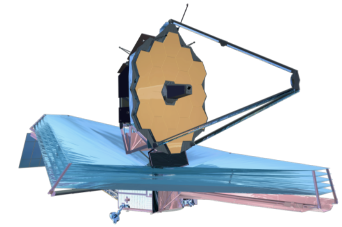
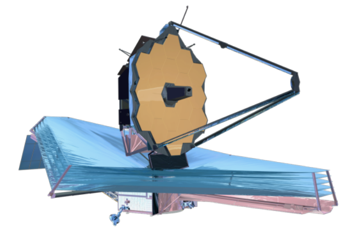


Studying the First Galaxies with the James Webb Space Telescope

M. Stiavelli

STScI, Baltimore

Main collaborator: Michele Trenti (U. Colorado)

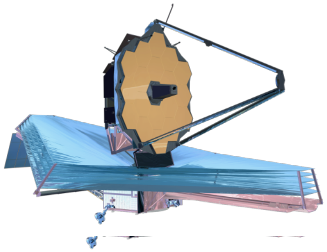


Studying the First Galaxies with the James Webb Space Telescope

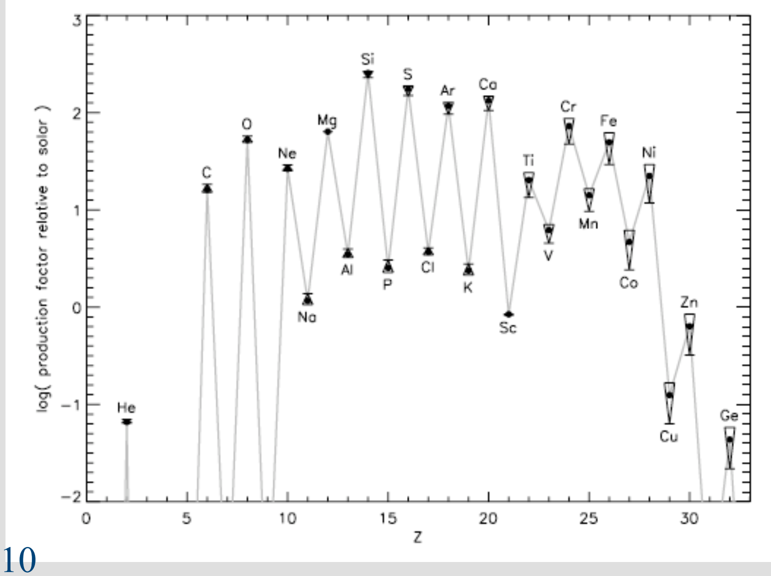
Plan:

- First stars and first star clusters
- Expected properties of the First Galaxies
- Indications from Observations
- Role of JWST
- Pair-Instability Supernovae
- First AGNs

The First Stars - 1



* We expect Population III stars to form in mini-halos due to molecular Hydrogen cooling. Individual Pop III stars are too faint to be observed directly with JWST except when they explode as supernovae. We will discuss SNae separately.
* JWST might be able to identify spectroscopically the abundance pattern signatures of PISN enrichment.

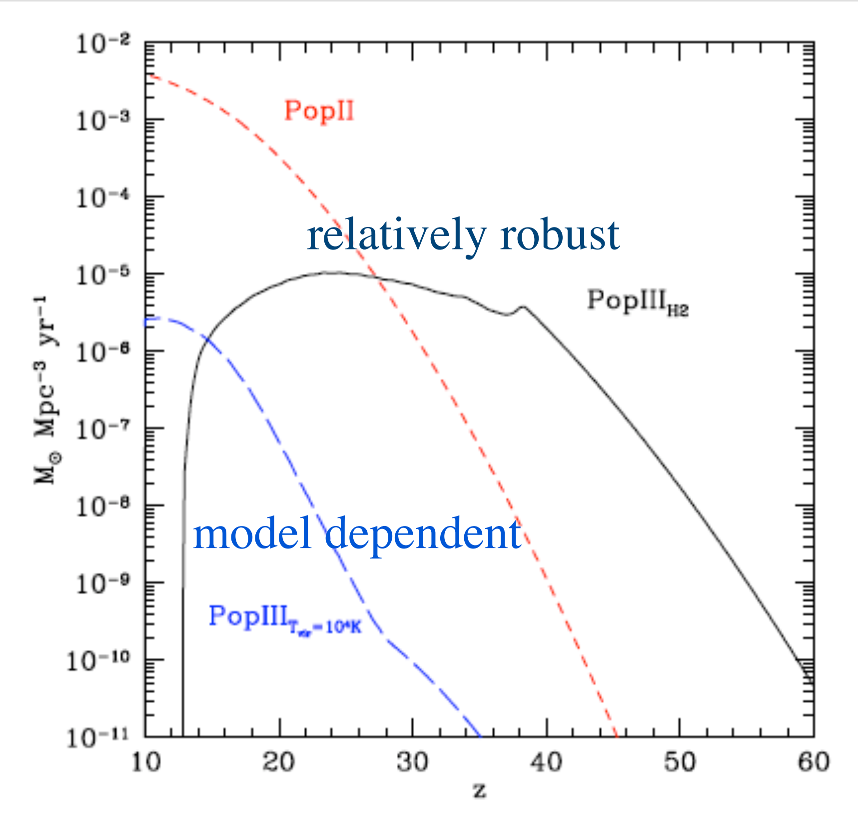


It would be useful to have a sample ready of z>7 QSOs for studying their LOS.

From Heger & Woosley 2002 for stars with mass 140-260 $M_{\odot}$.

The First Stars - 2

* An important point is that H_2 cooling Pop III.1 stars may be quite rare because of radiative feedback (see also P. Shapiro, delay is as good as suppression because the mass goes up).



* atomic H cooling Pop III stars may also be suppressed by in-situ pollution by minihalos.

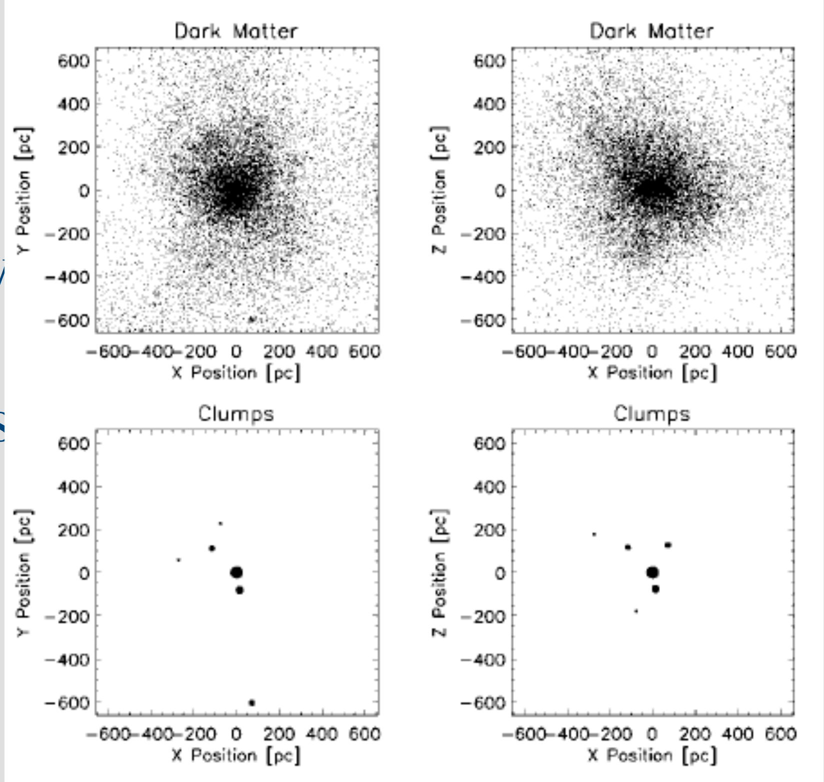
* finding Pop III abundance patterns locally might be hard (MW has a few tens Pop III.1 progenitors not several thousands).

From Trenti & Stiavelli (2009).

The First Star Clusters - 1

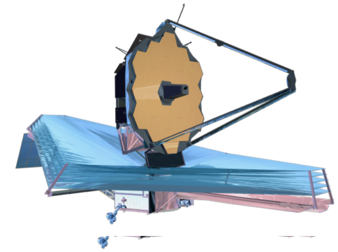
Early-on a sensitivity driver for JWST was that of detecting a 10^6 $M_\odot$ star cluster forming at 1 $M_\odot$/yr for 10^6 years. Such objects remain detectable in ultra deep exposures with JWST.

We do not know whether star clusters can form through such a process. Metal enrichment will likely enable the formation of low mass stars quite early so this process is in principle possible. What is the SF efficiency?

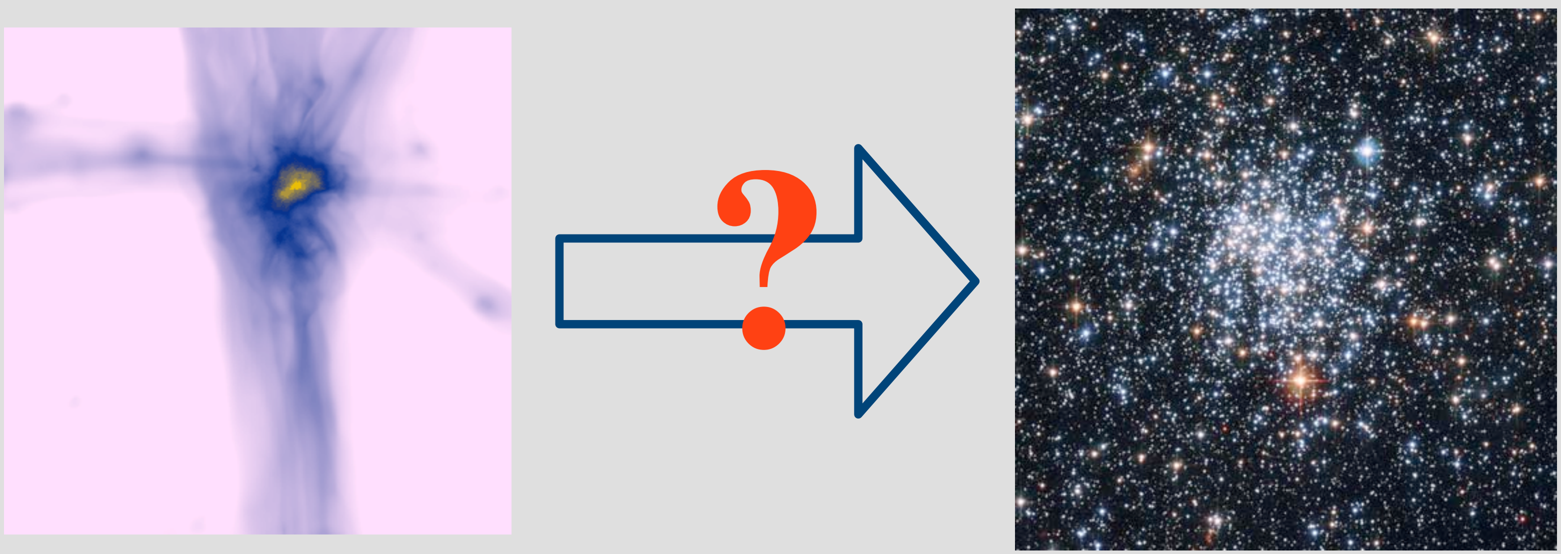


Bromm&Clarke 2002

The First Star Clusters - 2

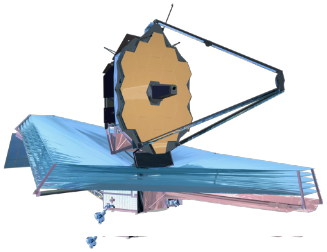


Open issue: how do you get to Pop III abundance patterns to those in the most metal poor galactic globular clusters? i.e. how many generations of reprocessing does it take?



M4 most likely age places its formation at z=6.

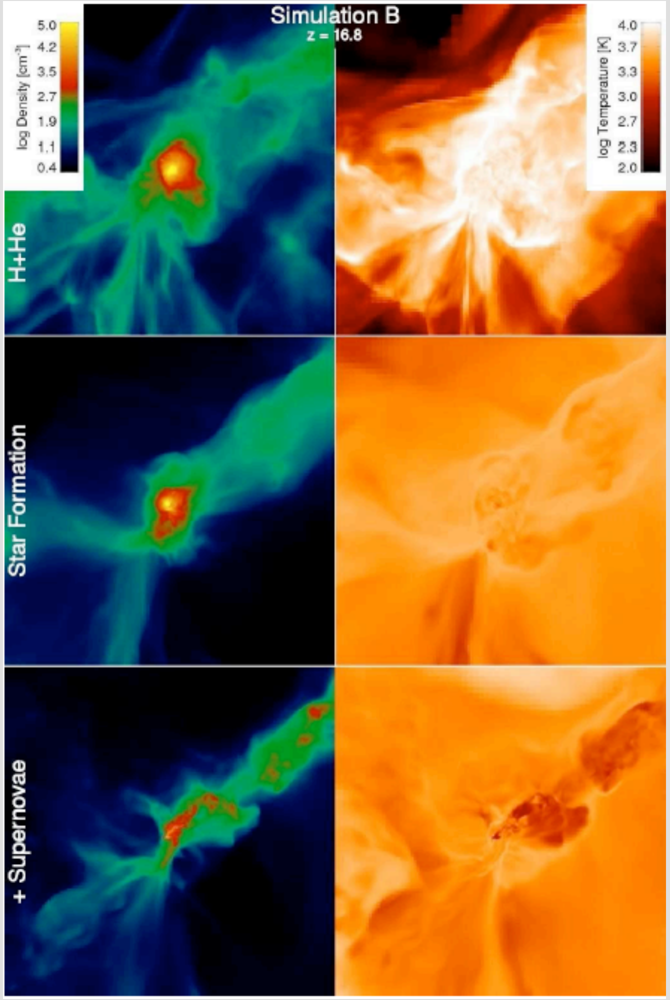
The First Galaxies



Numerical simulations for the formation of the first galaxies has been focussed so far on the early evolution of halos with mass $\lesssim 10^8\,M_\odot$ (e.g. Wise & Abel 2008, Greif et al. 2008).

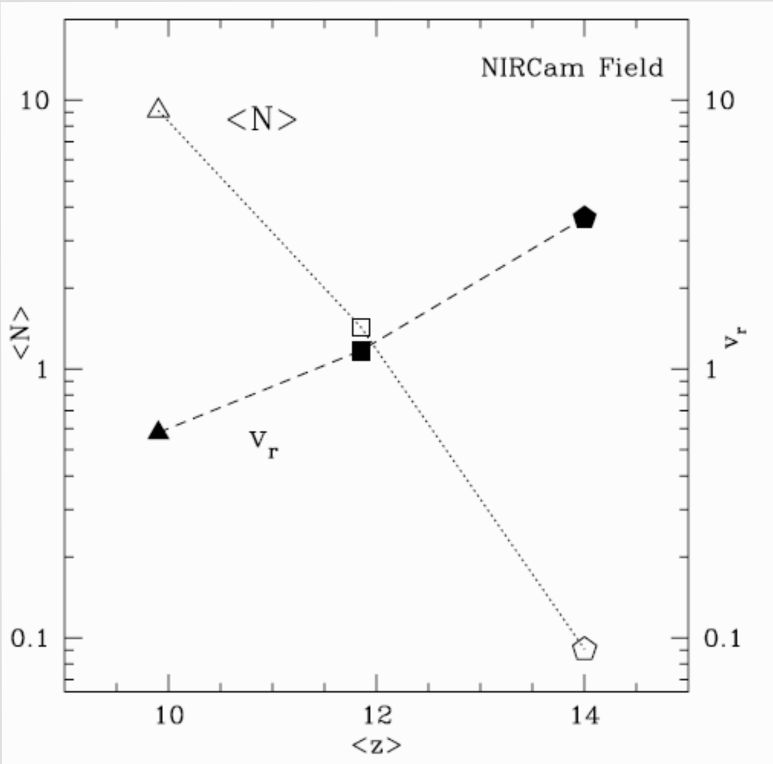
These objects are too faint to be observable with JWST. However, they are already enriched to $\sim 10^{-3}\,Z_\odot$.

More work is needed.



Luminosity estimates - 1

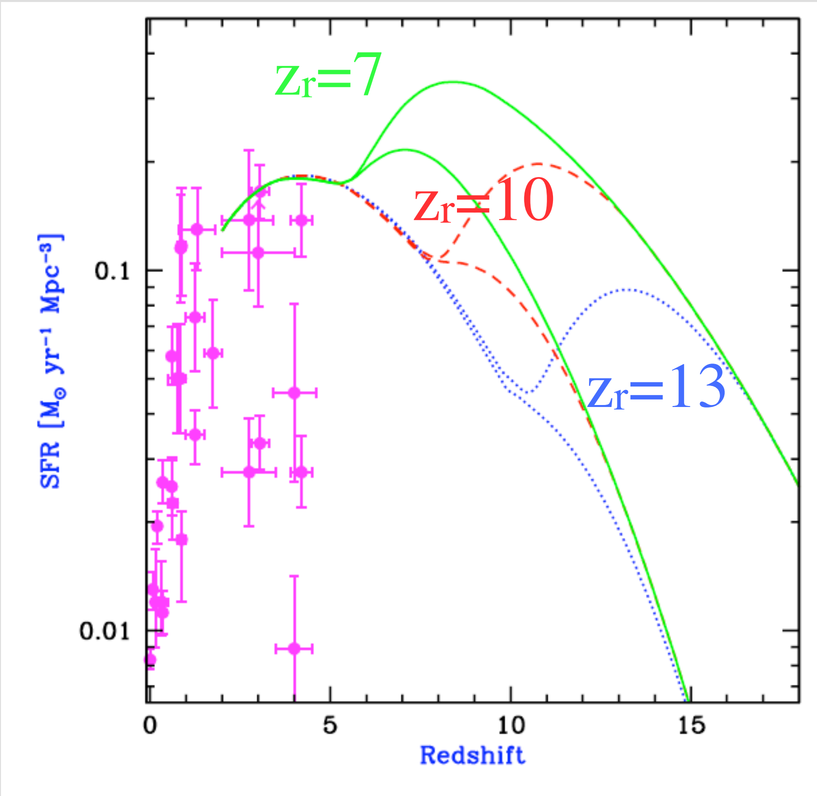
While waiting for numerical simulations for halos of higher mass, one can assume either a mass-to-light ratio or a star formation efficiency and see what this implies on the capability of JWST to detect these objects.



Simple model from Trenti&Stiavelli (2008). The open symbols show the expected target densities in a NIRCam FOV for F115W, F150W and F200W-dropouts, respectively.

Luminosity estimates - 2

Barkana & Loeb (2000) built a PS-based model to identify the signature of reionization in the global star formation rate. Most of the SF in this model is in objects below 0.25nJy

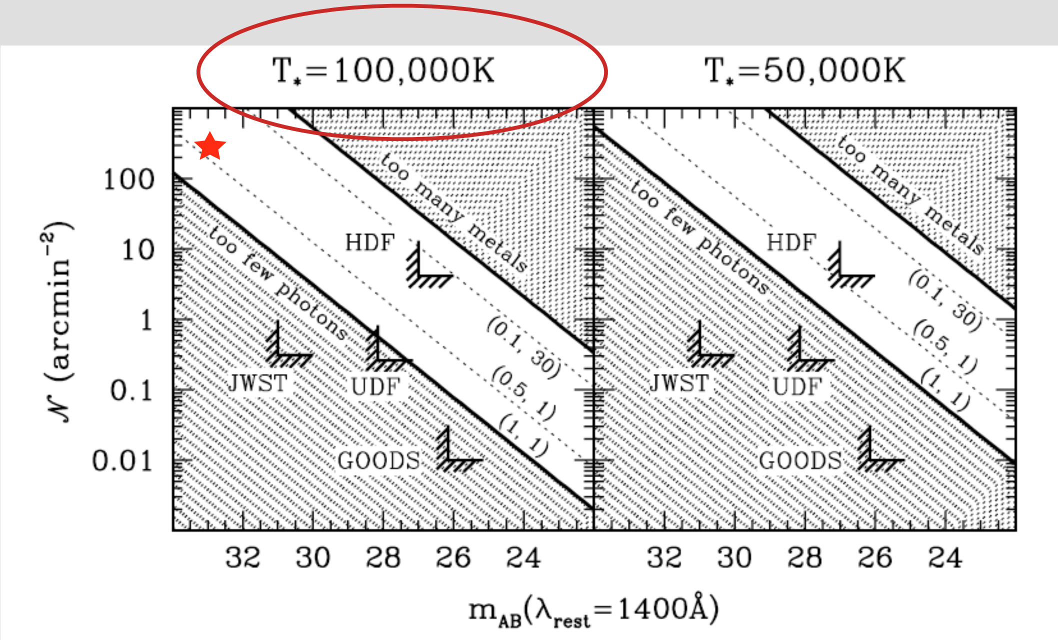


The different sets of curves are for different redshifts of reionization. The upper cure is the total SFR, the lower is for 0.25nJy flux limit.

If this model is right lensing will be crucial.

Luminosity estimates - 3

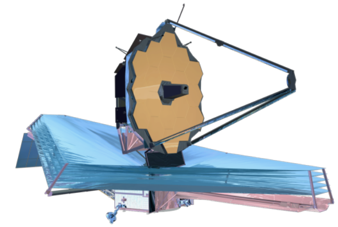
Alternatively one can focus on the minimum luminosity required to reionize Hydrogen. The minimum surface brightness in the observable non-ionizing continuum is obtained for the most efficient ionizers: Pop III stars.



Stiavelli et al. 2004a

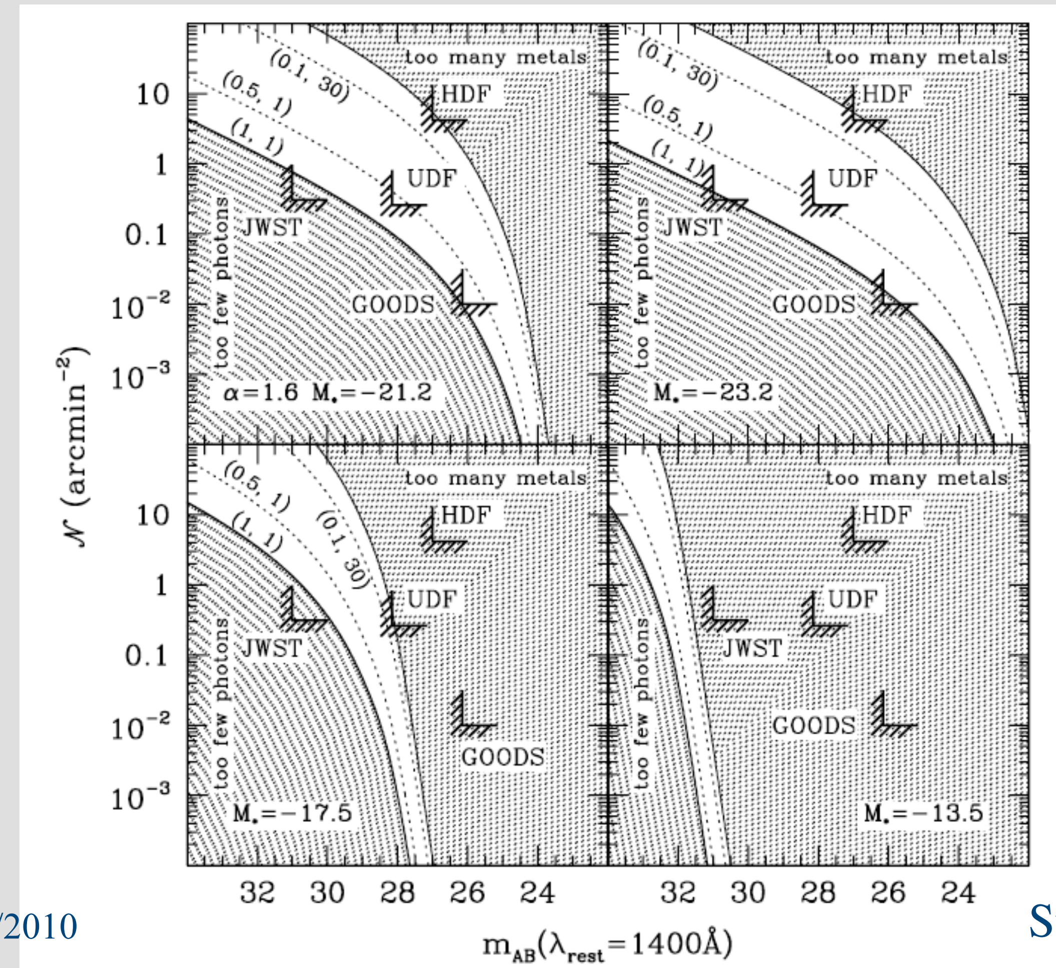
The minimum SB is μ_{AB} < 28.8 mag arcmin^2.

For equal luminosity objects and target densities 0.1-1 arcmin^2 this corresponds to AB=26.3-31.3



Luminosity estimates - 4

Alternatively one can assume a luminosity function and see what this implies in terms of object detectability.



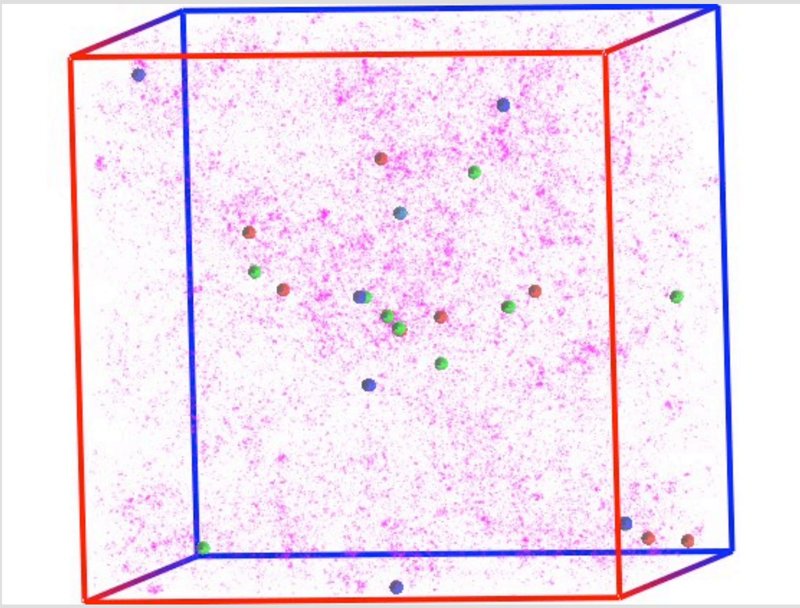
By changing the values of α and M_* one can explore the range of luminosities that are expected.

Stiavelli et al. 2004a

Should we worry about clustering?

The first galaxies are expected to be very clustered and cosmic variance can be an issue considering the relatively small field of view of JWST instruments.

For the simple model by TS2008, only the F115W-dropouts suffer from cosmic variance (with a total variance twice as large as that due to Poisson noise). The density of F150W and F200W is too low for cosmic variance to be important.

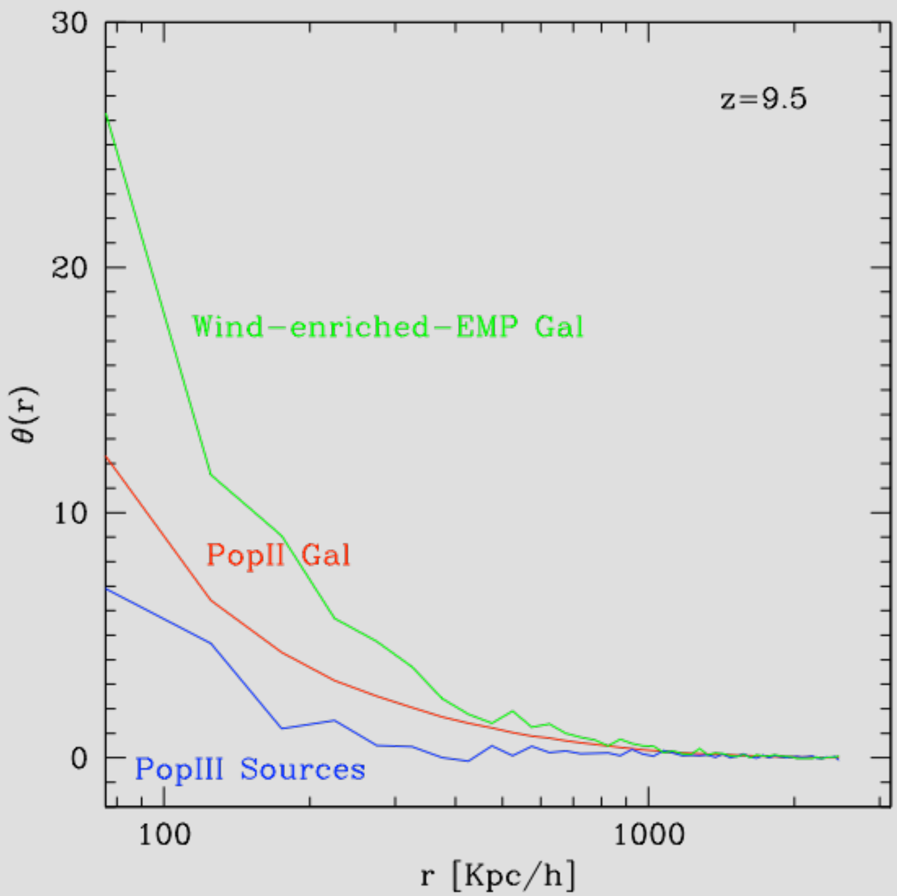


<u>This should be revisited in detailed simulations, particularly if local feedback is important.</u>

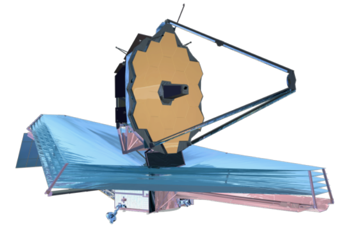
Clustering and metallicity

In principle it is possible to form a dwarf galaxy of Population III stars in a late forming halo that has been kept pristine by the Lyman-Werner background set up by the early generations of Population III stars.

The naive expectations is that these Pop III galaxies would not be clustered because clustered objects are more likely to be chemically polluted. This expectation is confirmed within our simple model (Stiavelli&Trenti 2010).



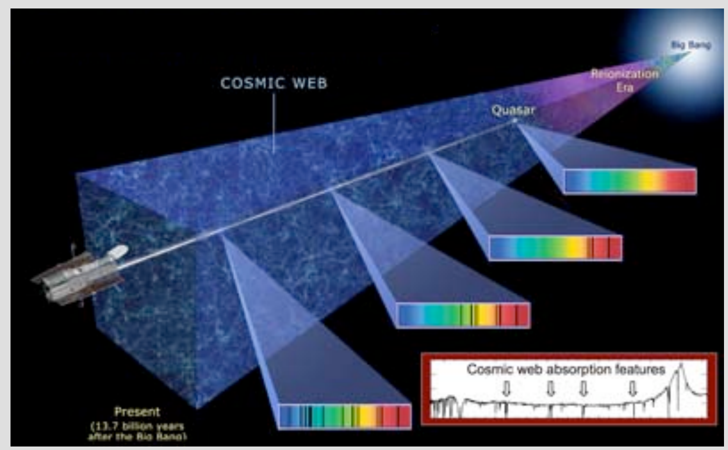
We might be able to observe these Pop III galaxies if lensed.



Should we worry about dust?

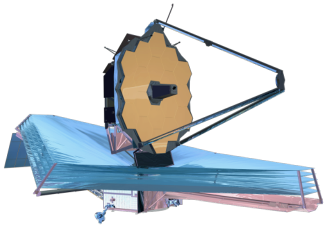
The faintest JWST objects will be found by color selection and will be too faint for spectroscopic confirmation. In the context of QSO studies, one had to face the worry that dust in hydrogen clouds along the line of side would progressively redden and dim high-z objects. Is this relevant for JWST?

Using methods similar to Fall&Pei and updated absorber catalogs, Trenti and Stiavelli (2006, see also Weinmann & Lilly 2005) concluded that this is not an issue for JWST:

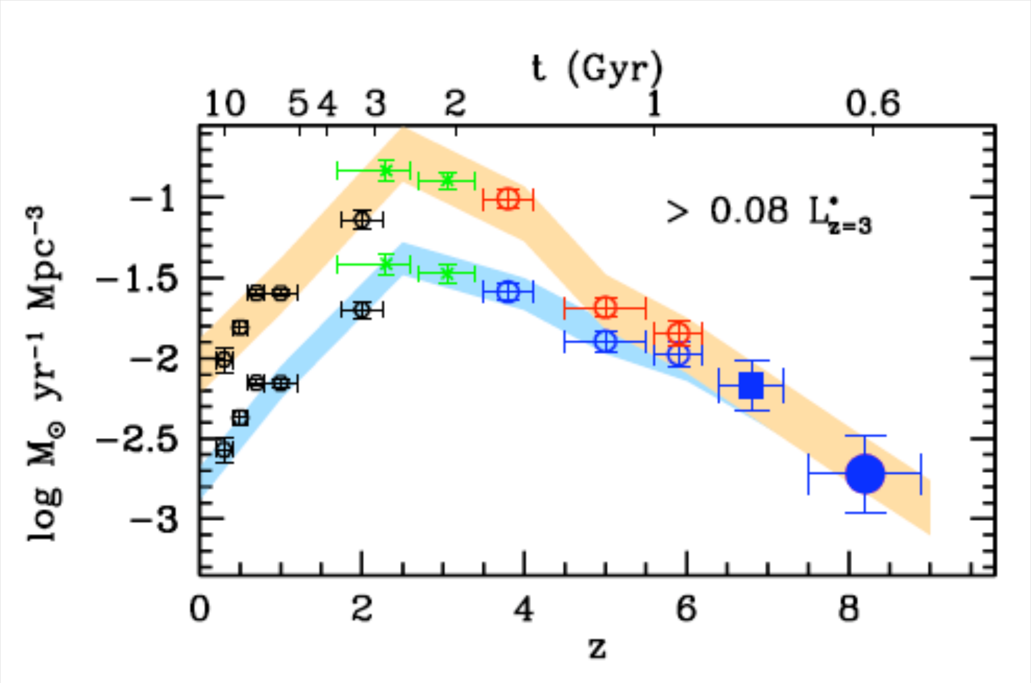


at $z \geq 10$ $\langle A_{1400} \rangle \leq 0.1$ and $A_{1400}(90\%) \leq 0.2$

Indications from Observations



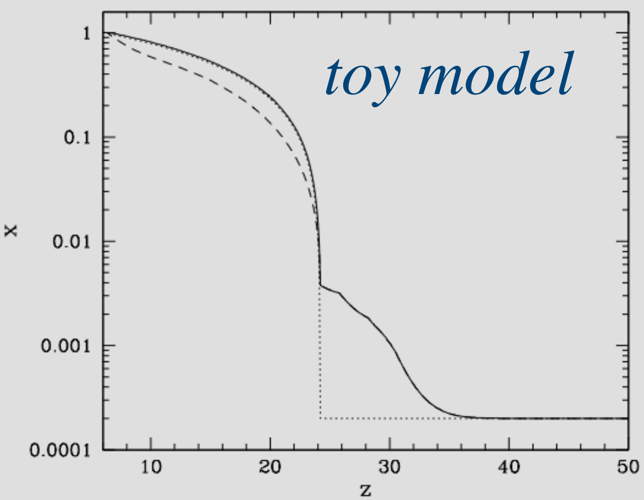
In the recent years we have been able to probe the luminosity function at z ≳ 6 observationally (e.g. Oesch et al. 2010, Bouwens et al. 2010a,b, Wilkins et al. 2010, Finklestein et al. 2010, Yan et al. 2010)



The number density of galaxies above the WFC3 UDF limit is decreasing with z and goes below 1 arcmin^2 at z~8-9.

JWST sensitivity

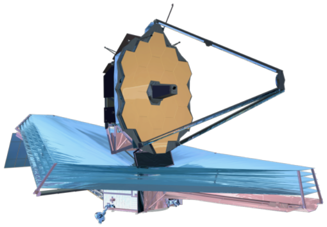
The sensitivity specifications of JWST had to be set several years ago and our expectations about the first galaxies were at the time less mature than they are now.



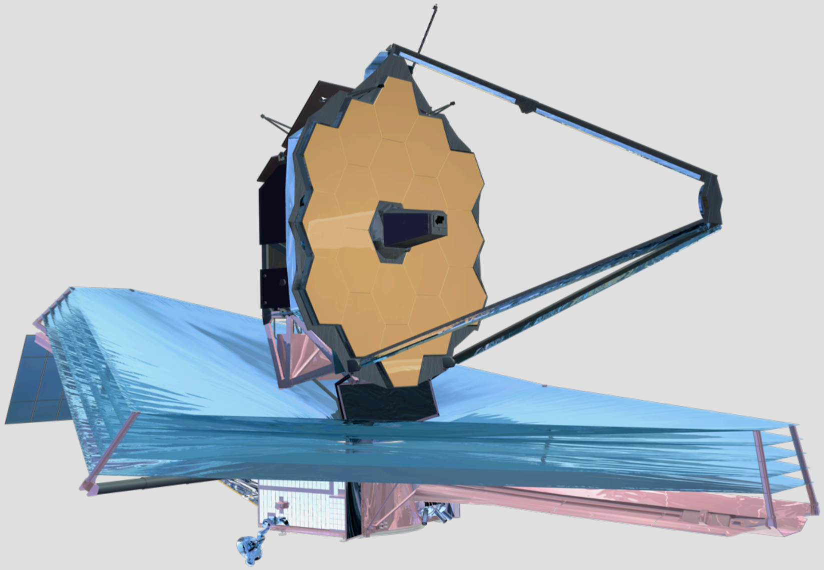
Because of WMAP we knew that we had to search at z>10.

Thus, <u>we based our requirement on the capability of observing at z=10-20 to the same relative depth as in the Hubble UDF at z=6</u>. The WFC3 UDF findings support the wisdom of this choice.

The James Webb Space Telescope



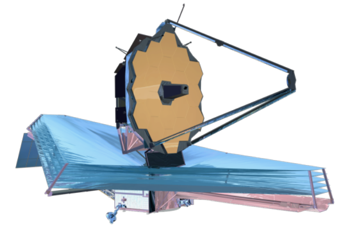
The James Webb Space Telescope was designed from the ground up to study high-z galaxies. For science themes guided the design, two extragalactic and two galactic. The one most relevant for us is the End of the Dark Ages theme.

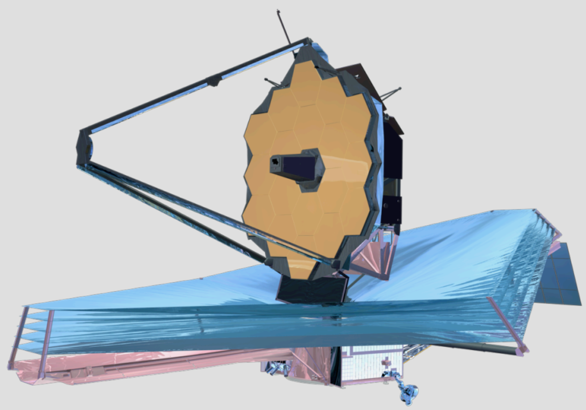


End of the dark ages:

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

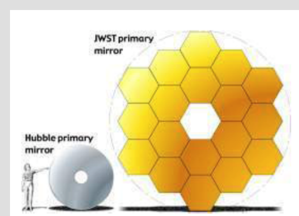
JWST
Quick Facts





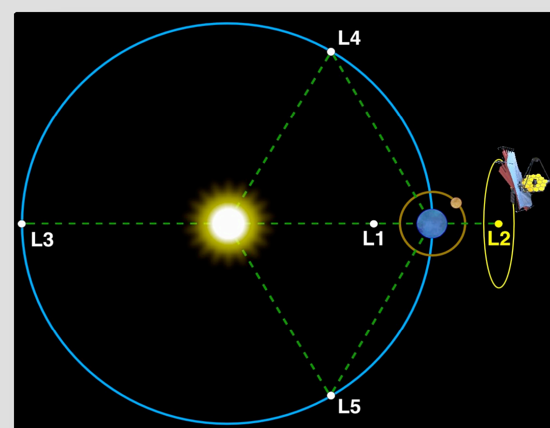
Organization

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)



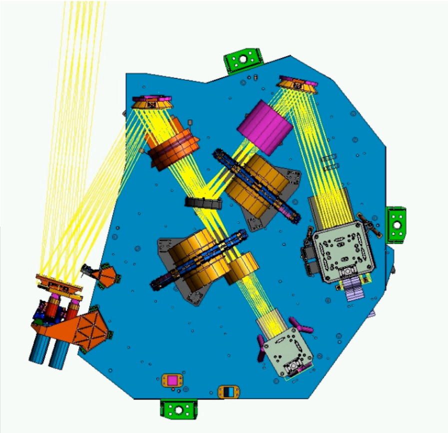
Description

- Deployable cryogenic telescope
  - 6.5 meter ø, segmented adjustable primary mirror
- Launch on an ESA-supplied Ariane 5 to Sun-Earth L2
- 5-year science mission (10-year goal): launch 2013



03/07/2010

Instrumentation



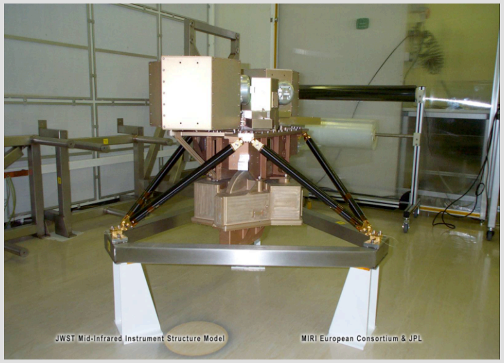
Arizona: Marcia Rieke PI

Lockheed-Martin & Rockwell

ESA: Peter Jakobsen

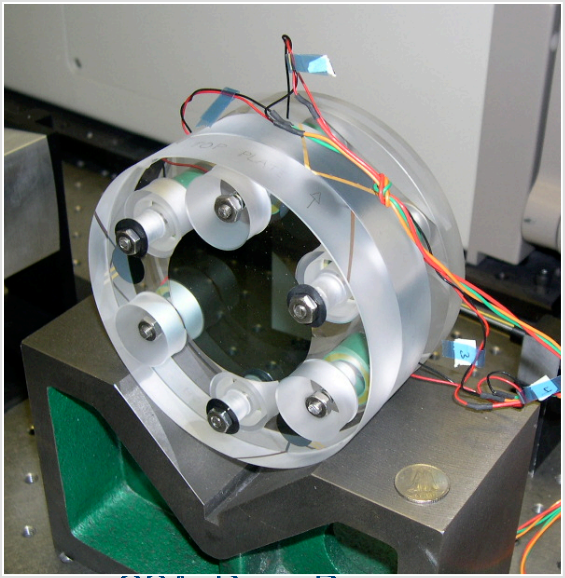
EADS Astrium & GSFC

- 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

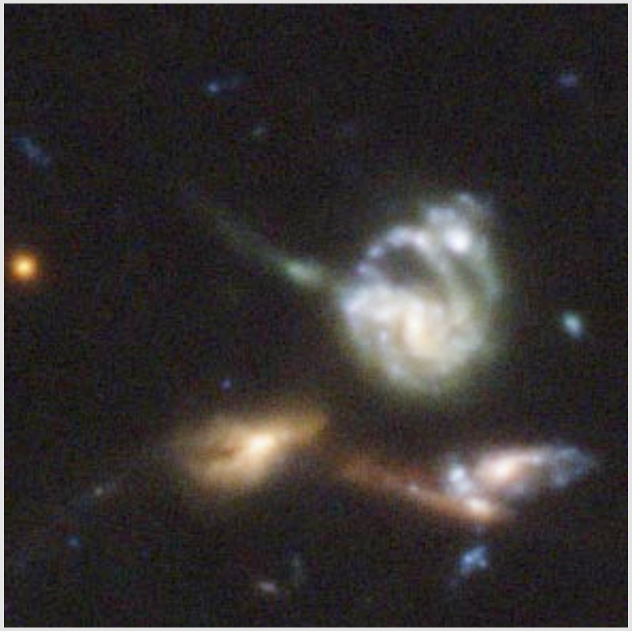
JPL and European Consortium



CSA: Rene Doyon

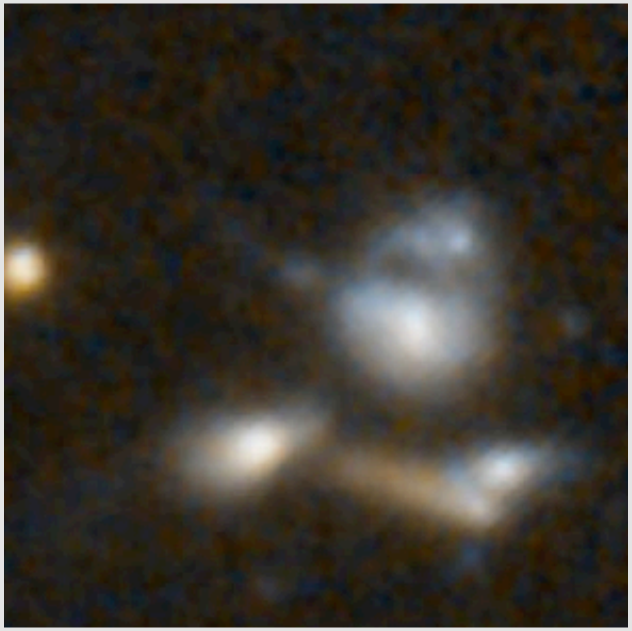
COM DEV

HST/ACS
Viz



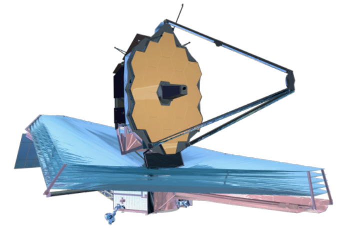
JWST/NIRCam
Viz

HST/NICMOS
J H

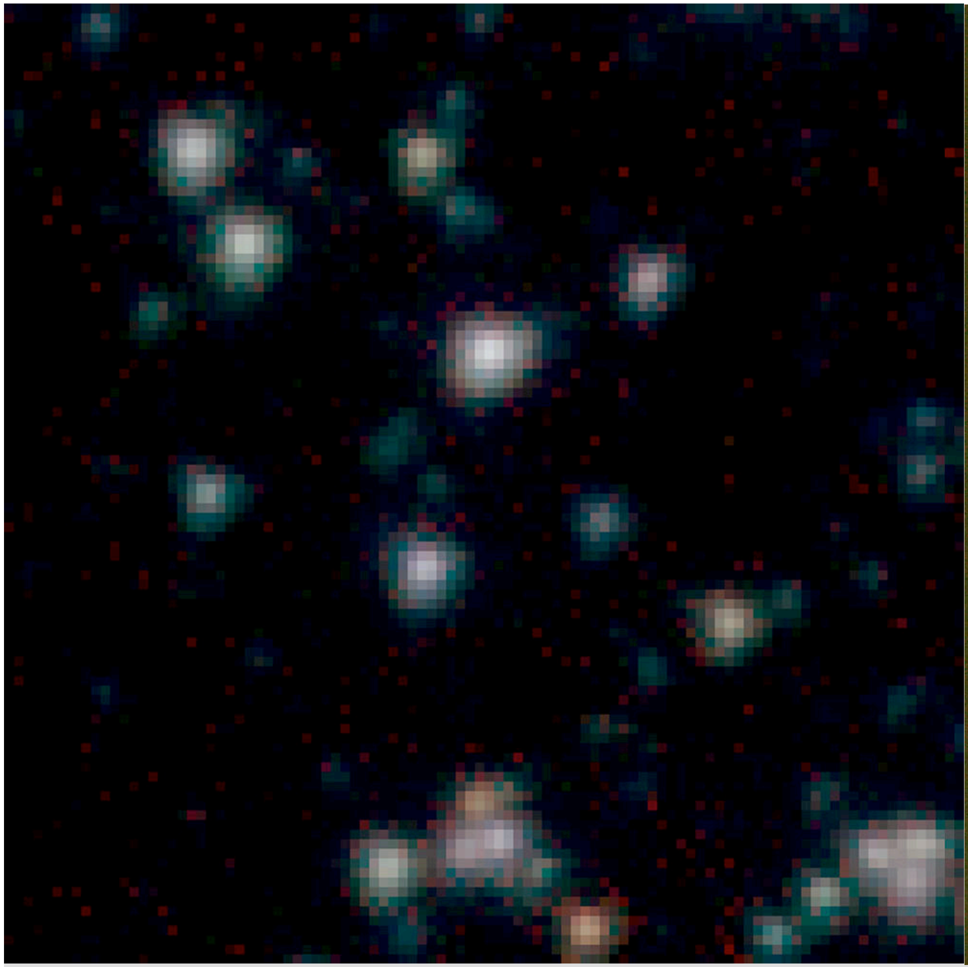


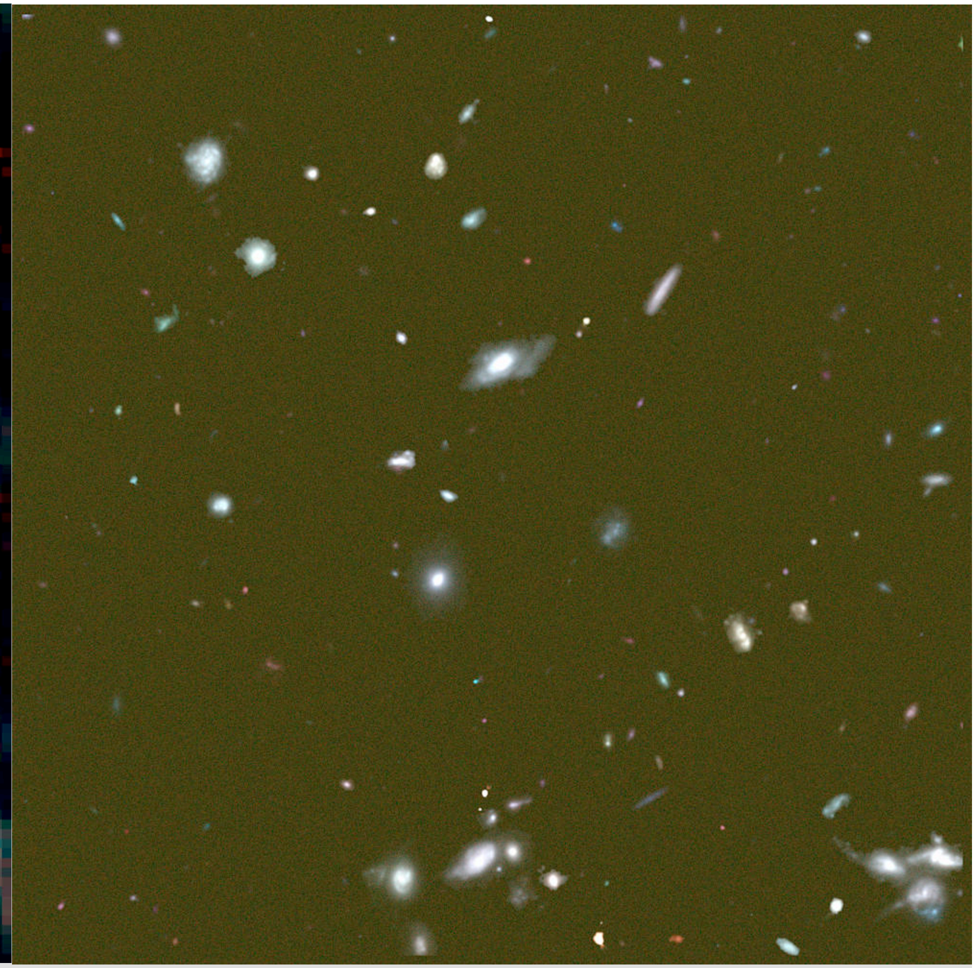
JWST/NIRCam
J H

JWST-Spitzer image comparison



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

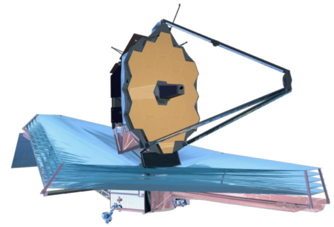




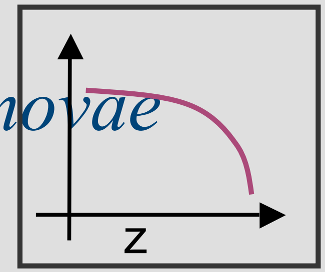
Spitzer, 25 hour per band (GOODS collaboration)

JWST, 1000s per band (simulated)

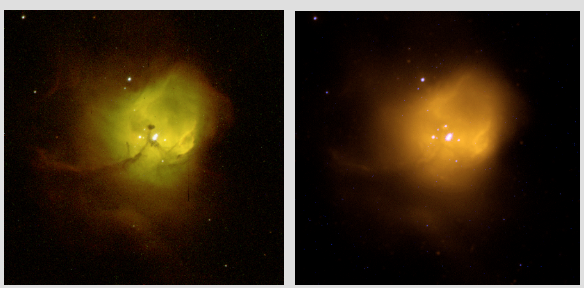
Detection of the First Galaxies

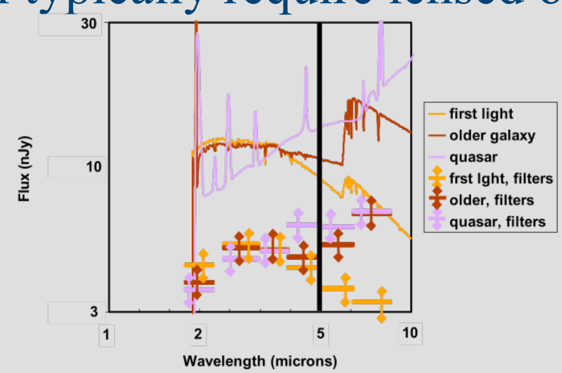


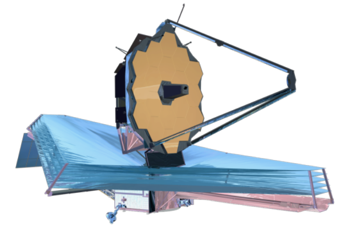
- Evolution of N(z), LF. *Identify candidates with Lyman break technique* → **NIRCam**
- Evolution of SFR(z). *Use Hα, Hβ and supernovae* → **NIRSpec and NIRCam**



- 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)





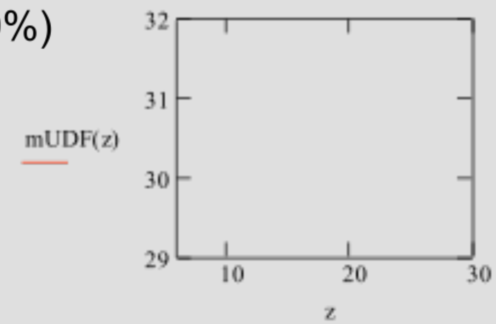


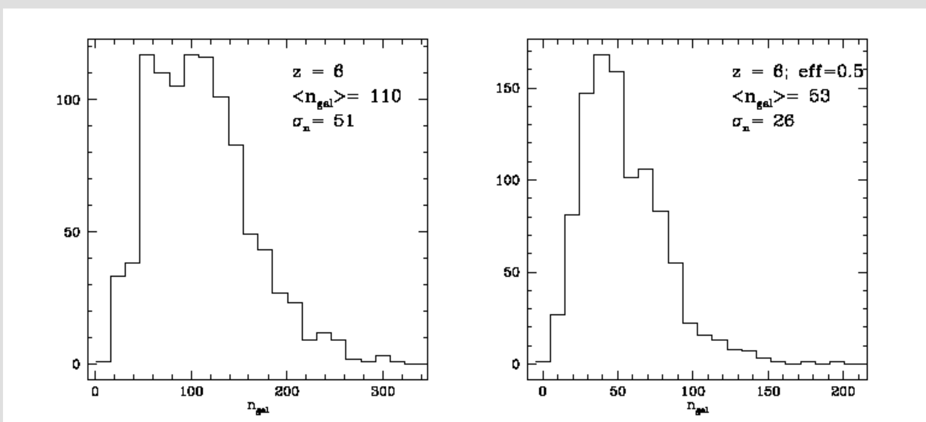
First Galaxies : Detection

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

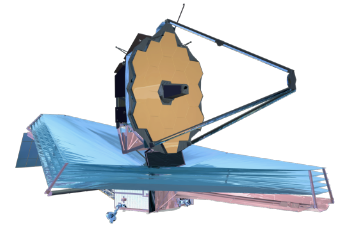
z	AB_1350	F_ν (nJy)	λ (μm)	$\langle A_{1400} \rangle$	A_{1400}(90%)
10	30.284	2.80	1.34	0.08	0.18
12	30.551	2.19	1.58	0.07	0.15
15	30.869	1.63	1.95	0.05	0.12
20	31.267	1.13	2.55	0.04	0.08





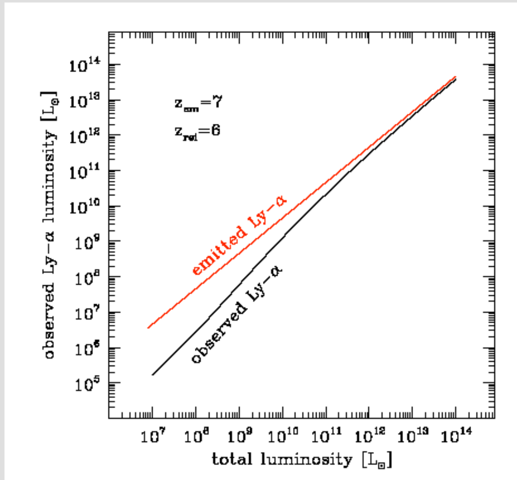
Distribution of the number of dark halos in the UDF assuming that all of them (left) or only 50% (right) are visible as galaxies. The mean number is roughly twice the rms of the distribution (Trenti & Stiavelli; see also Somerville).

First Galaxies : Ly α & properties



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

Adopt: Lyα escape fraction of 0.2.

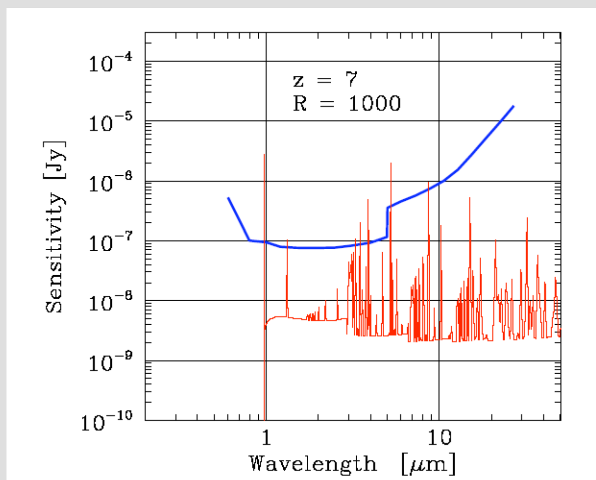


z	AB_1350	Ly α (cgs)	λ (μm)
10	30.284	1.7e-18	1.34
12	30.551	8.89e-19	1.58
15	30.869	4.02e-19	1.95
20	31.267	1.47e-19	2.55

Measuring the metallicity of first light sources

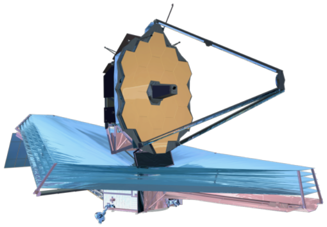
Let's consider a 5 nJy source with metallicity 1/1000 solar. The O line at 1665A will have a strength of:

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



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

JWST Plan of attack



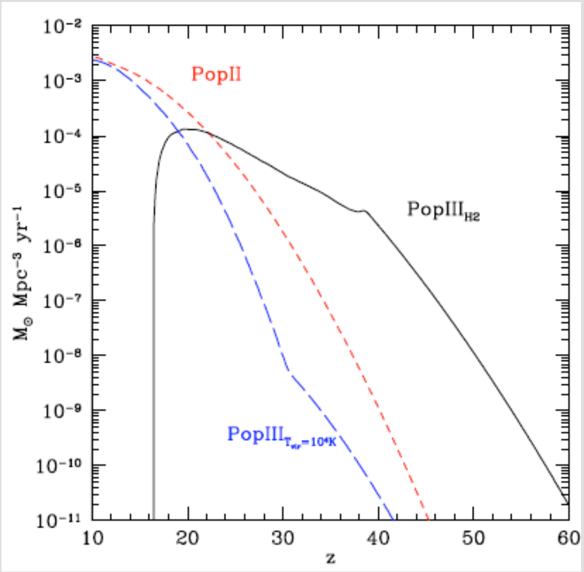
- Ultra deep survey to 1-2 nJy
  - Combine UDF with a north ecliptic pole survey (JWST CVZ) for z>6 SN searches
- Cluster survey:
  - 5 clusters to 5-8 nJy (amplified sources for followup)
- FGS-TF search
  - $10^{-18} - 10^{-19}$ erg cm^{-2} s^{-1}
- Spectroscopy
  - Lensed candidates
- MIRI Imaging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

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

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

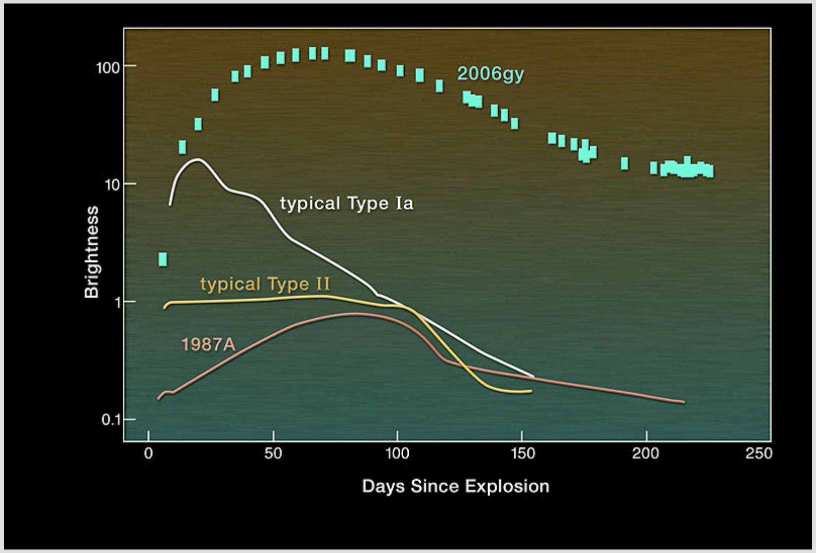
PISN Supernovae - 1

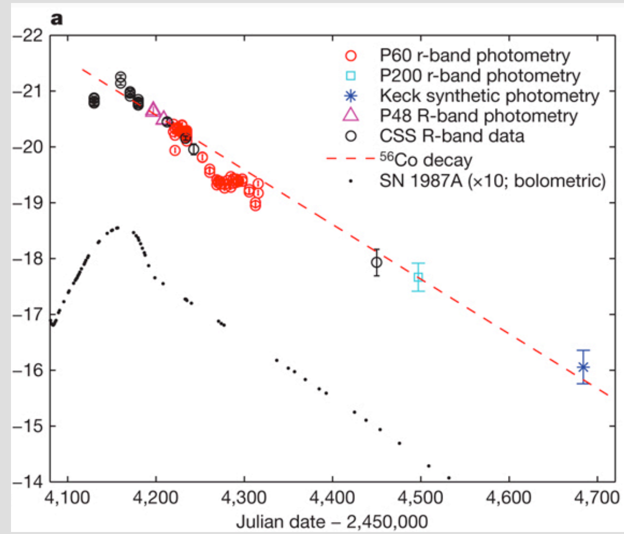
Weinmann & Lilly (2005) elaborating on previous results suggest densities of 4 deg^{-2} yr^{-1} at z~15 and 0.2 deg^{-2} yr^{-1} at z~25. The actual numbers may be lower if one considers negative feedback on mini-halos. However, SNae from atomic hydrogen cooling halos could boost up the rate. If the rate is as high as few tens deg^{-2} yr^{-1} direct searches with JWST NIRCam become possible.



Optimistic model by Trenti & Stiavelli 2009. With enhanced formation of Pop III in atomic H cooling halos we could have PISN common enough to be found by JWST.

PISN Supernovae - 2





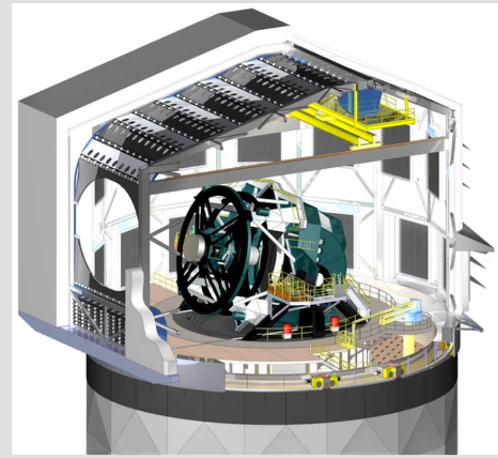
SN2006gy and 2007bi have been proposed as PISN analogs. If PISN have a light curve similar to that of 2006gy we can see that one might expect the SN to have at the peak a luminosity of AB~26-26.5 at z=10-15 and for observations at 4-5 μm. JWST/NIRCam can achieve such a depth at 4 μm with a exposures of 10 min so that a 100+100 hour survey (2 epochs) could search for PISN over an area of ~1 square degree. The slow decay of the light curve would hamper multi-epoch searches.

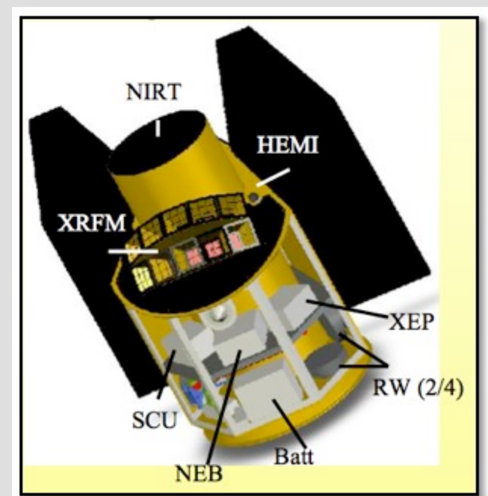
PISN Supernovae - 3

LSST and other ground based wide field projects may be able to detect lower redshift PISN (at z~6).

The contamination of the PISN rate with objects like 2006gy may require the spectroscopic confirmation of slowly decaying supernovae.

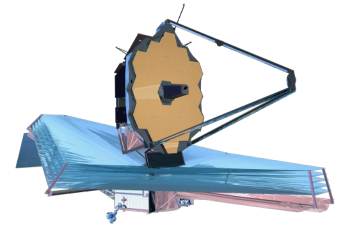
IF PISN were to be associated to a GRB, GRB finding missions would be able to provide the location. JWST can follow-up on TOO in 48 hours (mission requirement).



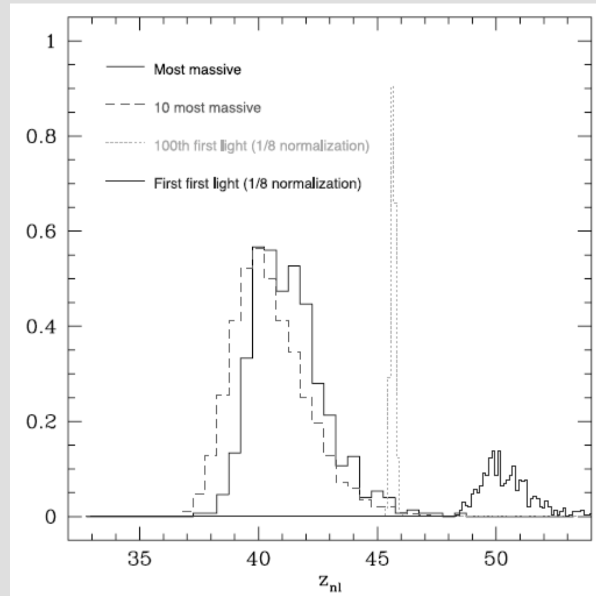


Janus SMEX concept (PI Roming)

Early Black Hole growth

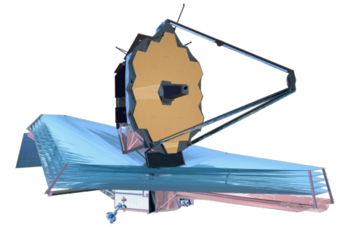


We do not know how the SDSS z=6 QSO black holes form. Direct growth from stellar mass seed is made difficult by merger kicks and by the need for constant Eddington limit accretion. However, there are tens of thousands of seeds available for each QSO so an unlikely combination might still work.



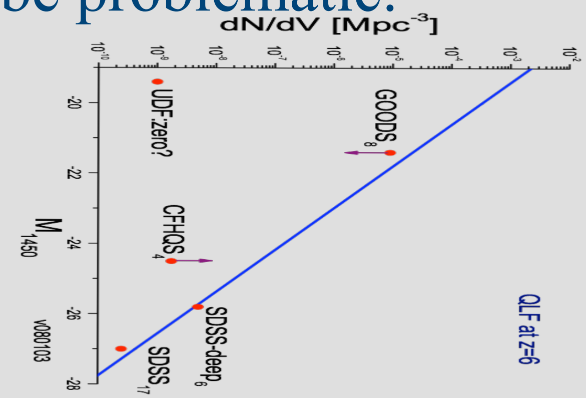
Direct collapse in 10^8 $M_\odot$ halos (Bromm&Loeb 2003, Begelman et al. 2006) requires halos that are not pre-enriched by mini-halos (and have low turbolence). This might lead to anti-biased QSOs which is not what we see at low-z.

First Active Galactic Nuclei



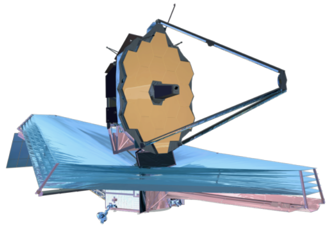
The stellar mass black hole remnants of Pop III stars are not directly observable. The star is already at the Eddington luminosity so the mini-AGN is not any brighter.

The Eddington luminosity of a 10^4 M⊙ black hole is ~ 3×10^8 L⊙. At z~10 with a typical QSO spectrum this corresponds to H_{AB}~31. Thus, discriminating between the growth from stellar seeds and direct collapse by the presence or absence of 10^3 M⊙ black holes may be problematic.



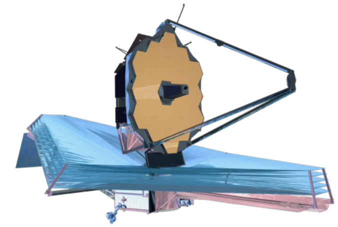
The z=6 QSO LF is in principle measurable to low luminosities. It would be useful to predict what it should be in the various models (figure from Jian Su).

Reionization



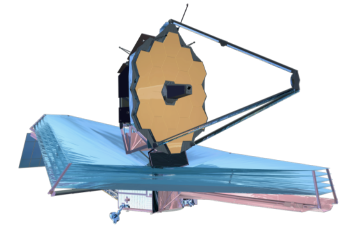
- Done by the time JWST is launched. WFC3 UDF still taking data and WFC3 MCT will start soon.
- Hard part may be to measure metallicities of reionizers. This requires JWST or 30+ ground based telescopes.
- If still an open question:
  - NIRSPEC R=100 spectra may show the Haiman-Loeb (1999) Lyman-island 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



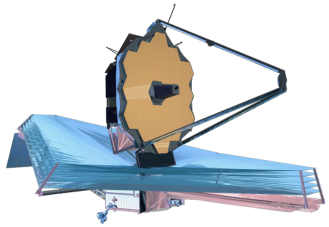
- Population III stars are rare and faint. Probably hopeless.
- JWST can observe Population III stars only as supernovae (but will need help to find them) or as (possibly lensed) small clusters if they exist.
- JWST will study the “first galaxies”, i.e. second generation objects pre-enriched by Pop III stars.
- Theoretical investigation of the first galaxies and their observational signatures must continue.

Community involvement - 1

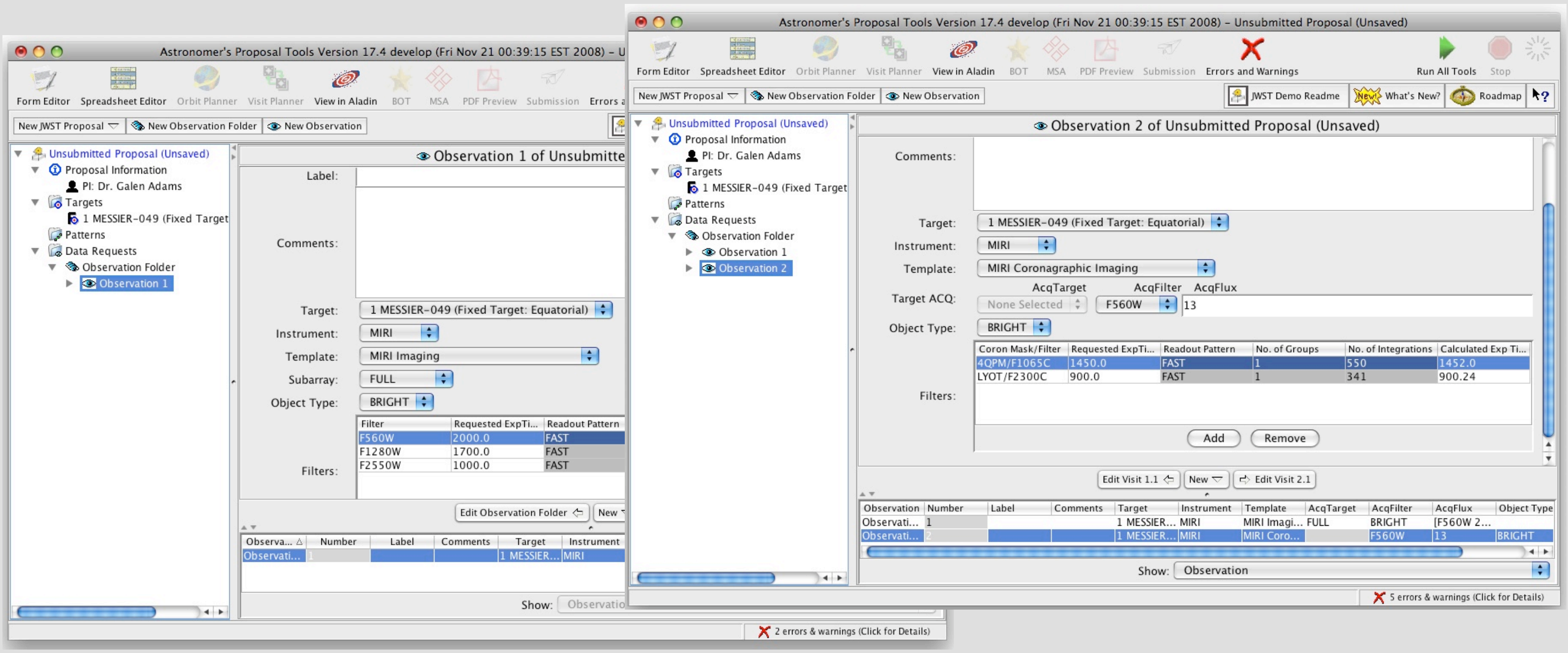


- Planning a data simulation/data challenges effort. We hope that we will be able to announce this soon.
- Planning conference *Frontier Science Opportunities with the James Webb Space Telescope,* Jackson Lodge, Grand Teton National Park, June 5-7 2011. Issues of Legacy/Treasure, program balance will 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)

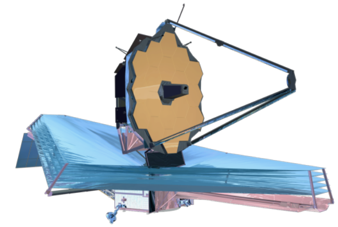
Observing with JWST



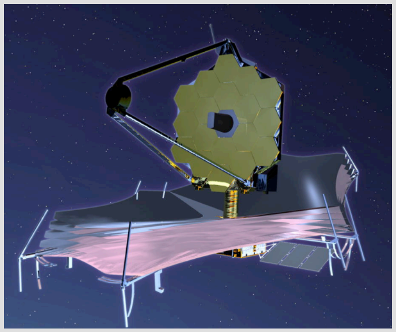
Observing time with JWST will be awarded similarly to HST with a TAC selecting GO proposals. Some form of Treasury/Legacy programs will likely exist. Thus, the science that is going to be done may end up being very different from the “plan” highlighted in the last slide.



Operations



THE ASTROPHYSICAL JOURNAL



JWST at L2

Ka

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Astronomer

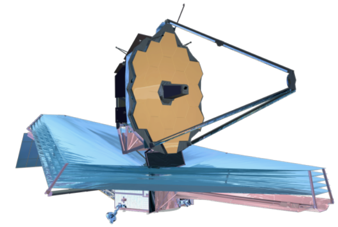
- STScI has been designated as Science Operations Center
- GO, Legacy/Treasury and GTO programs similar to HST

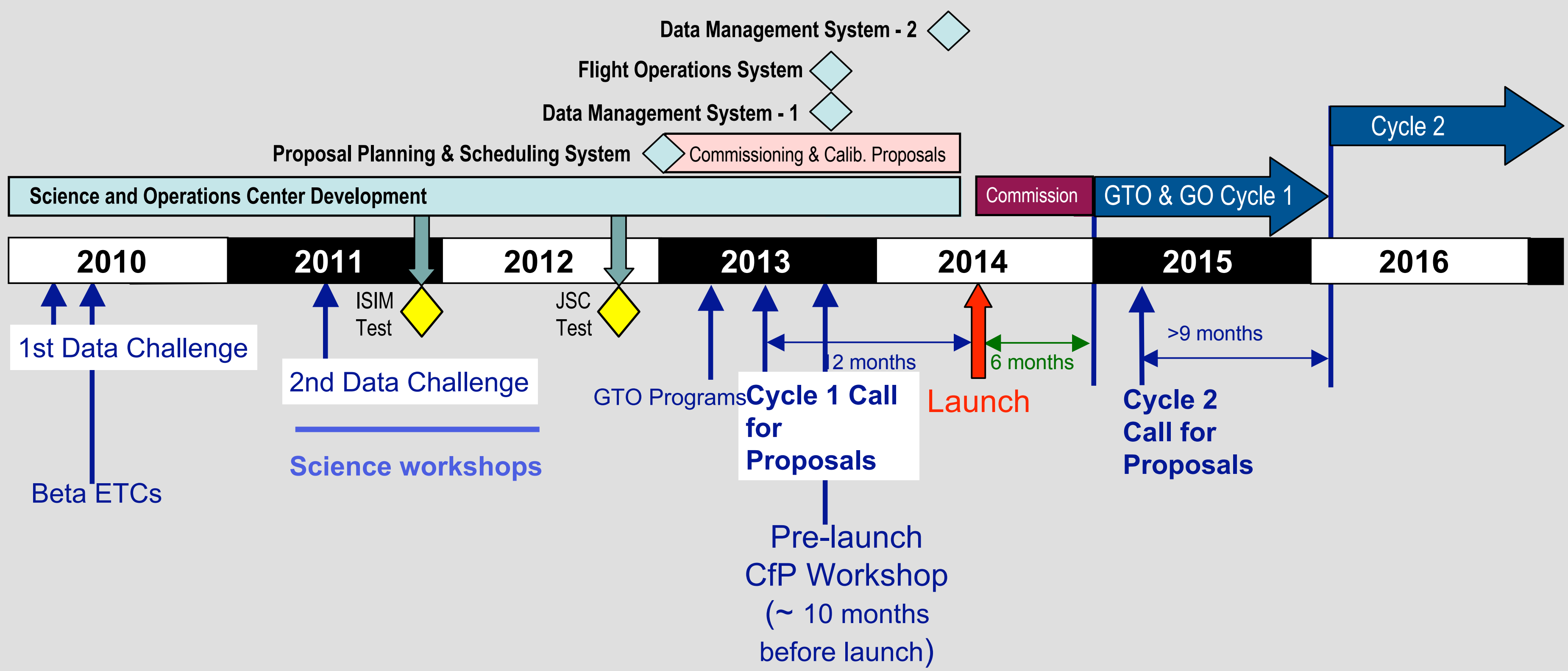
DSN

STScI

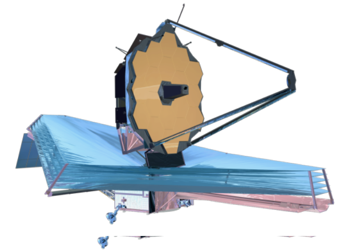
TAC

Community involvement - 2





The First Stars nomenclature



Pop III.1 : forms only under the effect of cosmology

Pop III.2 : formation affected by non cosmological effects

Pop III.2α : formation affected by cosmic rays

Pop III.2β : formation affected by electrons

Pop III.2γ : formation affected by radiation

Pop III.2γԱ: formation affected by Lyman-Werner

Pop III.2γԲ : formation affected by ionizing radiation

Pop III.2♬ : formation affected by mechanical feedback

Pop III.2☹ : formation affected by magnetic fields

Pop III.2✂ : formation affected by loss of grant

Pop III.2♻ : formation affected by insufficient resolution