When and how did the first stars and galaxies form?

How can we study reionization with galaxies?

This talk: bright targets which we can study spectroscopically in detail now
HST Legacy fields may not be the best place to look

- relatively small volumes
- restricted to a single selection technique (broad-band photo-z/Lyman-break)

CANDELS+ERS+BoRG (~all HST deep fields)

10,000 galaxies z>3 (e.g. Bouwens+2015), but only handful of bright objects at z>6
Our approach: very wide fields from the ground
Our typical coverage

- COSMOS/UltraVISTA
- UDS/XMM-LS
- SA22/CFHTLS
- Boötes/NDWFS

find bright targets

~20 times larger than combined HST fields, ~2 magnitudes shallower
The Narrow-Band Technique directly targets galaxies with redshifted Lyman-alpha (1216 Å) at z=2.2, 3.1, 4.8, 5.7, 6.6

Lyman-alpha typically traces young OB stars, low metallicity (low dust), hot sources


Sources which can be followed up easily
The set of wide-field NB surveys

\[ z = 2.2 \quad \text{deg}^2 \quad \text{CALYMHA} — \text{matched to Halpha; Sobral, JM+ in prep} \]

\[ z = 3.1/4.8 \quad \text{~25/4 deg}^2 \quad \text{ongoing with INT/Subaru + Keck/WHT follow-up} \]

\[ z = 5.7 \quad 7 \text{ deg}^2 \quad \text{Santos, Sobral & Matthee, 2016 arXiv:1606.07435} \]

\[ z = 6.6 \quad 5 \text{ deg}^2 \quad \text{Matthee+2015, MNRAS, 451, 4919 (arXiv:1502.07355)} \]
The set of wide-field NB surveys

\[ z=2.2: \] 1.2 deg^2 CALYMHA — matched to Halpha; Sobral, JM+ in prep

\[ z=3.1/4.8: \] ~25/4 deg^2 ongoing with INT/Subaru + Keck/WHT follow-up

\[ z=5.7: \] 7 deg^2 Santos, Sobral & Matthee, 2016 arXiv:1606.07435


Madau & Dickinson, 2014
DIFFERENT SURVEY FIELDS: COSMIC VARIANCE

Selection: $\text{EW}_0(\text{Ly}a) > 25$ Å & Lyman-break, 2" apertures

Allows to study changes in Lya luminosities (due to reionization?)
No selection biases of which UV searches suffer (c.f. Stark+2016, arXiv 1606.01304, talk by Oesch)
**COMBINED Z=5.7 LAE LF**

**Graphical Representation:**

- **x-axis:** $\log_{10} L_{\text{Ly}\alpha}$ (erg s$^{-1}$)
- **y-axis:** $\log_{10} \phi (\text{Mpc}^{-3} \text{dlogL}^{-1})$

**Key Points:**

- Alpha very steep: $-2.3 \pm 0.4$ (consistent with Dressler+2015)
- (c.f. -1.9 UV LF Bouwens+2015; theoretically argued by Gronke+2015)

---

**Citation:**

Santos, Sobral & Mathee, 2016, arXiv: 1606.07435
Number density evolves at the faint end, not at the bright end!

- no comparable wide survey $z>7$ yet.

Santos, Sobral & Matthee, 2016, arXiv: 1606.07435
What about extended emission?

At $z=2.2$, we find that Lya continues to increase up to 30kpc radii at least

$f_{\text{esc, Lya}} (15\text{kpc}): \text{HAEs: 1.6\%; LAEs: 42\%}$

SFRs: $\sim 30 \ M_{\odot}/\text{yr}$ vs $7 \ M_{\odot}/\text{yr}$

**CALYMHA:** Matthee+2016a, MNRAS, 458, 449; Sobral, JM+ in prep

extended Lya for LAEs/LBGs see also e.g. Rauch+2007, Steidel+2011, Momose+2014, Wisotzki+2016
Extended emission at $z=5.7-6.6$

Simple analysis: Mag-auto luminosity vs 2$''$ aperture luminosity
Faint LAEs become more extended at $z=6.6$!

Similar to Momose+2014: median LAE in UDS more extended at $z=6.6$ than at $z=5.7$

Santos, Sobral & Matthee, 2016, arXiv: 1606.07435
1. Faint LAEs are less abundant and more extended at $z=6.6$ than at $z=5.7$

2. Bright LAEs equally abundant and equally extended
Matthee+2015 toy-model: more luminous LAEs easier to observe

re-ionisation? clustering needed!

Drop in Lya LF similar to evolution in follow-up of faint UV selected galaxies:
less Lya for L* UV selected galaxies, except when you select on neb. lines in IRAC
(e.g. Ono+2010, Schenker+2014, Pentericci+2014, Schmidt+2016; c.f. Stark+2016)
THE PROPERTIES OF LUMINOUS LAEs AT Z=6.6

![Graph showing the properties of luminous LAEs at z=6.6. The graph plots log_{10}(\phi) (Mpc^{-3}) against log_{10} L_{Ly\alpha} (erg s^{-1}). The data from z=5.7 (This work), z=6.6 Matthee+2015, z=7.0 Ota+2010, z=7.3 Shibuya+2012, and z=7.3 Konno+2014 are shown. The graph includes a Schechter fit for each data set.]
CR7 and the team of luminous z=6.6 LAEs

Himiko: Ouchi+2009, 2013
CR7, MASOSA: Sobral+2015
COLA1: Hu+2016
VR7: Matthee+2015 & in prep
Luminous LAEs show a lot of diversity!

- Lya sizes

**COSMOS >L* LAEs**

NB816  
z=5.7

NB921  
z=6.6
Luminous LAEs show a lot of diversity!

- Lya sizes
- UV magnitudes
The Nature of Luminous LAEs

Luminous LAEs show a lot of diversity!

- Lya sizes
  - CR7: 266+-15 km/s
  - Himiko: 251+-21 km/s
- UV magnitudes
  - MASOSA: 386+-30 km/s
  - COLA1: 194 km/s
- Lya FWHM

UV selected:
- z=7.7 Oesch+2015: 360+-80 km/s
- z=8.6 Zitrin+2015: 280+-220 km/s
Detailed properties of CR7

<table>
<thead>
<tr>
<th>BVI</th>
<th>z</th>
<th>NB921</th>
<th>Y</th>
<th>J</th>
<th>YJHK</th>
<th>3.6 μm</th>
<th>4.5 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Selected as LAE, but already known in 2011 in Ilbert+ catalog and Bowler+2012 (but as brown dwarf/unreliable LBG z~6)
6 SIGMA HEII 1640 EMISSION LINE

FWHM = 130 +/− 30 km/s
EW₀ = 80 +/− 20 Å
HeII/Lya = 0.23 +/− 0.10

Velocity offset Lya-Hell 120 km/s

> Tₑff ~ 100,000 K

Very hard ionising source: similar to other LBGs with CIII], CIV emission

Cassata+13 VUDS:
Typical HeII emitter z = 3-5:
EW₀ < 7 Å
FWHM ~ 700 km/s

Sobral, Matthee et al. 2015 ApJ, 808, 139
NO METAL EMISSION LINES

No NV, CIV, CIII], other high excitation metal lines

Lya/NV > 70
HeII/OIII] > 3
HeII/CIII] > 2.5

Apart from bright narrow Lyα and HeII1640: no other emission lines detected

HeII/Lyα = 0.3

Looks” like it
“Moves” like it
“Smells” like it

No lines except Lyα and HeII

“Talks” like it

Metallicity must be very low: <1/200 Zsun

Stark+2014, z~2: Helium typically fainter!
HeII/CIII ~ <0.5
HeII/OIII] ~ <1-1.5

Sobral, Matthee et al. 2015 ApJ, 808, 139
(ARCHIVAL) HST VIEW OF CR7

NB921 (Lyα) Subaru

F110W (YJ) HST

F160W (H) HST

Bowler+2016: all luminous z~7 LBGs multiple components

Thanks Forster-Schreiber (PI HST data)!

Sobral, Matthee et al. 2015 ApJ, 808, 139
CURRENT DATA IS FULLY CONSISTENT WITH POPIII-LIKE CLUMP A+"NORMAL" STELLAR POP IN B+C

Not a fit!
PopIII-like formation scenario:

“waves of star-formation”

Himiko: no HeII, nor metal lines: Zabl+2015

Similar to CR7?

Himiko: no HeII, nor metal lines: Zabl+2015
However, many theorists ‘prefer’ that CR7 is the first detection of a Direct Collapse Black Hole (DCBH)

The Brightest Ly\(\alpha\) Emitter: Pop III or Black Hole?

Detecting Direct Collapse Black Holes: making the case for CR7

Exploring the nature of the Lyman-\(\alpha\) emitter CR7

Evidence for a direct collapse black hole in the Lyman \(\alpha\) source CR7

LY\(\alpha\) SIGNATURES FROM DIRECT COLLAPSE BLACK HOLES

*AB INITIO* COSMOLOGICAL SIMULATIONS OF CR7 AS AN ACTIVE BLACK HOLE

Formation of Massive Population III Galaxies through Photoionization Feedback: A Possible Explanation for CR7

Pallotini+2015, Agarwal+2015, Hartwig+2015, Smith+2016, Dijkstra+2016, Smidt+2016 (but Visbal+2016 argue PopIII through similar mechanism) see poster by Agarwal
DCBH formation scenario:

Radiative feedback prevents fragmentation in clump A


HST+Subaru image of CR7

Artist impression (Kornmesser, ESO)

see poster by Agarwal
DCBH formation scenario:

Radiative feedback prevents fragmentation in clump A

HST+Subaru image of CR7

(but Visbal+2016 argue PopIII through similar mechanism)

Artist impression (JM)

see poster by Agarwal
Ongoing ALMA+HST follow-up: metallicity of hot and warm ISM

ALMA data almost available for [CII] & dust…
Ongoing ALMA+HST follow-up: metallicity of hot and warm ISM

**CLOUDY modelling**
blackbody, T=100,000K
(motivated from Lya-HeII)

**Current constraint from X-SHOOTER:** \( Z/Z_{\odot} < 10^{-2.5} \)

**HST grism early 2017 will give** \( Z/Z_{\odot} < 10^{-4} \)

metal poor DLAs: Cooke, Pettini & Jorgensen 2015
LYMAN-WERNER FLUX FROM CR7?

Escaping Lyman-Werner+ hole in the IGM?

Unseen in other z>6 galaxies
spatially coincident with peak Lya & HeII — very compact!

Lya
LYMAN-WERNER FLUX FROM CR7?

Escaping Lyman-Werner + hole in the IGM?

Unseen in other z>6 galaxies 
spatially coincident with peak Lya & HeII — very compact!

Matthee+2016 in prep.
LYMAN-WERNER FLUX FROM CR7?

No flux observed below 912 Å

Escaping Lyman-Werner+ hole in the IGM?

Matthee+2016 in prep.
Faint LAEs are less abundant and more extended at z=6.6 than at z=5.7: patchy reionization?

Bright LAEs show a surprisingly variety: compact vs extended Lya, multiple clumps, narrow FWHMs, blue peaks, Lyman-Werner.

COSMOS Redshift 7 hosts an extreme ionising source in low metallicity gas: PopIII stars or DCBH? Follow-up of CR7 and similar sources is ongoing.
CLUMP B & C AT SAME REDSHIFT?

Clump B+C are not yet spectroscopically confirmed, but are z-dropouts, so photo-z>6.5 most likely

Sobral, Matthee et al. 2015 ApJ, 808, 139
Some (preliminary!!) indications that $L_{\text{Ly}a}$ scales with $f_{\text{esc, LyC}} Q_{\text{ion}}$

Indirect signs of LyC escape from Lya line-profile (e.g. Verhamme+2015):
- low velocity offset Lya-HeII (CR7)
- blue peak Lya (COLA1)

From matched Lya-Ha survey $z=2.2$:
- $\xi_{\text{ion}} (= Q_{\text{ion}} / L_{\text{UV}})$ higher for LAEs than HAEs
  - LAE: $10^{25.14}$ Hz erg$^{-1}$; HAE: $10^{24.77}$ Hz erg$^{-1}$
- $\xi_{\text{ion}}$ increases with EW(Ha), and thus increases with redshift

(Matthee+2016b, arXiv:1605.08782)