The contribution of faint galaxies to Cosmic Reionization

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Dark Ages: Universe is mostly neutral, very first stars form

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

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

The ionized Universe 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)
Timeline and sources of HI Reionization

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Reionization: open issues (1)

\[ \dot{N}_{ion} \left( \text{s}^{-1} Mpc^{-3} \right) = 10^{49.7} \left( \frac{\rho_{UV}}{6 \times 10^{25}} \right)^{3.0} \left( \alpha_s \right)^{f_{esc} 0.1} \]

- Luminosity function faint end
- Escape fraction
- Intrinsic spectrum

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)
What is the topology of reionization?

What distinguishes Lyα 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.*

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
The critical role of the faintest sources

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

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 $z>5$
No evidence of LF cut-off due to feedback

No evidence of cut-off at halo mass $M > 2-5 \times 10^9$ 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
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Bouwens+17
Ultra-faint, compact high-z galaxies: GC progenitors?

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. ($M_{UV} \sim -14.5 \pm 2\sigma$; Yue, MC et al. in prep.)
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Faint galaxies can dominate reionization
(2) Physical properties of confirmed $z \sim 7$ Ly\textalpha
galaxies
A closer look at z~7 sources: optical line emission

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

Smit+14

Stark+17

Zitrin+15
A closer look at z~7 sources: optical line emission

An extreme escape fraction can erase the Ly$\alpha$ line, what about other lines?

Zackrisson et al. 2013

\[ \text{L}_{\text{lines}} \sim (1 - f_{\text{esc}}) \times Q_{i} \]

a) Em. lines disappear when $f_{\text{esc}} \rightarrow 1$

b) Strong high ionization lines

Nakajima&Ouchi 2014: high [OIII]/[OII]

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

Evidence of strong optical line emission at $z \sim 7$

<table>
<thead>
<tr>
<th>Subsample</th>
<th>CH1–CH2</th>
<th>EW([O III]+H$\beta$) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ly$\alpha$-emitting, all</td>
<td>$-1.0 \pm 0.21$</td>
<td>$1500^{+580}_{-340}$</td>
</tr>
<tr>
<td>Ly$\alpha$-emitting, bright</td>
<td>$-0.28 \pm 0.14$</td>
<td>$290^{+170}_{-150}$</td>
</tr>
<tr>
<td>Ly$\alpha$-emitting, faint</td>
<td>$&lt;-1.5$</td>
<td>$&gt;2900$</td>
</tr>
<tr>
<td>No Ly$\alpha$, all</td>
<td>$-0.47 \pm 0.11$</td>
<td>$520^{+170}_{-150}$</td>
</tr>
<tr>
<td>No Ly$\alpha$, bright</td>
<td>$-0.23 \pm 0.07$</td>
<td>$230^{+70}_{-70}$</td>
</tr>
<tr>
<td>No Ly$\alpha$, faint</td>
<td>$-0.61 \pm 0.23$</td>
<td>$720^{+400}_{-330}$</td>
</tr>
</tbody>
</table>
Strong optical line emission: implications on $f_{\text{esc}}$

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

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 Ly\( \alpha \) 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 H\textsc{ii} region to explain line visibility (Vanzella+11).

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

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

MC+ ApJL, 2016a
Stacking of the six new LBGs: V606 and I814 undetected at $>30.2$ mag, I814-Y105$>3$, S/N$\sim2$ detection in J+K.

$Z_{\text{phot}}=6.95$. Consistent with the objects being at the same z of the emitters.
An overdensity of LBGs at $z \sim 7$

Observed = 8 objects in two pointings. Expected $\sim 1.8$-2.9 objects.

No clustering around $z \sim 7$ GOODS-S galaxies lacking Ly$\alpha$ emission.

MC+ ApJL, 2016a
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
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.

Connection between reionization and overdensities.
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

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 $z\sim 7$ galaxies disfavors high fesc

3) Two close-by $z \sim 7$ 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

Investigating physical properties is crucial
BACKUP SLIDES
IRAC colours of our deep spectroscopic sample

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

Possible explanations for the Ly$\alpha$ drop:

1) There is an increase in the amount of neutral hydrogen in the surrounding IGM that quenches the Ly$\alpha$ emission.

   → Assuming no change in galaxy properties $X_{\text{HI}} \sim 0.5$ at $z \sim 7$

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 $z \sim 7$.

   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.

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)

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

Bradac model
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 $z \sim 7$ sources: optical line emission

Known evidence for high-EW $\text{[OIII]}^++\text{H} \beta$ lines from IRAC colors at $z > 6$ (e.g. Labbe et al. 2013, Wilkins et al. 2013, Smit et al. 2014)

Good redshift indicator: we can check reliability of LBGs lacking Ly$\alpha$ confirmation.

EW(Ly$\alpha$) < 9Å from 52hrs FORS2 spectrum