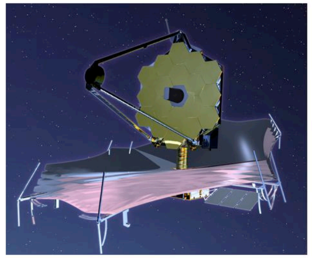


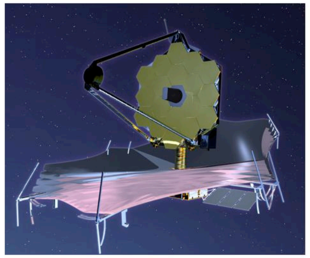
First Light and Reionization with HST and JWST

M. Stiavelli

STScI, Baltimore

Collaborators: Michele Trenti, Anton Koekemoer, Eddie Bergeron, Pascal Oesch, Soyoung Kim, Nino Panagia, Harry Ferguson, Bahram Mobasher, Mike Fall, and the UDF05 team.

12-06-2007

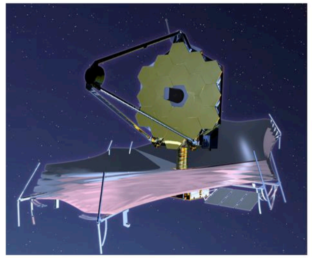


First Light and Reionization

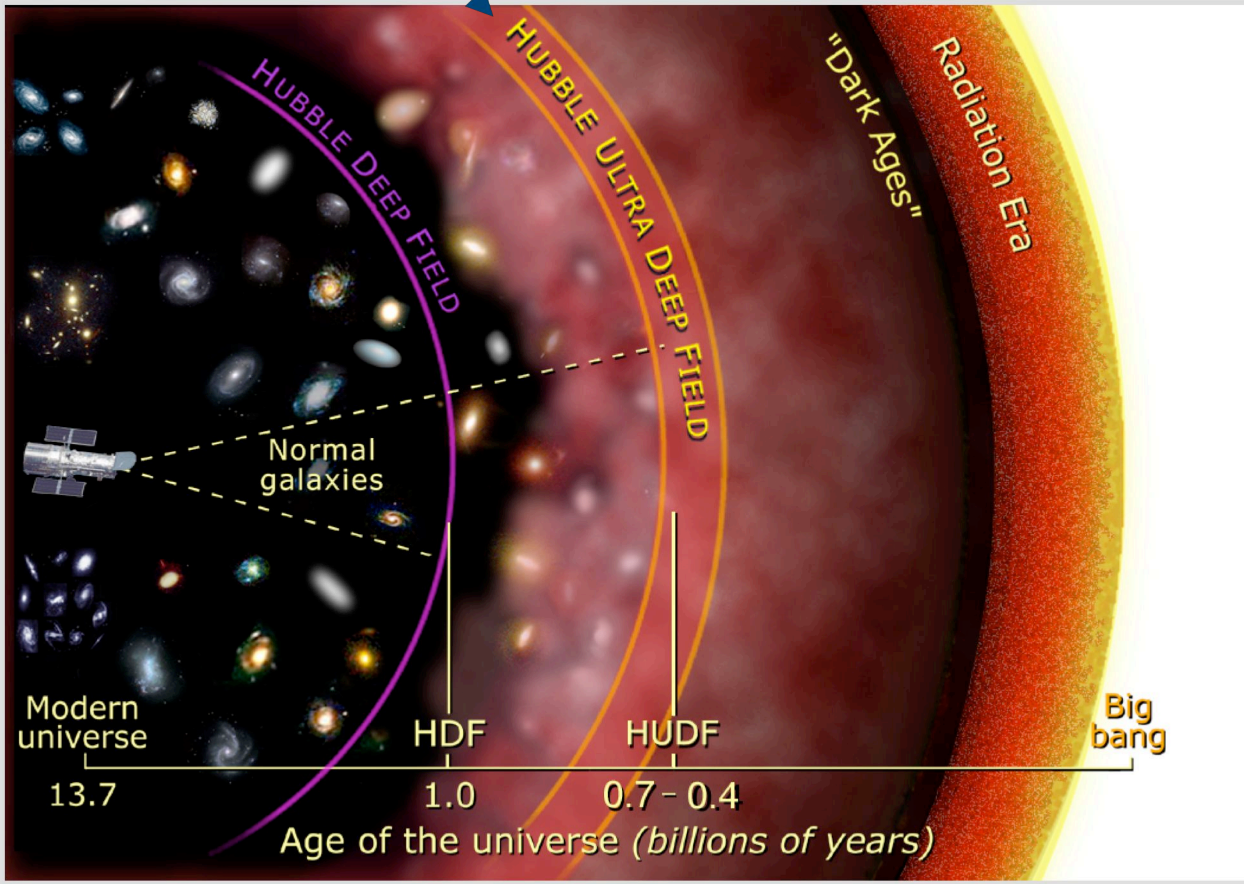
Plan:

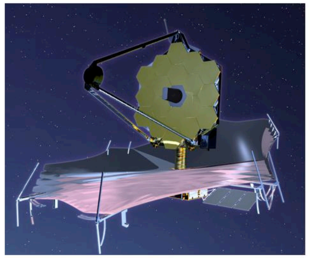
- Brief overview
- Reionization
- HST UDF and UDF05
- First light
- JWST

12-06-2007



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





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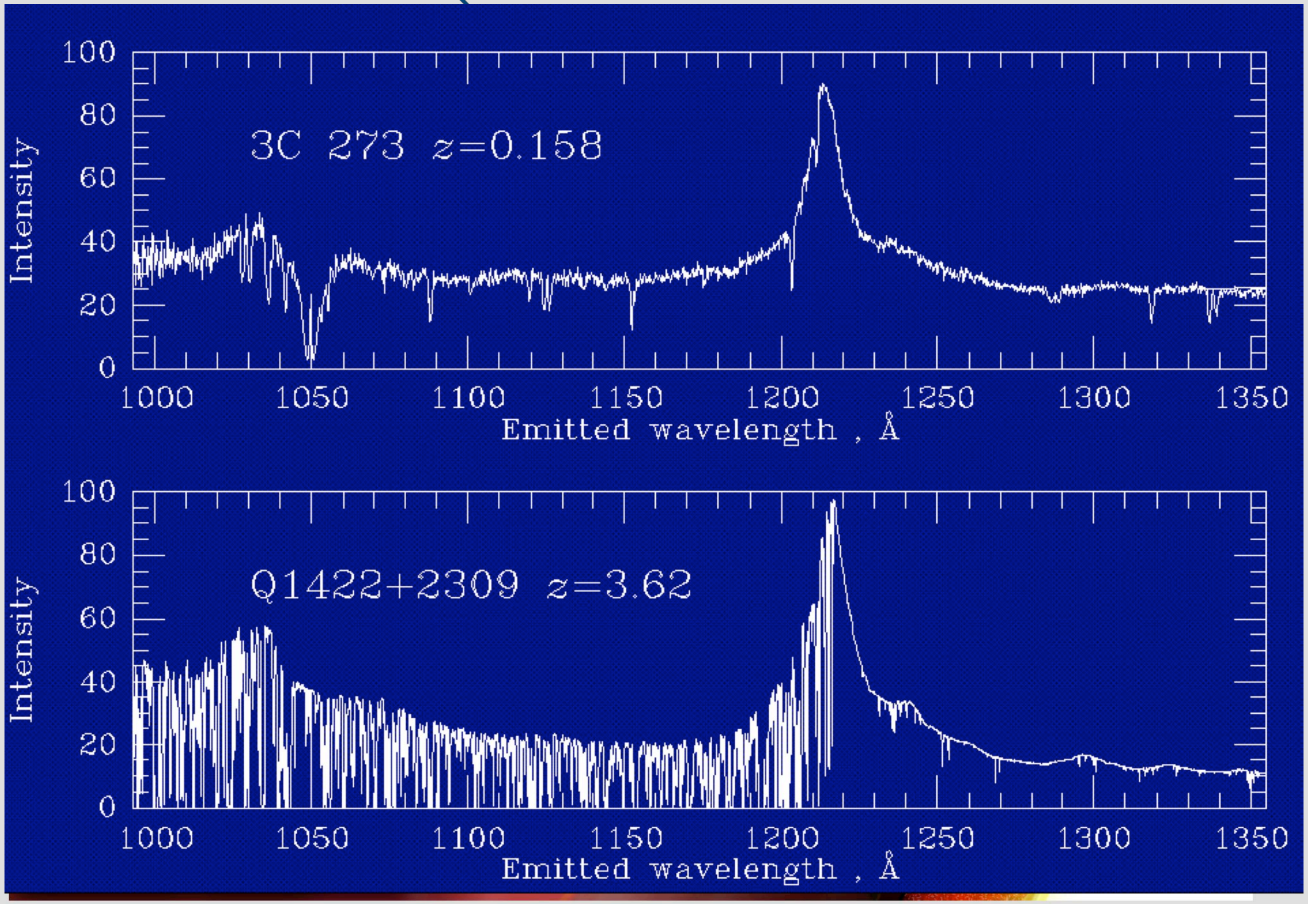
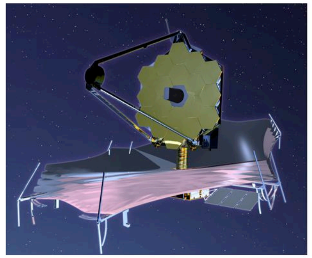
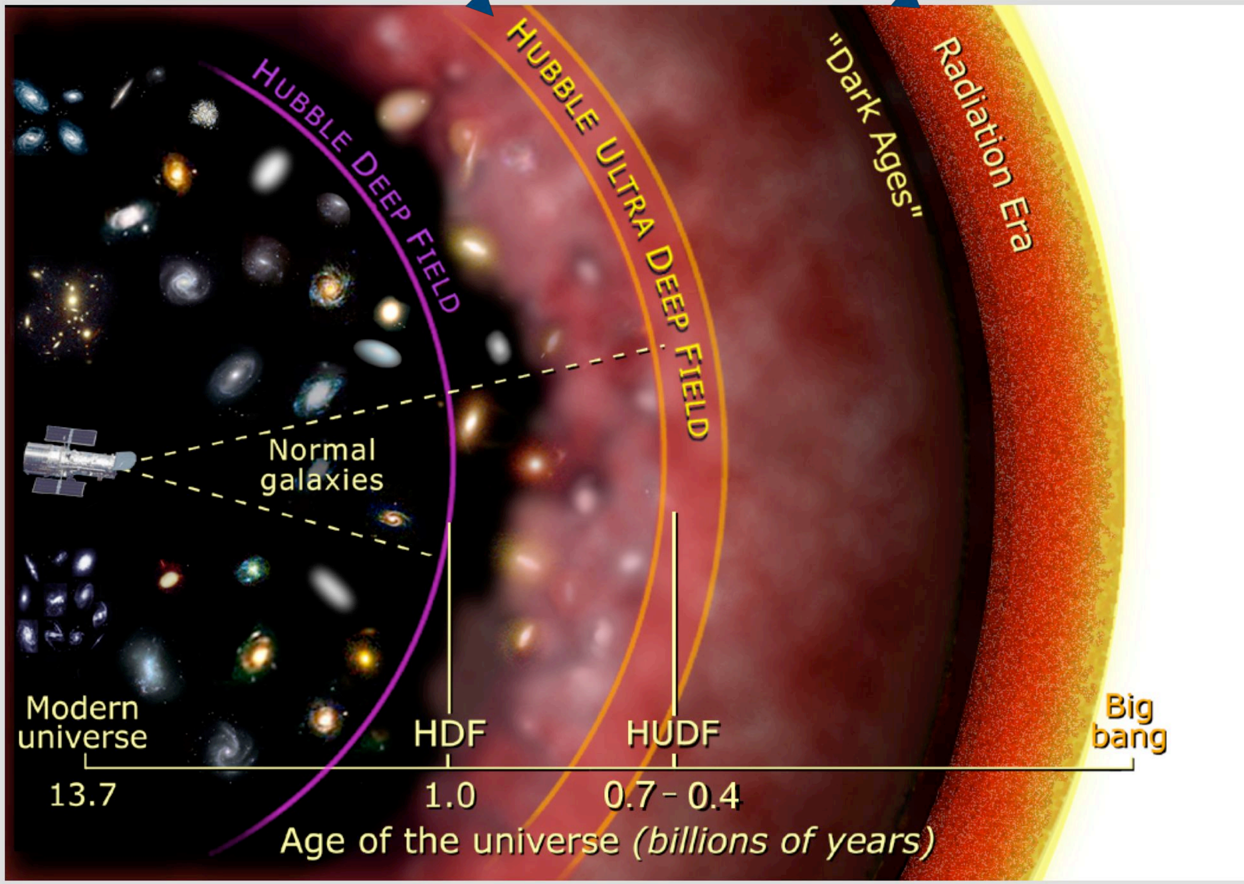
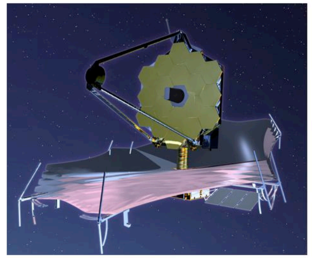




Hydrogen is ionized : we see radiation at 912 < λ < 1216 A in QSOs at z<6

z~1300, Hydrogen recombines, CMBR "released"

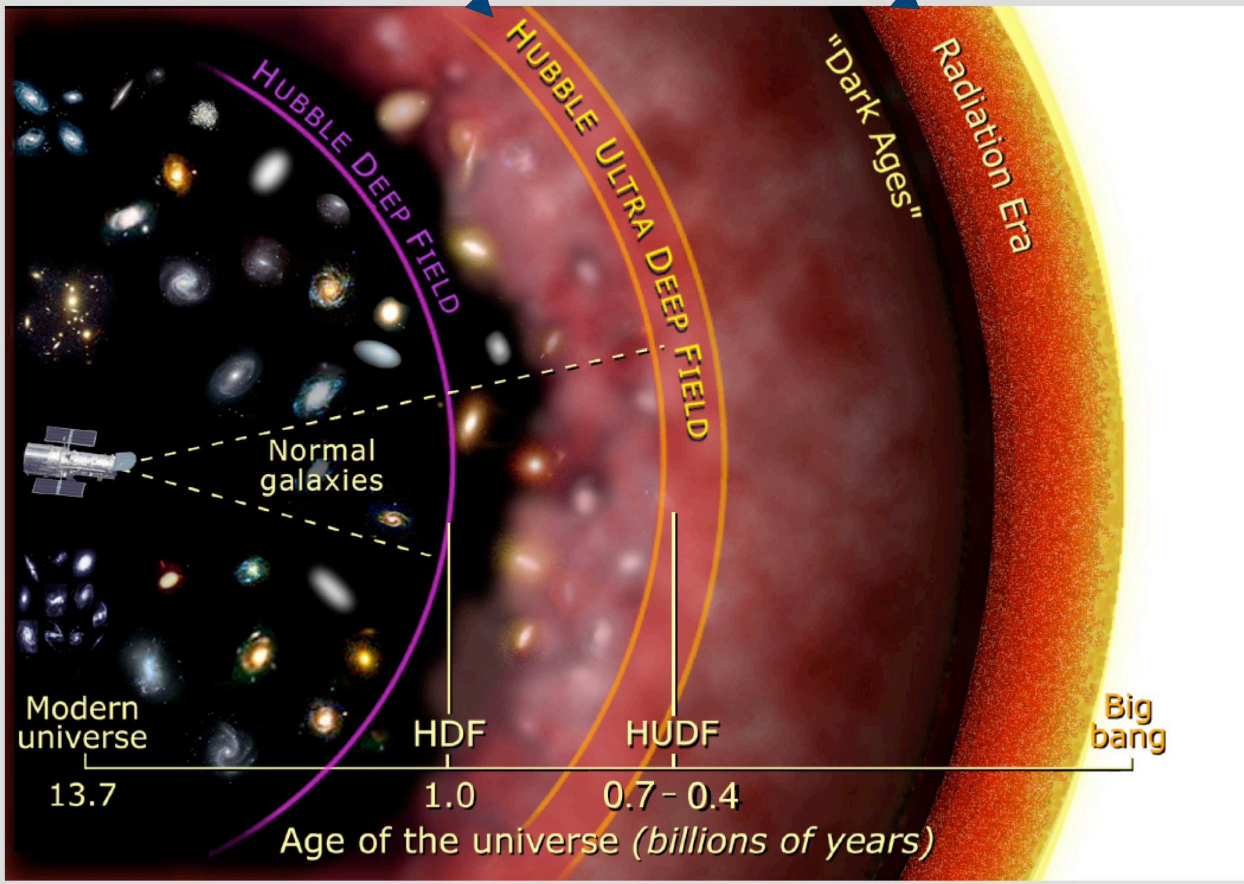


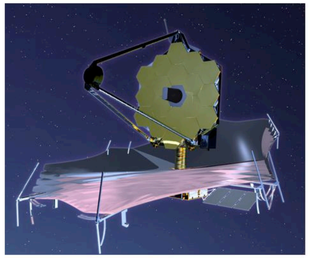


Hydrogen is ionized : we see radiation at 912 < λ < 1216 A in QSOs at z<6

Here something reionizes Hydrogen

z~1300, Hydrogen recombines, CMBR “released”

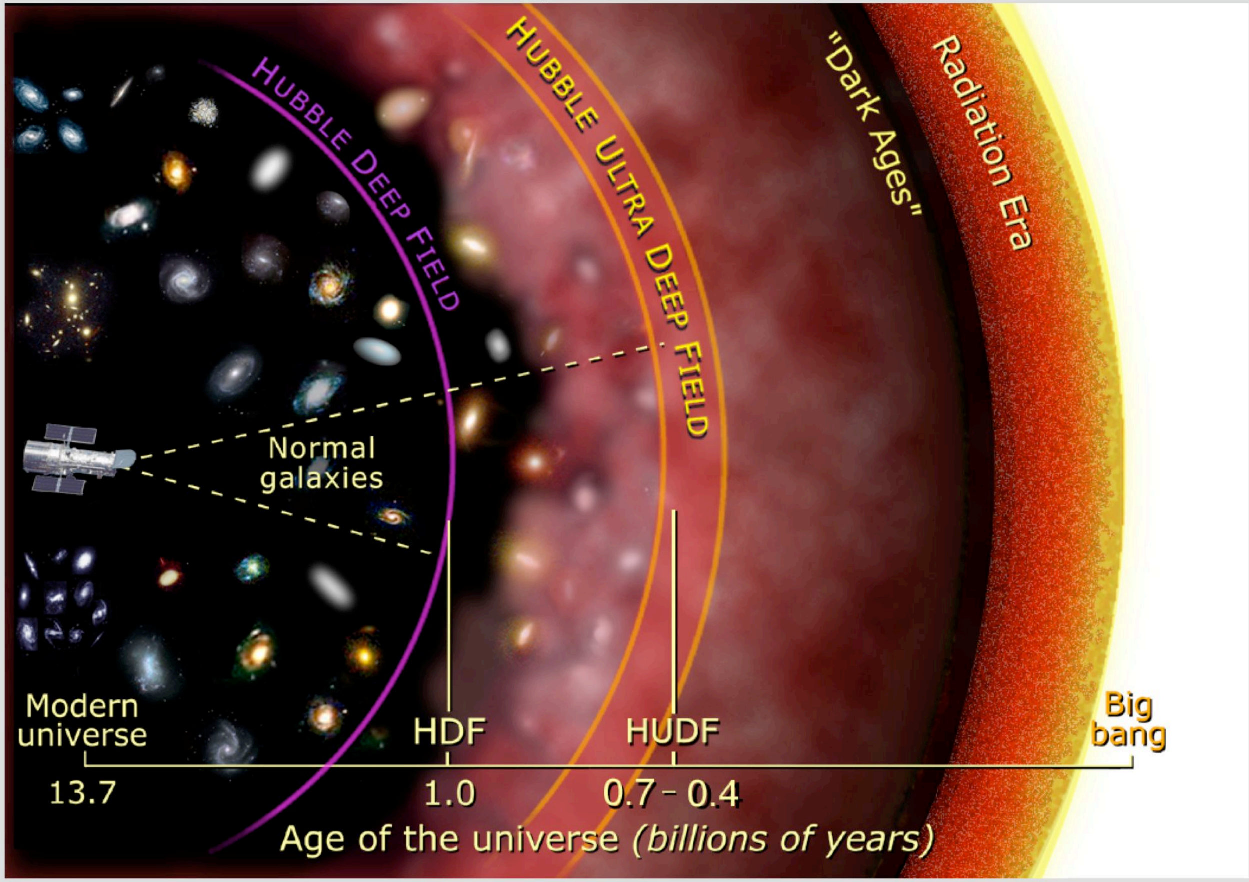




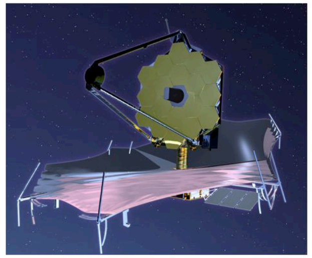
“Dark ages”

7% of the age of the Universe

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

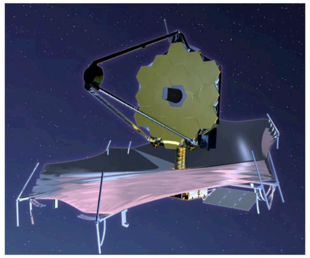


Why should we care?



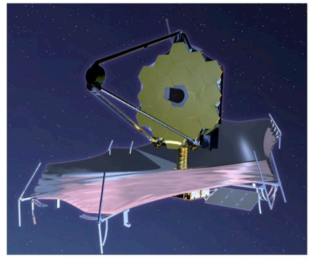
First light. First light sources are the first discrete objects forming in the Universe and the beginning of the hierarchical clustering process leading to the galaxies we see today.

Reionization. It's the last global phase transition in the Universe and directly affects the formation of structures. After reionization dwarf galaxy formation can be prevented by photo-ionization because the shielding provided by diffuse neutral hydrogen is no longer present.



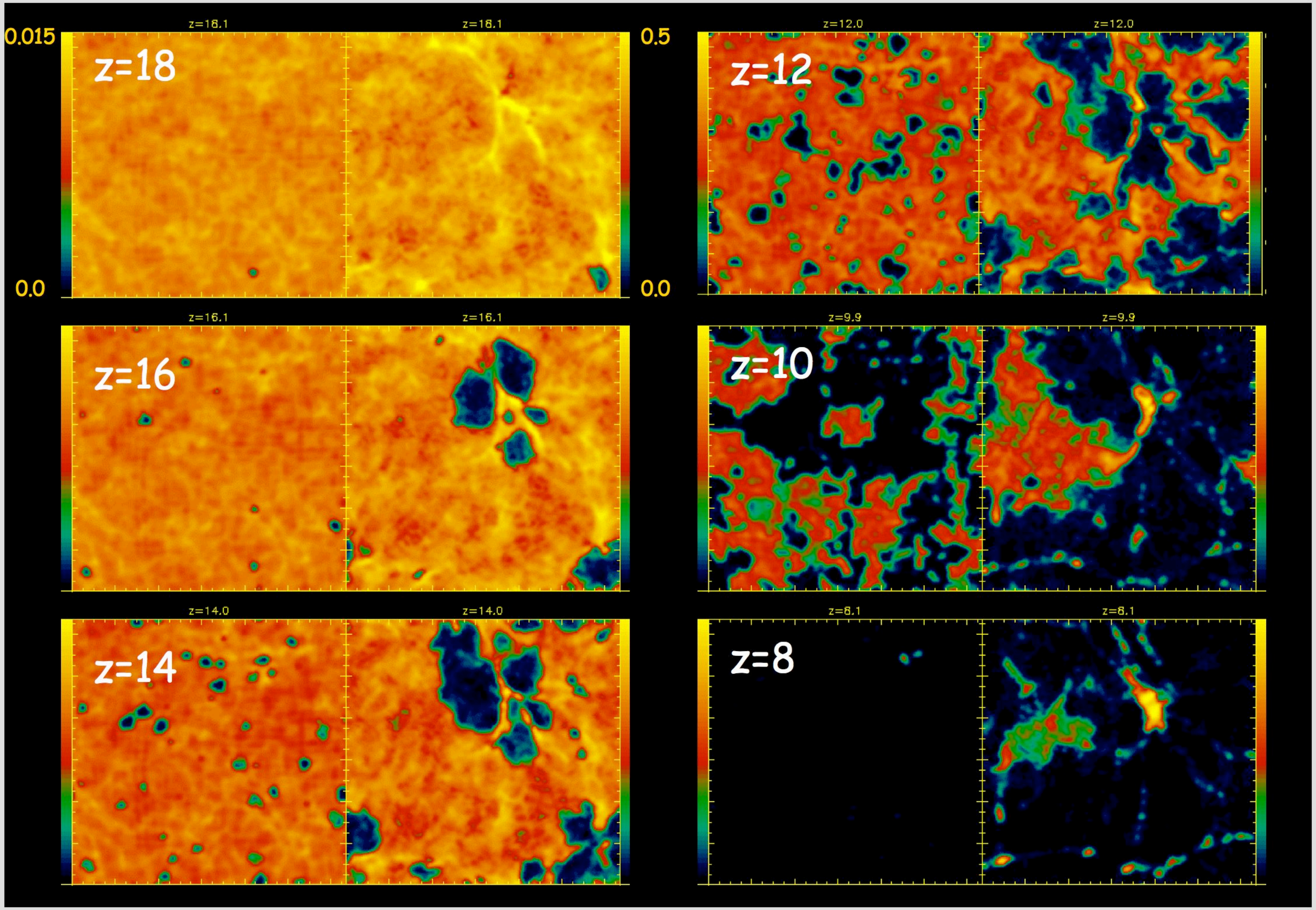
Reionization

12-06-2007



CAUTION: field to field variations!

Density of neutral hydrogen

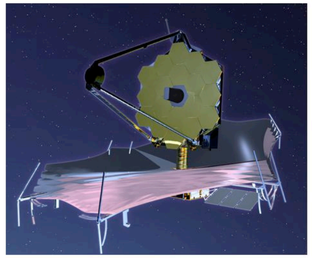


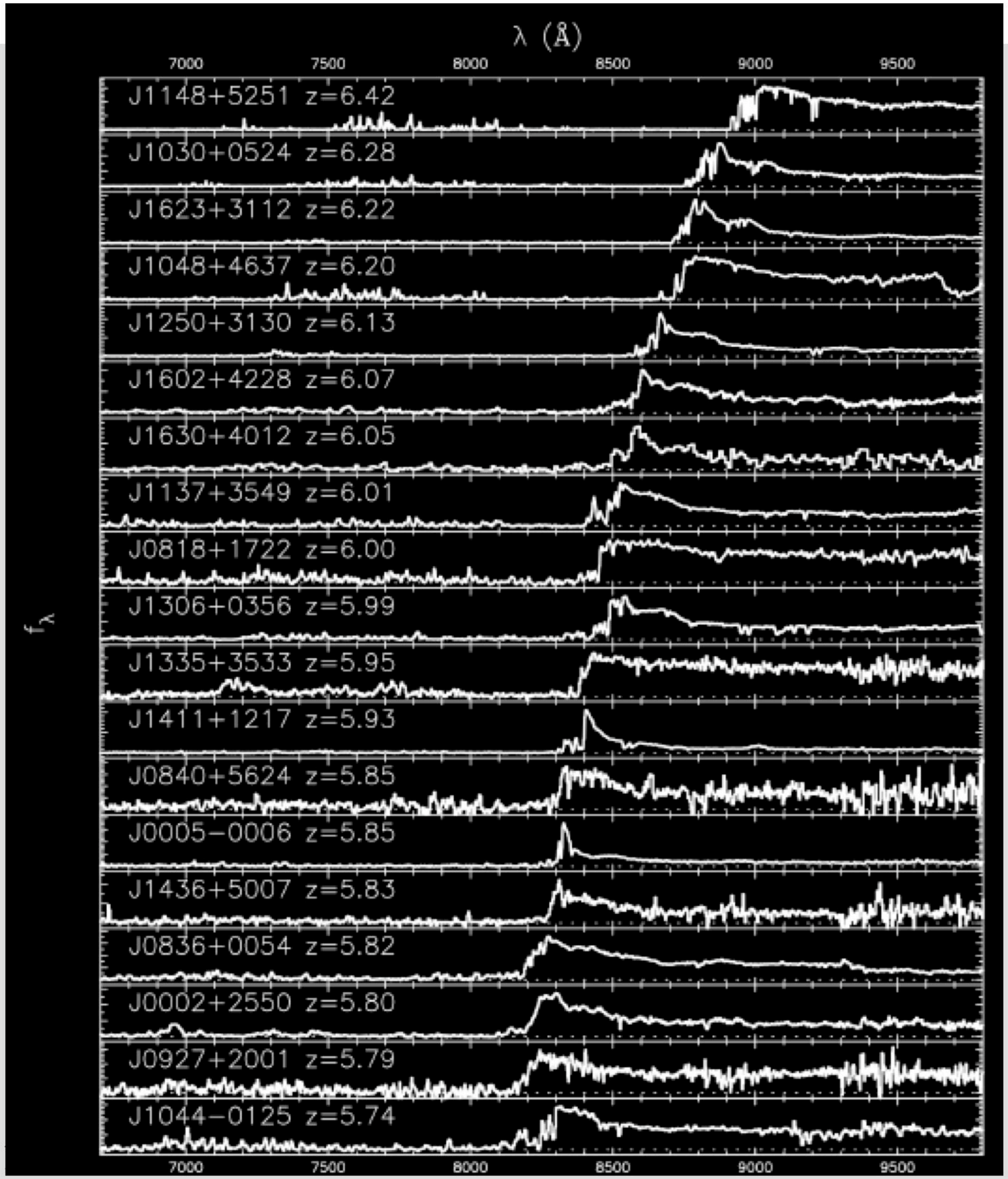
(BC, Stoehr & White 2003)

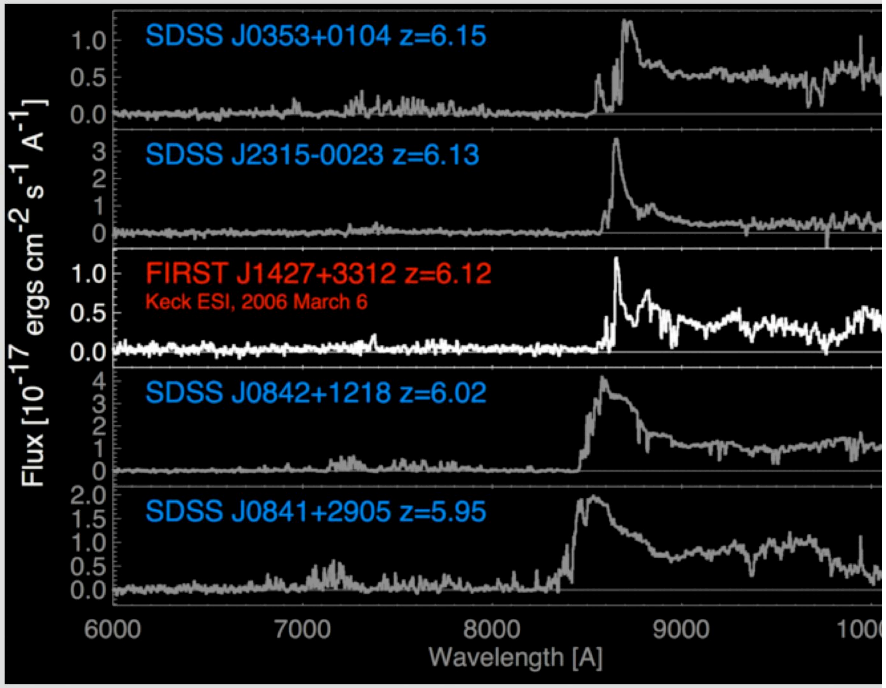
20/h Mpc 10/h Mpc

12-06-2007

End of Reionization







Courtesy of R. White

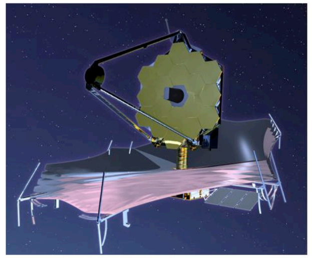
SDSS QSOs → ~z=6

Column density statistics

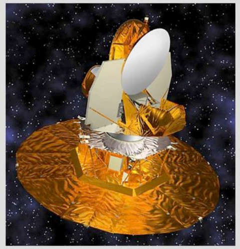
Compatibility with Lyα sources?

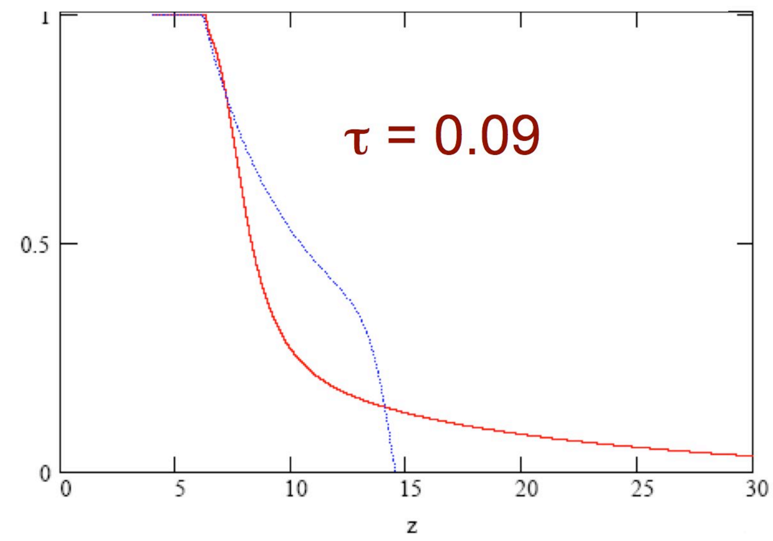
Fan et al., astro-ph/0512082

Reionization history



- WMAP indicates that reionization is an extended process



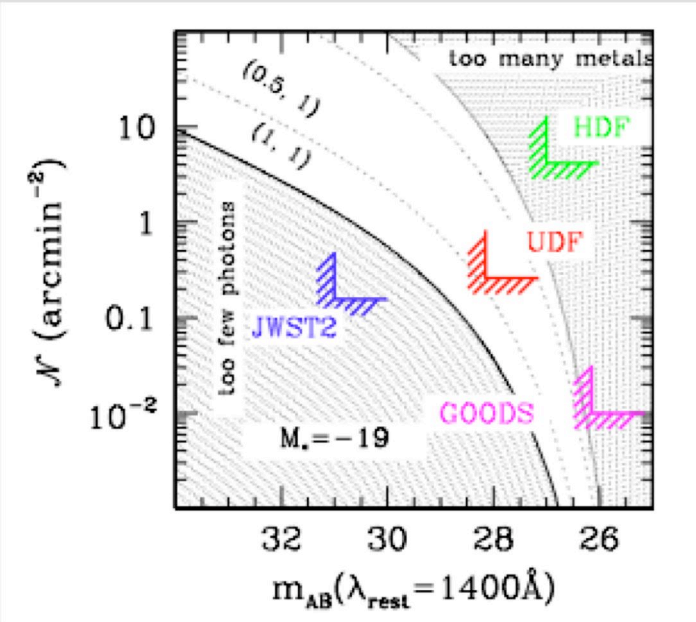


See also Shull and Venkatesan 2007

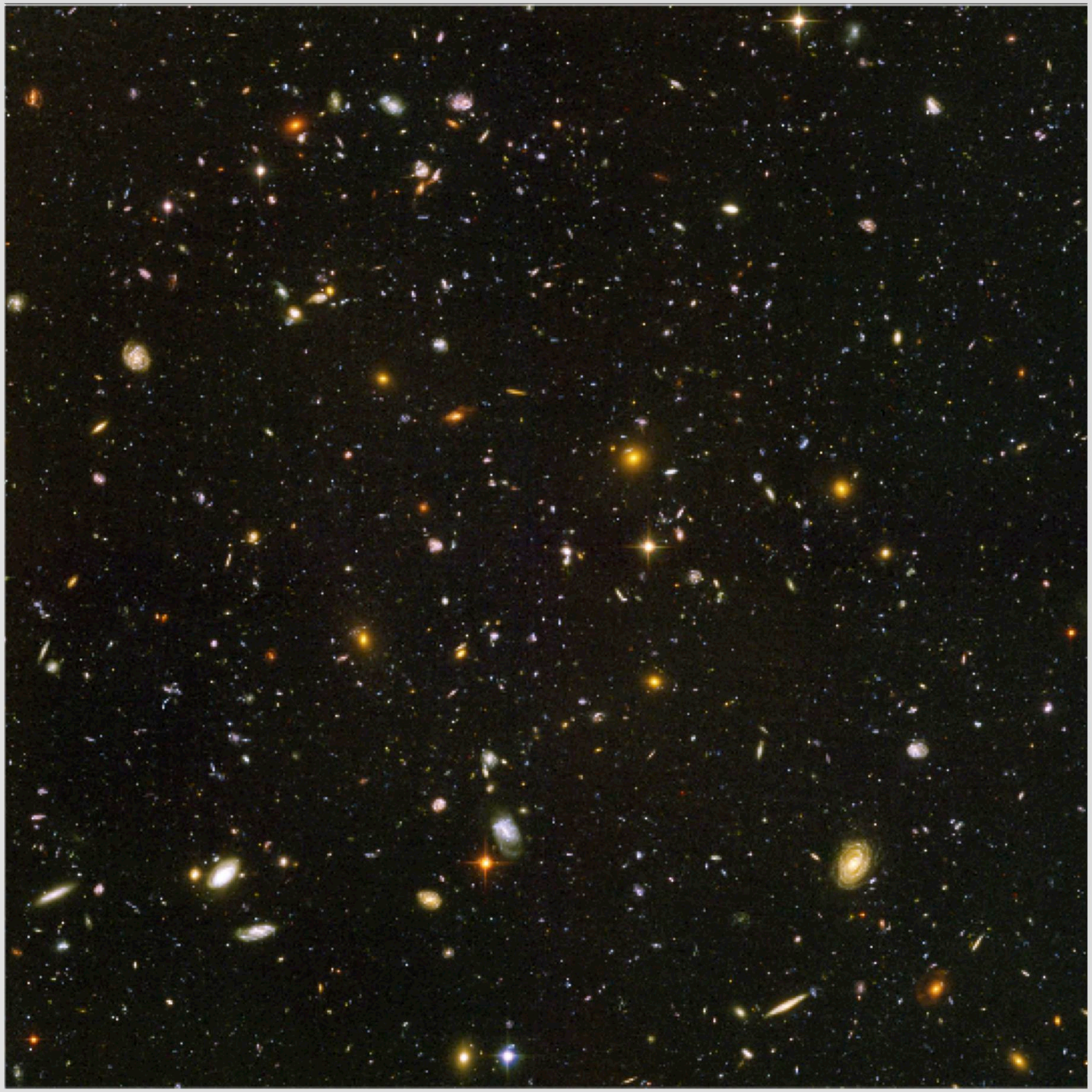
Extended reionization with τ = 0.09 gives first light between 15 and 50 even if reionization is completed at z=6. The red line corresponds to a simulation with varying C and star formation rate (~bumped up Gnedin and Ostriker). The blue line is for a simulation at constant C and star formation rate.

Ultra Deep Field

- Deep enough to study "typical" z=6 galaxies
- Include a known z=5.8 galaxy



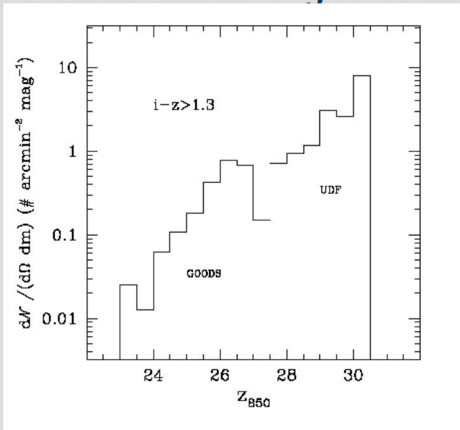
(Stiavelli, Fall, Panagia, 2004a)



Reionization

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

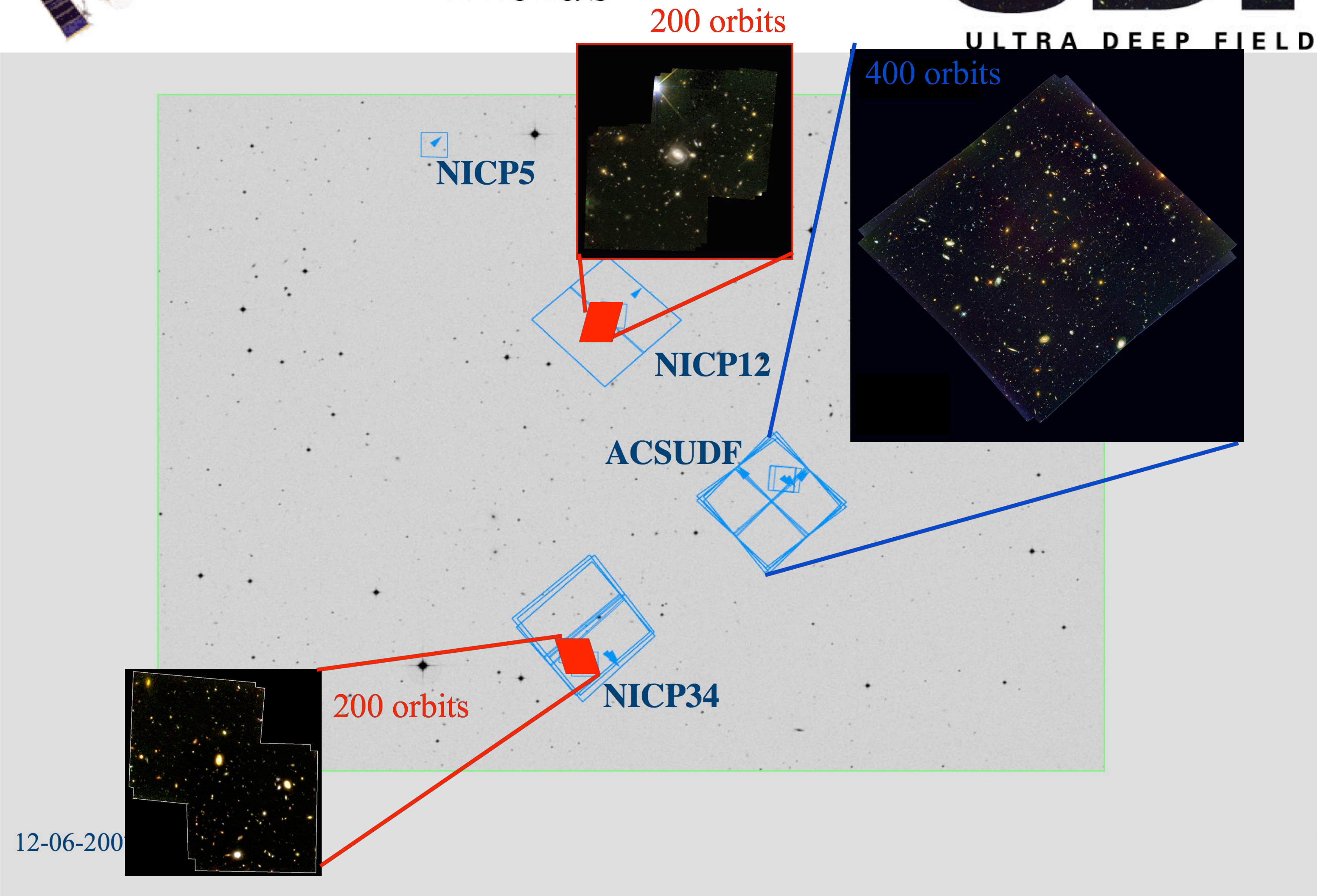
HUBBLE UDF ULTRA DEEP FIELD

Explore z=7-9 by obtaining NICMOS and ACS data complementary to the UDF.

UDF05 Team:

Beckwith, Bergeron, Ferguson, Koekemoer, Lucas, Mobasher, Panagia, Pavlovsky, Robberto, Stiavelli (PI) – STScI Baltimore
Carollo, Lilly, Oesch – ETH Zurich
Rix – MPA Heidelberg
Gardner – GSFC
Hook – ST ECF Garching

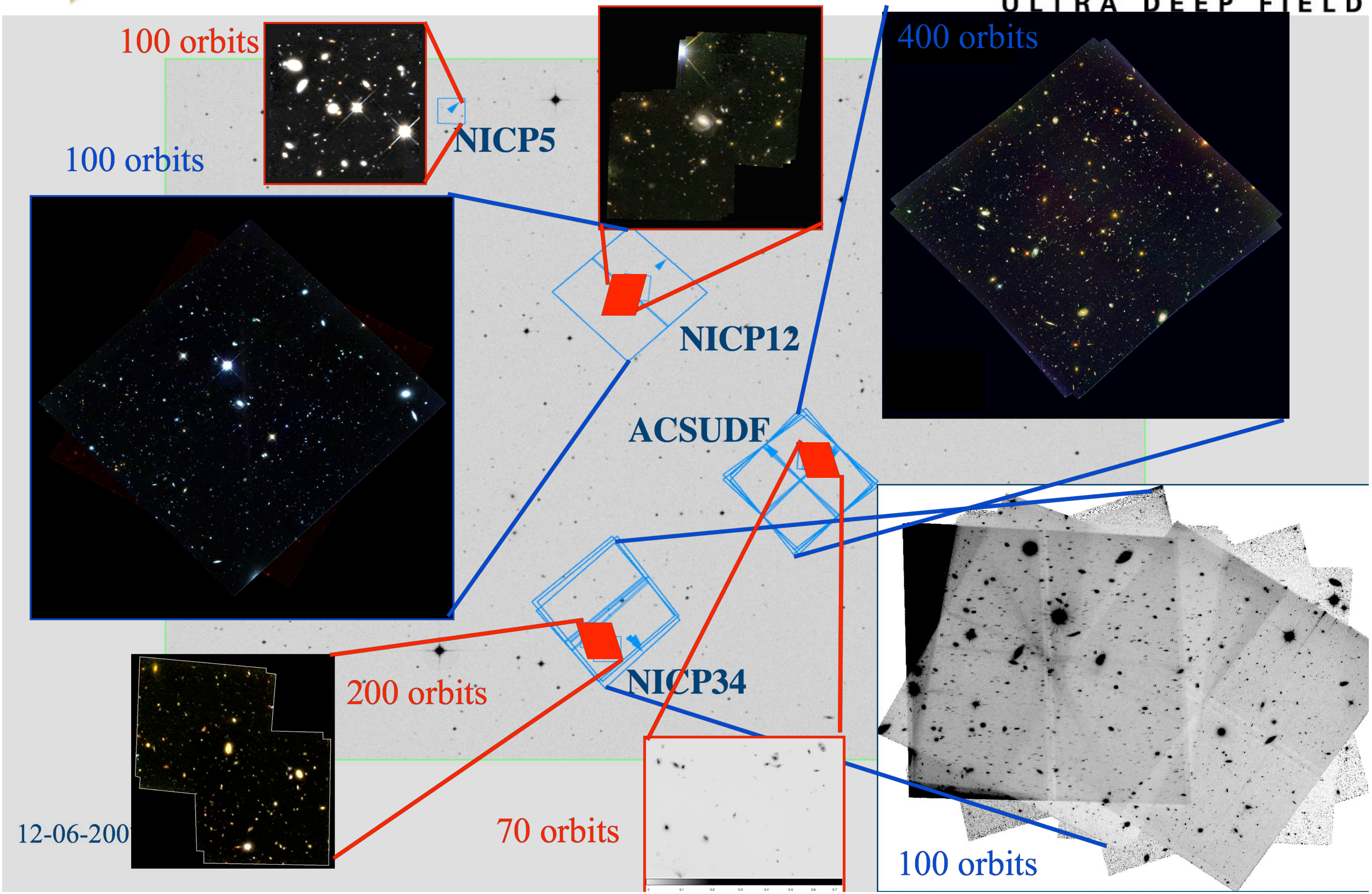
Fields



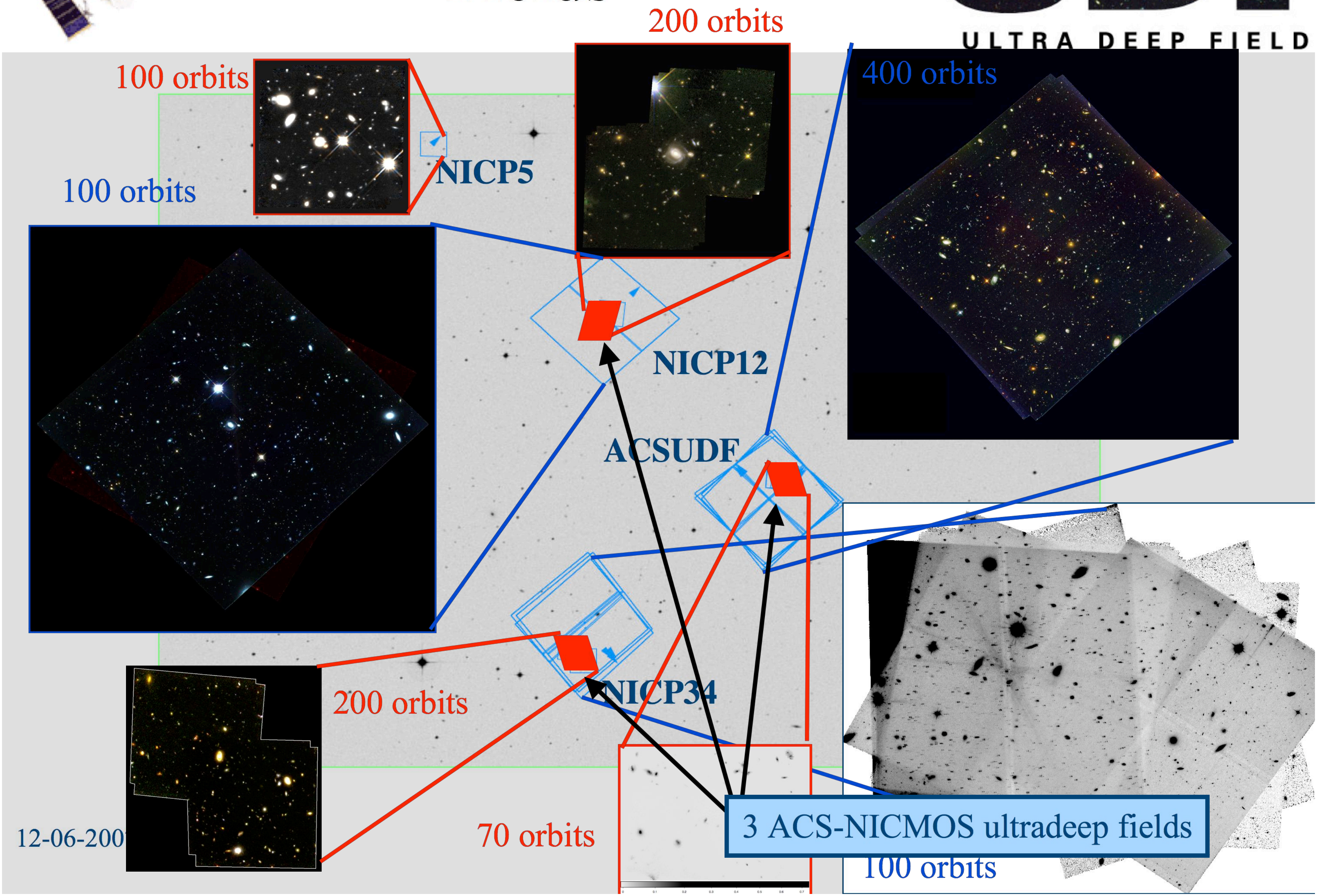
200 orbits
NICP5
400 orbits
NICP12
ACSUDF
NICP34
200 orbits

HUBBLE UDF ULTRA DEEP FIELD

Fields



Fields



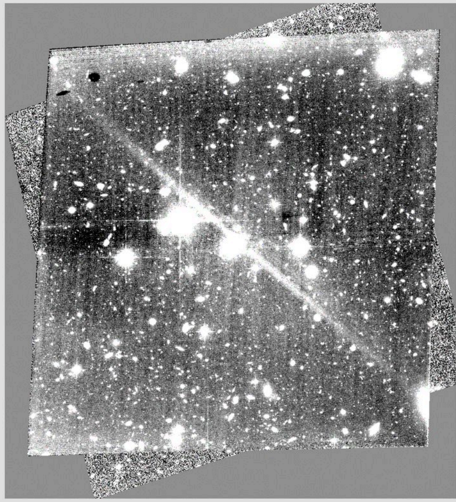
200 orbits
100 orbits
NICP5
400 orbits
100 orbits
NICP12
ACSUDF
200 orbits
NICP34
70 orbits
3 ACS-NICMOS ultradeep fields
100 orbits

HUBBLE UDF ULTRA DEEP FIELD

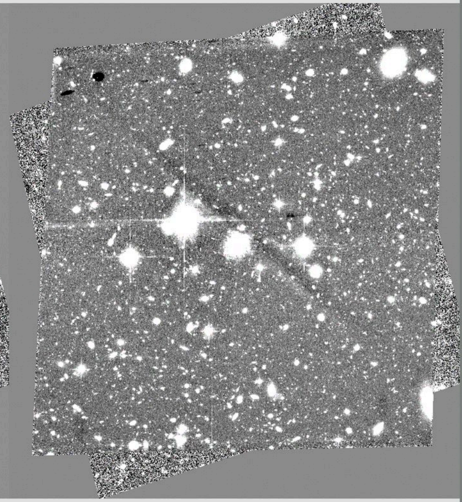
Data Release Plan

- Version 1 of NICP12 data released in January 2006
- Fields NICP34 and ACSUDF observed in June-November 2006 (delayed by ACS safing in June)
- Version 2 of all fields including original UDF (600+ orbits worth) released in the course of 2007.

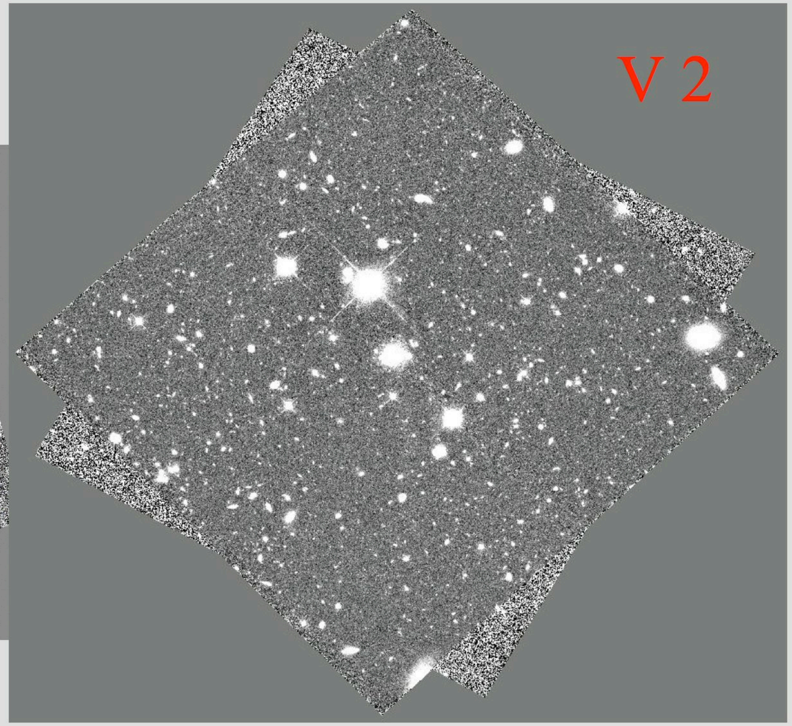
V 1



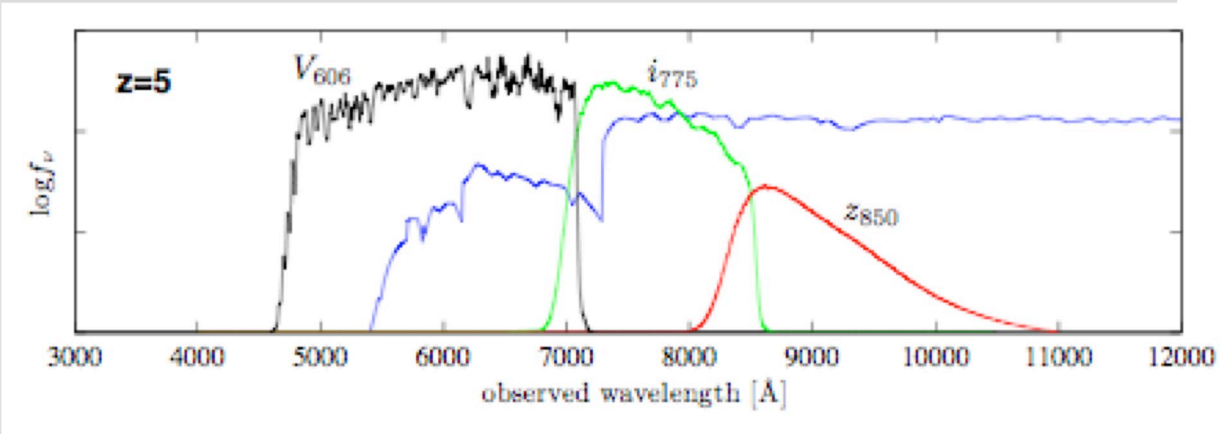
V 1.5

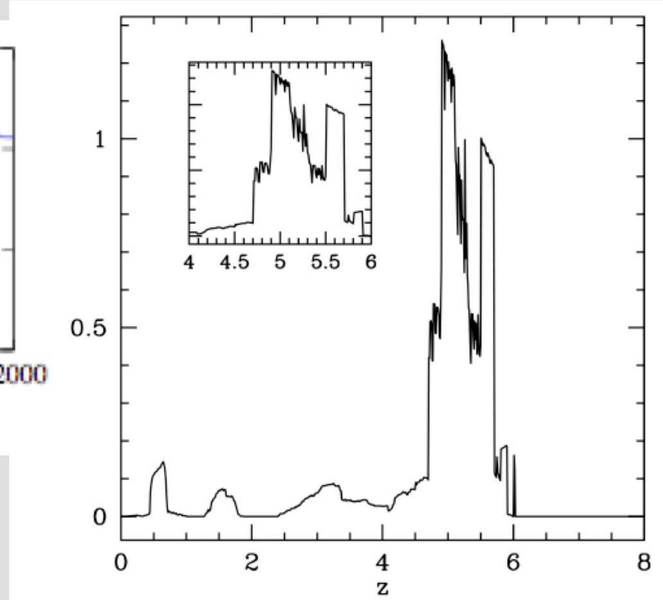


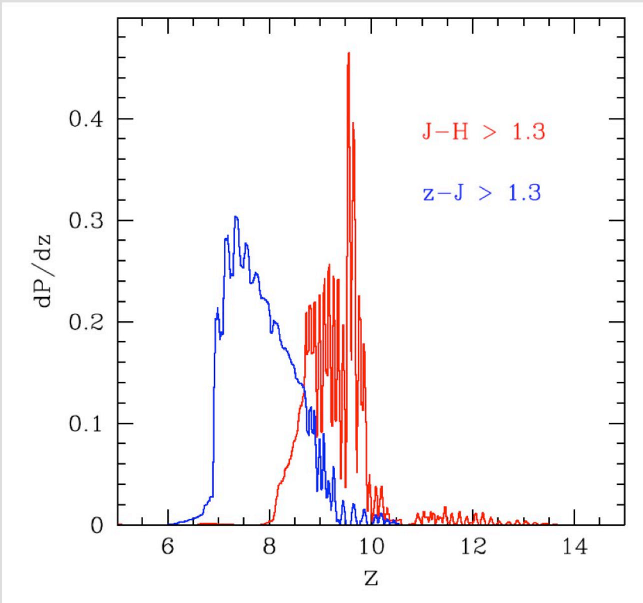
V 2



Object selection : Lyman break



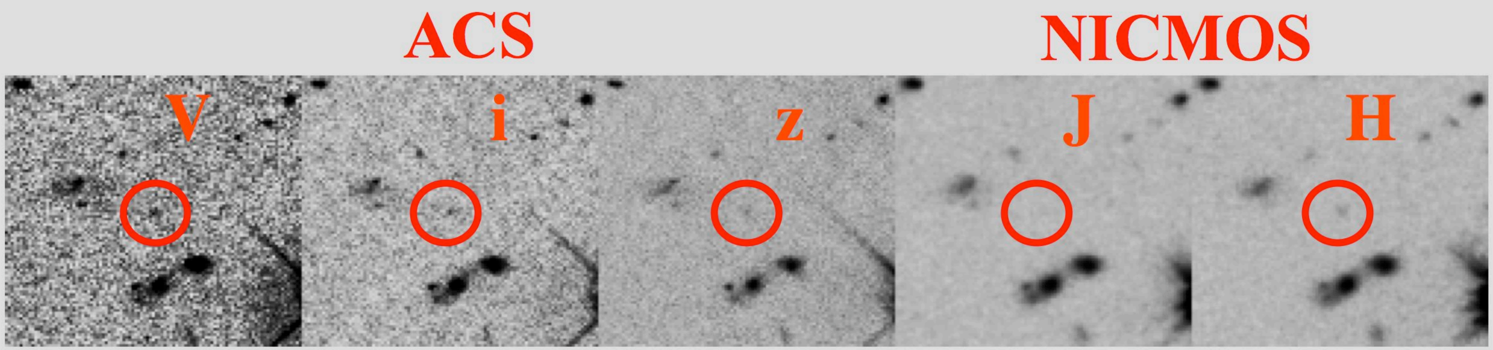




Theoretical redshift distribution from our synthetic SED models for z and J dropouts. The SED library contains about 3 million SEDs with a range of parameters including metallicity, dust, multiple populations, multiple star formation histories with or without emission lines. The basic input SED are from Bruzual and Charlot.

Status

ACS observations have been completed. We are still working on the data reduction and analysis. A first version of the NICP12 image was released in Jan. 2006 (2 months after they were obtained). Still working on the data for NICP34.



A preliminary result: there are no bright z- and J-dropout objects in NICP12. The three dropout candidates reported by Bouwens et al (2005) in this field are not confirmed. We show above one of the three Bouwens et al. candidates as seen in our NICMOS and ACS images.

Method

Direct: identify sources producing the required ionization flux
Indirect: detect a steepening of the LF slope (e.g. Wyithe & Loeb)

In both cases: completeness and corrections are critical

Need to compare  to  (e.g. Beckwith et al. 2006).

→ Derive LF(z) : same method on similar data. Corrections:

1- interlopers selected due to photometric errors scattering them into the selection box
2- real objects lost due to photometric errors scattering them out of the selection box
3- real objects lost due to (in)completeness in the catalog (either due to blending or to low S/N).
4- SED and z dependent corrections (from obs to rest frame mag.)

Method

Direct: iden [...] l ionization flux

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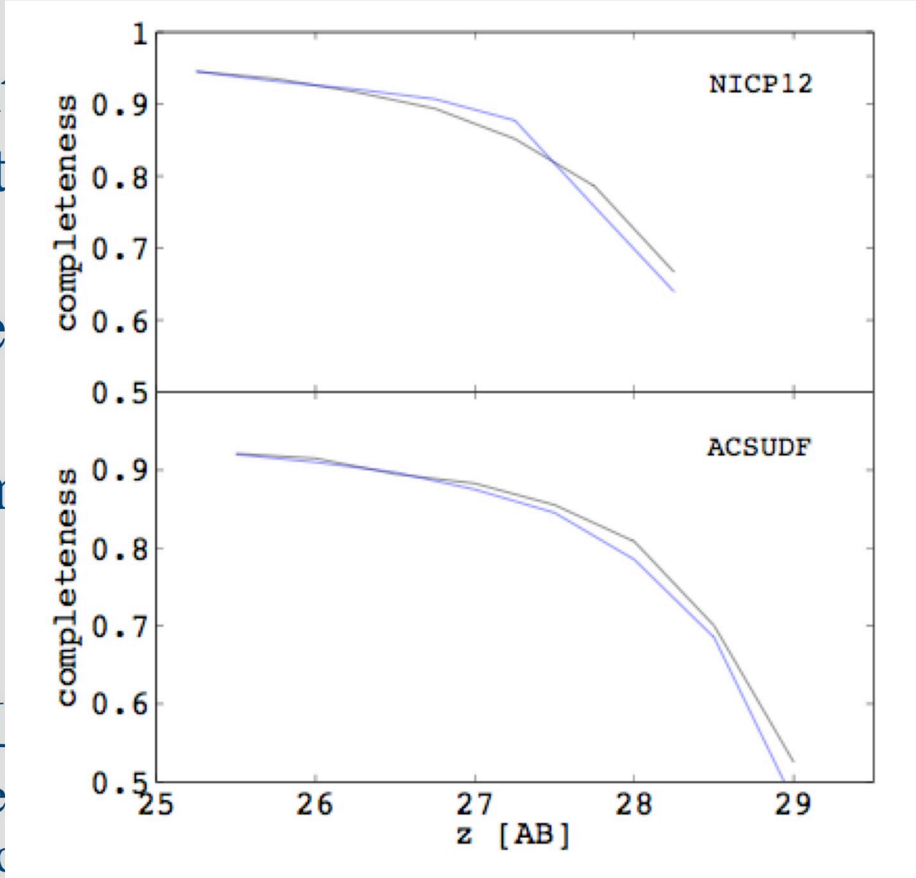


→ Derive L [...] a. Corrections:

1- interlopers se [...] m into the selection box

2- real objects lo [...] ut of the selection box

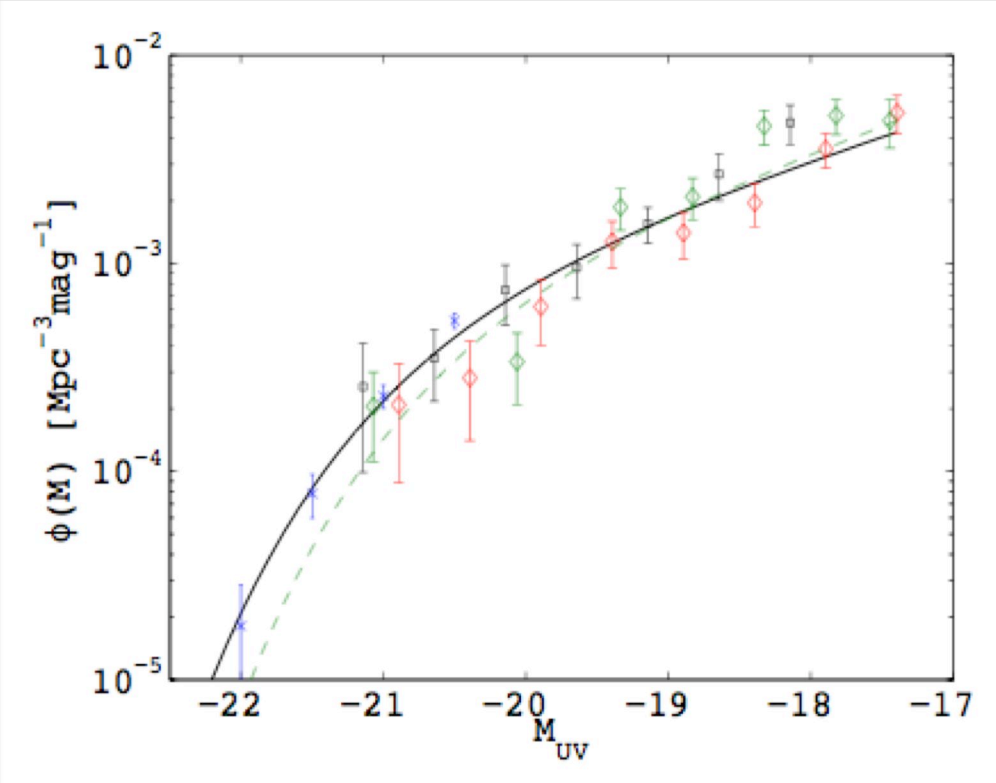
3- real objects lost due to (in)completeness in the catalog (either due to blending or to low S/N).

4- SED and z dependent corrections (from obs to rest frame mag.)

Some results…(1)

HUBBLE UDF ULTRA DEEP FIELD

V-dropout LF (z=5) from UDF05+UDF (Oesch, Stiavelli et al. 2007) in agreement with Beckwith et al. $\alpha = 1.57 \pm 0.10 \pm 0.03$.



Our combined LF (solid line) compared to the Beckwith et al. LF (dashed line) and the measurements by Yoshida et al. (blue crosses), UDF (diamonds: green our paper, red Beckwith et al.) and NICP12 (black squares).

Some results…(2)

Cosmic variance is an extra source of errors which is hard to quantify. We have attempted to do so by using cosmological N-body simulations (Trenti and Stiavelli 2007).

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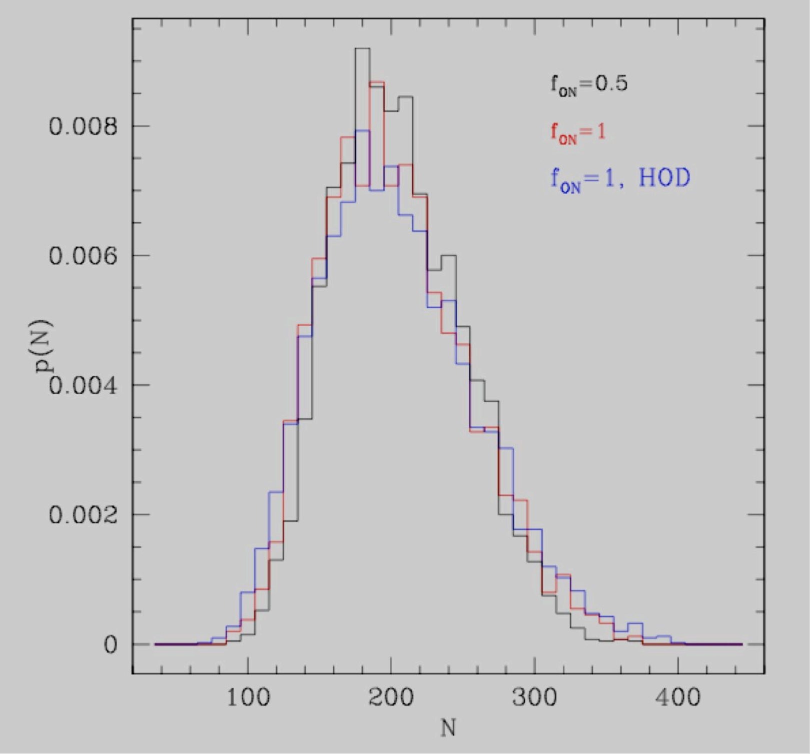


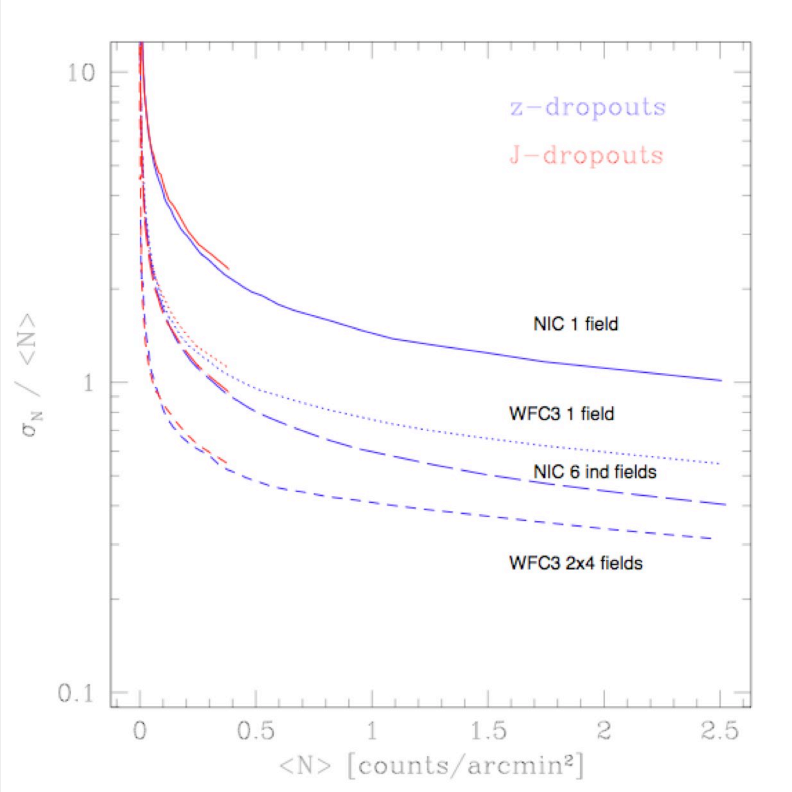
For the typical number of V-dropout objects in a single deep ACS field cosmic variance roughly corresponds to a 25% effect compared to a Poisson error of 7 per cent.

Some results…(2)

Cosmic variance is an extra source of errors which is hard to quantify. We have attempted to do so by using cosmological N-body simulations (Trenti and Stiavelli 2007).

The effect is more serious at higher z where we can detect even fewer objects.

On the plus side, the 6 NICMOS fields we now have lead to a significant reduction in variance



Some results…(3)

We can select objects as z=7-8 from z-J > 0.9 (z-dropouts). J-dropouts would be at even higher redshift.

Some results…(3)

We can select objects as z=7-8 from z-J > 0.9 (z-dropouts). J-dropouts would be at even higher redshift.

We expect:
8 ± 4 (Beckwith et al.)
16 ± 7 (Bouwens et al.)

We find:

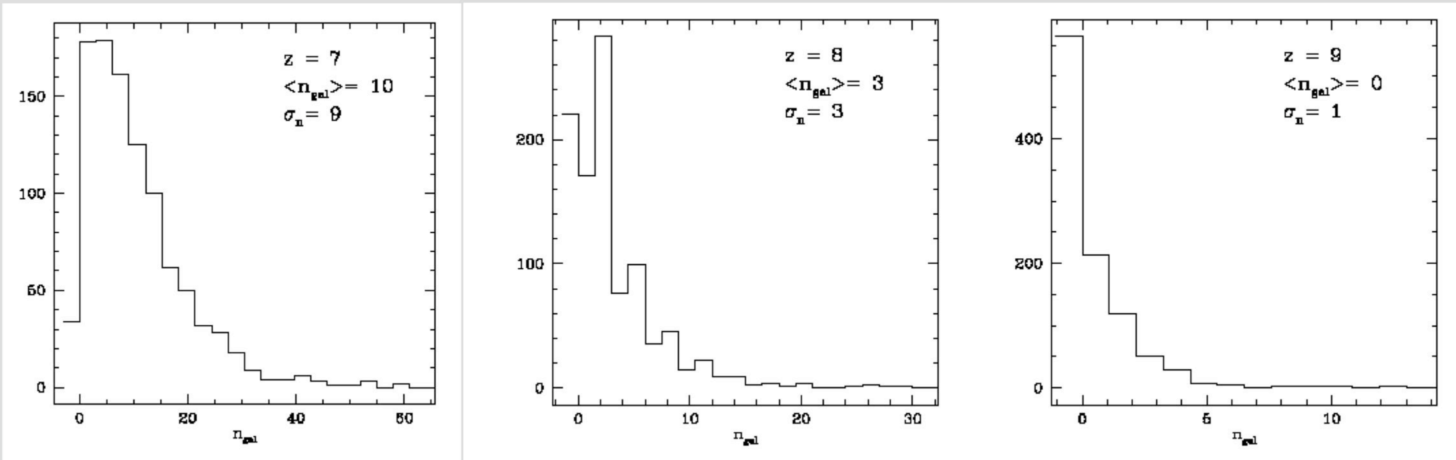
0

This is possible evidence for strong evolution but not as significant as one would like.

We have:
2 fields at J=28.5
2(4) fields at J=28.0
9 fields at J=27.3

Progress by others…

Bouwens & Illingworth (2006) combined the UDF, HDFN, HDFS and GOODS data and concluded that there is evidence for a rapid change in the LF of galaxies going from 6 to 7+. We find the same but have a different assessment of its significance.



CDM halos over an area 4 times that of NICMOS

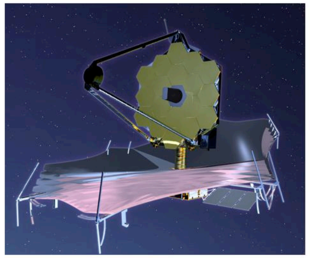
rms is as large as mean #.

If this result is confirmed it would imply that reionization is indeed completed between 6 and 7 and that some combination low metallicity and a dwarf-rich LF does the job.

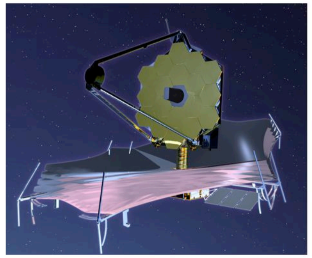
Future HST observations

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 will be possible with the IR channel of WFC3.

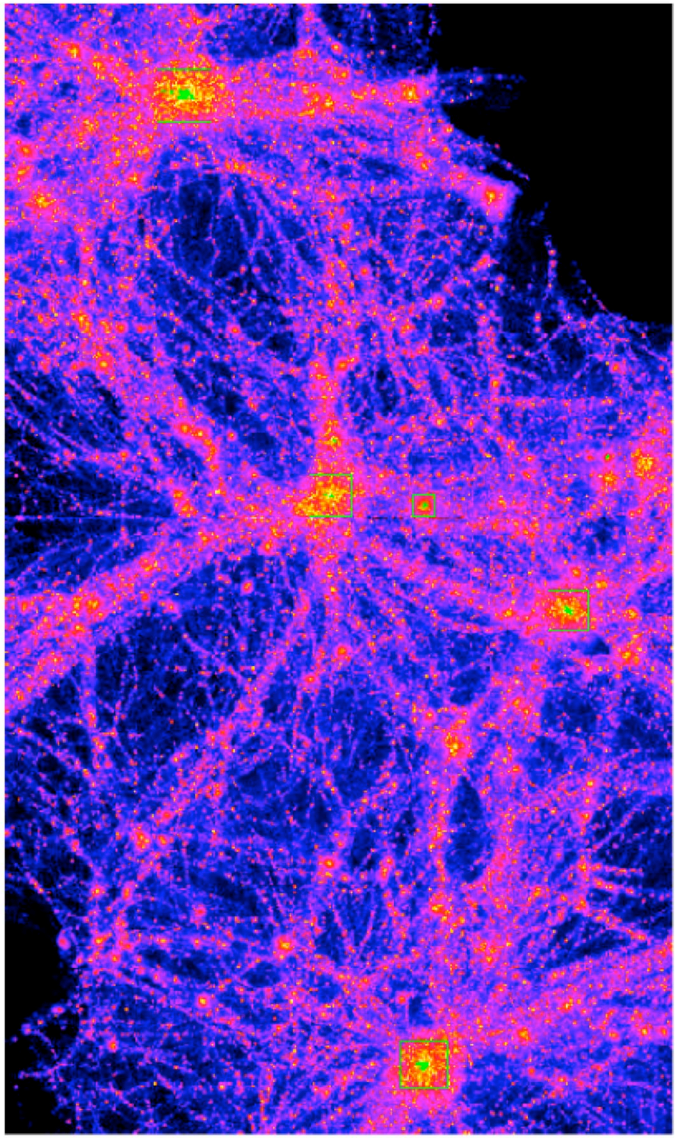
WFC3/IR can cover the same area as NICMOS Cam3 to the same depth in one tenth of the time. This would allow us in principle to extend to the near-IR surveys like GOODS and the UDF with *only* a few hundreds of orbits.



First light



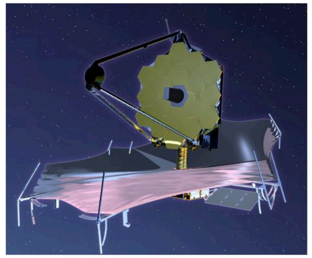
What are first light sources associated to?



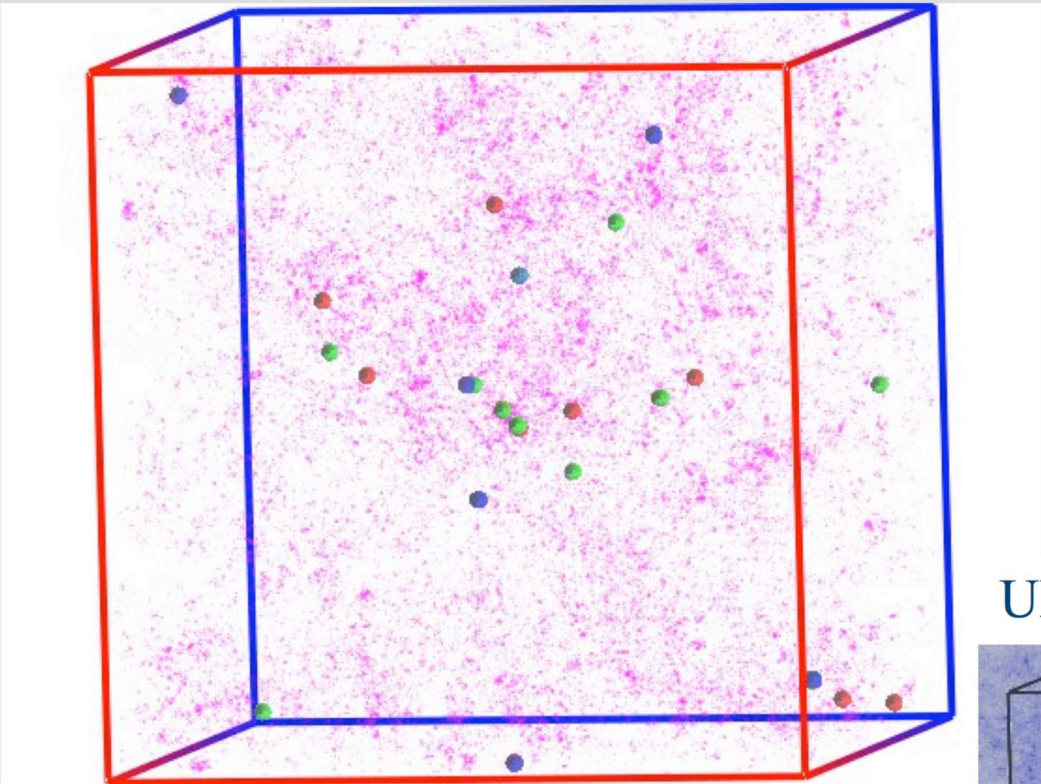
Diemand et al. find that early structures (green particles) tend to end up in the cores of larger structures at lower redshift. In the picture (at $z=0$), green particles were identified at $z=13.7$ as having a mass $> 4.9 \; 10^7 \; M_\odot$.

This is a region of about (10 Mpc)^3 selected to contain 5 galaxies at $z=0$. The individual DM particle mass is $\sim 6 \; 10^5 \; M_\odot$.

What are first light sources associated to?

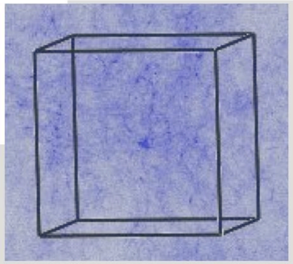


N-body simulation (Trenti & Stiavelli) with 350M particles over (80 Mpc)^3. DM distribution at z=6. Halos non linear at high-z : blue 47<z<45; green 45<z<43; red 43<z<41.



We find that half of these early perturbations are not associated to massive perturbations at z=6 and do not end up in the most massive halos at z=0.

UDF volume between z=5.8 & z=6.5



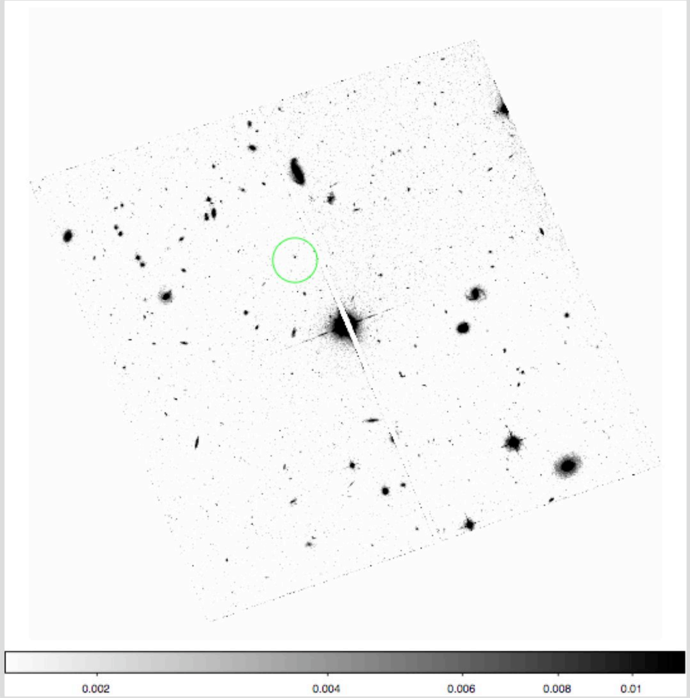
DM particle mass $10^8\ M_\odot$

Connection between z=6 QSOs and first light sources

- SDSS z=6 QSOs are extremely rare: there is on average one every (720 Mpc)^3.
- Some, but not all, are shown to be located in large overdensities (Stiavelli et al. 2004; Kim et al. 2007)
- It is unclear how a 10^9 Msun black hole can form in only one billion years:

  at the Eddington rate and for an <u>accretion efficiency of 0.1</u>, the mass of a BH increases to a few 10^9 only if the initial mass is about 100 Msun.

The remnant of a Pop III star could be a ~100 Msun black hole. This would serve as a seed for more massive black holes accelerating their growth.



HST ACS image in F850LP of J1030+0524

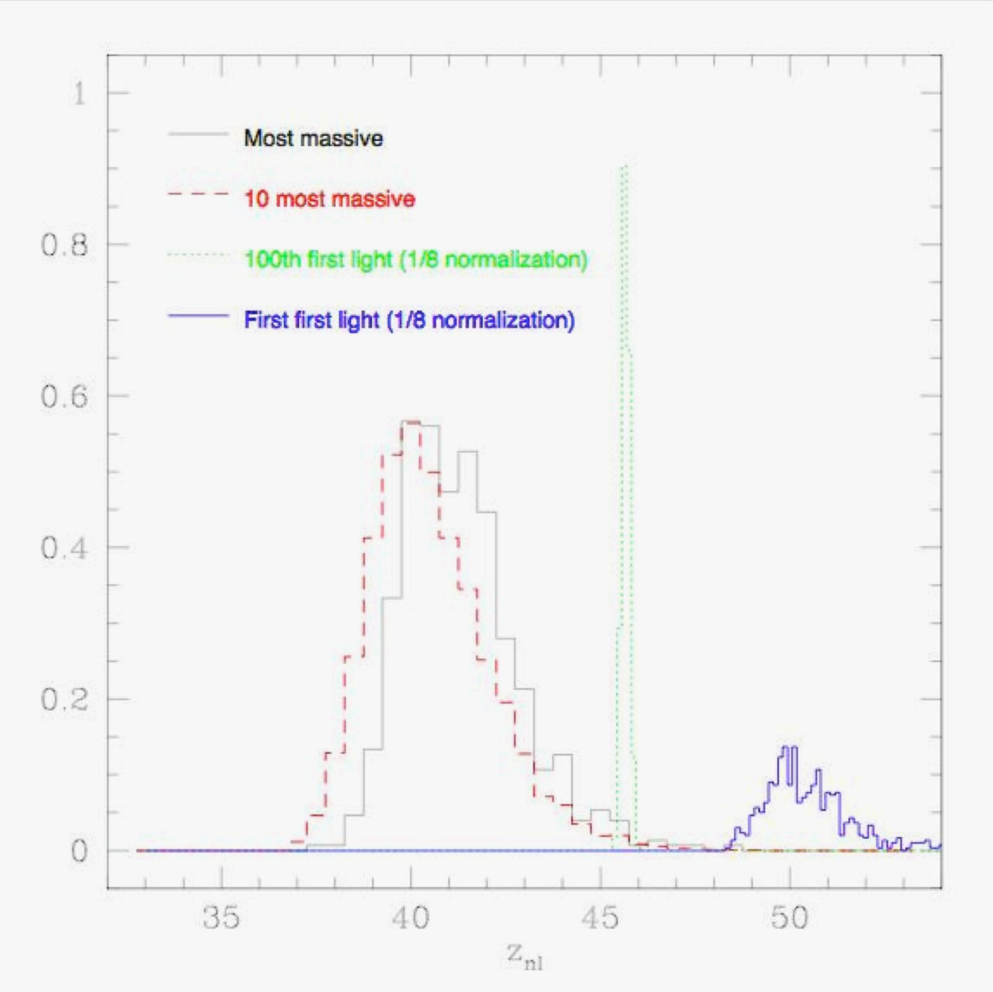
Connection between z=6 QSOs and first light sources

HUBBLE UDF ULTRA DEEP FIELD

→One of the common assumptions is that first light sources are the seeds for the z=6 QSOs. Can we verify that? Answer in Trenti & Stiavelli, 2007 ApJ submitted

A simulation with $(720\ \mathrm{Mpc})^3$ volume and resolution sufficient to probe first light sources (with a mass of 10^6 Msun) needs more than 13 orders of magnitudes of dynamic range. This is more than 10^3 times more resolution than the best simulation ever done.

We obtain this resolution by combining large N-body simulations with 512^3 particles with an analytical treatment of the linear phase at small scales and high-z.

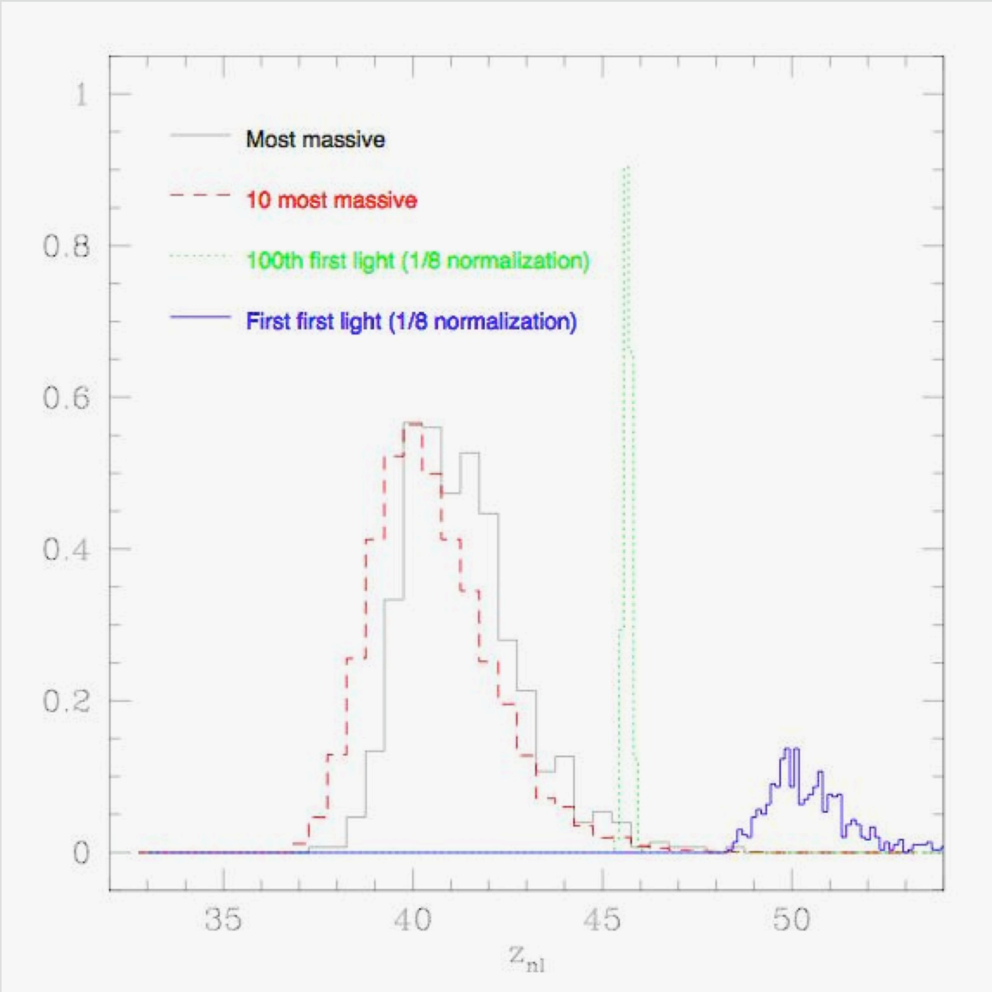


Over the large box first light source form at z=50, while the earliest QSO progenitors are at z=40-45.

These progenitors are still probably in the Pop III phase so they may leave intermediate mass black holes as remnants.

There were about 4000 first stars formed before the one in the z=6 QSO.

Why only the one in the QSO becomes a supermassive BH?

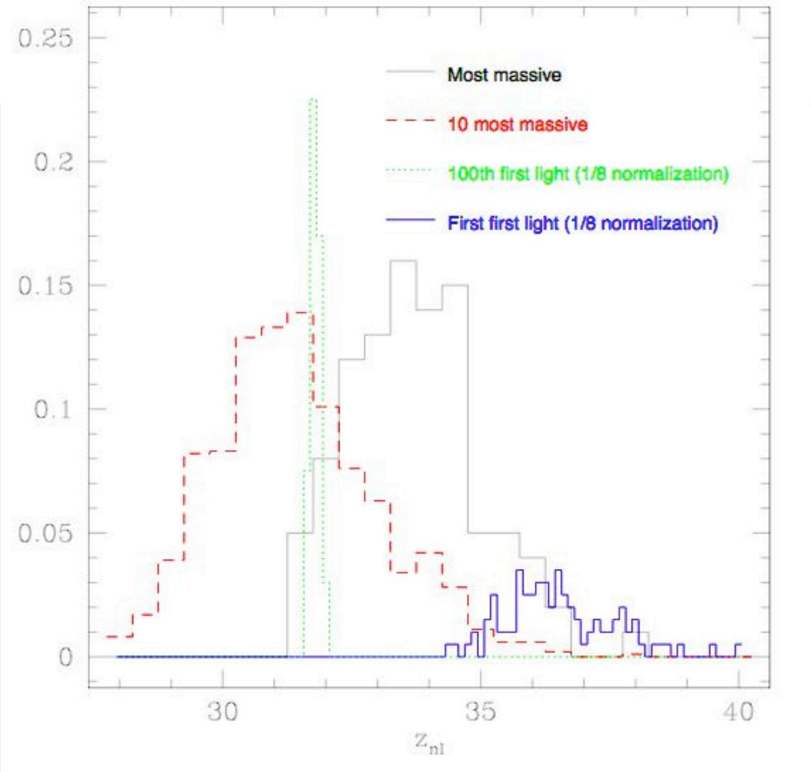


Over the large box first light source form at z=50, while the earliest QSO progenitors are at z=40-45.

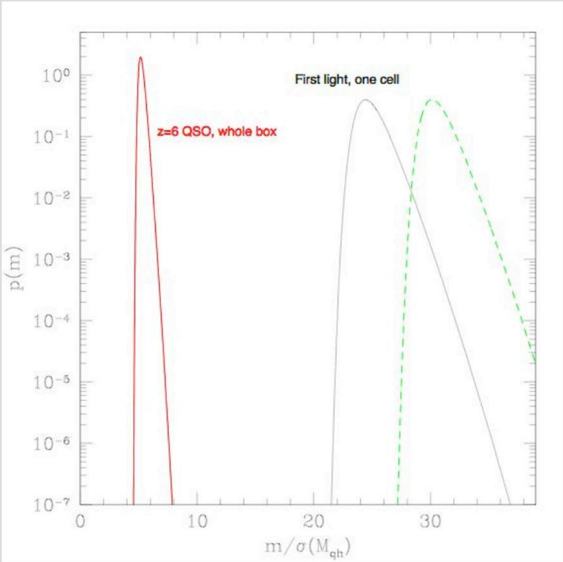
These progenitors are still probably in the Pop III phase so they may leave intermediate mass black holes as remnants.

There were about 4000 first stars formed before the one in the z=6 QSO.

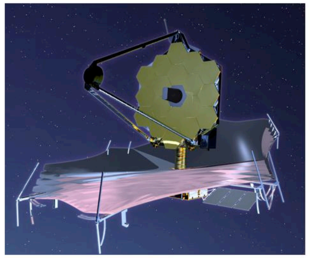
Probably only the one in the QSO had enough fuel.



We confirm previous claims that over smaller volumes, e.g. (60 Mpc)^3 , the first stars are seeds to the rarest structures.



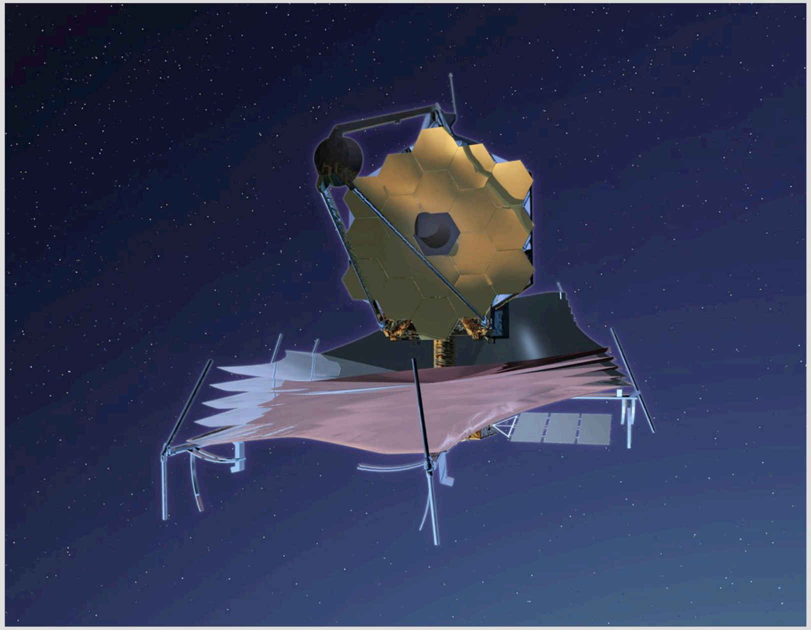
Note that the first Pop III stars are extremely rare objects.



Beyond HST

Probing the luminosity function of galaxies at z>12 (and probably already for z>8-9) or studying the properties of galaxies at z=6 requires an instrument more sensitive than HST :

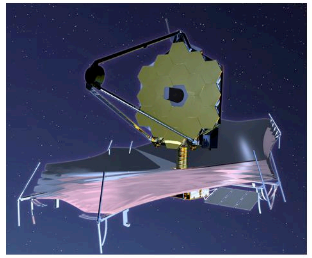
the **James Webb Space Telescope**



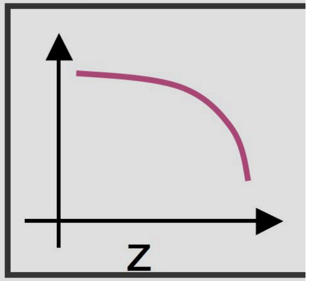
End of the dark ages:

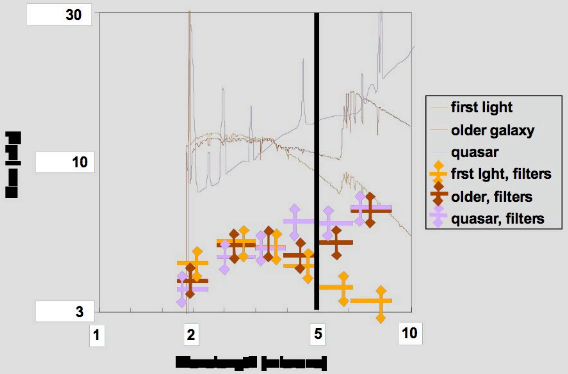
- **First light**
- Nature of reionization sources

I. Detection of first luminous objects

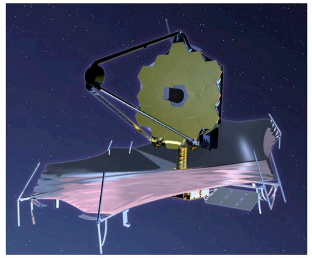


- Evolution of N(z). *Identify candidates with Lyman break technique* → **NIRCam**
- Evolution of SFR(z). *Use Hα, Hβ and supernovae* → **NIRSpec and NIRCam**
- Evolution of <Z>(z). *Use [OIII]/Hβ.*
- Confirm nature of first light objects. *Place upper limit to metallicity, search for older stellar component.*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





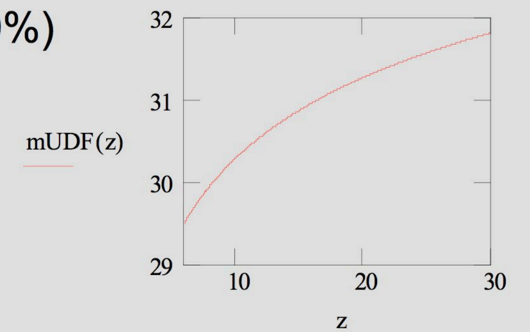
First light sources : detection

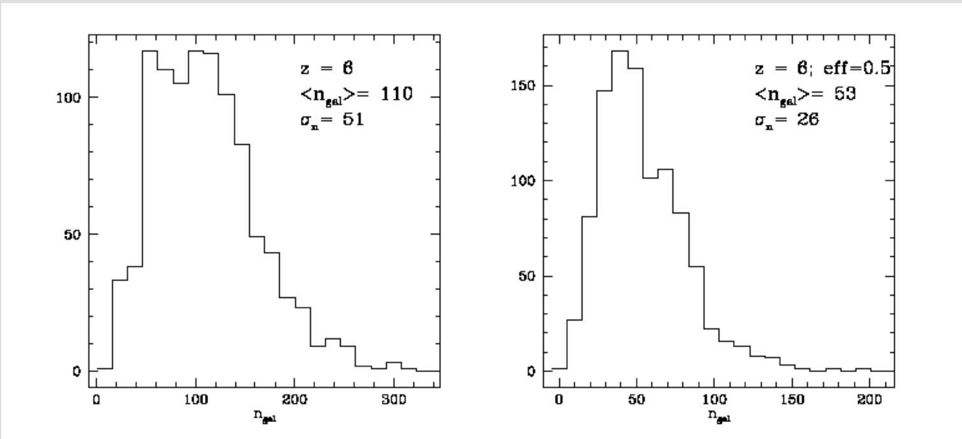


Probing the LF to the same relative depth as that of z=6 from the UDF gives us a required depth:

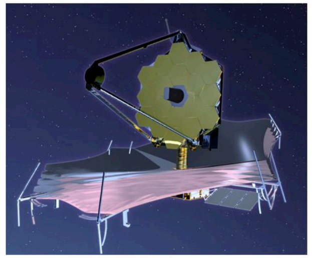
from Trenti & Stiavelli 2006 ApJ

z	AB_1350	F^{ν} (nJy)	λ (μm)	$<A_{1400}>$	$A_{1400}(90\%)$
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

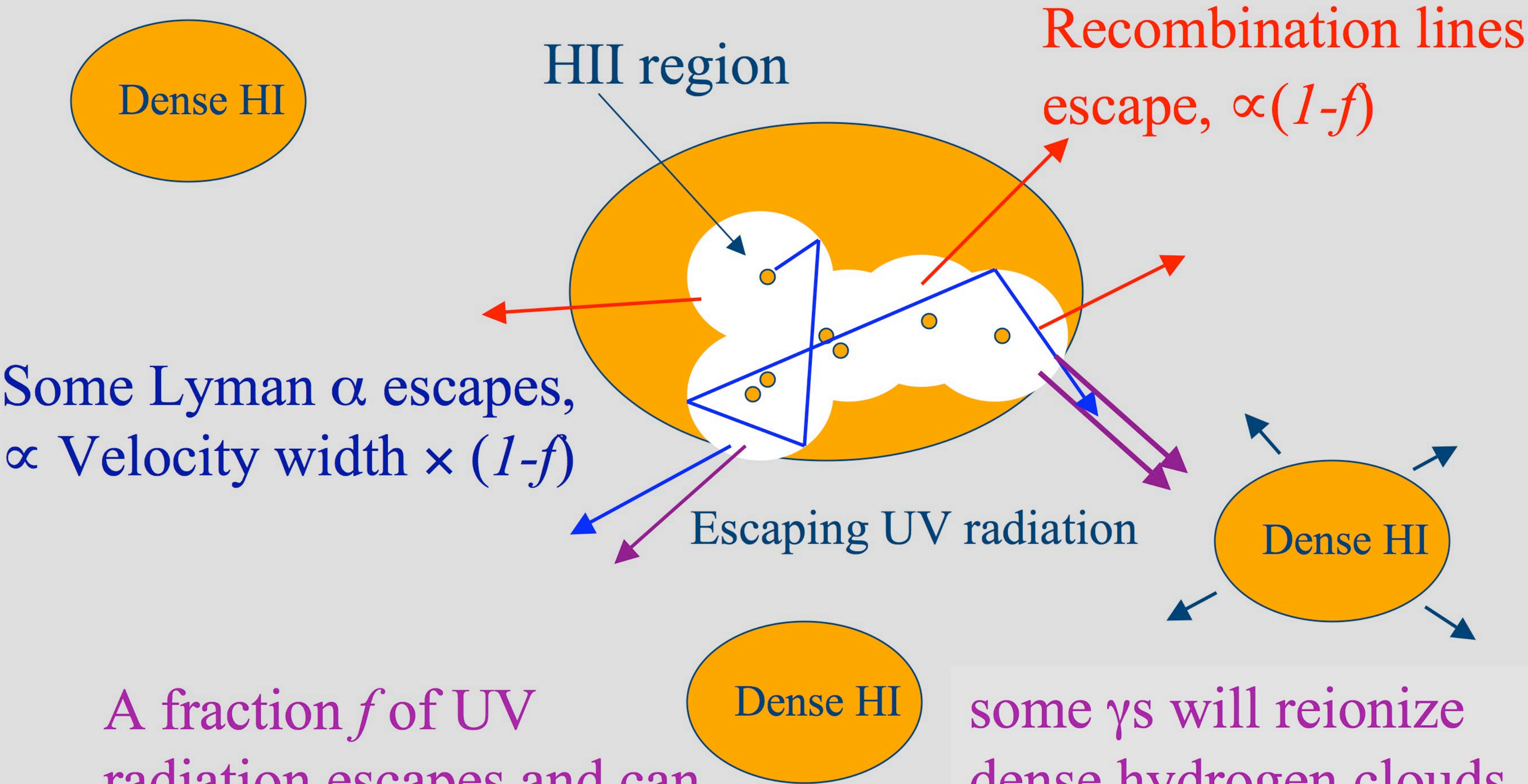




Distribution of the number of dark halos in the UDF assuming that all of them (left) or only 50% (right) are visible as galaxies. The mean number is roughly twice the rms of the distribution (Trenti & Stiavelli; see also Somerville).



Estimate luminosity of firsts light and reionizing sources from first principles

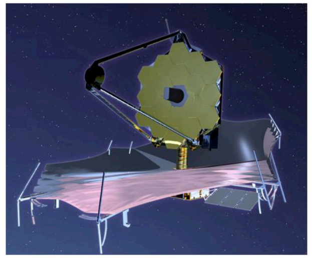


A fraction *f* of UV radiation escapes and can reionize the Universe

some γs will reionize dense hydrogen clouds that later recombine → (

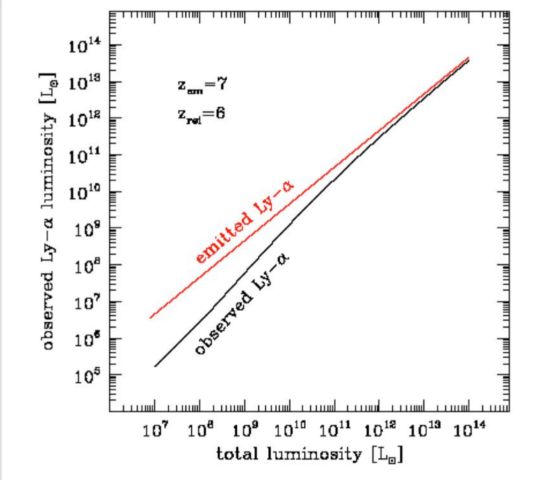
This prevents SF.

First Light Sources : Ly α & properties



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

Adopt: Lyα escape fraction of 0.2.

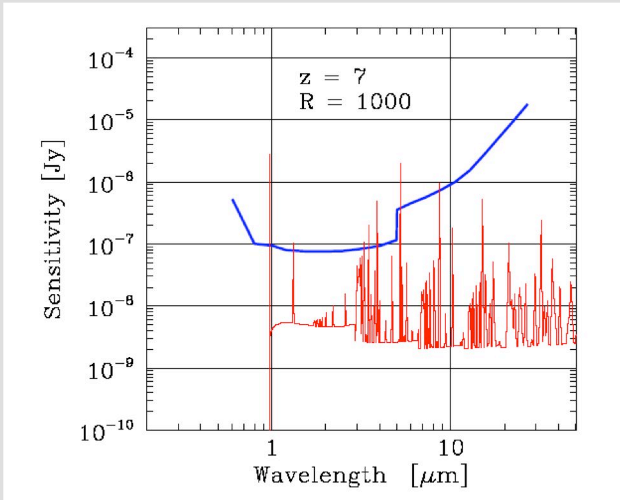


z	AB_1350	Ly α (cgs)	λ (μm)
10	30.284	1.7e-18	1.34
12	30.551	8.89e-19	1.58
15	30.869	4.02e-19	1.95
20	31.267	1.47e-19	2.55

Measuring the metallicity of first light sources

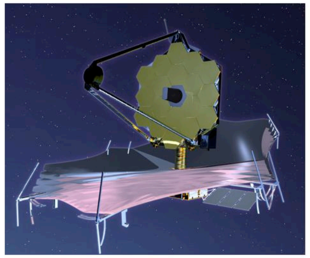
Let's consider a 5 nJy source with metallicity 1/1000 solar. The O line at 1665A will have a strength of:

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

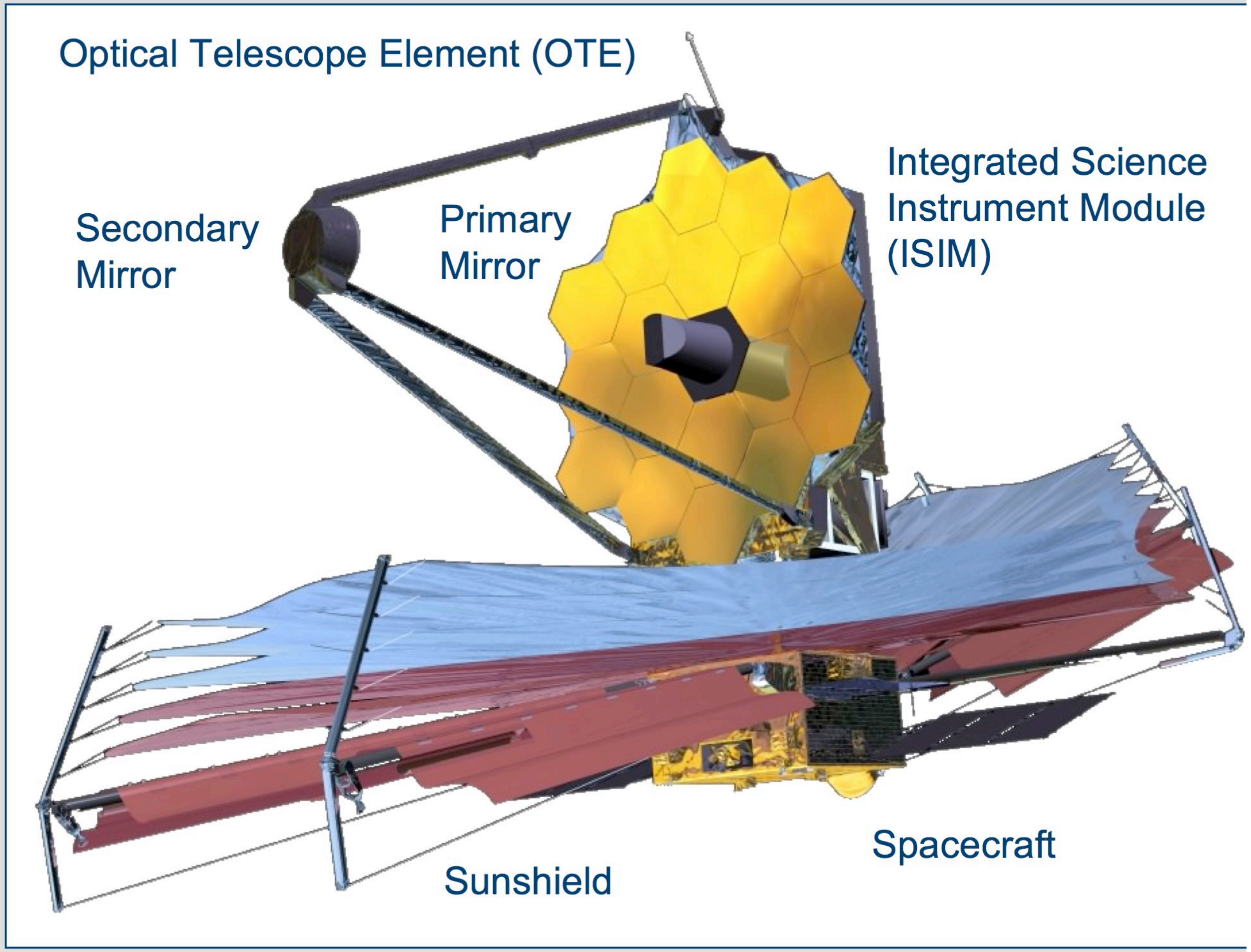


The metallicity measurement or the detection by MIRI will be possible for bright sources or sources amplified by lensing.

James Webb Space Telescope

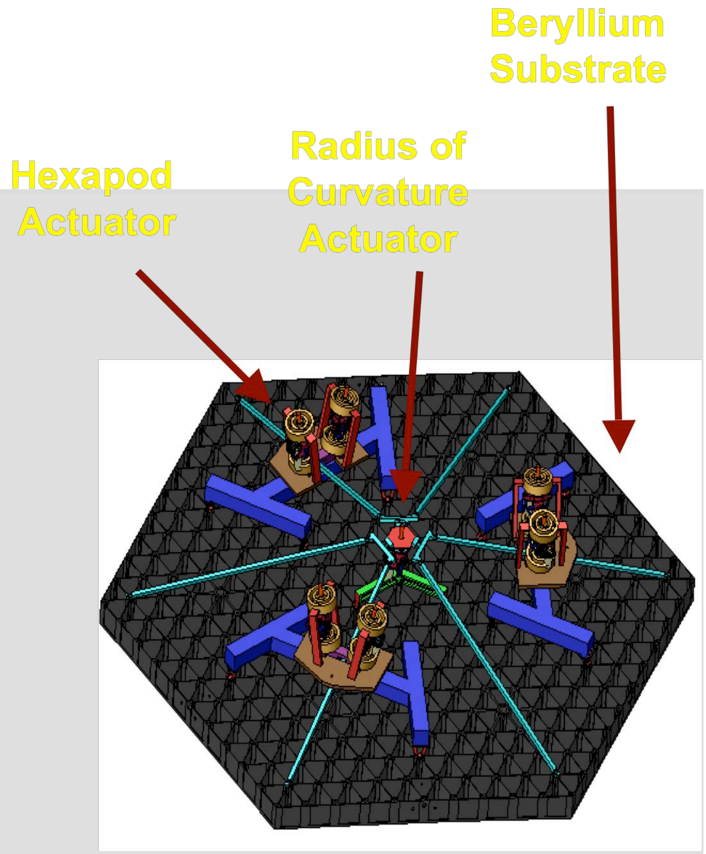


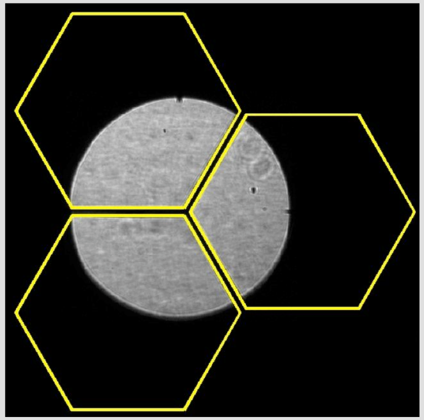
- 6.6m Telescope
- Launch in 2013 to L2.
- Successor to Hubble & Spitzer.
- Demonstrator of deployed optics.
- Passively cooled to 50K.
- Named for 2nd NASA Administrator
- NASA + ESA + CSA
- Lead: Goddard Space Flight Center
- Prime: Northrop Grumman Space Technology



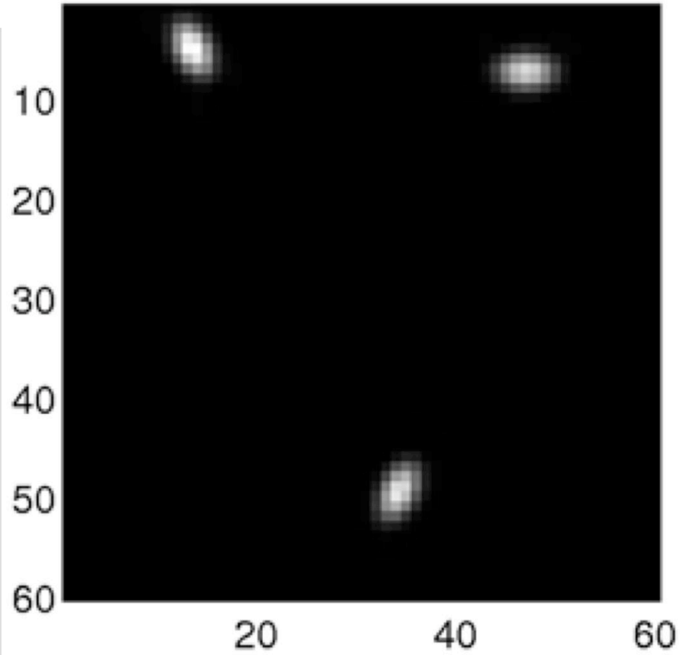
Mirror Segment Control

Testbed Mirror with 3 Segments



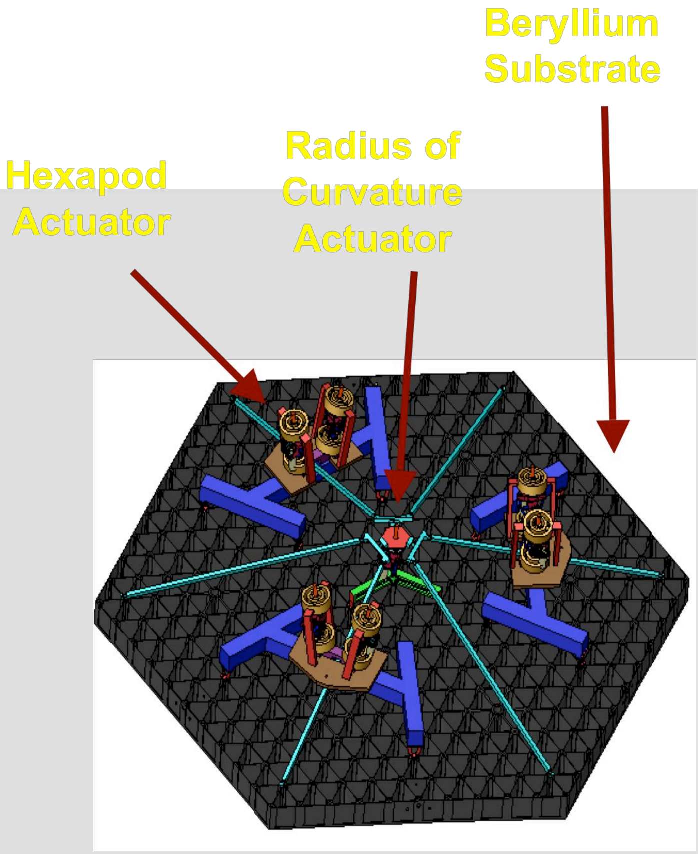


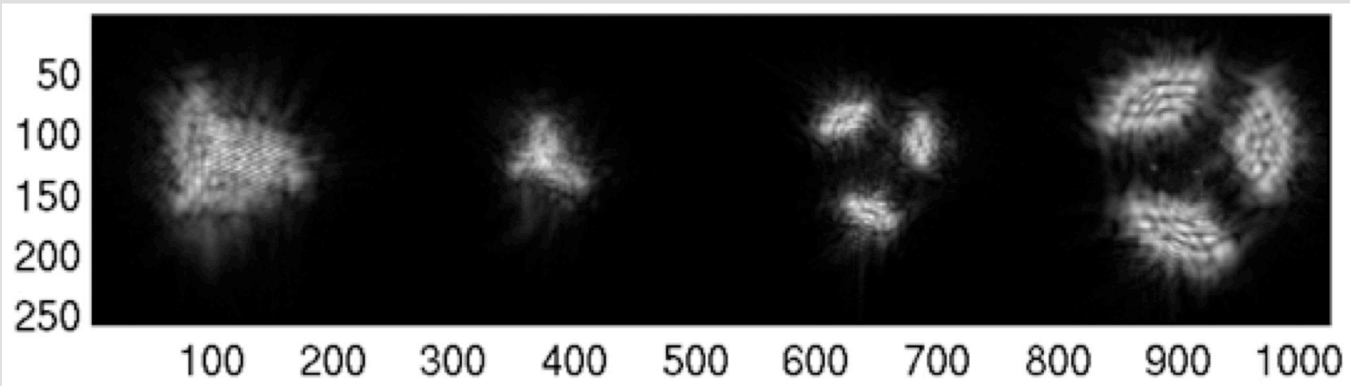
Mirror Segment Control



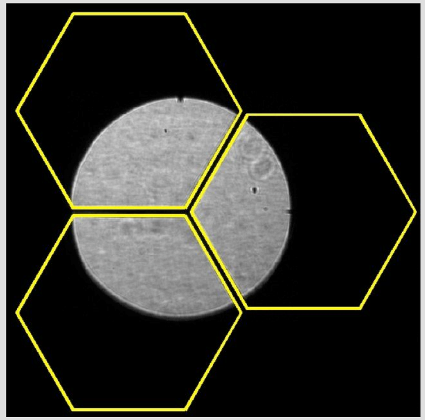
Focused Image

Testbed Mirror with 3 Segments

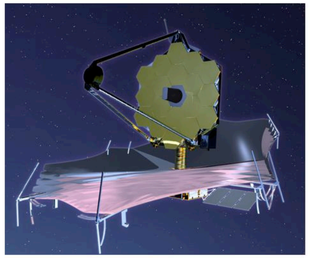


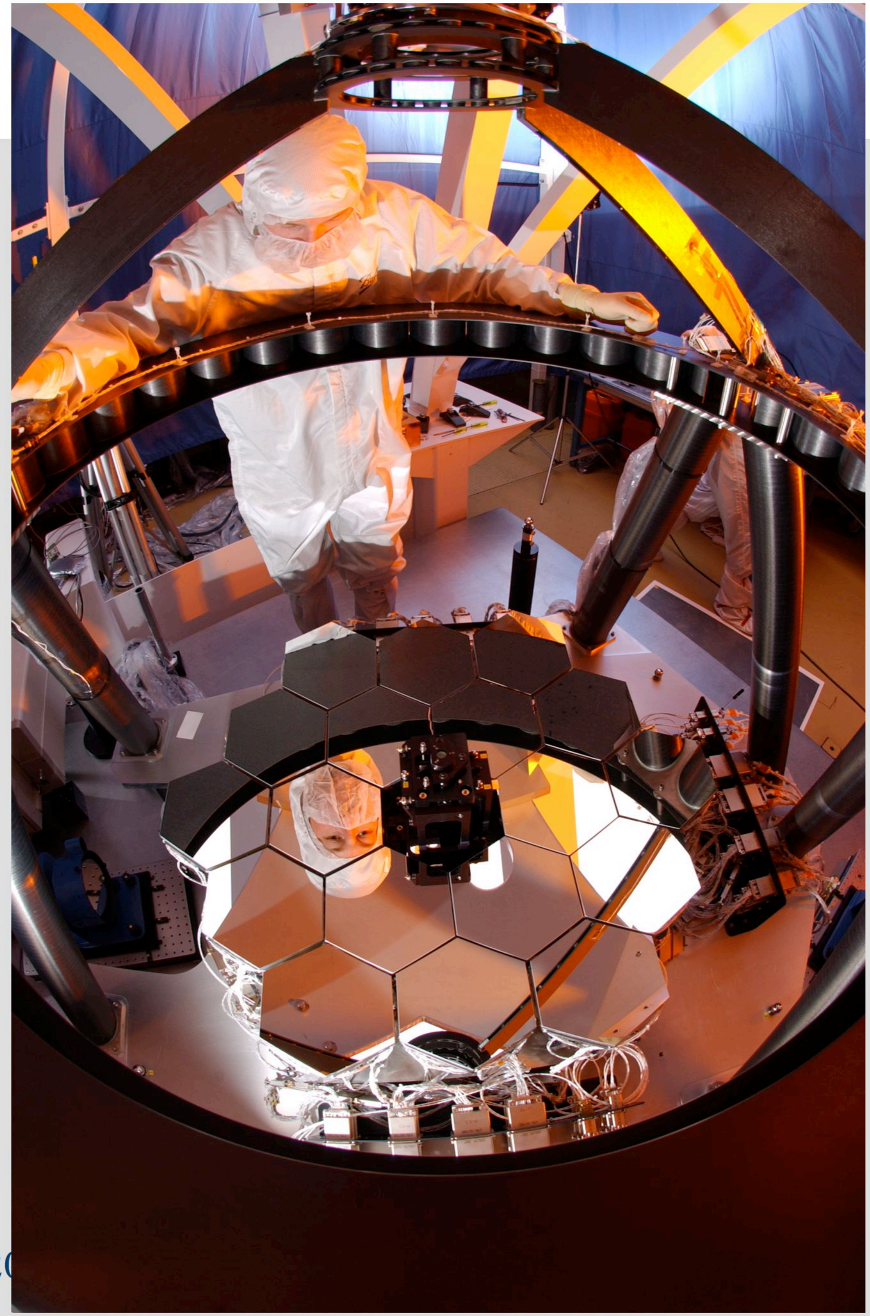


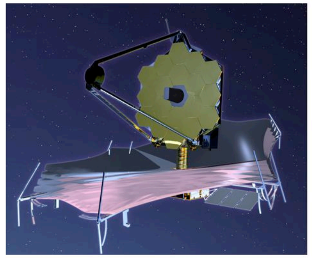
Unfocused Images

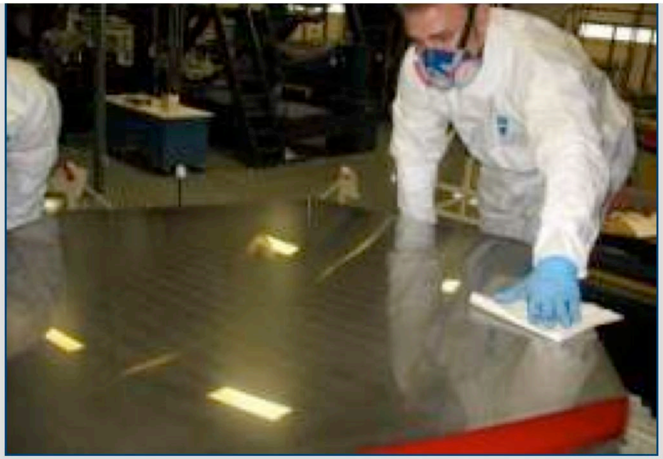


BRUSH WELLMAN has completed all JWST Primary, Secondary and Tertiary mirror blanks



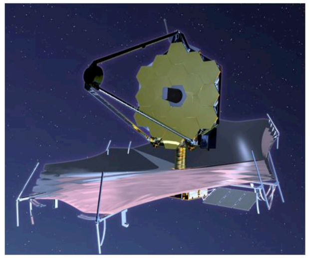


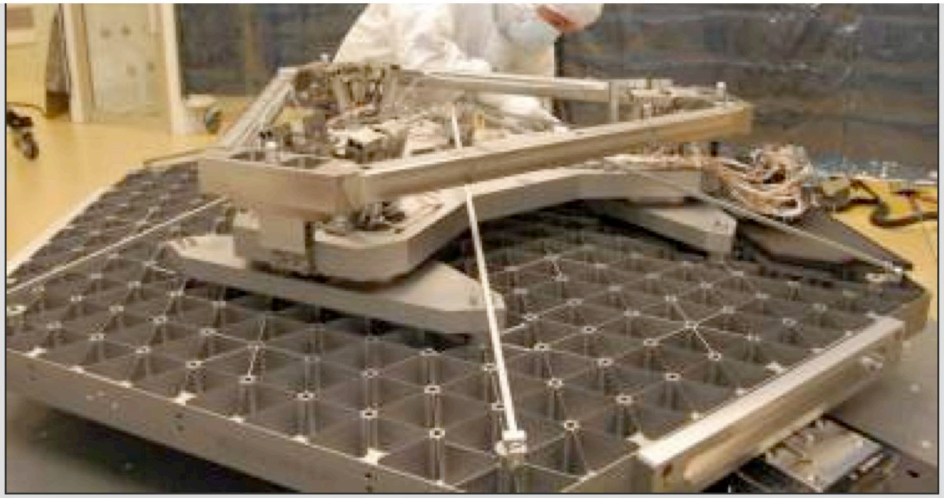




Machine 5 is ready
Machines 6 & 8: in Readiness Testing

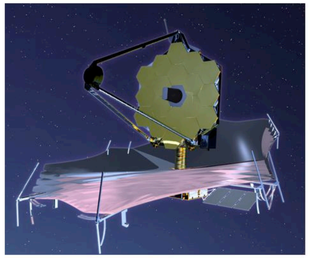
Smoothout Grind of EDU
32 Passes complete

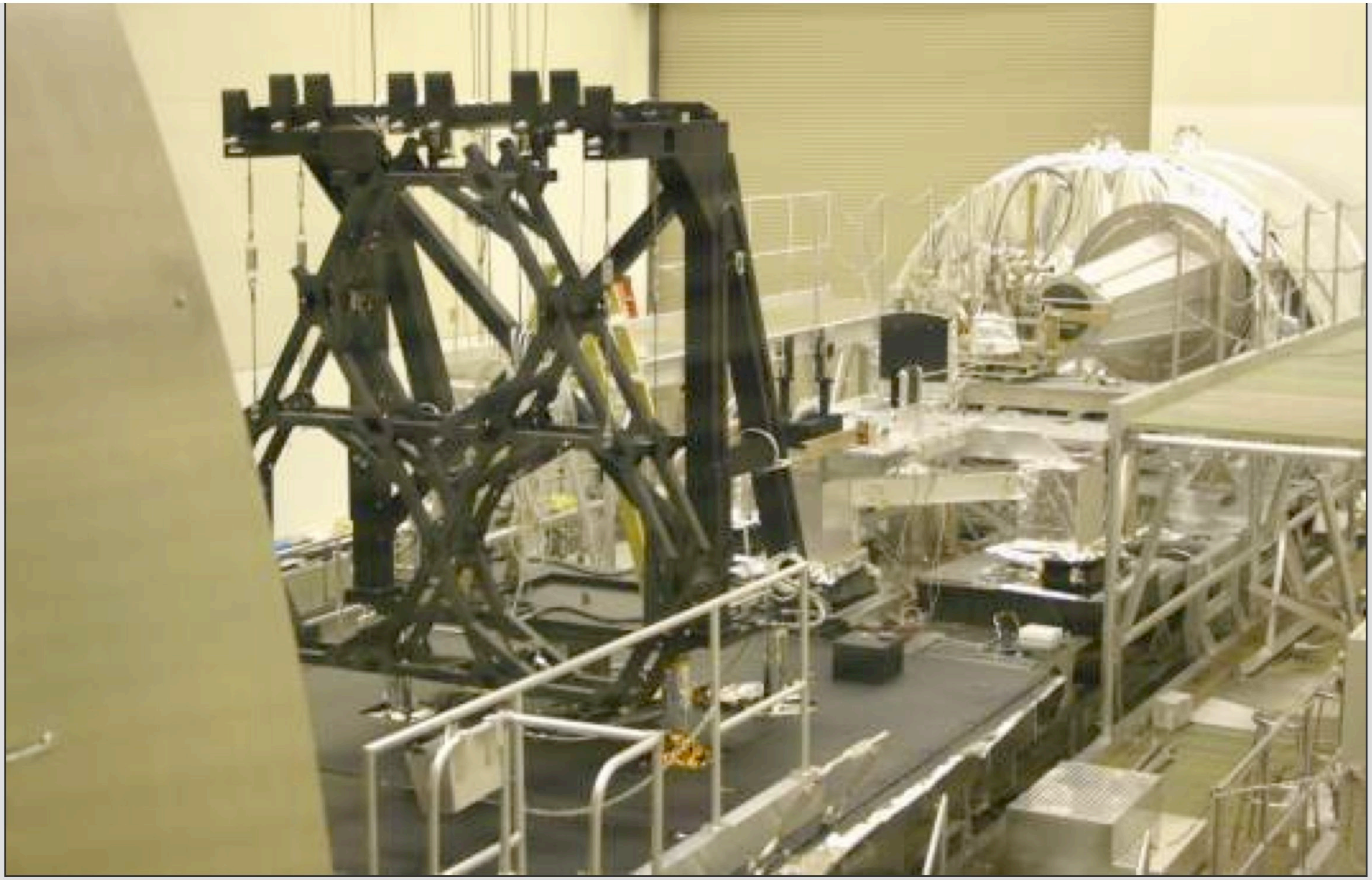




Acoustic test setup

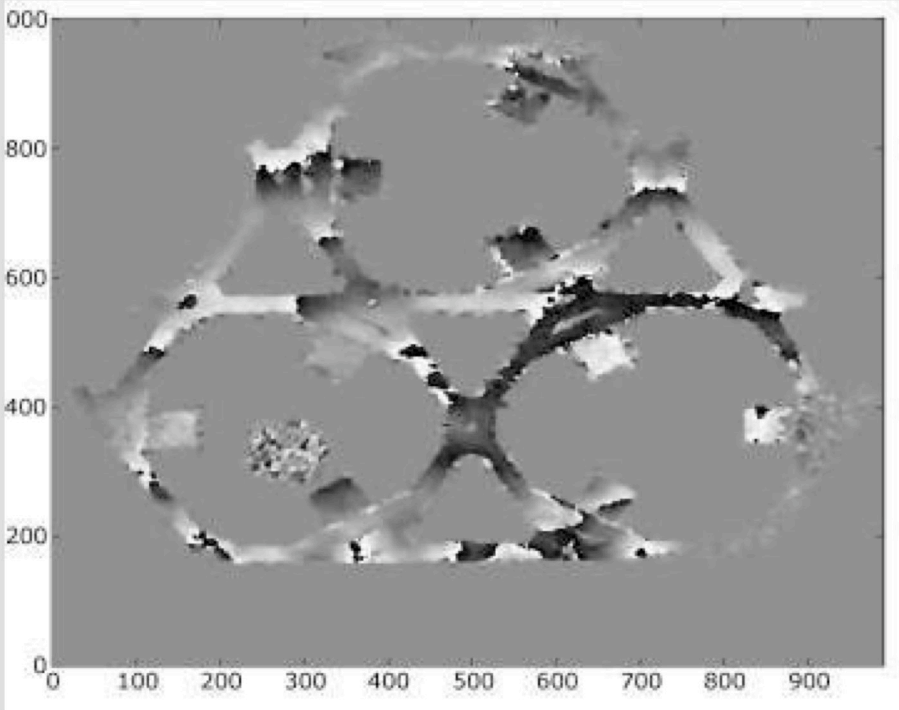
Sine burst test setup (z-axis)





BSTA resting in the BSS in the XRCF's 2K room. The grey arc on the left of the picture is the vacuum chamber

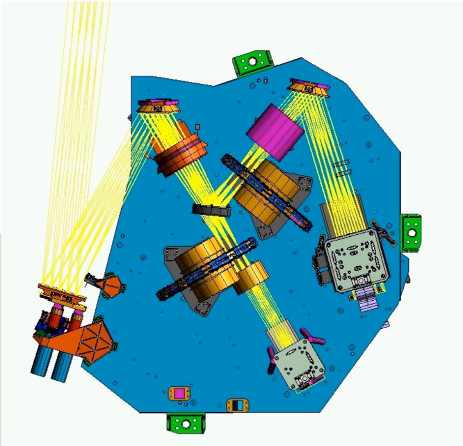
BSTA Structure



First Interferometric Fringe Of Entire BSTA

This major achievement indicates ESPI should be able to test the full BSTA cryo thermal stability

Instrumentation



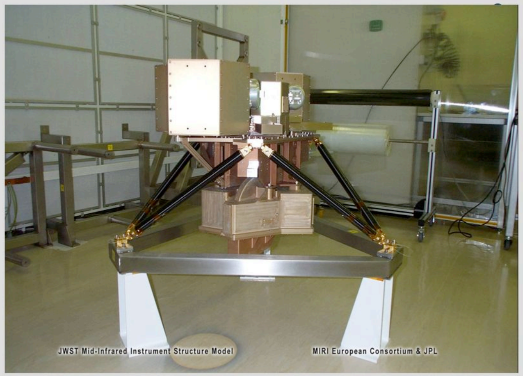
Arizona: Marcia Rieke PI

Lockheed-Martin & Rockwell

ESA: Peter Jakobsen

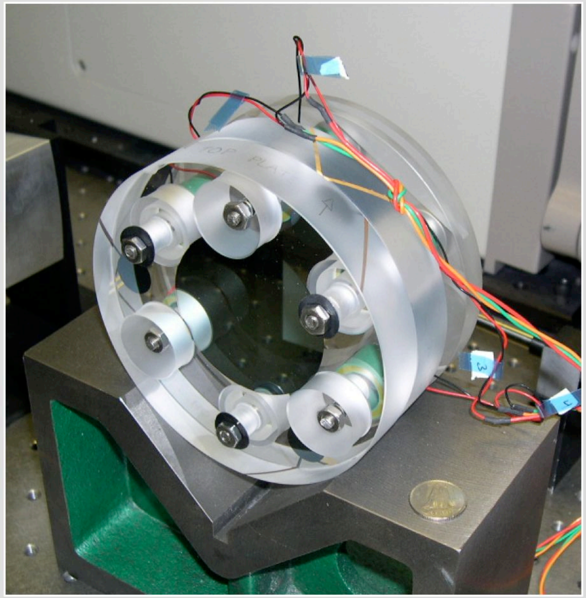
EADS Astrium & GSFC

- 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



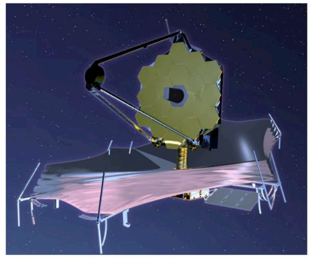
George Rieke & Gillian Wright

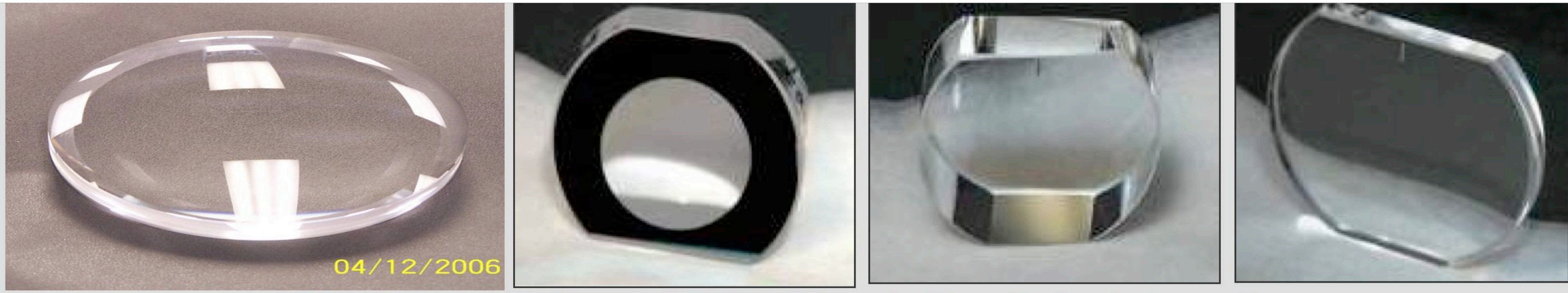
JPL and European Consortium



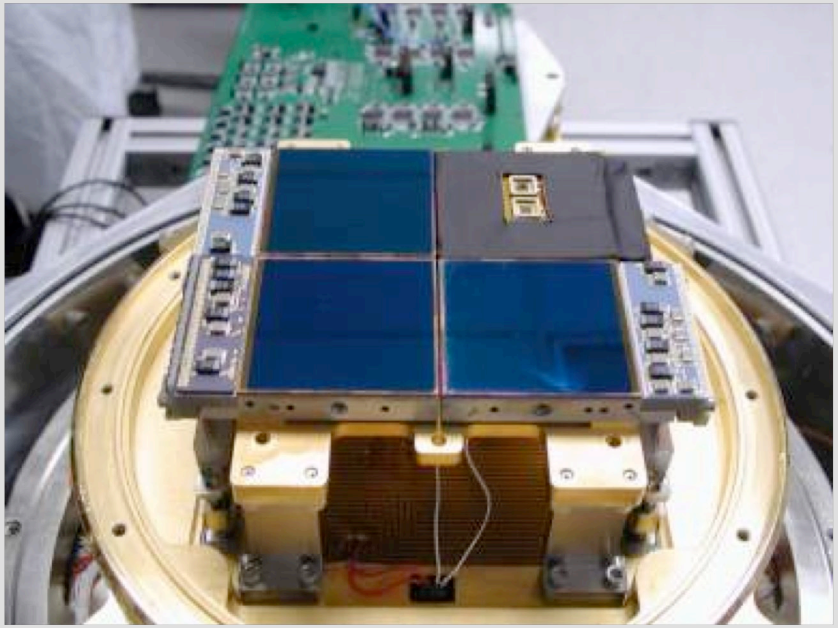
CSA: Rene Doyon

COM DEV



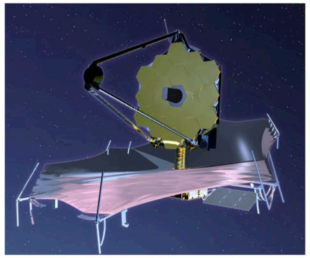


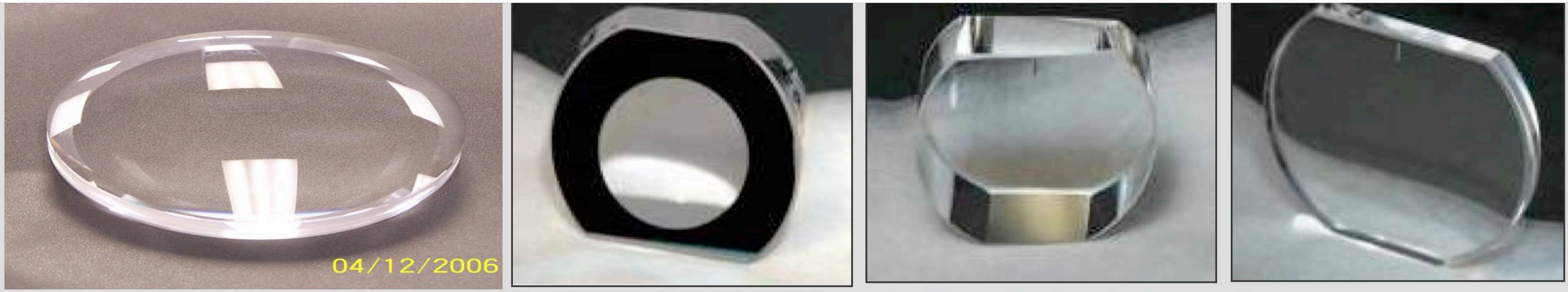
ETU Lenses Delivered to Lockheed - Ready for Integration



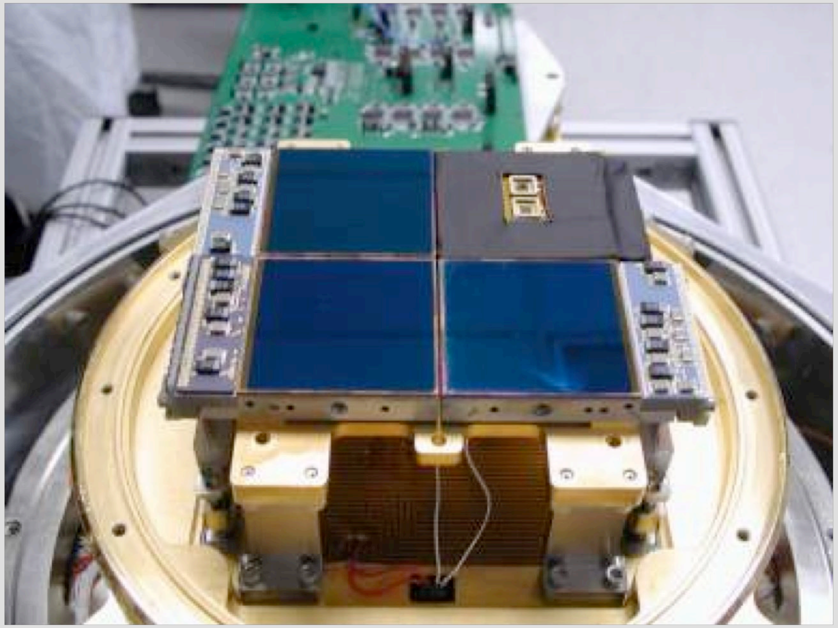
1st Flight Detectors in Test

1st ETU Optical Bench Complete





ETU Lenses Delivered to Lockheed - Ready for Integration



1st Flight Detectors in Test

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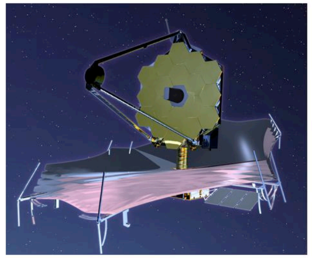
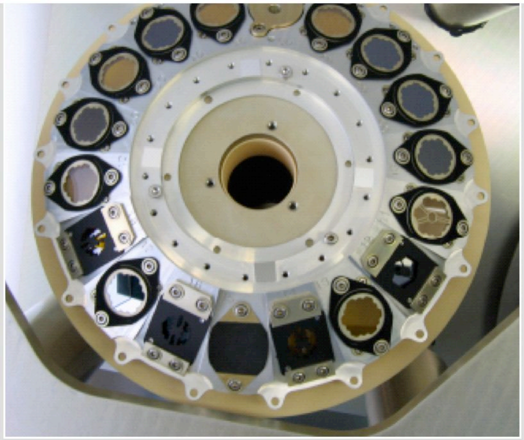
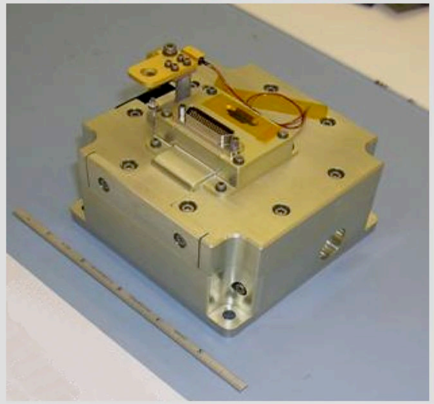


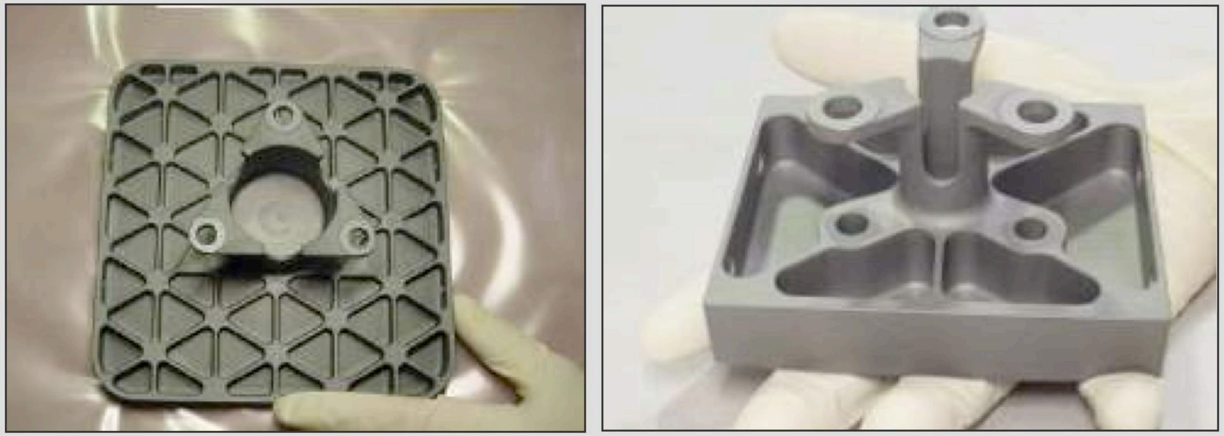
MIRI ETU Optical Benches



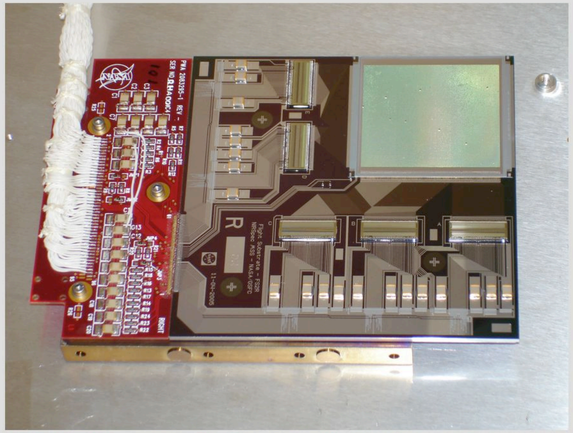
MIRI ETU Filter Wheel

MIRI ETU Detector

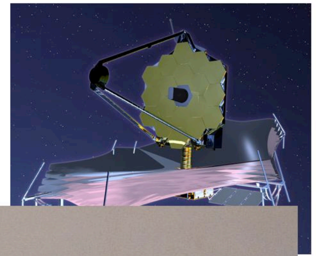




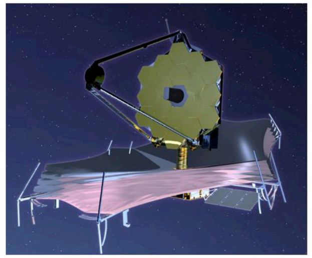
NIRSpec Silicon Carbide Mirrors



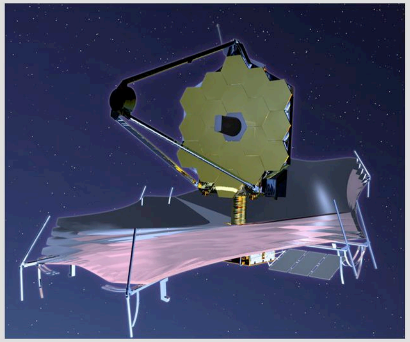
NIRSpec Microshutter Array
TRL6 Test Unit



Operations

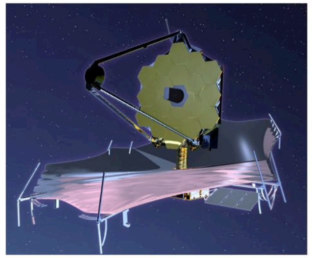


THE ASTROPHYSICAL JOURNAL

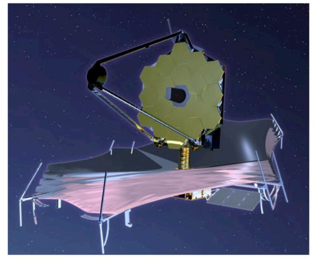


- STScI has been designated as Science Operations Center
- GO, Legacy/Treasury and GTO programs similar to HST

JWST is on track



JWST is on track



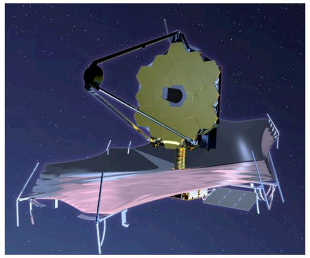
HST/ACS
Viz

JWST/NIRCa
Viz

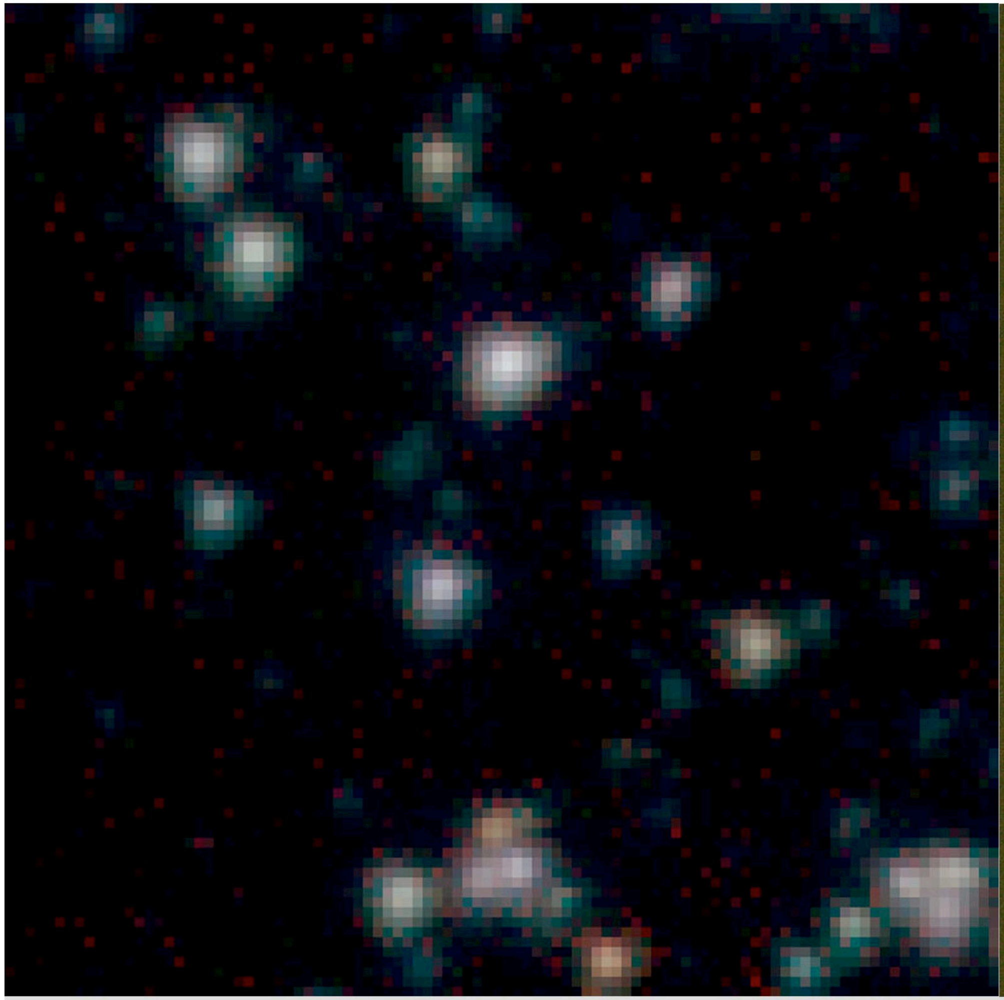
HST/NICMOS
J H

JWST/NIRCa
J H

JWST-Spitzer image comparison



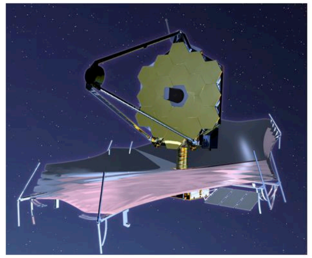
1’x1’ region in the UDF – 3.5 to 5.8 μm



Spitzer, 25 hour per band (GOODS collaboration)

JWST, 1000s per band (simulated)

JWST Plan of attack

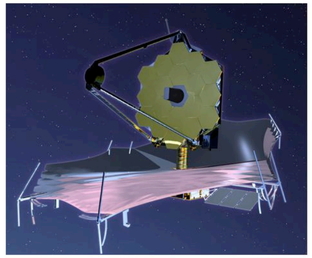


- Ultra deep survey to 1-2 nJy
  - Combine UDF with a north ecliptic pole survey (JWST CVZ) for z>6 SN searches
- Cluster survey:
  - 5 clusters to 5-8 nJy (amplified sources for followup)
- FGS-TF search
  - $10^{-18} – 10^{-19}$ erg cm^{-2} s^{-1}
- Spectroscopy
  - Lensed candidates
- MIRI Imaging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

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

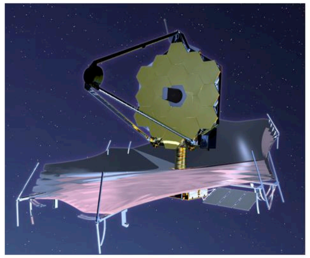
- low cirrus
- well placed for ALMA followup
- reasonably well placed for JWST

Conclusions : Reionization

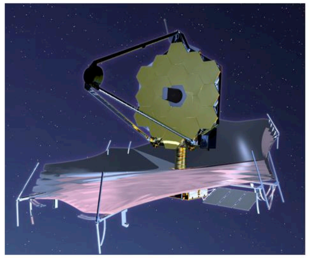


- Done by the time JWST is launched. Our survey when fully analyzed will identify the extent of the end of reionization. WFC3 will follow.
- Hard part may be to measure metallicities of reionizers. This requires JWST or 30+ ground based telescopes.
- If still an open question:
  - NIRSPEC R=100 spectra 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.

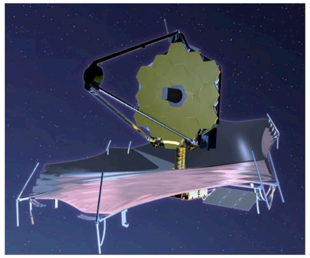
Conclusions : First light objects



- 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



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.