The HUGS survey:
A complete view of the first 2 billion years of galaxy formation

A. Fontana (INAF Rome Obs)

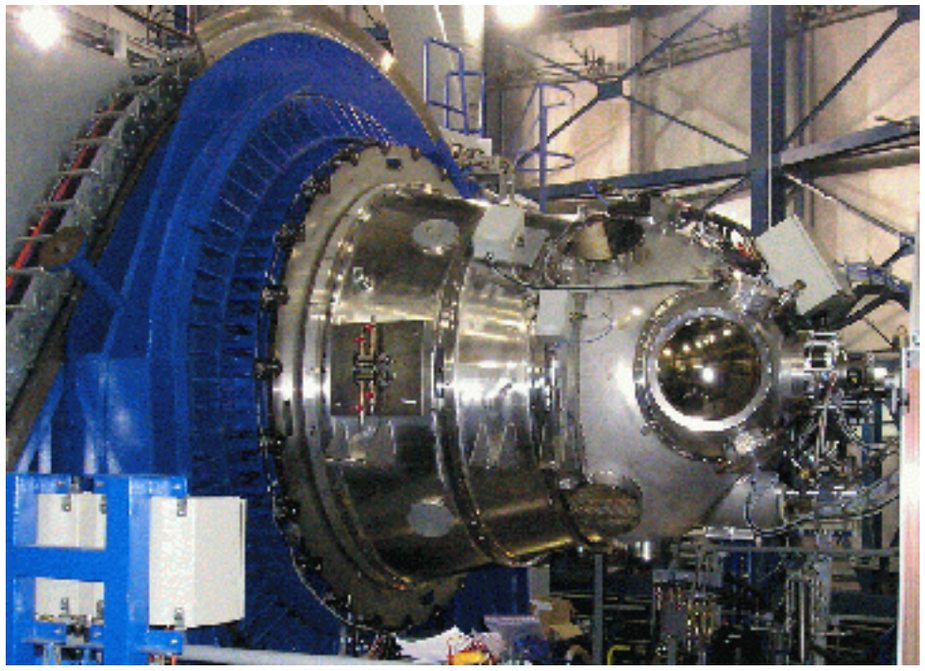
2 Large Programmes executed with Hawk-I

181.A0717 "*A deep infrared view of the early Universe: exploiting the unique capabilities of HAWK-I to explore the reionization epoch*"
"

186.A0898 "*A complete view of the first 2 billion years of galaxy formation*"

Both programs were designed to exploit the unique **Hawk-I** capabilities:

- extreme efficiency,
- "wide" FoV,
- image quality



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181.A0717 "*A deep infrared view of the early Universe: exploiting the unique capabilities of HAWK-I to explore the reionization epoch*"

- Exploration of the Early Universe
- How did first stars and galaxies formed?
- What/when re-ionized the Universe?

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- How did first stars and galaxies formed?
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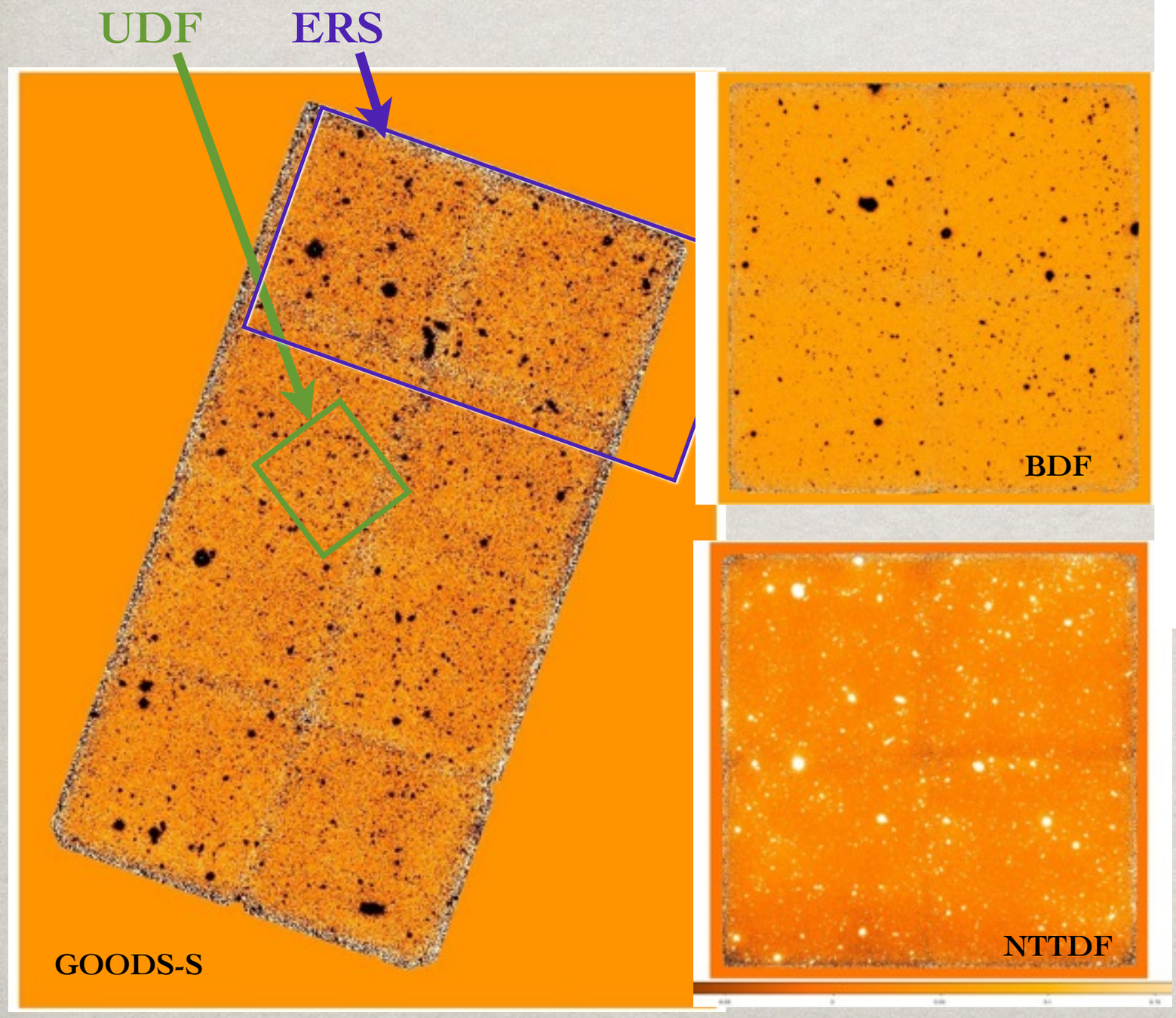
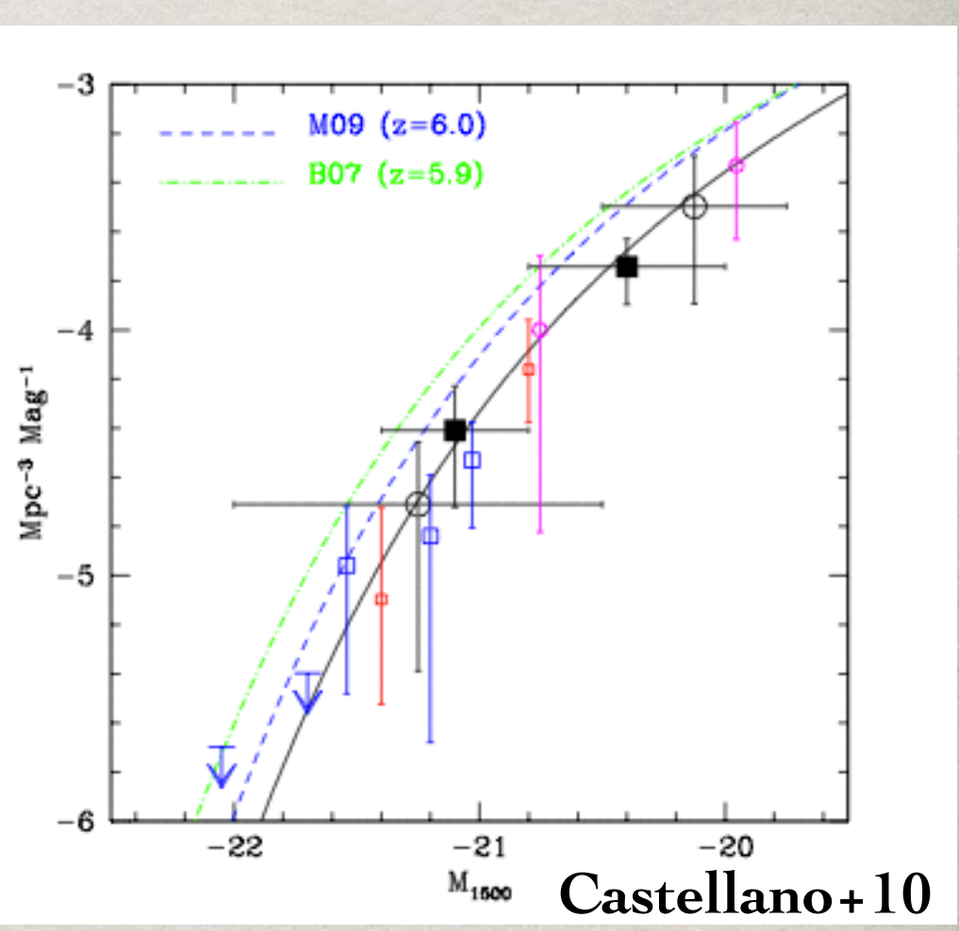
186.A0898 "*A complete view of the first 2 billion years of galaxy formation*"

- Assessing a complete picture of the Early Universe;
- Securing ESO contribution to CANDELS - the major HST survey
- Are there red galaxies (dust-reddened starbursts or quiescent) at high-z?
- Can we reliably trace the mass assembly process at z>4?
- Are our estimates of SFR and mass growth consistent?

Searching for z~7 galaxies with a deep Hawk-I survey

Hawk-I Science Verification
+
ESO LP (HAWK-I+FORS2) -*PI A. Fontana*
~ 160hr VLT time





Hawk-I: bright &rare
WFC3: faint & numerous

Our Hawk-I program was designed to allow for efficient spectroscopic follow-up:

P84 & P85: VLT Ultradeep spectroscopy

~30 targets in 3fields

~70hr with red-enhanced FORS2

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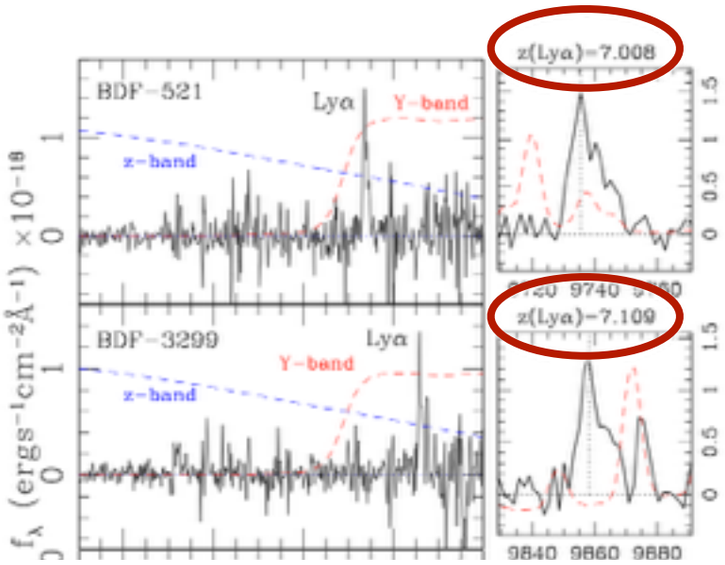
P84 & P85: VLT Ultradeep spectroscopy
~30 targets in 3fields
~70hr with red-enhanced FORS2

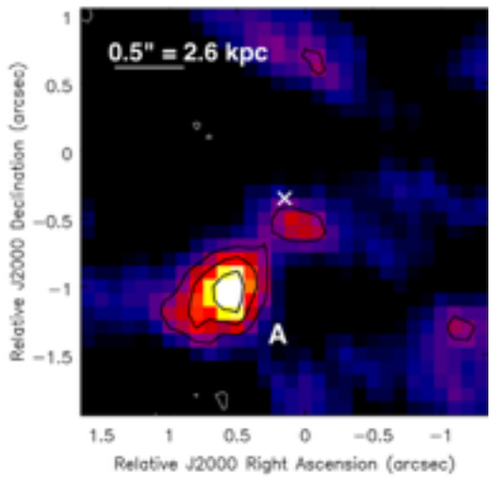
- The first reliable detection of galaxies at z>7 (Vanzella+11)

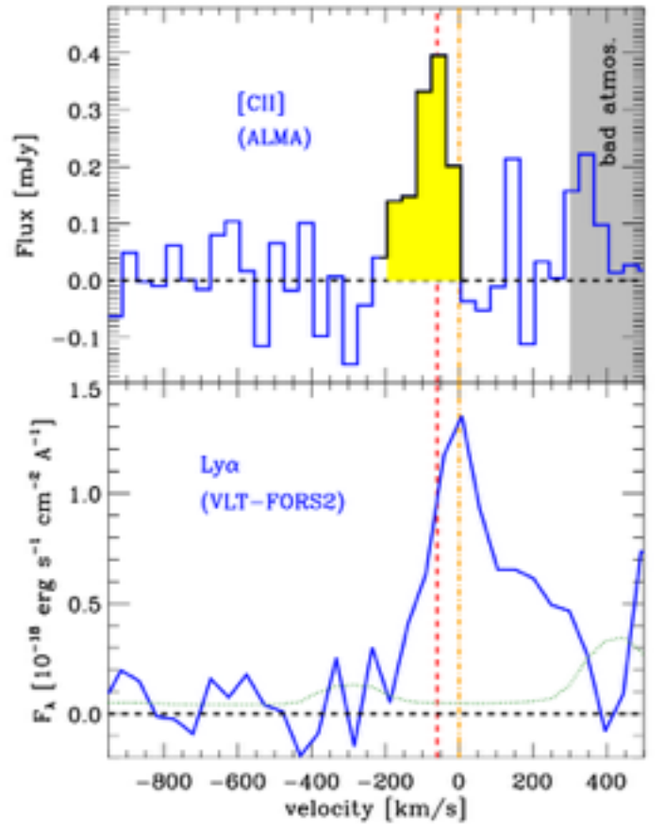
- Establish that the Lyα visibility drops at z>6.5: evidence for reionization? (Fontana+10, Pentericci+11, Pentericci+14, vs Stark+10),

- ALMA detection: the assembly of "normal" galaxies at z~7 (Maiolino+15)

- just started: KMOS LP on GLASS z=8 candidates (Fontana et al, 196.A-0778)







CANDELS: the largest HST program ever approved
WFC3 deep/wide exposures over 5 extragal. fields
P.I.: S. Faber, H. Ferguson.

Table 1
CANDELS at a Glance

Field	Coordinates	Tier	WFC3/IR Tiling	HST Orbits/Tile	IR Filters[a]	UV/Optical Filters[b]
GOODS-N	189.228621, +62.238572	Deep	~3 × 5	~13	*YJH*	*UV*,*UI*(*WVz*)
GOODS-N	189.228621, +62.238572	Wide	2 @ ~2 × 4	~3	*YJH*	*Iz*(*W*)
GOODS-S	53.122751, −27.805089	Deep	~3 × 5	~13	*YJH*	*I*(*WVz*)
GOODS-S	53.122751, −27.805089	Wide	~2 × 4	~3	*YJH*	*Iz*(*W*)
COSMOS	150.116321, +2.2009731	Wide	4 × 11	~2	*JH*	*VI*(*W*)
EGS	214.825000, +52.825000	Wide	3 × 15	~2	*JH*	*VI*(*W*)
UDS	34.406250, −5.2000000	Wide	4 × 11	~2	*JH*	*VI*(*W*)

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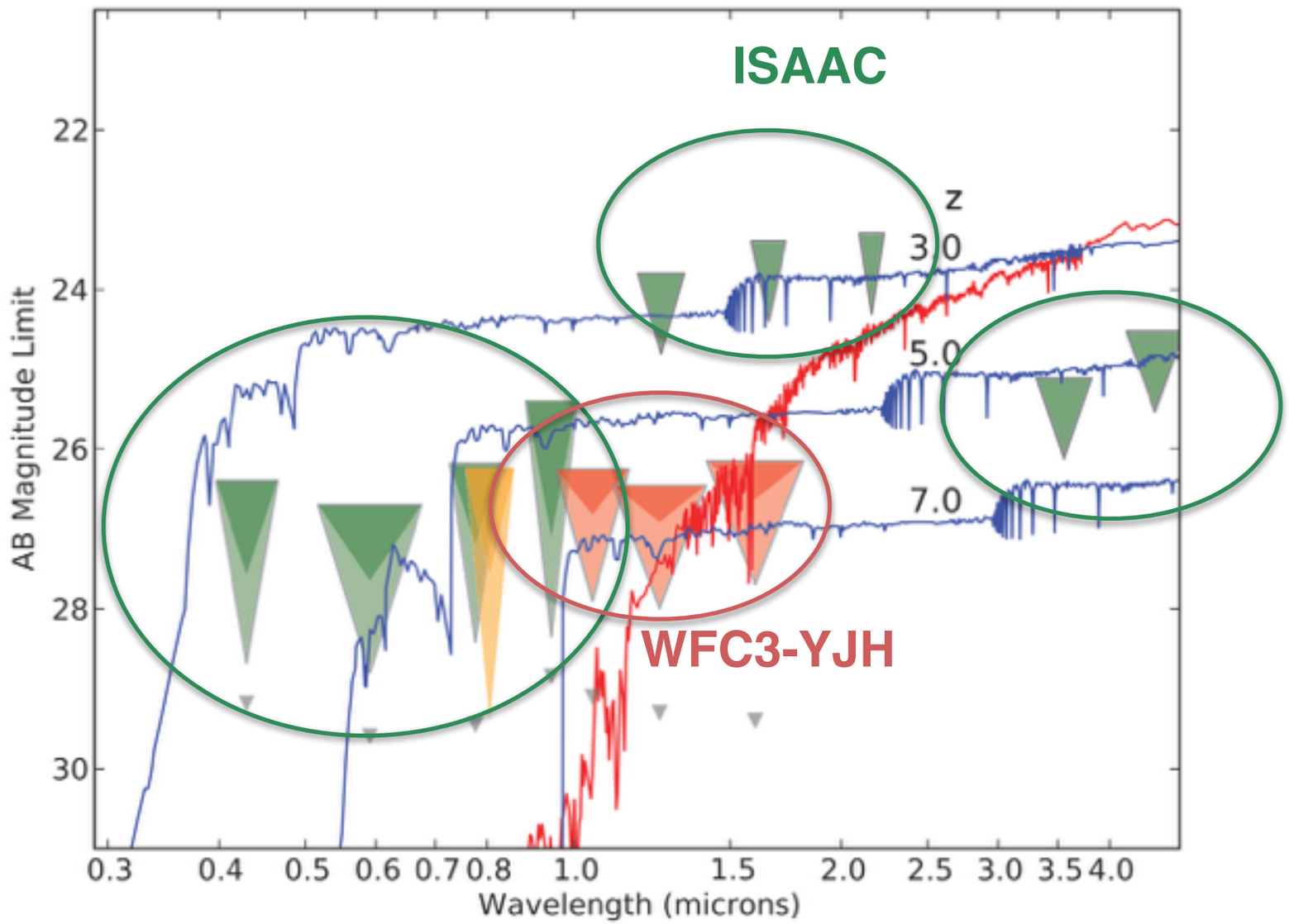


HUGS (Hawk-I UDS and GOODS Survey):

A Rome-Edinburgh+ CANDELS program

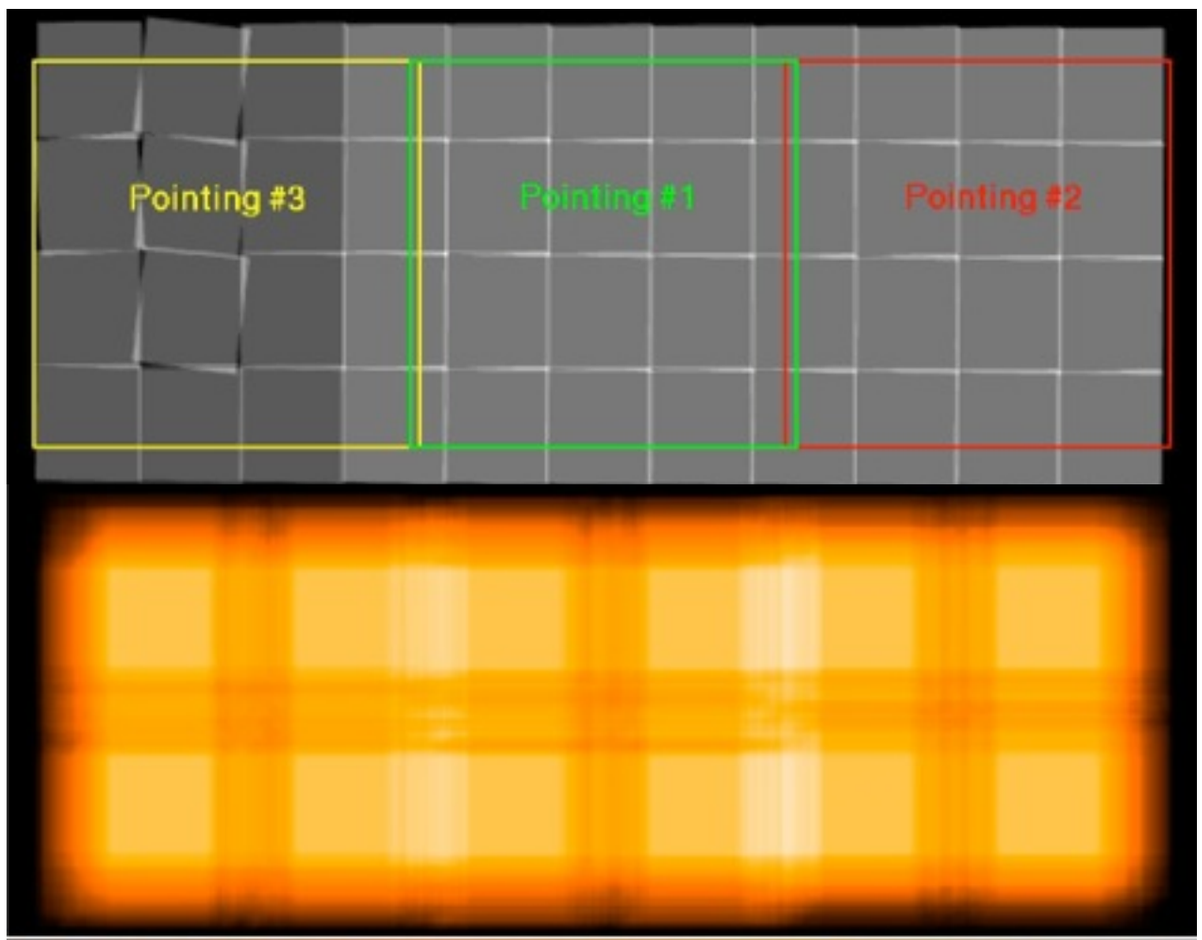
A.Fontana (PI), J. Dunlop, Faber, Ferguson et al...

Large Hawk-I@VLT program (250hr)

186.A- 0898 + 181.A- 0717 AND HAWK-I SV

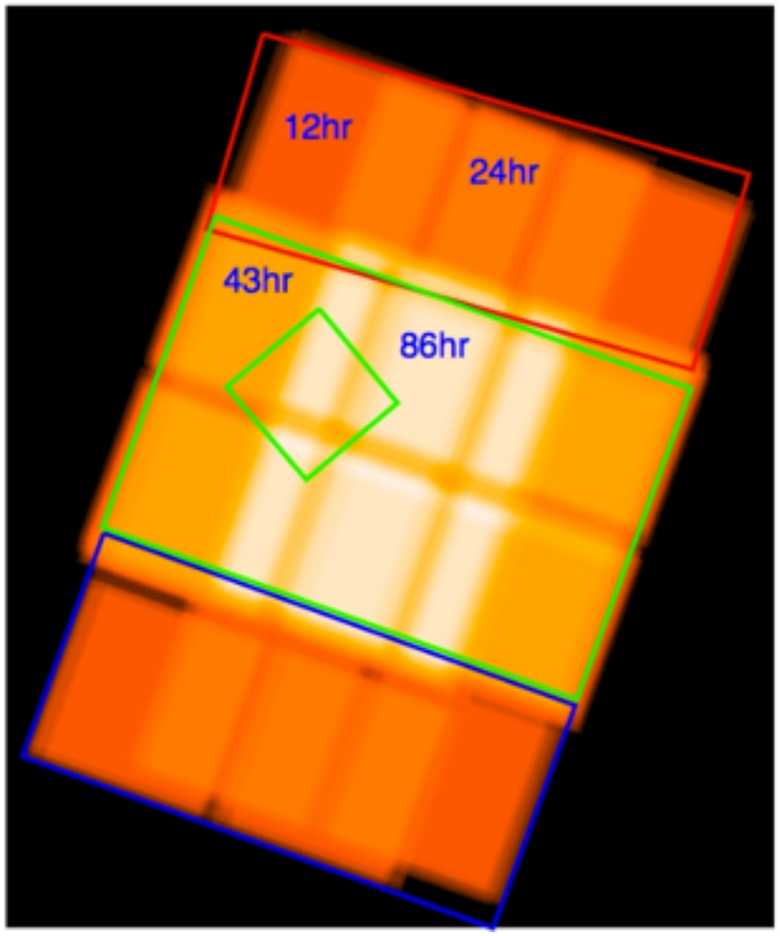
UDS Observing Plan:

- 3 pointings, 85% of the CANDELS area
- Y~26.5 (~8h per pointing) and K~26 (~13h per pointing)



GOODS Observing Plan:

- 100% of the CANDELS area
- The deepest K band ever
- Matches deep/wide depth



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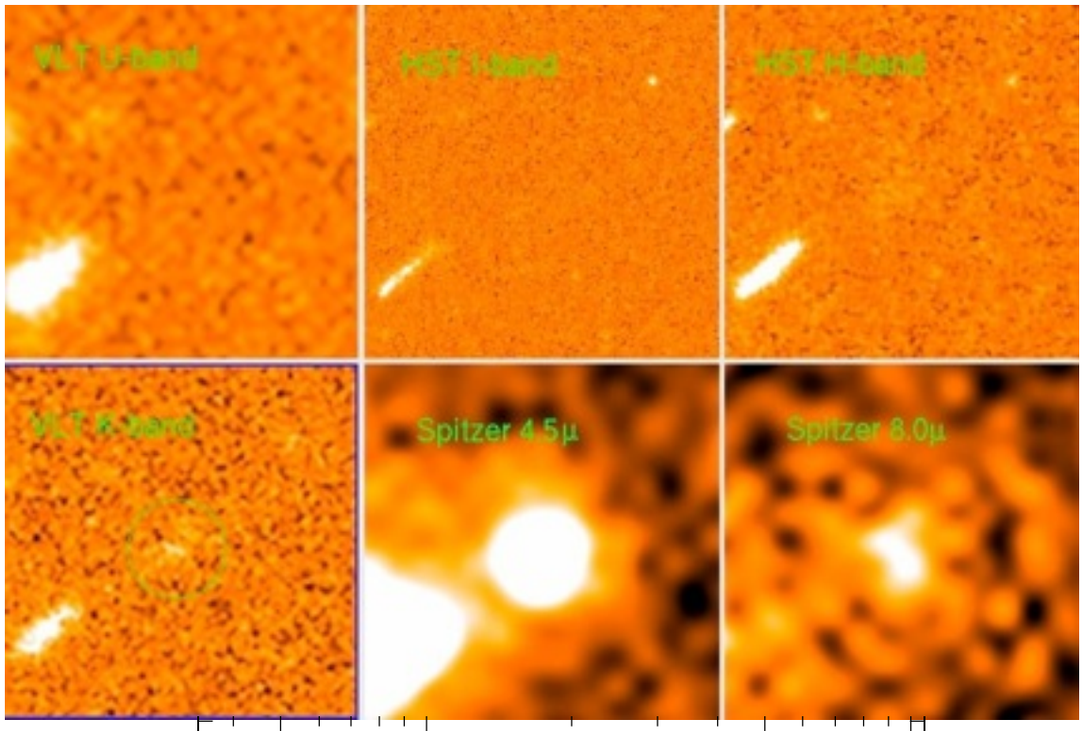
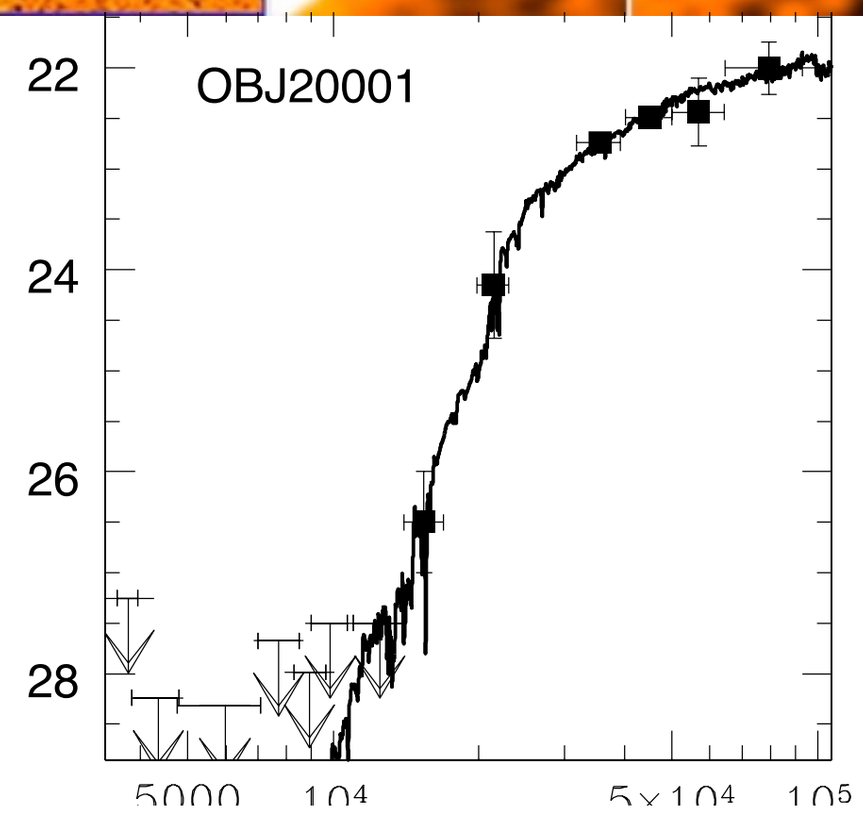
186.A- 0898 + 181.A- 0717 AND HAWK-I SV

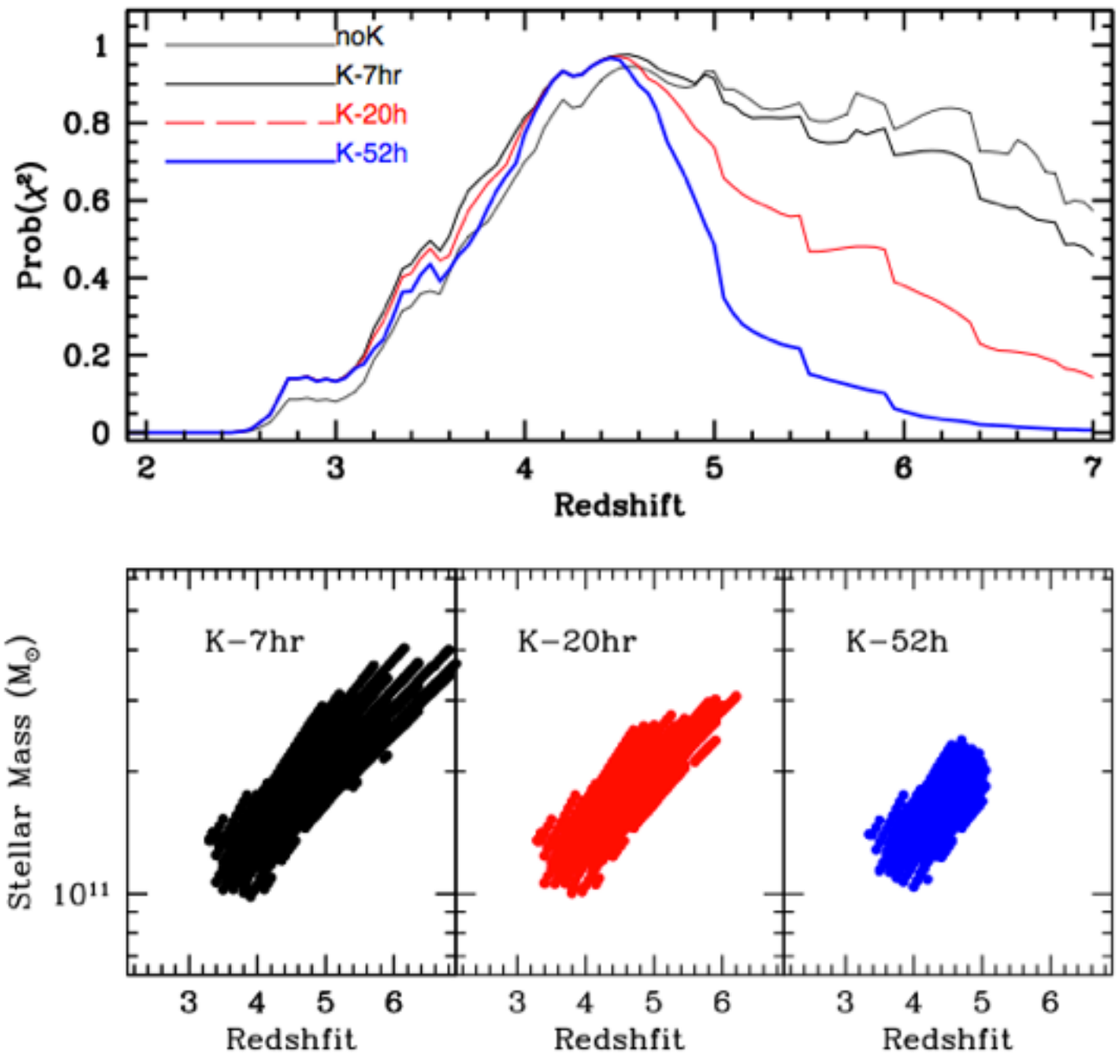
Science goals:

1. Locating and measuring the Balmer break at z>3.5
2. Improving photo-z accuracy for z>4 (Balmer break)
3. Improving photo-z accuracy for z>7 (Lyman break)
4. Assembling a complete sample of galaxies at z>4

Massive quiescent galaxy candidate at z>3 in CANDELS





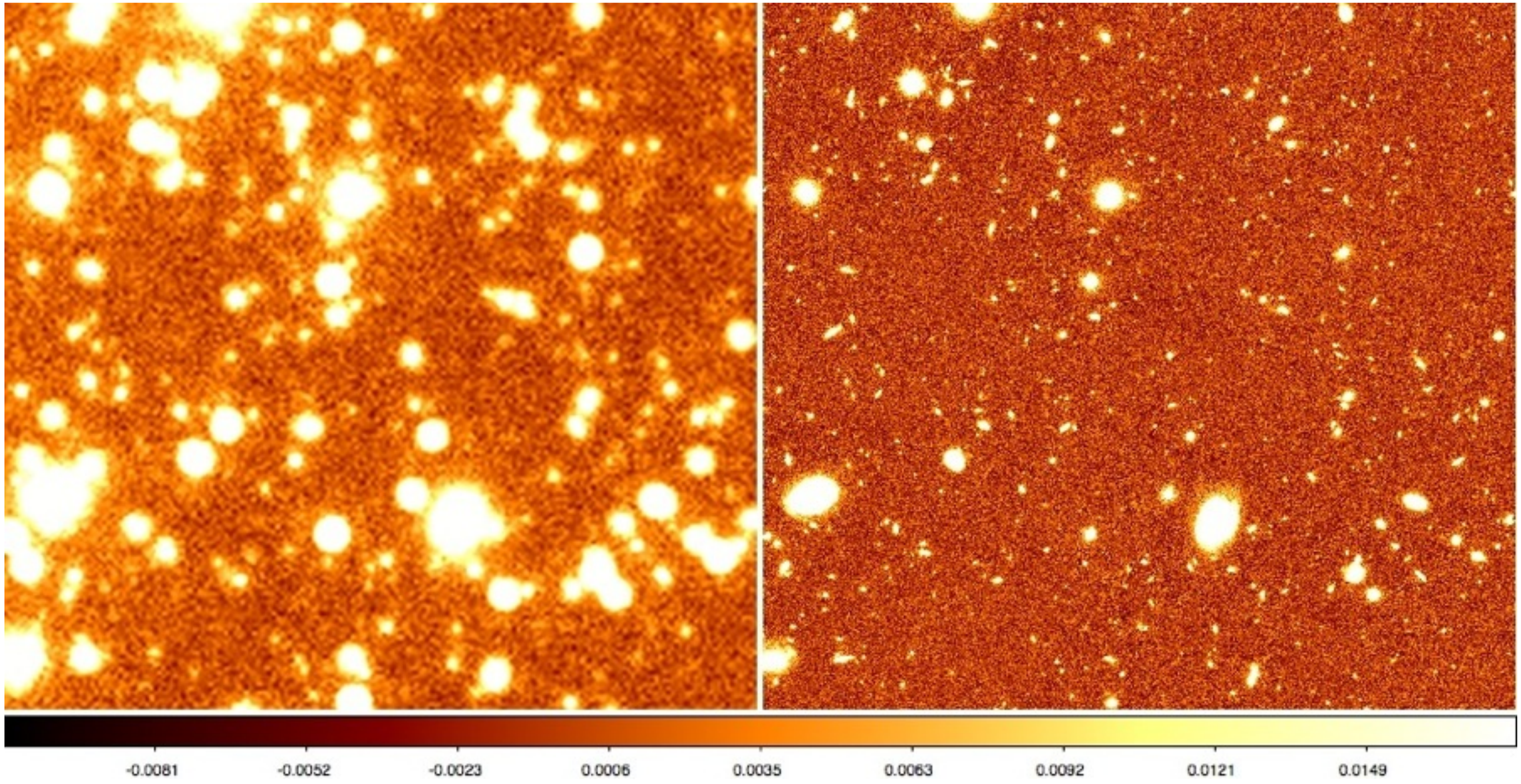


To extend the exercise at higher z we need to observe redder bands.

8mt. g.b. + Spitzer imaging essential:

Spitzer-SED

WFC3-CANDELS



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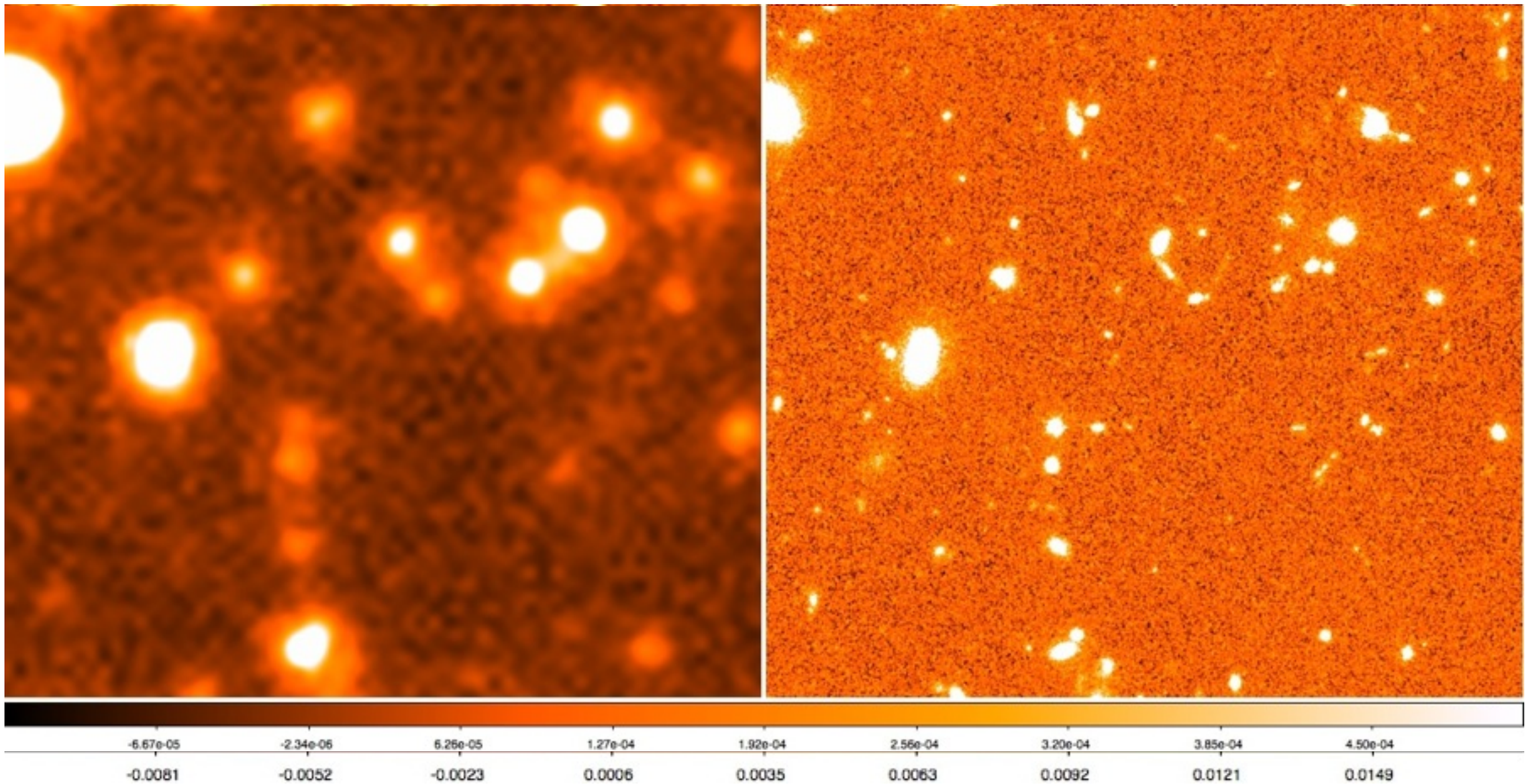

The difference in resolution has a twofold effect:
a) worsen the completeness;
b) makes photometry more complicated due to blending, requiring appropriate techniques for deconvolution.

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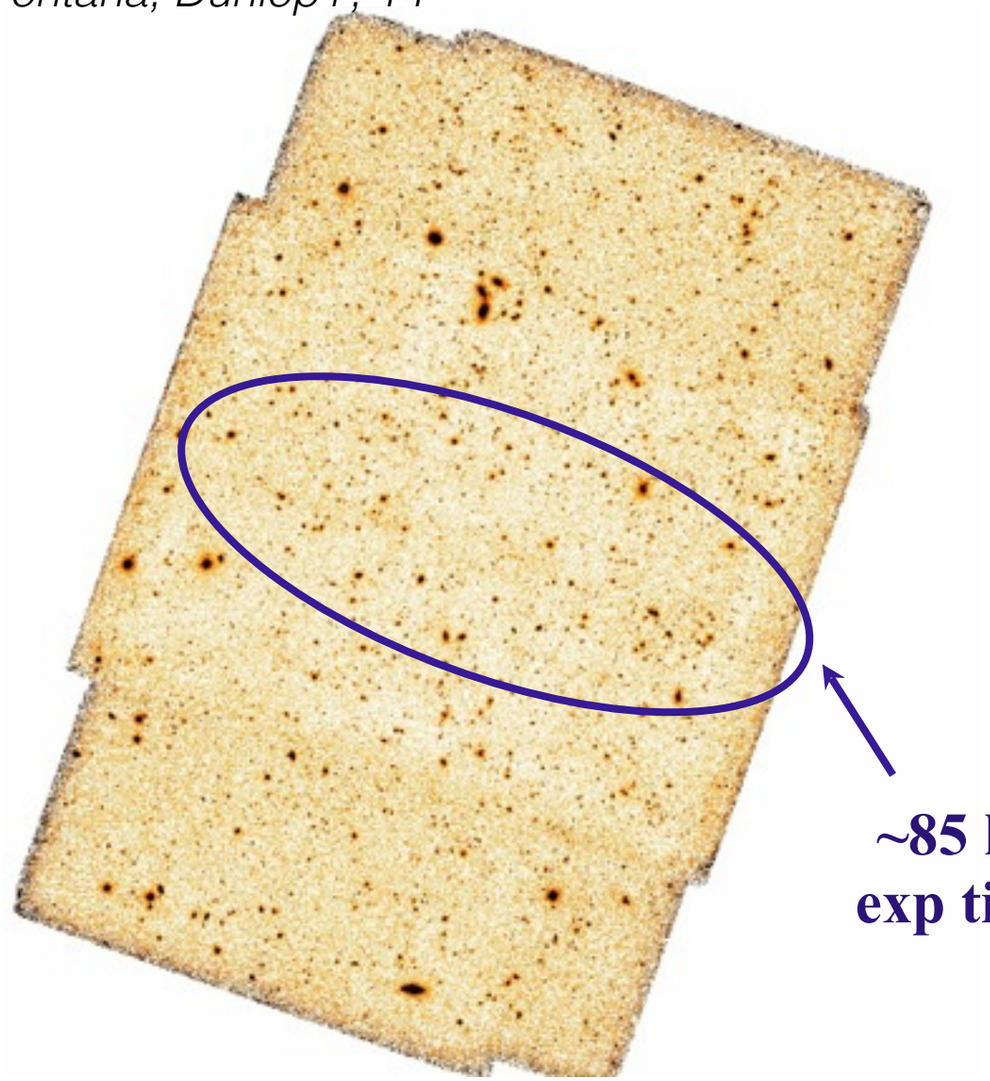
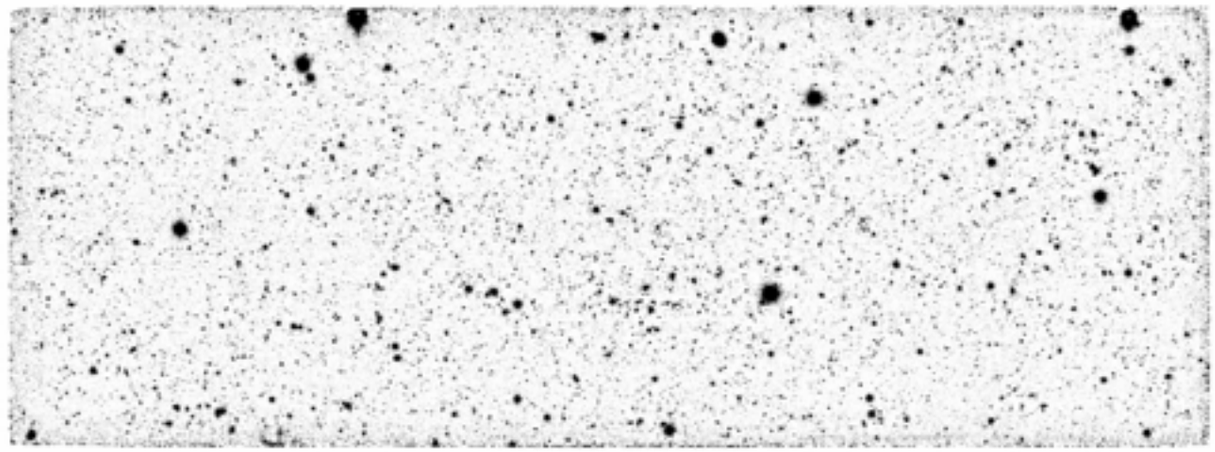
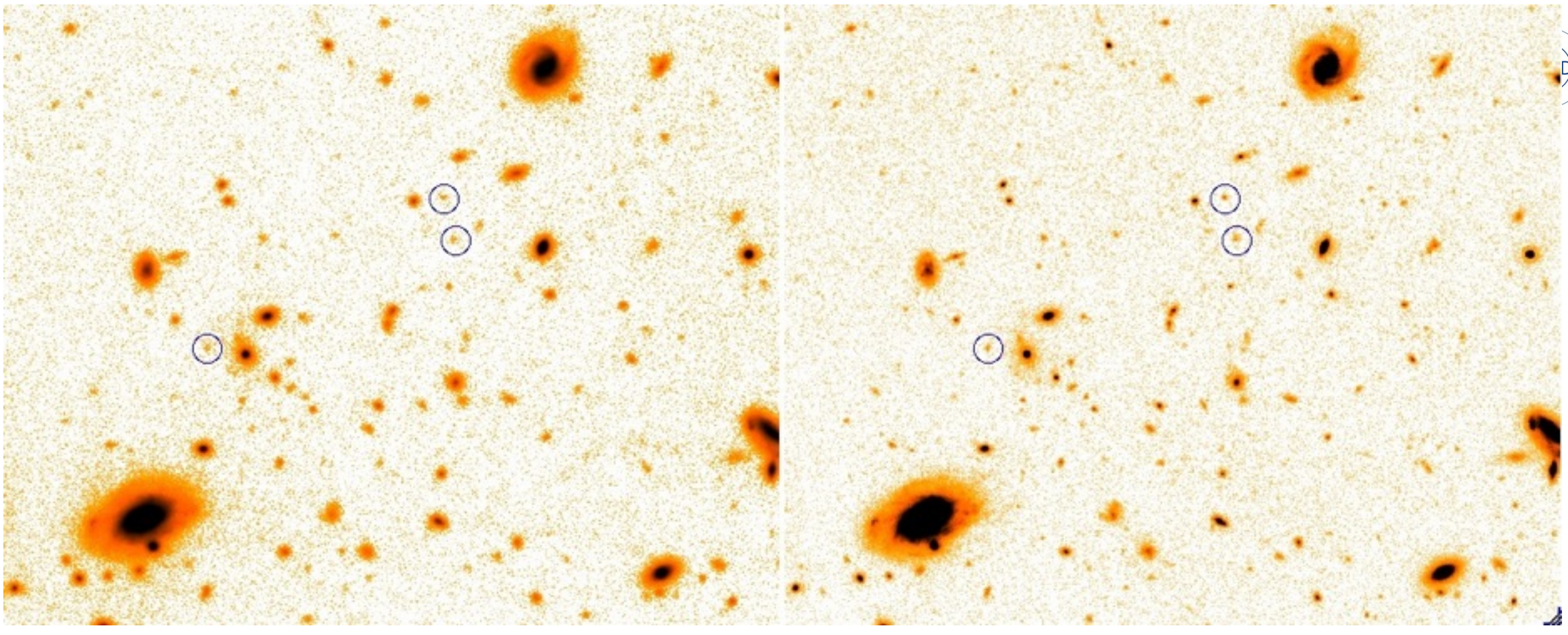
186.A- 0898 + 181.A- 0717 AND HAWK-I SV

Fontana, Dunlop+, 14







Fontana, Dunlop+, 14

1σ, 1arcsec^2 5σ, 1FWHM^2

Layout and summary of observations for the GOODS-S field. We note that each pointing has been rotated with PA=-19.5 degrees

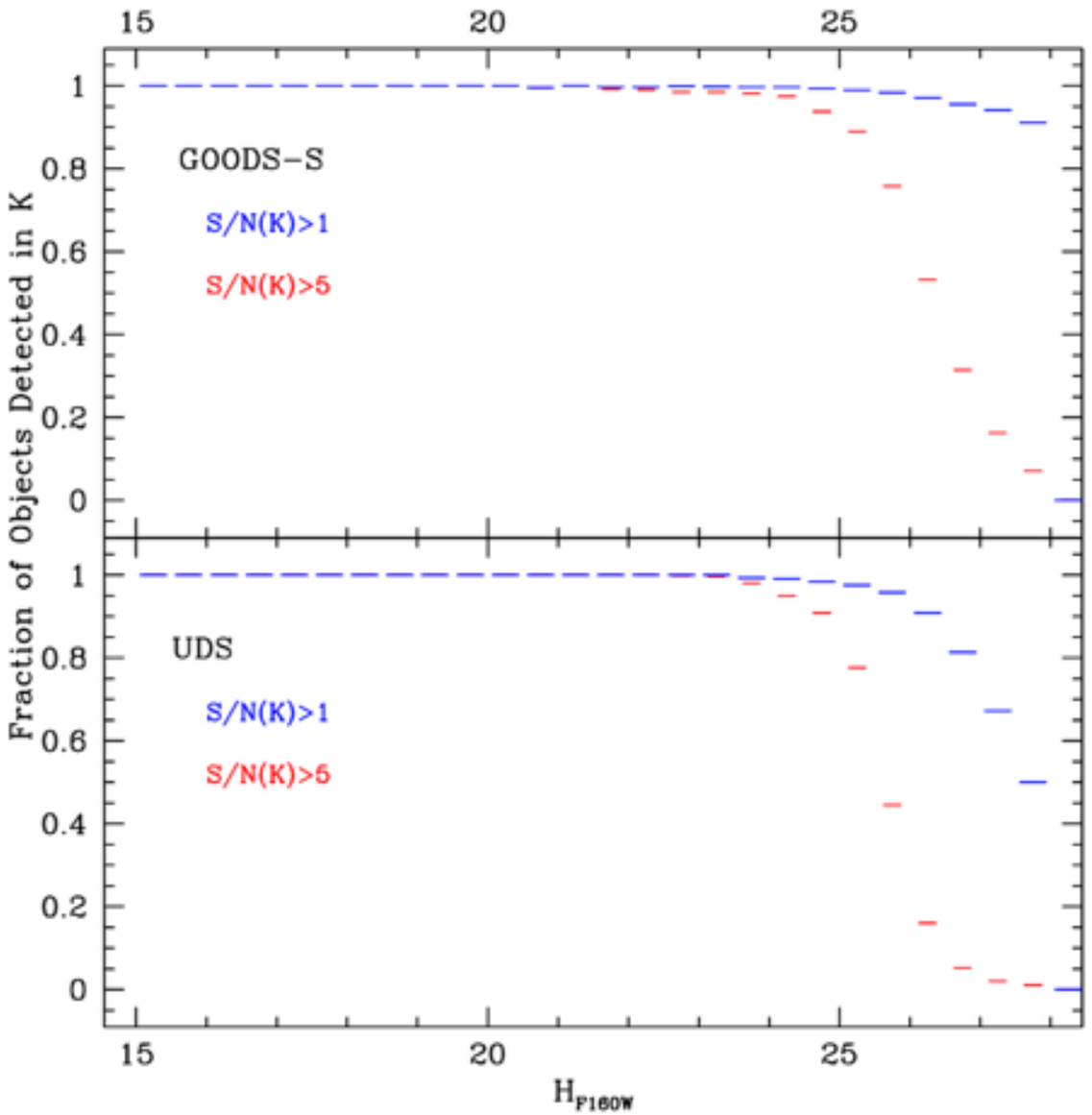
Pointing	Central RA	Central DEC	Exposure time (Sec)	Final seeing	maglim$^{(1)}$	maglim$^{(2)}$
			K band			
GOODS-D1	03:32:36.835	-27:47:45.24	113520	0.39	27.8	26.5
GOODS-D2	03:32:24.890	-27:48:33.22	112800	0.38	27.8	26.5
GOODS-W1	03:32:41.080	-27:51:44.32	47220	0.43	27.4	26.0
GOODS-W2	03:32:29.650	-27:44:37.26	40800	0.38	27.3	26.0
GOODS-W3	03:32:31.796	-27:51:01.74	37320	0.38	27.3	25.9
GOODS-W4	03:32:20.242	-27:44:59.97	41880	0.42	27.3	25.8

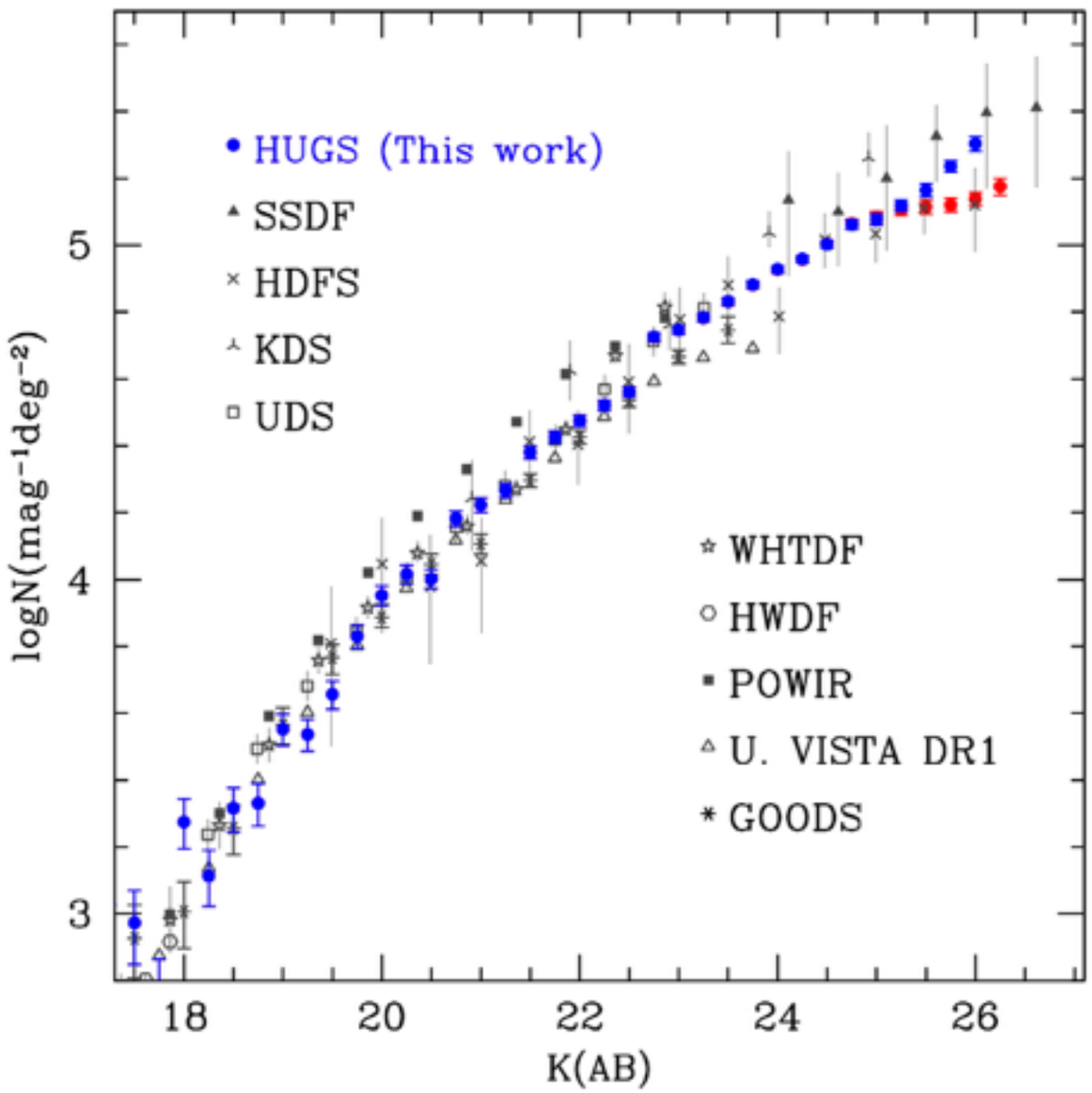
31h

Same for UDS - K_{lim}~26 (5σ), Y_{lim}~26.8 (5σ)

The Hawk-I UDS and GOODS Survey (HUGS): Survey design and deep *K*-band number counts⋆,⋆⋆

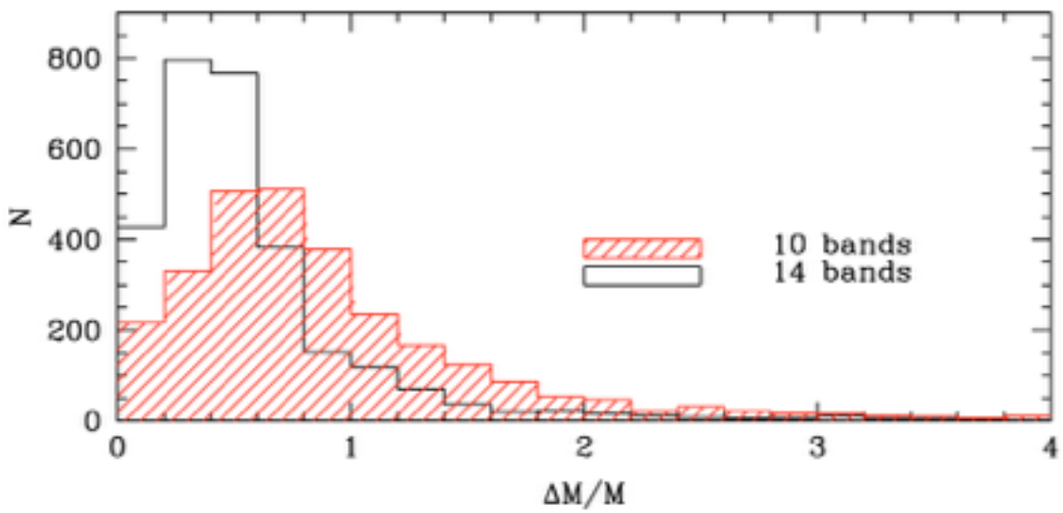
A. Fontana[1], J. S. Dunlop[2], D. Paris[1], T. A. Targett[2,3], K. Boutsia[1], M. Castellano[1], A. Galametz[1], A. Grazian[1], R. McLure[2], E. Merlin[1], L. Pentericci[1], S. Wuyts[4], O. Almaini[5], K. Caputi[6], R.-R. Chary[7], M. Cirasuolo[2], C. J. Conselice[5], A. Cooray[8], E. Daddi[9], M. Dickinson[10], S. M. Faber[11], G. Fazio[12], H. C. Ferguson[13], E. Giallongo[1], M. Giavalisco[14], N. A. Grogin[13], N. Hathi[15], A. M. Koekemoer[13], D. C. Koo[11], R. A. Lucas[13], M. Nonino[16], H. W. Rix[17], A. Renzini[18], D. Rosario[4], P. Santini[1], C. Scarlata[19], V. Sommariva[1,21], D. P. Stark[20], A. van der Wel[17], E. Vanzella[21], V. Wild[22,2], H. Yan[23], and S. Zibetti[24]





Improving the accuracy in mass determination

GOODS (A.F.+06) *z~2-4, K<24*



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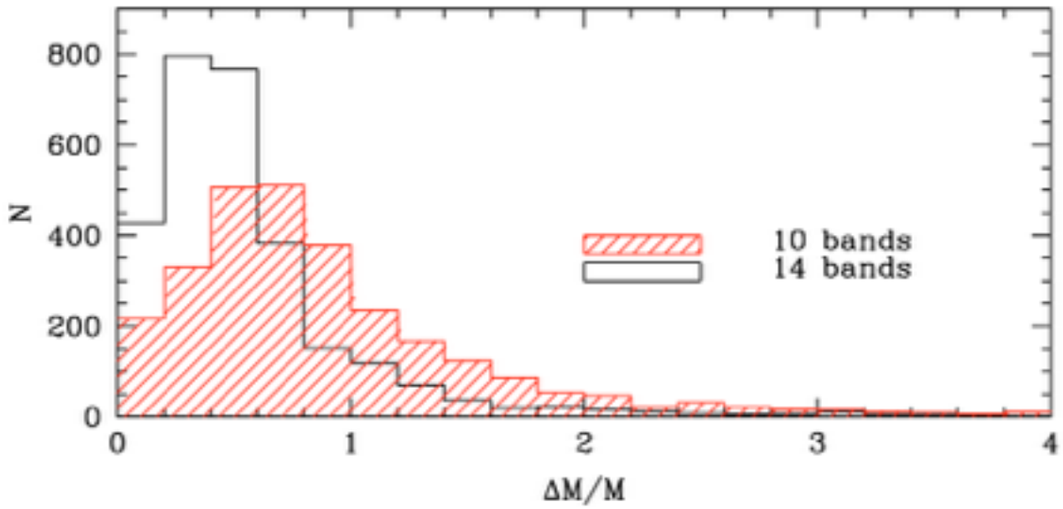
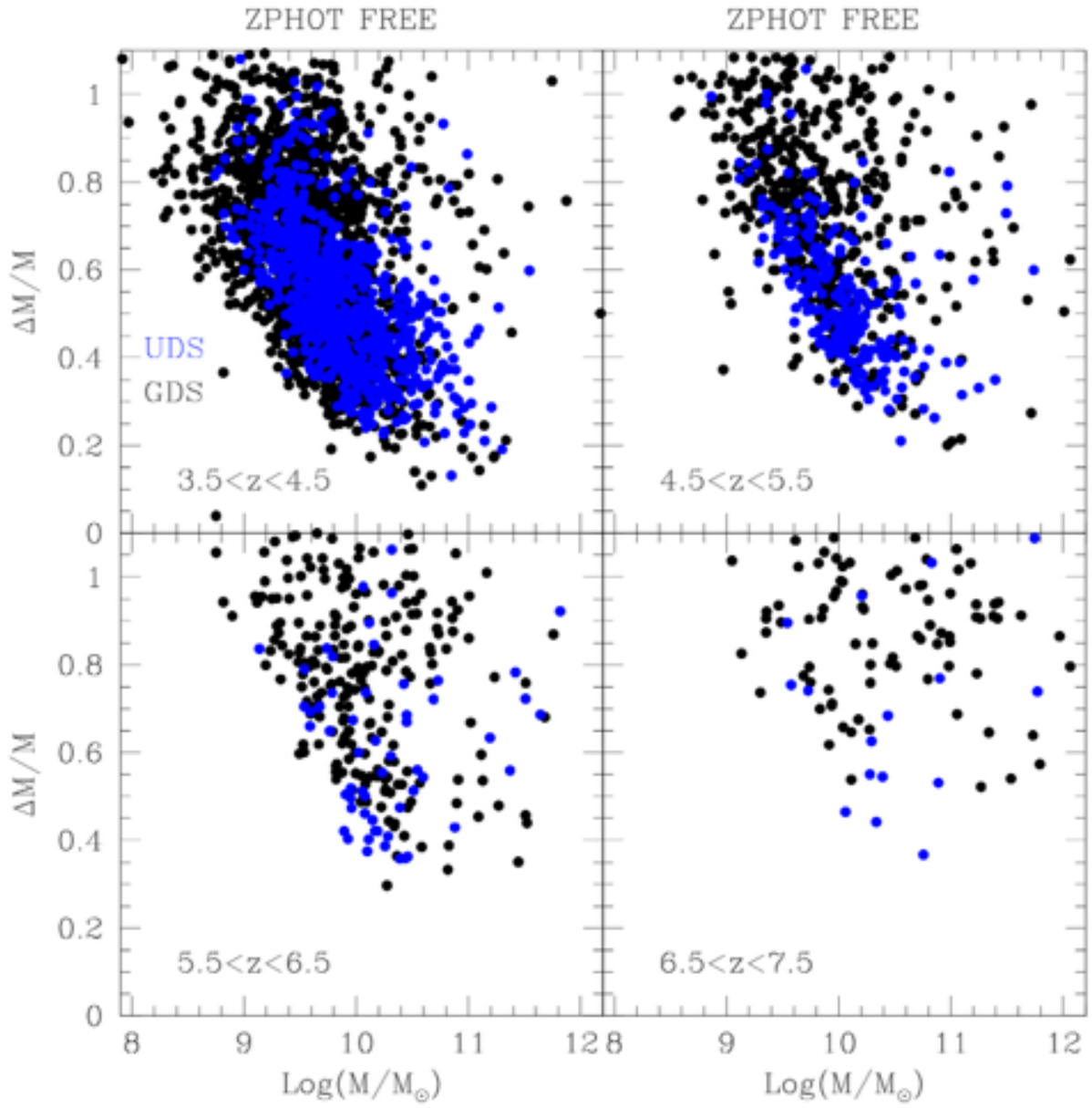


CANDELS (Grazian, AF+14)



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ASTRODEEP

CANDELS+HUGS data are public on the ESO archive (*we even passed Phase 3*):

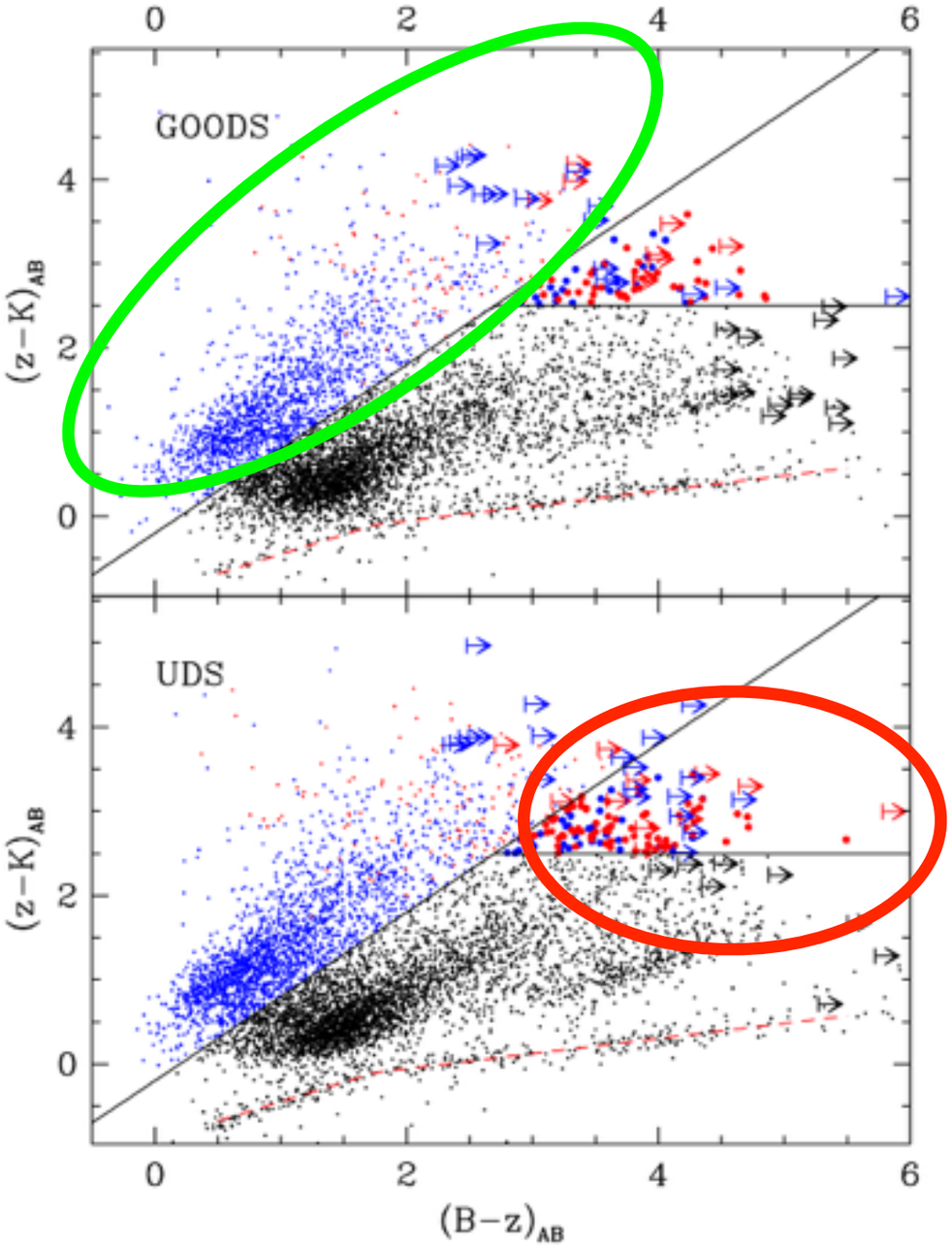
- 👍 UDS and GOODS-S images (Y and K)
- 👍 Multiwavelength Catalogs: HST + HUGS + Spitzer (including also photo-z, stellar masses etc)
  - ☑ Galametz et al (UDS) 2013
  - ☑ Guo et al (2013) (GOODS-S)
  - ☑ Fontana et al (2014) (Images+revised GOODS-S)

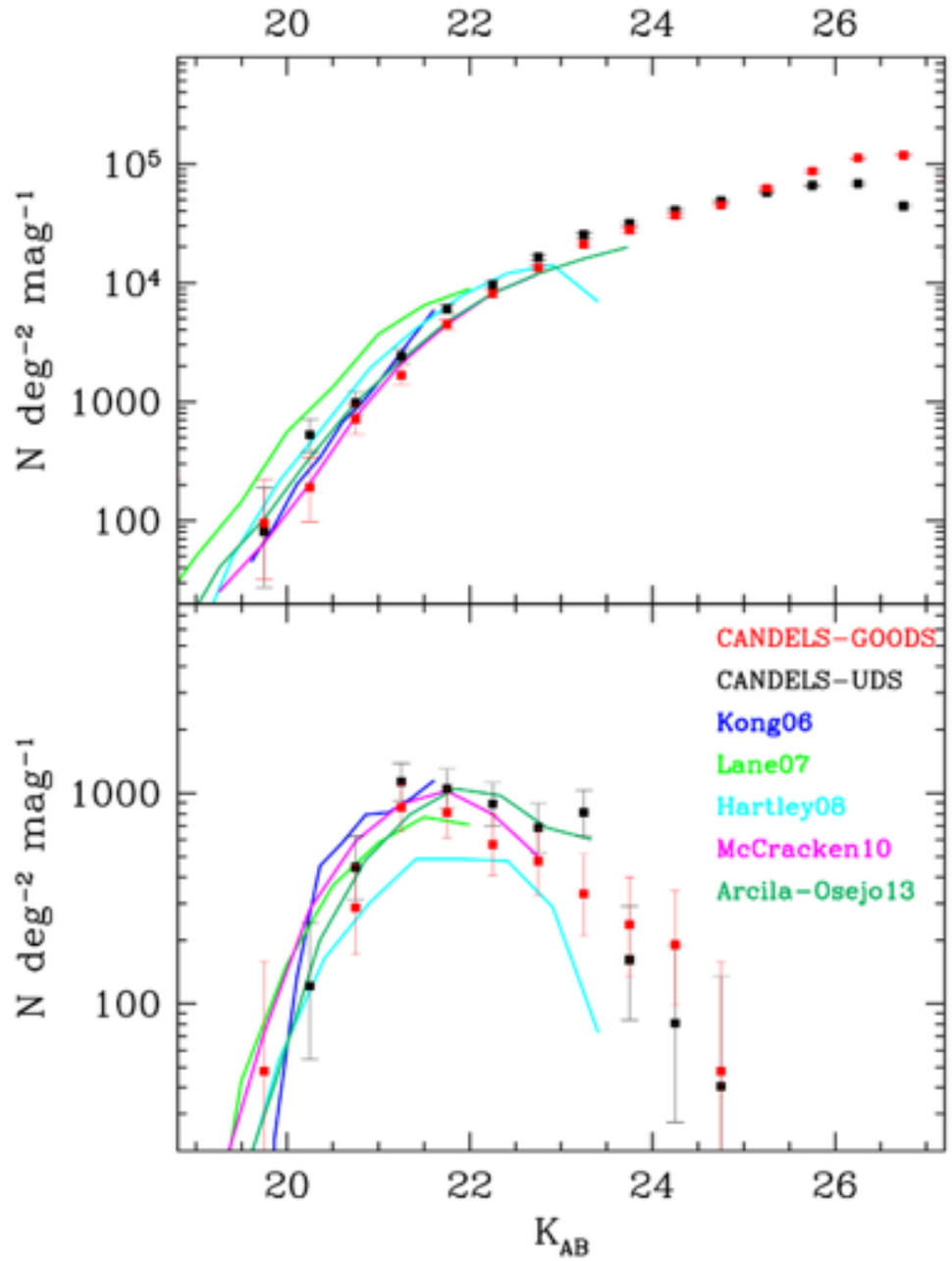
In total ~ 200 citations

The distribution of quiescent galaxies at z~2

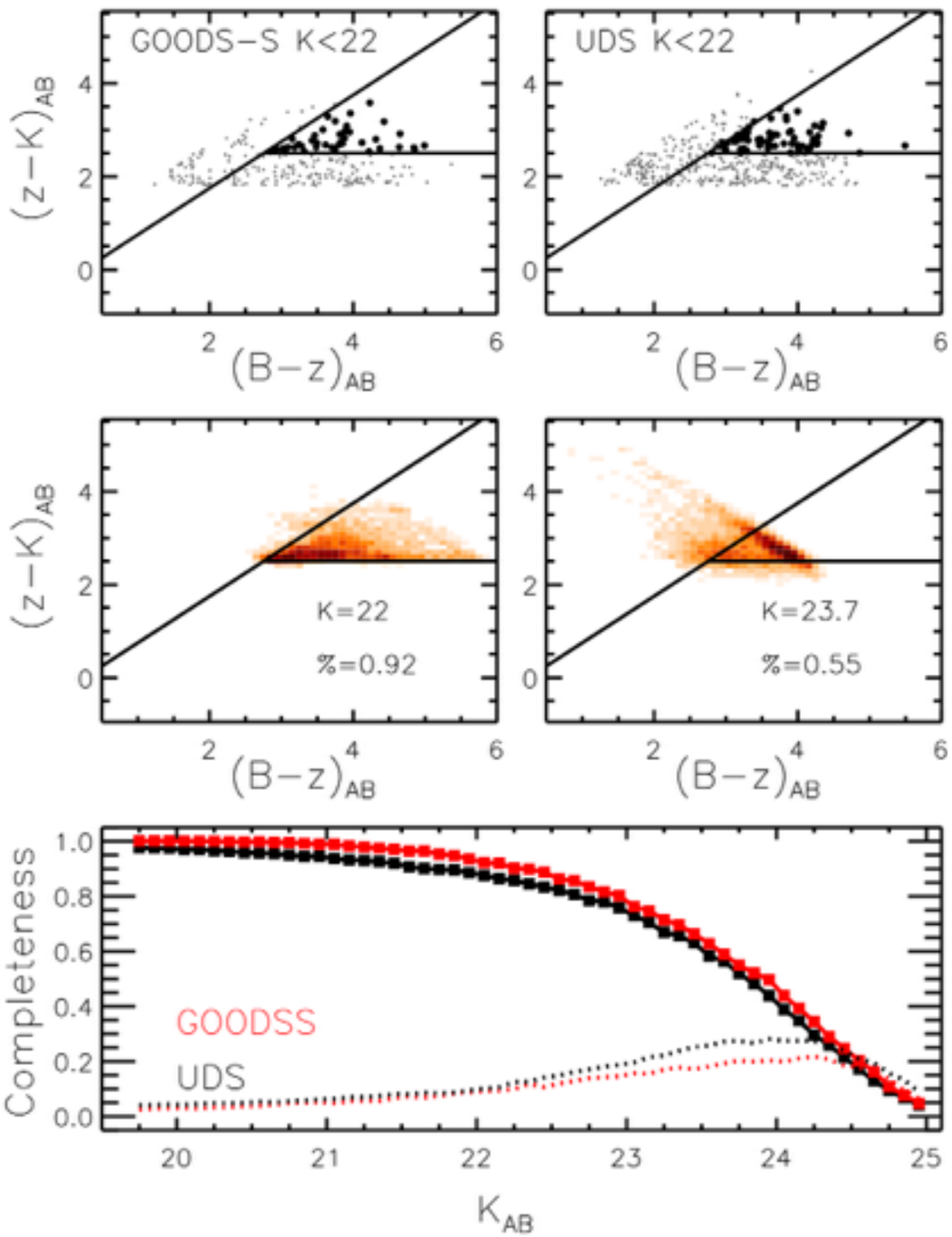
Sommariva, AF+2014

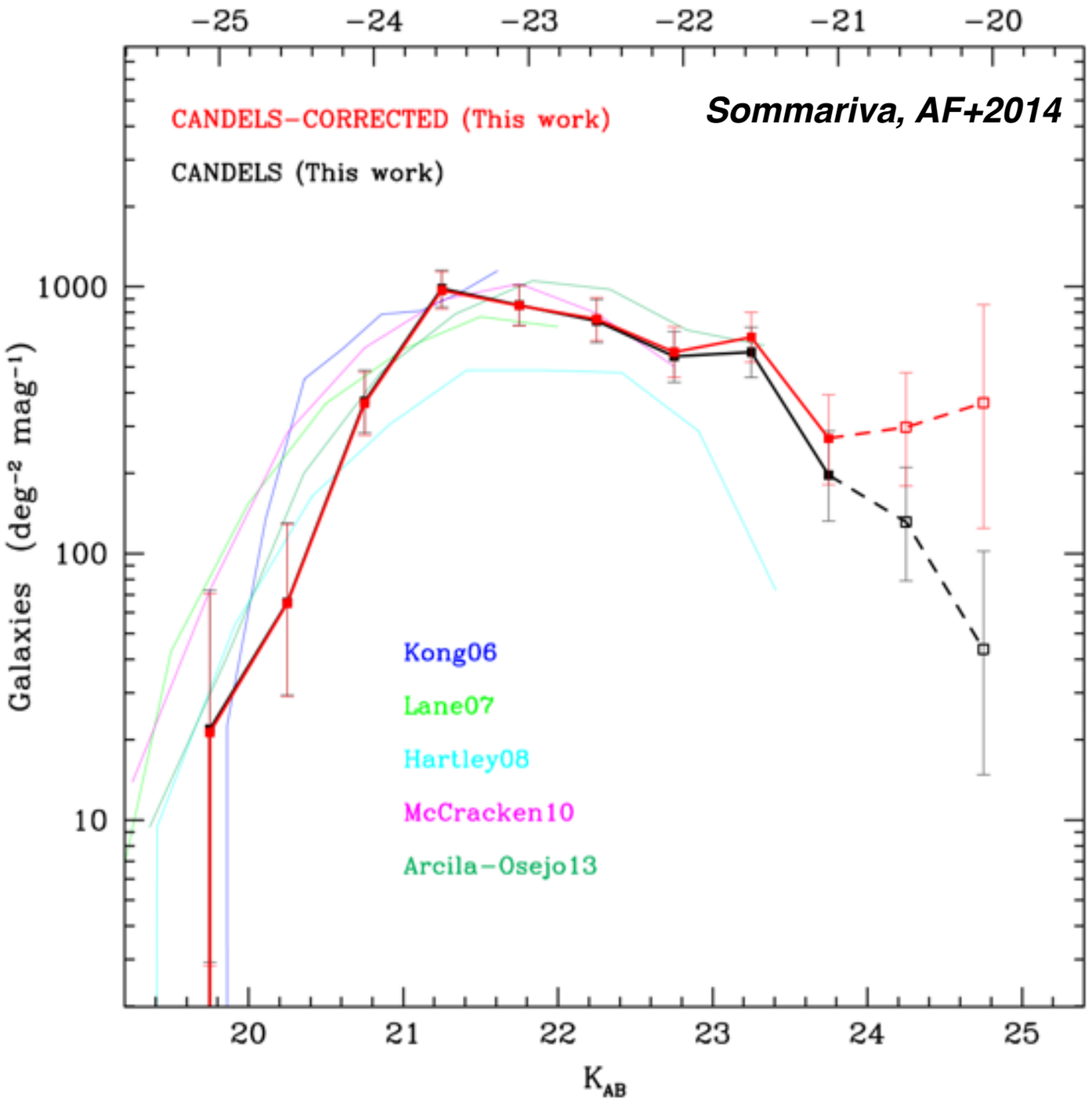
BzK selection criterion (Daddi+04)





Assessing the completeness via dedicated simulations



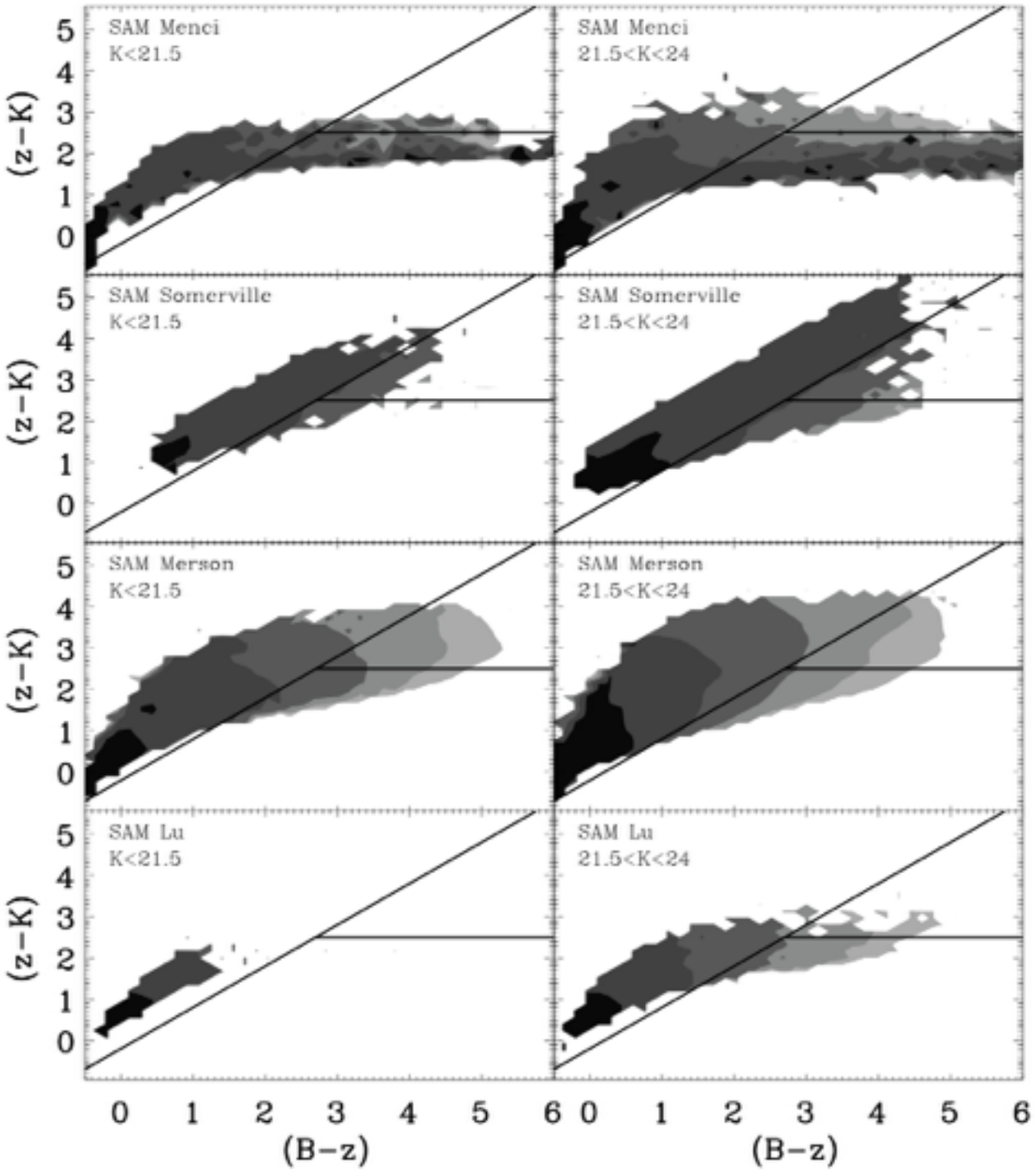


The drop is real:

quenching mechanism(s) are ineffective at low masses.

Is this feature predicted by models?

Sommariva, AF+2014



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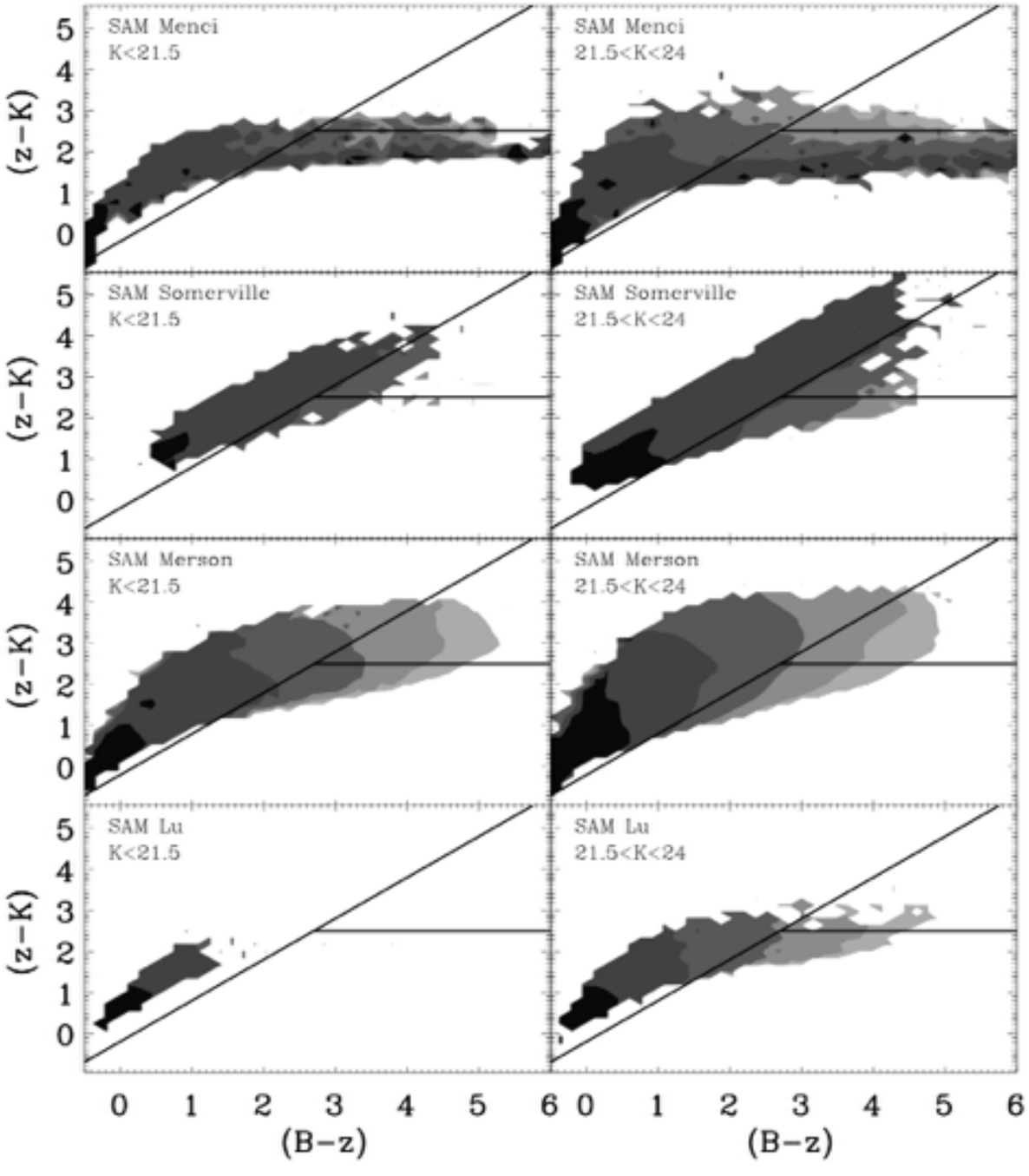
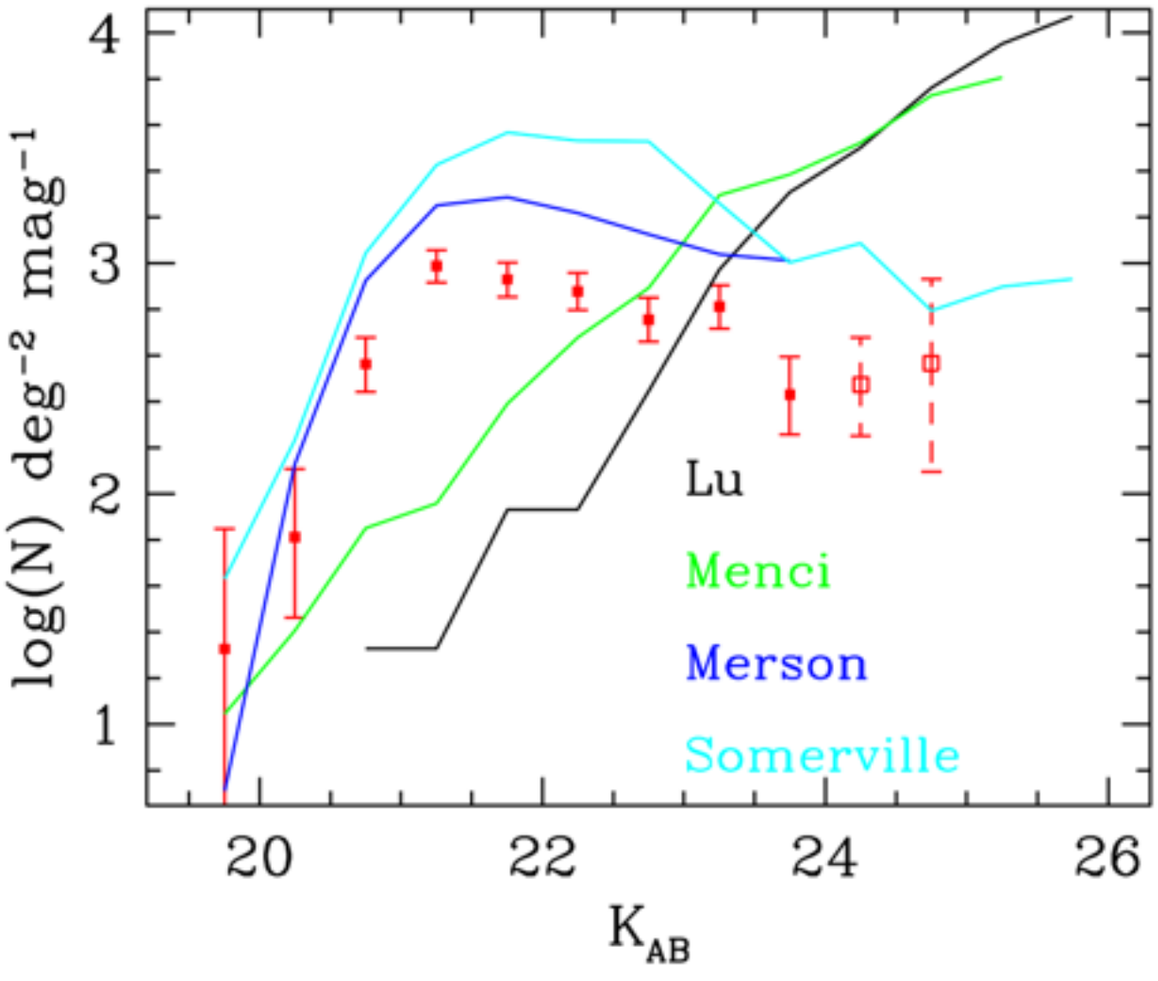
Sommariva, AF+2014



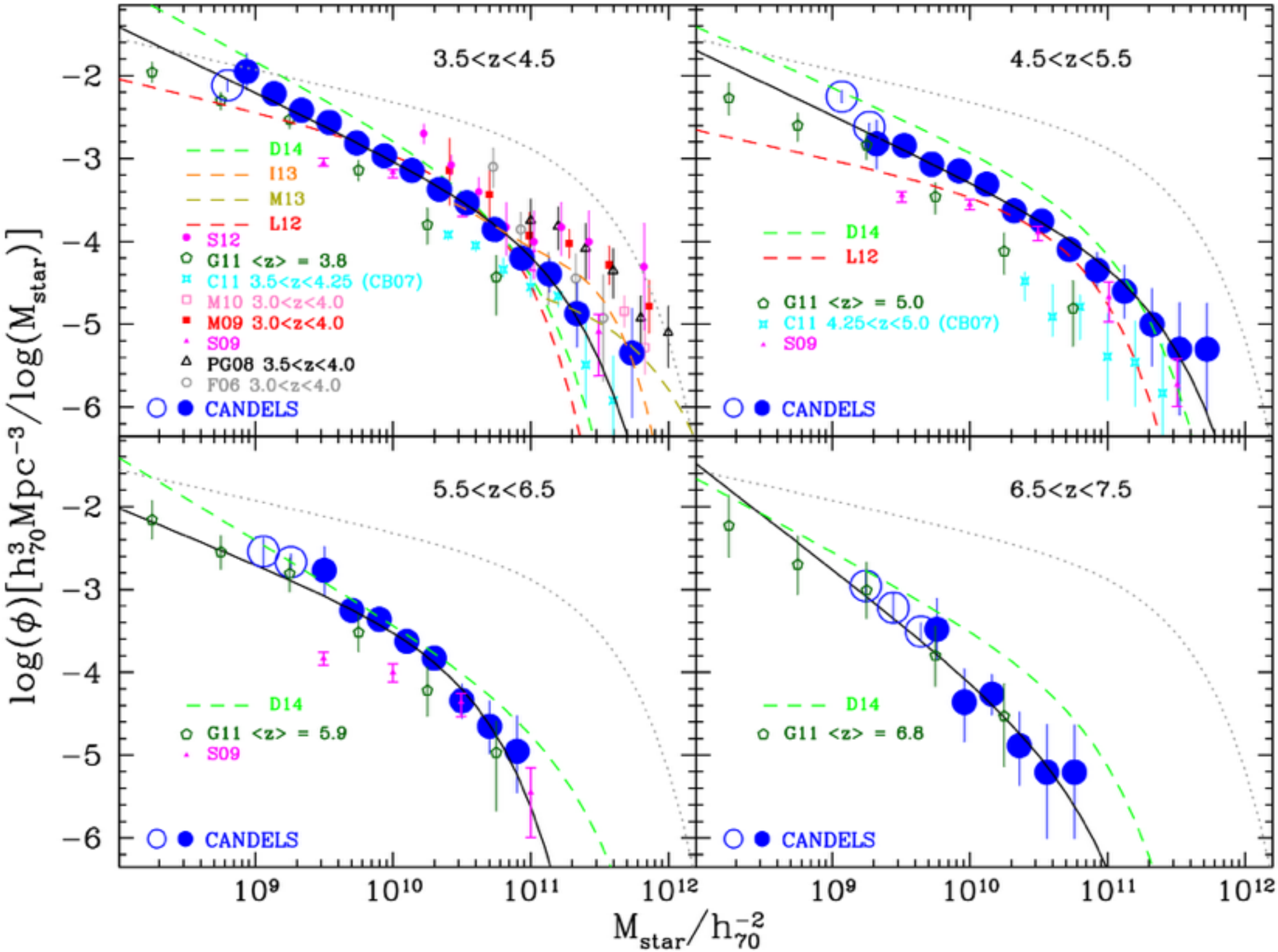
…mmmmm…;-)



The evolution of the mass function at z>4

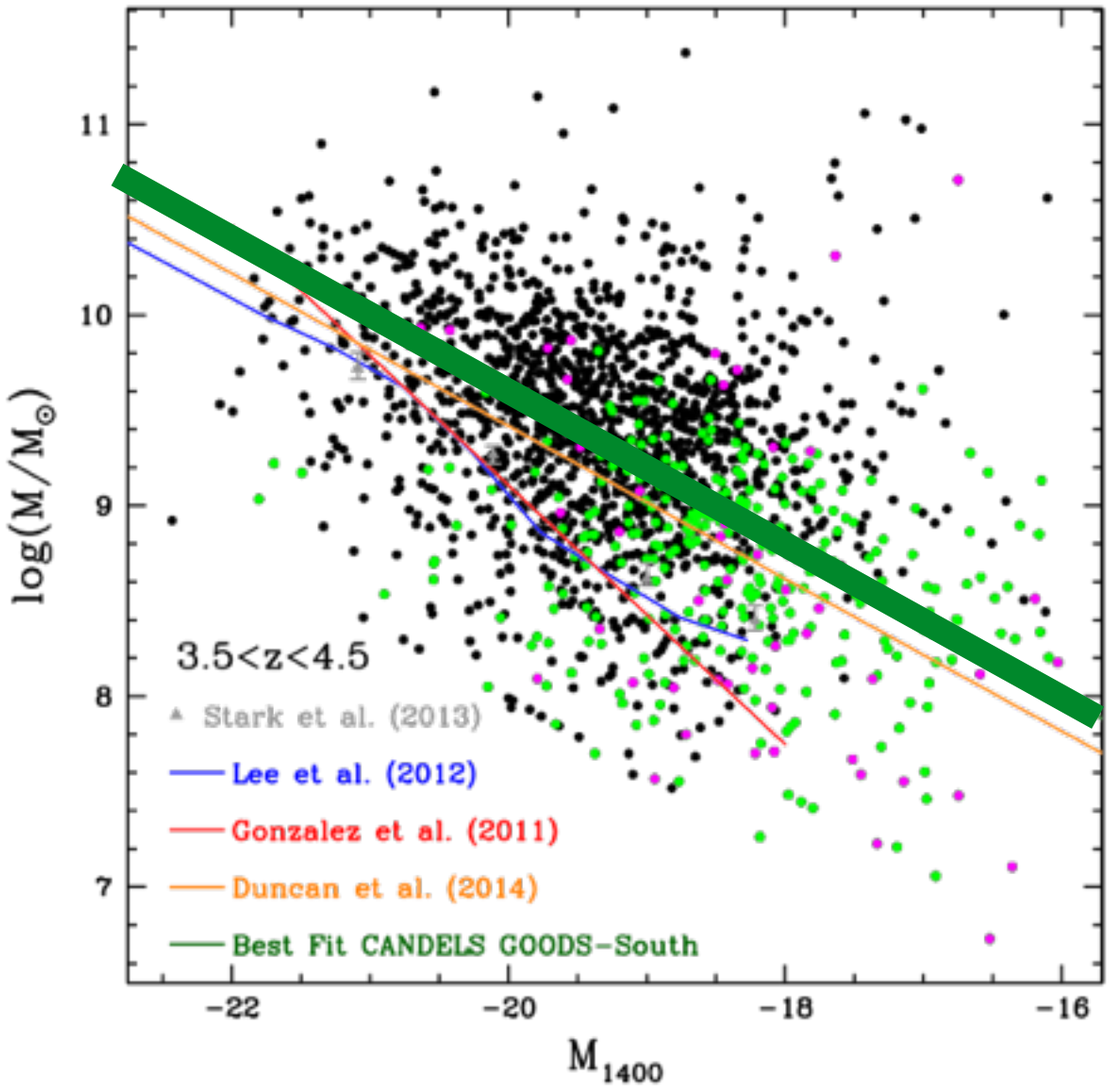
CANDELS +HUGS - GOODS-S+UDS. (Grazian, AF+15)

H-selected sample, full photo-z selection

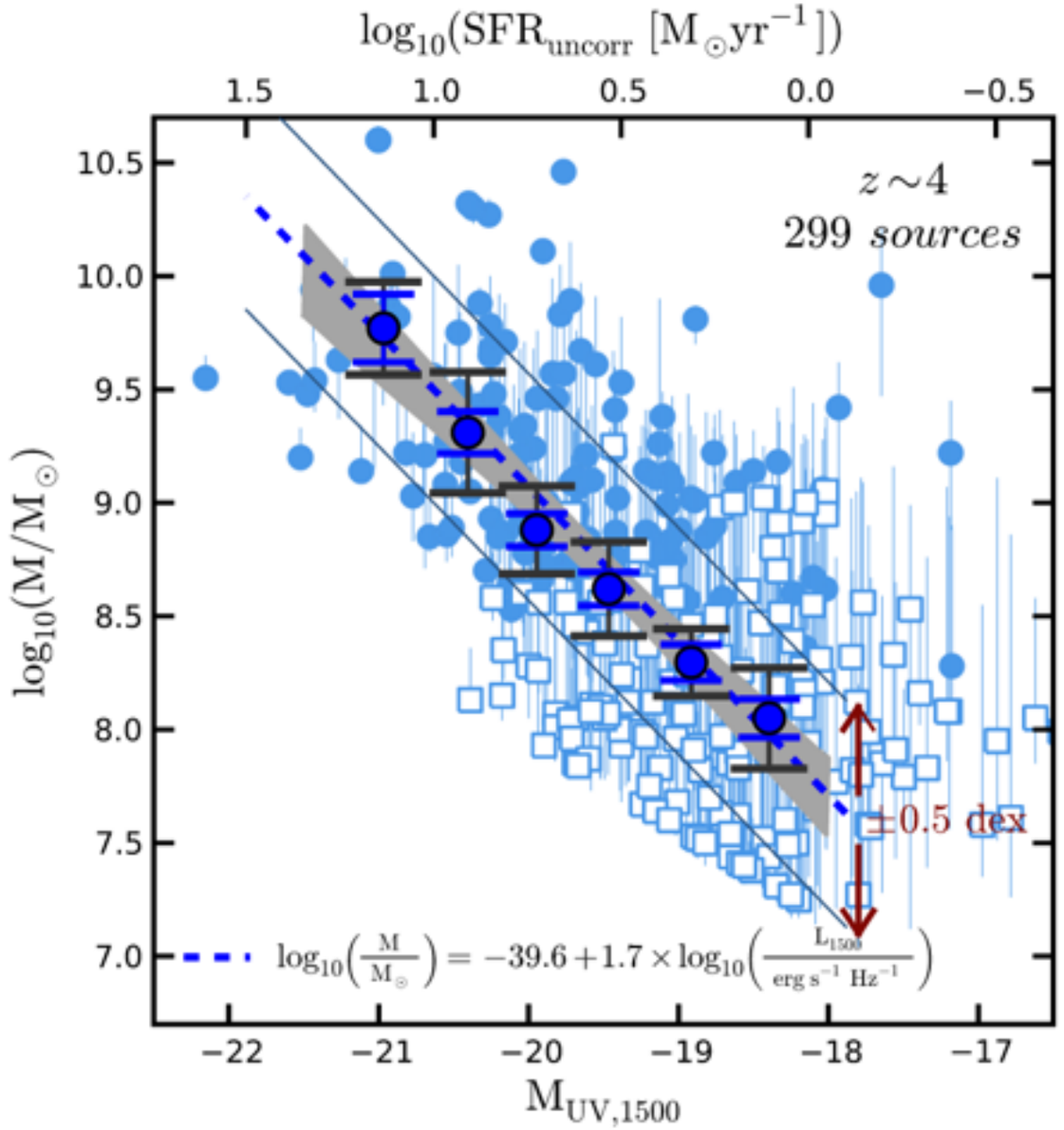


- What is the average M/L?

(Grazian, AF+15)

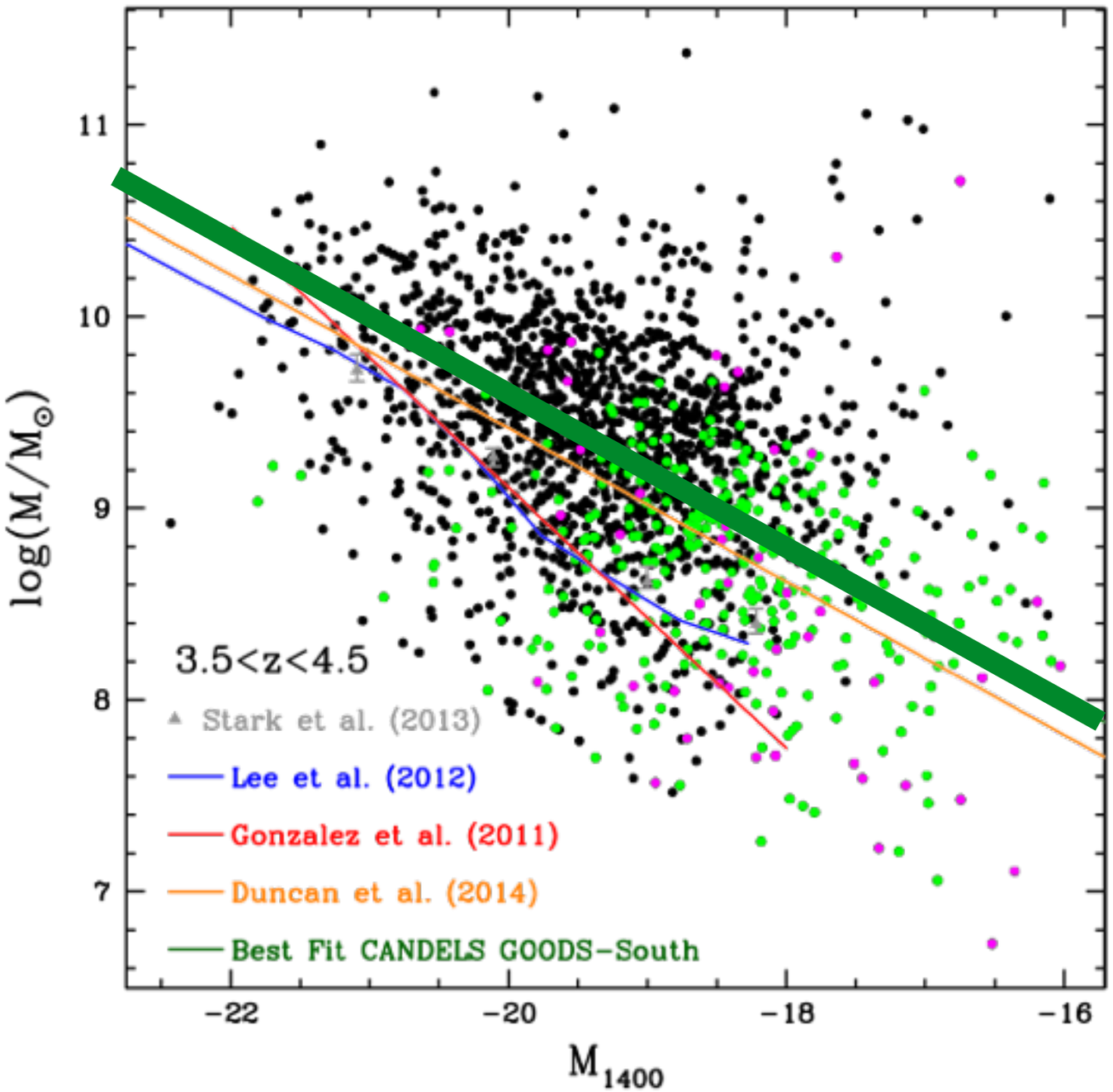


(Gonzalez+11)



- Red massive galaxies at z>4

(Grazian, AF+15)



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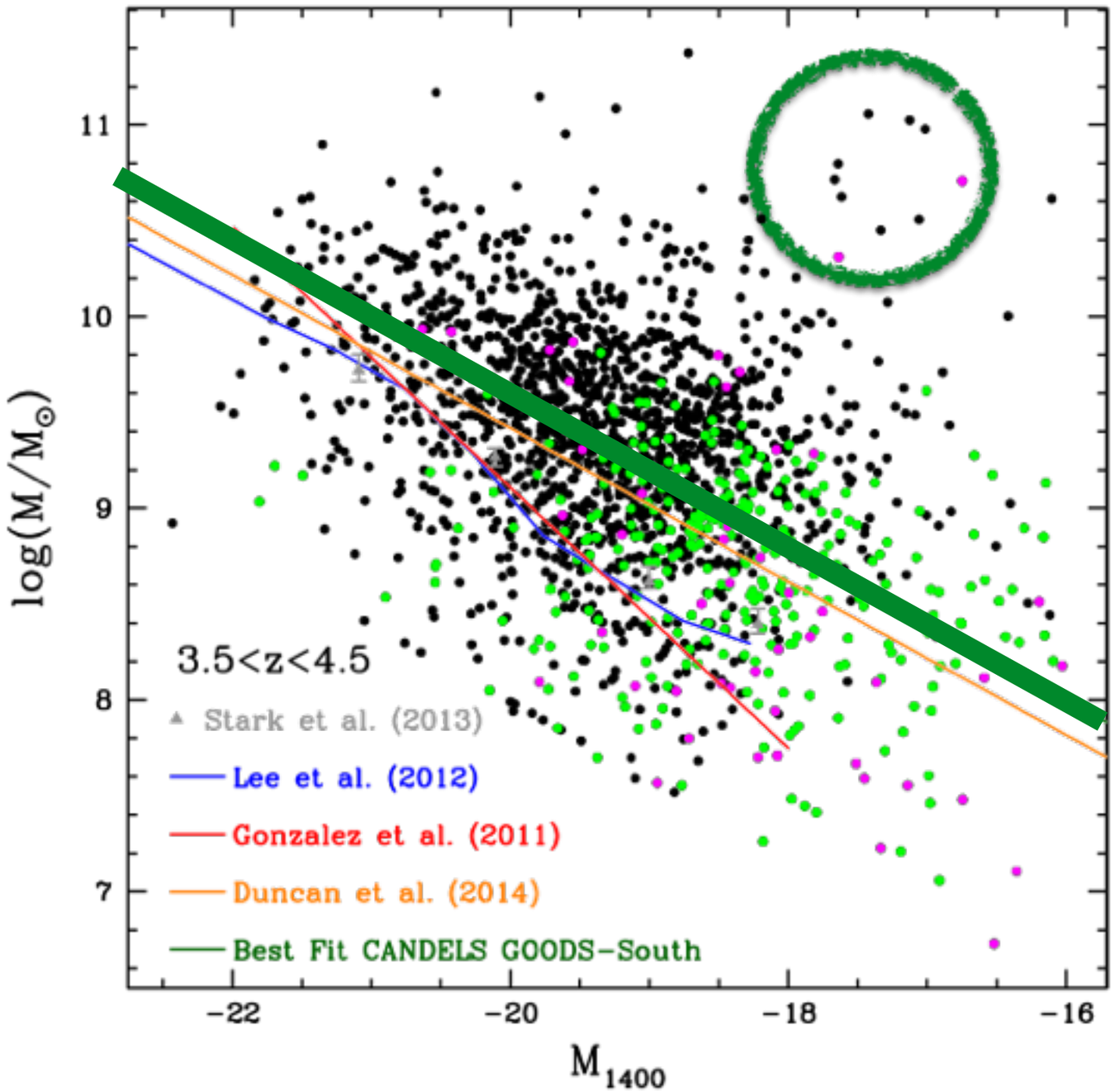

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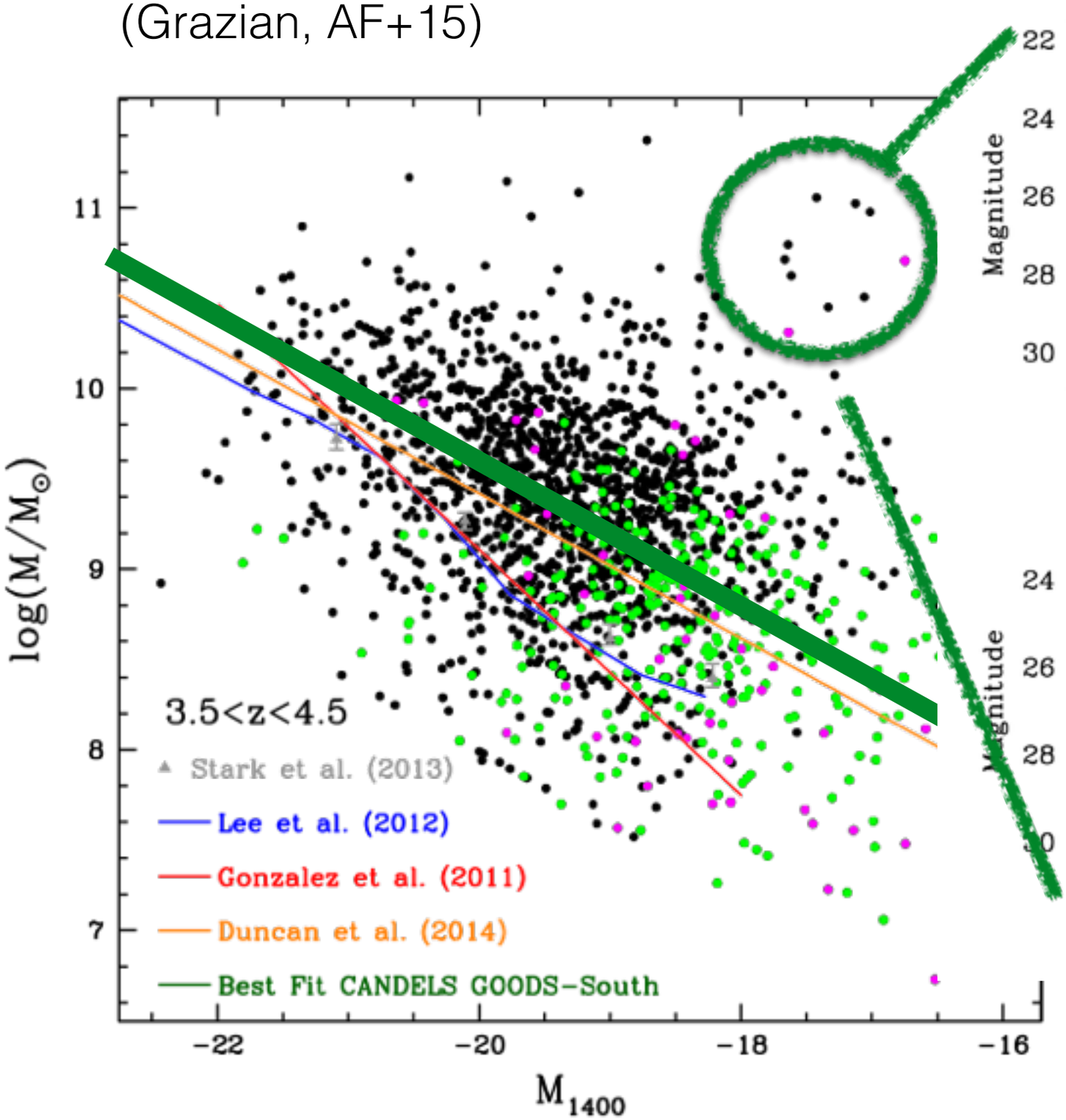
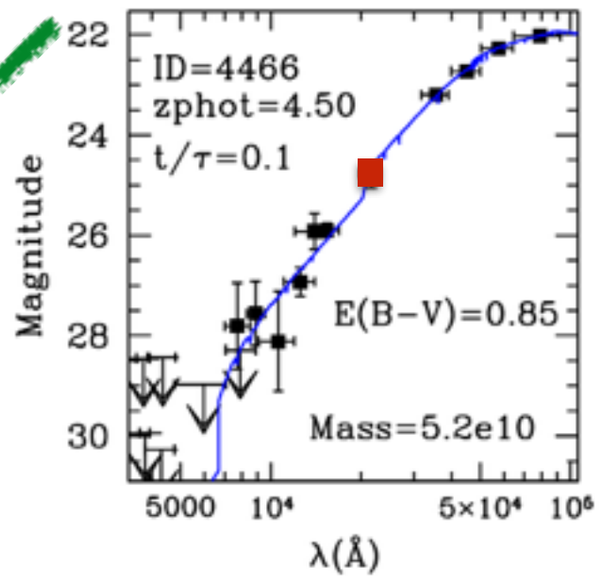
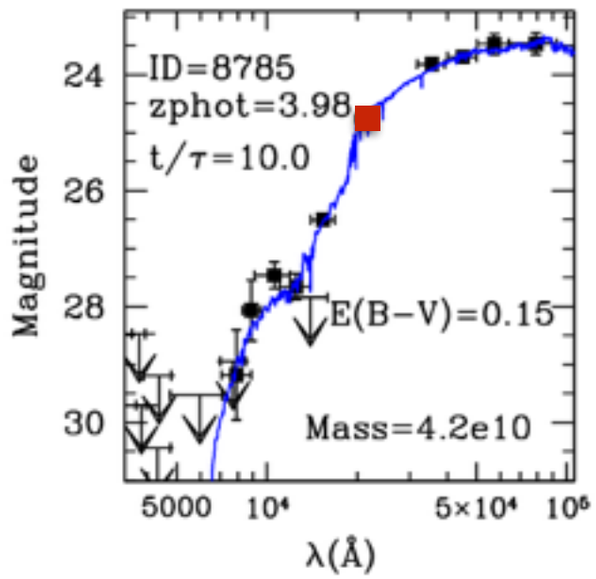
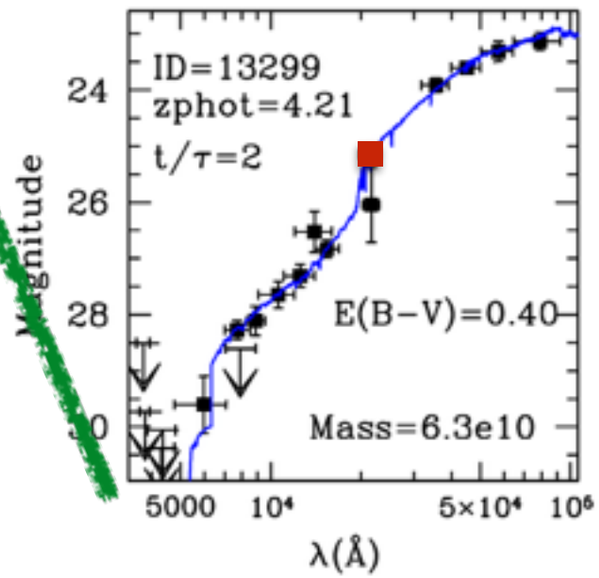
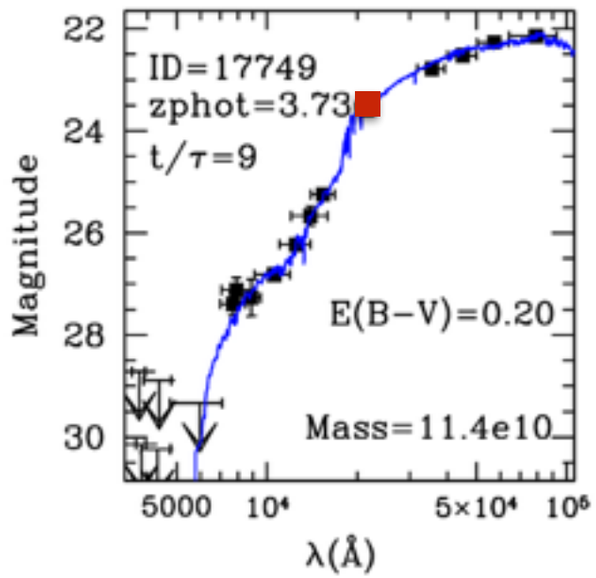


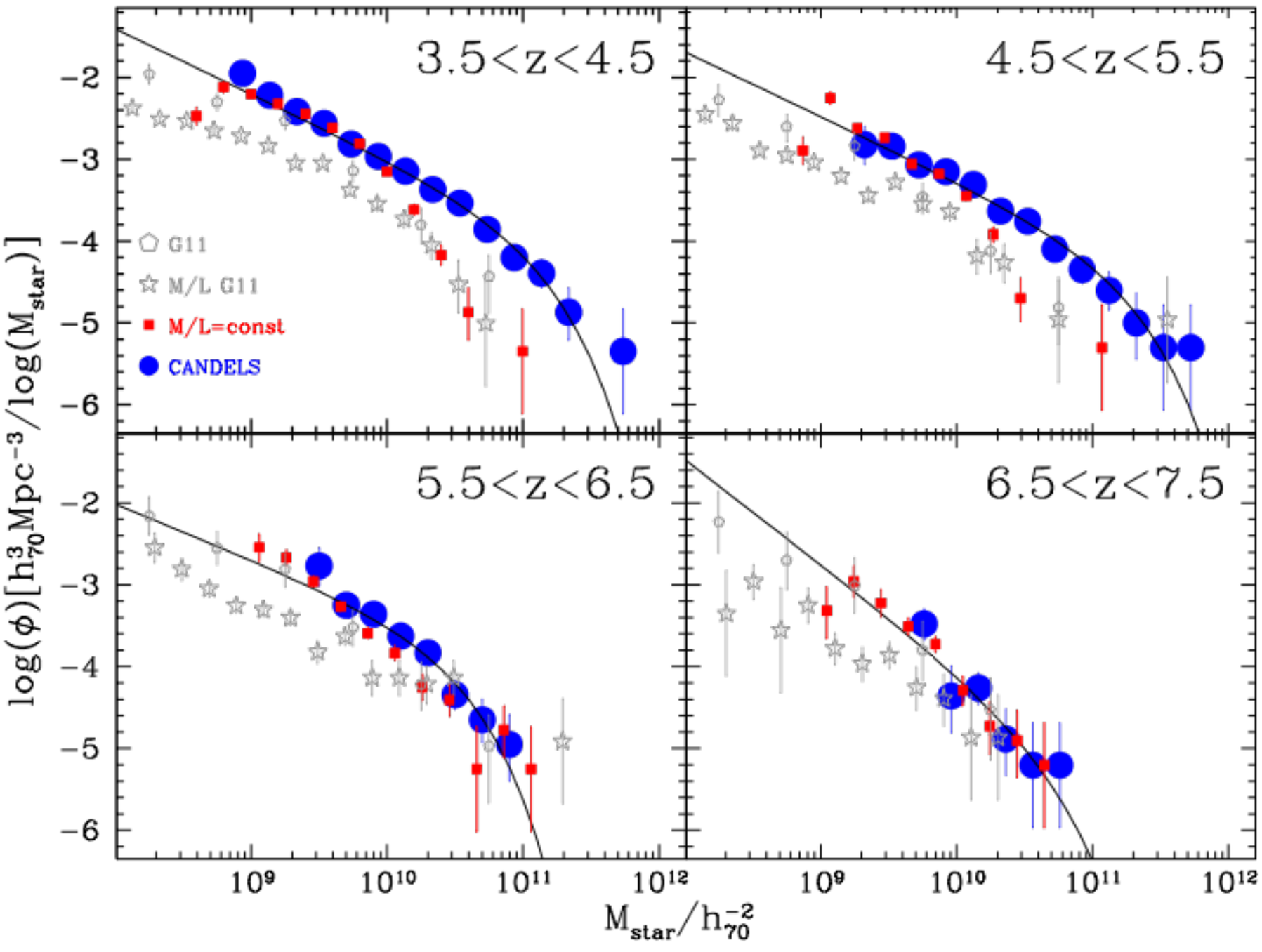








Grazian, AF,+15,



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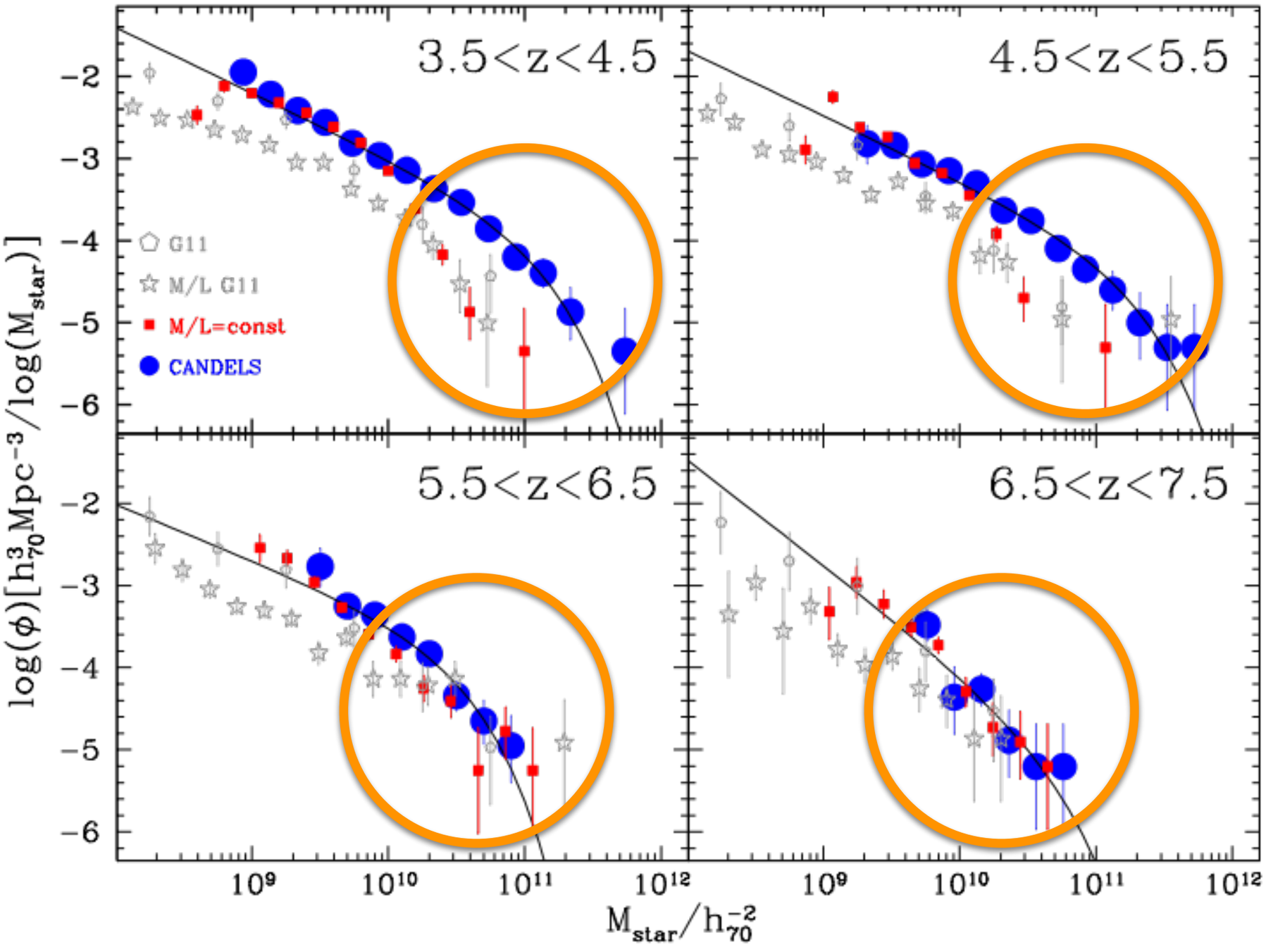

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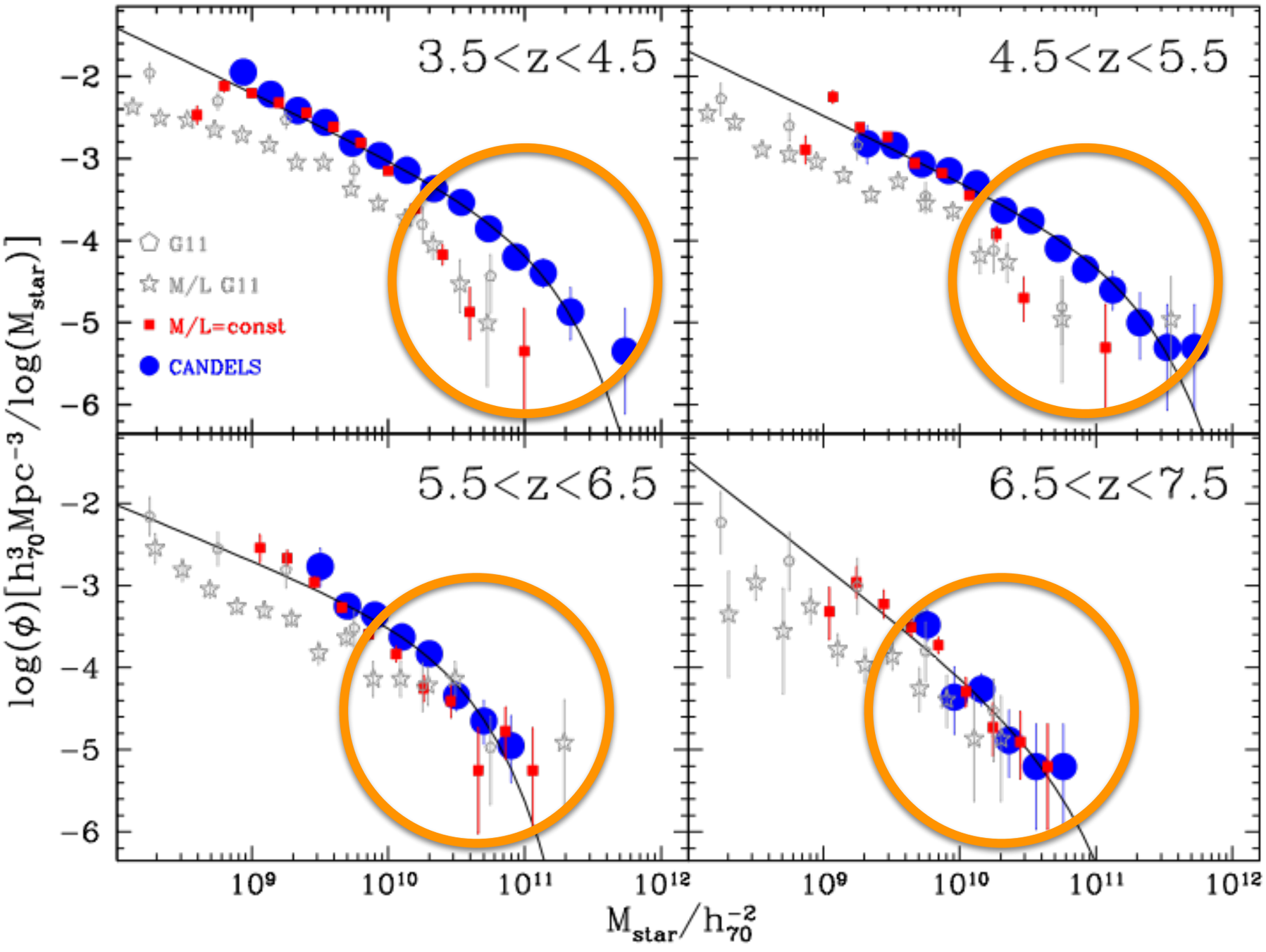
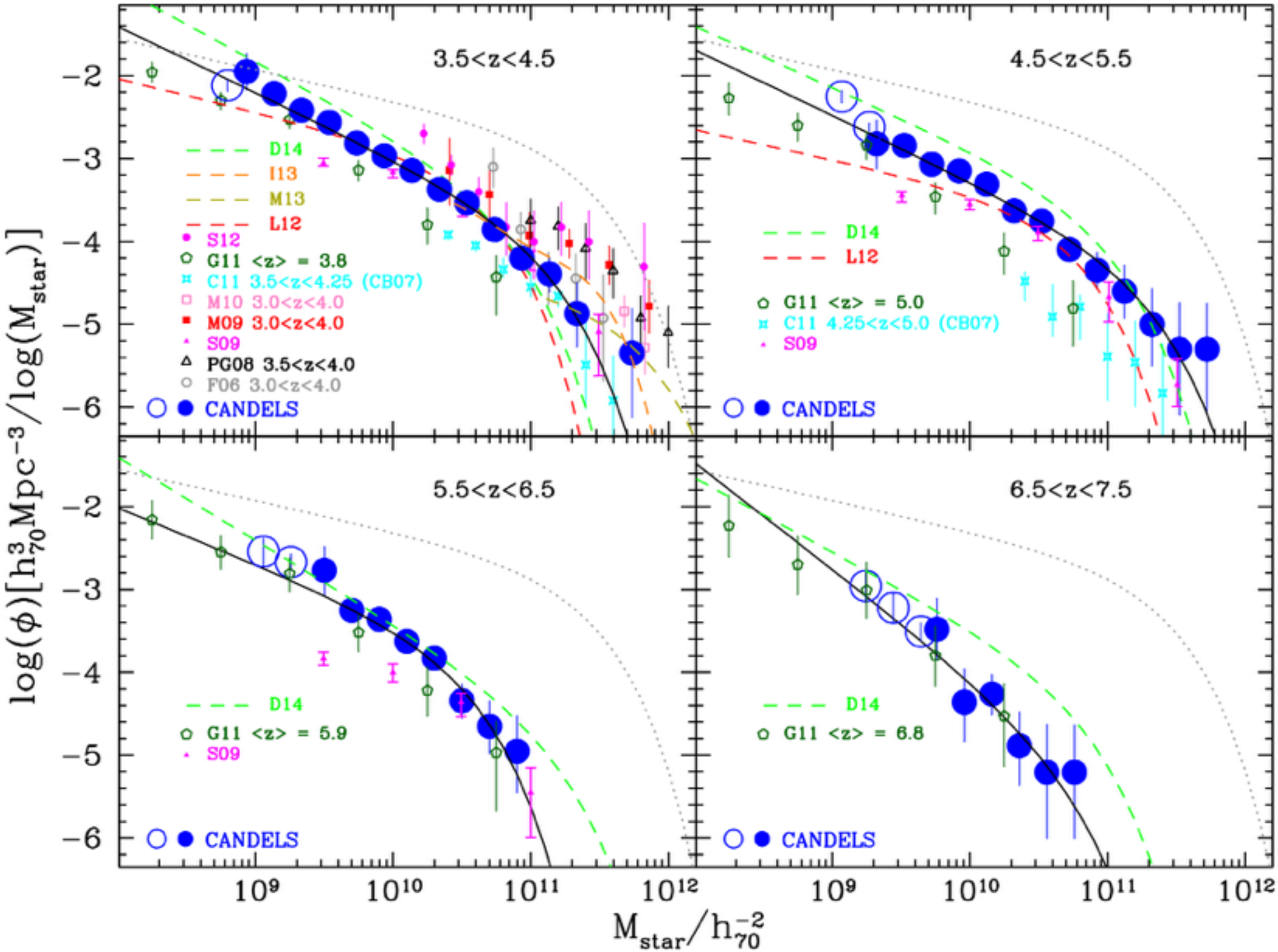


Real decrease or selection effects playing against?
We need JWST for NIRCam/MIRI-selected samples

The evolution of the mass function at z>4

CANDELS +HUGS - GOODS-S+UDS. (Grazian, AF+15)

H-selected sample, full photo-z selection



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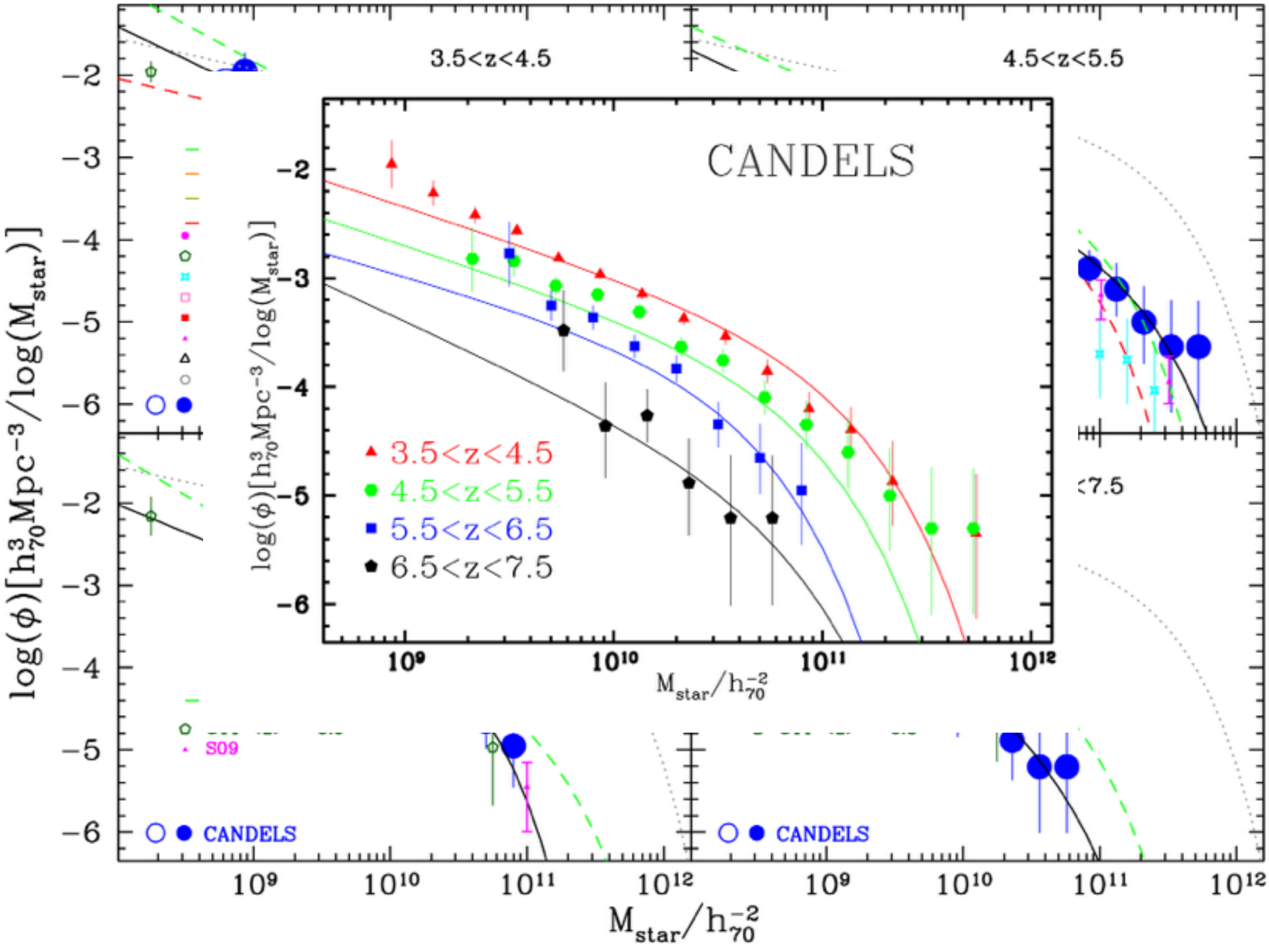
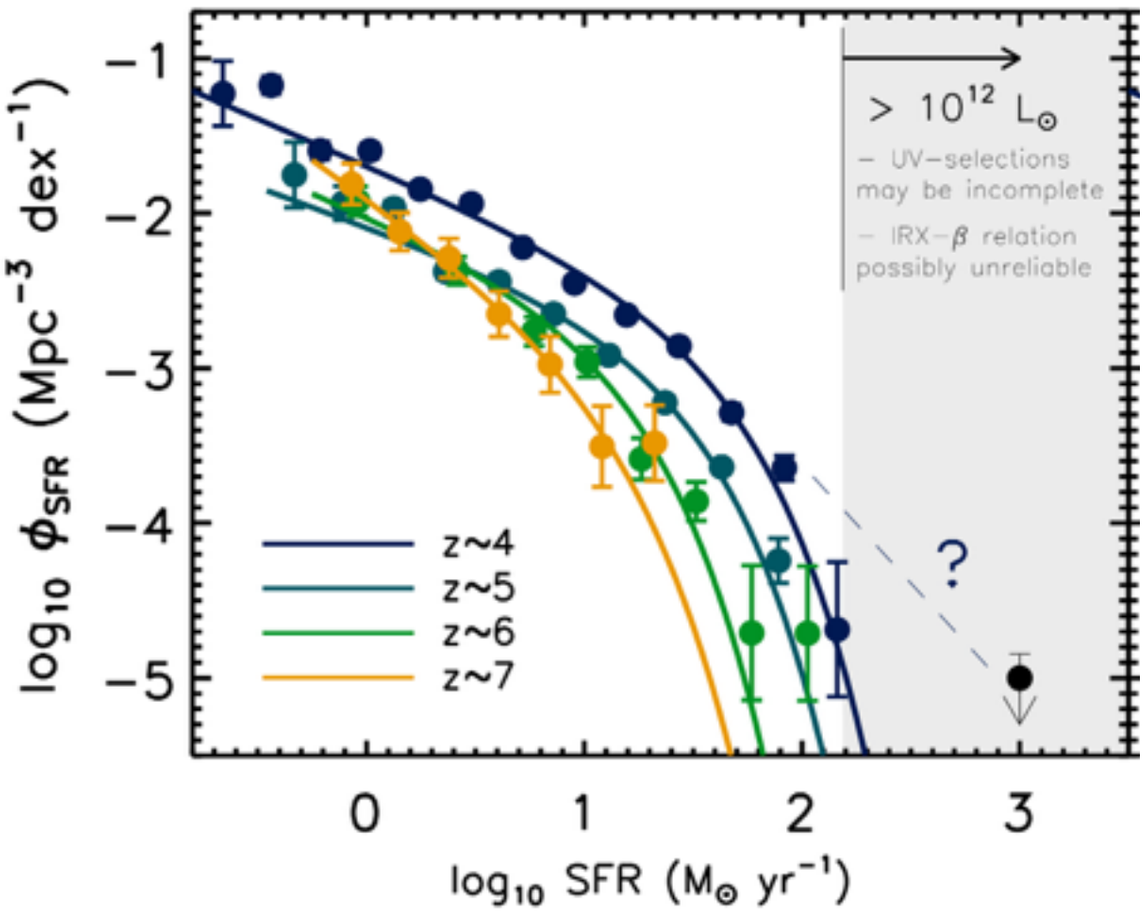


Is the overall picture consistent?

Smit+12 UV LF -> SFR Funct.



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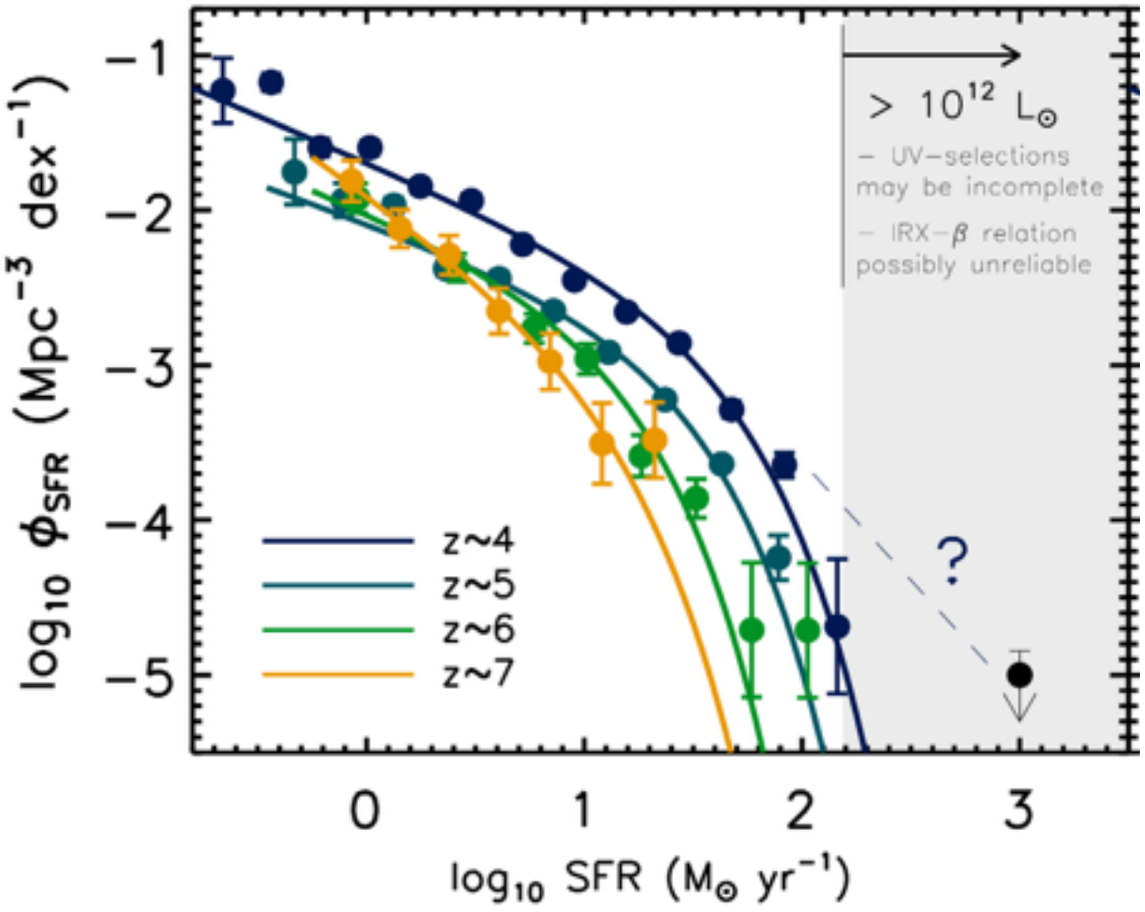
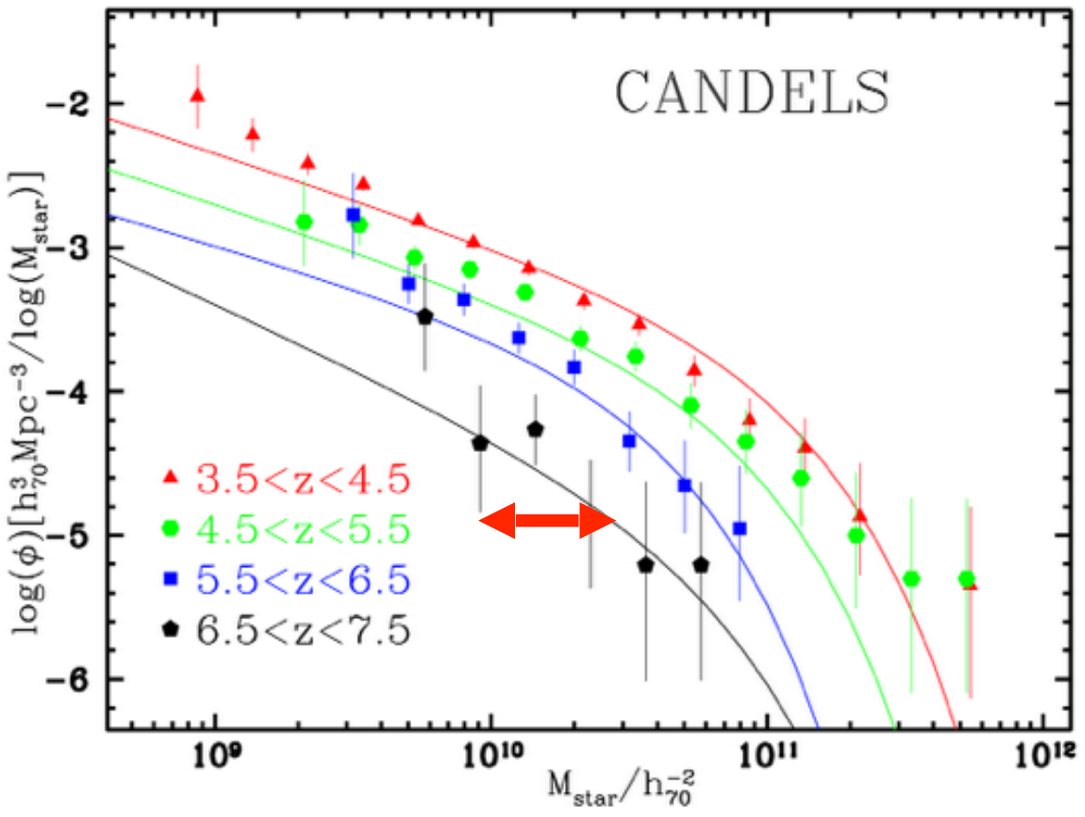


Grazian+15



z=6 ->4 ΔM / Δt: ~290 Msun/yr

Is the overall picture consistent?

Smit+12 UV LF -> SFR Funct.

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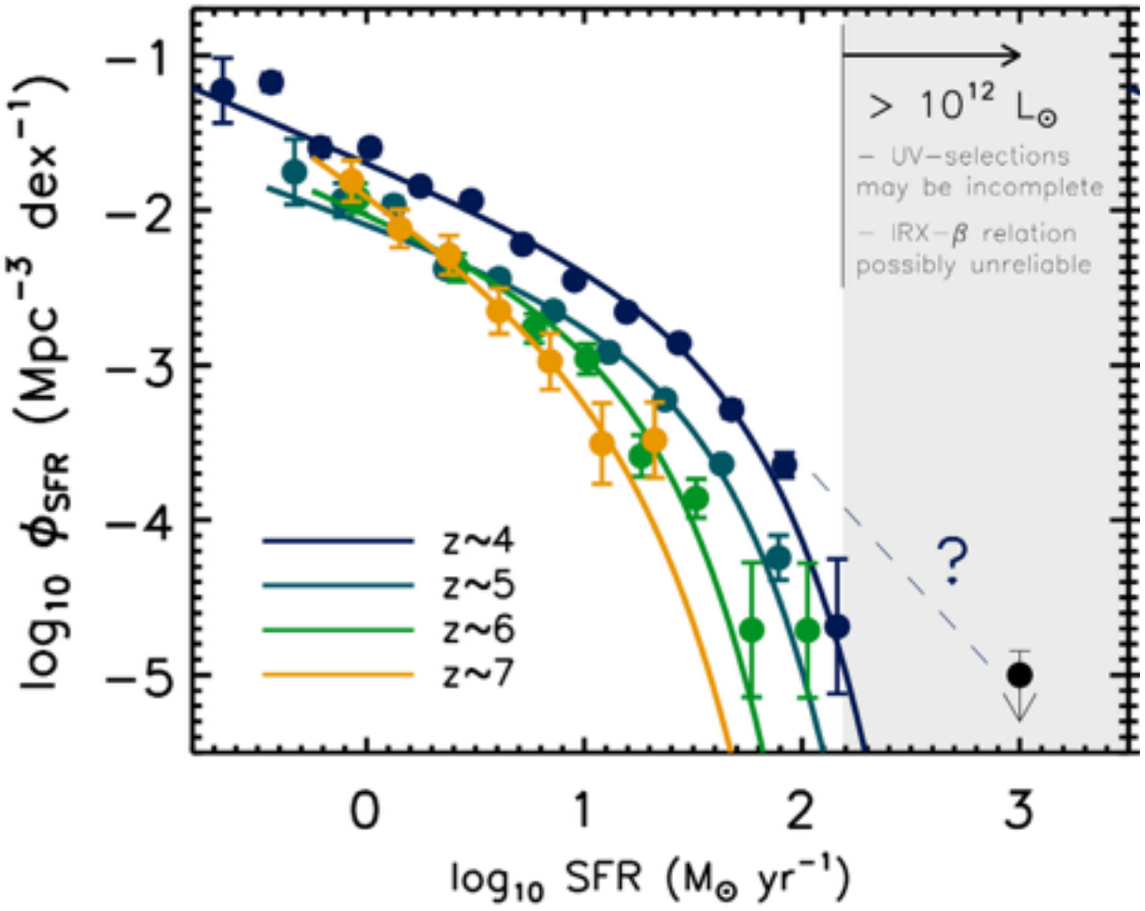
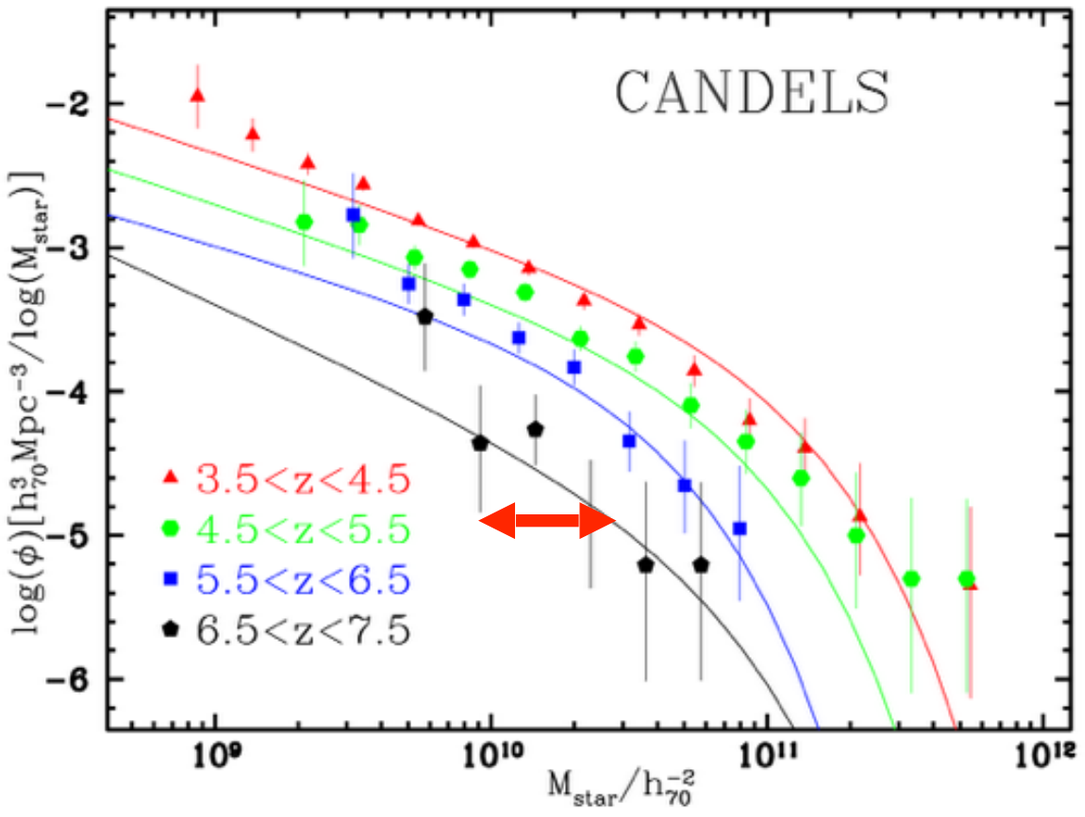


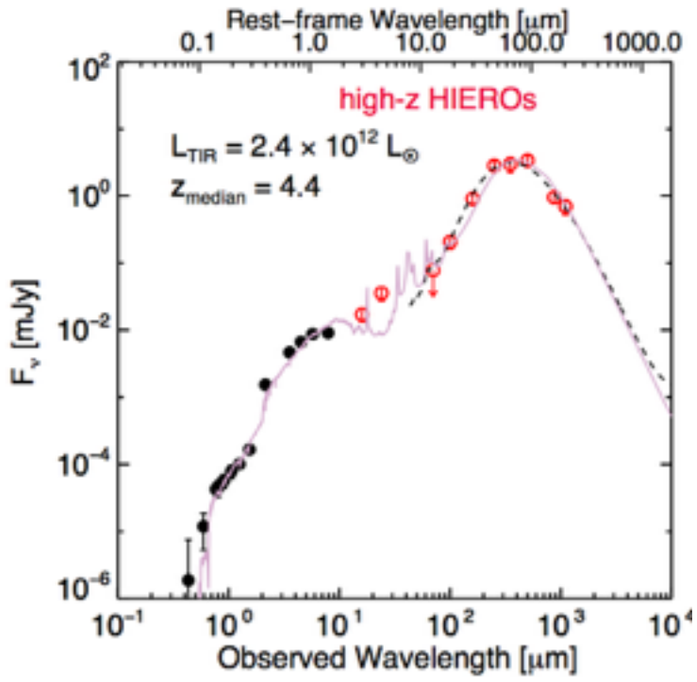


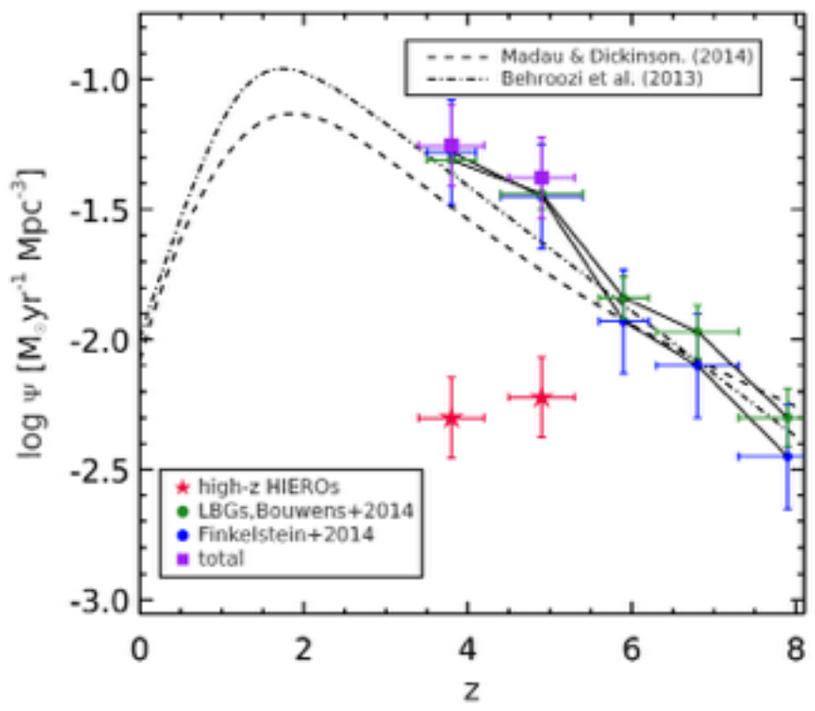
z=6 ->4 ΔM / Δt: ~290 Msun/yr

- To fix, among possible options
  - Revise (upward) SFR estimates in LBG;
  - A missing population of dusty sfr-ing galaxies at z>4

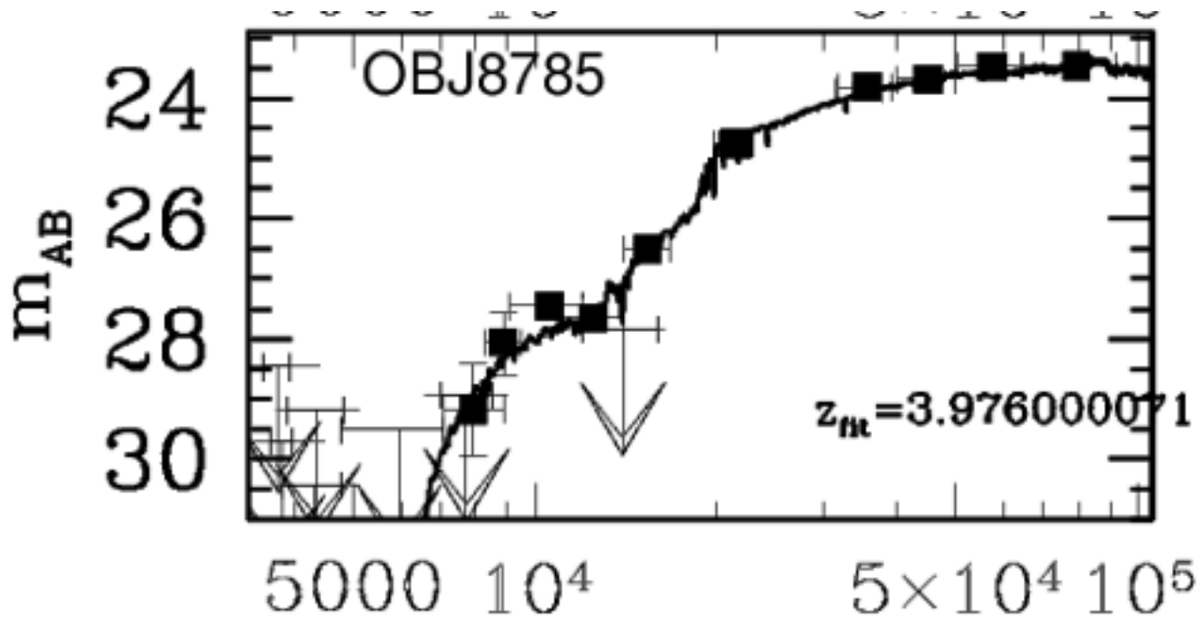
….more to come…

Dusty starbursts at z>4
(T. Wang et al, subm.)

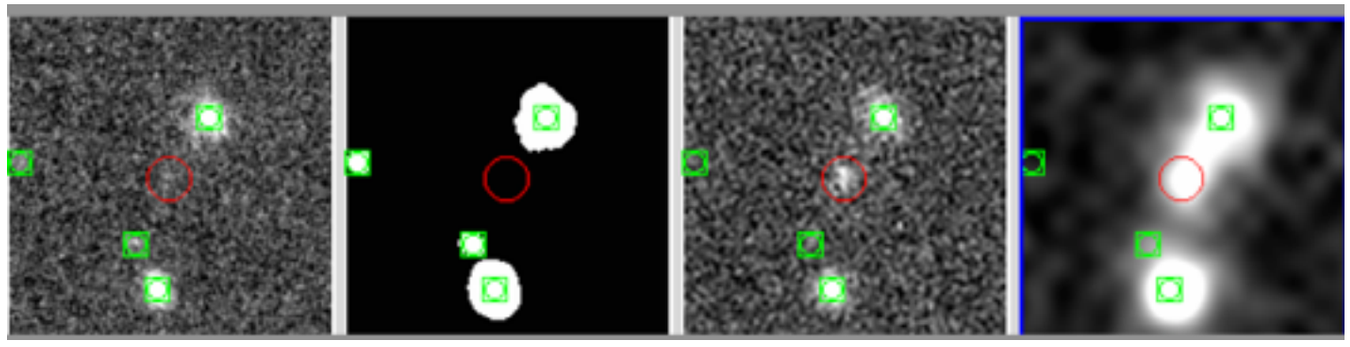




Quiescent galaxies at z>3
(E. Merlin et al, in prep)

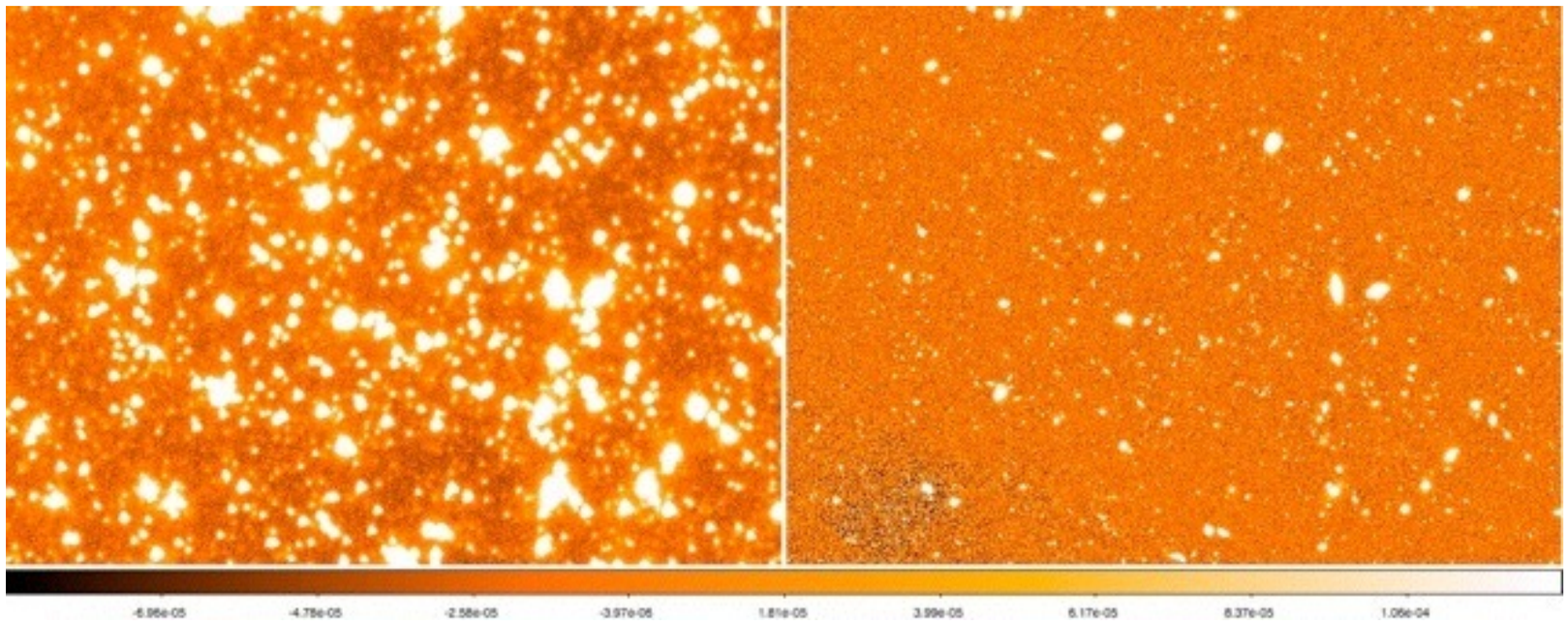


H-dropouts at z>3
(K. Boutsia et al, in prep)



Summary

- Hawk-I surveys can effectively complement medium-deep HST surveys;
- HUGS perfectly matches CANDELS depth
- HUGS data public
- Significantly improve the reliability of sample detection and SED analysis at z>3
- Open a window on red galaxies at z>4
- Allow to reliably measure the MF up to z~7



Public surveys delivers processed “clean” images that are not yet usable for science.

Need to be translated into catalogs.

This task:

- is time consuming / expensive: a bottleneck that hampers full scientific exploitation of the data;
- is still subject to considerable uncertainties: it presents conceptual challenges that need to be addressed

ASTRODEEP

Making Europe the world leader in the exploitation of the deepest multi-frequency data.

FP7 SPACE Program

4yr Program

European Coordinator: Adriano Fontana

ASTRODEEP

INAF-OAR

(A. Fontana)

University of Edinburgh

(J. Dunlop)

CEA (Paris)

(D. Elbaz)

CDS (Strasburg)

(S. Derrier)

+CANDELS

(S. Faber, H. Ferguson)

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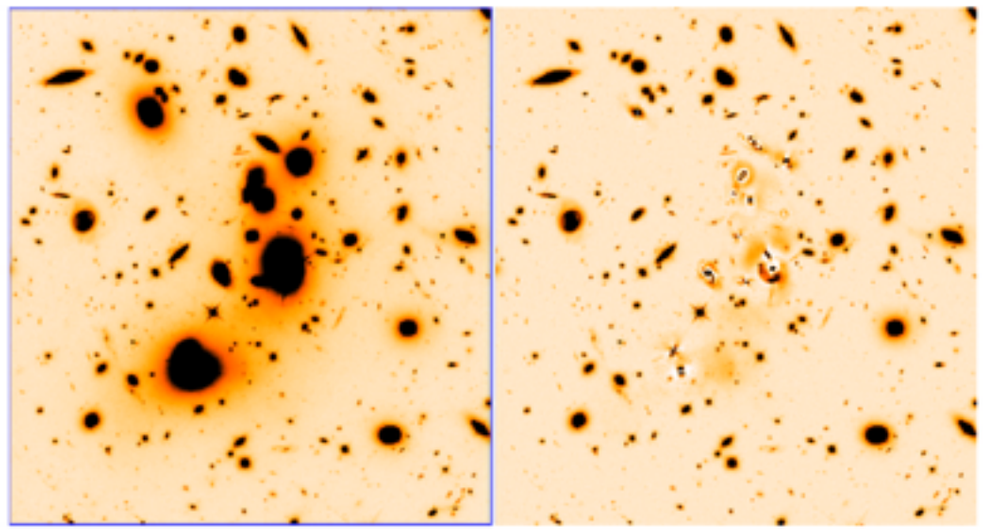
Developed much improved techniques to obtain de-confused catalogs:

- T-PHOT (built over TFIT heritage) Merlin et al, 2015, A&A in press
- A new method for Herschel images (Tao Wang+ in prep)
- A prior-based method for X-ray data (Cappelluti et al in prep)

First application: Frontier Fields (A2744 & MACS0416)

Catalogues complete (HST + K + IRAC) - Delivered to FF team

Castellano+, Merlin+, in prep



In progress:

- Revised GOODS-S photometry

In the long term, a priority list:

- Emphasis on Herschel data over CANDELS fields;
- Frontier Field #3 and #4
- Reprocessing CANDELS data in other 4 fields

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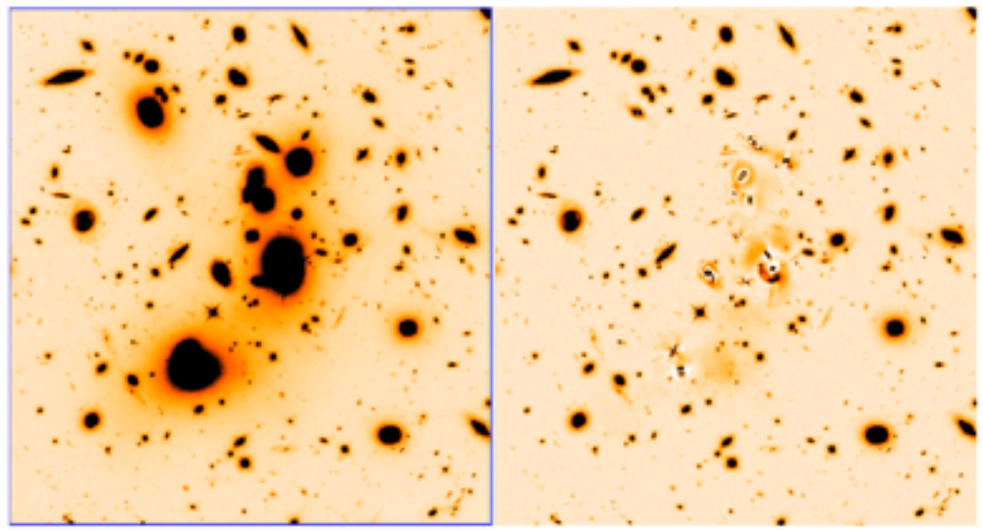

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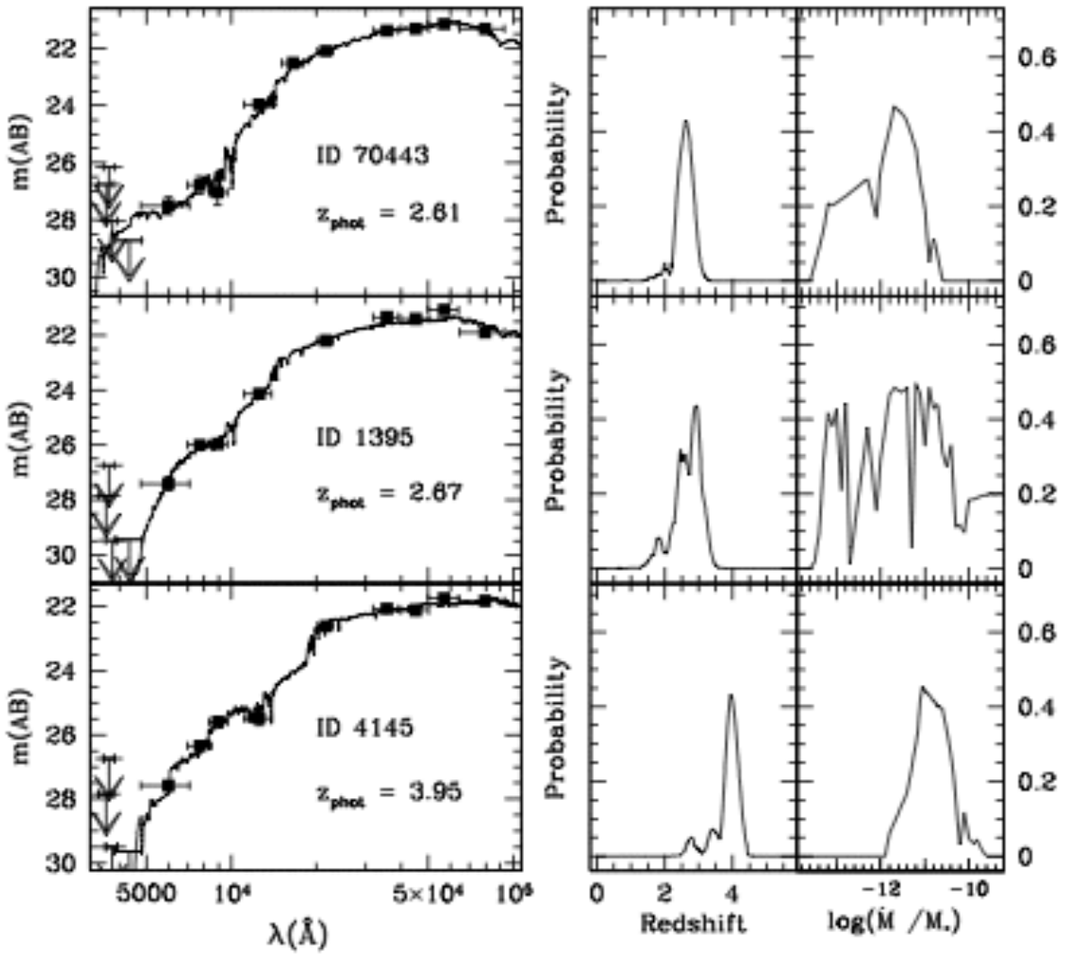
Passive galaxies at z>>2



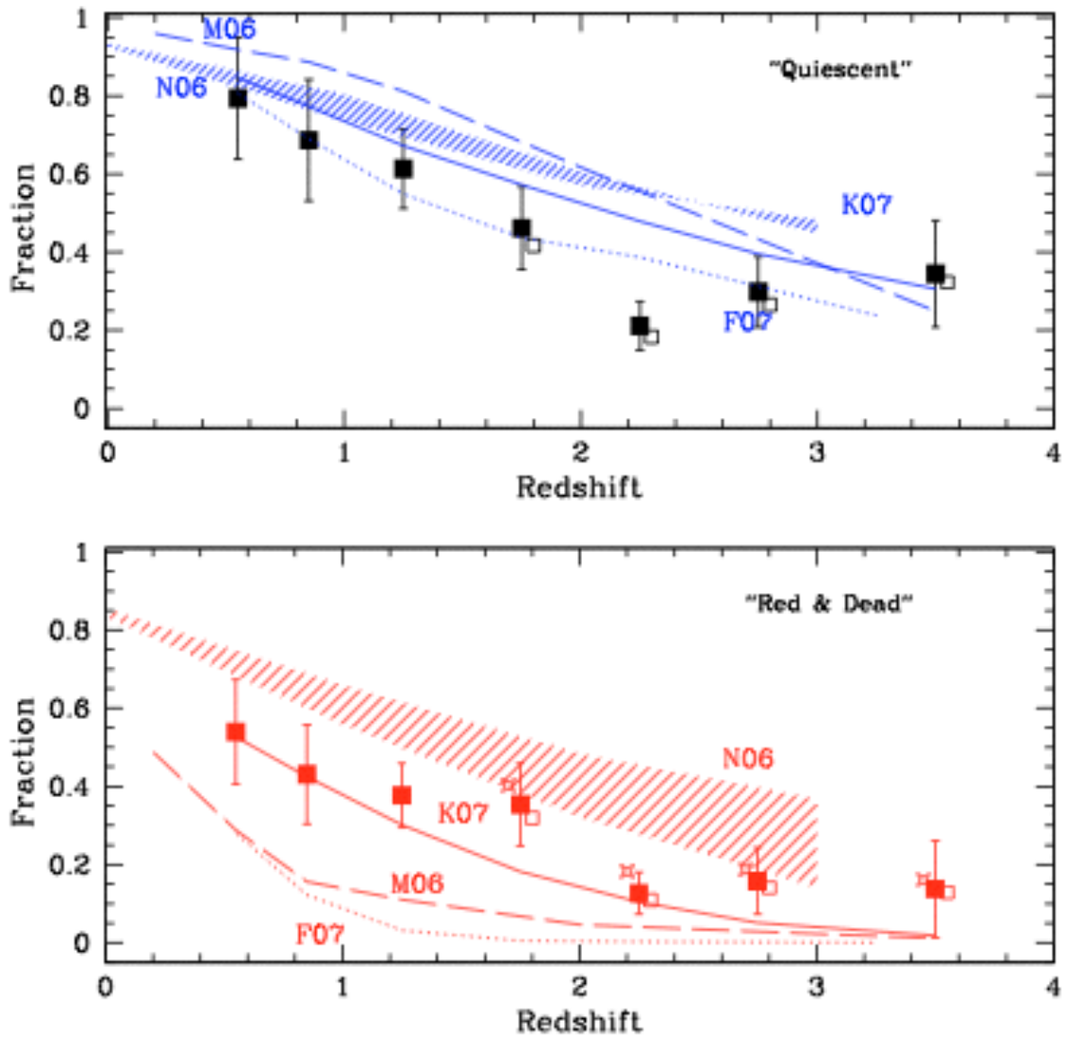
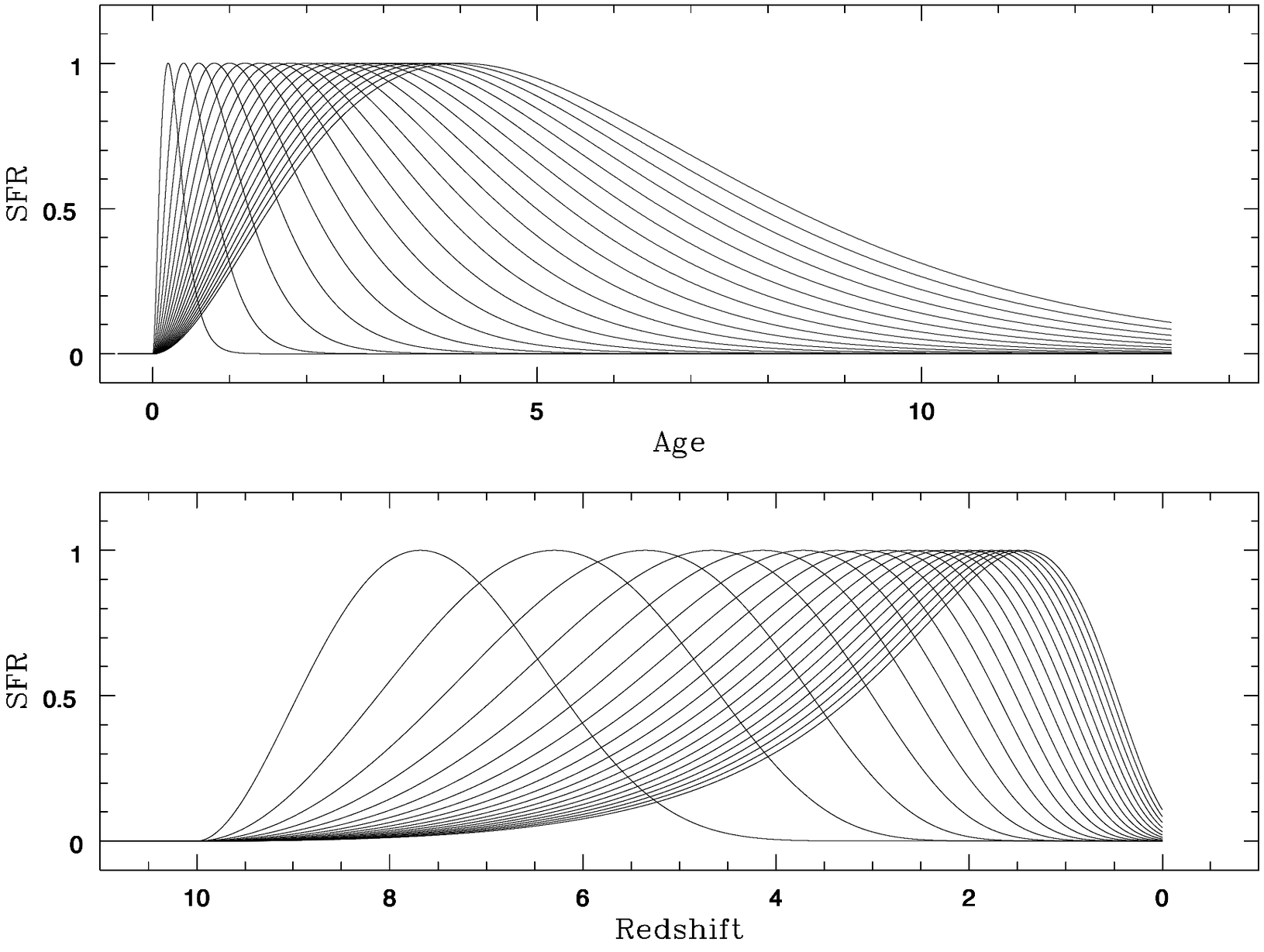


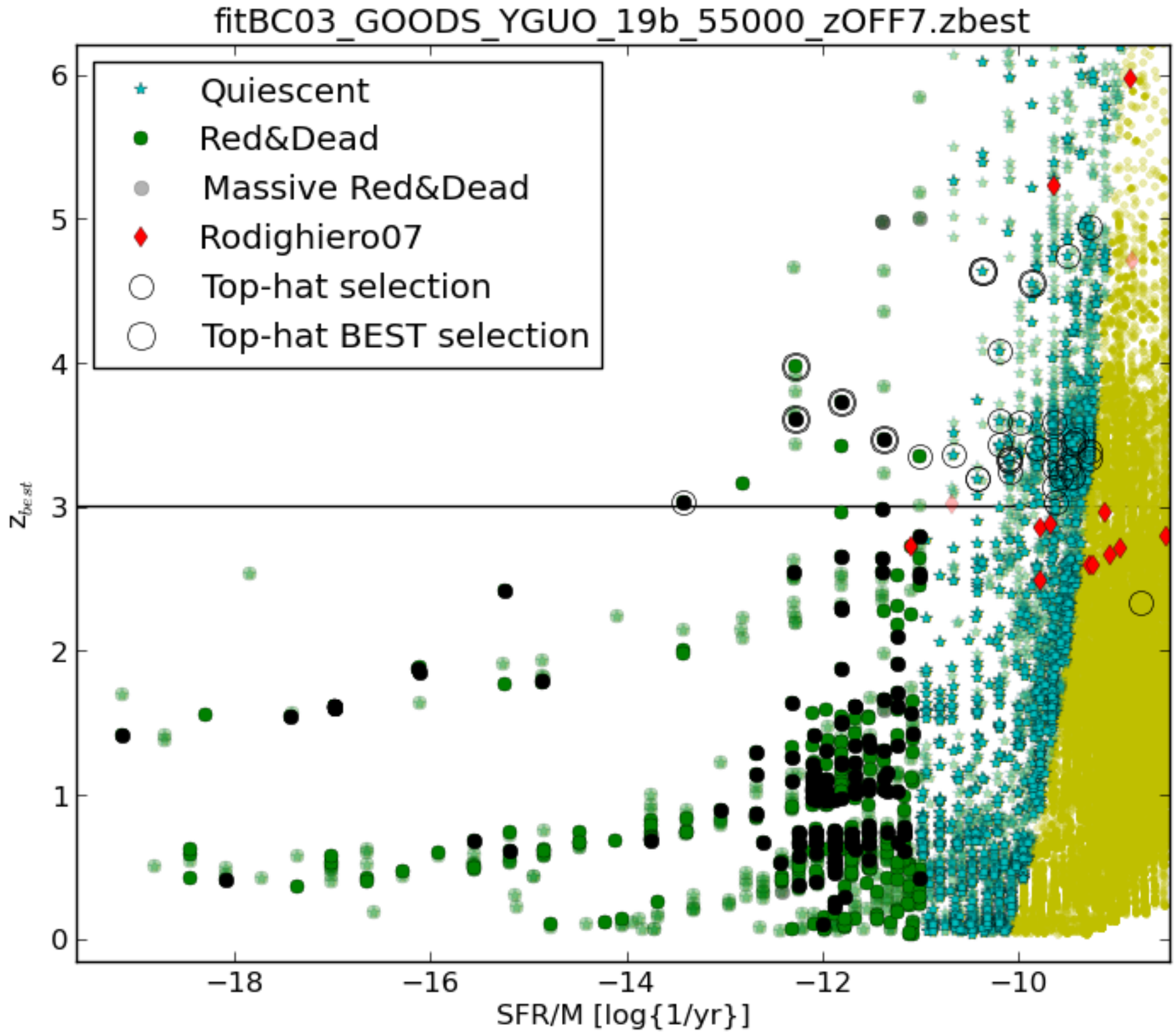
Fig. 4. Examples of "red and dead" galaxies at $z > 2.5$. For each object, from left to right: the observed flux in the GOODS band and the best-

Traditional tau-model stink

1) Inclusion of a variety of SFH:
   constant, exp. declin, inverted tau, $\mathbf{t^2 exp\text{-}t/\tau}$

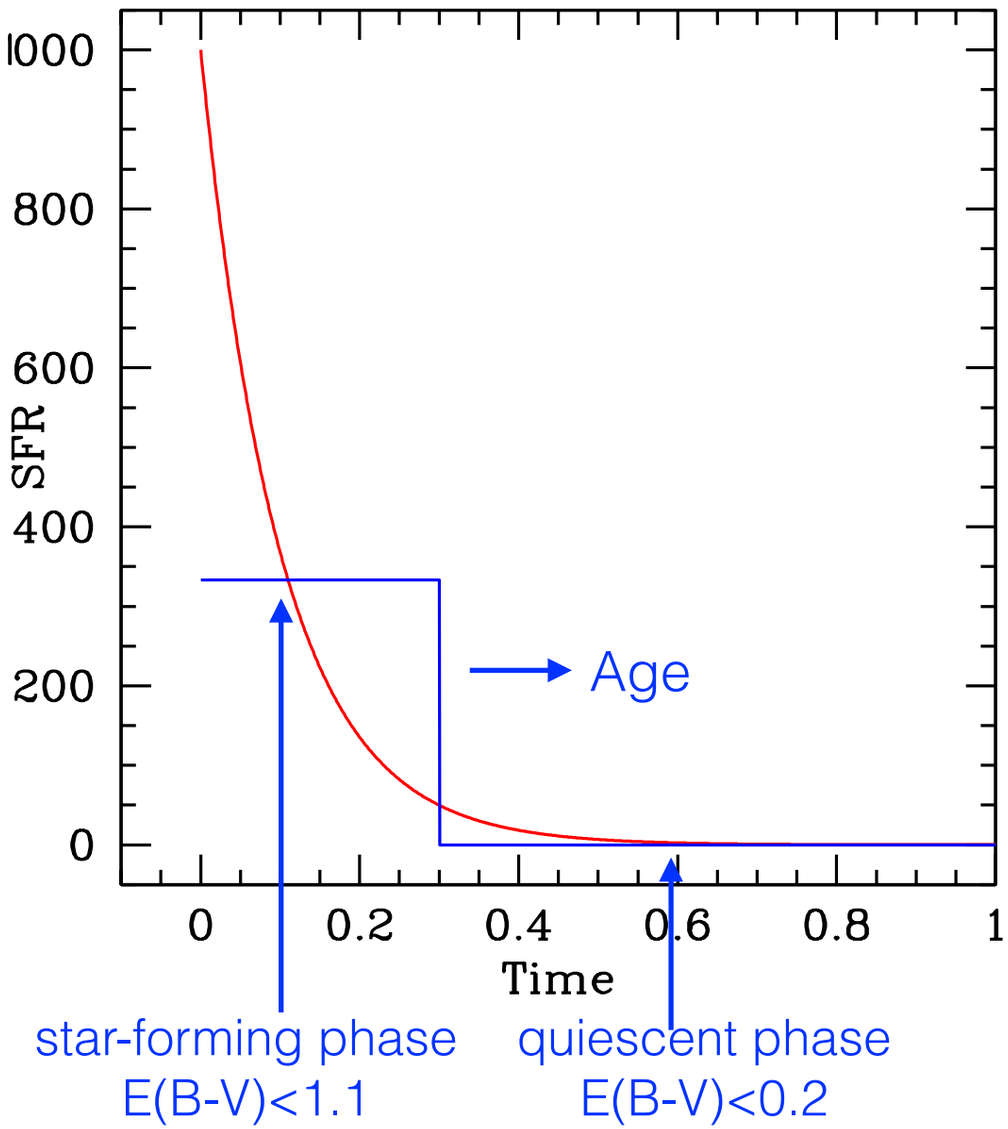


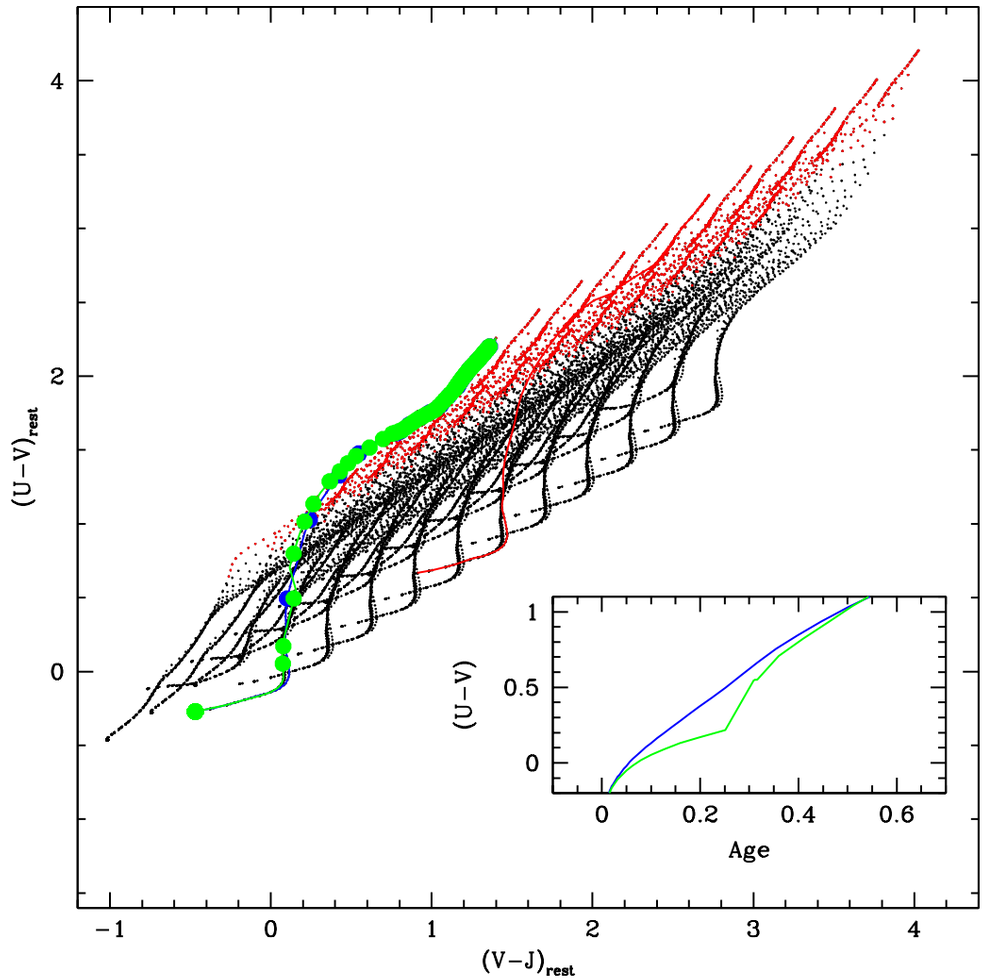
Merlin+15


fitBC03_GOODS_YGUO_19b_55000_zOFF7.zbest
Quiescent
Red&Dead
Massive Red&Dead
Rodighiero07
Top-hat selection
Top-hat BEST selection
z_{best}
SFR/M [log{1/yr}]
6
5
4
3
2
1
0
−18
−16
−14
−12
−10

“Top-hat” (aka truncated) SFH

BC03 + all metallicities + Calzetti law





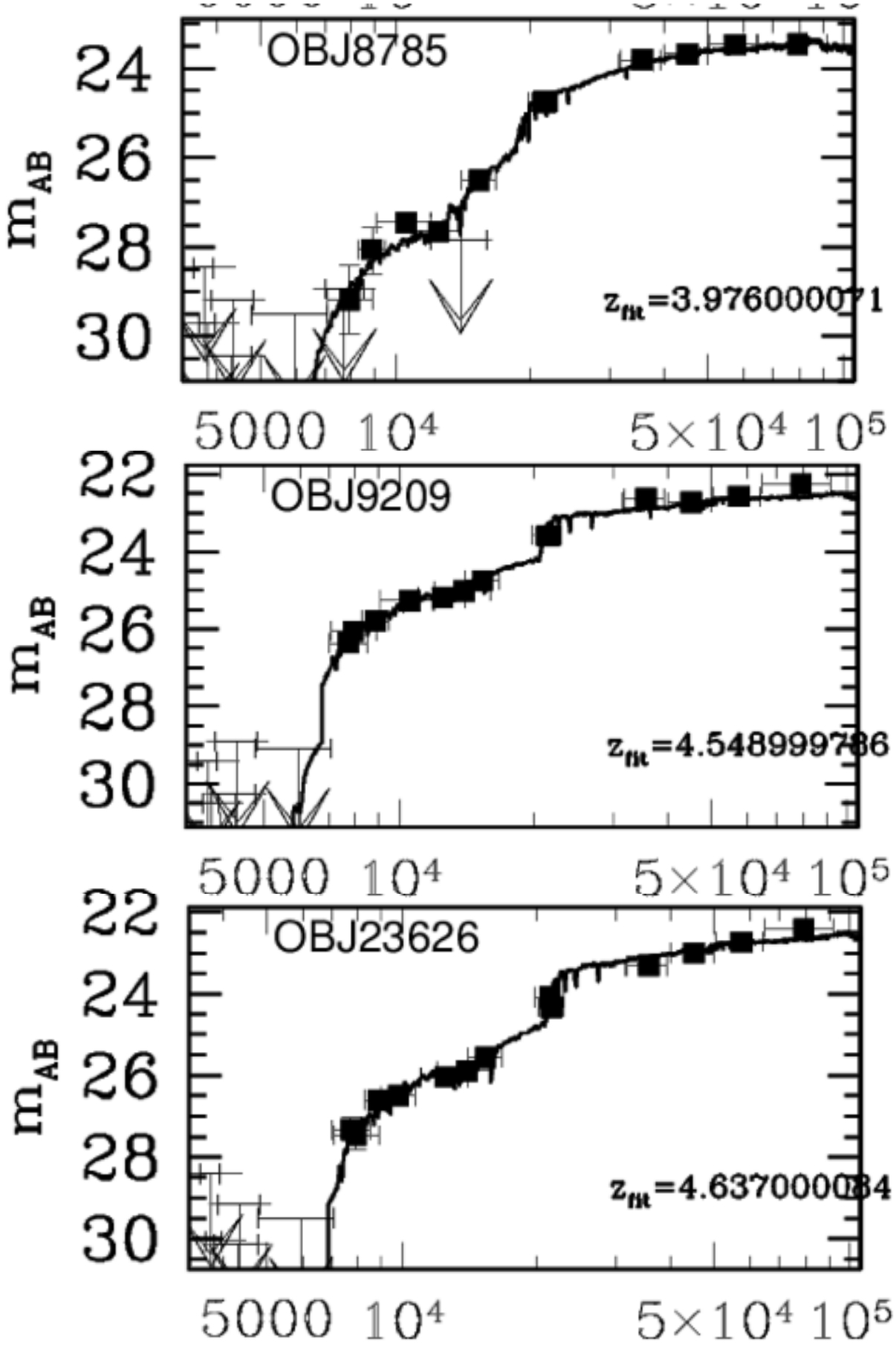
New selection:

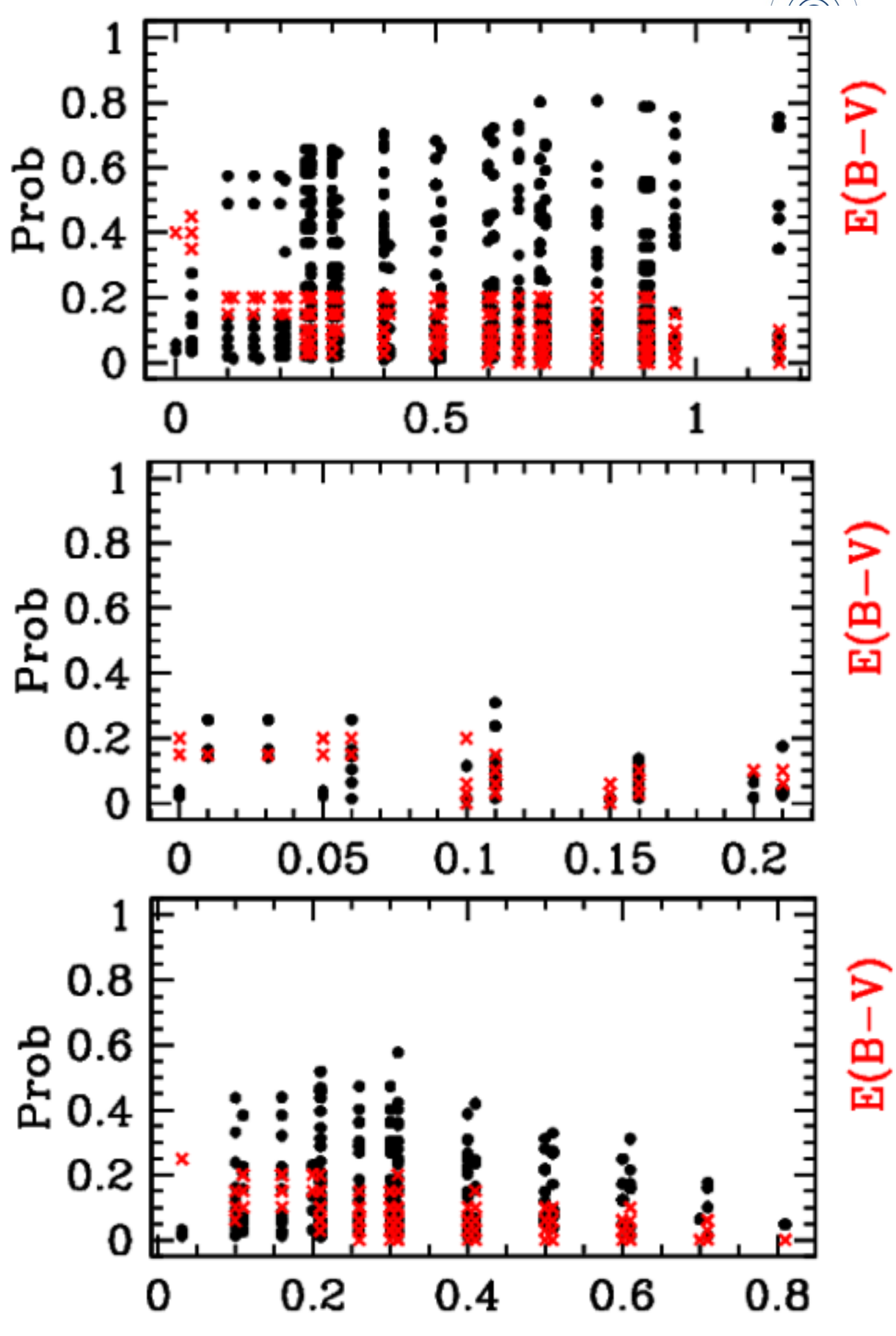
Use top-hat libraries with varying durations of the burst (tau parameter) from 0.3 to 3 Gyrs + dust reduced after burst max(E(B-V))=0.2 using CANDELS official photo-z

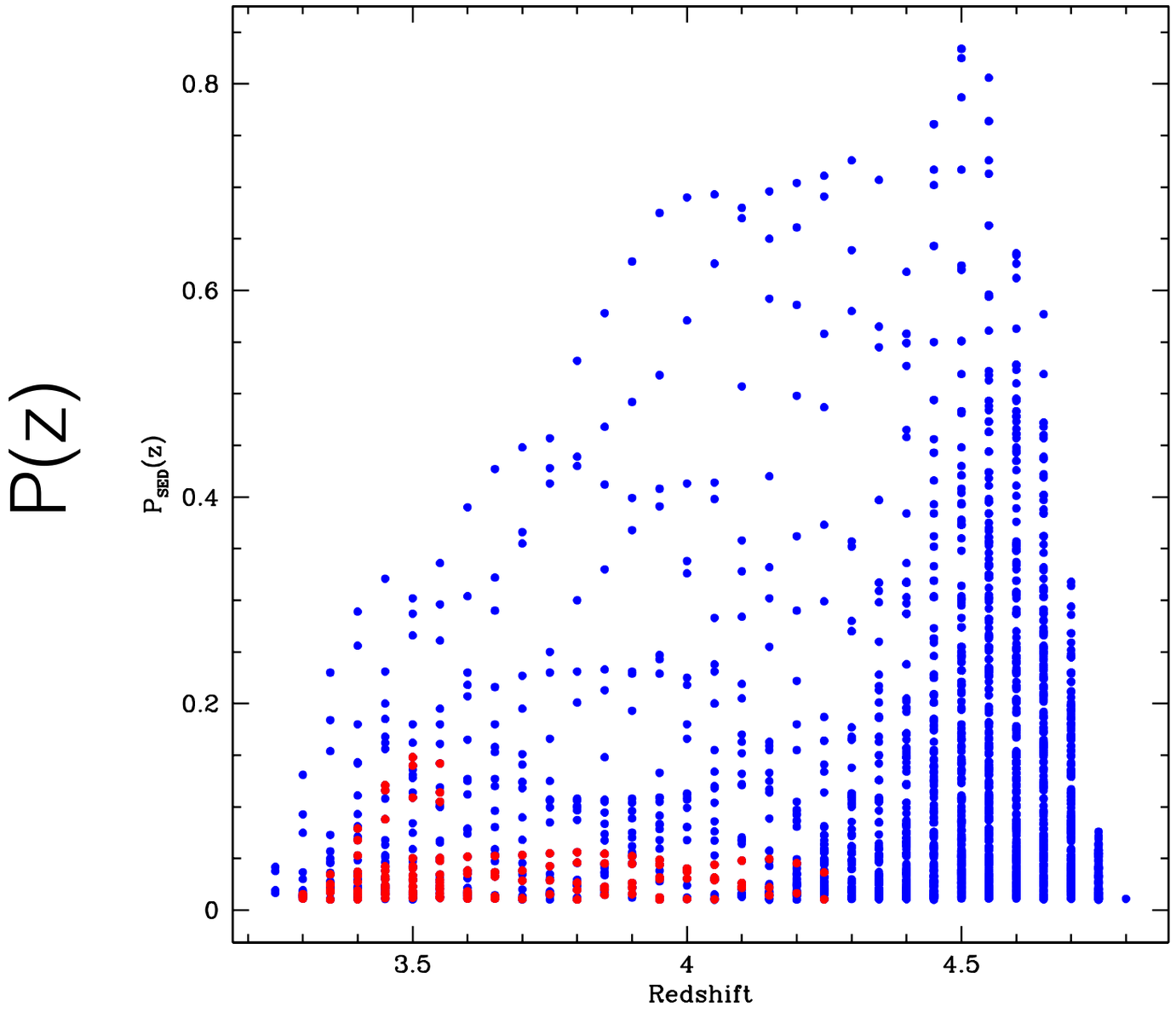
Models with age > 0 are after burst, passively evolving; models with age < 0 are still star forming ("age" has no sense)

K+IRAC1,2(,3,4) detected objects, z_off > 3,
quiescent (sSFR<1/t_U(z));
fit them with the top-hat library and select sources which have NO star forming solutions with prob > 2%

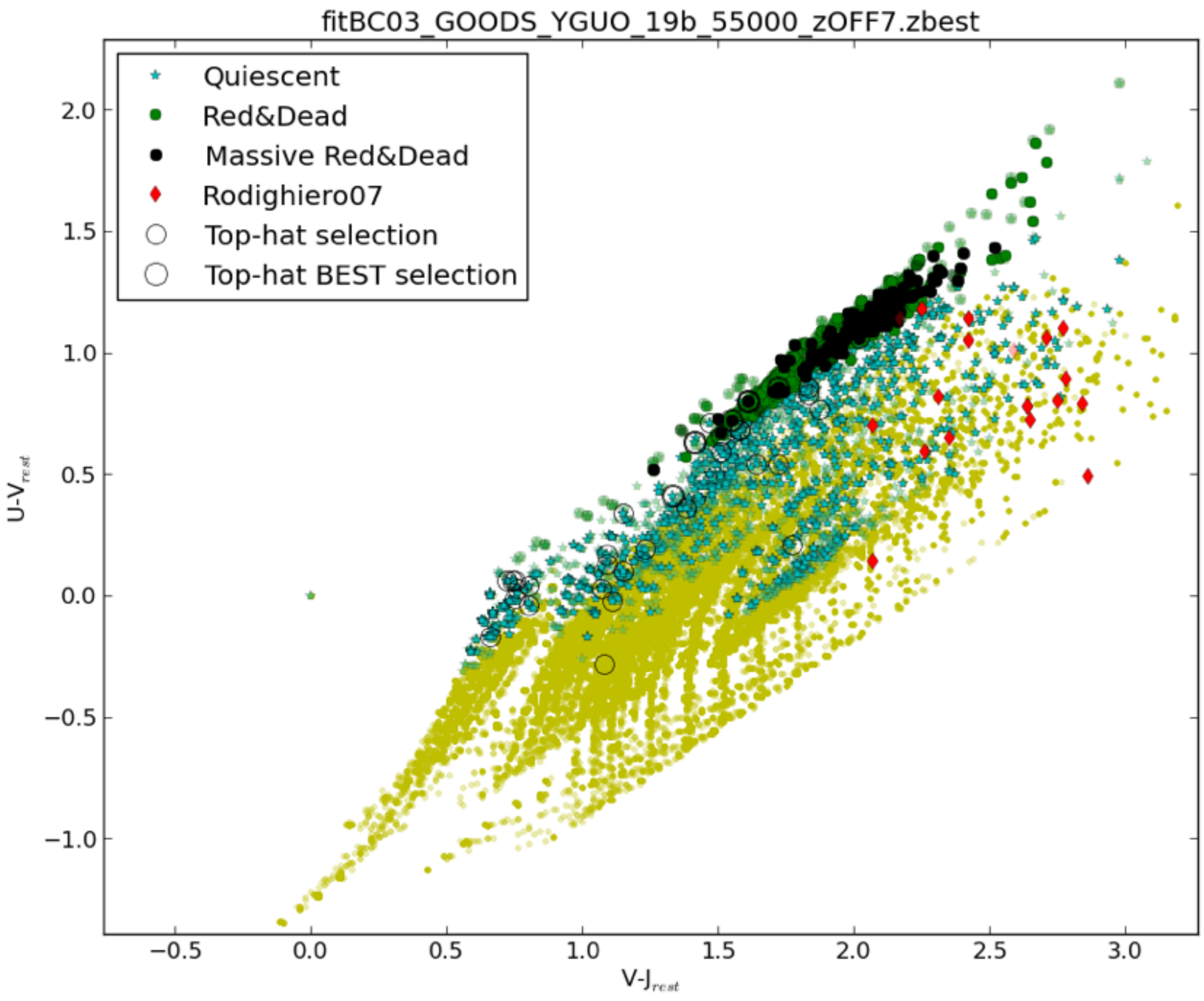
IRAC1234 detected (193 sources):
p*=2%: 34 sources
p*=5%: 51 sources
p*=10%: 67 sources
p*=20%: 193 sources (ALL)


OBJ8785
z_{fit}=3.976000071
OBJ9209
z_{fit}=4.548999786
OBJ23626
z_{fit}=4.637000084
m_{AB}
5000 10^4 5×10^4 10^5


Prob
E(B−V)



Redshift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Top-hat selection
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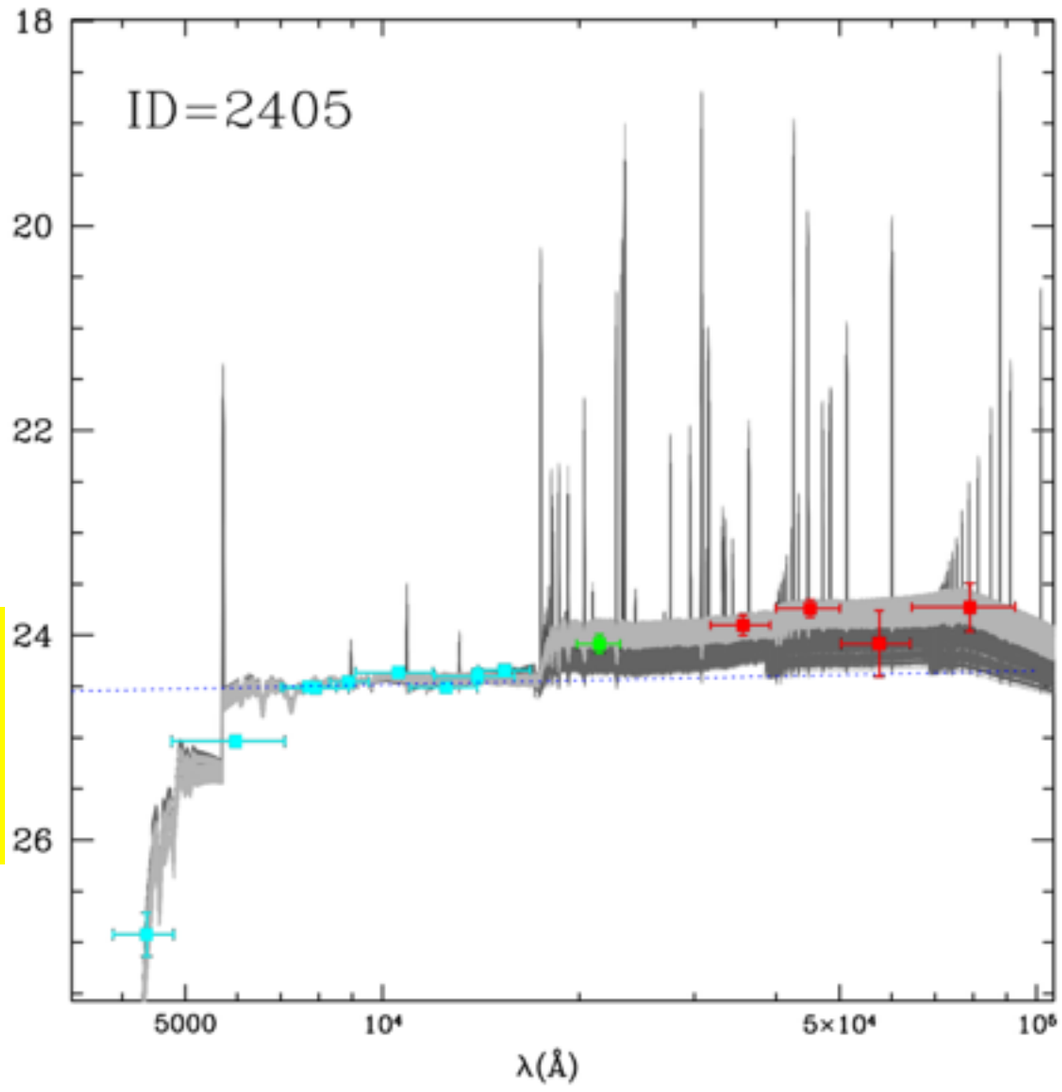
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
U-V$_{rest}$
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
V-J$_{rest}$

How does it work?

Castellano+14

z=3.7 galaxy
Z/Z_{sun}=0.3

- HST (CANDELS-GOODS)
- VLT (HUGS)
- SPITZER (SED)



BC03, *z* and Z fixed
BC03+neb. emission (Schaerer09), *z* and Z fixed

SED fitting —> Stellar Mass (M) but also SFR, E(B-V), Age
all with error budget!

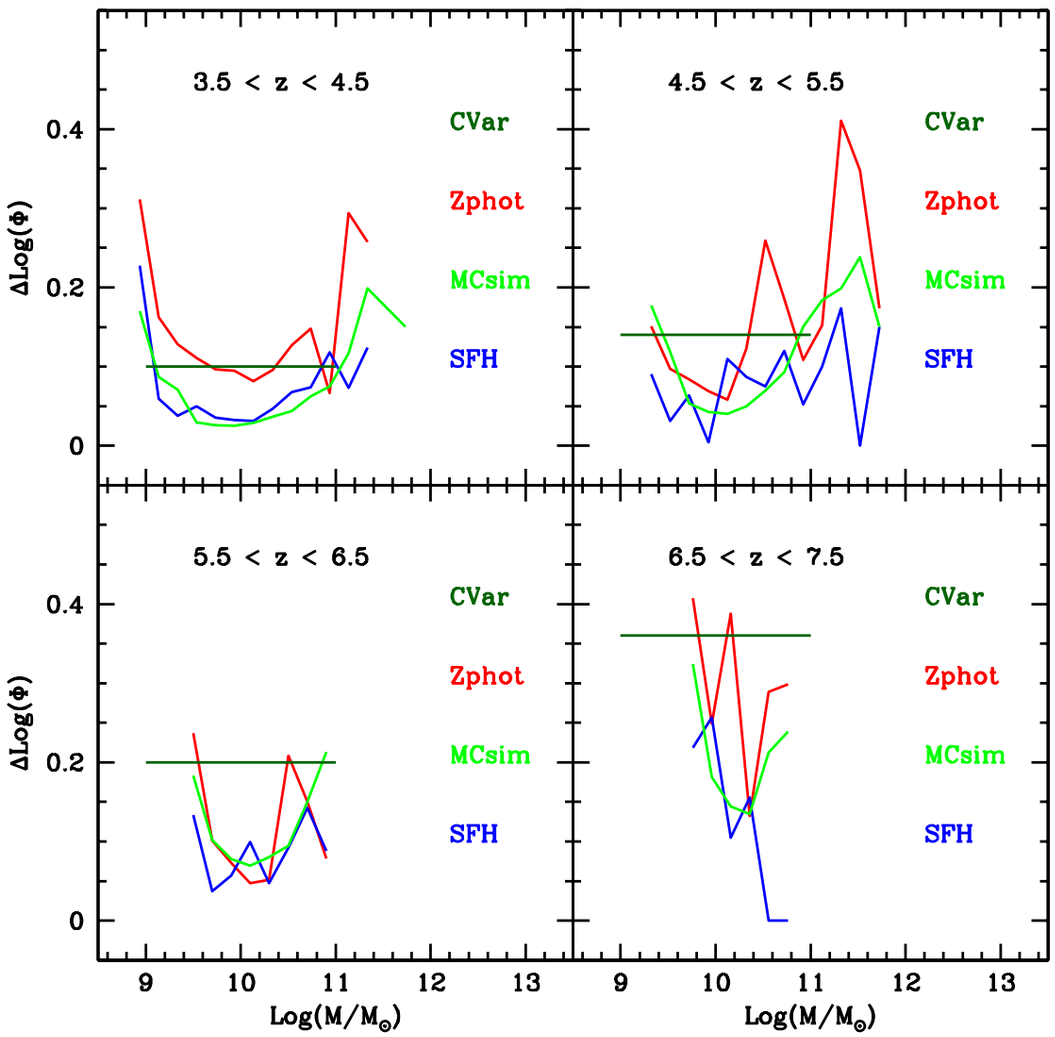
The strength of CANDELS: an arena to compare different recipes

A CRITICAL ASSESSMENT OF PHOTOMETRIC REDSHIFT METHODS: A CANDELS INVESTIGATION

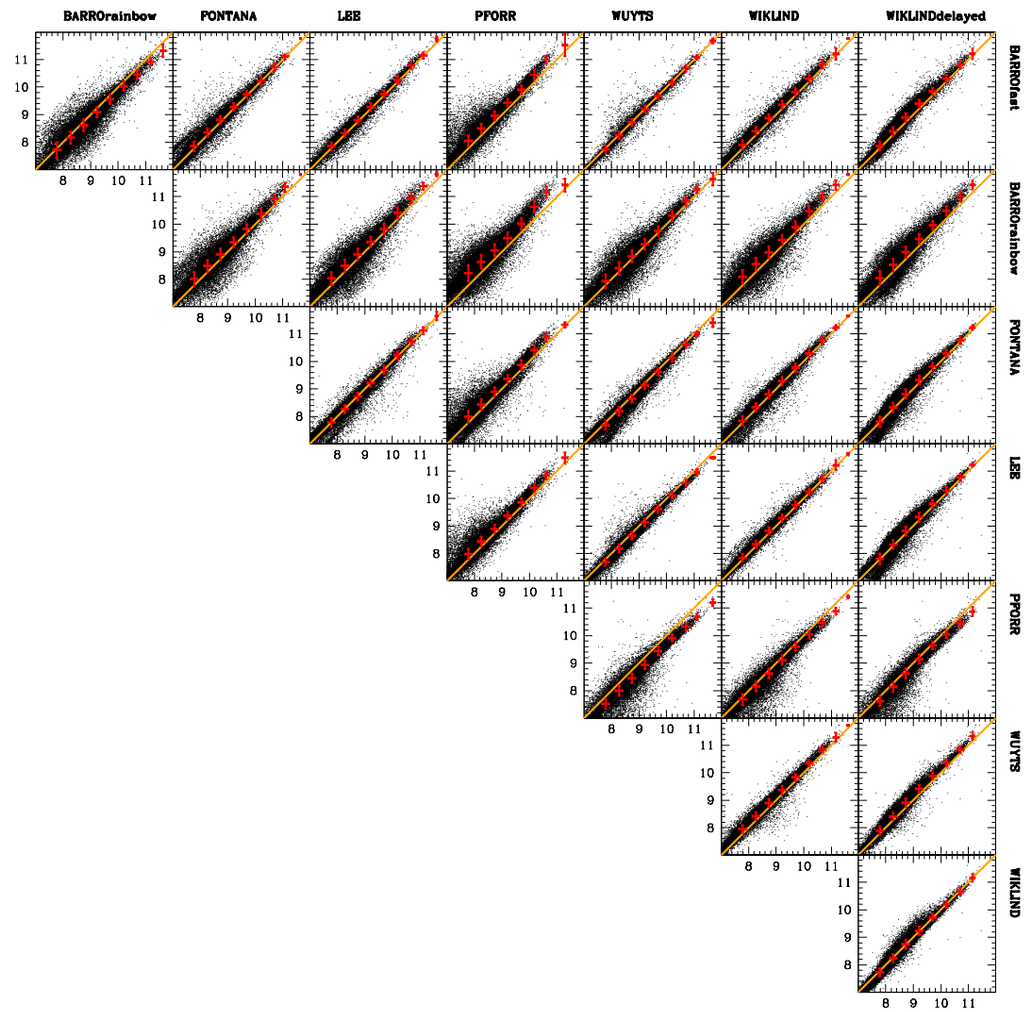
Tomas Dahlen[1], Bahram Mobasher[2], Sandra M. Faber[3], Henry C Ferguson[1], Guillermo

photo-z error decreases from σ=5% to 3%

CANDELS (Grazian, AF+14)



Mobasher et al.
Santini et al.
Grazian et al.

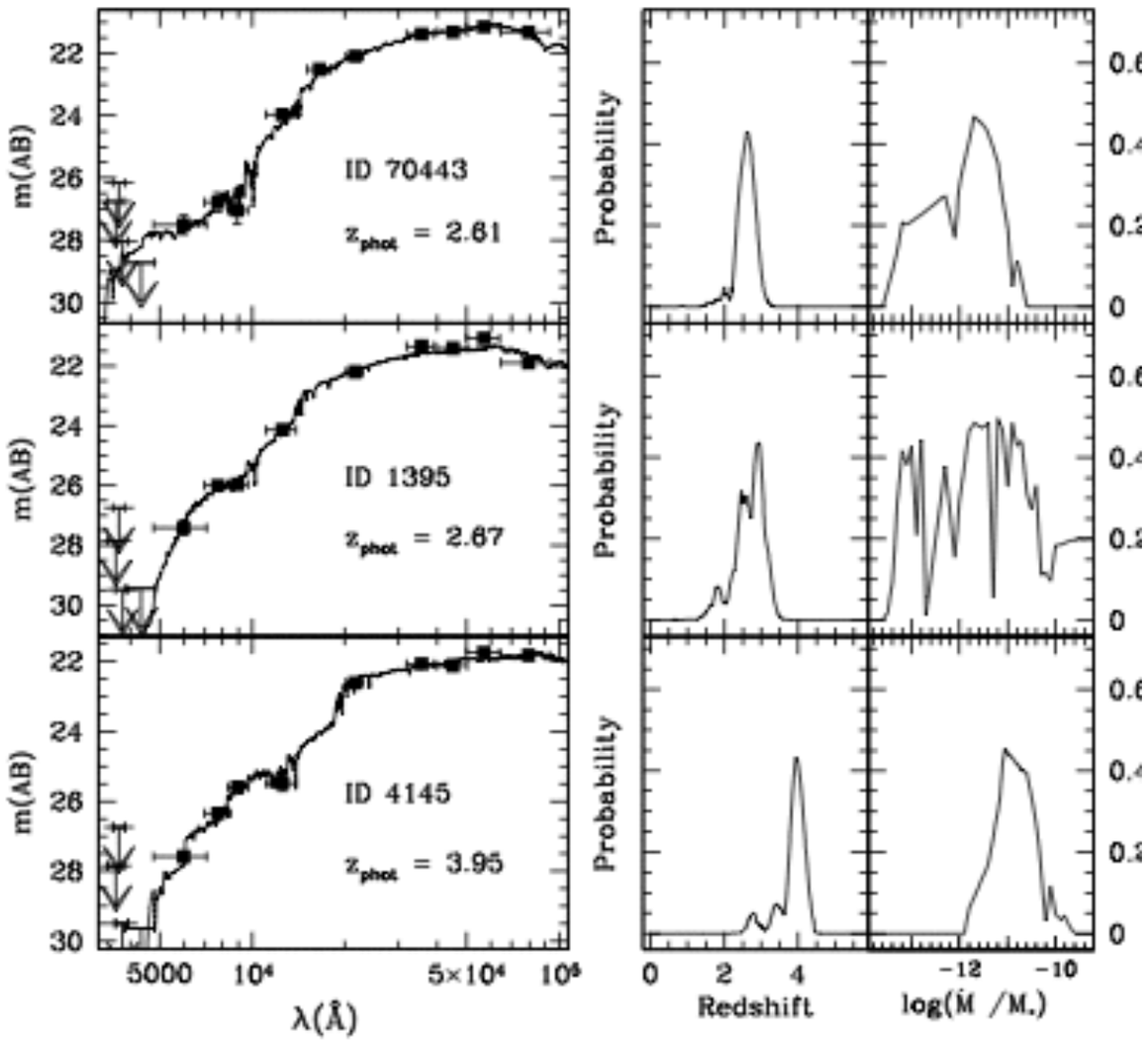


—> photo-z errors due to different *recipes* is the largest source of uncertainties

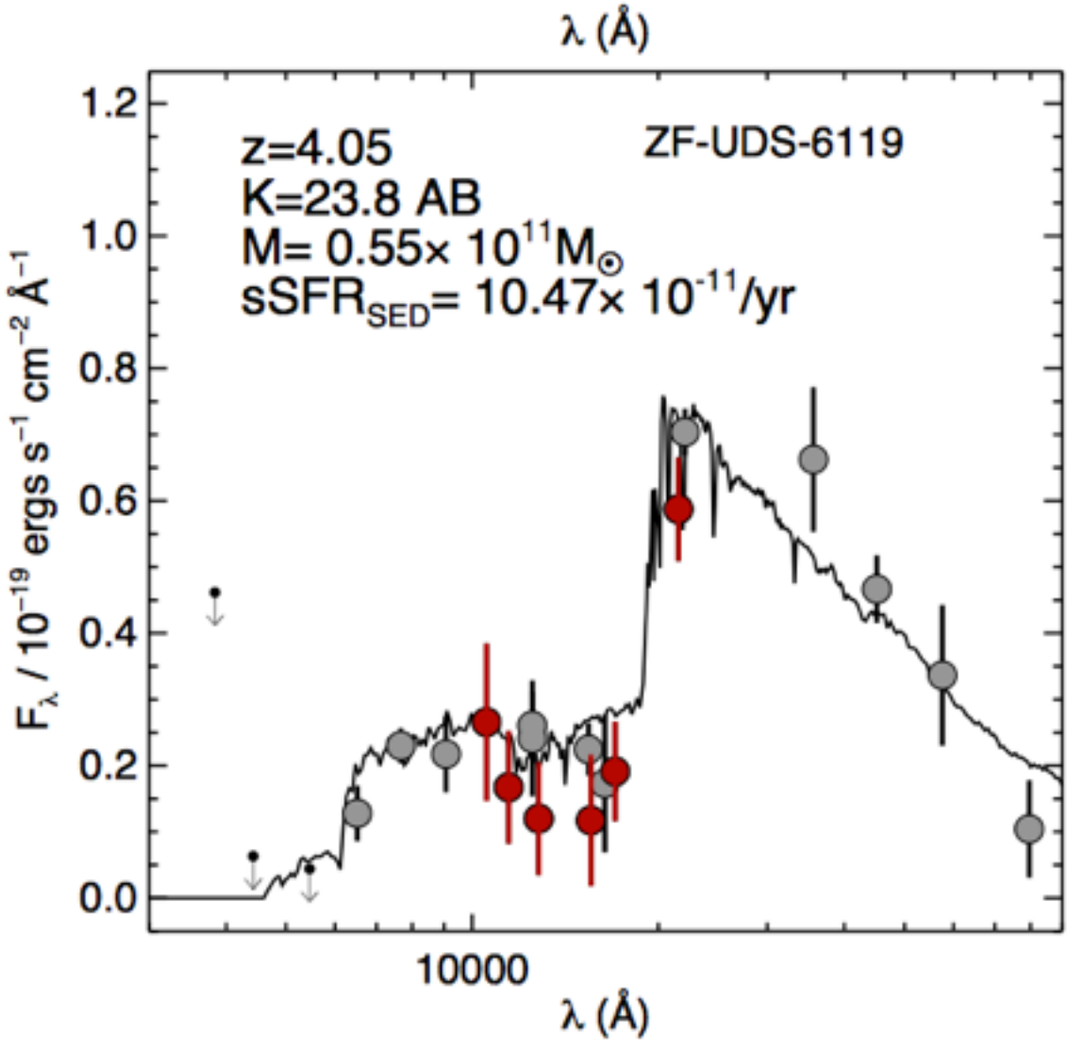
The very existence of passive galaxies at z~0 is a challenge to theoretical scenarios: need to avoid the "overcooling" problem.

AGN feedback is nowadays suggested as a main mechanism.

Passive galaxies at z≥ 2 are an even tougher challenge..
(e.g. Rodighiero+07, Kriek+08, Fontana+ 09,Domínguez Sánchez+11, Brammer 12 etc)



Fontana et al 2009



Straatman+14

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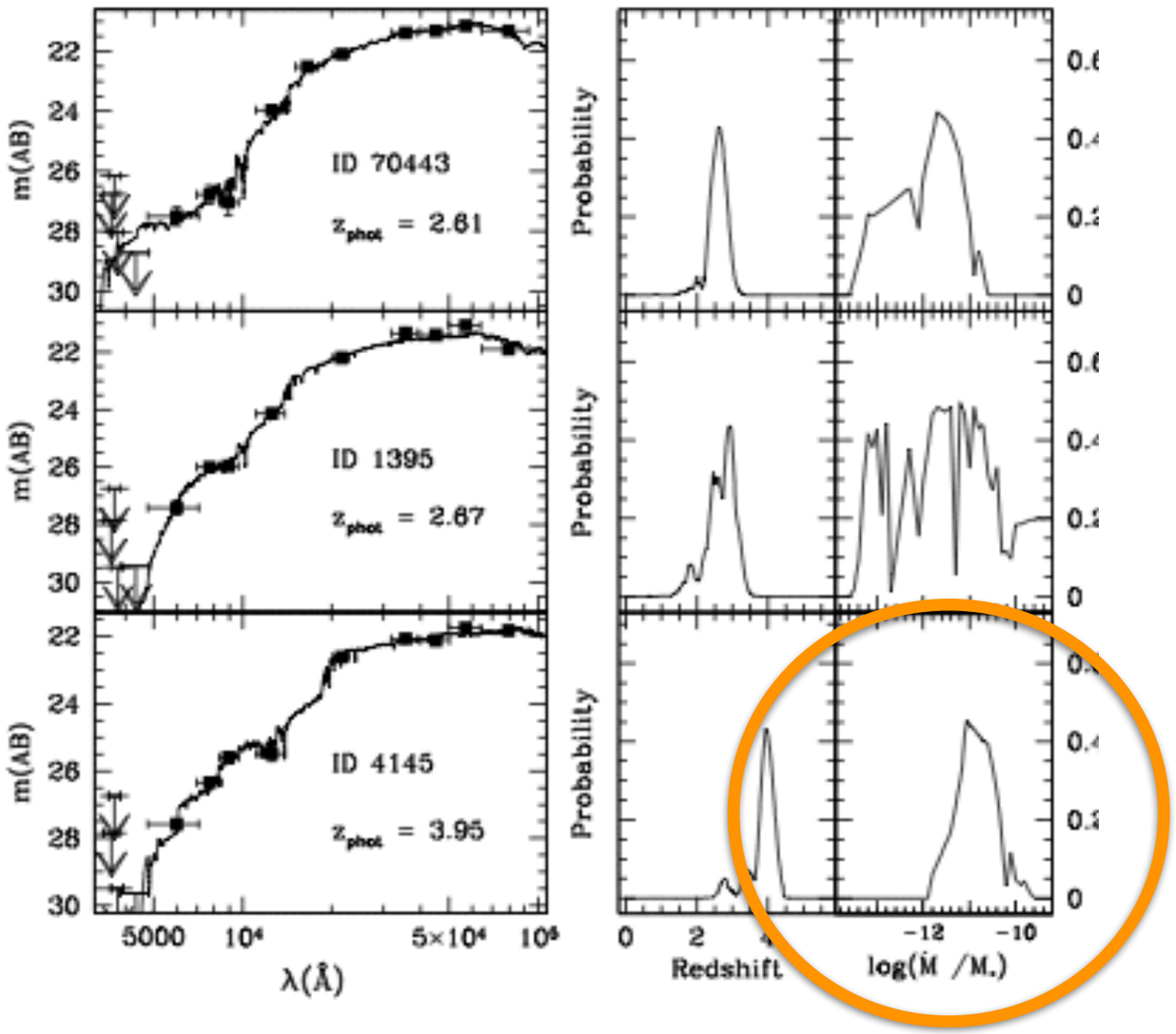

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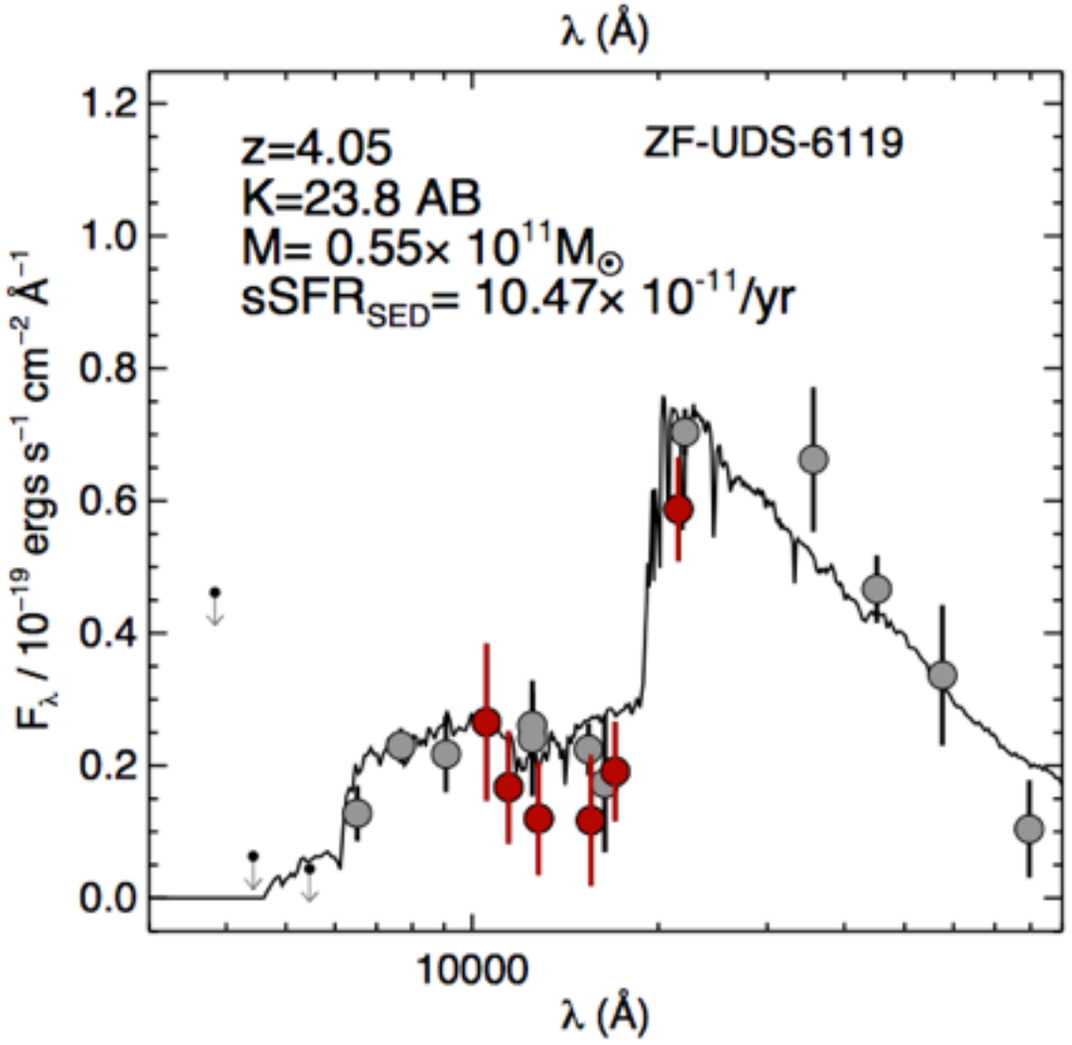
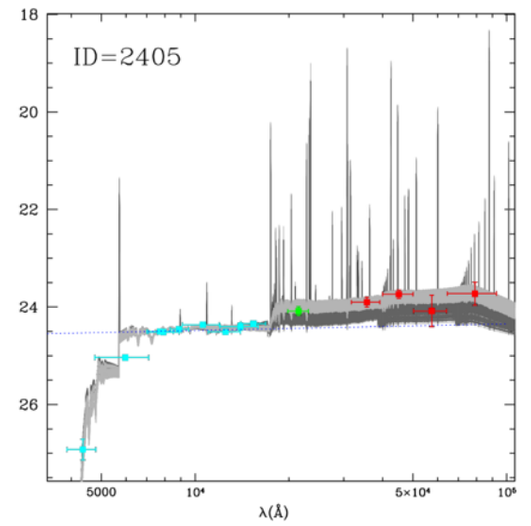


Straatman+14

Constrain the physical properties of high z galaxies using the exquisite photometric quality of CANDELS data

Accurate SED fitting of the ~14 "best" LBG at z=3-4



10 objects from AMAZE/LSD survey
+ 4 from public GMASS dataset

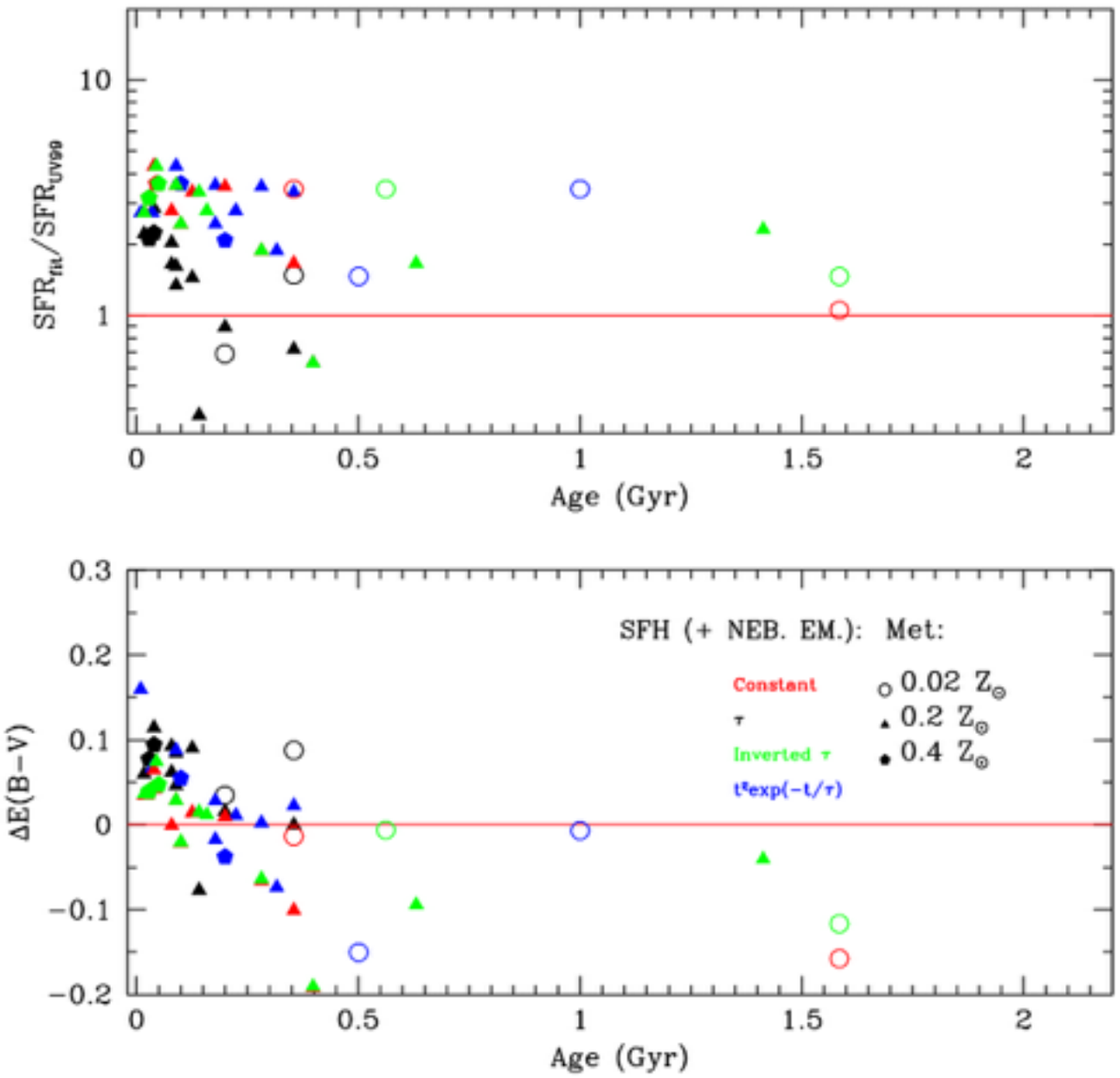
5 objects with stellar metallicity from UV absorption lines

All with gas-phase metallicity estimates

2.7<z<3.8

1.7 Gyr < U. age <2.4 Gyr

SFR is 2-5x larger than Madau98+Meurer99 relation



Castellano+14