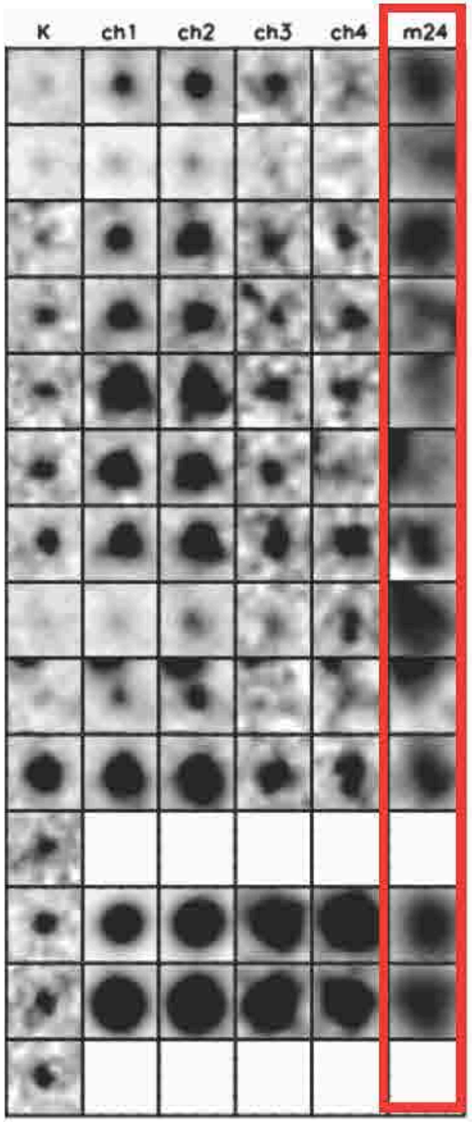
Stellar Mass-complete Sample of Galaxies at 3<z<4



(Marchesini et al. 2010)

- 14 galaxies at 3<z<4 with $M_{star}>10^{11.4}$ M_{sun} = 2.5×10^{11} M_{Sun} in COSMOS (10) and AEGIS (4) over an effective area of 0.44 deg^2
- Photometric redshift accuracy ~0.04 in dz/(1+z)
- ~50% with ages consistent with age of the universe at the targeted z (~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

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:

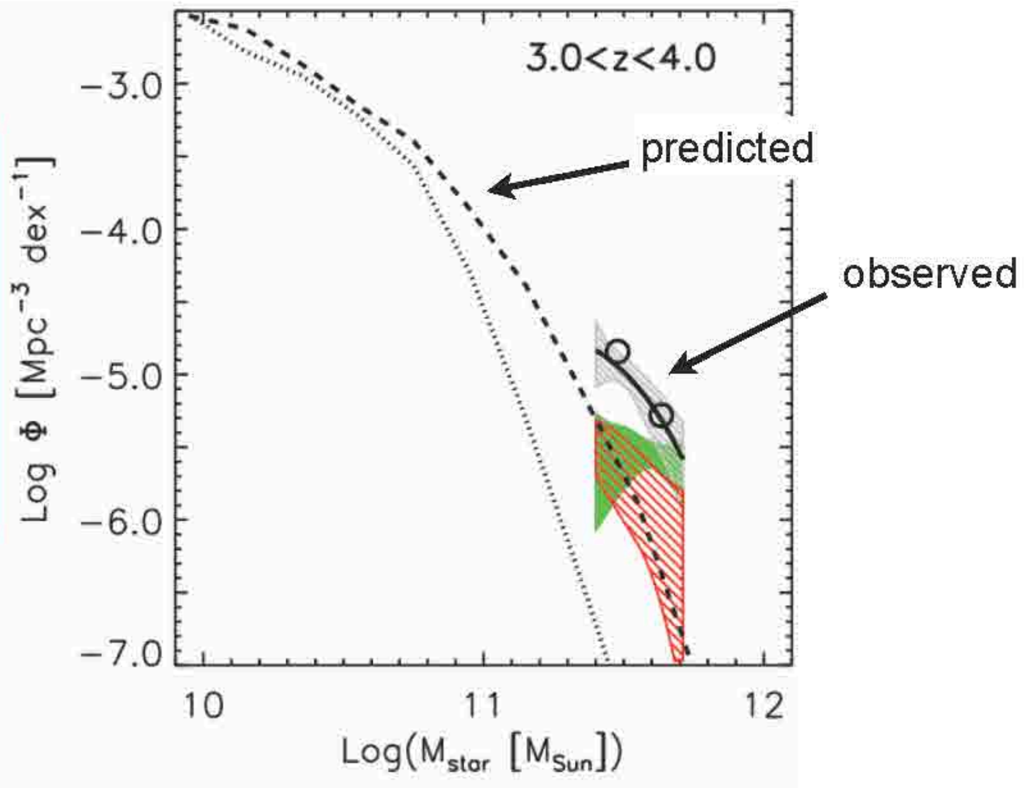
- IR-derived SFRs~600-4300 M_{sun}/yr (a few hundred times larger than the SFRs from SED modeling), implying mass-doubling times ~ 0.5-7x10^8 yr.
  - This very large star-forming activity has to be quickly quenched to be consistent with the little evolution in the SMF (Marchesini et al. 2009).
- HOWEVER, likely contamination from obscured AGN
  - 3 detected in X-rays (obscured, high-luminosity AGNs) + 1 RL-AGN
  - 24 μm corresponds to ~5.5 micron rest-frame, where hot dust dominates the MIR emission (no/little PAHs)

Massive, Old, and Dusty Galaxies at z~2.6?

- The EAZY default template set already includes a dusty starburst model (50 Myr old, A_V=2.75 mag)
- Added an additional template representative of an old (1 Gyr, tau=100 Myr) and very dusty galaxy (A_V=3 mag) galaxy
- 50% of the mass-selected sample could move to z~2.6, assuming properties of massive (M_{star}~2×10^{11} M_{Sun}), old (age~2 Gyr) and dusty (A_V~2-3 mag) stellar populations.

Up to 50% of the sample potentially contaminated by a previously unrecognized population of massive, old, and dusty galaxies at 2<z<3

(Marchesini et al. 2010)

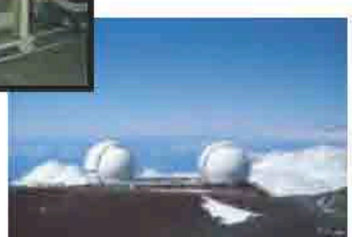


Spectroscopy of 3<z<4 Massive Galaxies

(PhD Thesis of Tufts student Cemile Marsan)

- ☑ Spectroscopic confirmation is required to break the ambiguity between massive z=3.5 galaxies and massive, old, AND dusty galaxies at z=2.6

- ☑ Magellan-IMACS MOS optical spectroscopy (PI: Marchesini; collected - Jan 2011)
- ☑ Keck-NIRSPEC NIR spectroscopy (PI: Marchesini; collected - Feb 2011)
- ☑ VLT-Xshooter UV-NIR spectroscopy (Brammer & Marchesini; collected - May 2011)
- ☑ GTC-OSIRIS OPT spectroscopy (Fernandez-Soto, Marchesini, Stefanon; collected - 2012)

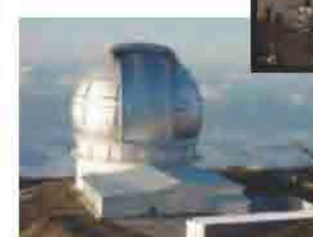
NIRSPEC

XSHOOTER



IMACS

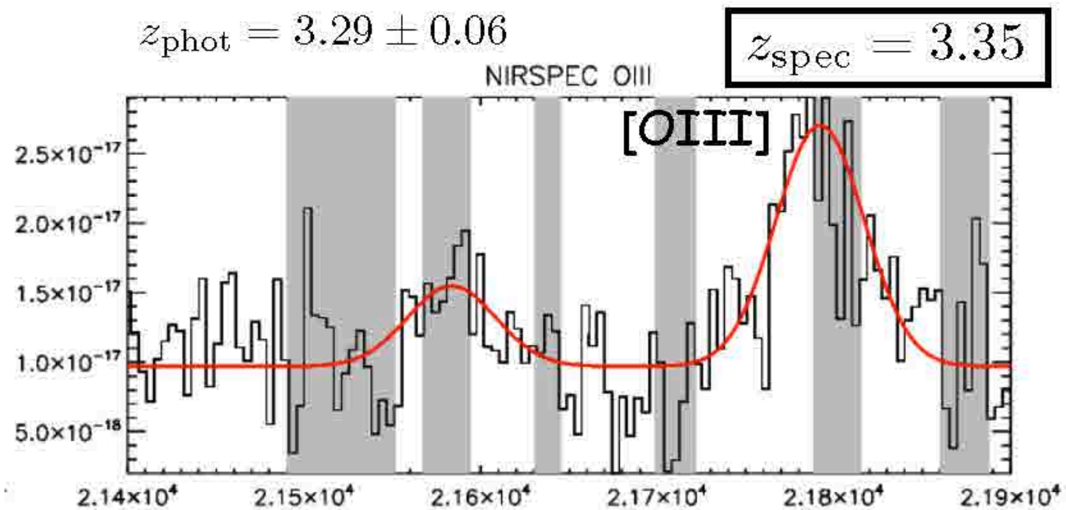
OSIRIS

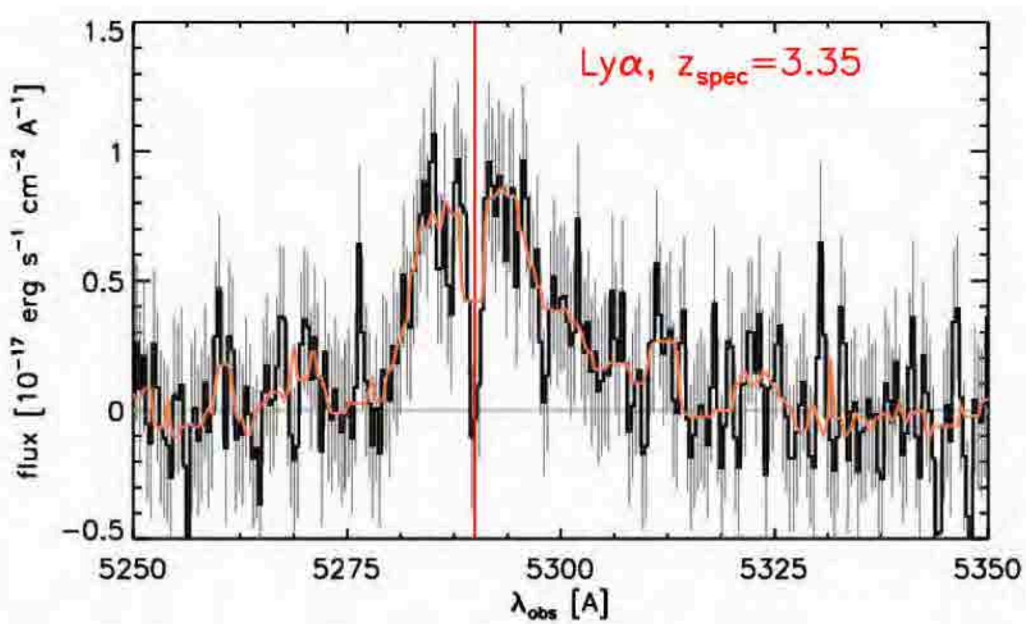
Spectroscopy of 3<z<4 Massive Galaxies

(Marsan, Marchesini, et al., 2013, to be submitted)

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



(CIV in emission also detected)



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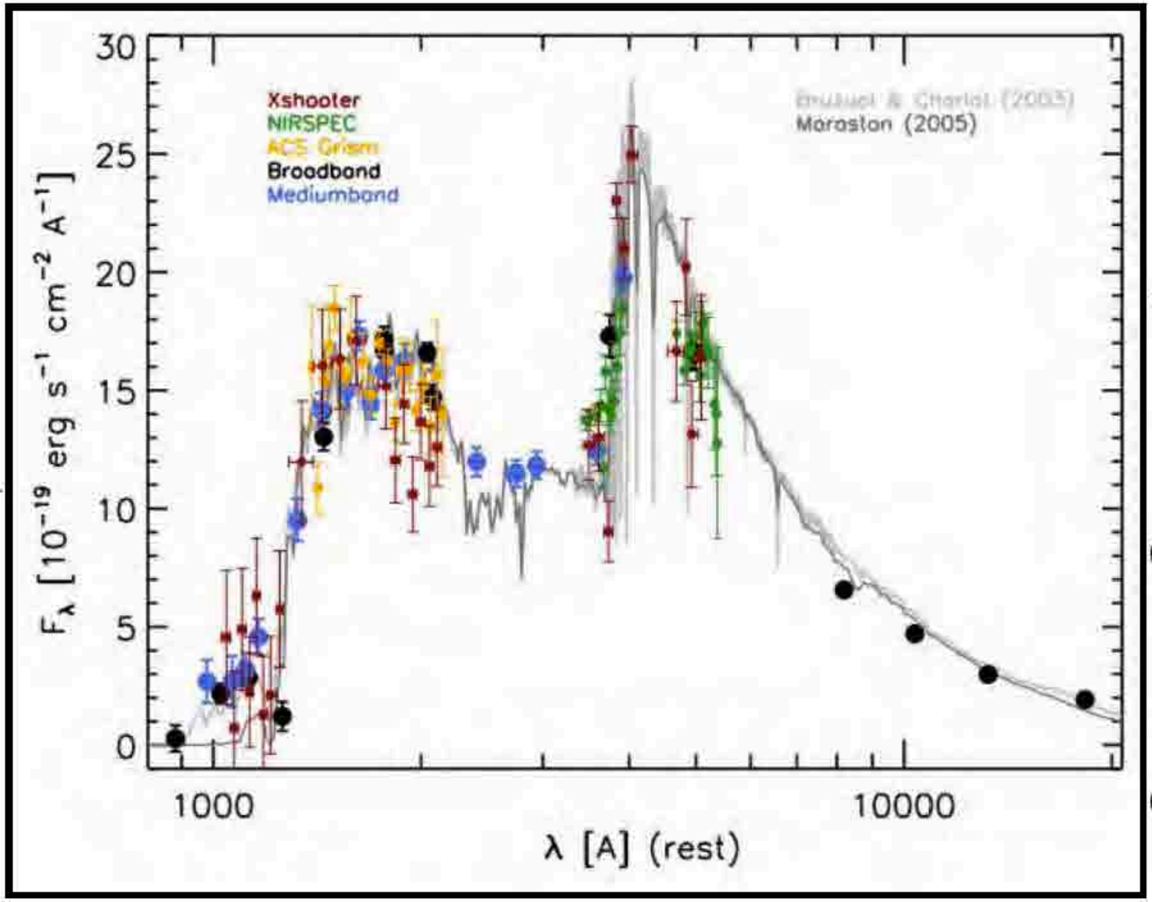

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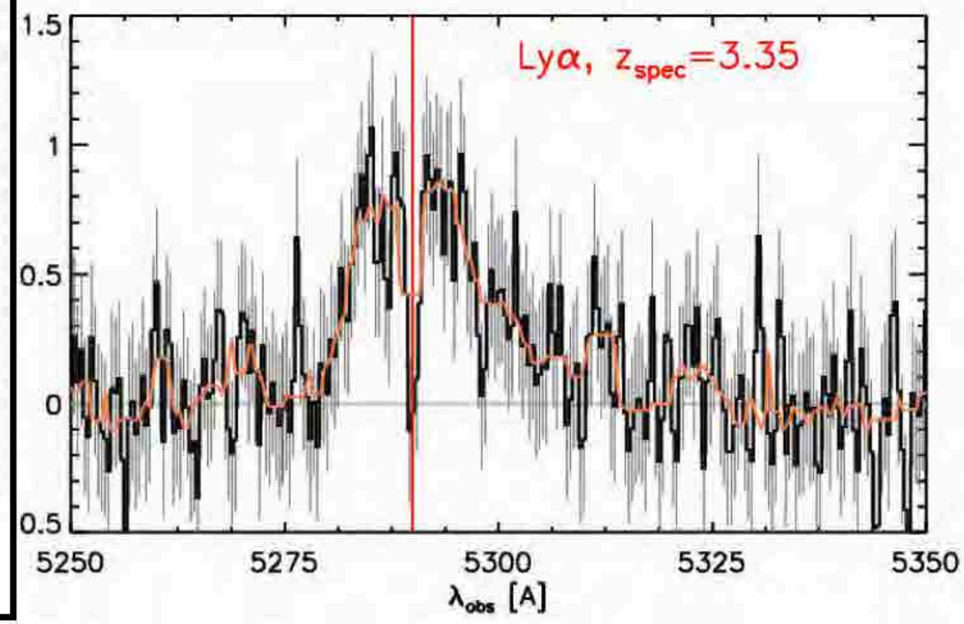
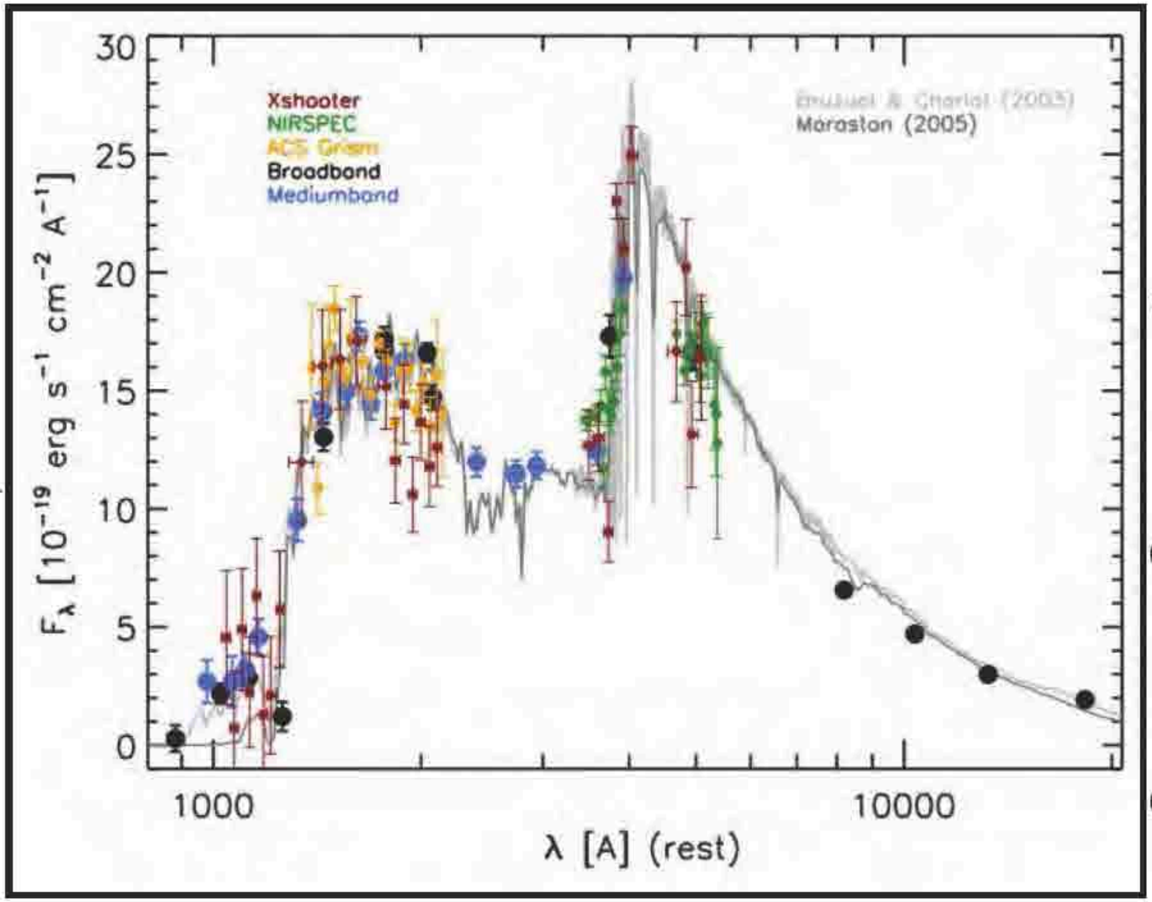


$M_{star} = 3 \times 10^{11}\ M_{sun}$ (Kroupa; BC03-MA05)
SFR=3 M_{sun}/yr, A_V=0
log(sSFR/yr) = -11
age = 200-400 Myr
tau = 50 Myr

Spectroscopy of 3<z<4 Massive Galaxies



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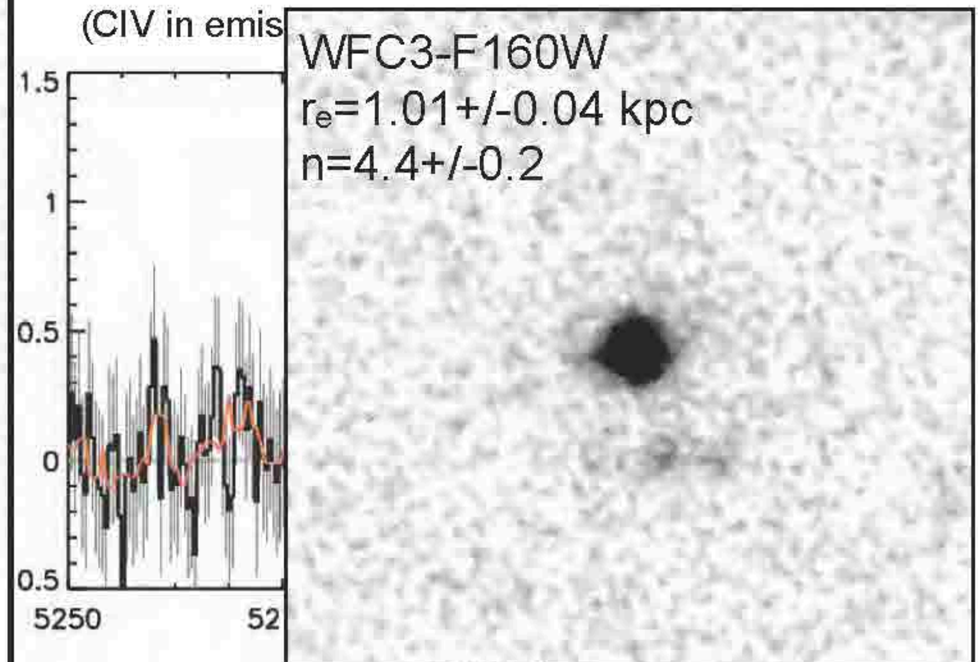

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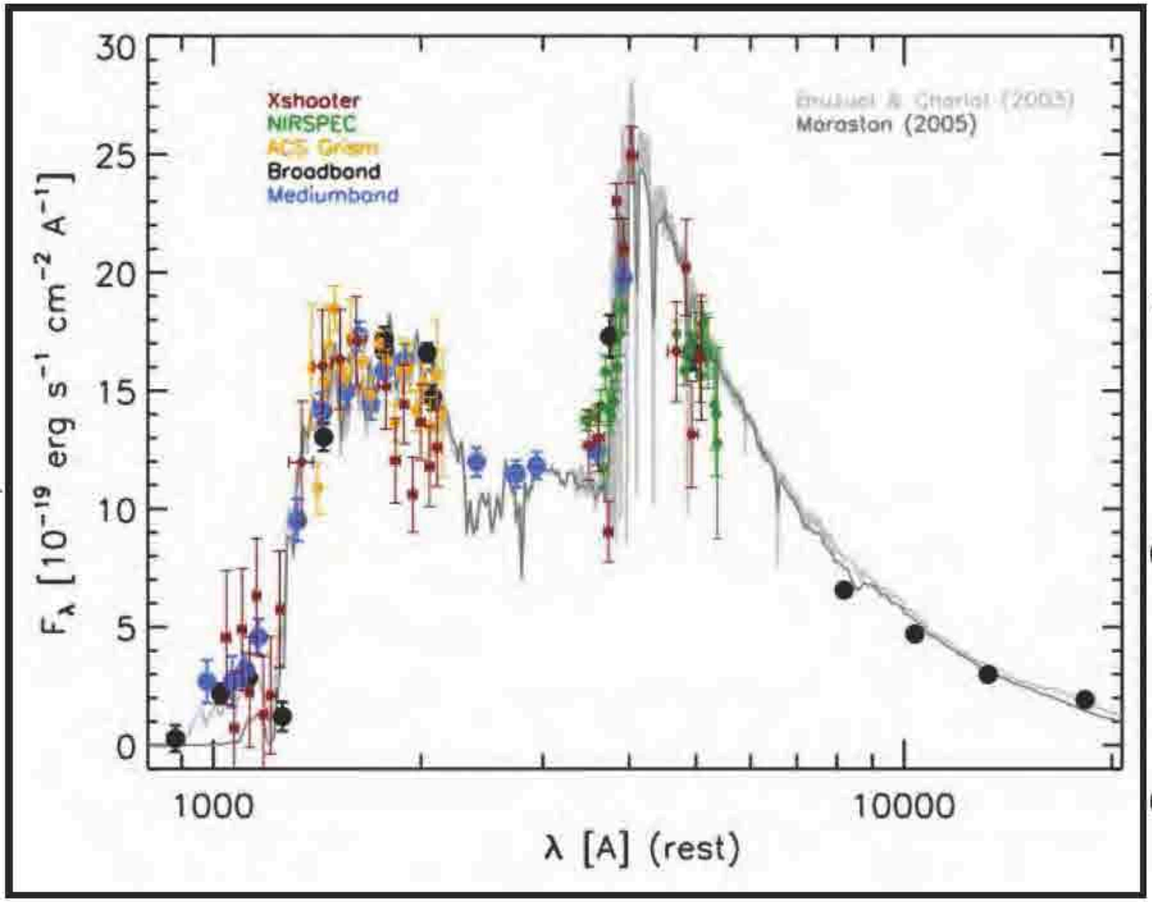

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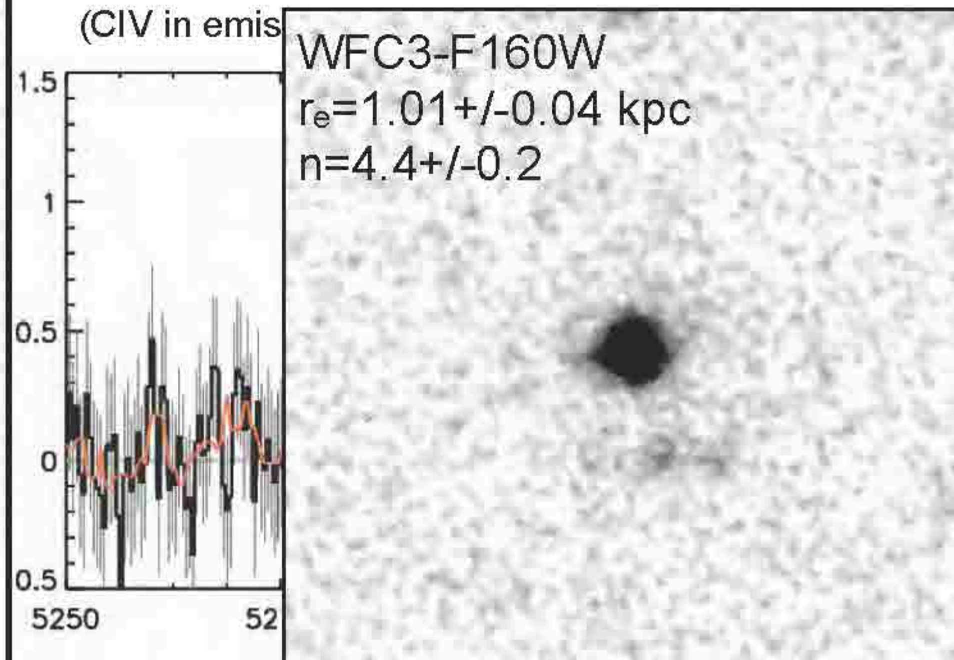

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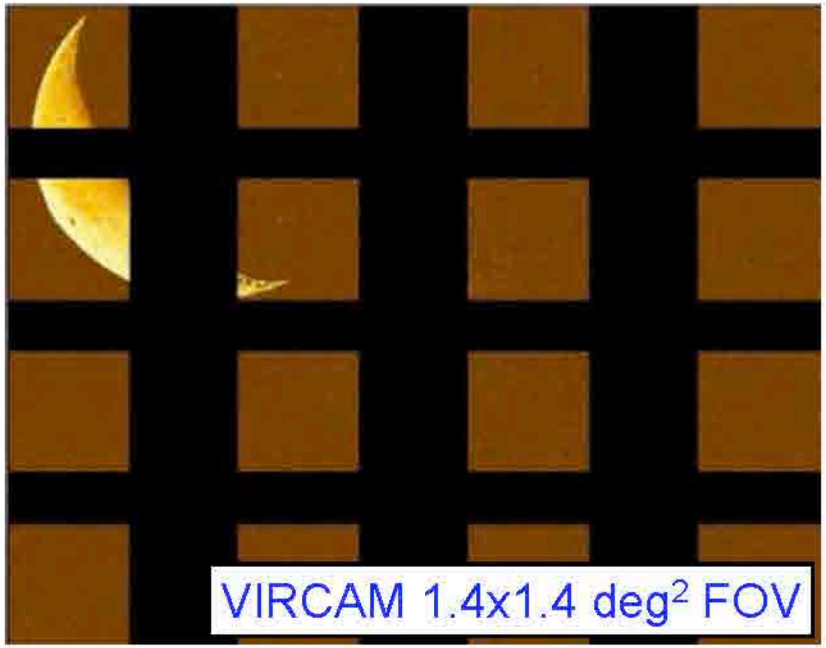
Prototype object of a massive, post-starburst galaxy that formed most of its stars in a short and intense burst at z_{form}~4.1 and likely hosting an AGN (from line properties and MIPS detection).

The UltraVISTA Survey

- Ultra deep, NIR (YJHK) imaging survey with the VISTA survey telescope (ESO) in COSMOS (5 years project).
- ***Deep component:*** K_{AB}=23.4, 90% completeness, 1.8 deg^2
- *<u>Ultra-deep component:</u>* K_{AB}=25.6, 0.7 deg^2
- Significant upgrade in both survey volume and data quality compared to many previous measurements.



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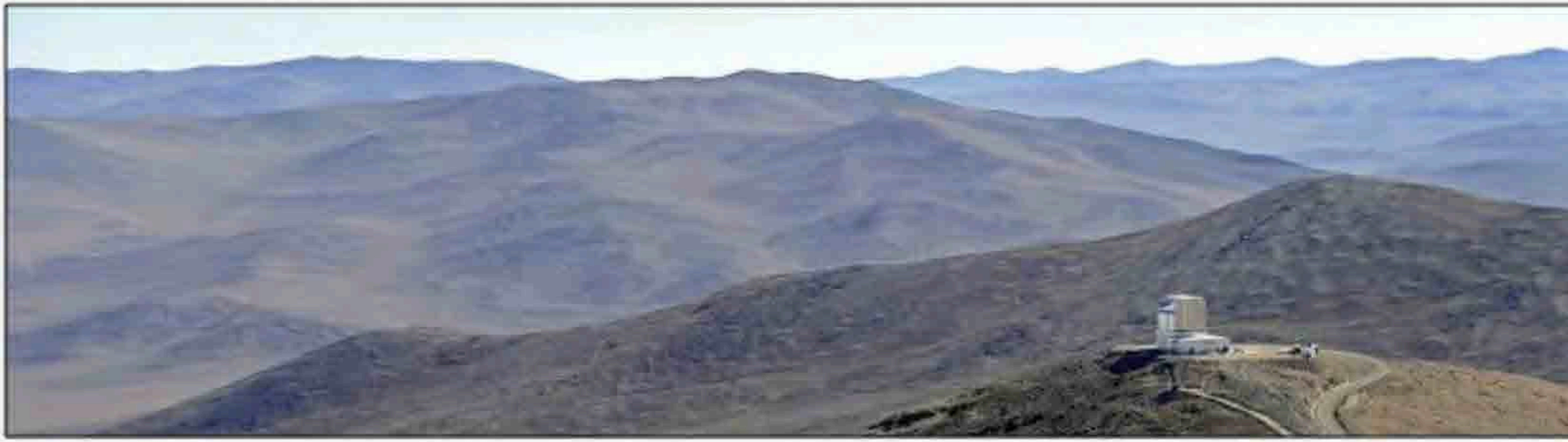


If you use this catalog in your research, please acknowledge it by citing the catalog paper, Muzzin et al. (2013), Apj, submitted, click here.

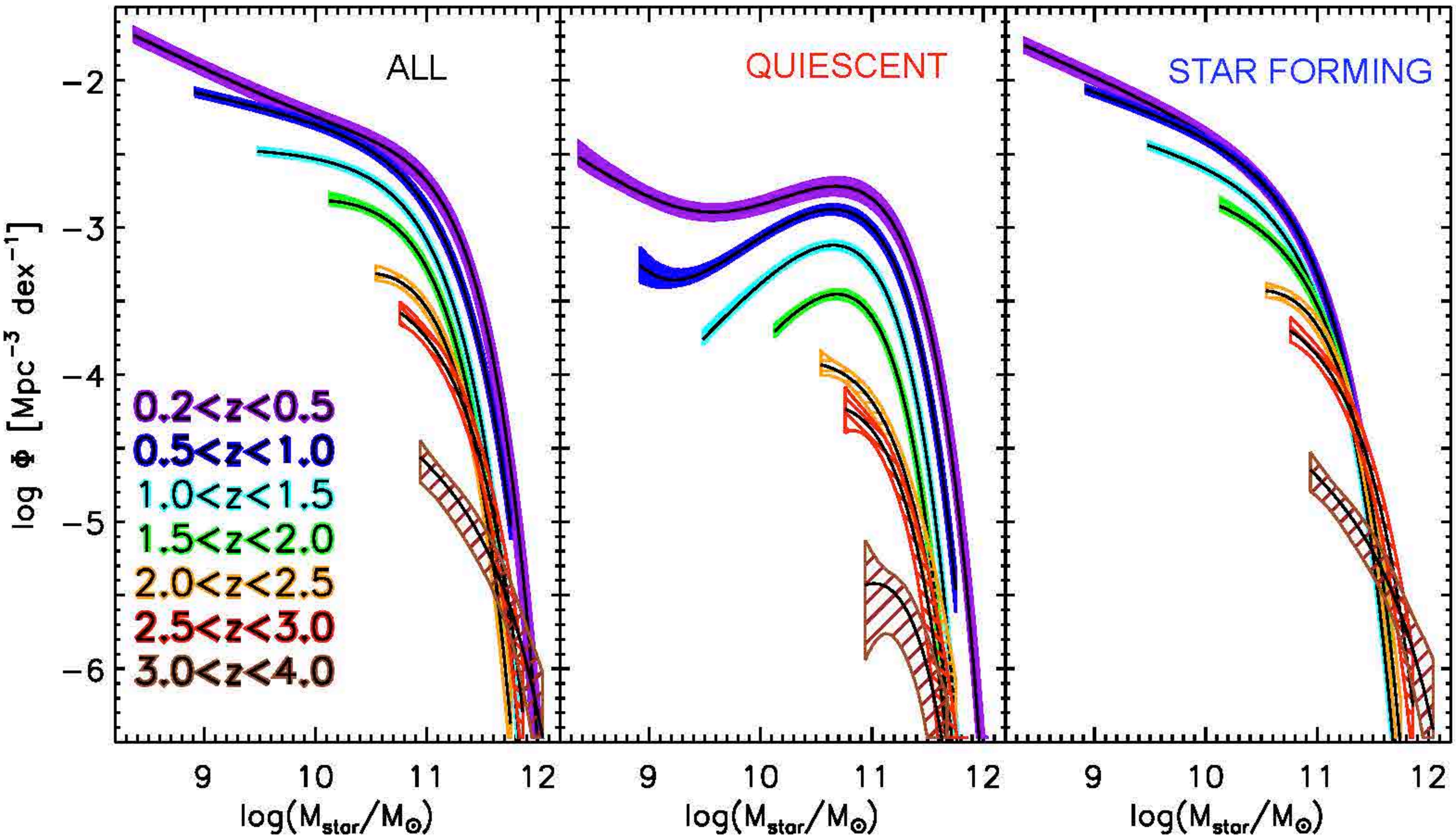
(Muzzin, Marchesini, Stefanon, et al., 2013A)

UltraVISTA DR1 Images and **Catalogs** are **Public**!

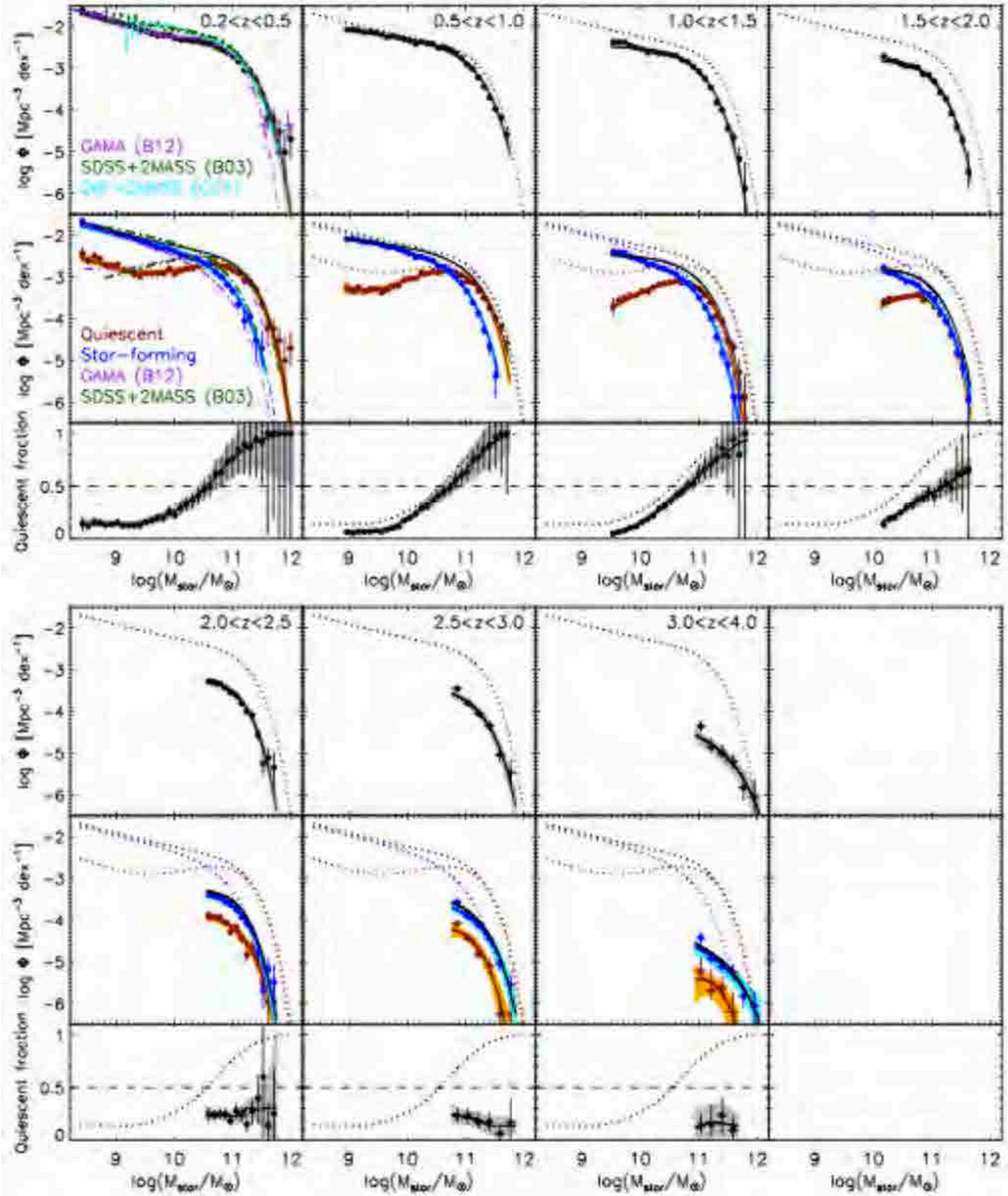
`http://www.strw.leidenuniv.nl/galaxyevolution/ULTRAVISTA/Ultravista/Data_Products_Download.html`

- Photometric catalog (GALEX-to-MIPS 24 micron, 30 bands, K_S-selected)
- Photometric redshift catalog (from EAZY)
- Stellar population parameters (from FAST), e.g., M_{star}, SFR, A_V...
- Rest-frame colors and luminosities (from EAZY)
- Infrared luminosities and SFR from infrared

SMFs of Galaxies from the UltraVISTA at 0.2<z<4.0



(Muzzin, Marchesini, et al., 2013B;
see also Ilbert et al. 2013)



ALL

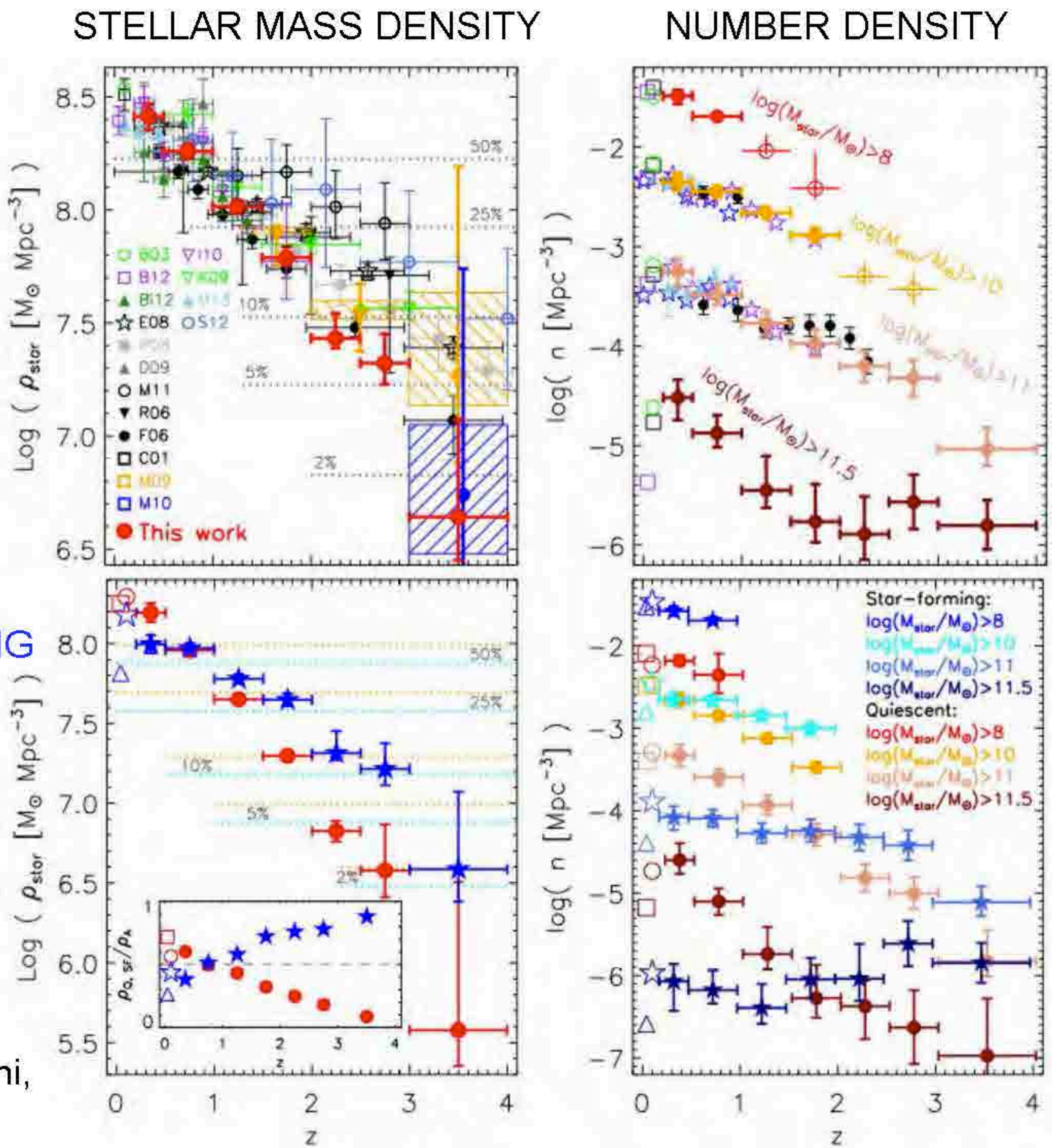
QUIESCENT

STAR FORMING

- Quiescent galaxies dominate the high-mass end at z<1.5
- At 1.5<z<2, quiescent and star-forming galaxies contribute equally to the densities at the high-mass end
- Star-forming galaxies dominate the total SMF at all stellar masses at z>2.5
- A population of quiescent galaxies is confirmed to exist at z=4

(Muzzin, Marchesini, et al., 2013B)

Densities' Evolution at 0.2<z<4.0 from UltraVISTA

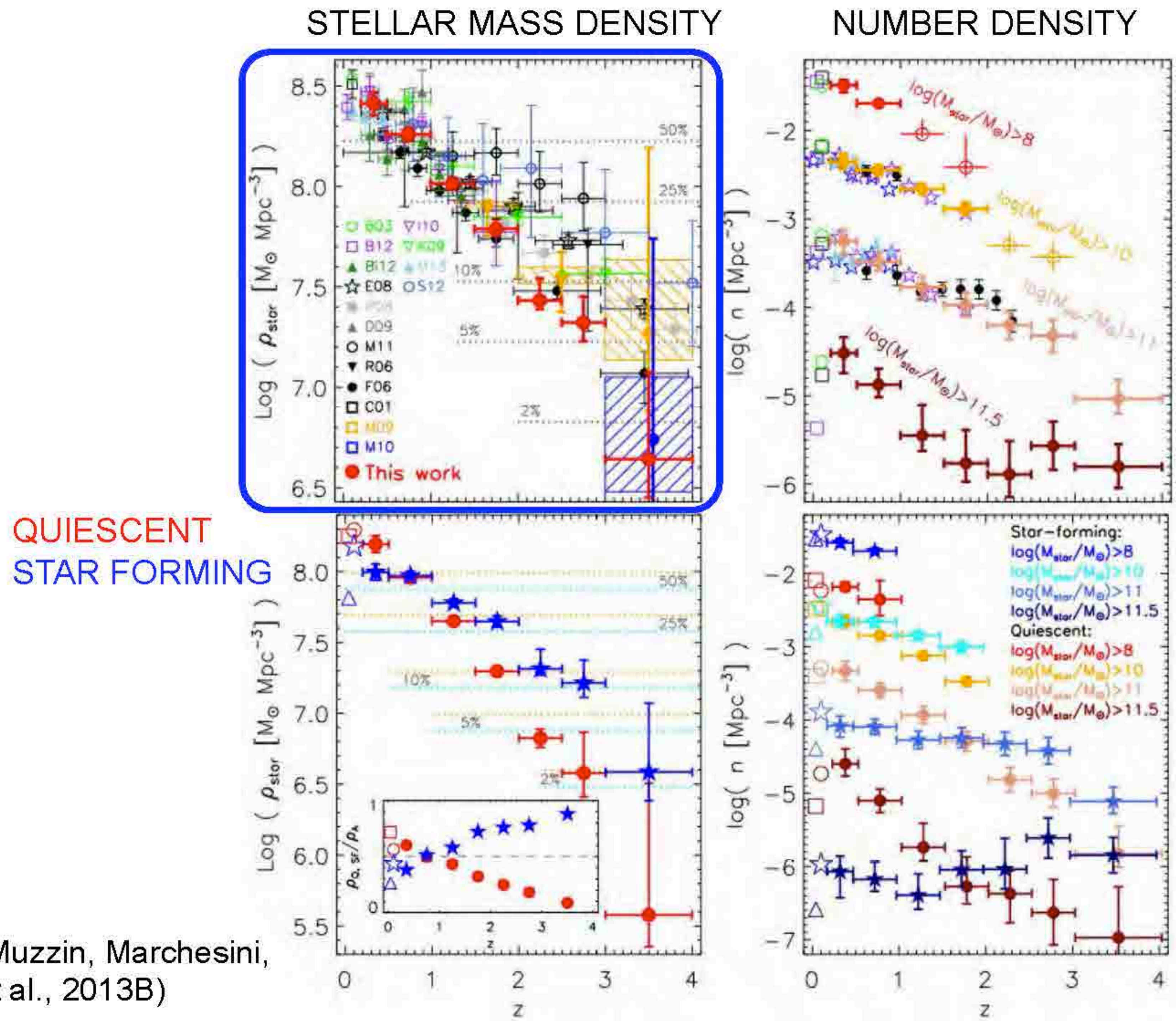


QUIESCENT

STAR FORMING

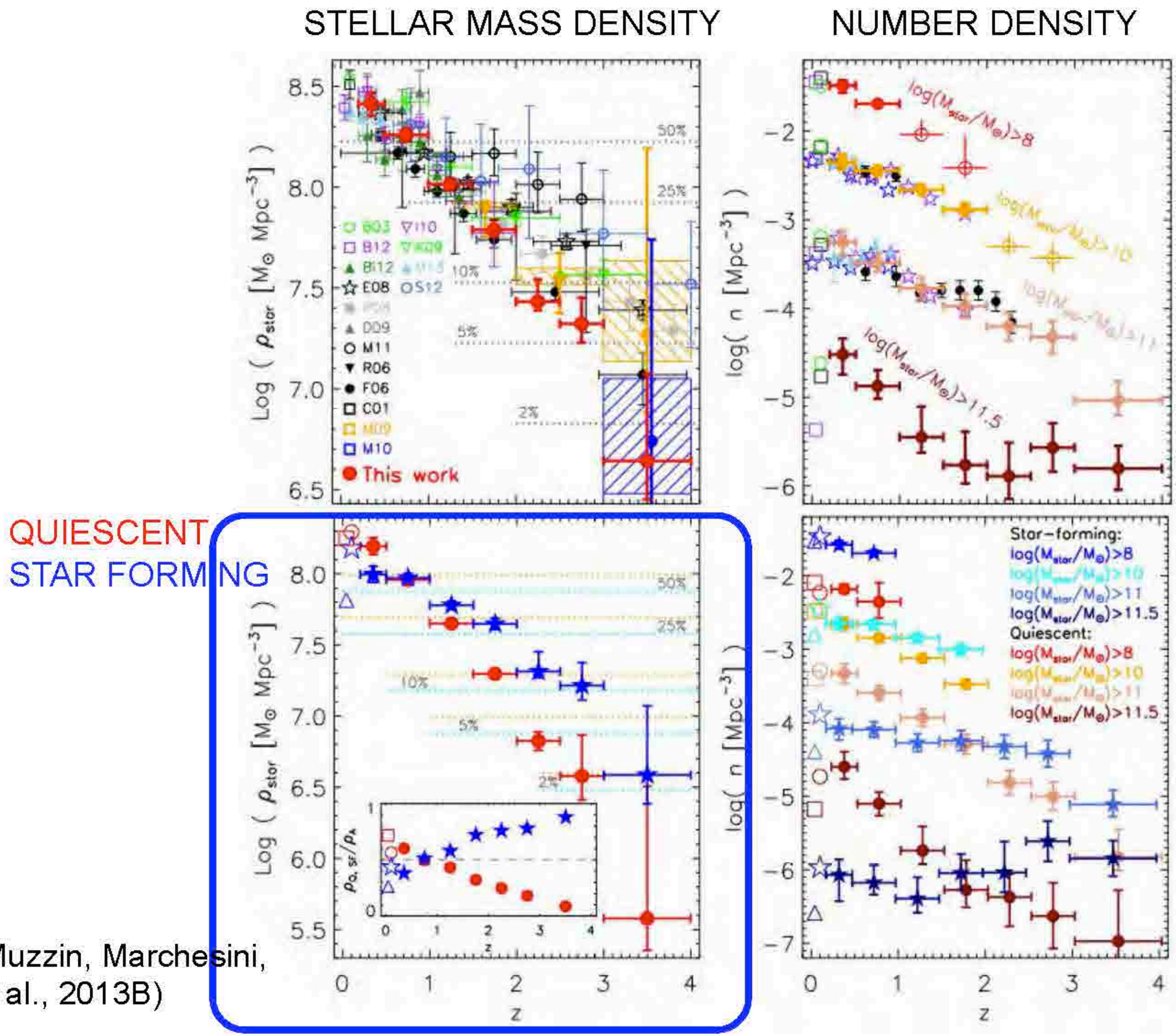
(Muzzin, Marchesini, et al., 2013B)

Densities' Evolution at 0.2<z<4.0 from UltraVISTA



(Muzzin, Marchesini, et al., 2013B)

Densities' Evolution at 0.2<z<4.0 from UltraVISTA



(Muzzin, Marchesini, et al., 2013B)

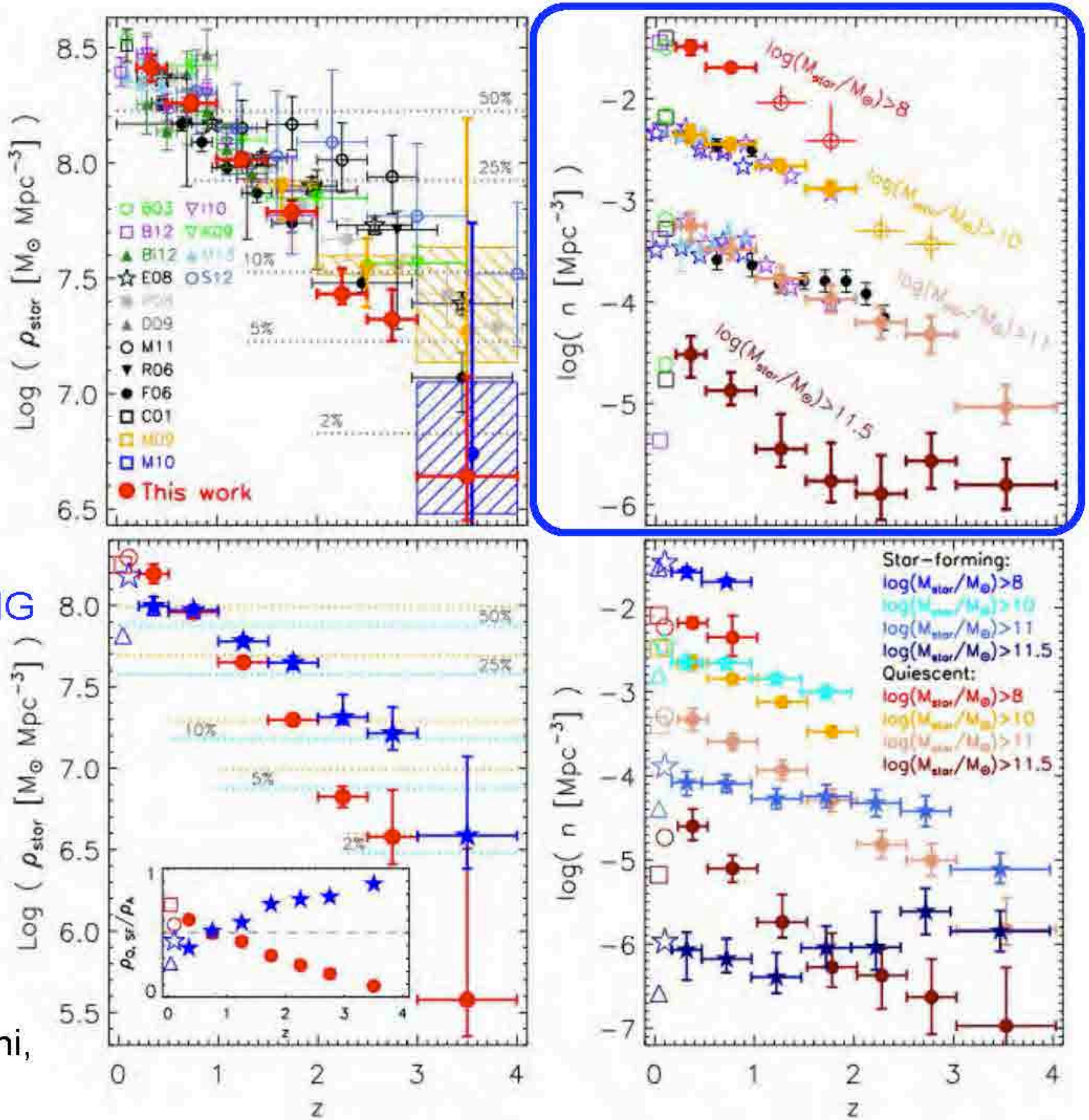
Densities' Evolution at 0.2<z<4.0 from UltraVISTA

STELLAR MASS DENSITY

NUMBER DENSITY

QUIESCENT

STAR FORMING



(Muzzin, Marchesini, et al., 2013B)

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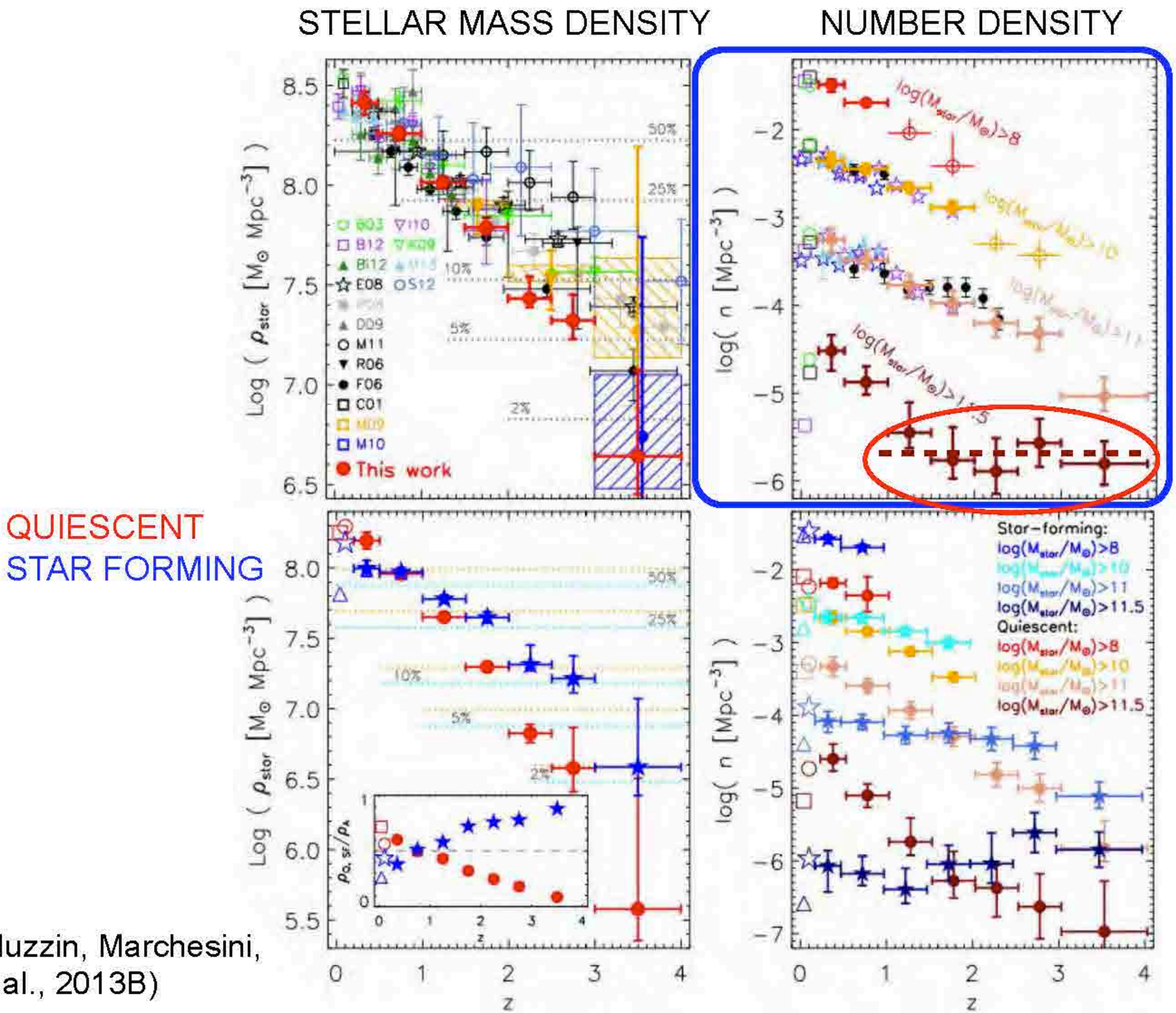
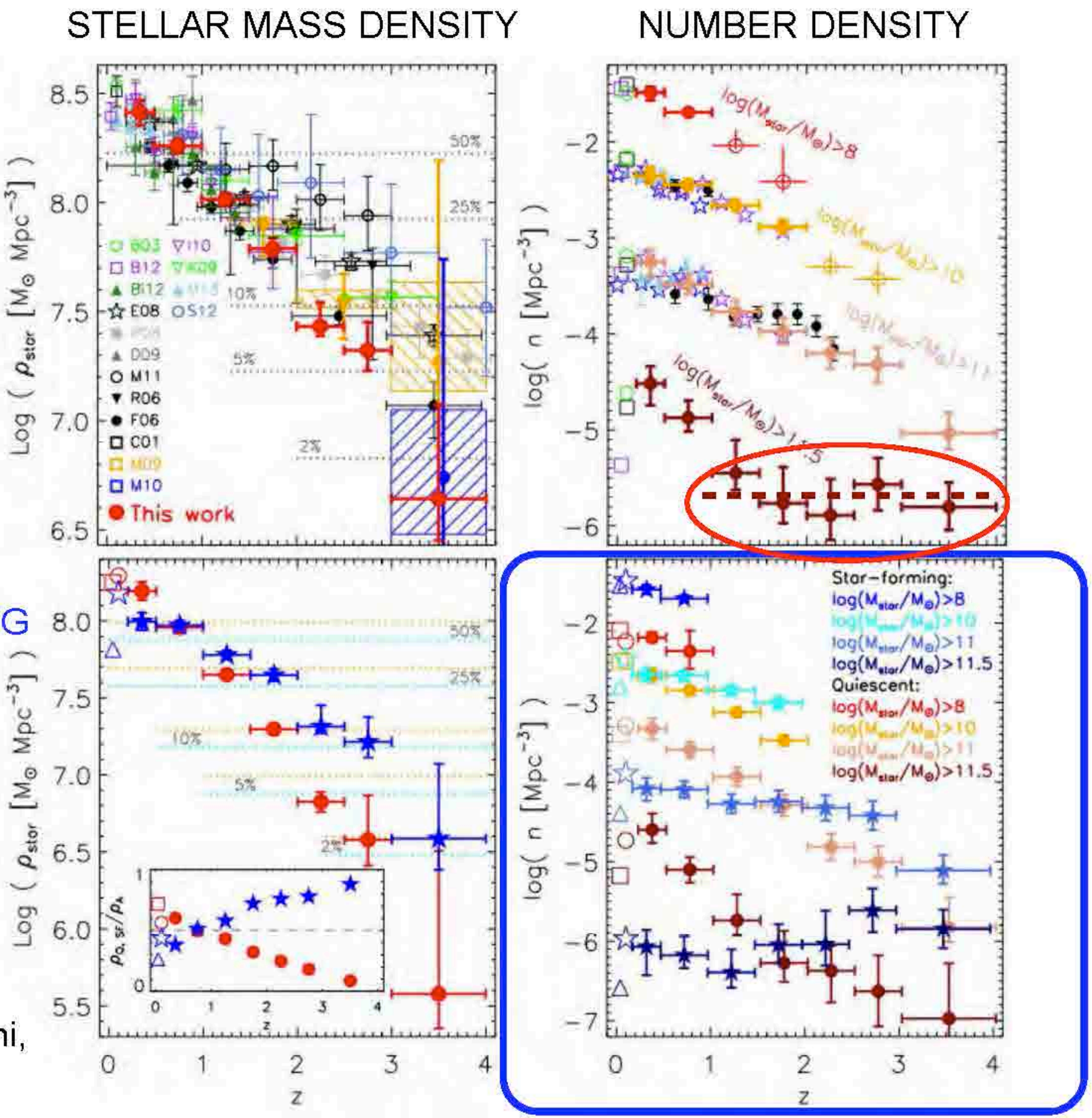


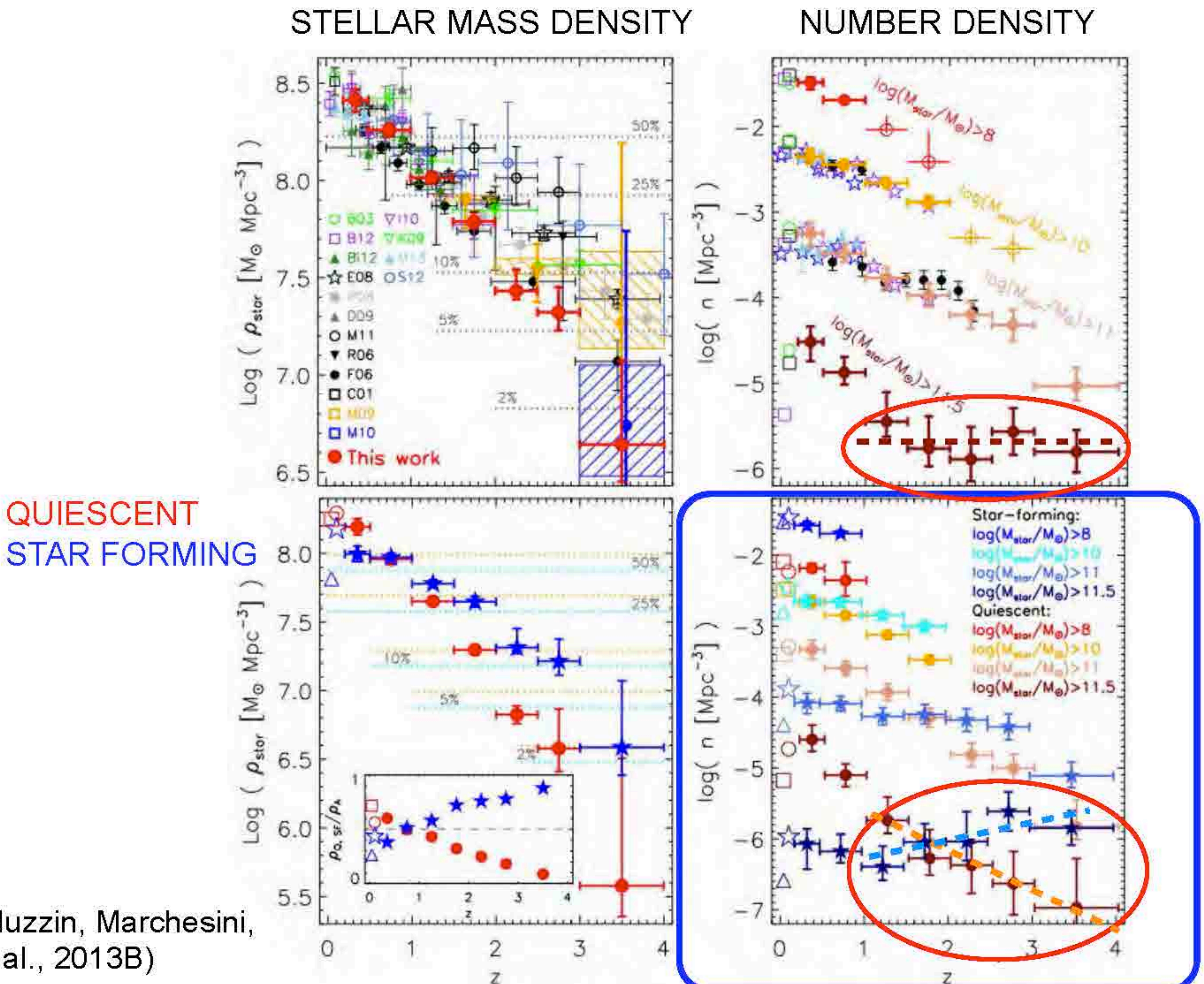
(Muzzin, Marchesini, et al., 2013B)

Densities' Evolution at 0.2<z<4.0 from UltraVISTA



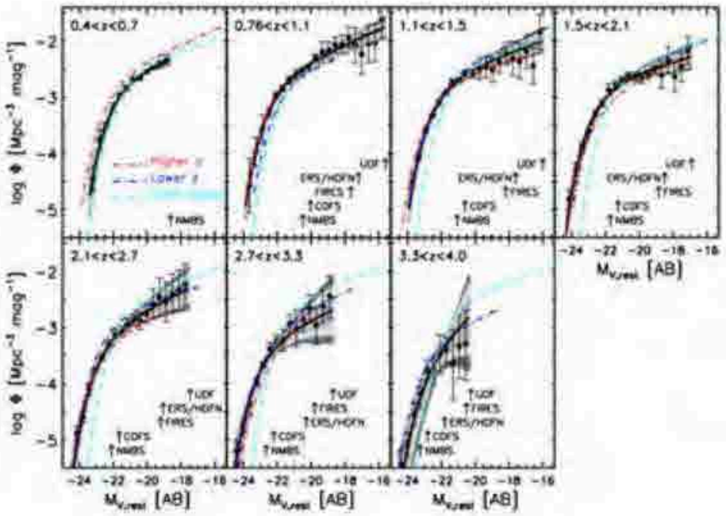
(Muzzin, Marchesini, et al., 2013B)

Densities' Evolution at 0.2<z<4.0 from UltraVISTA



(Muzzin, Marchesini, et al., 2013B)

Rest-frame Optical & NIR LFs and SMFs Downloadable at:



(Marchesini et al. 2012)

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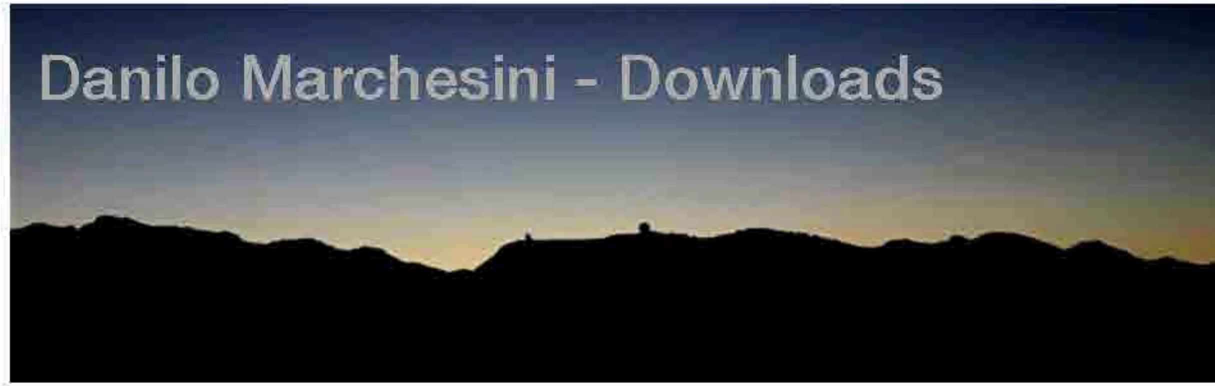


SURVEYS:

UltraVISTA/COSMOS catalogs from Muzzin et al. (2013a).

NMBS (NEWFIRM Medium-Band Survey) catalogs from Whitaker et al. (2011).

MUSYC (MUltiwavelength Survey by Yale-Chile) data releases from Gawiser et al. (2006), Quadri, Marchesini, et al. (2007), Blanc et al. (2008), Taylor et al. (2009), Cardamone et al. (2010).

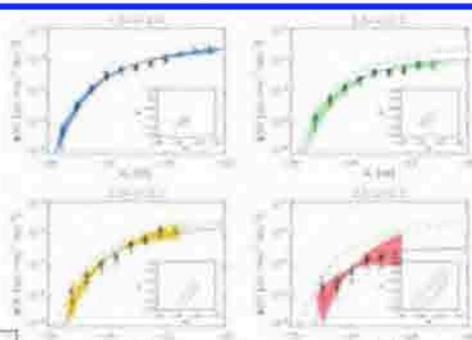
Spitzer/IRAC coverage in MUSYC: data and catalog release from Marchesini et al. (2009).

SIMPLE (Spitzer IRAC / MUSYC Public Legacy in E-CDFS) catalog from Damen et al. (2010).

GNIRS Survey for Massive Galaxies at z~2.5: data release from Kriek et al. (2008).

http://cosmos.phy.tufts.edu/~danilo/Downloads.html

(Stefanon, Marchesini, et al., 2012)



LUMINOSITY and STELLAR MASS FUNCTION MEASUREMENTS:

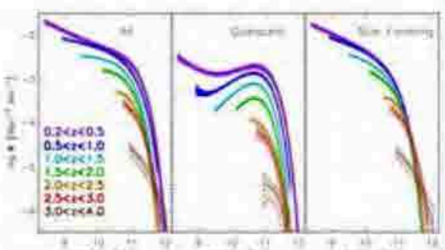
Stellar mass function at 0.2<z<4 from the UltraVISTA (presented in Muzzin, Marchesini, et al. 2013b).

Stellar mass function at 3<z<4 from the NMBS (presented in Marchesini et al. 2010).

Stellar mass functions from z=4.0 to z=1.3 (presented in Marchesini et al. 2009).

Rest-frame V-band luminosity functions from z=4 to z=0.4 (presented in Marchesini et al. 2012).

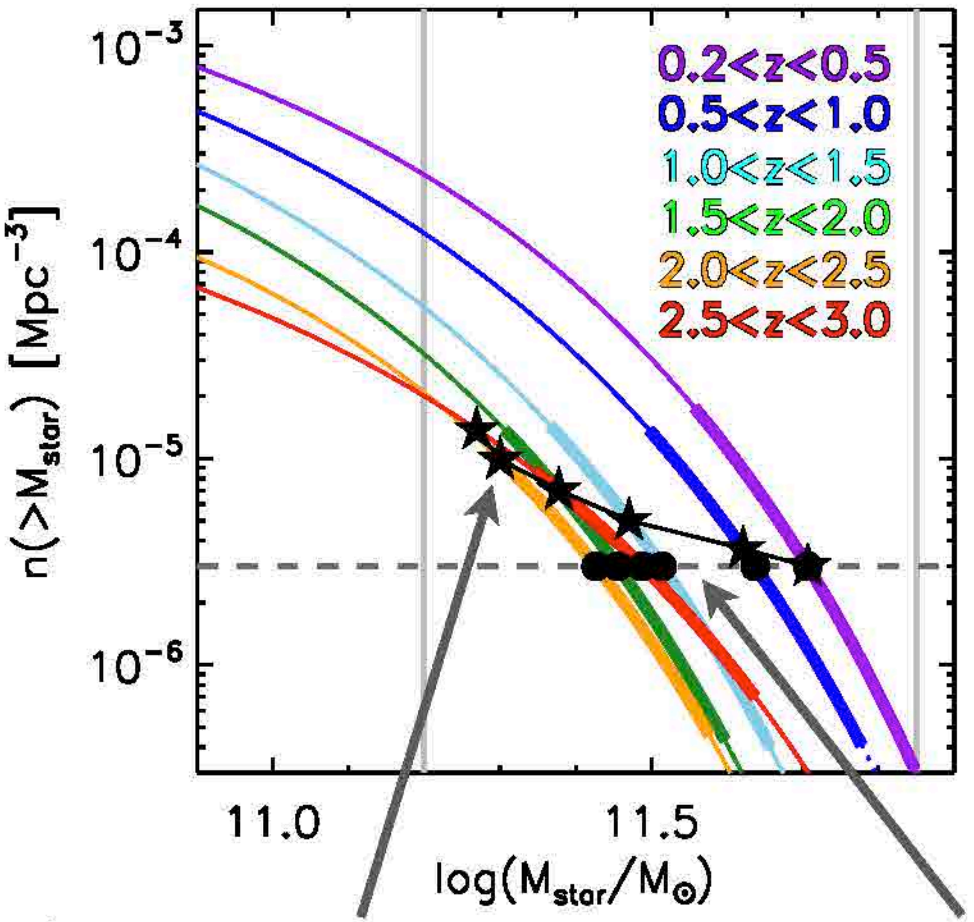
Rest-frame J- and H-band luminosity functions at 2<z<3.5 (presented in Stefanon & Marchesini 2011).



(Muzzin, Marchesini, et al., 2013B)

Selection of the Progenitors of Local Ultra-Massive Galaxies ($M_{star}=5\times10^{11}$ M_{sun}, i.e., $\log(M_{star}/M_{sun})=11.7$)

(Marchesini et al. 2013, to be submitted)



★ Abundance matching
(Behroozi, Marchesini, et al. 2013, submitted)

● Fixed cumulative number density
(e.g., Brammer, DM, et al. 2011; Leja et al. 2013)

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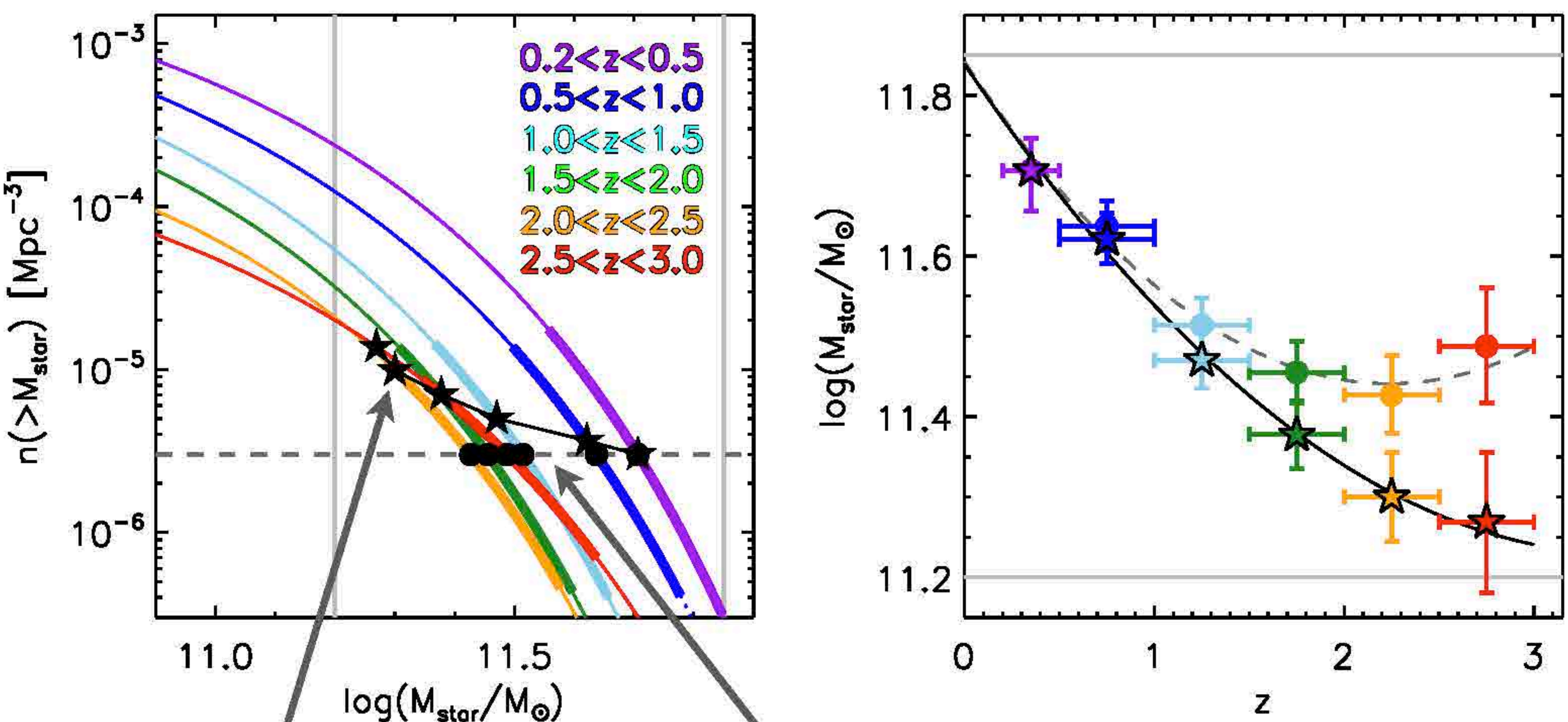
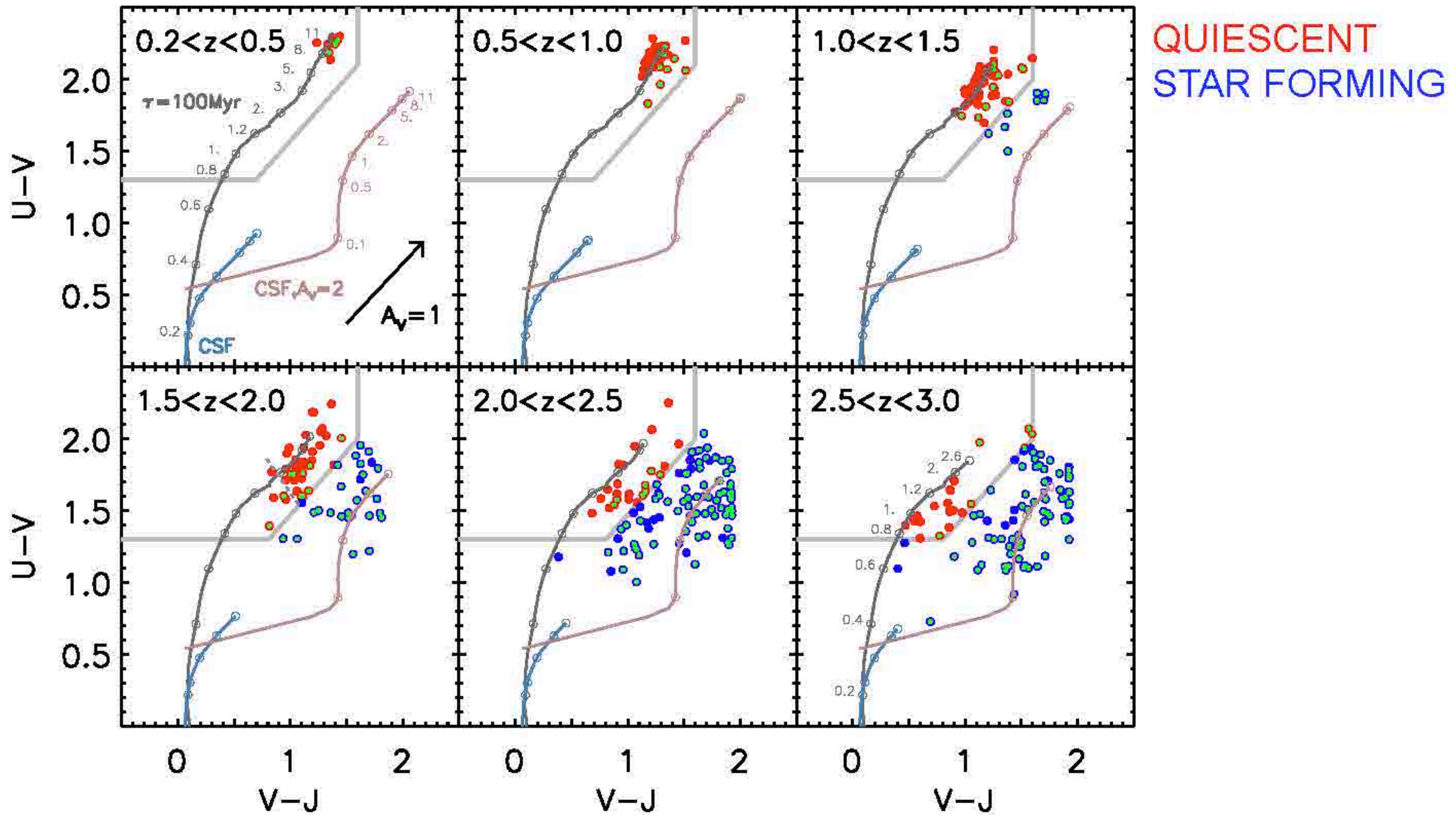


★ Abundance matching
(Behroozi, Marchesini, et al. 2013, submitted)

● Fixed cumulative number density
(e.g., Brammer, DM, et al. 2011; Leja et al. 2013)

- Mass growth by ~0.25 dex (<2x) from z=3 using fixed cumulative number density.
- Mass growth is 0.45 dex (~3x) using abundance matching techniques

Evolution of Progenitors in the UVJ diagram



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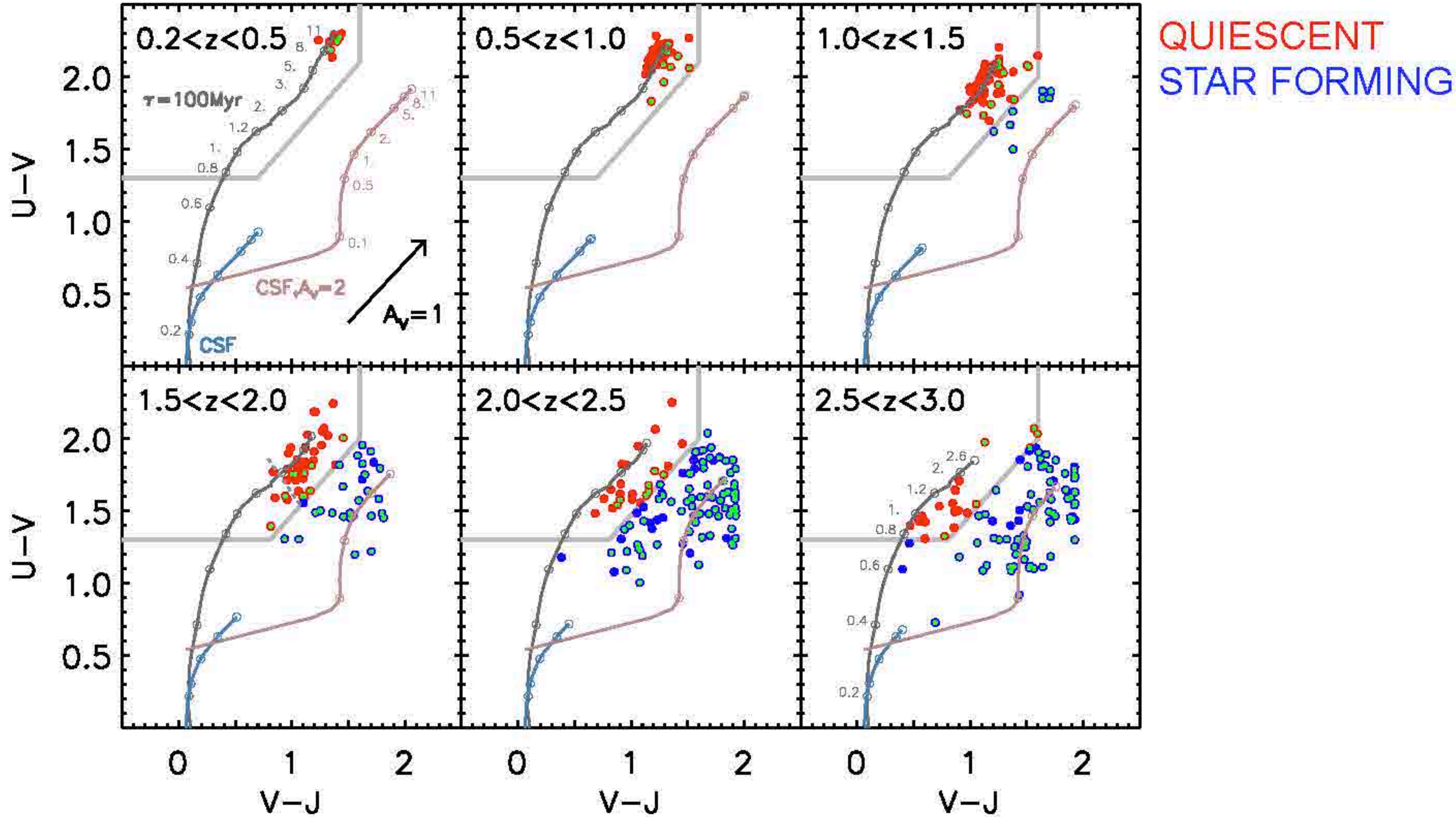
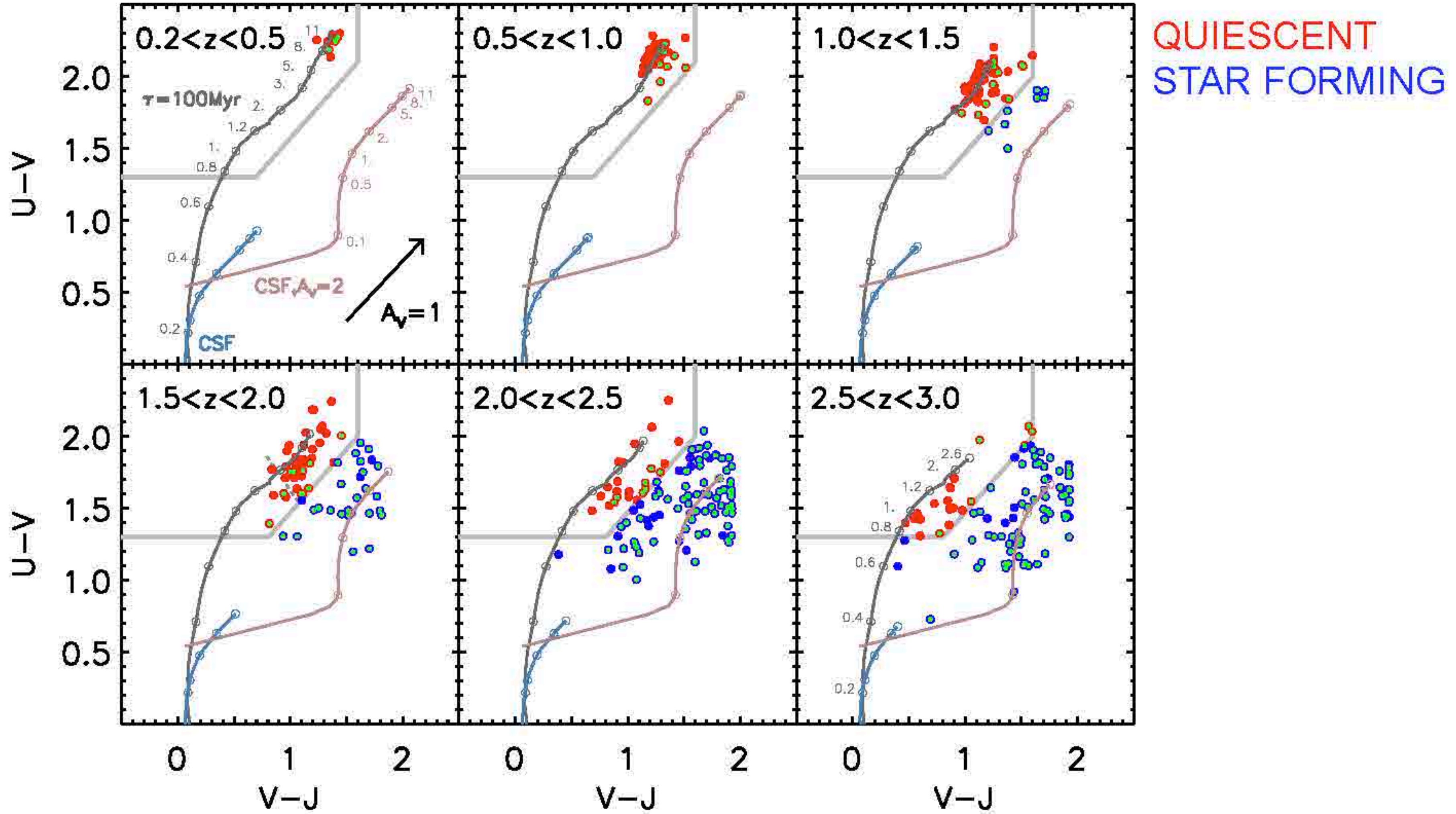


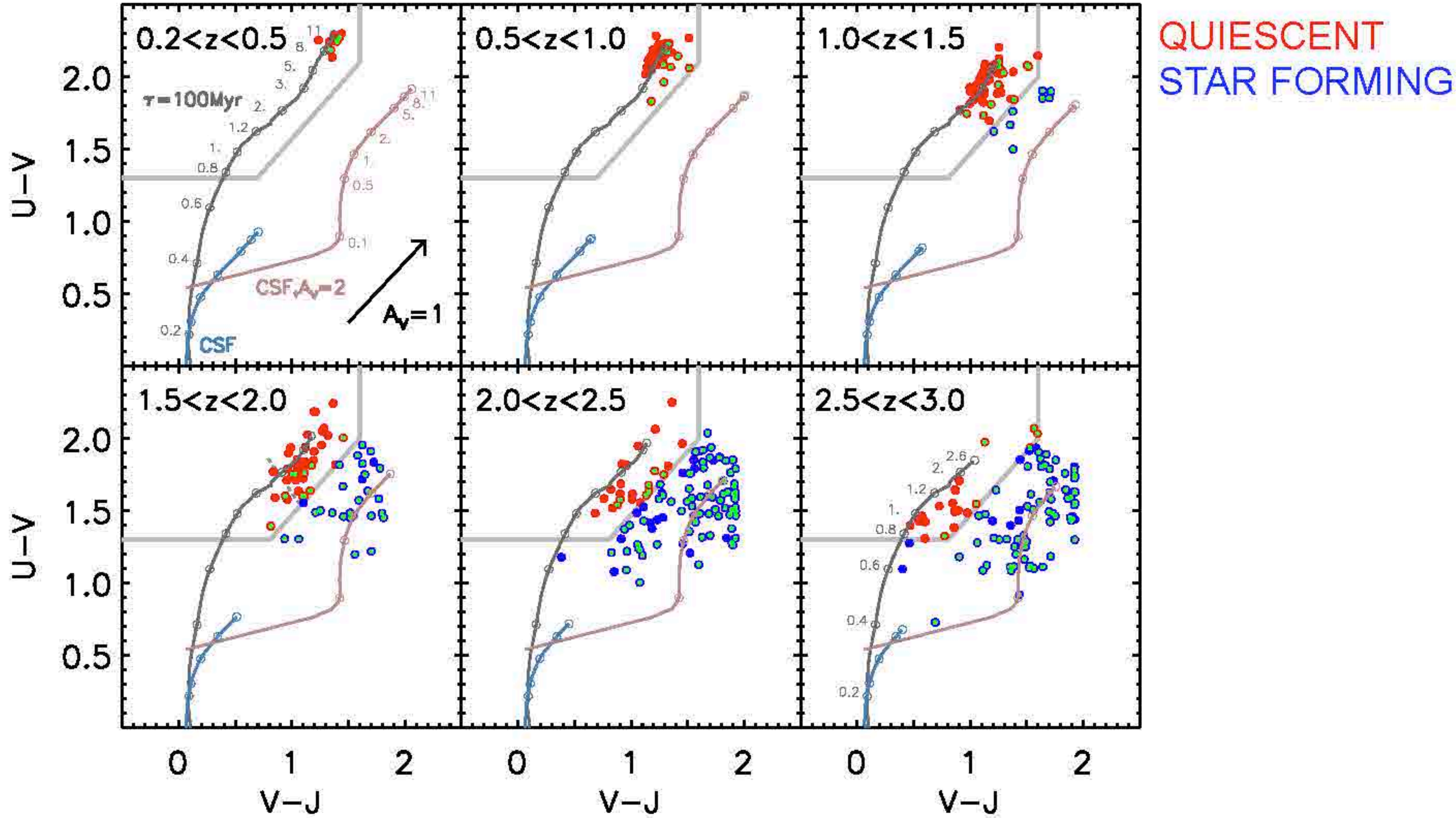
- At high-z, progenitors shows large range in properties; with cosmic time, they turn into a very homogeneous population of old, quiescent galaxies.

Evolution of Progenitors in the UVJ diagram



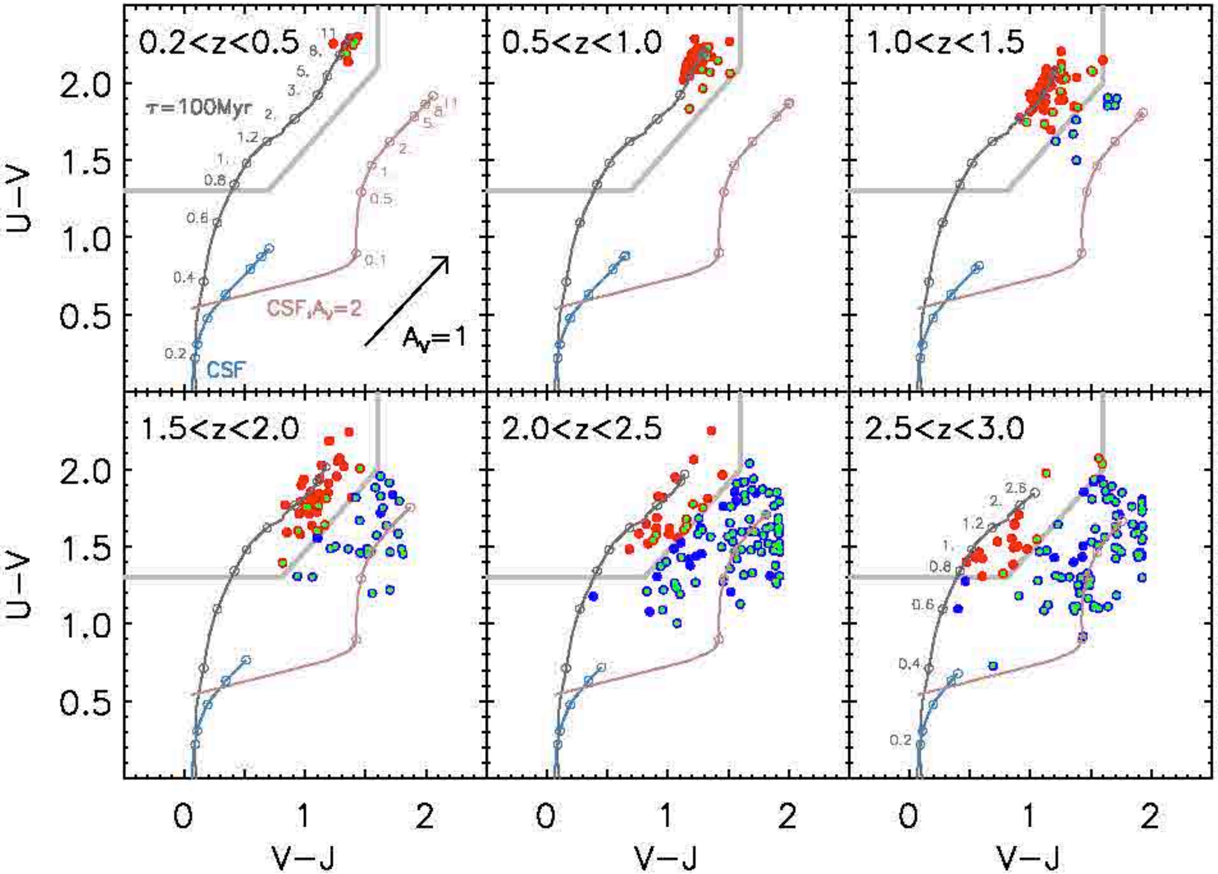
- At high-z, progenitors shows large range in properties; with cosmic time, they turn into a very homogeneous population of old, quiescent galaxies.
- No star-forming galaxies at z<1

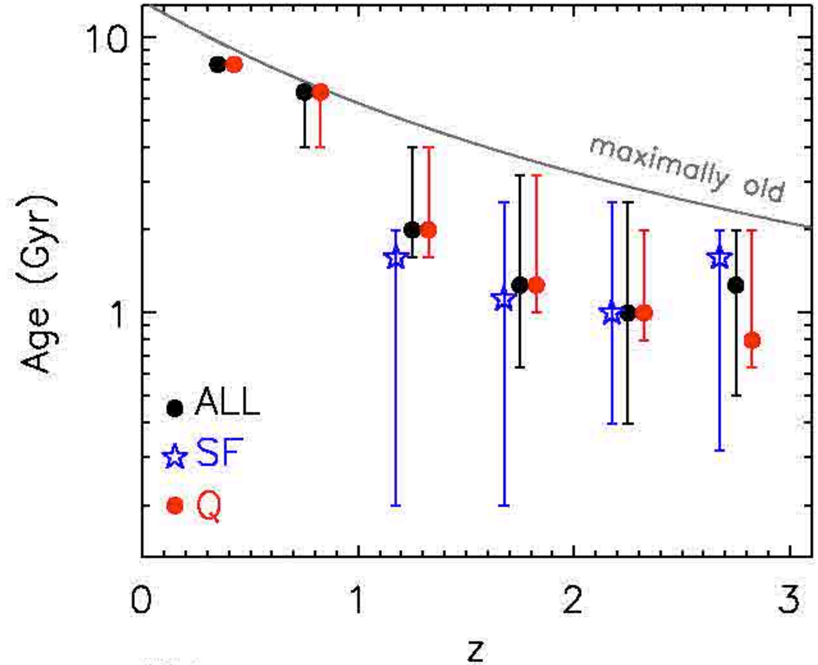
Evolution of Progenitors in the UVJ diagram



- At high-z, progenitors shows large range in properties; with cosmic time, they turn into a very homogeneous population of old, quiescent galaxies.
- No star-forming galaxies at z<1
- Aging of the stellar population of quiescent galaxies with cosmic time is evident.

Evolution of Progenitors in the UVJ diagram





ALL
QUIESCENT
STAR FORMING

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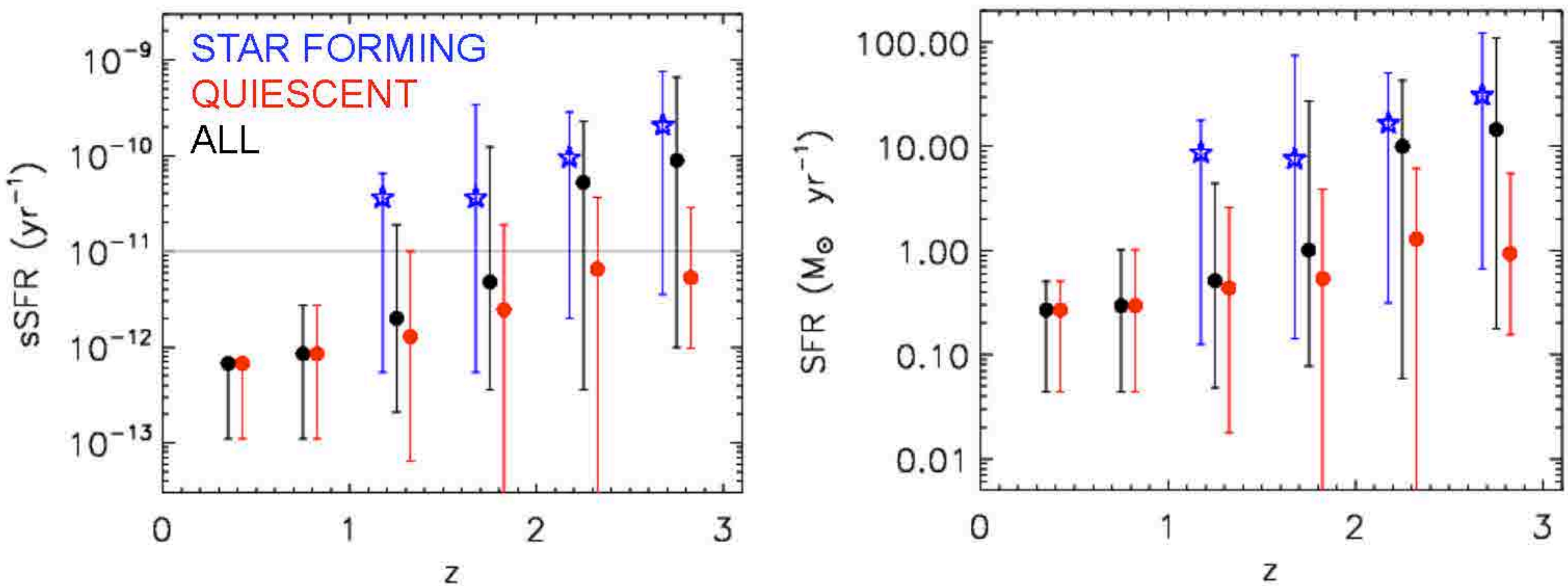
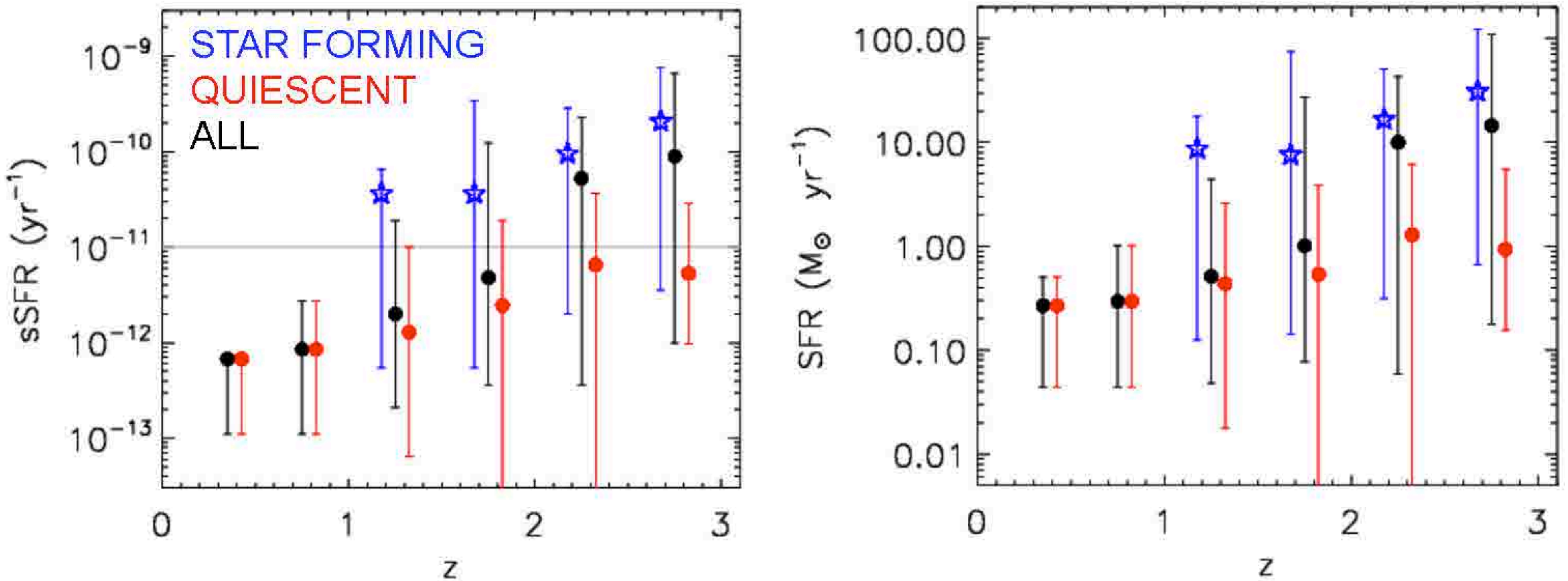
Evolution of the Star-Formation Activity



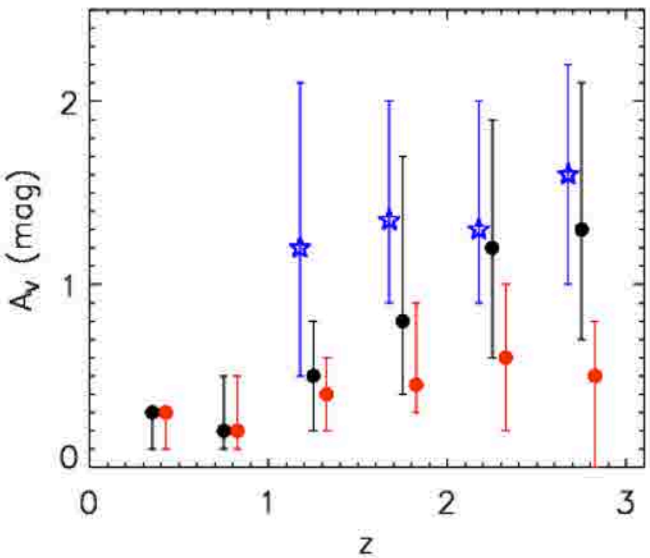
Evolution of the Star-Formation Activity



- At z<1.5, the progenitors of local ultra-massive galaxies are predominately quiescent, whereas at z>1.5 they become increasingly dominated by starburst galaxies.

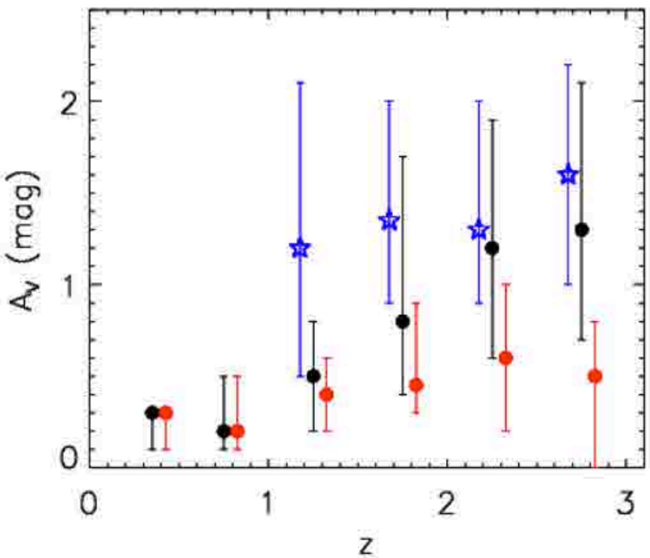
- “Quiescent” (in the UVJ diagram) galaxies become increasingly more actively star forming with redshift...

Evolution of the Extinction, Optical Rest-frame Luminosity, and M/L Ratio



STAR FORMING
QUIESCENT
ALL

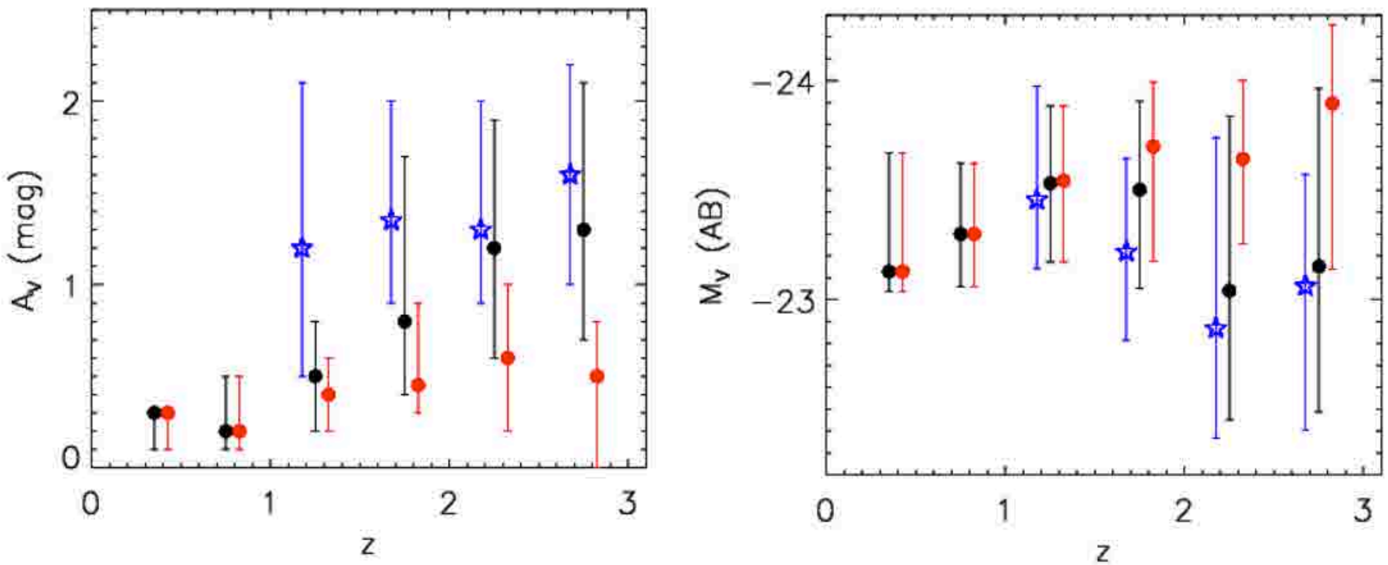
Evolution of the Extinction, Optical Rest-frame Luminosity, and M/L Ratio



STAR FORMING
QUIESCENT
ALL

- The progenitors of local ultra-massive galaxies become dustier with redshift, dominated by dusty (A_V>1) starburst galaxies at high z. Quiescent galaxies have typically little dust (A_V<1), although slightly more at earlier times.

Evolution of the Extinction, Optical Rest-frame Luminosity, and M/L Ratio



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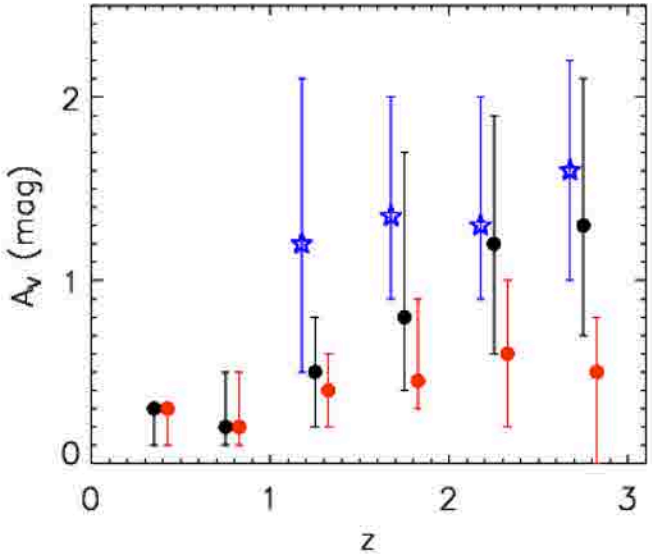

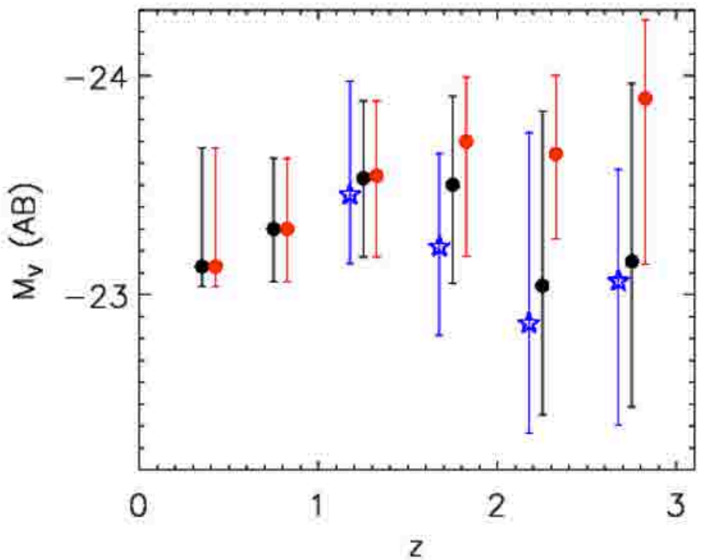

STAR FORMING
QUIESCENT
ALL

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- The rest-frame V-band luminosity of quiescent galaxies decreases with time (aging of the stellar population)

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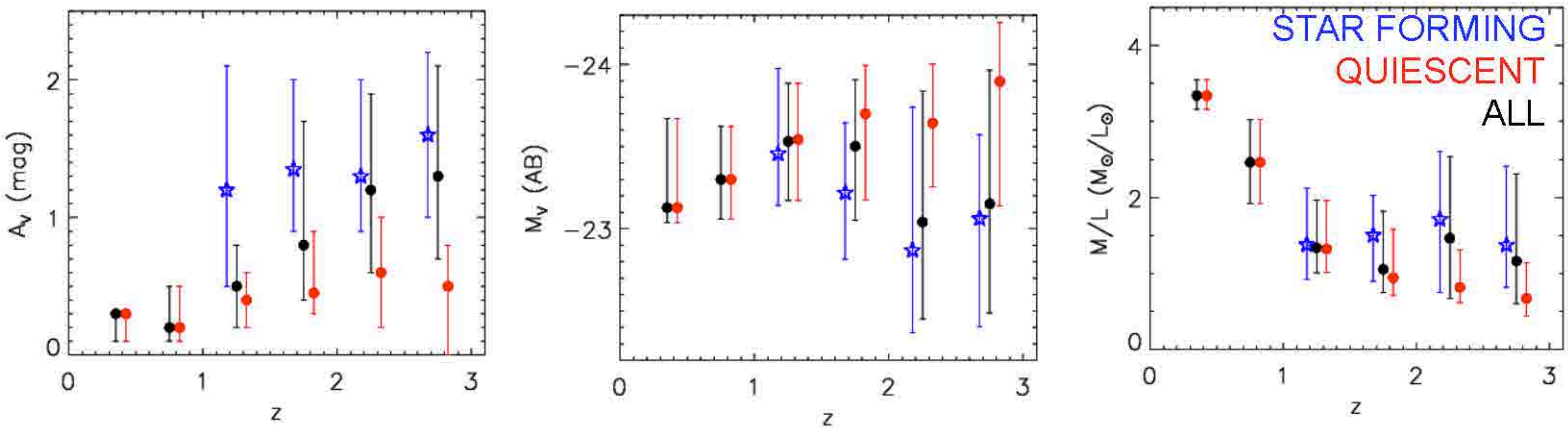

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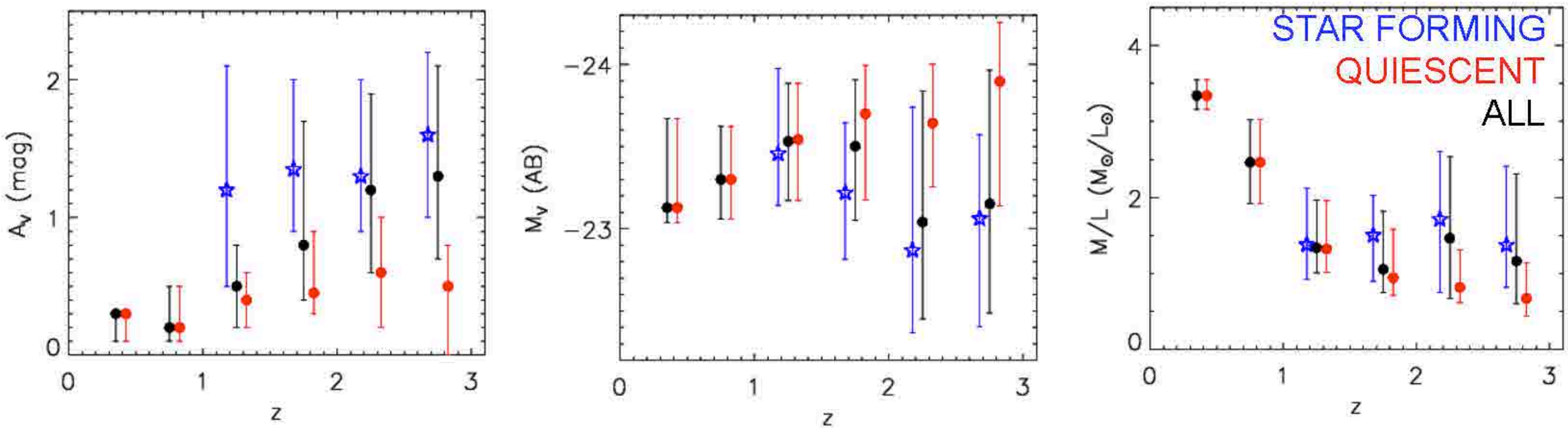

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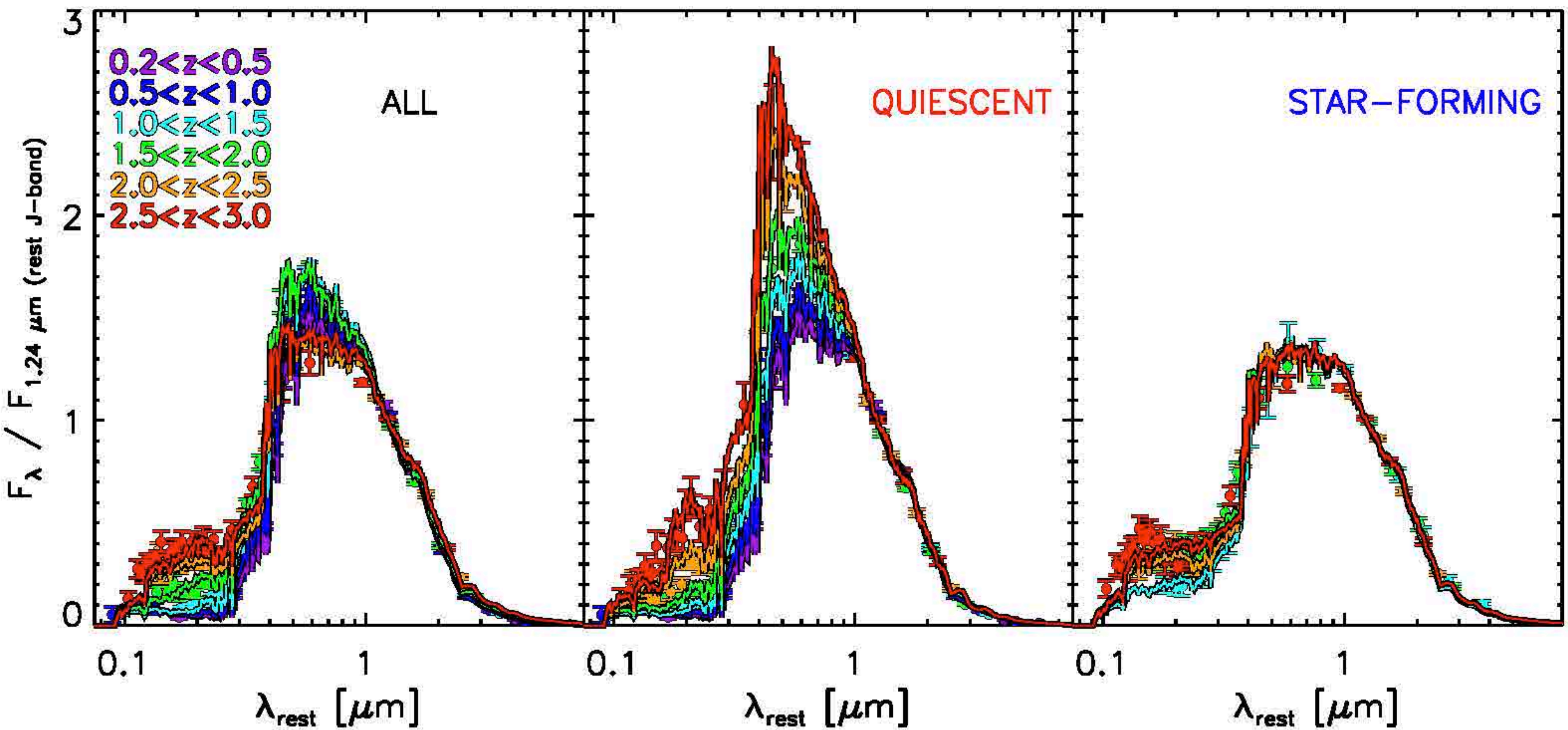
- The rest-frame V-band luminosity of quiescent galaxies decreases with time (aging of the stellar population)
- M/L is roughly constant for star-forming galaxies, but larger than the M/L of quiescent galaxies at z>1.5 (due to larger dust content). The M/L ratio of quiescent galaxies increases with time (aging of the stellar population).

Evolution of SEDs of the Progenitors

(Marchesini et al. 2013, to be submitted)



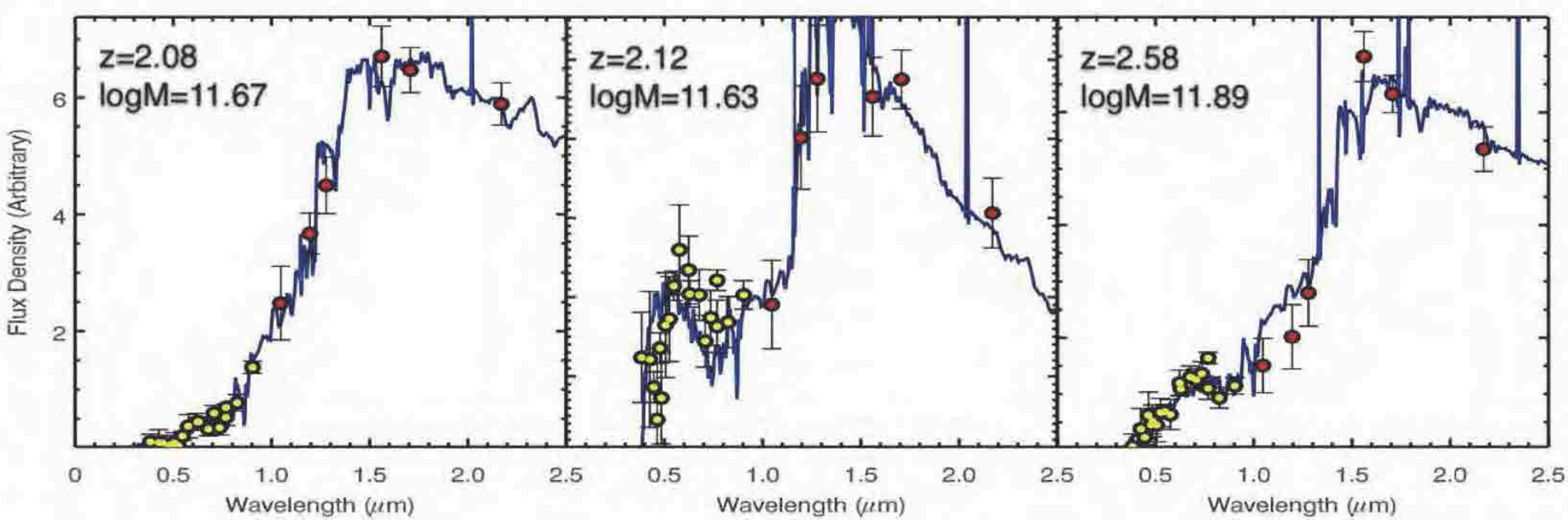
- The progenitors of $M_{star}=5x10^{11}$ M_{Sun} local galaxies (which are quiescent, maximally old galaxies with little dust) were (mostly) massive (M_{star}~$2x10^{11}$ M_{Sun}), dusty star-bursting galaxies at z=3.

NMBS-II

PI: van Dokkum; Muzzin, Marchesini, Stefanon, et al.

- 10 times wider (~5.3 deg^2) than NMBS down to K=20.5 (AB), and 3 times wider than UltraVISTA
- Designed with primary goal of surveying a sufficiently large volume to identify a large sample of "monster" (M_{star}>4x10^{11}=$10^{11.6}$ M_{sun}) galaxies at z>1.5
- Fields: **COSMOS** (2 deg^2), **CFHT-D1** (0.9 deg^2), **CFHT-D4** (0.6 deg^2), **MUSYC-1255** (0.3 deg^2), **E-CDFS** (0.3 deg^2), **MUSYC-1030** (0.3 deg^2), **EGS** (0.9 deg^2).

NMBS-II: Preliminary Sample of 30 Ultra-massive ($\log(M_{star}/M_{sun})>11.6$) Galaxies at $1.5<z<3.0$

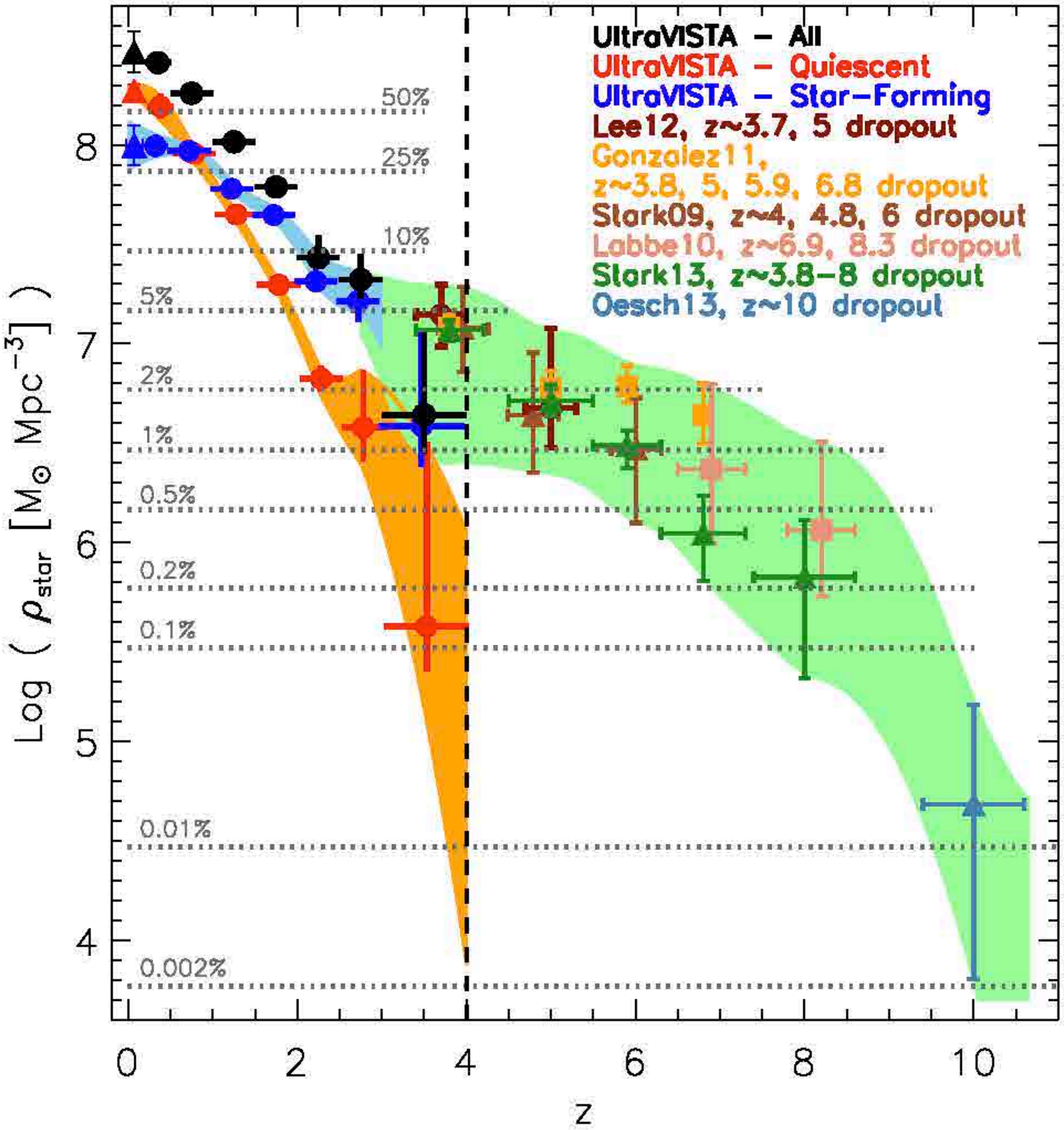


GNIRS

2013A awarded (pilot) program (PI: Marchesini) to spectroscopically confirm the sample and fully characterize the stellar population properties of this complete sample of ultra-massive galaxies at z~2.3.

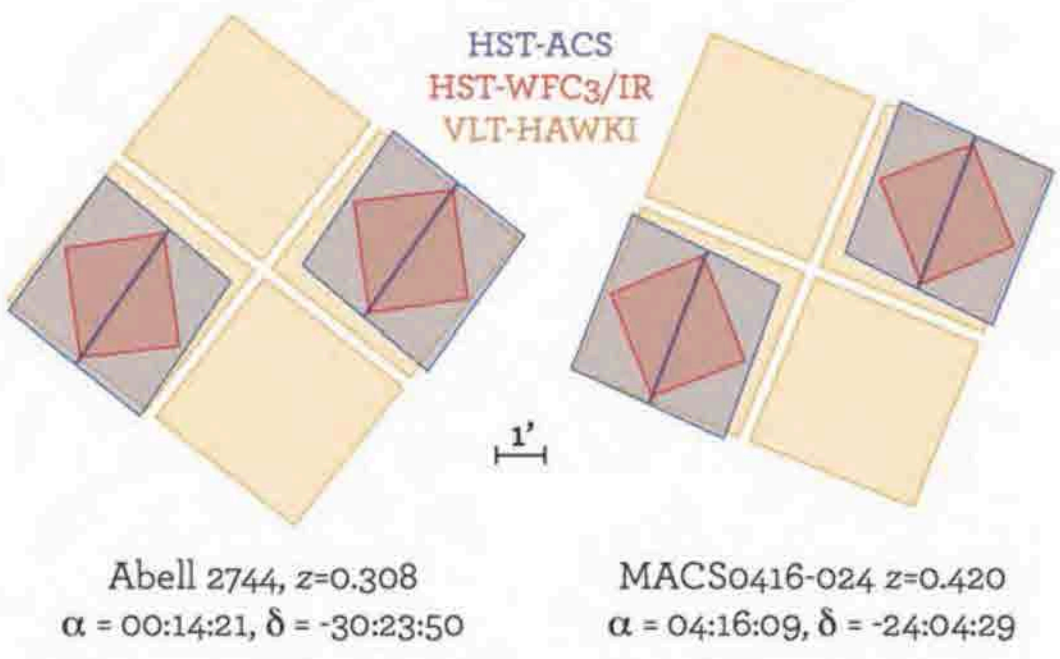
Cycle 20 awarded program (PI: Muzzin) to derive the structural properties of these ultra-massive galaxies

The Build Up of the Stellar Content of the Universe in the Last 13 Billion Year



VLT/HAWK-I deepest K-band imaging of the HST Frontier Fields

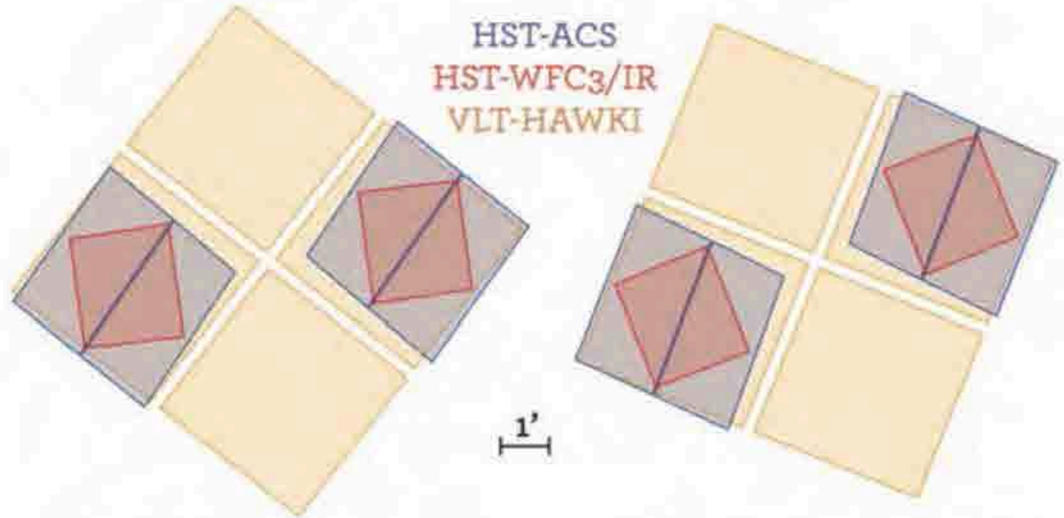
(PI: Brammer; Marchesini)



- 82 hours of VLT/HAWK-I data to image the first two HFF fields down to K=26.5, providing the deepest K-band images ever taken.
- Data collection has started

VLT/HAWK-I deepest K-band imaging of the HST Frontier Fields

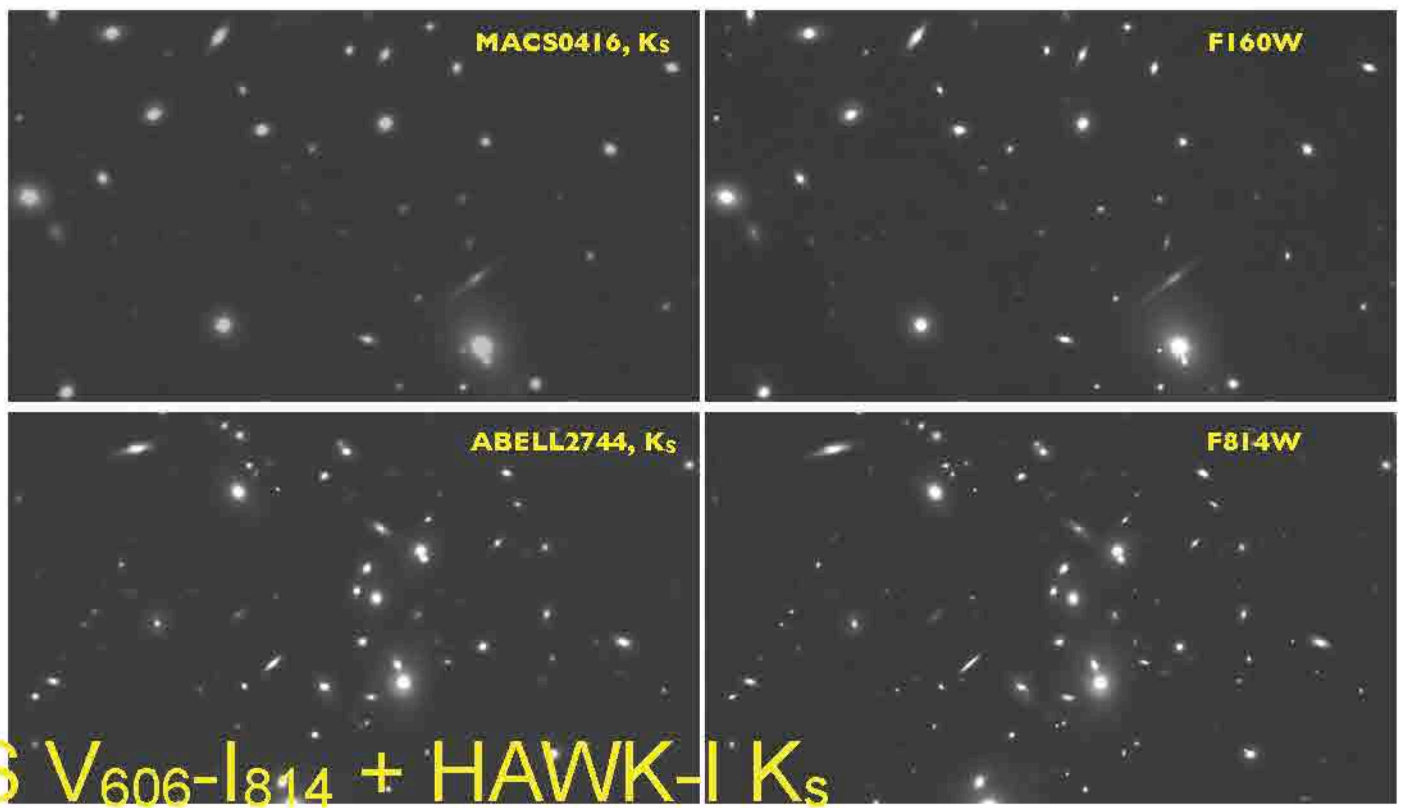
(PI: Brammer; Marchesini)



Abell 2744, z=0.308
α = 00:14:21, δ = -30:23:50

MACS0416-024 z=0.420
α = 04:16:09, δ = -24:04:29

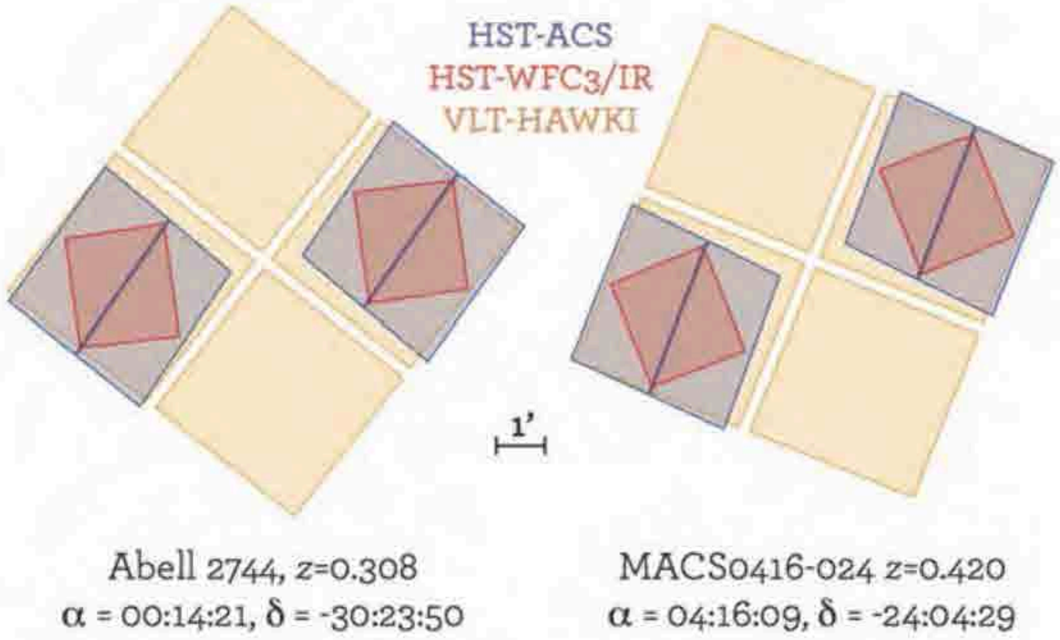
Only 2 hours!



ACS V_{606}-I_{814} + HAWK-I K_s

VLT/HAWK-I deepest K-band imaging of the HST Frontier Fields

(PI: Brammer; Marchesini)



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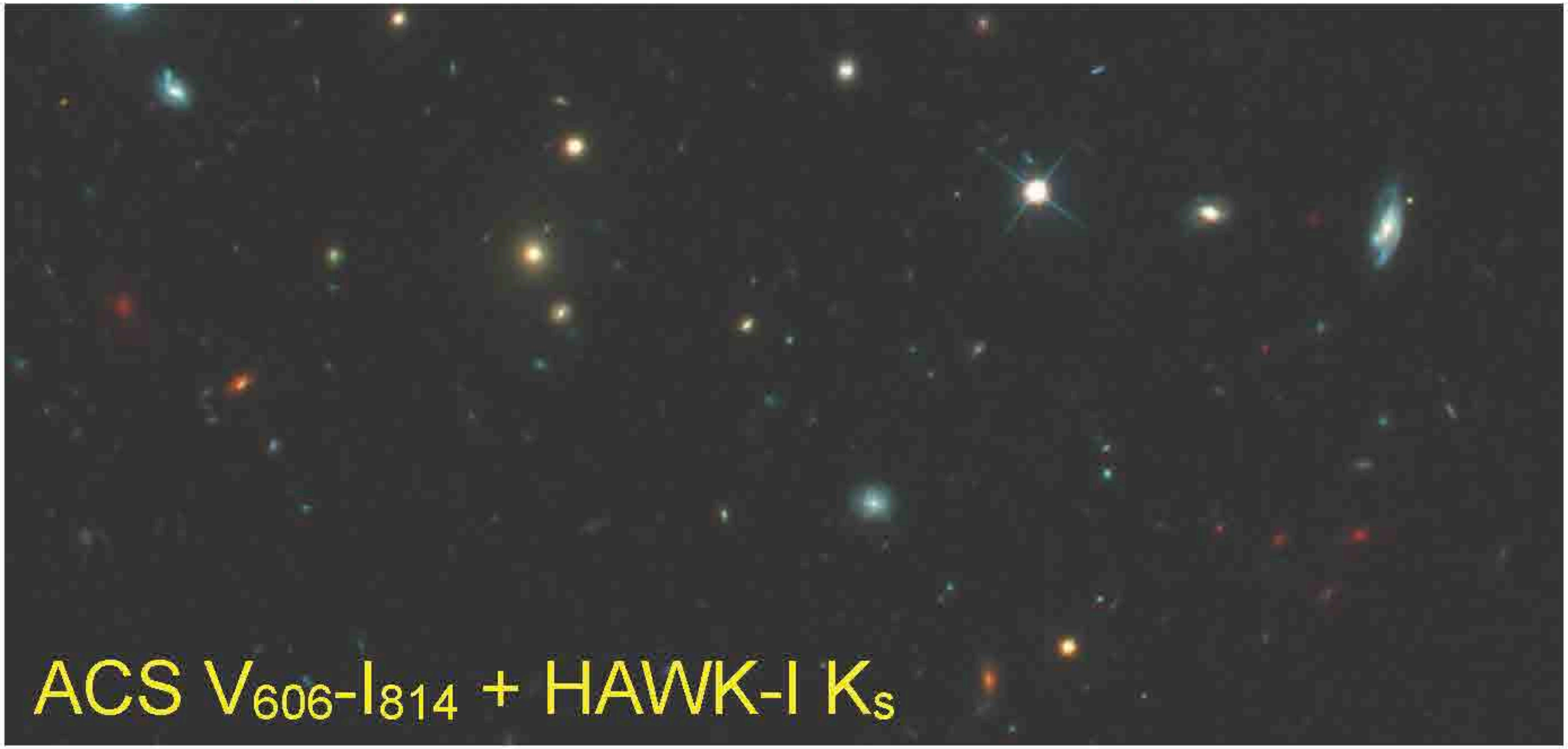

Summary 1

- ☑ Dramatic evolution of the stellar mass function of galaxies from z=4, mostly characterized by density evolution. Mass-dependent evolution is observed, with low-mass end evolving more than the high-mass end.
- ☑ About 5-10% of the current stellar mass content was in place at z=3.5
- ☑ The number density of the most massive galaxies ($\log(M_{star}/M_{sun})>11.5$) appears to have evolved very little from z=4 to z=1.5 (Marchesini et al. 2009).

- ☑ From the NEWFIRM Medium-Band Survey:
  - ☑ a red sequence is clearly detected out to z=2.5
  - ☑ most of the green valley galaxies are obscured star-forming galaxies
  - ☑ from z~2, the evolution of the SMF is driven by the build up of the quiescent galaxy population
  - ☑ a significant population of very massive galaxies appears in place at 3<z<4, in disagreement with the predictions of latest galaxy formation models
  - ☑ first detailed characterization of the population of very massive galaxies at z=3.5, showing intense activity (AGN and/or obscured starburst), and significant amount of dust.
  - ☑ Evidence for large evolution in the properties of massive galaxies from z=3.5 to z=2.3 (1 Gyr), such as fraction of quiescent galaxies, IR properties, and AGN activity.

Summary 2

- From the UltraVISTA survey:
  - confirmation of the above results
  - quiescent galaxies dominate the high-mass end of the SMF at z<1.5; star-forming galaxies dominate the total SMF at all masses at z>2.5
  - a population of quiescent massive galaxies at z~3.5 is confirmed
  - quiescent galaxies dominate the total stellar mass budget at z<0.75, with the universe at z=3.5 containing ~1-2% of the total stellar mass formed by z~0
  - the SEDs of galaxies at the high-mass end of the SMF are characterized by dusty star-bursting galaxies at high redshifts, evolving into quiescent, maximally-old galaxies with little dust at low redshifts (Marchesini et al. 2013, to be submitted).

- A large sample of ultra-massive ($\log(M_{star}/M_{sun})>11.6$) galaxies at 1.5<z<3 has been constructed from the NMBS-II and exciting follow-up studies are being performed

- All rest-frame OPT and NIR LFs and SMFs can be downloaded from: http://cosmos.phy.tufts.edu/~danilo/Downloads.html
- The UltraVISTA catalogs are publicly available at: www.strw.leidenuniv.nl/galaxyevolution/ULTRAVISTA/Ultravista/Data_Products_Download.html