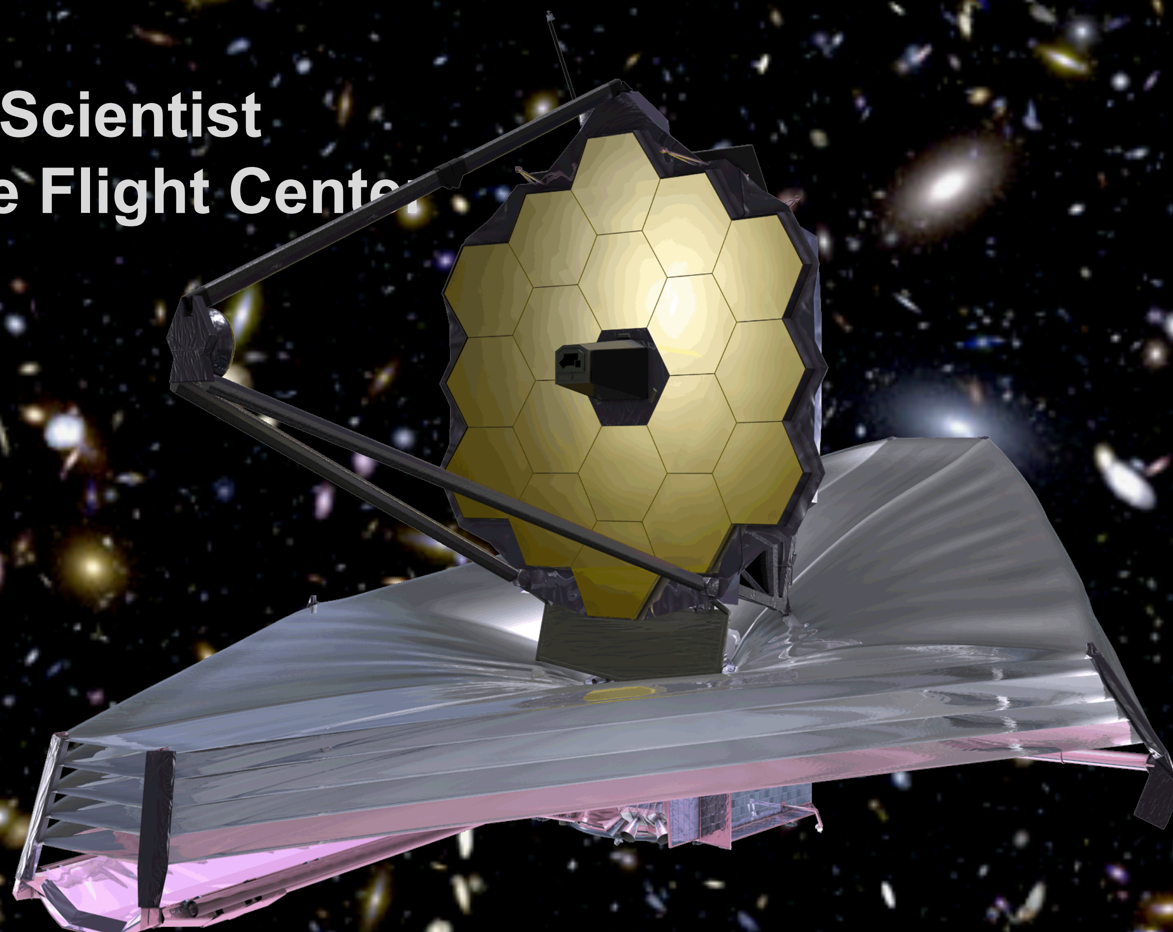
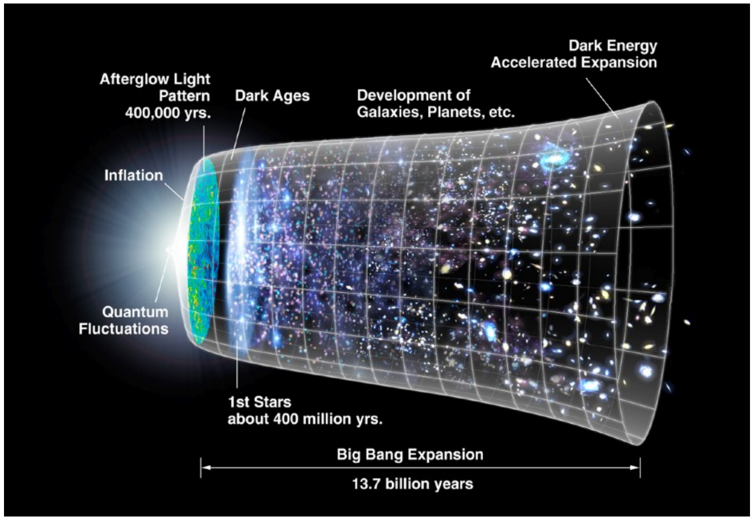
The James Webb Space Telescope Mission

First Stars and Galaxies

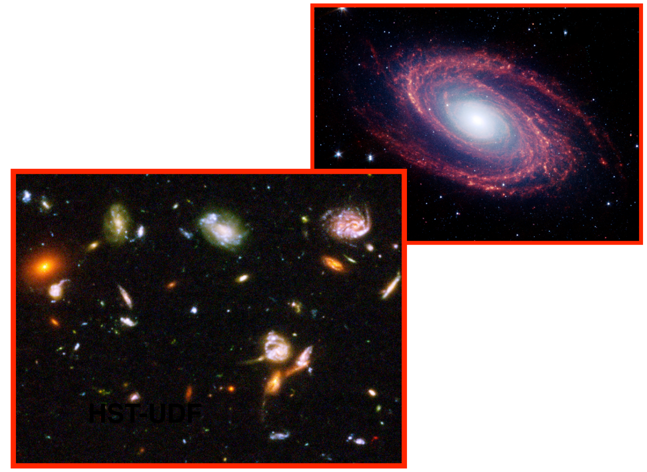
John Mather
JWST Senior Project Scientist
NASA Goddard Space Flight Cente
Mar. 8, 2010



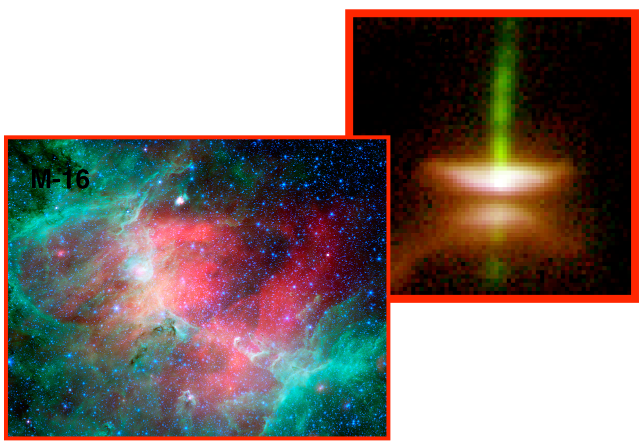
JWST Science



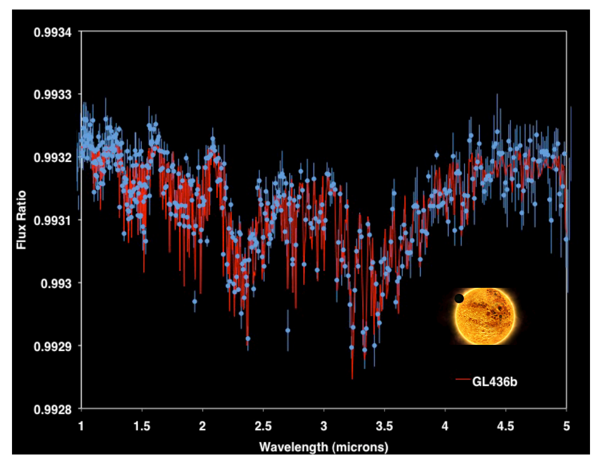
First Light and Reionization



Assembly of Galaxies

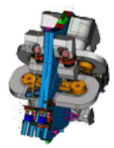
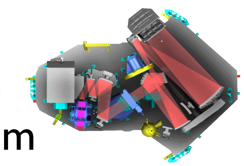
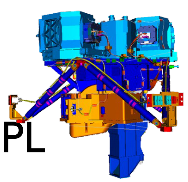
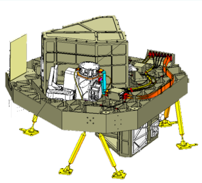


Birth of stars and
proto-planetary systems



Planetary systems and the
origin of life

JWST Instrumentation

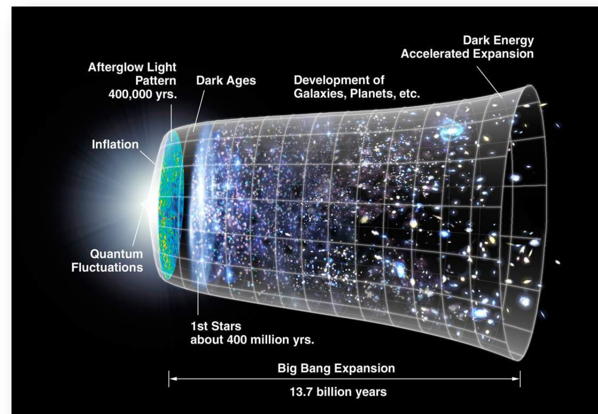
Instrument	Science Requirement	Capability
NIRCam Univ. Az/LMATC 	Wide field, deep imaging › 0.6 µm - 2.3 µm (SW) › 2.4 µm - 5.0 µm (LW)	Two 2.2’ x 2.2’ SW Two 2.2’ x 2.2’ LW Coronagraph
NIRSpec ESA/Astrium 	Multi-object spectroscopy › 0.6 µm - 5.0 µm	9.7 Sq arcmin Ω + IFU + slits MSA: 100 selectable targets R=100, 1000, 3000
MIRI ESA/UKATC/JPL 	Mid-infrared imaging › 5 µm - 27 µm Mid-infrared spectroscopy › 4.9 µm - 28.8 µm	1.9’ x1.4’ with coronagraph 3.7”x3.7” – 7.1”x7.7” IFU R=3000 - 2250
FGS/TFI CSA 	Fine Guidance Sensor 0.8 µm - 5.0 µm Tunable Filter Imager › 1.6 µm - 4.9 µm	Two 2.3’ x 2.3’ 2.2’ x 2.2’ R=100 with coronagraph

First Light and Re-Ionization

- **First Light and Reionization: .... to identify the first luminous sources to form and to determine the ionization history of the early universe**

- **First light**
  - Typical first light is defined as the appearance of the first galaxies or super-star clusters (associations of stars with 10^7-10^8 $L_\odot$)

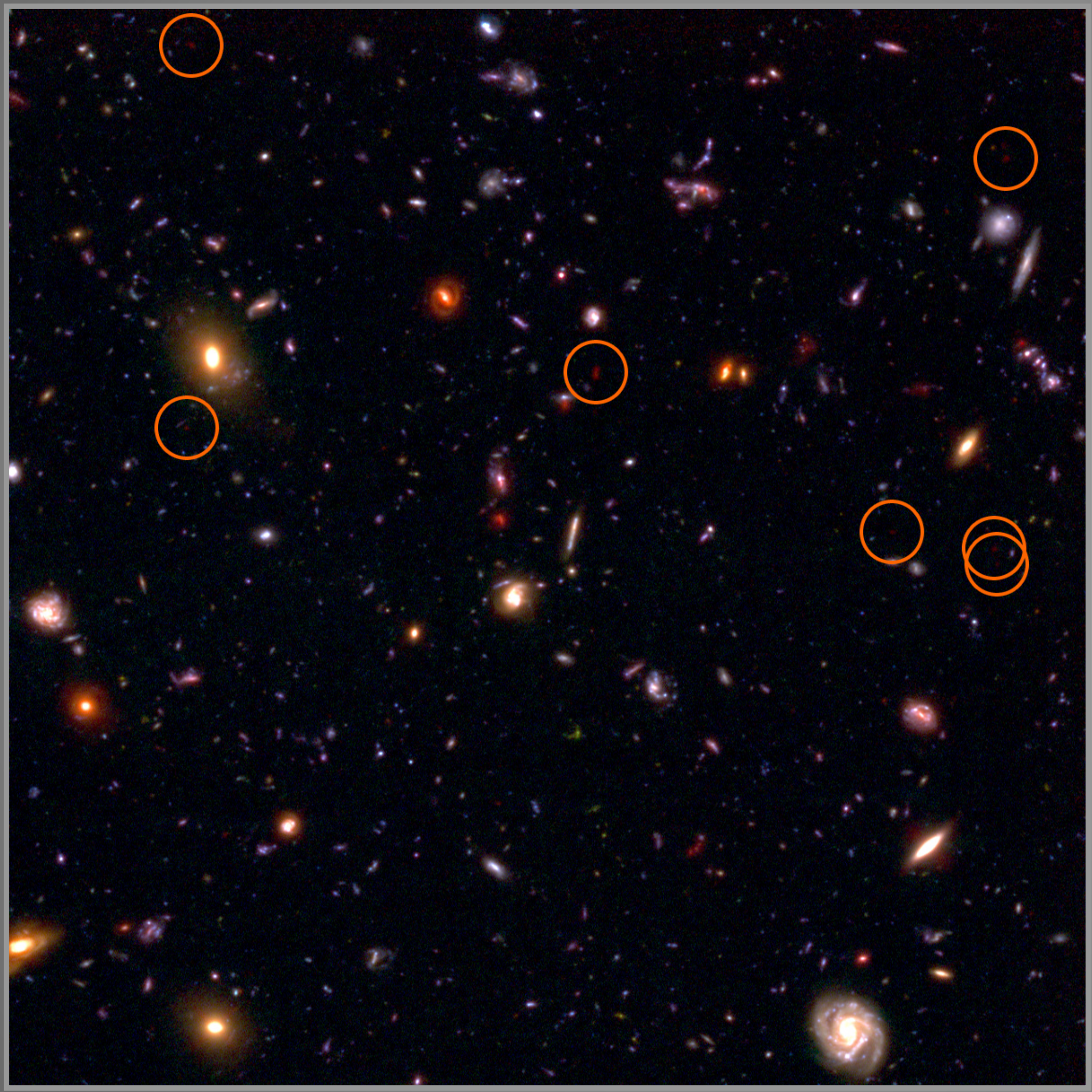
- **How do we know we have seen first light**
  - **Luminosity function (LF) evolution**: Models predict that the LF should evolve significantly for the first galaxies
  - **Metallicity**: First light galaxies should have lower metallicity than other objects
  - **Absence of older stellar populations**: First light galaxies should not have older stellar populations.



Redshift z	AB mag.	Fν (nJy)	Lyman Break wavelength
10	30.3	2.8	1.34 μm
15	30.9	1.6	1.95 μm
20	31.3	1.1	2.55 μm

Predicted sensitivity requirements to detect a change in LF slope, L_* and a change in the number density of objects (JWST Science Working Group paper on First Light)

HUDF: 40 hrs with WFC3 in August 2009



New objects found at z~8 (z-band dropouts)

> 15 papers submitted to astro-ph on these data since 9/9/09

WFC3/IR F105W + F125W + F160W

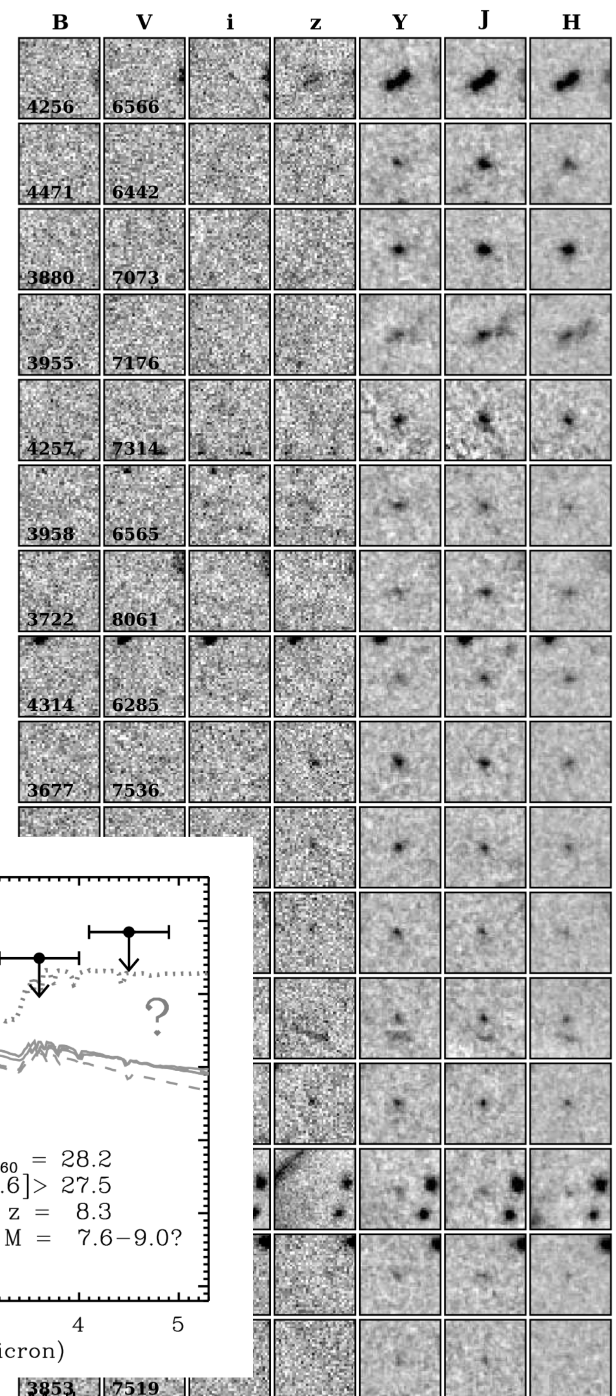
ACS F814W + F850LP

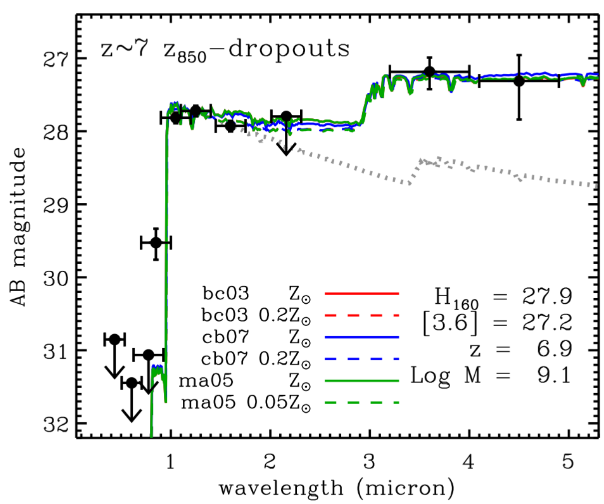
ACS F435W + F606W

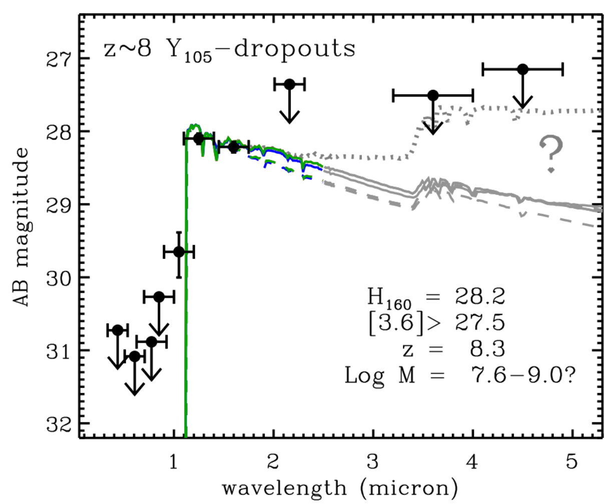
Courtesy of the HUDF09 team: Garth Illingworth (PI), Marcella Carollo, Rychard Bouwens, Marijn Franx, Ivo Labbe, Dan Magee, Pascal Oesch, Massimo Stiavelli, Michele Trenti, Pieter van Dokkum

z = 8 galaxies found in new HST/WFC3 images of HUDF

- **40 hours of observations in late August '09**
  - 5σ detections at Y ~27.5 mag
- **Vastly superior IR sensitivity (20-30X) over previous HST instruments**
- **Redshift from z-band (850 nm) and Y-band (1μm) dropouts (Oesch et al 2009, Bouwens et al 2009, Labbe et al 2009)**
- **JWST will provide a similar sensitivity gain over WFC3**







First Light: Measurements

- **First Light science drives the JWST sensitivity budget**

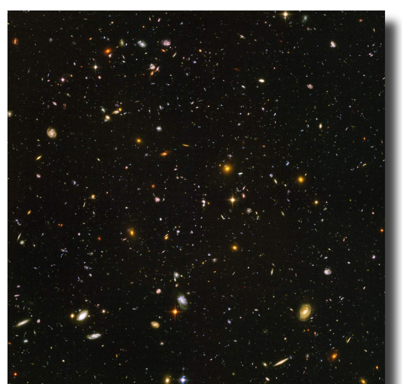
- **JWST measurements for the end of the dark ages theme**

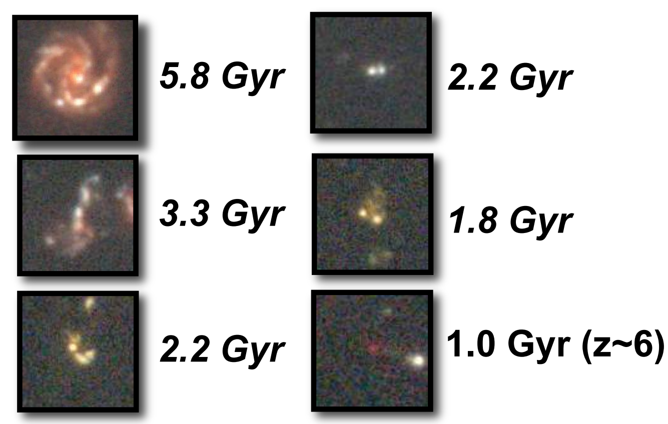
Observation	Primary Instrument	Depth, Mode	Target Density
Ultra-deep survey (UDS)	NIRCam	1.4 nJy @ 2 μm	10 arcmin^2
In depth source study	NIRSpec MIRI	23 nJy, R=100 23 nJy @ 5.6 μm	Galaxies in UDS area
Lyman α forest diagnostics	NIRSpec	2x10^{19} erg cm^{-2}s-^{1,} R~1000	Bright z>7 QSO or galaxy
Survey for Lyman α sources	FGS-TF	2x10^{-19} erg cm^{-2}s^{-1}, R~100	4 arcmin^2 (containing known high-z object)
Transition in Ly α/Balmer	NIRSpec	2x10^{-19} erg cm^{-2}s^{-1}, R~1000	UDS or wider survey area
Measure ionizing continuum	NIRSpec	2x10^{-19} erg cm^{-2}s^{-1}, R~1000	UDS or wider survey area
Ionization source nature	NIRSPec MIRI	2x10^{-19} erg cm^{-2}s^{-1}, R~1000 23 nJy@ 5.6 μm	UDS or wider survey area
Luminosity Function of dwarf galaxies	NIRCam	1.4 nJy @ 2 μm	UDS data

Assembly of Galaxies

- **Assembly of Galaxies:** Determine how galaxies and the dark matter, gas, stars, metals, morphological structures, and active nuclei within them evolved from the epoch of reionization to the present day.
  - Where were stars in the Hubble sequence of galaxies formed, when did luminous quiescent galaxies appear?
  - Where and when are the heavy elements produced and to what extent do galaxies exchange material with the intergalactic medium?
  - When and how are the global scaling relations for galaxies established?
  - Do luminous galaxies form through the hierarchical assembly of dark matter halos? What are the redshifts and power sources of the high redshift ultra luminous infrared galaxies?
  - What is the relation between the evolution of galaxies and the growth and development of black holes in their nuclei?

Assembly of Galaxy observations with JWST **will employ similar datasets to those obtained for the HST Ultra Deep Field, in order to study galaxy properties as a function of age.**





Assembly of Galaxies: Measurements

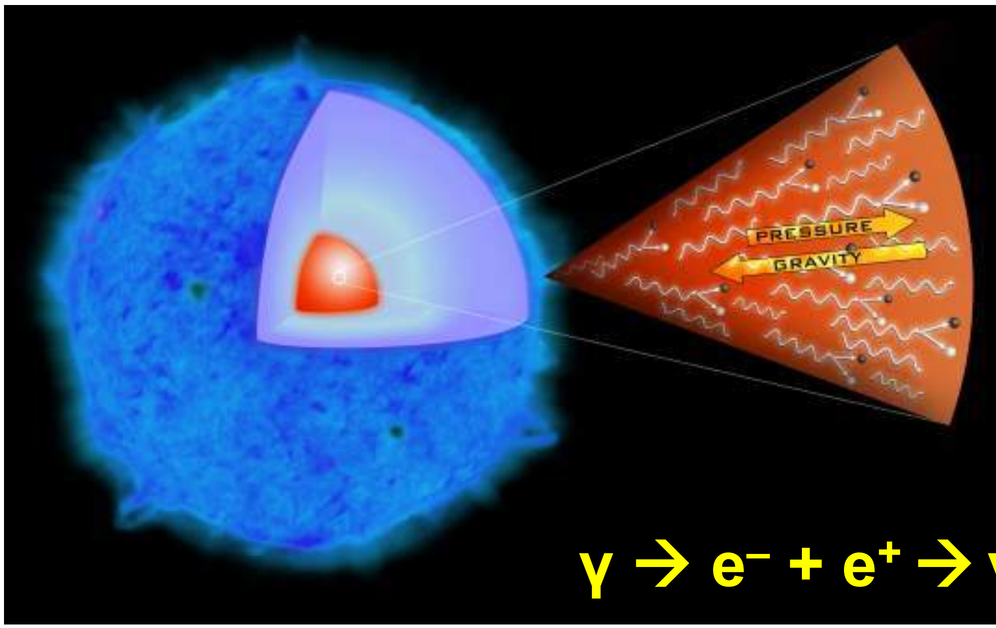
Observation	Primary Instrument	Depth, Mode	Target Density
Deep, wide survey (DWS)	NIRCam	3 nJy @ 3.5 μm	100 arcmin^2
Metallicity Determination	NIRSpec	5x10^{-19} erg s^{-1} cm^{-2}, R~1000	Galaxies in DWS
Scaling Relations	MIRI NIRCam	11 μJy @ 9 μm, R~3000 3 nJy @ 3.5 μm	Lyman break galaxies DWS data
Obscured galaxies	MIRI NIRSpec NIRSpec	23 nJy @ 5.6 mm 5x10^{-19} erg s^{-1}cm-^{2}, R~1000 1.4x10^{-16} erg s^{-1}cm^{-2} @ 24 μm, R~2000	ULIRGs ULIRGs and AGN ULIRGs and AGN

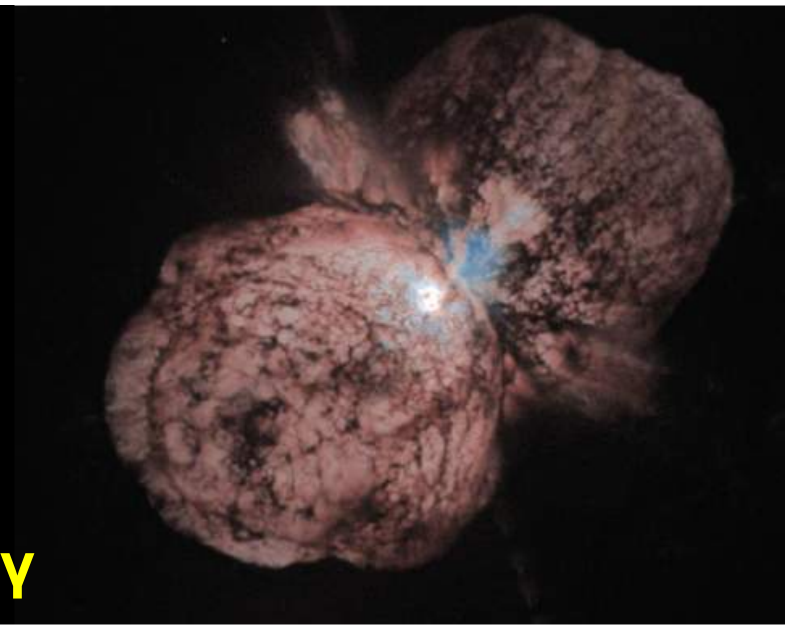
JWST, Dark Energy, Dark Matter

- JDEM/IDECS Science Coordinating Group report (Neil Gehrels, GSFC), http://jdem.gsfc.nasa.gov/docs/SCG_Report_final.pdf
- Problem: determine acceleration parameter now and in the past
- Multiple techniques required due to likely systematic errors
- JDEM/IDECS/LSST etc. wide-field surveys will find targets for JWST
- JWST contributes by extending HST techniques to IR:
  - Measuring very distant supernovae (Standard candles? Evolution?)
  - SNe rest-frame IR light curves – maybe better standard candles?
  - Measuring effects of dark matter too (distorted images of distant objects, masses of galaxies and clusters out to high redshift, rotation curves, etc.)
  - Cosmic archeology at high redshift (prior to acceleration, formation of galaxies and clusters)

SN 2006 gy – brightest supernova

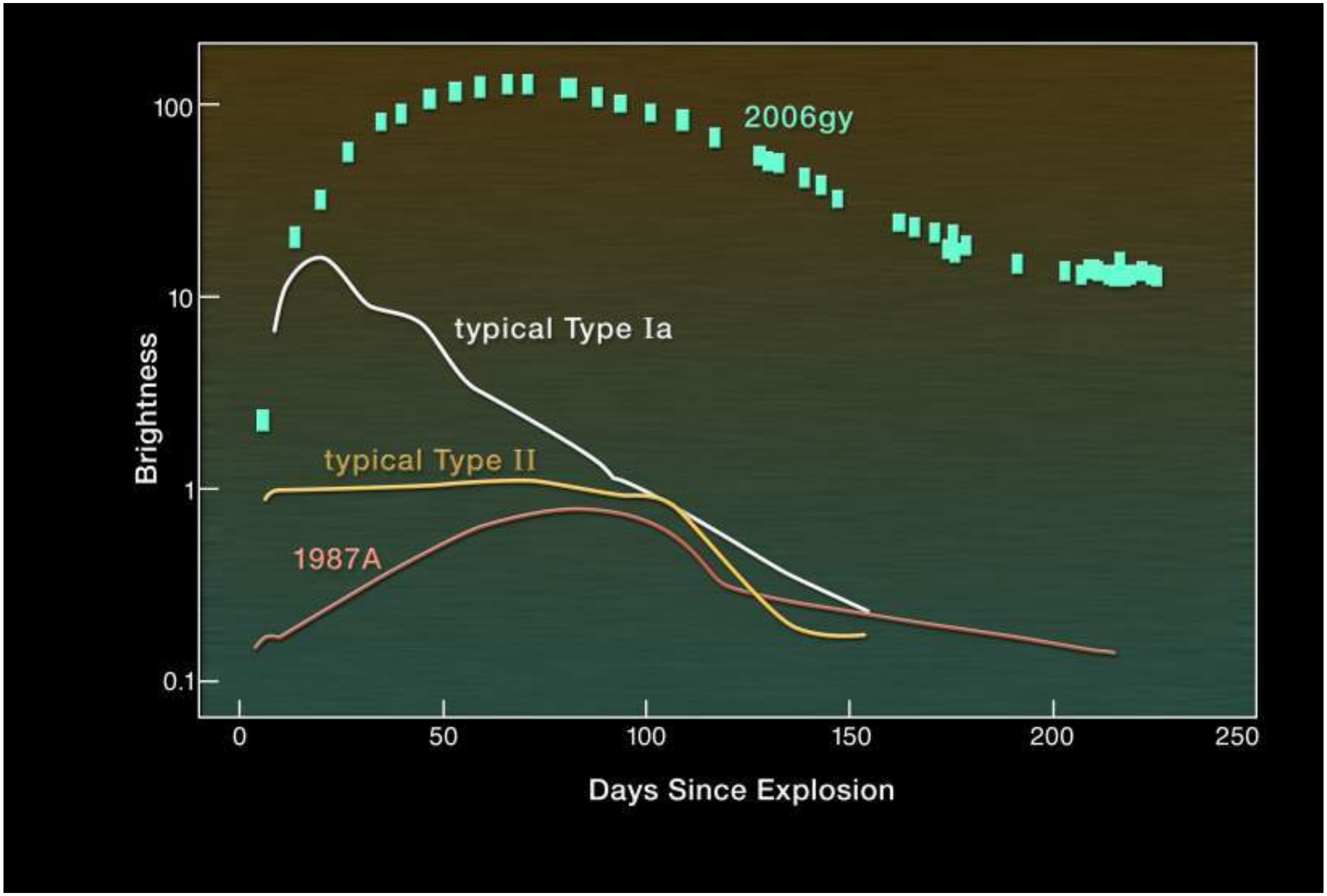
- **Could be the first observation of a pair-production instability, from the death of a very massive star.**
  - Stars are normally held up by the balance of light pressure and gravity
  - Gamma rays producing electron/positron pairs scatters light, reducing pressure. Instability creates runaway collapse.
- **A nearby analog for the first stars in the Universe.**





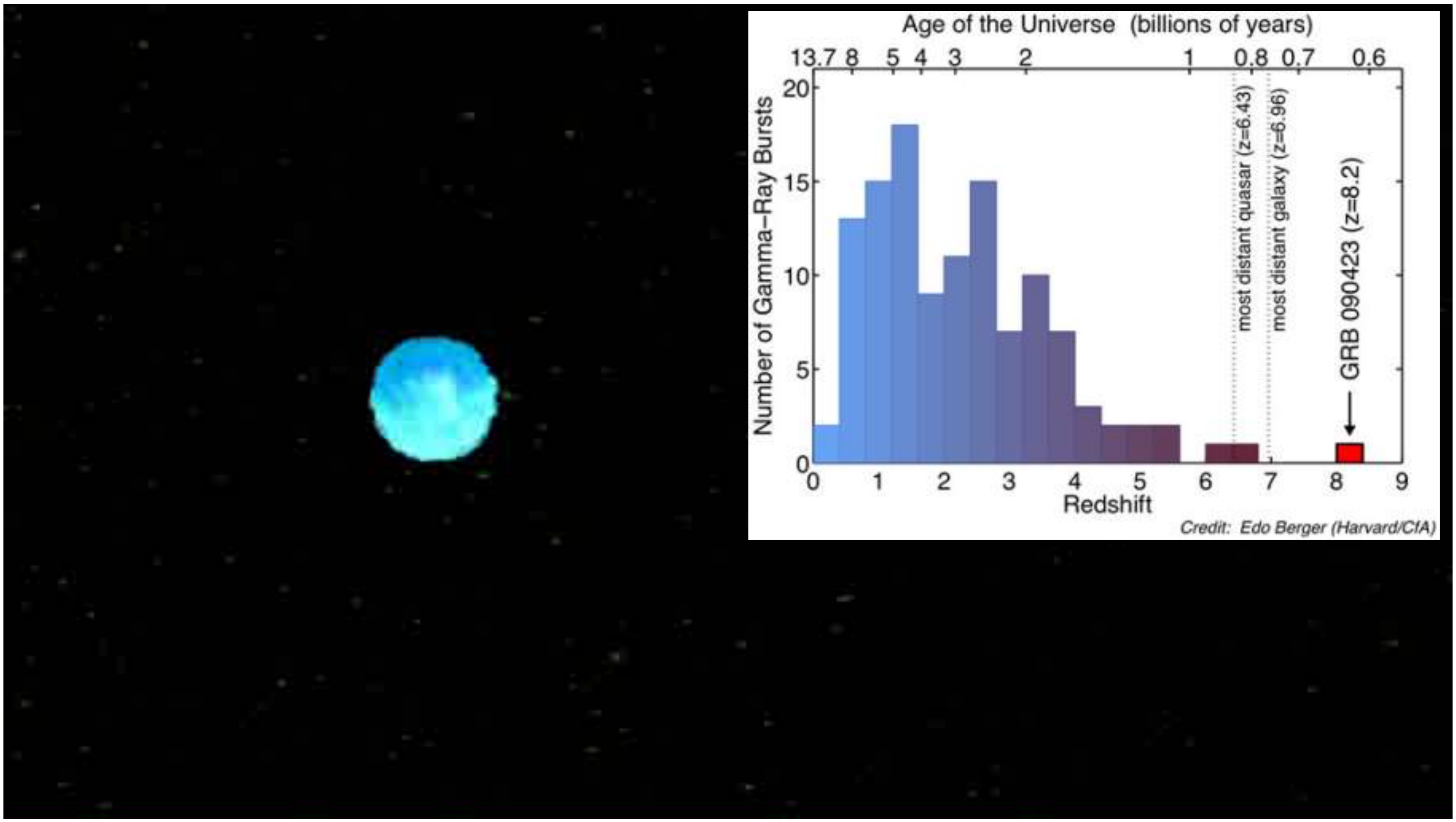
Progenitor was similar to Eta Carina. **Hubble Image of Eta Carina**

Pair-production SNe as First Stars



- Good news: JWST can easily detect these at very high redshift (but not as transients).
- Interesting news: pair-production instability doesn't necessarily require primordial composition.

Gamma Ray Burst 4/23/09 one of the most distant objects yet found (z = 8.2) – supernova jet aimed at us!



Birth of Stars and Protoplanetary Systems

- **Birth of Stars and Protoplanetary Systems:** Unravel the birth and early evolution of stars, from infall on to dust-enshrouded protostars, to the genesis of planetary systems.
  - How do protostellar clouds collapse?
  - What is the early evolution of protostars?
  - How do massive stars form and affect their environment?
  - What is the initial mass function at sub-stellar masses?
  - How do protoplanetary systems form?
  - What are the life cycles of gas and dust?

HH 30 (HST)

Barnard 68 Dark Cloud (VLT)

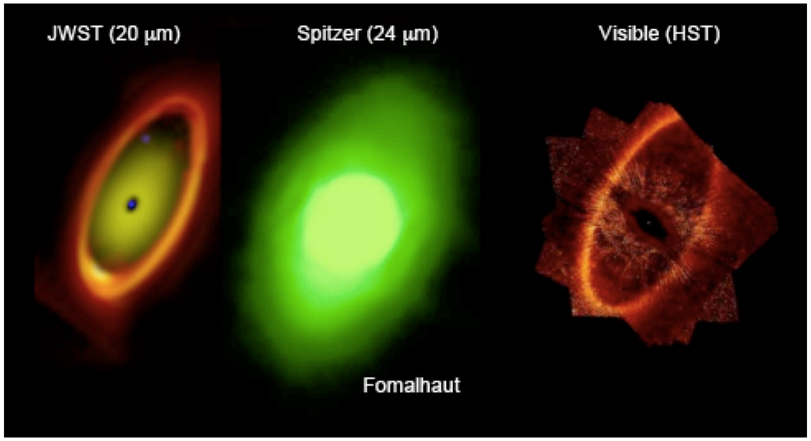
Eagle Nebula (HST/VLT)

Birth of Stars and Protoplanetary Systems

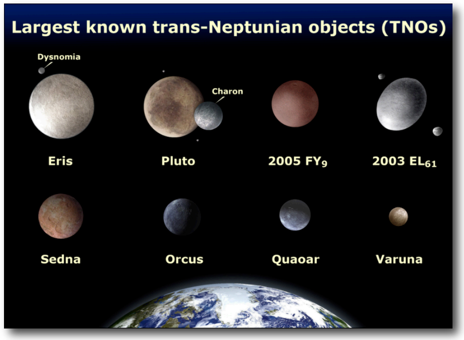
Observation	Primary Instrument	Depth/Mode	Target
Cloud Collapse	NIRCam MIRI (Imaging)	9 nJy at 2μm 1 μJy Arcsec^{-2} at 7 μm	e.g. Barnard 68
Evolution of Protostars	MIRI (Imaging) MIRI (Spectra)	0.1 μJy at 7 μm, 1 μJy at 15 μm 7x10^{-22} Wm^{-2} @ 15 μm	e.g. Taurus--Auriga Class 0 protostars in Taurus Auriga
Massive Stars	NIRCam NIRCam NIRSpec MIRI (Imaging)	2 μJy at 3.8 μm, 10 μJy at 15 μm 55 nJy at 3.5 μm, 2.3 μJy at 4.8 μm Fixed slits, IFU 34 μJy at 20 μm	e.g. Eagle nebula Sources in Eagle nebula
IMF	NIRCam NIRSpec or TFI MIRI	2.9 nJy at 2.2 μm 290 nJy @ 2.2 μm	e.g. Orion Nebula, 30 Doradus
Protoplanetary Systems	TFI	10^{-13} erg s^{-1} cm^{-2} arcsec^{-2} at 1.87 μm; coronagraph	e.g. Orion Nebula
Astrochemistry	MIRI (spectra)	2.6x10^{-17} erg s^{-1} cm^{-2} arcsec^{-2} at 17 μm	Protostars and debris disks

Planetary Systems and the Origins of Life (PSOL)

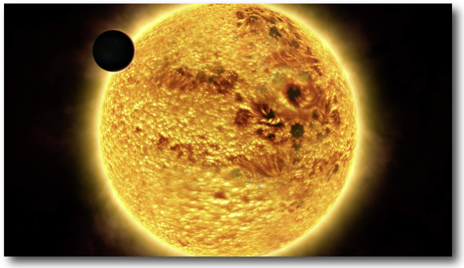
- **Planetary Systems and the Origins of Life:** To determine the physical and chemical properties of planetary systems including our own, and to investigate the potential for the origins of life in those systems
  - How do planets and brown dwarfs form?
  - How common are giant planets and what is their distribution of orbits?
  - How do giant planets affect the formation of terrestrial planets?
  - What comparisons, direct or indirect, can be made between our solar system and circumstellar disks (forming solar systems) and remnant disks?



Observations of Debris Disks in reflected light and emission



Observations of Kuiper belt Objects



Characterization of Exoplanets

Planetary Systems and the Origins of Life

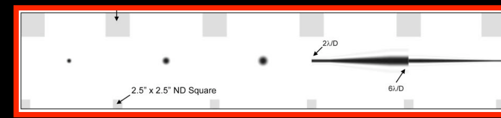
Observation	Primary Instrument	Depth/Mode	Target
Isolated exosolar giant planets **Bound Planets**	NIRCam TFI/NIRCam	4 nJy at 2 μm 200 μJy at 4 μm	Star forming regions Nearby stars
Exosolar Giant Planets Isolated (in depth studies)	TFI NIRSpec MIRI	60 nJy, R=100 1 μJy, R=3000 1 μJy at 15 μm	Nearby stars
Transiting Planets	NIRSpec	R~1000	Ground-based Surveys, Kepler & Corot
Circumstellar Disks	MIRI	1 μJy at 15 μm	Debris Disk Surveys
Comets	NIRSpec MIRI	1 μJy, R=3000 at 2 μm 1 μJy, R=3000 at 15 μm	10/yr
Kuiper Belt Objects	NIRCam NIRSpec MIRI	4 nJy at 2 μm 1 μJy, R=3000 at 2 μm 1 μJy at 25 μm	10 $arcmin^2$
Satellites	NIRSpec MIRI	1 μJy, R=3000 at 2 μm 1 μJy at 15 μm	e.g. Titan

Exoplanets

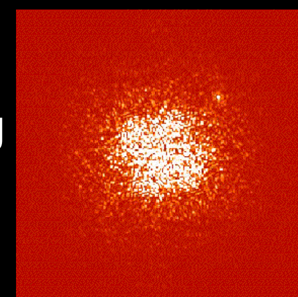
- **As of 2nd Nov 2009, 403 total:**
  - Radial velocity: 376 planets, 38 multiple planet systems
  - Transiting: 62 planets, 3 multiples (most good JWST targets)
  - Microlensing: 9 planets, 1 multiple system
  - Imaging: 11 planets, 1 system (a triple) (all good JWST targets)
  - Timing: 7 planets, 2 multiple planet systems
  - + predictions from dust disk structures
- **Kepler launched Mar. 6, 2009, will monitor ~ 100,000 stars, find handful of Earths, thousands of others**
- **TESS (Transiting Exoplanet Survey Satellite), proposed SMEX, would survey nearest stars, best candidates for detailed follow-up with JWST**
- **JWST Transits Working Group established – M. Clampin**

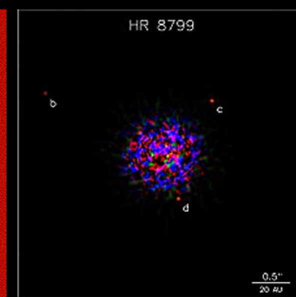
JWST Coronagraphs

- **NIRCam**
  - **Band-limited mask occulters**

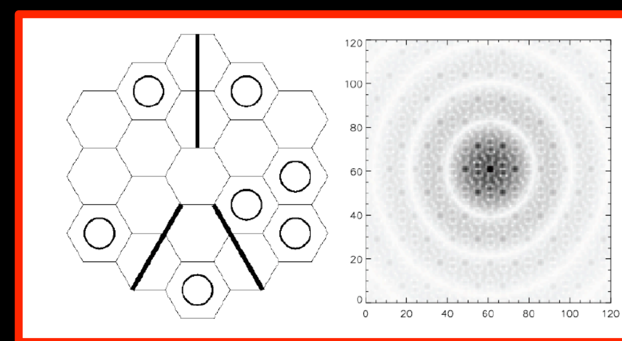


- **Tunable Filter Imager (TFI) Coronagraph**
  - Coronagraph: Differential Speckle Imaging
  - Contrast gain of ~10x versus NIRCam
    (Marois et al. 2008)



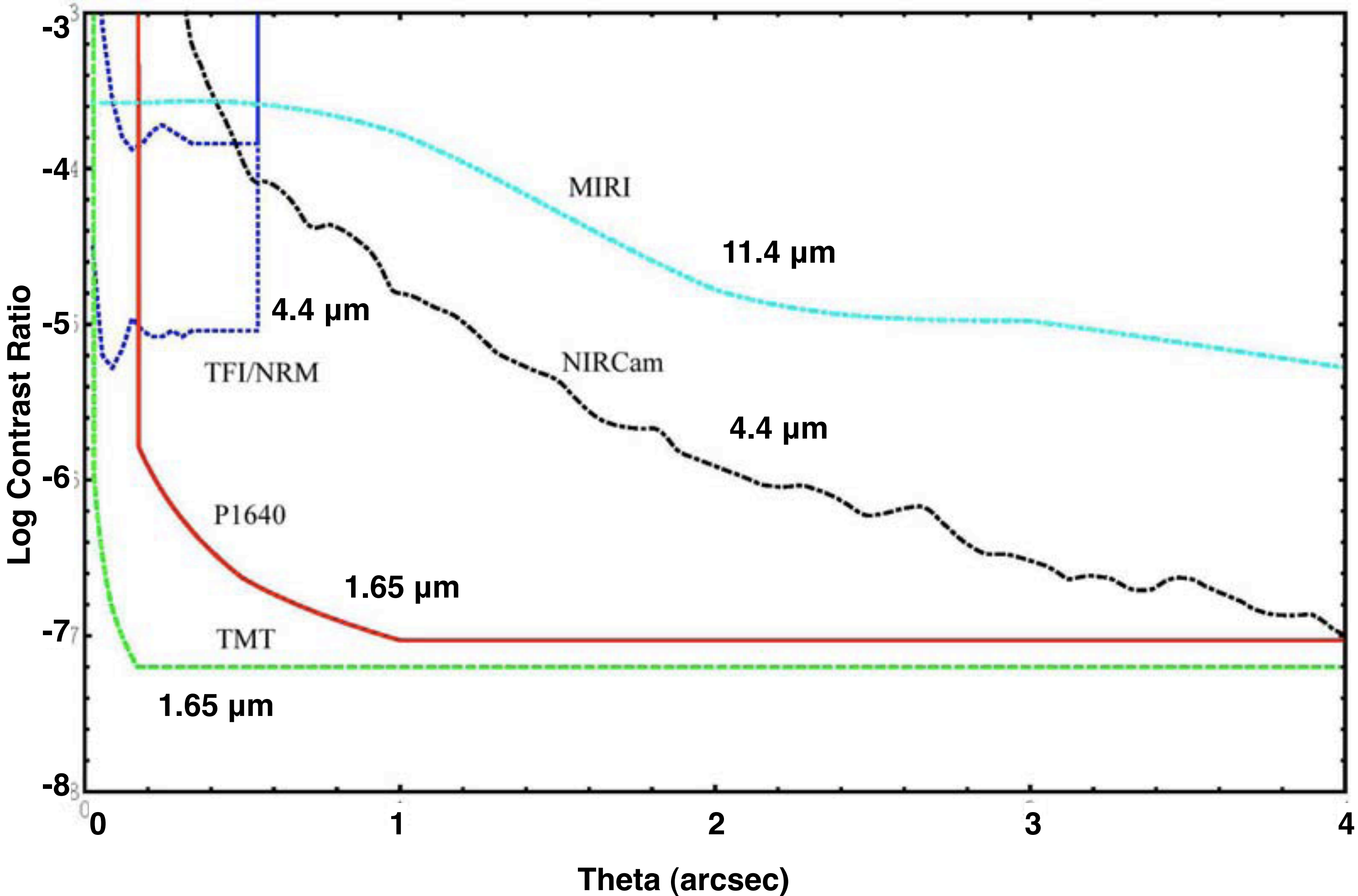


- **Non-redundant Mask**
  - Wavelength range: 1.5-2.5, 3.1-5.0 μm
  - Closure Phase Imaging
  - Trades inner working angle of 0.5 λ/D against contrast



- **MIRI**
  - 3 Quadrant Phase
  - 1 Lyot

JWST Coronagraph Performance



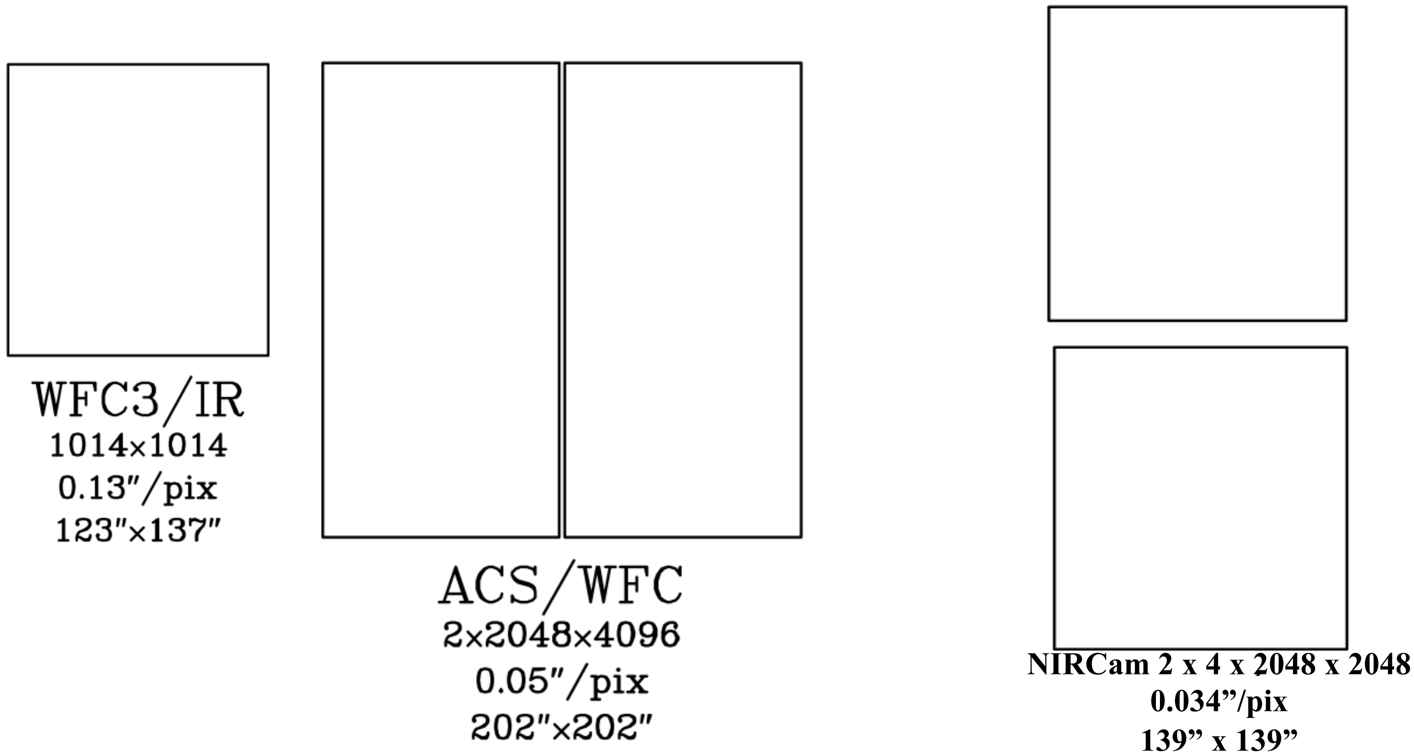
Beichman et al. 2009

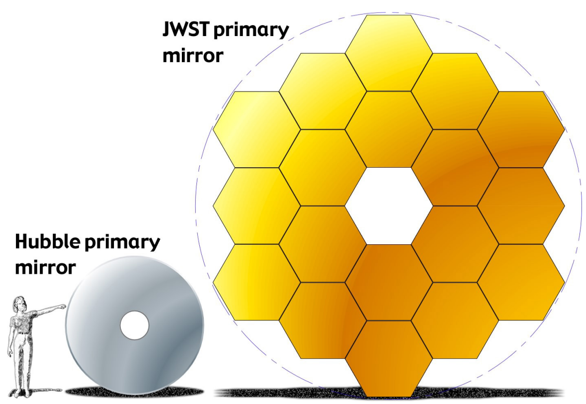
Moving Targets

- Capability approved Feb 7, 2008
- MT capability for rates ≤30 mas/sec enables breakthrough scientific investigations of the Kuiper Belt, asteroids, comets, satellites, and potentially the planets beyond Earth's orbit.
- Pointing stability requirement (50 mas 3σ at 3 mas/sec) can be met, with margin, for rates up to 30 mas/sec.
- No hardware changes are needed to implement this capability.
- Flight and ground software design, interfaces, and verification are straightforward.

Object	Min Rate (mas/s)	Max Rate (mas/s)	Observability
Mars	2.5	28.6	Subarrays
Jupiter	0.070	4.5	Subarrays
Io	0.004	10.2	Proximity of Jupiter
Saturn, Titan	0.040	2.9	Subarray for Saturn
Uranus	0.020	1.4	OK most wavelengths
Neptune	0.004	1.0	OK most wavelengths
Pluto	0.160	0.5	OK
KBO	0.002	0.5	OK

Comparison to HST SM4 Instruments



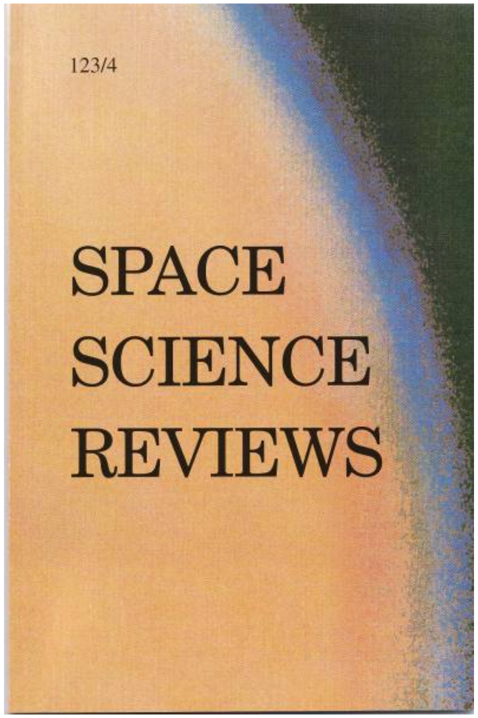


Instrument	A Ω (sq arcsec; HST A=1)
WFC3/IR	16851
ACS WF2	40804
NIRCam	34848 * 7.3 = 282,000

Operations Planning

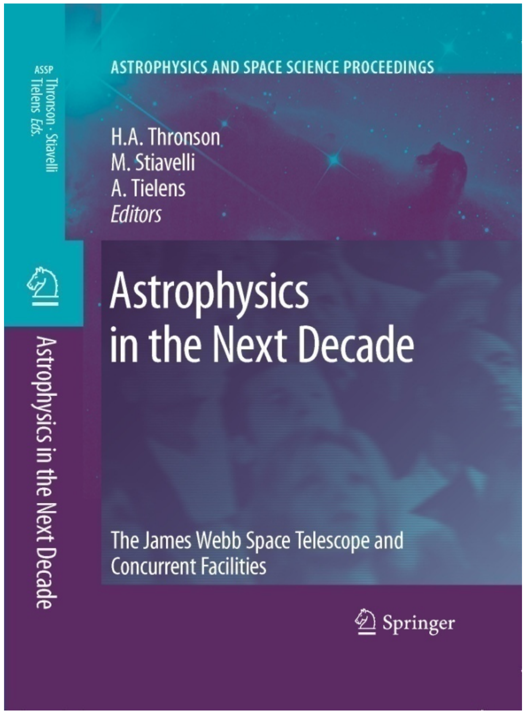
- **STScI to operate using similar process to HST**
- **GO's get 80% of 5 year mission, Director's Discretionary gets 10%, GTO gets 10%**
- **4 instrument teams and the interdisciplinary scientists have Guaranteed Time**
  - NIRCam PI: 900 hours
  - NIRSpec Team: 900 hours
  - U.S. MIRI Science Lead: 210 hours
  - Each US MIRI Science Team member (total 3): 60 hours
  - European MIRI Science Team: 450 hours
  - FGS/TFI PI : 450 hours
  - Each Interdisciplinary Scientist (IDS) (total 6): 110 hours
  - U.S. Telescope Scientist: 210 hours
- **STScI has advice from newly formed JSTAC: chair is Garth Illingworth; meets 3x/yr; will be replaced by Users Committee after launch**
- **First Call for Proposals expected 1 year before launch**
- **On-orbit checkout complete at L + 6 months**
  - 2 months to reach L2 and operating temperature
  - 4 months setup and checkout

Learn more about JWST science ….



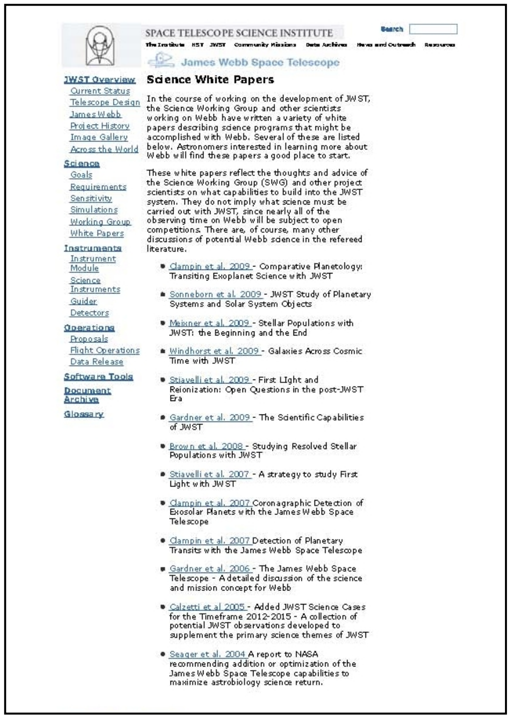
Download for free at:
jwst.gsfc.nasa.gov

New Book



Available Now

13 White Papers


SPACE TELESCOPE SCIENCE INSTITUTE

James Webb Space Telescope

JWST Overview: Current Status, Telescope Design, James Webb, Project History, Image Gallery, Across the World
Science: Goals, Requirements, Sensitivity, Simulations, Working Group, White Papers
Instruments: Instrument Module, Science Instruments, Guider, Detectors
Operations: Proposals, Flight Operations, Data Release
Software Tools
Document Archive
Glossary

Science White Papers

In the course of working on the development of JWST, the Science Working Group and other scientists working on Webb have written a variety of white papers describing science programs that might be accomplished with Webb. Several of these are listed below. Astronomers interested in learning more about Webb will find these papers a good place to start.

These white papers reflect the thoughts and advice of the Science Working Group (SWG) and other project scientists on what capabilities to build into the JWST system. They do not imply what science must be carried out with JWST, since nearly all of the observing time on Webb will be subject to open competitions. There are, of course, many other discussions of potential Webb science in the refereed literature.

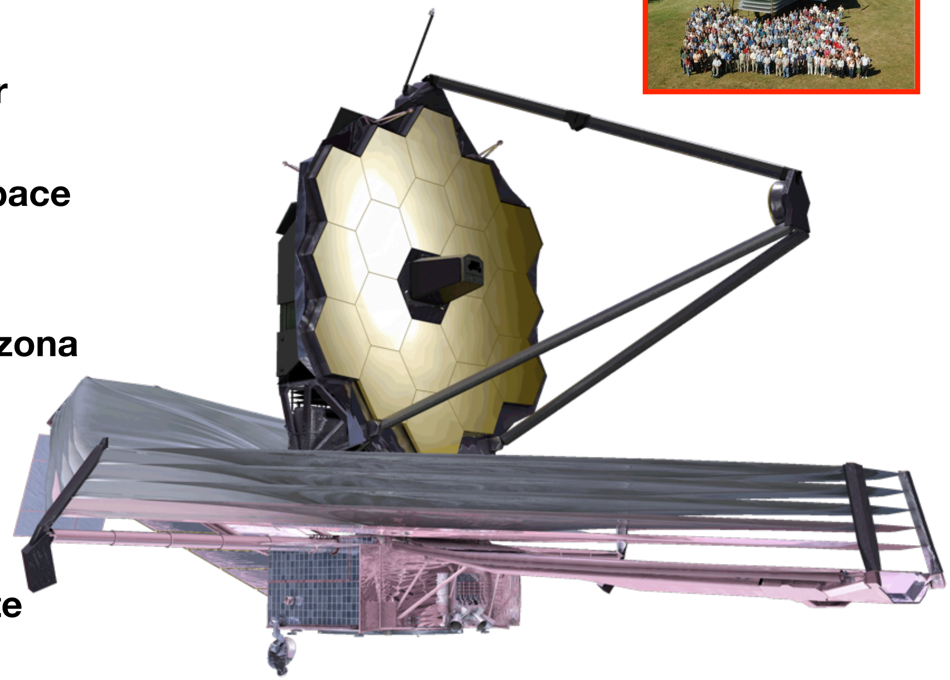
- Clampin et al. 2009 - Comparative Planetology: Transiting Exoplanet Science with JWST
- Sonneborn et al. 2009 - JWST Study of Planetary Systems and Solar System Objects
- Meixner et al. 2009 - Stellar Populations with JWST: the Beginning and the End
- Windhorst et al. 2009 - Galaxies Across Cosmic Time with JWST
- Stiavelli et al. 2009 - First LIght and Reionization: Open Questions in the post-JWST Era
- Gardner et al. 2009 - The Scientific Capabilities of JWST
- Brown et al. 2008 - Studying Resolved Stellar Populations with JWST
- Stiavelli et al. 2007 - A strategy to study First Light with JWST
- Clampin et al. 2007 Coronagraphic Detection of Exosolar Planets with the James Webb Space Telescope
- Clampin et al. 2007 Detection of Planetary Transits with the James Webb Space Telescope
- Gardner et al. 2006 - The James Webb Space Telescope - A detailed discussion of the science and mission concept for Webb
- Calzetti et al 2005 - Added JWST Science Cases for the Timeframe 2012-2015 - A collection of potential JWST observations developed to supplement the primary science themes of JWST
- Seager et al. 2004 A report to NASA recommending addition or optimization of the James Webb Space Telescope capabilities to maximize astrobiology science return.

www.stsci.edu/jwst/science/whitepapers/

- **ELT-JWST Synergy Conference, Garching, April 13-16, 2010**
- **Frontier Science Opportunities with the James Webb Space Telescope, Teton National Park, June 5-7, 2011**

Backup Charts

James Webb Space Telescope



Organization

- **Mission Lead:** Goddard Space Flight Center
    - Senior Project Scientist: Dr John Mather
- **International collaboration:** ESA & CSA
- Prime Contractor: Northrop Grumman Aerospace Systems
- **Instruments:**

  Near Infrared Camera (NIRCam) – Univ. of Arizona

  Near Infrared Spectrograph (NIRSpec) – ESA

  Mid-Infrared Instrument (MIRI) – JPL/ESA

  Fine Guidance Sensor (FGS) & Tunable Filter Imager – CSA
- **Operations:** Space Telescope Science Institute

Description

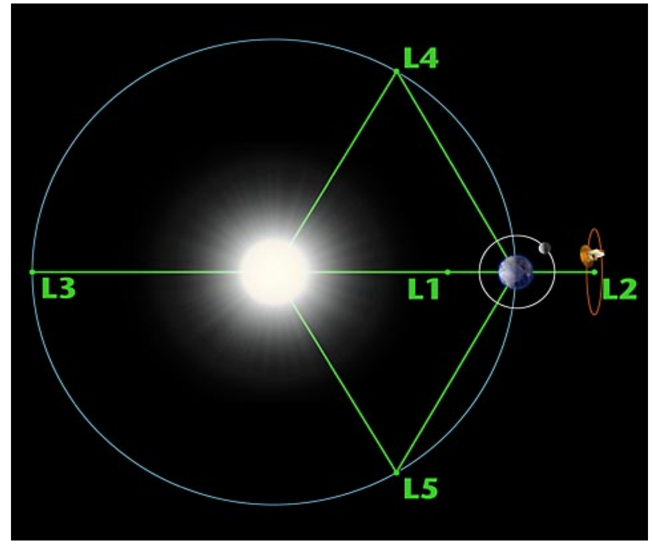
Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror

Cryogenic temperature telescope and instruments for infrared performance

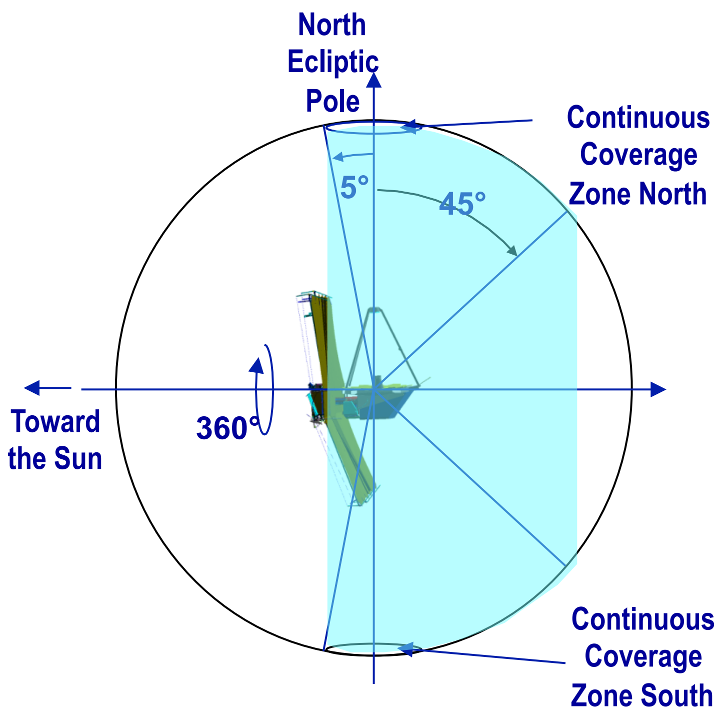
Launch June 2014 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2

5-year science mission requirement (10-year propellant lifetime)

JWST science objectives require largest cryogenic telescope ever constructed



- An L2 point orbit was selected for JWST to enable passive cryogenic cooling
  - Station keeping thrusters fire ~ every 3 weeks to maintain this orbit
  - Propellant sized for 11 years (delta-v ~ 93 m/s)



- The JWST can observe the whole sky while remaining continuously in the shadow of its sunshield
  - Field of Regard is an annulus covering 35% of the sky
  - The whole sky is covered each year with small continuous viewing zones at the Ecliptic poles

Flight Science Working Group: 2002 - present

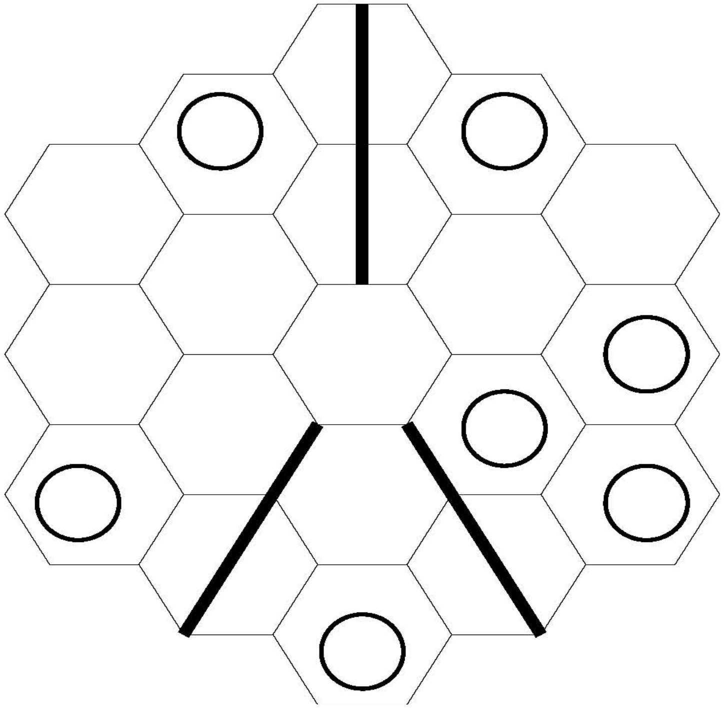
- 6 Interdisciplinary Scientists : H. Hammel, S. Lilly, J. Lunine, M. McCaughrean, M. Stiavelli, R. Windhorst
- Instrument Team Lead/ Science Representative: M. Rieke (NIRCam), G. Rieke and G. Wright (MIRI), Rene Doyon (FGS), & rotating scientist member, NIRSpec
- Telescope Scientist: M. Mountain (also STScI Director)
- Ex Officio: J. Mather (Chair & Senior Project Scientist), J. Gardner (Deputy Senior Project Scientist), M. Clampin (Observatory Scientist), M. Greenhouse (ISIM Scientist), K. Flanagan (STScI JWST Mission Head), G. Sonneborn (Operations Scientist), P. Jakobsen (ESA Project Scientist), J. Hutchings (CSA Project Scientist)

JSTAC membership

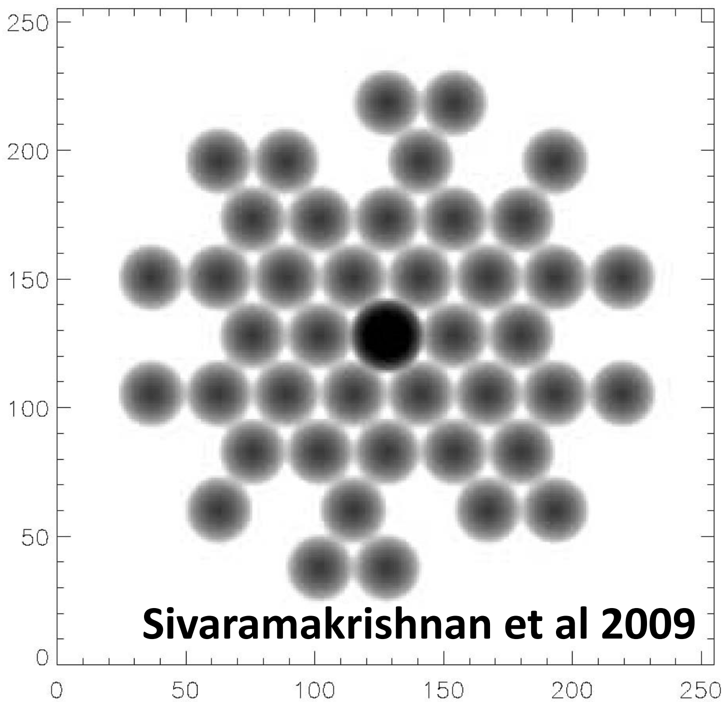
- Roberto Abraham, Toronto
- Neta Bahcall, Princeton
- Stefi Baum, RIT
- Roger Brissenden, CFA
- Timothy Heckman, JHU
- Garth Illingworth, UCSC (Chair) *****
- Lisa Storrie-Lombardi, IPAC
- Malcolm Longair, Cambridge
- Christopher McKee, Berkeley
- Bradley Peterson, OSU
- Joe Rothenberg, USpaceNet
- Sara Seager, MIT
- Monica Tosi, Bologna

- Ex-officio representatives of the space agencies:
- John Mather, GSFC (JWST Senior Project Scientist)
- Mark McCaughrean, ESTEC (ESA representative)
- Alain Berinstain, CSA (CSA representative)
- Eric Smith, NASA HQ (JWST Program Scientist/NASA representative)

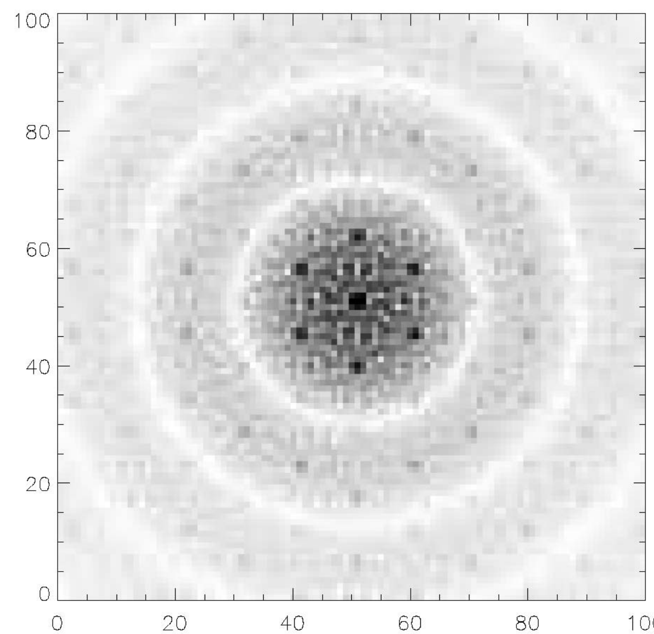
Non-Redundant Mask Imaging



- New mode for FGS/TFI utilizes "interferometric" mask producing 21 baselines and a narrow PSF (0.5λ/D)
- Ground-based contrast limits ~5 mag, in space > 10 mag possible at small IWA
- Flat fielding issues may be problem (>>Photon noise) for bright stars



Sivaramakrishnan et al 2009



High Contrast Imaging/Spectroscopy Modes

SI	Channel/Mode	λ (μm)	IWA	R (λ/δλ)	Contrast
NIRCam	Short λ Lyot Coronagraph	0.6 - 2.3	≥4λ/D	4, 10, 100	≤ 10^5
NIRCam	Long λ Lyot Coronagraph	2.4 - 5.0	≥4λ/D	4, 10, 100	~10^5
TFI	Multi-λ coronagraph	1.6 - 2.5	≥4λ/D	100	~10^6
TFI	Multi-λ coronagraph	3.2 - 4.9	≥4λ/D	100	~10^6
TFI	Non-redundant mask	1.6 - 2.5	0.5λ/D	100	~10^4
TFI	Non-redundant mask	3.2 - 4.9	0.5λ/D	100	~10^4
MIRI	Quadrant Phase Coronagraph	10.65	~3λ/D	20	~10^4
MIRI	Quadrant Phase Coronagraph	11.4	~3λ/D	20	~$5x10^5$
MIRI	Quadrant Phase Coronagraph	15.5	~3λ/D	20	~$2x10^5$
MIRI	Lyot Coronagraph	23	≥4λ/D	5	~10^5

Transit Science Instrument Modes

	Instrument Mode	λ (μm)	R (λ/δλ)	FOV	Application
Imaging	NIRCam	0.6 - 2.3 2.4 - 5.0	4, 10, 100 4, 10, 100	2 x (2.2' x 2.2') 2 x (2.2' x 2.2')	High precision light curves of primary and secondary eclipses
	NIRCam (Defocused)	0.6 - 2.3	4, 10, 100	Defocused images radius = 0.74'' radius = 1.42'' radius = 2.11''	High precision light curves of primary and secondary eclipses for - bright targets that need to be defocused to avoid rapid saturation - reduction of flat field and pointing errors
	MIRI	5 - 28	4 - 6	1.9' x 1.4'	High precision light curves of secondary eclipses
	TFI	1.6 - 2.6 3.2 - 4.9	100	2 x (2.2' x 2.2') 2 x (2.2' x 2.2')	High precision light curves of primary and secondary eclipses - bright targets that need to be defocused to avoid rapid saturation
Spectroscopy	NIRCam	2.4 - 5.0	1700	2 x (2.2' x 2.2')	Transmission and emission spectroscopy of transiting planets
	NIRSpec	1.0 - 5.0	100, 1000, 2700	1.6'' x 1.6''	Transmission and emission spectroscopy of transiting planets
	MIRI-LRS	5 -11	100	Slitless	Emission spectroscopy of transiting planets - Low spectroscopy
	MIRI-MRS	5.9 - 7.7 7.4 - 11.8 11.4 - 18.2 17.5 - 28.8	3000 3000 3000 3000	3.7'' x 3.7'' 4.7'' x 4.5'' 6.2'' x 6.1'' 7.1'' x 7.1''	Emission spectroscopy of transiting planets - suitable for specific spectral features e.g. CO_2 @ 15 μm