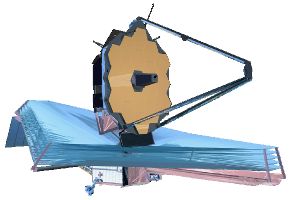
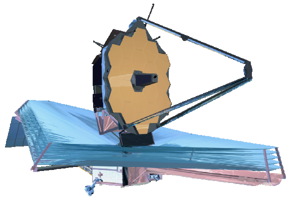
 

Reionization

M. Stiavelli
STScI, Baltimore

10/11/2010

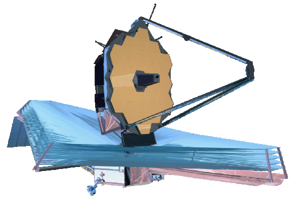



HUBBLE UDF ULTRA DEEP FIELD

Reionization

Plan:

- Brief overview
- When
- Who
    - Hubble's contribution
- James Webb Space Telescope

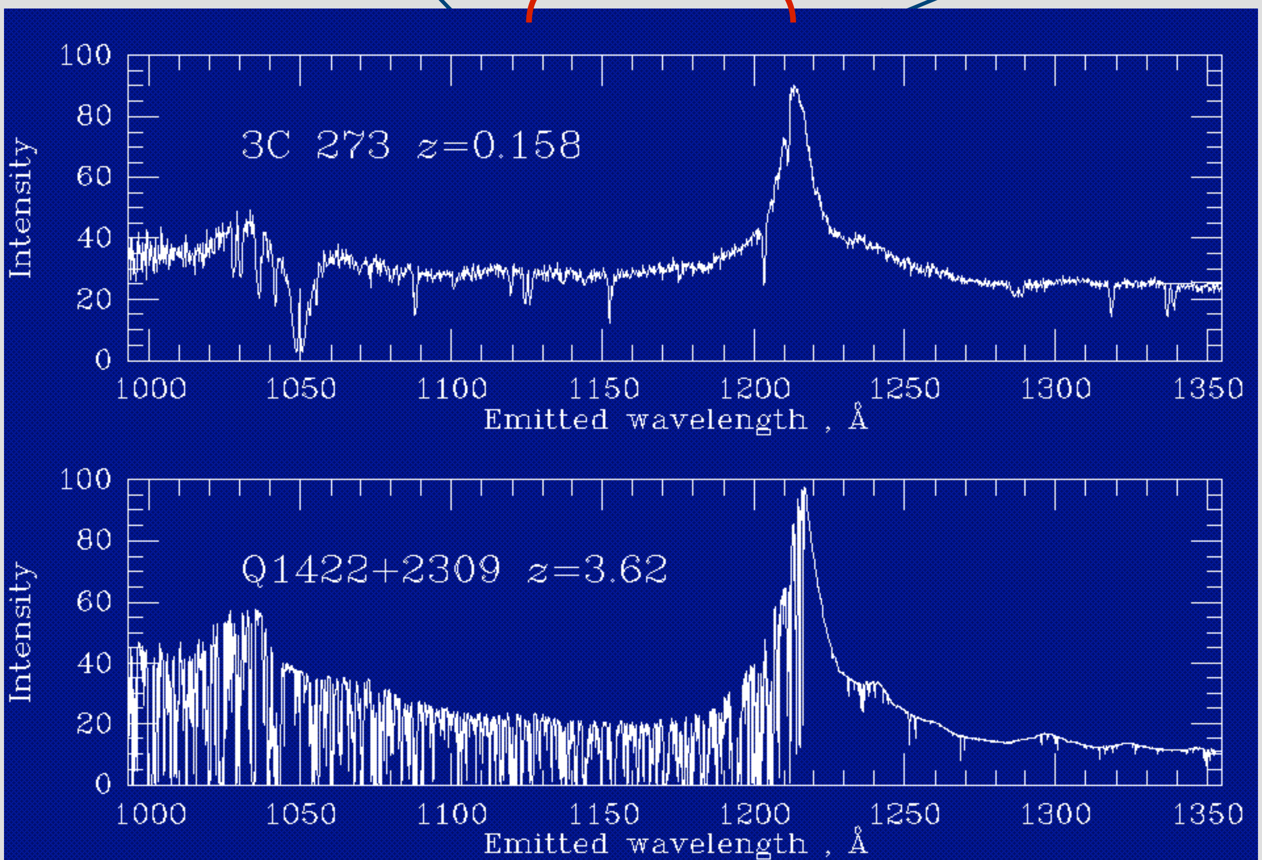


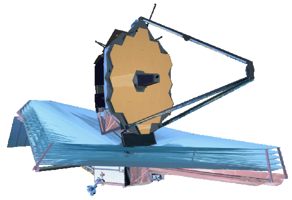
HUBBLE UDF ULTRA DEEP FIELD

Hydrogen is ionized : we see radiation at 912 < λ < 1216 A in QSOs at z<6

Here something reionizes Hydrogen

z~1300, Hydrogen recombines, CMBR “released”



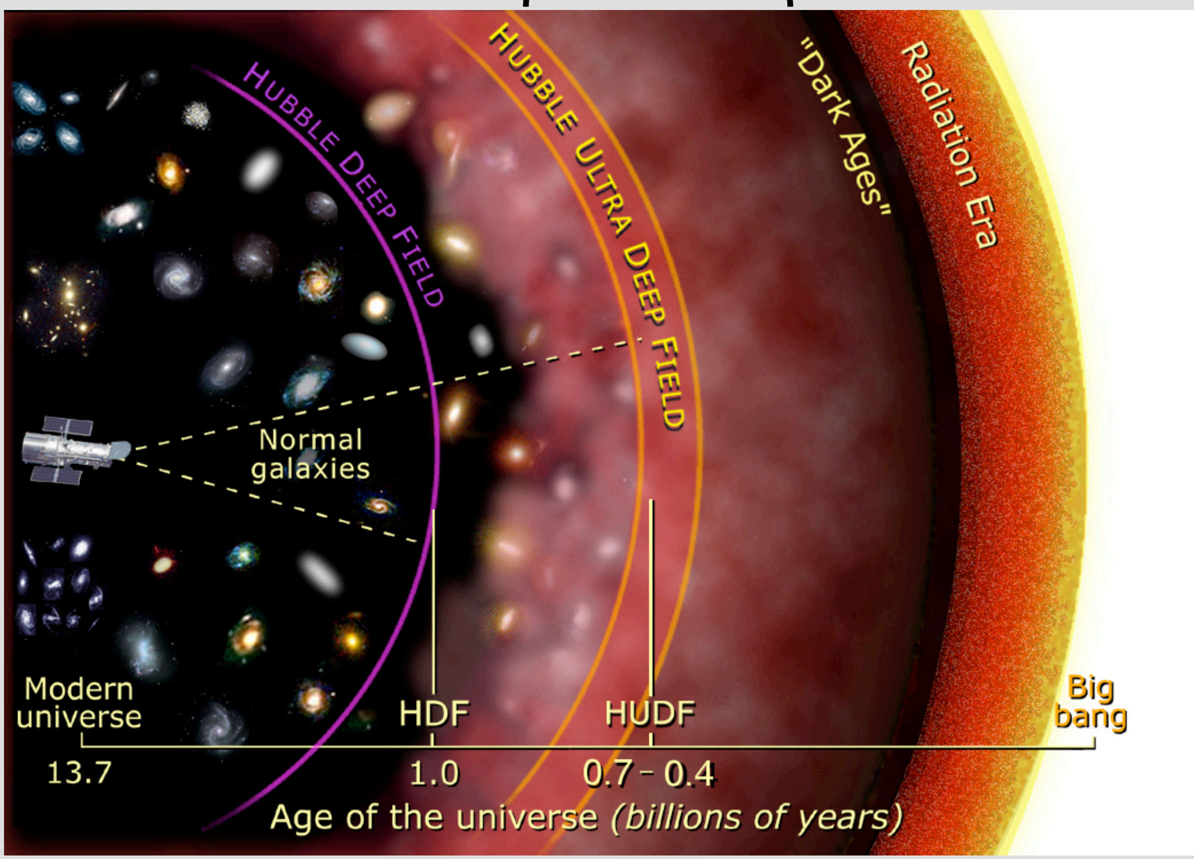


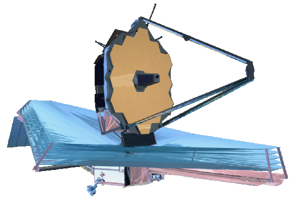
HUBBLE
UDF
ULTRA DEEP FIELD

"Dark ages"

7% of the age of the Universe

- first light sources
- Population III
- reionization of H
- reheating of IGM

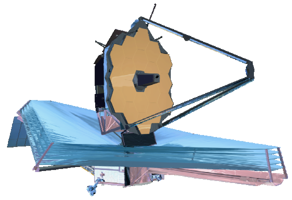




Energetics

Fusing 4 protons into an Helium nucleus releases ~7 Mev per proton. Ionizing an Hydrogen atom requires a minimum of 13.6 eV. Thus, if the energy source is fusion, reionization of Hydrogen will require a fraction of $2 \cdot 10^{-6}$ of all Hydrogen to be processed inside a star. In practice recombinations increase the number of required ionizing photons per Hydrogen atom and not all photons will be sufficiently energetic. With reasonable assumptions, the energetic need will be 30 times higher, thus requiring processing of a fraction $\sim 6 \cdot 10^{-5}$. If the yield in metals is 30% of the Hydrogen mass processed inside a star, the Universe will have a metallicity 10^{-3} solar at the end of reionization.

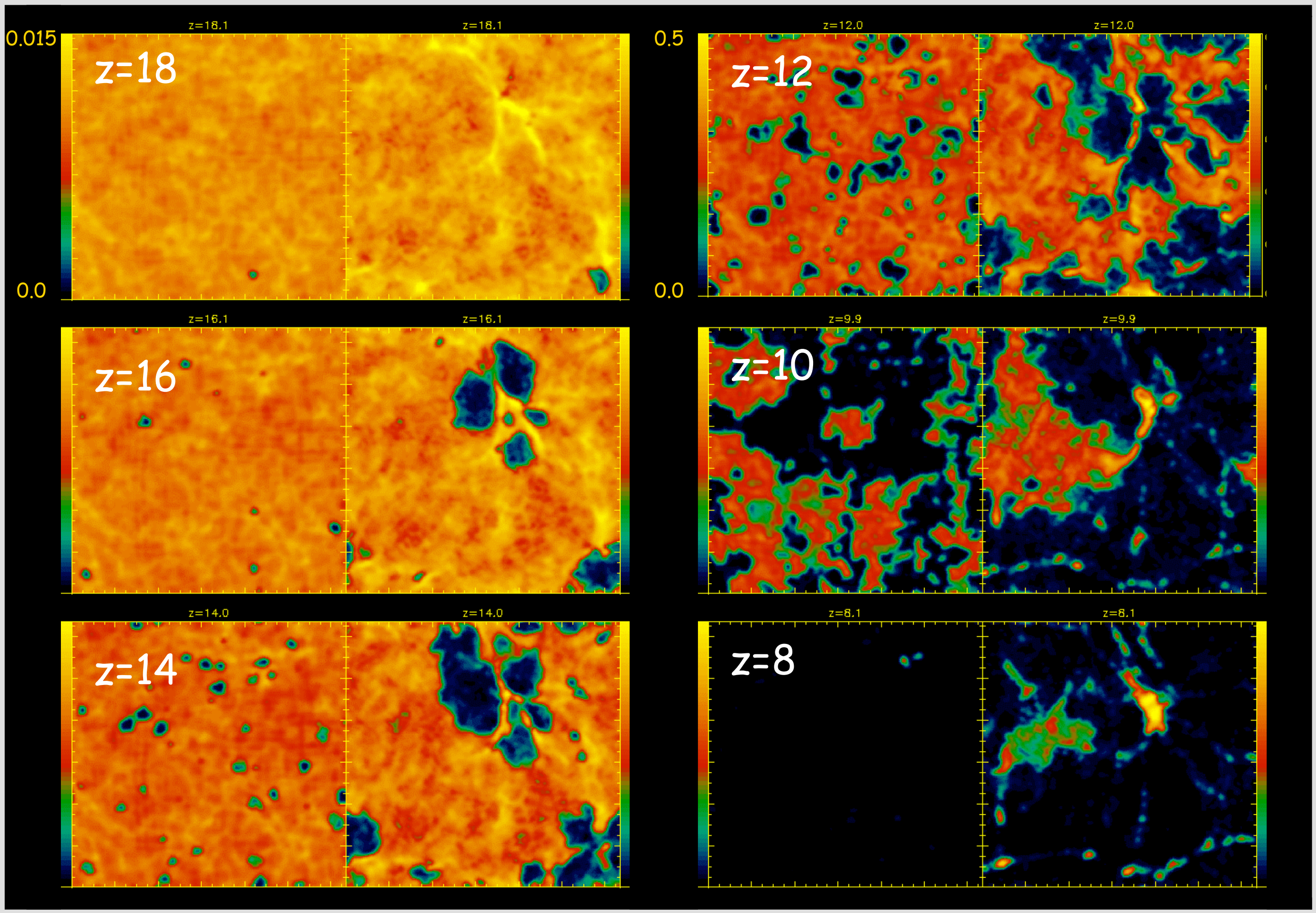
In the Universe there are $\sim 10^{10}$ photons for each proton. Thus, releasing ~30 photons for each proton during reionization will not leave a large signature in the cosmic background. A very inefficient process would leave a signature in the CMB (which is not observed).



HUBBLE UDF ULTRA DEEP FIELD

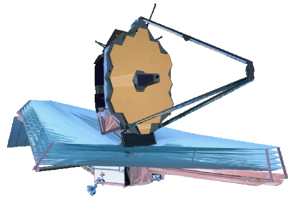
CAUTION: field to field variations!

Density of neutral hydrogen



(BC, Stoehr & White 2003)

20/h Mpc 10/h Mpc

Reionization of Helium

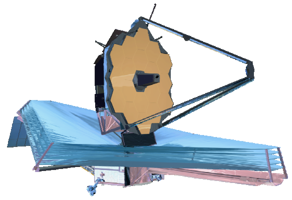
He reionizes at lower redshift, z~3 and most likely thanks to a major contribution by AGNs.

Hubble (and FUSE) have dominated this field. The first detection of a Gunn-Peterson effect was claimed by Jakobsen et al 1994 using FOC. STIS was used by many groups including Heap et al. 2000.

Recently, COS observations by Shull et al. (2010) have suggested that the reionization of Helium may occur at slightly lower redshift then previously assumed.

As for the case of Hydrogen, field to field variations remain a concern.

When?

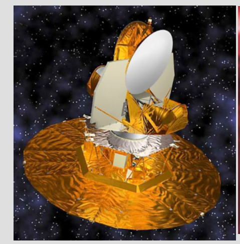
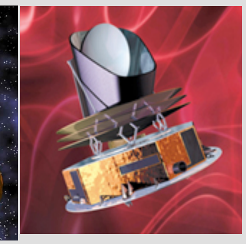



Backgrounds

HUBBLE UDF ULTRA DEEP FIELD

The reionization process leaves a small signature in the cosmic backgrounds:

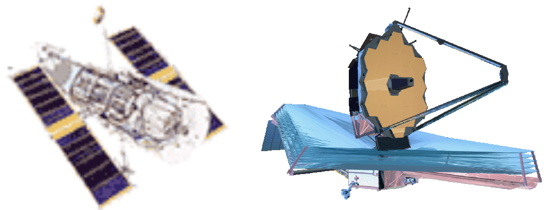
• CMB gives a value of the Thompson optical length → WMAP, Planck

• Lyman α leaves a trace of the history of reionization (I should say of recombination!) → JWST (?)

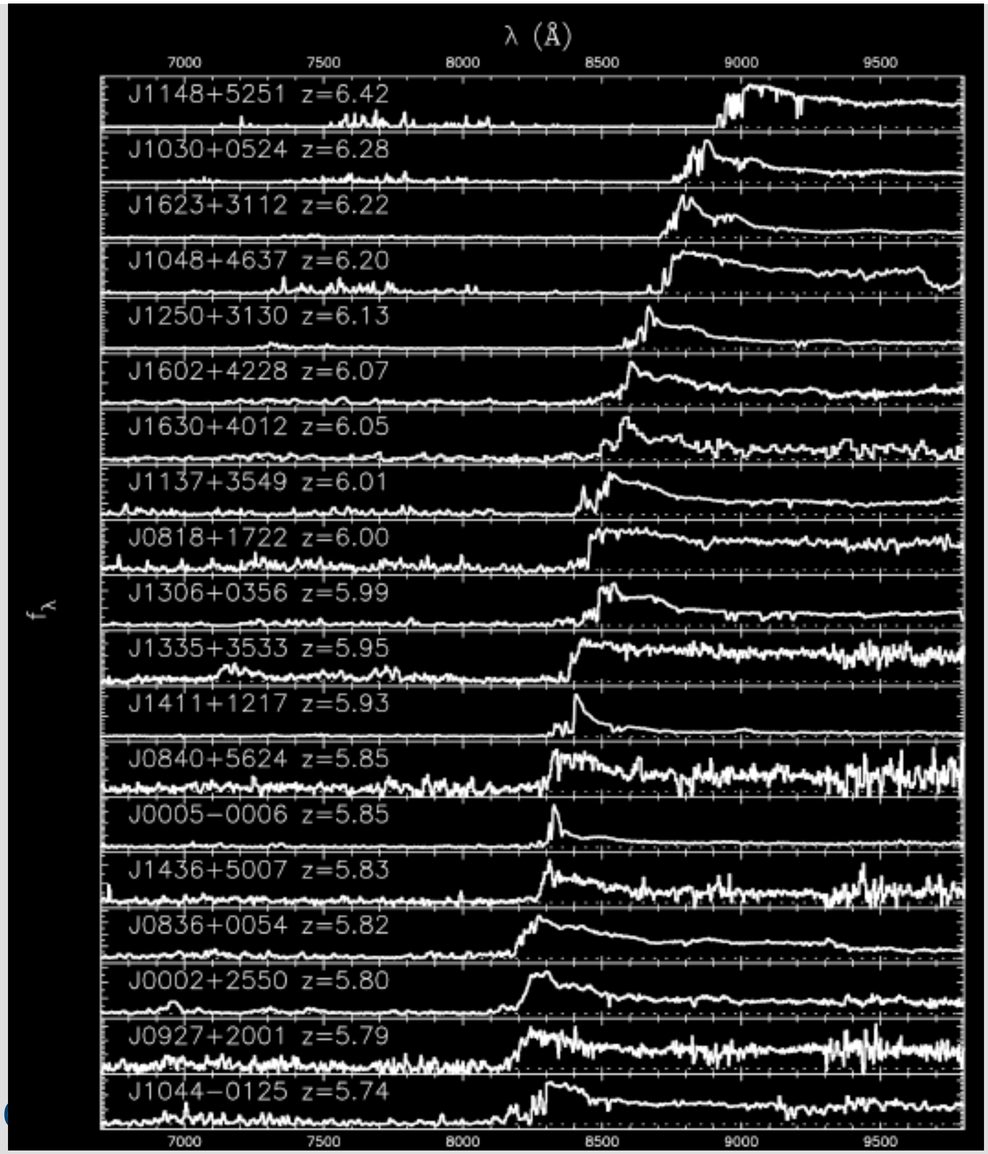
• 21cm also leaves a trace of the history of reionization → Lofar, MWA

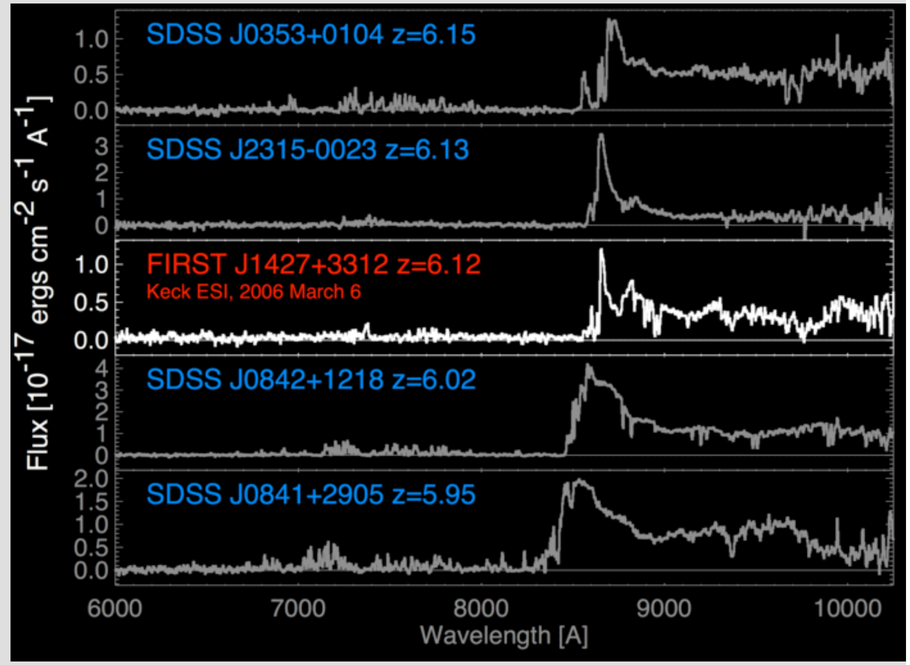
Essential but tells us nothing about "who did it!"



End of Reionization

HUBBLE UDF ULTRA DEEP FIELD





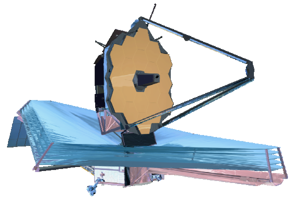
Courtesy of R. White

SDSS QSOs → ~z=6

Column density statistics

Compatibility with Lyα sources?

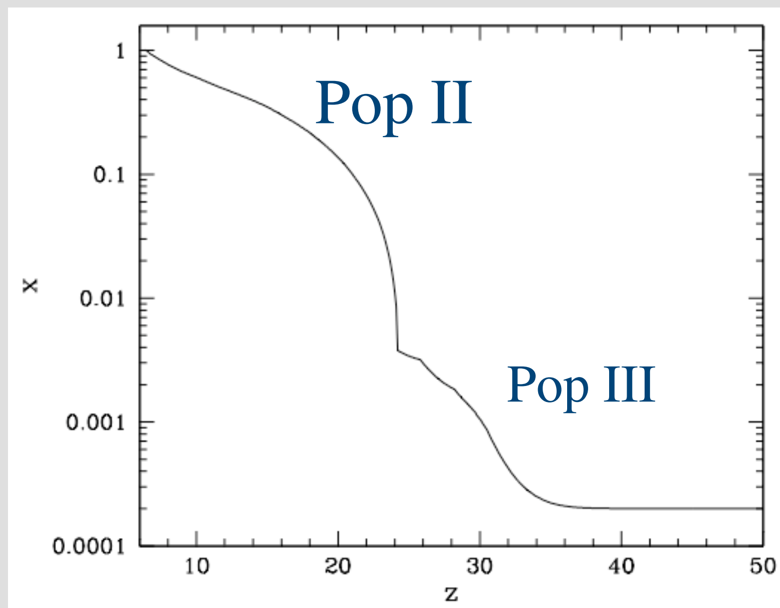
Fan et al., astro-ph/0512082

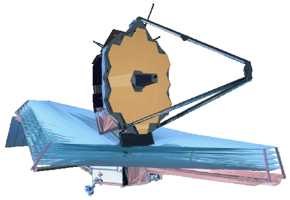
 

Summary of Tests of Reionization

- QSO Spectra suggest reionization ending at z~6
- WMAP 5yr suggest reionization at z=10.8±1.4
- Lyman α surveys suggest neutral hydrogen fraction below ~ 0.2 at z=6.7.
  - Different indicators are sensitive to different column densities.

It is possible to build toy models that satisfy all constraints.

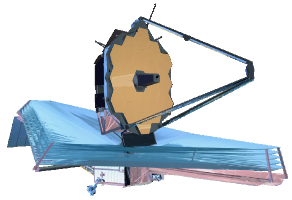


Summary of Tests of Reionization

- It is likely that reionization of Hydrogen started at very high-z (z > 10) and continued down to z~6.5

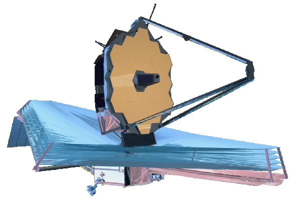
Who?

Expectations

HUBBLE ULTRA DEEP FIELD

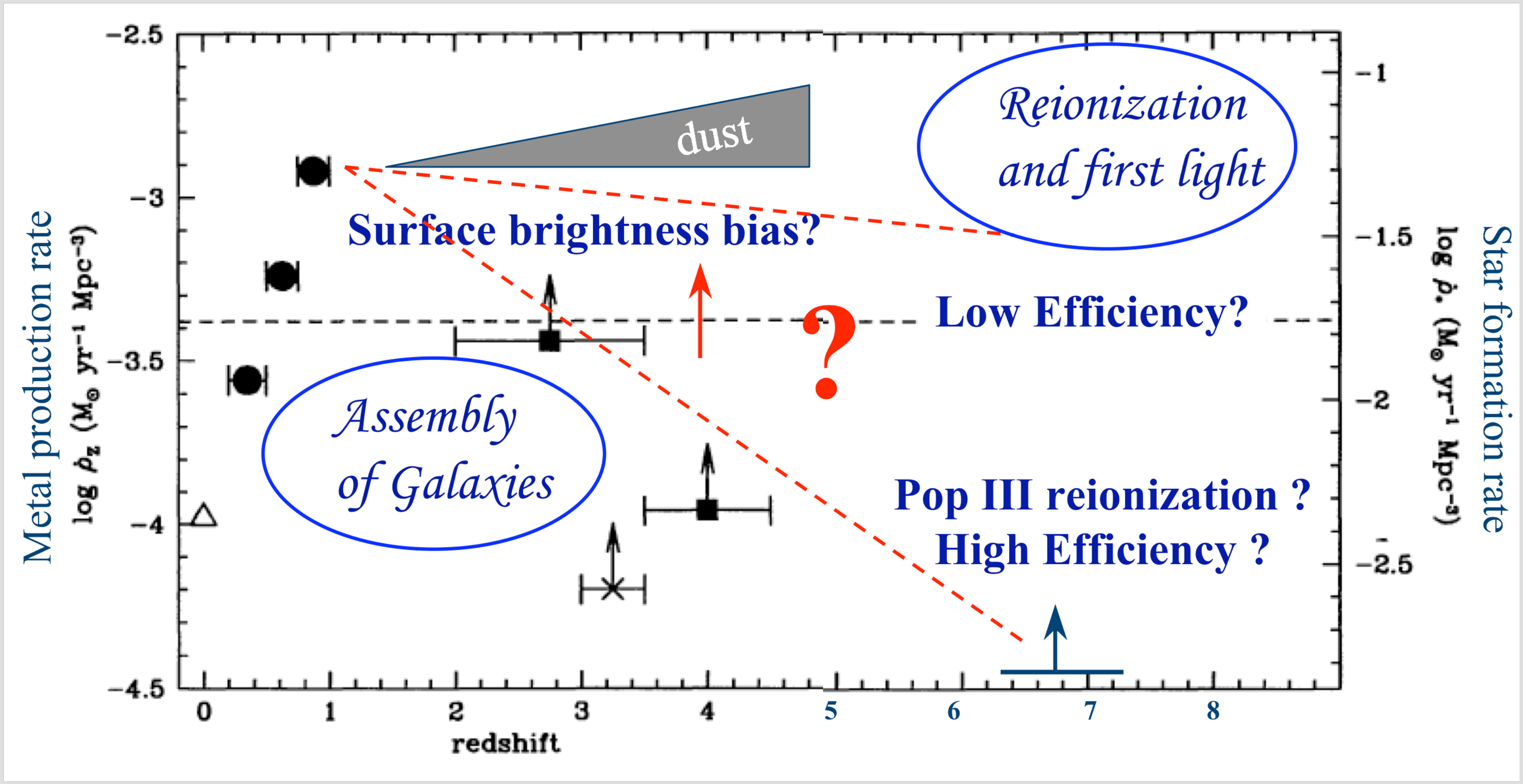
- It is generally assumed that galaxies are responsible for the reionization of Hydrogen.
- The idea that AGNs do not contribute significantly rests on two considerations:
  - If the main contribution was from AGNs they would also reionize Helium who would then need to recombine in order to reionize again at z~3.
  - The observed SDSS z~6 QSOs contribute only a fraction of the ionize flux needed.
- Thus, one has to look for galaxies



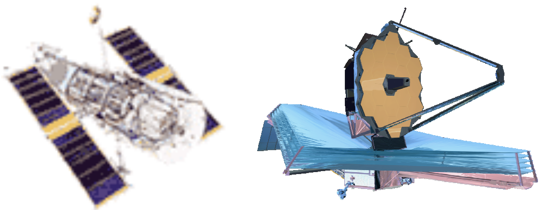
Star-formation history of the Universe

HUBBLE UDF ULTRA DEEP FIELD

Figure shown at the HST Treasury conference in Nov. 2002.

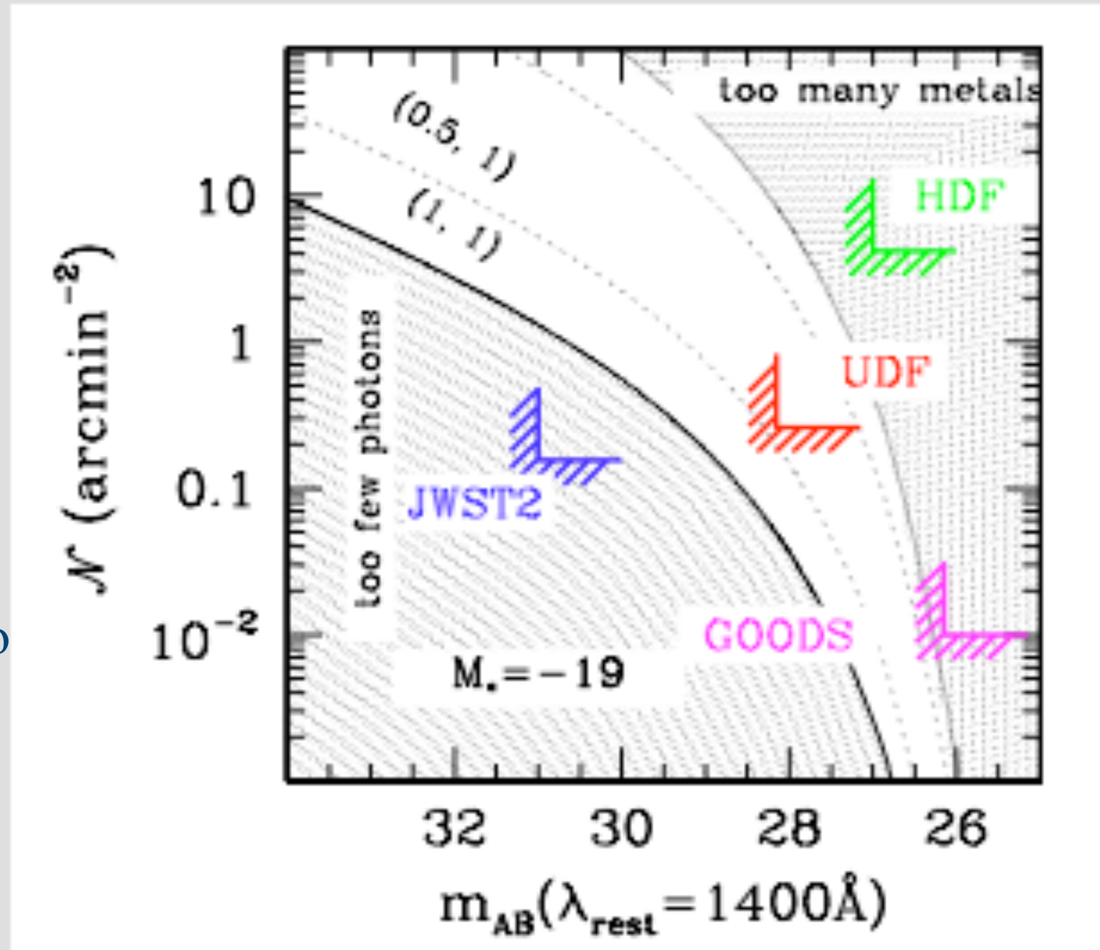


Based on Madau et al. 1996

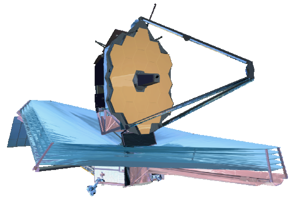


What to expect?

- With reasonable assumptions on LF and galaxy properties one can determine areas in the number density-mag plane where objects responsible for reionization would be found.
- the UDF had a chance to find some of these objects

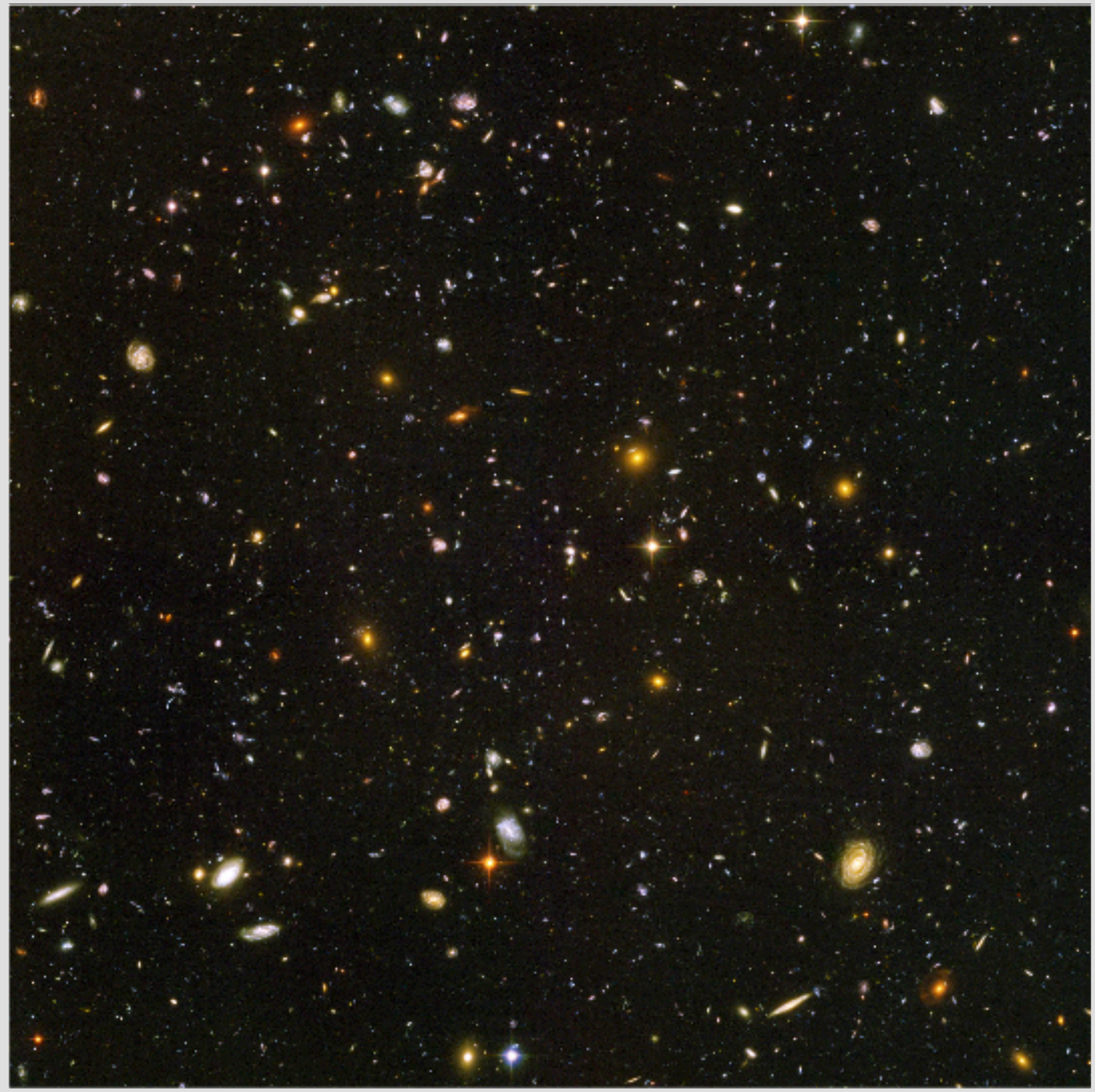


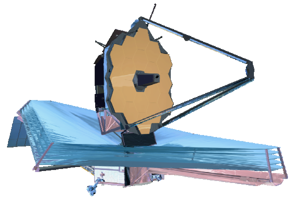
(Stiavelli, Fall, Panagia, 2004a)



Ultra Deep Field

- Deep enough to study "typical" $z=6$ galaxies
- $<10^{-34}$ W m^{-2} s^{-1} Hz^{-1}
- ~0.1 photon/s



Surveys

HUBBLE UDF ULTRA DEEP FIELD

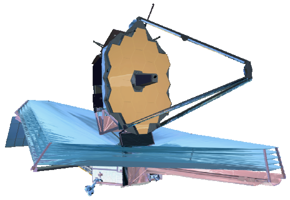
GOODS - PI Giavalisco (ACS)

UDF - PI Beckwith (ACS, NICMOS)
Thompson (NICMOS)

UDF05 - PI Stiavelli (ACS, NICMOS)

UDF09 - PI Illingworth (ACS, WFC3)
BoRG - PI Trenti (parallel survey, WFC3)

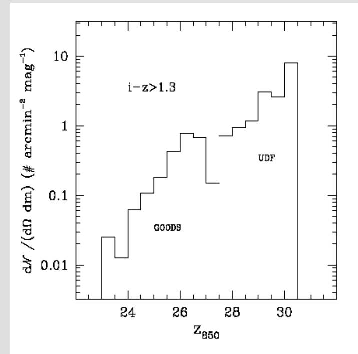
CANDELS - PI Faber/Ferguson (ACS, WFC3)

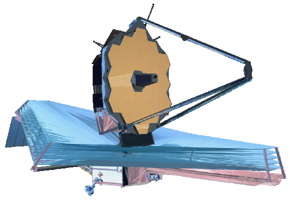


Reionization - 1

Today with UDF + GOODS we know more z=6 objects than we knew at z=4 ten years ago

(e.g. Bouwens et al. 2005, >500)

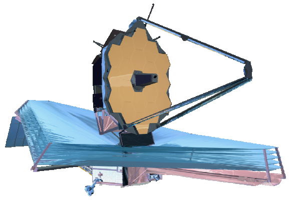




Reionization - 2

The contribution of a population to reionization can conveniently be expressed in terms of surface brightness. The faintest SB needed for reionization is only slowly varying with redshift.

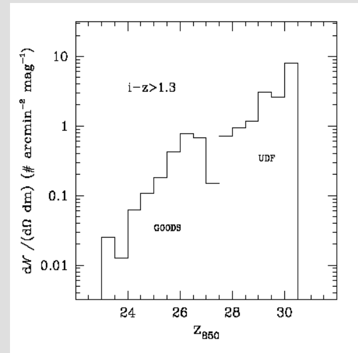
At z=6 observed galaxies contribute SB_{1400} = 25.4 mag arcmin^{-2} against a limit of 28.8. This gives only a factor ~23 of margin over the best case. The margin for a solar metallicity population with a Salpeter IMF would be only a factor of two: too little to accommodate a finite escape fraction and clumping.

Reionization - 3

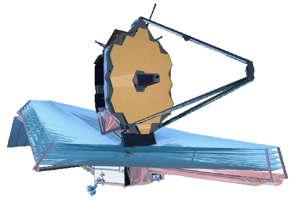
Today with UDF + GOODS we know more z=6 objects than we knew at z=4 ten years ago

(e.g. Bouwens et al. 2005, >500)



Ionizing flux from z=6 tantalizing close to what is needed for reionization but not quite enough. Possibilities:

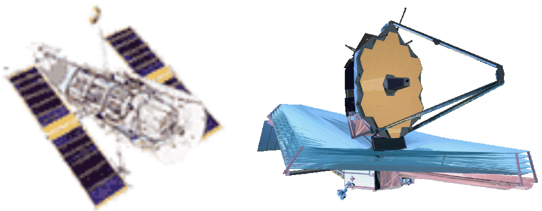
- **z=6 do the job because they are at very low metallicity**
  - Stiavelli et al. 2004b
- **z=6 do the job because LF has many dwarf galaxies**
  - Yan & Windhorst 2004
- **z=6 don’t do the job alone → look at z=7+**
  - Bunker et al. 2004, Bouwens et al. 2004, 2005



Enters WFC3

Objects at z>7 are faint and relatively rare. In order to characterize their properties we would need samples comparable to those for z=6 objects from GOODS and the UDF. This is possible with the IR channel of WFC3.

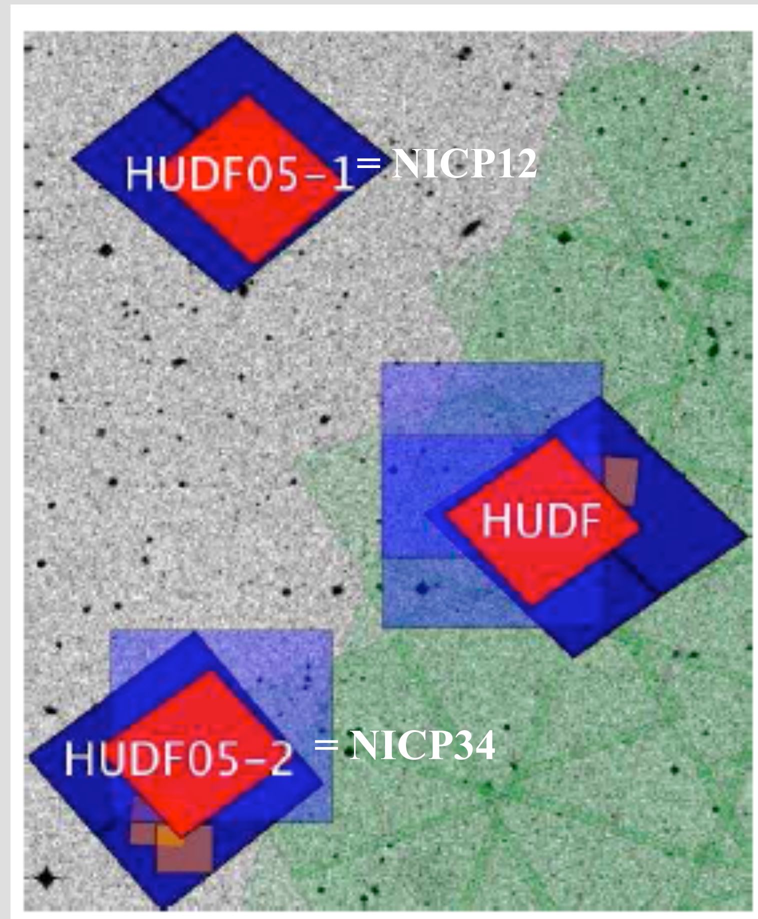
WFC3/IR can cover the same area as NICMOS Cam3 to the same depth in one tenth of the time. This allows us in principle to extend to the near-IR surveys like GOODS and the UDF.

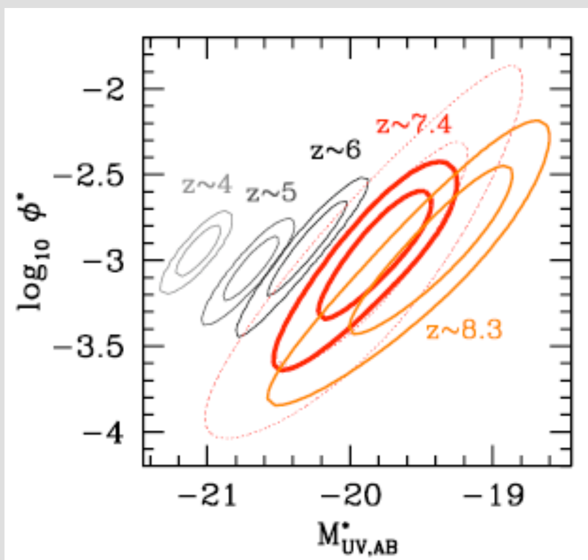


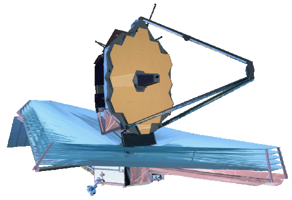
HUDF09

HUBBLE UDF ULTRA DEEP FIELD

The HUDF09 goal was to extend the UDF and UDF05 fields to the near-IR.







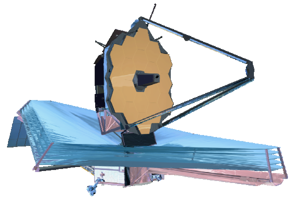
Reionization - 4

HUBBLE UDF ULTRA DEEP FIELD

At z=7 observed galaxies contribute SB_{1400} = 26.1 mag $arcmin^{-2}$ (Oesch et al. 2010) against a limit of 28.8 (for C=1 and Pop III population). This gives even a smaller margin over the best case. Thus the galaxies we see at z=7 can contribute but will not dominate the reionization budget.

The observed UV slope is steep (Bouwens et al. 2010a) leaving open the possibility of a large escape fraction.

The contribution from z=8 galaxies is even smaller (Bouwens et al. 2010b).

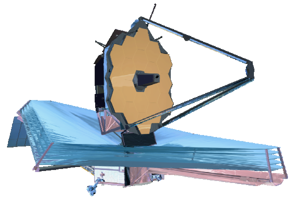



What's going on?

Trenti et al. (2010) built a theoretically-based model of the LF at z>5 and concluded that reionization can be accomplished even for solar metallicities by galaxies fainter than the detection limit.

→ this supports the Yan-Windhorst (2004) scenario.

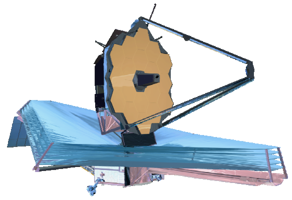
If faint galaxies dominate the ionizing flux, can we detect their integrated contribution?

Faint galaxies

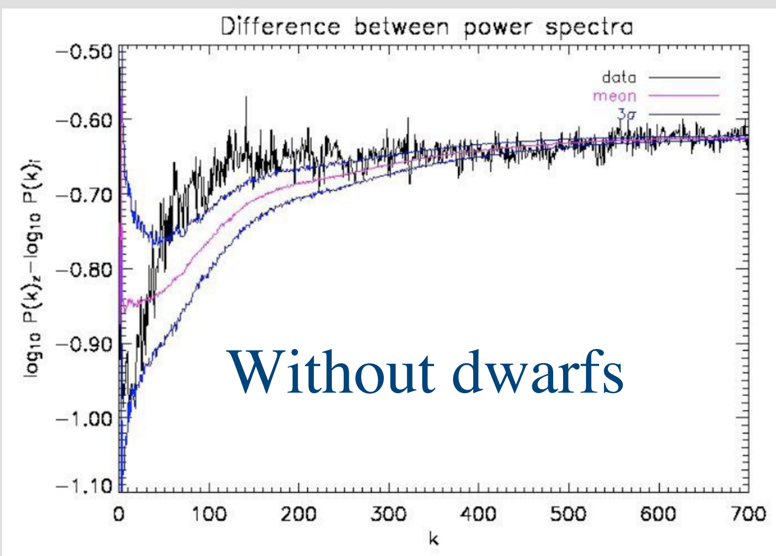
Faint galaxies can dominate the ionizing flux if the faint end LF slope is steep. This is supported by recent reanalysis of the z=6 slope (Su et al. 2010).

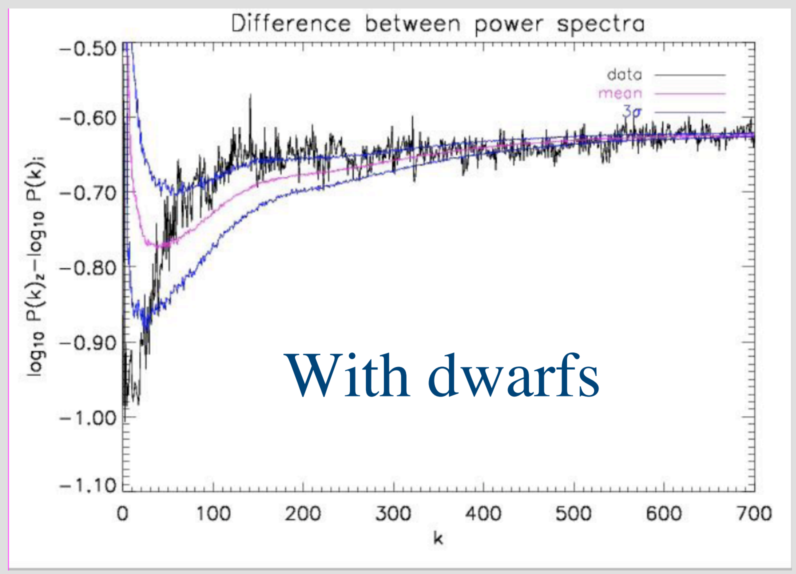
A contribution by undetected dwarf galaxies could leave a signature in the correlation properties of images. At z=6 this would be detectable as an enhanced correlation in the F850LP images over the F775W images. Preliminary indications suggest that this may detectable (Calvi et al. 2010, see poster).



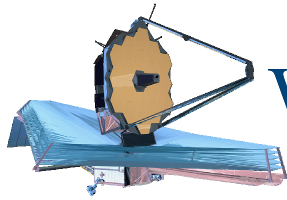
Faint galaxies

By measuring the power spectrum in several bands one can detect the presence of a population of objects individually under the detection threshold.





From Calvi et al. (this conference)

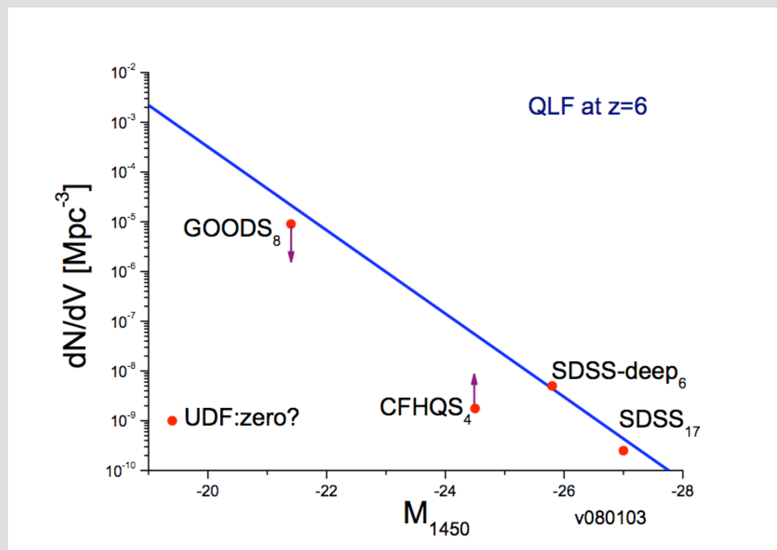


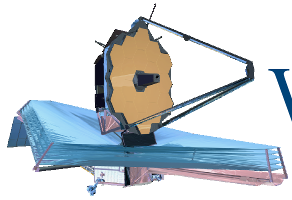
What about faint QSO?

The bright SDSS z=6 QSO LF slope - if extended to faint luminosities - indicates that QSOs could contribute significantly to reionization.

However, at lower z the QSO LF has a knee. Is there a knee at z=6?

This question can be explored with the HST deep field data. Figure from Jian et al. in preparation



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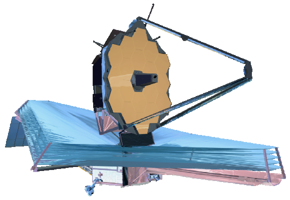
However, at lower z the QSO LF has a knee. Is there a knee at z=6?

Su et al. (in preparation) searched for faint QSOs in GOODS and found fewer objects that expected by direct extrapolation. Thus, there is a knee in the z=6 QSO LF and QSOs contribution to reionization is modest.

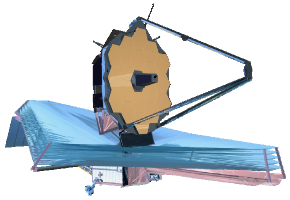
Tentative Conclusions

HUBBLE UDF ULTRA DEEP FIELD

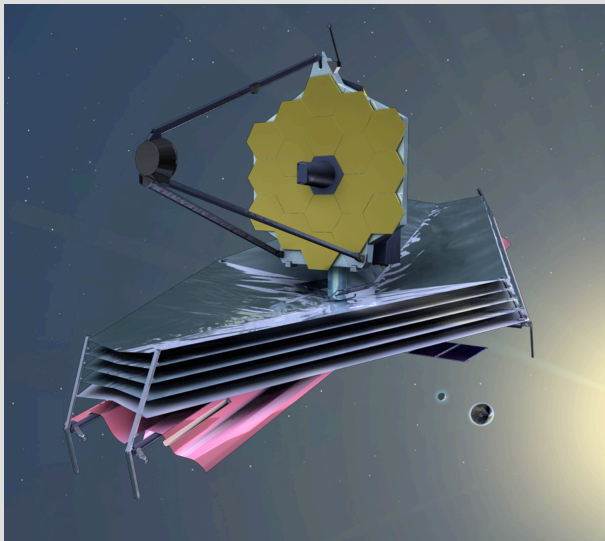
Reionization is dominated by faint and likely metal poor galaxies at z=6+

Bright galaxies and QSOs contribute but are not dominant.

James Webb Space Telescope

JWST: Quick Facts

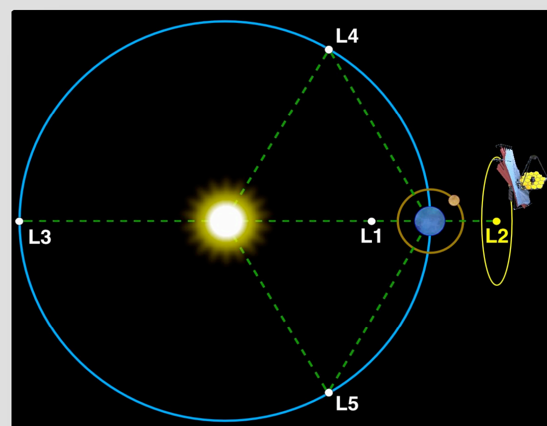


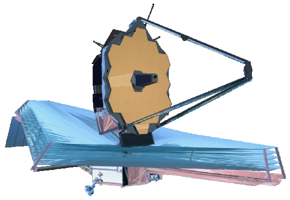
Organization

Mission Lead: Goddard Space Flight Center
International collaboration with ESA & CSA
Prime Contractor: Northrop Grumman Space Technology
Instruments:
Near Infrared Camera (NIRCam) – Univ. of Arizona
Near Infrared Spectrograph (NIRSpec) – ESA
Mid-Infrared Instrument (MIRI) – JPL/ESA
Fine Guidance Sensor (FGS) – CSA
Operations: Space Telescope Science Institute (STScI)

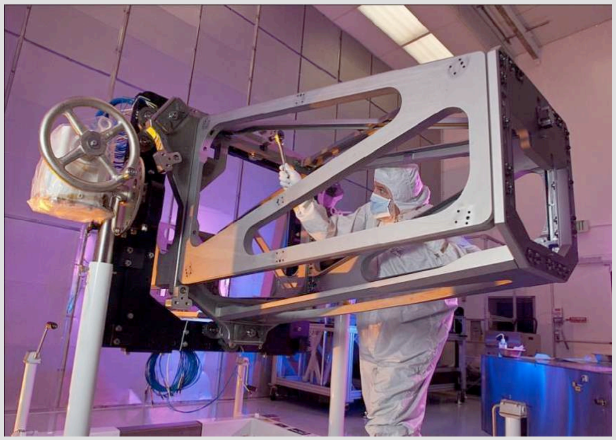
Description

- Deployable cryogenic telescope
  - 6.5 meter Φ, segmented adjustable primary mirror
- Launch on an ESA-supplied Ariane 5 to Sun-Earth L2
- 5-year science mission (10-year goal): launch 2015?



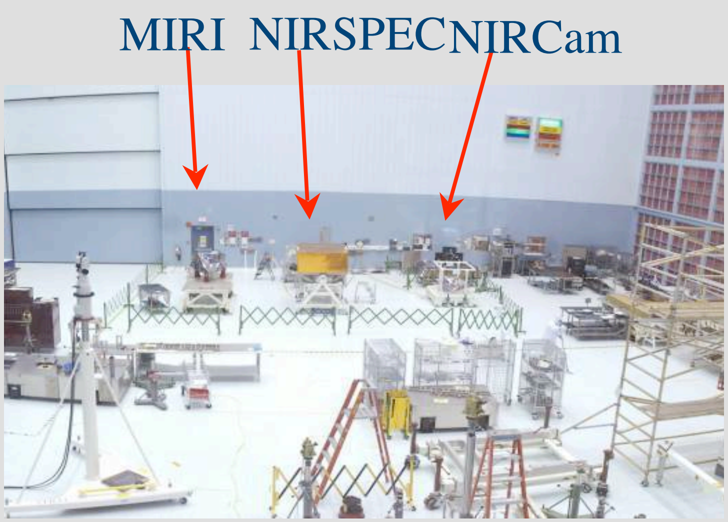
JWST : Status

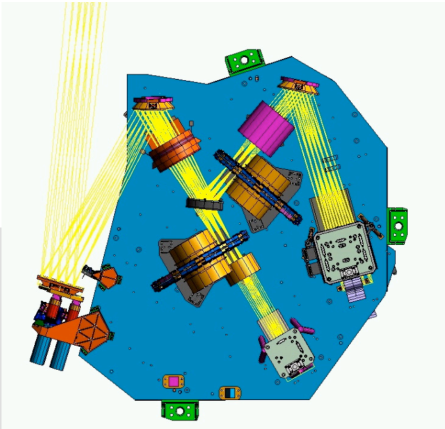


2/3 of the observatory mass is in fabrication

All mirror segment have completed rough polish to 150nm

EDU and one flight segment have been coated and are completed





Arizona: Marcia Rieke PI

Lockheed-Martin & Rockwell

Instrumentation

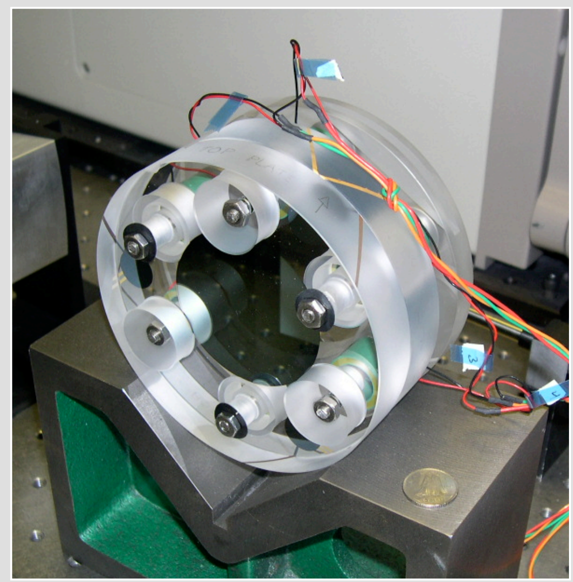
- NIRCam, 0.6 to 5.0 micron:
  - 2.3 x 4.5 arcmin FOV
  - Broad & narrow-band imaging
- NIRSpec, 0.6 to 5.0 micron
  - 3.4 x 3.4 arcmin FOV
  - Micro-shutter, IFU, slits
  - R~100, 1000, 3000
- TFI, 1.6 to 4.8 micron
  - 2.2 x 2.2 arcmin FOV
  - R~100 narrow-band imaging
- MIRI, 5.0 to 27.0 micron
  - 1.4 x 1.9 arcmin FOV imaging
  - 3 arcsec IFU at R~3000
- Coronagraphy
  - NIRCam, TFI & MIRI

ESA: Peter Jakobsen

EADS Astrium & GSFC

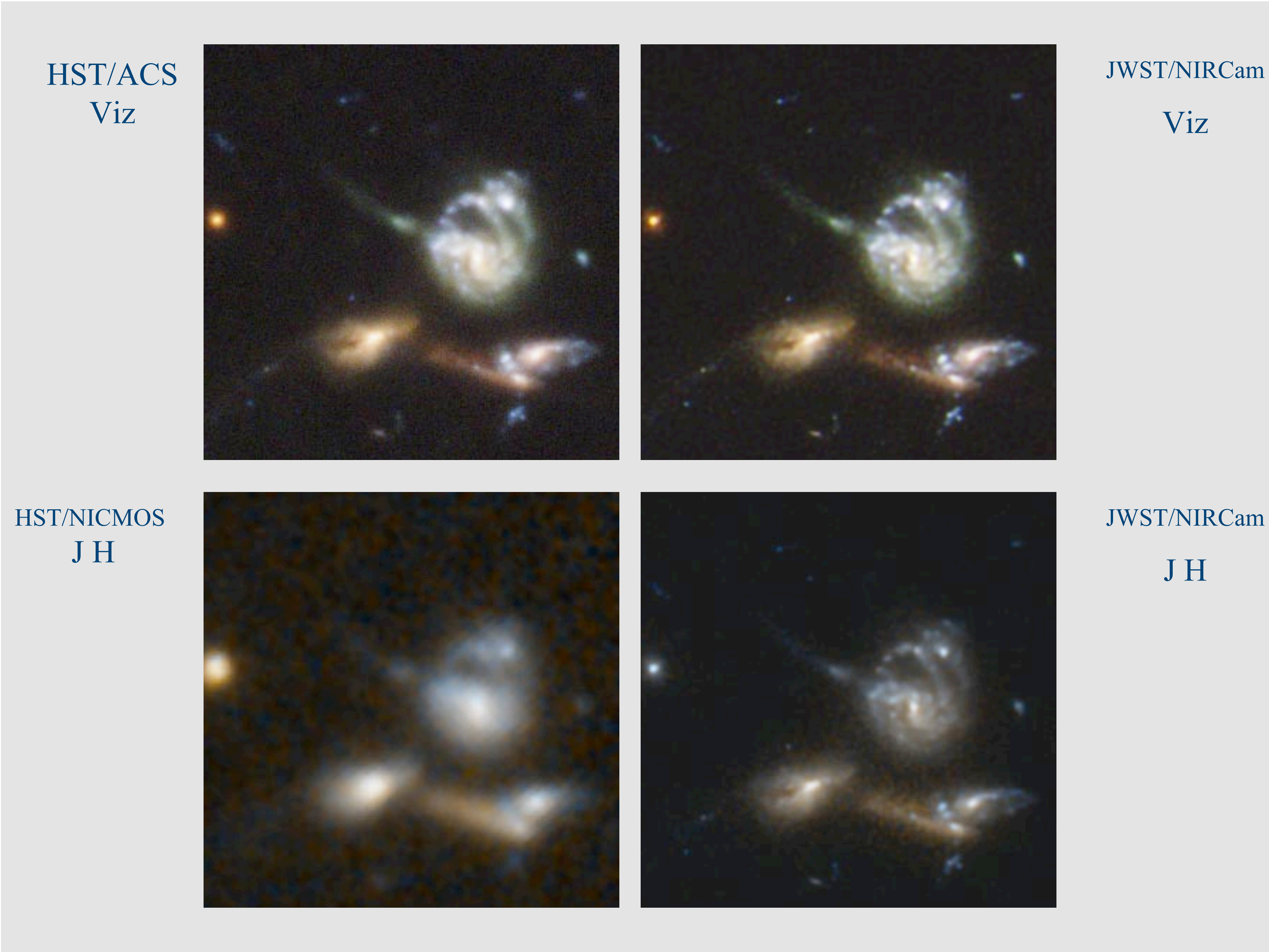
George Rieke & Gillian Wright

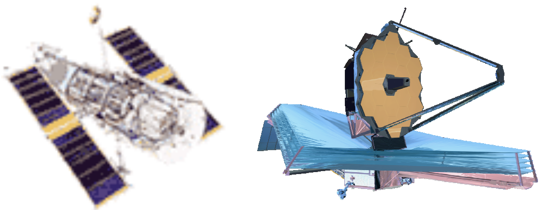
JPL and European Consortium



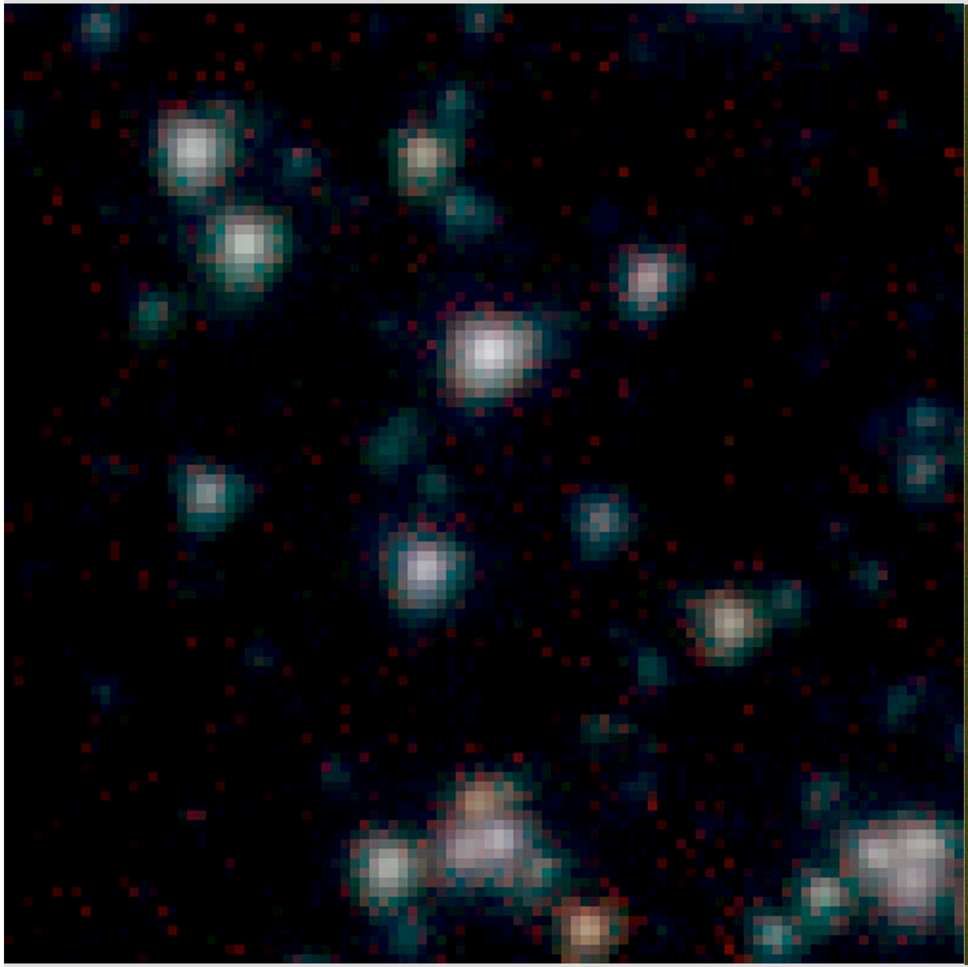
CSA: Rene Doyon

COM DEV

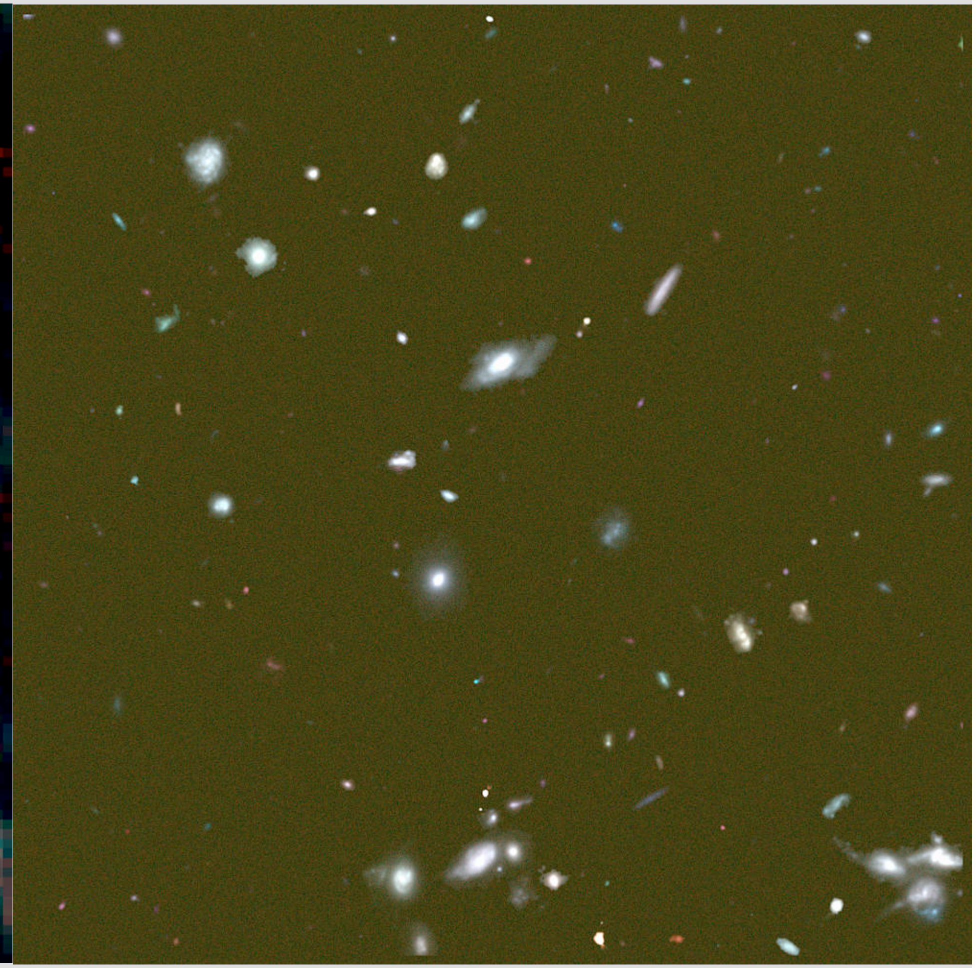

HST/ACS
Viz
JWST/NIRCam
Viz
HST/NICMOS
J H
JWST/NIRCam
J H



JWST-Spitzer image comparison



Spitzer, 25 hour per band (GOODS)

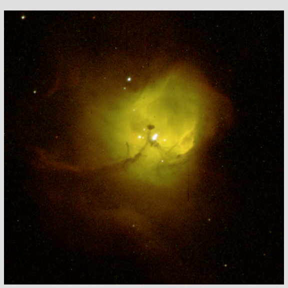


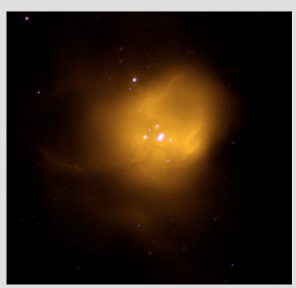
JWST, 1000s per band (simulated)

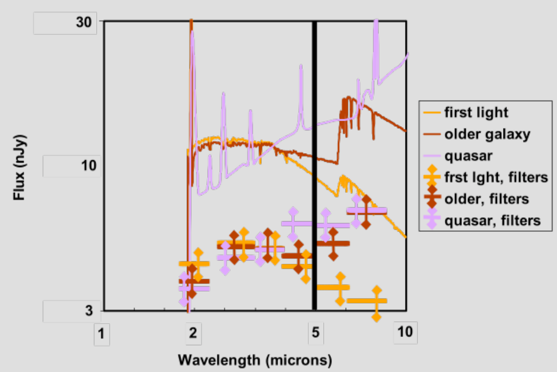
1’x1’ region in the UDF – 3.5 to 5.8 μm

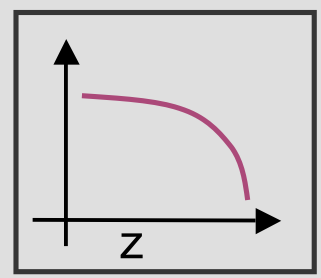
Detection of the First Galaxies

- Evolution of N(z), LF. *Identify candidates with Lyman break technique* → **NIRCam**
- Evolution of SFR(z). *Use $H\alpha$, $H\beta$ and supernovae* → **NIRSpec and NIRCam**
- Evolution of <Z>(z). *Use [OIII]/$H\beta$.*
- Confirm nature of first light objects. *Place upper limit to metallicity, search for older stellar component.* → **NIRSpec and MIRI** (this will typically require lensed or intrinsically very bright sources)







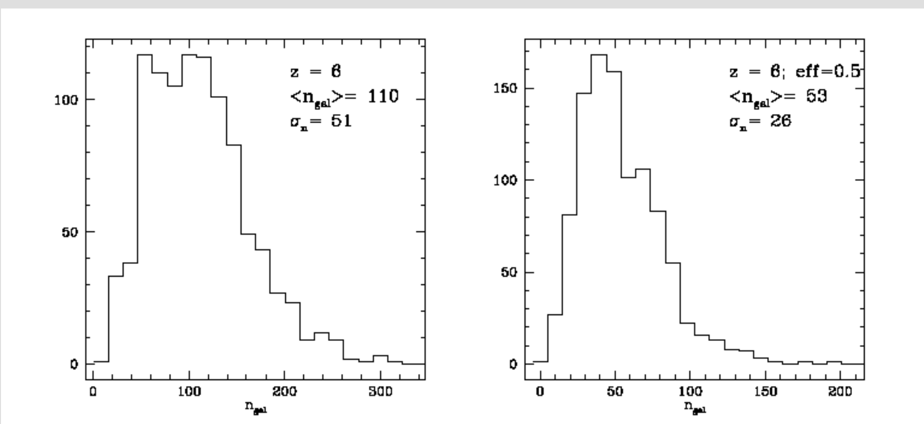


First Galaxies : Detection

Probing the LF to the same relative depth as that of z=6 from the UDF gives us a required depth:

from Trenti & Stiavelli 2006 ApJ

z	AB_1350	F^{ν} (nJy)	λ (μm)	$\langle A_{1400} \rangle$	A_{1400}(90%)
10	30.284	2.80	1.34	0.08	0.18
12	30.551	2.19	1.58	0.07	0.15
15	30.869	1.63	1.95	0.05	0.12
20	31.267	1.13	2.55	0.04	0.08

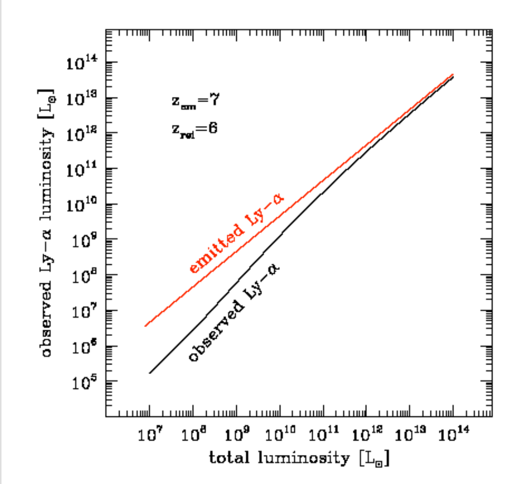


Distribution of the number of dark halos in the UDF assuming that all of them (left) or only 50% (right) are visible as galaxies. The mean number is roughly twice the rms of the distribution (Trenti & Stiavelli; see also Somerville).

First Galaxies : Ly α & properties

Assumptions: Pop III, ionizing photons escape fraction = 0.5.

Adopt: Lyα escape fraction of 0.2.

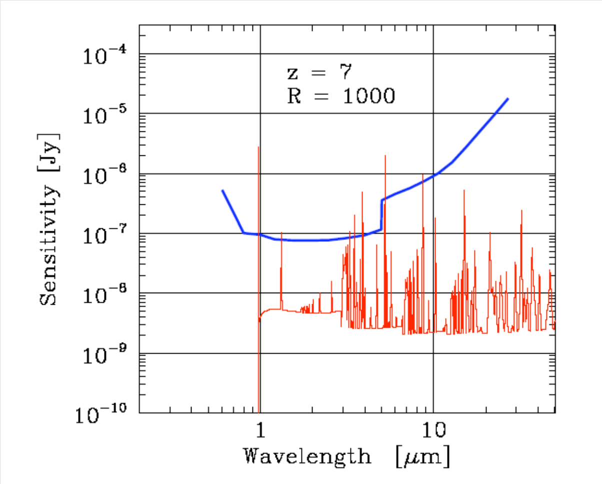


z	AB_1350	Ly α (cgs)	λ (μm)
10	30.284	1.7e-18	1.34
12	30.551	8.89e-19	1.58
15	30.869	4.02e-19	1.95
20	31.267	1.47e-19	2.55

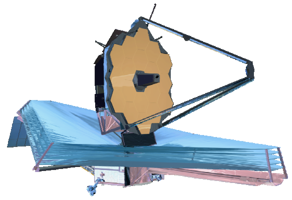
Measuring the metallicity of first light sources

Let's consider a 5 nJy source with metallicity 1/1000 solar. The O line at 1665A will have a strength of:

$4.5\ 10^{-19}$ erg cm^{-2} s^{-1}



The metallicity measurement or the detection by MIRI will be possible for bright sources or sources amplified by lensing.

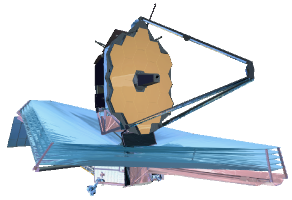


Possible JWST efforts

- Ultra deep survey to 1-2 nJy
  - Combine UDF with a north ecliptic pole survey (JWST CVZ) for z>6 SN searches
- Cluster survey:
  - 5 clusters to 5-8 nJy (amplified sources for followup)
- FGS-TF search
  - $10^{-18} - 10^{-19}$ erg cm^{-2} s^{-1}
- Spectroscopy
  - Lensed candidates
- MIRI Imaging
  - Lensed candidates

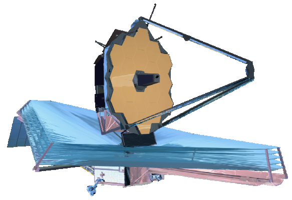
CDFS/GOODS-S/UDF is the best field:

- low cirrus
- well placed for ALMA followup
- reasonably well placed for JWST



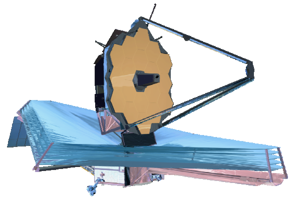
JWST and Reionization

- Done by the time JWST is launched. WFC3 continuing efforts as well as ground based.
- Hard part may be to measure metallicities of reionizers. This requires JWST or 30+ ground based telescopes.
- If still an open question:
  - NIRSPEC R=100 spectra may show the Haiman-Loeb (1999) Lyman-island signature identifying reionization
  - NIRSPEC R=1000 (or higher) spectra will aim at detecting a black Lyman α trough & a Lyman α damping wing
  - One could track Lyα or, even better, Lyα/Hα with z.



JWST and First light objects

- First light stars are extremely rare.
- JWST can observe first light stars only as supernovae (and it will be difficult!) or as lensed individual stars (or small cluster).
- JWST will study the "first galaxies", i.e. second generation objects pre-enriched by Pop III stars.
- Theoretical investigation of the first light stars and their observational signatures must continue.



Conclusions

HUBBLE UDF ULTRA DEEP FIELD

We may have observed the end of reionization and we have evidence that it is an extended process.

Studies with existing instruments and can help pushing our samples of galaxies beyond z=7 and help addressing the history of reionization.

JWST will be able to study the nature of reionization sources and the luminosity function of galaxies all the way to the first galaxies.

JWST may be able to detect SN from Pop III stars and clusters of Pop III stars if they exist.

JWST Information and Feedback

- Planning a data simulation/data challenges effort. We hope that we will be able to announce this soon.
- Conference *Frontier Science Opportunities with the James Webb Space Telescope,* Jackson Lodge, Grand Teton National Park, June 5-7 2011. Issues of Legacy/Treasure, program balance will be discussed.
- Web site at STScI : http://www.stsci.edu/jwst (being constantly updated).
- Email JWSTinfo@stsci.edu
- Contact members of the JWST Science Working Group (http://www.jwst.nasa.gov/workinggroup.html)