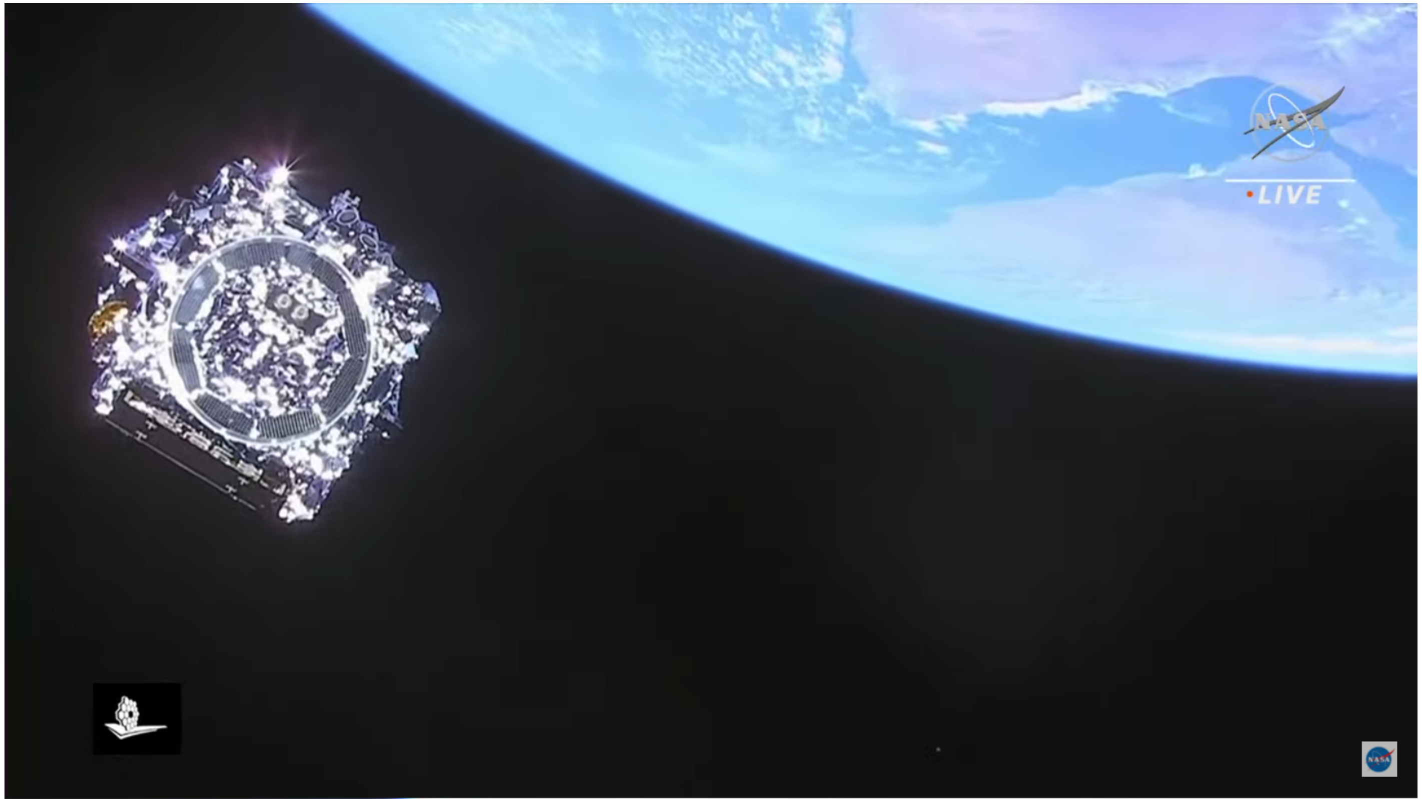
NIRSpec-GTO Multi-Object Spectroscopy of High Redshift Galaxies - the JWST Advanced Deep Extragalactic Survey

Andy Bunker (Oxford) on behalf of the NIRSpec Instrument Science Team and the JADES Team

PIs: Marcia Rieke & Pierre Ferruit

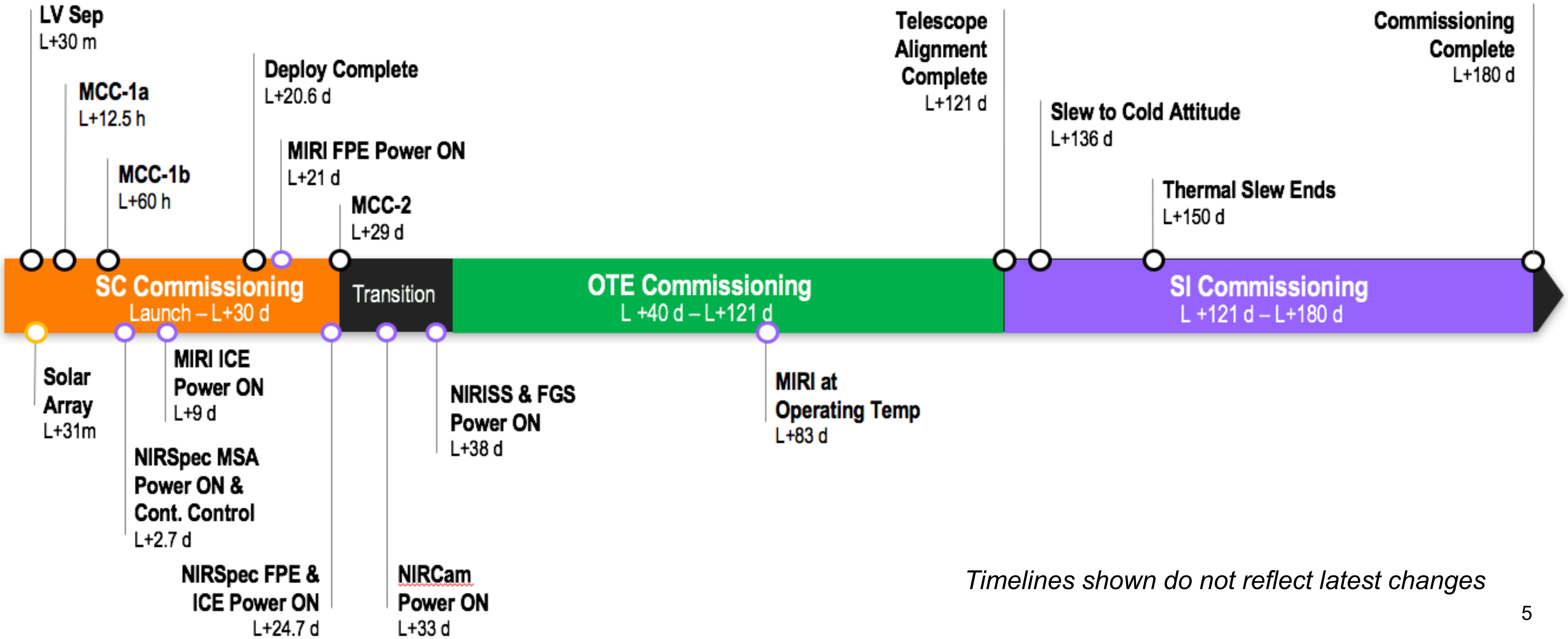
James Webb - in Space at Last


LIVE


LIVE

Observatory Commissioning Phases

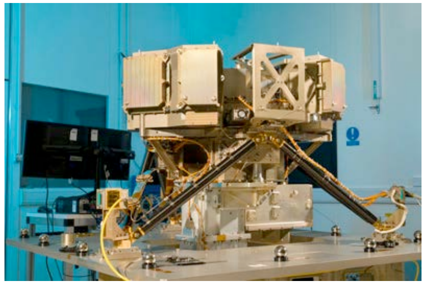
- **Spacecraft (SC) Commissioning**
  - Launch to Post MCC-2 burn activities (L+30d)
- **Thermal Cooldown**
  - Cooldown heaters enabled (L+45min) to MIRI reaching operating temp (L+83d)
- **Transition**
  - MOT shift cadence changes, OPE is activated and Observatory is transitioned to OPE control
- **Optical Telescope Element (OTE) Commissioning**
  - NIRCam reaches <80K (L+40d) to Telescope alignment (L+121d)
- **Science Instrument (SI) Commissioning**
  - Telescope alignment to completion of SI activities (L+166d)

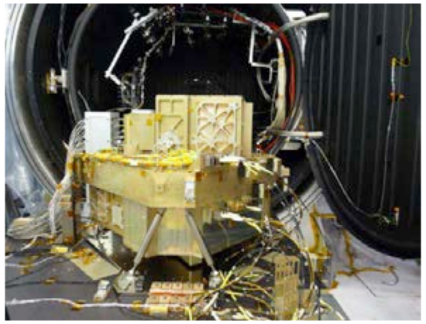


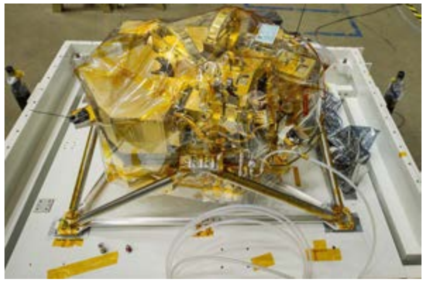
Timelines shown do not reflect latest changes

The James Webb Space Telescope (JWST) The mission in a nutshell

JAMES WEBB SPACE TELESCOPE







JWST's instruments

MIRI = Mid-InfraRed Instrument

50/50 partnership between a nationally funded consortium of European institutes (MIRI EC) under the auspices of ESA and NASA/JPL.

PIs: G. Wright and G. Rieke

NIRSpec = Near-infrared Spectrograph

Provided by the European Space Agency. Built for ESA by an industrial consortium led by Airbus Defence and Space.

NIRISS = Near-infrared Imager and Slit-less Spectrograph

FGS = Fine Guidance Sensor

Provided by the Canadian Space Agency.

PIs: R. Doyon & C. Willott

NIRCam = Near-InfraRed Camera

Developed under the responsibility of the University of Arizona.

PI: M. Rieke

Observing time

Early Release Science (ERS) proposals - CEERS, starburst-AGN connection, TEMPLATES, LookingGLASS, Q3D (QSO hosts)

GO proposals Cycle 1 announced March 2021 after TAC peer review

6000 hours (plus 1200 parallel time), 266 proposals approved

- 52% to small programs (less than 25 hours)
- 32% to medium programs (25 to 75 hours)
- 16% to large programs (more than 75 hours)

The 13 new large and treasury programs will produce data that are immediately available to the community (includes COSMOS-Web, PRIMER, WDEEP, UNCOVER

GTO programmes - 900 hours per instrument, across Cycles 1 & 2

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PIs: Marcia Rieke & Pierre Ferruit

In 2015, the **NIRSpec instrument GTO team** decided to join forces with NIRCam (PI: Marcia Rieke) to conduct a large extragalactic survey with JWST. ***Together we are the JADES collaboration***

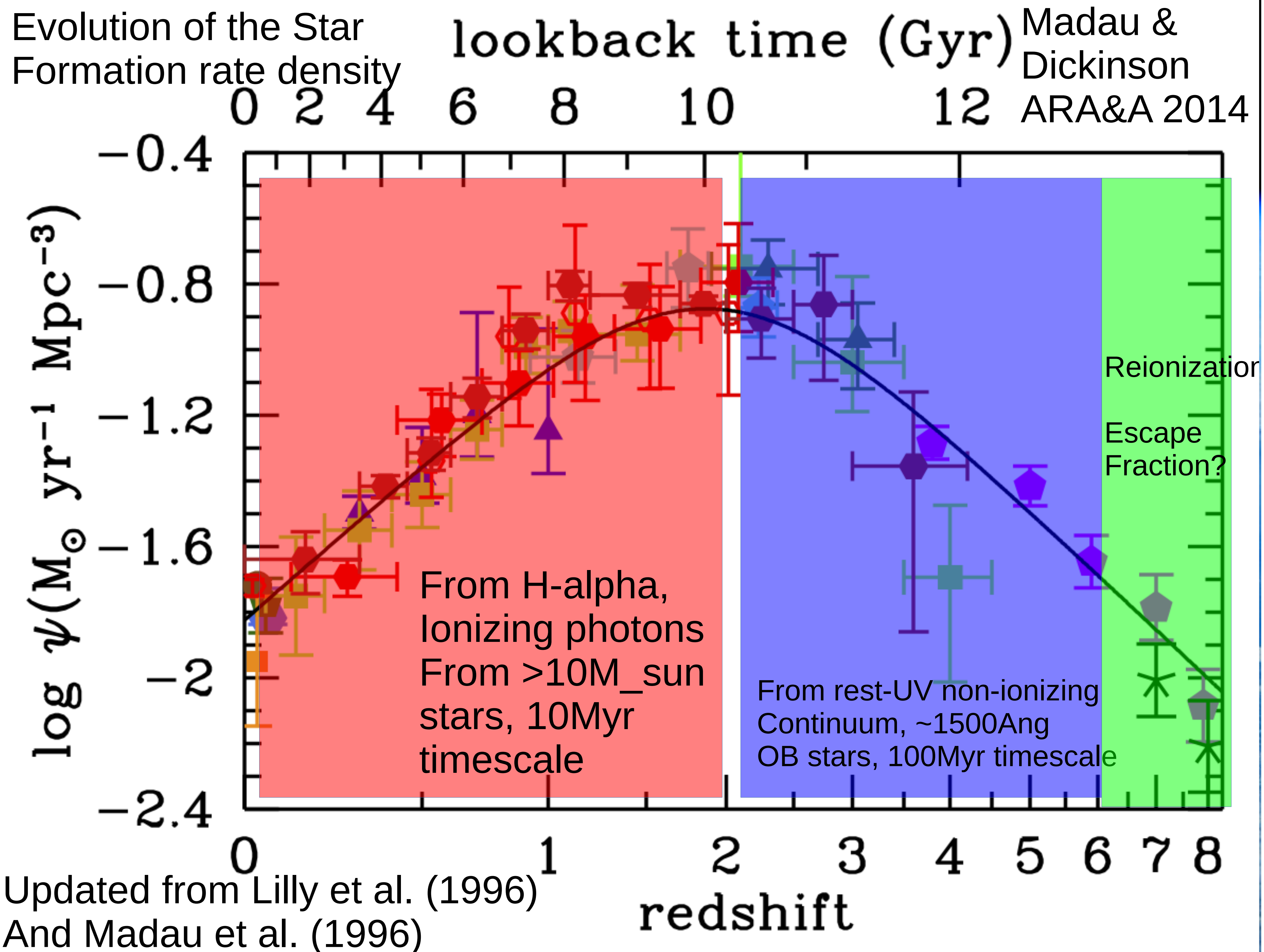
The largest single GTO programme for both NIRCam and NIRSpec (~600hours): we have a large and growing JADES team

Stacey Alberts, Ricardo Amorin, **Santiago Arribas**, Stefi Baum, Rachana Bhatawdekar, Nina Bonaventura, Rebecca Bowler, Kit Boyett, **Andy Bunker**, Alex Cameron, Stefano Carniani, **Stephane Charlot**, Jacopo Chevallard, Mirko Curti, Emma Curtis Lake, Anna de Graaff, Alan Dressler, Eiichi Egami, Daniel Eisenstein , Ryan Endsley , **Pierre Ferruit**, **Marijn Franx**, Giovanna Giardino, Kevin Hainline, Bernd Husemann, **Peter Jakobsen**, Ben Johnson, Sean Johnston, Gareth Jones, Nimisha Kumari, **Roberto Maiolino**, Michael Maseda, Michele Perna, Janine Pforr, Tim Rawle, Bruno Roderiguez, George Rieke, Marcia Rieke, **Hans-Walter Rix**, Brant Robertson, Lester Sandles, Aayush Saxena, Irene Shivaei, Renske Smit, Daniel Stark, Sandro Tacchella, Hannah Übler, Imaan Wallace, Christina Williams, Christopher Willmer , **Chris Willott**, Joris Witstok… (probably incomplete list)

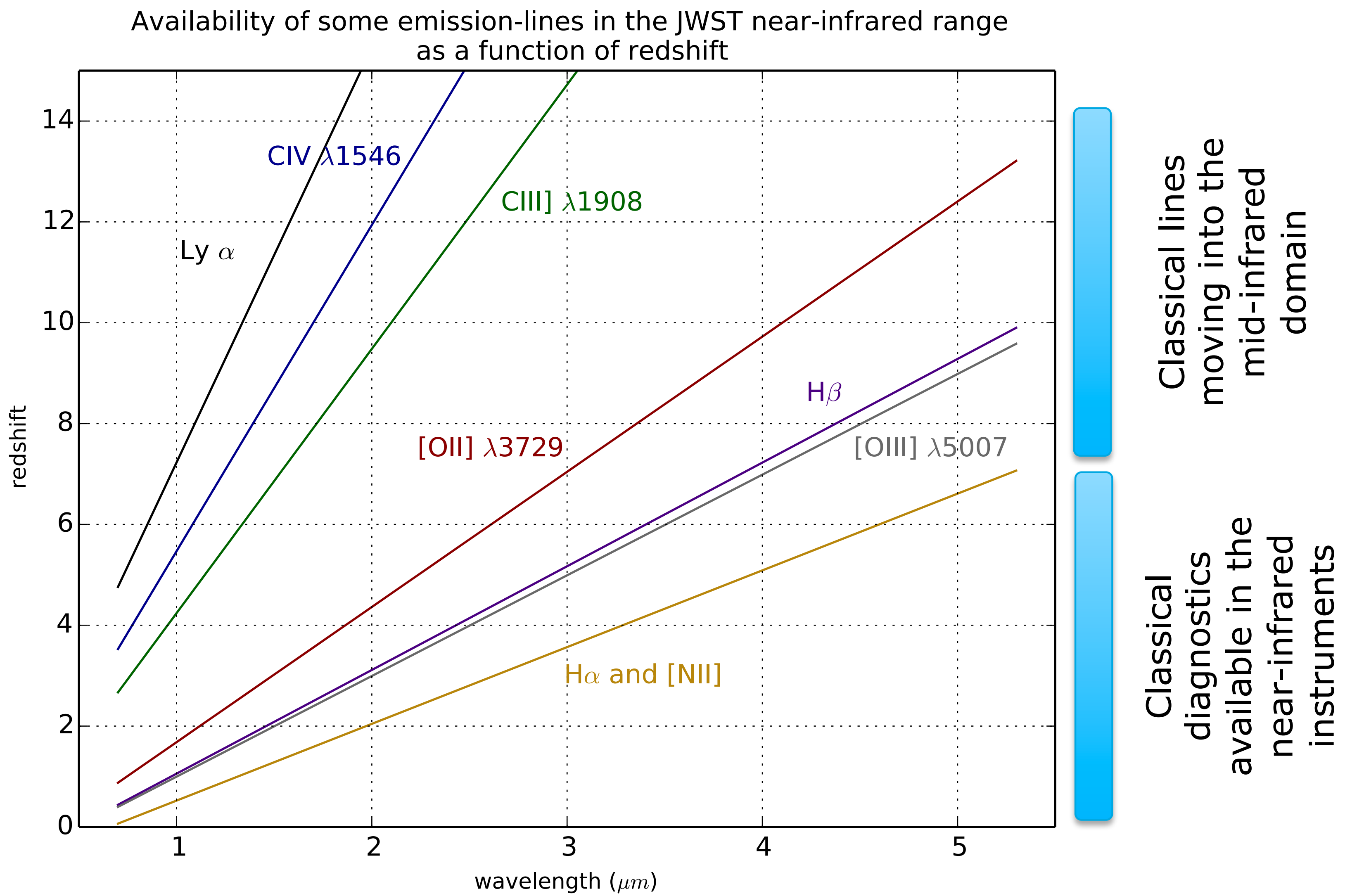
Big Questions

- 1) What is the history for star formation - i.e. how rapidly is the Universe converting its gas into stars, and how does this evolve with time?
- 2) How is this star formation divided up among galaxies of different masses/environments as a function of cosmic time (“downsizing” etc).
- 3) Is the measured stellar mass density consistent with the integrated past cosmic star formation rate?

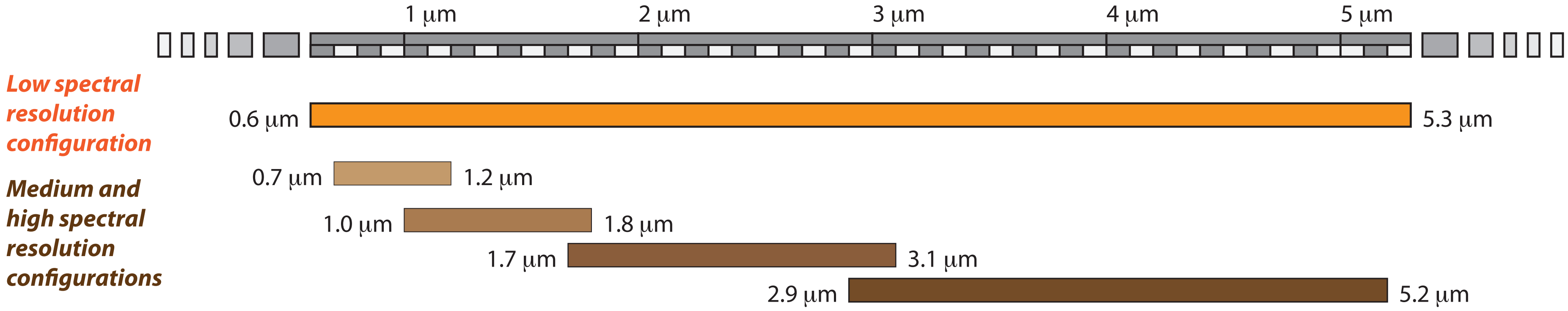
  4) As heavy elements are made in stars, how does the metal enrichment of the gas & stars proceed?
- 5) What is the contribution of UV photons from star formation to the reionization of the Intergalactic Medium (IGM)?


Evolution of the Star
Formation rate density
lookback time (Gyr)
0 2 4 6 8 10 12
Madau &
Dickinson
ARA&A 2014
log ψ(M⊙ yr⁻¹ Mpc⁻³)
−0.4
−0.8
−1.2
−1.6
−2
−2.4
From H-alpha,
Ionizing photons
From >10M_sun
stars, 10Myr
timescale
From rest-UV non-ionizing
Continuum, ~1500Ang
OB stars, 100Myr timescale
Reionization
Escape
Fraction?
0 1 2 3 4 5 6 7 8
redshift
Updated from Lilly et al. (1996)
And Madau et al. (1996)

JWST/NIRSpec – The instrument

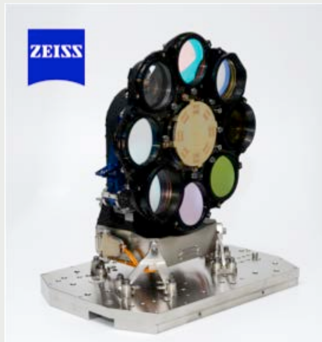


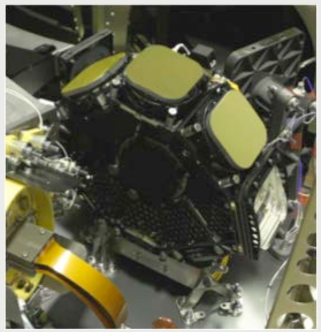
JWST/NIRSpec - spectral configurations



- **At low spectral resolution, full coverage of the 0.6-5.3 micron range in one shot.**
  - R ~30-300 (low).
- **At medium and high spectral resolution, several exposures are necessary to cover the full wavelength range of NIRSpec.**
  - R ~1000 and ~2700.

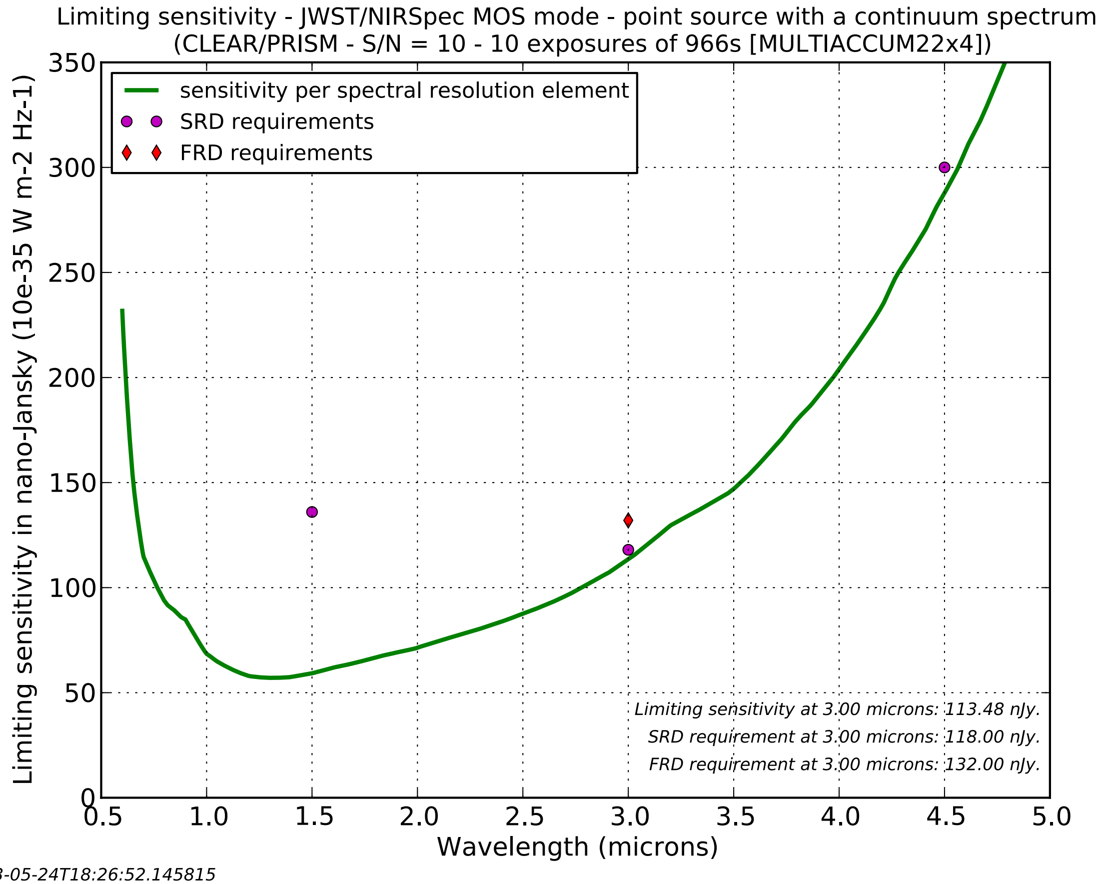
Configurations that can be obtained thanks to a combination of filters and dispersers installed on two wheels (FWA and GWA)





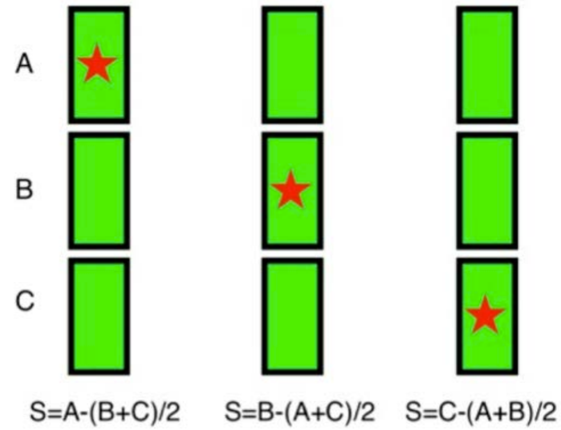
JWST/NIRSpec
Multi-object spectroscopy

- **Limiting sensitivity**
  - Conservative estimates including a recipe to account for data loss due to detector cosmetics.

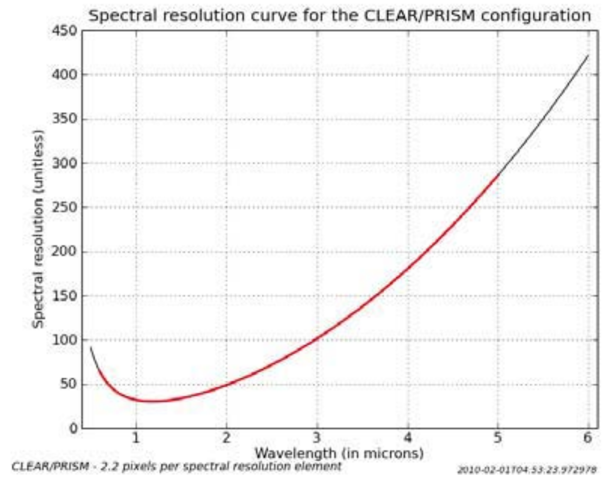


100 nJy = 1e-30 erg s-1 cm-2 Hz-1 = 1e-33 W m-2 Hz-1 = 26.4 AB mag = 24.3 K-band mag

Note the gaps between the shutters are real (pitch = 202 microns, aperture = 175 microns, 14% relative bar size)



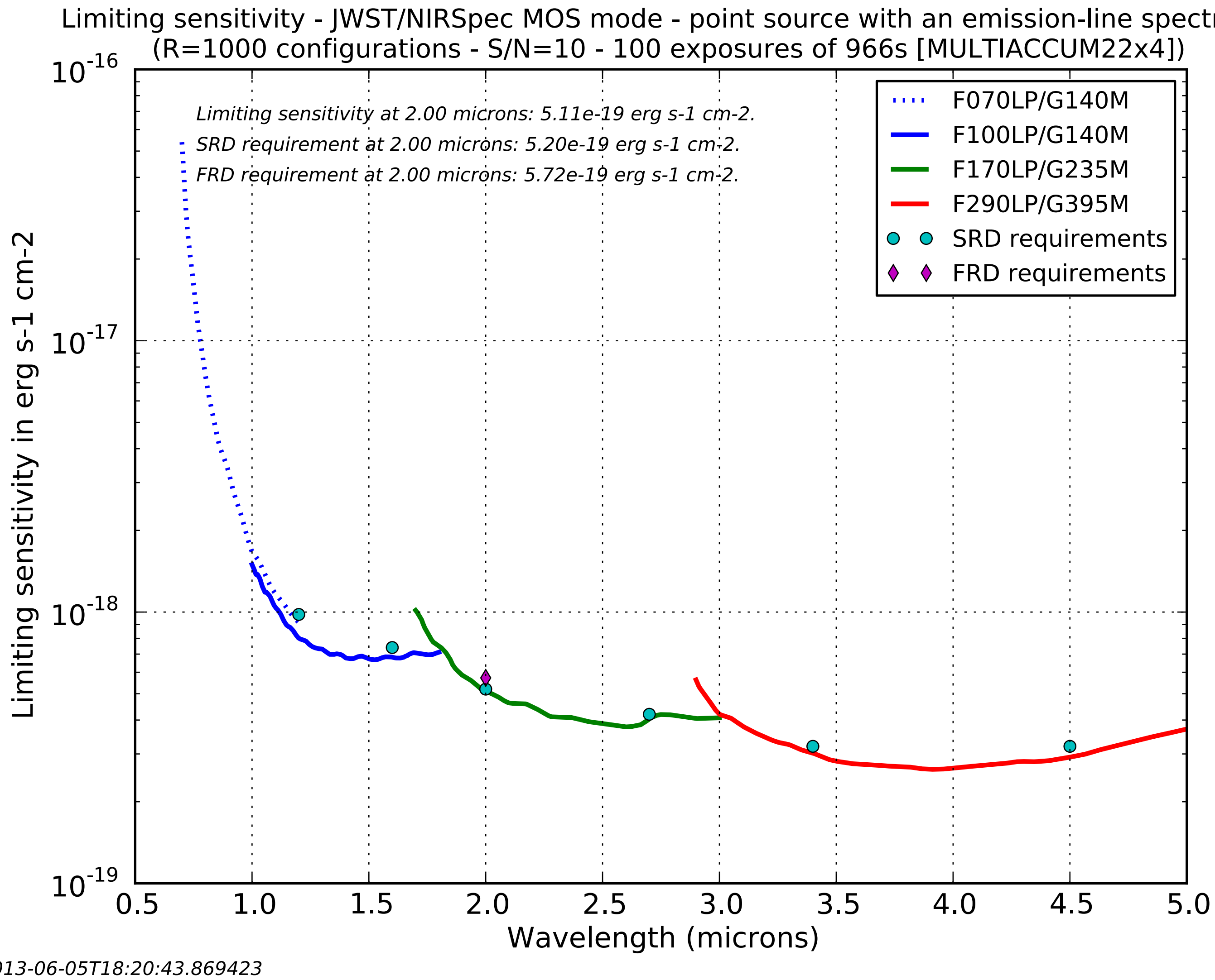
- Low spectral resolution



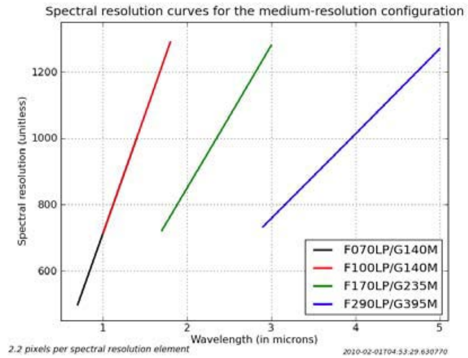
JAMES WEBB SPACE TELESCOPE

European Space Agency

JWST/NIRSpec Multi-object spectroscopy

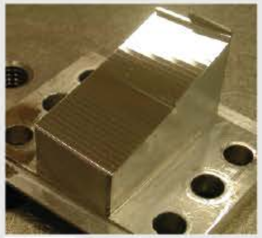


- Medium spectral resolution



JWST/NIRSpec – The instrument

JWST/NIRSpec

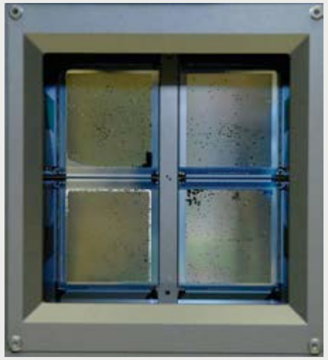
MOS		Multi-object spectroscopy with 0.2"-wide mini-slits.	- 9 square arcmin. field of view - Low spectral resolution (30 to 300), prism-based mode covering the 0.6-5.0 micron range in one exposure. - Medium spectral resolution (500 to 1300), grating-based mode covering the 0.7-5.0 range
IFU		IFU spectroscopy with a 0.1" sampling. (IFU made of 30 slices for a total of 900 "spaxels")	- 3"x3" field of view - Low spectral resolution (30 to 300), prism-based mode covering the 0.6-5.0 micron range in one exposure. - Medium (500 to 1300) and high (1400-3600) spectral resolution modes, covering the 0.7-5.0 range in 4 exposures. - IFU and MOS cannot be used at the same time.
SLIT		High-contrast slit spectroscopy. (including with a 1.6"x1.6" square aperture for extra-solar planet transit observation)	- 5 slits available All spectral resolution modes available. - SLIT can be used simultaneously to IFU or MOS.

JWST/NIRSpec
Multi-object spectroscopy (MOS)

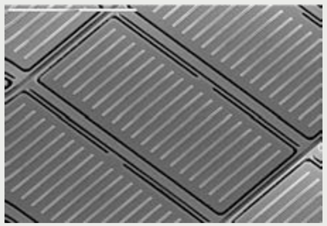
- **The challenge of multi-object spectroscopy**
  - Letting the light from selected objects go through while blocking the light from all the other objects.
  - A configurable mask was needed.

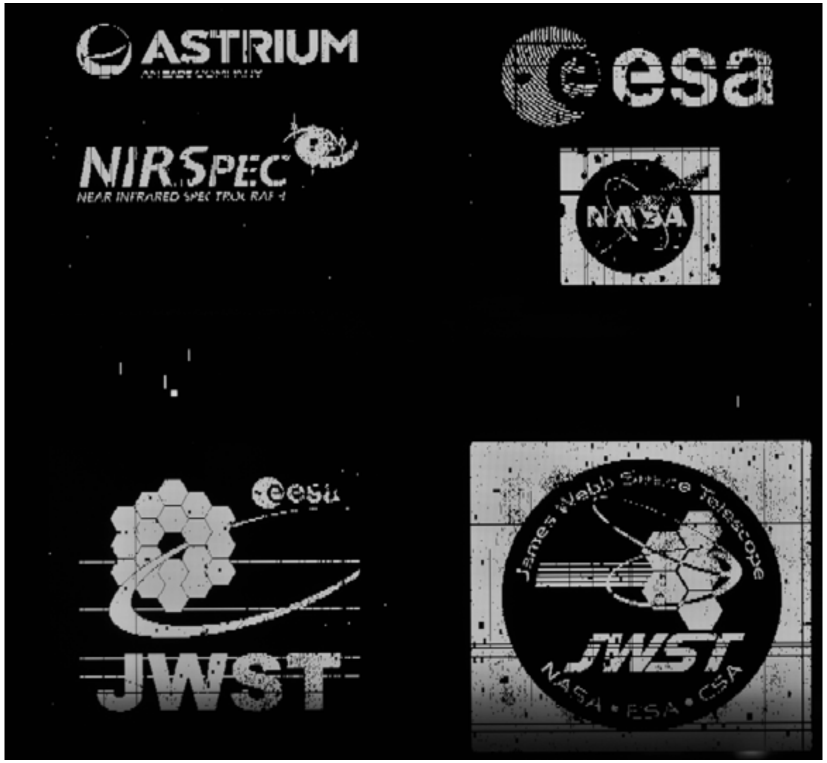
Using 4 arrays of 365x171 micro-shutters each, provided by NASA GSFC.

This gives us a total of almost **250 000** small apertures that can be individually opened/ closed



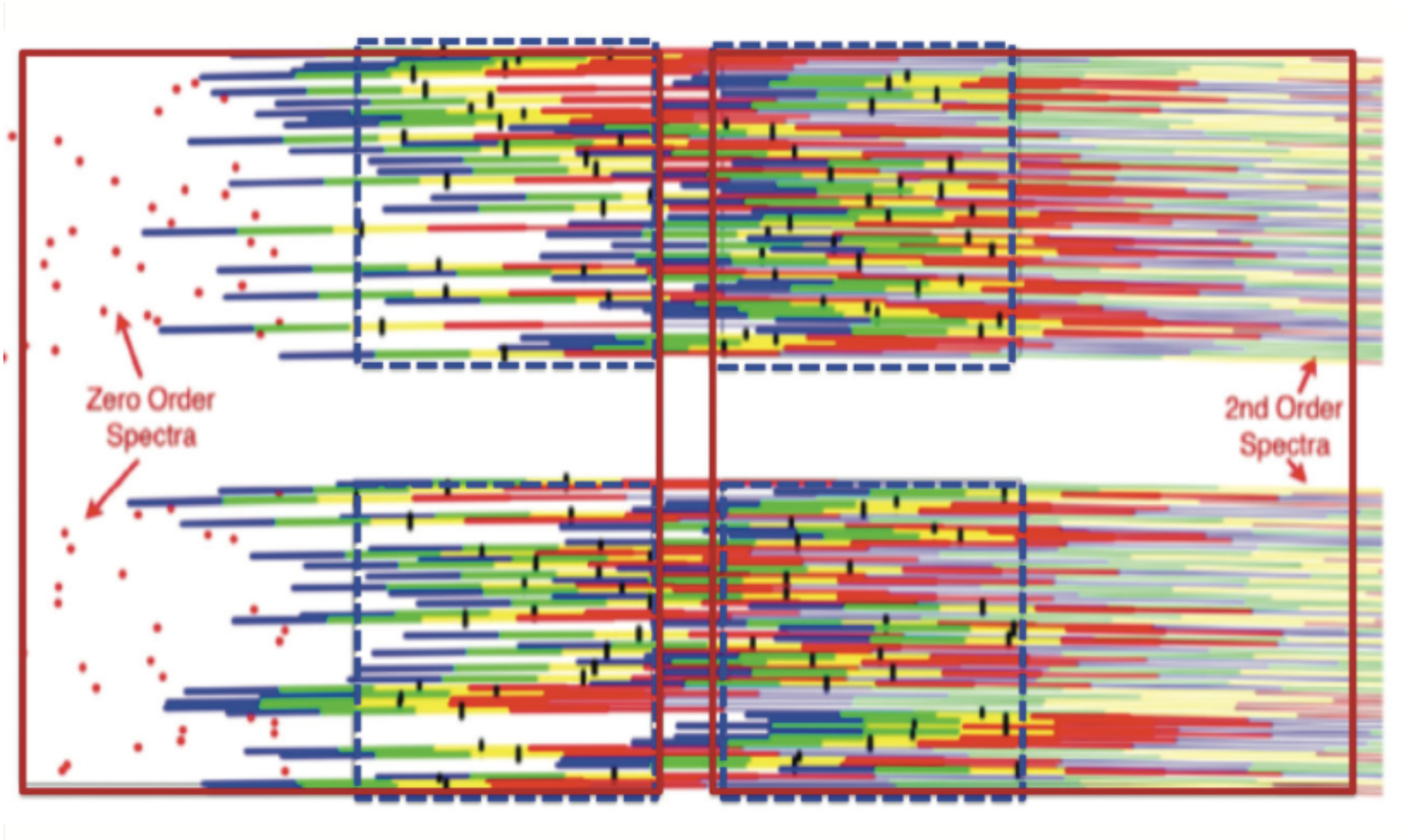
MEMS device – 105x204 micron shutters





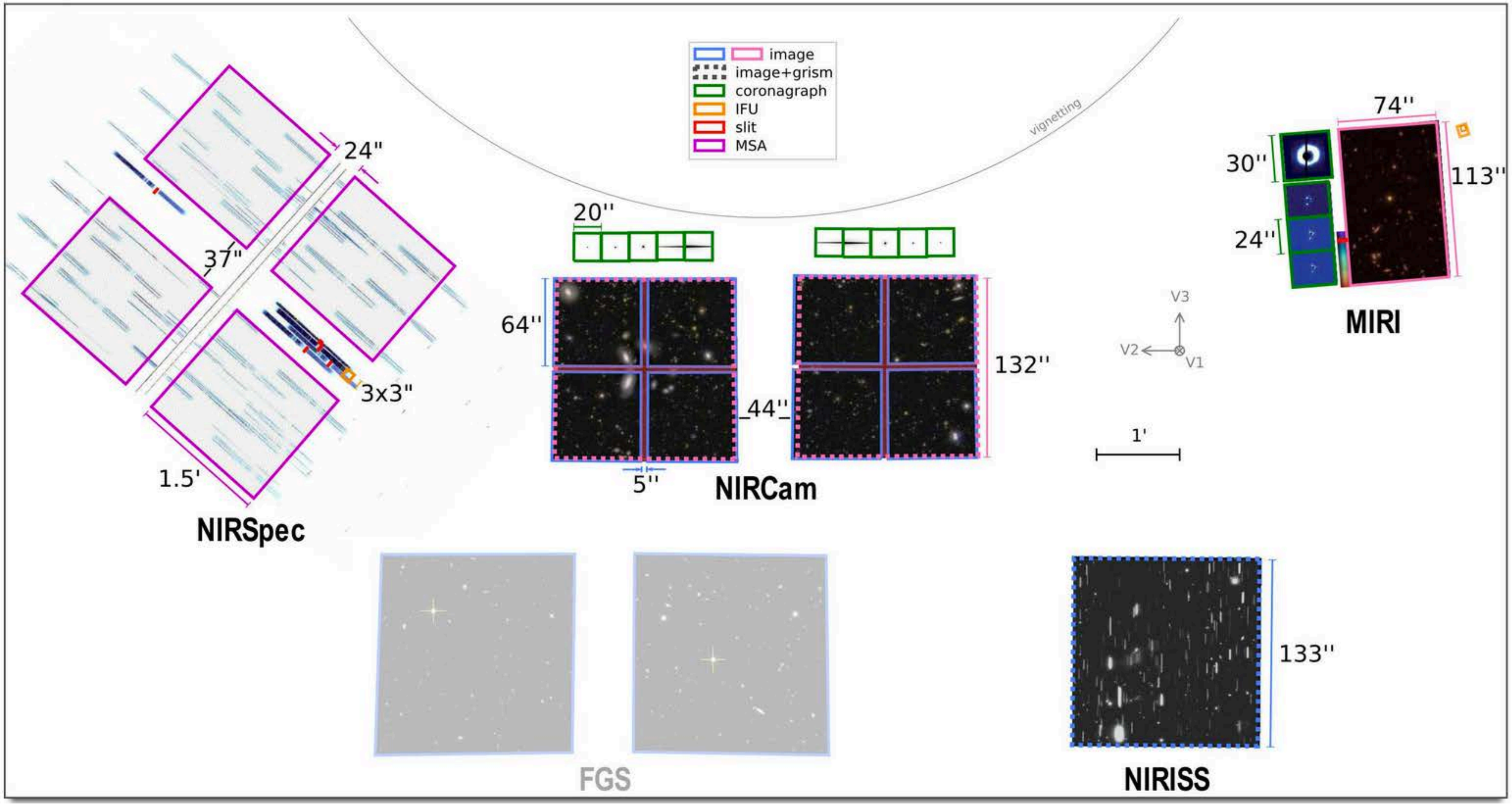
We typically need > 85-90 % of the shutters operable.

Spectra from NIRSpec

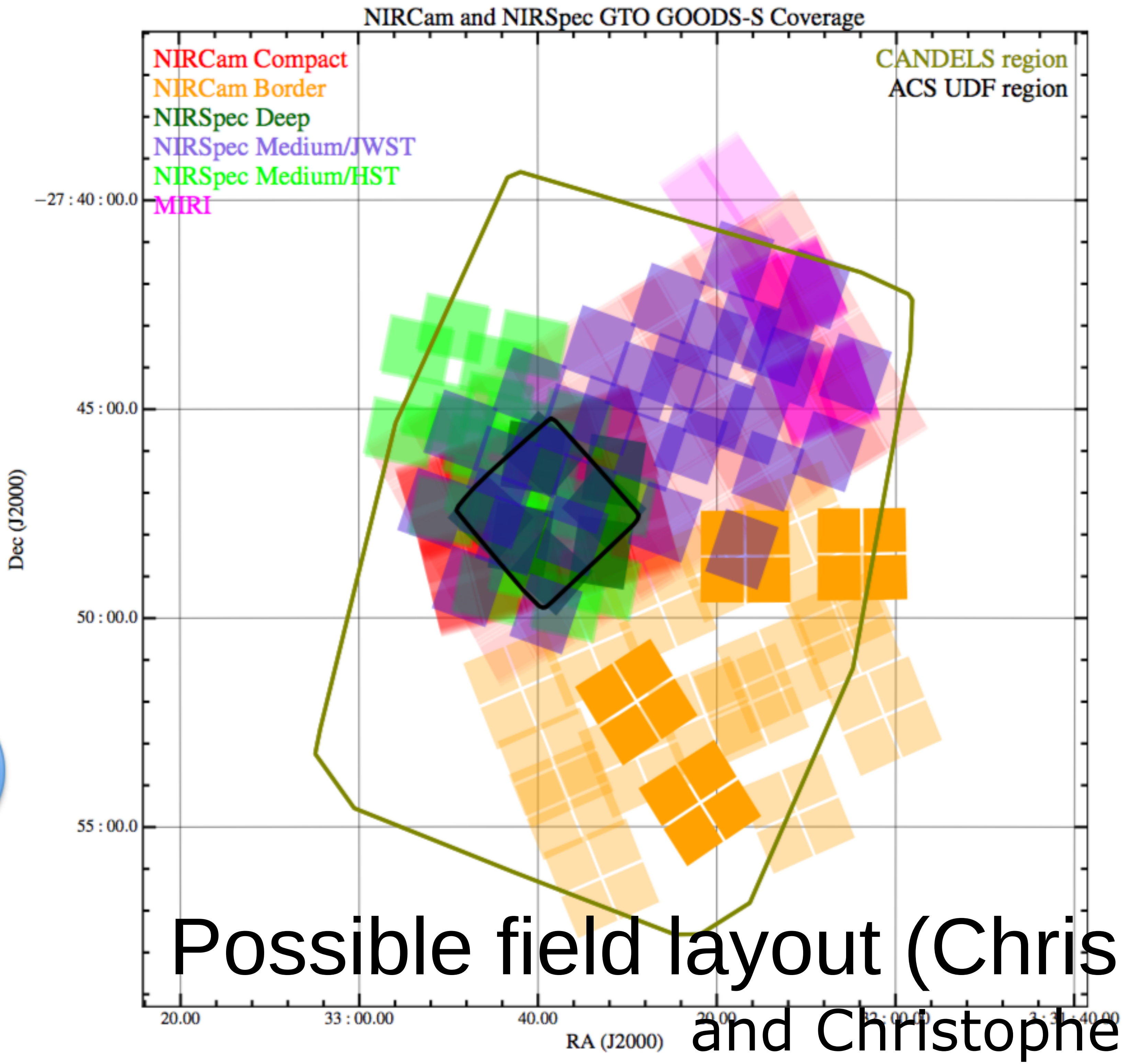


From STScI Newsletter, 2014, Karakla et al.

JWST imaging capabilities
Mapping of the focal plane



Credit: STScI



Possible field layout (Chris Willott) and Christopher Willmer

Overall NIRSpec Galaxy Assembly Plan

a wedding cake survey at R=100 and R=1000&2700 in well-studied HST fields GOODS-N&S with great ancillary data (VLA, ALMA, MUSE, X-ray…)

JADES Deep, 2 pointing GOODS-South (in/near HUDF), 1-5 µm, R=100 + R=1000 (3 grating) and on high-res R=2700 148 hours, AB≤29-30, 2<z<14. First one on HUDF based on HST selection.

- JADES Medium, 12 pointings follow-up NIRCam plus 12 parallels in GOODS-N+S 1-5µm, 200hours, AB≤27-28, 2<z<14
- Wide, 35 pointings, R100 and two high-res R2700 gratings, 100hours AB<25 (3microns), H-alpha > 10-17erg/cm^2/s, CANDELS fields

R=2700 IFU spectroscopy of extended objects 270 hours, 30 star forming galaxies at z=1-7, 23AGN, 6 z>6 LAEs, 3 z>4 SMGs

R=100
stellar continuum
& redshift

R=1000
nebular lines
full band

R=2700
kinematics

Subsurvey	# Targets	Exposure Times (Ksec) Prism	G140M	G235M	G395M	G395H
Deep/JWST	200	100	25	25	25	25
Deep/HST	200	100	25	25	25	25
Medium/JWST	2400	8.5	8.5	8.5	8.5	8.5
Medium/HST	up to 4800[a]	3.5	2.8	2.8	3.5	—
Wide/HST	6400	0.8				1.3 + G235H

Total ~ 14,000

Subsurvey	Limiting Emission Line Sensitivity (10-σ; cgs units) Prism (2.5 μm)	G140M (1.2 μm)	G235M (2.5 μm)	G395M (4.5 μm)	G395H (4.5 μm)
Deep	8.5×10^{-19}	1.9×10^{-18}	9.3×10^{-19}	5.8×10^{-19}	8.1×10^{-19}
Medium/JWST	2.8×10^{-18}	3.4×10^{-18}	1.6×10^{-18}	1.0×10^{-18}	1.4×10^{-18}
Medium/HST	4.5×10^{-18}	6.8×10^{-18}	3.2×10^{-18}	1.7×10^{-18}	—

NIRSpec GTO
MSA galaxy assembly program

Top priority science cases:

- Spectroscopic confirmation of the most distant galaxies
- Robust star formation rates from Hα, dust from Hα/Hb
- Escape of Ly continuum and Lyα photons
- Stellar populations, kinematics and chemical enrichment
- Searches for the first generations of stars (Population III)
- AGNs and their host galaxies
- Large scale structure, environment

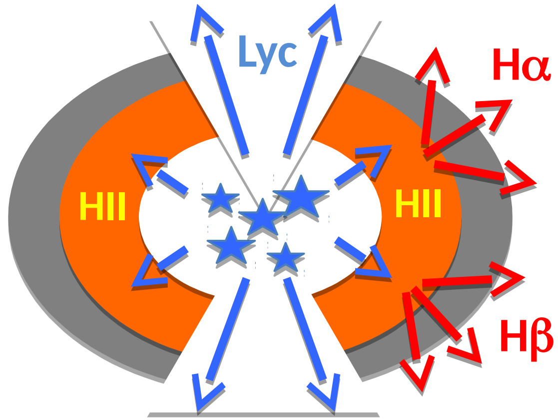
Confirming Highest-z sources & Dust

NIRSpec will get very accurate redshifts, and hence determine accurate rest-frame properties.
Measure emission lines (Hα, Hβ, [OIII], [OII], [SII] and also [NII] for R=1000) to constrain: attenuation by dust, star formation rate; ionization state and metallicity of the interstellar gas; presence of an AGN (NV and BPT); HeII-1640 for pop III? Potentially individual element abundances (C, N, O)

Dust at high redshift: Demographics of Balmer decrement (Hα/Hβ) across cosmic time and relation with galaxy properties (e.g., L_{UV}, β_{UV}, SFR, M_*, presence of an AGN, etc.)

- Constraints on the dust attenuation curve at $\lambda < \lambda(H\beta)$ from measurements of high-order Balmer lines; and at $\lambda > \lambda(H\alpha)$ from measurements of Pa-α (at z<1.7) and Pa-β (at z< 2.9)
- Constraints on UV attenuation from spectroscopy of z>4 galaxies (incl. strength of 2175 Å absorption feature)
- Differential attenuation suffered by young stars (still embedded in their molecular clouds) and older stars
- Consistency between attenuation from rest-UV/optical, and direct measurements of far-IR dust emission (e.g., IRX-β_{UV} relation)

The Lyman continuum escape fraction (1)

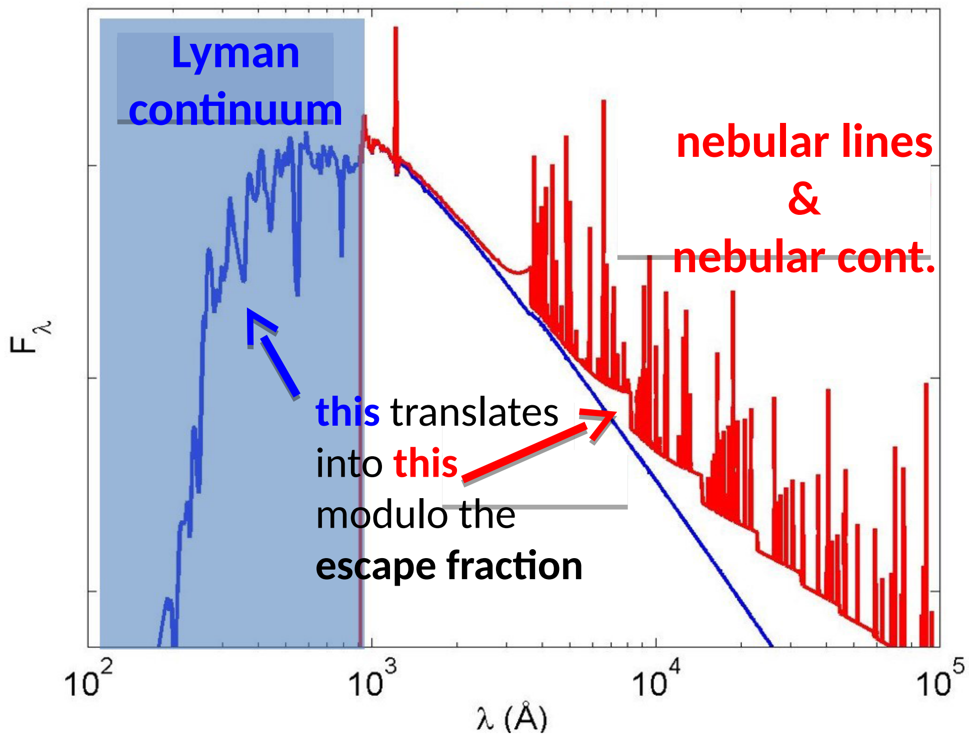


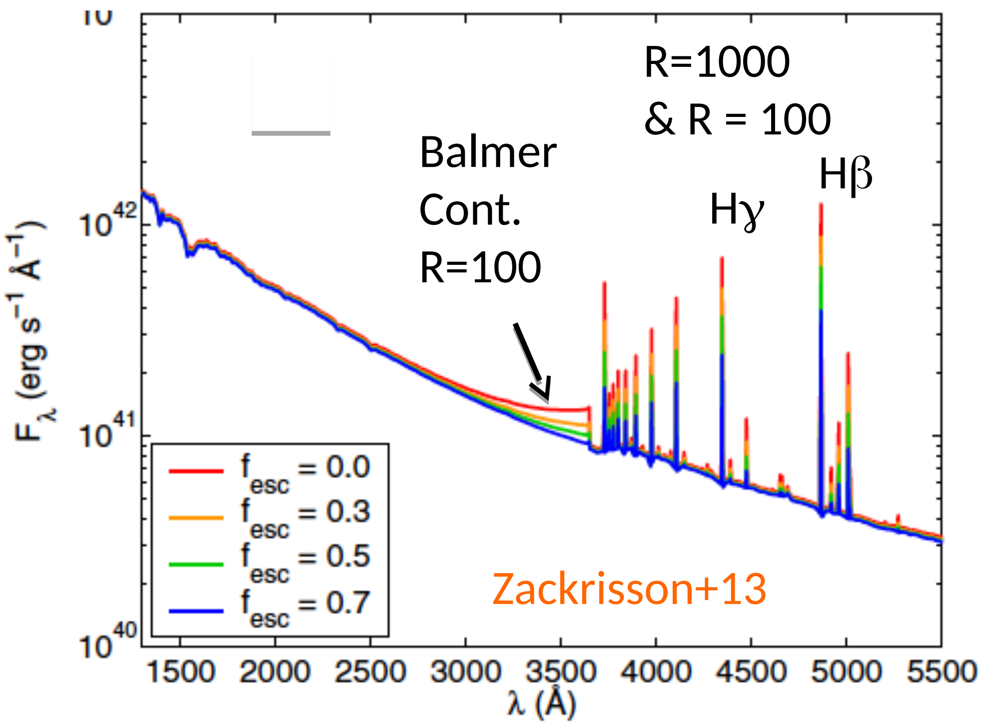
Science goals

- Escape fraction of Lyman continuum as a function of galaxy properties (mass, SFR, z,....)

Methods

- Balmer lines compared with UV continuum
- Balmer decrement and UV slope -> dust extinction + age
- HeII/HeI/H line ratio -> shape of ionizing continuum
- R = 1000 (R=100 for Balmer break)





JWST-NIRSpec – Escape Fraction and Reionization

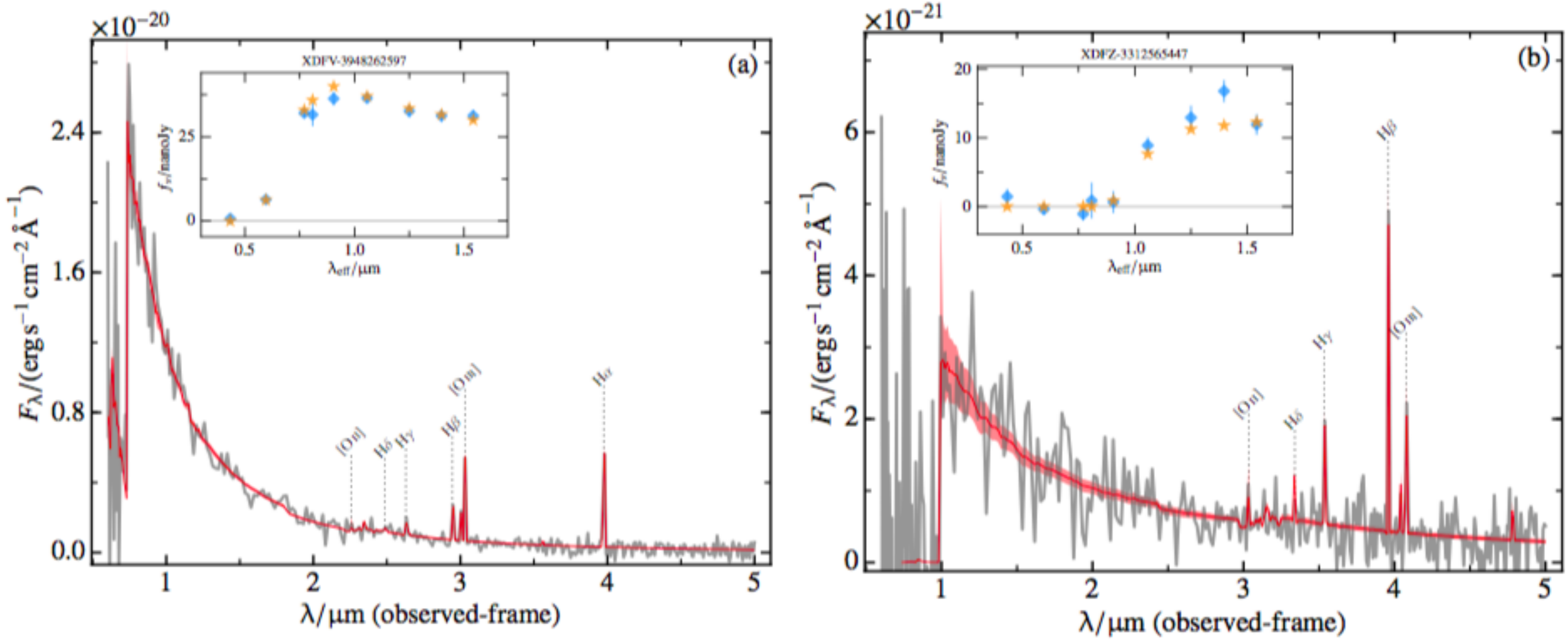
Escape fraction (from Balmer lines compared with UV) (dependence on mass, SFR; compare with Ly-a flux and profile, outflow velocities…)

The comparison of the H-alpha or H-beta photons with the UV continuum should provide a good constraint - a simple photon budget governed by well known photoionization and recombination physics.

[Modulo the UV extrapolation beyond Lyman-alpha, which may be model dependent, but can be constrained by the HeI/H ratio, or even HeII/HeI/H.]

- Interpretation of rest-frame UV / optical emission-line spectra to constrain sources of ionizing photons
- other hard spectra, AGN, SMBH; Pop III stars, DCBH, shocks), using simple diagnostics and Beagle
- Consider impact of binary stars on measurements (particularly HeII for PopIII indicator) including X-ray binaries

Simulated NIRSpec spectra from IST – Chevallard et al. (2018) arXiv 1711.07481



(also mock NIRCam catalogues: Williams et al. 2018 arXiv1802.05272)

Star-forming galaxies at high-z: stellar populations

- Emission-line properties of SFGs across cosmic time (BPT, MEx, EW distributions versus redshift, L_{UV}, β_{UV}, M*, etc.)
- Determine the existence of the Main Sequence, its scatter, shape, turnoff and its evolution out to the highest-z probed ($z>9$).
- R100 spectra offer the continuum shape in the rest-frame UV and across the Balmer break as well emission line strengths. Determine SFR and M* much better than broad-band SED
- physical parameters of stars (SFR, M*, SFH) and gas (ionization parameter, density, gas metallicity, dust attenuation parameters, ionization efficiency ξ_{ion}, etc.) across a wide redshift range

- **Are the blue spectral slopes real?**
- **Is the suggested severe contamination of broad-band magnitudes (e.g. Spitzer/IRAC) by huge EW line emission real?**

Chemical enrichment at high-z with NIRSpec

- Determine the redshift evolution of the metallicity and chemical enrichment of galaxies, particularly evolution at $z>3$
- Low metallicity systems (<0.1 Zsun all the way to Pop-III metal-free primordial galaxies), parameter space not yet probed by current observations.
- Primarily be done for the gas phase, also attempt for the stellar metallicities (although more difficult).
- Constrain the mass-metallicity (M-Z) relation and fundamental metallicity relation (M-Z-SFR) in different redshift bins.
- Constrain the evolution of the chemical abundances, specifically N/O (for gas phase), C/O and (though difficult) alpha/Fe - different timescales of evolution
- Detect auroral lines in individual galaxies and stacked spectra and recalibrate the empirical metallicity strong line diagnostics
-

Kinematics of high-z galaxies with NIRSpec (particularly R2700 grating work)

- linewidths from emission lines from z=2 to z=10 and beyond with NIRSpec, (and full 2D maps with the Integral Field Spectroscopy mode) & correlations with stellar mass, redshift
- dynamical state of the emission line gas in high redshift galaxies and correlation with specific star formation rate
- V/sigma, and sigma, with redshift and as a function of galaxy properties (Mstar, SFR)
- Extended rotation curves of star forming galaxies to z=10
- Tully-Fisher relation to z=10
- Identify mergers (kinematically), and infer their demographics and properties (and morphology with NIRCam)
- Mdyn vs Mstar (implications for DM, Mgas, IMF, MZR)
- redshift evolution of angular momentum and correlation with global galactic properties
- redshift evolution of the Fundamental Plane

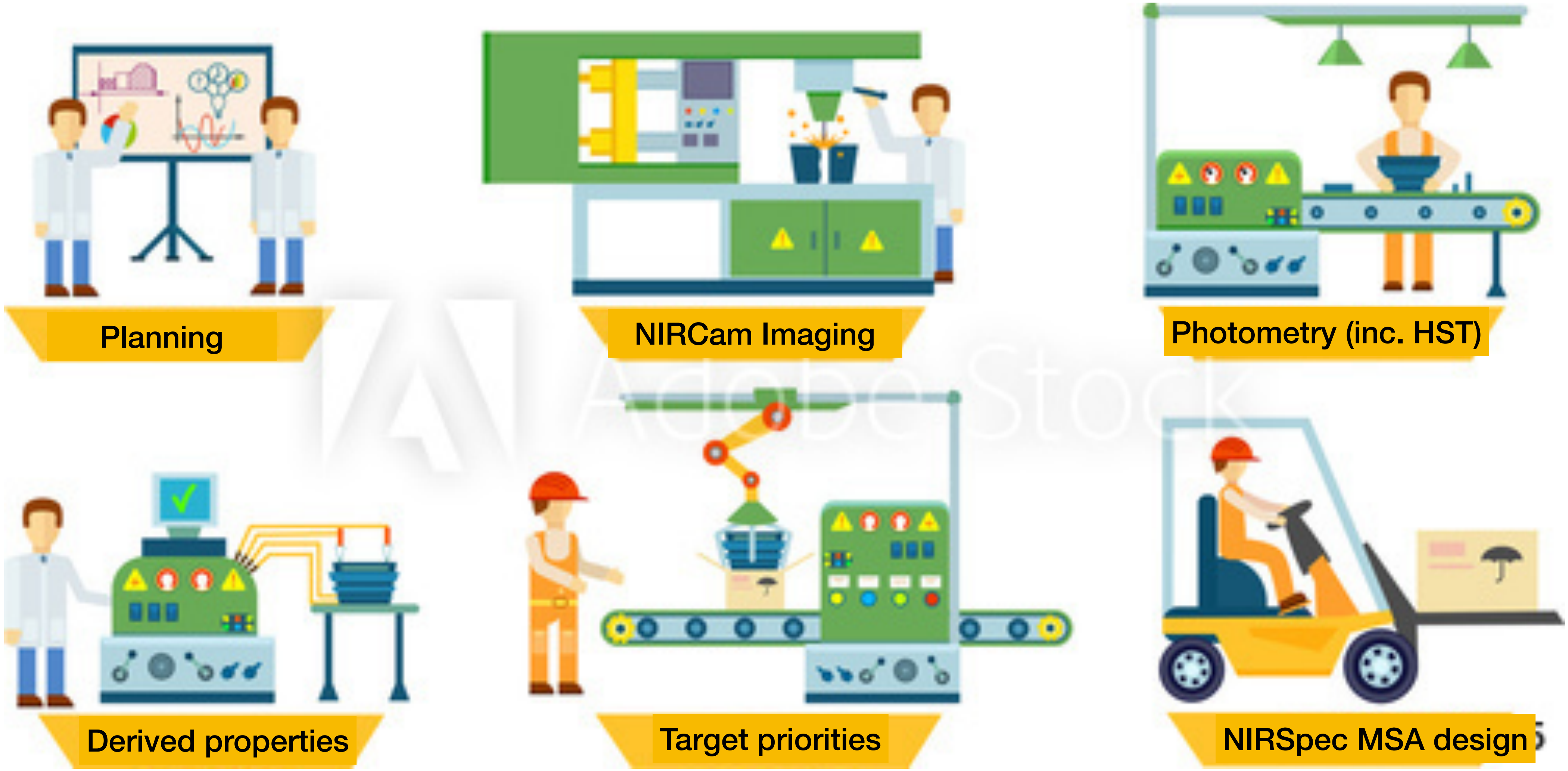
Allocation of targets - Imposing a Class System

- We anticipate a small number of very high priority targets (e.g. z>9 candidates) which drive the specific pointing, and are placed first on the MSA (using MPT or eMPT tool)
- Our next priority are z>6 galaxies which are sufficiently bright in the rest-UV that we expect sufficient S/N in the rest-optical lines to do line ratio diagnostics (e.g. metallcity). Can "promote" interesting sources (ALMA,high-EW emission lines, AGN, clustered objects)
- We then place in order descending slices in redshift (and increasing surface density) from z~6 to z~2, and fainter sources (with less reliable phot-z)
- In the lowest priority classes, the individual probability of a target being placed is low BUT there are a large number available, so we can build up statistics (e.g. want to populate the mass:metallicity relation over many redshifts)

From images to targets on MSA

- ~45 days between images and spectra when NIRCam and NIRSpec in same visibility window
- Need to reduce NIRCam images, check astrometry/photometry, build catalogues (usually including existing HST data, particularly ACS)
- From catalogues, need to allocate sources to the various target priority categories
- Requires redshift estimate. We will use:
    - simple colour:colour selection (e.g. Lyman break selection)
    - photometric redshift fits to SED, and M_UV (proxy for SFR) and approx stellar mass from 4.4micron flux
    - “full” fit using e.g. BEAGLE to get stellar mass, SFR, star formation history…

Data Challenges run: simulated NIRCam images based on the JAGUAR catalogue - test NIRCam reduction, photometry, photometric redshifts and our ability to select good candidates for NIRSpec MSA. Done against the clock to replicate situation where NIRSpec observes soon after NIRCam data is taken (same visibility window)



The JADES Factory

NIRSpec: Challenges as well as Opportunities

- **The Micro-Shutter Array (MSA) -1000s of galaxies**
  - Fixed 0.2arcsec x 0.4arcsec grid, so targets off-centre
  - PSF varies by ~3 spatially across 1-5microns
  - Need to model wavelength-dependent slit losses for light profile of galaxy (and slit position
  - Some shutters failed closed; failed open more serious but few
  - R100 unconfused; overlap of spectra at R1000, R2700

First "Deep" NIRSpec spectroscopy in late October around the Hubble Ultra Deep Field in GOODS-South (perhaps preceded by some Medium depth pointings).

JADES-NIRSpec GOODS-North likely to be done in 2023

Synergies with other JWST instruments

NIRCam:
- imaging (and slitless spectroscopy), target selection
- morphological parameters
- correction for slit losses
- calibration of physical parameters inferred from broad band photometry (e.g. photo-z calibration)

MIRI:
- mid-IR diagnostics of star formation and AGN
- complementary tracers of dust

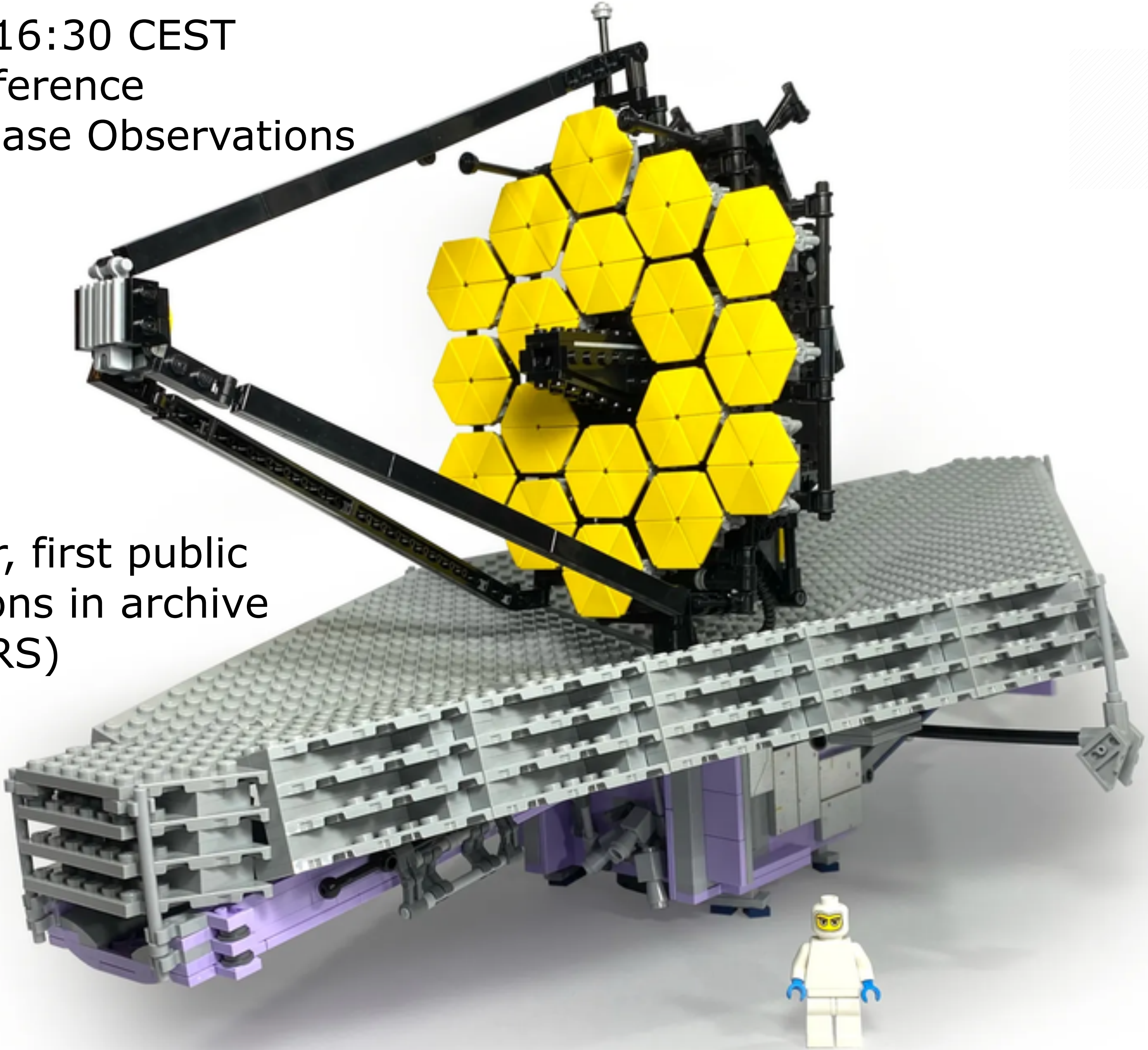
NIRISS: complementary survey
- larger statistics for line emitters
- diagnostics limited to lower redshifts (blue part of the spectrum)

CONCLUSIONS - what will JADES measure

- Get REAL redshifts for luminosity functions
- Stellar mass
- Galaxy age and star formation history
- Star Formation Rate
- Stellar& gas metallicity (including the search for Pop III) and individual element abundances)
- Attenuation by dust
- Presence and power of AGN
- Black hole masses
- Presence of shocks
- Outflows
- Dynamics
- ionising photon production and escape fraction

… and look for surprises!

12 July - 16:30 CEST
Press conference
Early Release Observations



Soon after, first public observations in archive (e.g. CEERS)