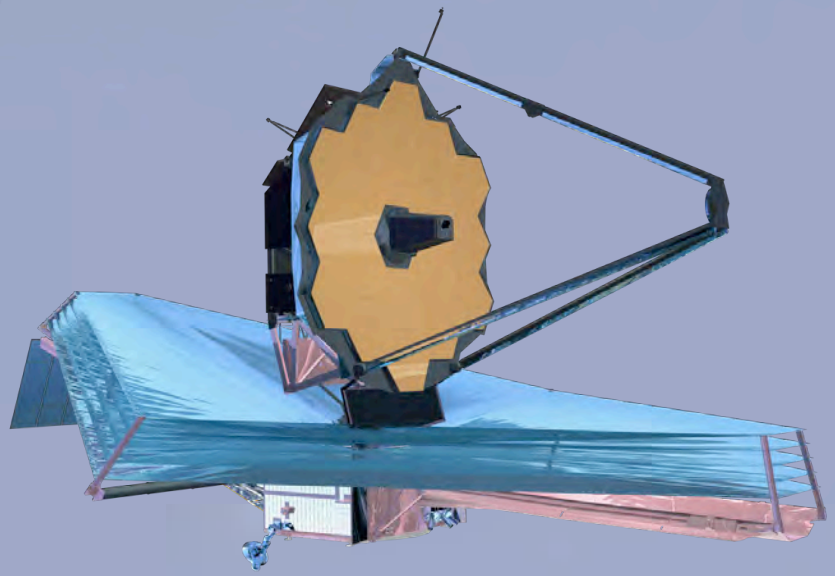
First Light and Reionization with the James Webb Space Telescope

Plan:

- What is JWST
- Expectations
- Detecting the First Stars
    - Pair instability supernovae
- Detecting the First Star Clusters
- Detecting the First Stars
- Status of JWST

The James Webb Space Telescope

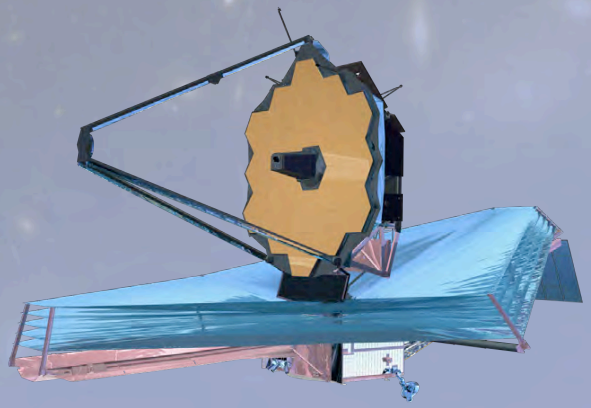
The James Webb Space Telescope was designed from the ground up to study high-z galaxies. For science themes guided the design, two extragalactic and two galactic. The one most relevant for us is the End of the Dark Ages theme.



End of the dark ages:

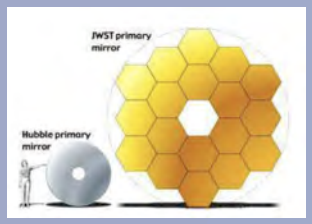
- **First light**
- Nature of reionization sources

JWST in brief



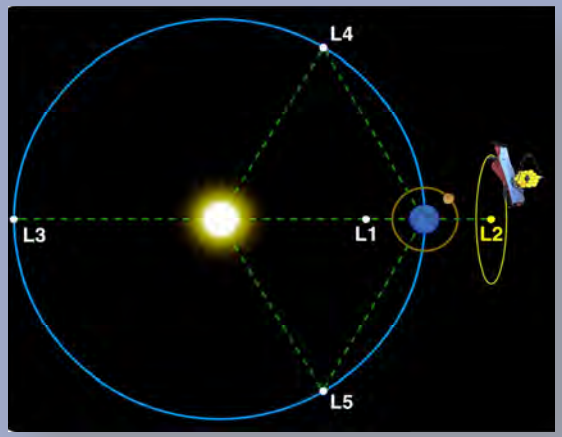
Organization

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)

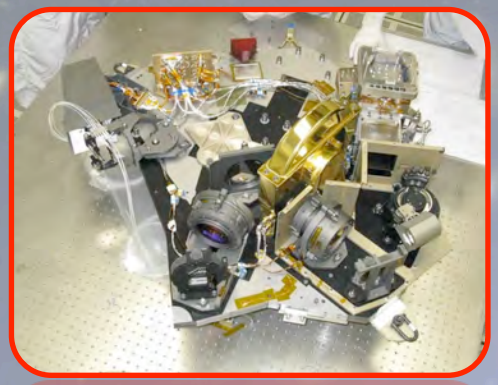


Description

- 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

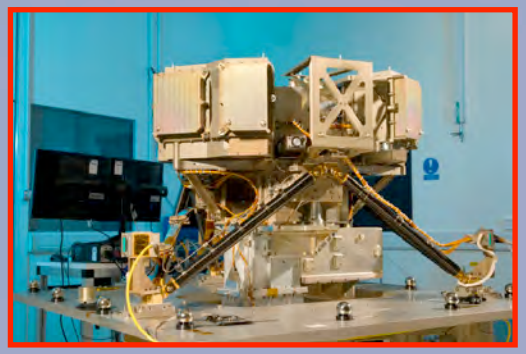


Instruments



Arizona: Marcia Rieke PI

Lockheed-Martin & Rockwell



George Rieke & Gillian Wright

JPL and European Consortium

- 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
  - **ready for ISIM CV1 testing**
- MIRI, 5.0 to 27.0 micron
  - 1.4 x 1.9 arcmin FOV imaging
  - 3 arcsec IFU at R~3000
  - **ready for ISIM CV1 testing**
- Coronagraphy
  - NIRCam, TFI & MIRI

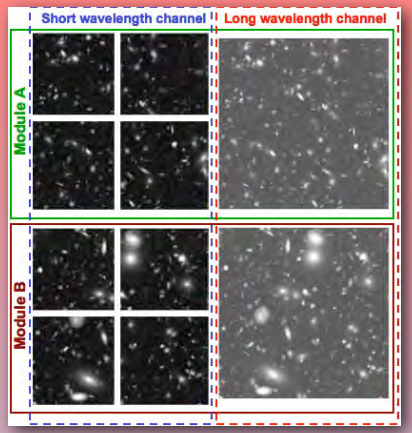
ESA: Pierre Ferruit

EADS Astrium & GSFC

CSA: Rene Doyon

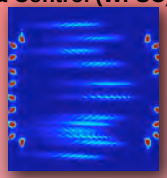
COM DEV

JWST Science Instruments



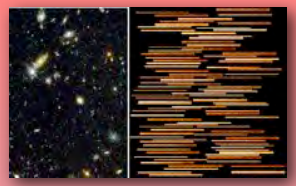
Deep, wide field broadband-imaging

Wavefront Sensing & Control (WFSC)

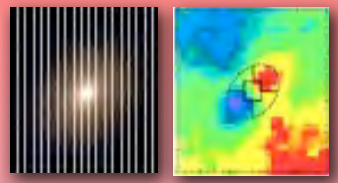


Coronagraphic Imaging

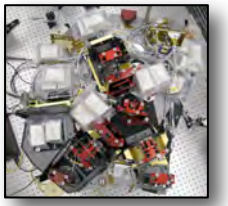
Multi-Object, IR spectroscopy



IFU spectroscopy



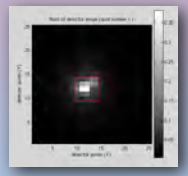
NIRCam



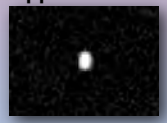
NIRSpec

Long Slit spectroscopy

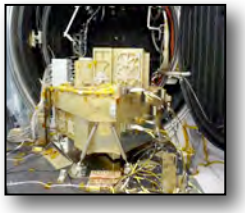
Fine Guidance Sensor



Moving Target Support

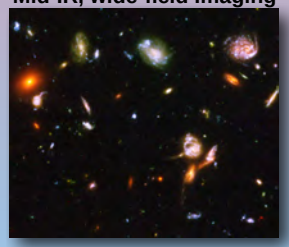


FGS/NIRISS

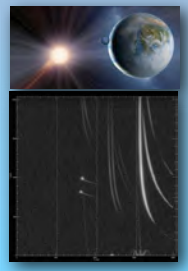


MIRI

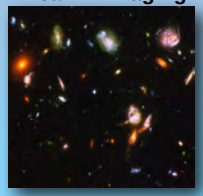
Mid-IR, wide-field Imaging



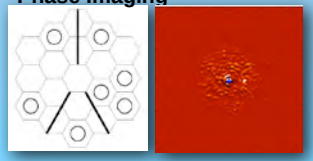
Slitless



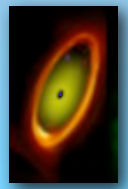
Near-IR imaging



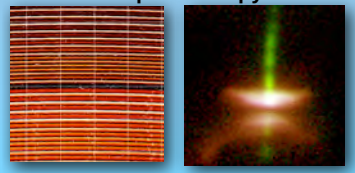
High Contrast Closure Phase Imaging



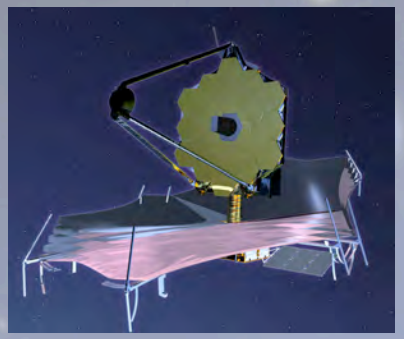
Mid-IR Coronagraphic Imaging



IFU spectroscopy



Operations



JWST at L2

Ka S

DSN

THE ASTROPHYSICAL JOURNAL

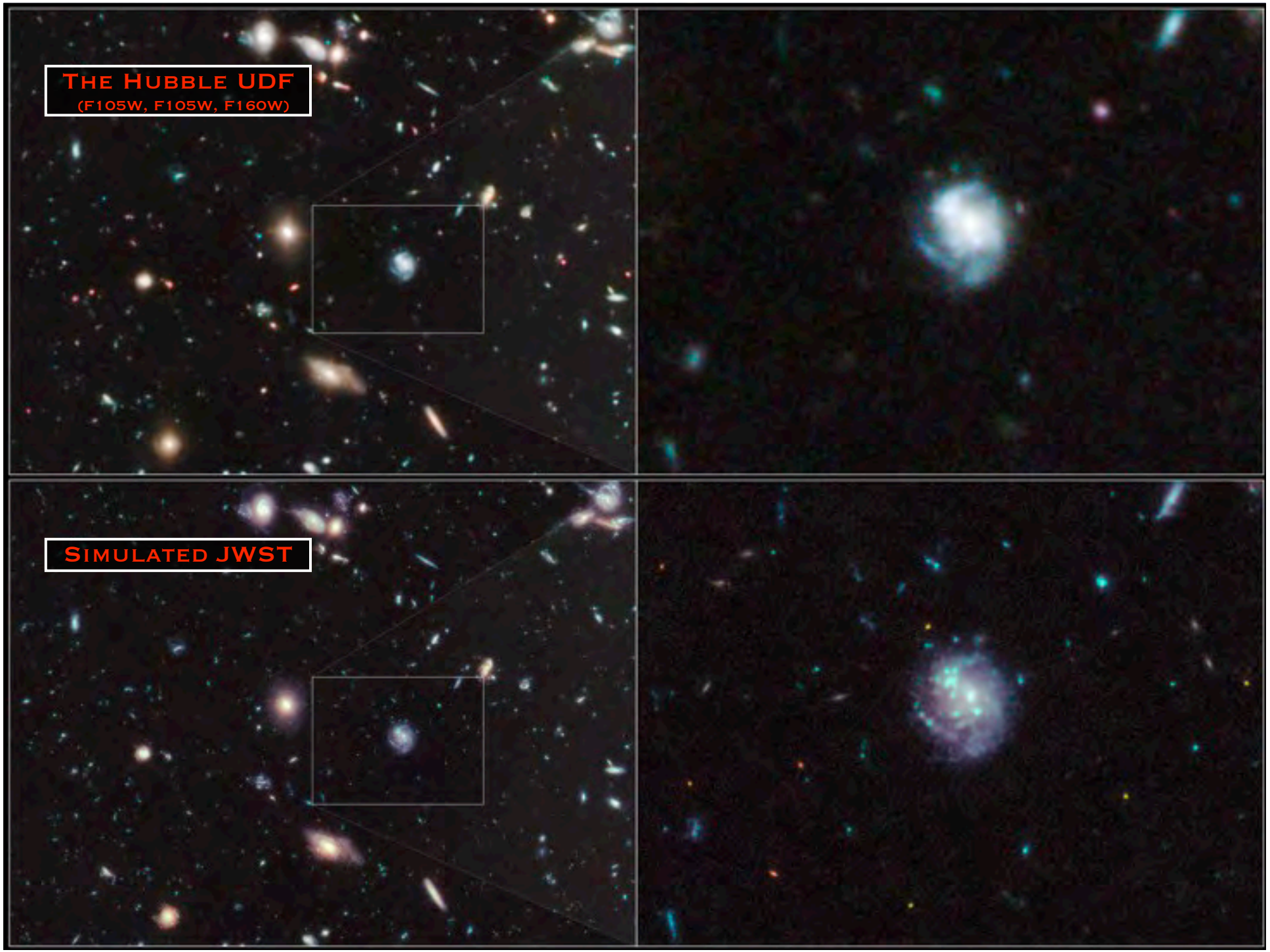
STScI is developing the Science Operations Center

GO, Legacy/Treasury and GTO programs similar to HST

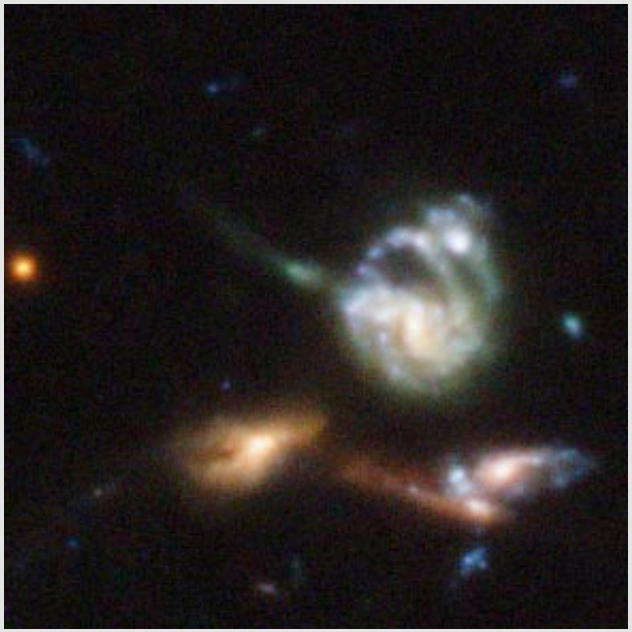
Astronomer

STScI

TAC

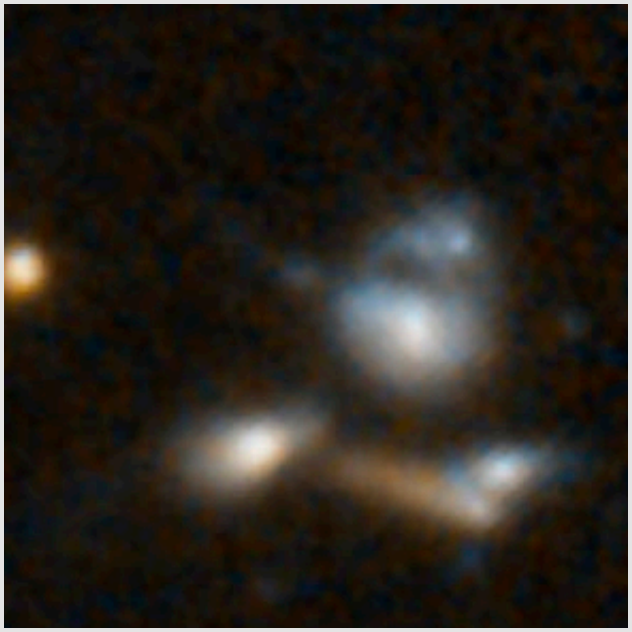

The Hubble UDF
(F105W, F105W, F160W)
Simulated JWST

HST/ACS
Viz



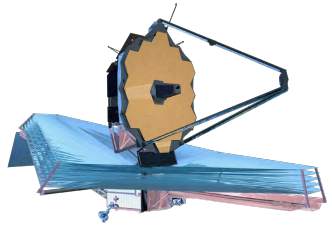
JWST/NIRCam
Viz

HST/NICMOS
J H

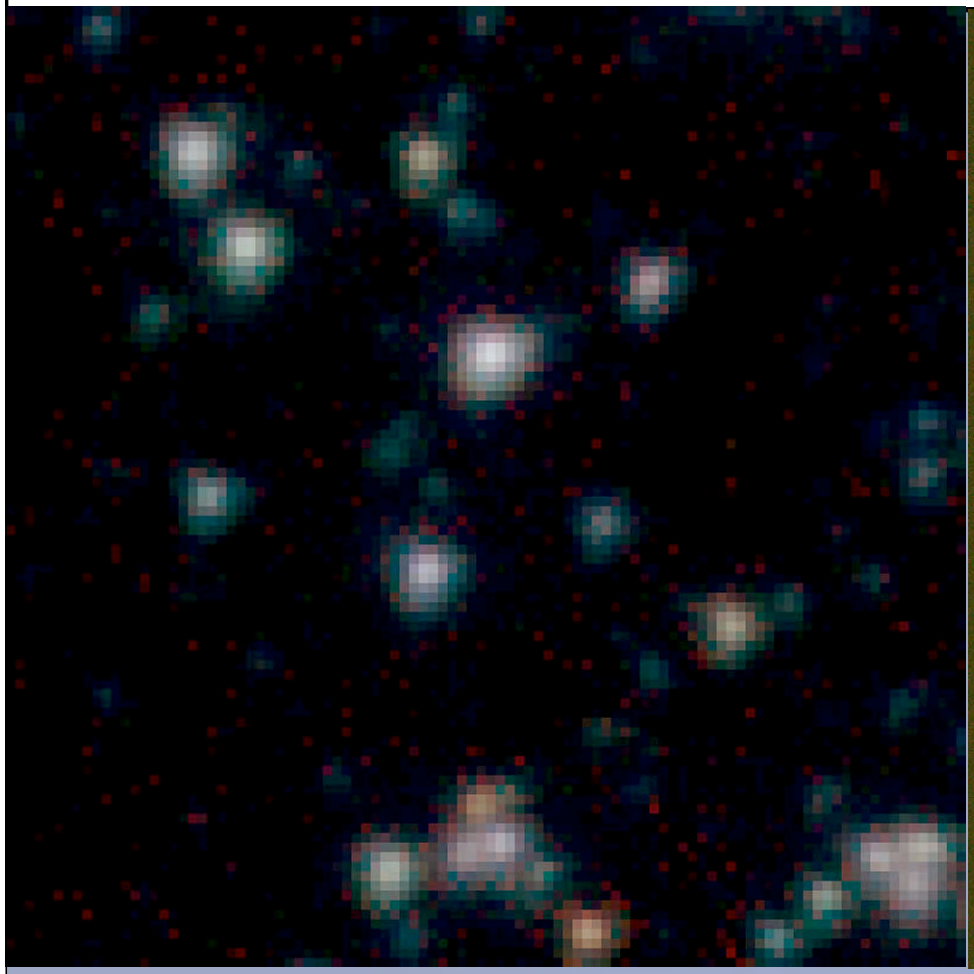


JWST/NIRCam
J H

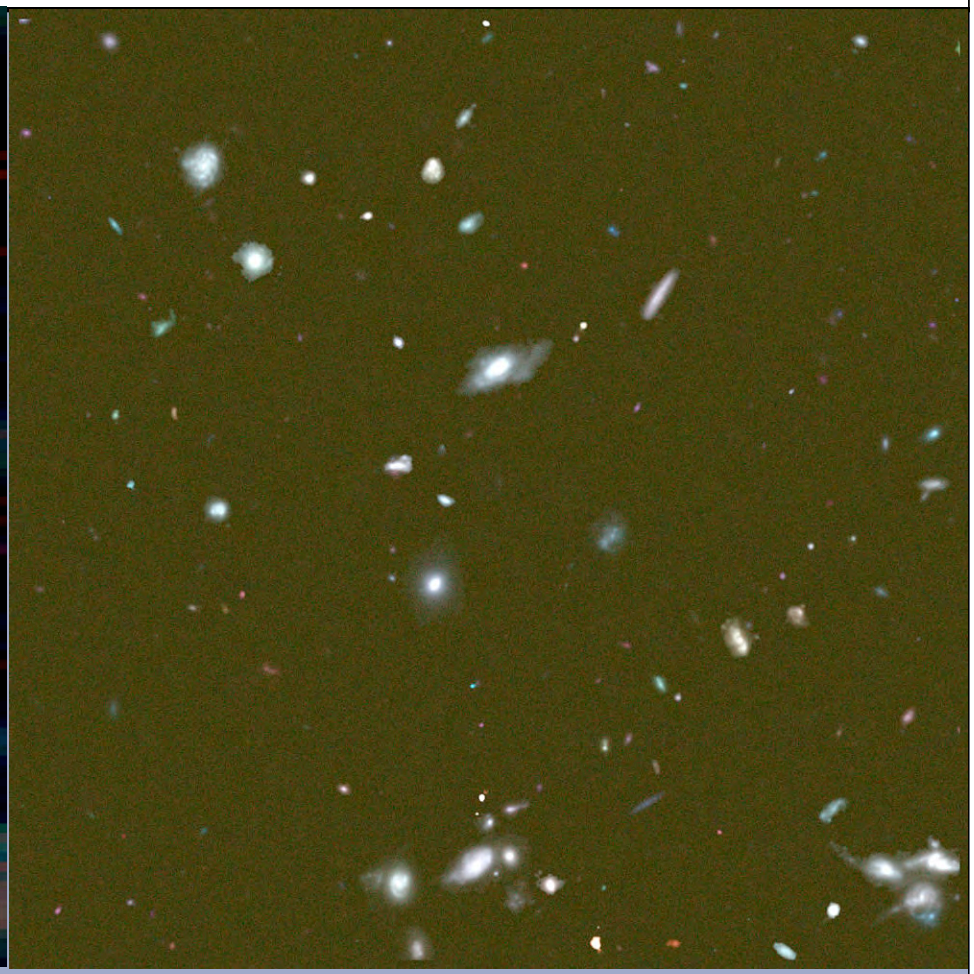
JWST–Spitzer image



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 x 10^{-19} erg cm^{-2} s^{-1} for line emission.

Expectations

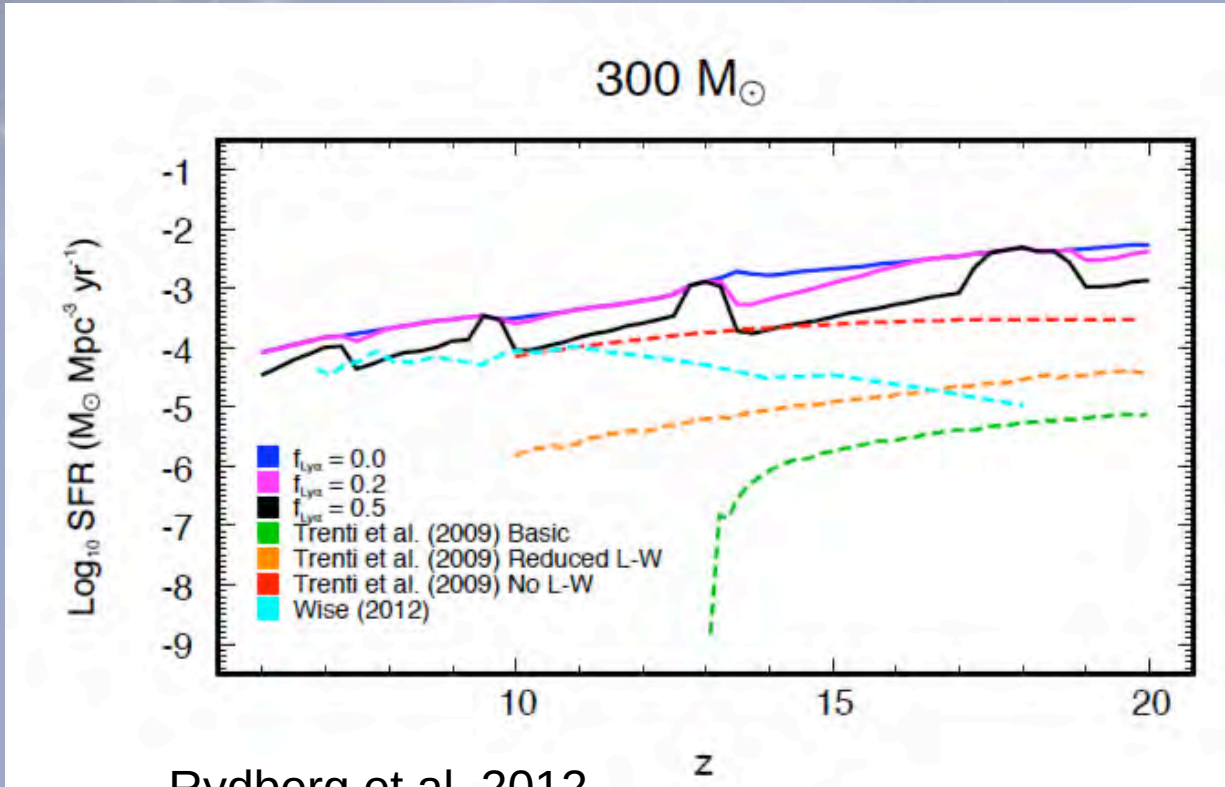
- Pop III stars are not individually detectable
- First galaxies are chemically enriched
- Pop III stars do not significantly contribute to reionization
- Pop III may indirectly help reionization by seeding ISM/IGM with metals.

First Stars

- direct unaided detection (hopeless even with JWST)
- indirect detection through fluctuations
- chemical abundance tracers
- detection of PISN supernovae
- expected contribution to reionization

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 $\Delta z=1$.

First Stars – Lensing

The probability of detecting lensed Pop III stars 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.

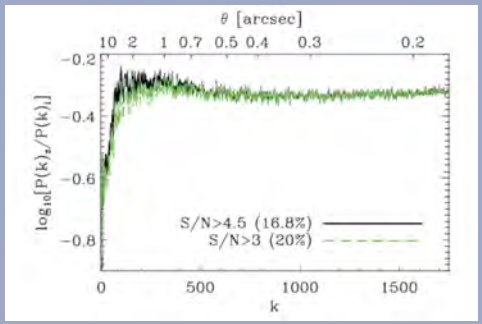
With luck we might be able to detect directly lensed Population III stars.

First Stars – 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

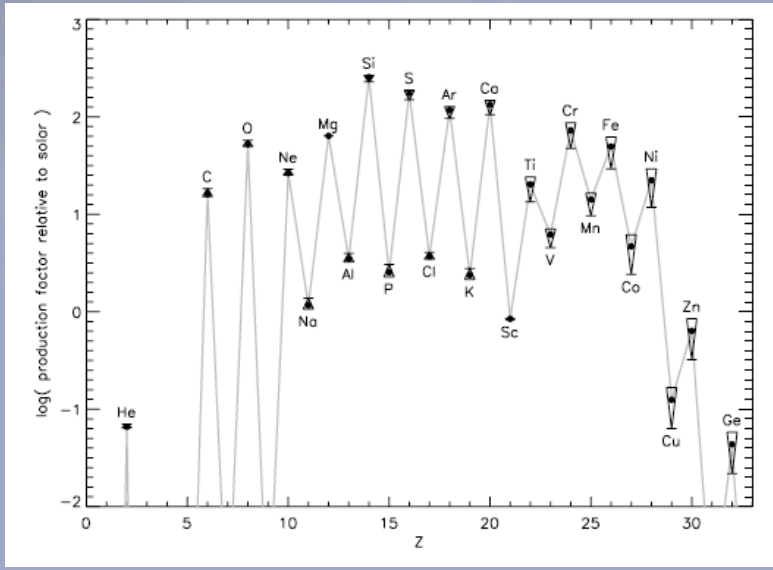


Calvi et al. 2013

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.
--> for an alternative approach see talk by G. Kulkarni

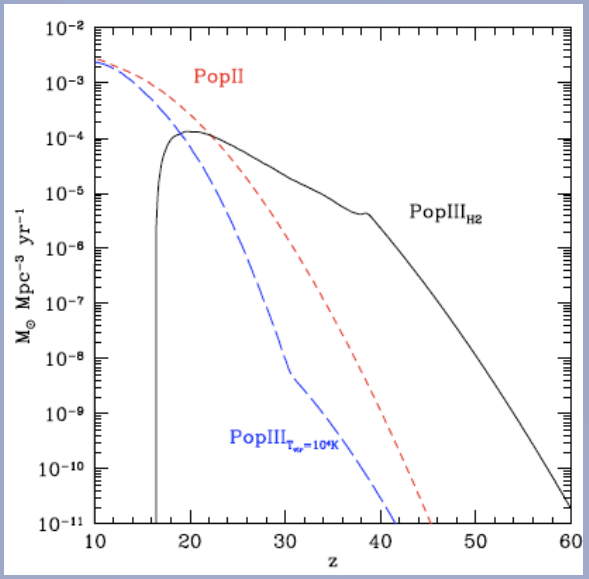
First Stars – Supernovae

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.

Note that there are stars up to 150 $M_\odot$ in the local Universe so the specific Pop III IMF likely simply affects rarity.

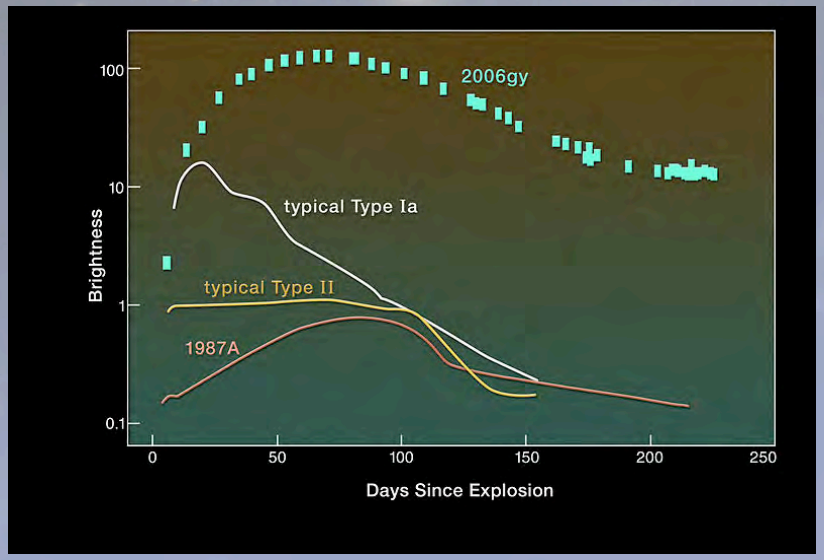
PISN Supernovae – expected rates

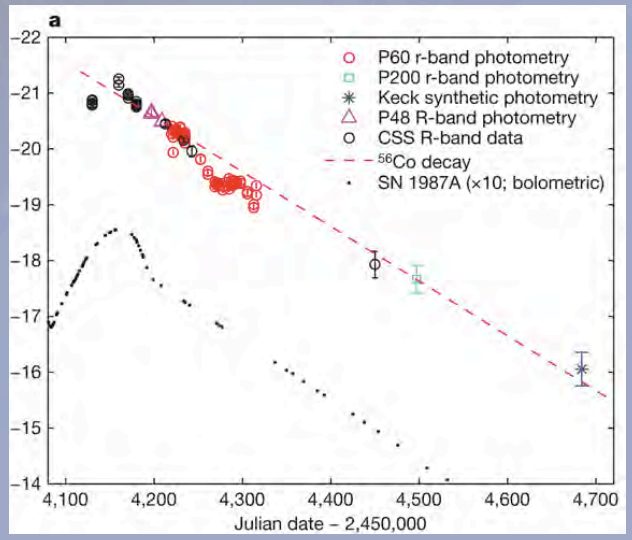
Weinmann & Lilly (2005) elaborating on previous results suggest densities of 4 deg^{-2} yr^{-1} at z~15 and 0.2 deg^{-2} yr^{-1} at z~25. The actual numbers may be lower if one considers negative feedback on mini-halos. However, SNae from atomic hydrogen cooling halos could boost up the rate. If the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

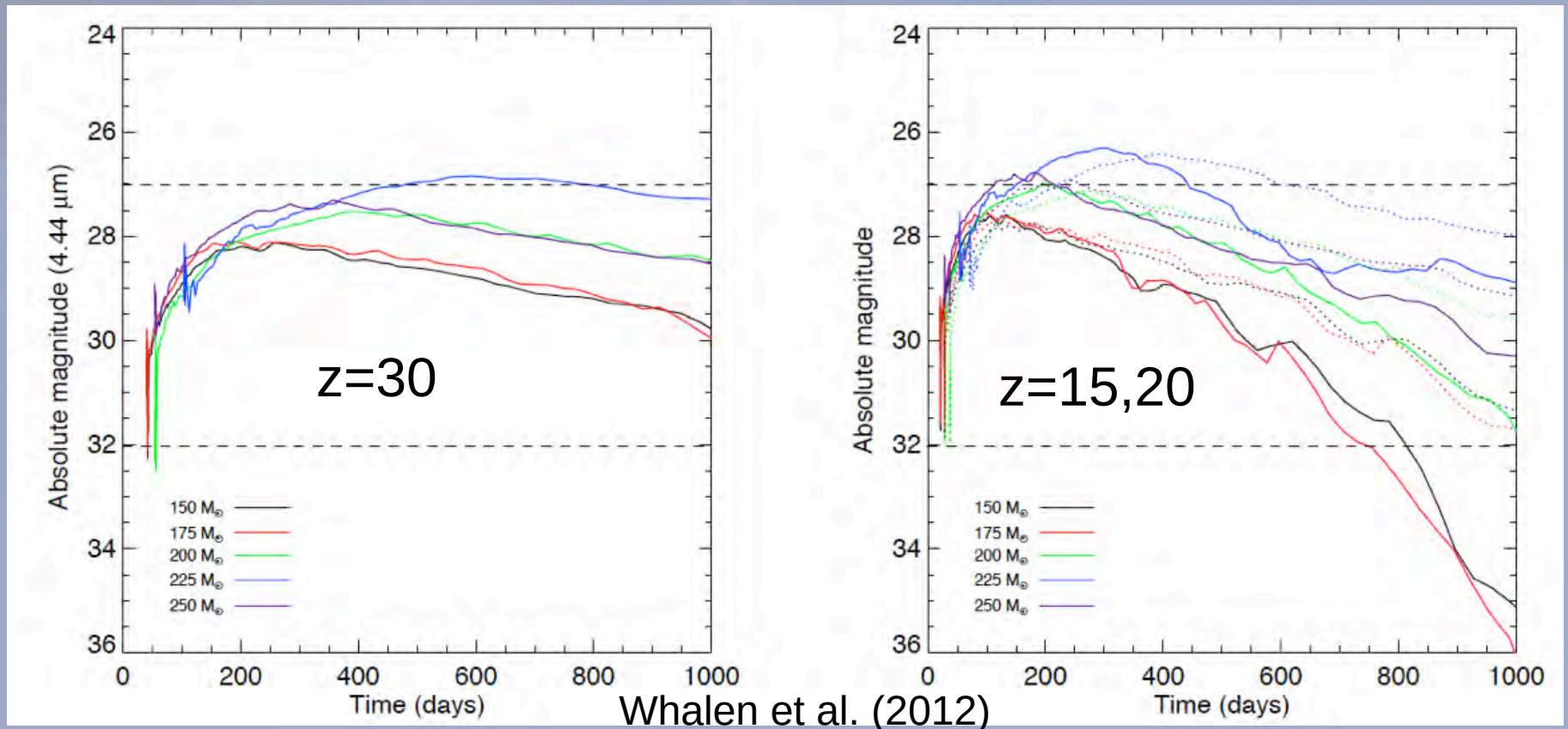




SN2006gy and 2007bi have been proposed as PISN analogs. If PISN have a light curve similar to that of 2006gy we can see that one might expect the SN to have at the peak a luminosity of AB~26-26.5 at z=10-15 and for observations at 4-5 μm. JWST/NIRCam can achieve such a depth at 4 μm with a exposures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

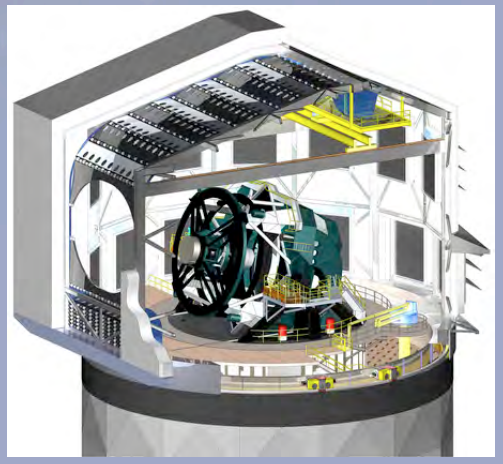
Light curves derived by Whalen et al. (2012) show that PISN should be easy to observe by JWST if we know where to look.



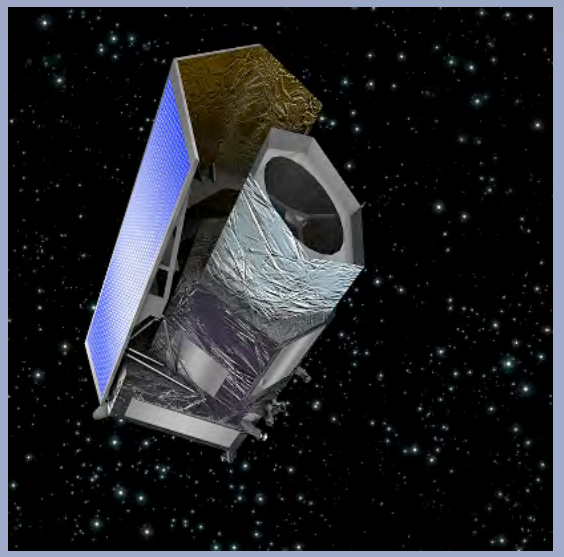
Whalen et al. (2012)

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.



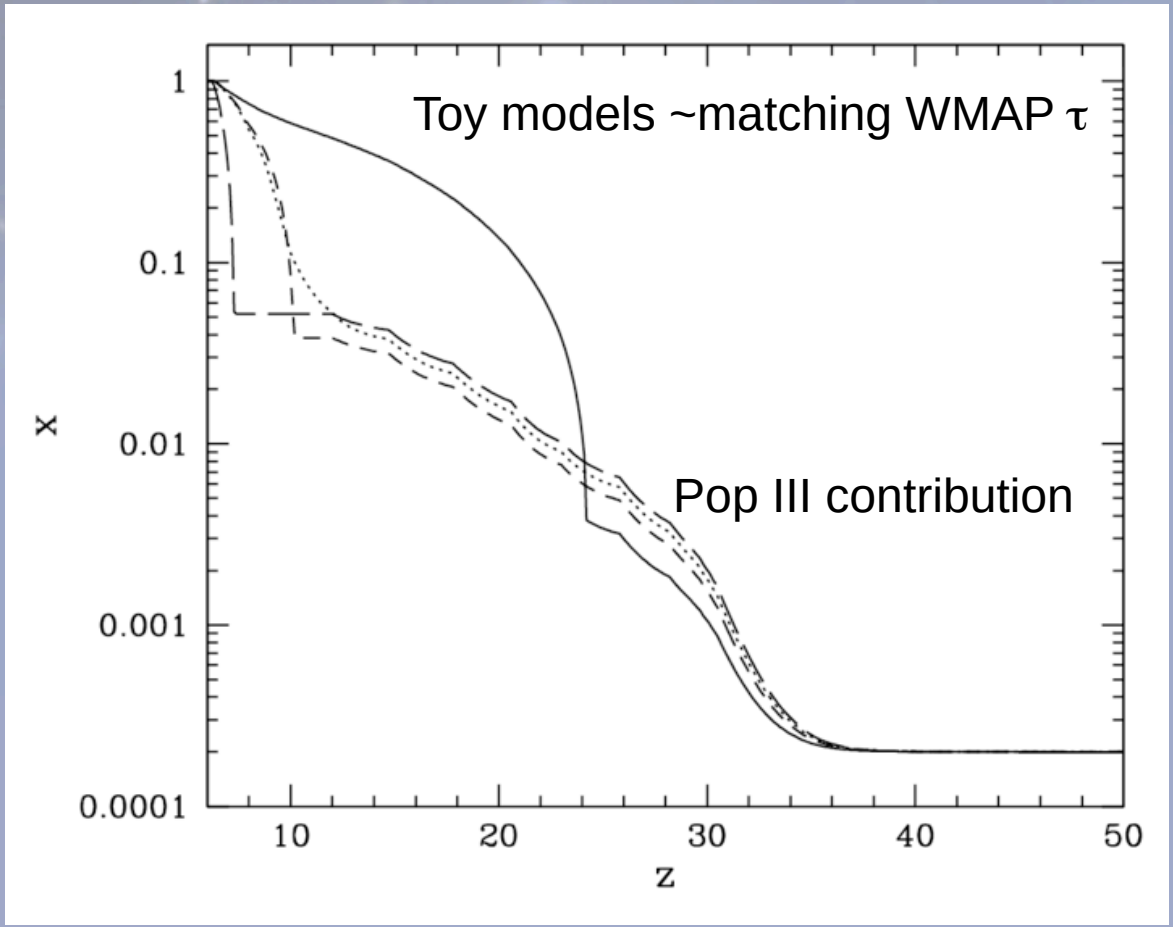
The contamination of the PISN rate with objects like 2006gy may require the spectroscopic confirmation of slowly decaying supernovae.



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).

First Stars contribution to reionization

- Estimating Population III contribution to reionization suggests only a small contribution.



Most important role of Pop III for reionization may be that of seeding IGM with metals, triggering Pop II formation.

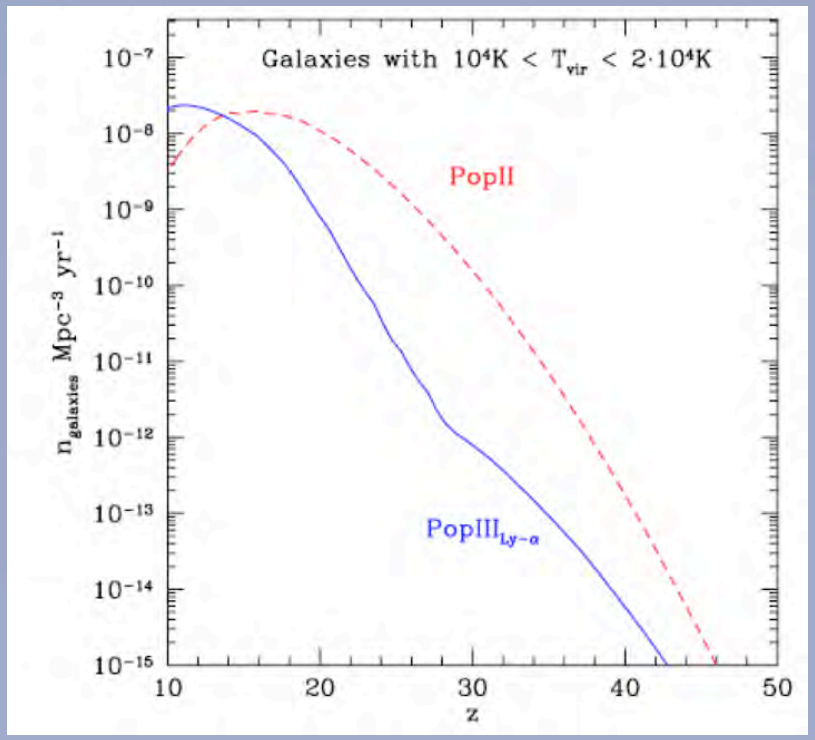
First and other Galaxies

- lensing of 10^8 M$\odot$ galaxies
- side note on the danger of over-interpreting β
- contribution to reionization
- JWST spectroscopy

Lensing of dwarf galaxies/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.

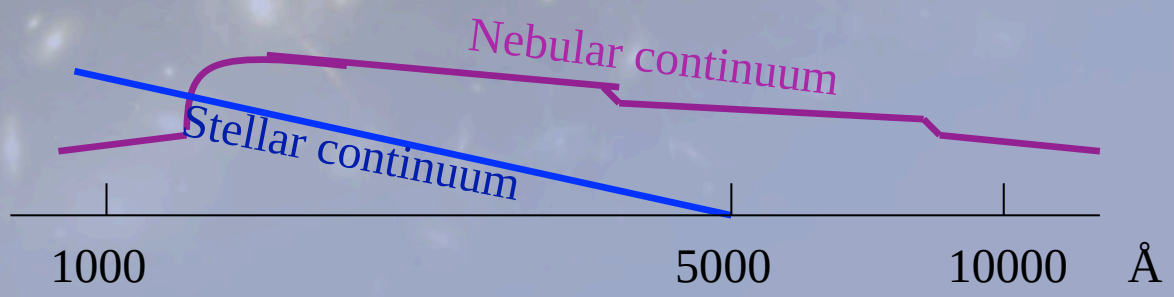
We expect 80 such objects per square arcmin per unit redshift so that the probability of lensing is not negligible. If the Lymanα escape fraction is high they may also be detectable directly at 2×10^{-18} erg cm^{-2} s^{-1}.



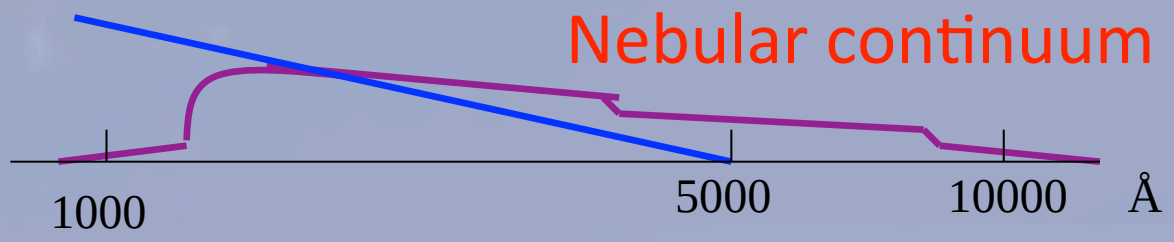
On the danger of over-interpreting data

for a Pop III with f_{esc}=0 the nebular continuum at 1400A is ~3 times the stellar SED

f_{esc}=0
No ionizing
γ escape

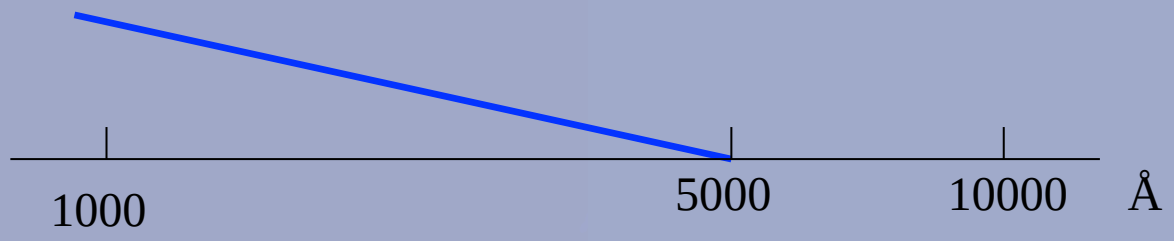


f_{esc}=0.5
Some ionizing
γ escape



Nebular continuum is red

f_{esc}=1
All ionizing
γ escape



β can constrain the stellar population only if f_{esc} is very high. Pop III HII regions with very low escape of ionizing photons will have a red continuum and mimic a more metal reach and possibly dusty system.

Only way out is spectroscopy

What is the contribution of the galaxies we see?

The galaxies we see can reionize the Universe if their metallicity is low and their UV escape fraction is high.

Redshift	10^{-3} solar, burst, C=5, 1-150M⊙	1/50 solar, Const SFR, C=5, 1-150M⊙	solar, Const SFR, C=5, 1-100M⊙
6	>0.19 >0.05	>0.63 >0.17	N/A >0.32
7	>0.37	N/A	N/A
8	>0.58	N/A	N/A
6+7+8	>0.14	>0.46	>0.86

Extrapolating to magz~30 (Calvi et al. 2013)

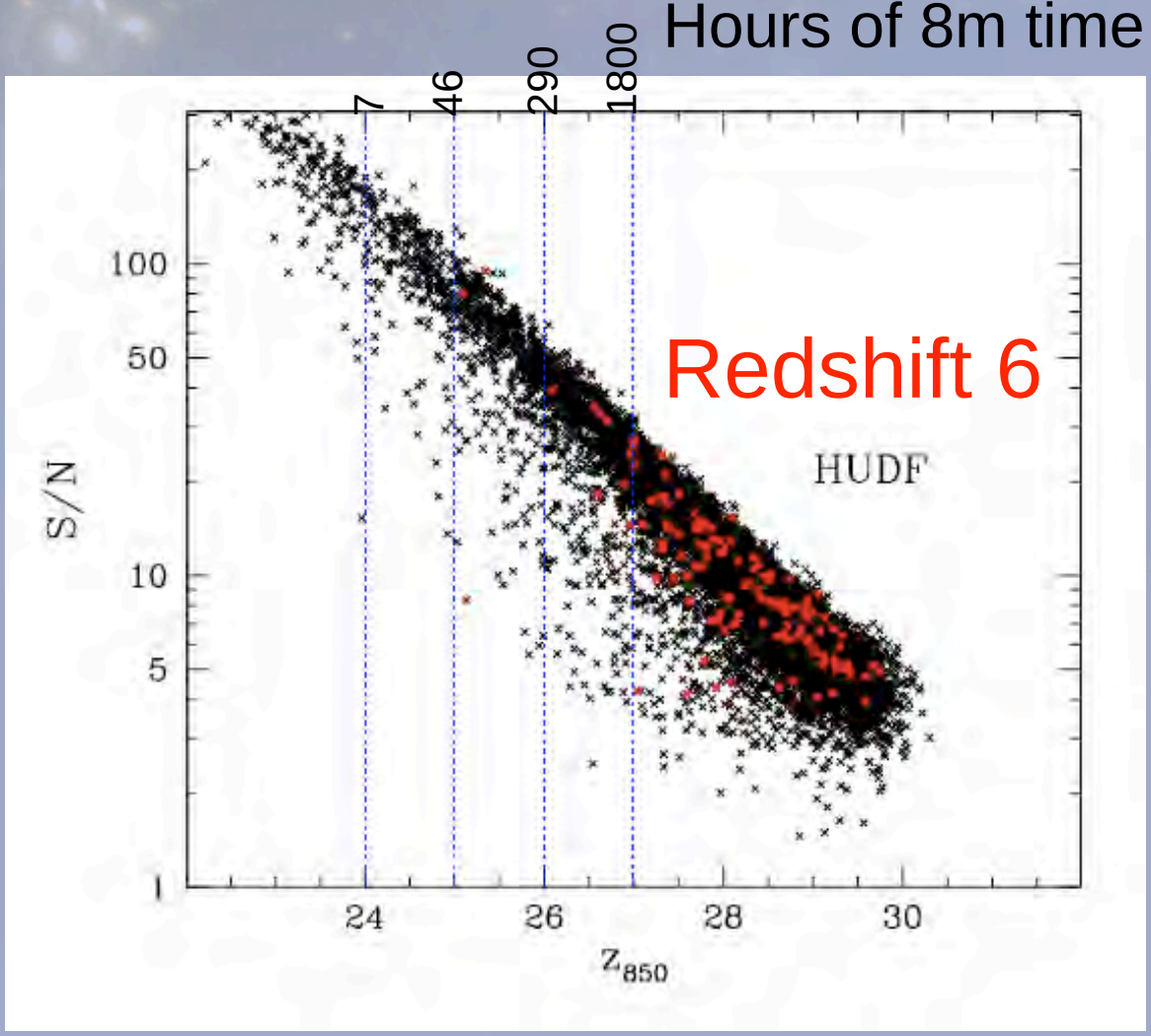
C is the clumping factor accounting for the non-uniform distribution of matter, f is the escape fraction of ionizing radiation.

>0.05

Spectroscopy is very hard

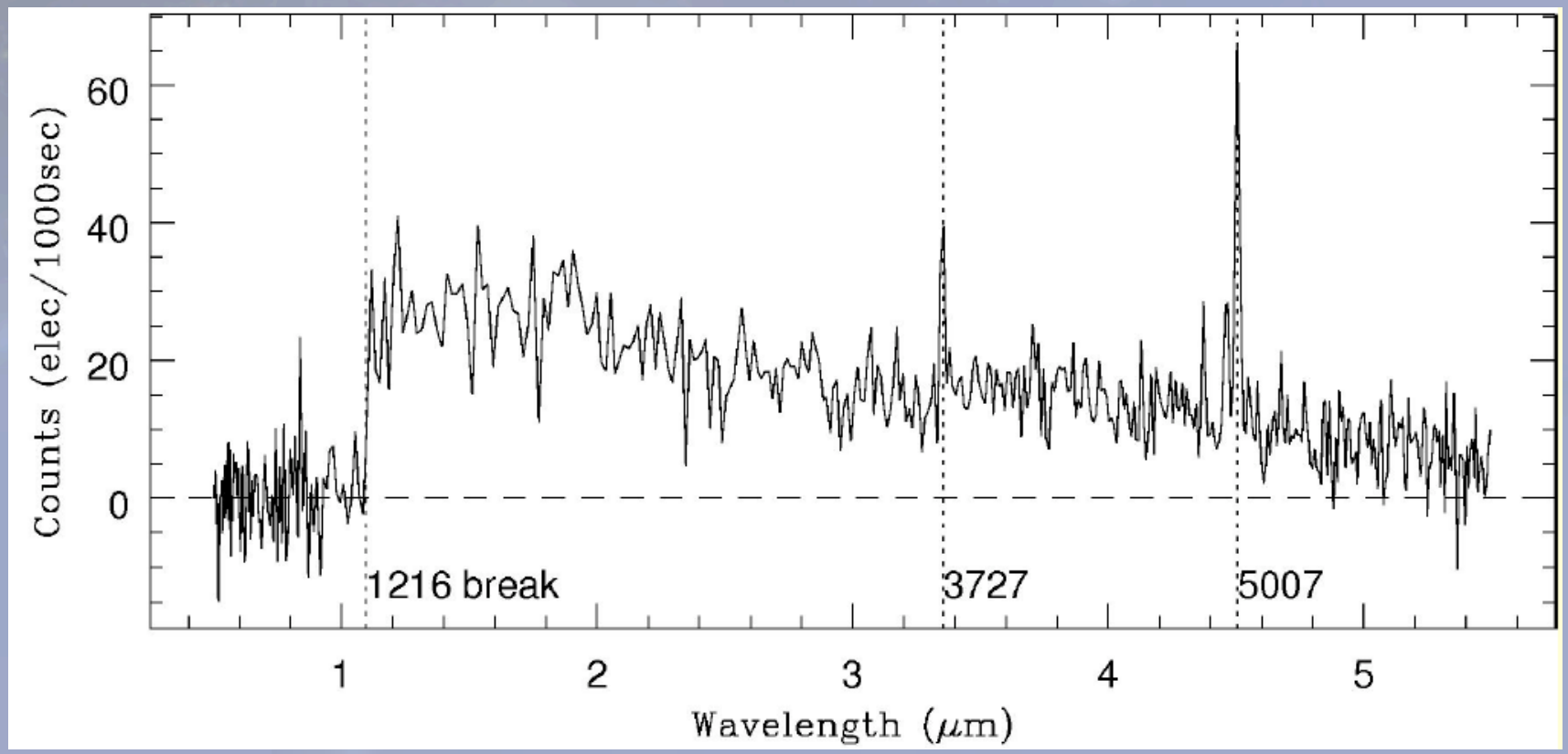
It is very hard to obtain spectra for the faintest objects in the UDF.

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

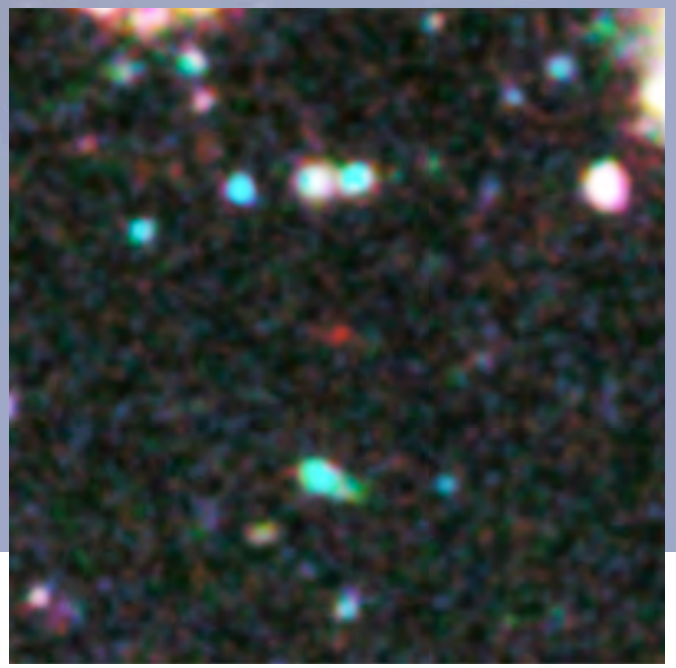
For galaxies at m_{JAB}=26, JWST can obtain high S/N spectra.

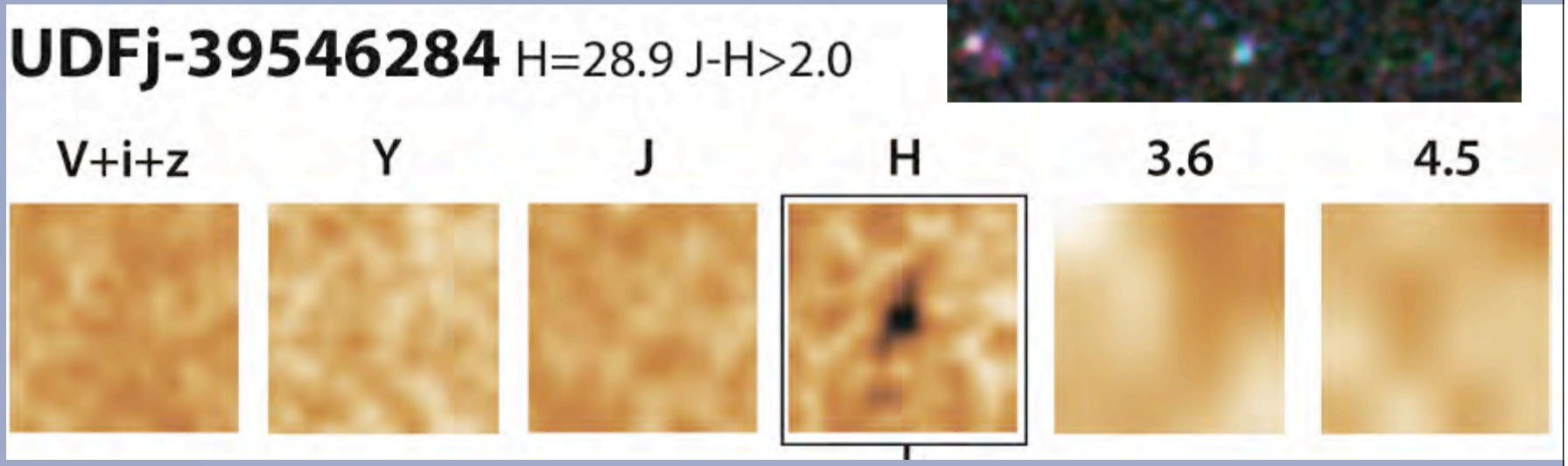


Simulation courtesy of M. Franx

One candidate at z~12

The HUDF09/HUDF12 candidate .

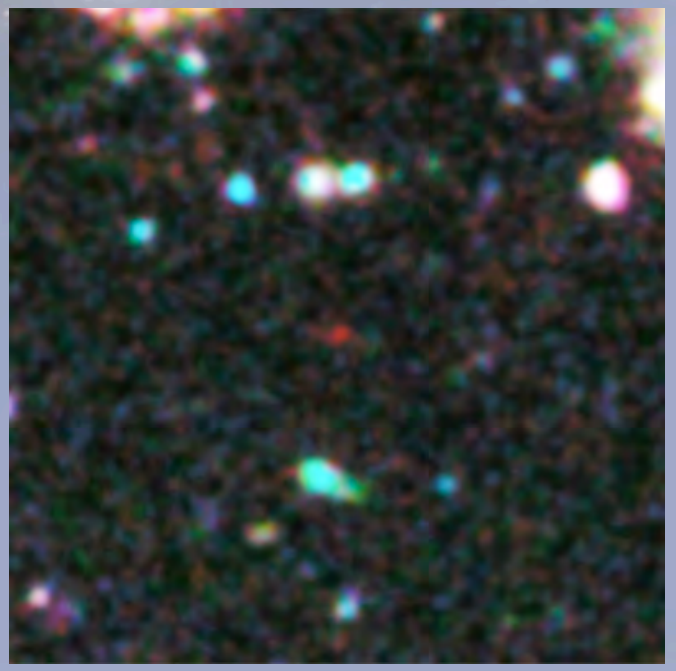




JWST Followup

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.

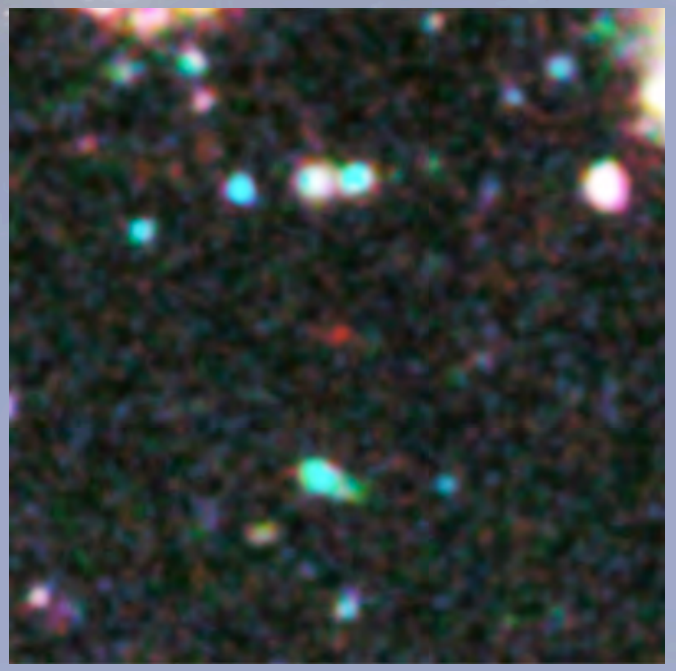


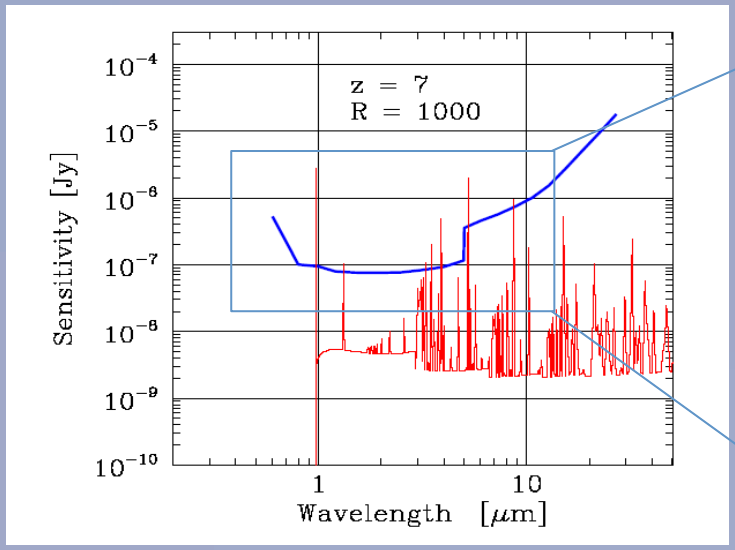
- The object is not detected by Spitzer/IRAC but JWST could detect it at 3.5micron in a parallel exposure to the H band one (at no extra “cost”).
- With an investment of 30,000s one could obtain a good photometric redshift for this object.
- A low resolution spectrum would take 100,000s.

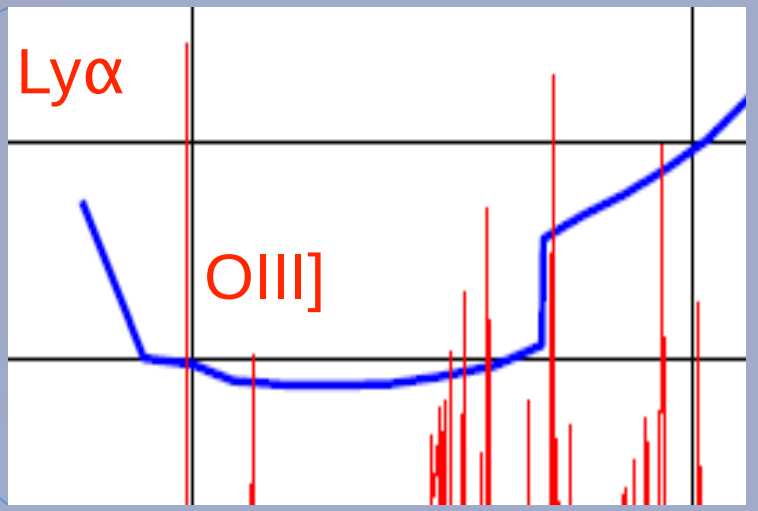
Physical properties

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.







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.

JWST will be able to characterize the physical properties of the galaxies responsible for reionization.

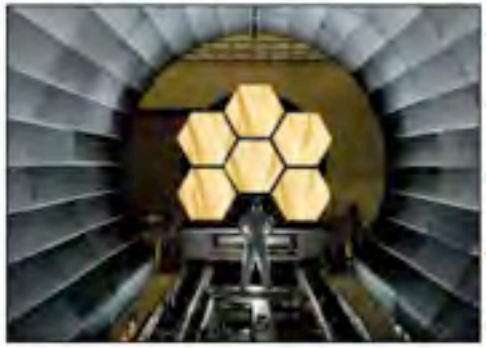
JWST Status

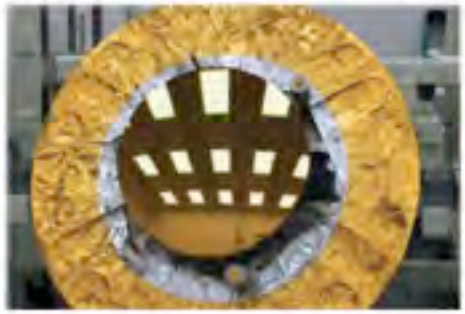
Project is doing well.

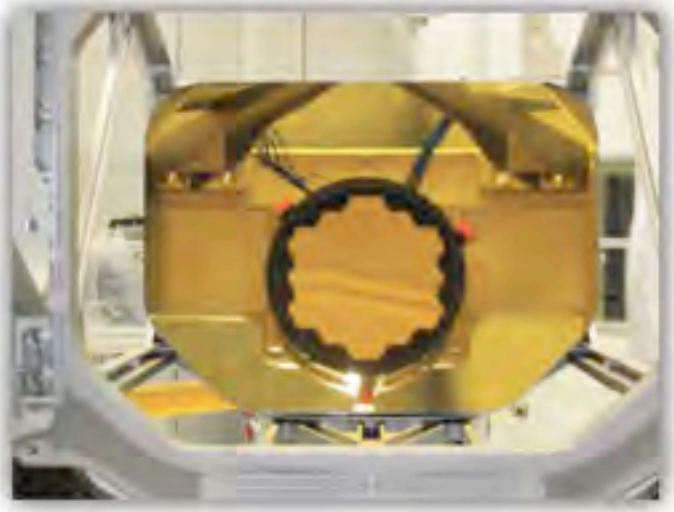
Funding and schedule reserves have been adequate to meet the challenges encountered so far.

Major risk would be funding uncertainty.

All Mirrors Are Complete!





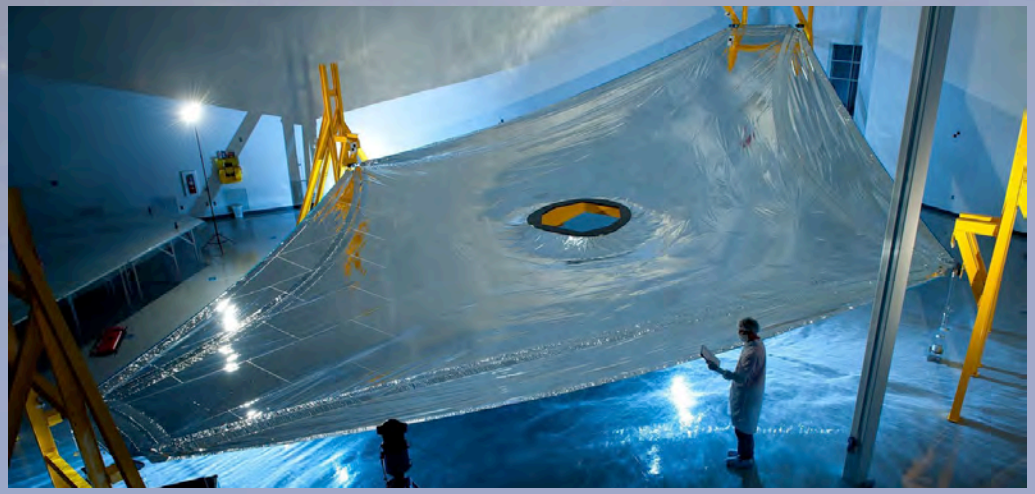


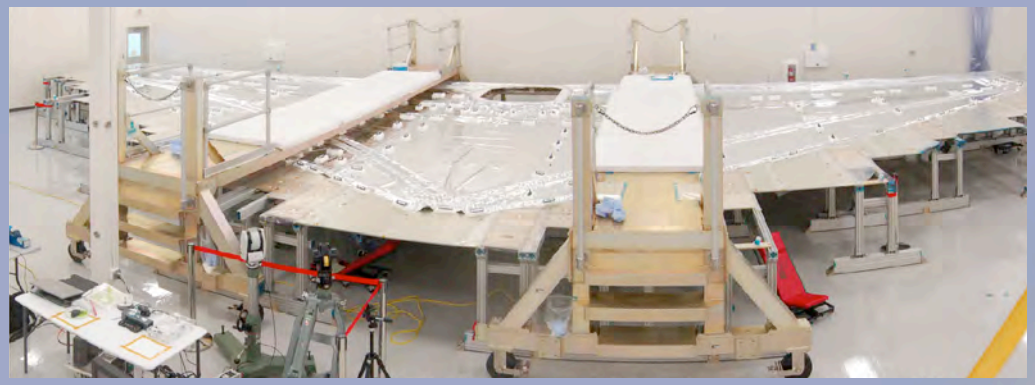
Status of Major Hardware

Sunshield

Template layers 2-5 completed and delivered.

Template layer 1 shape test and hole punching completed and to be delivered to NGAS soon.





Status of Major Hardware

ISIM

ISIM Structure – Completed

ISIM Command and Data Handling System (ICDH) – Completed

ISIM Remote Services Unit (IRSU) – Completed

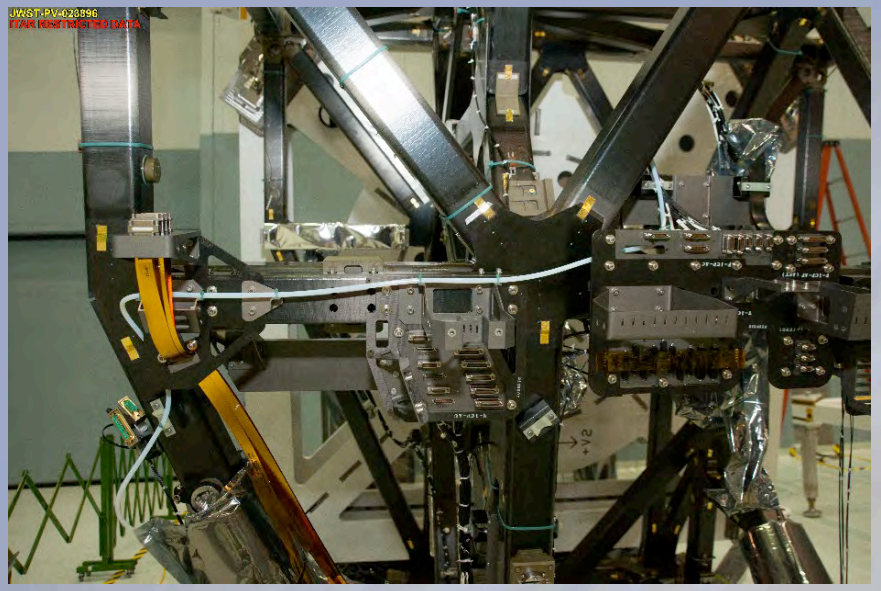
ISIM Electronics Compartment (IEC) – Completed

ISIM Flight Software System Build 12.82 for CV1-RR – Completed

ISIM Harness – 99% .. Finishing up final few harnesses (not required for CV1-RR)

ISIM Harness Radiator – Delivered to I&T on 6/12

On-Board Scripts System (OSS) – Completed for CV1-RR



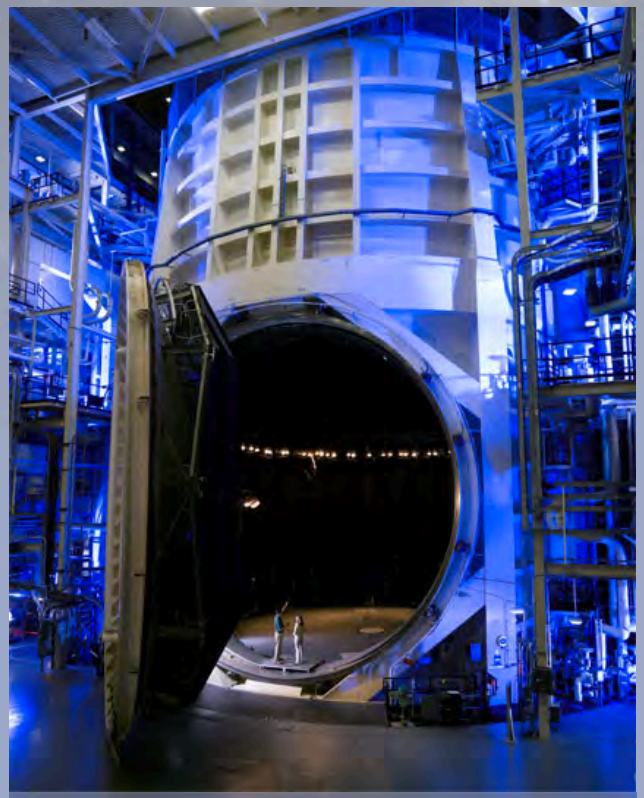
Status of Major Hardware

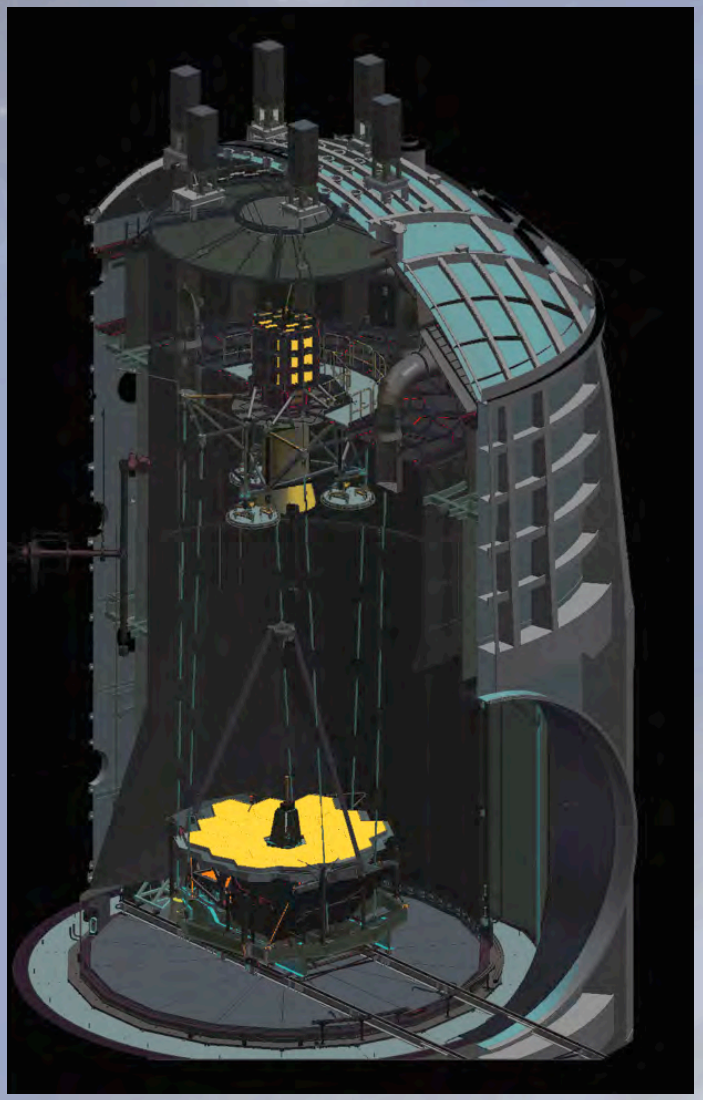
Spacecraft

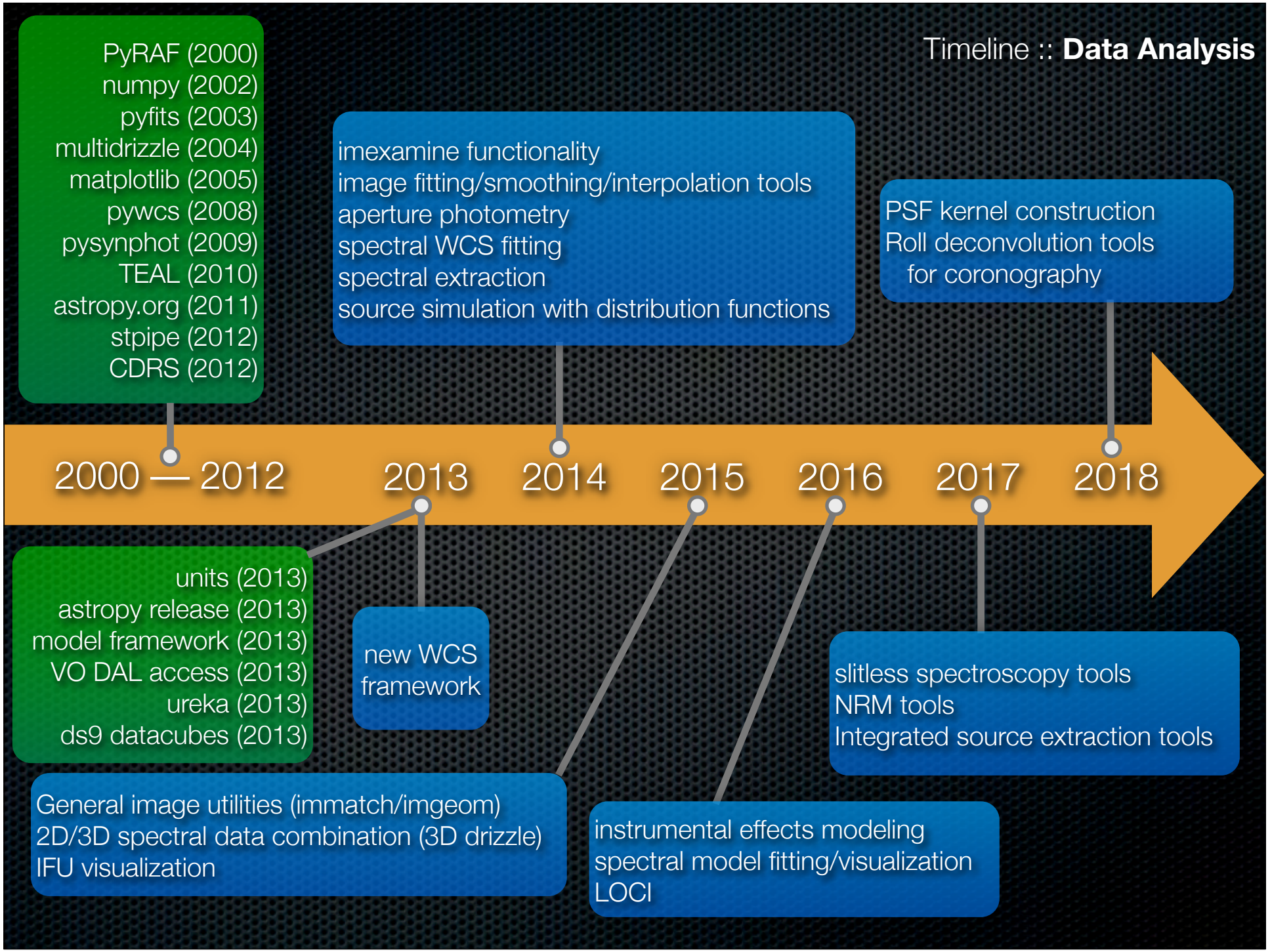
7 key reviews completed leading to S/C CDR

Spacecraft Mockup with Units for I&T Trades

Optical End-to-End test @ JSC






Timeline :: **Data Analysis**
PyRAF (2000)
numpy (2002)
pyfits (2003)
multidrizzle (2004)
matplotlib (2005)
pywcs (2008)
pysynphot (2009)
TEAL (2010)
astropy.org (2011)
stpipe (2012)
CDRS (2012)
imexamine functionality
image fitting/smoothing/interpolation tools
aperture photometry
spectral WCS fitting
spectral extraction
source simulation with distribution functions
PSF kernel construction
Roll deconvolution tools
for coronography
2000 — 2012
2013
2014
2015
2016
2017
2018
units (2013)
astropy release (2013)
model framework (2013)
VO DAL access (2013)
ureka (2013)
ds9 datacubes (2013)
new WCS framework
slitless spectroscopy tools
NRM tools
Integrated source extraction tools
General image utilities (immatch/imgeom)
2D/3D spectral data combination (3D drizzle)
IFU visualization
instrumental effects modeling
spectral model fitting/visualization
LOCI

Fiscal 2013 Milestones

Month	Milestone	Comment
Oct-12	1. Headquarters delivery to project of funding plan for fiscal 2013	1. Completed 9/15
	2. Spacecraft batteries preliminary design review	2. Completed 9/6
	3. Spacecraft command & telemetry computer review (Northrop internal review)	3. Completed 8/30
	4. Second review of optical test equipment for Johnson Space Center (JSC) thermal vacuum chamber test of telescope and instruments (OTIS)	4. Completed 10/17
	5. Spacecraft-to-Optical Telescope Element/science instruments stray light and thermal barrier structures preliminary design review	5. Completed 10/18
Nov-12	6. Port side spacecraft equipment panel design review (Northrop internal review)	6. Completed 10/4
	7. Complete electrical checkout of combined mid-infrared instrument (MIRI) and integrated science instrument module (ISIM)	7. Completed 11/19, 2 days of testing required in Jan. due to FSW bug (divide by zero)
	8. First engineering model of the spacecraft command and telemetry computer delivered to test bed	8. Completed 11/8
Dec-12	9. Reinstall beam image analyzer onto telescope simulator (OSIM) used in ISIM cryogenic testing	9. Completed 12/19
	10. Complete electrical checkout of combined fine guidance sensor (FGS) and ISIM	10. Completed 12/20
	11. Aft optical system complete	11. Completed 1/10
	12. Receive JWST carrier container to be used in moving the observatory to testing and launch sites	12. Completed 11/16
Jan-13	13. System design review of the software employed in managing all the data returned from the spacecraft to the operations center	13. Completed 12/6
	14. Deliver MIRI cover/thermal shield to ISIM integration and test (I&T)	14. Delivered to ISIM I&T 4/19
	15. Secondary Mirror Support Structure I&T tooling fixture complete	15. Completed 2/27
	16. Primary mirror backplane support wing assemblies complete	16. Completed 2/19
Feb-13	17. Spacecraft Primary Structure Manufacturing Readiness Review	17. Completed 1/28
	18. Start cryogenic certification test of OSIM	18. Completed 2/14 – delayed by Global Propagation Measurement exit from SES Chamber
	20. Deliver last primary mirror actuator motor electronics unit (Cryo Multiplex Unit)	20. Units completed, ship date is 4/26
	21. Spacecraft fine sun sensor critical design review	21. Completed 1/15
Mar-13	22. Space Vehicle Thermal Simulator systems requirements review	22. Completed 1/23
	23. Complete FGS & MIRI integration onto ISIM	23. MIRI installed 4/29 (accommodating April delivery of heat shield), FGS installed in February

Fiscal 2013 Milestones

Month	Milestone	Comment
Apr-13	24. Sunshield Template Membrane Layer #2 fabrication complete	24. Completed 4/13
	25. Spacecraft-to-ground communications subsystem critical design review	25. Completed 3/12
	26. Software build v 1.1 for the system that senses and controls Webb's active mirrors	26. Completed 2/13
May-13	27. Telescope primary mirror backplane support fixture (BSF) assembly complete (holds ISIM, primary mirror and spacecraft together for launch)	27. Completed 5/6
Jun-13	28. Spacecraft thermal control system critical design review	28. Completed 5/15
	29. Spacecraft wiring critical design review	29. Moved to July to complete actions from design review
	30. Rods that suspend telescope and instruments from ceiling of JSC thermal vacuum chamber for testing complete	30. Completed 5/21
	31. Start first ISIM cryogenic test (risk reduction activity)	31. Moved to July 2013 – delayed by optical Phase Diversity Measurement unit from SSS Chamber
Jul-13	32. MIRI detector cooling attachment (flight Cold Head Assembly) delivered to GSFC [delayed fiscal 2012 milestone]	32. Moved to November, latched issues; 3 months margin remains for CV2
	33. Spacecraft flight software build 2.1 test readiness review	
Aug-13	35. Latest acceptable date of Near Infrared Camera (NIRCam) into ISIM integration and test flow for inclusion in second ISIM cryogenic test	
	36. BSF/ Primary mirror backplane center section integration complete	
Sep-13	37. Latest acceptable arrival of Flight Near Infrared Spectrograph (NIRSpec) for inclusion in second ISIM cryogenic test	
	38. Sunshield membrane cover manufacturing readiness review	
	39. Completion of studies and trades for mission mass margin in preparation of spacecraft critical design review	
	40. Complete first ISIM cryogenic test	
	41. JSC thermal vacuum chamber frame that holds test equipment suspended above the JWST mirror and instruments ready for painting	

The JWST Corner

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James Webb Space Telescope
The JWST Corner

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The James Webb Space Telescope (JWST) is currently under construction, and will be launched in 2018. JWST is a cryogenic telescope with a 6.5-meter primary mirror and has four science instruments that offer sensitivity from 0.6 to 28.5 microns. The telescope will be diffraction limited at 2 microns, 4 microns, and 7+ microns. The instruments contain 40 imaging filters (pixel scale down to 0.032"), 8 spectroscopic modes (wide field grism, single object, IFU, multiobject), and 7 coronographs. More information on the JWST science instruments, telescope sensitivity and the exposure time calculator is available on the links listed below.

Science Instruments
Sensitivity
Exposure Time Calculator

On this page, we are collecting input related to the growing scientific case for JWST, as referenced in peer-review journals or conference proceedings. If you have recently submitted or published a research paper that discussed JWST's future role for the respective science case, please consider submitting this information to STScI. This information will be released to the community in the form of electronic newsletters and at the AAS meeting.

Required Information

First Author's Name (first and last)	
First Author's e-mail	
First Author's Affiliation	
Co-author Names (or "none")	