A strategy to study First Light with JWST

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1. Introduction

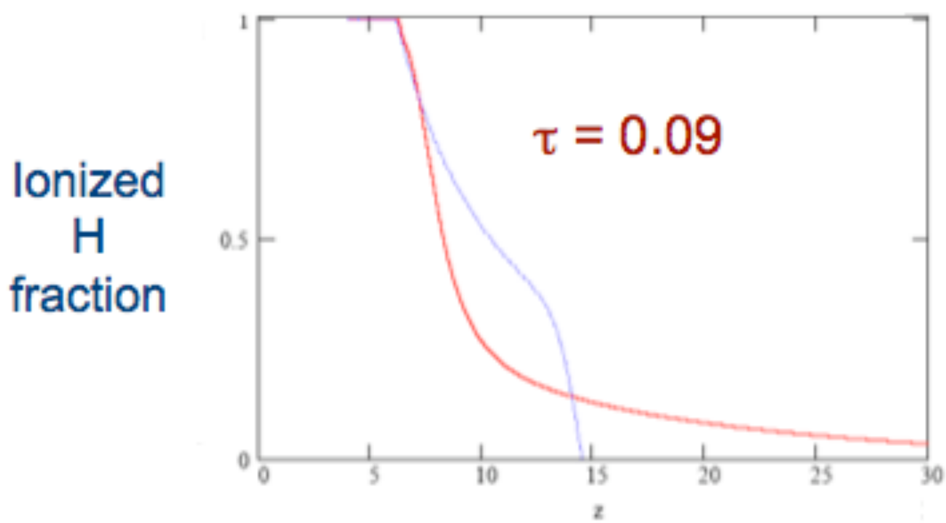
Before addressing how JWST can detect "First Light" we need to define what we mean by such term. First light is the appearance of the first stars (Population III) or mini-AGNs in the Universe. JWST is incapable of detecting individual Population III stars directly but could detected them as SNae, thought to be ultra-bright pair instability SNae or, even, Gamma Ray Bursts. The recent detection of the superluminous SN2006gy of absolute magnitude -22 (Smith et al. 2007, astro-ph/0612617) and detectable to z=20 and beyond highlights the appeal of this approach as a very effective way to identify the location of very high-z objects. It is worth noting that there are a number of possible explanations for SN2006gy one of which is that it is a pair instability SN. If that's the case and considering the relatively high metallicity of the host galaxy, we would have to abandon the idea that detecting a pair instability SN necessarily indicates detection of a Population III object. It is clear that detection of SNae and GRBs from Population III stars should be pursued, but in the following we denote by "First Light" the appearance of the first galaxies or first super star-clusters, i.e., associations of stars with luminosity of at least a few 10^{7-8} solar luminosities. First light objects (for any given mass) are very rare objects corresponding to rare density perturbations. For instance, the first light object within a ~0.5 Gpc^3 volume (roughly the volume containing one z=6 SDSS QSO) forms around z=50 (Trenti and Stiavelli 2007, ApJ submitted). The formation redshift of the first source decreases to roughly z=30 if one considers typical volumes that could be explored by JWST. Thus, strictly speaking we may be unable to see real first light objects but we will certainly detect "typical" first light, namely primordial or very low metallicity, objects corresponding to density perturbations of sufficient surface density to be seen by JWST.

One open issue is that of synchronicity, i.e. the range in redshift when Pop III stars form. Some authors argue that the transition from Pop III to other populations (Pop II or II.5) is relatively sharp in redshift and accompanied by an enrichment to 10^{-4} Z_{sun} or so (Bromm et al. 2003, ApJ 596, L135; MacKay et al. 2003 ApJ, 586, 1). It is possible that it is these second generation objects that grow to become the first galaxies. If this is the case, the first galaxies will have non-zero metallicity in the range 10^{-3} Z_{sun} - 10^{-4} Z_{sun} (see also Scannapieco et al, 2003 ApJ, 589, 35).

2. Why do we need JWST ? can it be done from the ground before JWST flies?

JWST is needed to find the first light sources. It is possible that the reionization epoch ends at low redshift (around 6) but there is no consensus on this, and on exactly how the first light epoch preceded the epoch of reionization. The following observational results argue for an early first light:

i) Compton optical depth from CMB measurements. Based on the three year WMAP data, Spergel et al. (2006, astro-ph/0603449) report a lower value of τ (0.09+/-0.03) than the one year WMAP data (Spergel et al. 2003 ApJS, 148, 175). This is compatible with previous estimates from a combination of techniques (McTavish et al. 2006, ApJ, 647, 799) and corresponds to a reionization redshift of z=11+/-2,5, but with a fairly asymmetric redshift distribution of the first reionizing sources that extends all the way up to z=20 or beyond (see also Venkatesan and Shull 2007, astro-ph/0702323). The three year WMAP optical depth value thus implies that the first light sources occurred at z>13 and possibly earlier. A constant ionizing photon production would give us z=16 for first light and a star formation rate slowly ramping up would push first light to higher redshift. The figure below illustrates this by showing the ionized fraction as a function of redshift for two models completing reionization at z=6.2 and characterized by the same value of $\tau = 0.09$ but with very different star formation histories. Detecting first light objects at z>13 requires extremely high sensitivity at wavelengths longer than 1.7 μm. Thus, it is inaccessible to HST even if equipped with WFC3 after SM4 in 2008, and so it is the exclusive domain of JWST.



ii) Galaxies at z~=7 with older stellar populations. A few objects have been discovered using Spitzer that appear to have old populations already in place at z=7 or so. Mobasher et al. (2005, ApJ, 635, 832) find that a galaxy likely at z=6.5 formed the bulk of its stars at z>9. Eyles et al. (2005, MNRAS, 364, 443; 2007, MNRAS, 374, 910) and Yan et al. (2005, ApJ, 634, 109) similarly found a number of very red objects at z=5-6, that imply a formation epoch at z>8 and possibly at z>10. Wiklind et al. find a larger sample of similar objects. Egami et al. (2005, ApJL, 618, L5) find that a galaxy at z=6.6-6.8 has a stellar population at least 50 Myrs old and possibly several hundreds Myrs old. This would place its formation at z=6.9 or higher. In conclusion, a number of galaxies with potentially very old SED's at z=5-7 has been found, constraining their epoch of first star formation to z>8-10.

iii) Lyman α sources at z=6.5. Malhotra and Rhoads (2006, ApJL, 647, L95) derive a minimum ionized volume fraction of 20-50% at z=6.5 from their sample of Lyman α sources. The only realistic way around this conclusion is that reionization was done by first light sources at z=6-7 and their metallicity is low so that the intrinsic Lyman α EW is very high. This is possible (e.g. Stiavelli et al. 2004, ApJL, 610, L1) but not very likely and would conflict with evidence of stellar populations formed at z>7. If the Malhotra and Rhoads conclusions are correct, then reionization was essentially completed at z=7 or earlier and first light occurred even earlier still.

3. *How can we tell that we have seen first light?*

Given the uncertainties in these measurements a number of techniques will need to be used to identify first light.

i) LF evolution. Models predict that the LF should evolve significantly for the first galaxies (e.g. Wyithe and Loeb, 2006, Nature, 441, 322). The break in their LF at luminosities L=Lstar will be much fainter than the present value, and, perhaps, the slope of the mass function will become steeper at lower masses and fainter luminosities (e.g. Yan and Windhorst, 2004, ApJL, 600, L1; Bouwens et al. 2006, ApJ, 653, 53). Equally importantly the value of the density of galaxies ϕstar is expected to decrease significantly at higher redshifts. We should aim at detecting both a change in the LF slope and value of Lstar and a change in the number density of objects.
ii) Metallicity. First light galaxies should have much lower metallicity than other objects. Their metallicity may be non-zero because of self-enrichment.
iii) Absence of an older stellar population. First light galaxies should not have older stellar populations. They will have SED ages no older than their first burst of star formation.

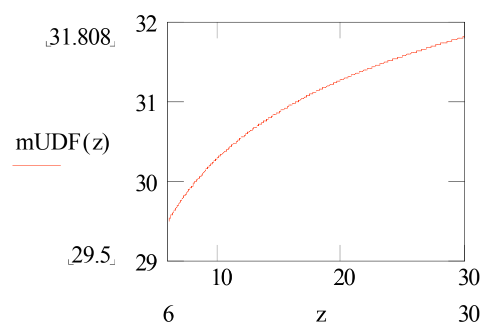
In the following we will focus mostly on item i) since it is the most relevant for NIRCam and it is the observations that would provide us with the candidates to be followed up spectroscopically by NIRSpec (for the metallicity determination) and MIRI (for the older population search).

4. *Detecting First light objects with NIRCam through the Lyman break technique*

4.1 Detecting a change in the LF slope and Lstar value

In order to study the slope and Lstar value of the Lf at z=6 we need to probe below the value of Lstar. Bouwens et al. (2006) have analyzed the combined GOODS and UDF extended data sets to derive a LF at z=6 extending down to zAB=29.5 (at S/N=8). This is 0.04 Lstar for the z=3 Lstar. They find evidence for both a steepening of the LF (in agreement with Yan & Windhorst 2004) and a dimming of the Lstar value with redshift. In order to see similar changes at z>6 we need to reach similar relative depths with JWST (see Figure).

z	AB_1350	Fnu (nJY)	lambda (micron)
10	30.284	2.80	1.34
12	30.551	2.19	1.58
15	30.869	1.63	1.95
20	31.267	1.13	2.55



The table gives the required depth (at S/N=8) in AB magnitudes and in nJy. The required sensitivity to identify these objects as Lyman break galaxies is the same for the filter longwards of the break (at the wavelength listed in the table) and shortwards of the break. Thus, in practice, this measurement requires a sensitivity of 30.3 in F090W, 30.6 in F110W, 30.9 in F150W, 31.3 in F200W, F277W, and F356W. The sensitivity requirement would continue to increase if we considered z>20 (see Figure). Trenti and Stiavelli (2006, ApJ, 651, 704) have shown that the extinction at rest frame 1400A due to dust in the intervening Damped Lyman a systems is on average less than 0.1 at these redshifts and less than 0.2 for 90 per cent of the lines of sight. Since we are looking for objects that have no dust and the intervening extinction is small we can safely ignore the effect of dust in our estimates.

4.2 *Detecting a change in the number density of high redshift galaxies*

The detection of a drop of a factor, say, 10 in the number density of galaxies might be indicative of having reached the first galaxies. Let's consider what this would imply for a NIRCam observing program obtaining data on a single ultra deep 2.2 by 2.2 arcmin field (using one camera) and on three adjacent 2.2 by 2.2 arcmin fields (using the other camera). This gives as 4.8 sq. arcmin at maximum depth and 14.5 sq. arcmin at one third of the exposure time. The combination of these two areas should give us a result not excessively dependent on changes of the luminosity function. Our predictions will be based, once again, on the Bouwens et al. luminosity function (corrected to match the UDF result to account for completeness effects), and we will assume that a factor 10 drop needs to be detected to 10 sigma, i.e, that we need at least 136 objects from the unevolving z=6 LF. The adopted dropout criterion is a standard one for lower redshift, namely a drop of 1.5 mag across Lymanα, a positive color shortwards of Lymanα, and a color bluer than 1 longwards of Lymanα.

The results are summarized in the table below:

F090W dropouts		z=7.9		Comments
Flux (nJy)	num obj	Npointings	Time (rel)	
2.8	174.04	1.0	1.0	
5	97.71	1.4	0.4	
10	41.19	3.3	0.3	
14	25.3	5.4	0.22	← optimal
F115W dropouts		z=9.8		
Flux (nJy)	num obj	Npointings	Time (rel)	
2.8	151.0	1.0	1.0	
5	80.8	1.7	0.5	
10	33.2	4.1	0.3	
14	20.0	6.8	0.27	← optimal
F150W dropouts		z=12.7		
Flux (nJy)	num obj	Npointings	Time (rel)	
2.8	57.9	2.4	2.4	
5	29.34	4.6	1.5	
10	11.046	12.3	1.0	
14	6.24	21.8	0.9	← optimal
F200W dropouts		z=17.0		
Flux (nJy)	num obj	Npointings	Time (rel)	
1.4	58.53	2.3	9.3	
2.8	27.1	5.0	5.0	
5	12.67	10.7	3.4	
10	4.09	33.3	2.6	← optimal
F277W dropouts		z=23.4		
Flux (nJy)	num obj	Npointings	Time (rel)	
1.4	11.82	11.5	46.0	
2.8	5.1	26.8	26.8	← optimal
5	2.15	63.3	63.3	

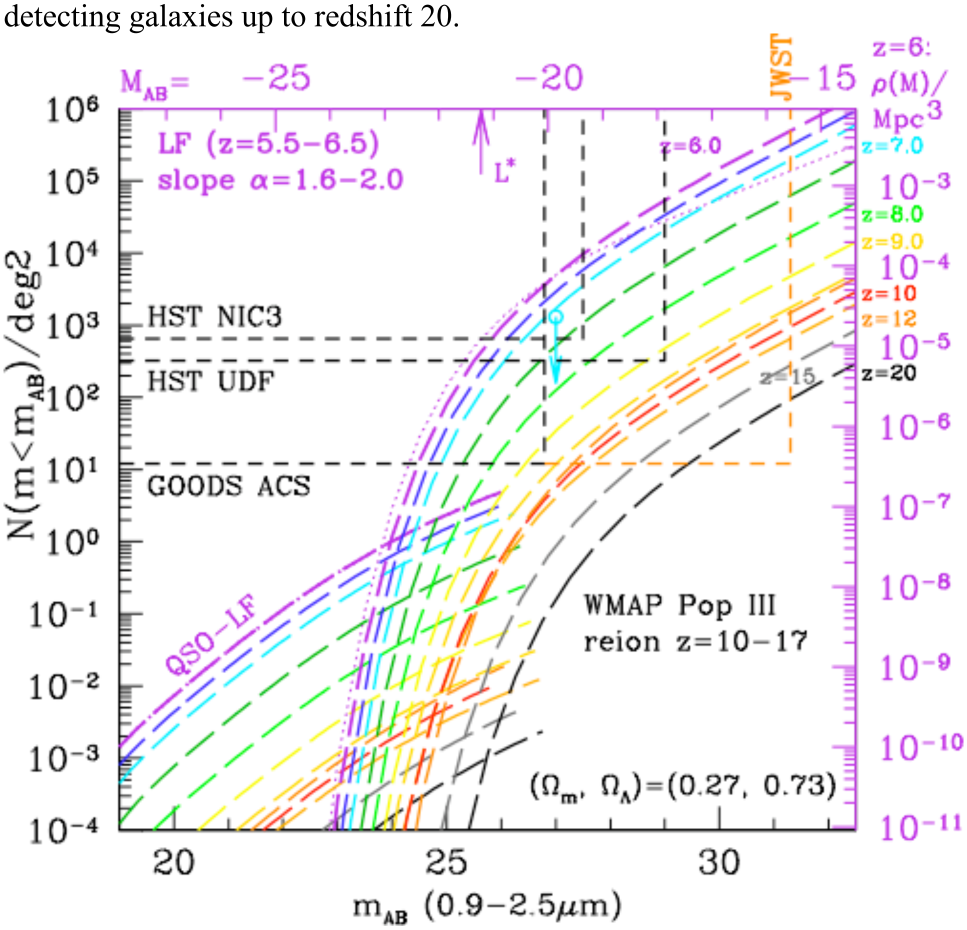
The first column gives the flux limit, the second the number of object observed with one pointing at three PA as described above, the third the number of pointings to detect 136 objects and the fourth column the exposure time relative to that to achieve 2.8nJy (about AB=30.3 at 1-2 micron) on a single pointing in the given band.

The table shows that if we assume that the LF will not evolve significantly apart from its normalization, we could meet the requirement of detecting a factor of ten drop in number density by going shallower over a larger area.

Considering all bands together a hypotetical survey would consist of the following combinations of pointings and depth:

N pointings	Filter	Flux (nJy)
27	F444W	5.6
27	F356W	2.8
27	F277W	8
27	F200W	14
7	F150W	14
7	F115W	14

In practice one would follow 27 fields also with the shortest filters as the exposures are done in parallel with the long exposures at long wavelengths. The figure below by Windhorst and collaborators (2007, astro-ph/0703171) shows how a comparable strategy consisting in observing with JWST an area comparable to GOODS would be effecting in detecting galaxies up to redshift 20.



One benefit of this approach is that it is robust with respect to cosmic scatter. However, its danger is that even modest evolution of the LF would have great impact and entirely change the optimization of the JWST survey. For instance, if the value of Lstar evolves beyond z=6 by one magnitude (which is roughly the evolution from z=3 to 6) then the 6 F200W dropouts per pointing detected at 14 nJy would decrease to 0.8 per pointing, increasing the required number of pointings to 172 (up from 21). With this modified LF one would be better off integrating down to 5 nJy and observing 18 pointings. Assuming successful installation in 2008, it is possible that WFC3 will provide sufficient knowledge of the faint end LF slope at redshifts z=7-8 that a more accurate prediction of the JWST survey strategy will be possible.

4.3 Ab initio estimate of a first galaxy luminosity

What are the first galaxies? The efficiency of cooling drops dramatically below 10^4 K and it is reasonable to define the "first galaxies" as the first haloes that achieve a virial temperature of 10^4 K.

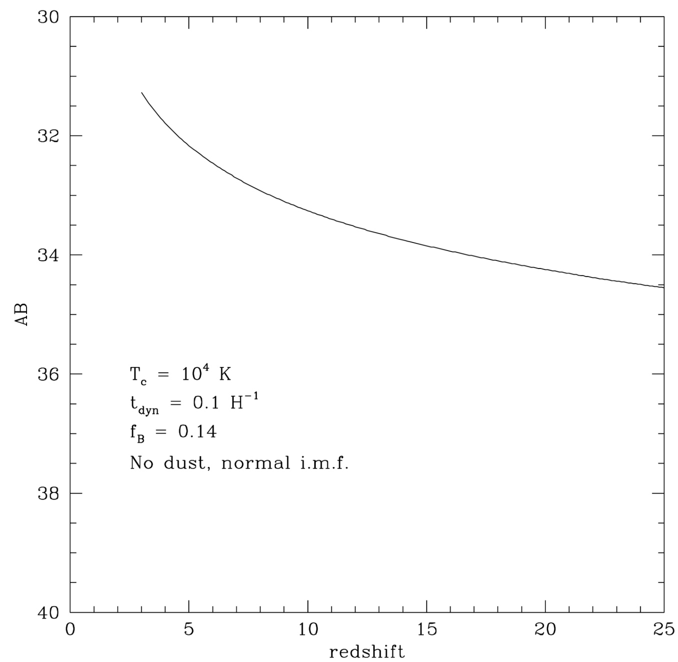
Defining a halo as a structure with an overdensity above 100, one can compute the minimum mass of a halo with $T_{vir} = 10^4$ K as a function of redshift. This is given e.g. by Hernquist and Springel as

$$M_c = \left(\frac{T_c}{9.5 \times 10^7 . \chi(z)} \right)^{3/2} 10^{15} h^{-1} \mathrm{M}_{solar} \,.$$

$\chi(z)$ is simply $(H/H_0)^{2/3}$.

The dynamical time will be of order 0.1 H^{-1} since the density is 100 times the surrounding critical density.

We assume that all of the baryons are transformed into stars on this dynamical timescale with a normal I.M.F.. This is optimistic, because likely not all baryons are formed into stars, but is pessimistic because the I.M.F. may be top heavy. With these caveats, his then gives a minimum luminosity and a minimum brightness for such "galaxies" as a function of redshift.



The very first galaxies will have the minimum mass and will therefore, in principle, lie on this line. This line therefore represents where one would like to achieve with JWST to assure detection of the first galaxies or super star-clusters, i.e. AB ~33 should allow us to detect the "first galaxies" almost independent of their redshift.. The objects will be somewhat brighter if their IMF is top heavy.

4.4 Summary of requirements for detection using the Lyman break technique

We have followed three different approaches to derive a requirement for the sensitivity needed to detect first light with JWST: i) use of the UDF relative depth as a guideline, ii) assumption of a non-evolving LF from z=6, and iii) an ab-initio calculation.

Method	F200W depth (nJy)
UDF relative depth	1.63 for z=15, 1.13 for z=20
Non-evolving LF from z=6	14 for z=13, 10 for z=17
Ab-initio	0.2 for z=10

Clearly, first galaxies in the sense of the ab-initio calculation will be extremely hard to detect at any redshift and the uncertainties in the LF and its evolution would suggest to retain as much sensitivity as possible. In the following, we will assume that JWST will carry out an ultra deep survey to explore the faint end of the luminosity function at z>8, and also a shallower wider area survey to better control cosmic scatter and sample the brighter part of the LF at z>7-8.

5. *Detection of the Lyman α line*

Let's compute the Lyman α intensity for objects with a 1350A flux compatible to the limits discussed previously. We follow the approach of Stiavelli et al. (2004 ApJ 600, 508) and assume that these sources have very low or zero metallicity and are not clustered so that each object has to grow its own Stroemgren sphere. The intensity of Lyman α is proportional to *1-f* where *f* is the escape fraction of ionizing photons which we take here to be 0.5. The observed Lyman α intensity depends on the Lyman α escape fraction and is proportional to the total ionizing intensity and to the line width. For the objects of interest a reasonable value for the Lyman α escape fraction is around 20 %.

This places the following requirement on the detection of first light sources by narrow band excess:

z	AB_1350	Ly α (cgs)	λ (μm)
10	30.284	1.7e-18	1.34
12	30.551	8.89e-19	1.58
15	30.869	4.02e-19	1.95
20	31.267	1.47e-19	2.55

It should be noted that reaching levels fainter than Lstar (as in this case) it is more demanding for Lyman α sources as the escaping Lyman α fraction decreases with decreasing luminosity.

6. *Detection of Supernovae from Pop III stars*

The detection of a supernova from a Population III star is the only reasonable possibility for JWST to directly detect a single Pop III star. Unfortunately the expected probability of such a detection is very low (e.g. Weinmann and Lilly, 2005 ApJ, 624, 526 find 4 per square degree per year at z=15) and this method has to rely on parallel observations with NIRCam or the FGS, or on serendipity discovery. If Pop III stars are also visible as GRB they could be studied by following up GRB events - detected by some other mission - with JWST.

7. *Deriving the properties of the first light sources*

Once a few candidate first galaxies are identified we need to verify that they have indeed young stellar populations of low metallicity without pre-existing, older, stars. This is best accomplished by JWST through NIRSpec spectroscopy and through MIRI imaging.

7.1 NIRSpec Spectroscopy

A good metallicity indicator for a first light source is the oxygen line at 1665A. One can establish a connection between metallicity, luminosity and line intensity using, e.g., Cloudy. Requiring detection of a metal content as low as 10^{-3} Zsun on a 5 nJy sources (e.g. one magnitude brighter than the limits discussed previously) gives us a line intensity of 4.5 10^{-19} erg cm^{-2} s^{-1}.

7.2 MIRI Imaging

In order to rule out the presence of an older stellar population it is sufficient to require detection with MIRI at 7 μm of the candidate first galaxies at a lower S/N of 2 or 3. The reason for this is that any older population would be much brighter in the MIRI bands than in the NIRCam bands and then easier to detect. Thus, the experiment is designed to provide a detection of a possible older population. A non-detection is a confirmation of the first-galaxy nature of the object, and the MIRI sensitivity should be chosen such that a >3-sigma detection can be made at wavelength > 7 μm for a given first light candidate found with NIRCam at wavelengths < 5 μm.

8. Lensing amplification

Gravitational lensing by a cluster is generally difficult to use to derive a luminosity function because of the significant dependence of the amplification on the lens model. However, once a LF has been measured, lensing can be used to obtain a significant amplification of sources with number densities of a few per square arcmin, as these sources would be likely to be amplified by a cluster (Kneib et al. 2004, ApJ, 607, 697; Stark et al. 2006, astro-ph/0701279). The gravitationally amplified sources would be much better candidates for followup with NIRSpec and MIRI.

9. A possible Observing program

We can estimate the time needed for the JWST Ultra Deep Field by requiring the sources to be detected at S/N=5. The total time estimates take into account the fact that the long wavelengths are observed in parallel to the short wavelengths.

	Ultra Deep		Shallow Wide		
Filter	AB S/N=5	Exposure Time (hrs)	AB S/N=3	Number of fields	Exposure Time (hrs)
F070W	30.3	23.4	28.5	7	8.8
F090W	30.6	35.8	28.5	7	7.7
F115W	30.9	54.2	28.5	7	6.8
F150W	31.3	97.6	28.6	7	5.8
F200W	31.3	83.2	28.7	27	5.0
F270W	31.3	83.2	28.7	27	15.2
F336W	31.3	83.2	28.7	27	124
F444W	30.9	99.8	28.2	27	77.7
Total		294.2			223.4

The total time in the Ultra Deep survey is dominated by the short wavelength channel while the total time in the shallow wide survey is dominated by the long wavelength channel. In total about 520 orbits would be needed to carry out the two surveys.

A Lyman a survey carried out at a few wavelengths to explore sources around z=15 would require about 35 hours per wavelengths for about 200 hrs with the FGS TF.

Studying spectroscopically candidates at the 5 nJy level will also required about 30 hrs with NIRSpec for a total of 180 hrs for 6 fields (assuming that the candidates will have low number density).

In total, this program would require about 900 hrs with JWST. This is a large commitment but, for instance, smaller than the shallow/intermediate/ultra deep survey carried out with HST/ACS with the combination of COSMOS, GOODS, and UDF. In fact, these HST surveys received 1600 orbits or 1065 hrs on target.