The contribution of faint galaxies to Cosmic Reionization

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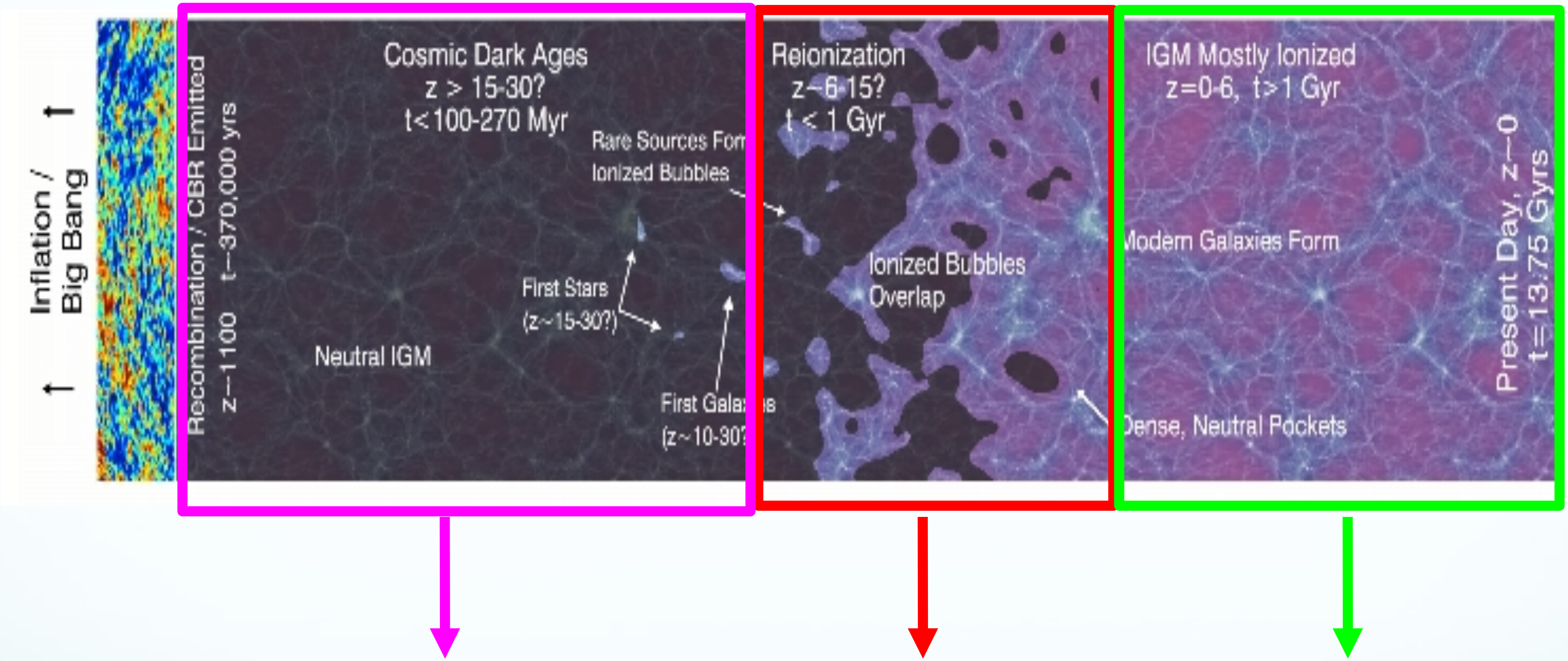
with L. Pentericci, P. Dayal, A. Hutter, B. Yue, A. Ferrara, A. Fontana, A. Grazian, E. Merlin, R. Amorin, R. Maiolino, S. De Barros, et al.

A synthetic view of cosmic history



<u>Dark Ages</u>: Universe is mostly neutral, very first stars form

End of dark age: first PopIII dominated galaxies (JWST, EELT)

<u>Reionization</u> Epoch:

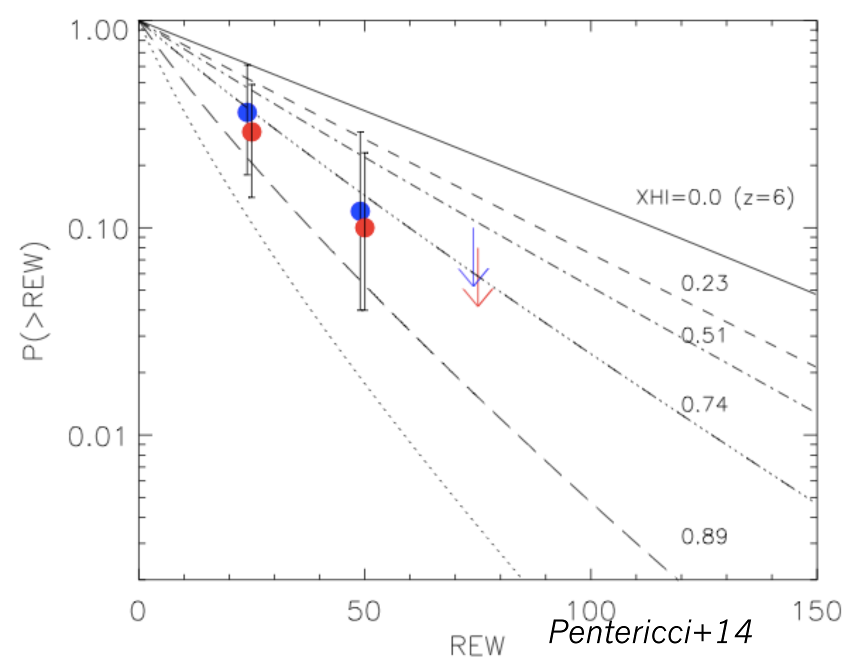
Star forming galaxies now observable from ground (VLT, SUBARU) and space (WFC3@HST)

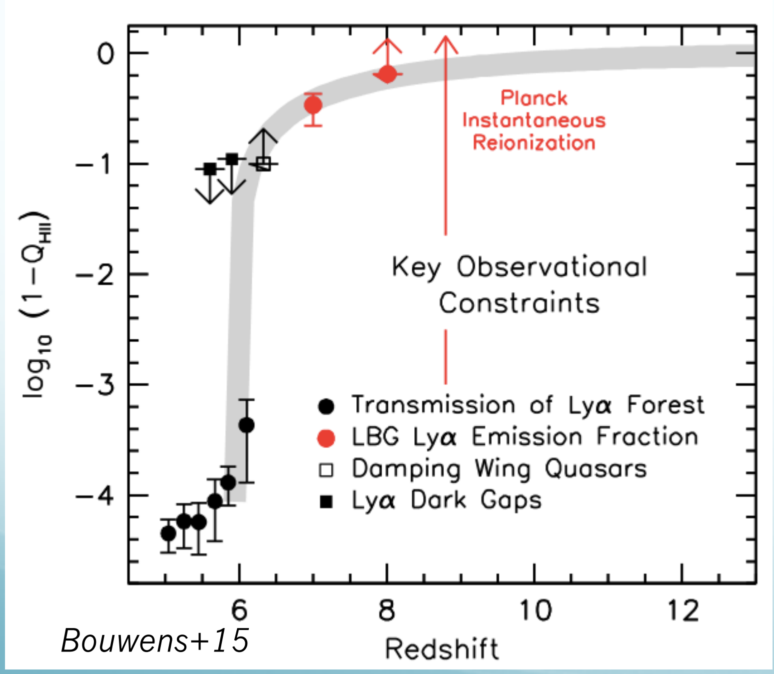
The <u>ionized Universe</u> we know well (right?)

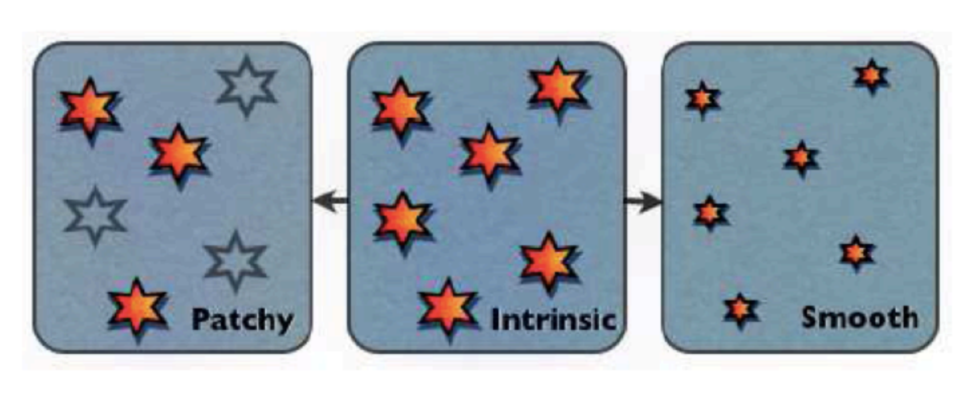
Timeline and sources of HI Reionization

***Decline of Lyα visibility in star-forming galaxies key probe of late reionization** (e.g. Stark+10, Fontana+10, Pentericci+11,+14, Schenker+12)

***Reionization timeline can be explained by the evolution of UV luminosity density** from star-forming galaxies (e.g. Bouwens+15, Robertson+15).







Patchy topology favoured (Treu+12, Pentericci+14)

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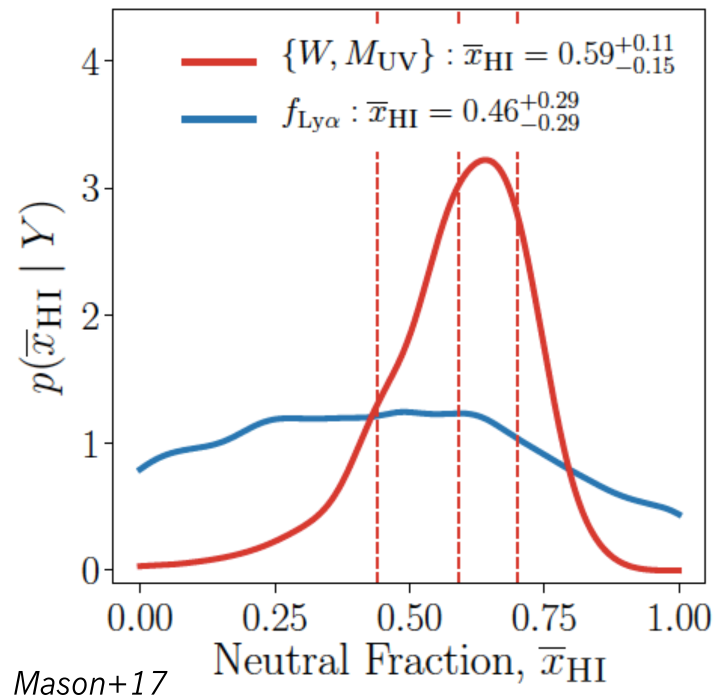
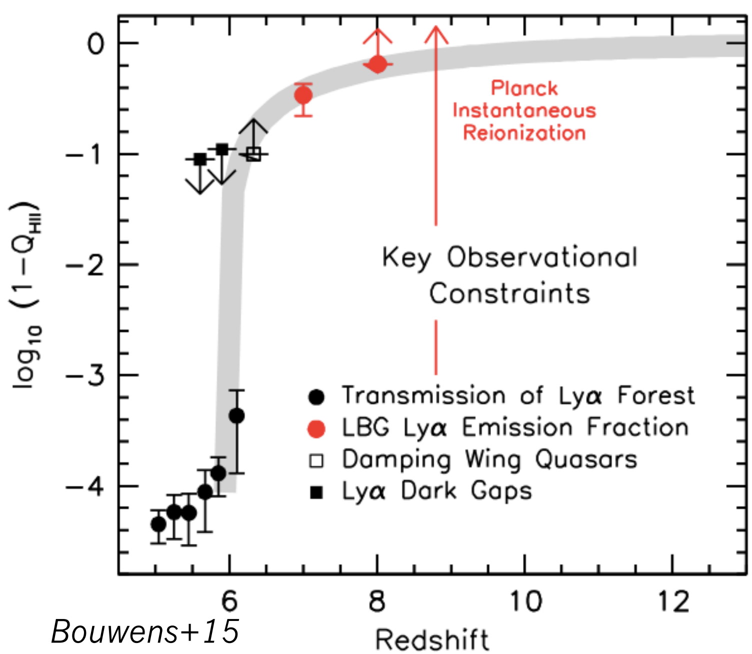
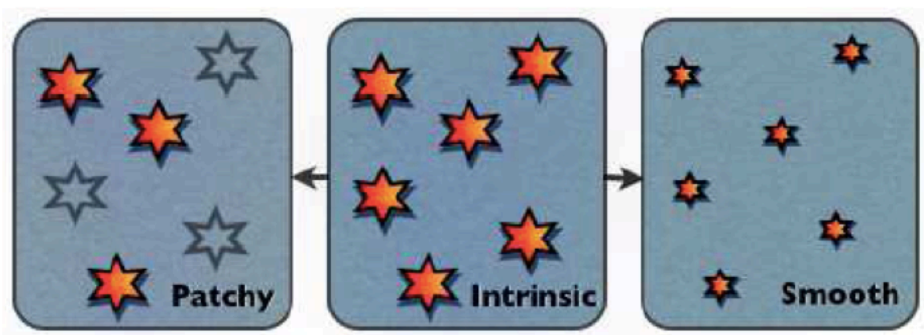


Mason+17

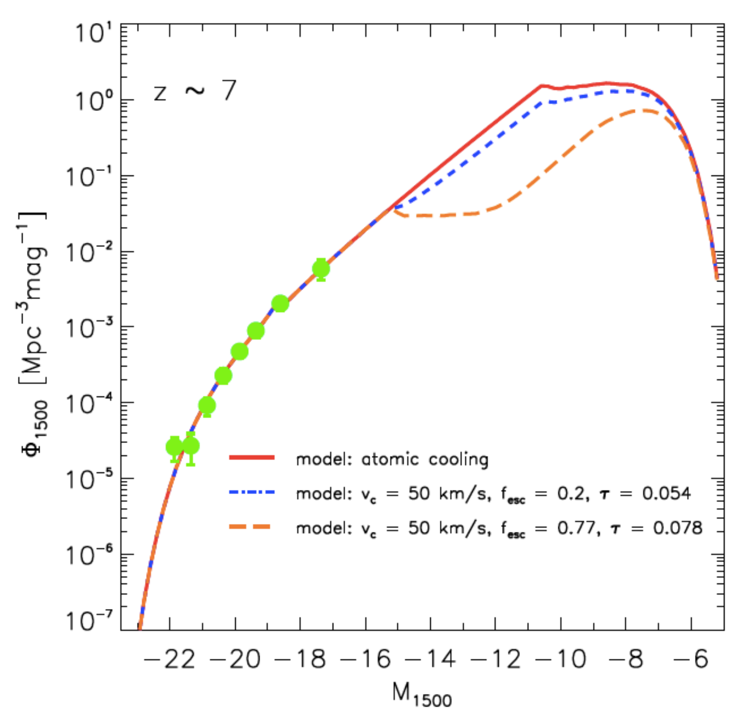


Bouwens+15



Patchy topology favoured (Treu+12, Pentericci+14)

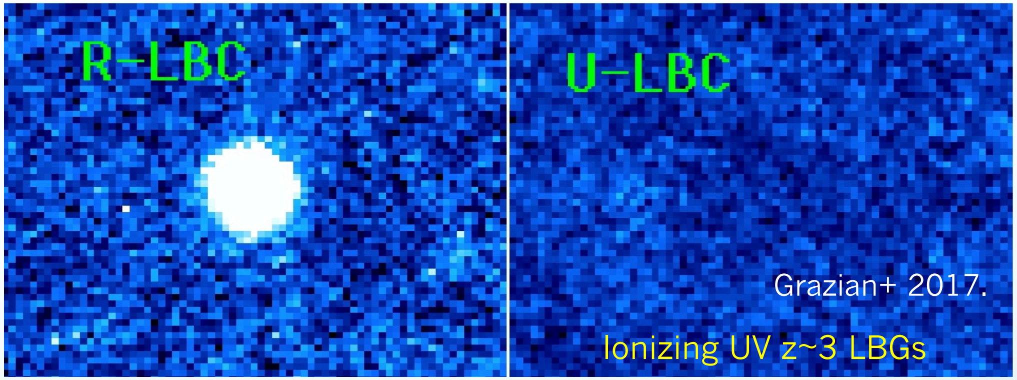
Reionization: open issues (1)



Yue, Ferrara et al. 2014

$$\dot{N}_{ion}(s^{-1}Mpc^{-3}) = 10^{49.7}\left(\frac{\rho_{UV}}{6\cdot 10^{25}}\right)\left(\frac{3.0}{\alpha_S}\right)\left(\frac{f_{esc}}{0.1}\right)$$

- Luminosity function faint end
- Escape fraction
- Intrinsic spectrum

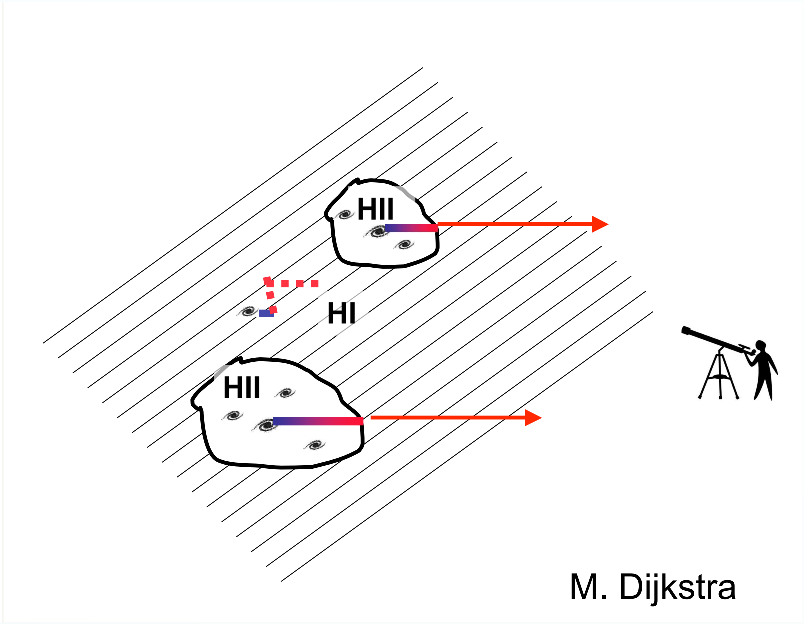


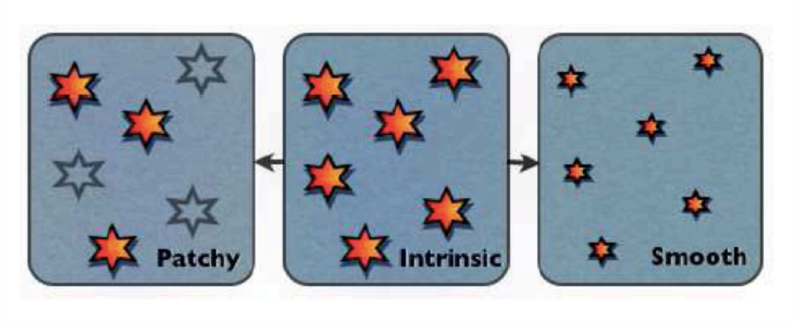
Low f_esc from bright galaxies, at z~3-4, also talk by F. Marchi

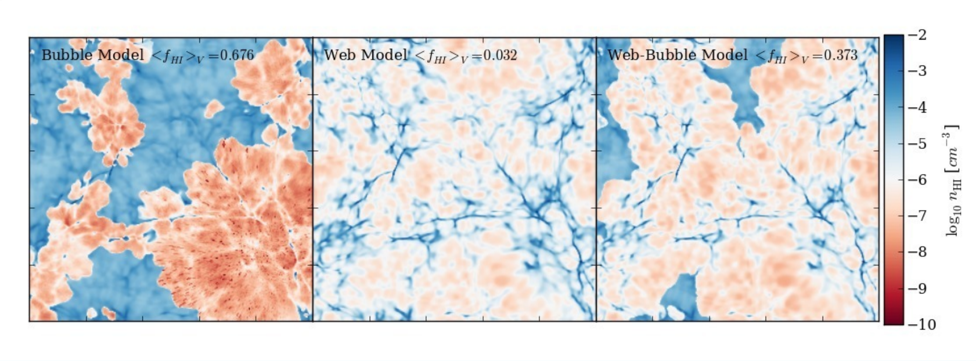
Is galaxy number density high enough?
Do they emit enough ionizing radiation?

Are other sources needed? (i.e. faint AGNs, Giallongo et al. 2012-2015)

Reionization: open issues (2)







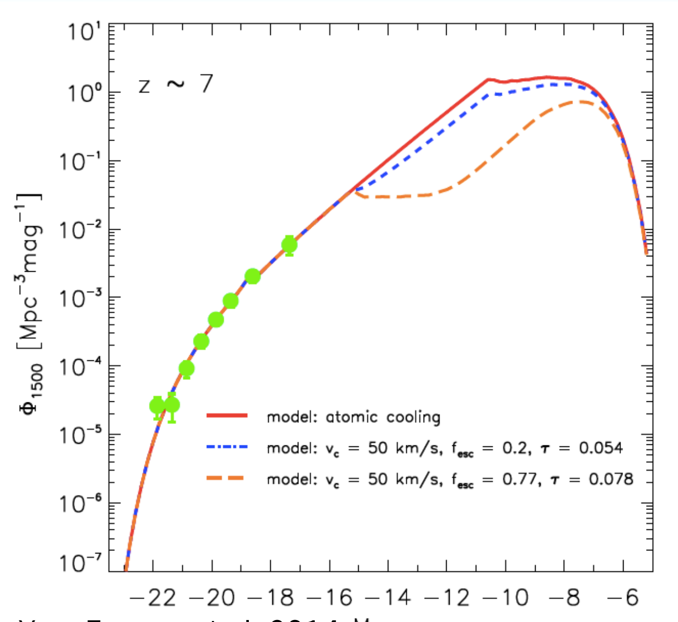
What is the topology of reionization?

What distinguishes Lya emitting and non emitting galaxies, what causes visibility patchiness?

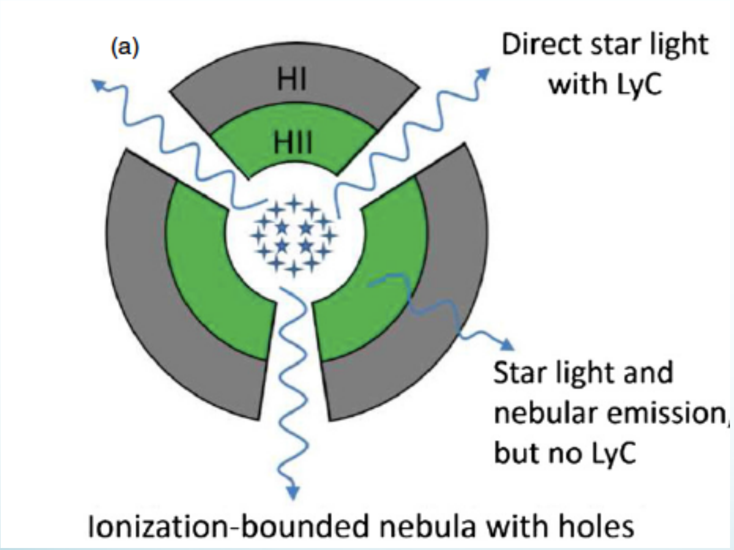
Outline of this talk

1) Constraints on LF cut-off at z>5 from ultrafaint galaxies in the Frontier Fields.

Number of faint galaxies during reionization.



Yue, Ferrara et al. 2014

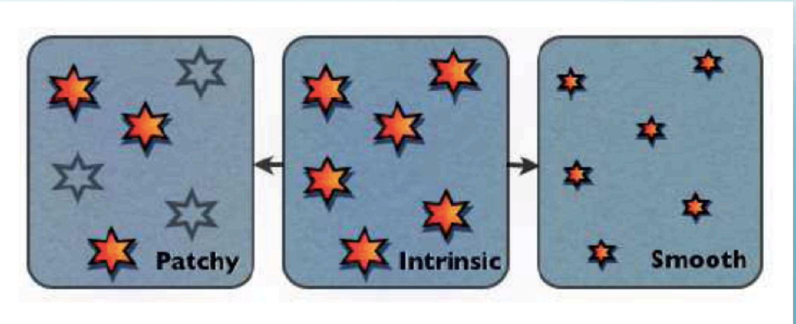


2) Physical properties of confirmed z~7 LAEs

Ionizing properties of galaxies during reionization.

3) Connection between Lya emitting galaxies and clustering.

The role of galaxy clustering during reionization.



(1)
The critical role of the faintest sources

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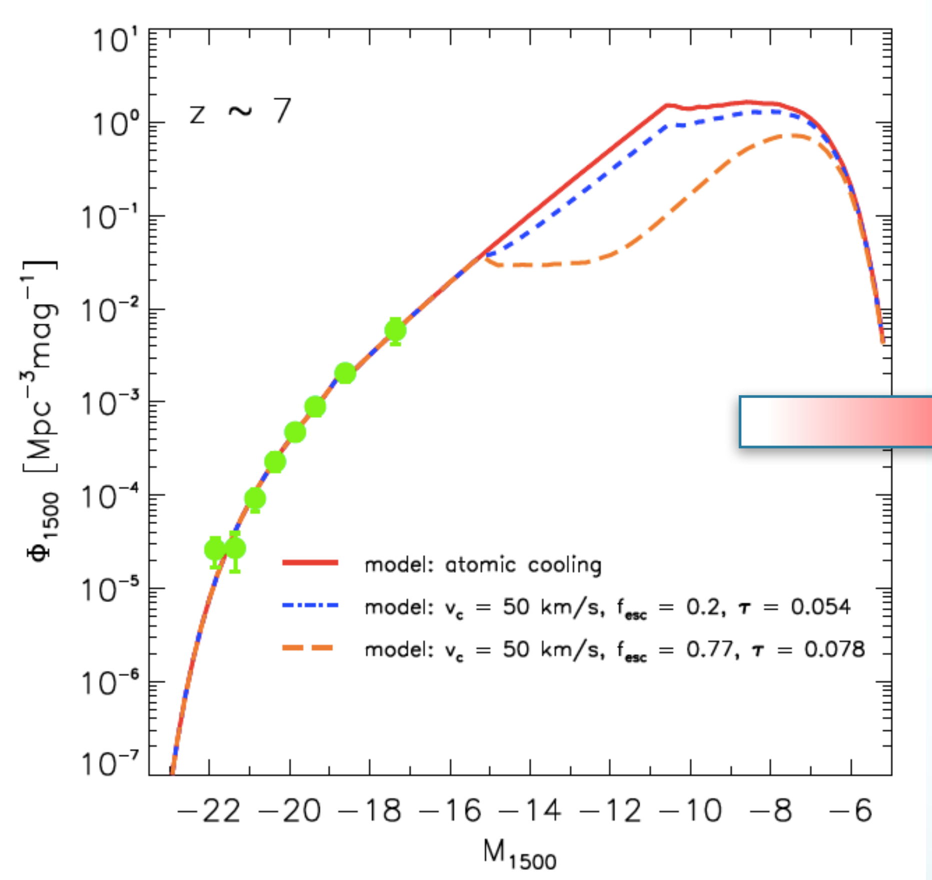
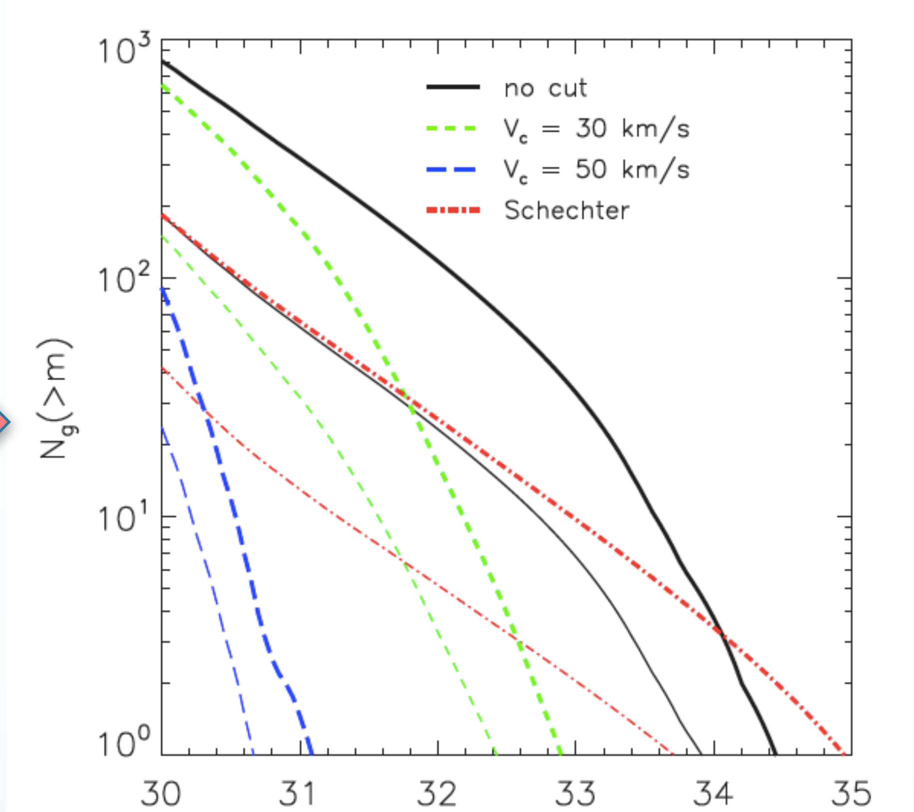
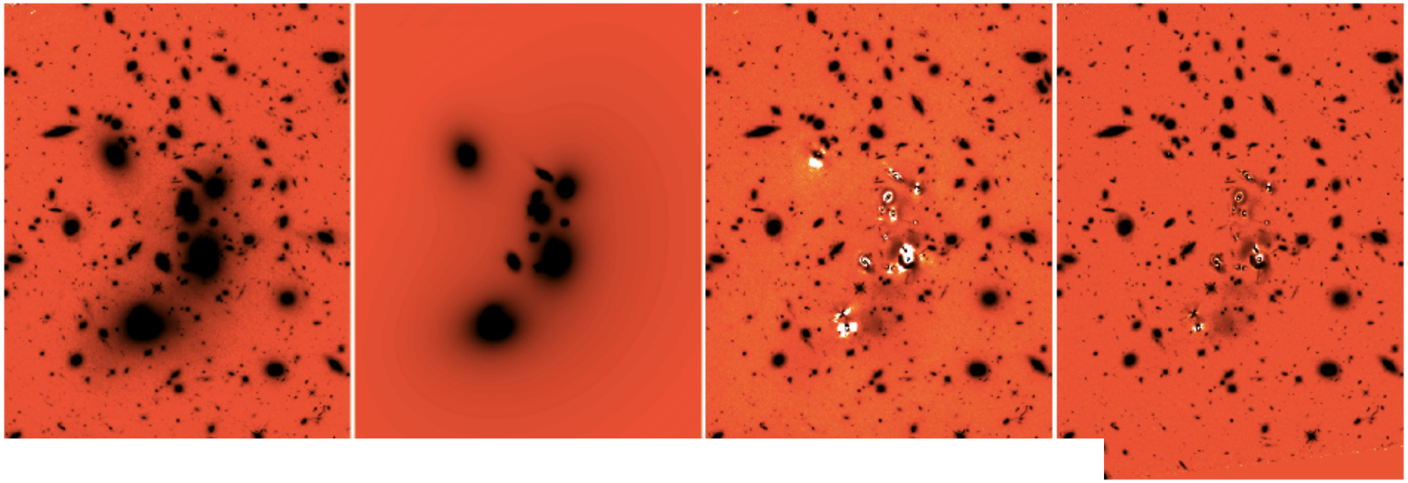


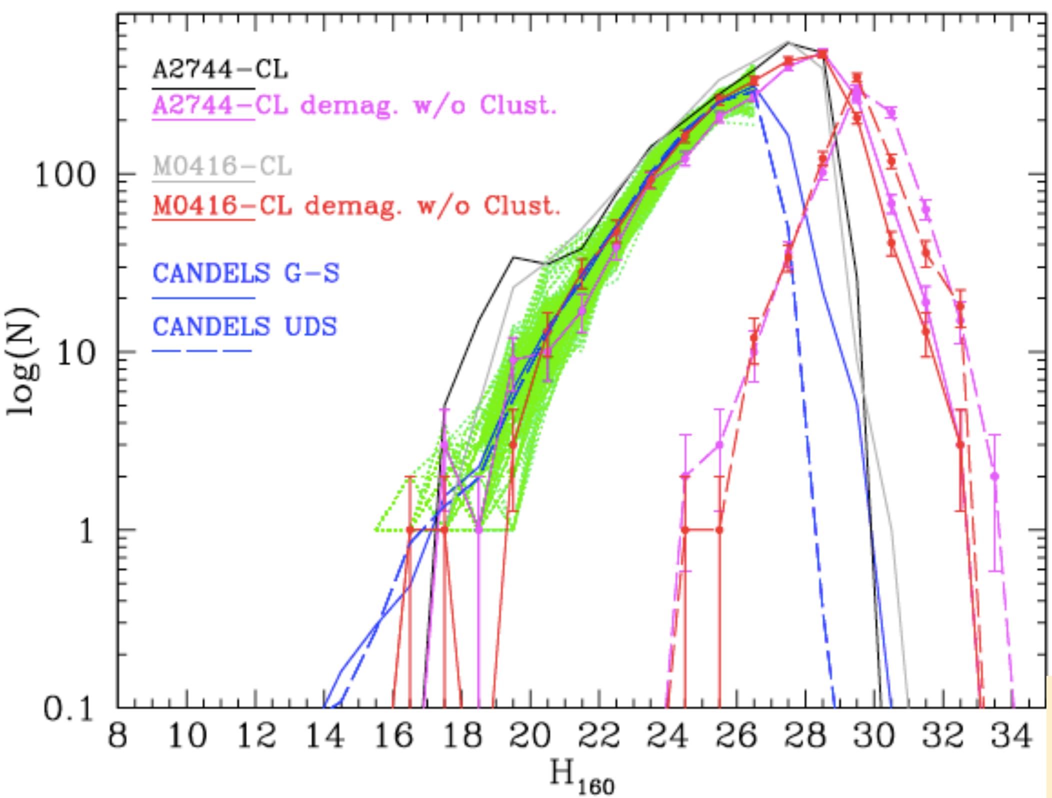


Yue, Ferrara et al. 2014

The LF cut-off (feedback due to UV background) affects the number counts of highly magnified sources.
We can probe the cut-off of the LF from galaxy number counts in the Frontier Fields survey.

High-z faint galaxies in the Frontier Fields





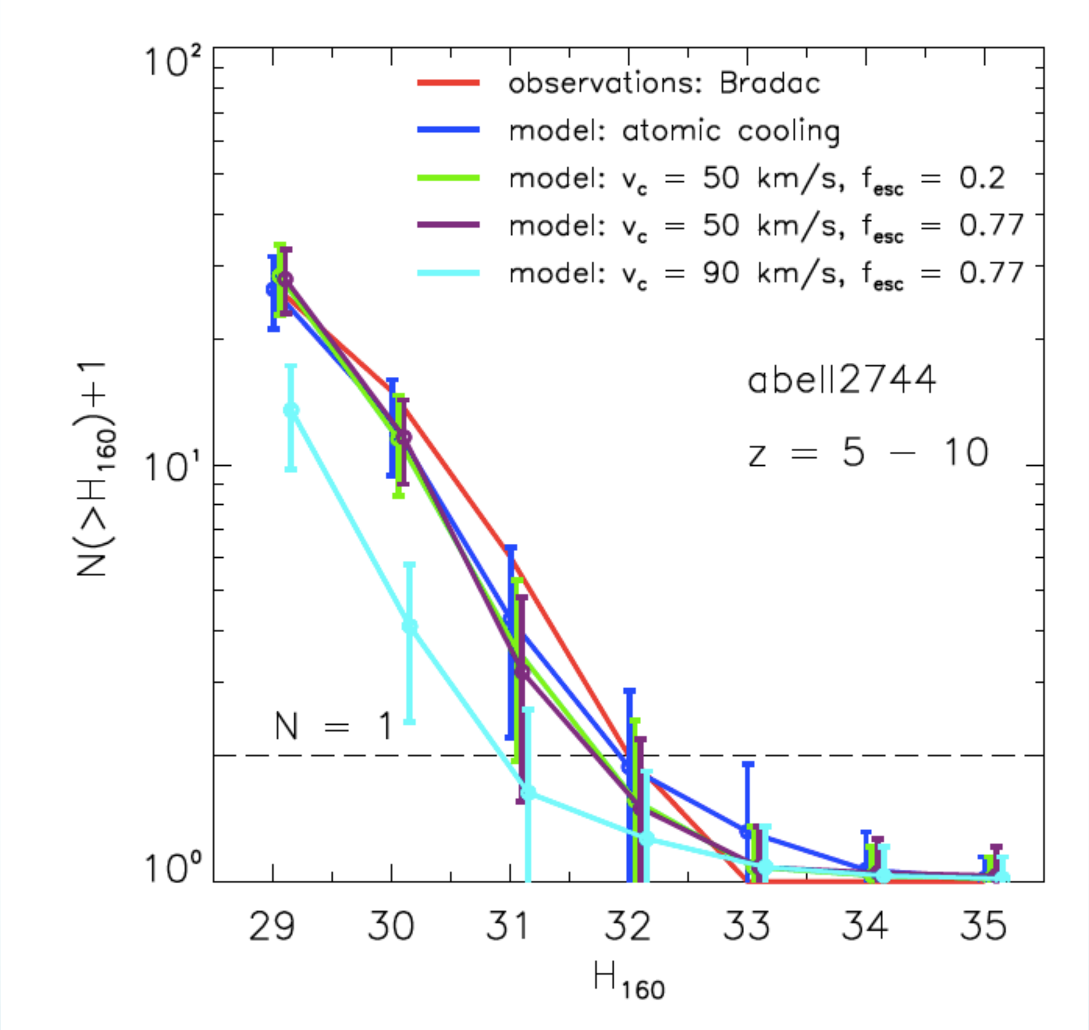
We looked for ultrafaint z>5 galaxies in the **ASTRODEEP catalogues** of A2744 and MACS0416

- 10 bands photozs
- Median from 6 different codes to minimize systematics

Merlin et al. A&A 2016
MC+ A&A, 2016b

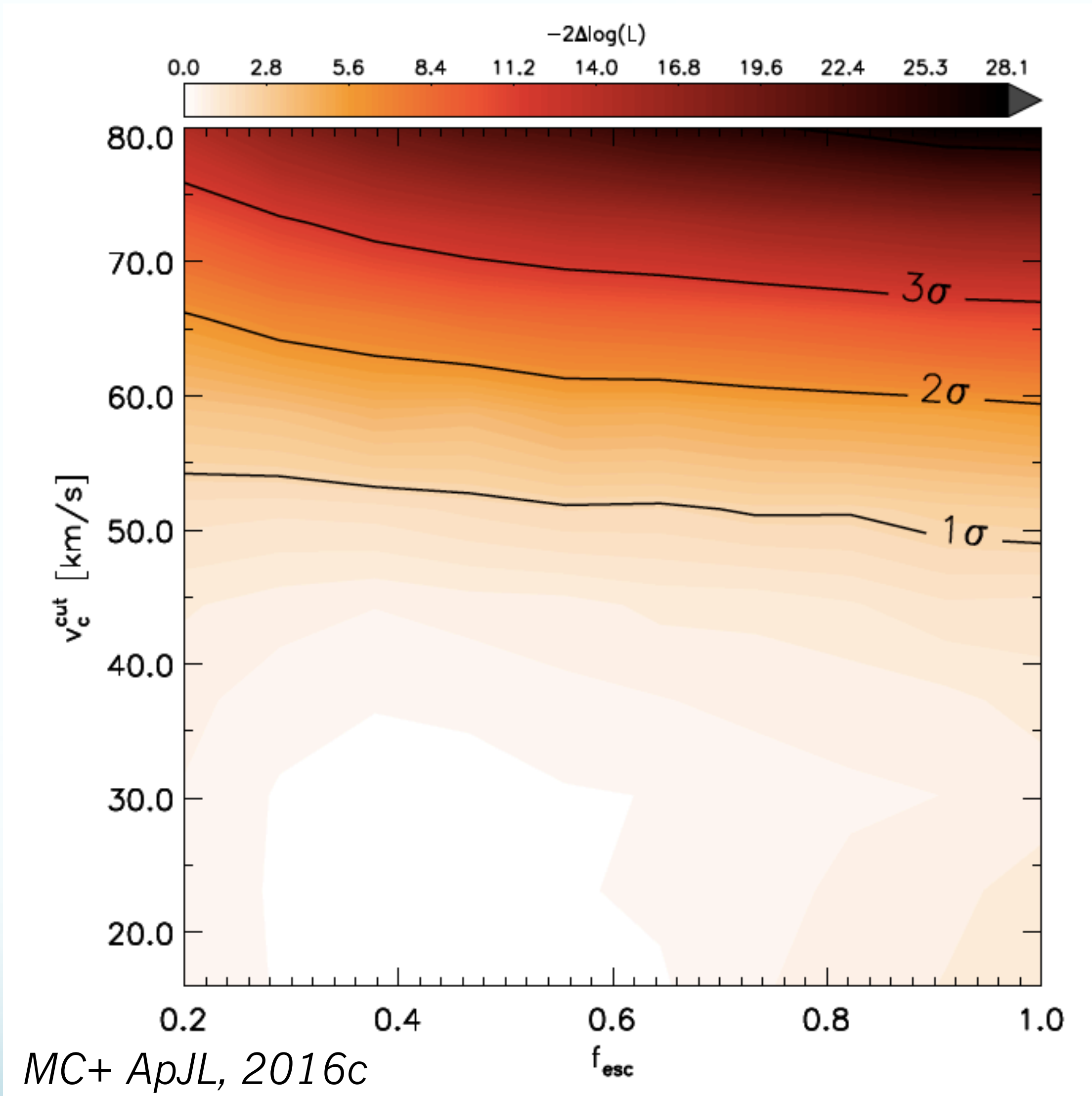
http://astrodeep.u-strasbg.fr/ff/
http://www.astrodeep.eu

High-z faint galaxies in the Frontier Fields



Comparison between Yue et al. 2016 model and observed counts.
All lensing models used to build a global likelihood minimizing systematics.

No evidence of LF cut-off due to feedback



First constraints on the cut-off circular velocity for star formation at z>5

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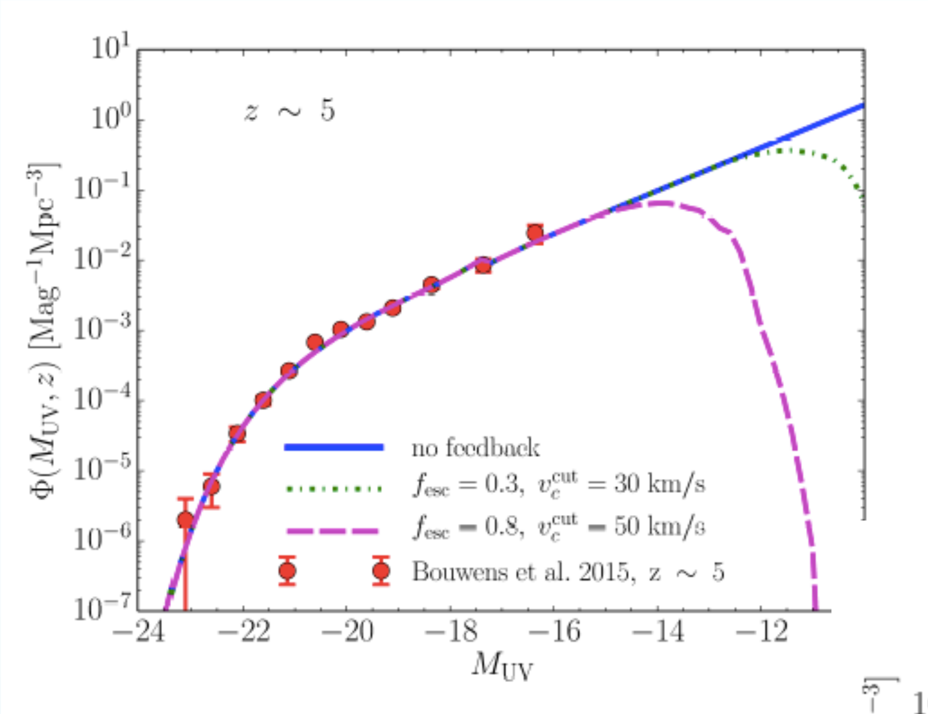
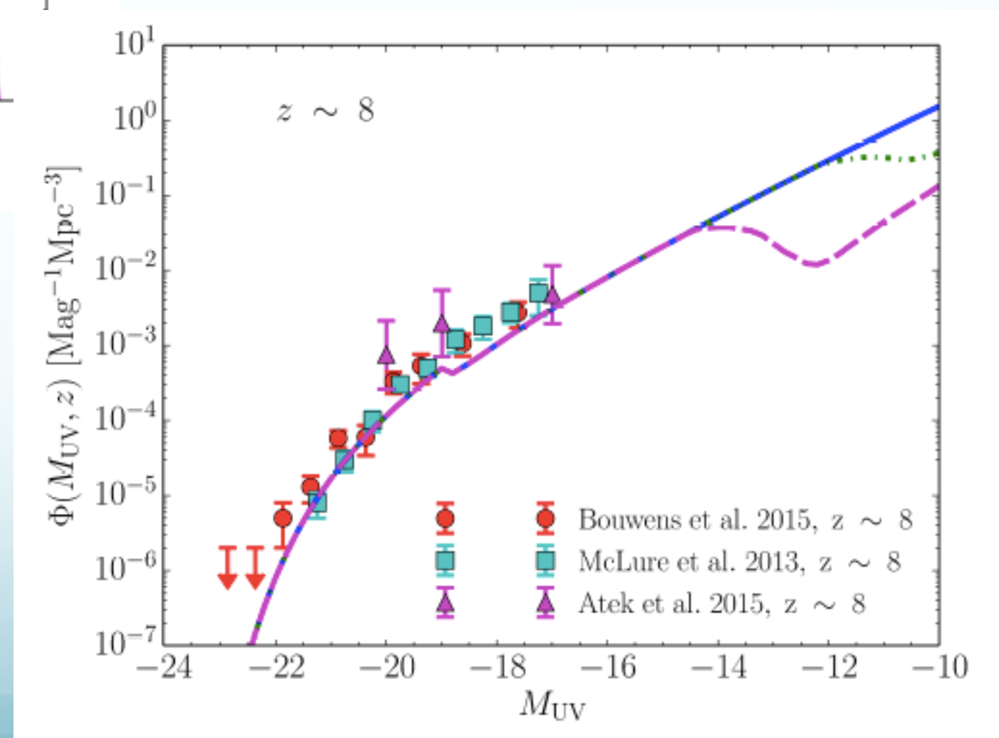


No evidence of cut-off at halo mass M>2-5 x 10^9 Msun (z=5-10)

LF cut-off must be at M_{UV}>-15

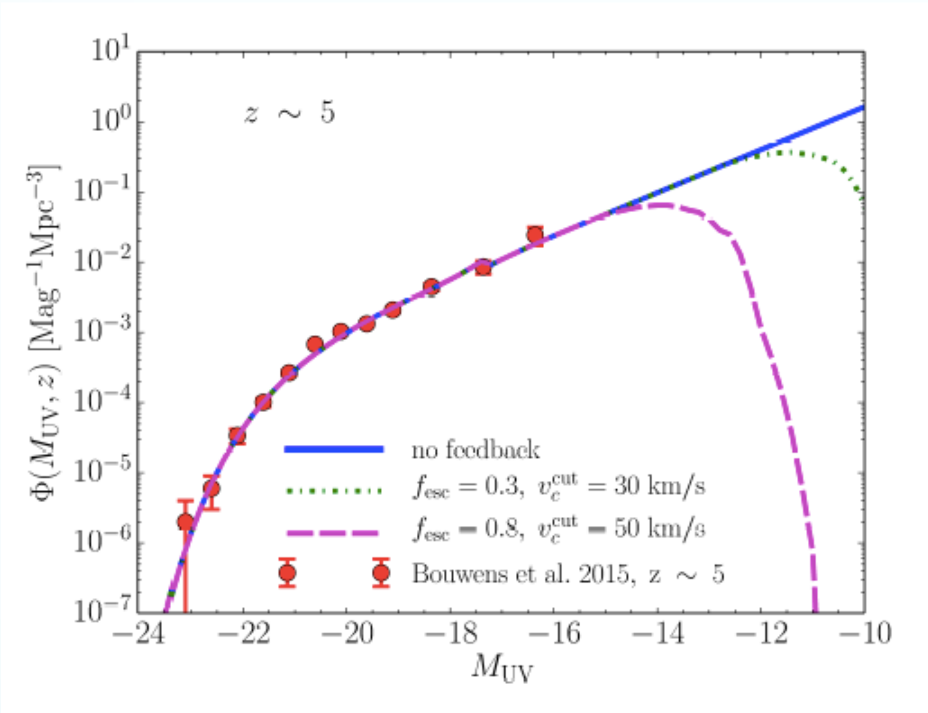
Consistent with Bouwens+17, looser constraints than in Livermore+17: but beware that lensing models uncertainties are the real limitation in this kind of analysis!



Faint galaxies likely have a dominant role in reionization

MC+ ApJL, 2016c

No evidence of LF cut-off due to feedback



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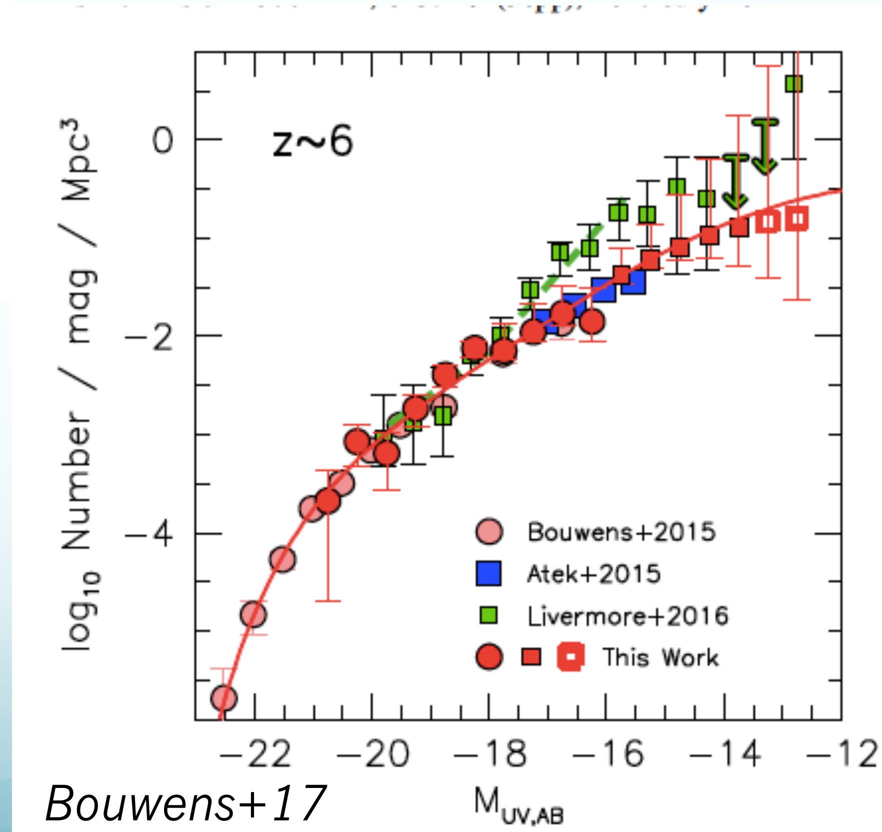

Bouwens+17

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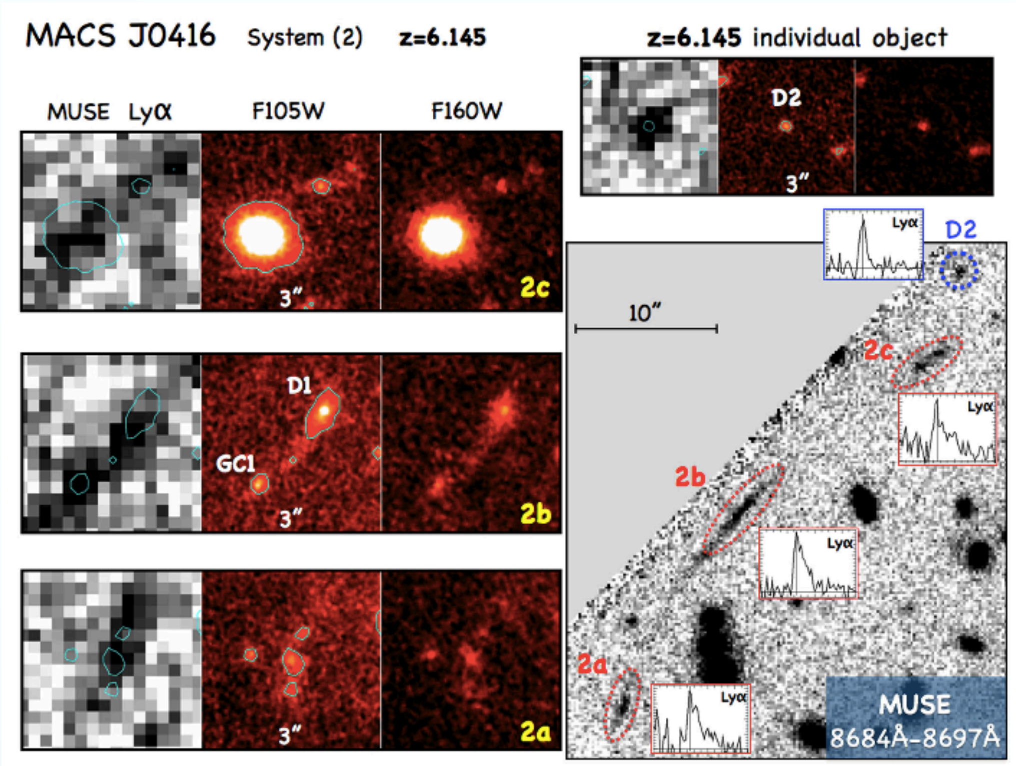
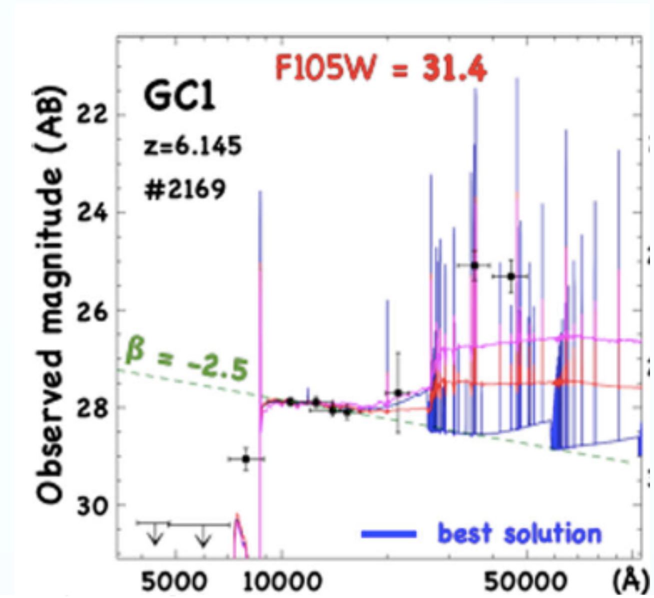
Ultra-faint, compact high-z galaxies: GC progenitors?





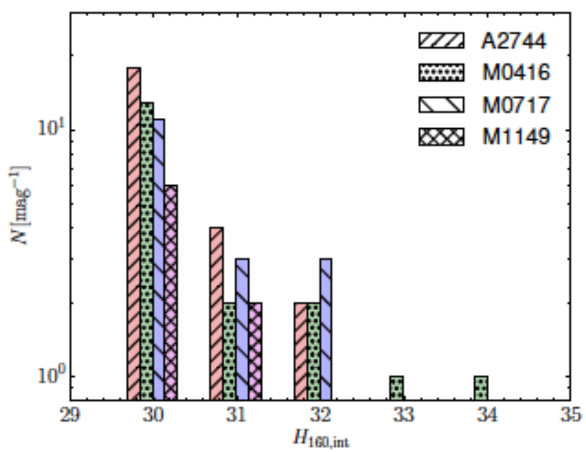
	Models Proto-GCs	GC1($z = 6.145$) (*)2169 04:16:11.56 −24:03:44.7	D1($z = 6.145$) 2179 04:16:11.48 −24:03:43.4	D2($z = 6.145$) 2411 04:16:10.31 −24:03:25.8
Stellar mass ($10^6\ M_\odot$)	1, 10	$68_{[21,3273]}\mu_{tot}^{-1}$	$380_{[368,585]}\mu_{tot}^{-1}$	$16_{[12,1027]}\mu_{tot}^{-1}$
SFR ($M_\odot\ yr^{-1}$)	0.2, 2.0	$54_{[1,165]}\mu_{tot}^{-1}$	$275_{[131,585]}\mu_{tot}^{-1}$	$5_{[0.5,48]}\mu_{tot}^{-1}$
Age (Myr)	5	$1.3_{[1,708]}$	$1.4_{[1,3]}$	$3.2_{[1,710]}$
$E(B-V)$	$\simeq 0$	$\lesssim 0.15$	0.10	0.0
R_e (UV) (pc)	16, 35(**)	16 ± 7	140 ± 13	<100
R_c (UV) (pc)	”	<30	150 ± 20	<100
Σ_{SMD} ($M_\odot\ pc^{-2}$)	800–1720	1400^{+2400}_{-900}	295^{+100}_{-80}	>85
Σ_{SFR} ($M_\odot\ yr^{-1} pc^{-2}$)	$(1.6–3.4)10^{-4}$	2.7×10^{-3}	2.3×10^{-4}	$>5.3 \times 10^{-5}$
m(1500 Å)	$\simeq$29–32	31.4 ± 0.2	29.7 ± 0.2	29.6 ± 0.3
M(1500 Å)	>−17	−15.3	−17.0	−17.1
β_{UV}	$\lesssim -2.5$	-2.52 ± 0.36	-2.40 ± 0.16	-2.85 ± 0.43
μ_{tot}	–	25.0 ± 2.5	19.0 ± 2.0	3.0 ± 0.2
μ_{tang}	–	17.5 ± 2.0	13.4 ± 1.5	1.7 ± 0.1
$f(+)/f(-)$	–	$\simeq 2.5$	$\simeq 2.5$	–

Spectroscopy from MUSE
(+ X-SHOOTER for z~3 dwarfs)

The luminosity, mass and size range we are probing is the one predicted for GC progenitors at z>3

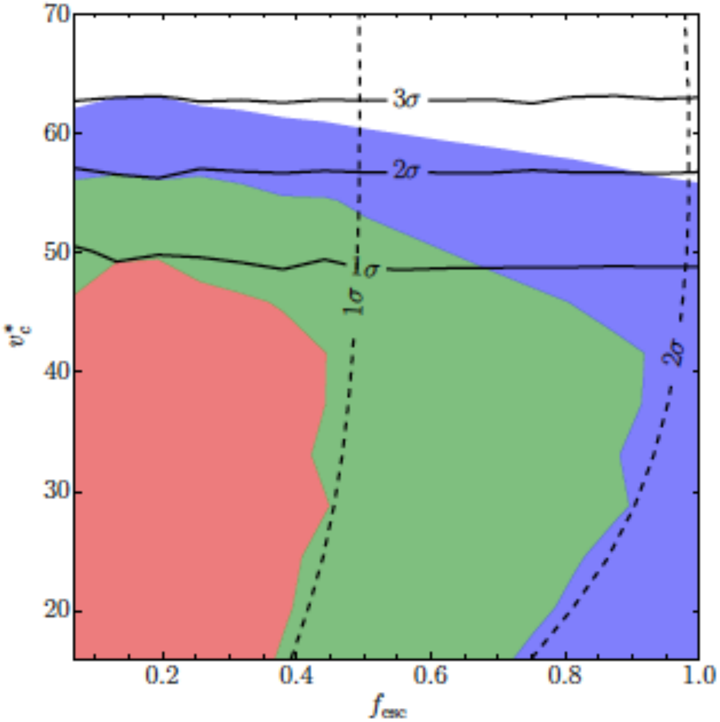
Vanzella, MC et al. 2017a
Vanzella et al. 2017b

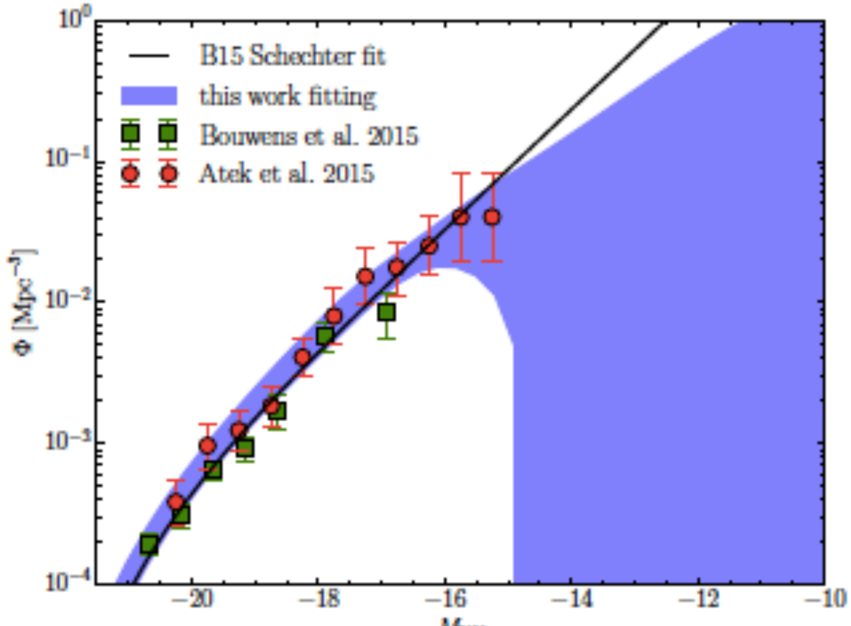
Tighter constraints adding FF#3-4



Including FF #3-4, public ASTRODEEP catalogs by Di Criscienzo et al. 2017.

No evident cut-off up to faintest magnitudes. (M_{UV}~-14.5 2σ; Yue, MC et al. in prep.)





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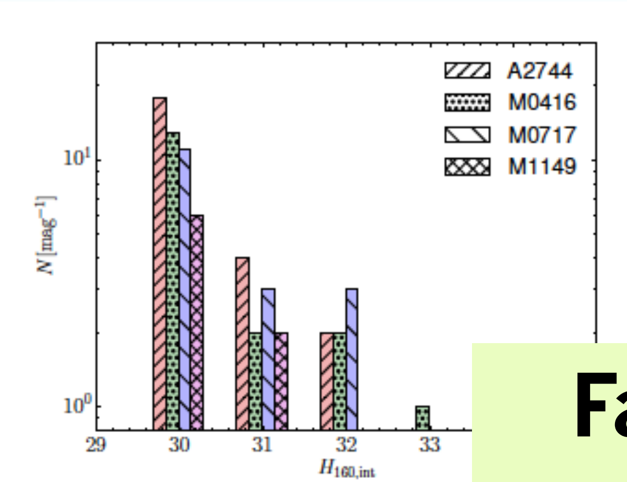

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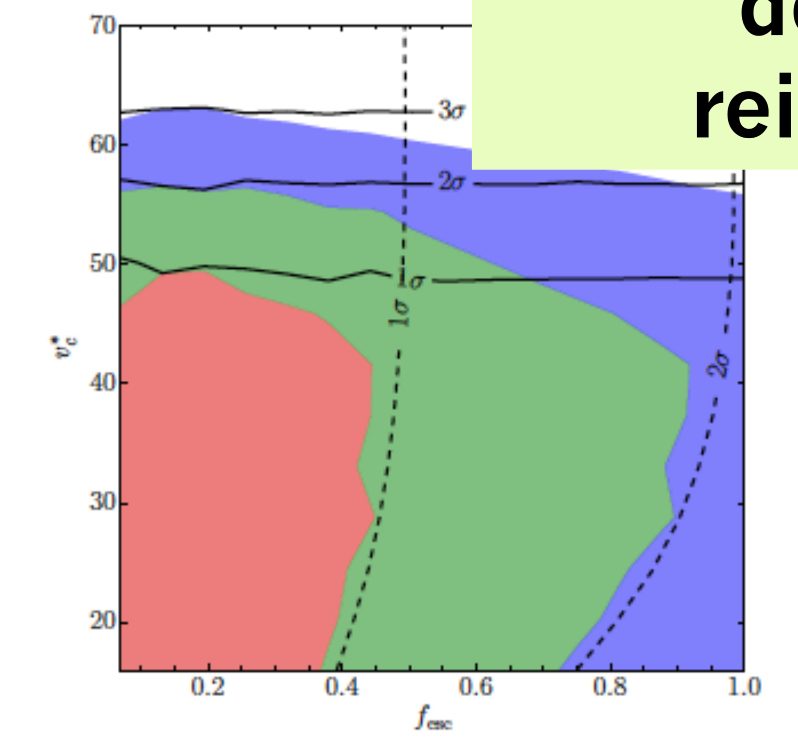
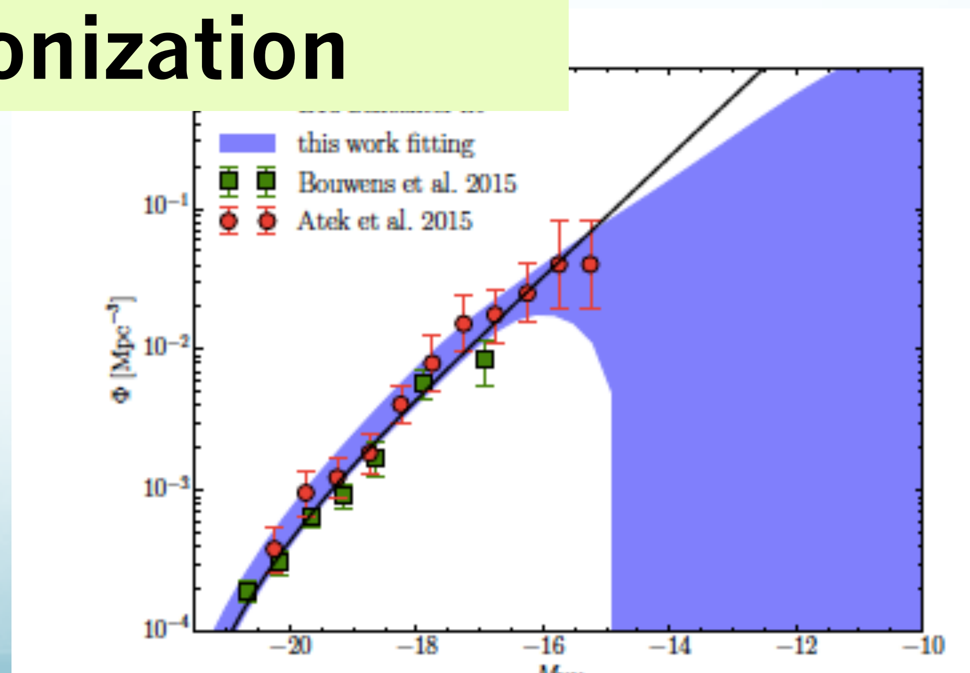
n prep.)

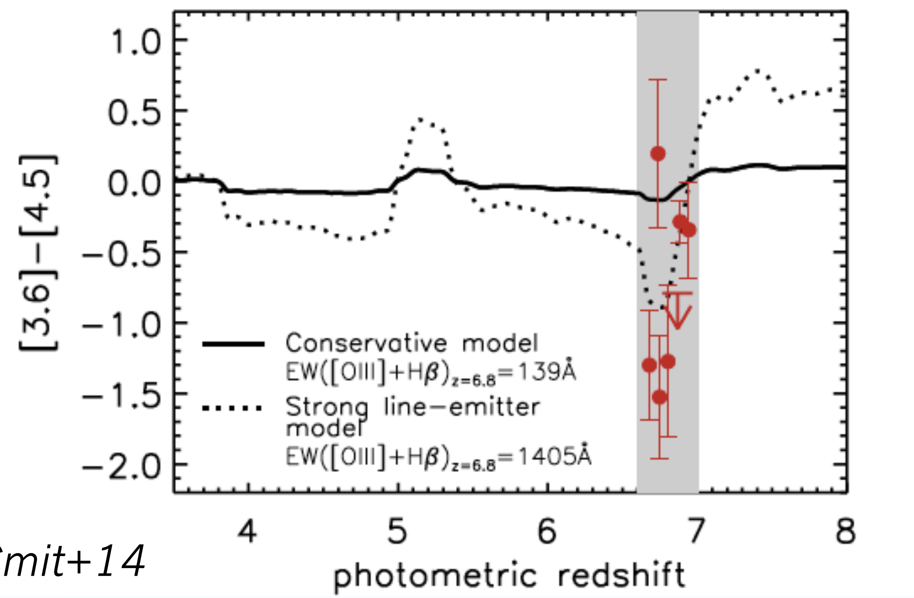
Faint galaxies can dominate reionization





(2)
Physical properties of confirmed z~7 Lyα galaxies

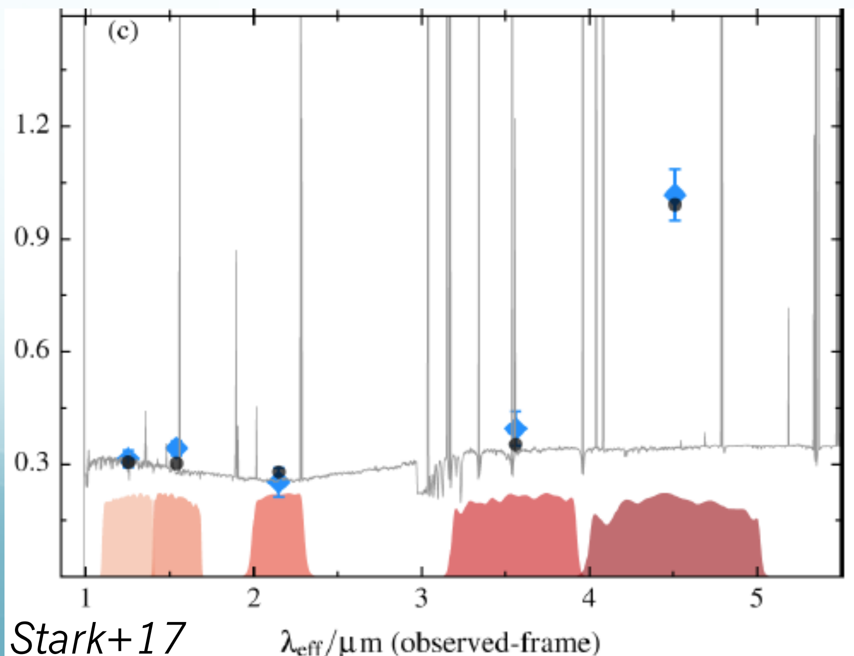
A closer look at z~7 sources: optical line emission



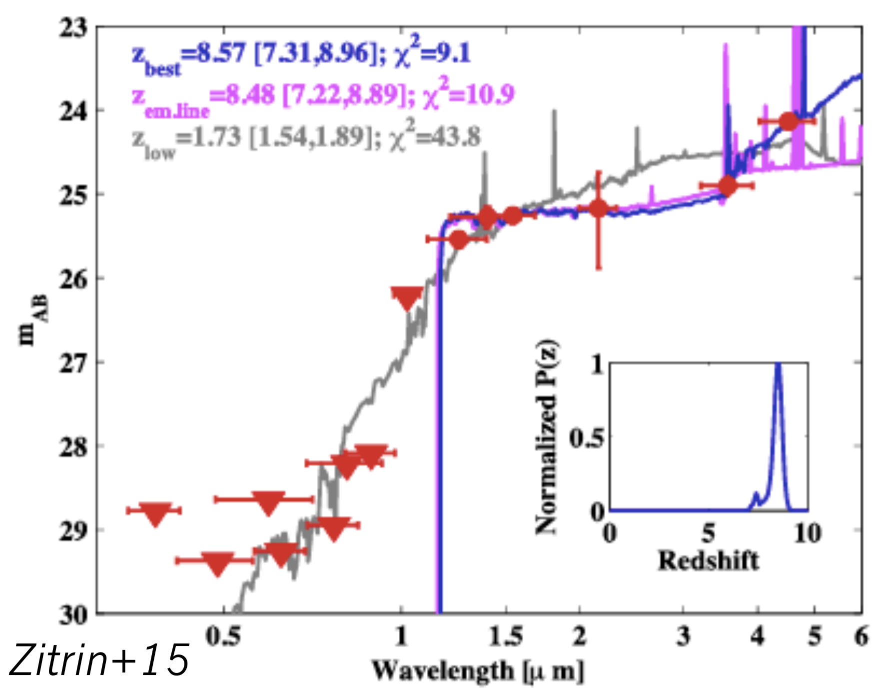
Smit+14

Known evidence for high-EW [OIII]+Hβ lines from IRAC colors at z>6 (e.g. Labbe et al. 2013, Wilkins et al. 2013, Smit et al. 2014, Roberts-Borsani et al. 2016)

Good redshift indicator



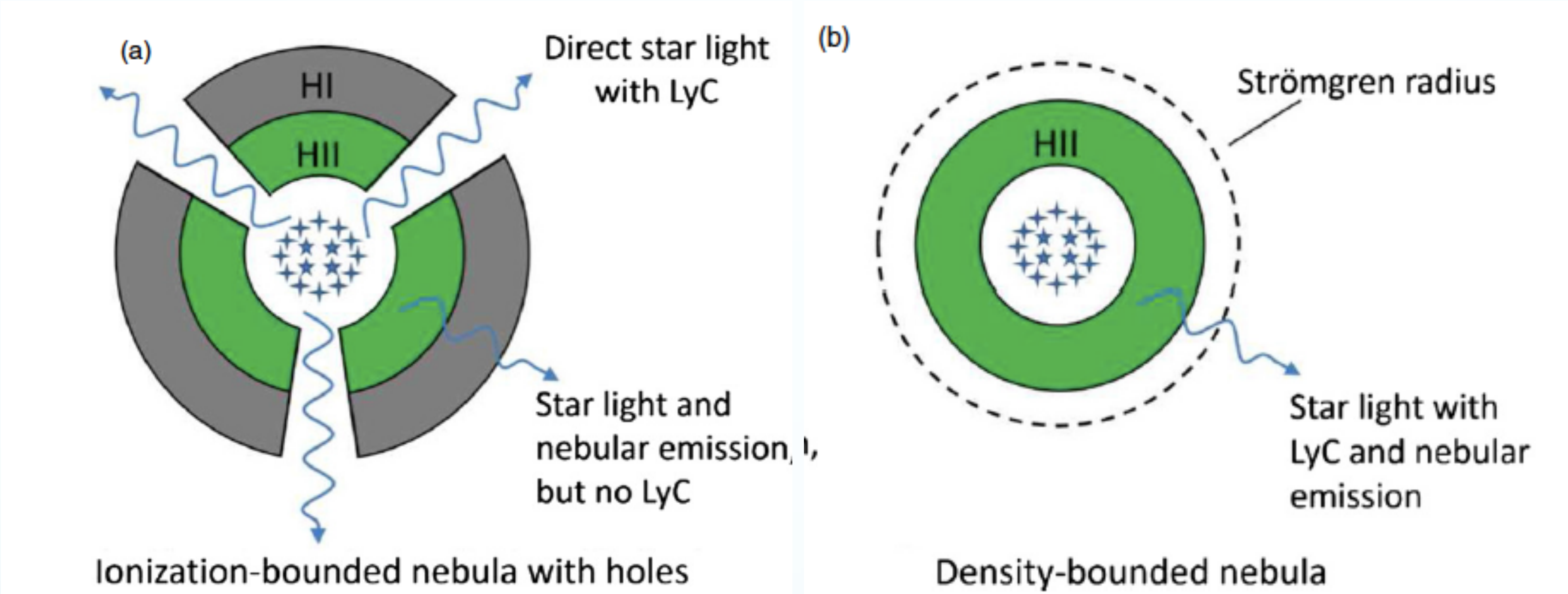
Stark+17



Zitrin+15

A closer look at z~7 sources: optical line emission

An extreme escape fraction can erase the Lyα line, what about other lines?



Zackrisson et al. 2013

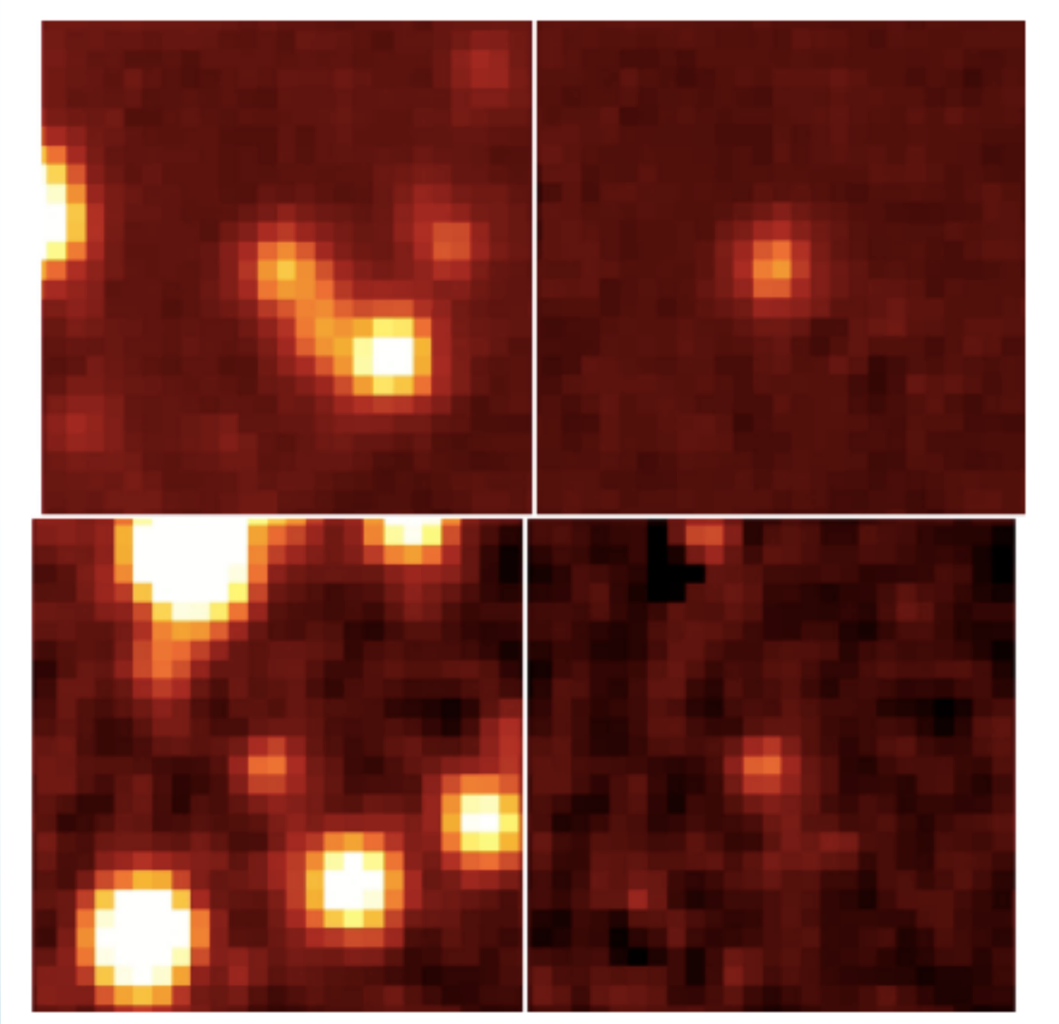
a) Em. lines disappear when fesc →1

b) Strong high ionization lines

Nakajima&Ouchi 2014: high [OIII]/[OII]
see also Stasinska et al 2015

$$L_{lines} \sim (1-f_{esc}) \times Q_i$$

IRAC colours of our deep spectroscopic sample



Goal: analyse optical line emission comparing 11 known emitters and 25 high quality non-emitters observed by CANDELSz7 FORS2 Large Programme (P.I. Pentericci)

How: stacking of deep IRAC observations (UDS and GOODS)

Stacking of IRAC bands, main concern: *confusion/blending/overlapping* of sources due to low resolution.

Close-by sources “removed” with **T-PHOT** (Merlin+2015, *http://www.astrodeep.eu/t-phot/*)

MC+ ApJ, 2017

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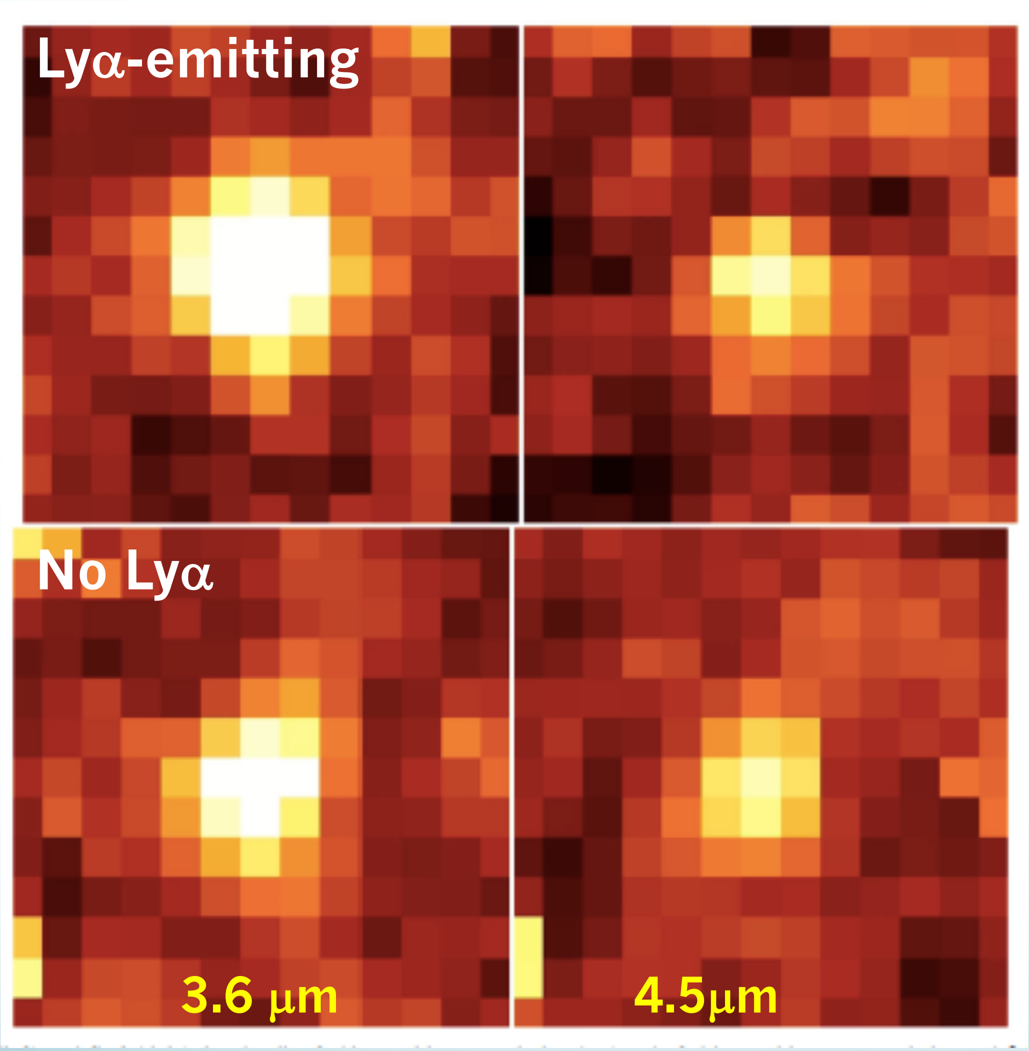

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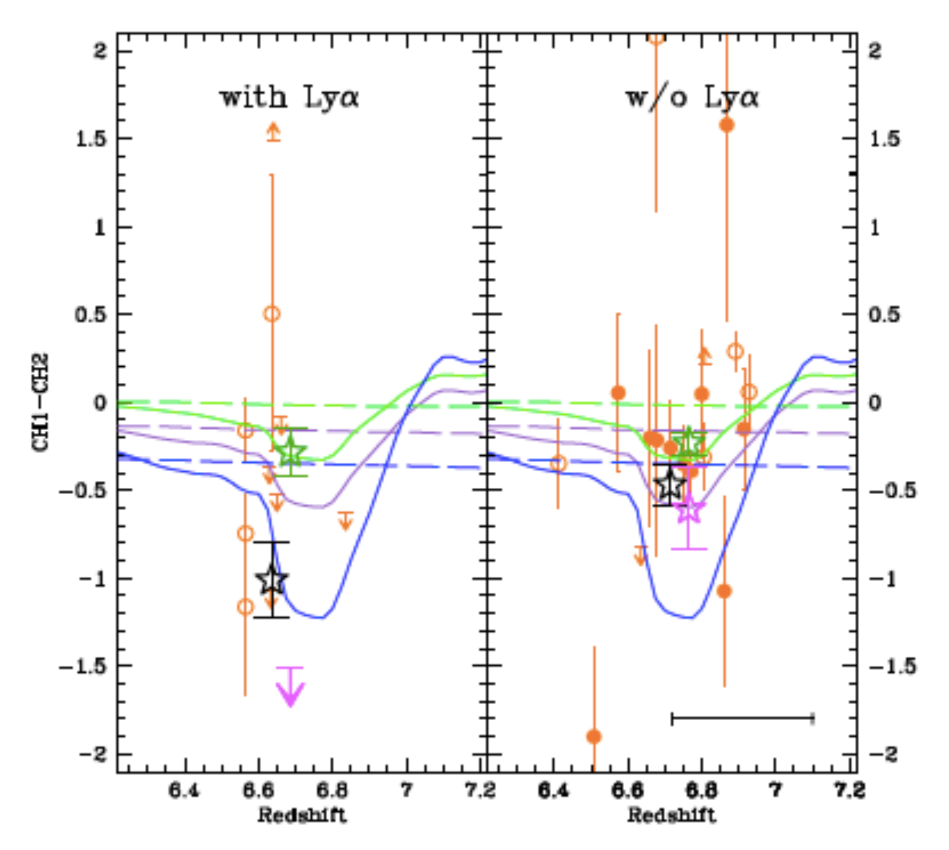
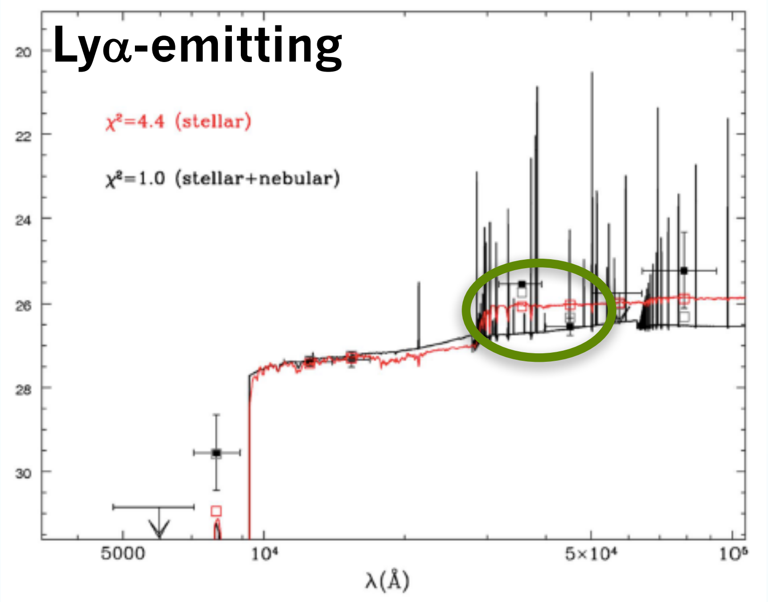
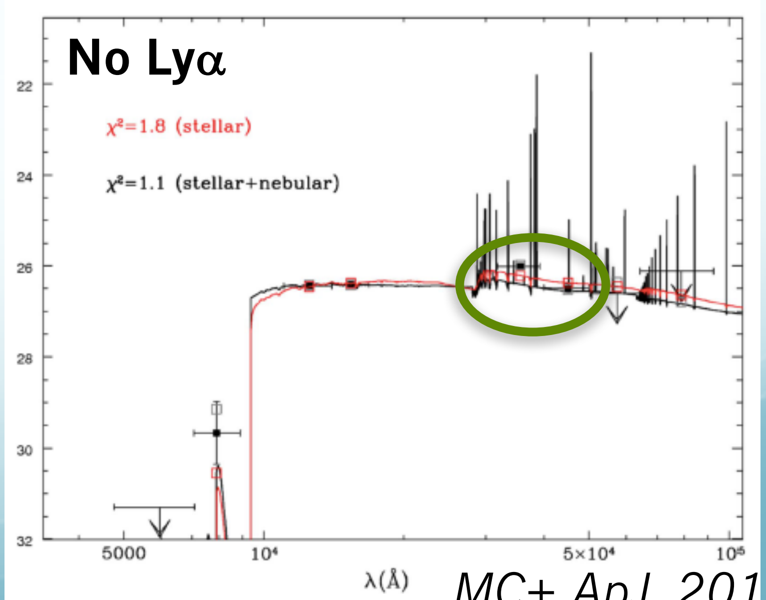
MC+ ApJ, 2017

Evidence of strong optical line emission at z~7



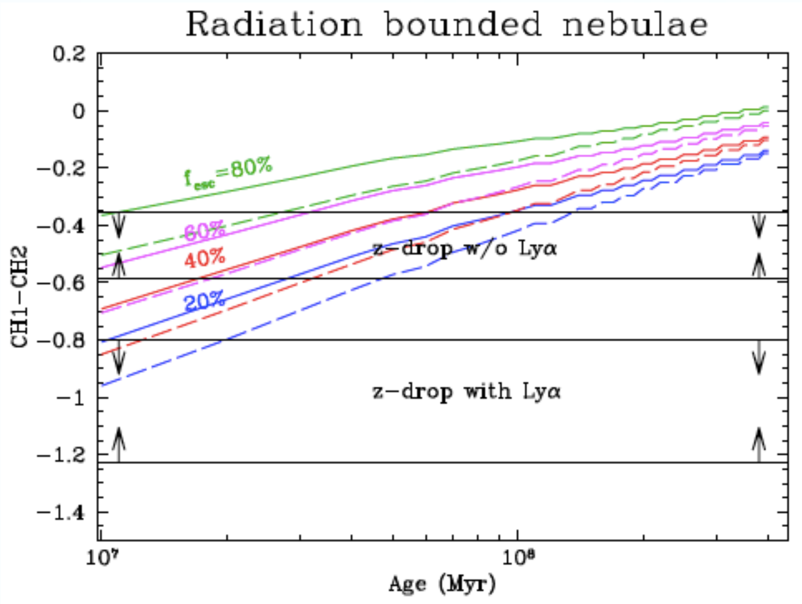


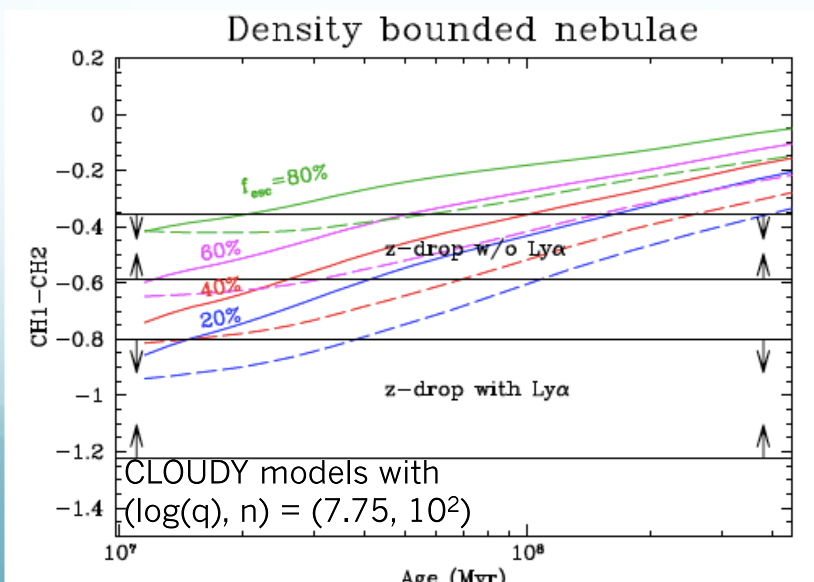


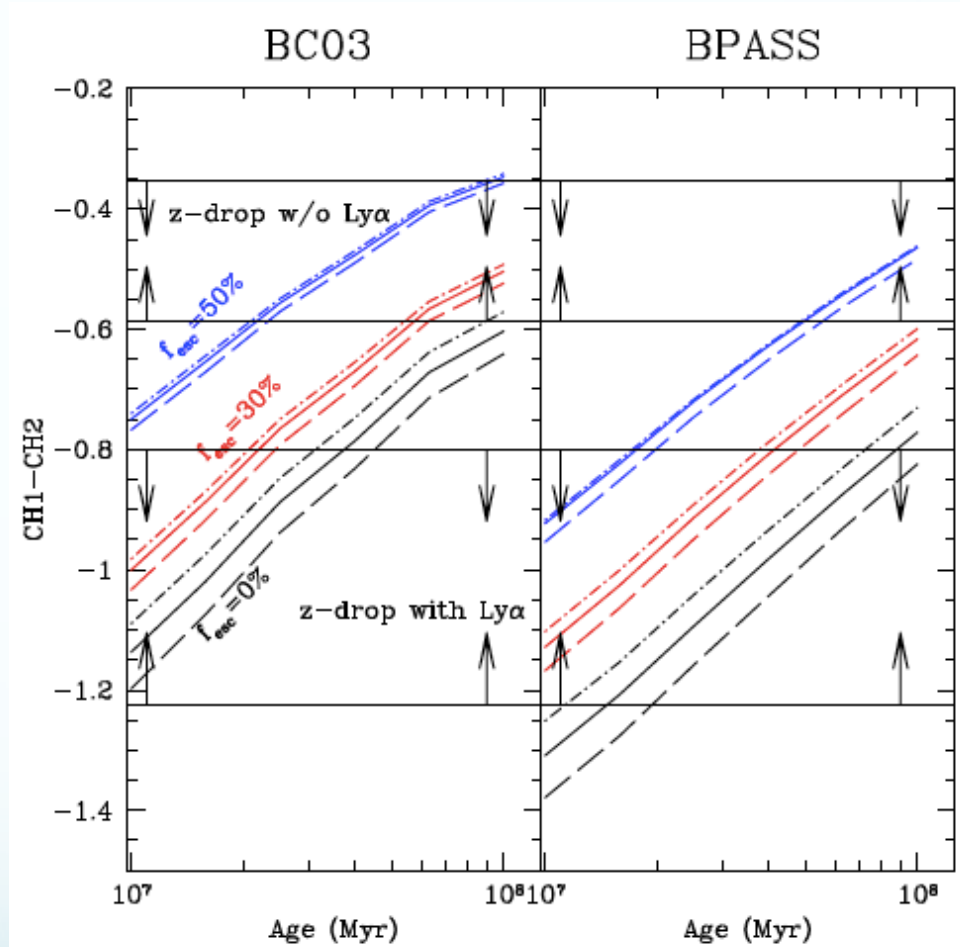
Subsample	CH1–CH2	EW([O III]+Hβ) (Å)
Lyα-emitting, all	-1.0 ± 0.21	1500^{+530}_{-440}
Lyα-emitting, bright	-0.28 ± 0.14	290^{+170}_{-150}
Lyα-emitting, faint	< -1.5	>2900
No Lyα, all	-0.47 ± 0.11	520^{+170}_{-150}
No Lyα, bright	-0.23 ± 0.07	230^{+70}_{-70}
No Lyα, faint	-0.61 ± 0.23	720^{+400}_{-330}

MC+ ApJ, 2017

Strong optical line emission: implications on f_{esc}

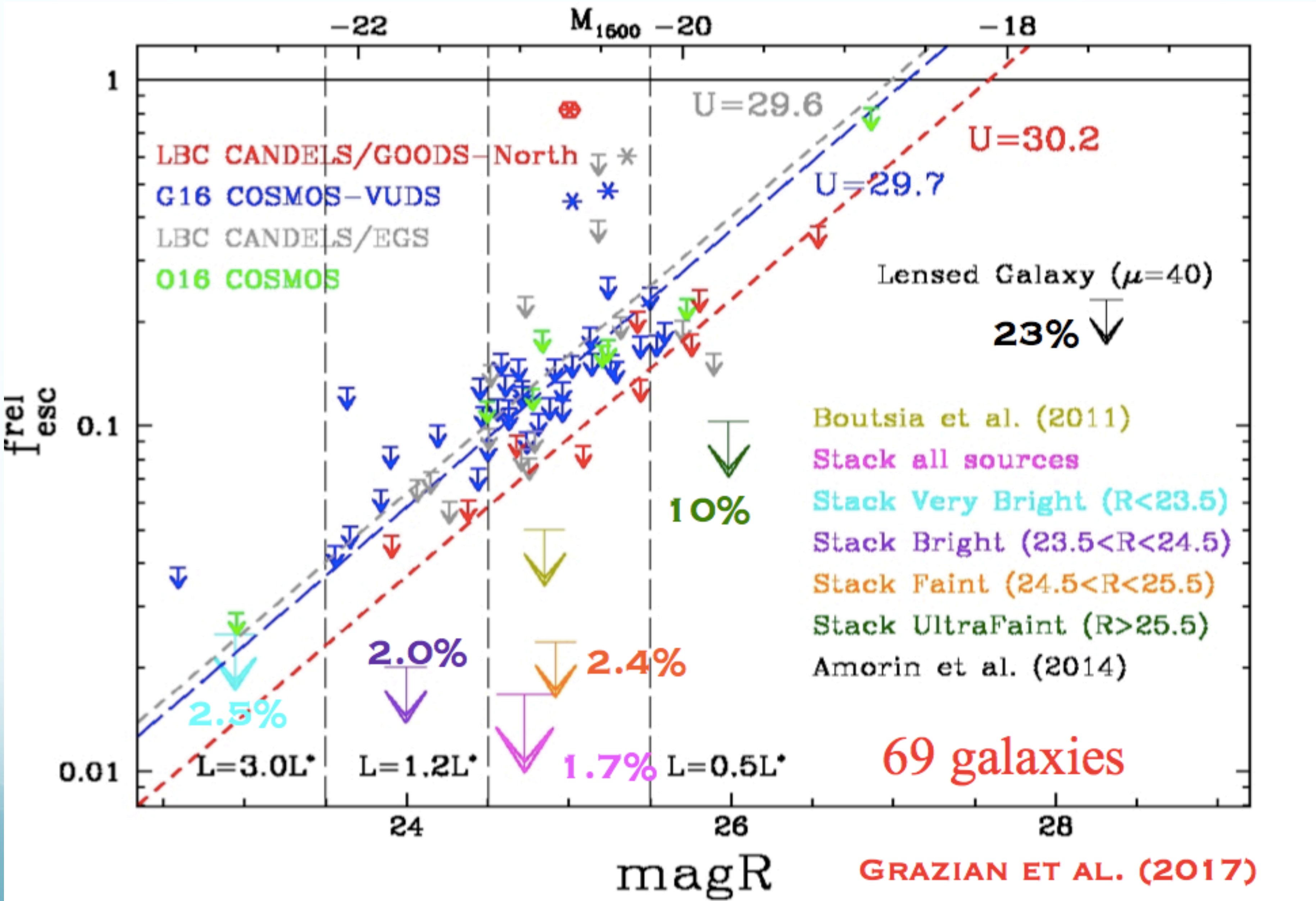






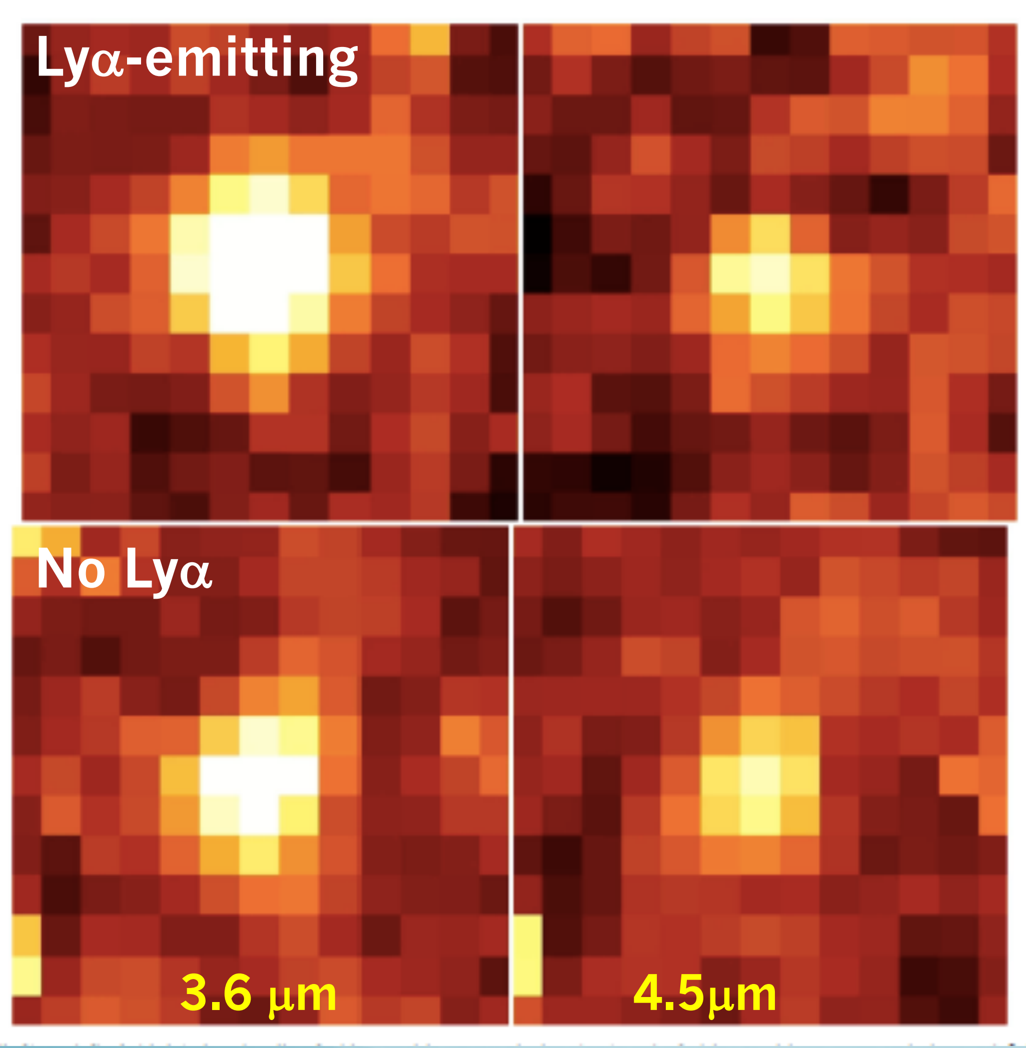
Dashed, continuous, and dotted–dashed lines indicate CLOUDY models with (log(q cm s^{-1}), n (cm^{-3})) = (9, 10^3), (9, 10^2) and (7.75, 10^3)

MC+ ApJ, 2017



M1600
−22
−20
−18
1
0.1
0.01
f rel esc
24
26
28
magR
LBC CANDELS/GOODS−North
G16 COSMOS−VUDS
LBC CANDELS/EGS
O16 COSMOS
U=29.6
U=30.2
U=29.7
Lensed Galaxy (μ=40)
23%
Boutsia et al. (2011)
Stack all sources
Stack Very Bright (R<23.5)
Stack Bright (23.5<R<24.5)
Stack Faint (24.5<R<25.5)
Stack UltraFaint (R>25.5)
Amorin et al. (2014)
10%
2.0%
2.4%
2.5%
1.7%
L=3.0L*
L=1.2L*
L=0.5L*
69 galaxies
GRAZIAN ET AL. (2017)

Strong optical line emission: conclusions



- Evidence of strong [O III]+Hβ emission in the stacked SEDs of both samples

- Differences possibly due to physical conditions of the H II regions (Lyα-emitting galaxies being younger, metal-poor, or with a lower fesc)

- The strong signature of optical line emission of Lyα detected objects yield to fesc < 20% (50% under extreme assumptions)

- Only with JWST we can fully constrain the presence of density bounded HII regions (e.g. Zackrisson et al. 2013, Nakajima&Ouchi 2014, De Barros+ 2015)

- Possible f_{esc} increase combined with IGM HI increase (Dijkstra et al. 2014) to explain Lyα drop at z>6

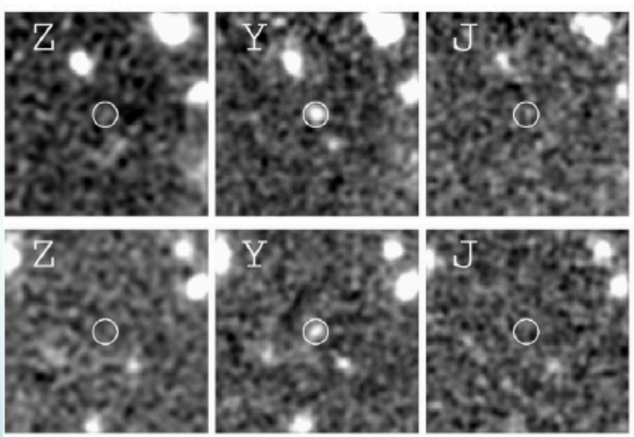
(3)
The role of (faint) galaxy clustering

A space oddity at z=7: two close-by LAEs

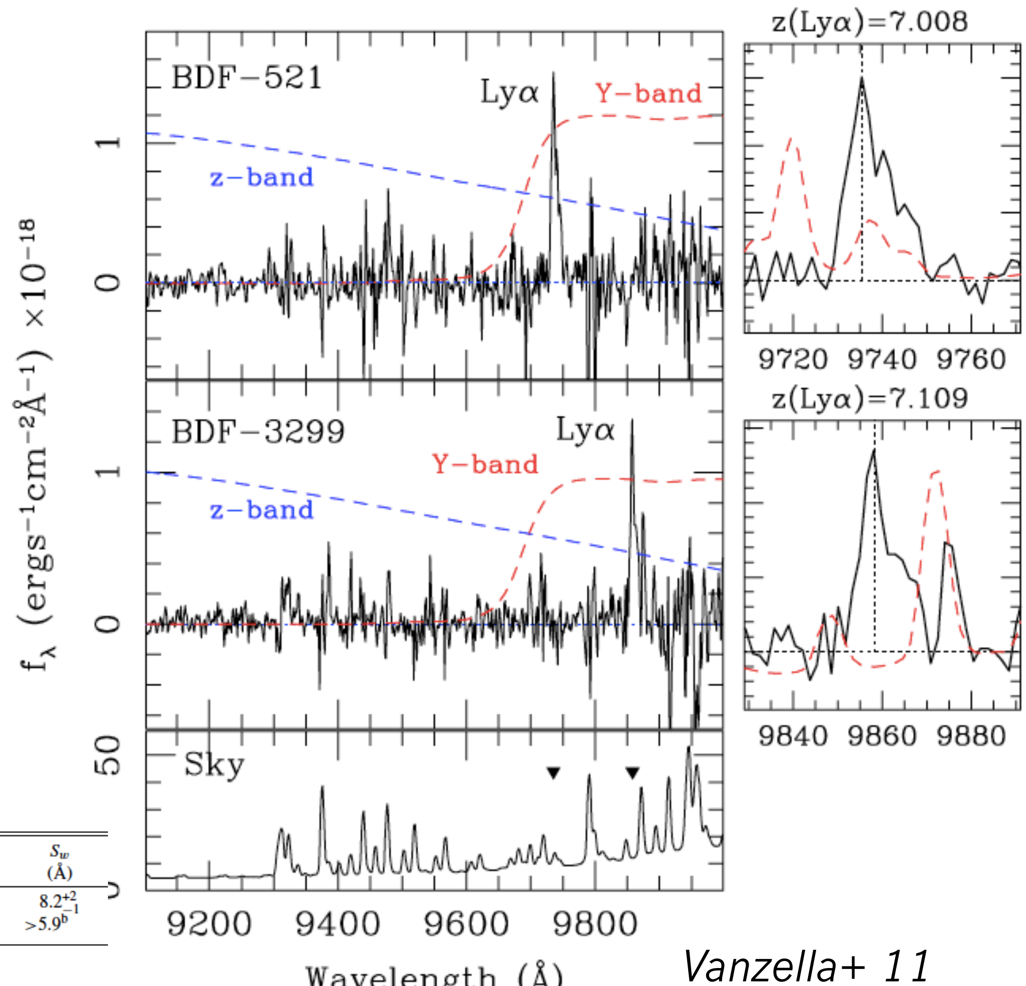
In the overall paucity of Lyα lines: one line of sight with twin bright emitters among the 8 l.o.s. investigated in Pentericci+ 14.

The BDF4 field hosts two close-by (4.4 proper Mpc) EW>50AA emitters. Their L_{UV} cannot build a large enough HII region to explain line visibility (Vanzella+11).

Additional sources required?
(e.g. Dayal+09)



MC+ 10b

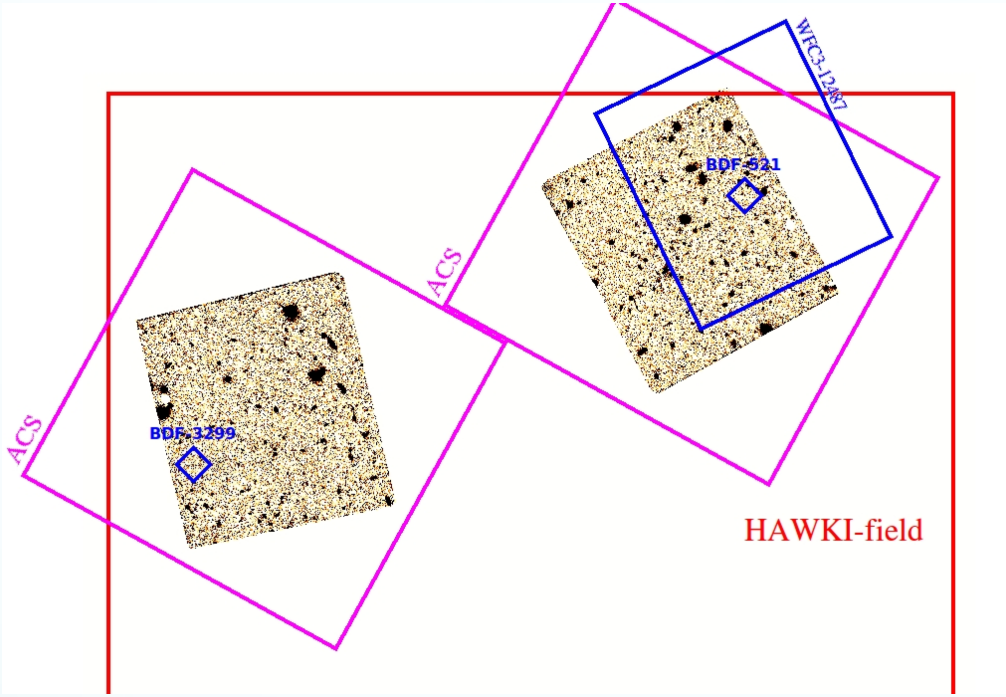


Vanzella+ 11

ID	R.A., Decl. J2000	Redshift	f(Lyα)	SFR(Lyα) ($M_\odot$ yr^{-1})	EW$_{rest}$ (Å)	FWHM^a (km s^{-1})	S_w (Å)
BDF−521	336.9444, −35.1188	7.008 ± 0.002	1.62 ± 0.16	8.5	64	240	8.2^{+2}_{-1}
BDF−3299	337.0511, −35.1665	7.109 ± 0.002	1.21 ± 0.14	6.6	50	200	$>5.9^b$

Notes. f(Lyα) in units of 10^{-17} erg s^{-1} cm^{-2} Å^{-1}.

A closer look at the BDF region with HST

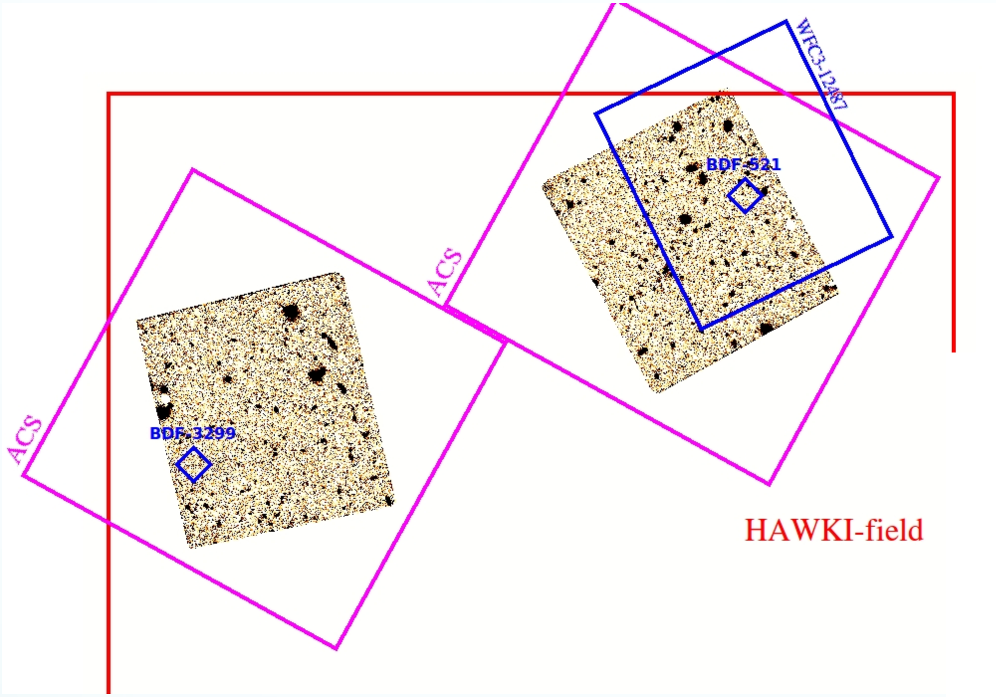


HST Cycle 22 program (PI MC) to look for surrounding, fainter LBGs.

14 orbits with V606, I814, Y105.

Previous Hawk-I data limited to Y~26.5.

A closer look at the BDF region with HST



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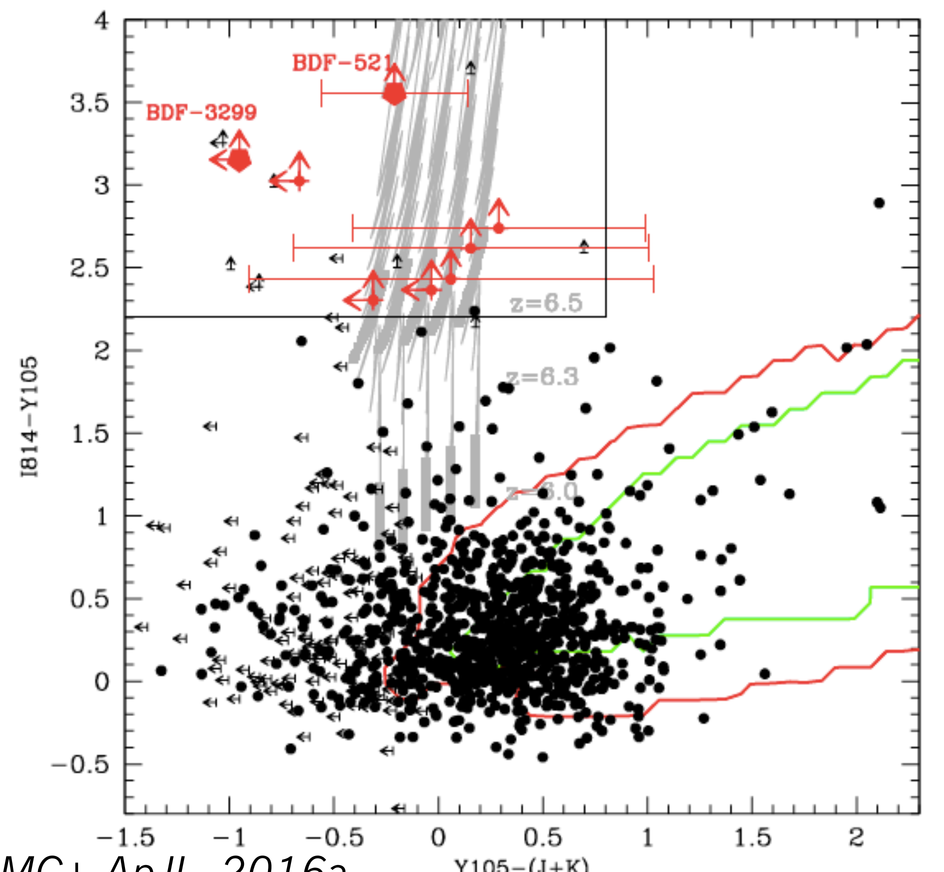


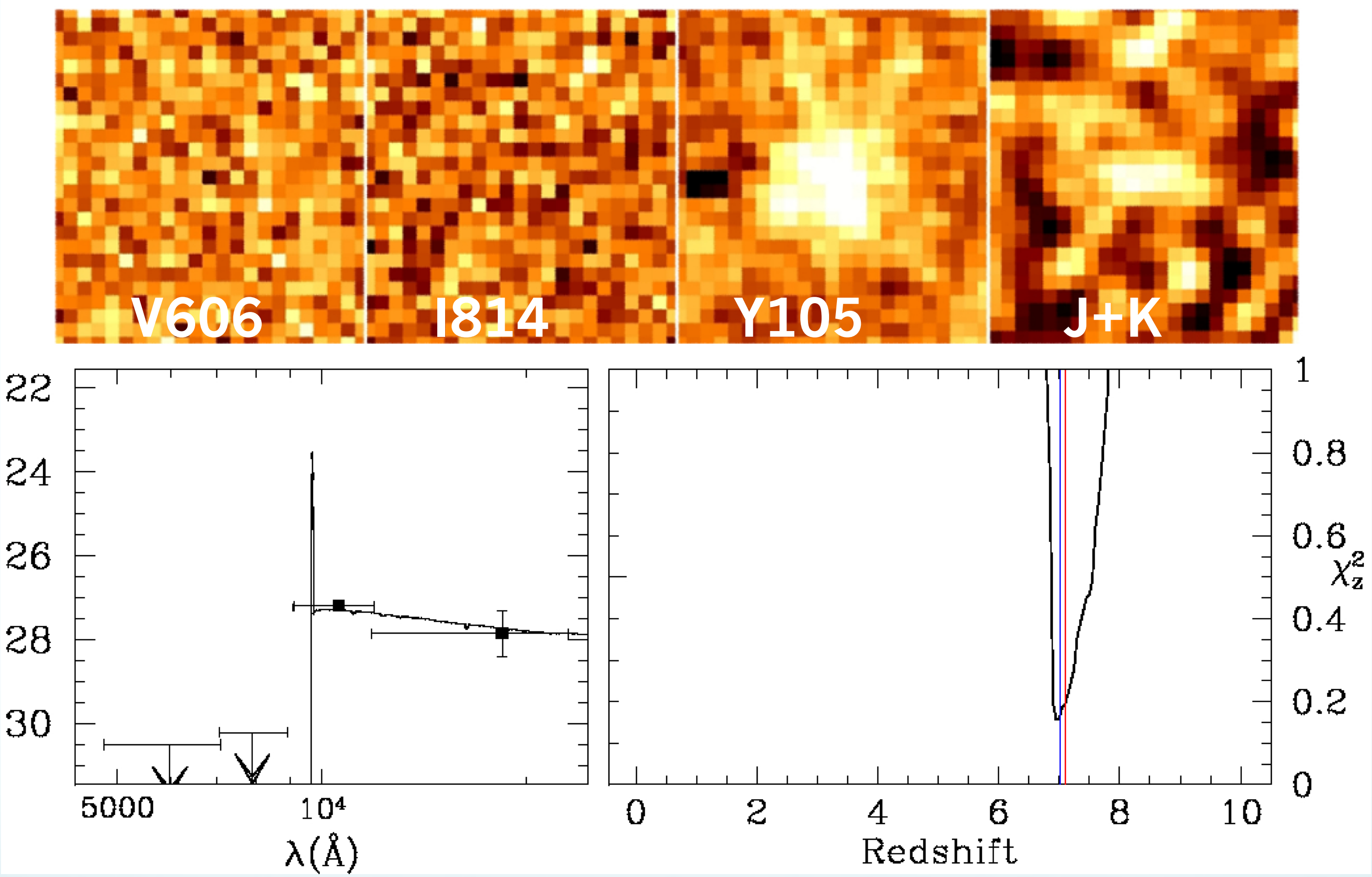
Previous Hawk-I data limited to Y~26.5.

Six robust LBGs recovered at Y105~26.5-27.5 (at S/N>10)

$$(S/N(I_{814}) < 1) \wedge (I_{814} - Y_{105} > 2.2)$$
$$Y_{105} - (J + K) < 0.8$$
$$(S/N(Y_{105}) > 10) \wedge (S/N(V_{606})) < 1,$$

MC+ ApJL, 2016a

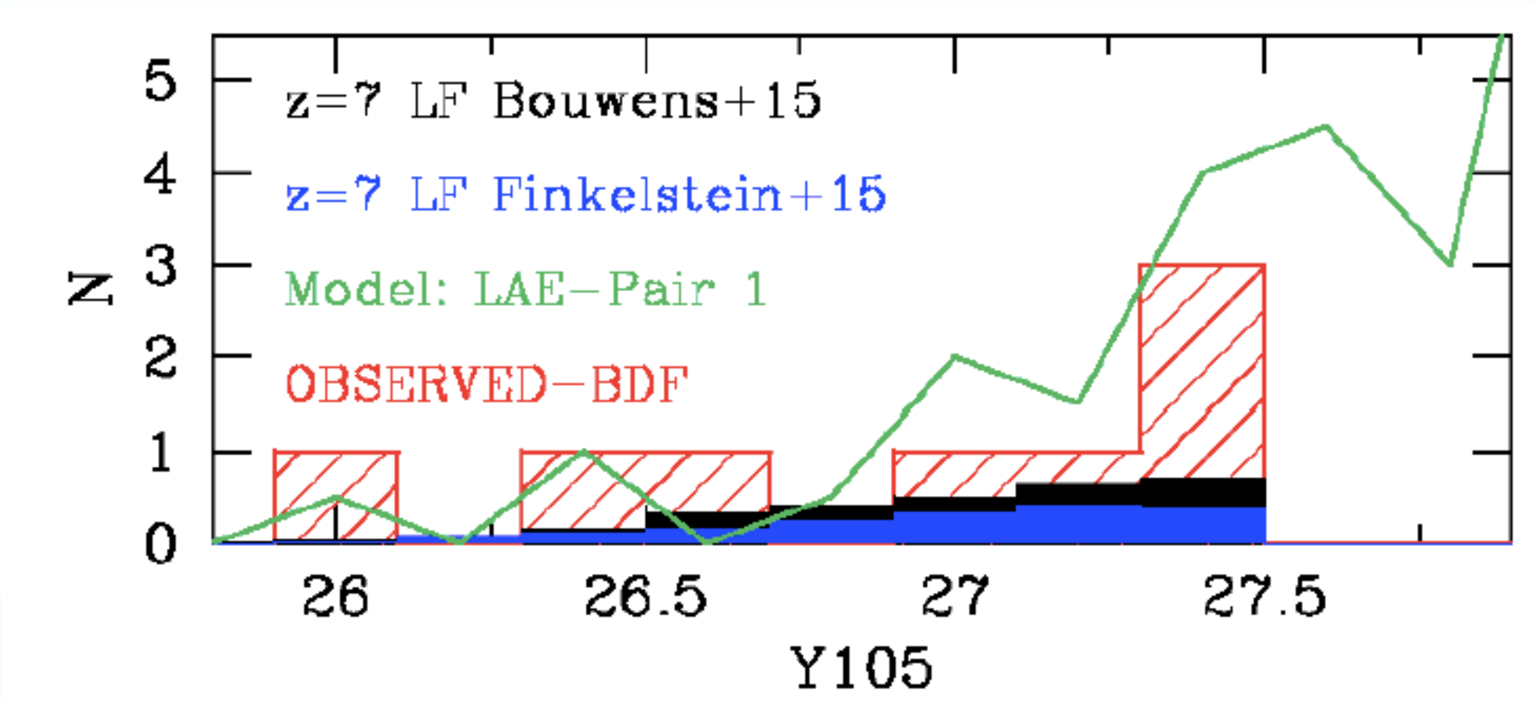
A closer look at the BDF region with HST



Stacking of the six new LBGs: V606 and I814 undetected at >30.2 mag, I814-Y105>3, S/N~2 detection in J+K.

Z_{phot}=6.95. **Consistent with the objects being at the same *z* of the emitters.**

An overdensity of LBGs at z~7

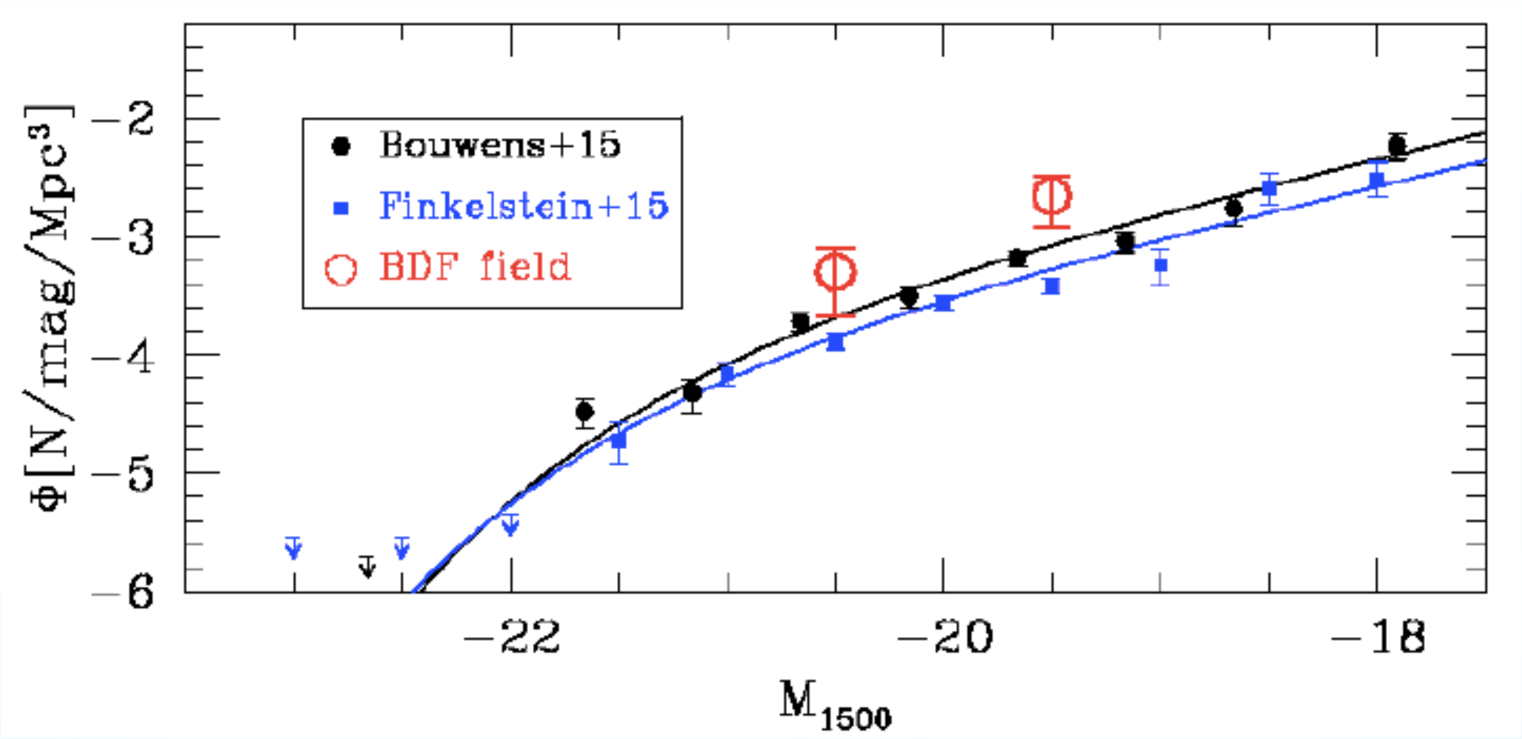


Observed= 8 objects in two pointings. Expected ~1.8-2.9 objects.

No clustering around z~7 GOODS-S galaxies lacking Lyα emission.

MC+ ApJL, 2016a

An overdensity of LBGs at z~7



Observed= 8 objects in two pointings. Expected ~1.8-2.9 objects.

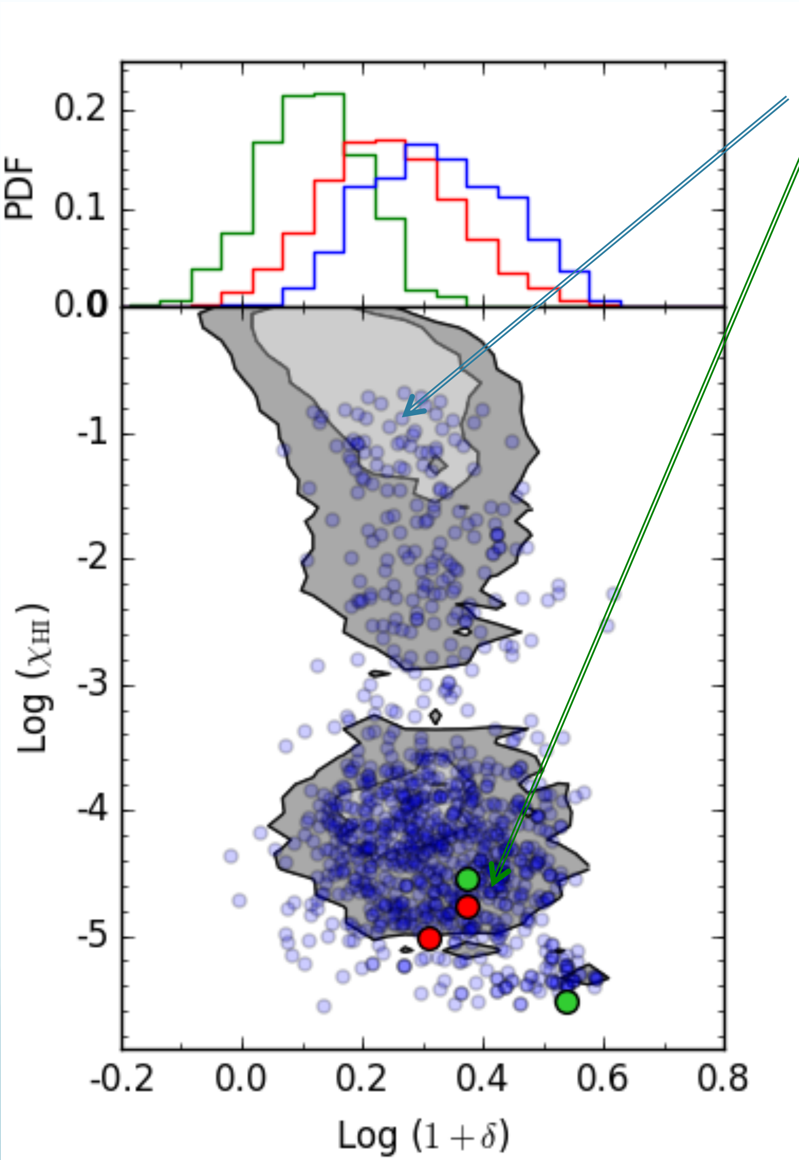
The BDF field is 3-4x overdense wrt average: consistent with a positive relation between line visibility and galaxy density as in ***inside-out reionization scenarios.*** (e.g. McQuinn+ 07, Wyithe&Loeb 07, Dayal+ 09).

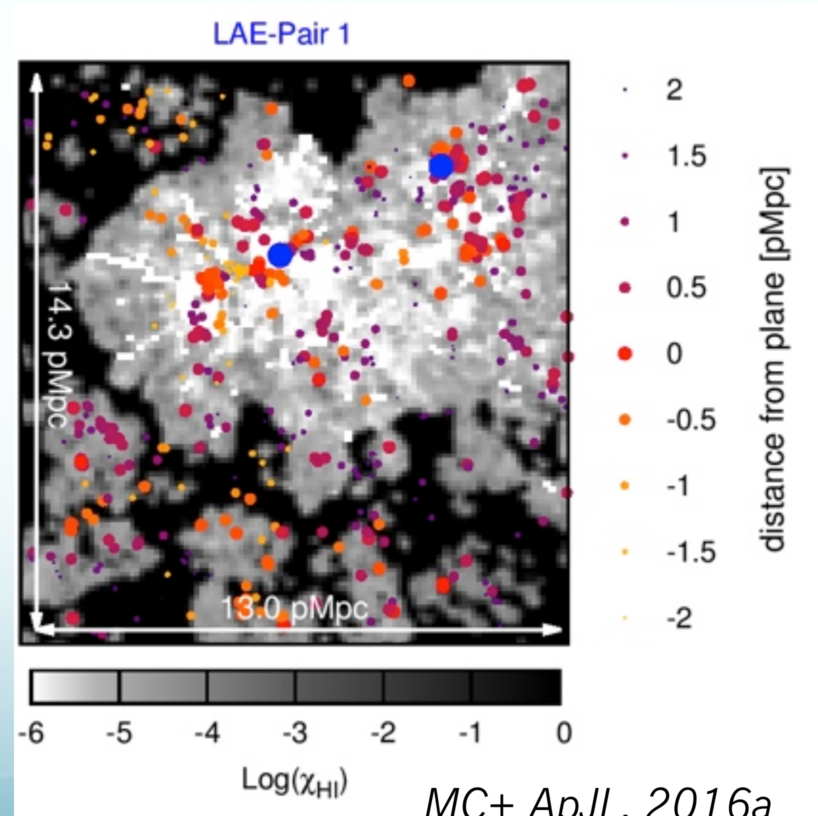
MC+ ApJL, 2016a

Connection between reionization and overdensities

Comparison with SPH model (Hutter+14,+15).

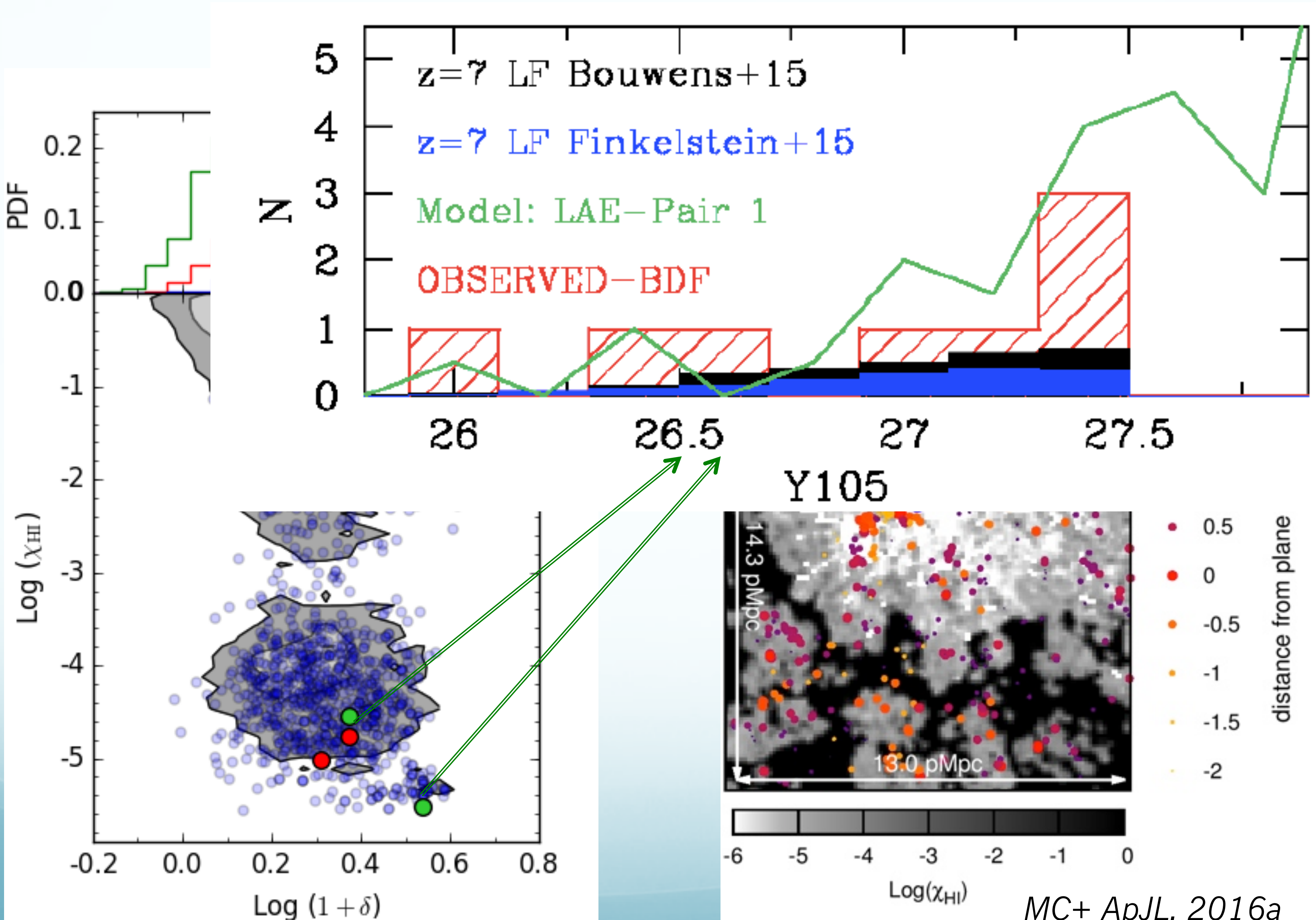
- Relation between density and HI fraction
- LAE pairs live in overdense regions with low HI
- BDF analogs are reionized, overdense bubbles





MC+ ApJL, 2016a

Connection between reionization and overdensities

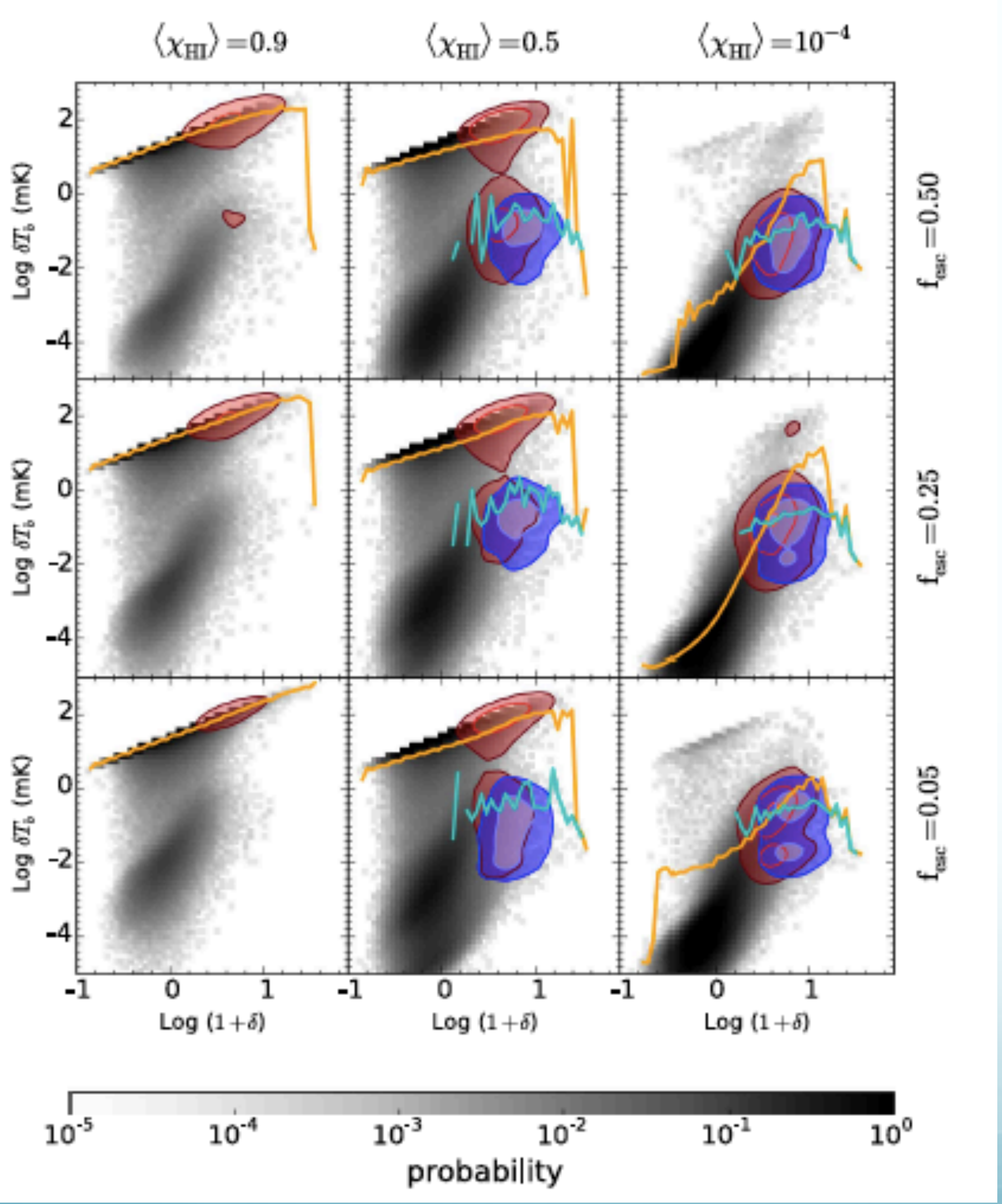


15).

ples

MC+ ApJL, 2016a

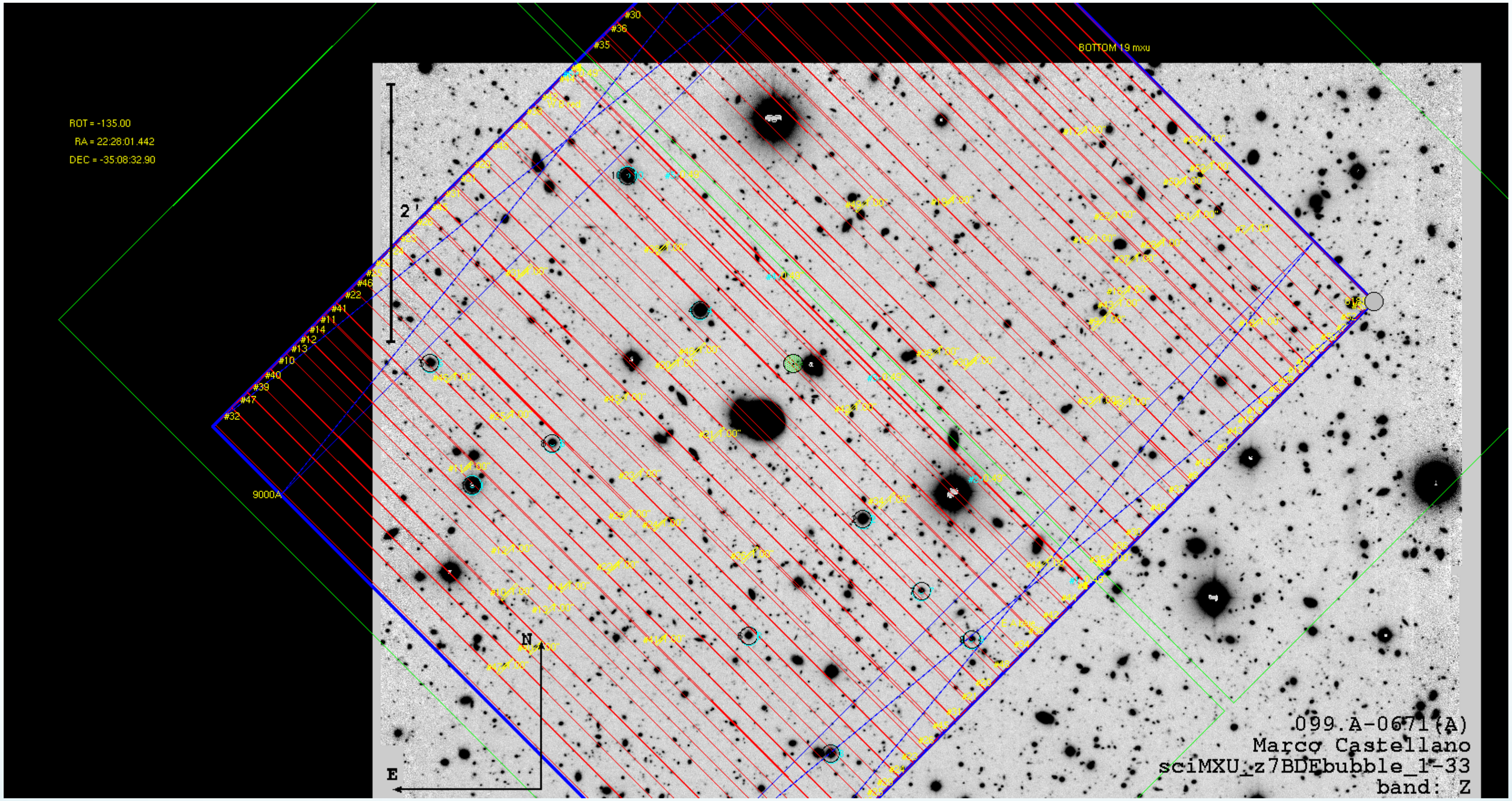
Connection between reionization and overdensities



Hot topic for the near future!

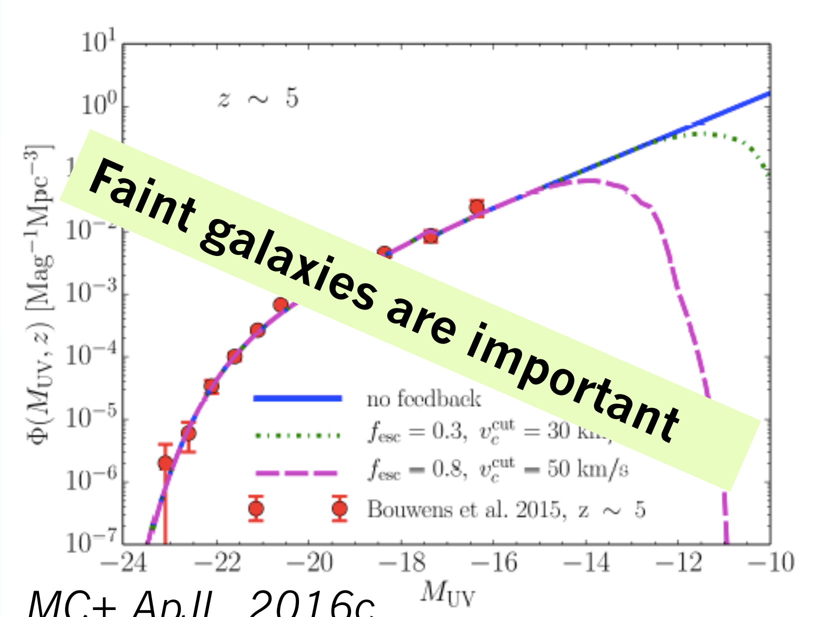
Connecting galaxy overdensity, reionization scenarios and 21cm signal with SKA (Hutter+16).

Spectroscopic follow-up is ongoing…



Awarded 33 hrs FORS2@VLT, program is near completion

Summary and conclusions



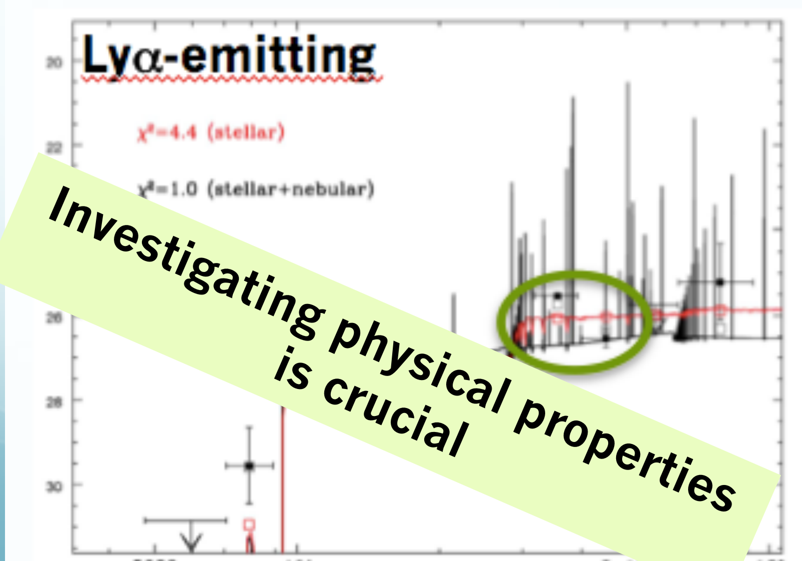
MC+ ApJL, 2016c

1) No evident cut-off of the UV LF at M_{UV}<-15: favours faint galaxy-driven reionization.

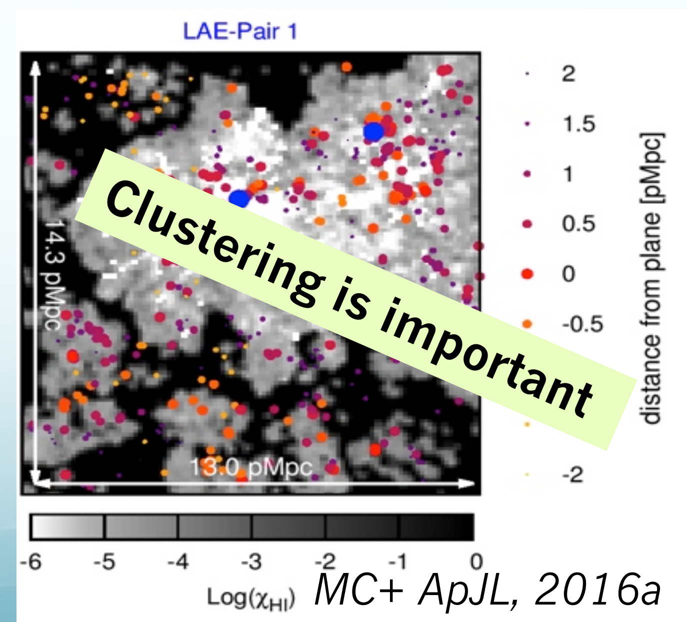
2) Evidende of strong optical line emission in faint z~ galaxies disfavors high fesc

3) Two close-by z~7 LAEs in the BDF field are embedded in an overdensity: connection between clustered faint galaxies and first “bubbles”.

We really need JWST to 1) go deeper into the LF; 2) constrain HII properties; 3) confirm relation between clustering and Lya visibility



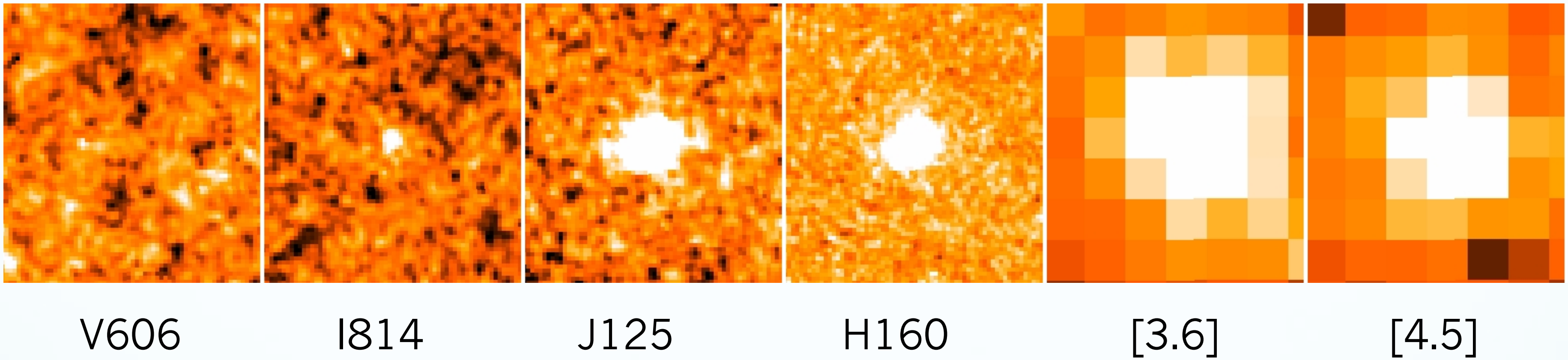
MC+ ApJ, 2017



MC+ ApJL, 2016a

BACKUP SLIDES

IRAC colours of our deep spectroscopic sample



Stacking of IRAC bands, main concern: *confusion/blending/overlapping* of sources due to low resolution.

Close-by sources "removed" with **T-PHOT** (Merlin+2015, *http://www.astrodeep.eu/t-phot/*)

A closer look at z~7 sources: optical line emission

Possible explanations for the Lyα drop:

1) There is an increase in the amount of neutral hydrogen in the surrounding IGM that quenches the Lyα emission.

→ Assuming no change in galaxy properties X_{HI}~0.5 at z~7

2) There is an increase in the Lyman Continuum escape fraction.

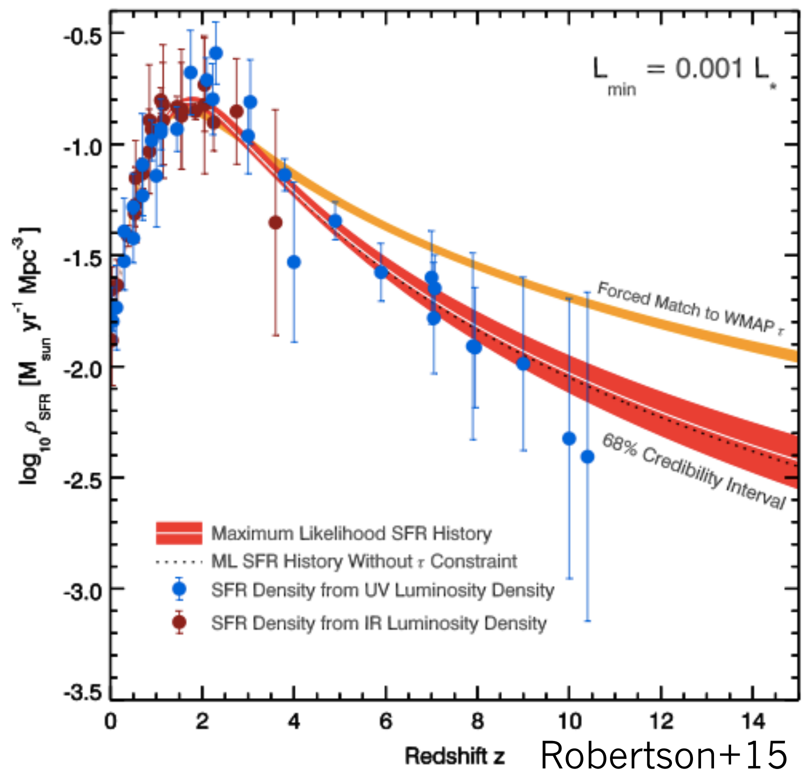
3) There is a sudden increase in dust extinction.

4) A significant fraction (> 60-70%) of selected galaxies is not at z~7.

Possibly V-faint low-z galaxies showing extreme line emission that can mimic the Lyman break (e.g. Hayes et al. 2012).

Sources of HI Reionizing emission

“Normal” star-forming galaxies?
Emission from second generation stars in star forming galaxies leaking into the IGM.



Robertson+15

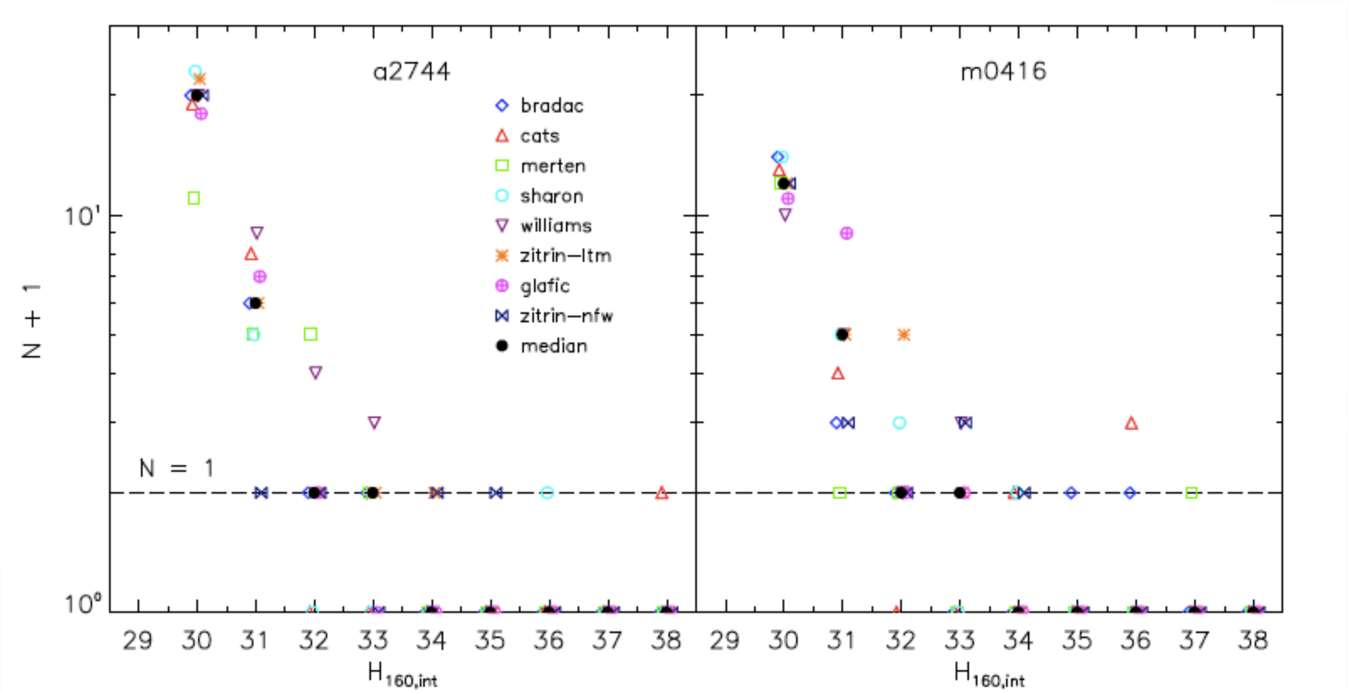
AGNs? Rapid decline at z > 2.5 (e.g. Cowie+ 09), but evidence that faint end slope is steeper than previously thought (Fiore et al. 2011, Giallongo et al. 2012, 2015).

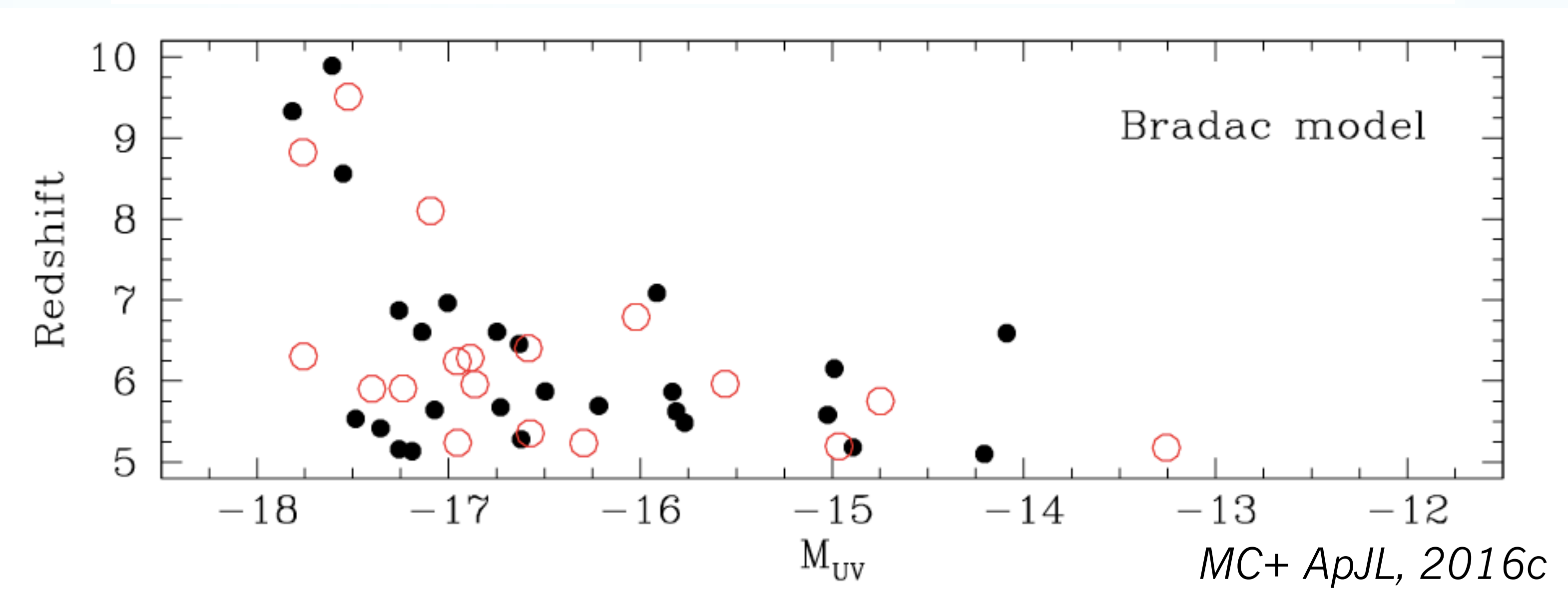
Still unknown sources ?
MiniQSOs (e.g. Madau et al. 2004)
PopIII emission (e.g. Vankatesan 2003, Pan 2012), Dark matter annihilation (Liu et al. 2016)

$$\dot{N}_{ion}(s^{-1}Mpc^{-3}) = 10^{49.7}\left(\frac{\rho_{UV}}{6\cdot 10^{25}}\right)\left(\frac{3.0}{\alpha_S}\right)\left(\frac{f_{esc}}{0.1}\right)$$

- Luminosity function faint end
- Escape fraction
- Intrinsic spectrum

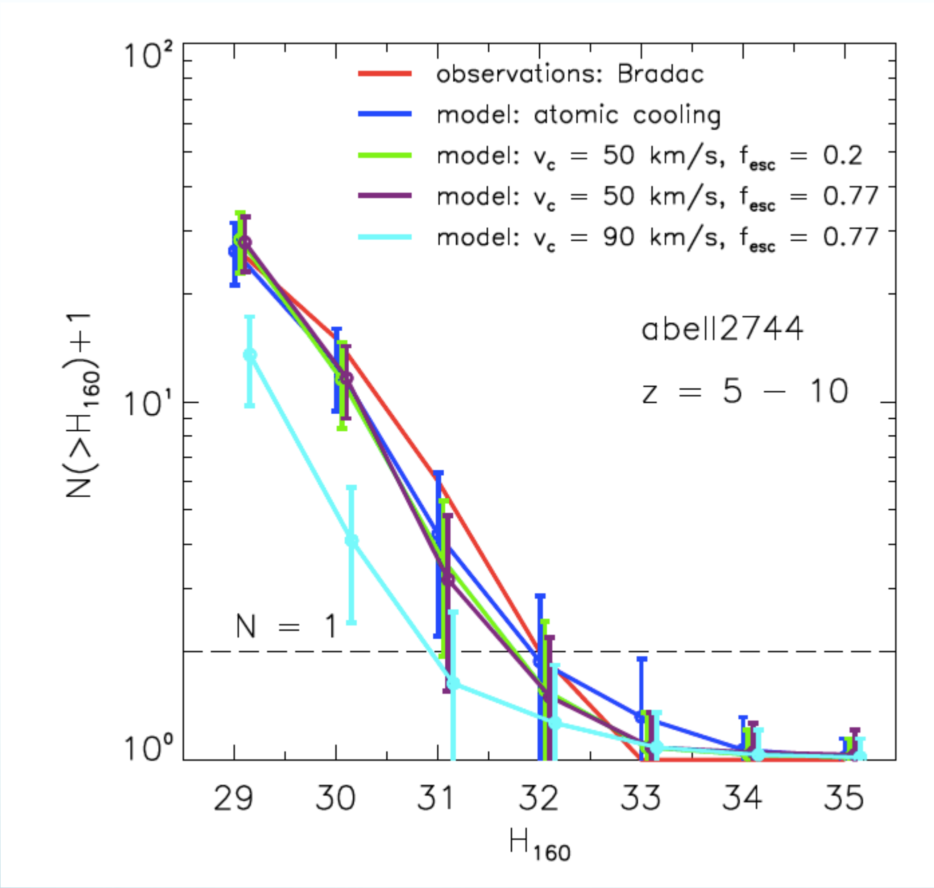
A closer look at z~7 sources: LF cut-off and feedback

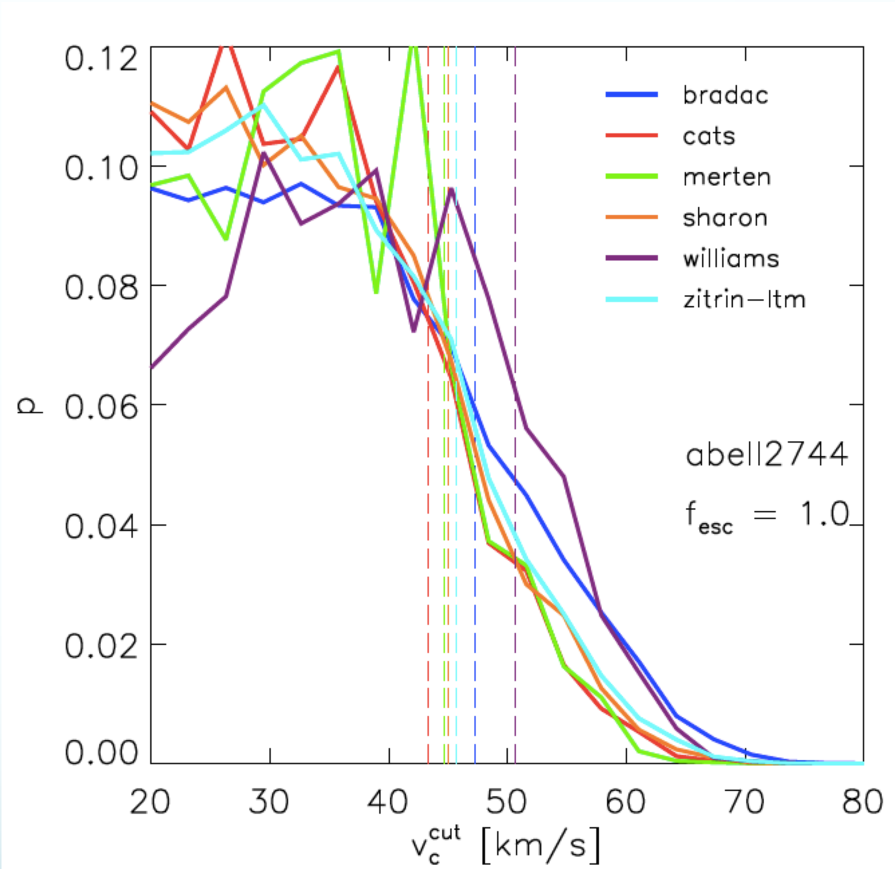




MC+ ApJL, 2016c

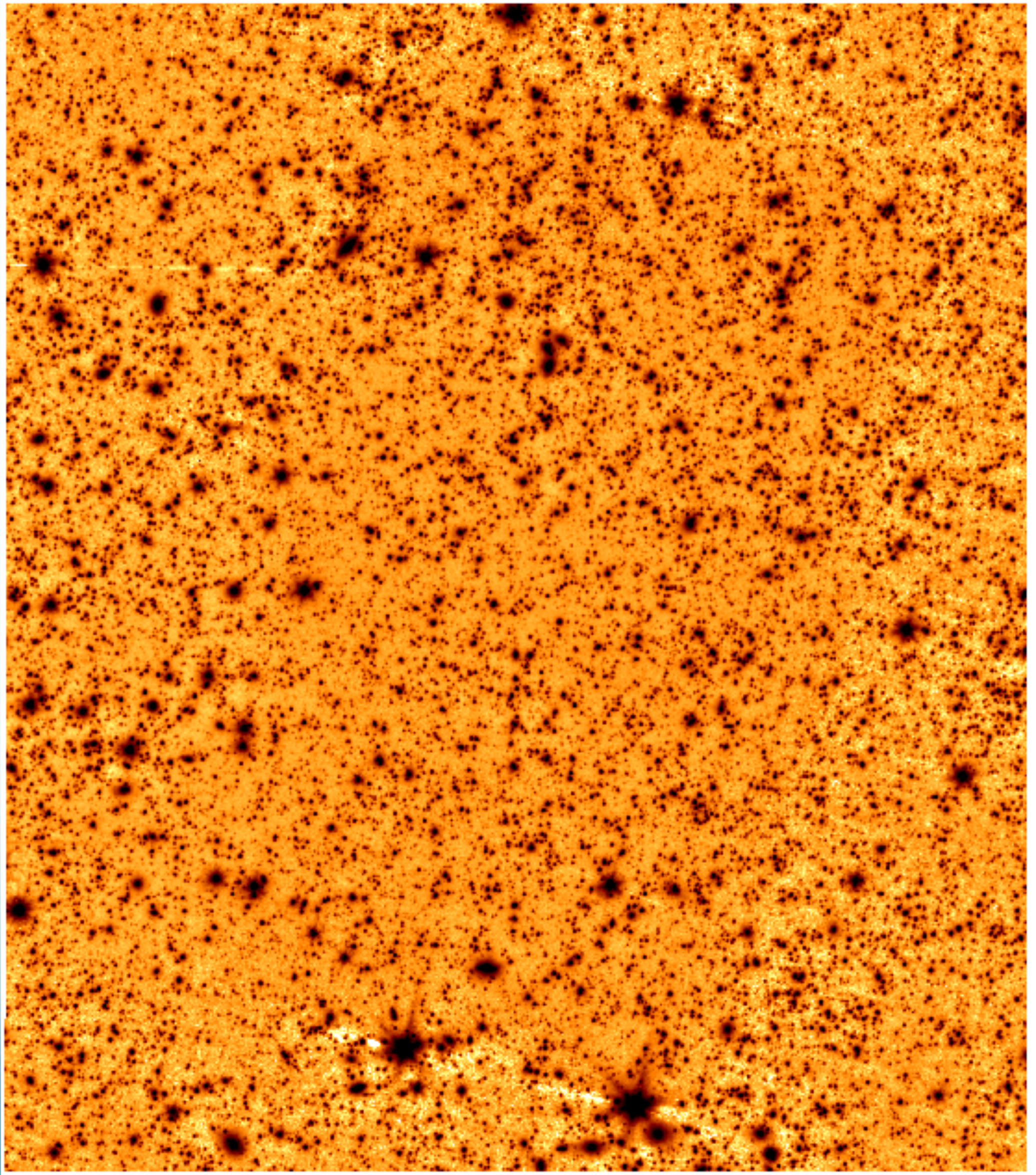
A closer look at z~7 sources: LF cut-off and feedback





Comparison between Yue et al. 2016 model and observed counts.
All lensing models used to build a global likelihood minimizing systematics.

GOODS-S ASTRODEEP catalog: ultradeep IRAC data



Improved constraints from full IRAC coverage of GOODS-S

ASTRODEEP is updating the CANDELS GOODS-S catalog:

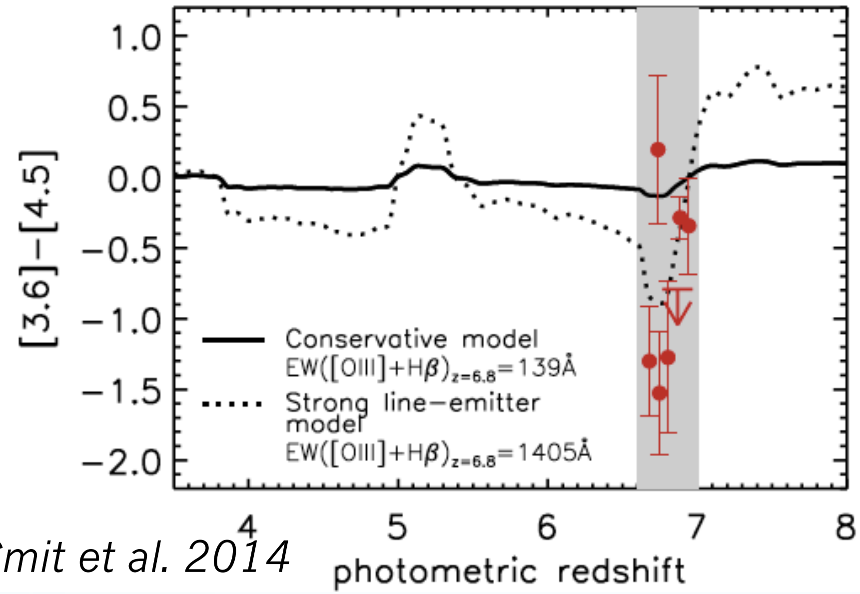
- IRAC CH1 and CH2 supermaps (GOODS+S-CANDELS and all available programs on CDFS, see e.g. Labbe+ 15)

- 18 medium band optical bands

- Deep optical coverage in U, B, R bands (VIMOS)

Everything reprocessed with improved procedures in T-PHOT

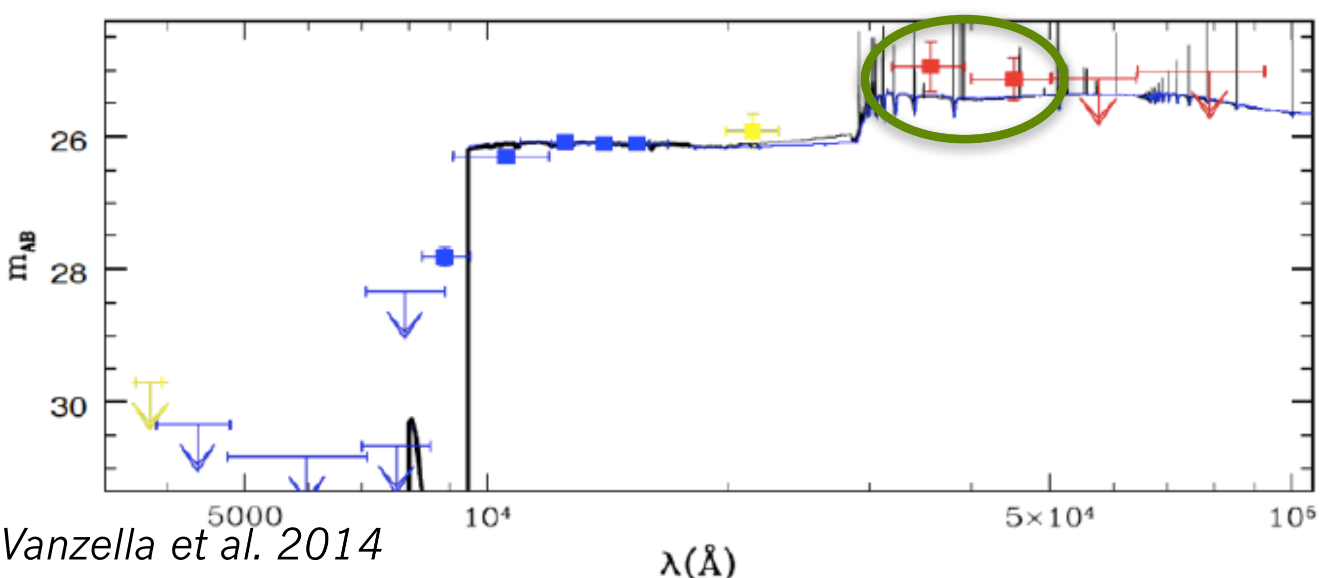
A closer look at z~7 sources: optical line emission



Smit et al. 2014

Known evidence for high-EW [OIII]+Hβ lines from IRAC colors at z>6 (e.g. Labbe et al. 2013, Wilkins et al. 2013, Smit et al. 2014)

Good redshift indicator: <u>we can check reliability of LBGs lacking Lyα confirmation.</u>



Vanzella et al. 2014

EW(Lyα)<9A from 52hrs FORS2 spectrum