Passive galaxies in the early Universe

The AO perspective

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Outline

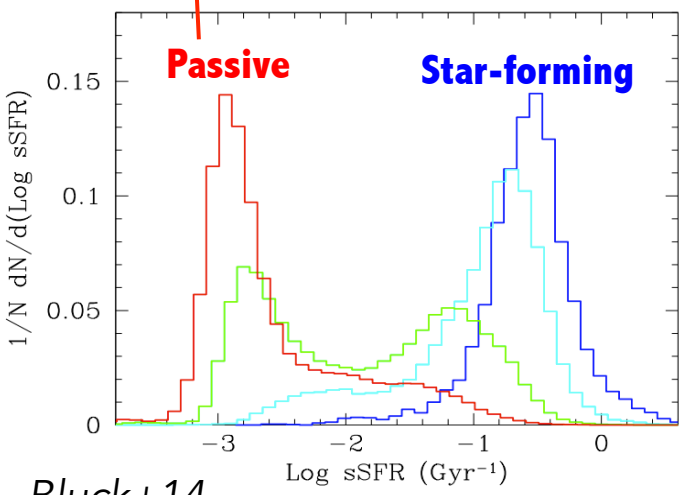
- Passive galaxies (what are they, why do we care, when did they appear...)
- Selection passive candidates at z>3
- Confirmation of their passive nature
- Physical properties
- Investigating the physics with AO
- Summary & conclusions

Further details in:
Merlin+18: selection technique (GOODS-S)
Santini+19: confirmation of the candidates
Merlin+19: selection in the 5 CANDELS fields
Santini+in prep: confirmation of the total sample + stellar MF

Introduction – Passive galaxies through cosmic time

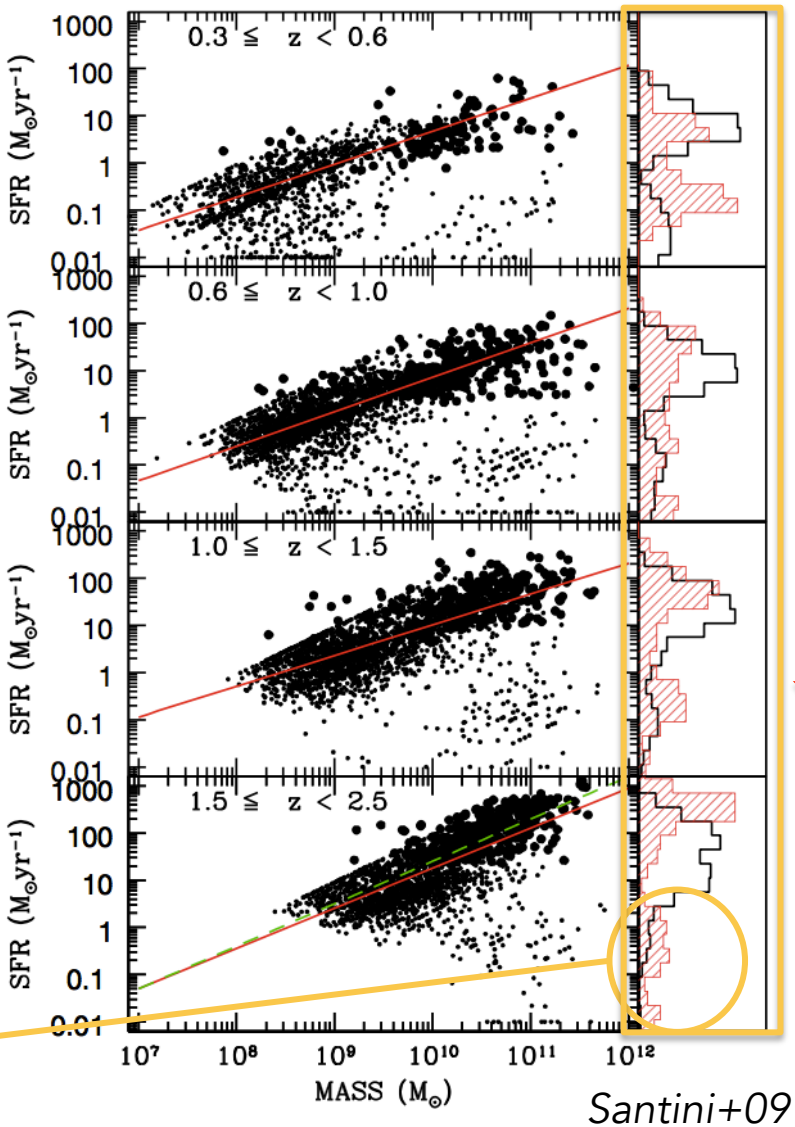
Not forming stars anymore

Local Universe



Bluck+14

High-z Universe



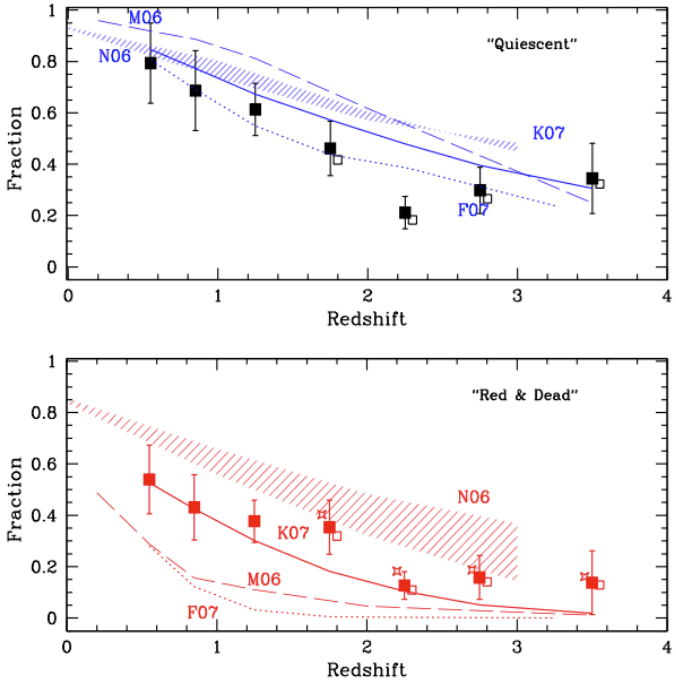
Santini+09

Passive galaxies are less abundant at high redshift

Introduction – High z passive gal: a challenge for theoretical models

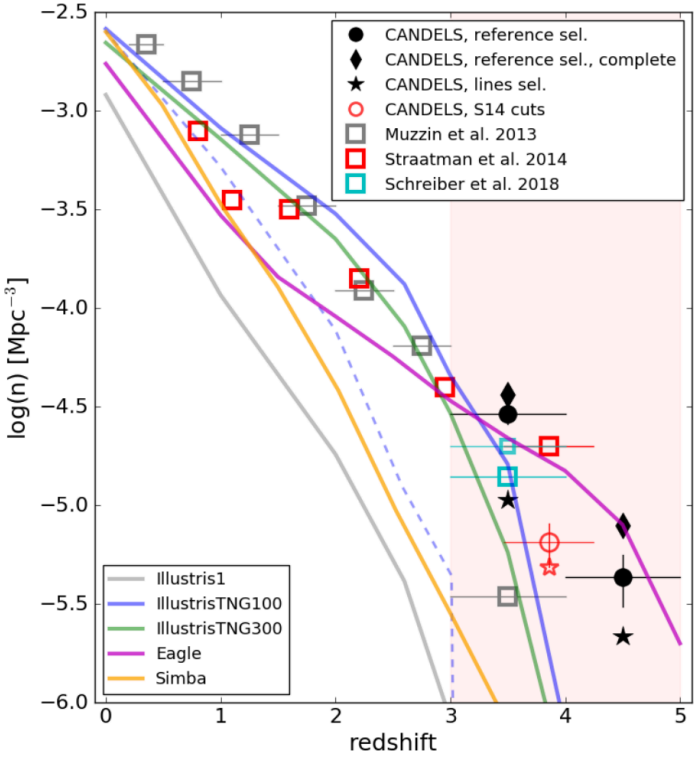
Theoretical models struggle to reproduce the observations
(Fontana+09, Vogelsberger+14, Feldmann+16, Merlin+19, Cecchi+19, Valentino+19, …)

The abundance of passive galaxies at different epochs is a powerful probe of the delicate interplay among the different physical processes responsible for their rapid assembly and for the abrupt shut-down of their SF activity (e.g. merger-driven starbursts, feedback, ..).



Fontana, PS,+09

Need for reliable selection criteria!!



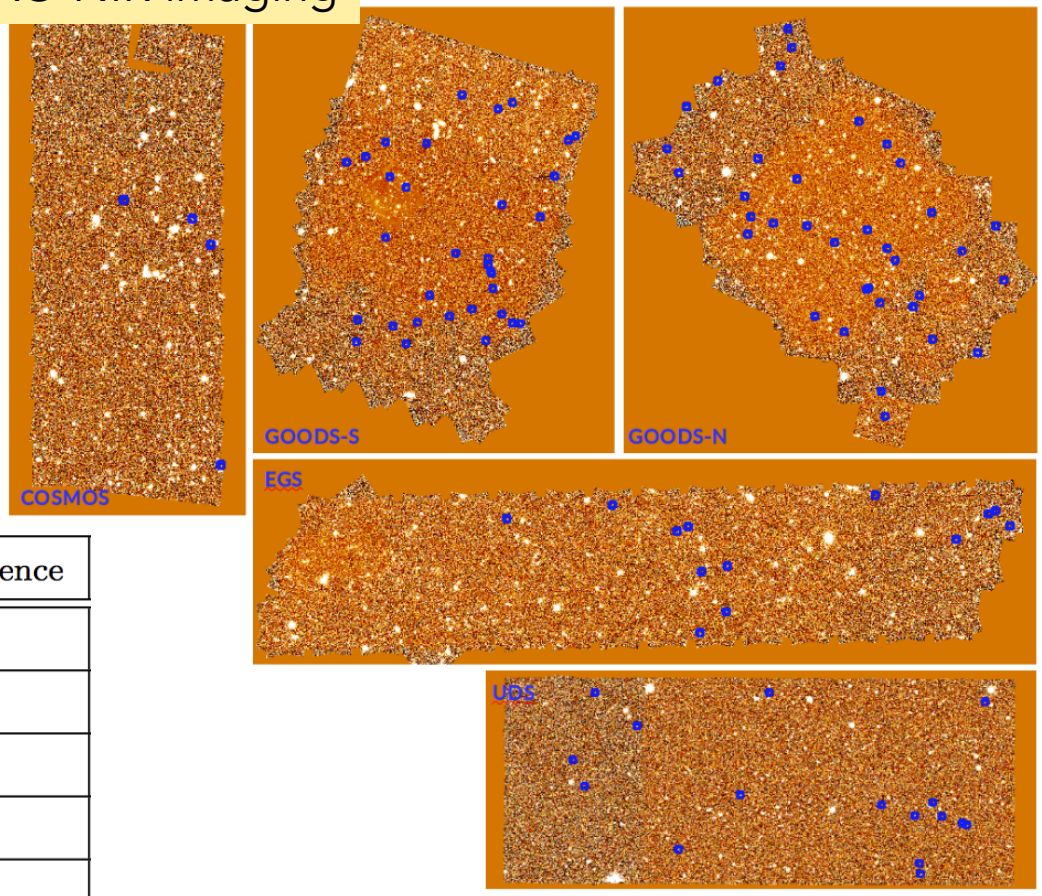
Merlin+19

Selection – z>3 passive galaxy candidates in CANDELS

Selection based on SED fitting assuming top-hat SFH with a probabilistic approach

- z>3
- H < 27
- SNR [Ks, IR1, IR2] > 1
- SED fitting with top-hat SFHs, BC03 w/ or w/o lines
- Probabilistic selection:
  - best solution with SFR=0
  - $P_{best\ (passive)} > 30\%$
  - no $P_{i\ (star\text{-}forming)} > 5\%$

Will benefit from AO NIR imaging



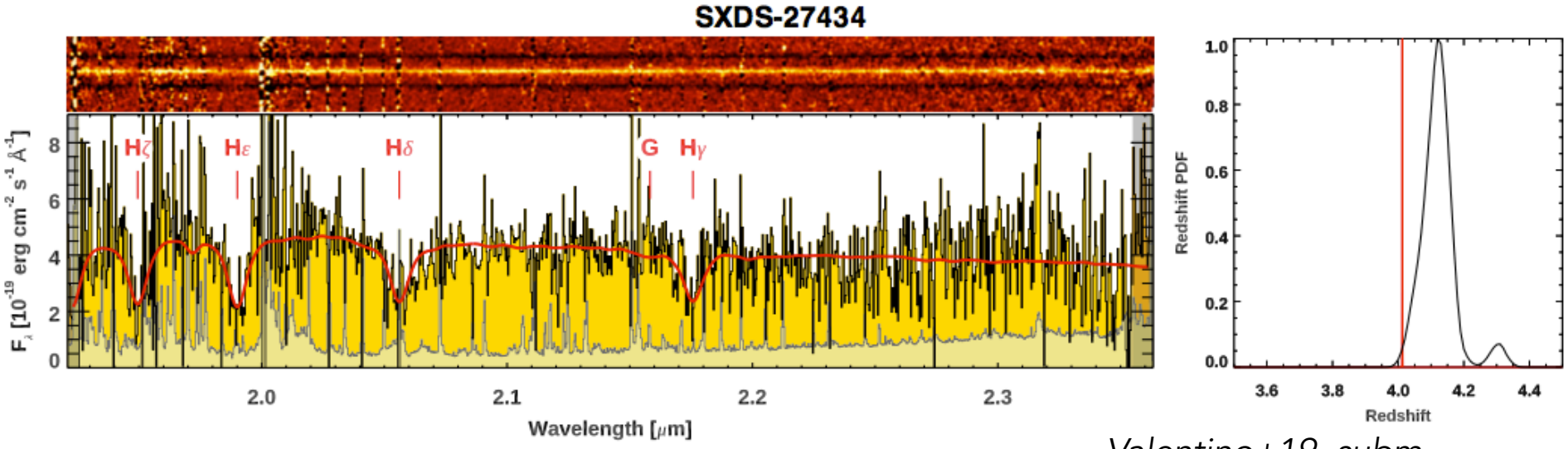
Field/Sample	Total	$z > 3$	$S/N_{z>3}$	Reference
COSMOS	38671	3778	1525	4
EGS	41457	4830	1775	13
GOODS-N	35445	3953	1793	36
GOODS-S	34930	5029	2884	33
UDS	35932	4018	2540	16
All fields	186435	21608	10517	102

Merlin+19

Confirmation – How to confirm the passive nature?

Spectroscopical confirmation is hard and very time demanding with current instrumentation

- *Cimatti+04* : 1.6<z<1.9, 18<K<19, 3-16 hr with FORS2
- *Glazebrook+17* : z=3.713, K=22.4, 4 (H) – 7 (K) hr with MOSFIRE
- *Schreiber+18* : 3<z<4, 22<~K<~24, 4–7 hr with MOSFIRE
- *Forrest+19* : z=3.493, K=20.97, 5 (H) – 2.45 (K) hr with MOSFIRE
- *Valentino+19* : z=3.775, K=22.26, 8.6 hr with X-Shooter + z=4.012, K=21.9, 7.75 hr with MOSFIRE
- See also: *Kriek+06,+09,+15, Gobat12, Onodera+12, Whitaker+13, Belli+14, van de Sande+16, Hill+16, …*

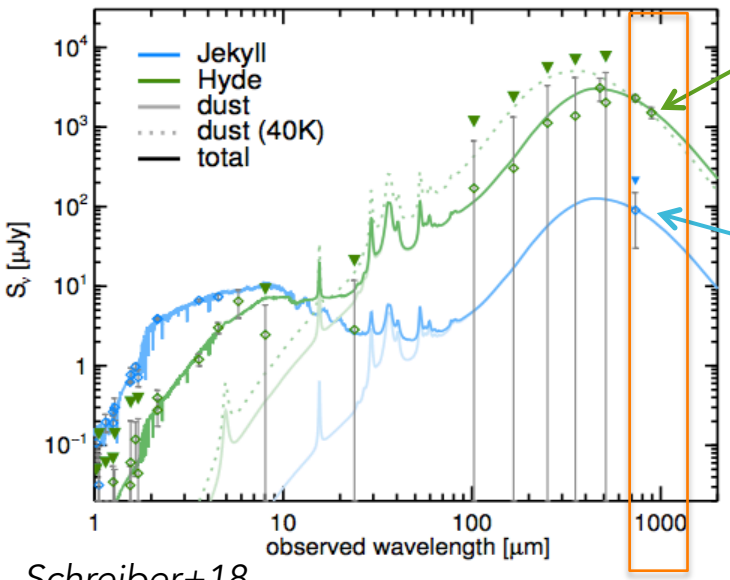


Valentino+19, subm.

Much faster with next generation instrumentation (e.g. NIRSPEC 10-15x faster wrt MOSFIRE)

Confirmation – Use ALMA!

Exclude contamination from dusty galaxies by means of FIR/submm observations



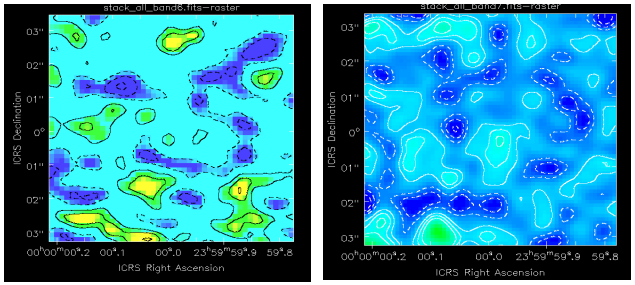
Schreiber+18

ALMA archive: 41(/53) targets observed in Band 6 or Band 7

Only 1 detection (4σ)

No >3σ detections even in the stacks

Band 6 (23 sources) Band 7 (30 sources)

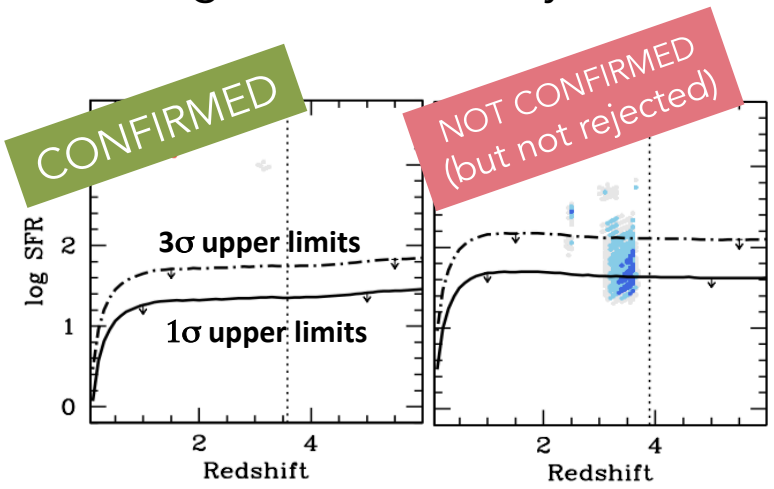


ALMA flux measurements converted into (constraints on the) SFR

Confirmation – Validation of the passive solutions

VALIDATION OF INDIVIDUAL ROBUST CANDIDATES

ALMA predictions vs opt fit
(SF-ing solutions at any redshift)



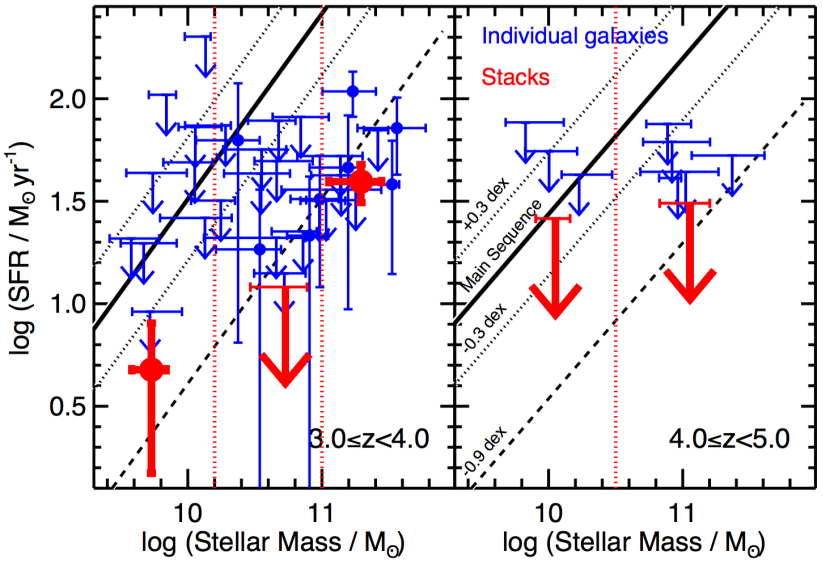
61% are robustly (≥3σ) confirmed
→ the SFing solutions of the optical fits are rejected by ALMA observations

The remaining sources are inconclusive (available ALMA data is not deep enough)

STATISTICAL VALIDATION OF THE WHOLE POPULATION

The stacks are on average consistent with being passive

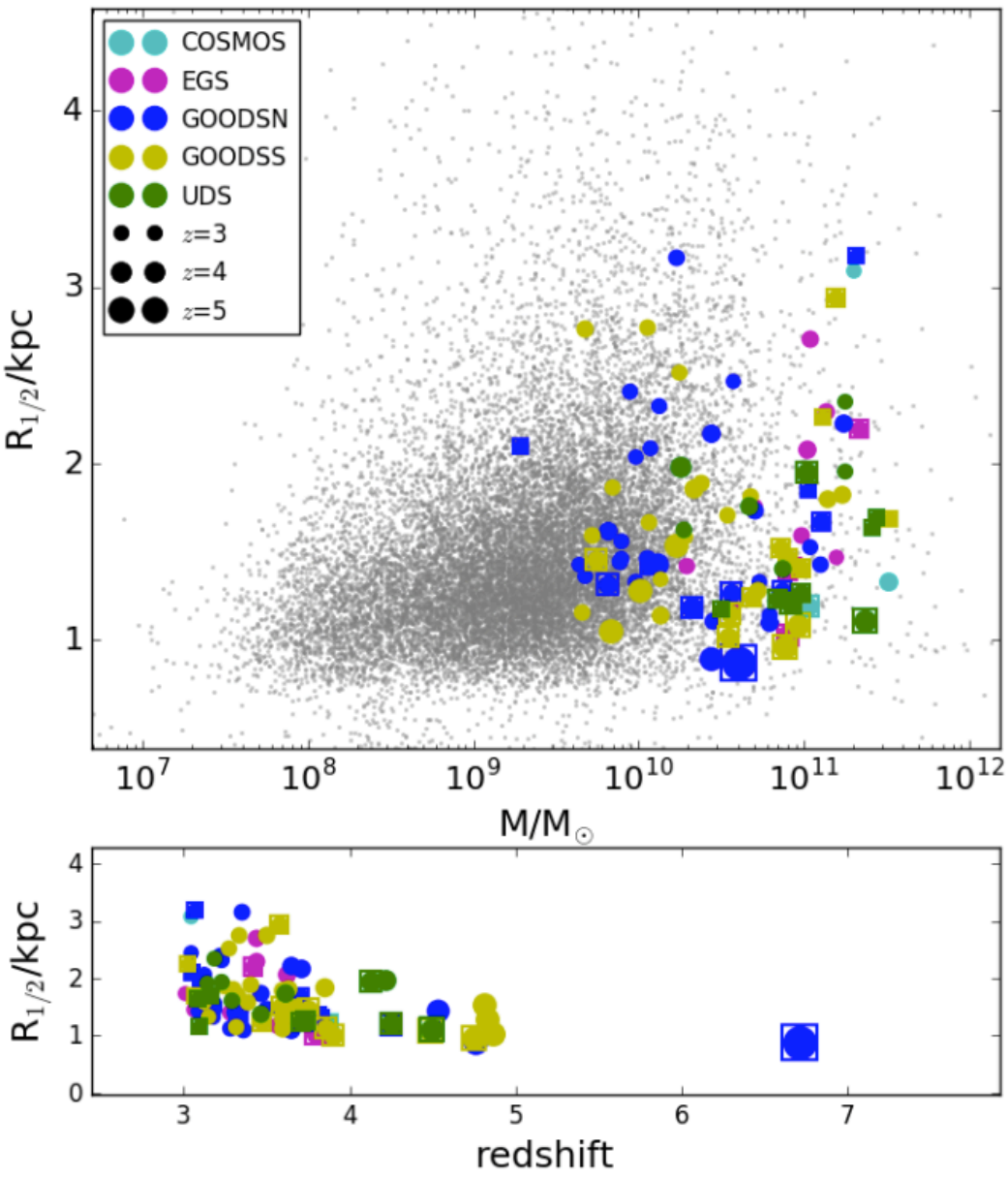
Comparison with the location of the MS

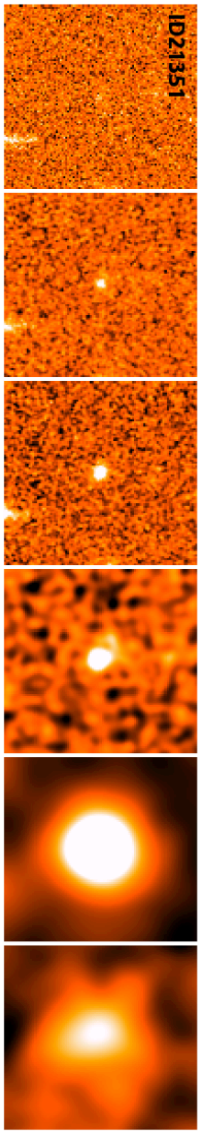


- 56% at least 1σ below the MS
- 24% at least 3σ below the MS
- Stacking supports the passive nature of the entire sample

Properties – Sizes

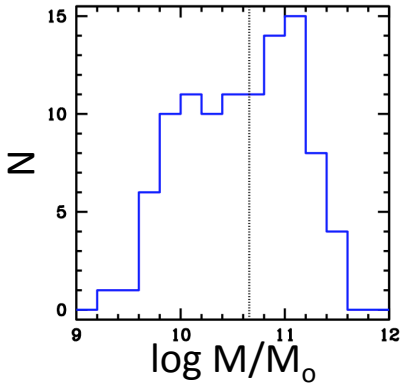
average size
0.22 arcsec
(H band)

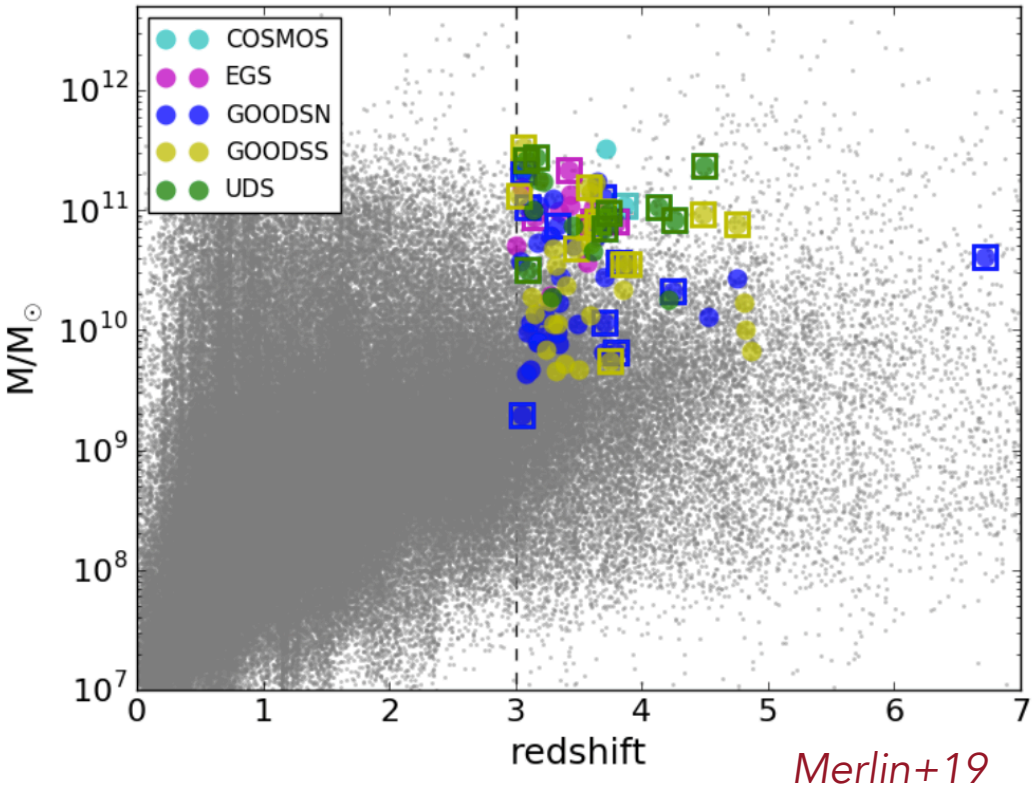




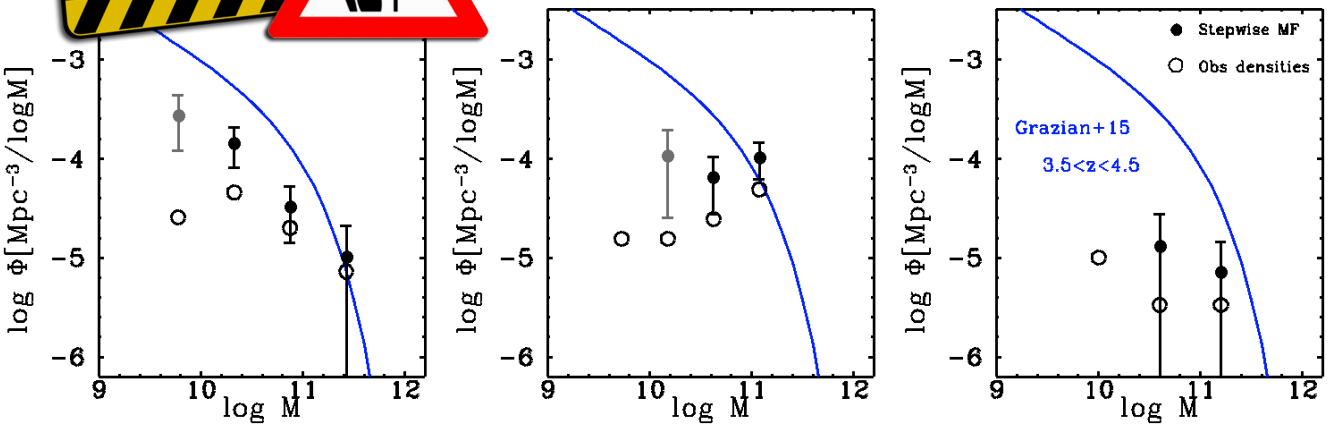
Merlin+19

Properties – Stellar masses





Merlin+19



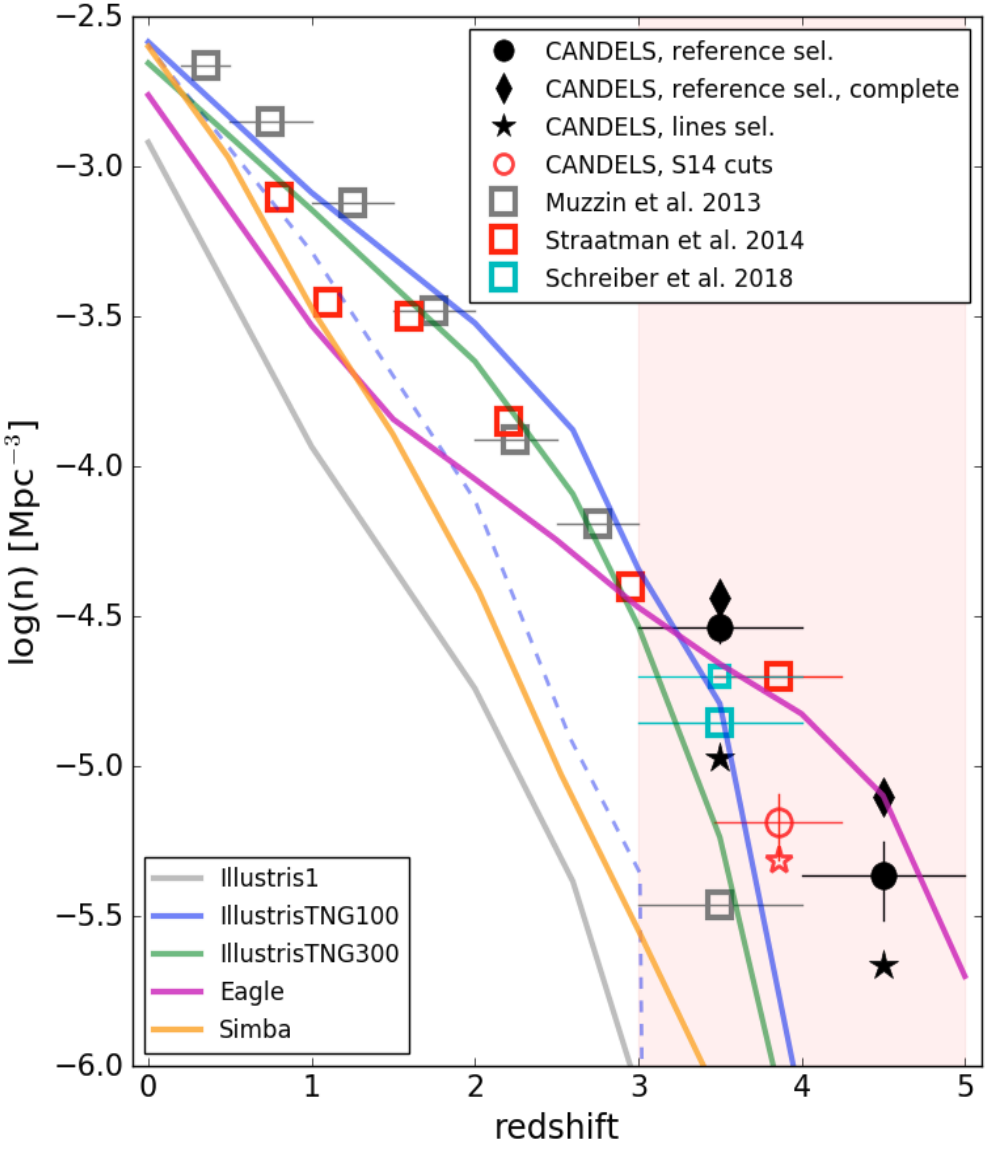
Santini+in prep

Properties – Number density

Quite rare: 0.5% of z>3 galaxies

Δz	Reference		Lines
	Observed	Corrected	
$3 < z \leq 5$	1.73×10^{-5}	2.30×10^{-5}	6.69×10^{-6}
$3 < z \leq 4$	2.90×10^{-5}	3.66×10^{-5}	1.08×10^{-5}
$4 < z \leq 5$	4.34×10^{-6}	7.94×10^{-6}	2.17×10^{-6}

Field	$3<z\leq5$	Reference	Lines
	Observed	Corrected	
COSMOS	3.08×10^{-6}	3.50×10^{-6}	1.54×10^{-6}
EGS	1.05×10^{-5}	1.34×10^{-5}	4.04×10^{-6}
GOODS-N	3.36×10^{-5}	4.38×10^{-5}	9.62×10^{-6}
GOODS-S	3.17×10^{-5}	4.44×10^{-5}	1.25×10^{-5}
UDS	1.32×10^{-5}	1.75×10^{-5}	7.42×10^{-6}



Merlin+19

Properties – Contribution to the cosmic SFRD

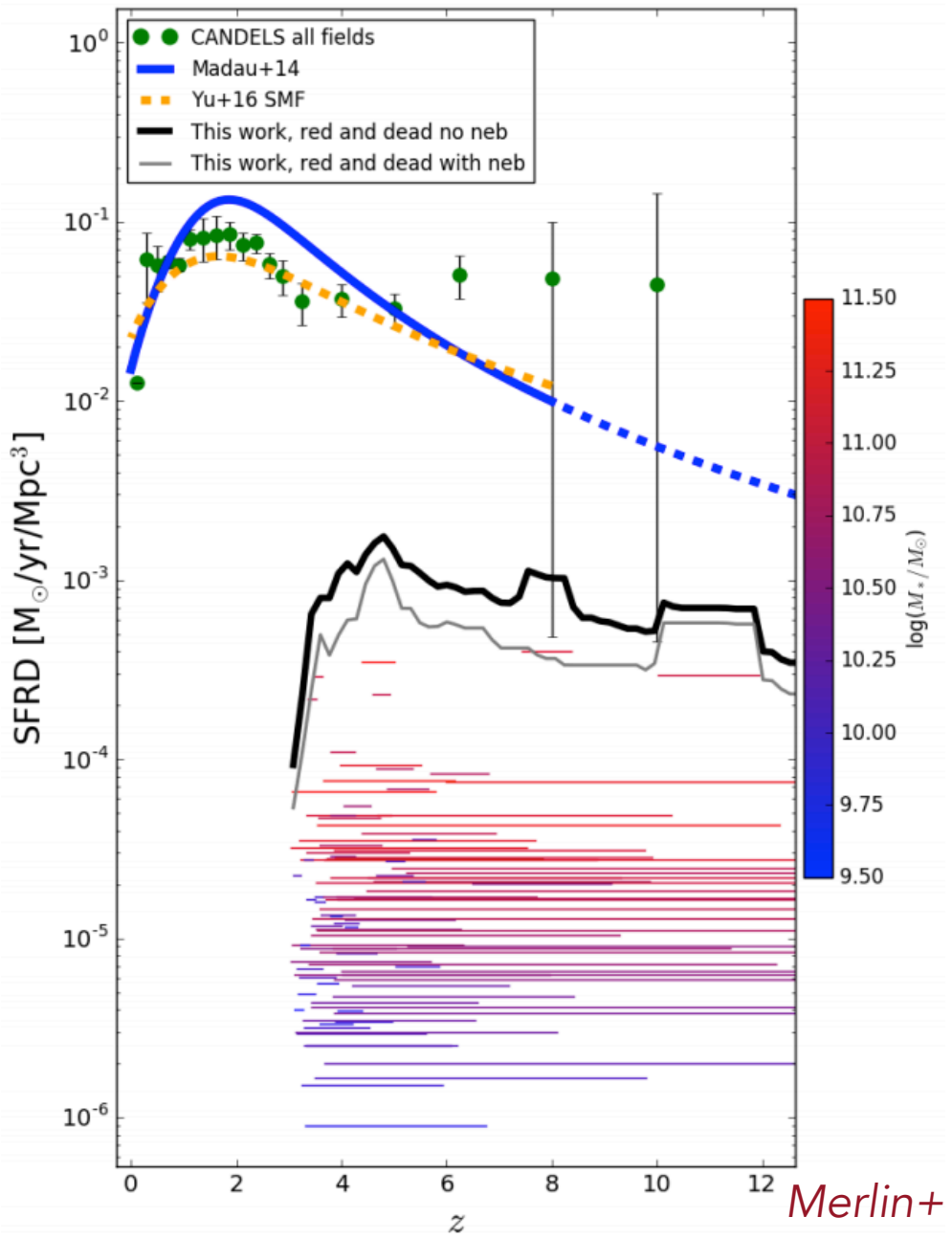
Quite rare: 0.5% of z>3 galaxies

BUT

provide 5-10% of the cosmic SFRD at 3<z<8

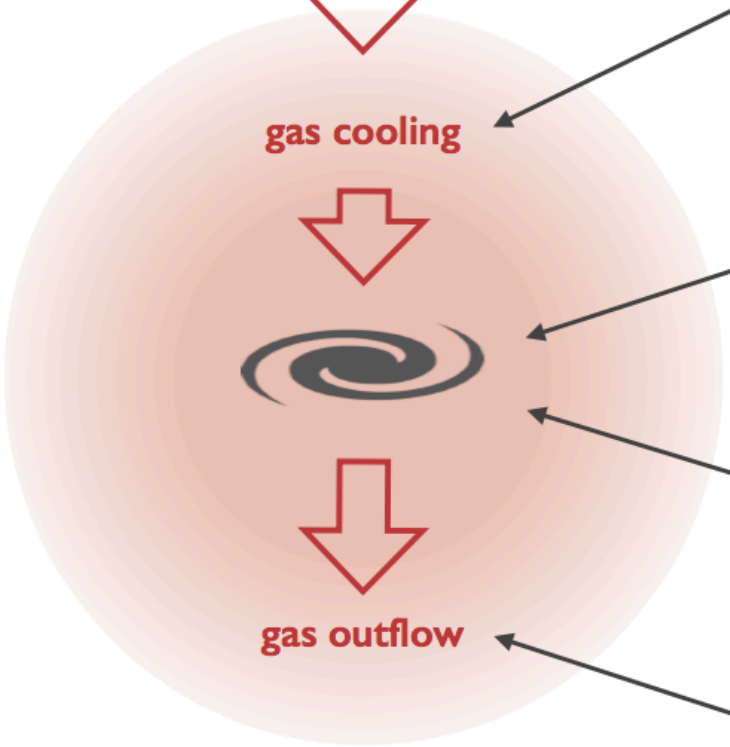
(10-20x more active than average)

Extremely fast and efficient SF activity (short bursts) abruptly quenched (gas consumption and/ or effective feedback mechanisms)



Merlin+19

What causes quenching in massive galaxies?



(i) Gas does not accrete
- Cosmological starvation

Absence of fuel

(ii) Gas does not cool
- Virial shock heating
- AGN feedback
- Gravitational heating
- Stellar feedback

No cooling (due to some heating source)

(iii) Cold gas does not form stars
- Morphological quenching
- Bar quenching
- AGN feedback
- Magnetic fields

Low SF efficiency (due to turbulence injection)

(iv) Cold gas is rapidly consumed
- Mergers
- Disk instabilities
- Positive AGN feedback

Run out of fuel

(v) Gas is removed
- AGN feedback

Gas removal

Man & Belli 18

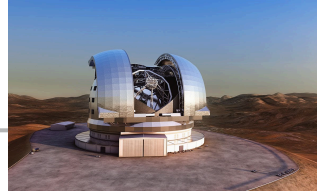
What causes quenching in massive galaxies?

- Deep resolved imaging and spectroscopic observations needed to study the stellar populations and the gas phases to disentangle among various quenching mechanisms
  (when, where and how did quenching occur)
  - morphology
  - rotation curves
  - metallicity gradients
  - stellar populations
  - gas phases (inflows/outflows/molecular gas reservoirs)
  - …

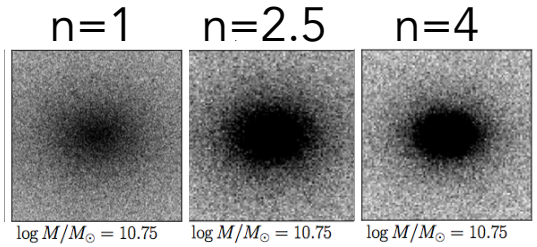
- Why quiescent galaxies at high-z?
  - Extremely fast assembly and quenching
  - Shorter available timescales reduce uncertainties in their age and degeneracy between mass *formation* and mass *assembly* history

Man & Belli 18

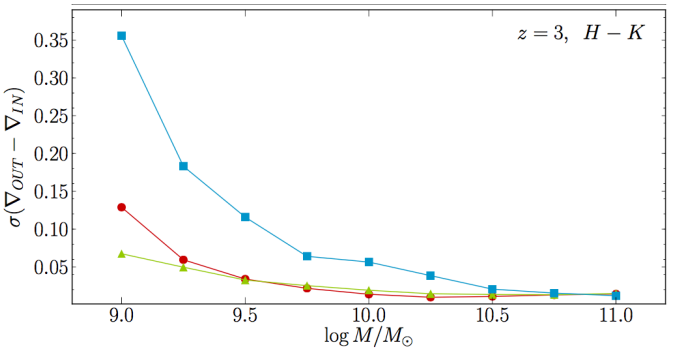
The AO perspective – Resolved imaging



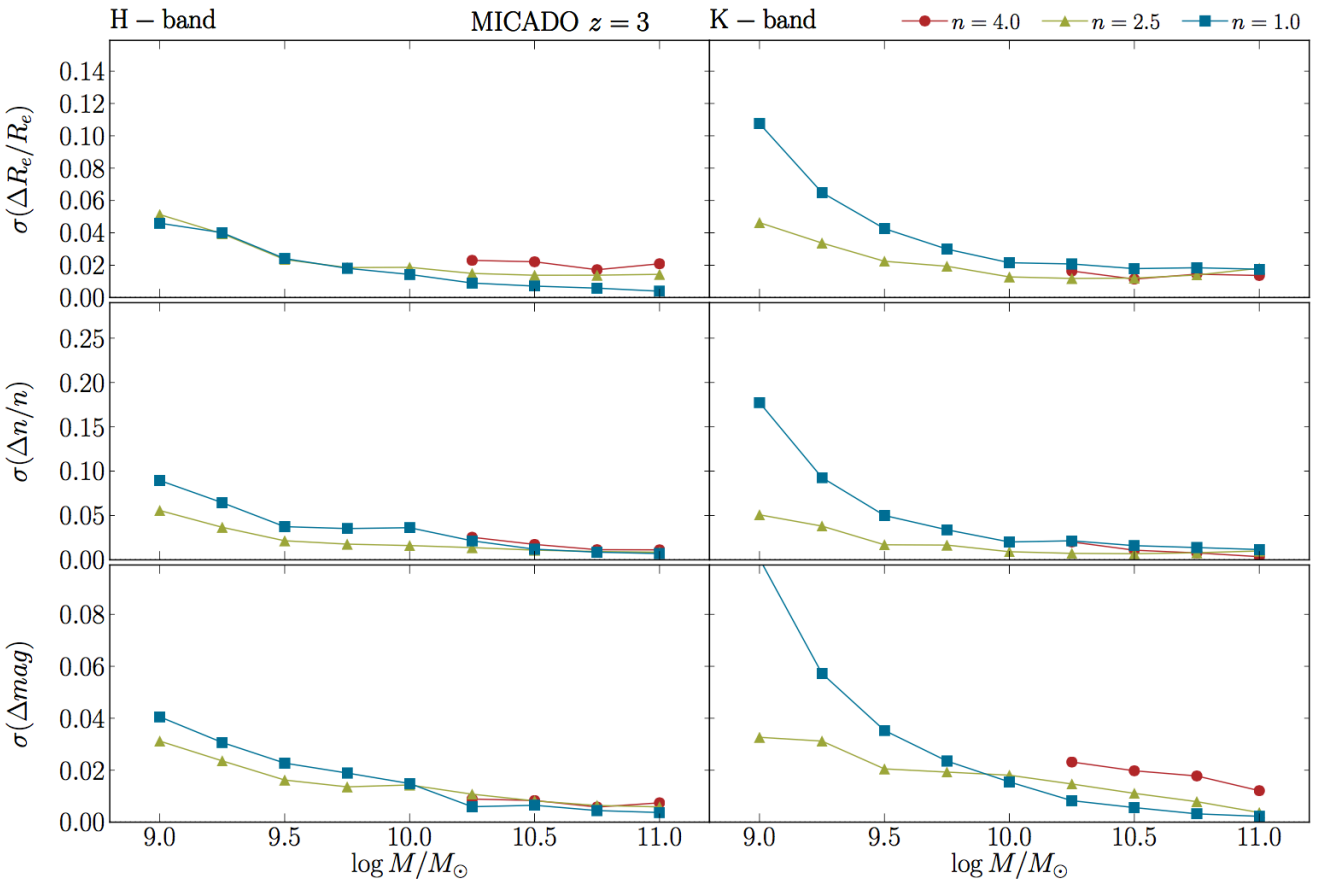
Simulated z~3 galaxies as seen in 3 hr by MICADO@E-ELT



Gullieuszik+16

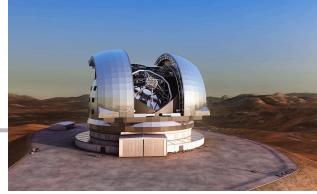


Structural parameters and colour gradients accurately reconstructed



"with an accuracy of 2–5% for objects as faint as H~25 and half-light size of 0.2 arcsec."

The AO perspective – Resolved spectroscopy



Kendrew+16

Used the simulation pipeline HSIM (Zieleniewski+15) to predict spectra for passive galaxies of various redshifts, masses and light profiles observed in 10 hr with HARMONI@E-ELT

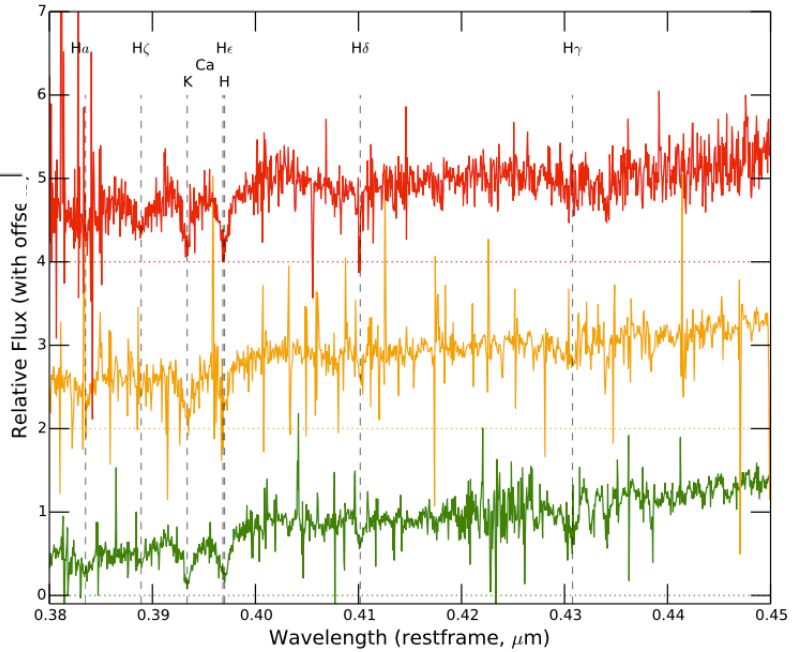
Redshift (z)	Stellar mass ($\log M/M_\odot$)	Age (Gyr)	Magnitude (AB)	HSIM S/N (PS)	HSIM S/N (dV)	HSIM S/N (Exp)
2	10	3	$J = 26.85$	3	1.4	0.9
3	10	2	$H = 27.06$	5	1.2	0.6
4	10	1	$K = 26.27$	3	0.6	0.4
2	11	3	$J = 24.35$	26	15	9
3	11	2	$H = 24.56$	37	12	6
4	11	1	$K = 23.77$	30	6	3
2	12	3	$J = 21.85$	141	125	85
3	12	2	$H = 22.06$	186	72	65
4	12	1	$K = 21.27$	195	47	26

log (M/M_{sun}) = 11
de Vaucouleur profile with R_e=0.2’

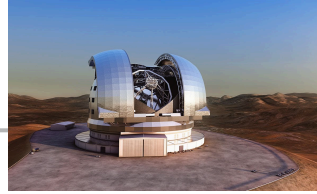
z=4

z=3

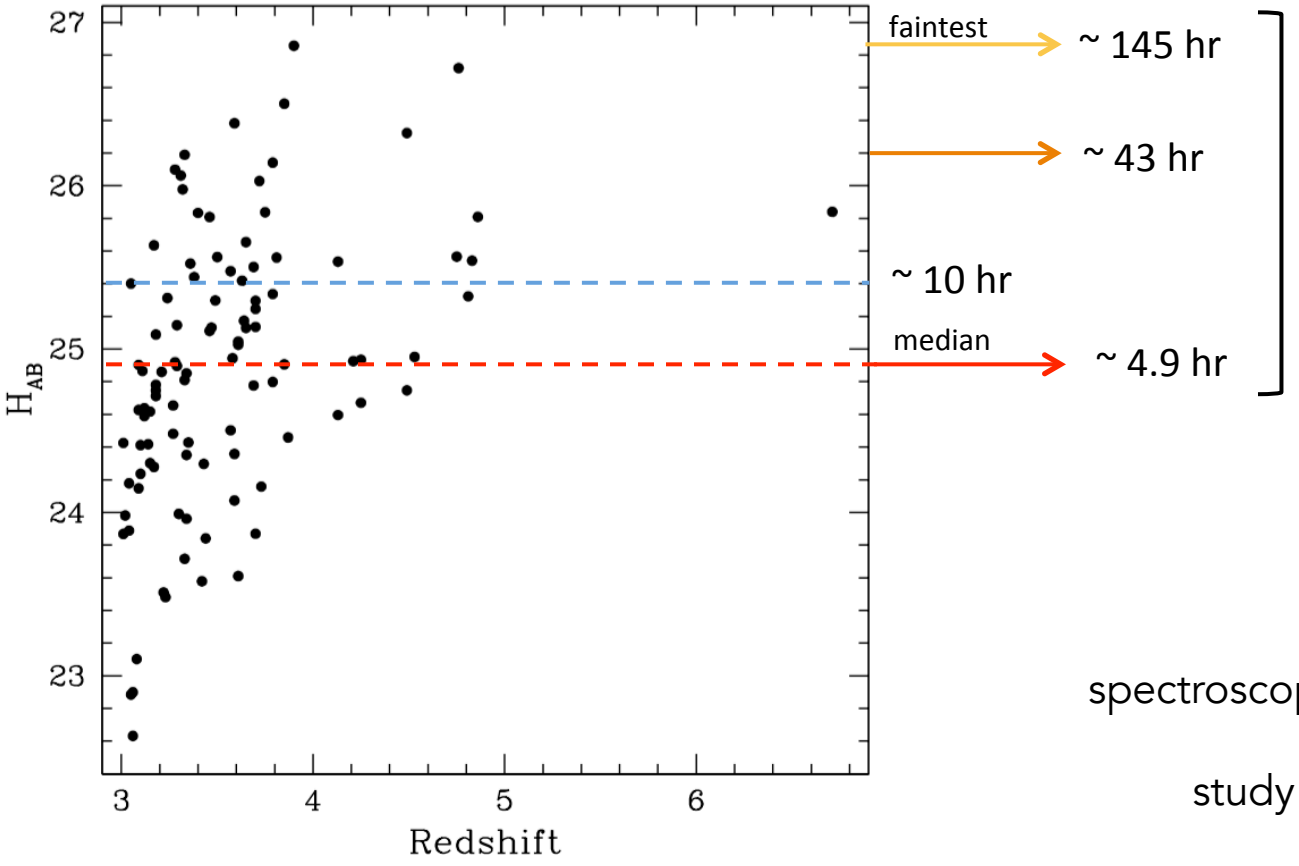
z=2



The AO perspective – Resolved spectroscopy



Source: Kendrew+16

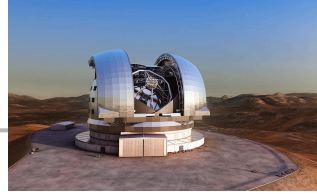


ELT-IFU HARMONI
λ=0.7– 2.45 mm
R=3100
30x60 mas spaxels

SNR=5

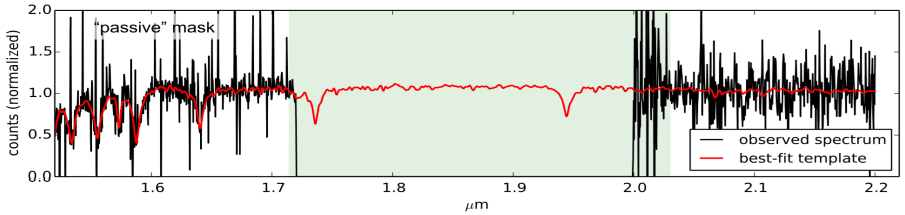
spectroscopical confirmation
+
study the physics!

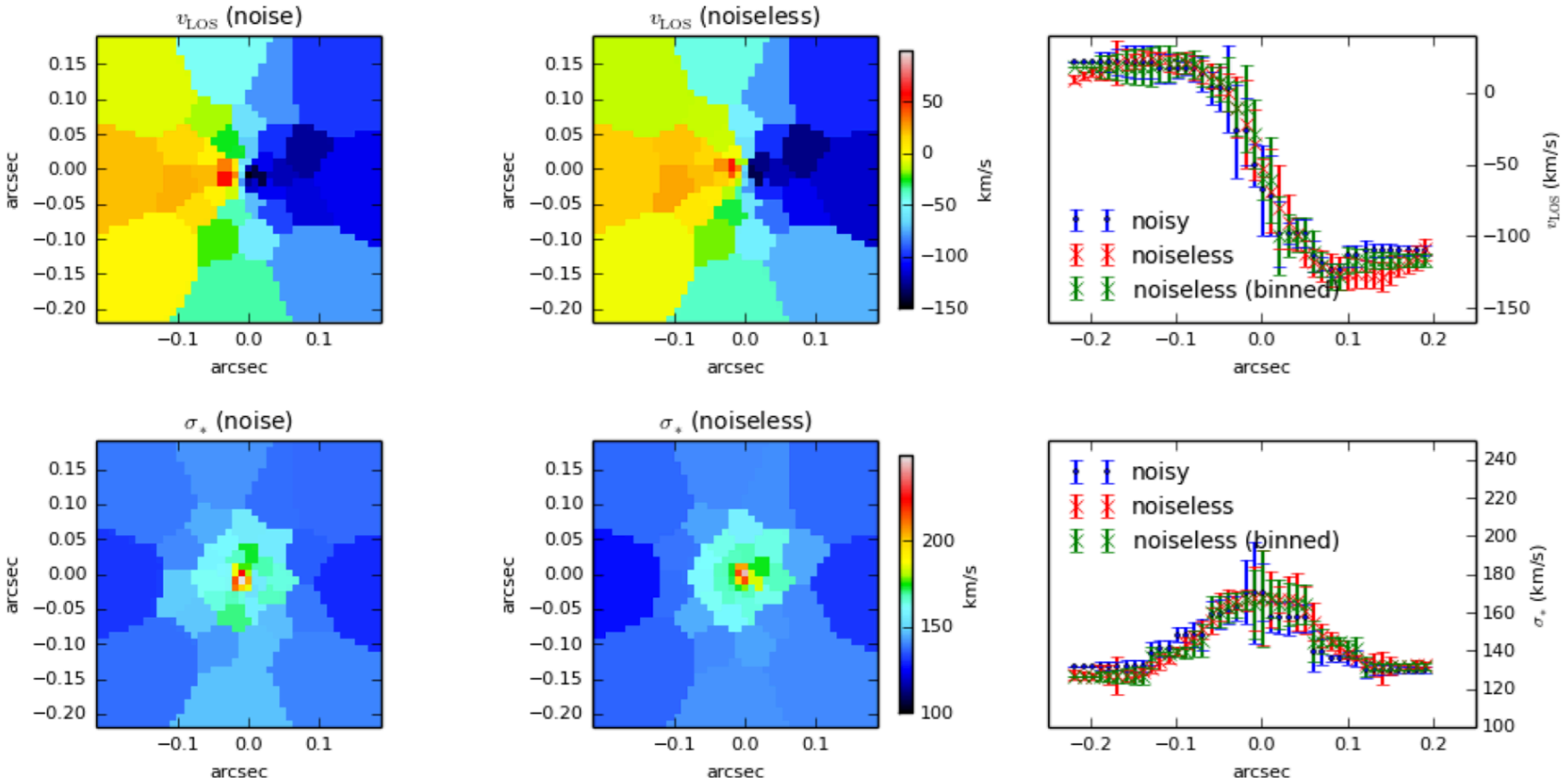
The AO perspective – Resolved spectroscopy



Kendrew+16

z=3, $M_*=10^{10}M_{sun}$ (x100)
(RAMSES NUTFB simulation)
15 hr with HARMONI@E-ELT





Summary & conclusions

- ❑ High-z passive galaxies are key to understand galaxy evolution, but very challenging
- ❑ 102 candidates at z>3 selected in CANDELS by ad-hoc SED fitting technique
- ❑ ALMA data lends decisive evidence to the quiescent nature of our candidates
- ❑ Red, compact, massive, few (0.5% of z>3 galaxies) but make 5-10% of cosmic SFRD at 3<z<8
- ❑ Extremely fast and effective feedback mechamisms still to be understood
- ❑ Need AO for deep resolved observations of high-z passive galaxies

Thanks

Further details in:
Merlin+18: selection technique (GOODS-S)
Santini+19: confirmation of the candidates
Merlin+19: selection in the 5 CANDELS fields
Santini+in prep: confirmation of the total sample + stellar MF