The evolution of bright galaxies at $z > 6$

the power of degree-scale, near-infrared surveys

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with Jim Dunlop, Ross McLure, Matt Jarvis, Derek McLeod, H. Furusawa, Y. Taniguchi and the UltraVISTA team
A family of surveys

- Canada-France-Hawaii Telescope [Legacy Survey, 4 deg²]
- Suprime-Cam from Subaru [COSMOS/UDS/SDF+]
- Hawk-I on the VLT
- FourStar/Magellan-Baade Telescope (zFourge, medium-band filters)
- Visible and Infrared Survey Telescope (VISTA)
- UK infrared telescope (UKIRT)
Subaru/Suprime-Cam

★ Subaru Deep Field [~0.25 deg²]
- z ~ 5-6
  - e.g. Kashikawa et al. 2006
  - Jiang et al. 2013ab, 2016
  - Ota et al. 2008

★ Subaru XMM-Newton Deep Survey (aka UKIDSS UDS) [~1 deg²]
- e.g. McLure et al. 2006, 2009
  - Rogers et al. 2014
  - Yoshida et al. 2006

★ COSMOS survey (+deep z’-band from Furusawa+16) [~2 deg²]
- e.g. Willott et al. 2013
  - Bowler et al. 2015
  - VUDS: Le Fevre et al. 2014
  - Van der Burg et al. 2010

- e.g. Ouchi et al. 2010
  - Furusawa et al. 2016
  - Konno et al. 2014
  - Ono et al. 2010
  - e.g. Ouchi et al. 2010
  - Capak et al. 2011
  - Bowler et al. 2014
  - Matthee et al. 2015

luminosity function  rest-frame UV slope  stellar pops.  Ly-a emitters  clustering  +++
The key role of near-infrared data

★ Near-infrared essential for the detection of optical drop-outs!

★ And for the identification of contaminants…

High-z galaxy  Low-z galaxy  Galactic brown dwarf
The key role of near-infrared data

★ Deep optical + near-infrared photometry constrains high-z nature

Strong break + blue continuum

Spitzer/IRAC removes red interlopers

High-z galaxy

Low-z galaxy

Finkelstein et al. 2010
Contamination by cool galactic brown dwarfs

Water + methane absorption

Ryan et al. 2011

Bowler et al. 2015
Why study the brightest galaxies?

- Constraining the luminosity function
- Probing astrophysics at high-redshift
- Accessible laboratories into the EoR
Why study the brightest galaxies?

★ Constraining the luminosity function

★ Probing astrophysics at high-redshift

★ Accessible laboratories into the EoR

SDF + GN
Ouchi et al. 2009

Only HST

Including ground-based data (Subaru Deep Field)
Why study the brightest galaxies?

- Constraining the luminosity function
- Probing astrophysics at high-redshift
- Accessible laboratories into the EoR

Silk & Mamon 2012

Bowler et al. 2015
Why study the brightest galaxies?

★ Constraining the luminosity function

★ Probing astrophysics at high-redshift

★ Accessible laboratories into the EoR

[CII] 158 microns
(z = 5-6) Capak et al. 2015

Stark et al. 2014, 2017
# Why study the brightest galaxies?

<table>
<thead>
<tr>
<th>name</th>
<th>Himiko</th>
<th>CR7</th>
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<tbody>
<tr>
<td>location</td>
<td>SXDS/UDS</td>
<td>COSMOS</td>
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<tr>
<td>special features</td>
<td>strong Lya &gt; 200Å, triple merger system</td>
<td>strong Lya &gt; 200Å, narrow HeII emission</td>
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- Ouchi+09,13
- Sobral+15

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+ emission line results from: Roberts-Borsani et al. 2016, Stark et al. 2017, Zitrin et al. 2015

Pop III ?

DCBH ?

other ?

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Visbal et al. 2016</td>
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<td>Pallottini et al. 2015</td>
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<td>Hartwig et al. 2015</td>
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<td>Agarwal et al. 2016</td>
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<td>Dijkstra et al. 2016</td>
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<td>Bowler et al. 2016b</td>
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</table>
Finding $z \sim 7$ LBGs in the COSMOS + UDS

### UltraVISTA/COSMOS

<table>
<thead>
<tr>
<th>filters</th>
<th>telescope/program</th>
<th>AB 5σ depth</th>
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<tbody>
<tr>
<td>$u^*, g, r, i, z$</td>
<td>CFHTLS</td>
<td>~ 27</td>
</tr>
<tr>
<td>$i$ (814)</td>
<td>HST/ACS</td>
<td>~ 27</td>
</tr>
<tr>
<td>$z'$</td>
<td>Subaru</td>
<td>~ 26.5</td>
</tr>
<tr>
<td>$Y, J, H, Ks$</td>
<td>UltraVISTA DR2</td>
<td>~ 24-25, 25-26</td>
</tr>
<tr>
<td>3.6μm, 4.5μm</td>
<td>Spitzer/SPLASH</td>
<td>~ 25</td>
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</table>

### UDS/SXDS

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</tr>
</thead>
<tbody>
<tr>
<td>$B, V, R, i$</td>
<td>Subaru/SXDS</td>
<td>~ 27</td>
</tr>
<tr>
<td>$z'$</td>
<td>Subaru (HF+16)</td>
<td>~ 26.5</td>
</tr>
<tr>
<td>$Y$</td>
<td>VISTA VIDEO</td>
<td>~ 25</td>
</tr>
<tr>
<td>$J, H, K$</td>
<td>UKIRT/UKIDSS</td>
<td>~ 25-26</td>
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The bright-end of the $z \sim 7$ luminosity function

Need wide-area, near-IR surveys!

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![Graph showing the bright-end of the luminosity function at $z \sim 7$. The x-axis represents the absolute magnitude ($M_{1500}$) and the y-axis represents the number of objects per magnitude per cubic Mpc. The graph includes data points from various studies and models, with error bars indicating the uncertainty in the measurements. The y-axis is logarithmic, ranging from $10^{-8}$ to $10^{-2}$. The x-axis ranges from $-24$ to $-18$. The graph highlights the importance of wide-area, near-IR surveys for understanding the evolution of galaxies at early times.]
The bright-end of the $z \sim 7$ luminosity function

Need wide-area, near-IR surveys!

Brightest point from full CANDELS only $\sim 1$ galaxy

Previous CFHT/UKIRT data not deep enough (“LBGs” all at $z \sim 2$)
The bright-end of the $z \sim 7$ luminosity function

UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

34 galaxies (including 9/10 Bowler et al. 2012 objects)

0.5-1 mag deeper near-IR data than DR1
UltraVISTA DR2 + UDS/SXDS

1.65 sq. degrees

34 galaxies (including 9/10 Bowler et al. 2012 objects)

0.5-1 mag deeper near-IR data than DR1

The bright-end of the $z \sim 7$ luminosity function
Quasar contamination / lensing

$z = 3$ LF from Bian et al. 2013
Quasar contamination / lensing

- Quasar contamination negligible

z = 3 LF from Bian et al. 2013

z = 7 LF

- Quasar contamination negligible
Quasar contamination / lensing

\[ z = 3 \text{ LF from Bian et al. 2013} \]

Effect of strong lensing from a galaxy cluster Bradley et al. 2013

- Quasar contamination negligible
- Moderate gravitational lensing by foreground objects of \( \sim 0.1 \text{ mag} \) is common (0.3 mag maximum)

see also Mason et al. 2015, Fialkov et al. 2015, Barone-Nugent et al. 2015
The evolution of the LF from $z = 5-7$

★ Is there an evolution in shape?
- As predicted by onset of feedback?
- Or from simulations which impose significant dust obscuration to match UV LF observations?

★ What is the form of the evolution?

Luminosity ($M^*$) evolution?
Bouwens et al. 2011
(also e.g. McLure et al. 2009)

Density ($\phi^*$) evolution?
Bouwens et al. 2015
(also Finkelstein et al. 2015)
The evolution of the LF from $z = 5-7$

CFHTLS @ $z = 5$, COSMOS/UDS @ $z = 6-7$

(Van der Burg et al. 2010)
The evolution of the LF from $z = 5-7$

Strong evolution around the knee

Steepening of the bright-end at $z < 7$?
Not a consensus on the form of the evolution at $z = 5-7$

- Ground-based data show an evolution in $M^*$
- Is a Schechter function appropriate? More power-law like?
Constraining the knee of the $z \sim 7$ LF

Knee of the LF at $z \sim 7$ still uncertain…

Future HSC + UltraVISTA DR3 + UDS/SXDS will help

see Bouwens et al. 2015, Finkelstein et al. 2015ab
Cosmic variance in the LF at $z \sim 6$

$\sim 2 \times$ the number density of bright galaxies in UltraVISTA/COSMOS compared to the UDS/SXDS

McLure et al. 2009

$\sim 0.6$ sq. degree UDS/SXDS field

$z = 6$ luminosity function from SXDS/UDS + COSMOS.UltraVISTA (Bowler et al. 2015)
Cosmic variance in the LF at z ~ 6

Large degree-scale fields with multiple sight-lines are required!

➡️ HSC
➡️ Euclid/LSST (40 deg²)

Also in CFHTLS (Willott et al. 2013)
And under-density of LAEs in SXDS (Ouchi et al. 2005)
Revealing the nature of bright LBGs

These samples include the **brightest** known $z \sim 7$ galaxies, which are ideal targets for detailed follow-up:

... in relatively modest integration times:
- few hours with near-IR spectrographs (e.g. Oesch+2015, Roberts-Borsani+2015…)
- modest integrations with ALMA (e.g. Capak+2015, Maolino+2015…)
Revealing the nature of bright LBGs

HST can reveal sizes/morphologies that are elusive in ground-based data.

ALMA provides unique view of dust emission.

Optical and near-infrared spectroscopy can reveal rest-UV emission lines.
Revealing the nature of bright LBGs

HST can reveal sizes/ morphologies that are elusive in ground-based data
The brightest Lyman-break galaxies at $z \sim 7$ are composed of multiple clumps at HST resolution - mergers or SF clumps?

Magnitude limited sample, not selected for line emission

- Sobral et al. 2015
- see also Jiang et al. 2013, Kawamata et al. 2015…

Bowler et al. 2016a
Measuring the sizes of bright LBGs

Size measurement method and interpretation challenging
Sizes can be inferred from the ground...

$z \sim 6$ LBGs, CFHT data (Willott+13)

Bowler et al. 2016a
Upcoming and ongoing near-infrared surveys

★ UltraVISTA
Extension will fill in ‘gaps’ to provide complete 1.5 deg$^2$ to 25-26 JHKs (y from HSC)

★ VIDEO -> VEILS
CDFS, Elias-S1, XMM-LSS
12 deg$^2$ to ~ 23.5-24.5 YJHKs
Extension will double area

★ Euclid - 40 deg$^2$ in deep fields should detect ~3000 LBGs @ z ~ 7 (and ~ 1000 in wide fields)
Summary

★ Near-infrared data is key for finding and studying $z \sim 7$ galaxies
★ Current leading fields are UltraVISTA/COSMOS and UDS/SXDS
★ Evolution in the rest-frame UV LF is around the knee (-> DPL?)
★ Bright galaxies are interesting! And ideal laboratories for further study

Exciting current and future science (biased!)

★ Form and evolution of the bright-end at $z \sim 7$ and $z > 7$
★ Lyman-$\alpha$ escape and astrophysics of UV/optical emission lines
★ More CR7/Himiko type-objects? Density of $\sim 1$ per deg$^2$
★ Overlap with quasars
★ Probing the dark matter haloes via clustering
★ The rest-frame optical view with JWST - mergers or clumpy objects?
★ ....