BEYOND THE HORIZON:
What is left to learn after Hubble about the first billion years?

STEVEN FINKELSTEIN
THE UNIVERSITY OF TEXAS AT AUSTIN

NASA/Goddard ATLAST Colloquium
July 15th, 2015
What are the (changing?) physical effects responsible for the rise and fall of the cosmic star-formation rate density?
GALAXY SELECTION

SHAPLEY+2003
GALAXY SELECTION

Redshift

Int P(z=5) = 0.02
Int P(z=6) = 0.14
Int P(z=7) = 0.52
Int P(z=8) = 0.26
Int P(z=9) = 0.01
OUR TOOLBOX

HUDF

CANDELS/GOODS

HFF
OUR TOOLBOX

HUDF

CANDELS/GOODS

HFF

GOODS − S Deep
GOODS − S Wide
GOODS − S ERS
GOODS − N Deep
GOODS − N Wide
HUDF Main
HUDF PAR1
HUDF PAR2
MACS0416 PAR
A2744 PAR

HUDF09/12+
HFFP

CANDELS

z ∼ 6

z ∼ 7

z ∼ 8

SF+2015a

Absolute UV Magnitude (1500Å)
3.2.2 — Near-Future Ly

and 3.5 nights with DEIMOS (PI'd by my postdoctoral research
myself through NASA; 5 nights PI'd by collaborators through
hr, and
3.2 — Summary of Spectroscopic Datasets
the sky, providing a robust sense of the spatial variations o
GOODS fields, but also in the six Hubble Frontier Fields, I wil

for spectroscopic follow up, and I propose to obtain deep spe
200 galaxies with
feasibly possible (given constraints on slit placement, et

and GOODS-N combined sample, I find I have 200 galaxies with

<z<
over 189
at
3.2.1 — In-Hand Spectroscopic Datasets:
2013 – 2016 is using
six parallel blank fields. This dataset is enhanced with the a

reionization, we clearly need obtain deeper spectroscopy o

My final sample will consist of nearly 12,000

SF+2015a

25 galaxies already have MOSFIRE integrations approaching

Hz

≈

z>

6( 7 ), probing stellar masses of

3.2 — Summary of Spectroscopic Datasets

α

z

phot

4, 5, 6, 7 and 8, which is consistent with my early work on HFF ob

photometric redshift

4

5

6

7

8

Spectroscopic Redshift

HST

http://www.stsci.edu/hst/campaigns/frontier-fields/H

GOODS Main

GOODS

GOODS

GOODS

GOODS

GOODS

GOODS

GOODS

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GOODS

HUDF Main

HUDF PAR1

HUDF PAR2

MACS0416 PAR

SF+2015

HUDF PAR2

HUDF PAR1

HUDF Main

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GOODS
WHAT HAVE WE LEARNED?

Over the past two years, I have collected a large amount of data from the Keck telescopes. These data total an astounding 1060 hours of spectroscopic observations over all fields. As a member of the committee which recommended this program to the STScI director, I have given voice to the importance of having their redshifts between 6.5 and the red-end of the M band. This dataset is enhanced with the acquisition of spectroscopic follow up, and I propose to obtain deep spectroscopy with MOSFIRE over as many of them as feasibly possible (given constraints on slit placement, etc.).

Out of my full CANDELS GOODS-S fields, but also in the six Hubble Frontier Fields, I will sample over all six clusters and parallel fields should reach the sky, providing a robust sense of the spatial variations of the sample, providing highly magnified galaxies suitable for spectroscopy with MOSFIRE:

- GOODS-S Deep
- GOODS-S ERS
- GOODS-S Wide
- GOODS-N Deep
- GOODS-N Wide
- HUDF Main
- HUDF PAR1
- HUDF PAR2
- HUDF09/12+
- HFFP
- MACS0416 PAR
- A2744 PAR
- HUDF PAR1
- HUDF PAR2
- HUDF Main
- SF+2015a

The total HFF cluster sample over 189 orbits to place deep fields on six highly lensing galaxy clusters, as well as GOODS fields, but also with using Ly

These data come from 10 nights with MOSFIRE, split over 58 orbits; 440 hr with MOSFIRE, split over 58 orbits; 1060 hours of spectroscopic observations over all fields. As a member of the committee which recommended this program to the STScI director, I have given voice to the importance of having their redshifts between 6.5 and the red-end of the M band. This dataset is enhanced with the acquisition of spectroscopic follow up, and I propose to obtain deep spectroscopy with MOSFIRE over as many of them as feasibly possible (given constraints on slit placement, etc.).

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The total HFF cluster sample over 189 orbits to place deep fields on six highly lensing galaxy clusters, as well as GOODS fields, but also with using Ly
CHEMICAL ENRICHMENT

WHEN DO THE FIRST GALAXIES FORM?
HOW EARLY DO METALS FORM?

Credit: Tiffany Davis - STScI
CHEMICAL ENRICHMENT

Credit: Tiffany Davis - STScI
$z = 0.5$

8.5 billion years after the Big Bang
$z = 4$

1.5 billion years after the Big Bang
GALAXIES ON AVERAGE ARE LESS DUSTY WITH INCREASING REDSHIFT

THE MOST MASSIVE GALAXIES APPEAR DUSTY, EVEN AT Z=7. LOW-MASS GALAXIES ARE LESS DUSTY, THOUGH NOT METAL-FREE.

SF+2012A, 2015B
**CHEMICAL ENRICHMENT**

Galaxies on average are less dusty with increasing redshift. The most massive galaxies appear dusty, even at $z=7$. Low-mass galaxies are less dusty, though not metal-free.

When do metals first appear? Need the ability to measure galaxy colors from very faint systems out to the highest redshifts.

SF+2012A, 2015B
LUMINOSITY FUNCTIONS

• Much effort has been spent computing the rest-frame UV luminosity functions.
Luminosity functions can tell us about the physical processes regulating star-formation in the distant universe.

The rest-UV luminosity function also allows us to calculate the star-formation rate density.
The Good News

Absolute UV Magnitude (1500 Å)

\[ M^* = -21.03^{+0.37}_{-0.50} \]
\[ \alpha = -2.03^{+0.21}_{-0.20} \]
\[ \varphi^* = 1.57^{+1.49}_{-0.95} \times 10^{-4} \]
Absolute UV Magnitude (1500 Å)

ϕ (# Mag$^{-1}$ Mpc$^{-3}$)

$z = 4$
$z = 5$
$z = 6$
$z = 7$
$z = 8$

SF+2015A
A SURPRISE!

Figure 15. Redshift evolution in the UV LF at $z\sim 4–6$ (Bouwens et al. 2009, blue lines), and $z\sim 7$ (magenta lines) and possibly as steep ($z\sim 8$). We do not include the constraints on the UV LF at $z\sim 4$ (Sections 8c). We remark that the derived slopes simply reflect the uncertainties.

Figure 16. Constraints we derive on the evolution in the UV LF at $z\sim 4$ (Bouwens et al. 2009) are shown as the large solid red circles, with the 1σ uncertainties.

Figure 17. The constraints we derive on the evolution in the UV LF at $z\sim 4$ (Bouwens et al. 2009) are shown as the large solid red circles, with the 1σ uncertainties. We do not include the constraints on the UV LF at $z\sim 4$ (Sections 8c). We remark that the derived slopes simply reflect the uncertainties.

Figure 18. Constraints we derive on the evolution in the UV LF at $z\sim 4$ (Bouwens et al. 2009) are shown as the large solid red circles, with the 1σ uncertainties. We do not include the constraints on the UV LF at $z\sim 4$ (Sections 8c). We remark that the derived slopes simply reflect the uncertainties.
WHAT'S HAPPENING AT THE BRIGHT END?

\[
\begin{align*}
M^* &= -21.03^{+0.37}_{-0.50} \\
\alpha &= -2.03^{+0.21}_{-0.20} \\
\varphi^* &= 1.57^{+1.49}_{-0.95} \times 10^{-4}
\end{align*}
\]

\[
\begin{align*}
M^* &= -20.89^{+0.74}_{-1.08} \\
\alpha &= -2.36^{+0.54}_{-0.40} \\
\varphi^* &= 0.72^{+2.52}_{-0.65} \times 10^{-4}
\end{align*}
\]
CAN WE UNDERSTAND THE INTERESTING EVOLUTION AT THE BRIGHT END?

To put this in context, we set out to measure the stellar mass growth of galaxies in context of their dark matter halos.

For this study, we considered $M_{UV}=-21$ galaxies ($\sim L^*$)

We can detected them with IRAC, and thus obtain more robust physical property measurements.

Halo masses estimated via abundance matching.
Can we understand the interesting evolution at the bright end?

To put this in context, we set out to measure the stellar mass growth of galaxies in the context of their dark matter halos.

For this study, we considered $M_{UV} = -21$ galaxies ($\sim L^*$).

We can detect them with IRAC, and thus obtain more robust physical property measurements.

Halo masses estimated via abundance matching.

<table>
<thead>
<tr>
<th>Redshift</th>
<th>$\log M_{\text{halo}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>11.9</td>
</tr>
<tr>
<td>5</td>
<td>11.7</td>
</tr>
<tr>
<td>6</td>
<td>11.6</td>
</tr>
<tr>
<td>7</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Halo masses estimated via abundance matching.

SF, MIMI SONG, PETER BEHROOZI+2015
A CHANGING ISM SHOULD REVEAL ITSELF IN THE STAR-FORMING PROPERTIES OF DISTANT GALAXIES

- Measured stellar masses via SED fitting using HST ACS +WFC3 and deep (50+ hr) IRAC imaging.
A changing ISM should reveal itself in the star-forming properties of distant galaxies

- Measured stellar masses via SED fitting using HST ACS + WFC3 and deep (50+ hr) IRAC imaging.

**Bottom line:** Galaxies with $M \sim -21$ at $z=4-7$ have very similar physical properties, yet live in progressively smaller halos at higher redshift.

<table>
<thead>
<tr>
<th>Redshift</th>
<th>log $M_{\text{halo}}$</th>
<th>log $M_*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>11.9</td>
<td>9.9</td>
</tr>
<tr>
<td>5</td>
<td>11.7</td>
<td>9.9</td>
</tr>
<tr>
<td>6</td>
<td>11.6</td>
<td>9.9</td>
</tr>
<tr>
<td>7</td>
<td>11.4</td>
<td>9.8</td>
</tr>
</tbody>
</table>
A CHANGING ISM SHOULD REVEAL ITSELF IN THE STAR-FORMING PROPERTIES OF DISTANT GALAXIES

<table>
<thead>
<tr>
<th>$z$</th>
<th>$\log M_{\text{halo}}$</th>
<th>$\log M^*$</th>
<th>SMHM</th>
<th>SBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>11.9</td>
<td>9.9</td>
<td>0.010</td>
<td>0.06</td>
</tr>
<tr>
<td>5</td>
<td>11.7</td>
<td>9.9</td>
<td>0.015</td>
<td>0.09</td>
</tr>
<tr>
<td>6</td>
<td>11.6</td>
<td>9.9</td>
<td>0.020</td>
<td>0.12</td>
</tr>
<tr>
<td>7</td>
<td>11.4</td>
<td>9.8</td>
<td>0.027</td>
<td>0.16</td>
</tr>
</tbody>
</table>

$\frac{d(SBF)}{dz} \propto (0.031 \pm 0.009)$

$$SBF = \frac{M^*/M_{\text{halo}}}{\Omega_b/\Omega_m}$$
A CHANGING ISM SHOULD REVEAL ITSELF IN THE

What physical effects could cause this result?

A) **Galaxies have a higher star formation efficiency.**
   
   • Increased redshift → increased gas density → faster freefall time →
     more star formation
   
   • More star formation happens in self-gravitating clumps, which have
     high SFE (e.g., Dekel+2009, Ceverino+2010; Genzel+2011)

B) **Galaxies have more fuel available for star formation.**
   
   • Higher gas density leads to more gas in the cool phase.
   
   • Weaker feedback leads to more gas available for star formation.
     
     • Higher gas density could lead to more energy from SNe being
       radiated away (e.g., Creasey+2013).
     
     • Less dust leads to less momentum-driven radiative feedback (e.g.,
     
     • Less/zero AGN feedback.
A CHANGING ISM SHOULD REVEAL ITSELF IN THE...

What physical effects could cause this result?

- **A) Galaxies have a higher star formation efficiency.**
  - Increased redshift $\rightarrow$ increased gas density $\rightarrow$ faster freefall time $\rightarrow$ more star formation
  - More star formation happens in self-gravitating clumps, which have high SFE (e.g., Dekel+2009, Ceverino+2010; Genzel+2011)

- **B) Galaxies have more fuel available for star formation.**
  - Weak or zero AGN feedback leads to more gas available for star formation
  - Higher gas density could lead to more energy from SNe being radiated away (e.g., Creasey+2013).

**If Scenario B is the answer, it could have a dramatic effect on the escape of Ly$\alpha$ photons from galaxies.**

**Can test this scenario directly with ALMA, by measuring the redshift evolution of the gas-to-stellar mass ratio.**
OTHER EVIDENCE FOR LACK OF FEEDBACK / INCREASED SFE?

STEELAR MASS FUNCTIONS

MIMI SONG, SF+2015
OTHER EVIDENCE FOR LACK OF FEEDBACK / INCREASED SFE?

STELLAR MASS FUNCTIONS

MIMI SONG, SF+2015
HOW DO WE OBTAIN REIONIZATION CONSTRAINTS FROM THE LUMINOSITY FUNCTION?

- Step 1: Integrate the UV LF to obtain the specific UV luminosity density: $\rho_{\text{UV}} [\text{erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^3]$

  - Assumption: Need to assume a minimum value of $M_{\text{UV}}$ (especially when $\alpha < 2$).

    - Common values in the literature: -17, -15, -13, -10

    - We see galaxies down to -17, so it's likely fainter. We assume $M_{\text{lim}} = -13$, though this bears watching from the theoretical side (e.g., Jaacks+12, O’Shea+15).

- Step 2: Choose a reionization model.

  - Assumptions: Madau (1999) model, $C=3$, $f_{\text{esc}} = 13\%$ (upper limit at $z=6$ from SF+2012b), conversion from ionizing to non-ionizing UV for a Salpeter IMF, and 20% Solar metallicity.
How do we obtain reionization constraints from the luminosity function?

Our Fiducial Model

$\rho_{UV} [10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}]$

$C/f_{esc} = 100$
$C/f_{esc} = 30$
$C/f_{esc} = 10$
$C/f_{esc} = 3$

This study (Integrated LF)
This study (50% complete)
Bouwens+15
Finkelstein+10/12

Redshift

SF+2015A
CONSTRAINTS ON THE REIONIZATION HISTORY
NEEDED IMPROVEMENTS

- Our current constraints from the LF give 68% confidence range on the 50% reionization redshift of $6.7 < z < 9.4$.
- This uncertainty is driven by the fact that faint galaxies dominate the photon budget, and the current uncertainties on $\alpha$ are large.
- Improvements will happen with JWST, but we are cracking this door open right now with the Hubble Frontier Fields.
  - Will not only improve LF at $M \sim -17$ to 19, but can also probe to $\sim -16$ to test assumptions on $M_{\text{lim}}$. 
FINDING THE FAINT GALAXIES

RACHAEL LIVERMORE, SF+2015
LF does seem to extend steeply to at least $M = -16$, but need all clusters to confirm
**WHAT DO WE NEED?**

- We need to understand the luminosity function down to -13. If it turns over at brighter magnitudes, we have a photon production crisis.

- JWST deep fields will only reach around -15.5 or so in UV absolute magnitude.

---

[JAACKS+13]

[PAARDEKOOPER+15]
ACCOUNTING FOR ALL REIONIZING PHOTONS

Absolute UV Magnitude (1500 Å)  

\[ \varphi (\text{# Mag}^{-1} \text{Mpc}^{-3}) \]

\[ 10^{-6} \]
\[ 10^{-4} \]
\[ 10^{-2} \]
\[ 10^{0} \]

- HST
- JWST
- 14m ATLAST
- Needed for Reionization

TELESCOPE | FRACTION OF REIONIZING PHOTONS ACCOUNTED
--- | ---
HST | 35%
JWST | 60%
ATLAST (14M) | 90%
So a 14m ATLAST can account for ~90% of the needed ionizing photons.

But, we need to consider this:

What if we assume that halos with $M > 10^{10} \, M_{\odot}$ do not have any escaping ionizing radiation?

<table>
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<tr>
<th>TELESCOPE</th>
<th>FRACTION OF REIONIZING PHOTONS ACCOUNTED</th>
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<tr>
<td>HST</td>
<td>5%</td>
</tr>
<tr>
<td>JWST</td>
<td>45%</td>
</tr>
<tr>
<td>ATLAST (14M)</td>
<td>80%</td>
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</tbody>
</table>

- PAARDEKOOPER+15
HOW ELSE CAN WE BETTER CONSTRAIN REIONIZATION?
LYMAN ALPHA EMISSION

- Over the past few years we have been collecting Keck spectroscopic data on our $z > 6$ galaxy candidates.
- Rather than hitting as many galaxies as possible for short integrations (similar to other MOSFIRE programs), we go deep, at least 5, and up to 20 hr/object.
- First run was in April 2013.

**Figure 1**

Redshift from Ly$\alpha$

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>1.025</th>
<th>1.030</th>
<th>1.035</th>
<th>1.040</th>
<th>1.045</th>
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<tbody>
<tr>
<td>8.8 arcsec</td>
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<tr>
<td>z = 7.5078 ± 0.0004</td>
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<tr>
<td>S/N = 7.8</td>
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**Figure 2**

Number evolution

- Dimming evolution

$\epsilon_{ne} < 0.30$ (84% C.I.)
$\epsilon_{de} < 0.25$ (84% C.I.)
$2\ln(Z_{ne} / Z_{de}) = 2.2$
We have continued to observe, obtaining data over 13.5 nights over the past two years (primarily through NASA, but also with collaborators at UC).

- We have observed ~40 candidate $z > 7$ galaxies at $J < 27$ to at least 5 hr depth, and these long integrations allow us to pick out more lines.

**LYMAN ALPHA EMISSION**

<table>
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<tr>
<th>Wavelength ($\mu$m)</th>
<th>Flux (counts/second)</th>
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<td>0.976</td>
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<td>0.978</td>
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<td>0.984</td>
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<td>0.986</td>
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<tr>
<td>0.988</td>
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<tr>
<td>0.990</td>
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</table>

- $z=7.0631$
- $S/N=4.8$

**LIVERMORE, SF, IN PREP**
FROM THE GROUND: AN EW-LIMITED SURVEY OF LYMAN ALPHA EMISSION AT 5.5 < z < 8.2

Figure 1
Left) Our Keck/MOSFIRE spectrum showing Lyα emission at z=7.51 (Finkelstein et al. 2013), among the highest redshift galaxies with a Lyα detection, shown here with increased signal-to-noise from a total of 10 hr of integration (the sky emission is shown as the filled gray curve; the residuals from the strongest sky lines are grayed out).

Middle/Right) Similar plots, for two higher redshift galaxies (Livermore & Finkelstein, in prep) from our new MOSFIRE observations over the past year, highlighting the power of Keck to observe Lyα in the epoch of reionization.

Figure 2

Figure 3

Figure 4
Probability (redshift) of a galaxy in our sample. Although the best-fit redshift is z~7.1, this galaxy has a significant probability of lying anywhere at 6 < z < 8.2.

The blue and red regions denote the redshifts probed DEIMOS and MOSFIRE, respectively, showing that this galaxy has an equal chance of exhibiting Lyα in the optical and near-infrared, necessitating coverage in both.

Figure 4

DEIMOS/MOSFIRE in-hand
HST FIGS grism program
DEIMOS/MOSFIRE proposed
VLT VANDELS (optical)
GOODS-S
GOODS-N

Will constrain EW < 15 (5) Å for 200 (30) J < 27 (26) galaxies
FROM SPACE: HST GRISMS

- The HST grisms are an untapped resource for spectroscopic studies of $z > 6$ galaxies.
- The exquisite sensitivity can allow spectroscopic confirmations from the break, with our without a line.

Log of DEIMOS Observations of PEARS-N-101687

- **hdf07c** 2007 Apr 14
- **hdf07d** 2007 Apr 14–15
- **hdf08a** 2008 Mar 6

**Duration** Total Time Conditions Comments

- **1800 s** 9000 s Good
- **1800 s** 10500 s Good
- **3600 s** 30900 s Good

**Differences in throughput** (e.g., due to differences in slit losses would require a 10% correction to the spectroscopic flux.

The exquisite sensitivity can allow spectroscopic confirmations from the break, with our without a line.

**Upper:** the 2D PEARS spectrum of PEARS-N-101687, displayed in a filter with 9210 Å central wavelength and 120 Å FWHM. The narrowband magnitude published in that work, $m_{775}^i = 26$ (AB), each panel is 1″ × 1″. We thereby found that differential slit seeing, $σ_e$, as indicated in Figure 1.

**Figure 1.** The extracted Keck + DEIMOS spectrum of PEARS-N-101687 in Figure 1 from the three useful masks together yields a better detection of excess in a filter with 9210 Å central wavelength and 120 Å FWHM. The narrowband magnitude published in that work, $m_{775}^i = 26$ (AB), each panel is 1″ × 1″. We thereby found that differential slit seeing, $σ_e$, as indicated in Figure 1.

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FROM SPACE: HST GRISMS

How can we make progress?

Go deep: Lyman alpha emission is clearly faint. by going deep, we can detect lyman breaks spectroscopically at \( z > 7 \) (as well as faint Lyman alpha lines).

Faint Infrared Grism Survey (FIGS; PI Malhotra; Co-I Finkelstein)

Go wide: A patchy reionization process should result in the attenuation of Lyman alpha from neutral regions, but not from ionized regions. This provides a simple test: do you see high EW LAEs? They are rare, so you need to go wide.

CANDELS Lya Emission at Reionization (CLEAR; PI Papovich; Co-I Finkelstein)
THE FUTURE

- Current surveys can really only hope to detect Lyα emission from bright (J < 27 galaxies), and even then, we have maxed out (more or less) with 10m-class ground-based telescopes.

- JWST will have the capability to explore these lines to somewhat fainter flux levels.

  - At best, a factor of ~4 fainter in an ultradeep (30 hr) survey. Likely not nearly enough to detect Lya from faint galaxies at z > 7.

  - And this only over a small field, and for a <10 year lifetime.

- The future is with the GSMTs, and future very large aperture space missions.

  - For example, the GMT will have a sensitivity at least as good as JWST between night sky lines. This, coupled with a wide field of view, will create a powerful reionization machine.

  - ATLAST can do even better - by being above the atmosphere, we will be able to access Lya over the full redshift range for distant galaxies, with no night sky lines to block us.

    - With no lines, lower resolution can be used to achieve even higher sensitivities, allowing detection of Lyα for the newly discovered faint galaxies from JWST.
CONCLUSIONS

- We have made significant progress over the past few years understanding the high-redshift universe.

**THREE THINGS WE’VE LEARNED**

- Observable galaxies at Z=7 are not metal free, even the faint ones.
- Galaxies likely reionized the universe by Z=6.
- Lyman alpha surveys imply a rapidly rising neutral fraction at Z > 6.5.

**THREE THINGS WE DON’T KNOW**

- When did metals first form, and are there metal-free populations at Z < 10?
- Can we account for all the needed ionizing photons?
- What is the temporal and spatial evolution of reionization, and can LyA emission tell us?