Studying Cosmic Dawn with WFIRST and Subaru

WFIRST can address all three top level goals of the New Worlds, New Horizons Decadal Survey Report: Cosmic Dawn, New Worlds, and Physics of the Universe.

• WFIRST’s dark energy surveys address Physics of the Universe
• WFIRST’s microlensing & coronagraphic surveys address New Worlds
• WFIRST’s Guest Observer & Guest Investigator Program will prove equally compelling for studying Cosmic Dawn.
Ways to Study Reionization

• Look for the ionizing sources, estimate ionizing photon production, and compare to requirements for (re)ionization.
  – Galaxies
  – Quasars [or AGN more generally]

• Look for evidence of neutral gas and/or evidence of free electrons.
  – Lyman alpha galaxy statistics
  – Quasar spectroscopy
  – 21 cm emission

What can a 2.4m space telescope do?

Lyman break galaxies with HST slitless grism redshifts from Malhotra et al 2005

Mellema, Iliev, Pen, Merz, Shapiro, & Alvarez: reionization simulation
Deep Slitless Spectroscopy from Space

HST slitless spectroscopy: Deep programs, looking for Lyman break and Lyman alpha galaxies in the epoch of reionization:

- **GRAPES**: HUDF, G800 10 orbits x 4 PAs
- **PEARS**: G800, 8 fields to 5 x 4 PAs
- **FIGS**: G102, 4 fields 8x5PAs
- **GLASS**

Shallower, wider surveys emphasizing galaxy physics:

- **3dHST**: G141, c. 2 orbit depth
- **WISPS**

WFIRST can do such surveys ~ 100 times more efficiently.
Deep Near-IR Imaging from Space

- The basis for most redshift records since WFC3-IR launched, including this example from Finkelstein et al 2013

GOODS and CANDELS have invested 1000+ orbits in deep HST imaging surveys.

These images show a z=7.51 LBG from Finkelstein et al 2013. Seen in NIR, not on optical.
Example of high redshift galaxy searching with HST: GOODS + CANDELS images of a z=7.51 LBG from Finkelstein et al 2013. Seen in NIR, not on optical.

FIGS HST G102 spectrum of this galaxy, showing a LyA line; from Tilvi et al 2016.
HST Spectra & Imaging Combined

Figures from Rebecca Larson et al: FIGS GS2_1406, a newly discovered $z = 7.452$ high-equivalent width emitter from the FIGS survey.
(Submitted 14 Dec 2017)

Figure 4. Images of GS2_1406 (circled in purple) from the CANDELS survey showing it to be a clear $z$-band dropout. *HST* images are $3.7'' \times 3.7''$ (61 x 61 pixels), while *Spitzer* images are $7.8'' \times 7.8''$ (13 x 13 pixels).
Approaches to Reionization with WFIRST

• Lyman break galaxy census
  – Science: ionizing photon budget; galaxy formation and evolution as a function of environment

• Lyman alpha galaxy hunting:
  – Science: Statistics (including clustering) indicate ionization fraction of IGM.

• Quasar hunting:
  – Science: Black hole growth; ionization fraction evolution from spectra
Lyman Break Galaxies with WFIRST

• Lyman break galaxy census
  – Science: ionizing photon budget; galaxy formation and evolution as a function of environment
  – Guest Investigator (archival) science:
    • Large samples at bright end from High Latitude Survey,
    • More sensitive search using Supernova Survey data,
  – Guest Observer deep field imaging.
## A Large-Scale View of the Distant Universe

### The Kinds of Numbers We’re Dealing With

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Expected # (HLS)</th>
<th>Expected # (deg² GO)</th>
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</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′$_{LSST}$ = 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~29.
- To survey a sq. deg. with JWST to this depth would take several 1000's of hours of integration, plus extensive overheads.

![Histograms for z=7 and z=10](chart.png)
Lyman Alpha Galaxies with WFIRST

- Lyman alpha galaxy hunting:
  - Science: Statistics (including clustering) indicate ionization fraction of IGM.
  - Primarily done using GO deep field slitless spectroscopy
  - Rare, extreme objects from High Latitude Spectroscopic Survey?
Neutral Fraction Test: Lyman α Galaxies

Neutral and ionized regions / observed Lyα galaxies.

WFIRST can map Lyα galaxies over a field this size.
(163 cMpc, ~ 1 deg.)

Figures from Jensen et al 2012.

Ionized bubbles modulate visibility of Lyα. This is used to infer properties of the bubbles.

Prospects for LAEs with WFIRST

Figure 1 from H. Jensen et al 2012:
Left: ionized (white) & neutral (black) regions in simulated IGM
Right: Distribution of detectable LyA galaxies.
The Cosmic Dawn team is developing tools to plan for deep slitless spectroscopy with WFIRST

- V. S. Tilvi is doing simulations based on COSMOS CANDELS data with addition of Lyman alpha emitting sources.
- Isak Wold is generalizing his 3d data cube reconstruction algorithms (first developed for the GALEX grism).

*Image: Simulated deep WFIRST grism images. Left hand panel is like the planned grism. This is for 120 ksec, which is comparable to a cosmic dawn deep field.*
Simulation results

Left: input direct image.
Right: continuum subtracted data cube slice, generated by Isak Wold using his 3d reconstruction algorithm
Lyman alpha recovery results:
So far we have demonstrated recovery of LyA emitters down to $1e^{-17}$ erg/cm$^2$/s. This brings us into the range of observed LyA galaxies in cosmic dawn.

E.g. Oesch et al source at $z=7.7$;

E.g., Zitrin et al source at $z=8.7$;

E.g., Zheng et al 2017, [https://arxiv.org/abs/1703.02985](https://arxiv.org/abs/1703.02985);


First Results from the Lyman Alpha Galaxies in the Epoch of Reionization (LAGER) Survey: Cosmological Reionization at $z \sim 7$


FIRST SPECTROSCOPIC CONFIRMATIONS OF $z \approx 7.0$ LY$\alpha$ EMITTING GALAXIES IN THE LAGER SURVEY

Weida Hu$^{1,5}$, Junxian Wang$^{1,5}$, Zhenya Zheng$^{2,3,6}$, Sangeeta Malhotra$^{4,7}$, Leopoldo Infante$^{3,6}$, James Rhoads$^{4,7}$, Alicia Gonzalez$^{4}$, Alistair R. Walker$^{5}$, Lihua Jiang$^{3}$, Chunyan Jiang$^{2}$, Pascale Hibon$^{10}$, Felipe L. Barrientos$^{3}$, Steven Finkelstein$^{11}$, Gaspar Galaz$^{3}$, Wenyong Kang$^{1,5}$, Xu Kong$^{1,5}$, Vithal Tilvi$^{4}$, Huan Yang$^{1,4}$, XianZong Zheng$^{12}$
Lyman alpha recovery results:

Hu et al 2017, [https://arxiv.org/abs/1706.03586](https://arxiv.org/abs/1706.03586) (6 sources all $>\sim 1e^{-17}$ cgs)
Ly-a LF at z~7 from LAGER

Little Evolution of LyA LF at z ~ 3-6:
(Dawson et al 2005, Ouchi+08, Faisst+2014, Zhen+2016, ..)

At z~7:
1. Different Evolution at Bright & Faint Ends.
2. Bright-End Excess.

High Redshift Quasars with WFIRST

• Quasar hunting:
  – Science: Black hole growth; ionization fraction evolution from spectra
  – Guest Investigator science:
    • Large area of High Latitude Survey needed for these rare objects
    • WFIRST grism from HLSS, WFIRST IFC observations, or ground-based followup needed for confident quasar IDs
    • Further ground based spectra may be needed for full reionization testing.
Hunting the Sources of Reionization:
Quasars and AGN

• Accretion onto black holes $\rightarrow$ hot accretion disks $\rightarrow$ ionizing photon production.

• Census of AGN used to say, not enough for reionization. Recent changes:
  – Lower redshift of reionization from Planck;
  – New census of AGN from GOODS + CANDELS + 4 Msec CXO observations (Giallongo et al 2015)
Quasar at $z=7.51$
But this is just one object with line-of-sight variance.
WFIRST Grism is a valuable tool for quasar hunting.

- Powerful redshift machine:
  - quasar broad line resolved
  - measure both flux and width
  - for z>5, reaches AB ~24 for detection of average CIV lines

<table>
<thead>
<tr>
<th>Survey</th>
<th>Wavelength</th>
<th>Resolution</th>
<th>Depth</th>
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<tbody>
<tr>
<td>3d-HST</td>
<td>1.1-1.6</td>
<td>150</td>
<td>5E-17</td>
</tr>
<tr>
<td>EUCLID</td>
<td>1.0 -2.0</td>
<td>250</td>
<td>3E-16</td>
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<tr>
<td>WFIRST</td>
<td>0.95 - 1.9</td>
<td>600</td>
<td>5E-17</td>
</tr>
<tr>
<td>PFS</td>
<td>0.38-1.26</td>
<td>1900-3500</td>
<td>5E-17</td>
</tr>
<tr>
<td>DESI</td>
<td>0.36-0.98</td>
<td>2000-5500</td>
<td>1E-16</td>
</tr>
</tbody>
</table>
AGN and Reionization with WFIRST

• The Willott et al (2010) quasar luminosity function would imply
  – 2500 z ~ 7 QSOs,
  – 600 z ~ 8 QSOs,
  – 130 z ~ 9 QSOs, and
  – A handful up to z ~ 12.
Cross-correlating the 21 cm signal with Ly$\alpha$-emitters in the epoch of reionization

Team member Erik Zackrisson leading this topic for Cosmic Dawn SIT

Ly$\alpha$ more easily transmitted from ionized bubbles in the intergalactic medium → Anti-correlation expected between 21 cm and Ly$\alpha$-emitters in the partially reionized Universe

Measuring this anti-correlation will confirm that the redshifted 21 cm signal seen by SKA is real (i.e. not due to foregrounds) and provides strong constraints on cosmic reionization scenarios

Image Credit: D. Reynolds
Coordination of WFIRST and SKA-LOW Deep Fields

Team member Erik Zackrisson leading this topic for Cosmic Dawn SIT

WFIRST HLS deep field grism observations over 5 deg² down to \(5 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}\) → 4000 LAEs at \(z = 7\)
1500 LAEs at \(z = 8\)
300 LAEs at \(z = 9\)

If IGM mostly ionized at \(z \approx 7\) →
Much stronger 21 cm – Ly\(\alpha\) cross-correlation \(\xi\) signal at \(z = 8-9\) (WFIRST)
than at \(z \approx 7\) (e.g. Subaru HSC)
Synergies with Subaru
Subaru and WFIRST Lyman Alpha Samples

• **For Lyman alpha out to z=9.35, PFS followup can tell us about line widths and asymmetries.**
  – We have been developing the use of LyA profiles as indicators of LyA escape in individual galaxies (Yang et al 2017, ApJ 844, 171)
  – Such followup can refine measurements of LyA transmission, and hence reionization tests

• **HSC medium band imaging** could complement a deep grism survey, providing photometric measurements of strong lines in the optical (e.g. LyA for 2<z<3, where WFIRST grism would get rest optical lines)

• **HSC Deep Optical Imaging** can help separate Lyman alpha emitters from other emission lines.
Subaru and WFIRST Lyman Break Samples

• **Deep z-band HSC imaging** can enhance $z \sim 7$ LBG samples from WFIRST dramatically.
  – The anticipated z-band depth of LSST is 26.2; HLS goes to 26.5. Would like to go $\sim 0.5$ mag deeper.
  – Over what area...? TBD, but at least a few square degrees.

• **PFS Spectra for Lyman Alpha Line Fractions in LBG Samples**
  – WFIRST grism spectroscopy will reach line fluxes $\sim 1e^{-16}$ erg/cm²/s over the 2000 sq. deg high latitude survey.
  – LyA lines from $z>7$ galaxies are rarely above $1e^{-17}$.
  – PFS spectroscopy can address this, for $z < 9.36$
  – Each night could follow up 2400-9600 targets to flux levels of $0.7e^{-17}$ to $1.5e^{-17}$ erg/cm²/s
  – *This would turn the LBG sample from “only” ionizing photon census to also testing IGM neutral fraction*
Subaru and WFIRST Quasar Studies

• QSOs found in HLIS may need followup spectroscopy to confirm their nature.
  – Surface density low $\rightarrow$ IRCS? Or PFS, as a small part of a larger target selection batch?
• Where the HLSS covers the field, the WFIRST grism may provide adequate confirmation of quasars... But the proximity zone may require a clean ground-based fiber or slit spectrum $\rightarrow$ PFS (or IRCS)
Deep Thoughts on Field Selection
Thoughts on Deep Field Selection

**JWST NEP Time-Domain Field:**
- Accessible to JWST, and WFIRST, 365/24/7
- Darkest spot in the sky
- Clean region for extragalactic survey
- Ancillary data from radio through X-ray (incl. Cy25 HST UV-visible of central r~5', and LBT/LBC Ugrz + Subaru/HSC giz)
- Initial JWST GTO (Windhorst IDS team) coverage with NIRCam+NIRISS WFSS of 4 discrete spokes extending to ~7' (~49hrs total)
  - Each epoch: AB~28.5 mag in 8 filters w.NIRcam imaging, and AB~27.5 mag for parallel low-resolution NIRISS grism spectroscopy over a 12x12' FOV.
  - Superluminous Supernovae found with JWST could still be there for WFIRST
Closing thought on Subaru WFIRST program

• Personally, I like the idea of mixing key projects and smaller projects with Subaru.

• 100 nights is a lot, yet it sounds very finite...

• But if even half of that is spent on PFS spectroscopy, we could be discussing $10^6$ spectra: A much bigger number to share!

• Work out a mechanism for many science cases to have a fraction of the fibers in each PFS field.
Conclusions

• WFIRST will be a powerful tool for exploring Cosmic Dawn.
  – Both sources of reionizing photons, and probes of the neutral fraction.
  – A combination of Guest Investigator (archival) studies, and Guest Observer WFIRST studies
  – Combining WFIRST with Subaru observations will enable science beyond the reach of either observatory alone.
    • PFS followup: LyA galaxies, quasars, and LBGs for LyA lines
    • HSC imaging: z band for LBG selection; deep optical for LyA identification; and medium or narrow bands to complement grism surveys.
  – I and other team members will be glad to discuss