A LARGE-SCALE VIEW OF THE DISTANT UNIVERSE

PRIMER: REDSHIFT AND LOOKBACK TIME

Lookback time = 12.9-13.3 Gyr
1-3 Gyr after Big Bang

Lookback time = 12.9-13.3 Gyr
0.5-1 Gyr after Big Bang

Lookback time = 13.3-13.6 Gyr
200-500 Myr after Big Bang

Epoch of Galaxy Formation
Lookback time = 13.3-13.6 Gyr
200-500 Myr after Big Bang

Epoch of Reionization
Lookback time = 12.9-13.3 Gyr
0.5-1 Gyr after Big Bang

Epoch of Galaxy Assembly
Lookback time = 12.9-13.3 Gyr
1-3 Gyr after Big Bang

Emergence of Hubble Sequence
Lookback time = 12.9-13.3 Gyr
1-3 Gyr after Big Bang
(SOME) QUESTIONS WE HAVE ANSWERED WITH HUBBLE

- Galaxies exist in great number between 500 Myr and 1 Gyr after the Big Bang, and the cosmic star-formation rate density evolves smoothly upward from $z=8$ to $z=4$ (e.g., work by Bowler+, Bouwens+, Finkelstein+, McLeod+, Oesch+, McLure+, Ishigaki+).

- Even the smallest galaxies we can see with Hubble are still enriched by previous generations of star-formation (e.g., Bouwens+12,14, Finkelstein+12, Dunlop+13, Rogers+14, Smit+15).

- Galaxies alone could reionize the universe if their ionizing photon escape fractions are relatively high, >10% (e.g., Kuhlen 12, Finkelstein+12, Robertson+13,15, Bouwens+15b, Livermore+17).
QUESTIONS WE HOPE TO ANSWER WITH JWST

- When is the epoch of the first galaxies?
  - What is the evolution of the cosmic SFR density at \( z > 8 \)?
  - Are the galaxies we can see enriched by Population II star-formation?
- Have we missed anything with our UV-only view of the distant universe?
- How do the conditions for star-formation and black hole growth evolve with cosmic time (e.g., spectroscopic studies)?
WHAT WFIRST BRINGS TO THE TABLE:

SCIENCE ENABLED BY A ~100X INCREASE IN FOV

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THE KINDS OF NUMBERS WE’RE DEALING WITH

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Expected # (HLS)</th>
<th>Expected # (deg$^2$ GO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>~3,300,000</td>
<td>~21,000</td>
</tr>
<tr>
<td>7</td>
<td>~530,000</td>
<td>~9200</td>
</tr>
<tr>
<td>8</td>
<td>~280,000</td>
<td>~4000</td>
</tr>
<tr>
<td>9</td>
<td>~75,000</td>
<td>~1700</td>
</tr>
<tr>
<td>10</td>
<td>~19,000</td>
<td>~700</td>
</tr>
</tbody>
</table>

- Predictions assume smoothly evolving Schechter UV LF (Finkelstein 16).
- Limiting magnitudes = 26.5 for HLS (except for $z=7$, which is limited by $z'_{\text{LSST}}=26.2$ depth), with empirically derived (from HST) magnitude-dependent completeness applied.
- GO deg$^2$ survey is a roughly 500 hr survey observing one square degree to m$\sim$29.
- To survey a sq. deg. with JWST to this depth would take several 1000’s of hours of integration, plus extensive overheads.
HST and JWST are severely limited in volumes that they can simultaneously probe. The following are some high priority questions likely to remain open in ~a decade:

- How do the physics which regulate star-formation evolve with cosmic time?
- How has cosmic variance affected our current results, particularly at faint luminosities?
- What is the impact of environment on reionization and galaxy evolution?
- What is the large-scale distribution of the detectability of Ly{$\alpha$} emission in the epoch of reionization?
- What is the contribution of AGNs to reionization?
OPEN QUESTIONS FOR WFIRST

- How do the physics which regulate star-formation evolve with cosmic time?
  - A phenomenological model which assumes that the star-formation rate tracks the halo mass accretion rate predict that the ratio of stellar-mass formed to halo mass (SMHM) increases with increasing redshift at $z > 4$ (Behroozi+13, Behroozi & Silk+15).
  - This implies that galaxies are perhaps better at converting gas into stars at higher redshifts, counter to a variety of theoretical predictions (e.g., lower-Z should reduce SF efficiency). Other factors, such as reduced negative feedback effects, could be at play.
  - One example - changing the timescale for converting gas into stars (Somerville+12) by a factor of four results in large changes at the bright end!
  
  - Current volumes probed do not contain enough galaxies to constrain these physics!

\[ \text{Median of Predictions} \]
\[ \text{Predicted from } z = 7.0 \text{ SMHM} + \text{SSFR} \]
\[ \text{Predicted from } z = 5.0 \text{ SMHM} + \text{SSFR} \]
\[ \text{Predicted from } z = 4.0 \text{ SMHM} + \text{SSFR} \]
\[ \text{Median of Predictions} \]
\[ \text{Predicted from } z = 6.0 \text{ SMHM} + \text{SSFR} \]
\[ \text{Predicted from } z = 4.0 \text{ SMHM} + \text{SSFR} \]
\[ \text{Median of Predictions} \]
\[ \text{Predicted from } z = 7.0 \text{ SMHM} + \text{SSFR} \]
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\[ \text{Median of Predictions} \]

\[ \text{Currently permitted range of models} \]
\[ \text{Finkelstein+15} \]
\[ \text{Bouwens+15} \]
\[ \Delta \text{UltraVISTA (Bowler+14}) \]
OBSERVATIONAL EVIDENCE?

- Galaxy clustering results have observationally found a similar trend - higher SMHM at fixed halo mass (Harikane+16,17).
- A similar result was found via abundance matching the UV luminosity function, and looking at evolution at fixed UV magnitude (~fixed stellar mass; Finkelstein+15b), though this is subject to UV scatter, and nebular contamination in M* estimates.
- Stefanon+17 found less evolution via rest-z' luminosity function abundance matching, though they were exploring progenitors/descendants, and had small numbers at z > 5.
- Most of these studies are limited by small sample sizes (the clustering study used HSC, so had large samples, but potentially much higher sample contamination), so conclusions remain difficult.
There is now some evidence that the bright end of the UV luminosity function may be "super"-Schechter, e.g., a double power law (e.g., Bowler+14, 15; Ono+17, Stefanon+17, Stevans in prep).

Interesting physics?
Dust attenuation?
Contamination by AGNs?

z=4 UV luminosity function by UT student Matt Stevans, using ~20 deg² SHELA survey data, and simultaneously fitting AGN and star-forming galaxy luminosity functions.
Fractional uncertainty due to cosmic variance is ~40% in the HUDF.

- Will be similar in a JWST UDF-style observation due to small volume probed.

- How much are our conclusions on faint galaxies biased by cosmic variance?

- Lensing helps provide independent lines-of-slight, though volumes are tiny, so still CV issues.
ROBUSTNESS OF BRIGHT-END ABUNDANCES TO COSMIC VARIANCE

WFIRST HLS will allow measurements of the abundance of bright galaxies at $z=6-8$ with S/N > 100 (S/N > 10 at $z=9-10$).

CV estimated by combining observed biases (Barone-Nugent+14) with dark matter CV estimates (Newman+Davis 02, Moster+11).
How do environmental factors affect star-formation in the epoch of reionization?

- Current volumes probed at $z > 6$ do not yet allow robust measures of environment to be made.

- The WFIRST HLS will probe 10-20 cGpc$^3$ volumes in unit-redshift bins at $z=10-6$, observing galaxies in the full range of cosmic environments.

- Will also allow measurements of the cosmic SFR density both robust against CV, and as a function of environment.
Environment is likely linked to reionization - the most overdense regions formed stars first, and likely ionized first.

- SKA 21cm line tomography should be able to resolve neutral/ionized regions on the order of a few pMpc, comparable to the expected size of ionized bubbles in the early universe (e.g., Furlanetto 06; Iliev+14).

- Could then target ionized regions with a deeper GO survey to explore whether reionization “feedback” is suppressing star formation (though this may be more applicable to a LUVOIR-type mission).

High spatial resolution will also allow improved searches for AGNs at high redshift, better constraining their contribution to reionization.
Ly$\alpha$ is resonantly scattered by neutral hydrogen, so if it is emitted from a galaxy with a surrounding neutral IGM, it will be significantly spatially diffused, well beyond detectable levels.

- Also, it is relatively “abundant” at $z=6$, just after the end of reionization.

- Simulations show that a patchy IGM should be directly traceable by the patchiness of Ly$\alpha$ emission.

- Real galaxies make this more complicated, as they create HII regions, and they can impart a kinematic offset to Ly$\alpha$ photons, escaping from even modestly neutral regions.
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PROBING REIONIZATION WITH LYMAN ALPHA EMISSION

- This has led to a booming industry of attempted Lya measurements at $z > 6.5$, with some notable successes (e.g., Shibuya+12, Finkelstein+13, Oesch+15, Zitrin+15, Roberts-Borsani+16, Song+16, LaPorte+17).

  $z=7.51$

  

  [Image: FINKELSTEIN+2013]

  $z=7.73$

  

  [Image: OESCH+2015]

  $z=8.68$

  

  [Image: ZITRIN+2015]

- However, the majority of galaxies go undetected with spectroscopic followup, leading to the inference that the IGM at $z \geq 7$ is highly neutral (e.g., Pentericci+11, 14, Treu+13, Fontana+10, Tilvi+14).
We in the midst of a multi-pronged survey for Lyα in the epoch of reionization, using ~300 HST orbits (FIGS: PI Malhotra; CLEAR: PI Papovich), and 20+ nights of Keck DEIMOS+MOSFIRE observations (PI Finkelstein, primarily through NASA).

Work currently being led by UT student Intae Jung, first paper out by end of summer on our optical dataset.
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Ground-based near-IR spectroscopy is hard! The night sky lines block ~half of our accessible wavelength range, and atmospheric absorption windows prevent probing the full likely redshift range for a given object.

Rebecca Larson

Likely Lyα emission at z=7.4 from the HST FIGS grism survey (see also Tilvi+16)

Proof of concept for Lyα detections with WFIRST!

Intae Jung
WFIRST CAN PROVIDE THE ABILITY TO PROBE LYA EMISSION OVER LARGE SCALES

- JWST will make progress, but the small FoV of NIRSpec/NIRISS and relatively low sensitivity at $\lambda < 1.3 \mu m$ will limit results.

- Our Cosmic Dawn SIT (PI Rhoads) has been advocating for extending the WFIRST grism spectral range down to 0.9/1.0 $\mu m$ (from baseline 1.3 $\mu m$) to allow wide-field Lya studies throughout the EoR.

- We’re working now to spec out potential GO spectroscopic programs spanning 10’s-100 arcmin in length (exploring issues such as depth, # of PAs, etc.)
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THANK YOU!

Questions?