The James Webb Space Telescope: From the Solar System to the Earliest Universe

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Unless noted otherwise, all figures are taken from https://jwst-docs.stsci.edu/

Some basic concepts (for the non-astronomers)

- Jargon: in astrophysics *any* element heavier than helium is a *metal*. Thus oxygen, carbon, nitrogen, neon are all *metals*.
- Jargon : *weak lens* is a lens that introduces a certain amount of de-focus rather than de-focussing the telescope. Used in the observation of bright sources and telescope focussing.
- Observations can be made in two modes:
  - Imaging.
  - Spectroscopy - decompose light through a disperser. Not as exciting to lay people but very exciting for astronomers since *spectra* reveal the physical properties of sources being examined.
- Additional modes used by JWST are
  - Time series observations (aka *TSO*)
  - High contrast imaging (using coronagraphs or interferometers).

Decomposing light (spectroscopy)

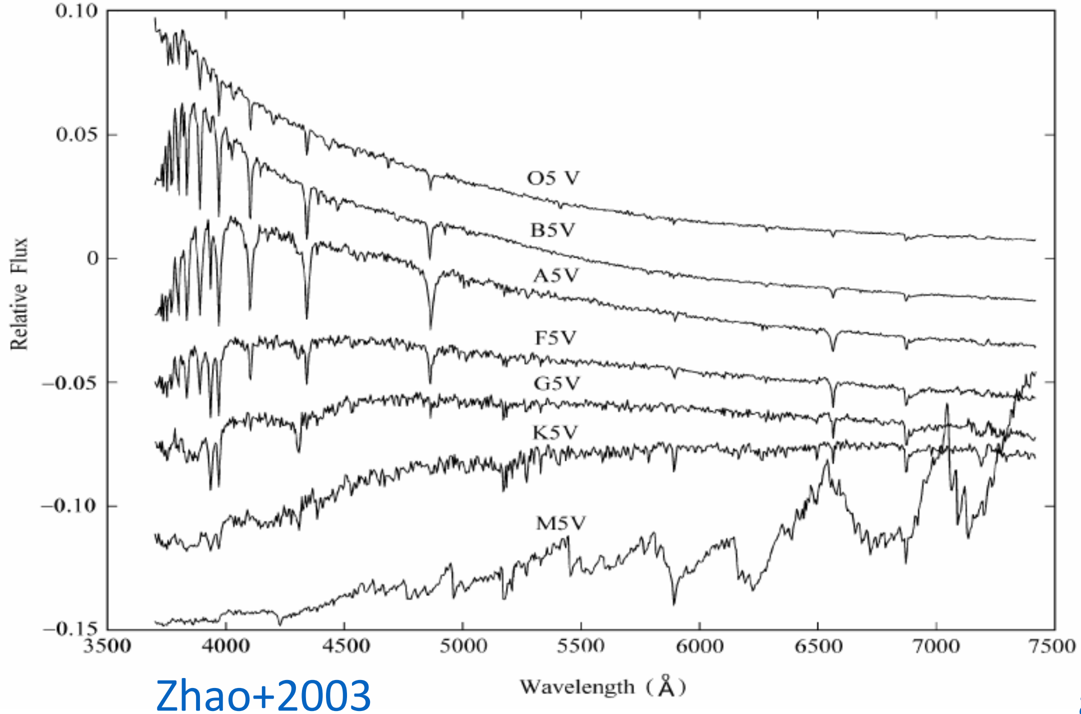
Source

Disperser

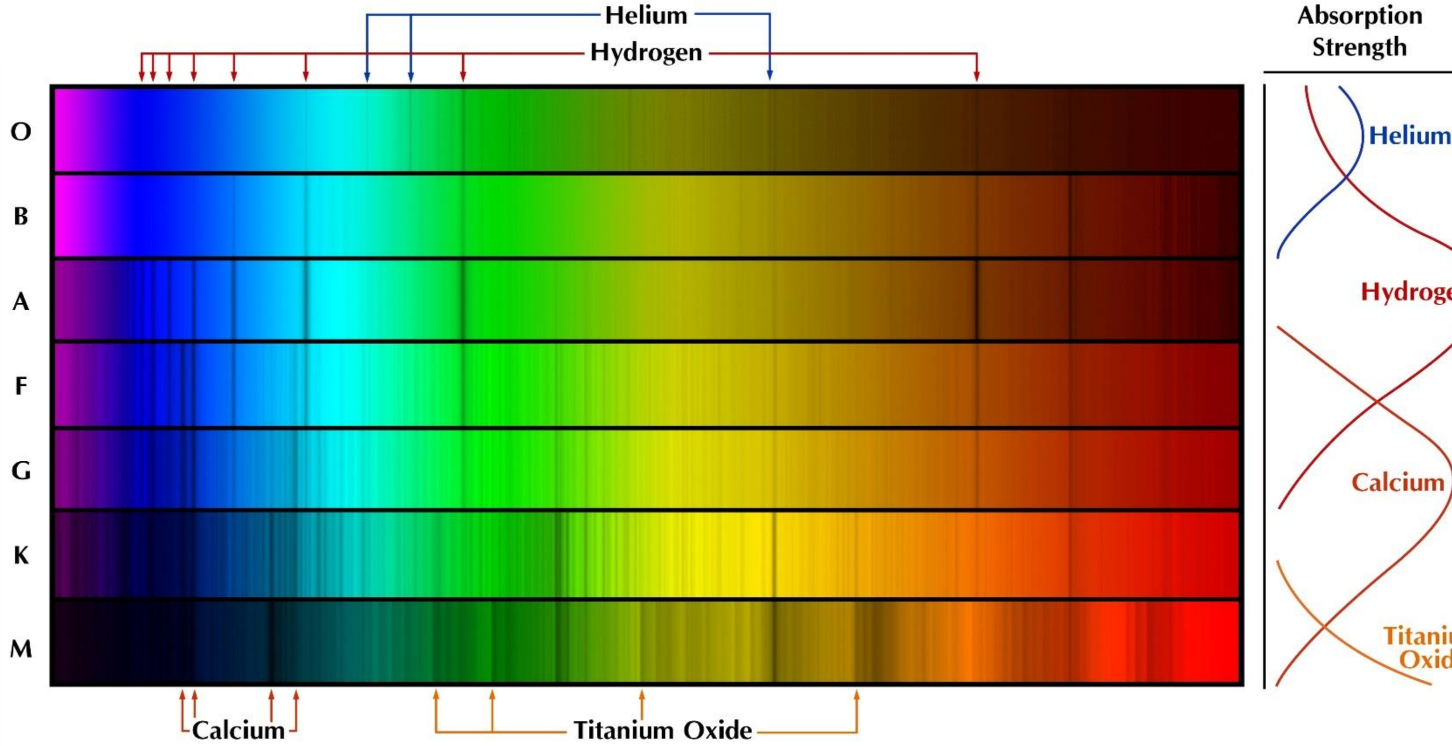
(water drops, prism, grating, grism)

Spectrum

The colors can be used to distinguish different types of objects (stars in this case)



[Zhao+2003]

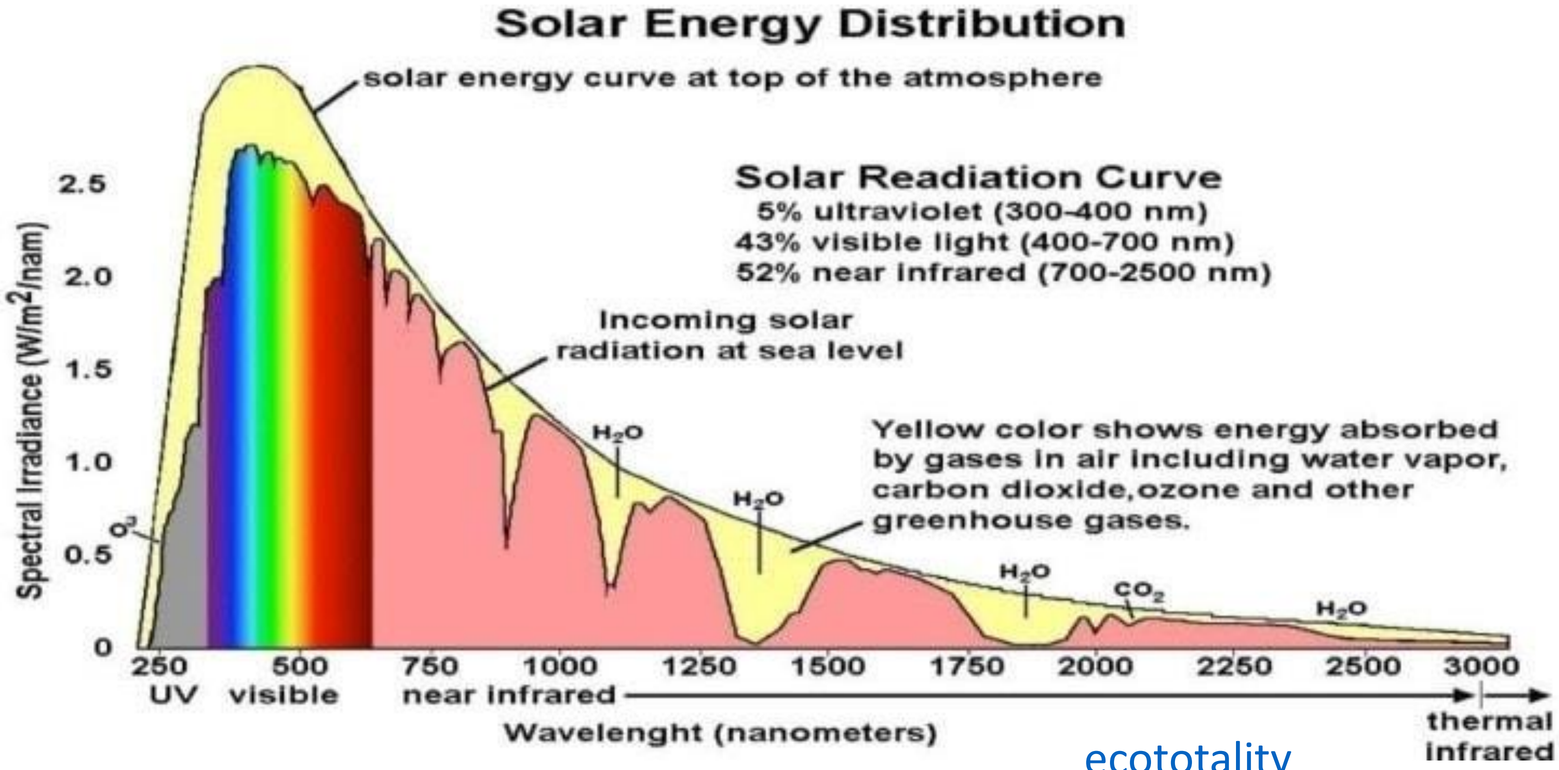


[azastro, from https://noirlab.edu/public/images/noao0134a/]

From the colors of stars we can measure the temperature of their outer layers (*photosphere*)

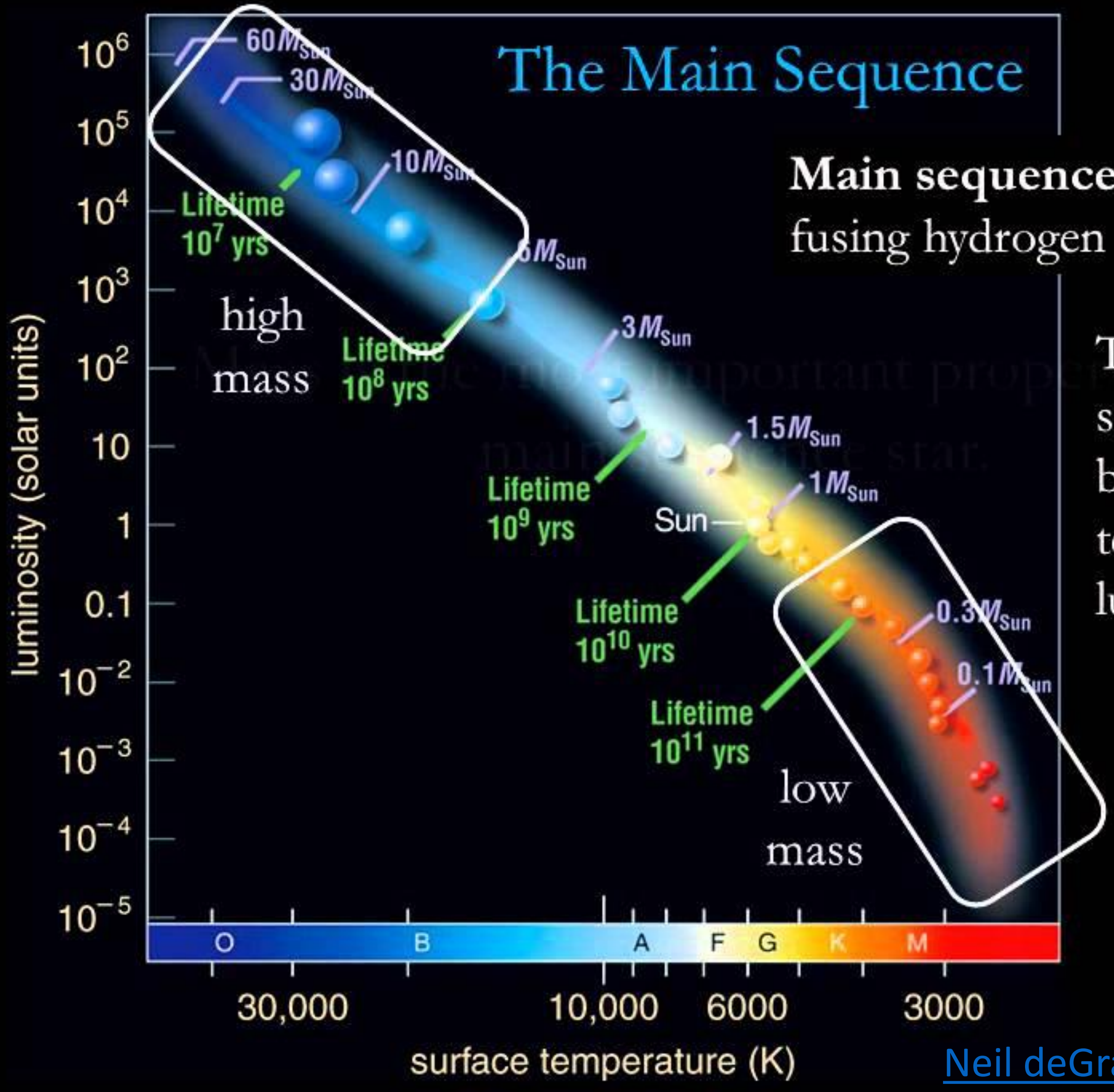
Filters are placed in the optical path to measure how the properties of sources change with wavelength.

freeimageslive



ecototality

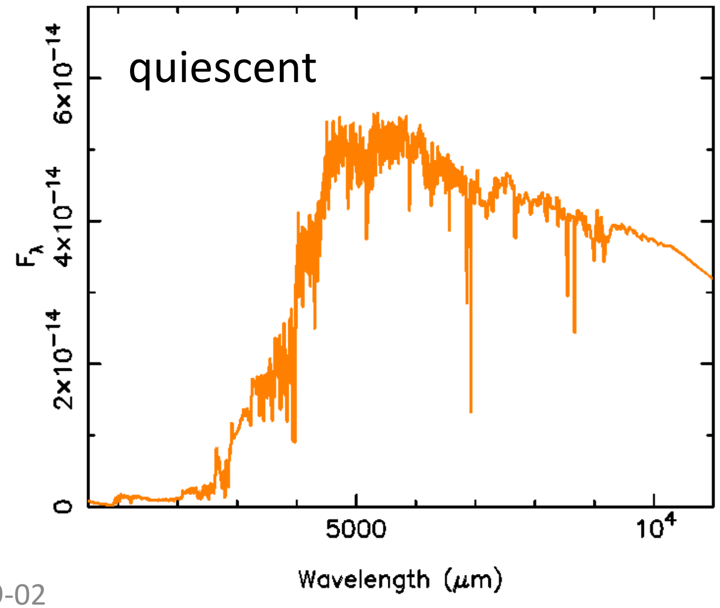
The Hertzsprung-Russell Diagram uses the difference between the light measured in two filters versus the total light of stars from which their underlying physical properties can be estimated.

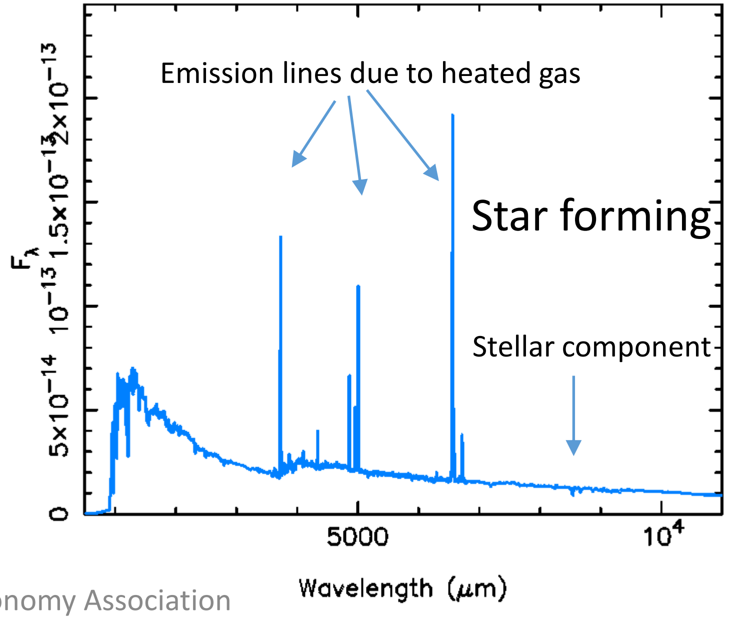


[Neil deGrasse Tyson master class]

Galaxies

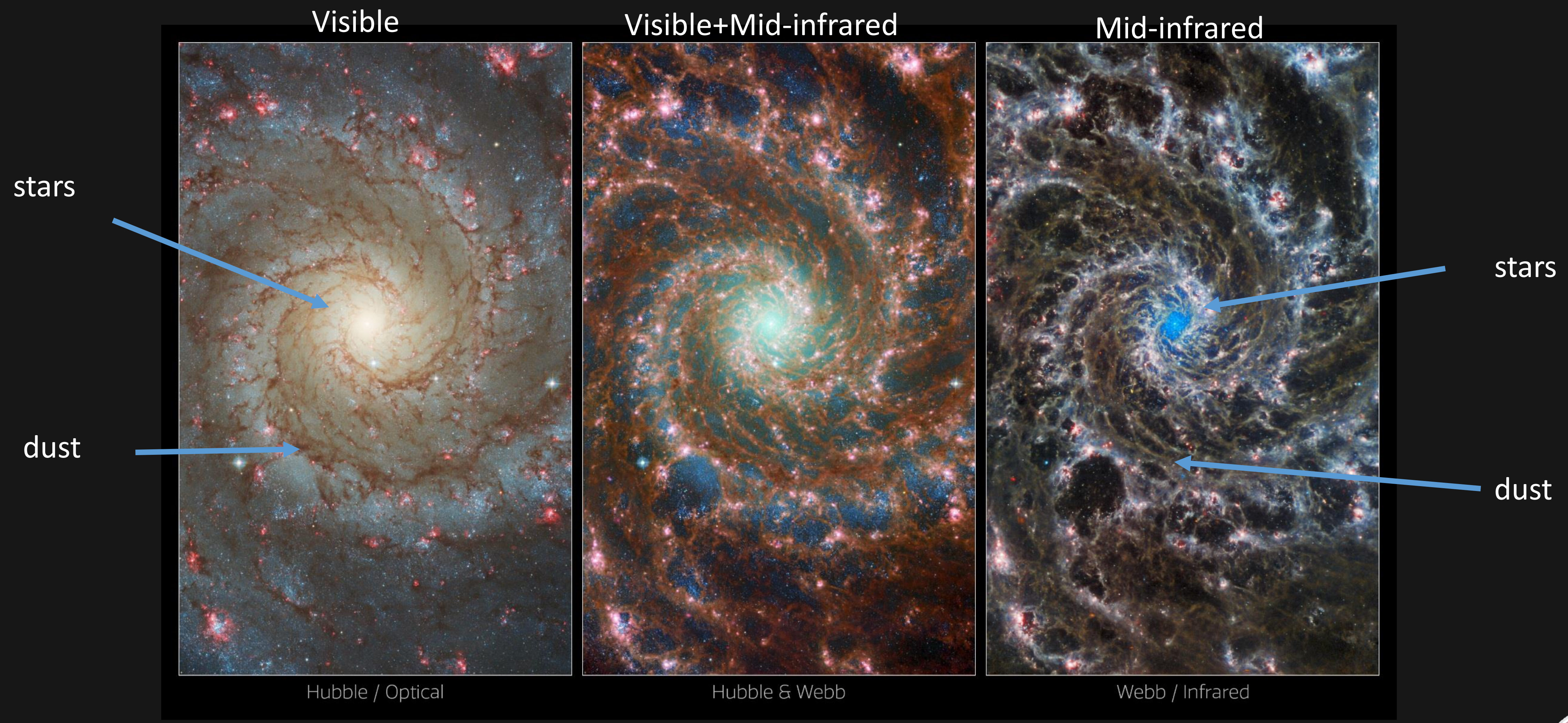
- Galaxy spectra are a *composite* of the stellar population mix (i.e., the different stellar types in the Hertzprung-Russell diagram), the amount of gas (hydrogen, helium, oxygen, iron etc.) that is heated by stars and the amount of dust. Below are two spectra from Brown+2014, highlighting a galaxy whose light is dominated by older stars (left) and one whose light is dominated by young stars and gas heated by these young stars (right).

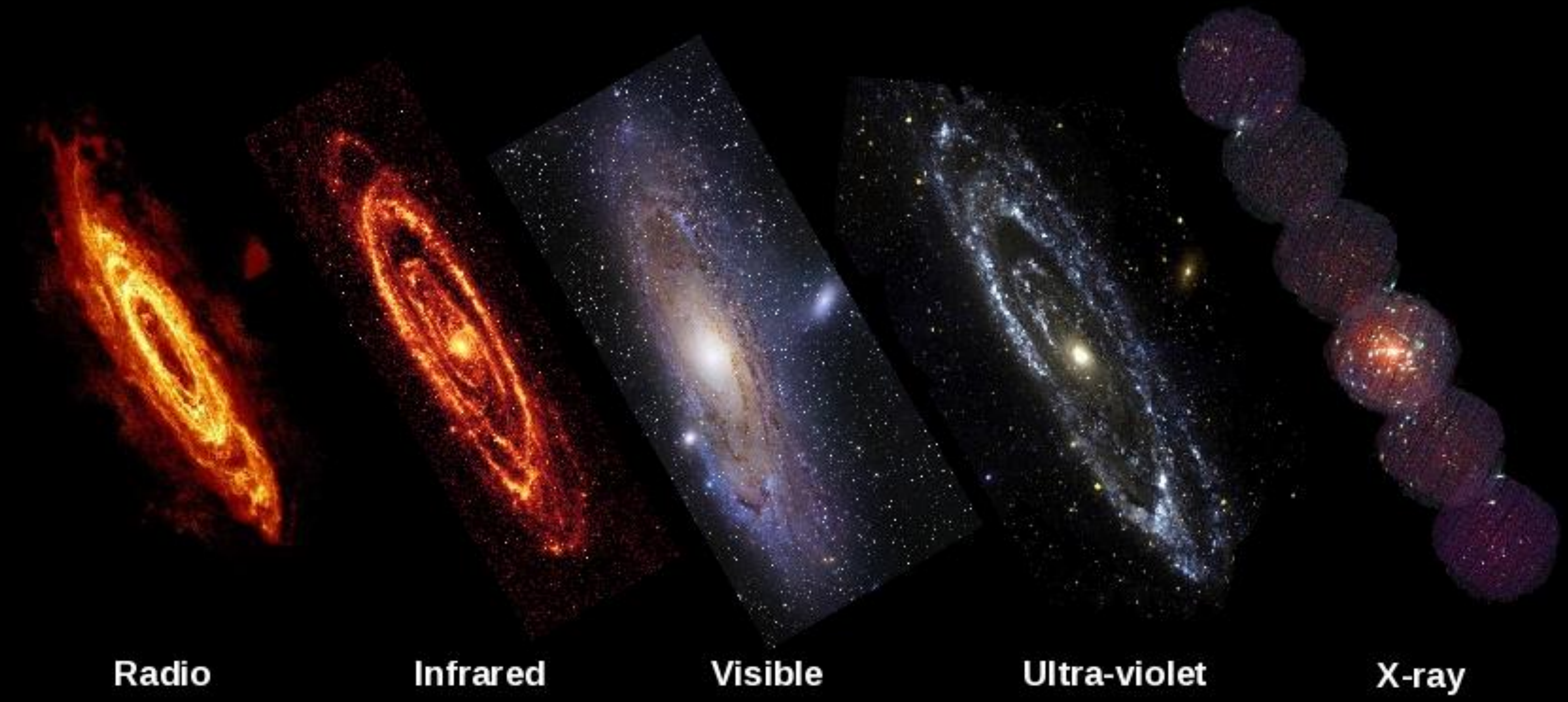




False color mapping

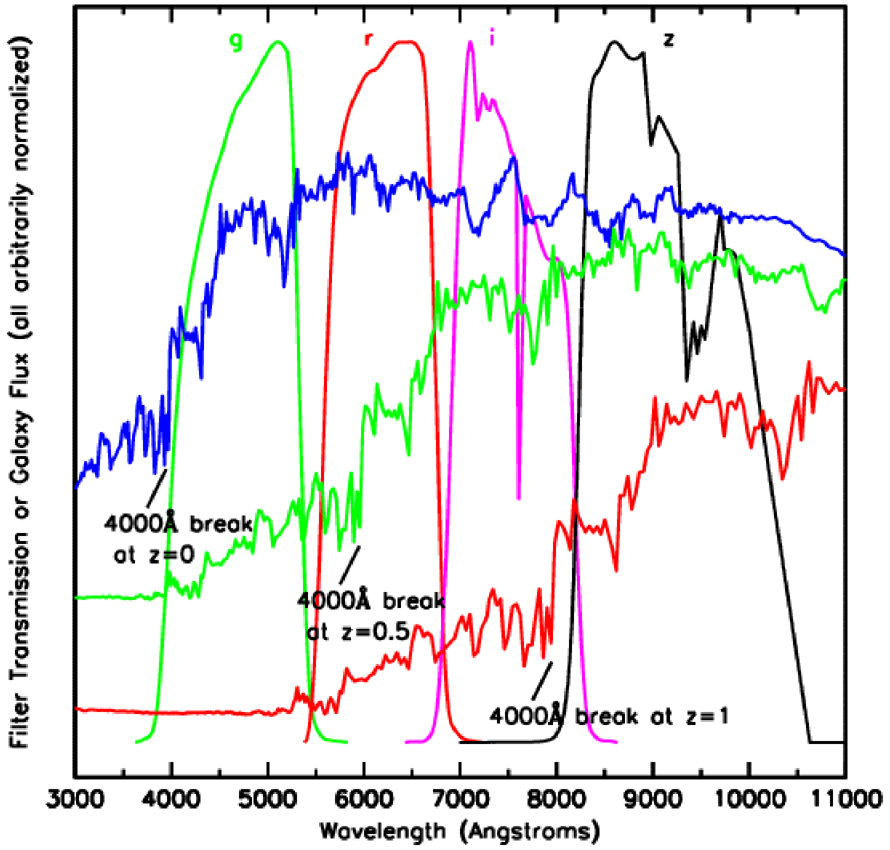
(M74, Lee)



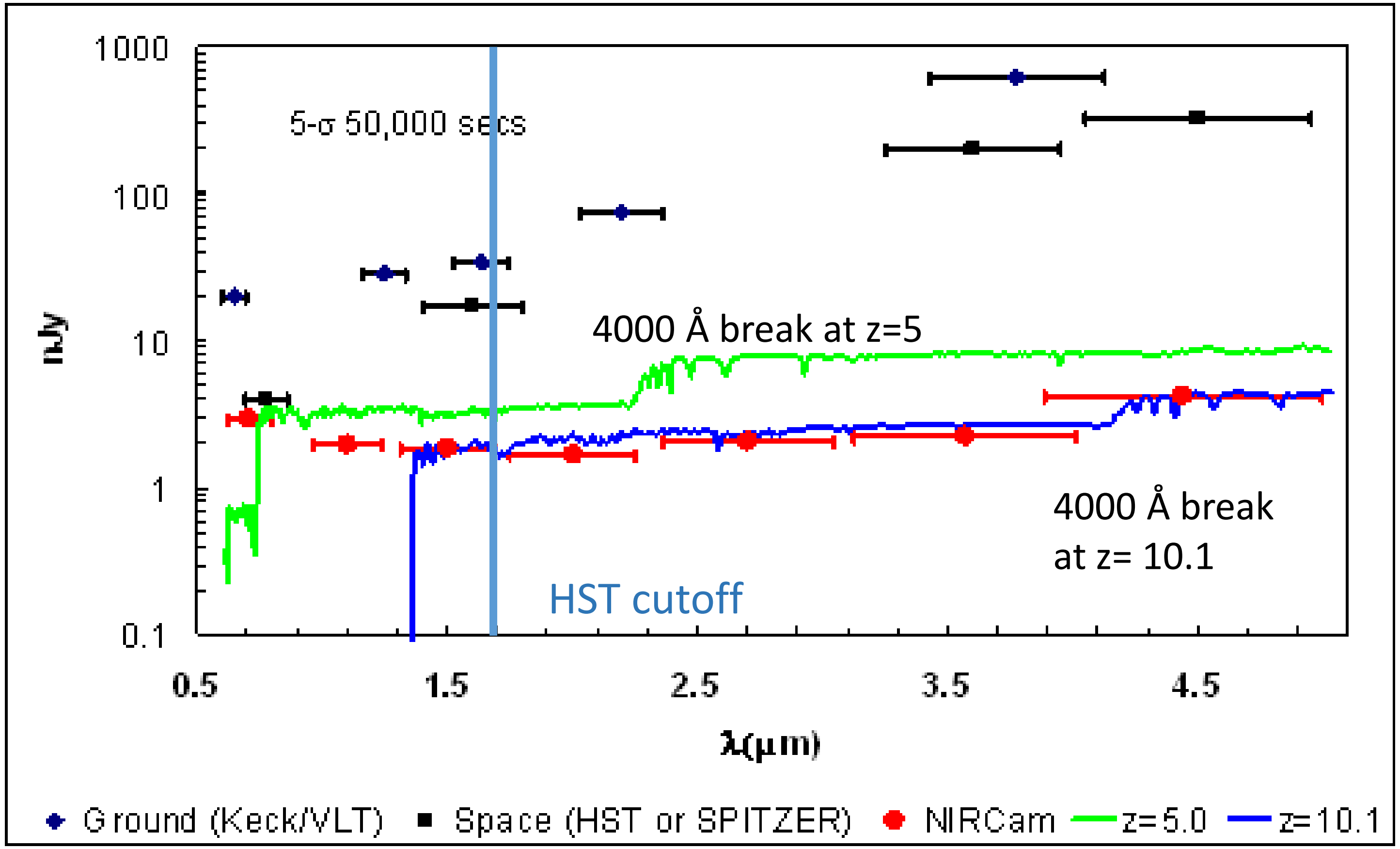


Multi-wavelength images of the Andromeda galaxy (Credit:Planck Collaboration)

Because of the expansion of the Universe, the farther a galaxy is from an observer, the faster it moves away. Thus ,the redshift caused by the Doppler effect can be used to estimate the galaxies' distances.



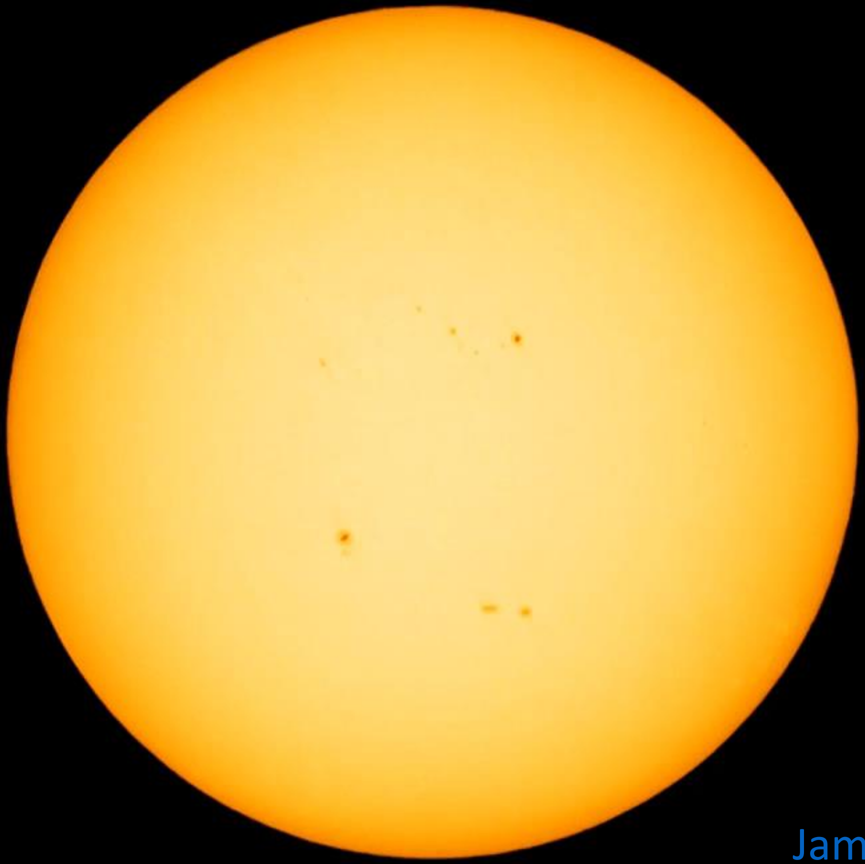
Credit: R. Wechsler

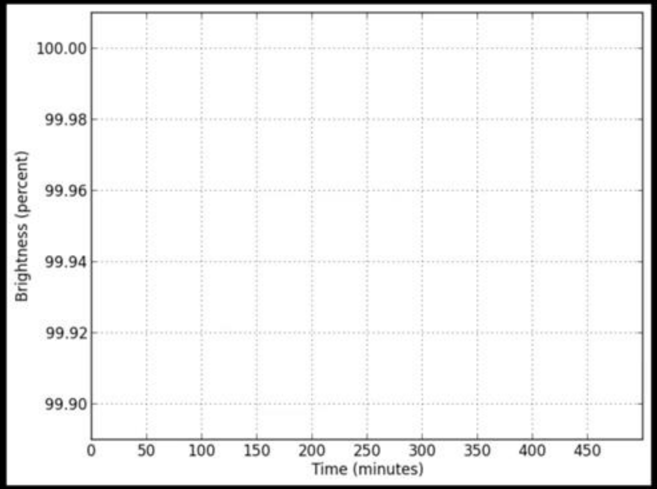


Credit: M. Rieke

- Measuring the galaxy spectra provides a reliable measure of distances
- However, acquiring galaxy spectra with enough signal that allows these measurements can be time consuming.
- An alternative process is to use the measurements of light through different filters (*photometry*) to estimate *photometric redshifts*.

Observing Modes:Time Series observation

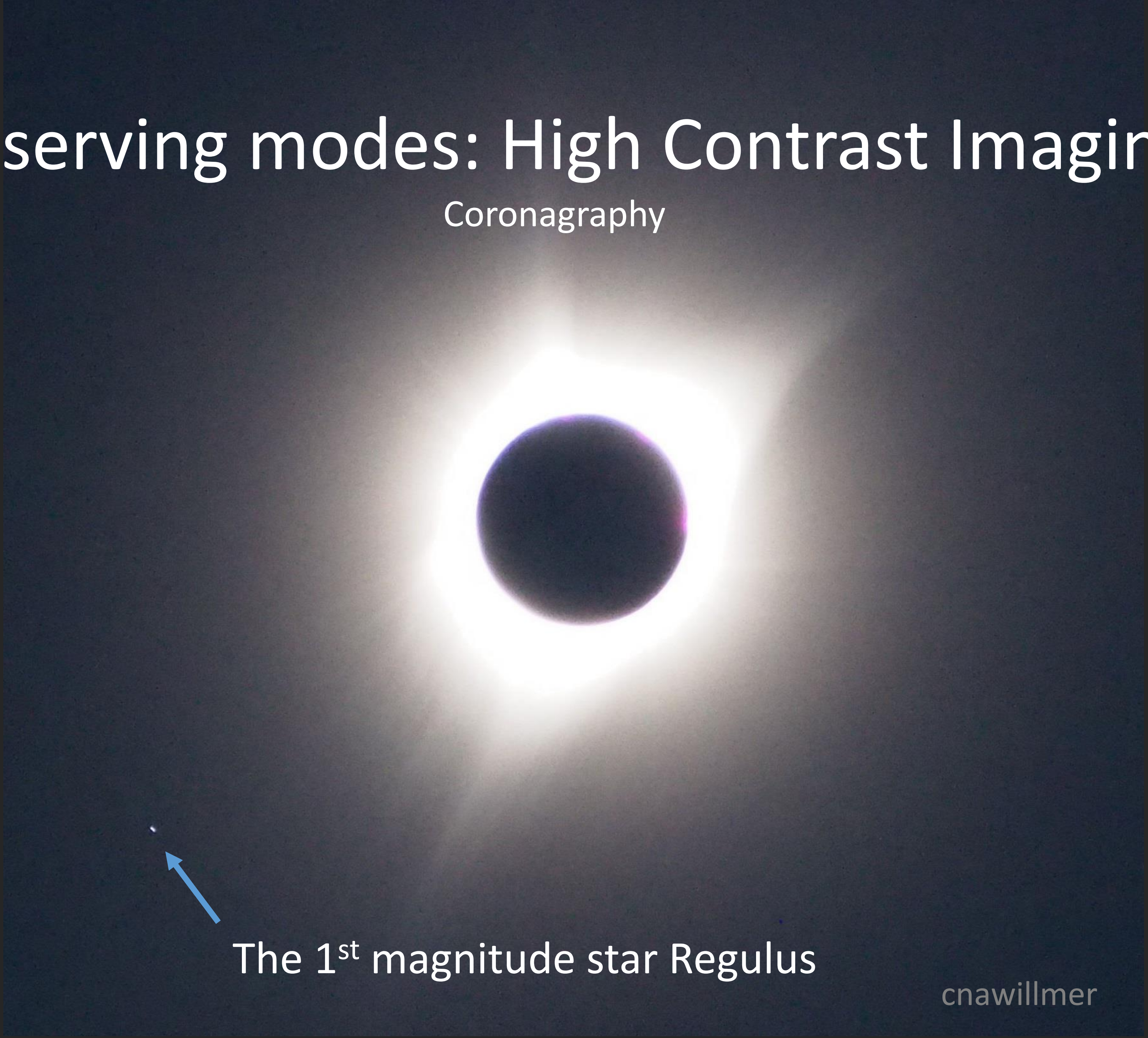




Jamie Gilbert: Transit of Venus 2012 June from Australia

Observing modes: High Contrast Imaging

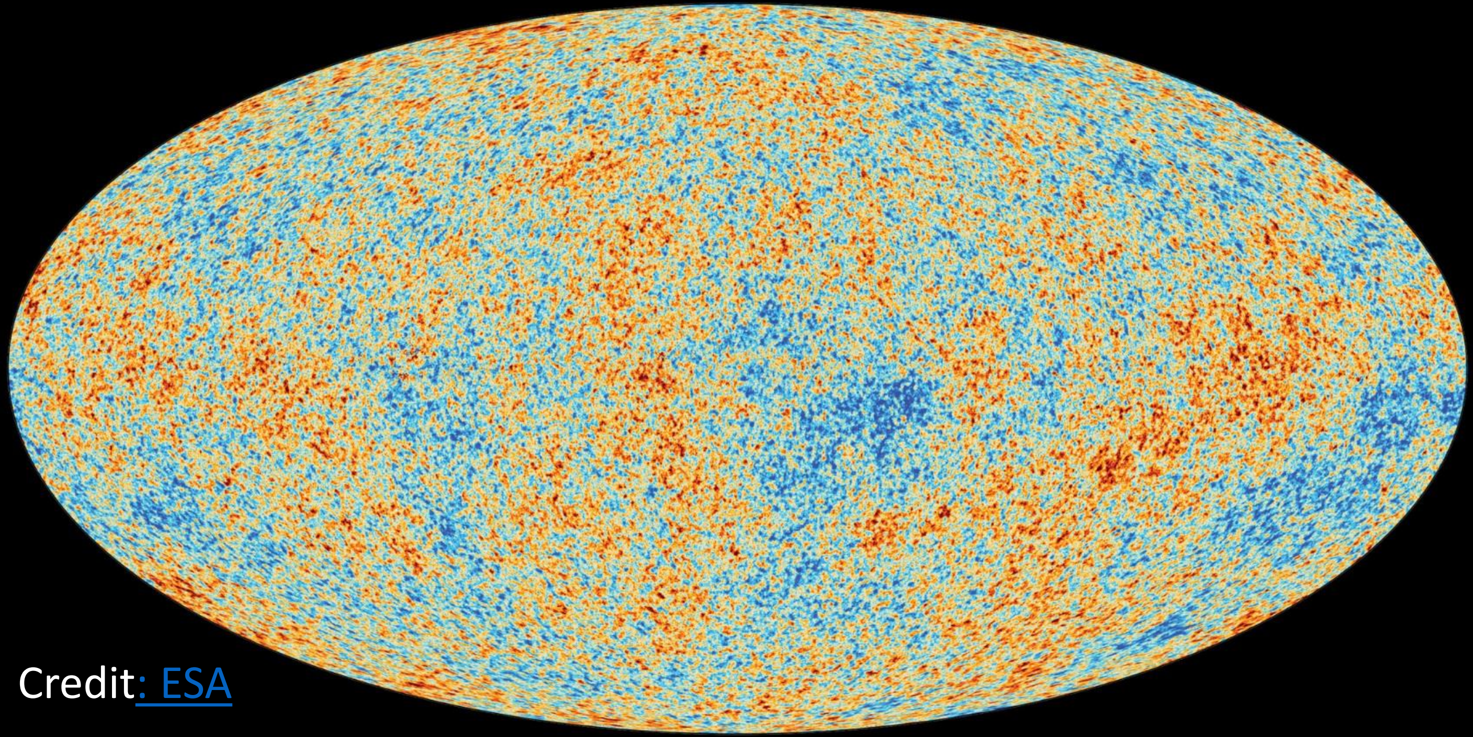
Coronagraphy



The James Webb Space Telescope

- The first conceptual designs for a large infrared-sensitive telecope date from the late 1980's (prior to the launch of HST).
- JWST is part of NASA's Cosmic Origins program.
- To investigate this connection JWST will address:
  - How did the first stars and galaxies form ?
  - What are the stellar life cycles and the evolution of elements ?
  - How did galaxies and super-massive black holes evolve?
  - What is the evolutionary history of the Milky Way and its neighbors?
  - How do planetary systems form and evolve ?

NASA's Cosmic Origins program seeks to explain the evolutionary connection between the



Credit: ESA

primordial fluctuations detected in the Cosmic Microwave background

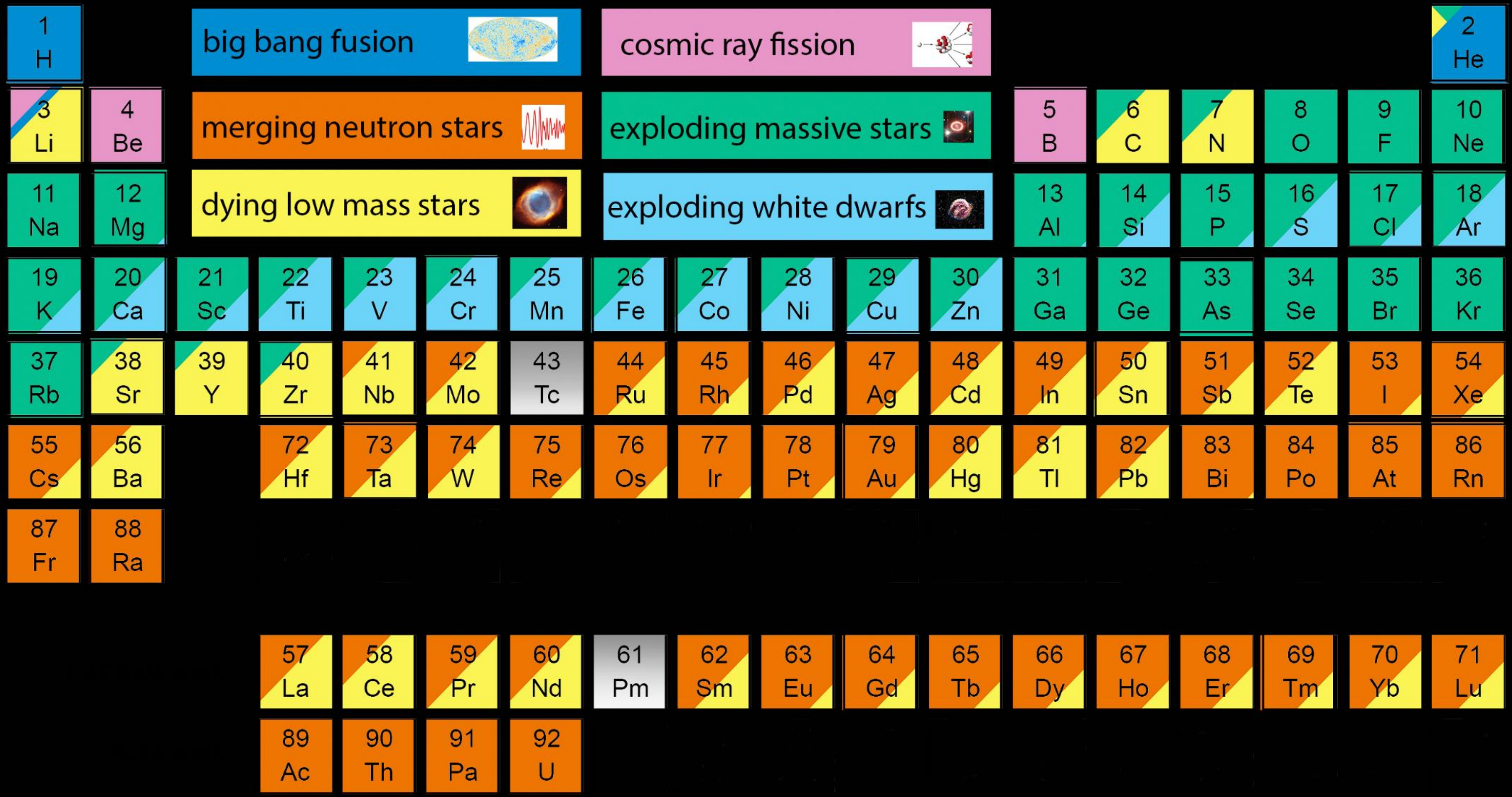
Credit : NASA

and conditions enabling habitability (and possibly life) on planets.

JWST as a "time-machine"
Probing the Redshift Frontier

- Light has a finite travel time and as we measure objects at greater distances we are also looking farther into the past.
- The Cosmic Microwave Background (CMB) is the most distant feature that can be observed.
- At the epoch CMB radiation was emitted, only the primordial elements (hydrogen, deuterium, helium, lithium) existed.
- The combination of theoretical models with observations allows inferring how non-primordial elements were formed.
- One of aims of Origins is to measure when these non-primordial elements were formed and how this fits in our models of star and galaxy formation.

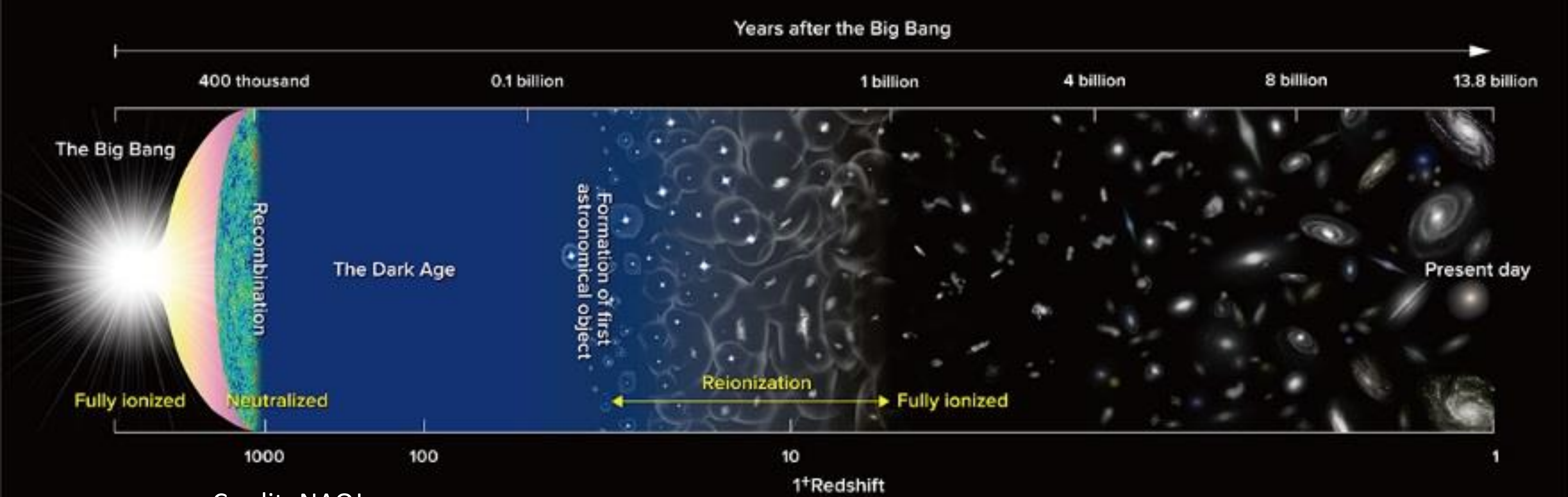
The Origin of the Solar System Elements



Graphic created by Jennifer Johnson

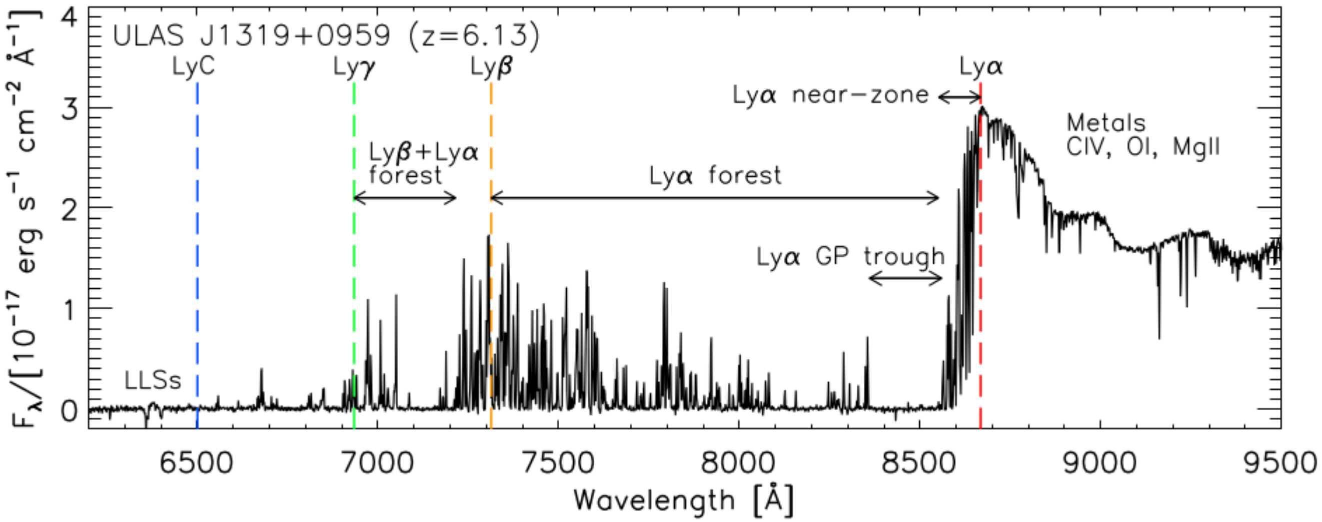
Astronomical Image Credits:
ESA/NASA/AASNova

Timeline of the Universe

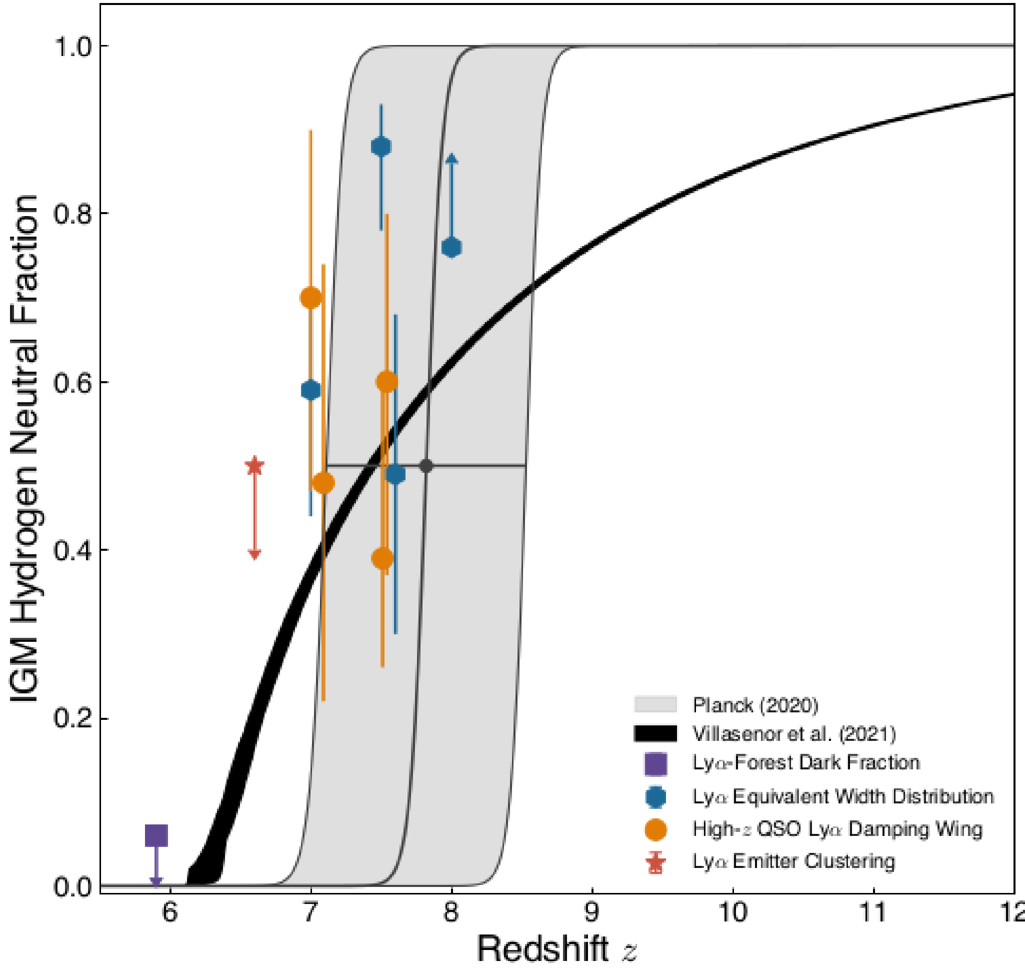


Credit: NAOJ

A major limitation prior to JWST has been the attenuation of ultra-violet light coming from early galaxies caused by neutral hydrogen along the line of sight in the so called "Era of Reionization".



Credit: Becker+2015

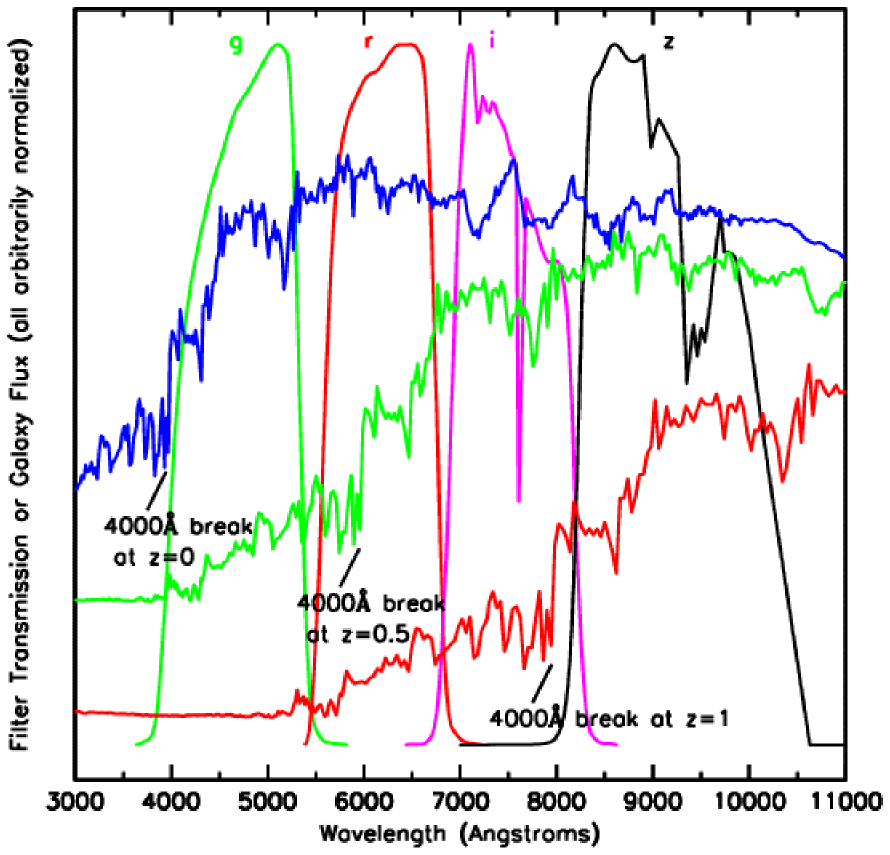


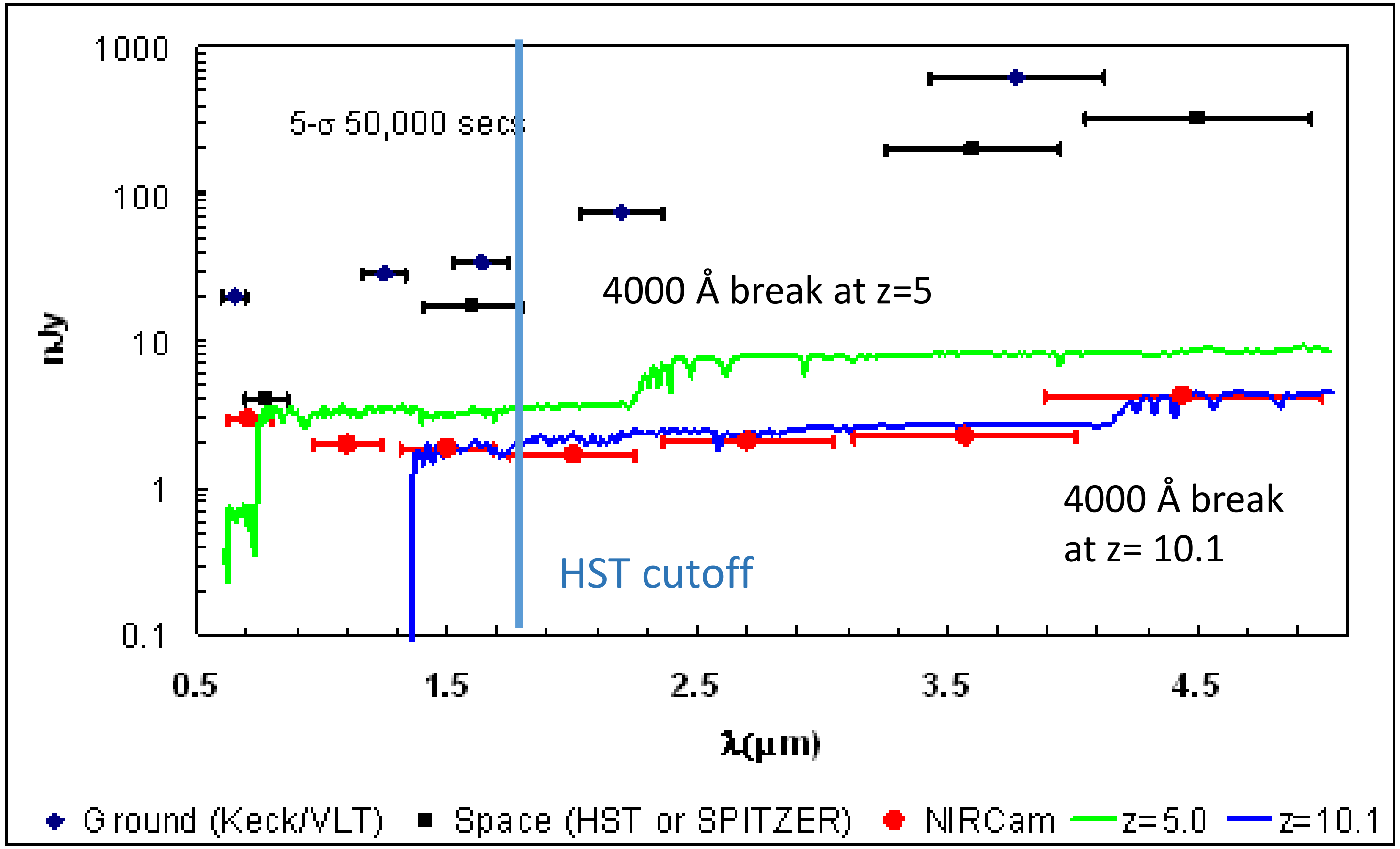
Credit: Robertson 2021

- These themes require observing in the Infrared ("IR"):
  - Because planets are colder than stars, the greatest contrast relative to their hosts is in the IR;
  - Dust absorption is smaller than in visible wavelengths – and actually *emits* in the longer wavelengths accessible to JWST

The Carina Nebula shows regions where dust is emitting light

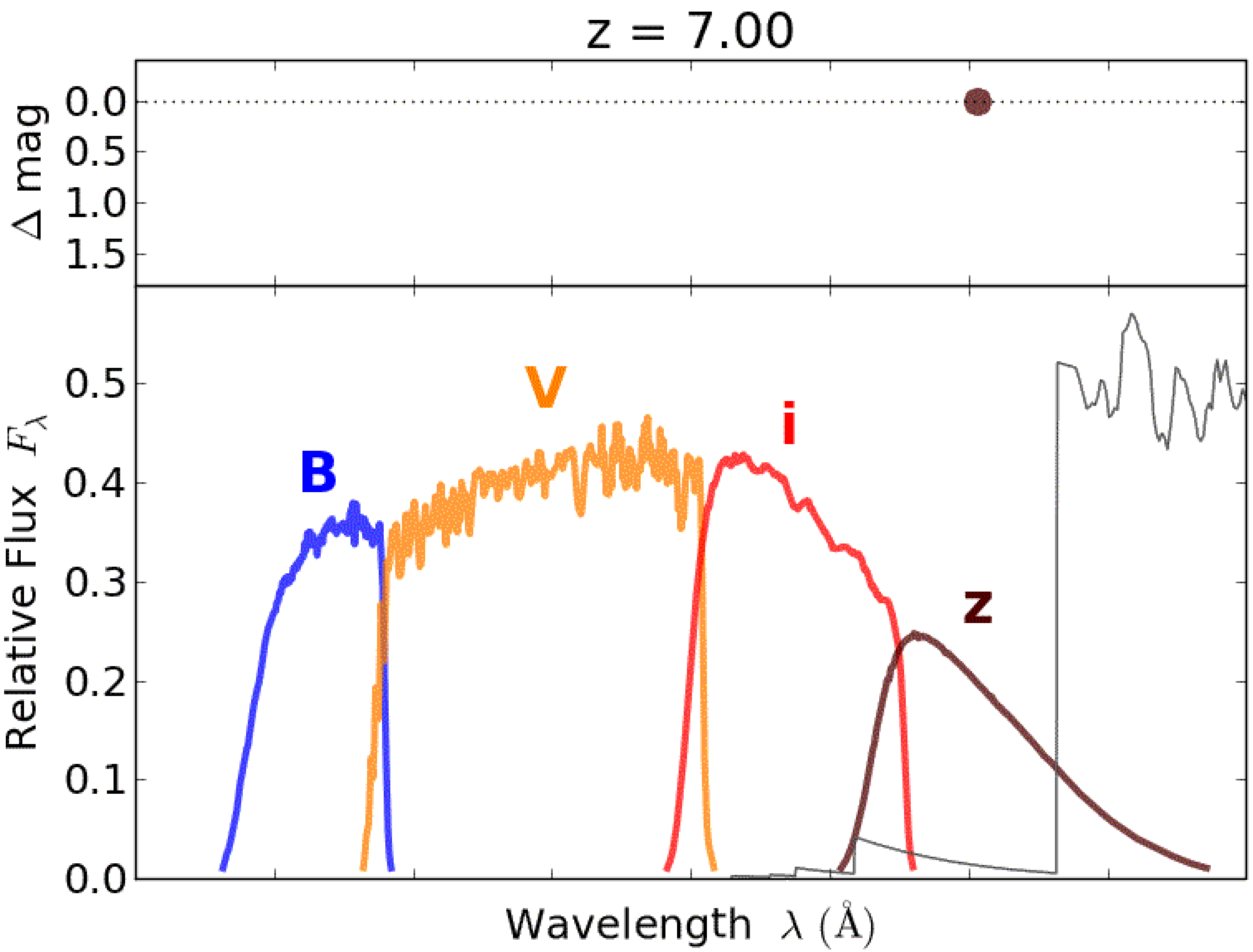
- These themes require observing in the Infrared (“IR”):
  - Because planets are colder than stars, the greatest contrast relative to their hosts is in the IR;
  - Dust absorption is smaller than in visible wavelengths – and actually *emits* in the longer wavelengths accessible to JWST
  - As we look at progressively more distant galaxies, their light is gets shifted further into the infrared because of the expansion of the universe;





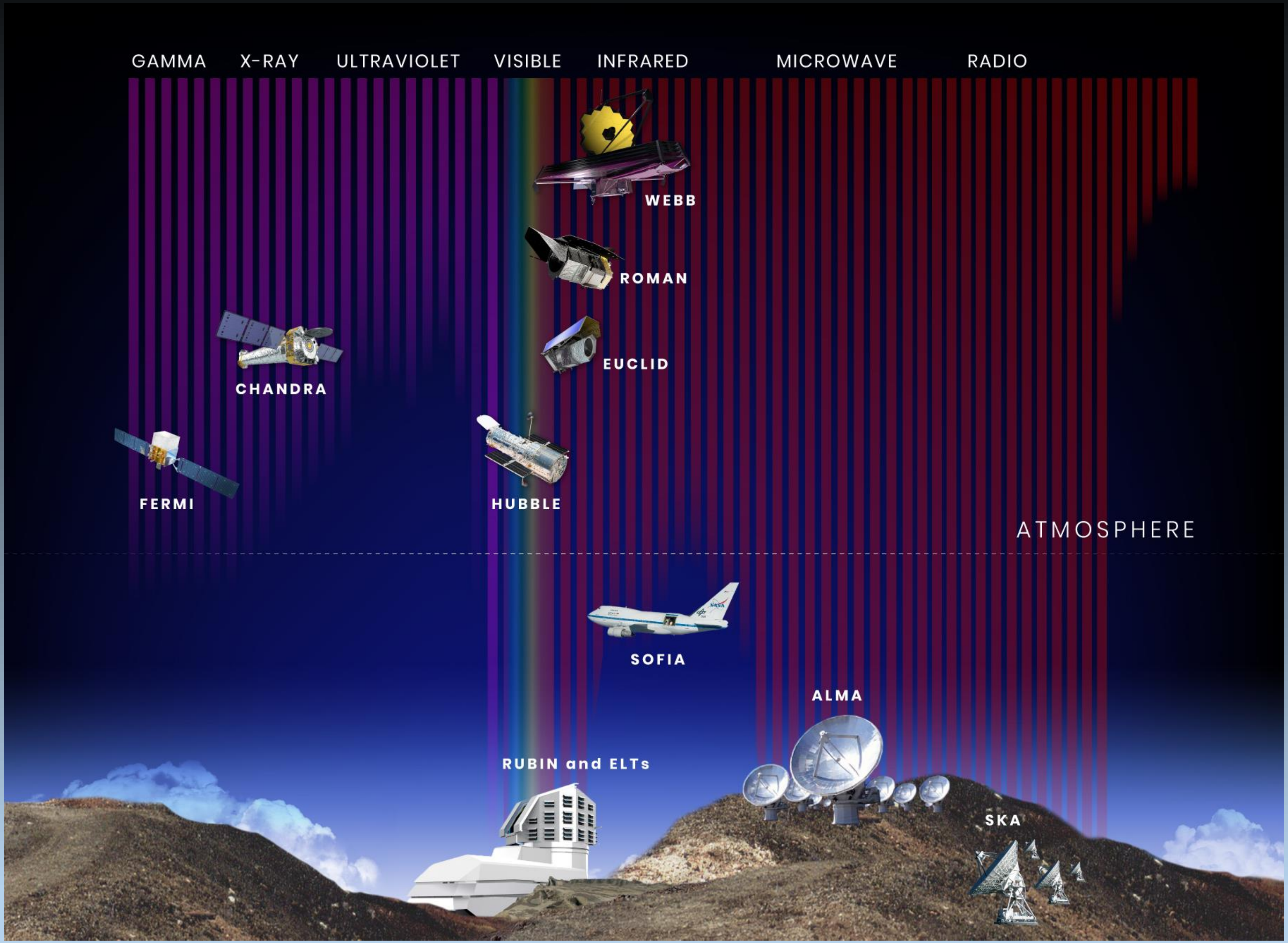
Credit: R. Wechsler

Credit: M. Rieke



z = 7.00
Δ mag
0.0
0.5
1.0
1.5
Relative Flux F_λ
0.5
0.4
0.3
0.2
0.1
0.0
B
V
i
z
Wavelength λ (Å)

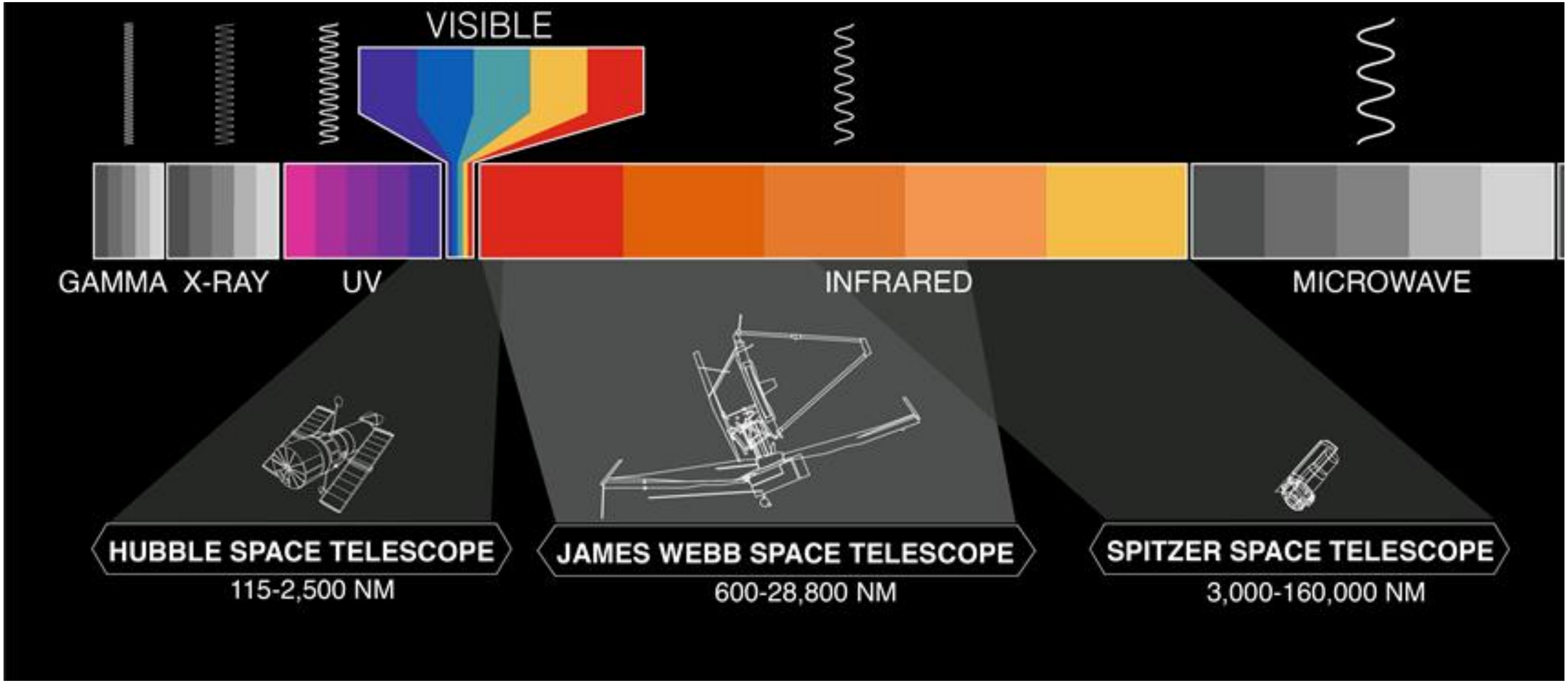
- IR observations from ground-based observatories are severely impacted by the emission by the atmosphere and telescopes themselves.
- In addition, there are wavelength ranges where the atmosphere is opaque, and no light from the sources detected, creating gaps in coverage.
- For these reasons to properly address the Origins science themes the observations need to be carried out from space.
- While Hubble Space Telescope is in space, its instruments are not cooled to the level where infrared detectors' noise becomes negligible.


GAMMA
X-RAY
ULTRAVIOLET
VISIBLE
INFRARED
MICROWAVE
RADIO
WEBB
ROMAN
EUCLID
CHANDRA
FERMI
HUBBLE
ATMOSPHERE
SOFIA
ALMA
RUBIN and ELTs
SKA

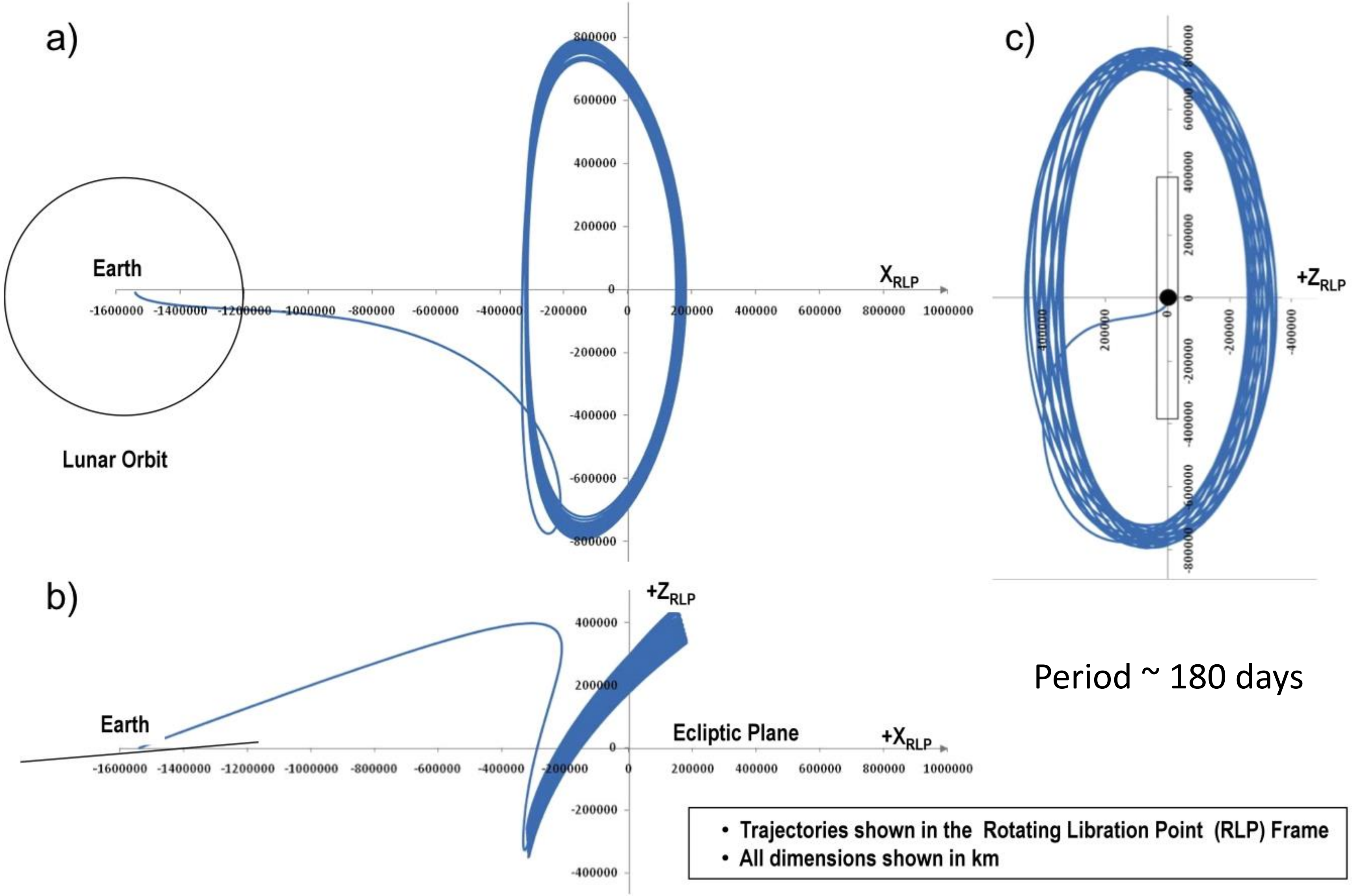
Trivia

- JWST is an infrared-optimized telescope initially designed to explore the high redshift universe and search for cold companions of stars (https://jwst-ngst.ucolick.org/assets/docs/NGST-JWST's-Early-Days-Overview.pdf).
- Joint project of NASA, ESA and CSA.
- JWST is in a solar orbit around the Second Lagrangian point (L2):
  - Efficient passive cooling as telescope is always pointed away from the Sun;
  - Keeps JWST out of shadows of Earth and Moon so solar panel is always illuminated;
  - Ease of communication (always visible from some Deep Space Network station);
  - Minimizes use of propellant ;
  - None of the limitations that affect HST by being in the Earth's orbit.

HST, JWST, SPITZER compared



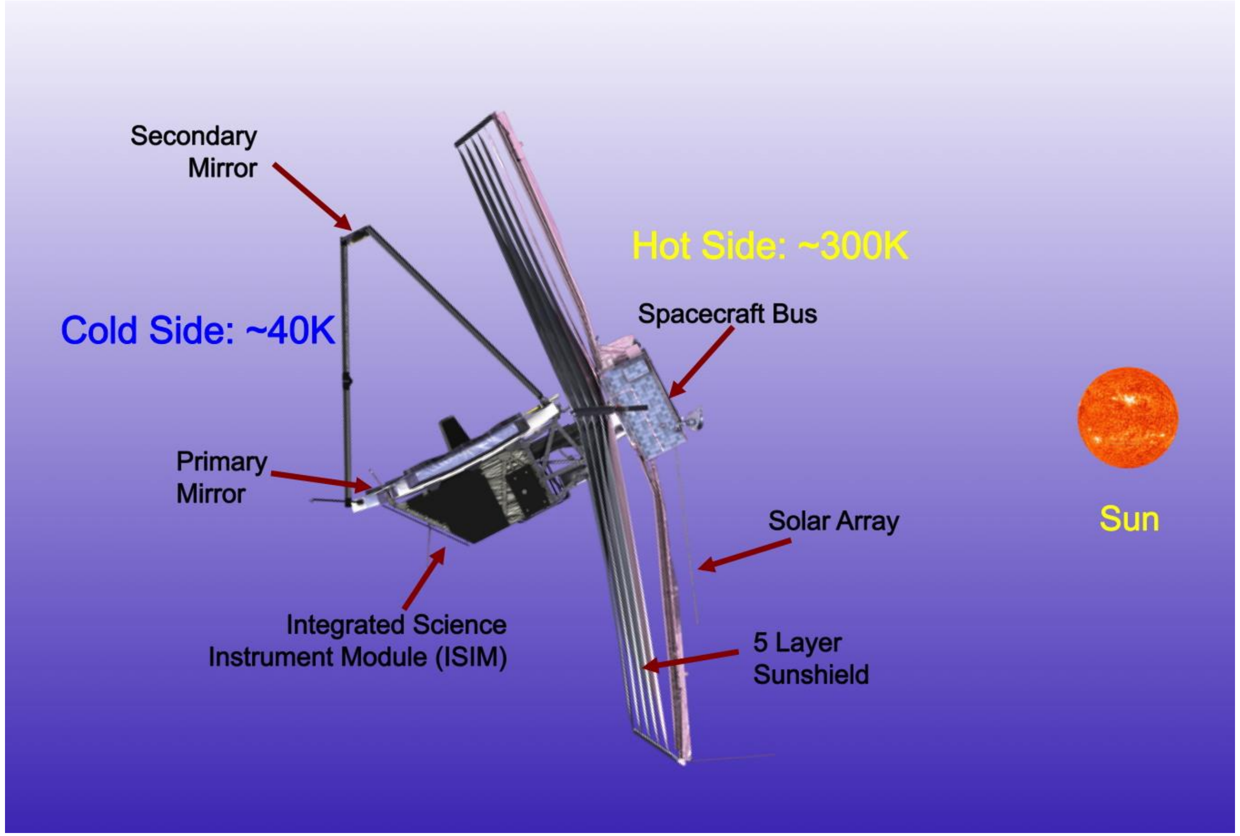
JWST's orbit around L2



Period ~ 180 days

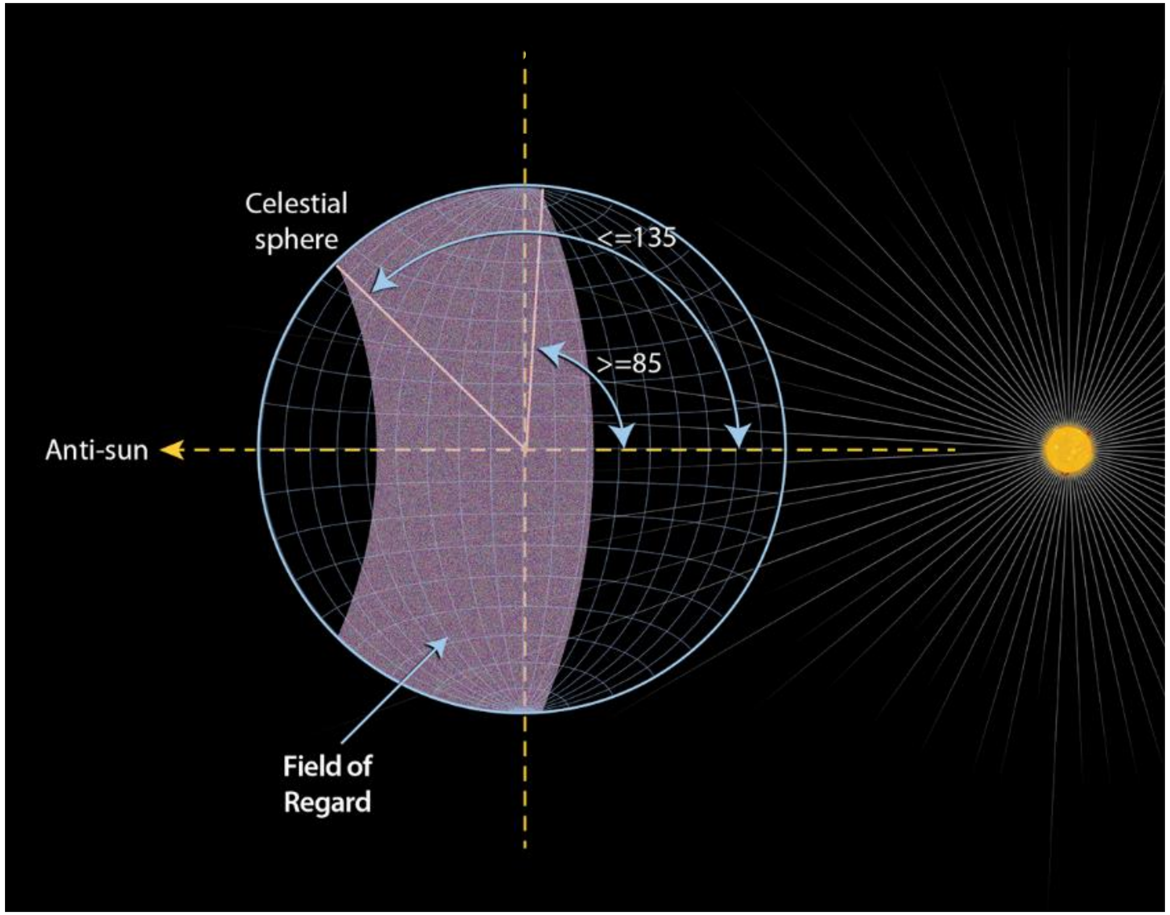
- Trajectories shown in the Rotating Libration Point (RLP) Frame
- All dimensions shown in km

JWST Components

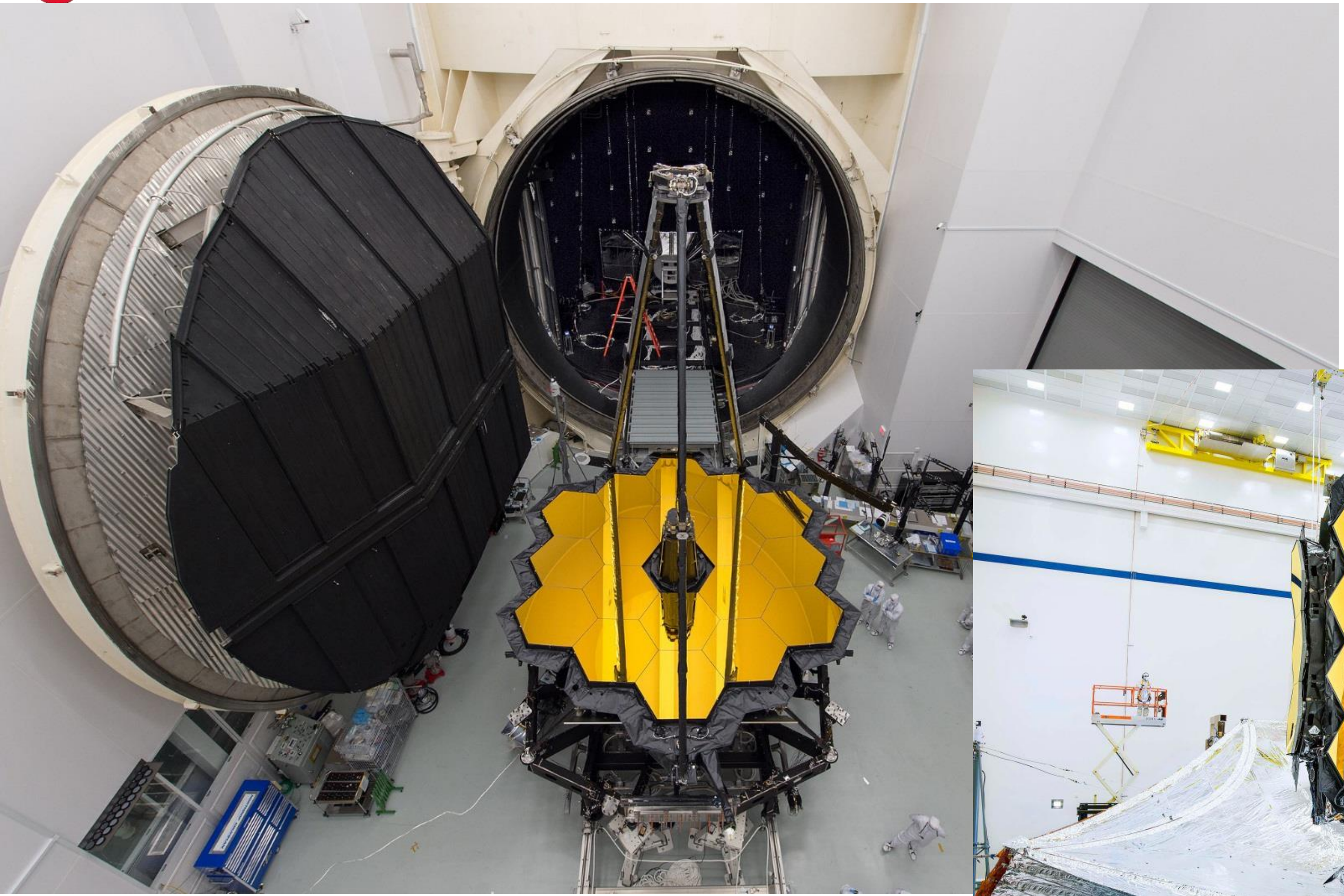


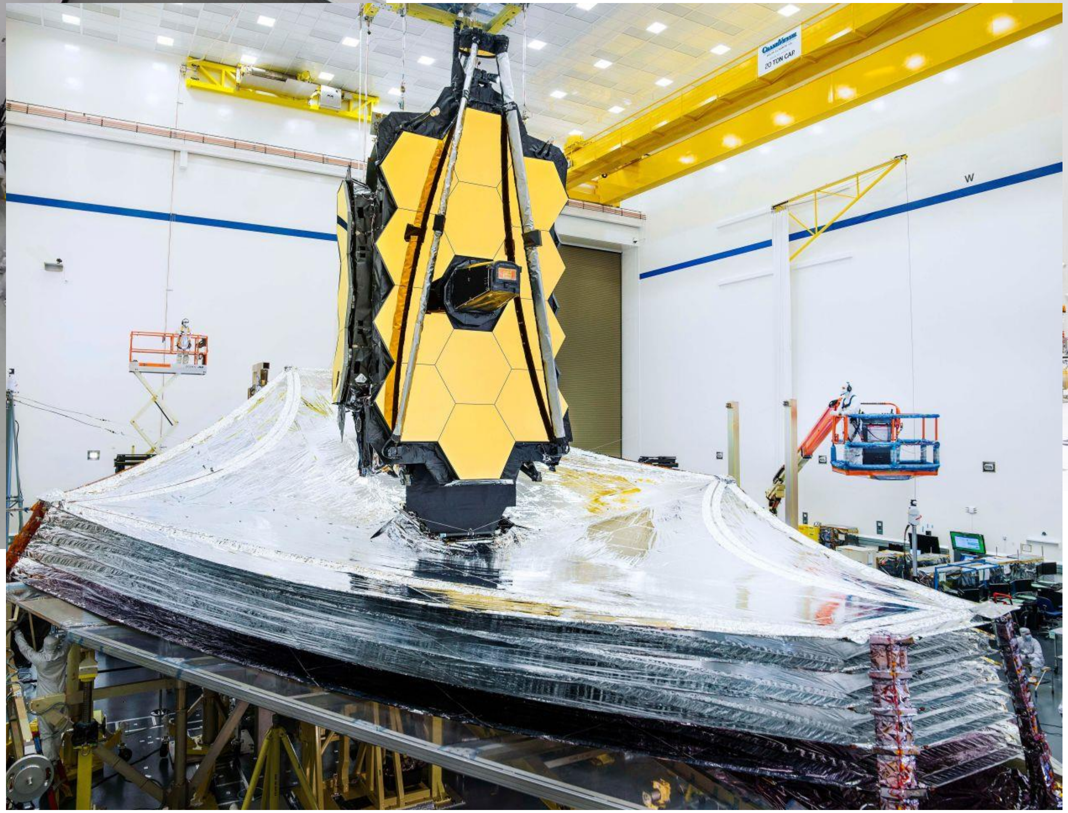
- JWST comprises:
  - The OTE (Optical Telescope Element);
  - The Integrated Science Instrument Module (ISIM);
  - The Spacecraft (sunshield, navigational devices, antennas, solar array)
- The OTE elements (primary, secondary and tertiary mirrors) are all gold-plated to optimize the infrared reflectance.
- The primary mirror has a diameter ~6.5 m and ~25.4 m^2 area with 18 segments made of beryllium (because of the light weight and low expansion coefficient).

JWST Field of regard



- Because JWST needs to maintain an attitude that blocks solar radiation from hitting the optics, and solar panel illuminated only a limited region of sky is accessible at a given instant. This restricts the dates and position angles in which an object can be observed. These observing windows are determined by the sources's ***ecliptic*** coordinates



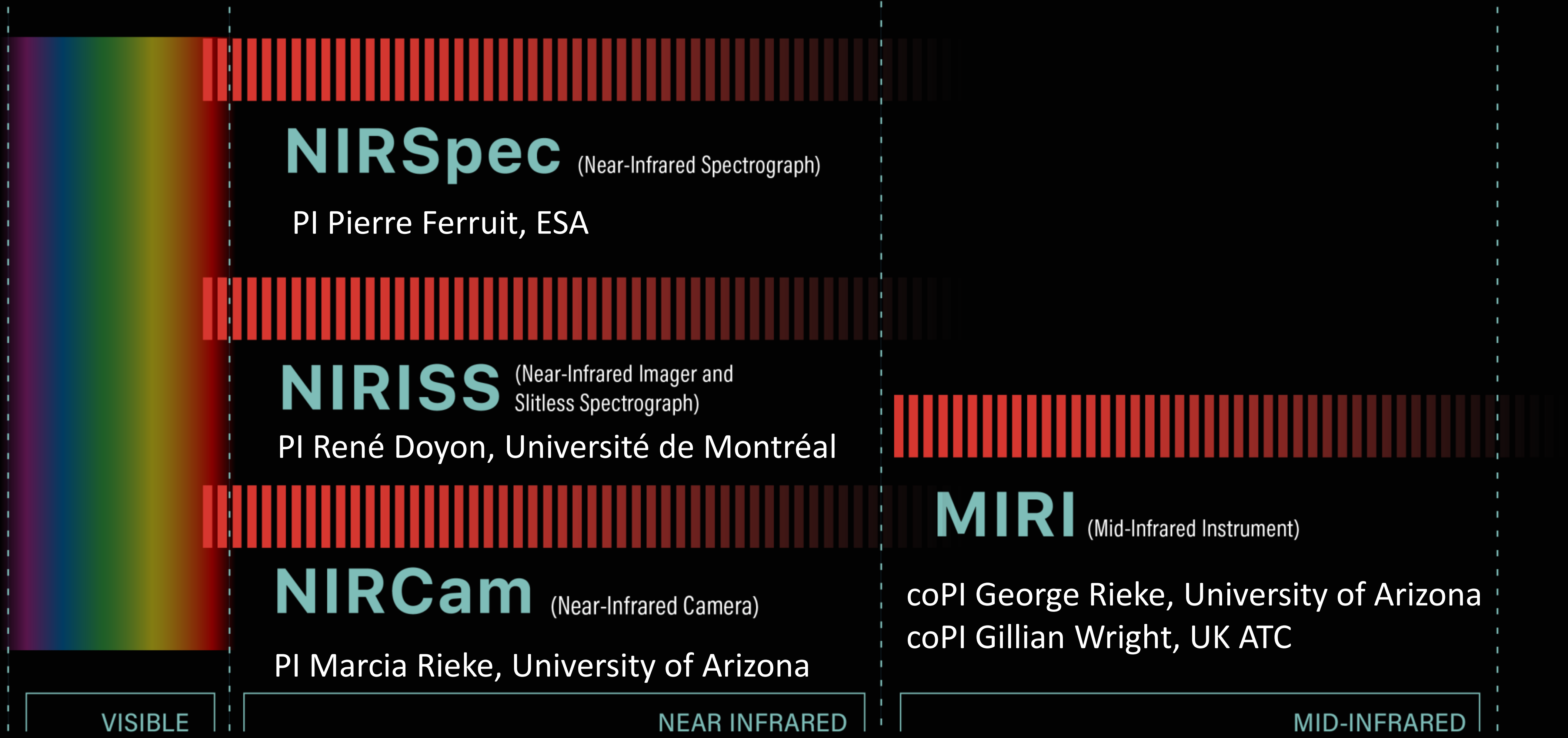


NASA Flickr

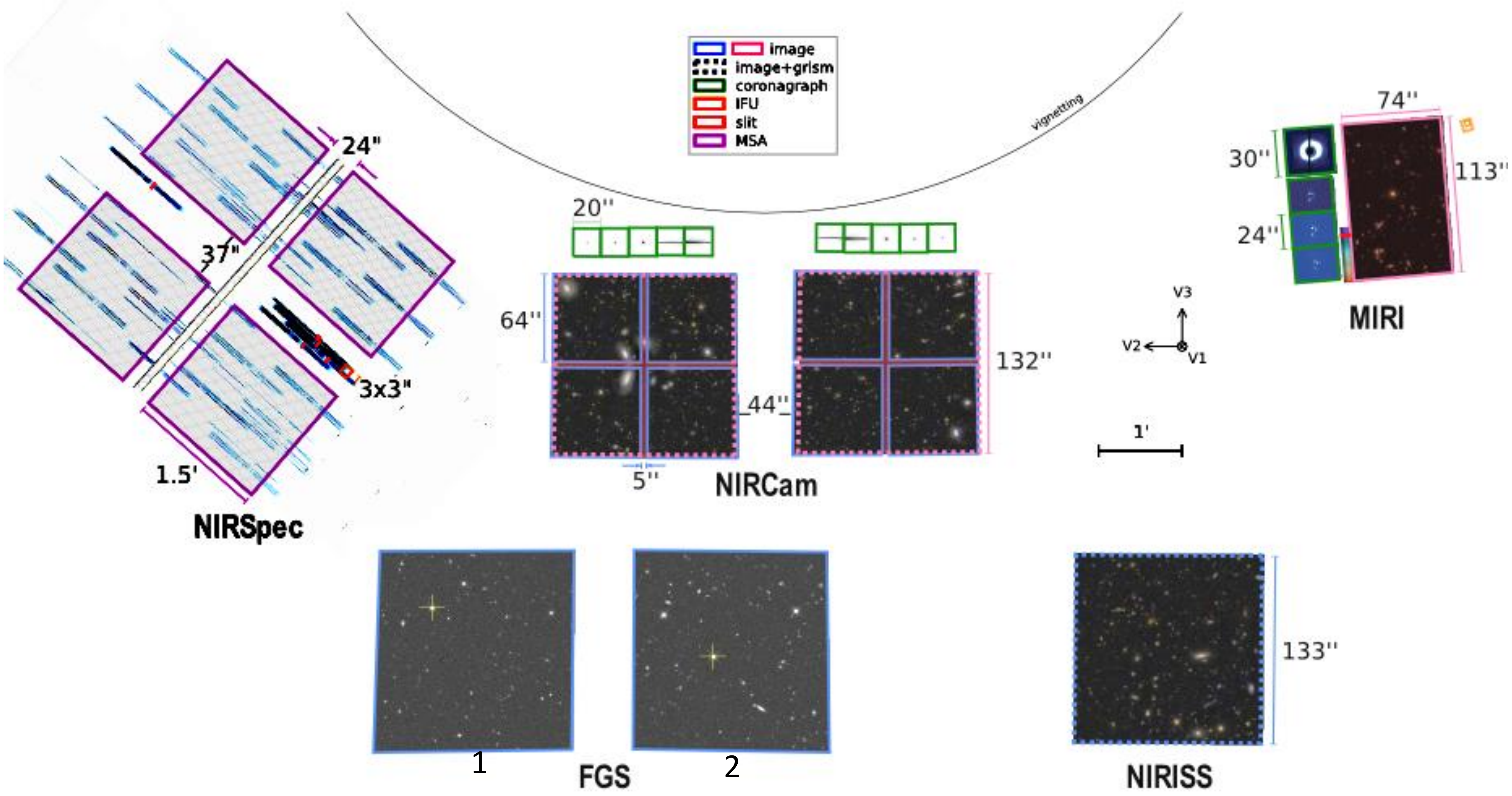
Instruments

- Fine Guidance Sensors (FGS1, FGS2);
- Mid Infrared Instrument (MIRI);
- Near Infrared Camera (NIRCam)
- Near Infrared Imager and Slitless Spectrograph (NIRISS);
- Near Infrared Spectrograph (NIRSpec);
- Most instruments are passively cooled to ~37 K, with the exception of MIRI which has an operational temperature of ~6K through the use of liquid helium.

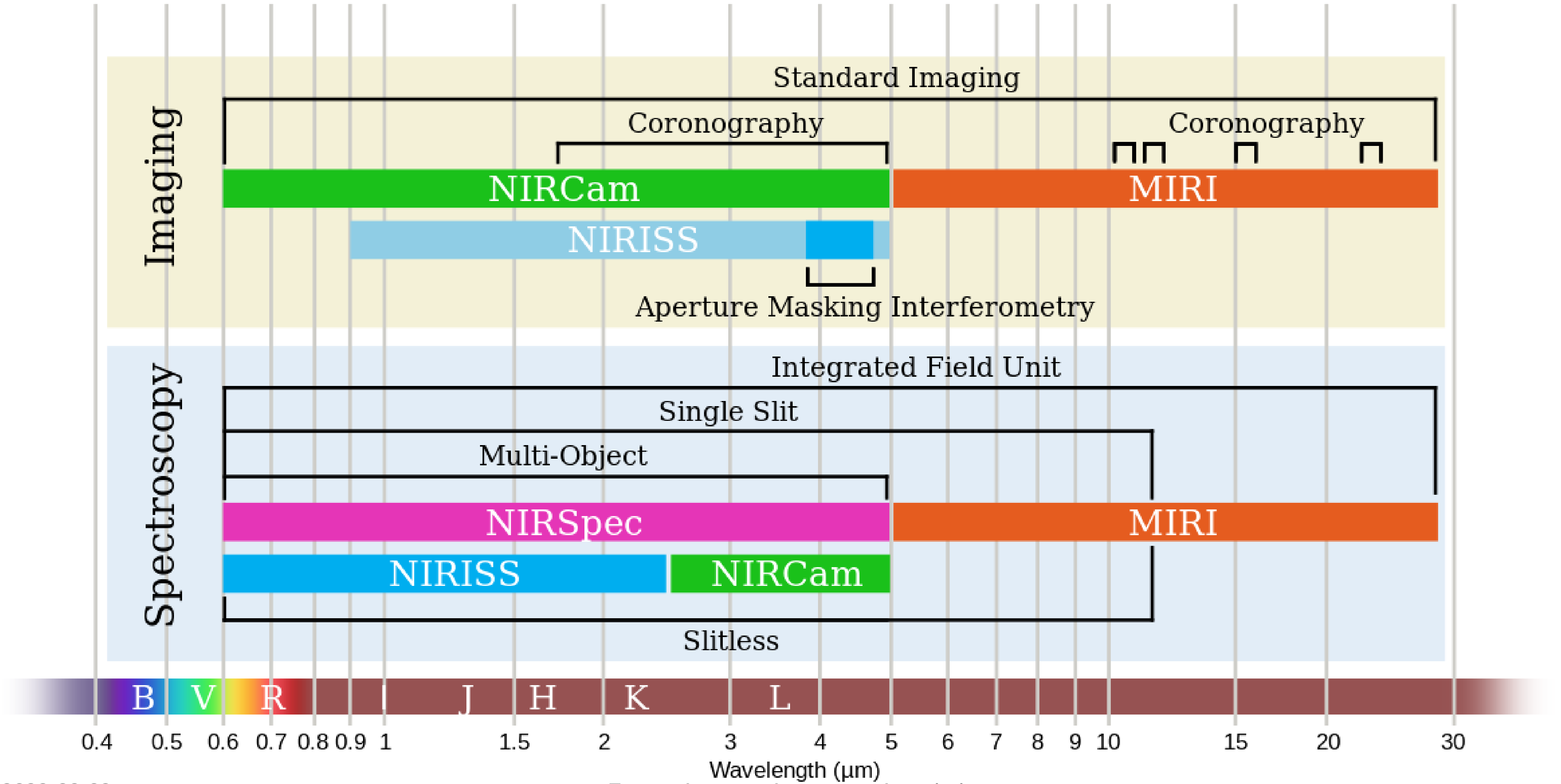
Webb's Powerful Hardware



JWST Focal Plane



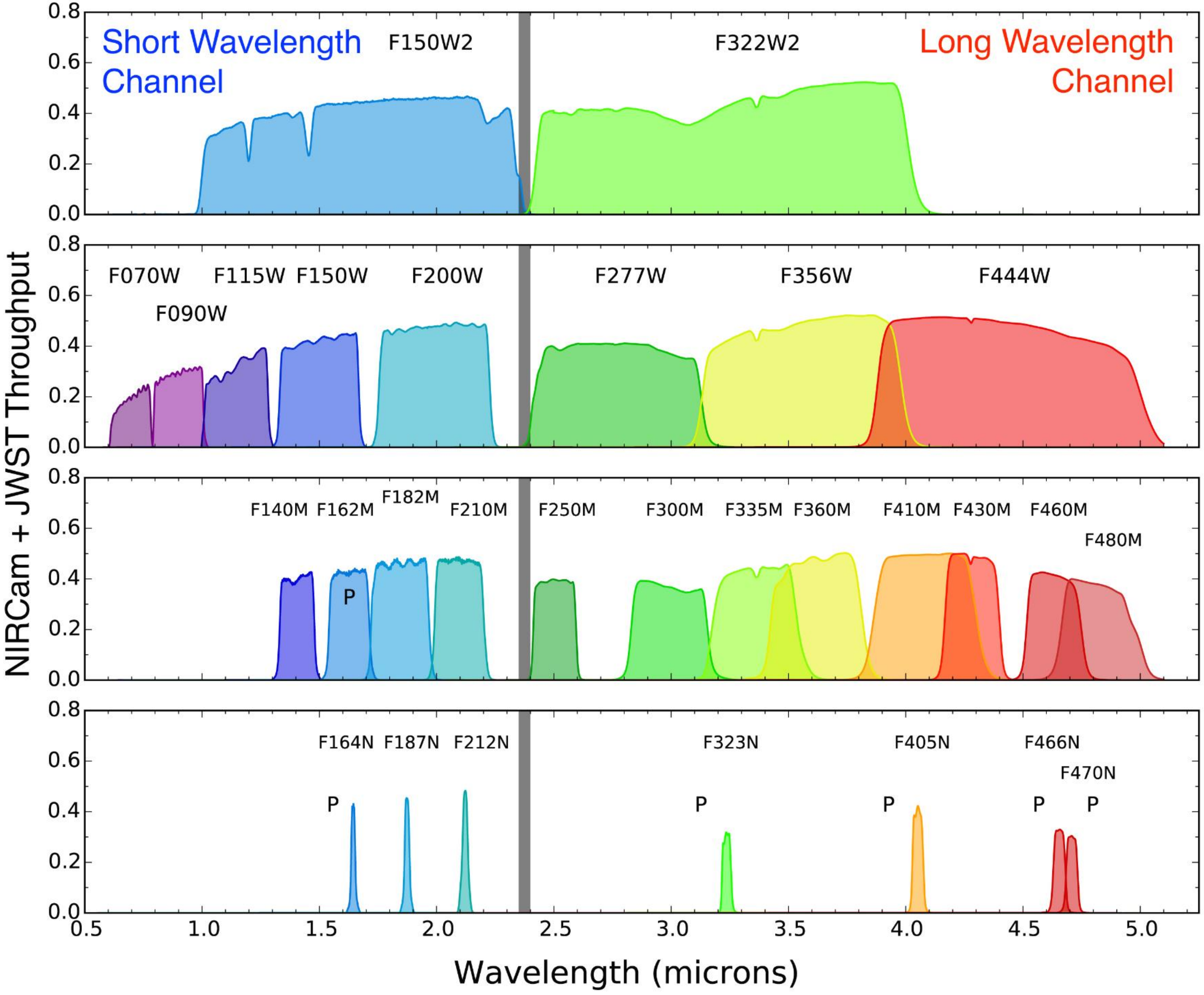
JWST observation modes and wavelength domain



NIRCam

- Wide field imaging (wide, medium and narrow band filters)
- Coronagraphy (high contrast imaging using round and bar Lyot stops, subset of filters)
- Wide Field Slitless Spectroscopy R~1699 from 2.4 to 5.0 μm (long wavelength channel)
- Time Series Observations: imaging
- Time Series Observations: spectroscopy

NIRCam Filters



NIRISS

- Wide Field Imaging
- Wide field slitless spectroscopy (R~150, WFSS, GR150, GC150 grisms)
- Single object slitless spectroscopy (R~ 700, SOSS, GR700XD grism)
- High resolution imaging through aperture masking interferometry (using a non-redundant mask - NRM).

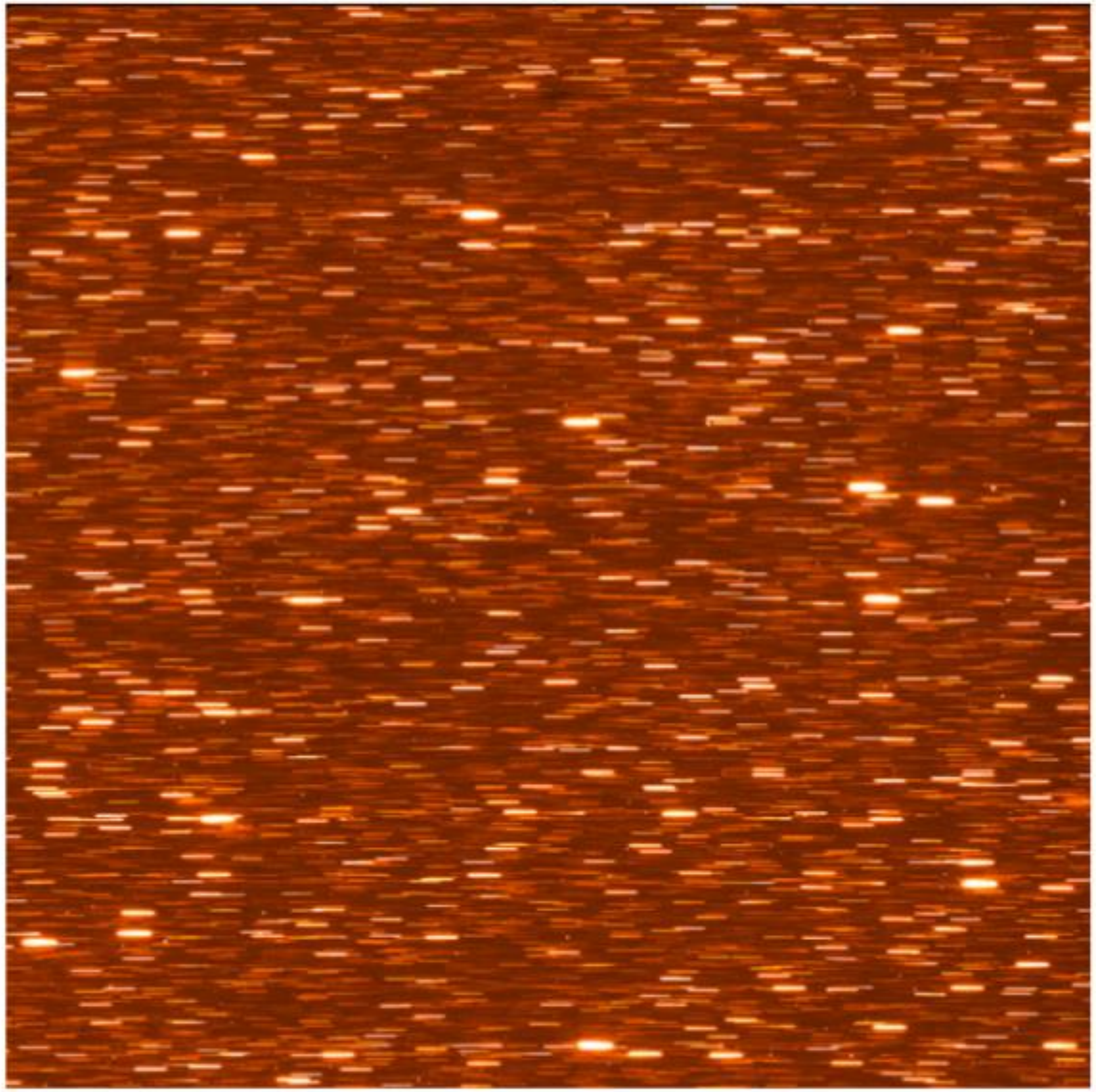
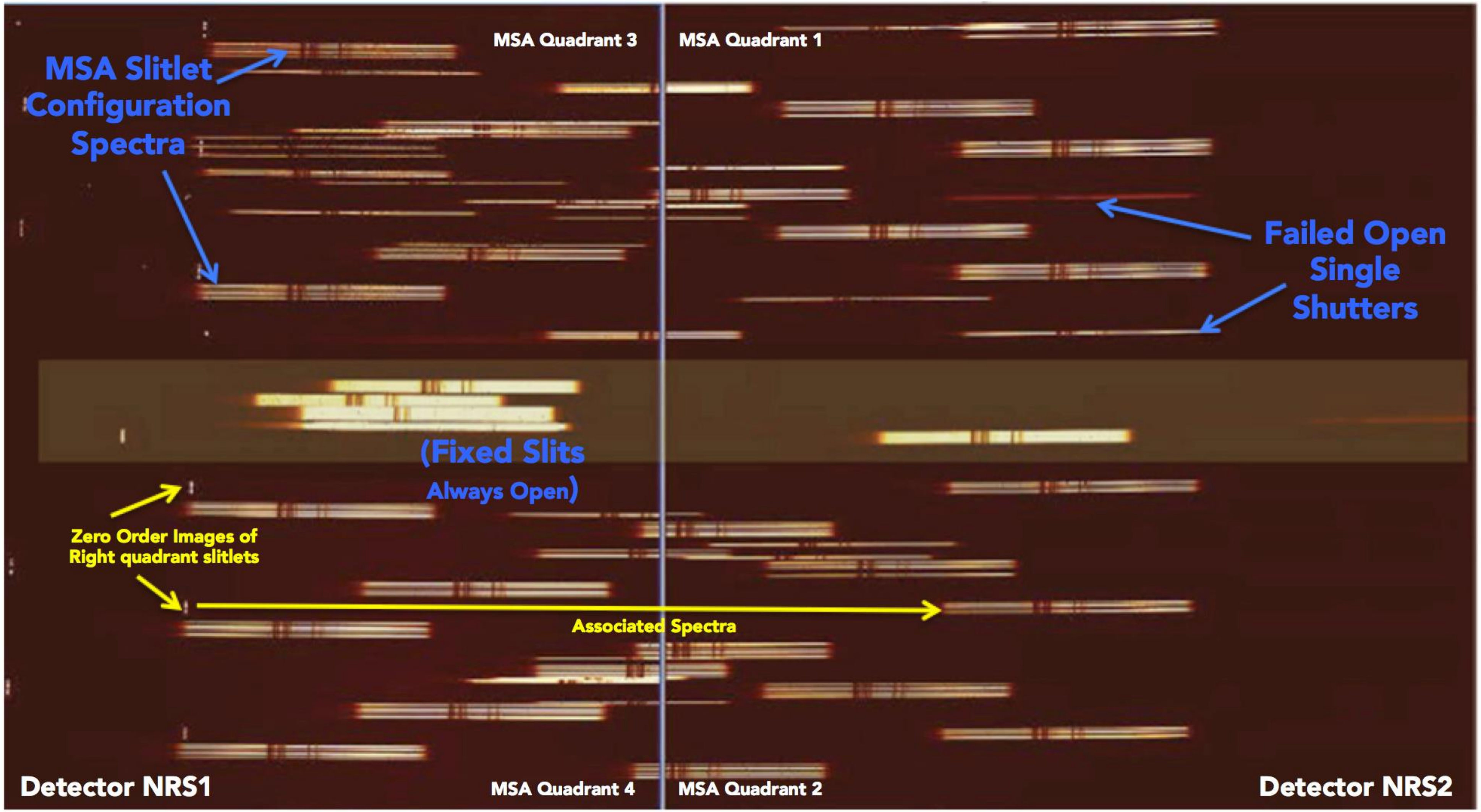


Figure 15: NIRISS WFSS. *Simultaneous spectroscopy of thousands of stars in the NIRISS focus field of the LMC. Configuration is grism GR150C and filter F115W. Data from PID 1085.*

NIRSpec

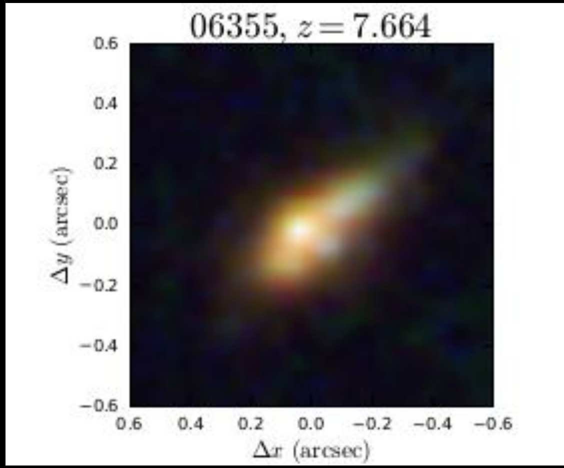
- Bright object time series (BOTS; wide square slit)
- Fixed slit spectroscopy (FS)
- Integral field unit spectroscopy (IFU)
- Multi-object spectroscopy with microslit shutter array (MSA)

NIRSpec : location of different components



Types of sources JWST will observe
(not a complete list!)

- Galaxies
  - From resolved galaxies in the local volume to the redshift frontier
  - Very high redshift quasars
- Interstellar Medium of the Galaxy
  - Dark clouds
  - Young Stellar Objects
  - Debris disks
  - Brown dwarfs
- Exoplanets
- Solar System
  - Planets
  - Asteroids, Kuiper Belt Objects
- JWST cannot observe any object to the interior of its orbit (e.g., Moon, Sun, Venus, Mercury)
- Full list of Cycle 1 approved programmes


06355, $z = 7.664$
0.6
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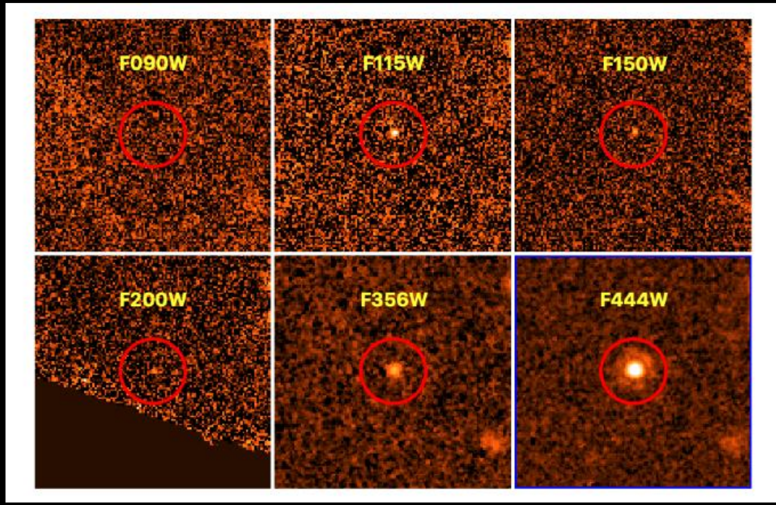
0.6 0.4 0.2 0.0 −0.2 −0.4 −0.6
Δx (arcsec)


F090W
F115W
F150W
F200W
F356W
F444W

Commissioning Tasks

- Commissioning allows characterizing and making initial calibrations of an observatory (true for space and ground-based)
- Calibrations
  - Mirror alignment
  - Precise map of instrument internal distortions (imaging and spectroscopy)
  - Precise map of the focal plane on orbit
  - Space-based dark current and flat-field images
  - Throughput measurement
- Demonstrate the instrument readiness for science observations
  - A total of 17 instrument observing modes were tested.
  - A few additional observing modes will be tested during Cycles 1 and 2.
- Tests involve
  - Imaging (wide field and high-contrast)
  - Spectroscopy
  - Time Series Observations (aka “TSO”)
  - Guiding on moving targets

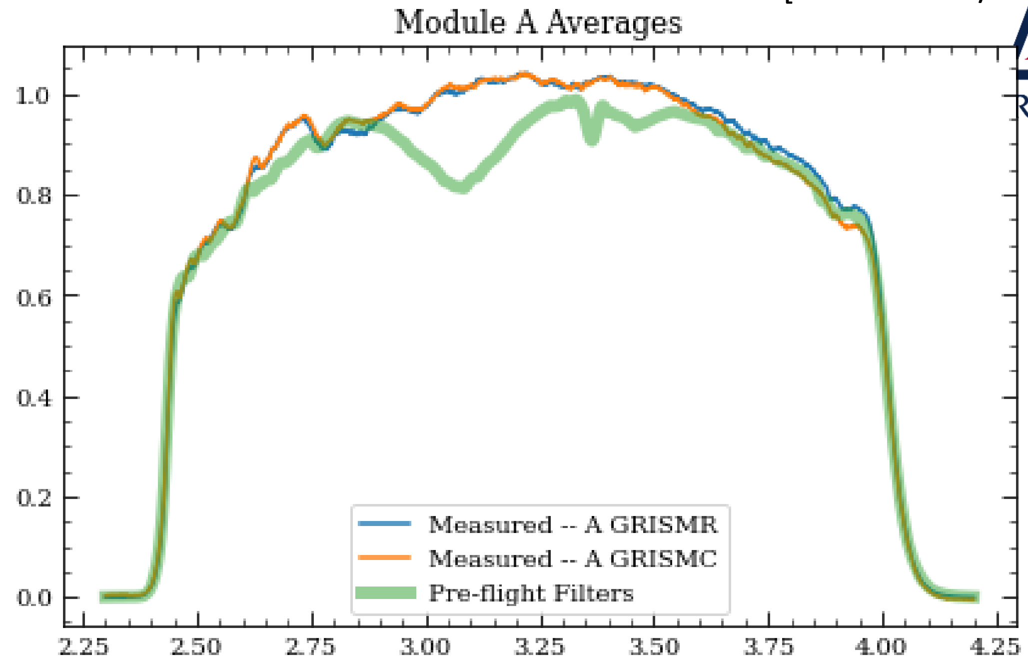
Some results

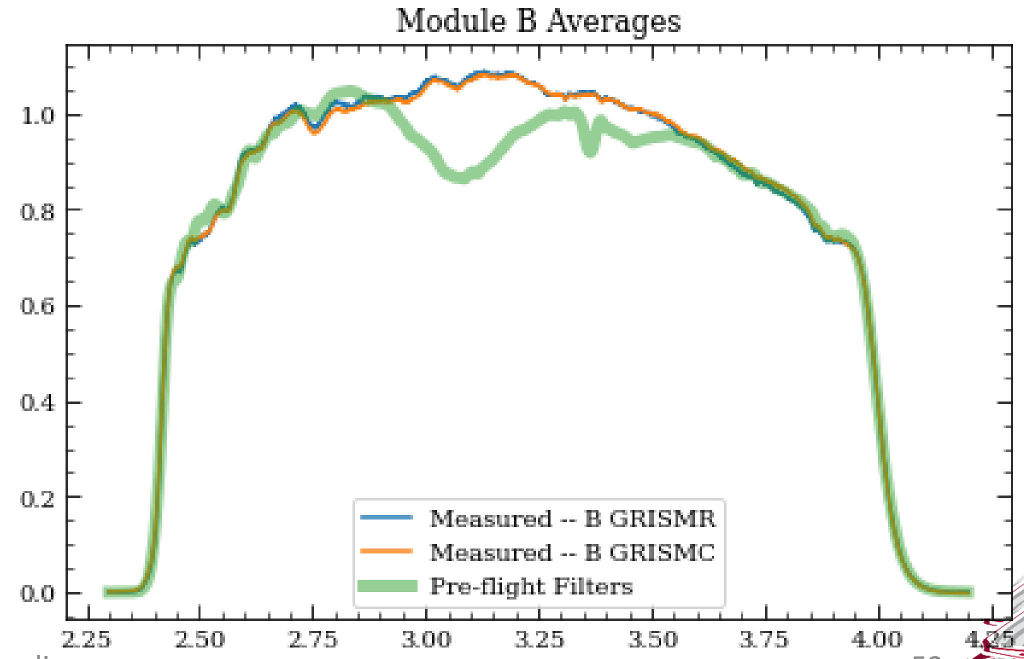
(for a detailed discussion see Rigby+ 2022)

- No signal of residual water ice on the optics has been detected.
- Throughput of mirror+instruments higher than requirements.
- While requirements were for diffraction limit at ~ 2 μm, the telescope is diffraction-limited at about 1 μm.
- Telescope pointing is very good and very stable (within 1 milliarcsec).
- JWST is able to track moving sources without any effect on the image quality.

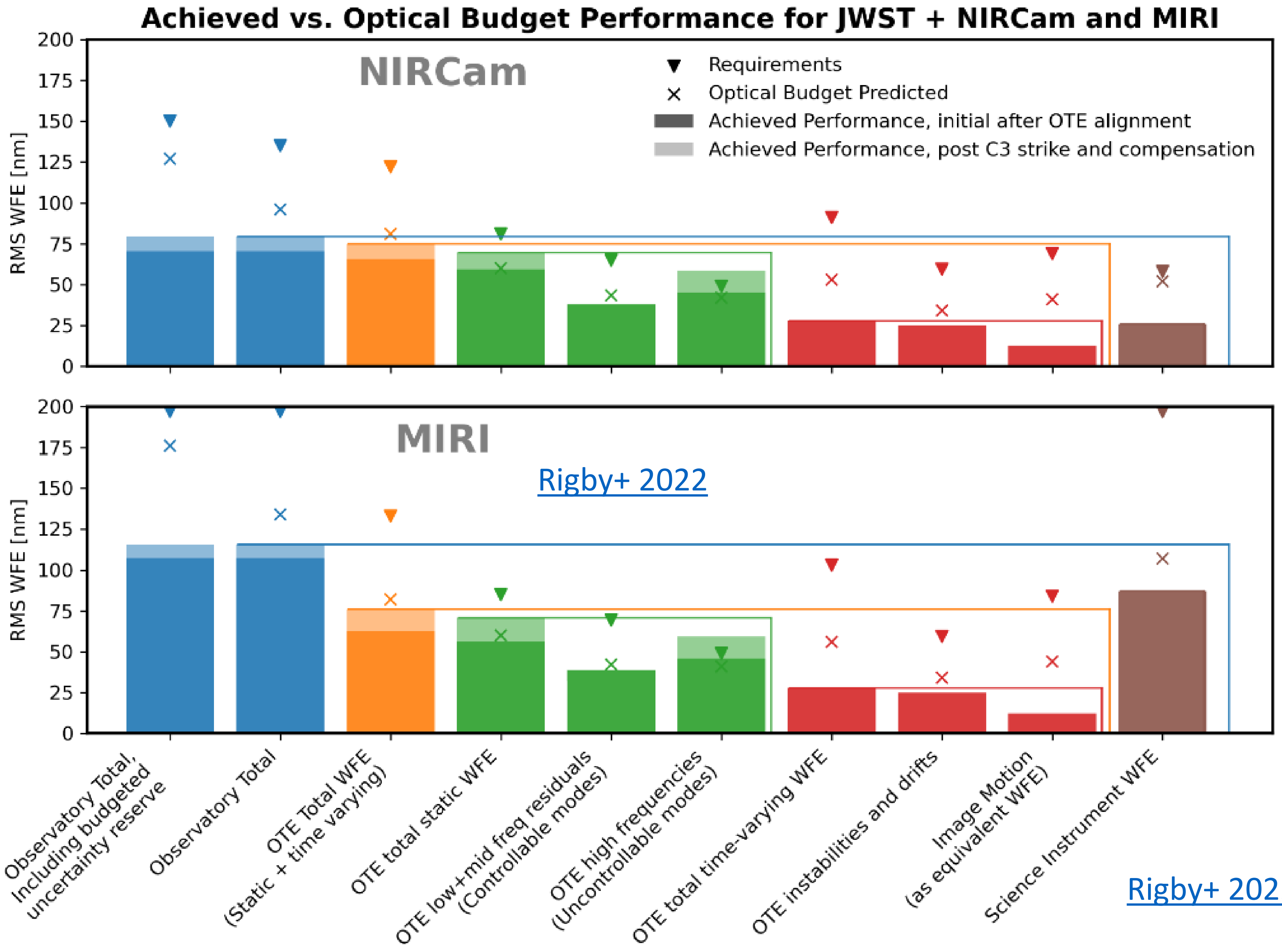
NIRCam: water ice and NVR upper limits

- Pre-flight requirements:
  - < 130 Å layer of water ice on the OTE
  - < 2800 Å layer of NVR in NIRCam
- 5 sigma upper limits
  - < 35 Å layer of water ice
  - < 50 Å layer of NVR





Jarron Leisenring



Achieved vs. Optical Budget Performance for JWST + NIRCam and MIRI
NIRCam
Requirements
Optical Budget Predicted
Achieved Performance, initial after OTE alignment
Achieved Performance, post C3 strike and compensation
RMS WFE [nm]
0
25
50
75
100
125
150
175
200
MIRI
Rigby+ 2022
Observatory Total, Including budgeted uncertainty reserve
Observatory Total
OTE Total WFE (Static + time varying)
OTE total static WFE
OTE low+mid freq residuals (Controllable modes)
OTE high frequencies (Uncontrollable modes)
OTE total time-varying WFE
OTE instabilities and drifts
Image Motion (as equivalent WFE)
Science Instrument WFE

Rigby+ 2022

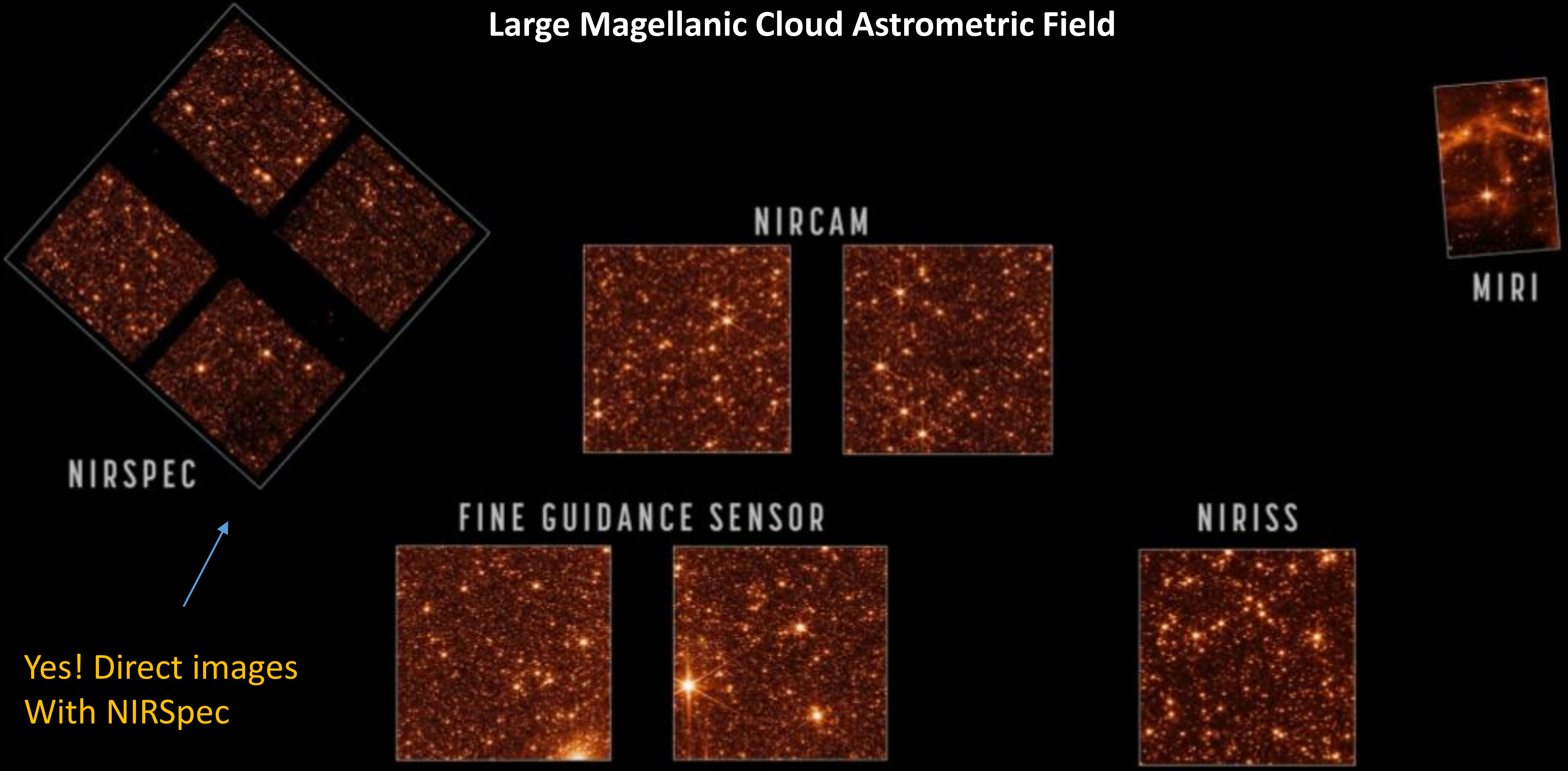
2MASS J17554042+6551277

First image of the fully collimated and focussed telescope

Rigby+ 2022

JWST Focal Plane

Large Magellanic Cloud Astrometric Field



Yes! Direct images
With NIRSpec

[DOY-123 2022-05-03]

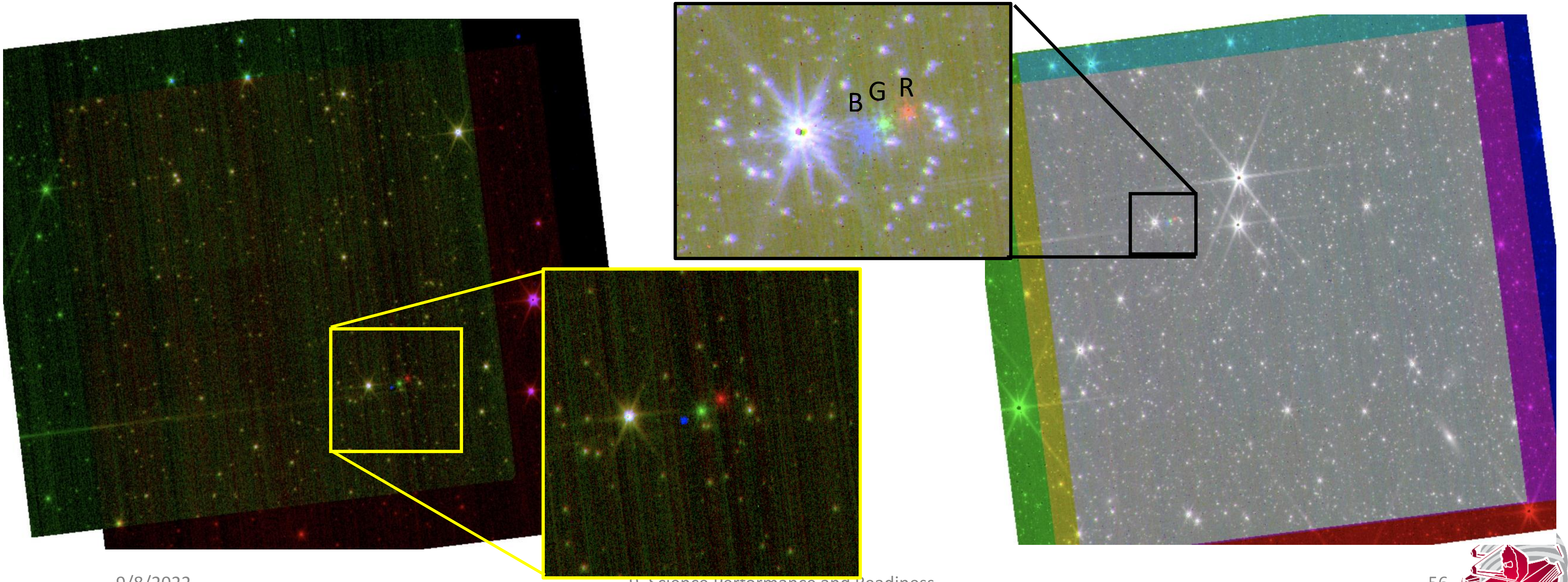
FGS-15 / APT 1021 Obs 2

(moving target guiding that enables observing Solar System sources)

Motion over 3 dither positions (and between integrations) readily seen in RGB overlay.
Exposures were short, so stars are not appreciably trailed.

F070W

F277W



NIRCam observes Jupiter

Guiding test using a very bright moving target

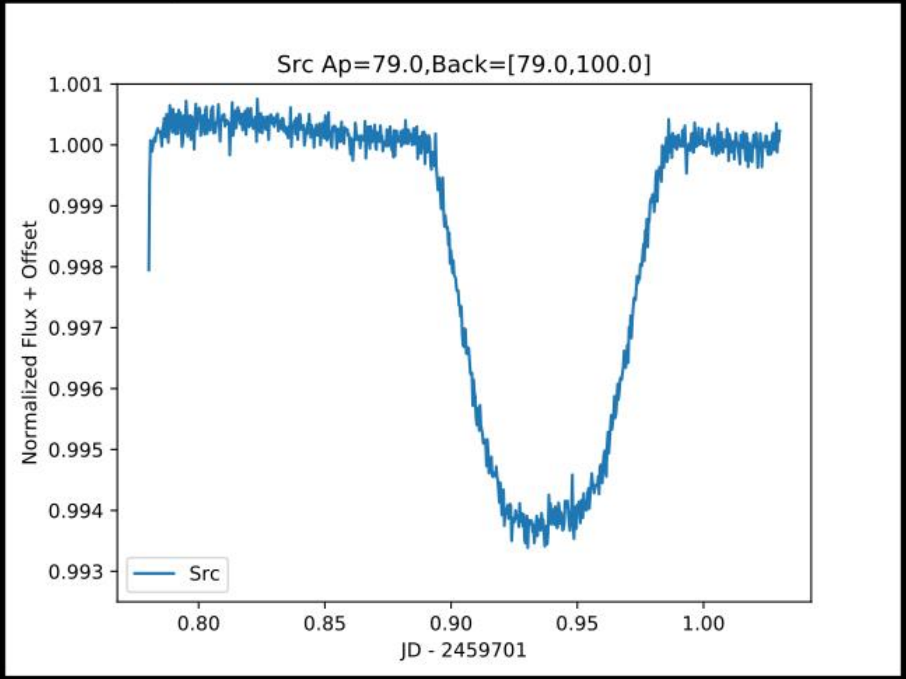
NIRCam Weak Lens and Grism TSO

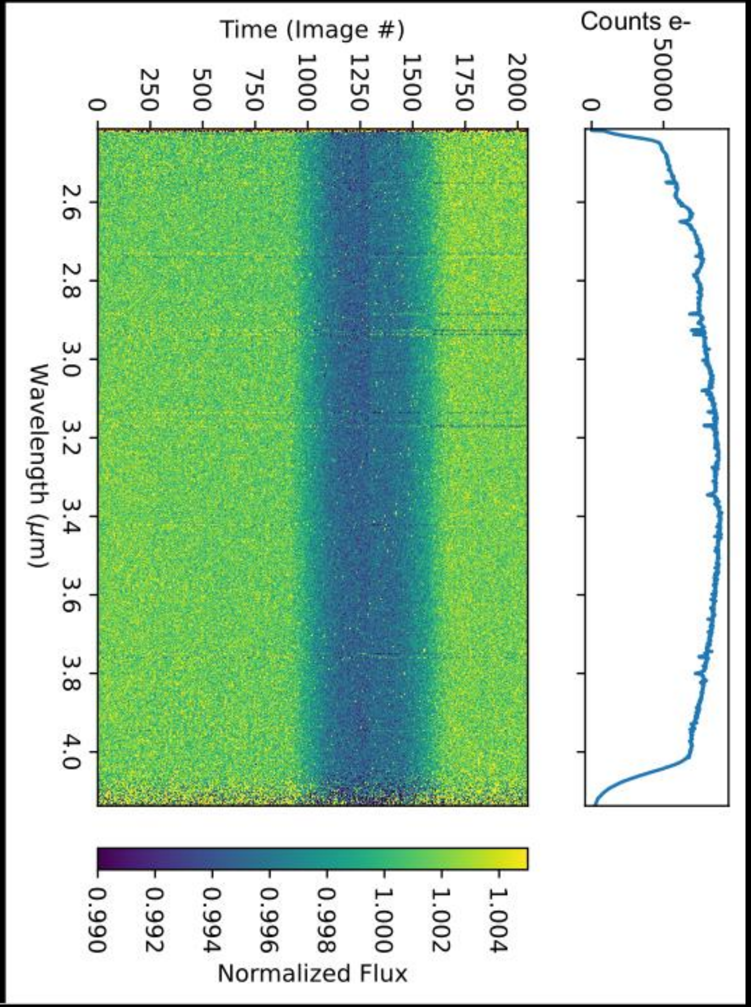
HAT-P 14 b

Both disperse the light to prevent saturation

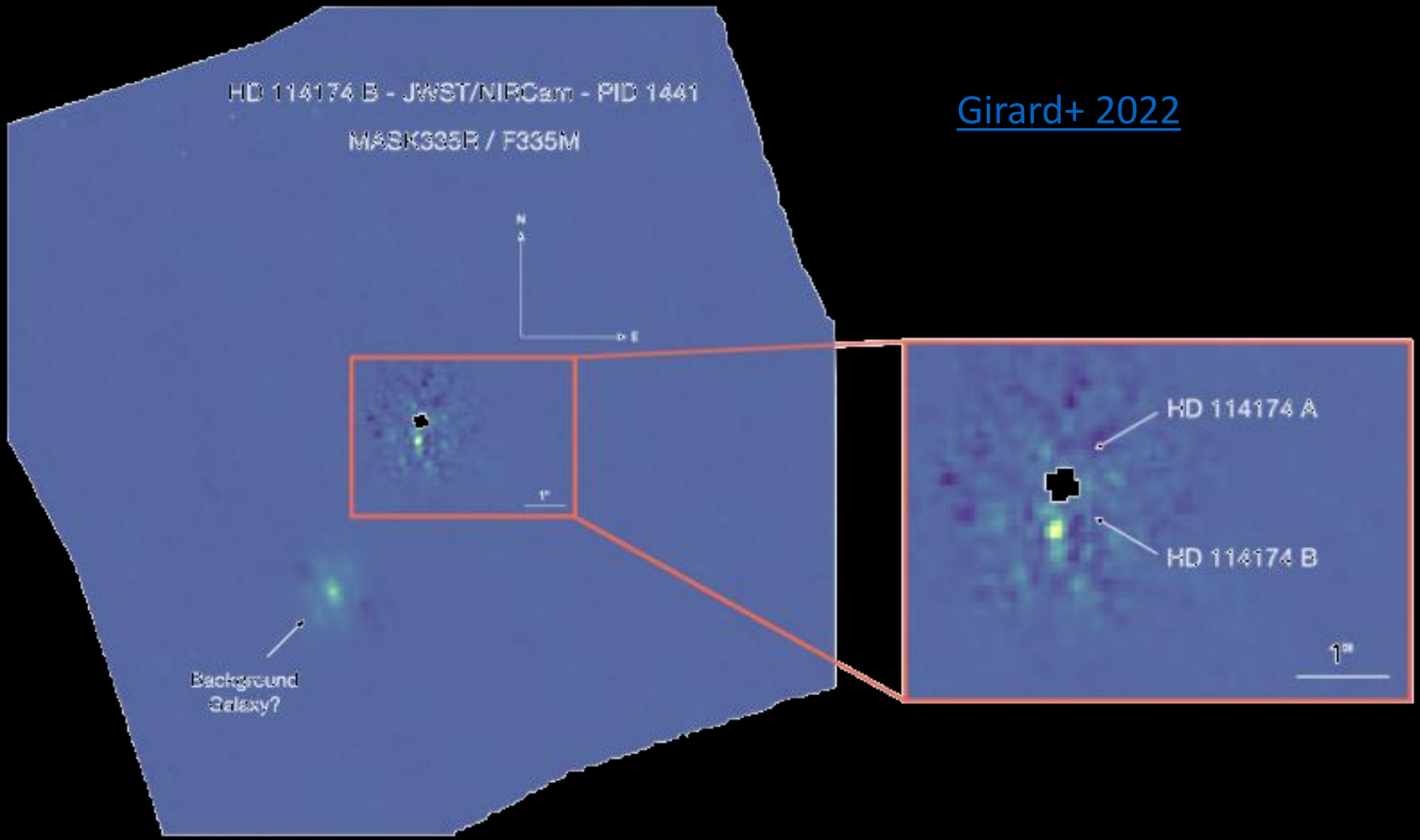
SW Weak Lens Photometry

130 ppm scatter (short timescales) vs 107 ppm theoretically



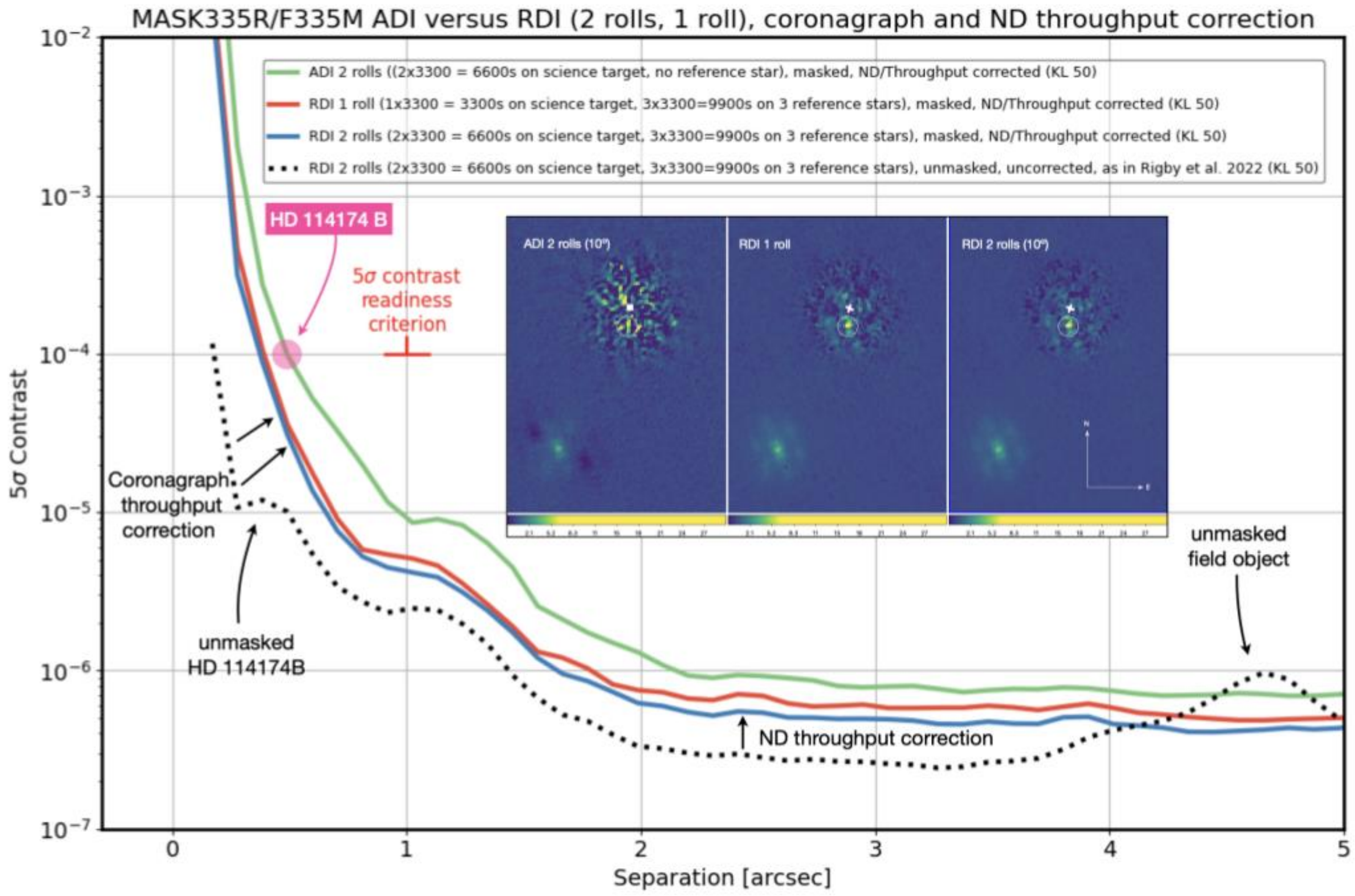


High Contrast Imaging



Girard+ 2022

Comparison between different methods used to subtract the PSF Residuals – either through as position angle rotation (ADI) or Using observations of reference stars (RDI) Girard+ 2022



A surprise in the NIRCam grism

(Fengwu Sun+, in Rigby+ 2022)

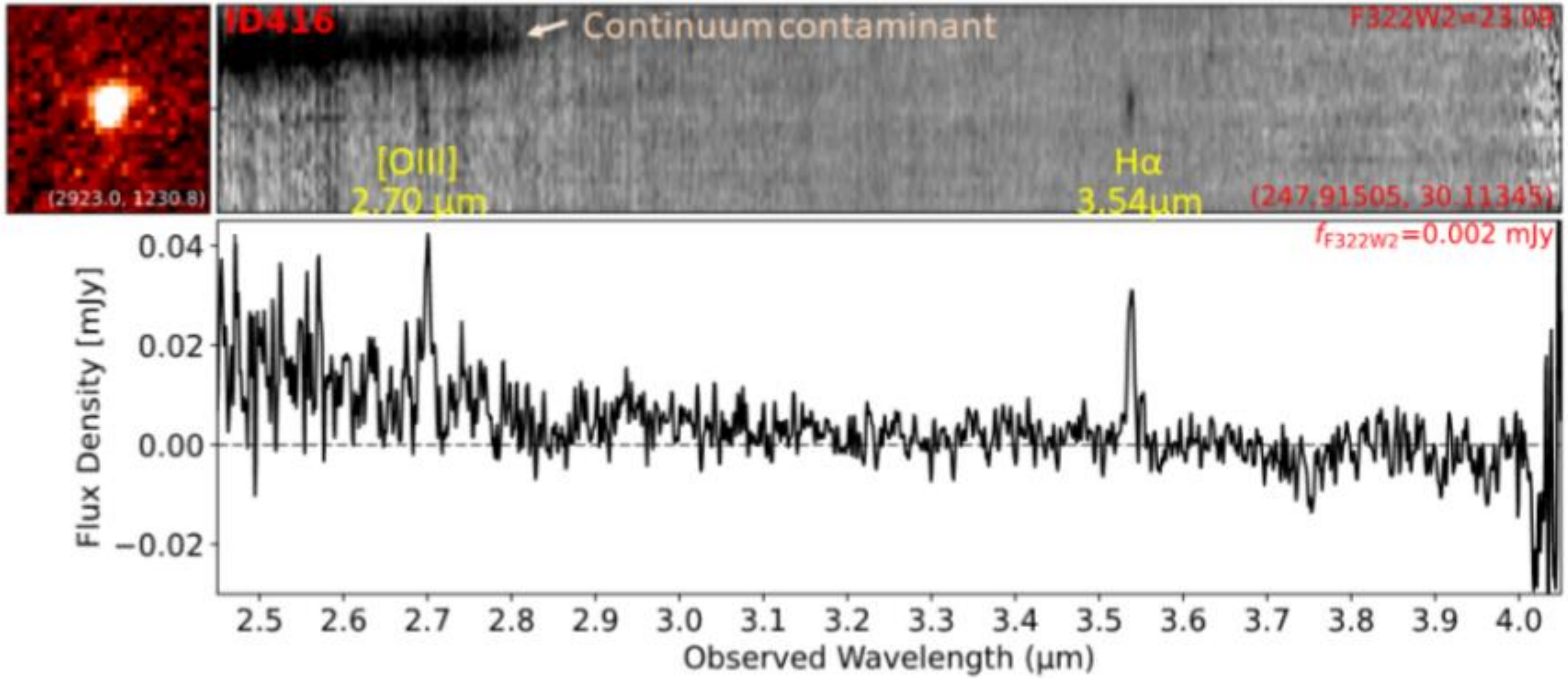


Figure 11: Spectrum of a z=4.39 emission-line galaxy. *This spectrum was detected serendipitously in 386 s of exposure time, in NIRCam wide field slitless spectroscopy mode data that targeted standard star P330-E for flux calibration, in PID 1076. Forbidden [O III] 5007 and H alpha are clearly detected.*

ERO and ERS observations

- The Early Release Observations (ERO), programmed by STScI astronomers were designed to showcase JWST's capabilities and enable scientific analyses immediately.
- These comprised fields targeting
  - A lensing cluster and parallel "blank field" (SMACS 0718);
  - A compact group of nearby galaxies (Stephan's Quintet);
  - A star forming region (NGC 3372 aka Carina Nebula/η carinae);
  - A planetary nebula (NGC 3132) ;
  - A transiting exoplanet (WASP 96 b).
- The Early Release Science (ERS) observations were also designed to use JWST on a variety (and more extensive) Science cases in projects led by the community and are part of the Cycle 1 approved programmes.

New results from JWST

- As of 2022-09-01 there were over 100 papers and telegrams submitted for publication using JWST data (ADS query)
  - Papers on Commissioning results;
  - Descriptions of science instruments;
  - Citizen Science Astronomy following the launch and deployment of JWST;
  - SN and transient discoveries;
  - Detection of exoplanets/brown dwarfs around main sequence stars
  - The detection of CO_2 in an exoplanet's atmosphere.
  - Properties of a proto-star;
  - A faint distant brown dwarf;
  - Extra-galactic globular (stellar) clusters in galaxy clusters;
  - Imaging of gravitationally lensed stars ;

New Results from JWST

- Heavily dust-obscured sources in galaxies with intense star formation ;
- Properties of infrared-bright galaxies that are dark in visible wavelengths;
- Characterization of galaxy structure;
- Properties of sub-millimetre galaxies observed with the ALMA array in Chile;
- Improved lensing models of the galaxy cluster SMACS J0723.3-7327;
- Protoclusters of galaxies being lensed by foreground galaxy clusters;
- Star formation history derived from spectroscopic and/or photometric measurements;
- Ultra-violet emission of high-redshift galaxies and sources of re-ionization.
- Finding the highest redshift galaxies and implication on the number of detections;

- With so many papers (and increasing daily!) it is clear that the following summary of new results will be very incomplete and biased.

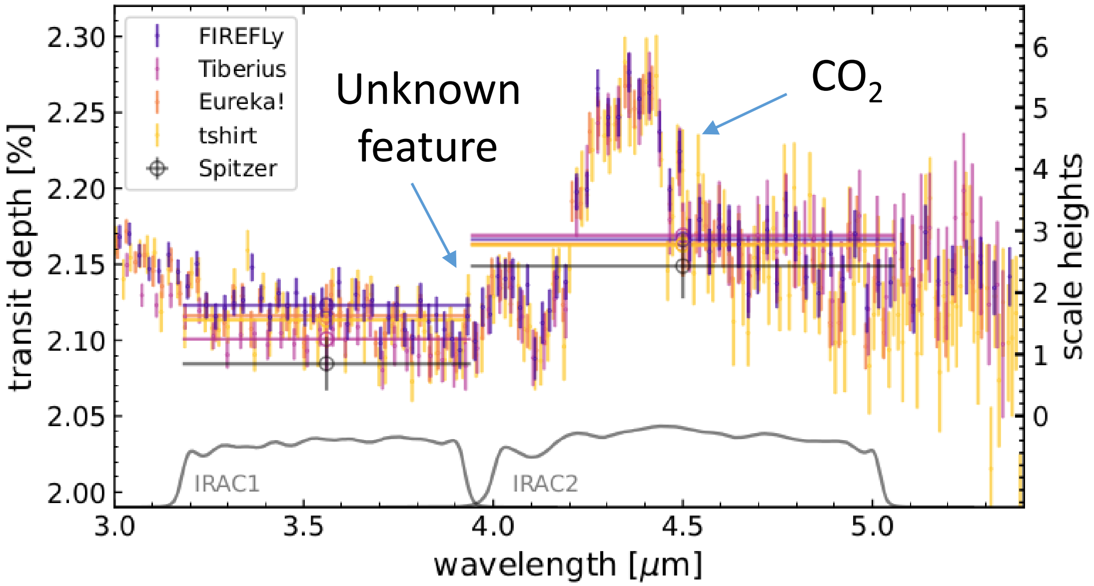
Exoplanets

- JWST observations are not specifically designed to discover stars with exoplanets;
- Many of the exoplanets observed by JWST were discovered through careful monitoring by the Kepler and TESS satellites or from the ground.
- The observations aim characterizing known exoplanets:
  - Physical properties (mass, size, surface temperature)
  - Chemical composition
- The new observations will show how other planetary systems compare to the Solar System.

WASP-39 b: CO_2 in an exoplanet atmosphere

(Ahrer+2022)

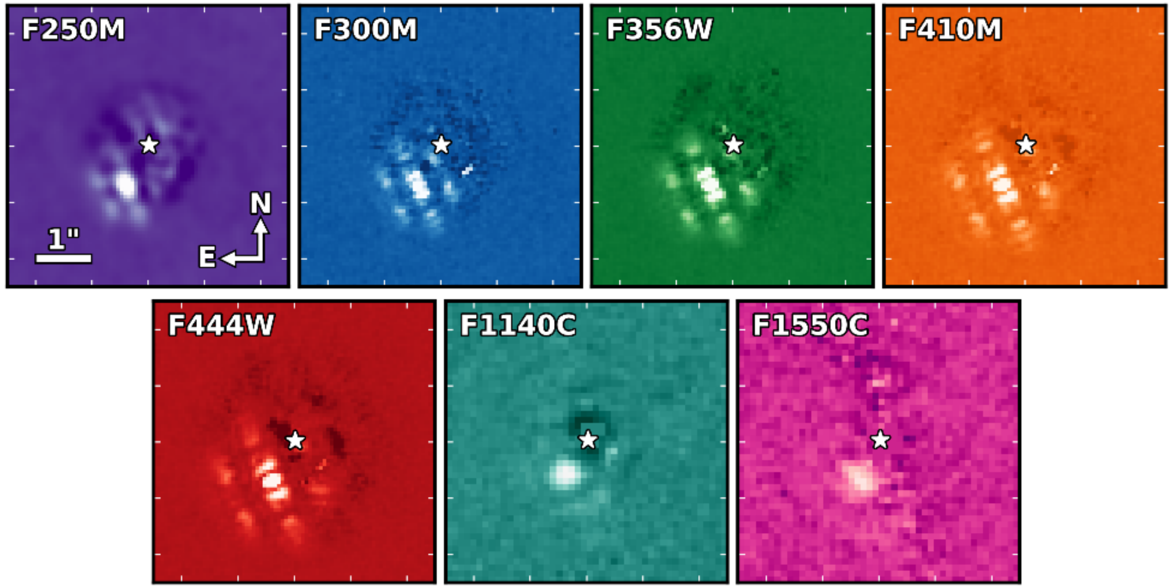
- WASP-39 b is a hot (1170K) transiting exoplanet, that orbits a G7 star with a period of 4.055 days.
- Same mass as Saturn (0.28 M_{jup}) with an R=1.28 $R_{jup.}$
- While the presence of CO_2 was hinted by Spitzer observations, JWST detects the CO_2 line at a S/N > 26.
- Best fit models have 10x solar metal enrichment and sub-solar C/O ~ 0.35 (solar is 0.55).

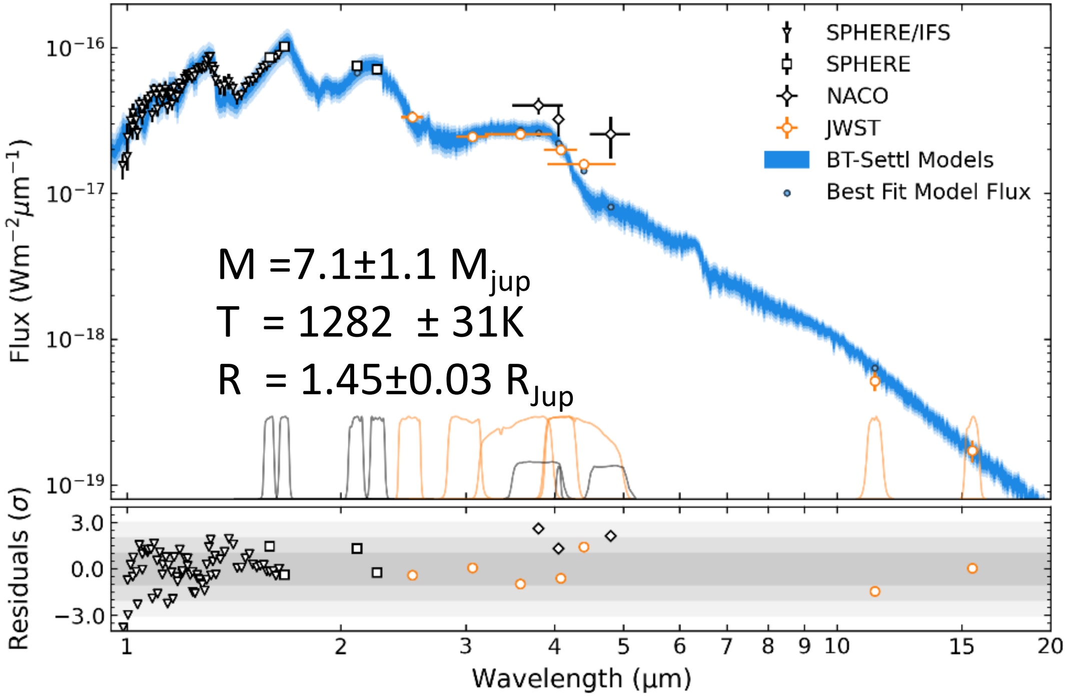


JWST direct detection of Exoplanet HIP65426 b

(Carter+2022)

Measurements using the NIRCam and MIRI coronagraphs have extended the wavelength coverage of observations for HIP 65426b that orbits an A star. The new observations enable a significant improvement in the exoplanet models.



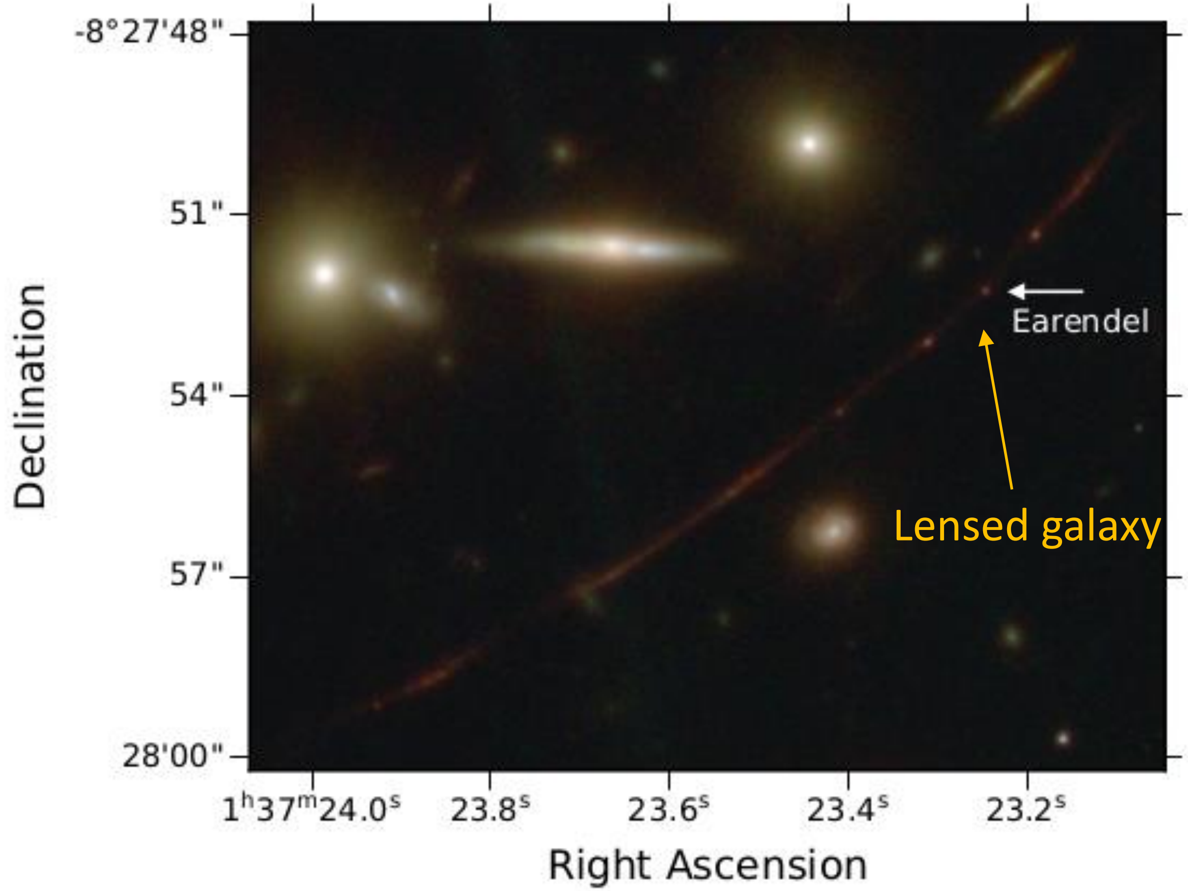


Observing single stars at large distances

- Possible because of strong gravitational lensing;
- Requires very favourable conditions – star needs to fall on a critical curve of the gravitational lens, where its signal can get amplified by up to thousands of times.
- Since stars move, these observations are considered as *transient* phenomena (though the time scale may be long).
- The use of gravitational lensing has been explored previously by the OGLE survey by measuring micro-lensing events in the Milky Way and Magellanic clouds.

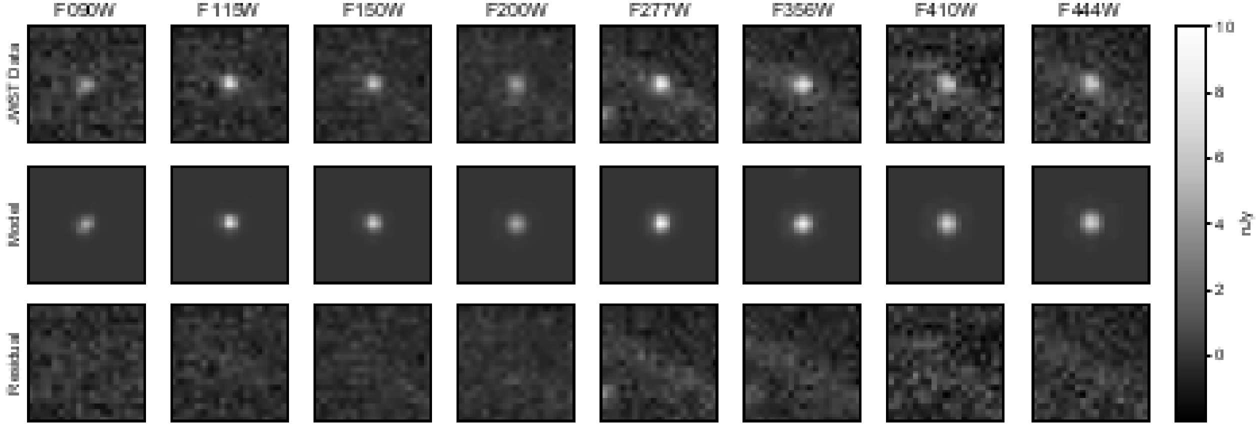
A magnified star at z = 6.2

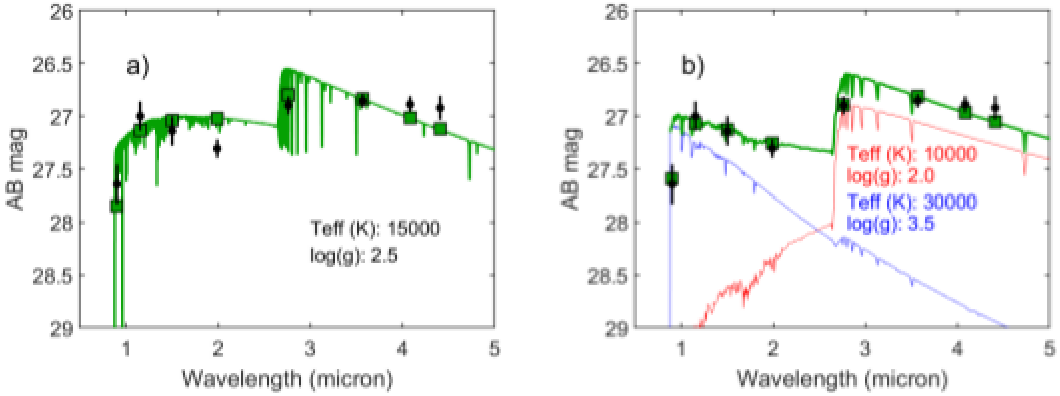
(Welch+ 2022)



Very metal poor star or pair of stars with of log(L/L$_{\odot}$) ~5.8

Appearance of star in several filters





Two possible model fits to the photometry

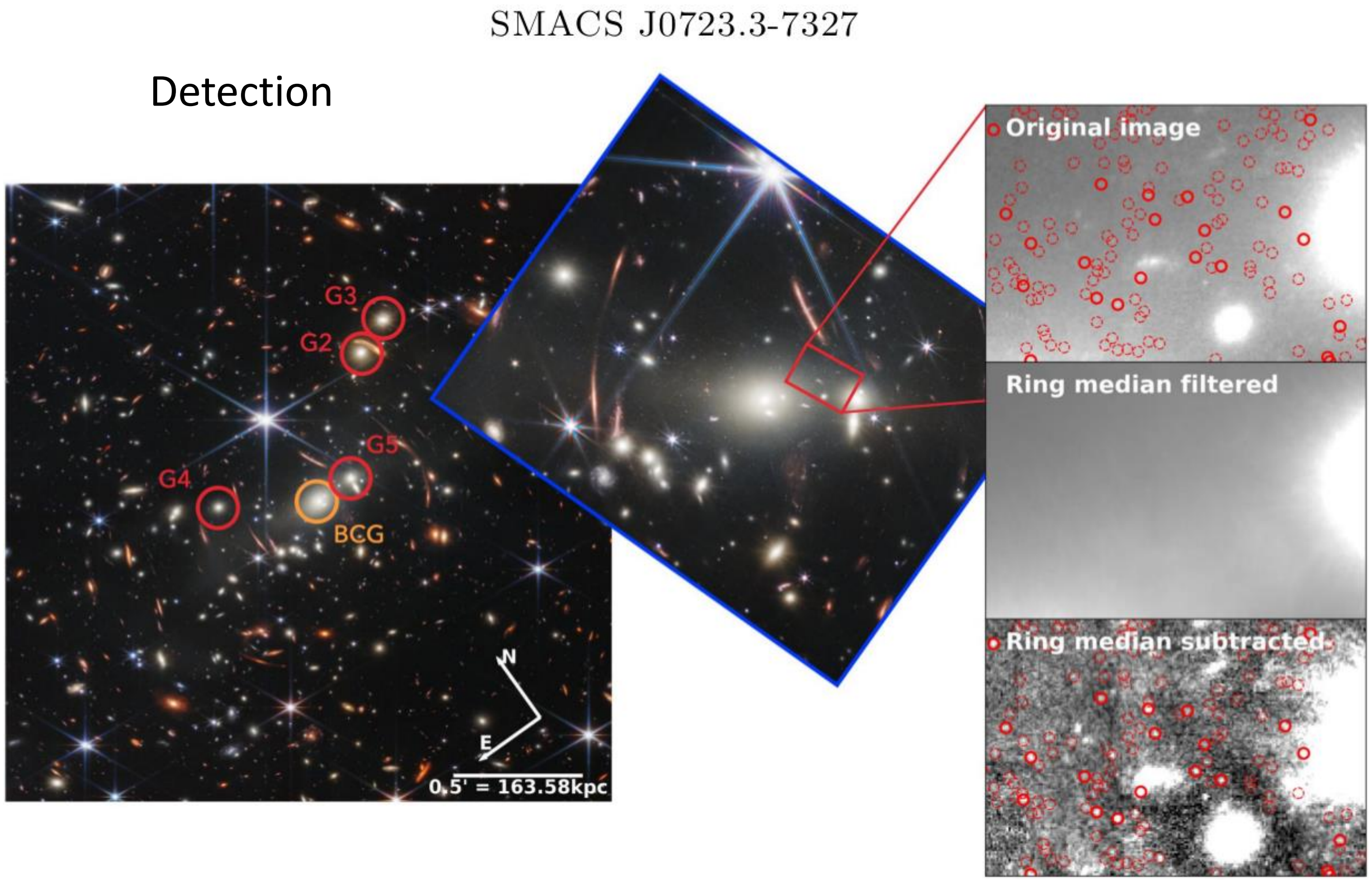
Extragalactic globular clusters

- Globular clusters are self-gravitating associations of stars that can contain up to 10 million stars with symmetrical shapes and mainly found in the Galaxy's halo.
- The globular clusters in the Galaxy contain some of the oldest stars that we know.
- Globular clusters have been detected in several nearby galaxies.
- The images of SMACS J0723.3-7327 show a large number of concentrated sources whose properties are consistent with globular clusters located in the *intracluster medium*.
- Also detected are globular clusters that are associated with a multiply lensed background galaxy giving some insight on the properties of globular clusters when the universe was half its present age.

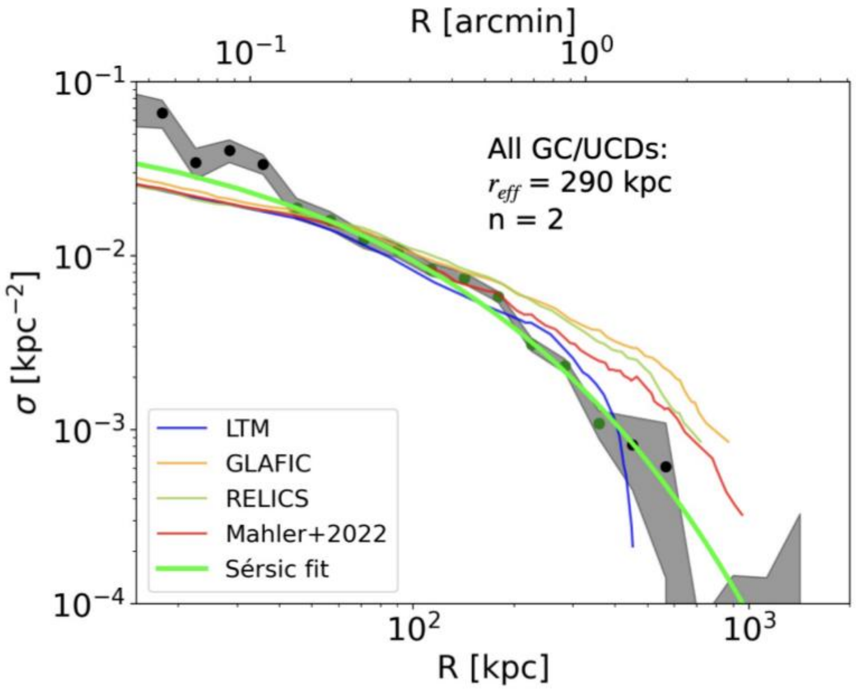
SMACS J0723.3-7327 Globular clusters

(Lee+2022)

Detection

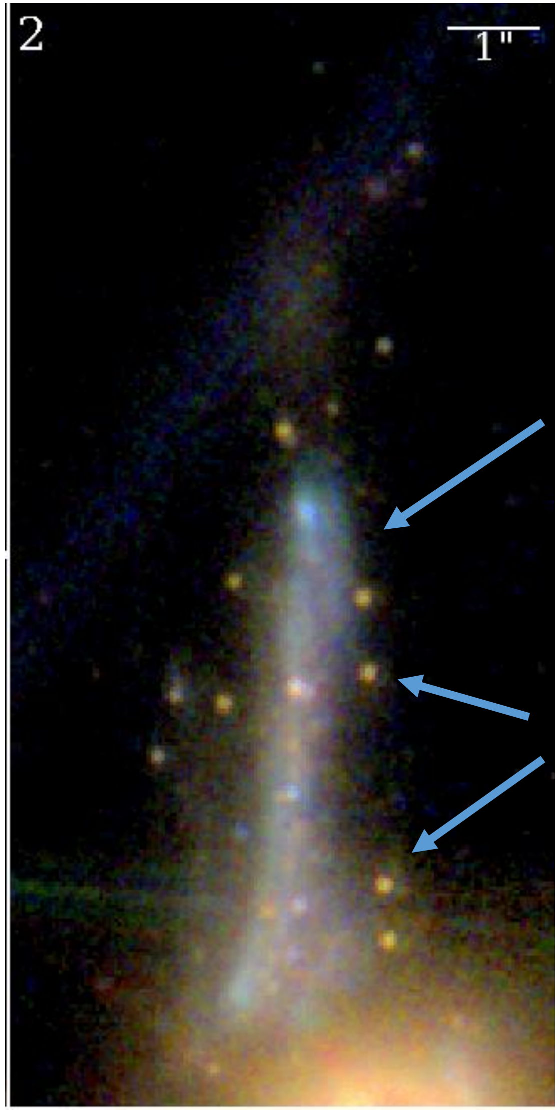


Measured profile compared to
Dark Matter distribution derived
From lensing models



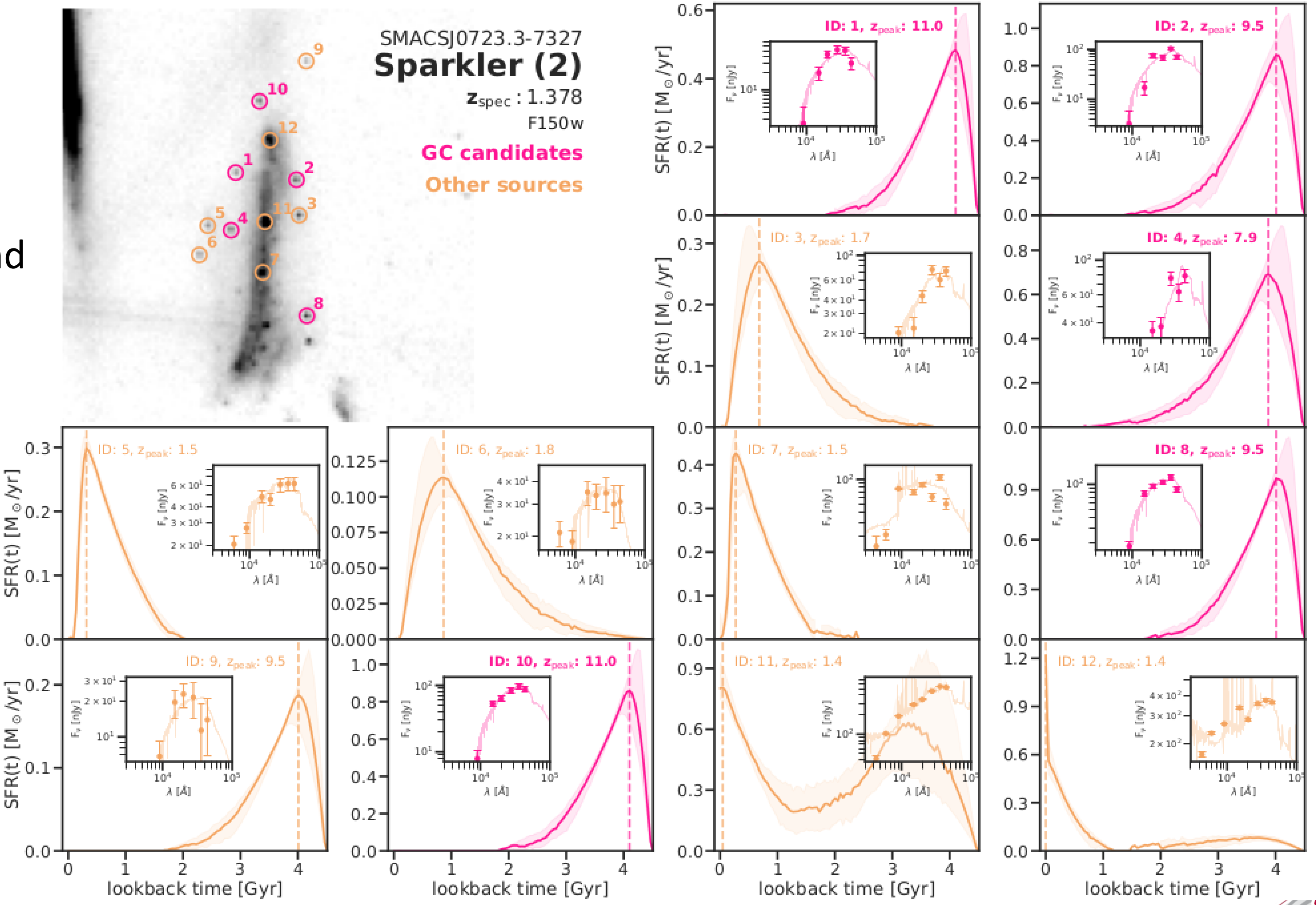
z=1.378 compact sources which are unresolved and with no evidence of star formation

(Mowla+2022)



Lensed background Galaxy (z=1.378)

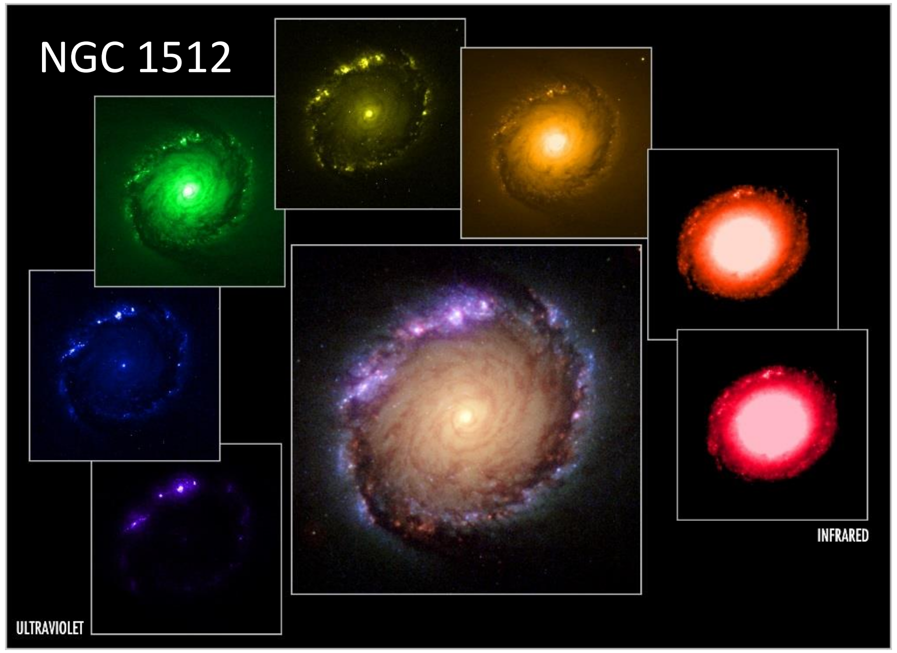
GC candidates



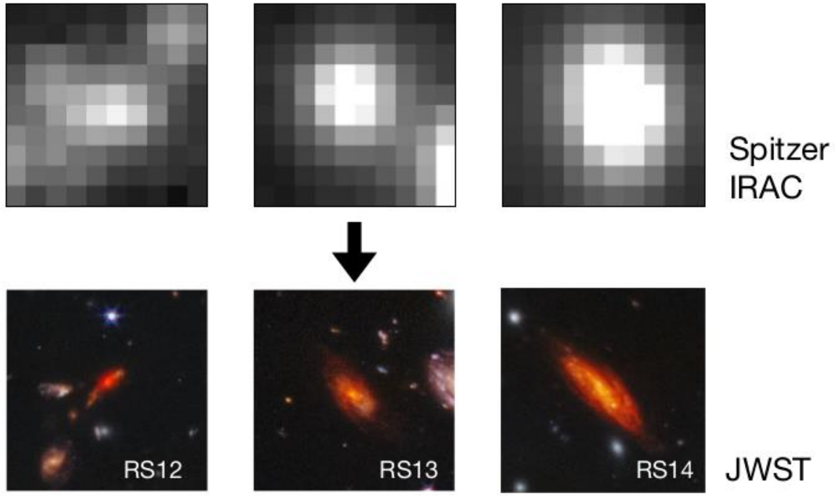
The ubiquity of disk galaxies at z > 2

- Factors limiting detection of galaxies at high redshifts
  - Cutoff in atmospheric transparency for ground-based observations;
  - The *seeing* caused by atmospheric turbulence (affects the resolution);
  - The relatively short wavelength cutoff of Hubble Space Telescope;
  - The lower resolution of the Spitzer Space Telescope;
- Many of the first papers using JWST analysed the morphological properties of galaxies at redshifts > 2.

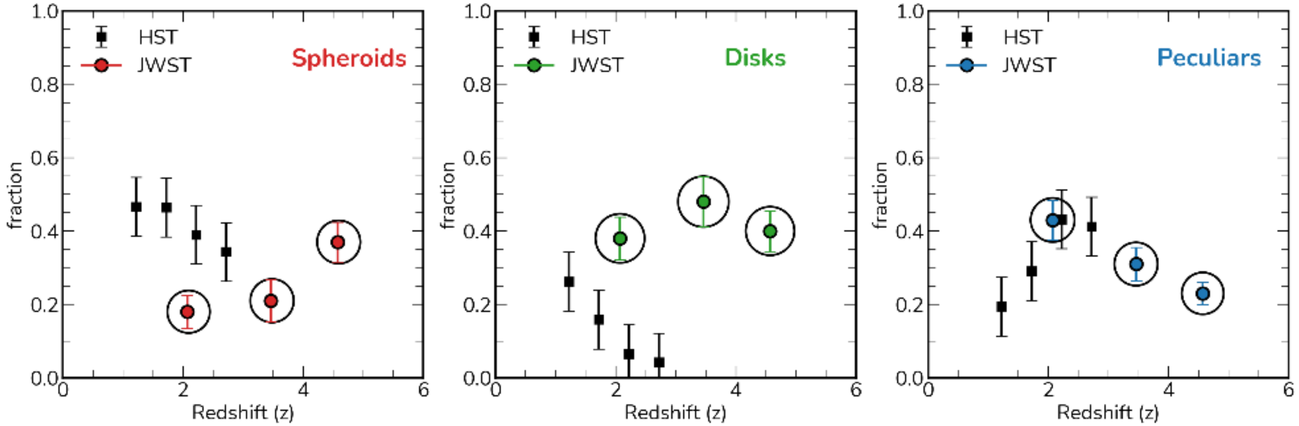
Maoz+2001



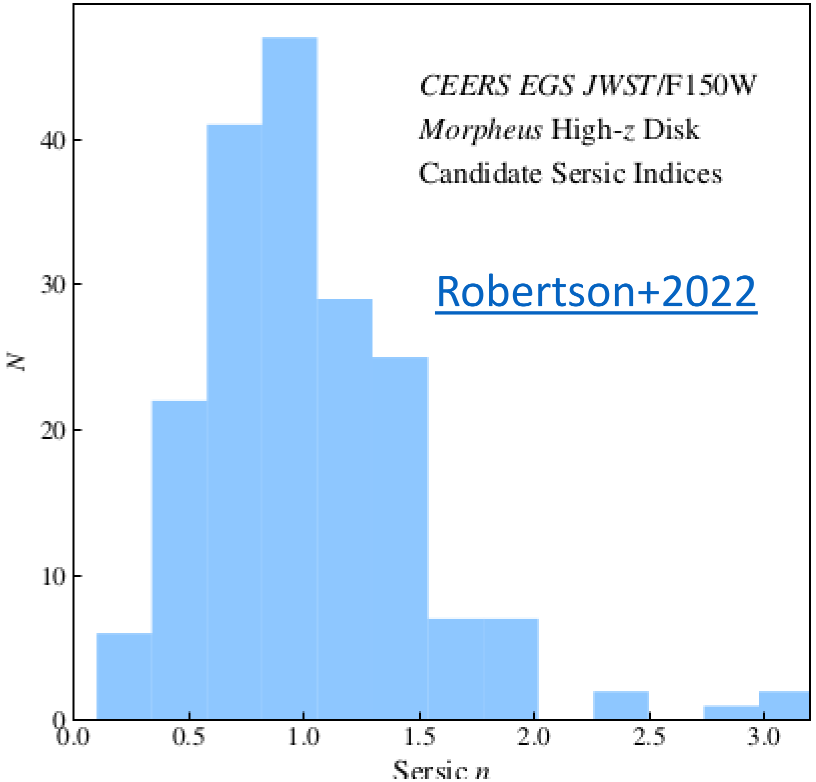
Fudamoto+2022



Ferreira+2022

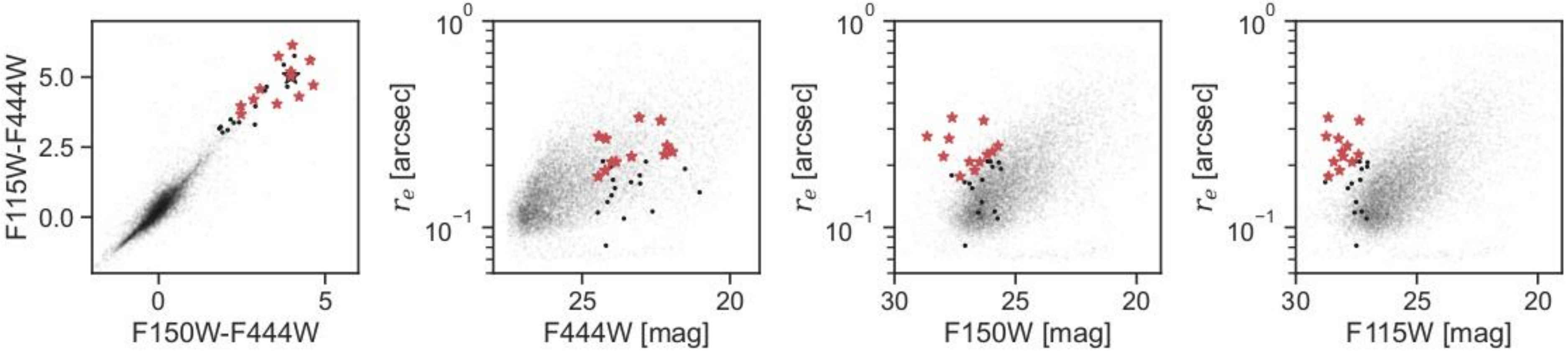


Robertson+2022



Red dusty disk galaxies undetected by HST

(Nelson+2022)

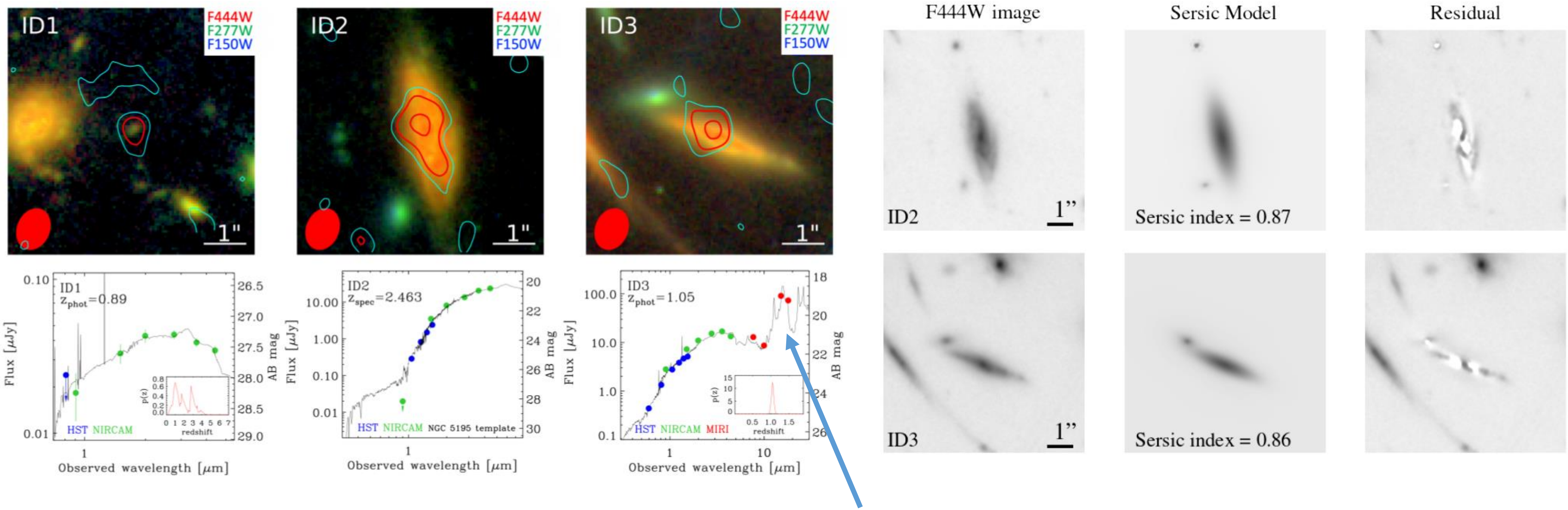


Sub-millimeter galaxies (*SMG*s)

- Initially detected using radio telescopes;
- Objects that are very bright in the 450—850 µm range but often have no counterparts in visible wavelengths (0.3—0.7 µm). Yet they are very bright when the total light emitted by the galaxy is measured.
- This is explained by the presence of intense formation of stars, but whose light is absorbed by dust and re-emitted at longer wavelengths.
- Very few counterparts in the local universe, but become more common as we look back into the past.
- Three facilities have been instrumental in studying these objects – the James Clerk Maxwell Telescope in Hawai'i (SCUBA, SCUBA2), the ALMA array in Chile and the NOEMA telescope in France.

Sub-millimeter Galaxies observed with ALMA and JWST

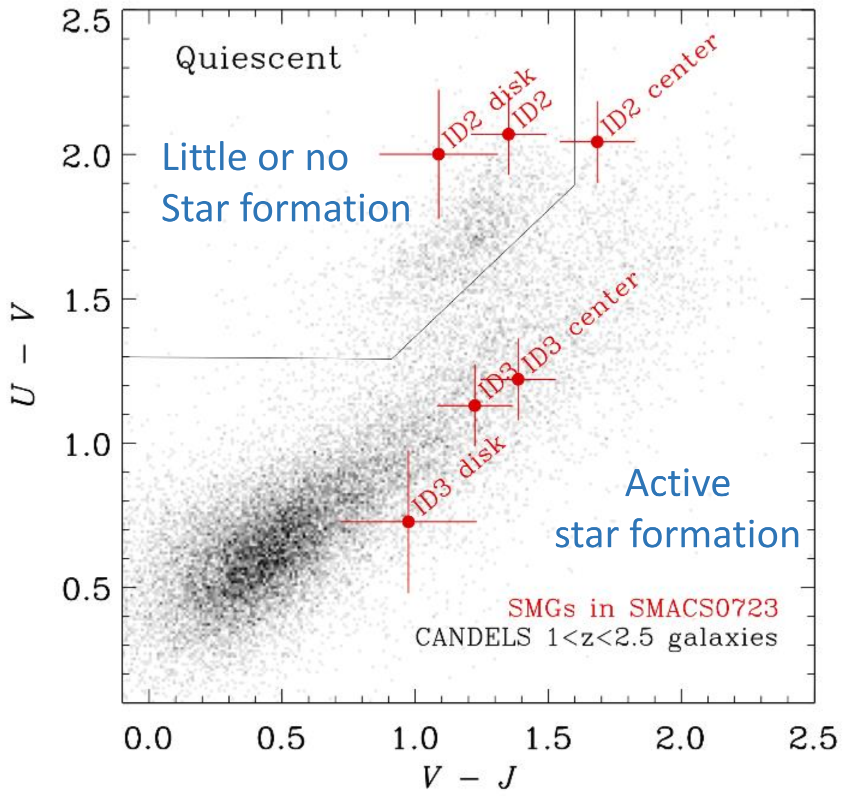
(Cheng+2022)



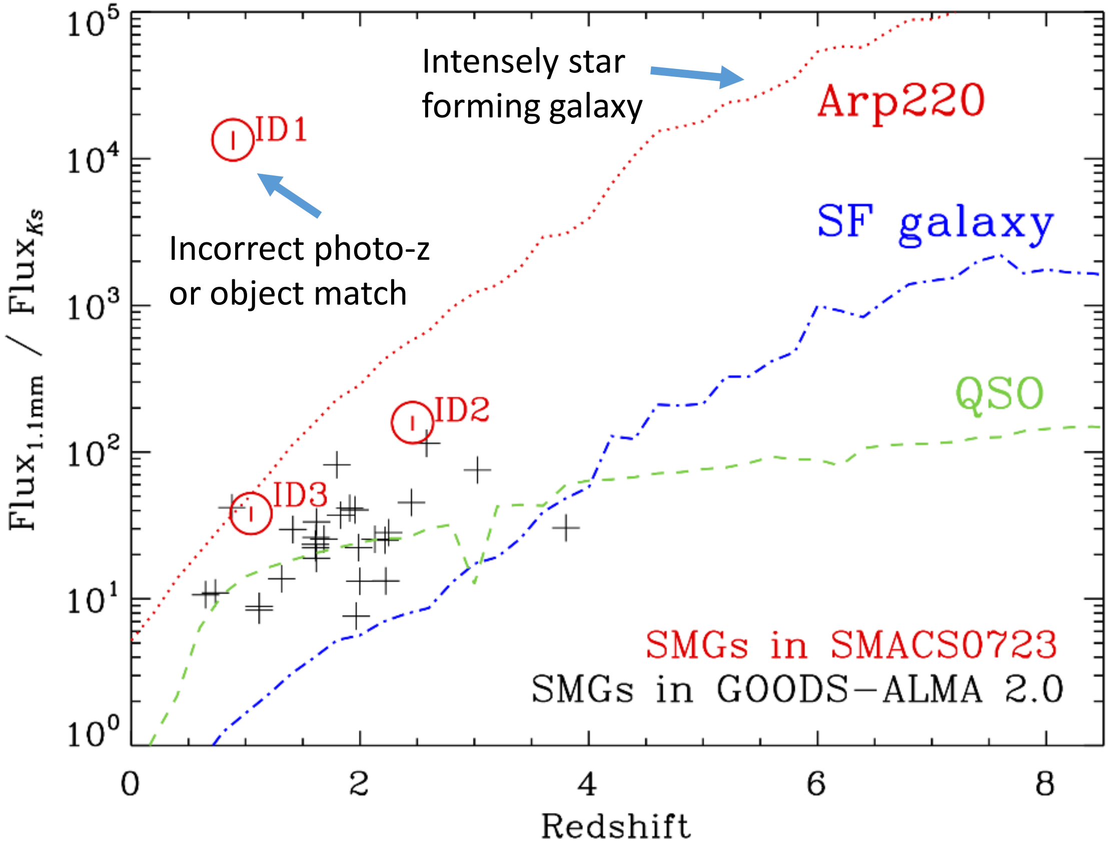
Light output by dust

The high resolution of JWST combined with that from ALMA allow measuring the properties of galaxy sub-components.

Properties of full galaxy vs. sub-components



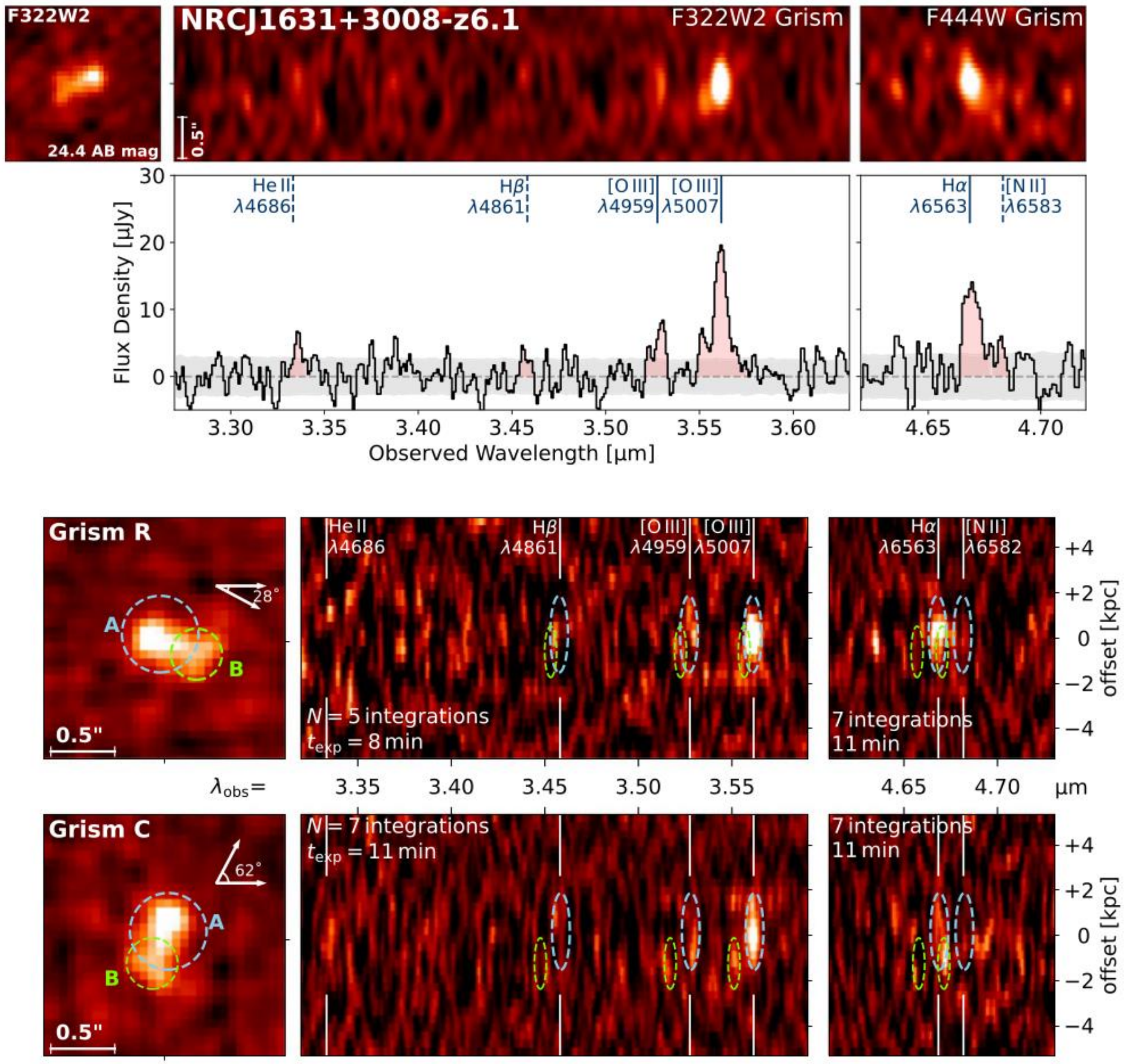
Brightness ratio between in Sub-mm and NIR



Curves represent flux ratios for different types of objects.

Reaching out to the Redshift Frontier

- Because of HST's cutoff at ~1.8 μm, the cutoff for an unambiguous detection of galaxies at high redshifts is at about z~11.
- Obtaining ground-based spectra for galaxies at z > 7 is severely limited by the OH emission in the night sky and atmospheric absorption.
- Most of the emphasis of the early science papers using JWST has been on characterizing galaxies at redshifts > 5
- Because the photometric calibration of the telescope is work in progress, combined with the paucity of spectroscopic redshifts to calibrate the photometric redshifts there can be differences in the photo-z measurements (e.g., Adams+2022) so some results should be considered tentative.



Serendipitous discovery of a z=6.1 galaxy

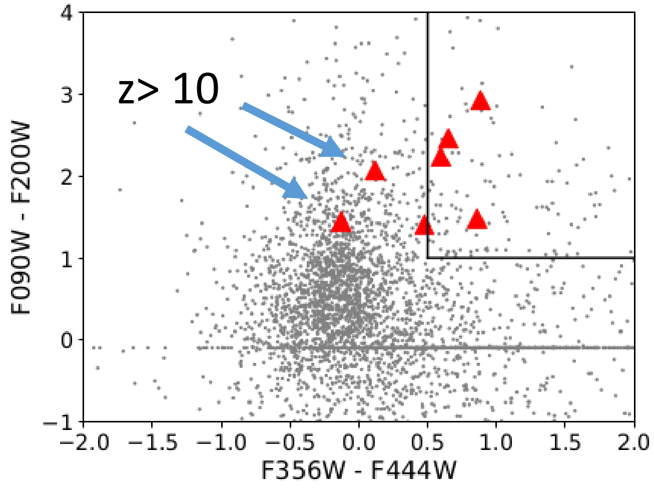
[Sun+2022](Sun+2022)

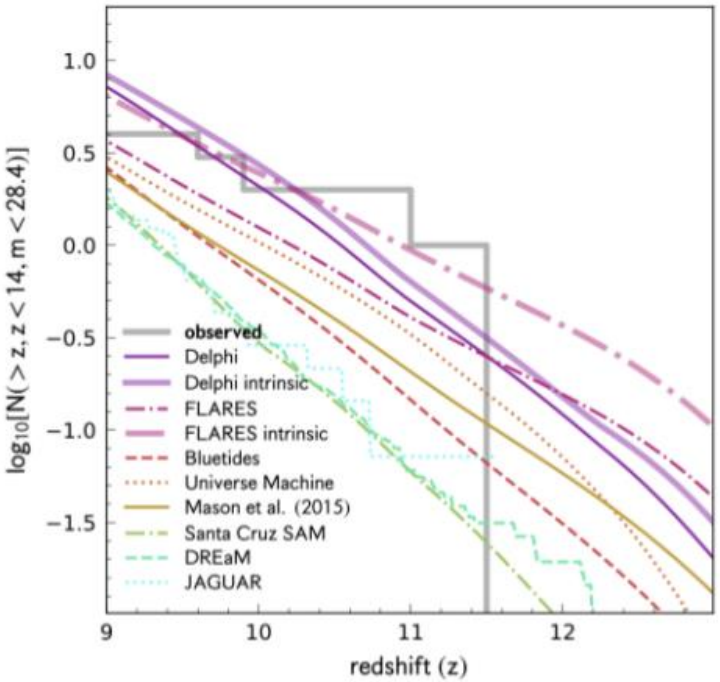
First z=6 spectrum *obtained* by JWST using NIRCam when observing a photometric calibration star.

This galaxy has strong optical emission lines and the spatial distribution suggests this is a galaxy undergoing a merger, thus triggering the star formation burst.

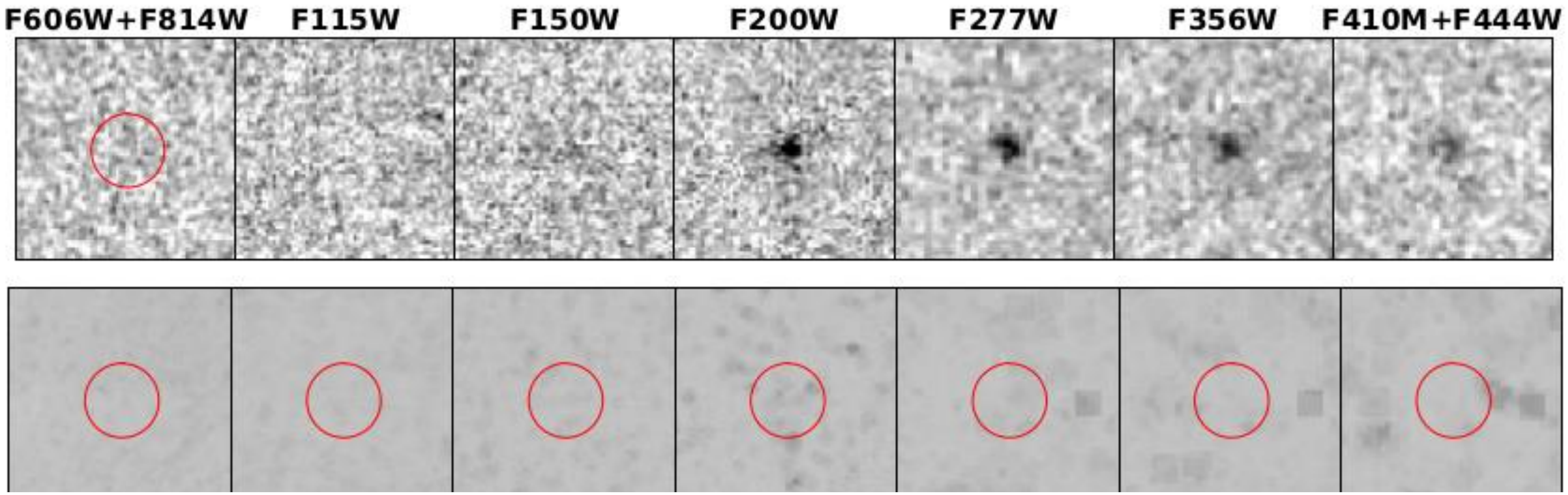
Adams+2022

NIRCam parallel field of J0723.3-7327





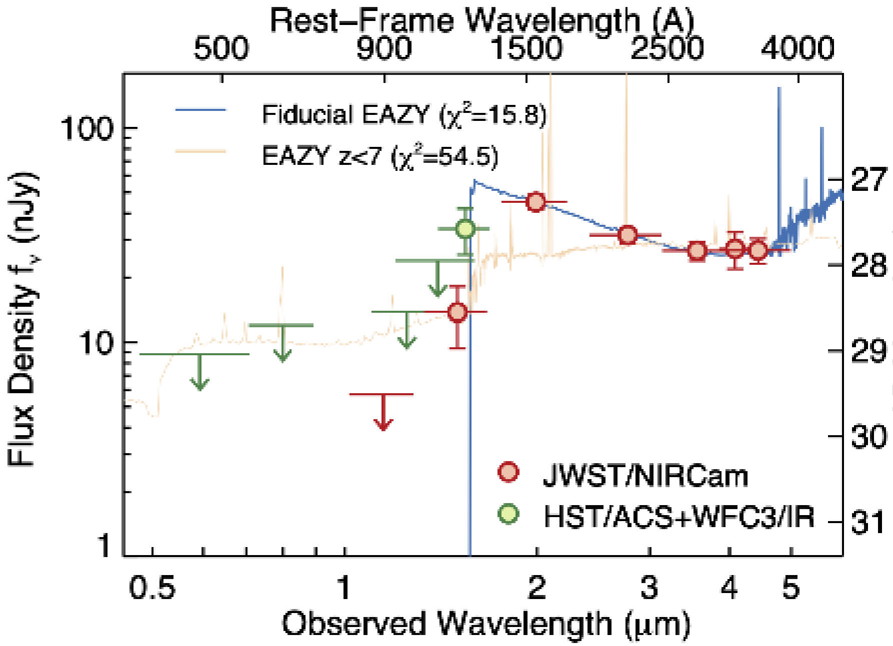
Number of detected galaxies compared to expected by several models “drop-out” technique

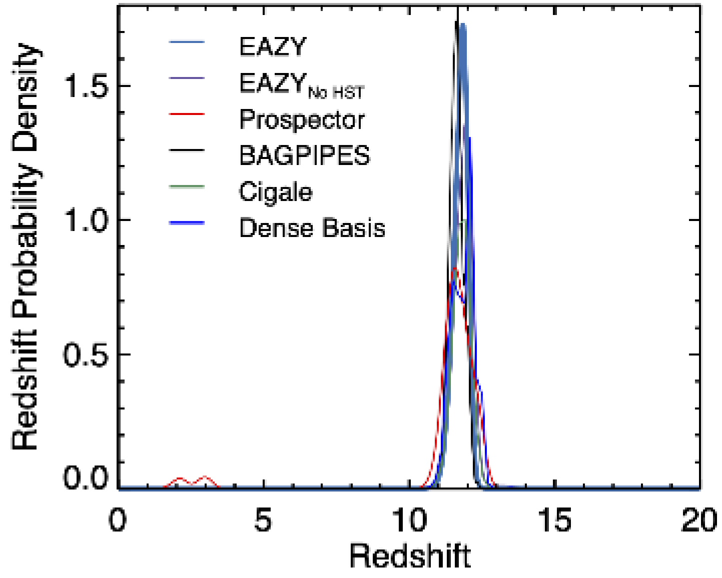


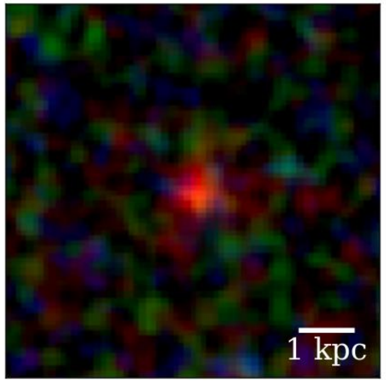
Maisie’s Galaxy

[Finkelstein+ 2022]

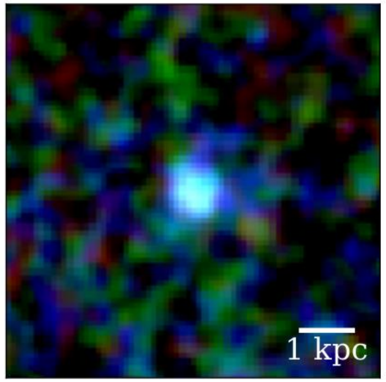
Z = 11.8 +- 0.2







Observed color

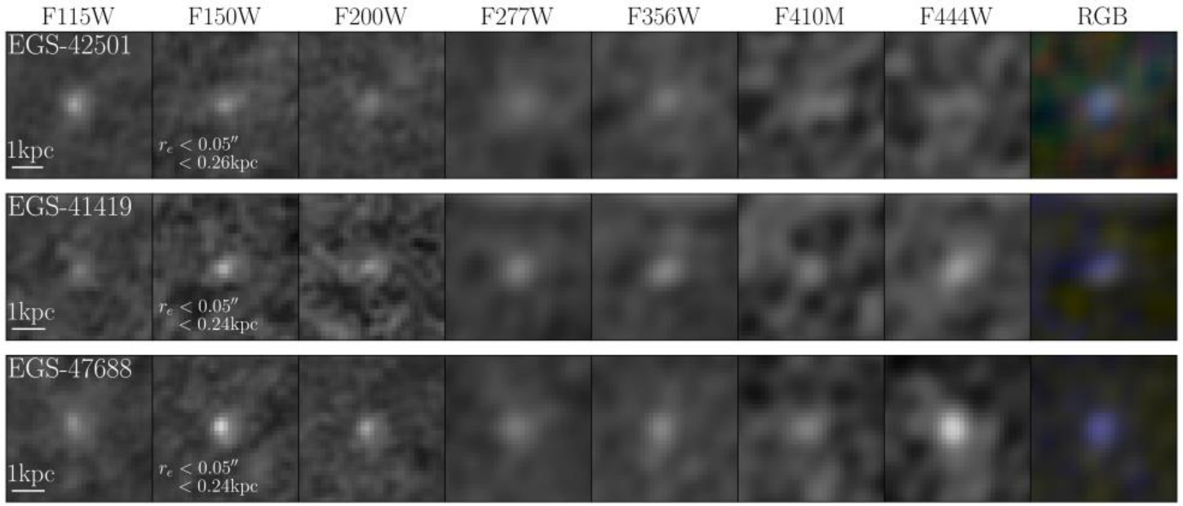


Estimated rest frame color

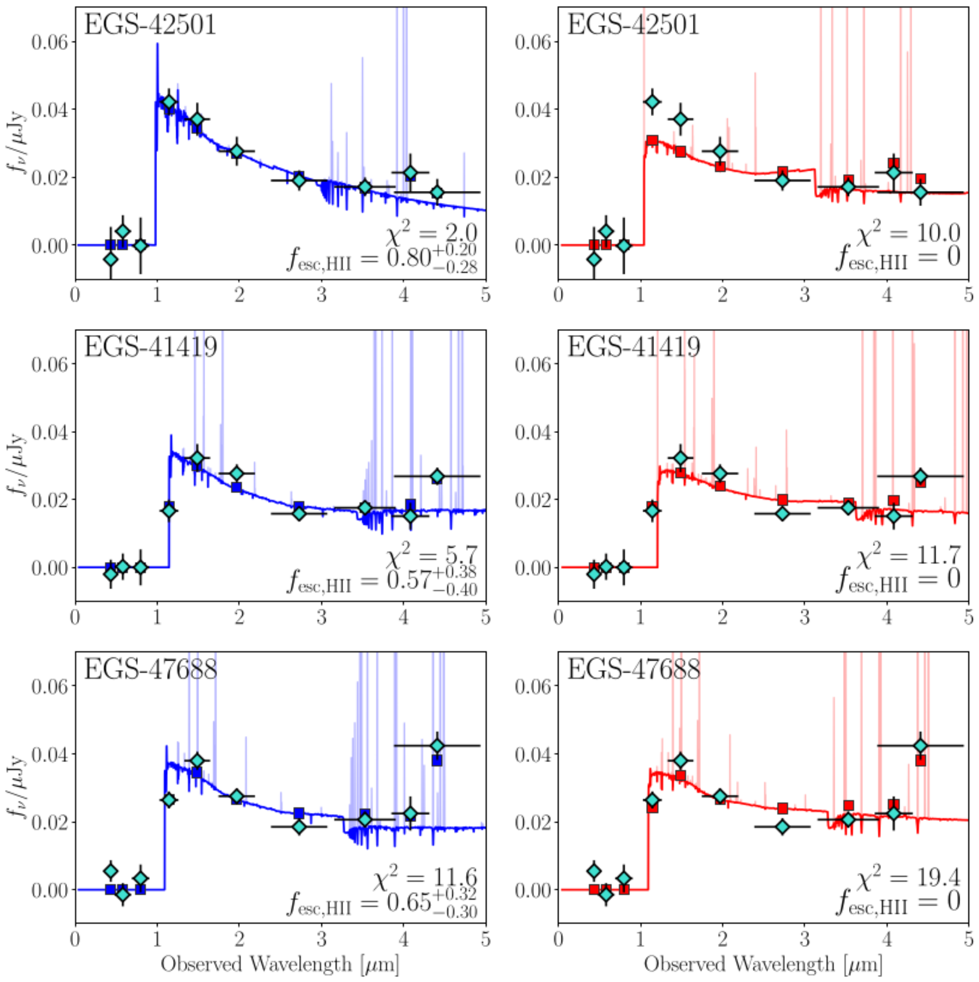
Which galaxies reionized the Inter Galactic Medium?

- The epoch of "recombination" is when the universe became transparent.
- The light from that era is detected as the Cosmic Microwave Background
- This is followed by the "dark ages" when the primeavel fluctuations were still growing but no stars existed and the most of the hydrogen in the universe is neutral.
- Once the first stars formed the neutral hydrogen absorbed some of the photons becoming ionized.
- Finding the galaxies hosting the stars has been an important topic for the last few years. Many studies have suggested that small galaxies beyond the detection limits of HST and ground-based observations could be the sources of UV photons to reionize the IGM.

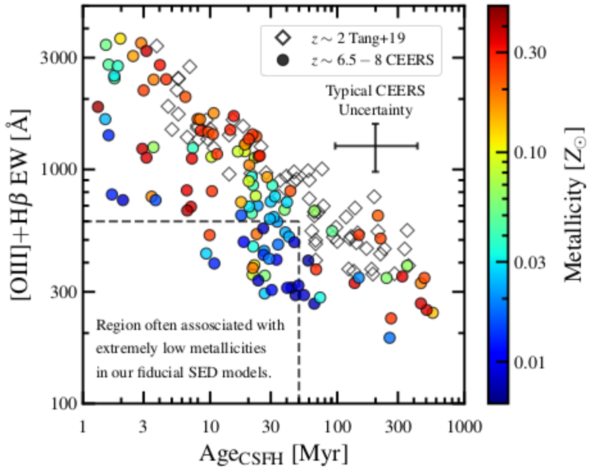
Topping+2022



Topping+202



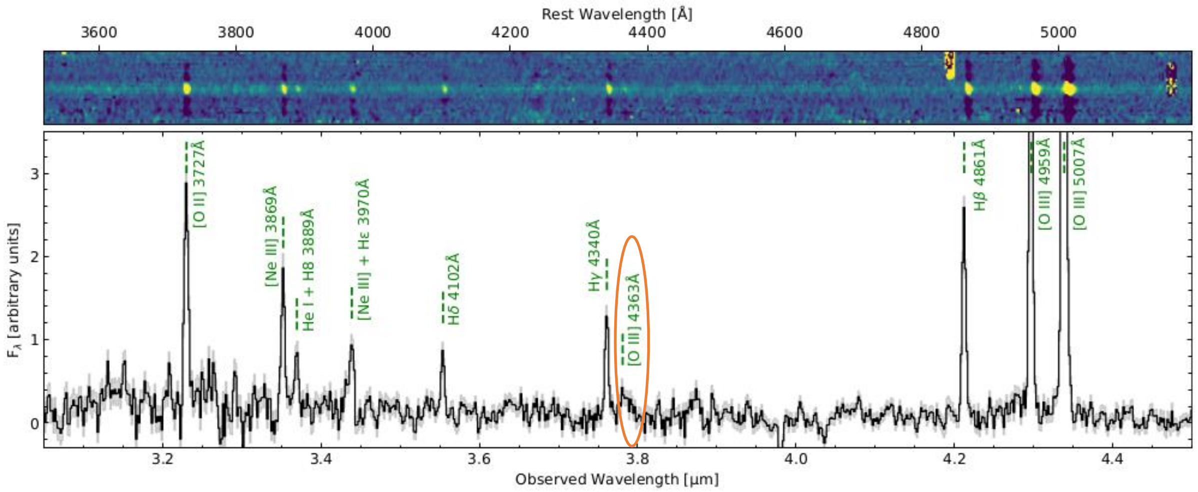
The sources that reionize the IGM are likely OB stars. These can be evidenced through the inclined slopes in the UV



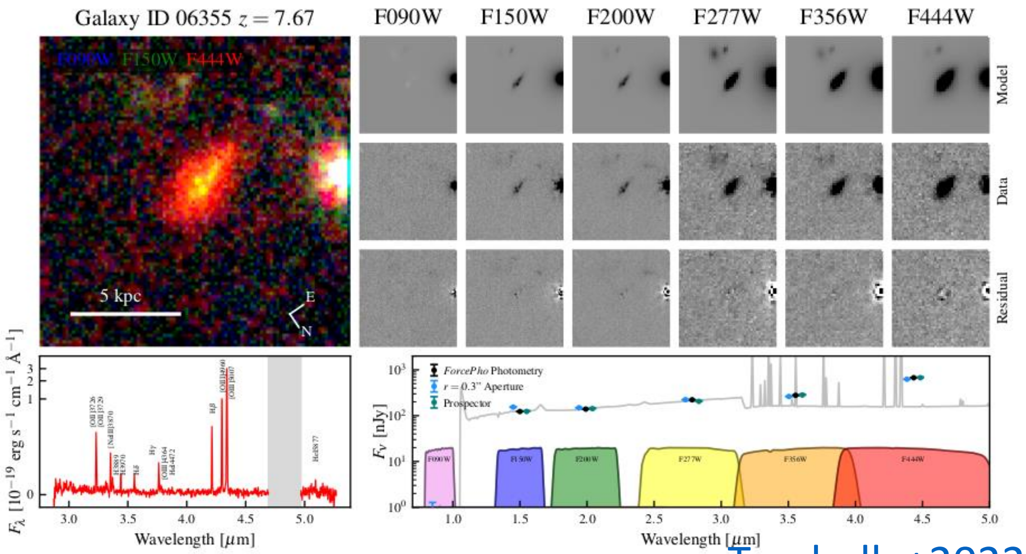
Endsley+2022

The presence of low-metallicity galaxies with young ages without significant Balmer breaks suggest that OB stars that can ionize the IGM are probably present.

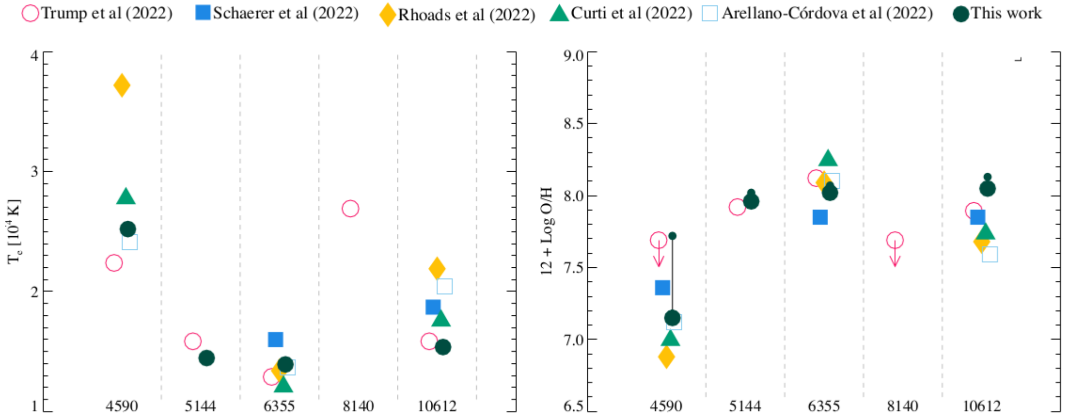
Chemical Enrichment at z > 7



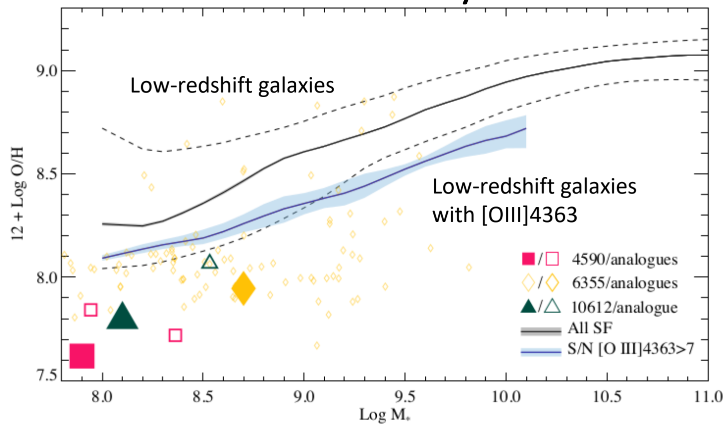
Schaerer+2022



Tacchella+2022



Mass-metallicity relation

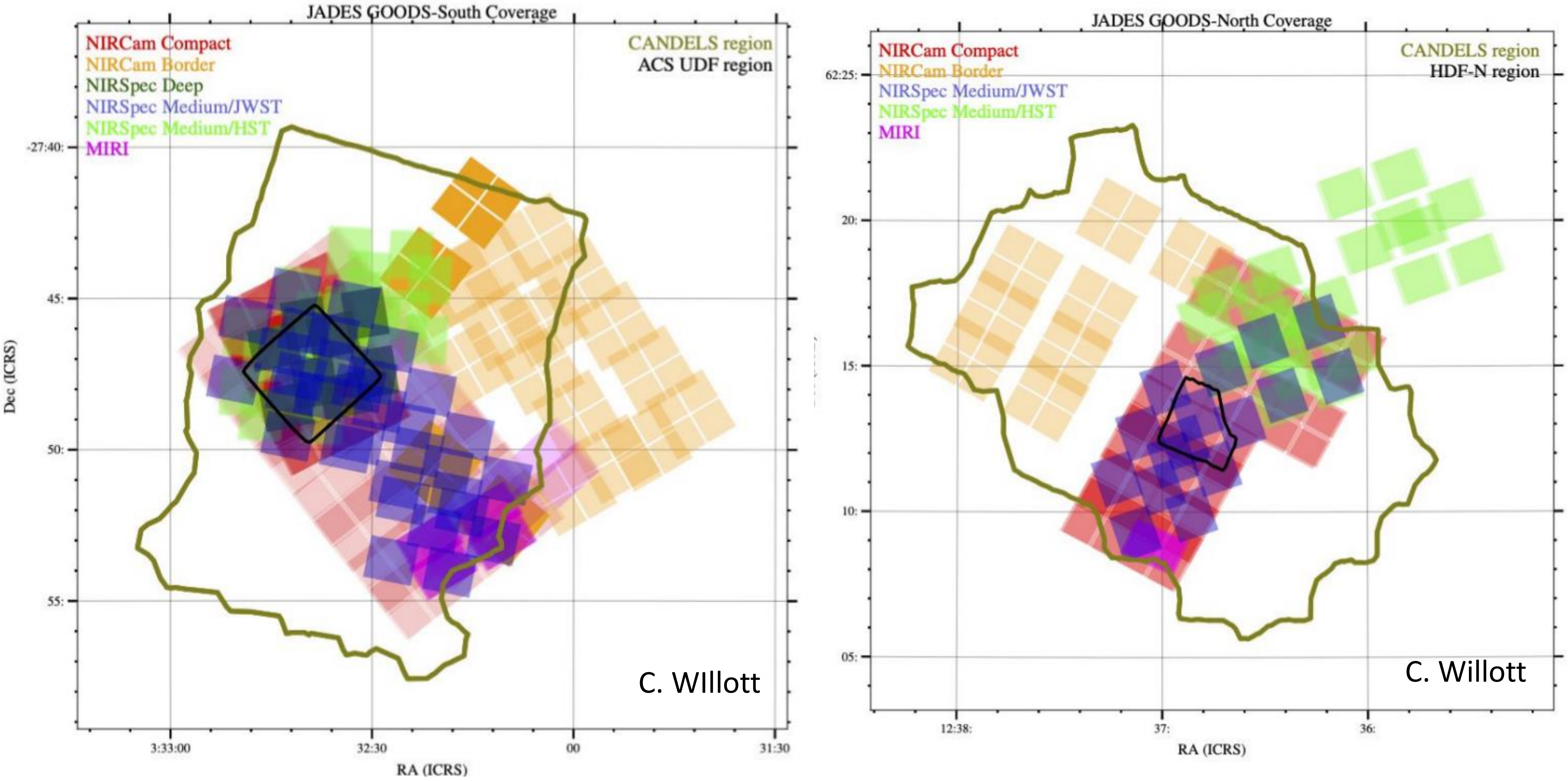


Brinchmann 2022

JWST activities at the U of Arizona

- Two instruments have UofA scientists as PI (NIRCam, Marcia Rieke) and co-PI (MIRI, George Rieke) and had hardware parts built in-house.
- UofA NIRCam and MIRI teams were actively involved in the instrument testing prior to launch and commissioning after.
- UofA scientists are involved in exoplanet searches, characterization of debris disks around stars, characterization of galaxies with nuclear activity.
- The NIRCam team has teamed up with NIRSpec in an ambitious photometric and spectroscopic survey using over 800 hours of JWST time in two specific regions of the sky (the JADES collaboration).
- The first observations start early in October 2022!

Outline of the JADES fields (not to scale)



Concluding remarks

- JWST is performing better than requirements
- Thanks to its optimal launch the expected lifetime of the observatory is estimated to be ~ 20 years
  - Micro-meteoroid impacts
  - Mechanical components
- The scientific analyses submitted for publication and/or published already have had an impact on our understanding of galaxy formation and evolution and the properties of exoplanets.
- As with the Hubble Space Telescope we should expect results that were unforeseen at the time of launch.

Thank you for your attention!