Probing the First Sources of Light with the James Webb Space Telescope

M. Stiavelli

STScI, Baltimore

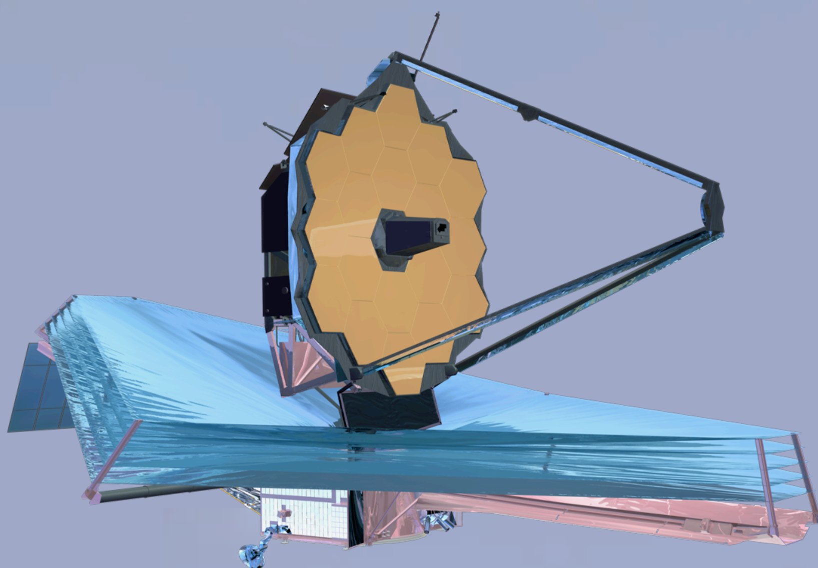
Probing the First Sources of Light with the James Webb Space Telescope

Plan:

- What is JWST
- Detecting the First Galaxies
- Detecting the First Star Clusters
- Detecting the First Stars
- Status of JWST

The James Webb Space Telescope

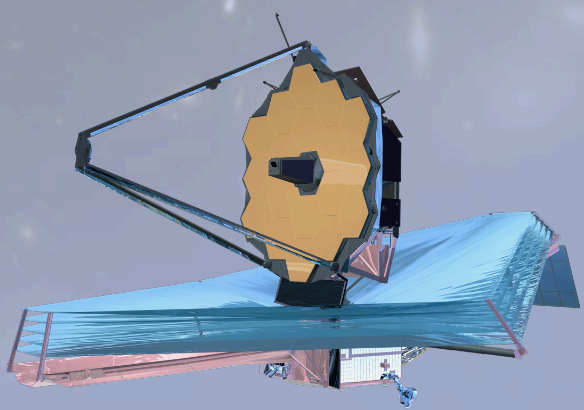
The James Webb Space Telescope was designed from the ground up to study high-z galaxies. For science themes guided the design, two extragalactic and two galactic. The one most relevant for us is the End of the Dark Ages theme.



End of the dark ages:

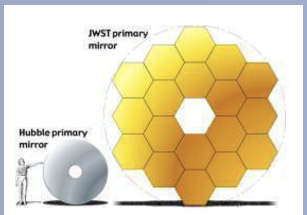
- **First light**
- Nature of reionization sources

JWST in brief



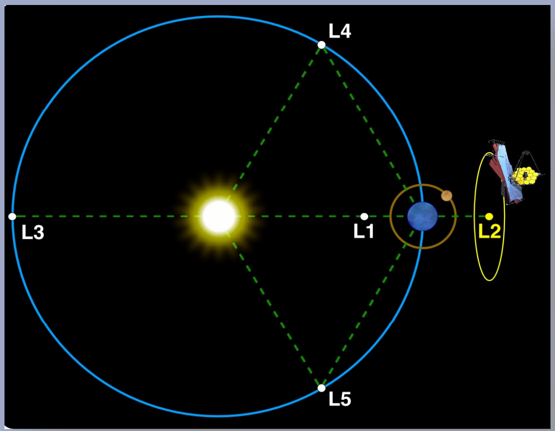
Organization

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 2018

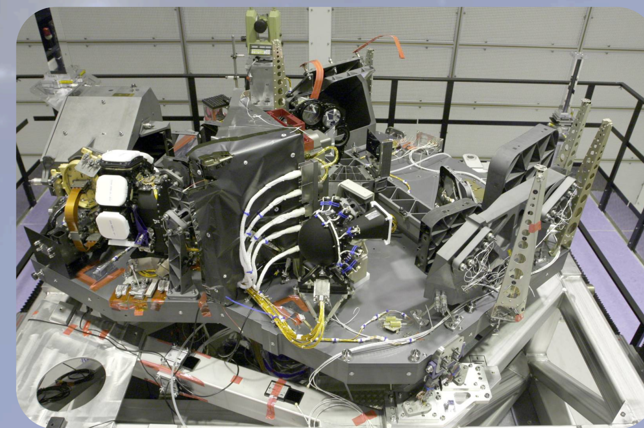


Instruments

Arizona: Marcia Rieke PI

Lockheed-Martin & Rockwell

- 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
- NIRISS, 1.6 to 4.8 micron
  - 2.2 x 2.2 arcmin FOV
  - imaging and slitless spectroscopy
- 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

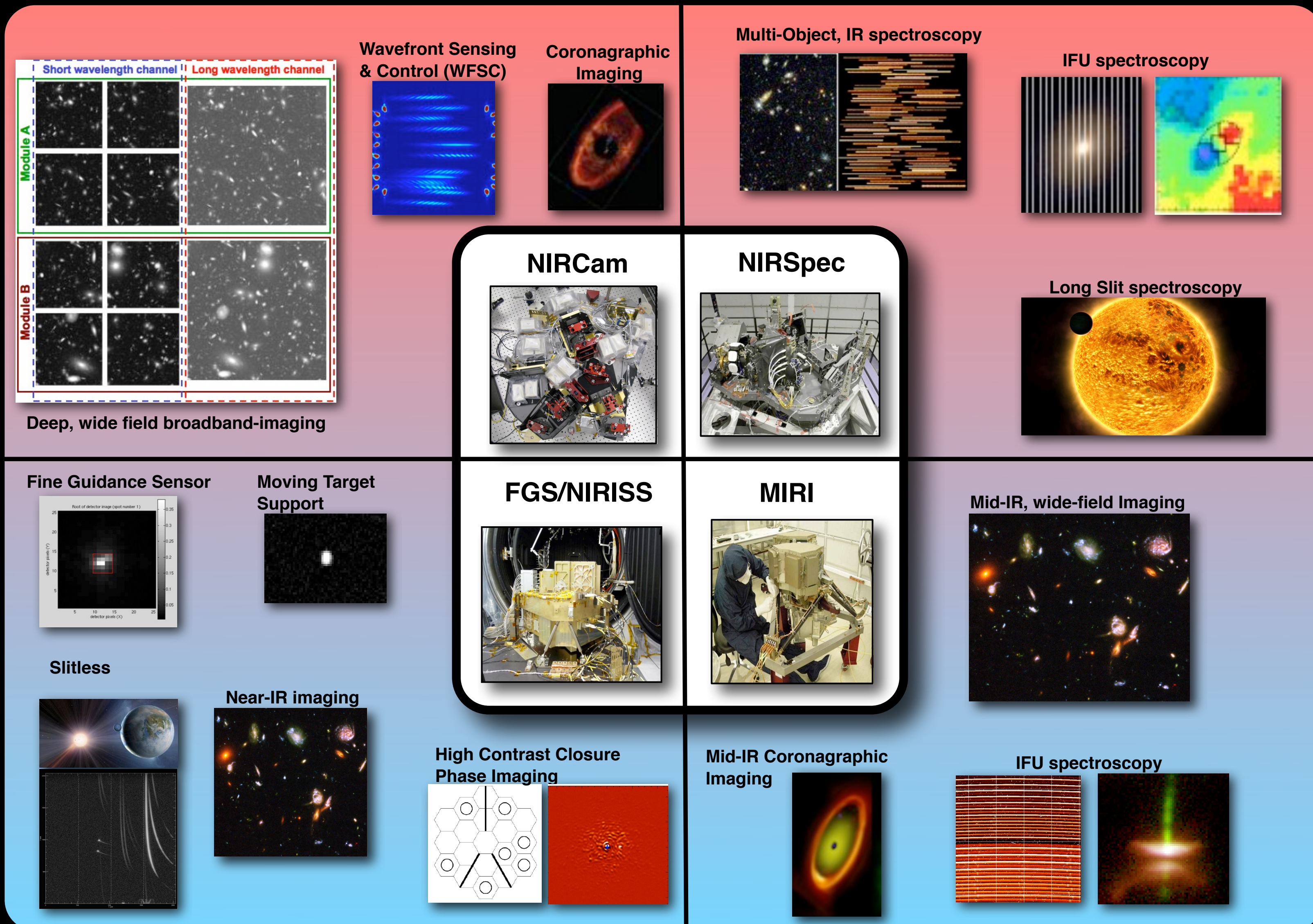
George Rieke & Gillian Wright

JPL and European Consortium

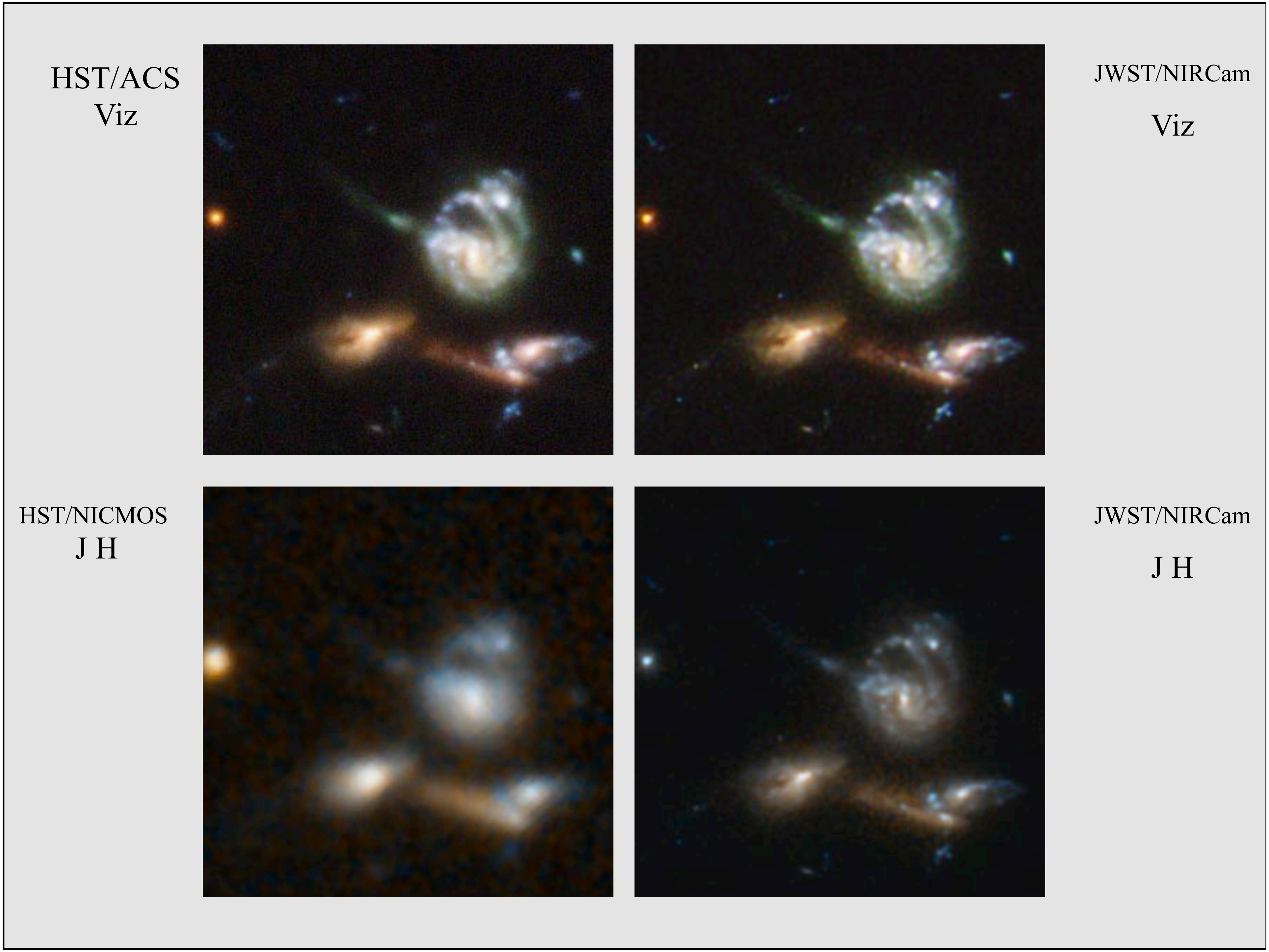
CSA: Rene Doyon

COM DEV

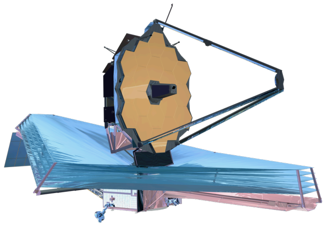
JWST Science Instruments



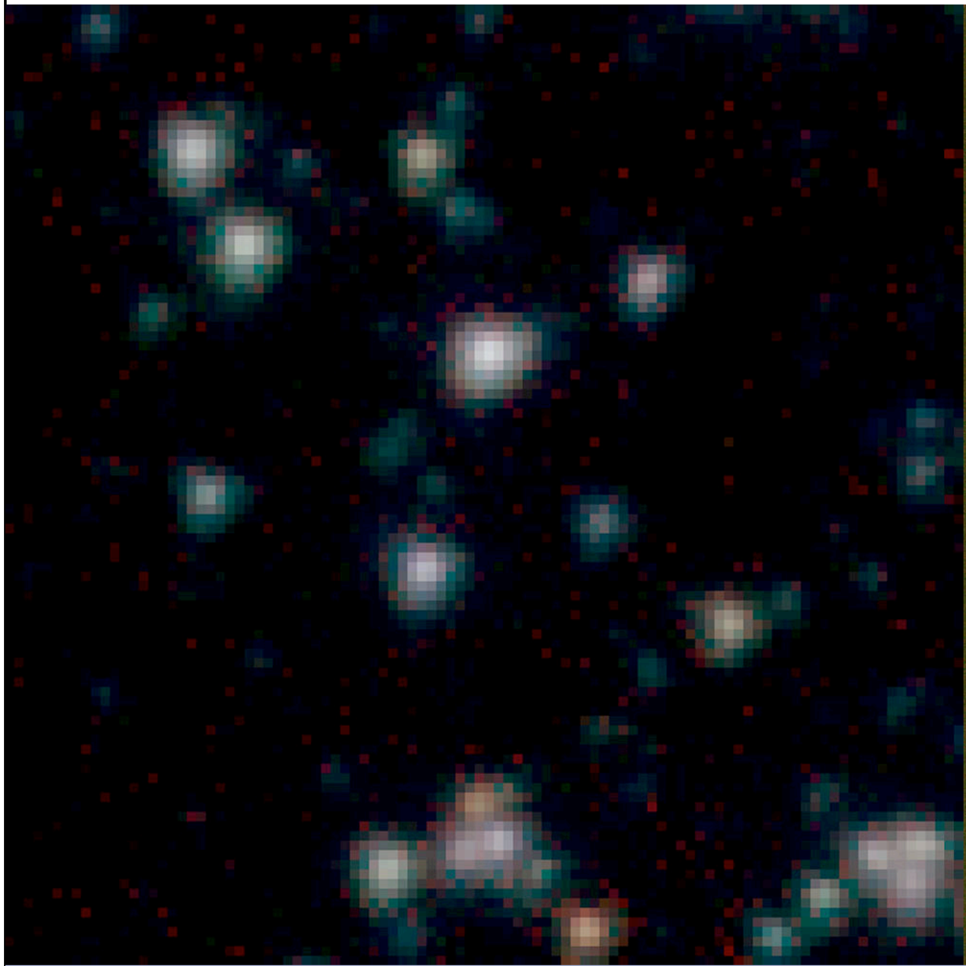
THE HUBBLE UDF
(F105W, F105W, F160W)
SIMULATED JWST


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

JWST-Spitzer image



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 : Sensitivity

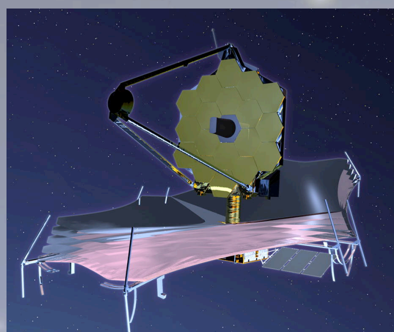
Probing the LF to the same relative depth as that of z=6 from the UDF gives us a required depth:

z	AB_1350	F_ν (nJy)	λ (μm)
10	30.284	2.80	1.34
12	30.551	2.19	1.58
15	30.869	1.63	1.95
20	31.267	1.13	2.55

The spectroscopic limit is ~27.5 for S/N=10 in the continuum, 5×10^{-19} erg cm^{-2} s^{-1} for line emission.

Operations

THE ASTROPHYSICAL JOURNAL



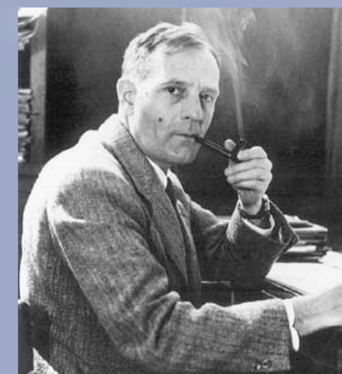
JWST at L2

Ka

S

STScI has been designated as Science Operations Center

GO, Legacy/Treasury and GTO programs similar to HST



Astronomer

DSN

STScI

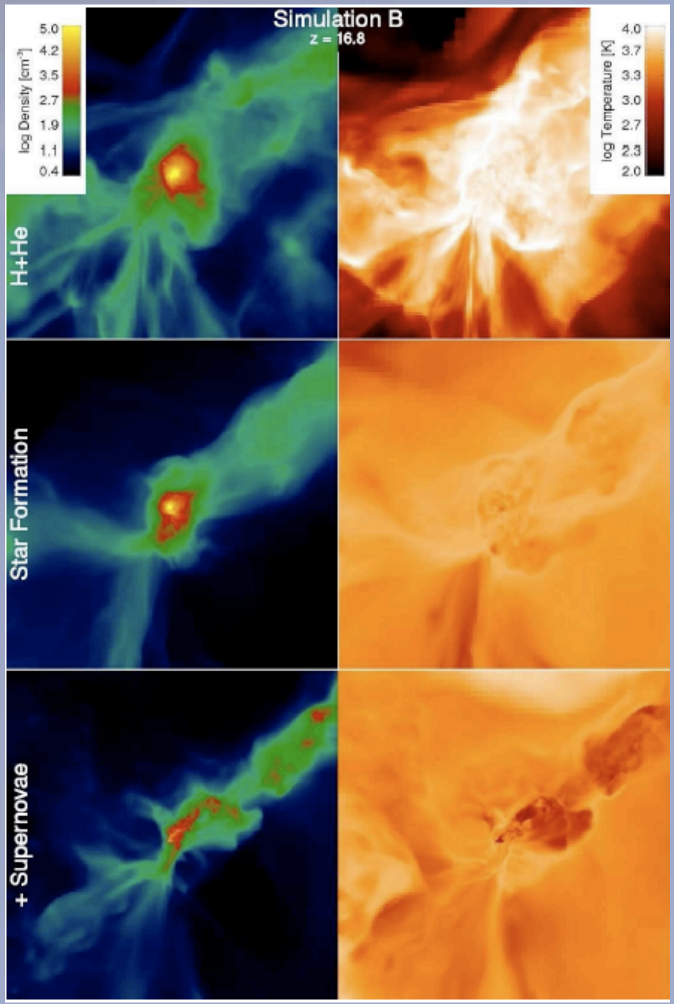
TAC

First Galaxies

- What do we expect?
- Luminosity Function Evolution
- Measuring redshifts and physical properties

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).

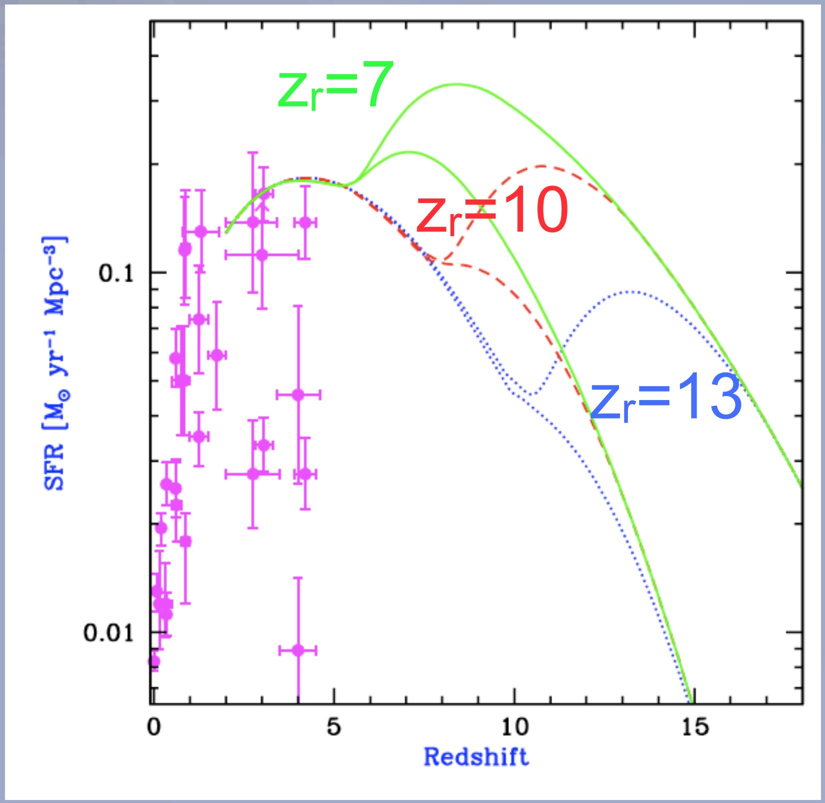


These objects are too faint to be observable with JWST. However, they are already enriched to $\sim 10^{-3}\,Z_\odot$.

More work is needed.

Luminosity estimates

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

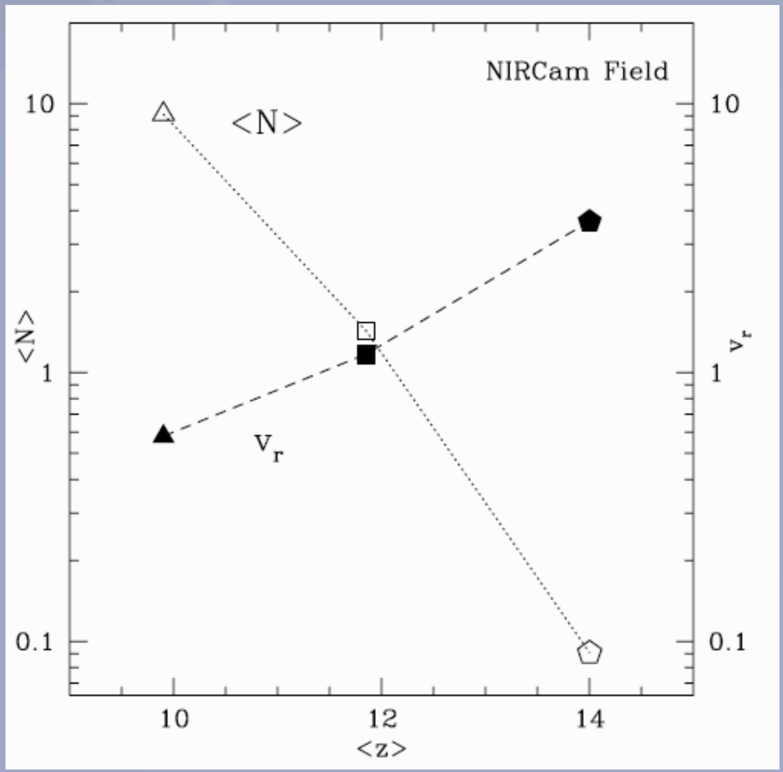


The different sets of curves are for different redshifts of reionization. The upper cure is the total SFR, the lower is for 0.25nJy flux limit.

If this model is right lensing will be crucial.

Luminosity estimates

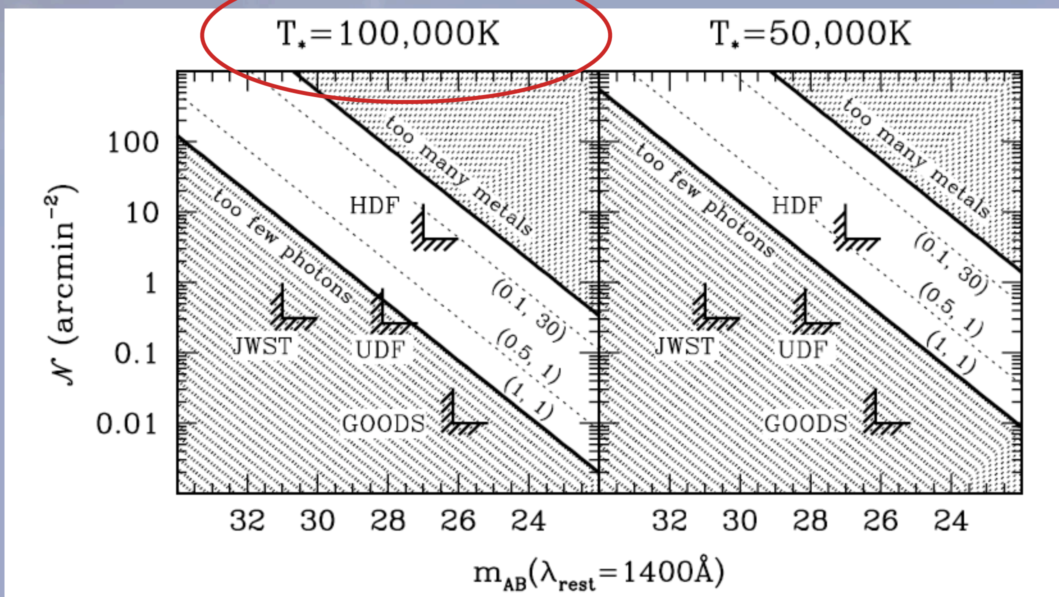
While waiting for numerical simulations for halos of higher mass, one can assume either a mass-to-light ratio or a star formation efficiency and see what this implies on the capability of JWST to detect these objects.



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

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.



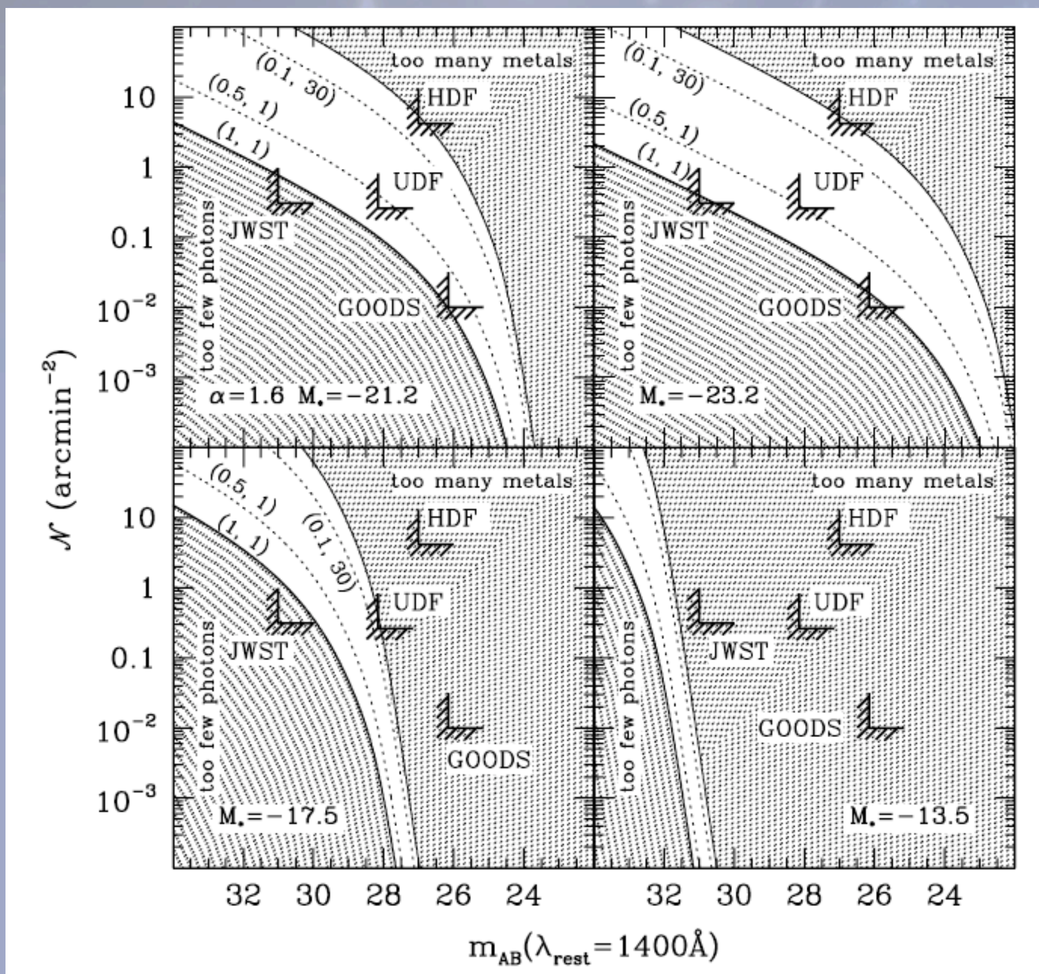
Stiavelli et al. 2004a

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

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



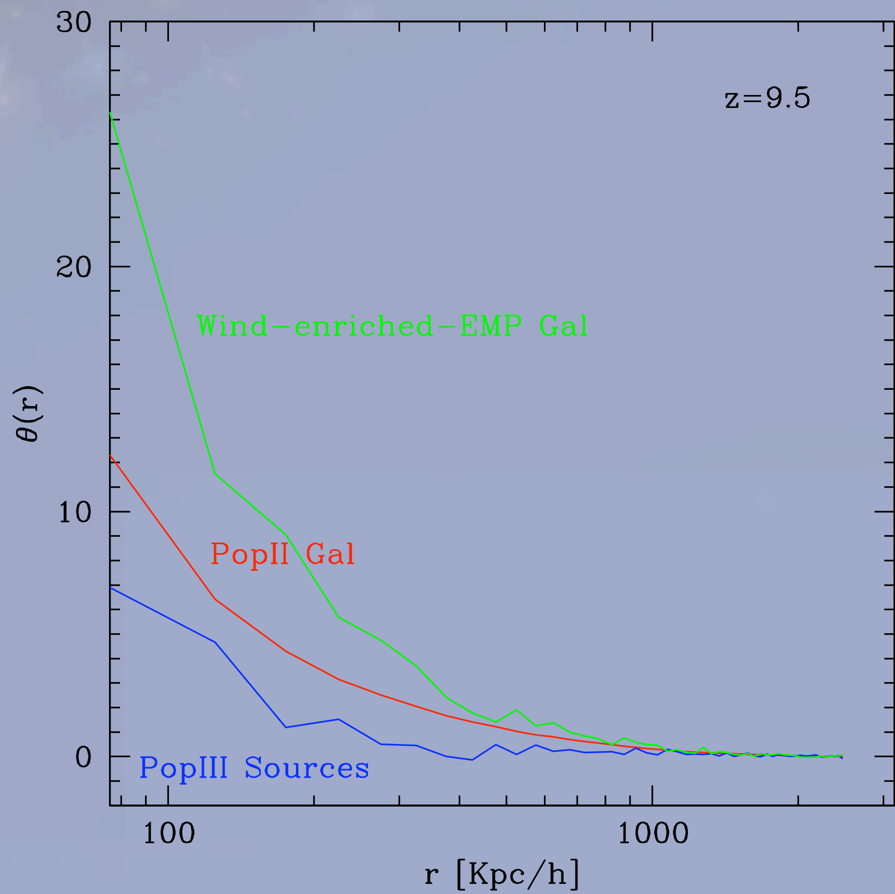
By changing the values of α and M_* one can explore the range of luminosities that are expected.

Stiavelli et al. 2004a

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).

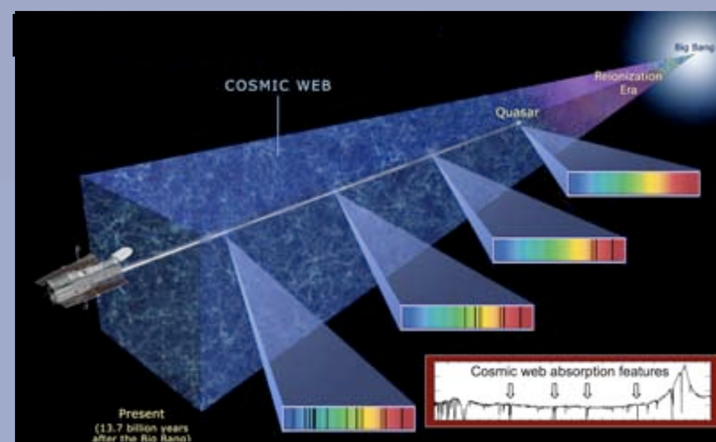


We might be able to observe these Pop III galaxies if lensed.

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:

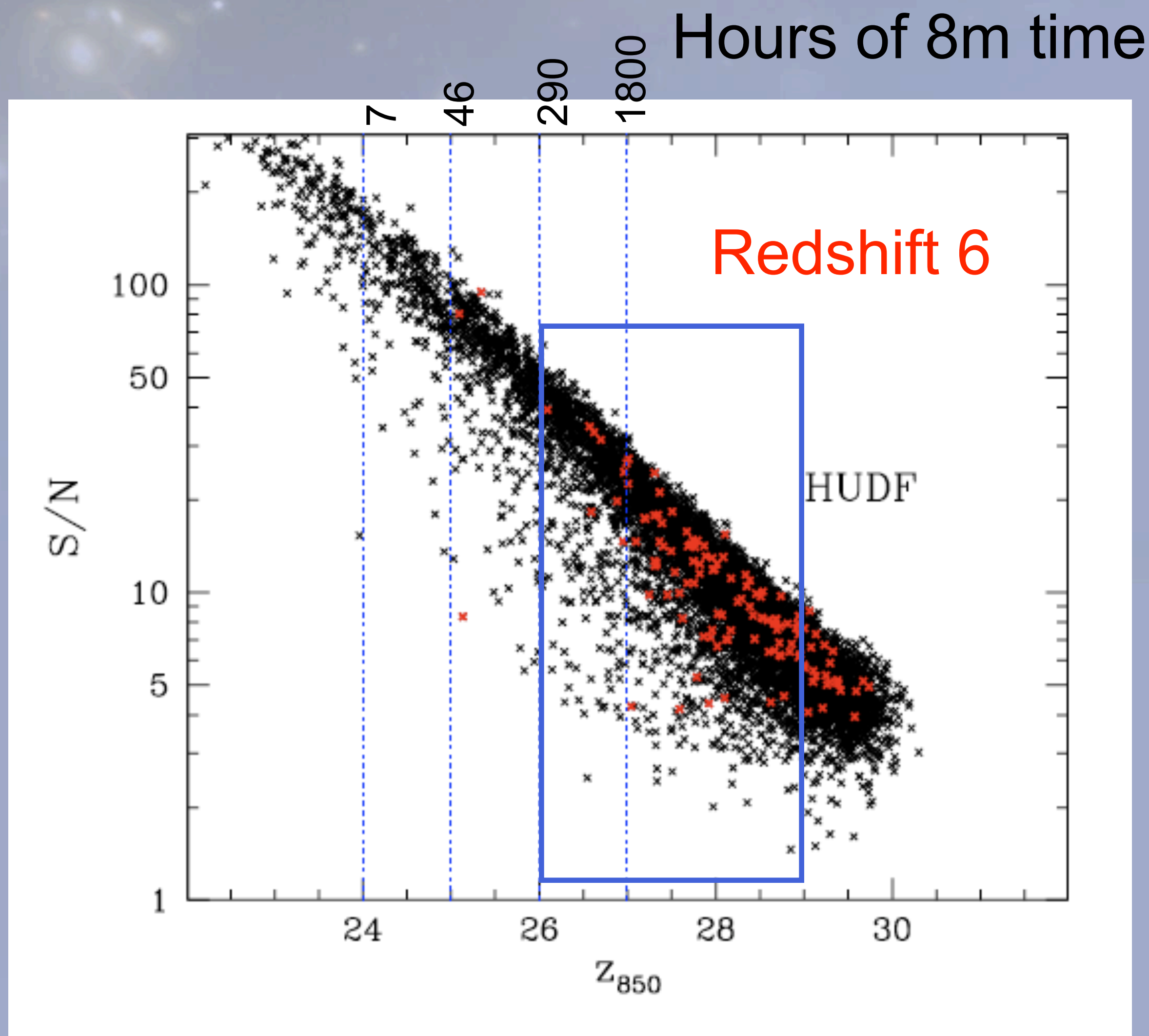


at $z \geq 10$ $\langle A_{1400} \rangle \leq 0.1$ and $A_{1400}(90\%) \leq 0.2$

Spectroscopy is hard

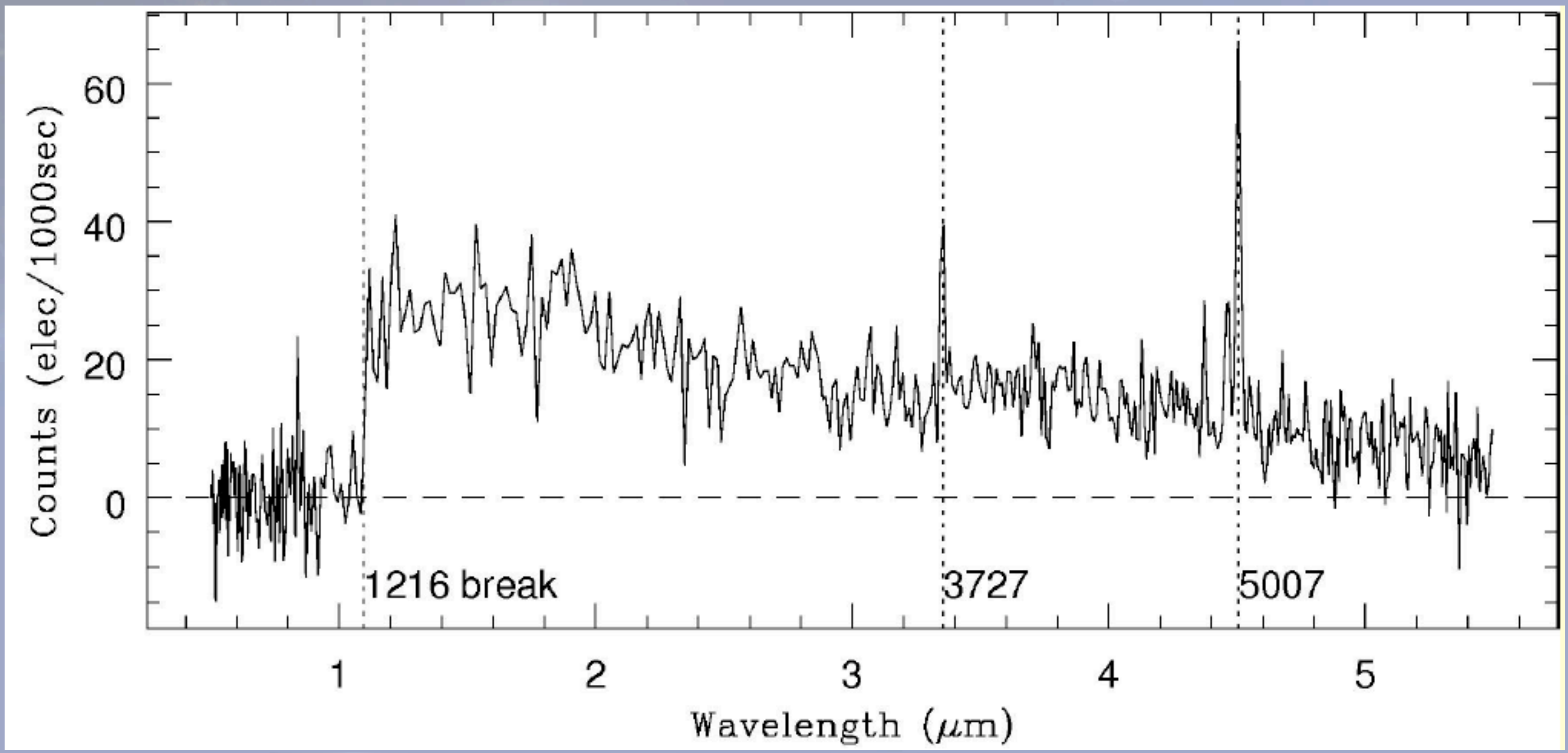
It is very hard to obtain spectra for the faintest objects in the UDF.

Red squares are i-dropout galaxies. The 4 vertical lines are the magnitude limits at S/N=3 for VLT+FORS2 in 7, 46, 290, 1800 hrs.



Bright galaxy at z~8

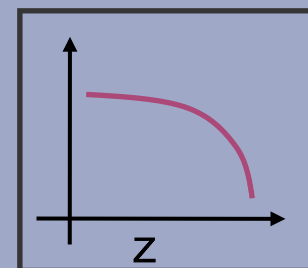
For galaxies at m_{JAB}=26, JWST can obtain high S/N spectra.



Simulation courtesy of M. Franx

How do we know we have seen the first galaxies?

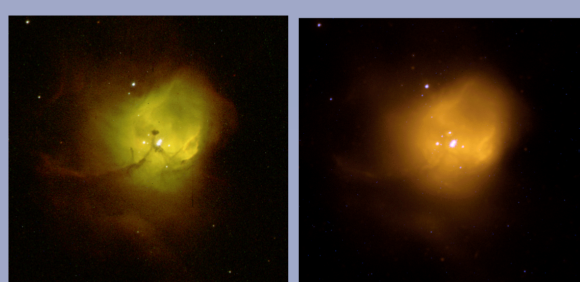
Evolution of N(z), LF. *Identify candidates with Lyman break technique* → **NIRCam**

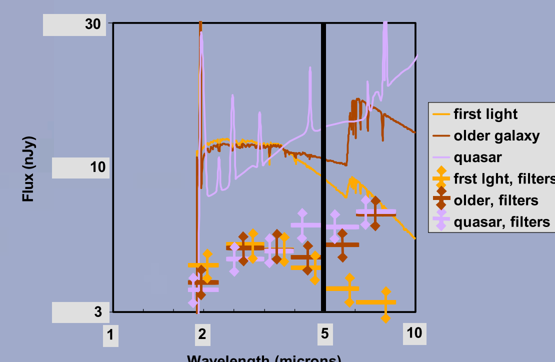


Evolution of SFR(z). *Use Hα, Hβ and supernovae*→ **NIRSpec and NIRCam**

Evolution of <Z>(z). *Use [OIII]/Hβ.*

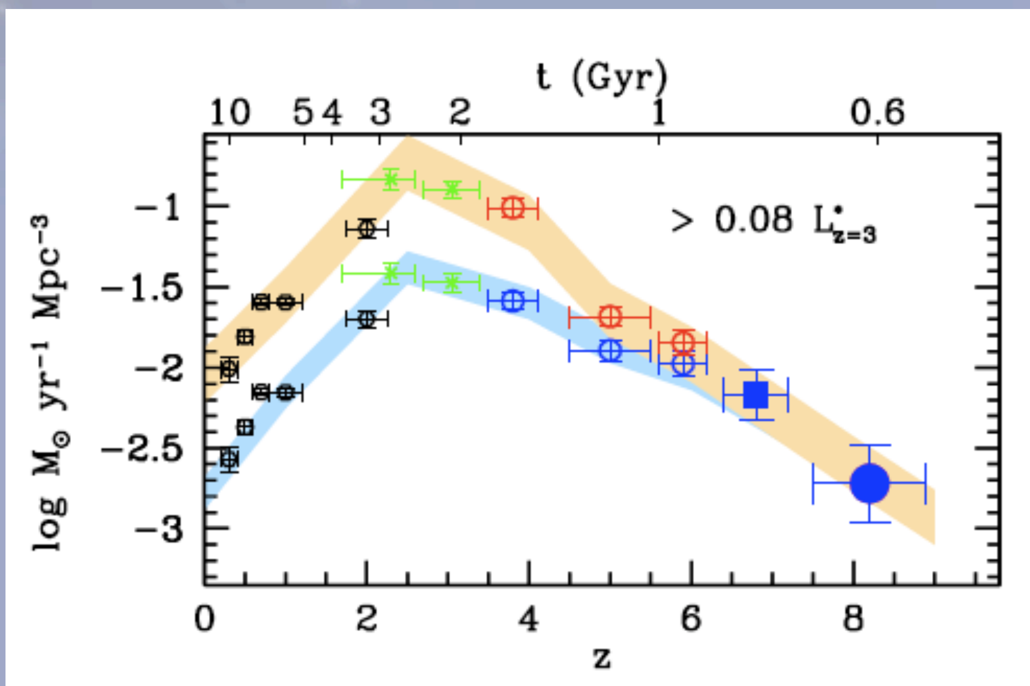
Confirm nature of first light objects. *Place upper limit to metallicity, search for older stellar component.* → **NIRSpec and MIRI** (this will typically require lensed or intrinsically very bright sources)





Indications from HST Observations

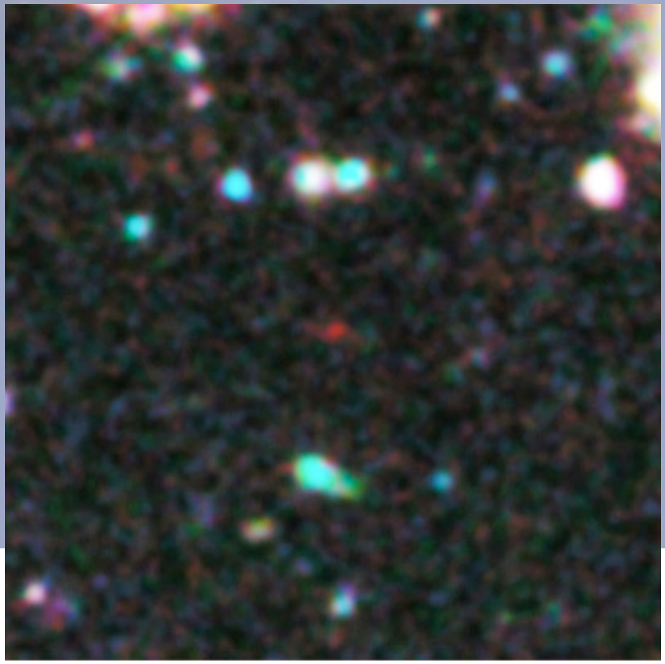
In the recent years we have been able to probe the luminosity function at z ≳ 6 observationally (e.g. Oesch et al. 2010, Bouwens et al. 2010a,b, Wilkins et al. 2010, Finklestein et al. 2010, Yan et al. 2010)

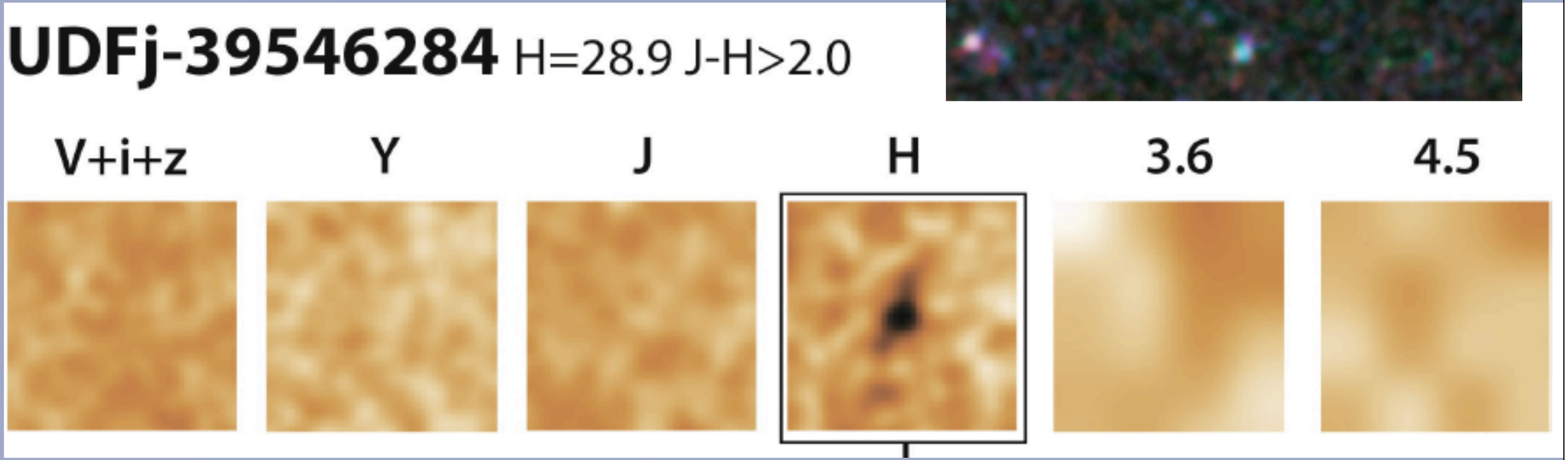


The number density of galaxies above the WFC3 UDF limit is decreasing with z and goes below 1 arcmin^2 at z~8-9.

One candidate at z~10

The HUDF09 team has detected one candidate at S/N > 5 (Bouwens et al. 2011).

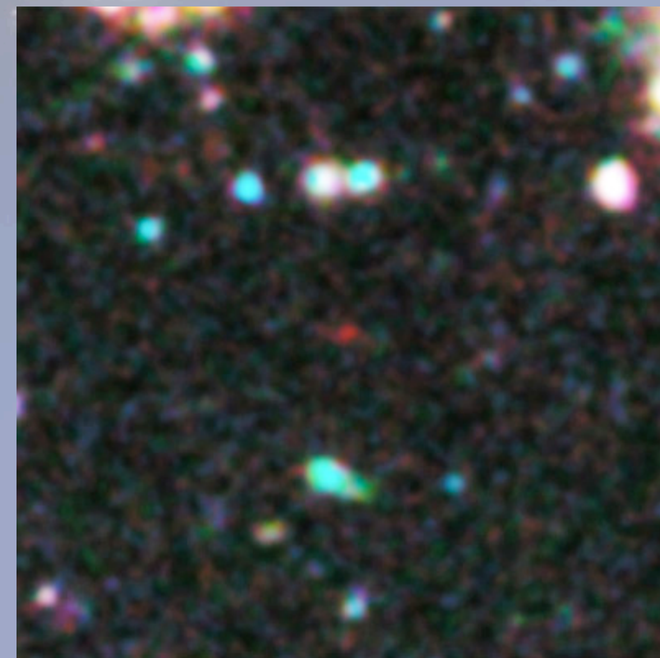




JWST Followup

It took 270,000s with HST and WFC3/IR to detect this object at S/N=5.8.

JWST can reach H=28.9 in 10,000s at S/N~10.

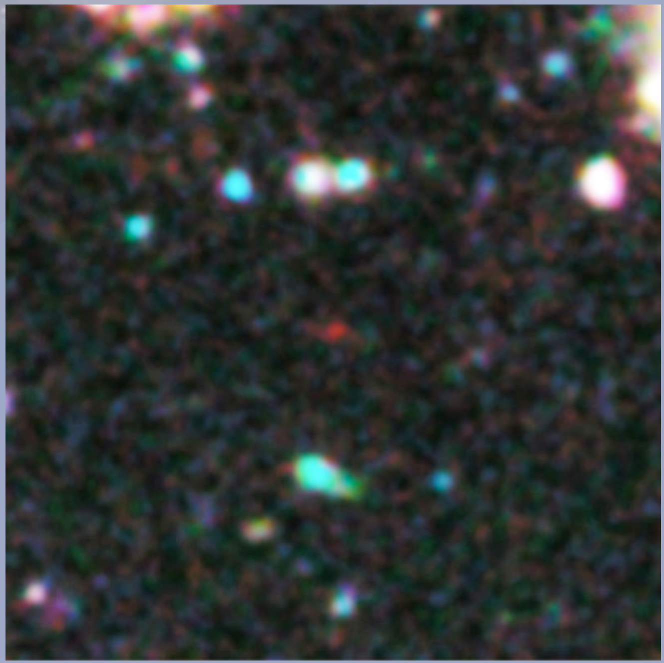


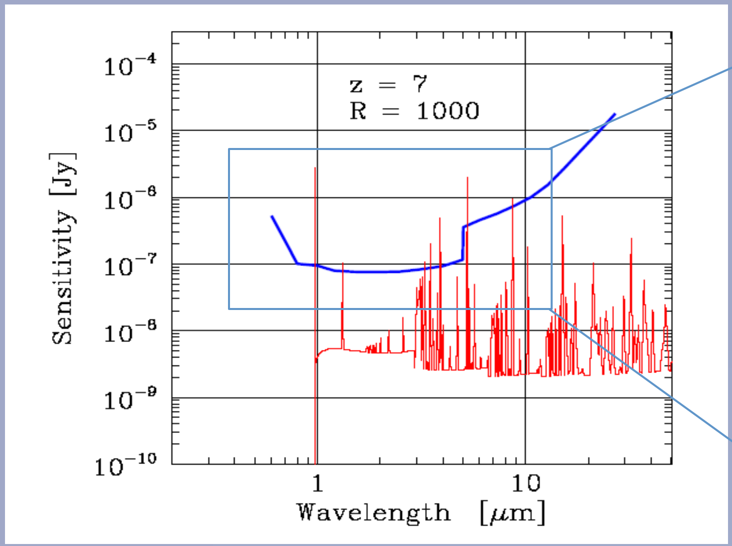
- The object is not detected by Spitzer/IRAC but JWST could detect it at 3.5micron in a parallel exposure to the H band one (at no extra “cost”).
- With an investment of 30,000s one could obtain a good photometric redshift for this object.
- A low resolution spectrum would take 100,000s.

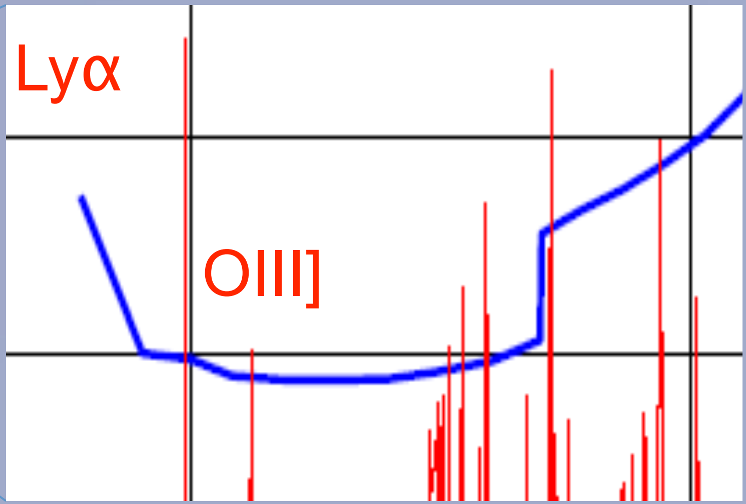
Physical properties

Emission lines can be detected with integrations of ~10^5s with JWST NIRSpec.

The resulting spectra would provide a spectroscopic redshift and also measure/constrain the metallicity.







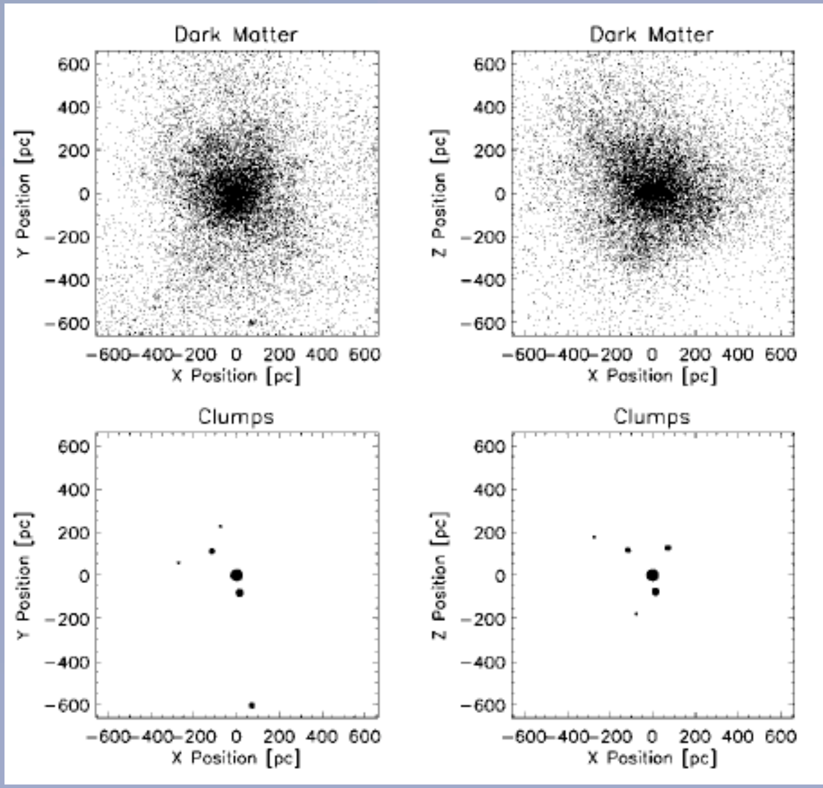
First Star Clusters

- direct detection
- lensing
- chemical abundance considerations

The First Star Clusters

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?

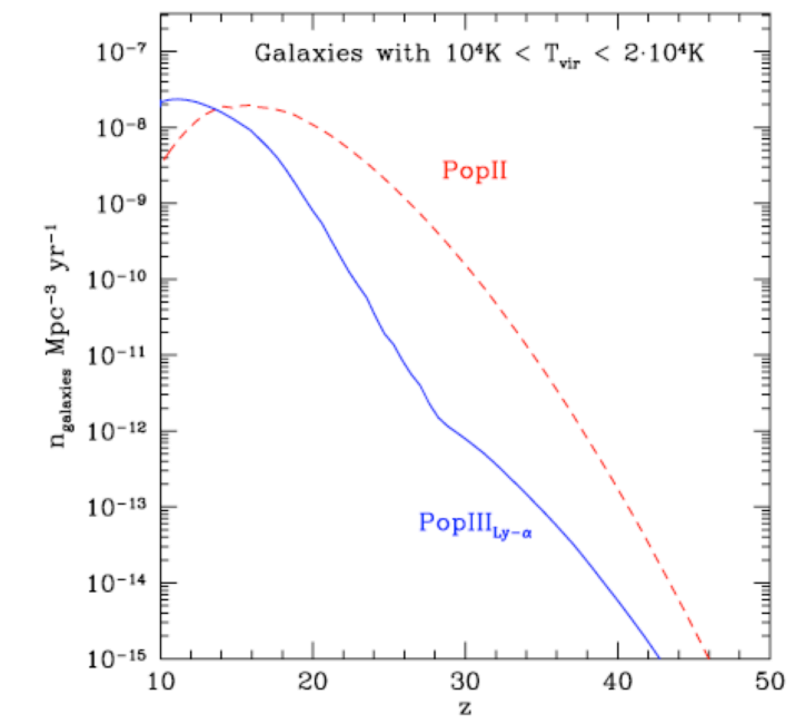


Bromm&Clarke 2002

Lensing of star clusters

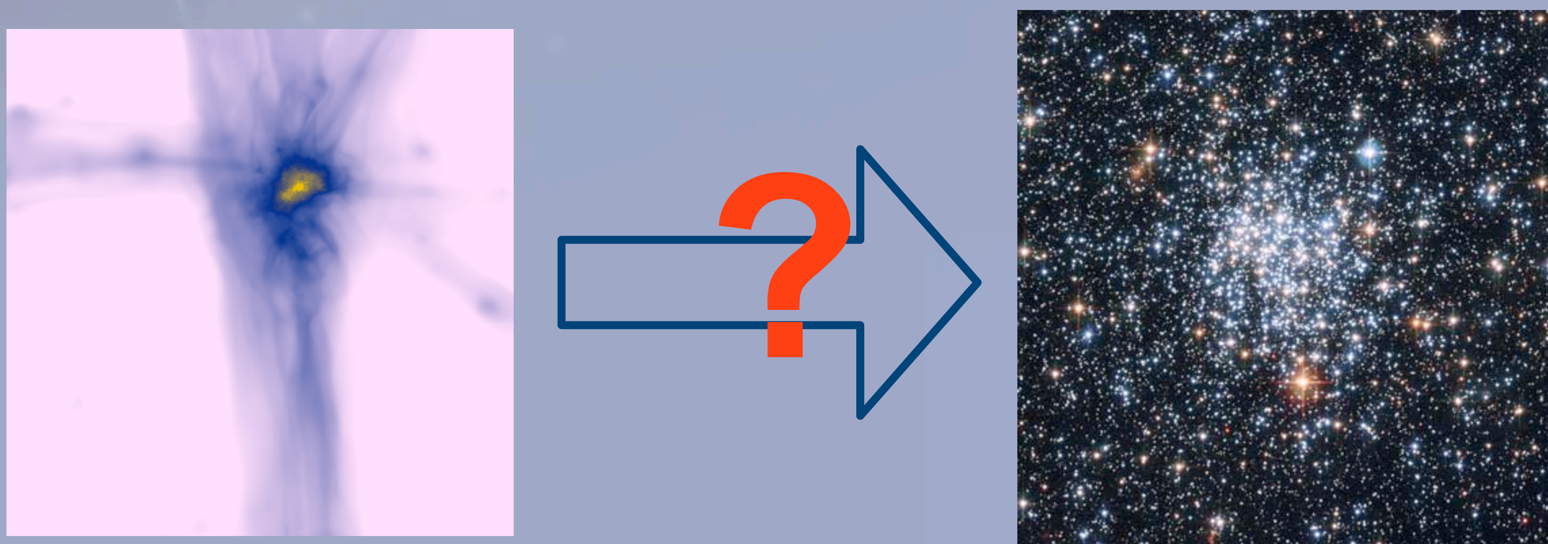
We looked at objects forming through Lymanα cooling in 10^8 solar masses halos (Stiavelli & Trenti 2010). The peak formation of slightly enriched objects of this mass occurs earlier than that of the metal free ones.

We expect 80 such objects per square arcmin per unit redshift so that the probability of lensing is not negligible. If the Lymanα escape fraction is high they may also be detectable directly at 2×10^{-18} erg cm^{-2} s^{-1}.



Chemical abundances

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.

Globular clusters abundances

It would be interesting to see if enrichment of 10^8 solar masses objects at high-z could provide the required reprocessing “bridge” between Population III abundances and the observed MW globular cluster abundances.

First Stars

- direct detection
- indirect detection through fluctuations
- chemical abundance tracers
- detection of supernova

First Stars – Direct Detection

For redshift z=10–25 the apparent magnitude is:

$m_{1400} \sim 38.5–40 \Rightarrow$ too faint for JWST

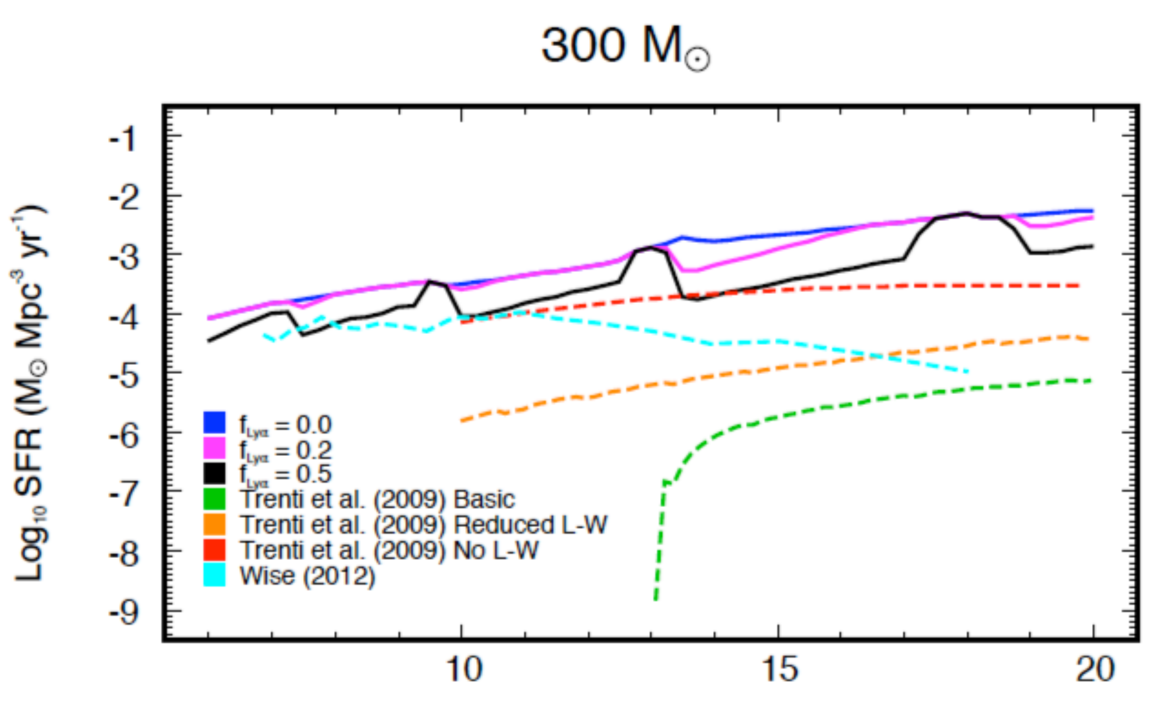
An HII region would have Lymanα emission at:

(5.5–0.7) 10^{-21} erg s^{-1} cm^{-2} which is also too faint.

One possibility could be gravitational lensing amplification by a factor ~100 or more. The issue here is the number of Population III stars and therefore the probability of strong lensing.

The First Stars – expected numbers

* Lyman-Werner feedback hinders the formation of Population III stars in mini-halos reducing their numbers (e.g. from green to red curve for the Trenti et al. models).



Rydberg et al. 2012

Still we could expect of the order 0.1-10 per square arcsec per Δz=1.

First Stars – Lensing

The lensing probability depends critically on the intensity of the LW feedback, on the IMF of Population III and to a lesser extent on the Lymanα escape fraction (determining whether we need to search in line emission or in broad band).

Other effects such as supersonic streaming (Greif et al. 2011) would further decrease the probability of lensing.

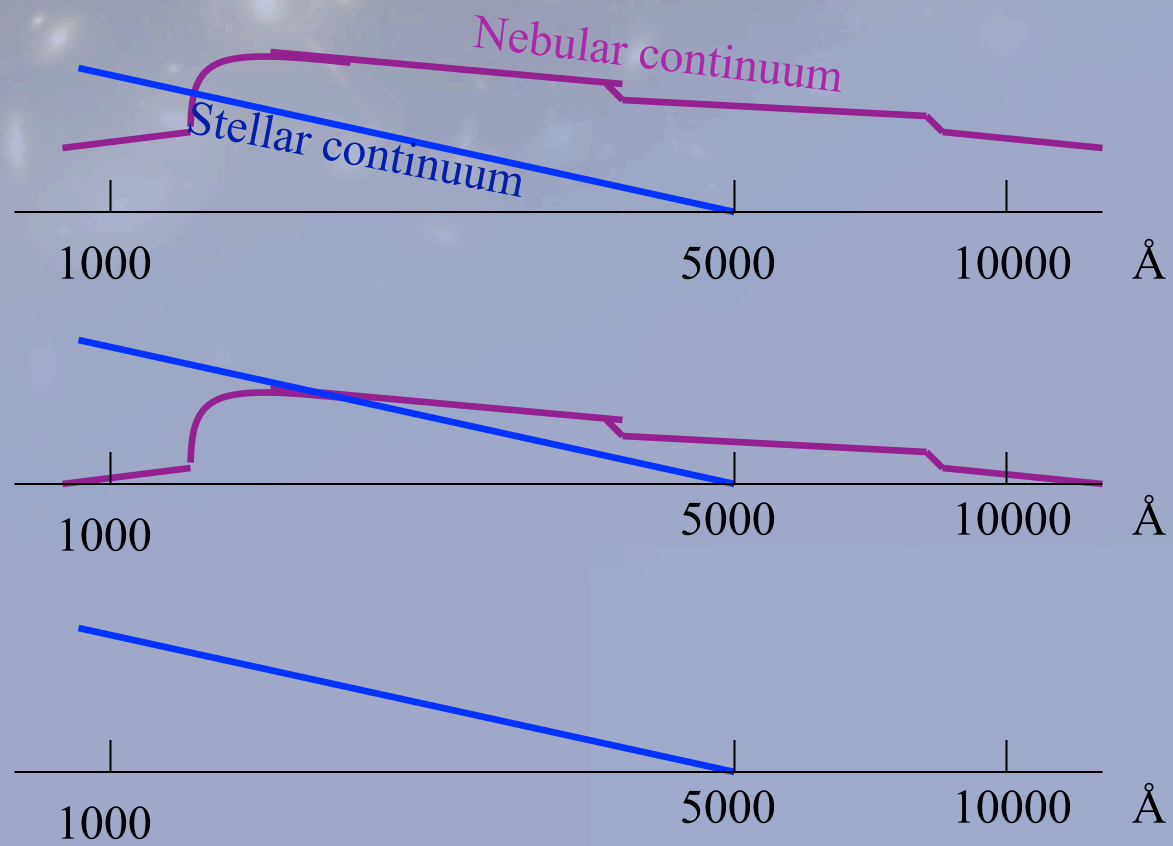
With luck we might be able to detect directly lensed Population III stars.

First Stars – How to recognize them

$f_{esc}=0$
No ionizing
γ escape

$f_{esc}=0.5$
Some ionizing
γ escape

$f_{esc}=1$
All ionizing
γ escape



A very steep SED implies both low metallicity and high escape fraction. A continuum detection without line detection would make identification uncertain.

First Stars - Fluctuations

Especially at the high end of the expected number density first stars would contribute to the unresolved near-IR background sufficiently to be detected by fluctuation analysis. Indeed this detection has been already claimed but it is so far not universally accepted (Kashlinsky et al. 2005, 2012).

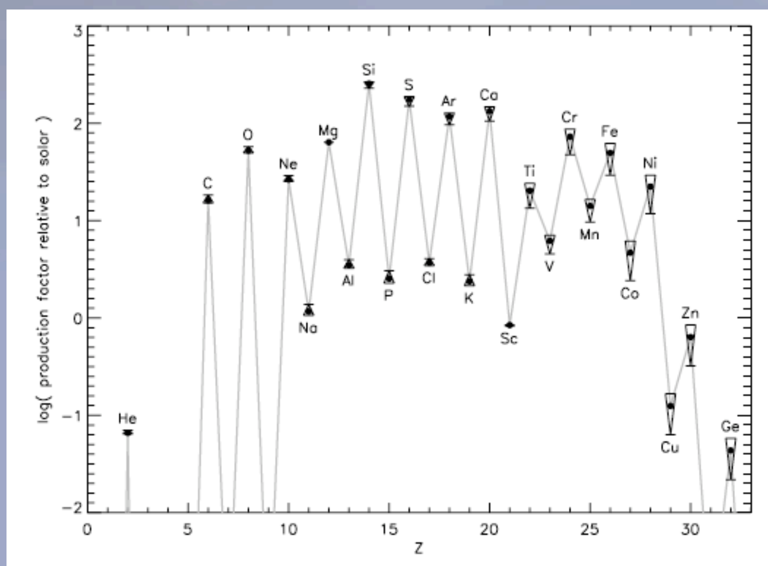
Major challenge today:

- no such claim can be believed without showing a “fluctuation dropout”
- this is very tricky as it depends on comparing different instruments

JWST enables this analysis within the same instrument and with greater sensitivity.

The First Stars – chemical tracers

* The idea is to identify spectroscopically the abundance pattern signatures of PISN enrichment.
* Large ground based telescope and perhaps JWST (spectral resolution limited)



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

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

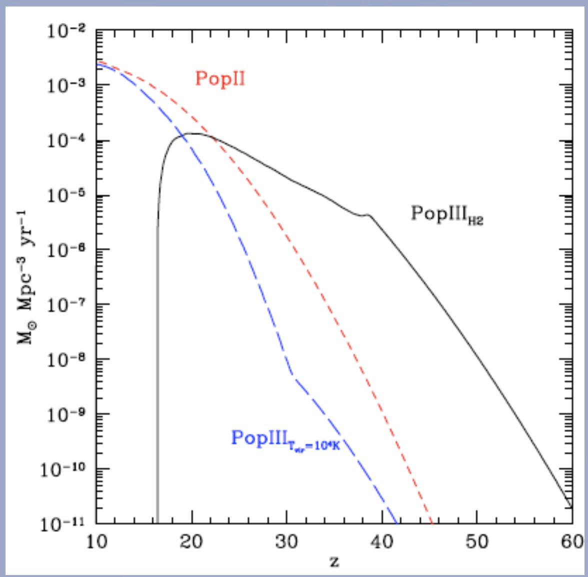
Many studies focus on elements at the peaks (C, O, Si, Fe, etc). We need to measure also those in the valleys.

First Stars - Supernovae

The two main issues are supernova brightness and rarity. The brightness is likely not an issue if Population III stars are massive enough to produce pair-instability supernovae. Rarity is harder to assess.

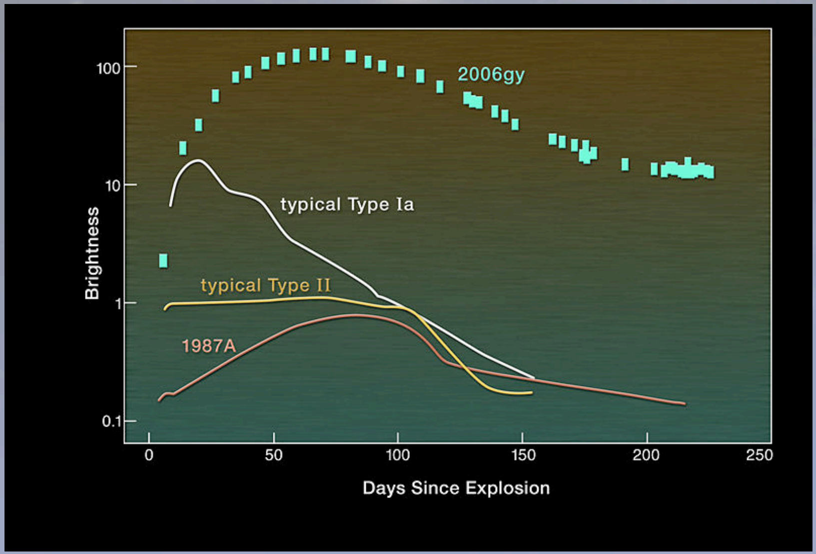
PISN Supernovae – expected rates

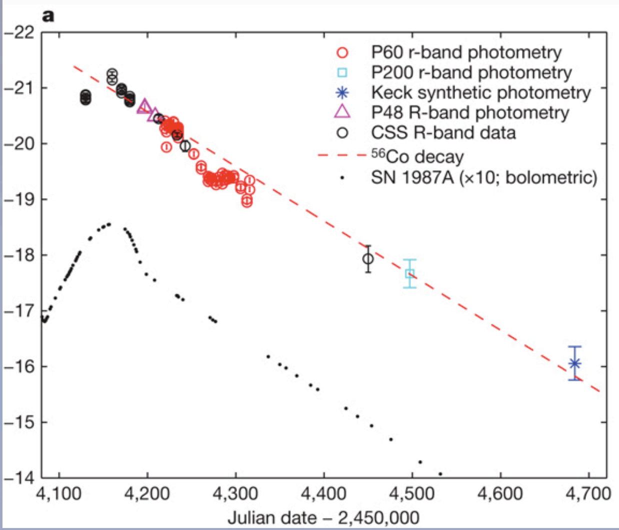
Weinmann & Lilly (2005) elaborating on previous results suggest densities of 4 $deg^{-2}\ yr^{-1}$ at z~15 and 0.2 $deg^{-2}\ yr^{-1}$ at z~25. The actual numbers may be lower if one considers negative feedback on mini-halos. However, SNae from atomic hydrogen cooling halos could boost up the rate. If 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 – finding them with JWST

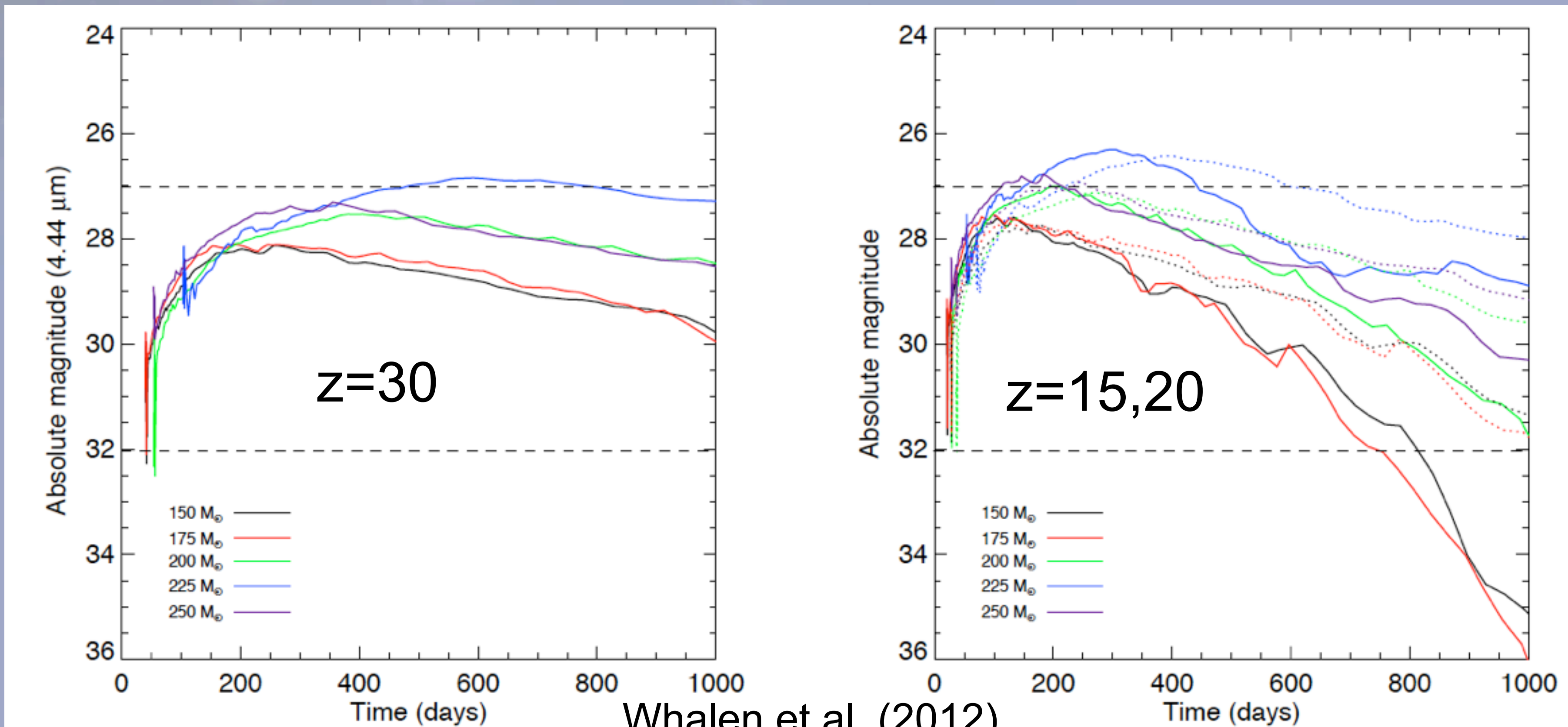




SN2006gy and 2007bi have been proposed as PISN analogs. If PISN have a light curve similar to that of 2006gy we can see that one might expect the SN to have at the peak a luminosity of AB~26-26.5 at z=10-15 and for observations at 4-5 μm. JWST/NIRCam can achieve such a depth at 4 μm with a exposures 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 – light curves

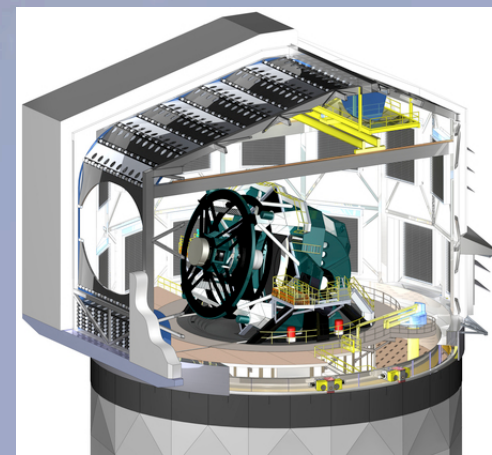
Light curves derived by Whalen et al. (2012) show that PISN should be easy to observe by JWST if we know where to look.



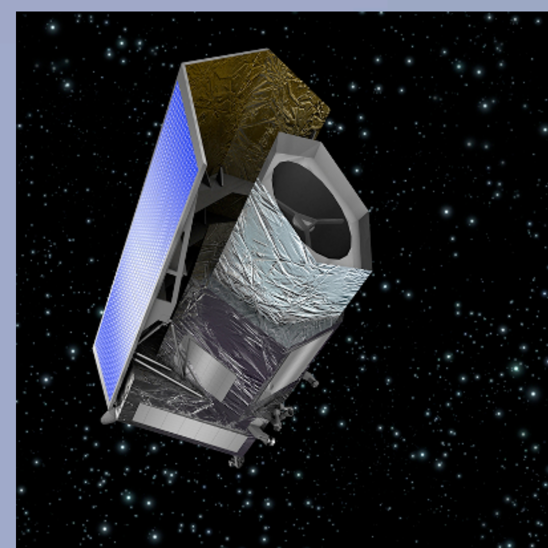
Whalen et al. (2012)

PISN Supernovae – finding them

LSST and other ground based wide field projects may be able to detect lower redshift PISN (at z~6). Large area space based missions like Euclid or WFIRST have the potential to discover PISN at higher redshift.



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

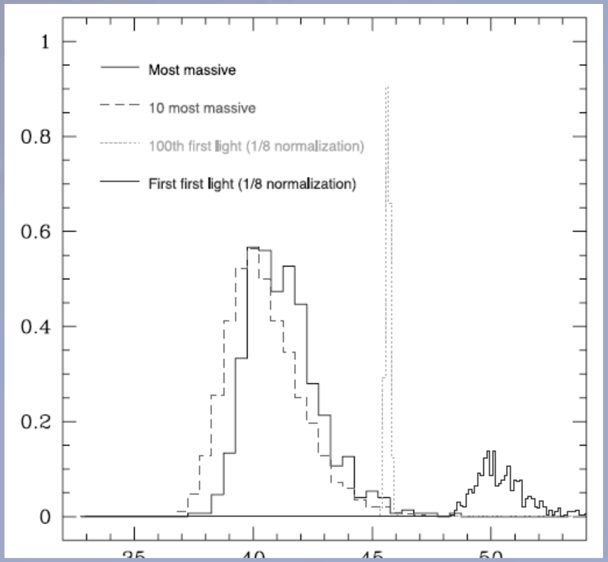


IF PISN were to be associated to a GRB, GRB finding missions would be able to provide the location. JWST can follow-up on TOO in 48 hours (mission requirement).

The First AGNs

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.

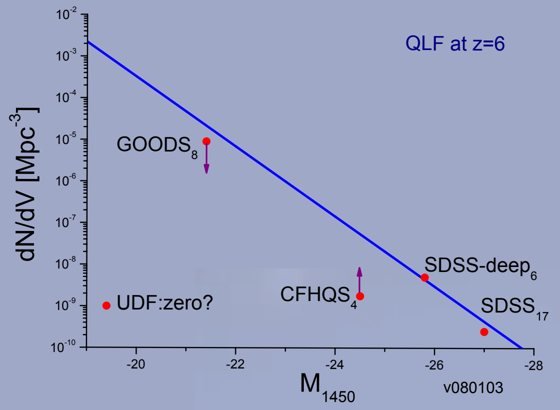


Direct collapse in 10^8 M$_\odot$ halos (Bromm&Loeb 2003, Begelman et al. 2006) requires halos that are not pre-enriched by mini-halos (and have low turbolence). This might lead to anti-biased QSOs which is not what we see at low-z.

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 $M_\odot$ black hole is ~ 3×10^8 $L_\odot$. 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 $M_\odot$ 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).

Conclusions

Population III stars are rare and faint. Direct detection is possible only through lensing (if at all).

JWST can likely 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.

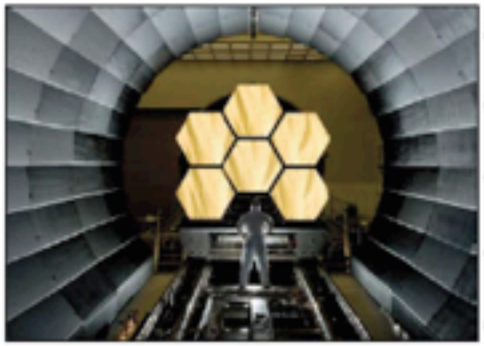
JWST Status

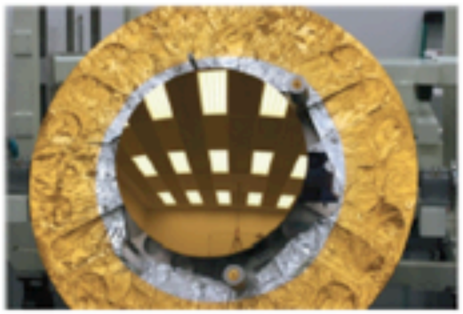
Project is doing well.

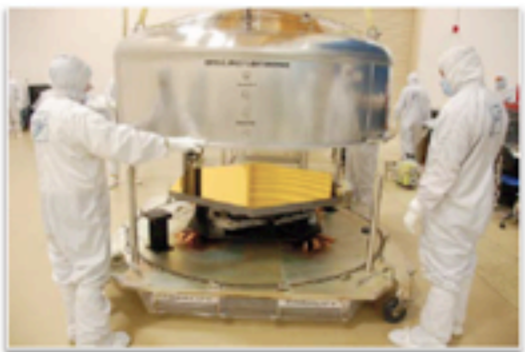
Funding and schedule reserves have been adequate to meet the challenges encountered so far.

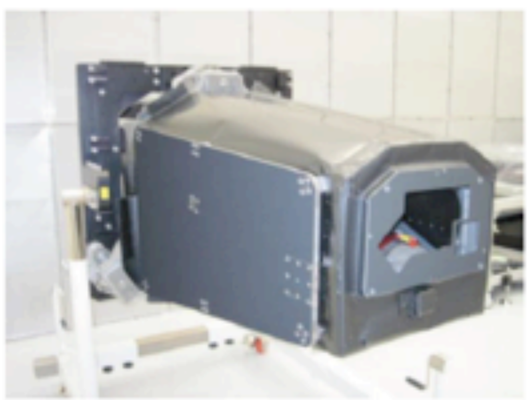
Major risk would be funding uncertainty.

All Mirrors Are Complete!

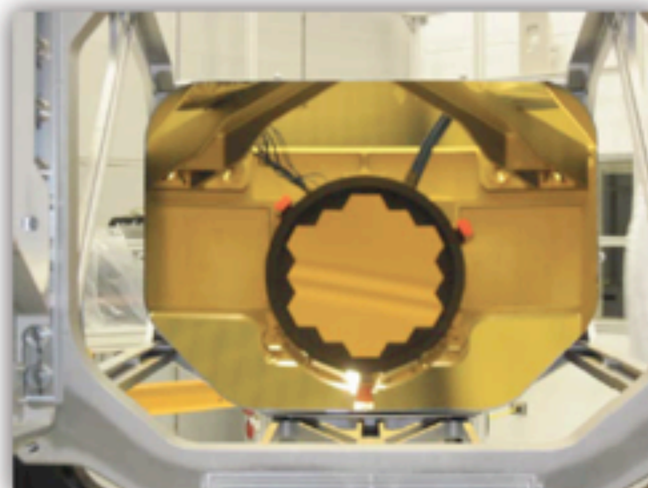






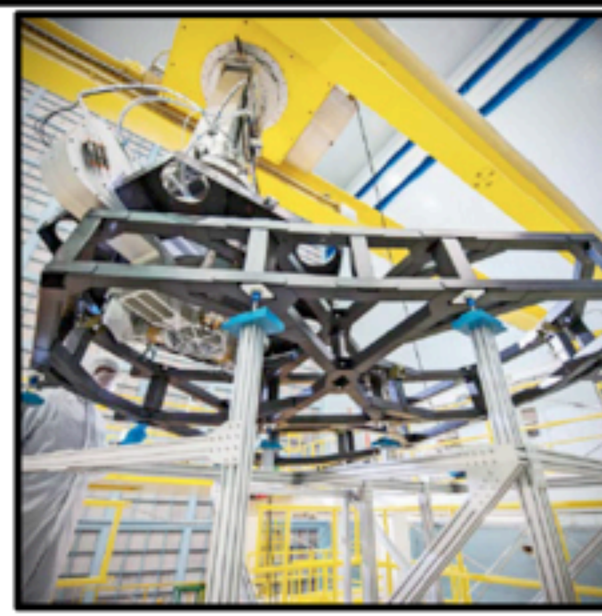


- **First two flight mirrors delivered to GSFC on Sept. 17th**
- **Aft Optics Assembly (AOS) integration complete**
  - Second cryo test complete
- **Flight Cryo Electronics**
  - All 21 CMUs have been assembled & completed cryo testing
  - CJB has been assembled and has completed its acceptance testing
  - EM ADU has been delivered and flight ADU is in board-level testing



Primary Mirror Segment Assembly (PSMA) Installation Fixture (PAIF) delivered and installed on AOAS

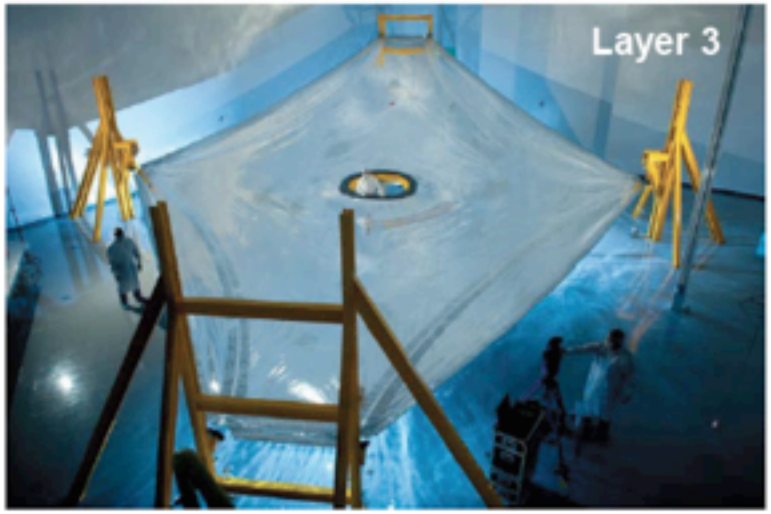
- Demonstrations of placement of mirror mass model on BESTA completed
- Placement of engineering/flight spare mirror on BESTA scheduled for Oct.

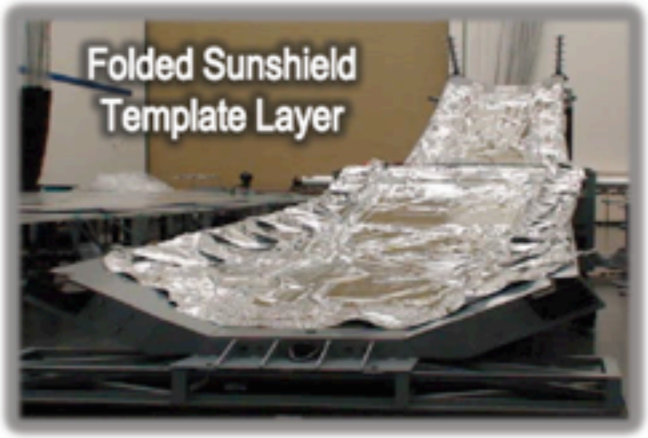


Sunshield Template Membrane Work On-Going

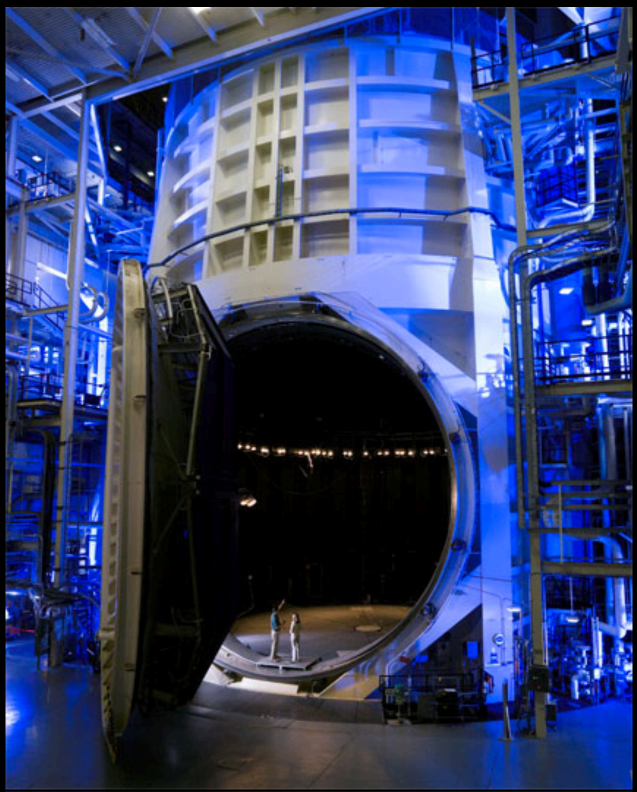
Templates Verify Design Prior to Flight Build

- **Template Layer 3 - Completed**
- **Template Layer 4**
  - Manufacturing and Testing Completed
  - Hole Tool Operation Completed
- **Template Layer 5**
  - Manufacturing and Testing Completed
  - Hole Tool Operation underway
- **Template Layer 2**
  - Manufacturing in process
- **Template Layer 1**
  - Manufacturing in process





Optical End-to-End Test @ JSC



- Goals of Cryogenic Optical Test
  - ➡ Optical workmanship
  - ➡ Optical alignment - are we within the capture range of the active optics ?
  - ➡ Thermal balance - will the telescope cool to 40K ?